

Large Scale Structure III

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3 Lectures

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

The population density map of Japan

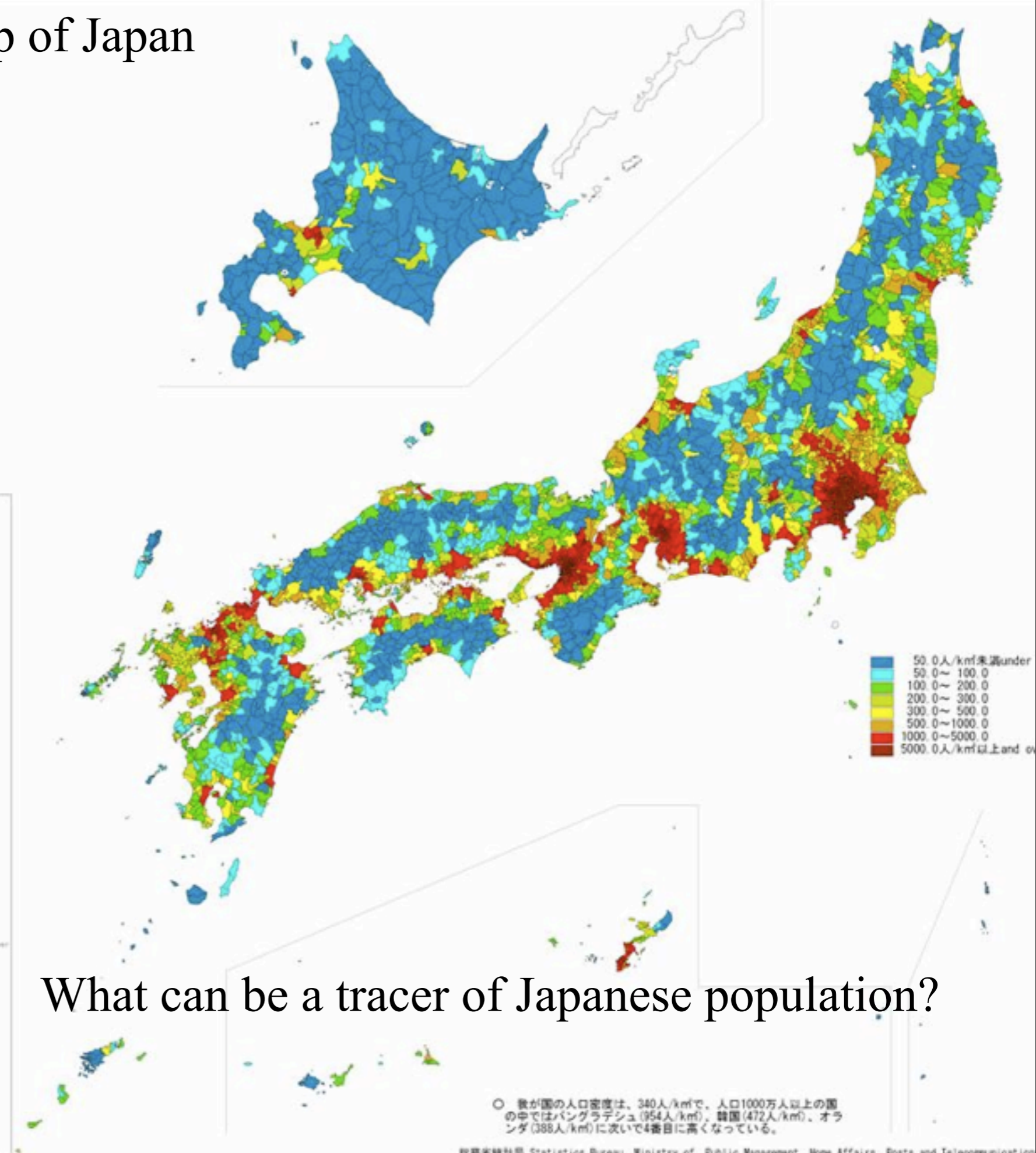
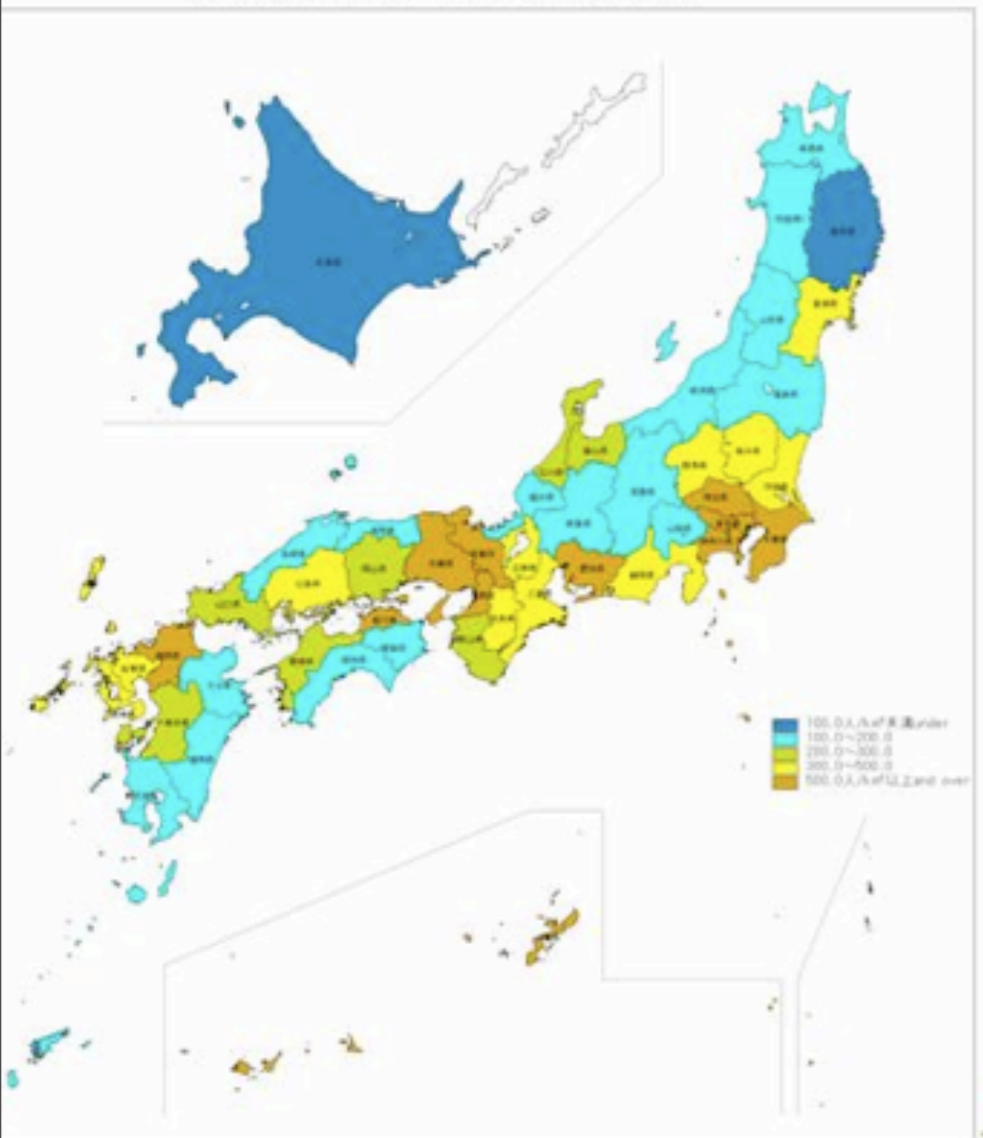
日本統計地図

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



What can be a tracer of Japanese population?

○ 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

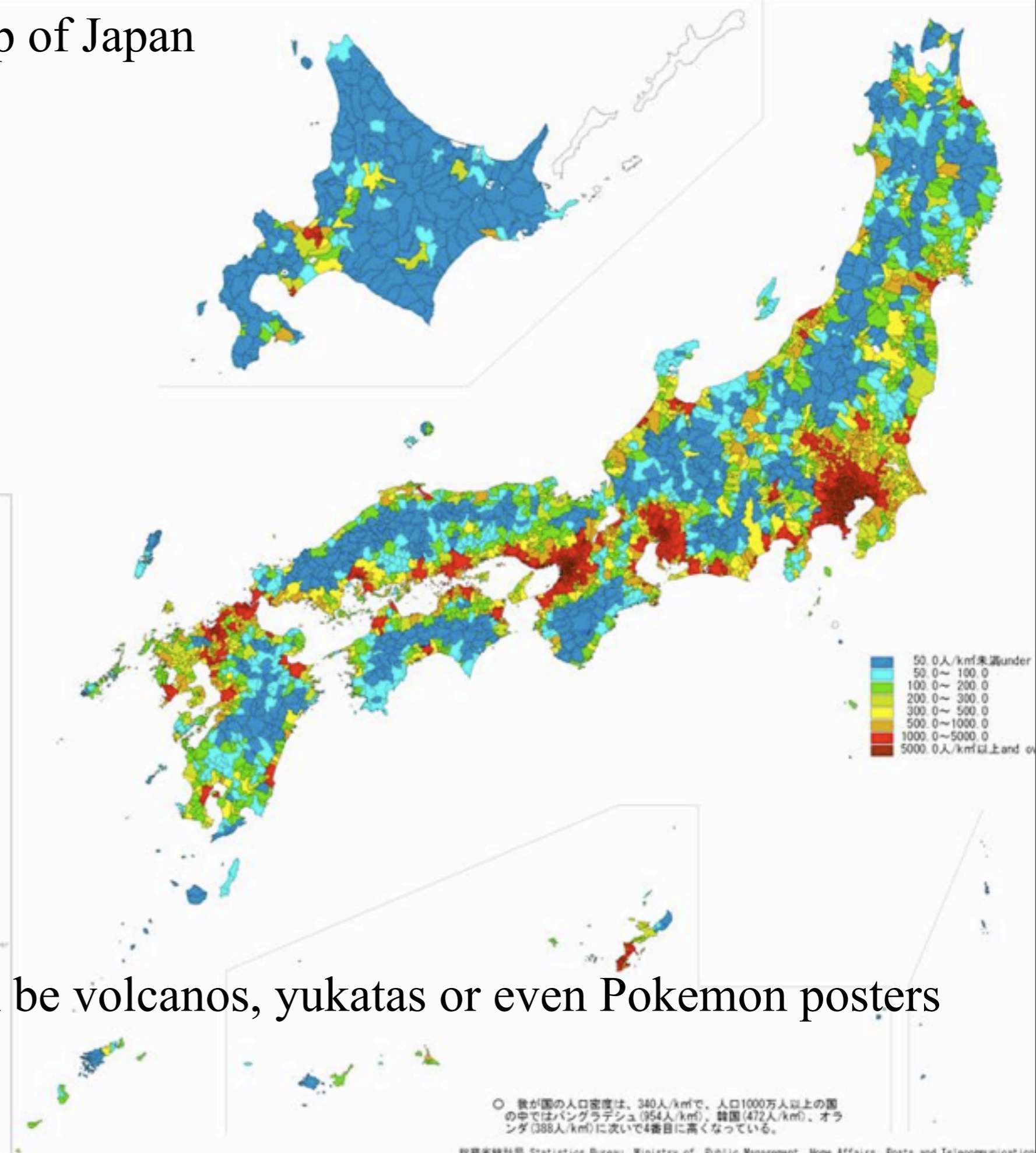
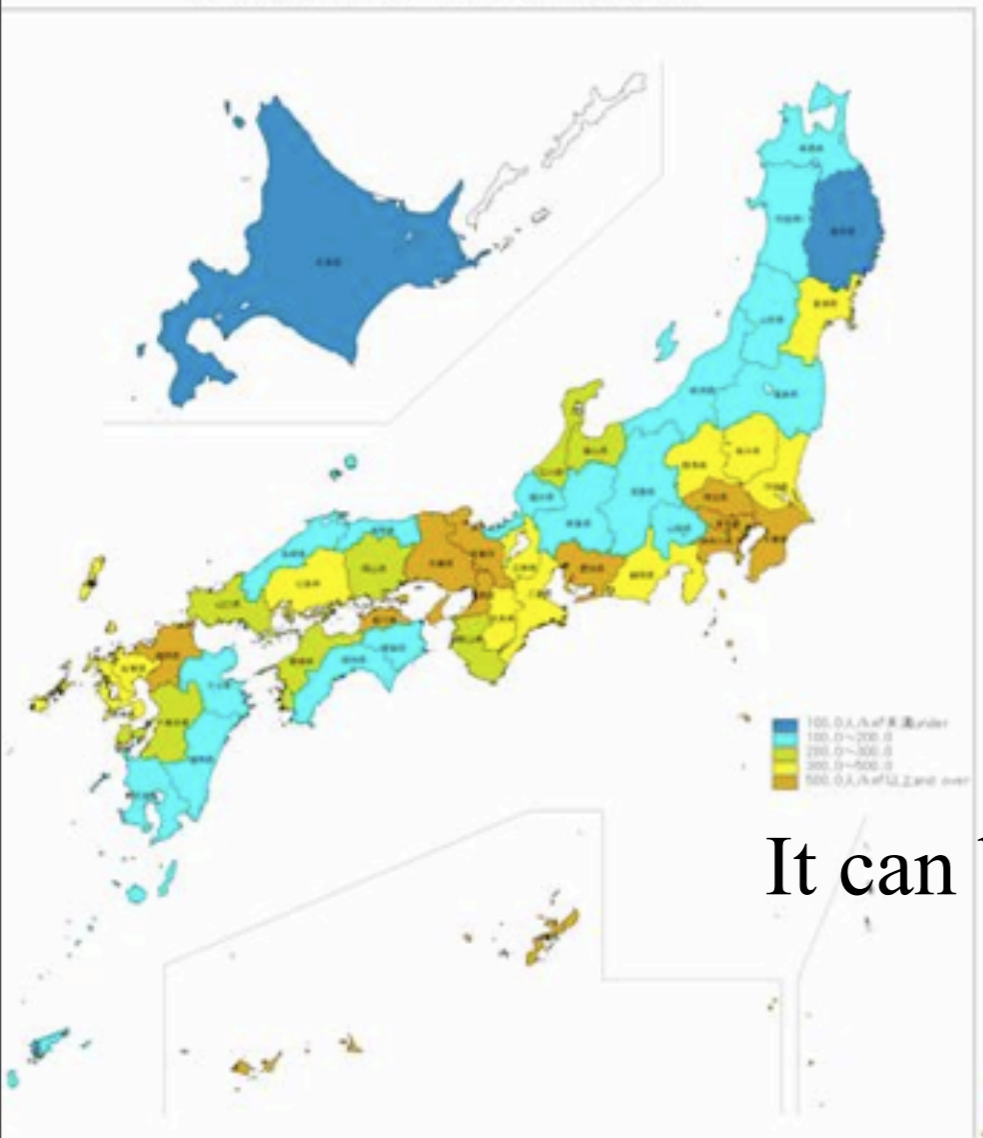
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It can be volcanos, yukatas or even Pokemon posters

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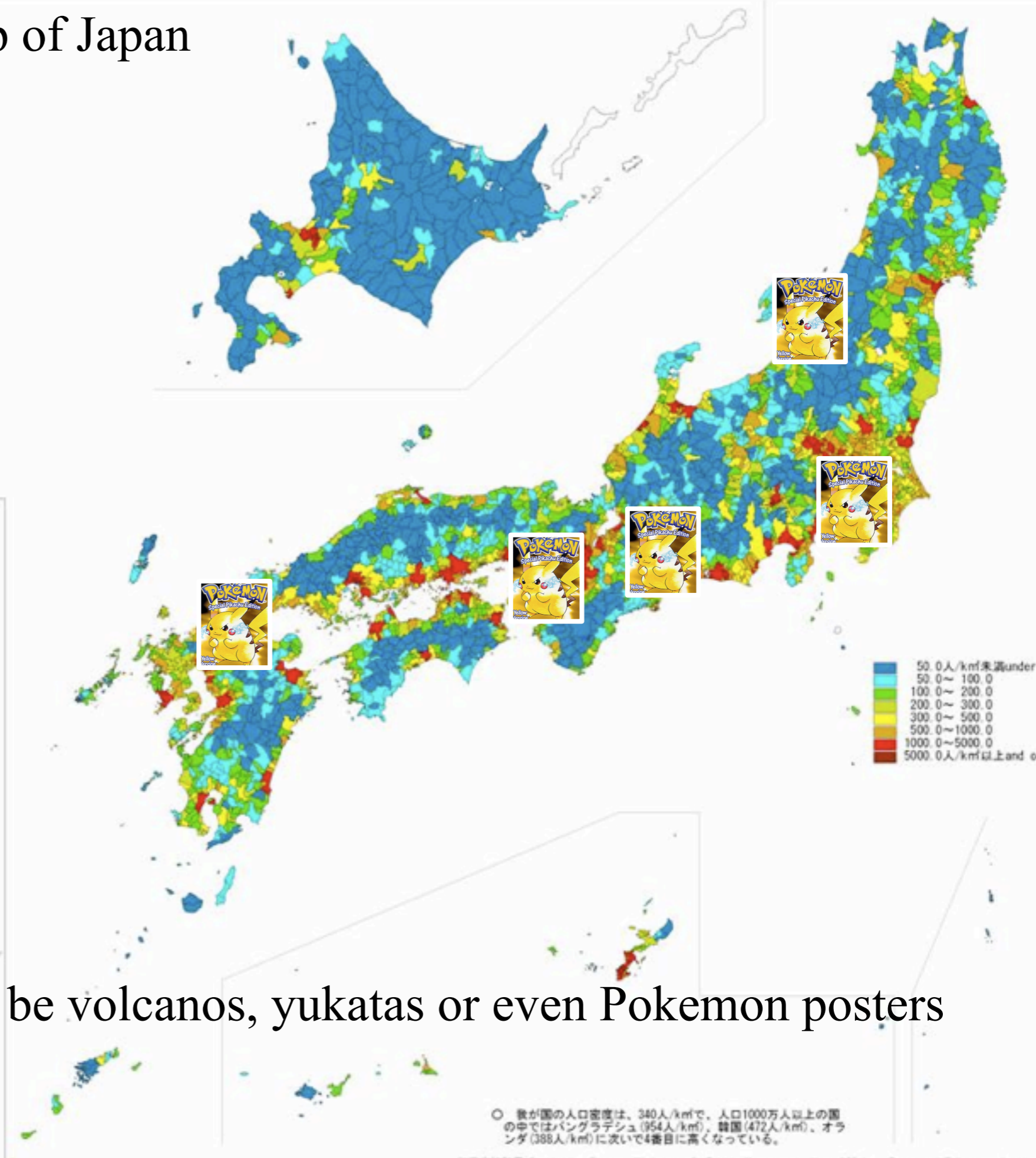
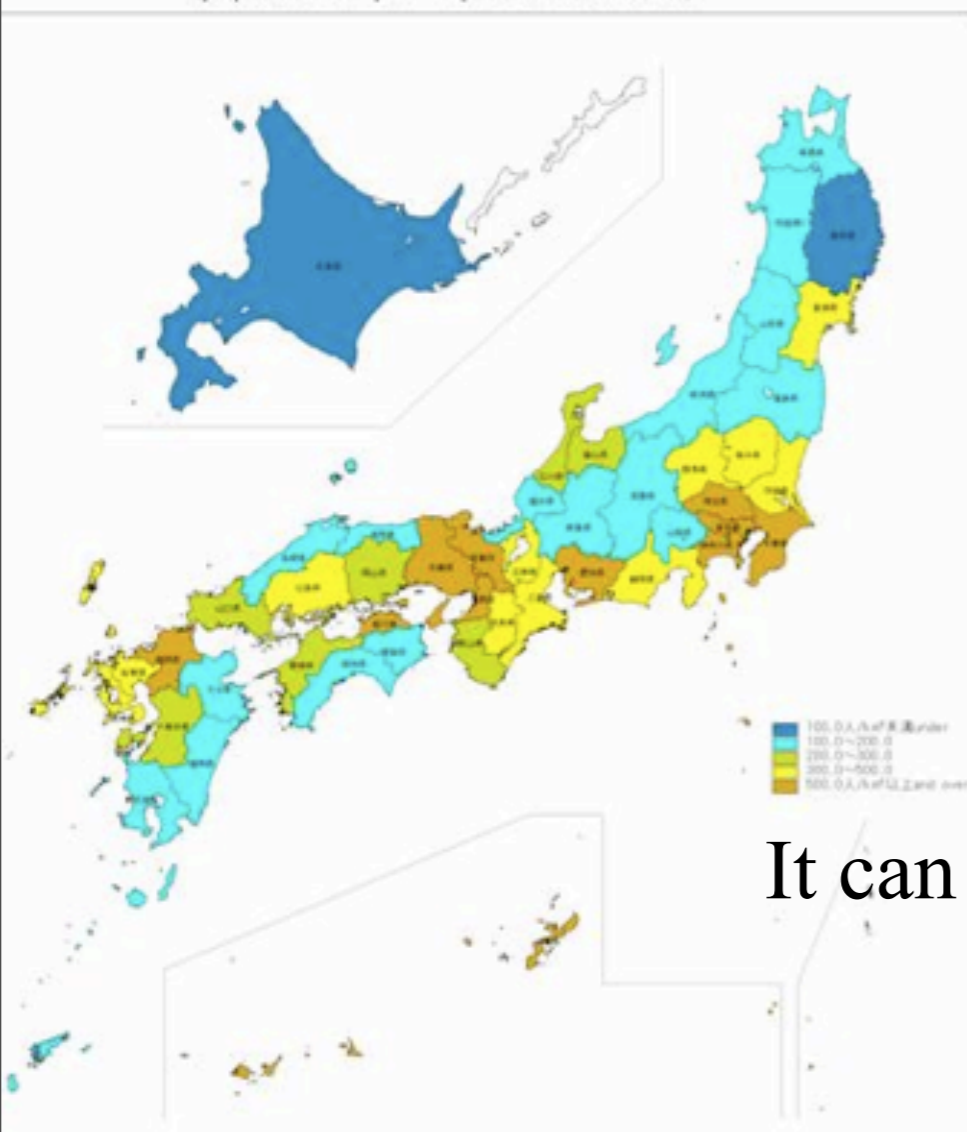
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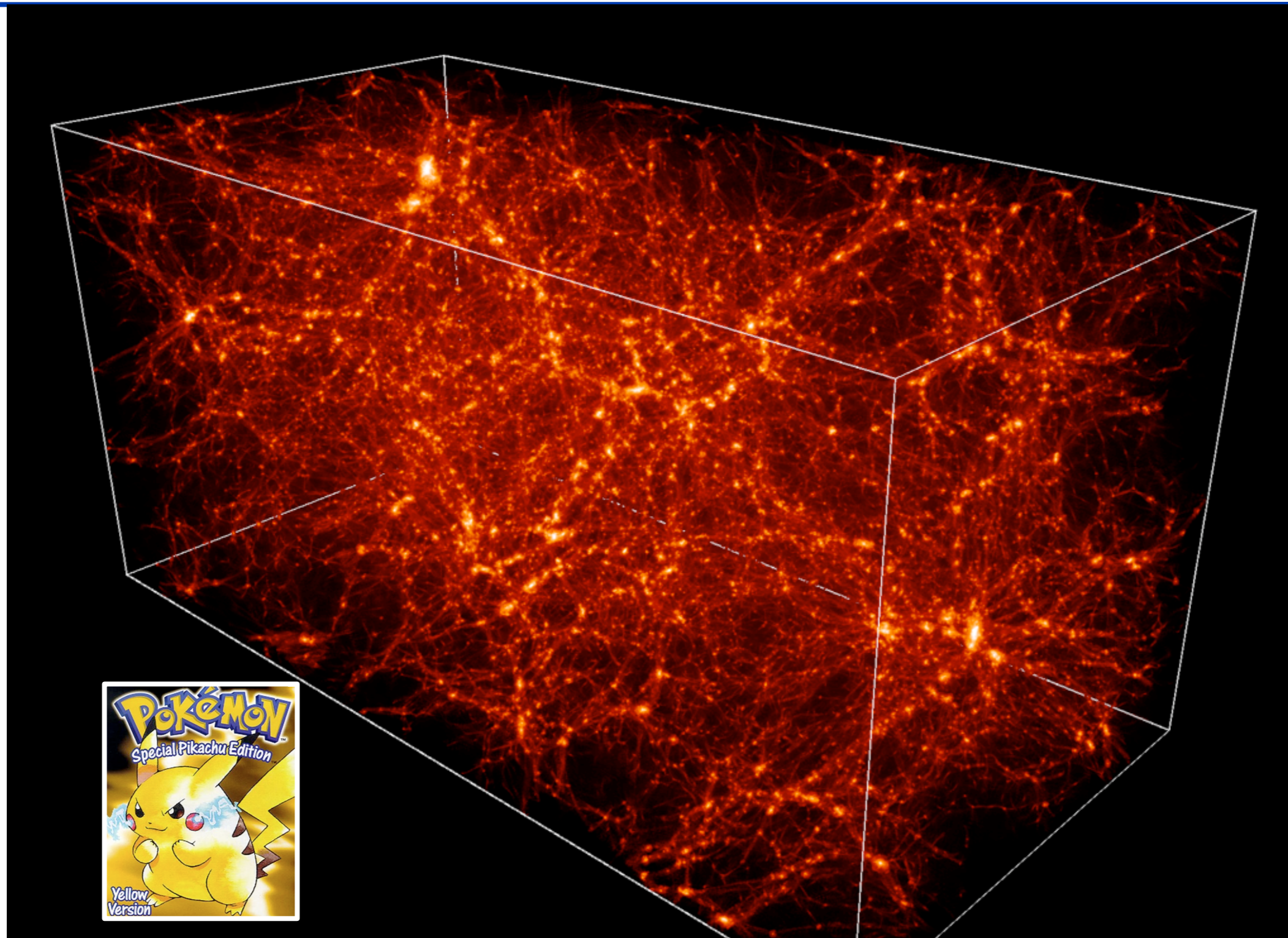
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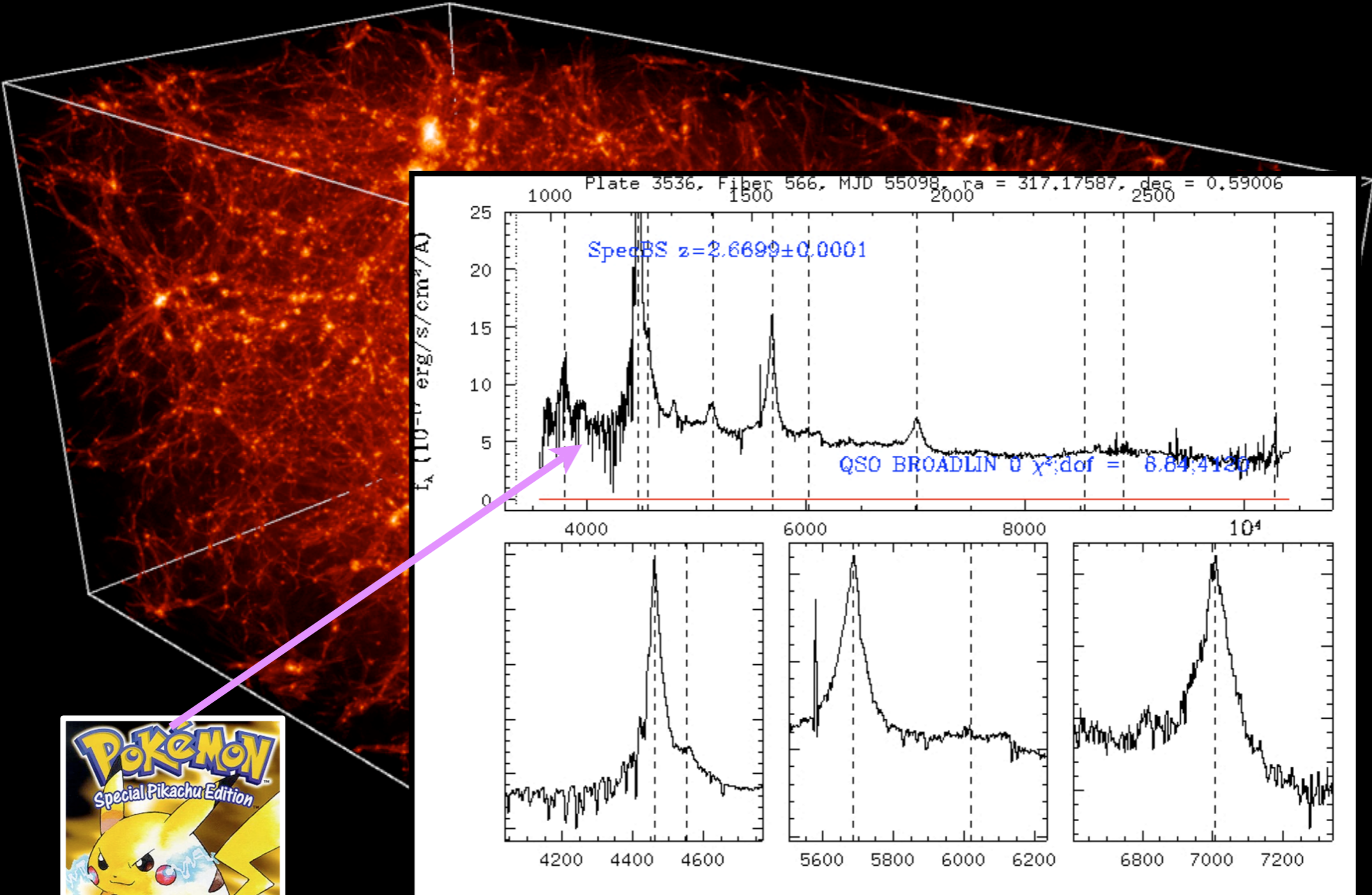
It can be volcanos, yukatas or even Pokemon posters

We can use Lya forest to trace Large Scale Structure



How do we find the equivalent of Pokemon for Dark Matter at high redshift ($z > \sim 2$) ?

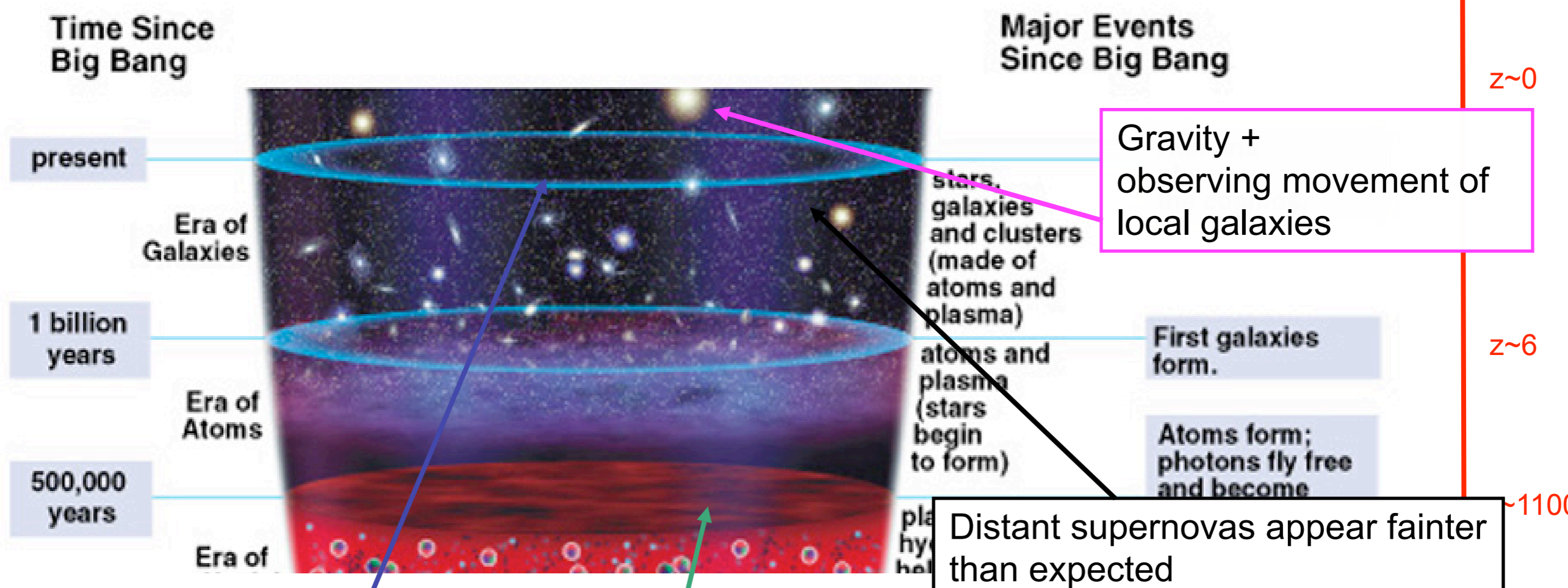
We can use Ly α forest to trace Large Scale Structure



- **Motivations**
- **Introduction (What is lighting up the what?)**
- **What can you do with Lyman-alpha forest?**
 - **Baryon Acoustic Oscillations**
 - Dark Energy
 - **Scale Dependent Bias**
 - Primordial Non-gaussianities -> Inflation
- **Conclusion**

Motivations

Time

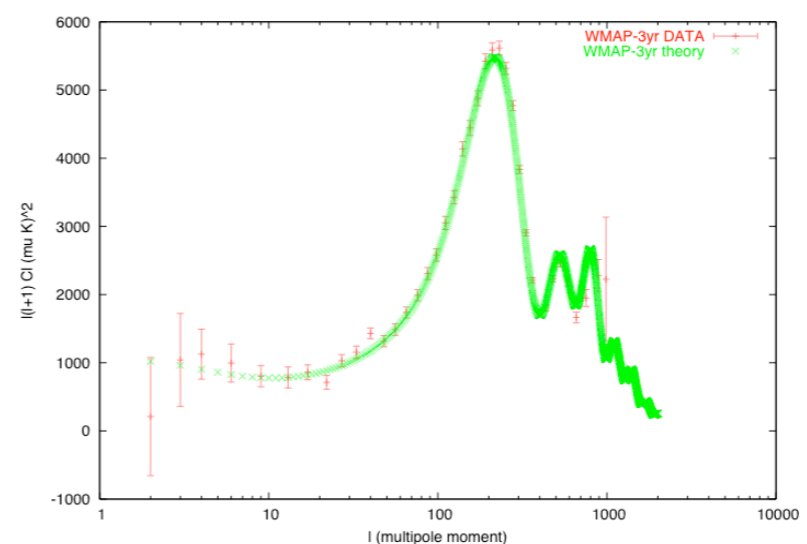


Gravity + observing movement of local galaxies

Distant supernovas appear fainter than expected

Observations of how galaxies cluster

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



Redshift

Motivations

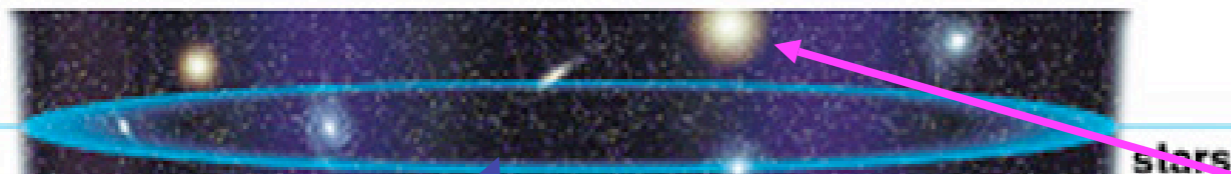
Time

Time Since Big Bang

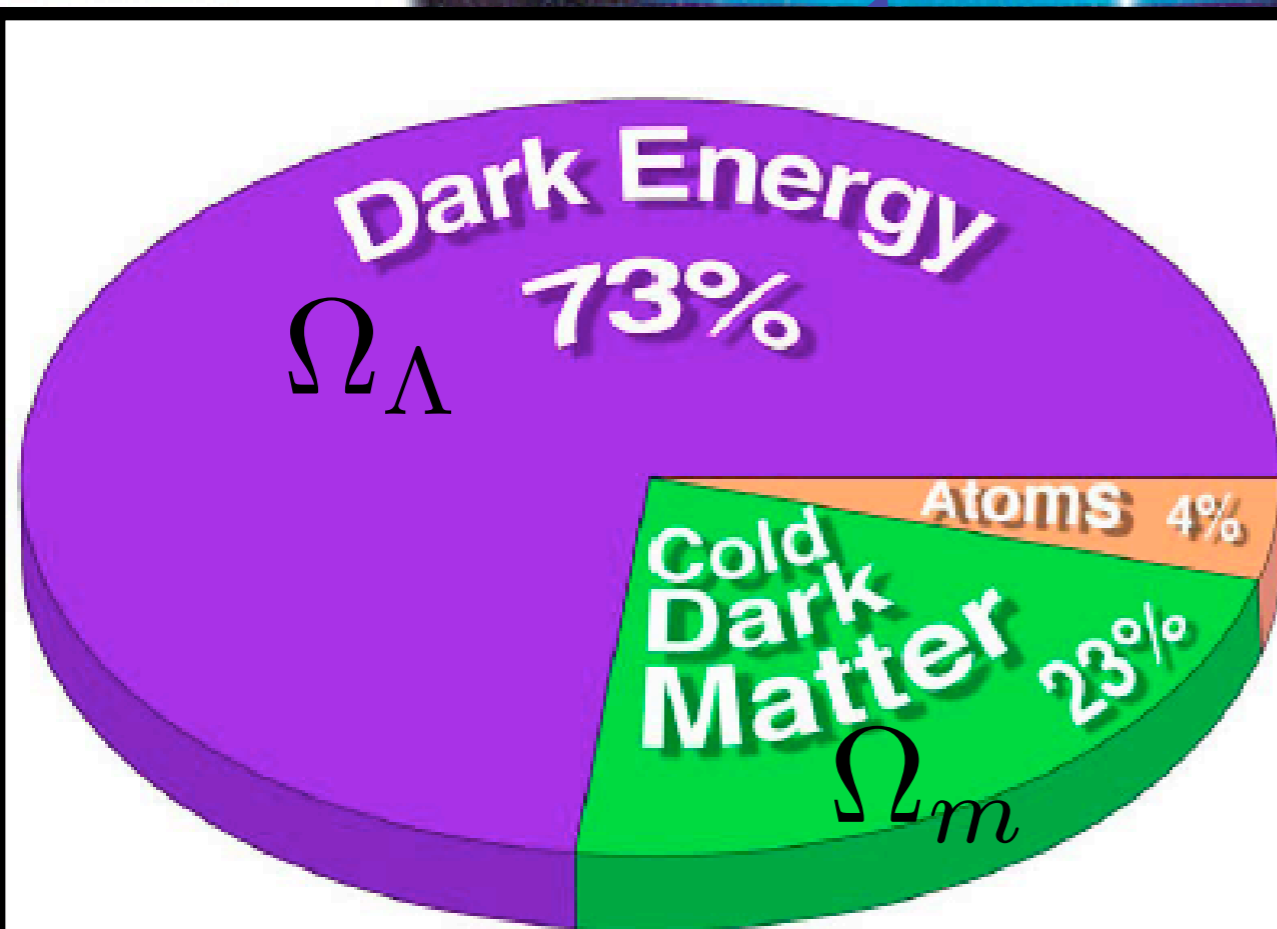
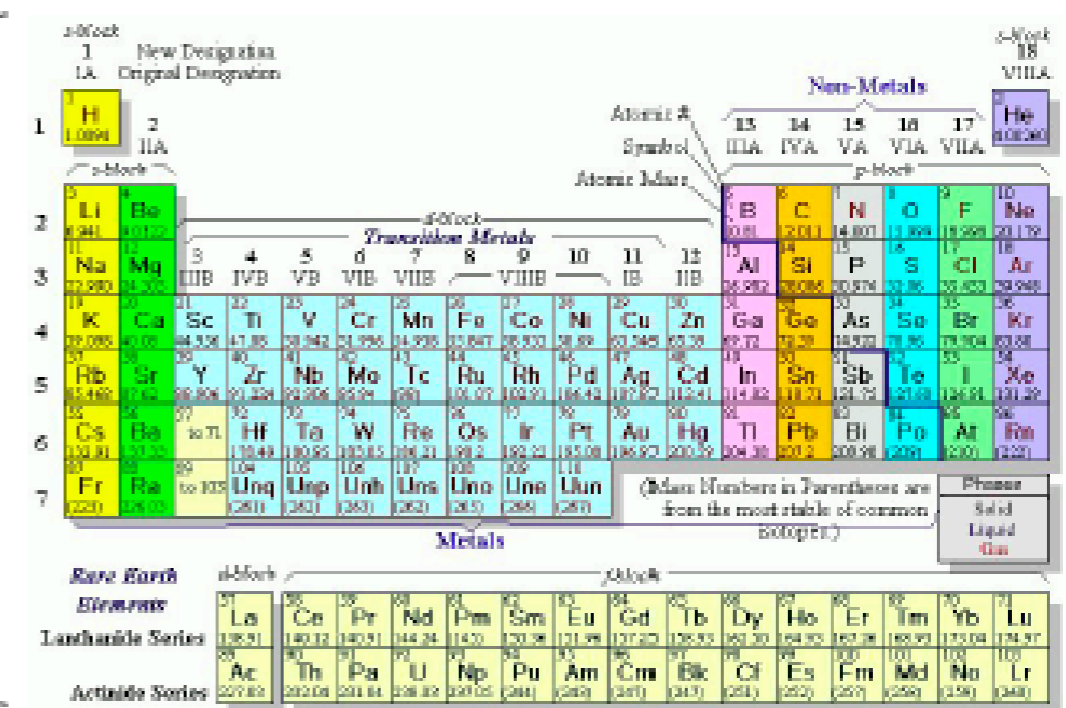
Major Events Since Big Bang

$z \sim 0$

present



Gravity + observing movement of

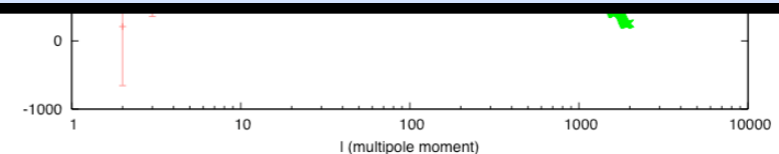



Periodic table showing elements grouped by blocks: s-block, p-block, d-block (Transition Metals), f-block (Lanthanide and Actinide Series), and g-block (New Designation). Includes atomic numbers, symbols, and names.

100

What happened at the Beginning of the Universe?

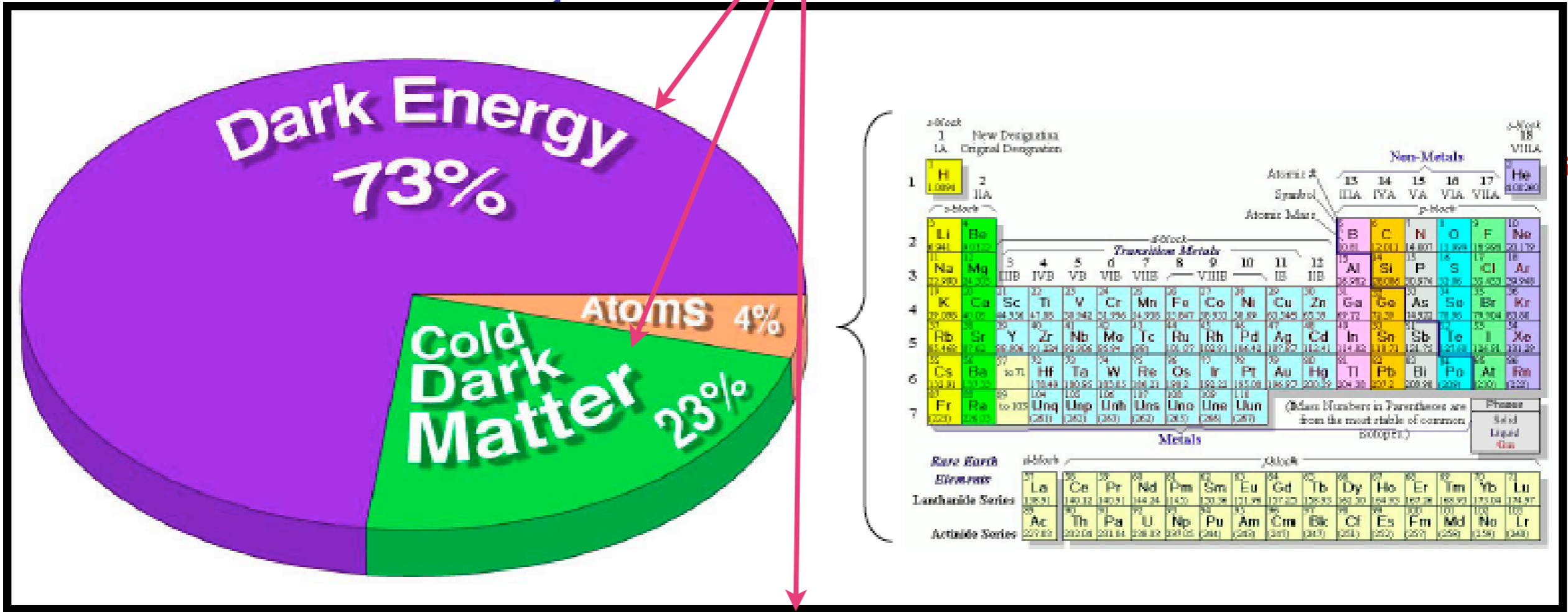
-> angular powerspectrum of temperature anisotropies



Redshift

Motivations

??



What happened at the Beginning of the Universe?

What happened at the beginning of the 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)

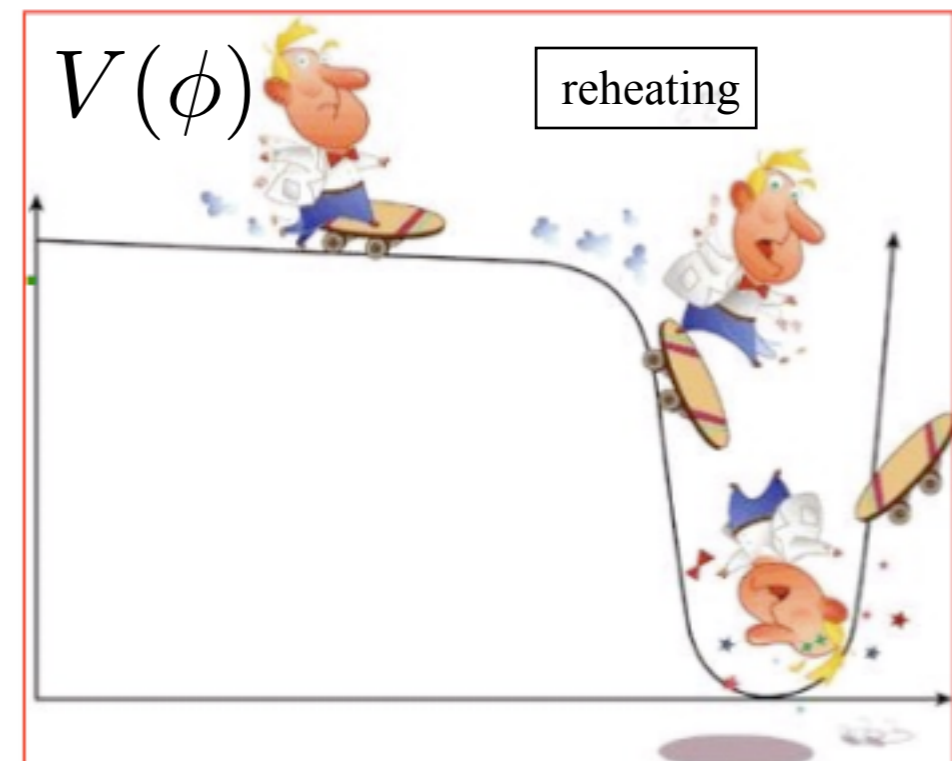
Non-Gaussianity from Inflation

$f_{NL} \sim 0.05$ canonical inflation (single field, couple of derivatives)
(Maldacena 2003, Acquaviva et al 2003)

$f_{NL} \sim 0.1--100$ higher order derivatives
DBI inflation (Alishahiha, Silverstein and Tong 2004)
UV cutoff (Craminelli 2003)

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

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



Inflation

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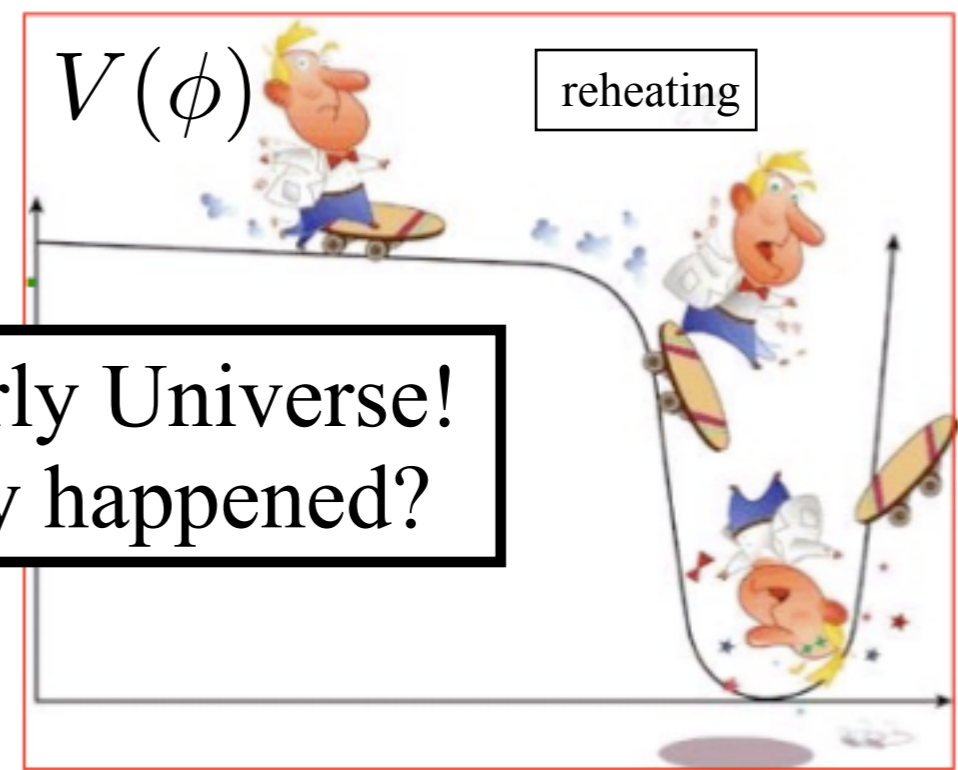
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We have many models of early Universe!
 How do we tell what actually happened?

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

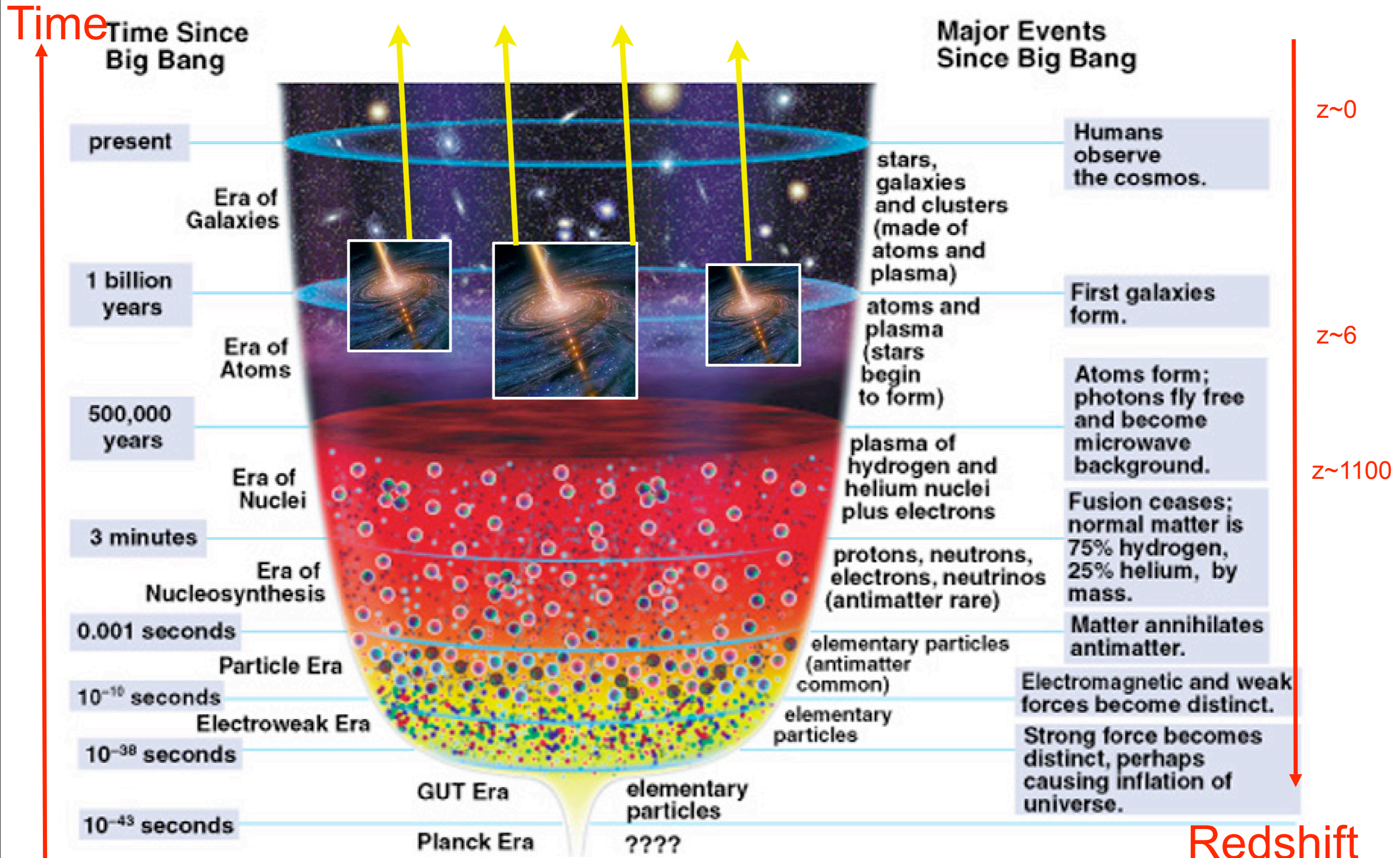
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← Inflation →

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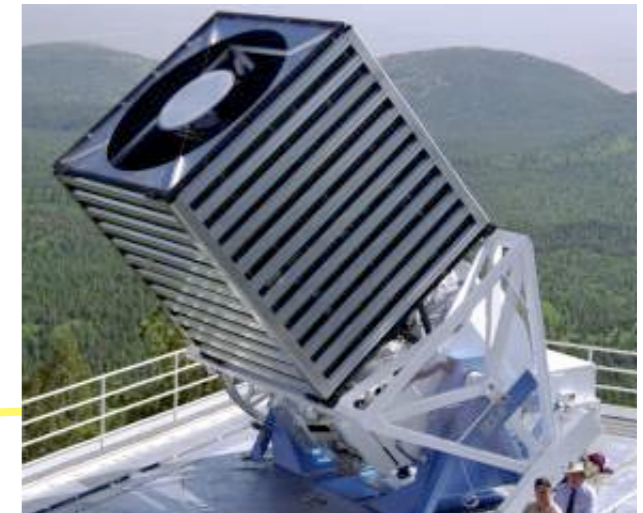
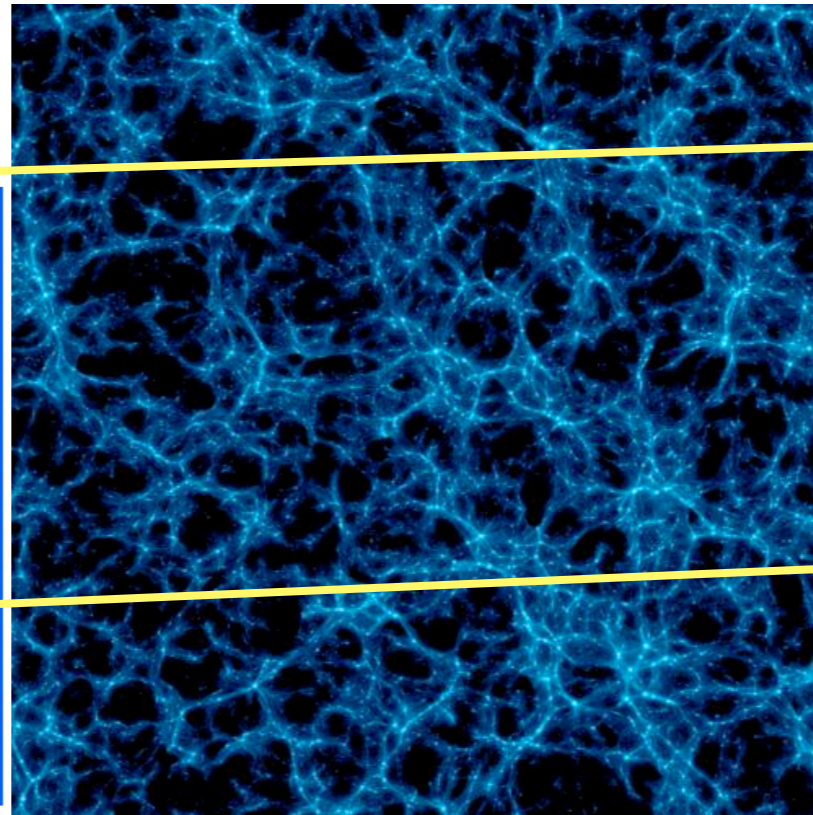
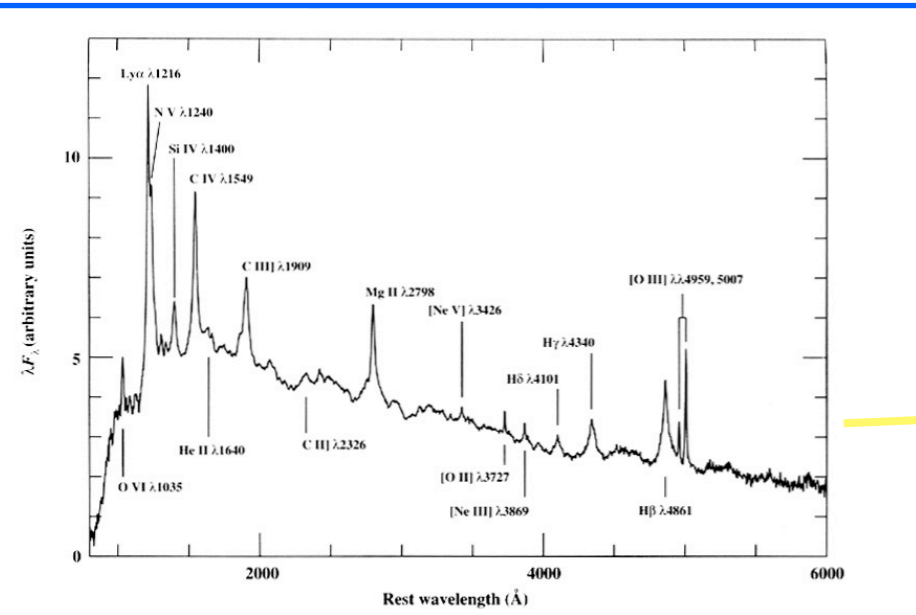
Using Quasars to light up the Universe: How?



Using Quasars to light up the Universe: How?



