What the Cosmic Microwave Background Taught us about the Epoch of Reionization?

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on behalf of the Planck Collaboration

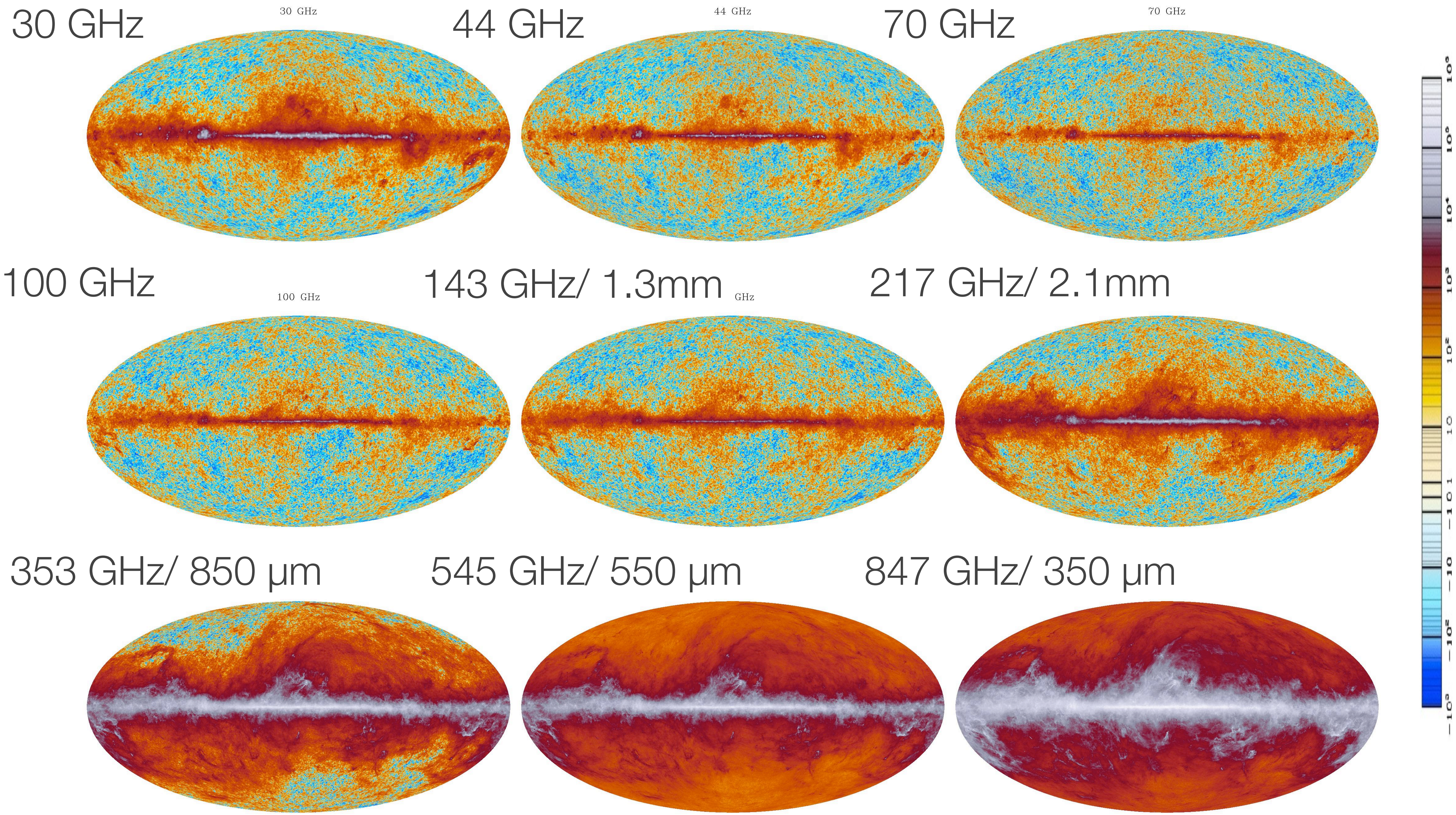
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

Outline

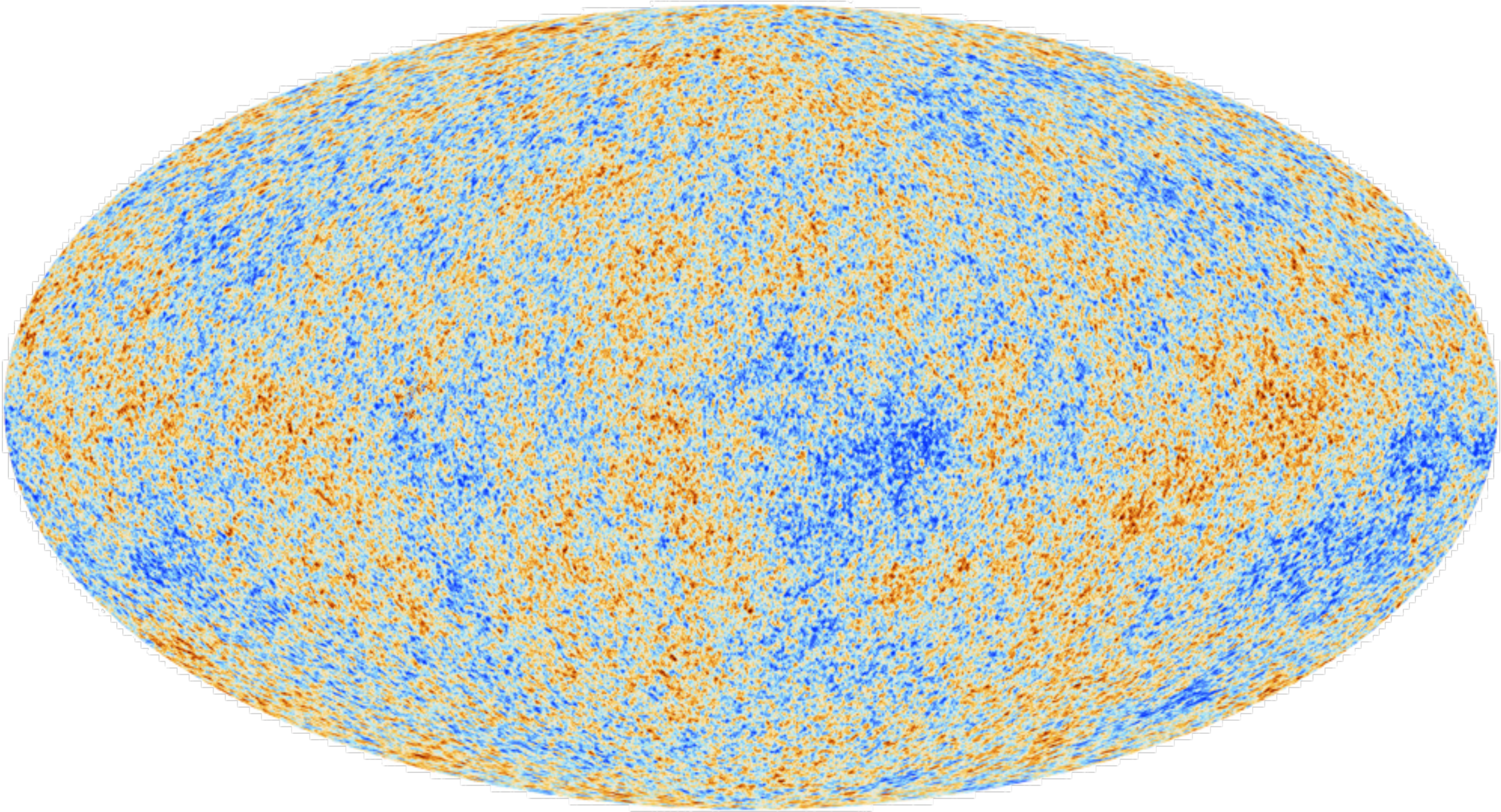
- CMB: An Amazing Success Story
  - ➡ The Planck example.
- Constraining Reionization with CMB Polarization and Temperature:
  - ➡ The latest constraints lead to a more coherent picture of reionization.
- Some lessons from CMB/Planck for the 21 cm “cult followers”.

