Cosmic Microwave Background: anisotropies and fundamentals

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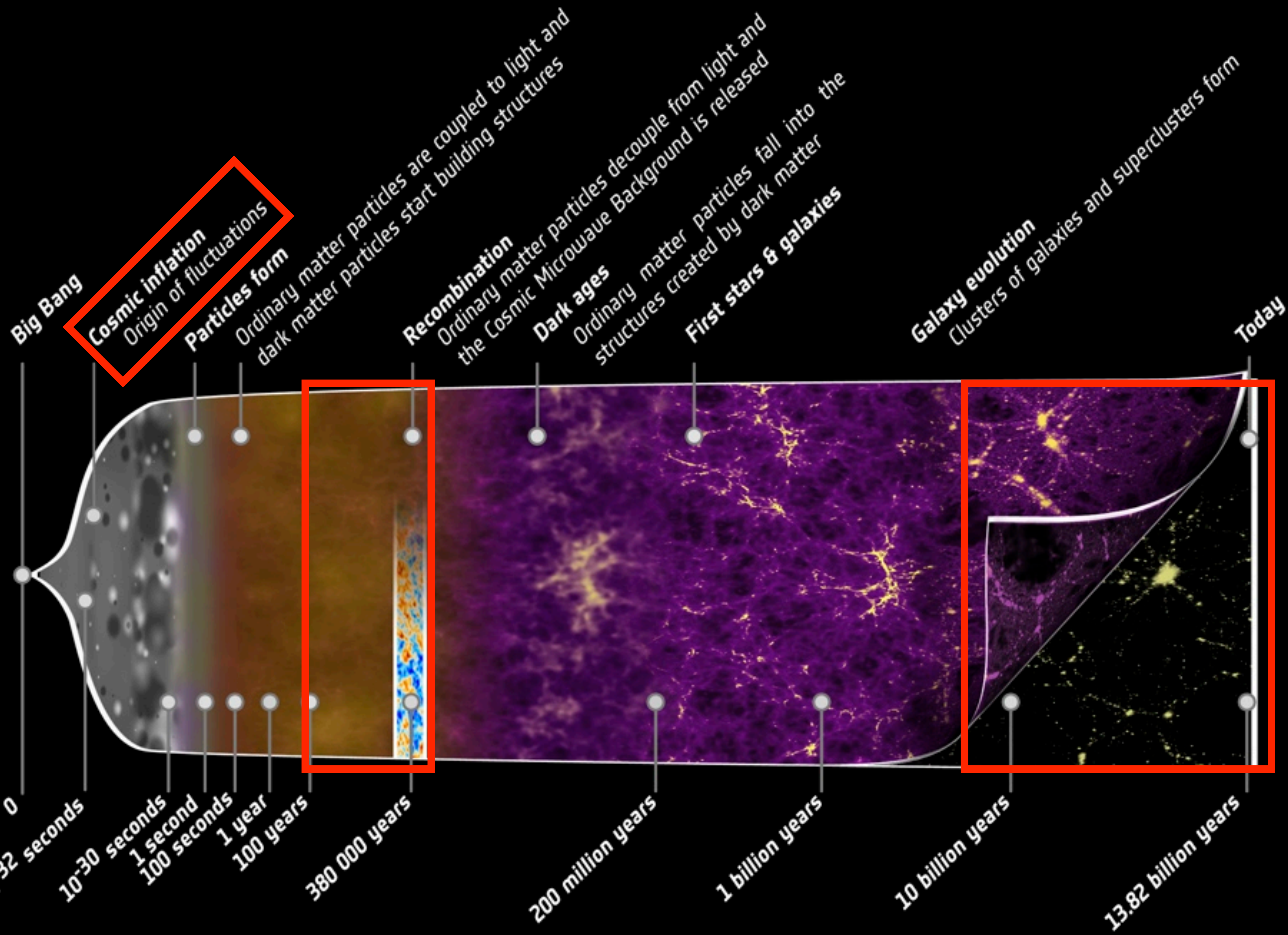
Petnica Cosmology Summer school 2017

Outline

- Few words on some basic concepts:
  - What is CMB
  - What are CMB anisotropies
  - CMB polarization
- Few very recent research topics/findings:
  - CMB polarization experiments
  - CMB lensing
  - CMB-LSS correlation
- Data analysis in cosmology: CMB examples and beyond

The Universe and the CMB



The CMB radiation: a bit of history

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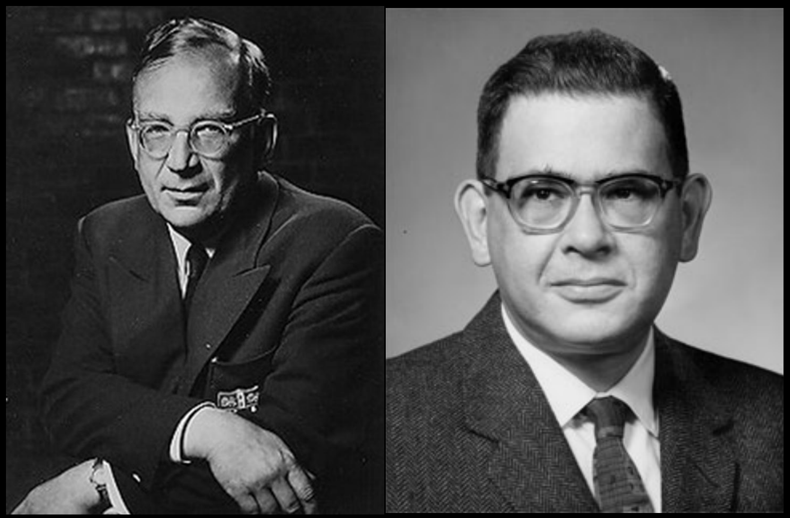
Penzias & Wilson, 1964

The CMB radiation: a bit of history

Gamow & Alpher



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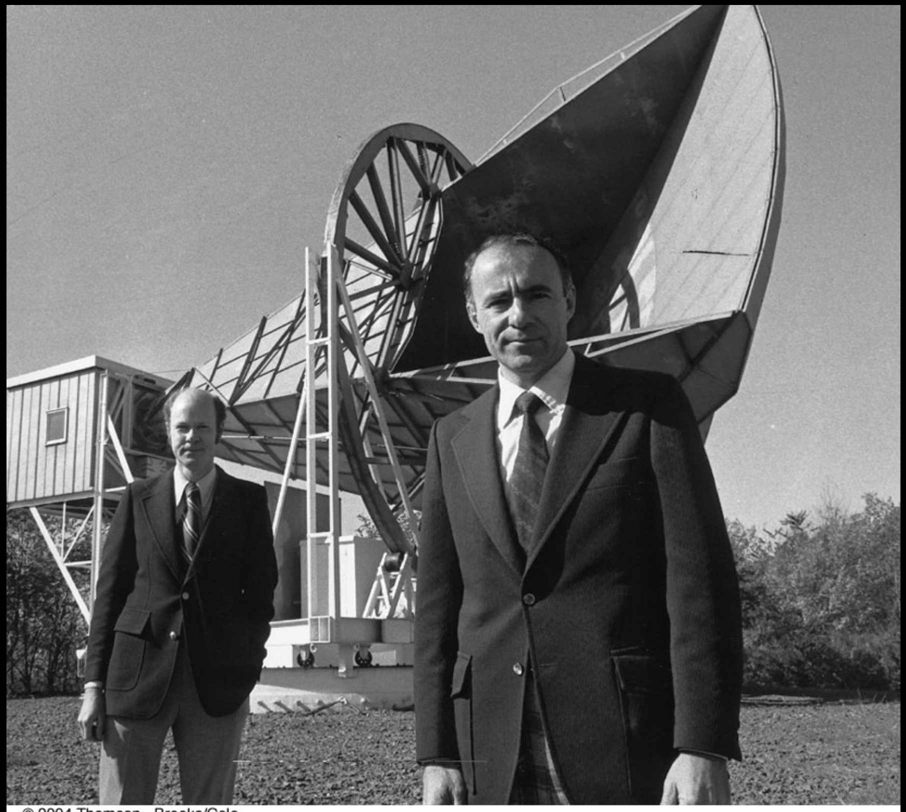

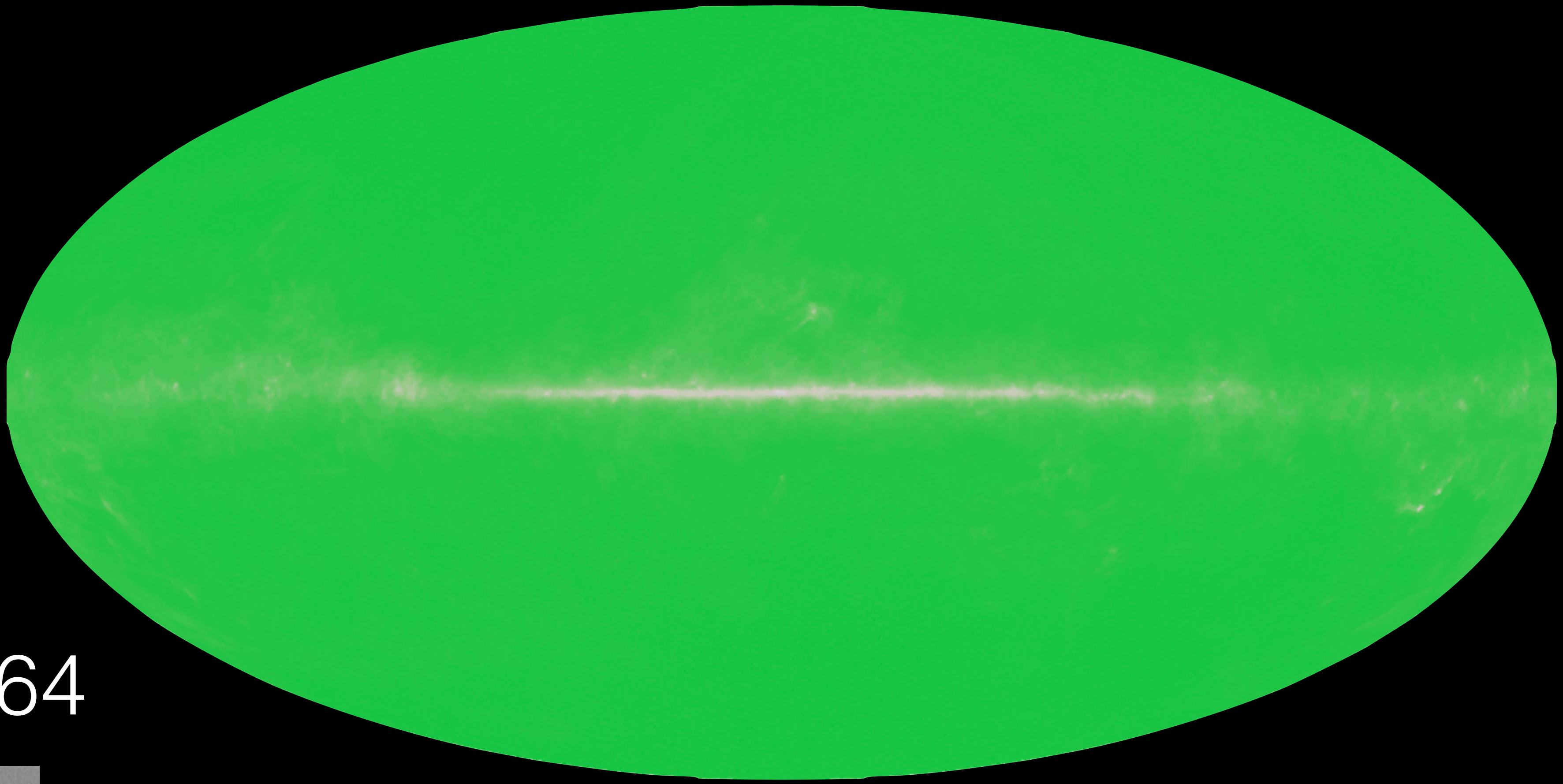

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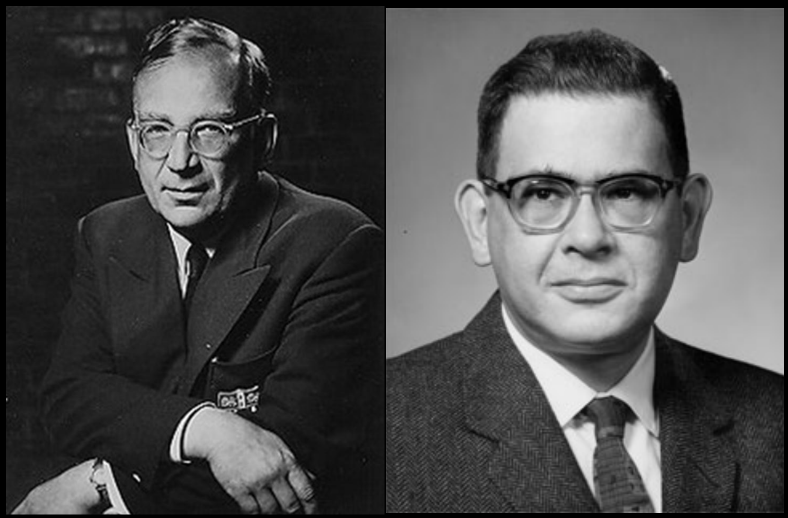

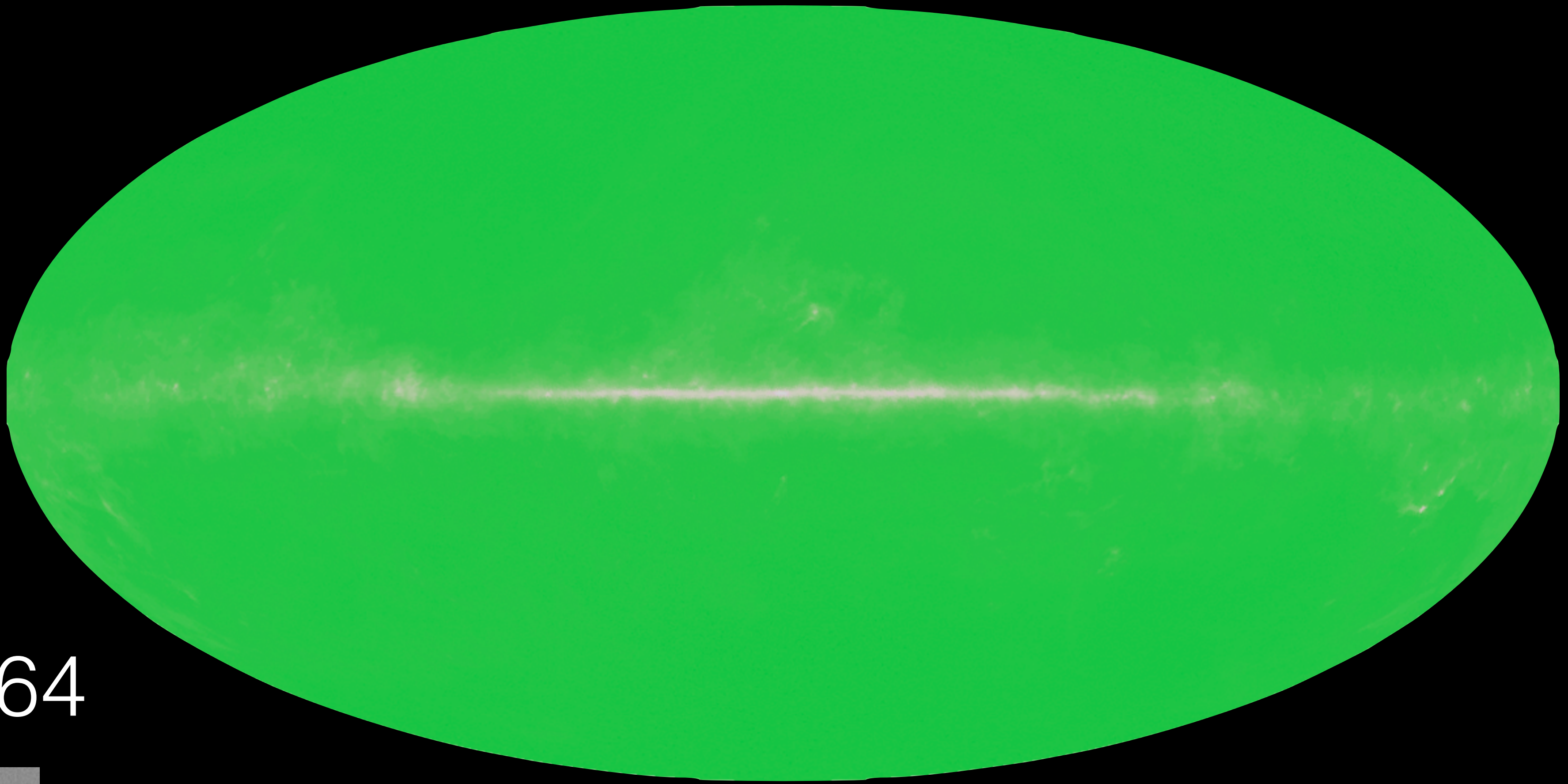

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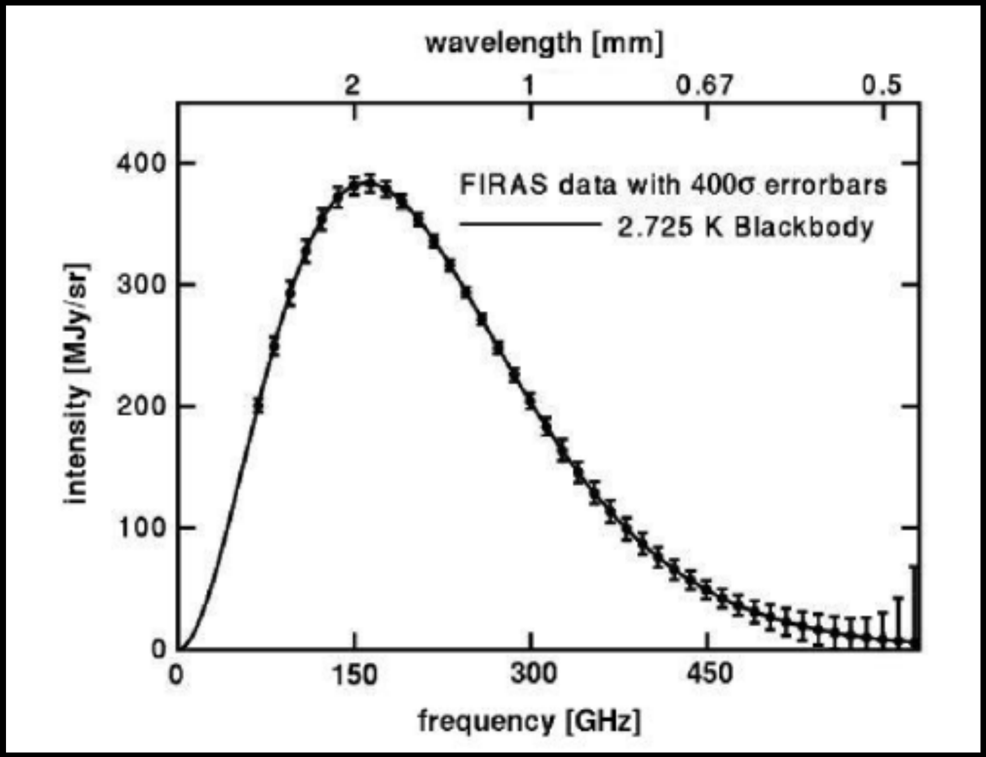
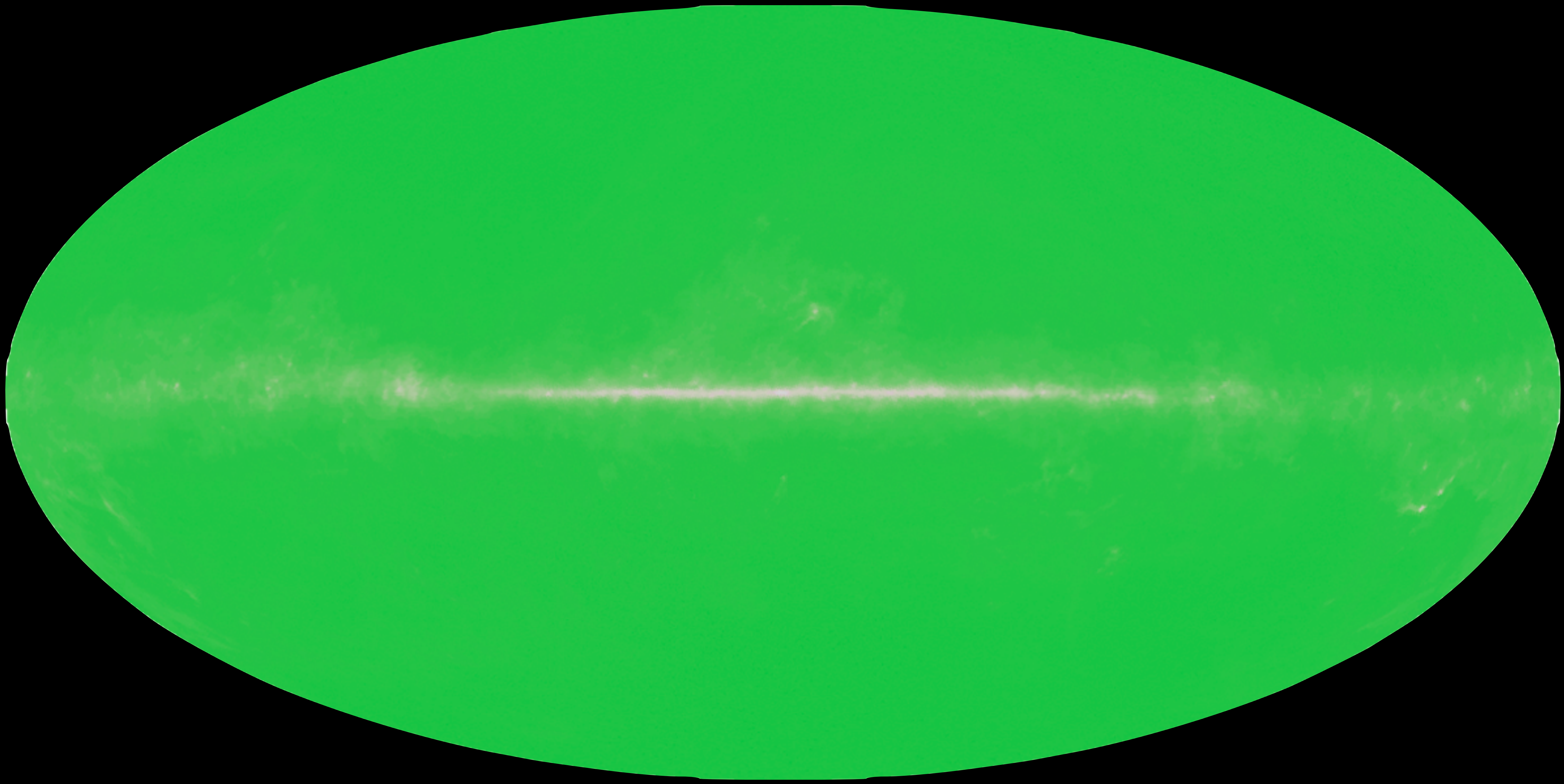


Nuove misure, nuovi problemi



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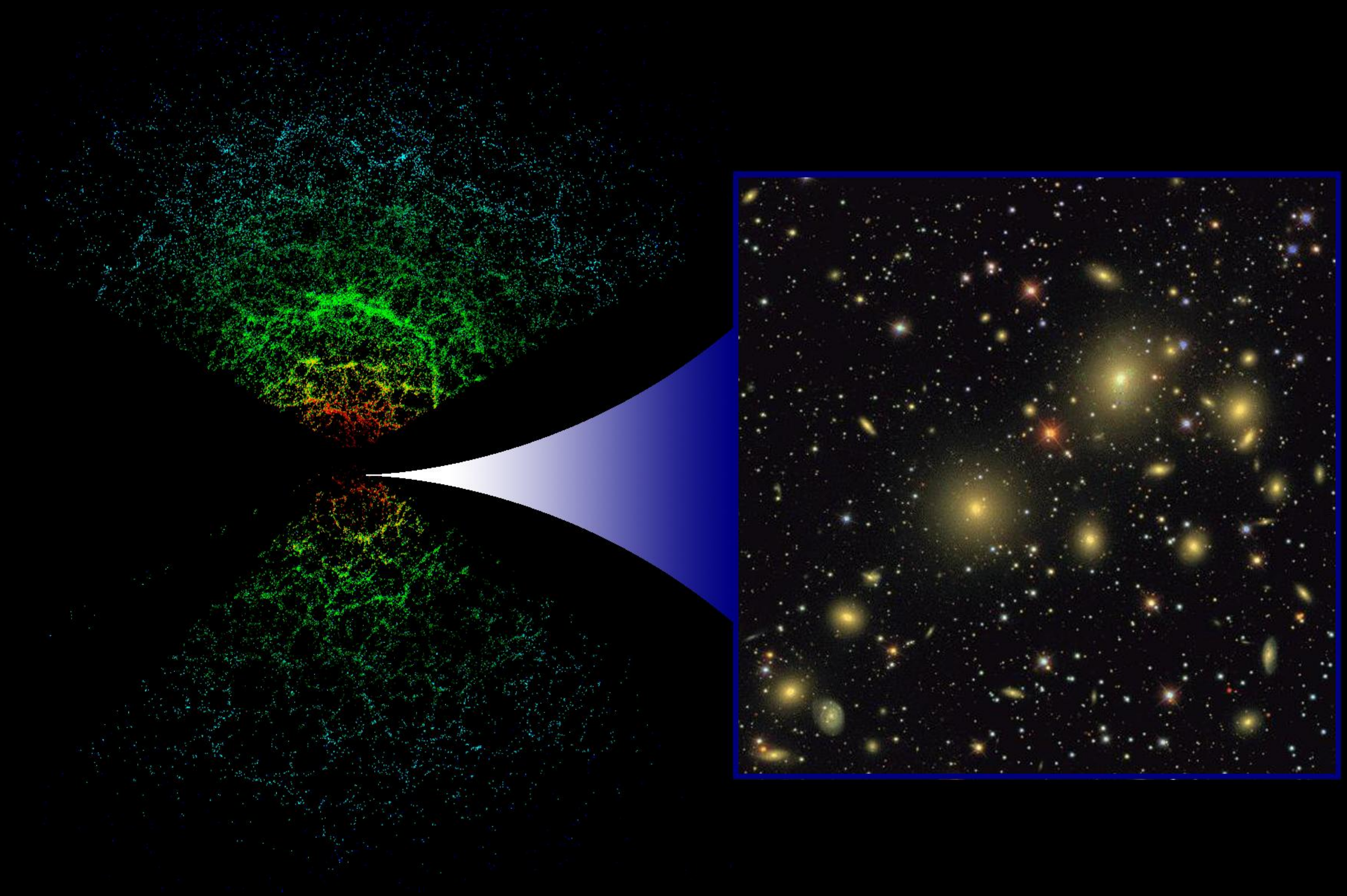
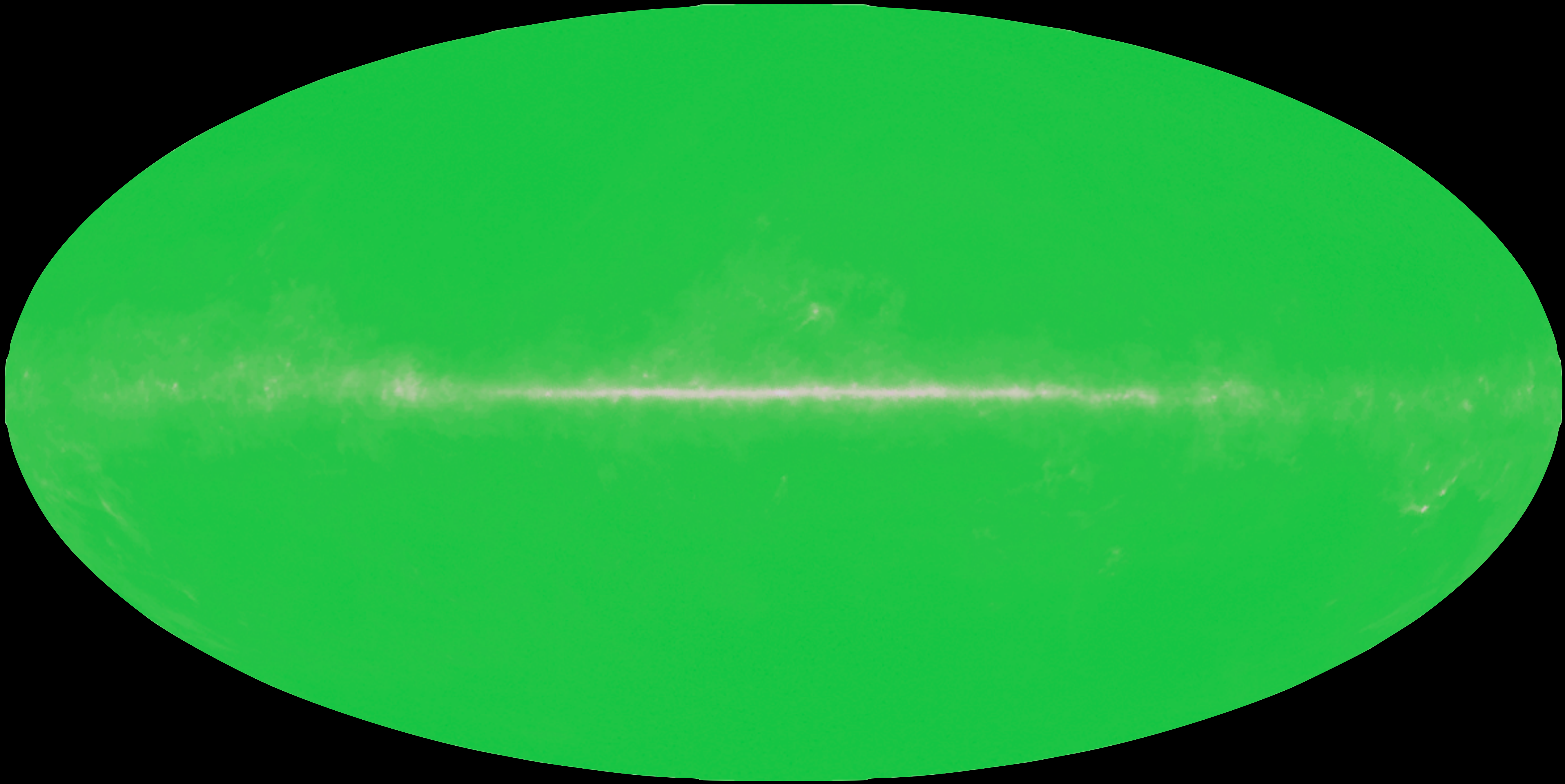


Anisotropies discovery: COBE, WMAP, Planck



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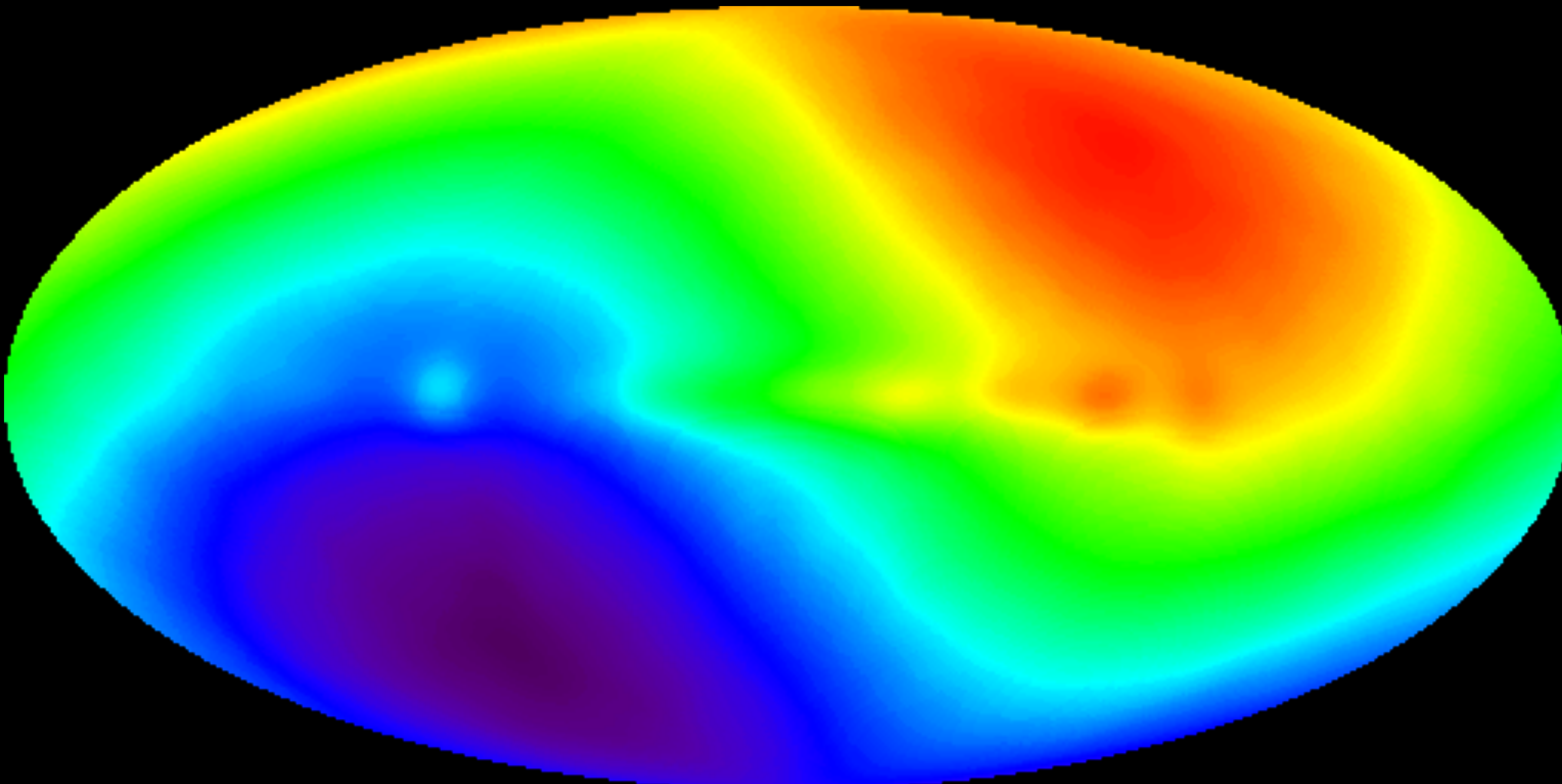

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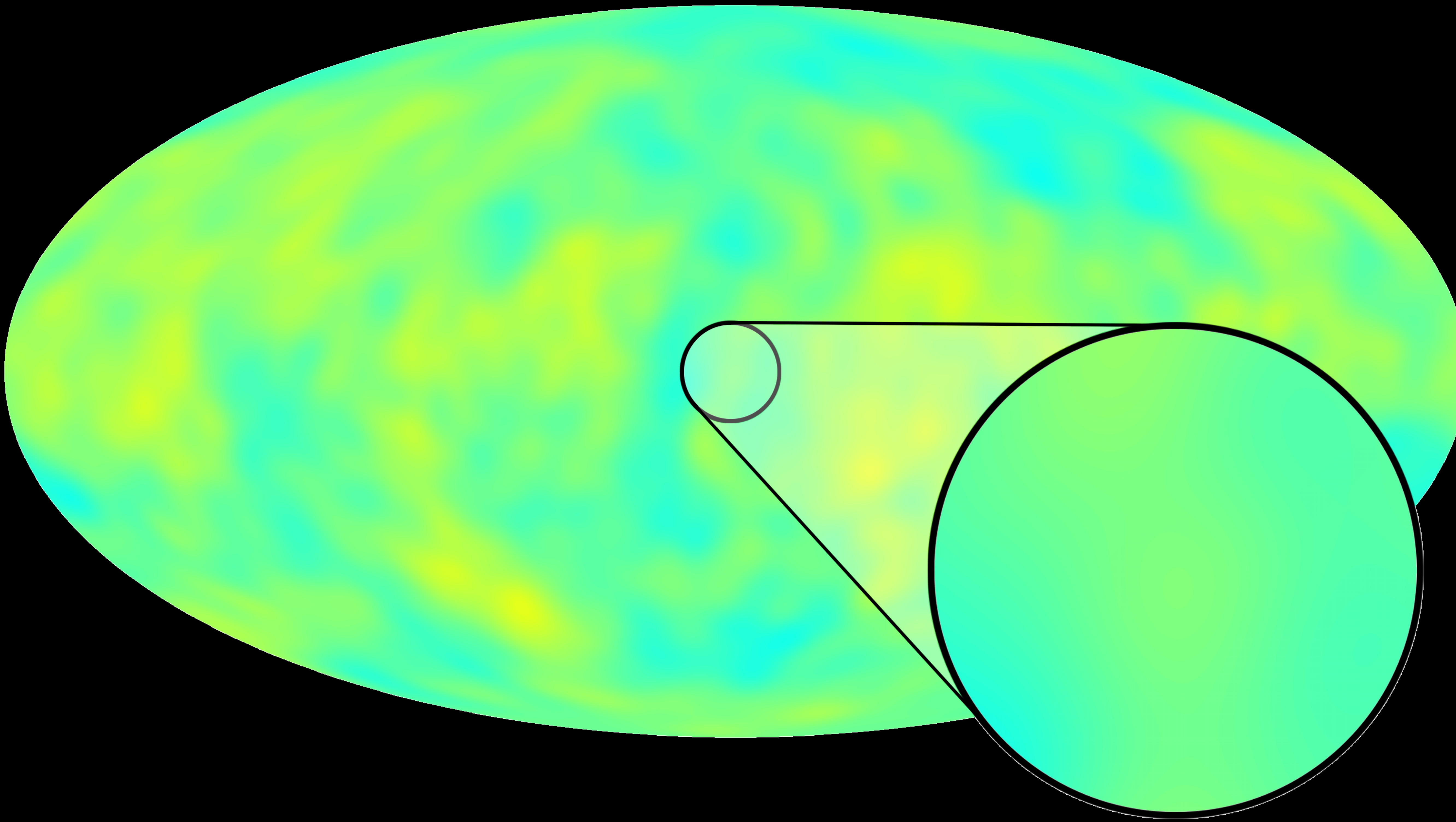

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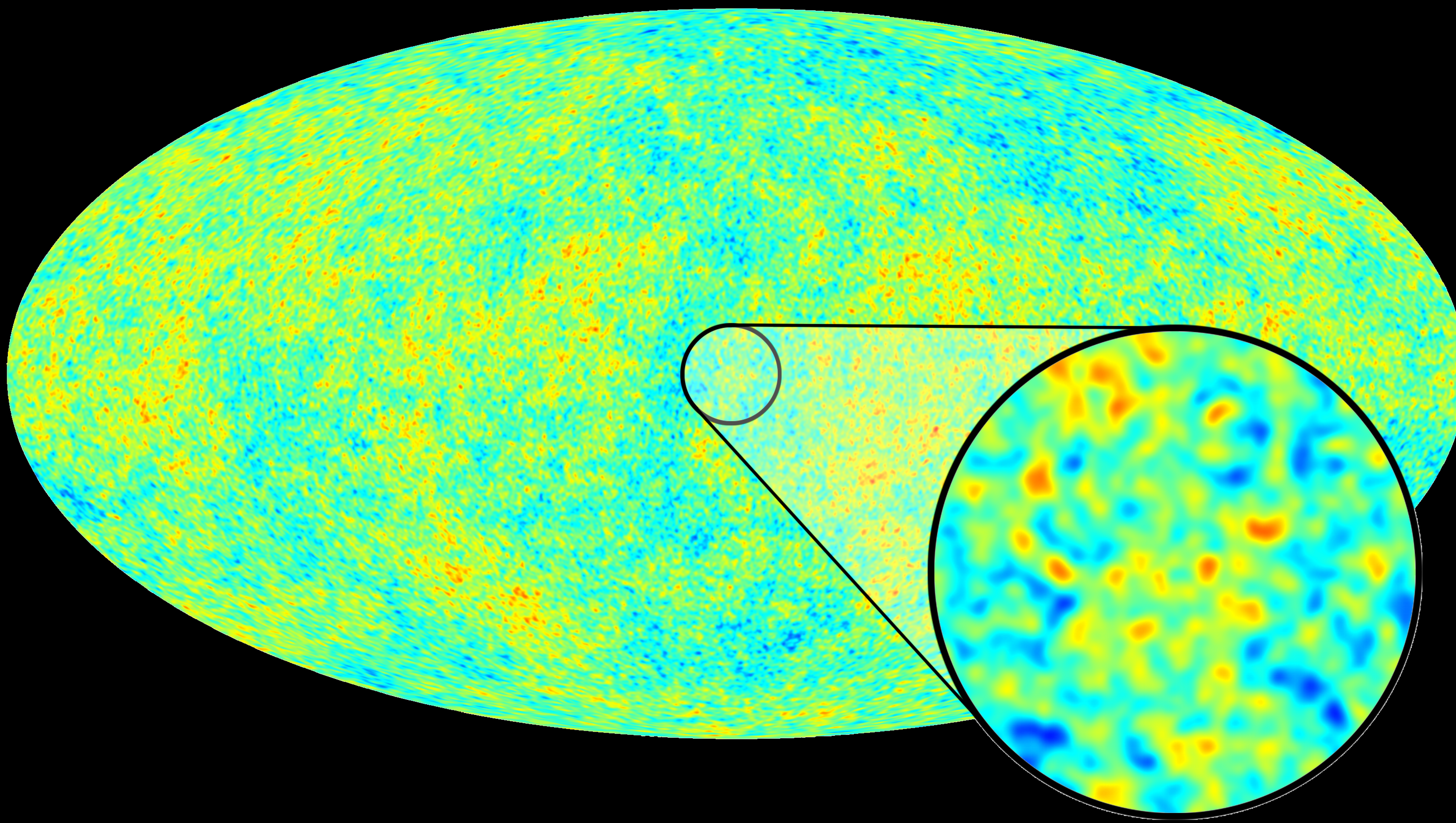

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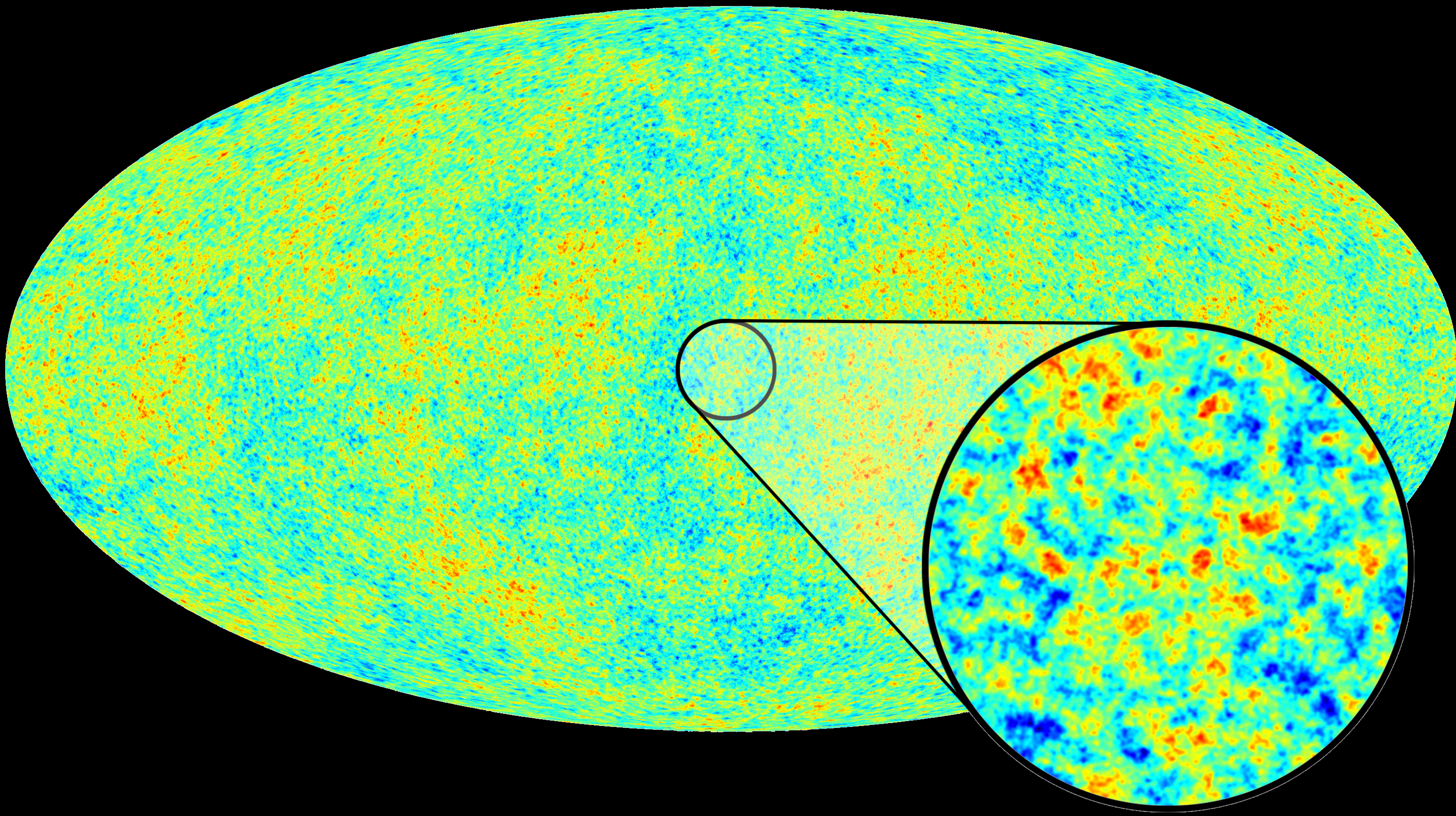
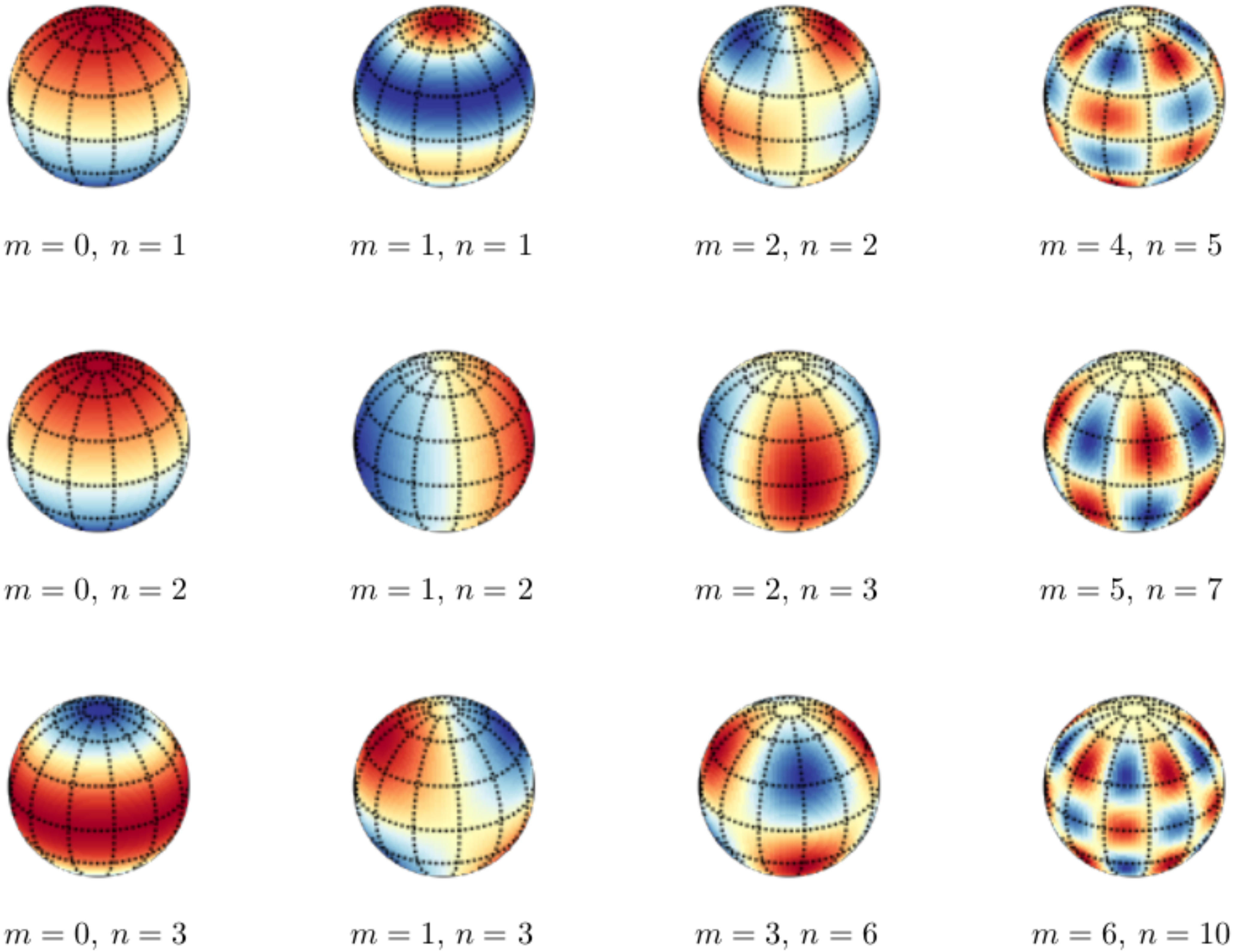
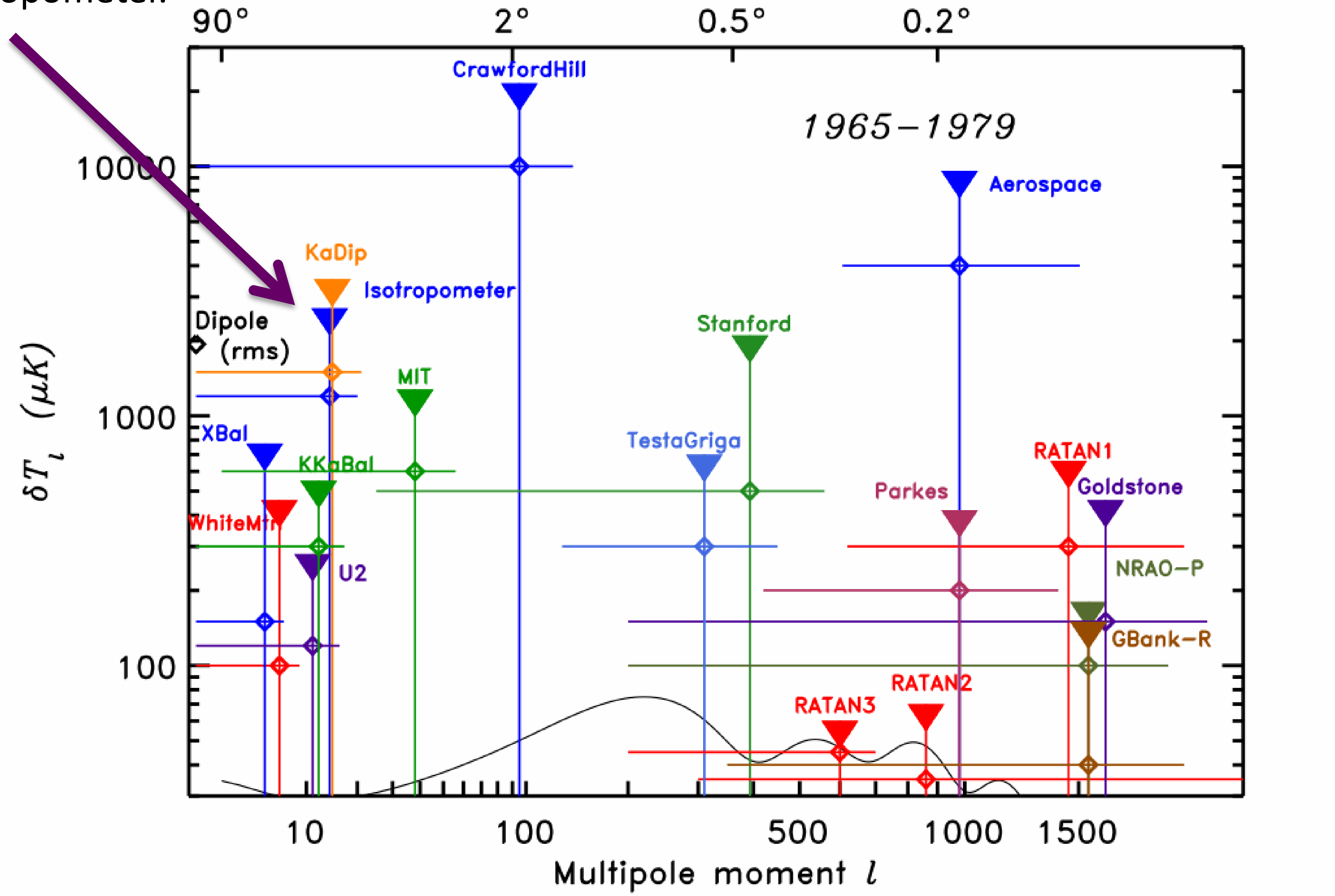


Spherical harmonics (caveat: n=l)



The hunt for CMB angular power spectrum

The beginning: Partridge and Wilkinson, dedicated "Isotropometer."



Credits: Lyman Page

The hunt for CMB angular power spectrum

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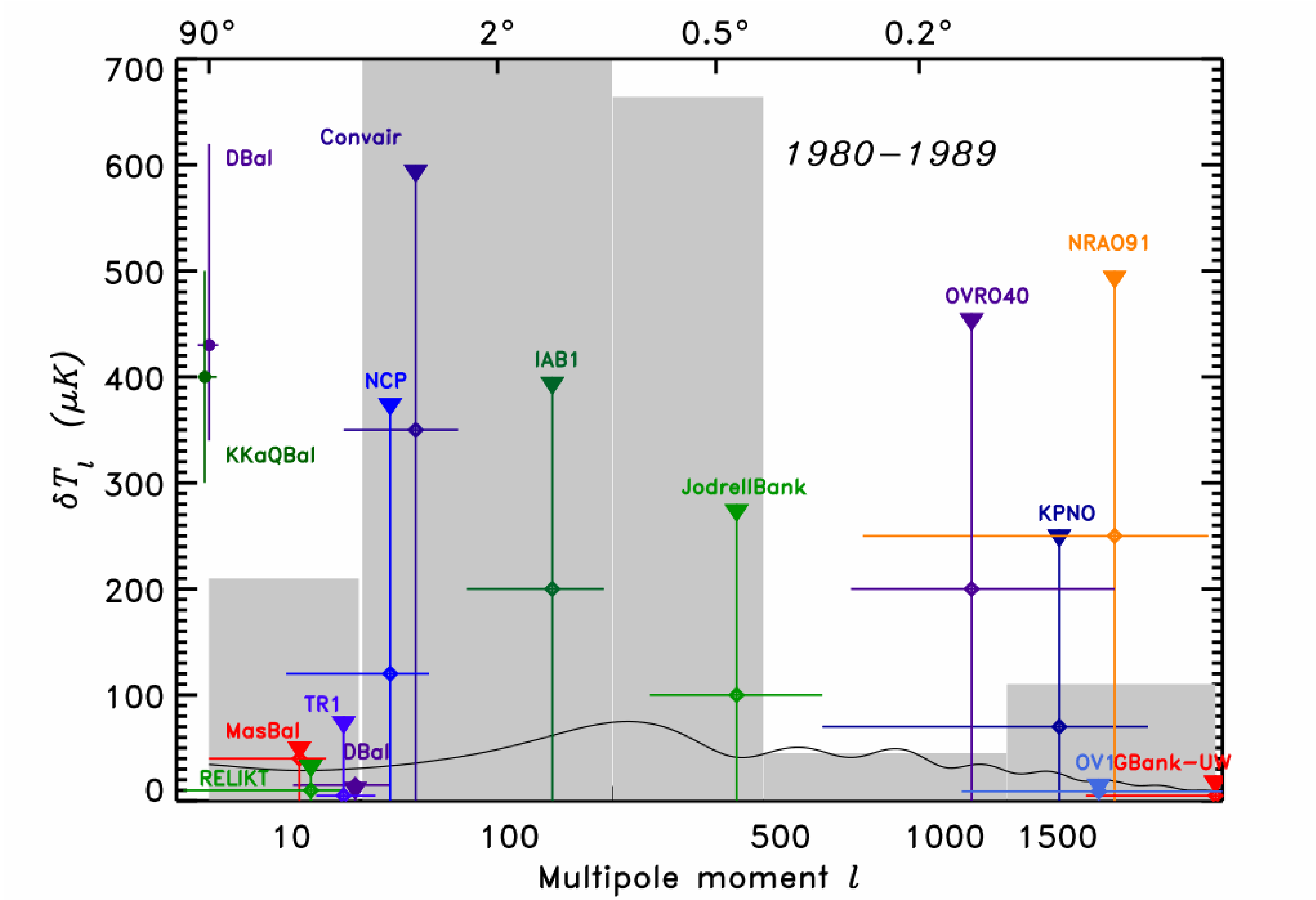

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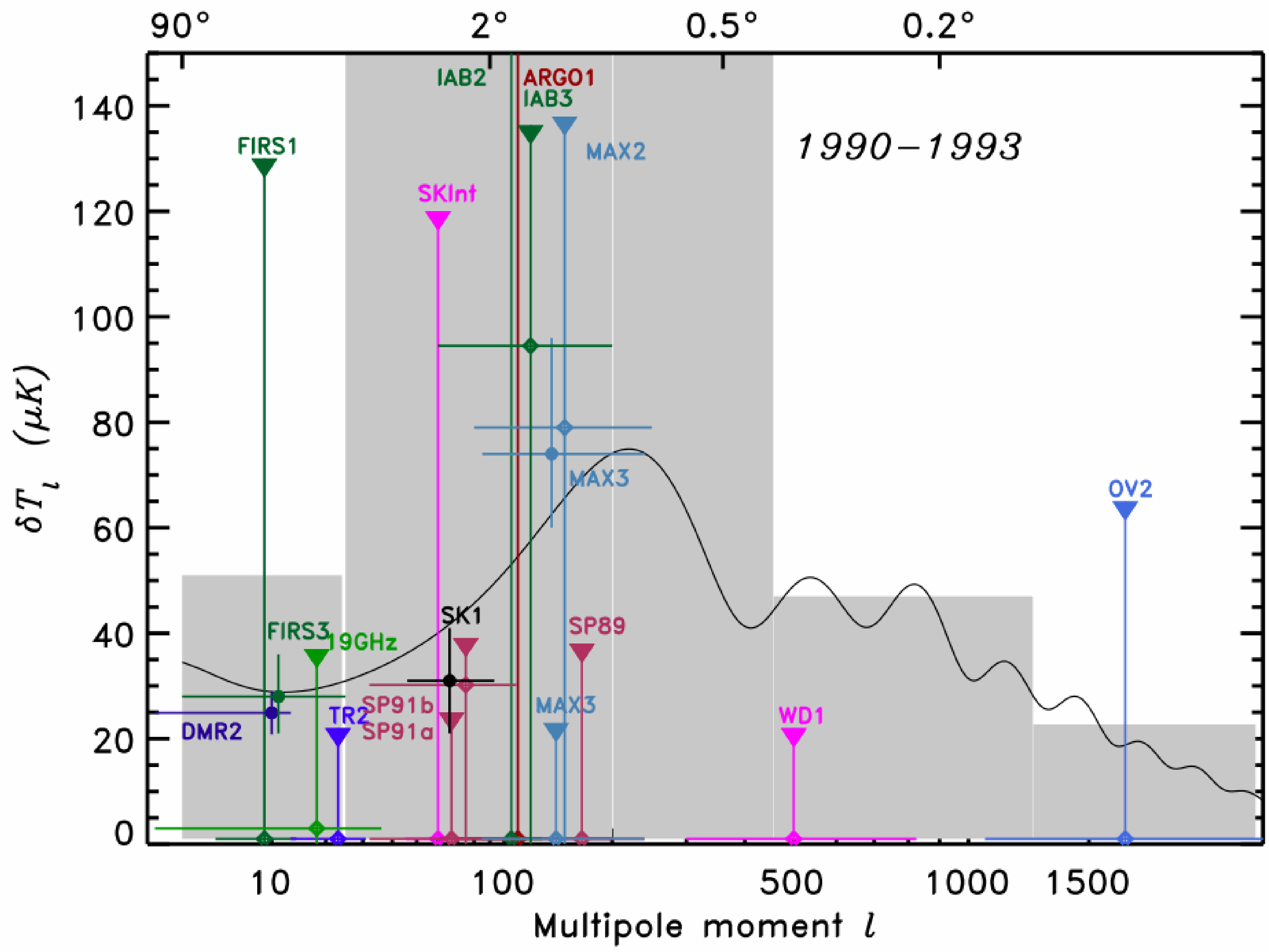

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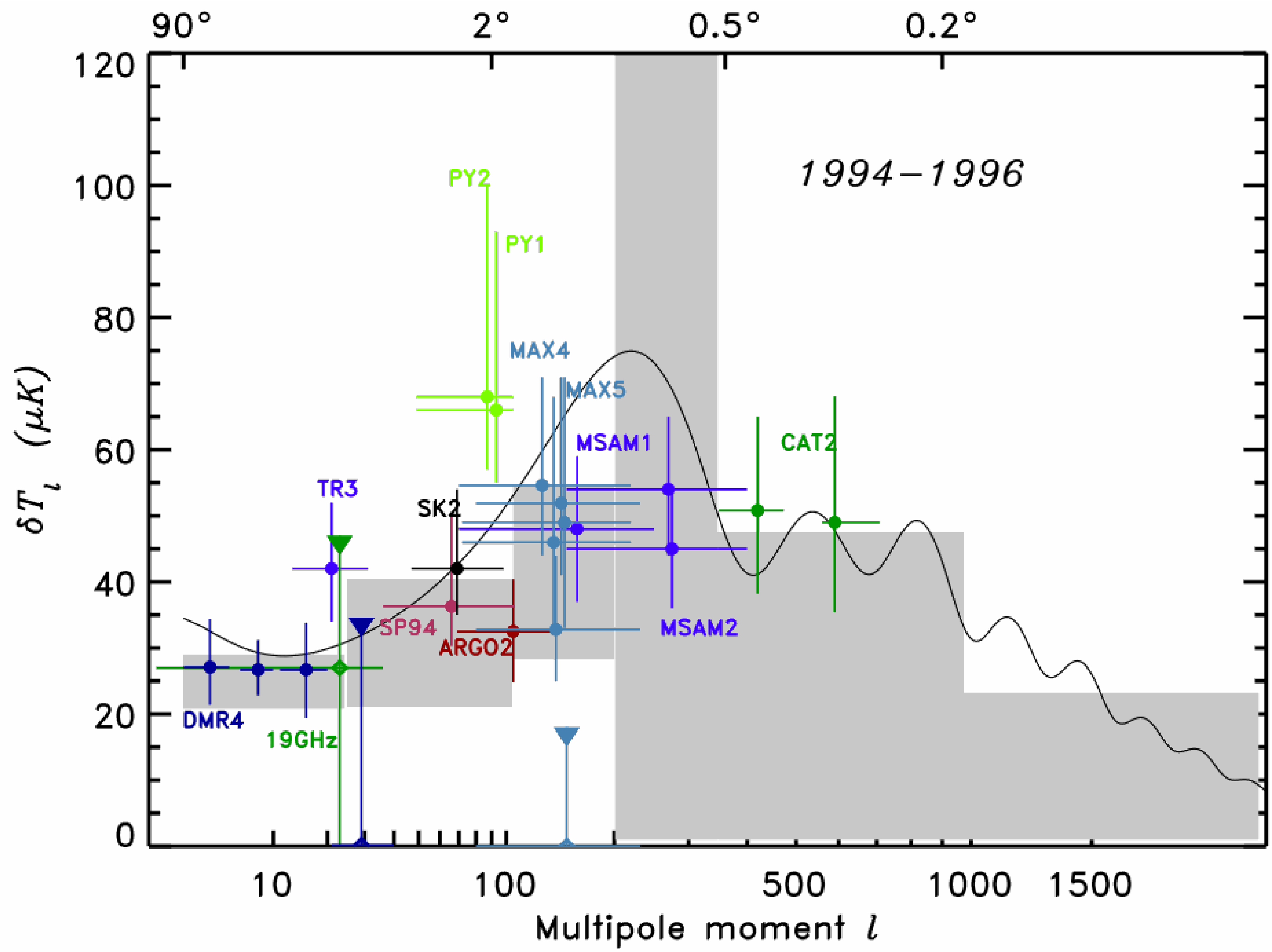

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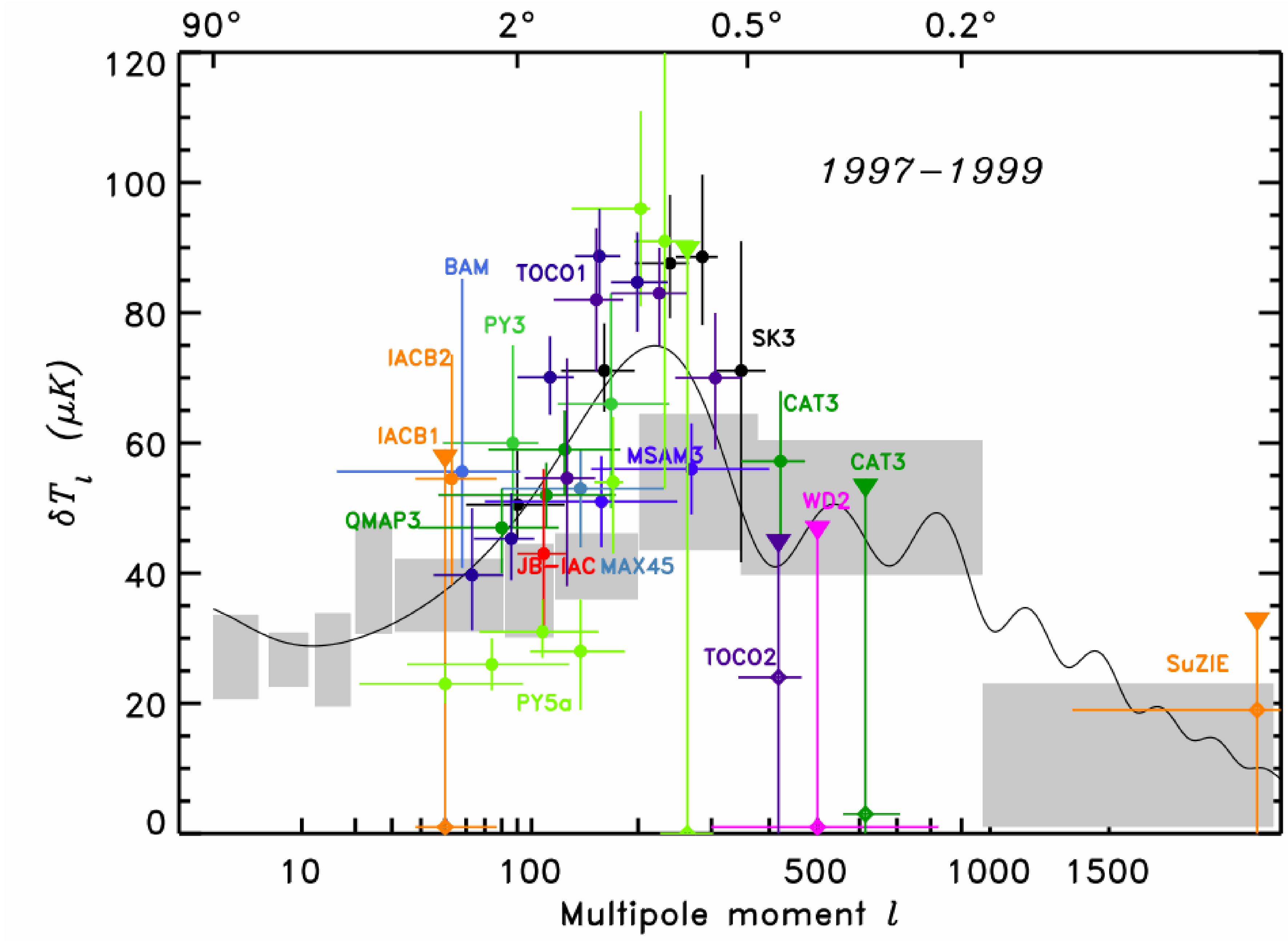

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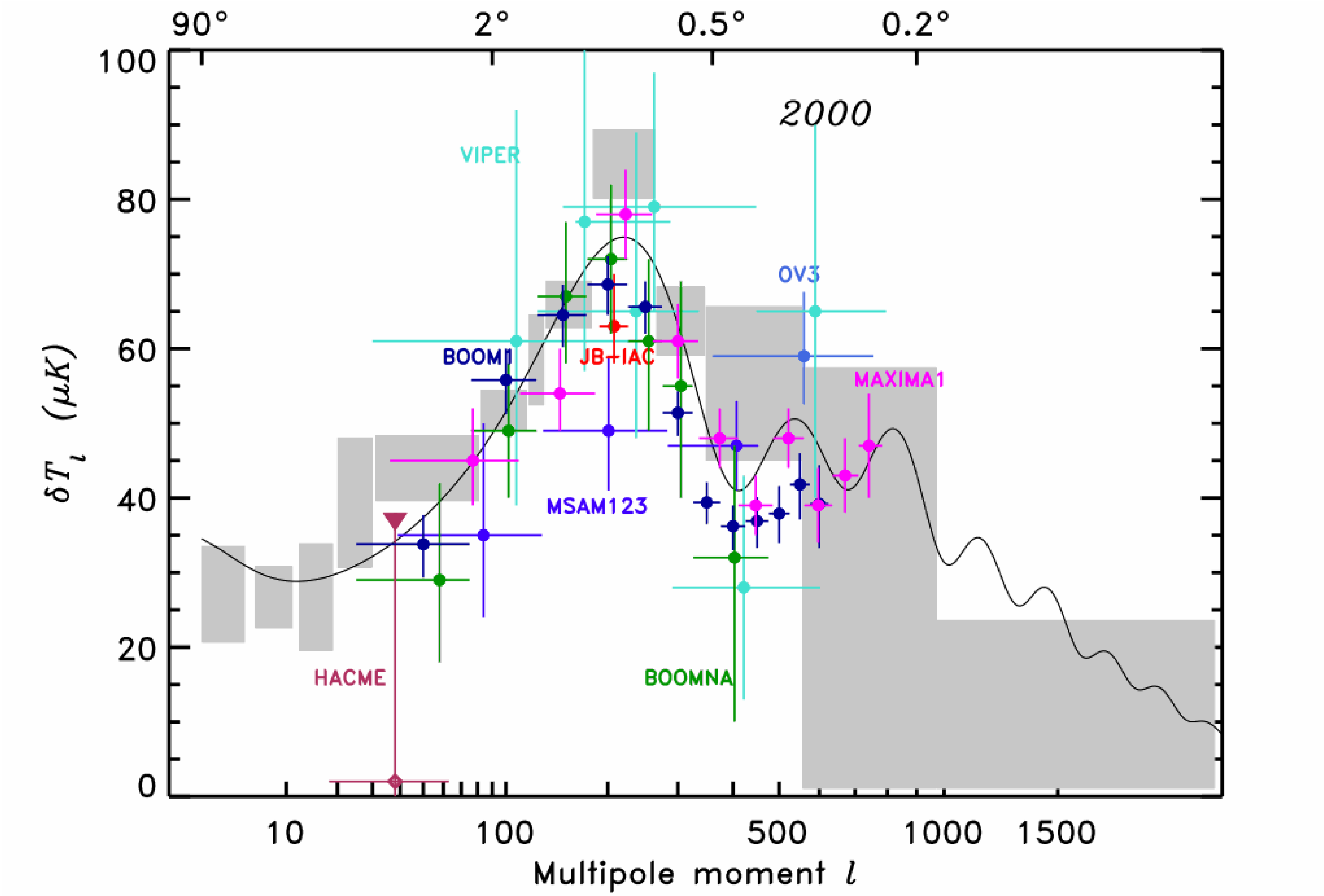