Quasar Spectra

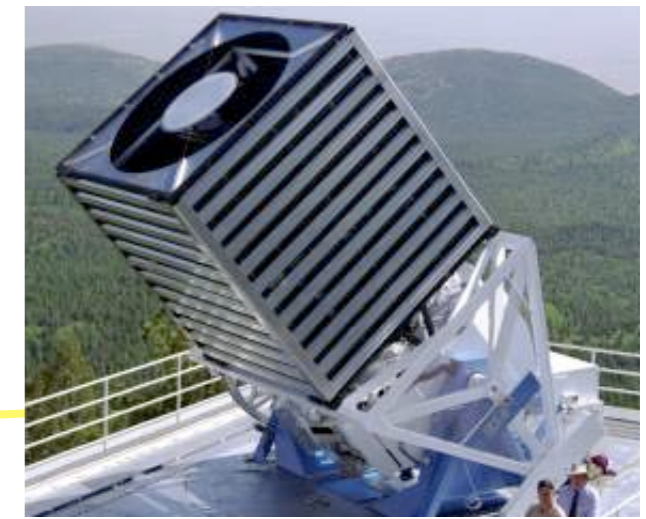
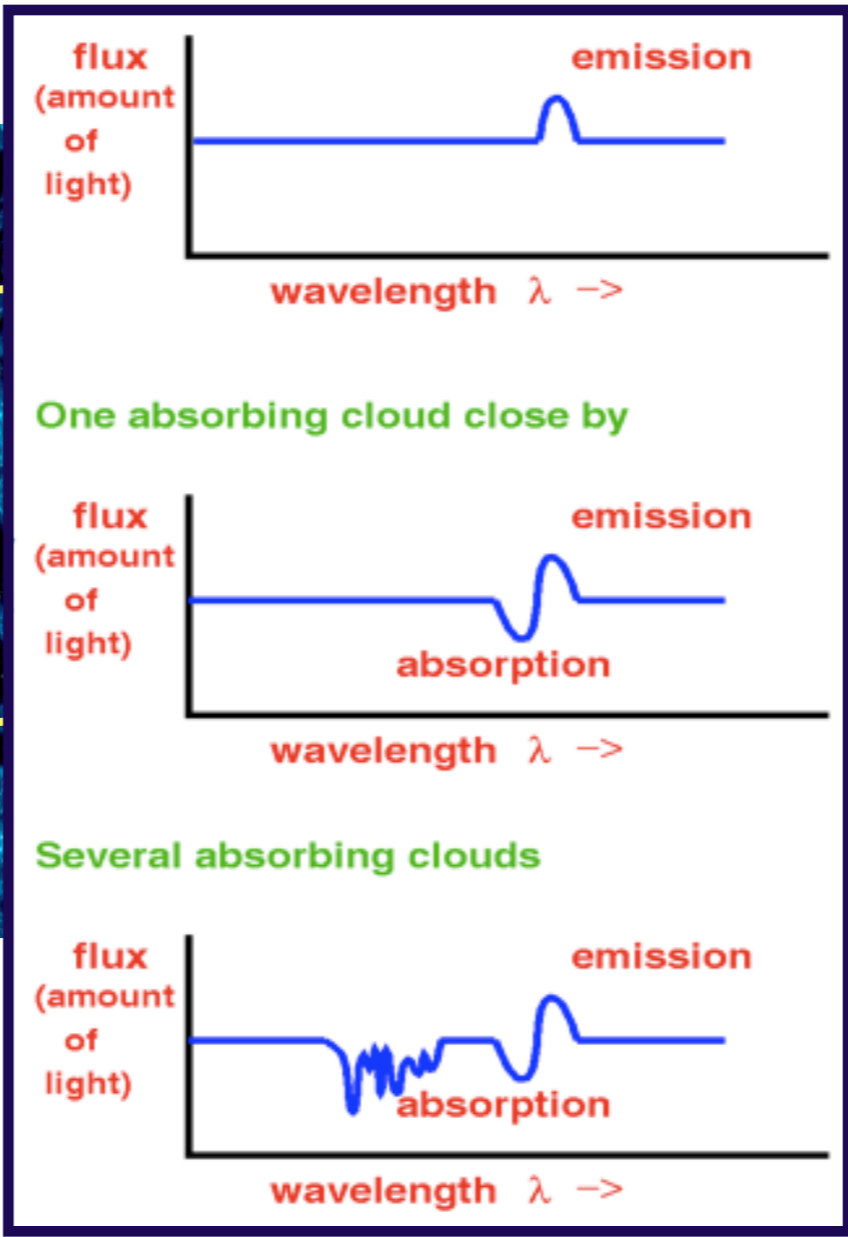
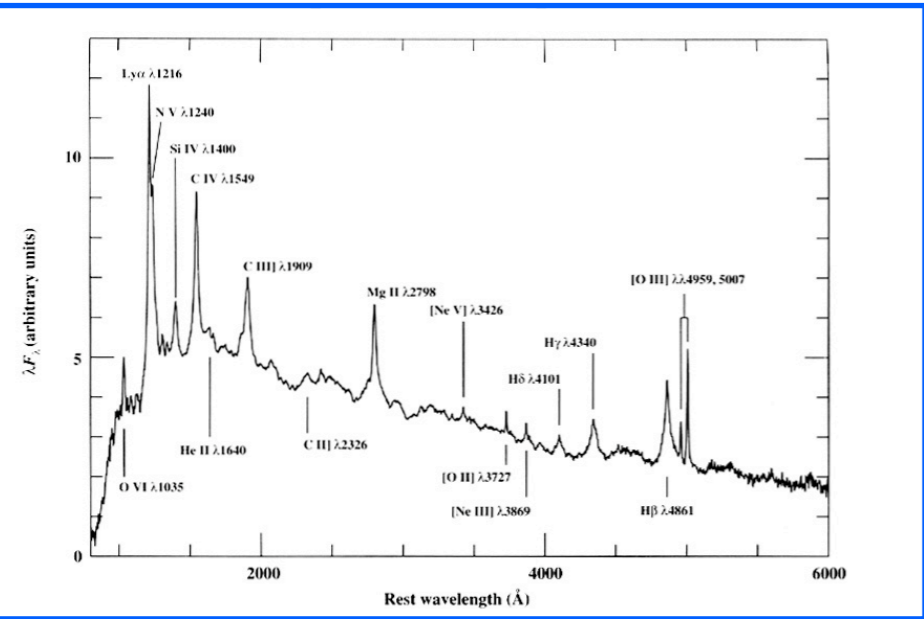


Courtesy simulation of gas from Renyue Cen and Jerry Ostriker

Using Quasars to light up the Universe: How?



Quasar Spectra



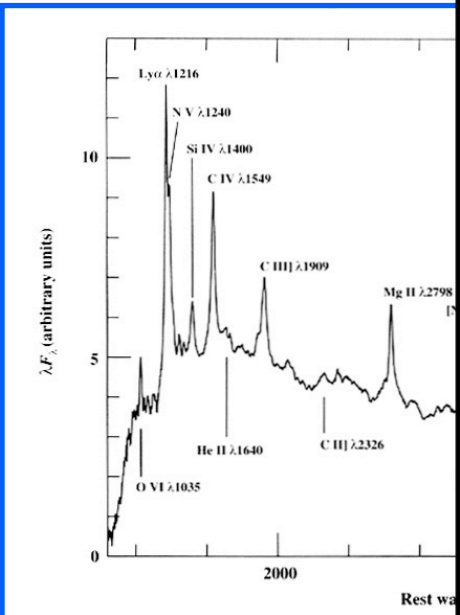
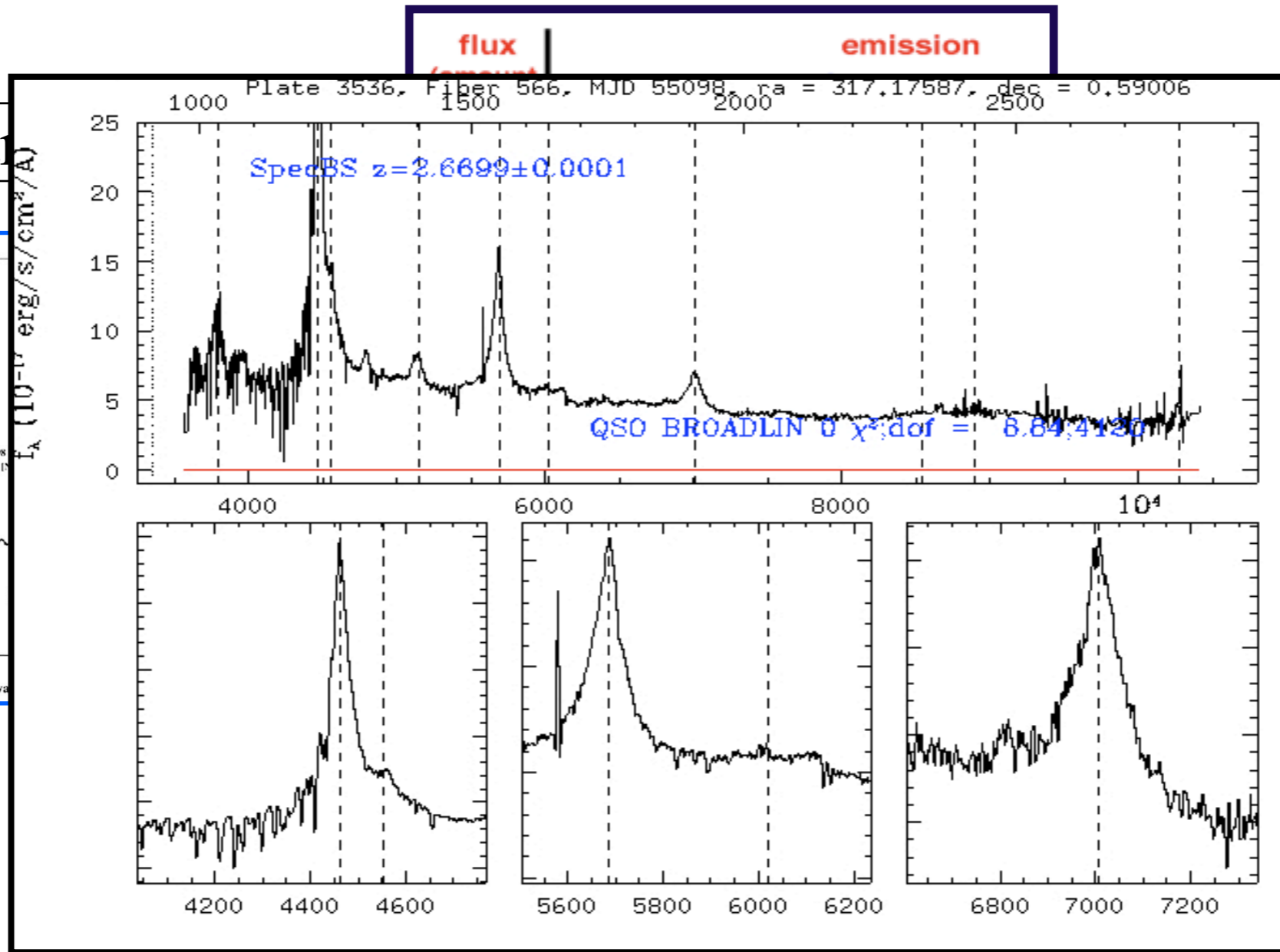
from
iker

Using Quasars to light up the Universe: How?

Also recall all the quasar spectra we saw from Yamada-san's lecture



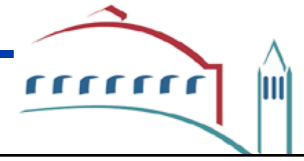
Quasar



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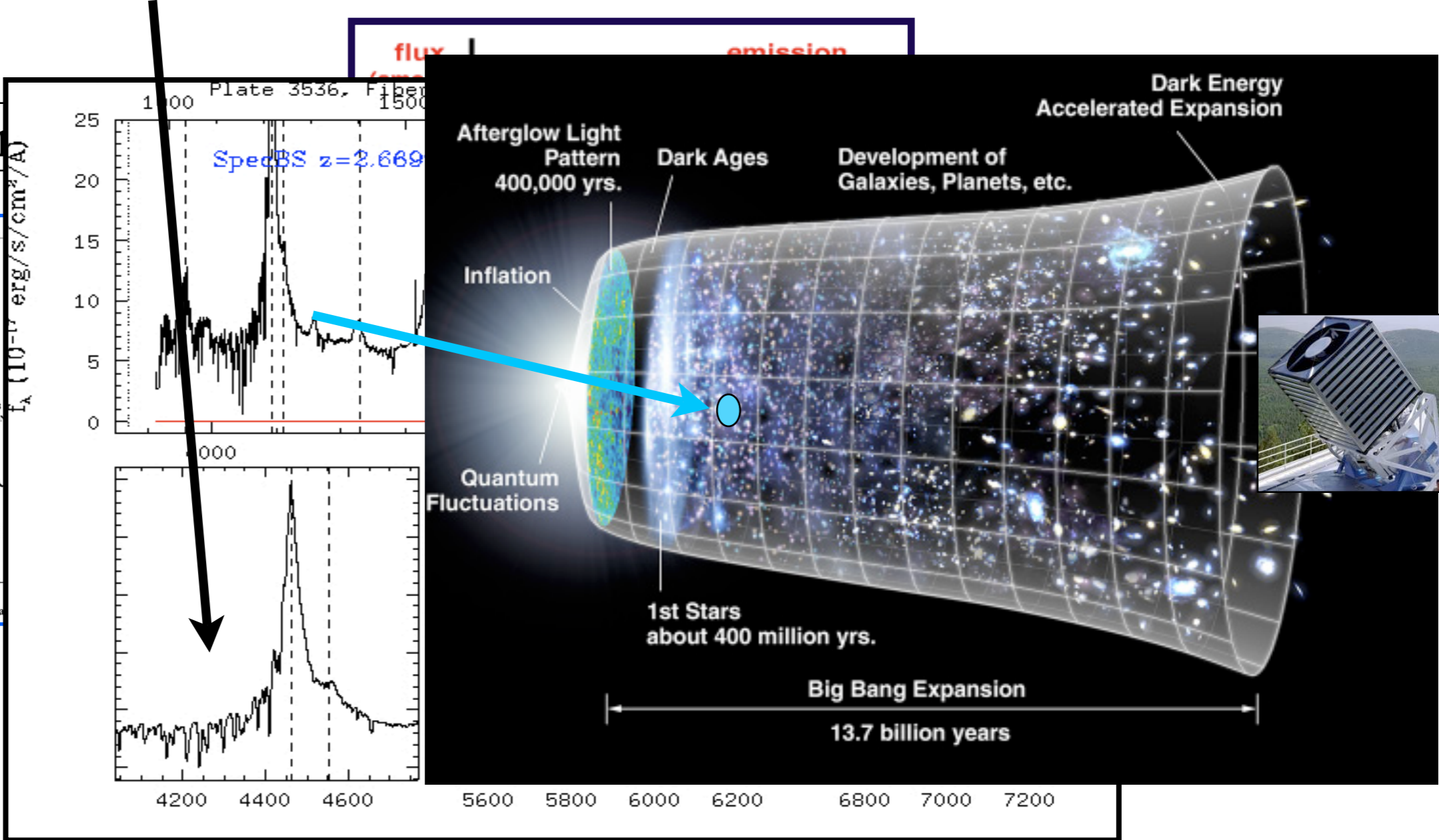
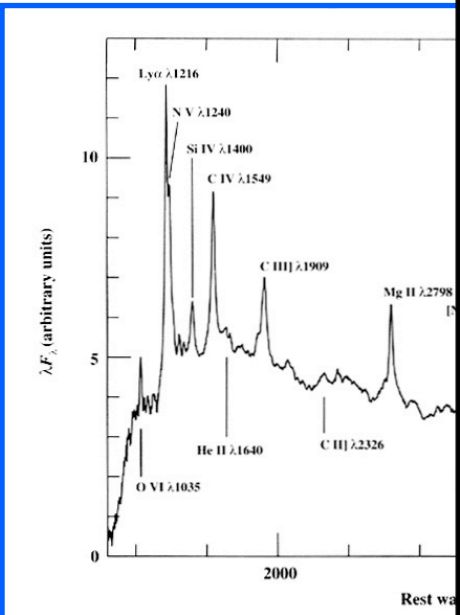
From Joanne Cohn's website

Using Quasars to light up the Universe: How?



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

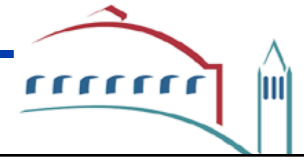
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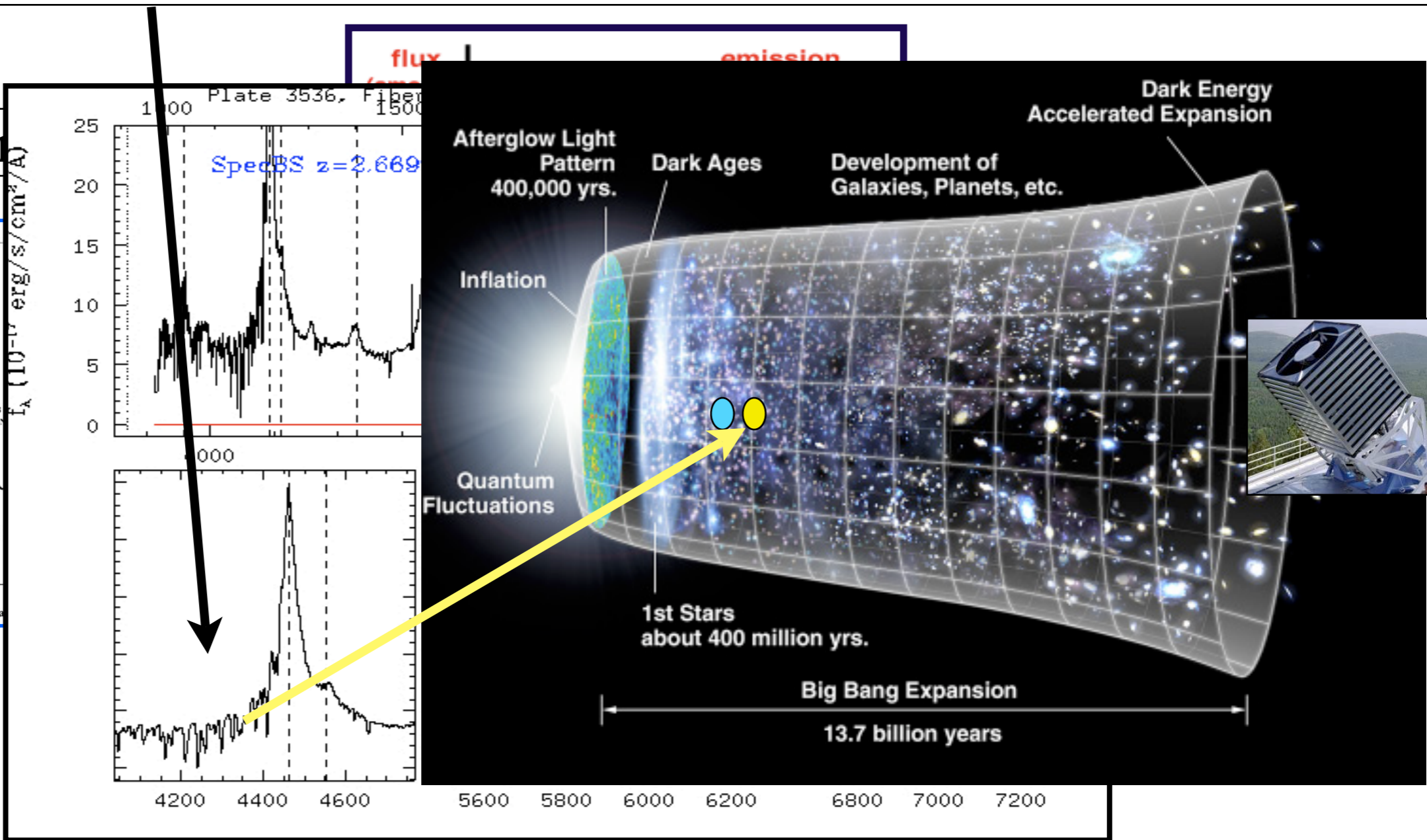
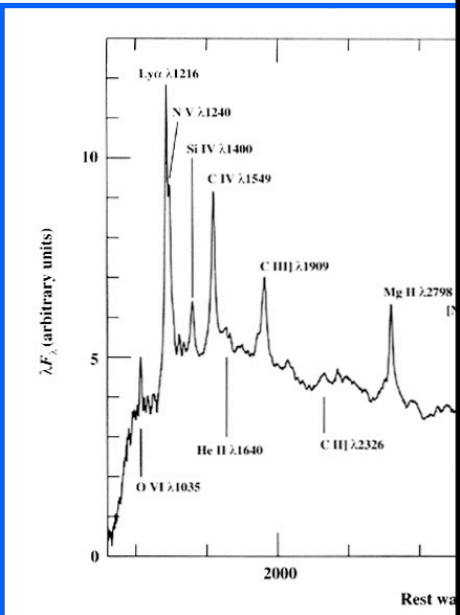
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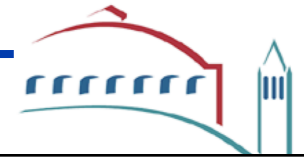
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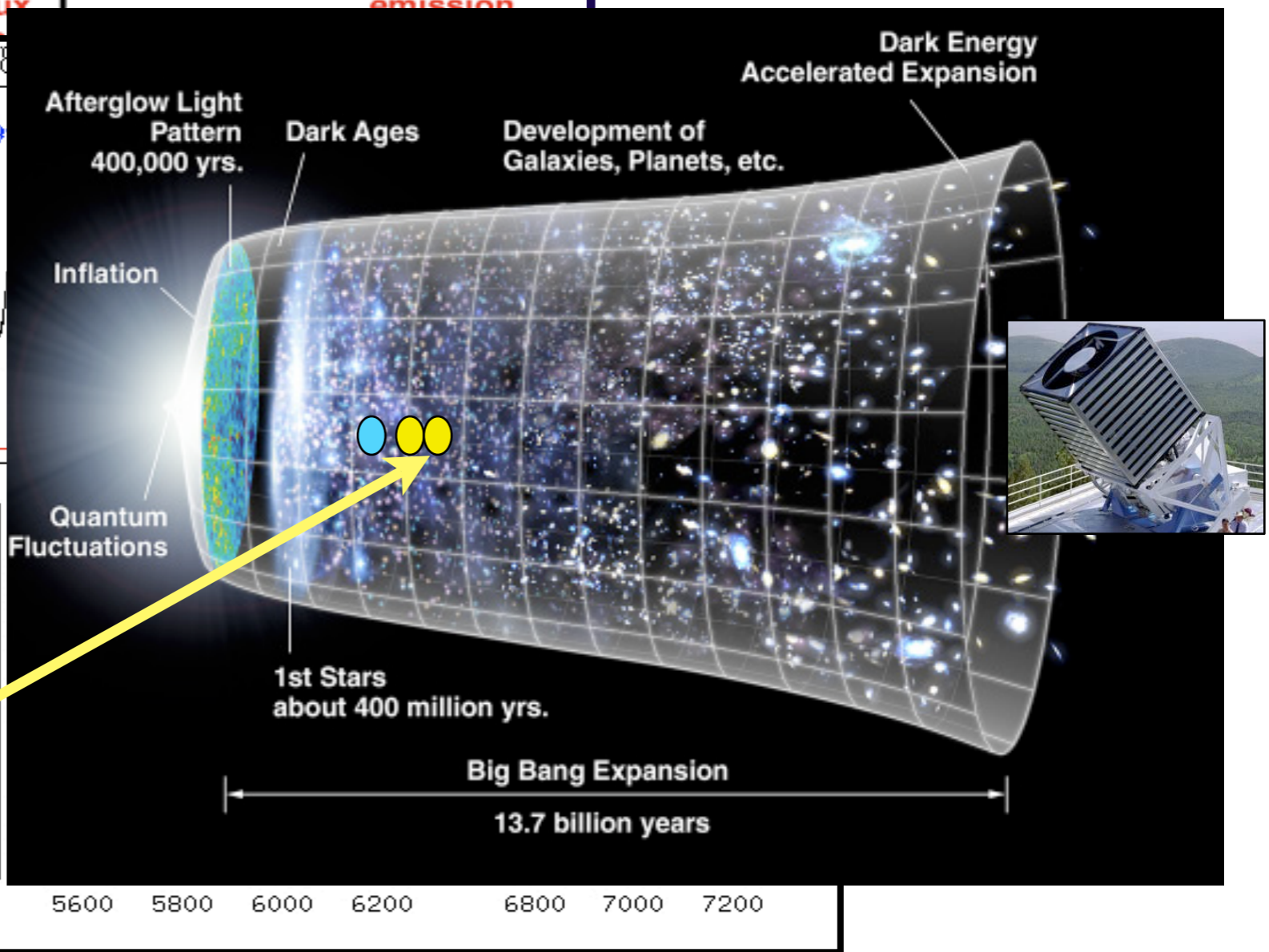
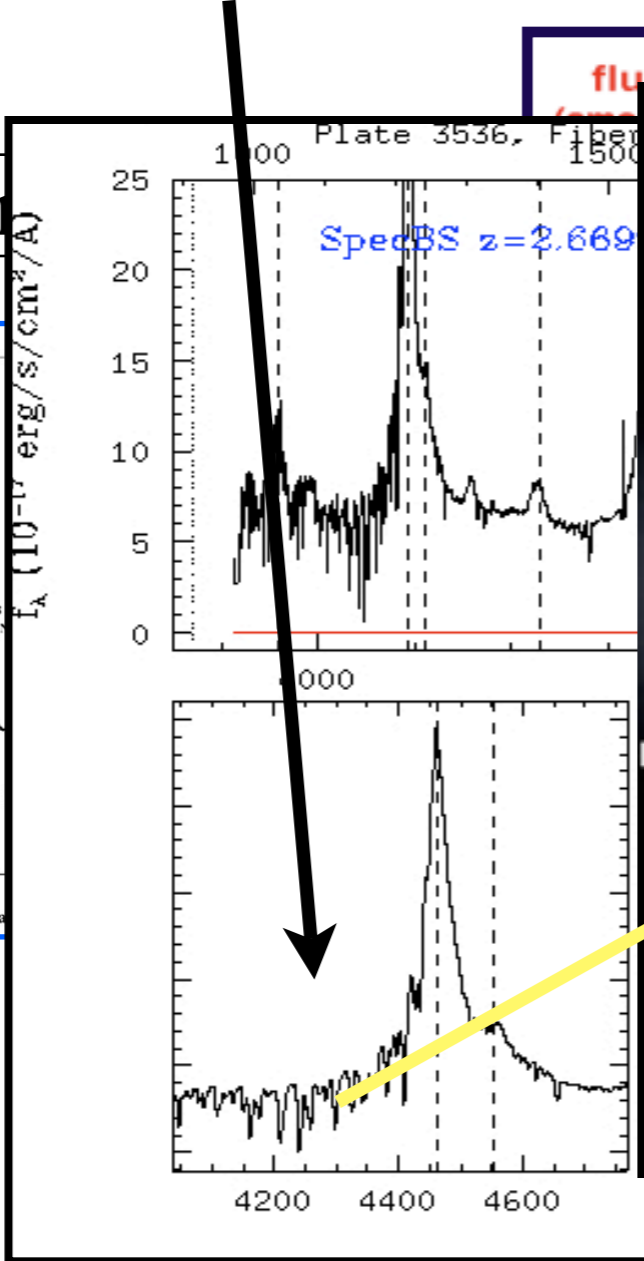
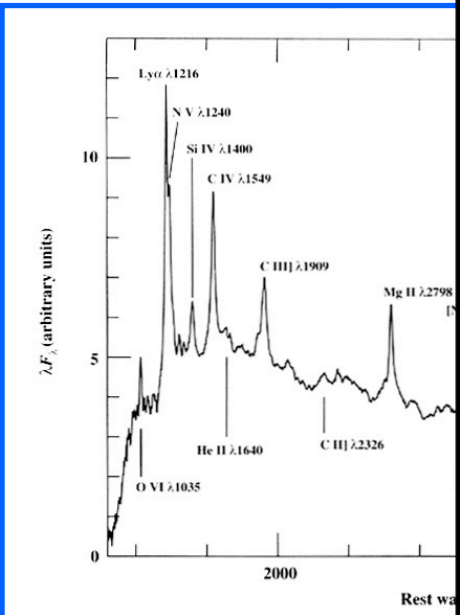
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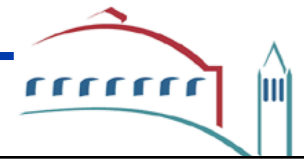
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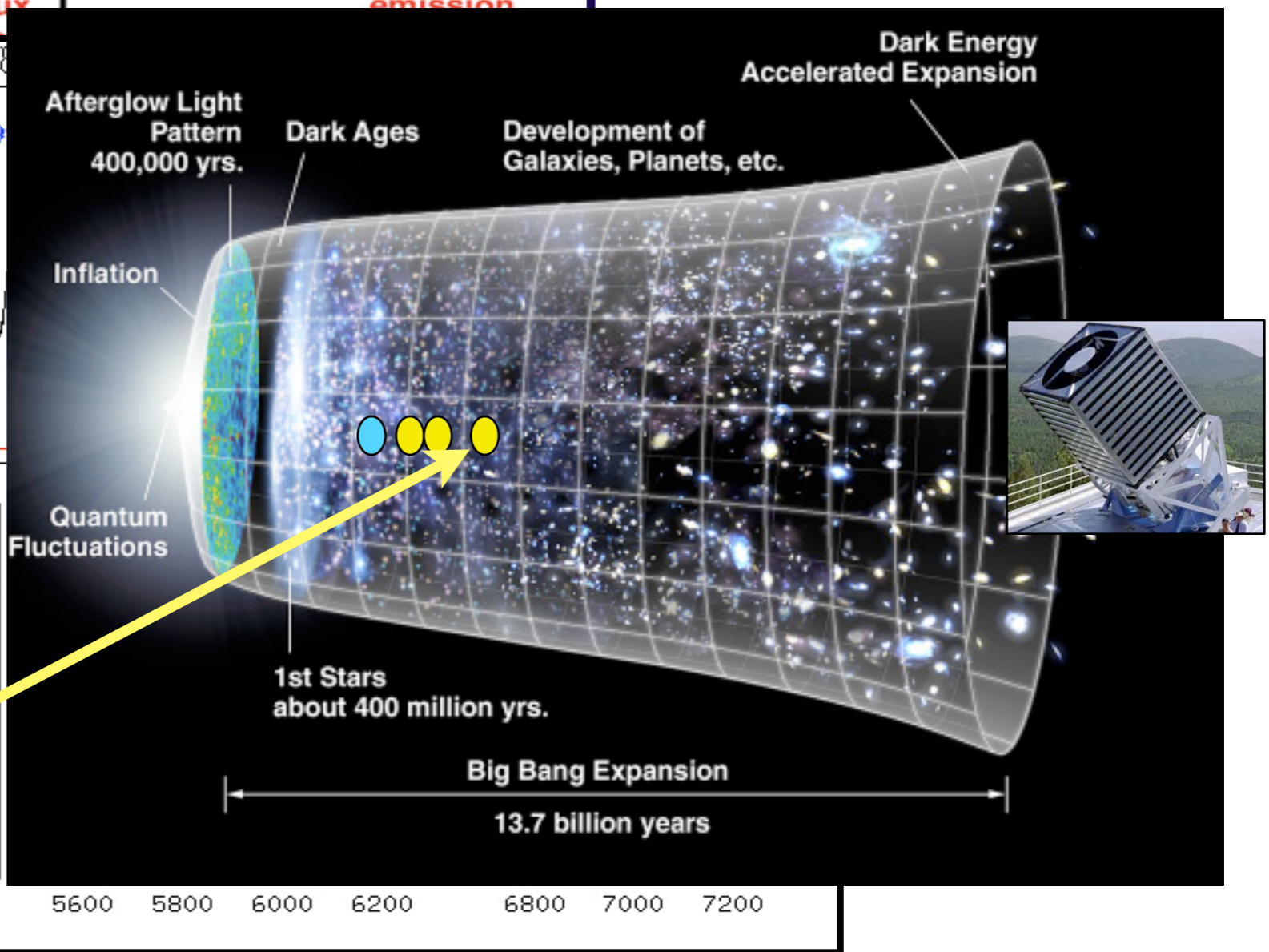
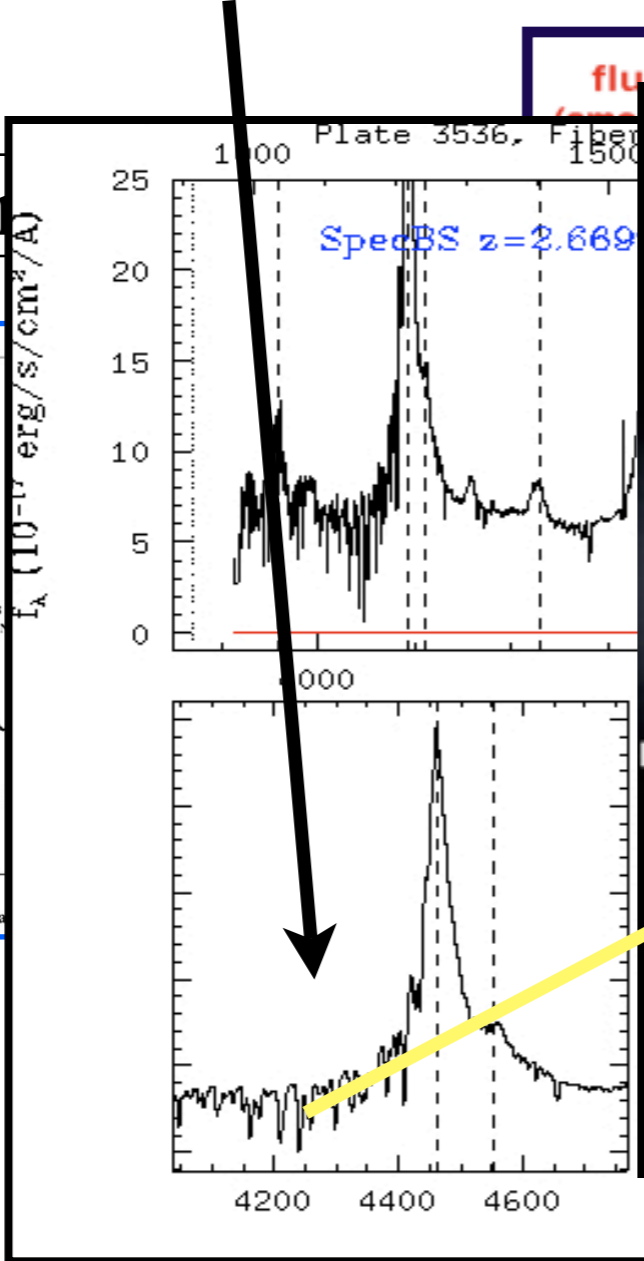
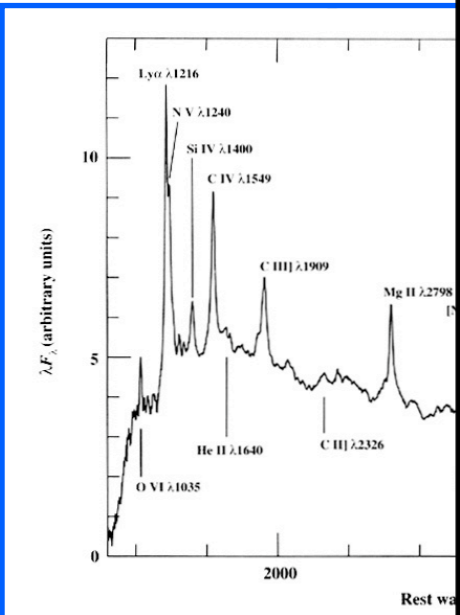
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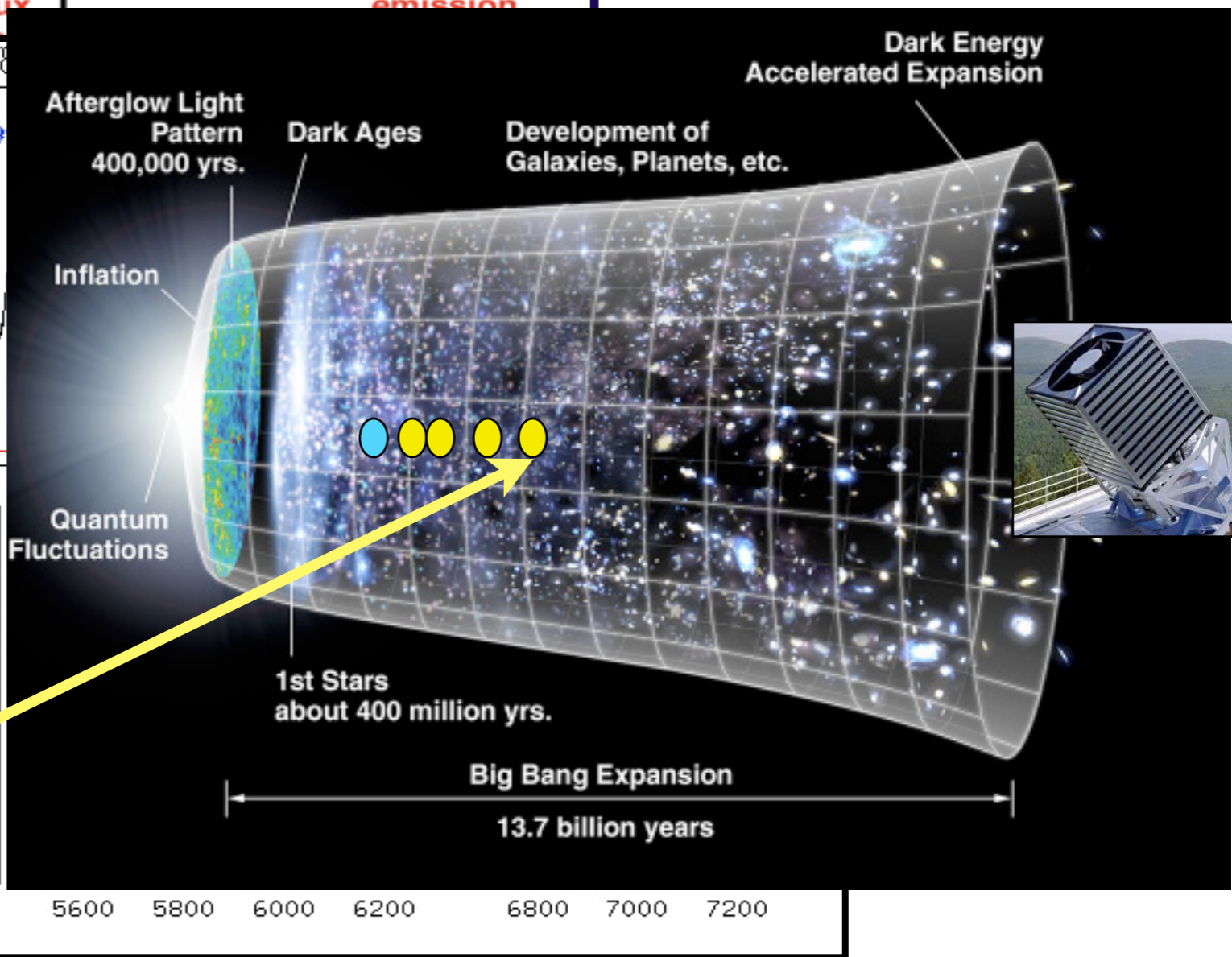
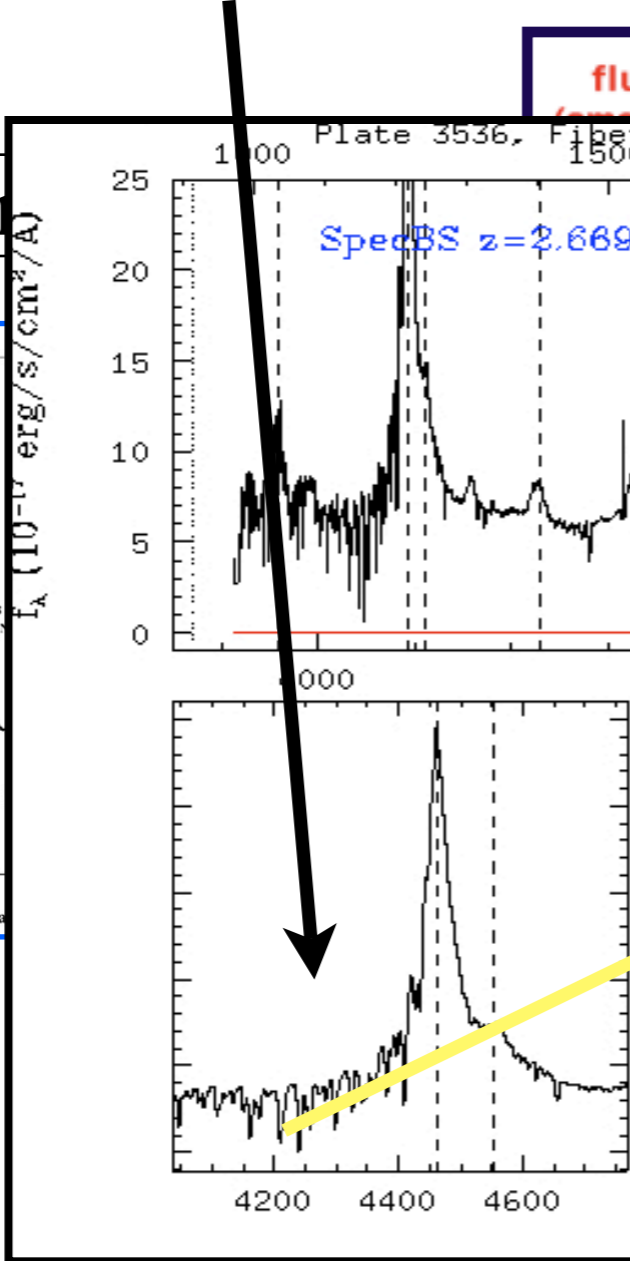
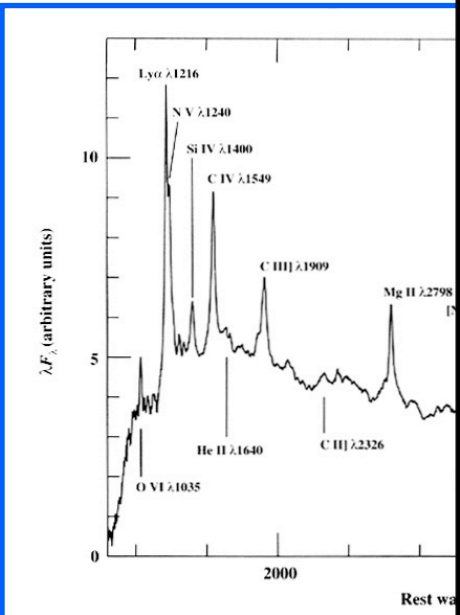
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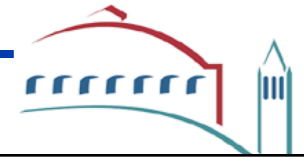
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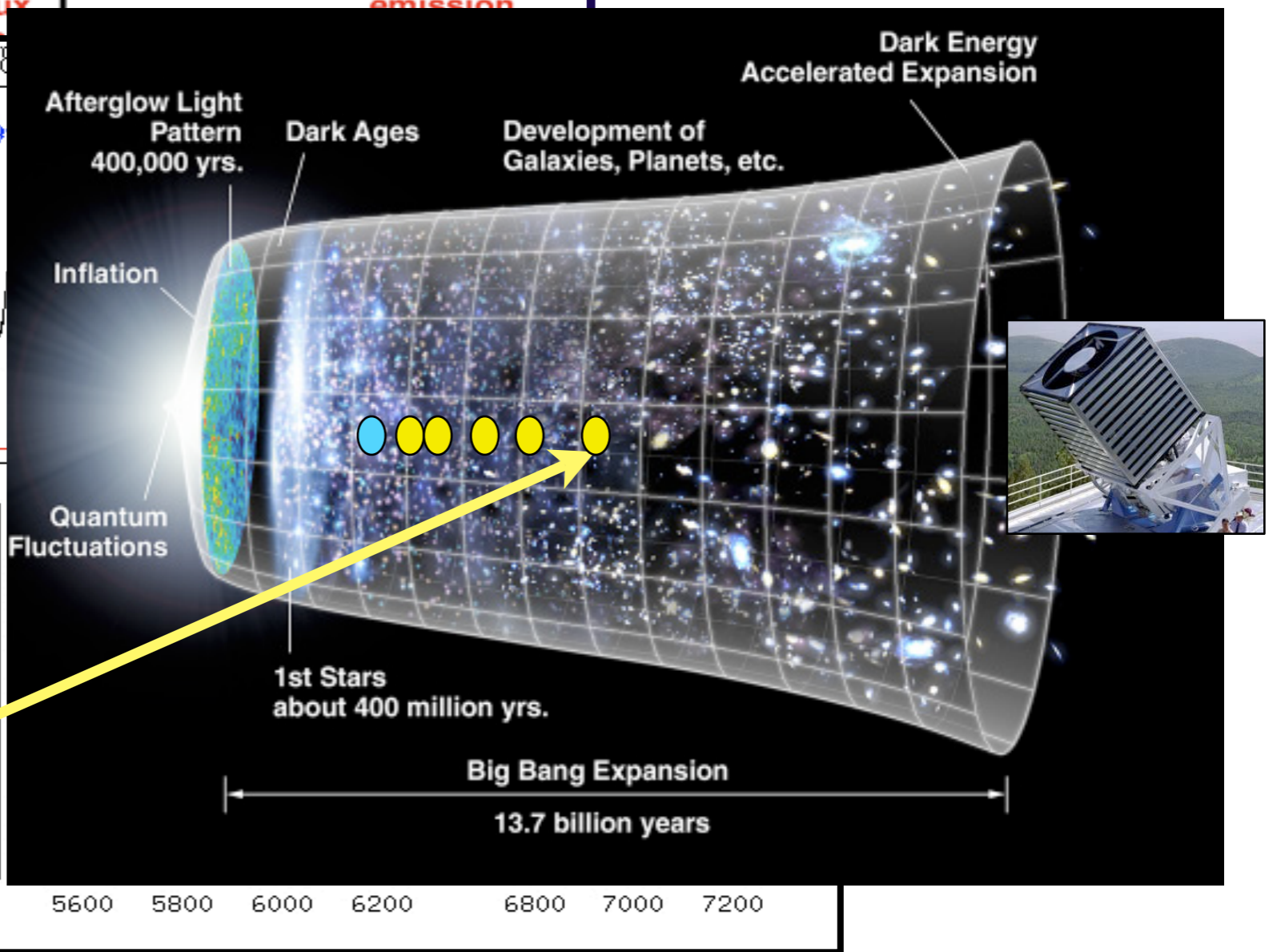
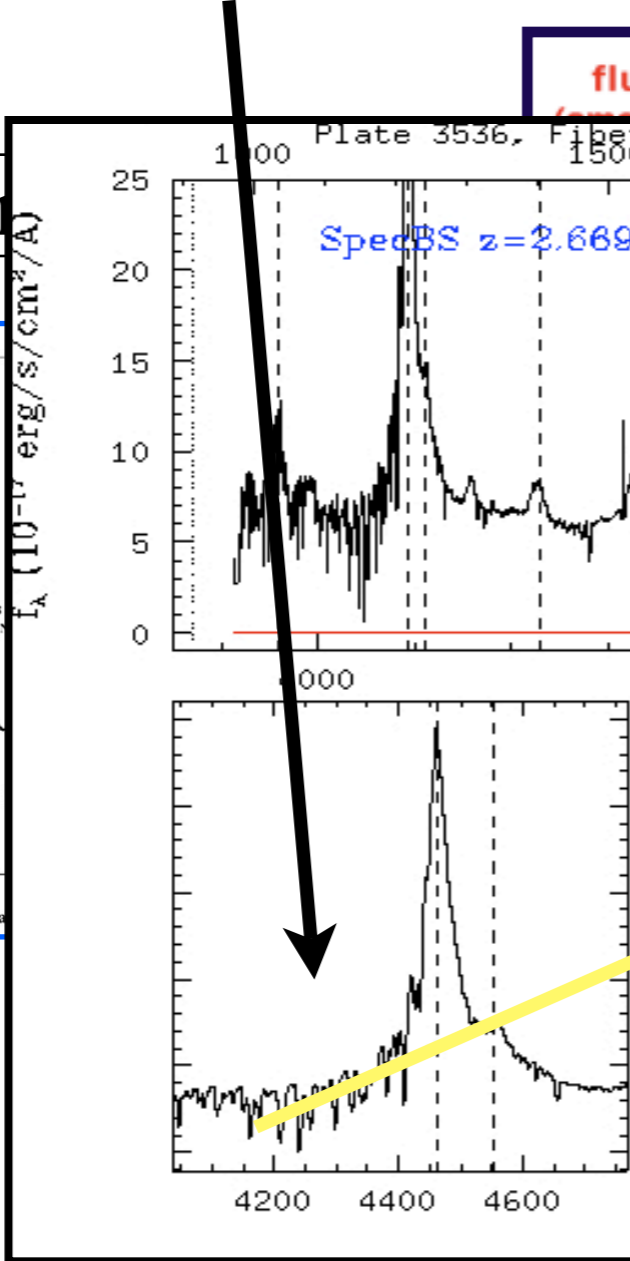
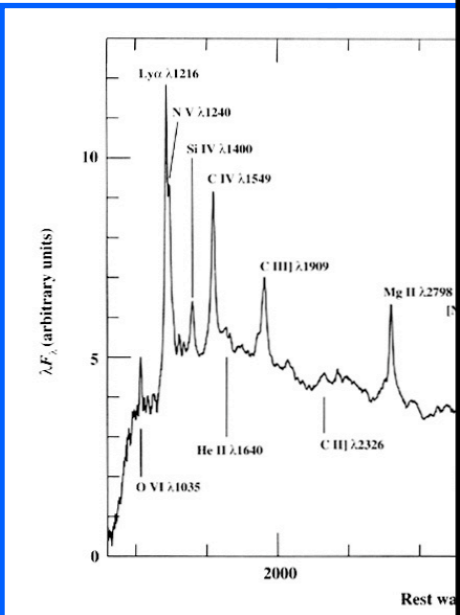
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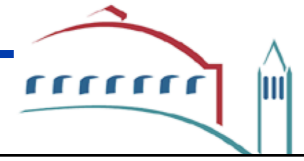
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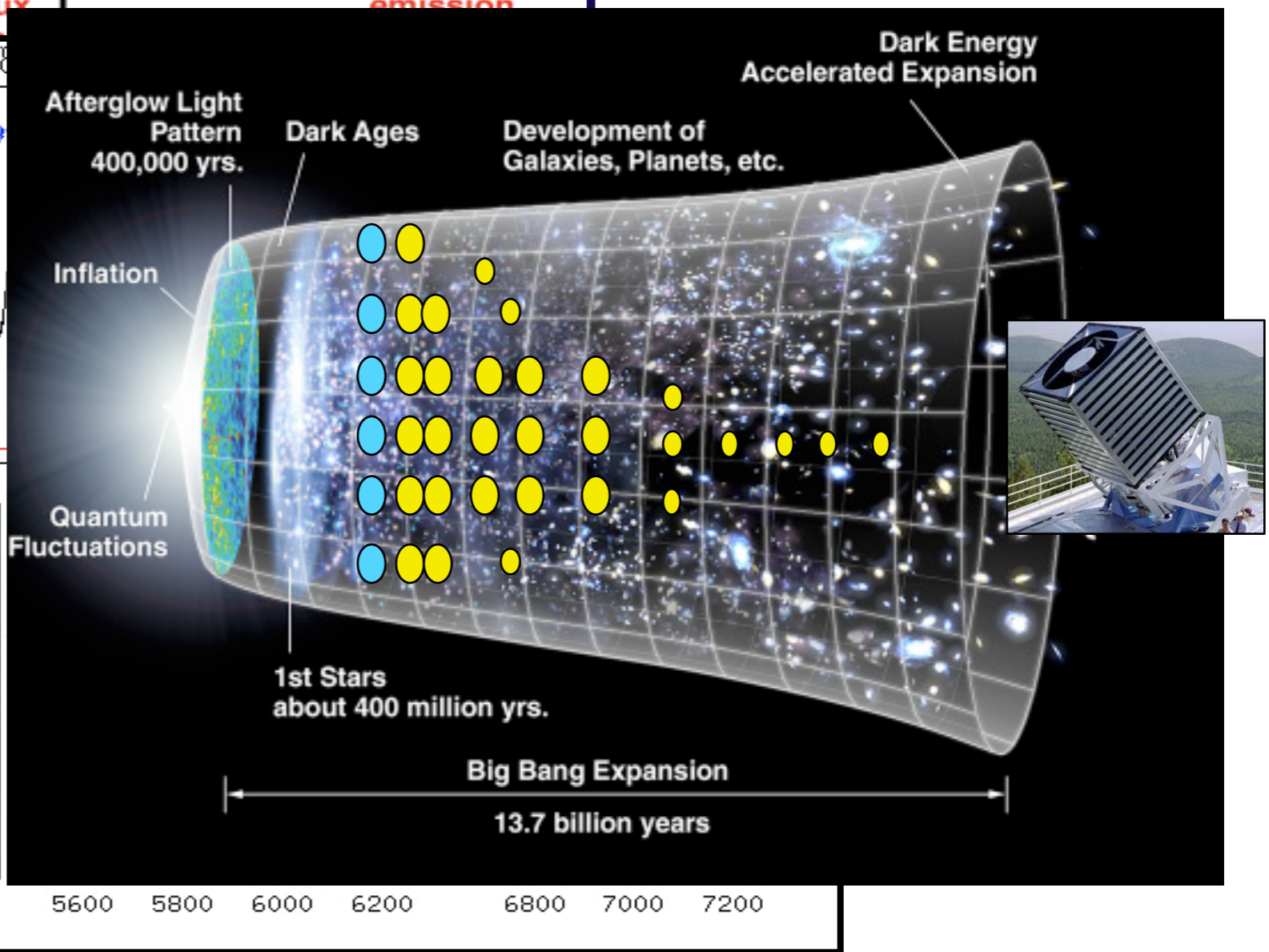
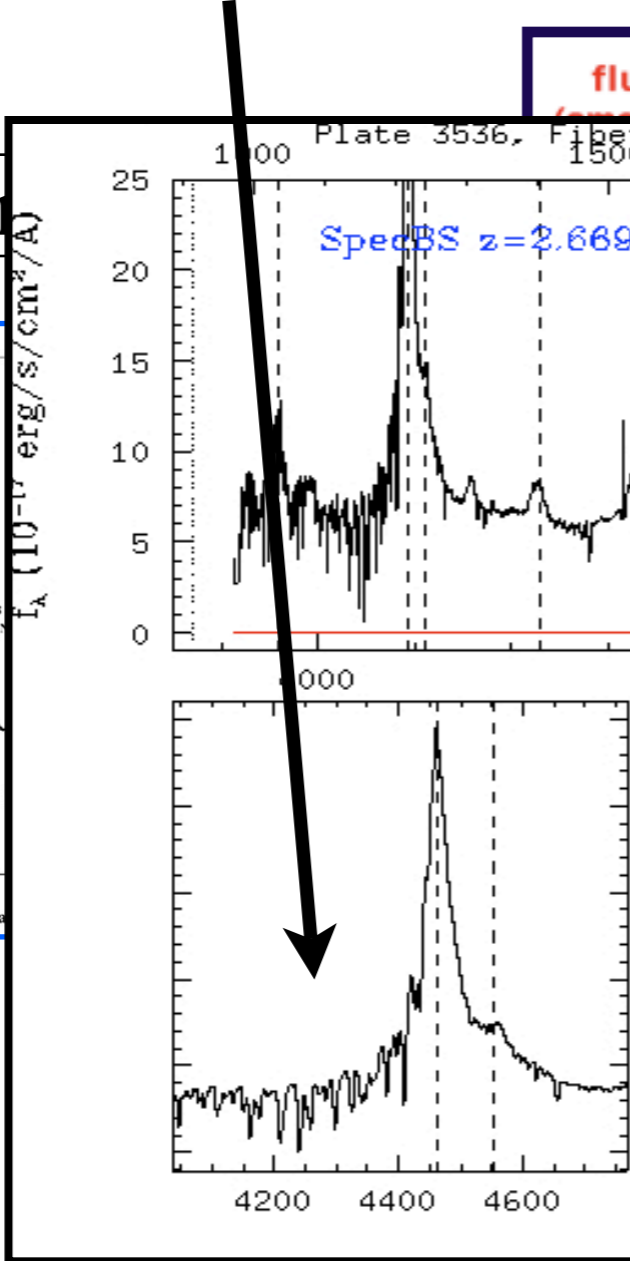
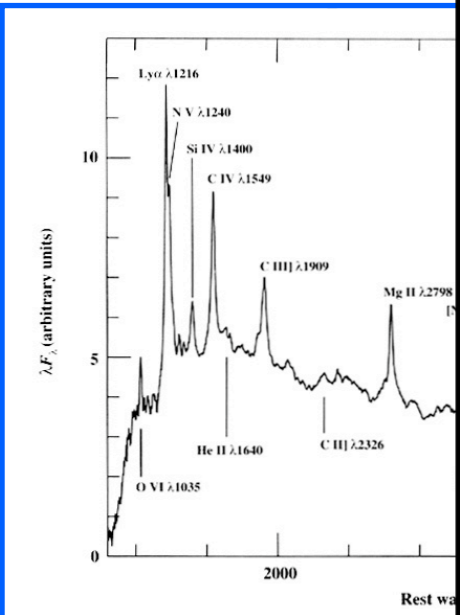
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Outline



- **Motivations**
- **Introduction (What is lighting up the what?)**
- **What can you do with Lyman-alpha forest?**
 - **Baryon Acoustic Oscillations**
 - **Dark Energy**
 - **Scale Dependent Bias**
 - **Primordial Non-gaussianities -> Inflation**
- **Conclusion**

Constraining Dark Energy with Ly α forest BAO



How do we detect Baryon Acoustic Oscillations?
We calculate the correlation functions!

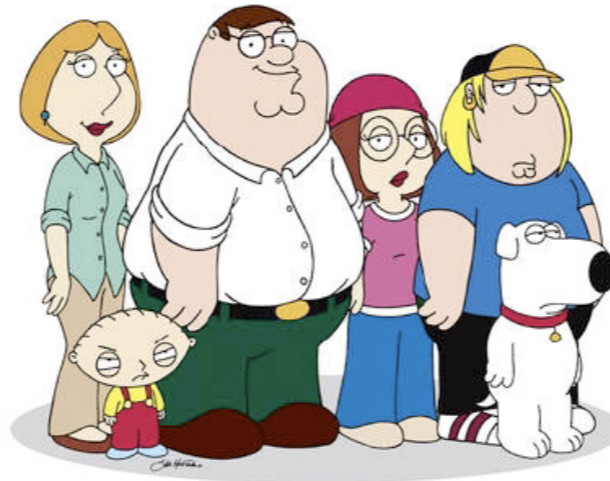
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How do we detect Baryon Acoustic Oscillations?
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What is the correlation function ?

$$\xi_f(r) = \langle \delta_f(\hat{x}) \delta_f(\hat{x} + \hat{r}) \rangle$$



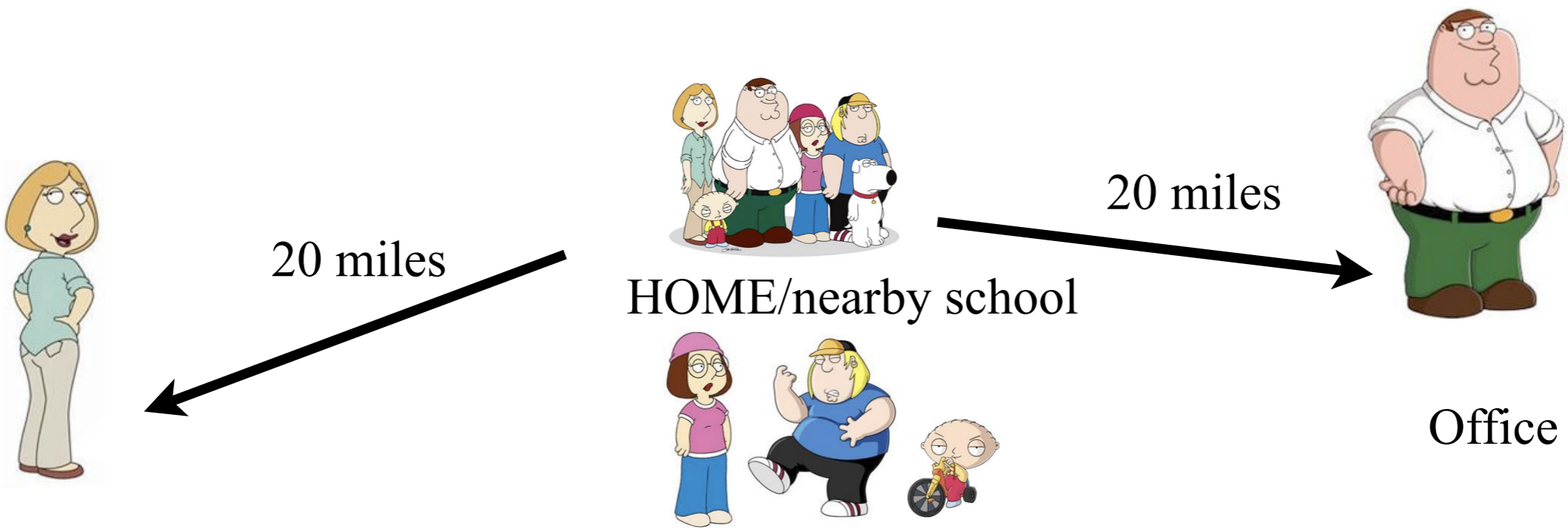
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Office

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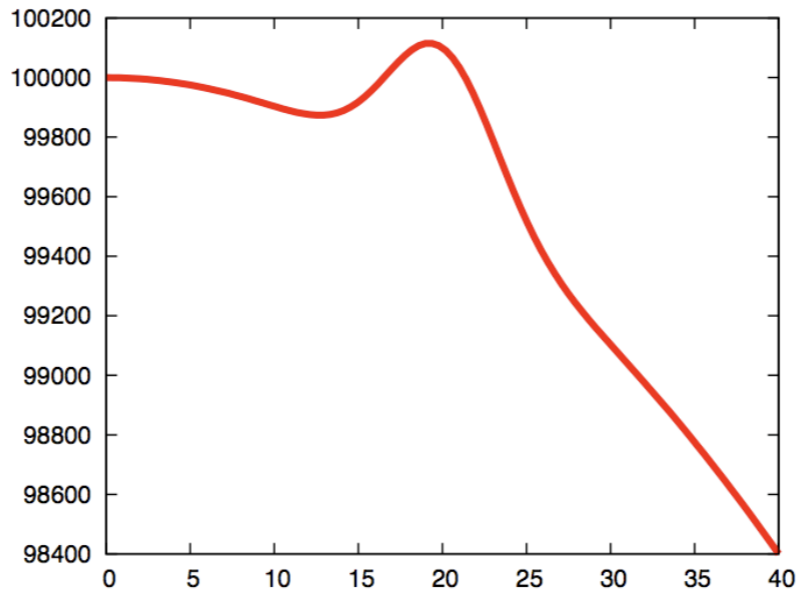


Office

20 miles



Population correlation function during the day



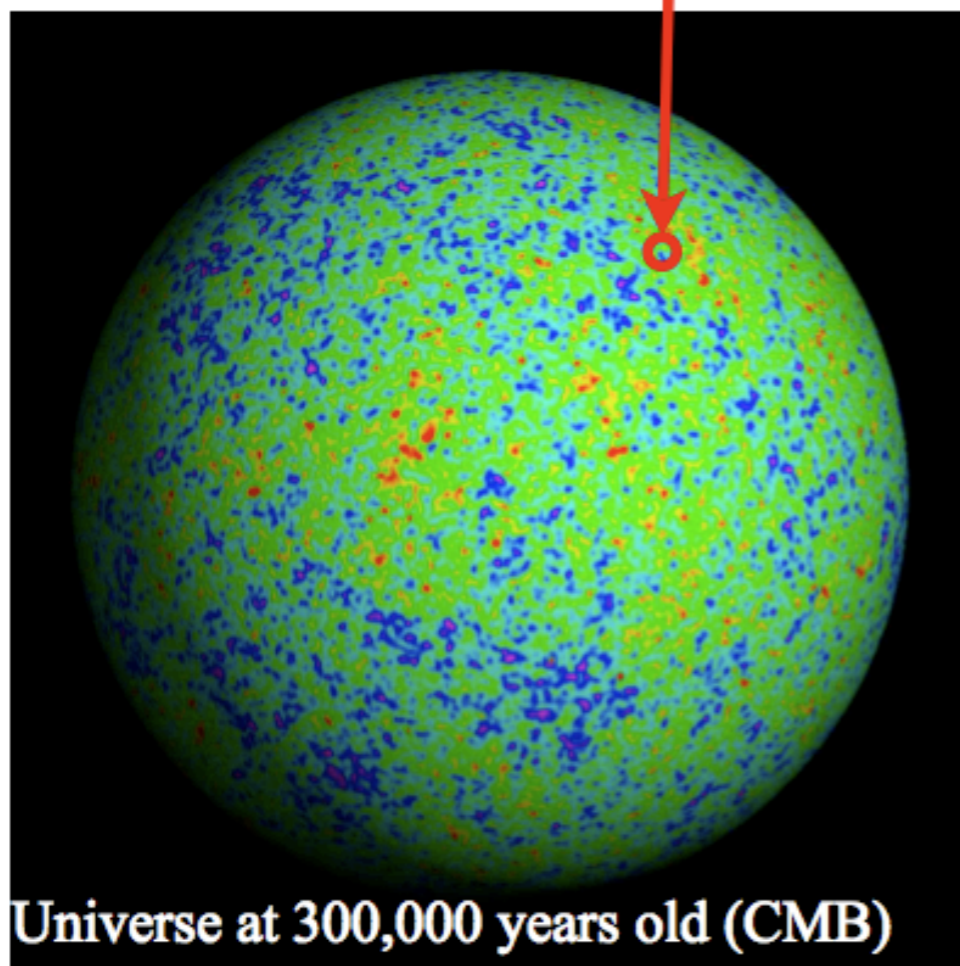
Office

The bump will be at 20 miles!

