Large Scale Structure II

Shirley Ho
Lawrence Berkeley National Laboratory/
UC Berkeley/
Carnegie Mellon University

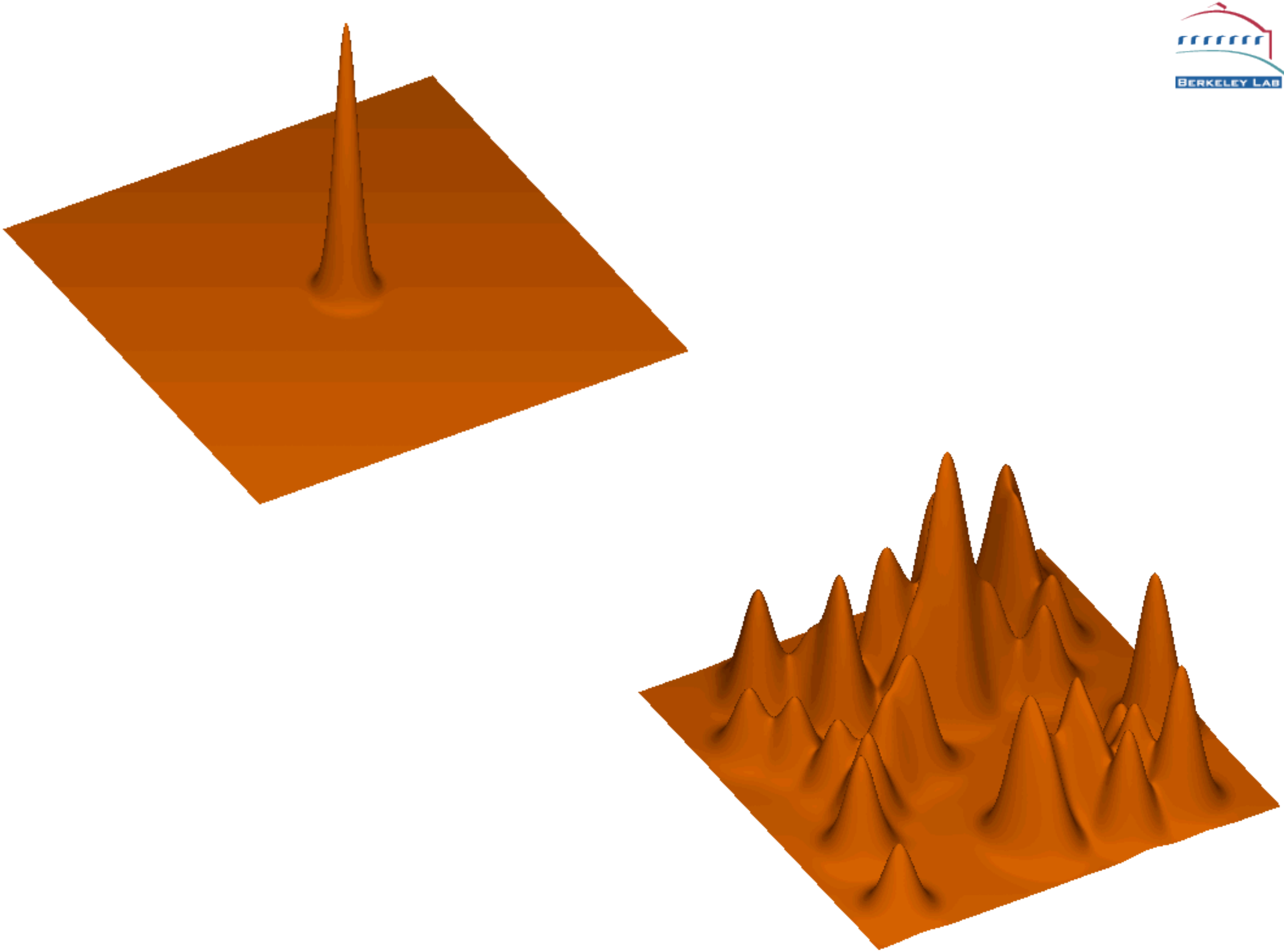
RESCEU/ DENET summer school, Kyushu, Japan

3 Lectures

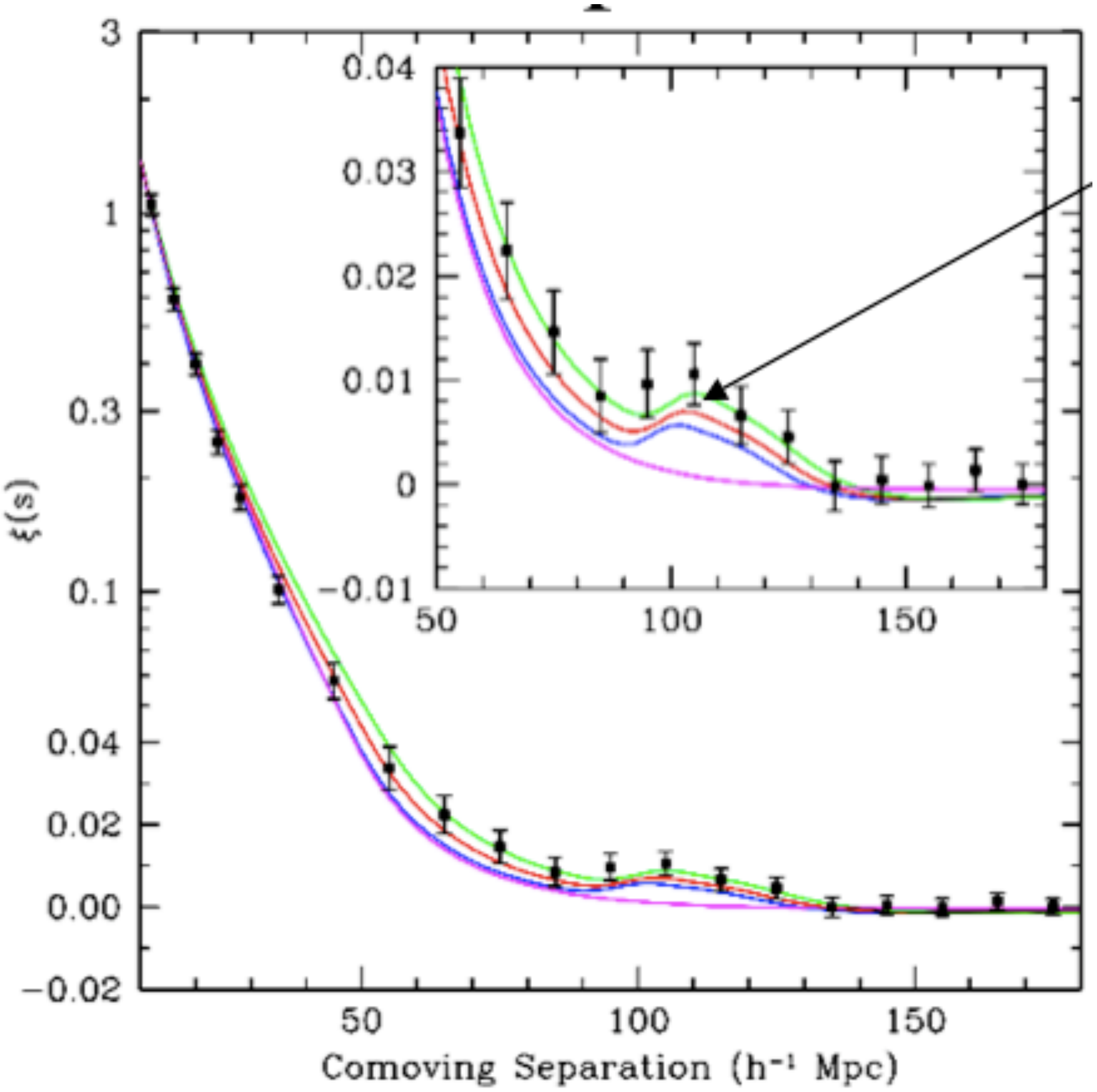
- Dark Energy, Baryon Acoustic Oscillations and more
- Observational Cosmology in Action
- A new large scale structure tracer:
  - Lyman alpha forest

Quick reminder of last lecture

Large scale structure exists in our real universe.
There are voids, clusters, web-like features.

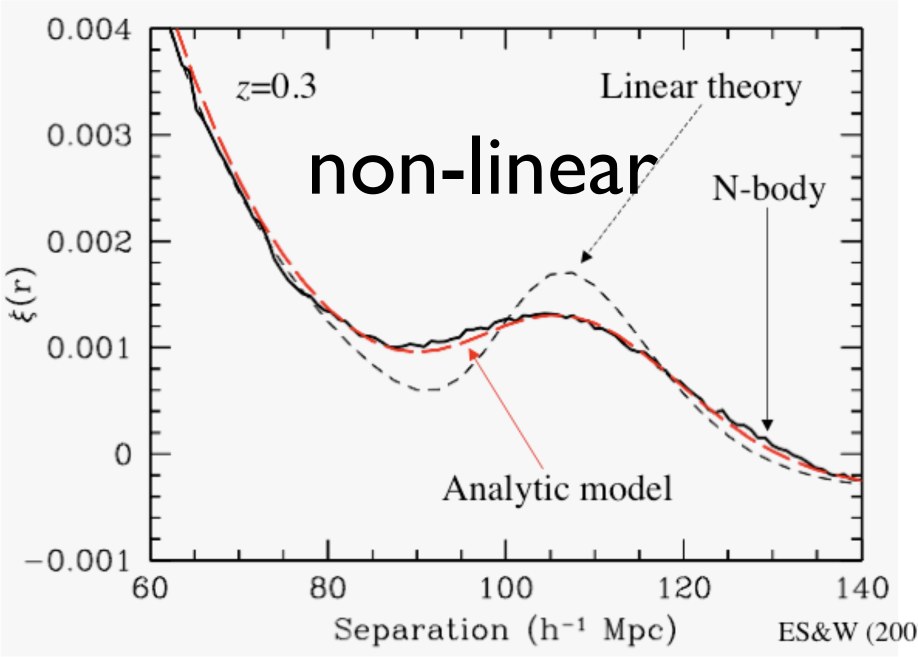


First Detection of this standard ruler: Baryon Acoustic Oscillations



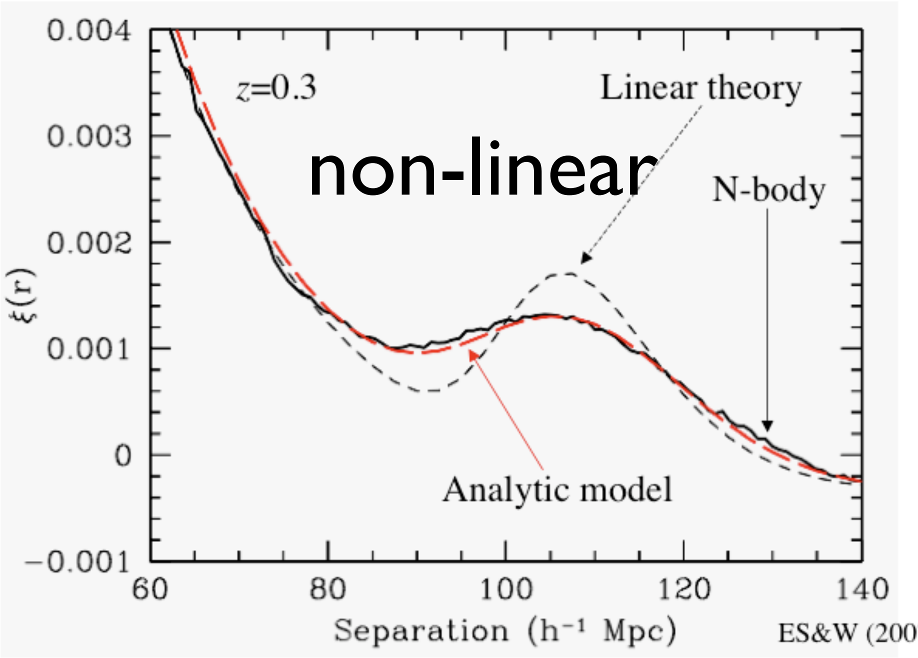
Eisenstein et al. 2005

We measure non-linear galaxy power-spectrum in redshift space instead of linear dark matter power-spectrum in real space



ES&W (2007)

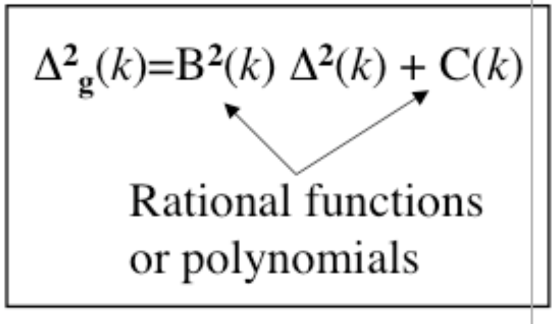
We measure non-linear galaxy power-spectrum in redshift space instead of linear dark matter power-spectrum in real space



non-linear

ES&W (2007)

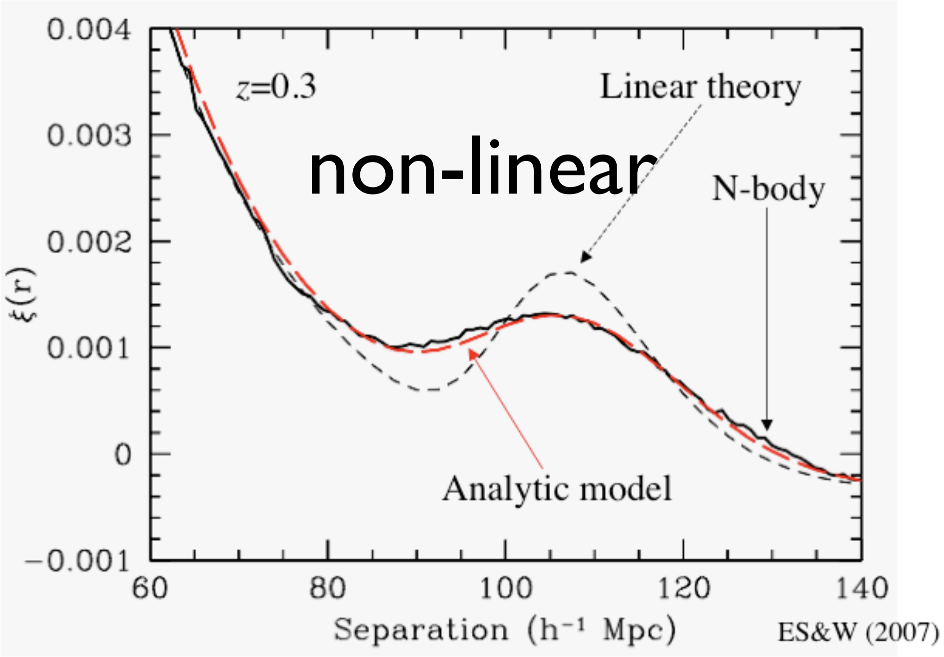
Galaxy power-spectrum



$\Delta^2_g(k)=B^2(k)\ \Delta^2(k) + C(k)$

Rational functions
or polynomials

We measure non-linear galaxy power-spectrum in redshift space instead of linear dark matter power-spectrum in real space



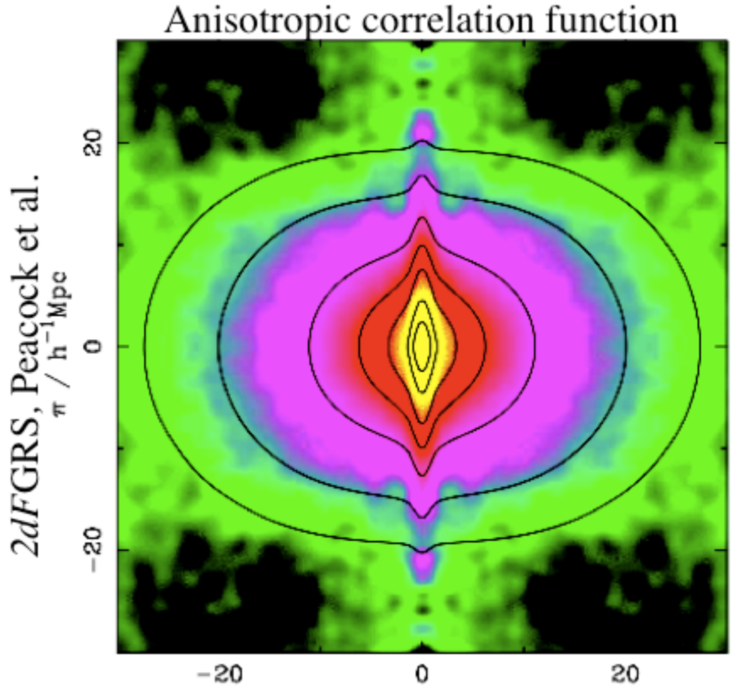
non-linear

ES&W (2007)

Galaxy power-spectrum

$$\Delta^2_g(k) = B^2(k)\, \Delta^2(k) + C(k)$$

Rational functions
or polynomials

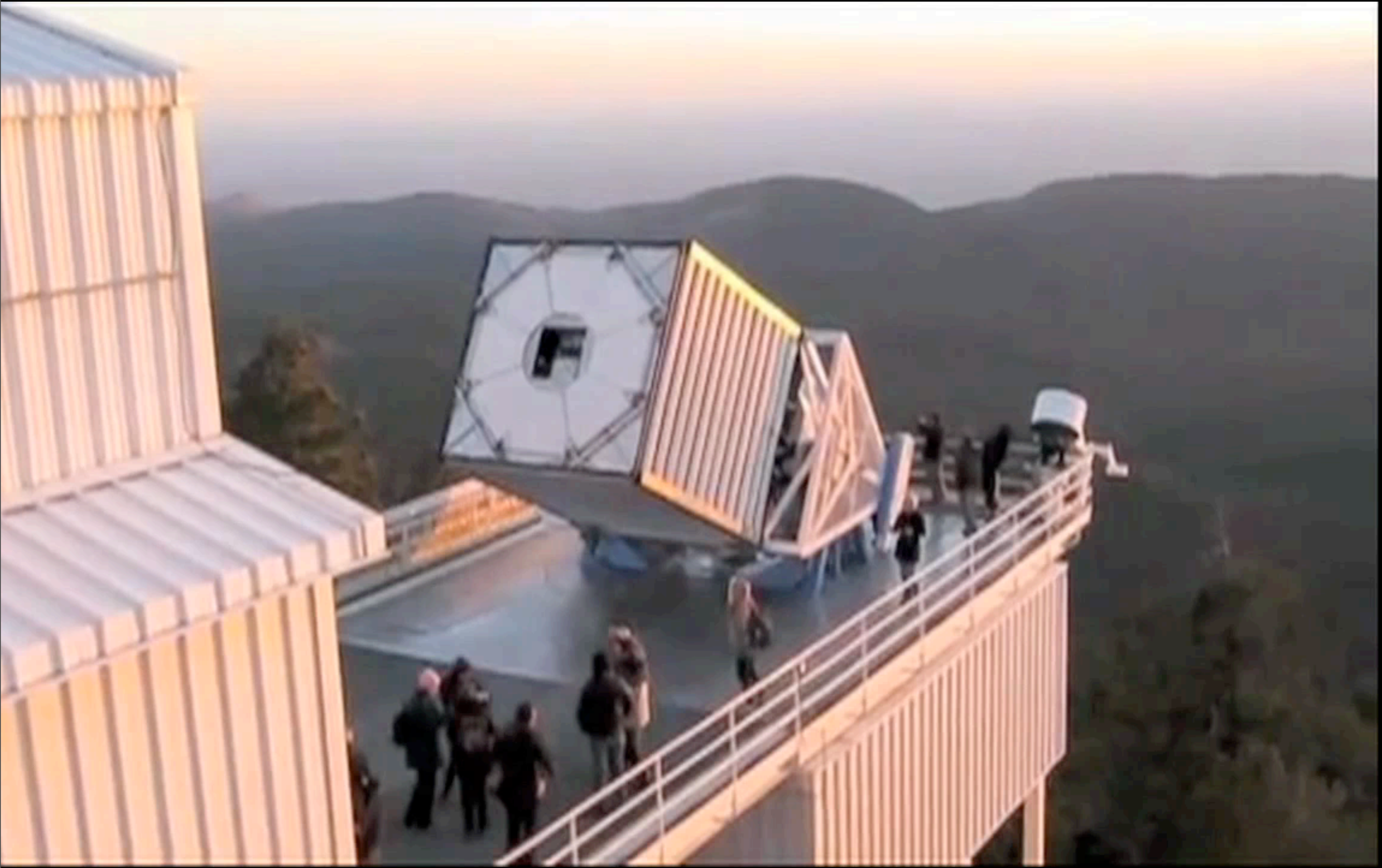


2dFGRS, Peacock et al.

Redshift space

3 Lectures

- Dark Energy, Baryon Acoustic Oscillations and more
- Observational Cosmology in Action
- A new large scale structure tracer:
  - Lyman alpha forest

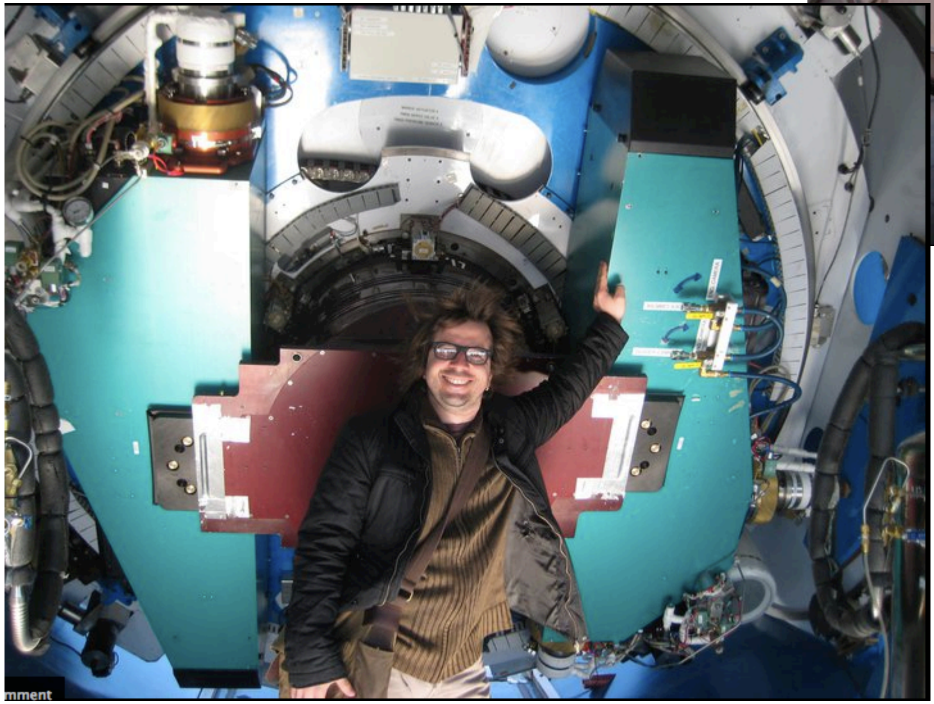


And the next day, facebook changes...

All over the world, we have many facebook profile changes....

Jessica Kirkpatrick

Anze Slosar



Me!

Outline

- Motivations
- How can we use large scale structure to learn about the Universe?
  - Early Universe (with large scale clustering)
  - Dark Energy (with Baryon Acoustic Oscillations)
- Worked Example of Angular clustering
  - With Luminous Red galaxies

Outline

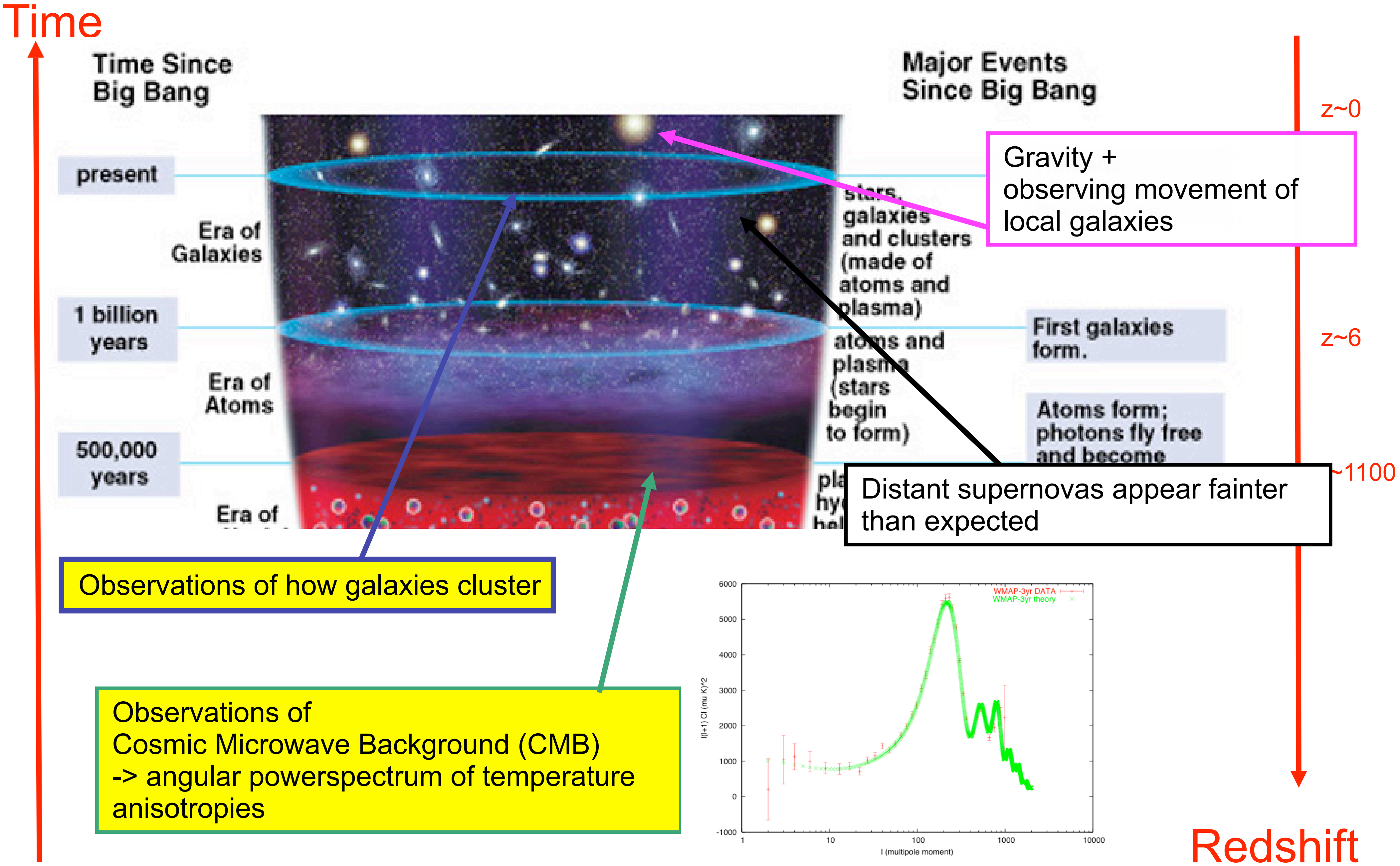
- **Motivations**
- **How can we use large scale structure to learn about the Universe?**
  - **— Early Universe (with large scale clustering)**
  - **— Dark Energy (with Baryon Acoustic Oscillations)**

There is more !! such as testing modified gravity using a combination of clustering + weak lensing (Reyes, Mandelbaumn et al. 2010) [Please refer to Roy's next lecture]

Outline

- Motivations
- How can we use large scale structure to learn about the Universe?
  - Early Universe (with large scale clustering)
  - Dark Energy (with Baryon Acoustic Oscillations)
- Worked Example of Angular clustering
  - With Luminous Red galaxies

Motivations



Gravity + observing movement of local galaxies

Distant supernovas appear fainter than expected

Observations of how galaxies cluster

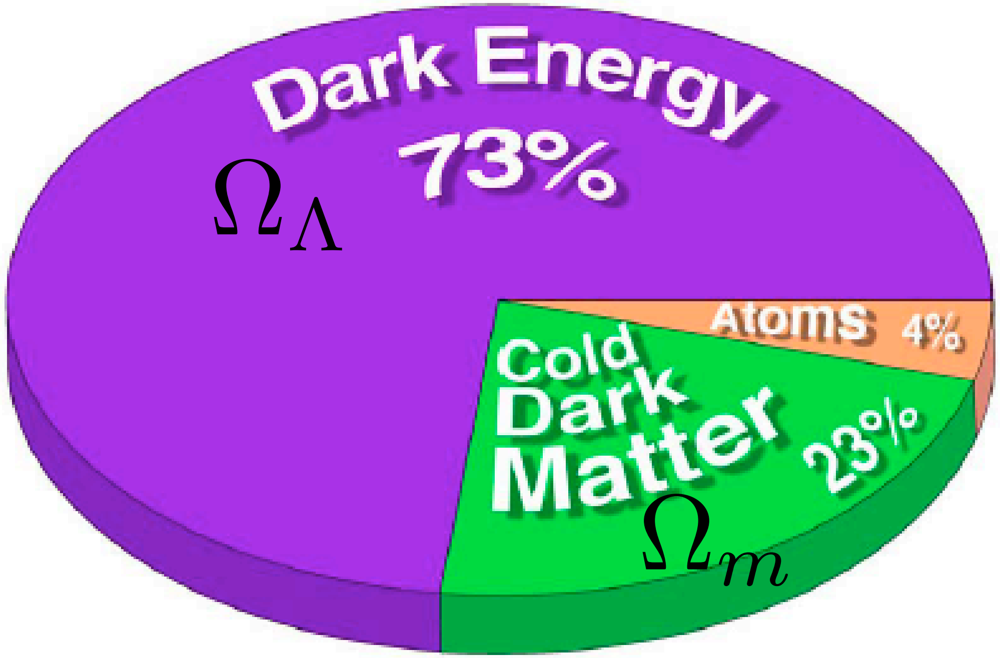
Observations of Cosmic Microwave Background (CMB) -> angular powerspectrum of temperature anisotropies

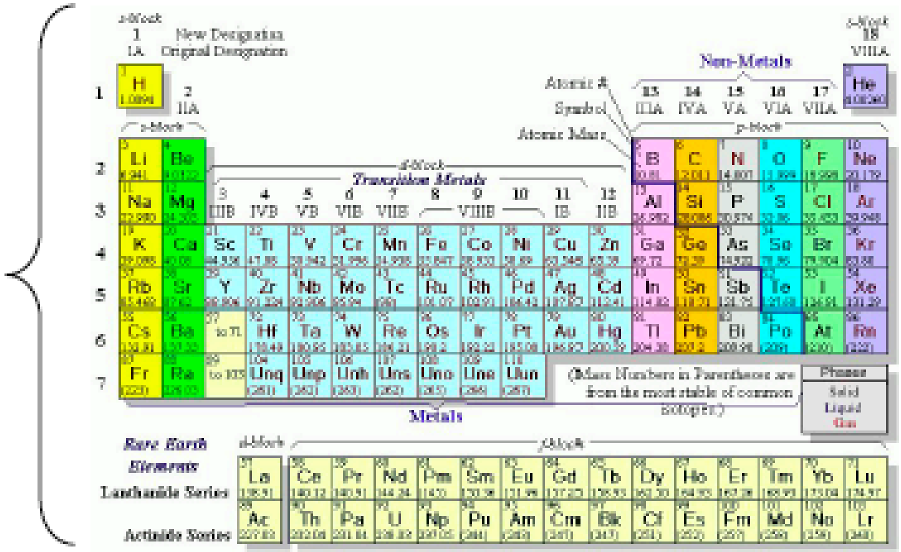
Motivations

Time

z~0

Gravity +
observing movement of

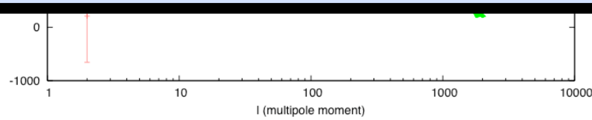




100

What happened at the Very Beginning of the Universe?

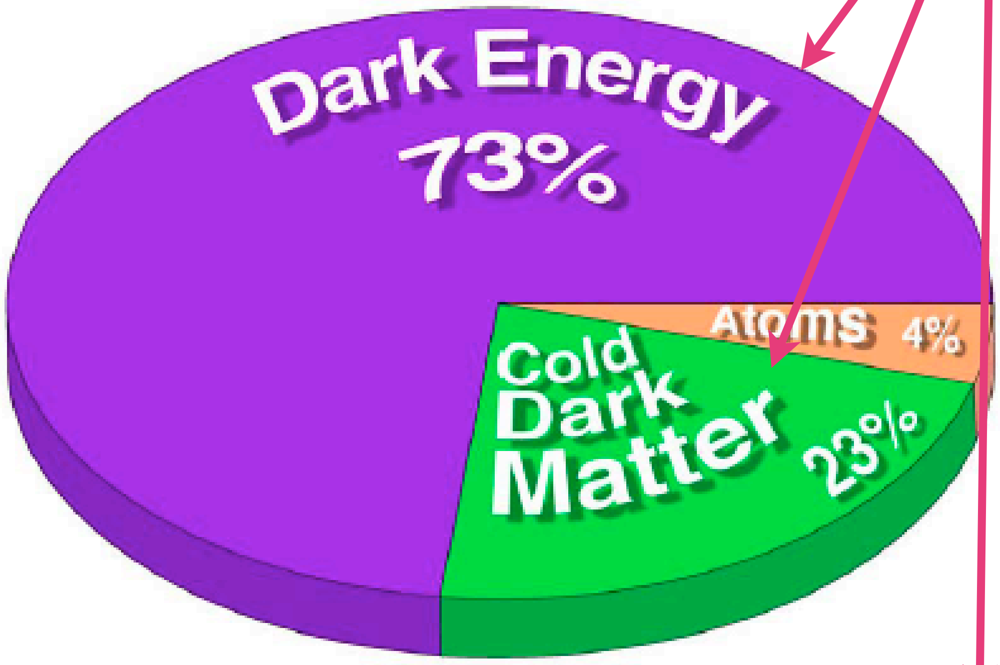
temperature anisotropies

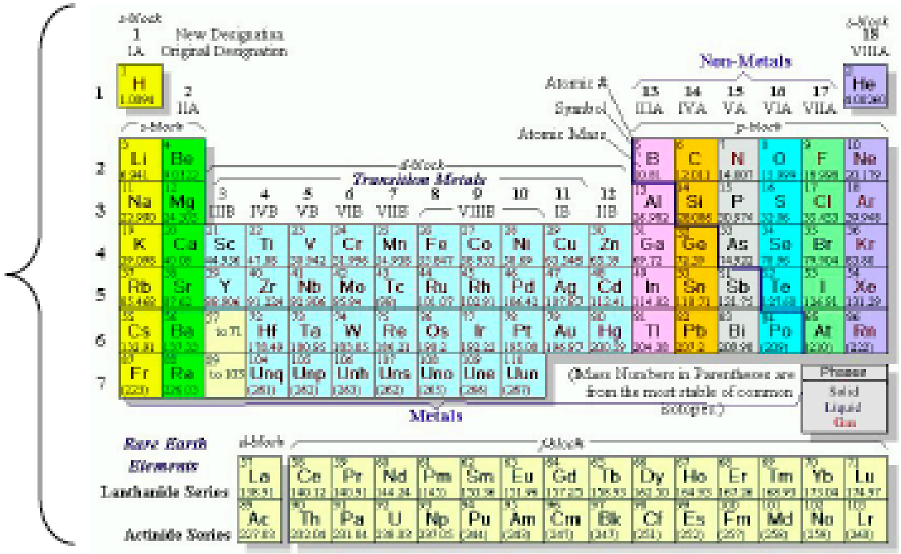


Redshift

Motivations

??





What happened at the Very Beginning of the Universe?

Outline

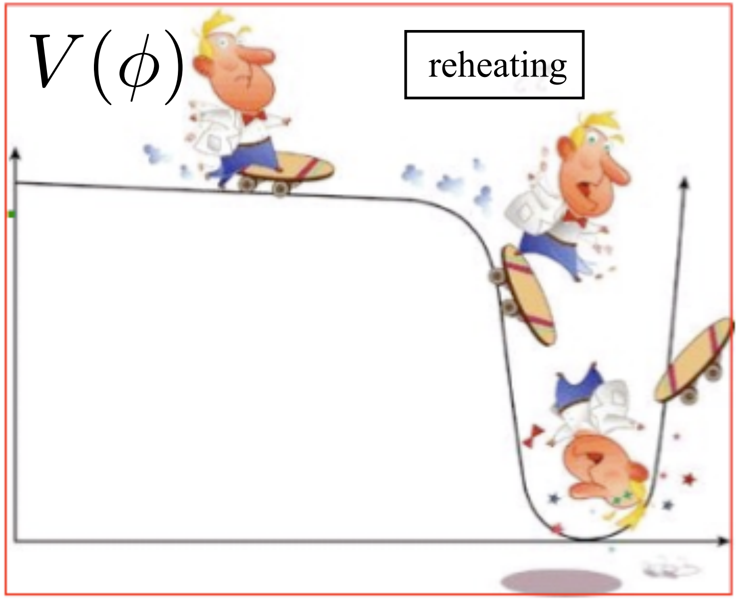
- Motivations
- How can we use large scale structure to learn about the Universe?
  - Early Universe (with large scale clustering)
  - Dark Energy (with Baryon Acoustic Oscillations)
- Worked Example of Angular clustering
  - With Luminous Red galaxies

Non-Gaussianities in early Universe

parameterize how much non-linear corrections are there to the potential

$$\Phi = \phi + f_{NL}\phi^2$$

Primordial potential (assumed to be gaussian random field)



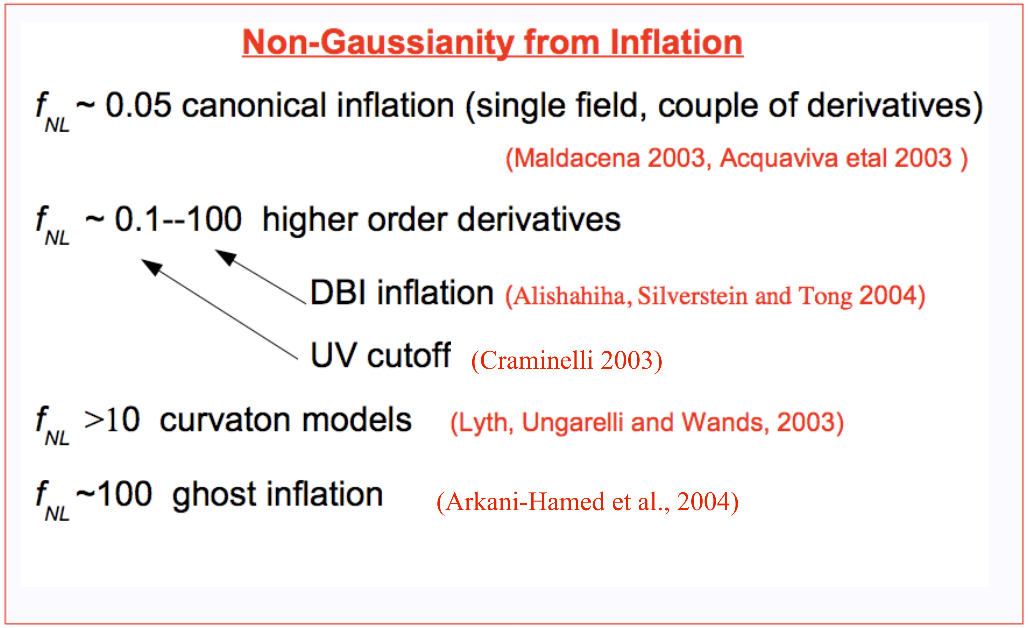
← Inflation →

Non-Gaussianities in early Universe

parameterize how much non-linear corrections are there to the potential

$$\Phi = \phi + f_{NL}\phi^2$$

Primordial potential (assumed to be gaussian random field)



Non-Gaussianity from Inflation

f_{NL} ~ 0.05 canonical inflation (single field, couple of derivatives) (Maldacena 2003, Acquaviva etal 2003)

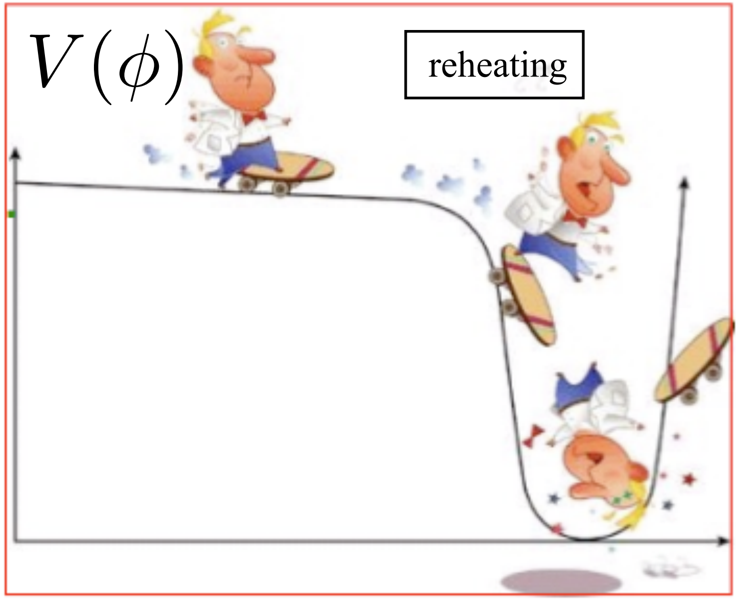
f_{NL} ~ 0.1--100 higher order derivatives

DBI inflation (Alishahiha, Silverstein and Tong 2004)

UV cutoff (Craminelli 2003)

f_{NL} >10 curvaton models (Lyth, Ungarelli and Wands, 2003)

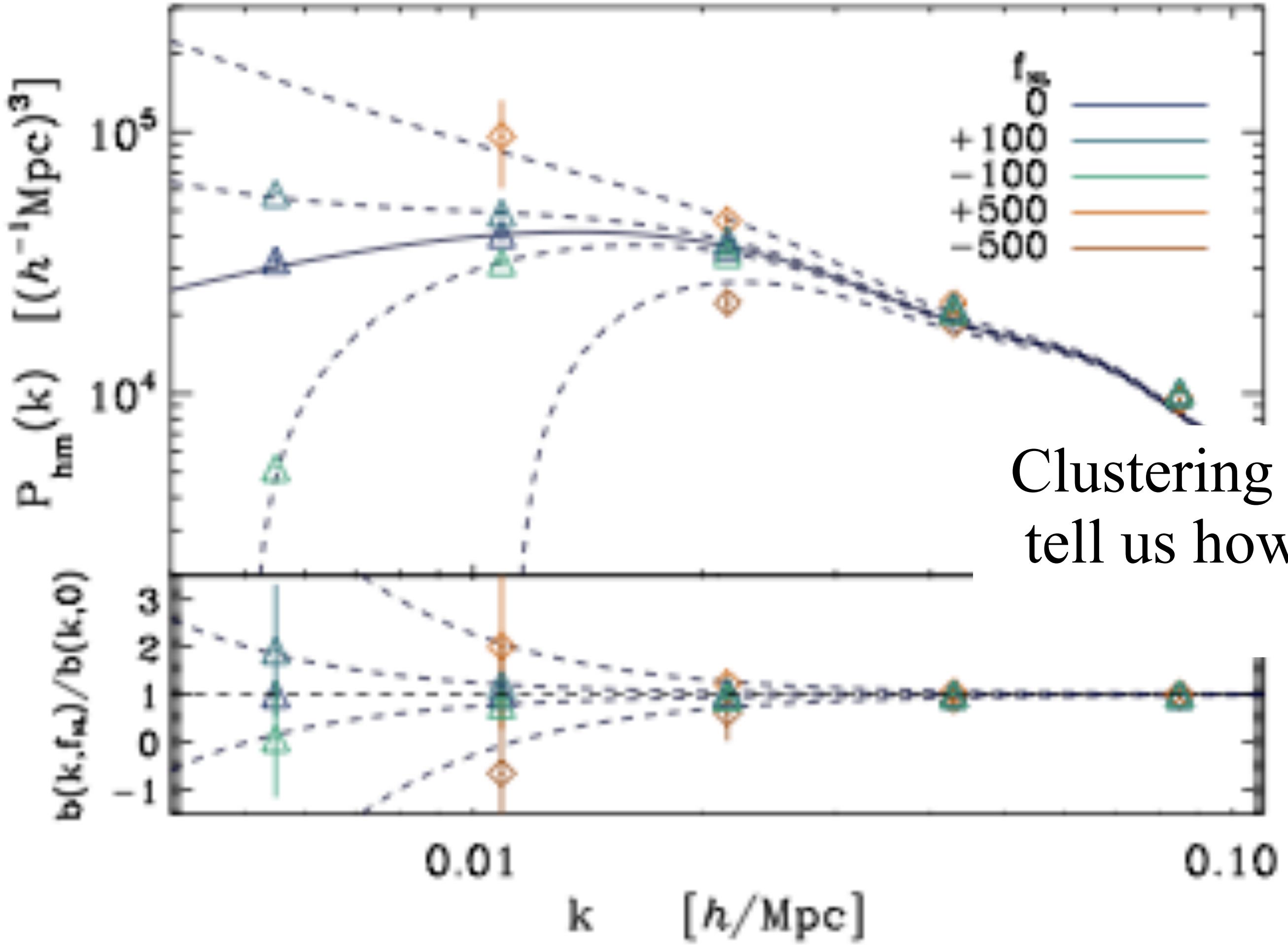
f_{NL} ~100 ghost inflation (Arkani-Hamed et al., 2004)



← Inflation →

Using Large scale structure to learn about the beginning of the Universe

Power spectrum of dark matter halos

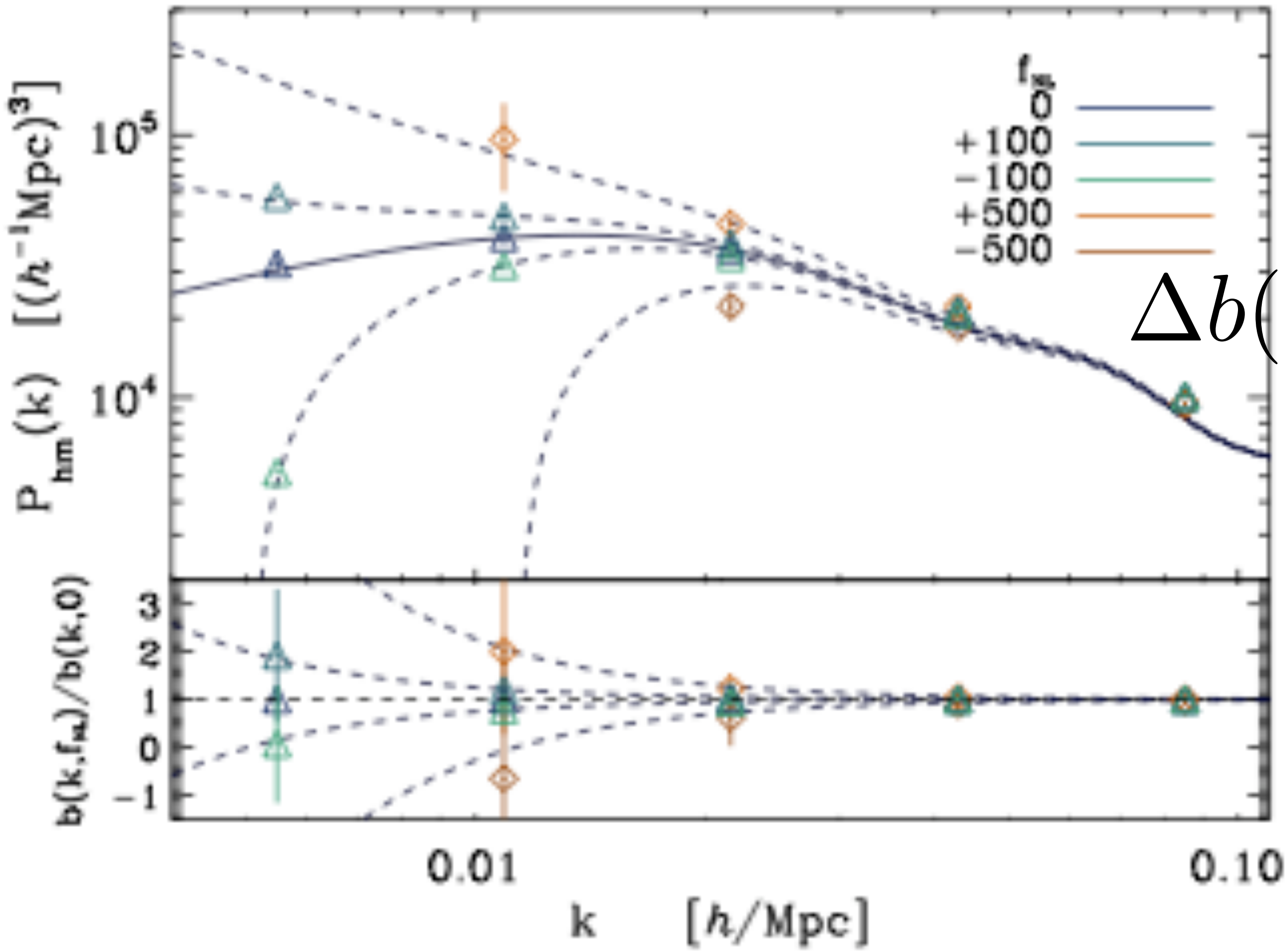


Clustering of dark matter halos can tell us how non-gaussian the early Universe is

Dalal, Dore, Huterer, Shirokov 2008

Using Large scale structure to learn about the beginning of the Universe

Power spectrum of dark matter halos



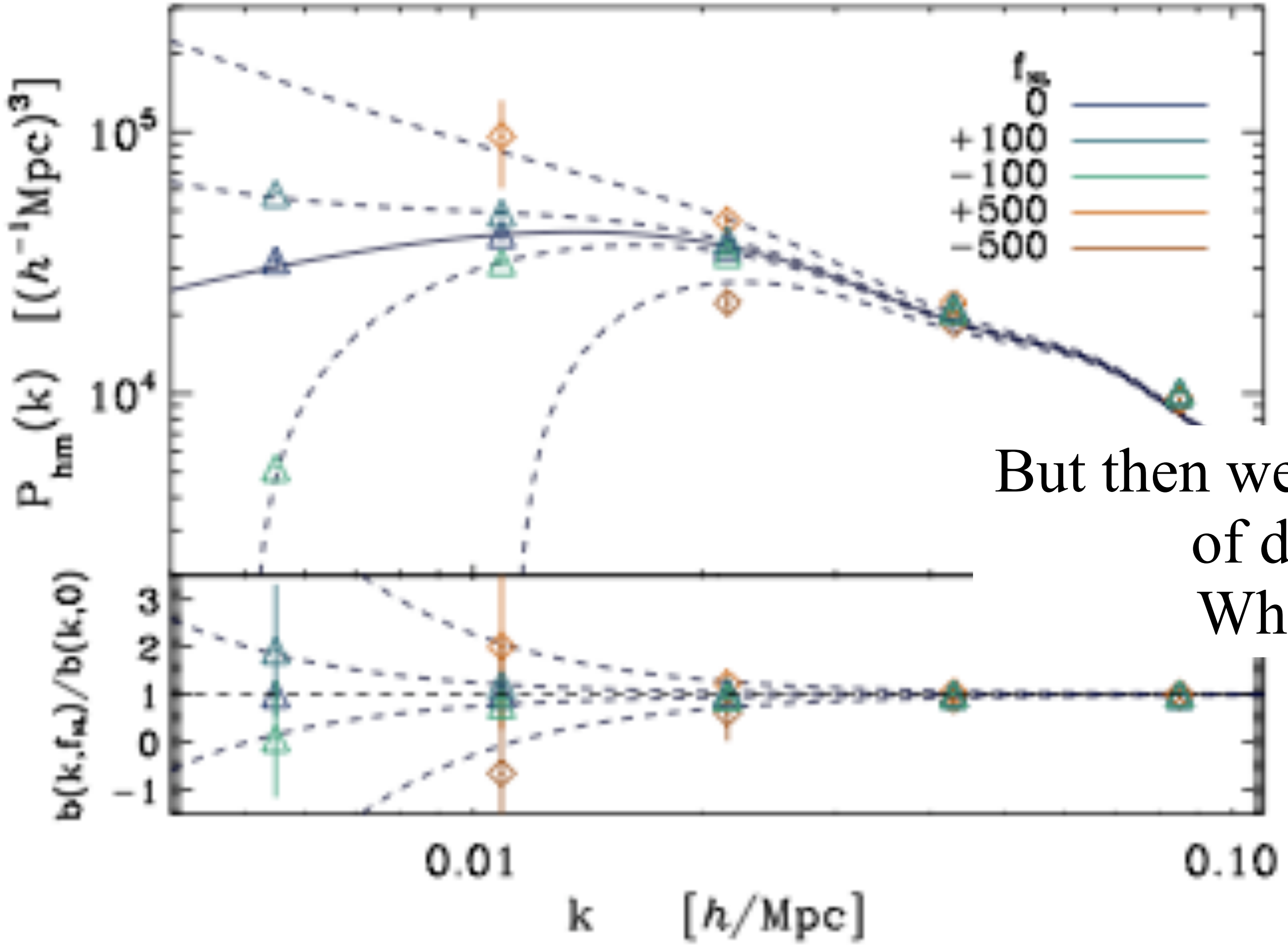
$$\delta_{tracer} = b\delta_m$$

$$\Delta b(k) \propto \frac{(b-1)f_{NL}}{k^2}$$

Dalal, Dore, Huterer, Shirokov 2008

Using Large scale structure to learn about the beginning of the Universe

Power spectrum of dark matter halos

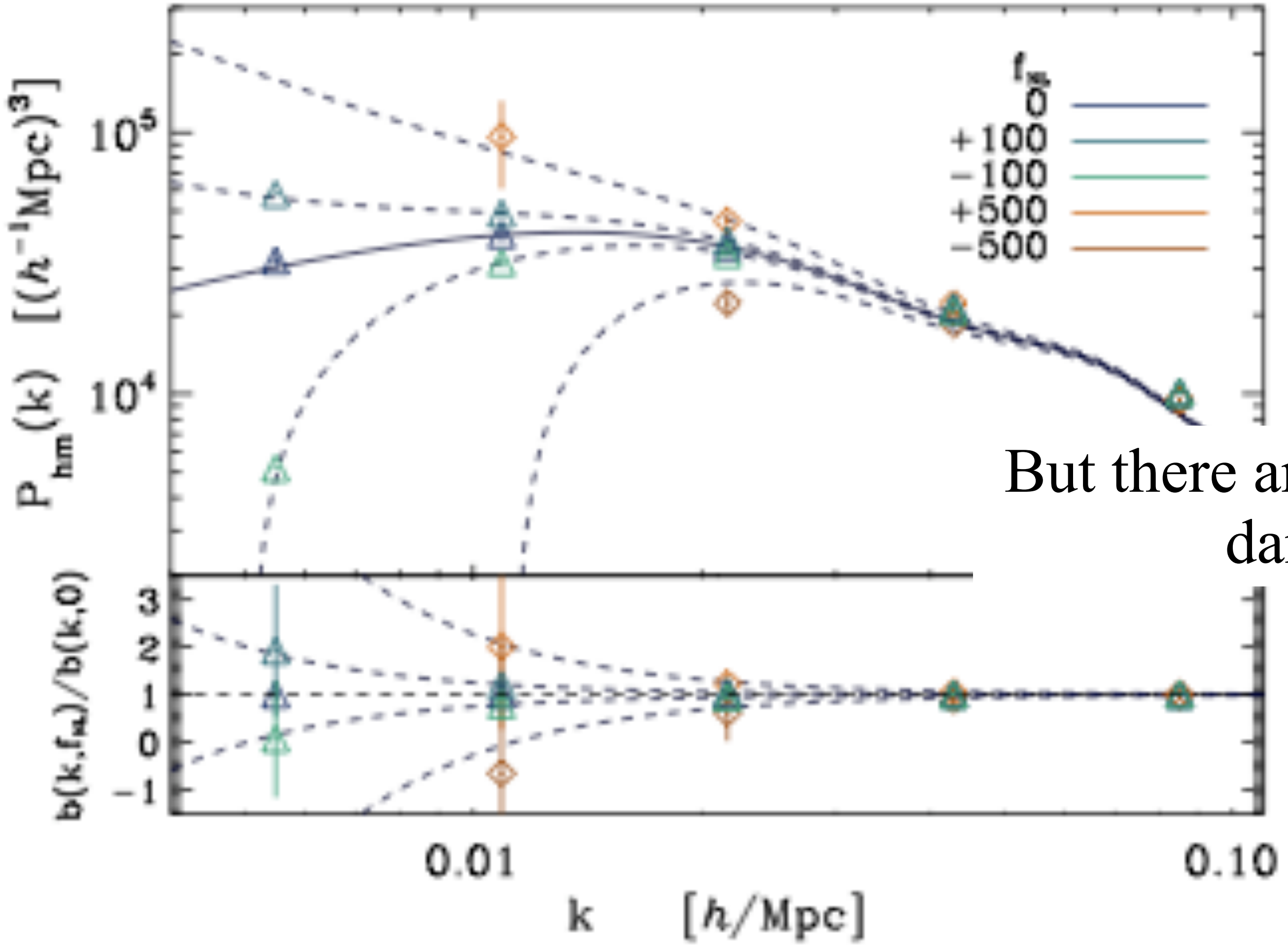


But then we don’t find large number of dark matter halos!
What should we do?

Dalal, Dore, Huterer, Shirokov 2008

Using Large scale structure to learn about the beginning of the Universe

Power spectrum of dark matter halos



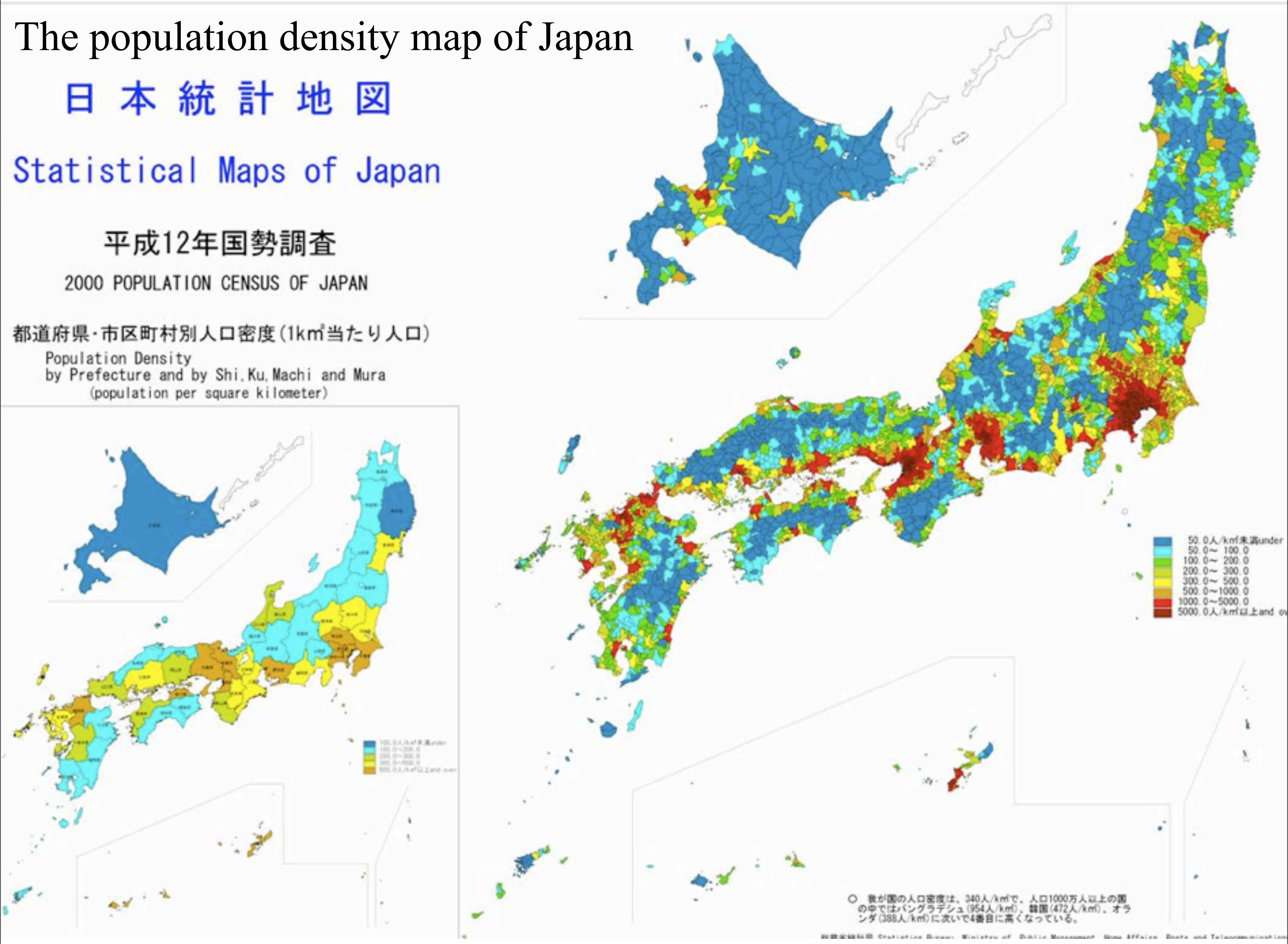
But there are many things that trace dark matter halos!

Dalal, Dore, Huterer, Shirokov 2008

What is a tracer of LSS?

Let’s take a look at the following example.

The population density map of Japan



日本統計地図

Statistical Maps of Japan

平成12年国勢調査

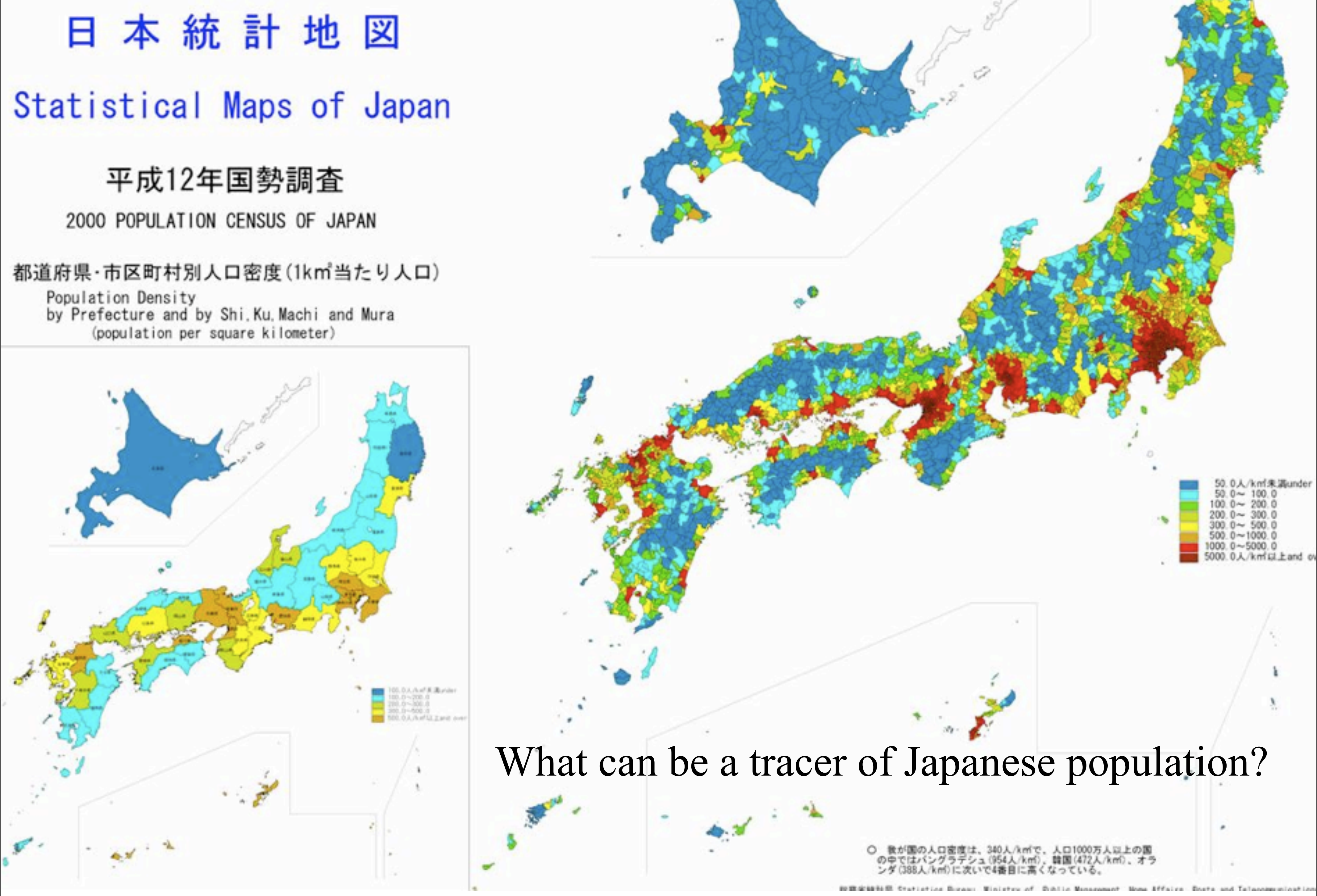
2000 POPULATION CENSUS OF JAPAN

都道府県・市区町村別人口密度（1km²当たり人口）

Population Density
by Prefecture and by Shi, Ku, Machi and Mura
(population per square kilometer)

○ 我が国の人口密度は、340人/km²で、人口1000万人以上の国の中ではバングラデシュ(954人/km²)、韓国(472人/km²)、オランダ(388人/km²)に次いで4番目に高くなっている。

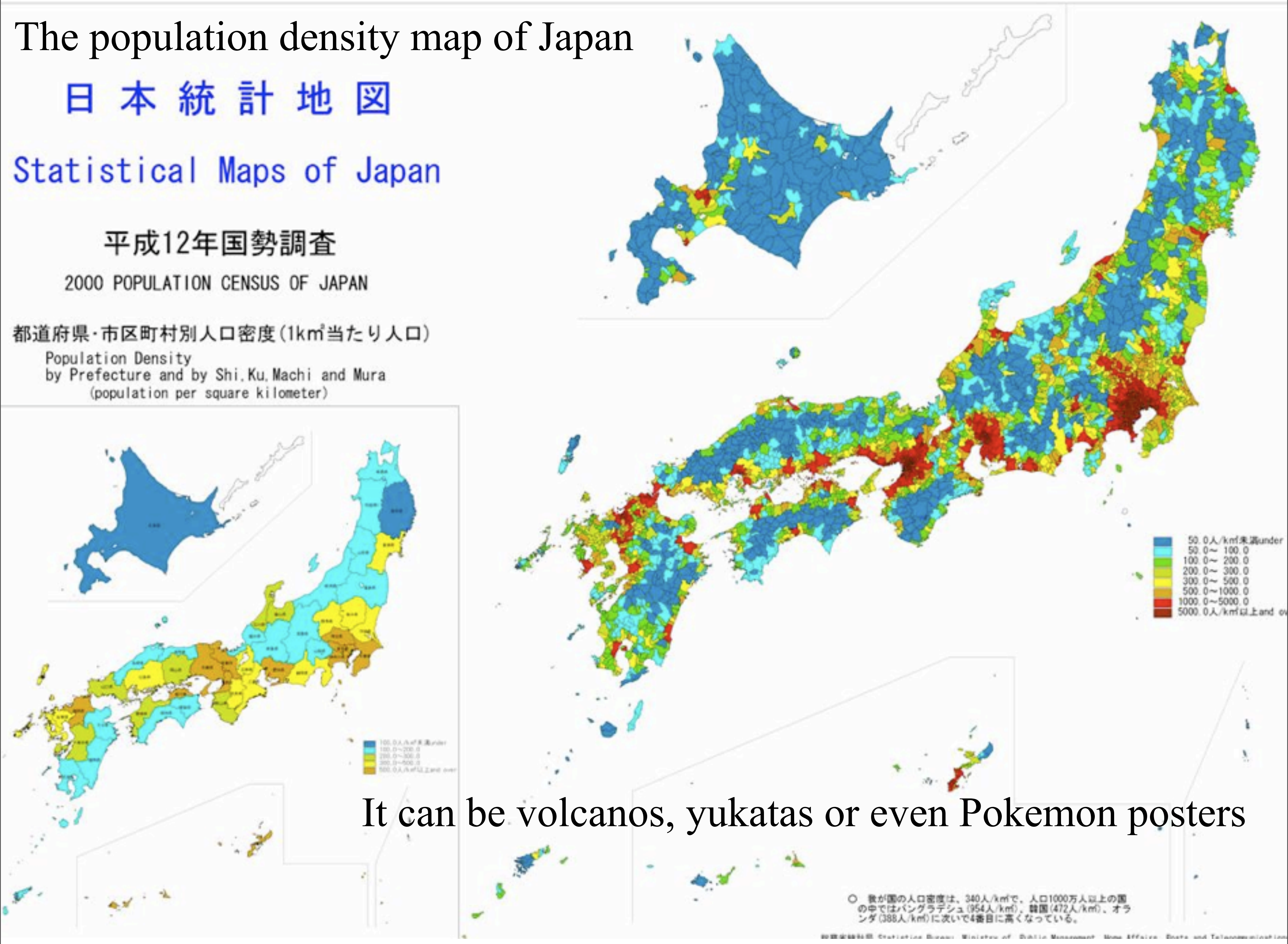
The population density map of Japan



○ 我が国の人口密度は、340人/km²で、人口1000万人以上の国の中ではバングラデシュ(954人/km²)、韓国(472人/km²)、オランダ(388人/km²)に次いで4番目に高くなっている。

What can be a tracer of Japanese population?

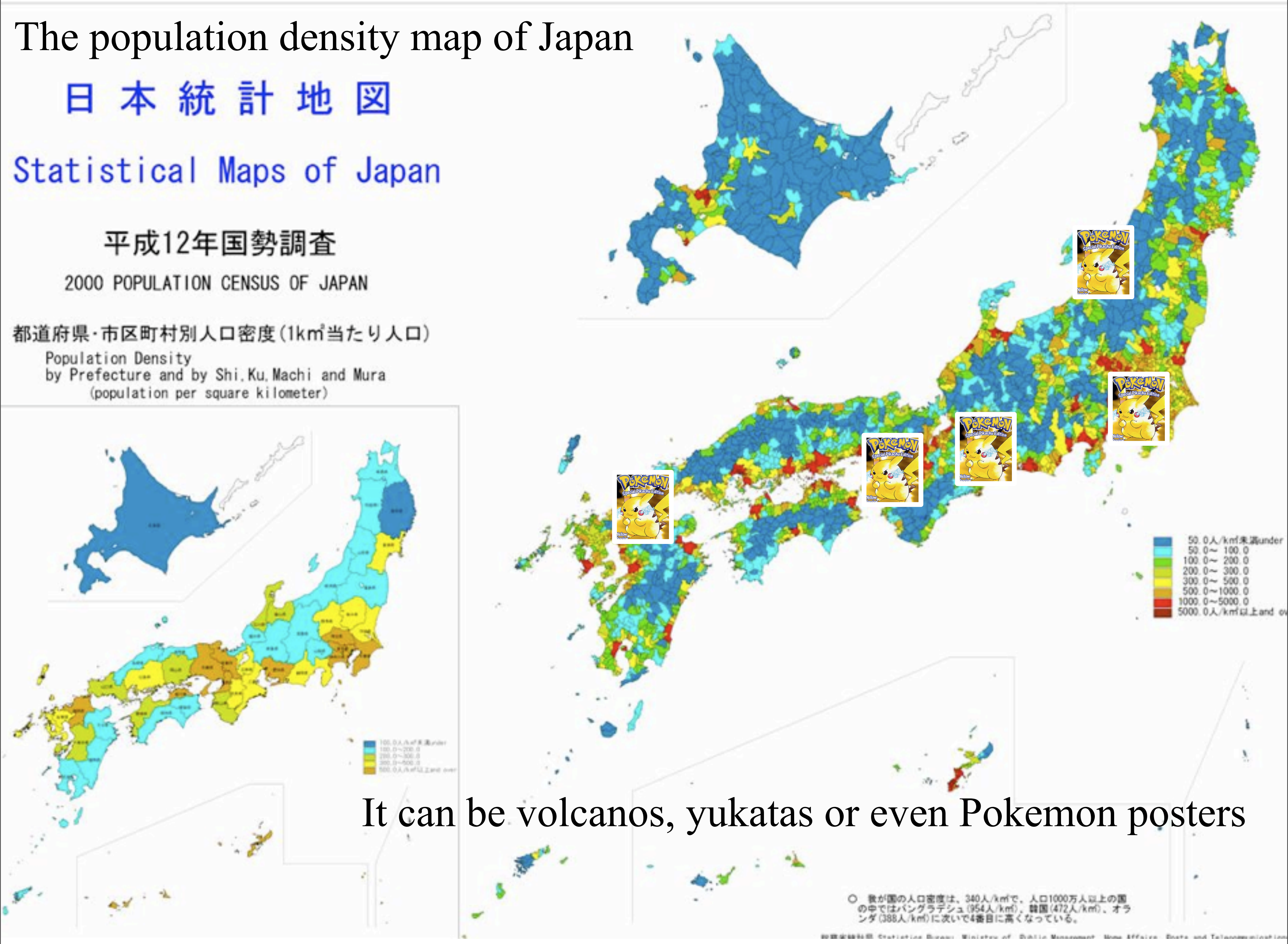
The population density map of Japan



○ 我が国の人口密度は、340人/km²で、人口1000万人以上の国の中ではバングラデシュ(954人/km²)、韓国(472人/km²)、オランダ(388人/km²)に次いで4番目に高くなっている。

It can be volcanos, yukatas or even Pokemon posters

The population density map of Japan

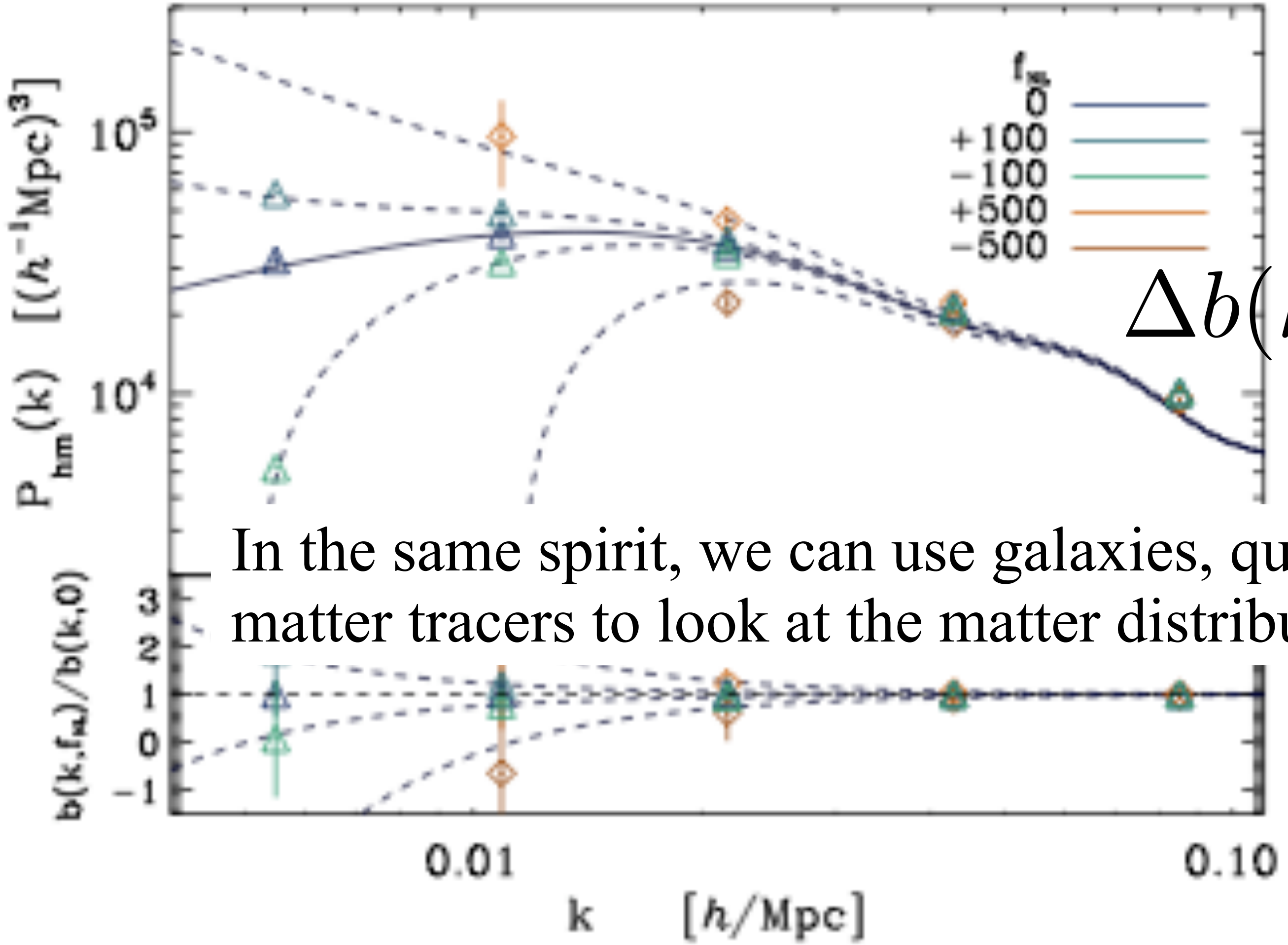


○ 我が国の人口密度は、340人/km²で、人口1000万人以上の国の中ではバングラデシュ（954人/km²）、韓国（472人/km²）、オランダ（388人/km²）に次いで4番目に高くなっている。

It can be volcanos, yukatas or even Pokemon posters

Using Large scale structure to learn about the beginning of the Universe

Power spectrum of dark matter halos



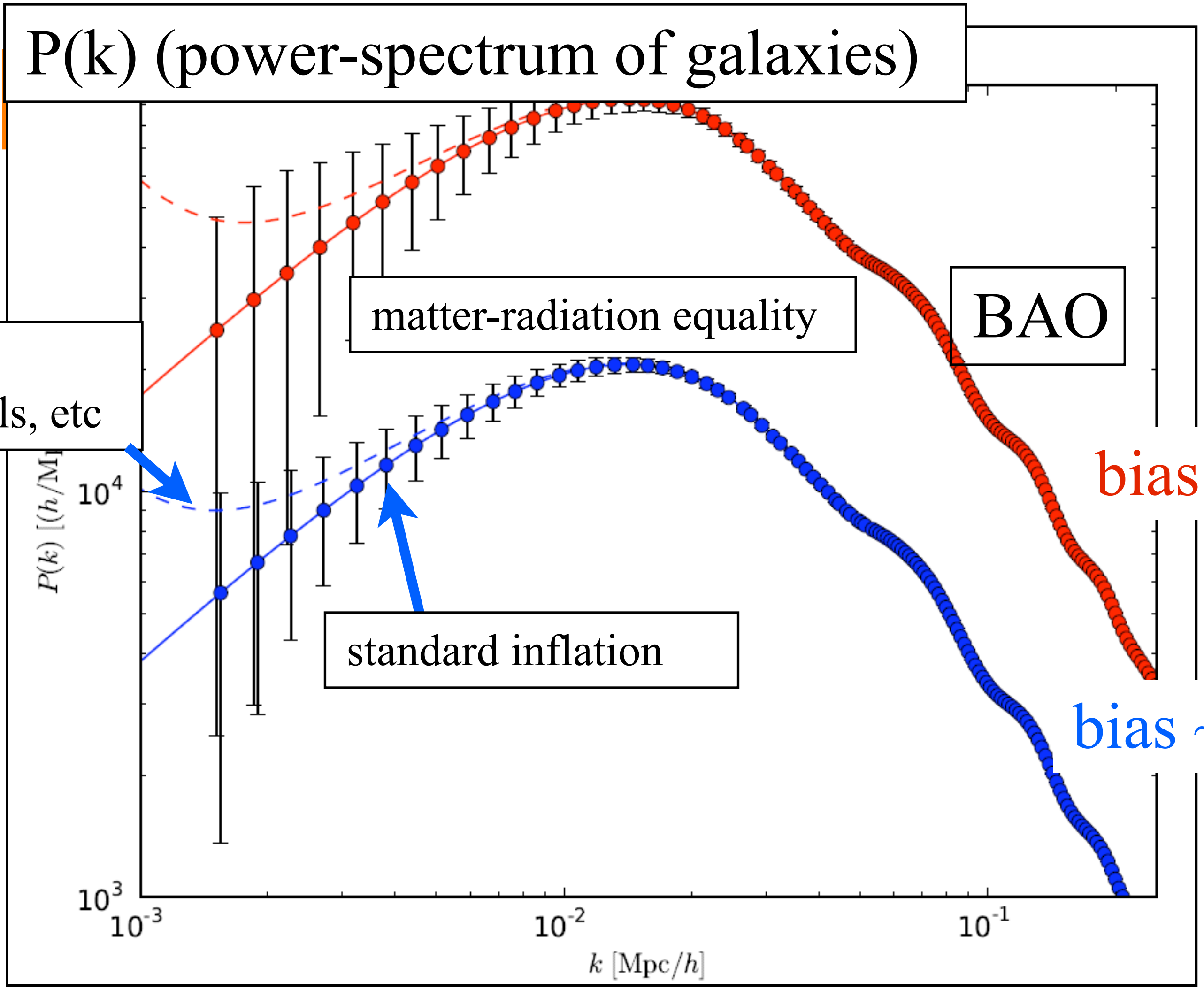
$$\delta_{tracer} = b\delta_m$$

$$\Delta b(k) \propto \frac{(b-1)f_{NL}}{k^2}$$

In the same spirit, we can use galaxies, quasars, or any other dark matter tracers to look at the matter distribution of the Universe.