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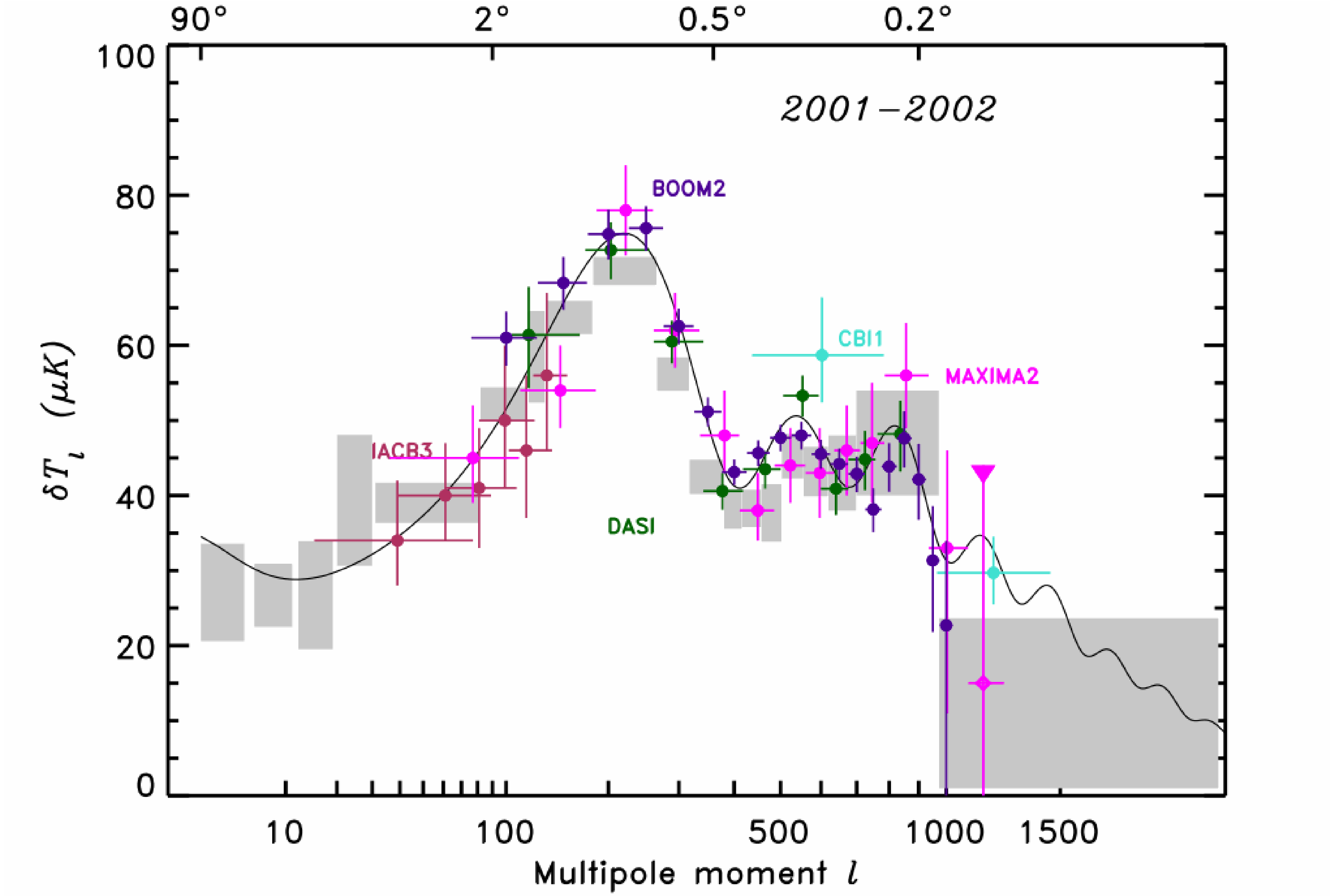

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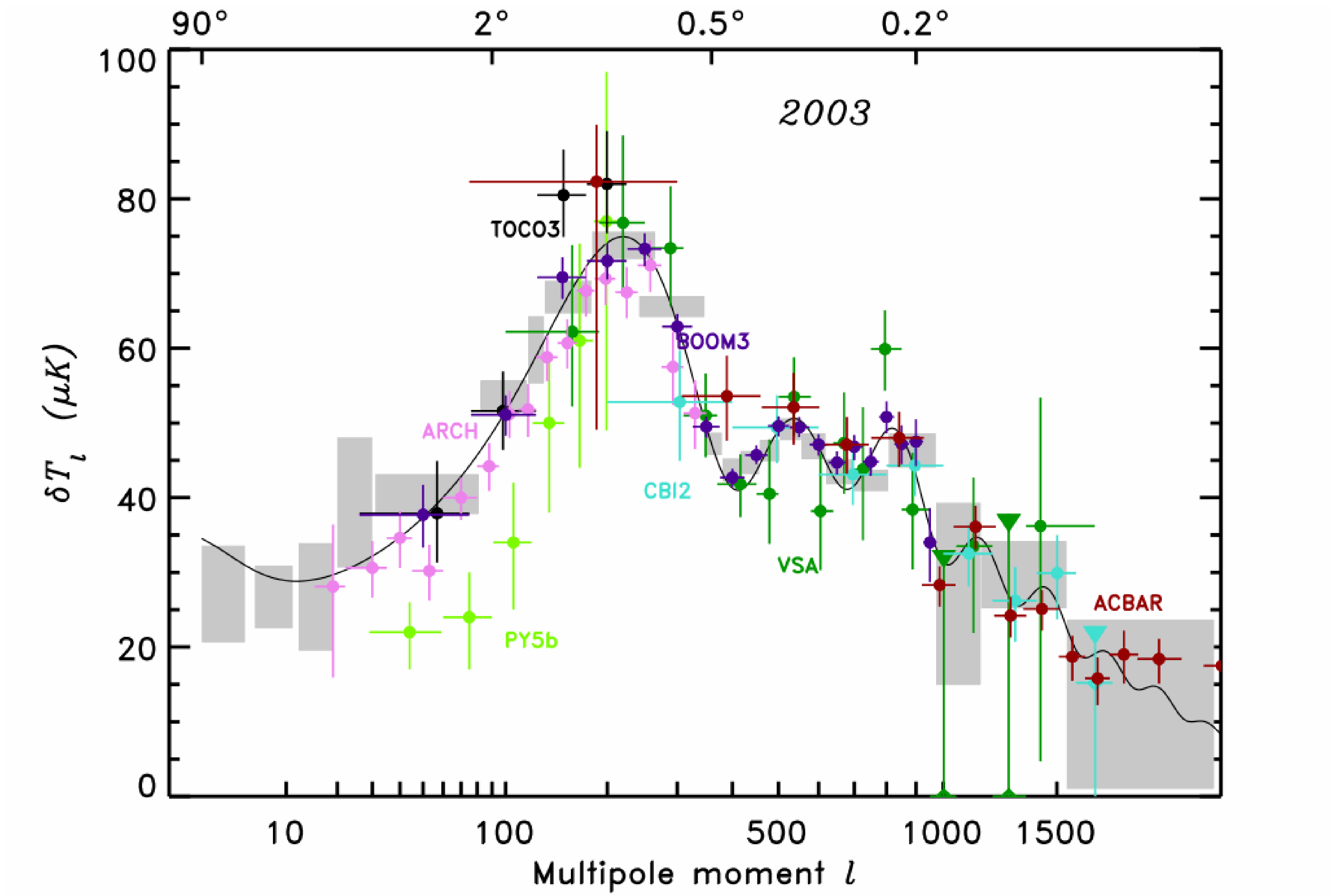

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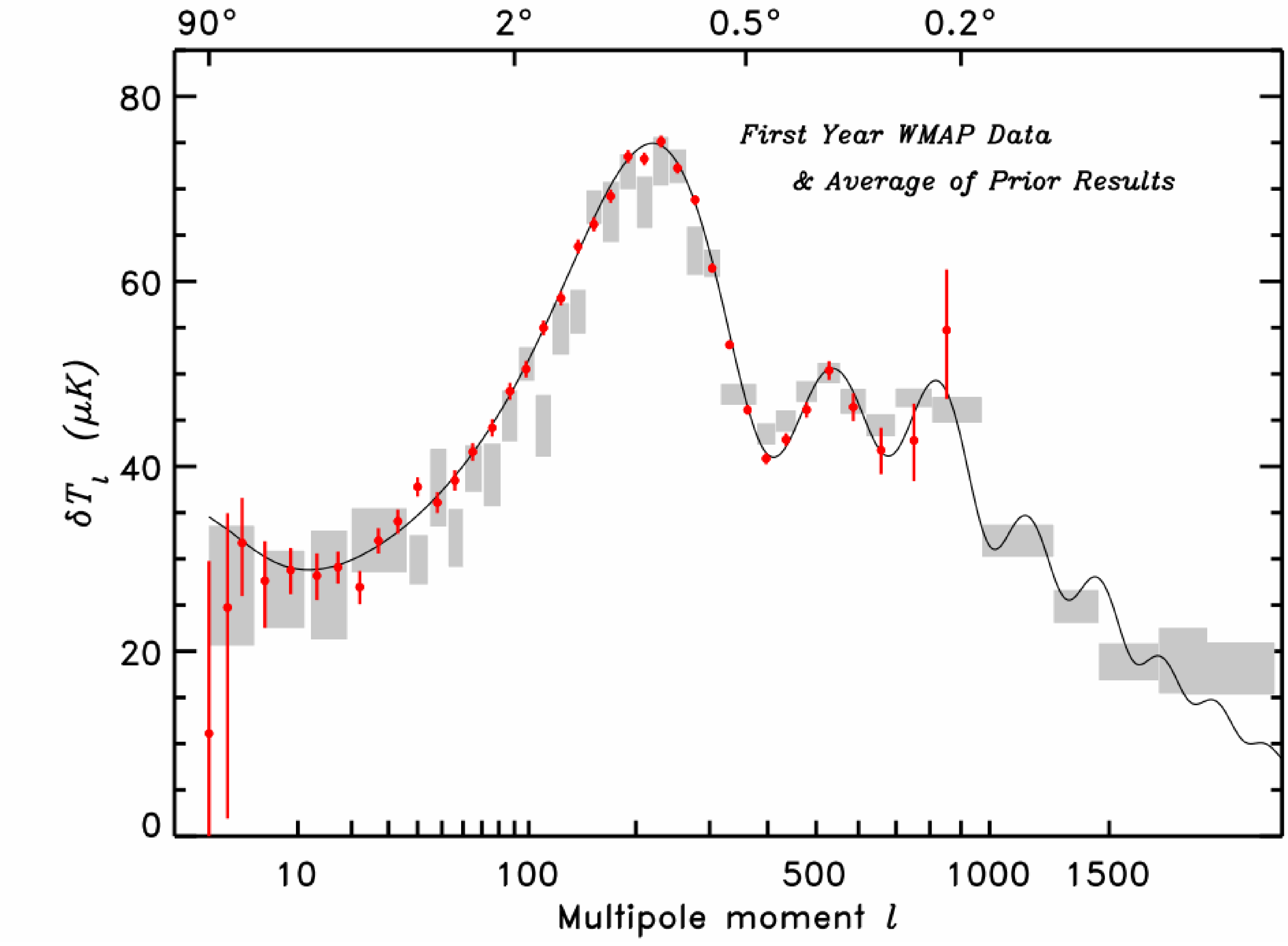
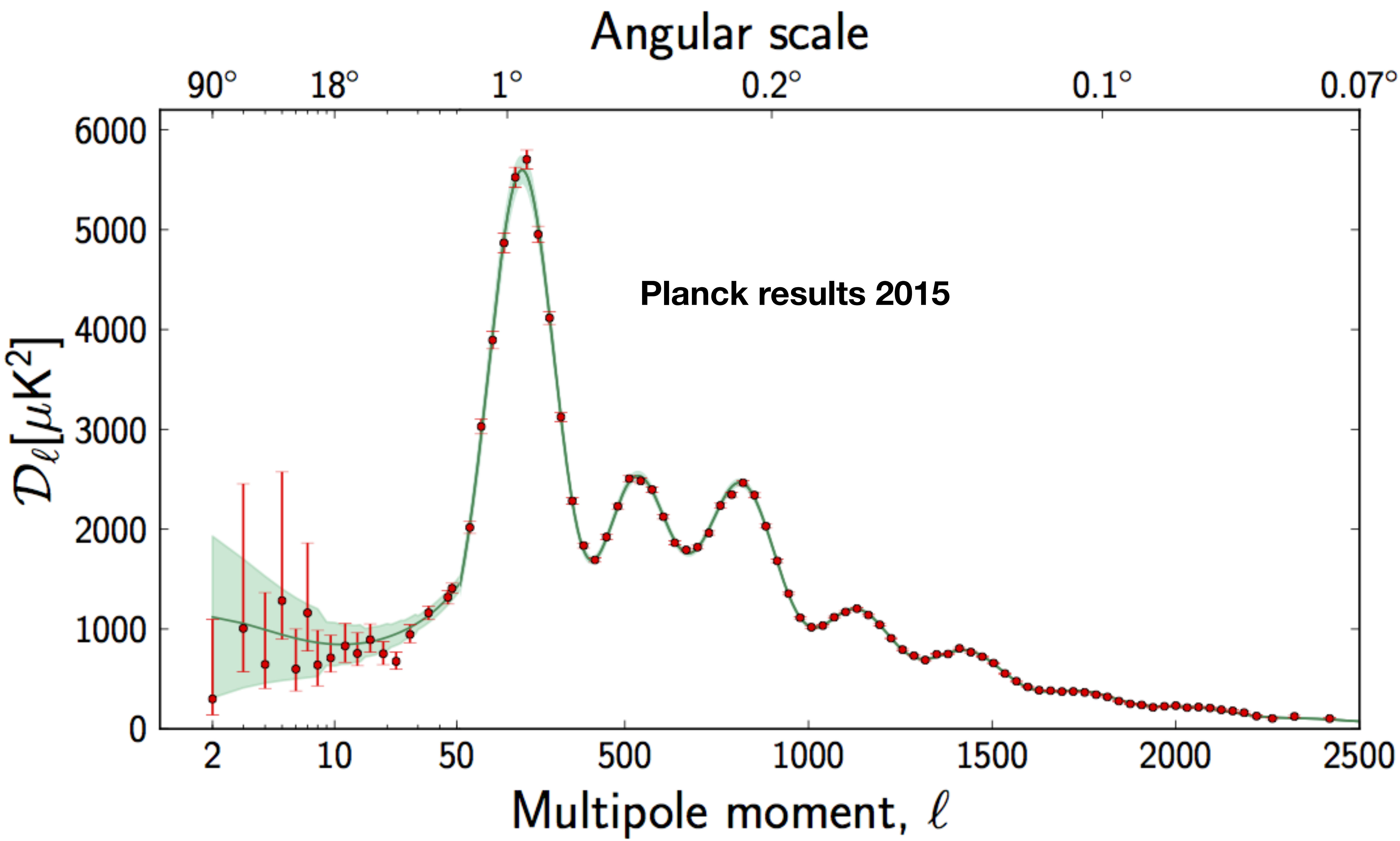
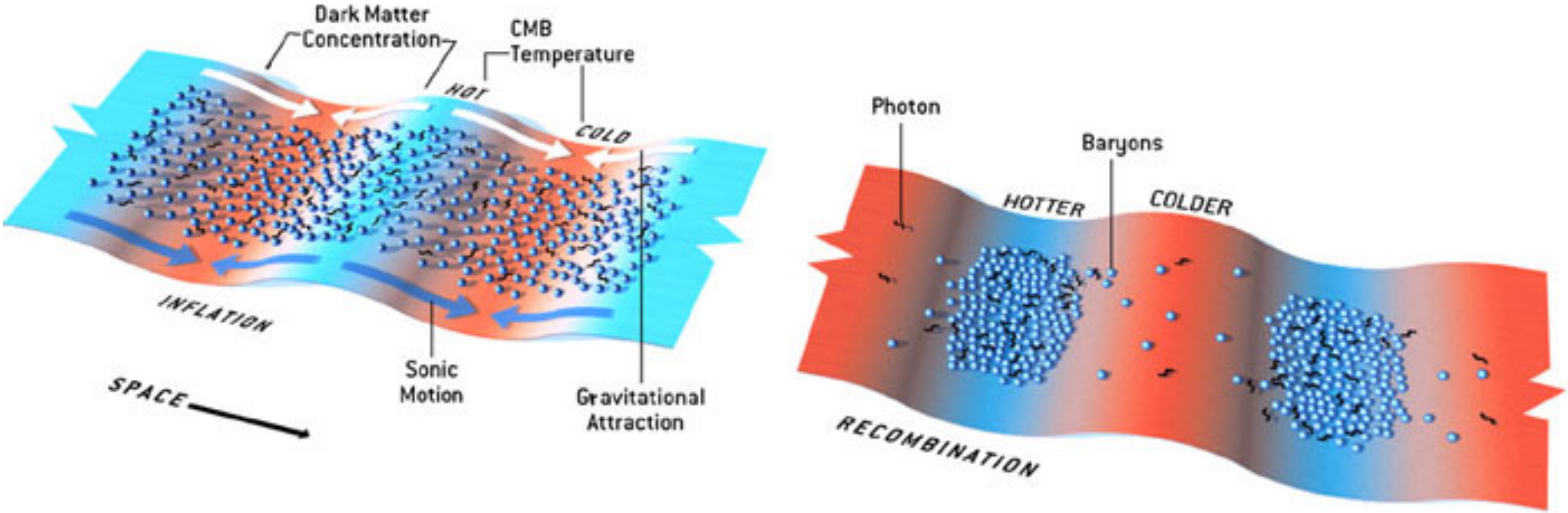


Credits: Lyman Page

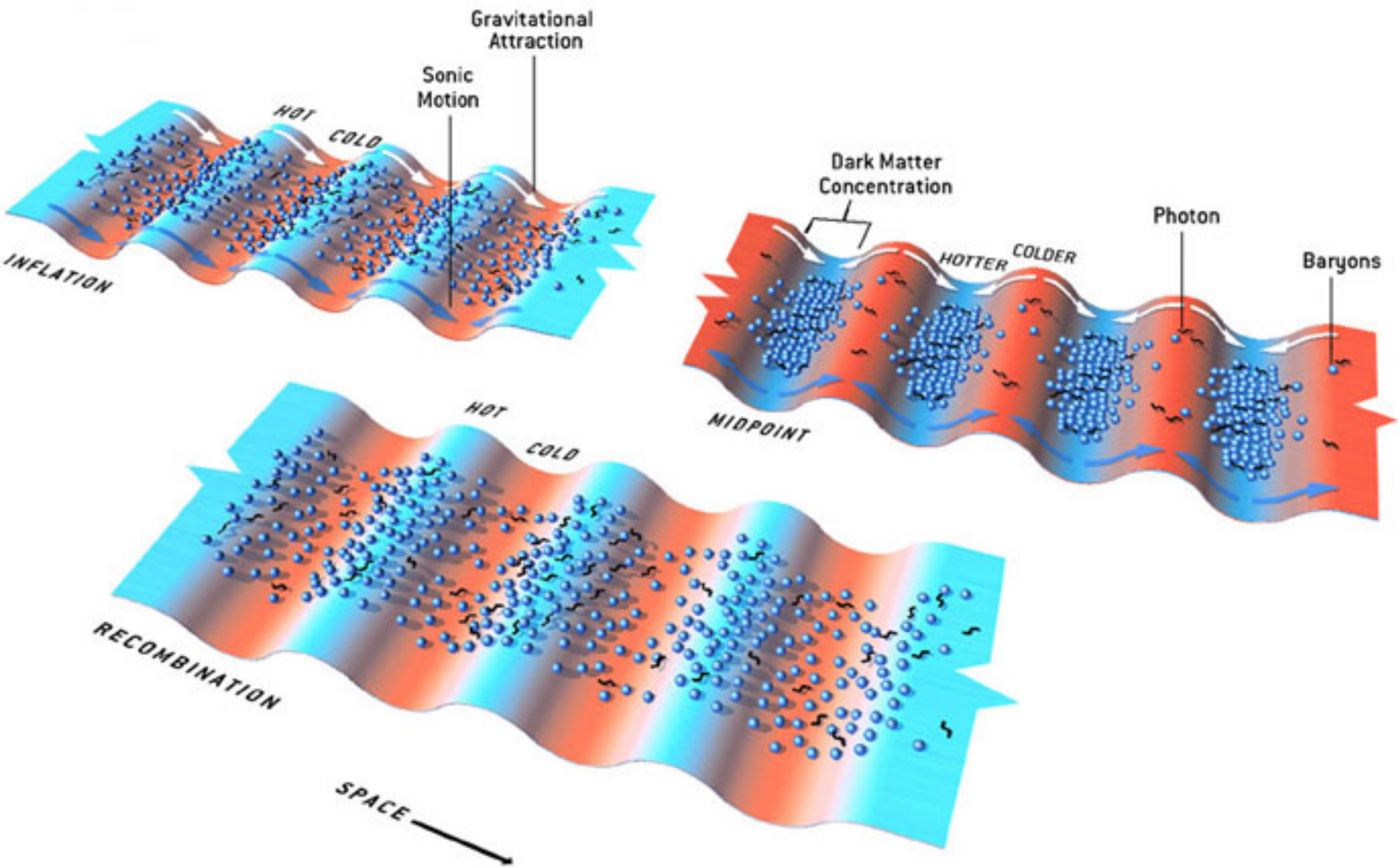
Our goals: understand this figure



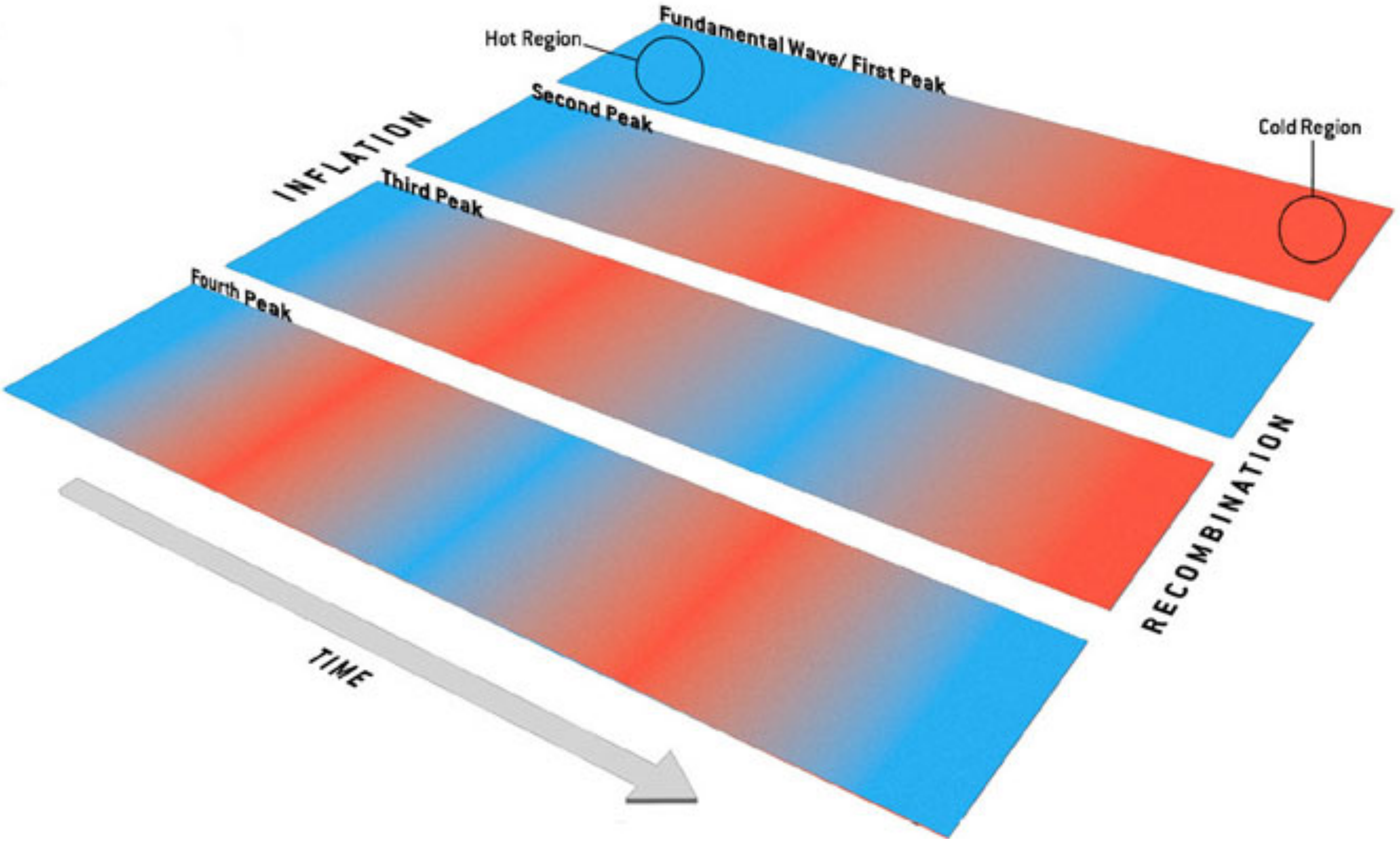
The first peak



The second peak



The other peaks



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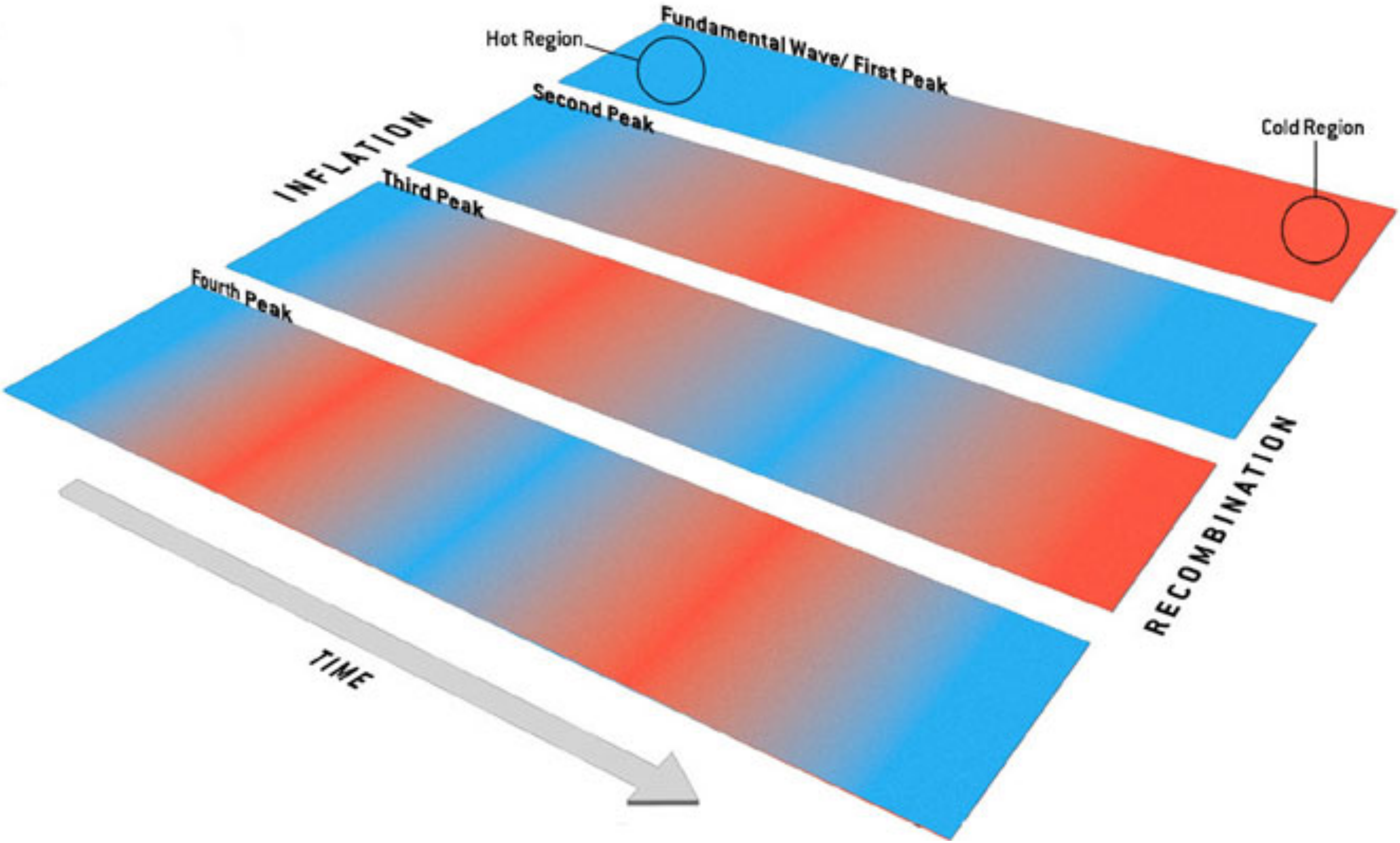
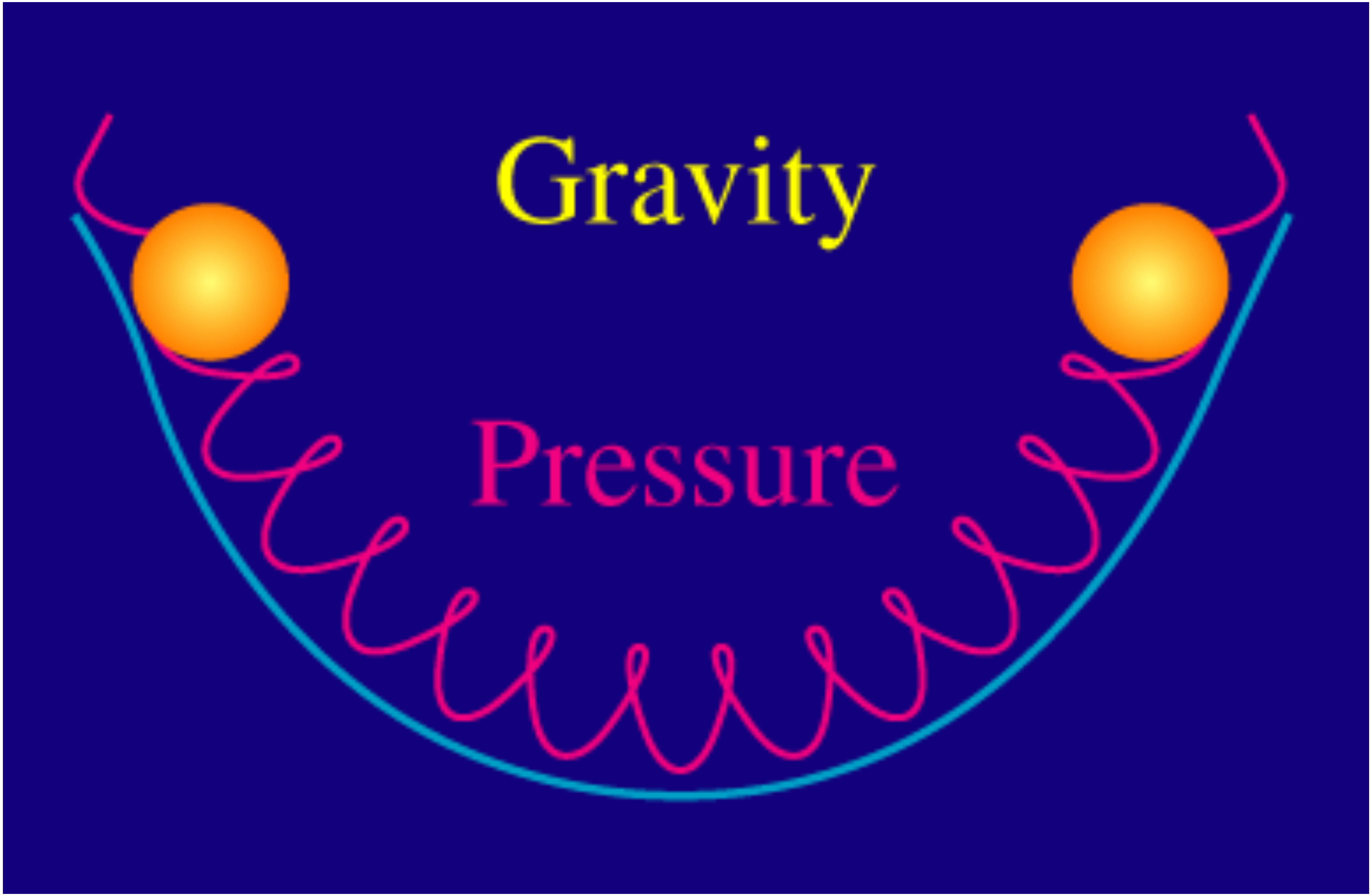


Radiation driving



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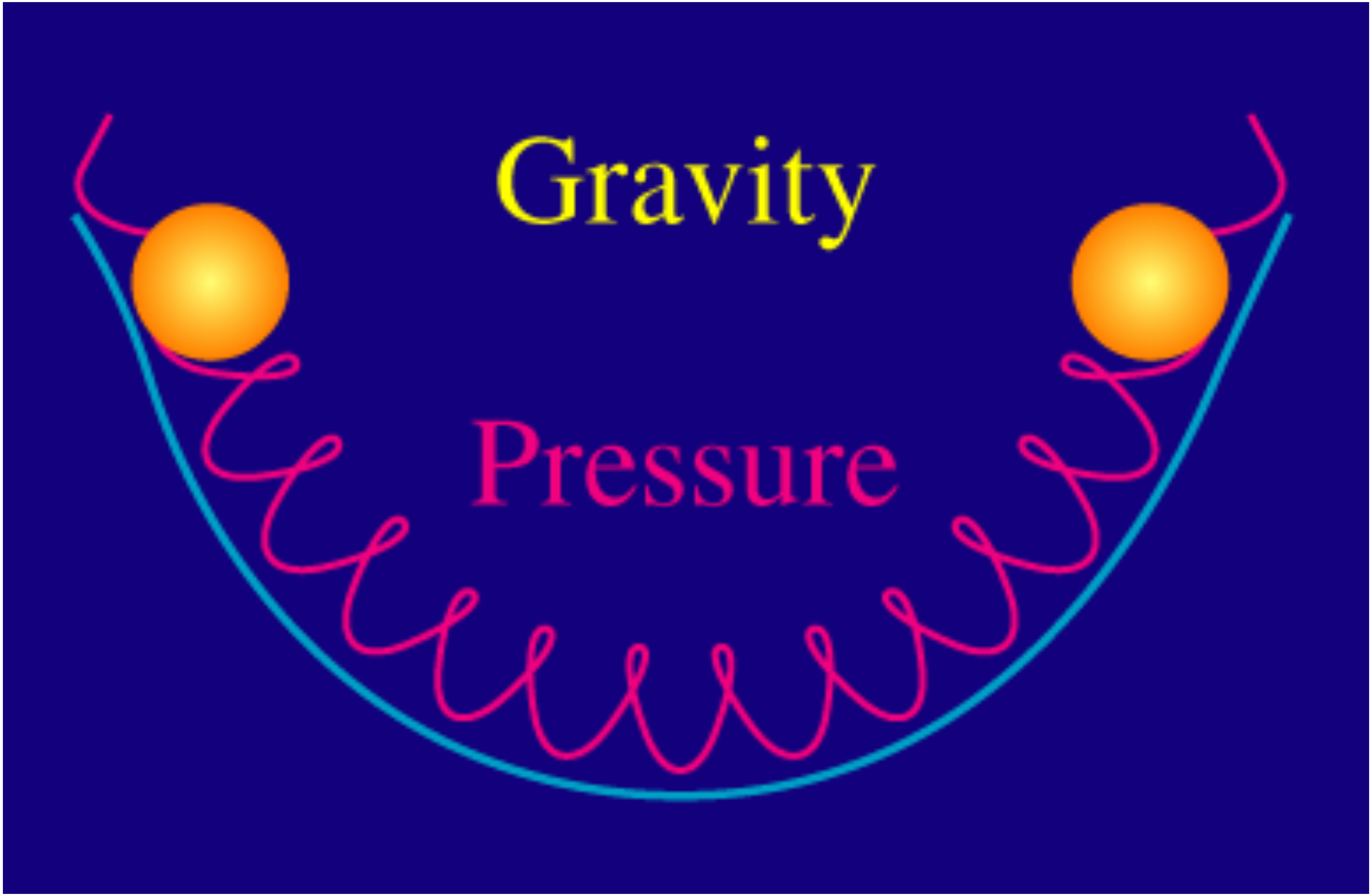
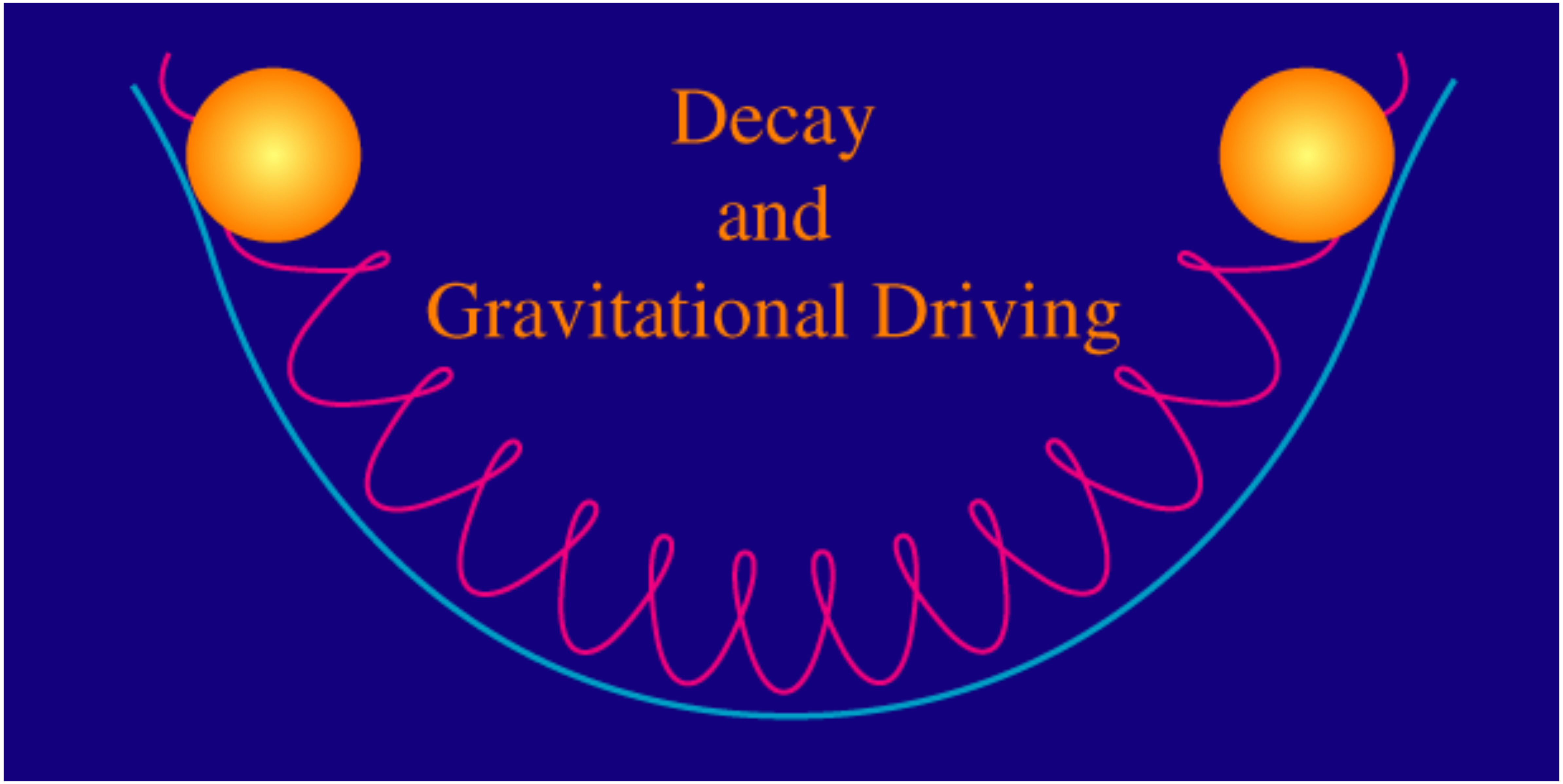


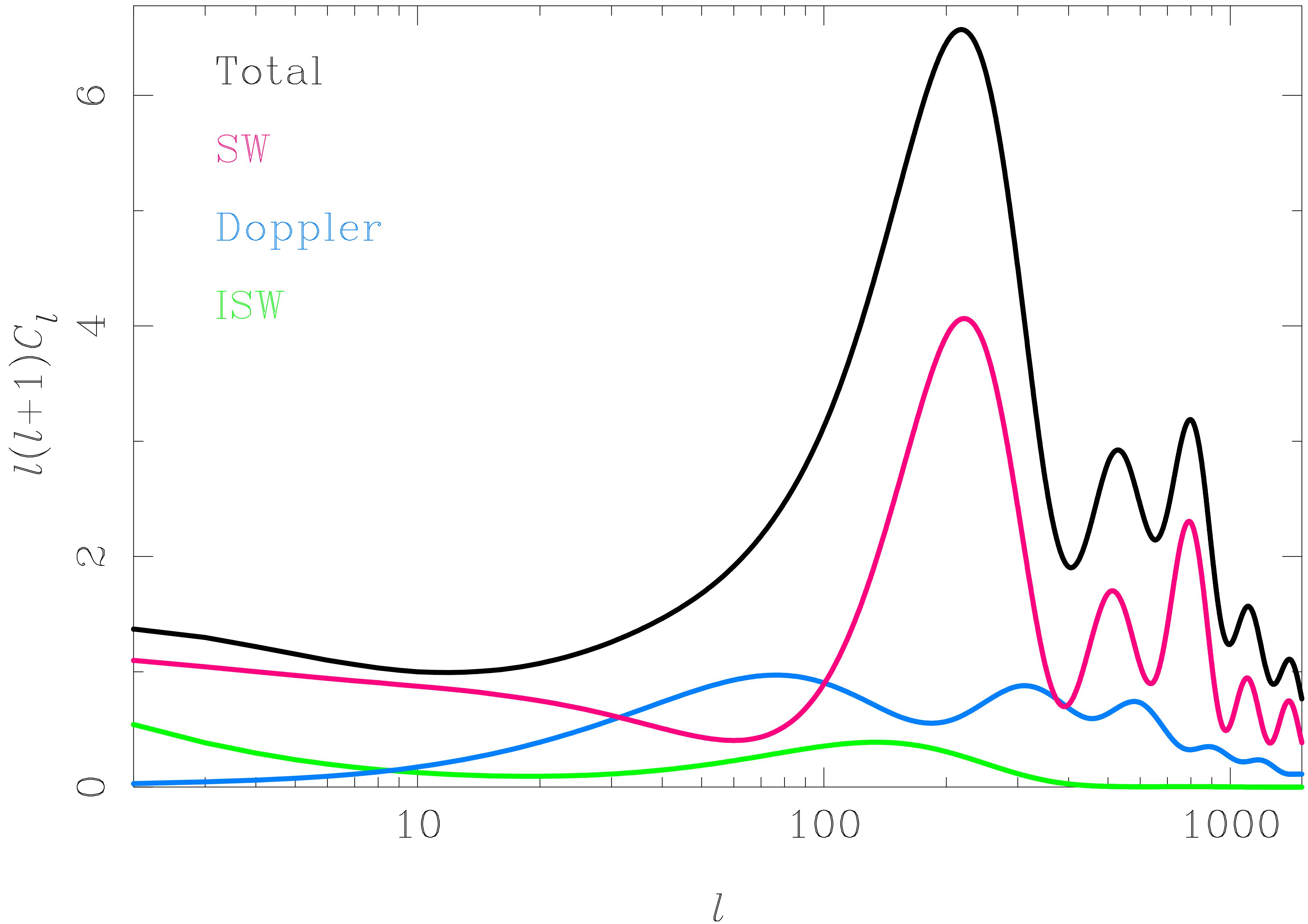
Radiation driving

- Gravitational potentials in radiation dominated era decay with time
- When fluids inverts oscillations there is no potential well: larger rarefaction amplitudes, information on **matter-radiation equality**



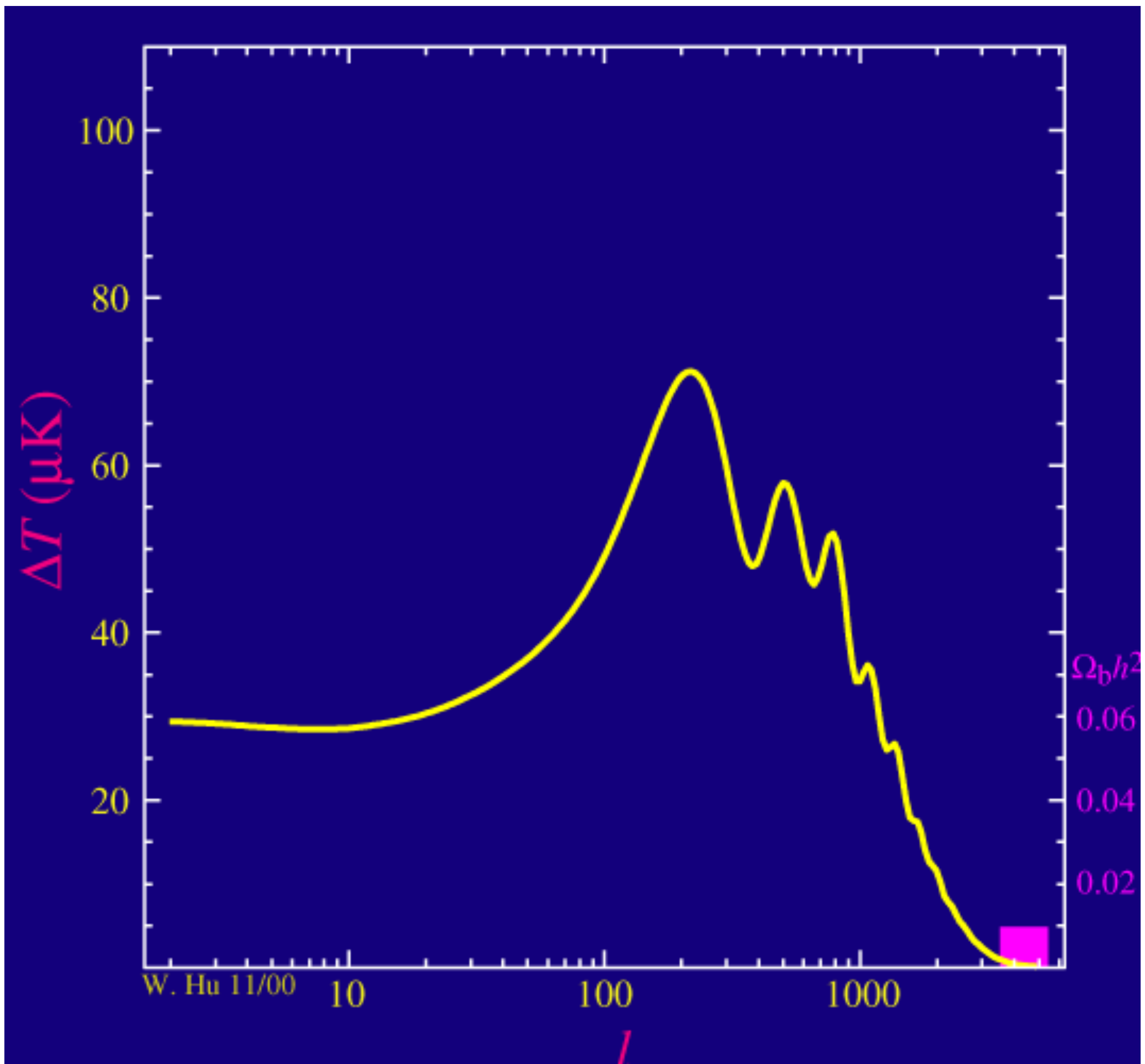
Total contributions

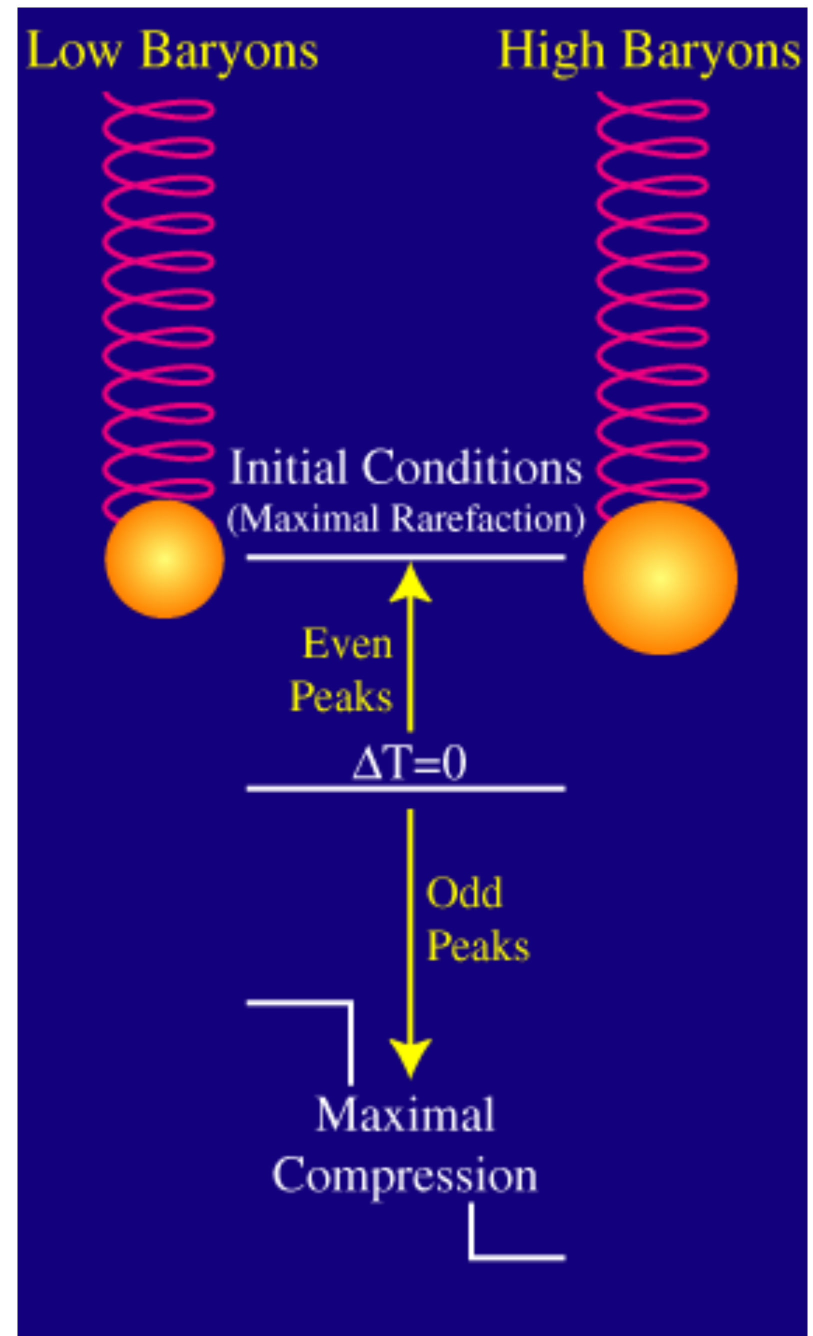
$$c_s^2 \frac{d}{d\eta}(c_s^{-2}\dot{\Theta}) + \frac{k^2 c_s^2}{\dot{\tau}}[A_\mathrm{v} + A_\mathrm{h}]\dot{\Theta} + c_s^2 k^2 \Theta \quad = \quad -\frac{k^2}{3}\Psi - c_s^2 \frac{d}{d\eta}(c_s^{-2}\dot{\Phi})$$



Baryon effects

- Enhance compression and shift 0-point of oscillations
- Slow down sound speed and change sound horizon





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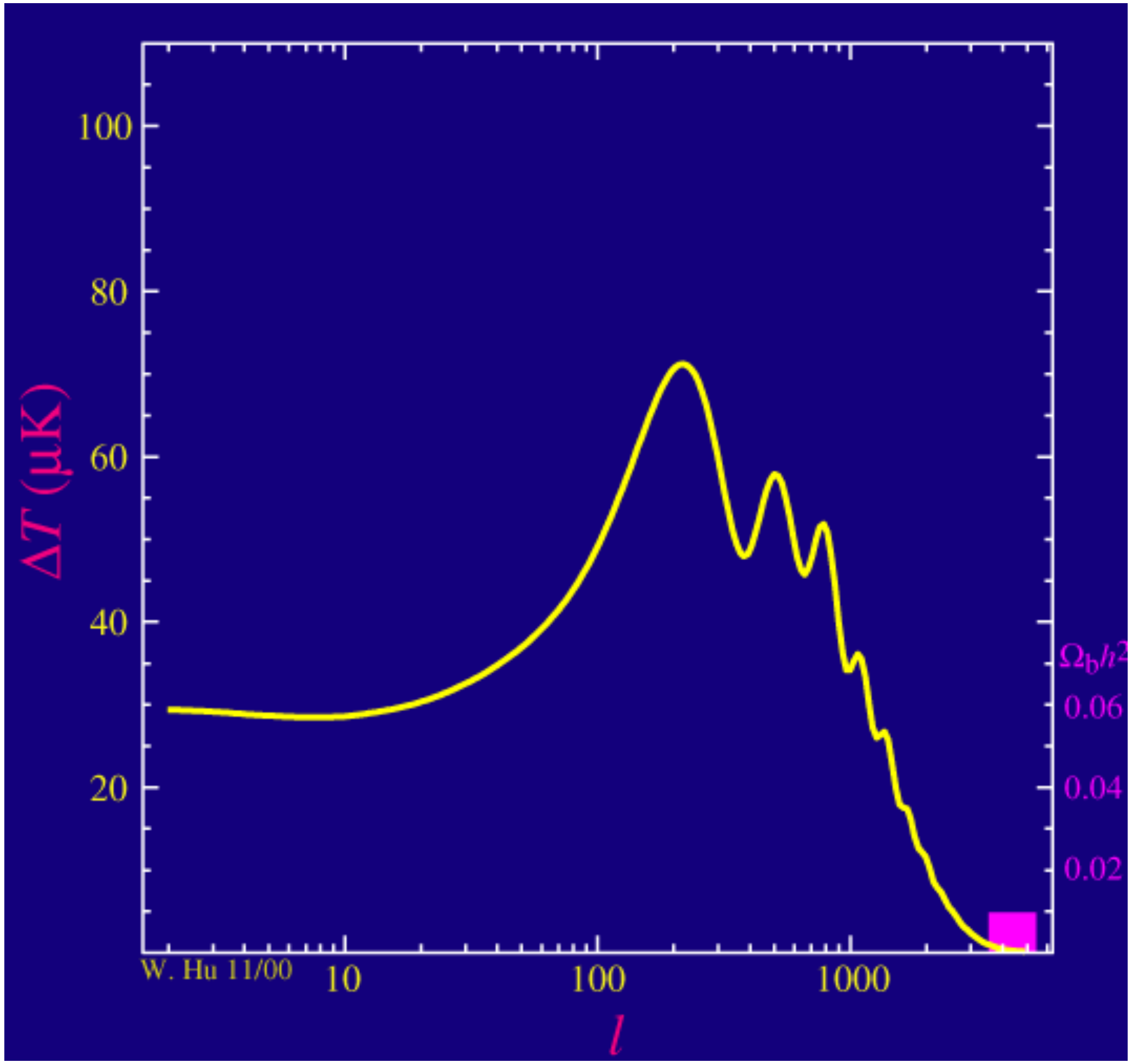

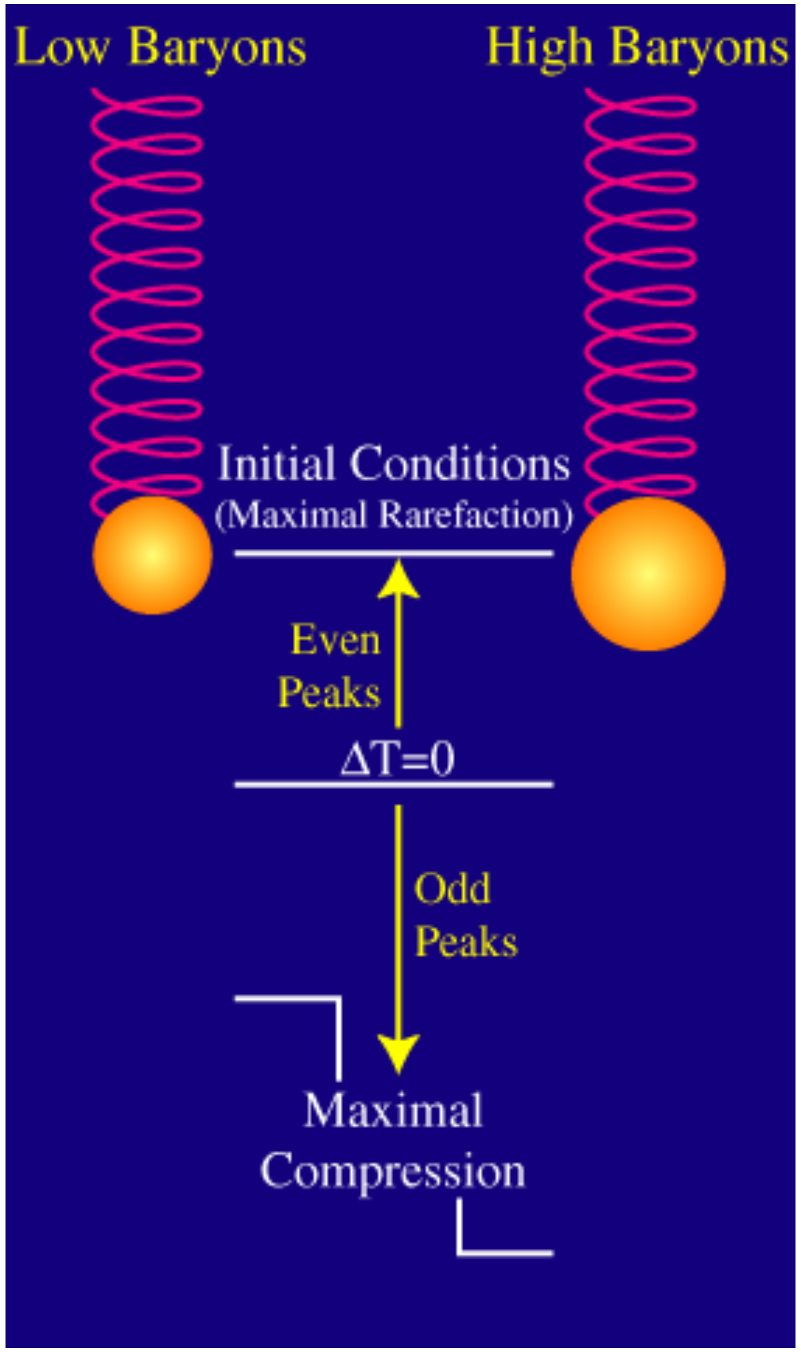

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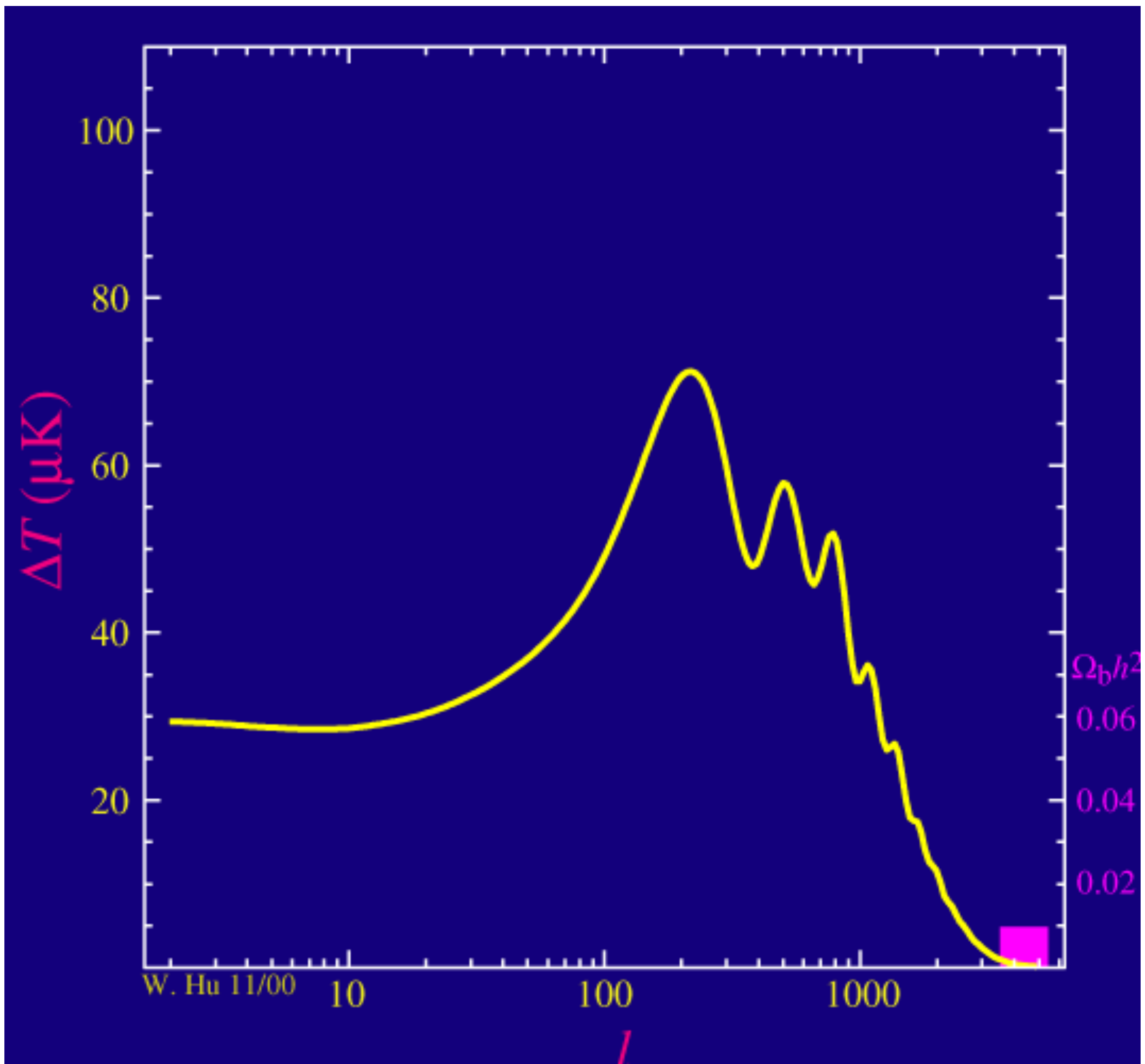
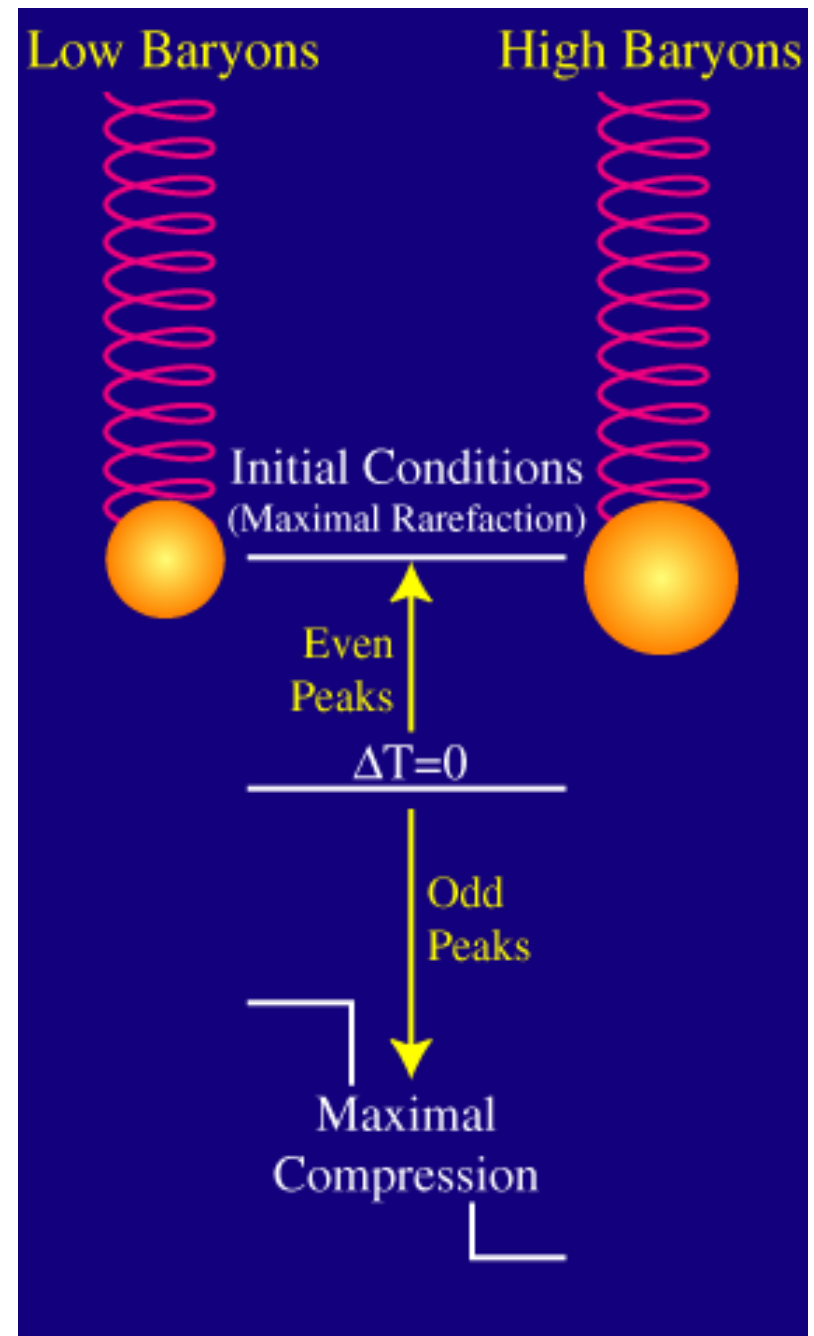
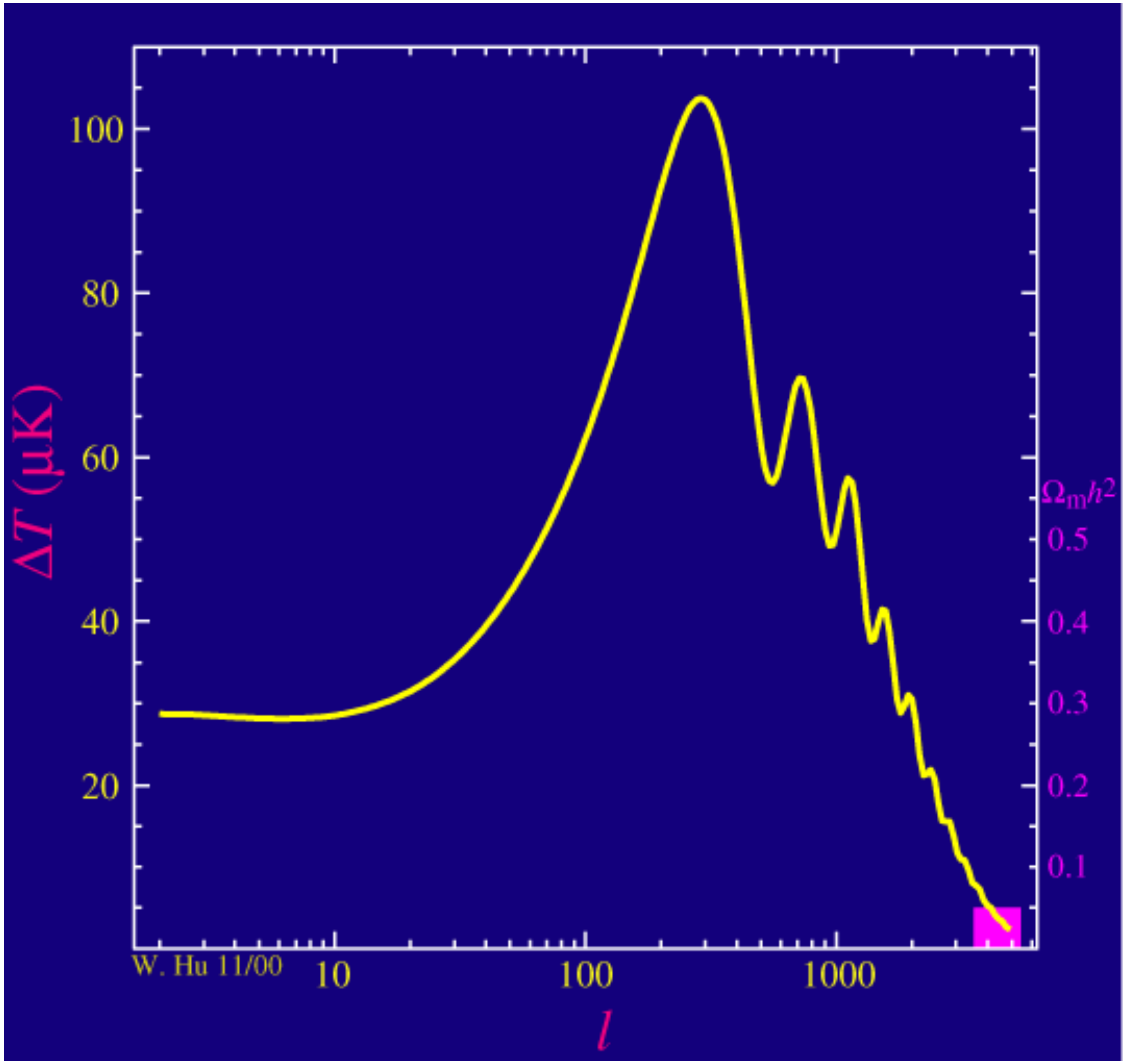