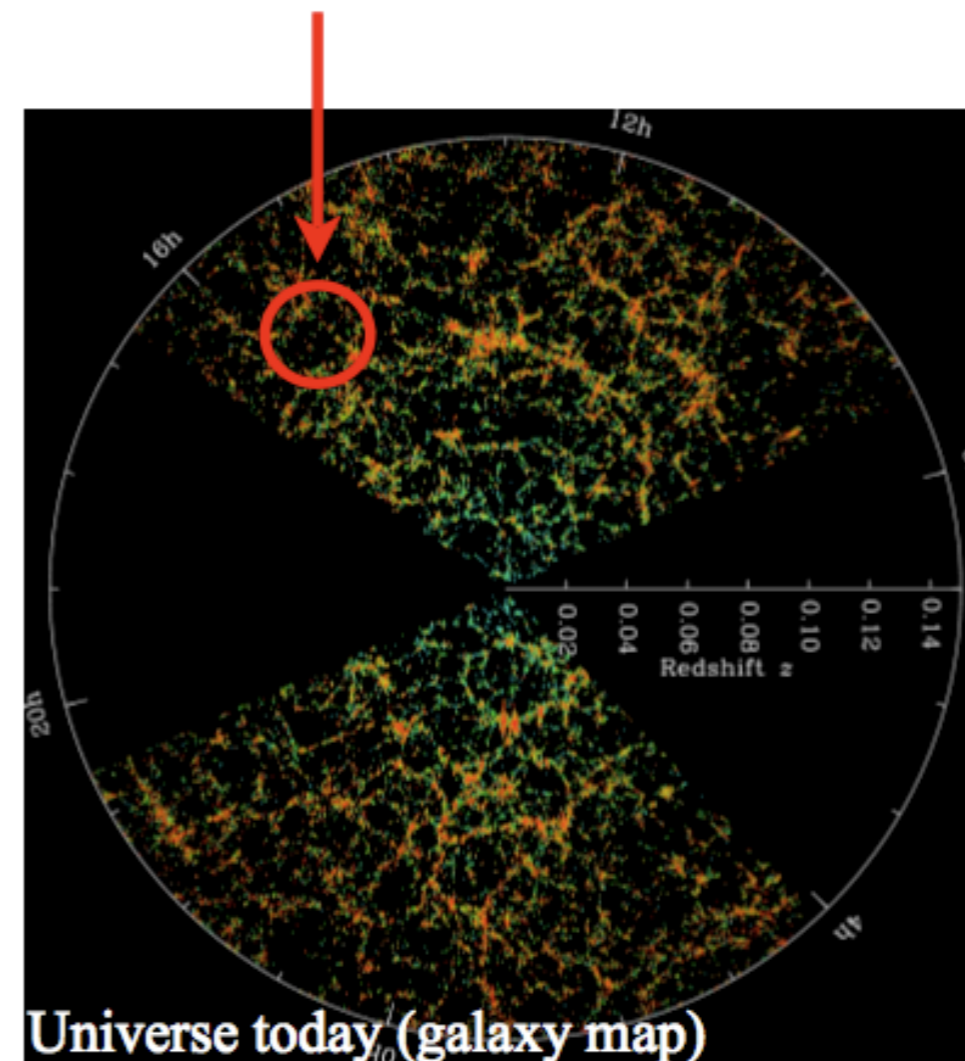
Constraining Dark Energy with Ly α forest BAO

What are baryon acoustic oscillations (BAO)?

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



...these ~unity fluctuations today



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

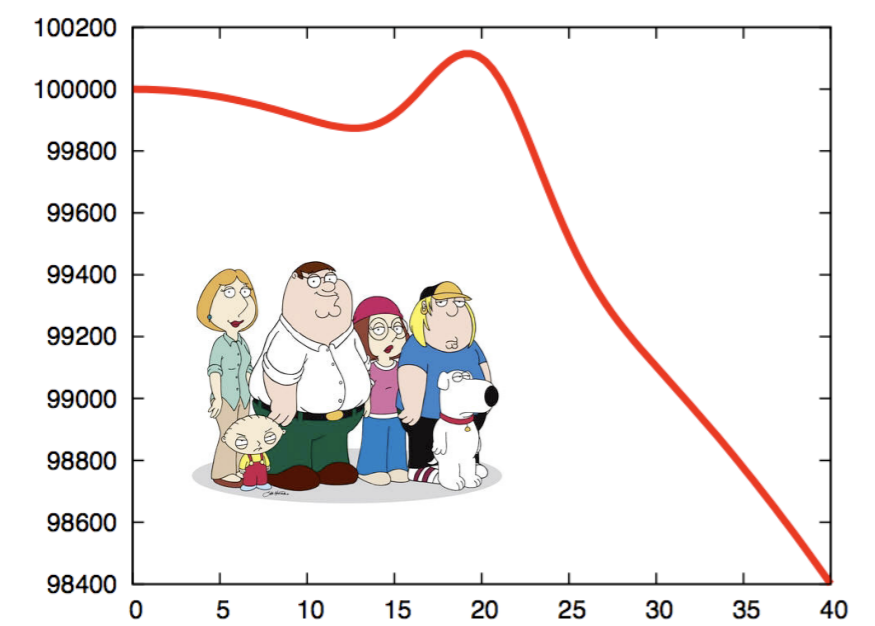
Courtesy slide from David Schlegel

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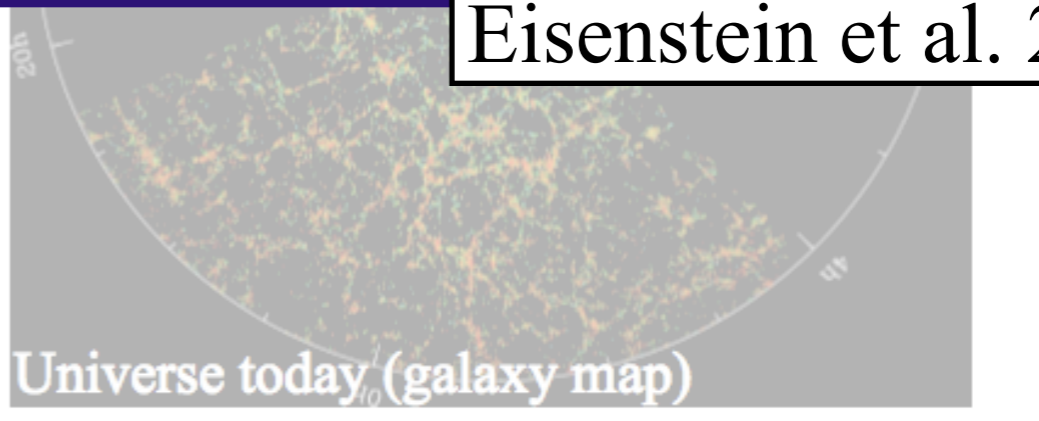
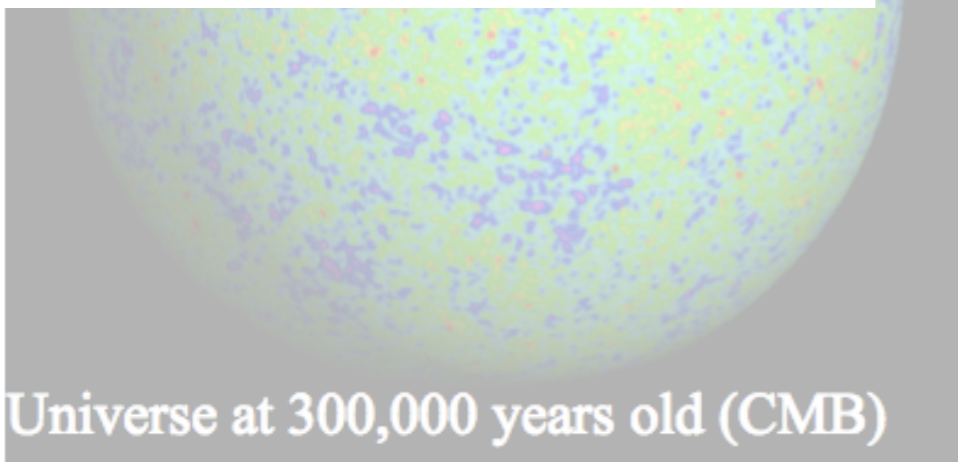
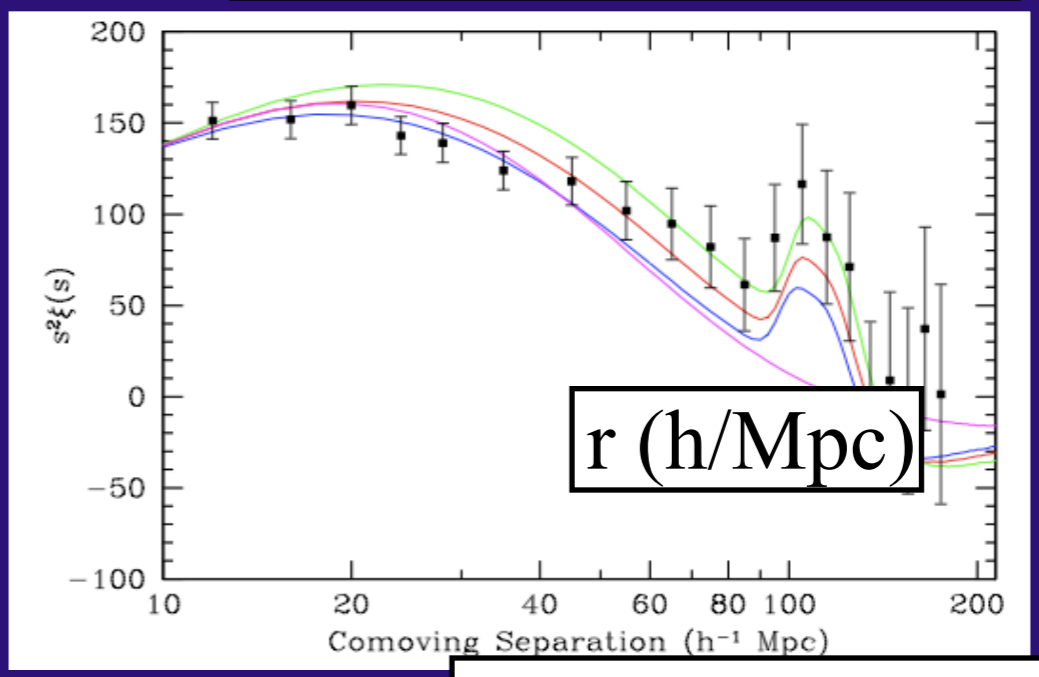


What are baryon acoustic oscillations (BAO)?

Population correlation function during the day



$r^2 \xi(r)$ Galaxy correlation function



Eisenstein et al. 2005

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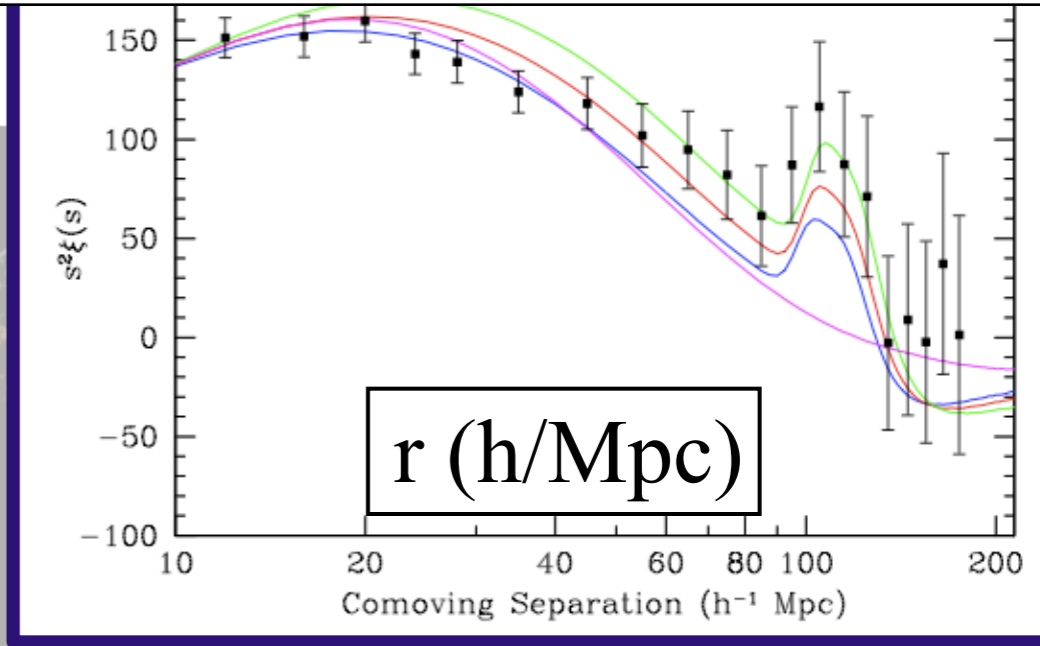
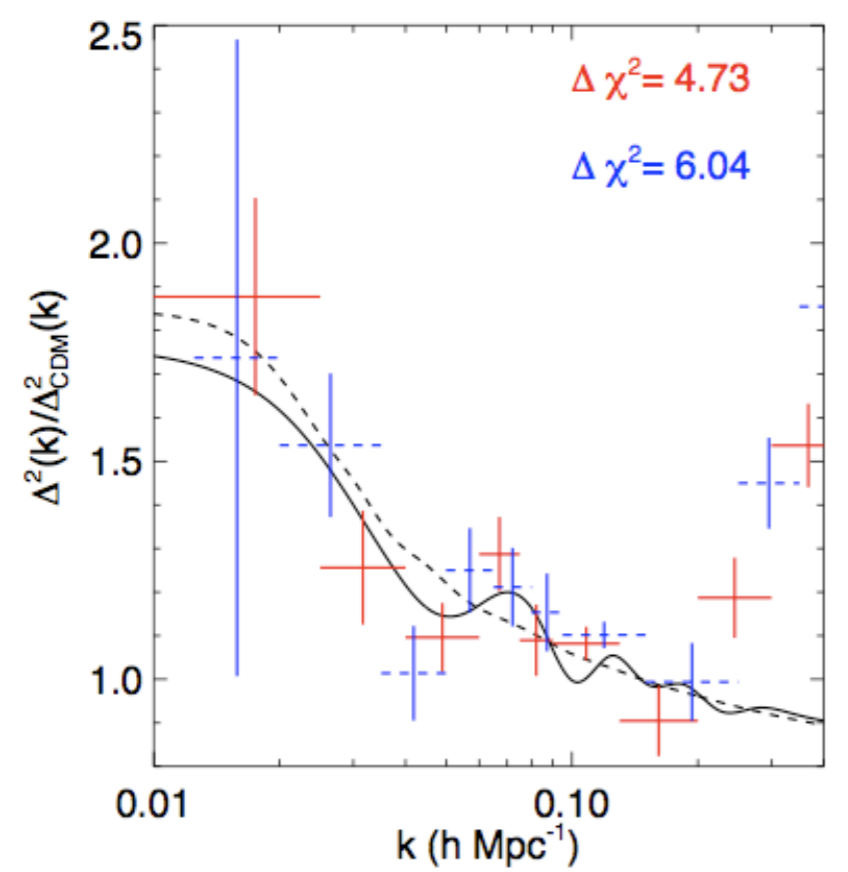
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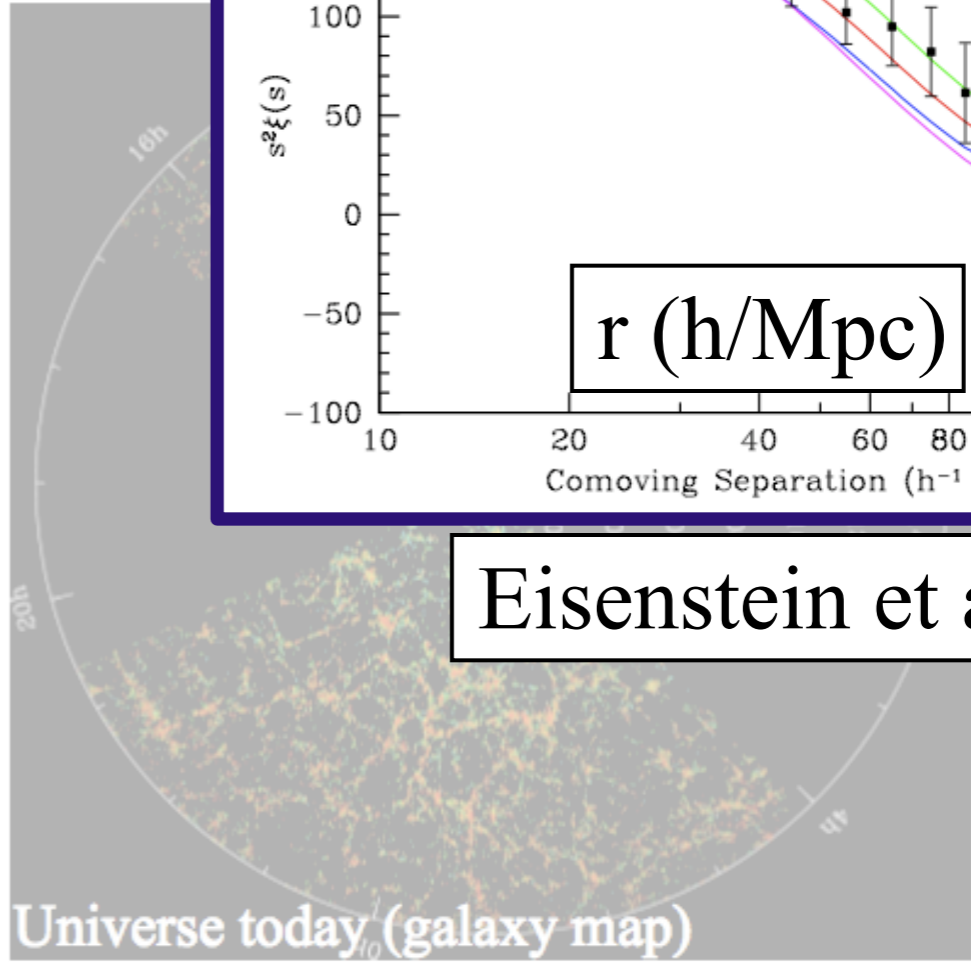
...these

SDSS spectroscopic data of 3800 sq deg

SDSS photometric data of 3500 sq deg



Eisenstein et al. 2005



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apparent ruler size

Padmanabhan et al. 2006

Courtesy slide from David Schlegel

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What are baryon acoustic oscillations (BAO)?

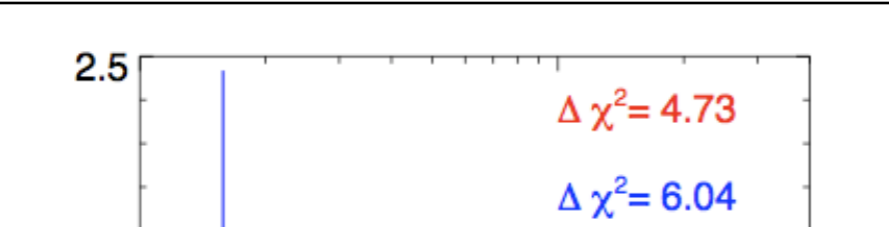
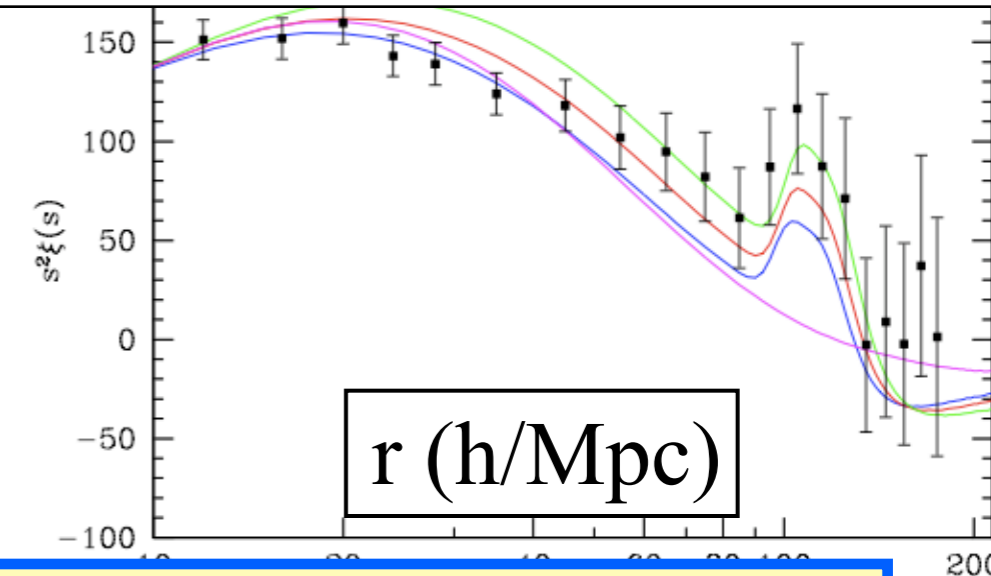
$$r^2 \xi(r)$$

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

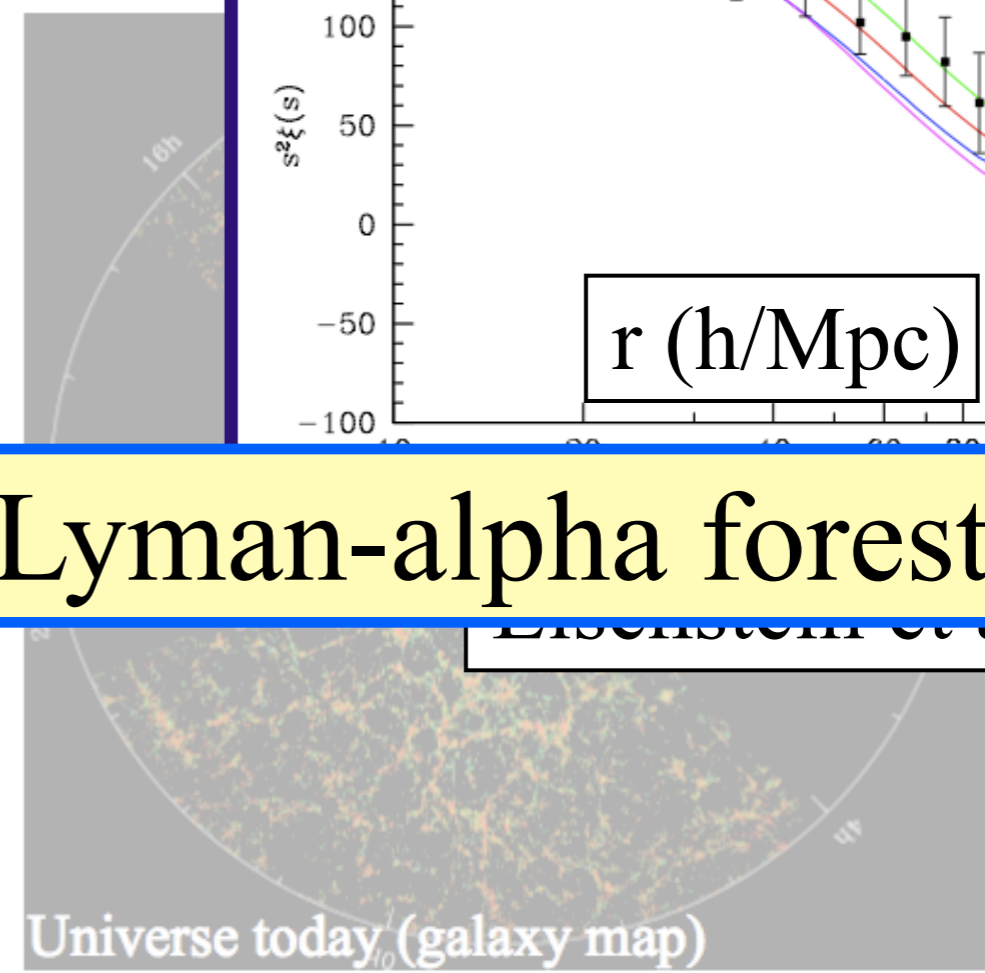
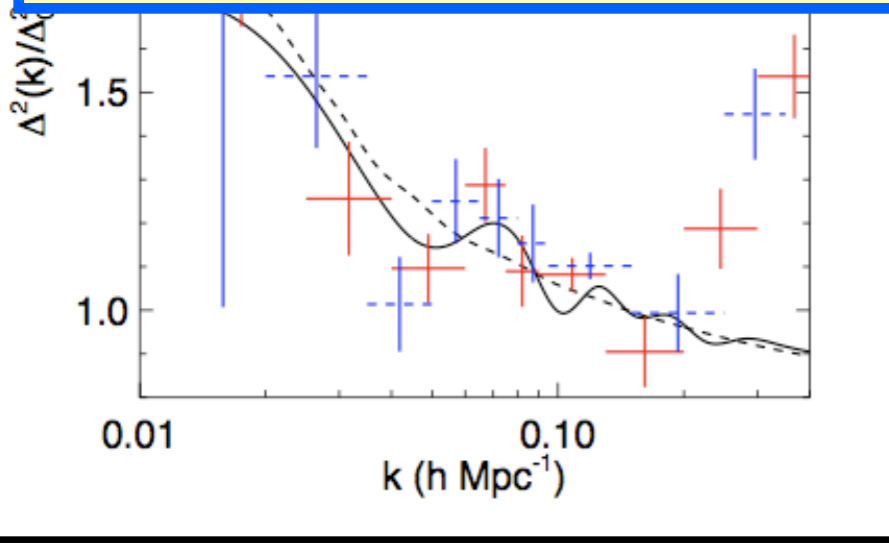
...these

SDSS spectroscopic data of 3800 sq deg

SDSS photometric data of 3500 sq deg



What happens if we use Lyman-alpha forest ?

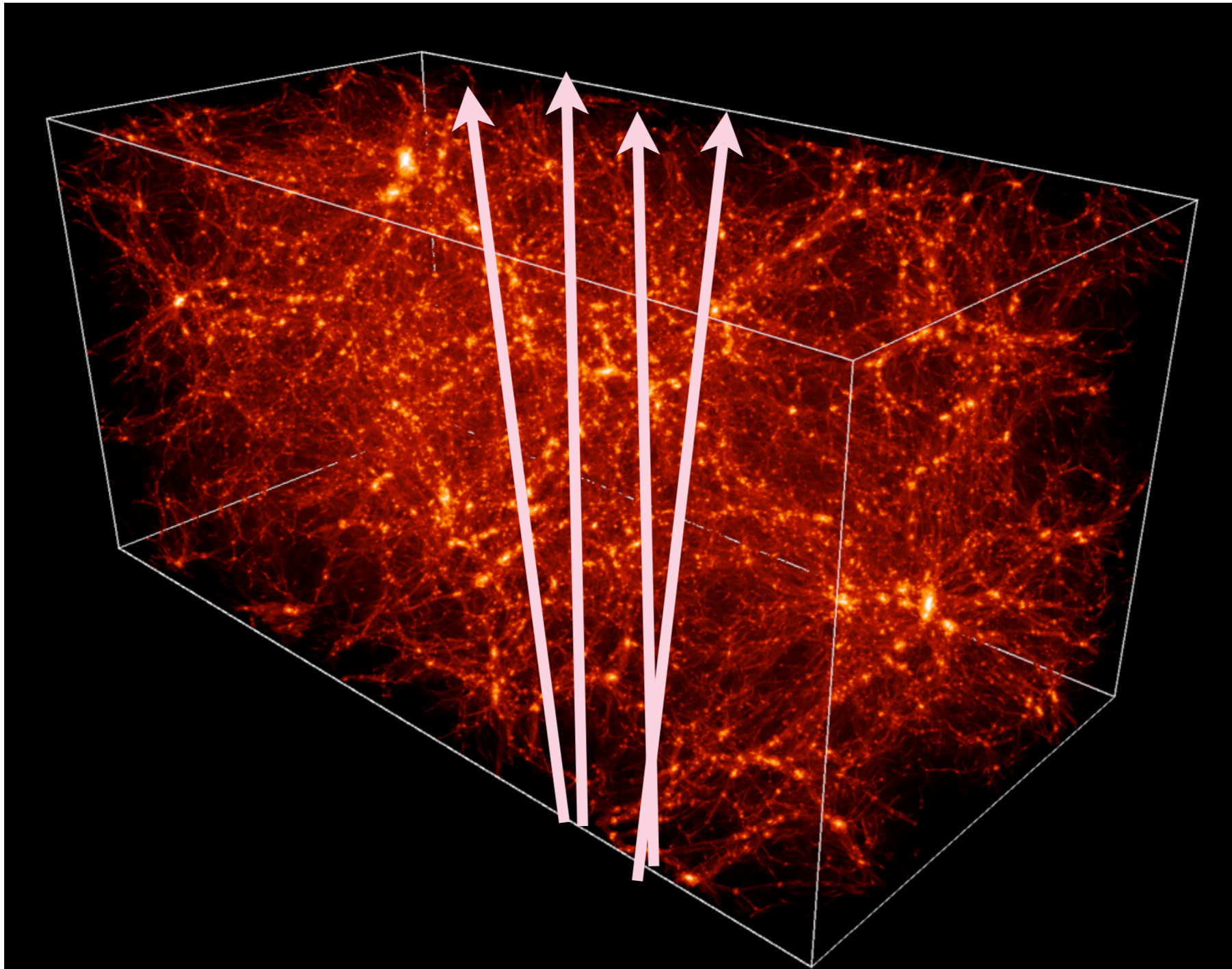


ed as a "standard ruler"
apparent ruler size

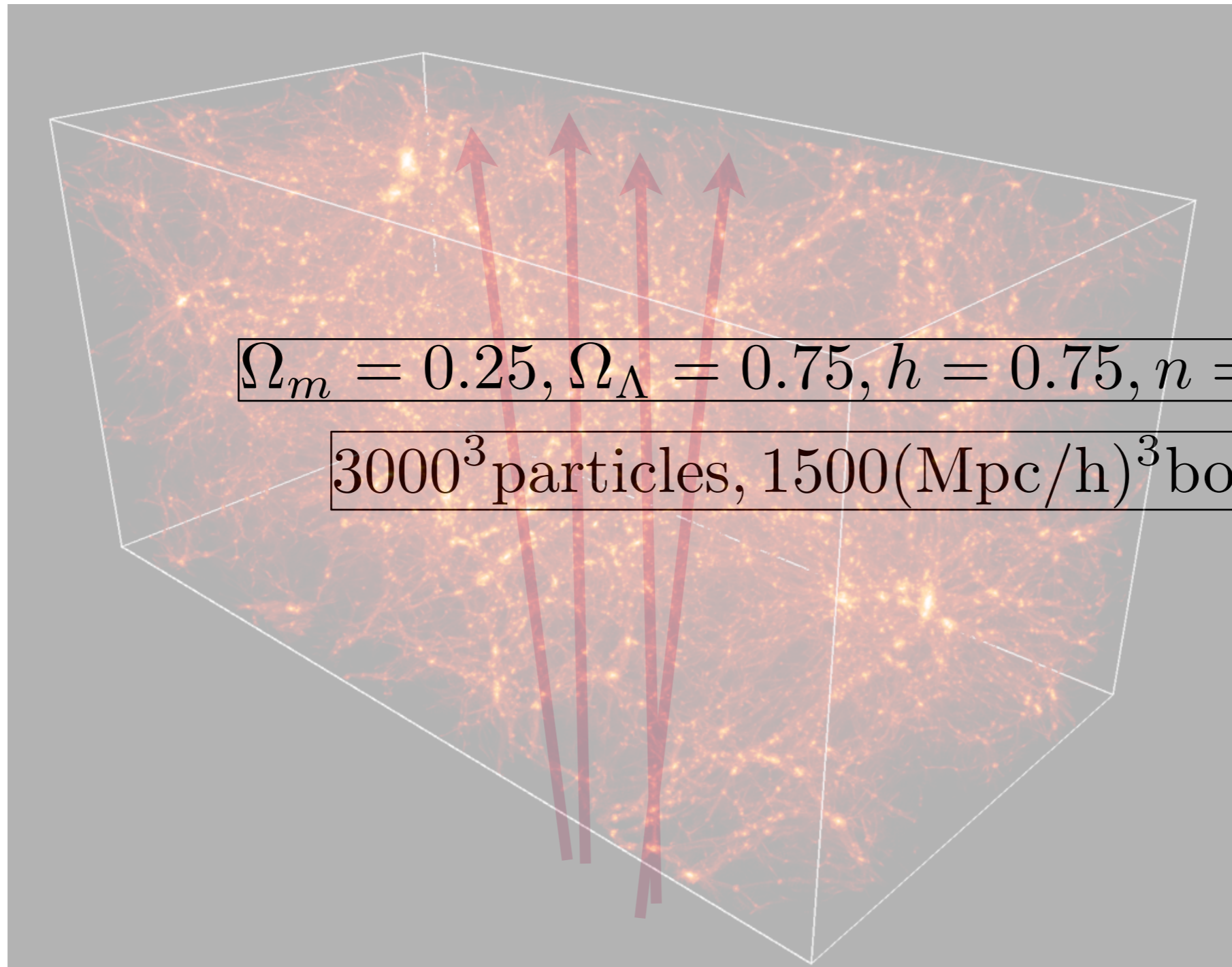
Padmanabhan et al. 2006

Courtesy slide from David Schlegel

Constraining Dark Energy with Ly α forest BAO



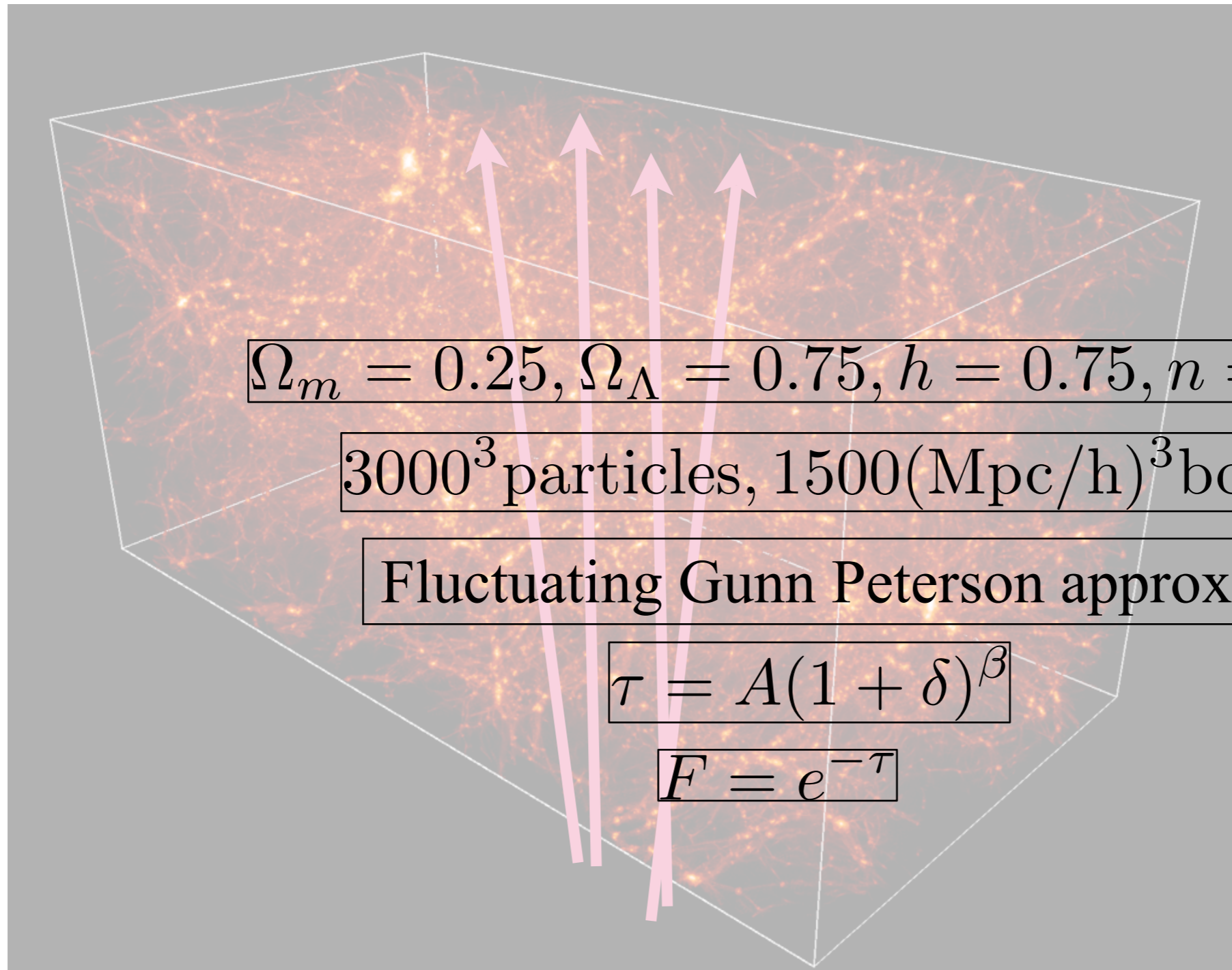
Constraining Dark Energy with Ly α forest BAO



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

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

Constraining Dark Energy with Ly α forest BAO



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

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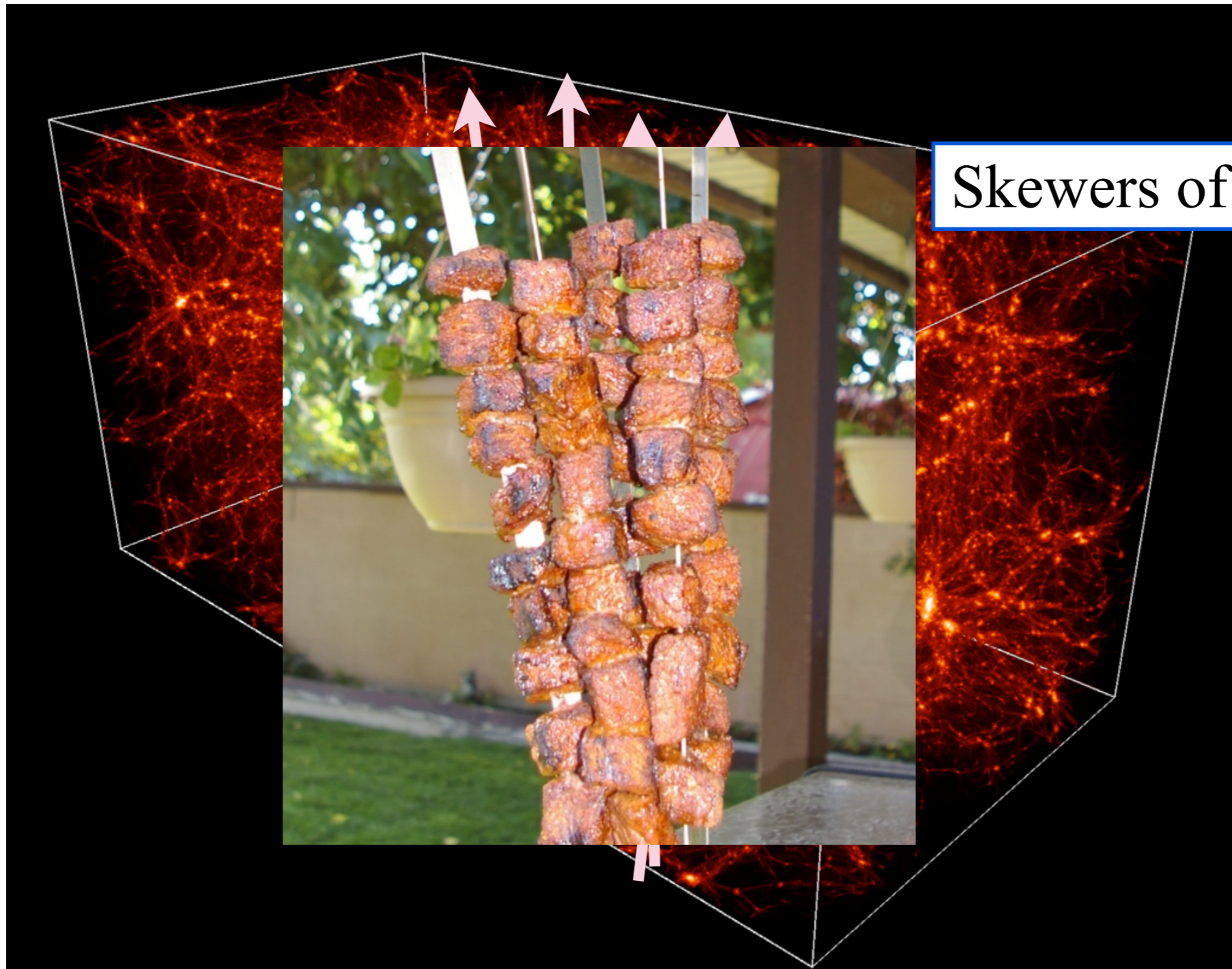
Fluctuating Gunn Peterson approximation

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

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

Constraining Dark Energy with Ly α forest BAO

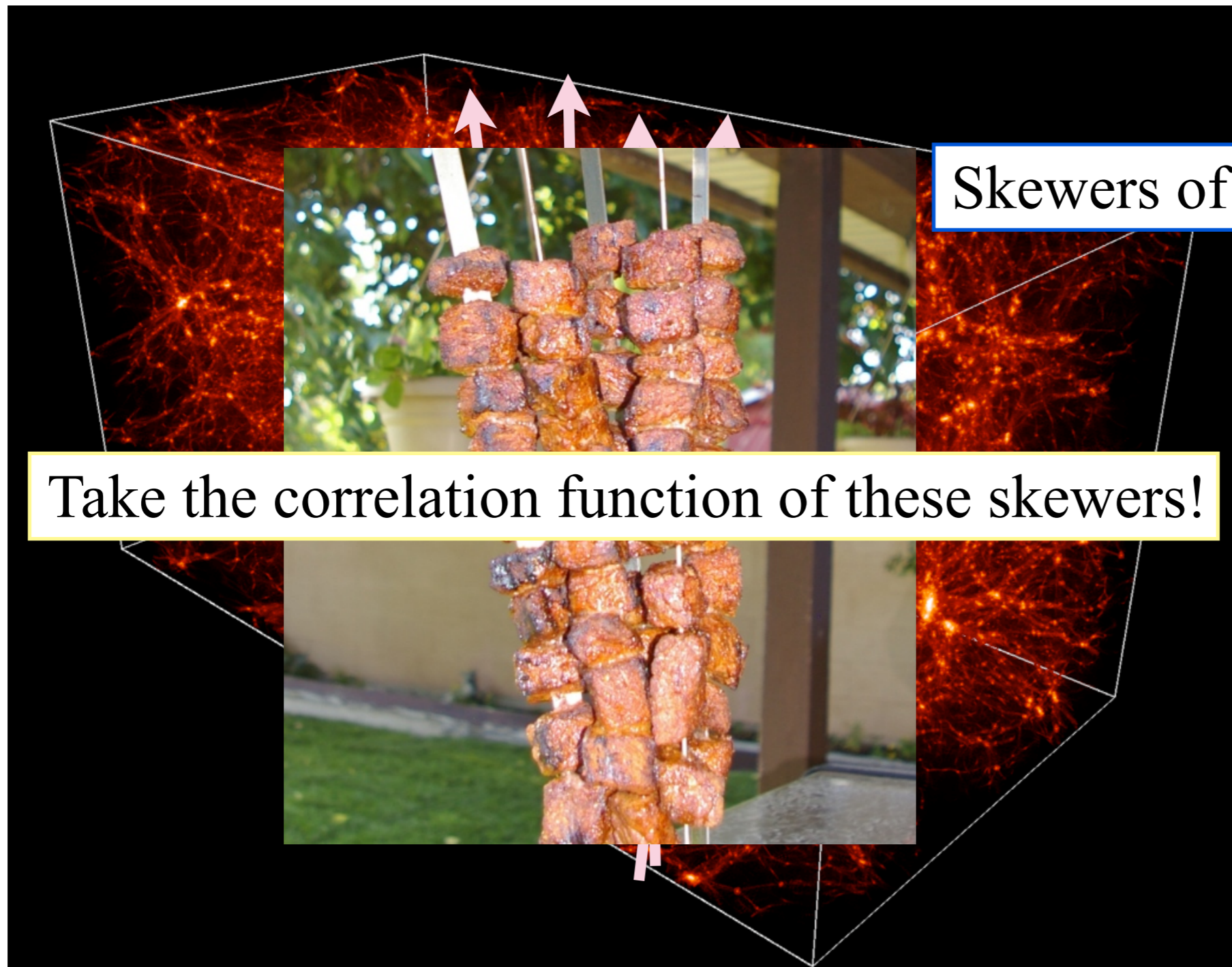
- Dark Energy via Baryon Acoustic Oscillations



Skewers of Neutral Hydrogen

Constraining Dark Energy with Ly α forest BAO

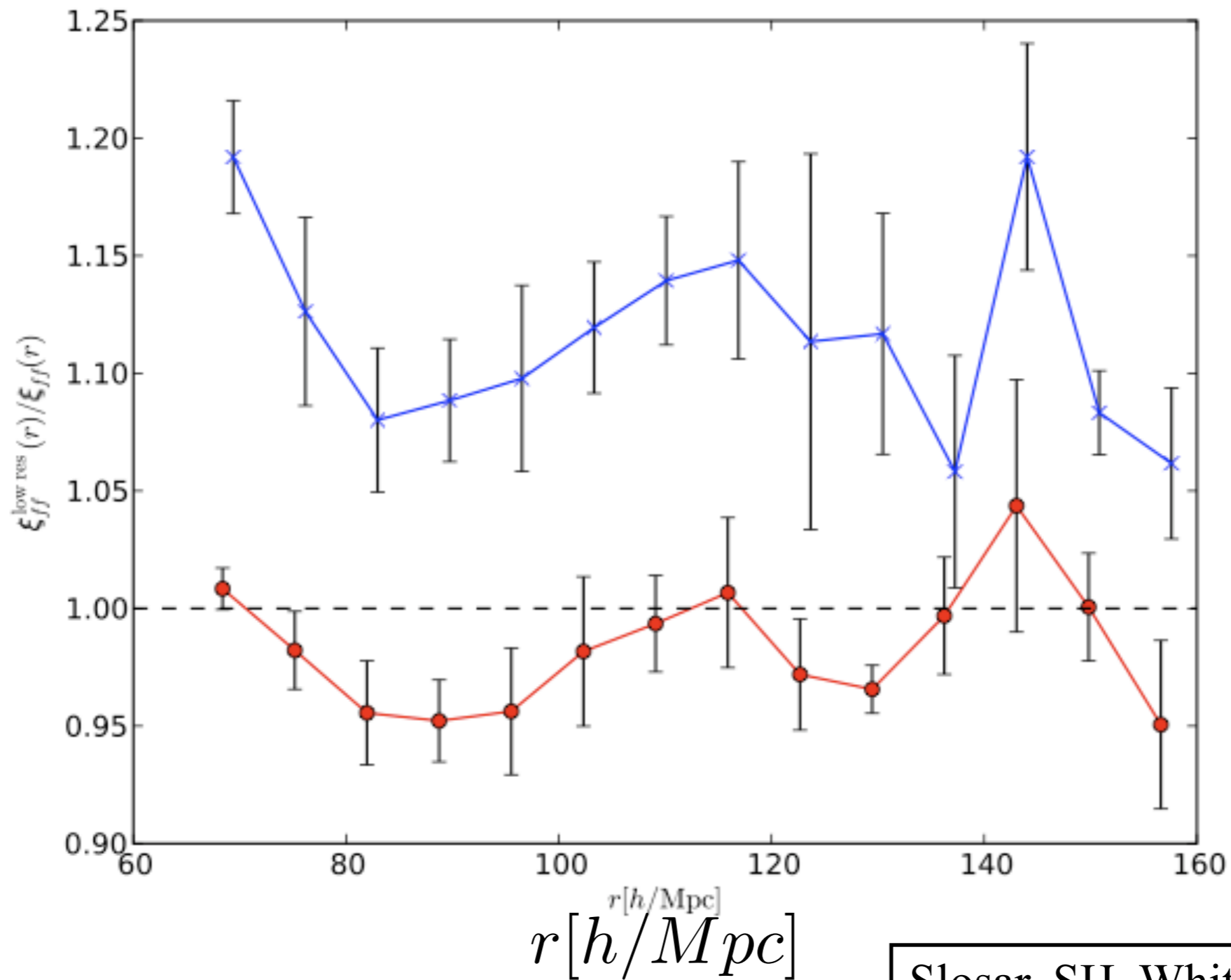
- Dark Energy via Baryon Acoustic Oscillations



How about the resolution effect?



$$\xi_{ff}^{\text{low res}}(r) / \xi_{ff}(r)$$



resolution 4X worse

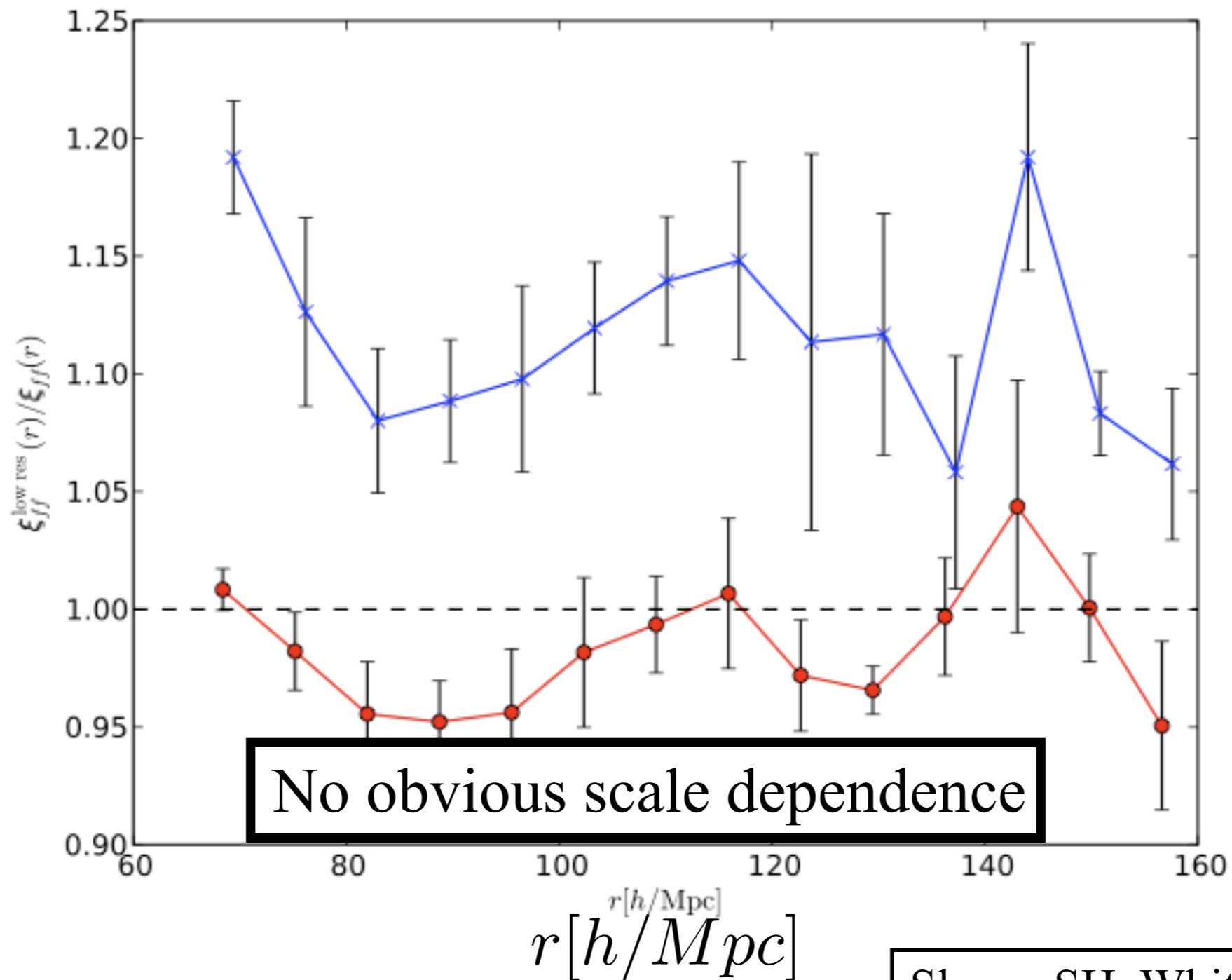
resolution 2X worse

Slosar, SH, White & Louis (2009)

How about the resolution effect?



$$\xi_{ff}^{\text{low res}}(r) / \xi_{ff}(r)$$



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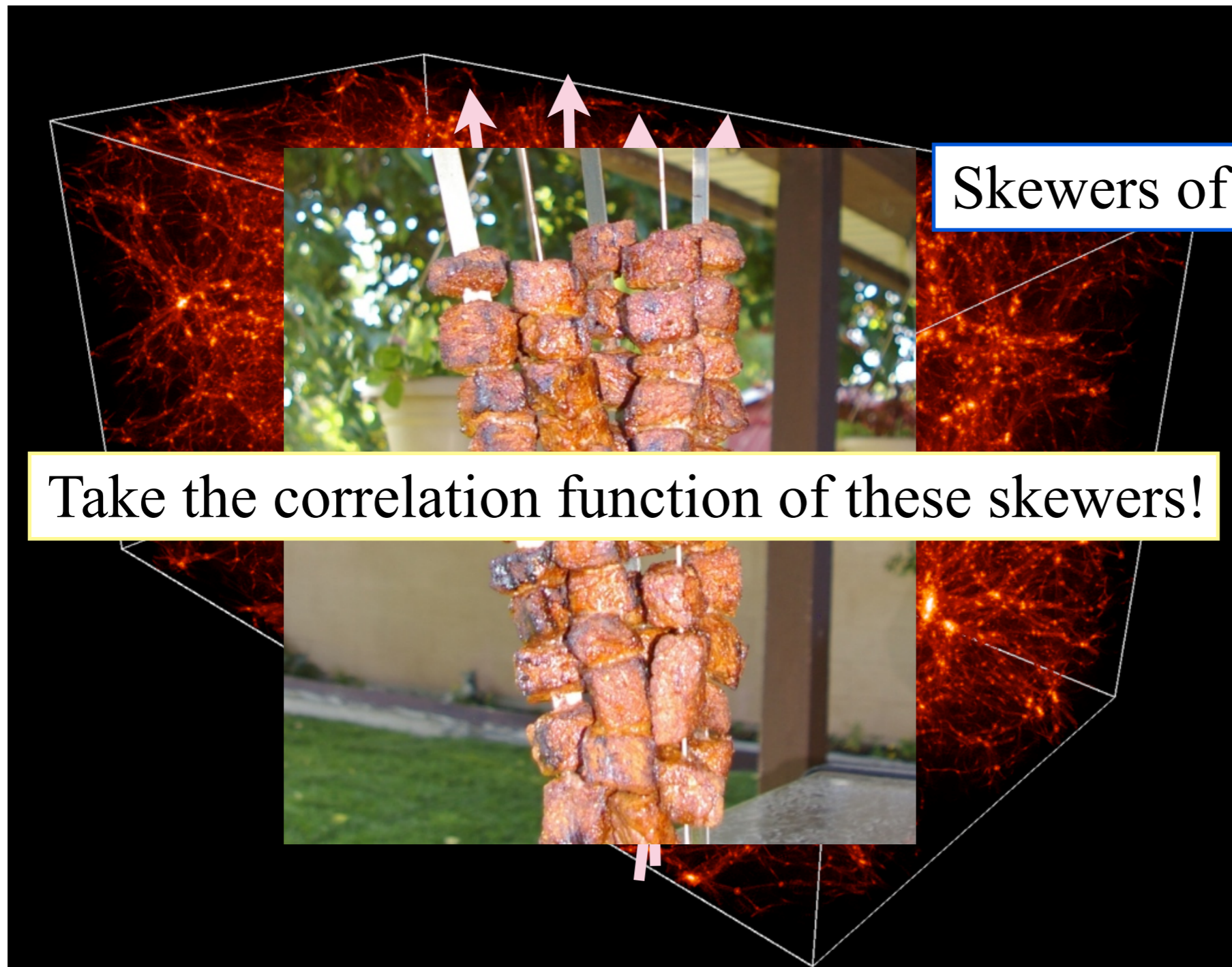
resolution 2X worse

No obvious scale dependence

Slosar, SH, White & Louis (2009)

Constraining Dark Energy with Ly α forest BAO

- Dark Energy via Baryon Acoustic Oscillations



Skewers of Neutral Hydrogen

Take the correlation function of these skewers!