Dalal, Dore, Huterer, Shirokov 2008

The 3D power-spectrum of galaxies



P(k) (power-spectrum of galaxies)

matter-radiation equality

BAO

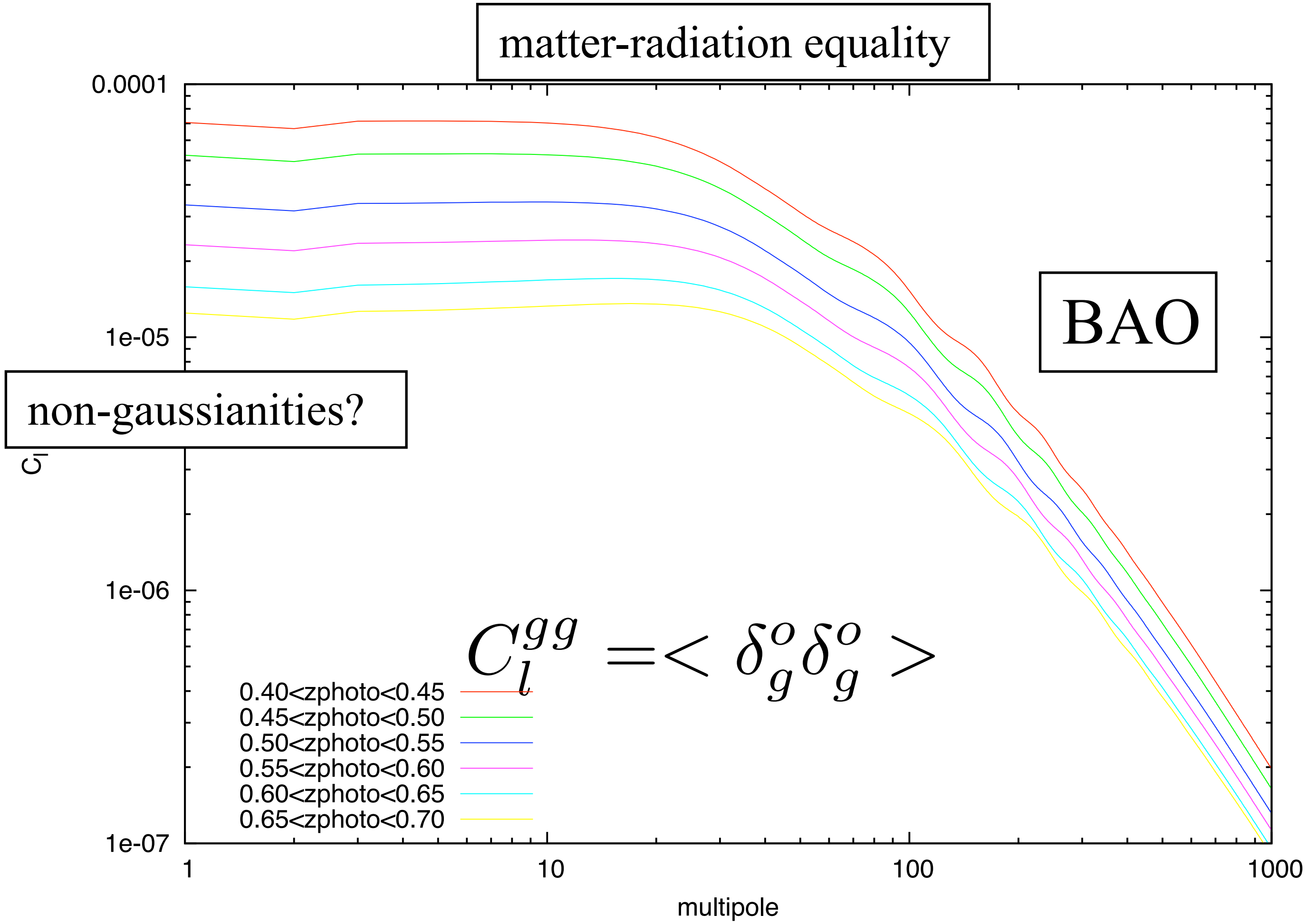
ghost inflation,
curvaton models, etc

standard inflation

bias ~ 2.5 galaxies

bias ~ 1.5 galaxies

Angular Power-spectrum



matter-radiation equality

BAO

non-gaussianities?

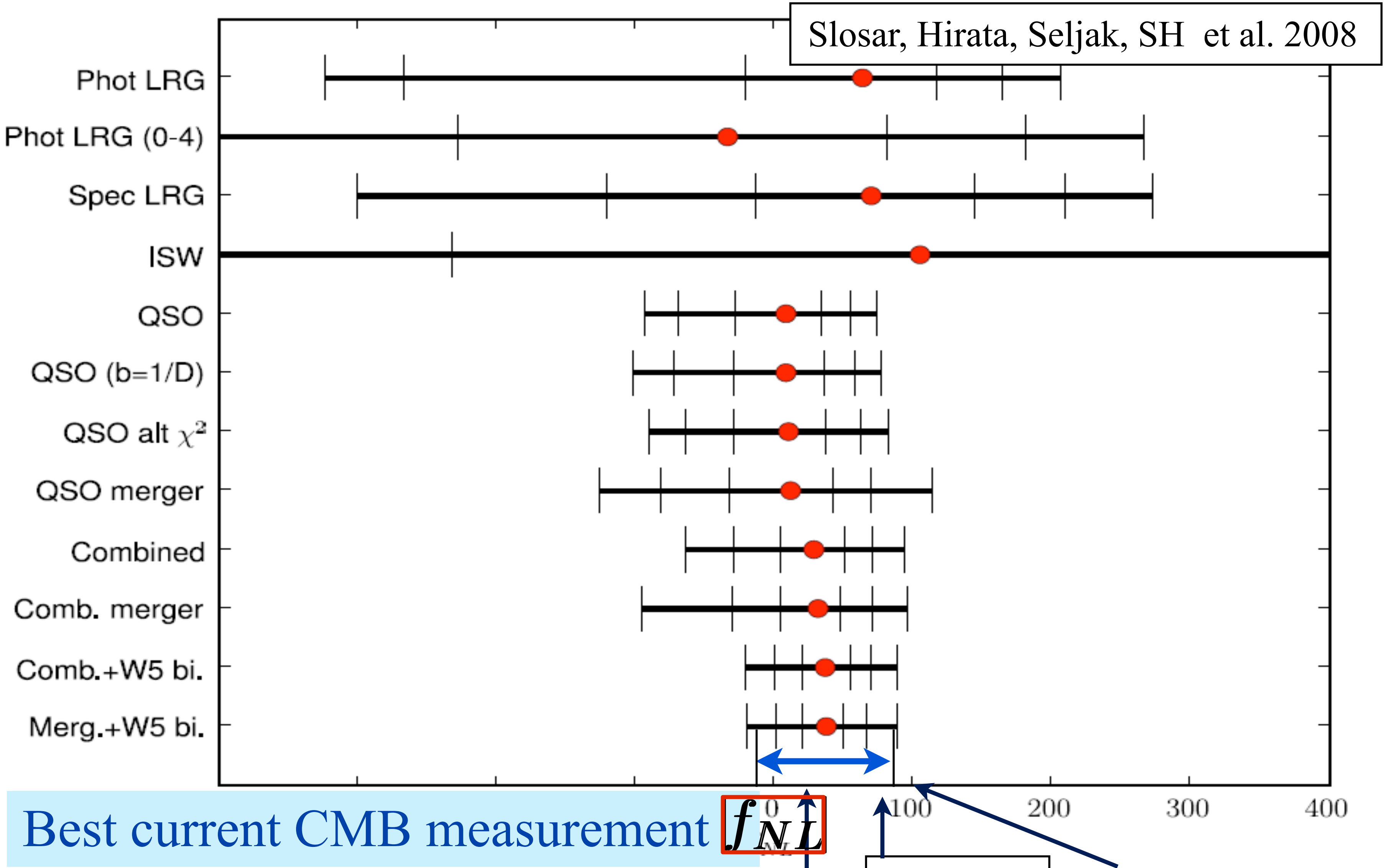
$$C_l^{gg} = < \delta_g^o \delta_g^o >$$

Slosar, Hirata, Seljak, SH, Padmanabhan 2008

Xia, Baccigalupi, Mattarese, Verde, Viel 2011

Xia et al. 2010

Using Large scale structure to learn about the beginning of the Universe



Slosar, Hirata, Seljak, SH et al. 2008

Best current CMB measurement f_{NL}

canonical inflation

curvaton models, DBI inflation

ghost inflation

Outline

- Motivations
- How can we use large scale structure to learn about the Universe?
  - Early Universe (with large scale clustering)
  - Dark Energy (with Baryon Acoustic Oscillations)
- Worked Example of Angular clustering
  - With Luminous Red galaxies

What are the Baryon Acoustic Oscillations?

How do we detect Baryon Acoustic Oscillations?
We calculate the correlation function or its Fourier Transform: power-spectrum

What are the Baryon Acoustic Oscillations?

How do we detect Baryon Acoustic Oscillations?
We calculate the correlation function or its Fourier Transform: power-spectrum

What is the correlation function ?

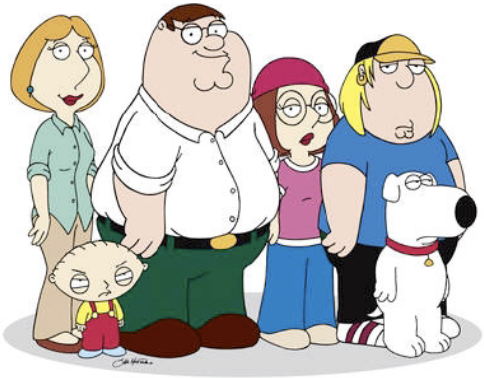
$$\xi_f(r) =< \delta_f(\hat{x})\delta_f(\hat{x}+\hat{r}) >$$

What are the Baryon Acoustic Oscillations?

How do we detect Baryon Acoustic Oscillations?
We calculate the correlation function or its Fourier Transform: power-spectrum

What is the correlation function ?

$$\xi_f(r) =< \delta_f(\hat{x})\delta_f(\hat{x}+\hat{r}) >$$



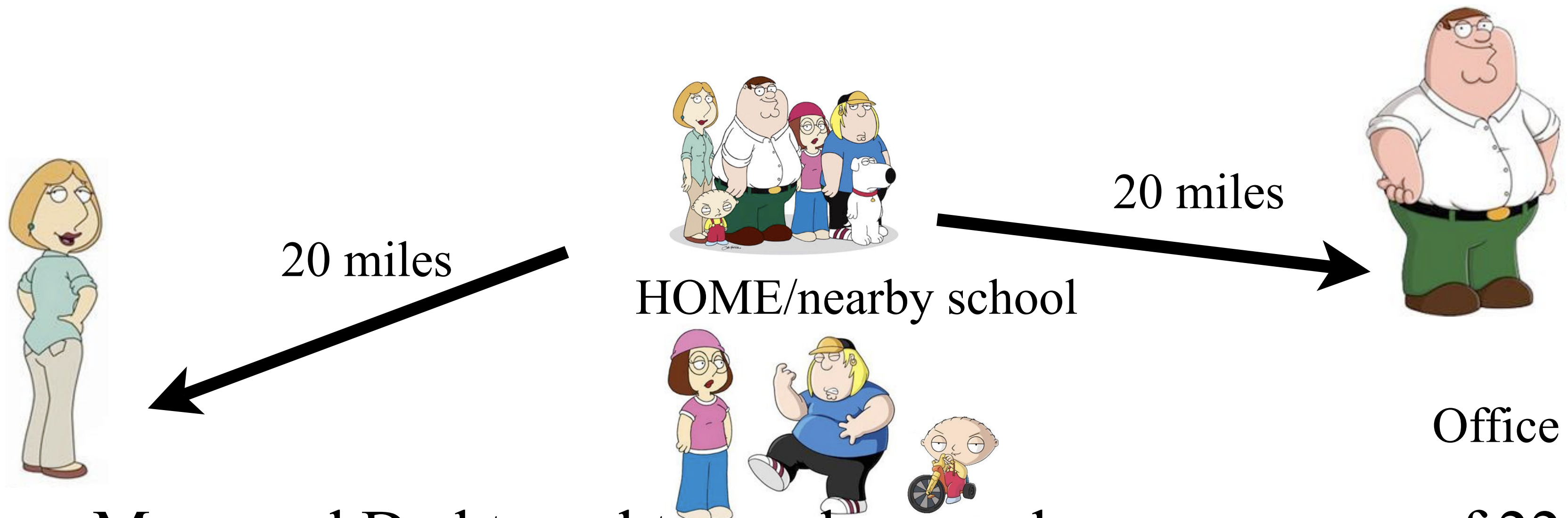
Looking at a typical American family

What are the Baryon Acoustic Oscillations?

How do we detect Baryon Acoustic Oscillations?
We calculate the correlation functions or its Fourier Transform: power-spectrum

What is the correlation function ?

$$\xi_f(r) = < \delta_f(\hat{x})\delta_f(\hat{x}+\hat{r}) >$$



20 miles

HOME/nearby school

20 miles

Office

Mum and Dad travel to work everyday on average of 22 min
Kids stay at home or go to nearby school

Office

What are the Baryon Acoustic Oscillations?

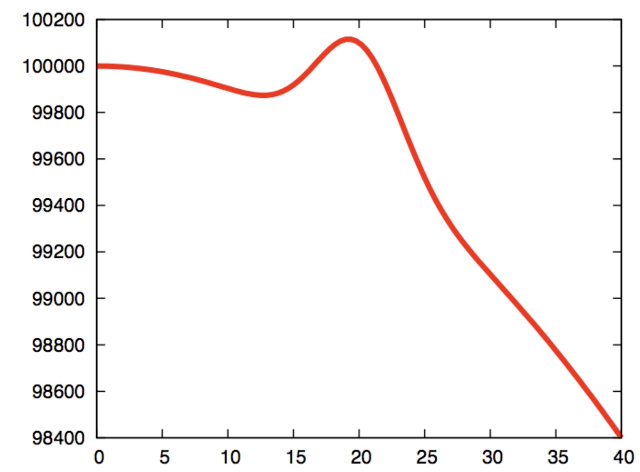
How do we detect Baryon Acoustic Oscillations?
We calculate the correlation functions or its Fourier Transform: power-spectrum

What is the correlation function ?

$$\xi_f(r) =< \delta_f(\hat{x})\delta_f(\hat{x}+\hat{r}) >$$

Population correlation function during the day

20 miles



Office

Office

The bump will be at 20 miles!

What are the Baryon Acoustic Oscillations?

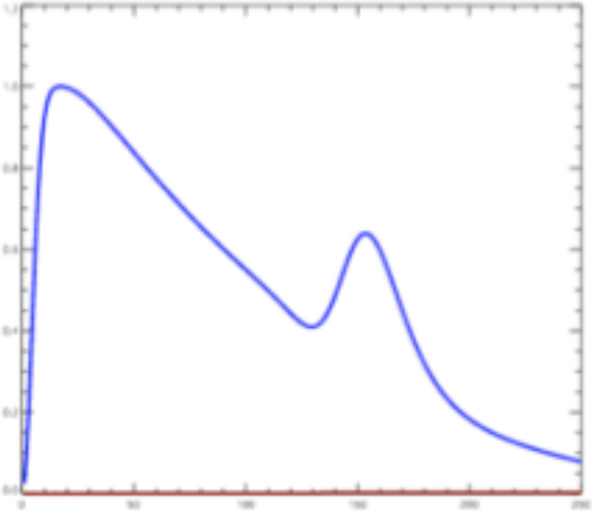
How do we detect Baryon Acoustic Oscillations?
We calculate the correlation functions or its Fourier Transform: power-spectrum

What is the correlation function ?

$$\xi_f(r) =< \delta_f(\hat{x})\delta_f(\hat{x}+\hat{r}) >$$

Galaxy correlation function

100 Mpc



The bump will be at ~100 Mpc

What are the Baryon Acoustic Oscillations?

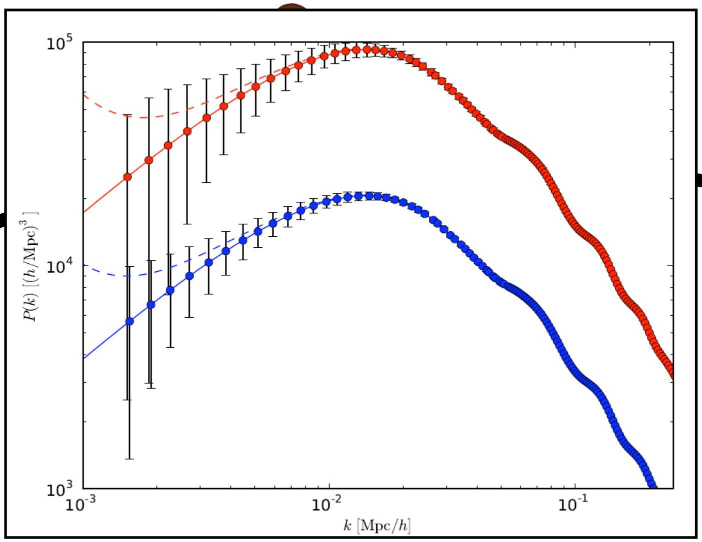
How do we detect Baryon Acoustic Oscillations?
We calculate the correlation functions or its Fourier Transform: power-spectrum

What is the correlation function ?

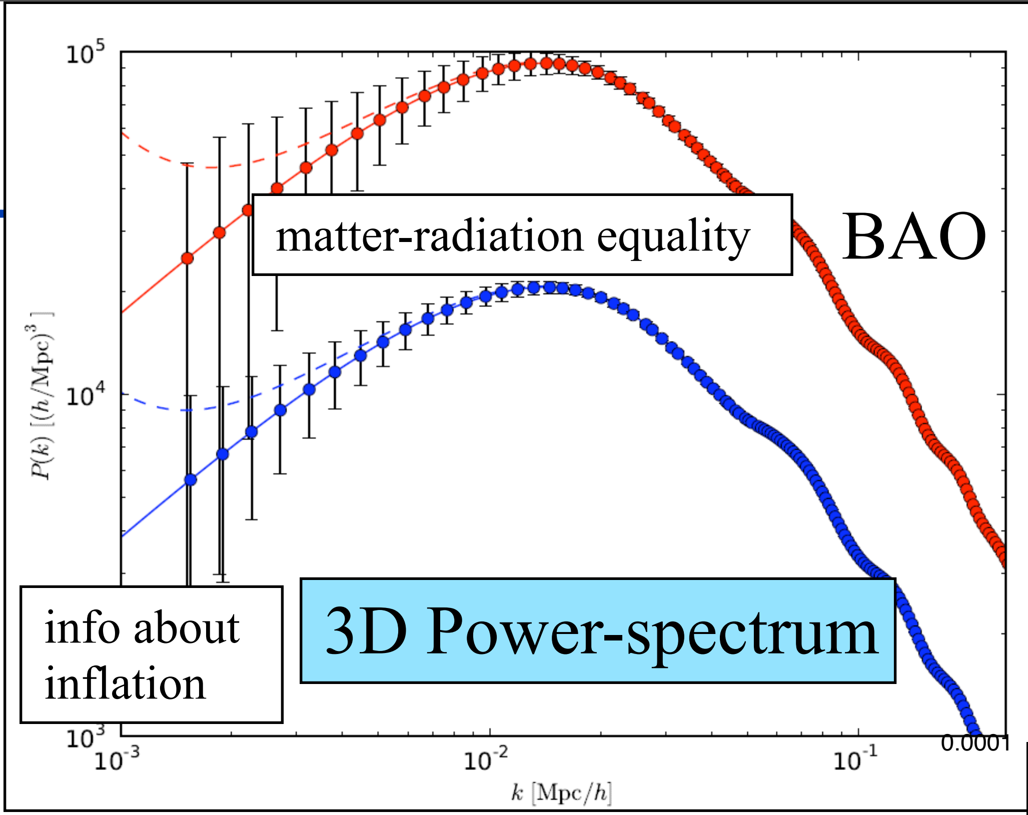
$$\xi_f(r) =< \delta_f(\hat{x})\delta_f(\hat{x}+\hat{r}) >$$

Fourier Transform: correlation function-> **power-spectrum**

100 Mpc



There will be wiggles



matter-radiation equality

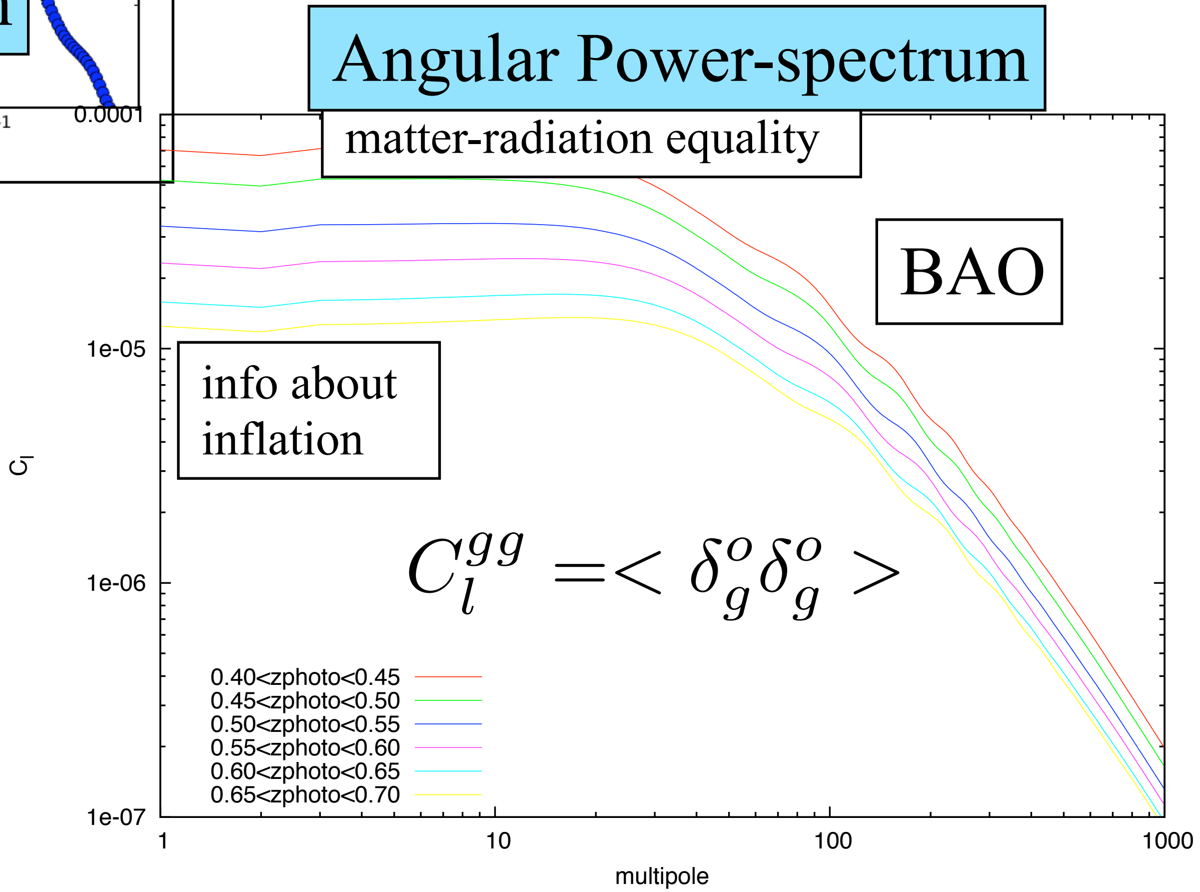
BAO

info about inflation

3D Power-spectrum

plot borrowed from Anze Slosar

Recall: Eisenstein et al.(2005), Percival & Reid et al. (2010)



Angular Power-spectrum

matter-radiation equality

BAO

info about inflation

$$C_l^{gg} = < \delta_g^o \delta_g^o >$$

Outline

- Motivations
- How can we use large scale structure to learn about the Universe?
  - Early Universe (with large scale clustering)
  - Dark Energy (with Baryon Acoustic Oscillations)
- Worked Example of Angular clustering
  - With Luminous Red galaxies

BAO: with Luminous Red Galaxies
Physics of Angular Clustering

$b = \frac{\delta g}{\delta \rho}$ describe how galaxies are related to cold dark matter

$\frac{dN}{dz}$ describe how many galaxies are there at each dz bin

Galaxy angular power-spectrum

$$C_l^{gg} = \int dz \frac{H_0}{c} b^2(z)(dN/dz)^2 D^2(z) P(\frac{l+\frac{1}{2}}{\chi})$$

BAO: with Luminous Red Galaxies
Physics of Angular Clustering

$b = \frac{\delta g}{\delta \rho}$ describe how galaxies are related to cold dark matter

$\frac{dN}{dz}$ describe how many galaxies are there at each dz bin

$D(z)$ describe how matter grows

$P(\frac{l+\frac{1}{2}}{\chi})$ describe how matter cluster (matter powerspectrum, describes the rms fluctuations)

Galaxy angular power-spectrum

$$C_l^{gg} = \int dz \frac{H_0}{c} b^2(z)(dN/dz)^2 D^2(z) P(\frac{l+\frac{1}{2}}{\chi})$$

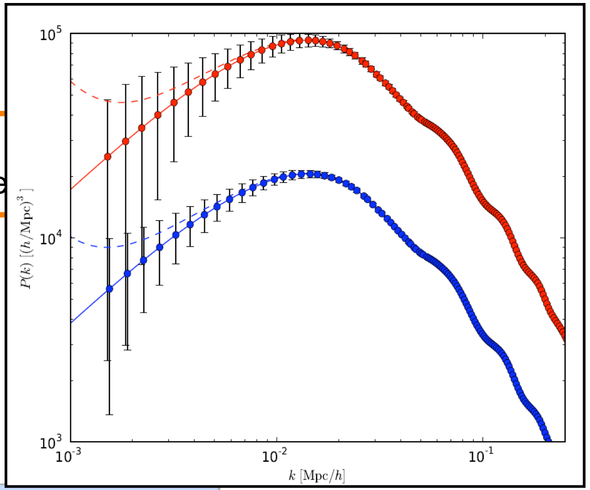
BAO: with Luminous Red Galaxies
Physics of Angular Clustering

$b = \frac{\delta g}{\delta \rho}$ describe how galaxies are related to cold dark matter

$\frac{dN}{dz}$ describe how many galaxies are there at each dz bin

$D(z)$ describe how matter grows

$P(\frac{l+\frac{1}{2}}{\chi})$ describe how matter cluster (matter powerspectrum, describes the



Galaxy angular power-spectrum

$$C_l^{gg} = \int dz \frac{H_0}{c} b^2(z)(dN/dz)^2 D^2(z) P\left(\frac{l+\frac{1}{2}}{\chi}\right)$$

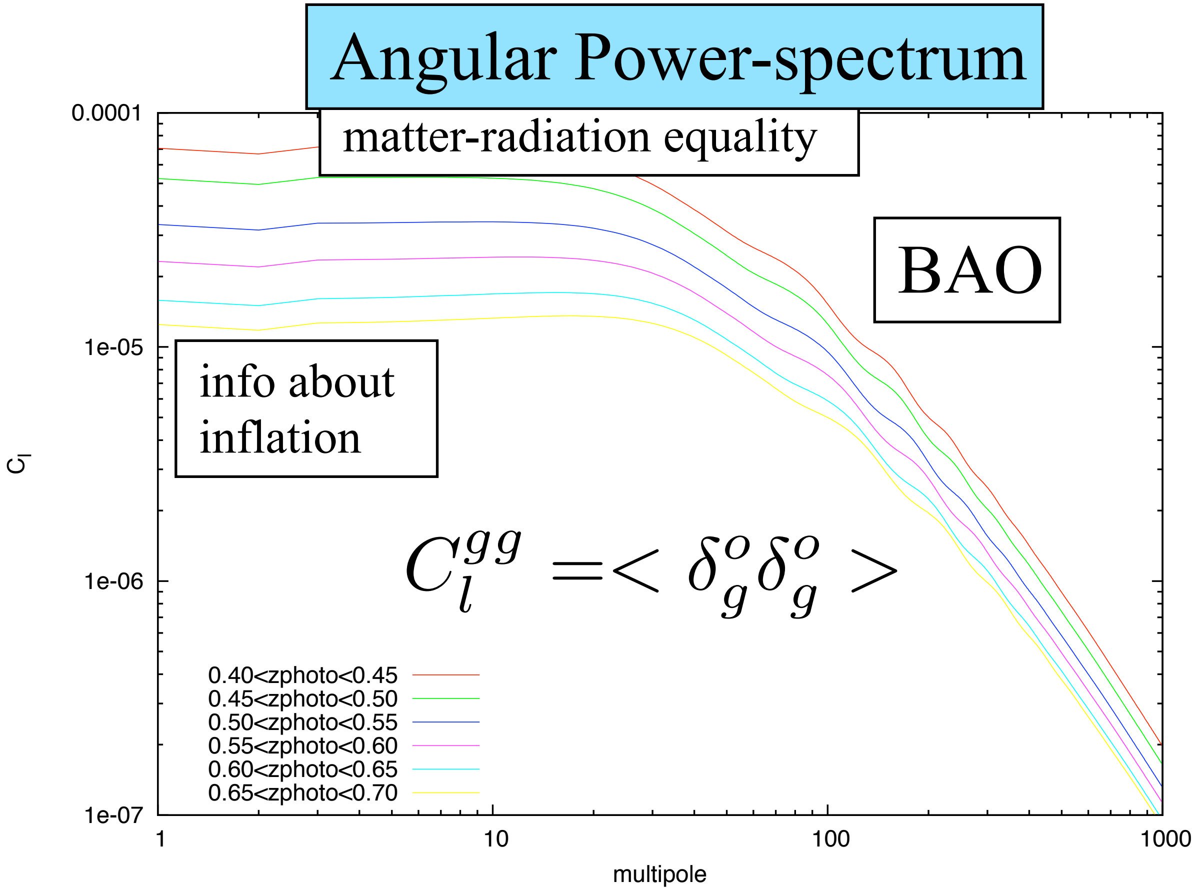
Galaxy Angular power-spectrum contains a wealth of cosmological information ranging from

a) What is **dark energy**? to

b) What happened at the very early Universe? Inflation? What kind?

Angular power-spectrum

- BAO
- Overall shape of the spectrum
- inflationary parameters affect the largest scale



Angular Power-spectrum

matter-radiation equality

BAO

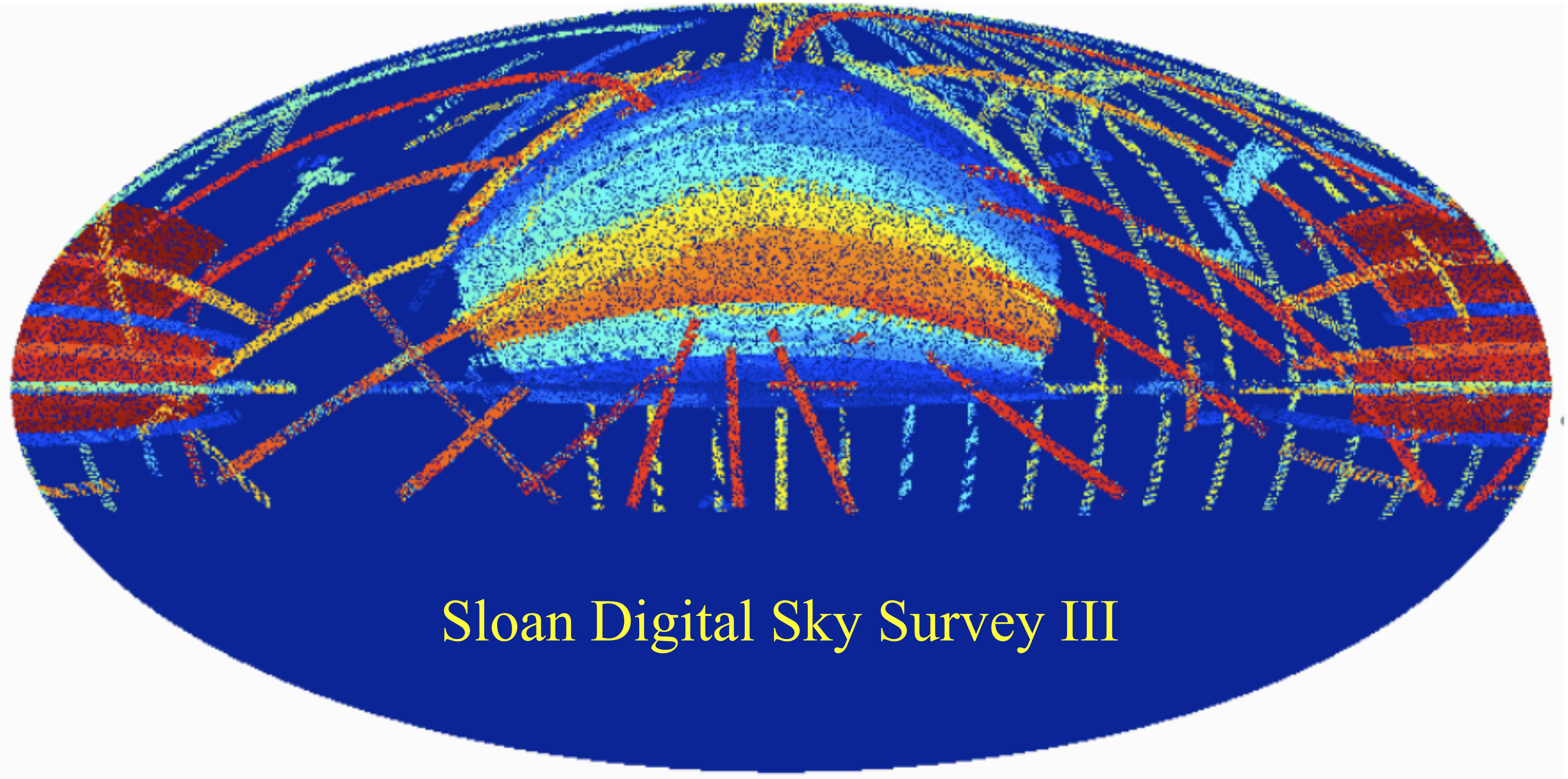
info about inflation

$$C_l^{gg} = < \delta_g^o \delta_g^o >$$

BAO: with Luminous Red Galaxies
The Data

Total Area: 14,555 sq deg

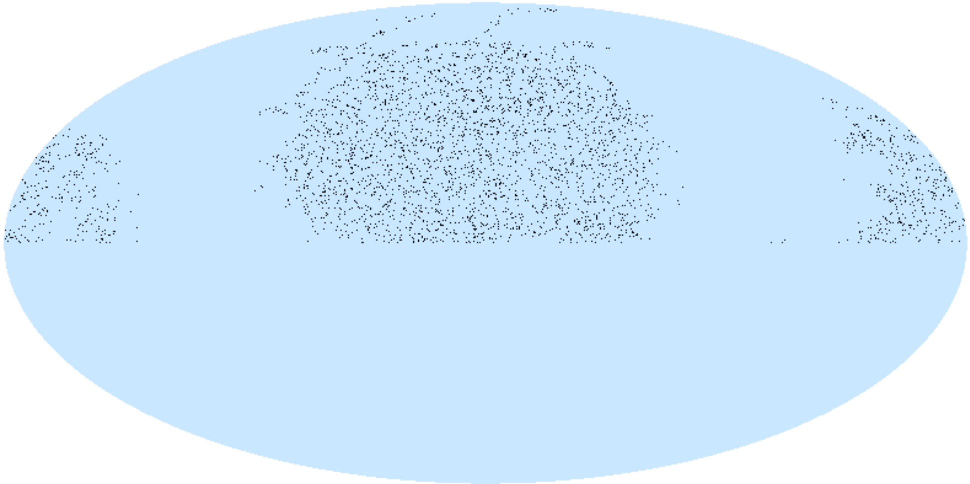
1.5 million LRGs: 0.4<z<0.7



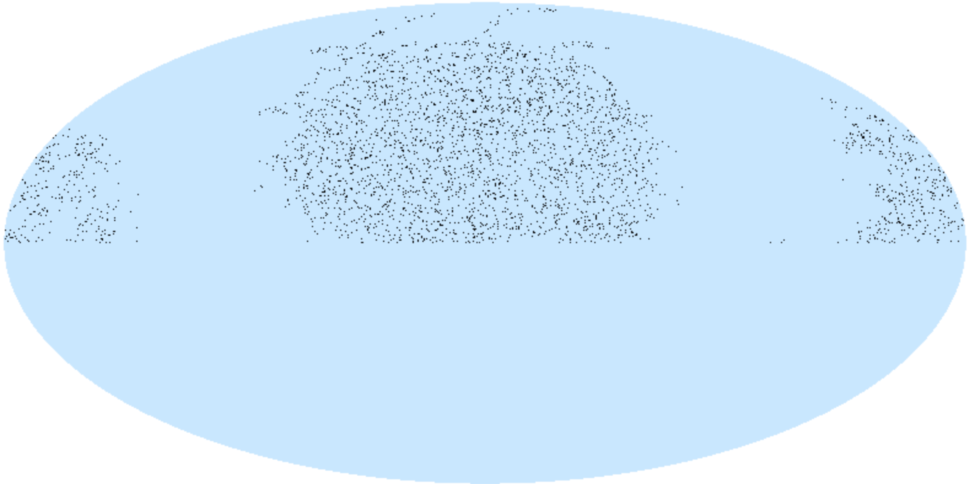
note: Colors only indicates the when a certain area of the sky is surveyed.

BAO: with Luminous Red Galaxies
The Data: Splitting them into redshift bins

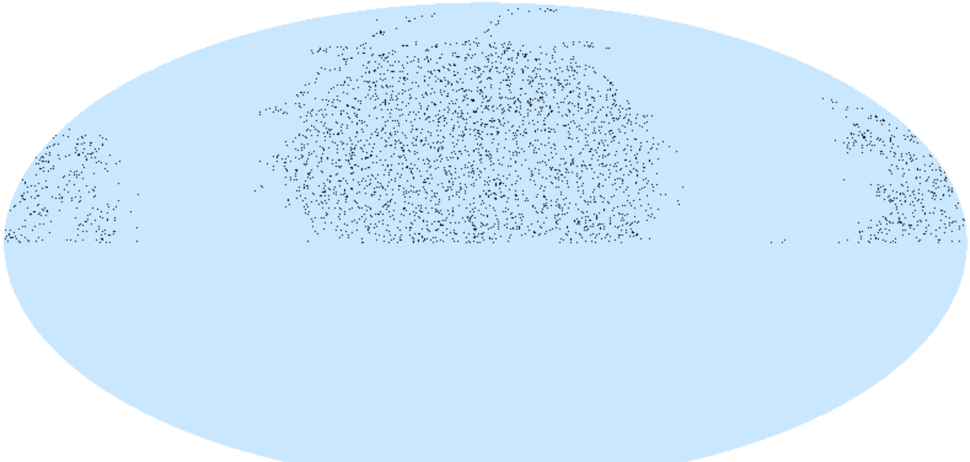
z=0.45-0.5



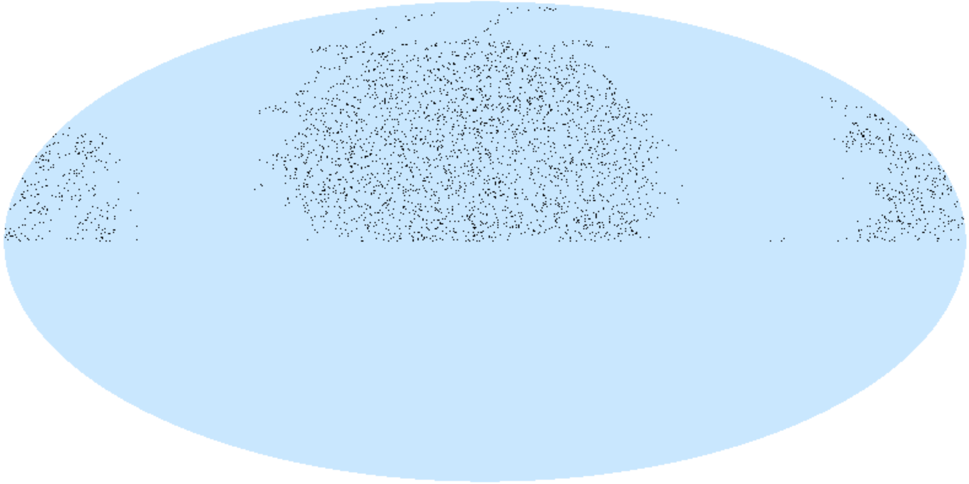
z=0.5-0.55



z=0.55-0.6



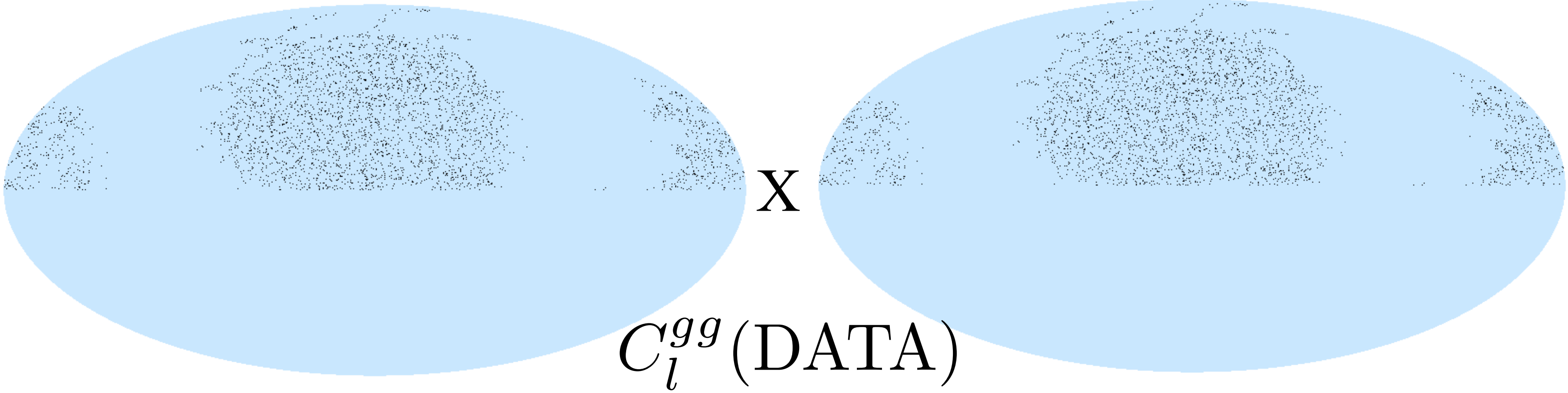
z=0.6-0.65



Ho, Seo, Ross, White, Schlegel et al. (in prep)

BAO: with Luminous Red Galaxies
How to do this?

- For each of the redshift bin, we cross-correlates the Luminous Red Galaxies with themselves, and we get the angular power-spectra of the galaxies.

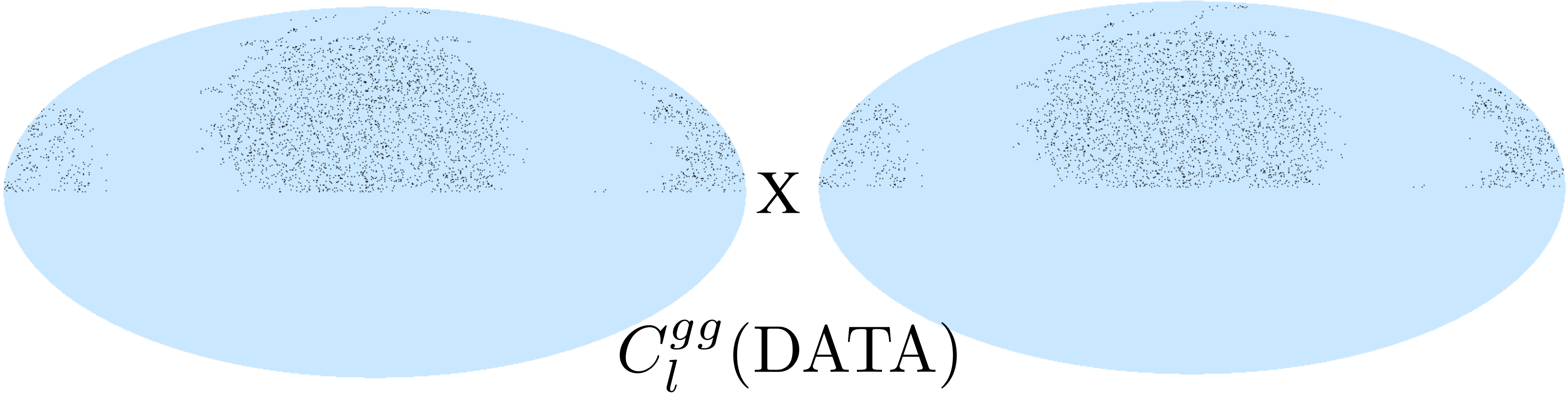


$$C_l^{gg}(\mathrm{DATA})$$

- We want the best measurement of the angular power-spectra possible, from the stand point of not only statistical error, but also systematic errors.
- To get the best statistical errorbar, we apply “Quadratic Estimator”, which are proven to provide:
  - Unbiased Minimum variance measurement of the parameters that are being estimated if the field is gaussian.
  - Many people have worked on this Quadratic Estimators: Hamilton, Tegmark, Bond, Jaffe and Knox, White, Padmanabhan, Hirata, Blake, et al.

BAO: with Luminous Red Galaxies
How to do this?

- For each of the redshift bin, we cross-correlates the Luminous Red Galaxies with themselves, and we get the angular power-spectra of the galaxies.

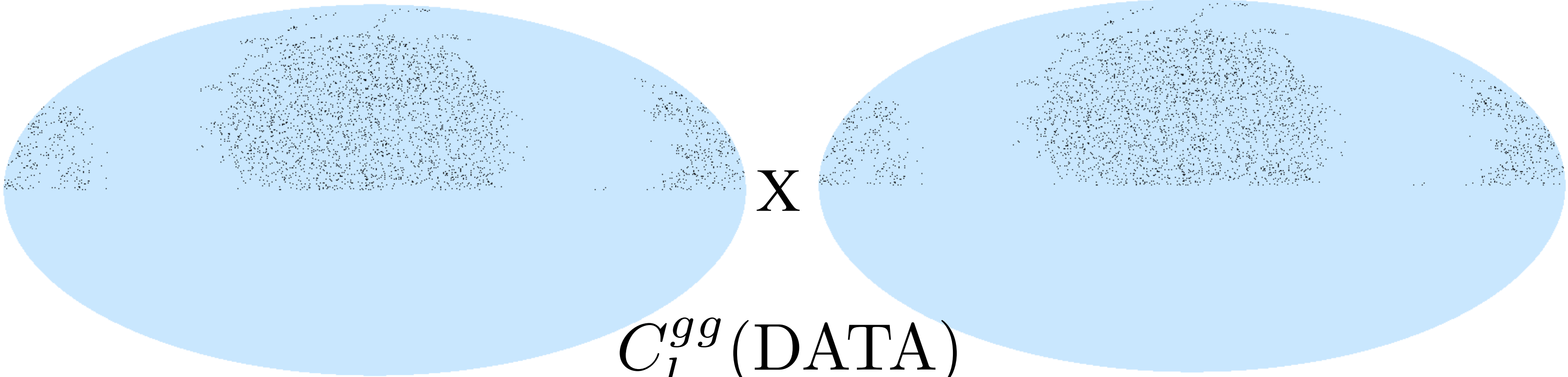


$$C_l^{gg}(\mathrm{DATA})$$

- We want the best measurement of the angular power-spectra possible, from the stand point of not only statistical error, but also systematic errors.
- To get the best statistical errorbar, we apply “Quadratic Estimator”, which are proven to provide:
  - Unbiased Minimum variance measurement of the parameters that are being estimated if the field is gaussian.
  - Many people have worked on this Quadratic Estimators: Hamilton, Tegmark, Bond, Jaffe and Knox, White, Padmanabhan, Hirata, Blake, et al.

BAO: with Luminous Red Galaxies
How to do this?

- For each of the redshift bin, we cross-correlates the Luminous Red Galaxies with themselves, and we get the angular power-spectra of the galaxies.

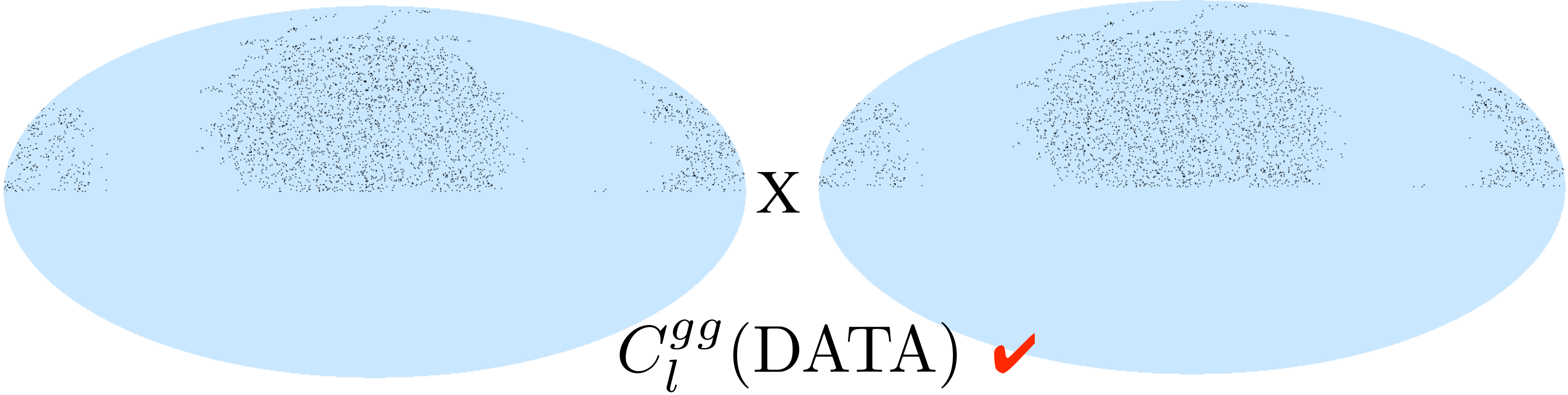


$$C_l^{gg}(\mathrm{DATA})$$

- We want the best measurement of the angular power-spectra possible, from the stand point of not only statistical error, but also systematic errors.
- To get the best statistical error, we apply “Quadratic Estimator”, which are proven to provide:
  - Unbiased Minimum variance measurement of the parameters that are being estimated if the field is gaussian.
  - Many people have worked on Quadratic Estimators: Hamilton, Tegmark, Bond, Jaffe and Knox, White, Padmanabhan, Hirata, Blake, et al.

BAO: with Luminous Red Galaxies
How to do this?

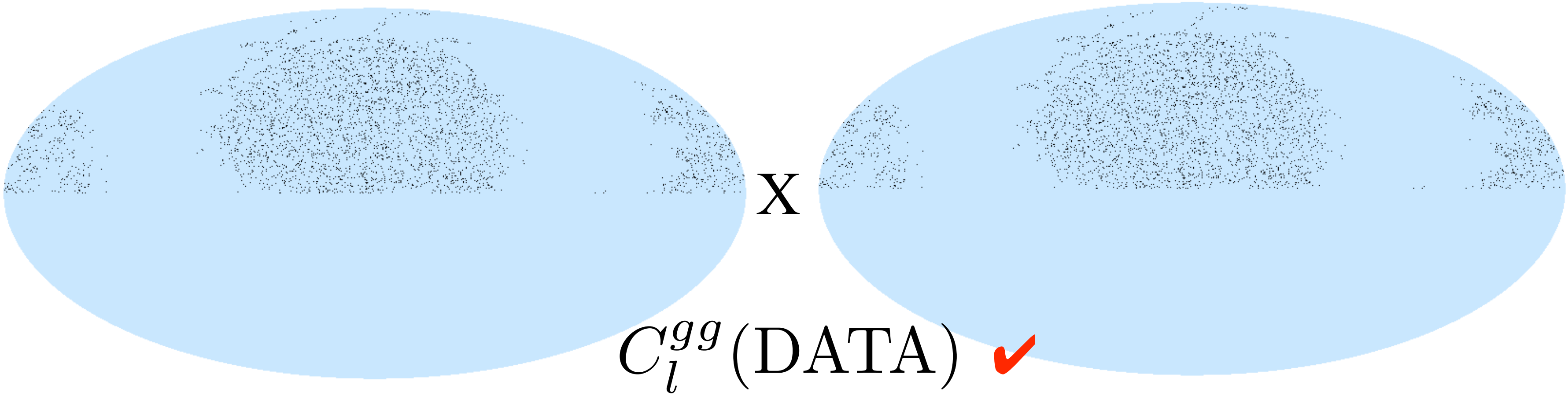
- For each of the redshift bin, we cross-correlates the Luminous Red Galaxies with themselves, and we get the angular power-spectra of the galaxies.



$$C_l^{gg}(\mathrm{DATA})$$ ✔

BAO: with Luminous Red Galaxies
How to do this?

- For each of the redshift bin, we cross-correlates the Luminous Red Galaxies with themselves, and we get the angular power-spectra of the galaxies.



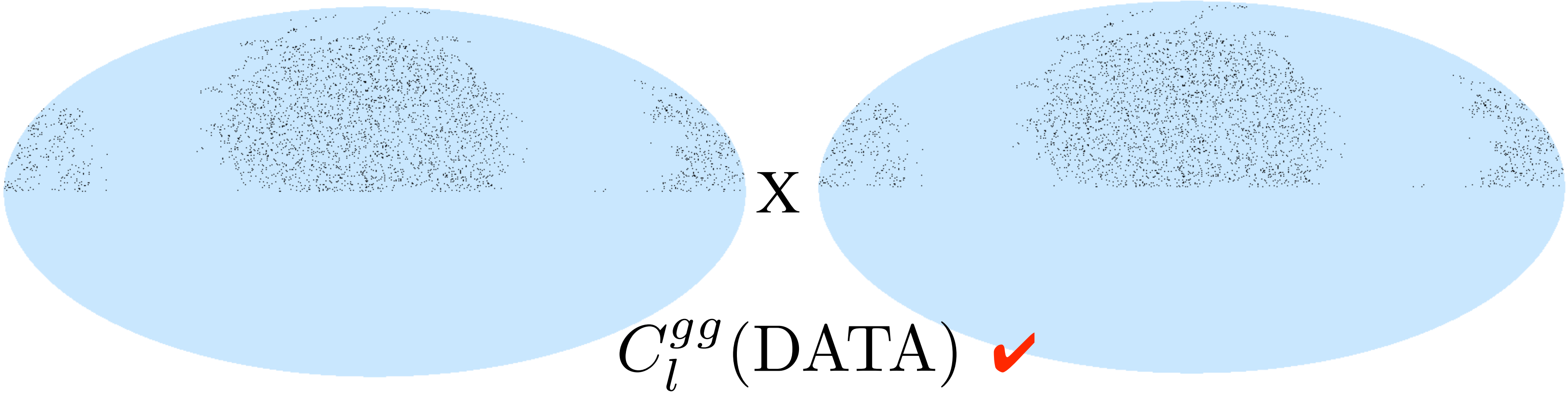
$$C_l^{gg}(\mathrm{DATA}) \checkmark$$

- But in order to derive cosmological constraints, we need to be able to predict the angular power-spectra given any cosmological models.
- That’s why: we need the **theory**:

$$C_l^{gg} = \int dz \frac{H_0}{c} b^2(z)(dN/dz)^2 D^2(z) P(\frac{l+\frac{1}{2}}{\chi})$$

BAO: with Luminous Red Galaxies
How to do this?

- For each of the redshift bin, we cross-correlates the Luminous Red Galaxies with themselves, and we get the angular power-spectra of the galaxies.



$C_l^{gg}(\mathrm{DATA})$ ✓

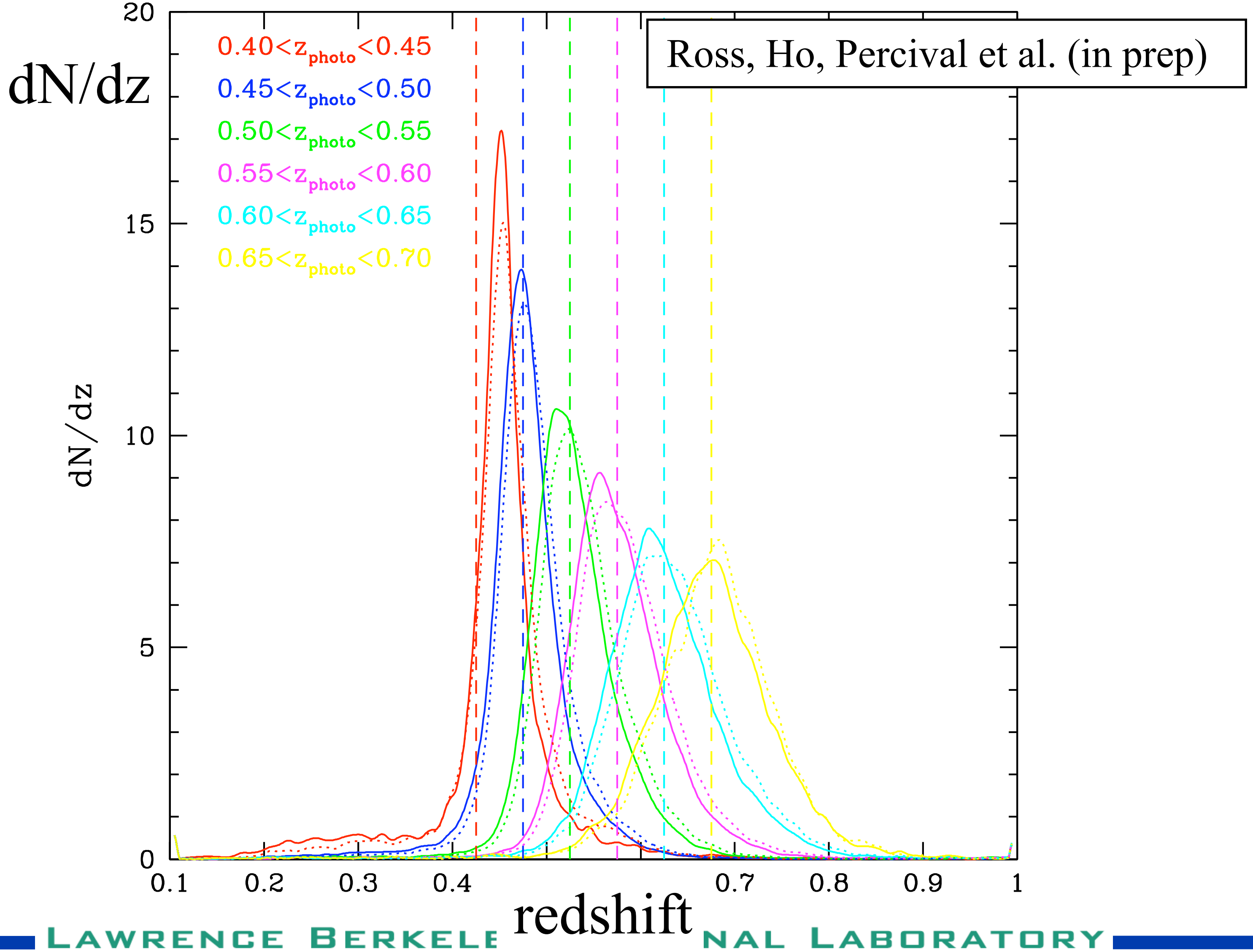
- But in order to derive cosmological constraints, we need to be able to predict the angular power-spectra given any cosmological models.
- That's why: we need the **theory**:

$$C_l^{gg} = \int dz \frac{H_0}{c} b^2(z)(dN/dz)^2 D^2(z) P(\frac{l+\frac{1}{2}}{\chi})$$

- Given a cosmological model, we can predict the theory, except we need two inputs: bias b(z) and redshift distribution dN/dz.

BAO: with Luminous Red Galaxies
The Data: Redshift distribution

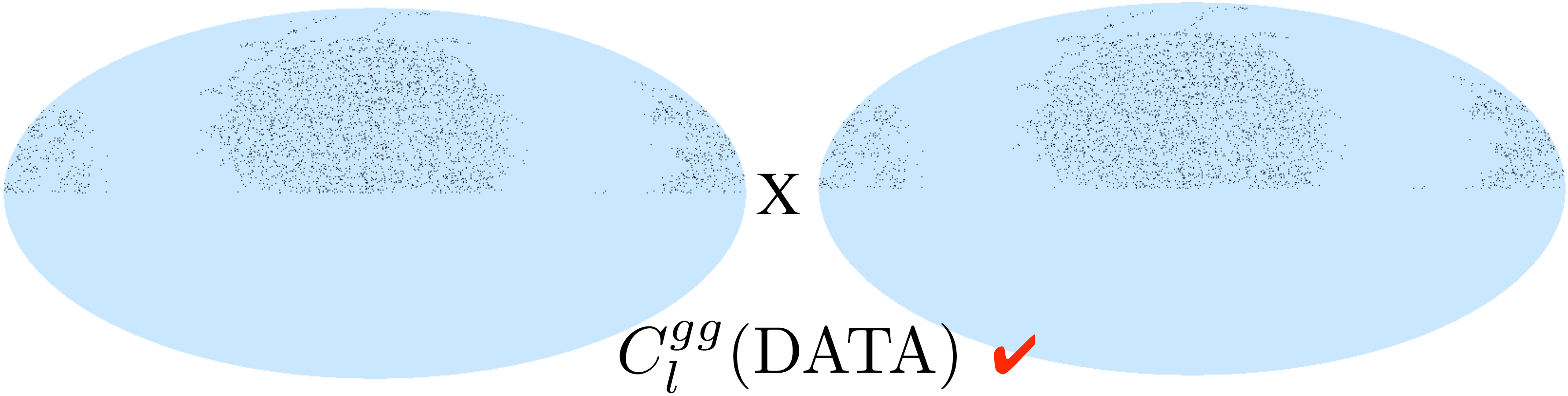
SDSS III has been taking spectra of all of these photometric LRGs, therefore, we have an unbiased spectroscopic confirmation of the photometric redshifts for ~10% of the sample, therefore, we have very good understanding of the redshift distribution of the sample.



Ross, Ho, Percival et al. (in prep)

BAO: with Luminous Red Galaxies
How to do this?

- For each of the redshift bin, we cross-correlates the Luminous Red Galaxies with themselves, and we get the angular power-spectra of the galaxies.



$C_l^{gg}(\mathrm{DATA})$ ✓

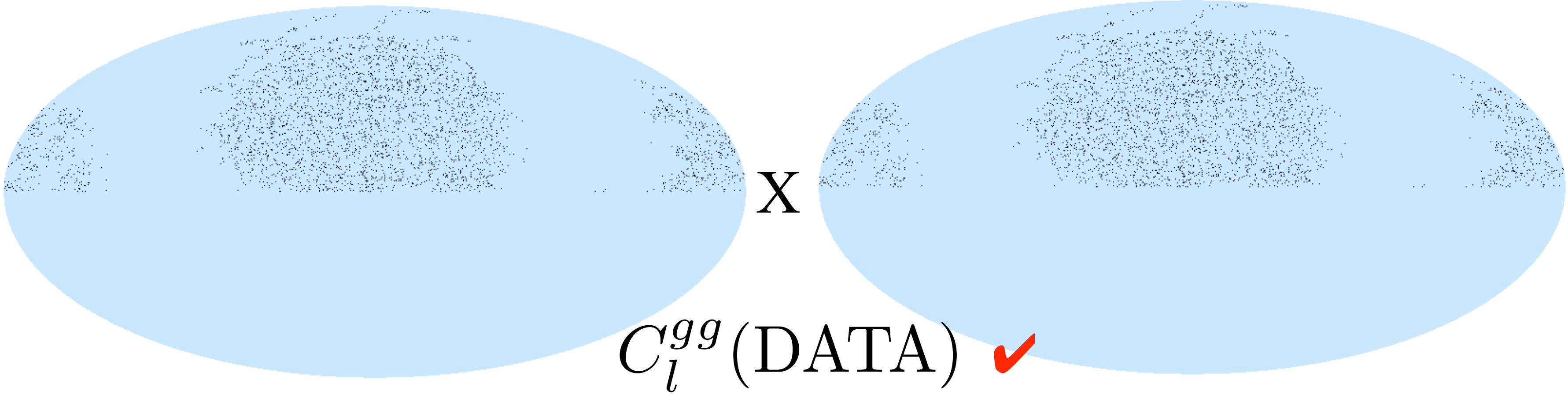
- But in order to derive cosmological constraints, we need to be able to predict the angular power-spectra given any cosmological models.
- That's why: we need the theory:

$$C_l^{gg} = \int dz \frac{H_0}{c} b^2(z) (dN/dz)^2 D^2(z) P(\frac{l+\frac{1}{2}}{\chi})$$

- We then only need to know bias, but since it only changes the overall amplitude of the angular power-spectrum.
- We don't need to worry about this for BAO

BAO: with Luminous Red Galaxies
How to do this?

- For each of the redshift bin, we cross-correlates the Luminous Red Galaxies with themselves, and we get the angular power-spectra of the galaxies.



$$C_l^{gg}(\mathrm{DATA})$$ ✓

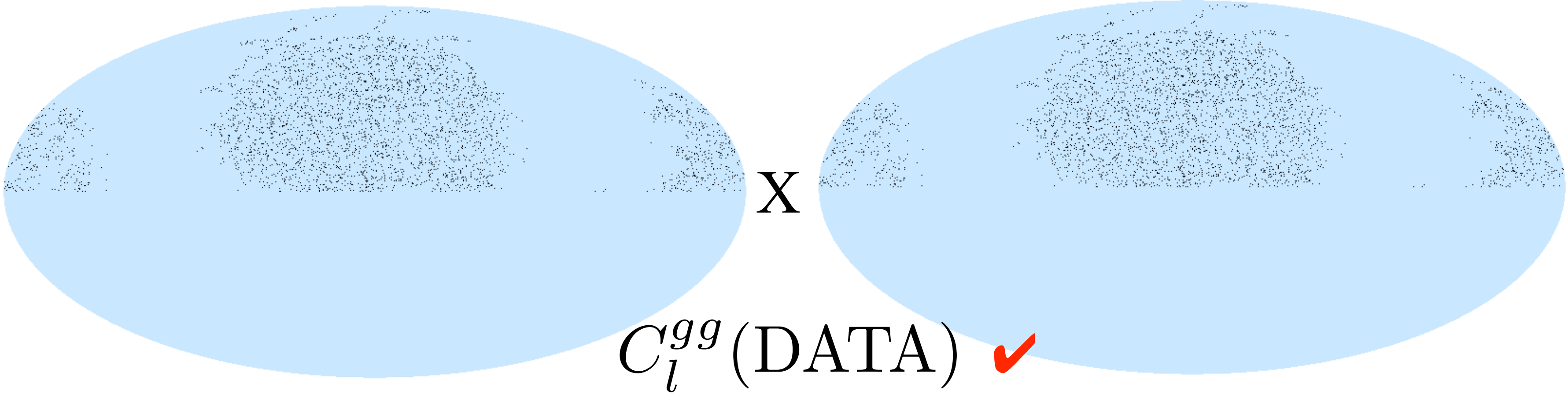
- But in order to derive cosmological constraints, we need to be able to predict the angular power-spectra given any cosmological models.
- That's why: we need the theory:

$$C_l^{gg} = \int dz \frac{H_0}{c} b^2(z) (dN/dz)^2 D^2(z) P(\frac{l+\frac{1}{2}}{\chi})$$

- We then only need to know bias, but since it only changes the overall amplitude of the angular power-spectrum.
- We don't need to worry about this for BAO

BAO: with Luminous Red Galaxies
How to do this?

- For each of the redshift bin, we cross-correlates the Luminous Red Galaxies with themselves, and we get the angular power-spectra of the galaxies.



$C_l^{gg}(\mathrm{DATA})$ ✓

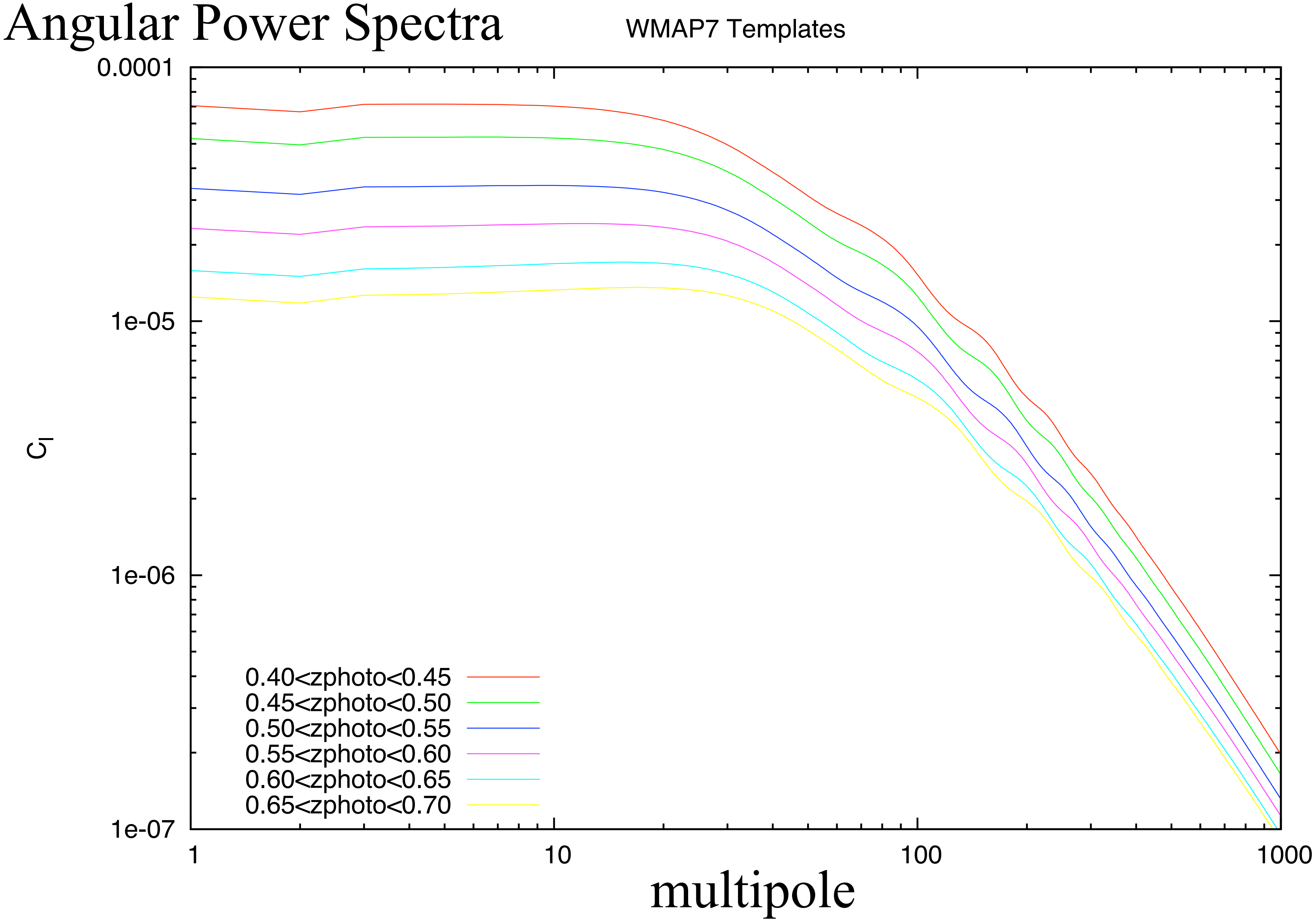
- But in order to derive cosmological constraints, we need to be able to predict the angular power-spectra given any cosmological models.
- That's why: we need the theory:

$$C_l^{gg} = \int dz \frac{H_0}{c} b^2(z)(dN/dz)^2 D^2(z) P\left(\frac{l+\frac{1}{2}}{\chi}\right)$$ ✓

- We then only need to know bias, but since it only changes the overall amplitude of the angular power-spectrum.
- We don't need to worry about this for BAO

What we expect to see

Angular Power Spectra



BAO: with Luminous Red Galaxies
Systematics

- The Reason why BAO become so popular is that it is one of the cleanest probe of cosmology, since there are not that many systematics that can cause a shift in BAO scale (~100 Mpc)
- Therefore, the systematics I am going through here are mostly for getting a clean angular power-spectrum which contains other information such as the shape of matter power-spectrum, scale dependent bias that can be caused by non-gaussianities at the early Universe.

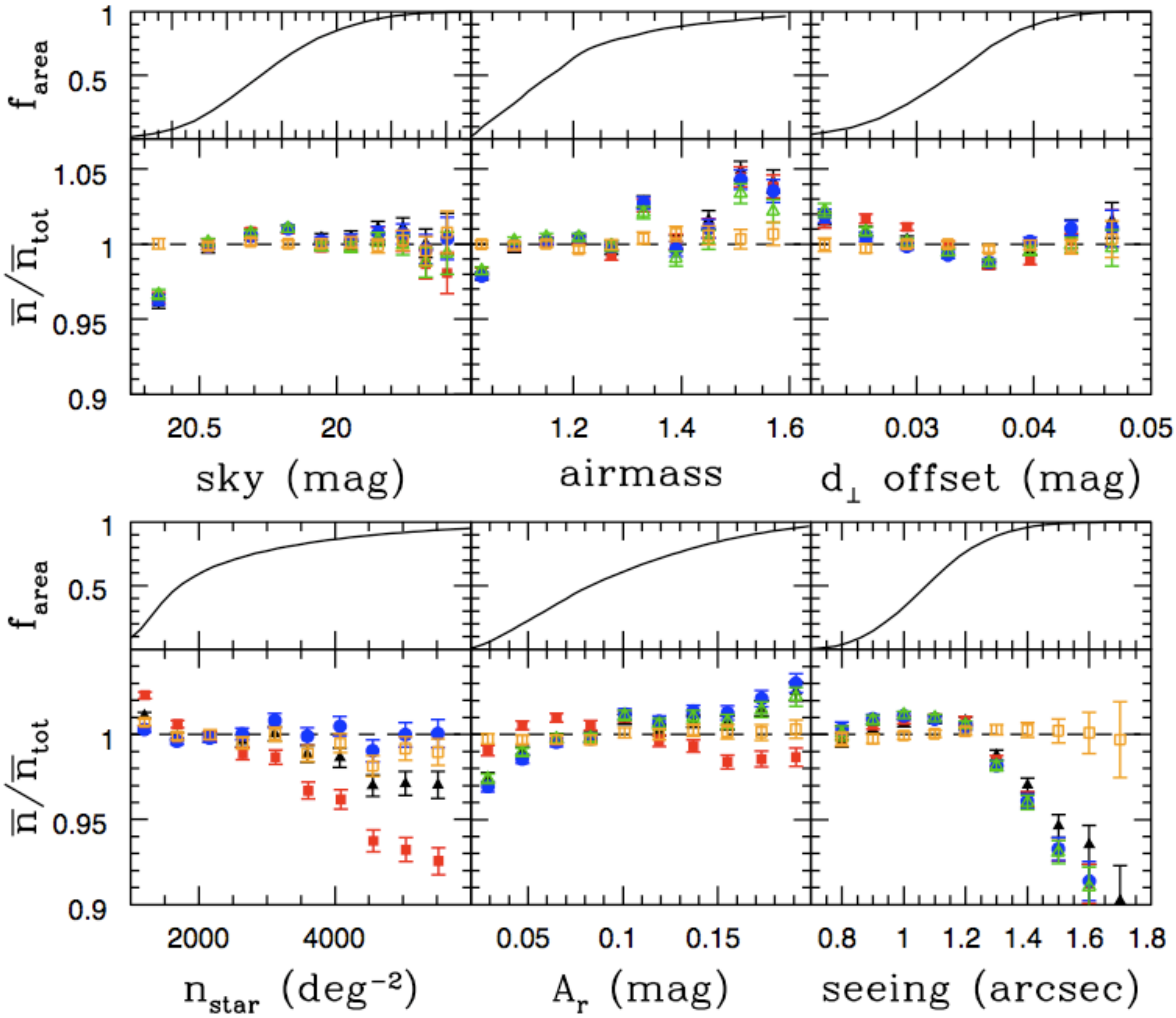
$$C_l^{gg}(\mathrm{DATA}) = \mathrm{b}^2\mathrm{C}_\mathrm{l}^{\delta_\mathrm{m}\delta_\mathrm{m}} + \mathrm{C}_\mathrm{l}^{\mathrm{d},\mathrm{d}} + \mathrm{C}_\mathrm{l}^{\mathrm{s},\mathrm{s}} + \mathrm{C}_\mathrm{l}^{\mathrm{g}(\mathrm{z}),\mathrm{g}(\mathrm{z}')} + \ldots$$

BAO: with Luminous Red Galaxies
Systematics

- The Reason why BAO become so popular is that it is one of the cleanest probe of cosmology, since there are not that many systematics that can cause a shift in BAO scale (~100 Mpc)
- Therefore, the systematics I am going through here are mostly for getting a clean angular power-spectrum which contains other information such as the shape of matter power-spectrum, scale dependent bias that can be caused by non-gaussianities at the early Universe.

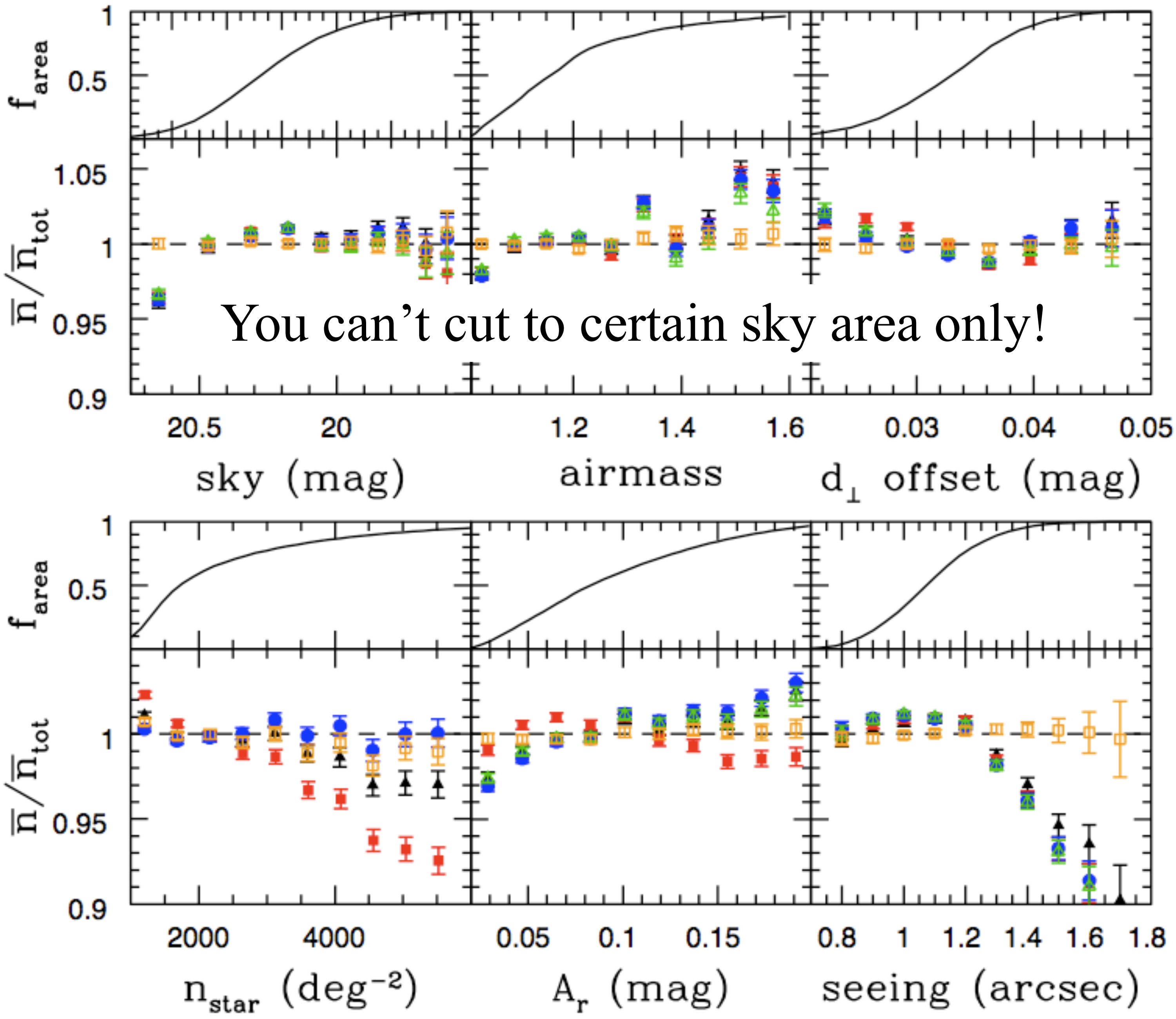
$$C_l^{gg}(\mathrm{DATA}) = \mathrm{b}^2 \mathrm{C}_\mathrm{l}^{\delta_\mathrm{m}\delta_\mathrm{m}} + \underbrace{\mathrm{C}_\mathrm{l}^{\mathrm{d,d}}}_{\text{Dust Extinction}} + \underbrace{\mathrm{C}_\mathrm{l}^{\mathrm{s,s}}}_{\text{Stellar Contamination}} + \underbrace{\mathrm{C}_\mathrm{l}^{\mathrm{g(z),g(z')}}}_{\text{Galaxies from next photometric slice}} + \overbrace{\ldots}^{\text{Color offsets}}$$

Short summary:



Ross, SH, Cuesta et al. (2011)

Short summary:



You can't cut to certain sky area only!

Ross, SH, Cuesta et al. (2011)

Systematics

- Therefore, the systematics I am going through here are mostly for getting a clean angular power-spectrum which contains information such as the shape of matter power-spectrum, scale dependent bias that can be caused by non-gaussianities at the early Universe.

Can we restrict ourselves to certain l-modes?

$$C_l^{gg}(Data) = C_l^{g_{real}g_{real}} + \epsilon_1 C_l^{stars,stars} + \epsilon_2 C_l^{sky,sky} + \epsilon_3 C_l^{c,c} + \ldots$$

Real Galaxy Power Stars Sky Brightness Color Offset

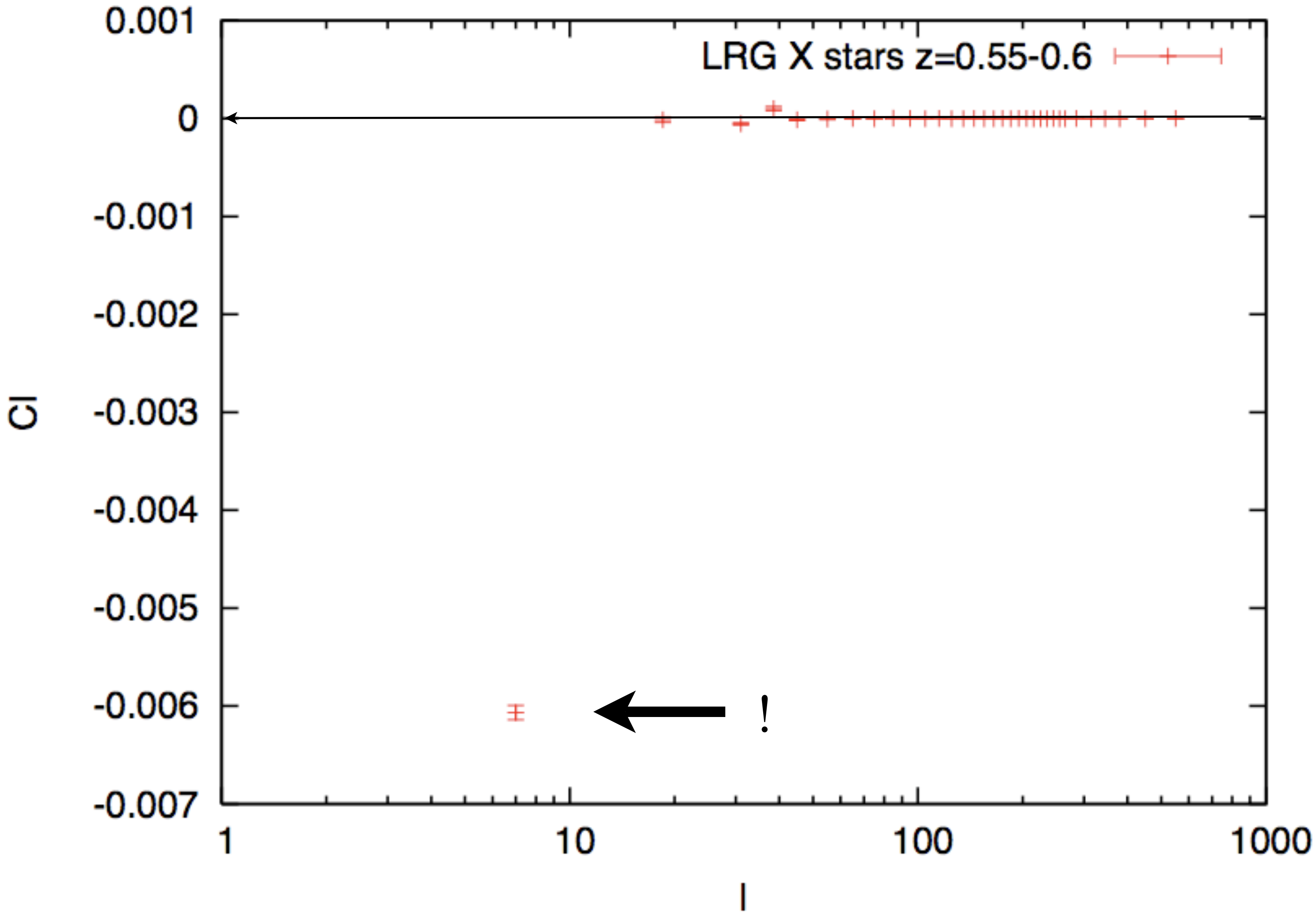
Systematics

- Therefore, the systematics I am going through here are mostly for getting a clean angular power-spectrum which contains information such as the shape of matter power-spectrum, scale dependent bias that can be caused by non-gaussianities at the early Universe.