What Planck Has Done for Astrophysics in 2013/15



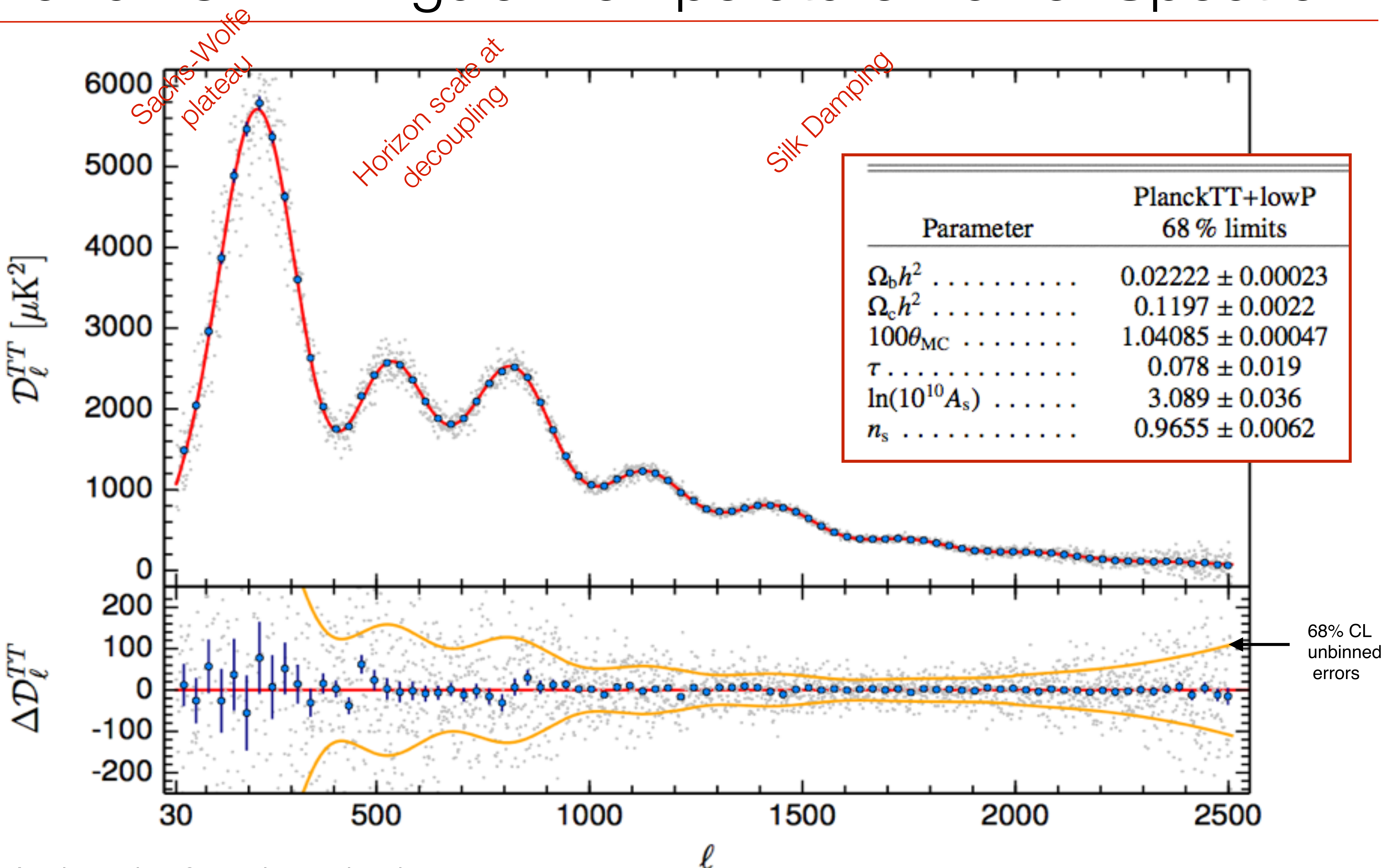
- Noise properties on maps meet or exceed goals:
    - ➡ Precision on cosmological parameters is as per pre-flight “Blue Book” values.
- These temperature maps and many more (~200 maps) are available for download on ESA and NASA/IPAC websites.
- Lead to more than 6- published papers in 2013-15 (2000 pages of science!), and more to come.

What Planck Has Done for Cosmology



- The analysis of this map allows us to address many questions (~60 papers so far):
  - ➡ Is flat ΛCDM still a good model?
  - ➡ What is the nature of Inflation? Did it happen?
  - ➡ Is Dark Energy constant?
  - ➡ What are the neutrino masses?
  - ➡ Are there extra relativistic species?
  - ➡ Are there other unexpected signatures?