Constraining Dark Energy with Ly α forest BAO

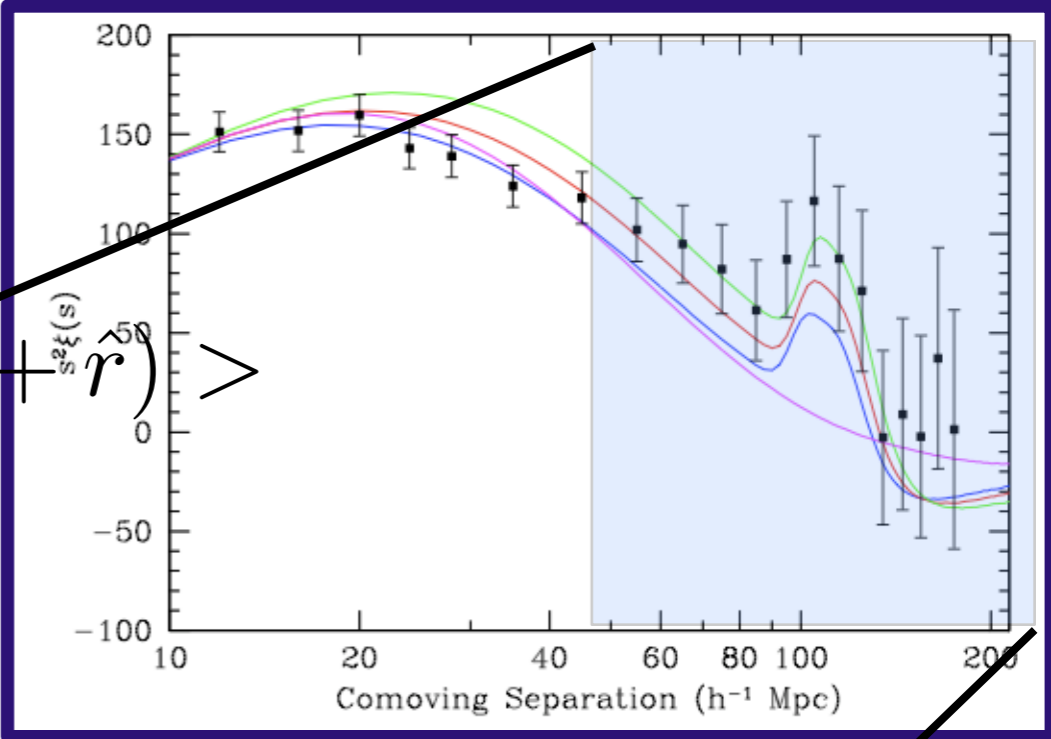


$$\xi_f(r) = \langle \delta_f(\hat{x}) \delta_f(\hat{x} + \hat{r}) \rangle$$

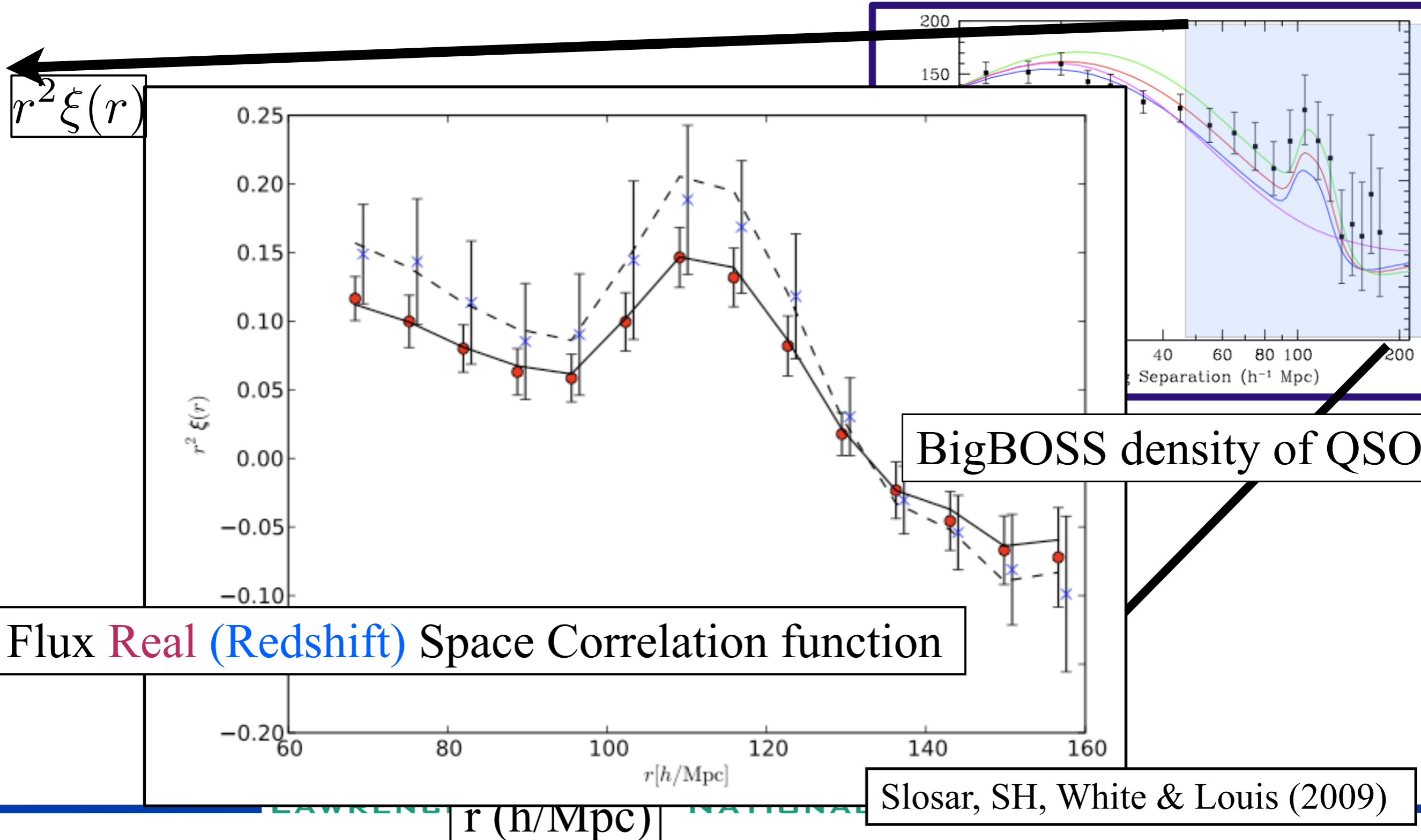
Constraining Dark Energy with Ly α forest BAO



$$\xi_f(r) = \langle \delta_f(\hat{x}) \delta_f(\hat{x} + \hat{r}) \rangle$$



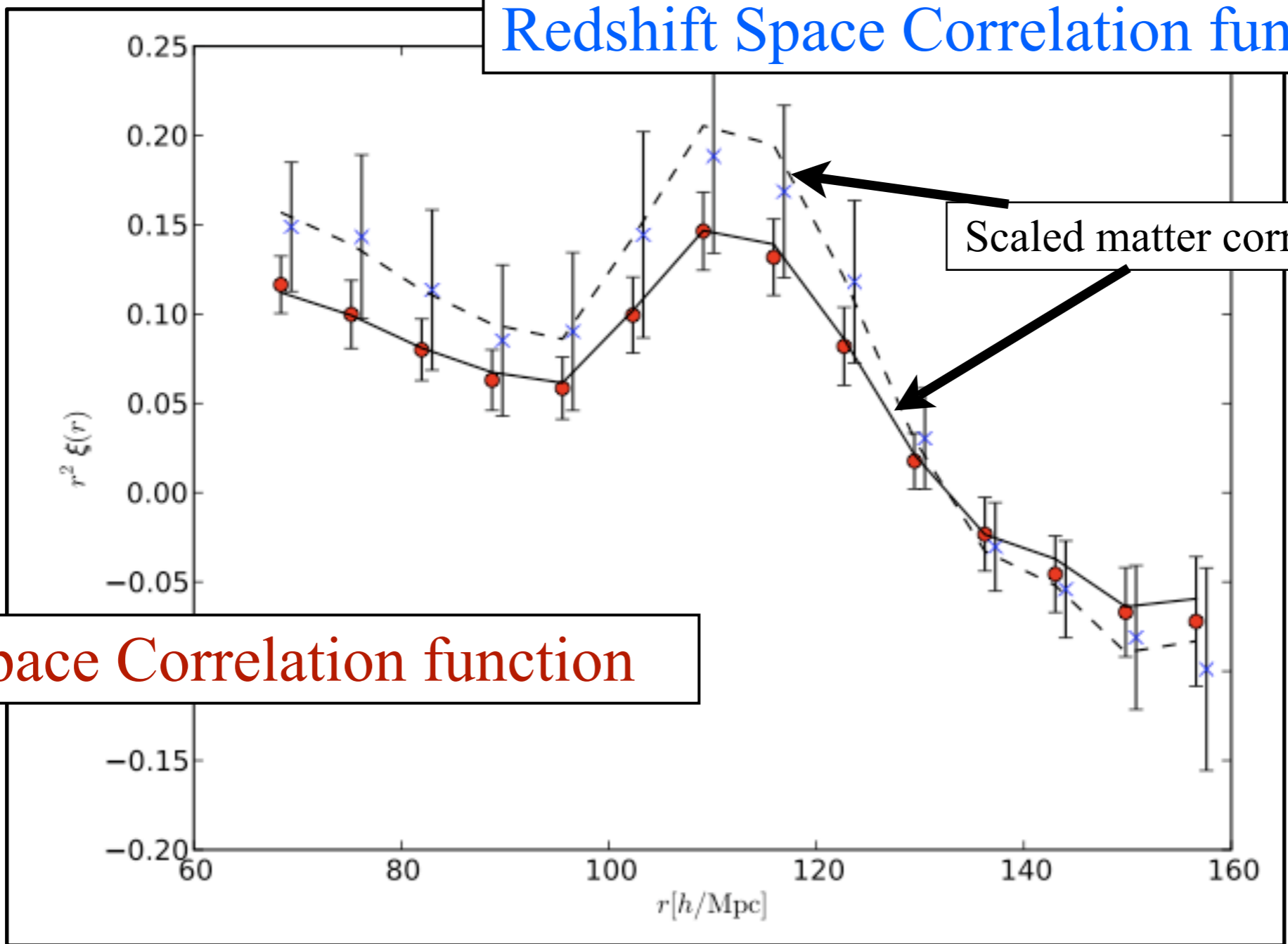
Constraining Dark Energy with Ly α forest BAO



Constraining Dark Energy with Ly α forest BAO

$$r^2 \xi(r)$$

Redshift Space Correlation function



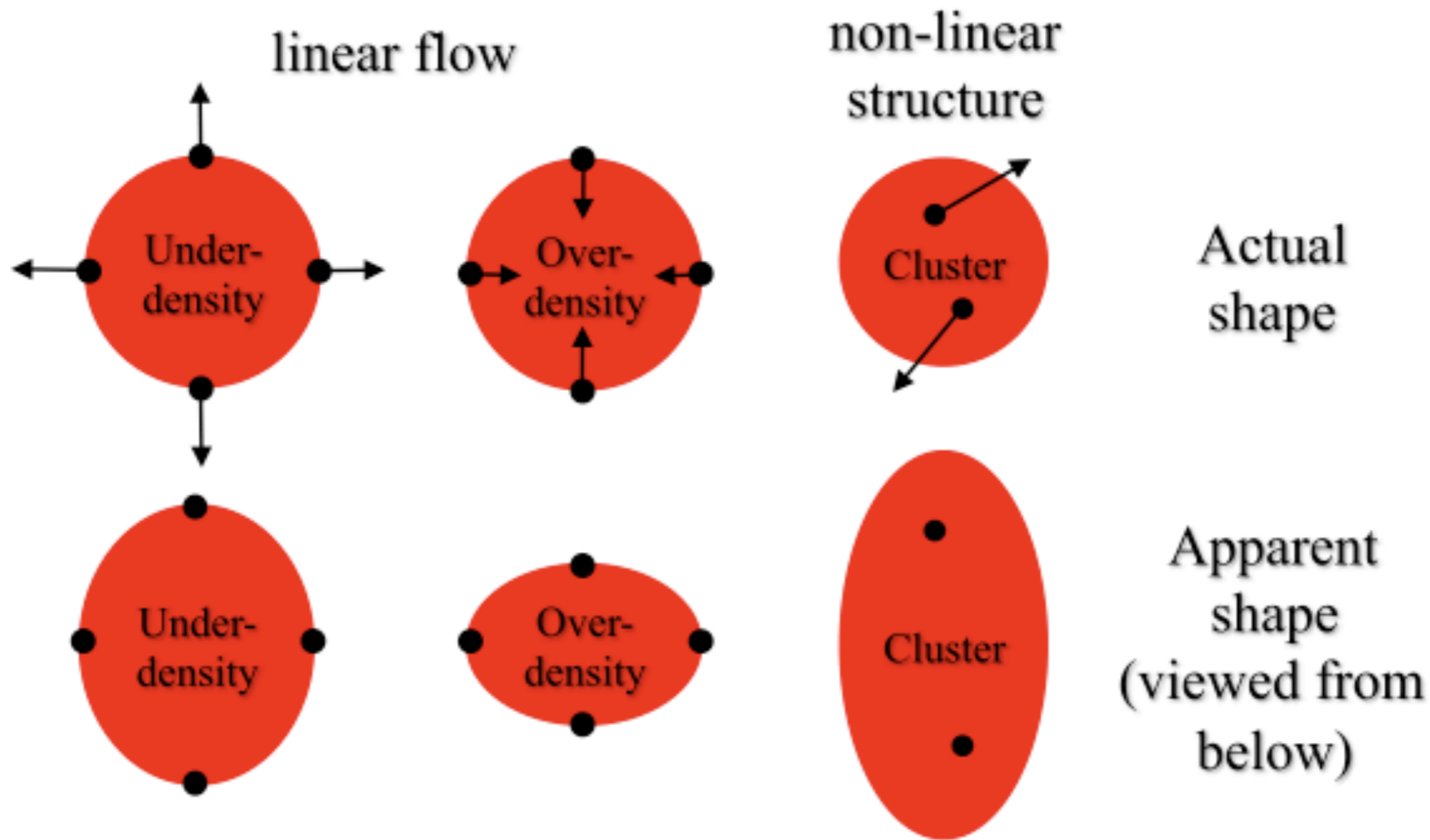
Scaled matter correlation functions

Real Space Correlation function

r (h/Mpc)

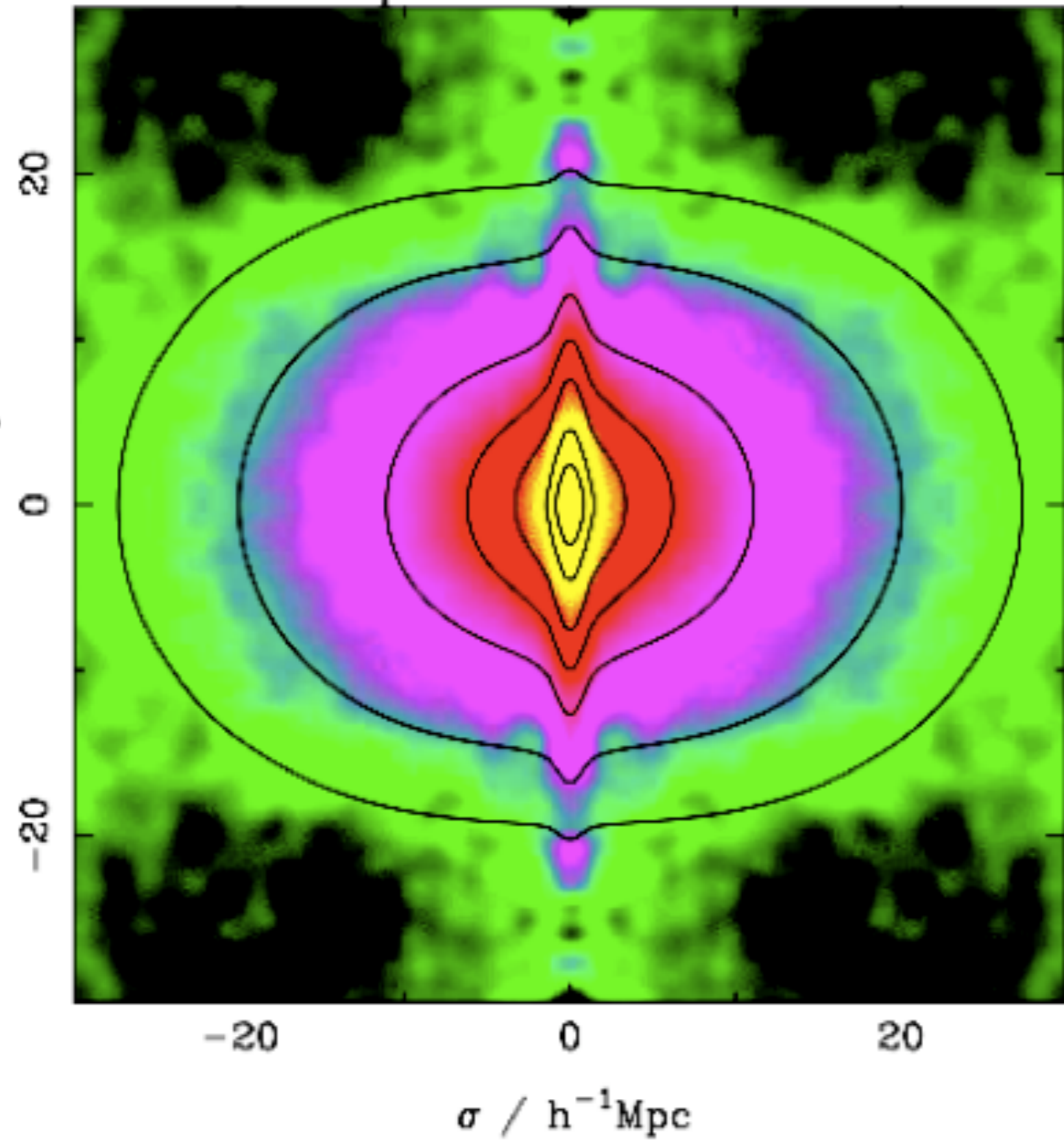
Slosar, SH, White & Louis (2009)

Recall Redshift space distortions



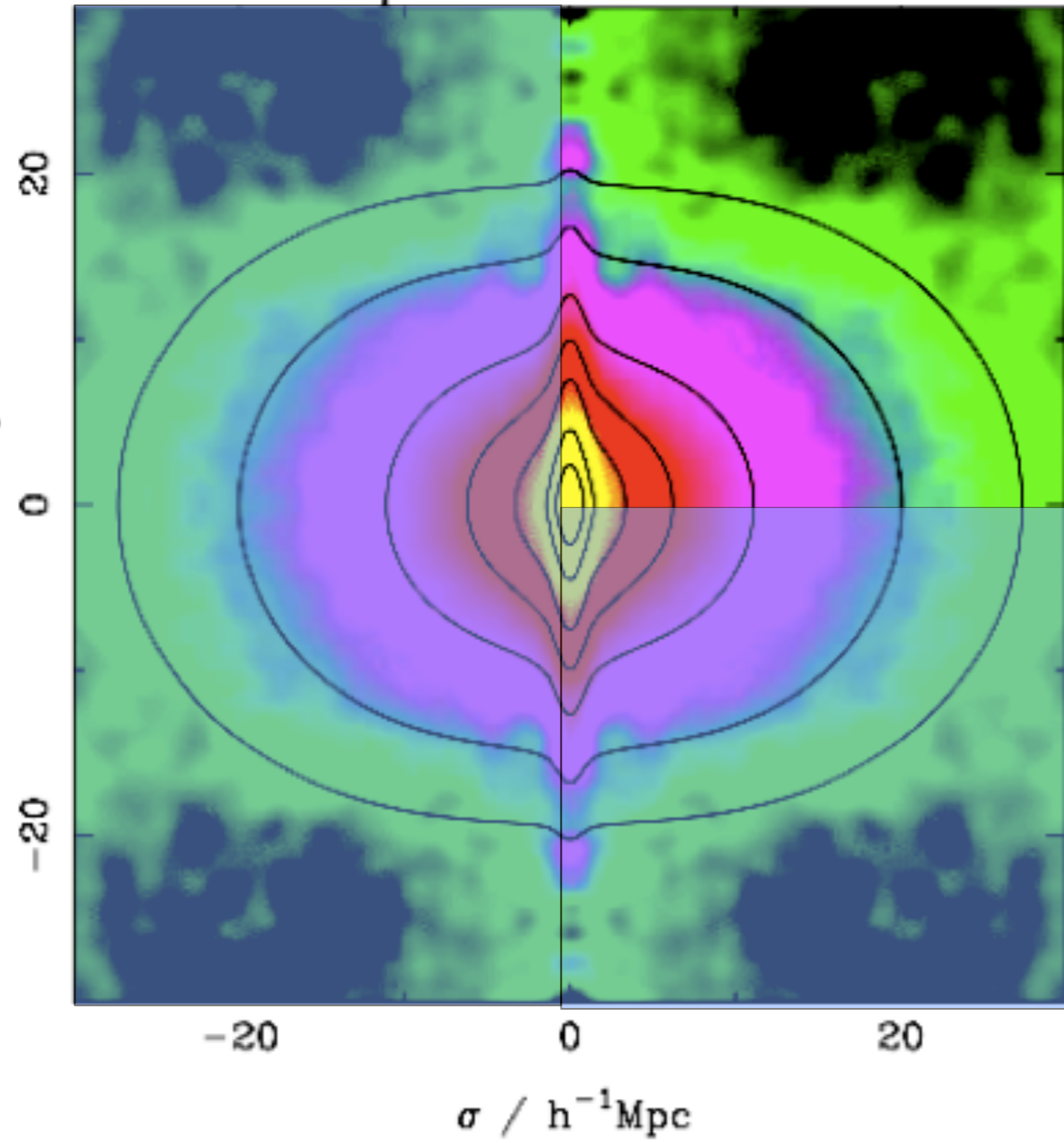
Anisotropic correlation function

2dFGRS, Peacock et al.



Anisotropic correlation function

2dFGRS, Peacock et al.



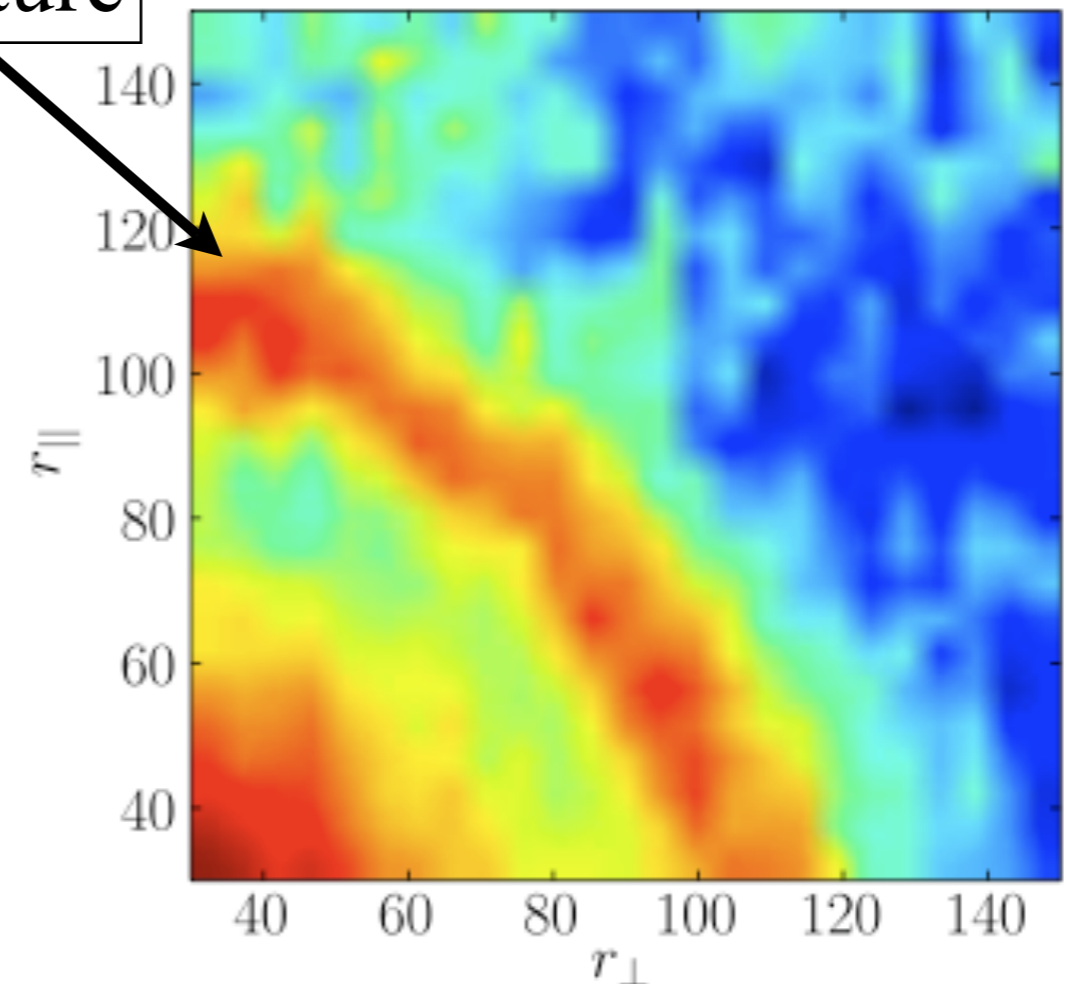
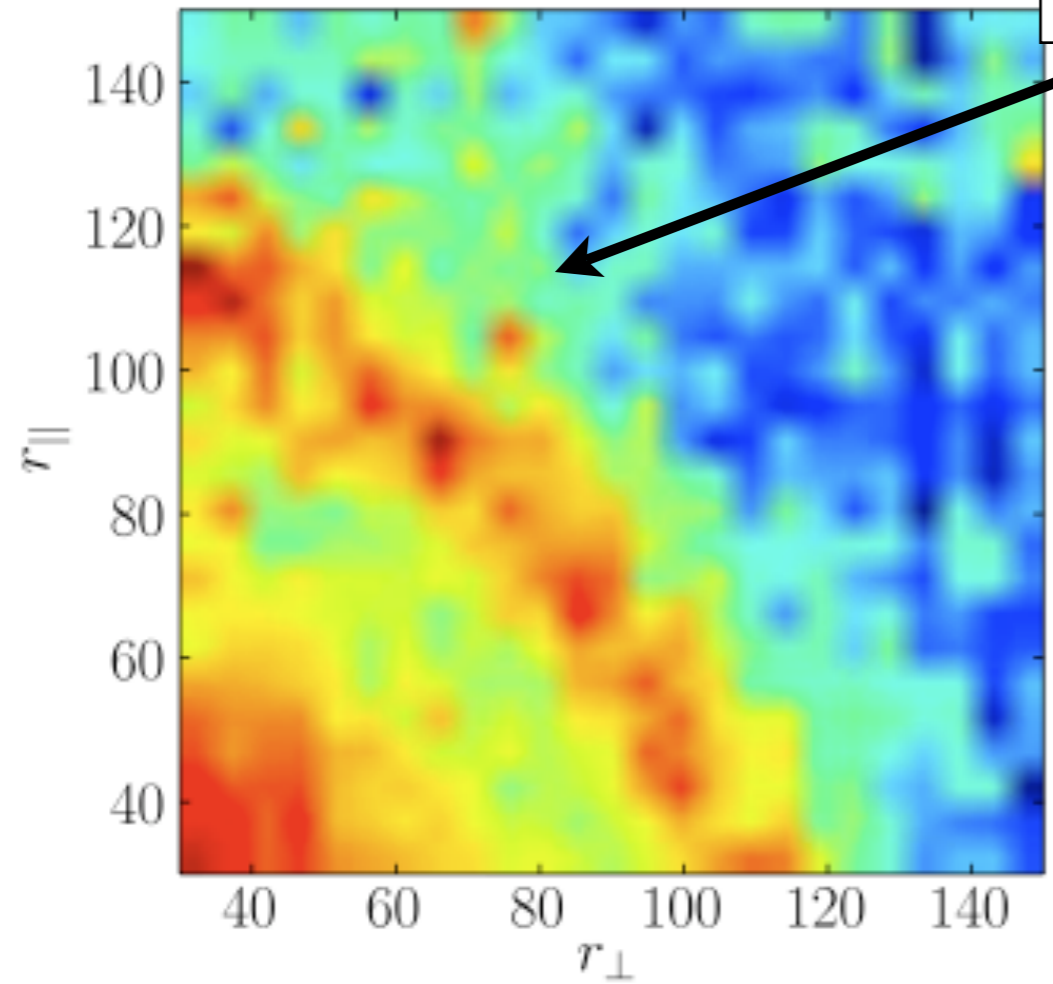
Constraining Dark Energy with Ly α forest BAO

Real Space Correlation function

Matter

Flux

BAO feature



Slosar, SH, White & Louis (2009)

Constraining Dark Energy with Ly α forest BAO

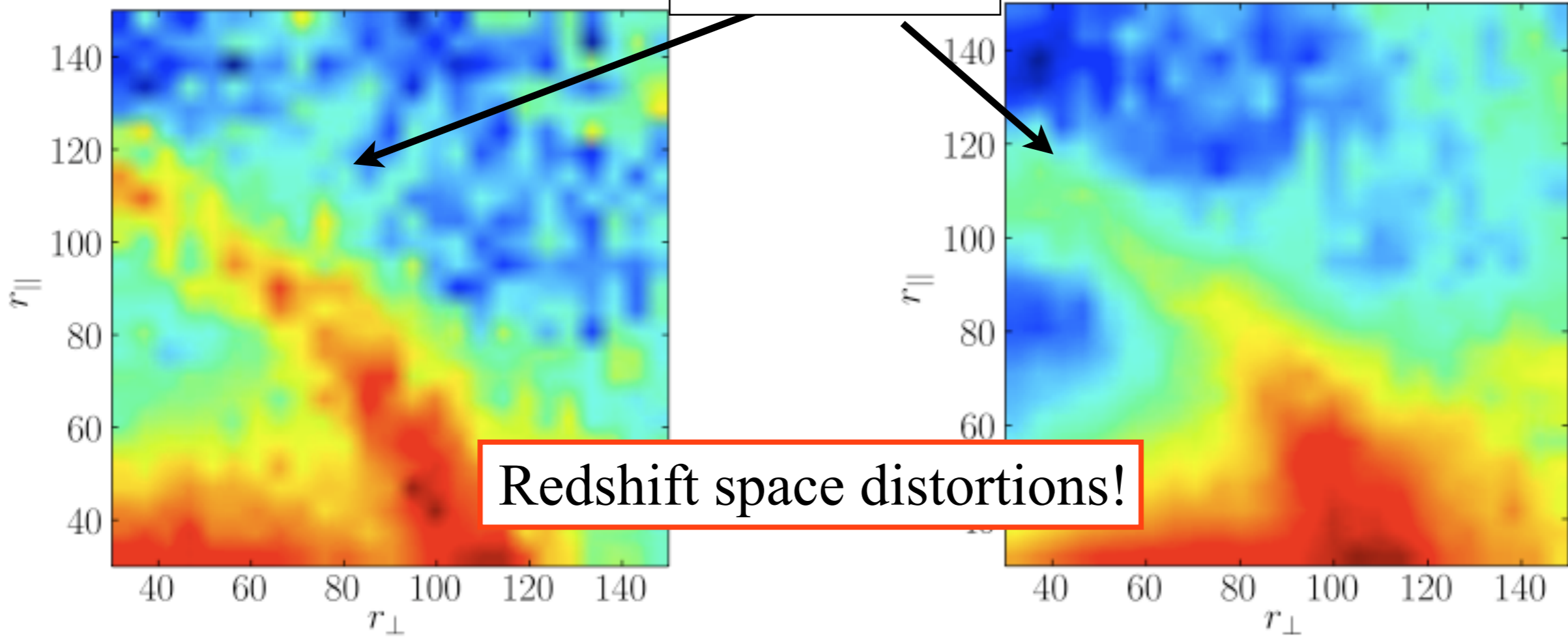


Redshift Space Correlation function

Matter

Flux

BAO feature



Redshift space distortions!

Slosar, SH, White & Louis (2009)

Constraining Dark Energy with Ly α forest BAO

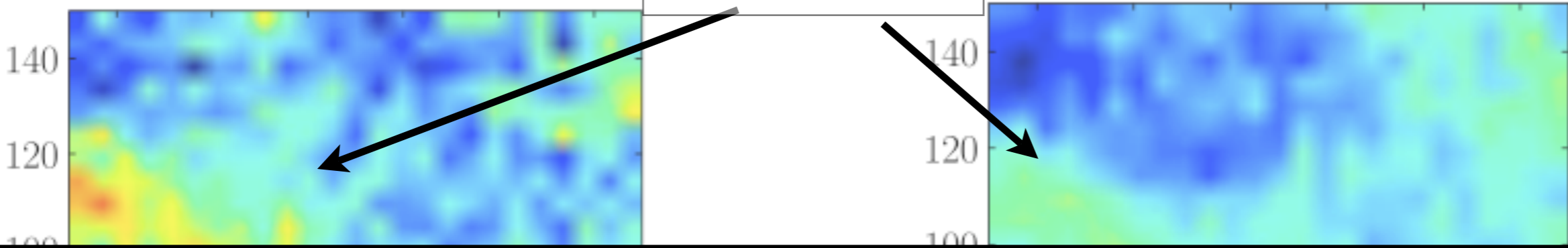


Redshift Space Correlation function

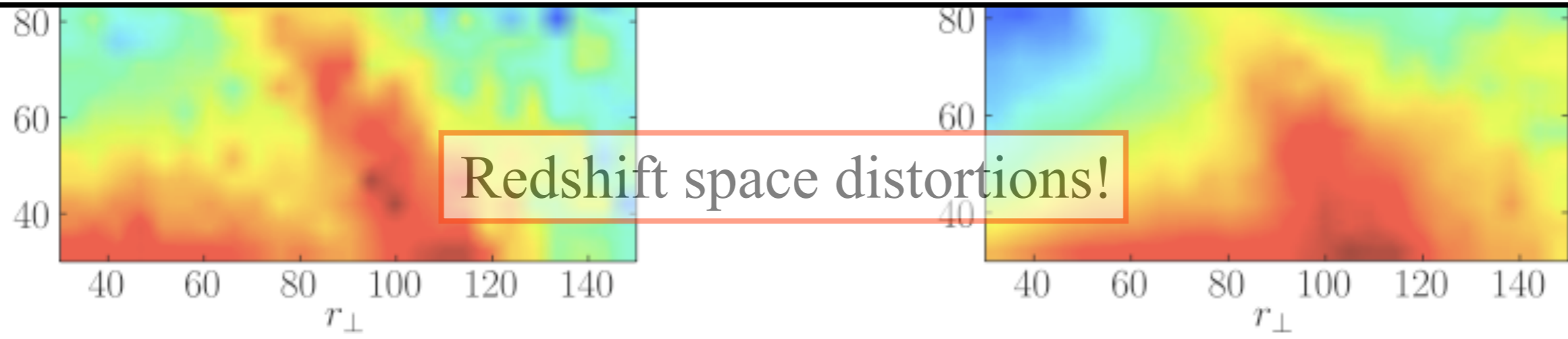
Matter

Flux

BAO feature



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



Slosar, SH, White & Louis (2009)

Constraining Dark Energy with Ly α forest BAO

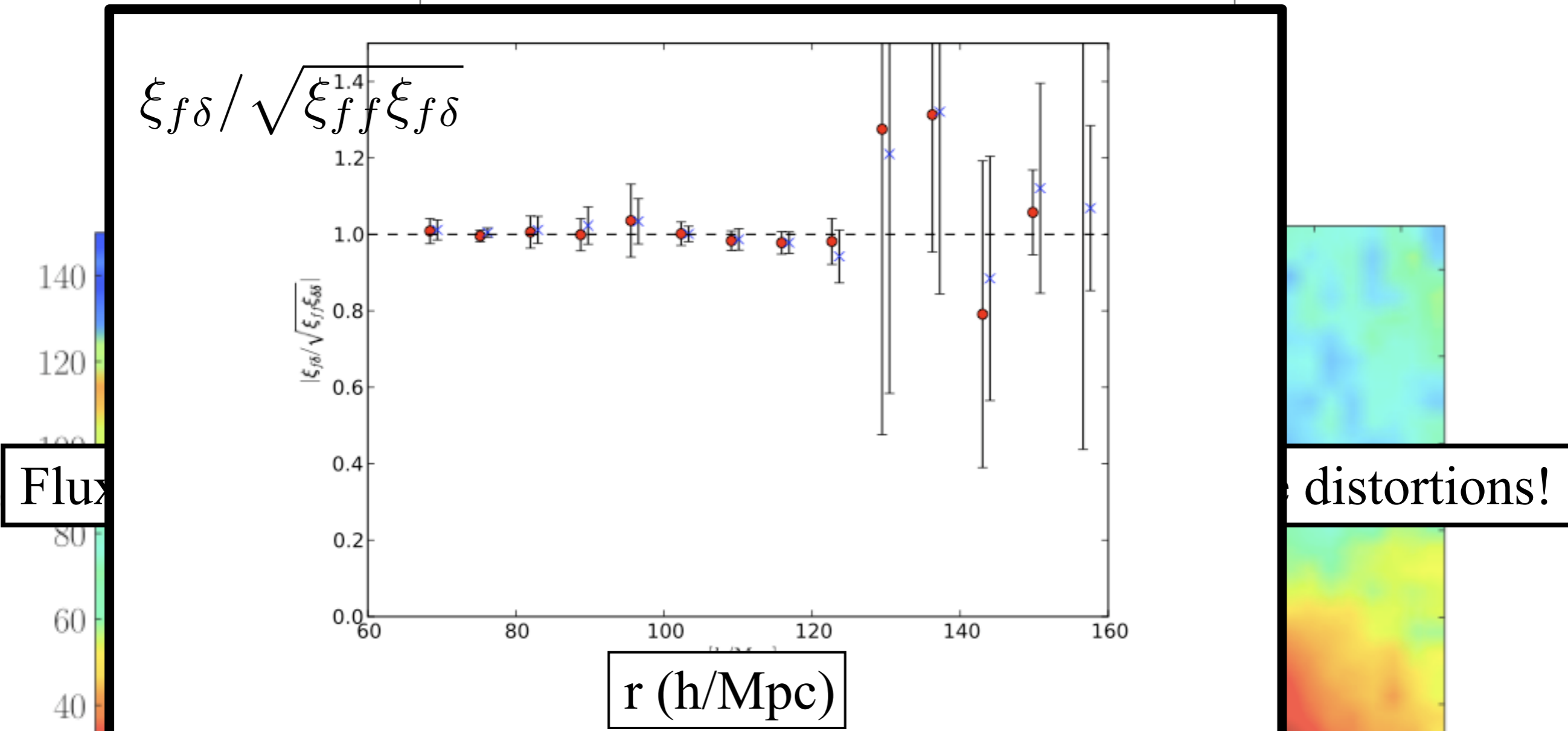


FIG. 7: The cross-correlation coefficient between flux and matter over-density in real (red) and redshift (blue) space.

Slosar, SH, White & Louis (2009)

Constraining Dark Energy with Ly α forest BAO

Redshift Space Correlation function

Matter

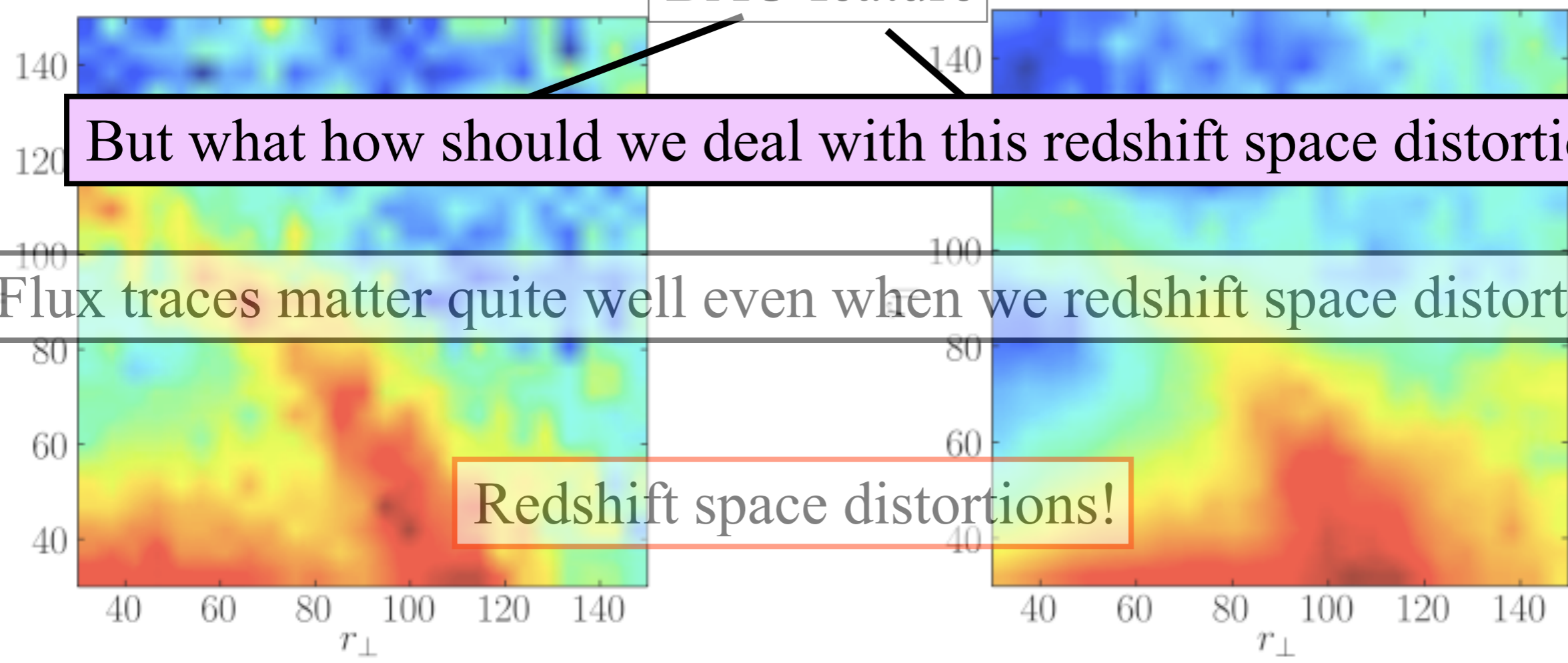
Flux

BAO feature

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

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

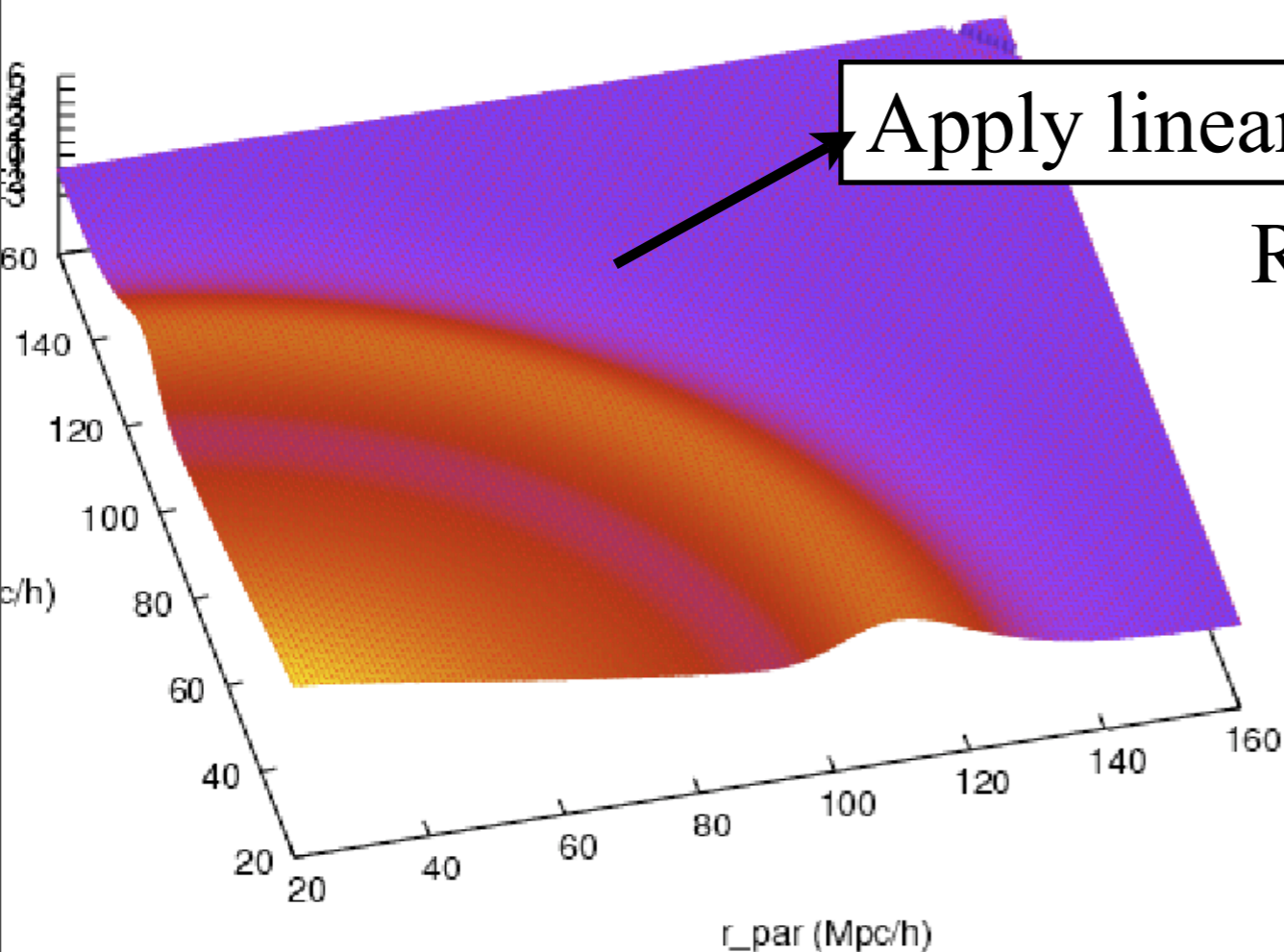
Redshift space distortions!



Constraining Dark Energy with Ly α forest BAO

No z-space distortion

z-space distortions



Apply linear Kaiser formula

Ref: Kaiser 1989

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

$$\xi_0(r) = C_0 \xi_R(r),$$

$$\xi_2(r) = C_2 (\xi_R(r) - \bar{\xi}(r)),$$

$$\xi_4(r) = C_4 (\xi_R(r) + 2.5 \bar{\xi}(r) - 3.5 \bar{\bar{\xi}}(r)),$$

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

$$C_i = f_i(\beta)$$

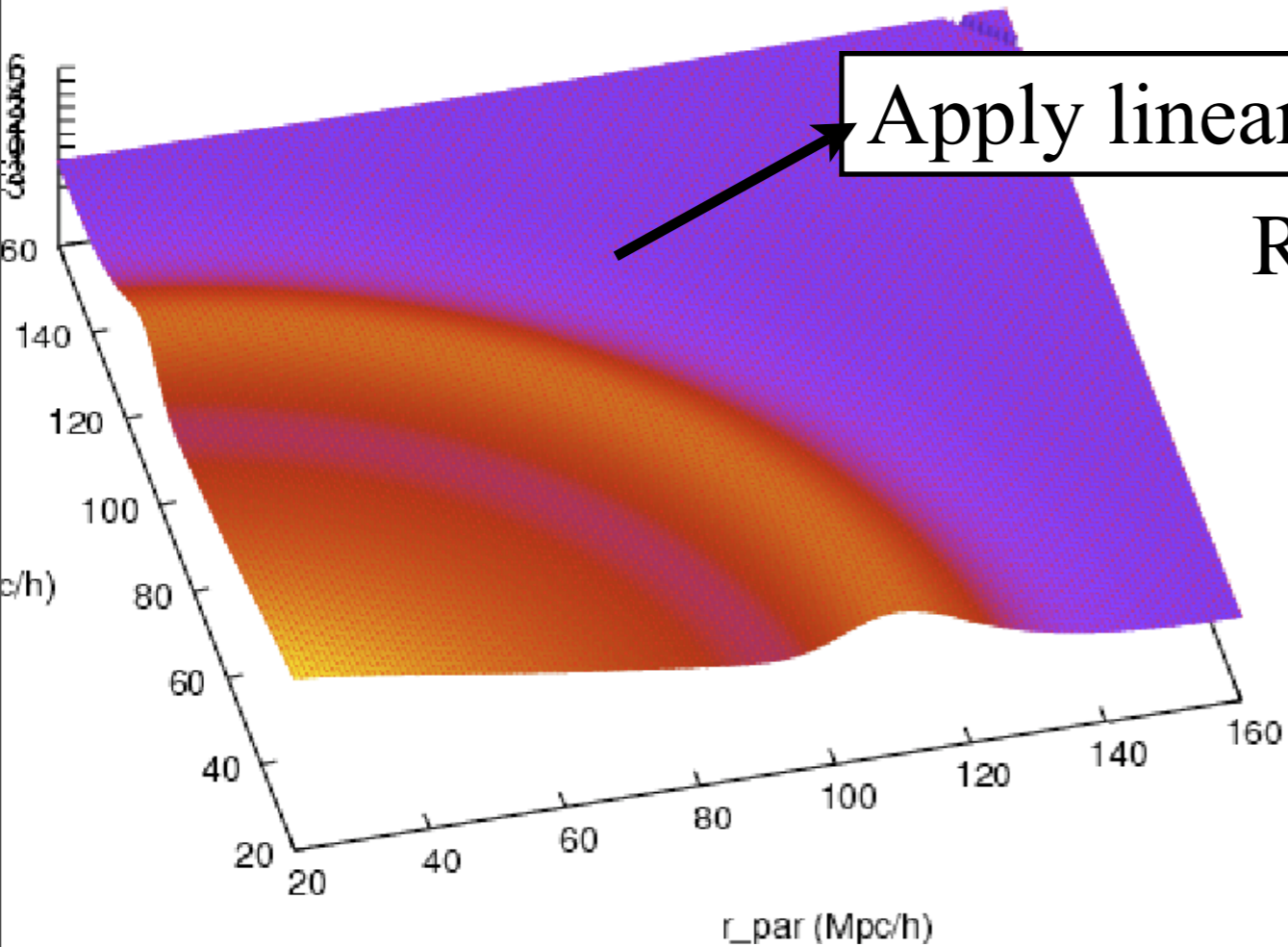
$$\beta = d \ln \delta / d \ln a = \Omega_m^{0.6}$$

Constraining Dark Energy with Ly α forest BAO



No z-space distortion

z-space distortions



Apply linear Kaiser formula

Ref: Kaiser 1989

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$$\xi_4(r) = C_4 (\xi_R(r) + 2.5 \bar{\xi}(r) - 3.5 \bar{\bar{\xi}}(r)),$$

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

Kaiser formula can be derived from the fact that the number of galaxies is conserved (even including z-space distortions)

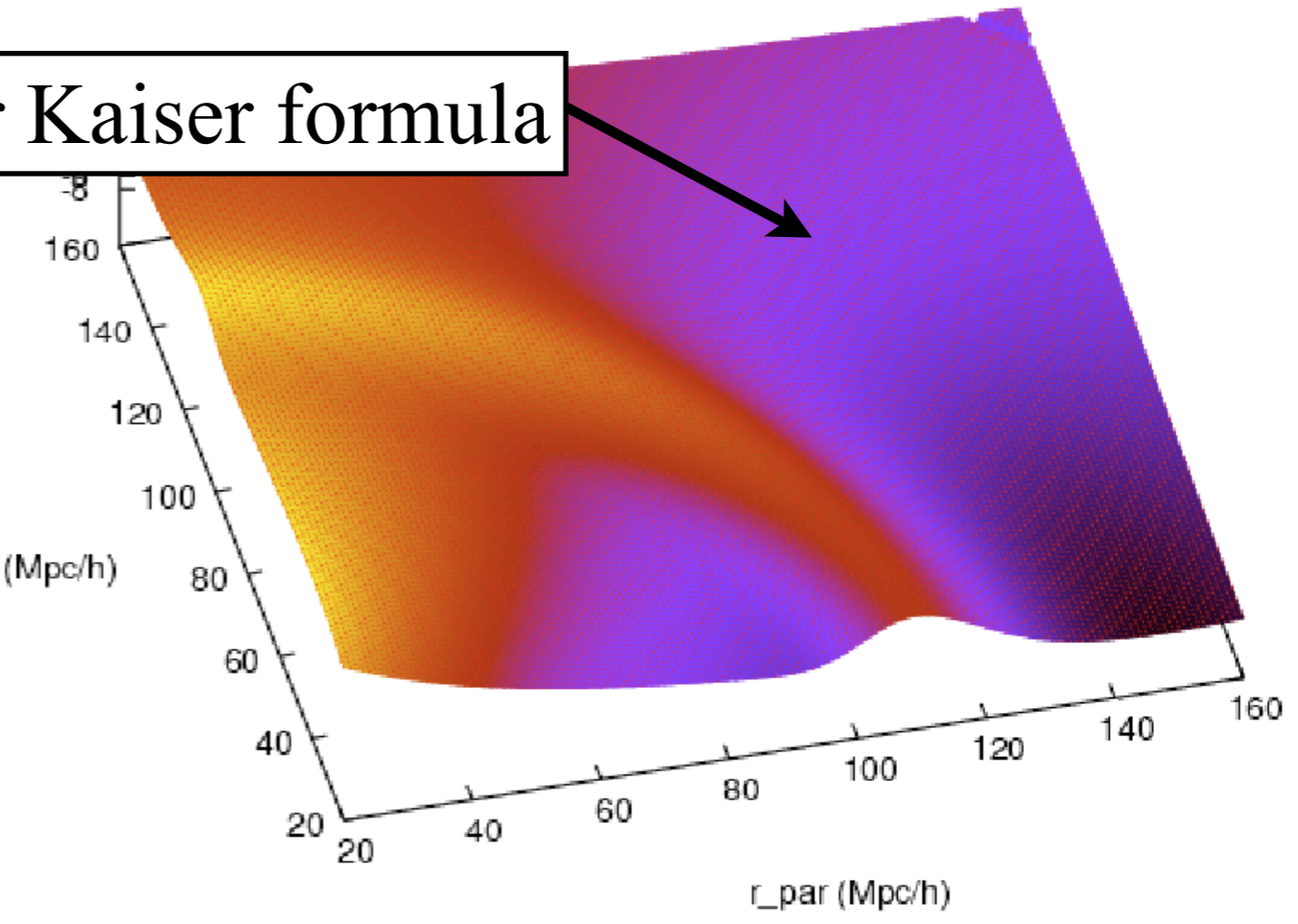
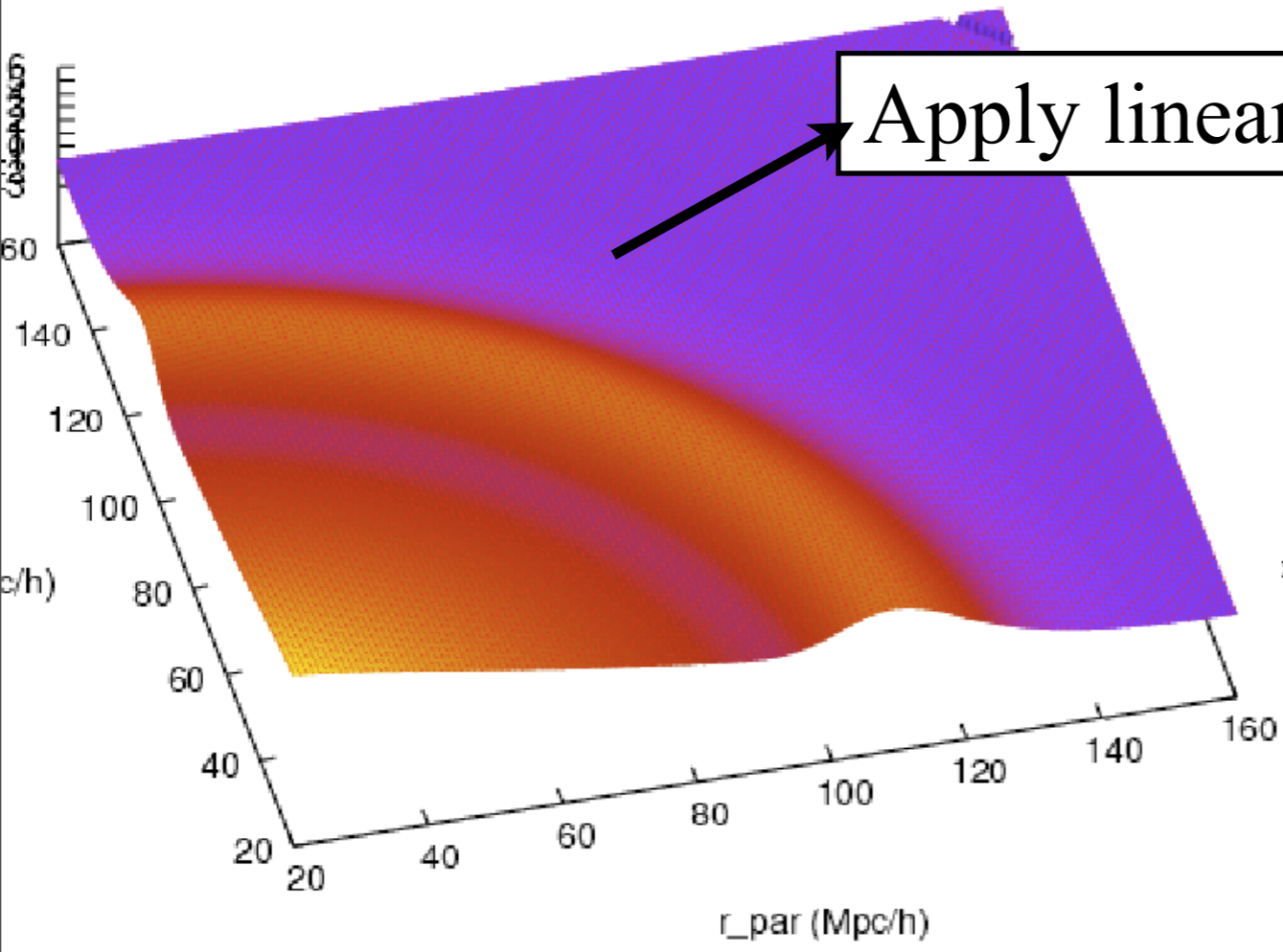
Constraining Dark Energy with Lya forest BAO



No z-space distortion

z-space distortions

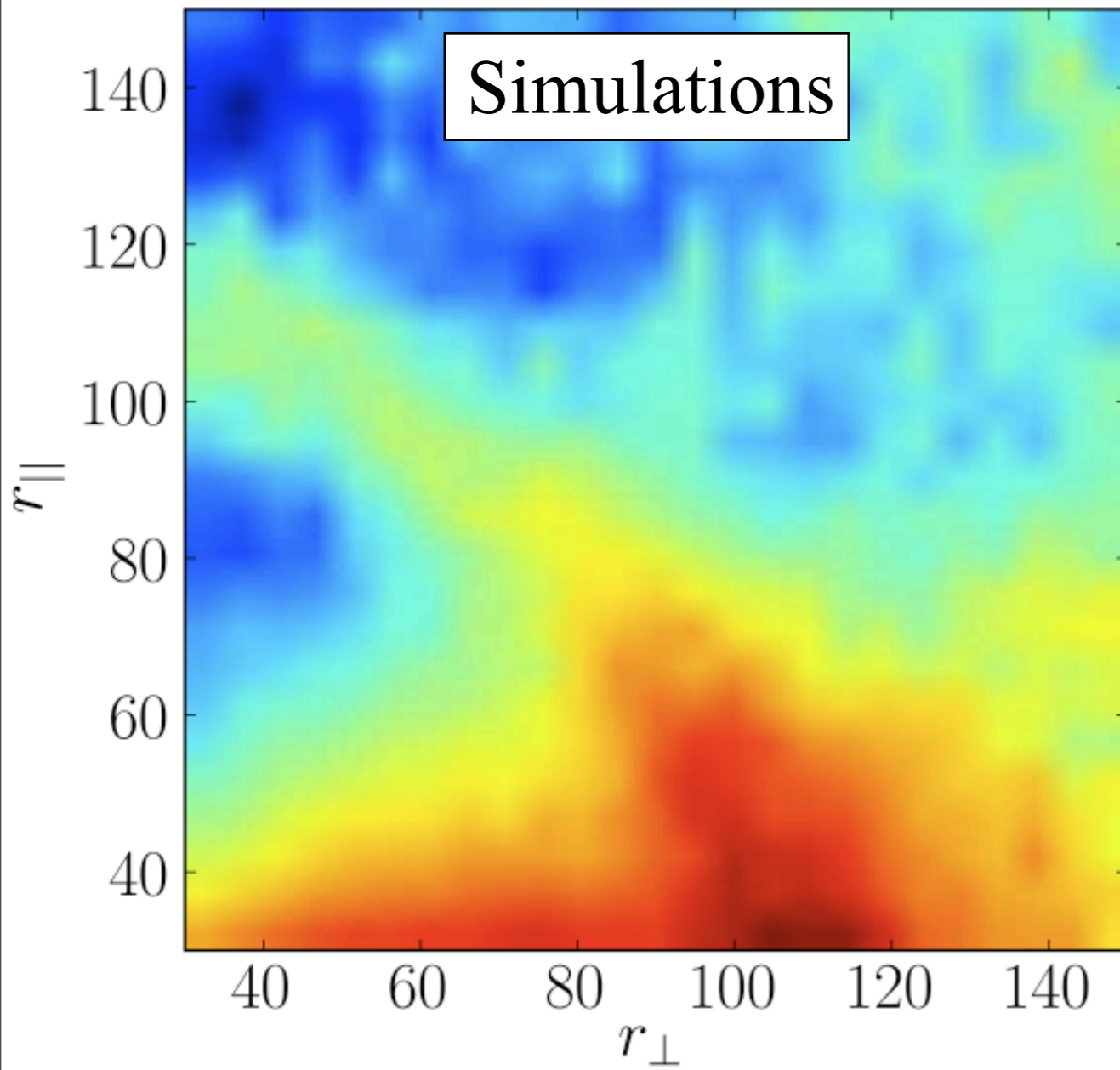
Apply linear Kaiser formula



Constraining Dark Energy with Ly α forest BAO



Flux



Constraining Dark Energy with Ly α forest BAO



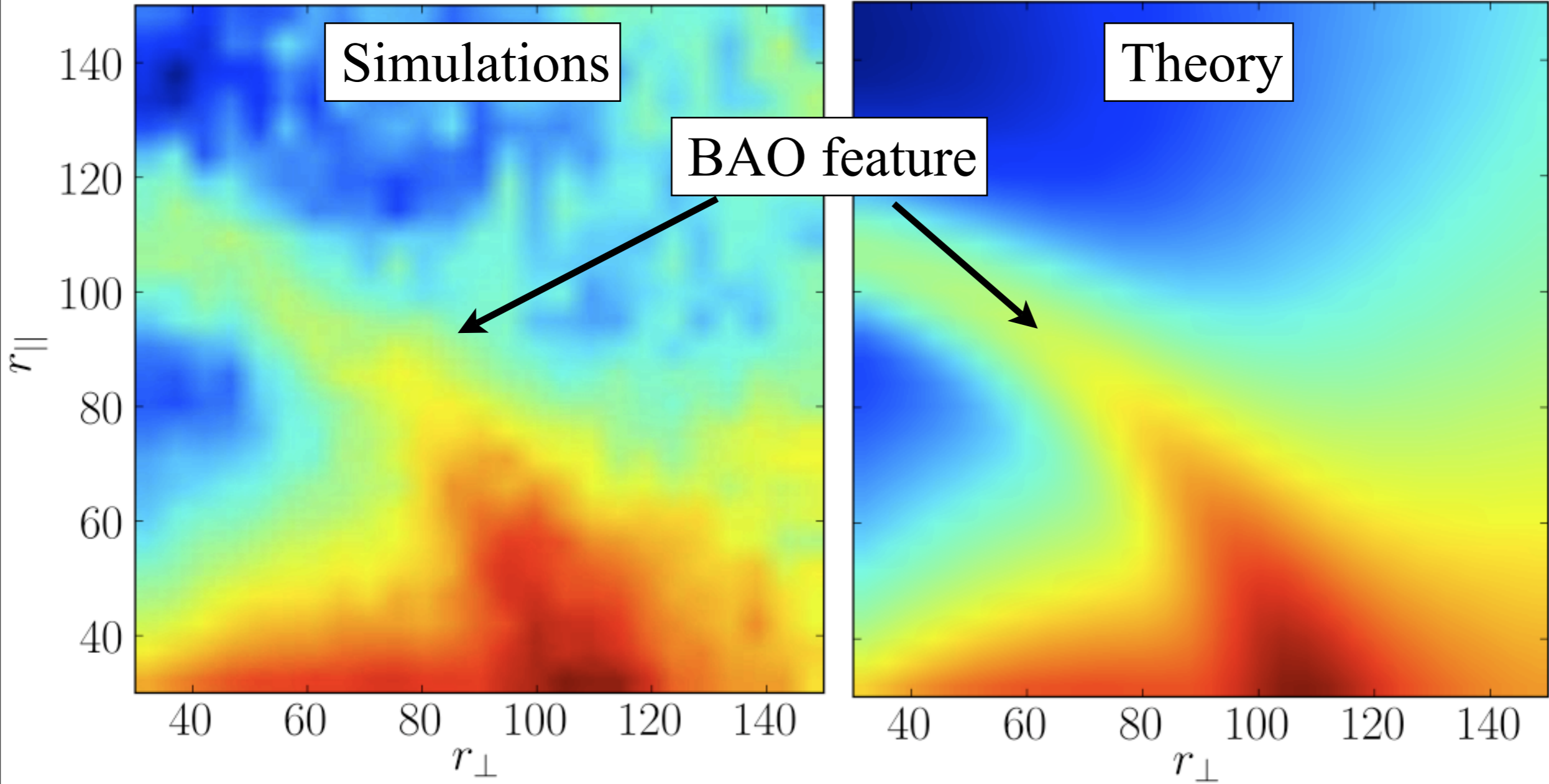
Flux

Flux

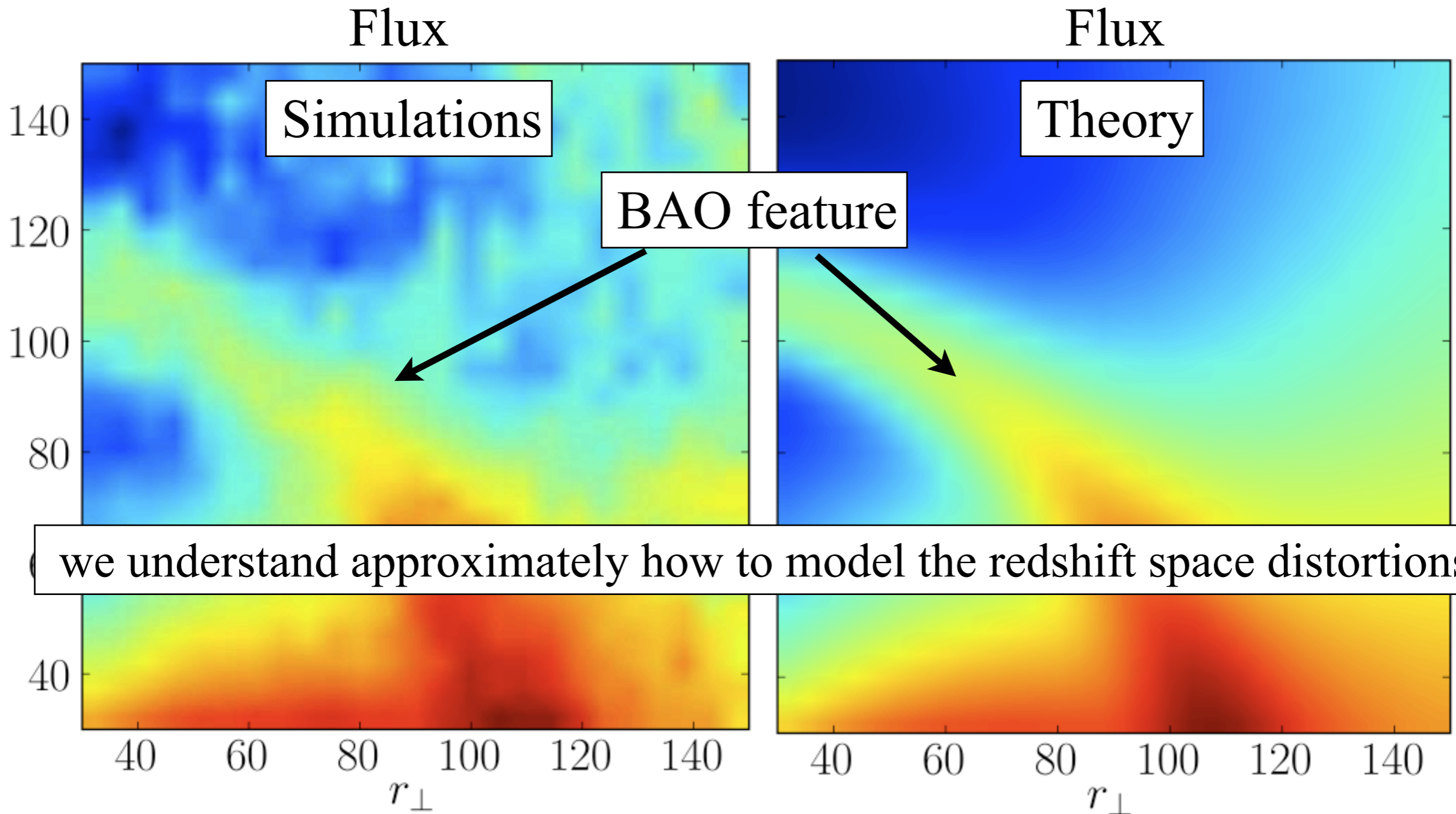
Simulations

Theory

BAO feature



Constraining Dark Energy with Ly α forest BAO



Slosar, SH, White & Louis (2009)

