Spectral distortions in the cosmic microwave background polarization

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Outline

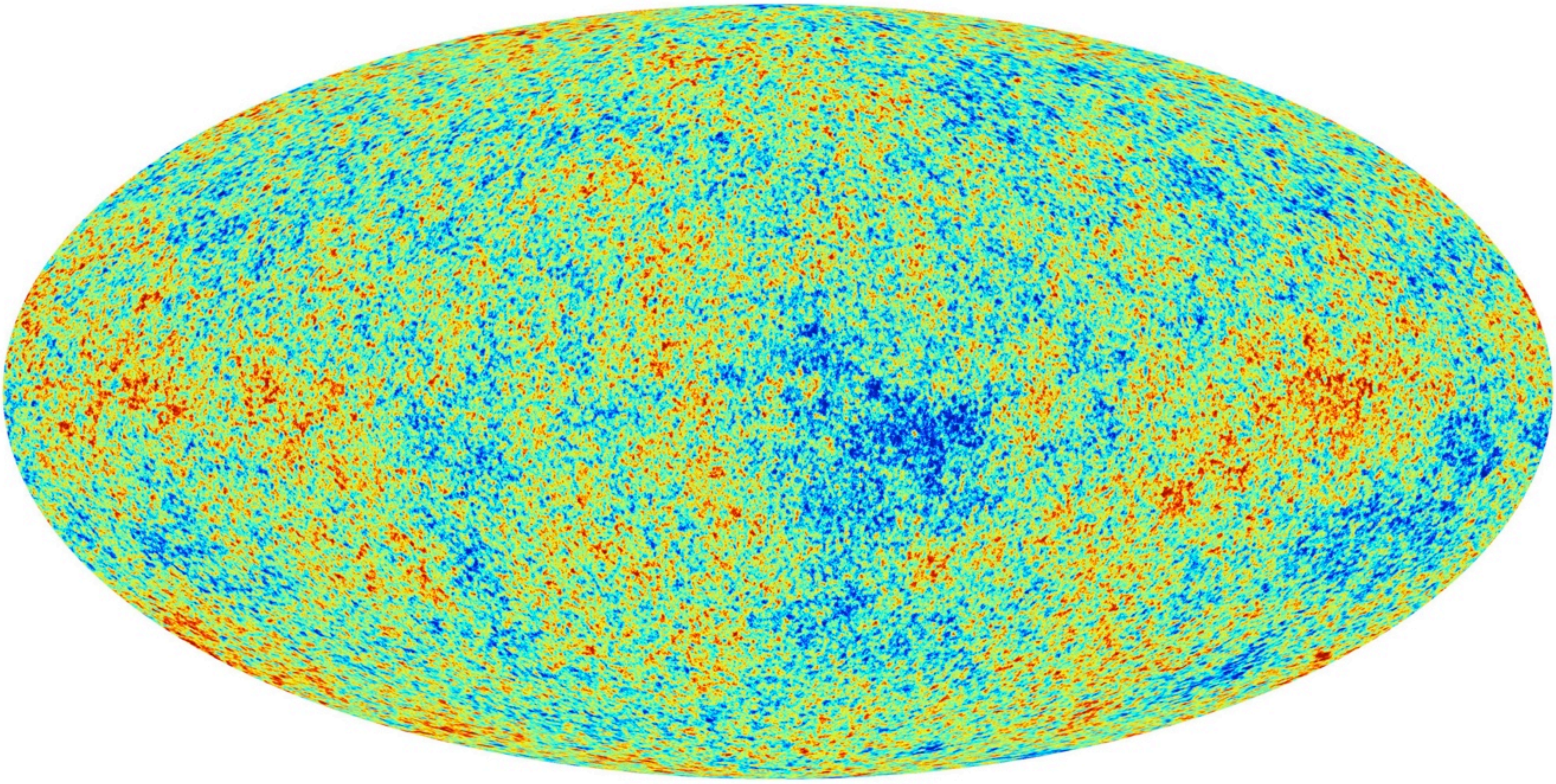
1. ***Spectral distortions***

2. ***Our work***

arXiv: 1312.4448 (JCAP)

SRP, C. Fidler (Louvain), C. Pitrou (IAP), G. Pettinari (Sussex)

Cosmic Microwave Background temperature fluctuations



Planck all sky map

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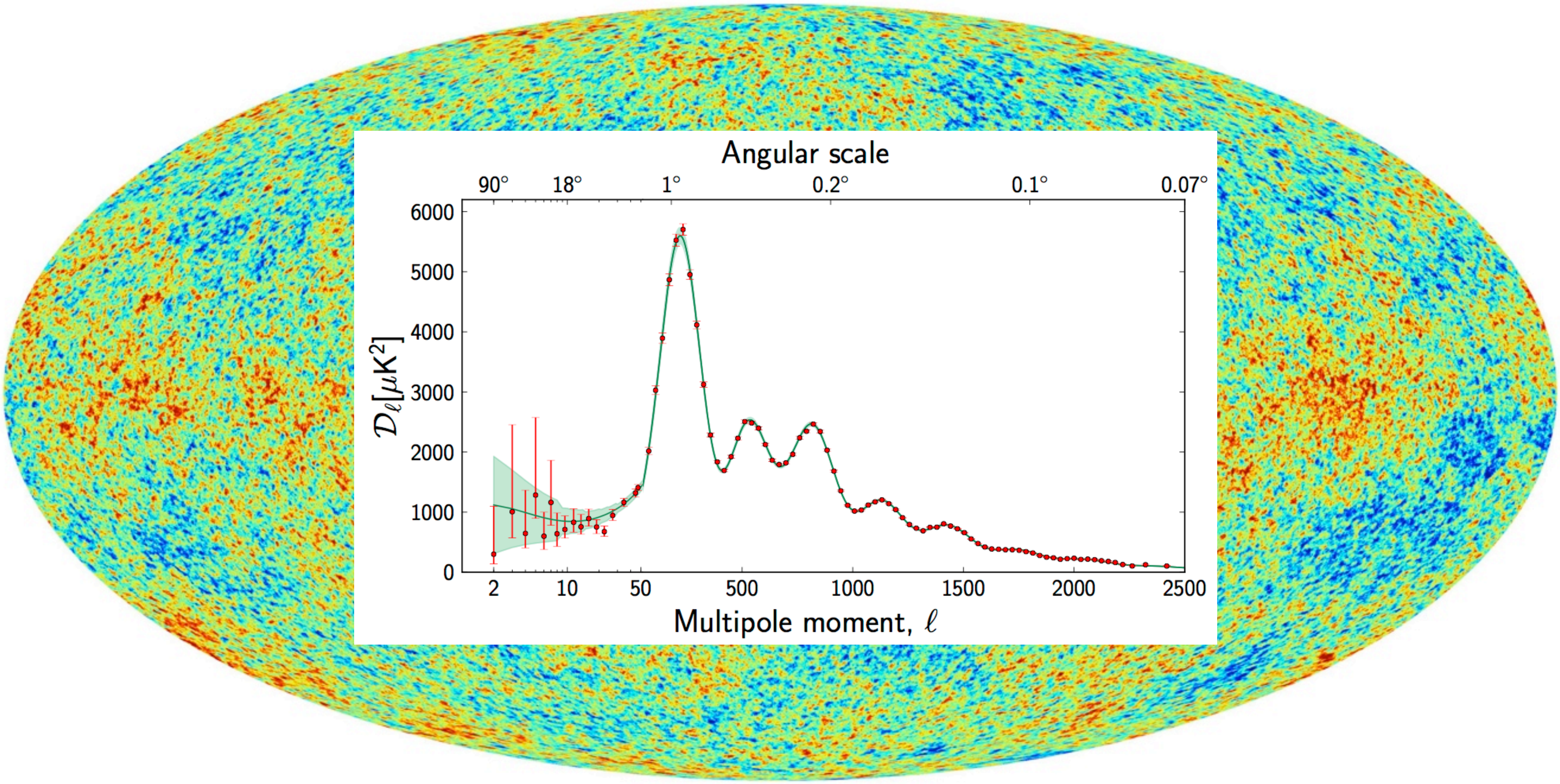

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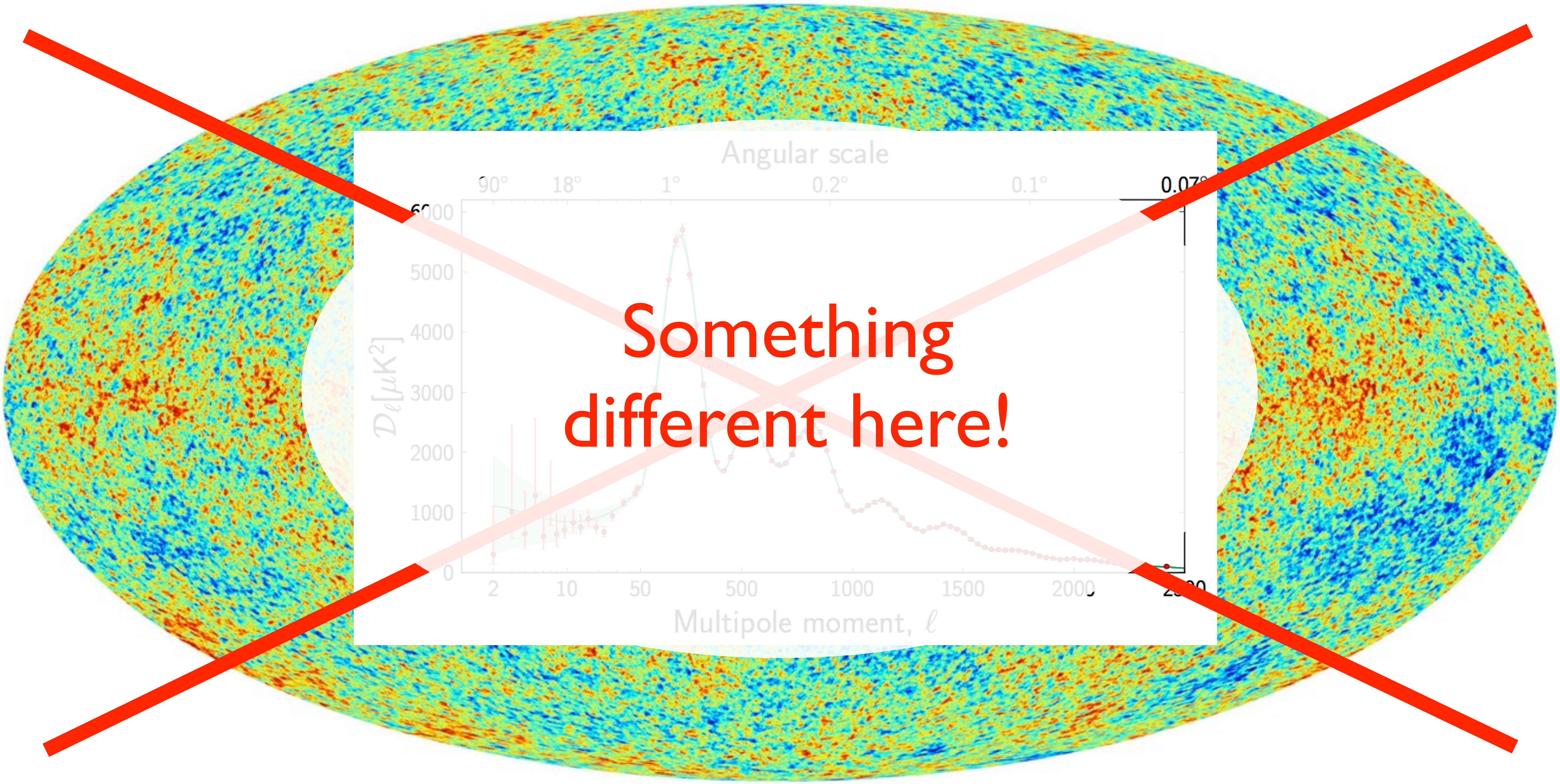


Planck all sky map

Energy dependence

- Previous picture assumed:

$$I_{BB}(E,\hat{n}) = \frac{2}{e^{\frac{E}{T(\hat{n})}} - 1}$$

- Blackbody (BB) distribution of the CMB intensity with direction-dependent temperature.

