CMB cosmology

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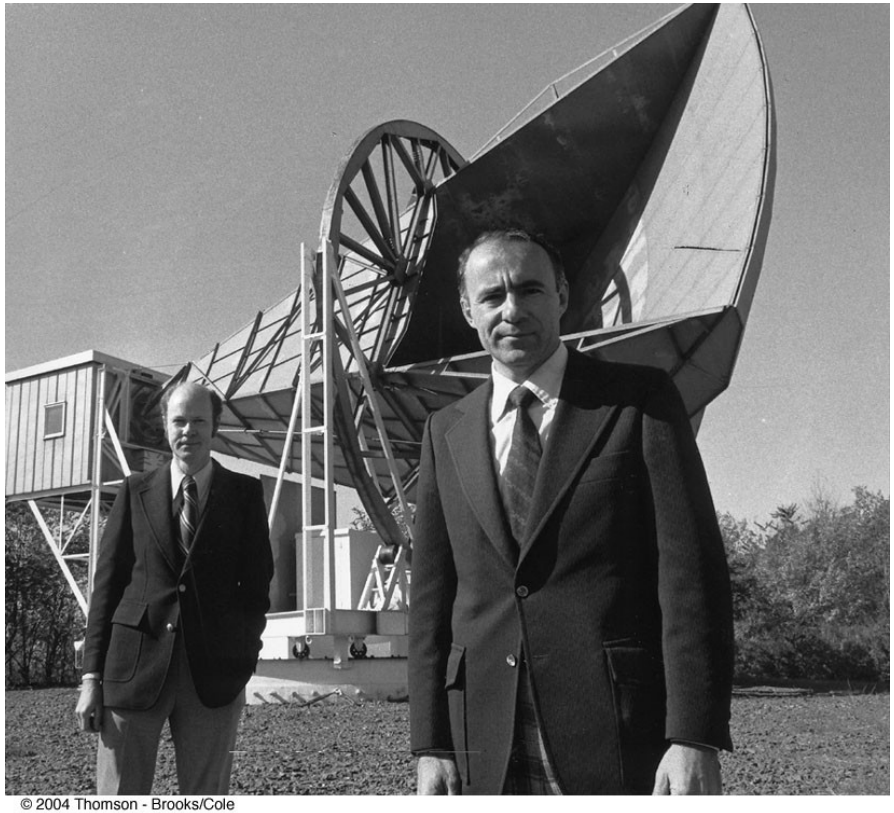
The University of New South Wales

CosPA 2017, Kyoto, December 11 – 15, 2017

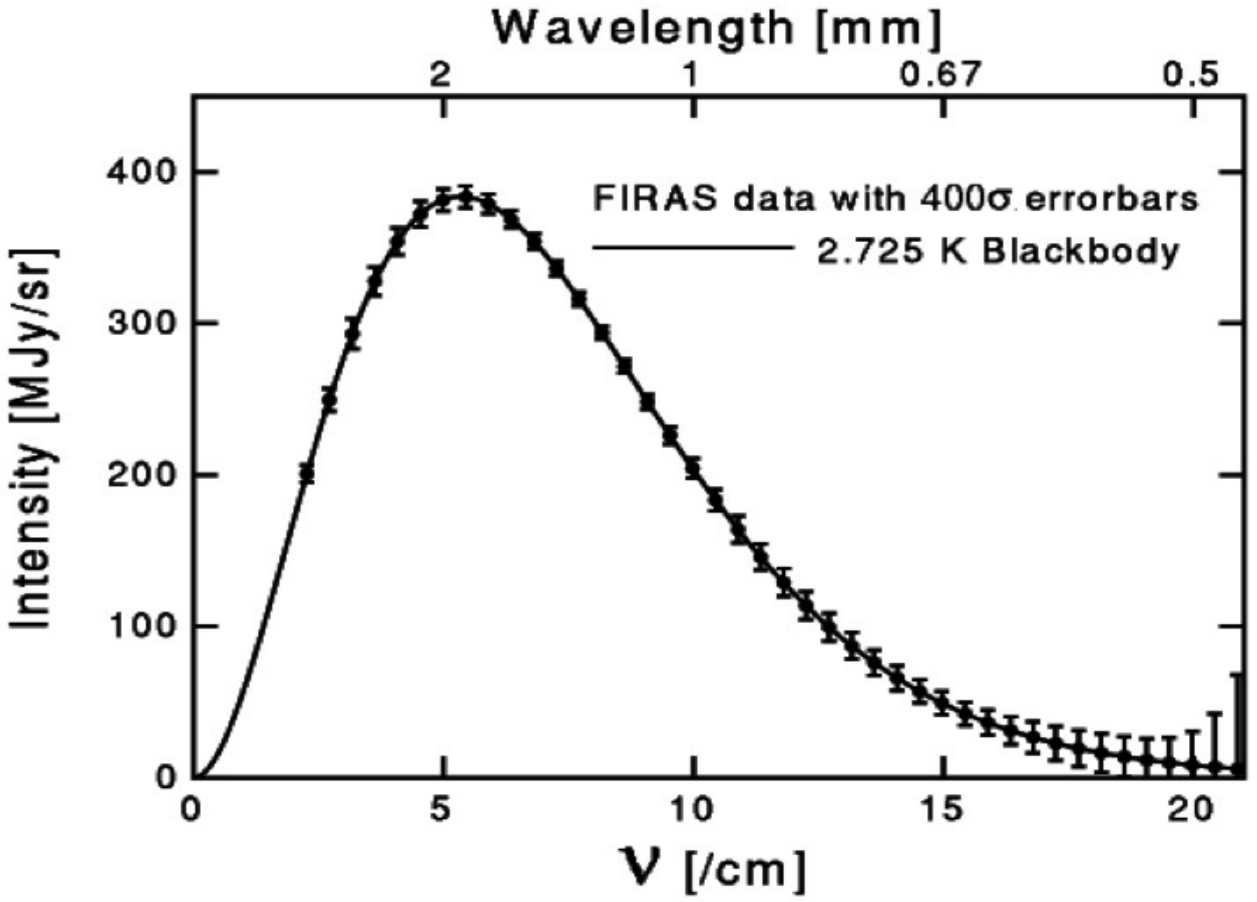
52 years of CMB measurements...

CMB = thermal relic radiation left over from ~400,000 years post big bang, first observed in 1965.



Arno Penzias &
Robert Woodrow Wilson
@ the Holmdel Horn Antenna

The most perfect blackbody ever measured...

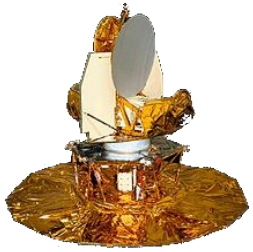


$$T_\gamma = 2.725 \pm 0.001\,\mathrm{K}$$

Mather et al., 1994

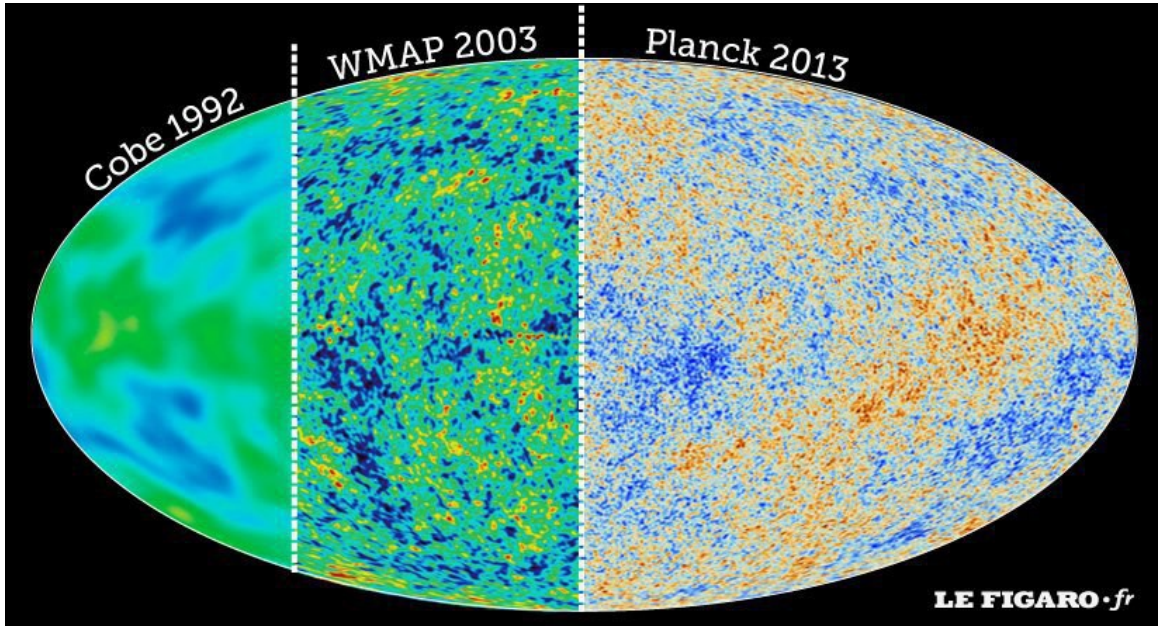
3 generations of space-based anisotropies probes...

7°



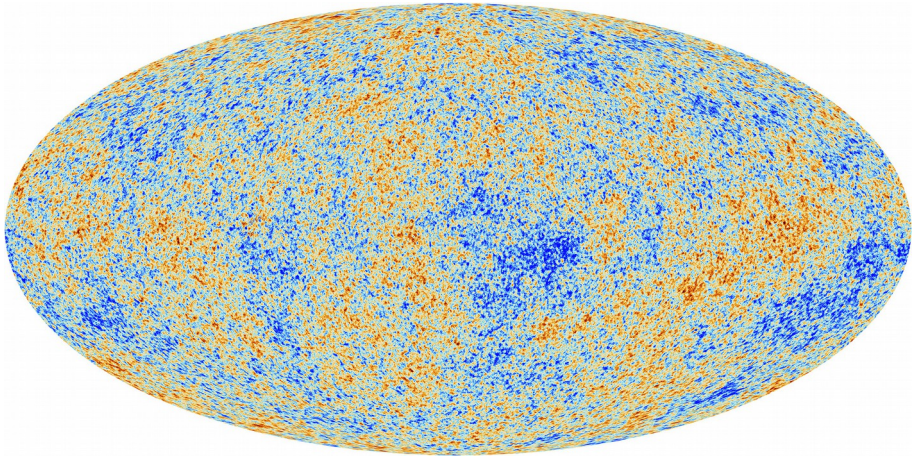
0.3°

<0.1°

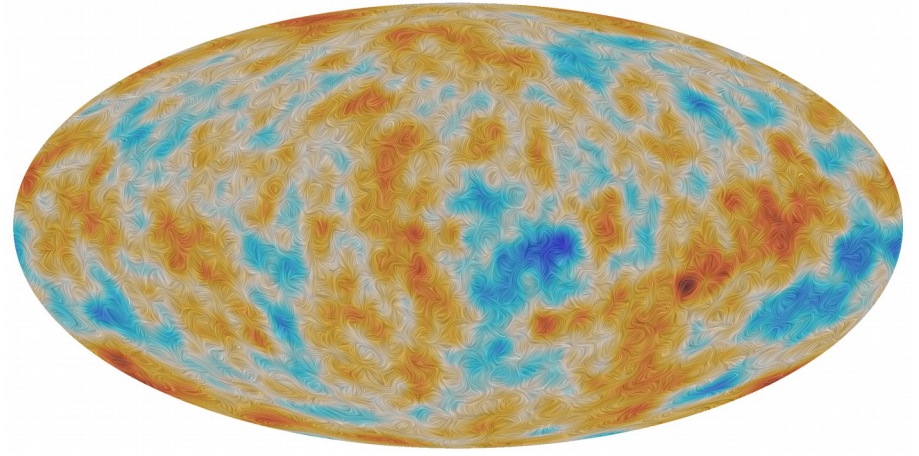


CMB anisotropies as seen by Planck 2015...

Temperature fluctuations

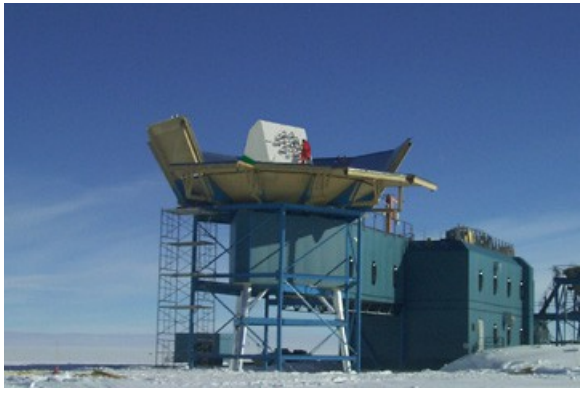


Polarisation fluctuations
(from Thomson scattering of photons off electrons)

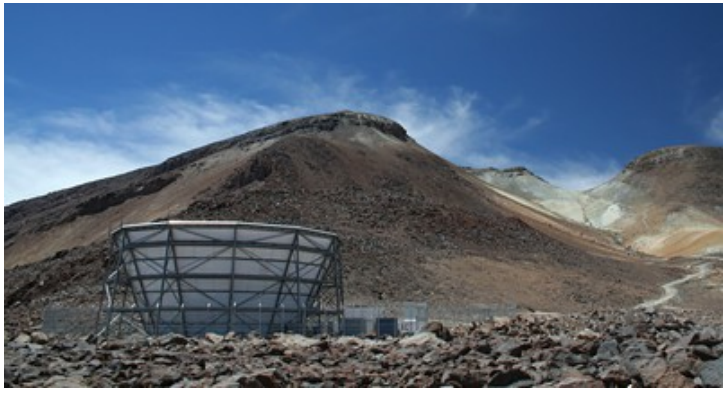


Don't forget the ground-based/balloon experiments...