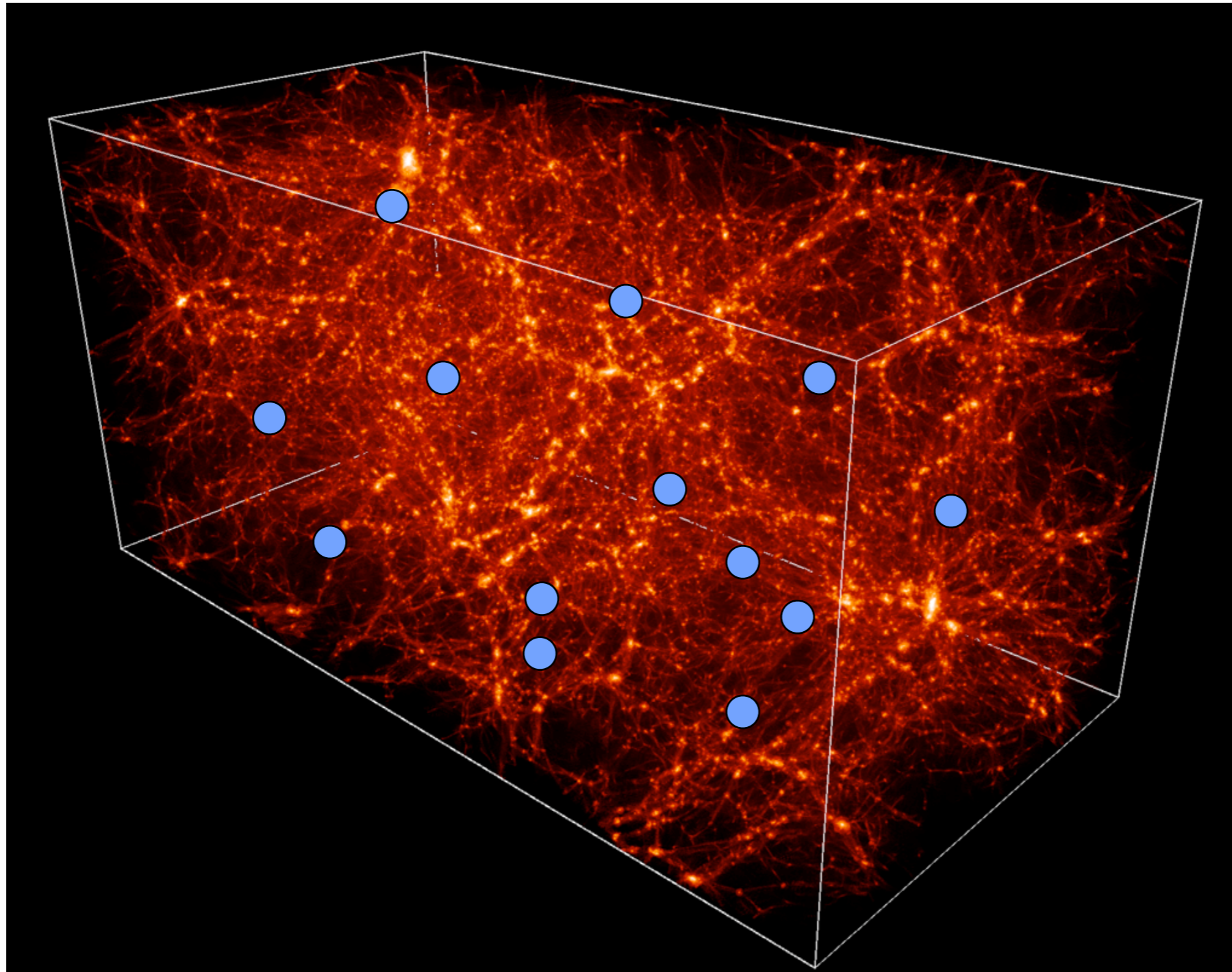
Possible Systematics



- **UV background fluctuations**
- **Metal Line contaminations**
- **Continuum subtractions**
- **Other IGM physics? ...**

Possible Systematics: UV background fluctuations

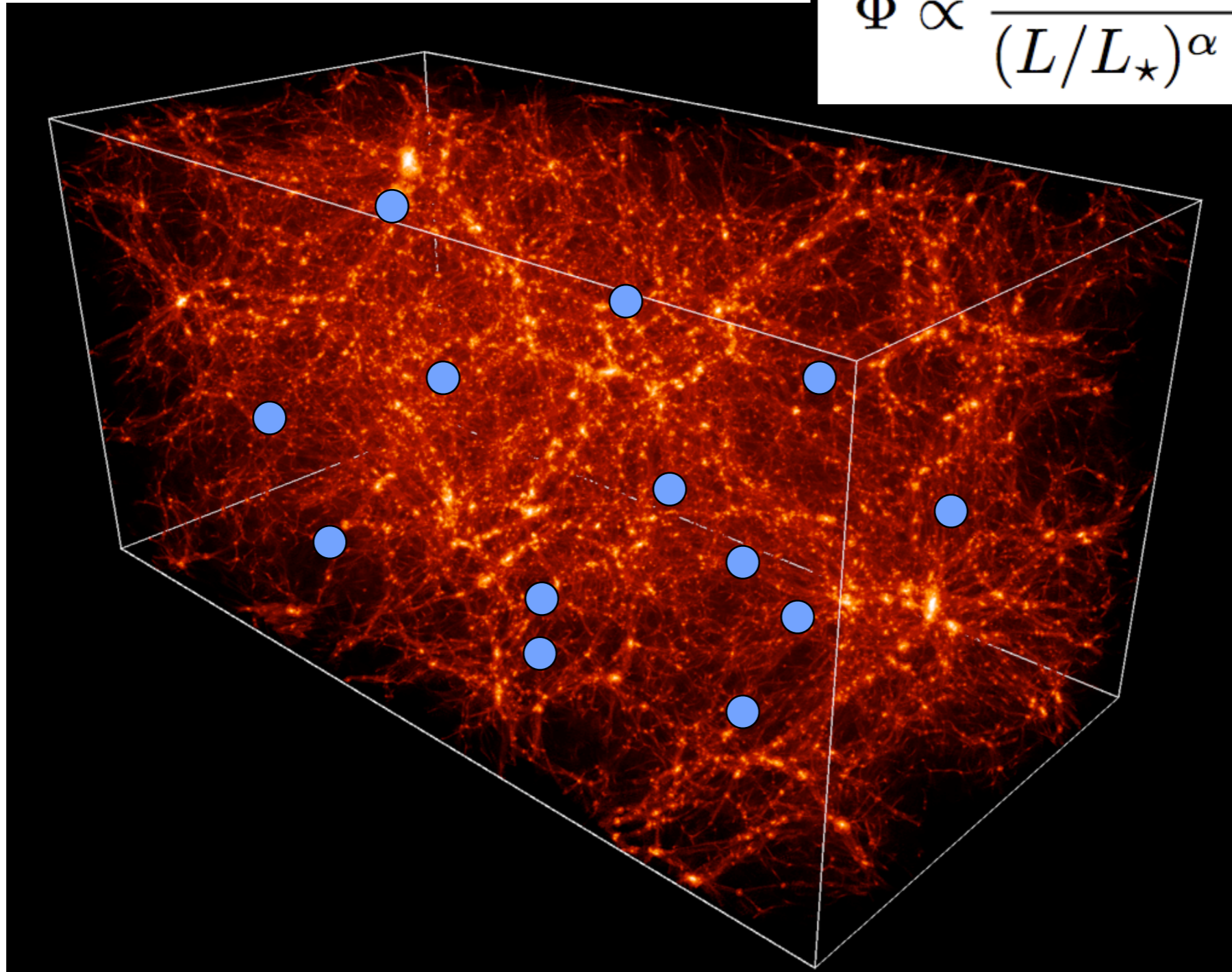
Adding Quasars at redshift ~ 2



Possible Systematics: UV background fluctuations

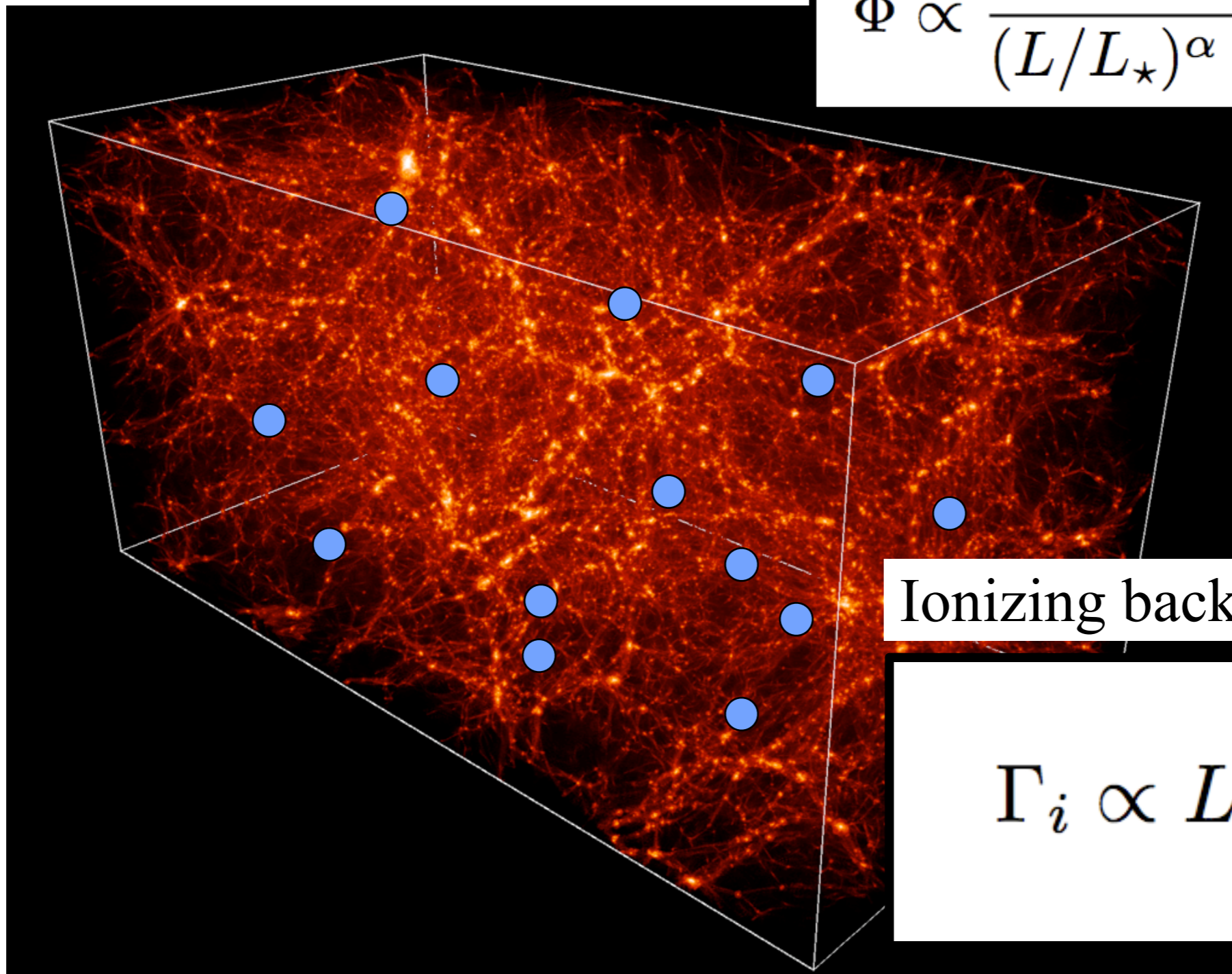
With a luminosity function:

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



Possible Systematics: UV background fluctuations

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



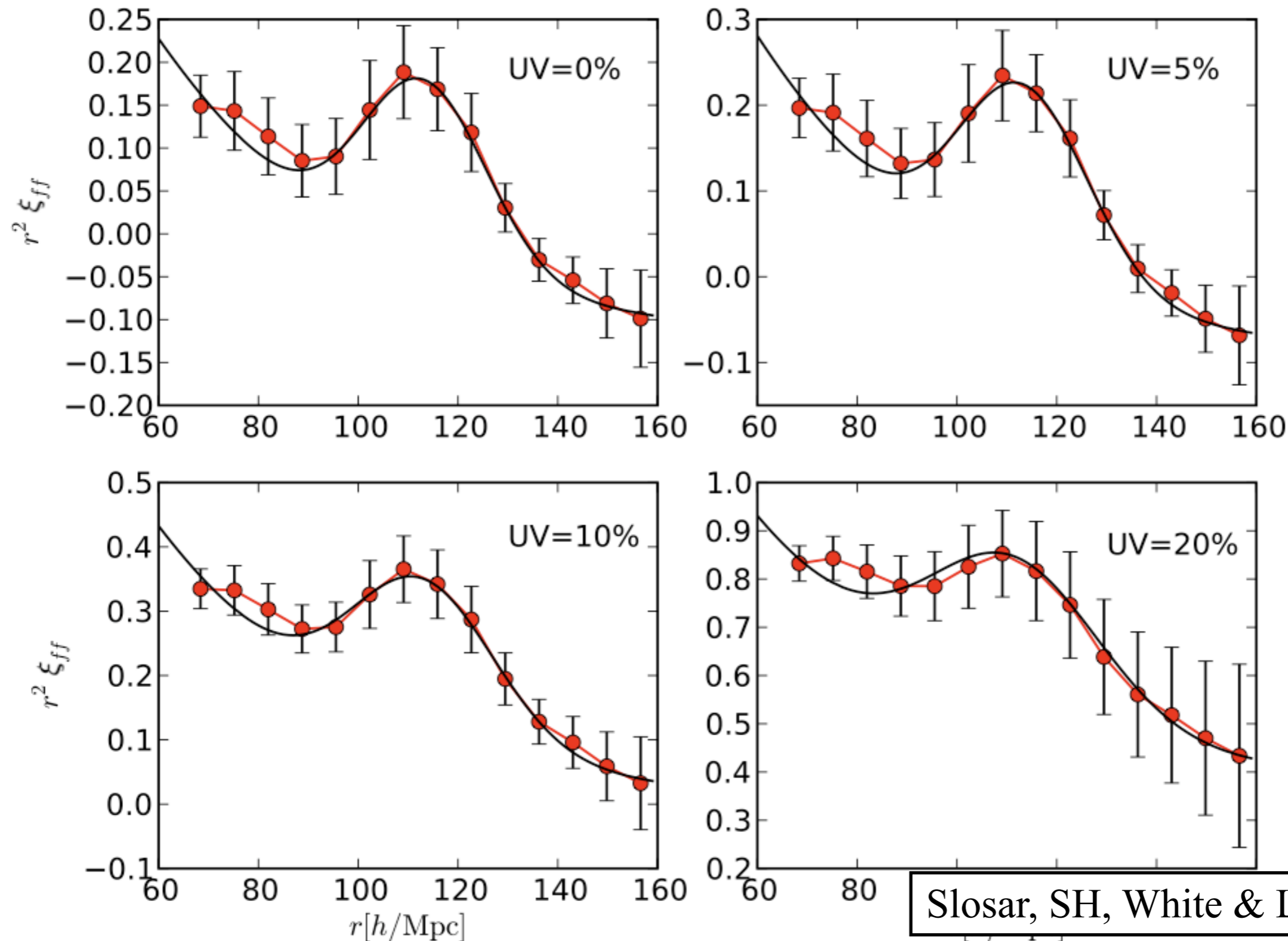
Ionizing background:

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

Possible Systematics: UV background fluctuations

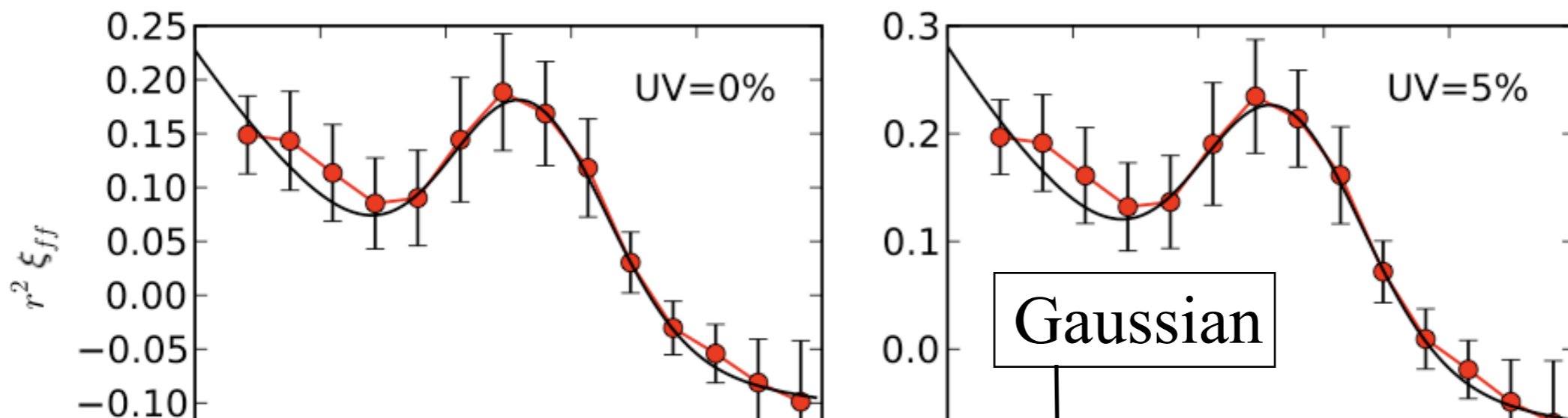


Correlation function

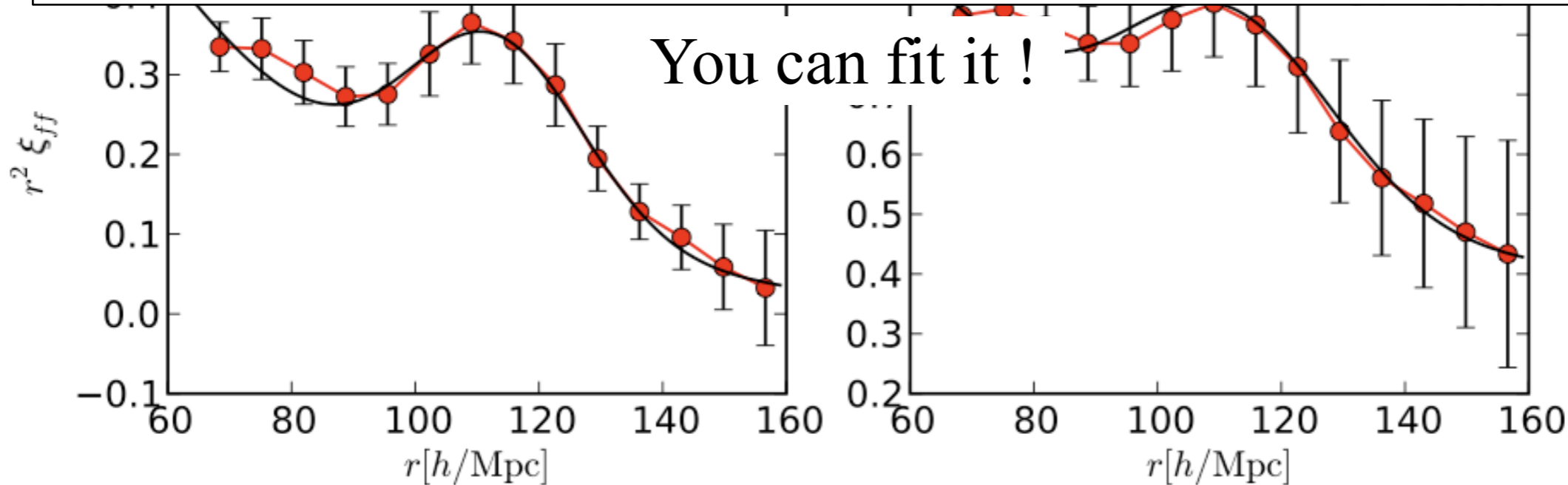


Slosar, SH, White & Louis (2009)

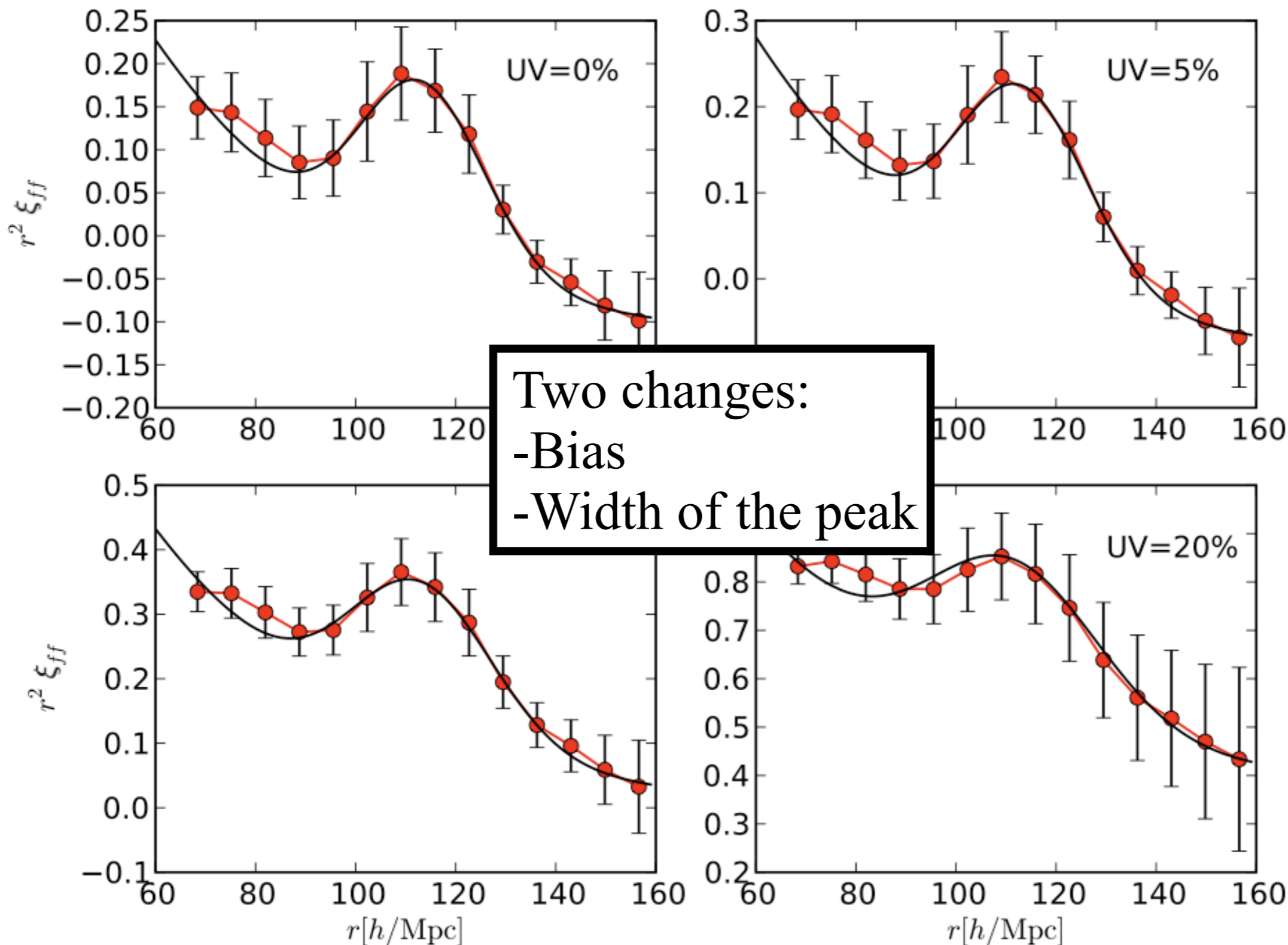
Possible Systematics: UV background fluctuations



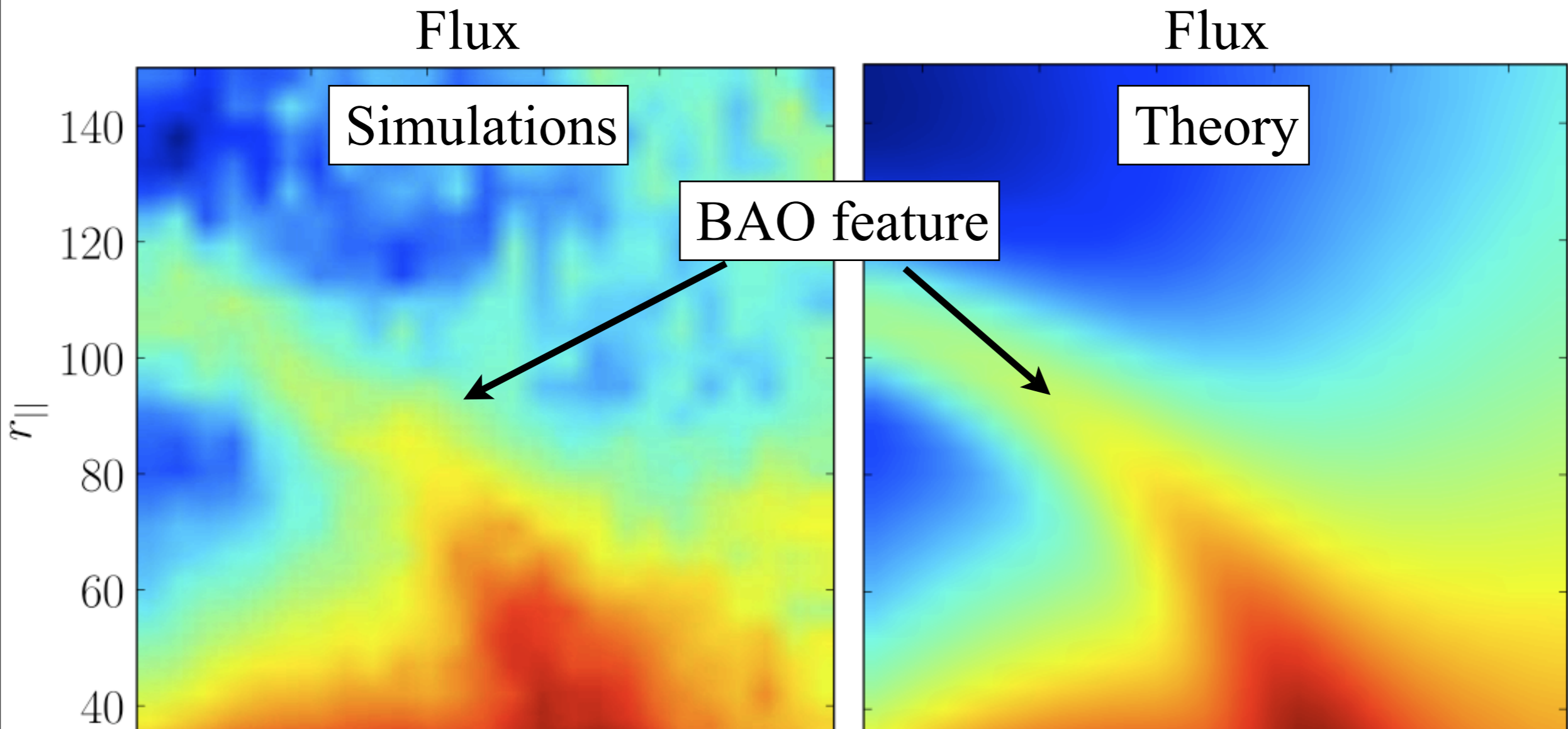
$$\xi(r) = b^2 \left(\xi_{\text{nb}}(r) + \frac{h}{r^2} G(r_{\text{peak}}, \sigma_{\text{peak}}) \right) + \lambda$$



Possible Systematics: UV background fluctuations



Constraining Dark Energy with Ly α forest BAO



To conclude for Ly α BAO, we approximately understand how to model the redshift space distortions, and what happens when we include systematics such as UV background fluctuations.

Outline



- **Motivations**
- **Introduction (What is lighting up the what?)**
- **What can you do with Lyman-alpha forest?**
 - **Baryon Acoustic Oscillations**
 - Dark Energy
 - **Scale Dependent Bias**
 - **Primordial Non-gaussianities -> Inflation**
- **Conclusion**

What happened at the beginning of the 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

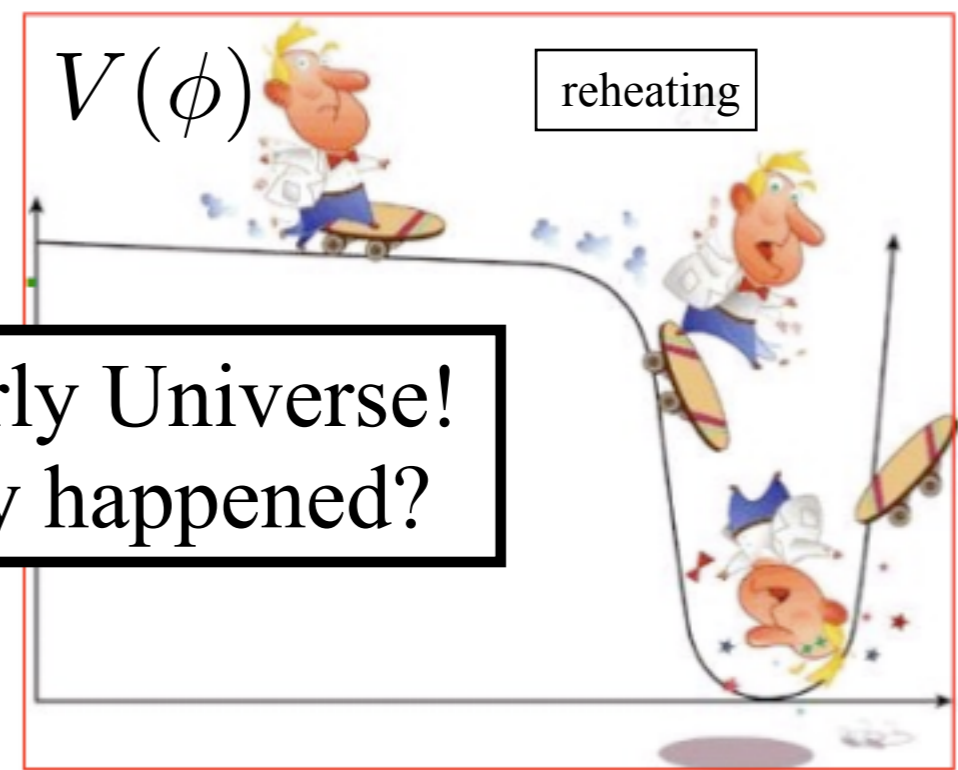
$f_{NL} \sim 0.05$ canonical inflation (single field, couple of derivatives)
 (Maldacena 2003, Acquaviva et al 2003)

$f_{NL} \sim 0.1-100$ higher order derivatives

We have many models of early Universe!
 How do we tell what actually happened?

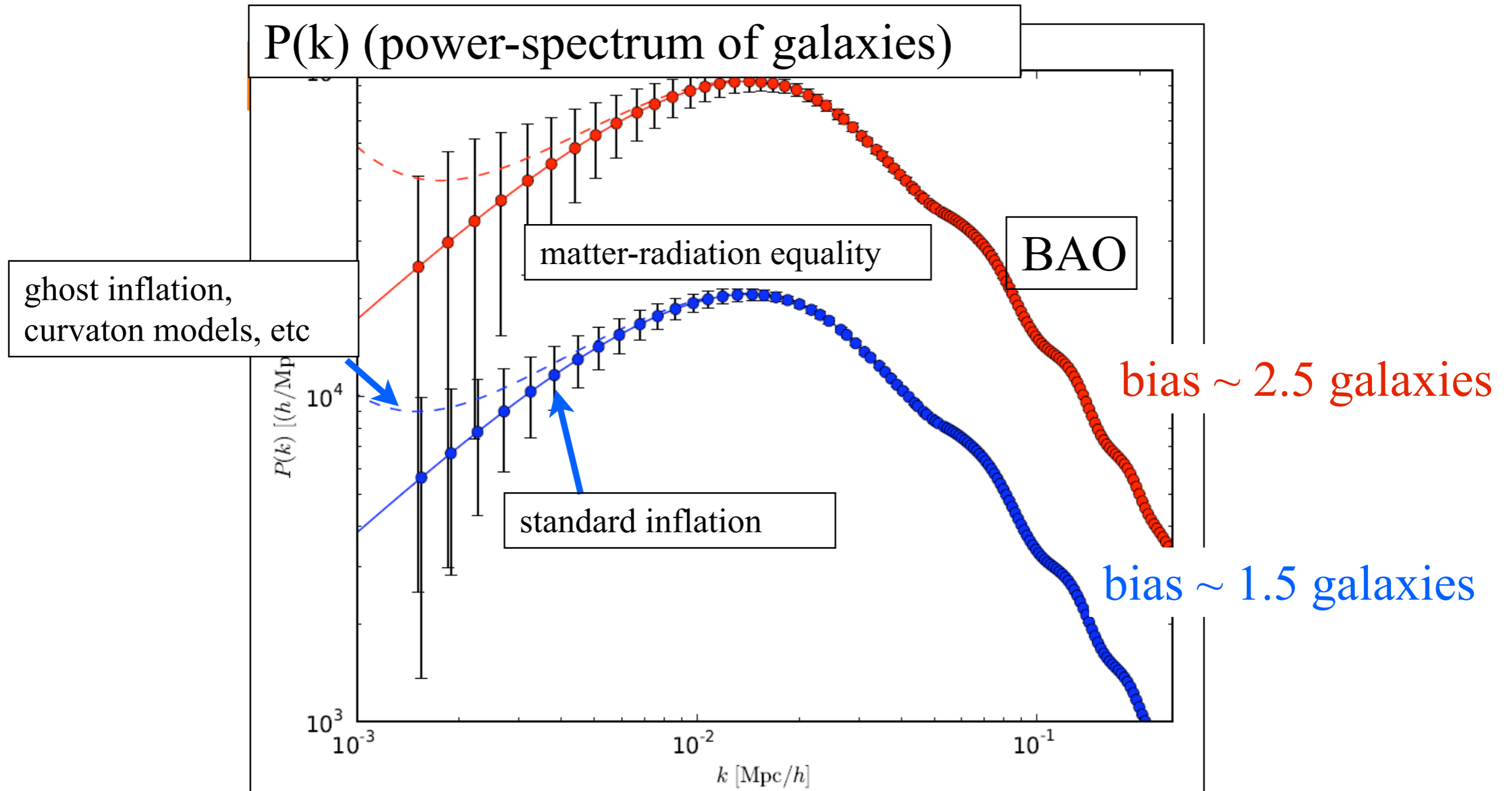
$f_{NL} > 10$ curvaton models (Lyth, Ungarelli and Wands, 2003)

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

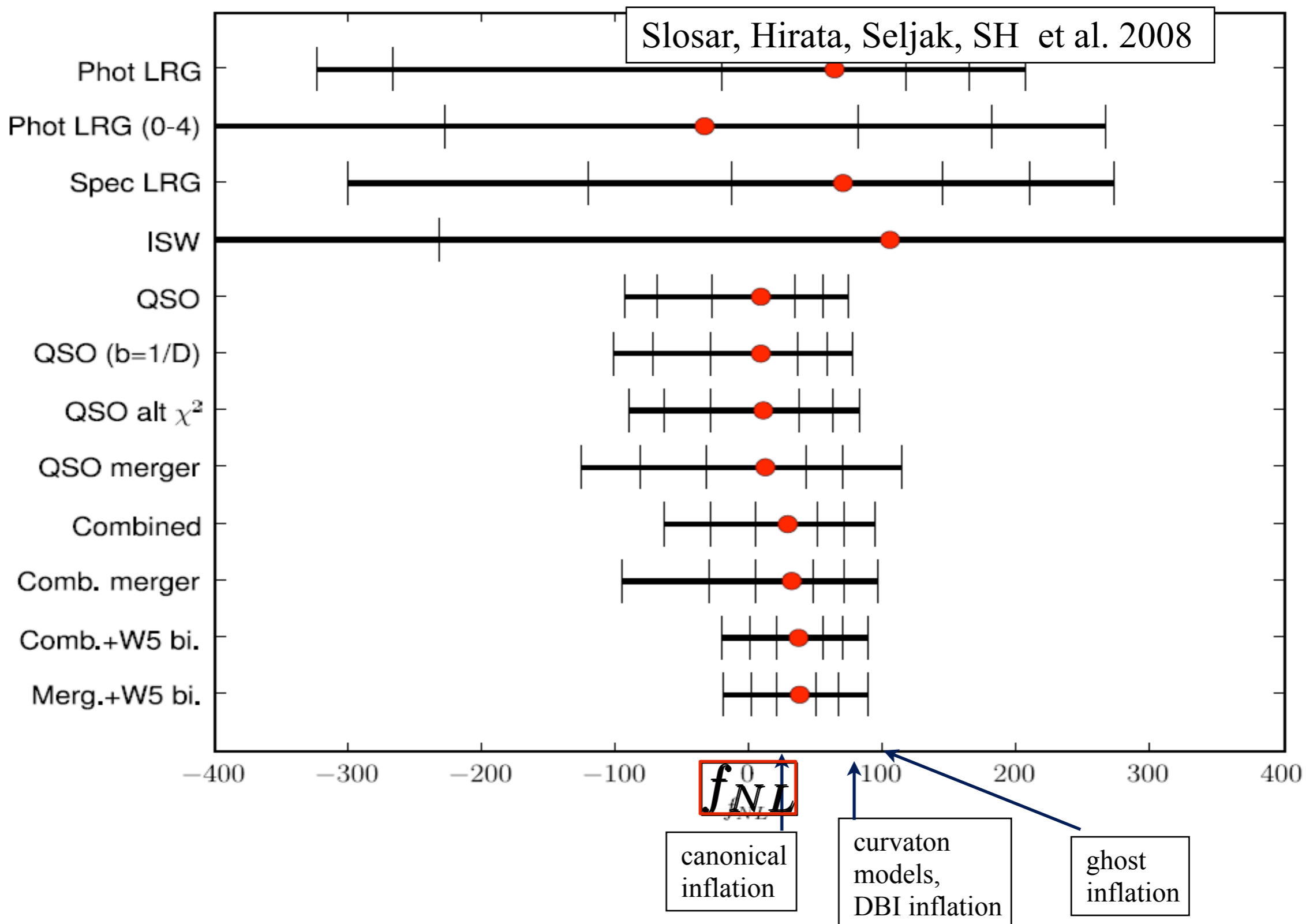


Inflation

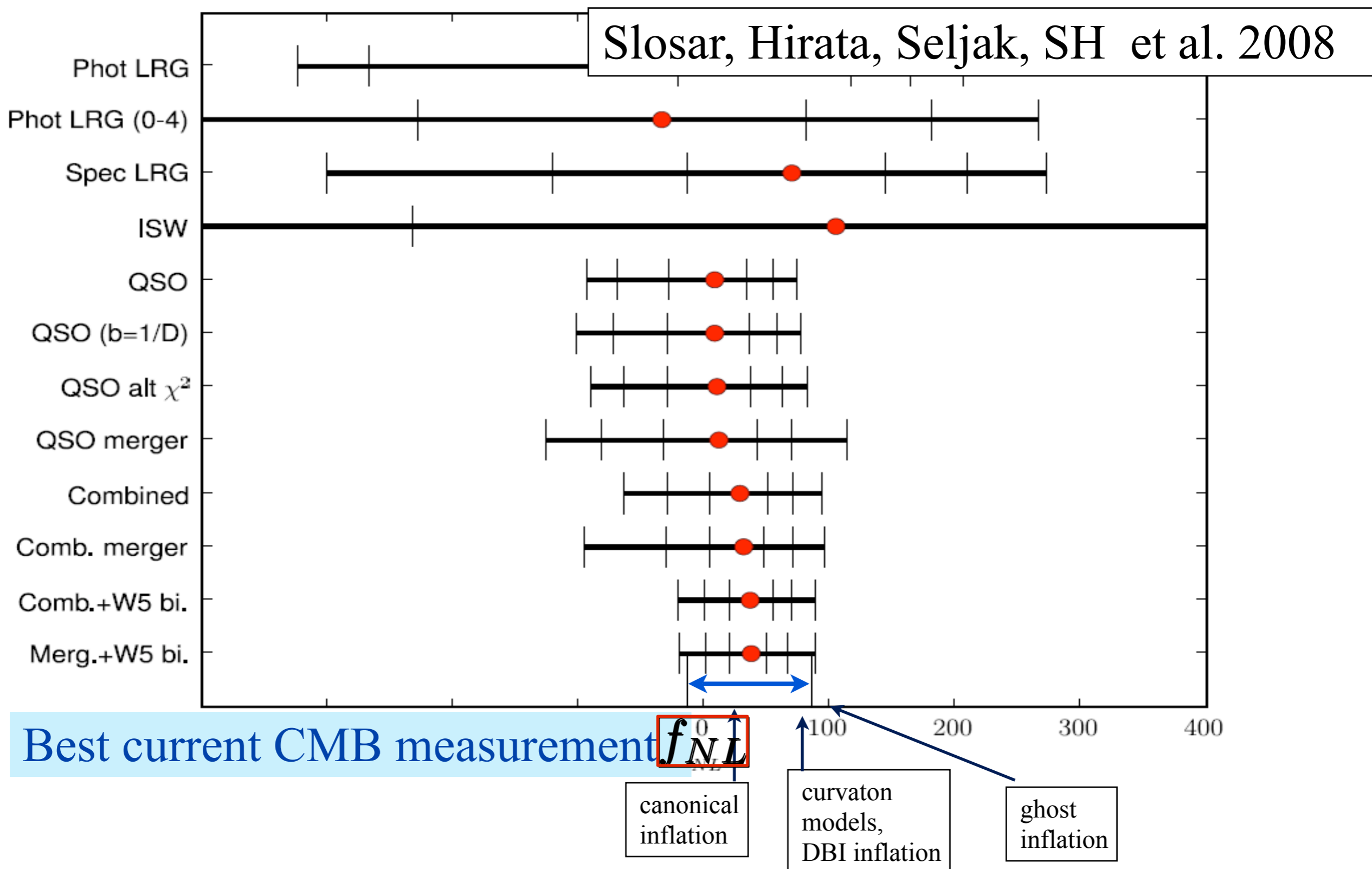
Recall from last lecture: The 3D power-spectrum of galaxies



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



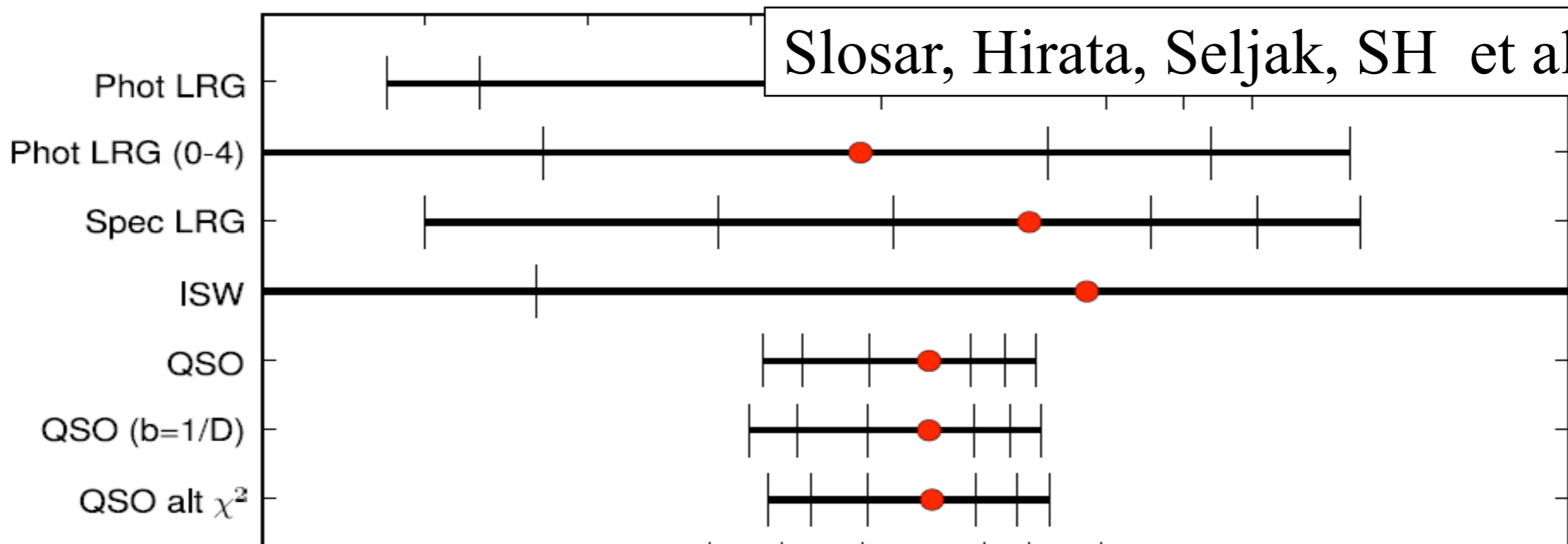
Using Large scale structure to learn about the beginning of the Universe



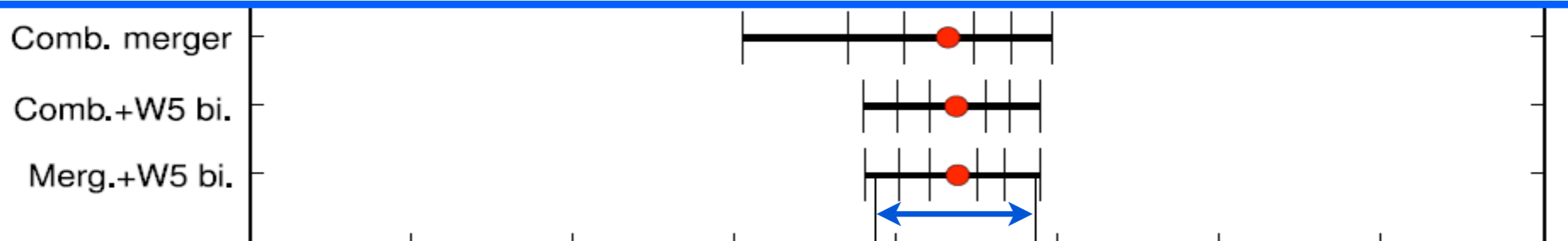
Using Large scale structure to learn about the beginning of the Universe



Slosar, Hirata, Seljak, SH et al. 2008



What happens if we use Lyman-alpha forest ?



Best current CMB measurement

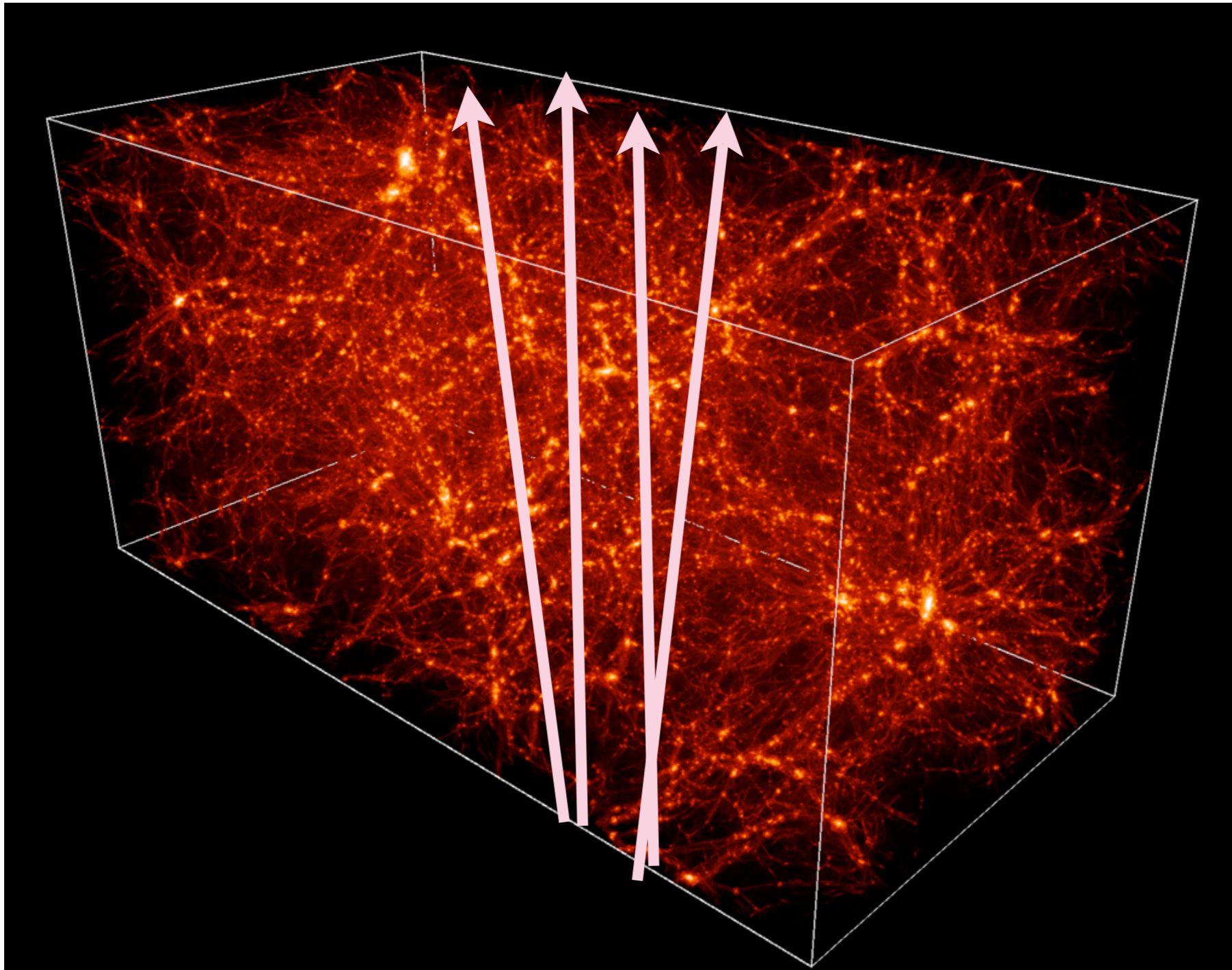
f_{NL}^0

canonical inflation

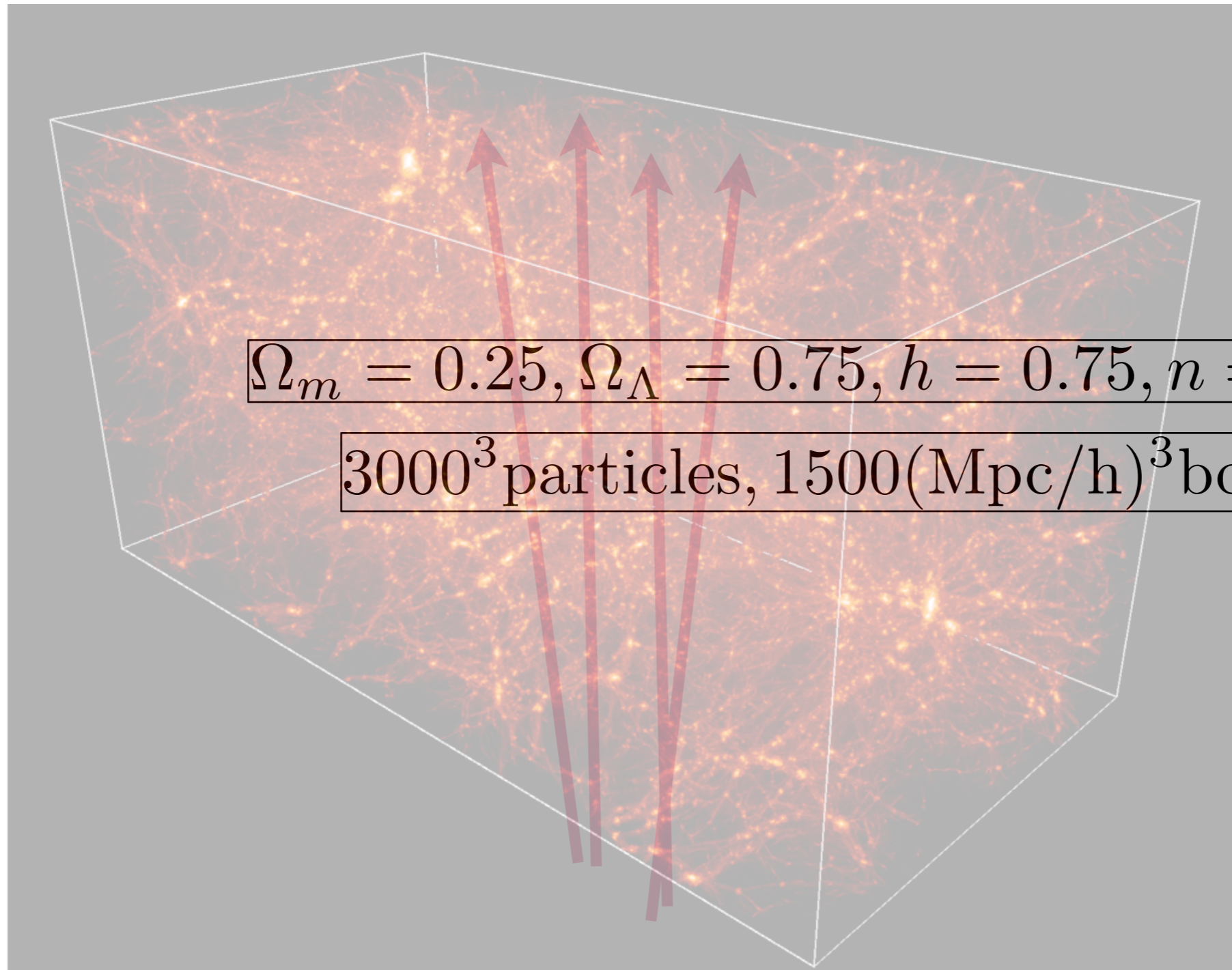
curvaton models, DBI inflation

ghost inflation

Constraining Primordial Non-gaussianities with Ly α forest Clustering



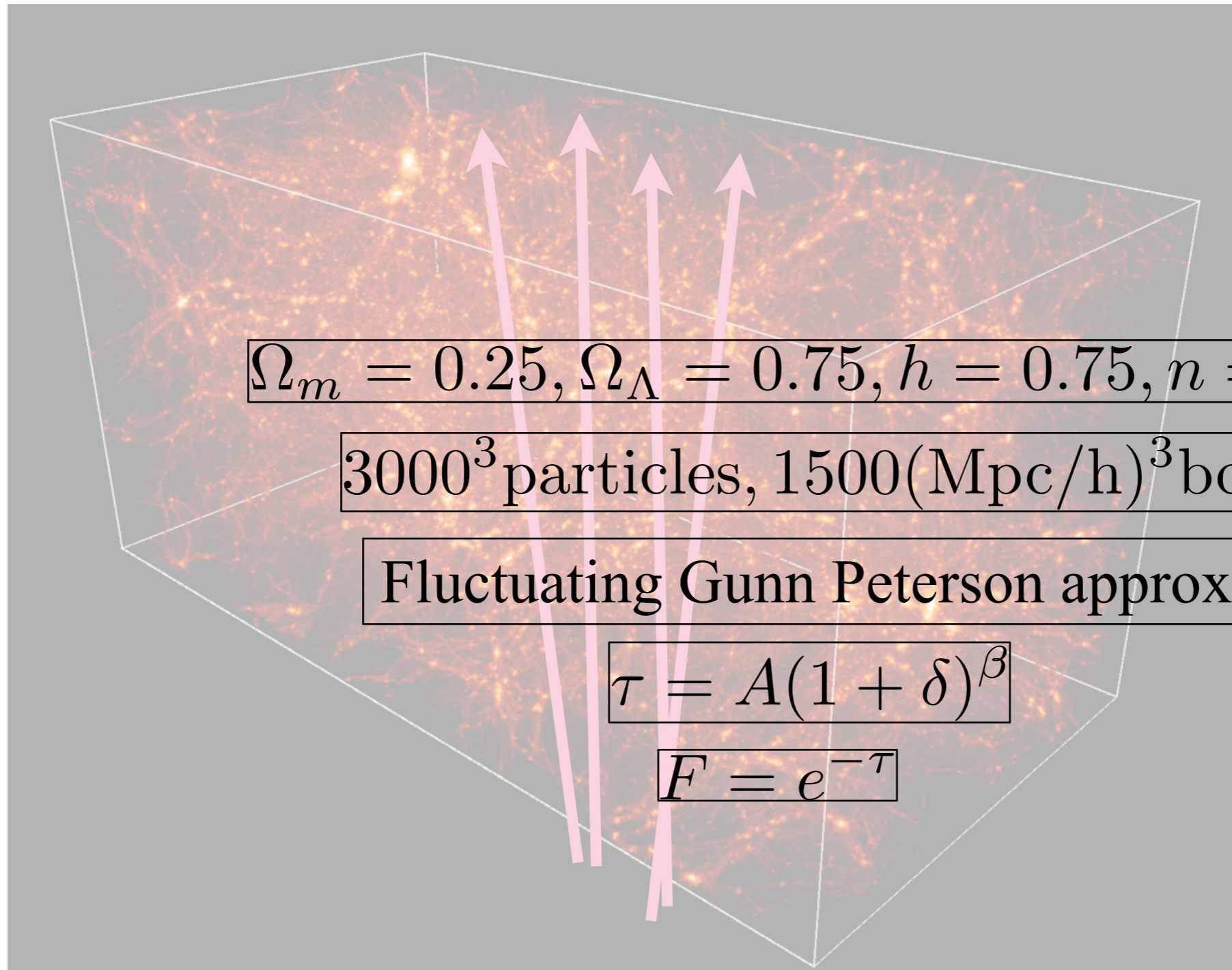
Constraining Primordial Non-gaussianities with Ly α forest Clustering