Planck CMB Angular Temperature Power Spectra

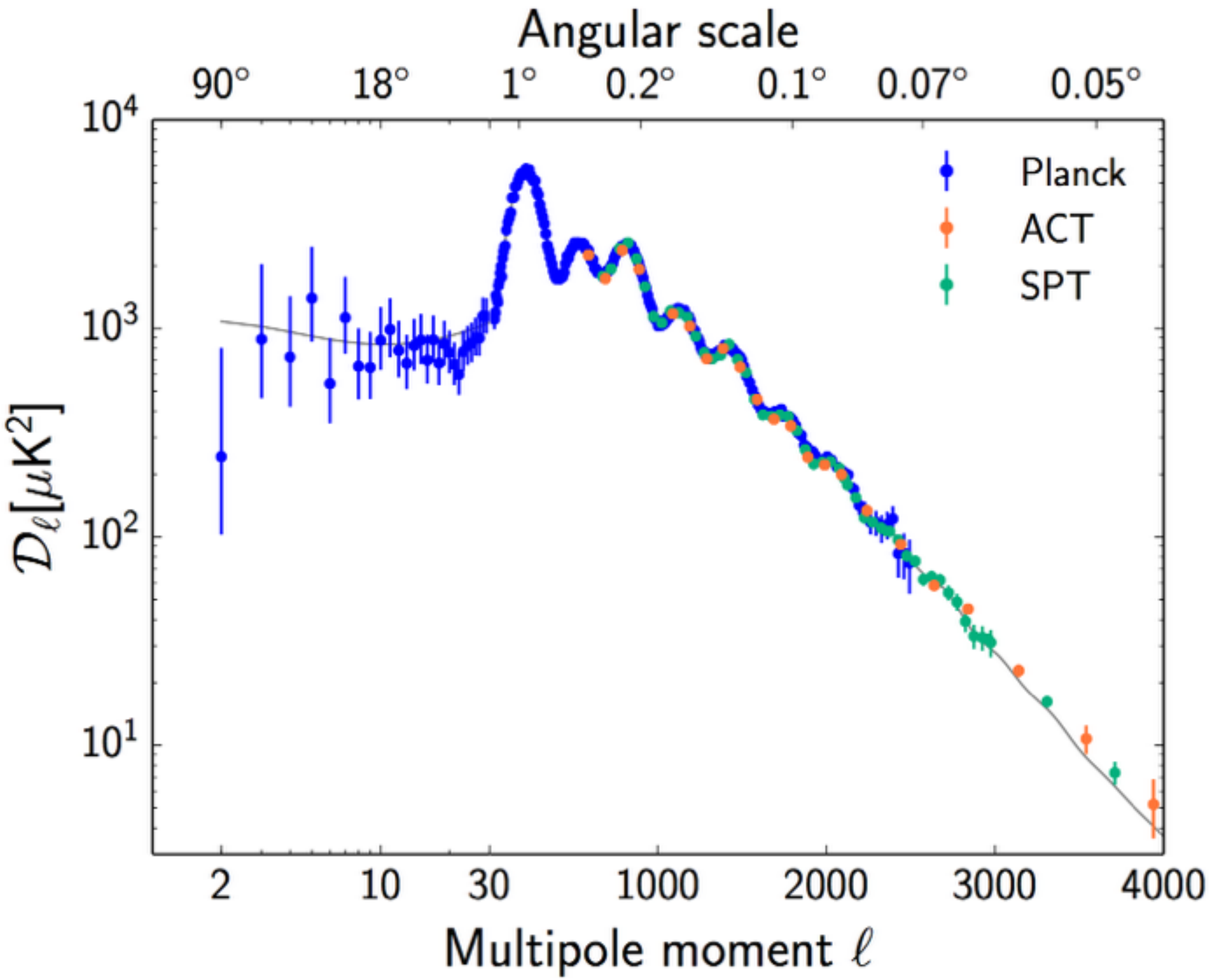


Parameter	PlanckTT+lowP 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022
$100\theta_{MC}$	1.04085 ± 0.00047
τ	0.078 ± 0.019
$\ln(10^{10} A_s)$	3.089 ± 0.036
n_s	0.9655 ± 0.0062

- A triumph of modern physics:
  - ➡ A 6 parameter "standard" model (Ω_{cdm}, Ω_b, n_s, τ, A_s, Ω_{DE}) based on cosmological perturbation theory fits multiple data-sets across cosmic times.

Planck 2015 Results. XI

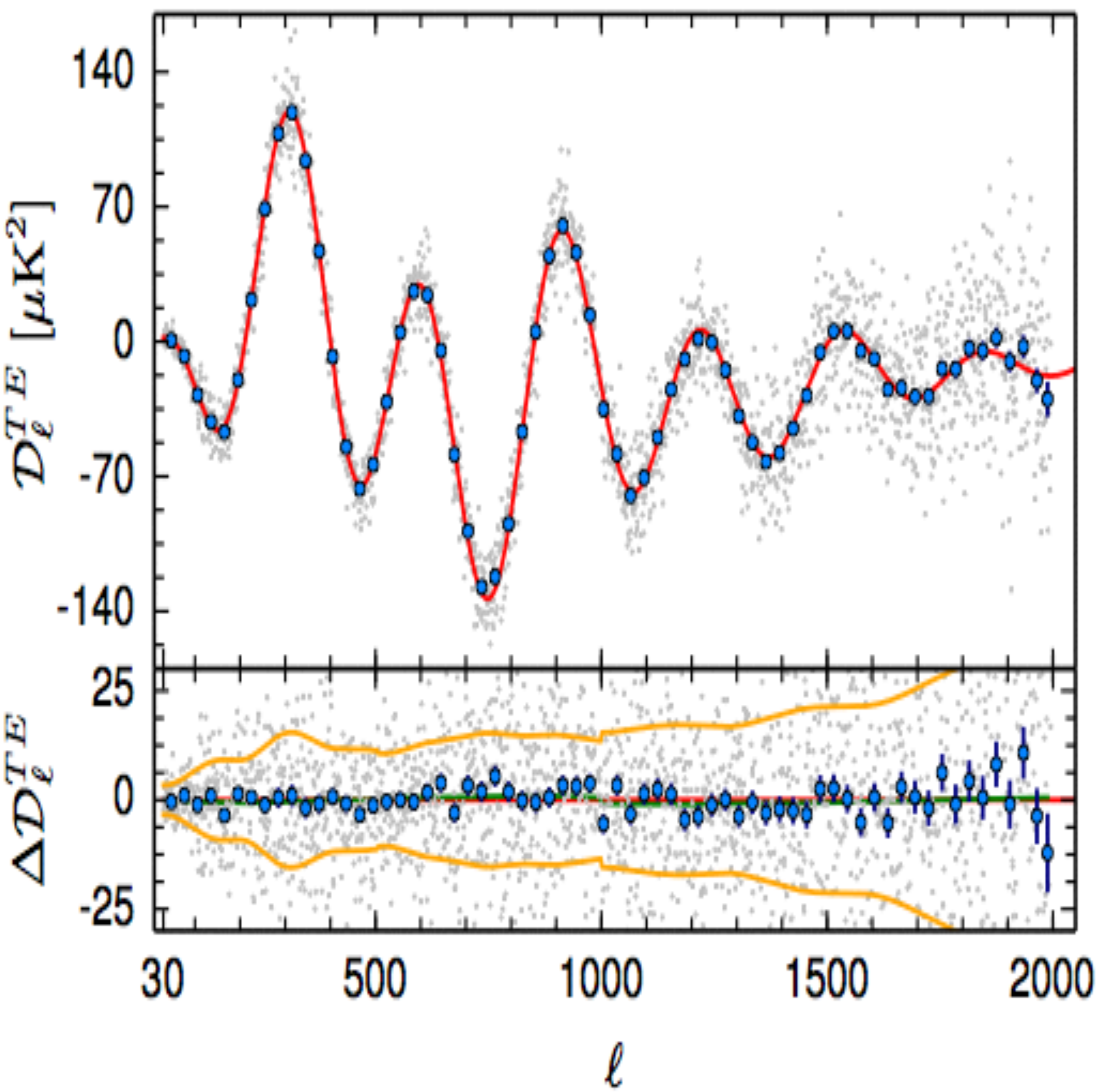
Planck and Small Scale Experiments, ACT and SPT