Can we restrict ourselves to certain l-modes?

$$C_l^{gg}(Data) = \underbrace{C_l^{g_{real}g_{real}}}_{\text{Real Galaxy Power}} + \underbrace{\epsilon_1 C_l^{stars,stars}}_{\text{Stars}} + \underbrace{\epsilon_2 C_l^{sky,sky}}_{\text{Sky Brightness}} + \underbrace{\epsilon_3 C_l^{c,c}}_{\text{Color Offset}} + \ldots$$

Effect of stars



SH, Ross, Cuesta, Seo, White, Schlegel et al. (in prep)

Systematics

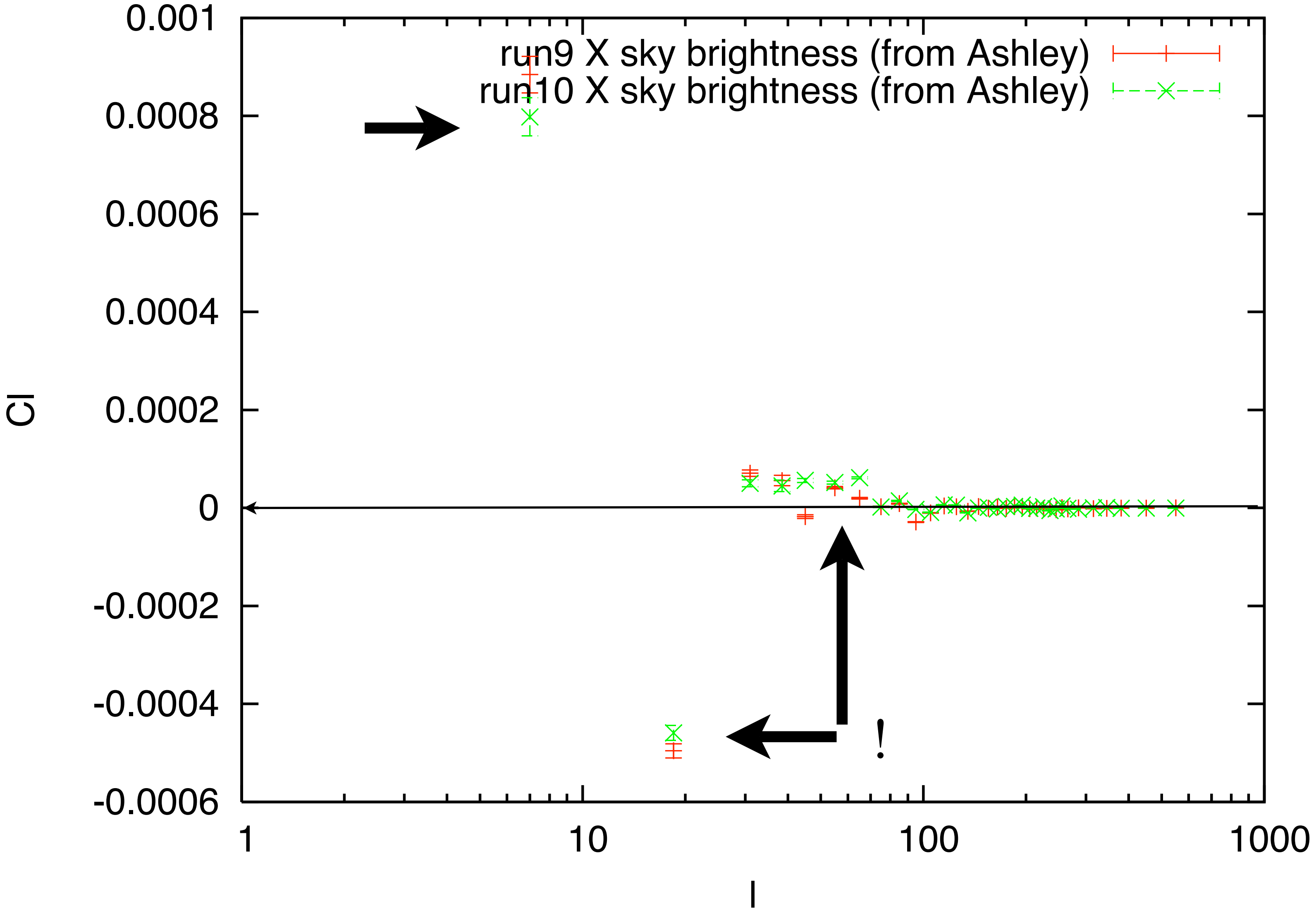
- Therefore, the systematics I am going through here are mostly for getting a clean angular power-spectrum which contains information such as the shape of matter power-spectrum, scale dependent bias that can be caused by non-gaussianities at the early Universe.

Can we restrict ourselves to certain l-modes?

$$C_l^{gg}(Data) = C_l^{g_{real}g_{real}} + \epsilon_1 C_l^{stars,stars} + \epsilon_2 C_l^{sky,sky} + \epsilon_3 C_l^{c,c} + \ldots$$

Real Galaxy Power Stars Sky Brightness Color Offset

The effect of sky brightness



SH, Ross, Cuesta, Seo, White, Schlegel et al. (in prep)

Systematics

- Therefore, the systematics I am going through here are mostly for getting a clean angular power-spectrum which contains information such as the shape of matter power-spectrum, scale dependent bias that can be caused by non-gaussianities at the early Universe.

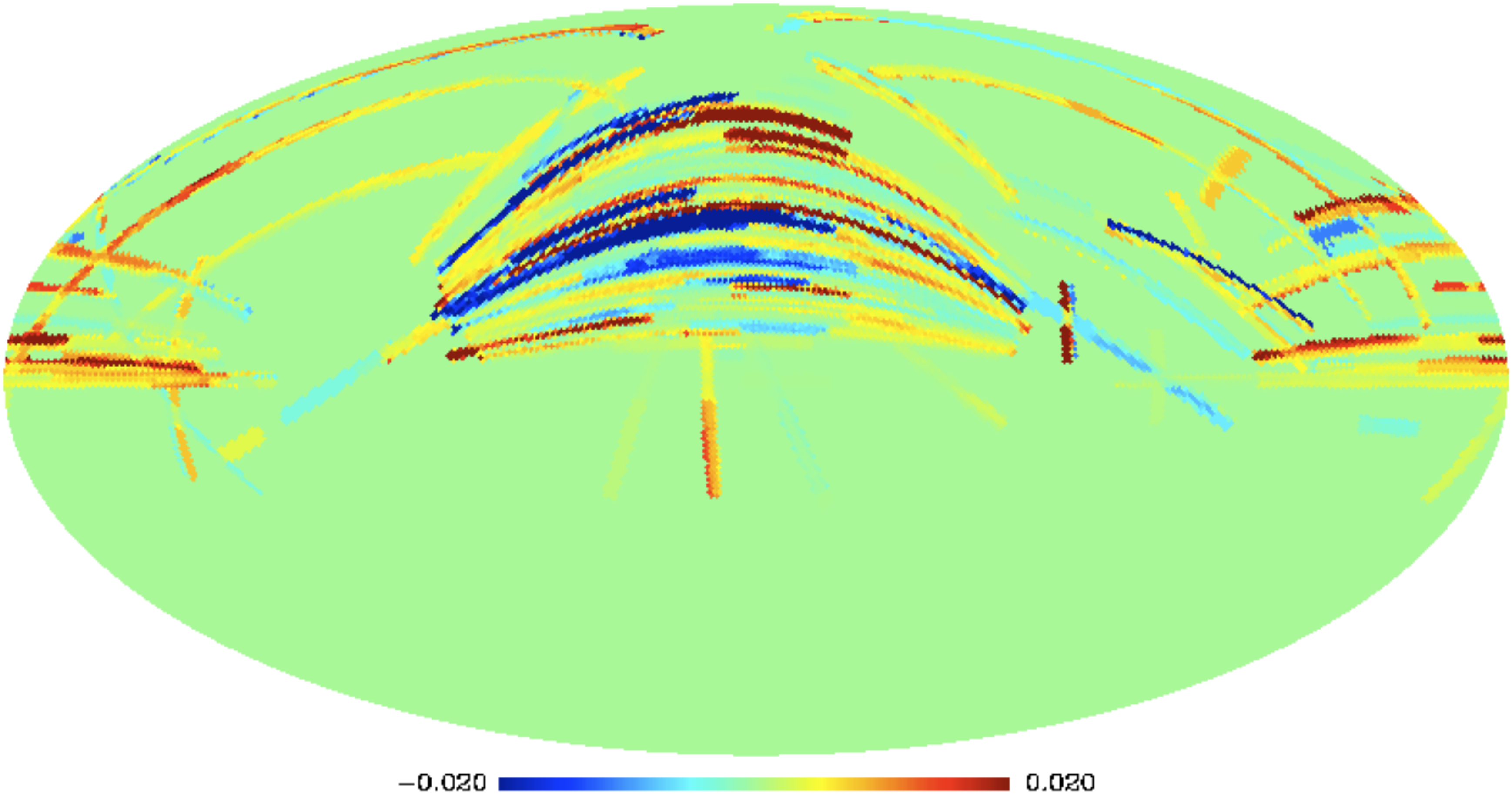
Can we restrict ourselves to certain l-modes?

$$C_l^{gg}(Data) = C_l^{g_{real}g_{real}} + \epsilon_1 C_l^{stars,stars} + \epsilon_2 C_l^{sky,sky} + \epsilon_3 C_l^{c,c} + \ldots$$

Real Galaxy Power Stars Sky Brightness Color Offset

Color offsets

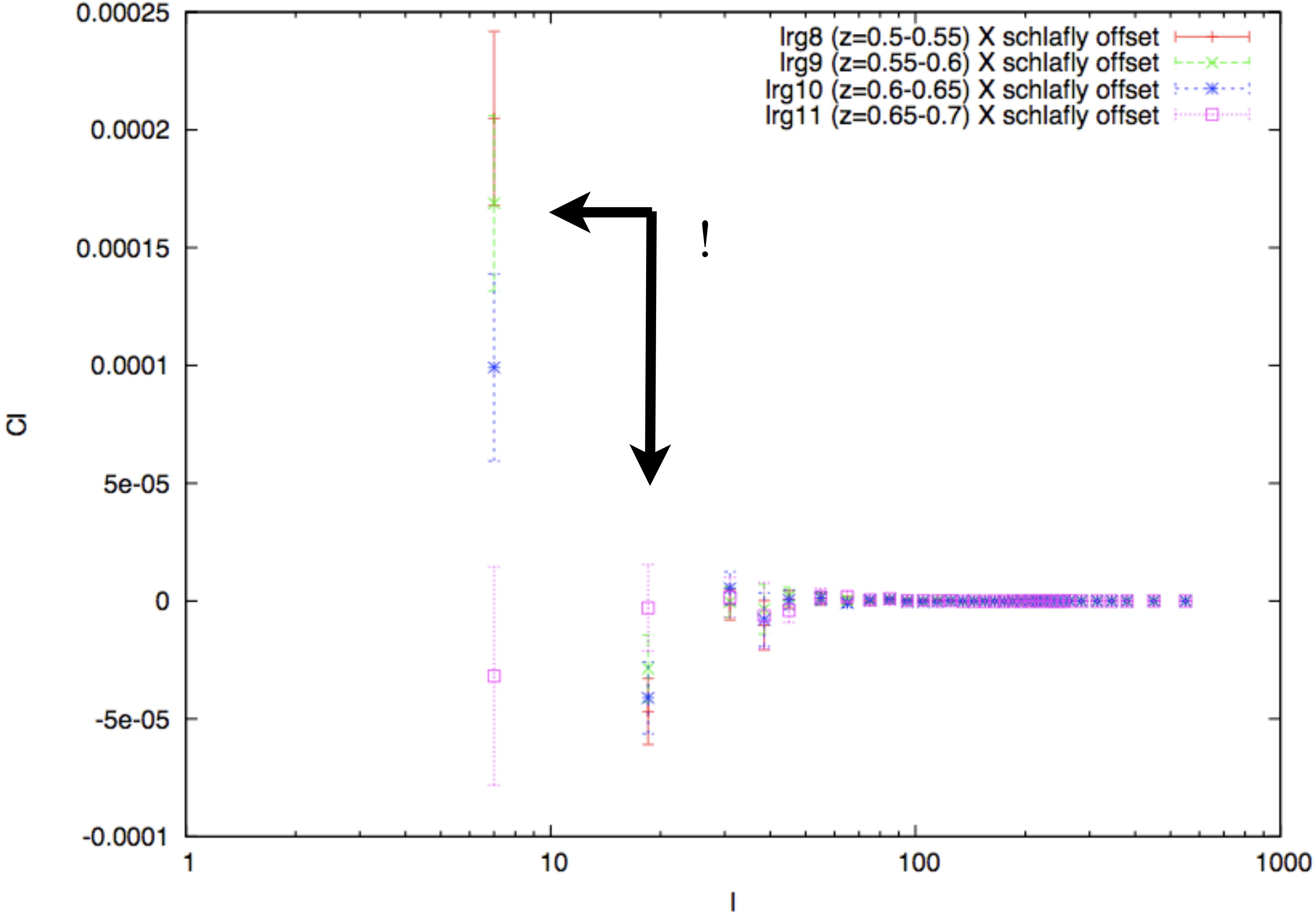
DR8 Color offsets in g-r



These are color (difference in magnitudes) zero points of SDSS

Color offsets as discussed in Schlafly et al. 2010

The effect of the color offsets



SH, Ross, Cuesta, Seo, White, Schlegel et al. (in prep)

Systematics

What can we do when we can’t/ don’t want to cut to a certain l-range?

Systematics: Taking them out of the equation

True galaxy overdensity

Observed galaxy overdensity

$$\delta_g^o = \delta_g^t + \sum_{i=0}^{N} \epsilon_i \delta_{s_i}$$

Various systematics

For example, if i=2 only:

$$< \delta_g^o \delta_{s_1} >=< \delta_g^t \delta_g^t > +\epsilon_1 < \delta_{s_1} \delta_{s_1} > +\epsilon_2 < \delta_{s_2} \delta_{s_1} >$$

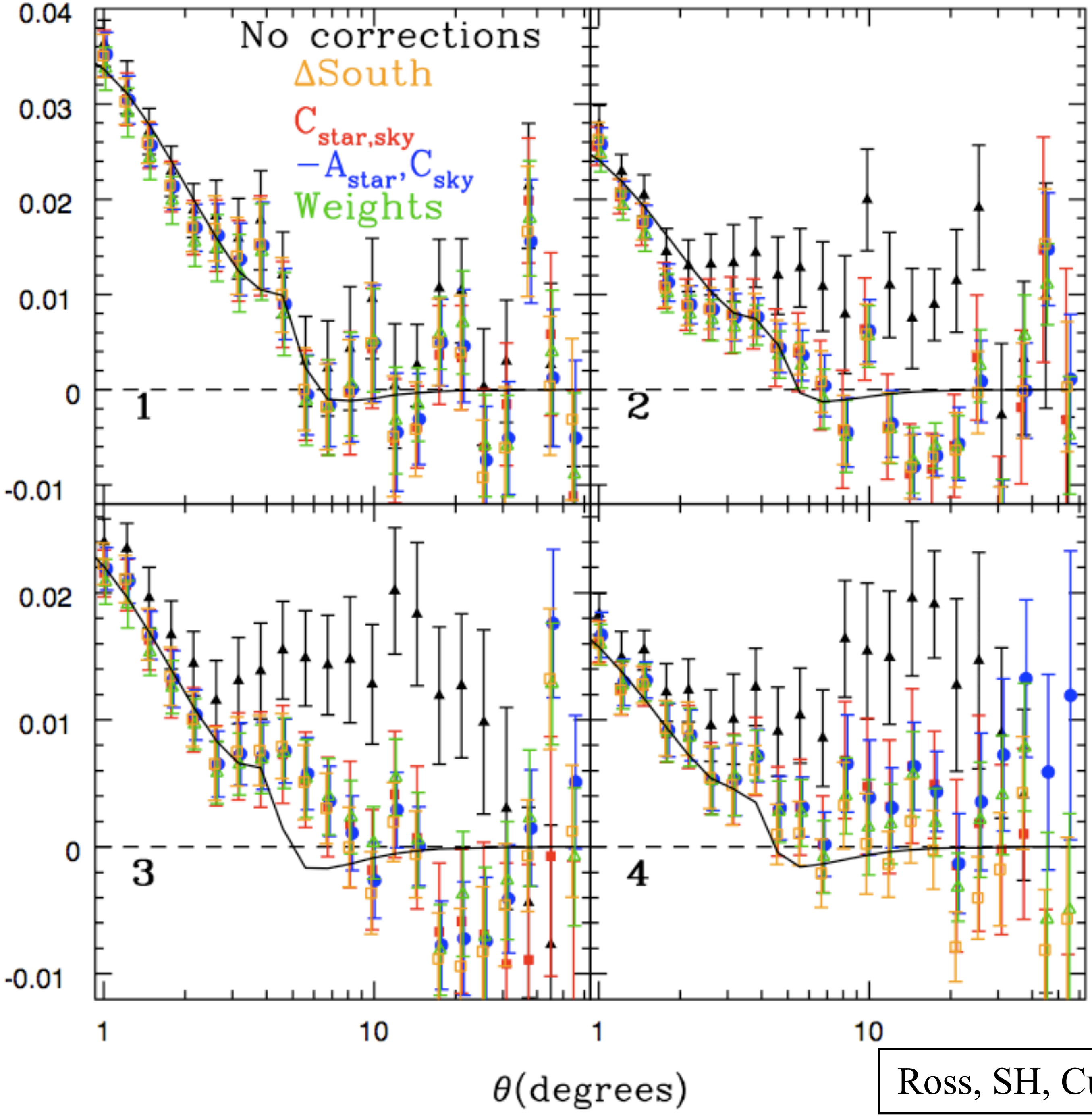
$$< \delta_g^o \delta_{s_2} >=< \delta_g^t \delta_g^t > +\epsilon_1 < \delta_{s_1} \delta_{s_2} > +\epsilon_2 < \delta_{s_2} \delta_{s_2} >$$

$$< \delta_g^o \delta_g^o >=< \delta_g^t \delta_g^t > +\epsilon_1^2 < \delta_{s_1} \delta_{s_1} > +2\epsilon_1 \epsilon_2 < \delta_{s_2} \delta_{s_1} > +\epsilon_2^2 < \delta_{s_2} \delta_{s_2} >$$

We also need to take into account of all the covariances between systematics and across different band power

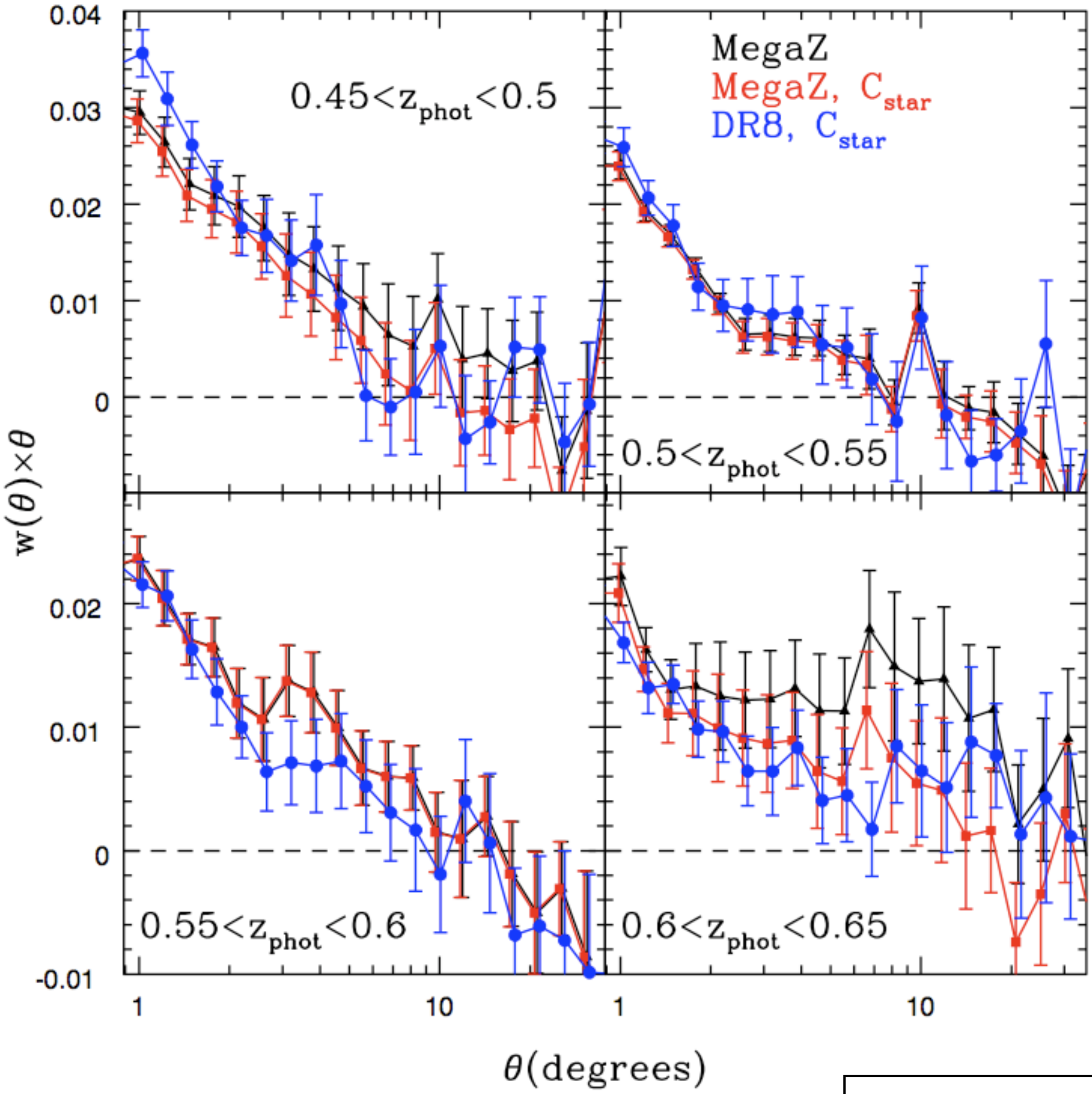
SH, Ross, Cuesta, Seo, White, Schlegel et al. (in prep)

In configuration space: Auto-correlation functions



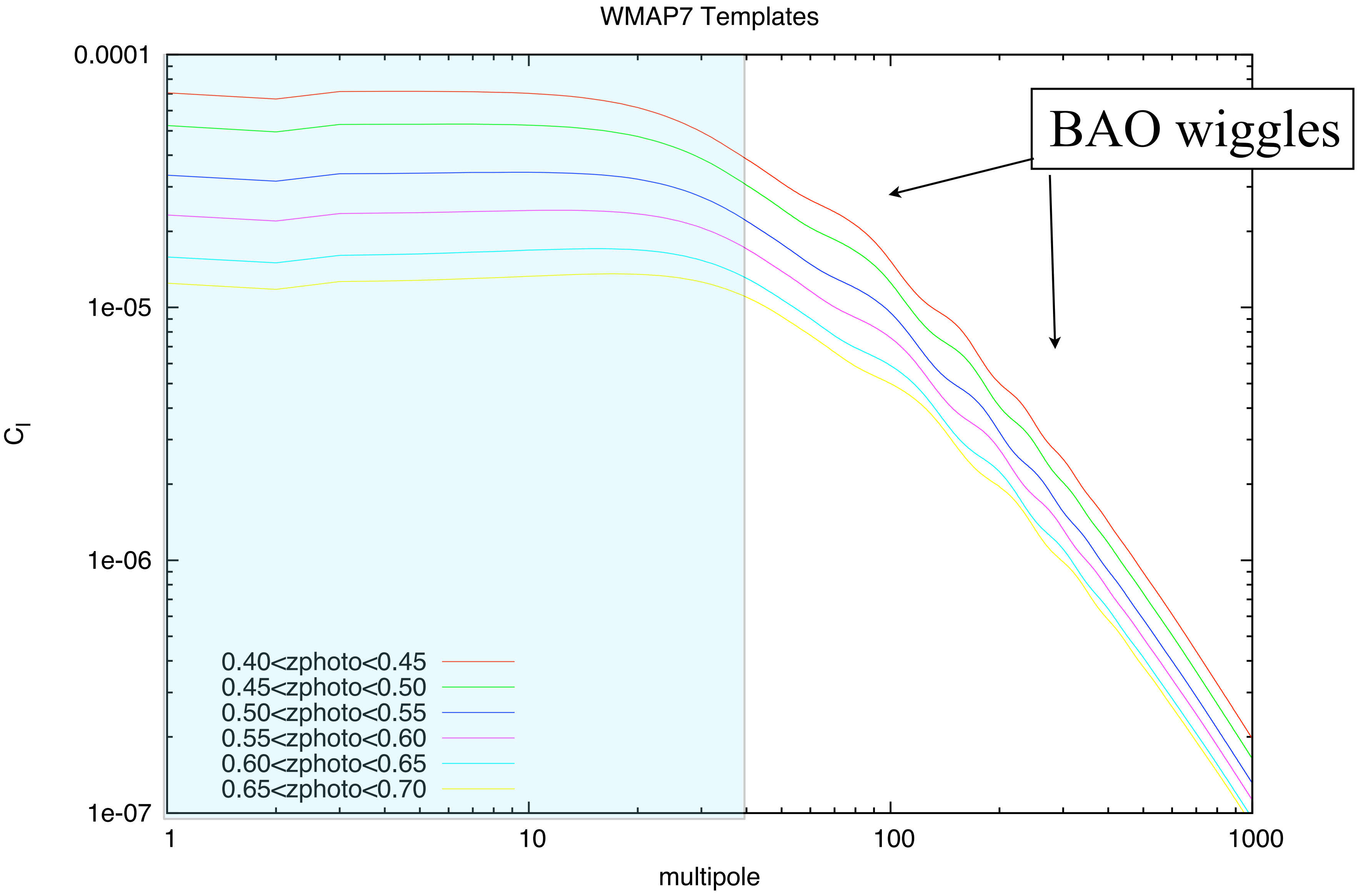
Ross, SH, Cuesta et al. (2011)

People has made claims on extra power in large scales and that it points to primordial non-gaussianities, but it can be explained away by systematics we just talked about



Ross, SH, Cuesta et al. (2011)

Remember? What we expect to see



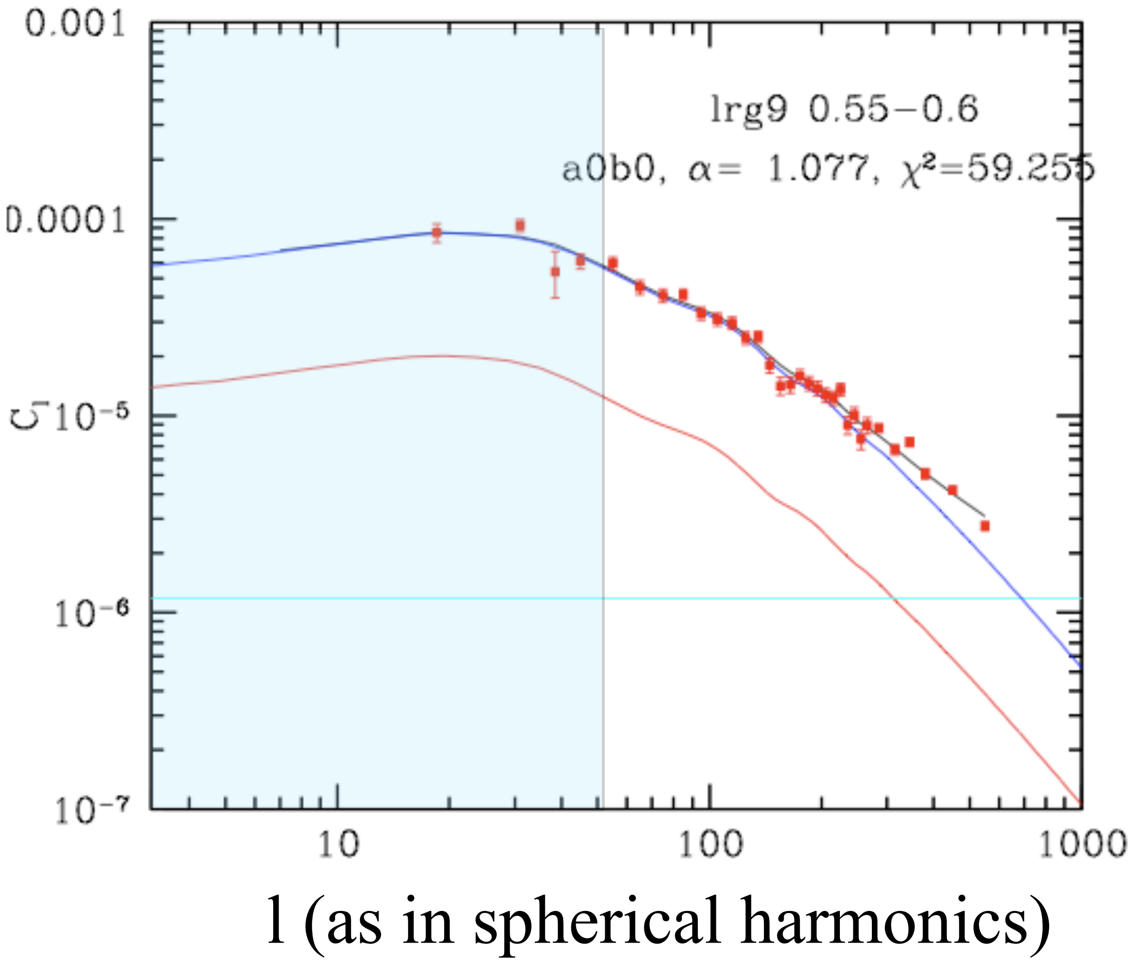
BAO wiggles

BAO: with Luminous Red Galaxies

Preliminary Results before taking out systematics

Angular Power-spectrum

z=0.55-0.6



It is really hard to see the BAO feature, but one can divide out the smooth part of the spectrum

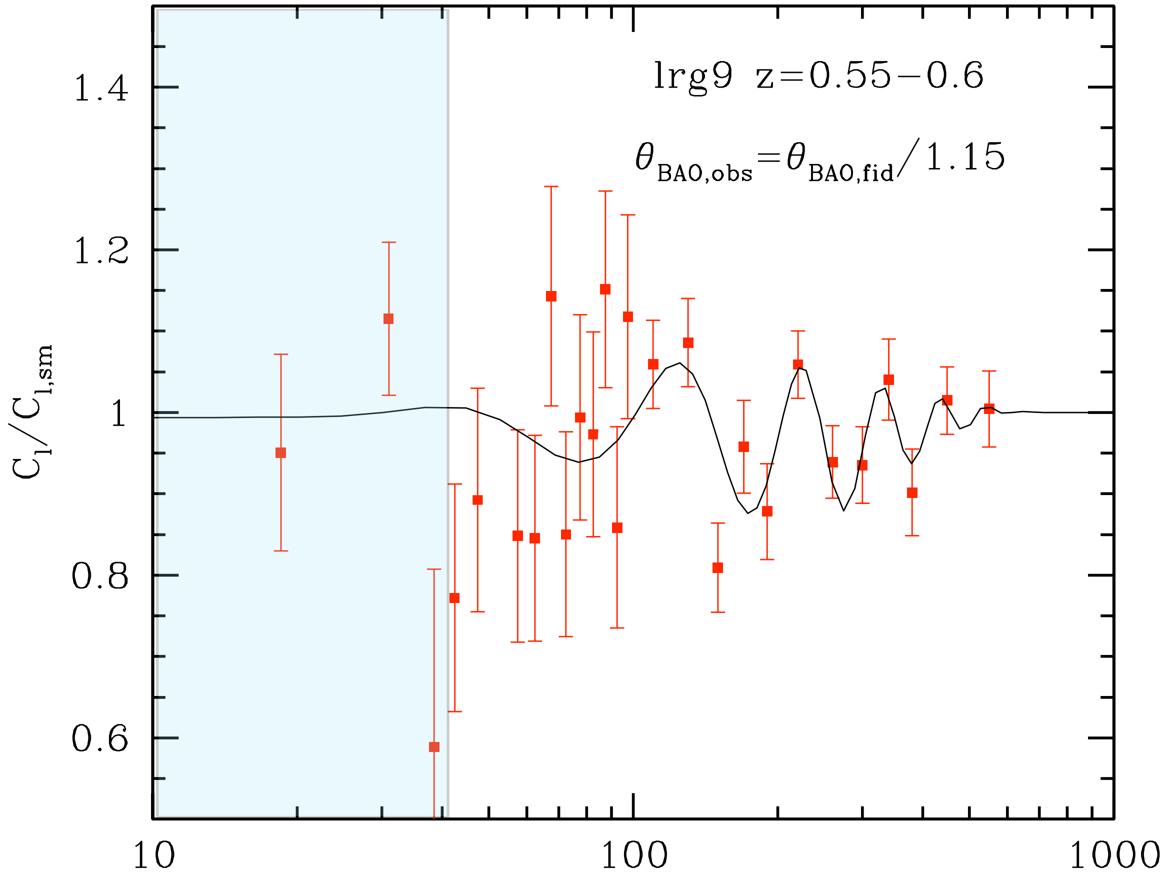
SH, Seo, Ross, White, Schlegel et al. (in prep)

BAO: with Luminous Red Galaxies

Preliminary BAO before taking out systematics

$$C_l/C^{smoothed}(l)$$

z=0.55-0.6



l (as in spherical harmonics)

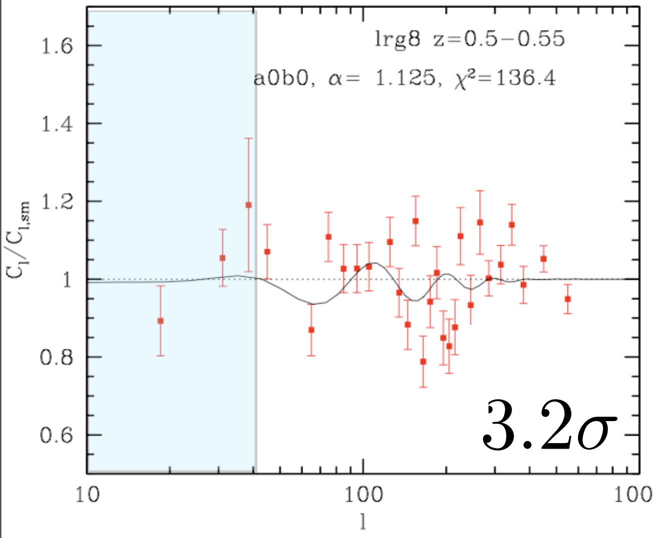
SH, Seo, Ross, White, Schlegel et al. (in prep)

BAO: with Luminous Red Galaxies

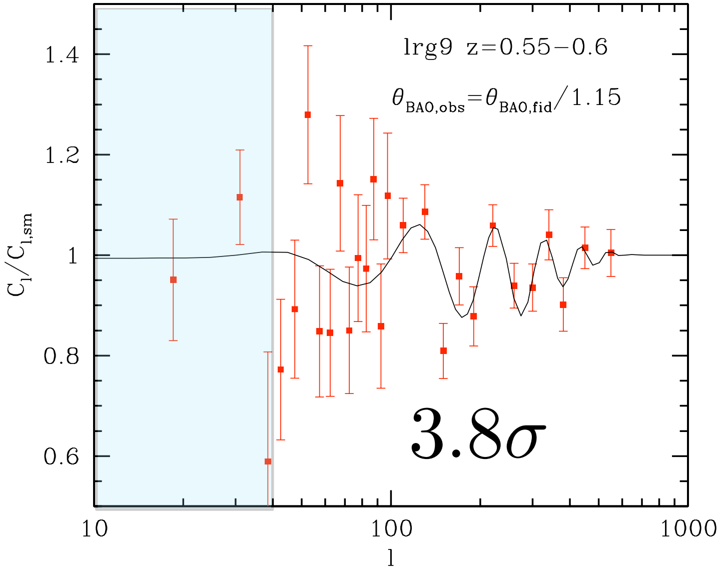
Preliminary BAO before taking out systematics

SH, Seo, Ross, White, Schlegel et al. (in prep)

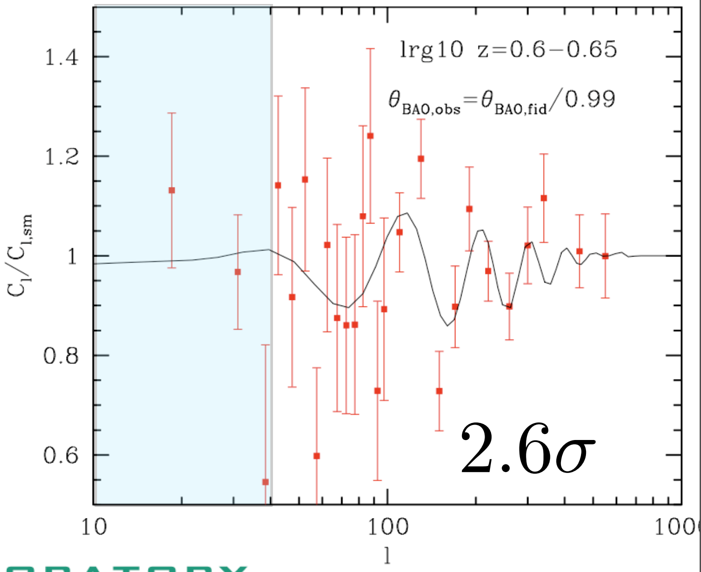
z=0.5-0.55



z=0.55-0.6



z=0.6-0.65

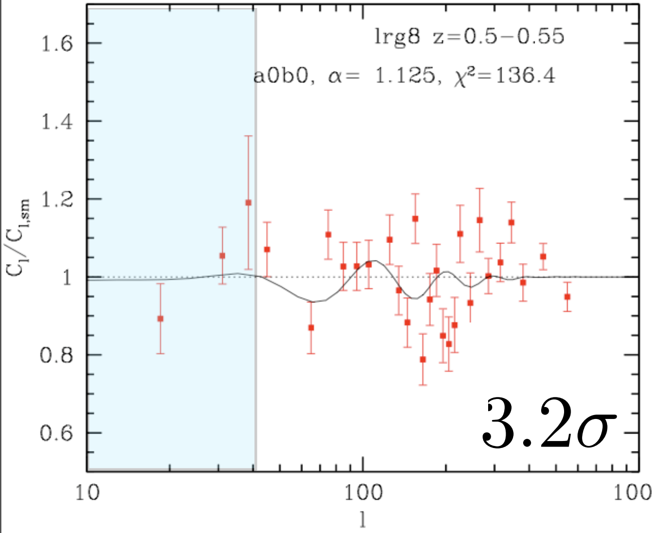


BAO: with Luminous Red Galaxies

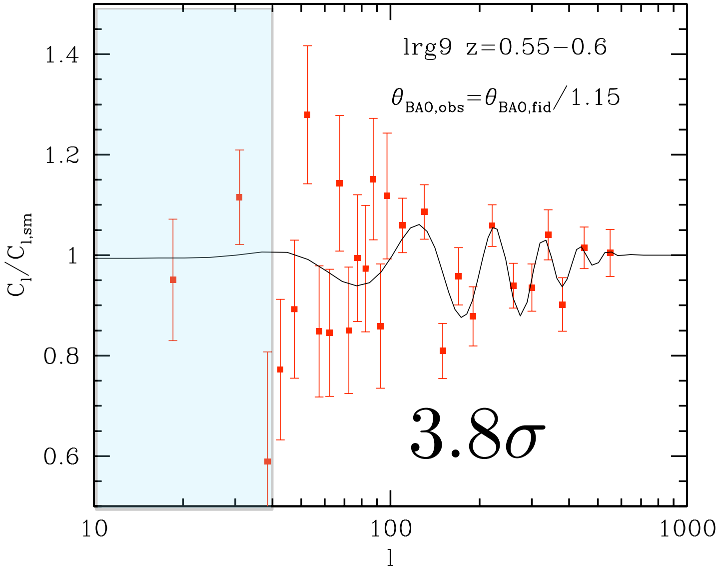
Preliminary BAO before taking out systematics

SH, Seo, Ross, White, Schlegel et al. (in prep)

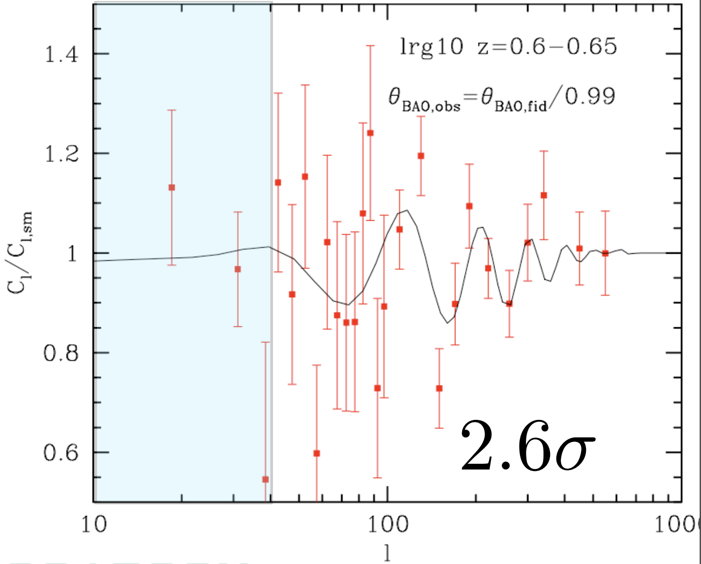
z=0.5-0.55



z=0.55-0.6



z=0.6-0.65



However, there may still be small remaining systematics in higher l...

BAO: with Luminous Red Galaxies
Systematics: Taking them out of the equation

True galaxy overdensity

Observed galaxy overdensity

$$\delta_g^o = \delta_g^t + \sum_{i=0}^{N} \epsilon_i \delta_{s_i}$$

Various systematics

For example, if i=2 only:

$$< \delta_g^o \delta_{s_1} > = < \delta_g^t \delta_g^t > + \epsilon_1 < \delta_{s_1} \delta_{s_1} > + \epsilon_2 < \delta_{s_2} \delta_{s_1} >$$

$$< \delta_g^o \delta_{s_2} > = < \delta_g^t \delta_g^t > + \epsilon_1 < \delta_{s_1} \delta_{s_2} > + \epsilon_2 < \delta_{s_2} \delta_{s_2} >$$

$$< \delta_g^o \delta_g^o > = < \delta_g^t \delta_g^t > + \epsilon_1^2 < \delta_{s_1} \delta_{s_1} > + 2\epsilon_1 \epsilon_2 < \delta_{s_2} \delta_{s_1} > + \epsilon_2^2 < \delta_{s_2} \delta_{s_2} >$$

We also need to take into account of all the covariances between systematics and across different band power

Awaiting for the new answers ...

SH, Seo, Ross, White, Schlegel et al. (in prep)

Preliminary results
without taking out all of the systematics

(if you really want to know)

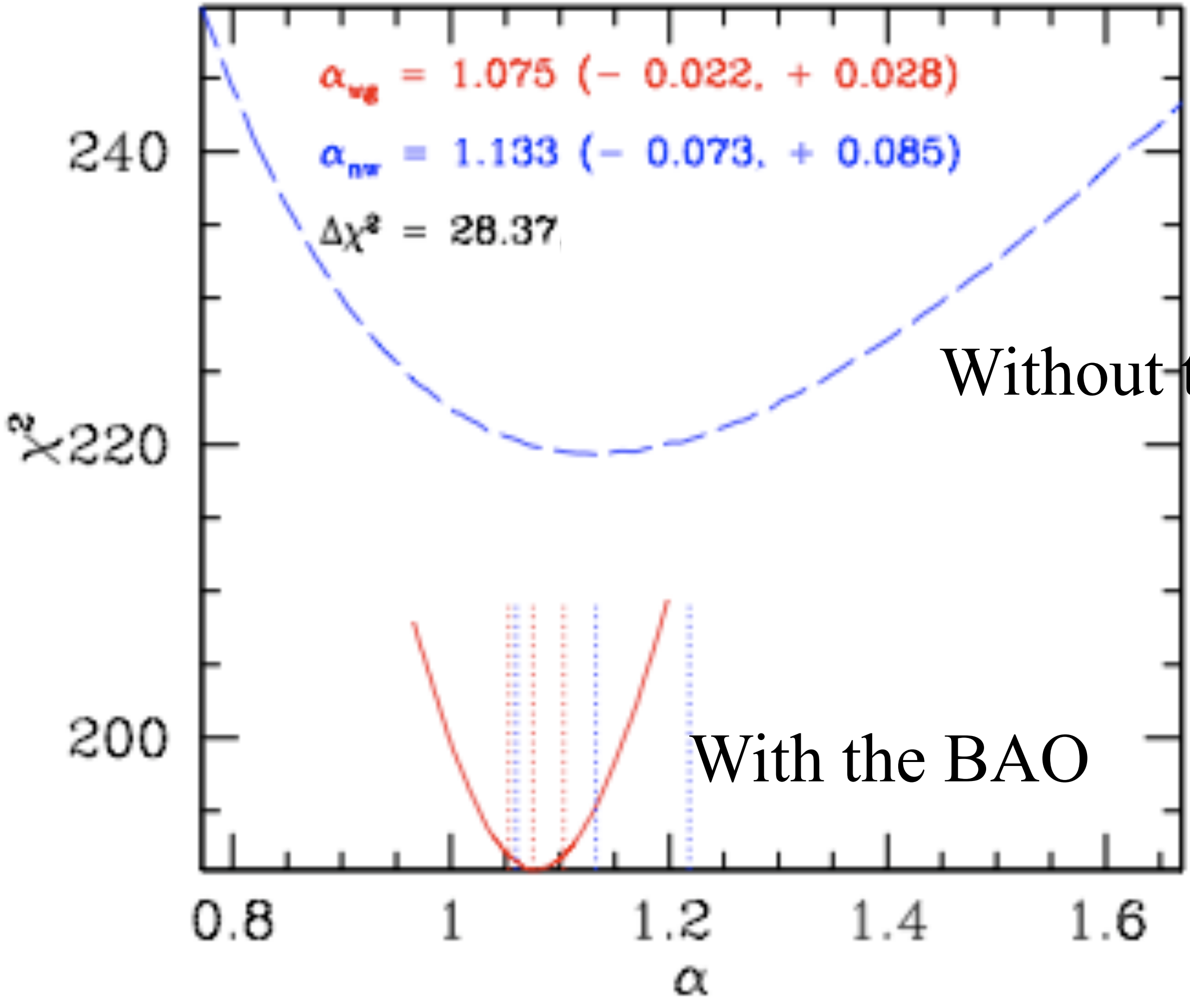
The following results are derived:

by taking into account of angular power-spectra from l >40 from z=0.45-0.65.

It should be quite clean of systematics, but there are probably some residuals which we are going to take out with our new method.

Preliminary results
without taking out all of the systematics

We look at the difference in chi-square for BAO and no-BAO models

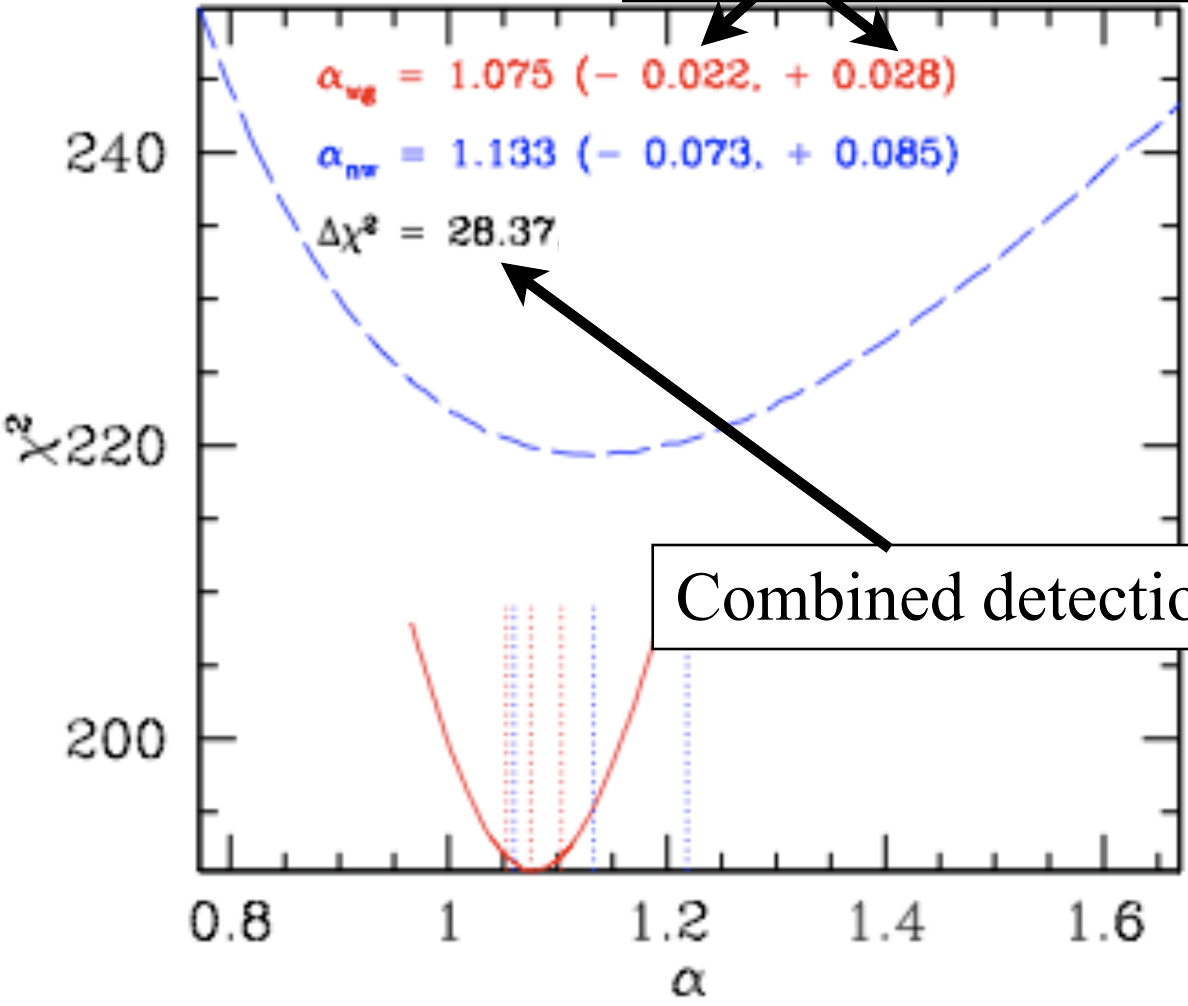


Without the BAO

With the BAO

Preliminary results
without taking out all of the systematics

~2.5% measurement of the angular diameter distance



Combined detection of ~5.3 sigmas

BAO: with Luminous Red Galaxies

What is new?

- Data: **Largest volume** ever used for galaxy clustering: 14,000 sq deg up to z=0.7, this is equivalent to $15\mathrm{Gpc}^3$

BAO: with Luminous Red Galaxies
What is new?

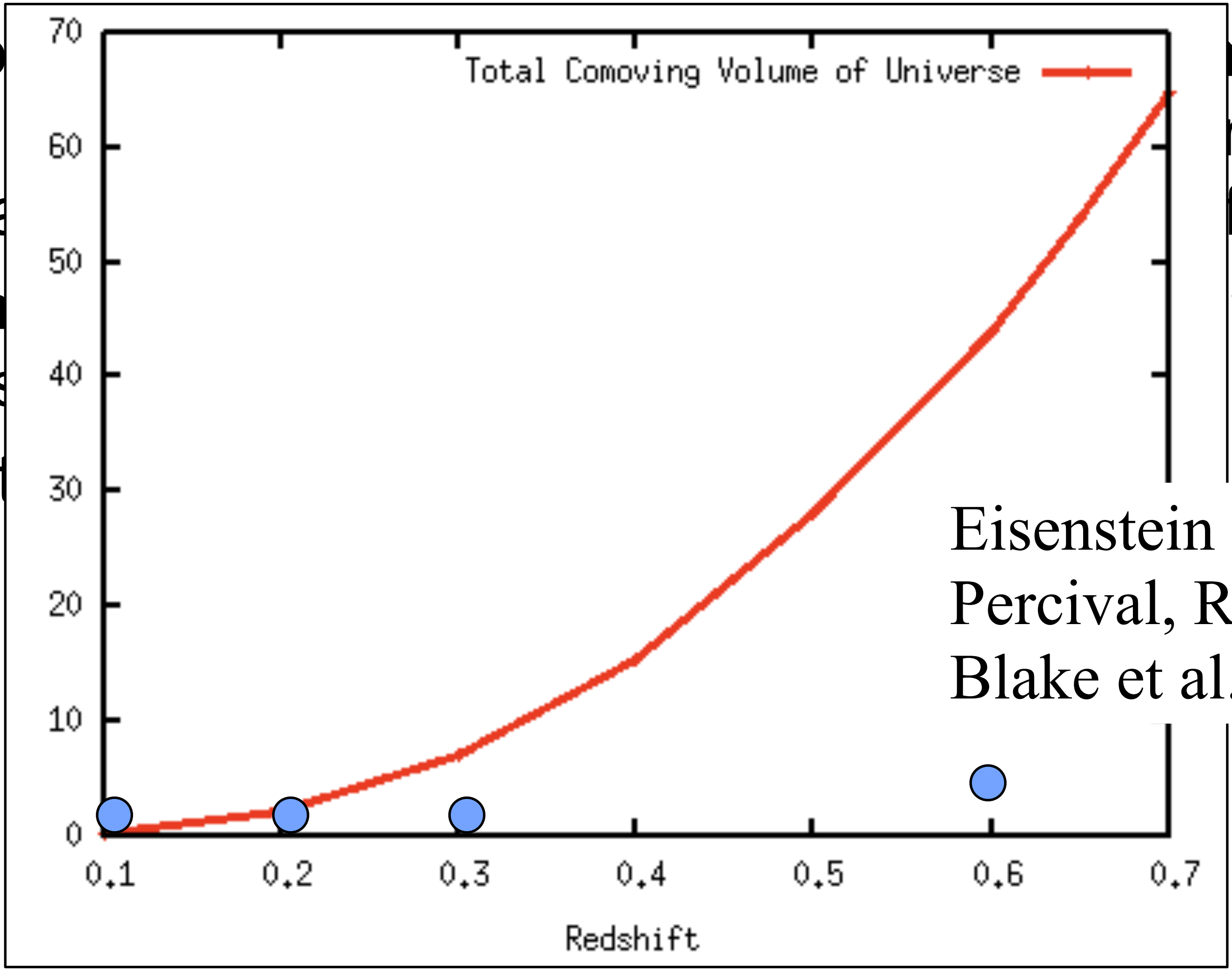
- Data: **Largest volume** ever used for galaxy clustering: 14,000 sq deg up to z=0.7, this is equivalent to $15\mathrm{Gpc}^3$
- Method: **First application of Quadratic Estimator** on all redshift slices for BAO while taking into account of all the correlations between different redshift slices of galaxies.
  - **Unbiased minimum variance** measurement with various systematics taken into account.

BAO: with Luminous Red Galaxies
What is new?

- Data: **Largest volume** ever used for galaxy clustering: 14,000 sq deg up to z=0.7, this is equivalent to $15 \mathrm{Gpc}^3$
- Method: **First application of Quadratic Estimator** on all redshift slices for BAO while taking into account of all the correlations between different redshift slices of galaxies.
    - **Unbiased minimum variance** measurement with various systematics taken into account.
- Detection:

BAO: with Luminous Red Galaxies
What is new?

- Data: **Largest volume** ever used for galaxy clustering: 14,000 sq deg up to z=0.7, this is equivalent to $15\mathrm{Gpc}^3$
- Metho **nator** on all redshi nt of all the correla f galaxies.
  - — **Un** with various sys
- Detect

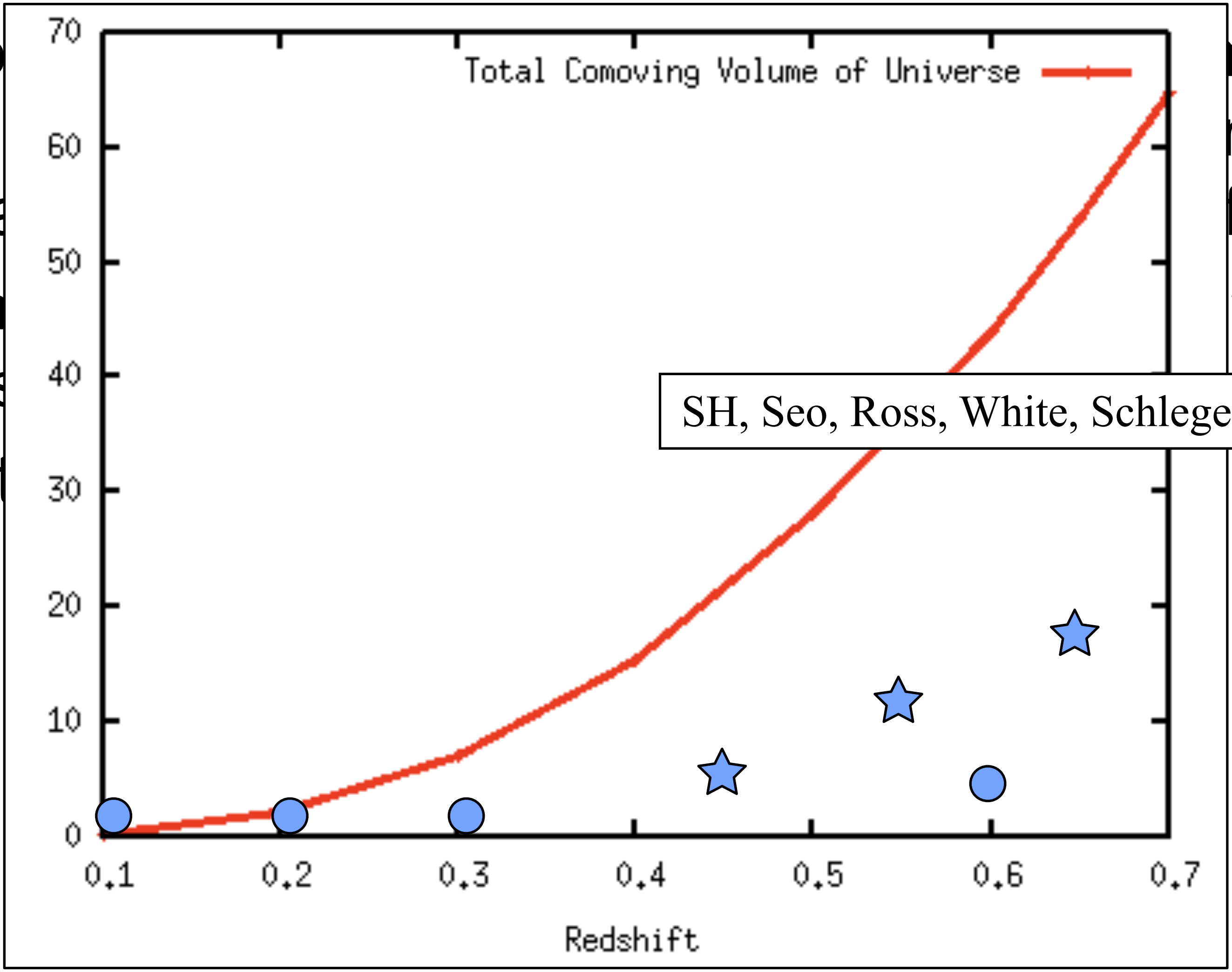


Eisenstein et al. 2005
Percival, Reid et al. 2008
Blake et al. 2011

BAO: with Luminous Red Galaxies

What is new?

- Data: **Largest volume** ever used for galaxy clustering: 14,000 sq deg up to z=0.7, this is equivalent to $15\mathrm{Gpc}^3$
- Metho **nator** on all redshi nt of all the correla f galaxies.
  - — **Un** with various sys
- Detect



SH, Seo, Ross, White, Schlegel et al. (in prep)

BAO: with Luminous Red Galaxies
What is new?

- Data: **Largest volume** ever used for galaxy clustering: 14,000 sq deg up to z=0.7, this is equivalent to $15\mathrm{Gpc}^3$
- Method: **First application of Quadratic Estimator** on all redshift slices for BAO while taking into account of all the correlations between different redshift slices of galaxies.
  - — **Unbiased minimum variance** measurement with various systematics taken into account.
- Detection:
  - — This work: Significant Detections at **high redshift** range: 0.45<z<0.65 (competitive to constraints from spectroscopic survey WiggleZ [Blake et al. 2011])

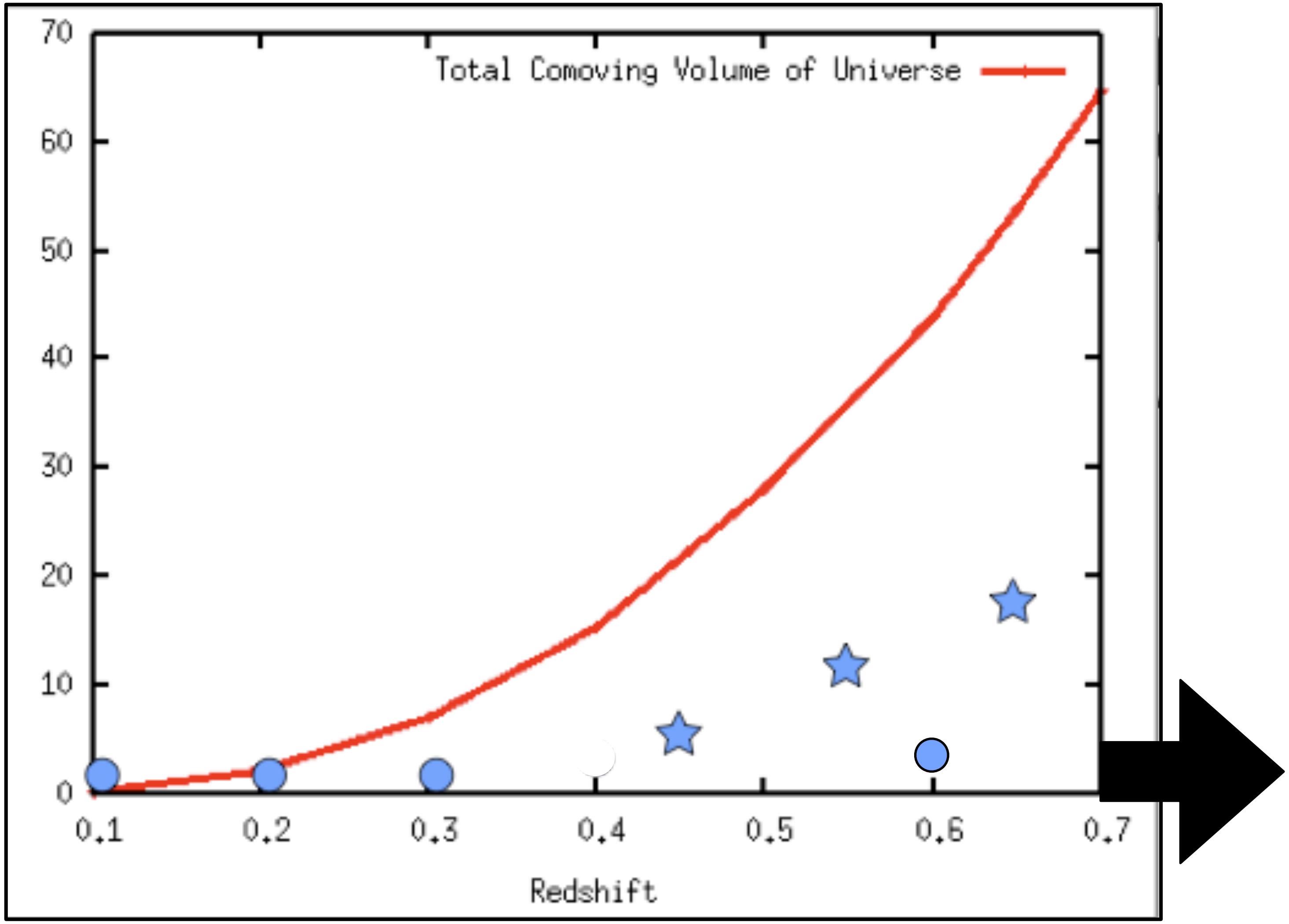
BAO: with Luminous Red Galaxies

Looking forward

- Cosmological Constraints from BAO will be coming soon.
- More detailed systematic tests have to be carried out.
- Photometric LRGs can be used for BAO in upcoming surveys such as DES, PanStarrs and LSST.
- A variant of the Quadratic Estimator can be applied to any Spectroscopic LRGs (in SDSS III-BOSS, BigBOSS, SuMire-PFS, WFIRST...) will provide < 10% constraint on equation of state of Dark Energy.

BAO: Beyond Galaxies

- How can we learn about cosmology at much higher redshift ?



z>2?

Next lecture ...

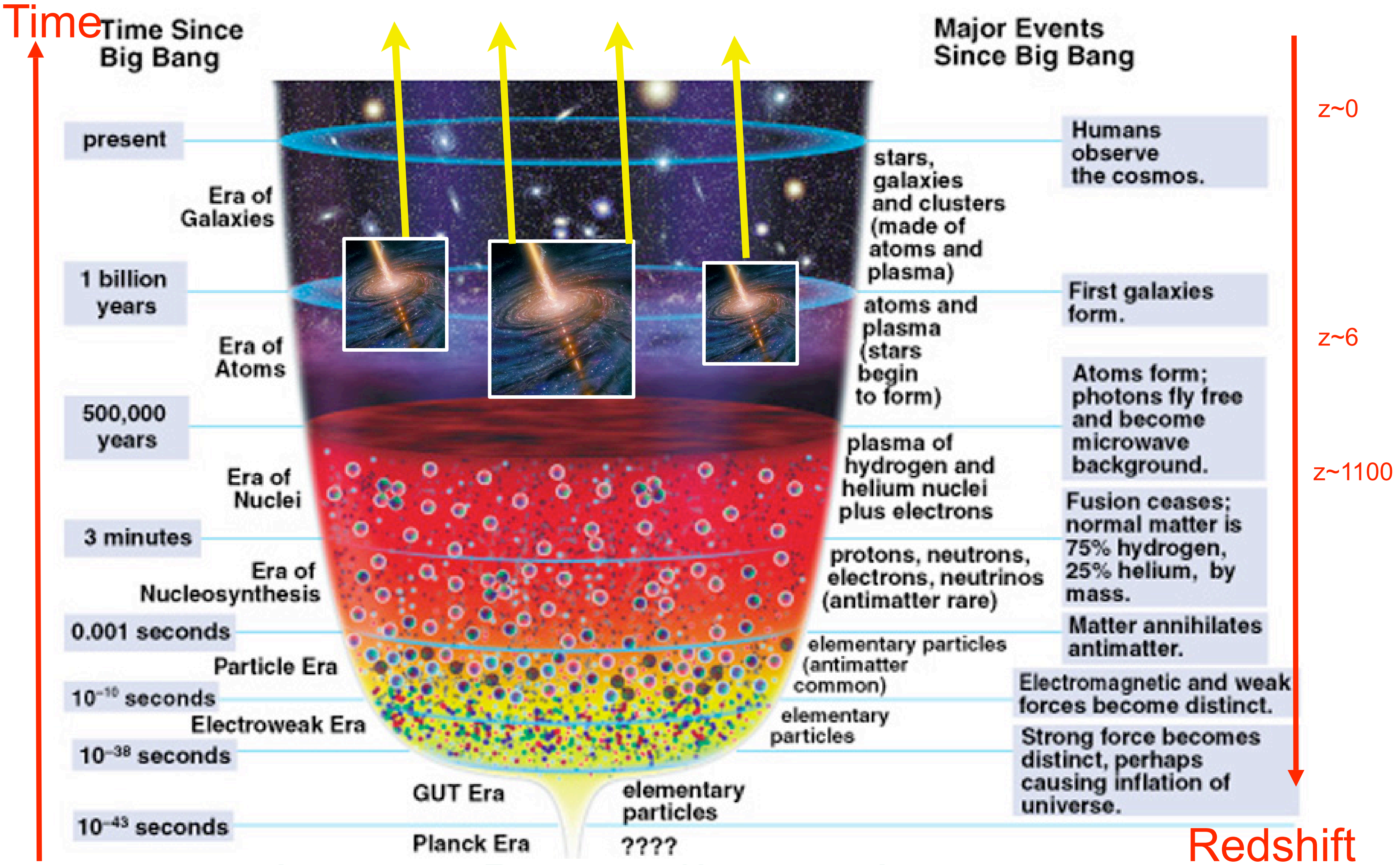
3 Lectures

- Dark Energy, Baryon Acoustic Oscillations and more
- Observational Cosmology in Action
- A new large scale structure tracer:
  - Lyman alpha forest

End of slides

Beyond: With Lyman Alpha Forest

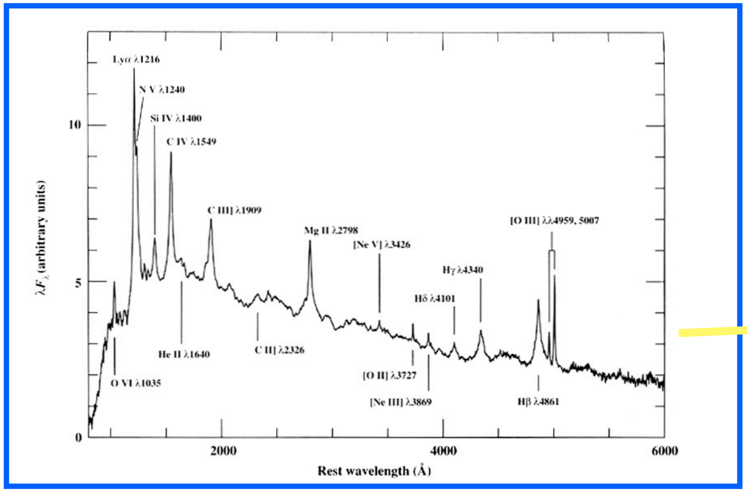
What is it?

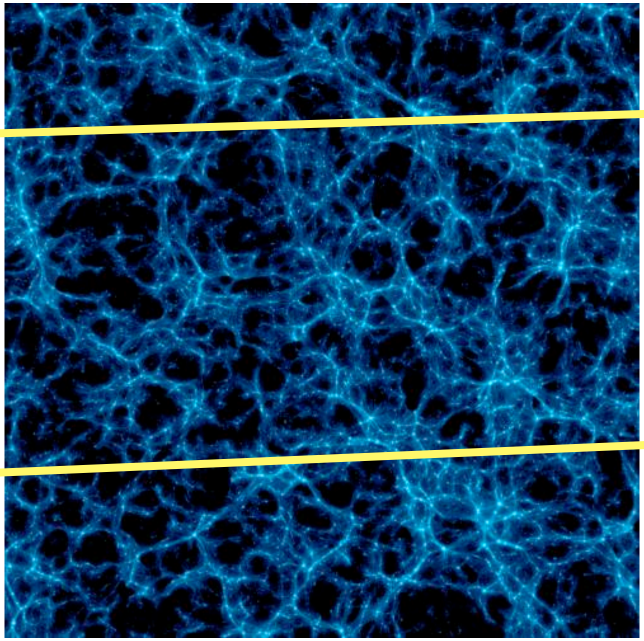


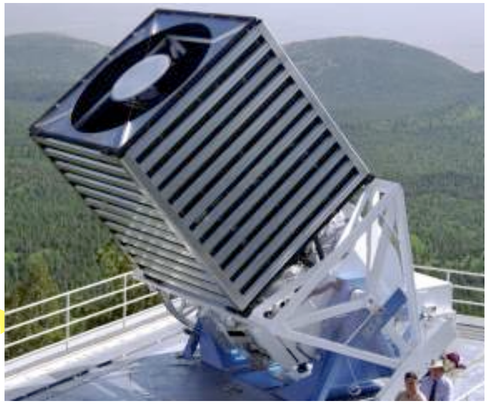
Beyond: With Lyman Alpha Forest

What is it?

Quasar Spectra





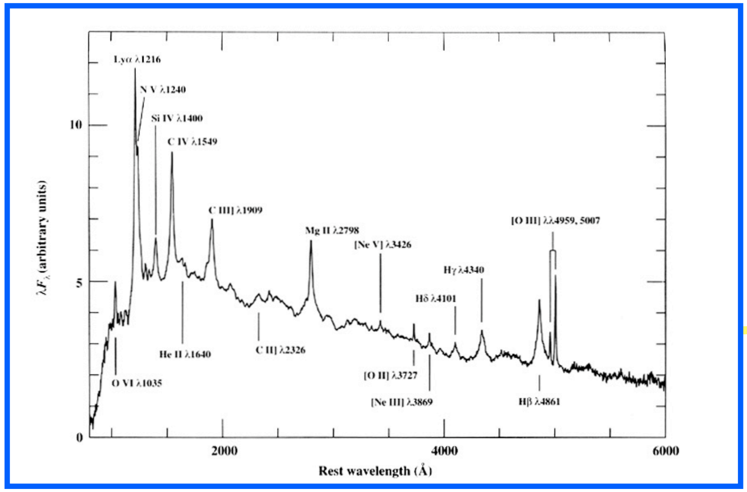


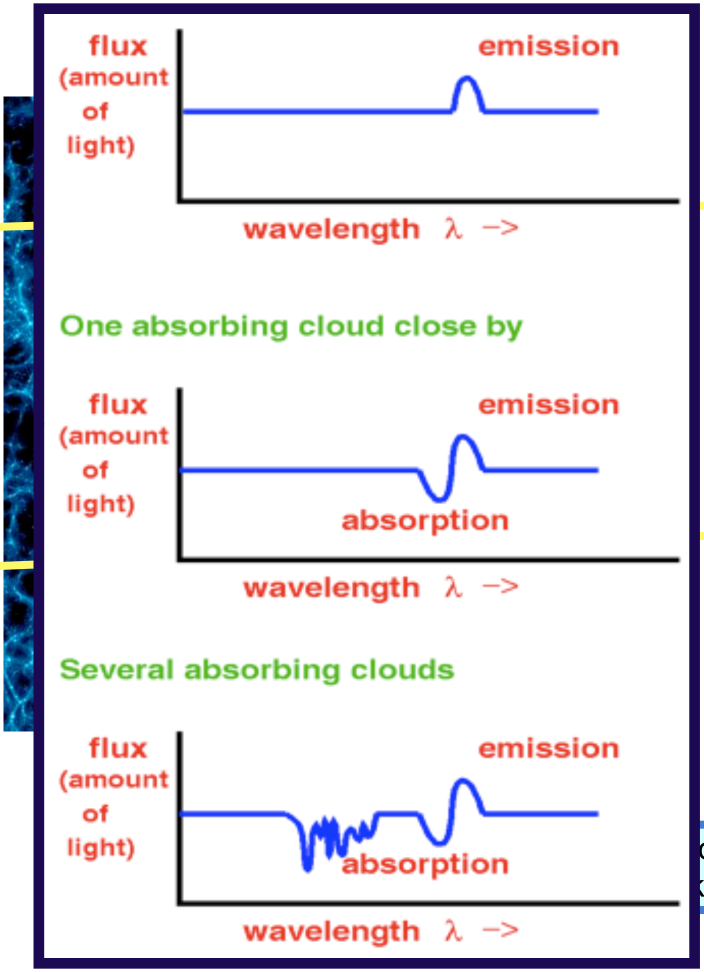
Courtesy simulation of gas from Renyue Cen and Jerry Ostriker

Beyond: With Lyman Alpha Forest

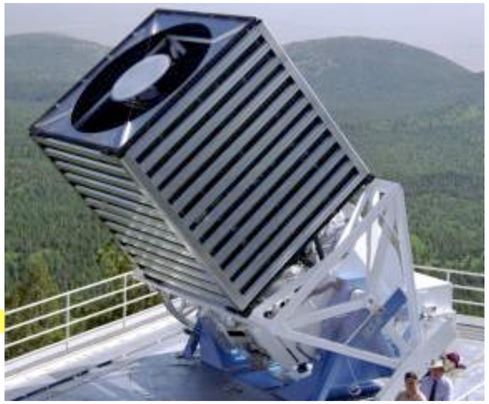
What is it?

Quasar Spectra





om
ker



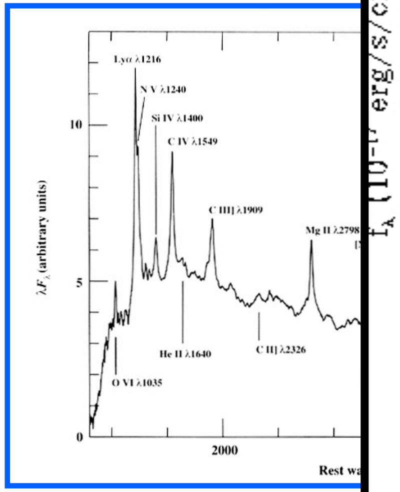
From Joanne Cohn’s website

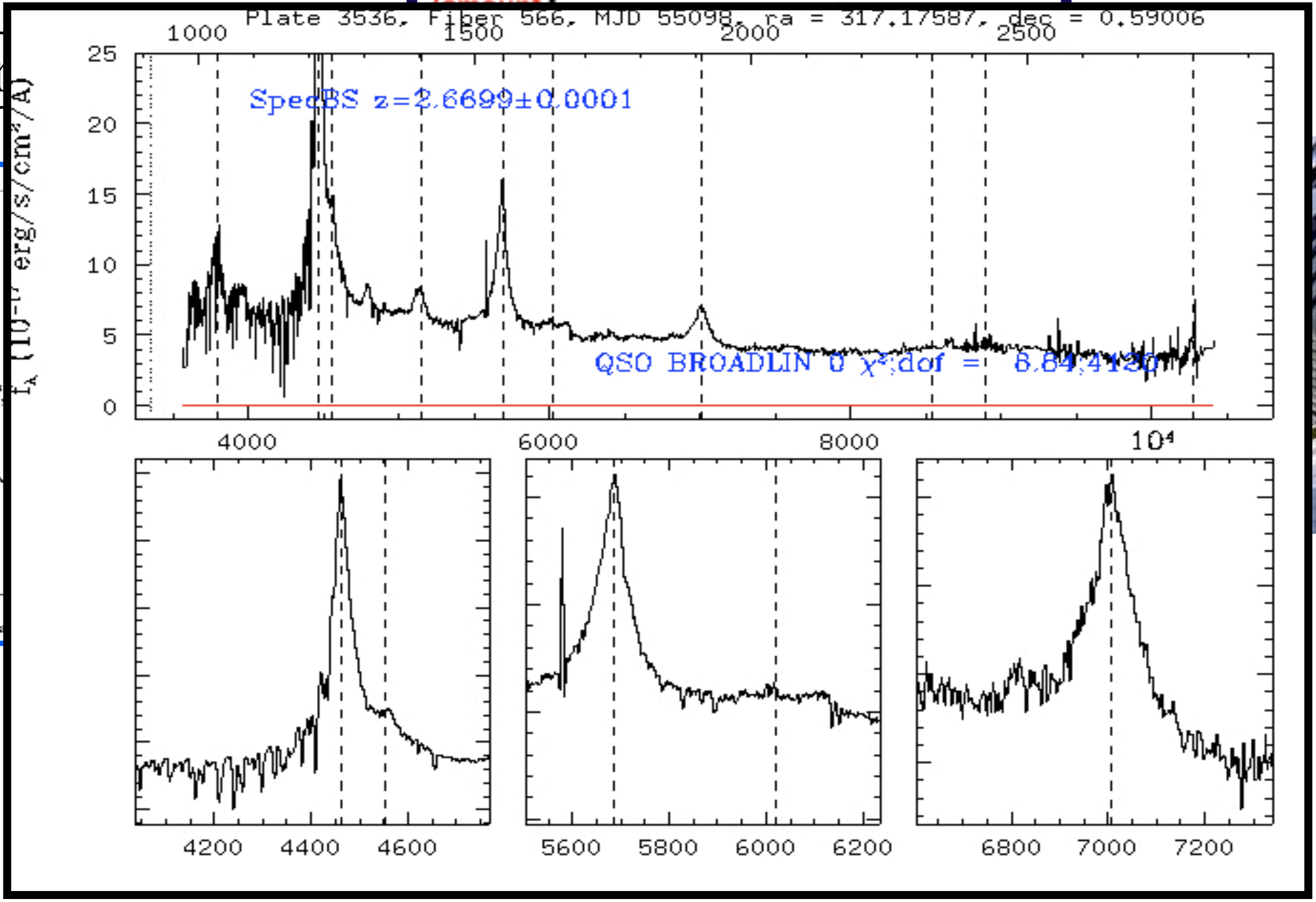
Beyond: With Lyman Alpha Forest

What is it?

Locates the Neutral Hydrogen of the Universe, thus tracing overdensities of the Universe

Quasar



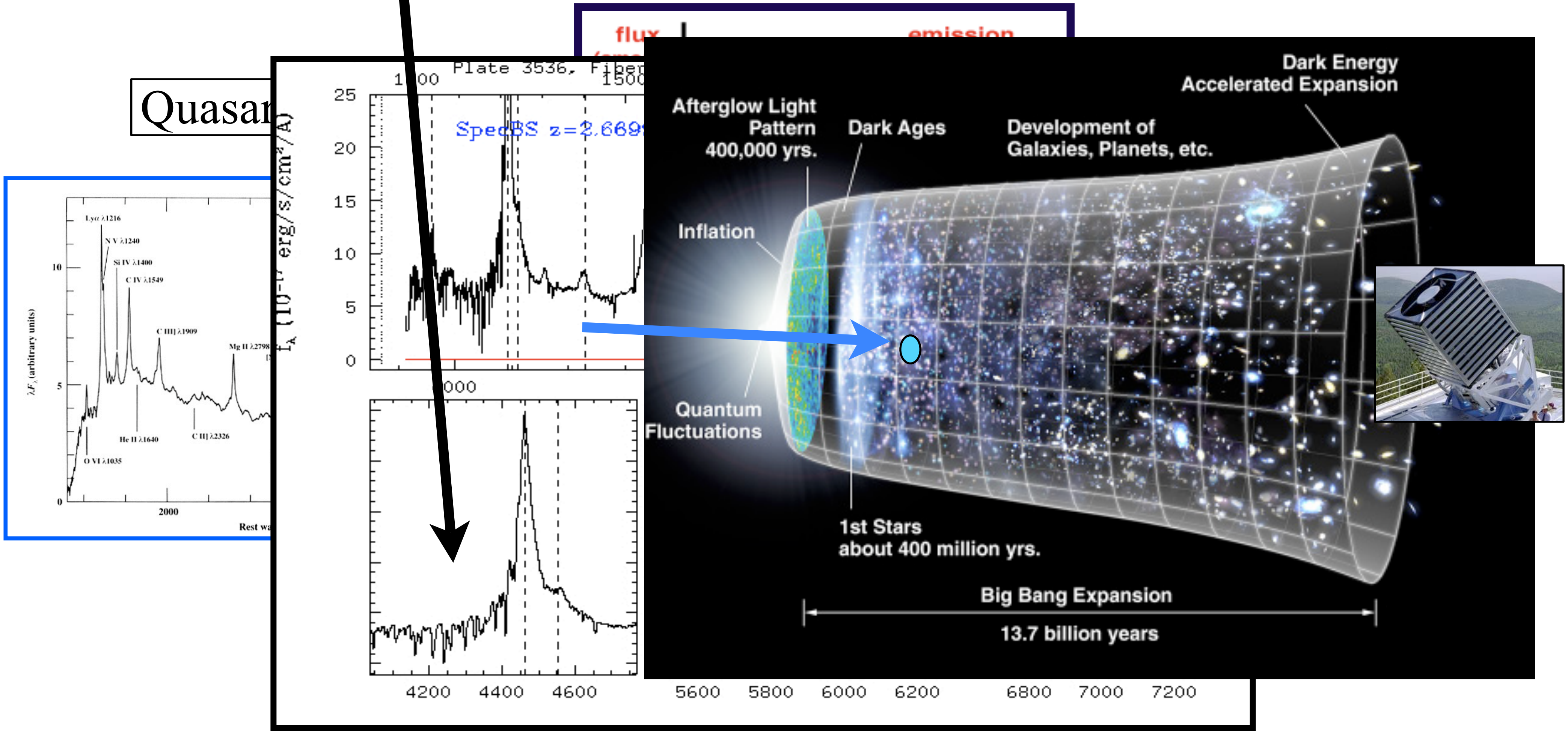


Beyond: With Lyman Alpha Forest

What is it?