BOOMERanG (flat spatial geometry 1999)



DASI (polarisation anisotropies 2002)



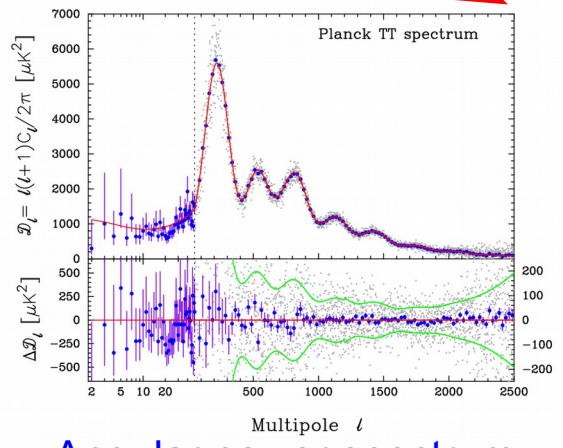
ACT...

… and SPT (damping tail 2011)

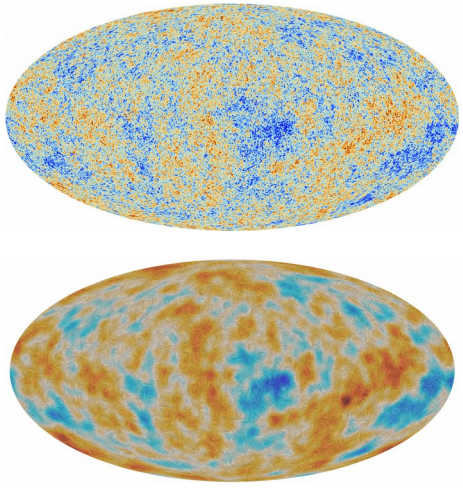
Plus many others...

CMB observables: what can be extracted from maps...

2-point correlation

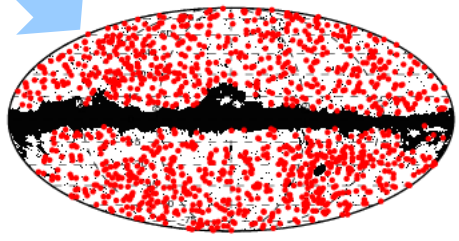


Angular power spectrum

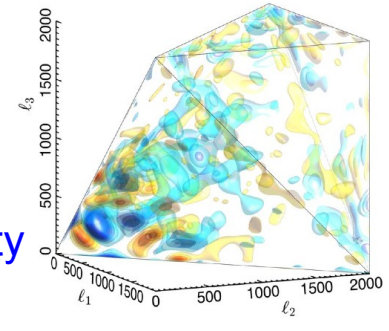


Higher-order correlations

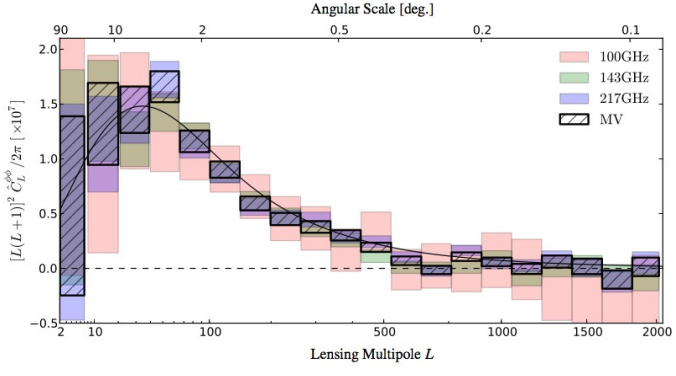
Sunyaev-Zeldovich effect



Cluster mass function (when combined with X-ray cluster mass measurements)



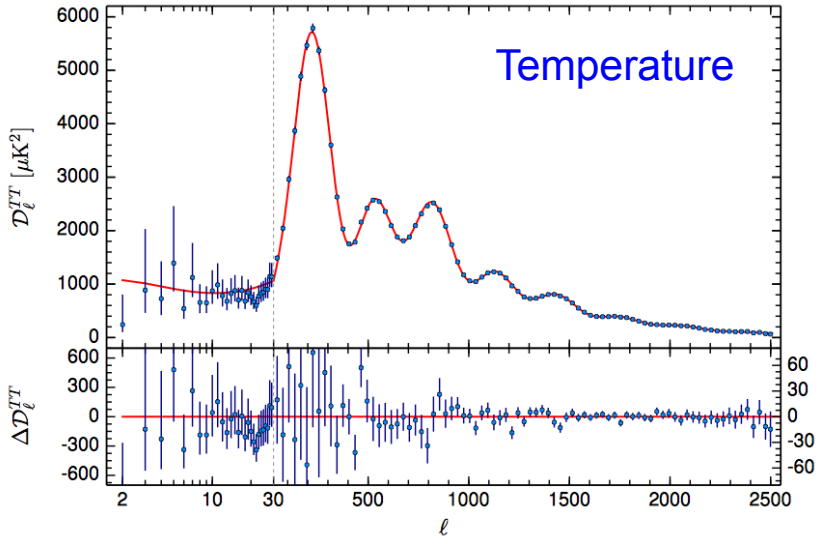
Primordial non-Gaussianity

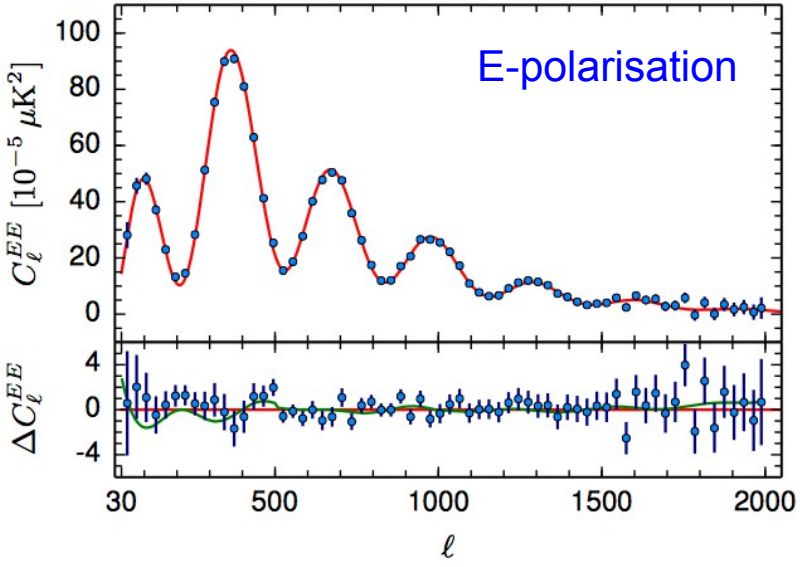


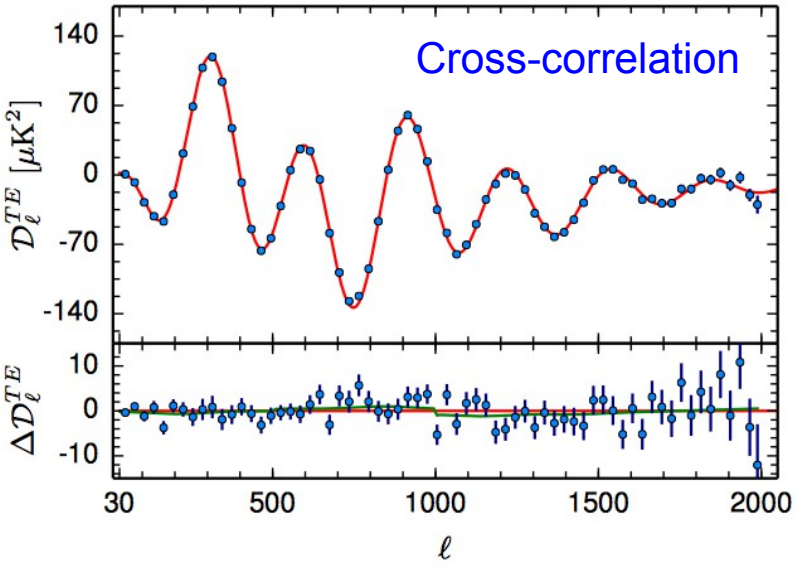
Lensing potential power spectrum

2-point correlation: angular power spectra...

Ade et al. [Planck] 2015







A combination of:

- Photon-baryon acoustic oscillations frozen on the LSS.
- Projection effects.
- Late-time secondaries, e.g., reionisation, ISW, lensing.

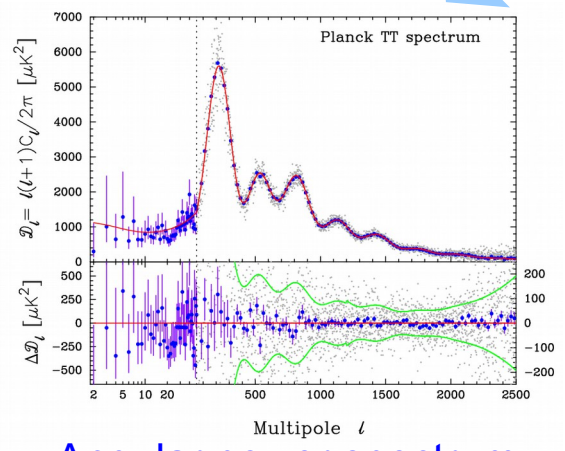
Initial conditions

Energy densities

Spatial geometry

CMB observables: what can be extracted from maps...

2-point correlation



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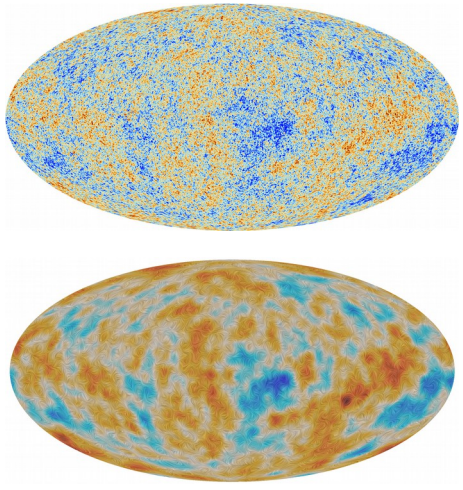

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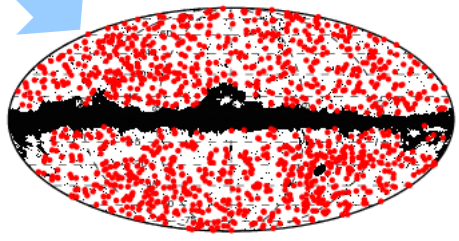

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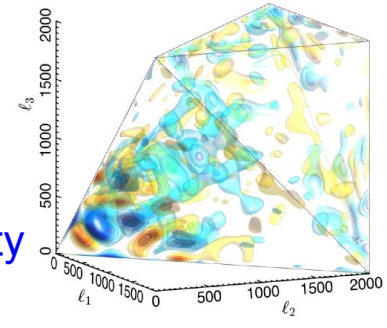

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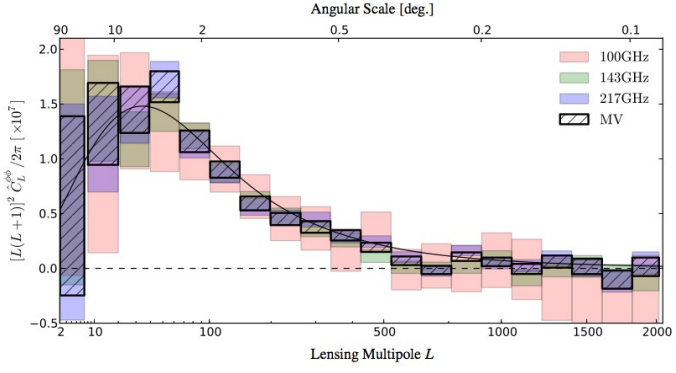
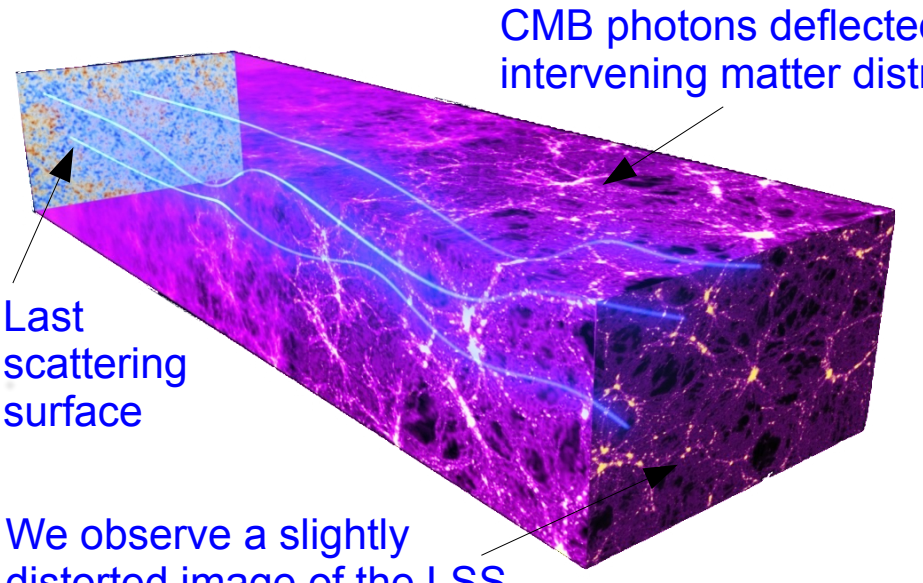
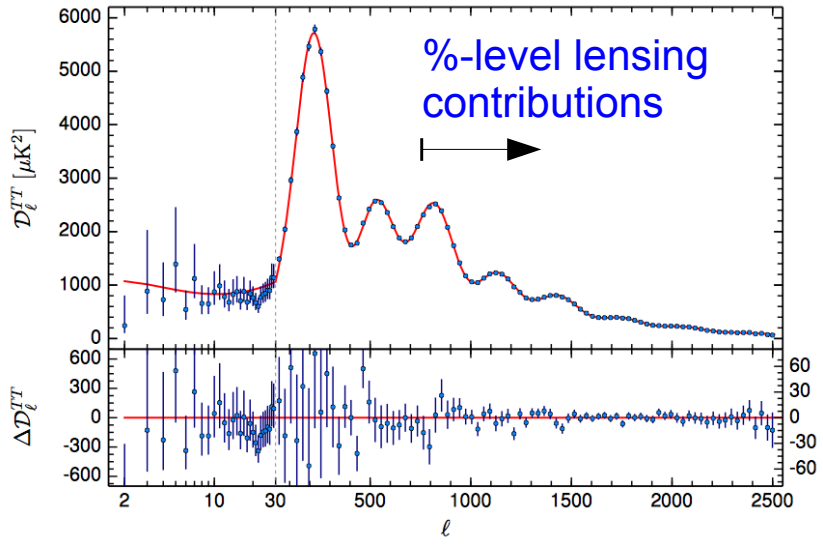