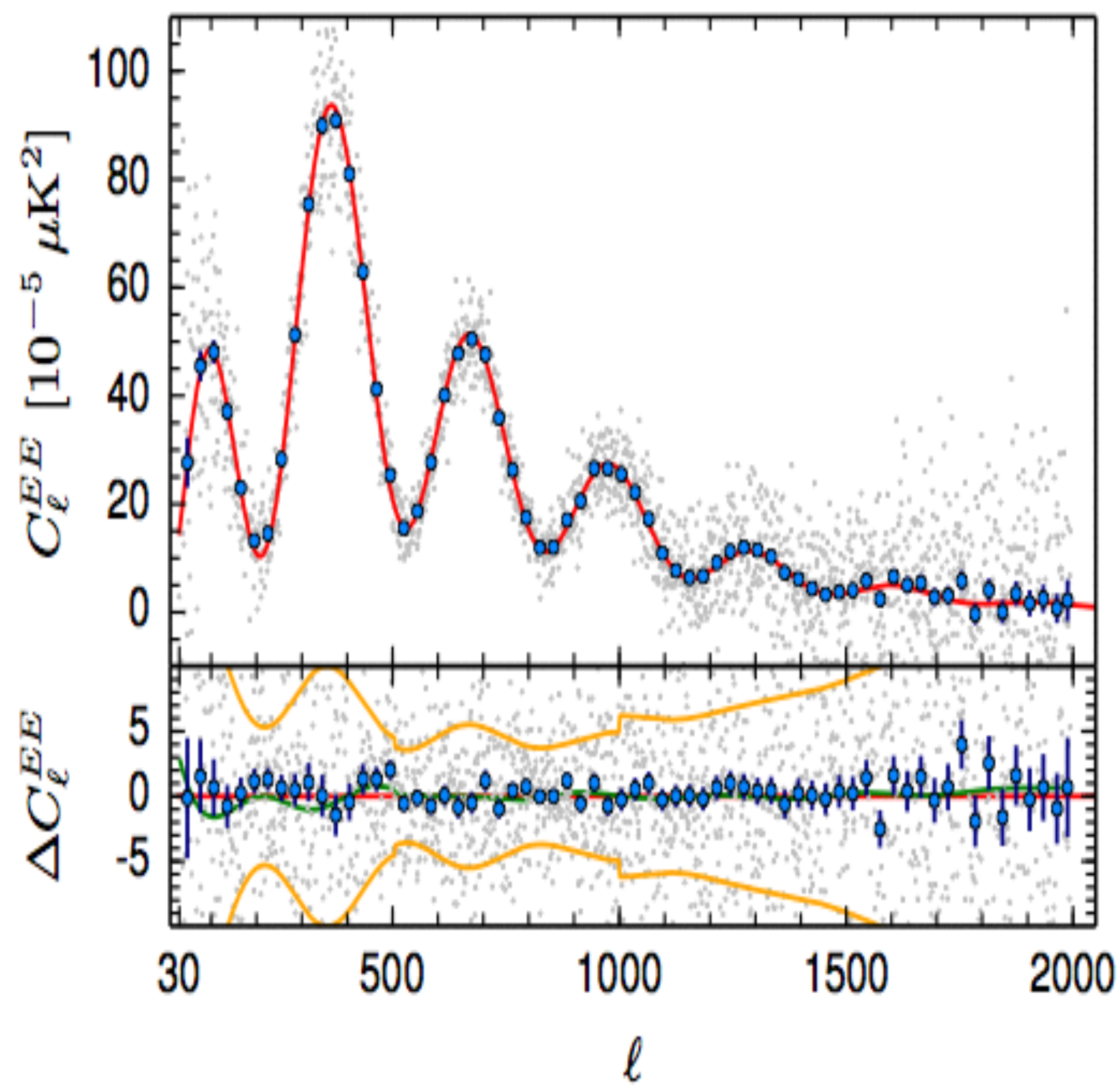


CMB Only

Planck 2015 Results. XI

Planck CMB Polarization Angular Power Spectra

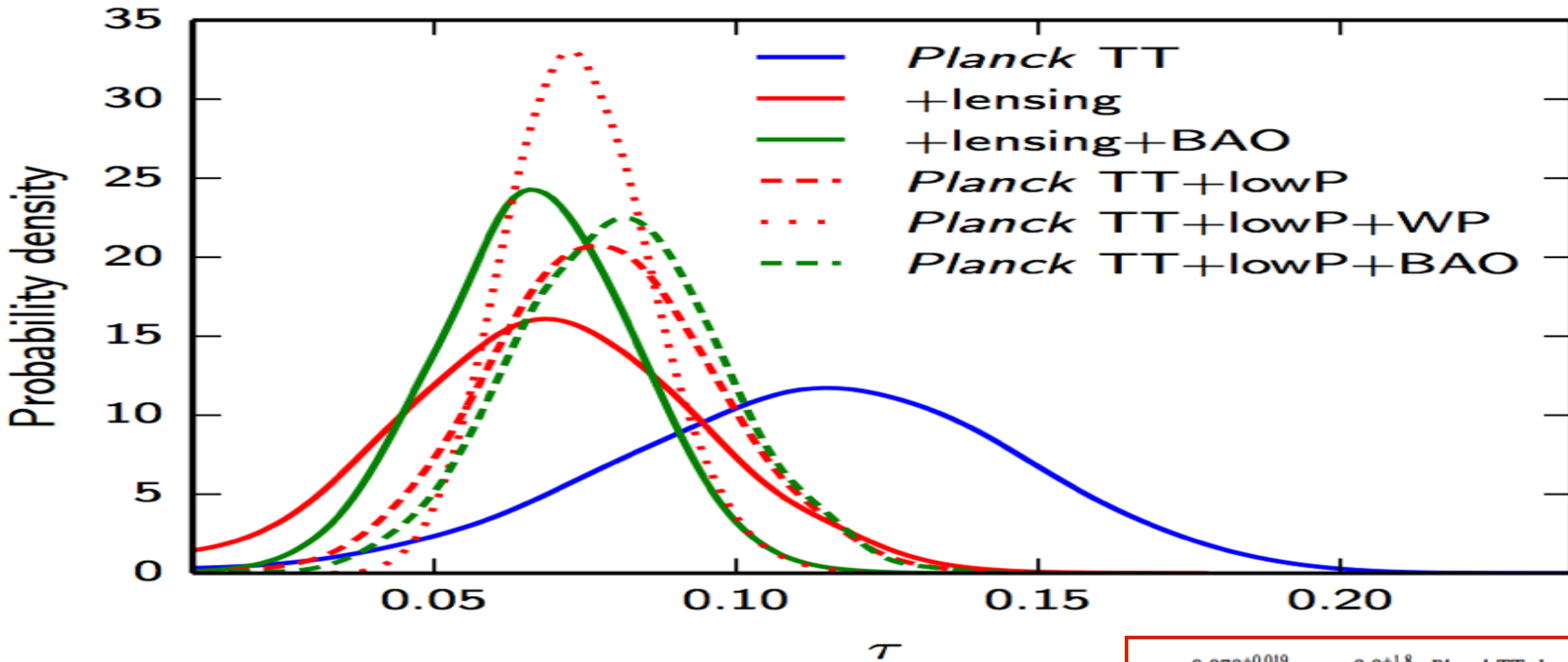




- Red line is best fit temperature only (and τ prior)