Dark matter effects

- No baryons = no acoustic oscillations



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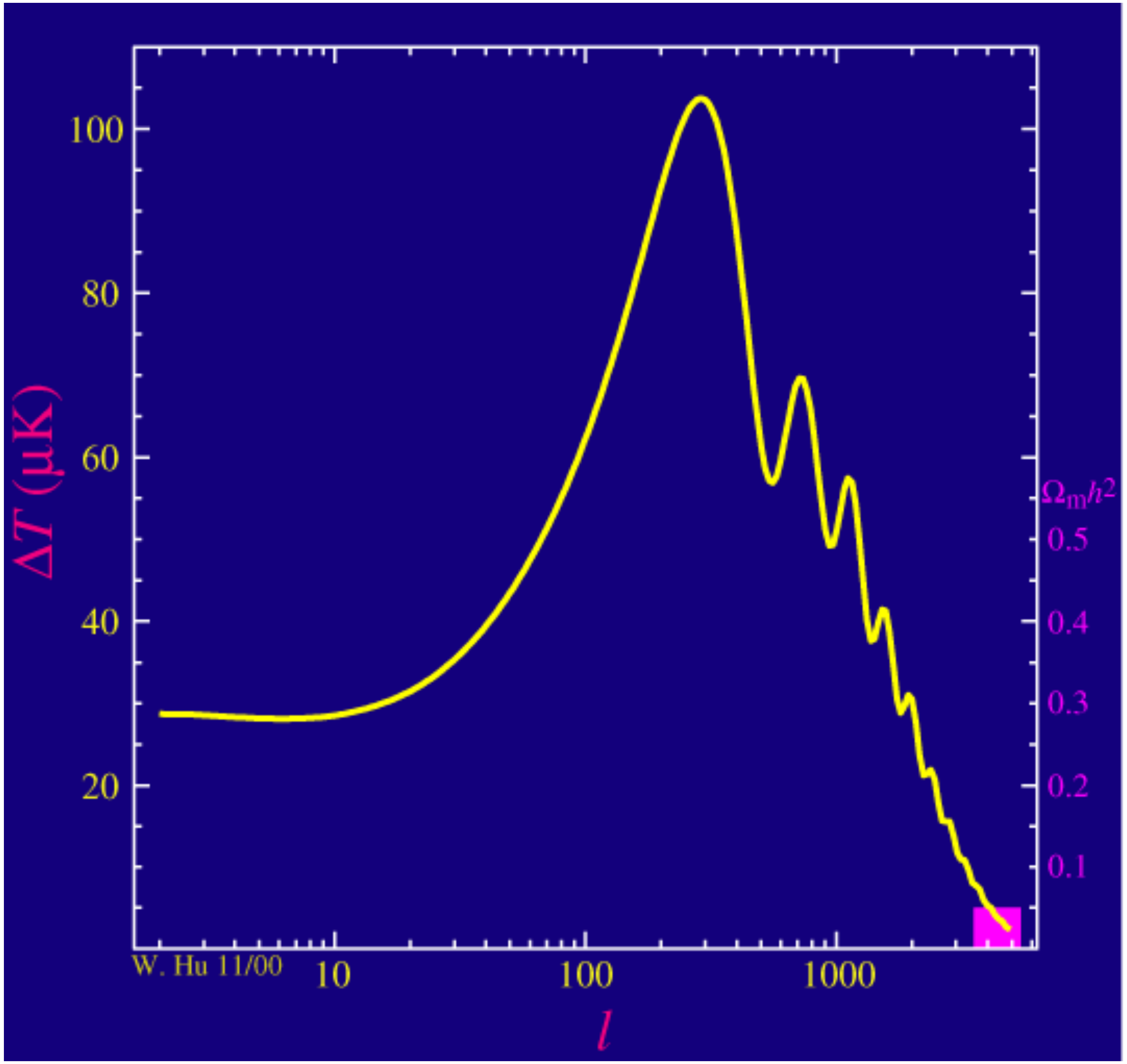
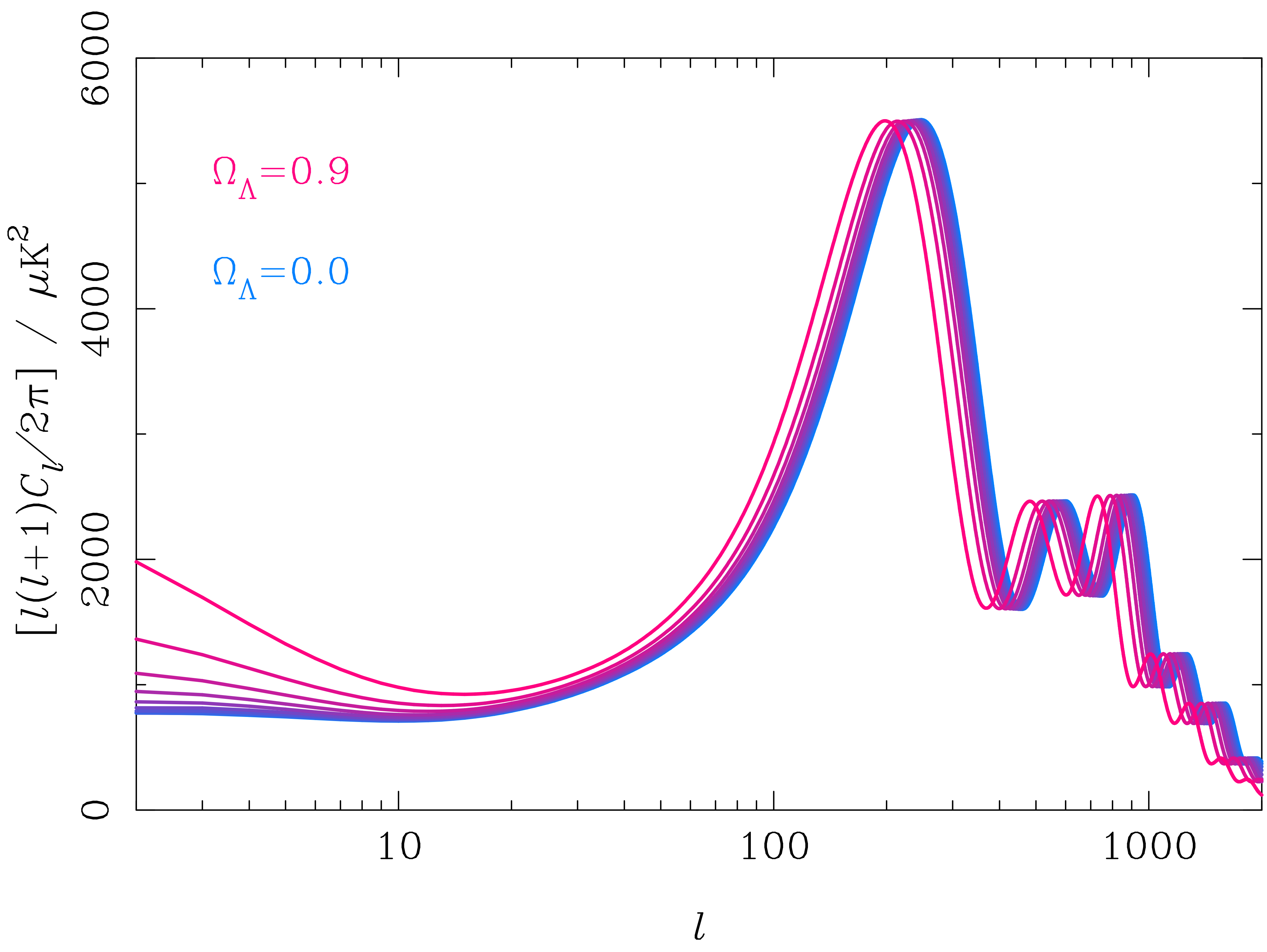


Dark Energy effects



The full picture

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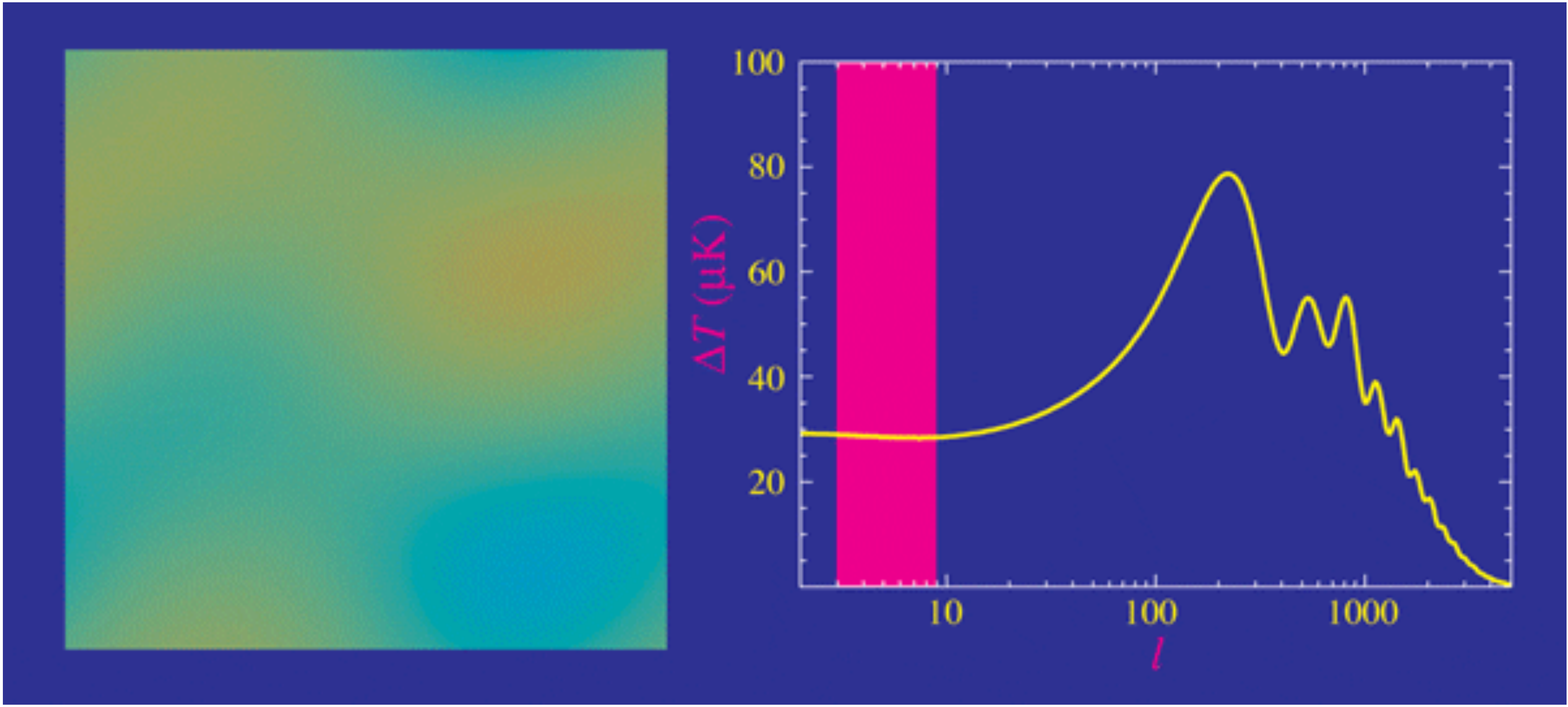
Composition



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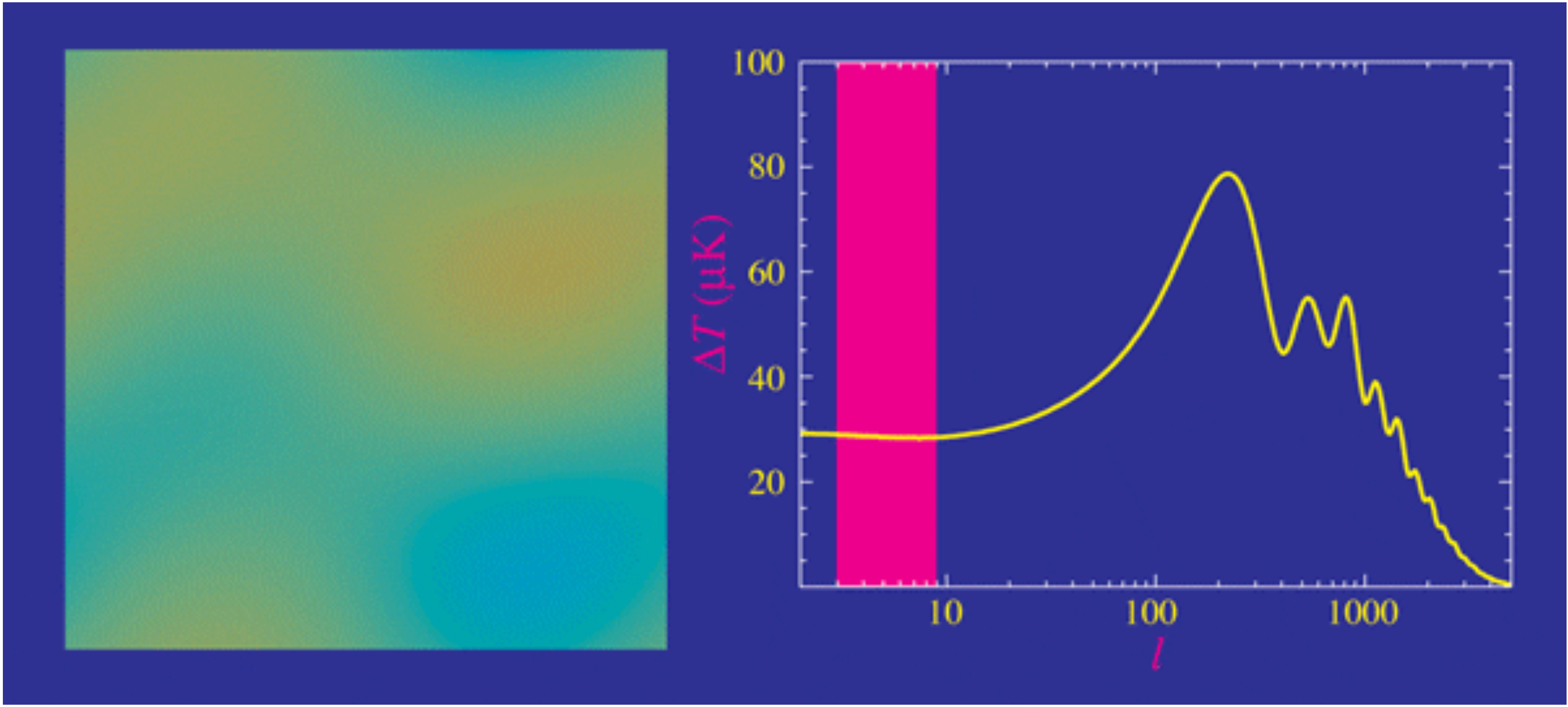
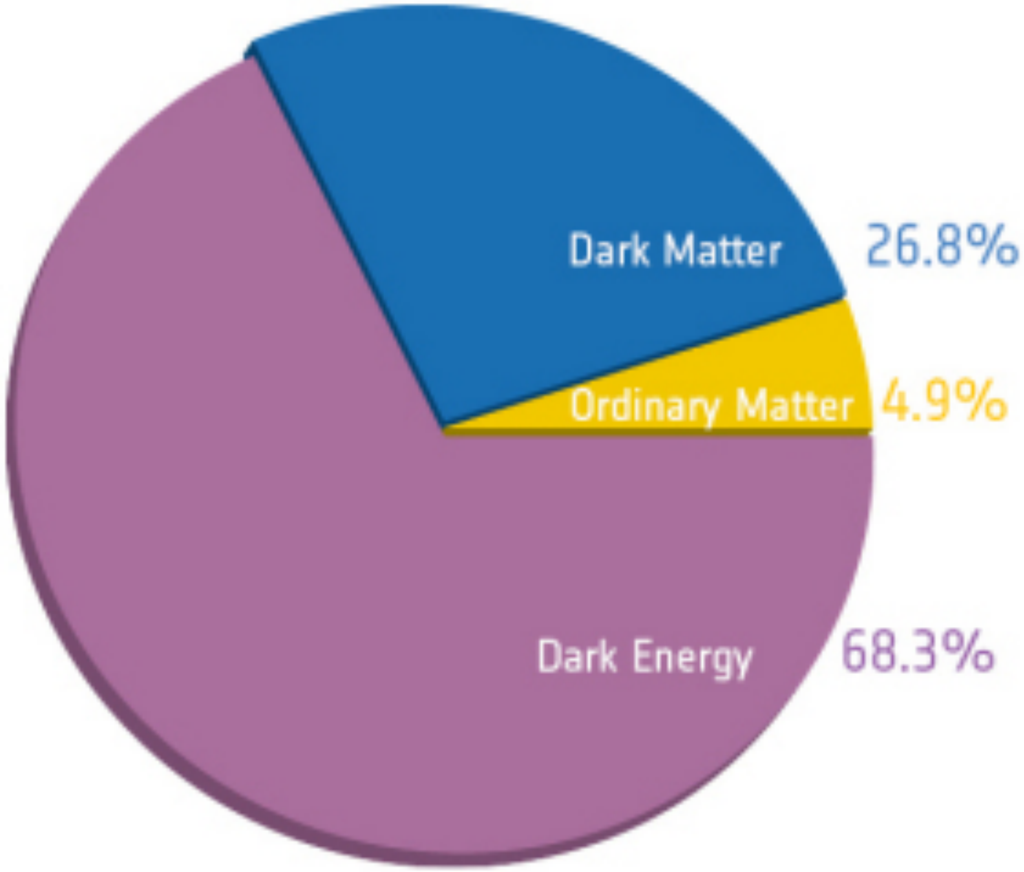


The cosmic pie in 2017



- Detection of scalar spectral: confirm one prediction of inflation
- Reconcile astrophysical data of galaxy + star formation

Polarization of the CMB

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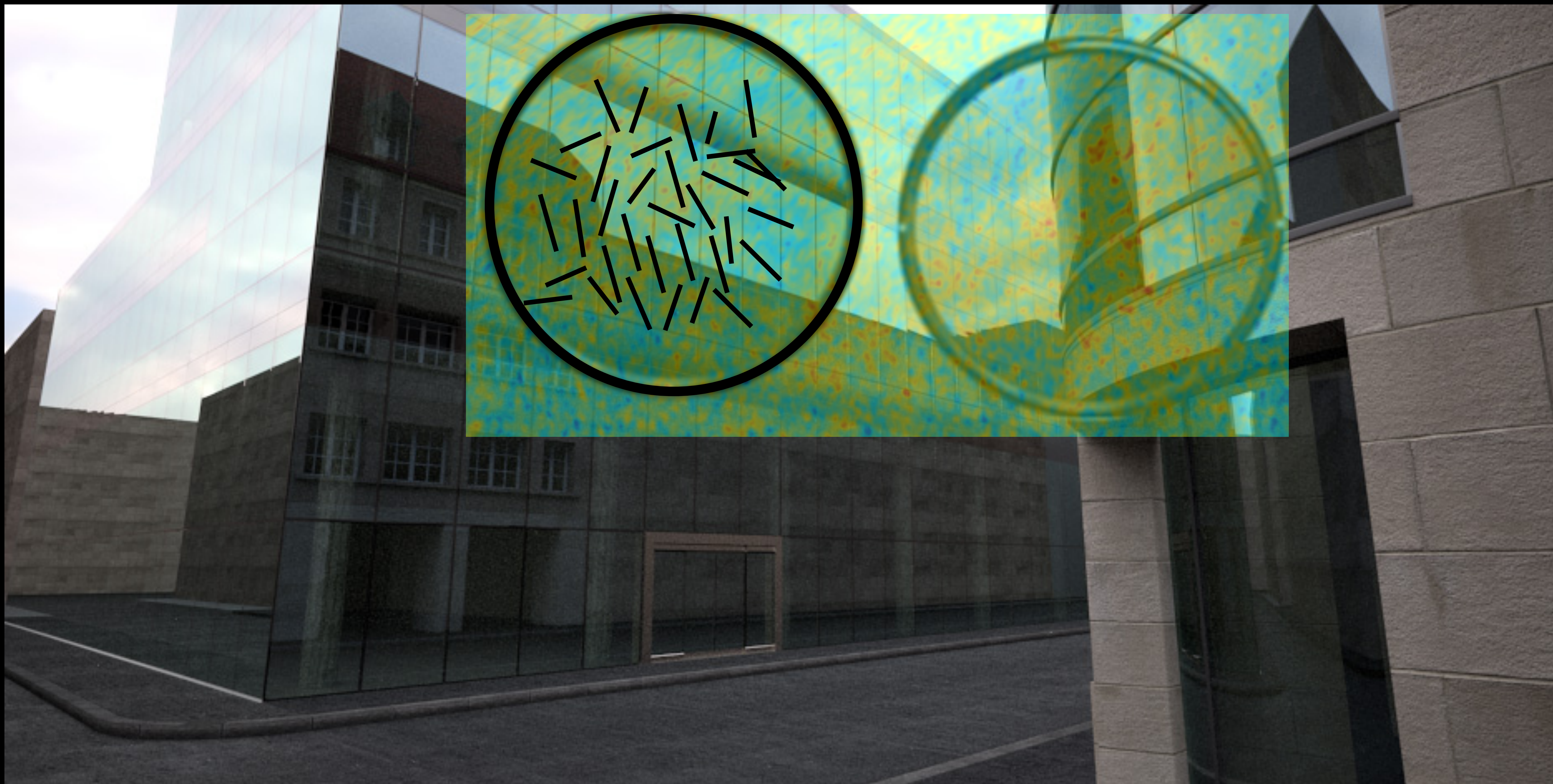

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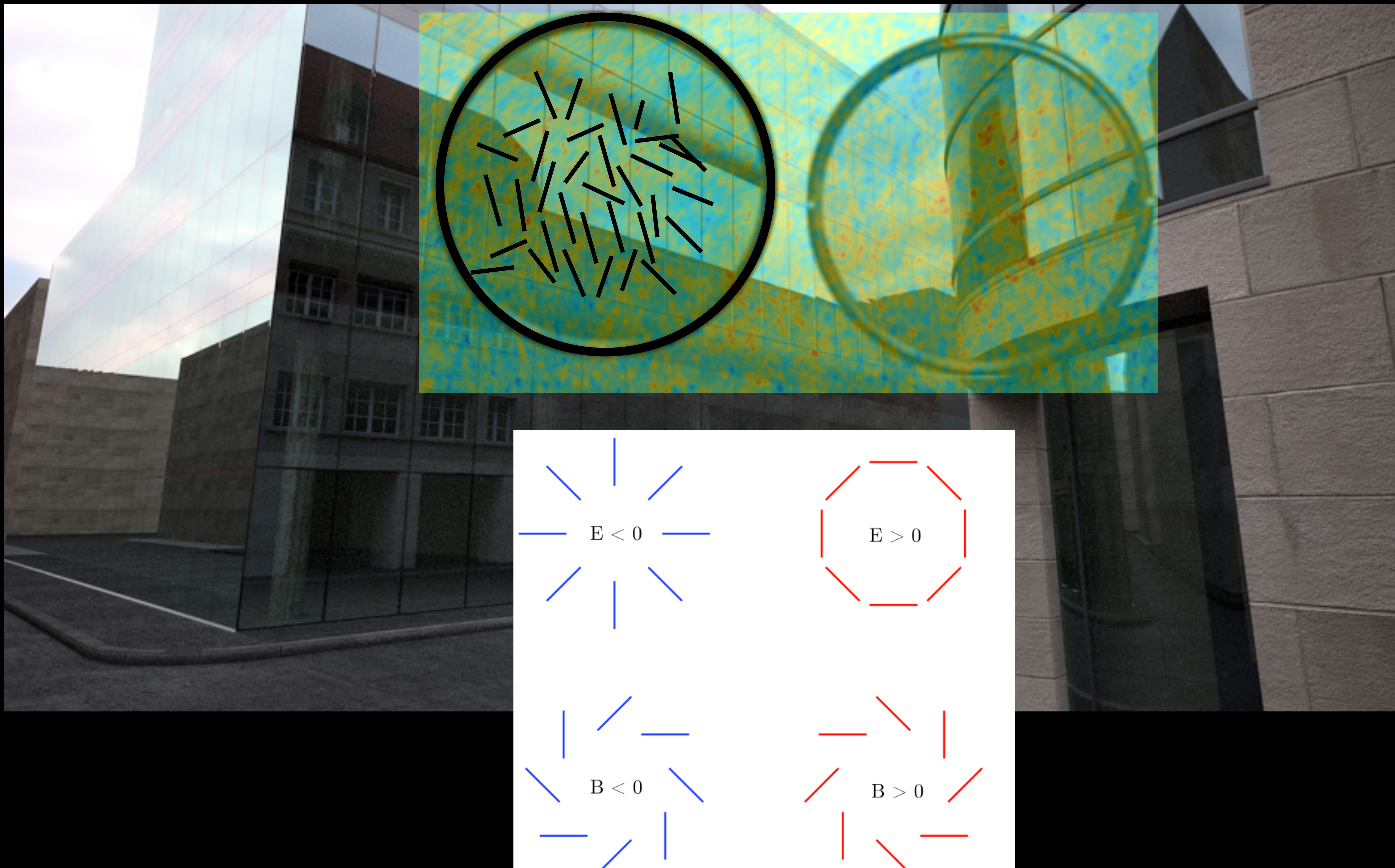
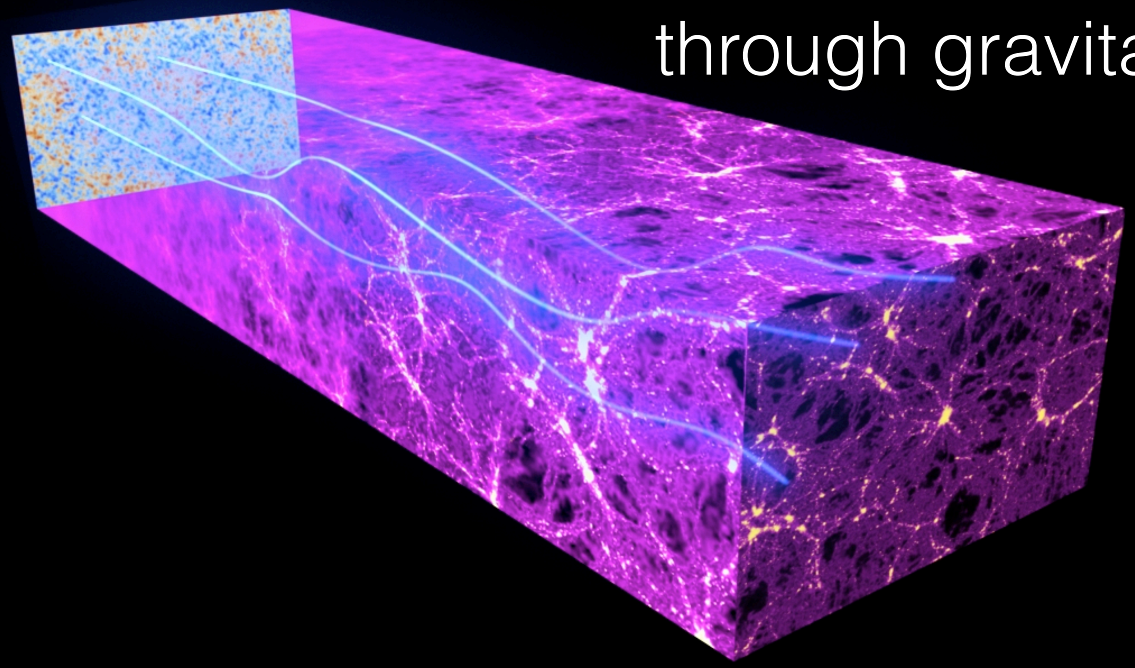
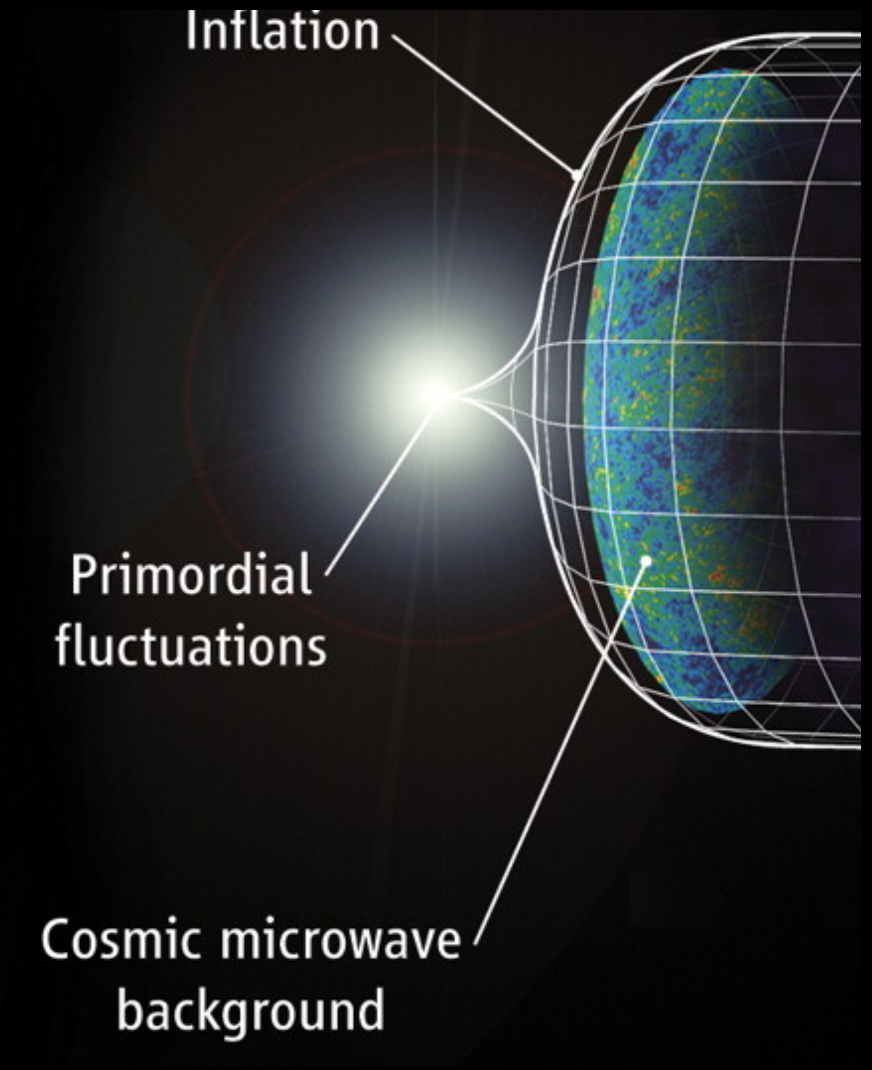


Why it is useful?

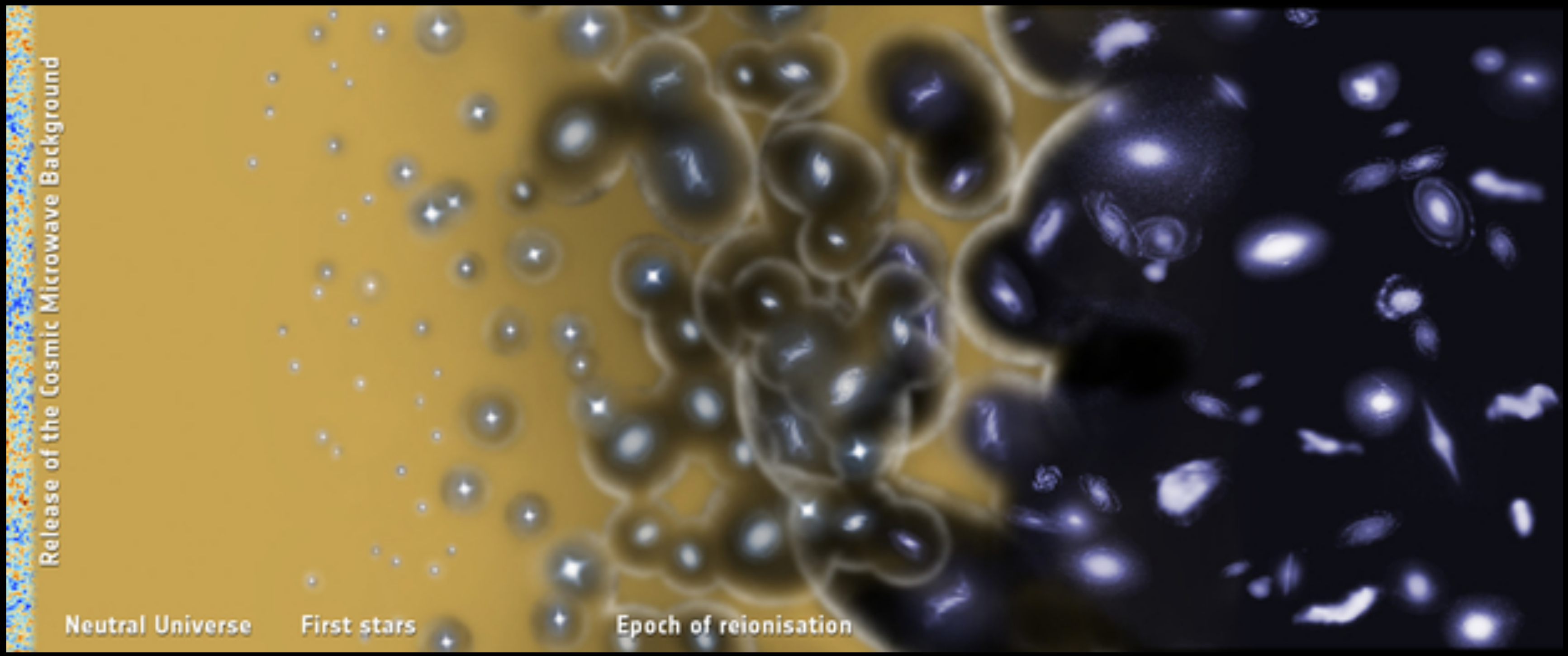
History of galaxy formation through gravitational lensing



Inflation physics



First formation of stars



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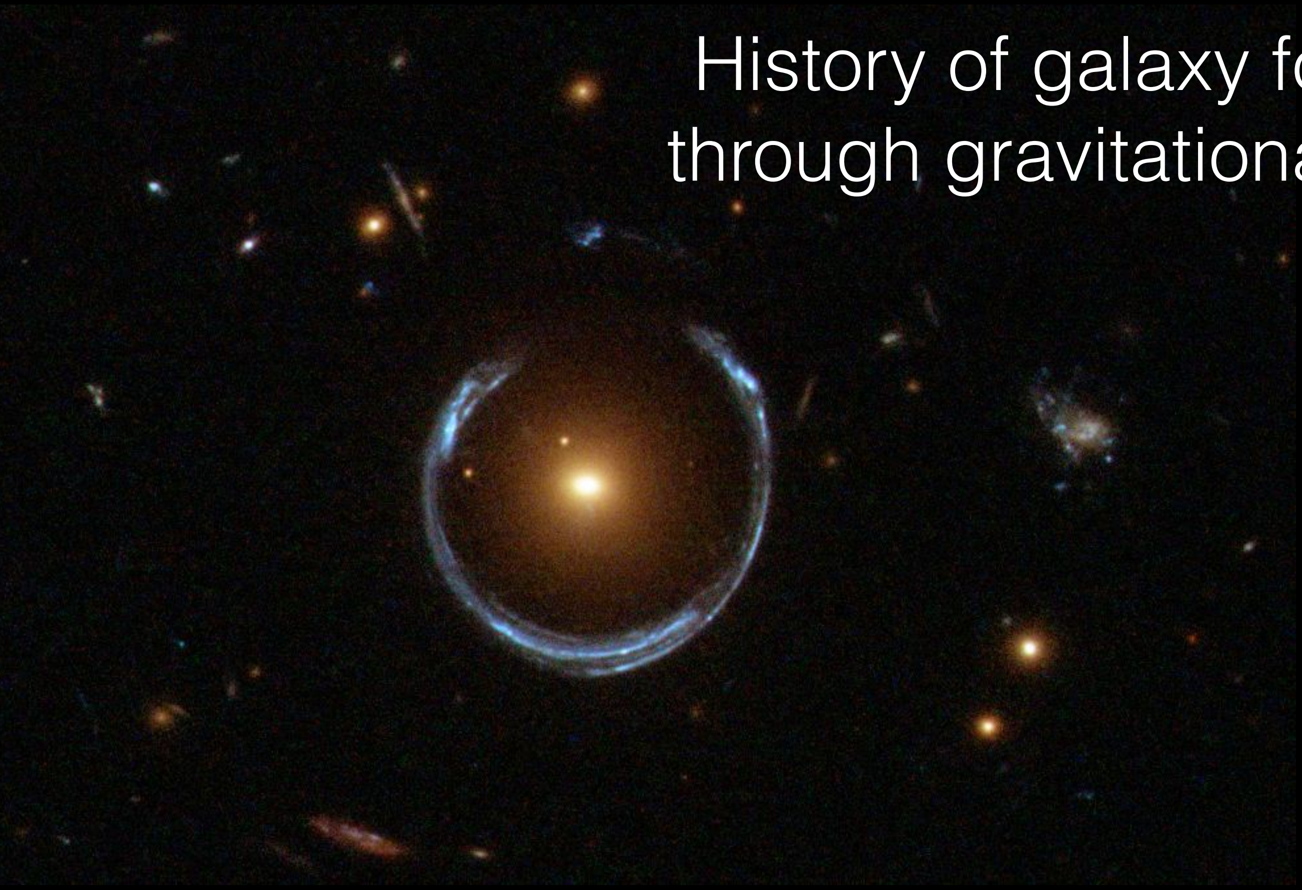

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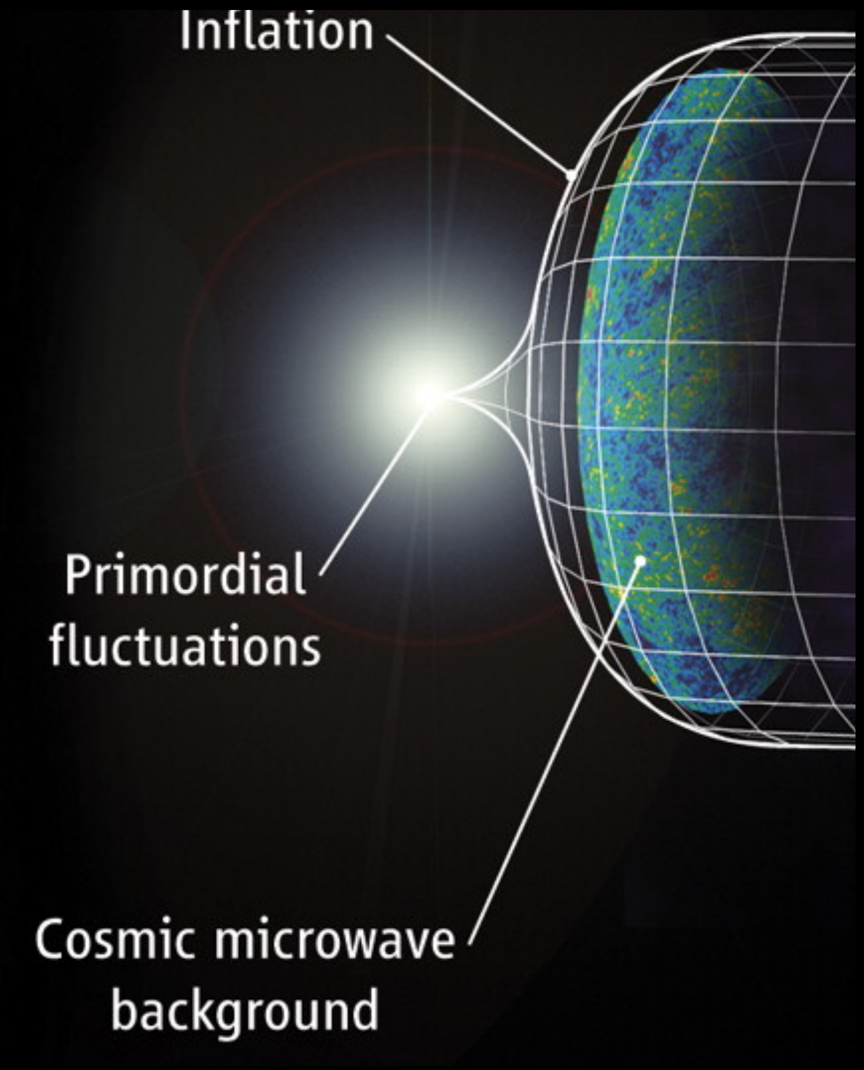

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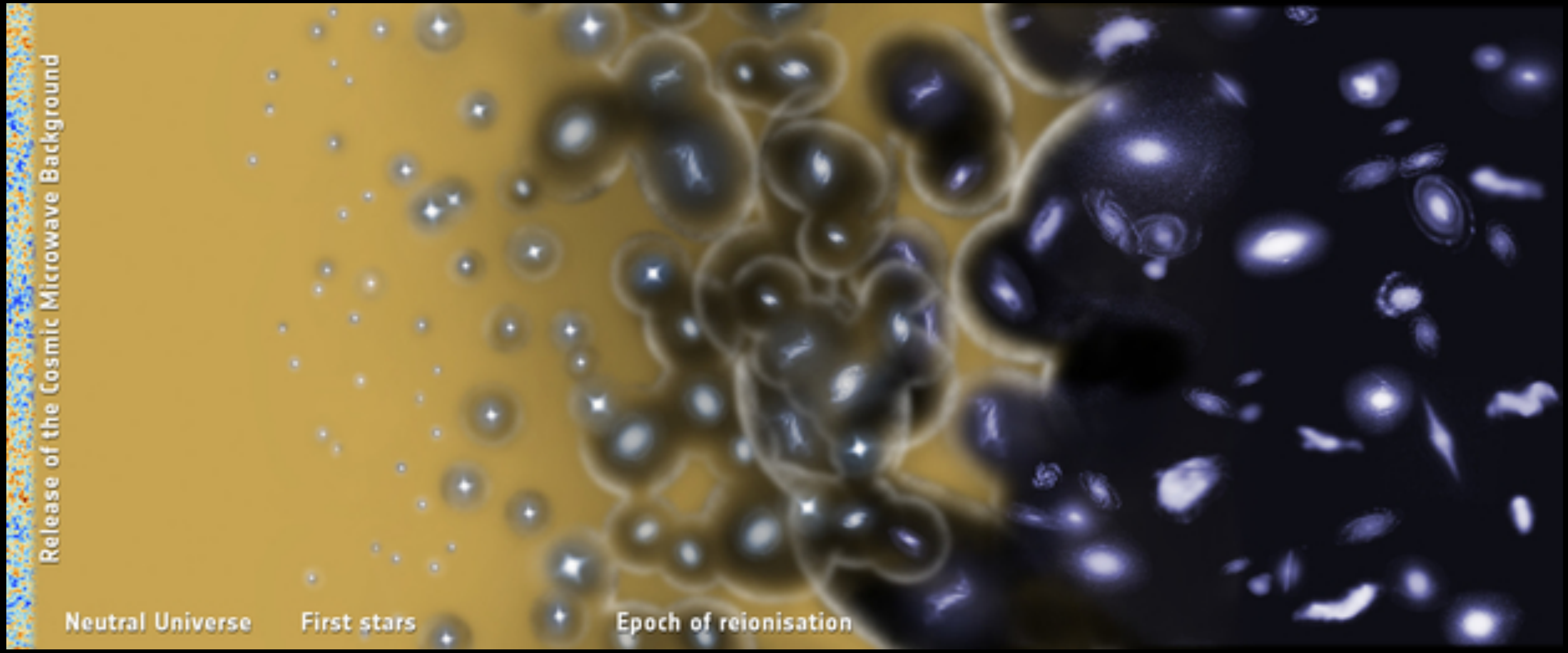
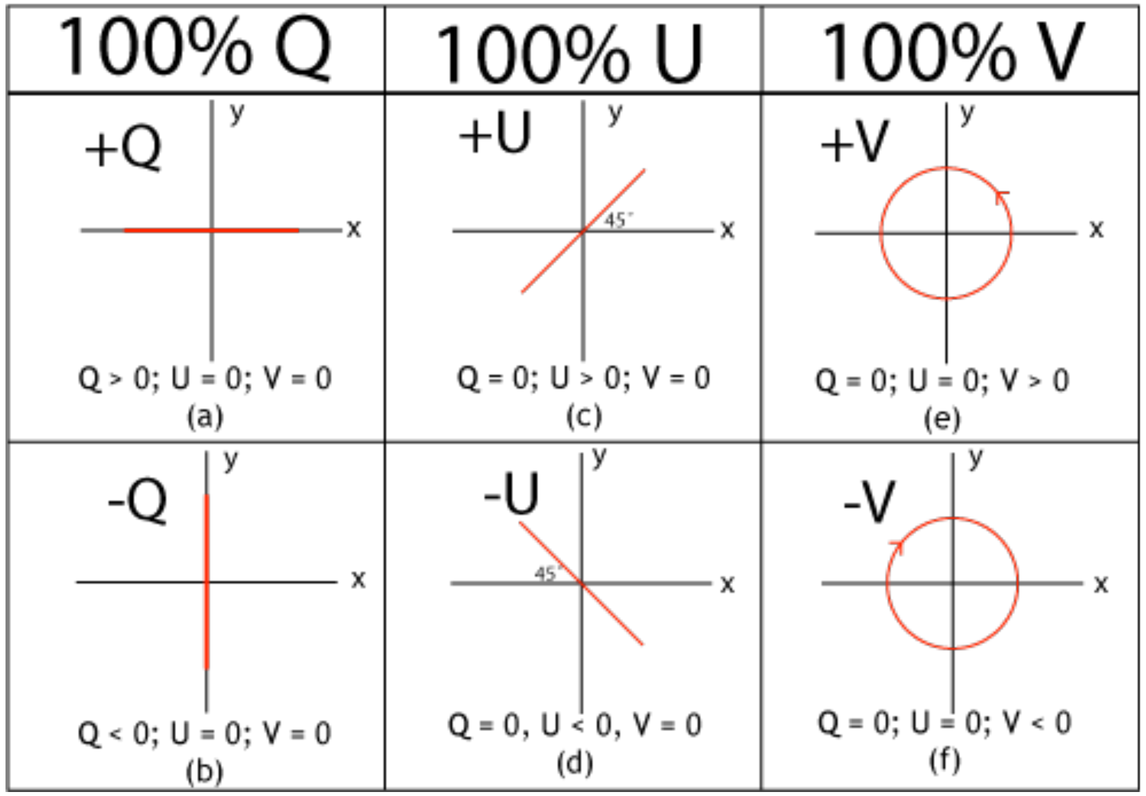


Stokes parameters and polarization

- A polarized field is defined by its Stokes parameters:

$$E_x = a_x \cos\left[\omega_0 t - \theta_x(t)\right] \qquad E_y = a_y \cos\left[\omega_0 t - \theta_y(t)\right]$$



$$\begin{aligned} I &\equiv \left\langle a_x^2 \right\rangle + \left\langle a_y^2 \right\rangle \\ Q &\equiv \left\langle a_x^2 \right\rangle - \left\langle a_y^2 \right\rangle \\ U &\equiv \langle 2 a_x a_y \cos(\theta_x - \theta_y) \rangle \\ V &\equiv \langle 2 a_x a_y \sin(\theta_x - \theta_y) \rangle \end{aligned}$$

- Polarization is a headless vector, identical to itself for right-handed rotation of 180deg: it's a spin-2 complex field

$$Q \pm iU \rightarrow (Q \pm iU) e^{\mp 2i\psi} \quad \Rightarrow \quad Q + iU \text{ is spin -2}$$

- Circular polarization not produced by Thomson scattering, let's neglect it for the time being...

Spin-weighted spherical harmonics

- Generalization of scalar spherical harmonics for spin fields:

$$ {}_sY_{l,m}(\theta,\varphi) = e^{im\phi}\left[\frac{(l+m)!(l-m)!}{(l+s)!(l-s)!}\frac{2l+1}{4\pi}\right]^{\frac{1}{2}}\sin^{2l}(\theta/2) $$

- $$ \times\sum_r \begin{pmatrix} l-s \\ r \end{pmatrix}\begin{pmatrix} l+s \\ r+s-m \end{pmatrix}(-1)^{l-r-s+m}\cot^{2r+s-m}(\theta/2). $$

- Can be related to scalar harmonics through spin raising/lowering operators (essential for calculations!)

$$ \begin{aligned} \eth_s f(\theta,\phi) &= -\sin^s\theta\left[\frac{\partial}{\partial\theta}+i\csc\theta\frac{\partial}{\partial\phi}\right]\sin^{-s}\theta_s f(\theta,\phi) \\ \bar{\eth}_s f(\theta,\phi) &= -\sin^{-s}\theta\left[\frac{\partial}{\partial\theta}-i\csc\theta\frac{\partial}{\partial\phi}\right]\sin^{s}\theta_s f(\theta,\phi) \end{aligned} $$

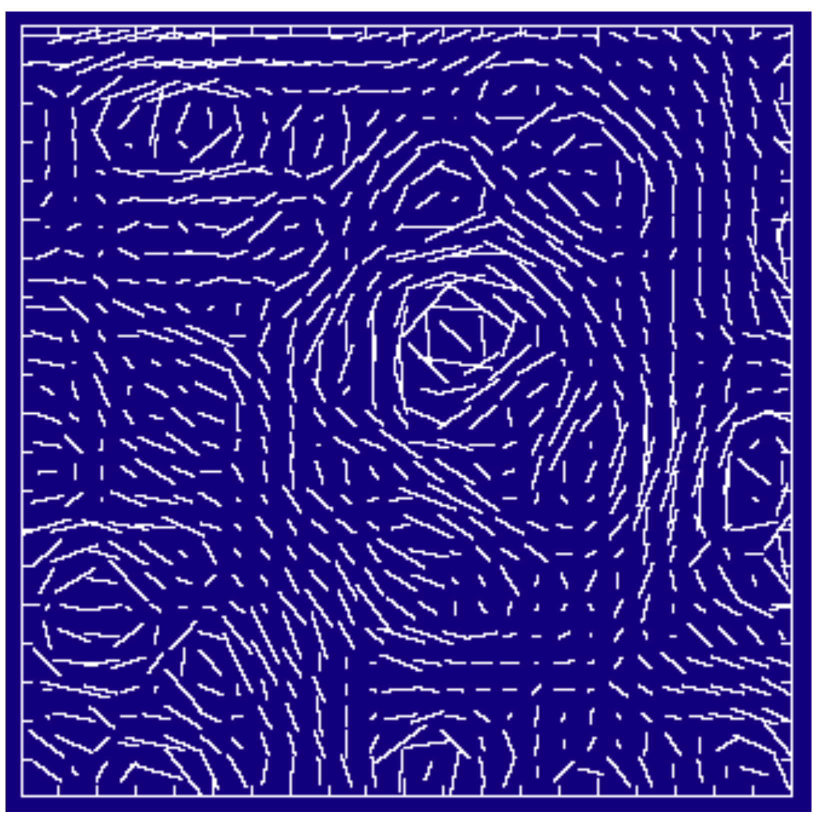
$$ \begin{aligned} \eth_s Y_{l,m}(\theta,\varphi) &= \sqrt{(l-s)(l+s+1)}\,{}_{s+1}Y_{l,m}(\theta,\varphi) \\ \bar{\eth}_s Y_{l,m}(\theta,\varphi) &= -\sqrt{(l+s)(l-s+1)}\,{}_{s-1}Y_{l,m}(\theta,\varphi) \end{aligned} $$

E/B decomposition

- Coordinate independent decomposition of spin-fields in the harmonic domain

$$
\begin{aligned}
(Q+iU)(\theta,\phi) &= \sum {}_2a_{\ell m\,2}Y_{l,m}(\theta,\varphi)\\
(Q-iU)(\theta,\phi) &= \sum {}_{-2}a_{\ell m\,-2}Y_{l,m}(\theta,\varphi)
\end{aligned}
\longrightarrow
\begin{aligned}
{}_sE_{\ell m} = {}_sa^E_{\ell m} &= \frac{{}_sa_{\ell m}+{}_{-s}a_{\ell m}}{2}\\
{}_sB_{\ell m} = {}_sa^B_{\ell m} &= i\frac{{}_sa_{\ell m}-{}_{-s}a_{\ell m}}{2}
\end{aligned}
$$

- Non-local quantity, analogy with decomposition of electromagnetic field



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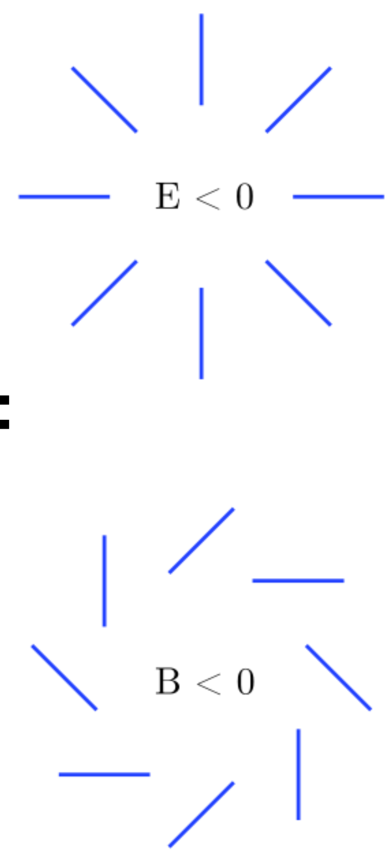

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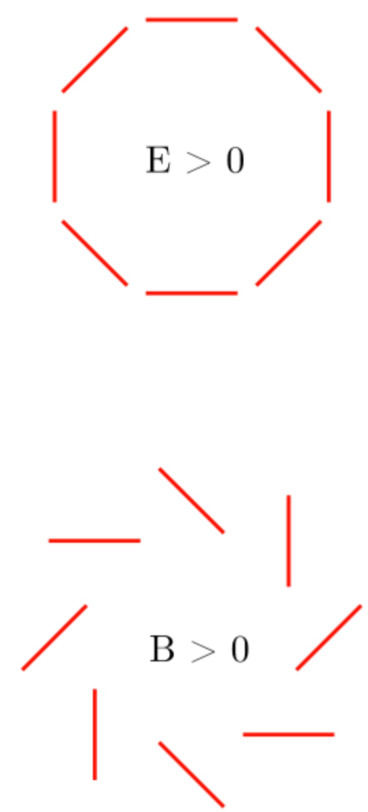

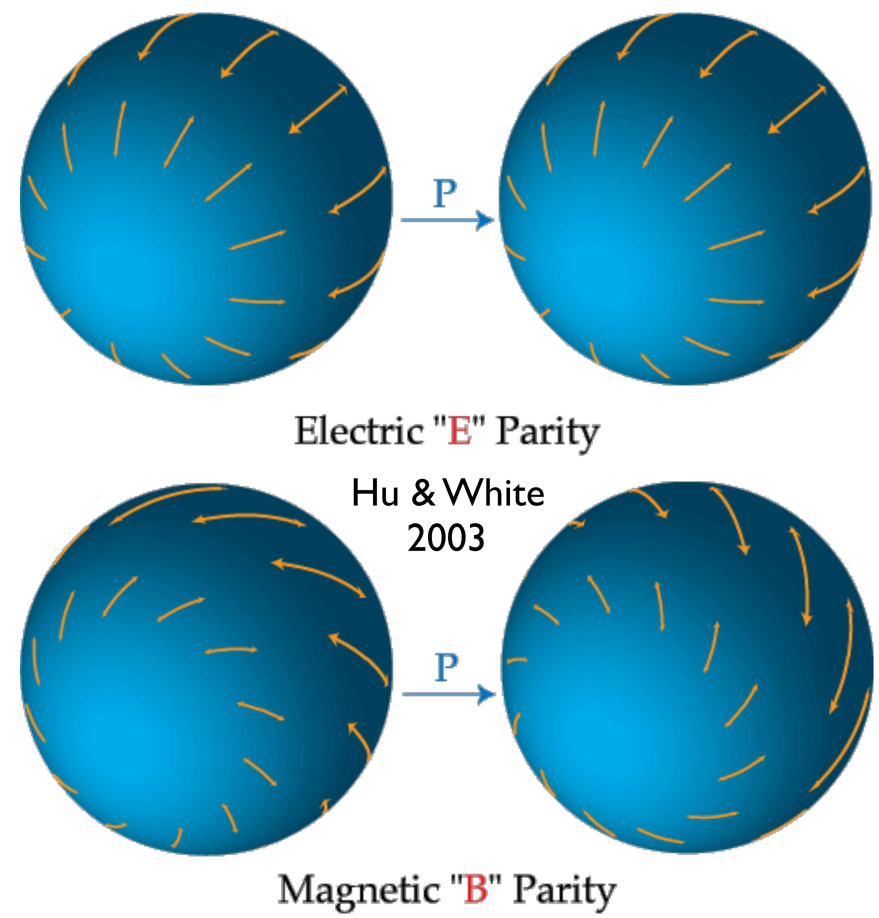

Hu & White 2003

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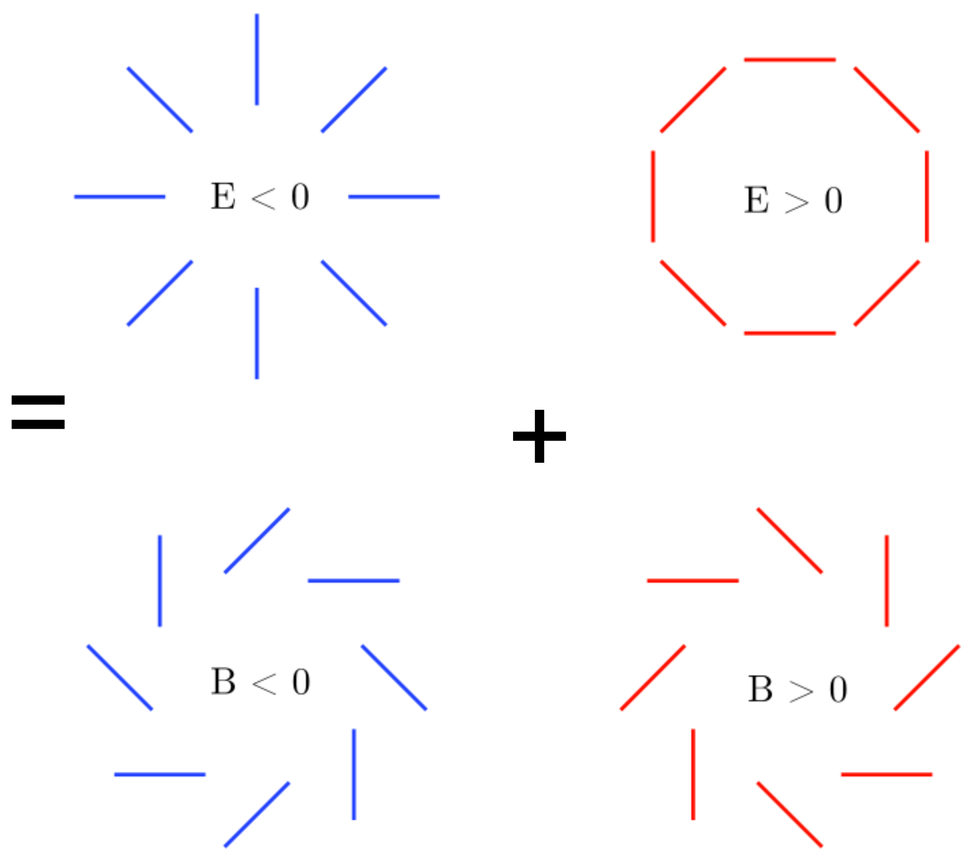
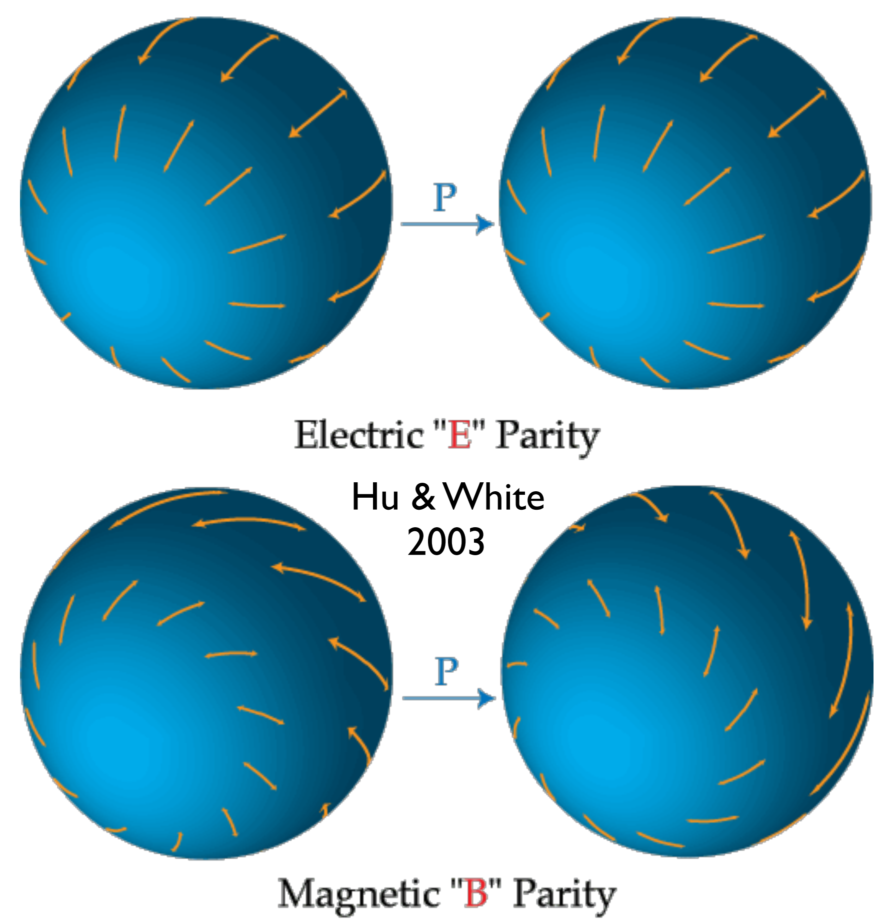
\end{aligned}
$$

- Non-local quantity, analogy with decomposition of electromagnetic field

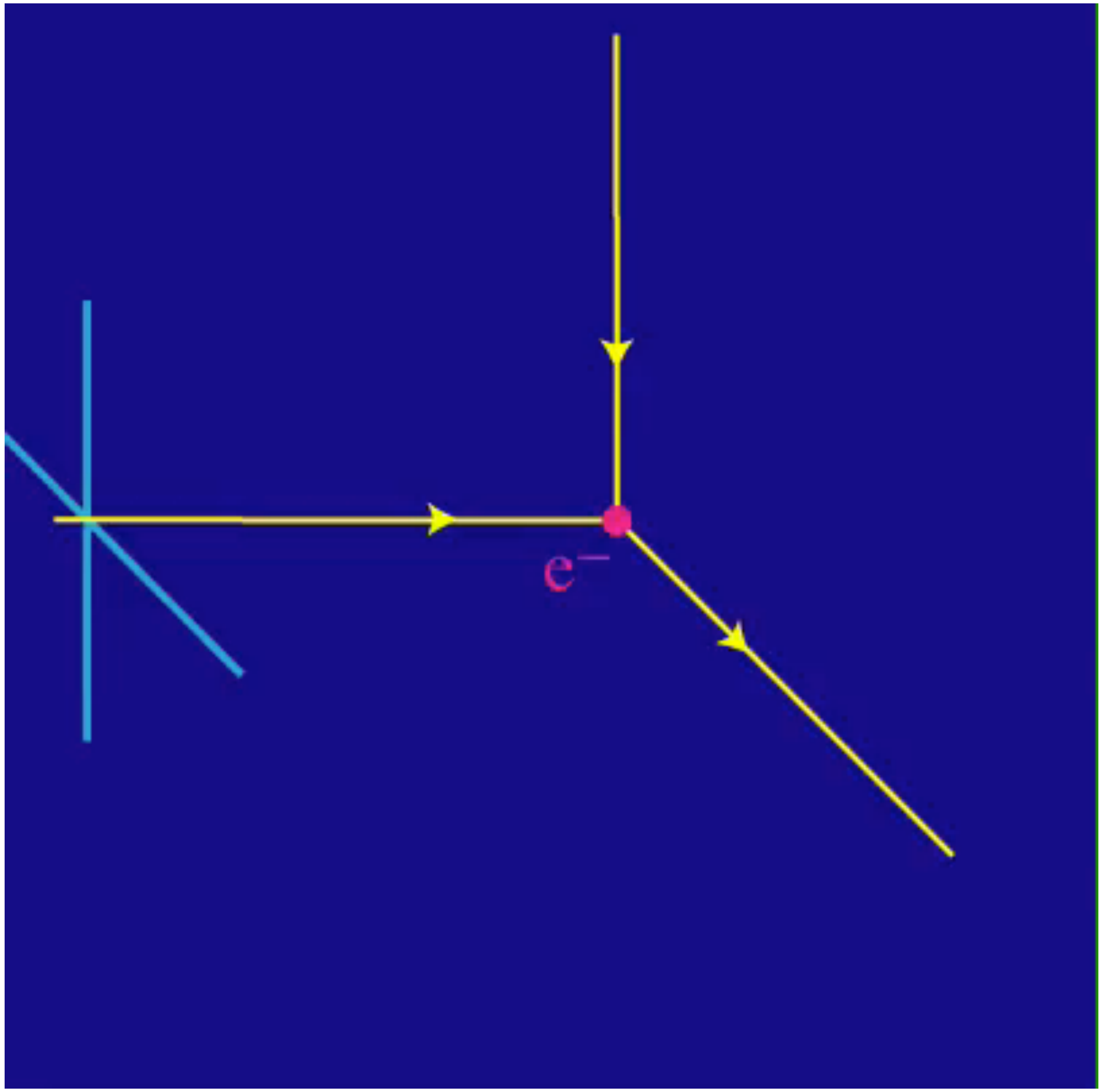
$$
\begin{aligned}
\langle E_{\ell m} E^*_{\ell' m'}\rangle &= \delta_{\ell\ell'}\delta_{mm'}C^{EE}_\ell \\
\langle B_{\ell m} B^*_{\ell' m'}\rangle &= \delta_{\ell\ell'}\delta_{mm'}C^{BB}_\ell \\
\langle E_{\ell m} B^*_{\ell' m'}\rangle &= \delta_{\ell\ell'}\delta_{mm'}C^{EB}_\ell \\
\langle \Theta_{\ell m} E^*_{\ell' m'}\rangle &= \delta_{\ell\ell'}\delta_{mm'}C^{\Theta E}_\ell \\
\langle \Theta_{\ell m} B^*_{\ell' m'}\rangle &= \delta_{\ell\ell'}\delta_{mm'}C^{\Theta B}_\ell \\
\langle \Theta_{\ell m} B^*_{\ell' m'}\rangle &= \delta_{\ell\ell'}\delta_{mm'}C^{\Theta B}_\ell
\end{aligned}
$$





Thomson scattering in action

- Maxwell's equation: waves propagate in the orthogonal w.r.t. their electric field direction
- When a incoming wave scatters, only a given component of the incoming wave is diffuse
- What happens when you have more than a single waves interacting....
- Let's assume we have an isotropic distribution (i.e only monopole)



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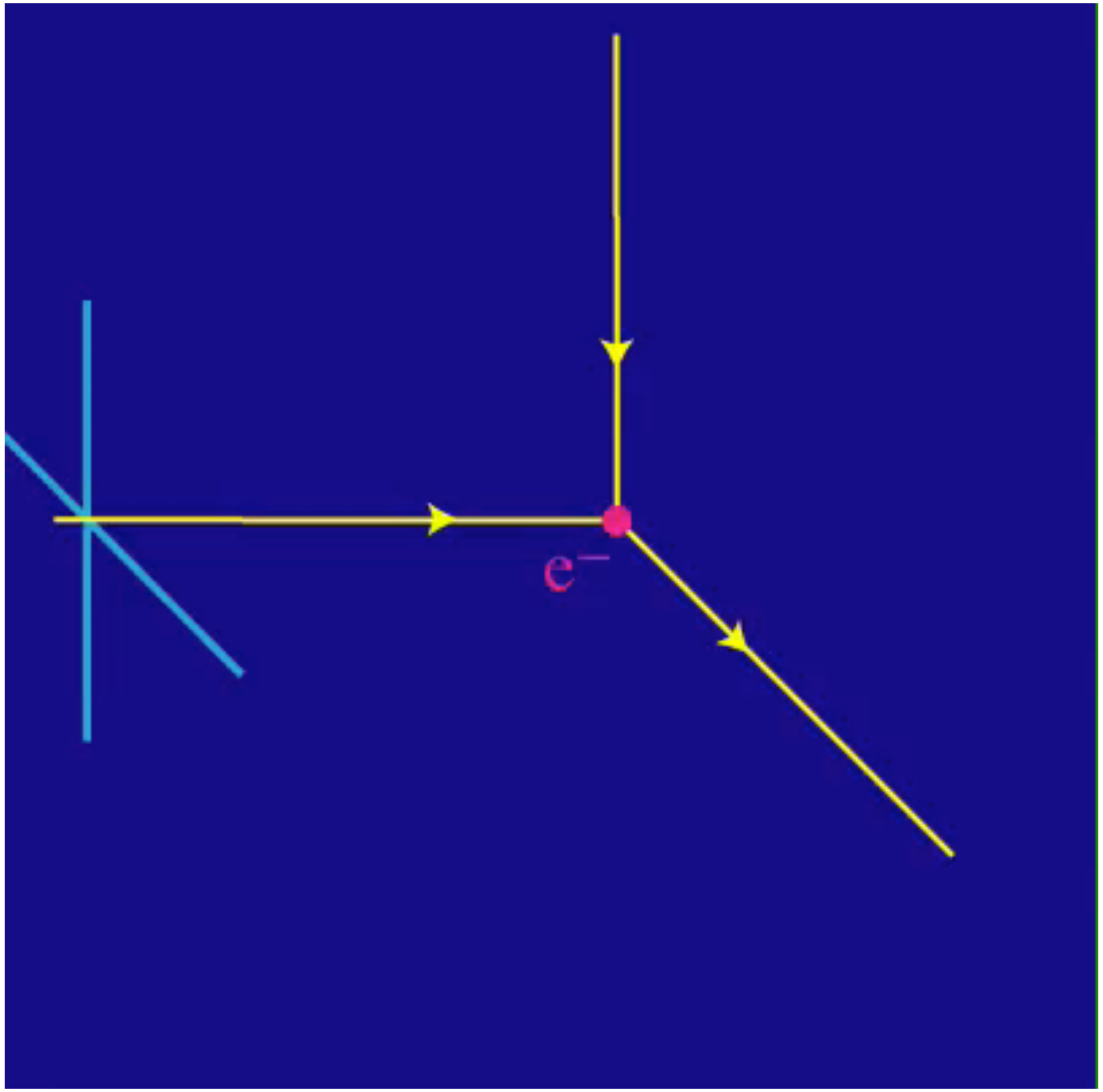

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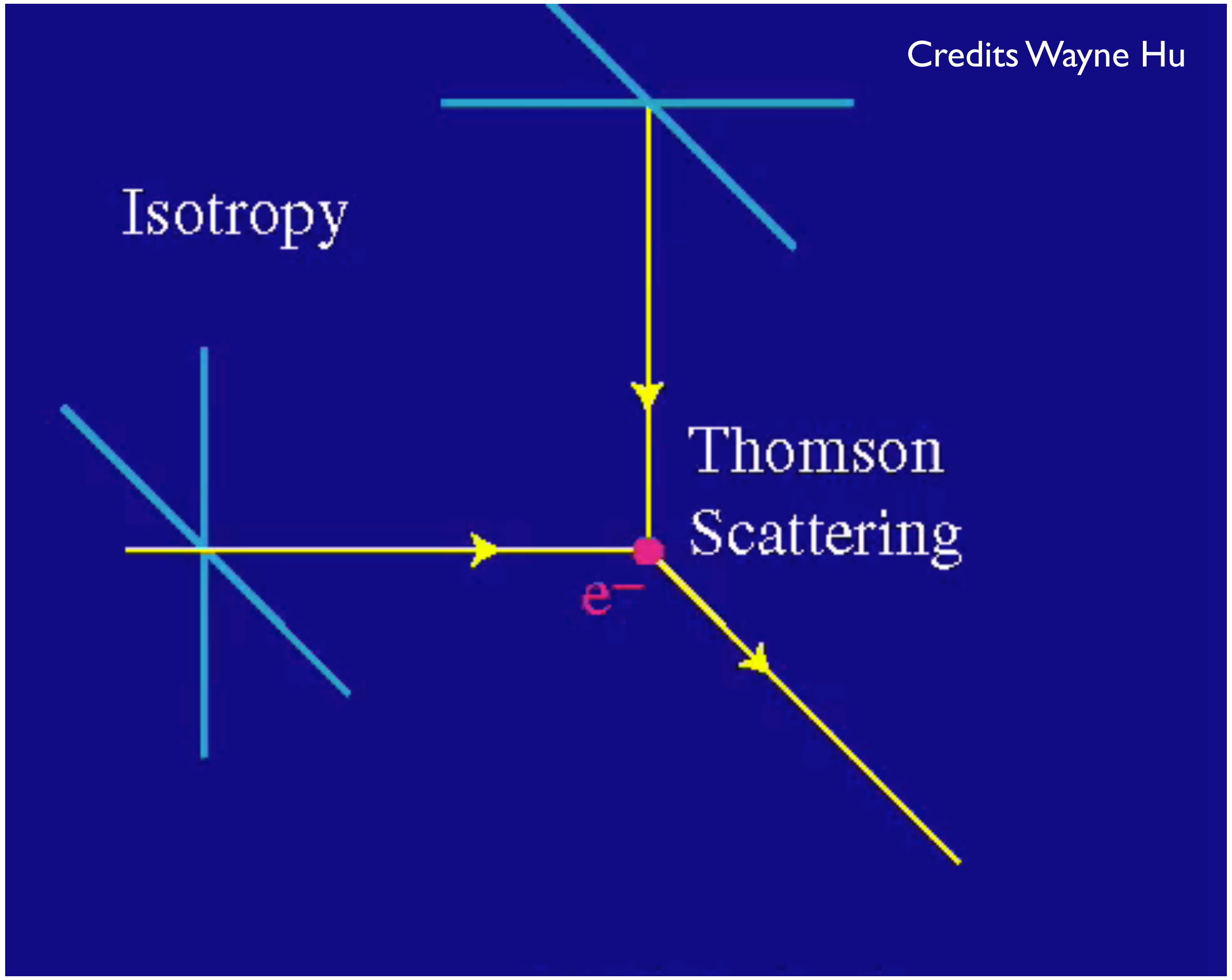

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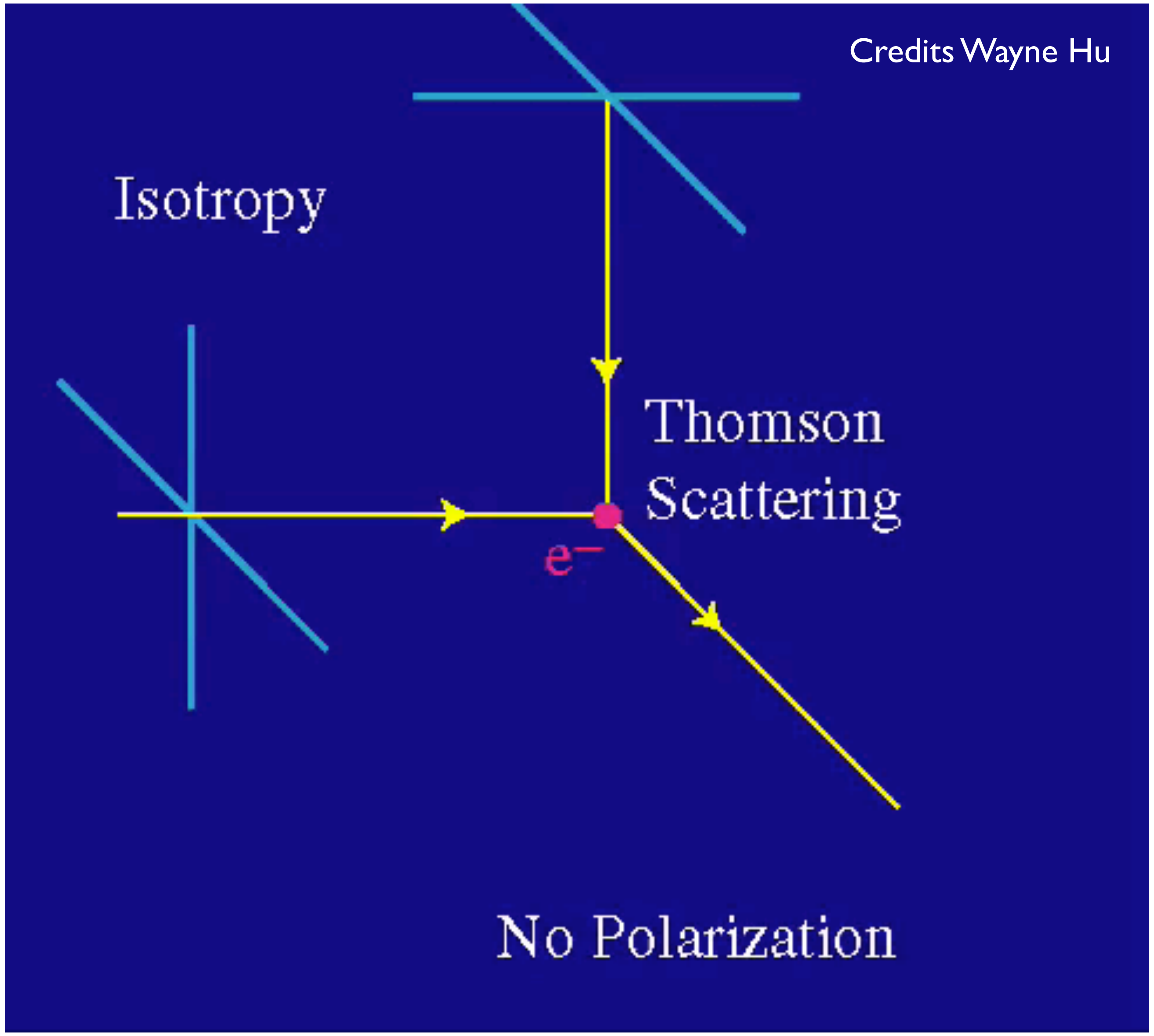
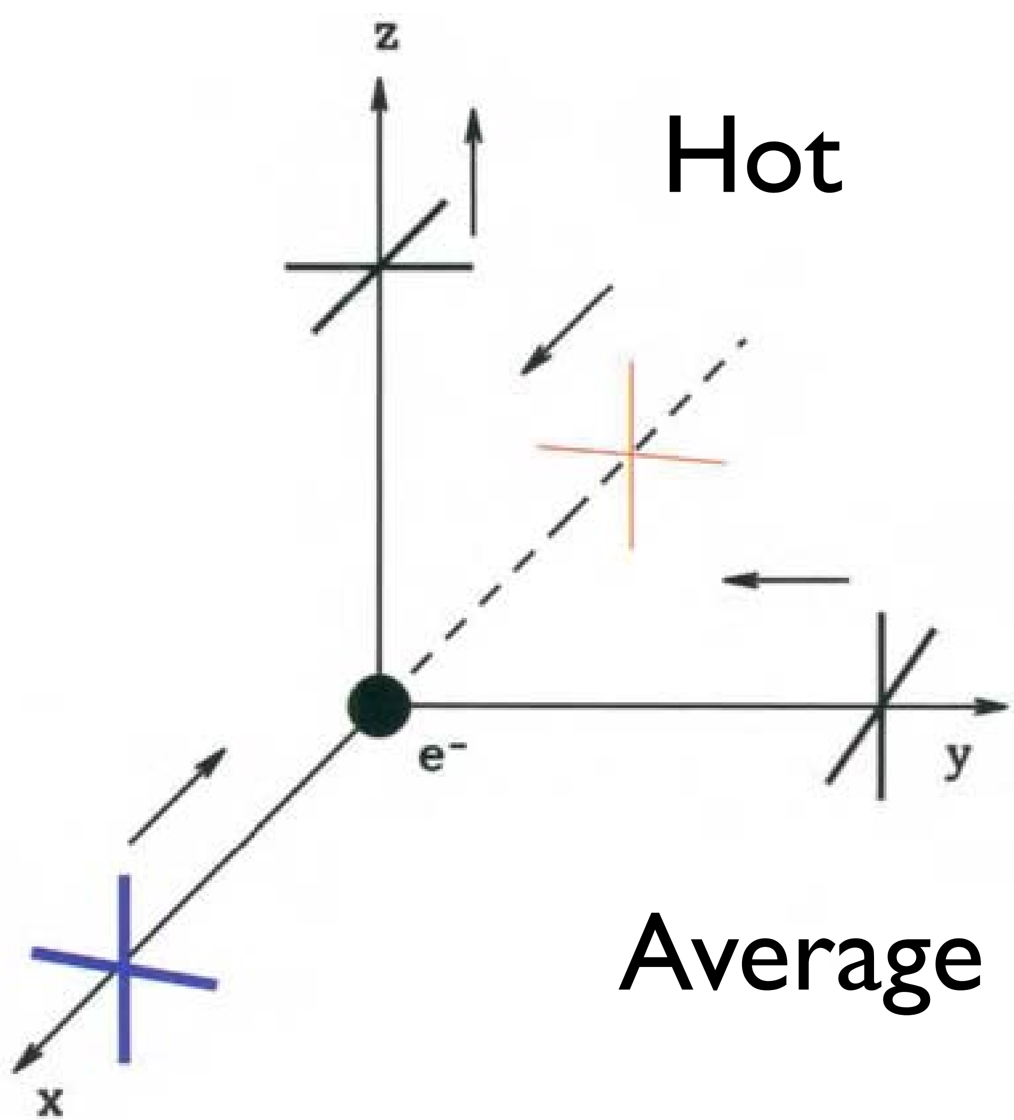


Thomson scattering in action - II

- What if we have a dipole anisotropy?