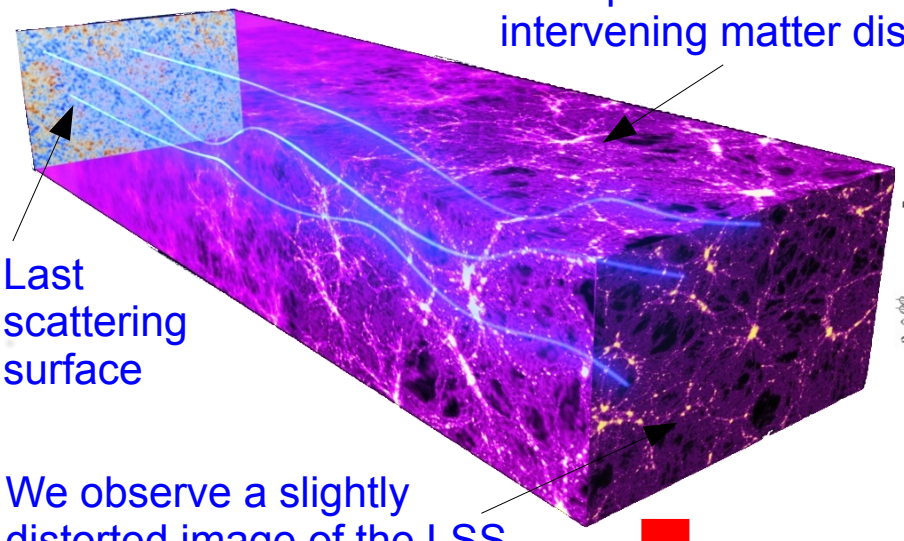
Lensing potential power spectrum

Lensing...


CMB photons deflected by intervening matter distribution
Last scattering surface
We observe a slightly distorted image of the LSS


%-level lensing contributions
$\mathcal{D}_\ell^{TT}\ [\mu K^2]$
$\Delta\mathcal{D}_\ell^{TT}$
ℓ

Lensing potential power spectrum...



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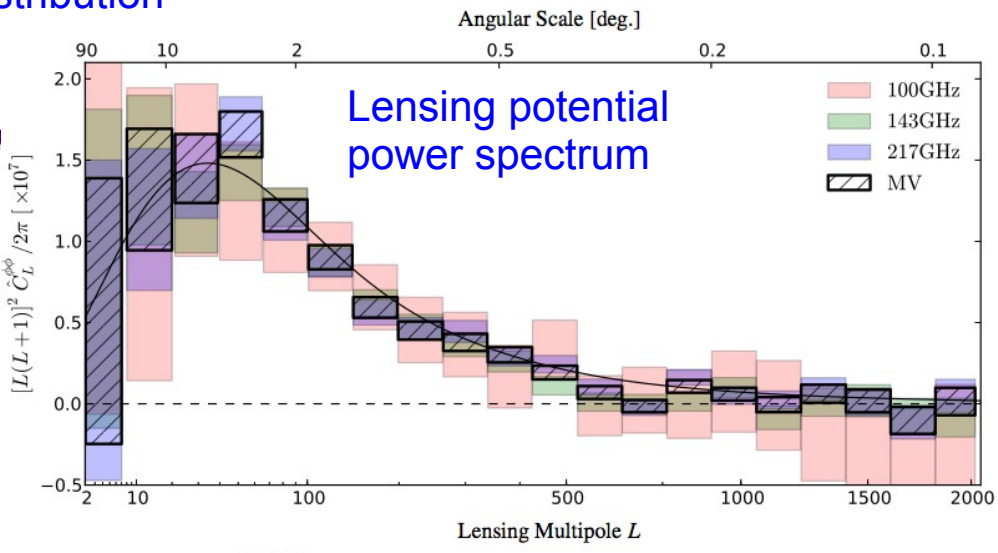
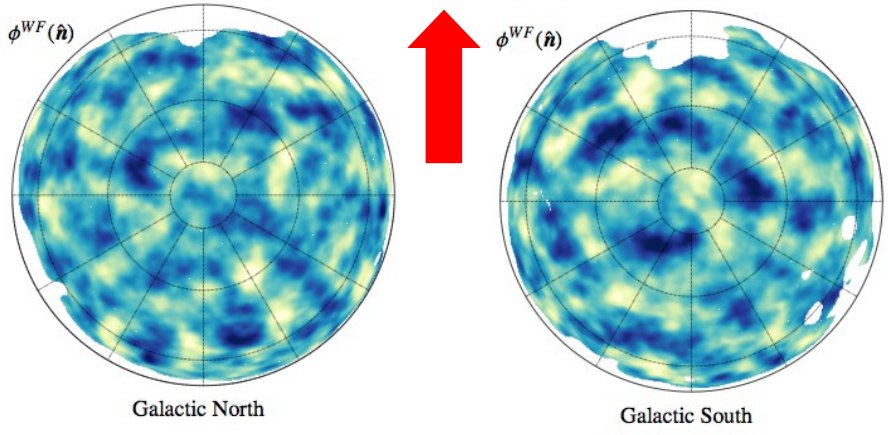
Ade et al. [Planck] 2013



Use **4-point correlation** of observed temperature map to infer the *unlensed* image.

→ Reconstruct deflection angle

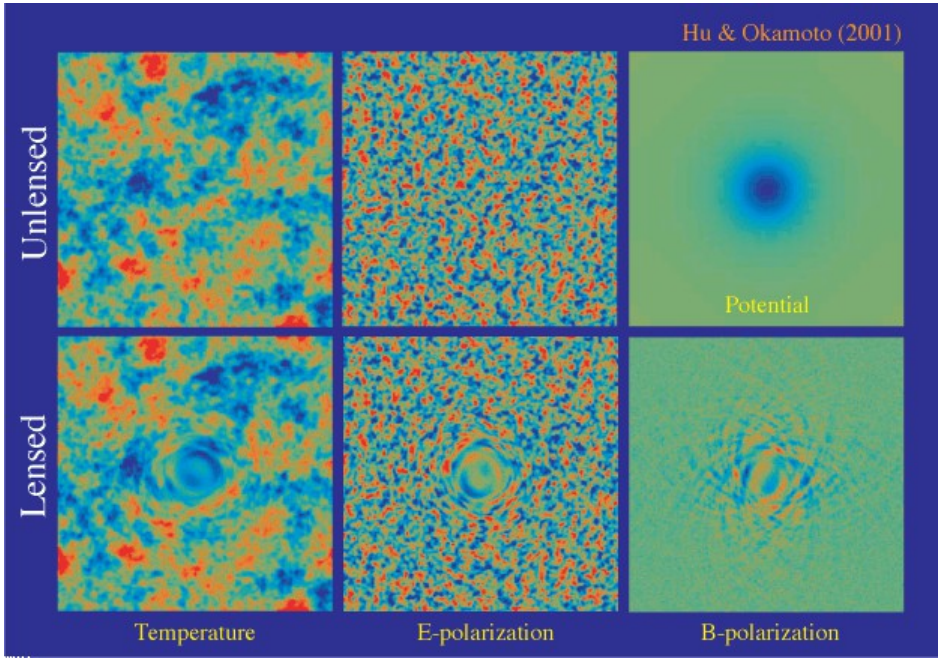
→ Construct lensing potential map

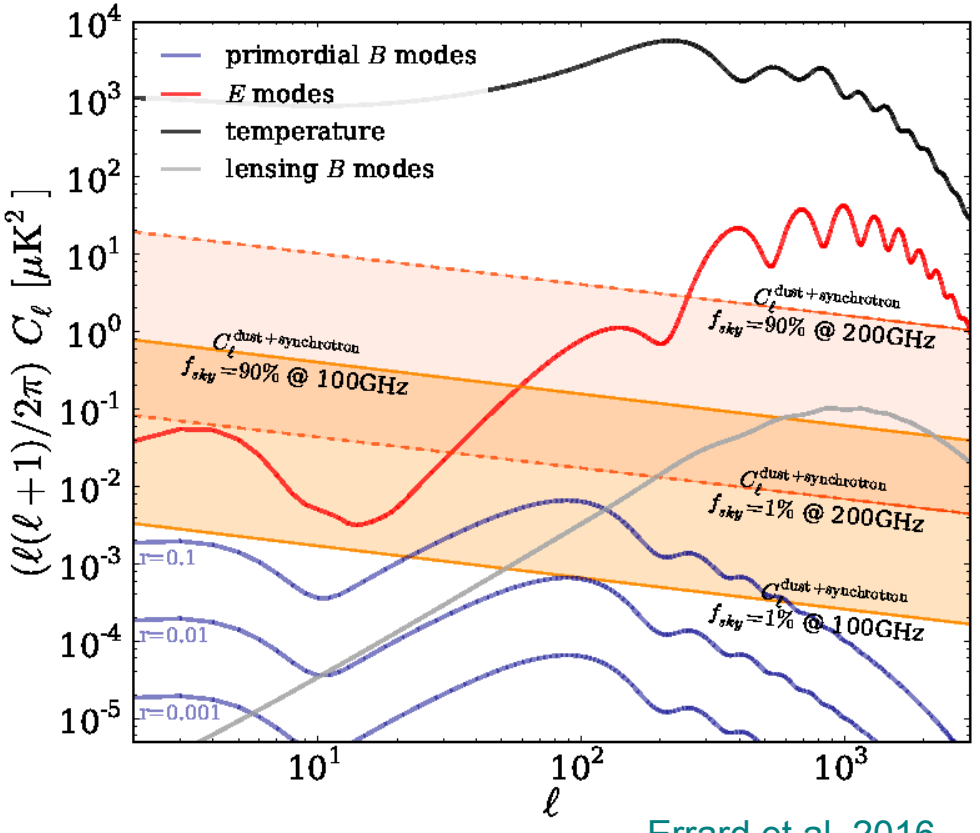


Lensing of polarisation...

See next 2 talks
+ CMB parallel session
this afternoon

Lensing transfers power from the E-mode to the B-mode.





Errard et al. 2016

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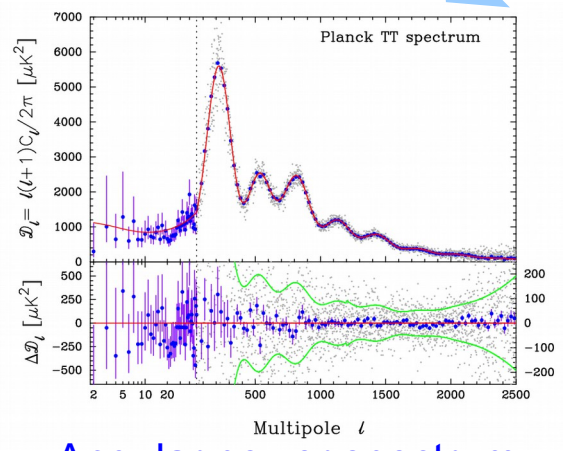

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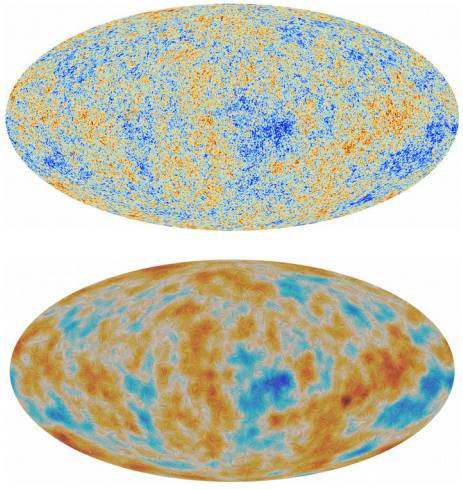

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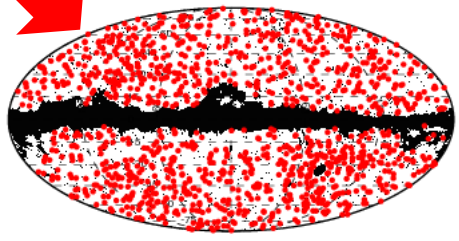