Planck 2015 Results. XI

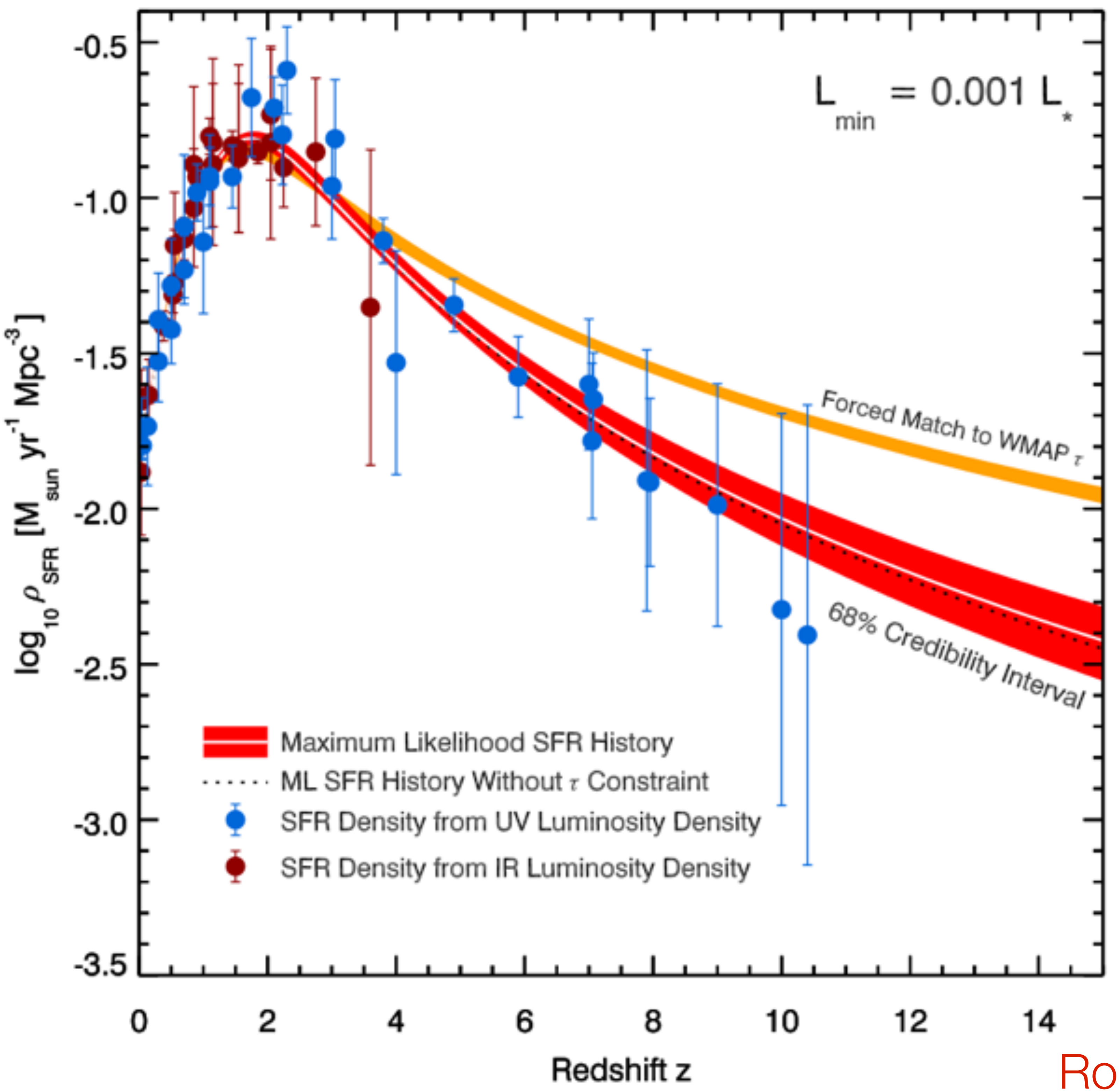
Constrains on Reionization from Planck 70 GHz Maps



$\tau = 0.078^{+0.019}_{-0.019}$, $z_{re} = 9.9^{+1.8}_{-1.6}$, *Planck* TT+lowP;
$\tau = 0.070^{+0.024}_{-0.024}$, $z_{re} = 9.0^{+2.5}_{-2.1}$, *Planck* TT+lensing;
$\tau = 0.066^{+0.016}_{-0.016}$, $z_{re} = 8.8^{+1.7}_{-1.4}$, *Planck* TT+lowP+lensing;
$\tau = 0.067^{+0.016}_{-0.016}$, $z_{re} = 8.9^{+1.7}_{-1.4}$, *Planck* TT+lensing+BAO;
$\tau = 0.066^{+0.013}_{-0.013}$, $z_{re} = 8.8^{+1.3}_{-1.2}$, *Planck* TT+lowP+lensing+BAO.

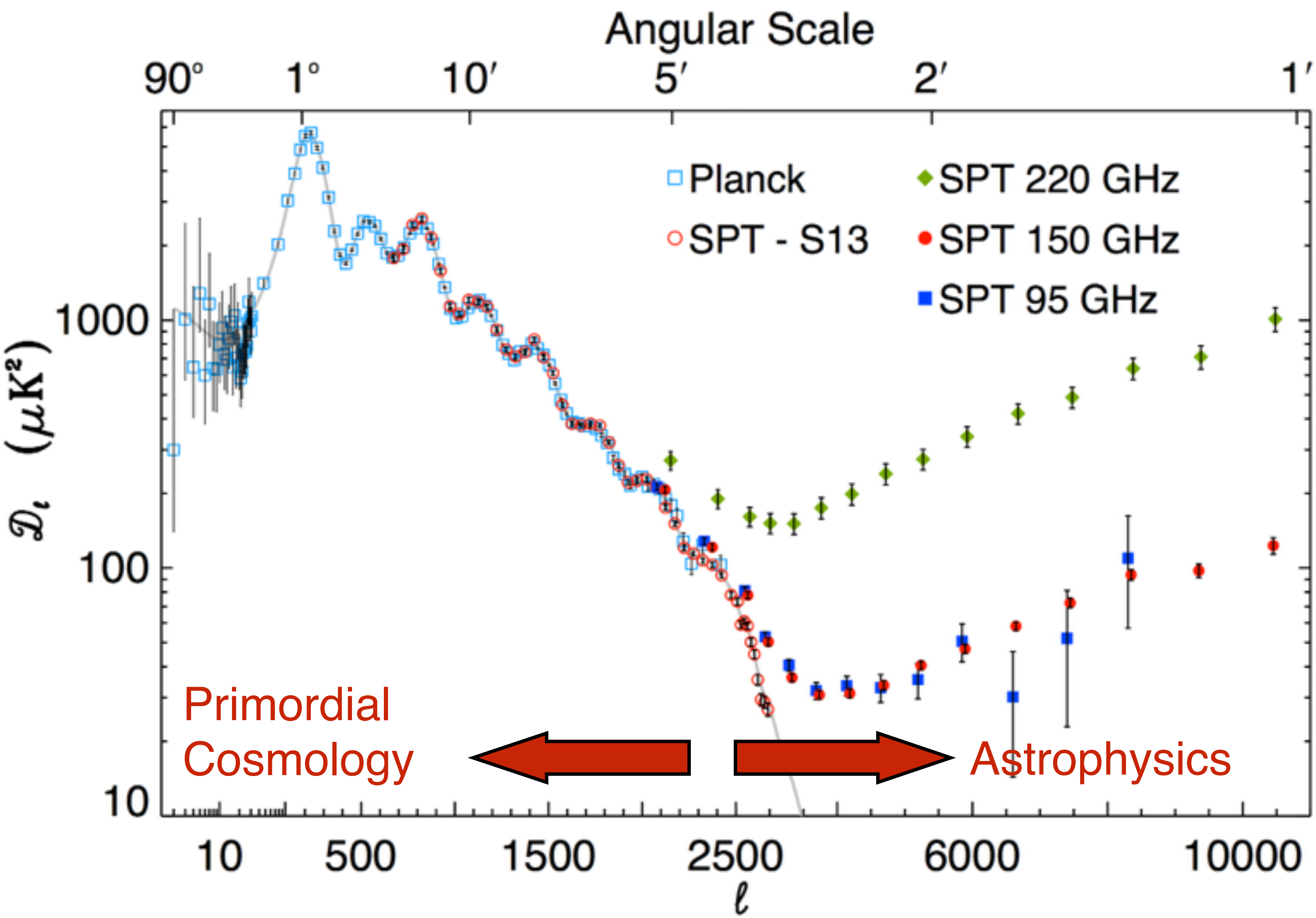
- Planck next data release should decrease these uncertainties by a factor of 2-3.
  - ➡ We will learn more than one number from the large scale CMB polarization. (Probably ~ 2-3, see e.g., Holder & Haiman 02, Hu & Mortonson 12).
  - ➡ This will saturate the information we can extract from large scale CMB Pol.
  - ➡ It will have to be verified. Difficult from the ground but several groups are trying.