Locates the Neutral Hydrogen of the Universe, thus tracing overdensities of the Universe

Quasar

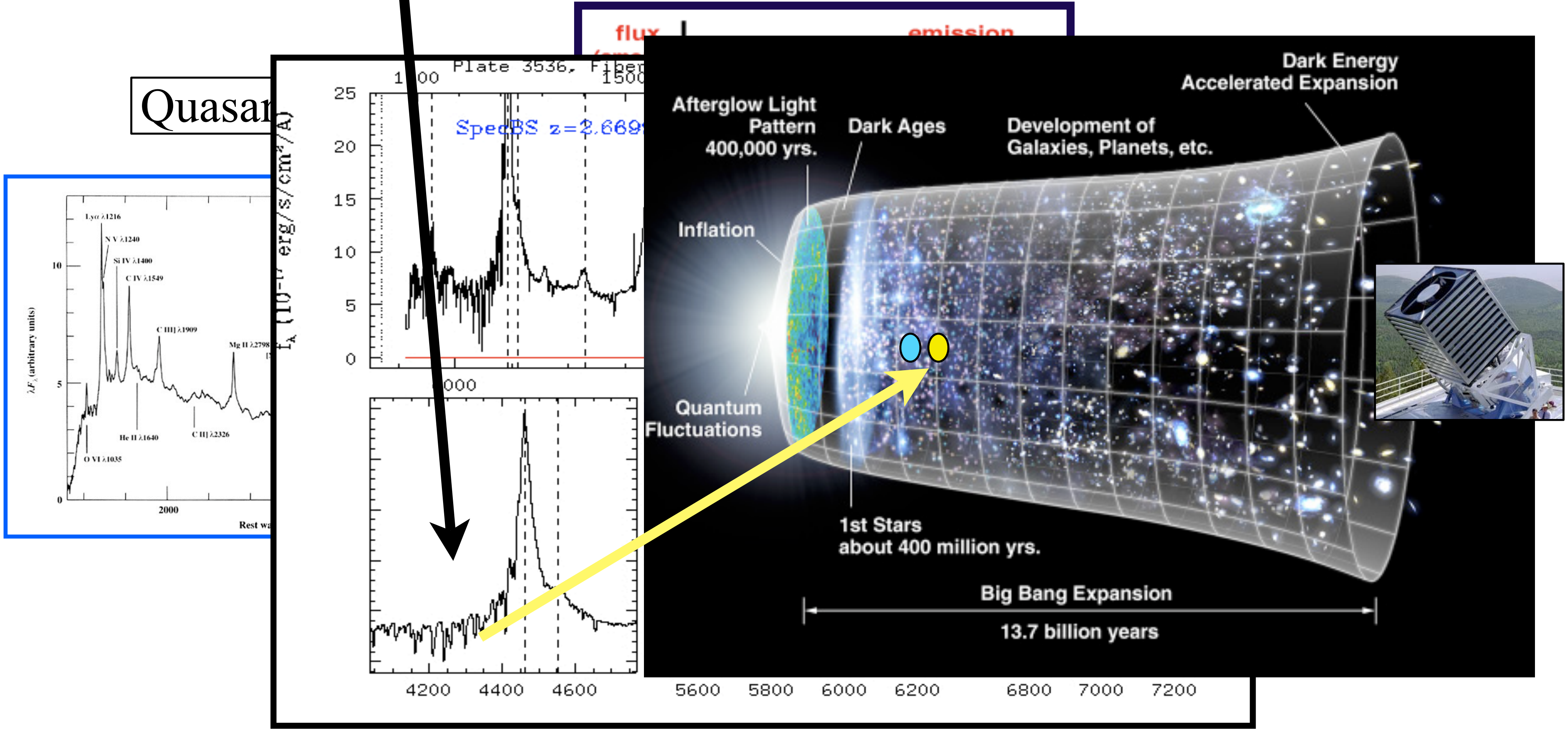


Beyond: With Lyman Alpha Forest

What is it?

Locates the Neutral Hydrogen of the Universe, thus tracing overdensities of the Universe

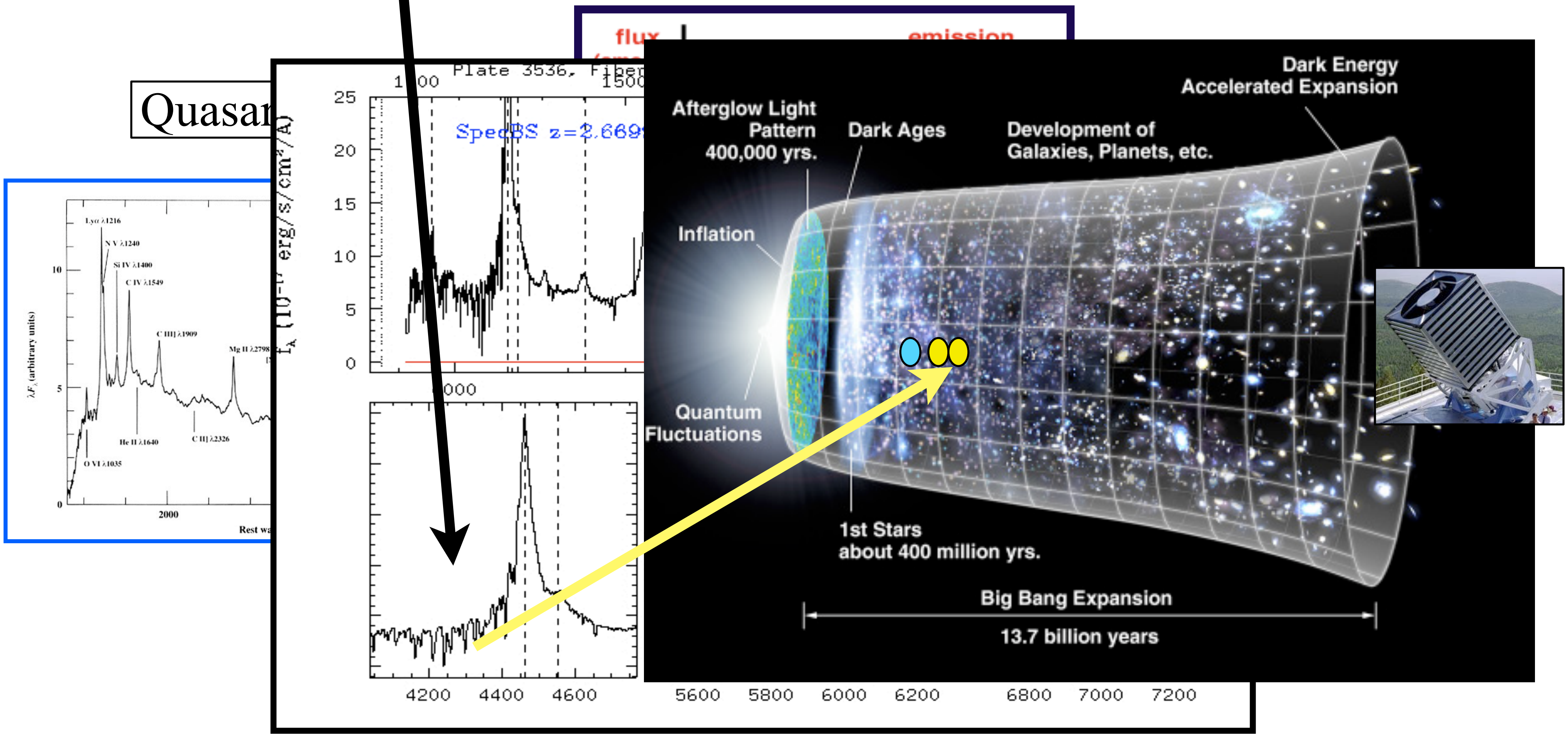
Quasar



Beyond: With Lyman Alpha Forest

What is it?

Locates the Neutral Hydrogen of the Universe, thus tracing overdensities of the Universe

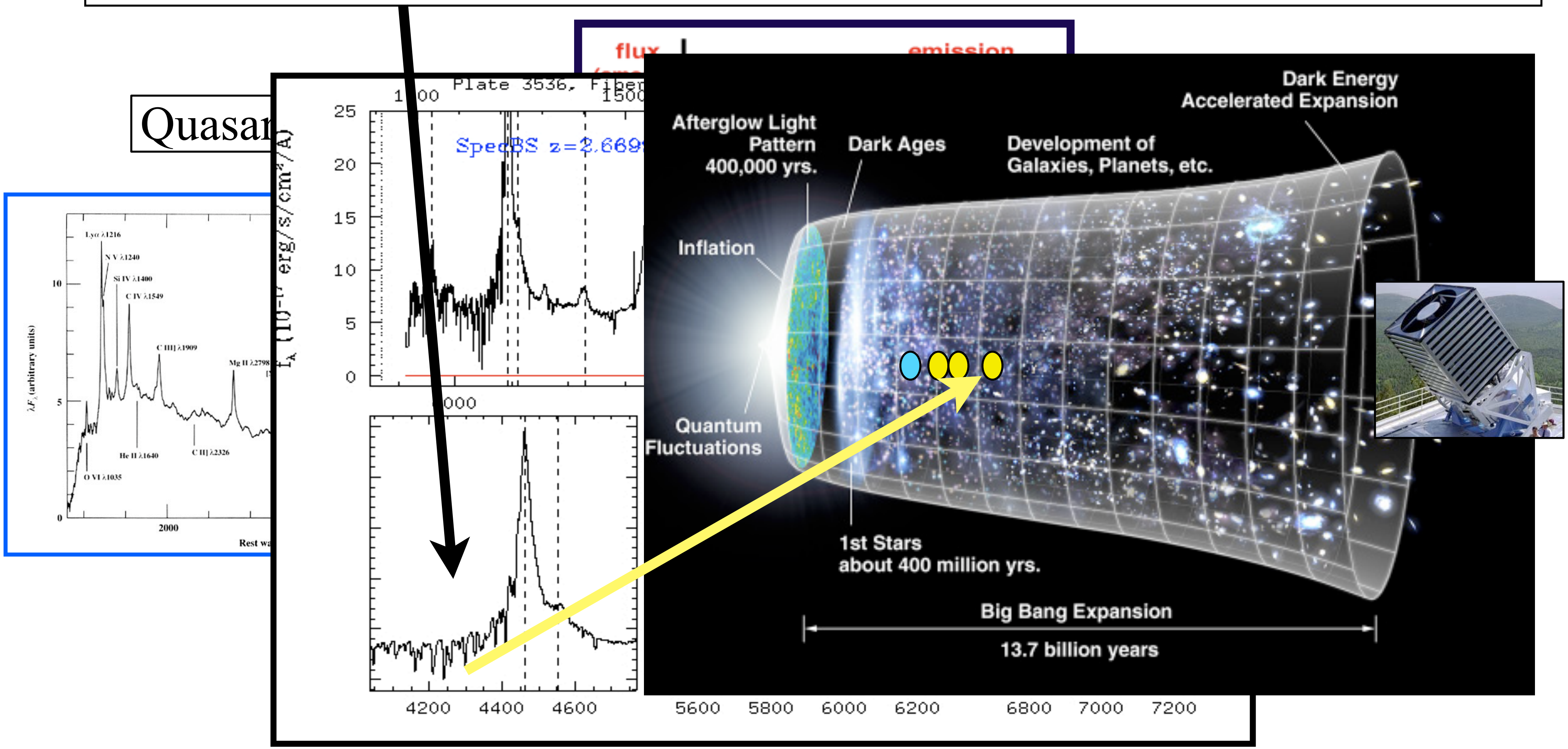


Quasar

Beyond: With Lyman Alpha Forest

What is it?

Locates the Neutral Hydrogen of the Universe, thus tracing overdensities of the Universe

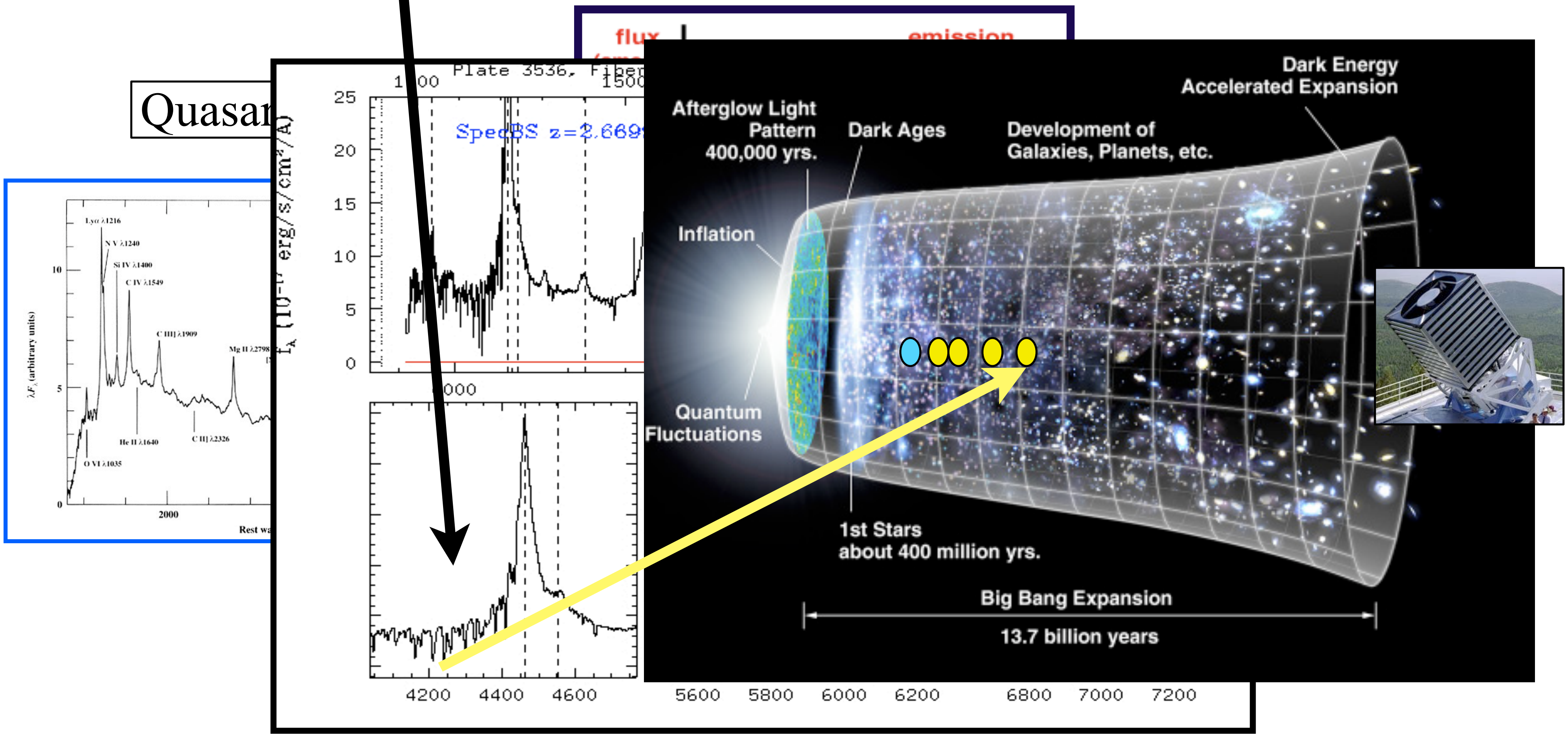


Beyond: With Lyman Alpha Forest

What is it?

Locates the Neutral Hydrogen of the Universe, thus tracing overdensities of the Universe

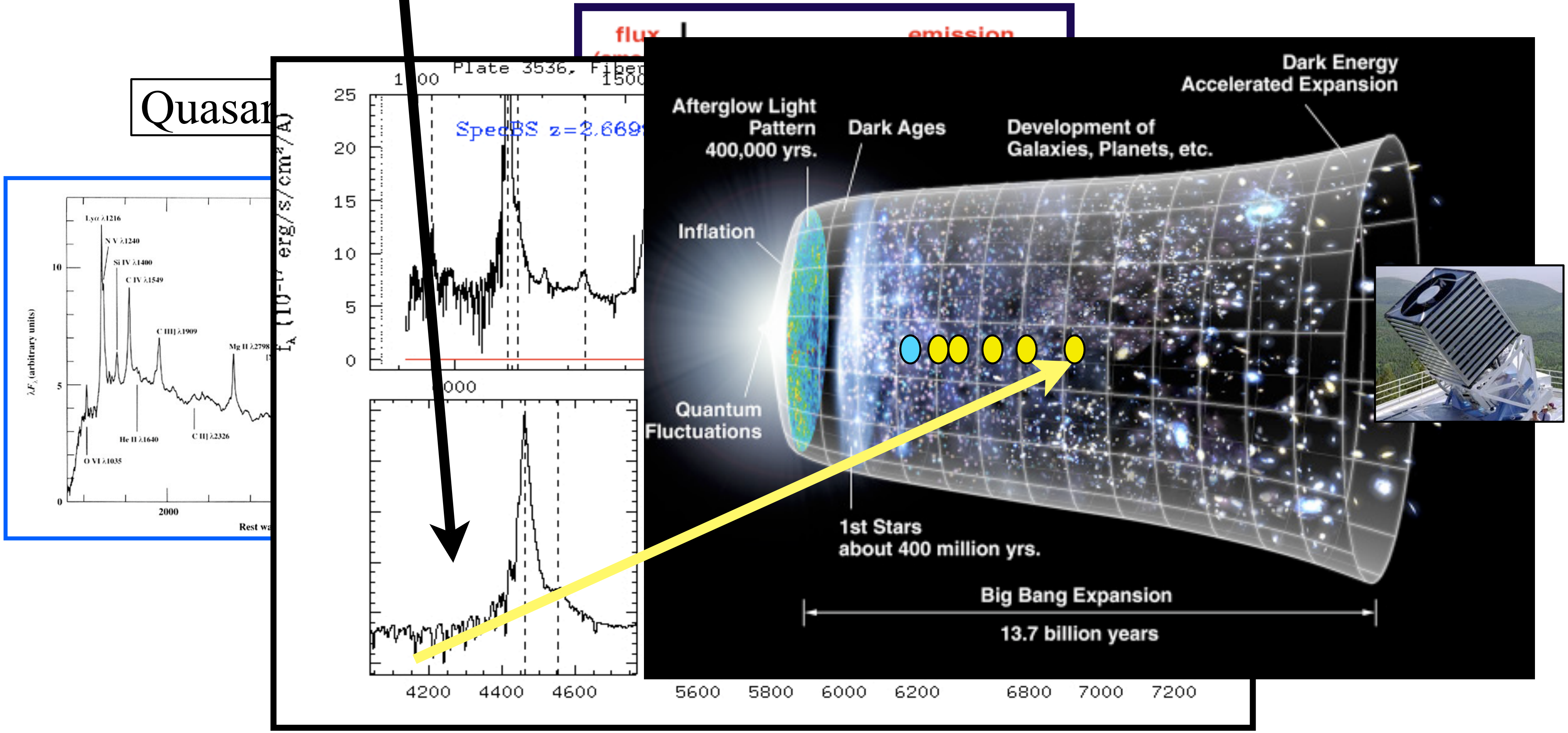
Quasar



Beyond: With Lyman Alpha Forest

What is it?

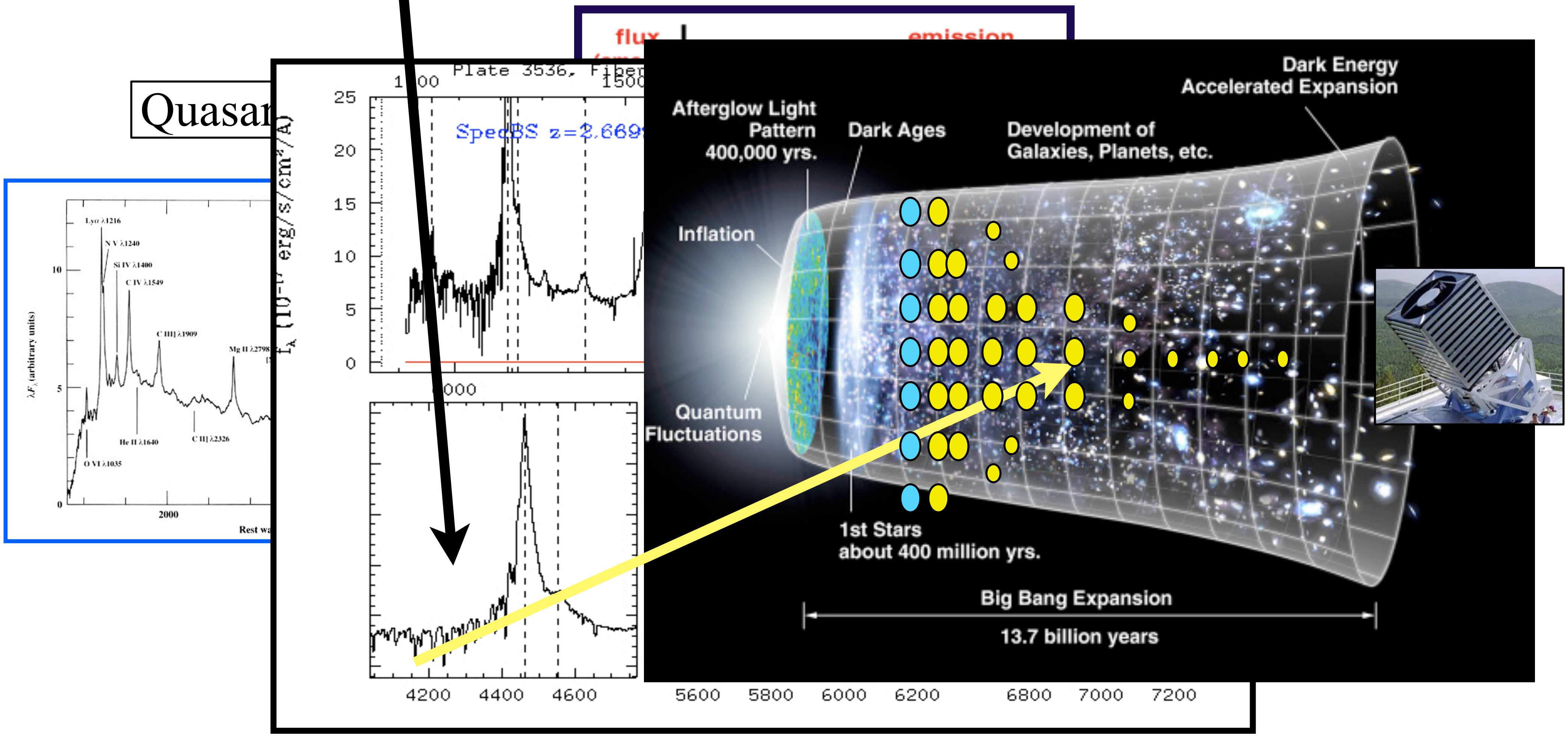
Locates the Neutral Hydrogen of the Universe, thus tracing overdensities of the Universe



Beyond: With Lyman Alpha Forest

What is it?

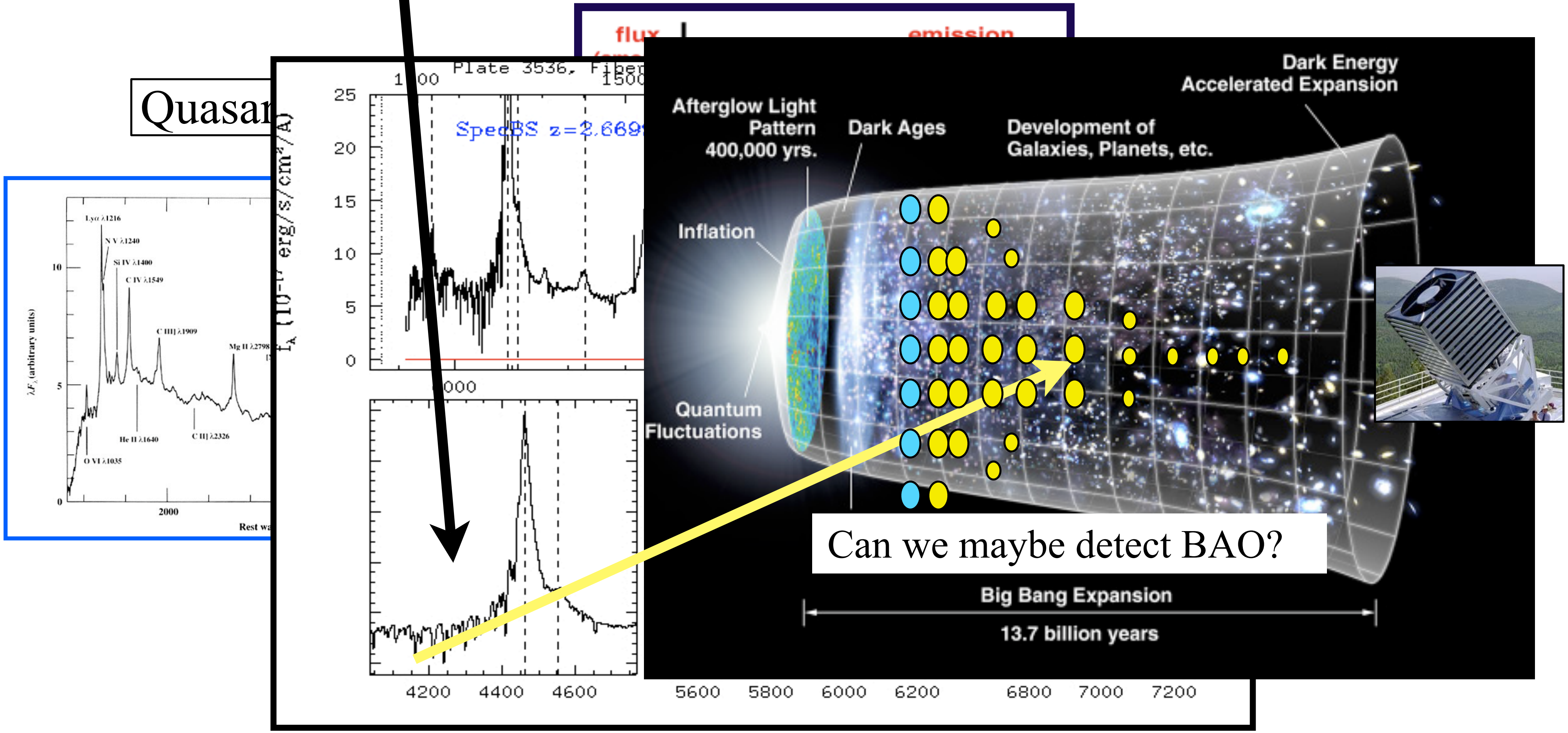
Locates the Neutral Hydrogen of the Universe, thus tracing overdensities of the Universe



Beyond: With Lyman Alpha Forest

What is it?

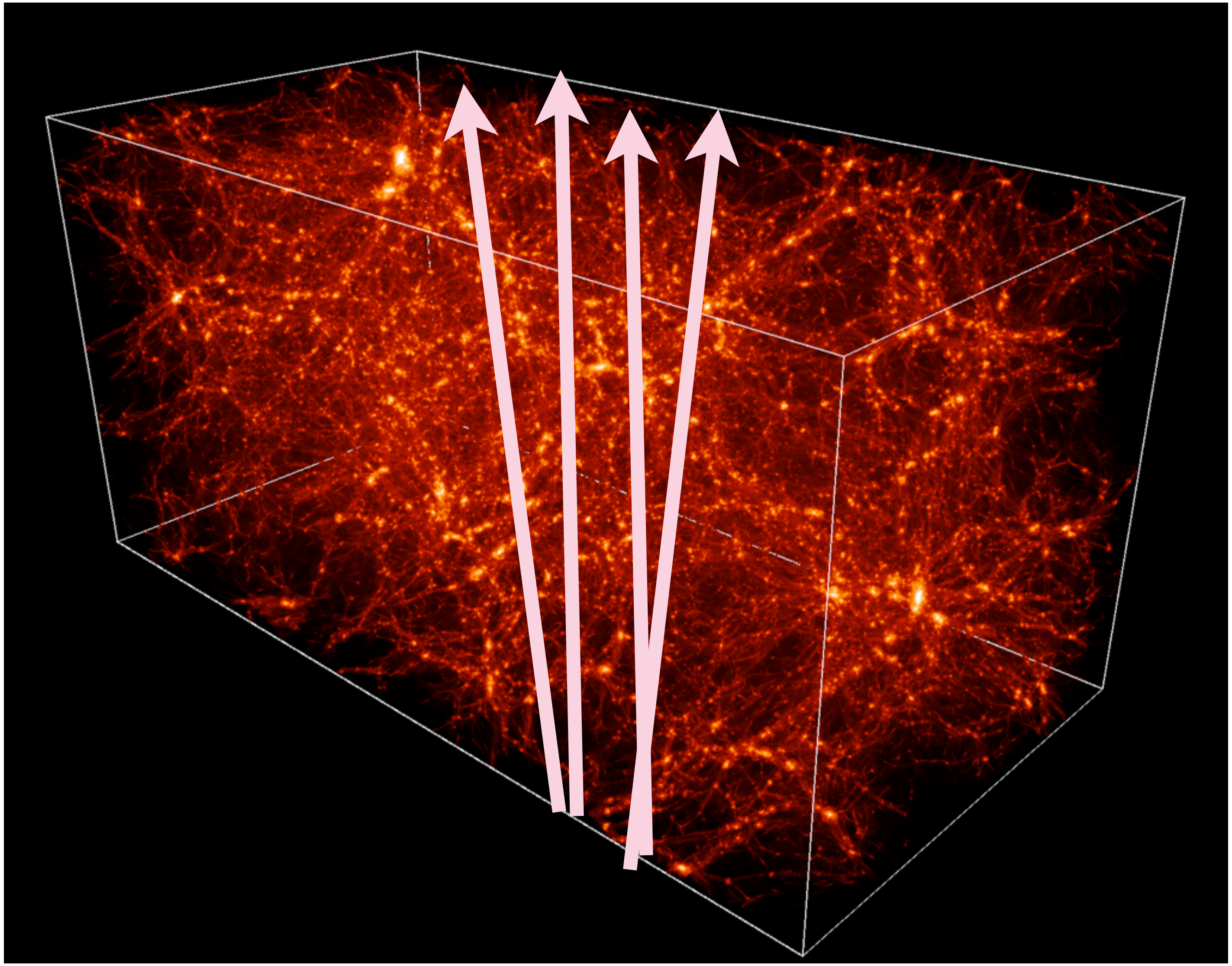
Locates the Neutral Hydrogen of the Universe, thus tracing overdensities of the Universe



Can we maybe detect BAO?

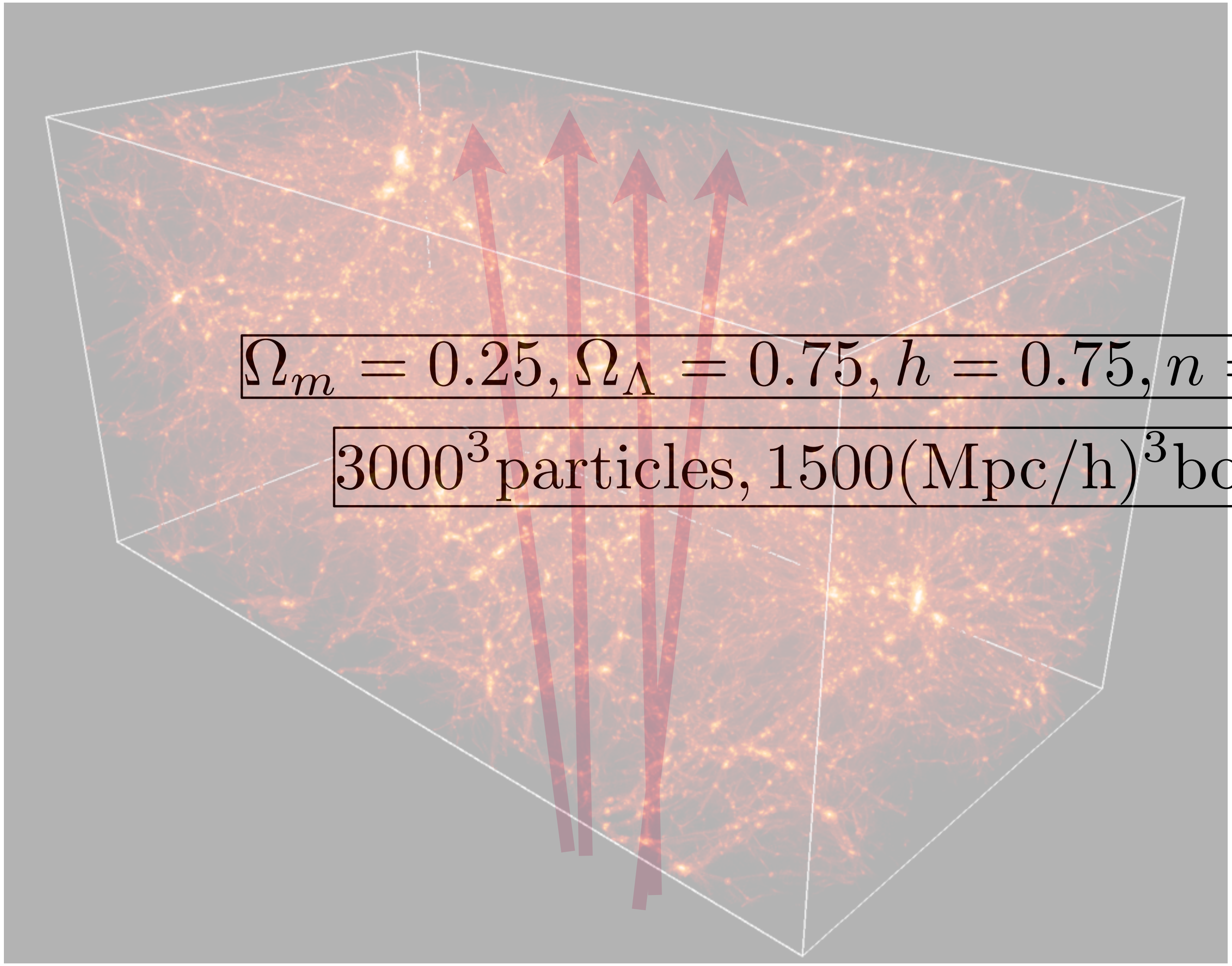
Beyond: With Lyman Alpha Forest

Simulations



Beyond: With Lyman Alpha Forest

Simulations

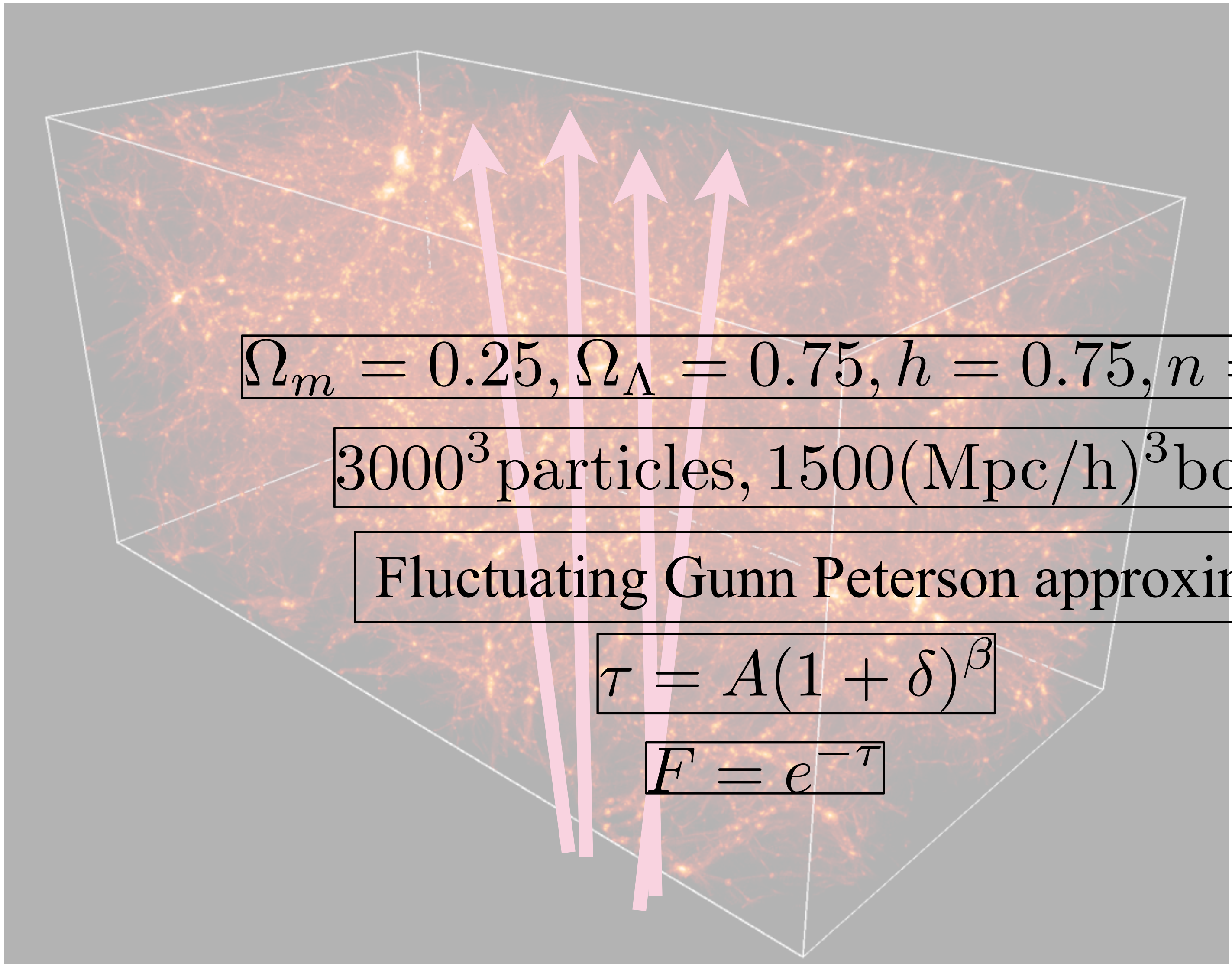


$$\boxed{\Omega_m = 0.25, \Omega_\Lambda = 0.75, h = 0.75, n = 0.97, \sigma_8 = 0.8}$$

$$\boxed{3000^3 \text{particles}, 1500(\text{Mpc/h})^3 \text{box}, 3000^3 \text{grid}}$$

Beyond: With Lyman Alpha Forest

Simulations



$$\boxed{\Omega_m = 0.25, \Omega_\Lambda = 0.75, h = 0.75, n = 0.97, \sigma_8 = 0.8}$$

$$\boxed{3000^3 \text{particles}, 1500(\mathrm{Mpc/h})^3 \text{box}, 3000^3 \text{grid}}$$

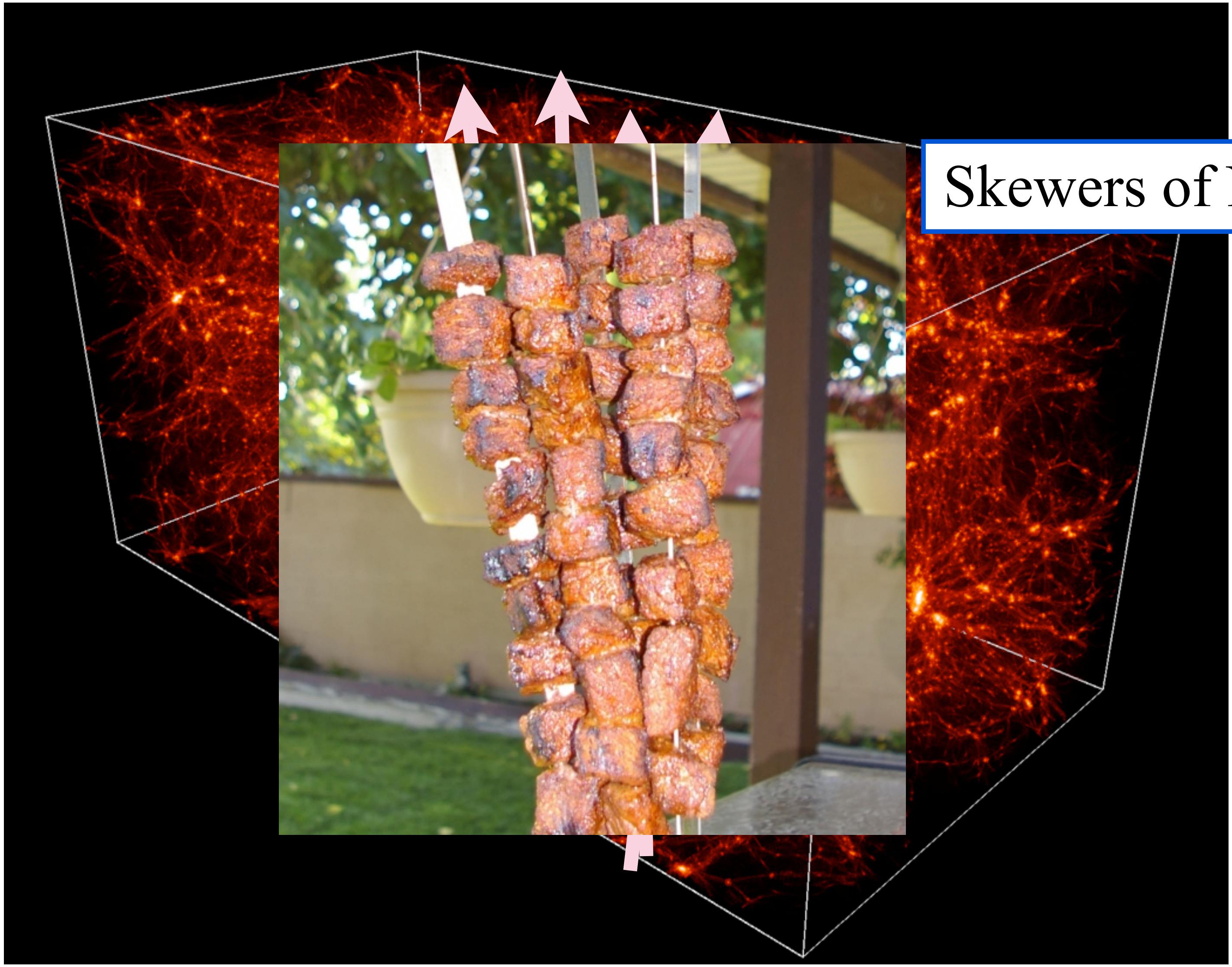
Fluctuating Gunn Peterson approximation

$$\boxed{\tau = A(1+\delta)^\beta}$$

$$\boxed{F = e^{-\tau}}$$

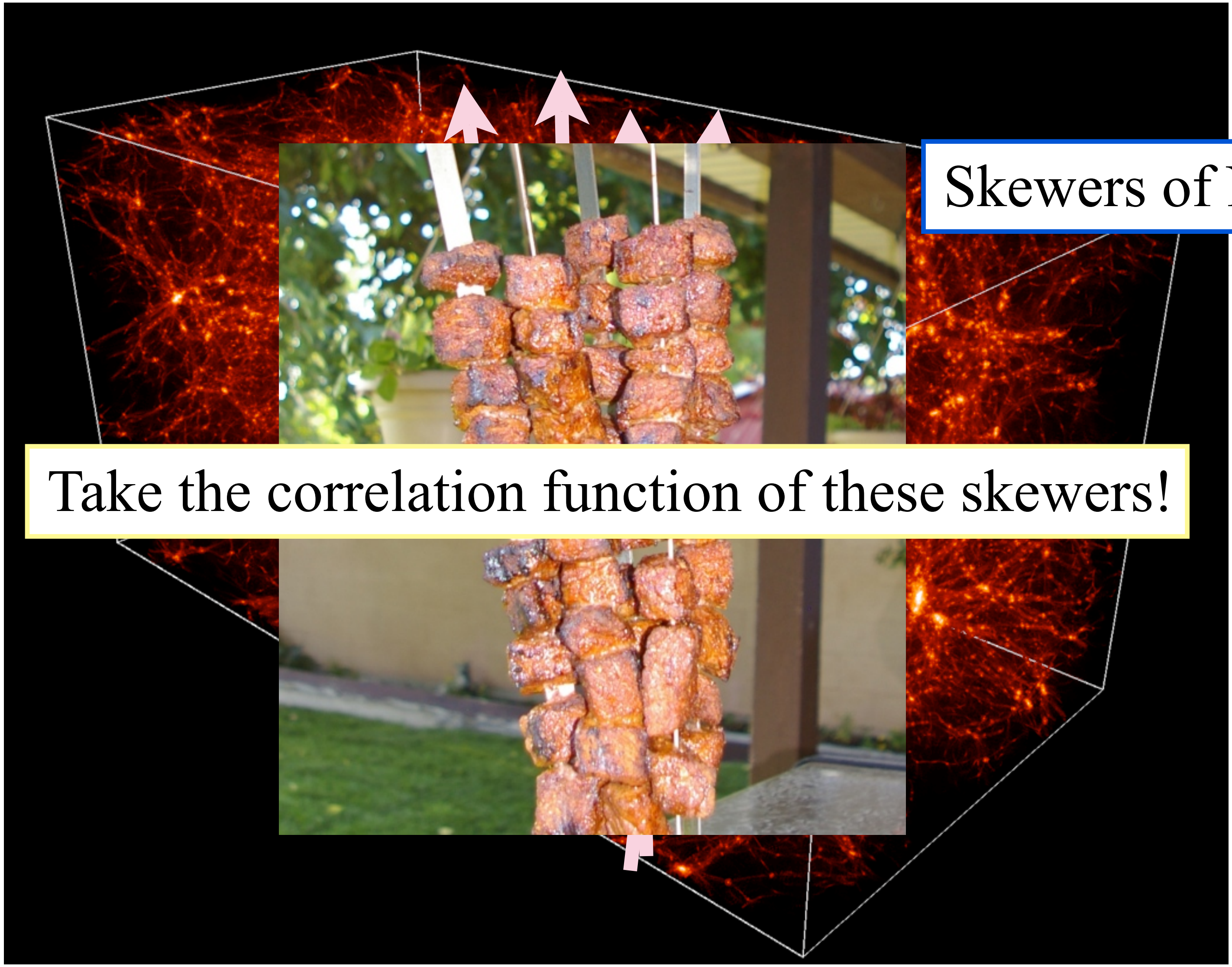
Beyond: With Lyman Alpha Forest

Simulations



Skewers of Neutral Hydrogen

Beyond: With Lyman Alpha Forest
Simulations



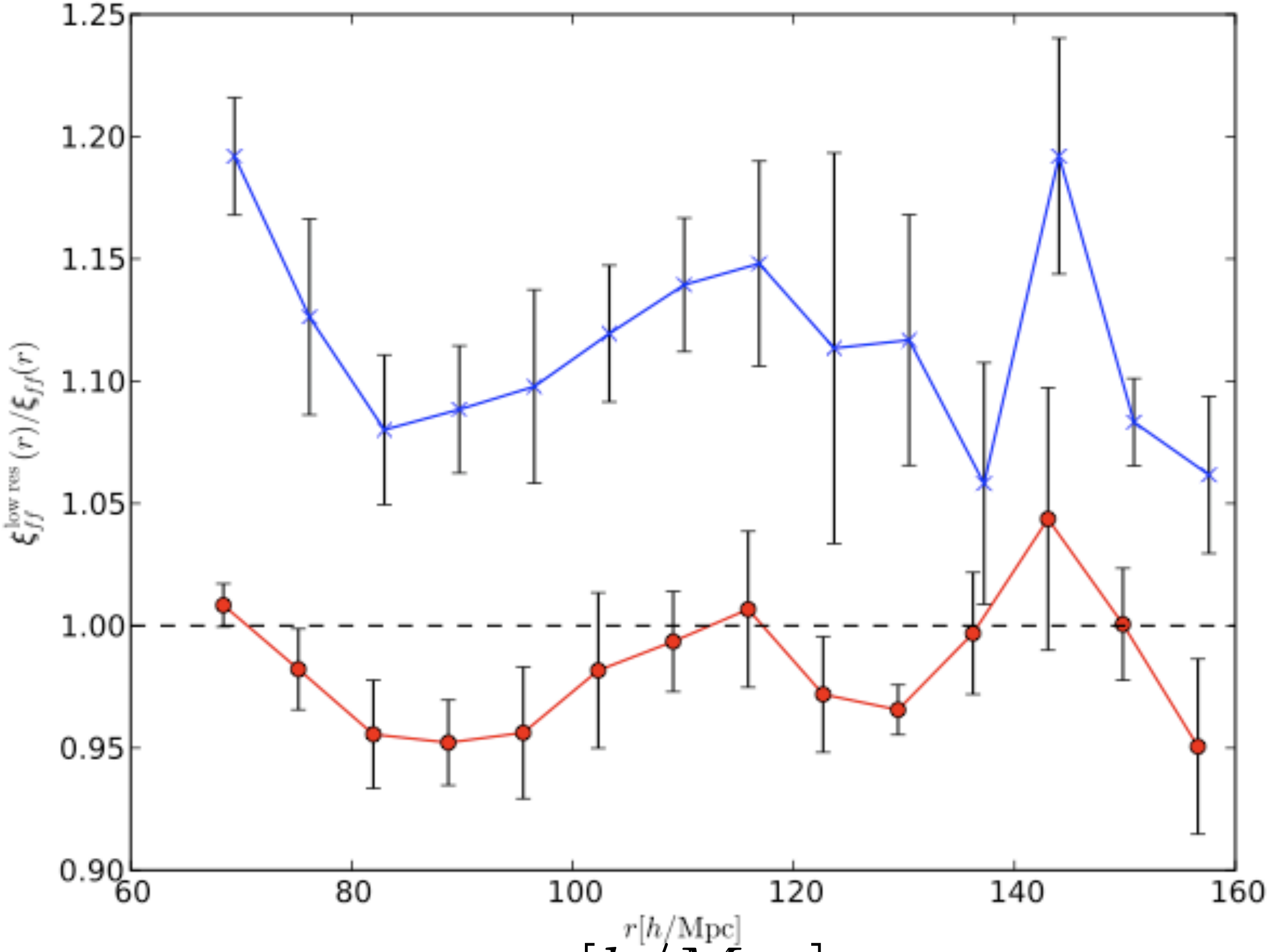
Skewers of Neutral Hydrogen

Take the correlation function of these skewers!

Beyond: With Lyman Alpha Forest

Simulations: Resolution Effects?

$$\xi_{ff}^{\mathrm{lowres}}(r)/\xi_{ff}(r)$$



$$r[h/Mpc]$$

resolution 4X worse

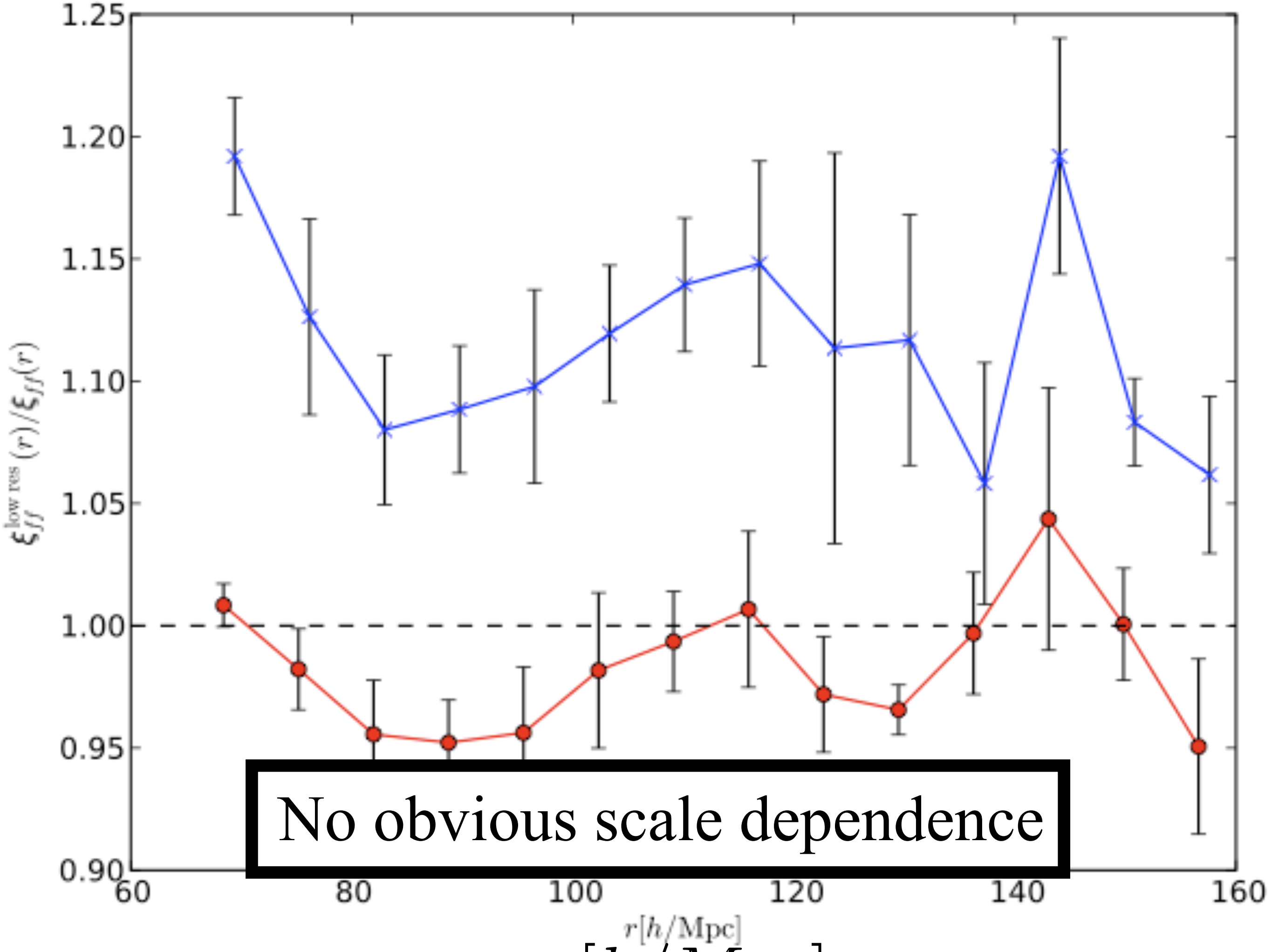
resolution 2X worse

Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest

Simulations: Resolution Effects?

$$\xi_{ff}^{\mathrm{lowres}}(r)/\xi_{ff}(r)$$



resolution 4X worse

resolution 2X worse

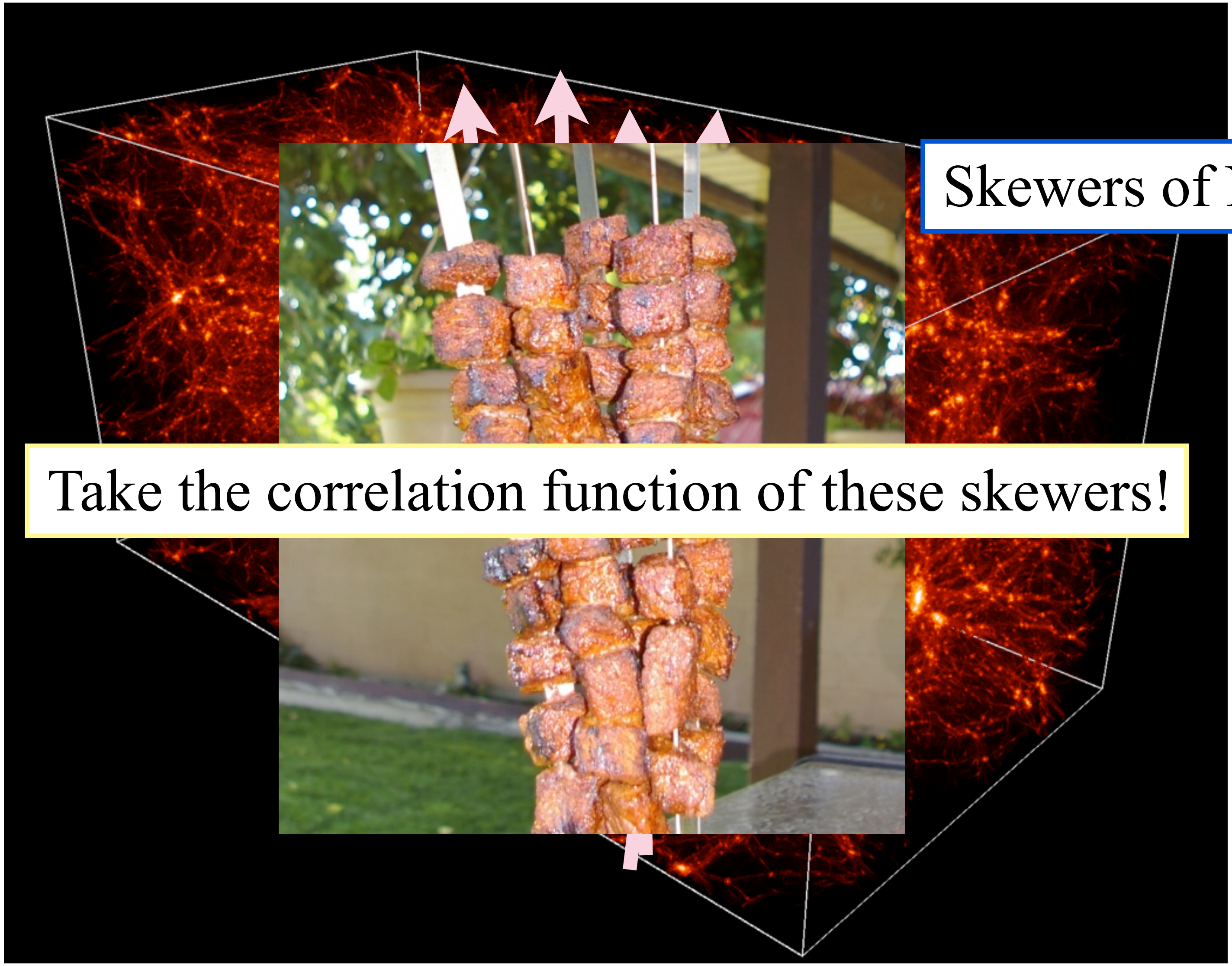
No obvious scale dependence

$$r[h/Mpc]$$

Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest

Simulations



Skewers of Neutral Hydrogen

Take the correlation function of these skewers!

Beyond: With Lyman Alpha Forest

Correlation function (in configuration space)

$$\xi_f(r) =< \delta_f(\hat{x})\delta_f(\hat{x}+\hat{r}) >$$

BAO: with Luminous Red Galaxies
Systematics

- The Reason why BAO become so popular is that it is one of the cleanest probe of cosmology, since there are not that many systematics that can cause a shift in BAO scale (~100 Mpc)
- Therefore, the systematics I am going through here are mostly for getting a clean angular power-spectrum which contains other information such as the shape of matter power-spectrum, scale dependent bias that can be caused by non-gaussianities at the early Universe.

Color offsets: We compute cross-correlations between all of the photometric offsets (from Schlafly et al. 2010)

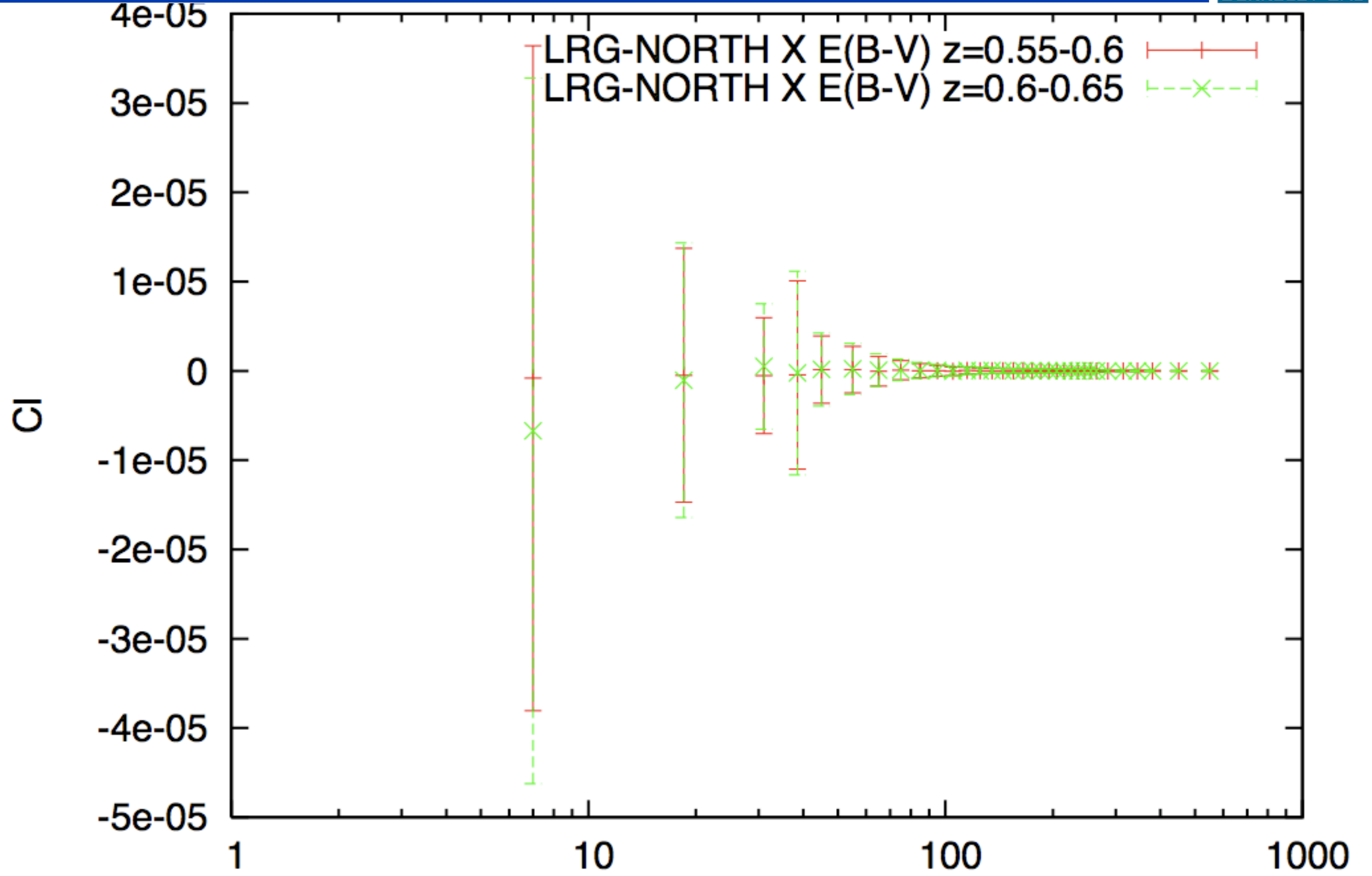
$$C_l^{gg}(\mathrm{DATA}) = \mathrm{b}^2\mathrm{C}_\mathrm{l}^{\delta_\mathrm{m}\delta_\mathrm{m}} + \mathrm{C}_\mathrm{l}^{\mathrm{d,d}} + \mathrm{C}_\mathrm{l}^{\mathrm{s,s}} + \mathrm{C}_\mathrm{l}^{\mathrm{g(z),g(z')}} + \ldots$$

Dust Extinction: We cross-correlate the extinction map (SFD) with the galaxies to see if there is any correlations.

Stellar Contamination: We cross-correlate the stellar density maps (generated from SDSS) with the galaxies.

Galaxies from next photometric slice: We compute all the correlations between different redshift slices, and take into account of the covariances and correlations between different slices.

The effect of dust extinction



Ho, Seo, Ross, White, Schlegel et al. (in prep)

BAO: with Luminous Red Galaxies
Systematics

- The Reason why BAO become so popular is that it is one of the cleanest probe of cosmology, since there are not that many systematics that can cause a shift in BAO scale (~100 Mpc)
- Therefore, the systematics I am going through here are mostly for getting a clean angular power-spectrum which contains other information such as the shape of matter power-spectrum, scale dependent bias that can be caused by non-gaussianities at the early Universe.

Color offsets: We compute cross-correlations between all of the photometric offsets (from Schlafly et al. 2010)

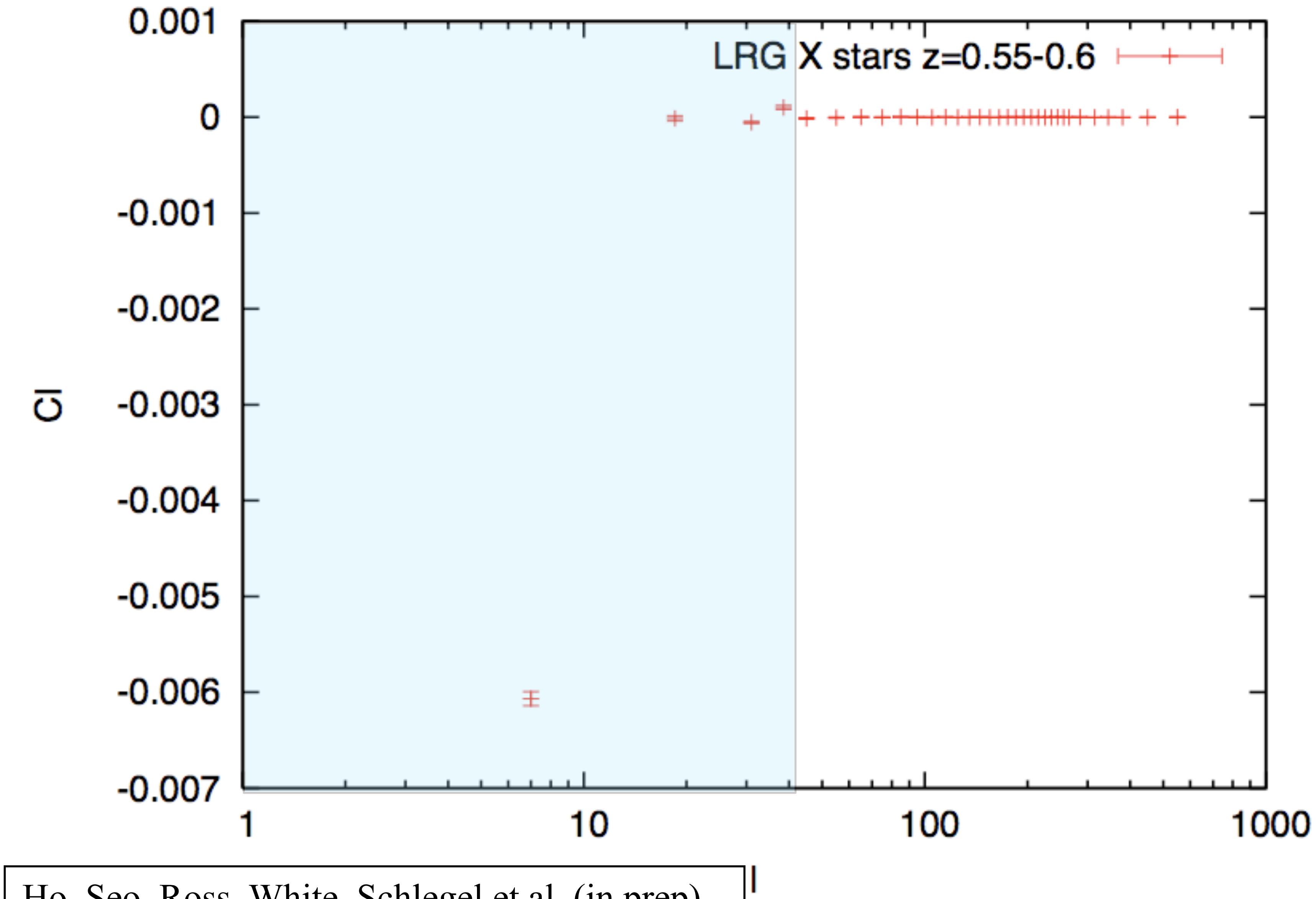
$$C_l^{gg}(\mathrm{DATA}) = \mathrm{b}^2\mathrm{C}_\mathrm{l}^{\delta_\mathrm{m}\delta_\mathrm{m}} + \mathrm{C}_\mathrm{l}^{\mathrm{d,d}} + \mathrm{C}_\mathrm{l}^{\mathrm{s,s}} + \mathrm{C}_\mathrm{l}^{\mathrm{g(z),g(z')}} + \ldots$$

Dust Extinction: We cross-correlate the extinction map (SFD) with the galaxies to see if there is any correlations.

Stellar Contamination: We cross-correlate the stellar density maps (generated from SDSS) with the galaxies.

Galaxies from next photometric slice: We compute all the correlations between different redshift slices, and take into account of the covariances and correlations between different slices.

The effect of stars



Ho, Seo, Ross, White, Schlegel et al. (in prep)

BAO: with Luminous Red Galaxies
Systematics

- The Reason why BAO become so popular is that it is one of the cleanest probe of cosmology, since there are not that many systematics that can cause a shift in BAO scale (~100 Mpc)
- Therefore, the systematics I am going through here are mostly for getting a clean angular power-spectrum which contains other information such as the shape of matter power-spectrum, scale dependent bias that can be caused by non-gaussianities at the early Universe.

Color offsets: We compute cross-correlations between all of the photometric offsets (from Schlafly et al. 2010)

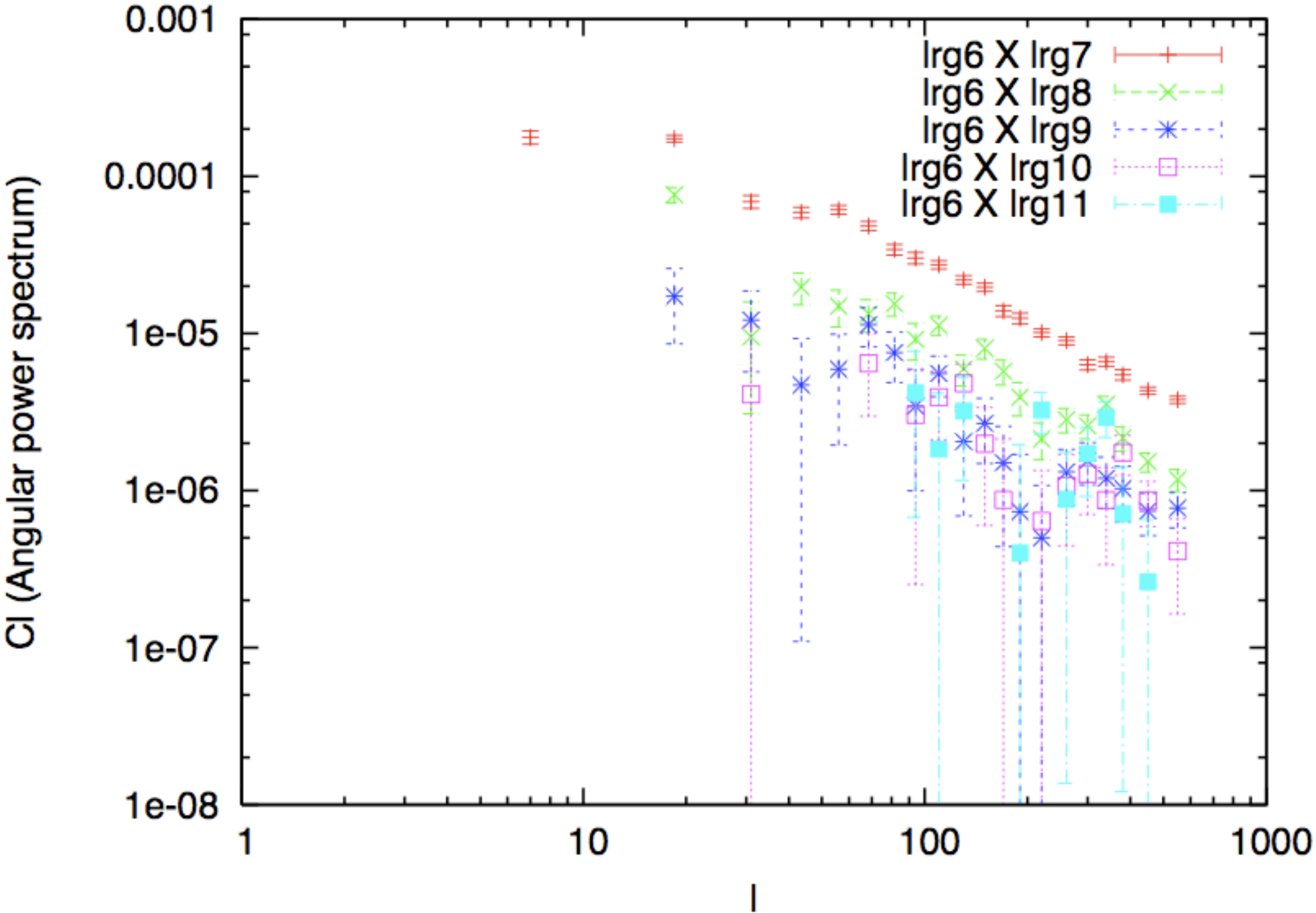
$$C_l^{gg}(\mathrm{DATA}) = \mathrm{b}^2\mathrm{C}_\mathrm{l}^{\delta_\mathrm{m}\delta_\mathrm{m}} + \mathrm{C}_\mathrm{l}^{\mathrm{d,d}} + \mathrm{C}_\mathrm{l}^{\mathrm{s,s}} + \mathrm{C}_\mathrm{l}^{\mathrm{g(z),g(z')}} + \ldots$$

Dust Extinction: We cross-correlate the extinction map (SFD) with the galaxies to see if there is any correlations.

Stellar Contamination: We cross-correlate the stellar density maps (generated from SDSS) with the galaxies.

Galaxies from next photometric slice: We compute all the correlations between different redshift slices, and take into account of the covariances and correlations between different slices.

Overlap of the redshift bins



Ho, Ross, Seo, White, Schlegel et al. (in prep)

BAO: with Luminous Red Galaxies
Systematics

- The Reason why BAO become so popular is that it is one of the cleanest probe of cosmology, since there are not that many systematics that can cause a shift in BAO scale (~100 Mpc)
- Therefore, the systematics I am going through here are mostly for getting a clean angular power-spectrum which contains other information such as the shape of matter power-spectrum, scale dependent bias that can be caused by non-gaussianities at the early Universe.

Color offsets: We compute cross-correlations between all of the photometric offsets (from Schlafly et al. 2010)

$$C_l^{gg}(\mathrm{DATA}) = \mathrm{b}^2\mathrm{C}_\mathrm{l}^{\delta_\mathrm{m}\delta_\mathrm{m}} + \mathrm{C}_\mathrm{l}^{\mathrm{d,d}} + \mathrm{C}_\mathrm{l}^{\mathrm{s,s}} + \mathrm{C}_\mathrm{l}^{\mathrm{g(z),g(z')}} + \ldots$$

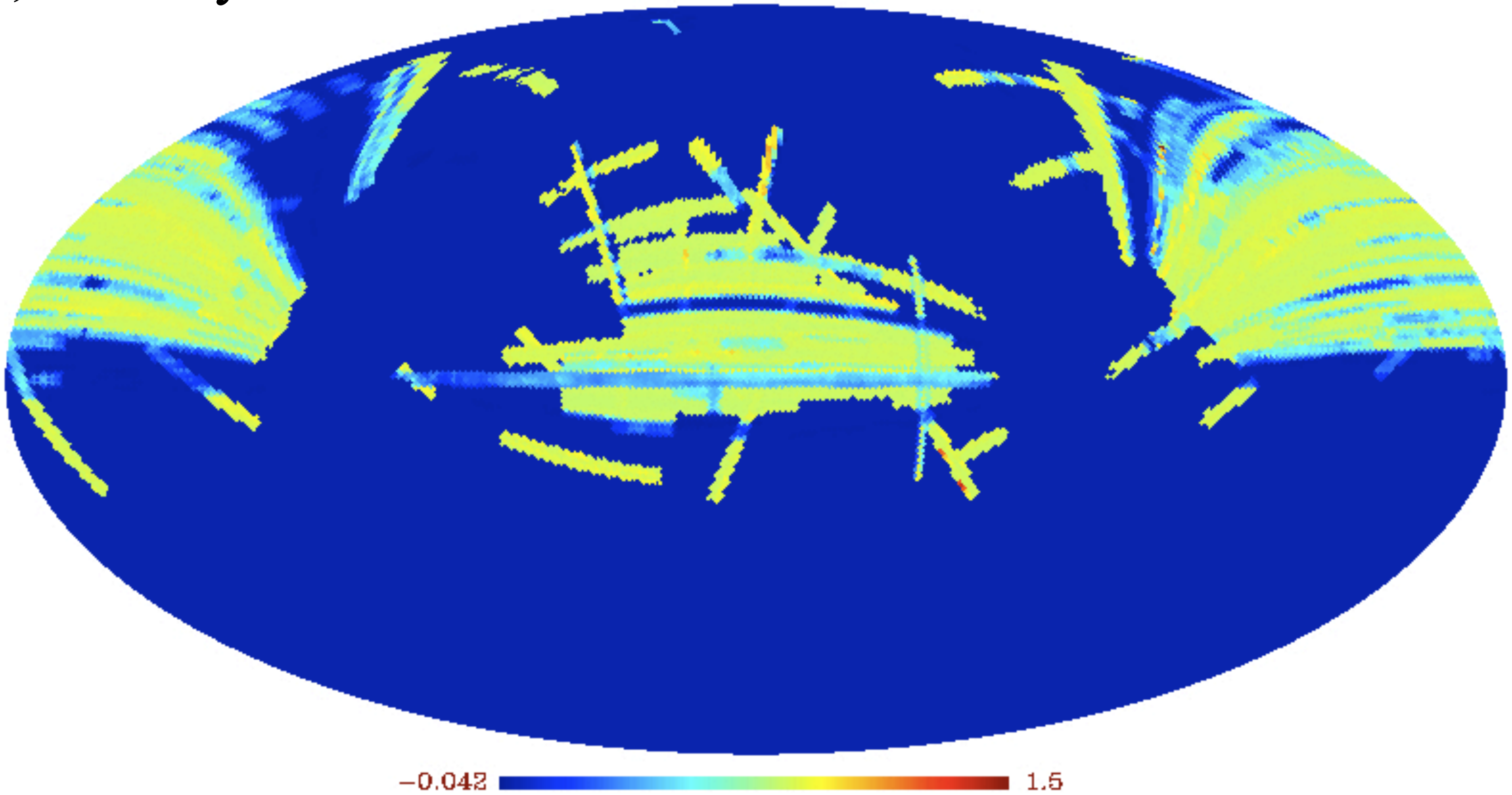
Dust Extinction: We cross-correlate the extinction map (SFD) with the galaxies to see if there is any correlations.

Stellar Contamination: We cross-correlate the stellar density maps (generated from SDSS) with the galaxies.

Galaxies from next photometric slice: We compute all the correlations between different redshift slices, and take into account of the covariances and correlations between different slices.

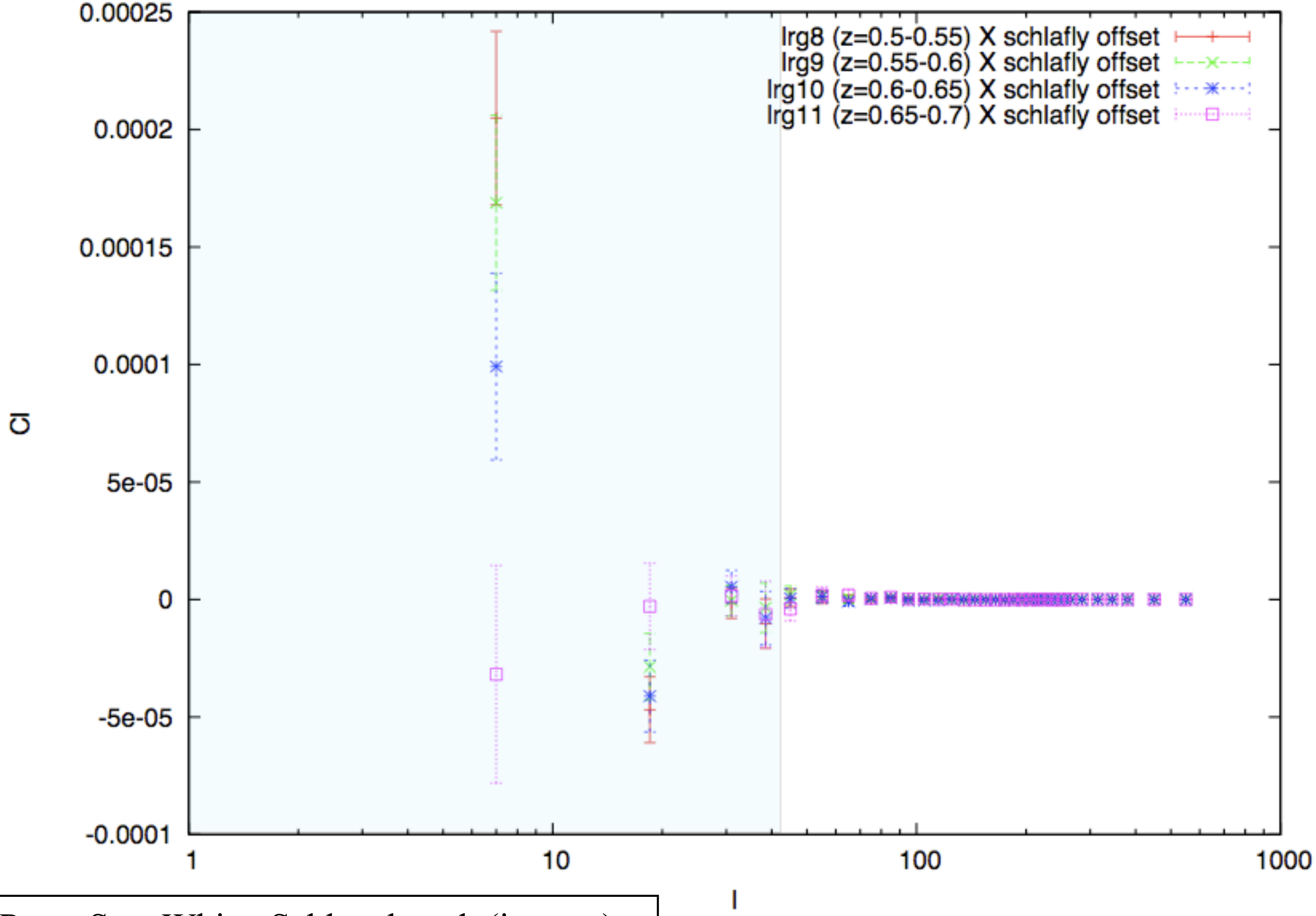
What are the photometric offsets?

These are the “zero points” of colors (difference in magnitudes) of the survey, but they are not zero!