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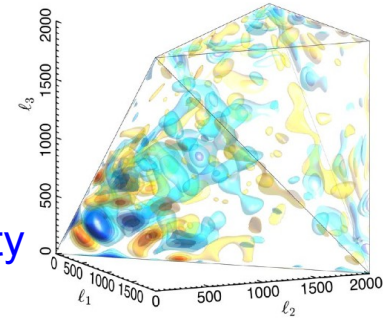
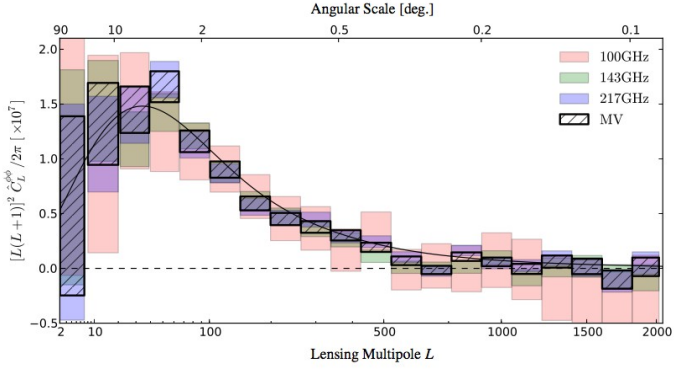


Primordial non-Gaussianity



Lensing potential power spectrum

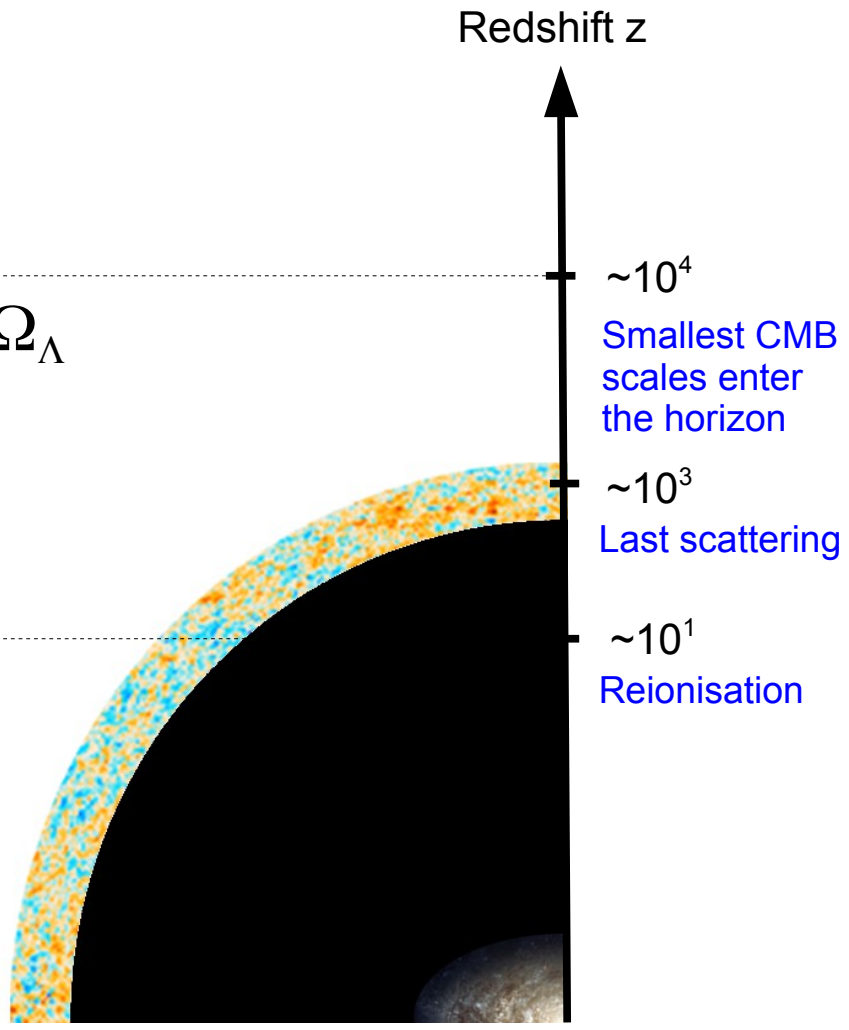
Status 2017

Vanilla ΛCDM still rules...

A 6-parameter model + flat spatial geometry.

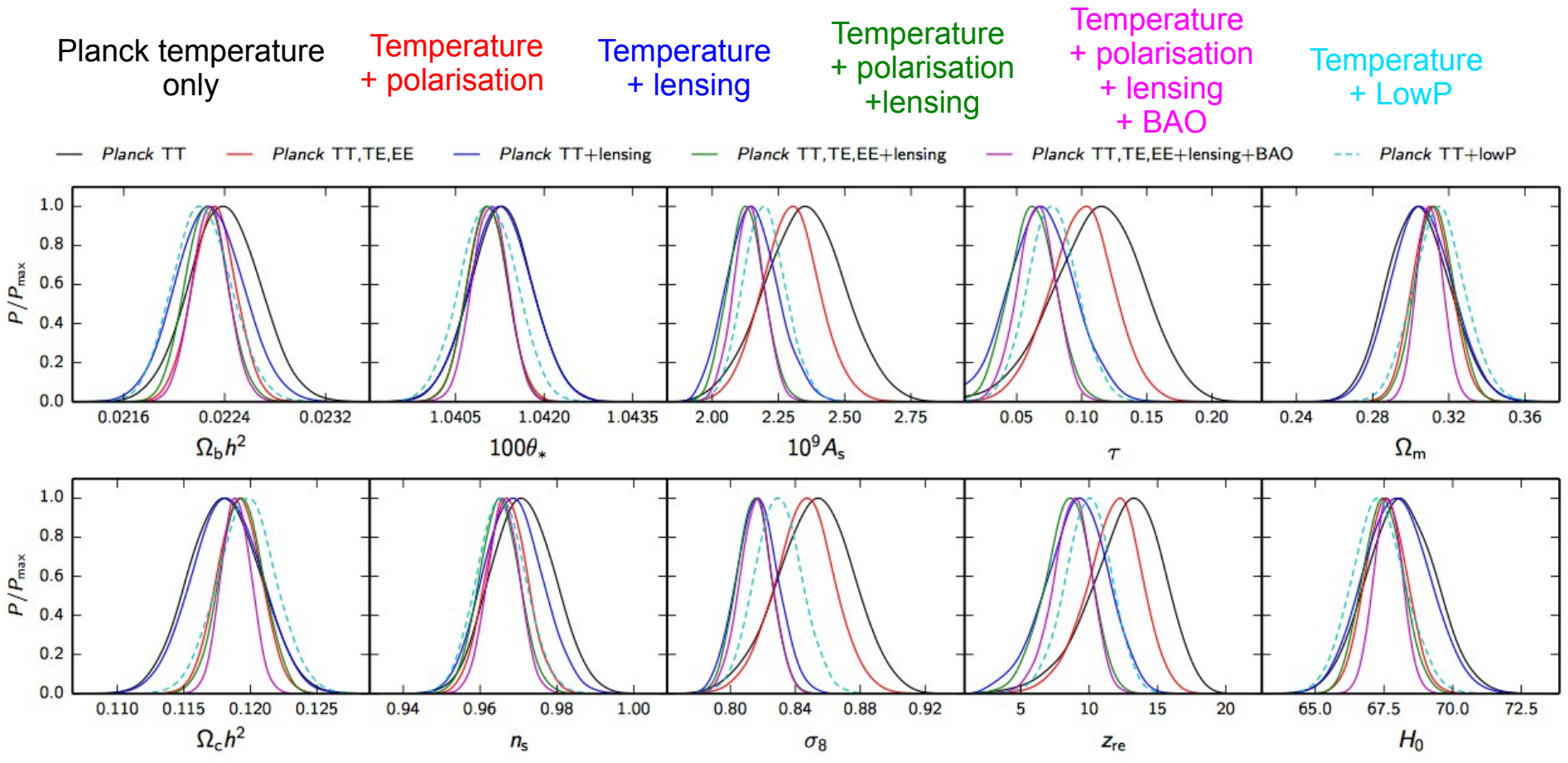
- Initial conditions (2): $P_{\rm ini}(k) = A_s k^{n_s - 1}$
- Energy densities (3): $\omega_{\rm baryon}$, $\omega_{\rm dark\ matter}$, Ω_Λ
- Optical depth to reionisation (1): τ

- Plus nuisance parameters to model systematics:
  - 14 for Planck CMB data
  - Non-CMB data: e.g., tracer bias.



Constraints on ΛCDM parameters...

Ade et al. [Planck] 2015



ΛCDM+X...

There are many ways in which the ΛCDM parameter space can be extended:

- **Initial conditions**:
  - Primordial gravitational waves
  - Running of scalar spectral index
  - Primordial non-Gaussianity
  - Isocurvature modes
  - …
- **Energy content**:
  - Nonzero neutrino mass
  - Extra relativistic particle species
  - Dynamical dark energy
  - Interacting dark sector (DM-nu, DM-DR, nu-nu, DM-DE, DE-nu, etc.)
  - Dark matter decay/annihilation
  - ...
- Nonzero **spatial curvature**

Currently no evidence for any of these from CMB data alone...

But...

Flies in the ointment: 2-3σ tensions...

- **Hubble parameter H_0**: Planck-inferred value lower than local HST measurement.
- **Small-scale RMS fluctuation σ_8**: Planck CMB prefers a higher value than galaxy cluster count and galaxy shear from CFHTLenS.

Ade et al. [Planck] 2015

Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP	$([1]-[4])/\sigma_{[1]}$
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$	0.079 ± 0.017	−0.1
$\ln(10^{10}A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$	3.094 ± 0.034	−0.1
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016	0.9645 ± 0.0049	0.2
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0	67.27 ± 0.66	0.0
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$	0.3156 ± 0.0091	0.0
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024	0.831 ± 0.013	0.0
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027	1.882 ± 0.012	−0.1

HST

$$H_0 = 73.24 \pm 1.74 \,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Riess et al. 2016

Planck SZ clusters $\sigma_8 (\Omega_m/0.27)^{0.3} = 0.782 \pm 0.01$

CFHTLenS galaxy shear $\sigma_8 (\Omega_m/0.27)^{0.46} = 0.774 \pm 0.04$

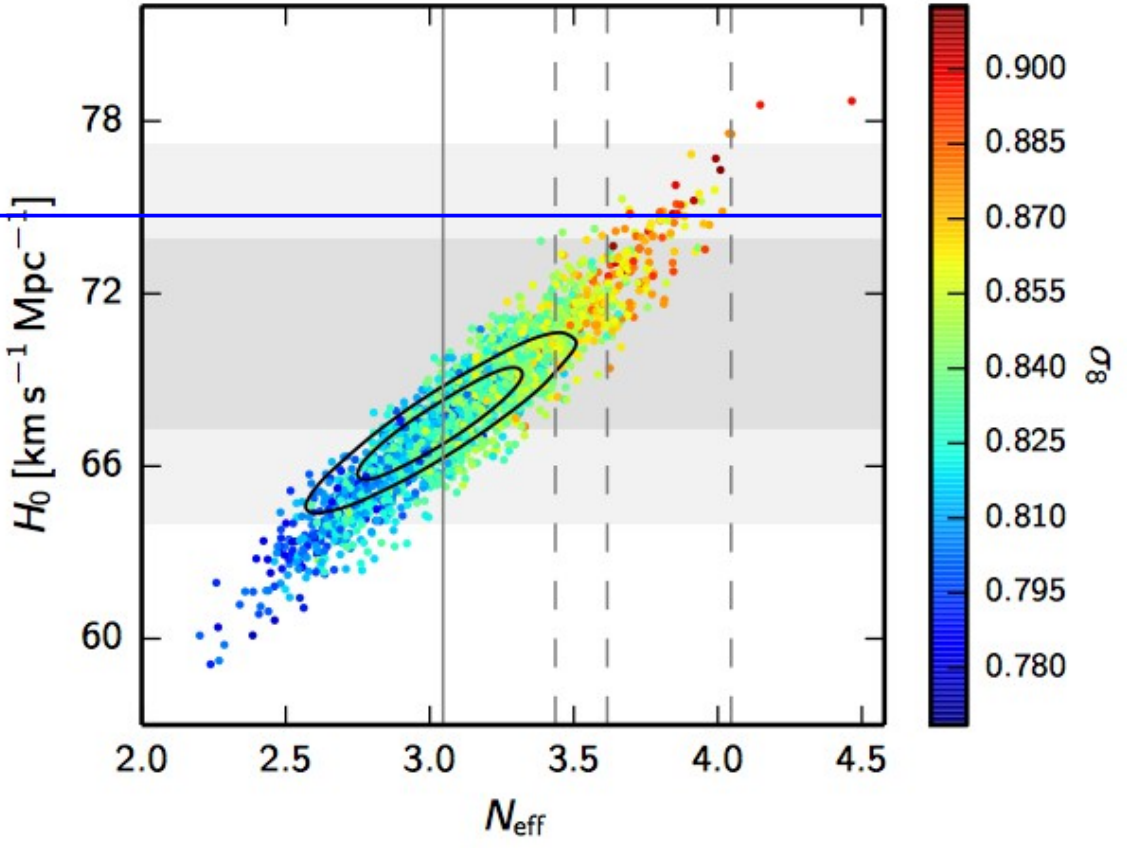
Heymans et al. 2013

The N_{eff}-H_0 degeneracy...