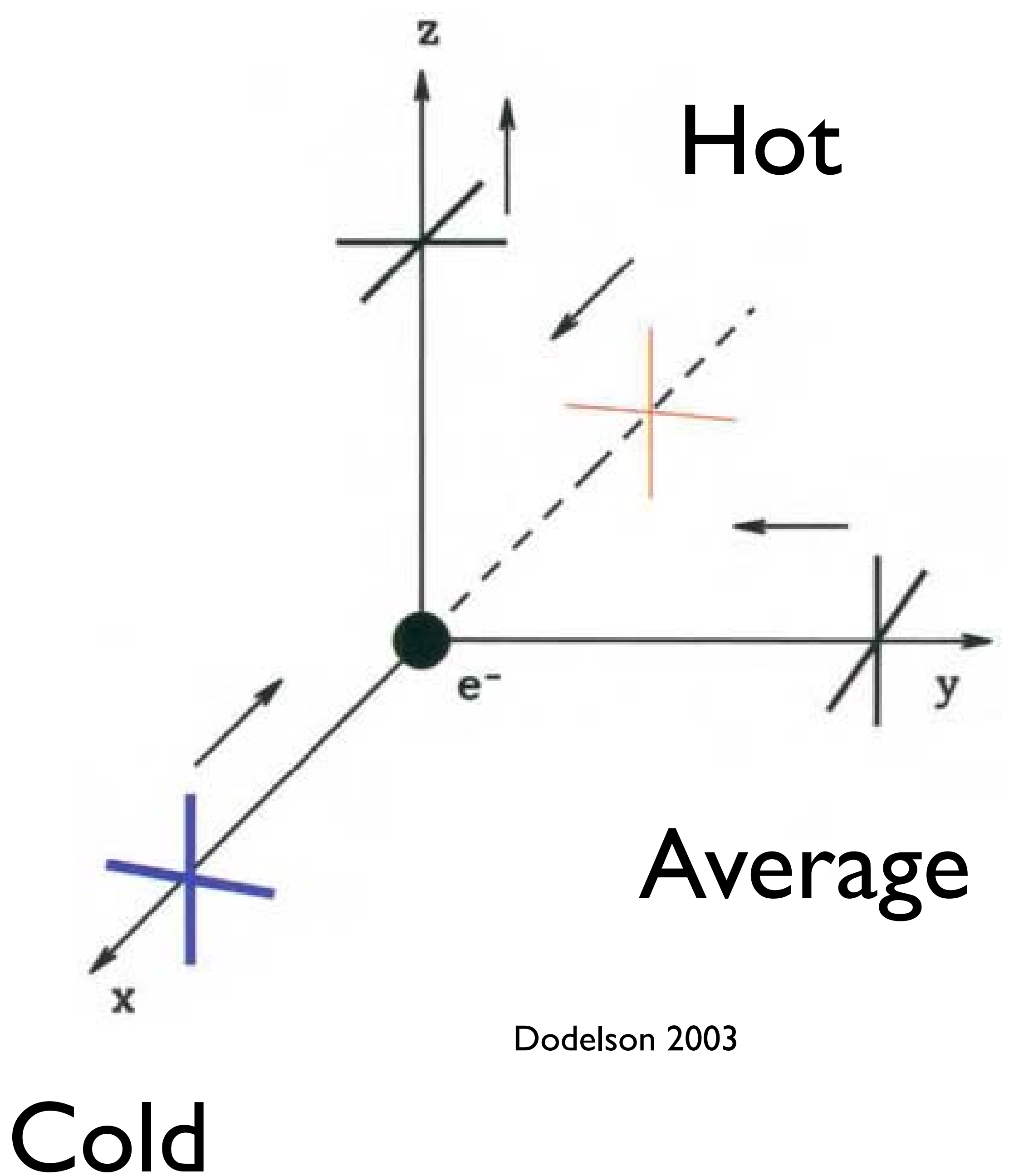


Dodelson 2003

Cold

Thomson scattering in action - II

- What if we have a dipole anisotropy?
- What if we have a quadrupolar anisotropy?



Dodelson 2003

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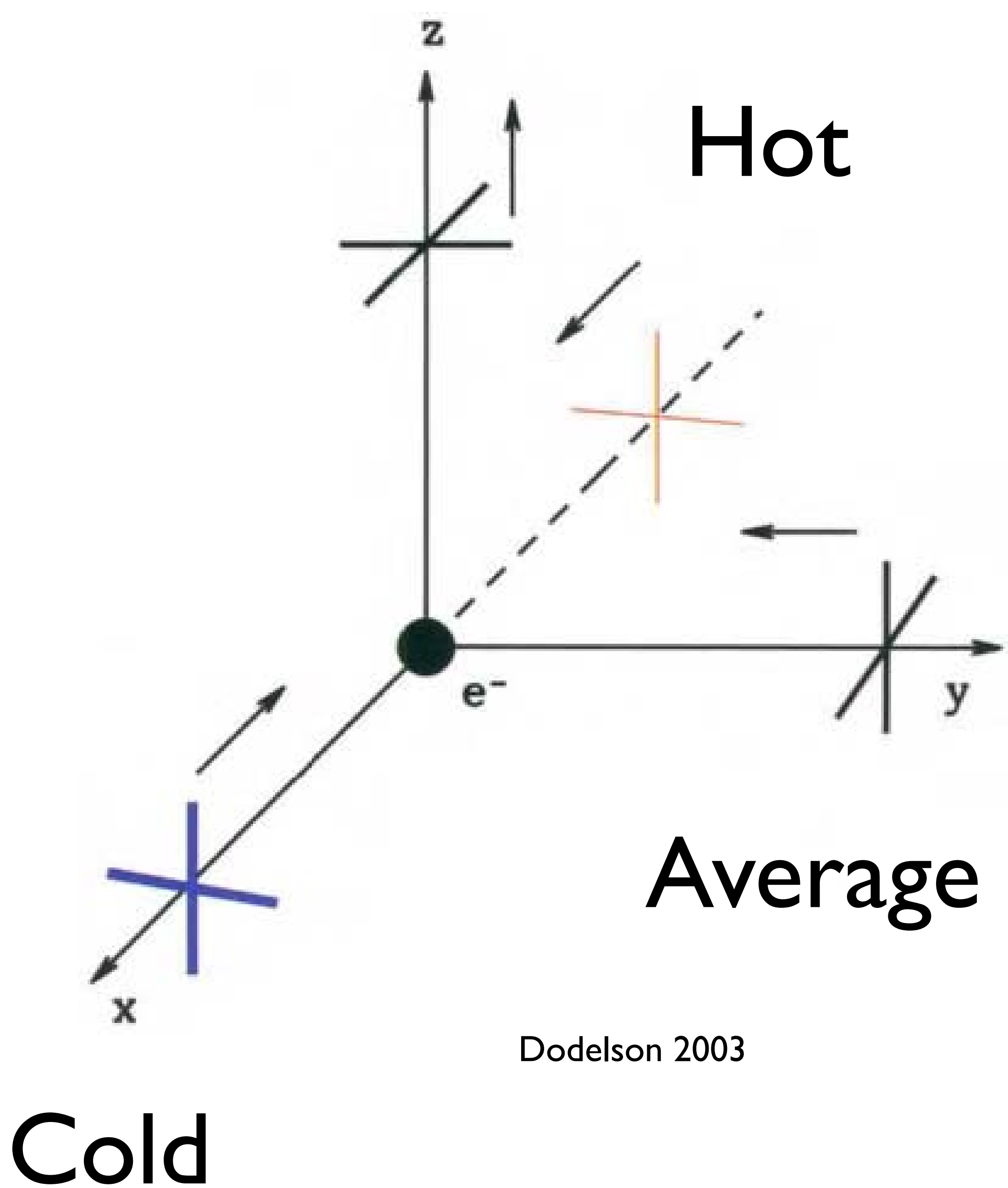
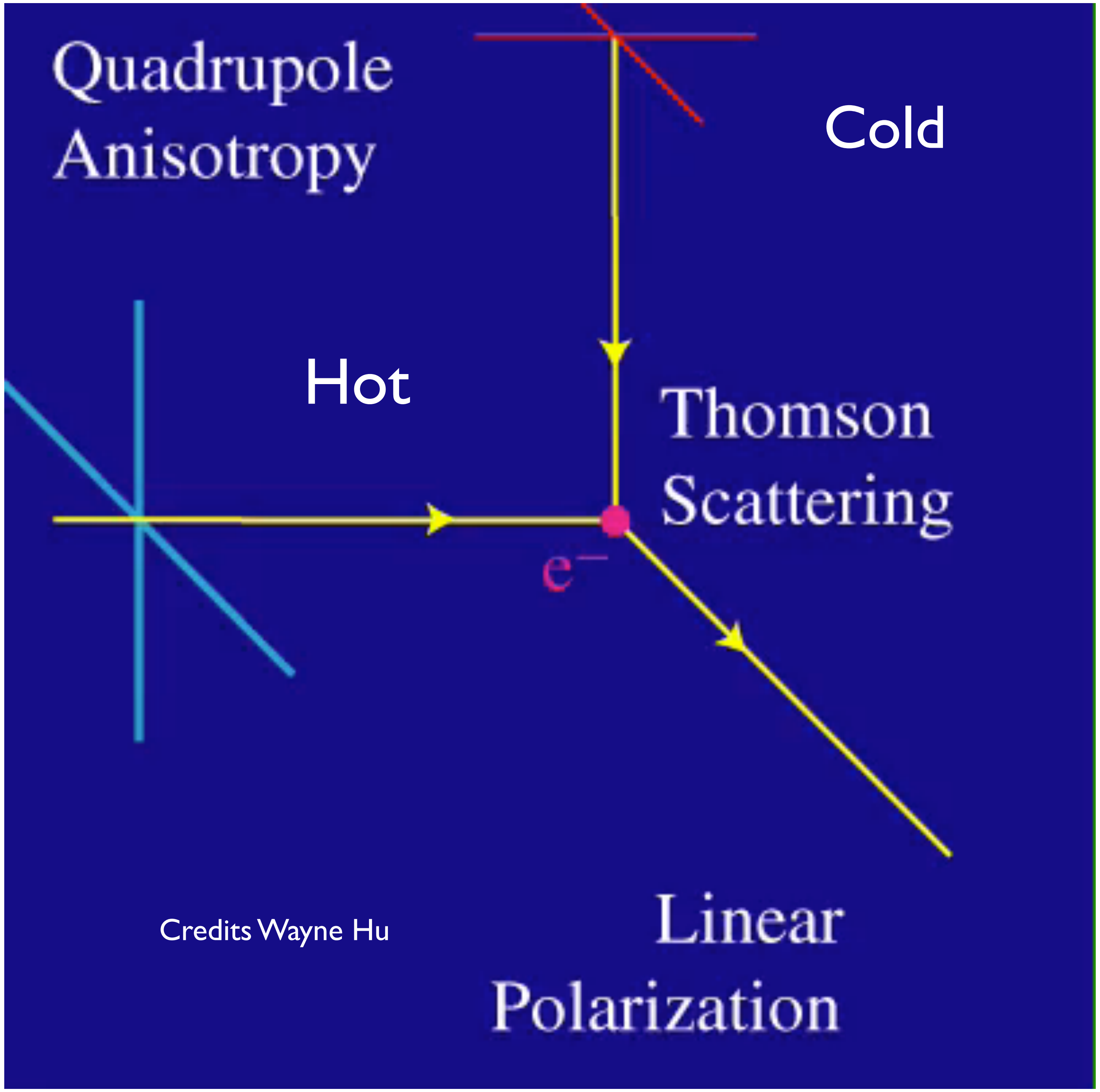


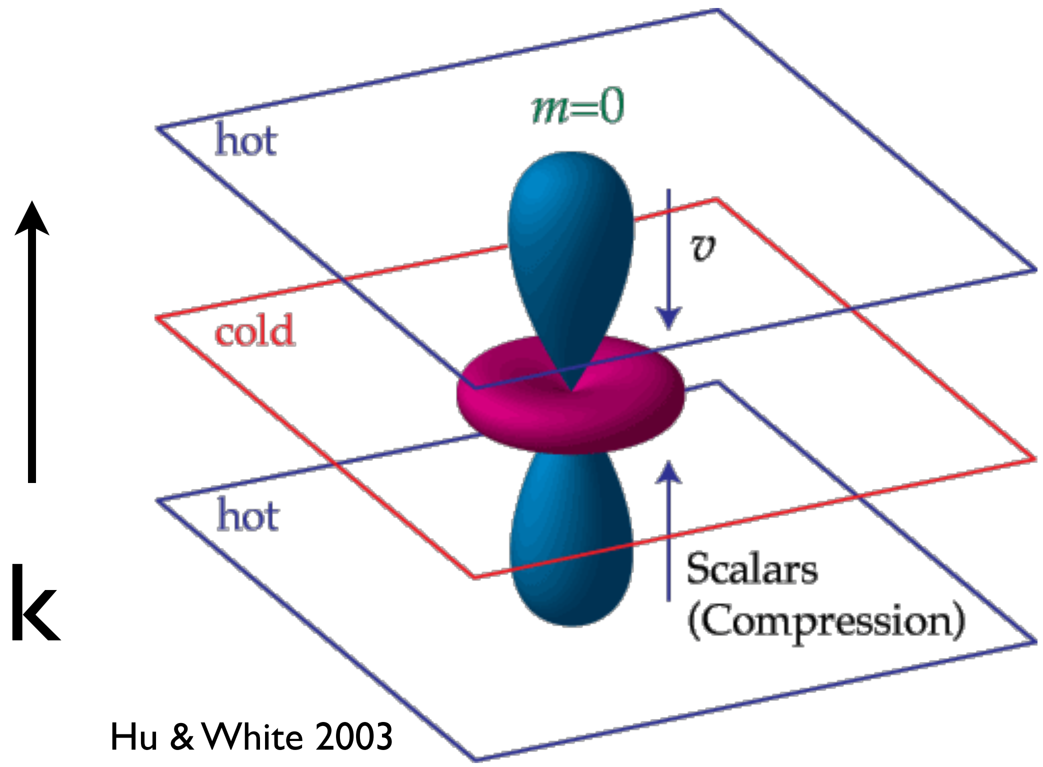
Dodelson 2003



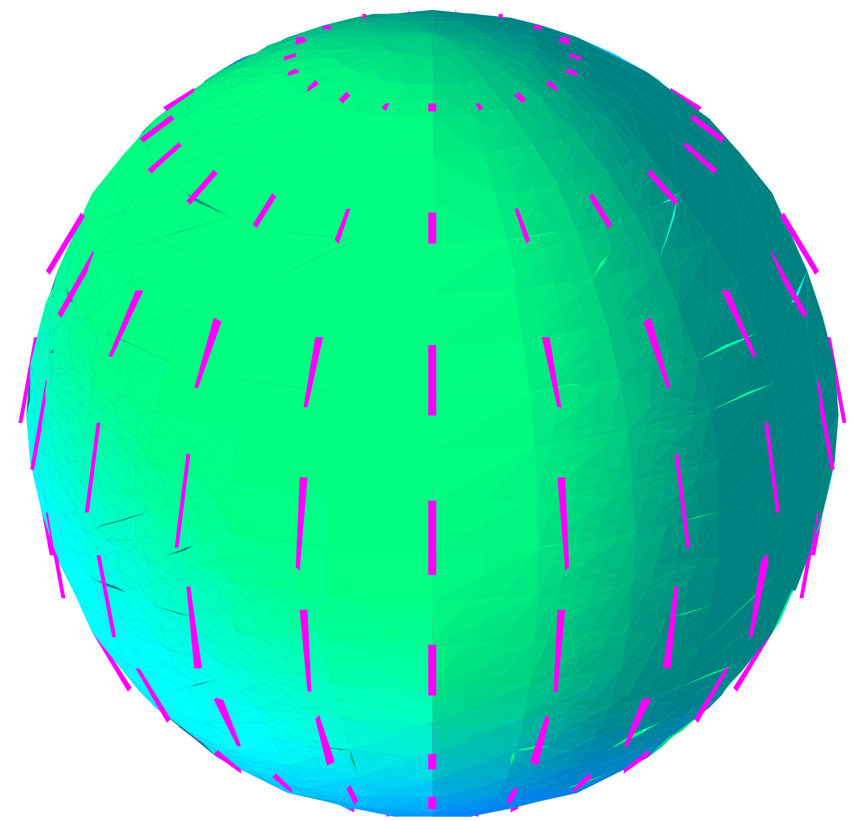
Credits Wayne Hu

How to generate a quadrupole: scalar perturbations

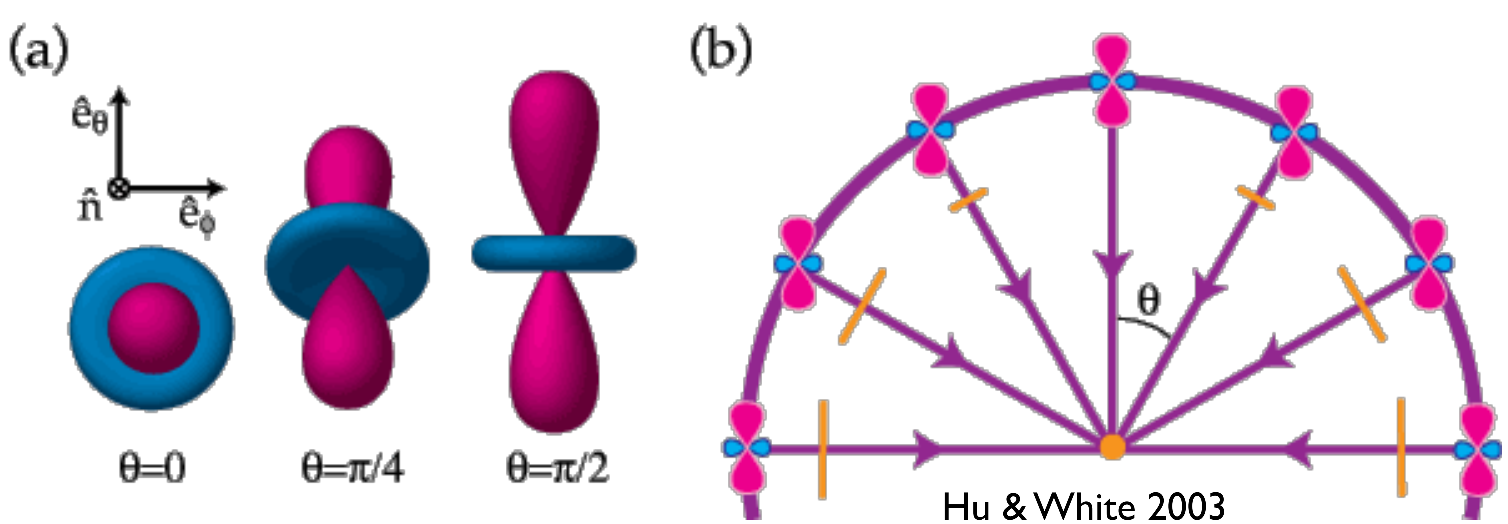
- Single plane wave of scalar perturbation propagating along z



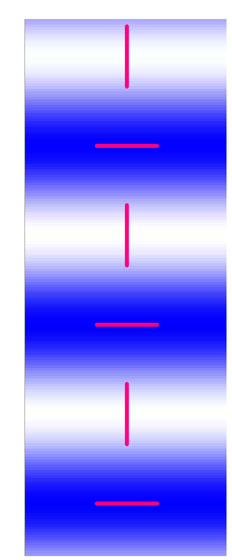
Scattering



- Polarization modulated by quadrupole orientation and projection effects

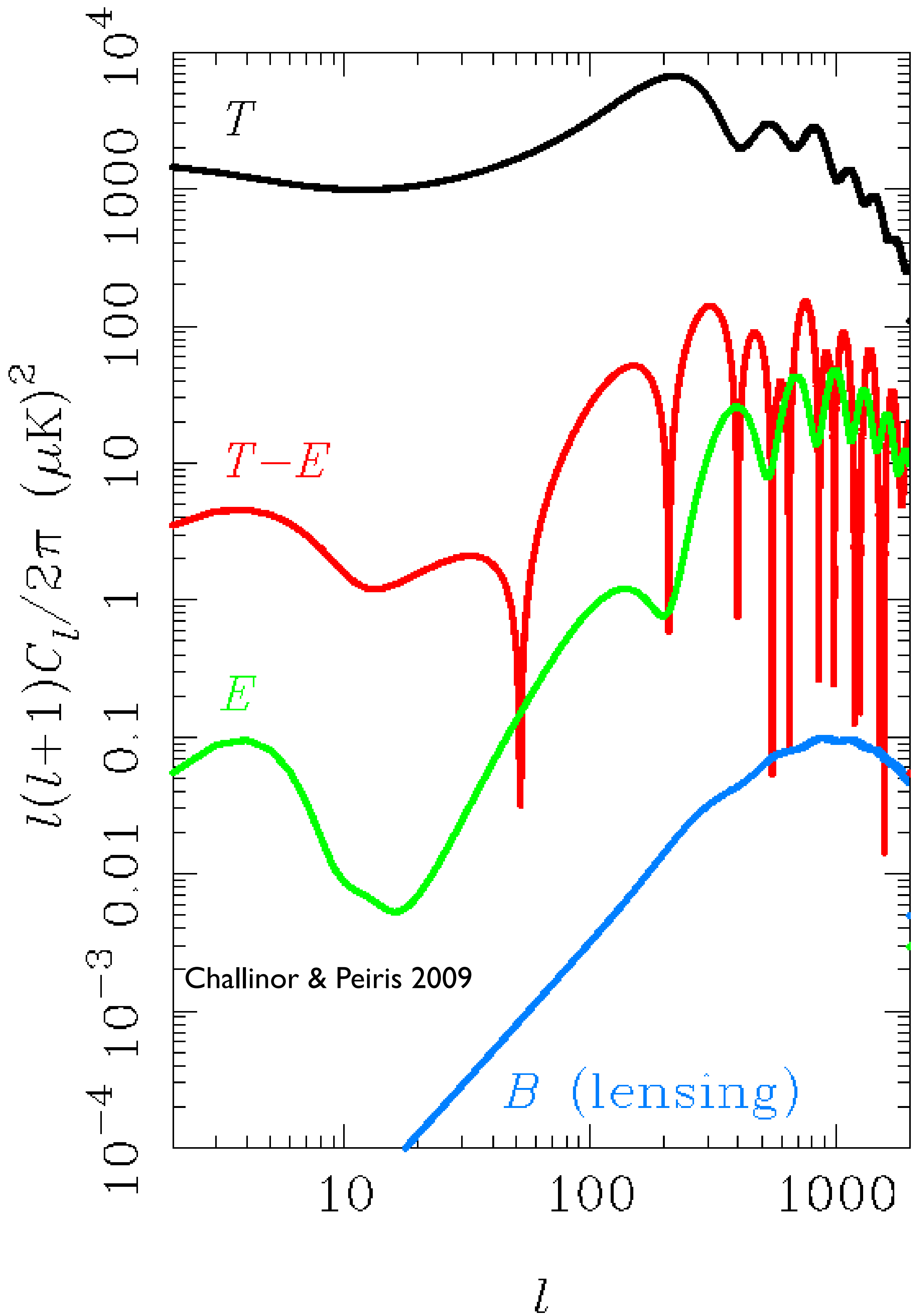


Observed pattern



Pure E-modes

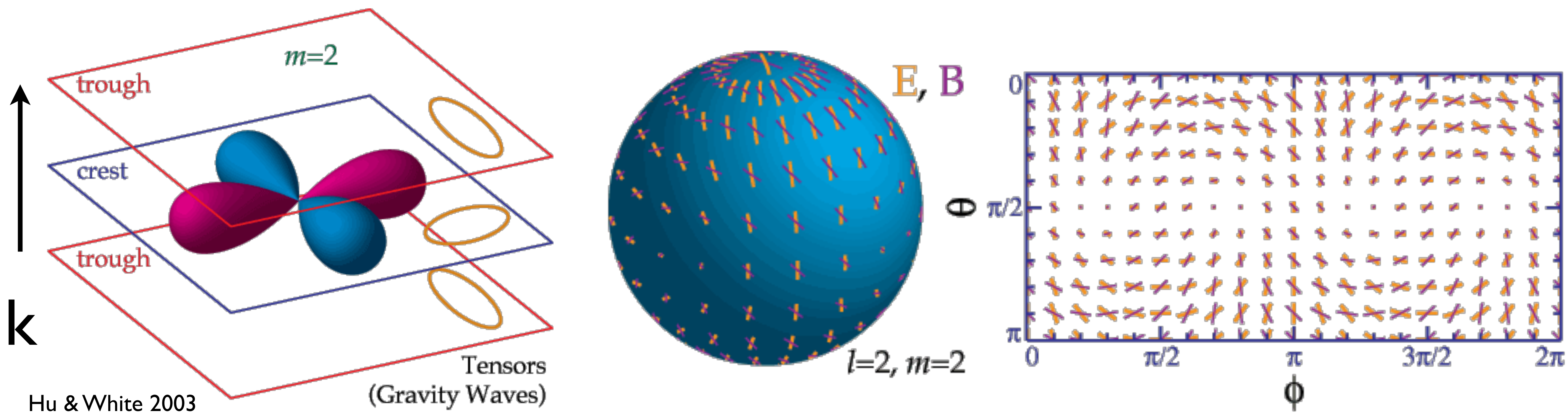
Polarization from scalar perturbation



- Polarization probes mainly baryon velocity at last scattering
- E-modes peak at minima of T (pressure and velocity are out of phase)
- T and E-modes are correlated
- Probe nature of pertubations
- B-modes are generated at second order in perturbation theory or through gravitational lensing

Tensor perturbations

- Transverse-traceless perturbation behave like gravity waves: distortion of space in the plane of the perturbation

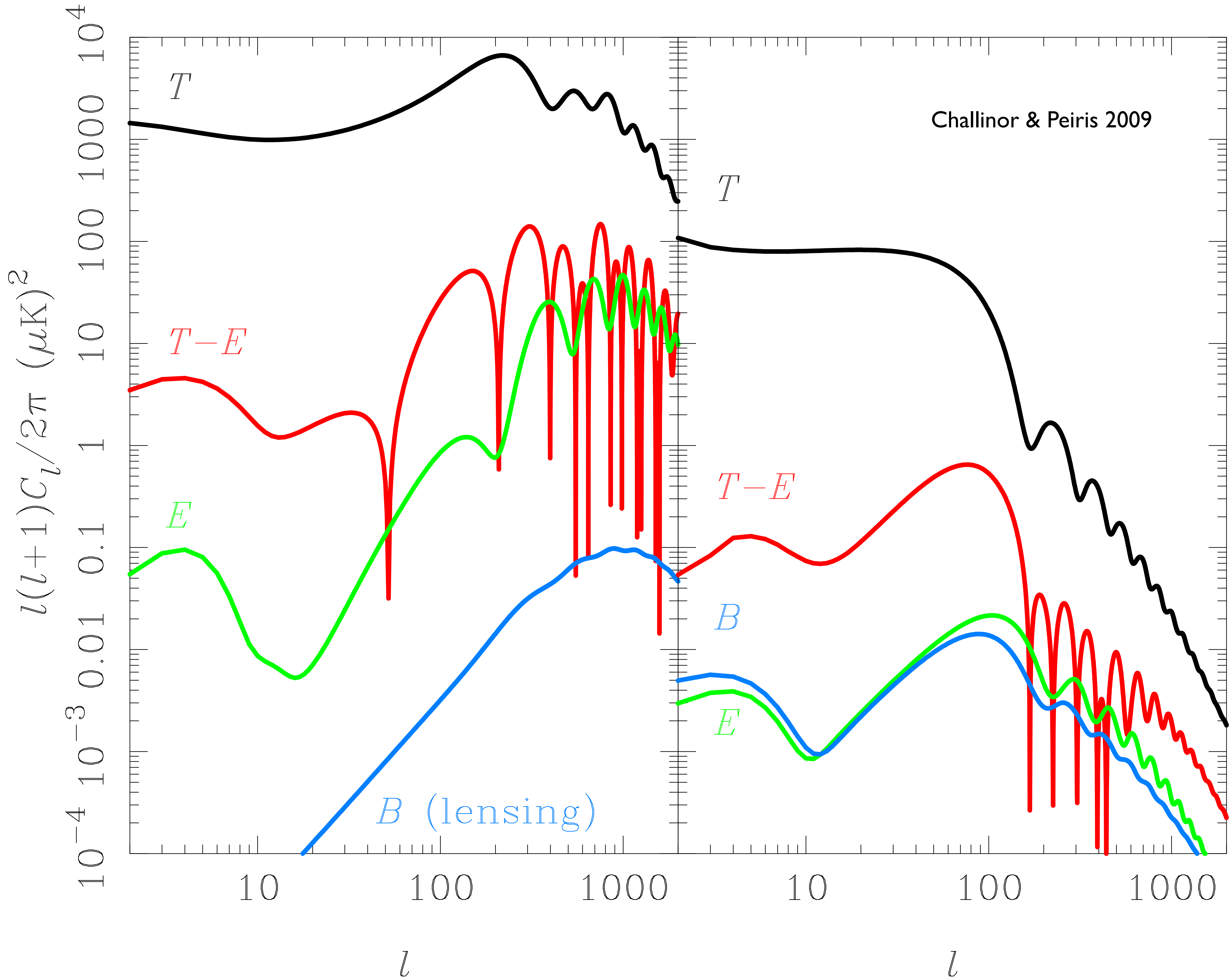


- Generation of E and B at the same time and with the same amplitude

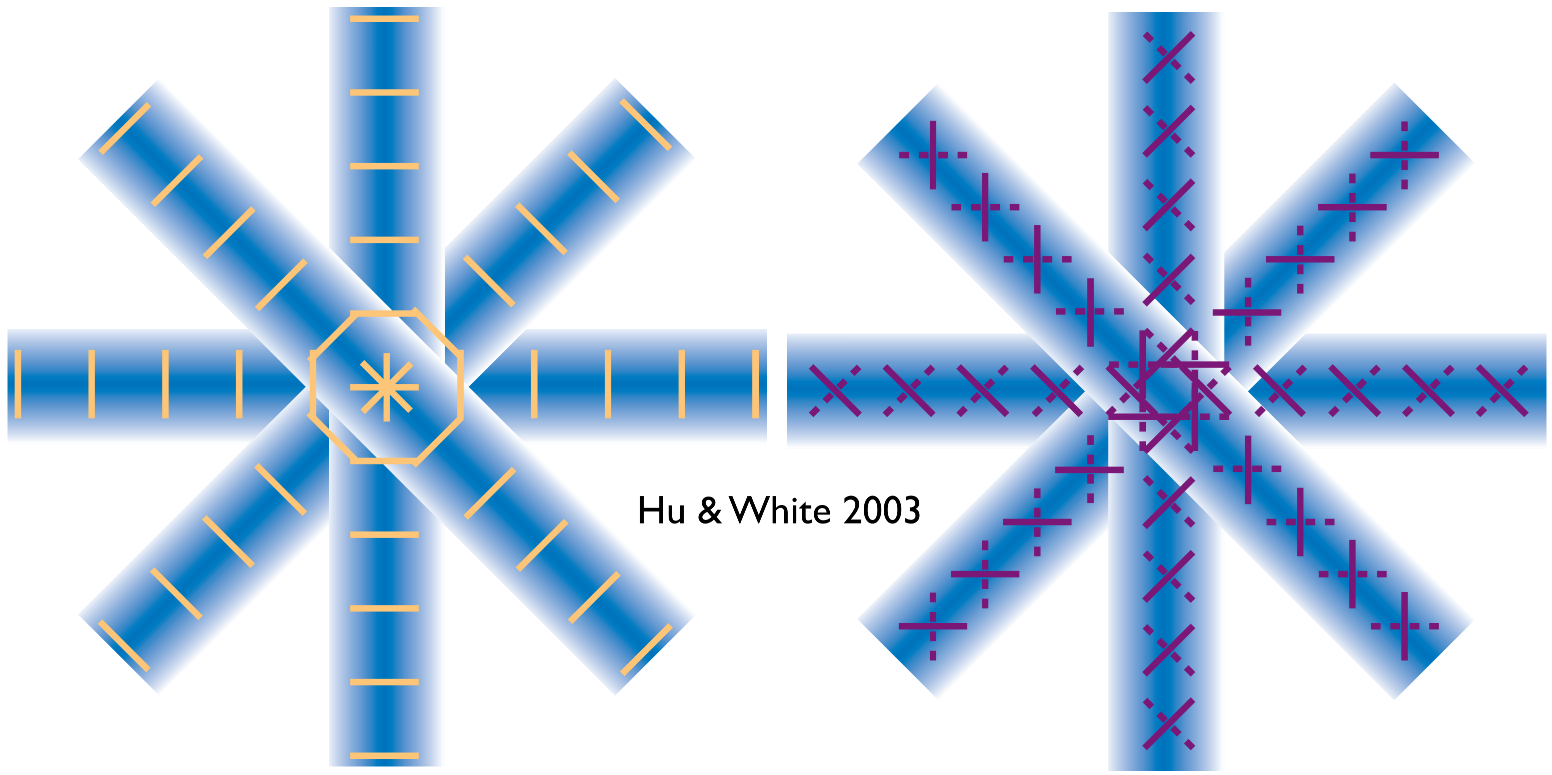
- Gravity waves decay once entered in the horizon: contribution confined to large scales

$$\ddot{H}_T^{(\pm 2)} + 2\mathcal{H}\dot{H}_T^{(\pm 2)} + (k^2 + 2K)H_T^{(\pm 2)} = 8\pi G a^2 p \pi_T^{(\pm 2)}$$

Tensor power spectrum r=0.2



Large scale T-E correlation



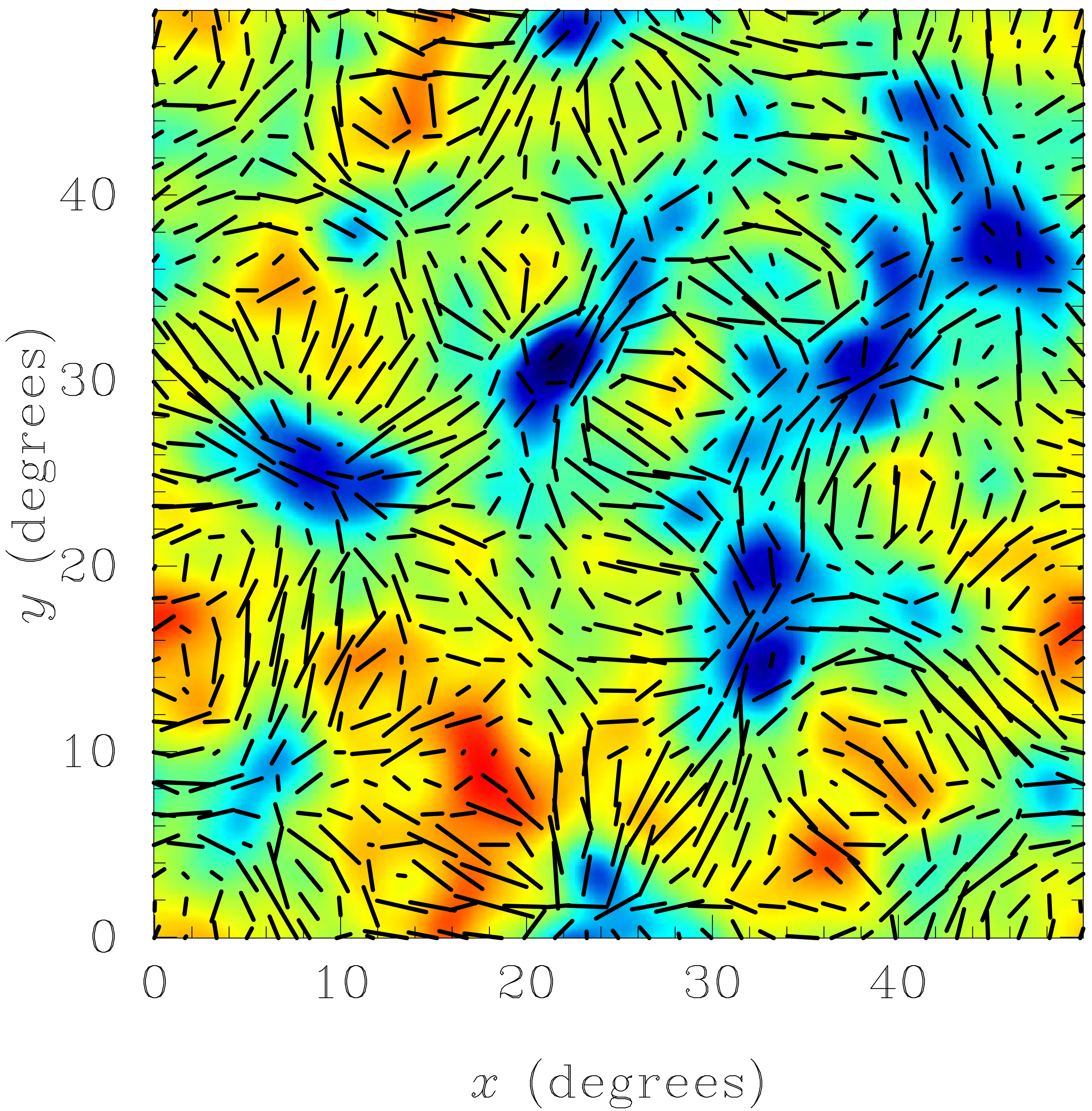
E (anti) correlation

B no correlation

- Photon fluid flows from hot regions to cold initially
- Around a crest: intensity peaks in the directions along the crest and falls off to the neighboring troughs

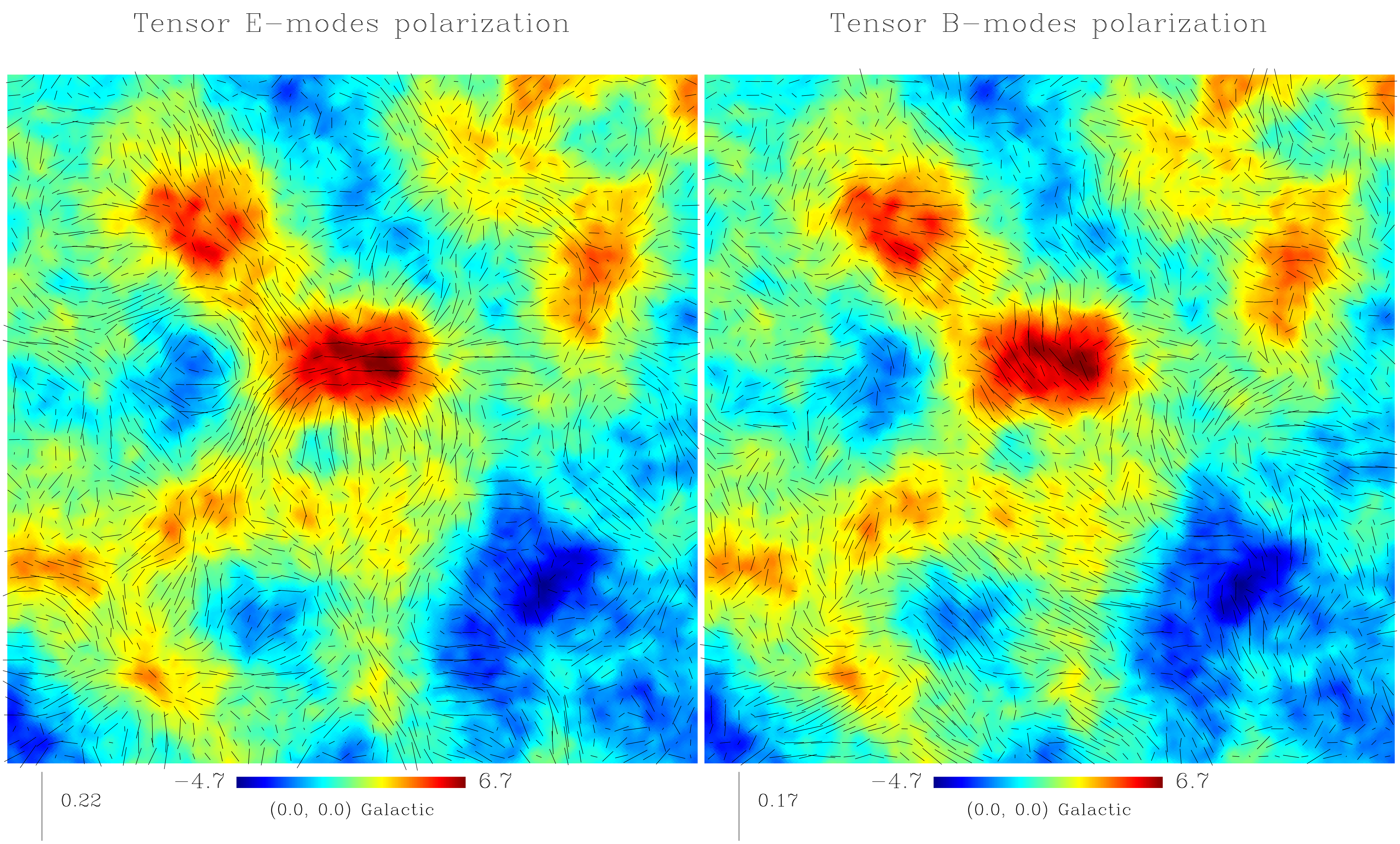
- Final polarization is orthogonal to the crest or parallel to the trough for points on the through
- Pattern is tangential around hot spots and radial around cold spots

Real space T-E correlation (scalar)

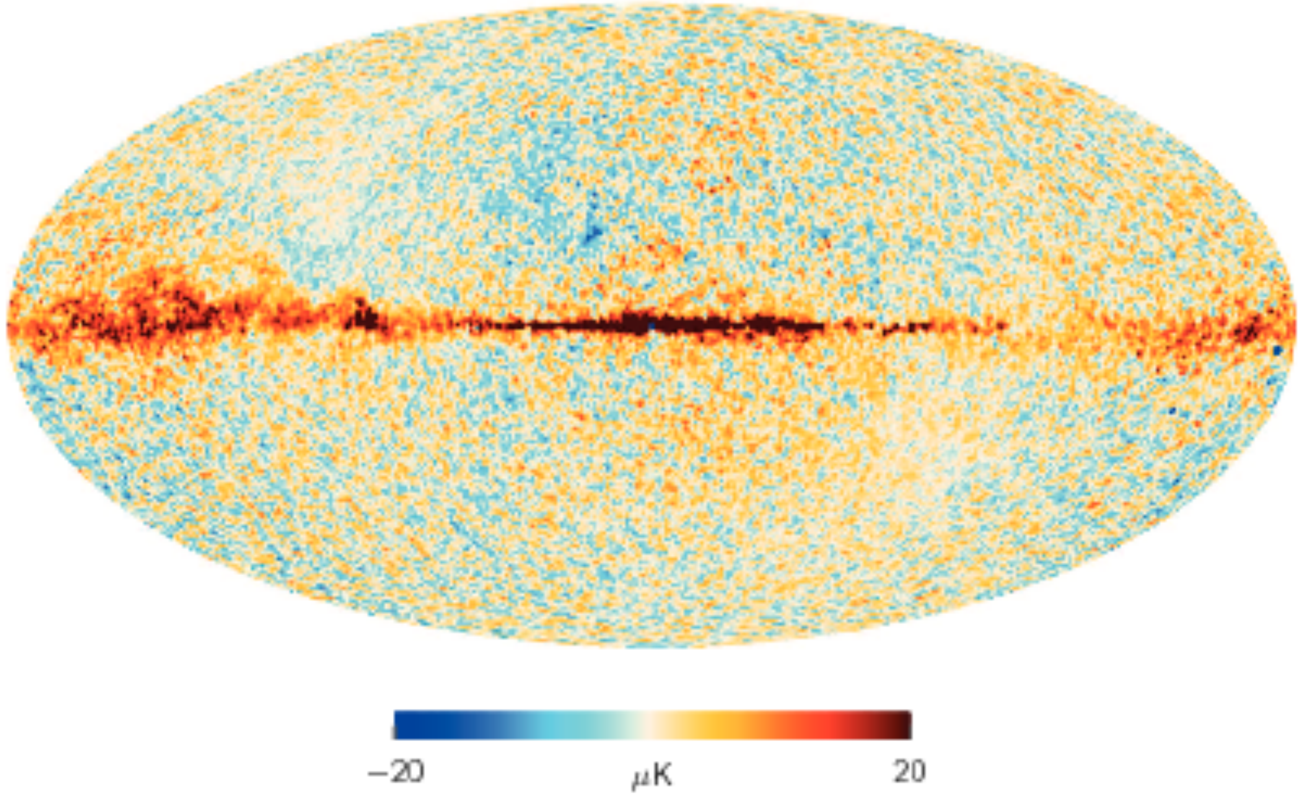


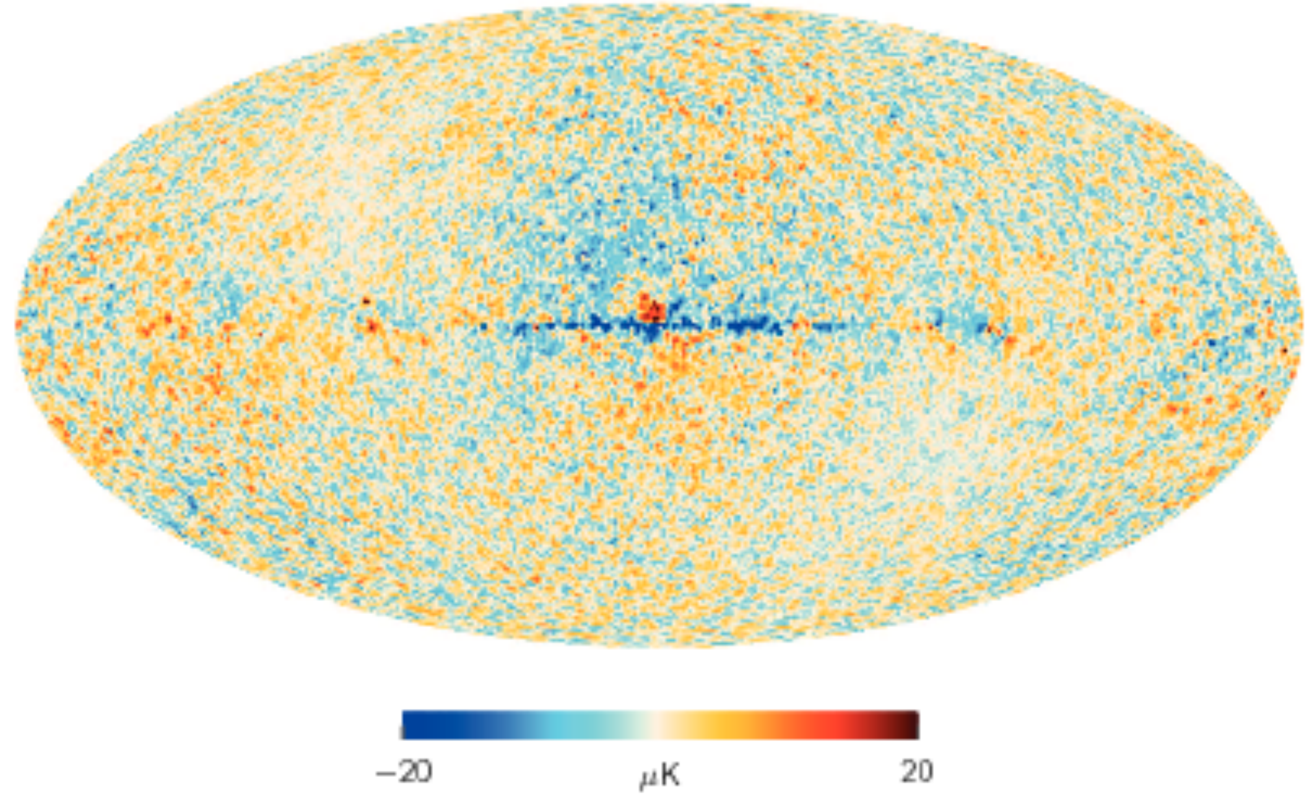
Credits Anthony Challinor

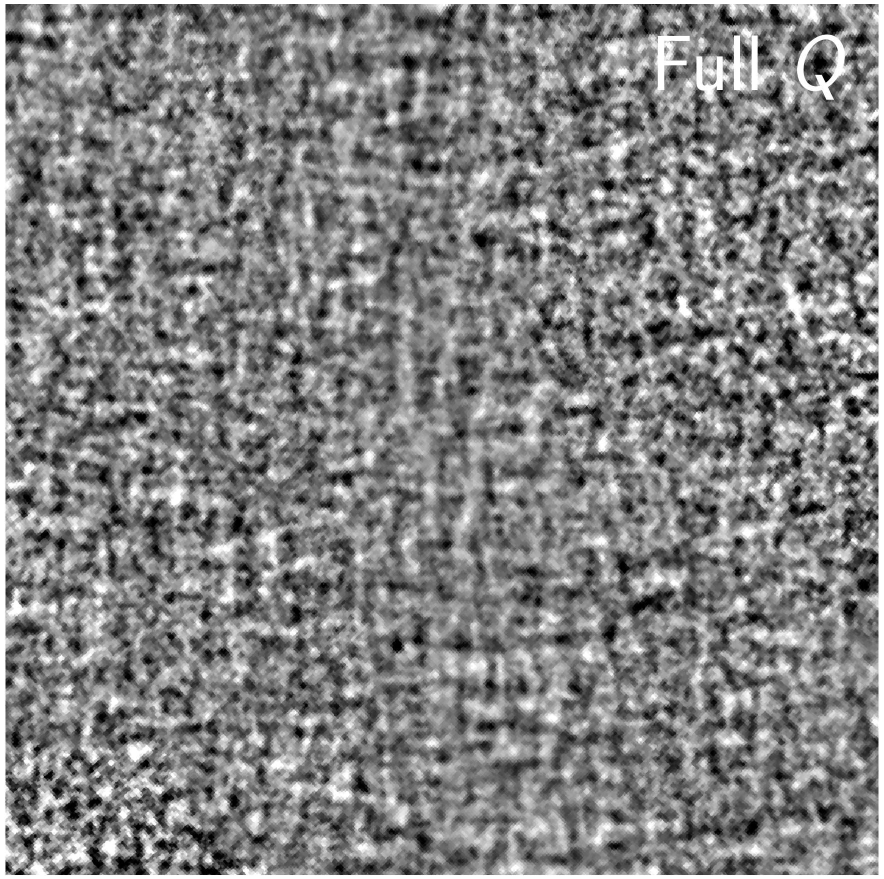
Real space T-E correlation (tensors)

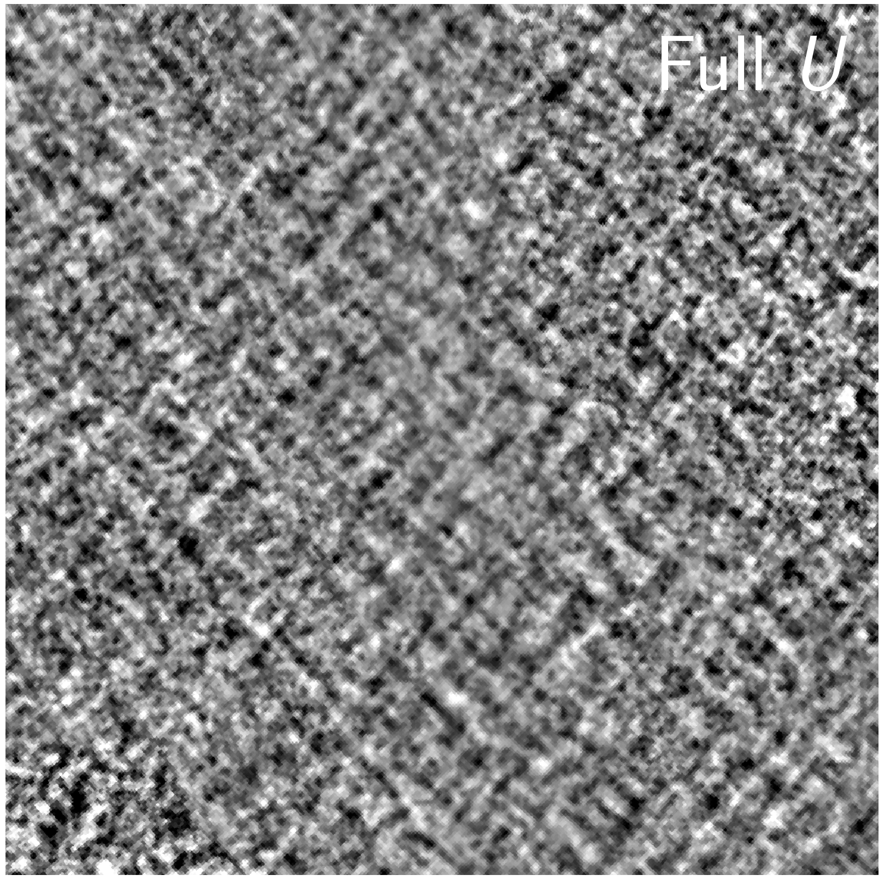


Current maps from Planck (satellite)









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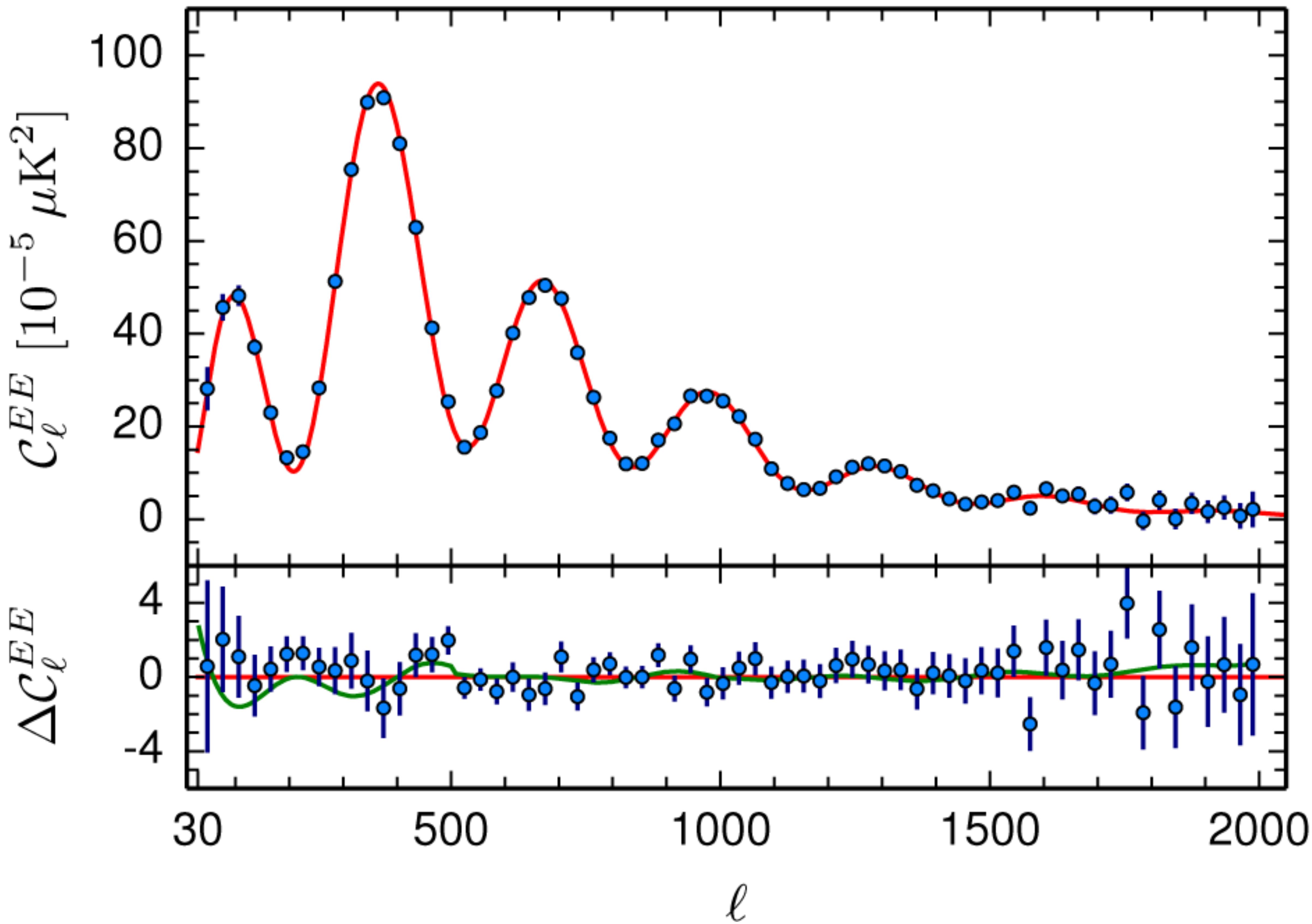

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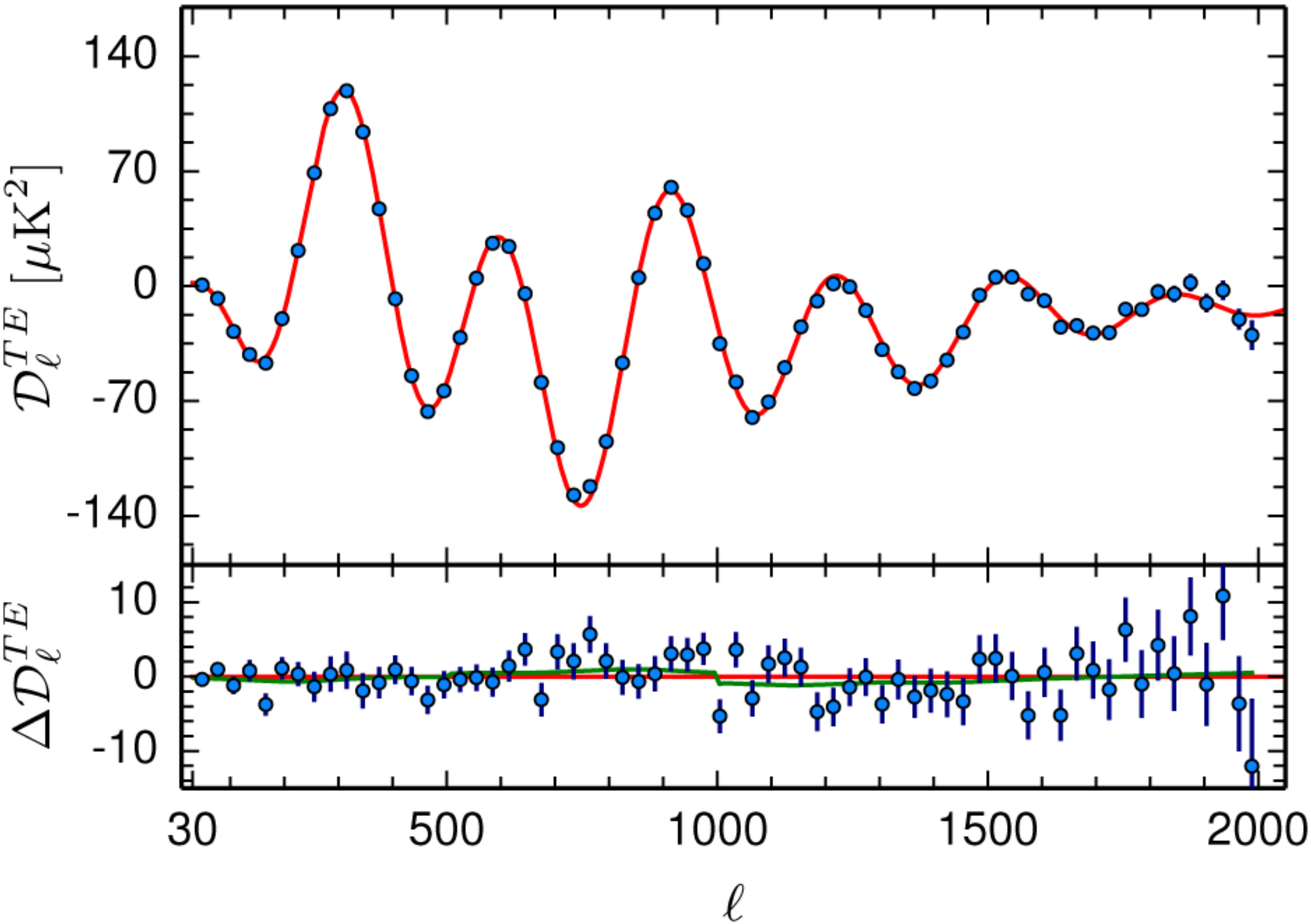
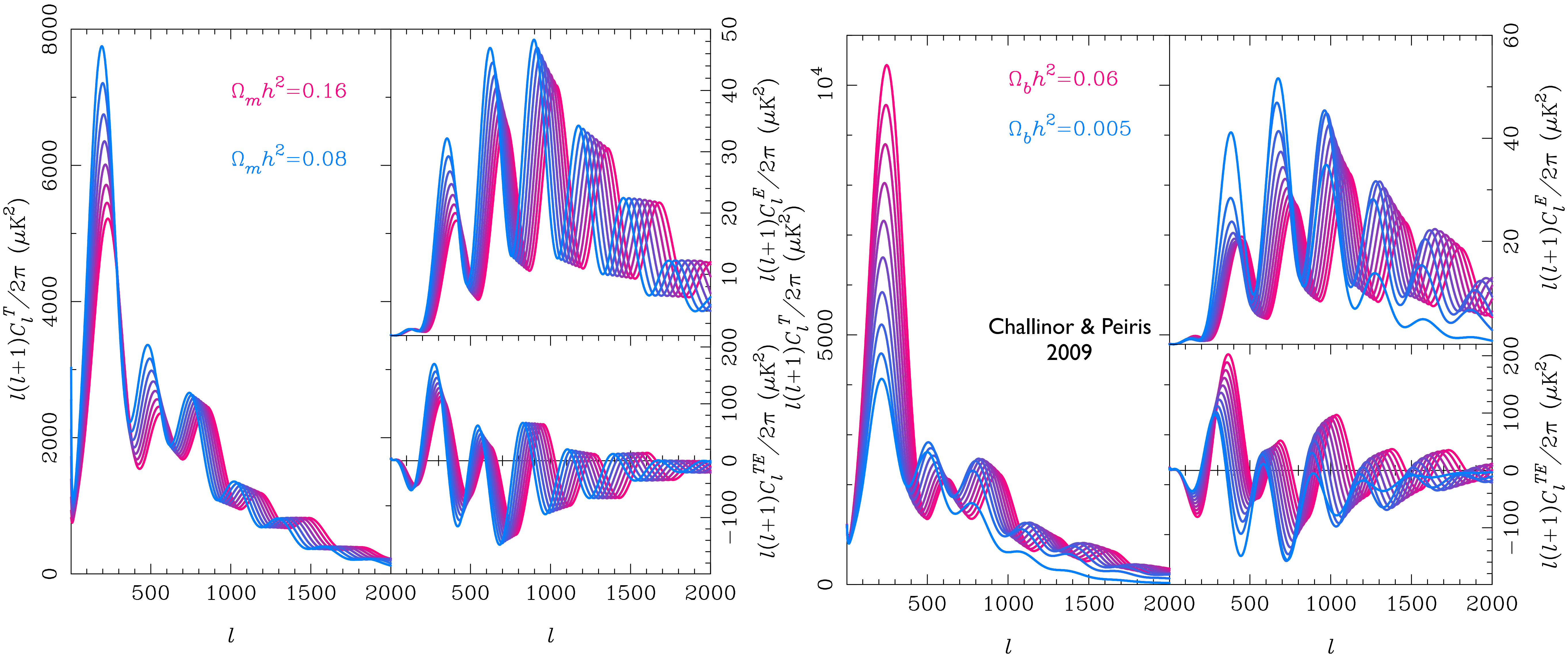


Cosmological constraints of CMB polarization

- E-modes, TE correlation sensible to physics of acoustic oscillations
- No Sachs-Wolf, ISW, nor Doppler terms for polarization: signal is cleaner (if noise is sufficiently low)