- **But**: no full thermodynamic equilibrium throughout the universe history

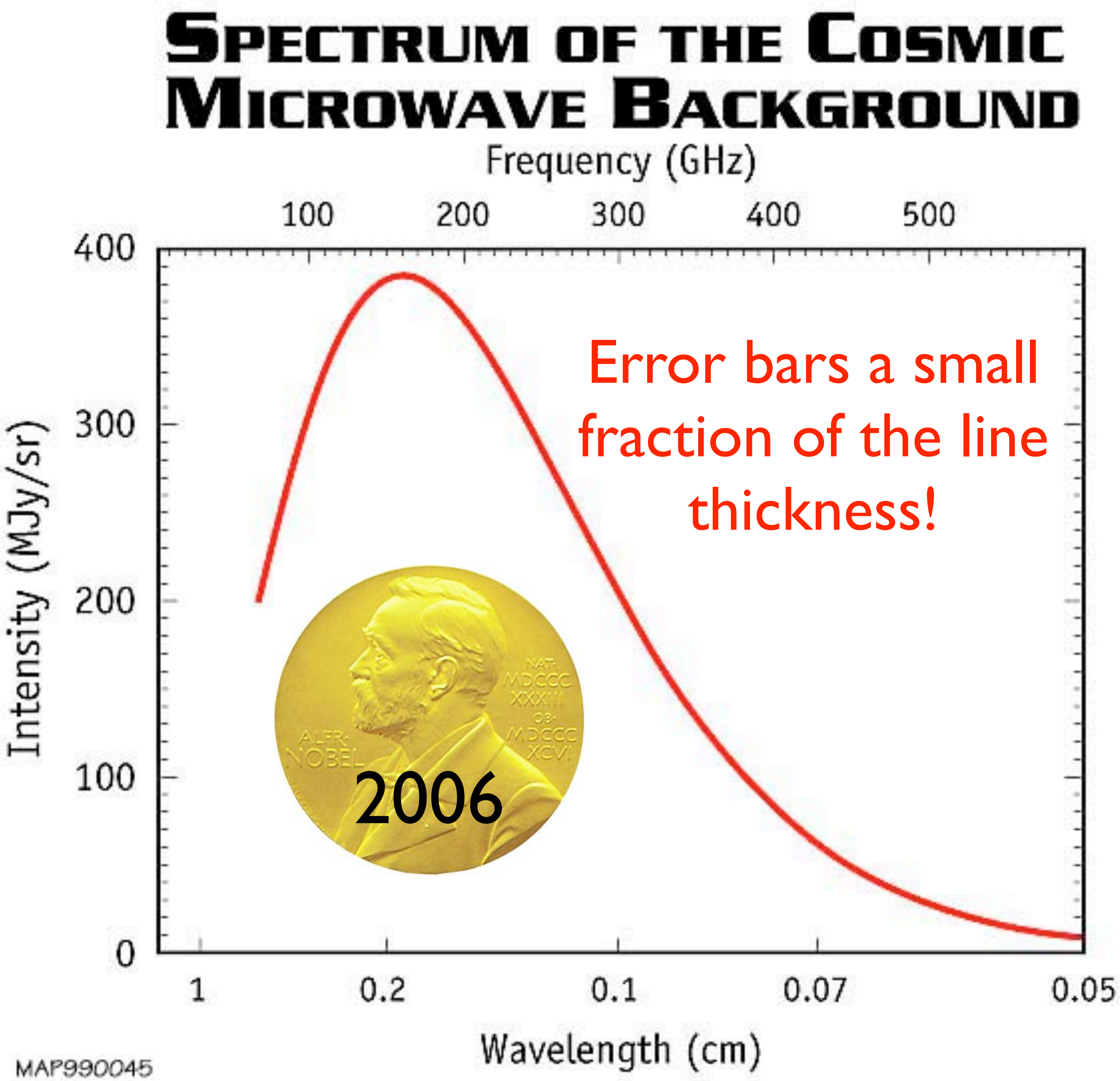
→

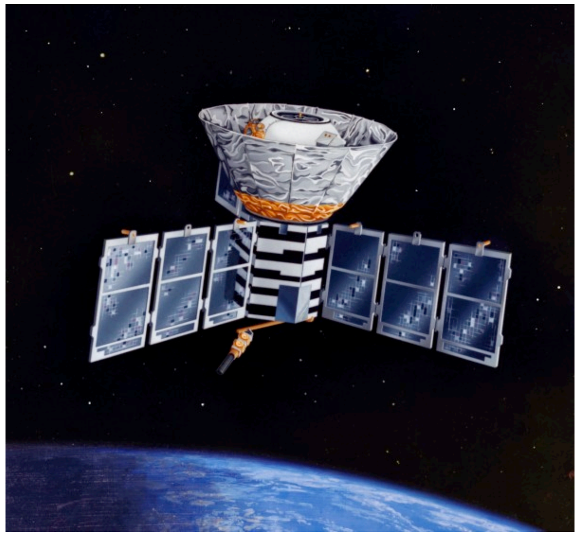
- The energy dependence **is** more complicated

- The temperature is not enough to characterize the CMB signal. Its spectral dependence contains another independent piece of information.

Current spectral distortions constraints

COBE/FIRAS **(Far InfraRed Absolute Spectrophotometer)**





Compton y-distortion:

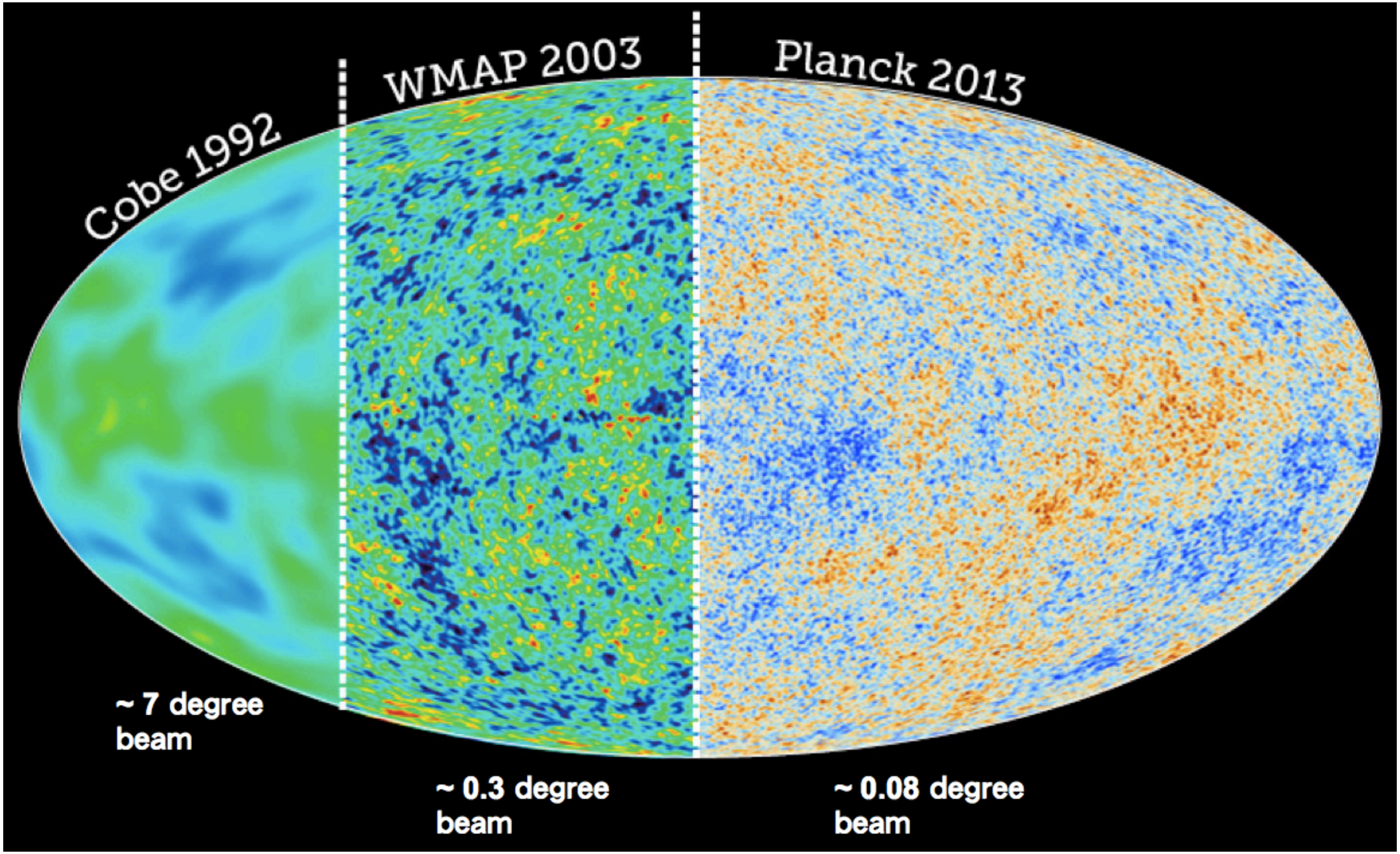
$$|y| \leq 1.5 \times 10^{-5}$$

Chemical potential mu-distortion:

$$|\mu| \leq 9 \times 10^{-5}$$

Only very small distortions of the CMB spectrum are allowed

Dramatic improvement in angular resolution and sensitivity in the past decades



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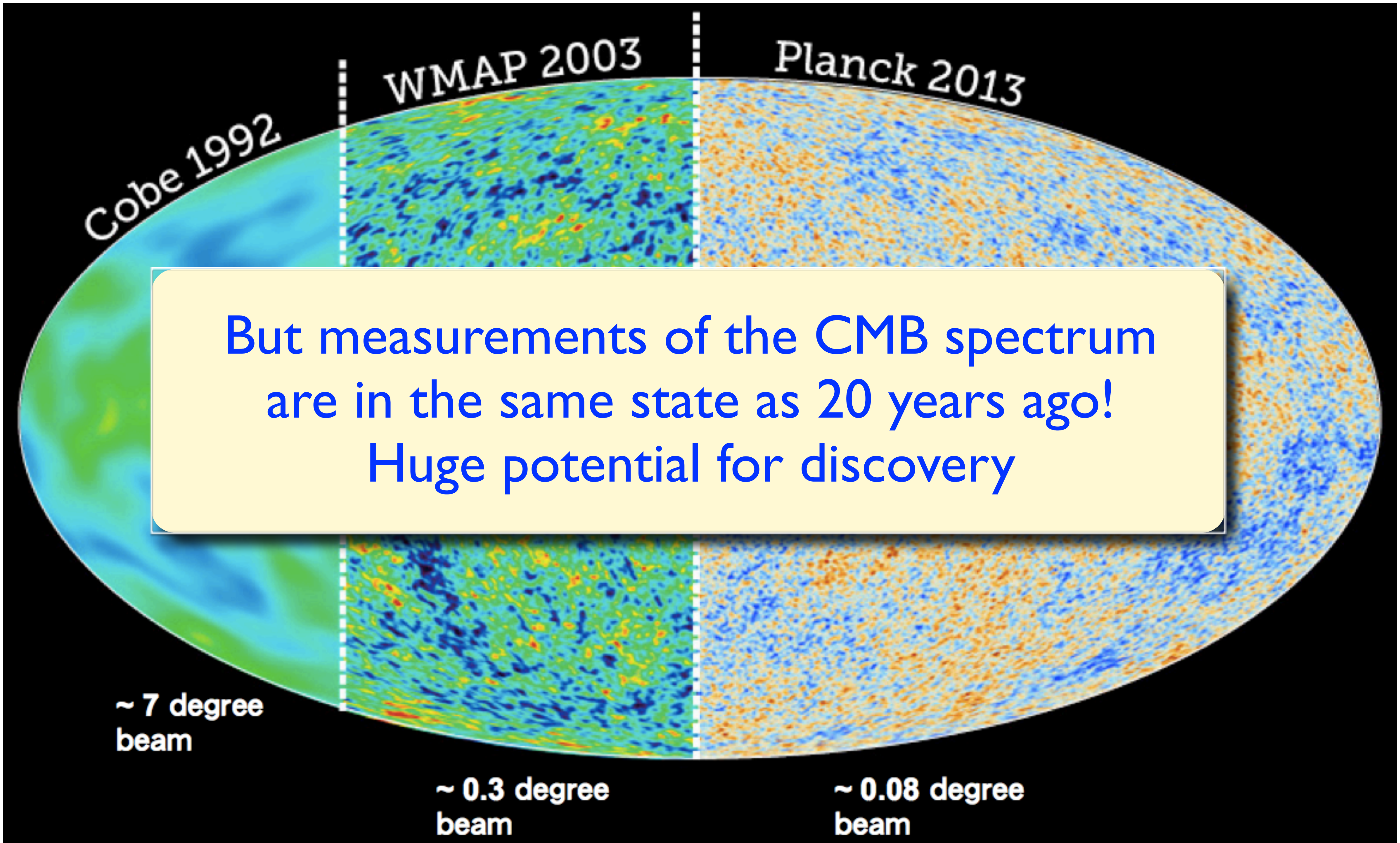
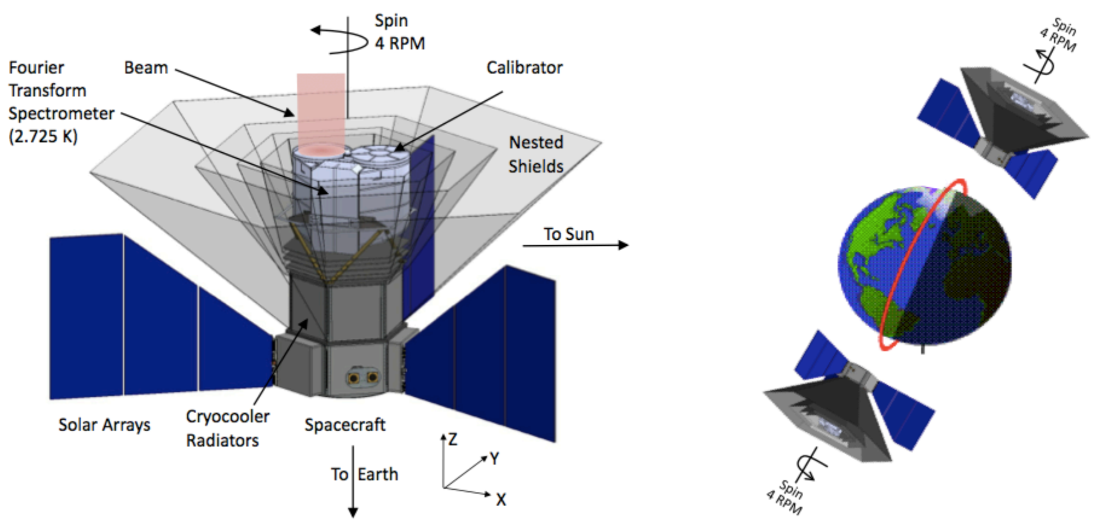


But measurements of the CMB spectrum are in the same state as 20 years ago!
Huge potential for discovery

Future expected constraints

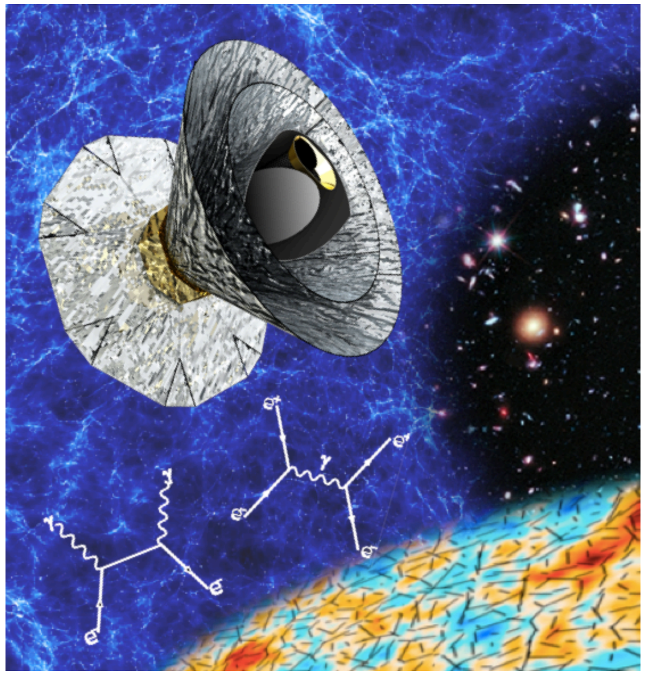
PIXIE

arXiv:1105.2044



COrE+

arXiv:1310.1554



see J. Delabrouille's talk

- 400 spectral channels in the frequency range 30 GHz - 6 THz (9 for Planck)
- About 1000 times more sensitive than COBE/FIRAS

- Improved limits on mu and y by 3 orders of magnitude!

Physical mechanisms that lead to spectral distortions

- Energy injection in the primordial plasma at $z < \text{few} \times 10^6$
- Heating by decaying or annihilating relic particles
- Dissipation of primordial acoustic waves (window into small scale power spectrum)

see R. Khatri's talk

- Cosmological recombination

Les Houches lecture notes, Chluba 13

- SZ effect from galaxy clusters, effects of reionization ...

Lots of effects within the reach of future experiments

The field of CMB spectral distortions is observationally and theoretically very promising.

Our work

arXiv: 1312.4448 (JCAP)
SRP, C. Fidler (Louvain), C. Pitrou (IAP), G. Pettinari (Sussex)

- The field of CMB spectral distortions is still in its infancy

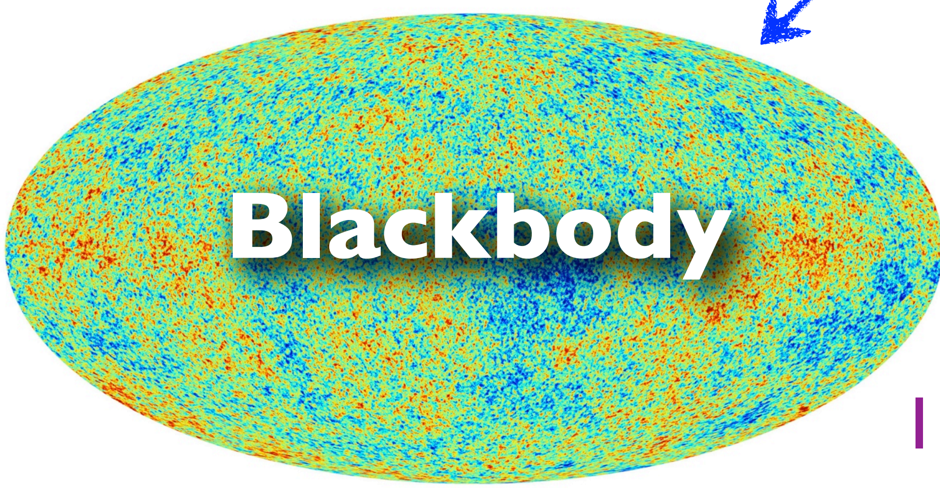
- Most work to date concentrate on the CMB intensity, and its monopole

- But future experiments will characterize the spectrum of the CMB anisotropies, both in intensity and polarization.