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

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

Constraining Primordial Non-gaussianities with Ly α forest Clustering



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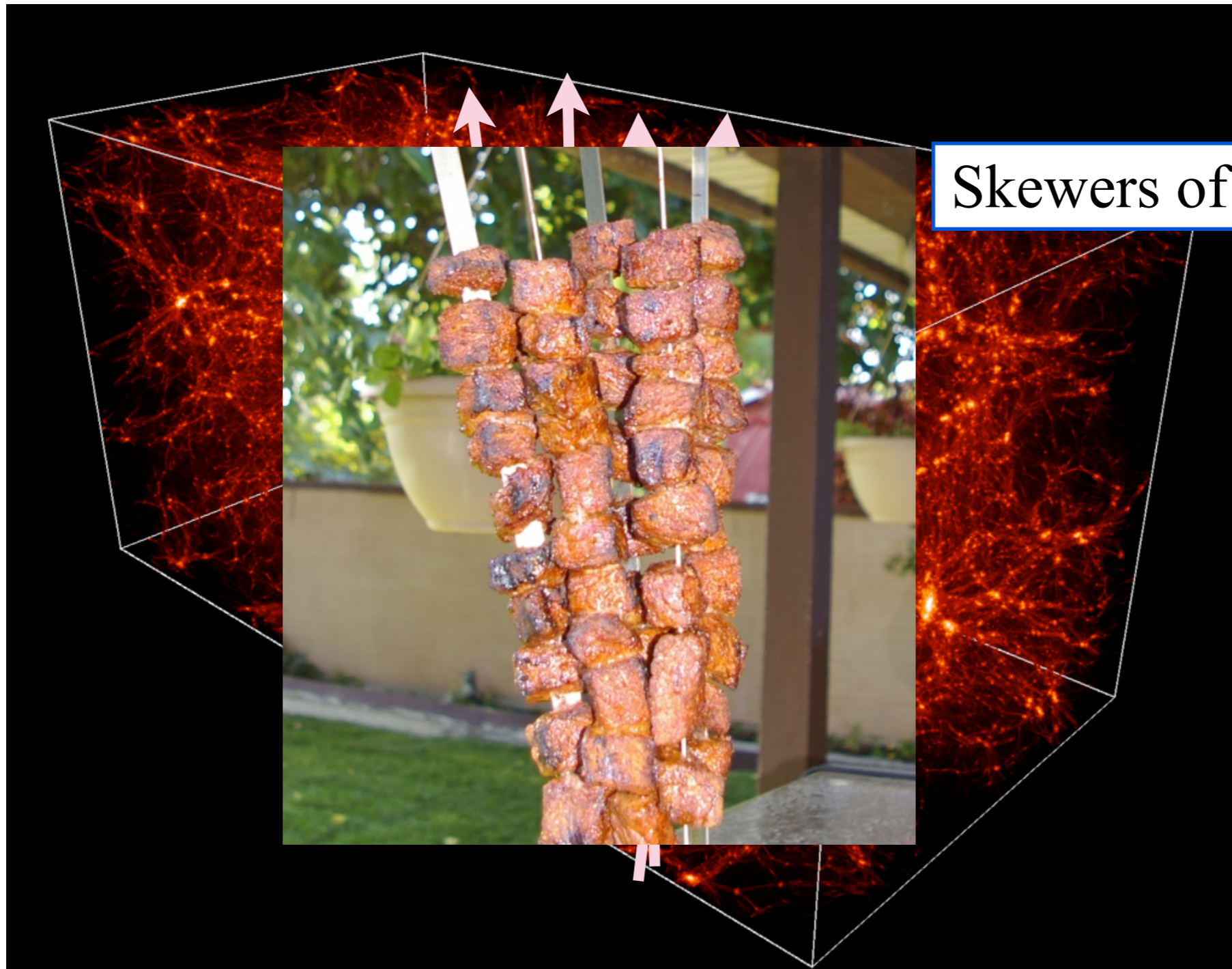
3000^3 particles, $1500(\text{Mpc}/h)^3$ box, 3000^3 grid

Fluctuating Gunn Peterson approximation

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

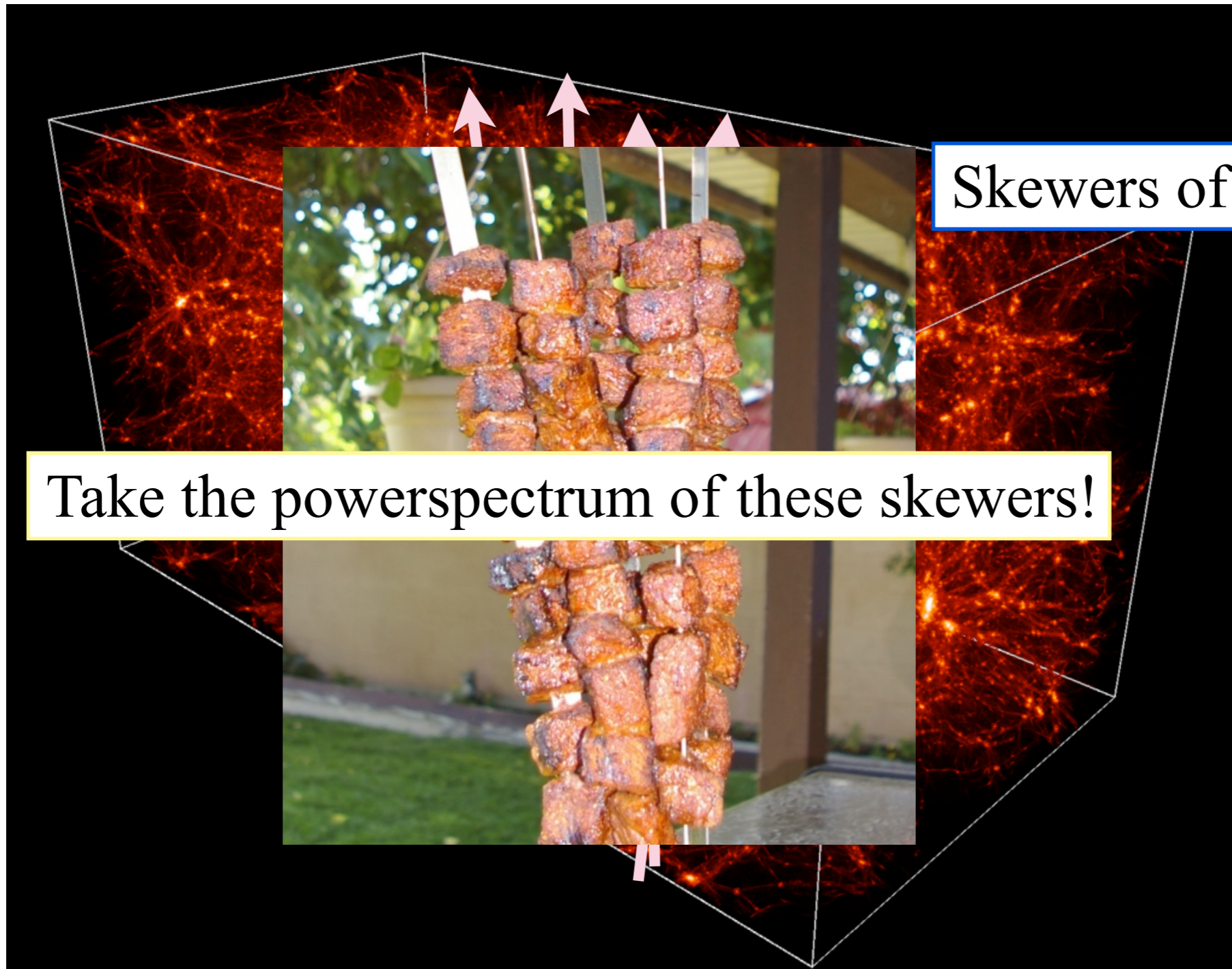
$$F = e^{-\tau}$$

Constraining Primordial Non-gaussianities with Lya forest Clustering



Skewers of Neutral Hydrogen

Constraining Primordial Non-gaussianities with Lya forest Clustering



Skewers of Neutral Hydrogen

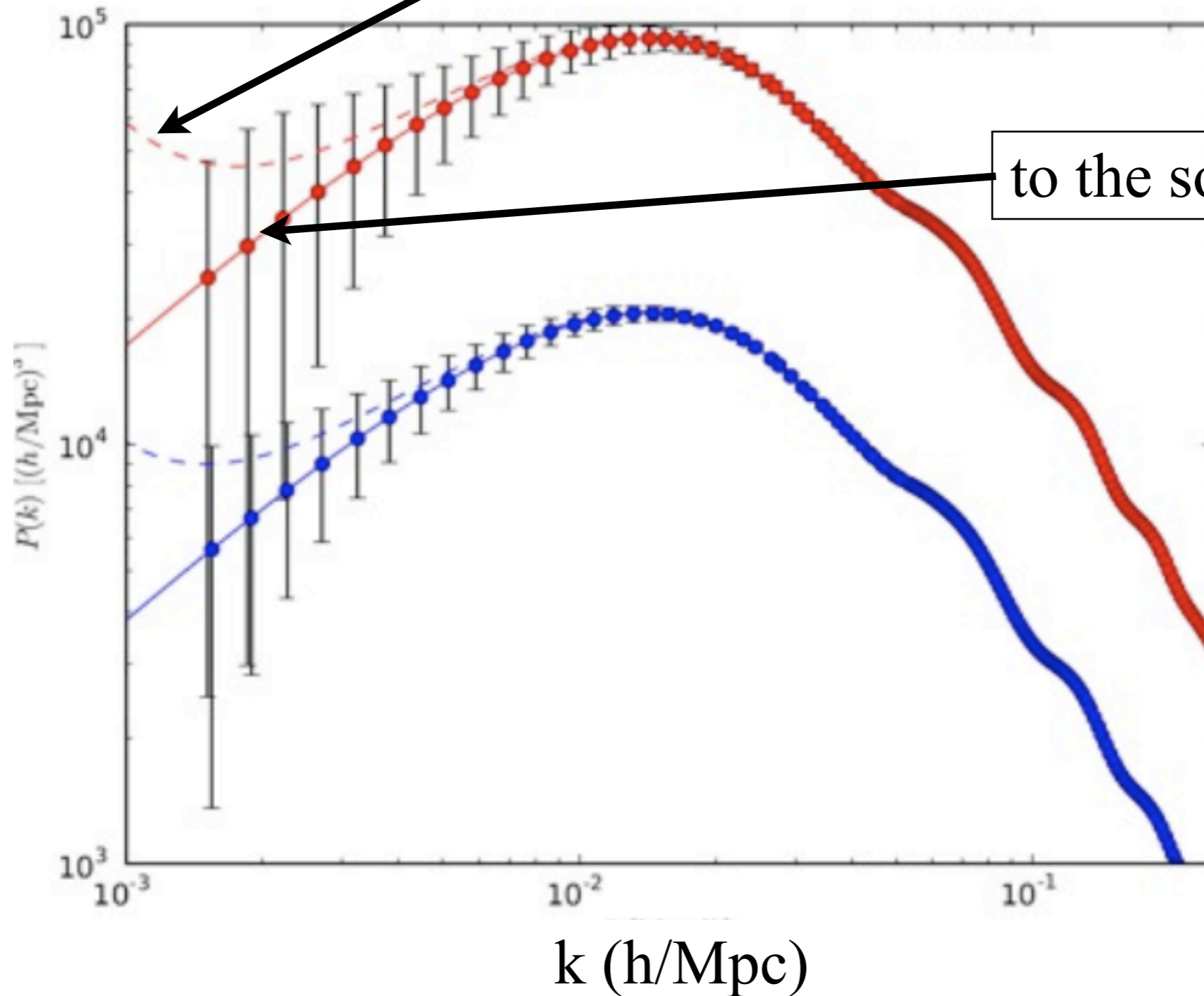
Take the powerspectrum of these skewers!

What will we be plotting?

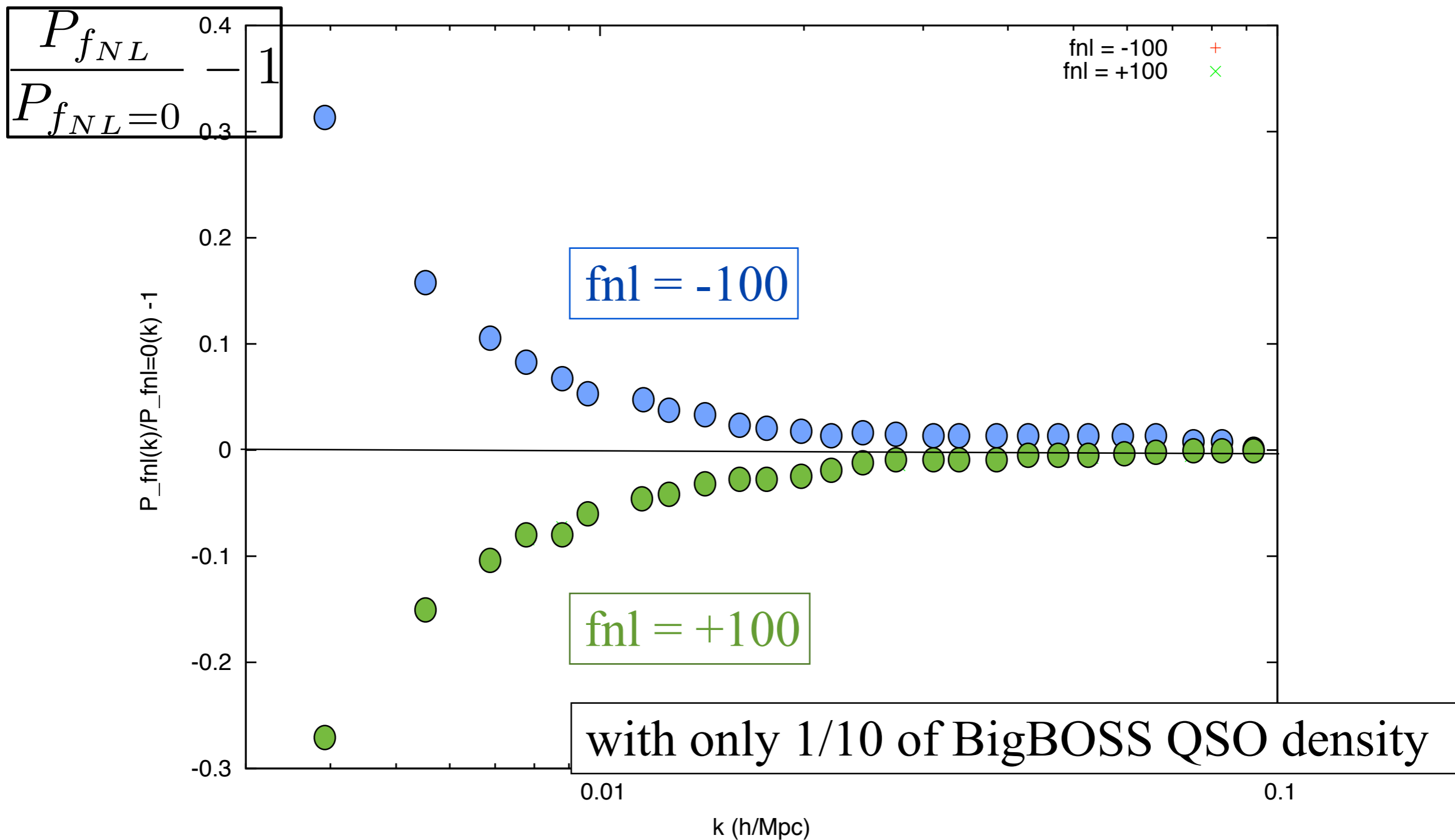
$P(k) \text{ (Mpc/h)}^3$

Taking the ratio of dashed line

to the solid line



Constraining Primordial Non-gaussianities with Ly α forest Clustering



Ho, Desjacques, Slosar & Seljak (in prep)

Constraining Primordial Non-gaussianities with Ly α forest Clustering



Preliminary theory predictions

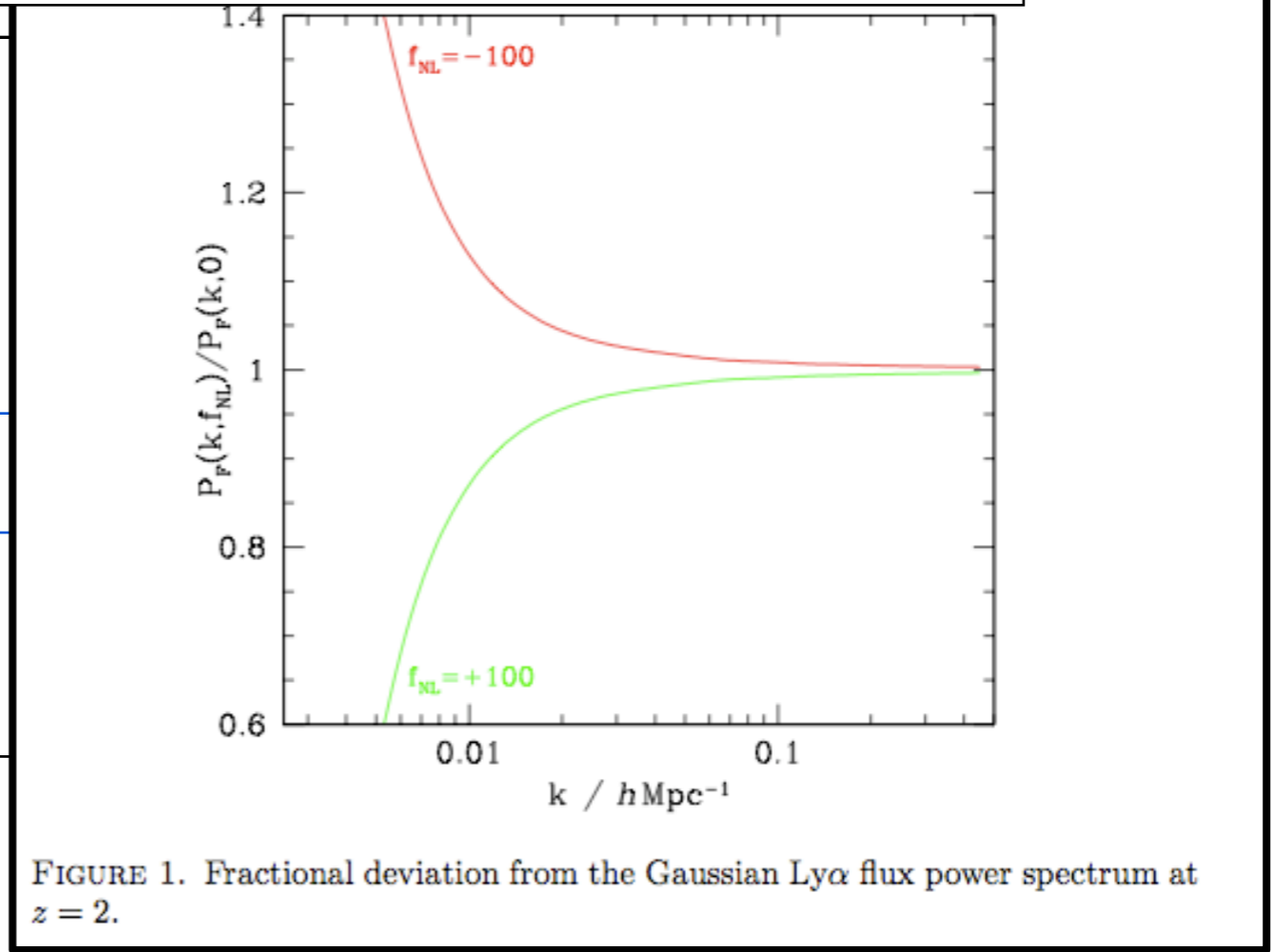
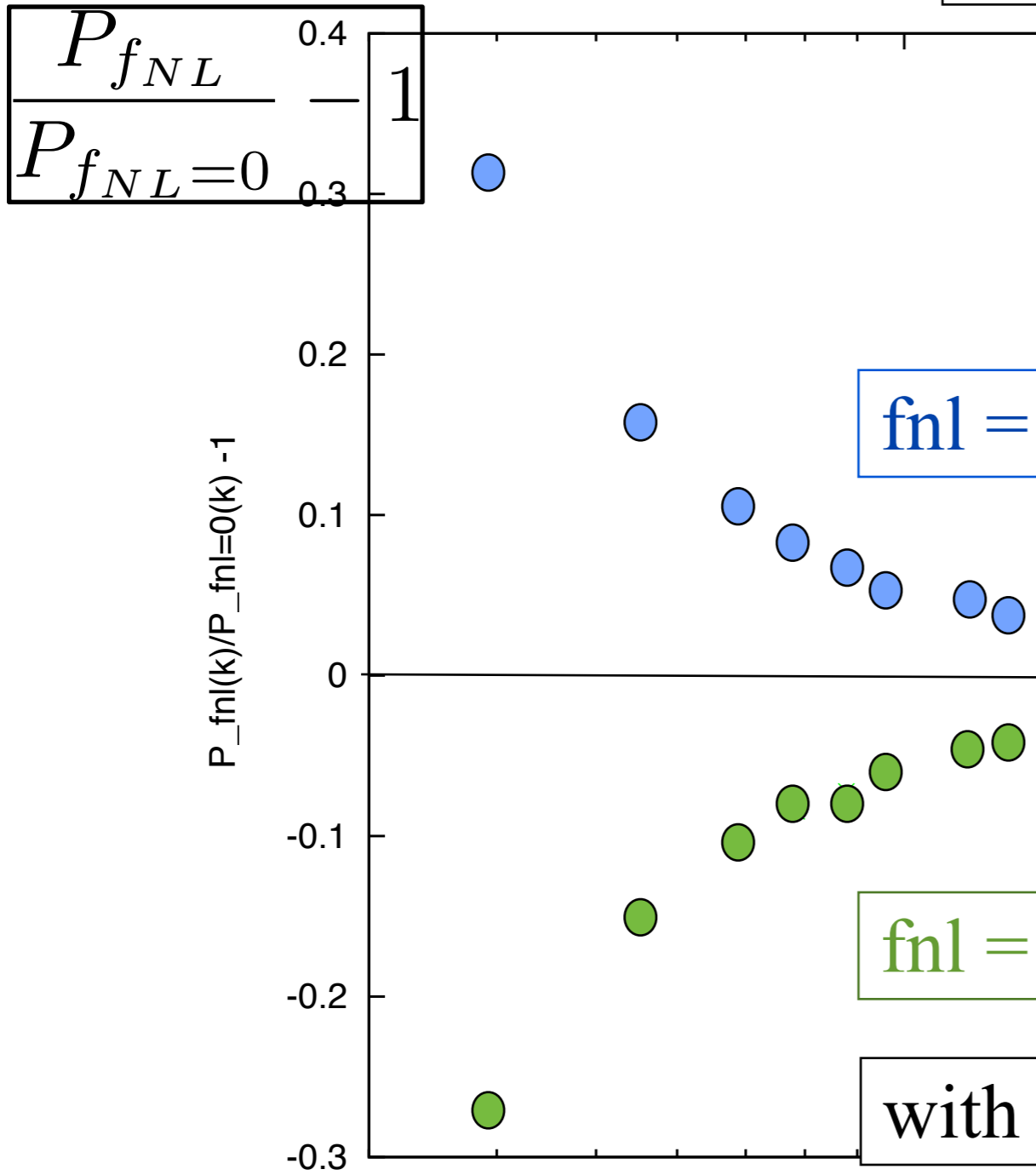


FIGURE 1. Fractional deviation from the Gaussian Ly α flux power spectrum at $z = 2$.

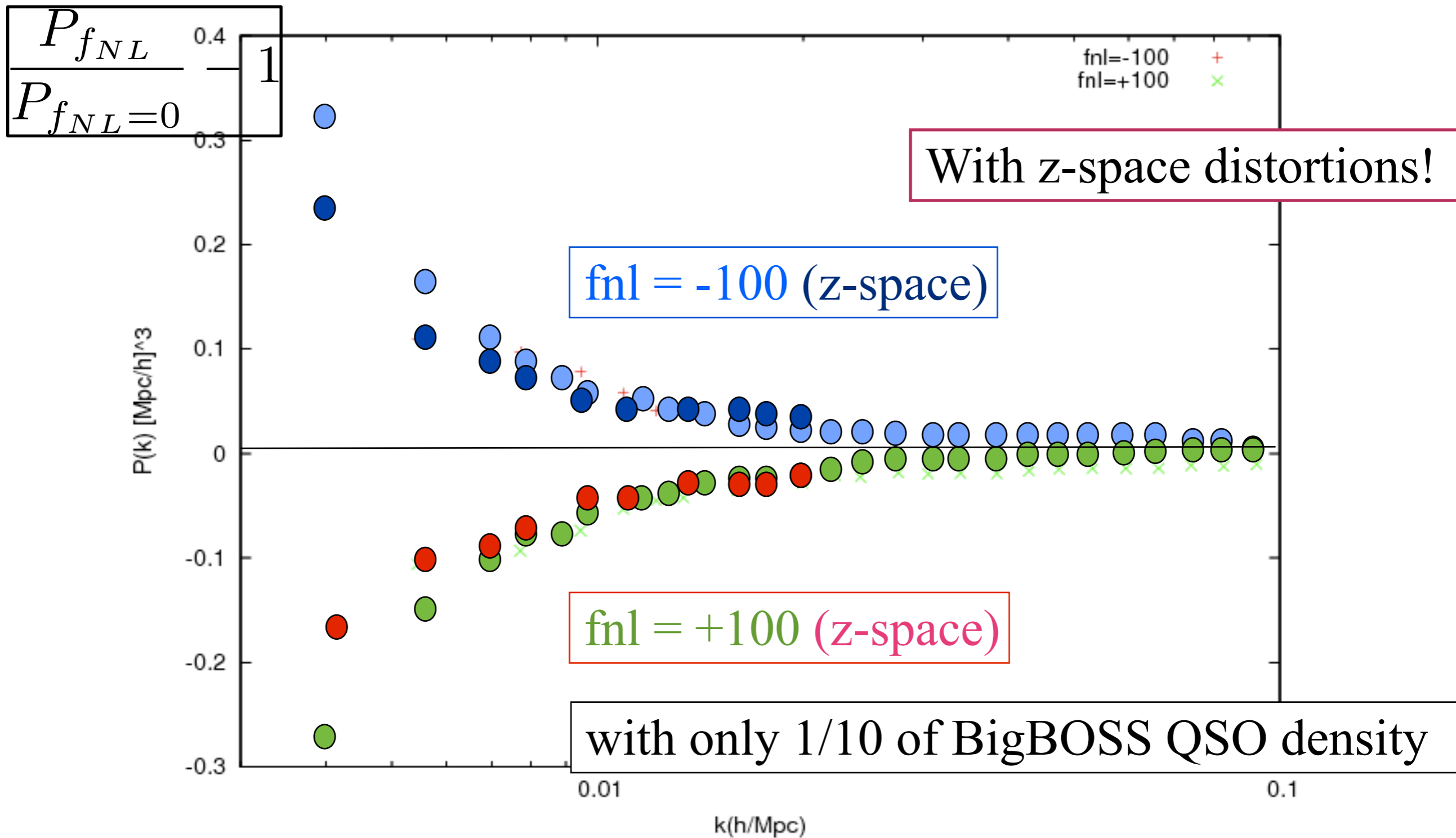
with only 1/10 of BigBOSS QSO density

0.1

Ref to Roy's talk: We need to consider gauge effects !
 Or we can change this around and use this to probe the gauge effects!

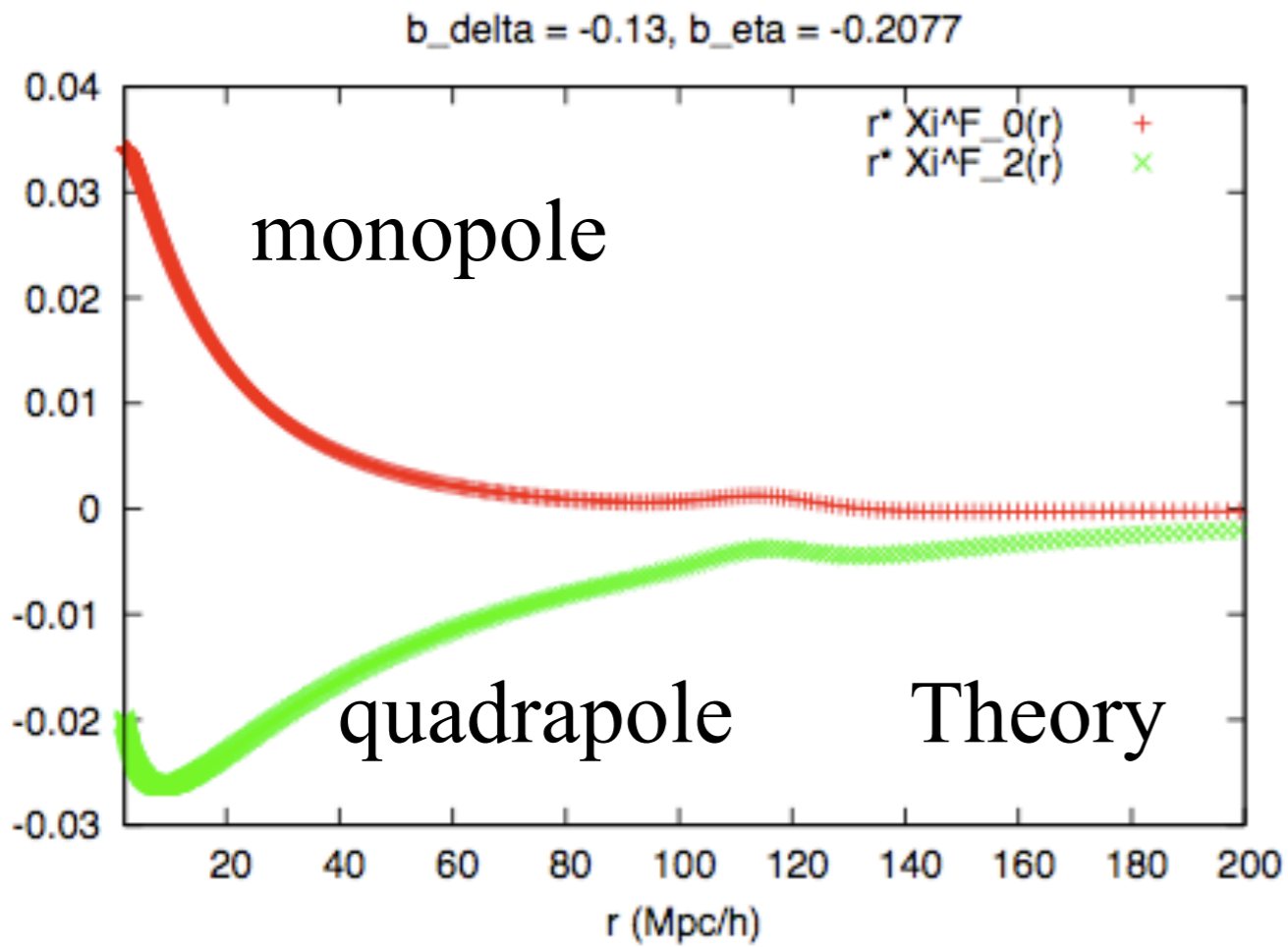
Ho, Desjacques, Slosar & Seljak (in prep)

Constraining Primordial Non-gaussianities with Ly α forest Clustering



Ho, Desjacques, Slosar & Seljak (in prep)

Modeling z-space distortions

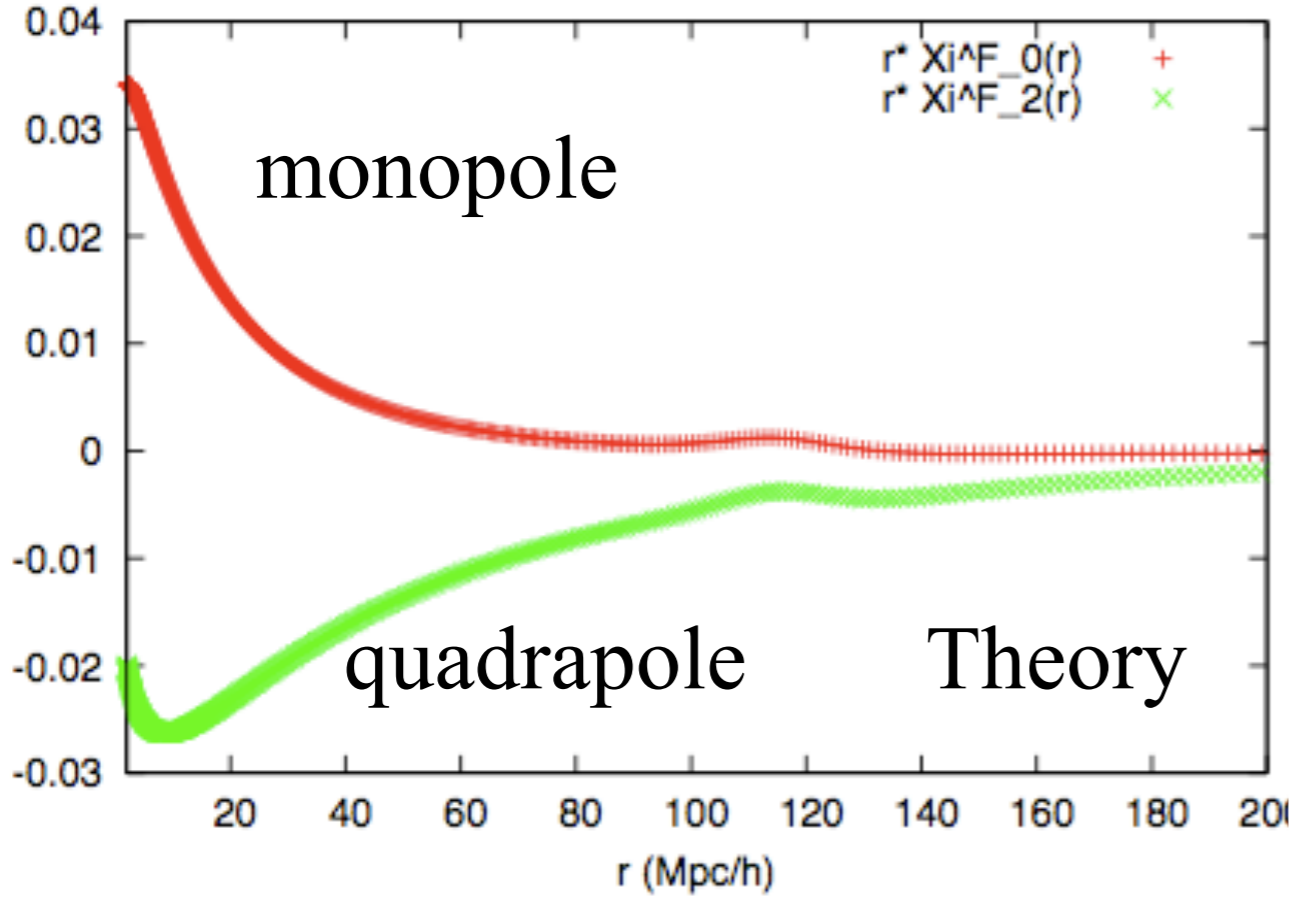


Ho, Desjacques, Slosar, White et al. (in prep)

Modeling z-space distortions

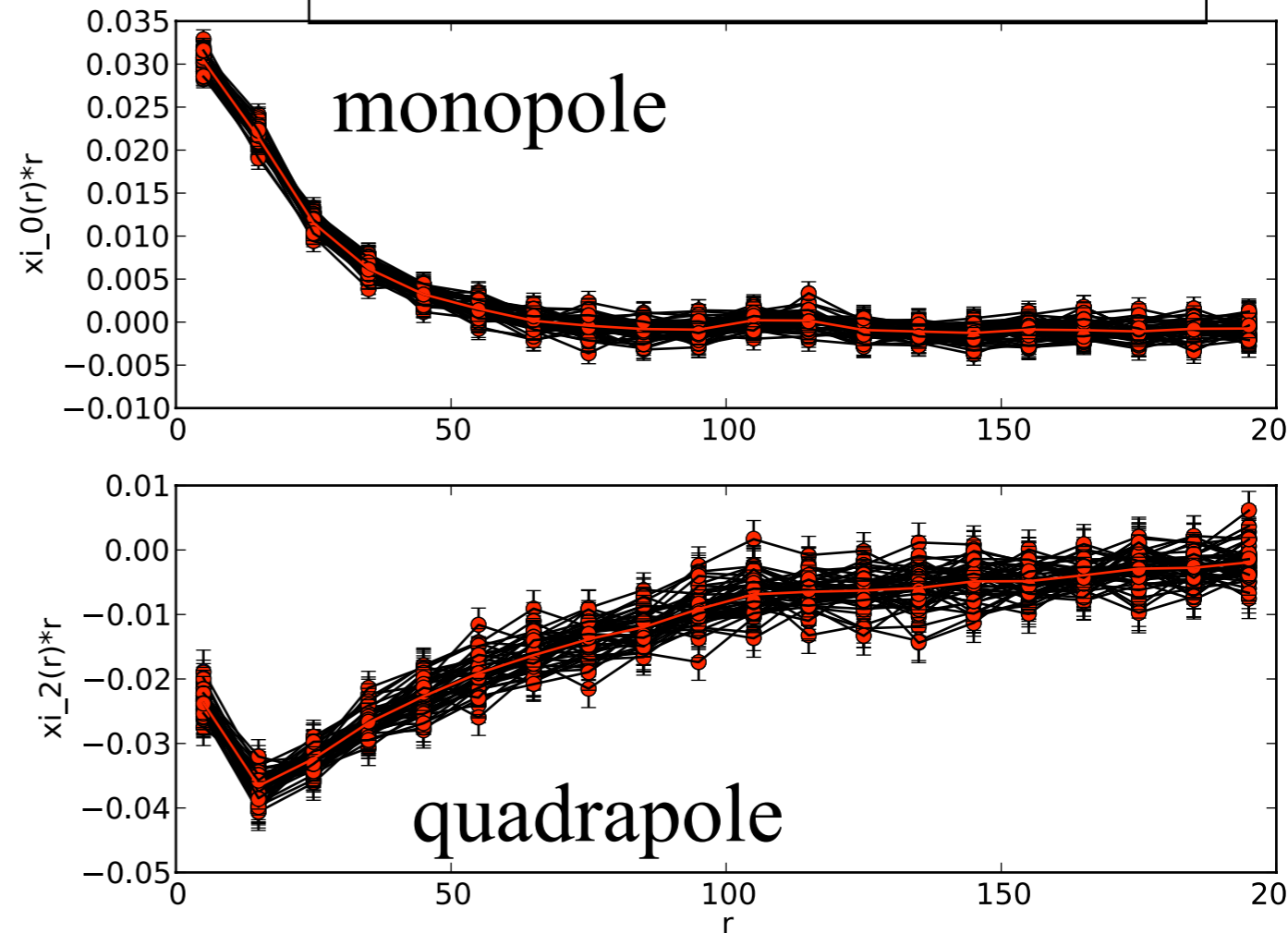


$b_{\Delta} = -0.13, b_{\eta} = -0.2077$



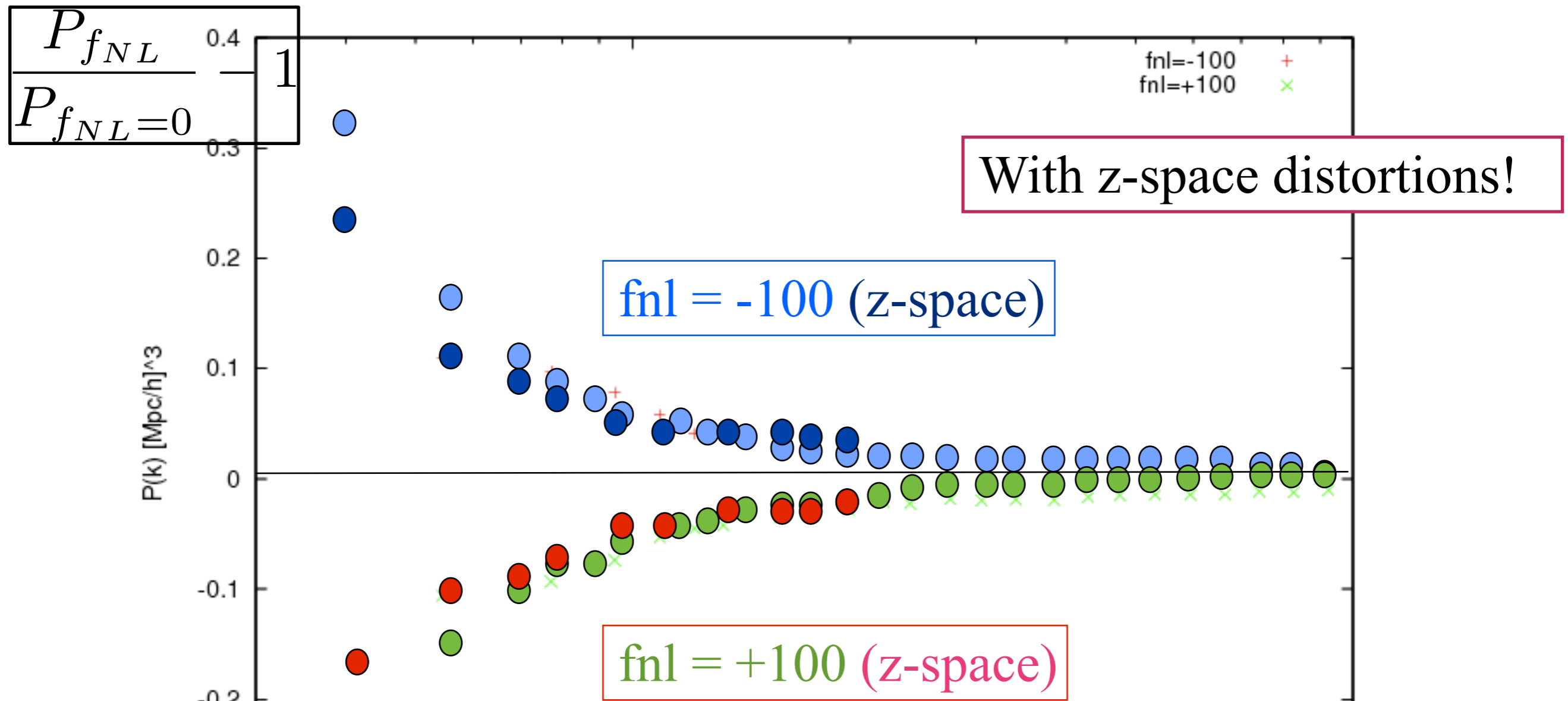
Ho, Desjacques, Slosar, White et al. (in prep)

Recent SDSS III results



Slosar et al. (2011)

Constraining Primordial Non-gaussianities with Ly α forest Clustering

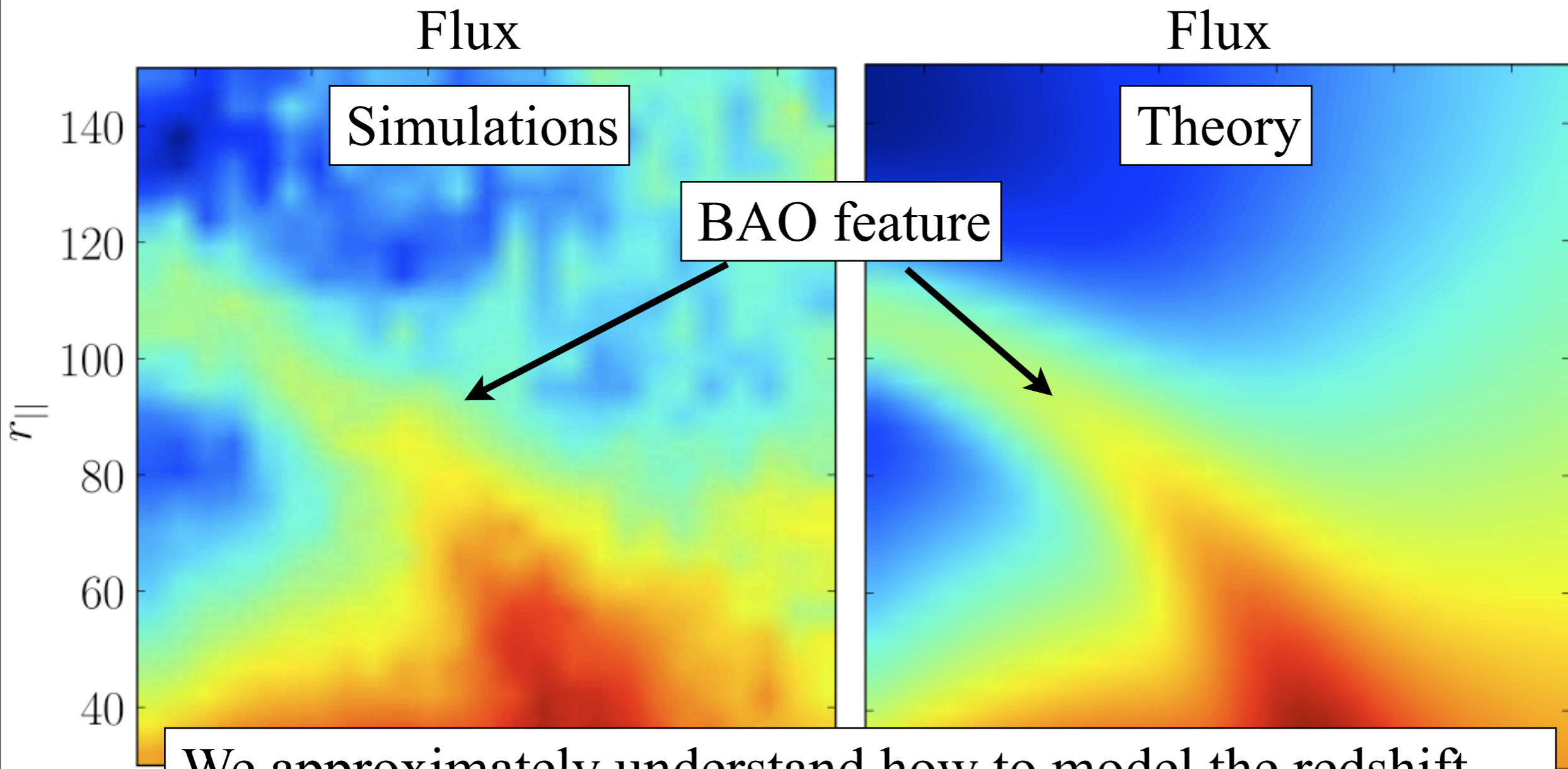


We approximately understand how to model the redshift space distortions, and we are investigating what happens when we include other systematics such as UV background fluctuations.

Ho, Desjacques, Slosar & Seljak (in prep)

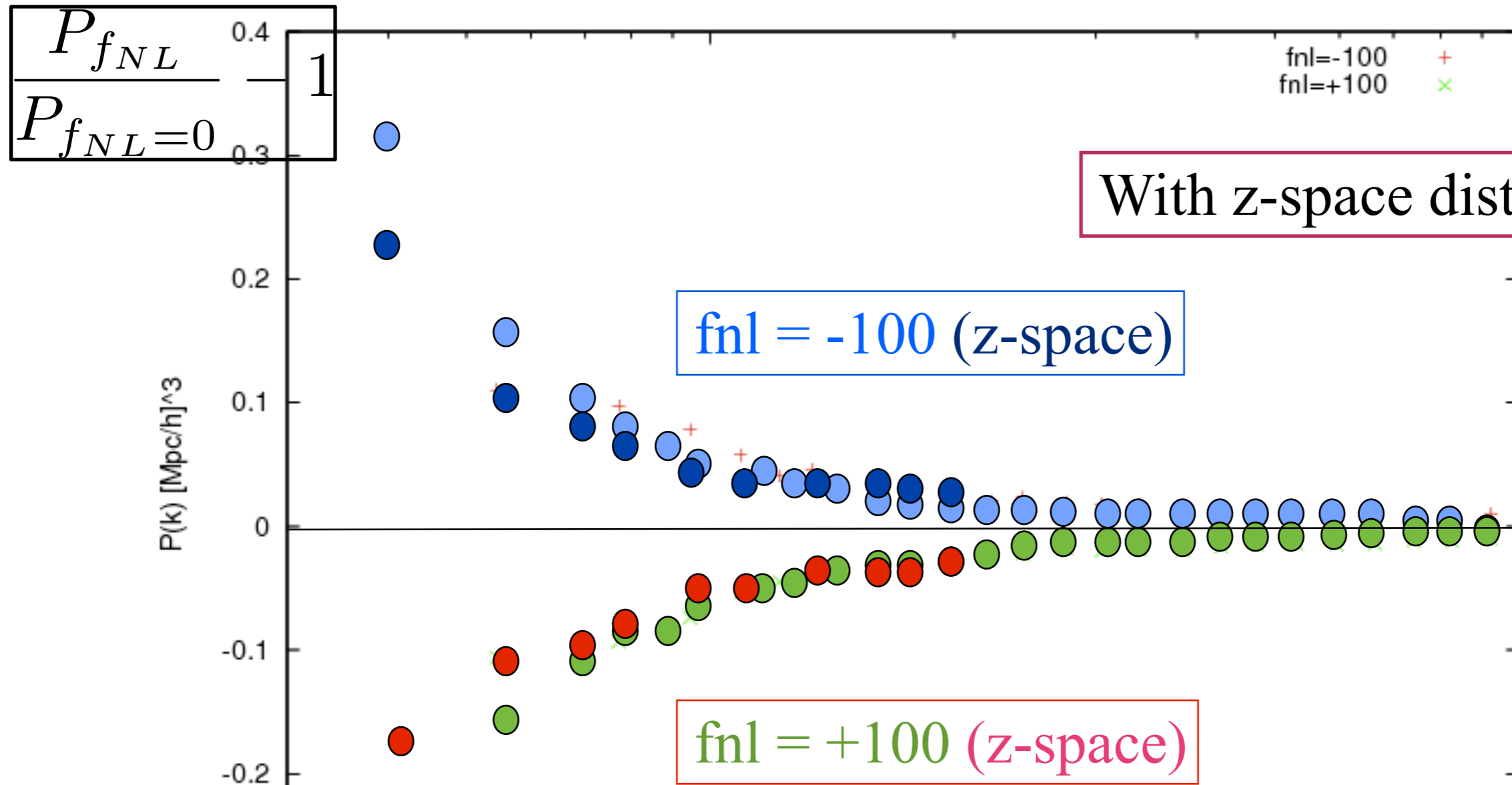
- **Motivations**
- **Introduction (What is lighting up the what?)**
- **What can you do with Lyman-alpha forest?**
 - **Baryon Acoustic Oscillations**
 - Dark Energy
 - **Scale Dependent Bias**
 - Primordial Non-gaussianities -> Inflation
- **Conclusion**

Constraining Dark Energy with Ly α forest BAO



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

Constraining Primordial Non-gaussianities with Ly α forest Clustering



With z-space distortions!

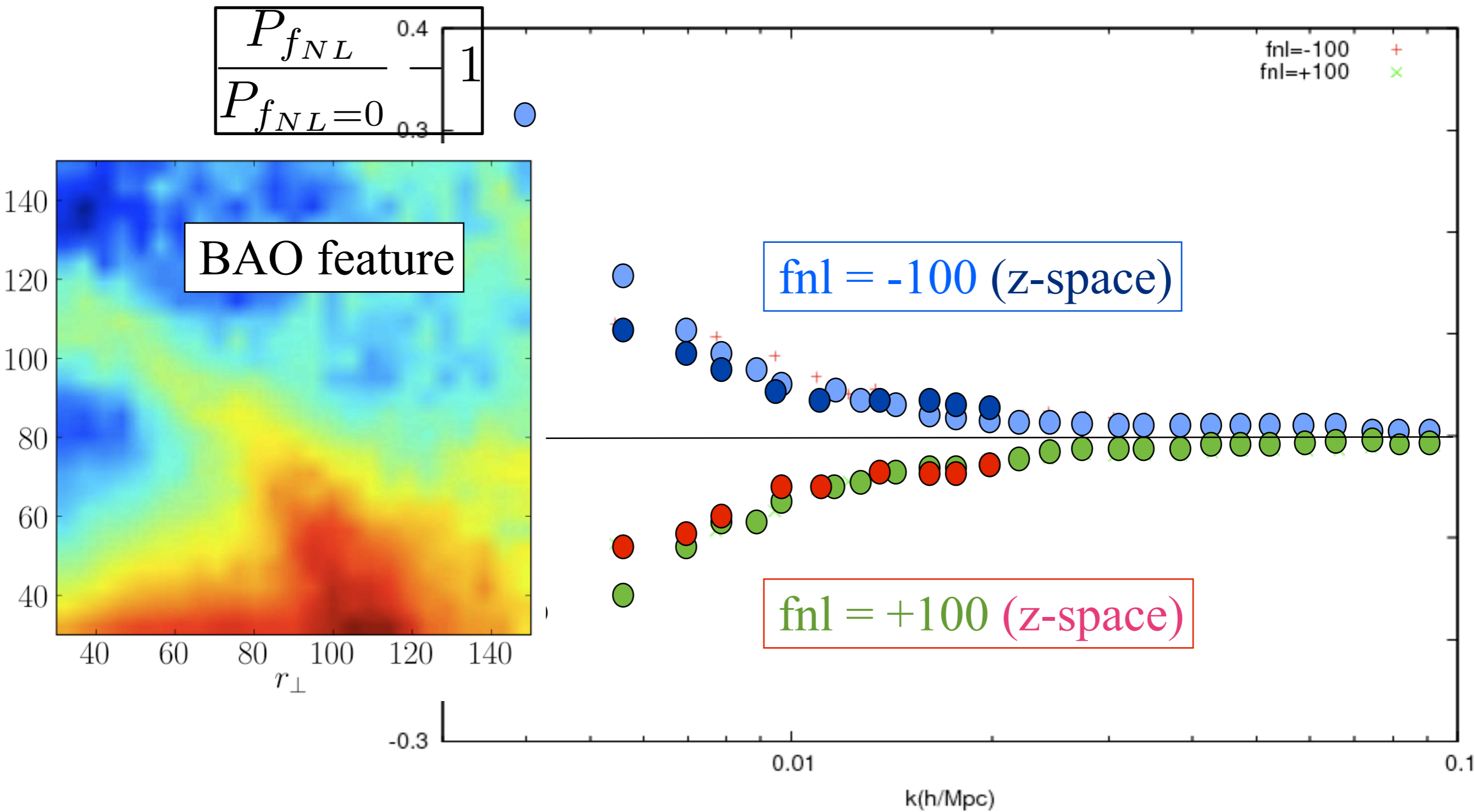
$f_{NL} = -100$ (z-space)

$f_{NL} = +100$ (z-space)

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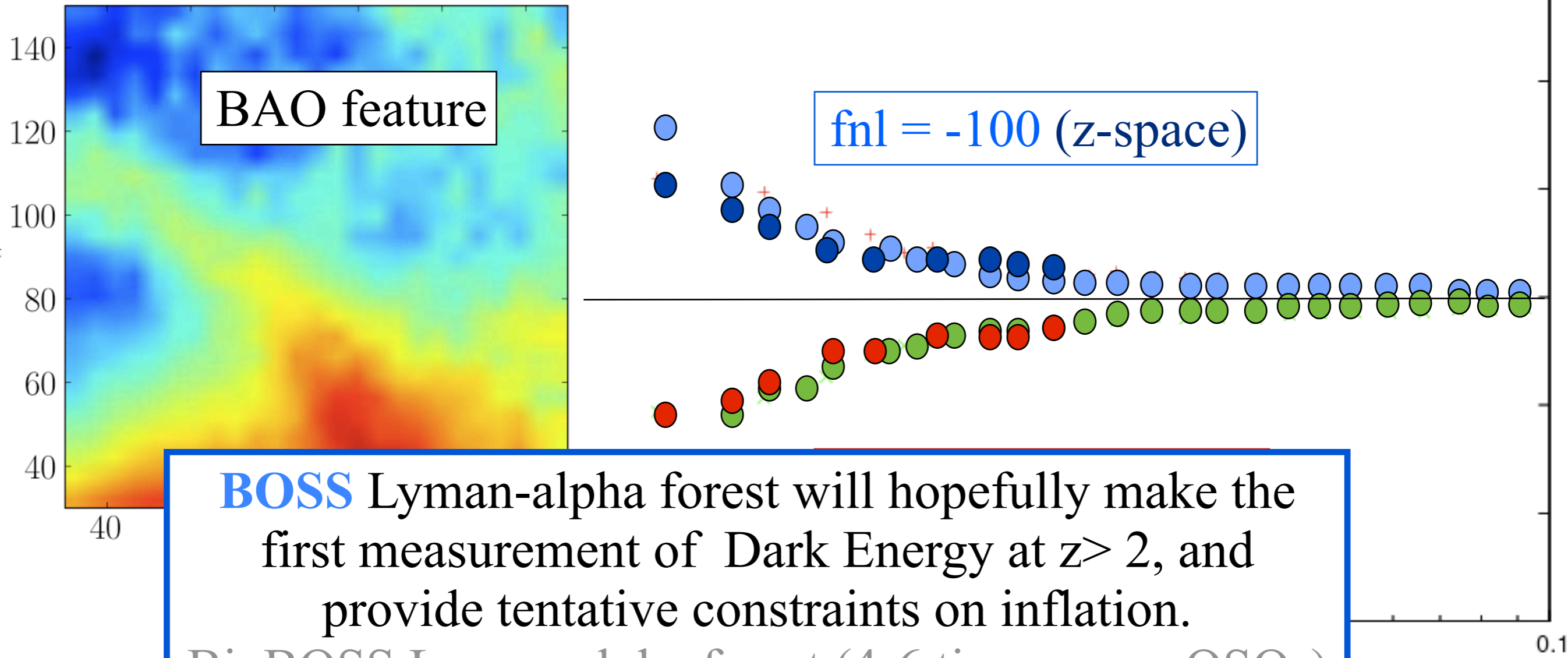
Constraining Dark Energy and inflation with Lyman alpha forest



Constraining Dark Energy and inflation with Lyman alpha forest



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



BOSS Lyman-alpha forest will hopefully make the first measurement of Dark Energy at $z > 2$, and provide tentative constraints on inflation.

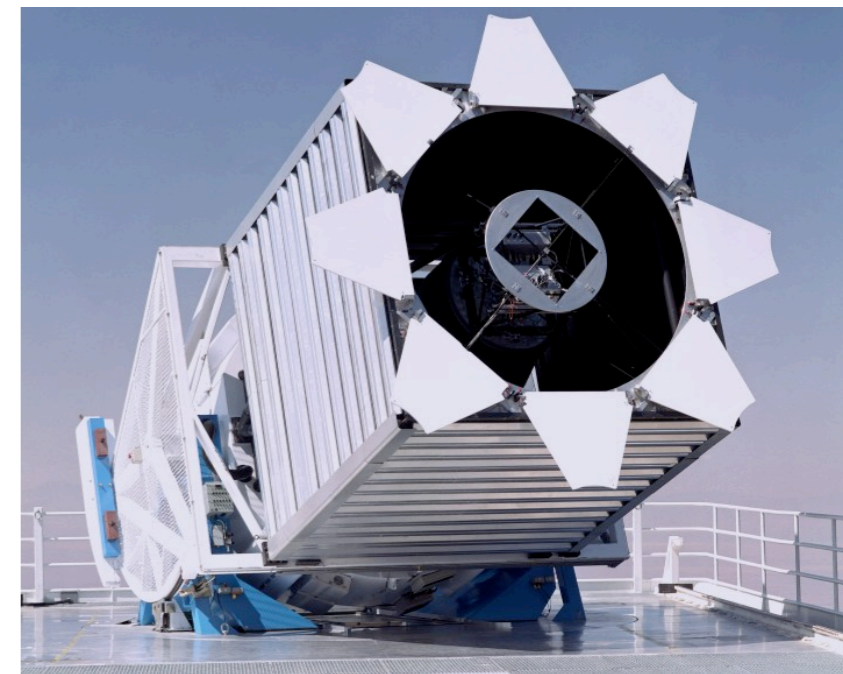
BigBOSS Lyman-alpha forest (4-6 times more QSOs) will make even better measurement of DE at $z > 2$ and provide significant constraints on inflation.

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 deg² 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.