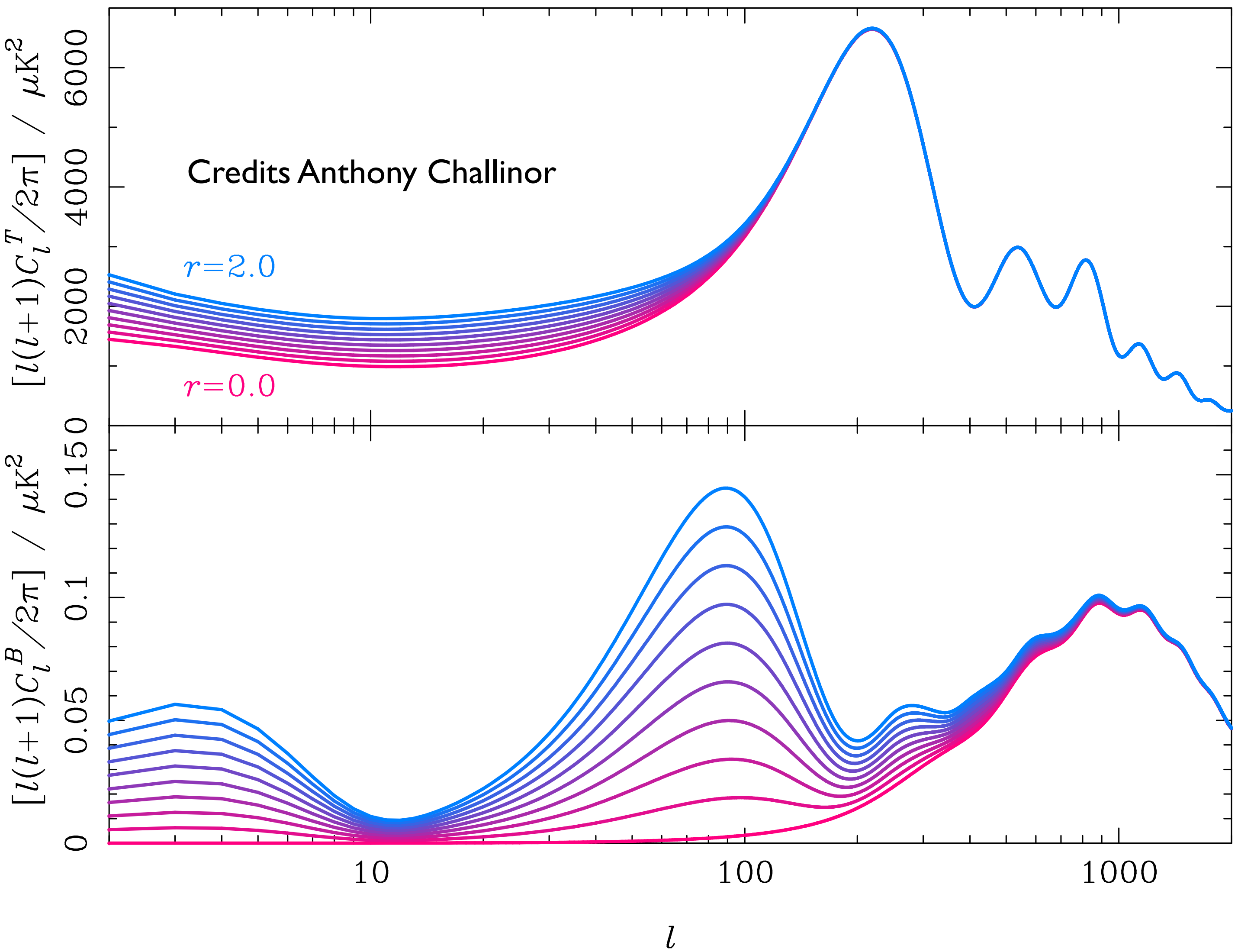
T/S constraints

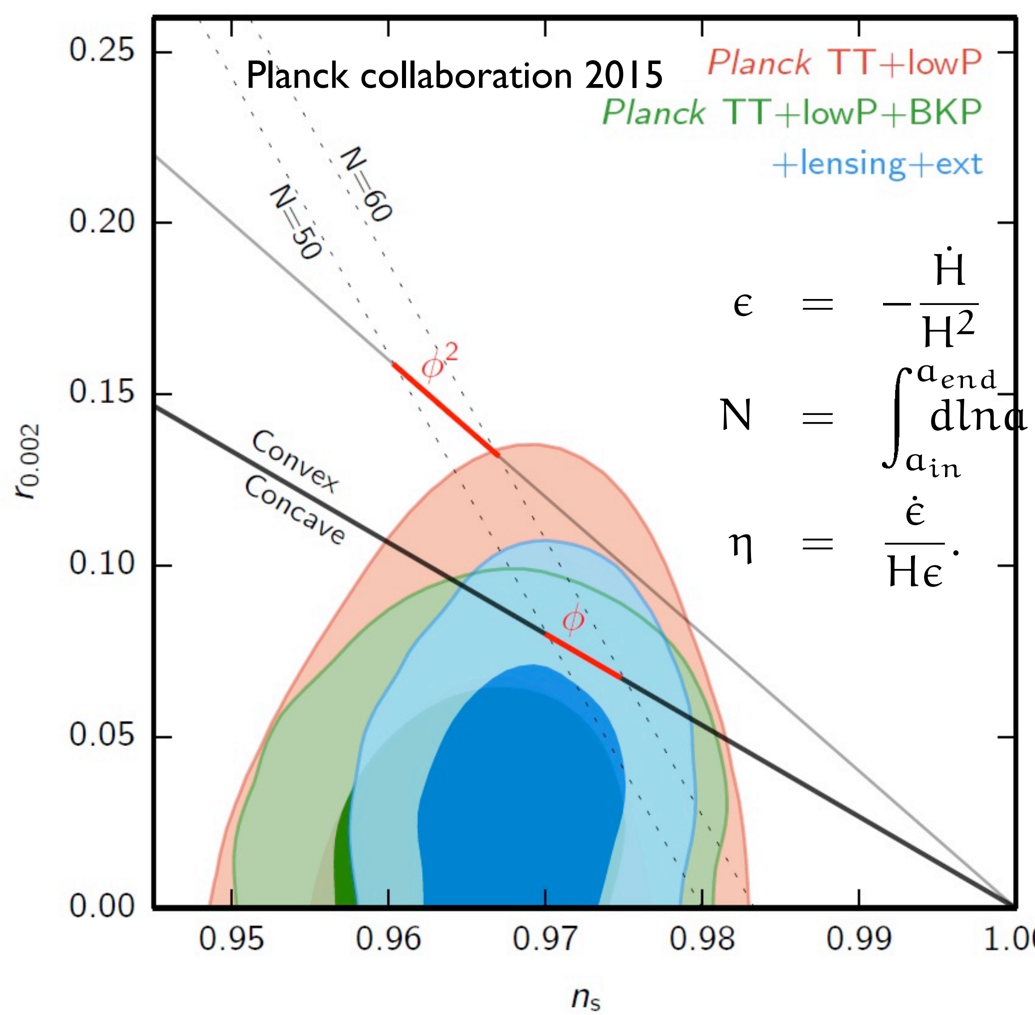
- B-modes : smoking-gun evidence for gravitational waves in the early universe

$$\Delta_s^2(k) \approx A_s k^{n_s - 1} \quad n_s = 1 - 6\epsilon + 2\eta \quad \longrightarrow \quad r \equiv \frac{\Delta_t^2(k)}{\Delta_s^2(k)} = 16\epsilon$$

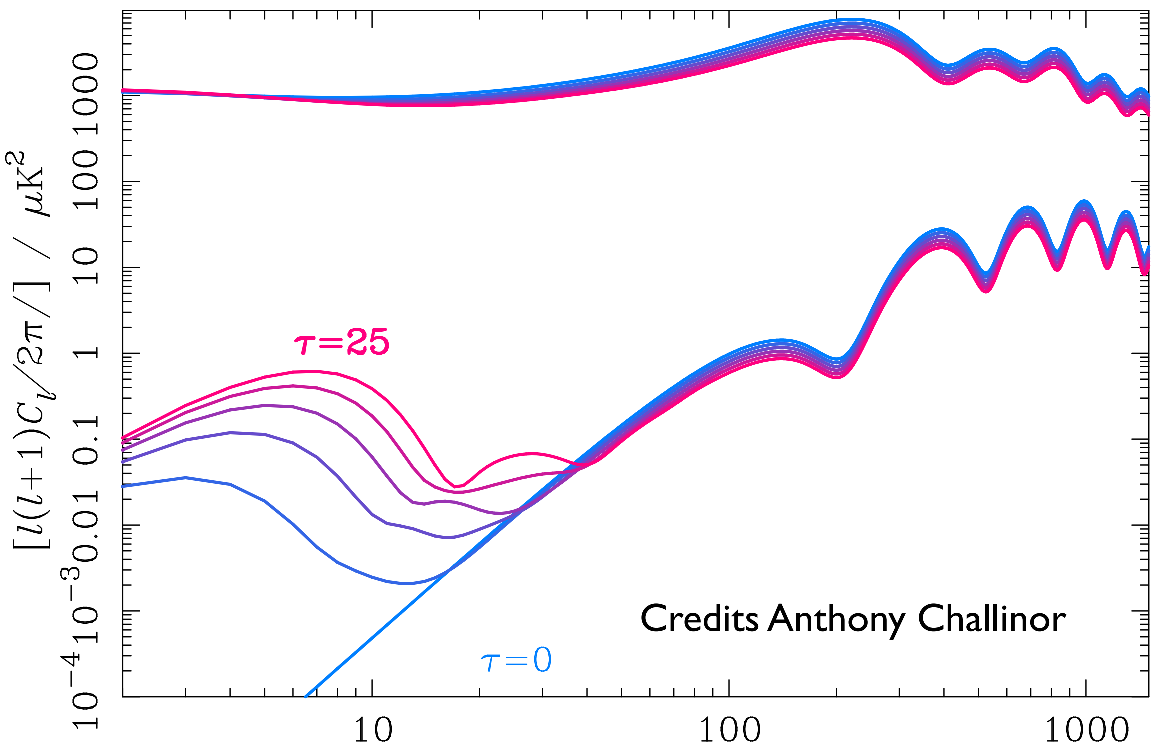
$$\Delta_t^2(k) \equiv A_T k^{n_t} \quad n_t \approx -2\epsilon$$

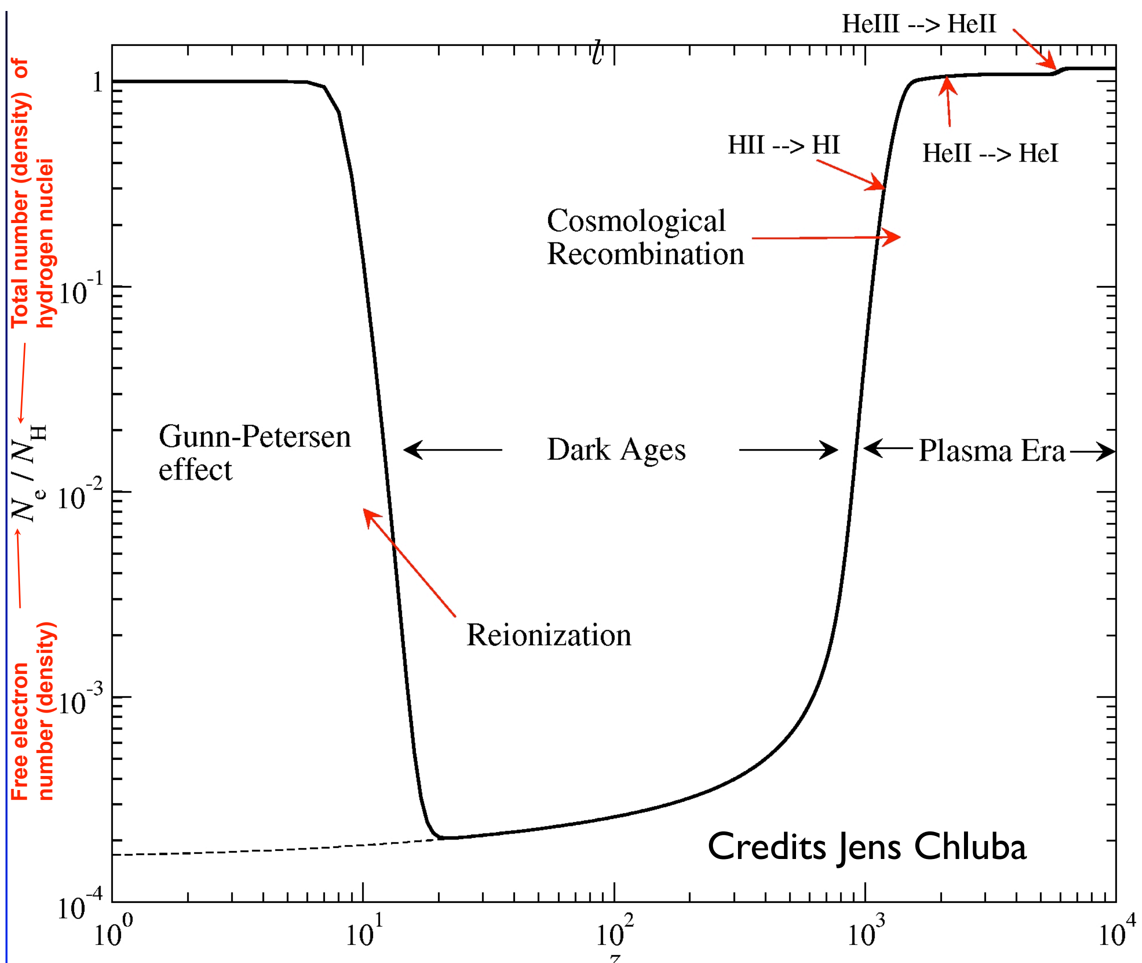
- Can constraints model and energy scale of inflation $V^{1/4} \approx \left(\frac{r}{0.01}\right)^{1/4} 10^{16}\mathrm{GeV}$





Reionization



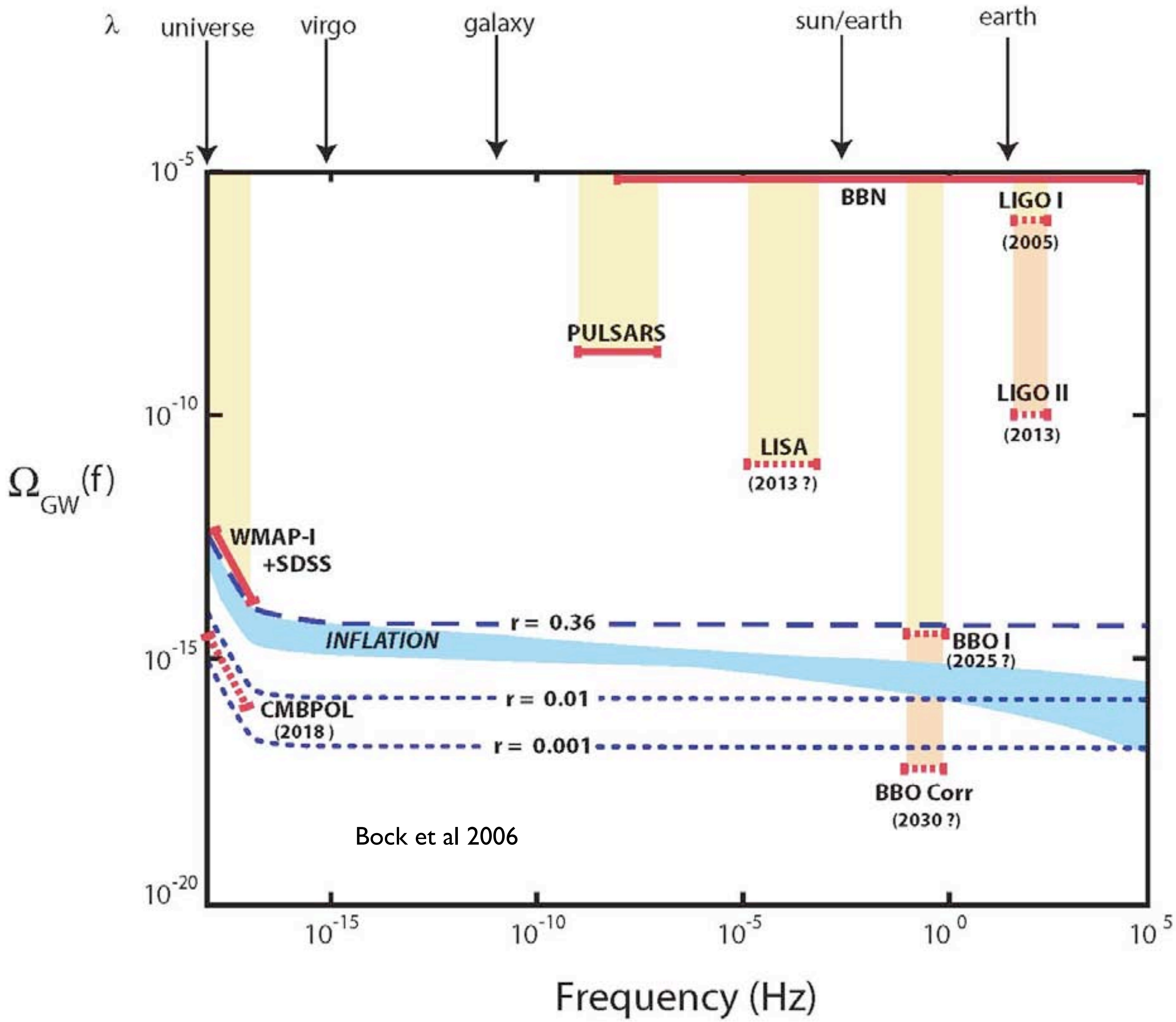


- New stars re-ionize the plasma in the universe
- Rescattering erases fluctuations below the horizon scale and regenerates them on the horizon scale at that time

$$\ell_{re} \approx 2\frac{(\eta_0 - \eta_{re})}{\eta_{re} - \eta_*}$$

- Change in the overall normalization for T and E at small scales
- Large scale E & B proportional to optical depth
- Limitation due to cosmic variance

Inflationary GW and ground-based detectors



Parity violating physics

- Non-zero TB, EB power spectra
- E.g. chiral gravity different amount of l.h and r.h GWs

$$C_\ell^{BB} = \int dk \left(\Delta^B_{\ell,,\mathrm{T}}(k,\eta_0)\right)^2 \mathcal{P}_\mathrm{T}^{(+)}(k),$$

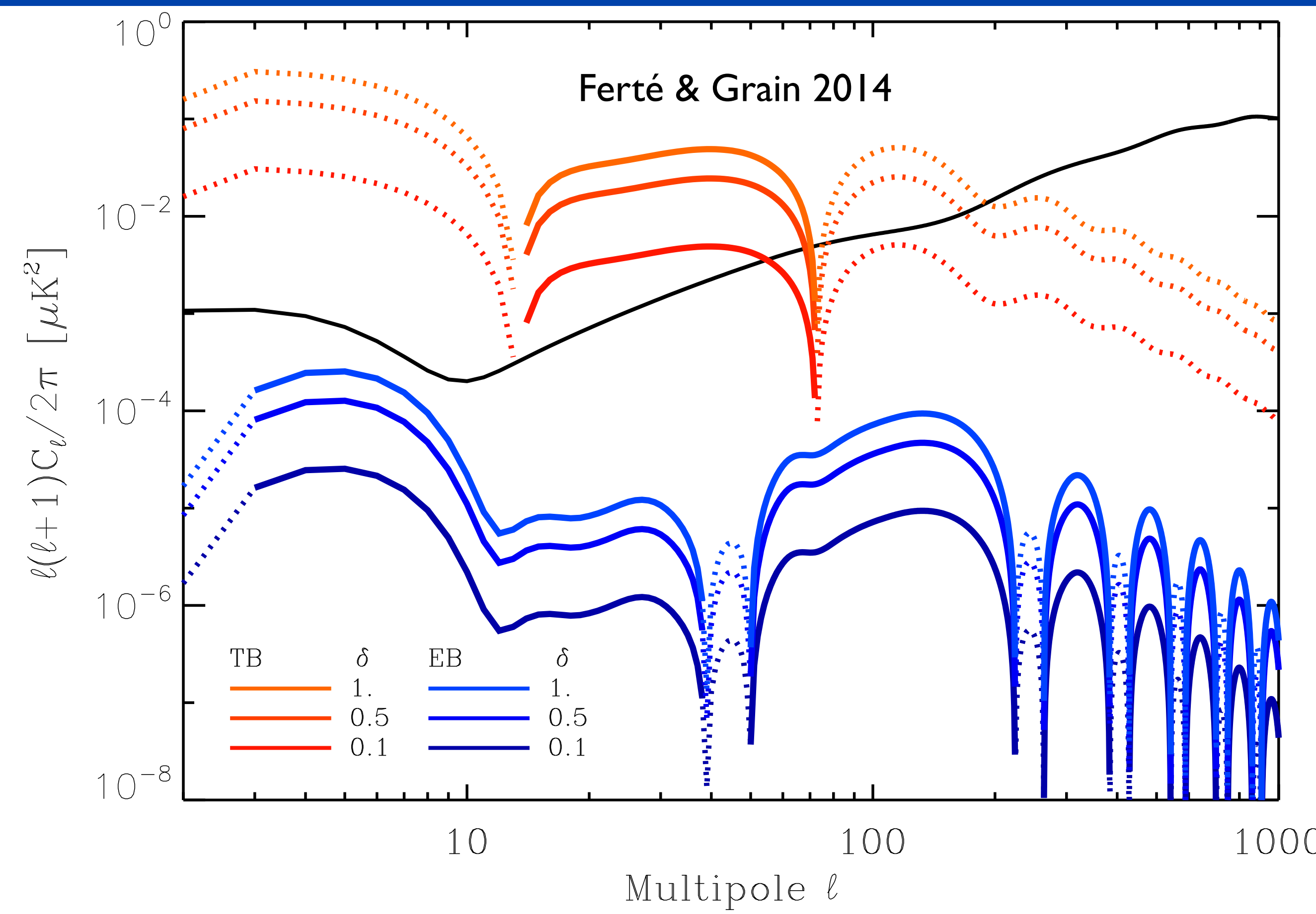
$$C_\ell^{TB} = \int dk \Delta^T_{\ell,\mathrm{T}}(k,\eta_0)\Delta^B_{\ell,\mathrm{T}}(k,\eta_0)\mathcal{P}_\mathrm{T}^{(-)}(k),$$

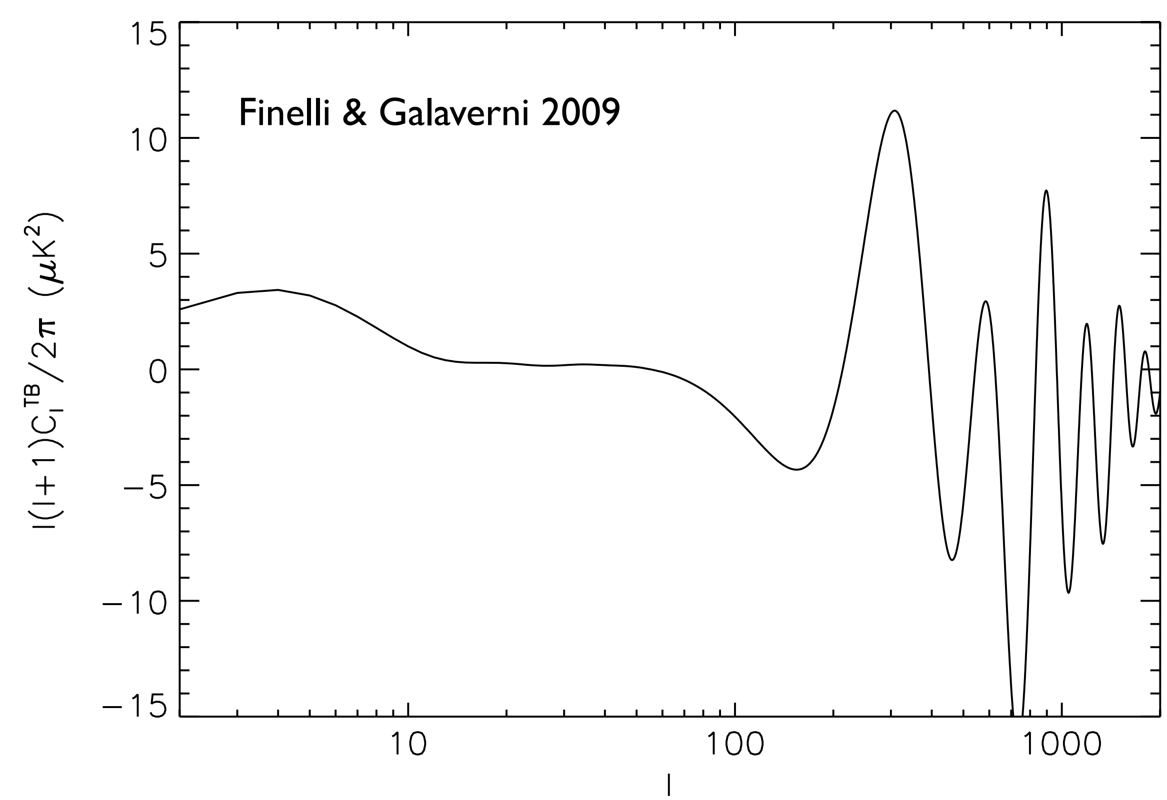
$$C_\ell^{EB} = \int dk \Delta^E_{\ell,\mathrm{T}}(k,\eta_0)\Delta^B_{\ell,\mathrm{T}}(k,\eta_0)\mathcal{P}_\mathrm{T}^{(-)}(k),$$

$$\mathcal{P}_\mathrm{T}^{(\pm)}(k) = r_{(\pm)} \times \mathcal{A}_\mathrm{S} \times \left(\frac{k}{k_0}\right)^{n_\mathrm{T}}$$

- Primordial magnetic fields
- Another alternative: axion interactions

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - V(\phi) - \frac{g_\phi}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}.$$





The forgotten V

- Thomson scattering does not produce V but does not erase it either

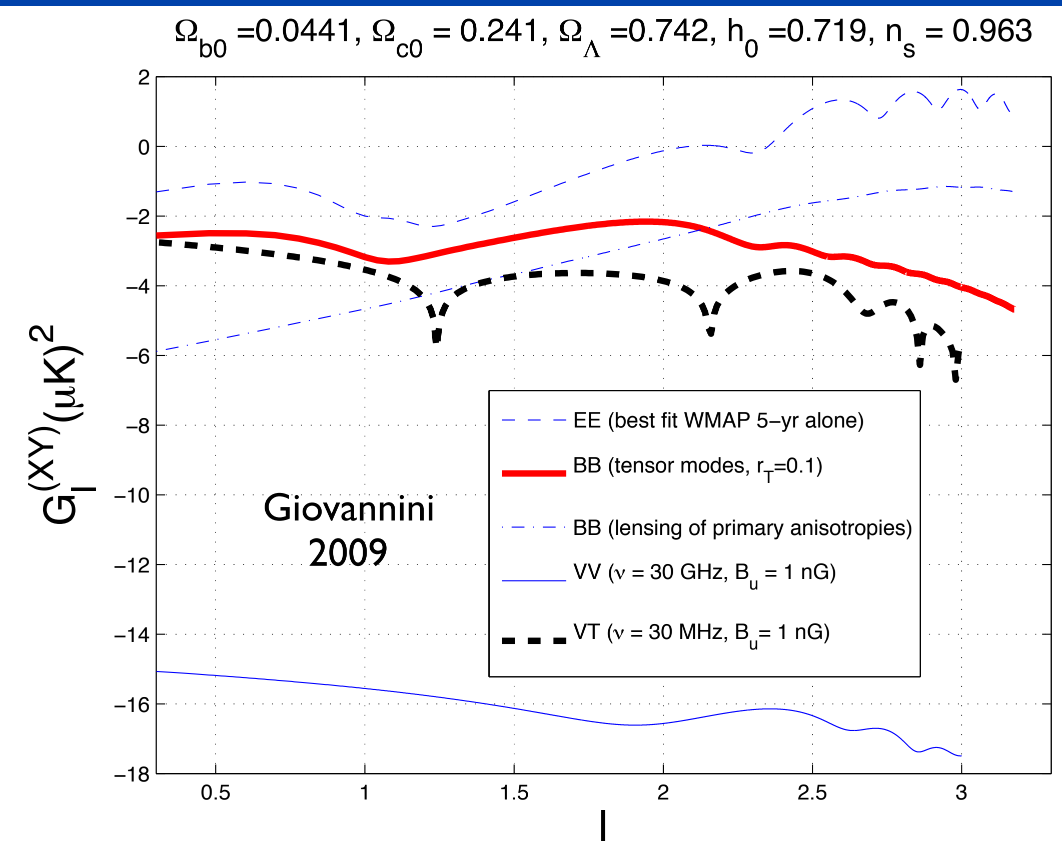
- Extension of standard model of EM interactions or primordial magnetic fields...

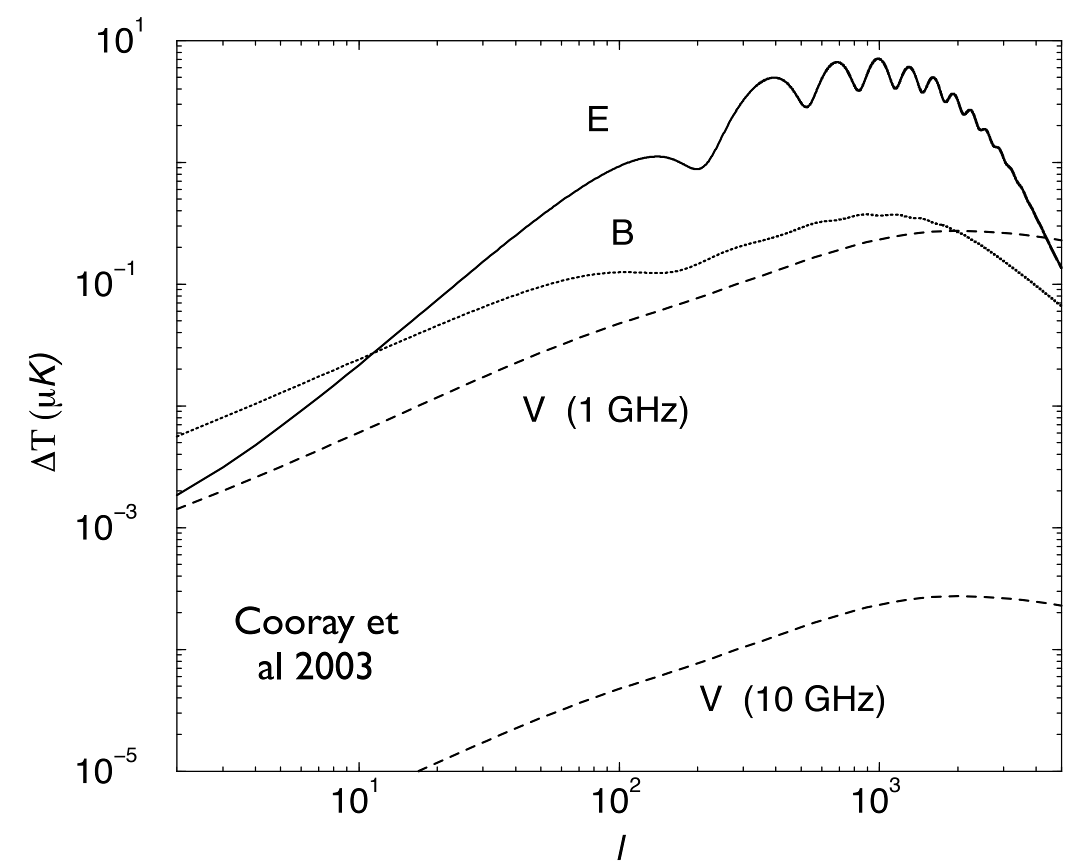
$$\dot{\Delta}_V + ik\mu\Delta_V + \dot{\tau}\Delta_V = \dot{\tau}\mathcal{C}_V(\nu, k, \mu)$$

$$f(\nu) = 2.79 \times 10^{-12}\left(\frac{B}{nG}\right)\left(\frac{GHz}{\nu}\right)(1+z_*)$$

- or by astrophysical magnetic fields

$$\begin{aligned}\dot{V} &= 2U\frac{d\delta\phi_{FC}}{dt} \\ \delta\phi_{FC} &\approx 3\times10^{-7}(1+z)^{-3}\left(\frac{\lambda_{obs}}{1cm}\right)\left(\frac{\beta-1}{\beta-2}\right) \\ &\times \int\frac{dl}{1kpc}\left(\frac{n_{rel}}{0.1cm^{-3}}\right)\left(\frac{\gamma_{min}}{300}\right)\left(\frac{|B|}{10\mu G}\right)^2(1-\mu^2)\end{aligned}$$





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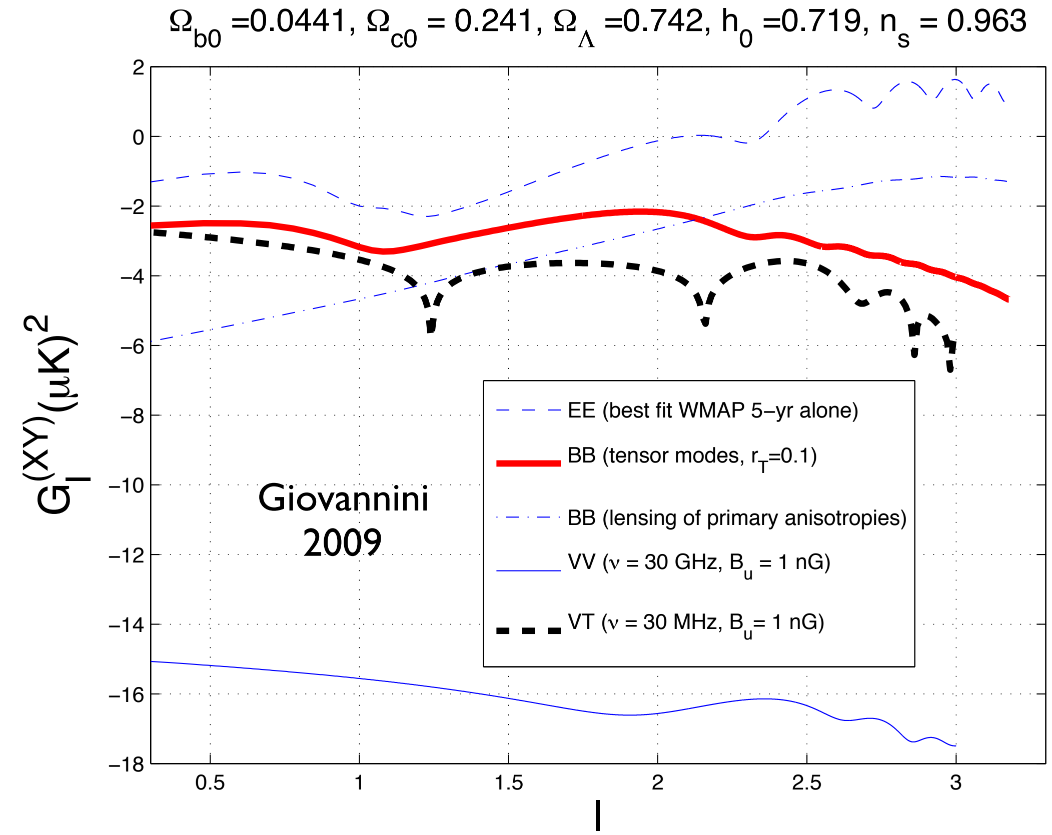
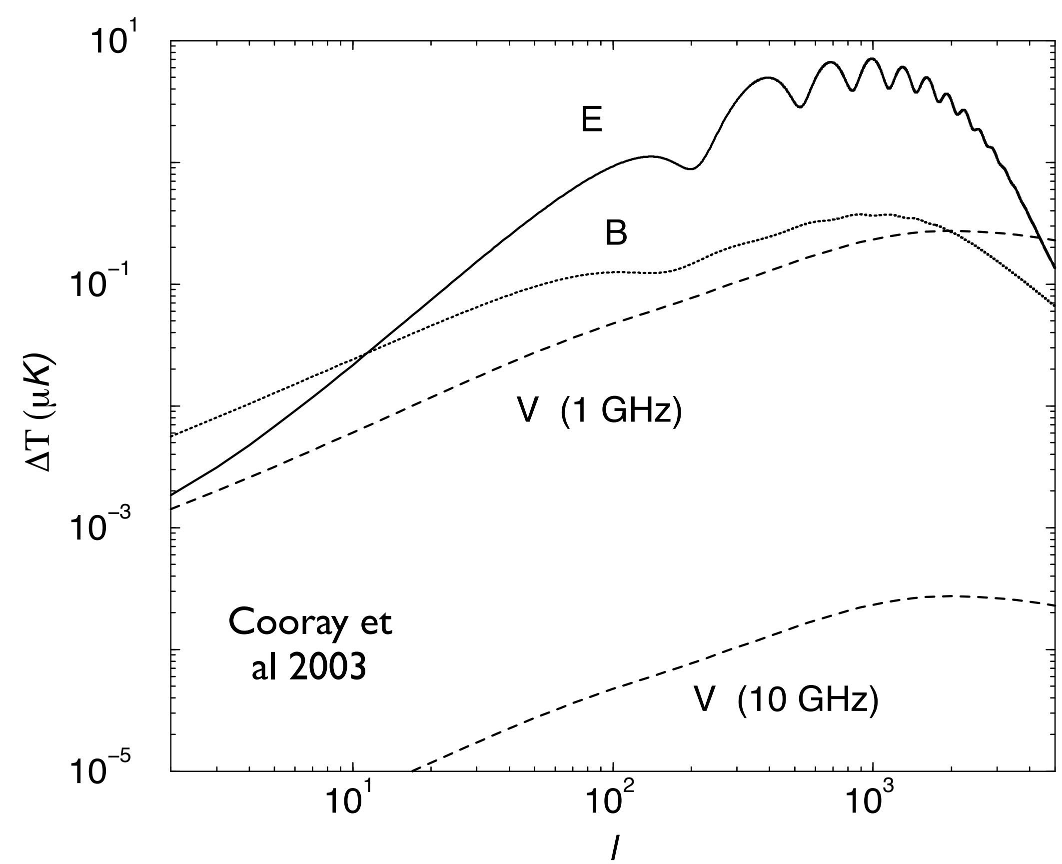
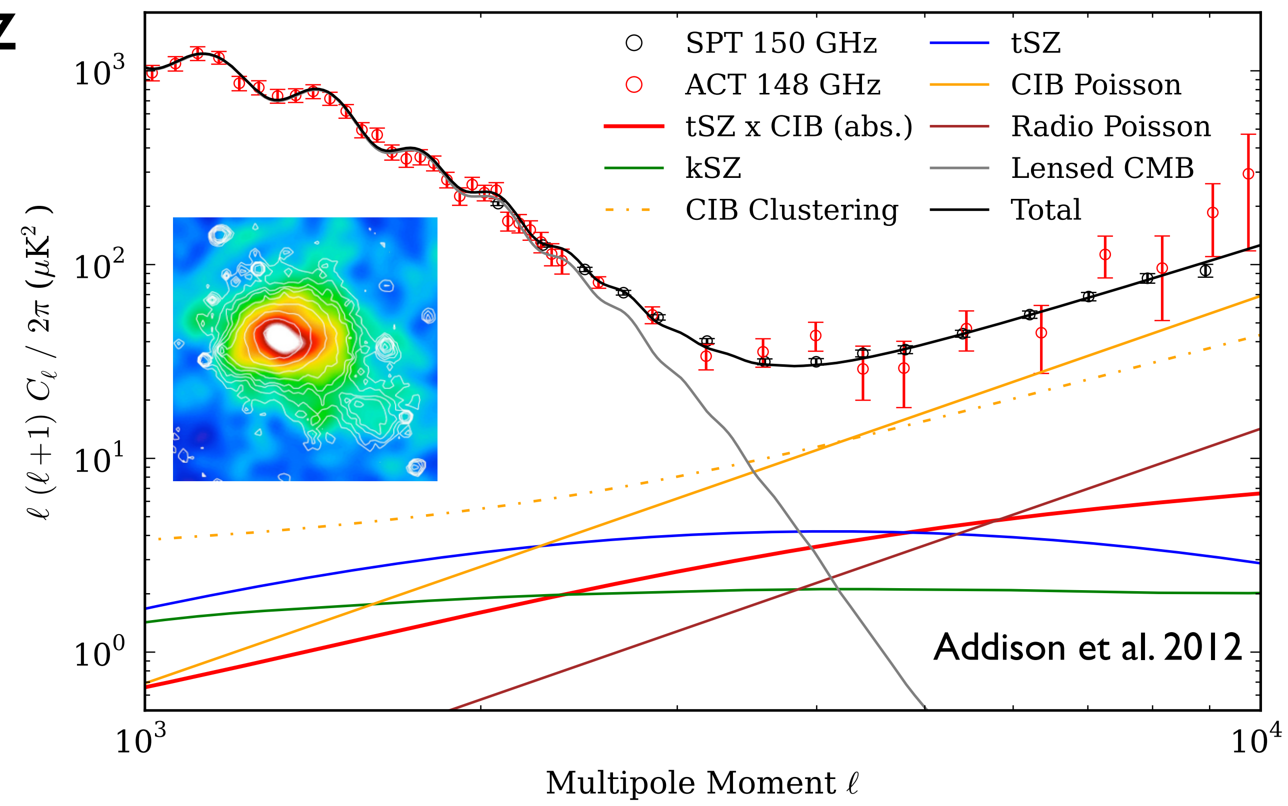
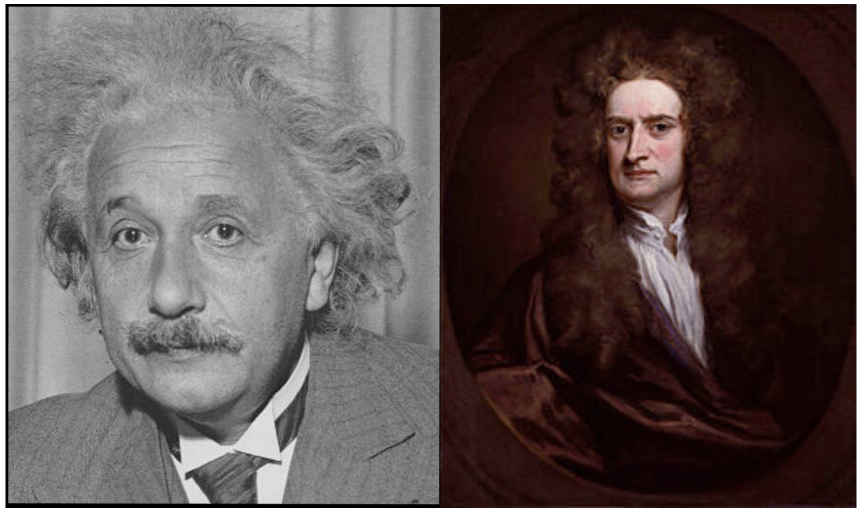


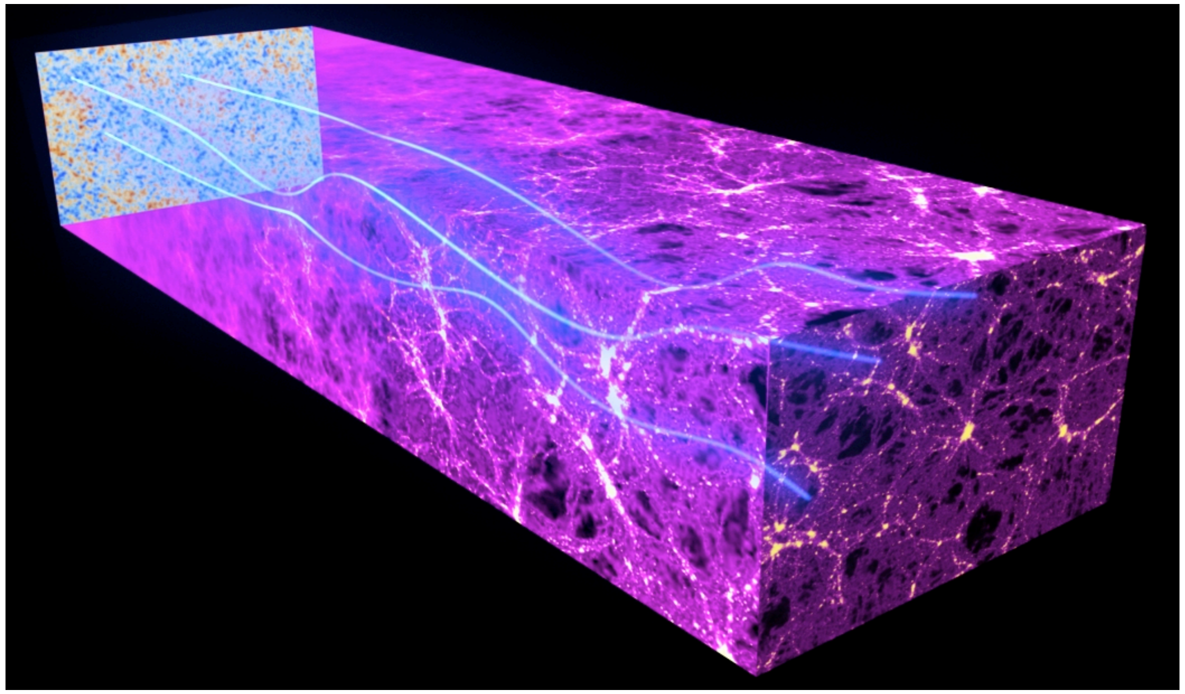


Is CMB "the" CMB?

- CMB is a snapshot of the universe at z 1100.... plus something else
- CMB gets contaminated by evolving astrophysical objects and foregrounds
- Imprint of ongoing large scale structures formation
- Photons deviated through the gravitational lensing effect

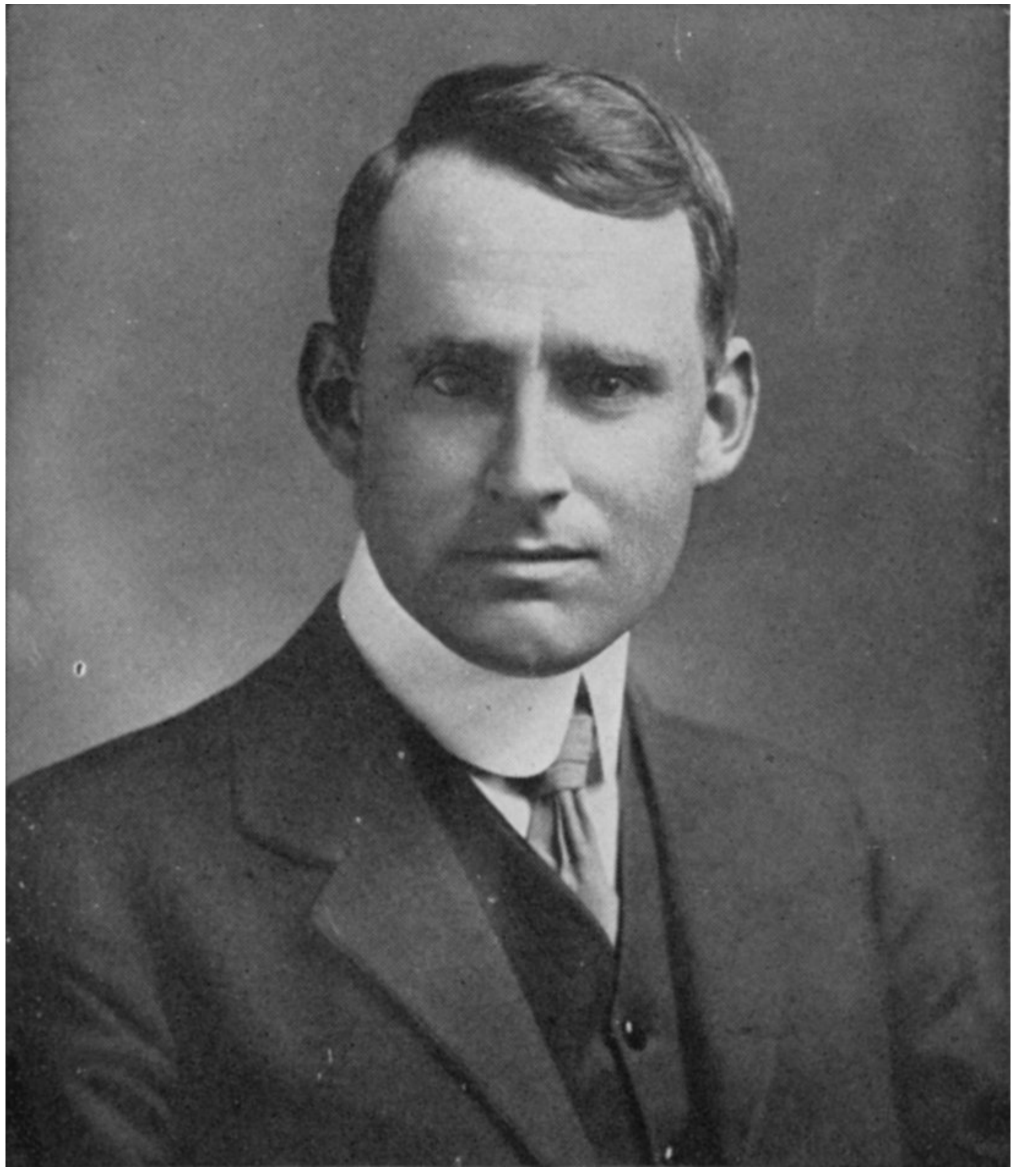


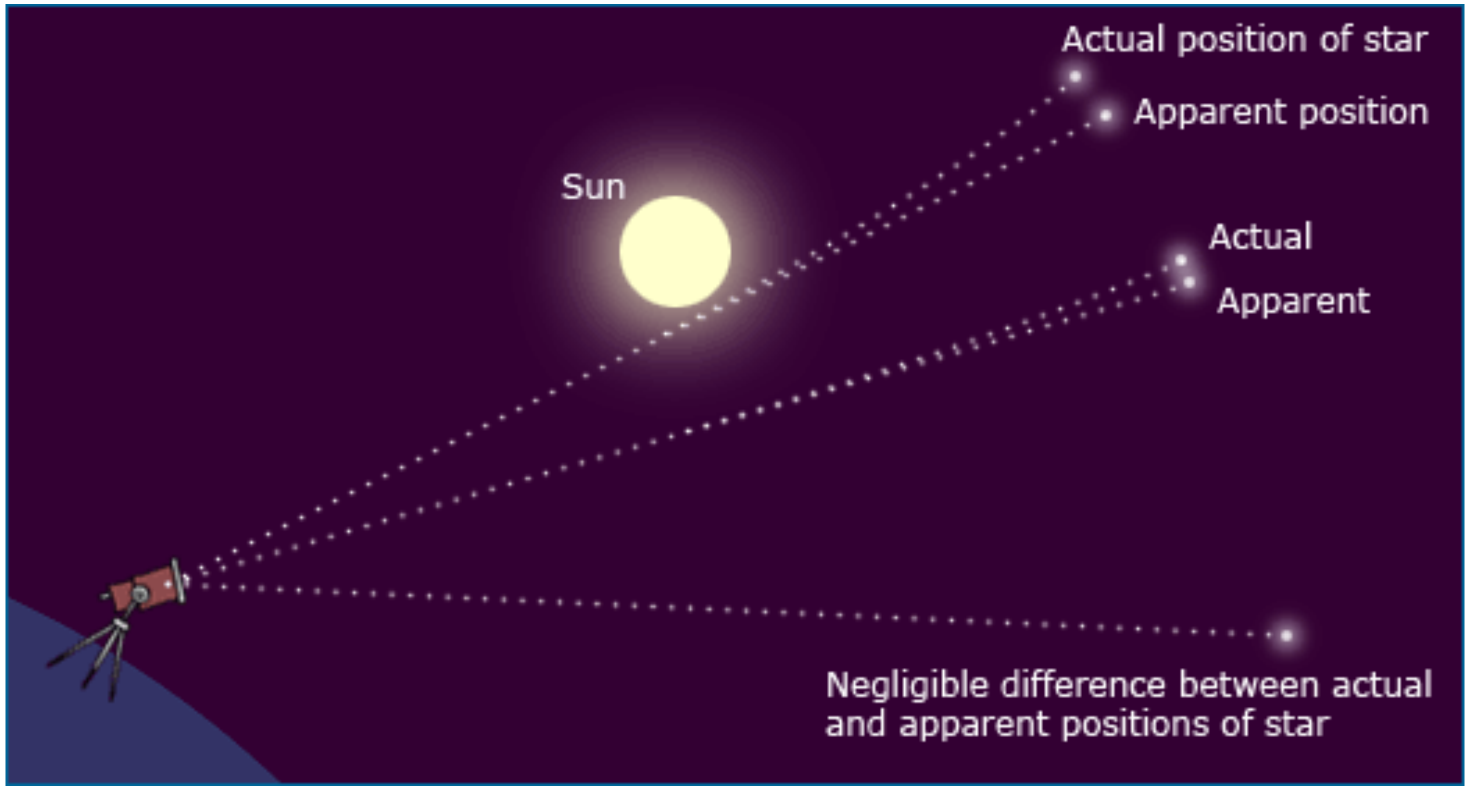


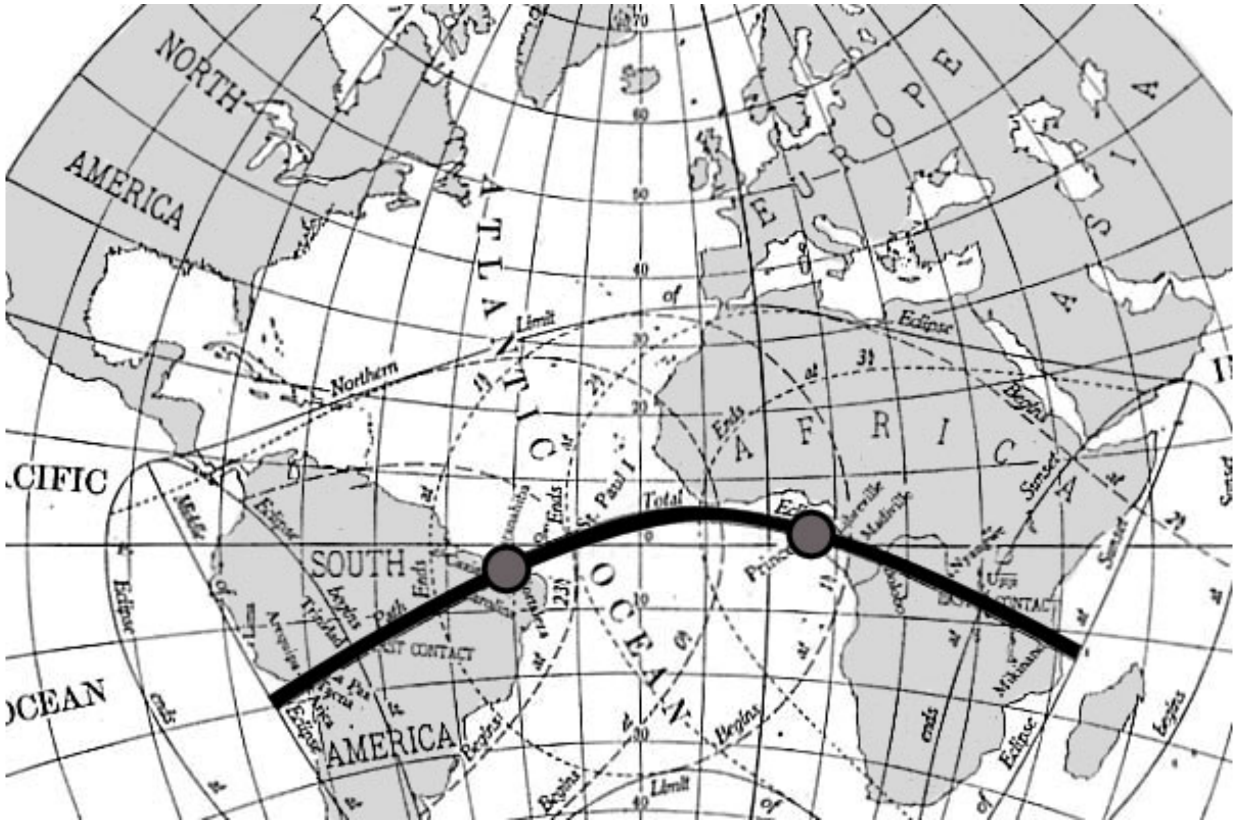


An historical introduction to gravitational lensing

Sir Arthur Eddington







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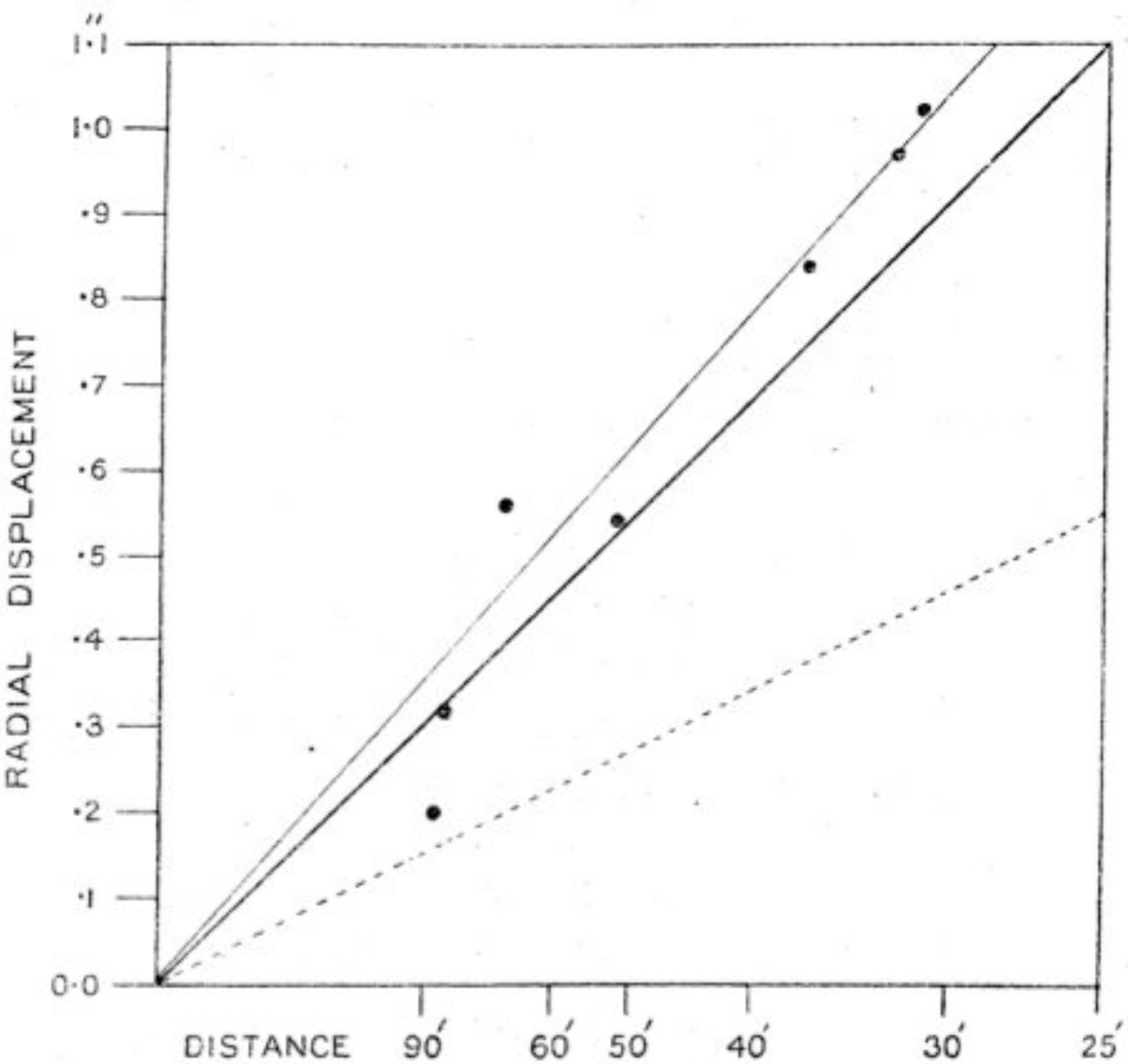
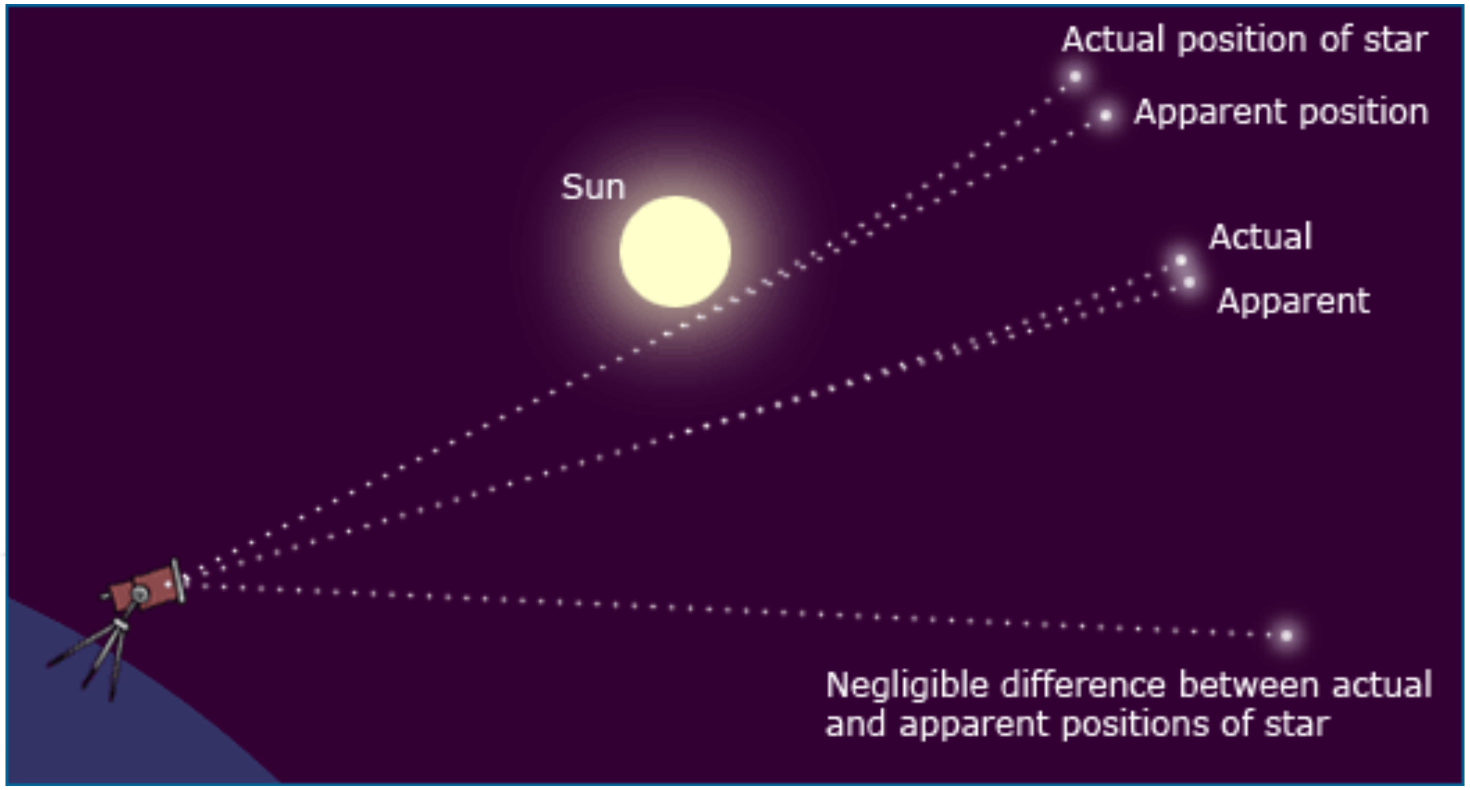
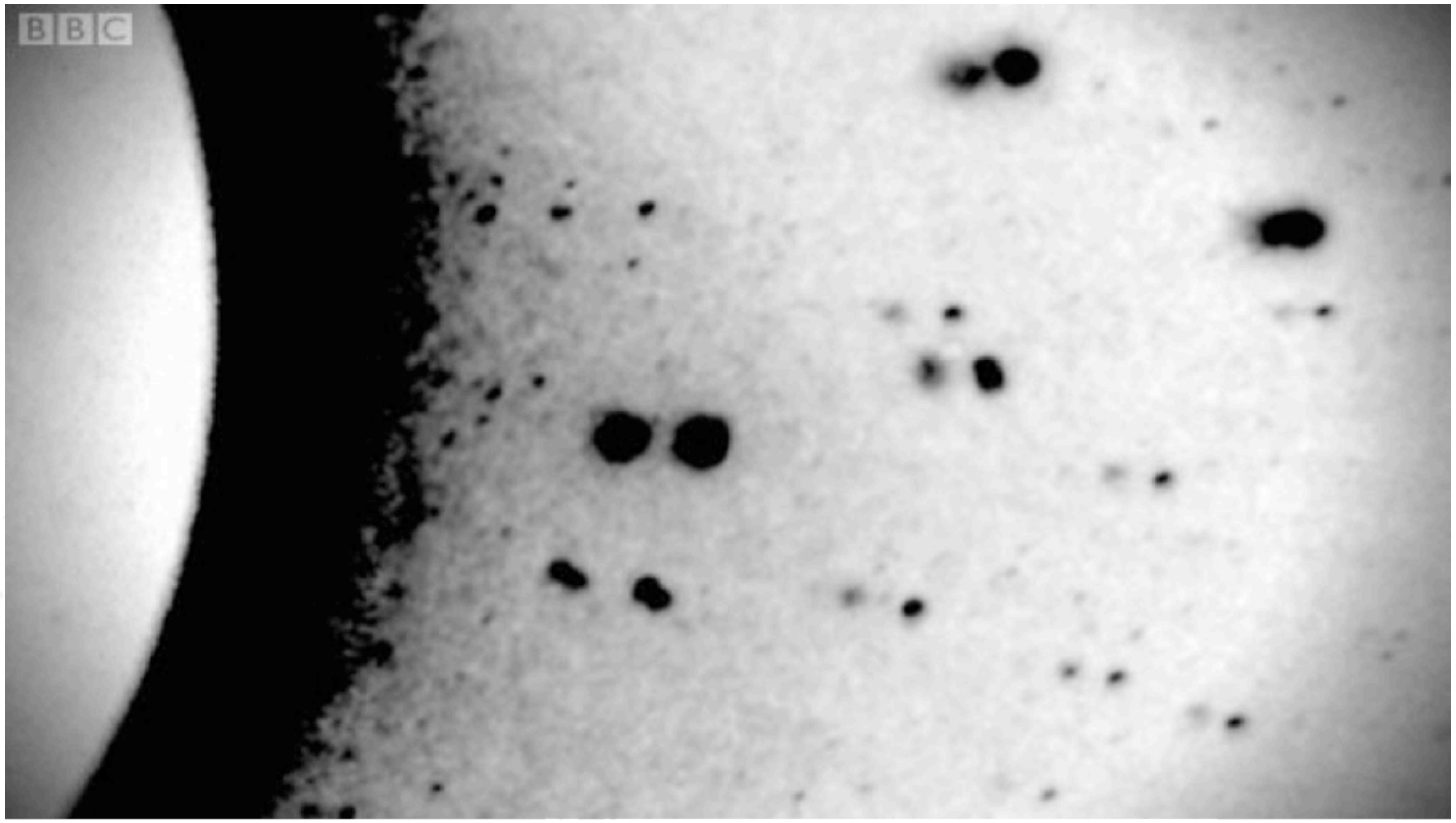
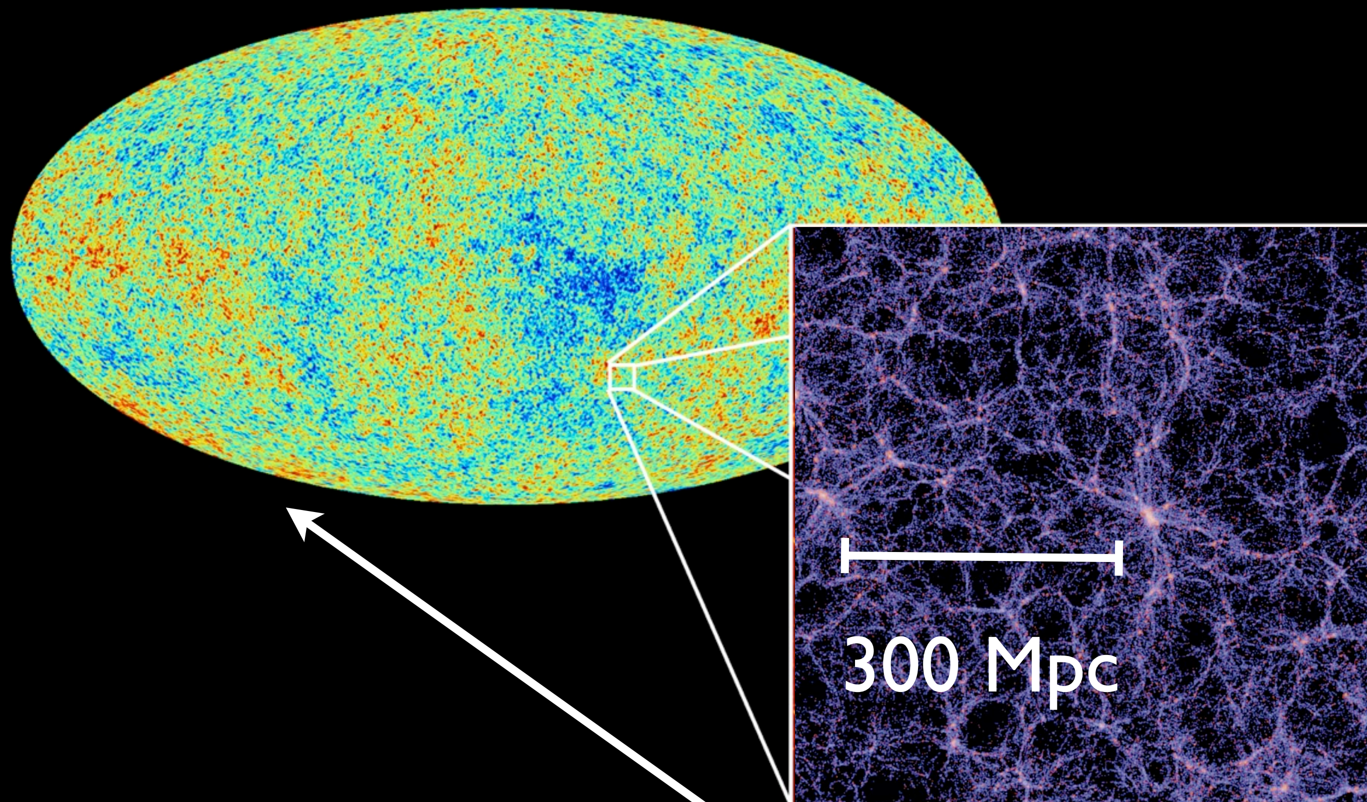
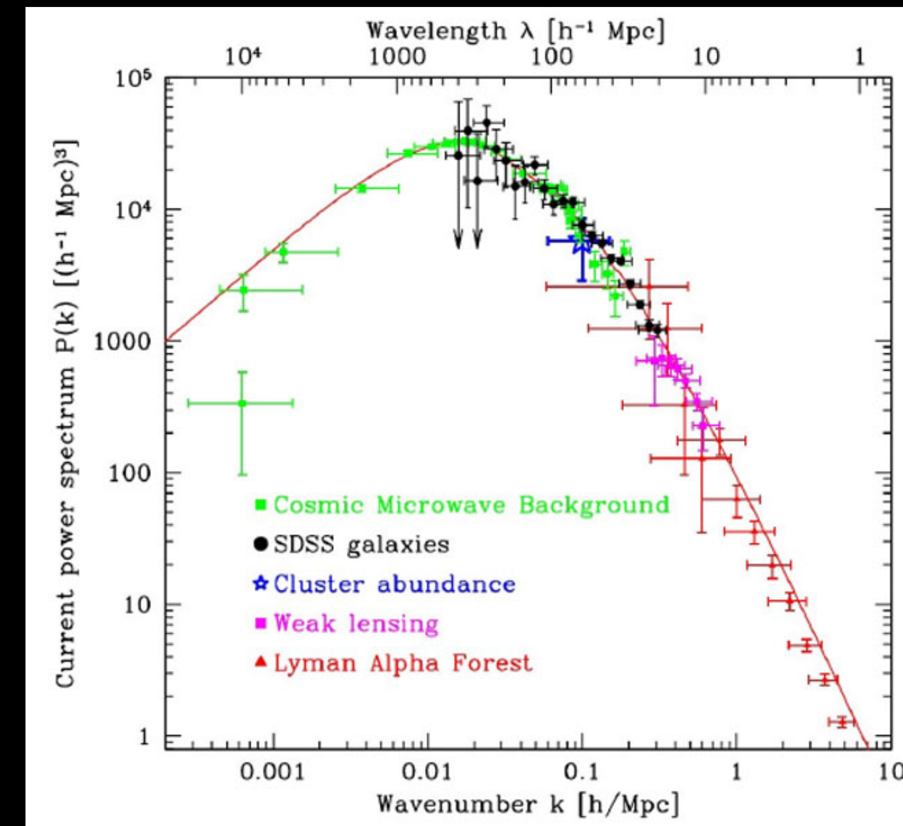