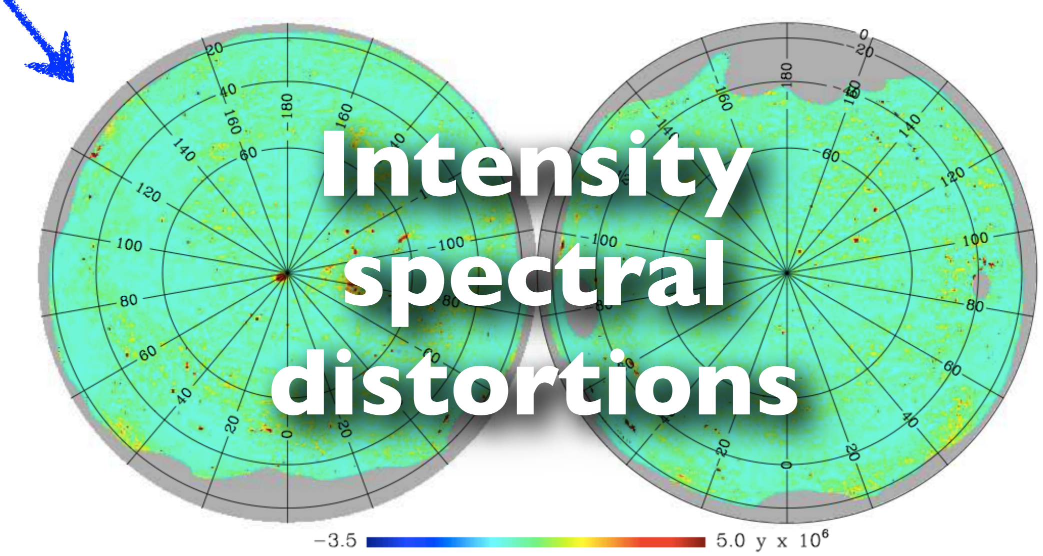
- In 1312.4448, we computed the unavoidable spectral distortions of the CMB polarization induced by non-linear effects in the Compton interactions between CMB photons and the flow of intergalactic electrons (non-linear kinetic Sunyaev Zel'dovich, kSZ^2)

CMB spectral distortions

$$I\left(E,\hat{n}\right) = I_{\text{Planck}}\left(E; T(\hat{n})\right) + y(\hat{n}) \times \left(\begin{matrix}\text{Other}\\ \text{spectral dependence}\end{matrix}\right)$$

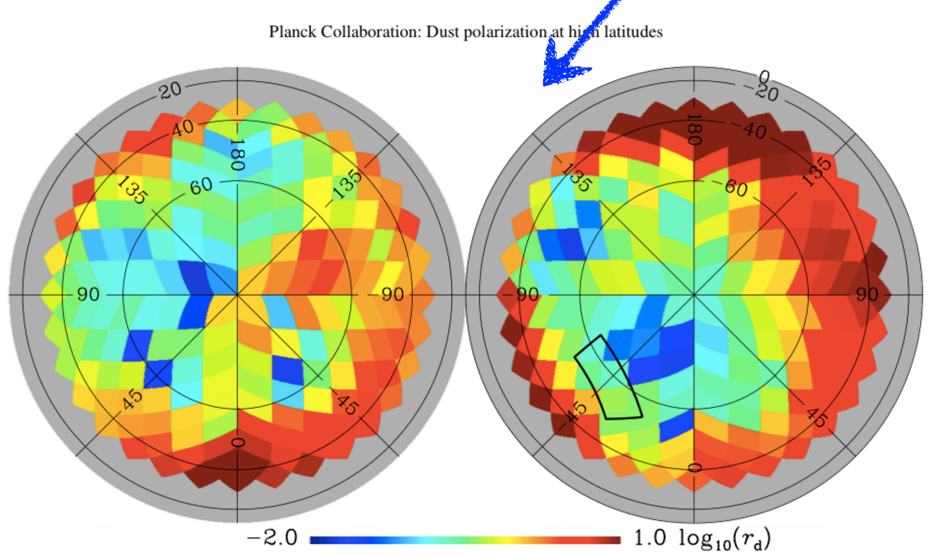


Planck 1303.5062



Planck 1303.5081

$$P_{\mu\nu}\left(E,\hat{n}\right) = \text{Standard polarization} + \textbf{?}$$



Planck 1409.5738

Polarization spectral distortions

Intensity y-type distortions

$$I\left(E,\hat{n}\right) = I_{\rm BB}\left(\frac{E}{T(\hat{n})}\right) + y(\hat{n})\,\mathcal{D}_E^2\, I_{\rm BB}\left(\frac{E}{T(\hat{n})}\right)$$

Energy

direction of photon propagation

$$\mathcal{D}_E^2 \equiv E^{-3}\frac{\partial}{\partial \ln E}\left(E^3\frac{\partial}{\partial \ln E}\right) = \frac{\partial^2}{\partial \ln E^2} + 3\,\frac{\partial}{\partial \ln E}$$

Number density of photons:

$$n \propto \int I\, E^3\, \mathrm{d}\ln E$$

→ T: temperature of a blackbody that would have the same number density

see Pitrou, Stebbins, 1402.0968

Polarization y-type distortions

$$P_{\mu\nu}\left(E,\hat{n}\right) = -\mathcal{P}_{\mu\nu}(\hat{n})\,\frac{\partial}{\partial \ln E}\, I_{\rm BB}\left(\frac{E}{T(\hat{n})}\right) + y_{\mu\nu}(\hat{n})\,\mathcal{D}^2_E\, I_{\rm BB}\left(\frac{E}{T(\hat{n})}\right)$$

Polarization tensor

'Standard polarization'

Polarization distortion

E and B modes

E^y and B^y modes

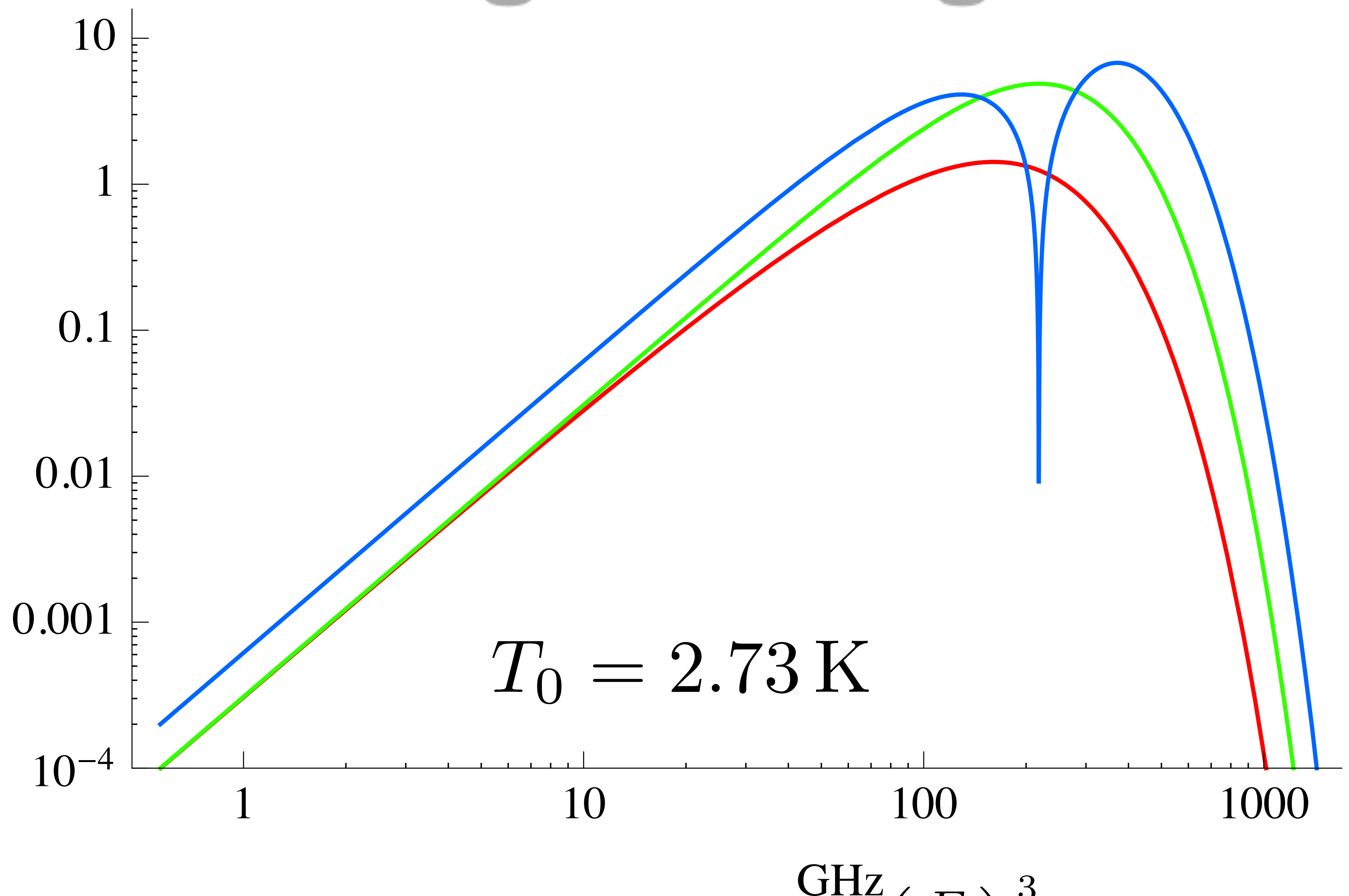
- Similarly to y, Compton scattering generates a non-zero polarization distortion only beyond first-order perturbation theory

→

- Need for polarized Boltzmann equation at second order, with proper spectral dependence decomposition

Naruko, **Pitrou**, Koyama, Sasaki 1304.6929

Brightness signals



Blackbody spectrum $\left(\frac{E}{T_0}\right)^3 I_{\rm BB}(E/T_0)$

Standard polarization $\left(\frac{E}{T_0}\right)^3 \frac{\partial I_{\rm BB}(E/T_0)}{\partial \ln E}$

Polarization distortion $\left(\frac{E}{T_0}\right)^3 \mathcal{D}_E^2 I_{\rm BB}(E/T_0)$

Boltzmann equation for polarization distortion

Boltzmann equation:

$$y'_{ij} + n^l \partial_l y_{ij} = \tau' \left(-y_{ij} + C^y_{ij}\right)$$

free-streaming

Thomson interaction rate

$$\tau' \equiv a\,\overline{n}_e\,\sigma_{\rm T}$$

Collision term

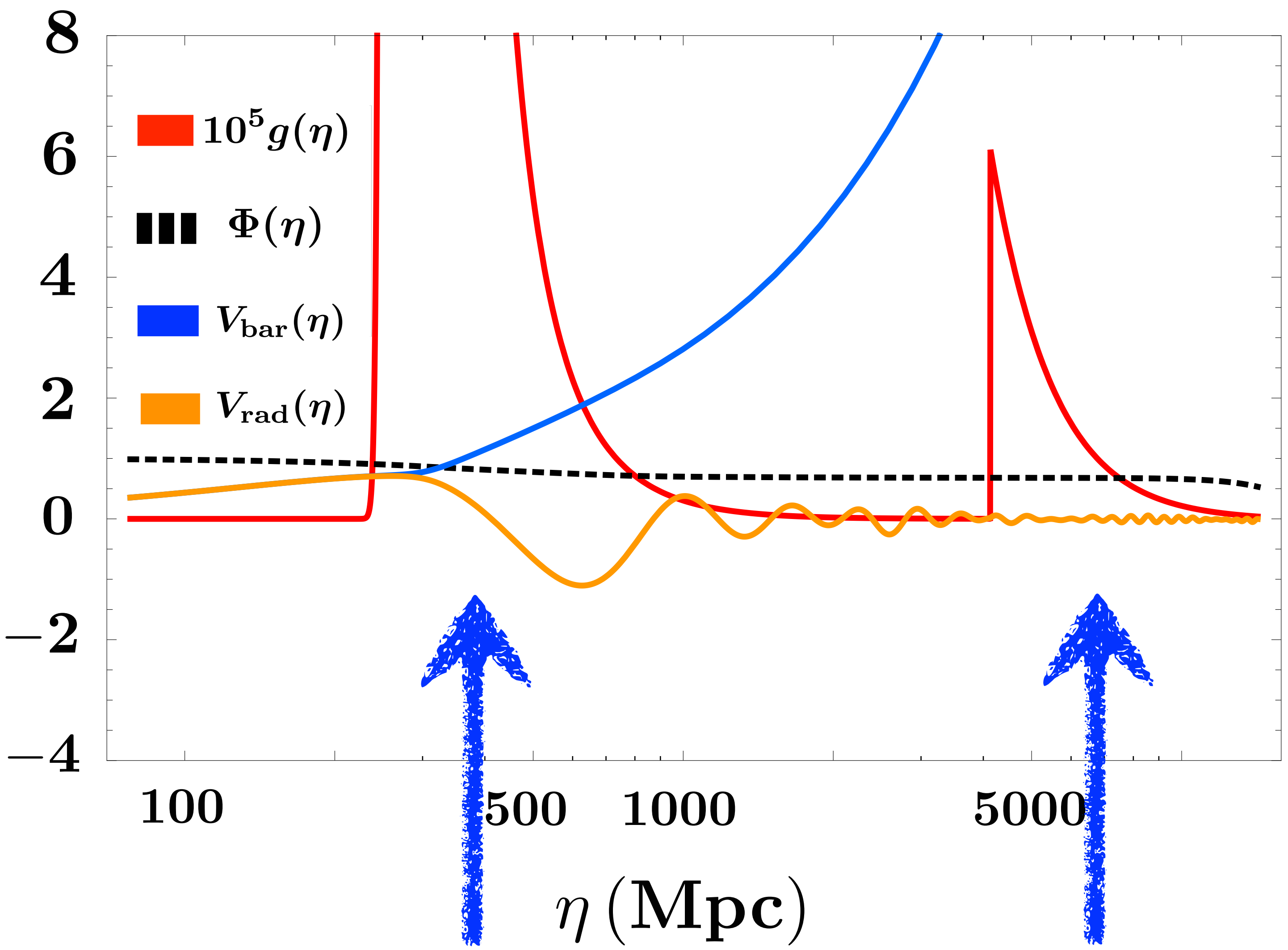
Line of sight formal solution:

$$y_{ij}(\eta_0, k_i, n^i) = \int^{\eta_0} \mathrm{d}\eta\, \tau'\, e^{-\tau} e^{-\mathrm{i}\, k_i\, n^i (\eta_0 - \eta)}\, C^y_{ij}(\eta, k_i, n^i)$$

$$g(\eta) = \tau' e^{-\tau}$$

Visibility function

Non-linear kSZ effect (kSZ²)



Recombination

Reionization

Leading-order collision term:

$$C^{y\,(\mathrm{L.O.})}_{ij} = -\frac{1}{10}\,[\,v_i\,v_j\,]^{\mathrm{TT}}$$

Difference between the first-order electron and photon velocities.

Grows after recombination.

Main signal originates from reionization (z < 15)

Multipolar expansion of the collision term

Leading-order collision term quadratic in

$$v_i(\eta, \mathbf{k}) \;=\; -i\,\hat{k}_i\, F(k,\eta)\,\Phi(\mathbf{k})$$

transfer function of the baryon velocity

primordial potential

$$E[C^y]_{\ell m}(\mathbf{k}) = \delta^2_\ell\, \mathcal{K}\left\{ S_m(\hat{\mathbf{k}}_1, \hat{\mathbf{k}}_2)\, F(k_1,\eta)\, F(k_2,\eta)\, \Phi(k_1)\Phi(k_2) \right\}$$

$(\ell = 1) \otimes (\ell = 1)$

geometrical factor

Convolution operator

$$\mathcal{K}\{\dots\} \;\equiv\; \int \frac{\mathrm{d}^3\mathbf{k}_1 \mathrm{d}^3\mathbf{k}_2}{(2\pi)^3}\, \delta^3_{\mathrm{D}}(\mathbf{k}_1 + \mathbf{k}_2 - \mathbf{k})\; \dots$$

Analytical result

$$(2\ell+1)^2\, C_\ell^{E^y} = \frac{2}{\pi} \sum_{m=-2}^{2} \int \mathrm{d}k\, k^2\, \mathcal{Q}_{\ell m}^{E^y}(k)$$

with

Primordial power spectra

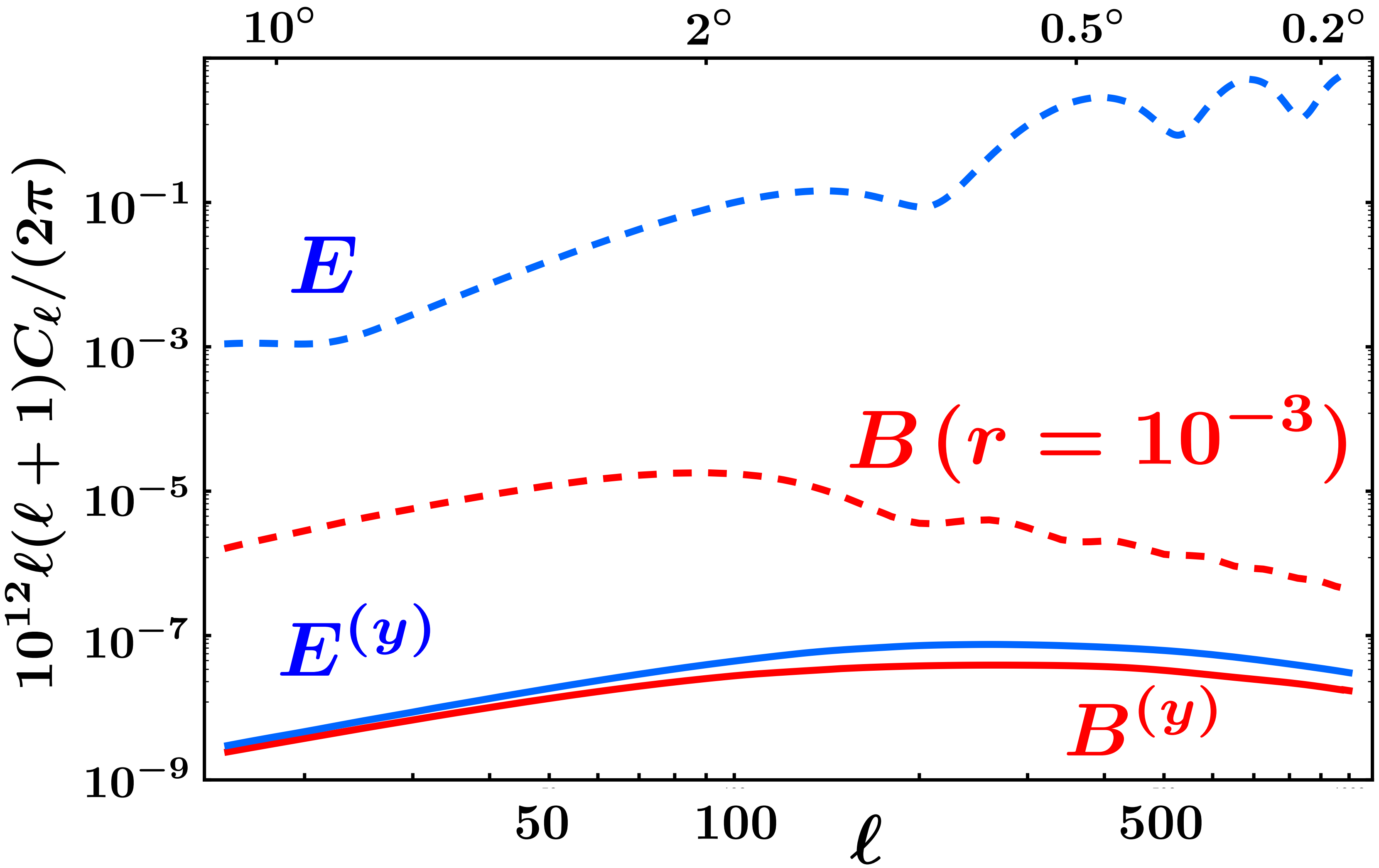
$$\mathcal{Q}_{\ell m}^{E^y}(k) = \frac{2(2\ell+1)^2}{(2\pi)^3} \int \mathrm{d}^3\mathbf{k}_1 P(k_1) P(k_2) \left| S_m(\hat{\mathbf{k}}_1, \hat{\mathbf{k}}_2) \right|^2 \times \left| \int_{\eta_{\rm re}}^{\eta_0} \mathrm{d}\eta\, g(\eta)\, \epsilon_\ell^{(m)}[kr(\eta)] F(k_1,\eta) F(k_2,\eta) \right|^2$$

Built out of
spherical Bessel functions

$$\mathbf{k_2} = \mathbf{k} - \mathbf{k_1}$$

Similarly for B^y modes

Numerical results



SONG, Pettinari, Fidler et al, 1302.0832

- E^y and B^y modes of similar magnitude (same sources)
- Smooth spectra (no acoustic oscillation structure)
- Naive suppression for a second-order effect mitigated by the growth of the electron velocity

Measurability

borrowed from Komatsu

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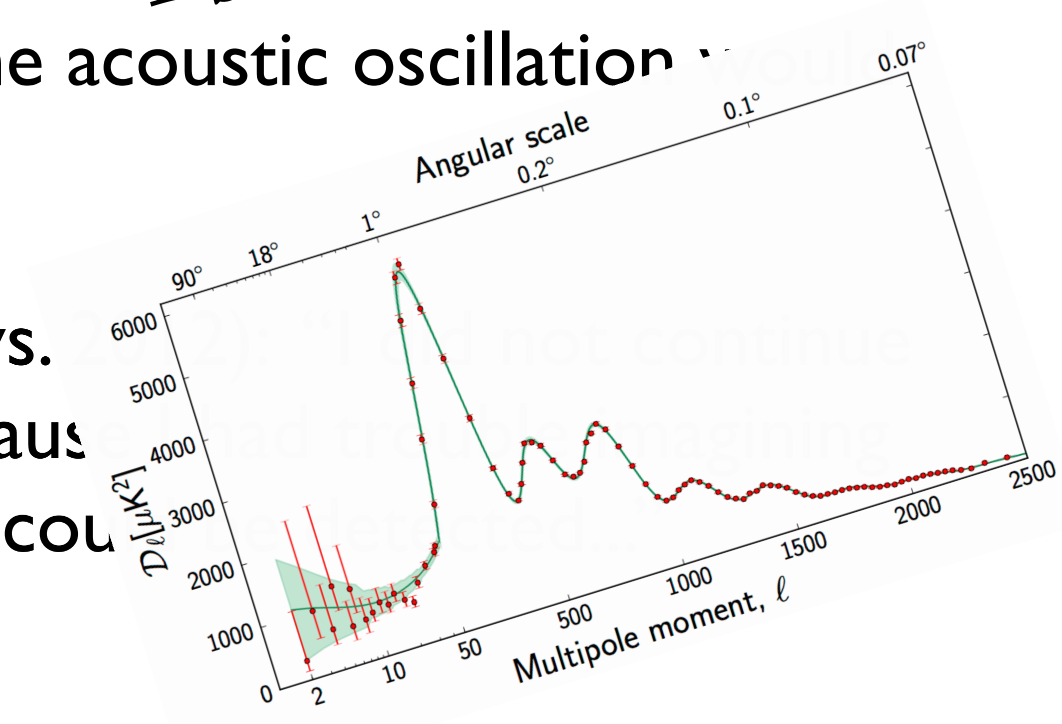