A larger $N_{\rm eff}$ does bring the Planck-inferred H_0 into better agreement with the HST measurement of the local expansion rate .

$$H_0 = 73.24 \pm 1.74 \,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

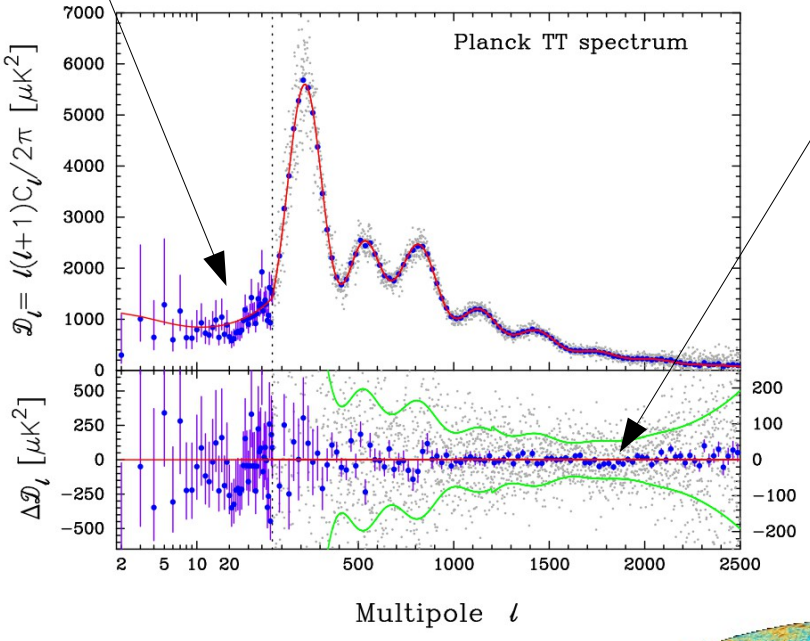
Riess et al. 2016



Other oddities...

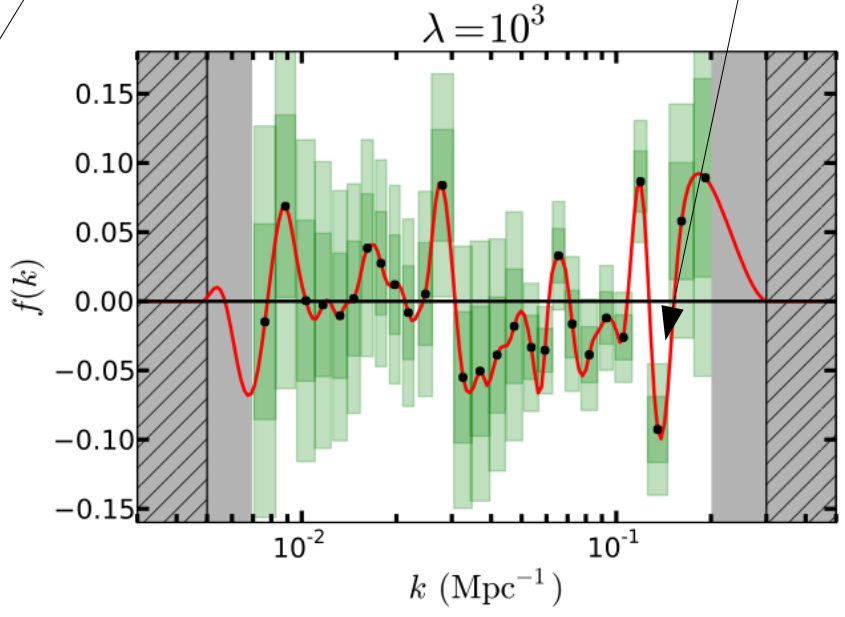
Lack of power on large scales

Already present in WMAP; Now exacerbated by better small-scale data



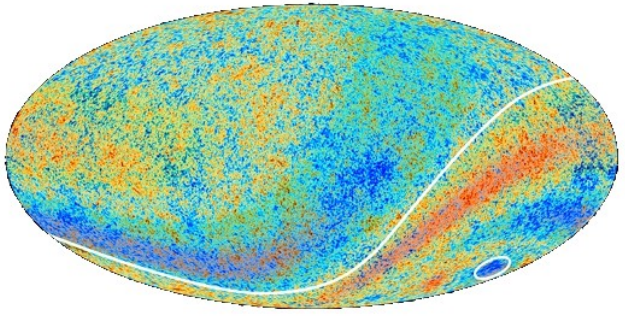
A small feature on small scales

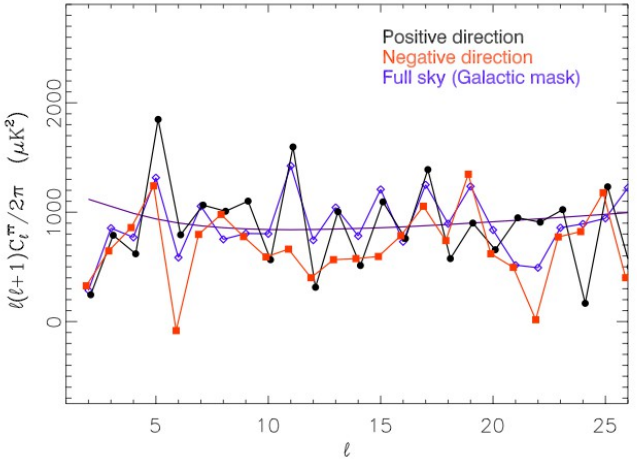
Nonparameteric reconstruction of the primordial power spectrum



Hemispherical difference in power & the cold spot

Already present in WMAP;
Planck confirms that these are not due to data processing





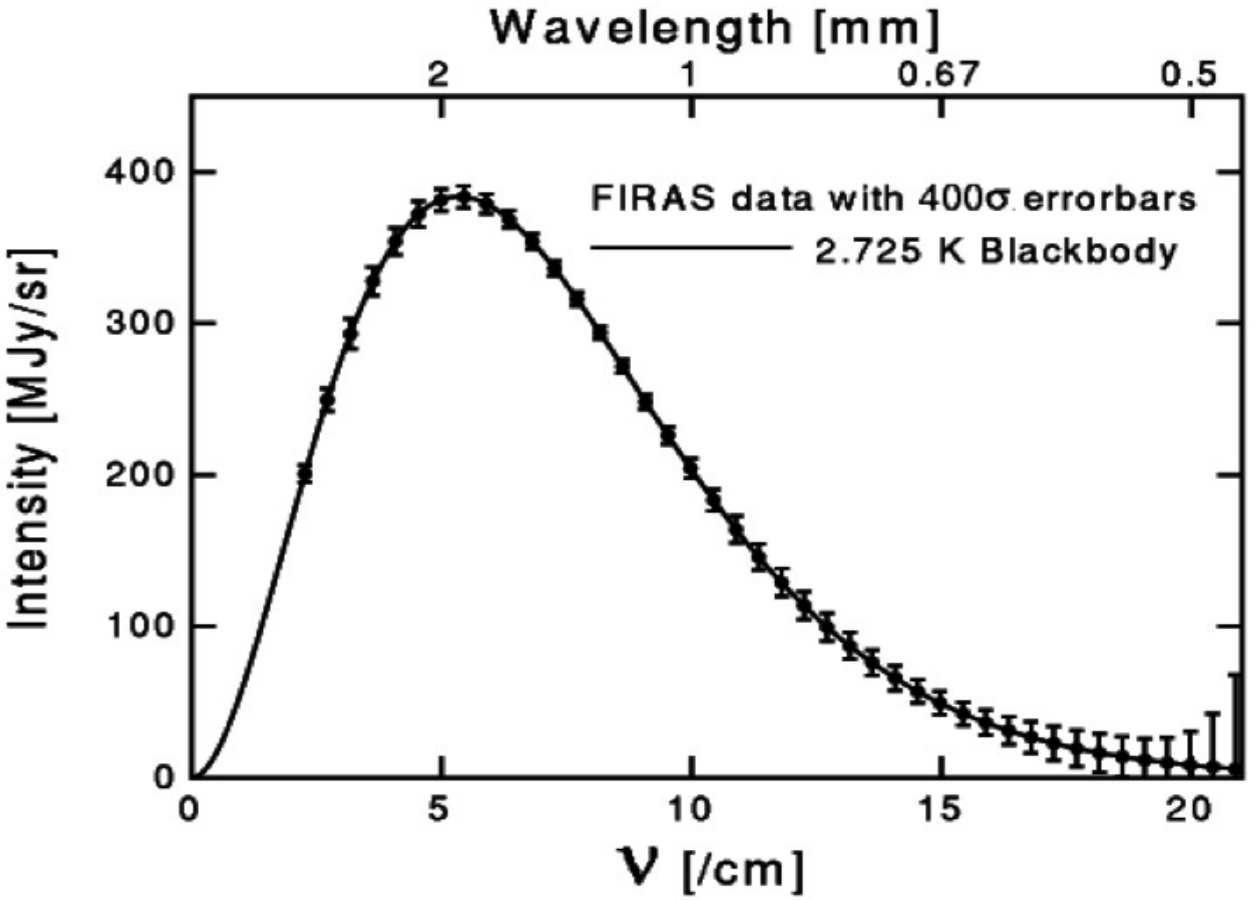
Quick recap...

- Not much has changed since 2016 in terms of ΛCDM parameter constraints.
  - No evidence for beyond ΛCDM physics.

- **2-3σ tensions** between CMB-inference, and local H_0 measurements and σ_8 determination from cosmic shear are still there.
  - These could be hinting at beyond ΛCDM physics..
  - Modifications to the neutrino/dark radiation sector are a popular explanation, but likely not the only possibility.

CMB spectral distortions...

The most perfect blackbody ever measured??



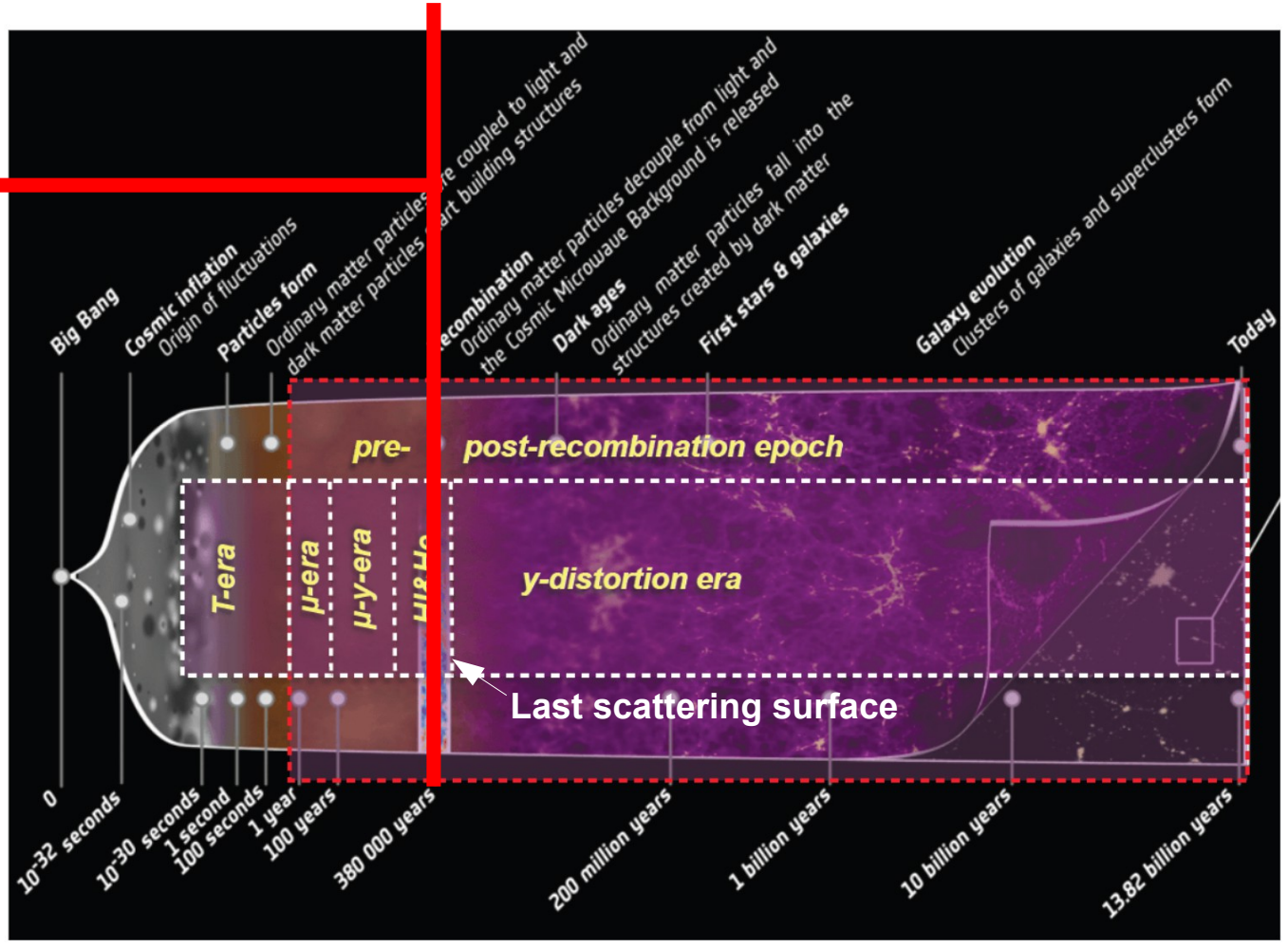
$$T_\gamma = 2.725 \pm 0.001\,\mathrm{K}$$

Mather et al., 1994

History of the CMB...