0-th order calculation



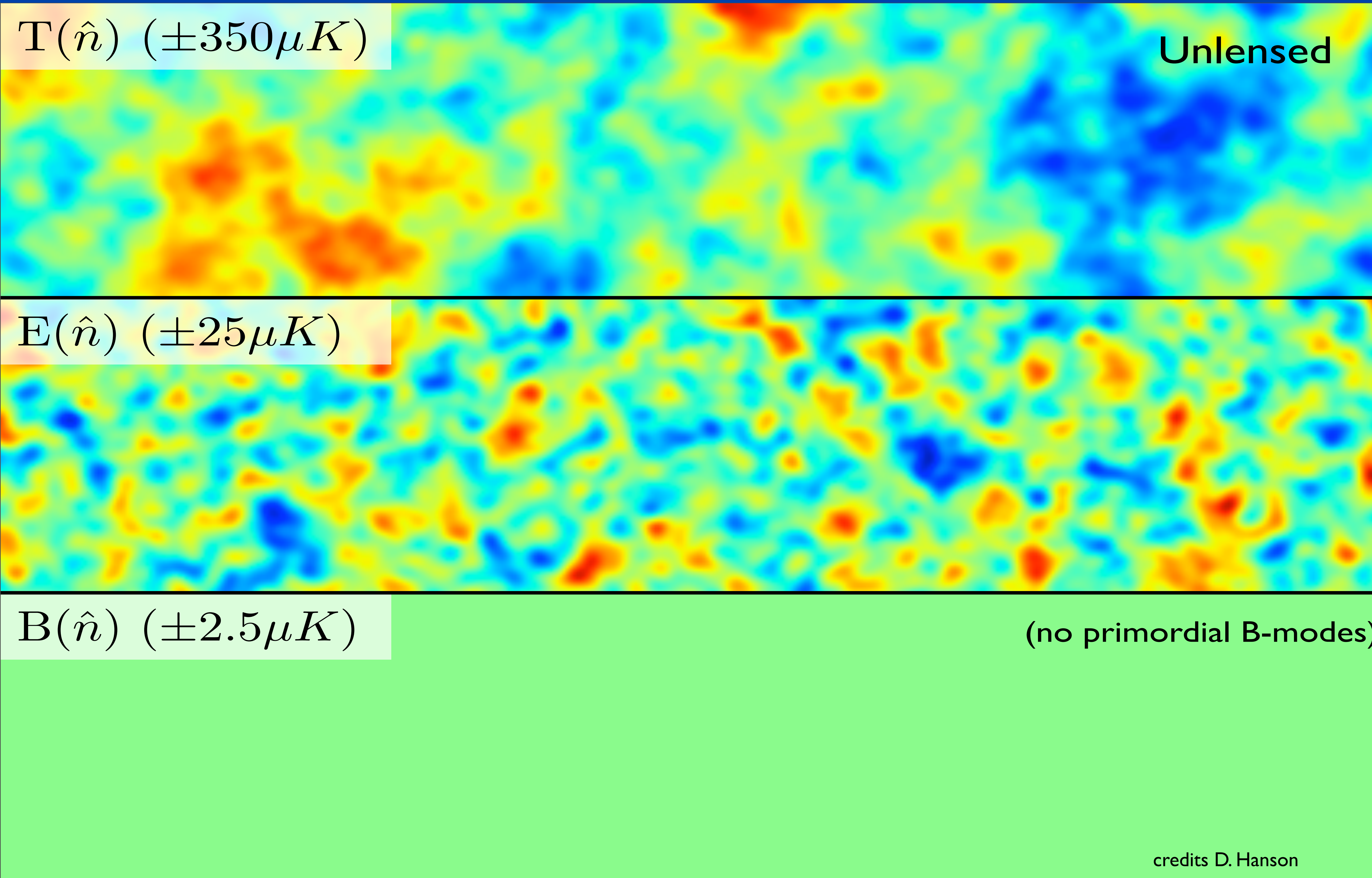


~7000 Mpc

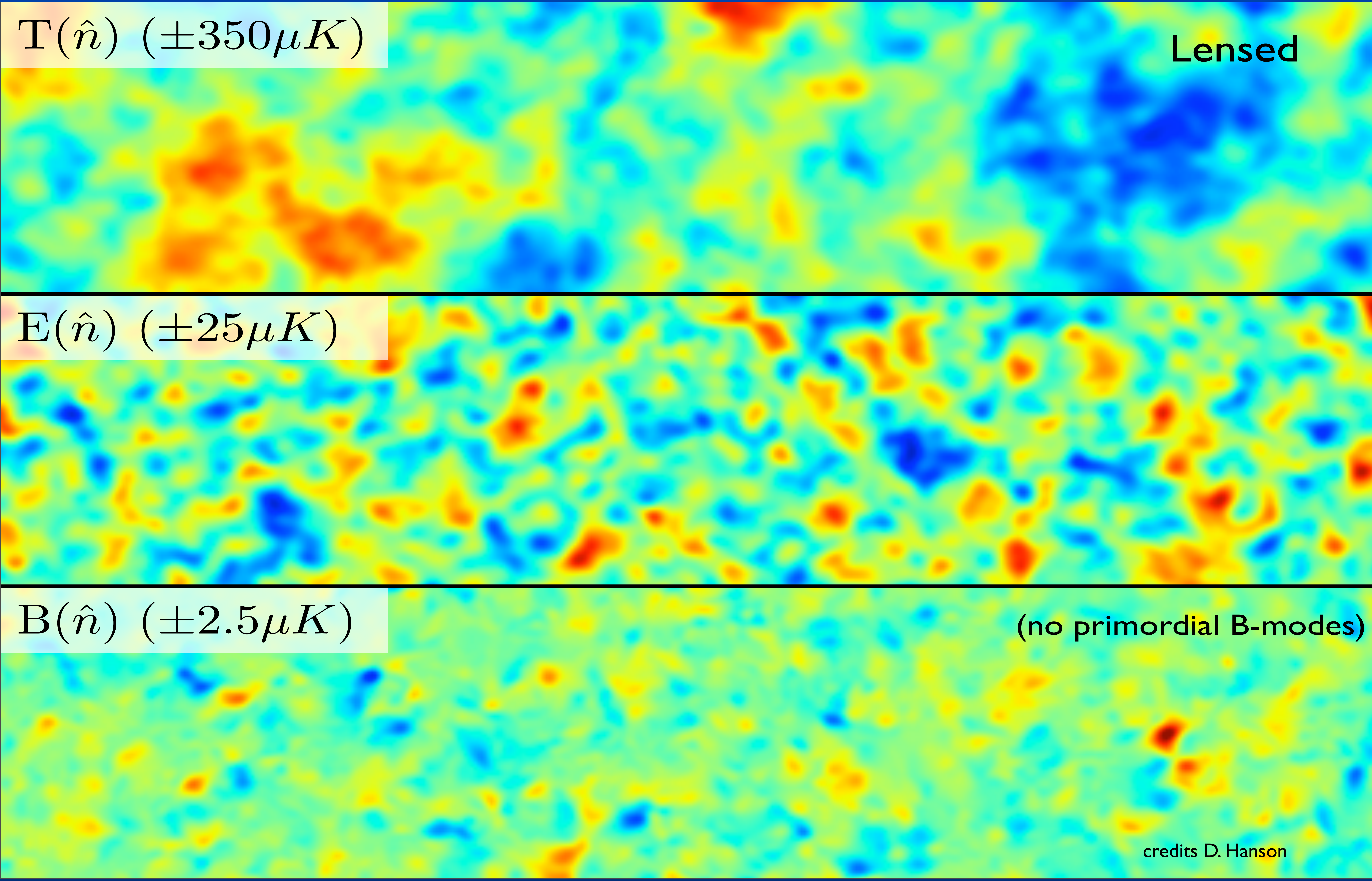
~14000 Mpc

$$
\begin{aligned}
\Psi(R) &\approx 2 \cdot 10^{-5} \\
\delta\beta &\approx \frac{2\Psi(R)}{c^2} \approx 10^{-4} \\
N_{dev} &\simeq 50 \\
\Delta\theta &\approx \sqrt{N_{dev}} \times \delta\beta \approx 7 \times 10^{-4} = 2 \ arcmin \\
\Delta\theta_{coherence} &\simeq \frac{300}{7000} \approx 2^\circ
\end{aligned}
$$

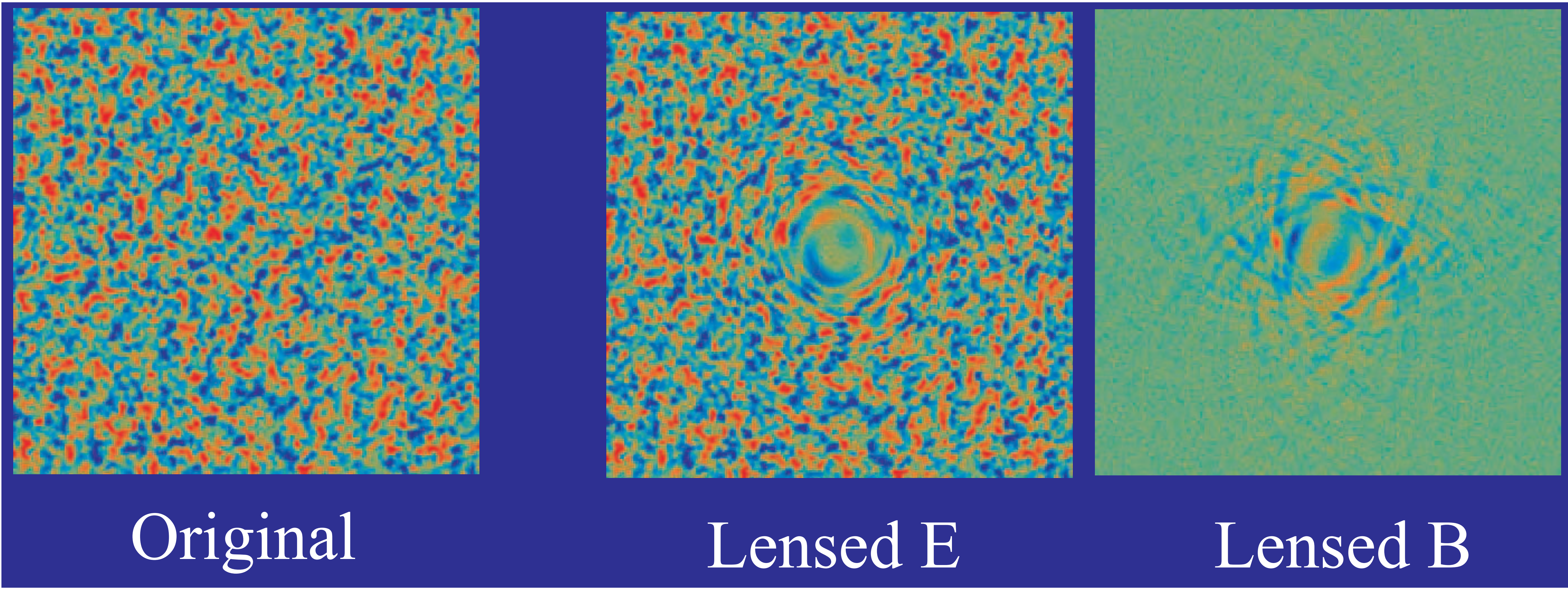
Lensing on CMB maps



Lensing on CMB maps



Exagerating a bit…



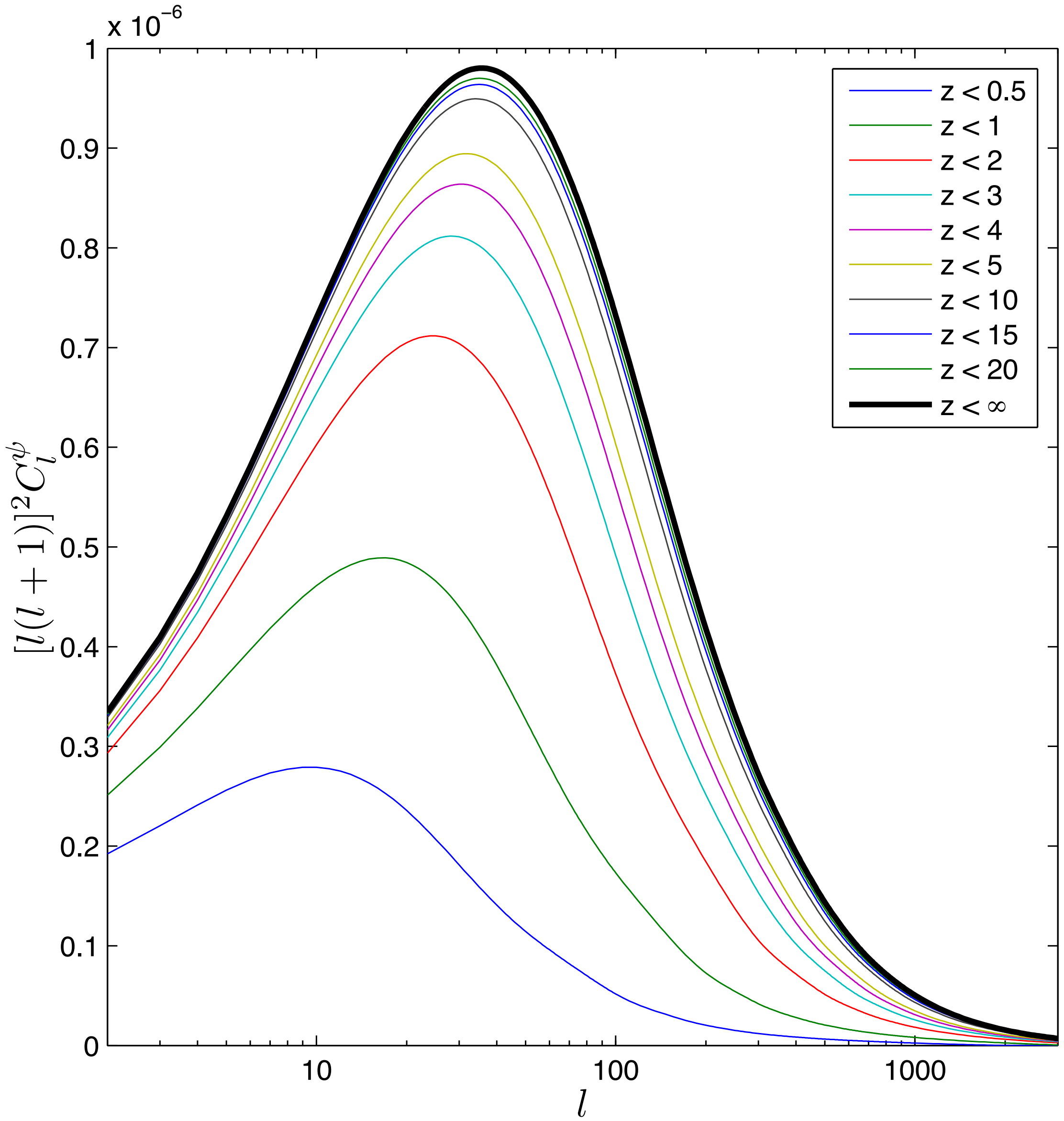
Lensing more in detail

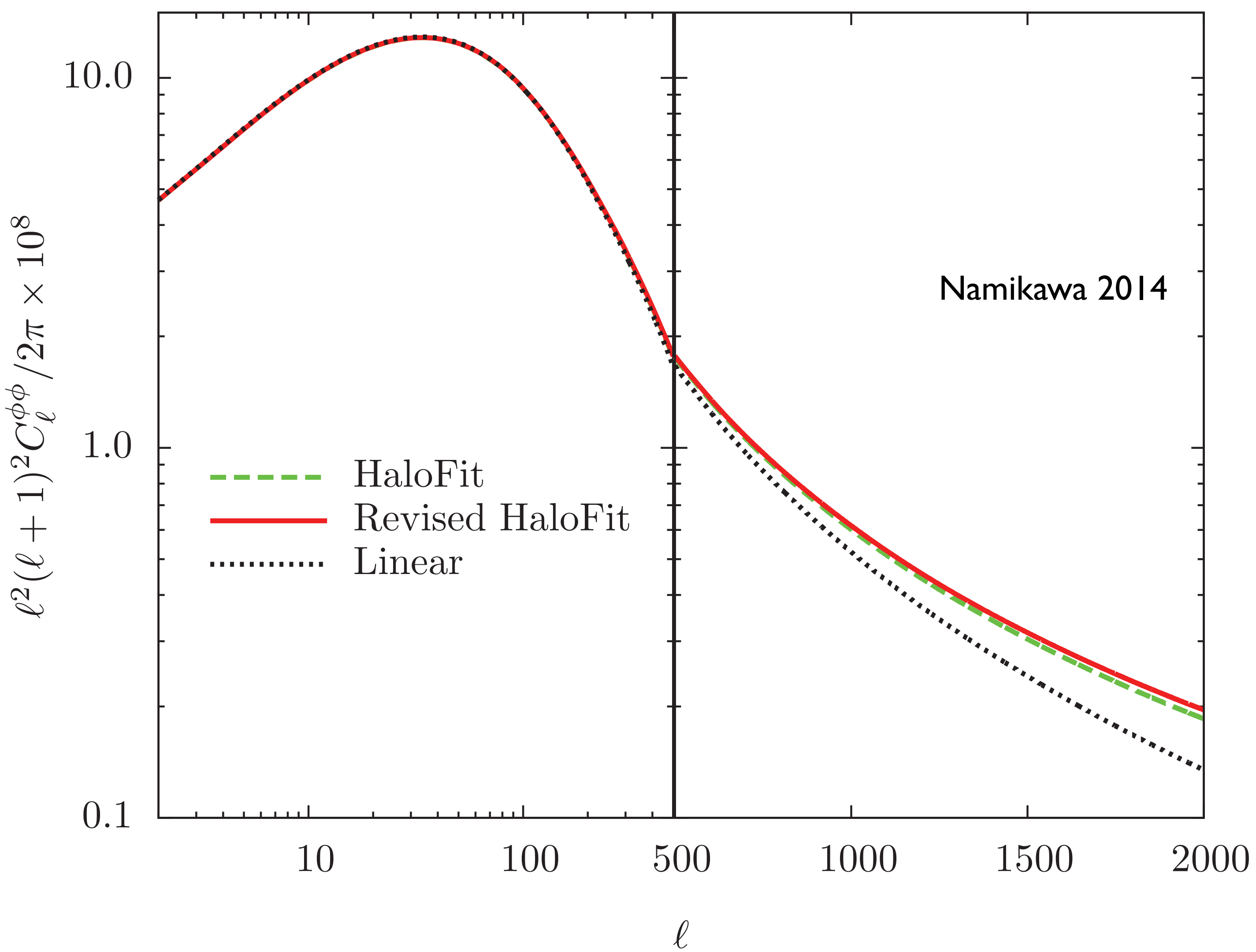
- Photon deviation given by the gradient of a scalar field called *lensing potential*

$$\psi(\hat{\mathbf{n}}) \equiv -2\int_0^{\chi_*} \mathrm{d}\chi\, \frac{f_K(\chi_* - \chi)}{f_K(\chi_*) f_K(\chi)} \Psi(\chi\hat{\mathbf{n}}; \eta_0 - \chi)$$

- Not much sensitive to non linear evolution (work in progress)

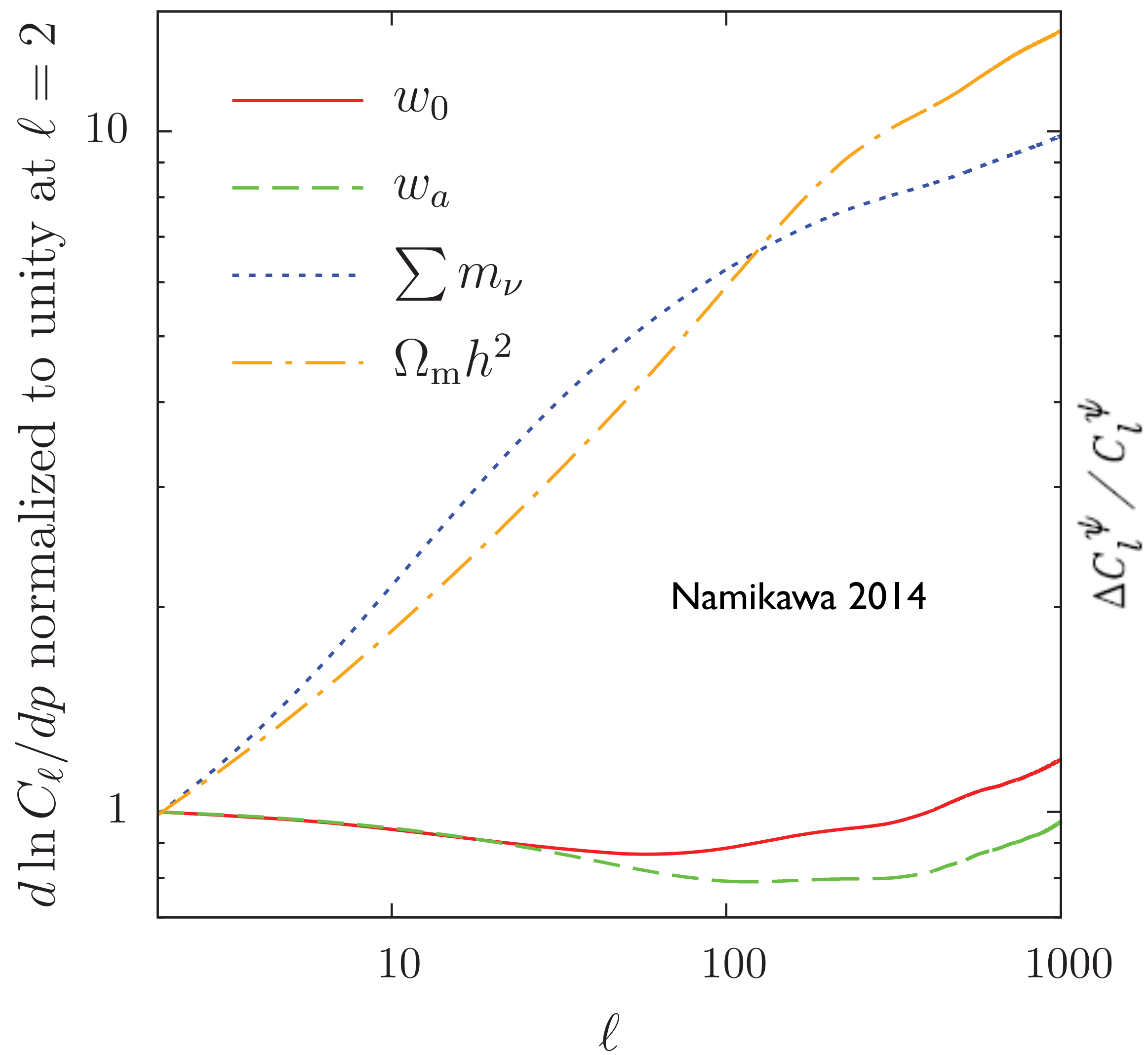
Lewis & Challinor 2006

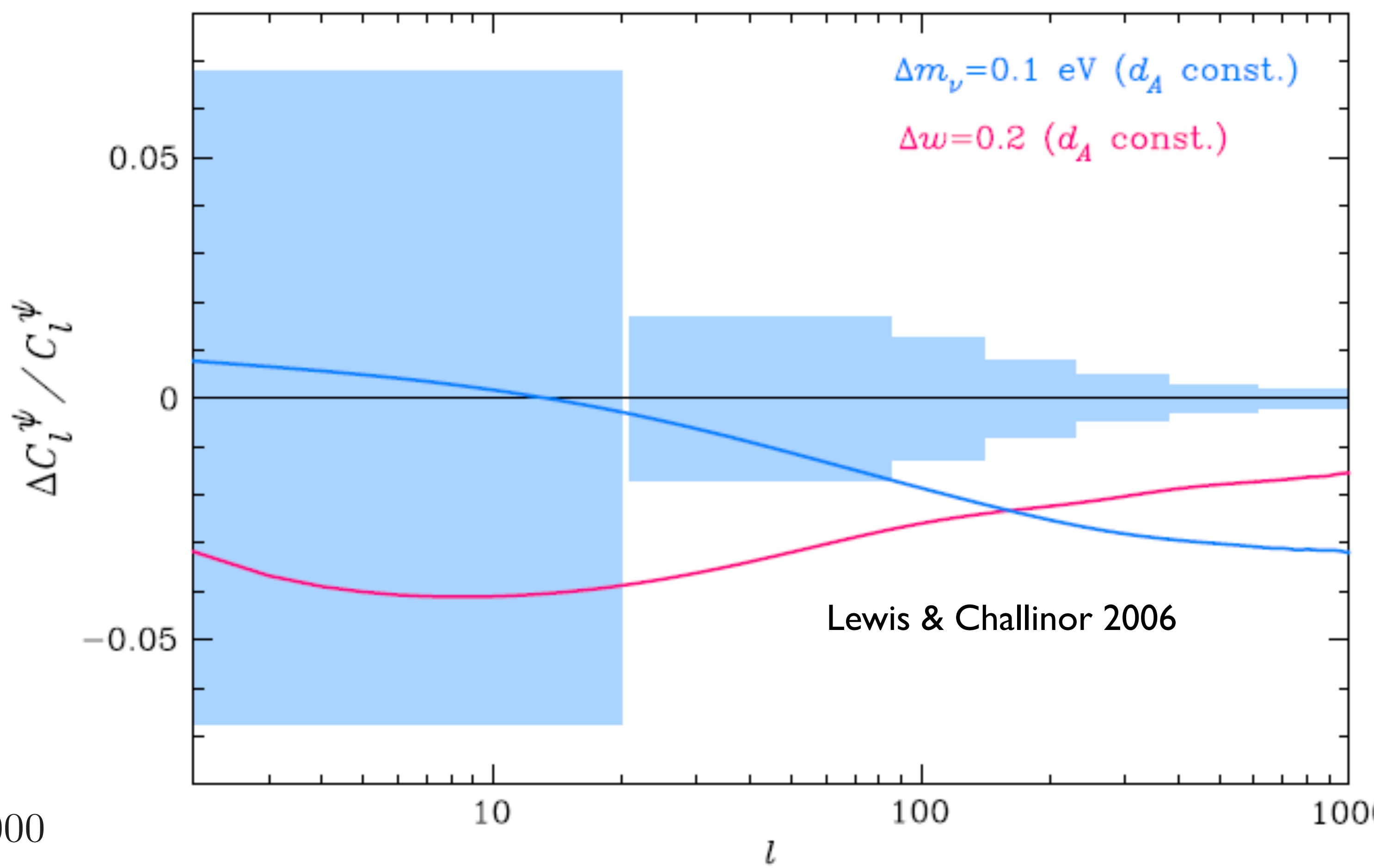




Lensing potential cosmological sensitivity

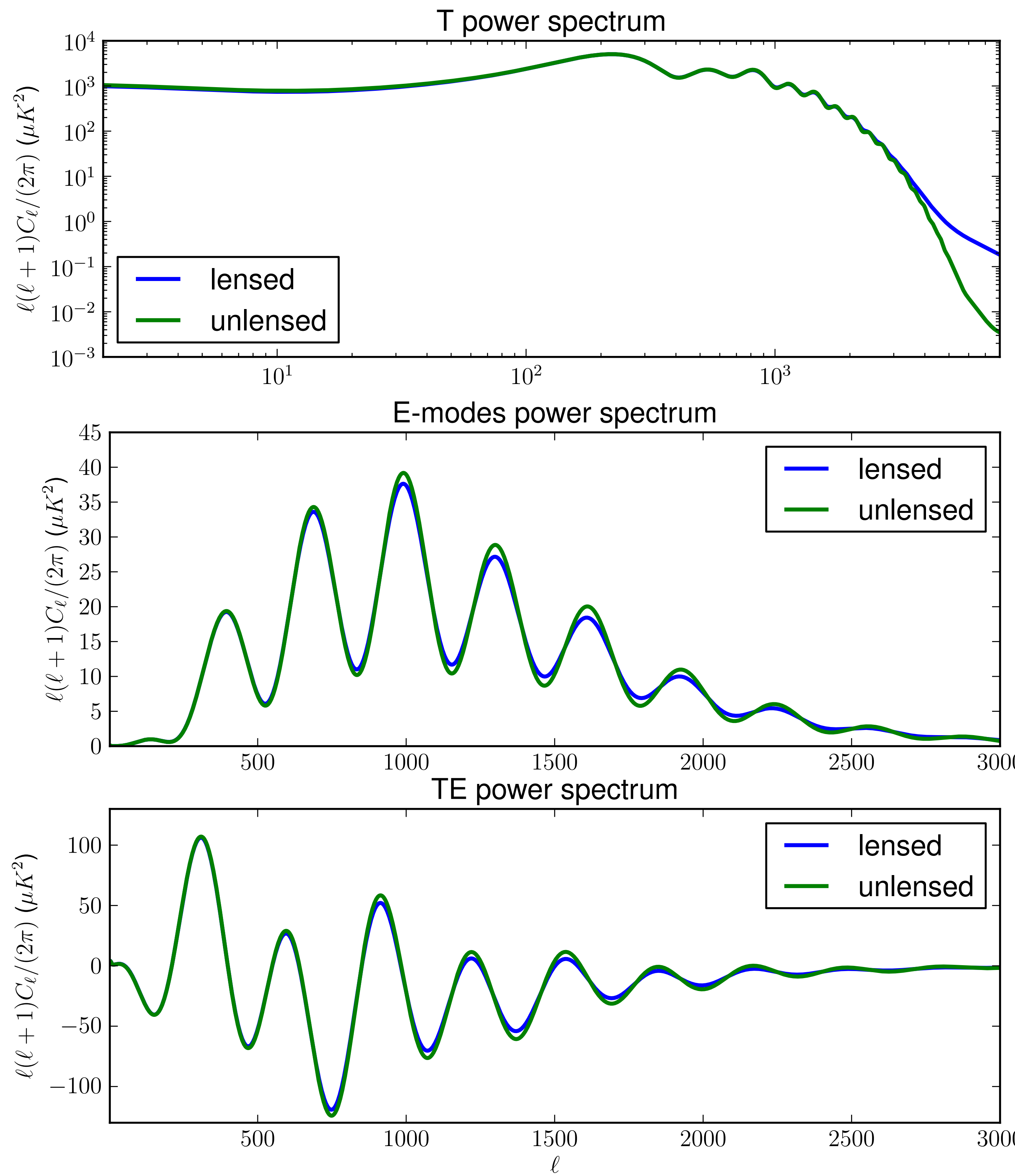
- Sensitive to parameters affecting structure formation rate
- Early dark energy, neutrino masses, modified gravity….
- One of the most important cosmological observable in the next years!





Effects on power spectrum

- Variance is preserved but power is reshuffled
- Small effect on Temperature, more important on E-modes
- B-modes: main source of signal, contaminant for inflationary signal detection
- Lensing correlates angular scales: non-Gaussian feature
- We can reconstruct the lensing potential from CMB



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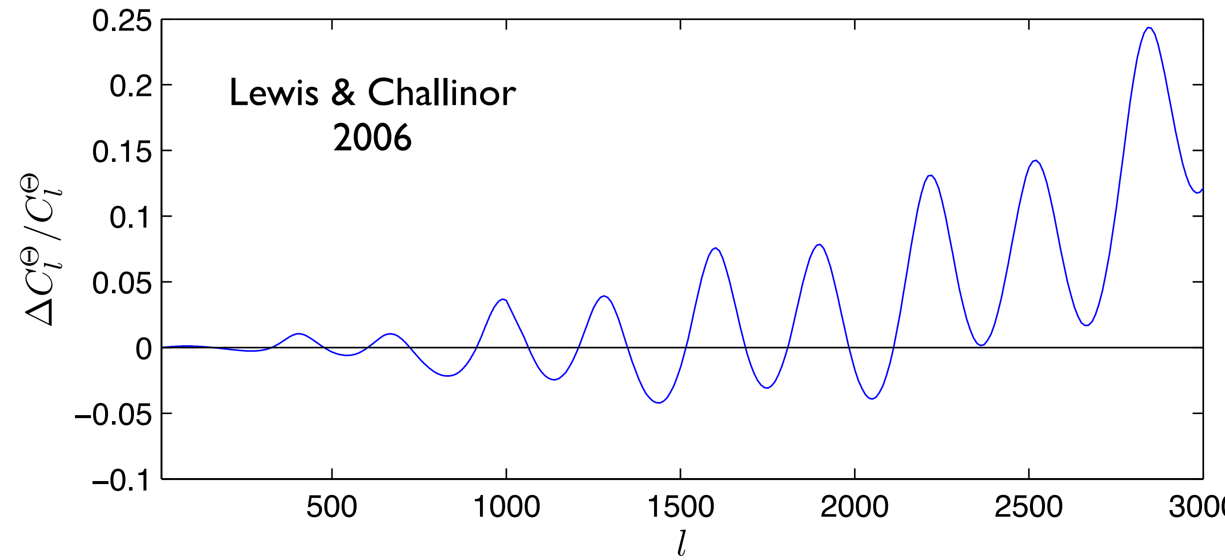
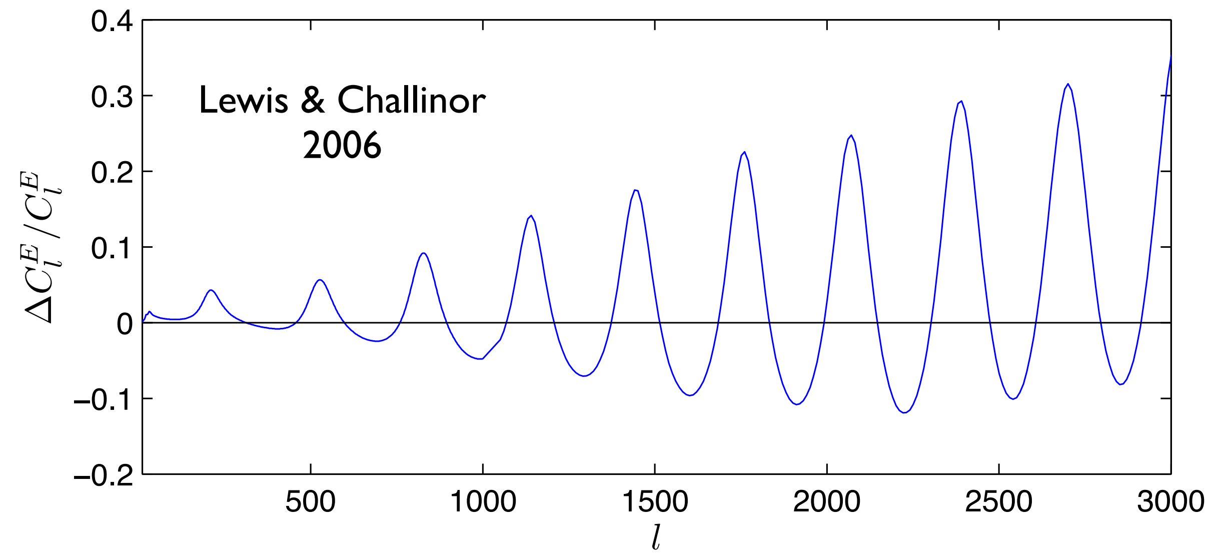
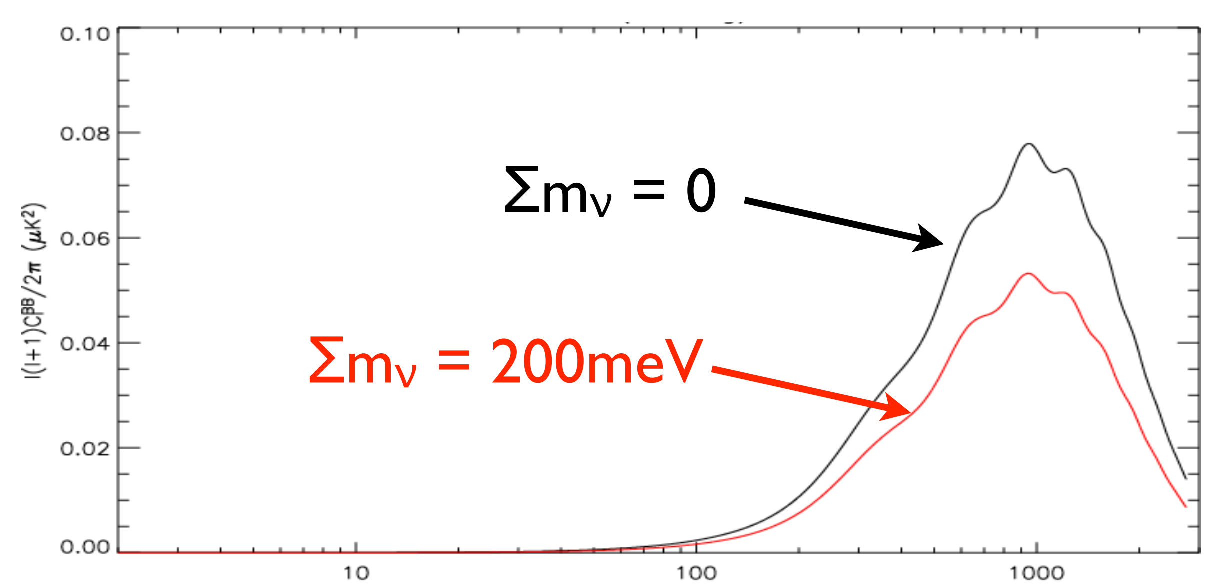
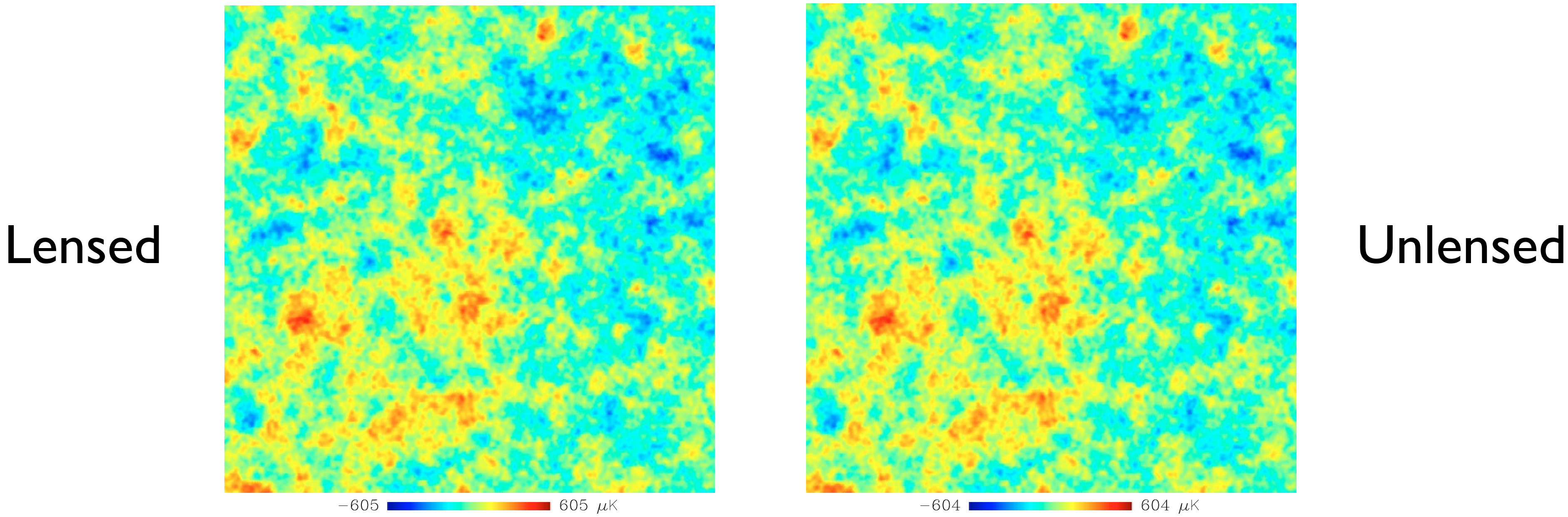




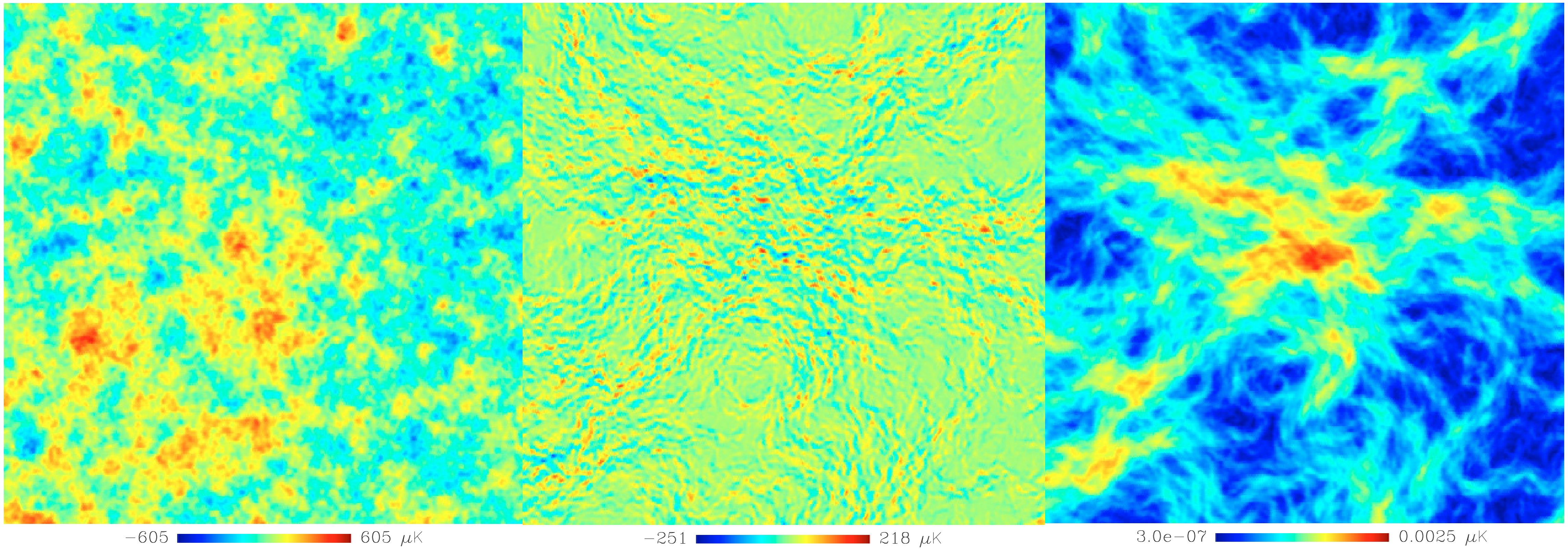


Effects on maps

- Lensed and unlensed maps are practically indistinguishable by eye



- Their difference shows a pattern similar to the LSS which lensed the signal



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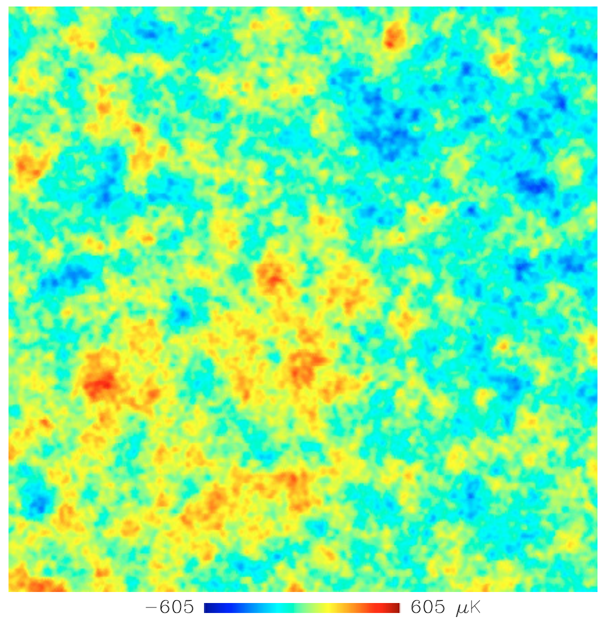
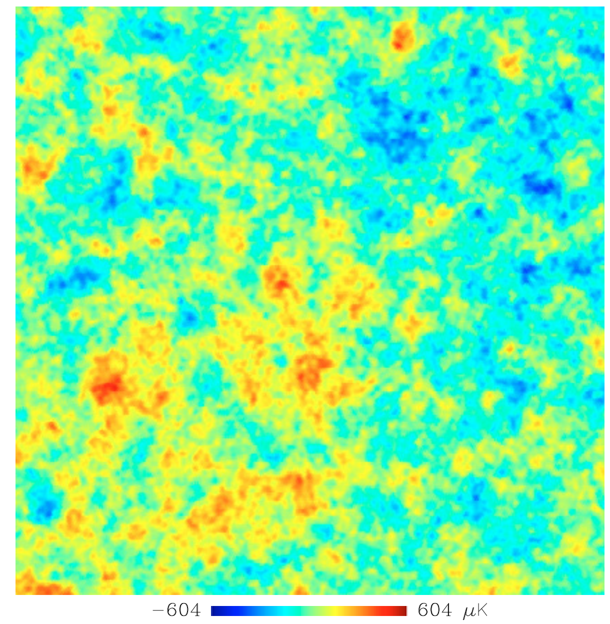
Lensed





Unlensed

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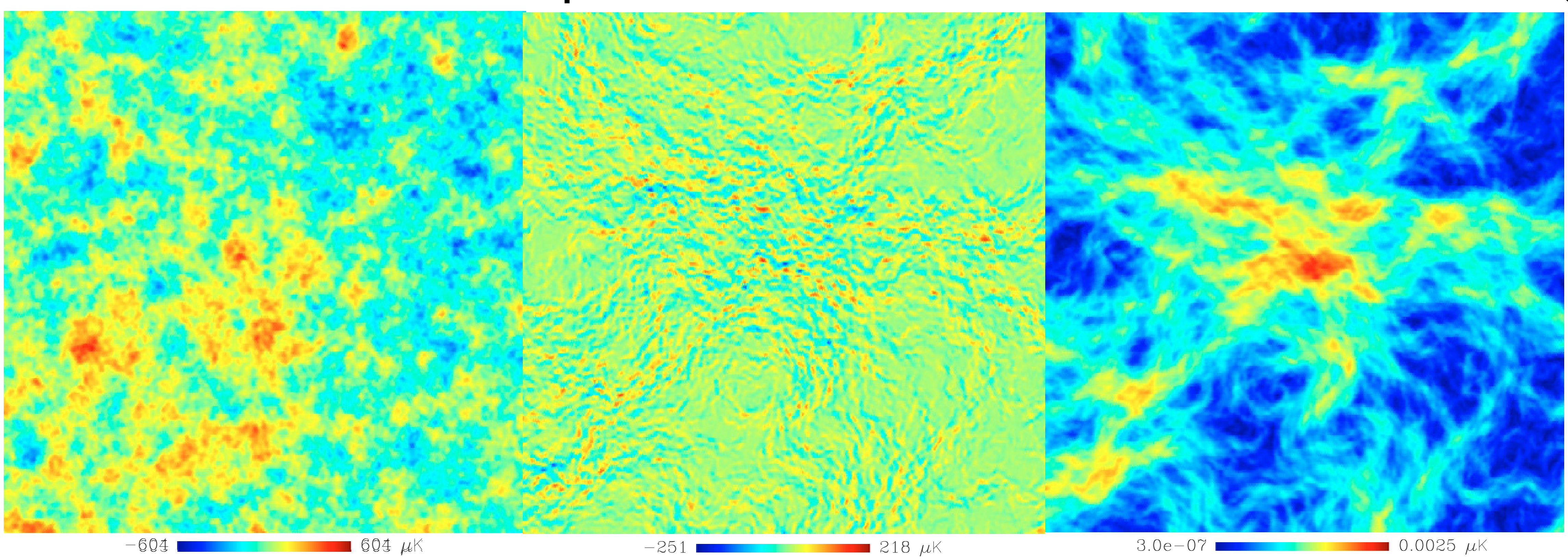

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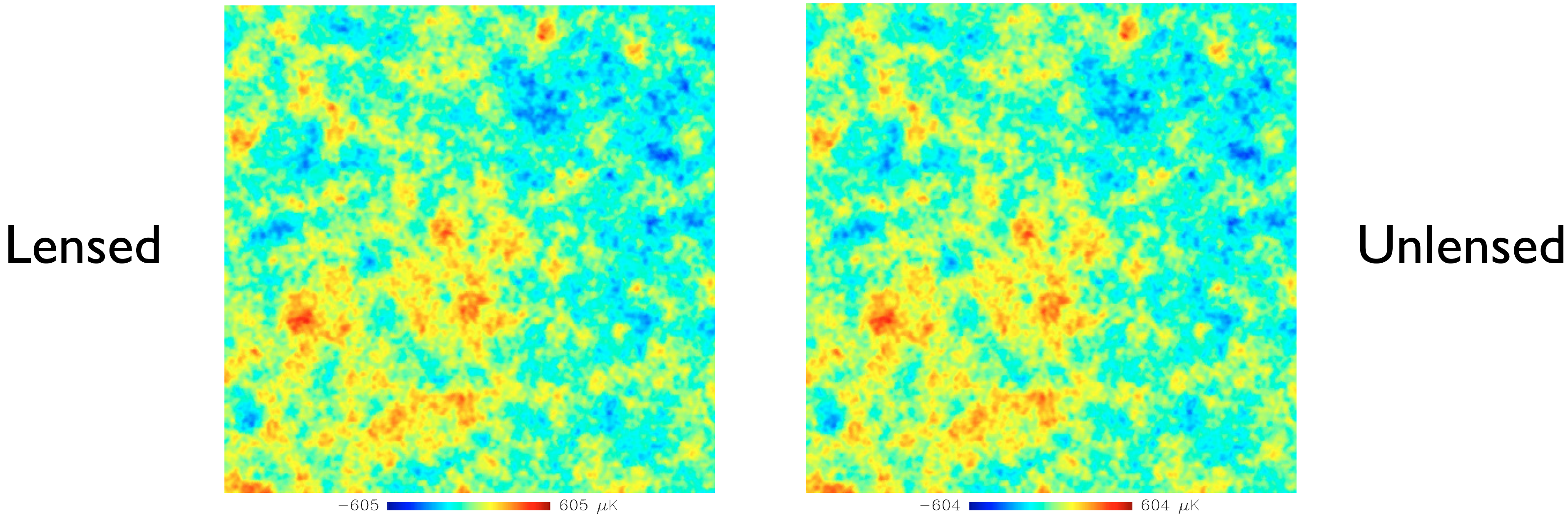

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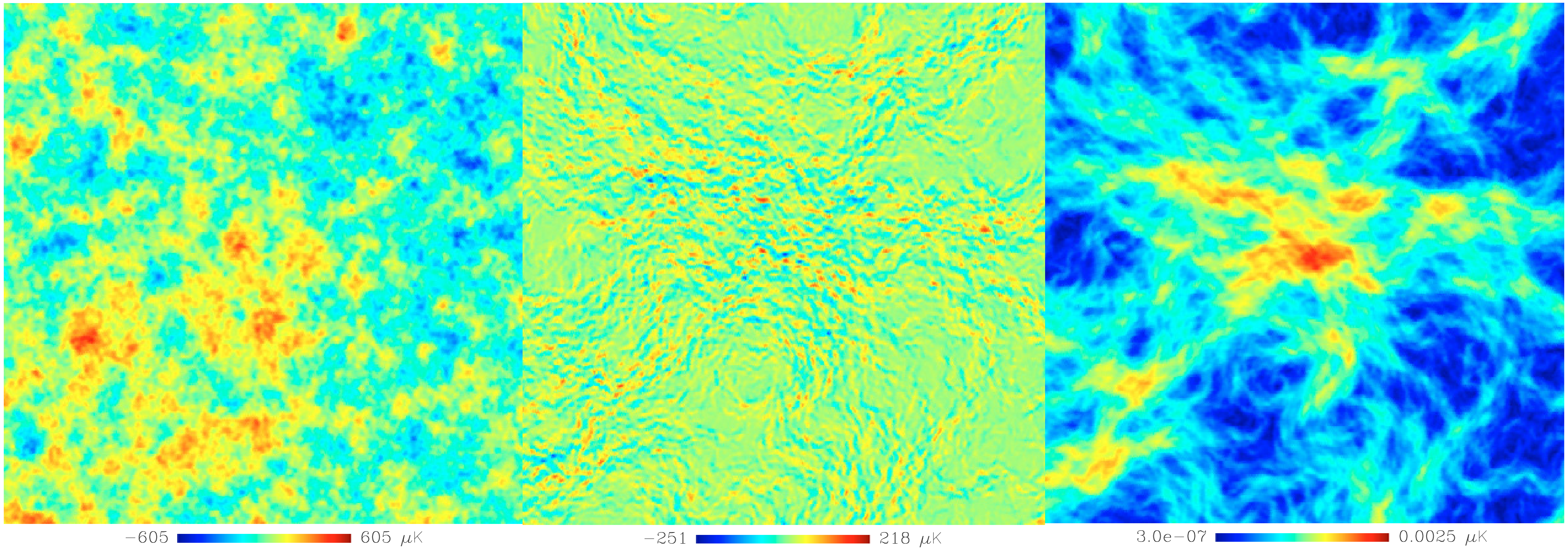

Lensing reconstruction basis

- Lensing in real domain:

$$\Theta(\hat{\boldsymbol{n}}) = \tilde{\Theta}(\hat{\boldsymbol{n}} + \boldsymbol{d}(\hat{\boldsymbol{n}}))\ ,$$

$$(Q \pm iU)(\hat{\boldsymbol{n}}) = (\tilde{Q} \pm i\tilde{U})[\hat{\boldsymbol{n}} + \boldsymbol{d}(\hat{\boldsymbol{n}})]$$

$$\boldsymbol{d} = \boldsymbol{\nabla}\phi$$

- Lensing is a convolution in harmonic domain:

- 6 different unbiased estimators:

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$\longrightarrow$

$$x, x' = \Theta, E, B$$

$$\langle x(\boldsymbol{l}) x'(\boldsymbol{l}') \rangle_{\mathrm{CMB}} = f_\alpha(\boldsymbol{l}, \boldsymbol{l}') \phi(\boldsymbol{L})$$

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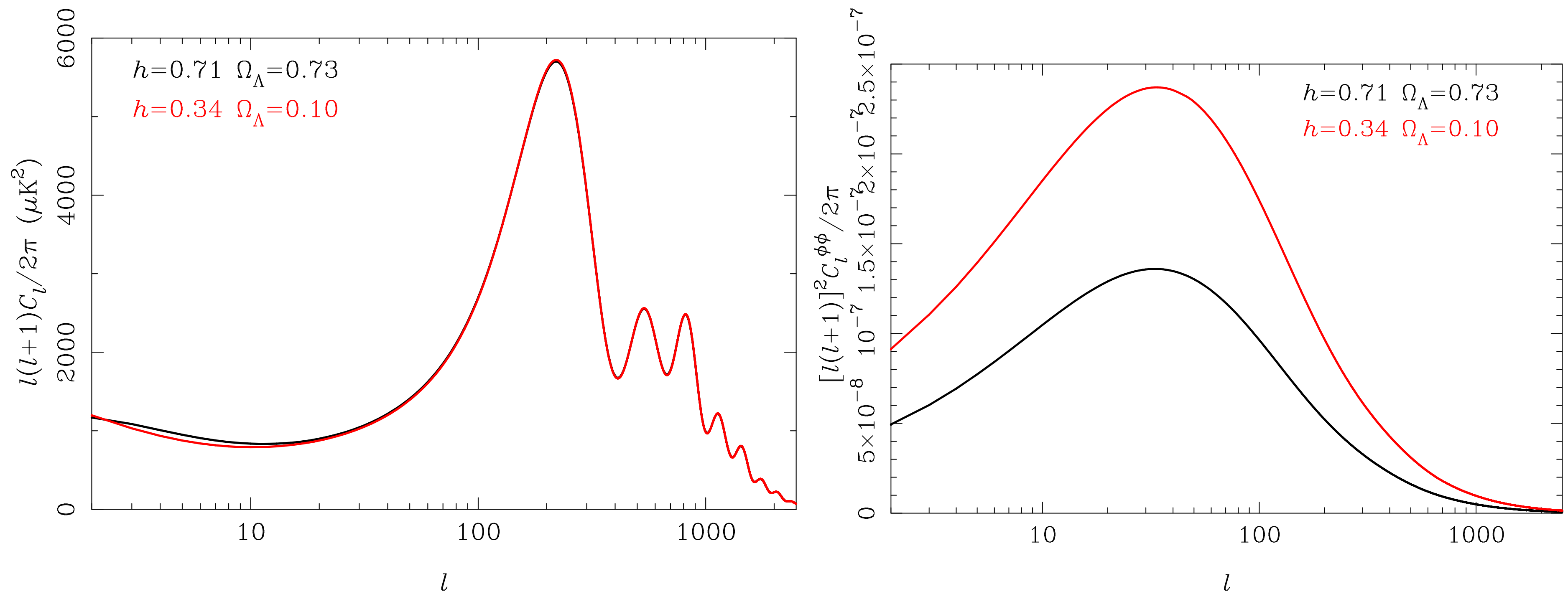
$$\begin{aligned} \langle d_\alpha(\mathbf{L}) d^*_\beta(\mathbf{L}') \rangle &= (2\pi)^2 \delta(\mathbf{L} - \mathbf{L}')(C_L^{dd} + N^{(0)}_{\alpha\beta}(L) \\ &+ \text{higher-order terms}). \end{aligned}$$

$$N_{\alpha\beta}(L) = L^{-2} A_\alpha(L) A_\beta(L) \int \frac{d^2 l_1}{(2\pi)^2} F_\alpha(\boldsymbol{l}_1, \boldsymbol{l}_2) \Big(F_\beta(\boldsymbol{l}_1, \boldsymbol{l}_2) \times C_{l_1}^{x_\alpha x_\beta} C_{l_2}^{x'_\alpha x'_\beta} + F_\beta(\boldsymbol{l}_2, \boldsymbol{l}_1) C_{l_1}^{x_\alpha x'_\beta} C_{l_2}^{x'_\alpha x_\beta} \Big) \ .$$

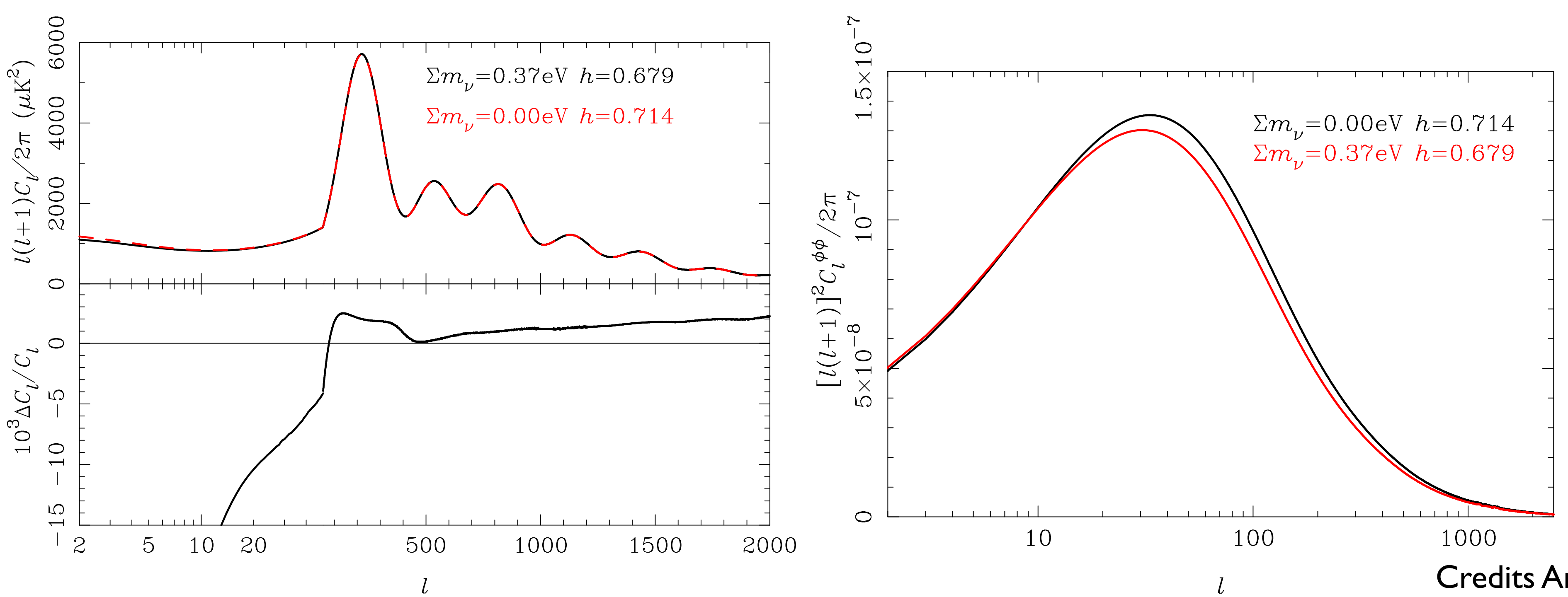
$$\langle d_\alpha(\boldsymbol{L}) \rangle_{\mathrm{CMB}} = d(\boldsymbol{L}) \equiv L\phi(\boldsymbol{L})$$

Breaking degeneracies with CMB lensing

- Lensing sensitive to geometry and late-time growth of structure: curvature



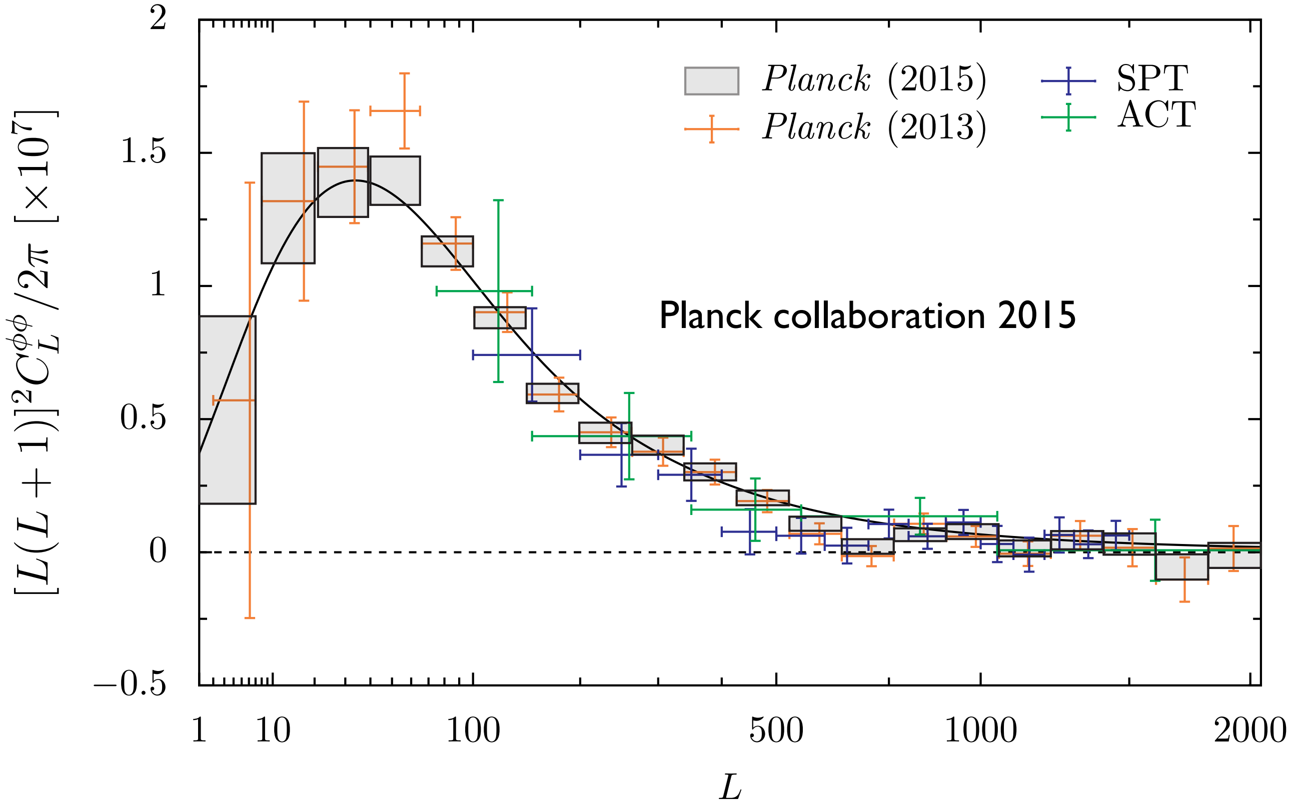
- Neutrino masses:

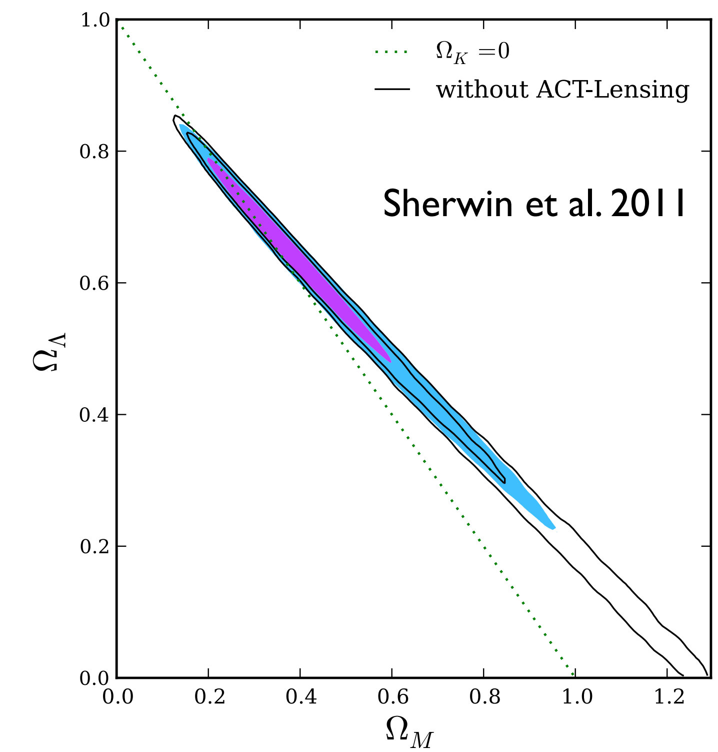


Credits Anthony Challinor

CMB lensing and large scale structures

- Planck established CMB lensing as a high-precision tool for cosmology



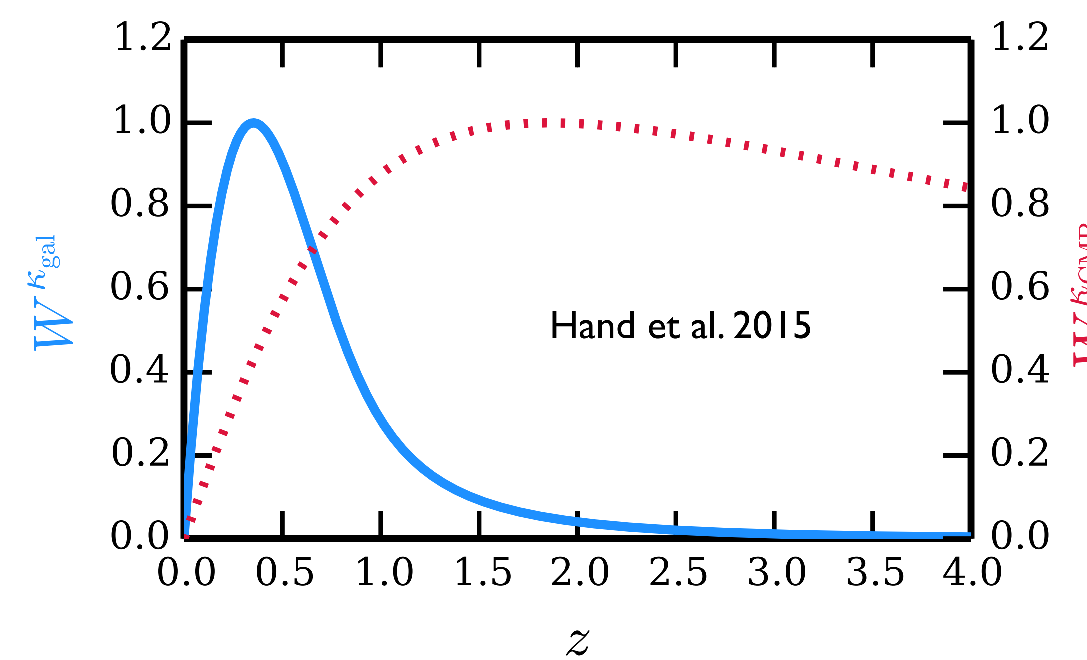


- Cross correlation with astrophysical surveys is the next big thing!

$$W^\kappa(z) = \frac{3}{2H(z)}\Omega_0 H_0^2 (1+z)\eta(z)\frac{(\eta^* - \eta(z))}{\eta^*}$$

$$W^I(z) = \frac{3}{2}\Omega_m H_0^2 \frac{(1+z)}{H(z)}\frac{\eta(z)}{c}\int_z^\infty dz' \frac{dN^I}{dz'}\frac{\eta(z') - \eta(z)}{\eta(z')}$$

$$C_\ell^{\kappa I} = \int \frac{dz H(z)}{\eta^2(z)} W^\kappa(z) W^I(z) P(k = \ell/\eta(z), z)$$



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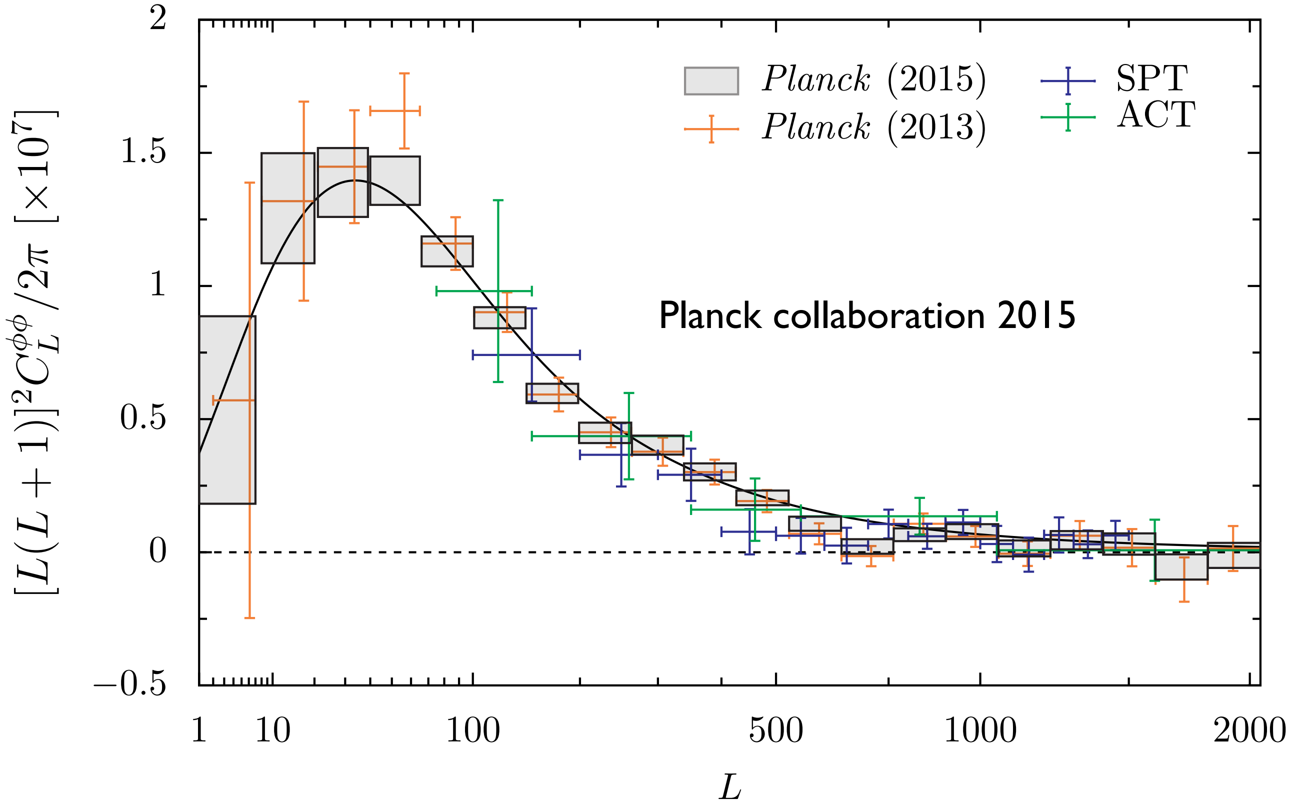