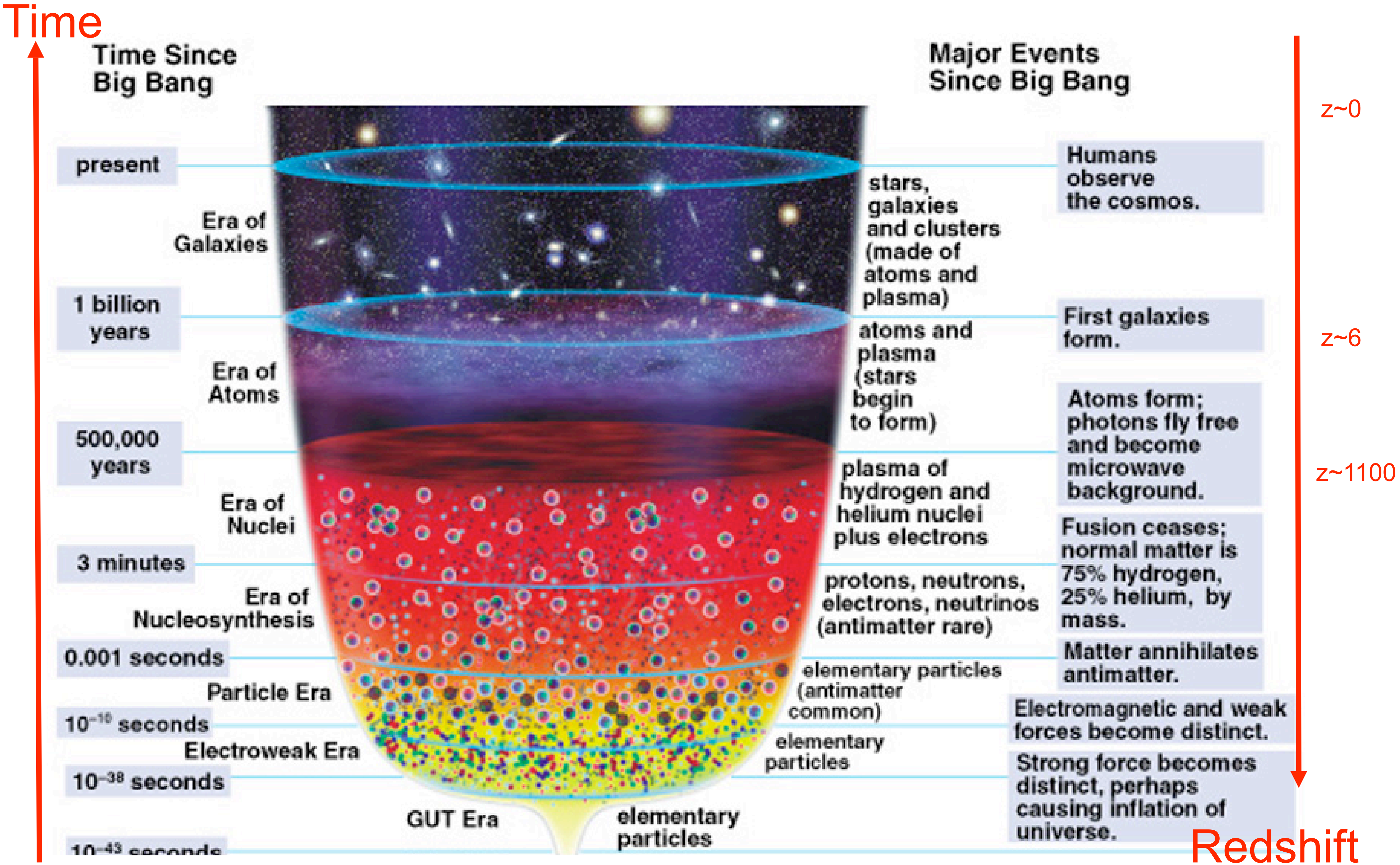
Color offsets as discussed in Schlafly et al. 2010

The effect of the photometric offsets



Ho, Ross, Seo, White, Schlegel et al. (in prep)

Motivations



Motivations

Time

Gravity +
observing movement of local galaxies ->
"Dark Matter"

z~0

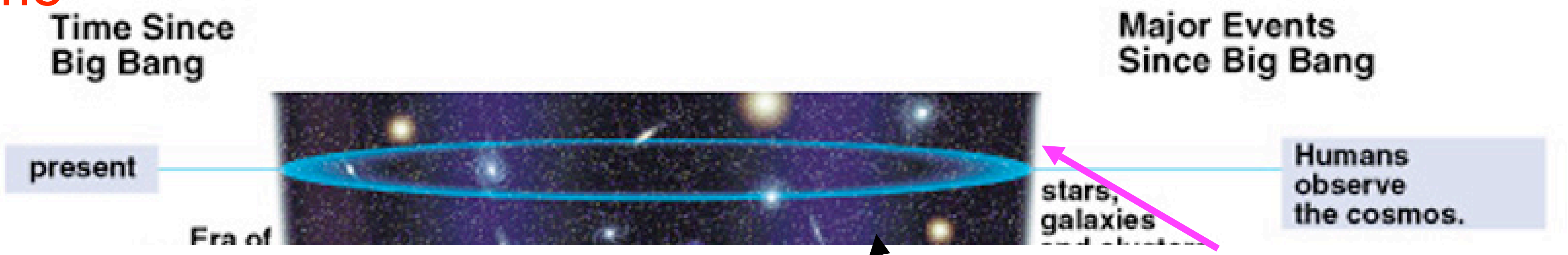
z~6

z~1100

Redshift

Motivations

Time

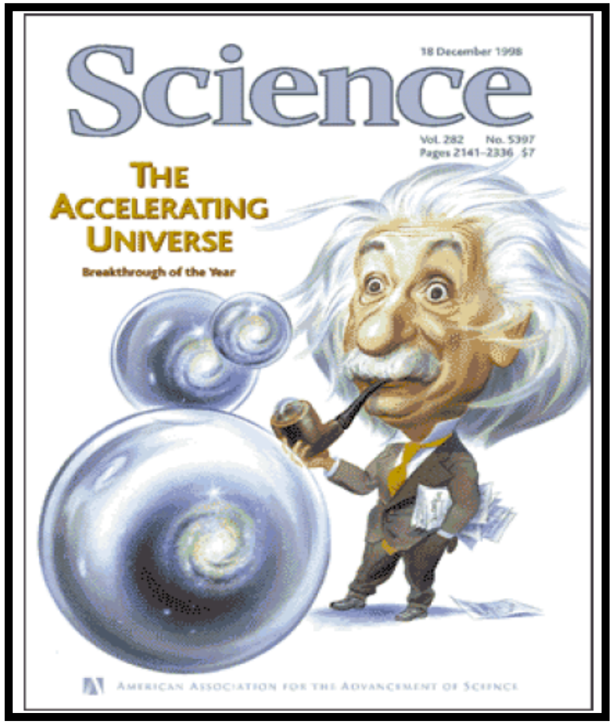


z~0

z~6

z~1100

Gravity +
observing movement of local galaxies ->
 “Dark Matter”



Distant supernovas appear fainter than expected (1998)->
Universe is accelerating ->
Cosmological Constant?
Dark Energy?

Redshift

BAO: with Luminous Red Galaxies
Systematics

- The Reason why BAO become so popular is that it is one of the cleanest probe of cosmology, since there are not that many systematics that can cause a shift in BAO scale (~100 Mpc)
- Therefore, the systematics I am going through here are mostly for getting a clean angular power-spectrum which contains other information such as the shape of matter power-spectrum, scale dependent bias that can be caused by non-gaussianities at the early Universe.

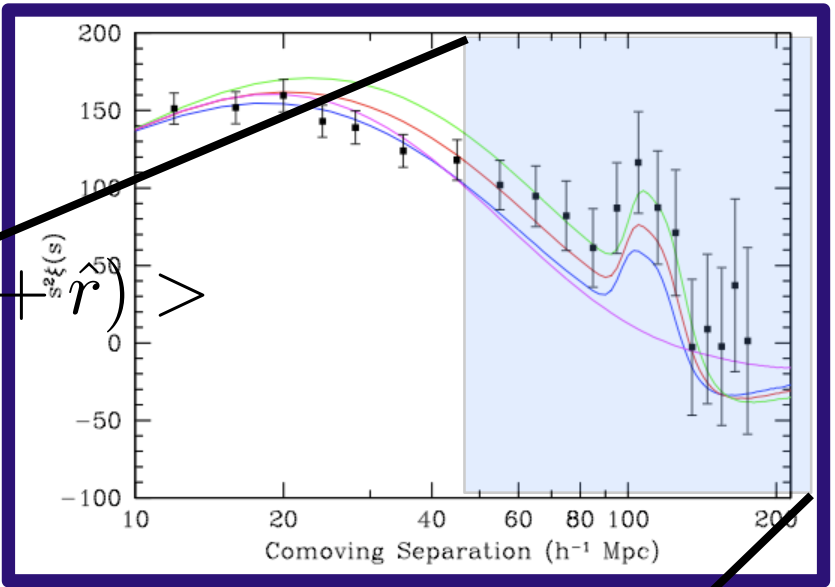
✔ $$C_l^{gg}(\mathrm{DATA}) = \mathrm{b}^2 \mathrm{C}_\mathrm{l}^{\delta_\mathrm{m}\delta_\mathrm{m}} + \underbrace{\mathrm{C}_\mathrm{l}^{\mathrm{d,d}}}_{\text{Dust Extinction}} + \underbrace{\mathrm{C}_\mathrm{l}^{\mathrm{s,s}}}_{\text{Stellar Contamination}} + \underbrace{\mathrm{C}_\mathrm{l}^{\mathrm{g(z),g(z')}}}_{\text{Galaxies from next photometric slice}} + \overbrace{\ldots}^{\text{Color offsets}}$$

If we don't take out the systematics, we won't be able to trust the power-spectra until at least **l> 40**

Beyond: With Lyman Alpha Forest

Correlation function (in configuration space)

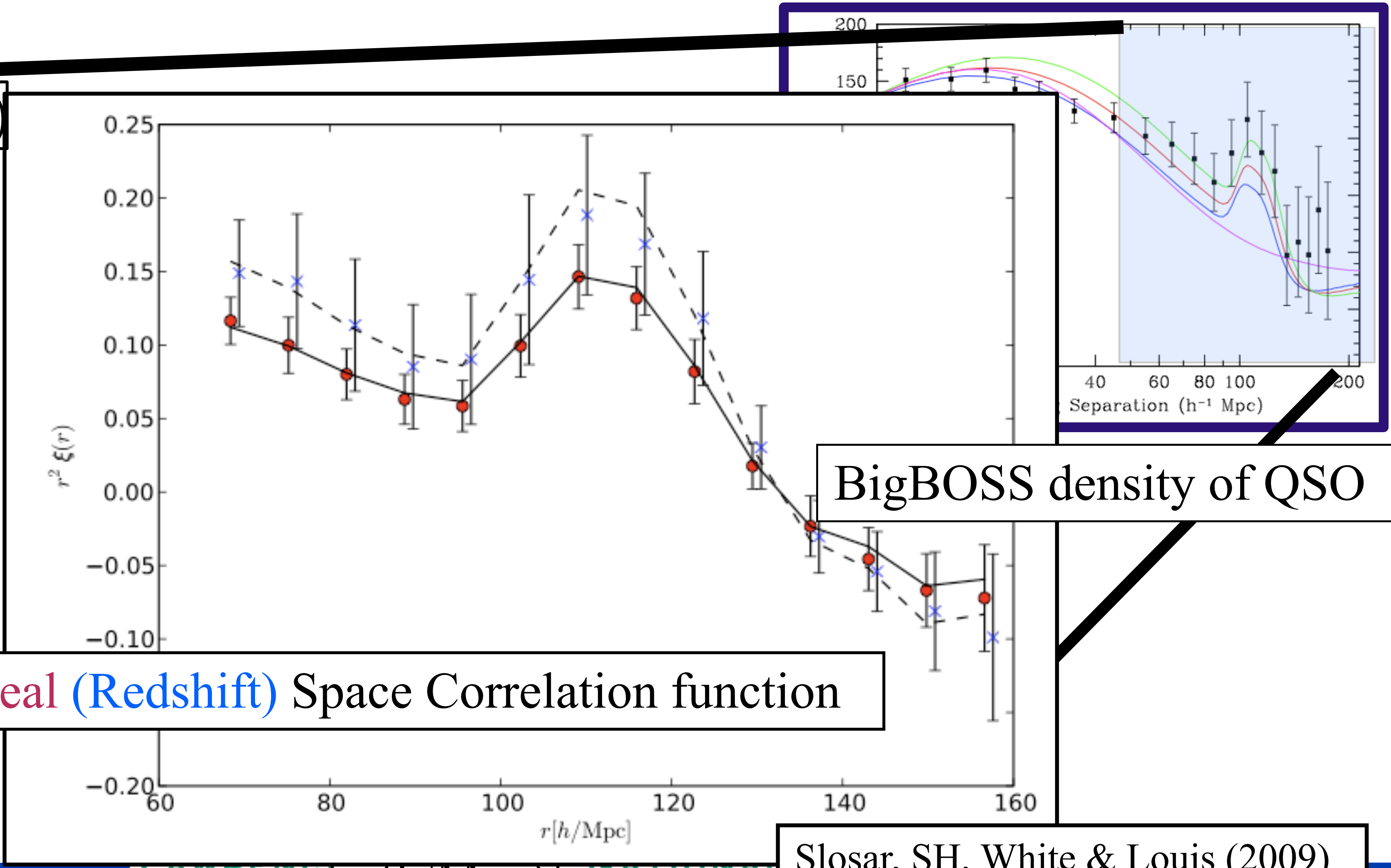
$$\xi_f(r) =< \delta_f(\hat{x})\delta_f(\hat{x}+\hat{r}) >$$



Beyond: With Lyman Alpha Forest

Correlation function (in configuration space)

$r^2\xi(r)$



BigBOSS density of QSO

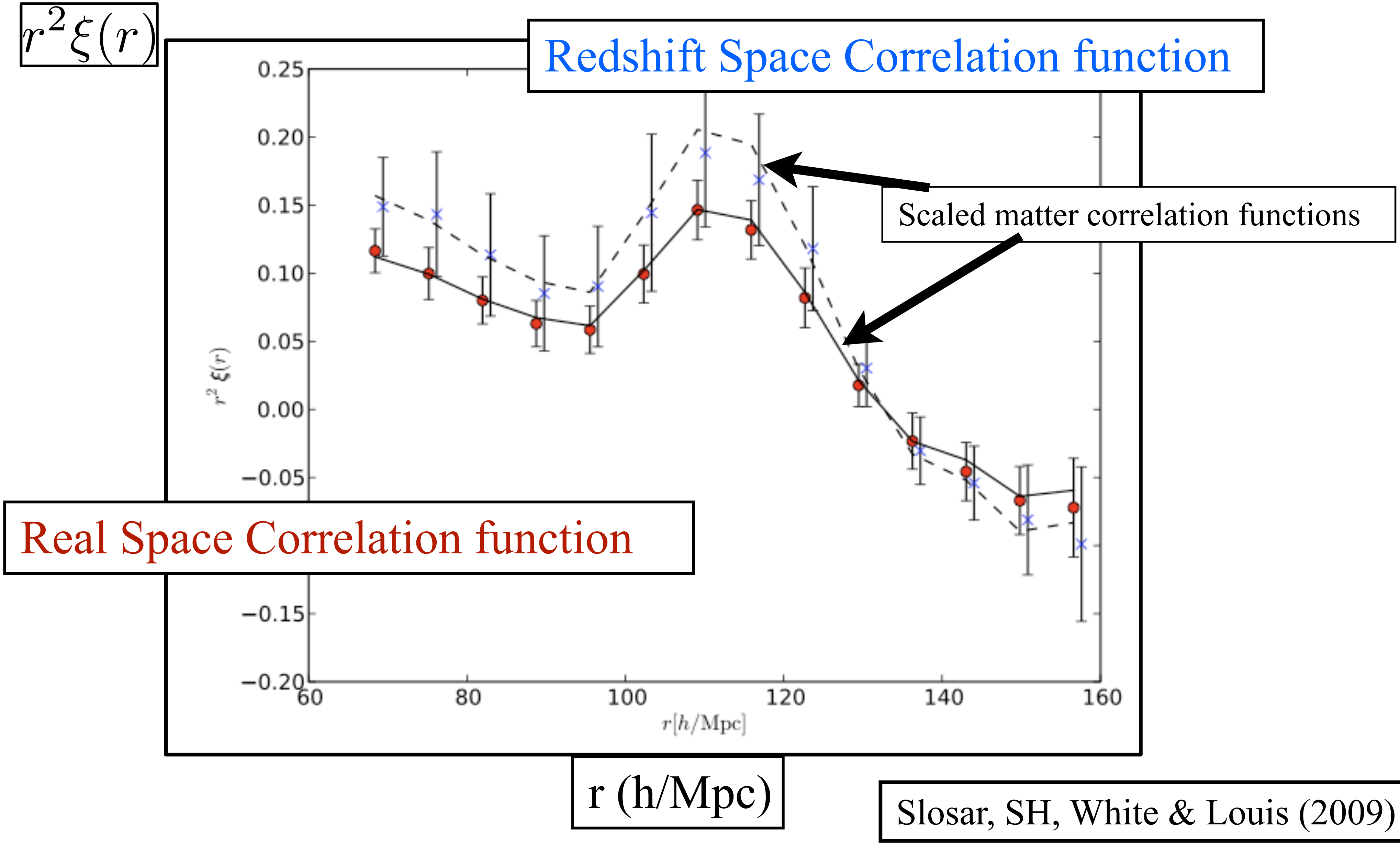
Flux Real (Redshift) Space Correlation function

r (h/Mpc)

Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest

Correlation function (in configuration space)



Slosar, SH, White & Louis (2009)

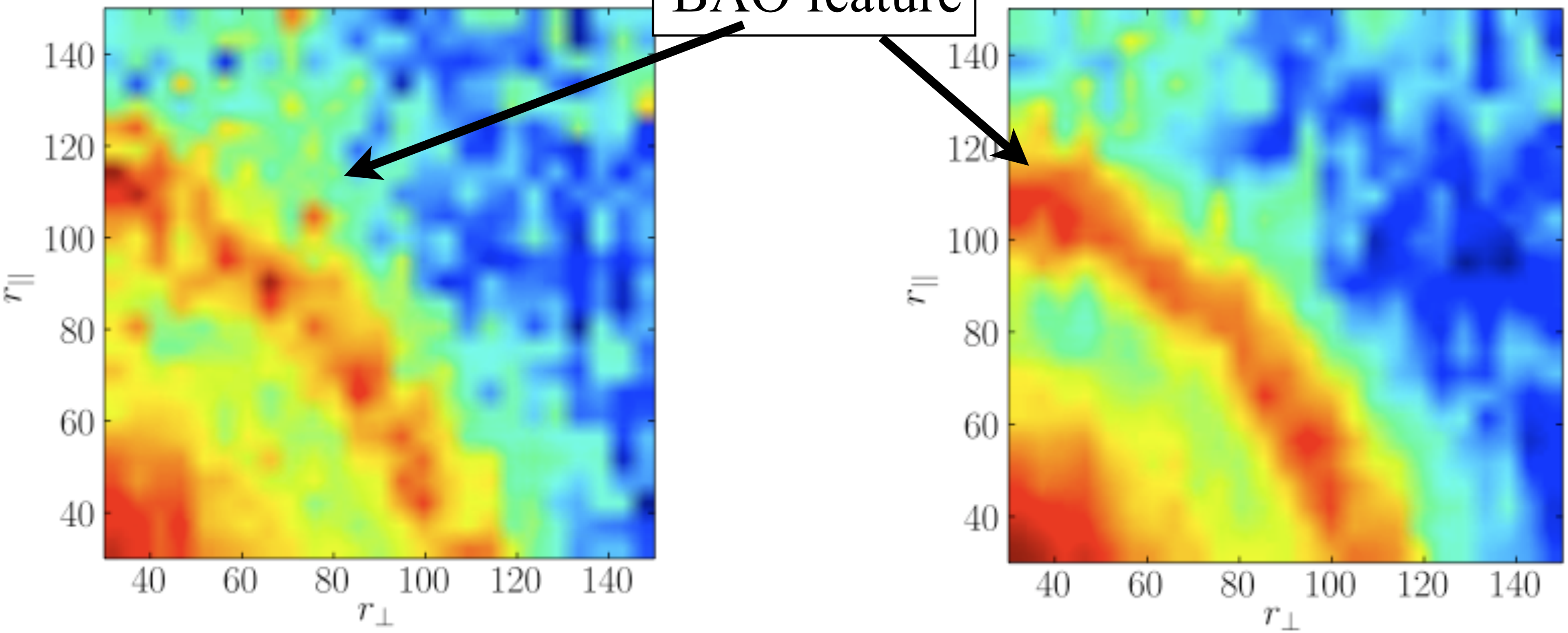
Beyond: With Lyman Alpha Forest
Correlation function (in configuration space)

Real Space Correlation function

Matter

Flux

BAO feature



Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest

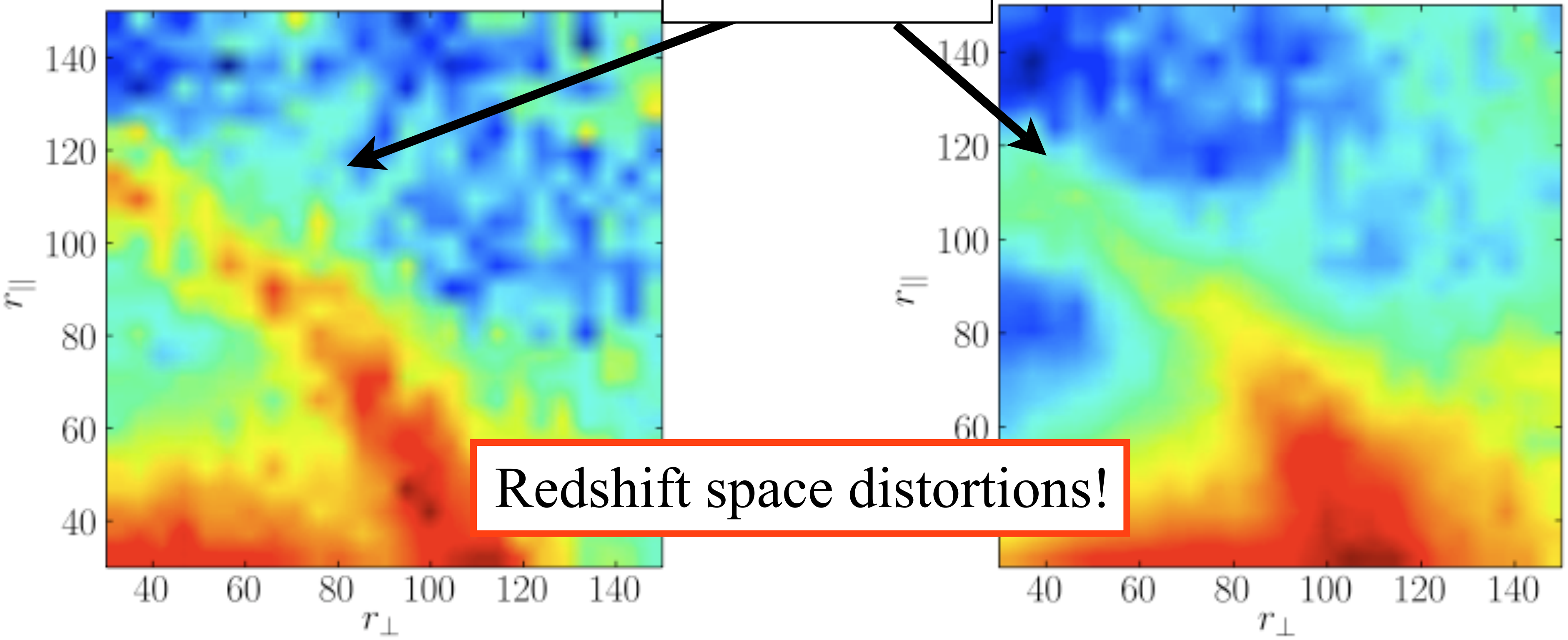
Correlation function (in configuration space)

Redshift Space Correlation function

Matter

Flux

BAO feature



Redshift space distortions!

Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest

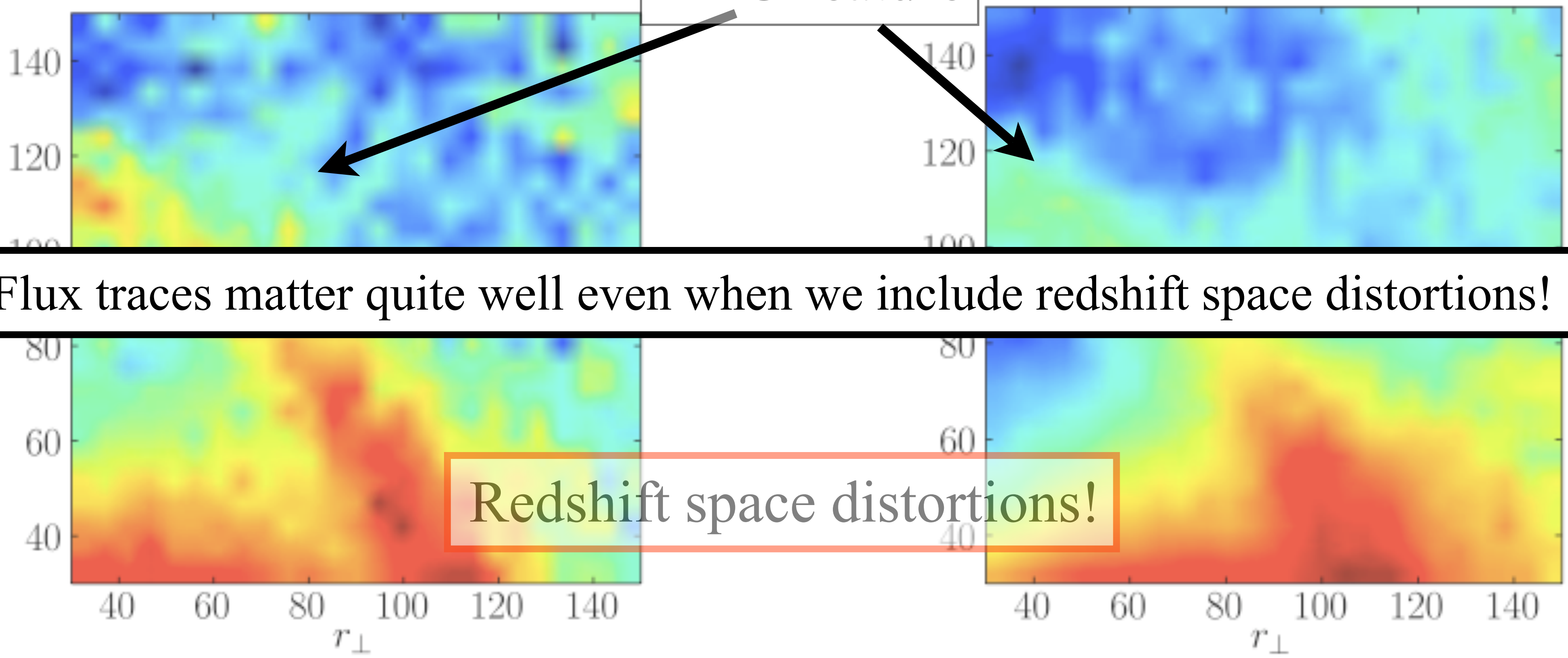
Correlation function (in configuration space)

Redshift Space Correlation function

Matter

Flux

BAO feature



Flux traces matter quite well even when we include redshift space distortions!

Redshift space distortions!

Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest

Correlation function (in configuration space)

Flux

distortions!

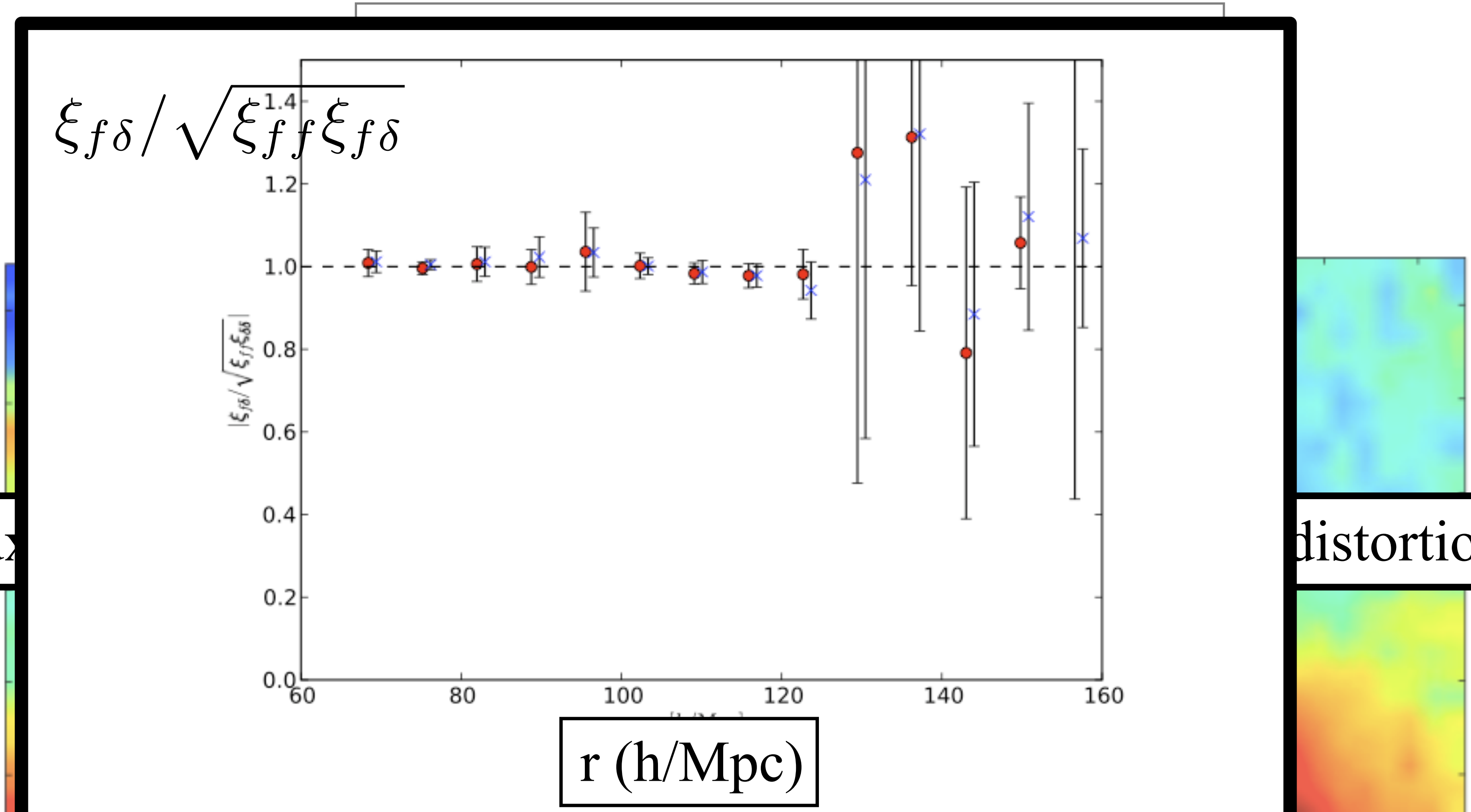


FIG. 7: The cross-correlation coefficient between flux and matter over-density in real (red) and redshift (blue) space.

Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest

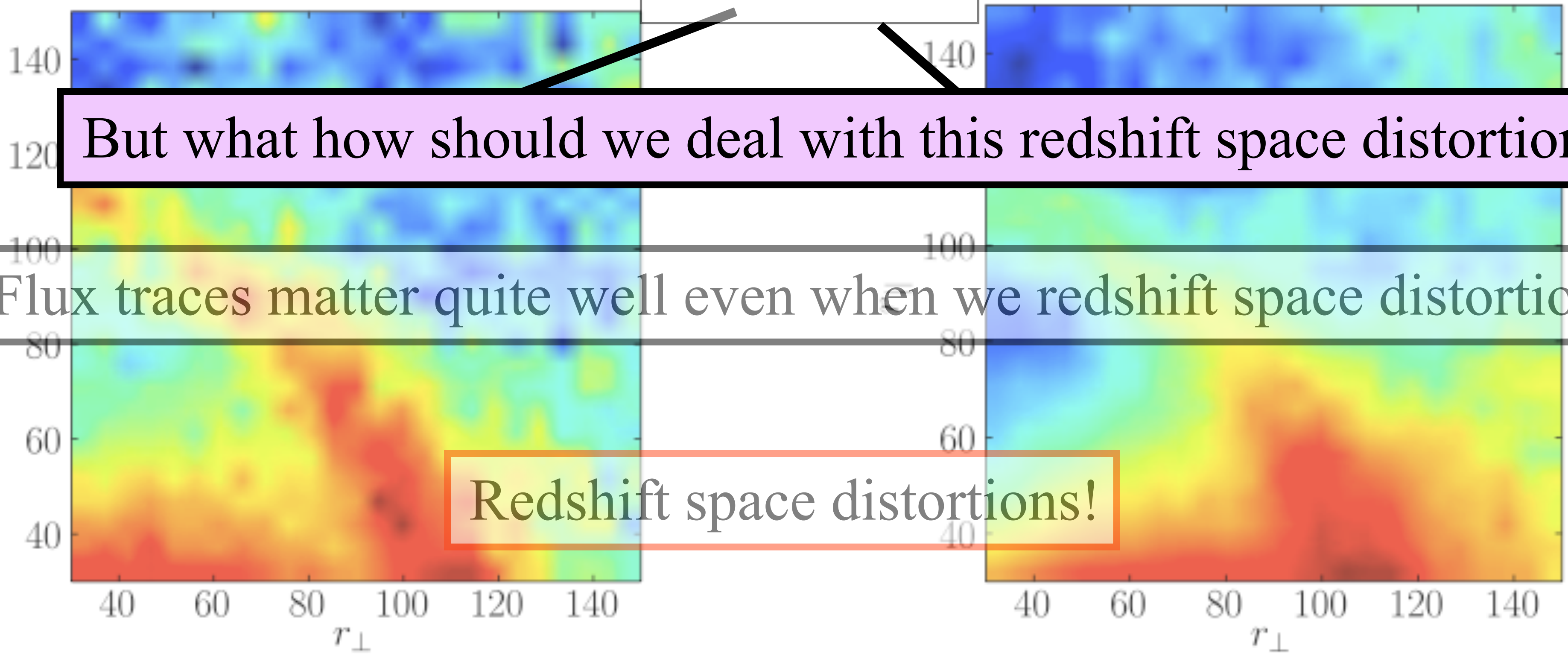
Redshift space distortions

Redshift Space Correlation function

Matter

Flux

BAO feature



But what how should we deal with this redshift space distortion ?

Flux traces matter quite well even when we redshift space distortions!

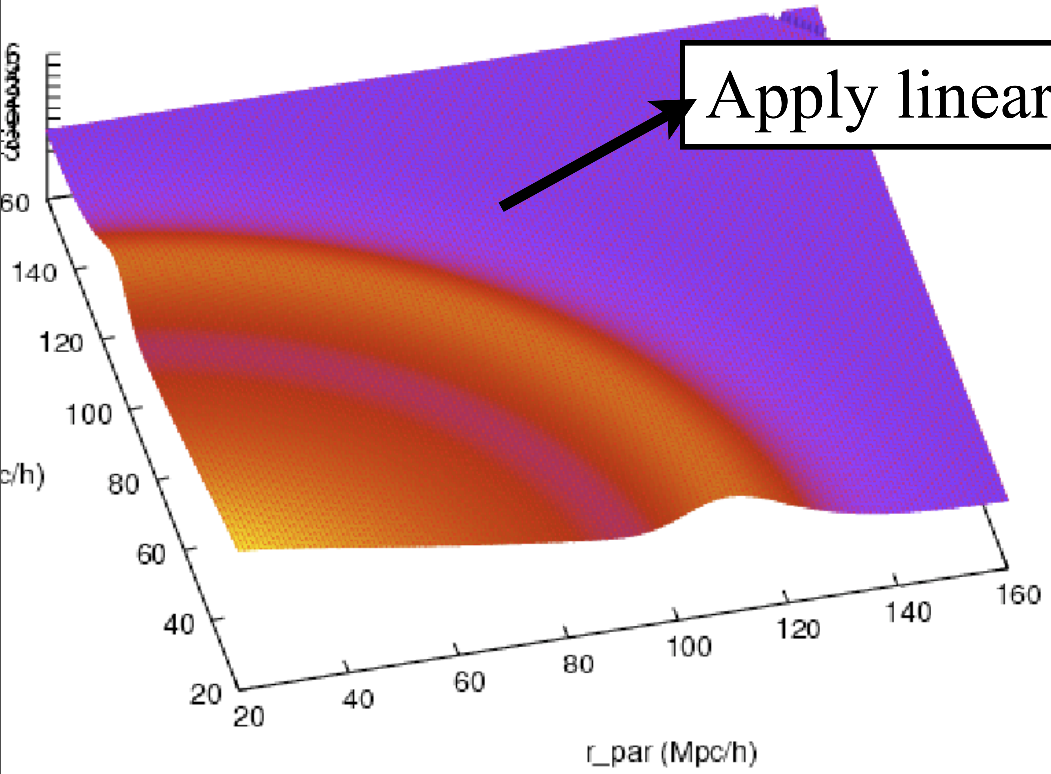
Redshift space distortions!

Beyond: With Lyman Alpha Forest

Redshift space distortions

No z-space distortion

z-space distortions



Apply linear Kaiser formula

$$\xi(r,\mu) = \sum_{\ell=0,2,4} L_\ell(\mu)\xi_l(r),$$

$$\xi_0(r) = C_0\xi_{\rm R}(r),$$

$$\xi_2(r) = C_2\left(\xi_{\rm R}(r) - \bar{\xi}(r)\right),$$

$$\xi_4(r) = C_4\left(\xi_{\rm R}(r) + 2.5\bar{\xi}(r) - 3.5\bar{\bar{\xi}}(r)\right),$$

$$\mu = r_{par}/|\vec{r}|$$

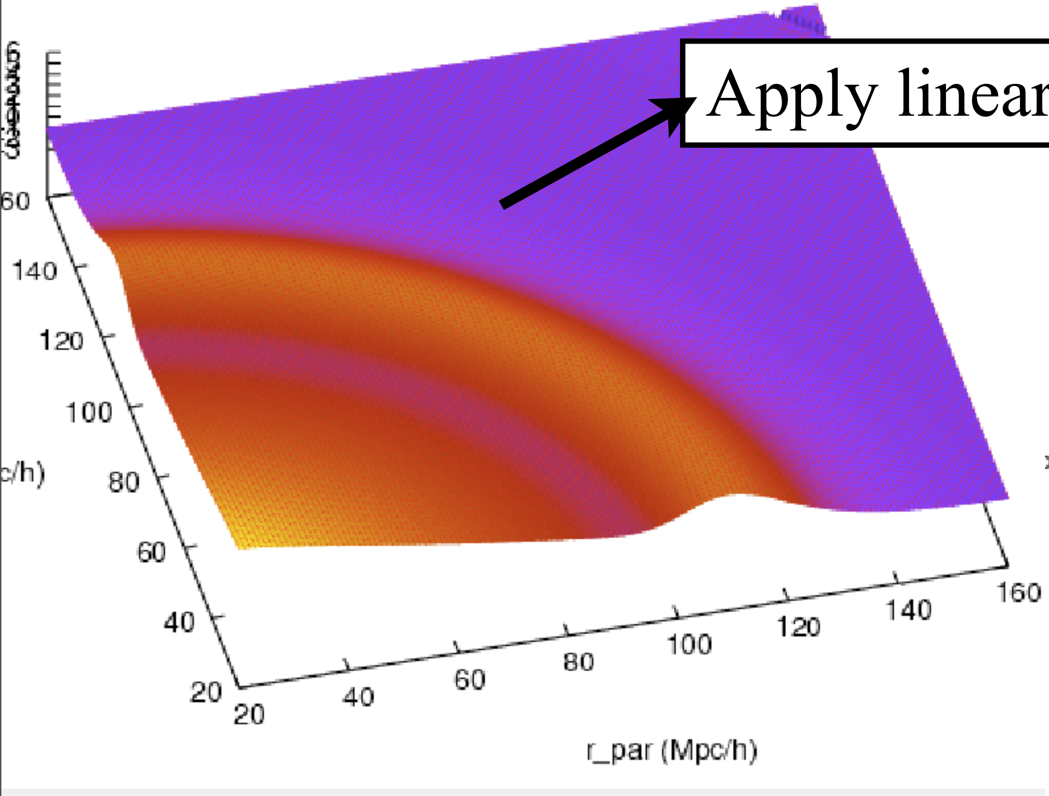
$$C_i = f_i(\beta)$$

$$\beta = dln\delta/dlna = \Omega_m^{0.6}$$

Beyond: With Lyman Alpha Forest

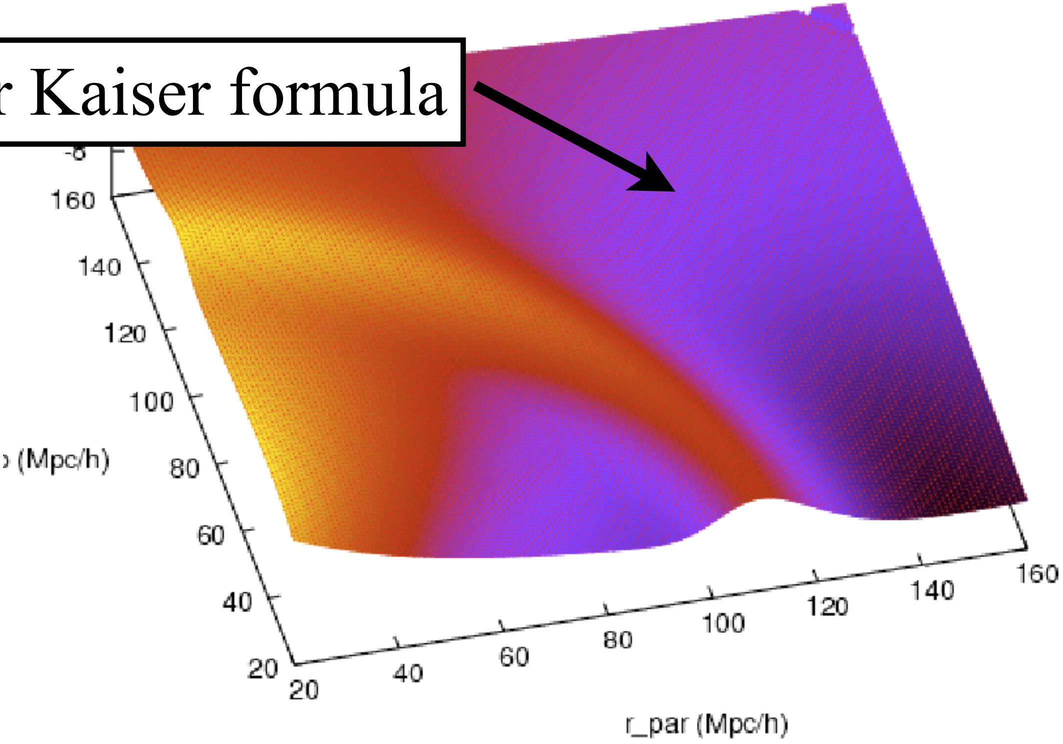
Redshift space distortions

No z-space distortion



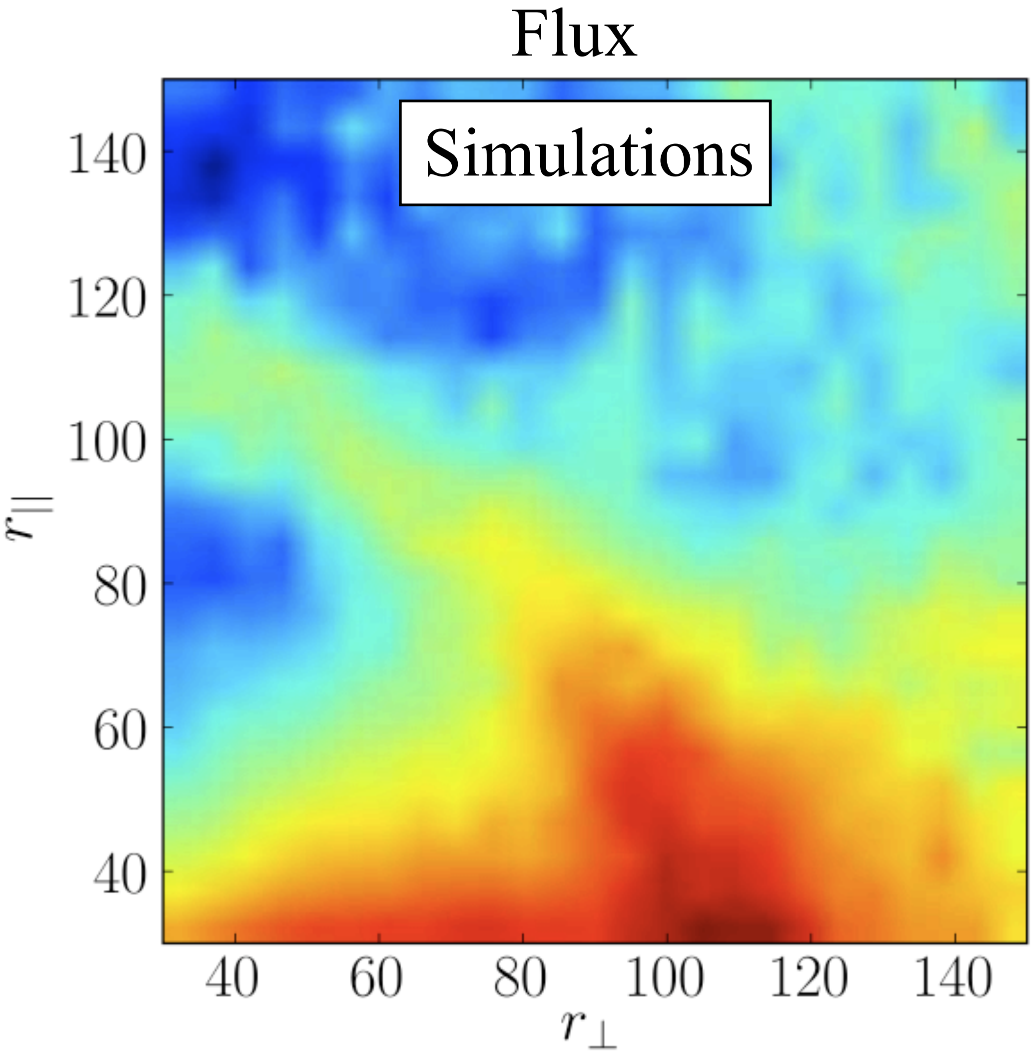
Apply linear Kaiser formula

z-space distortions



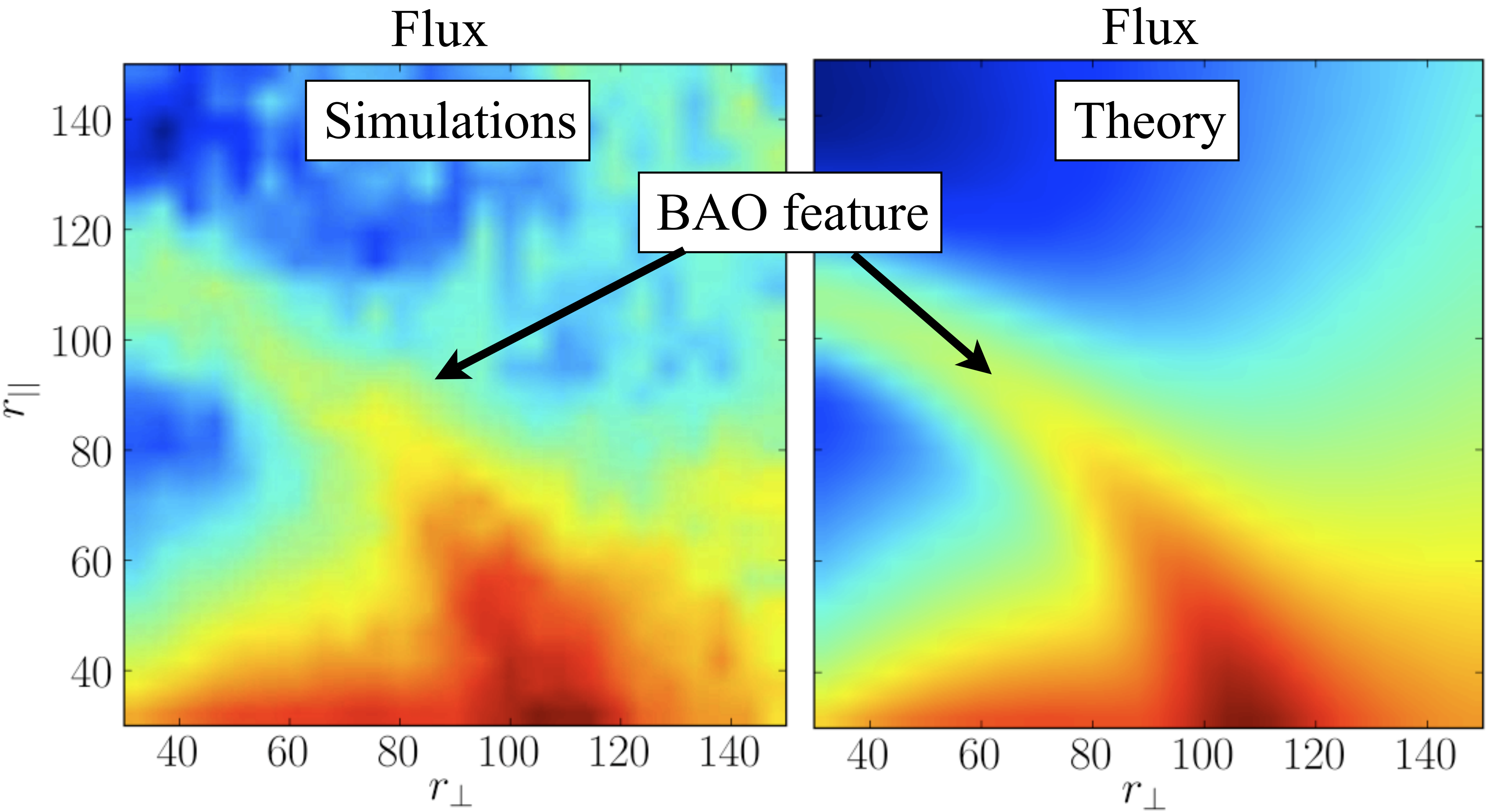
Beyond: With Lyman Alpha Forest

Redshift space distortions



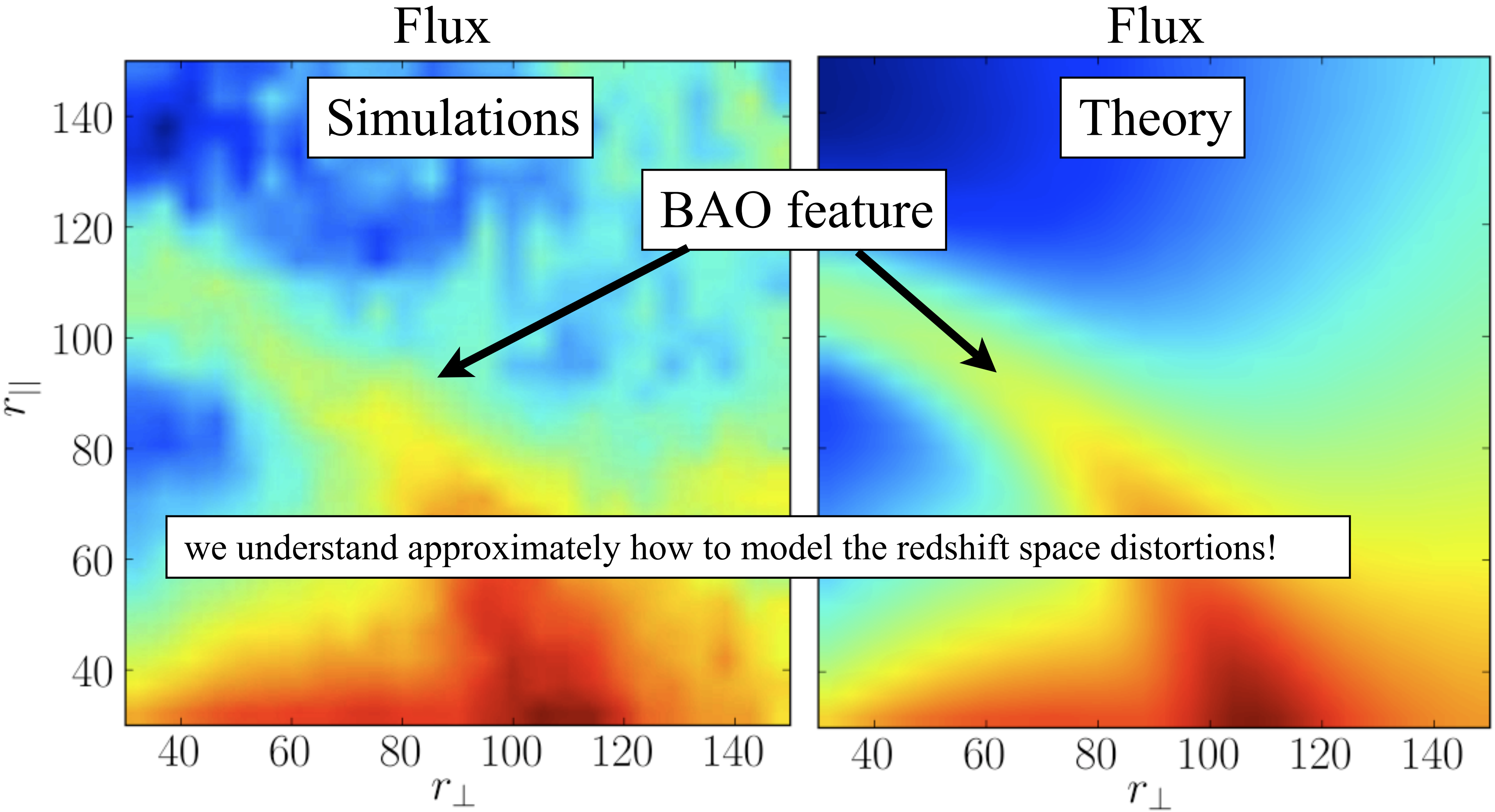
Beyond: With Lyman Alpha Forest

Redshift space distortions



Beyond: With Lyman Alpha Forest

Redshift space distortions



Simulations

Theory

BAO feature

we understand approximately how to model the redshift space distortions!

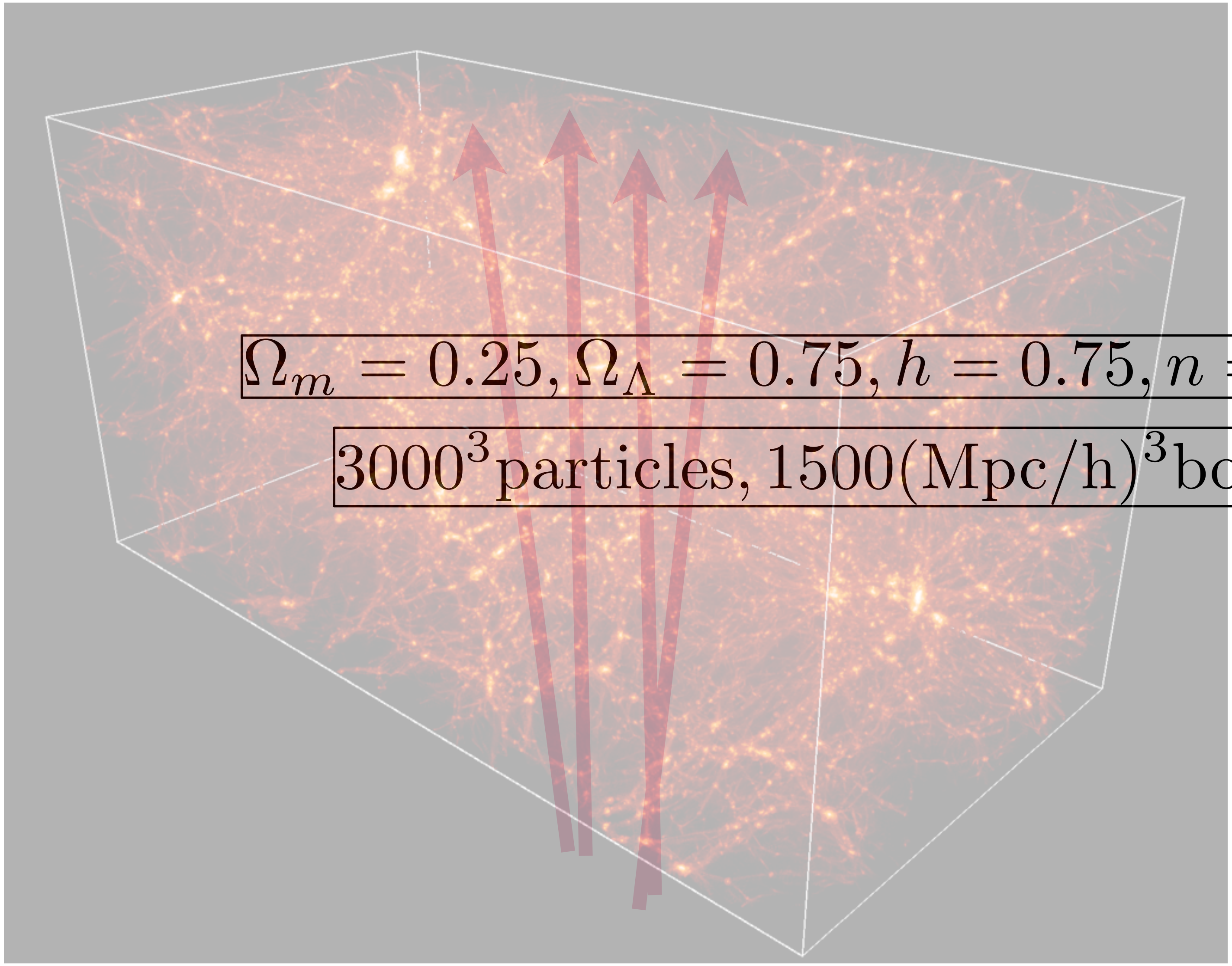
Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest

Possible systematics

- UV background fluctuations
- Metal Line contaminations
- Continuum fitting errors
- Damped Lyman alpha systems
- Broad Absorption Line systems

Lyman Alpha Forest: what can it do?

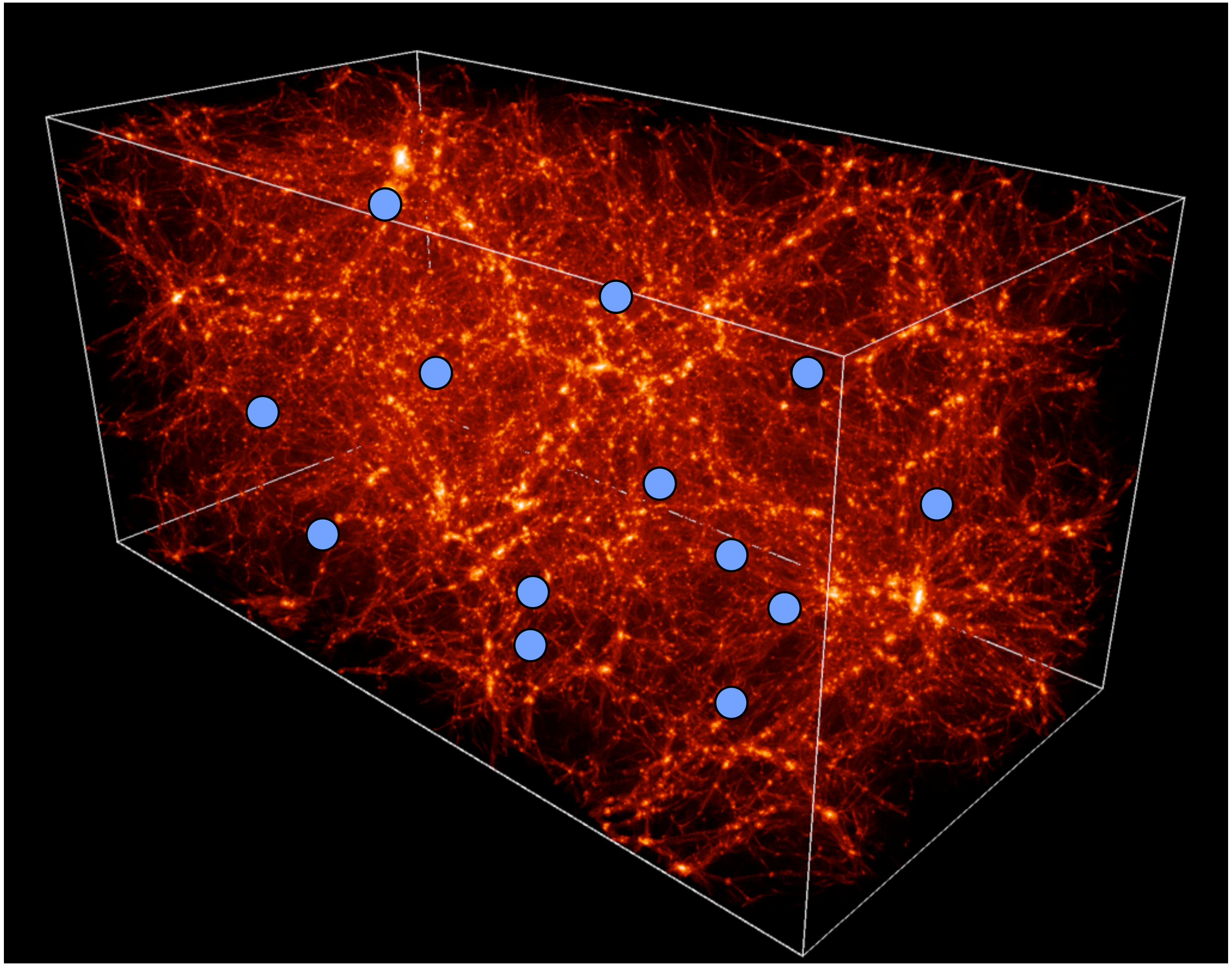


$\boxed{\Omega_m = 0.25, \Omega_\Lambda = 0.75, h = 0.75, n = 0.97, \sigma_8 = 0.8}$

$\boxed{3000^3 \text{particles}, 1500(\text{Mpc/h})^3 \text{box}, 3000^3 \text{grid}}$

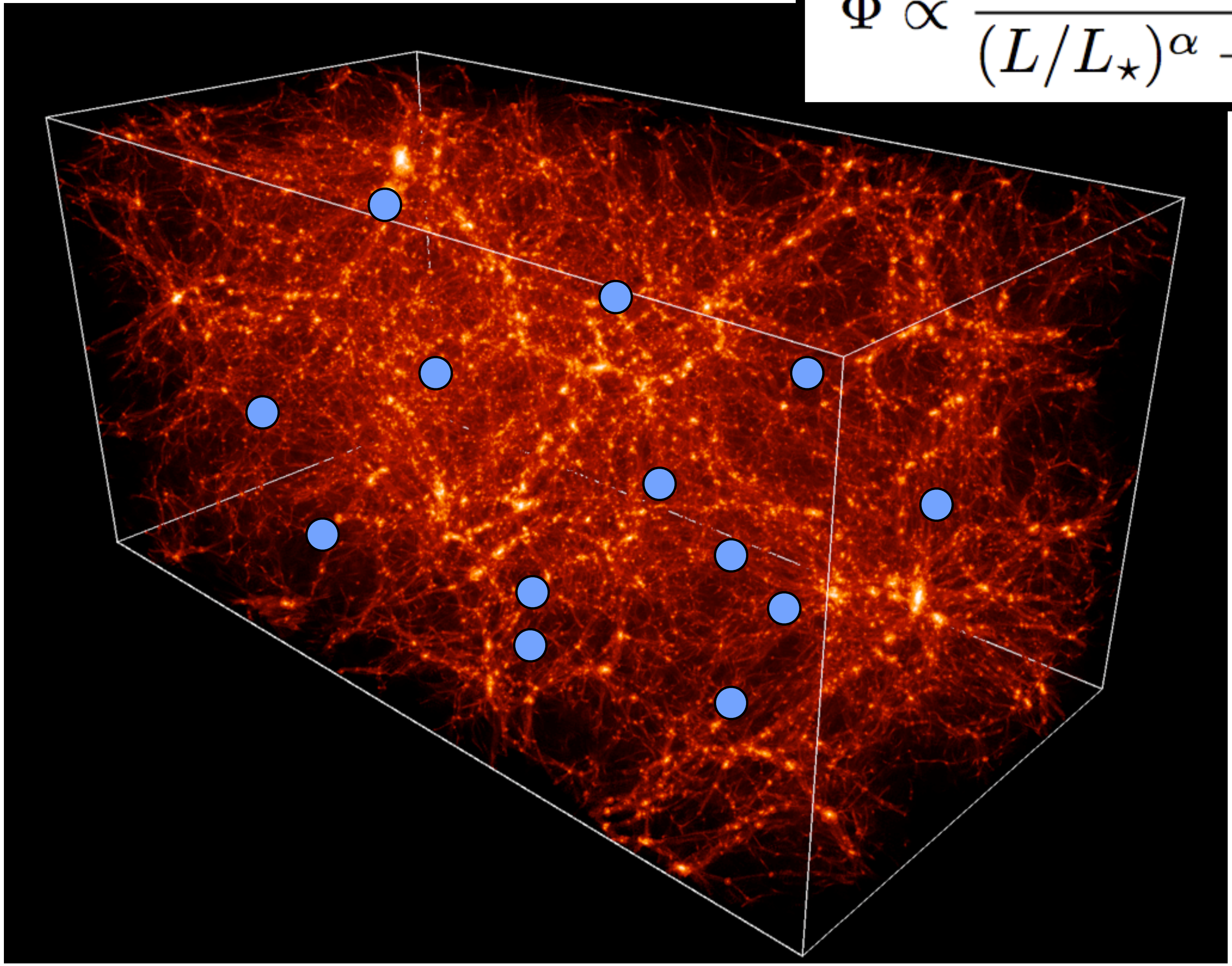
Beyond: With Lyman Alpha Forest

Possible systematics: UV background fluctuations



Beyond: With Lyman Alpha Forest

Possible systematics: UV background fluctuations

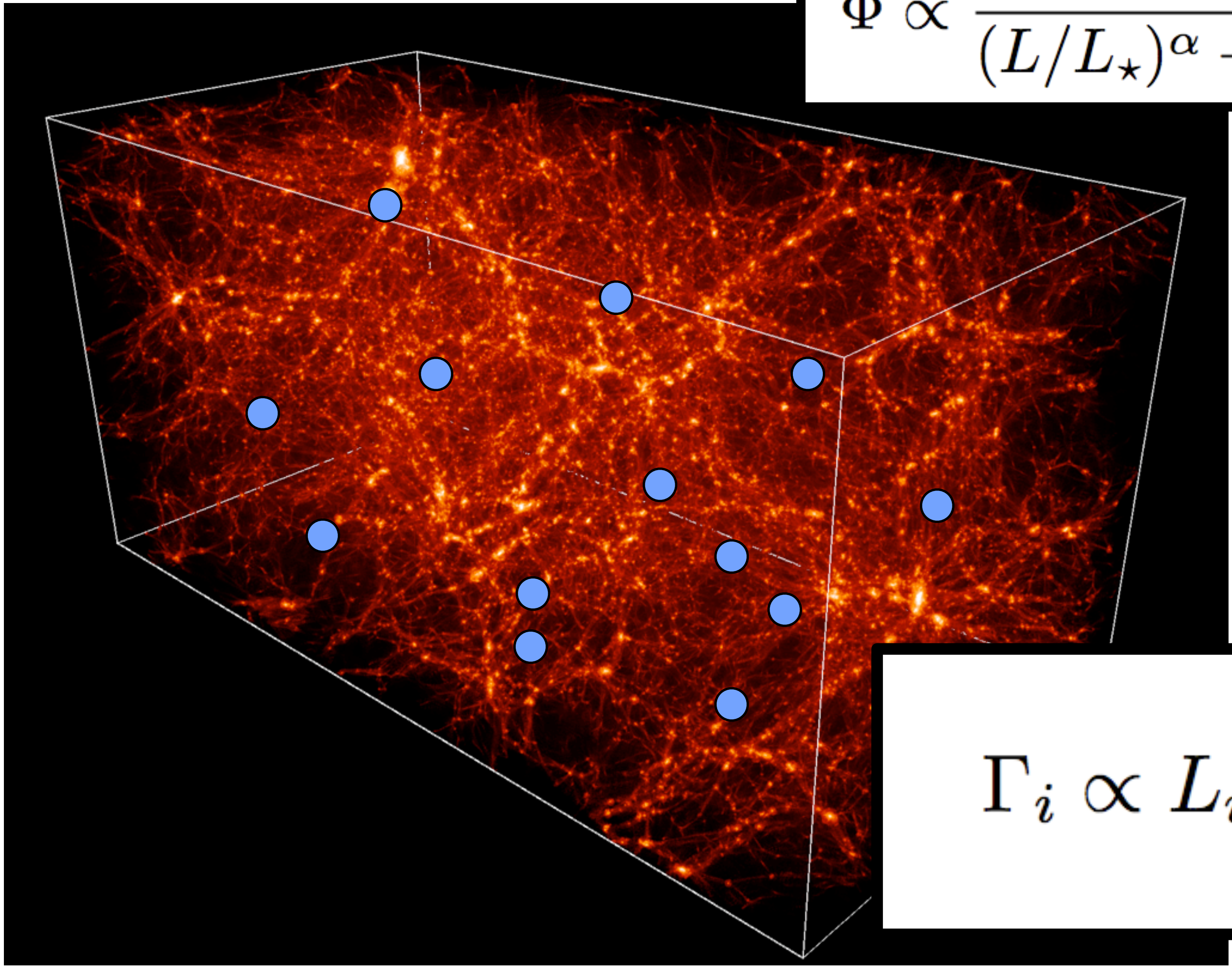


$$\Phi \propto \frac{1}{(L/L_\star)^\alpha + (L/L_\star)^\beta}$$

Beyond: With Lyman Alpha Forest

Possible systematics: UV background fluctuations

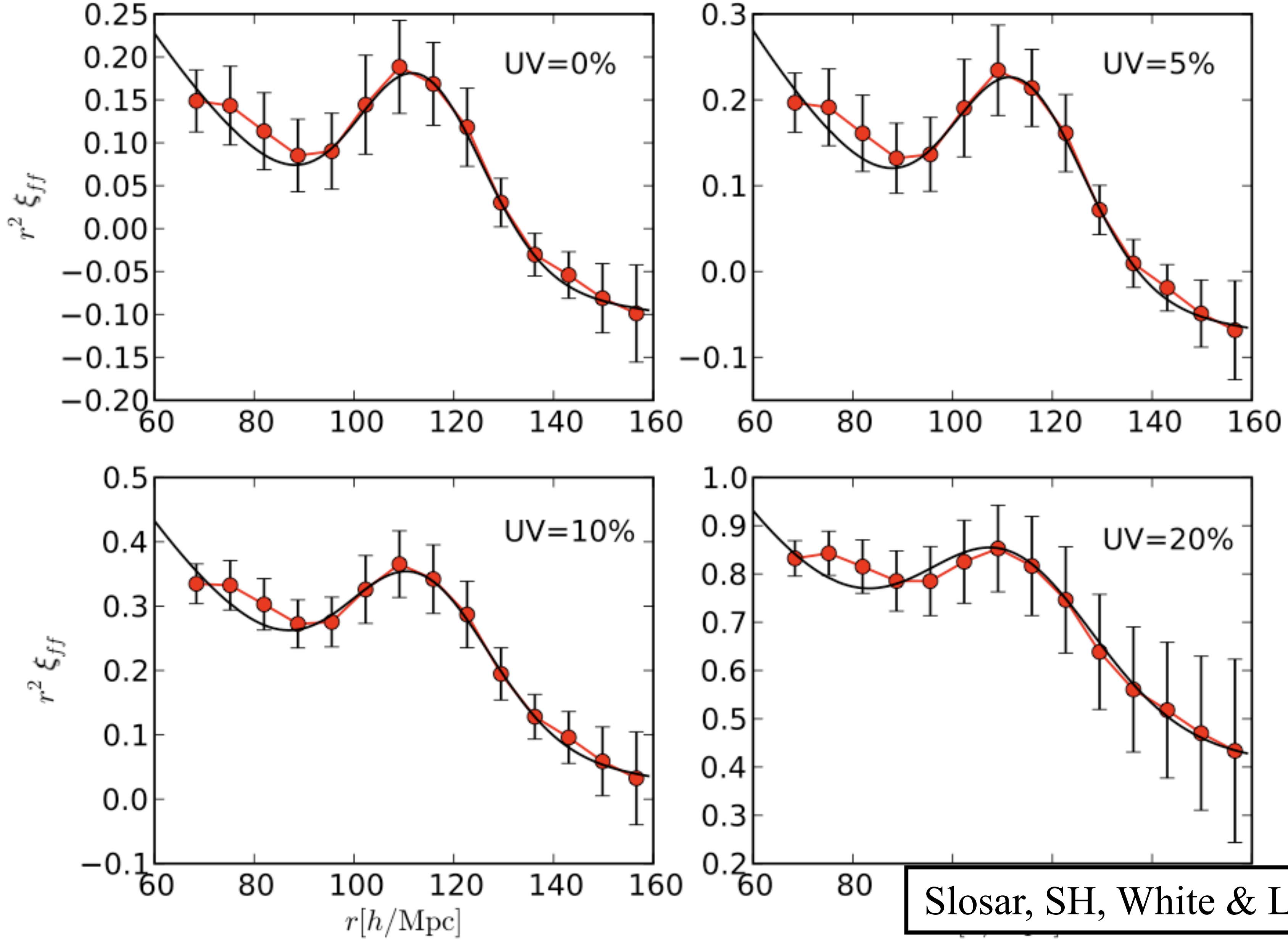
$$\Phi \propto \frac{1}{(L/L_\star)^\alpha + (L/L_\star)^\beta}$$



$$\Gamma_i \propto L_i \, \frac{e^{-r_i/r_0}}{4\pi r_i^2}$$

Beyond: With Lyman Alpha Forest

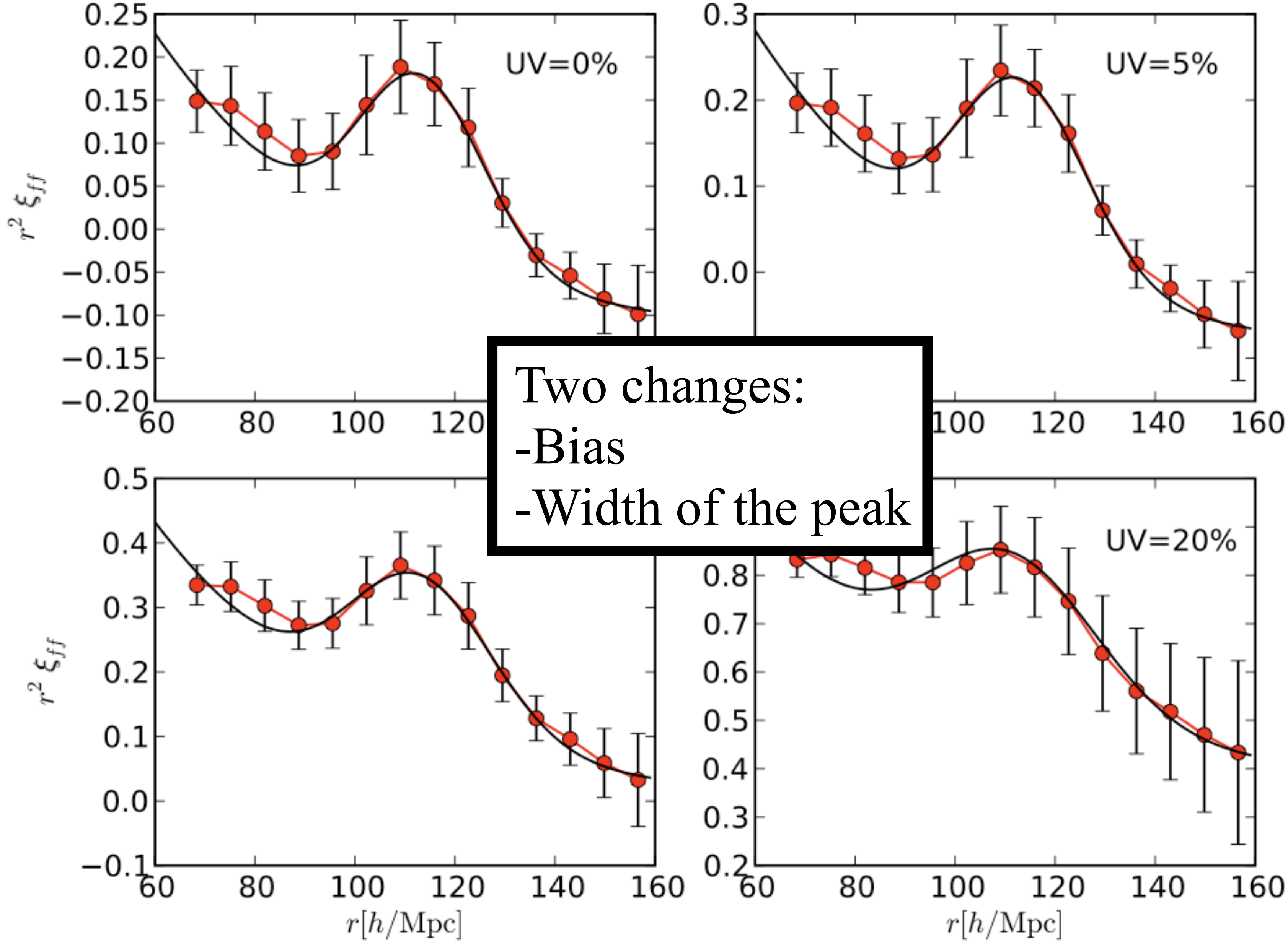
Possible systematics: UV background fluctuations



Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest

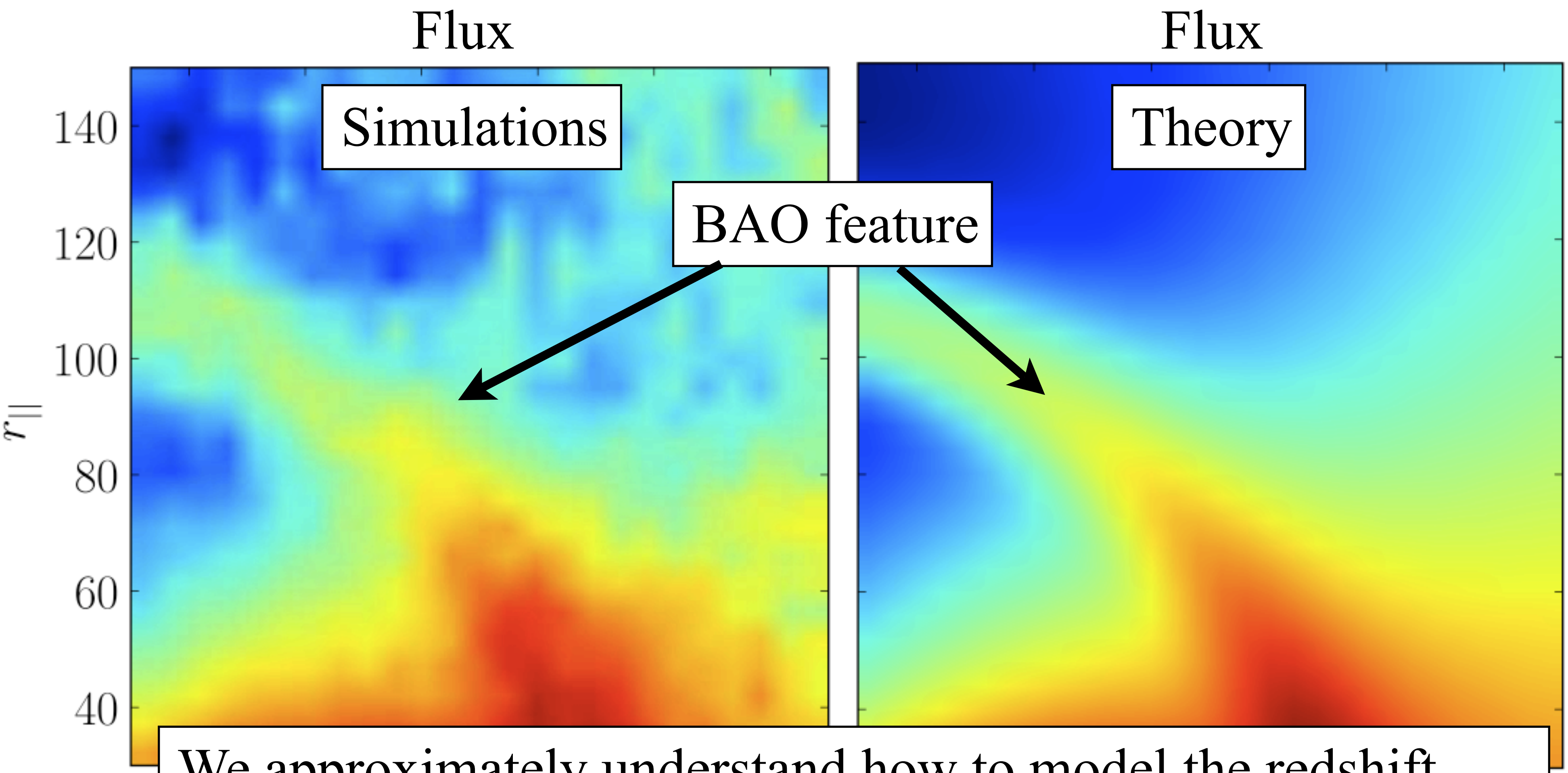
Possible systematics: UV background fluctuations



Two changes:
-Bias
-Width of the peak

Beyond: With Lyman Alpha Forest

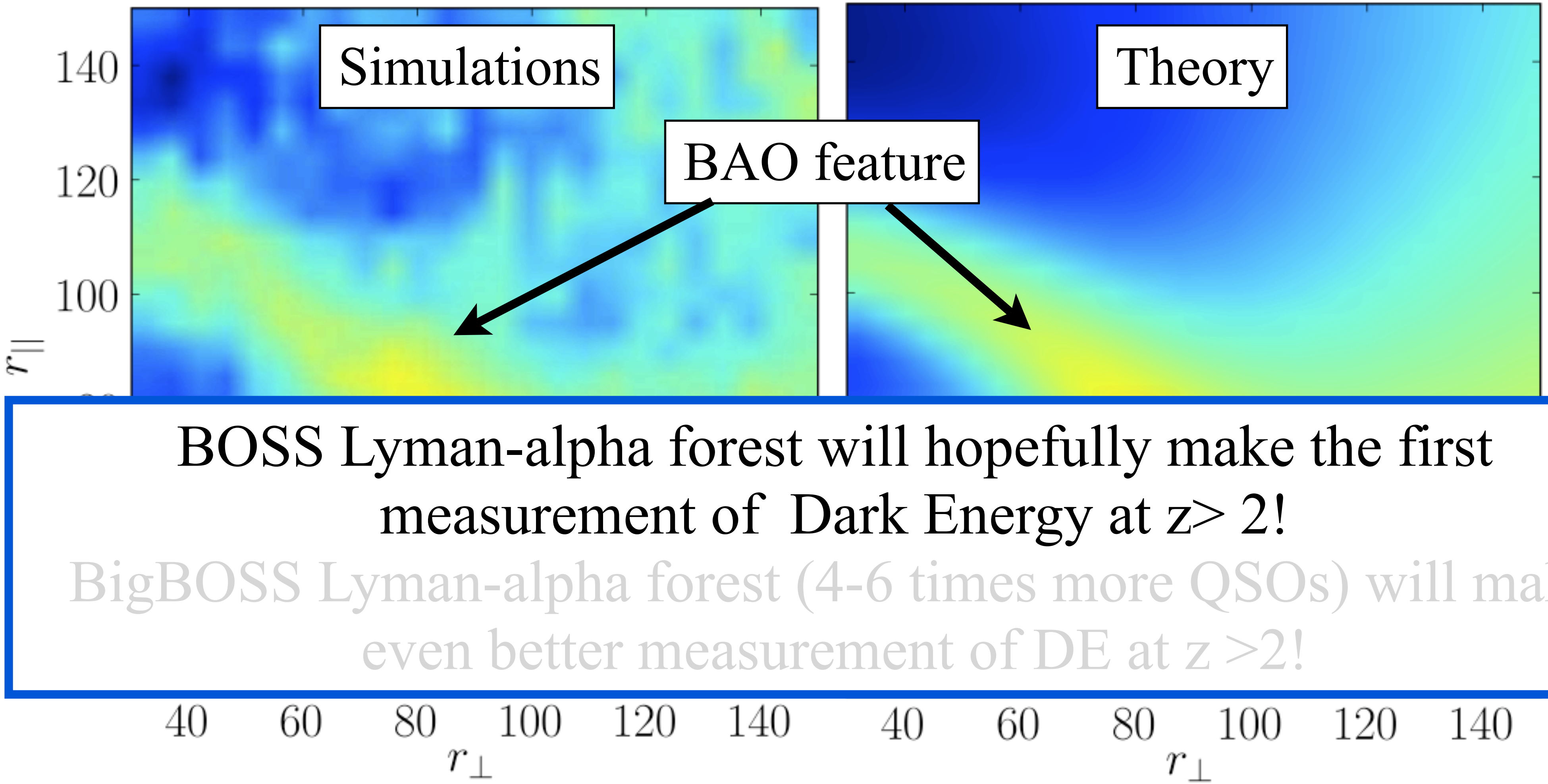
Mini Conclusion



We approximately understand how to model the redshift space distortions, and what happens when we include systematics such as UV background fluctuations.