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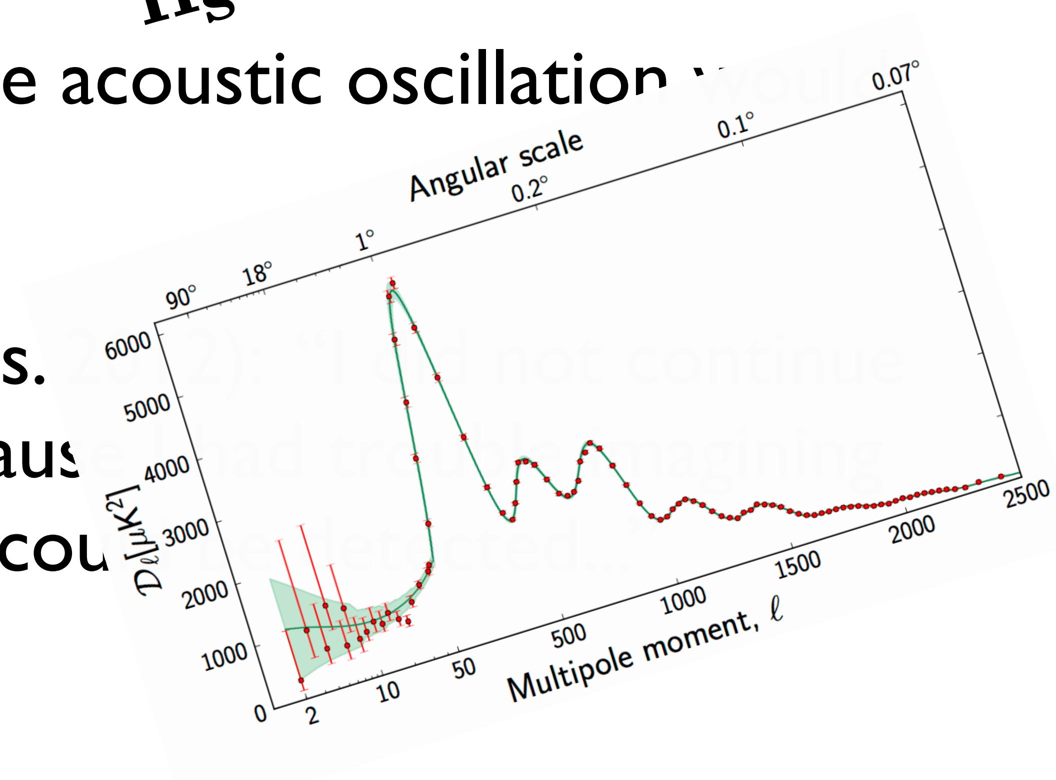

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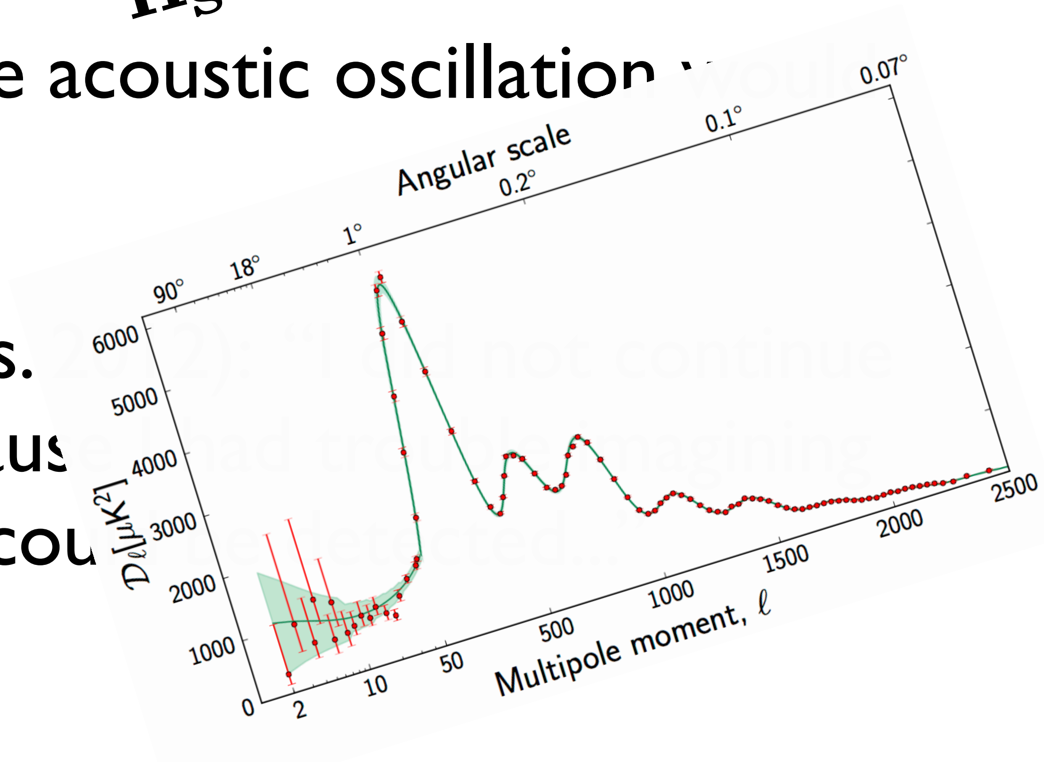

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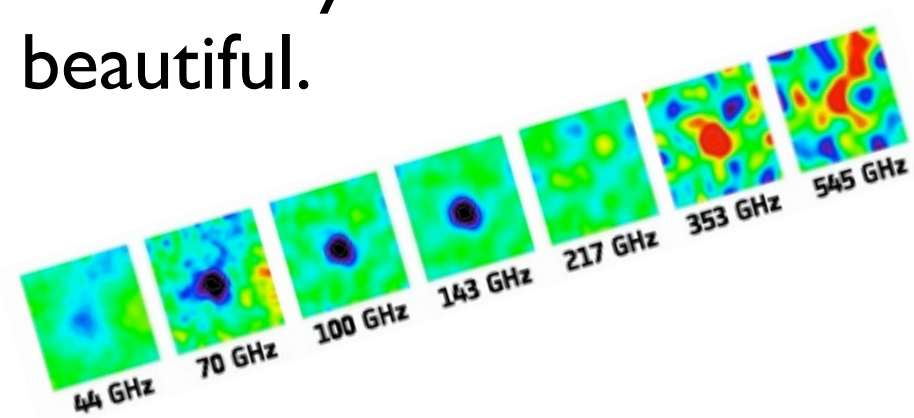
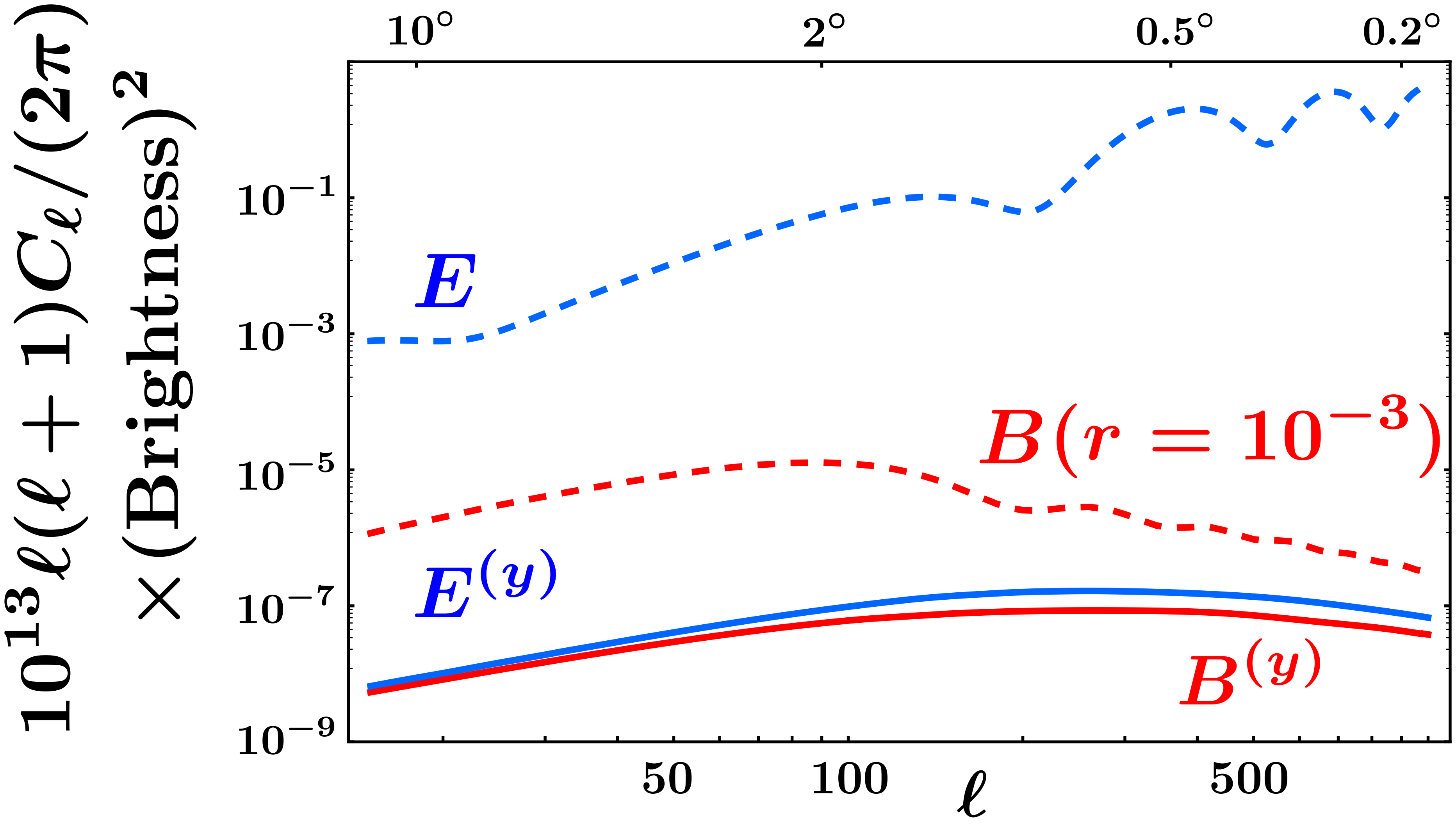
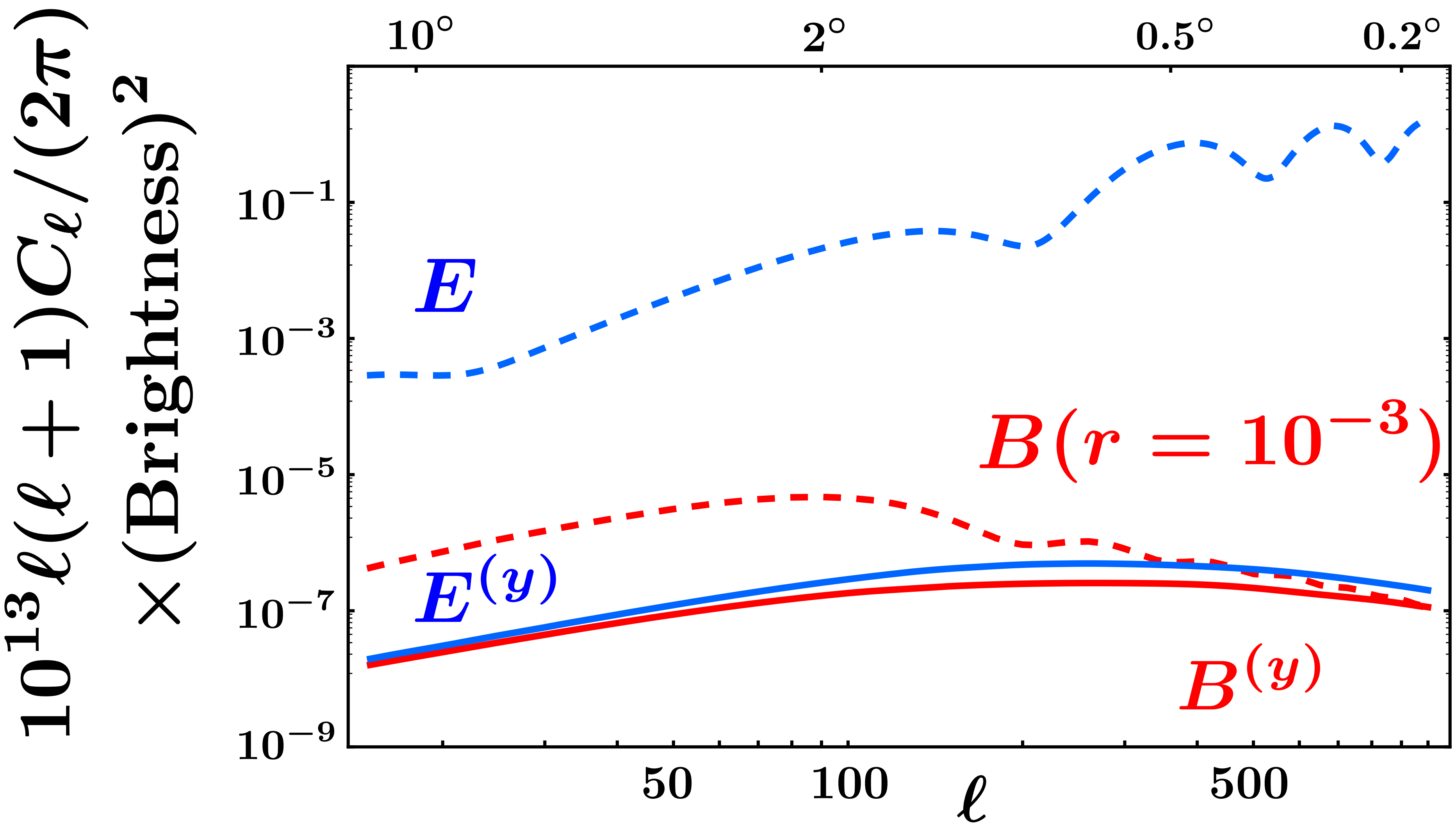