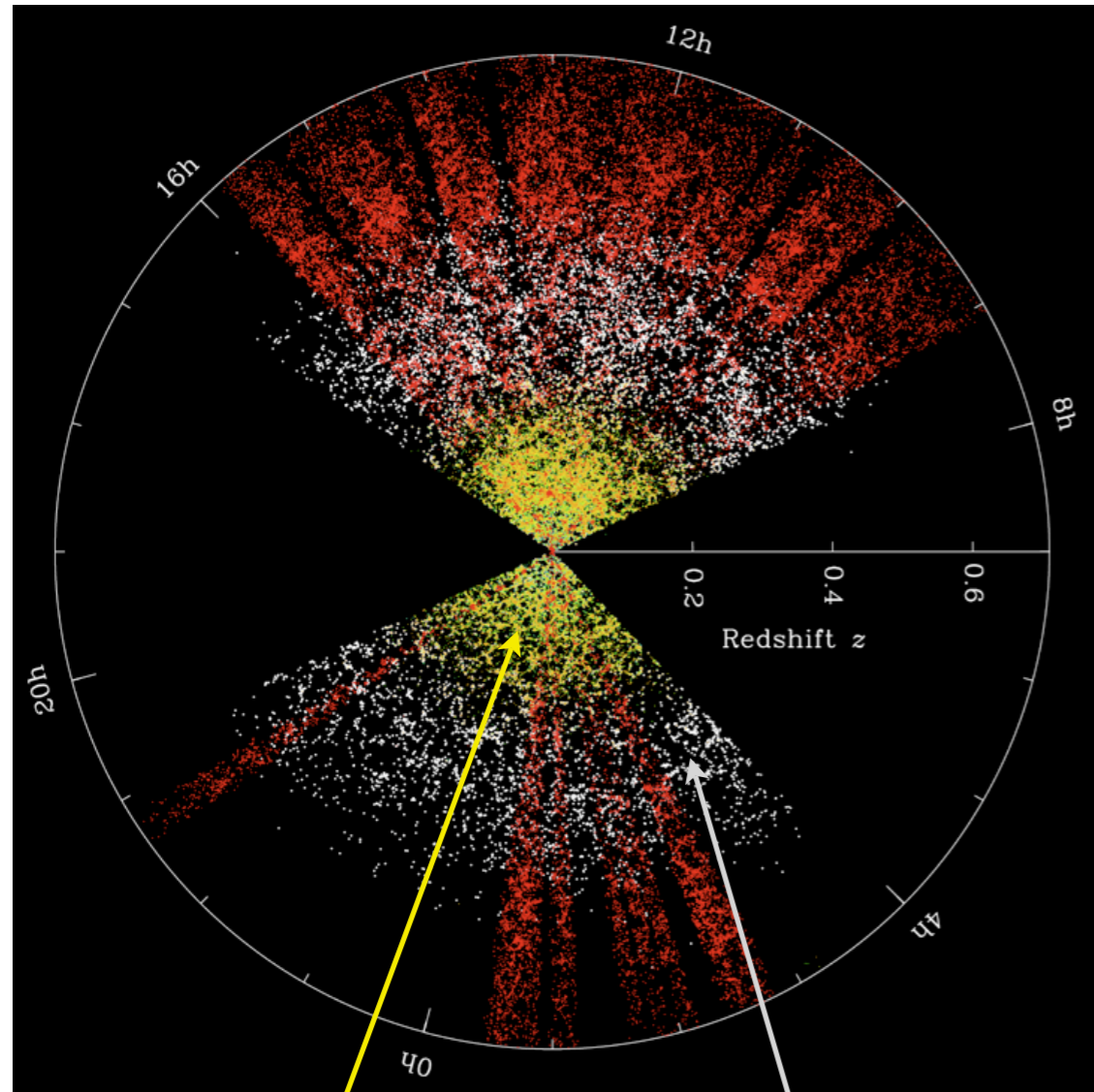


Courtesy Slide from David Schlegel

BOSS



Volume of the Universe probed by SDSS



SDSS main galaxies

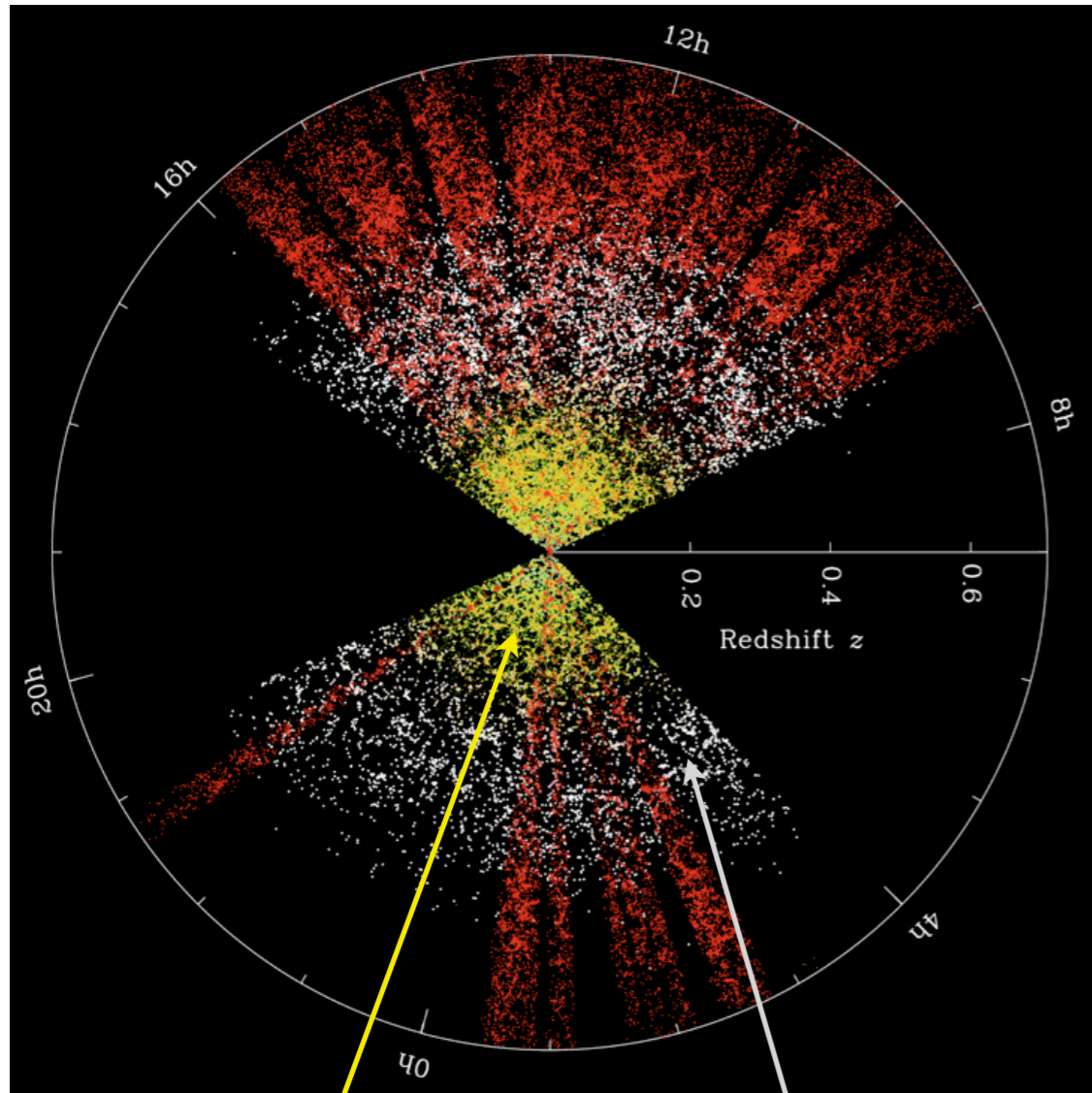
SDSS spectroscopic LRGs

Courtesy plots from Michael Blanton

BOSS



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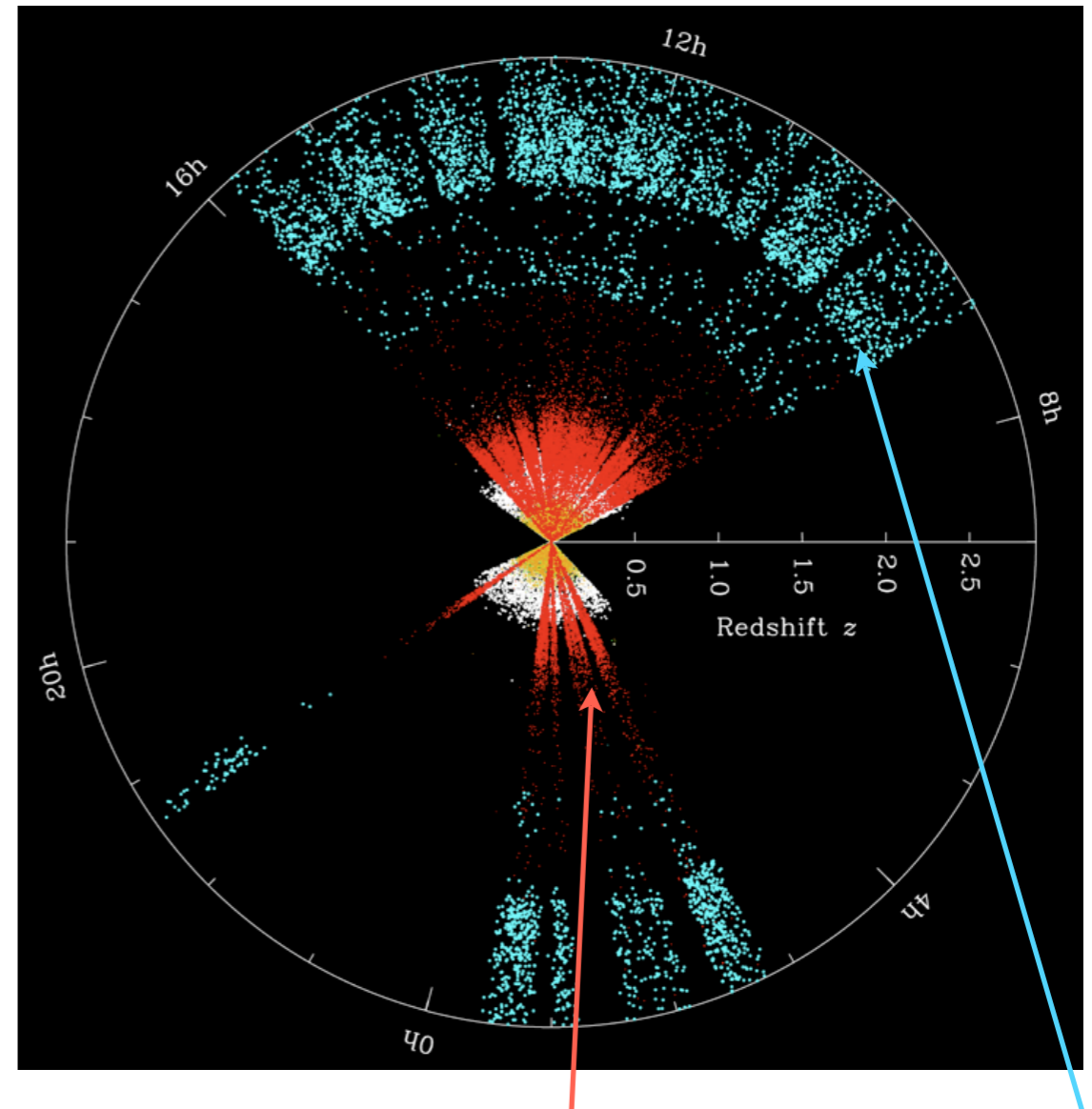


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Volume of the Universe probed by BOSS



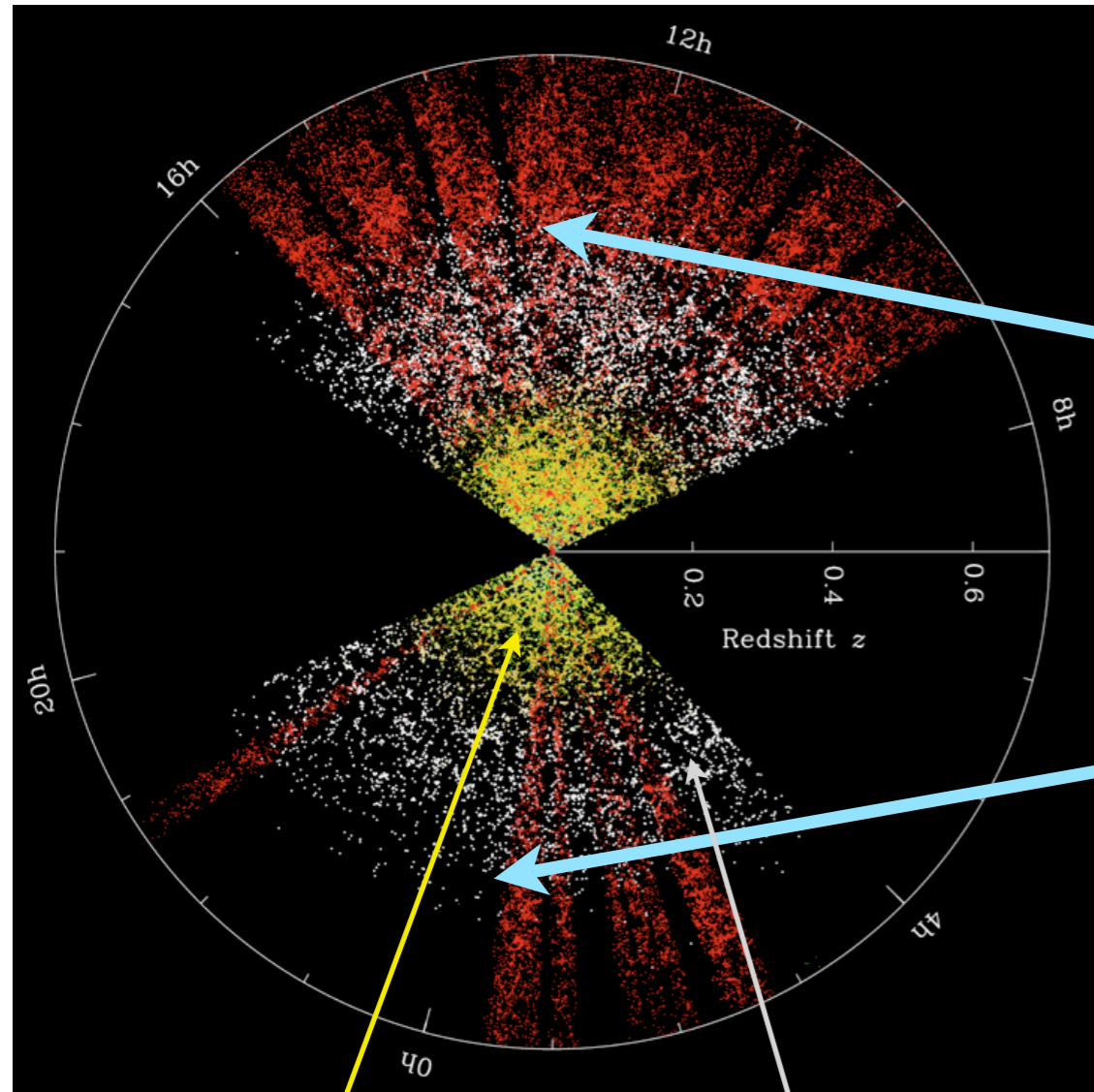
BOSS spectroscopic galaxies: >150,000

SDSS III/BOSS spectroscopic quasars: >15,000

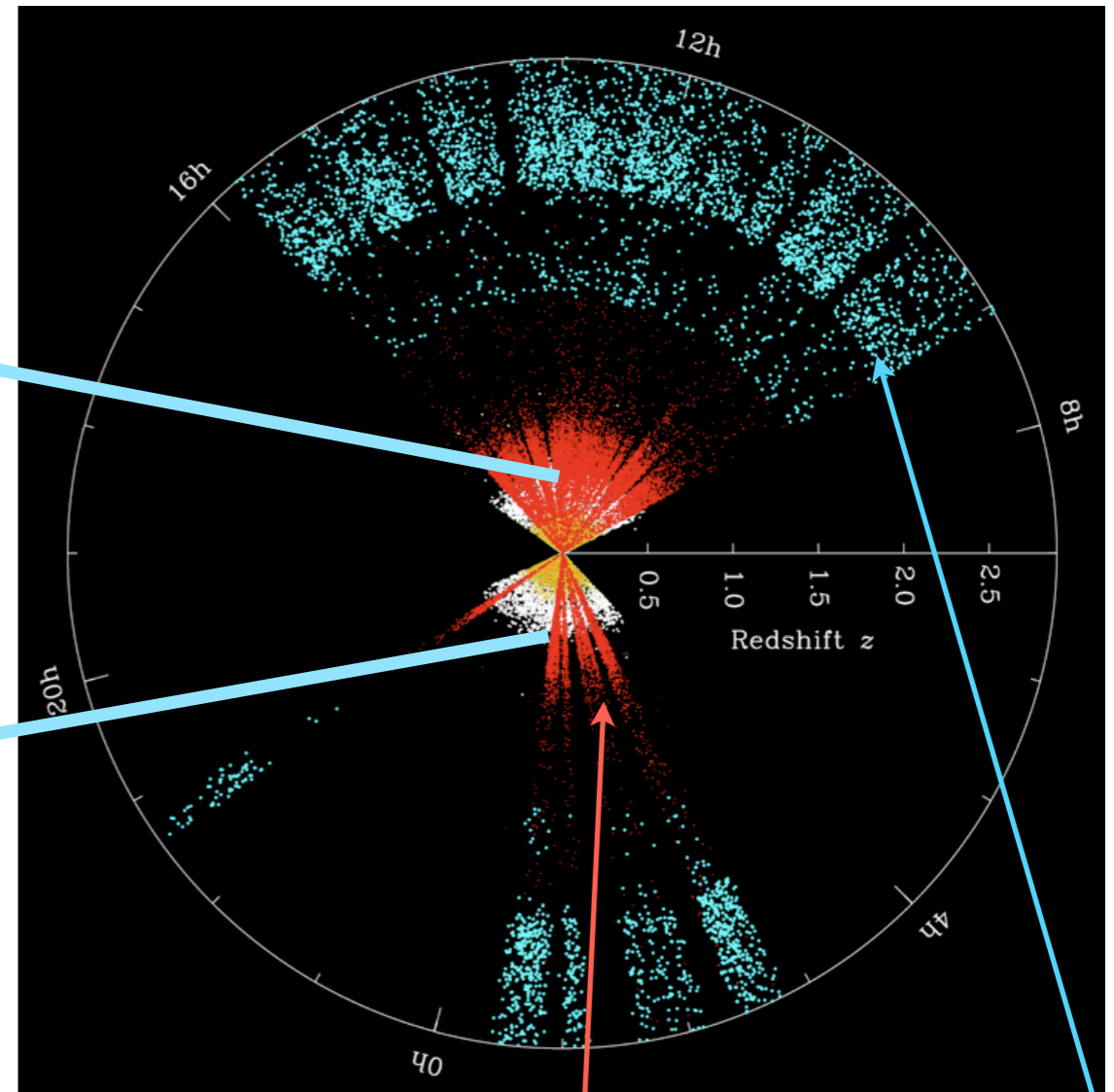
BOSS



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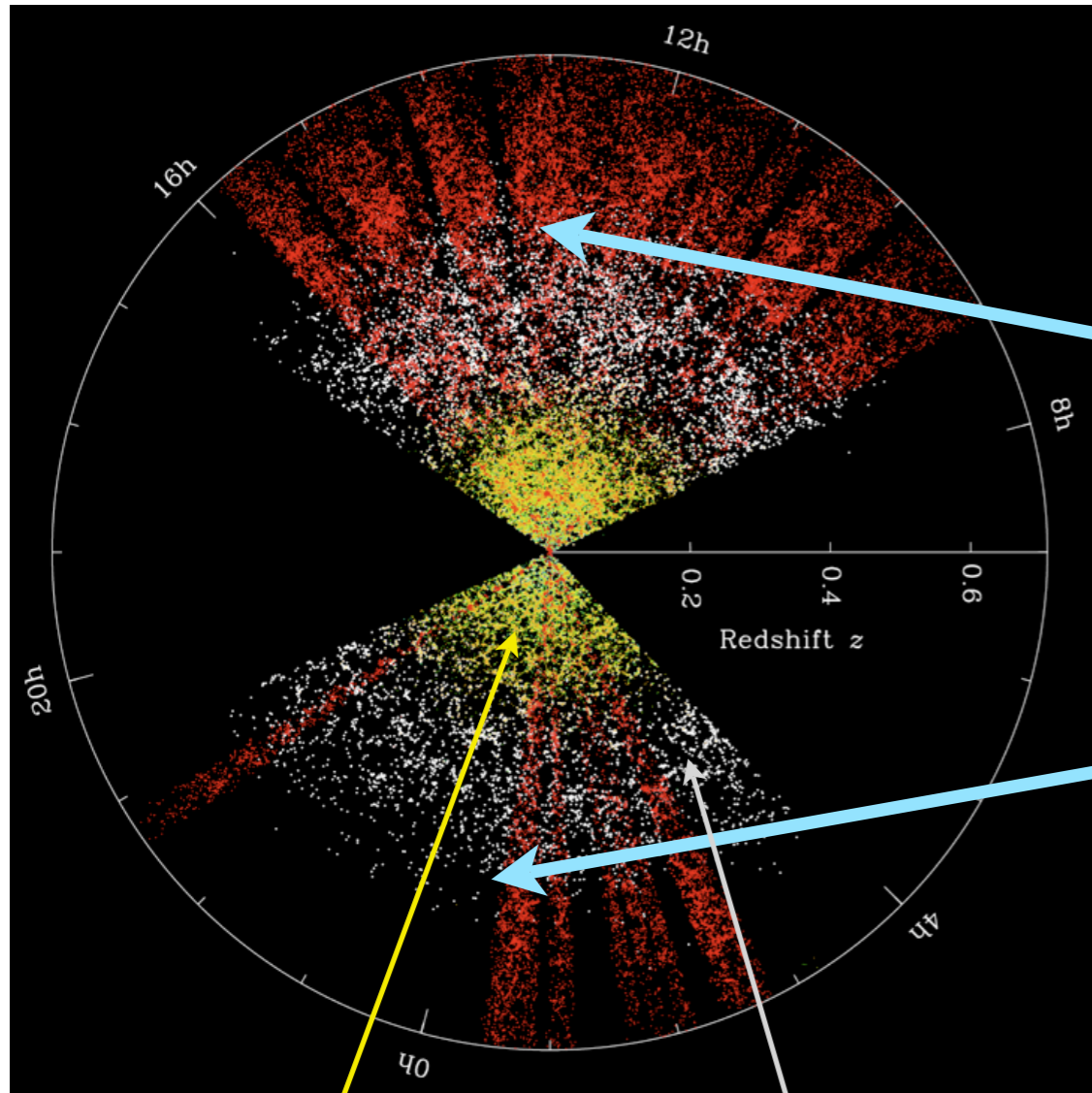
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BOSS

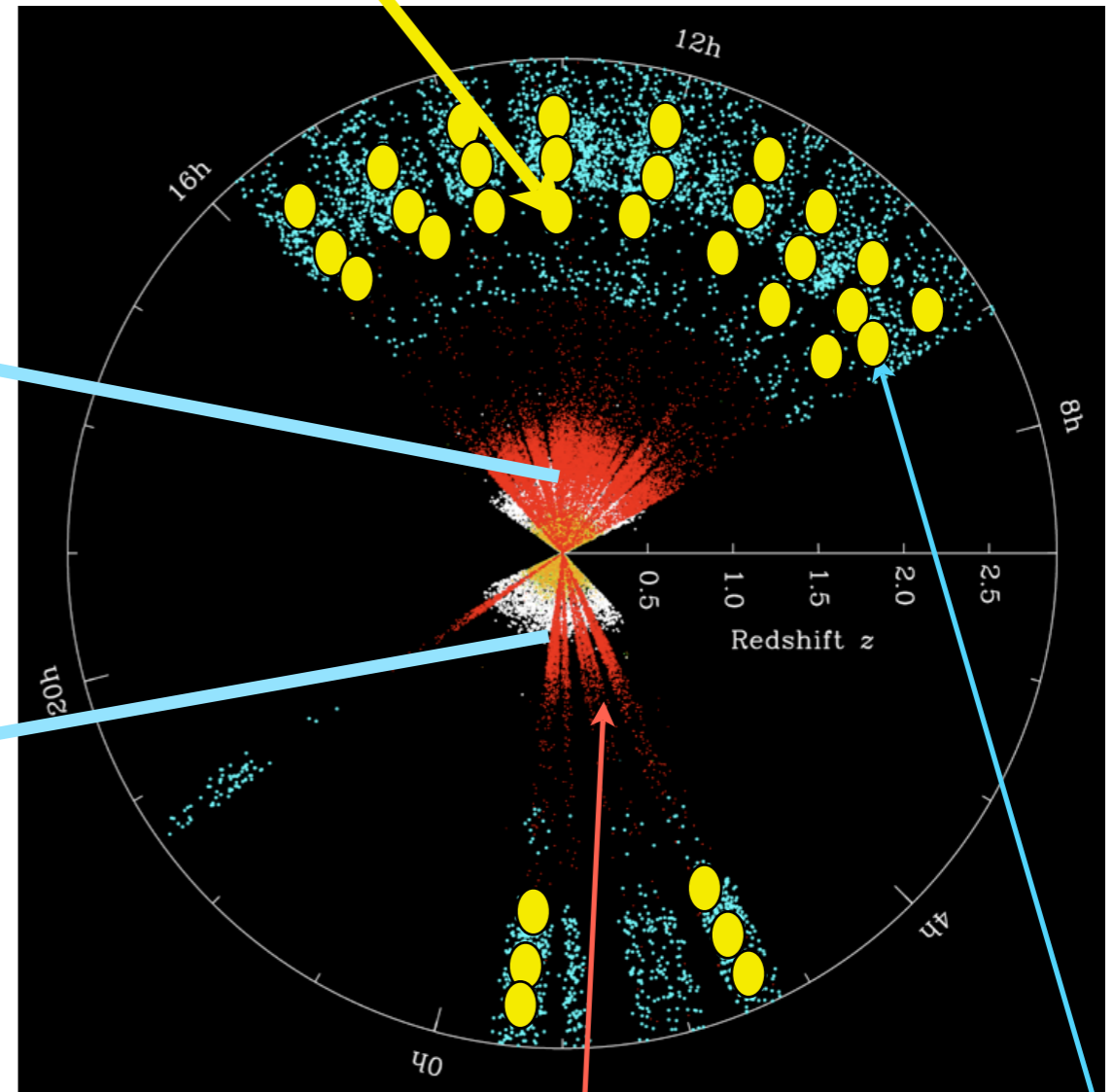


Lyman alpha forest probing high redshift with high density.

Volume of the Universe probed by SDSS



Volume of the Universe probed by BOSS



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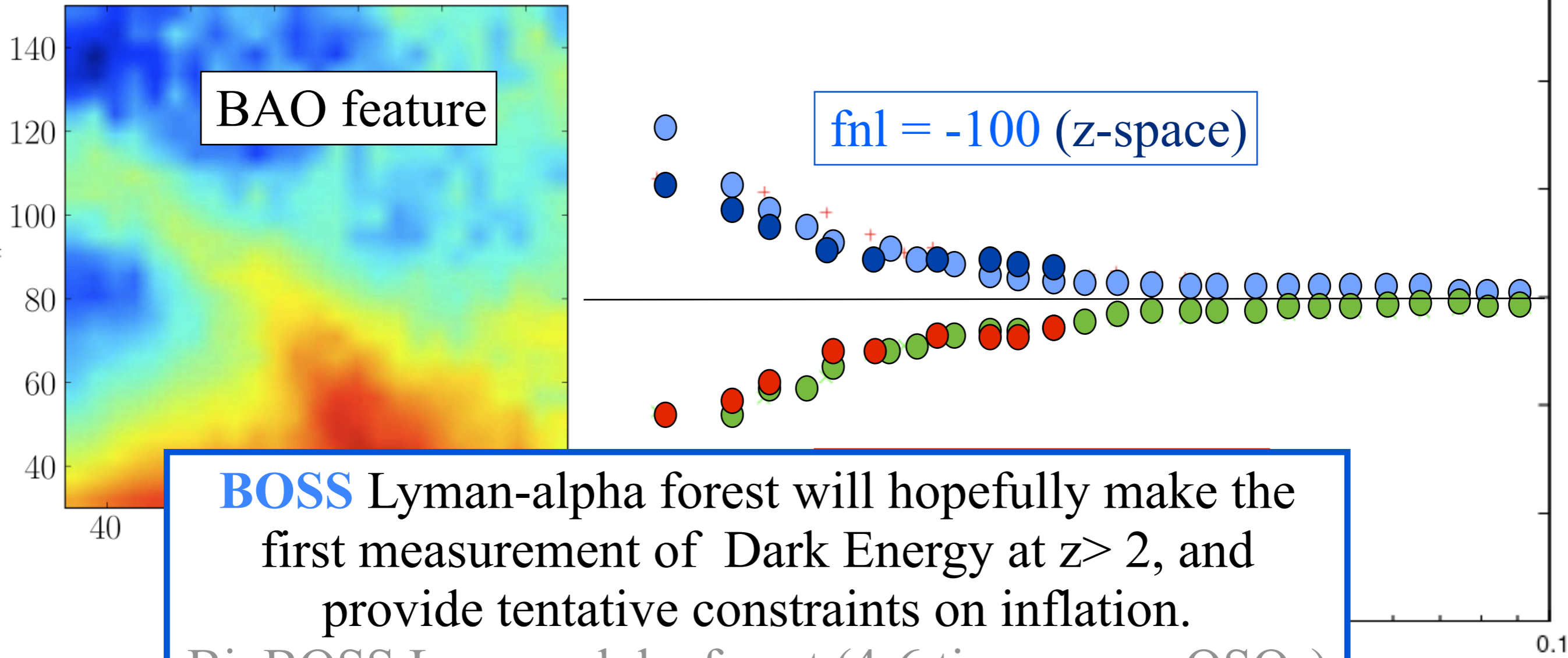
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Constraining Dark Energy and inflation with Lyman alpha forest



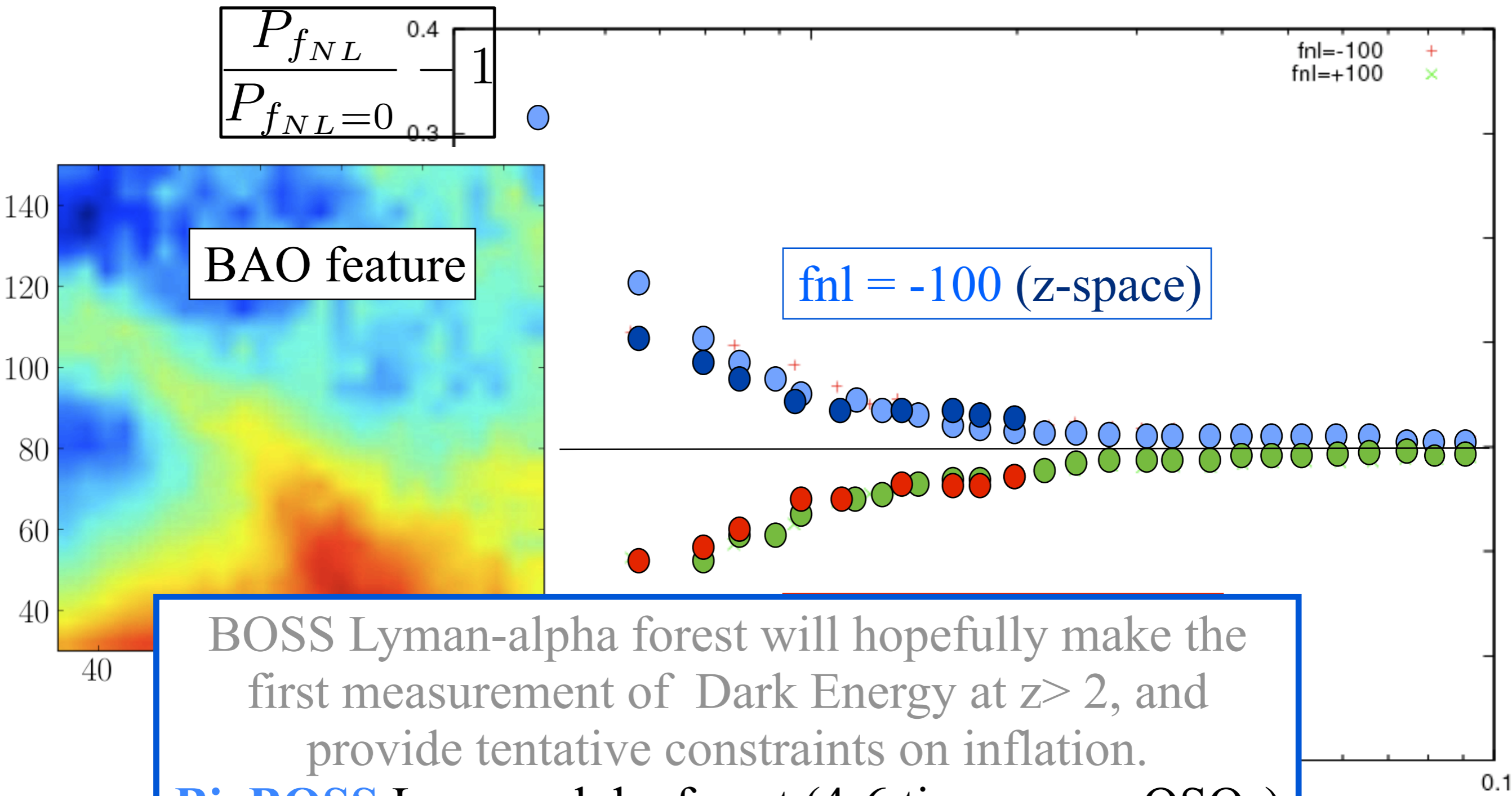
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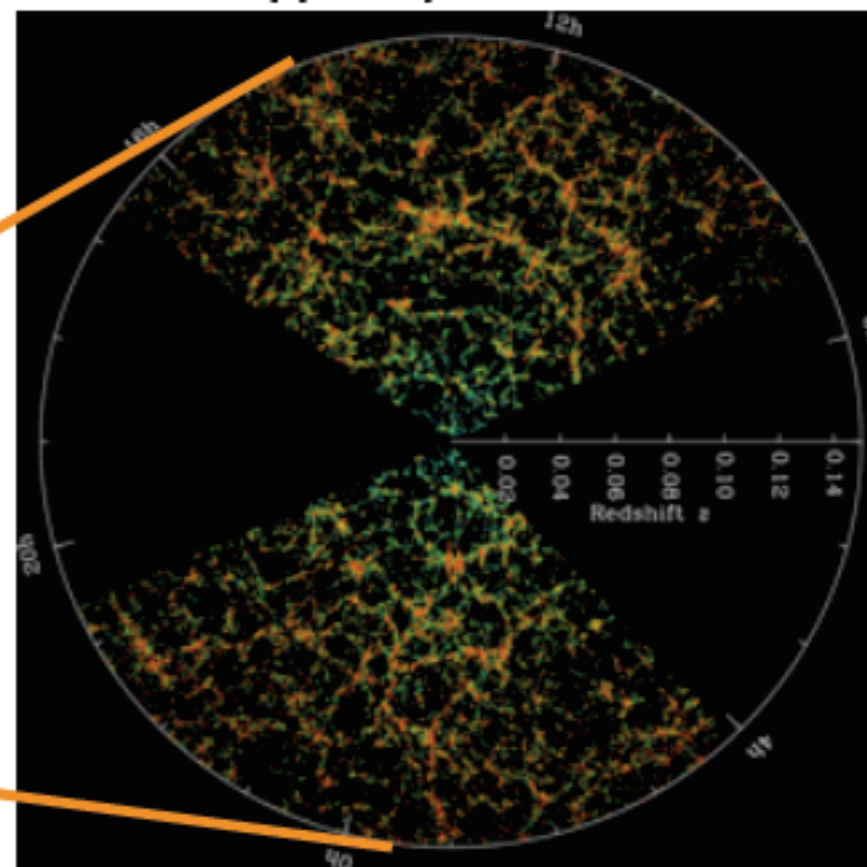
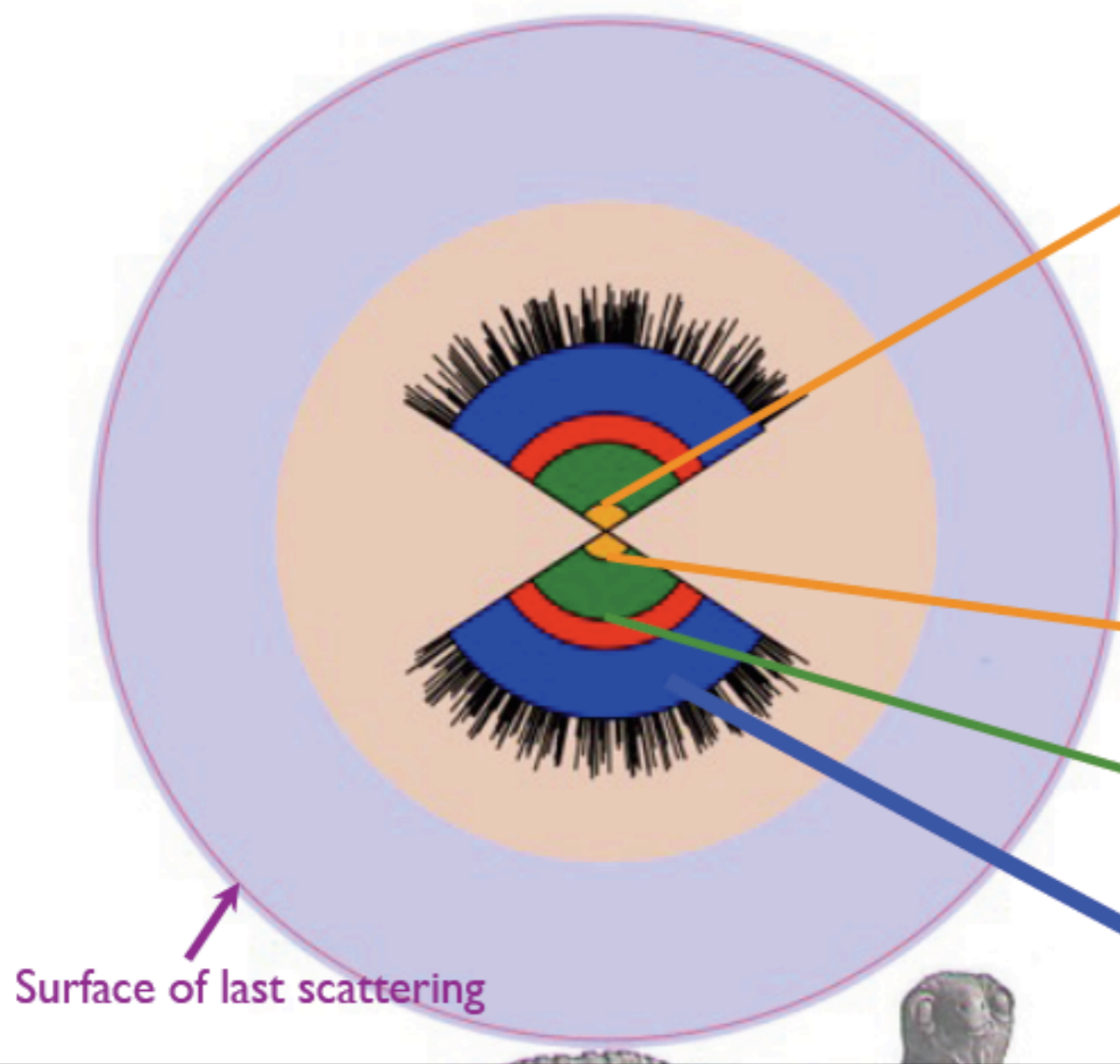
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Science Goals: 50 million redshifts

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

Courtesy Slide from David Schlegel

Conclusion



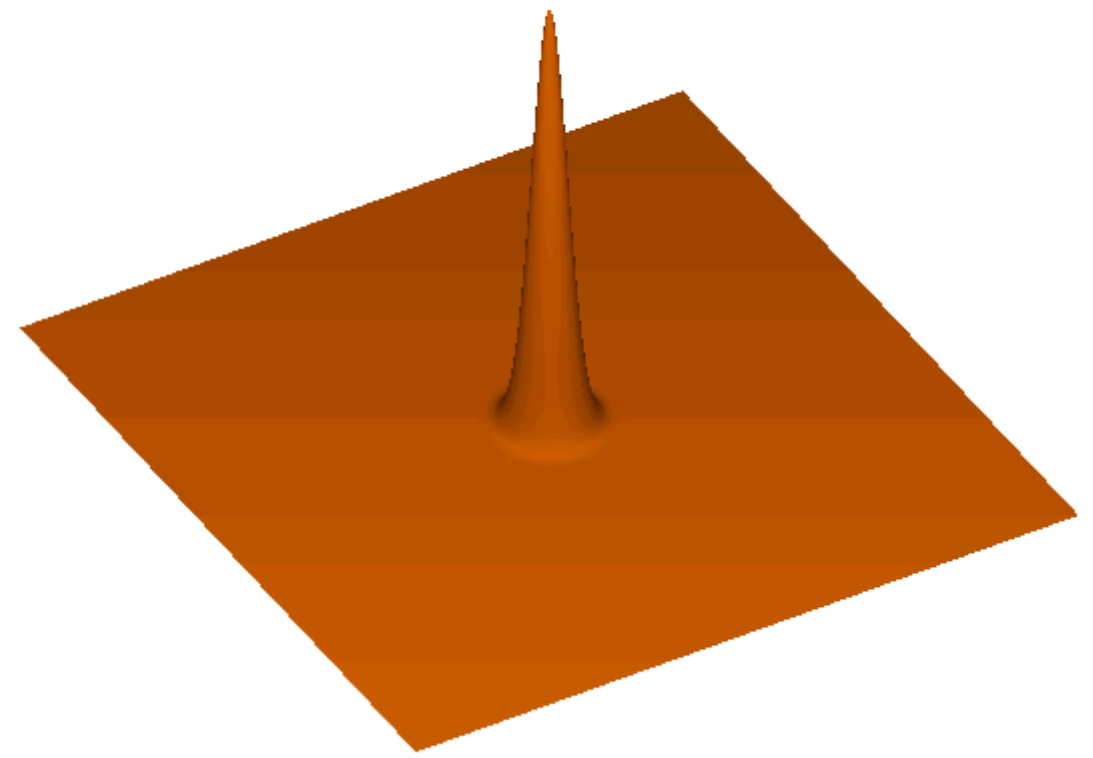
- **Lyman-alpha forest in BOSS and BigBOSS will (hopefully) do the following:**
 - **Lya BAO to measure Dark Energy at $z > 2$**
 - **Lya probes non-gaussianity of the Early Universe**
 - **Other applications:**
 - **Lya $P(k)$ tighten the cosmological constraints**
 - **Probing temperature density relation in the IGM**
 - **3D clustering of Lya forest constrains UV background fluctuations**
 - **Finding missing baryons when combined with Cosmic Microwave Background at higher redshift**

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

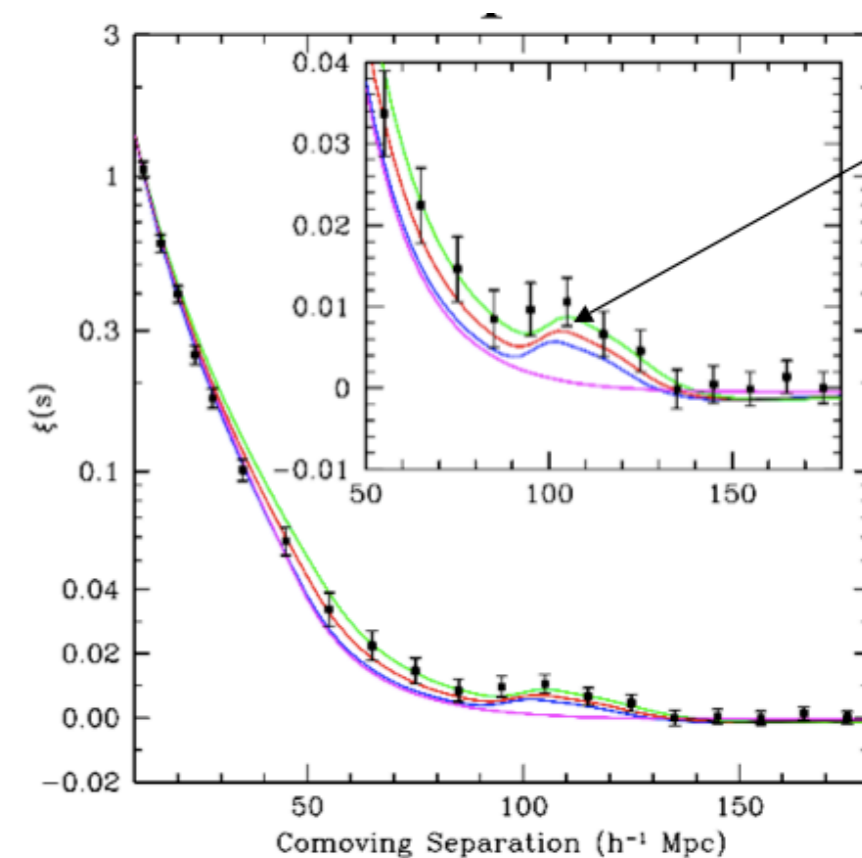


- **Effects of DLAs (Damped Ly α systems), BALs (Broad Absorption line systems), Metals**
- **Effect of incomplete continuum subtractions**
- **Effect of UV background fluctuations.**
- **The other systematic error that will be coming from the experiment/analysis.**

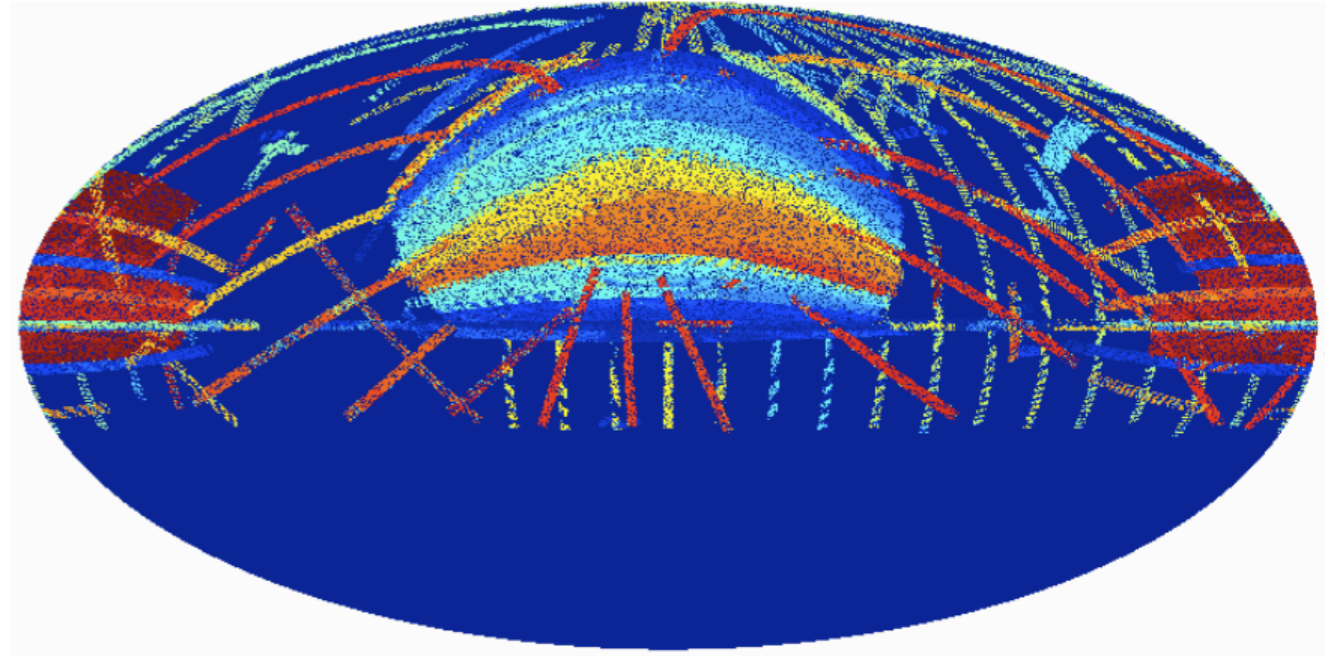
3 Lectures



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

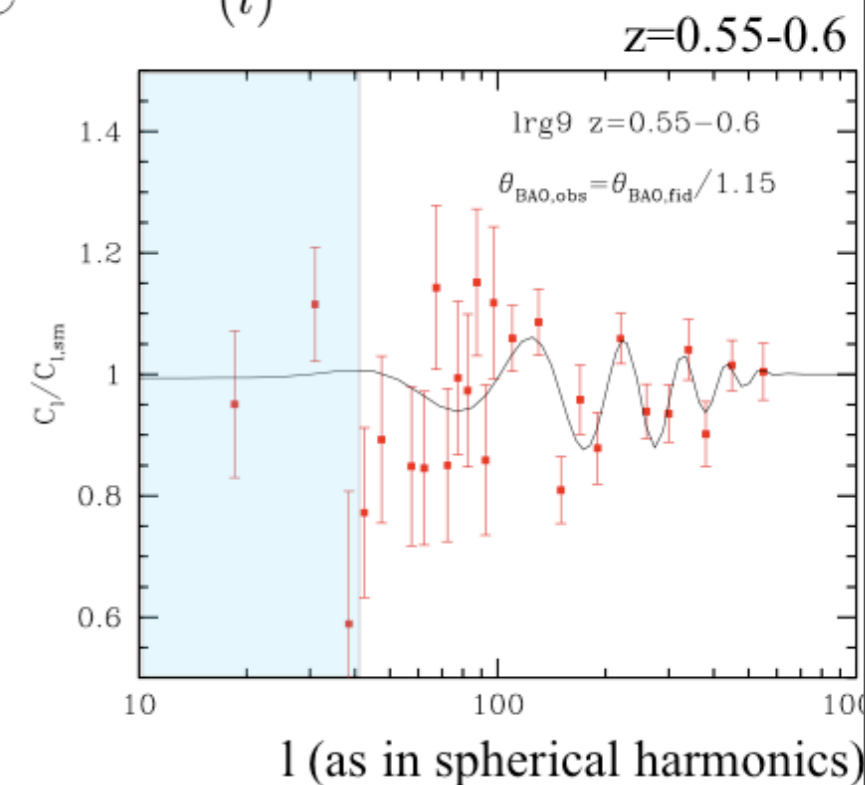


3 Lectures



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

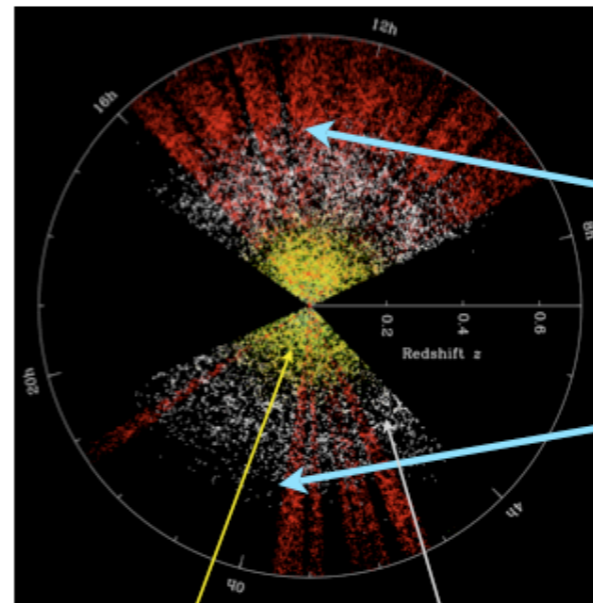


3 Lectures

Lyman alpha forest probing high redshift with high density.



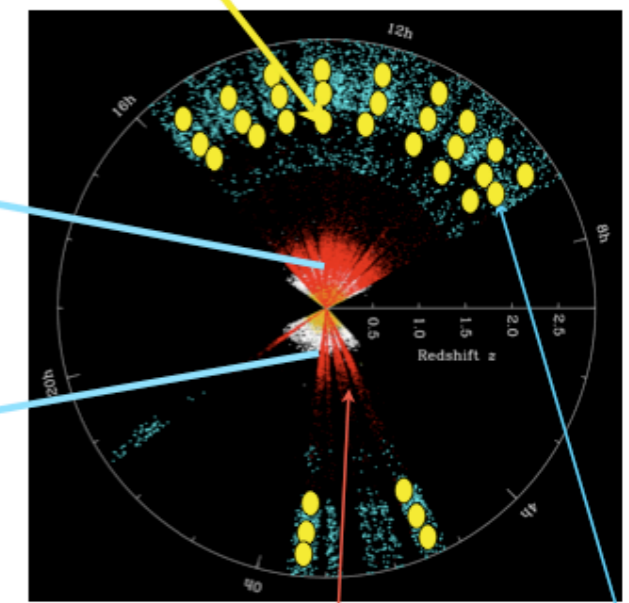
Volume of the Universe probed by SDSS



SDSS main galaxies SDSS spectroscopic LRGs

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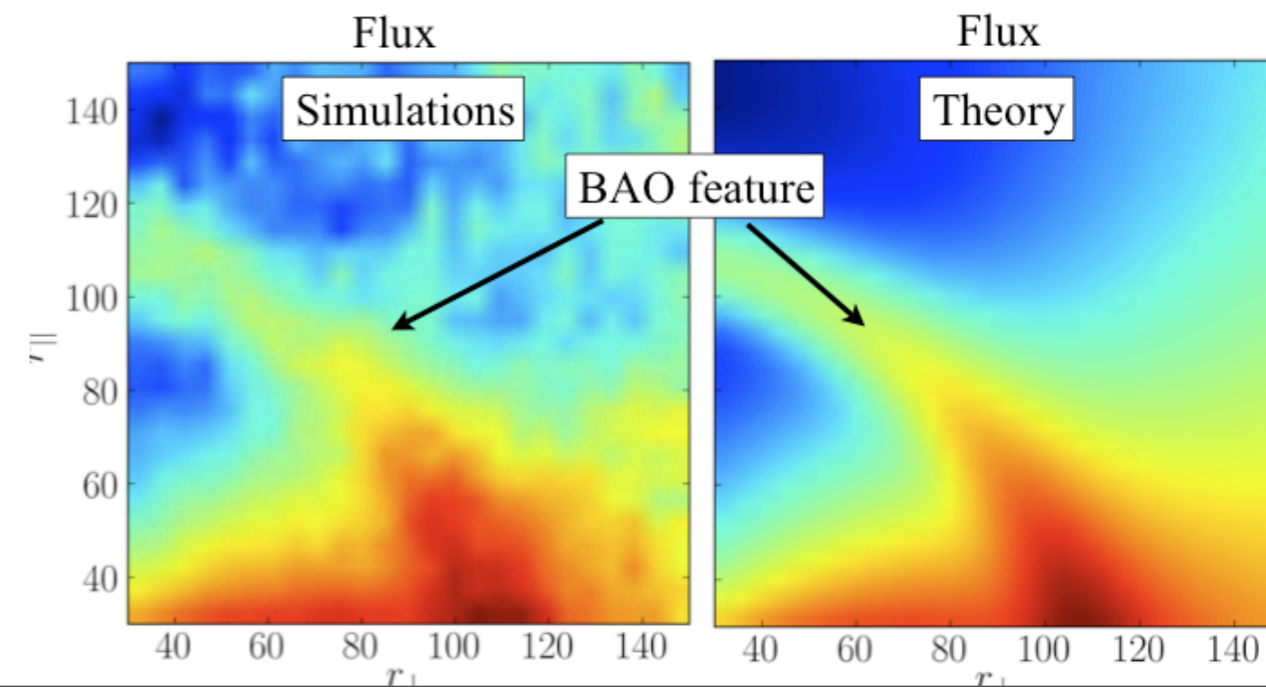
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End of Slides

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

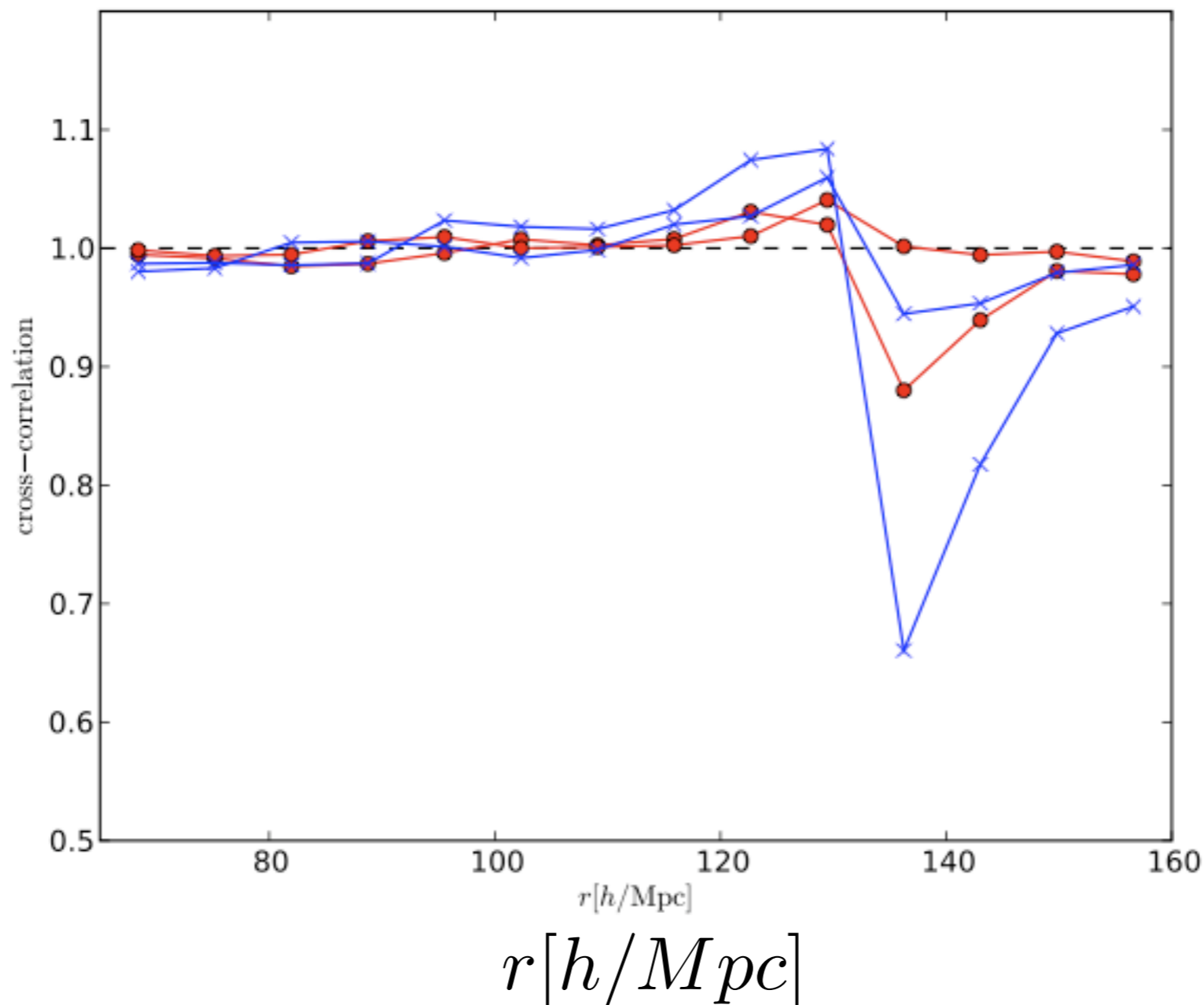
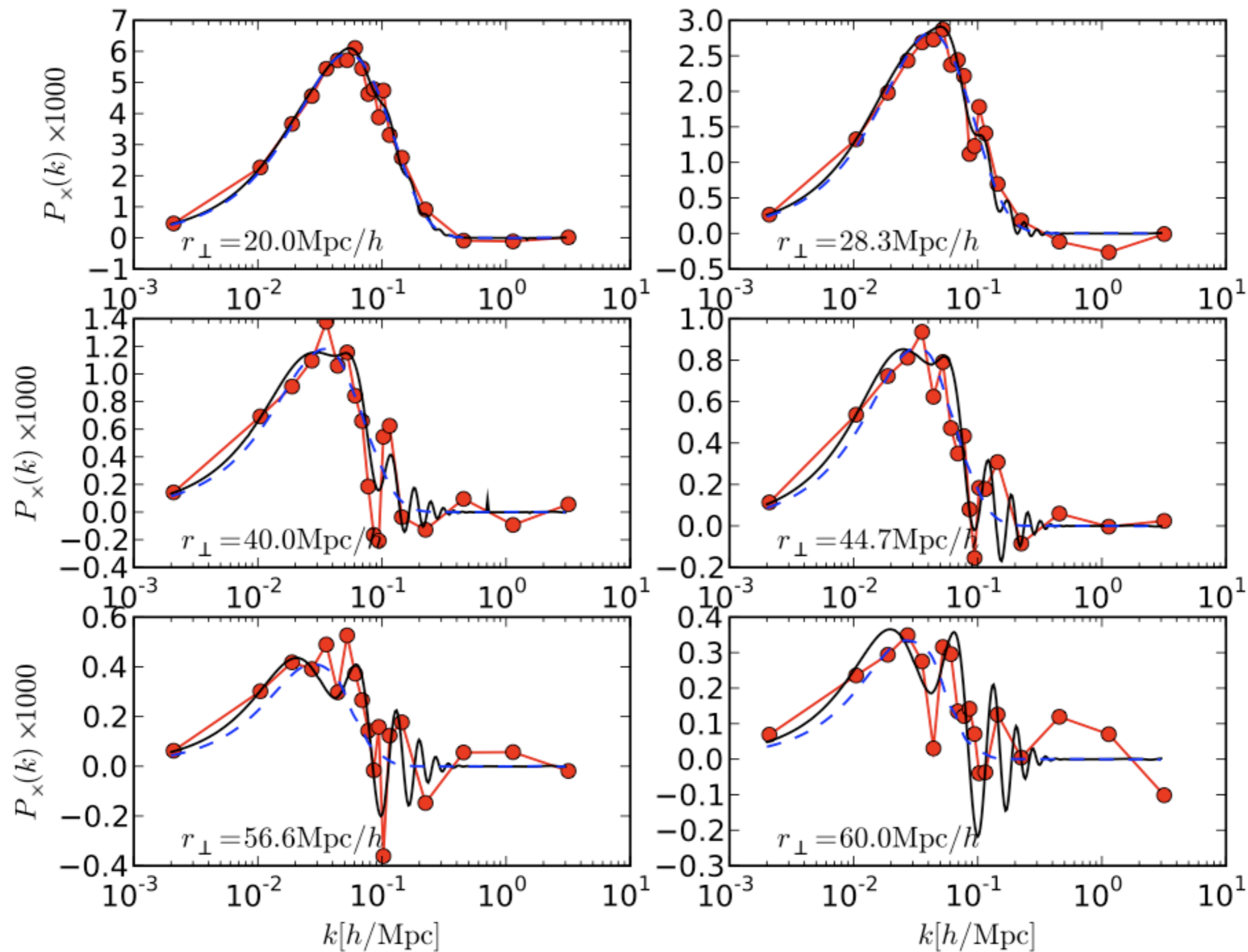


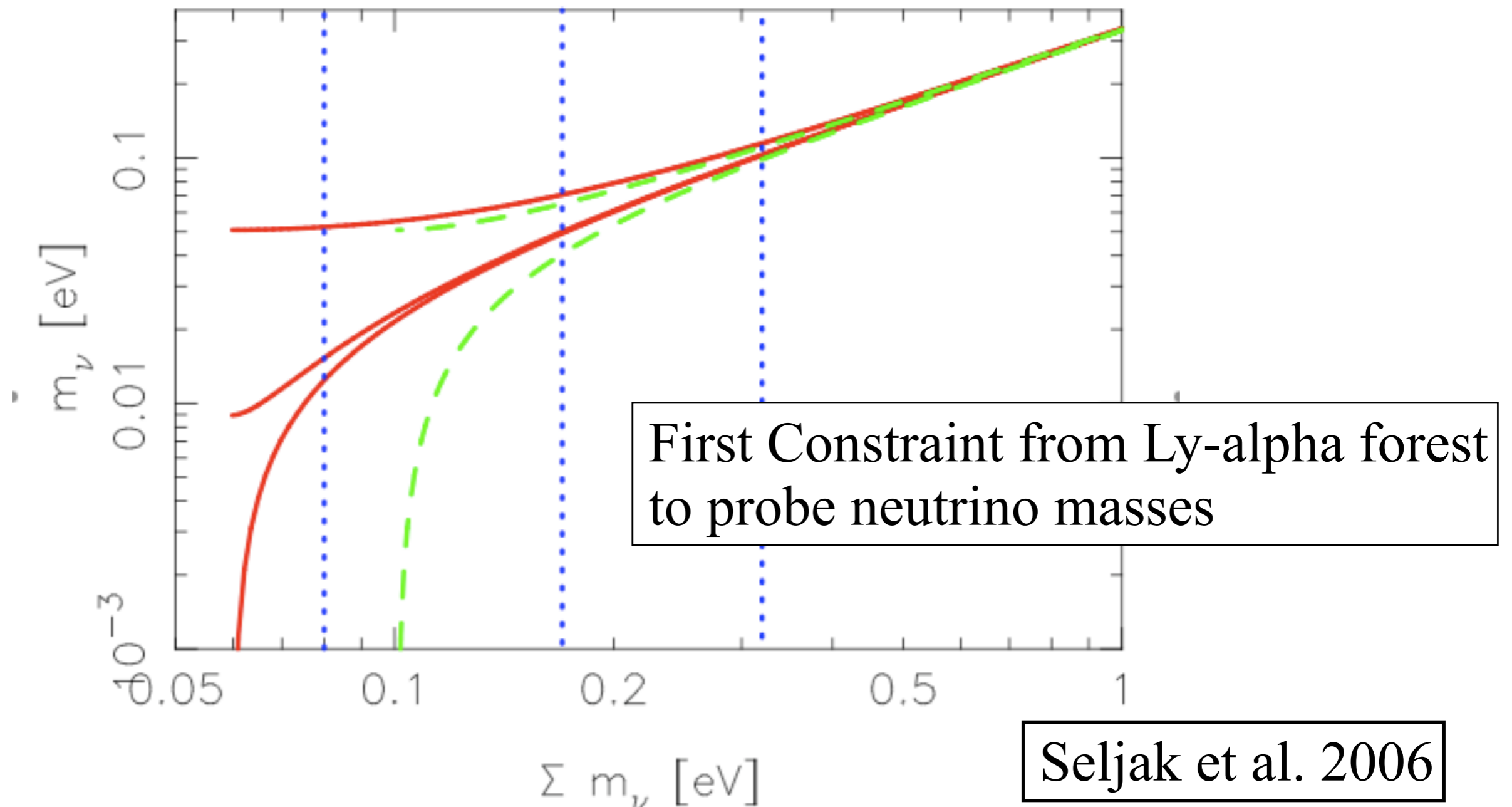
FIG. 2: The cross-correlation coefficient between the flux in our low and high resolution boxes, $\sqrt{\xi_{lh}^2 / \xi_{ll} \xi_{hh}}$. Red points show the result for the two low resolution boxes having twice the smoothing length of the high resolution box, blue is the same for $4\times$ smoothing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



Lyman Alpha Forest: what can it do?