Beyond: With Lyman Alpha Forest

Mini Conclusion

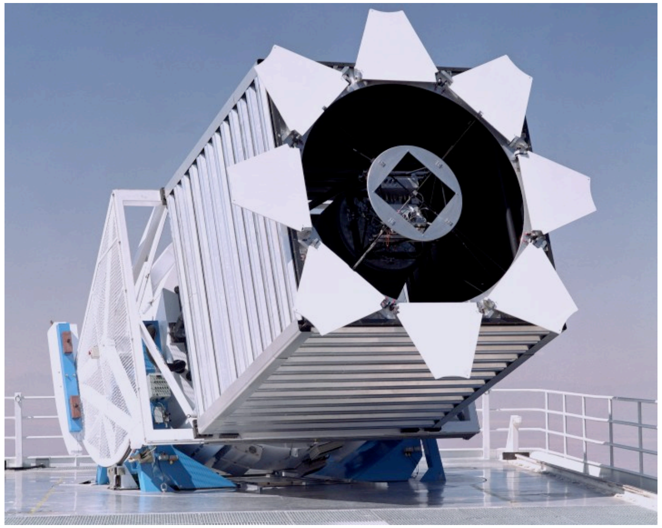


BOSS Lyman-alpha forest will hopefully make the first measurement of Dark Energy at z> 2!

BigBOSS Lyman-alpha forest (4-6 times more QSOs) will make even better measurement of DE at z >2!

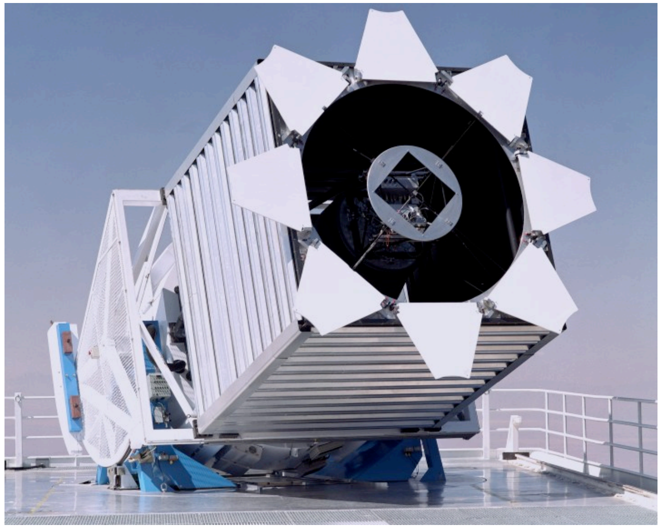
SDSS III - BOSS
Baryon Oscillation Spectroscopic Survey

- New program for the SDSS telescope for 2008–2014 (already working and providing data!).
- Definitive study of the low-redshift acoustic oscillations. 10,000 deg^2 of new spectroscopy from SDSS imaging.
    - 1.5 million LRGs to z=0.8, including 4x more density at z<0.5.
    - 7-fold improvement on large-scale structure data from entire SDSS survey; measure the distance scale to 1% at z=0.35 and z=0.6.
    - Easy extension of current program.
- Simultaneous project to discover the BAO in the Lyman α forest.
    - 160,000 quasars. 20% of fibers.
    - 1.5% measurement of distance to z=2.3.
    - Higher risk but opportunity to open the high-redshift distance scale.



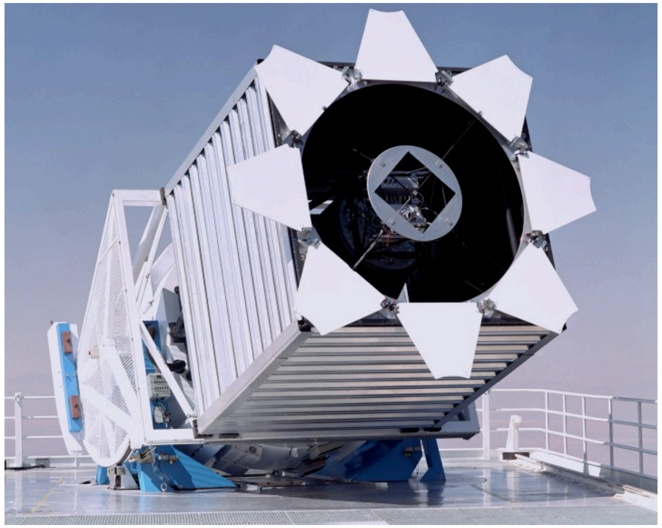
SDSS III - BOSS
Baryon Oscillation Spectroscopic Survey

- New program for the SDSS telescope for 2008–2014 (already working and providing data!).
- Definitive study of the low-redshift acoustic oscillations. 10,000 deg^2 of new spectroscopy from SDSS imaging.
  - 1.5 million LRGs to z=0.8, including 4x more density at z<0.5.
  - 7-fold improvement on large-scale structure data from entire SDSS survey; measure the distance scale to 1% at z=0.35 and z=0.6.
  - Easy extension of current program.
- Simultaneous project to discover the BAO in the Lyman α forest.
  - 160,000 quasars. 20% of fibers.
  - 1.5% measurement of distance to z=2.3.
  - Higher risk but opportunity to open the high-redshift distance scale.



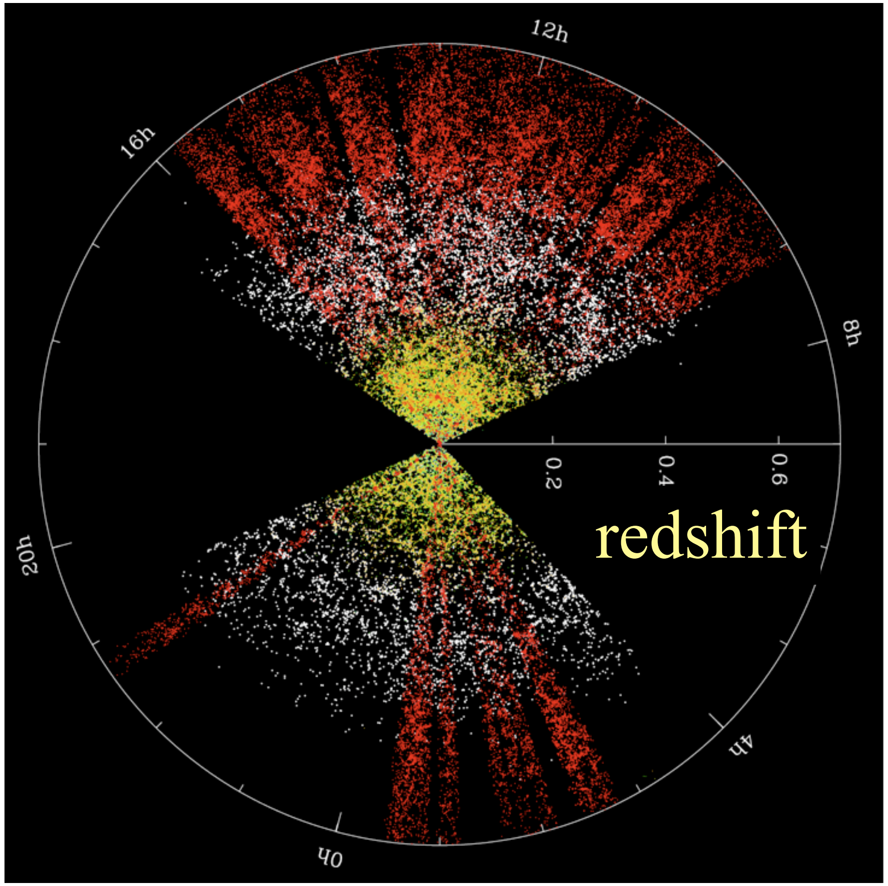
SDSS III - BOSS
Baryon Oscillation Spectroscopic Survey

- New program for the SDSS telescope for 2008–2014 (already working and providing data!).
- Definitive study of the low-redshift acoustic oscillations. 10,000 deg^2 of new spectroscopy from SDSS imaging.
  - 1.5 million LRGs to $z=0.8$, including 4x more density at $z<0.5$.
  - 7-fold improvement on large-scale structure data from entire SDSS survey; measure the distance scale to 1% at $z=0.35$ and $z=0.6$.
  - Easy extension of current program.
- Simultaneous project to discover the BAO in the Lyman α forest.
  - 160,000 quasars. 20% of fibers.
  - 1.5% measurement of distance to $z=2.3$.
  - Higher risk but opportunity to open the high-redshift distance scale.



SDSS III - BOSS
Baryon Oscillation Spectroscopic Survey

Volume of the Universe probed by SDSS

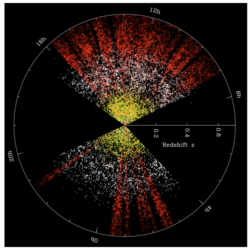


Courtesy plots from Michael Blanton

SDSS III - BOSS
Baryon Oscillation Spectroscopic Survey

Volume of the Universe probed by SDSS

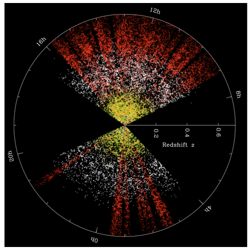
Volume of the Universe probed by BOSS



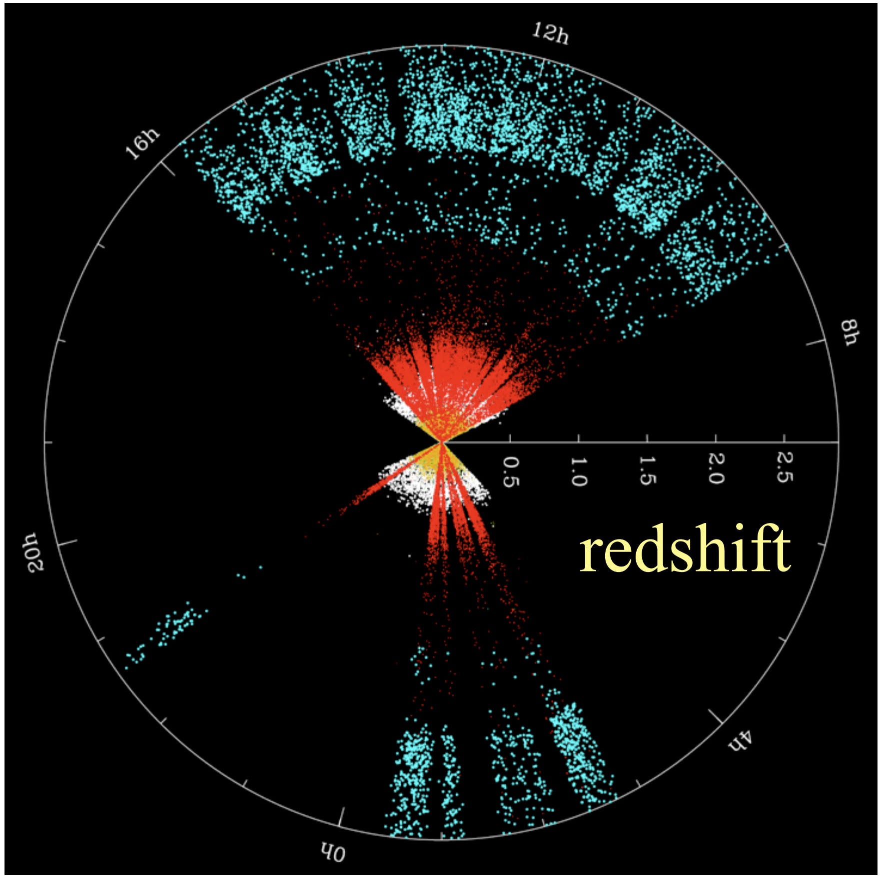
Courtesy plots from Michael Blanton

SDSS III - BOSS
Baryon Oscillation Spectroscopic Survey

Volume of the Universe probed by SDSS



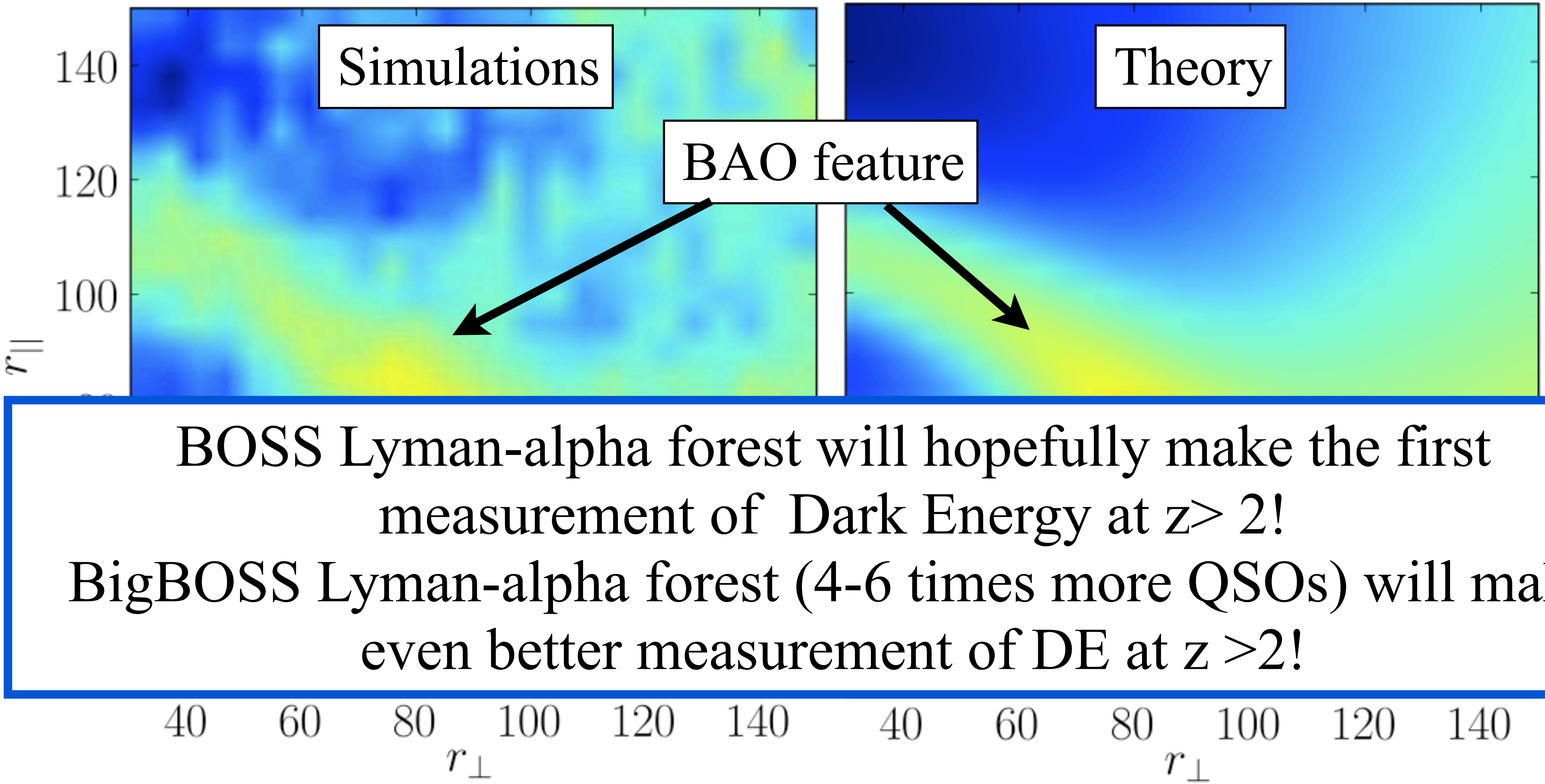
Volume of the Universe probed by BOSS



Courtesy plots from Michael Blanton

Beyond: With Lyman Alpha Forest

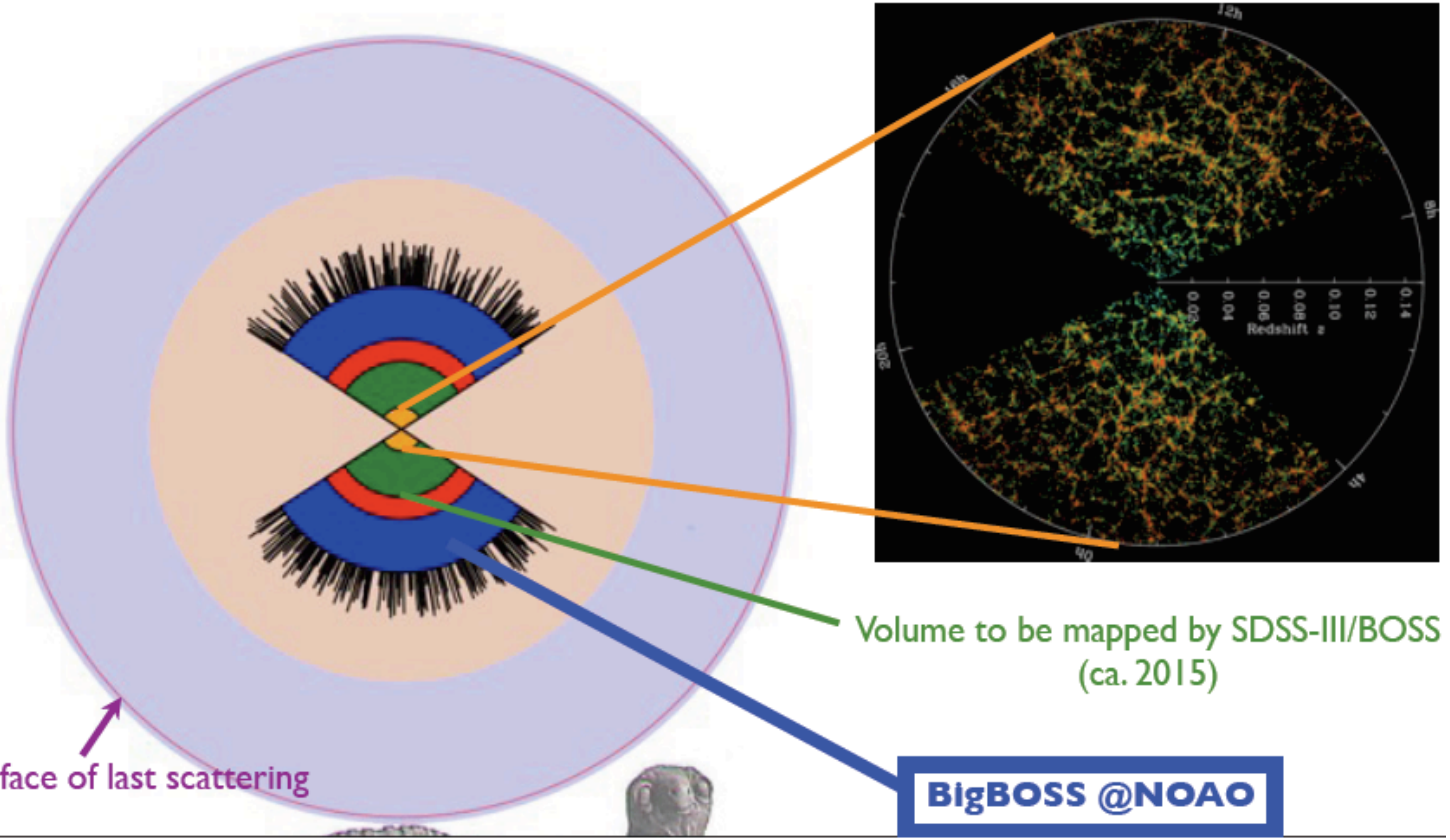
Mini Conclusion



BOSS Lyman-alpha forest will hopefully make the first measurement of Dark Energy at z> 2!
BigBOSS Lyman-alpha forest (4-6 times more QSOs) will make even better measurement of DE at z >2!

Science Goals: 50 million redshifts

Sensitivity to new physics scales as volume surveys -- # of modes



Our observable Universe

Volume mapped by SDSS + SDSS-II

Volume to be mapped by SDSS-III/BOSS (ca. 2015)

BigBOSS @NOAO

Surface of last scattering

Courtesy Slide from David Schlegel

Outline

- Motivations
- Introduction
  - What are Baryon Acoustic Oscillations?
- Baryon Acoustic Oscillations: Now and Beyond
  - Now: With Luminous Red Galaxies
  - Beyond: With Lyman Alpha Forest
- Conclusions

Conclusions

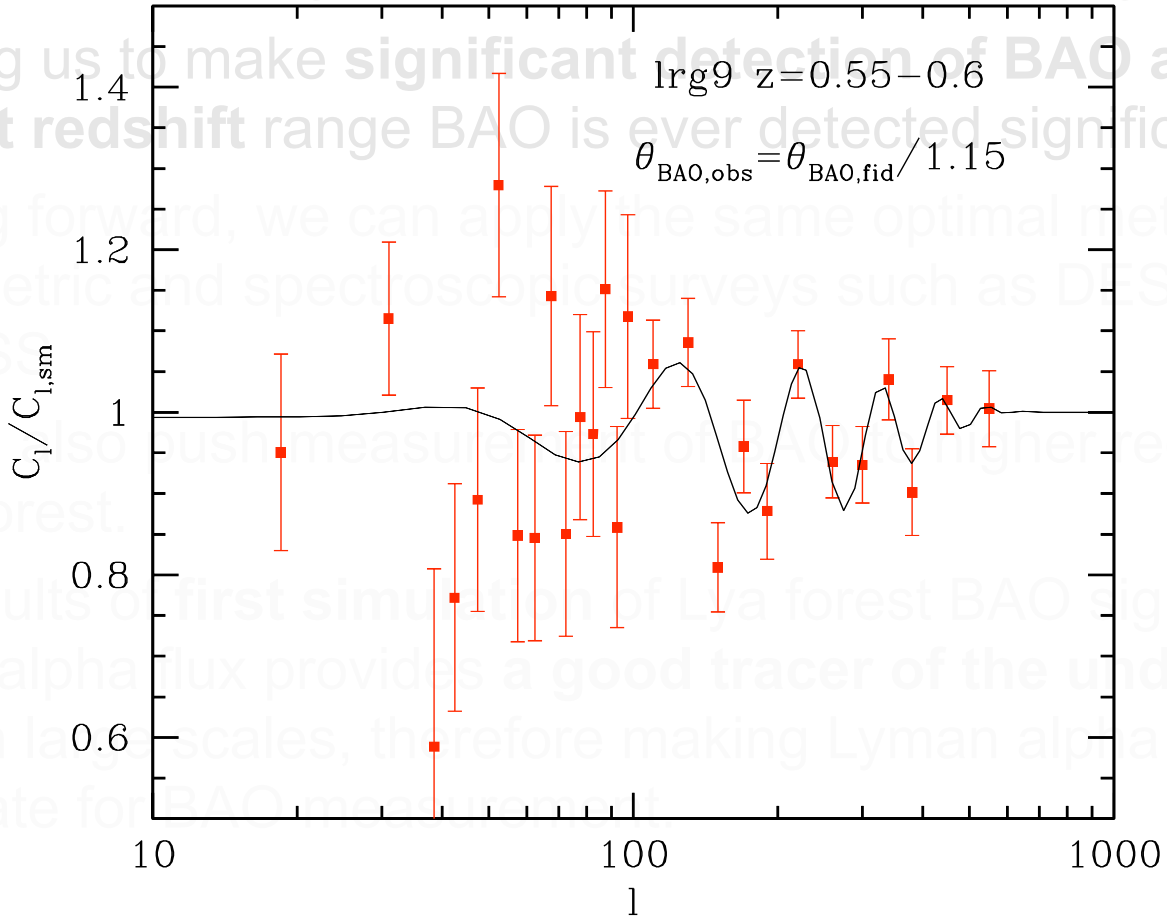
- Baryon Acoustic Oscillations is one of the cleanest probes of **Dark Energy**
- We made the **minimum variance measurement** of galaxy clustering for **largest volume** of galaxies ever used for clustering
- Allowing us to make **significant detection of BAO at z=0.45-0.65**, the **highest redshift** range BAO is ever detected significantly.
- Looking forward, we can apply the same optimal method to both photometric and spectroscopic surveys such as DES, LSST, BOSS and BigBOSS
- We can also push measurement of BAO to higher redshift via Lyman alpha forest.
- Our results of **first simulation** of Lya forest BAO signals indicate that Lyman alpha flux provides **a good tracer of the underlying dark matter field** on large scales, therefore making Lyman alpha forest a well-suited candidate for BAO measurement.

Conclusions

- Baryon Acoustic Oscillations is one of the cleanest probes of **Dark Energy**
- We made the **minimum variance measurement** of galaxy clustering for **largest volume** of galaxies ever used for clustering
- Allowing us to make **significant detection of BAO at z=0.45-0.65**, the **highest redshift** range BAO is ever detected significantly.
- Looking forward, we can apply the same optimal method to both photometric and spectroscopic surveys such as DES, LSST, BOSS and BigBOSS
- We can also push measurement of BAO to higher redshift via Lyman alpha forest.
- Our results of **first simulation** of Lya forest BAO signals indicate that Lyman alpha flux provides **a good tracer of the underlying dark matter field** on large scales, therefore making Lyman alpha forest a well-suited candidate for BAO measurement.

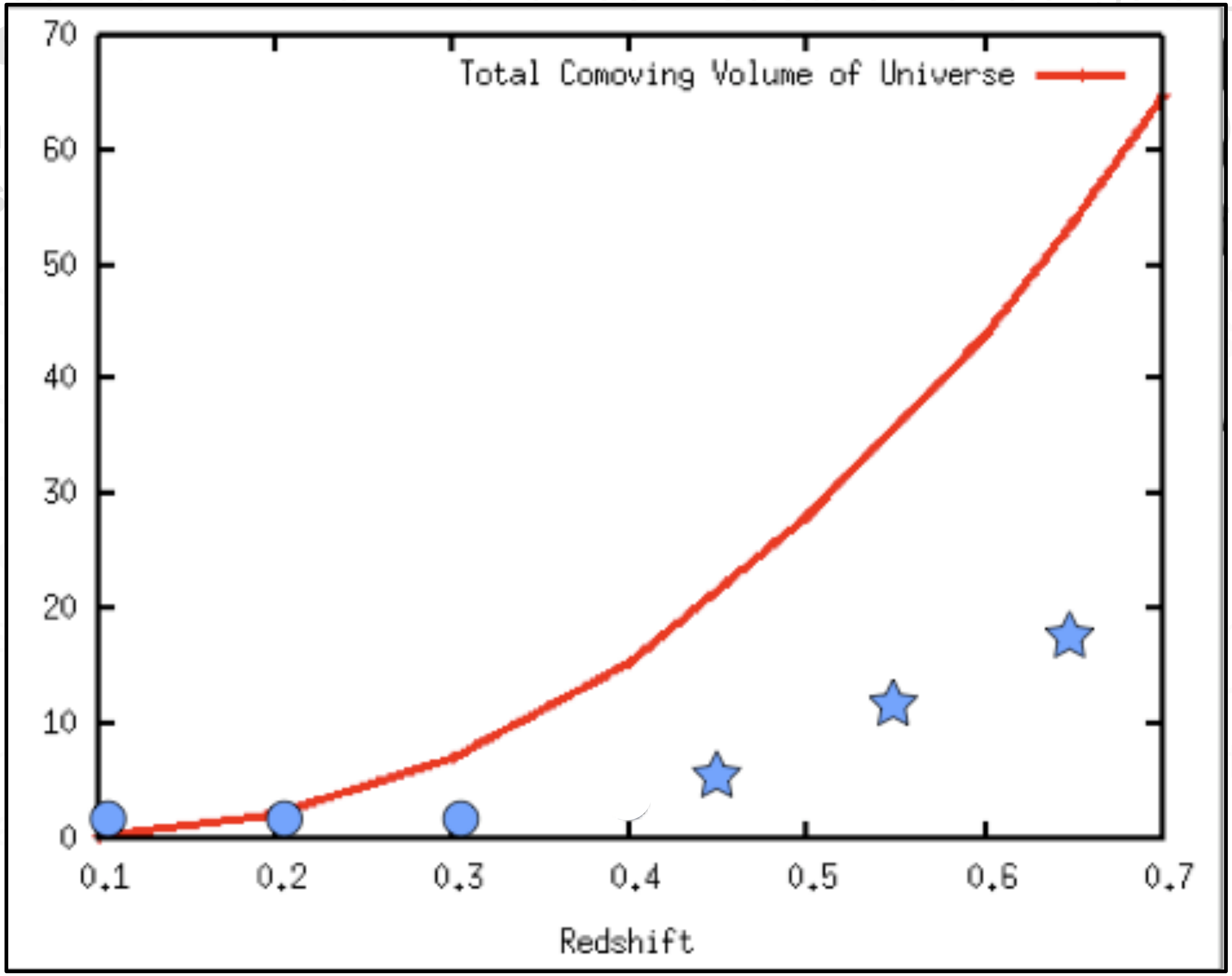
Conclusions

- Baryon Acoustic Oscillations is one of the cleanest probe of Dark Energy
- We made the **minimum variance measurement** of galaxy clustering for **largest volume** of galaxies ever used for clustering
- Allowing us to make **significant detection of BAO at z=0.45-0.65**, the **highest redshift** range BAO is ever detected significantly.
- Looking forward, we can apply the same optimal method to both photometric and spectroscopic surveys such as DES, LSST, BOSS and BigBOSS.
- We can also push measurement of BAO to higher redshift via Lyman alpha forest.
- Our results of **first simulation** of Lya forest BAO signals indicate that Lyman alpha flux provides **a good tracer of the underlying dark matter field** on large scales, therefore making Lyman alpha forest a well-suited candidate for BAO measurement.



Conclusions

- Baryon Acoustic Oscillations is one of the cleanest probe of Dark Energy
- We made the **minimum variance measurement** of galaxy clustering for **largest**
- Allowin **.45-0.65**, the **highes**



- Lookin o both photom T, BOSS and BigBOS
- We car via Lyman alpha f
- Our res ndicate that Lyman **g dark matter field** o t a well-suited candid

Conclusions

- Baryon Acoustic Oscillations is one of the cleanest probes of **Dark Energy**
- We made the **minimum variance measurement** of galaxy clustering for **largest volume** of galaxies ever used for clustering
- Allowing us to make **significant detection of BAO at z=0.45-0.65**, the **highest redshift** range BAO is ever detected significantly.
- Looking forward, we can apply the same optimal method to both photometric and spectroscopic surveys such as DES, LSST, BOSS and BigBOSS
- We can also push measurement of BAO to higher redshift via Lyman alpha forest.
- Our results of **first simulation** of Lya forest BAO signals indicate that Lyman alpha flux provides **a good tracer of the underlying dark matter field** on large scales, therefore making Lyman alpha forest a well-suited candidate for BAO measurement.

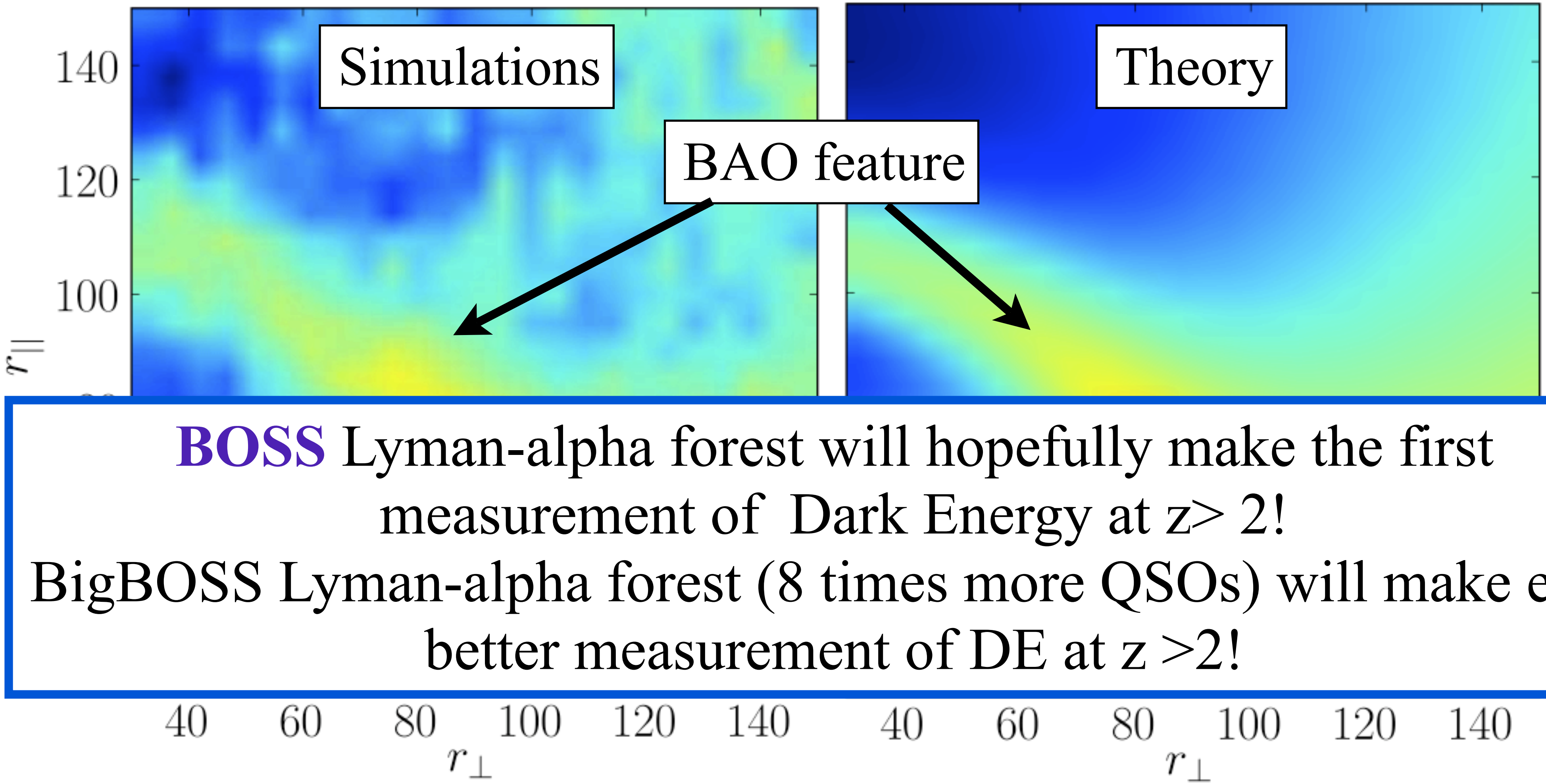
Conclusions

- Baryon Acoustic Oscillations is one of the cleanest probes of **Dark Energy**
- We made the **minimum variance measurement** of galaxy clustering for **largest volume** of galaxies ever used for clustering
- Allowing us to make **significant detection of BAO at z=0.45-0.65**, the **highest redshift** range BAO is ever detected significantly.
- Looking forward, we can apply the same optimal method to both photometric and spectroscopic surveys such as DES, LSST, BOSS and BigBOSS
- We can also push measurement of BAO to higher redshift via Lyman alpha forest.
- Our results of **first simulation** of Lya forest BAO signals indicate that Lyman alpha flux provides **a good tracer of the underlying dark matter field** on large scales, therefore making Lyman alpha forest a well-suited candidate for BAO measurement.

The End

Beyond: With Lyman Alpha Forest

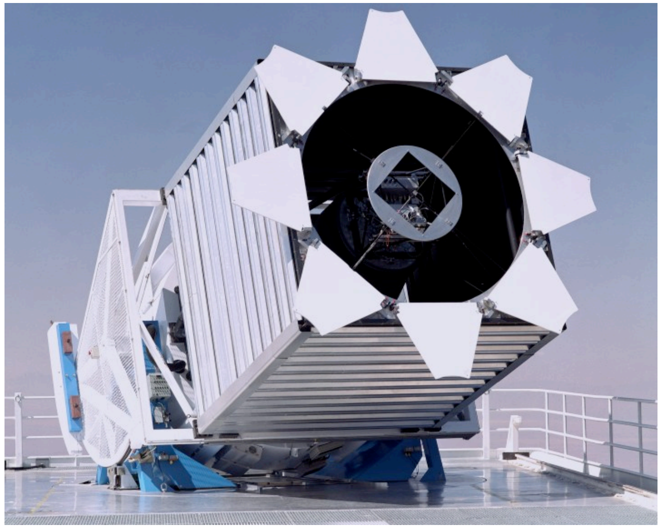
Mini Conclusion



BOSS Lyman-alpha forest will hopefully make the first measurement of Dark Energy at z> 2!
BigBOSS Lyman-alpha forest (8 times more QSOs) will make even better measurement of DE at z >2!

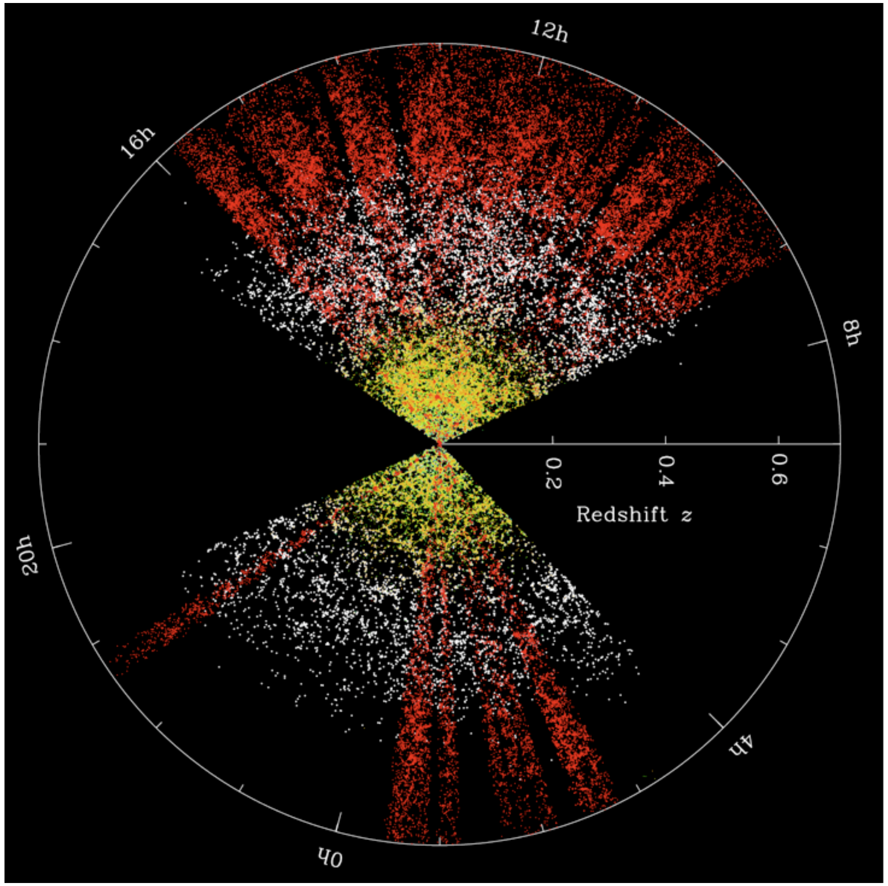
What is BOSS? Baryon Oscillation Spectroscopic Survey

- New program for the SDSS telescope for 2008–2014 (already working and providing data!).
- Definitive study of the low-redshift acoustic oscillations. 10,000 deg^2 of new spectroscopy from SDSS imaging.
  - 1.5 million LRGs to $z=0.8$, including 4x more density at $z<0.5$.
  - 7-fold improvement on large-scale structure data from entire SDSS survey; measure the distance scale to 1% at $z=0.35$ and $z=0.6$.
  - Easy extension of current program.
- Simultaneous project to discover the BAO in the Lyman α forest.
  - 160,000 quasars. 20% of fibers.
  - 1.5% measurement of distance to $z=2.3$.
  - Higher risk but opportunity to open the high-redshift distance scale.

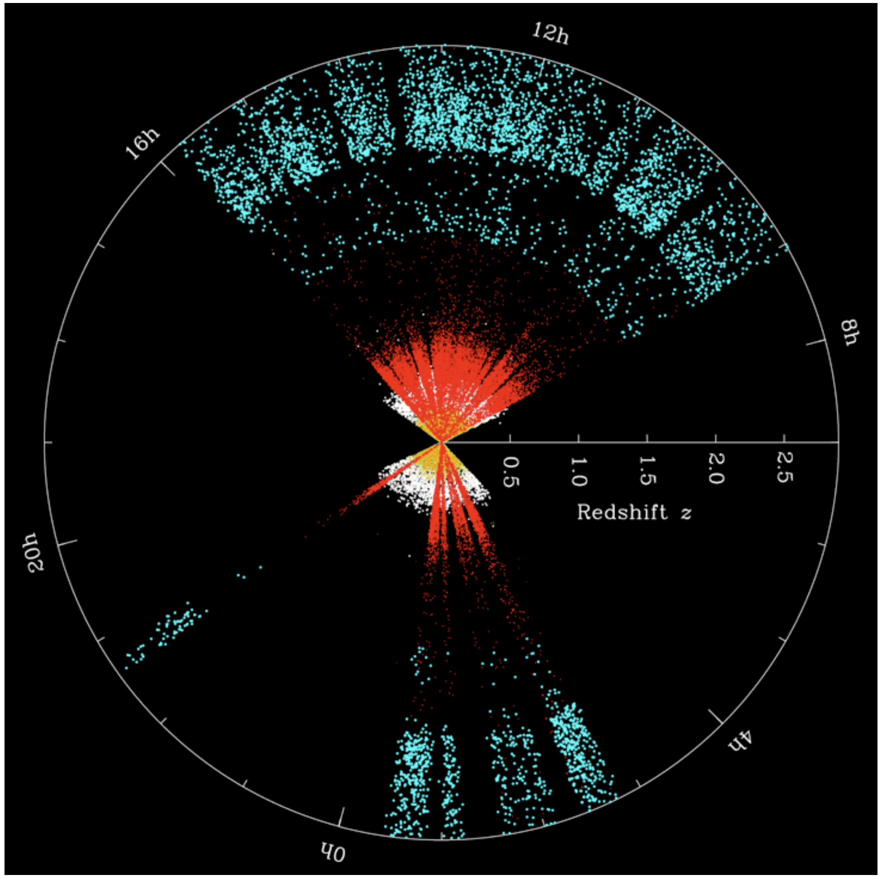


BOSS

Volume of the Universe probed by SDSS



Volume of the Universe probed by BOSS

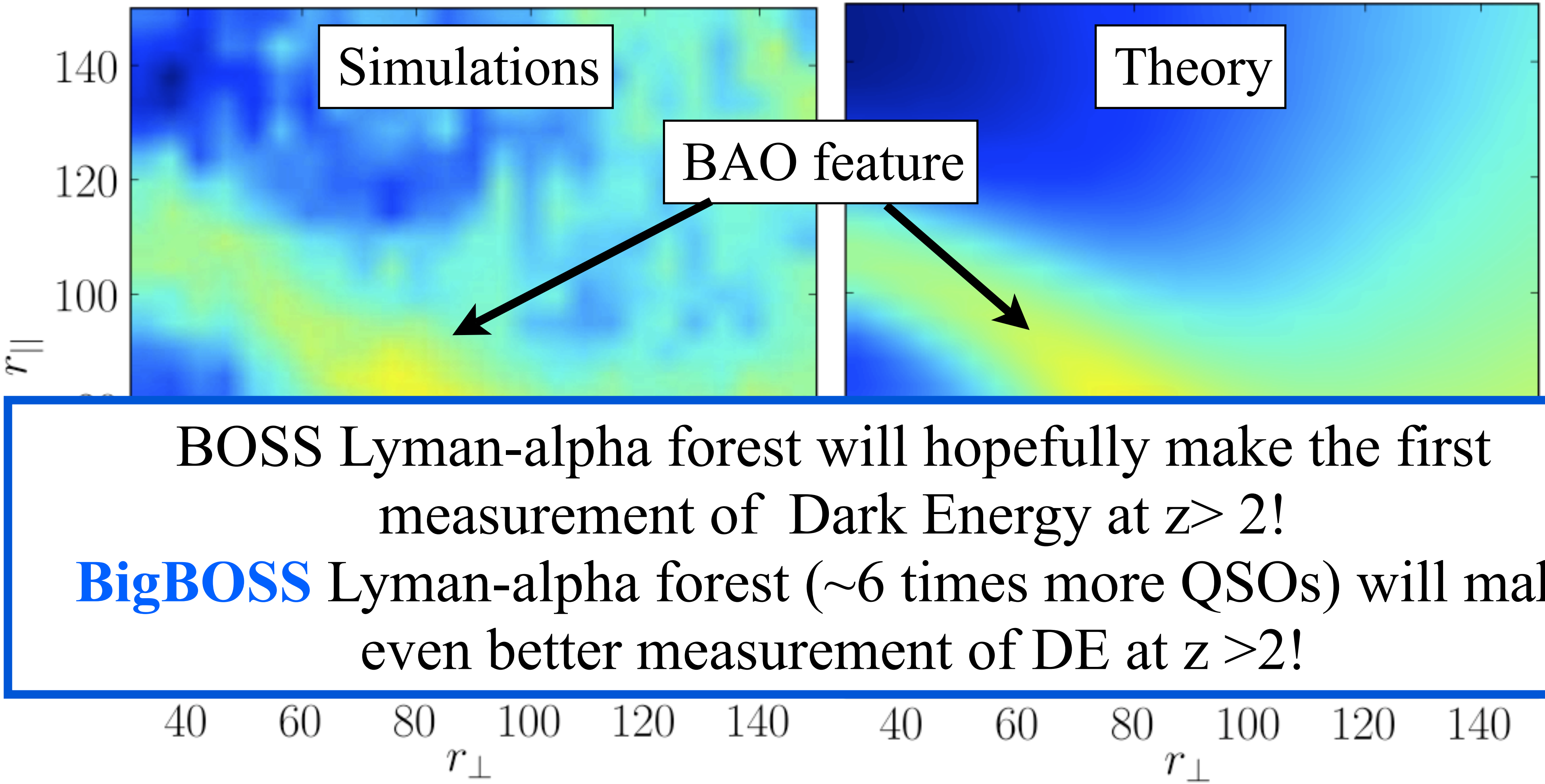


Courtesy plots from Michael Blanton

Beyond: With Lyman Alpha Forest

Mini Conclusion

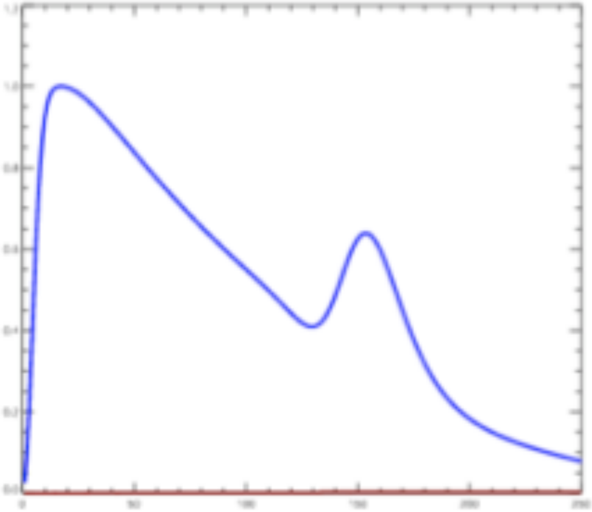
- **Dark Energy via Baryon Acoustic Oscillations**

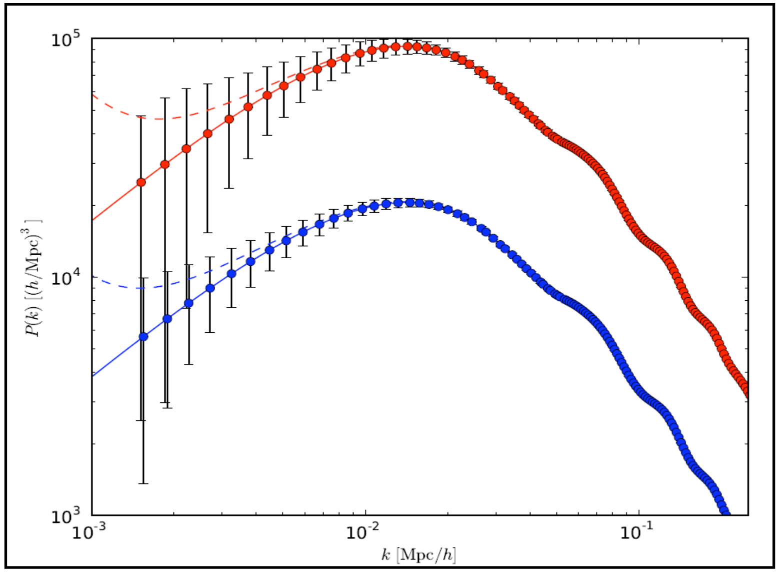


BOSS Lyman-alpha forest will hopefully make the first measurement of Dark Energy at z> 2!
BigBOSS Lyman-alpha forest (~6 times more QSOs) will make even better measurement of DE at z >2!

How do you go about measuring BAO?

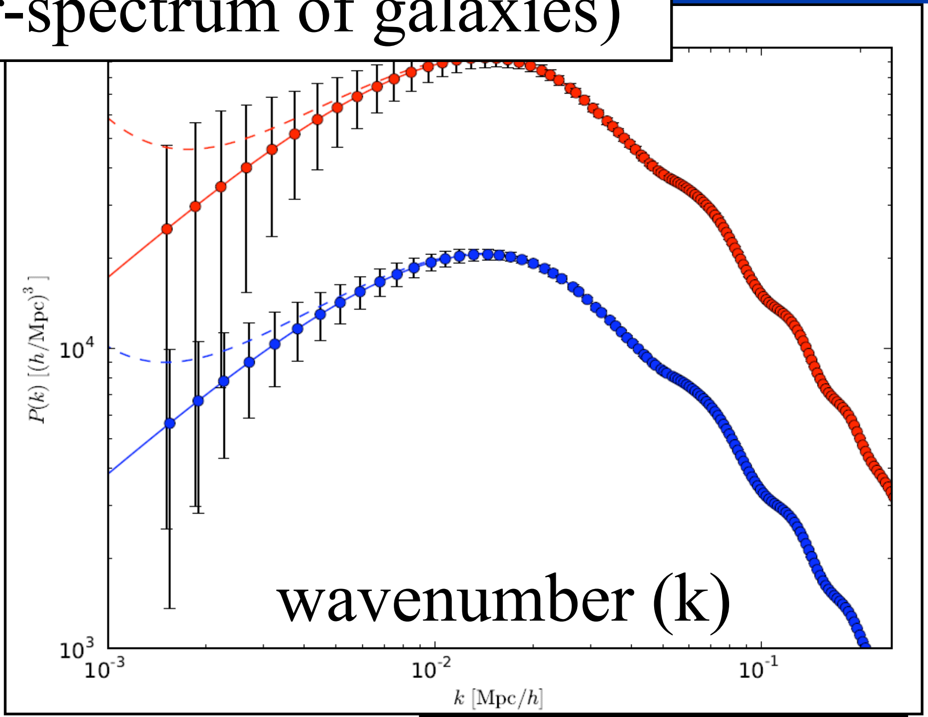
- Since there are many ripples, how do we actually measure the BAO?
- We measure the correlation function or its Fourier transform, called the power-spectrum.





Predicted signals of BAO

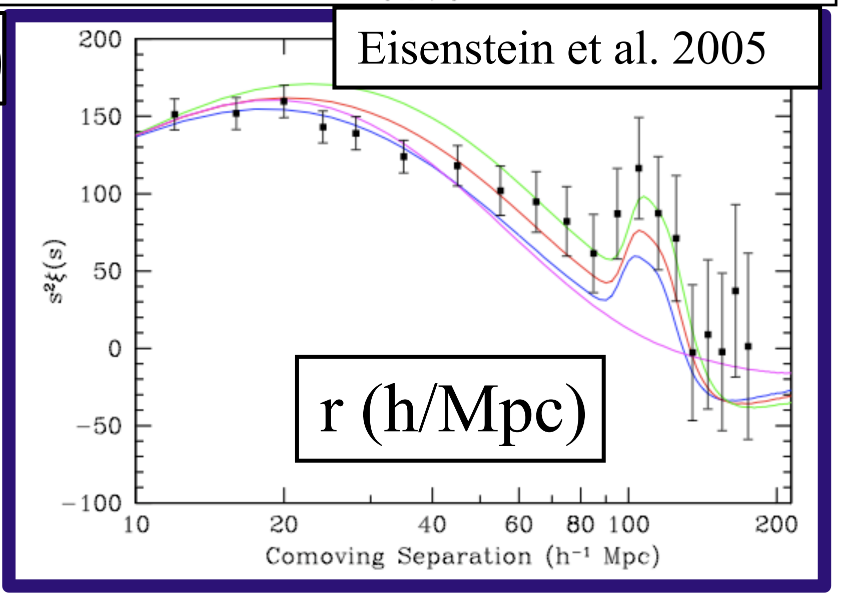
P(k) (power-spectrum of galaxies)



wavenumber (k)

Fourier space

$r^2\xi(r)$



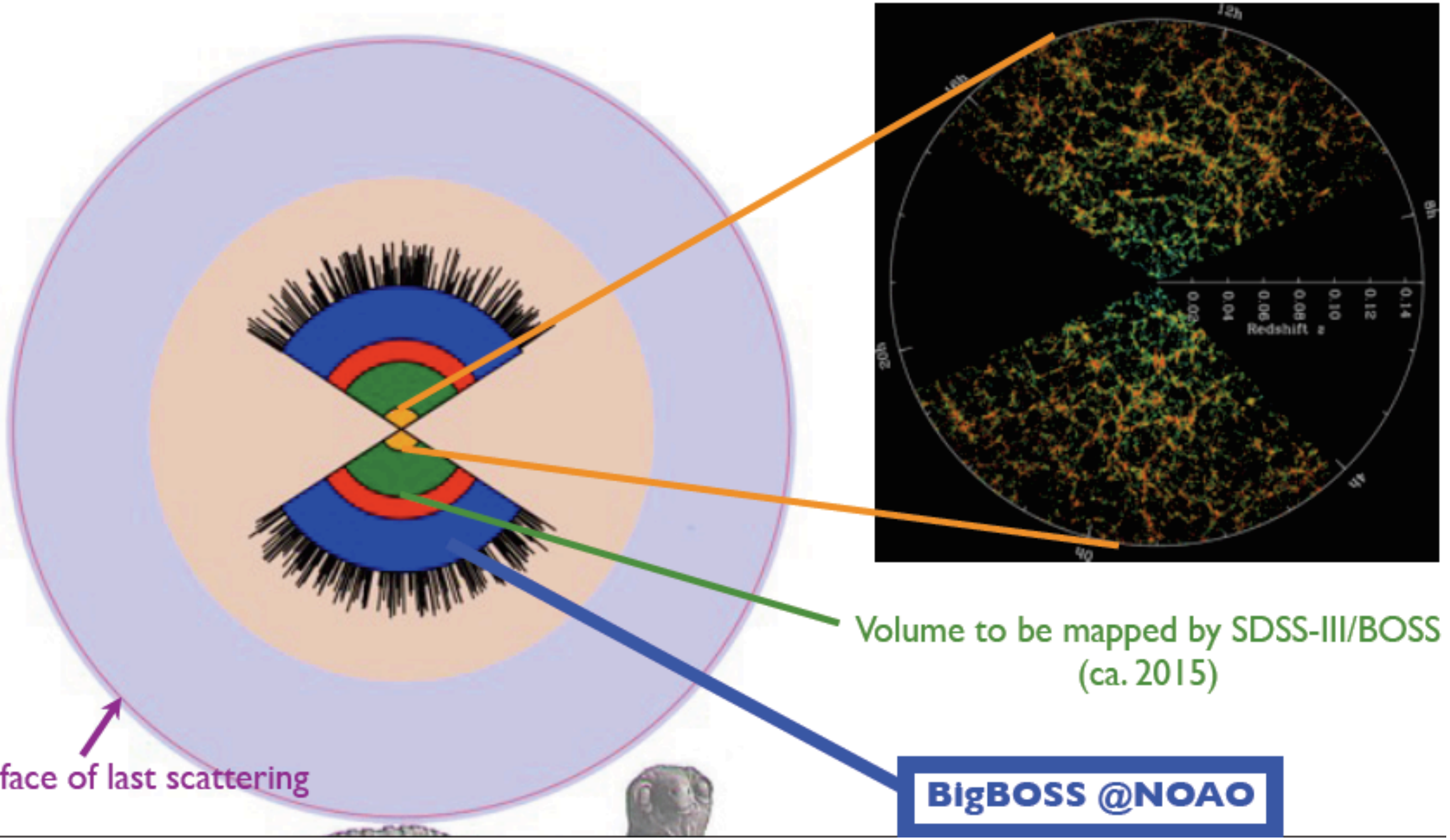
Eisenstein et al. 2005

r (h/Mpc)

Configuration space

Science Goals:
50 million redshifts

Sensitivity to new physics scales as volume surveys -- # of modes



Our observable Universe

Volume mapped by SDSS + SDSS-II

Volume to be mapped by SDSS-III/BOSS
(ca. 2015)

Surface of last scattering

BigBOSS @NOAO

Courtesy Slide from David Schlegel

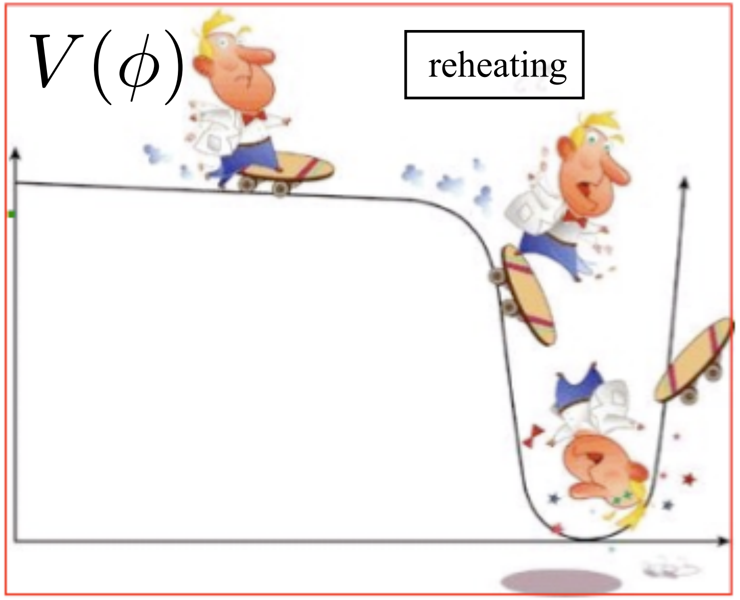
Lyman Alpha Forest: what can it do?

— Non-gaussianities in Early Universe

parameterize how much non-linear corrections are there to the potential

$$\Phi = \phi + f_{NL}\phi^2$$

Primordial potential (assumed to be gaussian random field)



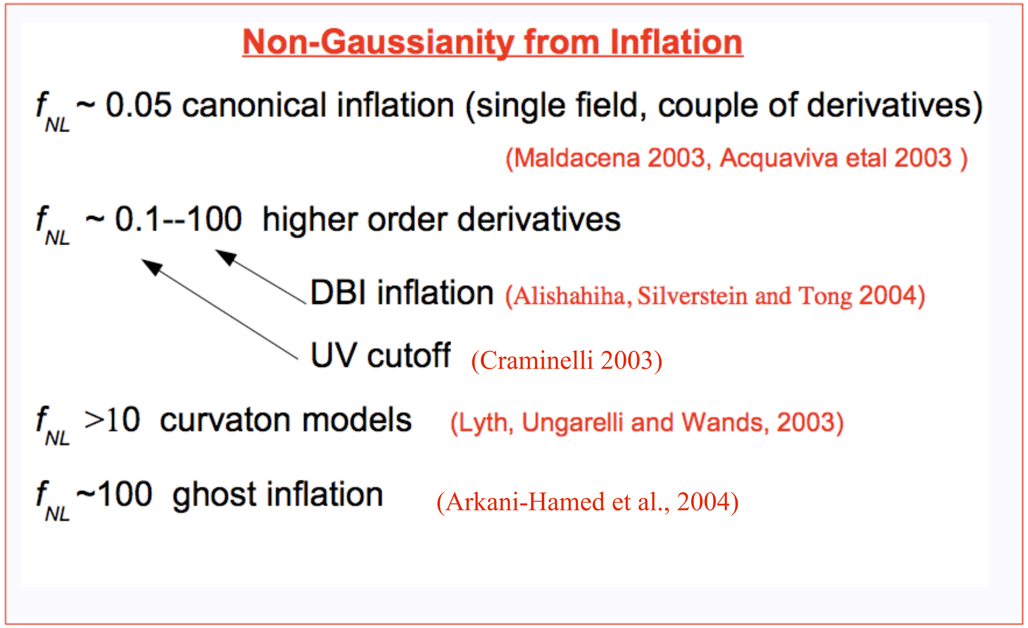
← Inflation →

Lyman Alpha Forest: what can it do?
— Non-gaussianities in Early Universe

parameterize how much non-linear corrections are there to the potential

$$\Phi = \phi + f_{NL}\phi^2$$

Primordial potential (assumed to be gaussian random field)



Non-Gaussianity from Inflation

f_{NL} ~ 0.05 canonical inflation (single field, couple of derivatives)

(Maldacena 2003, Acquaviva etal 2003)

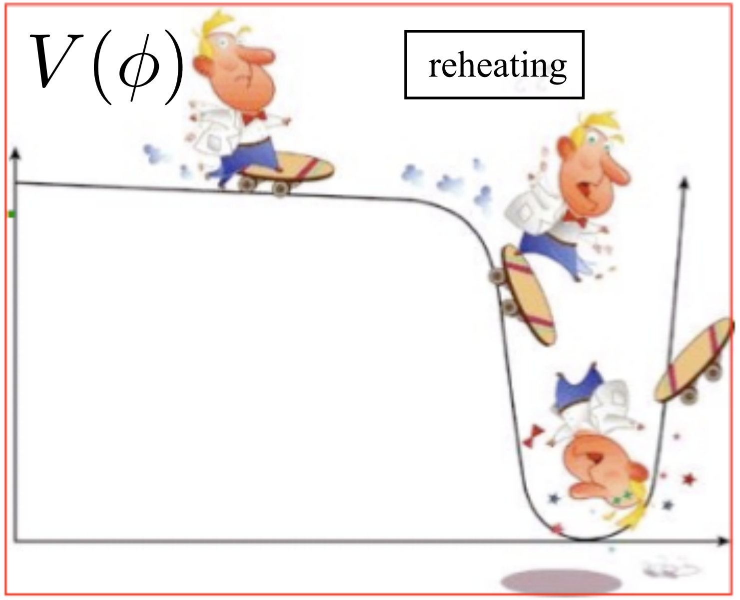
f_{NL} ~ 0.1--100 higher order derivatives

DBI inflation (Alishahiha, Silverstein and Tong 2004)

UV cutoff (Craminelli 2003)

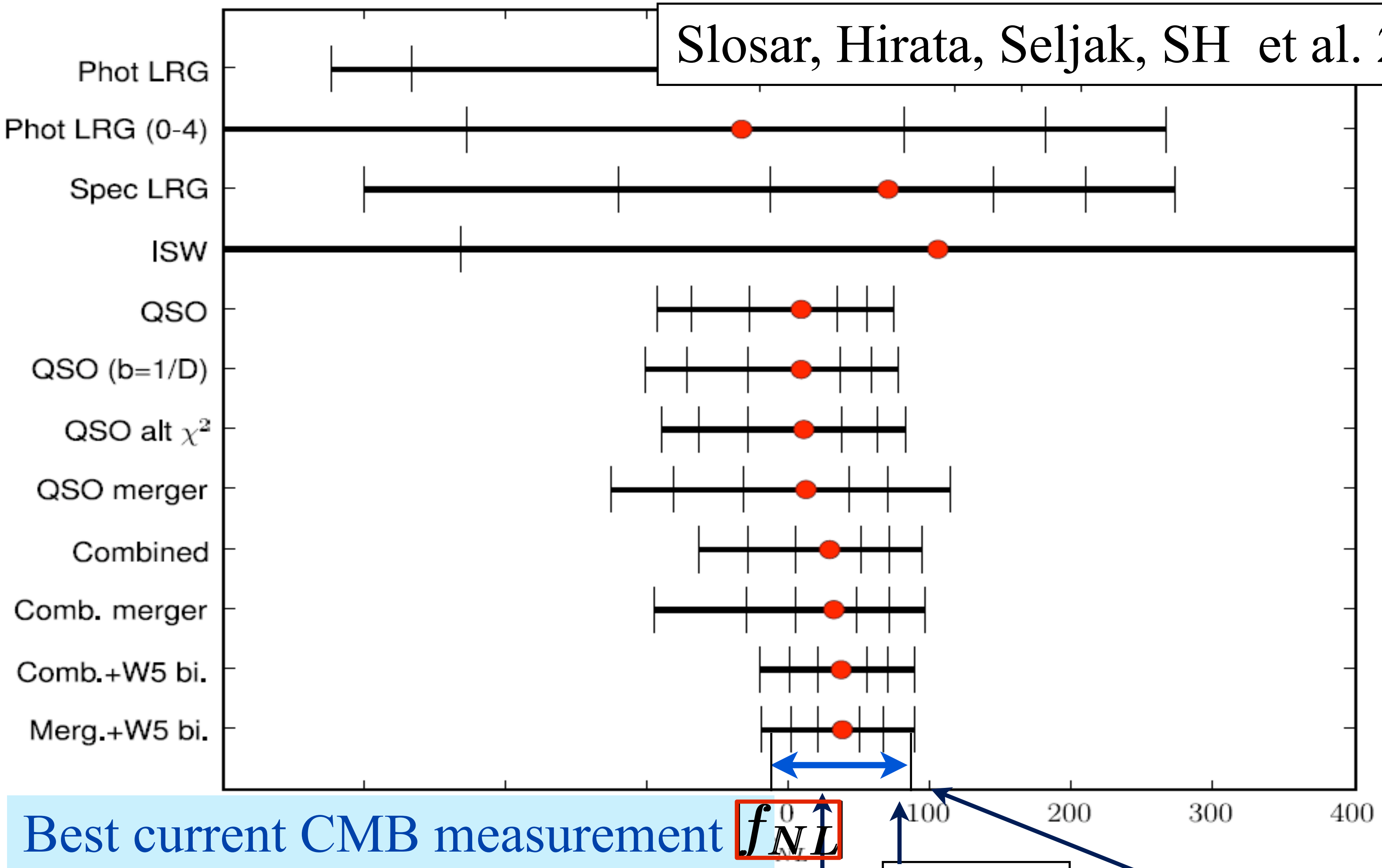
f_{NL} >10 curvaton models (Lyth, Ungarelli and Wands, 2003)

f_{NL} ~100 ghost inflation (Arkani-Hamed et al., 2004)



← Inflation →

Lyman Alpha Forest: what can it do?
— Non-gaussianities in Early Universe



Slosar, Hirata, Seljak, SH et al. 2008

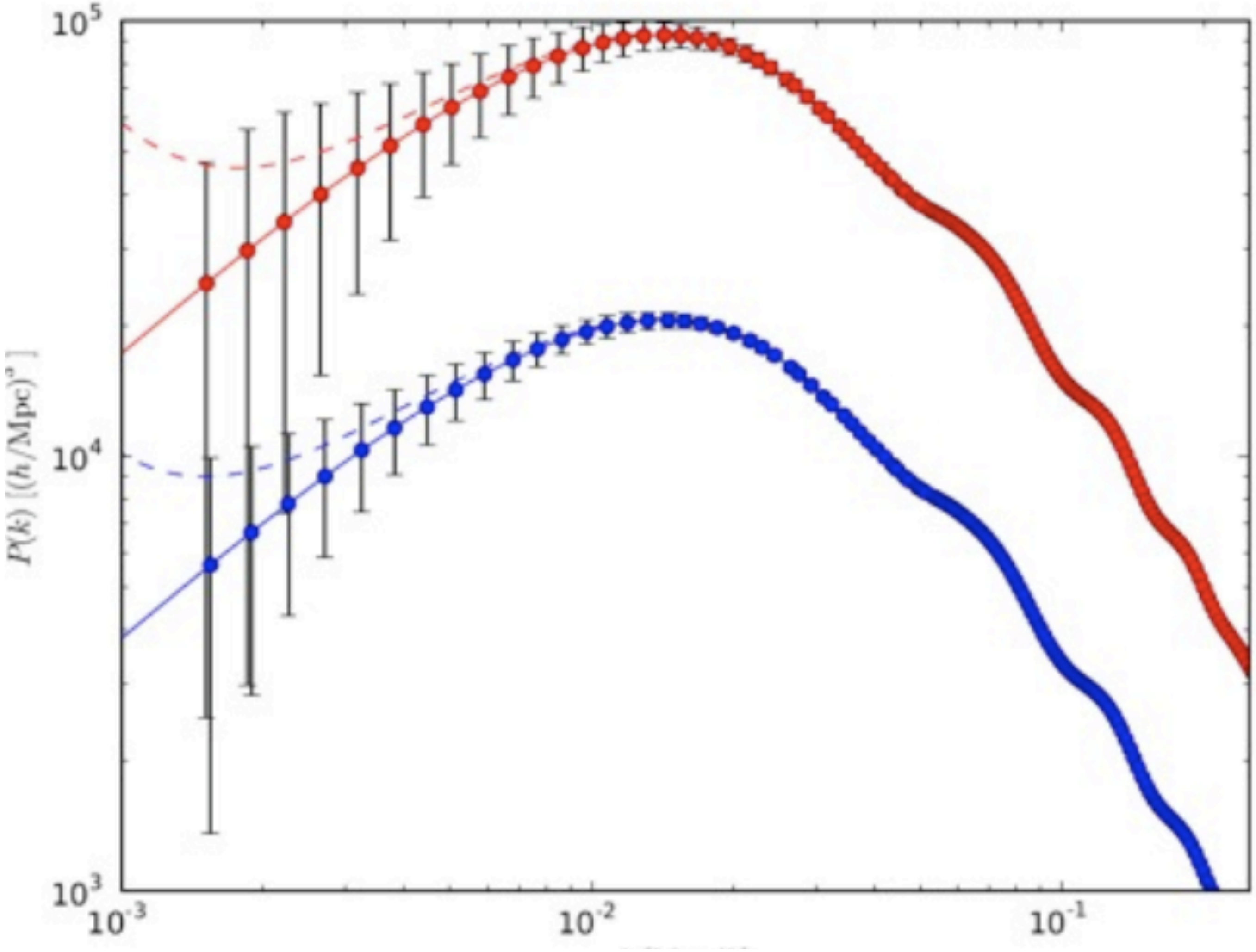
Best current CMB measurement

canonical inflation

curvaton models, DBI inflation

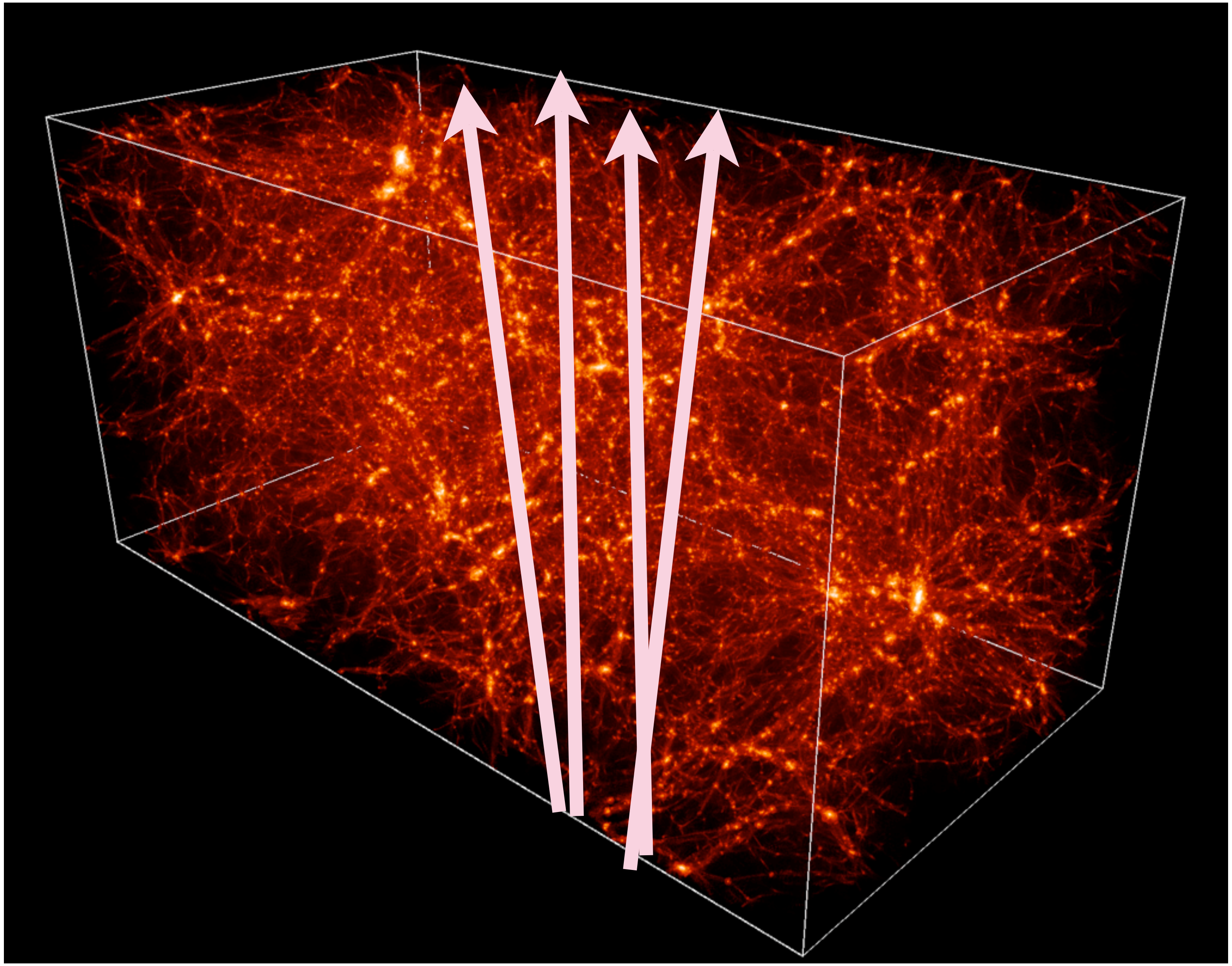
ghost inflation

P(k) (Mpc/h)^3

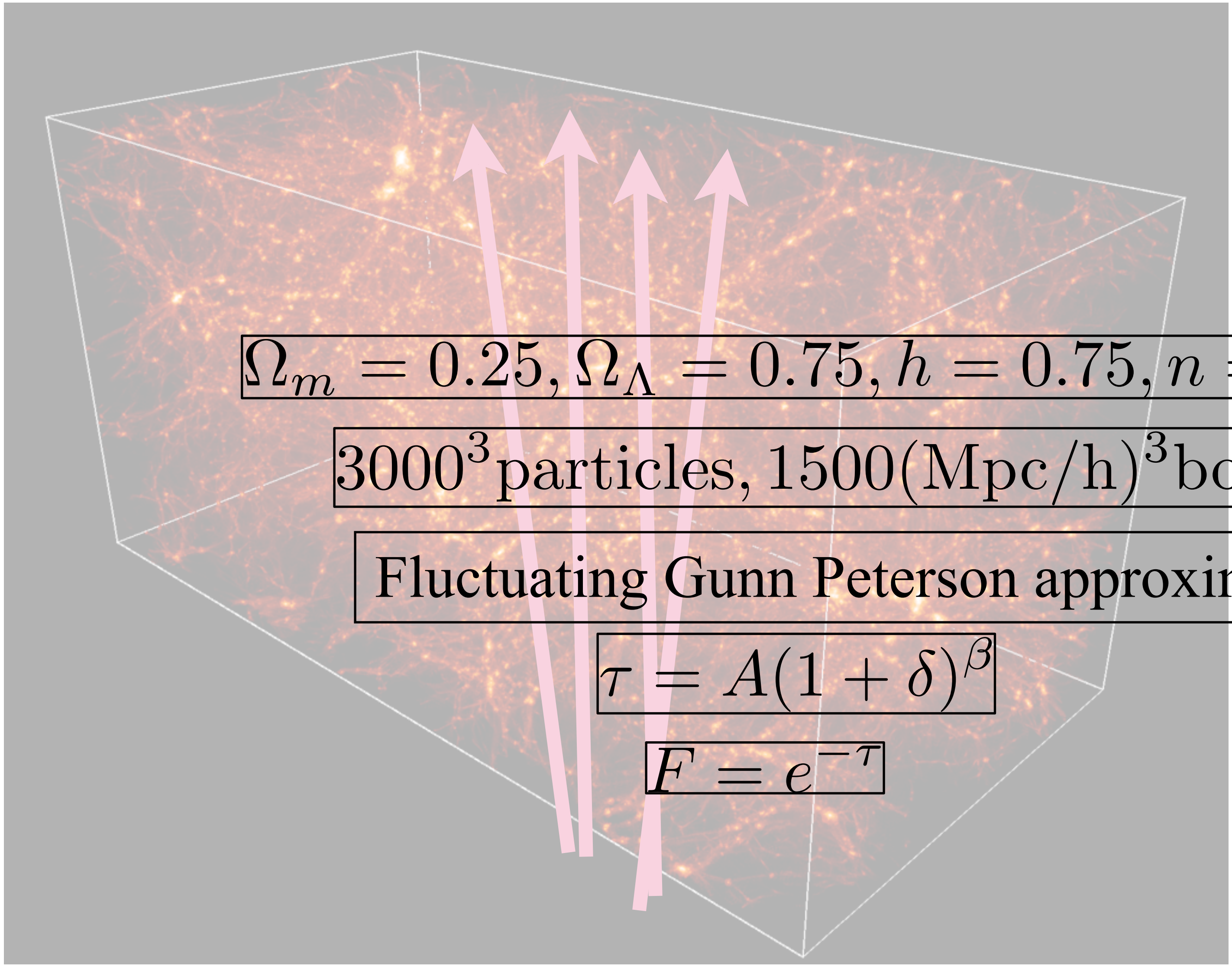


k (h/Mpc)

Lyman Alpha Forest: what can it do?



Lyman Alpha Forest: what can it do?



$$\boxed{\Omega_m = 0.25, \Omega_\Lambda = 0.75, h = 0.75, n = 0.97, \sigma_8 = 0.8}$$

$$\boxed{3000^3\,\mathrm{particles}, 1500(\mathrm{Mpc/h})^3\,\mathrm{box}, 3000^3\,\mathrm{grid}}$$

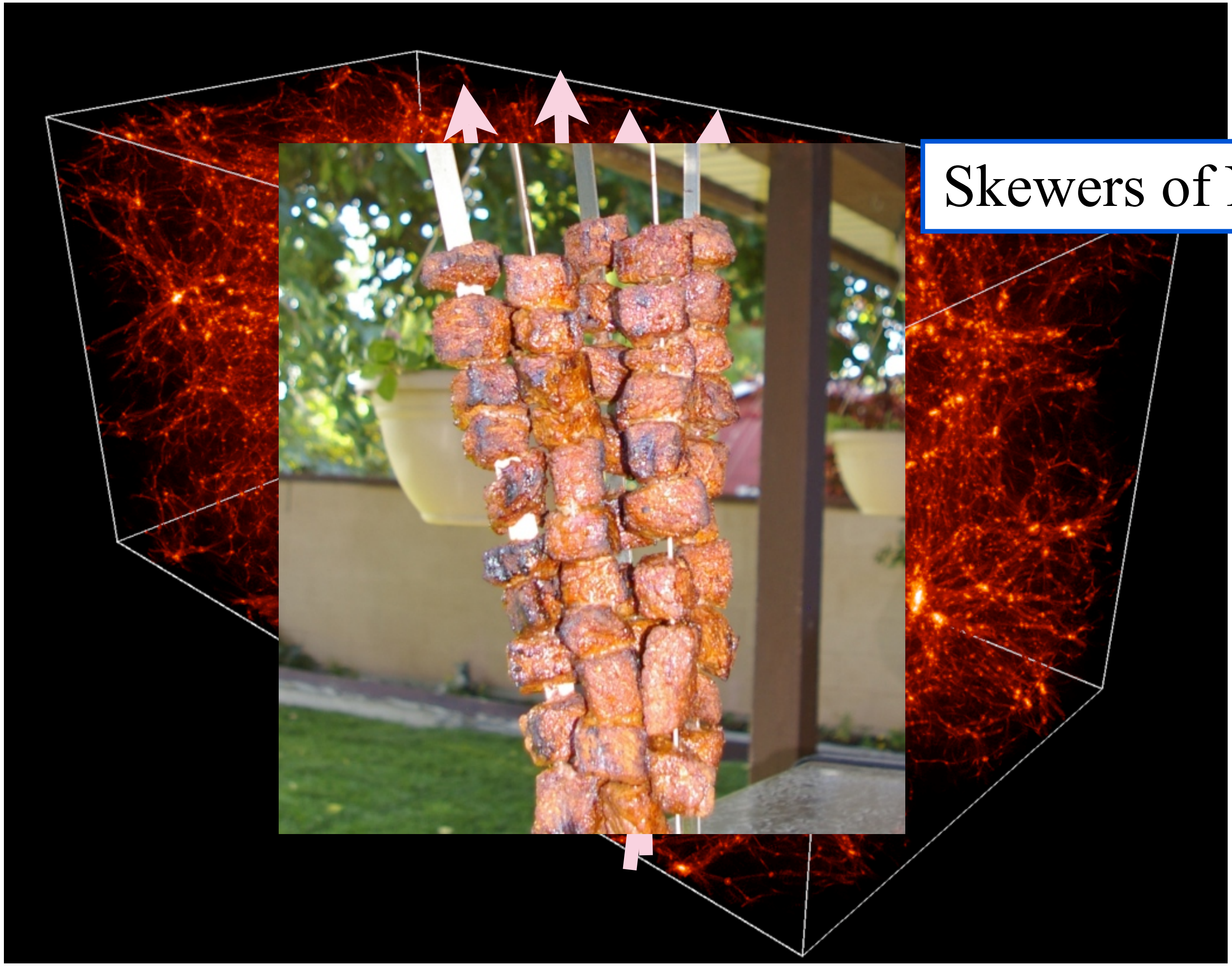
$$\boxed{\text{Fluctuating Gunn Peterson approximation}}$$

$$\boxed{\tau = A(1+\delta)^\beta}$$

$$\boxed{F = e^{-\tau}}$$

Lyman Alpha Forest: what can it do?