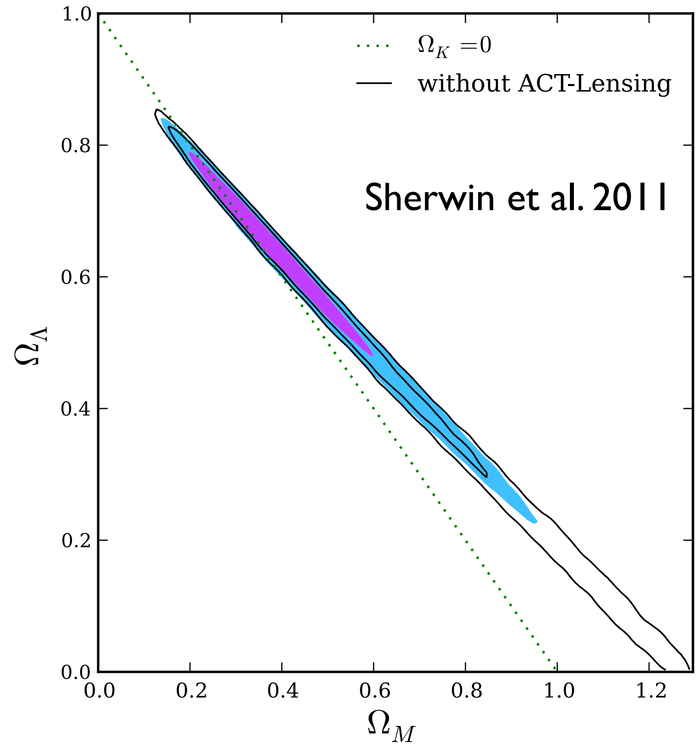

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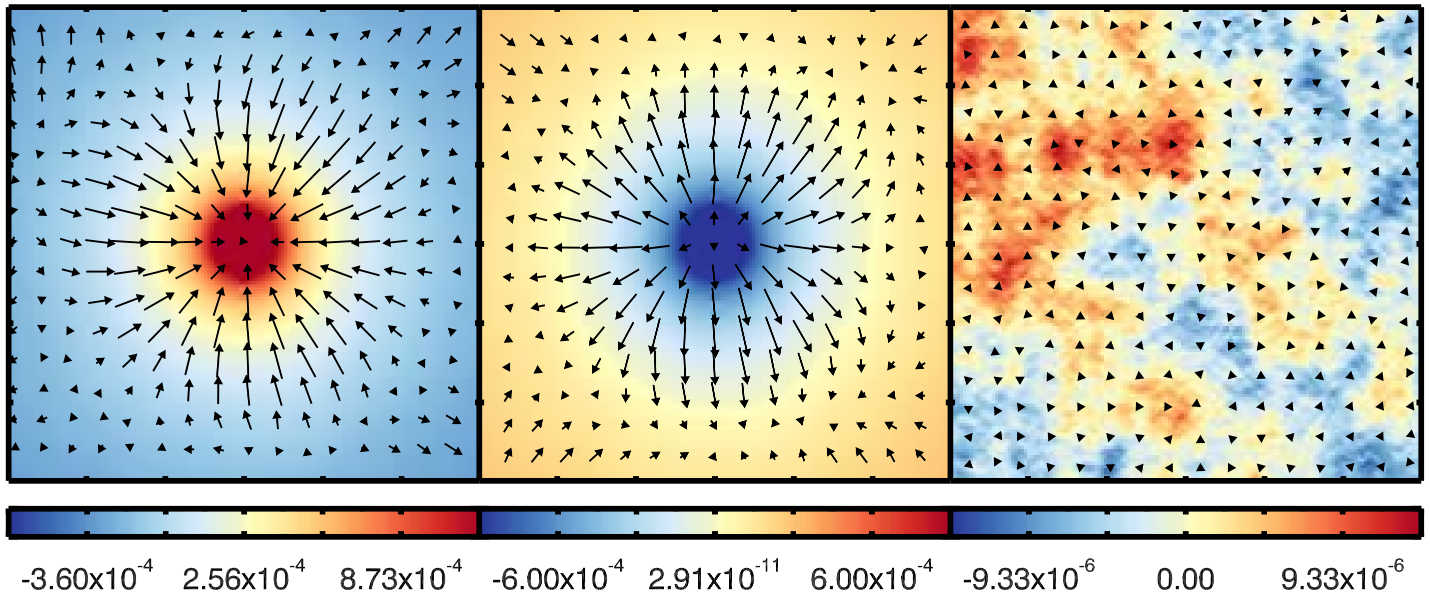
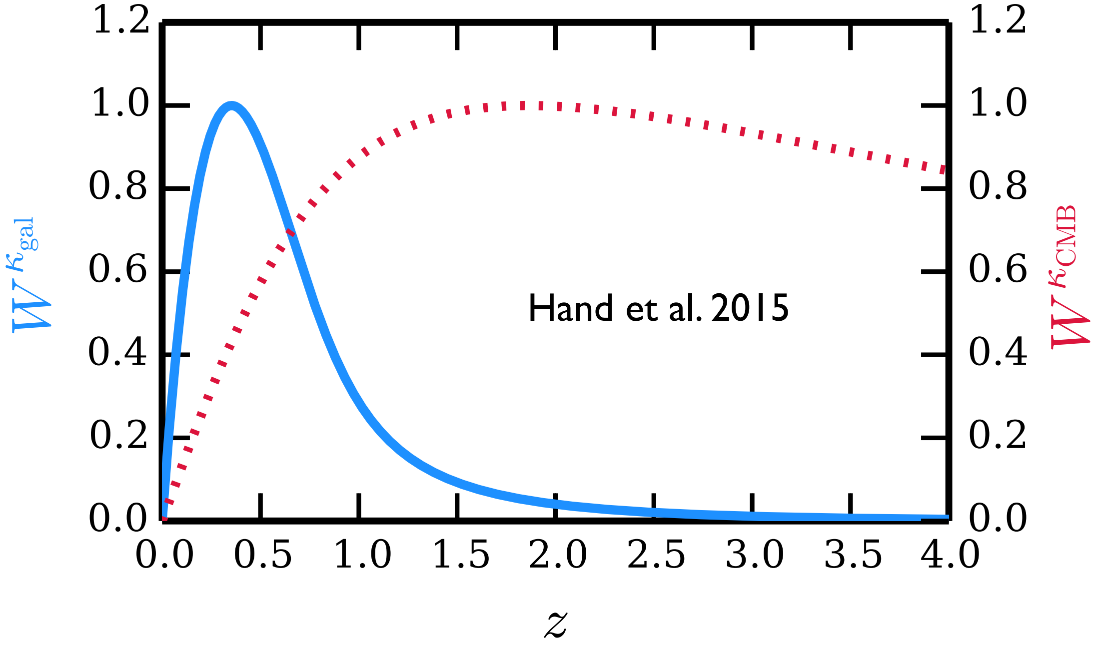
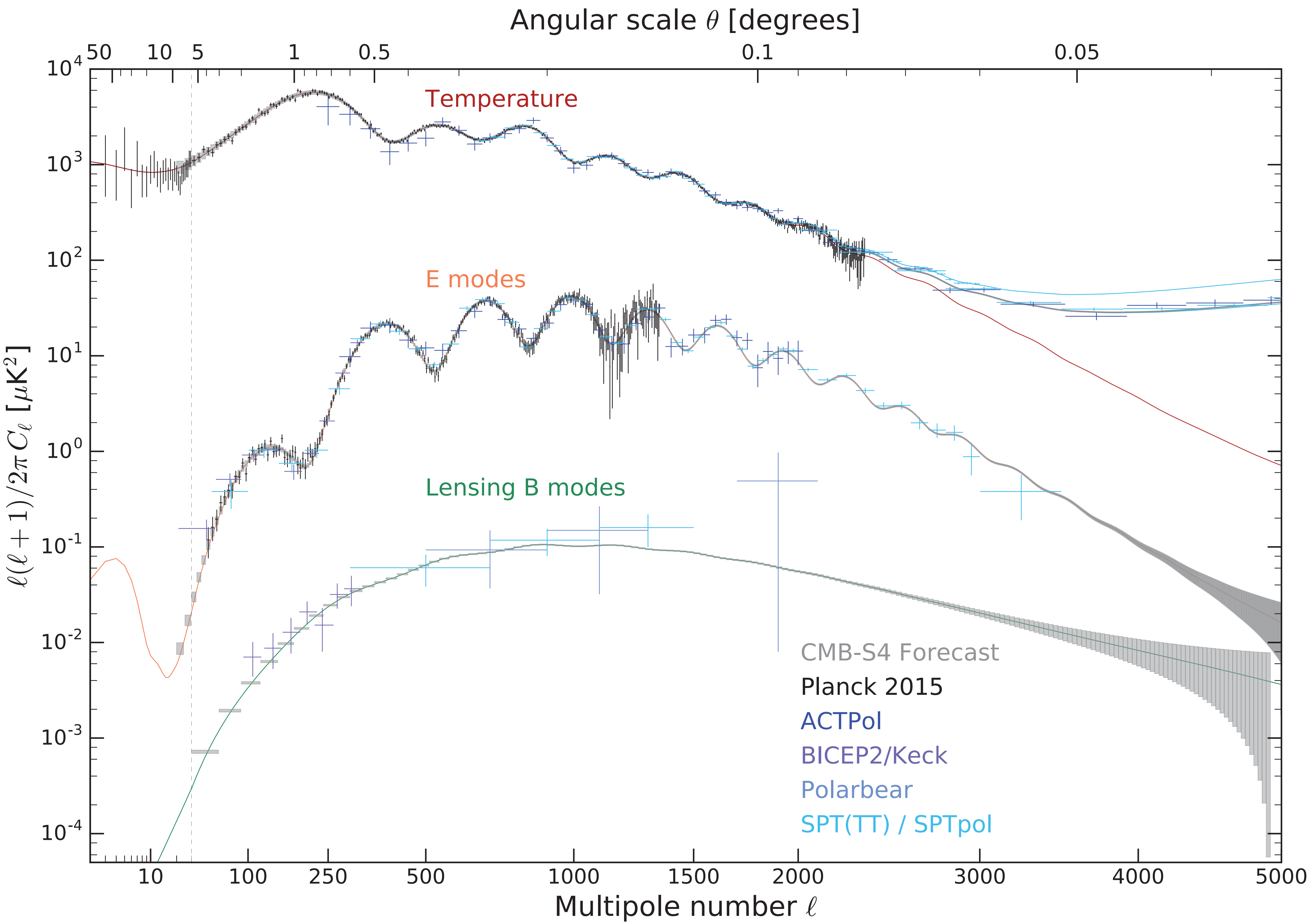




Tomorrow…



Angular scale θ [degrees]
50
10
5
1
0.5
0.1
0.05
Temperature
E modes
Lensing B modes
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\ell(\ell+1)/2\pi C_\ell$ [μK^2]
CMB-S4 Forecast
Planck 2015
ACTPol
BICEP2/Keck
Polarbear
SPT(TT) / SPTpol
10
100
250
500
1000
1500
2000
3000
4000
5000
Multipole number ℓ

L'osservatorio Simons: 100 volte meglio

L’osservatorio Simons: 100 volte meglio

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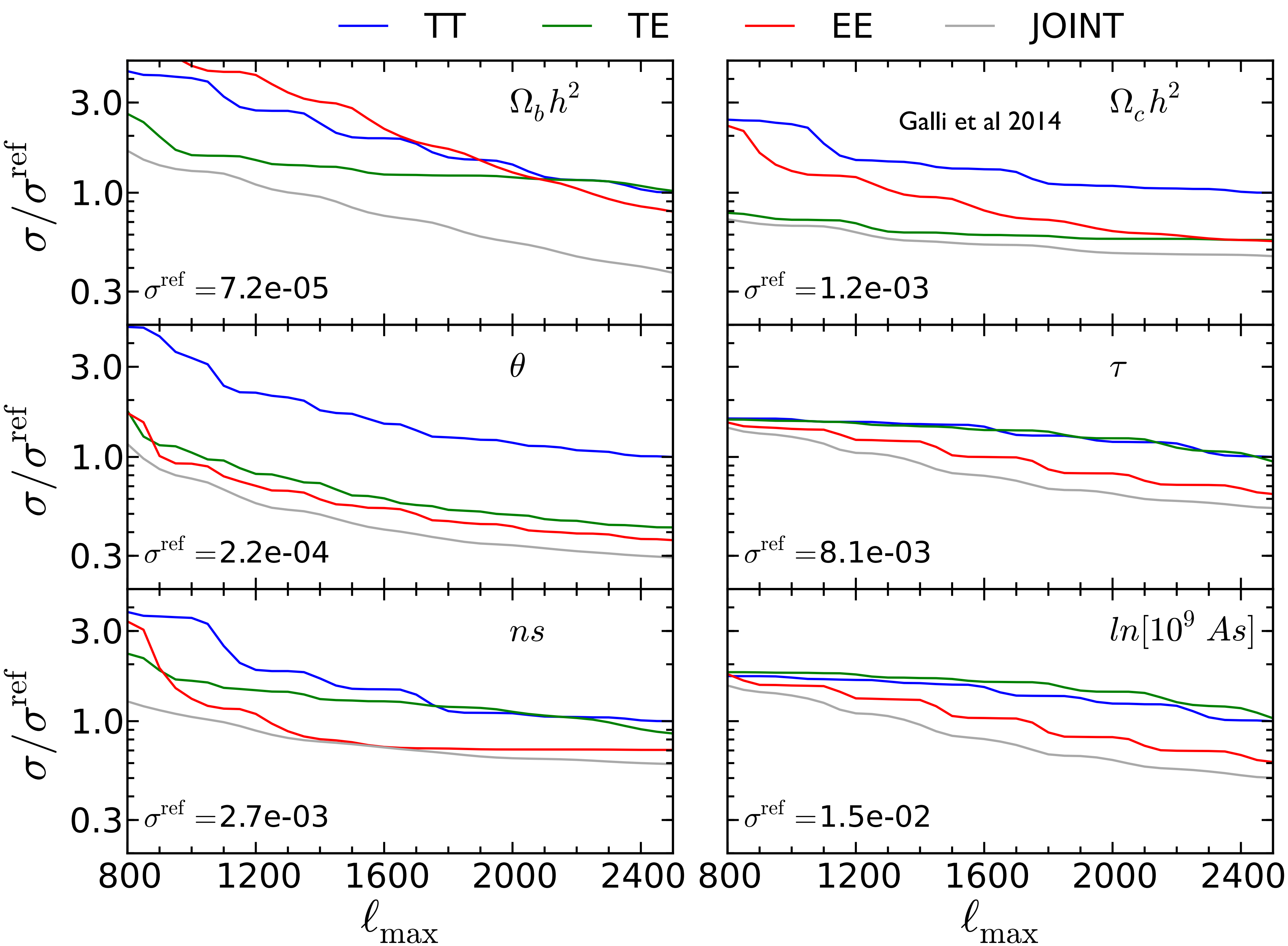
giulio.fabbian@ias.u-psud.fr

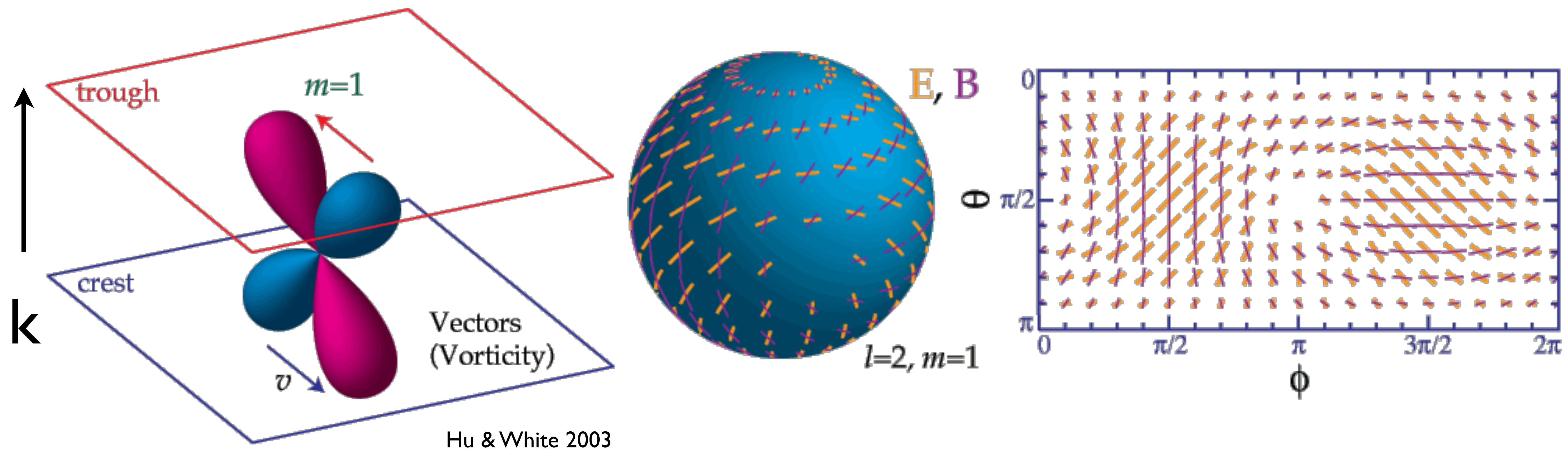
Cosmological constraints of CMB polarization

- Dependency on cosmological parameters is similar but not the same: break parameter degeneracies!



Vector perturbations

- Vortical motion of the matter, i.e. with curl like velocity field
- Decay with $1/a^2$ while super horizon but can still affect CMB through vorticity of baryons or neutrinos

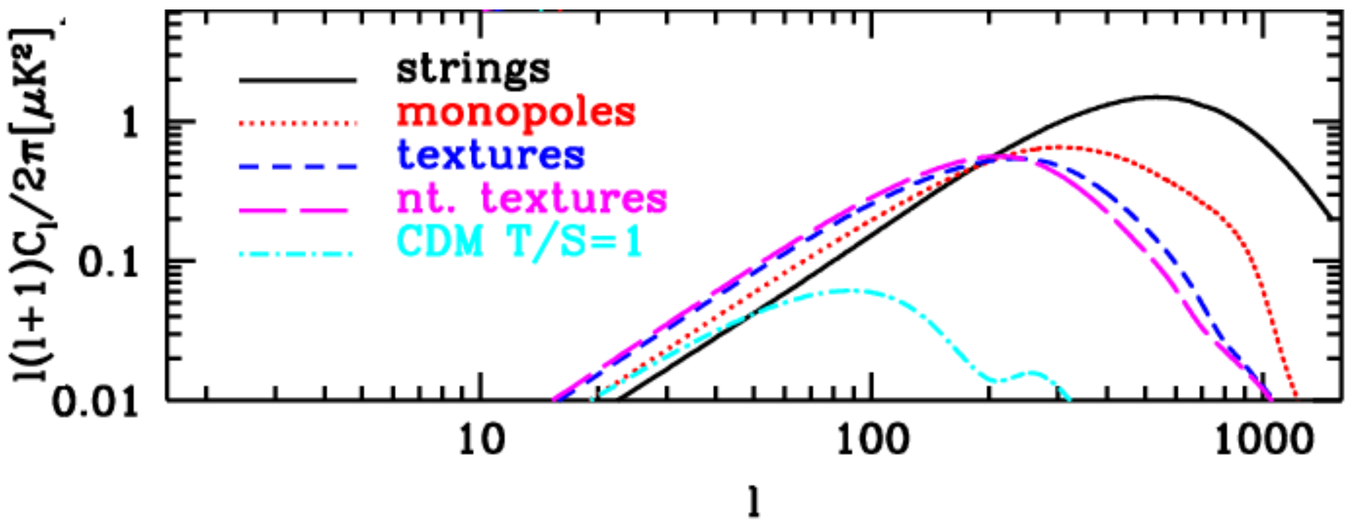


Hu & White 2003

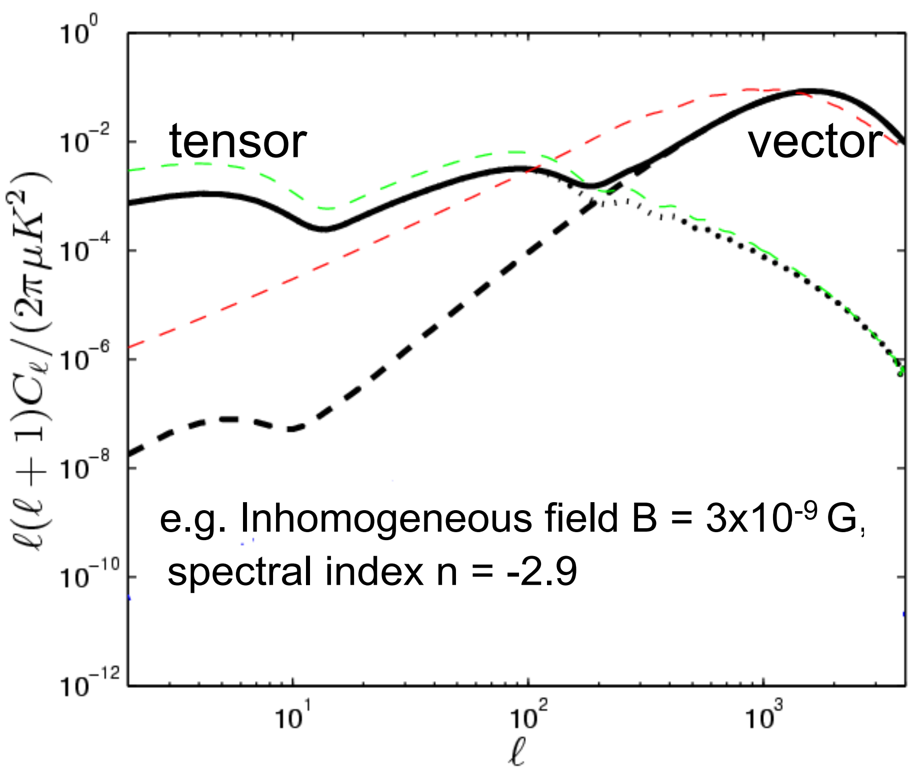
- Can produce B-modes very efficiently since they couple to dipole

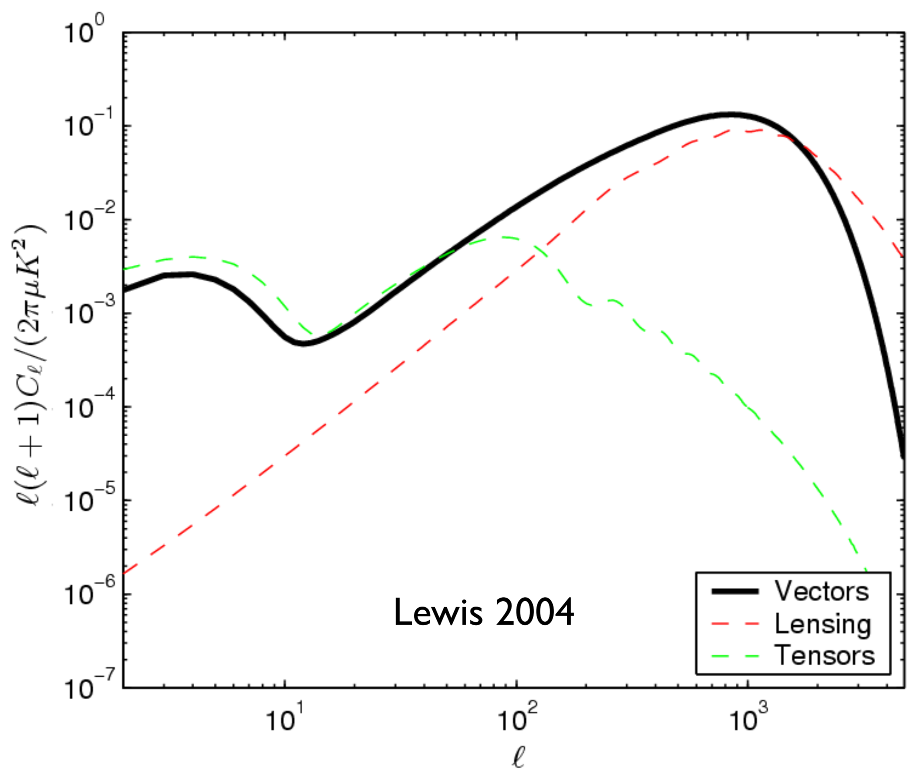
Polarization from vector perturbations

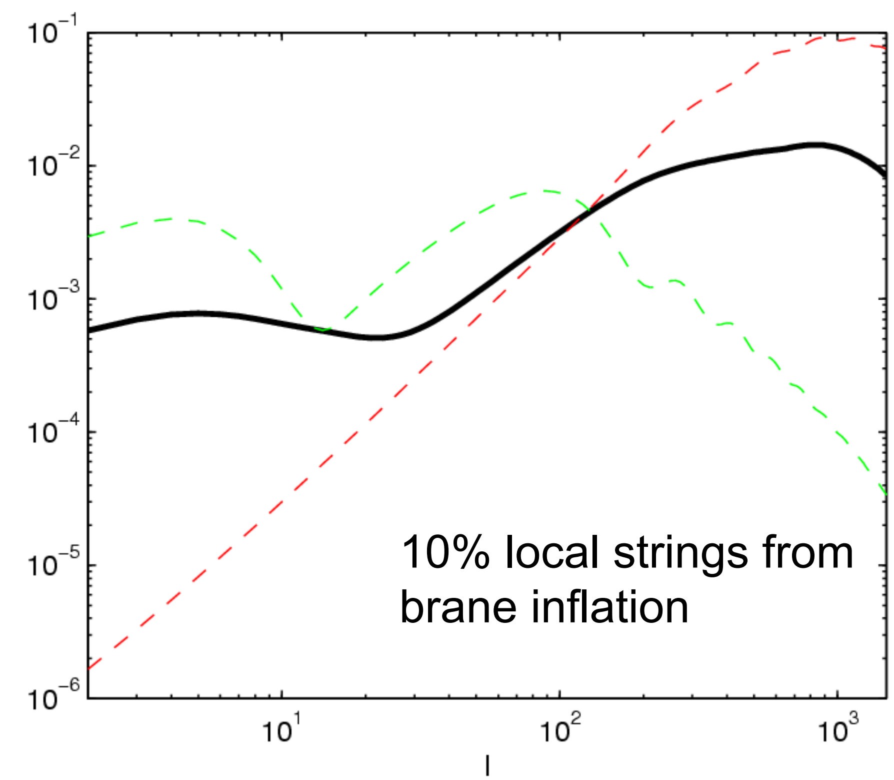
- Highly model dependent
- Various global topological defects



- Inhomogenous magnetic fields (to be motivated theoretically)
- Multi-field or brane inflation, second order perturbation theory







Cosmic Microwave Background: data analysis and experimental perspectives

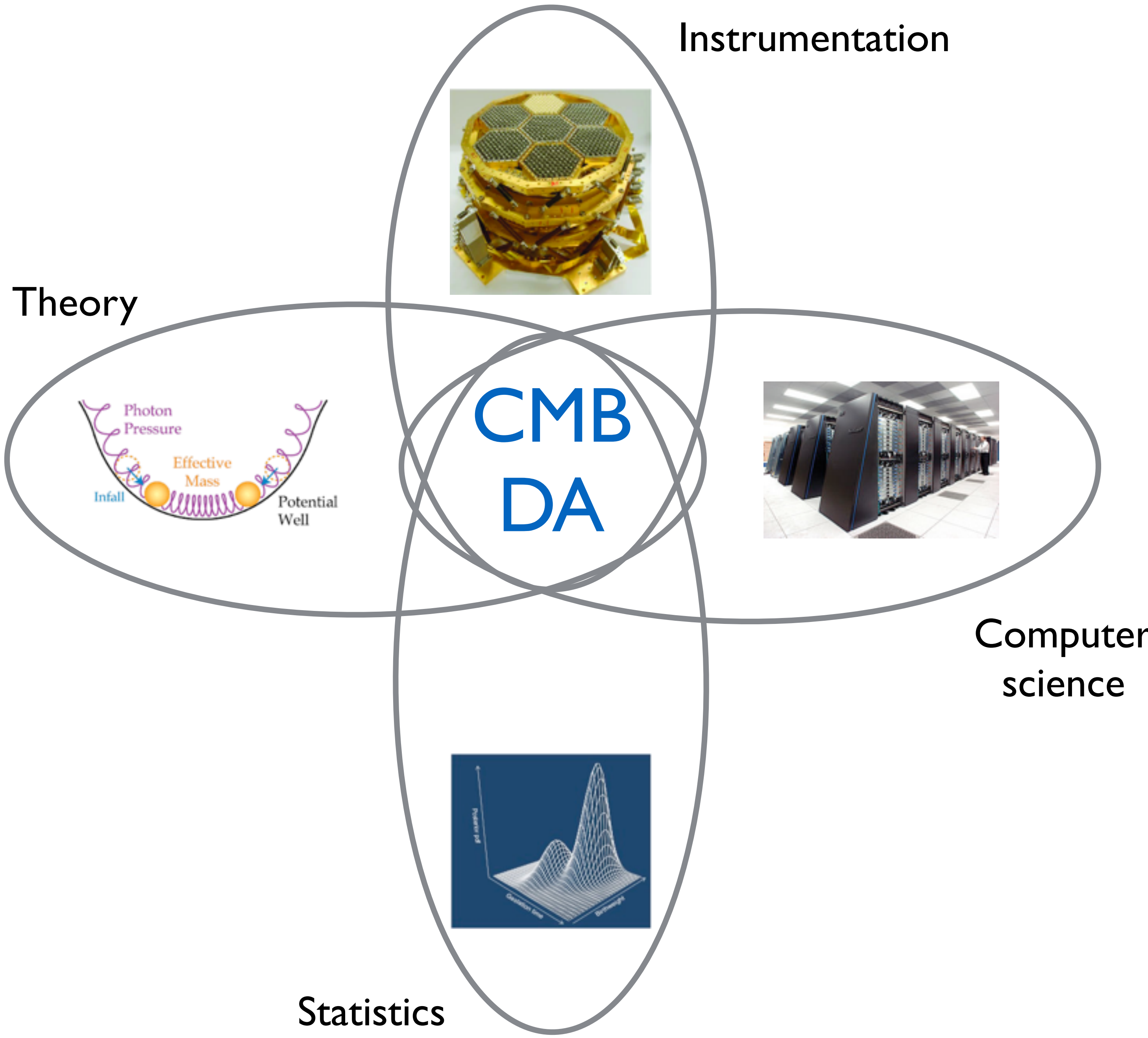
Giulio Fabbian

giulio.fabbian@ias.u-psud.fr

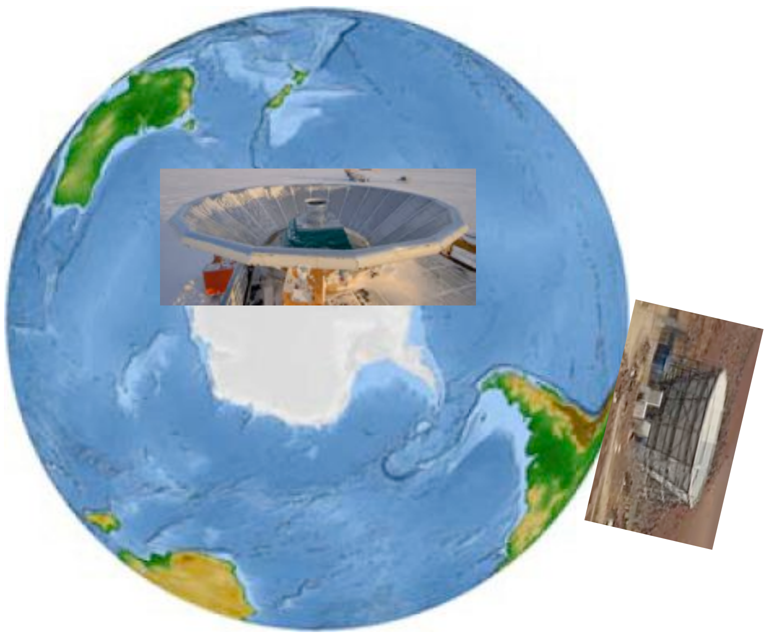
Petnica Cosmology Summer school 2017

Outline

- Some background on experimental CMB concepts
  - Data analysis chain
  - Instrumental systematics
  - Perspectives on recent experimental results
- Few more words on cosmological parameters
  - Maximum likelihood methods
  - Markov Chain Monte Carlo methods

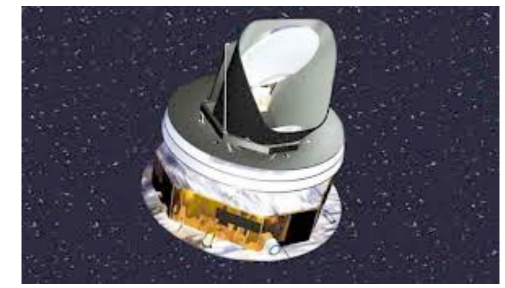


Where do the data come from?



Ground

- Heavy hardware
  - large telescopes (resolution)
  - large receivers (sensitivity)
- Environment contamination (atmosphere, ground…)
- Cutting-edge technology
- Maintenance possible
- <10y to deploy
- ~ 10 M€



Space

- Light hardware
- Extremely reliable technology
- Stable environment
- ~20y to deploy
- around G€
- full sky
- ~Only galactic contamination

Balloon are midway:
(notably, limited atmosphere)

Current ongoing experiments I

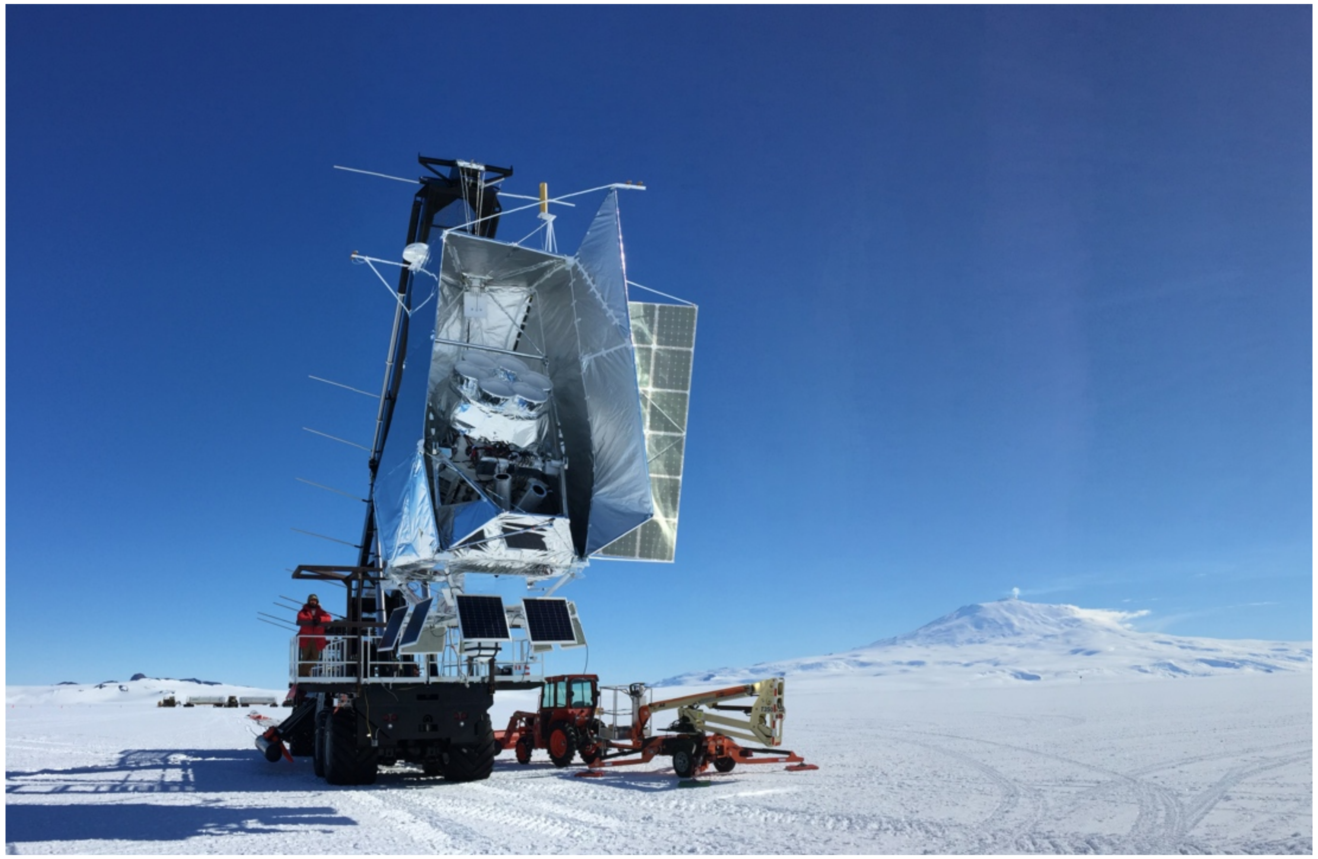
Ground Based

	Chile	Have data	Current or planned freqs
*	ABS		145 GHz
	ACTPol/AdvACt		30, 40, 90, 150, 230 GHz
	POLARBEAR		90, 150 GHz
*	CLASS		40, 90, 150 GHz
	Antarctica		
*	BICEP/KECK		90, 150, 220 GHz
	SPTPol		90, 150 GHz
	QUBIC-Bolo int.	2016	90, 150, 220 GHz
	Elsewhere (for now)		
	B-Machine –WMRS		40 GHz
*	GroundBIRD, LiteBIRD	2016	150 GHz
*	GLP – Greenland	TBD	150, 210, 270 GHz
*	MuSE-Multimoded	TBD	44, 95, 145, 225, 275 GHz
	QUIJOTE –Canaries, HEM		11-20, 30 GHz

Current ongoing experiments II

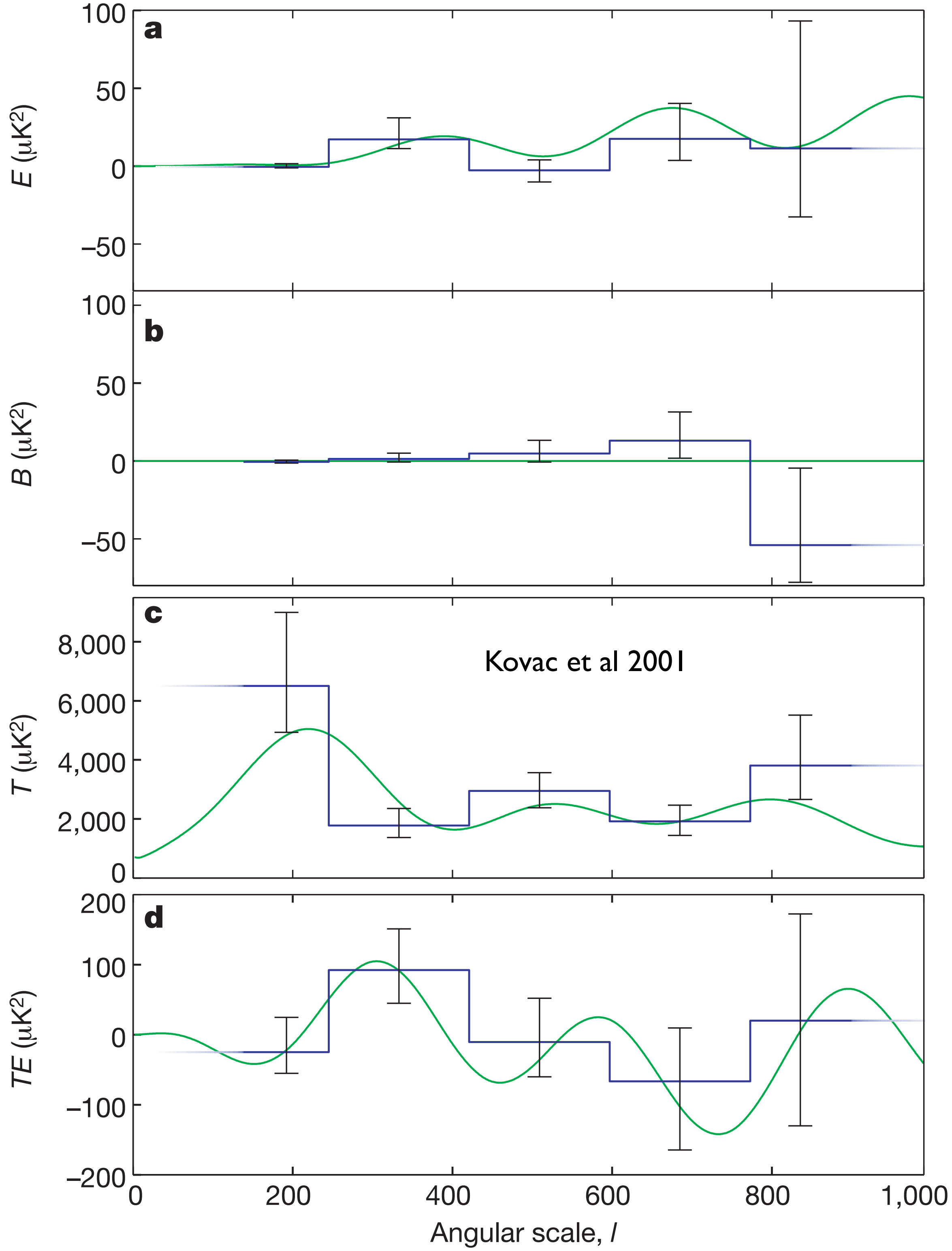
Balloons

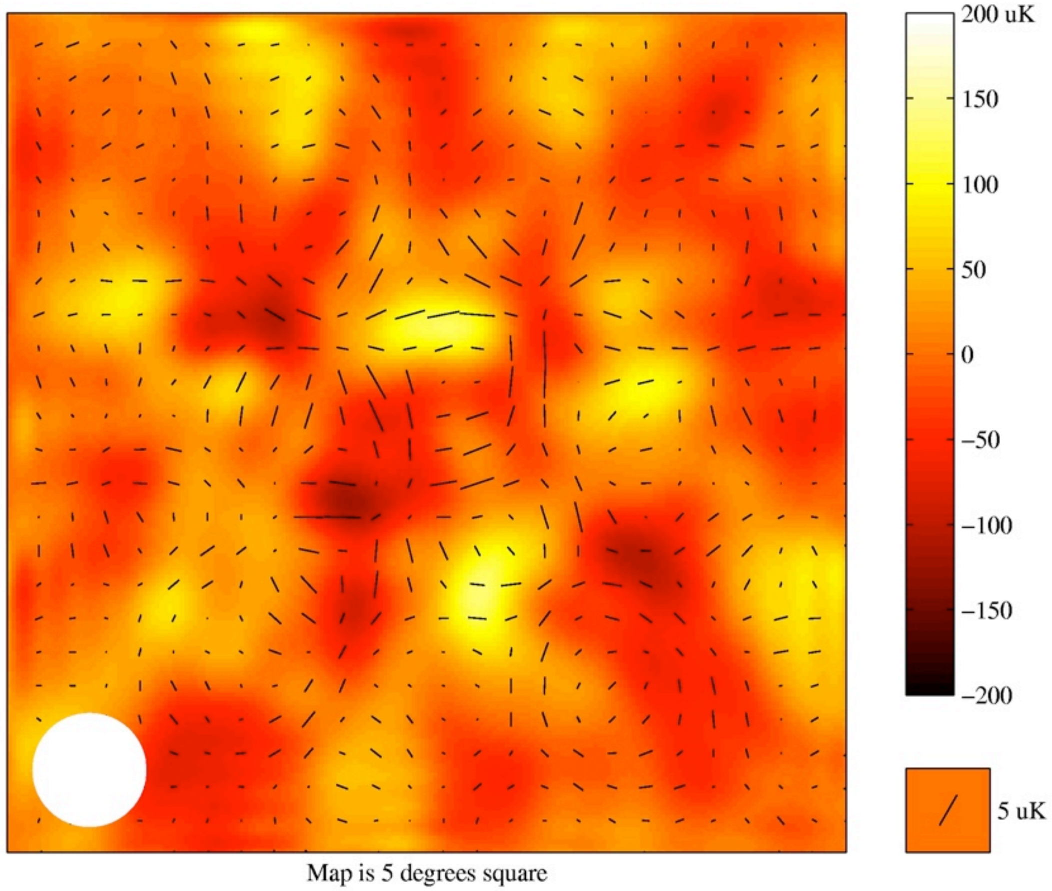
	Have data	Current or planned freqs
* EBEX	▆ (dark green)	150, 250, 210 GHz
LPSE	TBD	5 chan 40-250 GHz
* PIPER	2015	200, 270, 350, 600 GHz
* SPIDER	▆ (light green)	90, 150, 280 GHz



Pictures courtesy of Zigmund Kermish

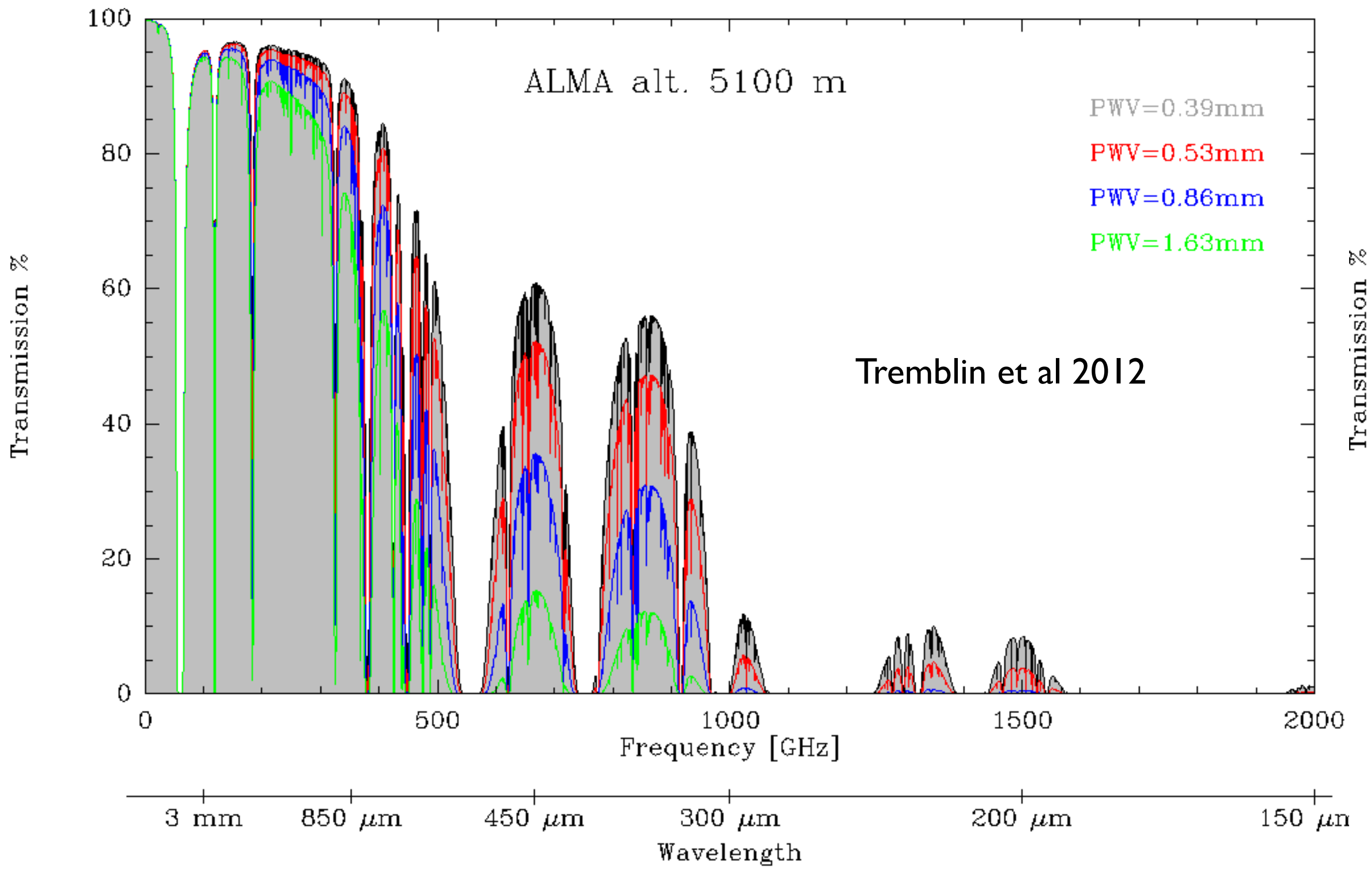
DASI: first detection of CMB polarization

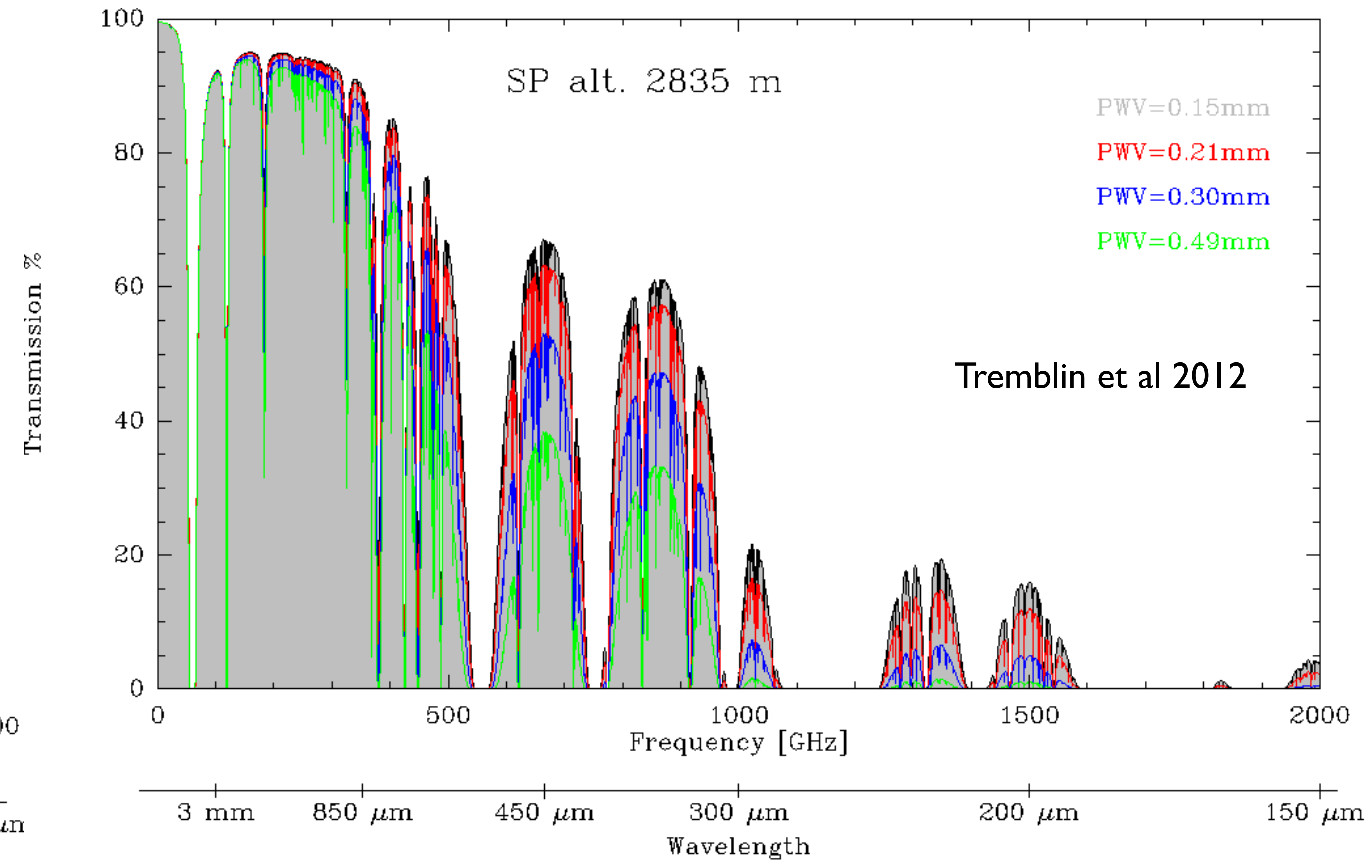




Ground-based observatories requirements

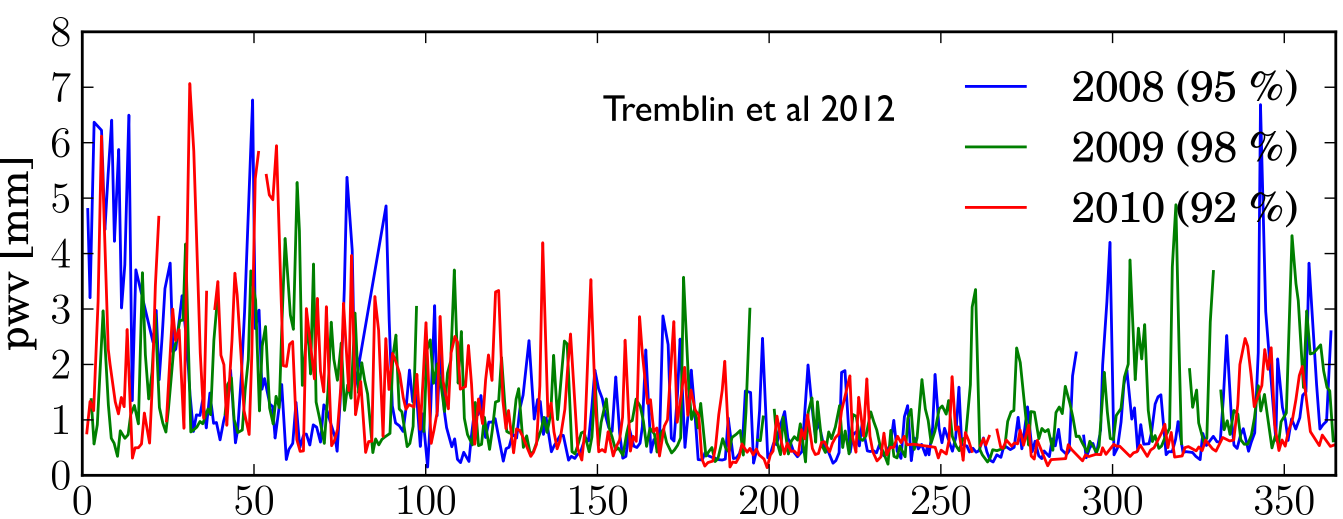
- Observation from the ground limited by atmospheric transparency



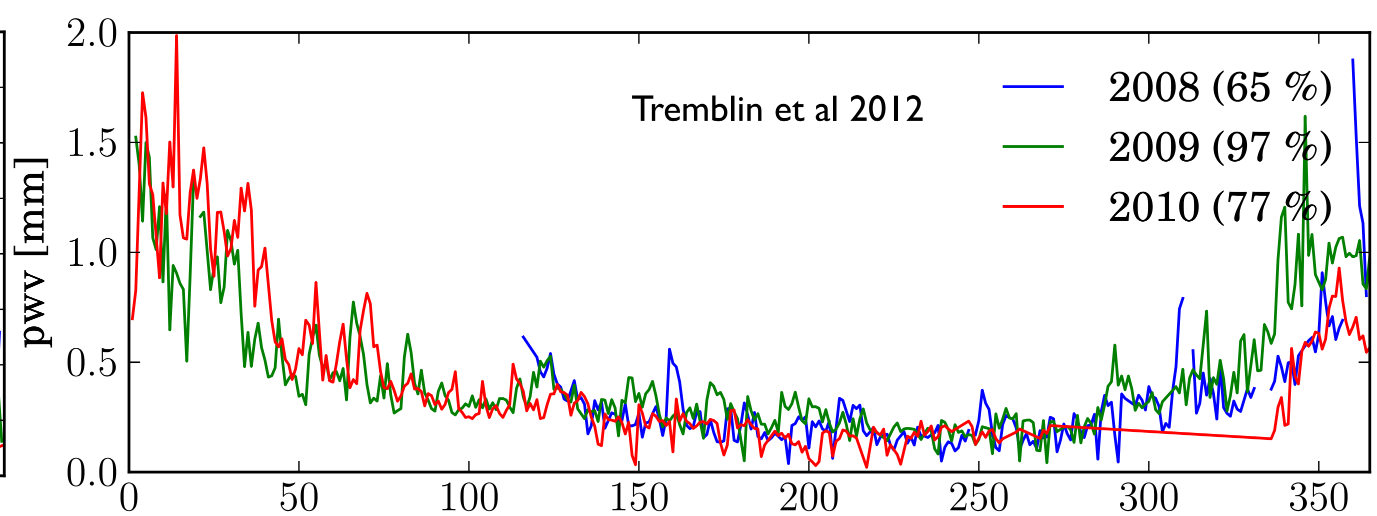


- Reduce as much as possible atmospheric emissivity: altitude and dryness

Chajnantor Plateau

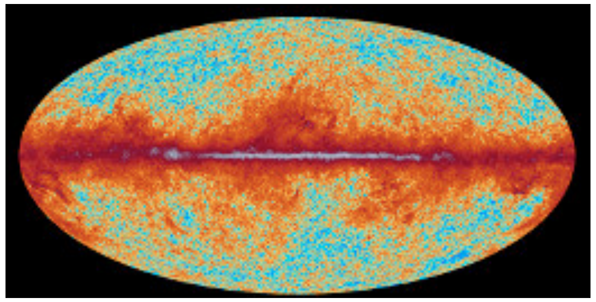


South Pole

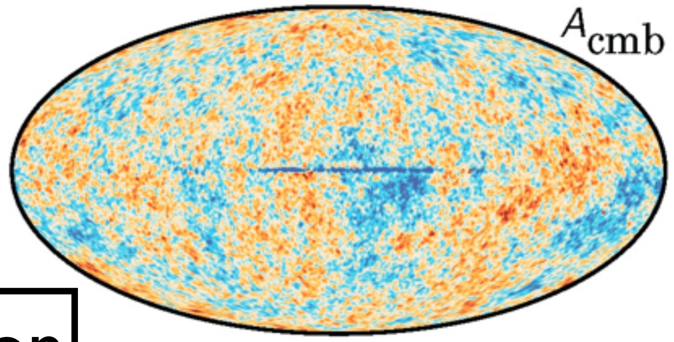


Data analysis overview

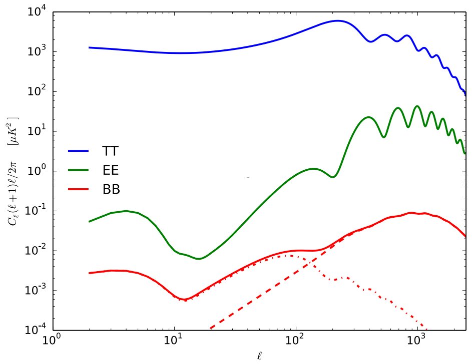
Timestream



Map-making



Component separation



Power spectrum estimation

$\Omega_b, \Omega_m, \sigma_8, \ldots$

Parameter estimation

Few order of magnitudes

- **Time-Ordered data**:
  Polarbear:
  Volume = *sampling rate* x *detector number* x *observation time*
  = *~100 Hz* *x* *~1000* *x* ~10^7 s = ~$\mathbf{10^{12}}$ *samples (~10 TB)*

- **Map-making**
  Planck HF maps: 1.7 arcmin resolution, full sky: 5 x $\mathbf{10^7}$ pixels
  Polarbear: 1.7 arcmin, 0.1% sky: 5 x $\mathbf{10^4}$ pixels

- **Component separation**
  Typically, information compression of *O(1)*

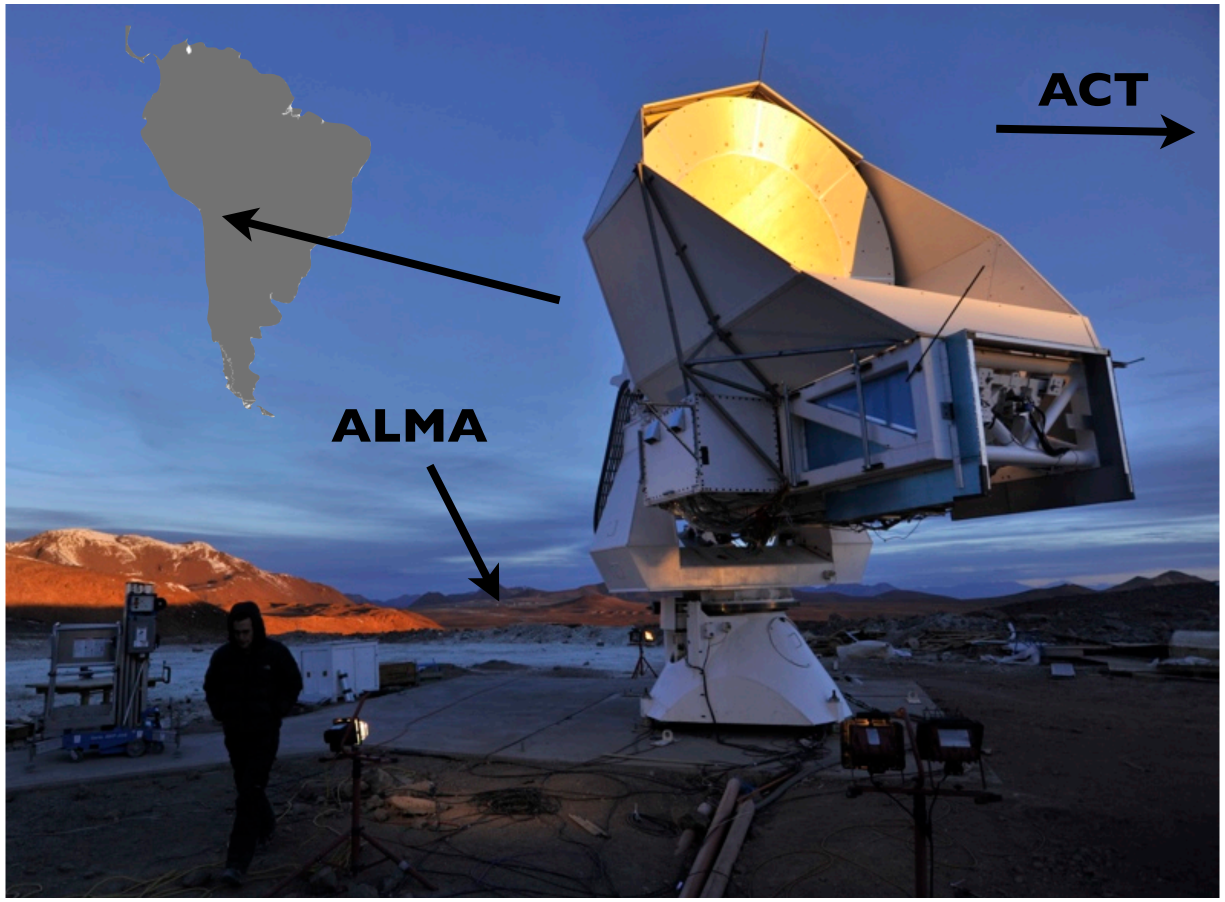
- **Power spectrum estimation**
  Typically *O(**10**)-O(**100**)* power spectrum points

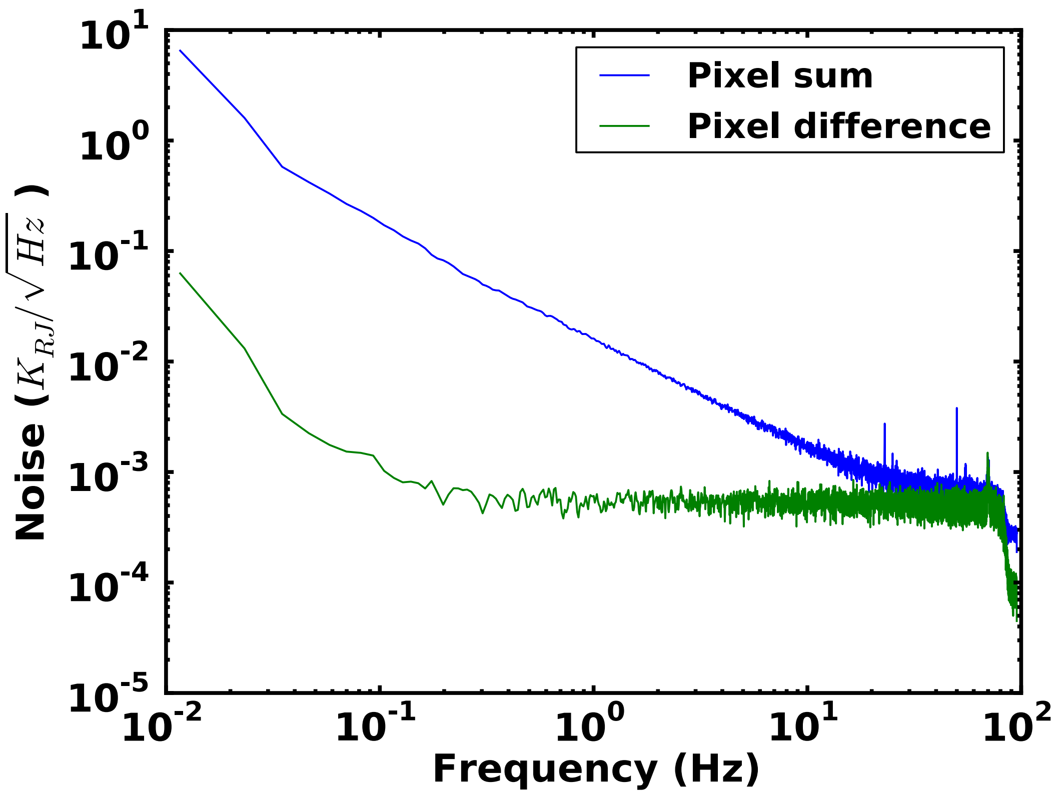
- Estimation of *O(**1**)-O(**10**)* **cosmological parameters**

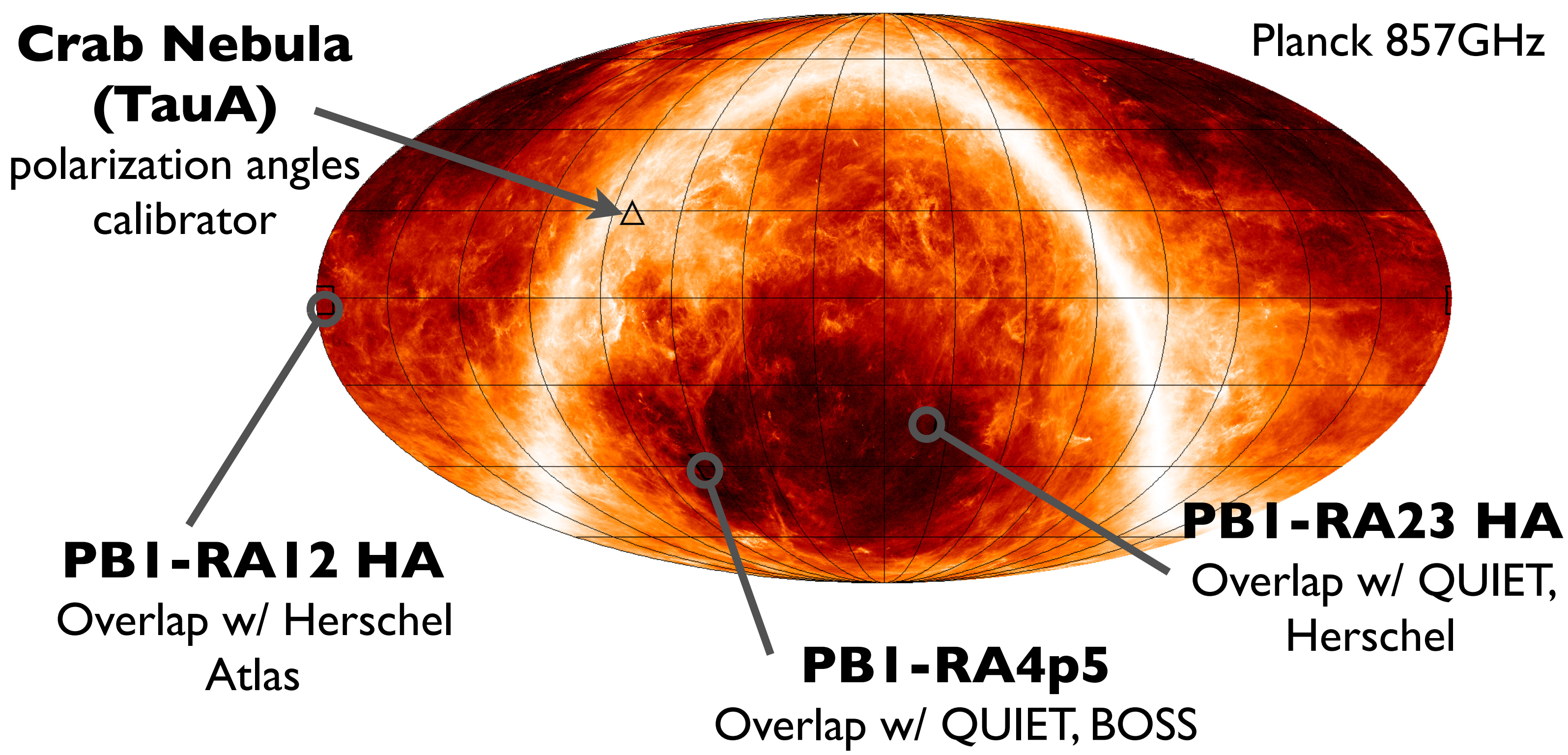
Compression has to be efficient and effective
➡ computer science and statistics play important roles

The POLARBEAR experiment

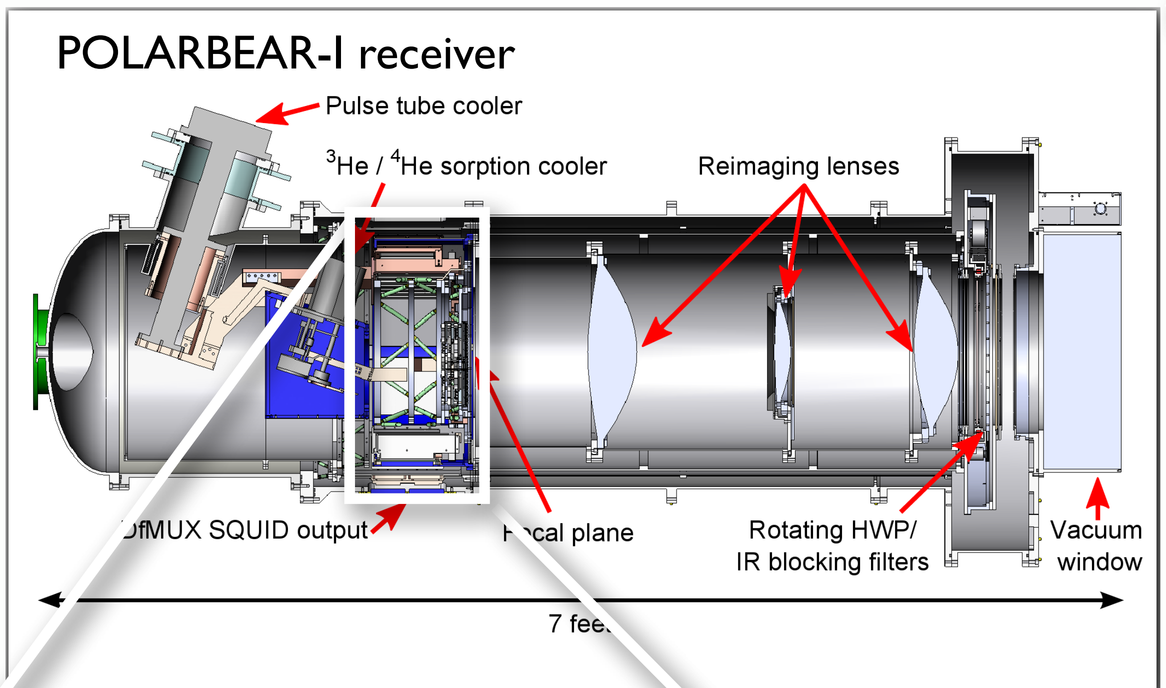
- CMB polarization dedicated experiment in Atacama Desert
- Targeting both large and small scales
- 80% of the sky with *el* > 30 accessible
- First season: deep 5x5 patches integration for lensing B-modes signal

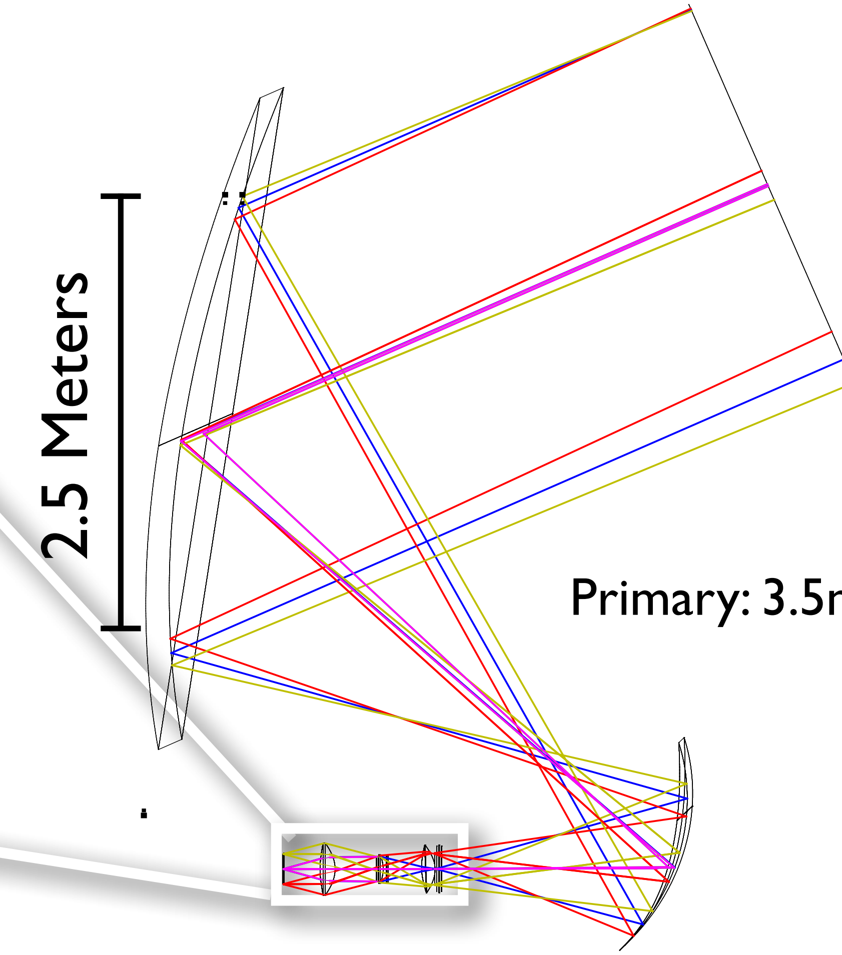






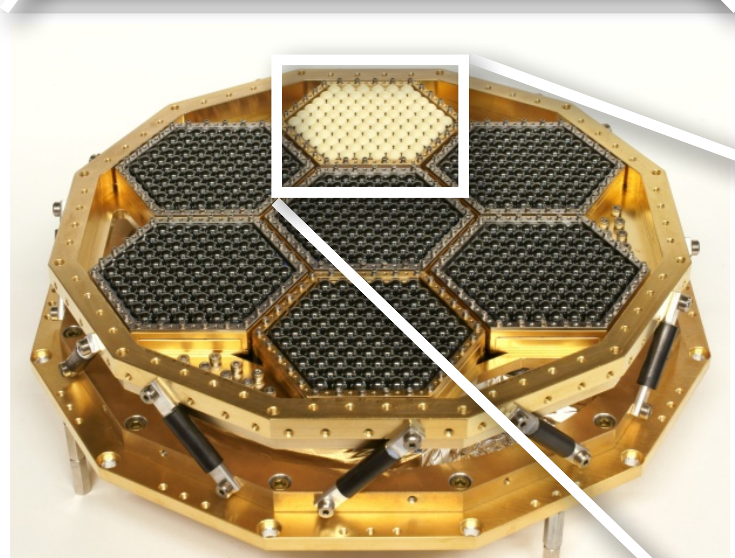
Instrument design: POLARBEAR example





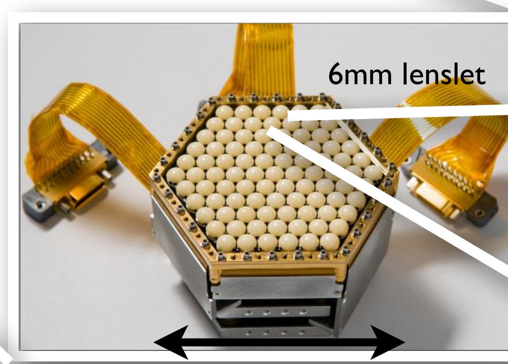
Huan Tran Telescope

Focal plane



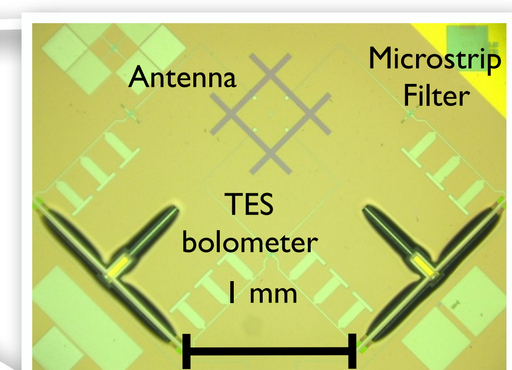
1274 bolometers @ 150 GHz
Cooled to 250 mK