Compatible with Other Astrophysical Constrains on Reionization



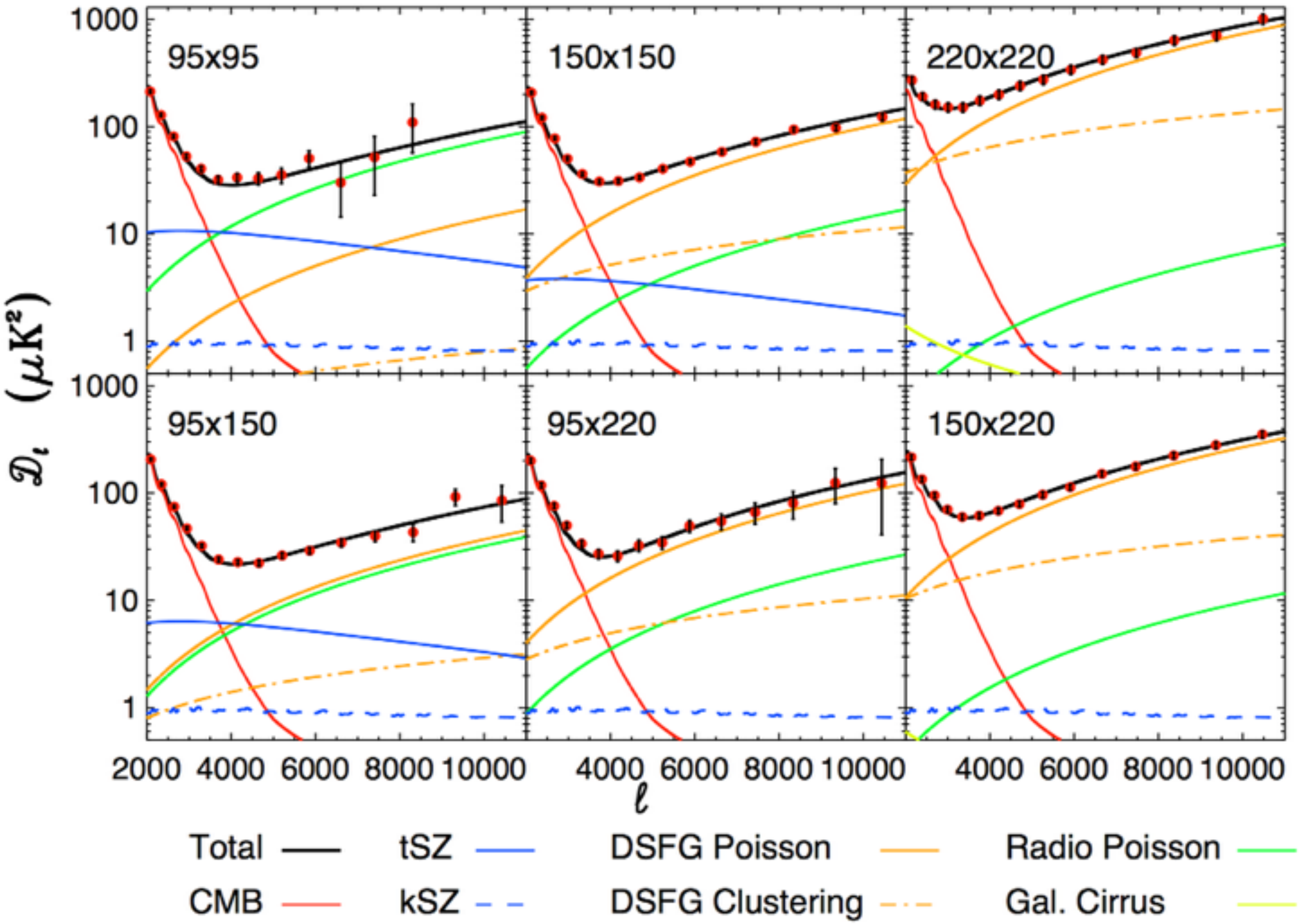
Robertson++13,15
Bouewen++15

Planck and Small Scale CMB Experiments



George++, SPT, 2014
Also ACT

Learning (from) Astrophysics



George++, SPT, 2014
Also ACT

Effect of Reionization on CMB Temperature

- Damping: blending of photons from different line of sight

$$\bar{T} + \Delta T \quad \rightarrow \quad (\bar{T} + \Delta T) - (\bar{T} + \Delta T)\left(1 - e^{-\tau}\right) + \bar{T}\left(1 - e^{-\tau}\right)$$
$$\rightarrow \quad \bar{T} + \Delta T e^{-\tau}$$

$$C_\ell = C_\ell e^{-2\tau}$$

(Ignore scale dependance here)

30% suppression for l greater than 40 (thus hard to measure absolute normalization of the initial conditions)

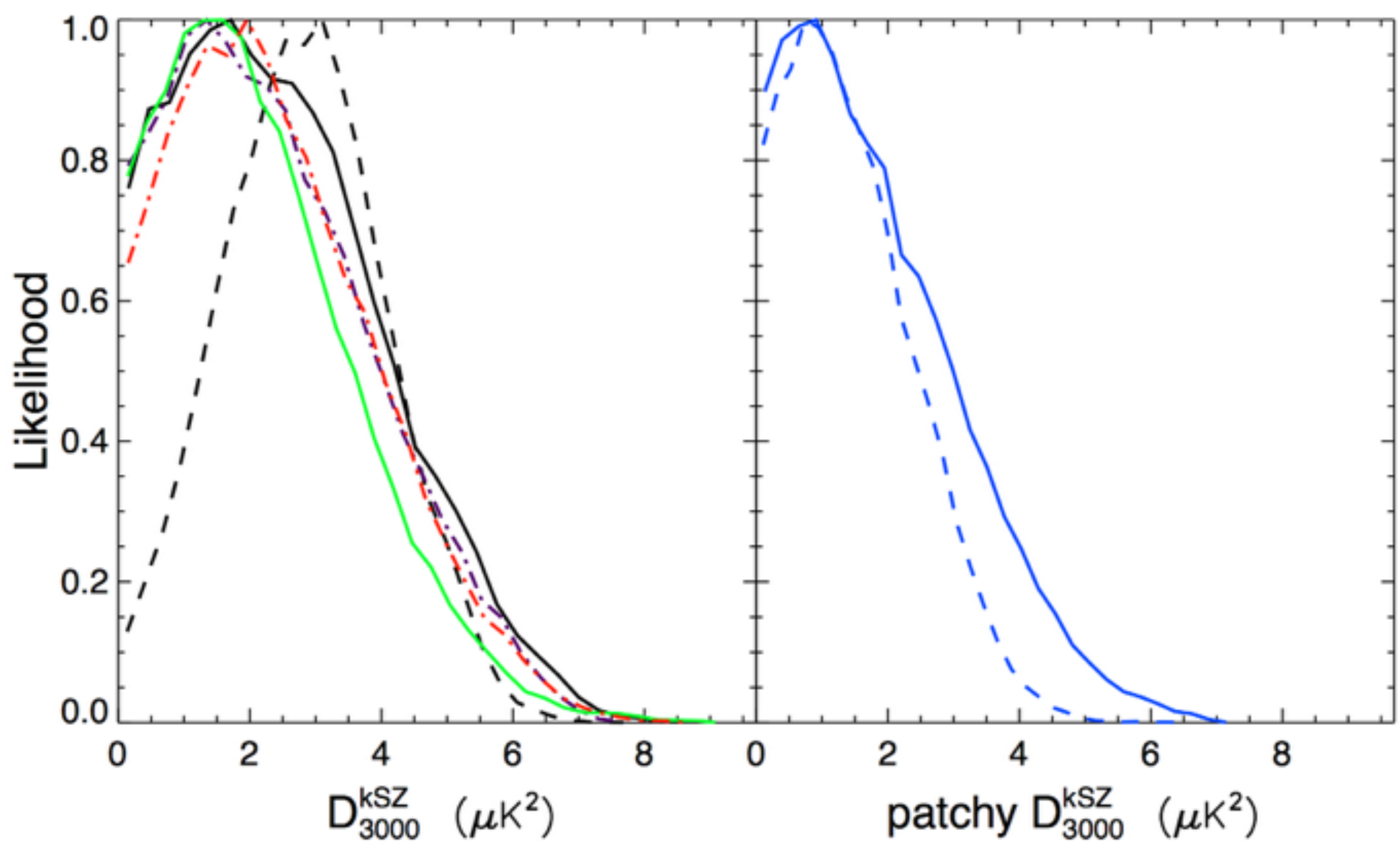
see Liu++15 for cosmological consequences

$$\frac{\Delta T}{T}(\hat{n}) = \sigma_T \int_{\eta_{ion}}^{\eta_0} d\eta \; x_e(\hat{x}) n_p(\hat{x}) \hat{n} \cdot v_e(\hat{x})$$