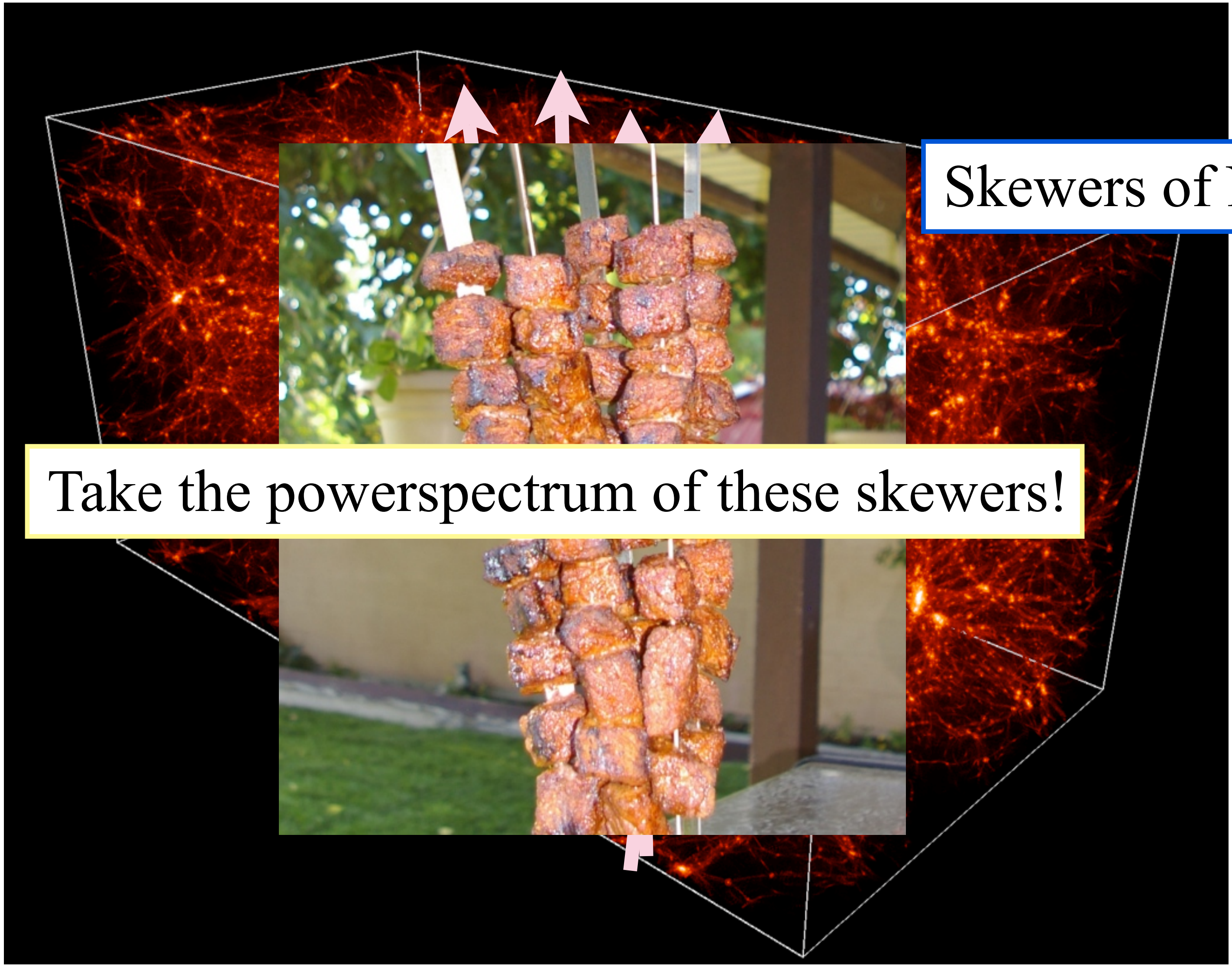
- **Dark Energy via Baryon Acoustic Oscillations**



Skewers of Neutral Hydrogen

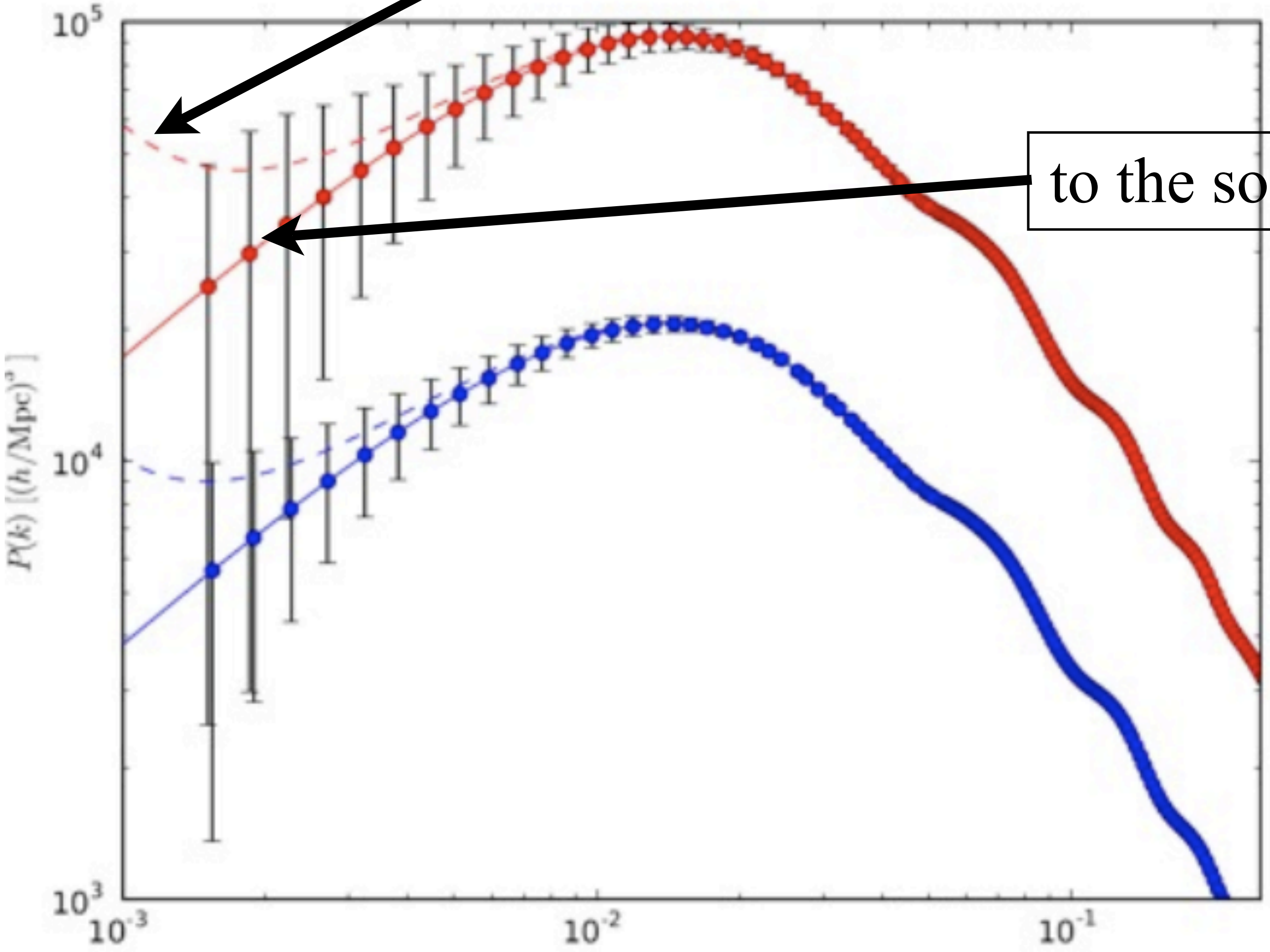
Lyman Alpha Forest: what can it do?

- **Dark Energy via Baryon Acoustic Oscillations**



Skewers of Neutral Hydrogen

Take the powerspectrum of these skewers!



P(k) (Mpc/h)^3

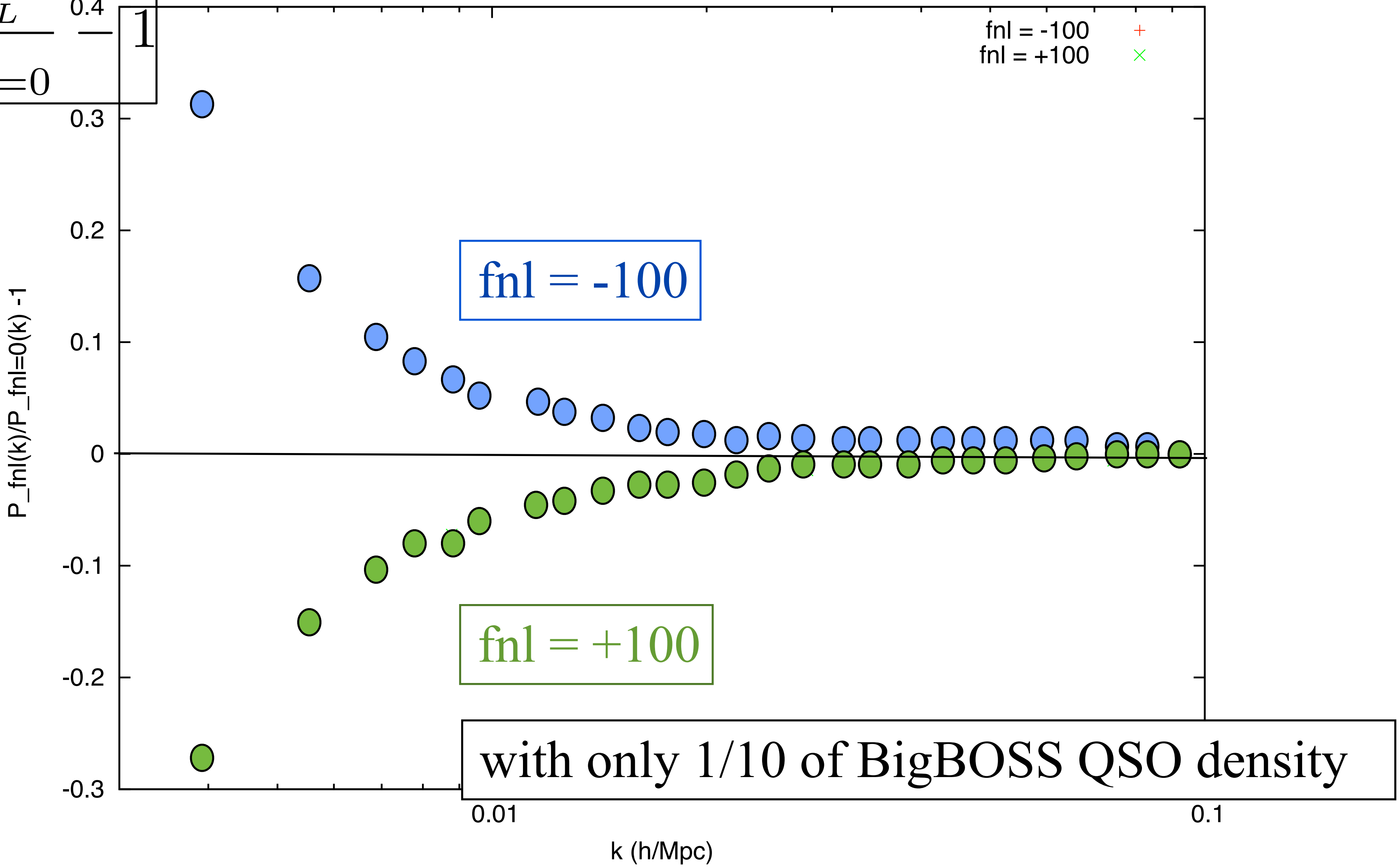
Taking the ratio of dashed line

to the solid line

k (h/Mpc)

What can we do with Lya and fnl?

$$\frac{P_{f_{NL}}}{P_{f_{NL}=0}} - 1$$



fnl = -100

fnl = +100

with only 1/10 of BigBOSS QSO density

Ho, Desjacques, Slosar & Seljak (in prep)

What can we do with Lya and fnl?

Preliminary theory predictions

$$\frac{P_{f_{NL}}}{P_{f_{NL}=0}} - 1$$

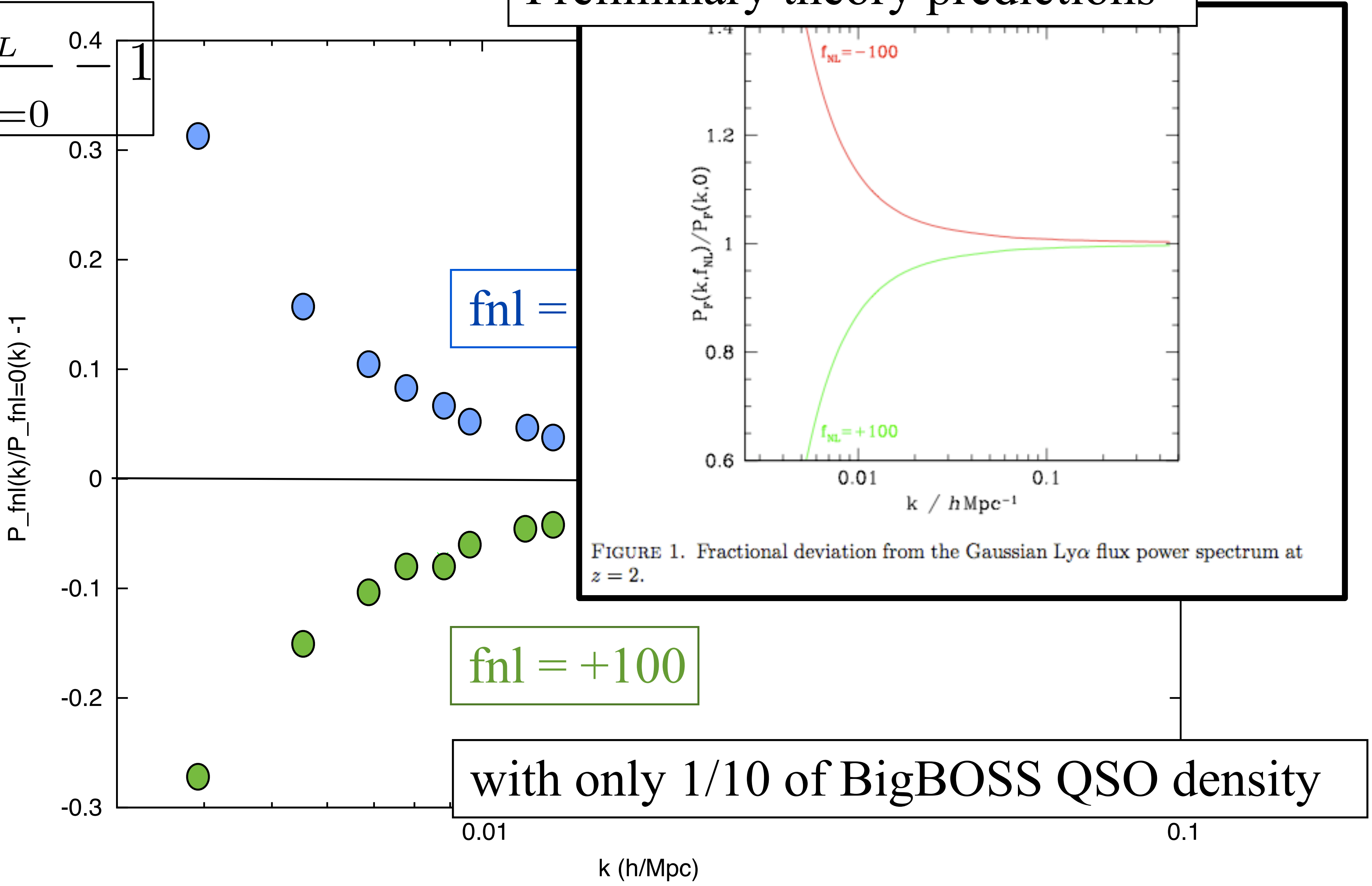
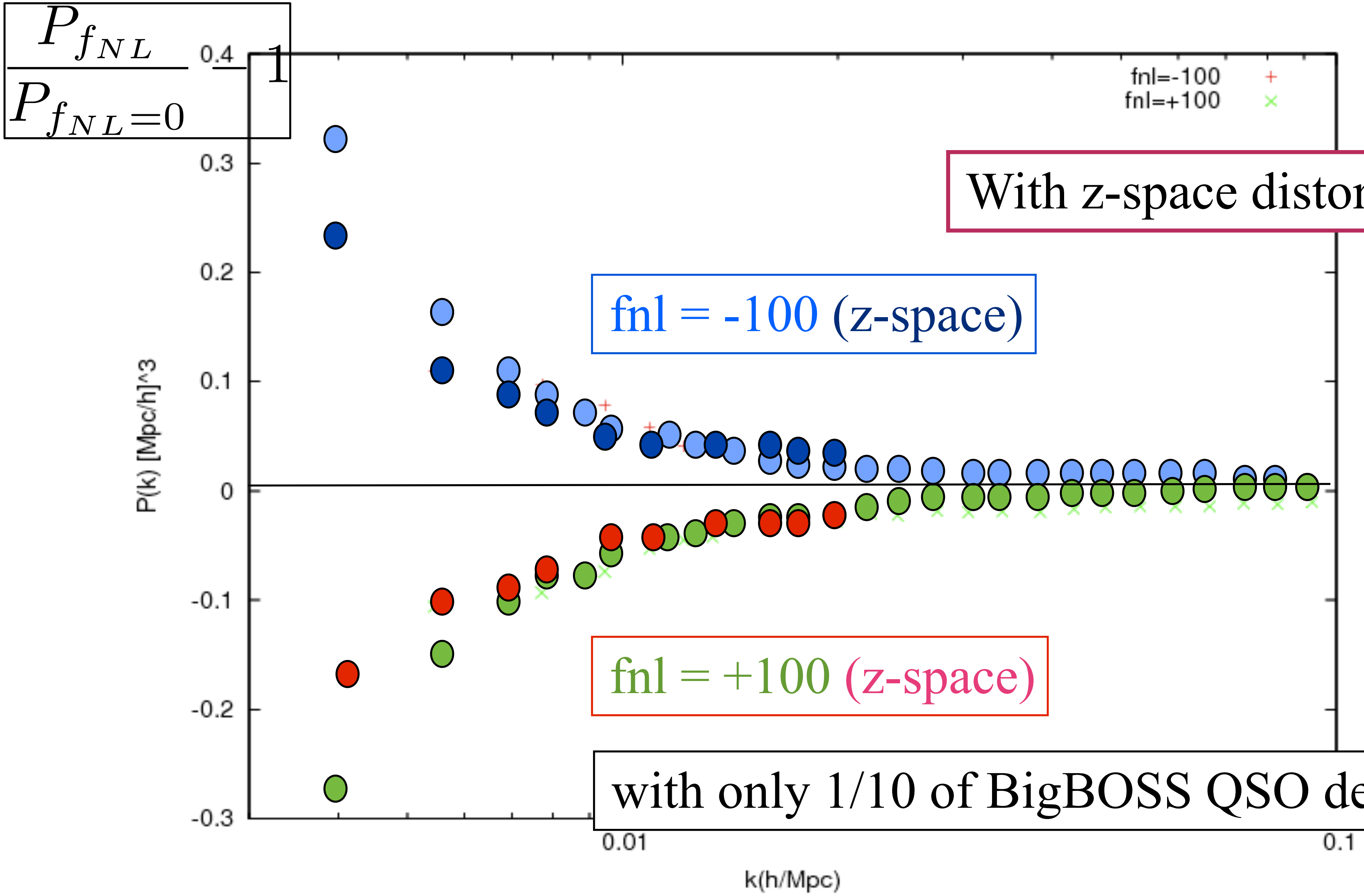


FIGURE 1. Fractional deviation from the Gaussian Lyα flux power spectrum at $z = 2$.

with only 1/10 of BigBOSS QSO density

Ho, Desjacques, Slosar & Seljak (in prep)

What can we do with Lya and fnl?



$$\frac{P_{f_{NL}}}{P_{f_{NL}=0}} - 1$$

With z-space distortions!

fnl = -100 (z-space)

fnl = +100 (z-space)

with only 1/10 of BigBOSS QSO density

Ho, Desjacques, Slosar & Seljak (in prep)

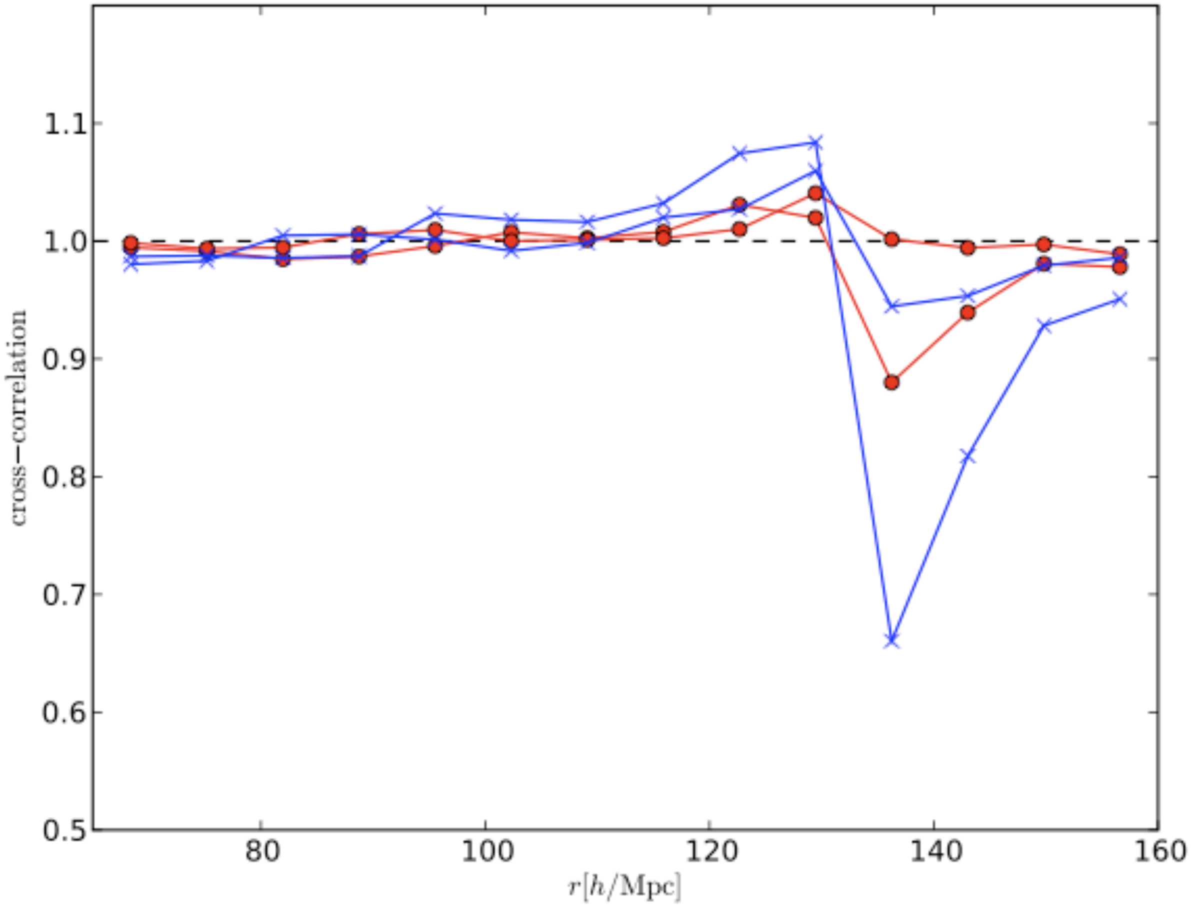
Things I can talk about, but won't...

- Redshift space distortions' effect
- Effects of DLAs (Damped Lya systems), BALs (Broad Absorption line systems), Metals
- Effect of incomplete continuum subtractions
- The other systematic error that will be coming from the experiment/analysis.

Conclusion

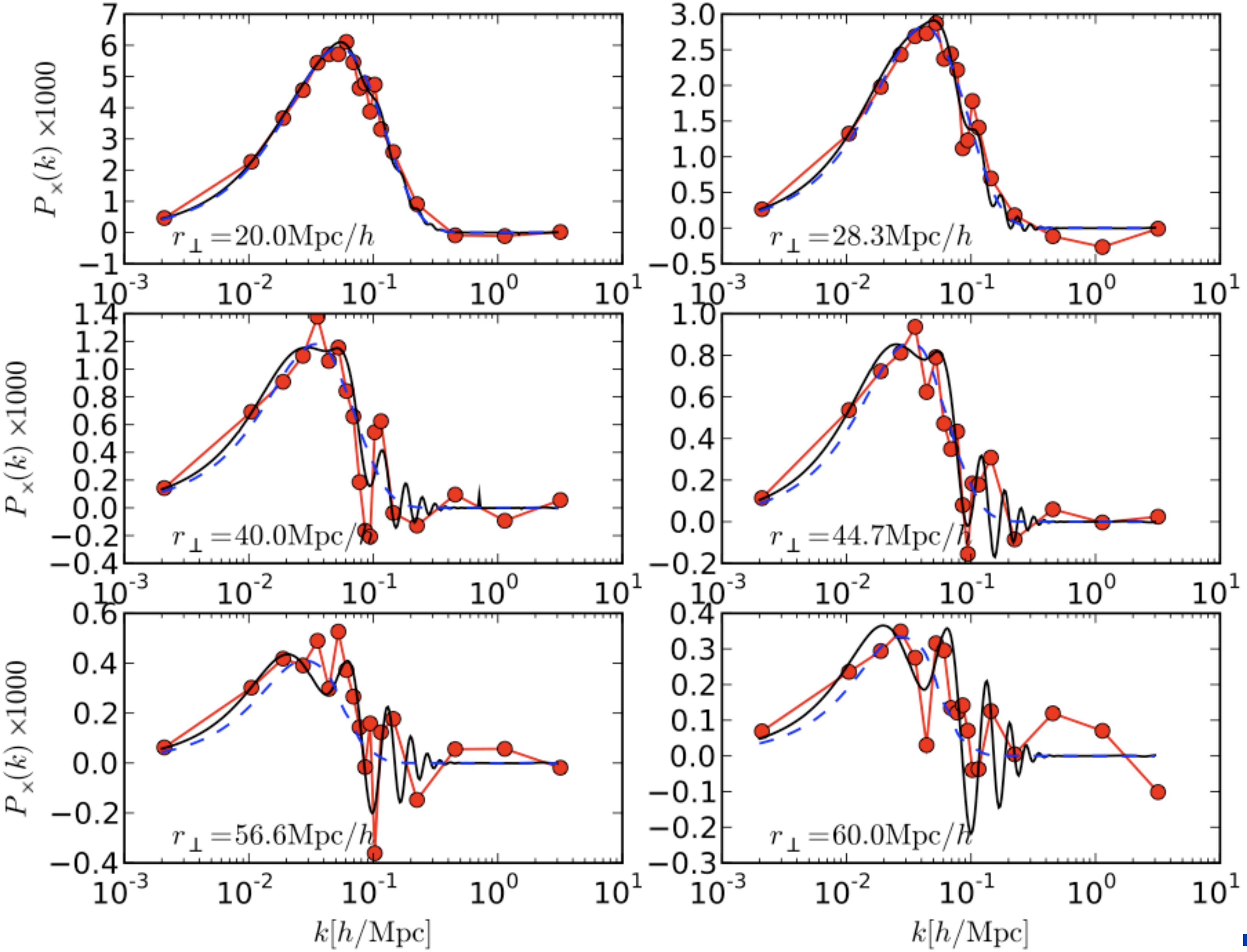
- Lyman-alpha forest in BOSS and BigBOSS will (hopefully) do the following:
  - Lya BAO to measure Dark Energy at z>2
  - Lya probes non-gaussianity of the Early Universe
  - Other applications:
    - Lya P(k) tighten the cosmological constraints
    - temperature density relation in the IGM
    - finding missing baryons at higher z

$$\sqrt{\xi_{lh}^2/\xi_{ll}\xi_{hh}}$$



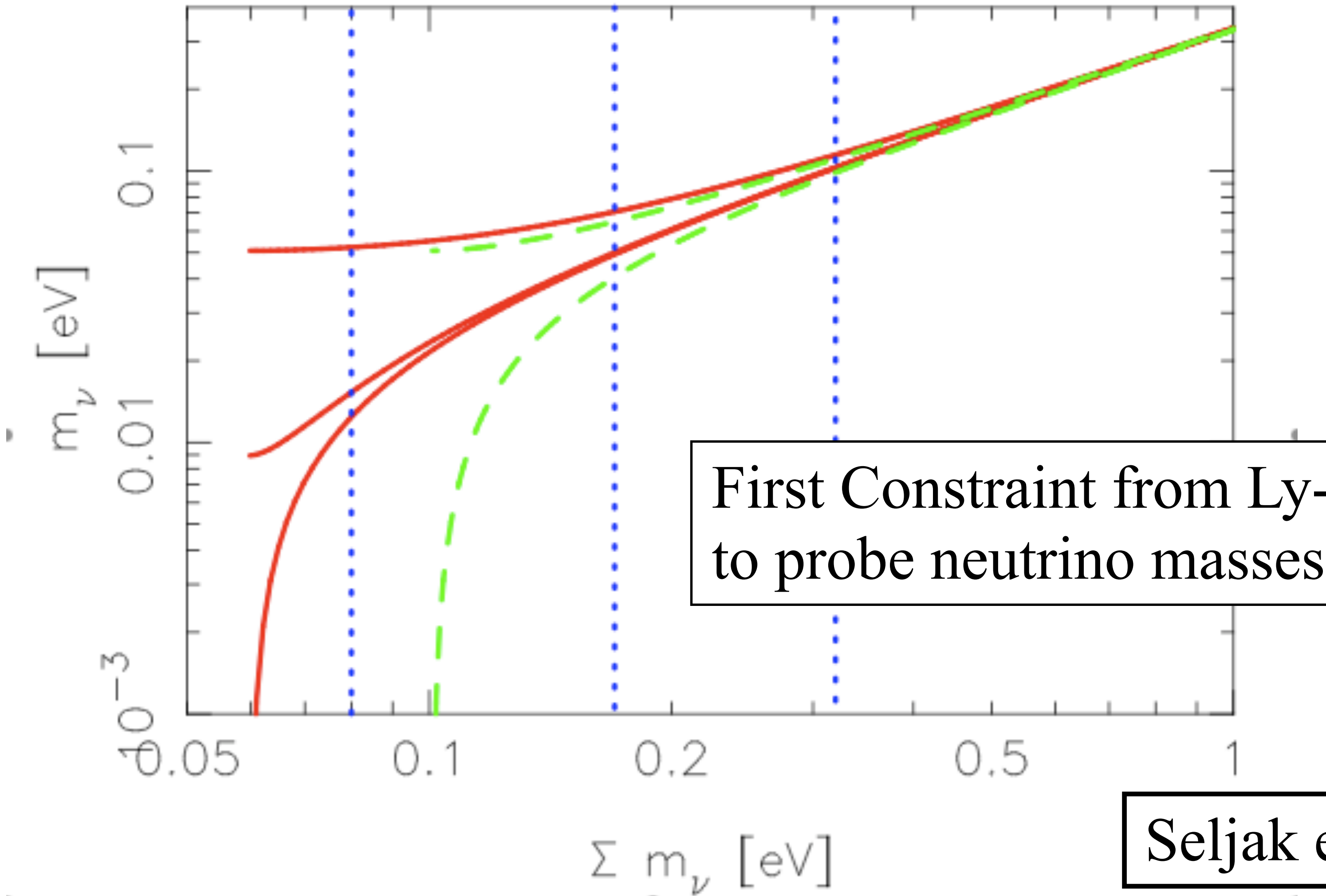
$$r[h/Mpc]$$

FIG. 2: The cross-correlation coefficient between the flux in our low and high resolution boxes, $\sqrt{\xi_{lh}^2/\xi_{ll}\xi_{hh}}$. Red points show the result for the two low resolution boxes having twice the smoothing length of the high resolution box, blue is the same for 4× smoothing length.


$P_\times(k)\times1000$
$r_\perp=20.0\mathrm{Mpc}/h$
$r_\perp=28.3\mathrm{Mpc}/h$
$r_\perp=40.0\mathrm{Mpc}/h$
$r_\perp=44.7\mathrm{Mpc}/h$
$r_\perp=56.6\mathrm{Mpc}/h$
$r_\perp=60.0\mathrm{Mpc}/h$
10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}
$k[h/\mathrm{Mpc}]$

Lyman Alpha Forest: what can it do?

- **Cosmological Constraints from Lyman-alpha power spectrum**



First Constraint from Ly-alpha forest to probe neutrino masses

Seljak et al. 2006

Lyman Alpha Forest: what can it do?

- **Cosmological constraints from Lyman-alpha power spectrum (with no BAO)**

	Planck	Planck + BigBOSS Lya	Planck + BigBOSS Lya + Galaxies
$(\sum m_\nu$	0.307	0.048	0.006
$\sigma(\Omega_K)$	0.011	0.0041	0.00038
$\sigma(n_s)$	0.0034	0.0023	0.001
$\sigma(dn_s/dln(k))$	0.003	0.0028	0.0005

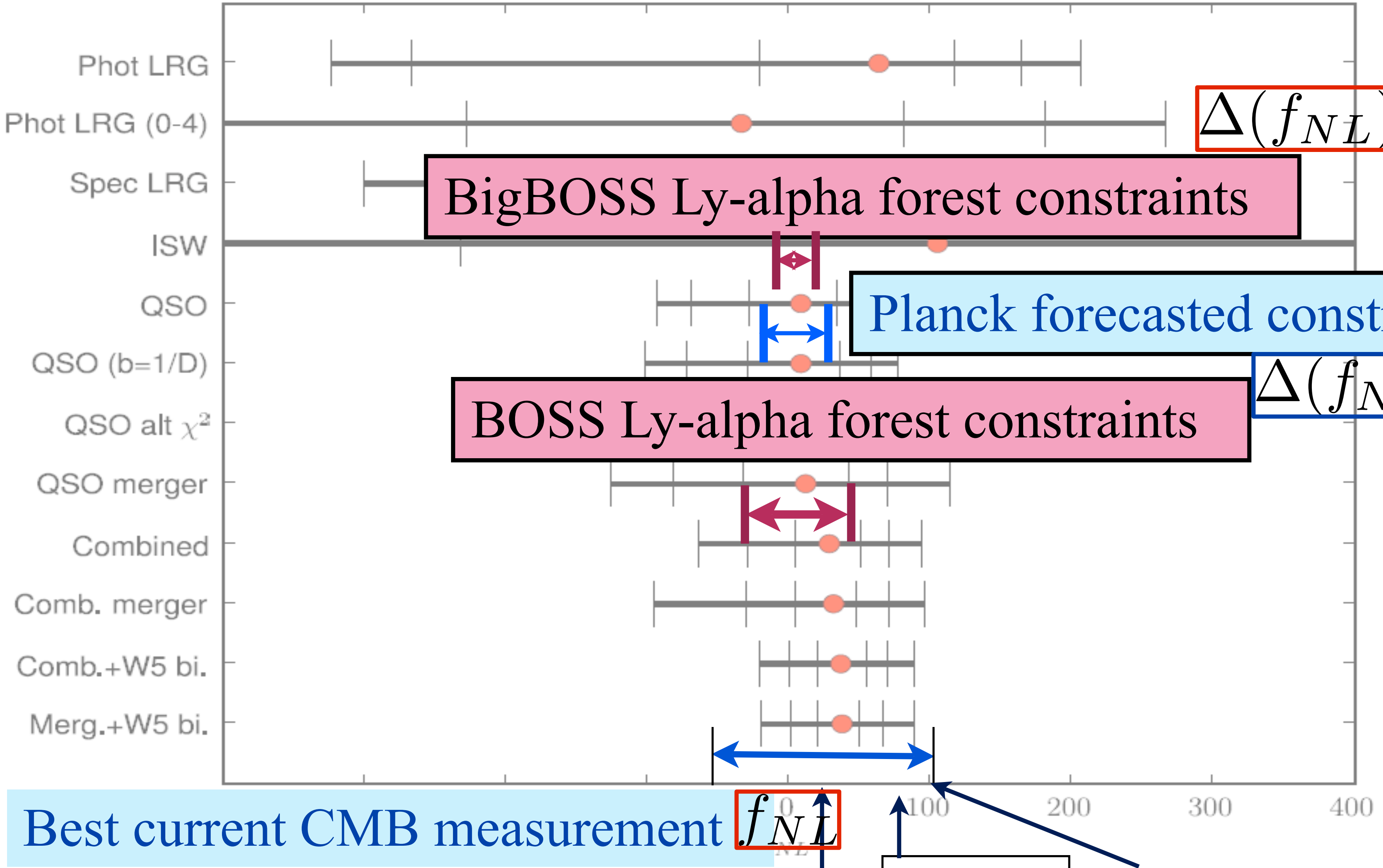
Courtesy from Anze Slosar

Outline

- **Motivations**
- **Introduction (What is Lyman-alpha forest?)**
- **What can you do with Lyman-alpha forest?**
    - **Baryon Acoustic Oscillations -> Dark Energy**
    - **Lyman-alpha power spectrum**
    - **Non-gaussianities in Early Universe**

- **Conclusion**

Lyman Alpha Forest: what can it do?
— Non-gaussianities in Early Universe



$\Delta(f_{NL}) \sim 1$

BigBOSS Ly-alpha forest constraints

Planck forecasted constraints

$\Delta(f_{NL}) \sim 5$

BOSS Ly-alpha forest constraints

Best current CMB measurement f_{NL}

with Slosar and Seljak (work in progress)

canonical inflation

curvaton models, DBI inflation

ghost inflation

Outline

- Motivations
- Introduction (What is Lyman-alpha forest?)
- What can you do with Lyman-alpha forest?
  - Baryon Acoustic Oscillations -> Dark Energy
  - Lyman-alpha power spectrum
  - Non-gaussianities in Early Universe

- Conclusion

Outline

- Motivations
- Introduction (What is Lyman-alpha forest?)
- What can you do with Lyman-alpha forest?
  - Baryon Acoustic Oscillations -> Dark Energy
  - Lyman-alpha power spectrum
  - Non-gaussianities in Early Universe

- Conclusion

Lyman Alpha Forest: what can it do?

- **Simulation boxes of Dark matter**
- 3000^3 particles

  3000^3 mesh

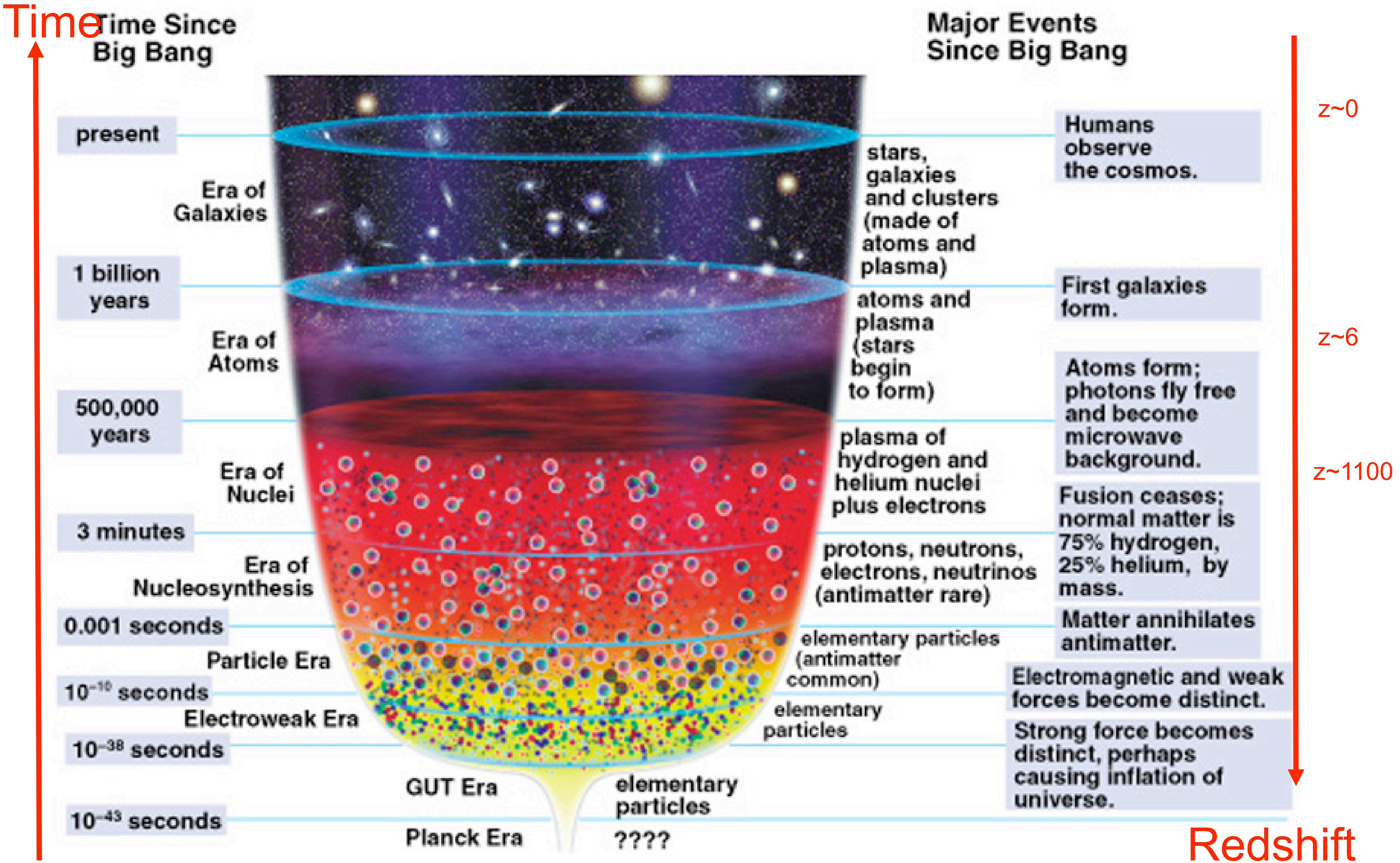
  $1500\ (h^{-1}Mpc)^3$ on the side

  $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $\mathrm{h} = 0.75$, $\mathrm{n} = 0.97$, $\sigma_8 = 0.8$

  Fluctuating Gunn Peterson approximation

  Peculiar velocities included

Motivations



Humans observe the cosmos.

First galaxies form.

Atoms form; photons fly free and become microwave background.

Fusion ceases; normal matter is 75% hydrogen, 25% helium, by mass.

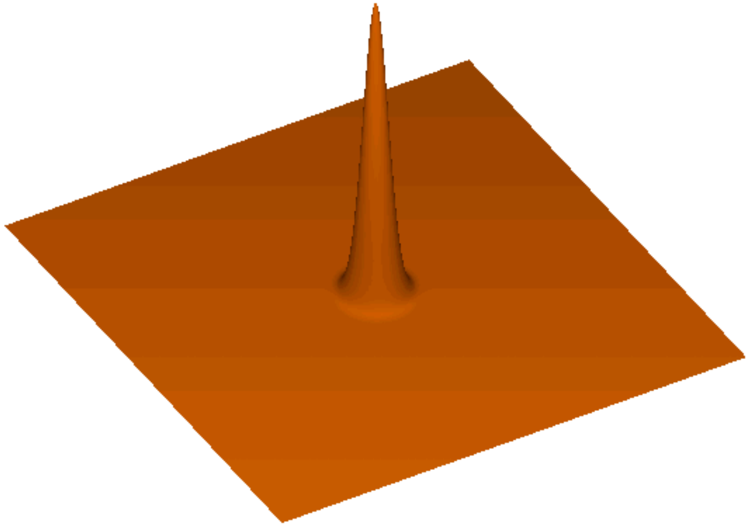
Matter annihilates antimatter.

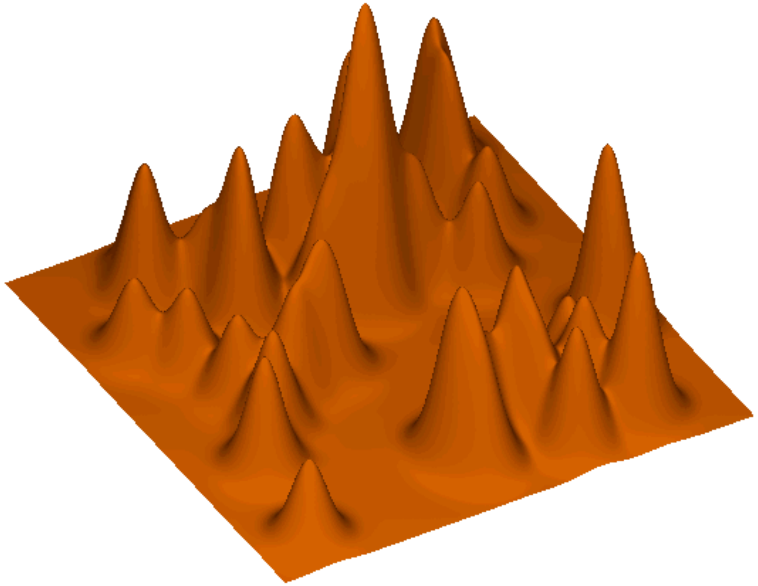
Electromagnetic and weak forces become distinct.

Strong force becomes distinct, perhaps causing inflation of universe.

What are these Sound Waves?

- Each initial overdensity (in DM & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at ~half of the speed of light.
- Pressure-providing photons decouple at recombination. CMB travels to us from these spheres.
- Sound speed plummets. Wave stalls at a radius of 150 Mpc.
- Overdensity in shell (gas) and in the original center (DM) both seed the formation of galaxies.

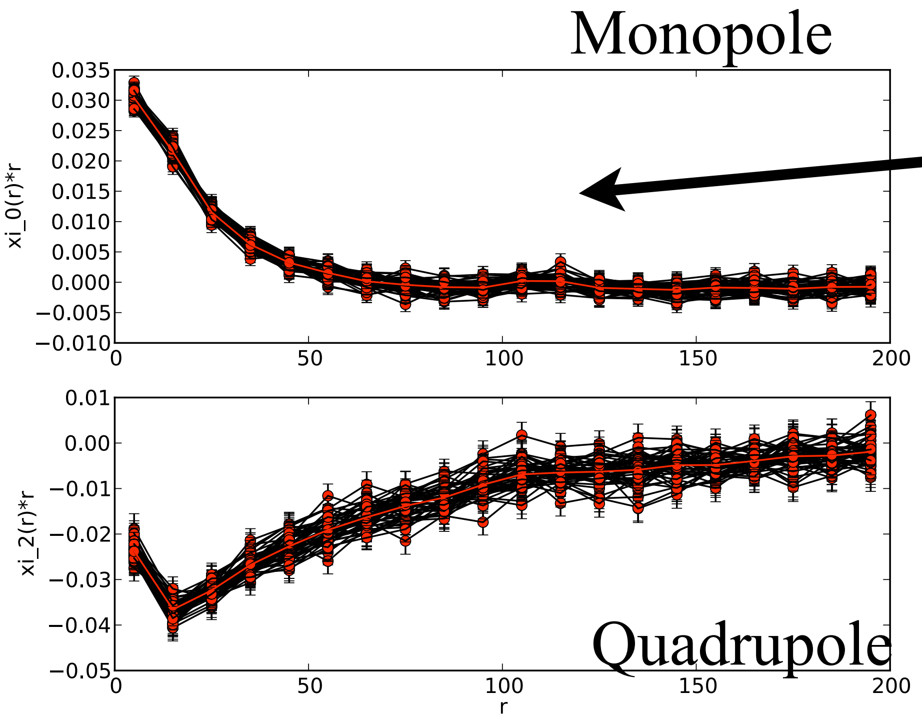




Courtesy slide from Daniel Eisenstein

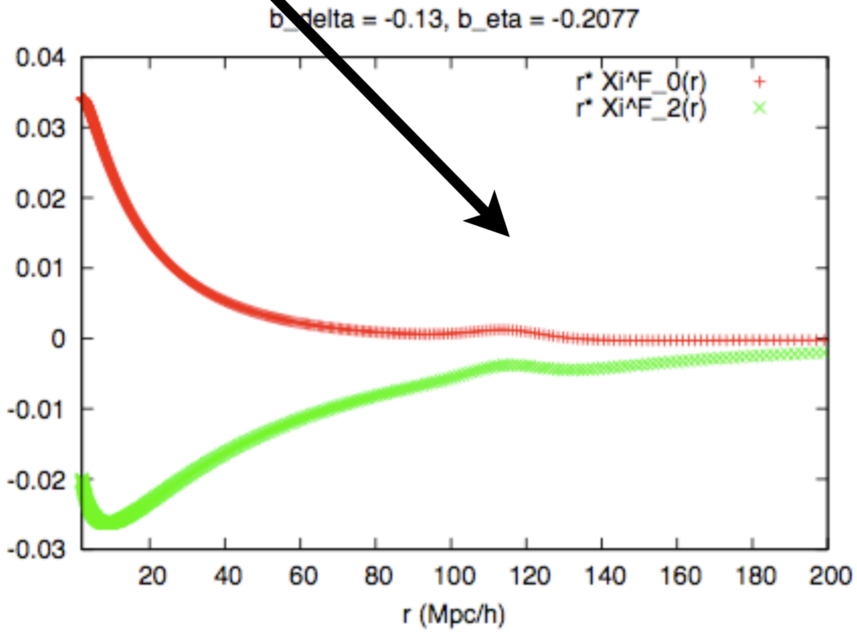
Recall? Modeling z-space distortions

Simulations



Recall that we are looking for an enhancement of power at ~110 Mpc/h?

Predictions

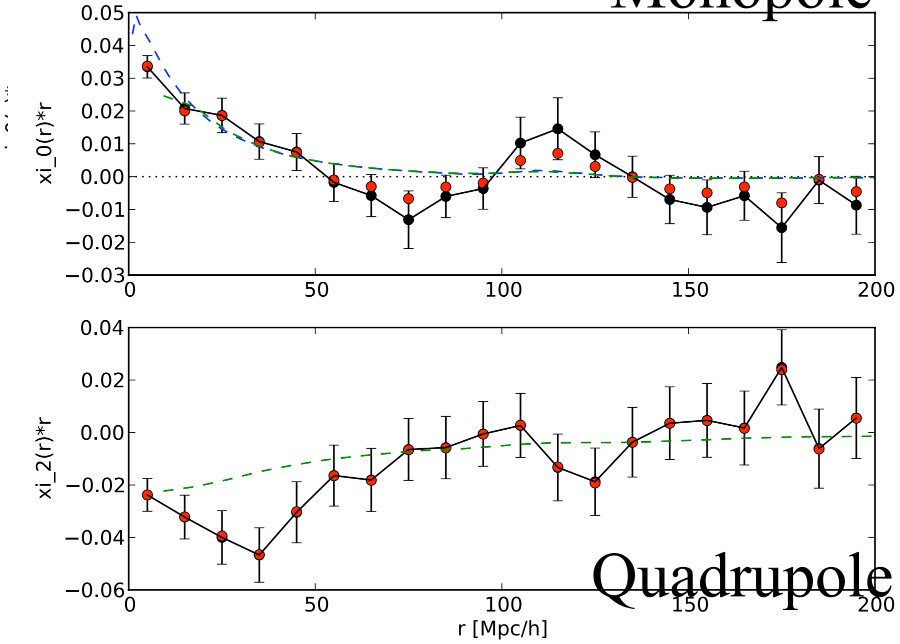


The large scale correlation functions from simulations of Lyman alpha forest

SH, Slosar & White (in prep)

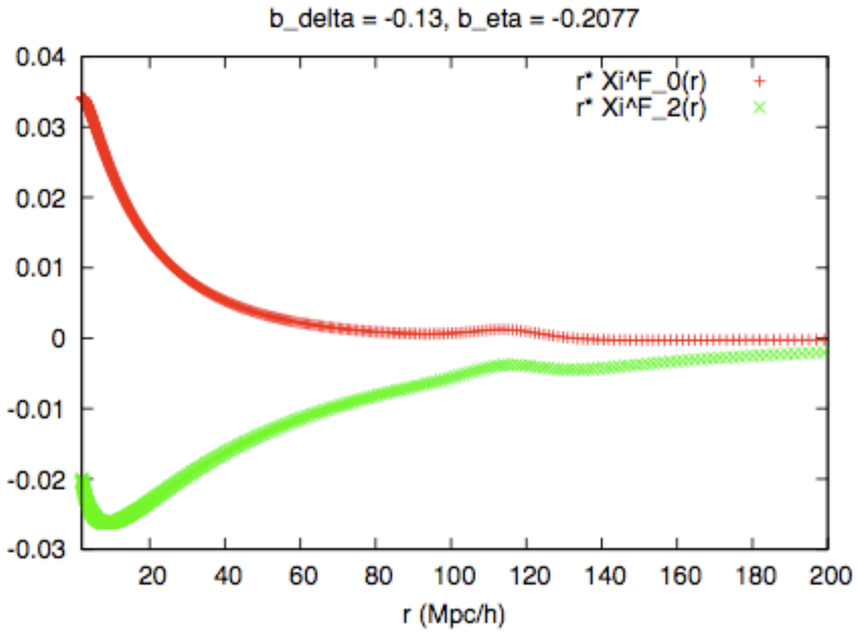
Recall? Modeling z-space distortions

DATA



Recall that we are looking for an enhancement of power at ~110 Mpc/h?

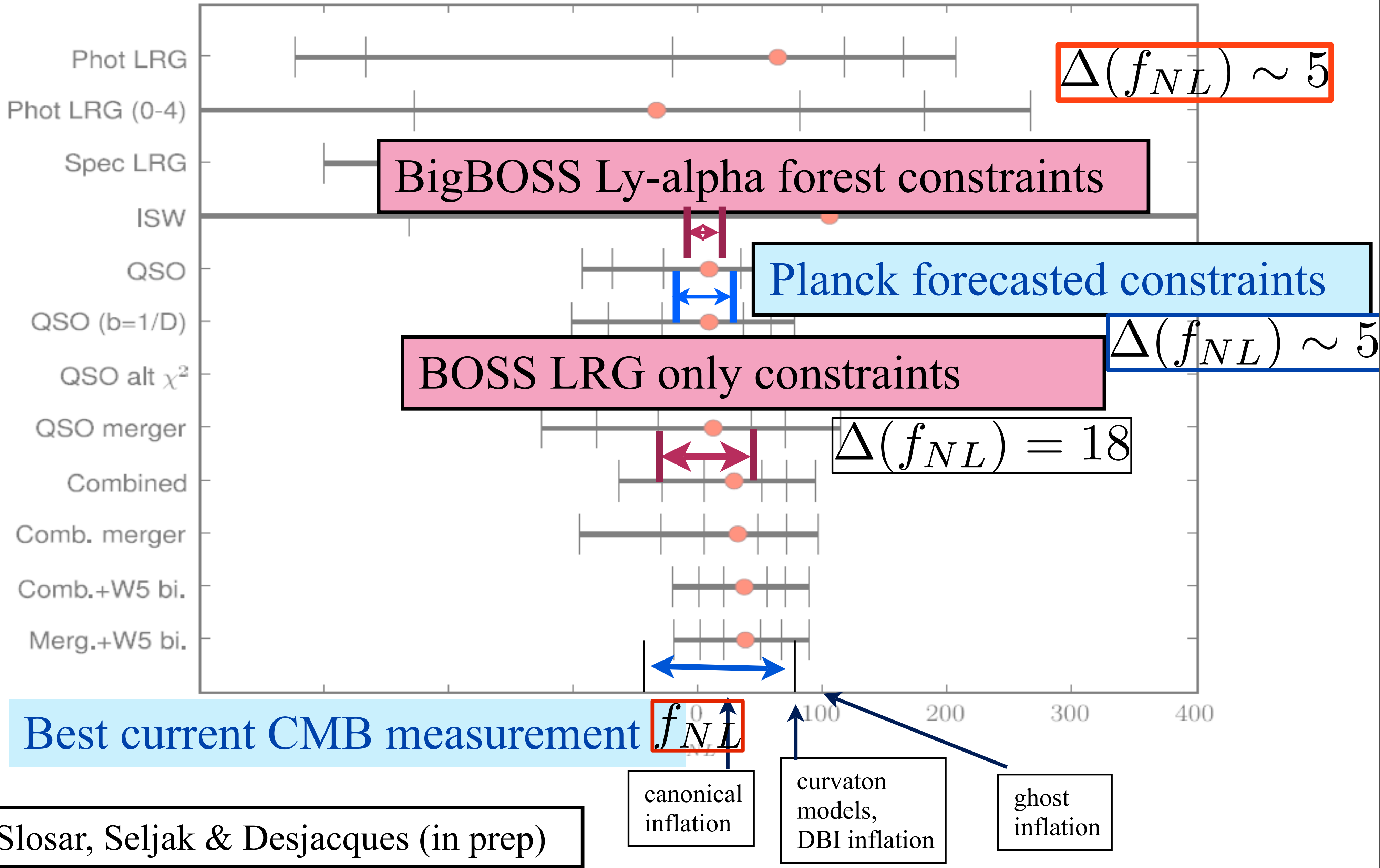
Predictions



The large scale correlation functions from 5% of Lyman alpha forest in BOSS

SH, Slosar & White (in prep)

What can we do with Lya and fnl?
— Non-gaussianities in Early Universe



$\Delta(f_{NL}) \sim 5$

BigBOSS Ly-alpha forest constraints

Planck forecasted constraints

$\Delta(f_{NL}) \sim 5$

BOSS LRG only constraints

$\Delta(f_{NL}) = 18$

Best current CMB measurement

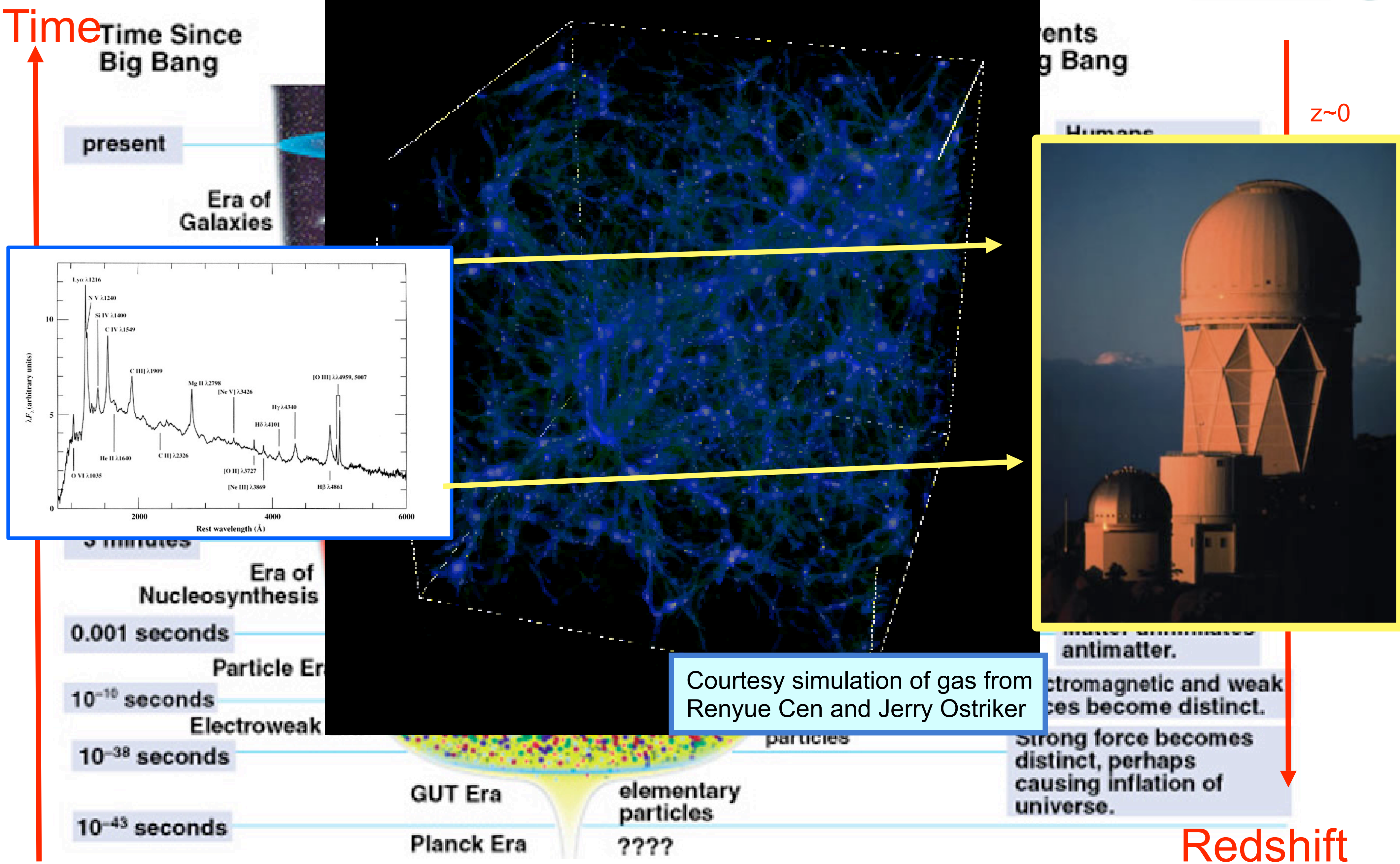
canonical inflation

curvaton models, DBI inflation

ghost inflation

Ho, Slosar, Seljak & Desjacques (in prep)

Lyman Alpha Forest: what is it?



Courtesy simulation of gas from Renyue Cen and Jerry Ostriker

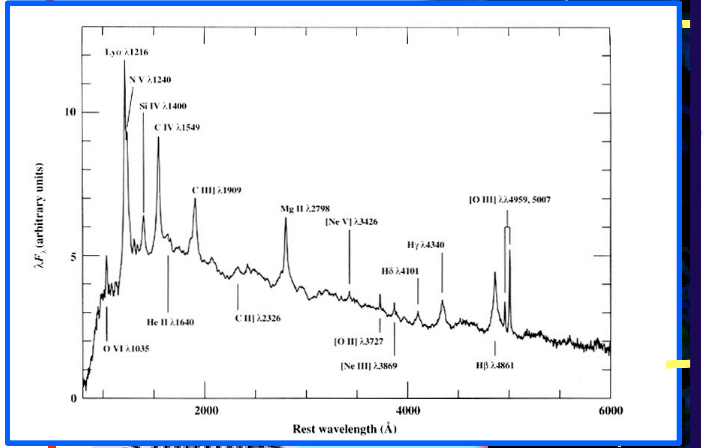
Lyman Alpha Forest: what is it?

Time

Time Since Big Bang

present

Era of Galaxies



3 minutes

Era of Nucleosynthesis

0.001 seconds

Particle Er

10^{-10} seconds

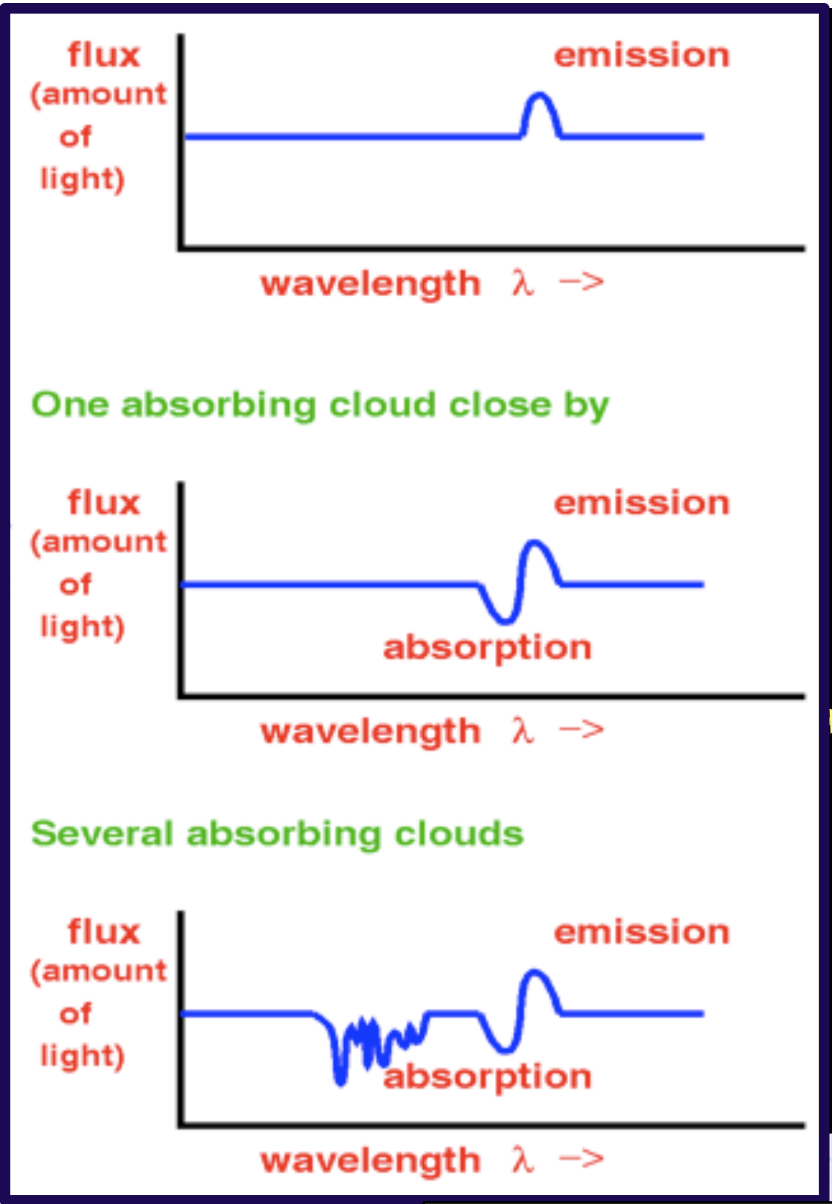
Electroweak

10^{-38} seconds

GUT Era

10^{-43} seconds

Planck Era



ents
g Bang

z~0

Humans

antimatter.

ctromagnetic and weak
ces become distinct.

Strong force becomes
distinct, perhaps

elementary particles

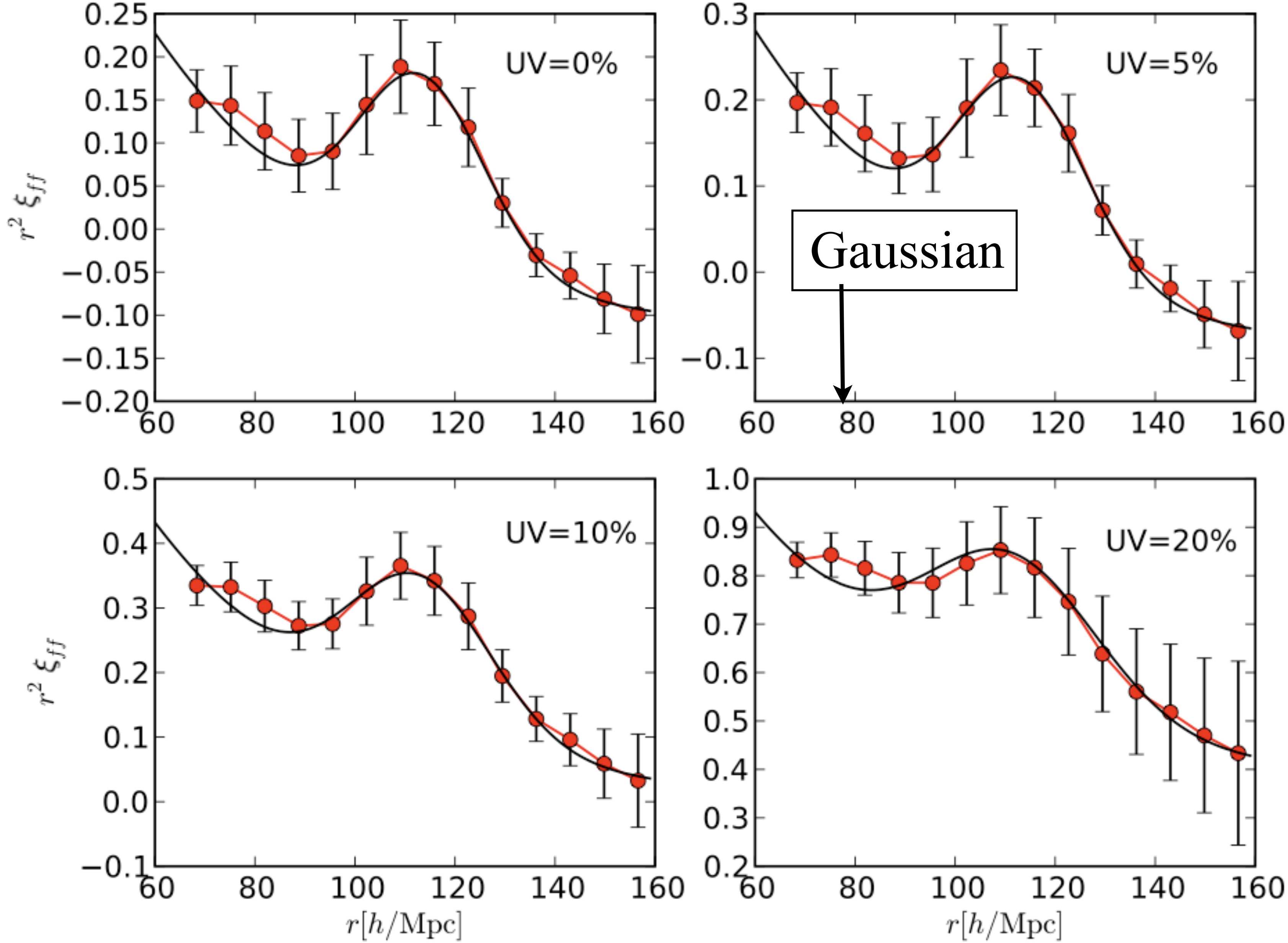
????

Courtesy image from Joanne Cohn's website

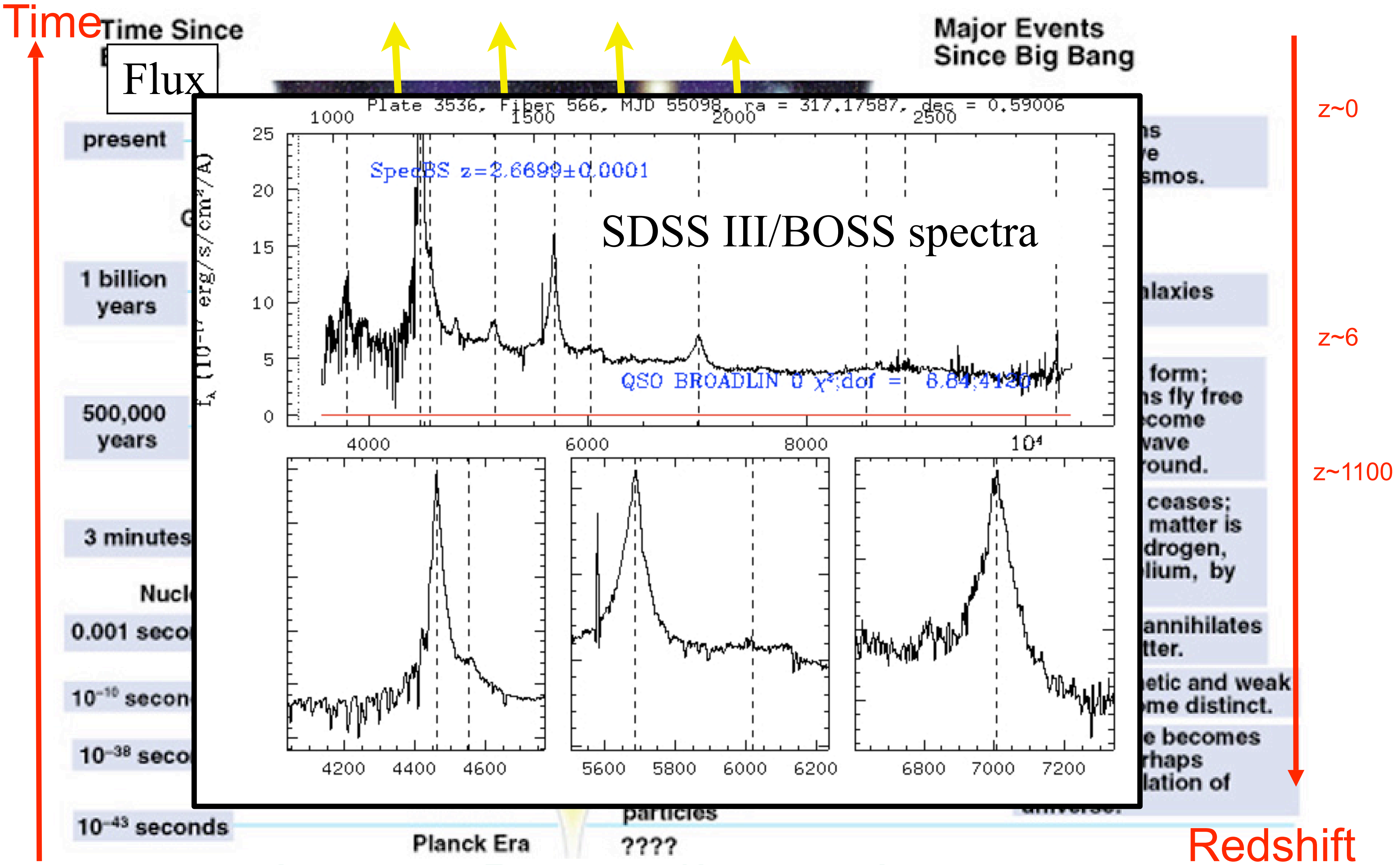
Redshift

Beyond: With Lyman Alpha Forest

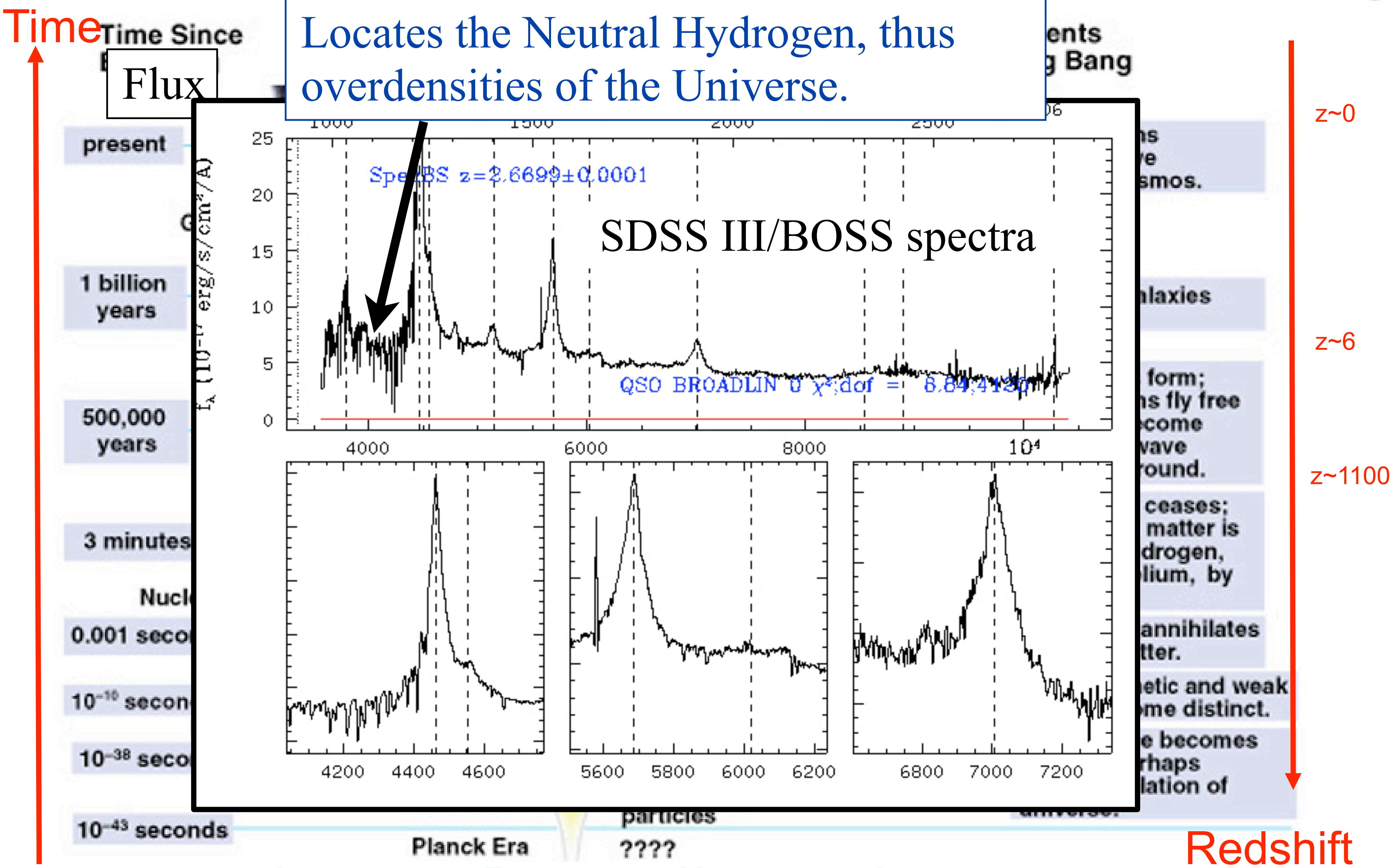
Possible systematics: UV background fluctuations



Lyman Alpha Forest: what is it?



Lyman Alpha Forest: what is it?



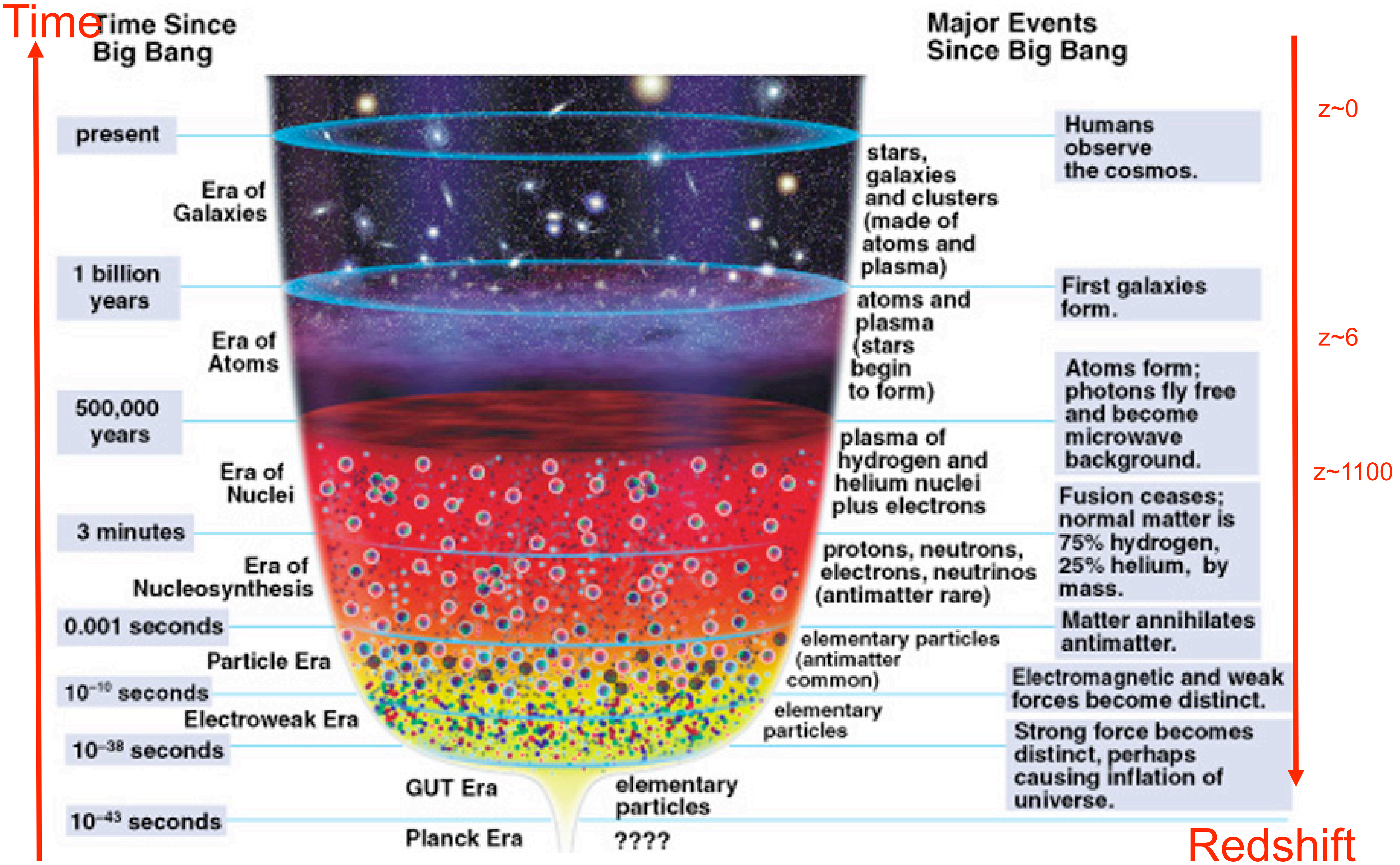
Locates the Neutral Hydrogen, thus overdensities of the Universe.