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



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
$\sigma(\sum m_\nu)$	0.307	0.048	0.006
$\sigma(\Omega_K)$	0.011	0.0041	0.00038
$\sigma(n_s)$	0.0034	0.0023	0.001
$\sigma(dn_s/d\ln(k))$	0.003	0.0028	0.0005

Courtesy from Anze Slosar

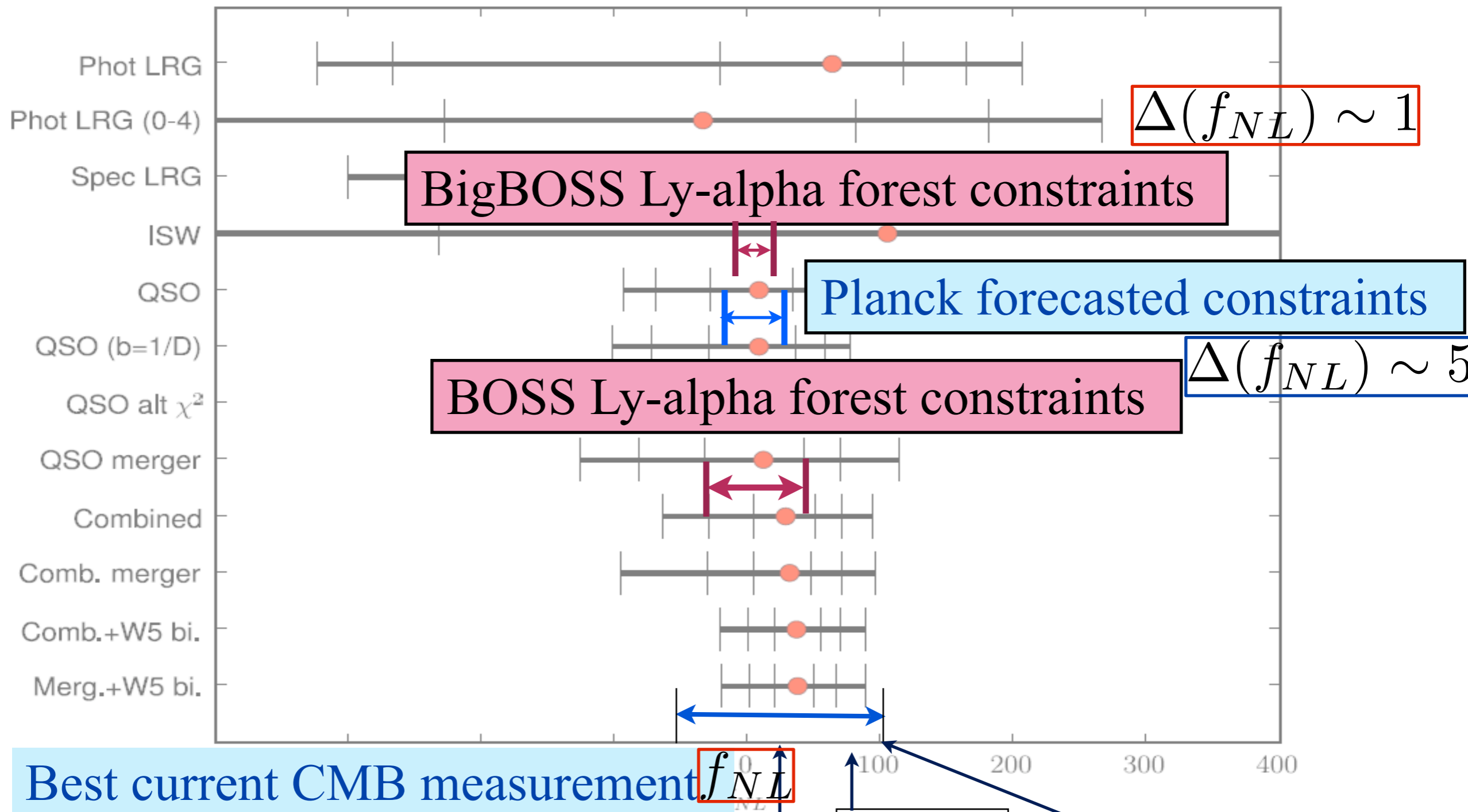
Outline



- **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



with Slosar and Seljak (work in progress)

canonical inflation

curvaton models, DBI inflation

ghost inflation

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Lyman Alpha Forest: what can it do?



- **Simulation boxes of Dark matter**

- 3000^3 particles

- 3000^3 mesh

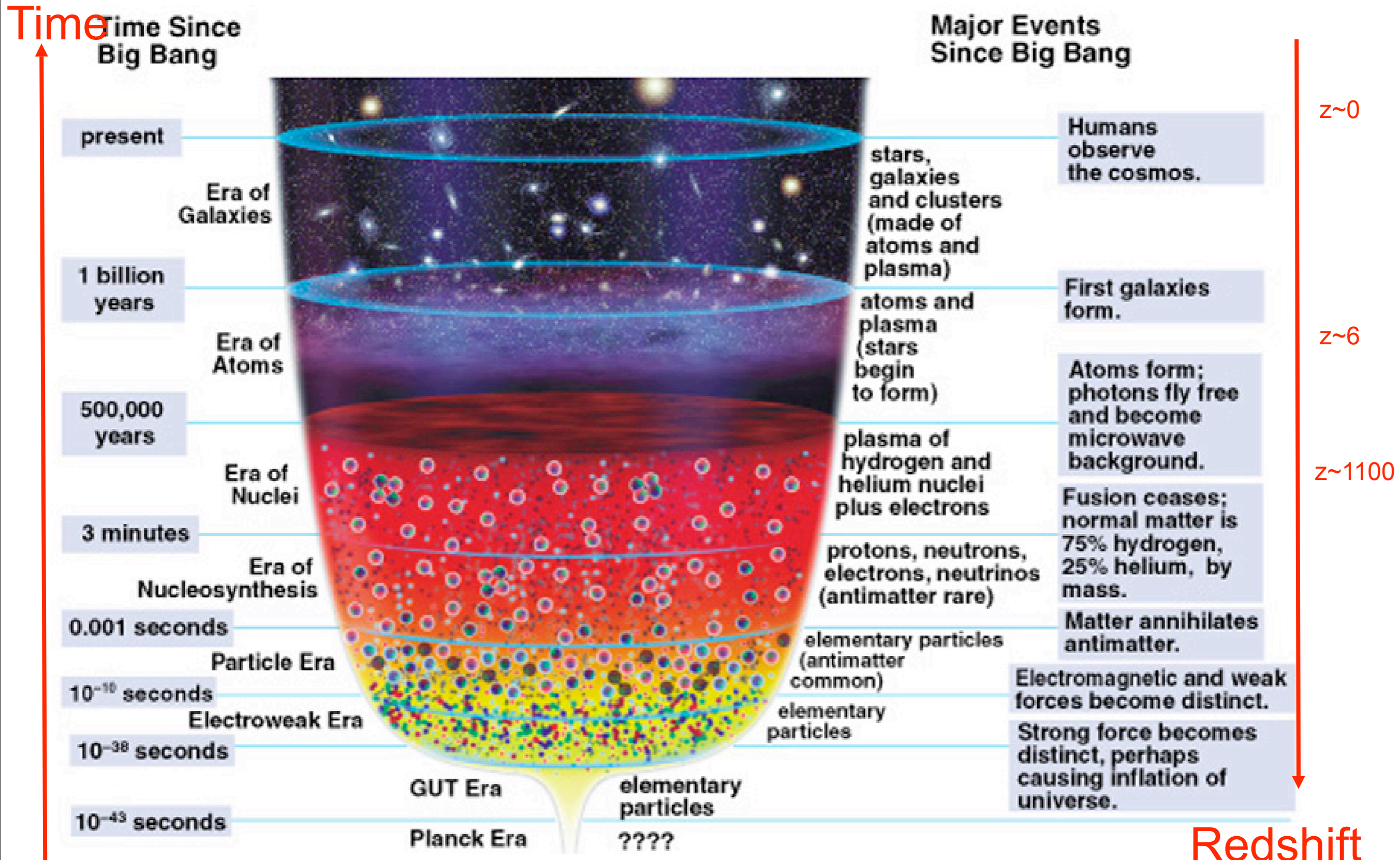
- $1500 (h^{-1} Mpc)^3$ on the side

- $\Omega_m = 0.25, \Omega_\Lambda = 0.75, h = 0.75, n = 0.97, \sigma_8 = 0.8$

- **Fluctuating Gunn Peterson approximation**

- **Peculiar velocities included**

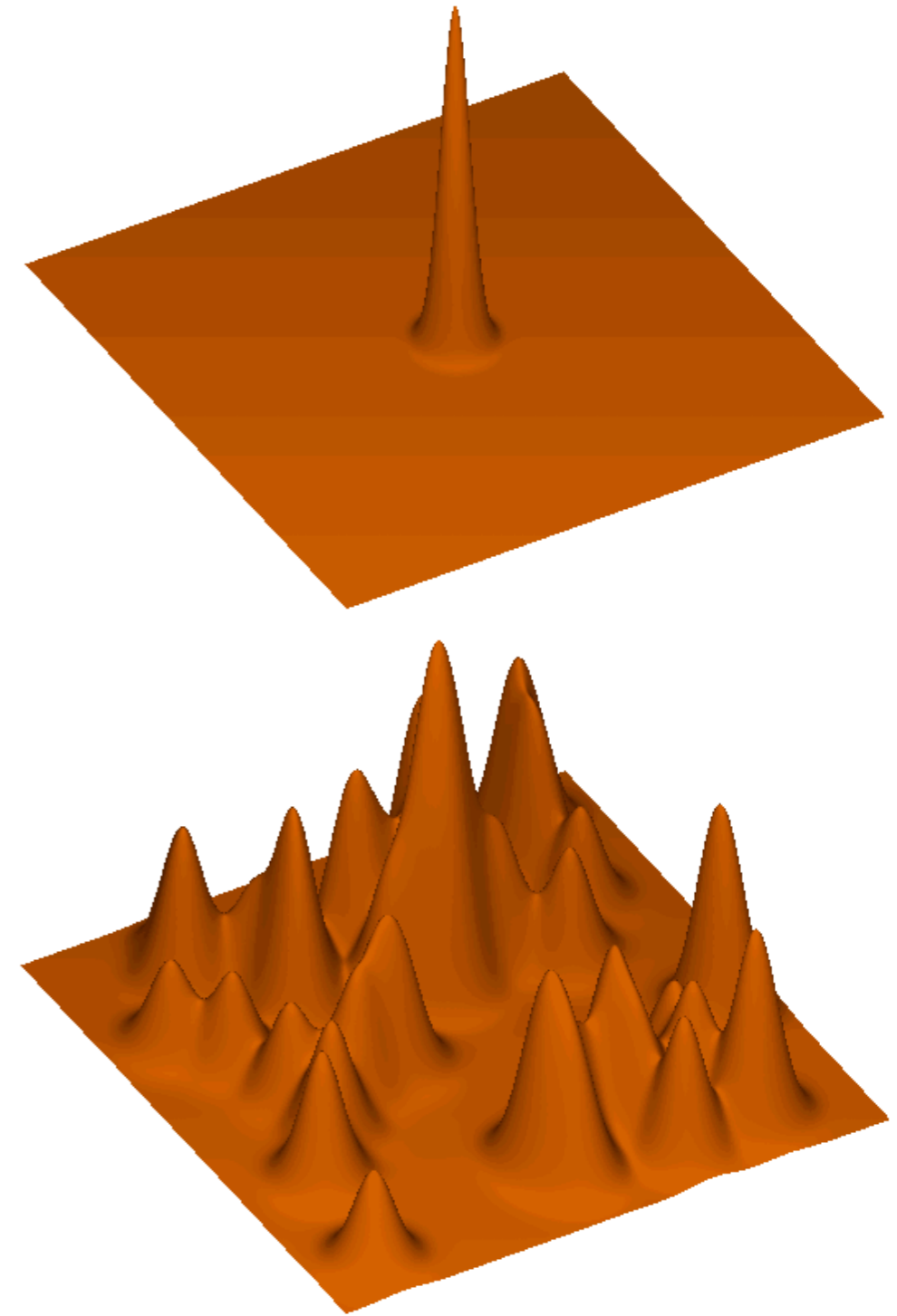
Motivations



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.**



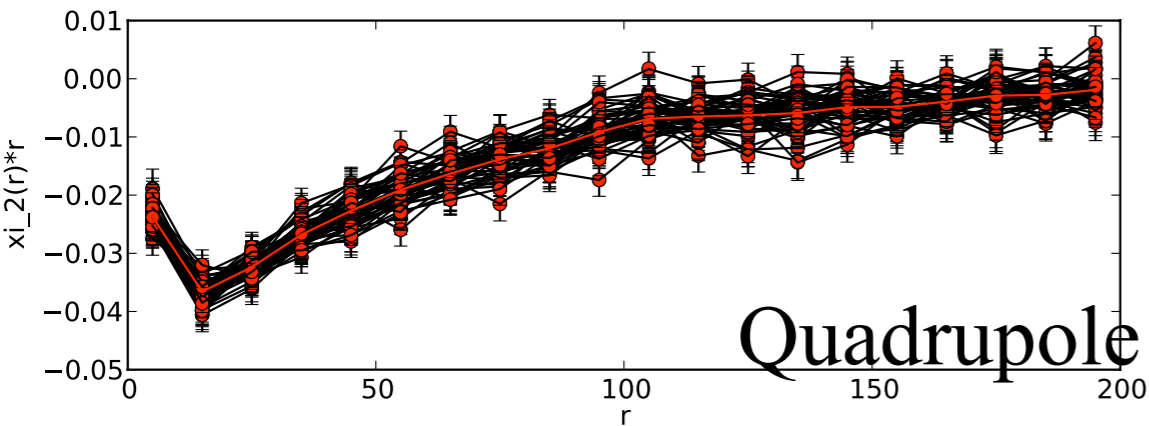
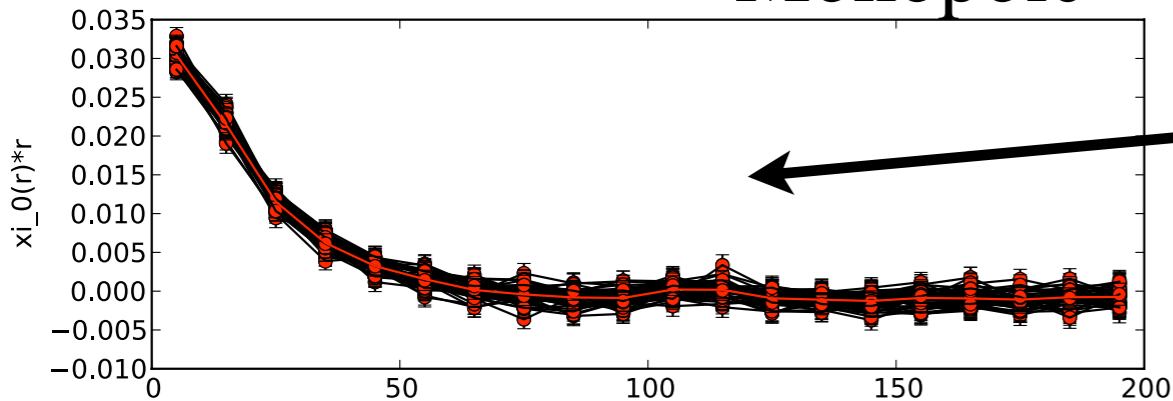
Courtesy slide from Daniel Eisenstein

Recall? Modeling z-space distortions



Simulations

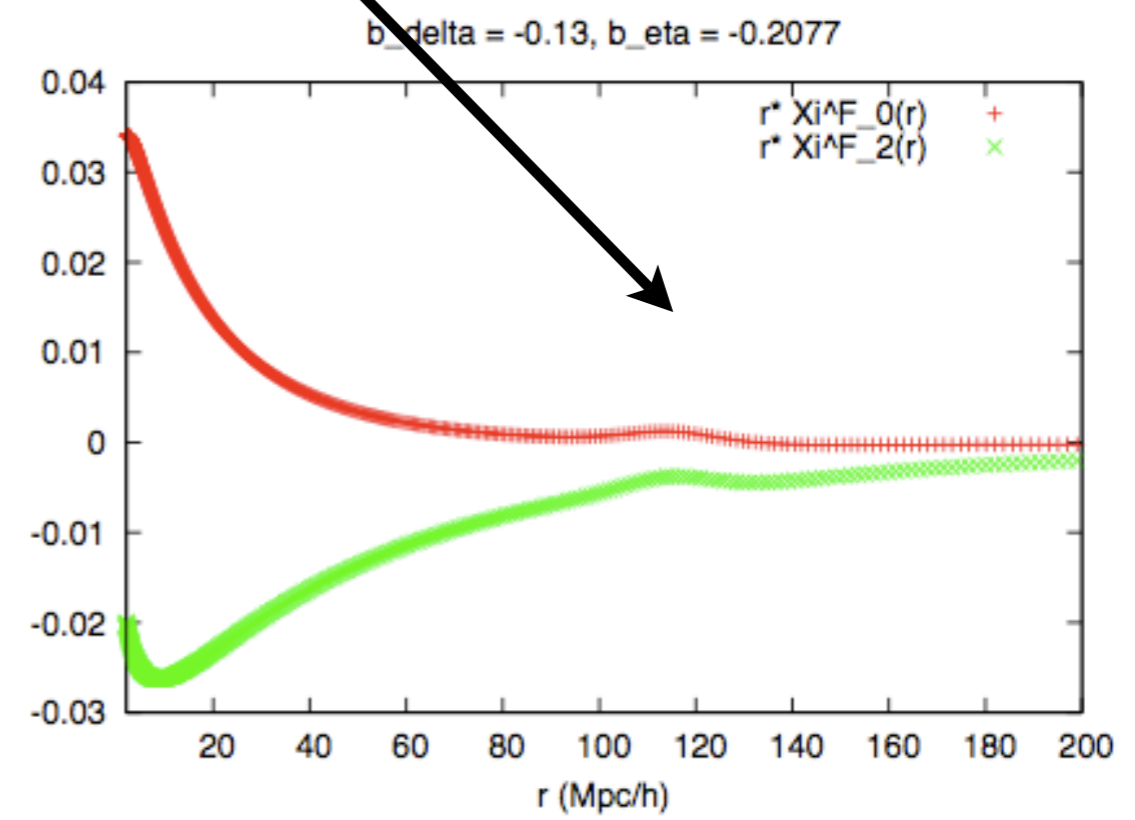
Monopole



Quadrupole

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

Predictions



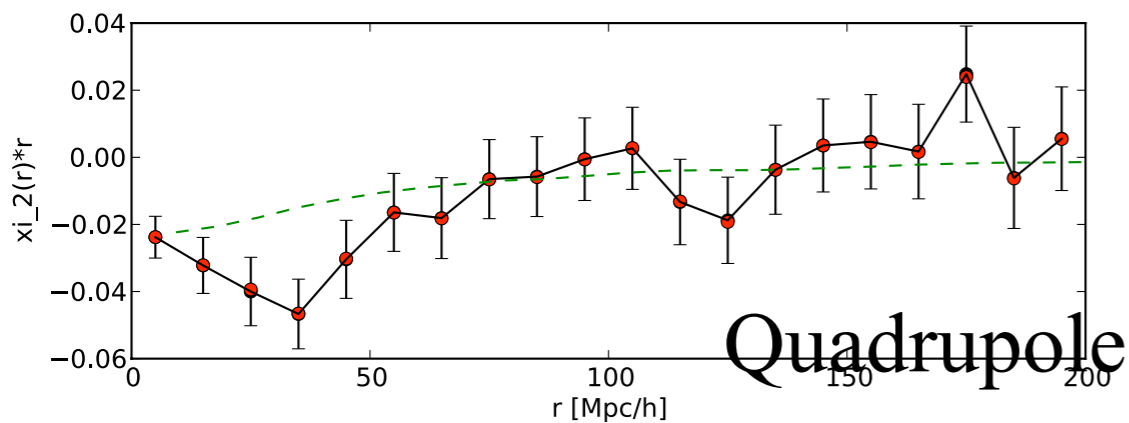
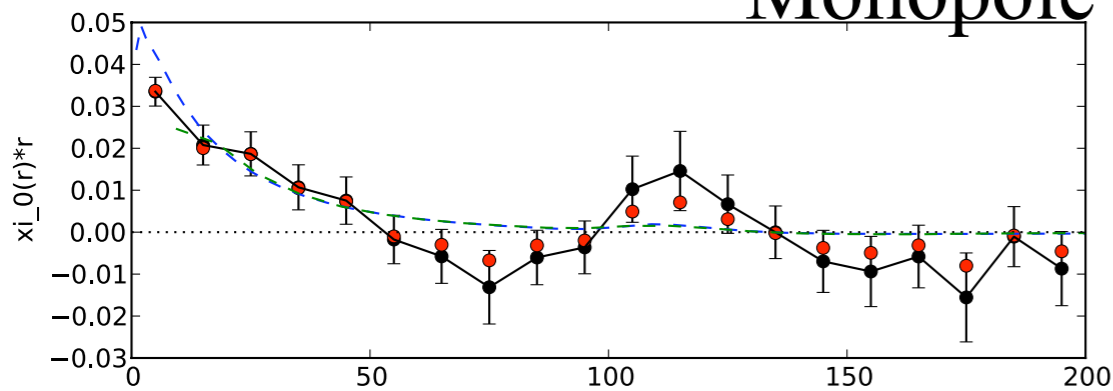
The large scale correlation functions from simulations of Lyman alpha fores

Recall? Modeling z-space distortions



DATA

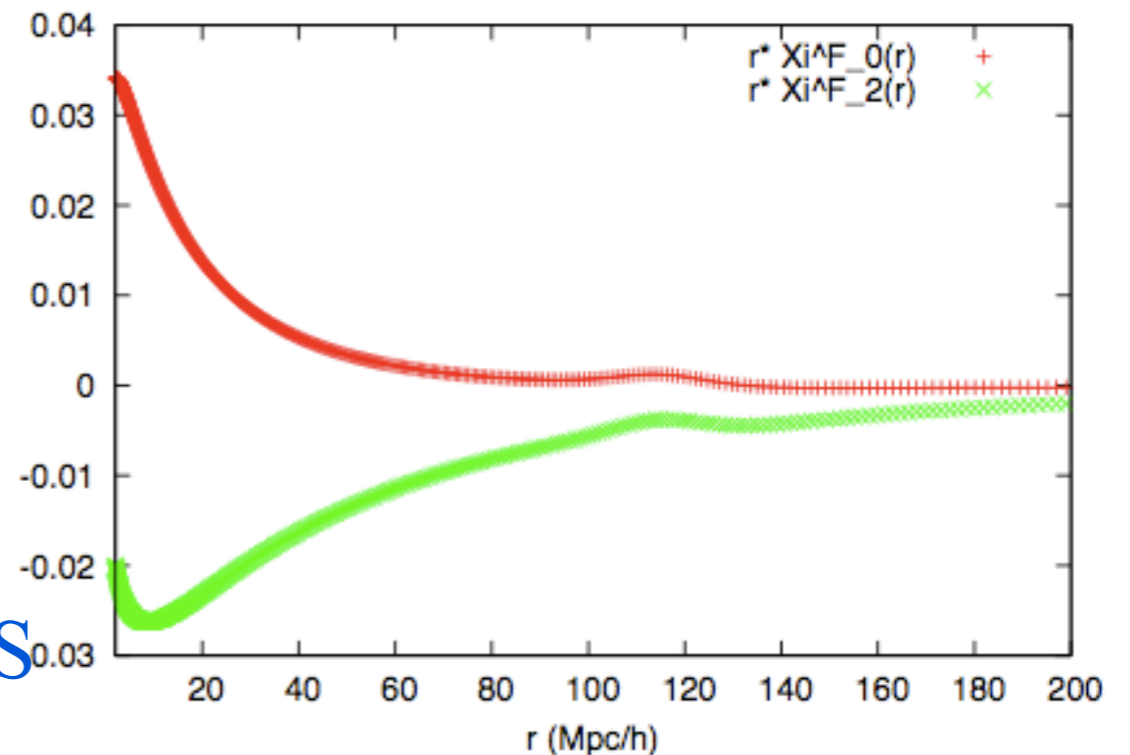
Monopole



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

Predictions

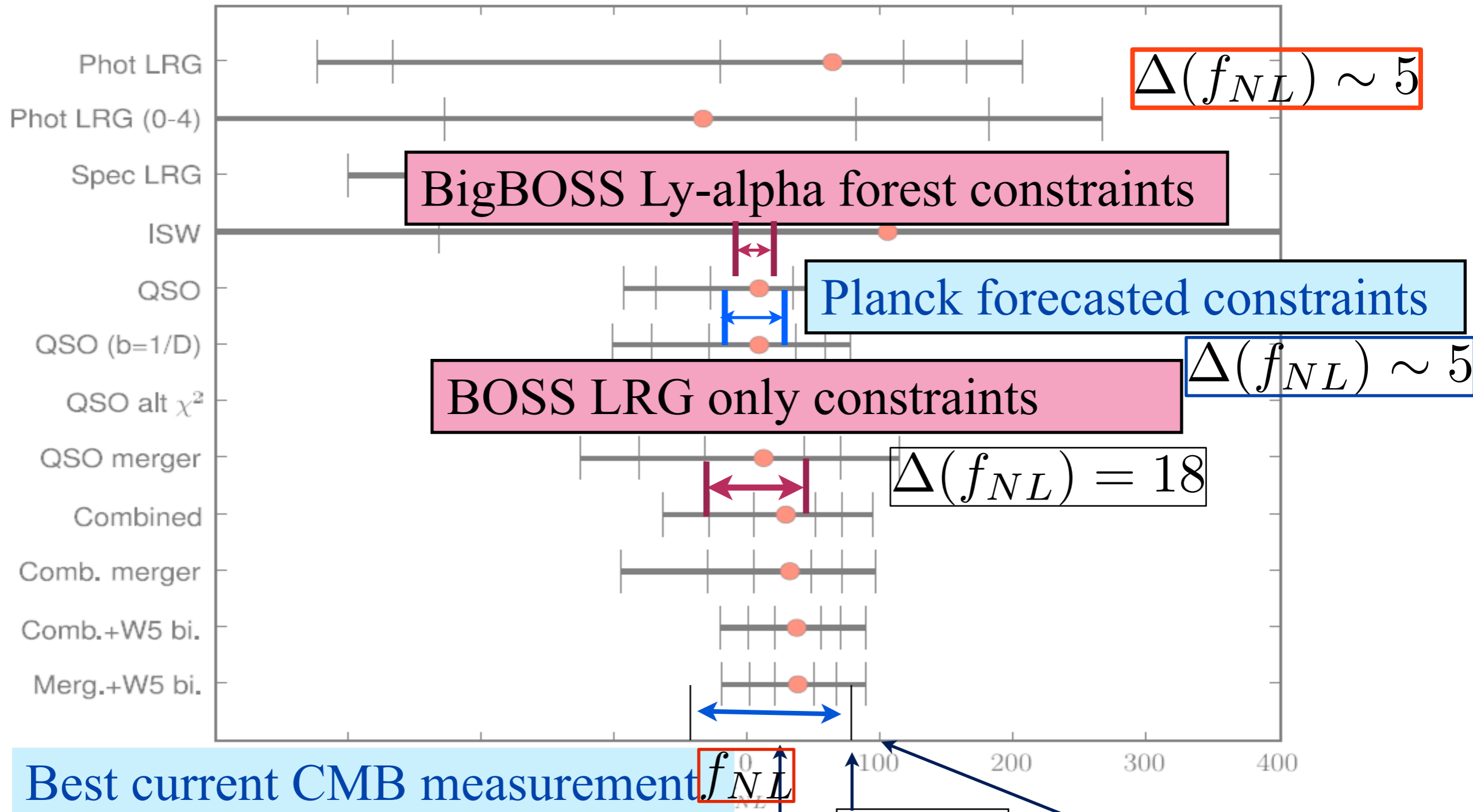
$b_{\Delta} = -0.13, b_{\eta} = -0.2077$



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

What can we do with $L\alpha$ and f_{NL} ?

—Non-gaussianities in Early Universe



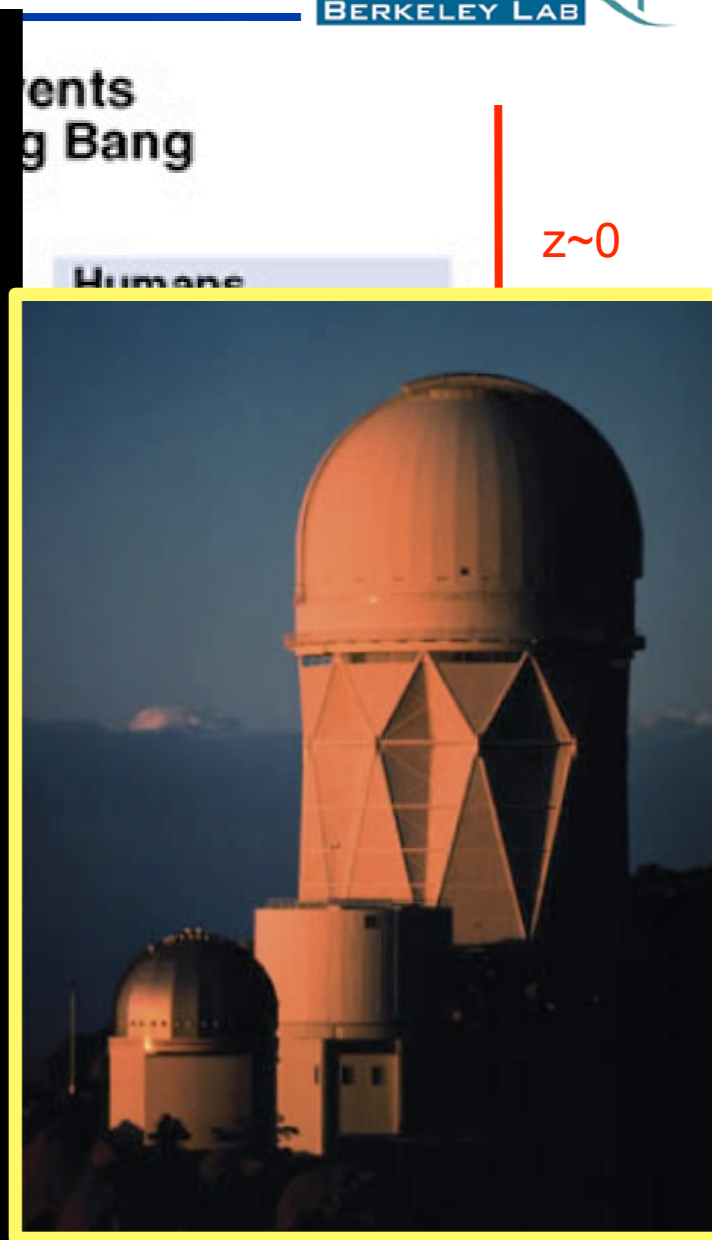
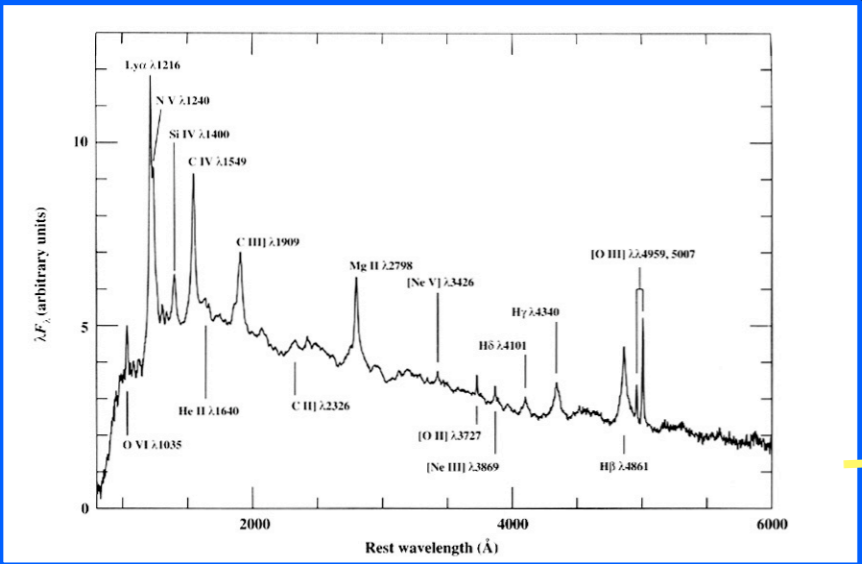
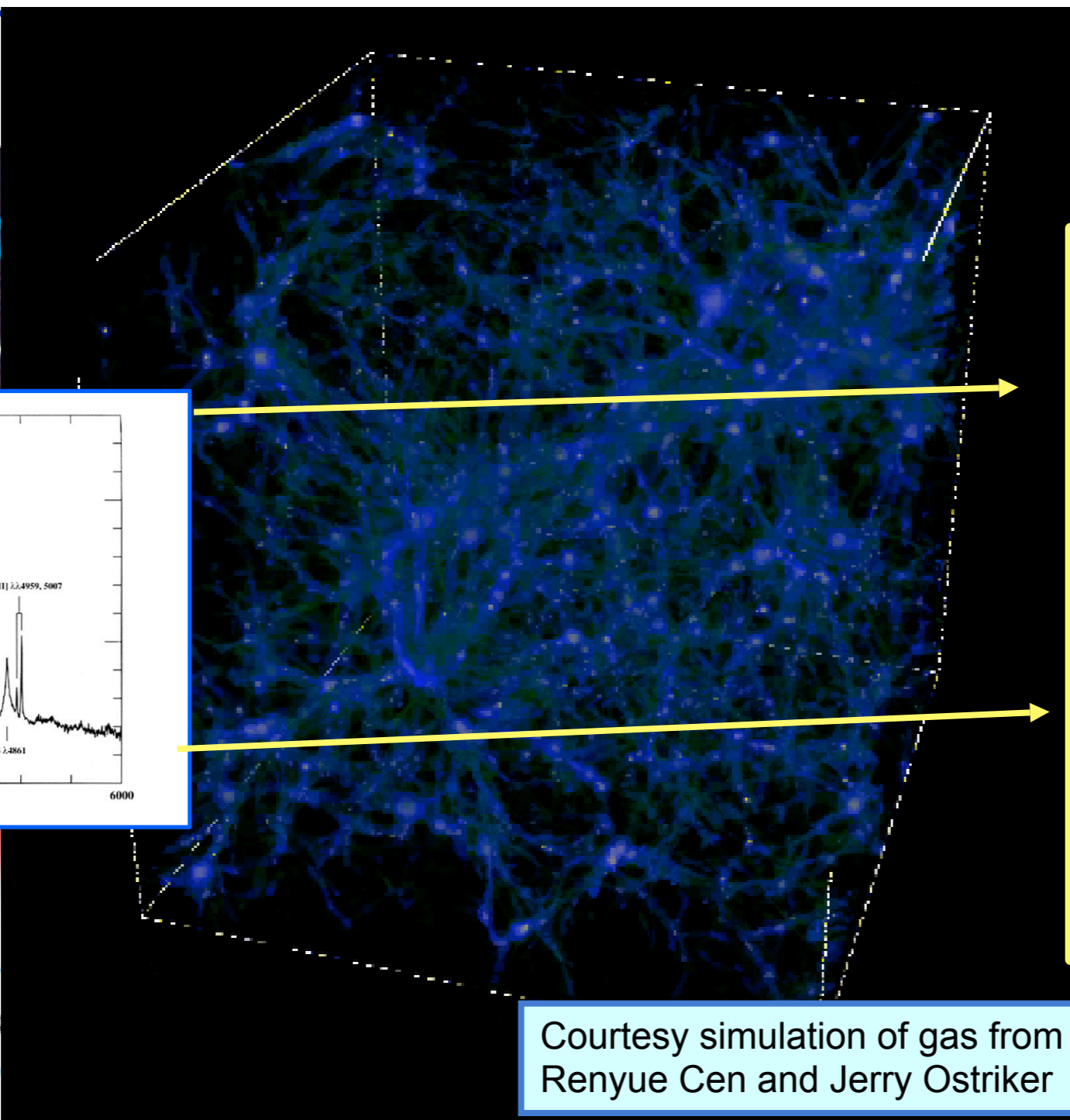
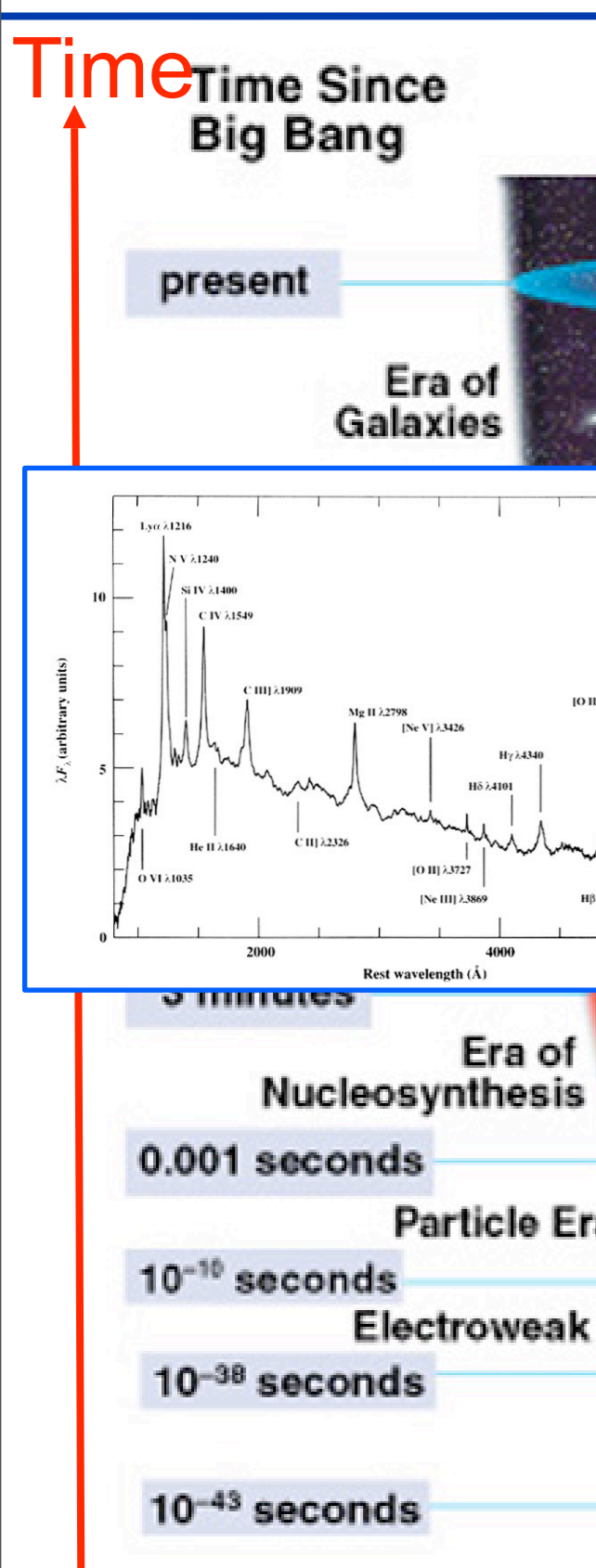
canonical inflation

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Ho, Slosar, Seljak & Desjacques (in prep)

Lyman Alpha Forest: what is it?



Courtesy simulation of gas from Renyue Cen and Jerry Ostriker

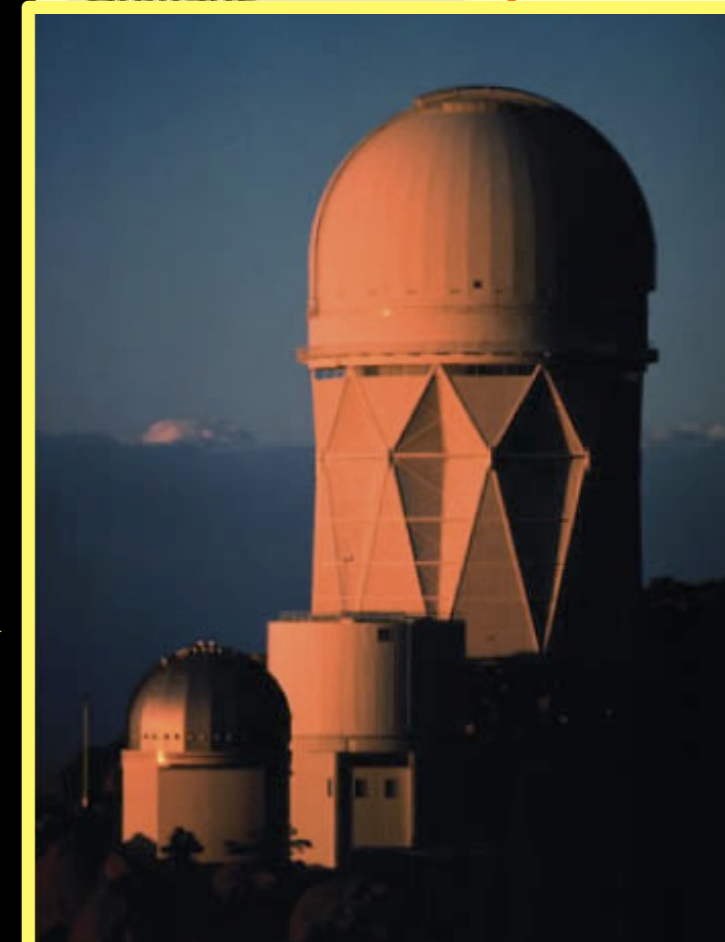
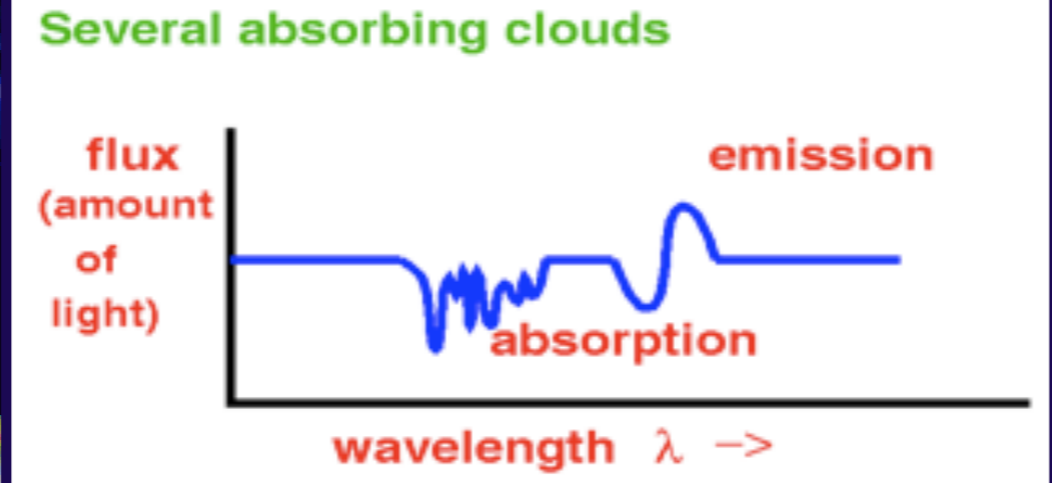
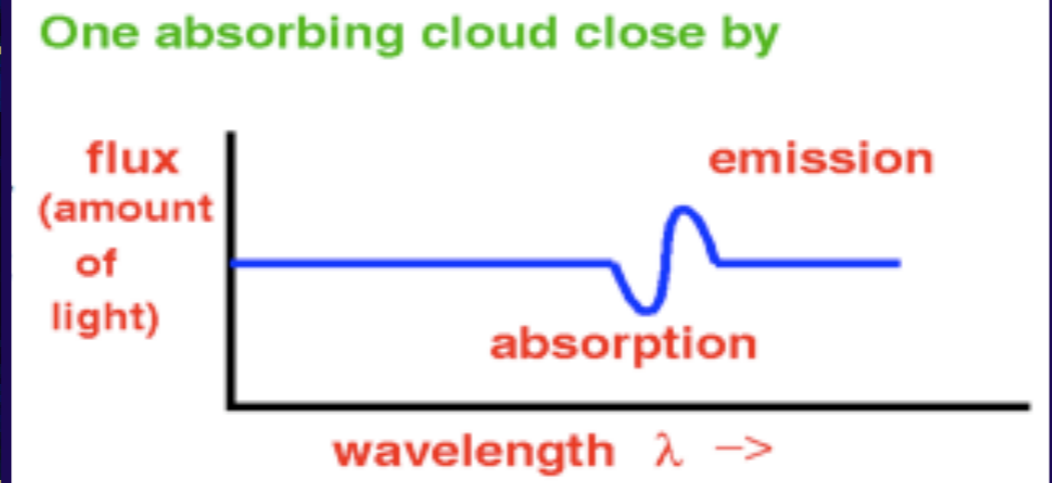
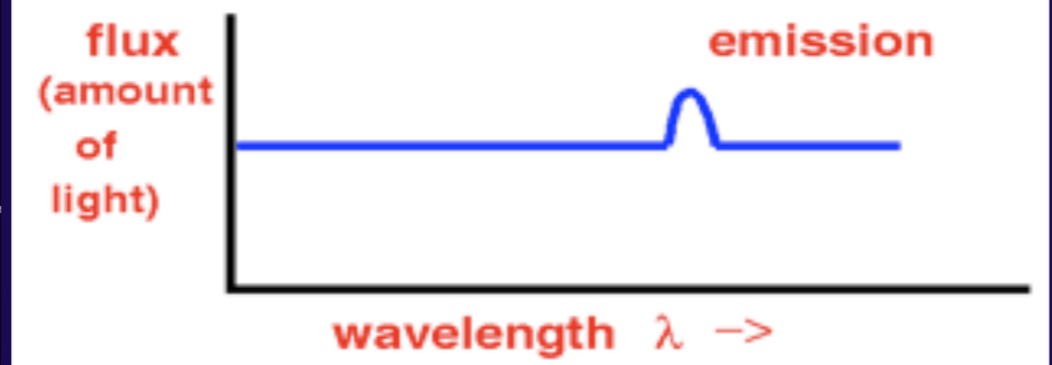
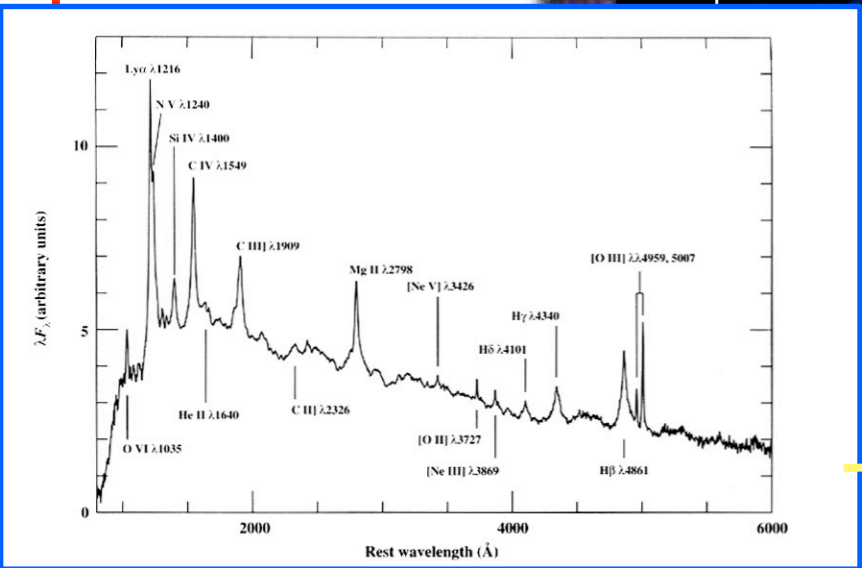
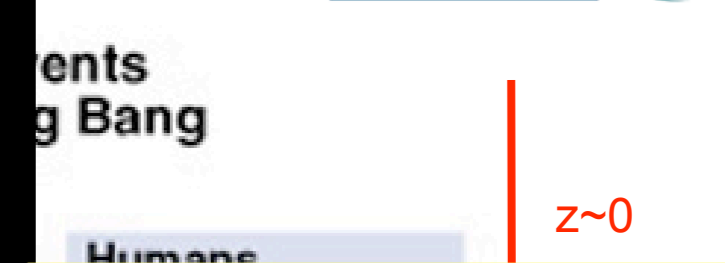
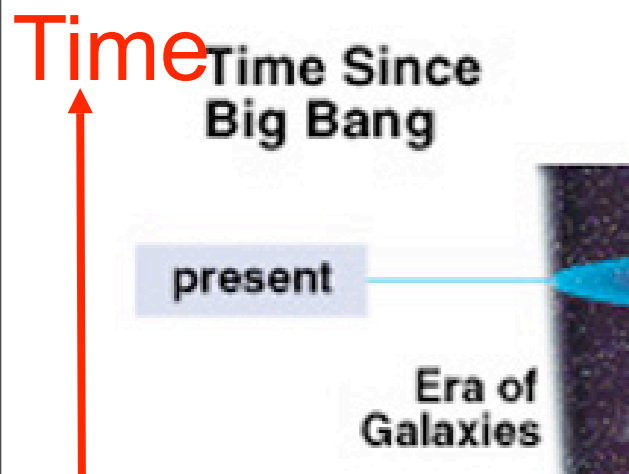
Strong force becomes distinct, perhaps causing inflation of universe.

Electromagnetic and weak forces become distinct.

Matter annihilates antimatter.

Redshift ↓

Lyman Alpha Forest: what is it?

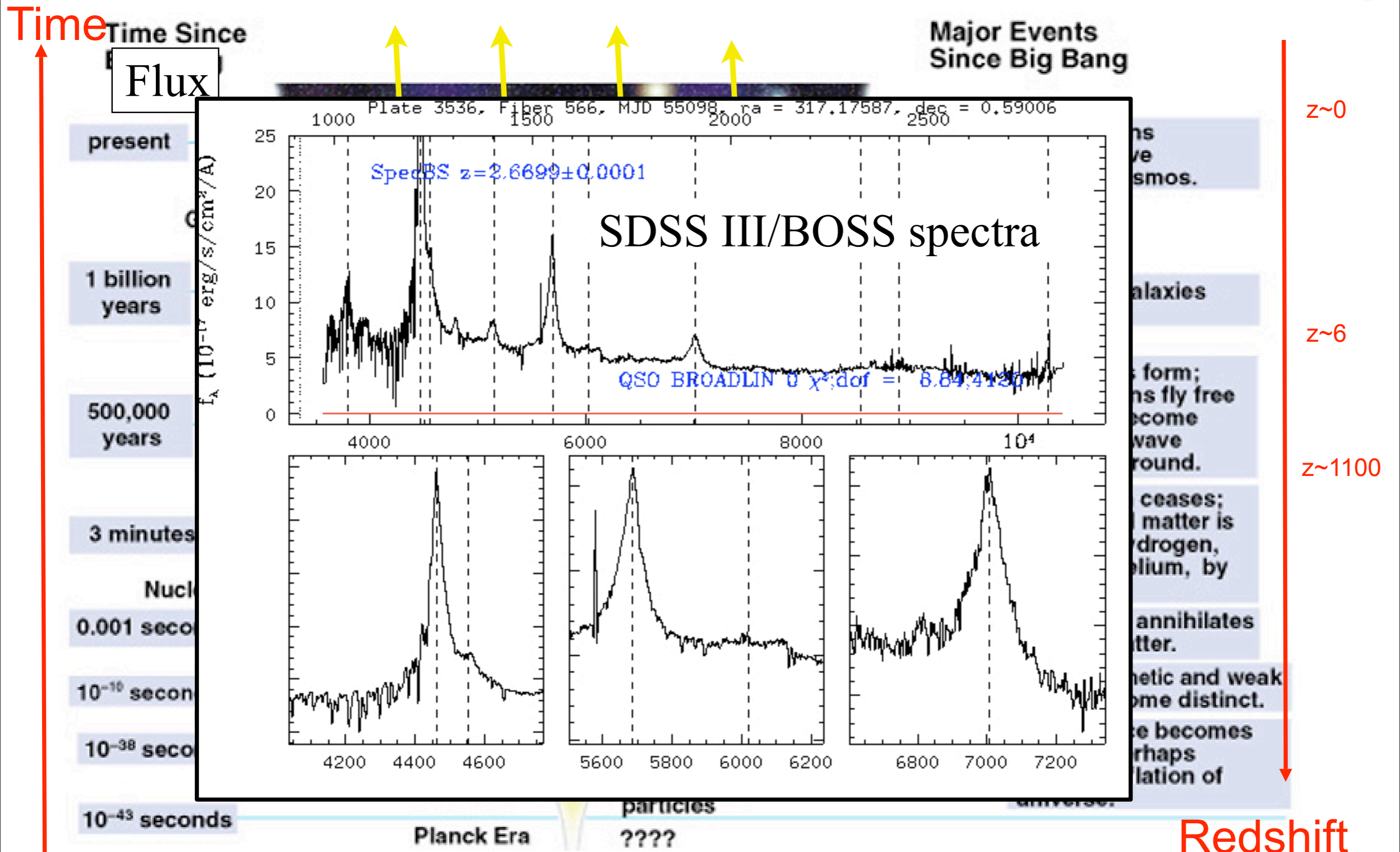


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Courtesy image from Joanne Cohn's website

Redshift

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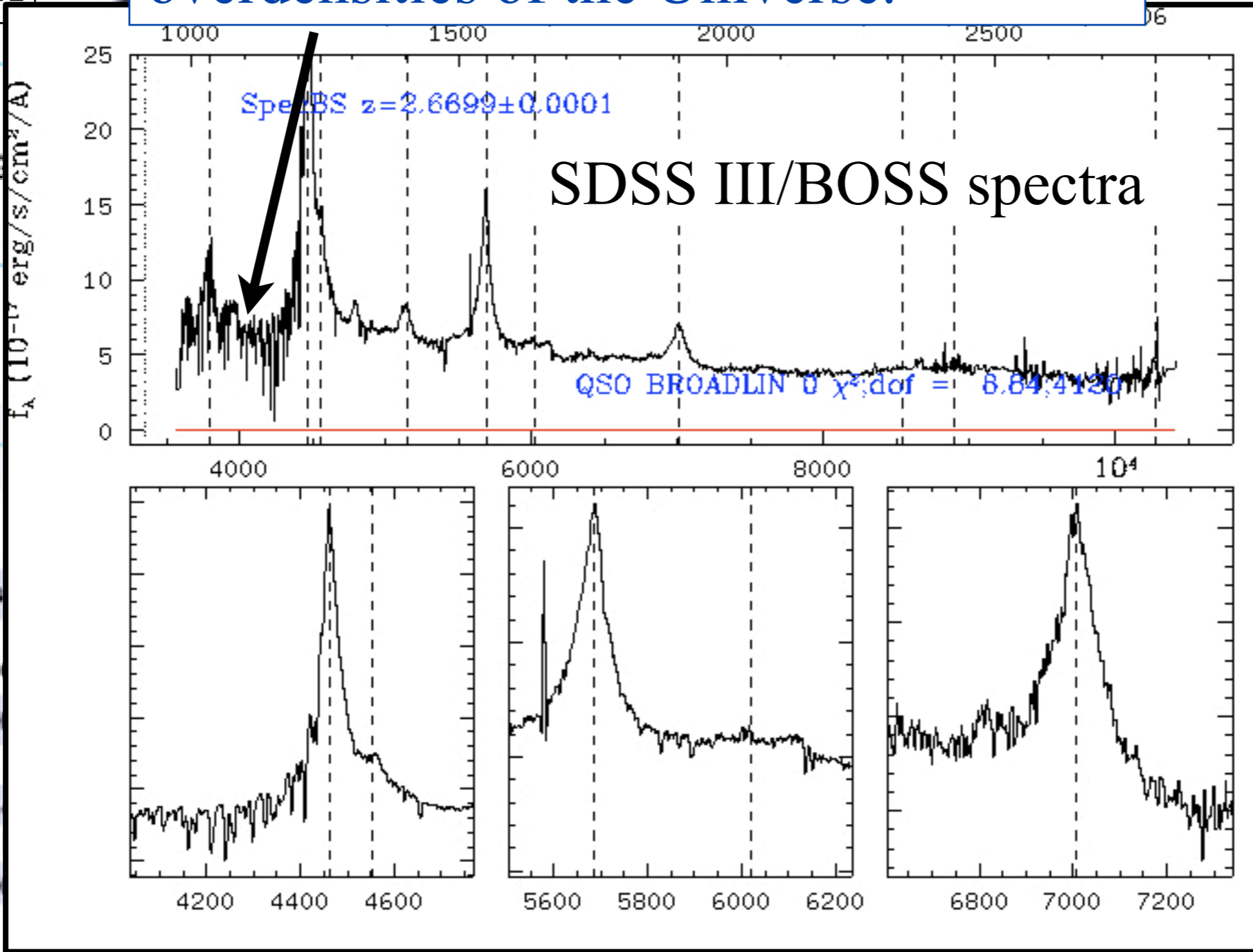


Lyman Alpha Forest: what is it?

Locates the Neutral Hydrogen, thus overdensities of the Universe.

Time
Time Since
Flux

present
1 billion years
500,000 years
3 minutes
Nucleosynthesis
0.001 seconds
10⁻¹⁰ seconds
10⁻³⁸ seconds
10⁻⁴³ seconds



Time Since Big Bang

$z \sim 0$

Galaxies

$z \sim 6$

Structure forms; galaxies fly free and become wave ground.

$z \sim 1100$

Nucleosynthesis ceases; matter is hydrogen, helium, by

annihilates matter.

Strong and weak become distinct.

Universe becomes perhaps

Universe.

Redshift

Outline

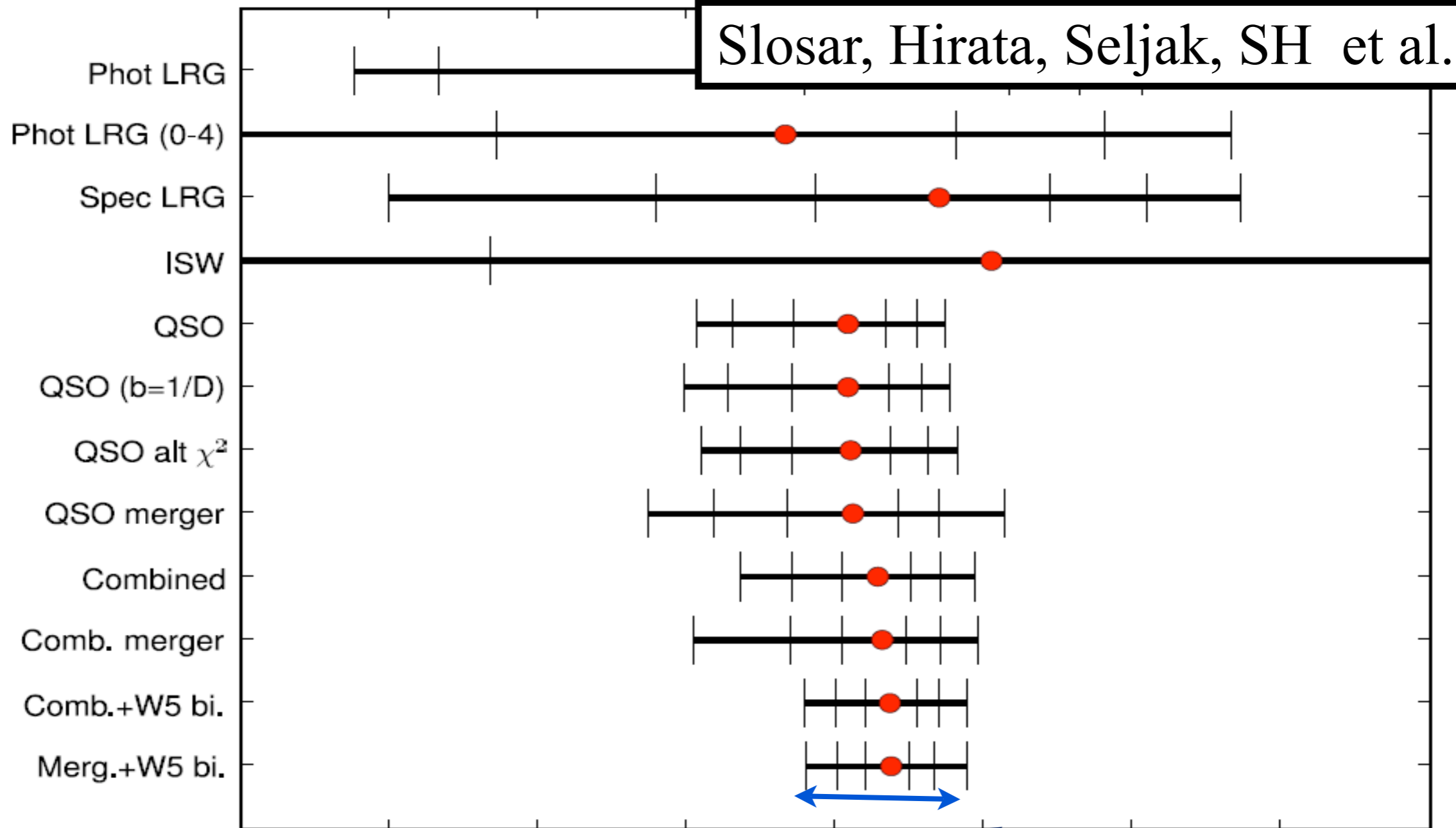


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Slosar, Hirata, Seljak, SH et al. 2008



Best current CMB measurement f_{NL}^0

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ghost inflation