Elastic, $z > 10^4$

$$e^- + \gamma \rightarrow e^- + \gamma$$



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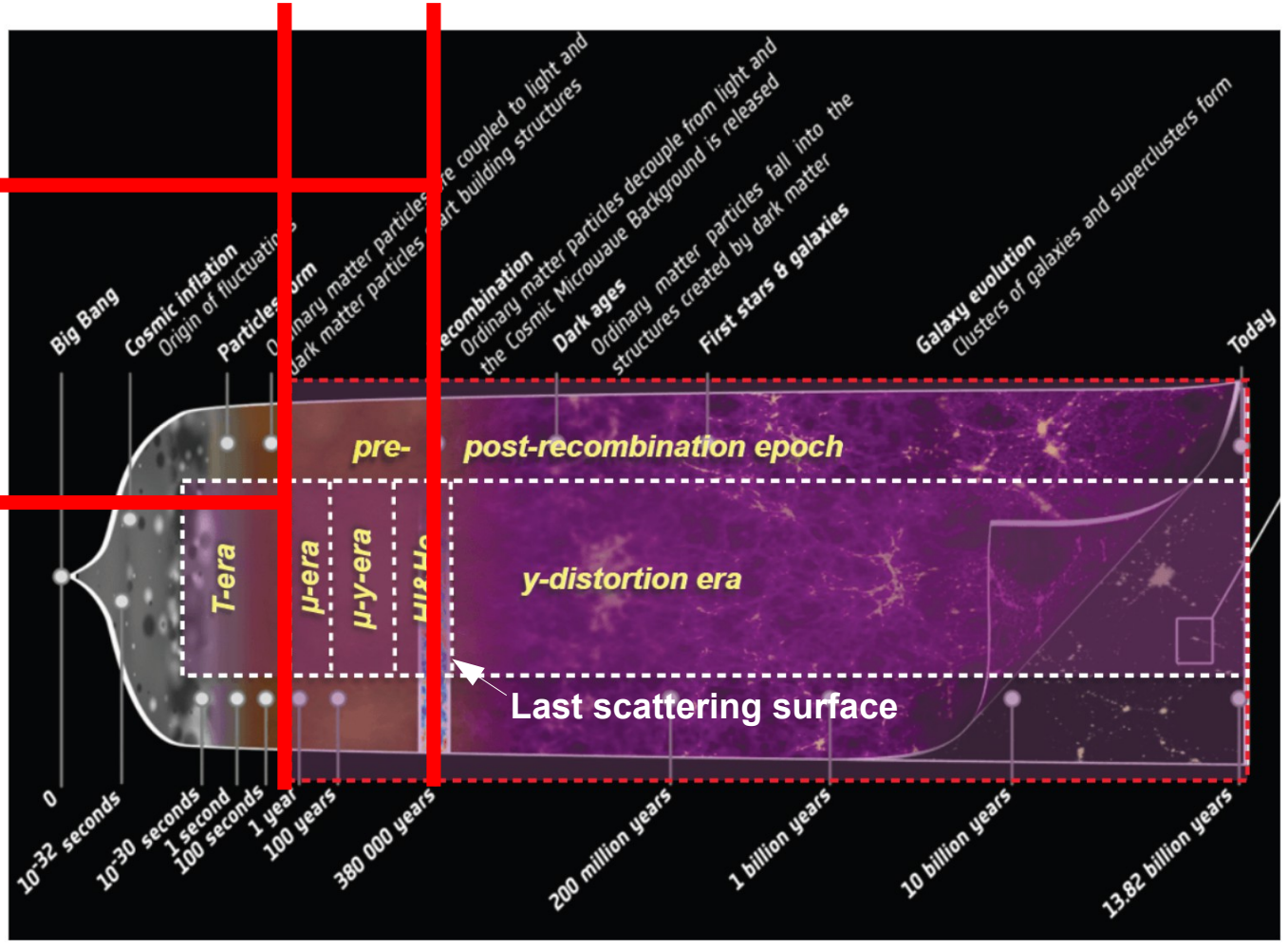
$$e^- + \gamma \rightarrow e^- + \gamma$$

$$e + \gamma \rightarrow e + \gamma + \gamma$$

$$e + X^+ \rightarrow e + X^+ + \gamma$$

Number changing, $z > 10^6$



History of the CMB...

Energy injection will lead to **deviations from the blackbody spectrum**

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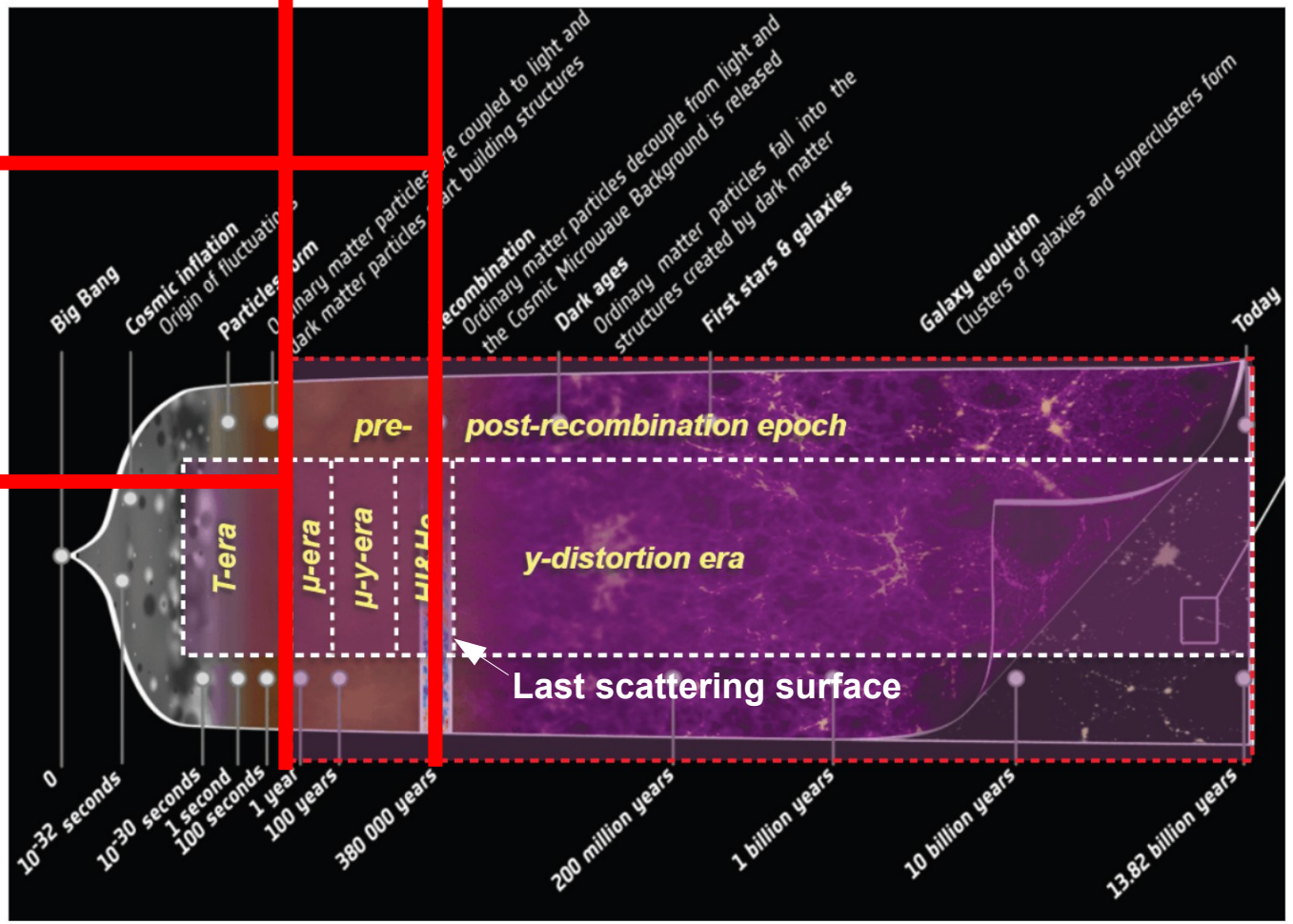
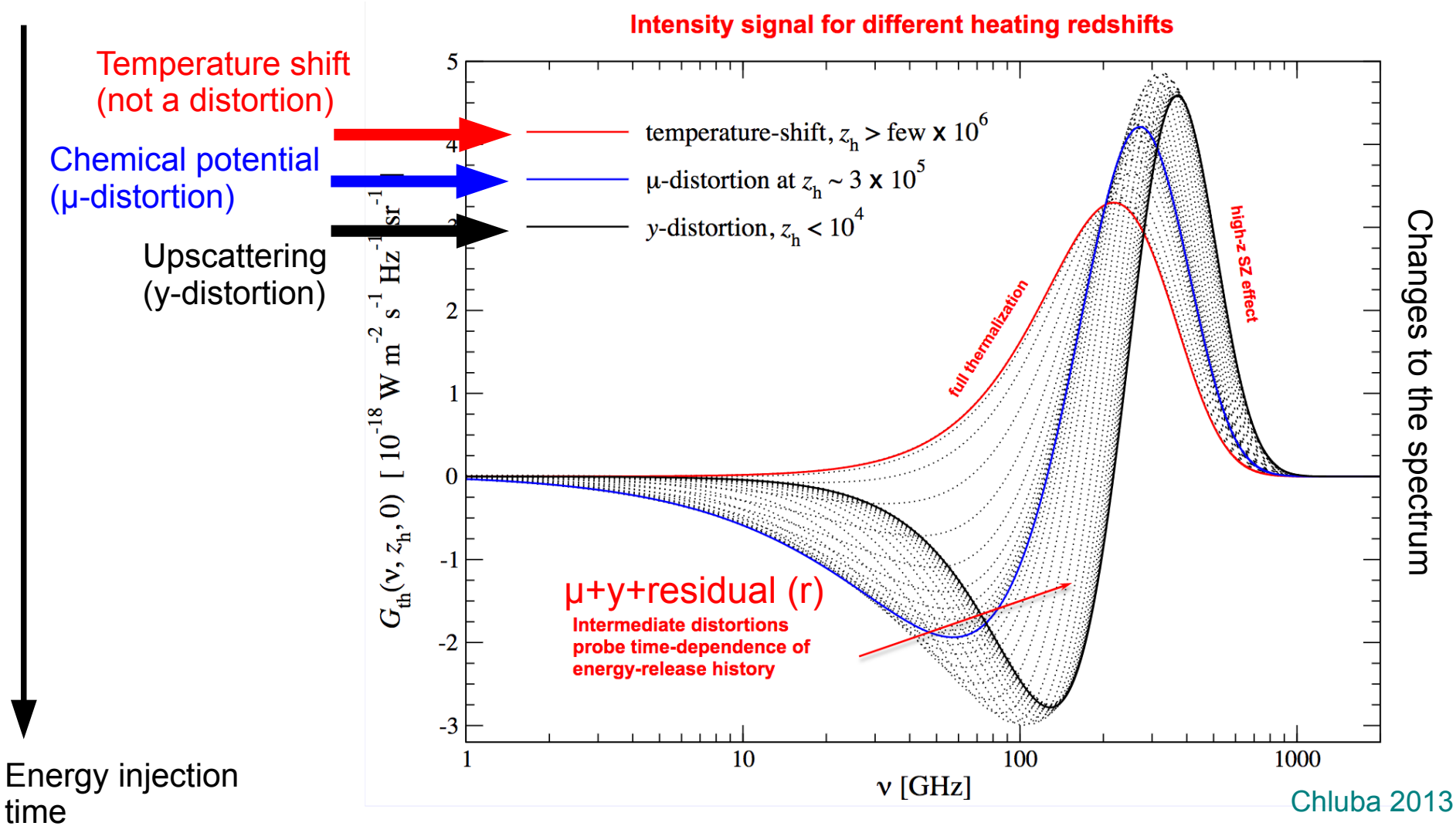


μ-, y-, and r-distortions...