SDSS III/BOSS spectra

Outline

- Motivations
- Introduction (What is Lyman-alpha forest?)
- What can you do with Lyman-alpha forest?
  - Baryon Acoustic Oscillations
    - Dark Energy
  - Scale Dependent Bias
    - Primordial Non-gaussianities (f_nl)
- Conclusion

Motivations



Motivations

Time

Gravity +
observing movement of
local galaxies ->
“Dark Matter”

z~0

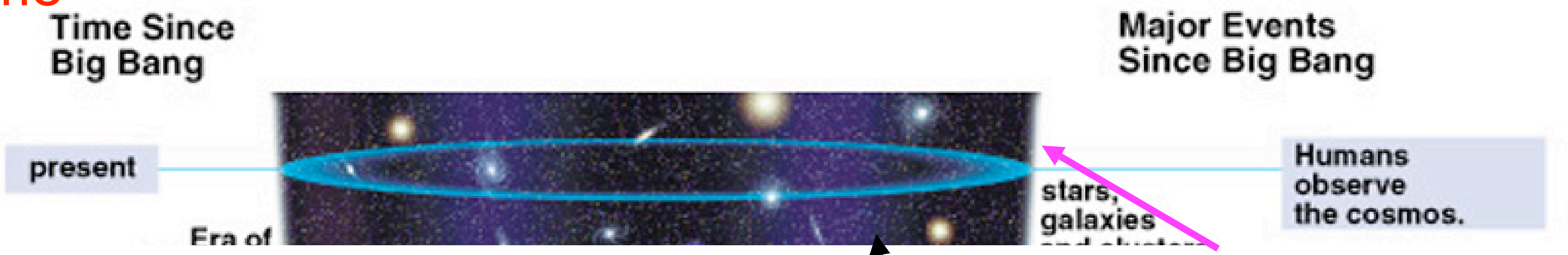
z~6

z~1100

Redshift

Motivations

Time

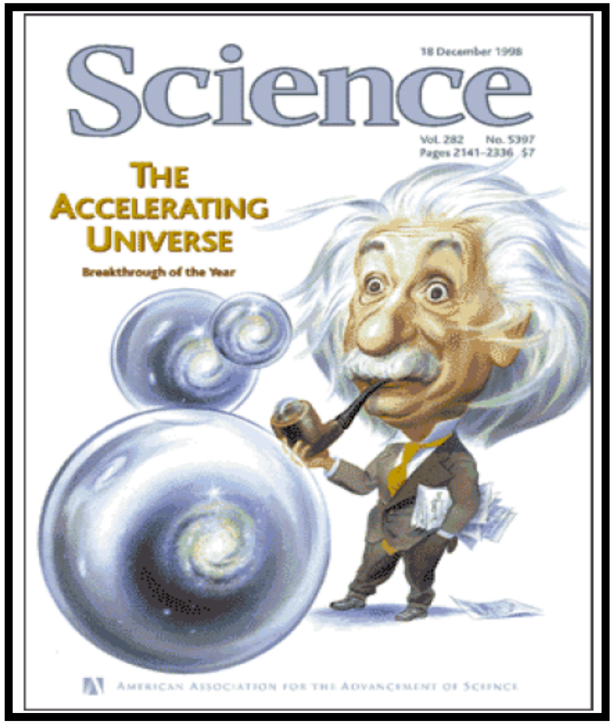


z~0

z~6

z~1100

Gravity +
observing movement of
local galaxies ->
 "Dark Matter"



Science

18 December 1998

Vol. 282 No. 5397
Pages 2141–2336 $7

The Accelerating Universe

Breakthrough of the Year

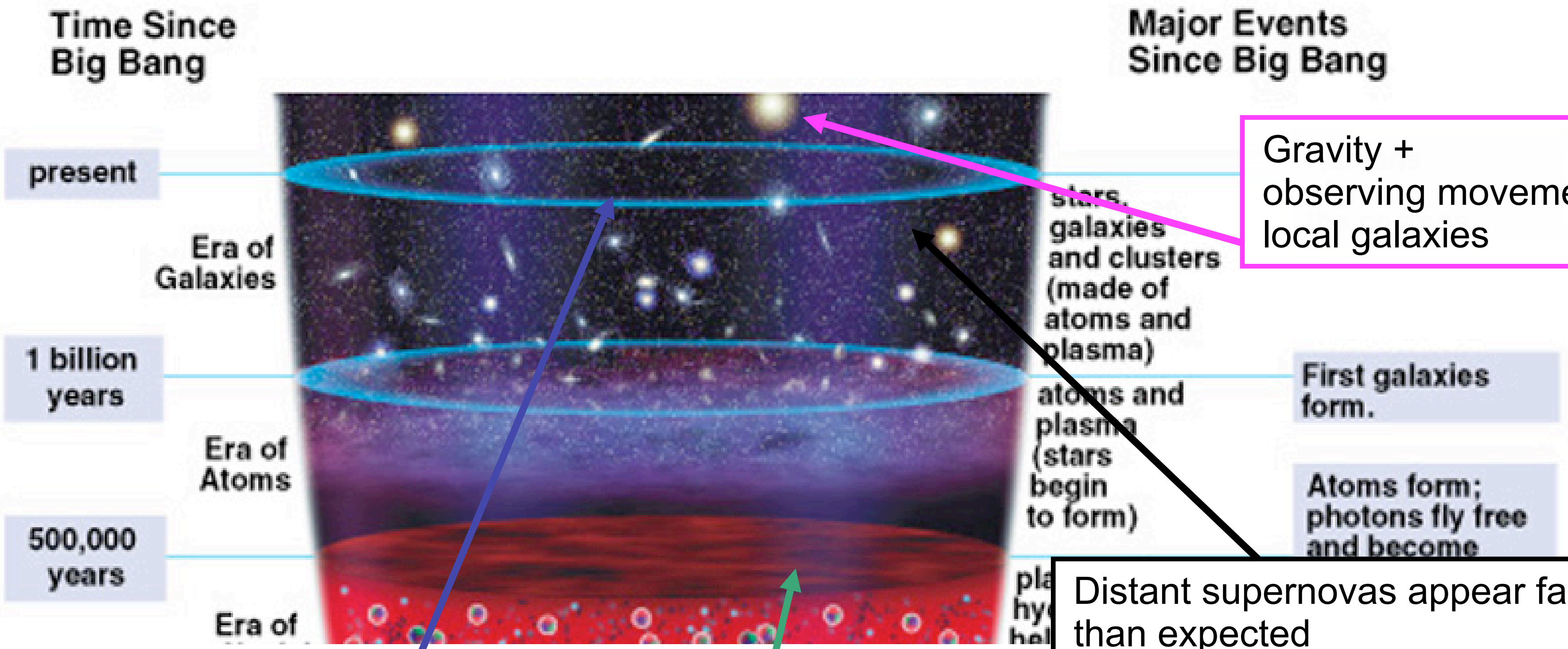
American Association for the Advancement of Science

Distant supernovas appear fainter
than expected (1998)->
Universe is accelerating ->
Cosmological Constant?
Dark Energy?

Redshift

Motivations

Time



z~0

z~6

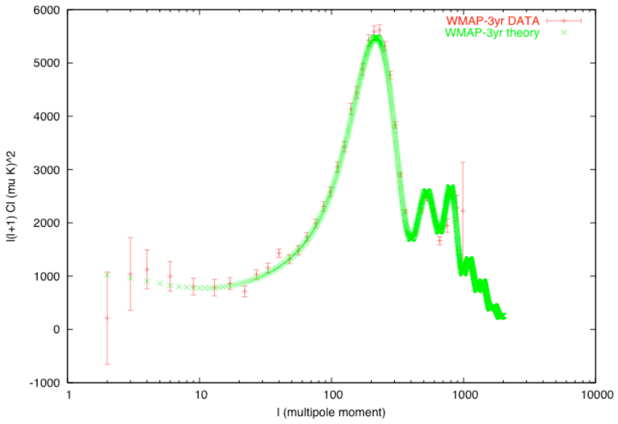
~1100

Gravity +
observing movement of
local galaxies

Distant supernovas appear fainter than expected

Observations of how galaxies cluster

Observations of
Cosmic Microwave Background (CMB)
-> angular powerspectrum of temperature anisotropies



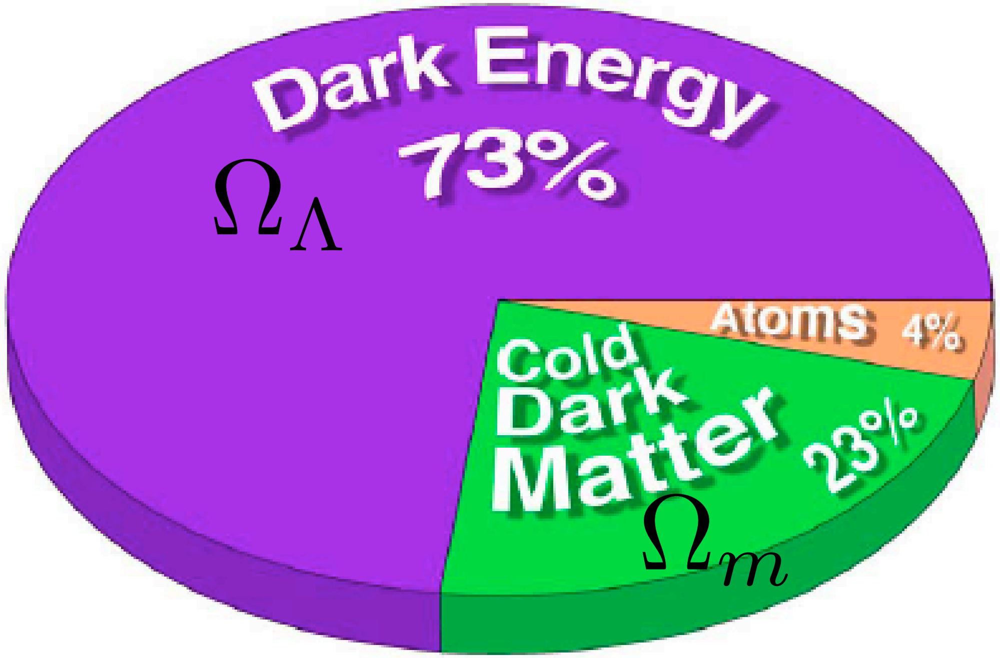
Redshift

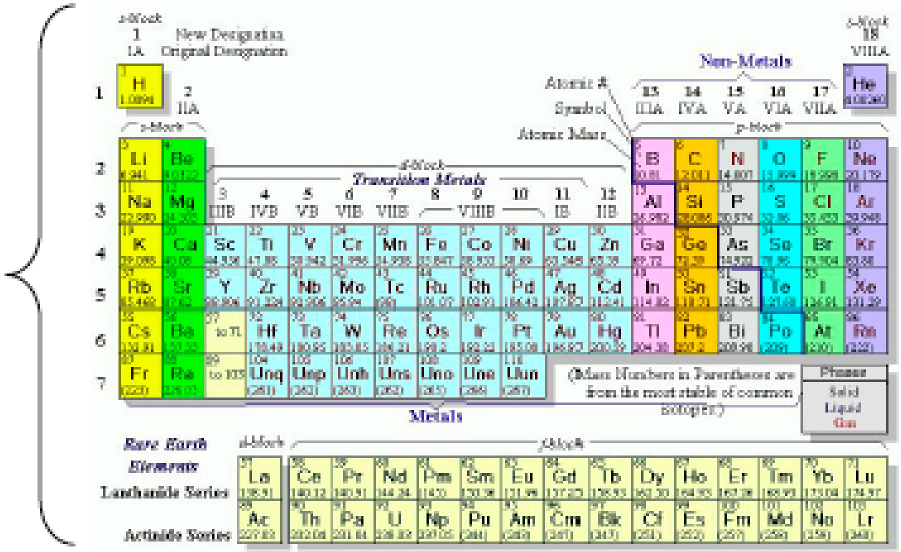
Motivations

Time

z~0

Gravity +
observing movement of





s-block
New Designation
Original Designation
Non-Metals
Atomic #
Symbol
Atomic Mass
p-block
d-block
Transition Metals

	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIIIB	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	H																	He
2	Li	Be											B	C	N	O	F	Ne
3	Na	Mg											Al	Si	P	S	Cl	Ar
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs	Ba	to 71	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	Ra	to 103	Unq	Unp	Unh	Uns	Uno	Une	Uun								

Metals

(Mass Numbers in Parentheses are from the most stable of common isotopes)

Phases
Solid
Liquid
Gas

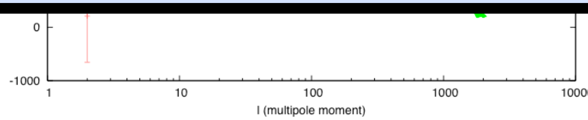
Rare Earth Elements
d-block
f-block

Lanthanide Series	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Actinide Series	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

100

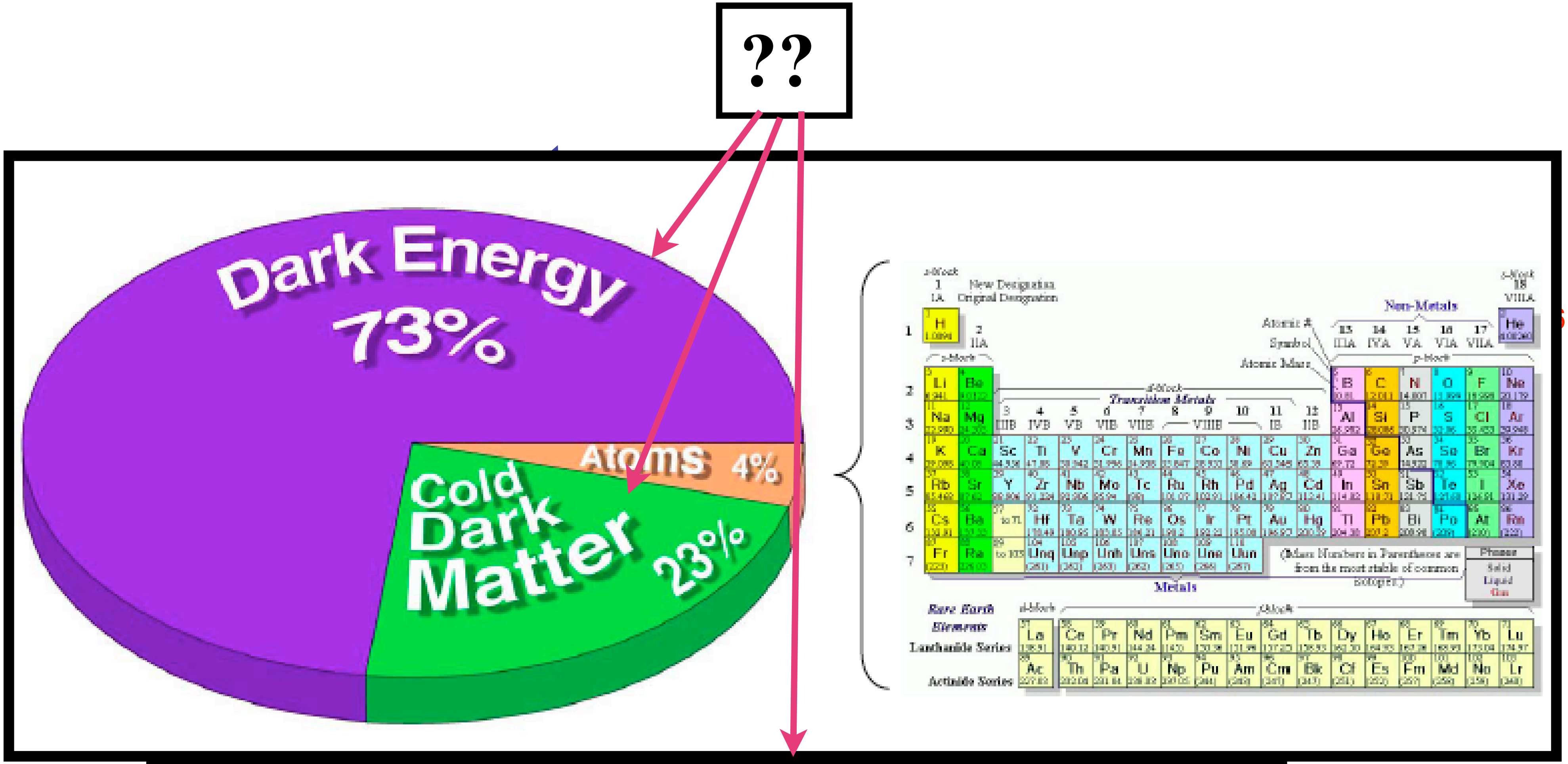
What happened at the Beginning of the Universe?

temperature anisotropies



Redshift

Motivations

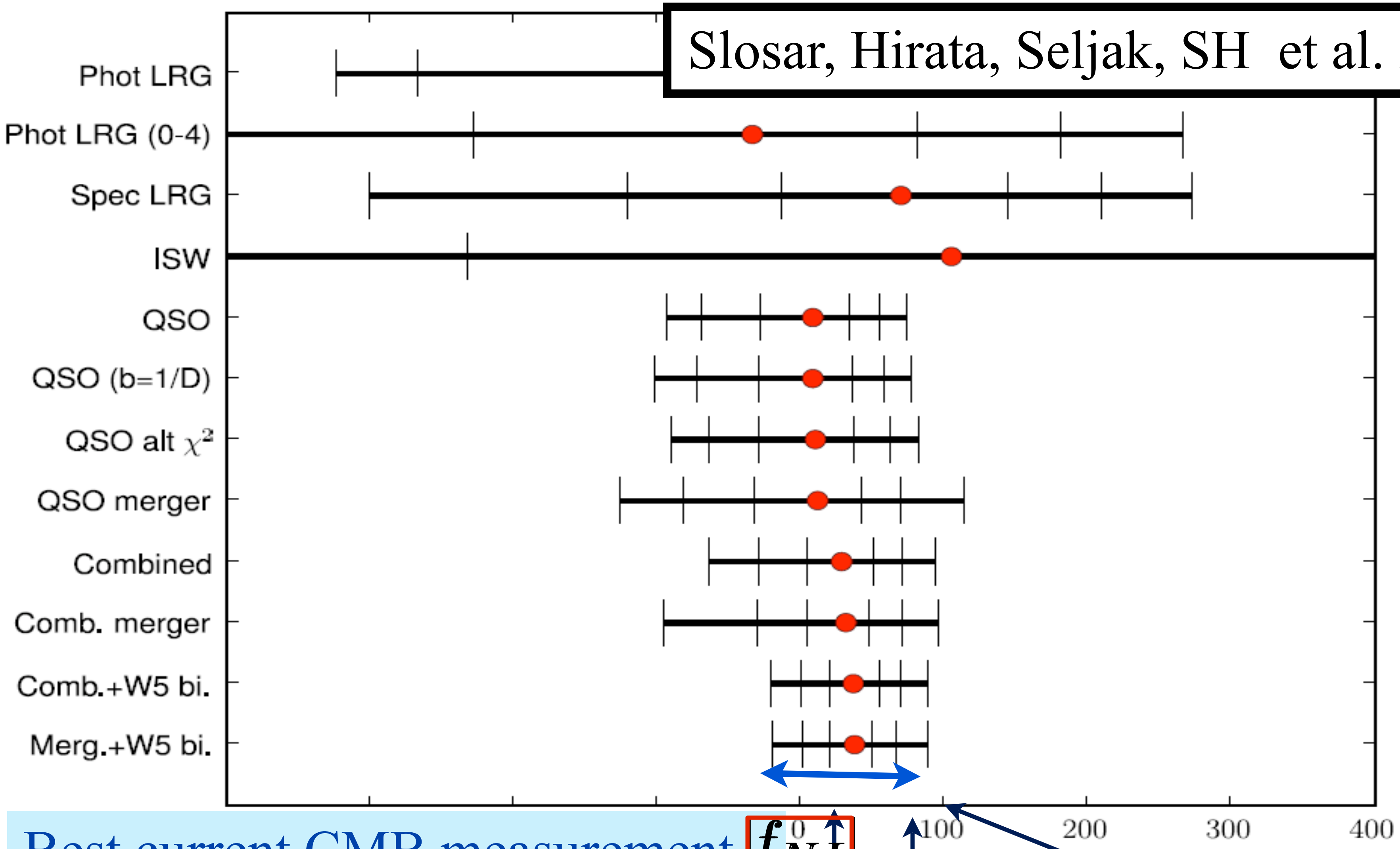


What happened at the Beginning of the Universe?

Lyman Alpha Forest: what can it do?

— Non-gaussianities in Early Universe

Slosar, Hirata, Seljak, SH et al. 2008



Best current CMB measurement

canonical inflation

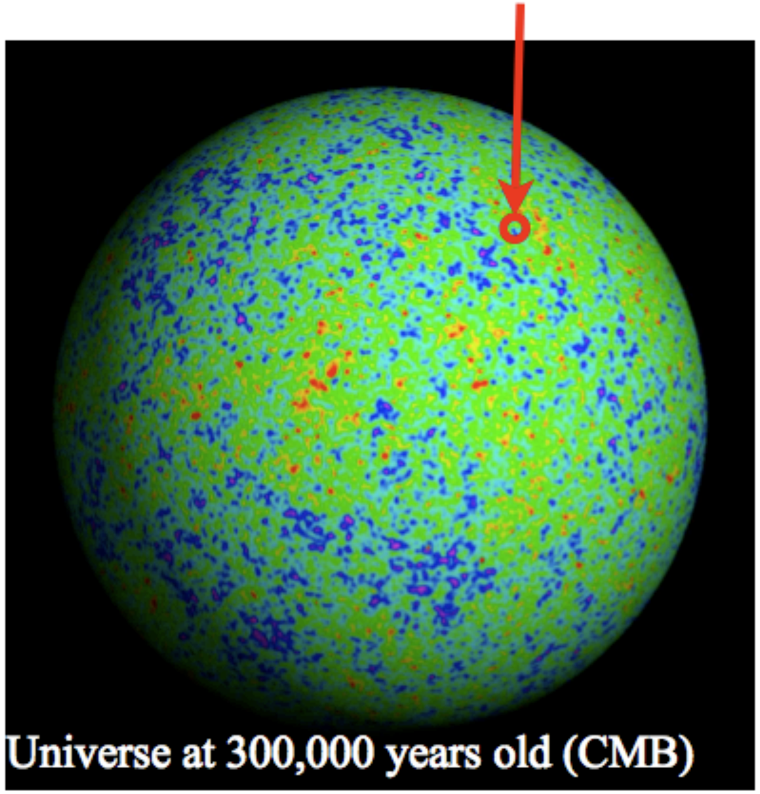
curvaton models, DBI inflation

ghost inflation

What are the Baryon Acoustic Oscillations?

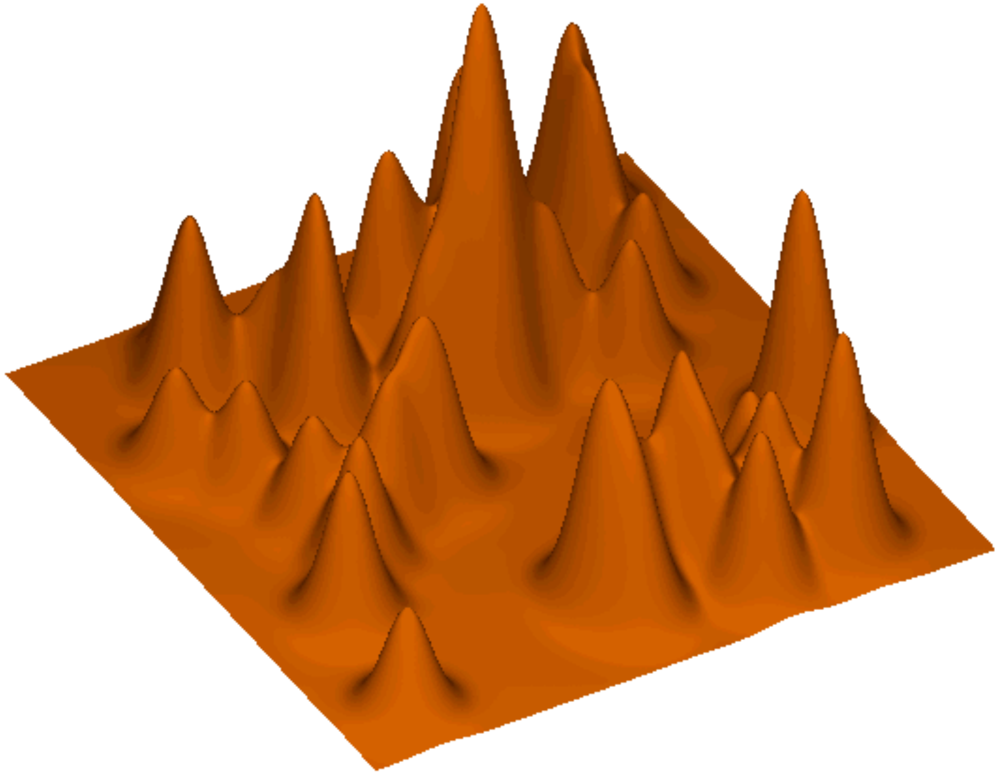
What are baryon acoustic oscillations (BAO)?

These fluctuations of 1 part in 10^5 gravitationally grow into...



Universe at 300,000 years old (CMB)

...these ~unity fluctuations today

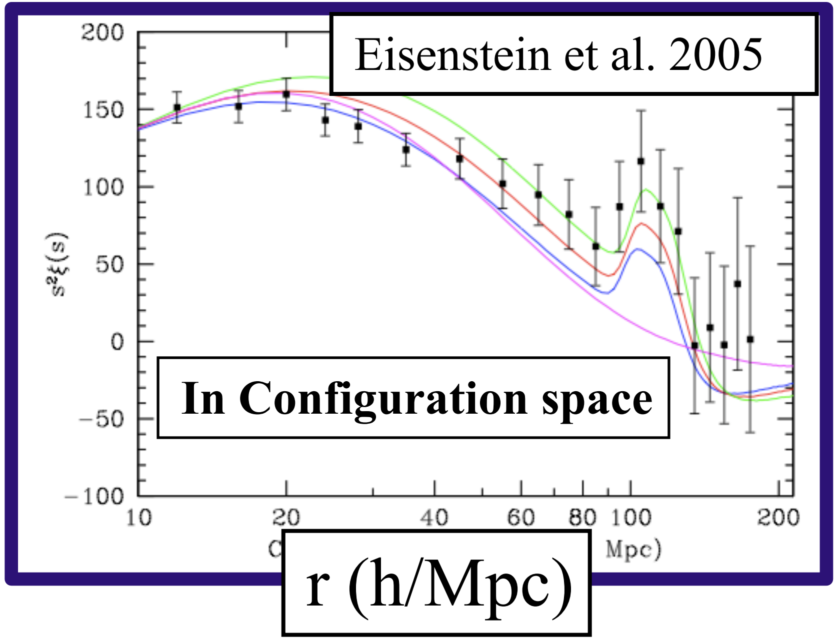


This sound wave can be used as a "standard ruler"
Dark energy changes this apparent ruler size

Courtesy slide from David Schlegel and animation from Daniel Eisenstein

First detections of BAO

$r^2\xi(r)$

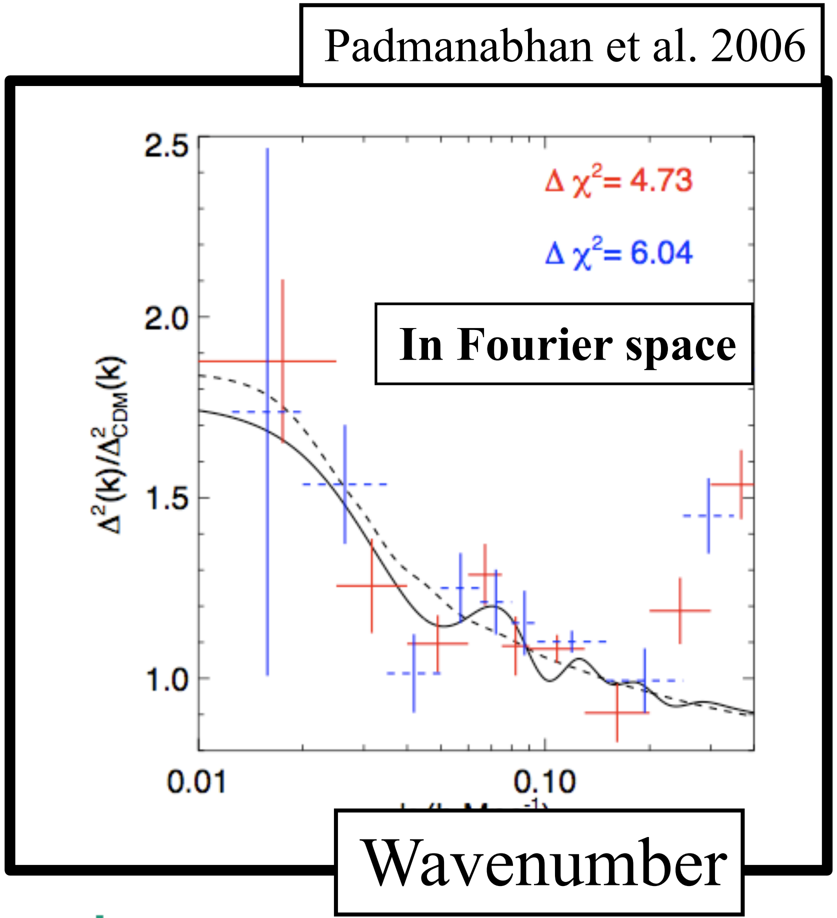


Eisenstein et al. 2005

In Configuration space

r (h/Mpc)

Padmanabhan et al. 2006



In Fourier space

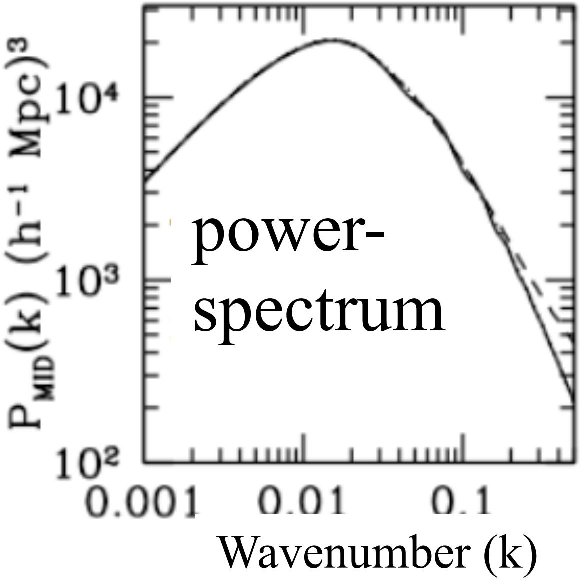
Wavenumber

Outline

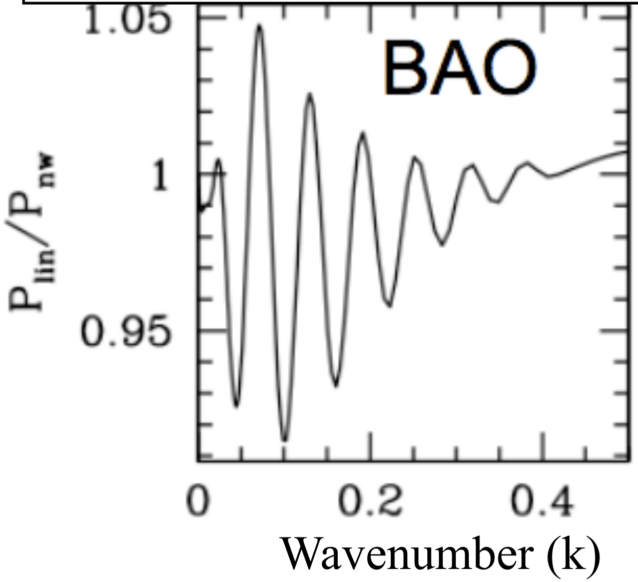
- Motivations
- Introduction (What is Lyman-alpha forest?)
- What can you do with Lyman-alpha forest?
  - Baryon Acoustic Oscillations -> Dark Energy
  - Lyman-alpha power spectrum
  - Non-gaussianities in Early Universe

- Conclusion

Predicted signals of BAO

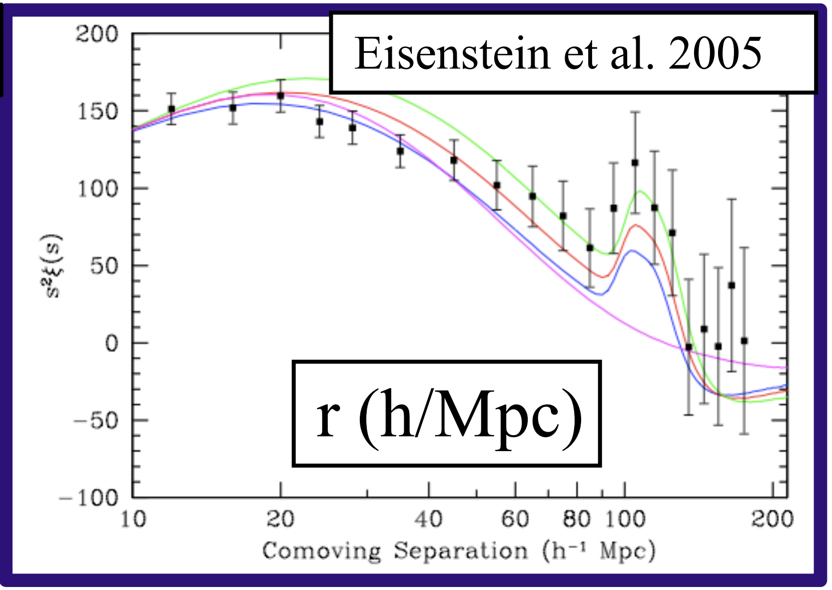


power-spectrum with smoothed part divided out



Fourier space

$r^2\xi(r)$



Configuration space

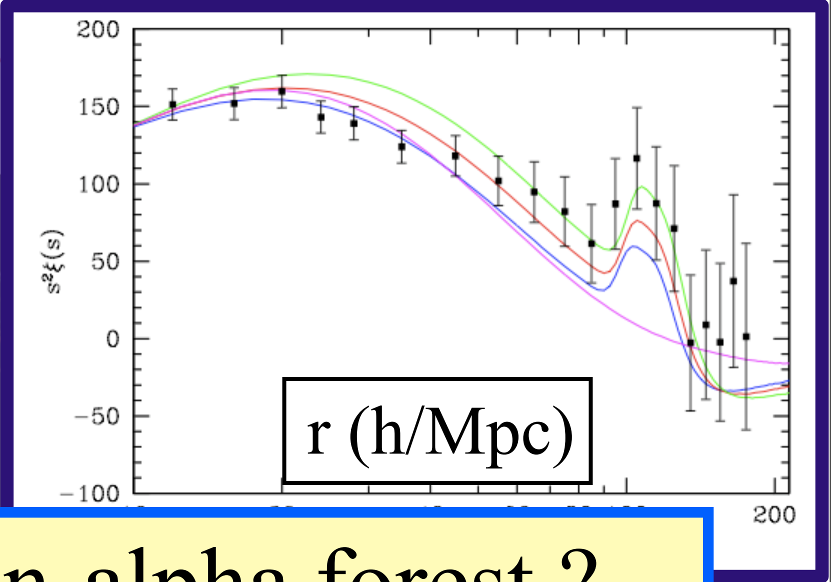
BAO: with Luminous Red Galaxies
Systematics: Dust

- As pointed out by Schlafly, Finkbeiner et al (2010), there is a normalization difference in galactic north and south of ~15%. There is also reddening factor overestimates by factor ~1.4.
- These all possibly contribute to extra power in galaxy power-spectra

Lyman Alpha Forest: what can it do?

What are baryon acoustic oscillations (BAO)?

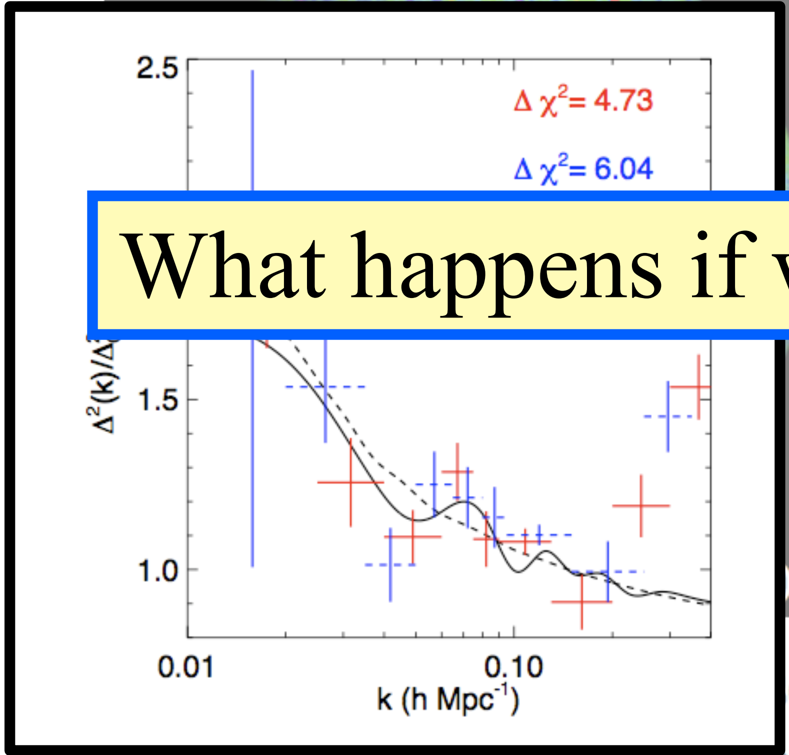
$r^2\xi(r)$



r (h/Mpc)

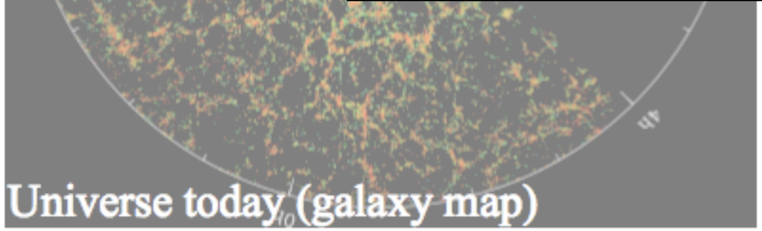
These fluctuations of 1 part in 10^5 gravitationally grow into...

...these ~



What happens if we use Lyman-alpha forest ?

Eisenstein et al. 2005



Universe today (galaxy map)

ed as a “standard ruler”

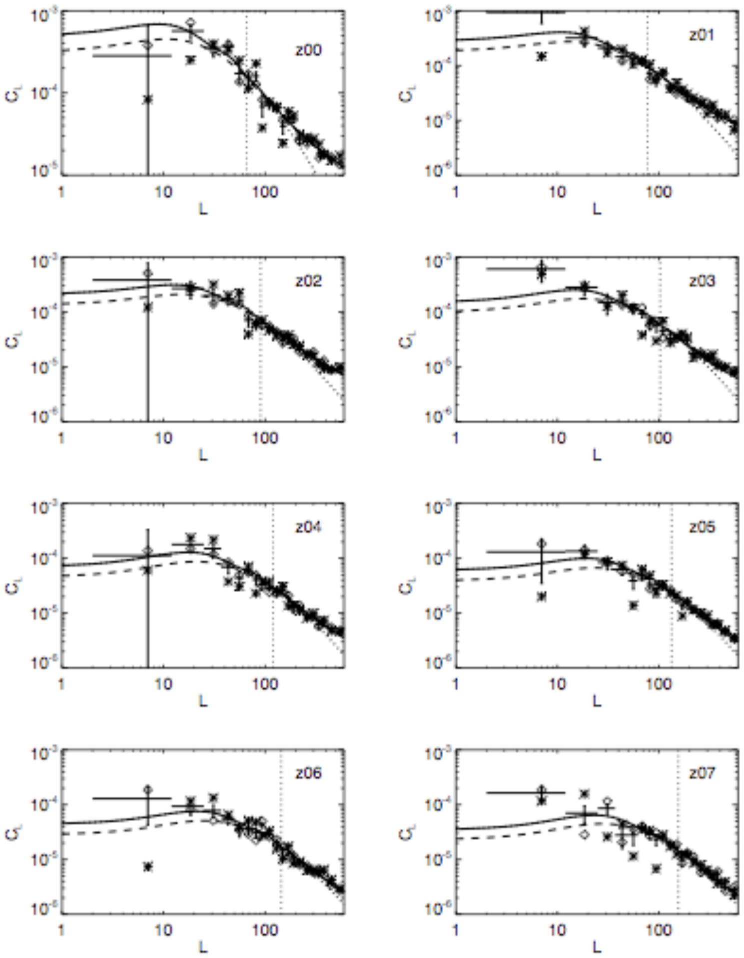
apparent ruler size

Padmanabhan et al. 2006

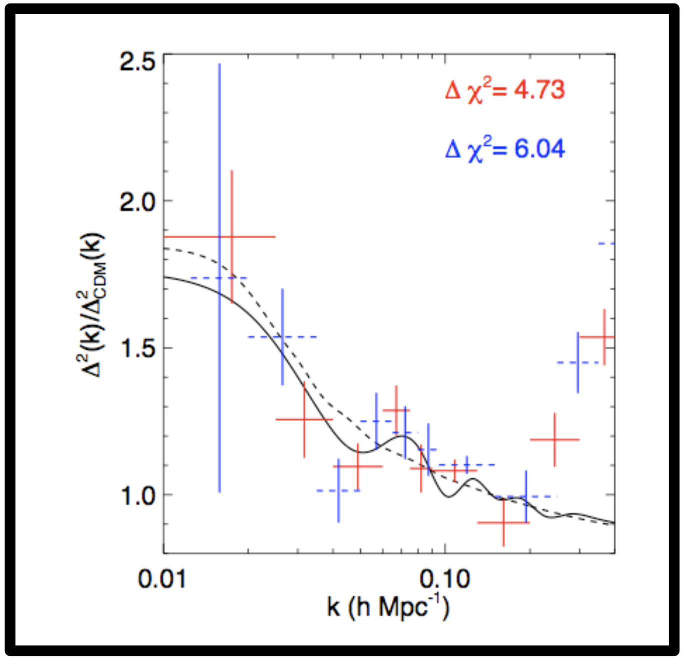
Courtesy slide from David Schlegel

How do you detect BAO with photometric data?

Angular power-spectrum
with 3500 sq deg of SDSS I/II imaging



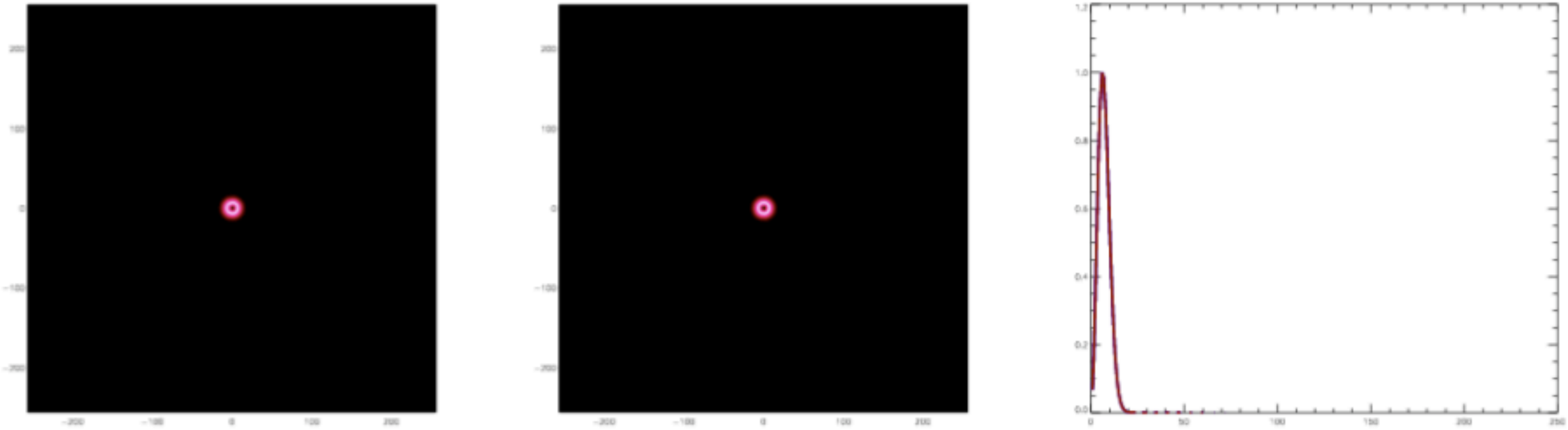
Reconstructed Galaxy power-spectrum
with ~2.6 sigma 'detection' of BAO



Padmanabhan et al. 2006

What are the Baryon Acoustic Oscillations?

- **We start with single perturbation and the plasma is totally uniform except for an excess of matter at the origin**
- **High pressure drives the gas+photon fluid outwards approaching speed of light.**

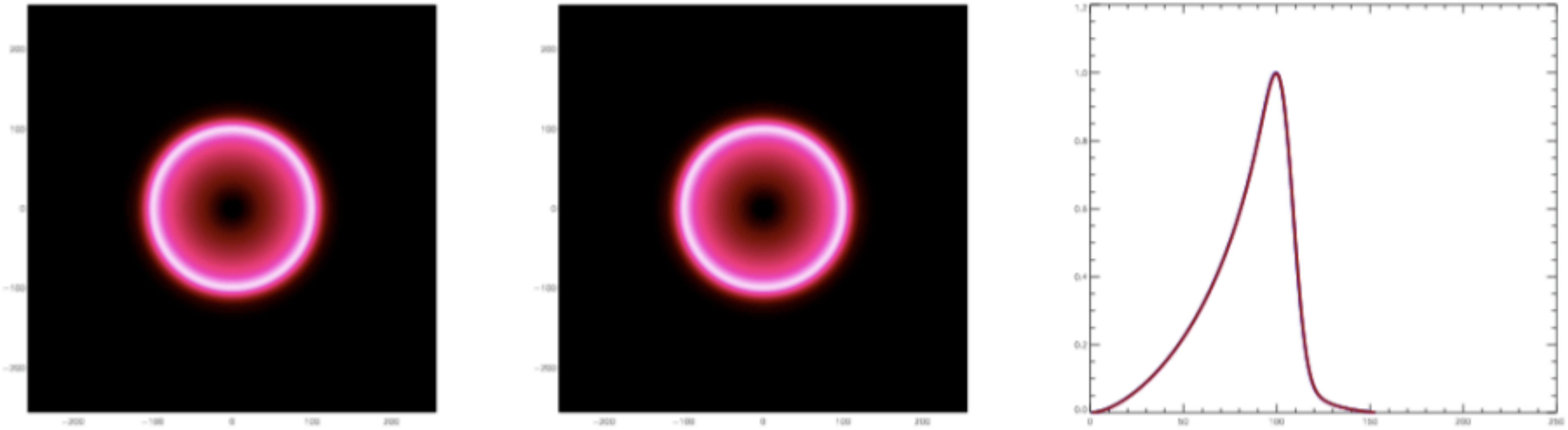


Baryons Photons Mass profile

Eisenstein, Seo and White (2006)

What are the Baryon Acoustic Oscillations?

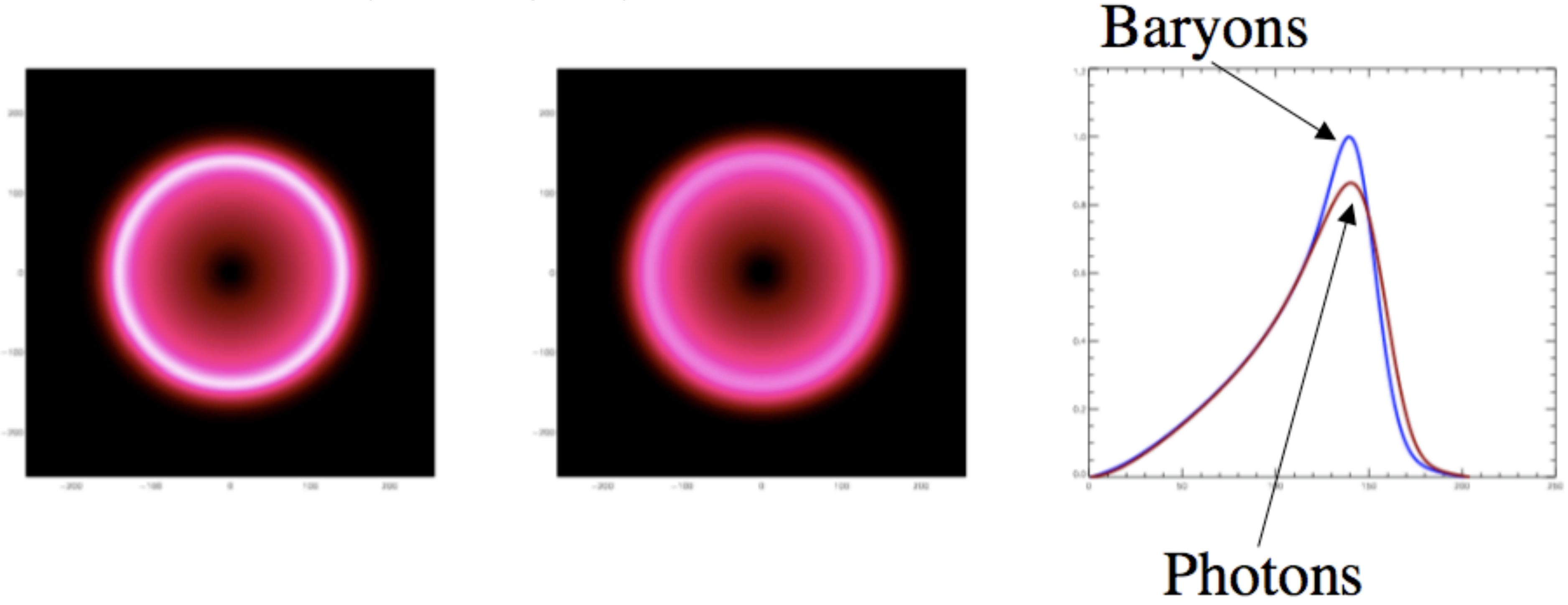
- **This expansion continues for 100,000 years.**



Eisenstein, Seo and White (2006)

What are the Baryon Acoustic Oscillations?

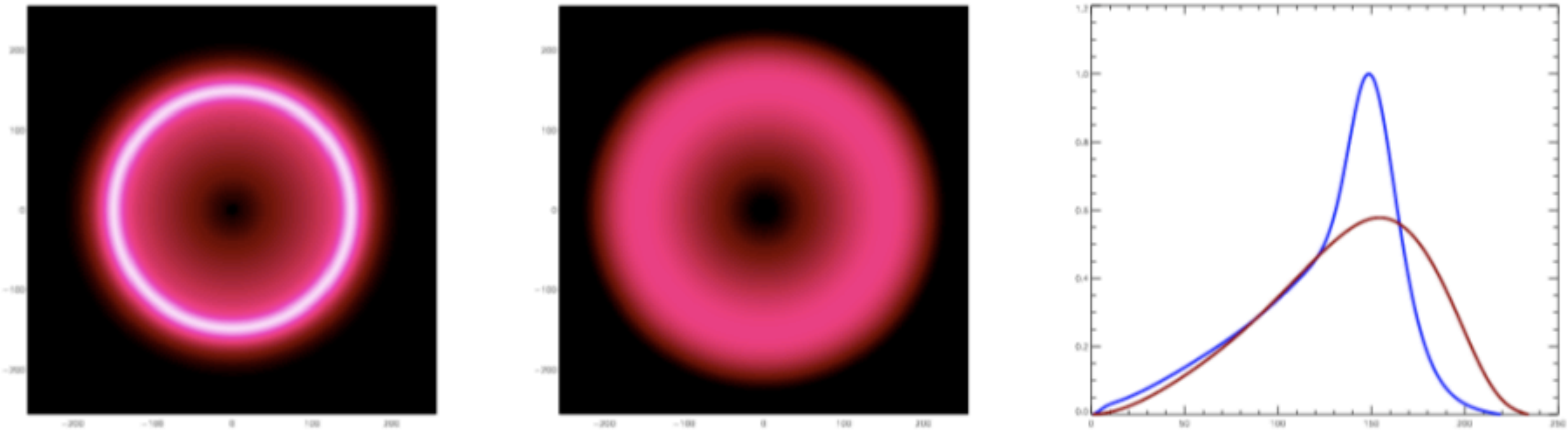
- **After 100,000 years, the Universe is cool enough that protons capture electrons to form neutral hydrogen**
- **This decouples the photons from the baryons. The photons quickly streamed away, leaving baryon peak stalled.**



Eisenstein, Seo and White (2006)

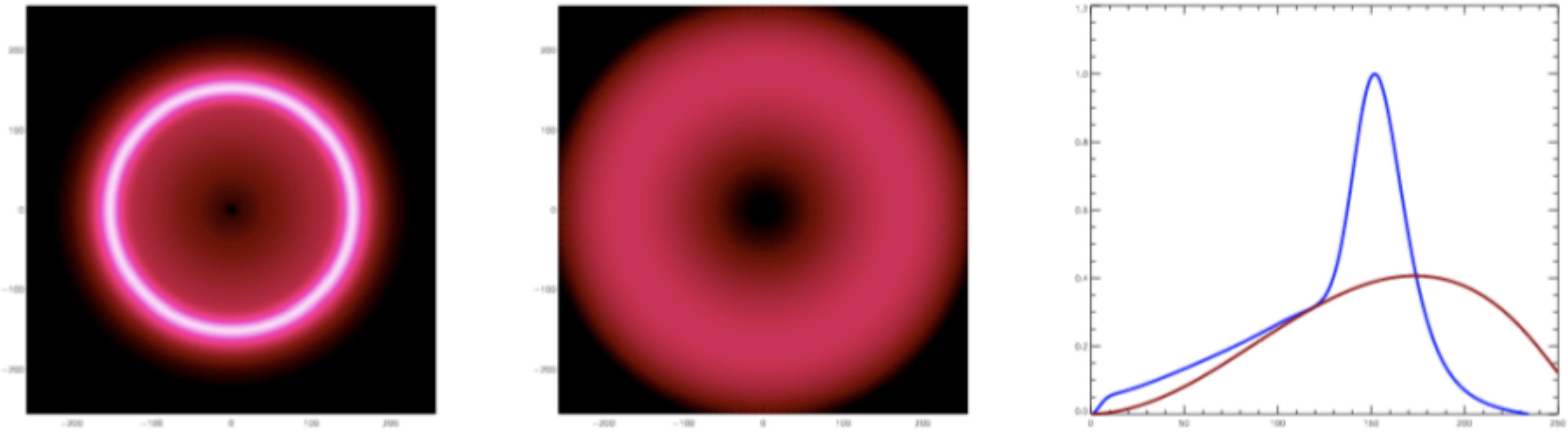
What are the Baryon Acoustic Oscillations?

- **The photons continue to stream away, while baryons, having lost the motive pressure, remain in place.**



Eisenstein, Seo and White (2006)

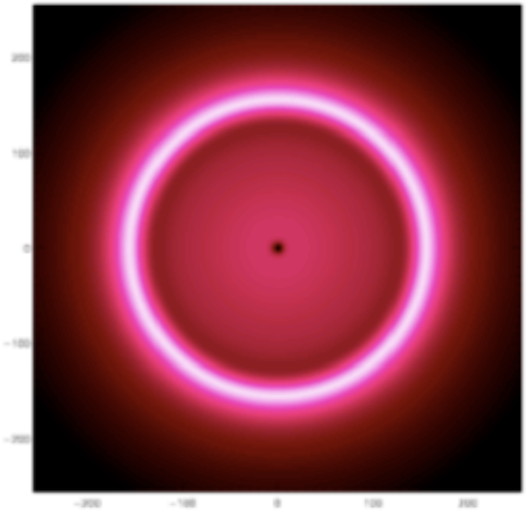
What are the Baryon Acoustic Oscillations?

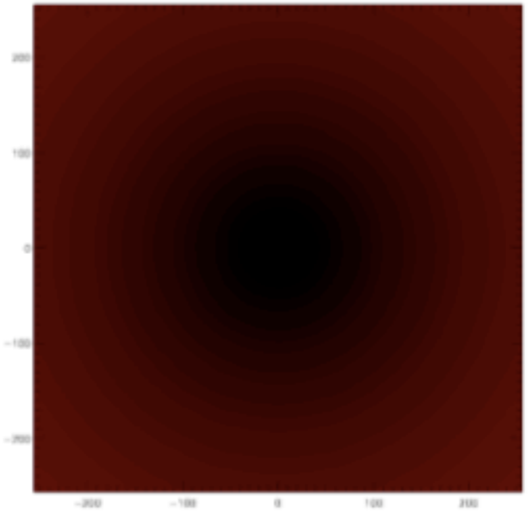


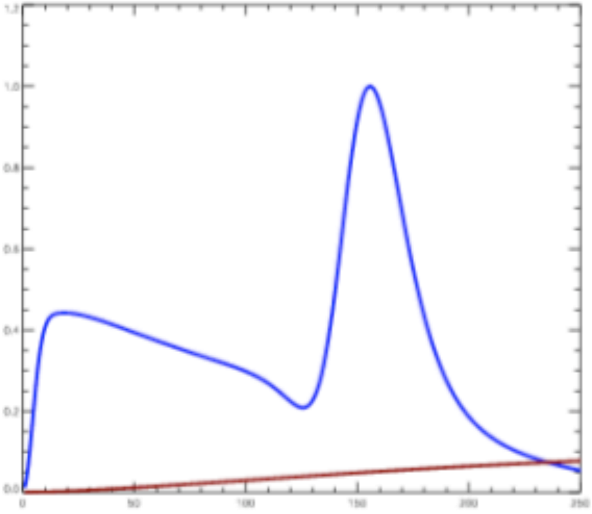
Eisenstein, Seo and White (2006)

What are the Baryon Acoustic Oscillations?

- The photons are nearly completely uniform now, but the baryons remain overdense in a shell of ~100 Mpc in radius
- In addition, the large gravitational potential well which we started with starts to draw the material back to it.



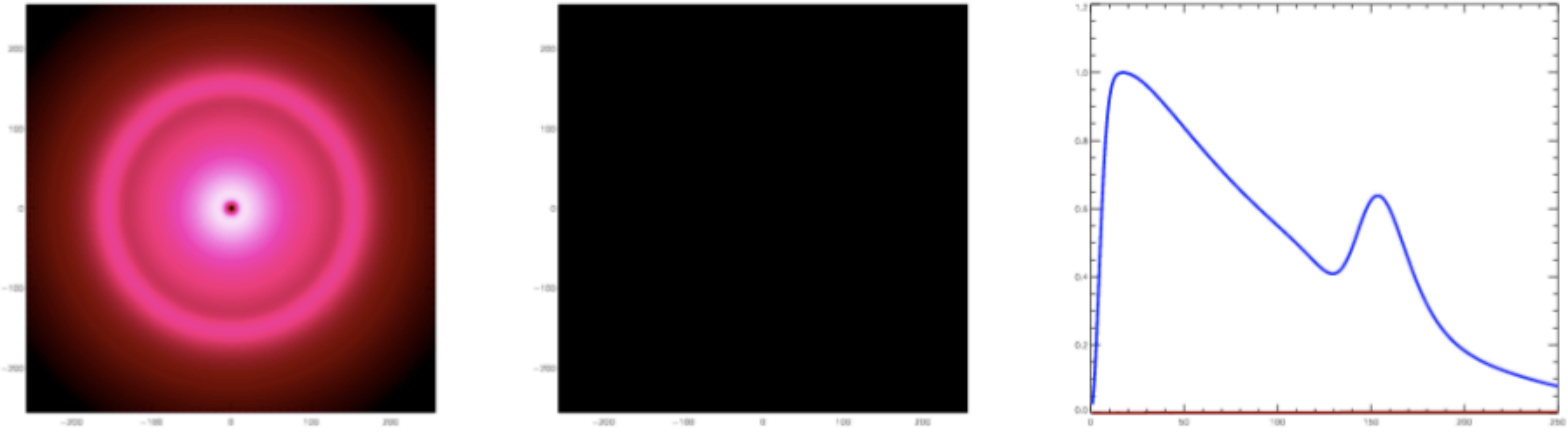




Eisenstein, Seo and White (2006)

What are the Baryon Acoustic Oscillations?

- As the perturbation grows, the baryons and dark matter reach equilibrium densities in the ratio of global baryon-to-dark matter ratio.
- The final configuration is our original peak at the center and an ‘echo’ in a shell roughly 100 Mpc in radius with width ~10%



Eisenstein, Seo and White (2006)

What are the Baryon Acoustic Oscillations?

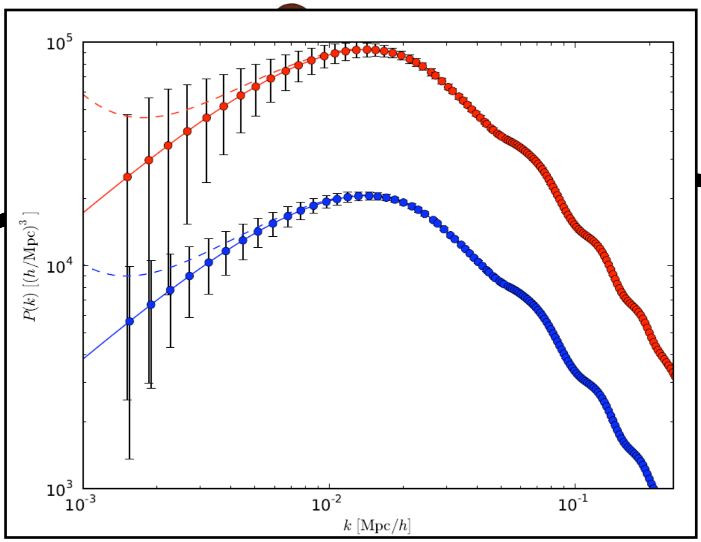
How do we detect Baryon Acoustic Oscillations?
We calculate the correlation functions or its Fourier Transform: power-spectrum

What is the correlation function ?

$$\xi_f(r) =< \delta_f(\hat{x})\delta_f(\hat{x}+\hat{r}) >$$

Fourier Transform: correlation function-> **power-spectrum**

100 Mpc



There will be wiggles

BAO: with Luminous Red Galaxies
Physics of Angular Clustering

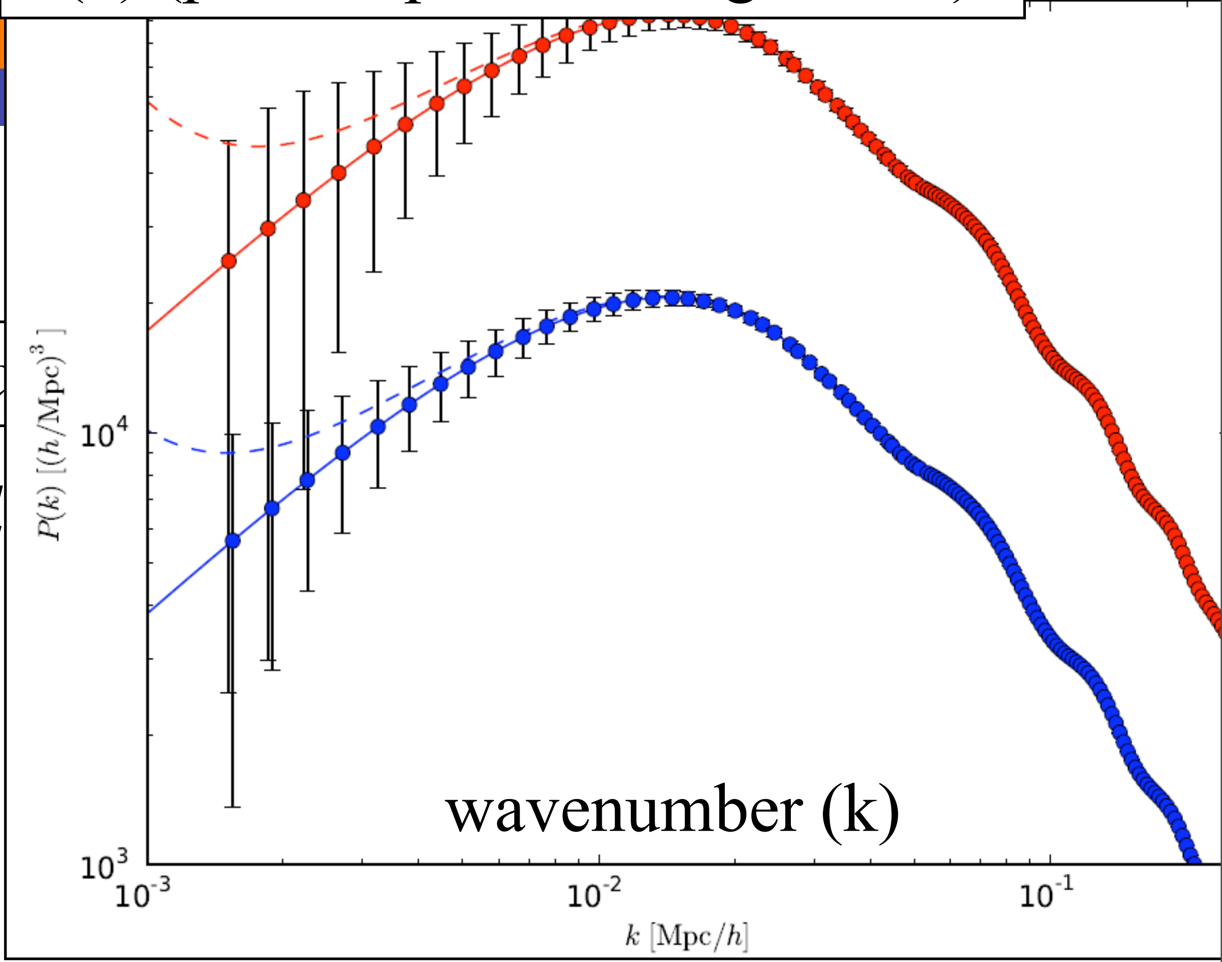
$b = \frac{\delta g}{\delta \rho}$ describe how galaxies are related to cold dark matter

$\frac{dN}{dz}$ describe how many galaxies are there at each dz bin

$D(z)$ describe how matter grows

$P(\frac{l+\frac{1}{2}}{\chi})$

P(k) (power-spectrum of galaxies)



Galaxy angular power-spectru

$$C_l^{gg} = \int dz \frac{H_0}{c} b^2(z)(d$$

BAO: with Luminous Red Galaxies
Physics of Angular Clustering

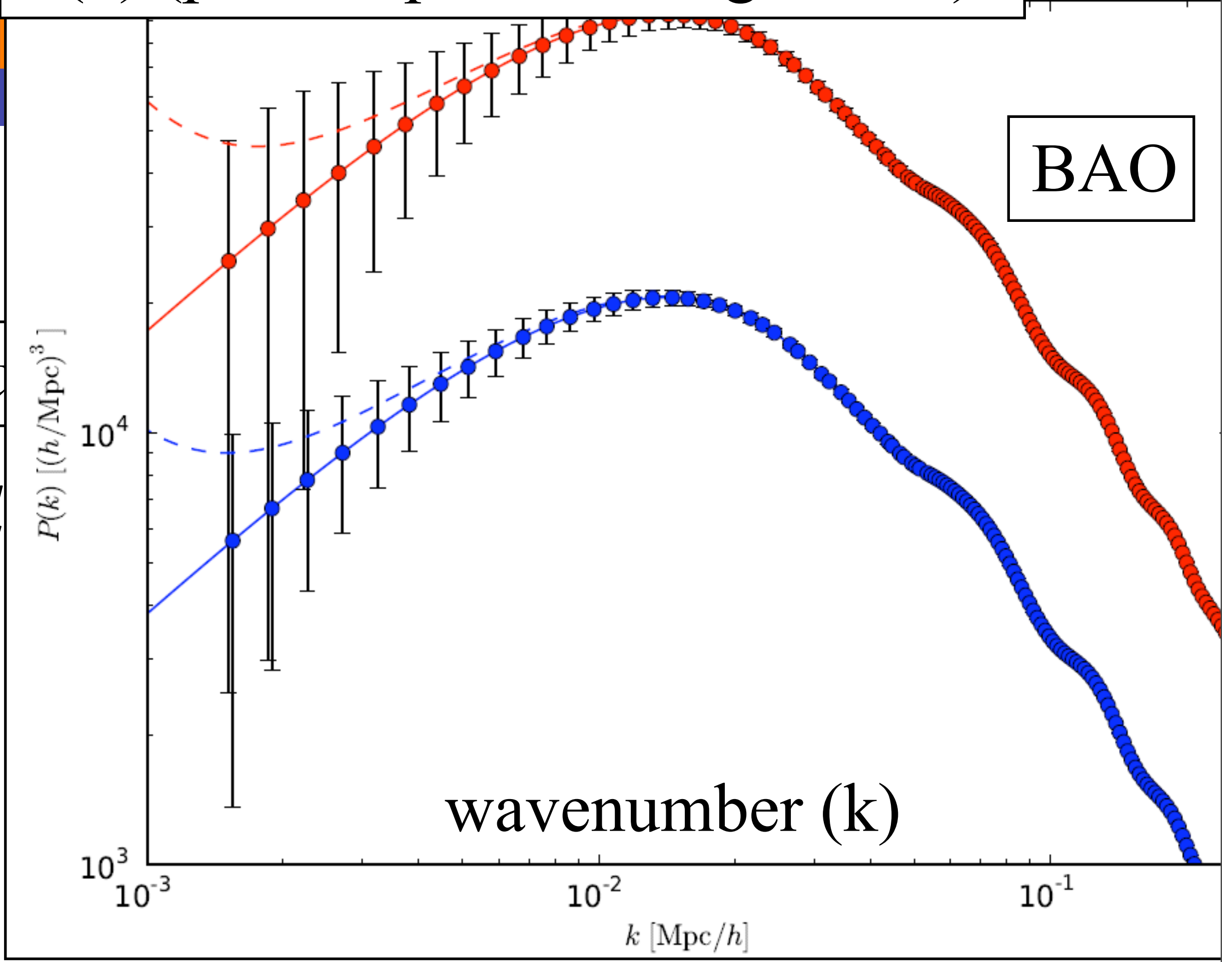
$b = \frac{\delta g}{\delta \rho}$ describe how galaxies are related to cold dark matter

$\frac{dN}{dz}$ describe how many galaxies are there at each dz bin

$D(z)$ describe how matter grows

$P(\frac{l+\frac{1}{2}}{\chi})$

P(k) (power-spectrum of galaxies)



Galaxy angular power-spectru

$$C_l^{gg} = \int dz \frac{H_0}{c} b^2(z)(d$$

BAO: with Luminous Red Galaxies
Physics of Angular Clustering

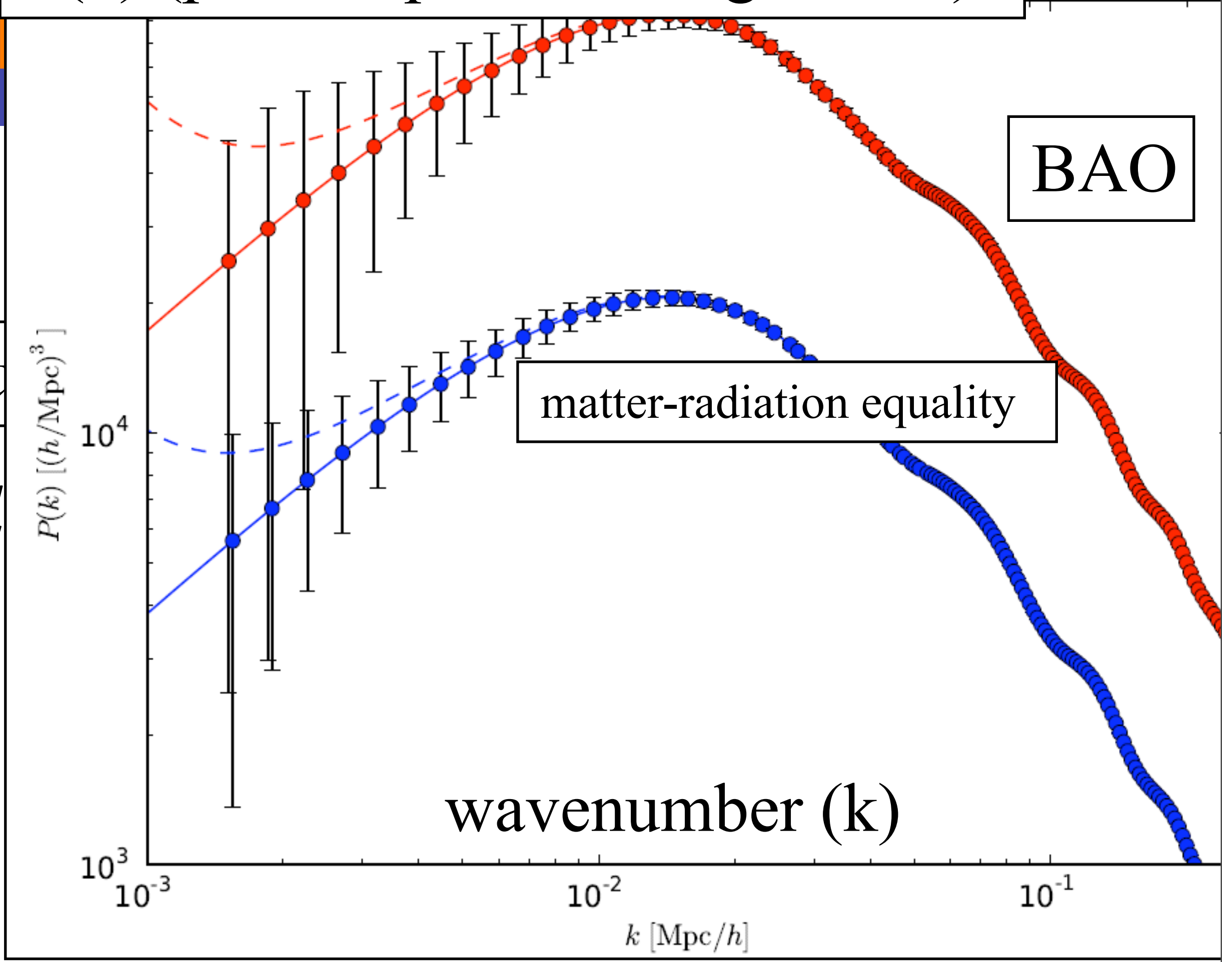
$b = \frac{\delta g}{\delta \rho}$ describe how galaxies are related to cold dark matter

$\frac{dN}{dz}$ describe how many galaxies are there at each dz bin

$D(z)$ describe how matter grows

$P(\frac{l+\frac{1}{2}}{\chi})$

P(k) (power-spectrum of galaxies)



Galaxy angular power-spectru

$$C_l^{gg} = \int dz \frac{H_0}{c} b^2(z)(d$$

BAO: with Luminous Red Galaxies

Physics of Angular Clustering

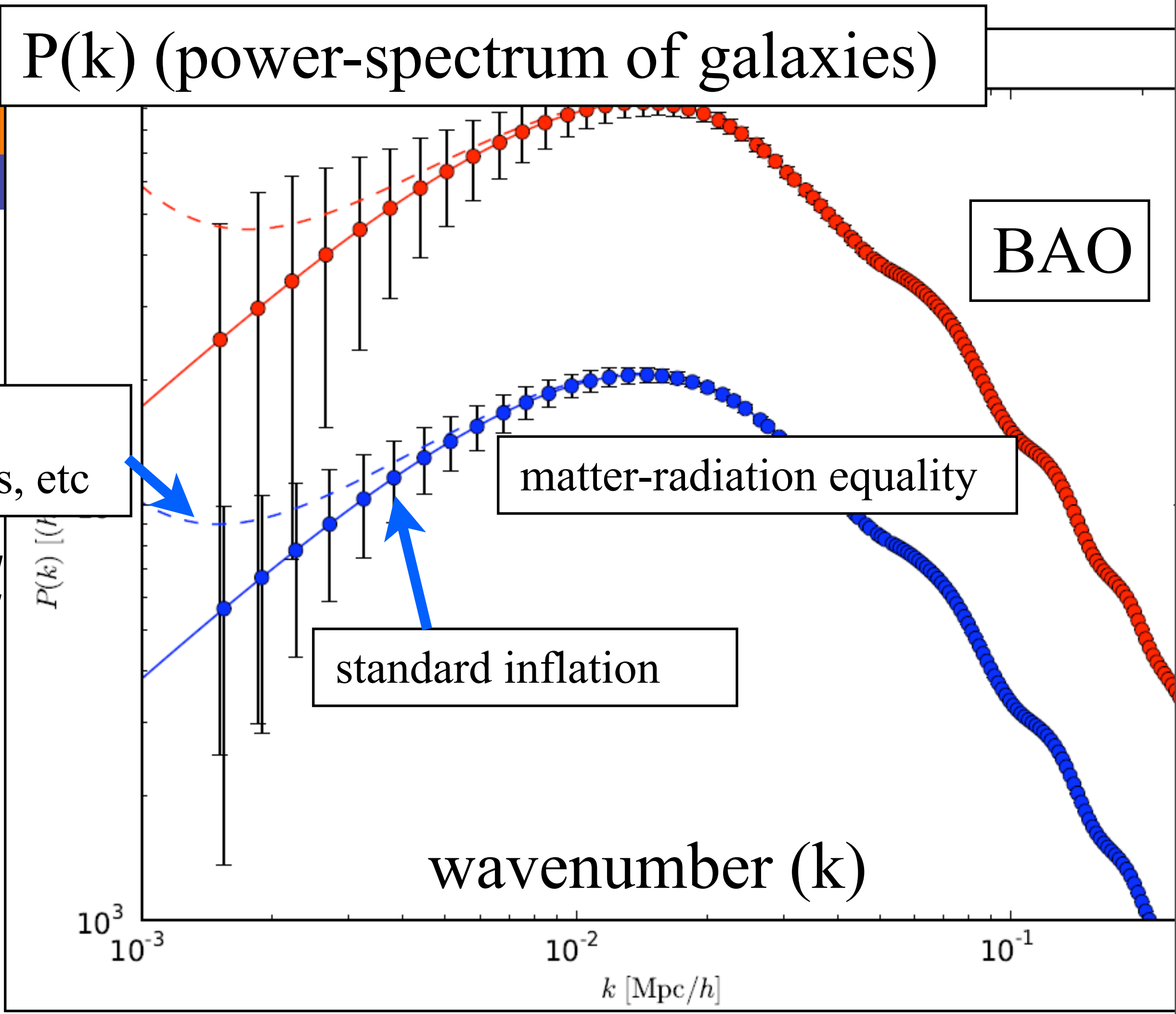
$b = \frac{\delta g}{\delta \rho}$ describe how galaxies are related to cold dark matter

$\frac{dN}{dz}$ describe how many galaxies are there at each dz bin

$D(z)$ describe how matter grows

$P\left(\frac{l+\frac{1}{2}}{\chi}\right)$

P(k) (power-spectrum of galaxies)



BAO

matter-radiation equality

standard inflation

wavenumber (k)

Galaxy angular po

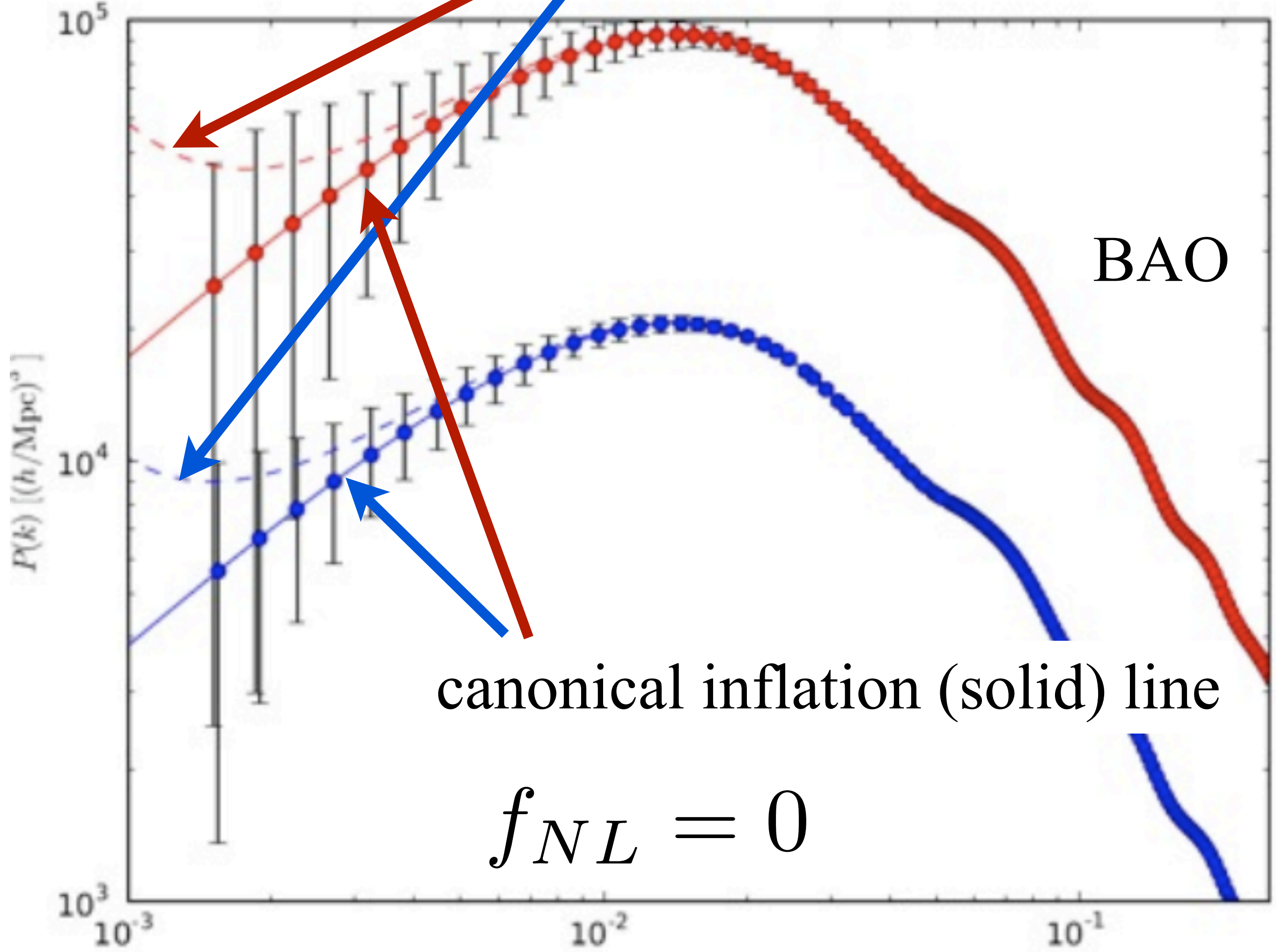
ghost inflation,
curvaton models, etc

$$C_l^{gg} = \int dz \frac{H_0}{c} b^2(z)(d$$

$f_{NL} = 100$

P(k) (Mpc/h)^3

ghost inflation (dashed line)



BAO

canonical inflation (solid) line

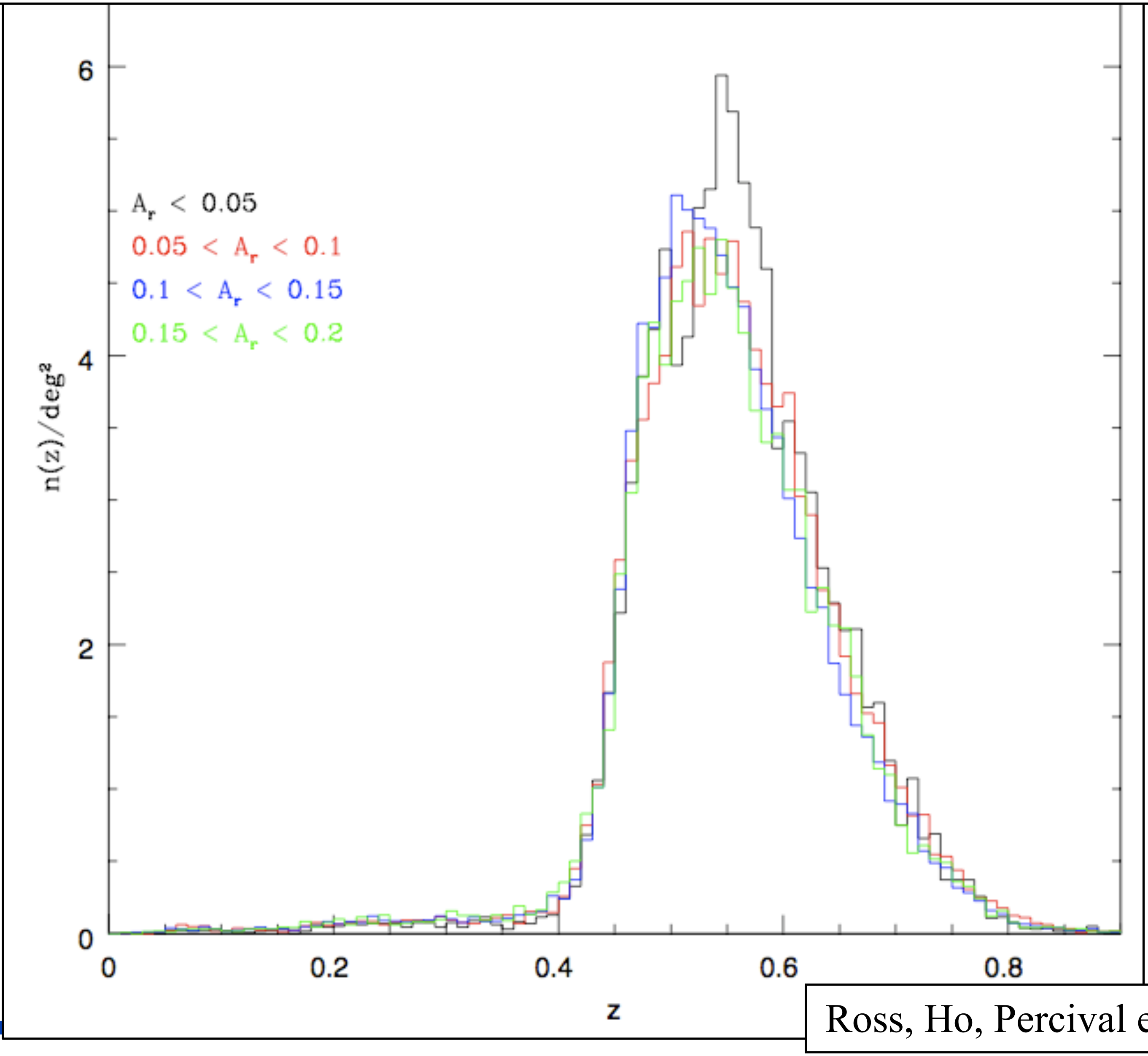
$f_{NL} = 0$

k (h/Mpc)

BAO: with Luminous Red Galaxies

Systematics: Dust

Dust extinction affects redshift distribution of the galaxies



Ross, Ho, Percival et al. (in prep)