- Doppler effects: cancellation along the line of sight due to the variation in n
  - ➡ Except large scales: *l*~100
  - ➡ Reduced if modulation in n_p : *Ostriker-Vishniac* effect (*kinetic Sunyaev-Zeldovich*)
  - ➡ Reduced if modulations in x_e: *Patchy reionization*

see Knox & Haiman 99 for a review

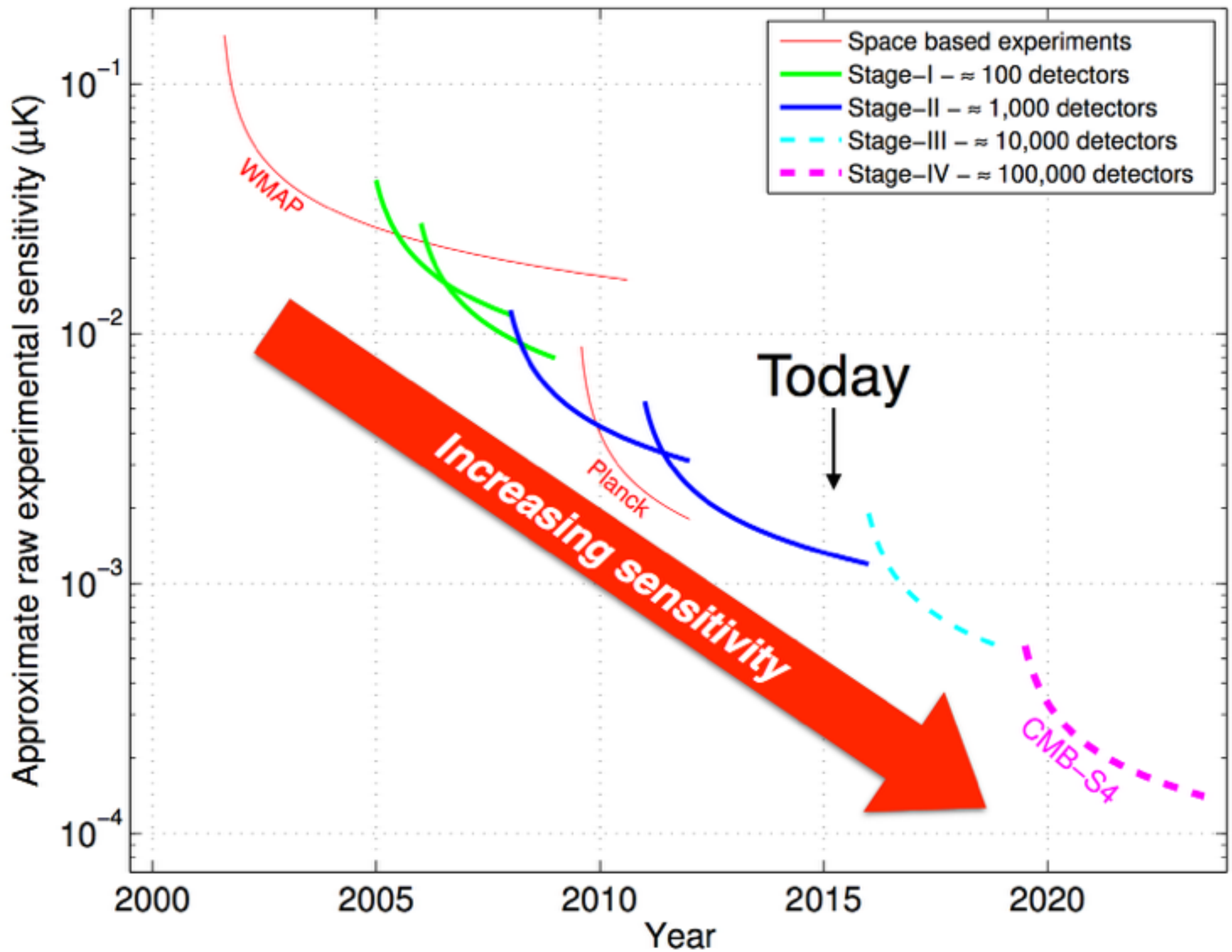
A Faint kSZ Effect



- Better analysis are in progress in SPT-Pol and ACT-Pol team using Herschel data to constrain CIB.

George++, SPT, 2014
Also ACT

The next great step forward - Stage IV



future Satellite?

A Moore's Law of CMB sensitivity

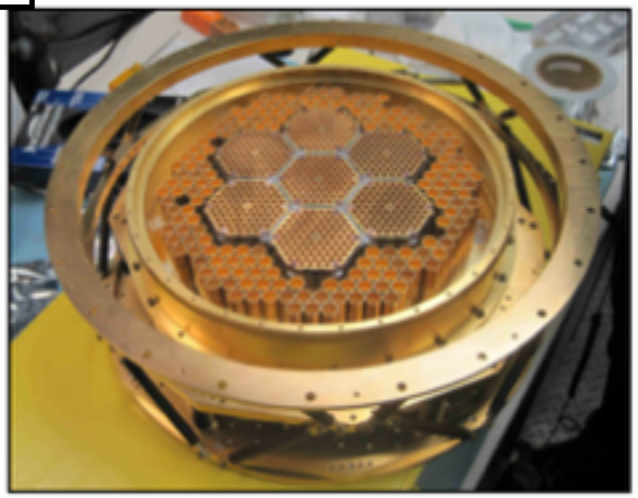
Snowmass CF5 Neutrinos Document arxiv:1309.5383; figure by Clem Pryke

Slide by J. Carlstrom

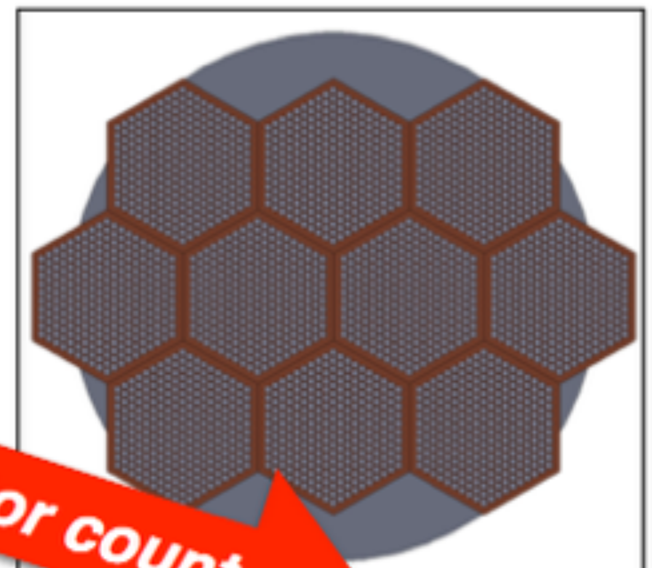
Maintaining Moore's Law: focal planes are saturated so must use parallel processing and multiple telescopes.