Total signal: angular times energy dependence



@ 70 GHz

Total signal: angular times energy dependence



@ 512 GHz

Non-linear kSZ effect from clusters

- The same effect is discussed in the context of galaxy clusters

astro-ph/0307293, astro-ph/0208511 ...

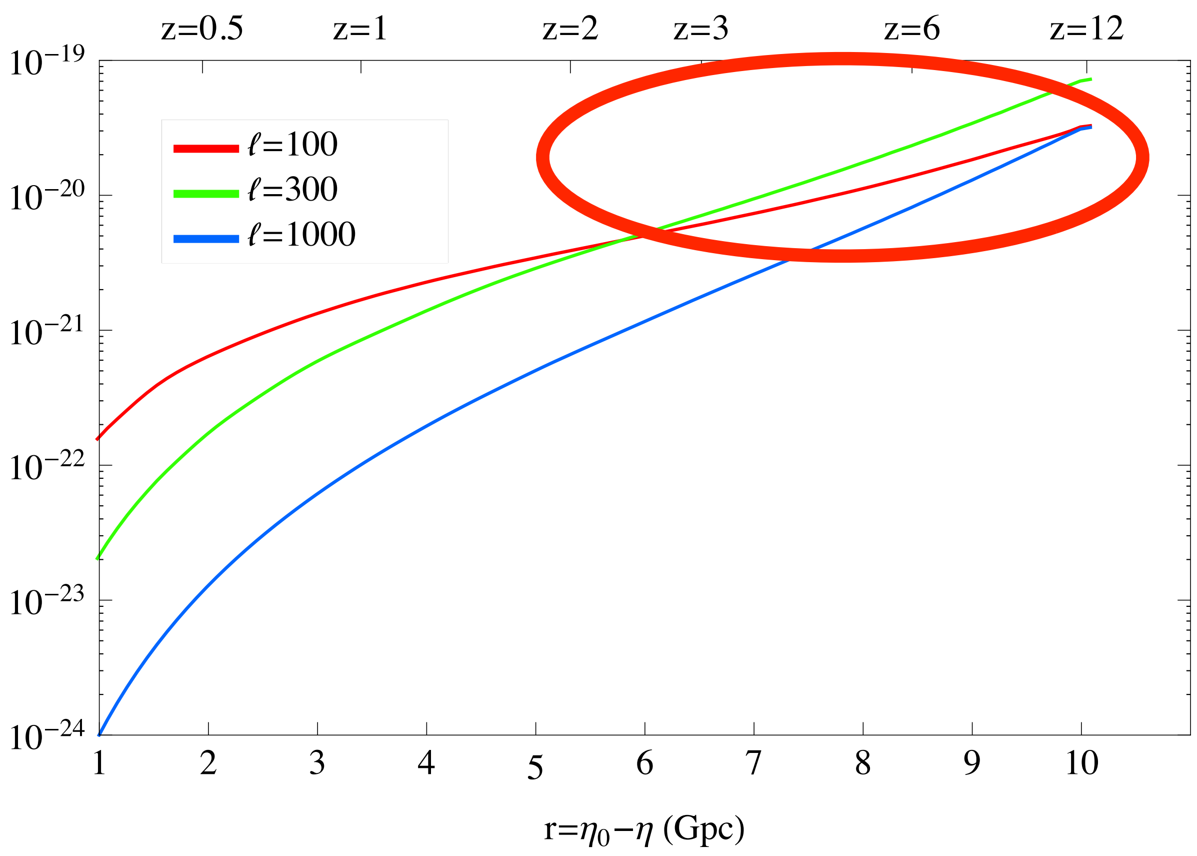
- Our signal is ***one order of magnitude larger***

- Simple understanding:

- on angular scales at which clusters are unresolved, $\ell \lesssim 500$, linear description is enough to model the electron number density

- ***additional contribution pre-formation of clusters***, for $2 \lesssim z \lesssim 12$, when the visibility function is the largest.

Contribution(z) to $\ell(\ell+1)C_{\ell\,\mathrm{Limber}}^{E^y}$



Improving the detectability with cross-correlations

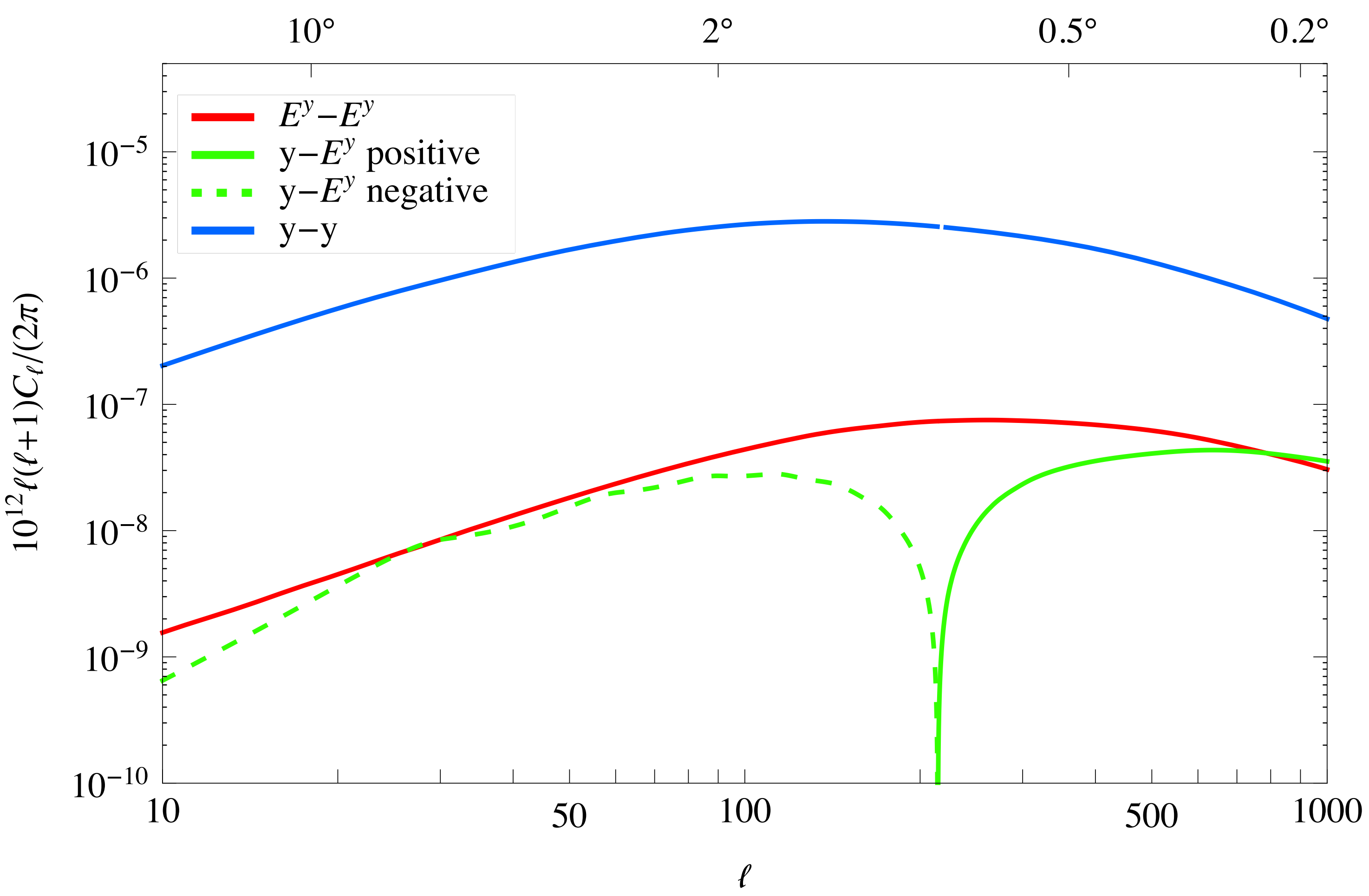
- ***Standard polarization*** has a similar contribution:

$$\mathcal{P}_{\mu\nu} = (\mathcal{P}_{\mu\nu})_{\rm linear} + 4\,(\mathcal{P}_{\mu\nu})_{kSZ^2}$$

$$\langle E^{\rm st} E^{y*} \rangle = 4 \langle E^{y} E^{y*} \rangle$$

$$\langle B^{\rm st} B^{y*} \rangle = 4 \langle B^{y} B^{y*} \rangle$$

- Correlation with the ***y-type intensity distortion*** (sourced by tSZ effect + kSZ^2 effect)