Chluba 2013

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Energy injection will lead to **deviations from the blackbody spectrum**

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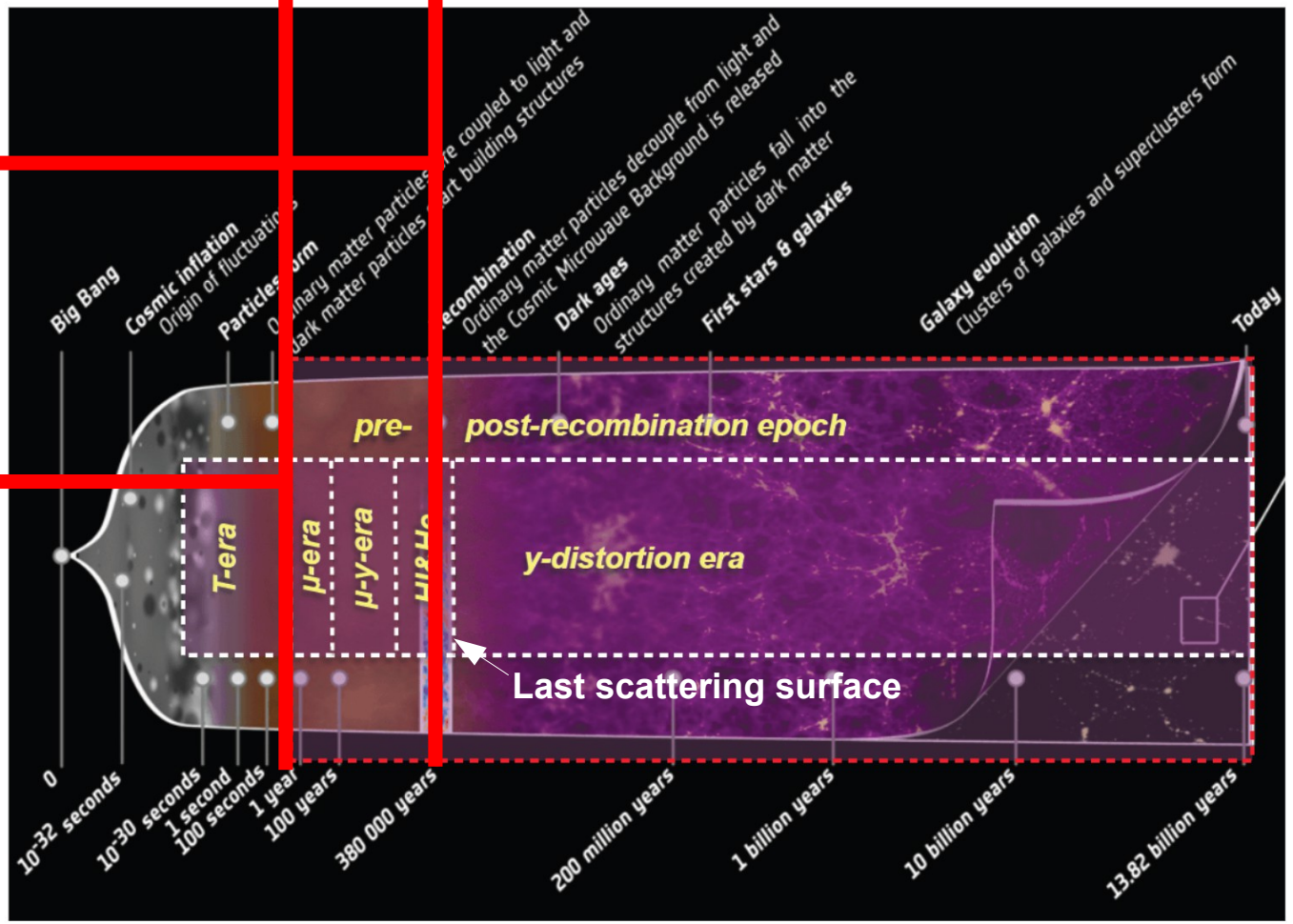
$$e + \gamma \rightarrow e + \gamma + \gamma$$

$$e + X^+ \rightarrow e + X^+ + \gamma$$

Number changing, $z > 10^6$



History of the CMB...

Energy injection will lead to **deviations from the blackbody spectrum**

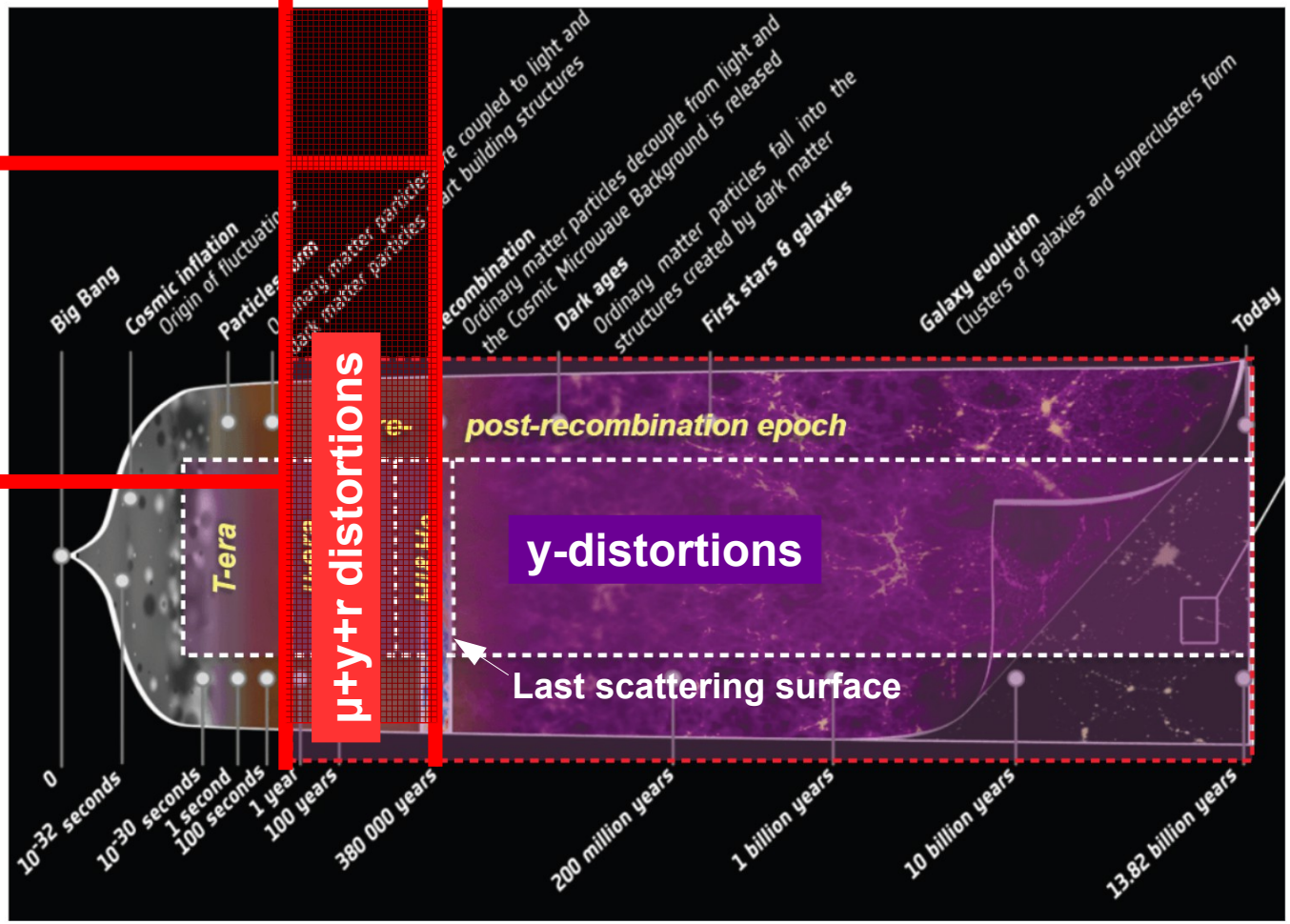
Elastic, $z > 10^4$

$$e^- + \gamma \rightarrow e^- + \gamma$$

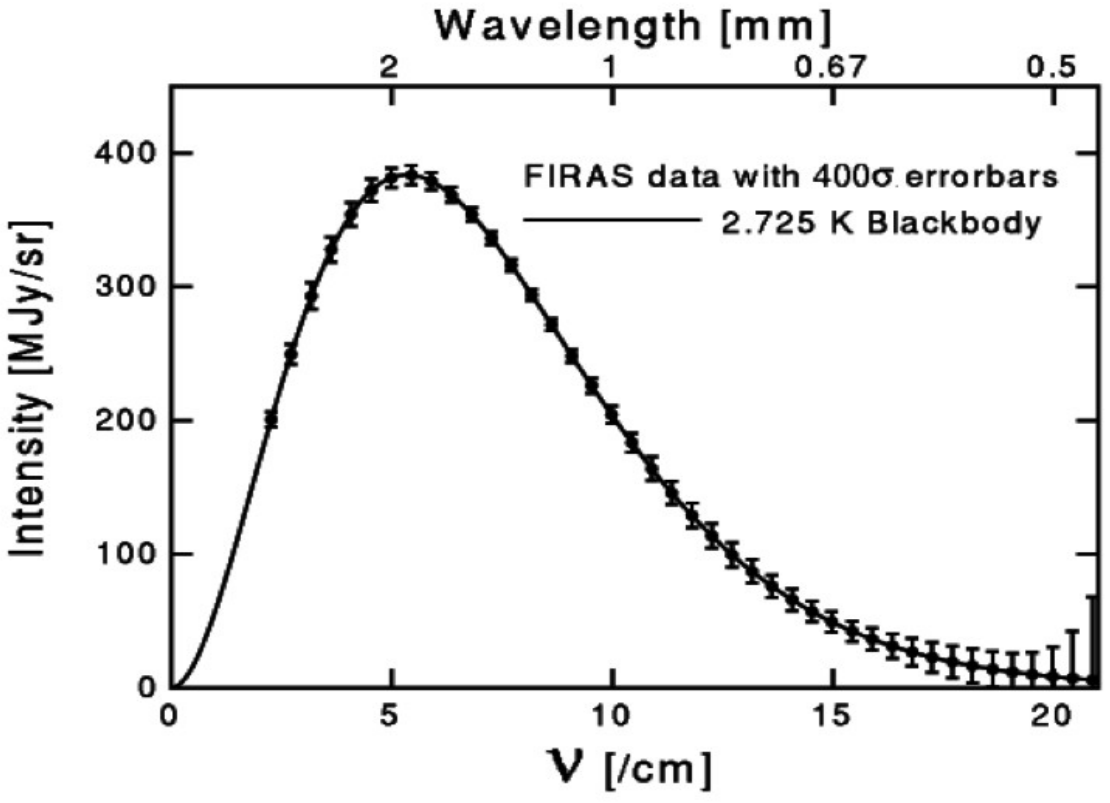
$$e + \gamma \rightarrow e + \gamma + \gamma$$

$$e + X^+ \rightarrow e + X^+ + \gamma$$

Number changing, $z > 10^6$



COBE FIRAS constraints on distortions...



$$|\mu| < 9 \times 10^{-5}$$
$$|y| < 1.5 \times 10^{-5}$$

Mather et al., 1990
Fixsen et al. 1996

Spectral distortions from dissipation of sound waves...

Sunyaev & Zel'dovich 1970

Spectral distortions are also expected within standard ΛCDM.

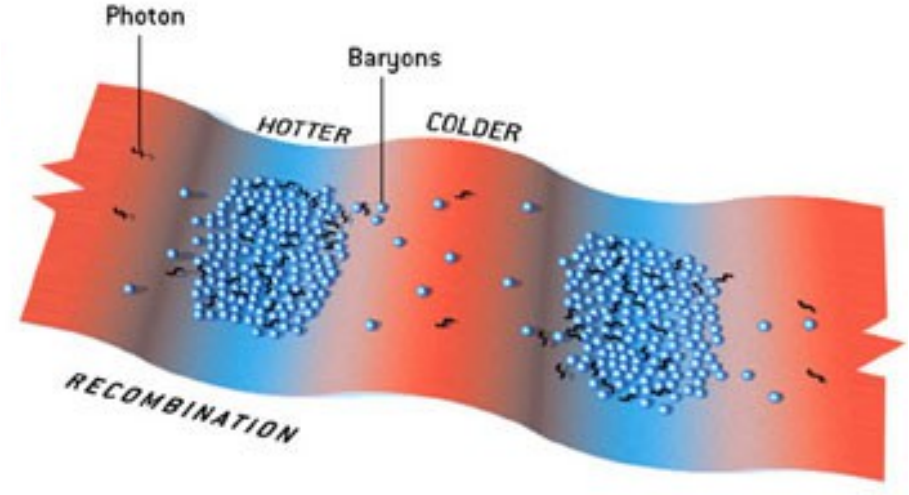
- **Photon diffusion** mixes blackbodies of different temperatures.

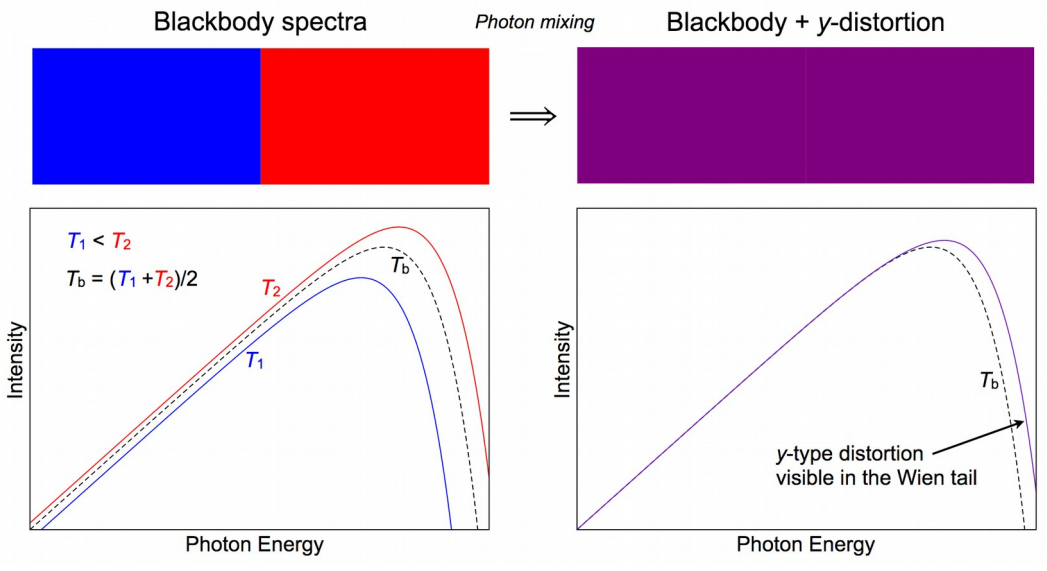
  → Spectral distortions (unless thermalisation processes are efficient)

- ΛCDM prediction:

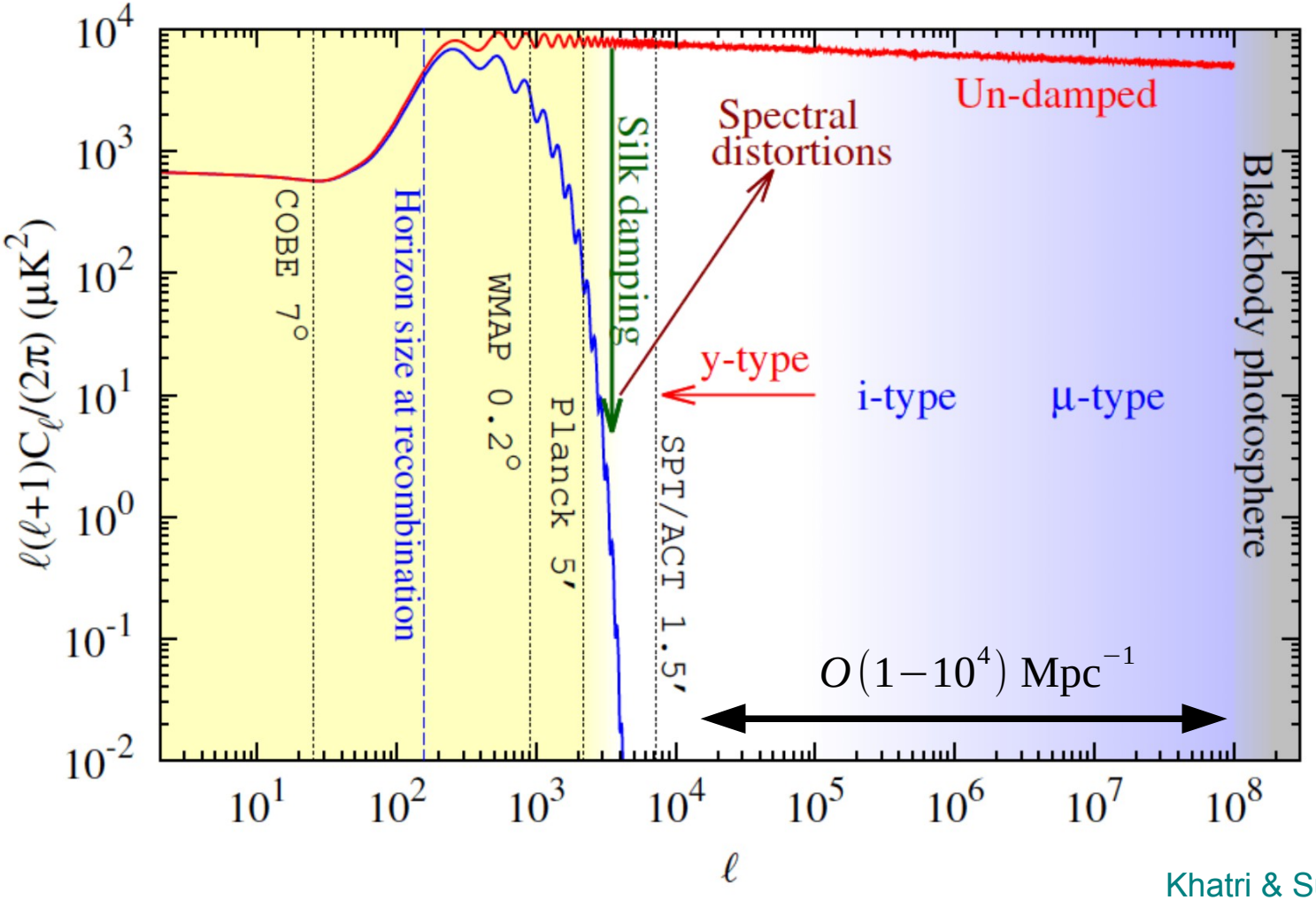
$$\mu = O\left(10^{-8}\right)$$

Chluba, Khatri, Sunyaev, ... 2012--





Spectral distortions as a probe of small-scales...



Khatri & Sunyaev 2013

Energy injection rate...

Chluba, Khatri & Sunyaev 2012
Khatri, Sunyaev & Chluba 2012

Fractional energy injection per unit redshift in ΛCDM:

Thomson scattering rate

Baryon velocity transfer function

Photon temperature and polarisation transfer functions

Primordial curvature power spectrum

$$\frac{\mathrm{d}\left(Q/\rho_\gamma\right)}{\mathrm{d}z} = \frac{4a\dot{\kappa}}{\mathcal{H}} \int \frac{k^2 \mathrm{d}k}{2\pi^2} P_{\mathcal{R}}(k) \left[\frac{\left(3\Theta_1 - v_b\right)^2}{3} + \frac{9}{2}\Theta_2^2 - \frac{1}{2}\Theta_2\left(\Theta_0^{\mathrm{P}} + \Theta_2^{\mathrm{P}}\right) + \sum_{\ell \geq 3} (2\ell+1)\Theta_\ell^2 \right].$$

Energy injection rate...

Chluba, Khatri & Sunyaev 2012
Khatri, Sunyaev & Chluba 2012

Fractional energy injection per unit redshift in ΛCDM and beyond:

Thomson scattering rate

Baryon velocity transfer function

(Modified energy content & interactions)

Photon temperature and polarisation transfer functions

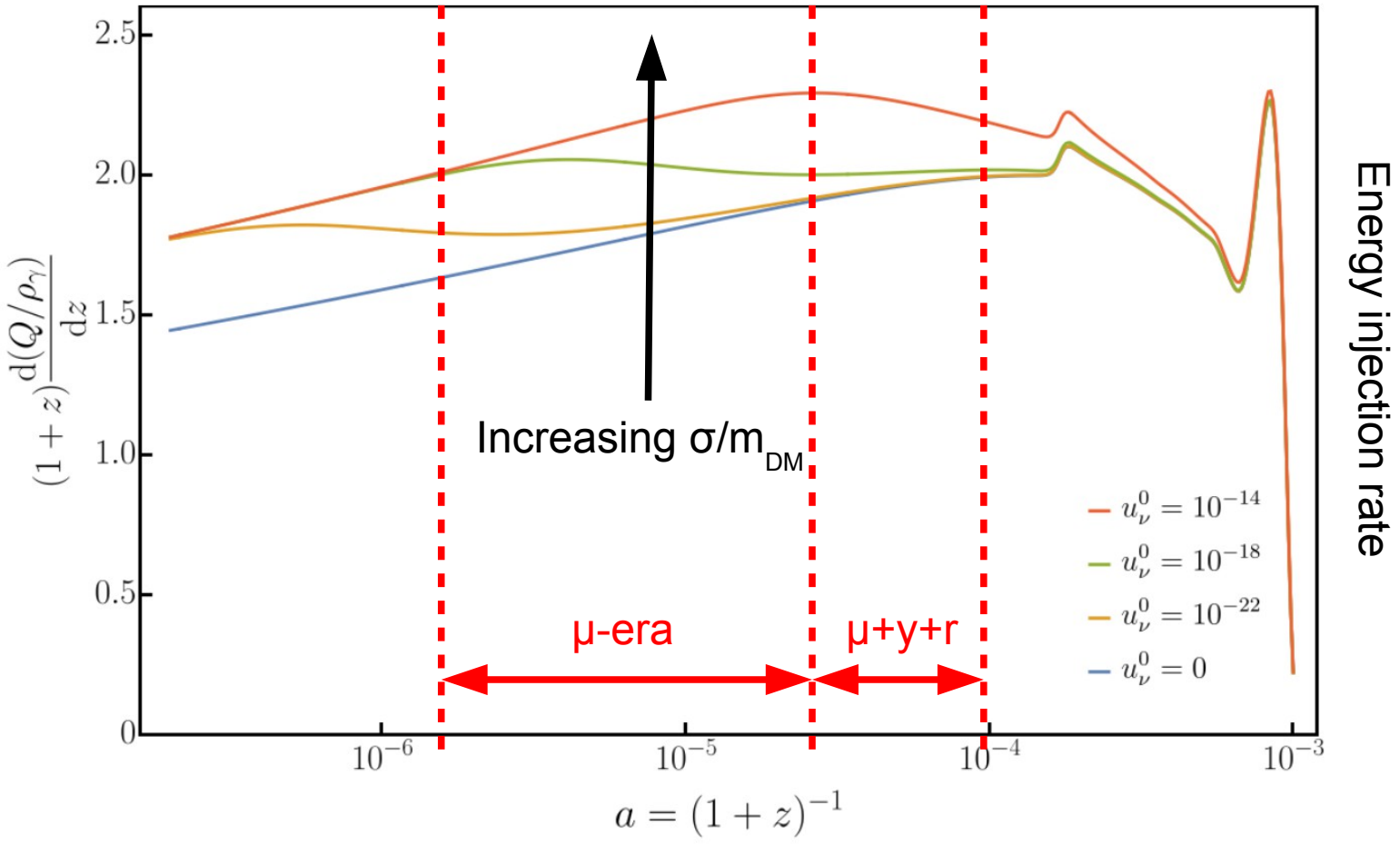
Primordial curvature power spectrum

(Isocurvature, tensors, running)

$$\frac{\mathrm{d}\,(Q/\rho_\gamma)}{\mathrm{d}z} = \frac{4a\dot{\kappa}}{\mathcal{H}} \int \frac{k^2 \mathrm{d}k}{2\pi^2} P_{\mathcal{R}}(k) \left[\frac{(3\Theta_1 - v_b)^2}{3} + \frac{9}{2}\Theta_2^2 - \frac{1}{2}\Theta_2 \left(\Theta_0^{\mathrm{P}} + \Theta_2^{\mathrm{P}}\right) + \sum_{\ell \geq 3} (2\ell+1)\Theta_\ell^2 \right].$$

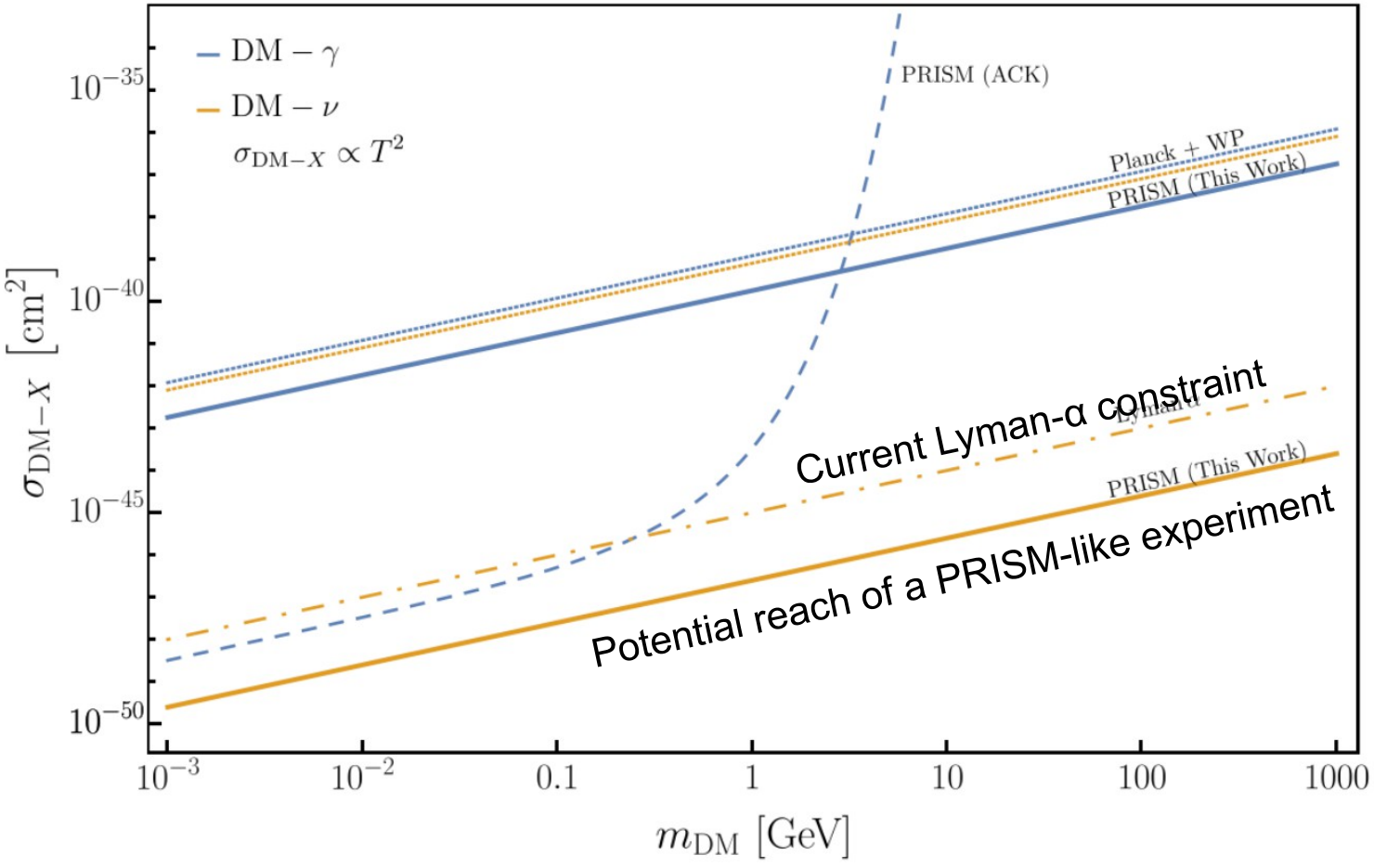
+ new dissipation channel (e.g., photon-DM scattering)

e.g., DM-neutrino elastic scattering...



Diacoumis & Y^{3}W 2017

e.g., DM-neutrino elastic scattering...



Diacoumis & Y^{3}W 2017

Summary...

- Precision cosmological observations of the CMB and non-CMB probes allow us to explore the robustness of the assumptions underpinning ΛCDM.
  - Currently **no evidence for physics beyond ΛCDM** from CMB data alone.
  - However, **several persistent 2-3σ tensions** with non-CMB data could be hinting at something new (or just unresolved systematics).
- CMB spectral distortions offer a novel way to probe small-scale fluctuations at early times.
  - Potentially interesting for inflation physics, dark matter physics, and possibly more.