Planck
Now
52 detectors
in space

Stage II
Now
~1000 detectors

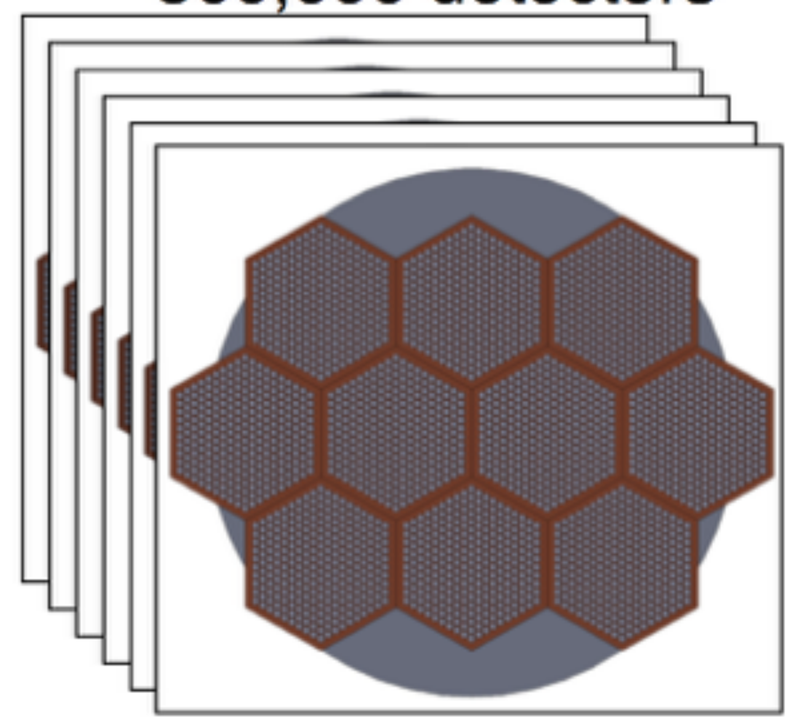


Stage III
ramping up
~10,000 detectors



increasing detector count
(the trend being followed by all CMB projects, not just SPT)

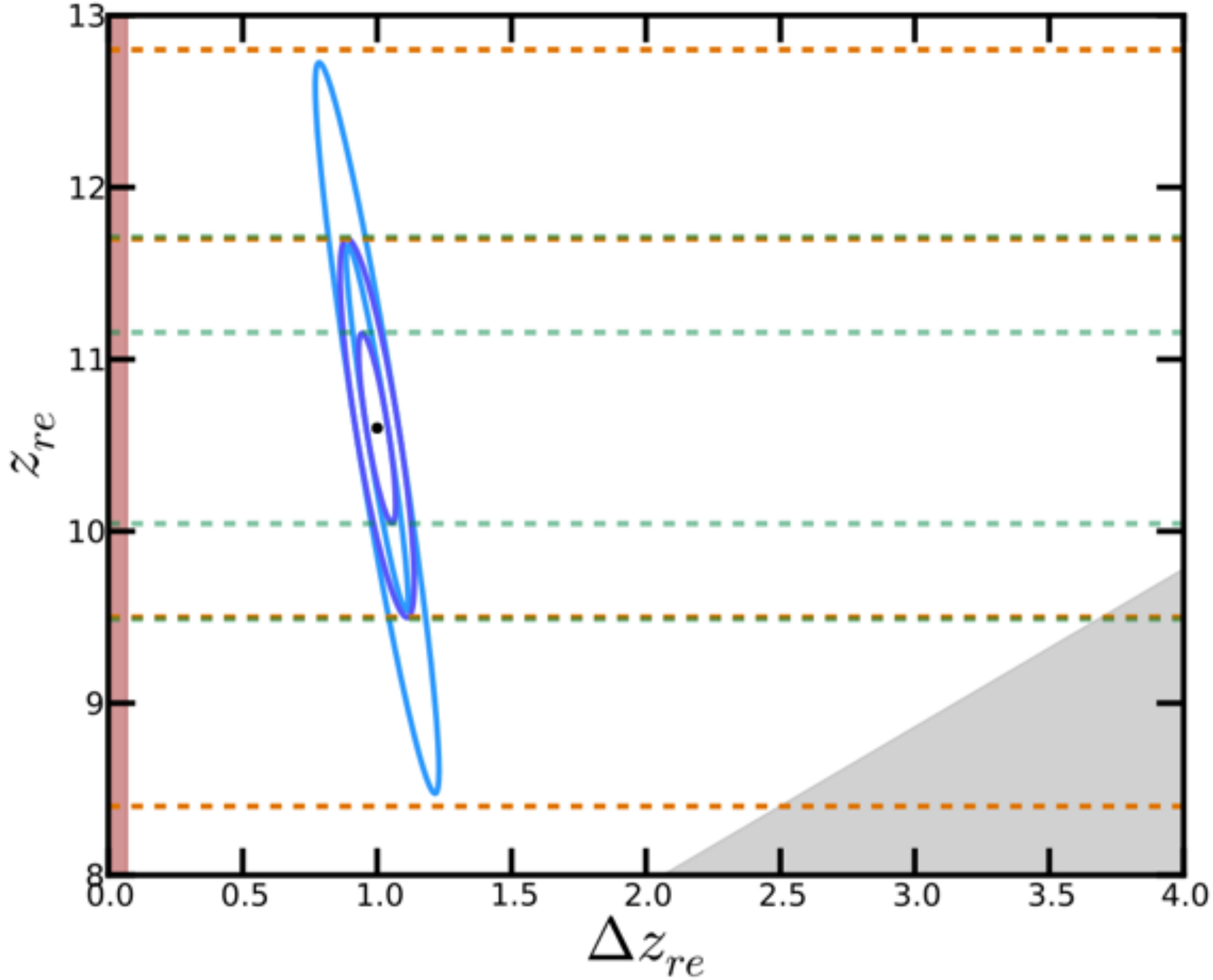
Stage IV
~2020 - CMB-S4
~500,000 detectors



CMB-S4: A program to put O(500,000) detectors spanning 30 - 300 GHz using multiple telescopes and sites to map ≳70% of sky.

Slide by J. Carlstrom

The kSZ signal “Should” be Seen At ~ 15σ



$\sigma(z_{re}) \sim 1.1$
$\sigma(\Delta z_{re}) \sim 0.2$

Zahn++, SPT,2012
Calabrese++, ACT, 2014

Concluding Remarks

- Planck and the CMB observational program in general has been amazingly successful.
  - ➡ Planck reached its precision goals on cosmological parameters.
  - ➡ Key cosmological parameters are *robustly* constrained to sub-percent accuracy.
  - ➡ Truly a triumph of modern physics.

- Planck should (soon…) extract all the information coming from large scale polarization.

- It is not over yet:
  - ➡ Very large area (half-sky) deep and high-angular resolution polarized surveys are happening.
    - They promise exquisite CMB lensing signal, neutrino mass measurements, etc. and new constraints on reionization.
  - ➡ A new space mission(s) focussing on large scale polarization is being discussed (foregrounds/systematics are a serious worry besides raw sensitivity).

- Some lessons from Planck are:
  - ➡ Large scale polarization is hard. REALLY hard.
    - Build-in margins are essential. Multiple pipelines and consistency tests at every stage are critical. Fast end-to-end pipeline are very valuable.
  - ➡ Foregrounds, galactic and extra-galactics are a serious challenge.
    - Planck TT (and other small scale experiments) and large scale P are limited by foreground uncertainties.
  - ➡ Cross-correlations (CMB lensing, CIB, …) are important and will be key.
    - Be good friend with the CO, CII, Lyα IM surveys.

- SPHEREx!!

FIN