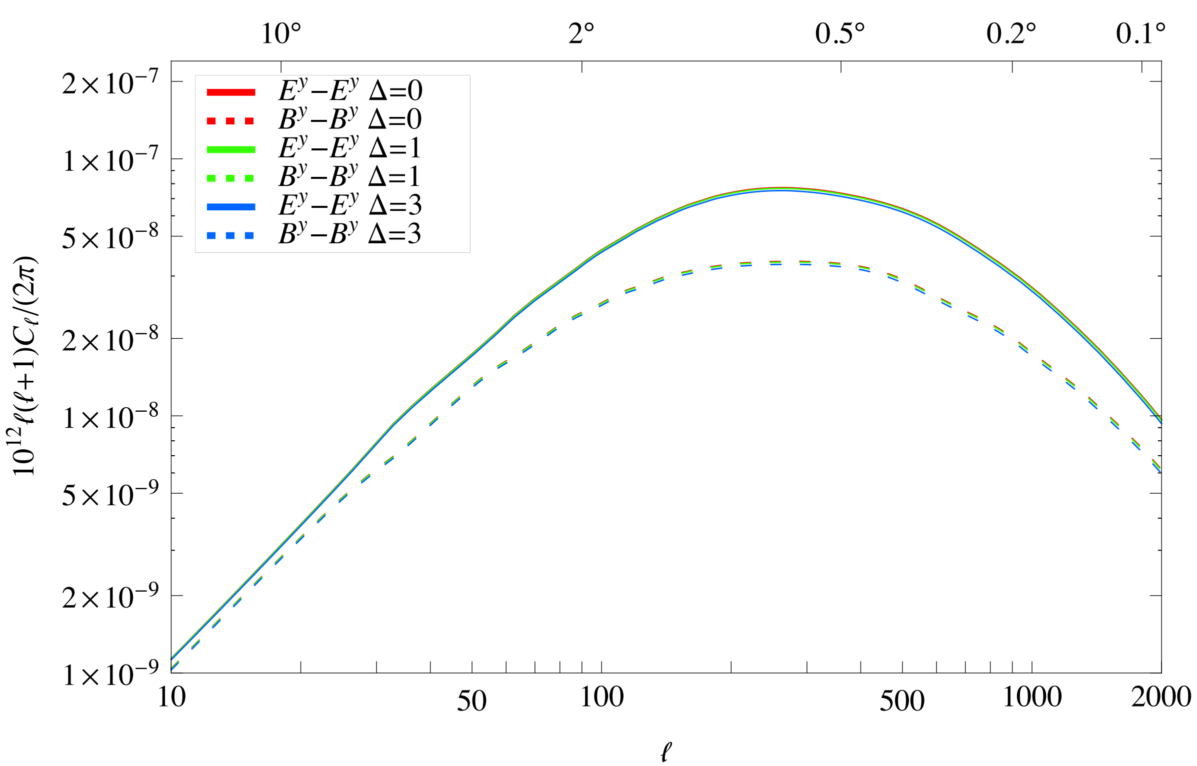


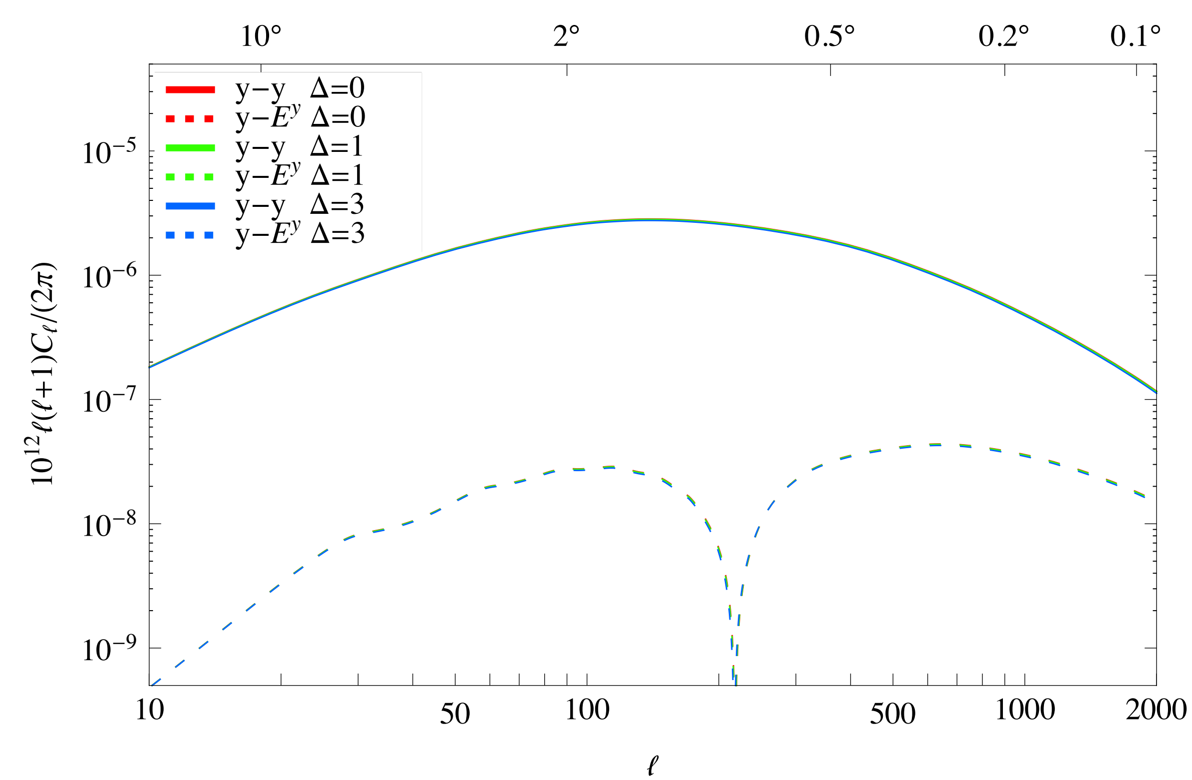
Effects of an extended period of reionization

• Reionization history is unknown but is necessarily more complicated than the simple scenario of instantaneous reionization (patchy etc).

$$x_e(z) \equiv \frac{n_e(z)}{n_H(z)} = \frac{1}{2}\left\{1 + \tanh\left[\frac{(1+z_r)^{3/2} - (1+z)^{3/2}}{\Delta}\right]\right\}$$

built such that total optical depth independent of Delta.





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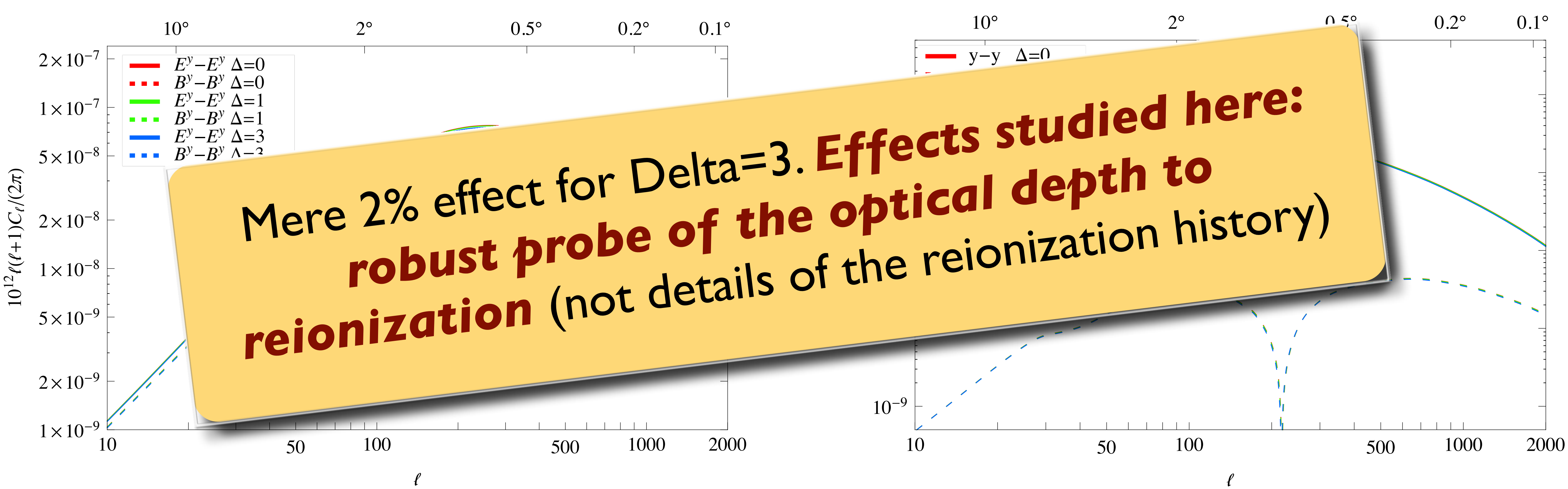

Mere 2% effect for Delta=3. **Effects studied here: robust probe of the optical depth to reionization** (not details of the reionization history)

Conclusions

- CMB spectral distortions: new promising observational window in cosmology

- Probe of the thermal history of the universe, inflation, dark matter, reionization...

- It should be studied at the level of the anisotropies of the intensity and polarization

- First step in this direction: unavoidable contribution to diffuse polarization distortion generated by non-linear kSZ effect from reionization. Larger than contribution from clusters.

- Guaranteed signal in the vanilla cosmological model.
Worth studying for extensions.