Hex Module



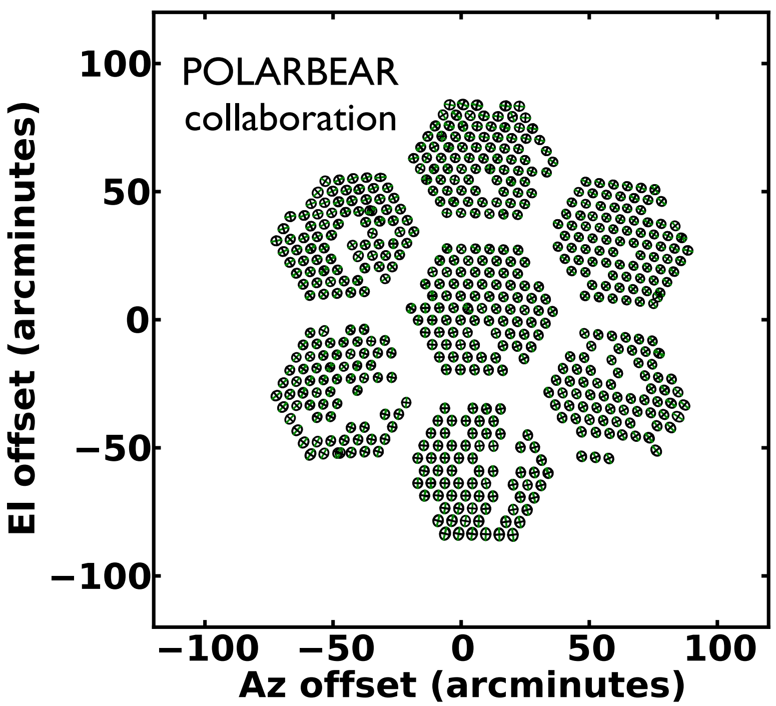
8cm

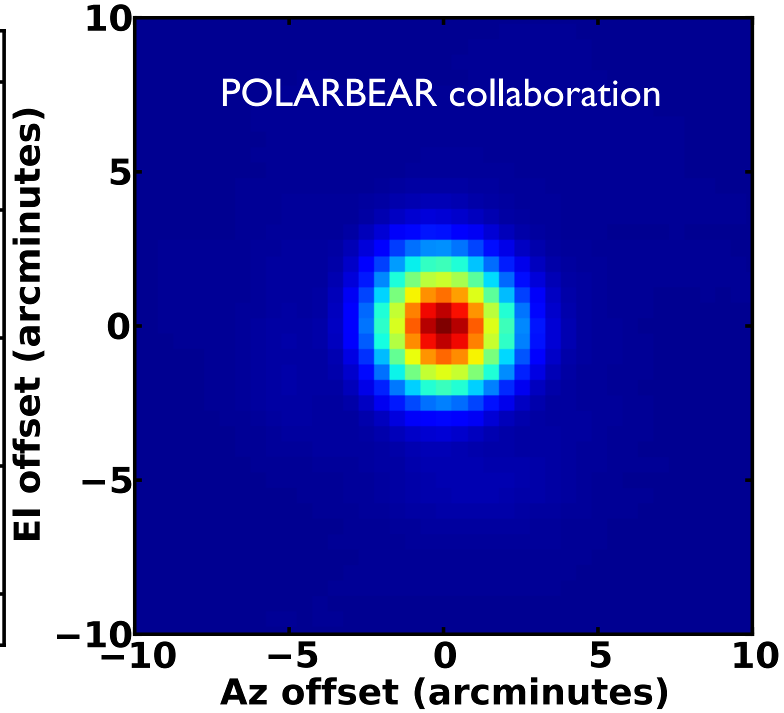
$$d^t(t) = g_{top}\left[I(\hat{\mathbf{n}}(t)) + Q(\hat{\mathbf{n}}(t))\cos(2\psi(t)) + U(\hat{\mathbf{n}}(t))\sin(2\psi(t))\right]$$
$$d^b(t) = g_{bot}\left[I(\hat{\mathbf{n}}(t)) - Q(\hat{\mathbf{n}}(t))\cos(2\psi(t)) - U(\hat{\mathbf{n}}(t))\sin(2\psi(t))\right]$$

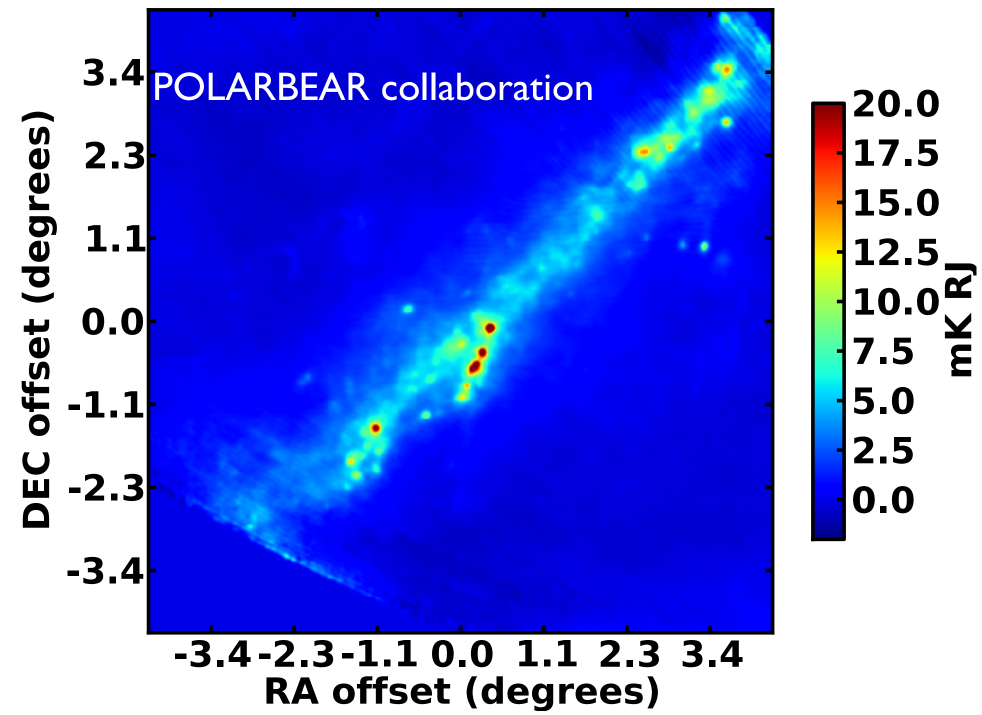


Instrument characterization

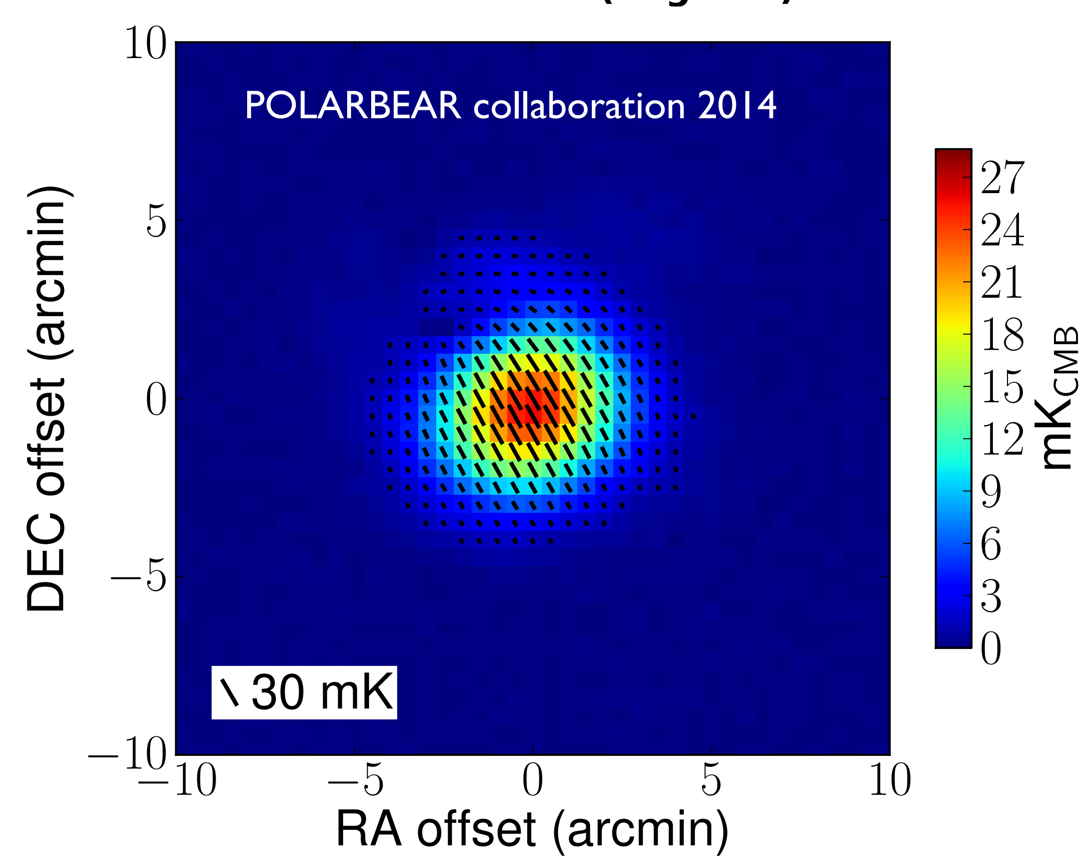
- Estimate telescope pointing and optical response (antenna beam)







- Convert current to physical units (detector calibration)
- Estimate detectors orientation w.r.t the sky (polarization angle)
- Detector instant sensitivity (time domain noise estimation)



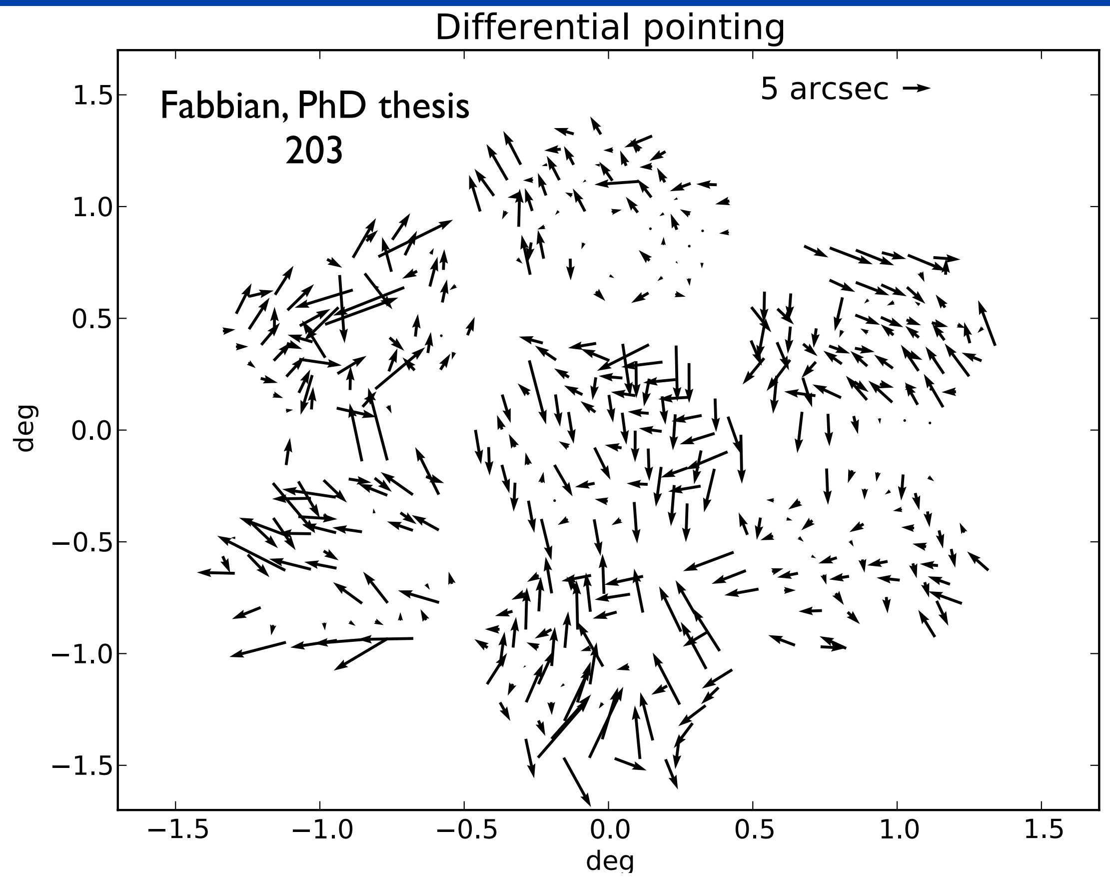
Systematics error example

- Differential pointing: two detectors looking in different direction

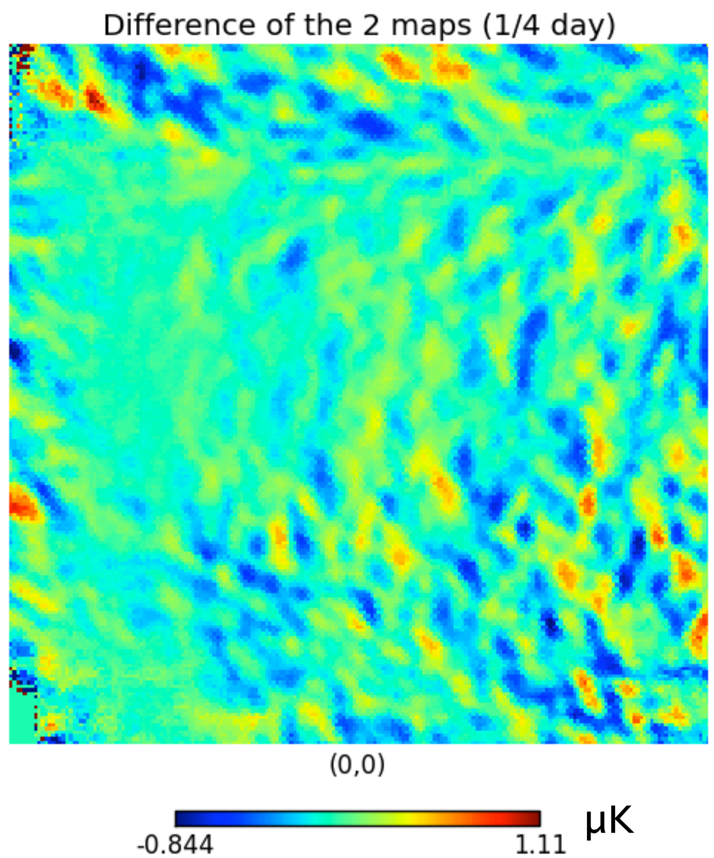
$$d^t(t) = g_{top}\left[I(\hat{\mathbf{n}}(t)) + Q(\hat{\mathbf{n}}(t))\cos(2\psi(t)) + U(\hat{\mathbf{n}}(t))\sin(2\psi(t))\right]$$
$$d^b(t) = g_{bot}\left[I(\hat{\mathbf{n}}(t)) - Q(\hat{\mathbf{n}}(t))\cos(2\psi(t)) - U(\hat{\mathbf{n}}(t))\sin(2\psi(t))\right]$$

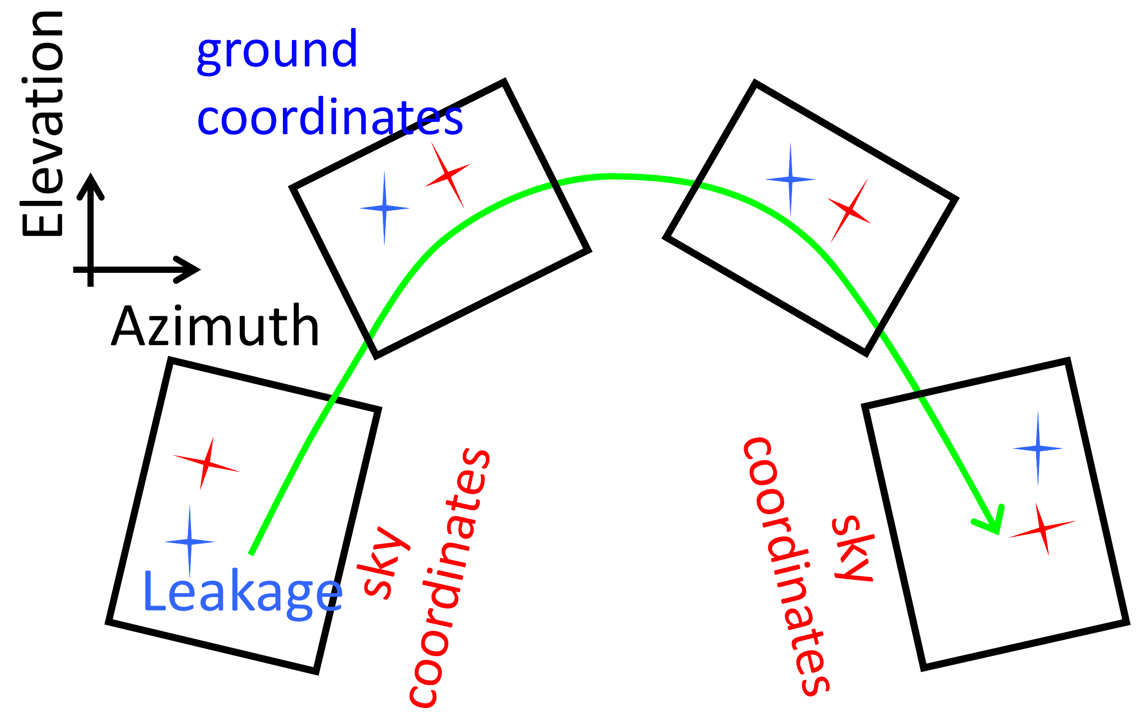
- Temperature to polarization leakage can prevent detection of B-modes

- Polarization modulation can reduce it



Q





Systematics error example

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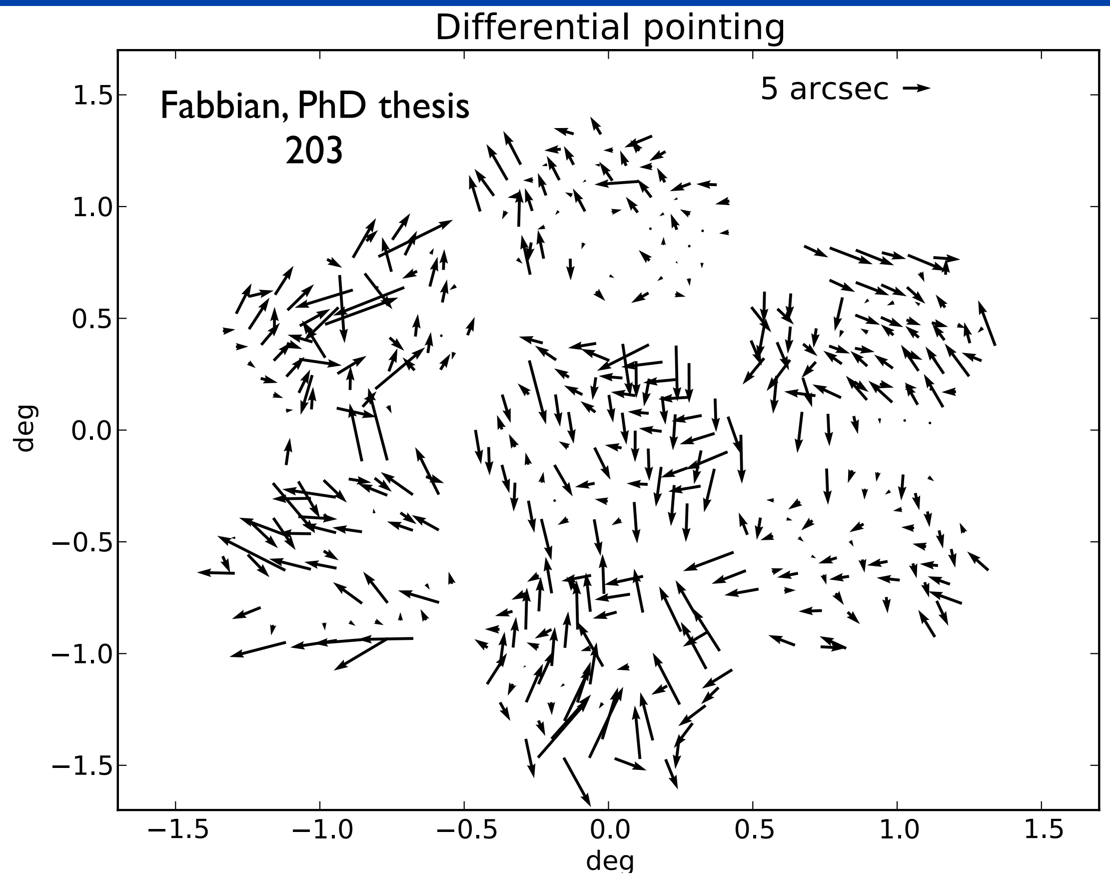
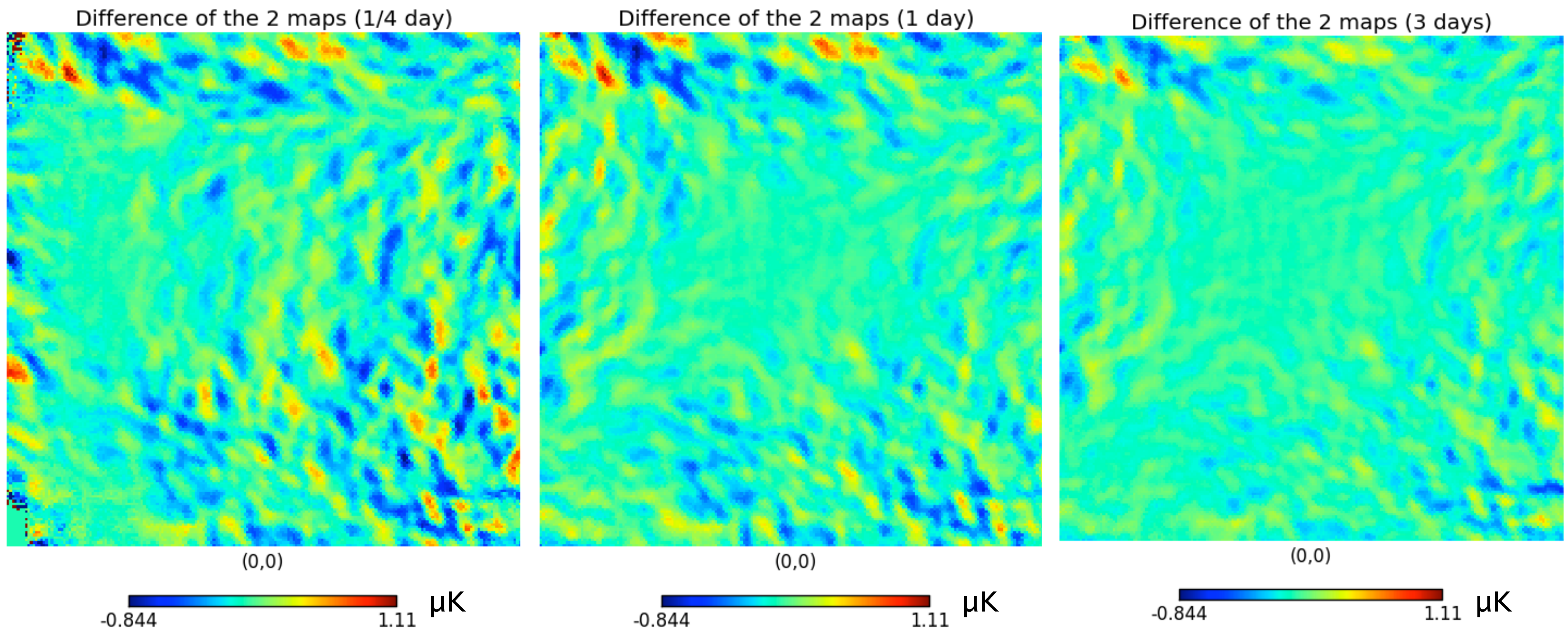
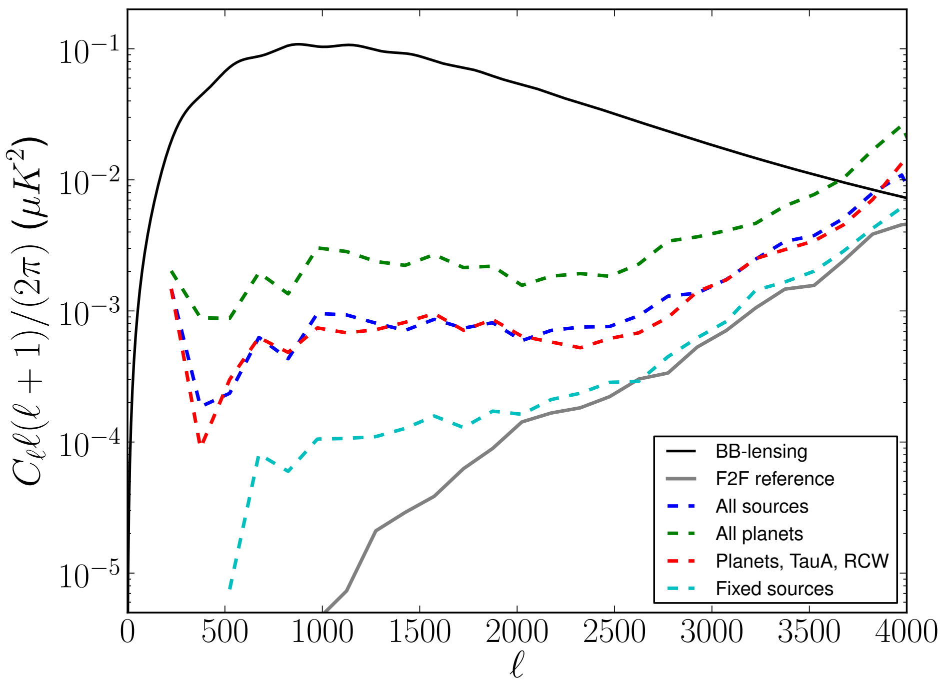


Q

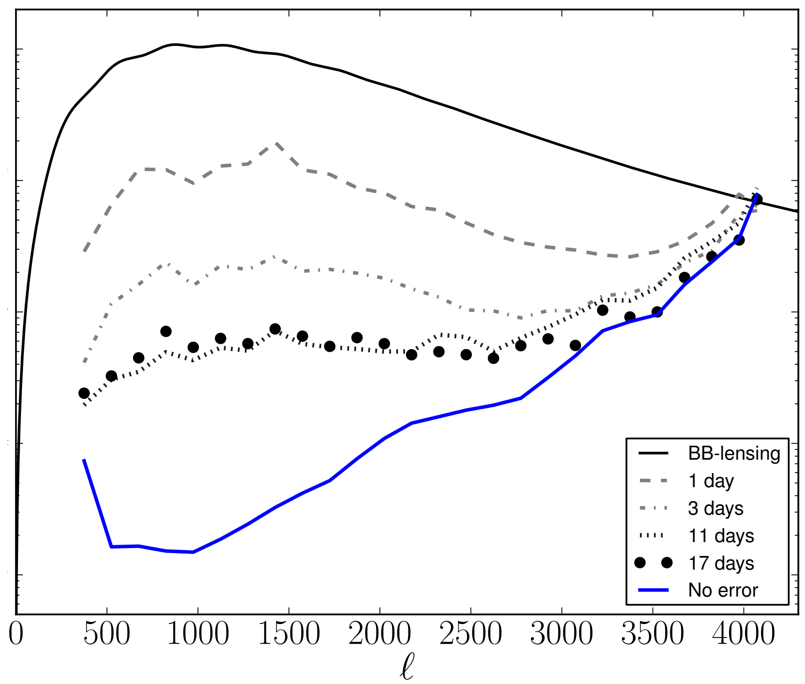


Systematic error examples

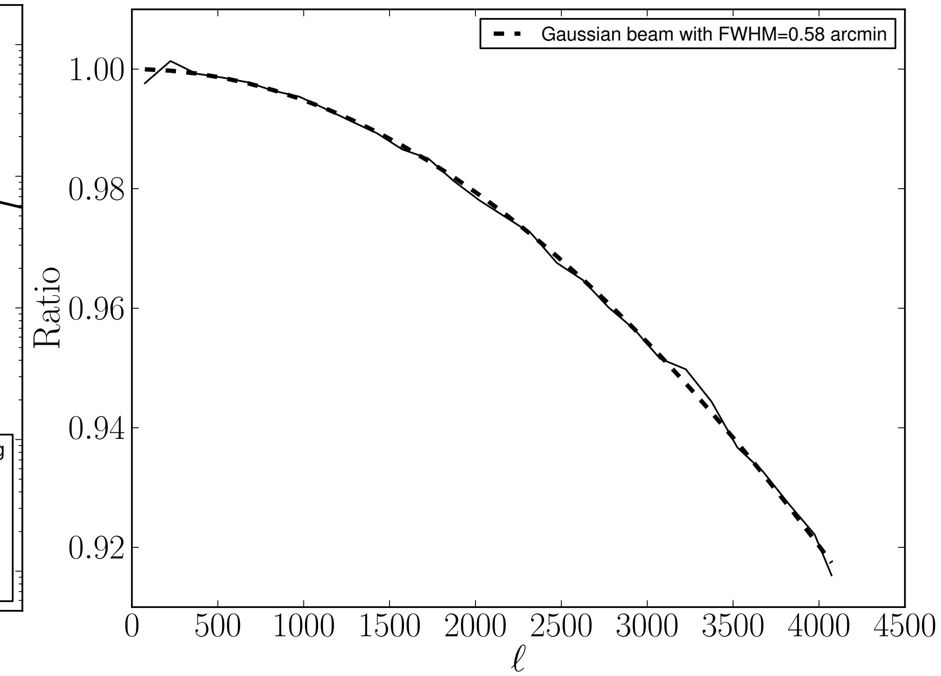
Pointing model



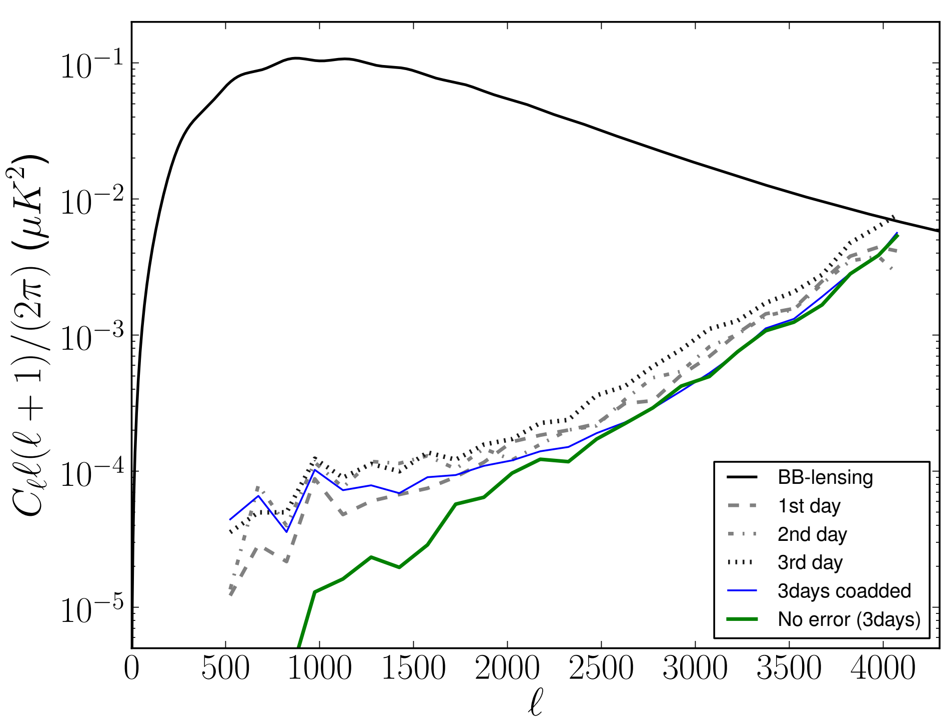
Differential pointing



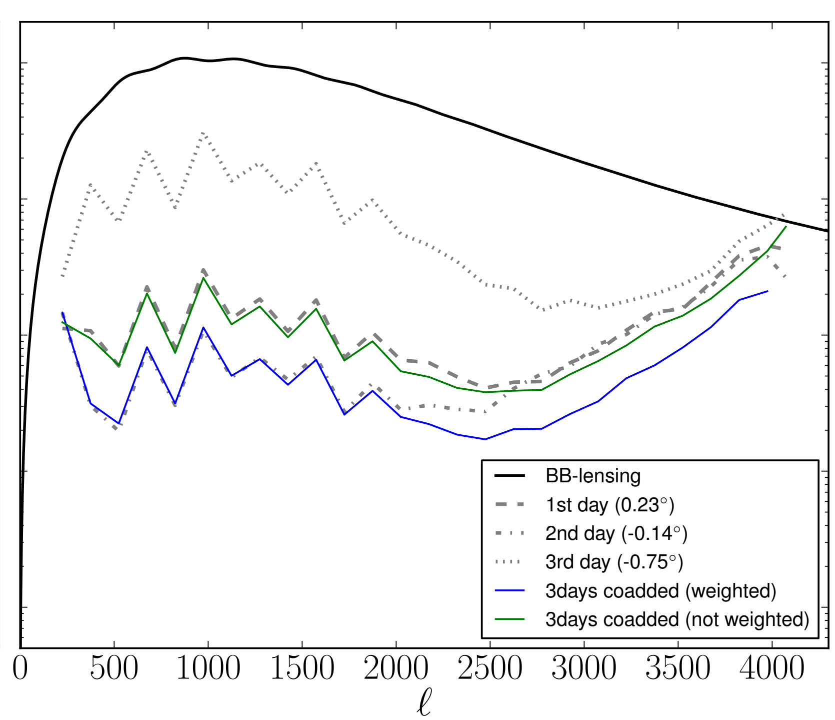
Pointing errors



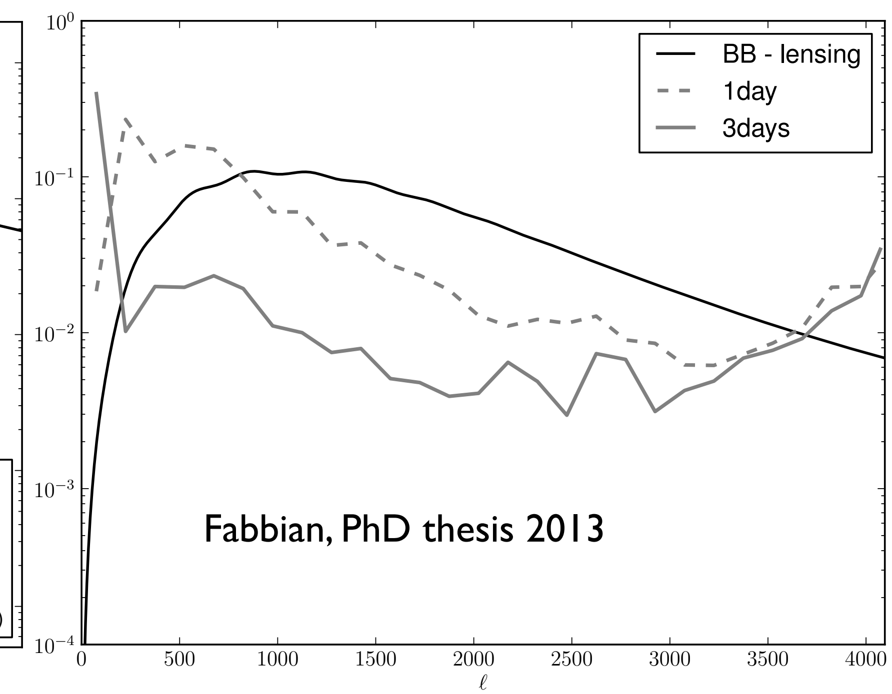
Detector polarization errors



Systematic polarization angle error

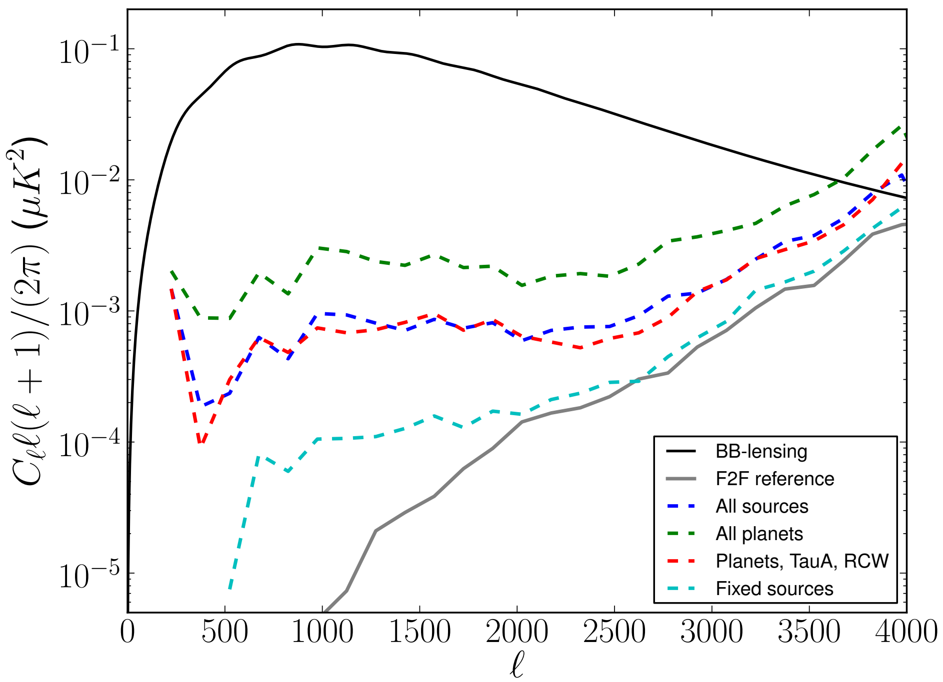


Gain model error

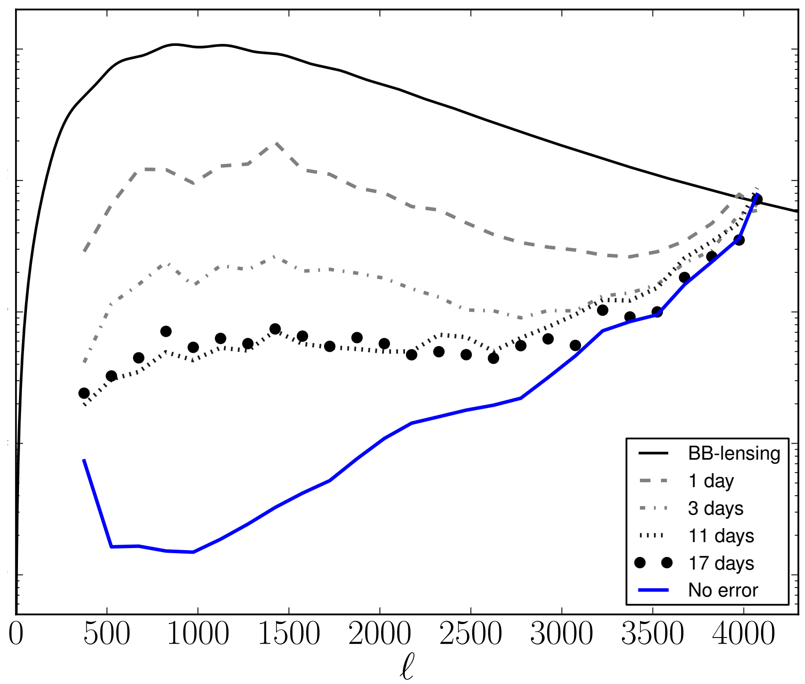


Systematic error examples

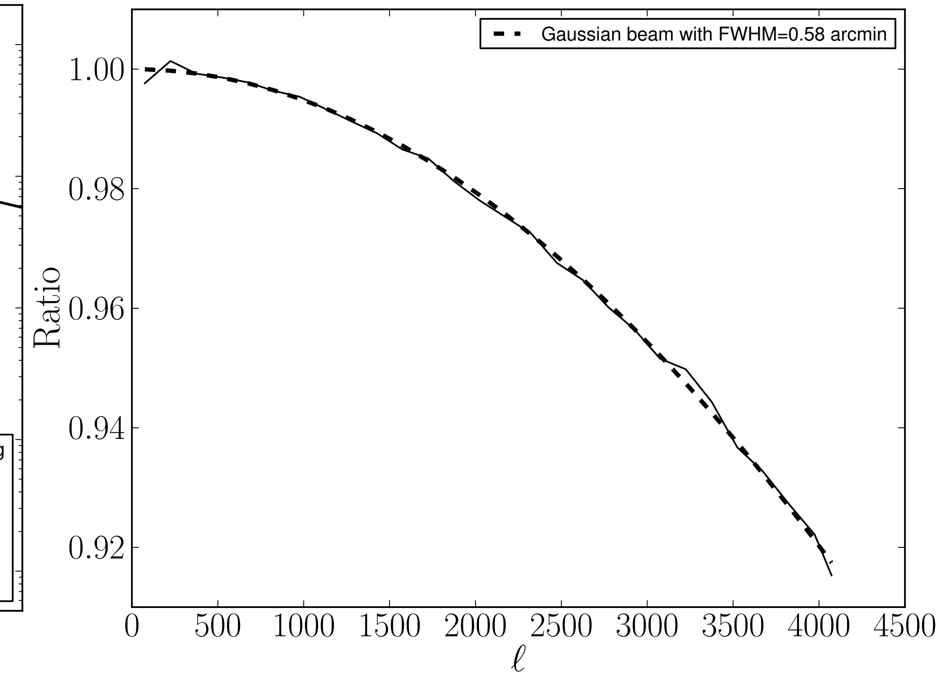
Pointing model



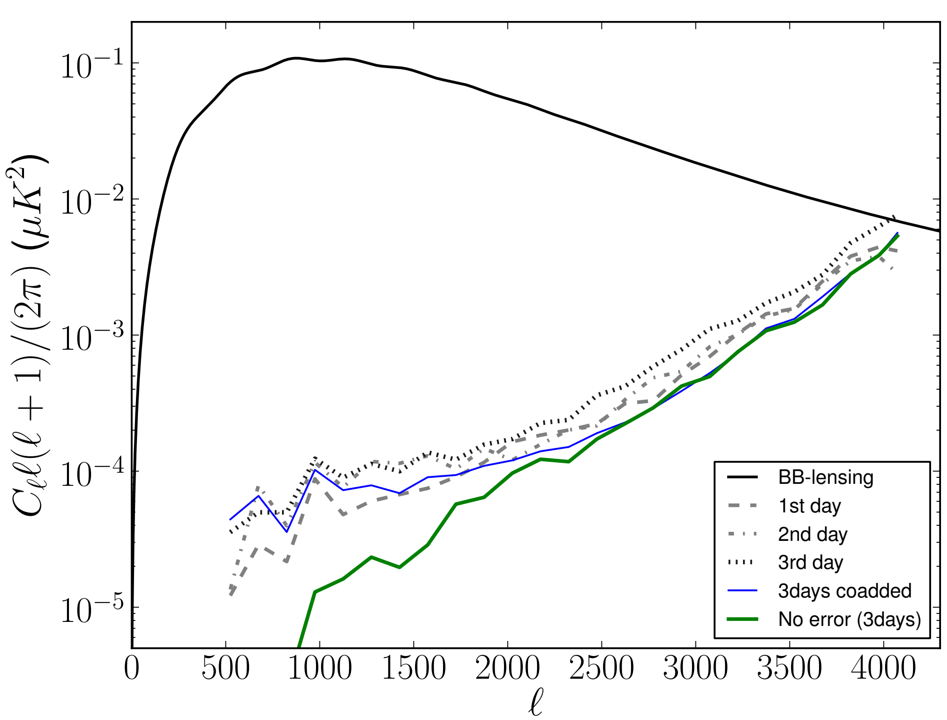
Differential pointing



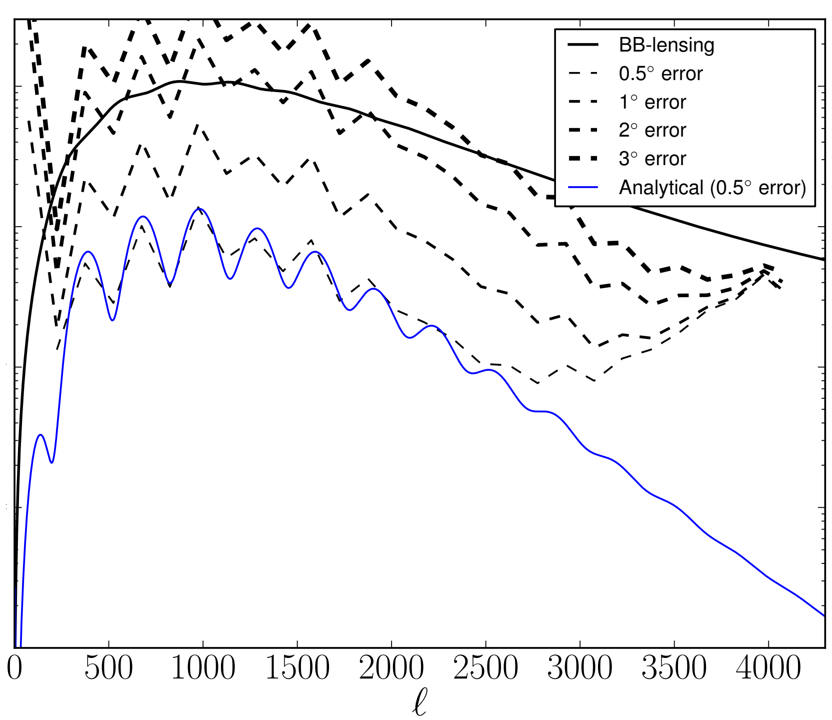
Pointing errors



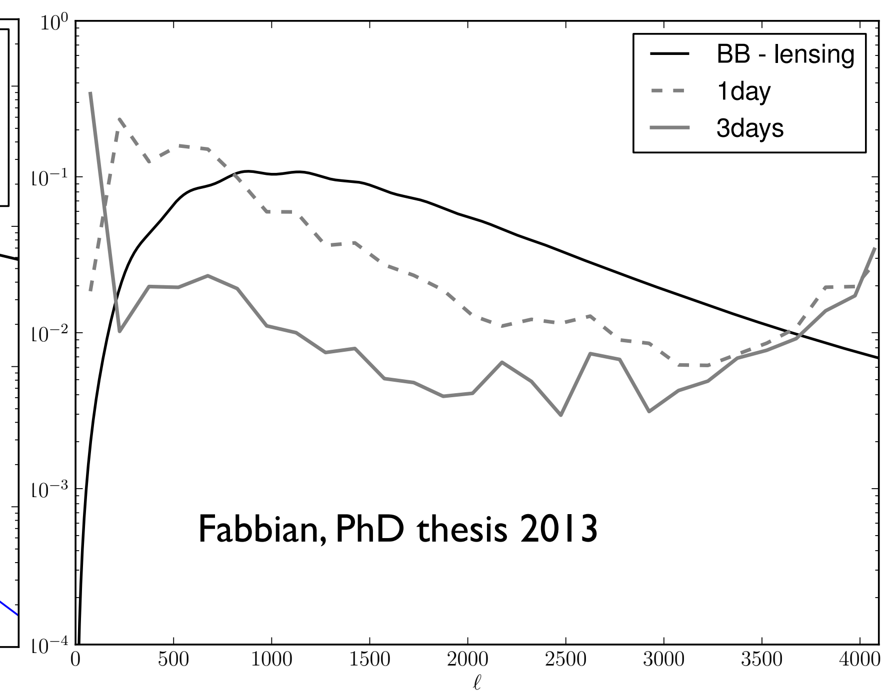
Detector polarization errors



Systematic polarization angle error

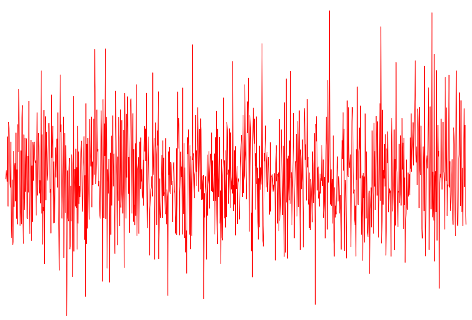
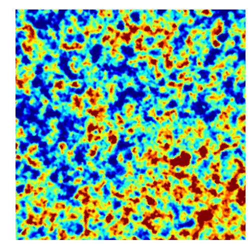
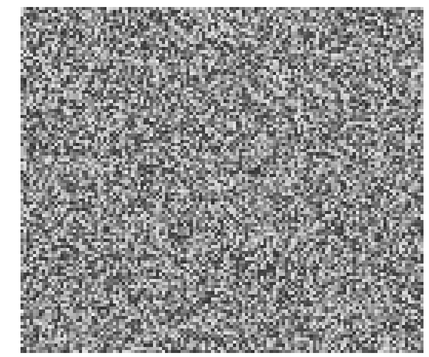


Gain model error



Mapmaking

$$\mathbf{d} = \mathbf{A} \cdot \mathbf{s} + \mathbf{n}$$

 $=$  $\Big($  $\Big)$ $+$ 

$$\mathbf{N} \equiv \langle \mathbf{n}^{\mathsf{T}} \mathbf{n} \rangle \longrightarrow \hat{\mathbf{s}} = (\mathbf{A}^{\mathsf{T}} \mathbf{N}^{-1} \mathbf{A})^{-1} \mathbf{A}^{\mathsf{T}} \mathbf{N}^{-1} \mathbf{d}$$

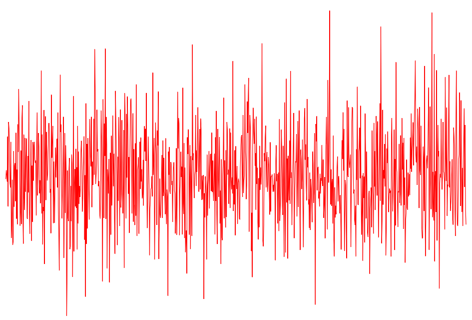
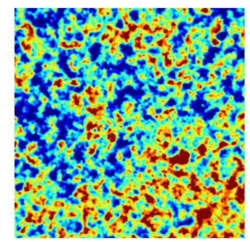
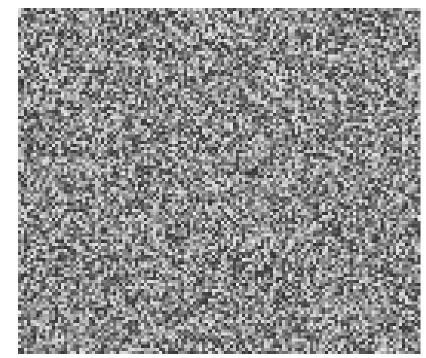
- Numerically challenging, need to use advanced numerical linear algebra techniques

- Atmosphere = more problems

Courtesy of Julian Borril

Mapmaking

$$\mathbf{d} = \mathbf{A} \cdot \mathbf{s} + \mathbf{n}$$

 $=$  $\Big($  $\Big)$ $+$ 

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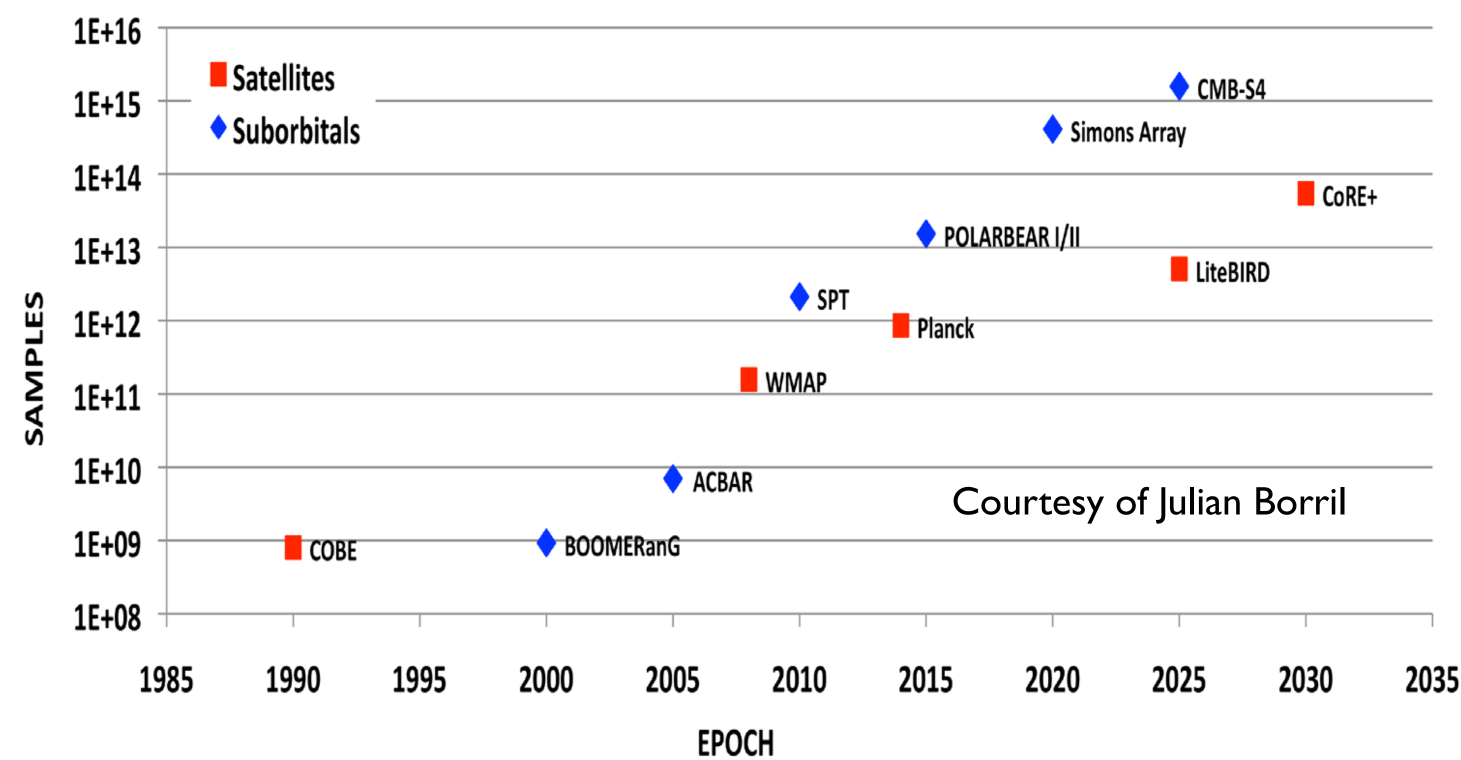
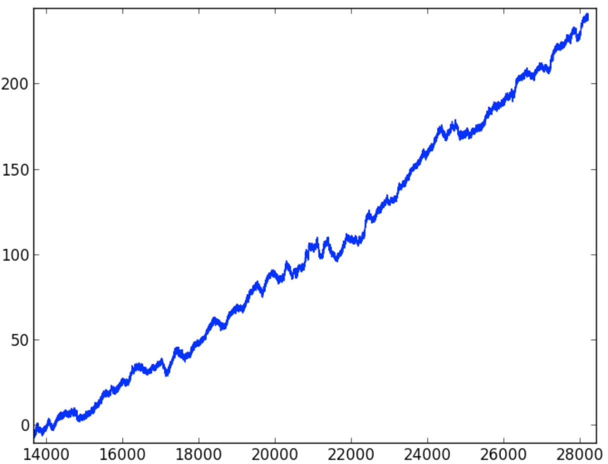


Mapmaking

$$\mathbf{d} = \mathbf{A} \cdot \mathbf{s} + \mathbf{n}$$



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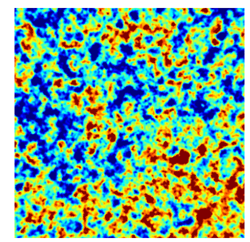
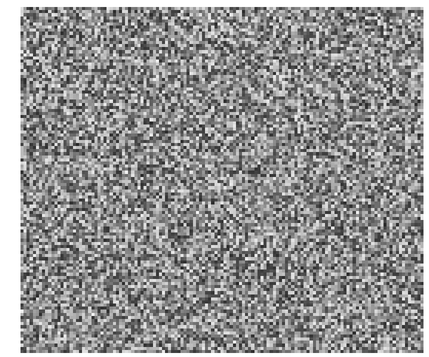
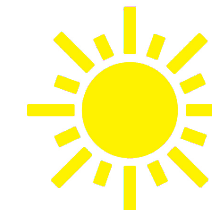
$\Big($  $\Big)$ $+$  $+$ $\Big\{$



$\ldots$

$$\mathbf{N} \equiv \langle \mathbf{n}^T \mathbf{n} \rangle \longrightarrow \hat{\mathbf{s}} = (\mathbf{A}^T \mathbf{N}^{-1} \mathbf{A})^{-1} \mathbf{A}^T \mathbf{N}^{-1} \mathbf{d}$$

- Numerically challenging, need to use advanced numerical linear algebra techniques
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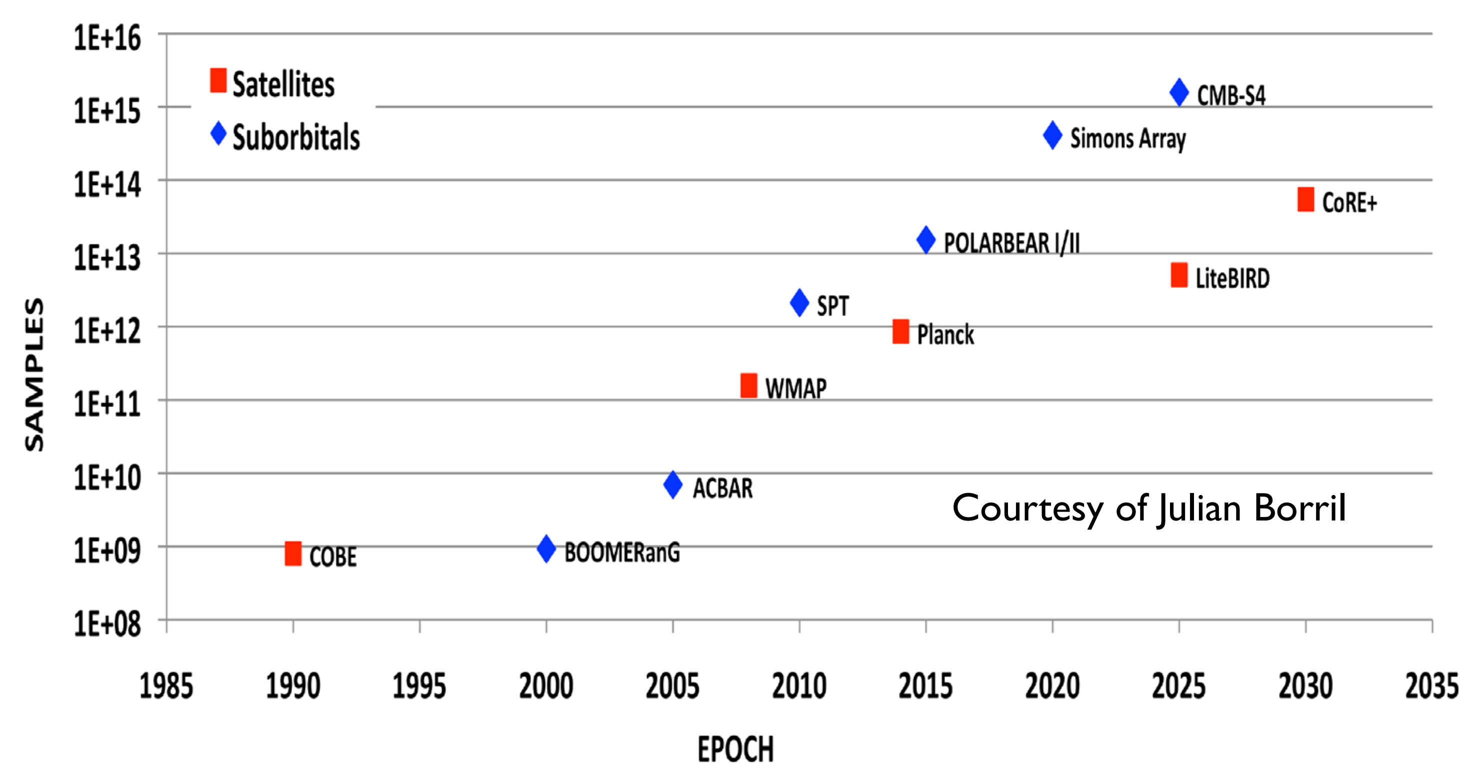

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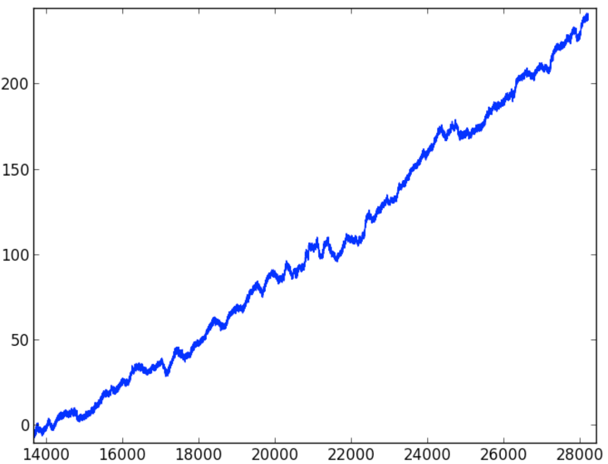

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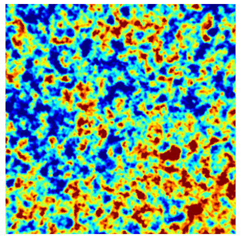
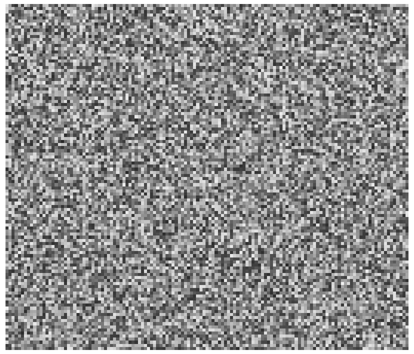


$\Big)$ $+$



$+ \Bigg\{$

$\dots$

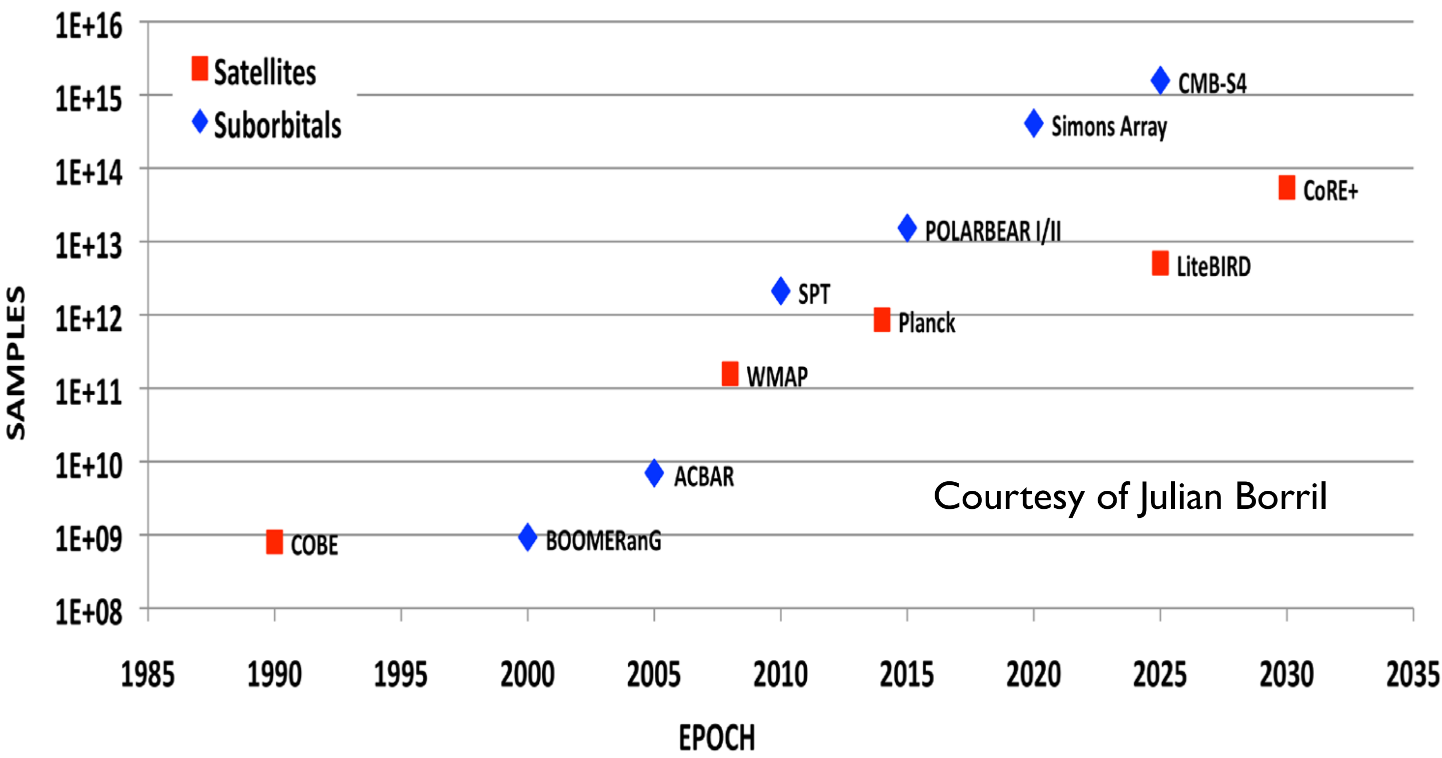
$$\mathbf{N} \equiv \langle \mathbf{n}^T\mathbf{n}\rangle \longrightarrow \hat{\mathbf{s}} = (\mathbf{A}^T\mathbf{N}^{-1}\mathbf{A})^{-1}\mathbf{A}^T\mathbf{N}^{-1}\mathbf{d}$$

- Numerically challenging, need to use advanced numerical linear algebra techniques

- Atmosphere = more problems

$$\hat{s} = (A^T N^{-1} A)^{-1} A^T N^{-1} F d$$

$$(A^T N^{-1} F A)\hat{s}_{ith} = A^T N^{-1} F d$$



Mapmaking: how to solve a (too) large problem

How to invert this $\mathcal{N}_p \times \mathcal{N}_p$ matrix? Inversion requires $\mathcal{N}_p^3 \sim 10^{18}$ operations (100 cpu y)

➡ Find approximate solution without explicit inversion using the **P**reconditioned **C**onjugate **G**radient technique

Solve $\mathbf{B}\,\mathbf{x} = \mathbf{b}$ with $\mathbf{B}$ symmetric positive definite.

Idea:

- use $\mathbf{B}$ as scalar product, given a search direction $\hat{\mathbf{p}}$ (with $\hat{\mathbf{p}}^t\,\mathbf{B}\,\hat{\mathbf{p}} = 1$), the projection onto it

  $$\hat{\mathbf{p}}(\hat{\mathbf{p}}^t\,\mathbf{B}\,\mathbf{x}) = \hat{\mathbf{p}}(\hat{\mathbf{p}}^t\,\mathbf{b})$$

  can be interpreted as an approximate solution.
- project the solution on an increasingly larger subspace until the approximate solution is "good enough": e.g., $|\mathbf{B}\,\mathbf{x} - \mathbf{b}|/|\mathbf{b}| < 10^{-6}$

$$\mathcal{N}_p^2 \times \mathcal{N}_{\rm iter} \sim 10^{12} \times [O(10) \text{ to } O(1000)] \sim 0.1 \text{ cpu y (optimistic)}$$

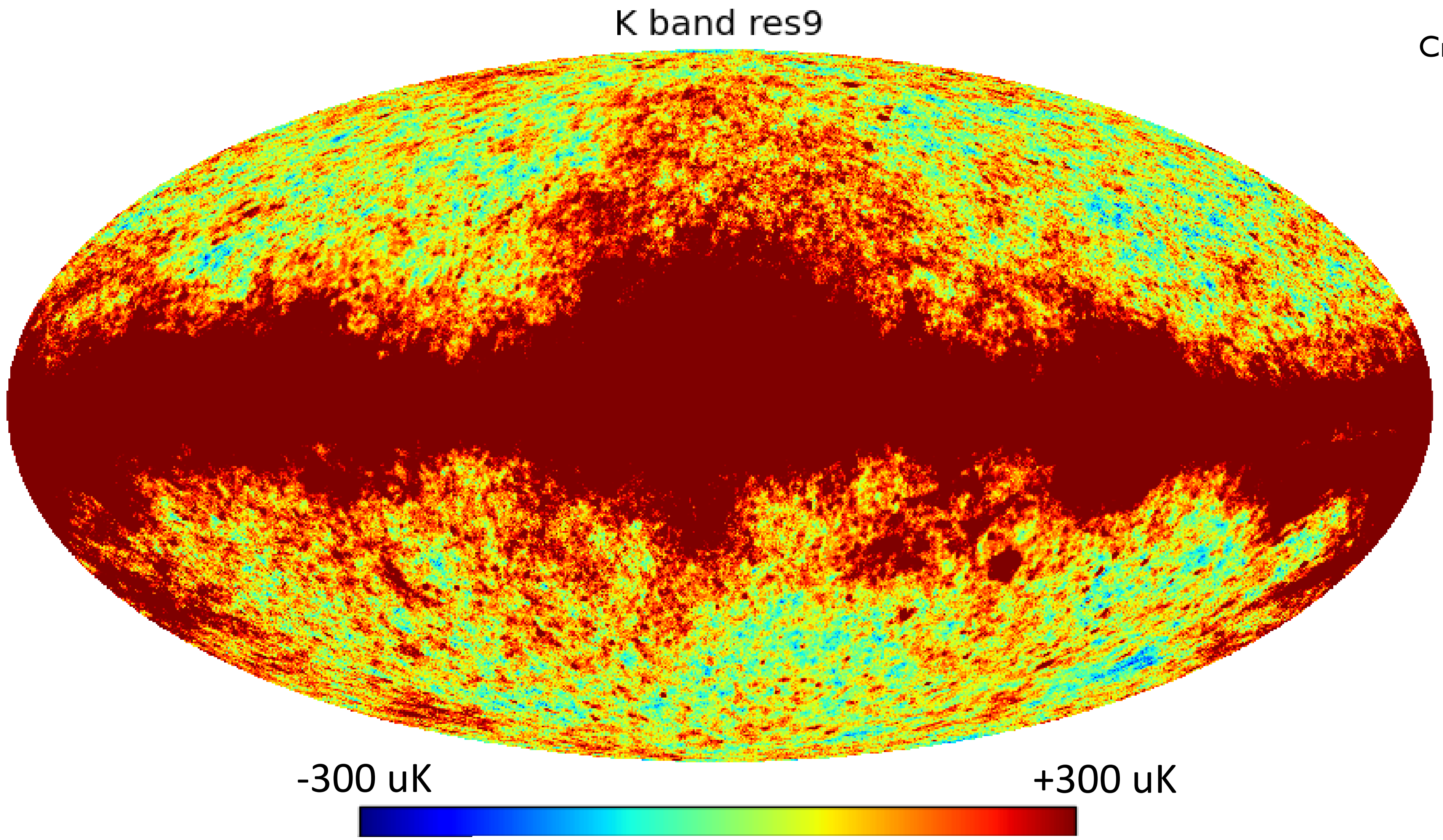
It assumes $\mathbf{B}$ precomputed and stored (often it isn't)

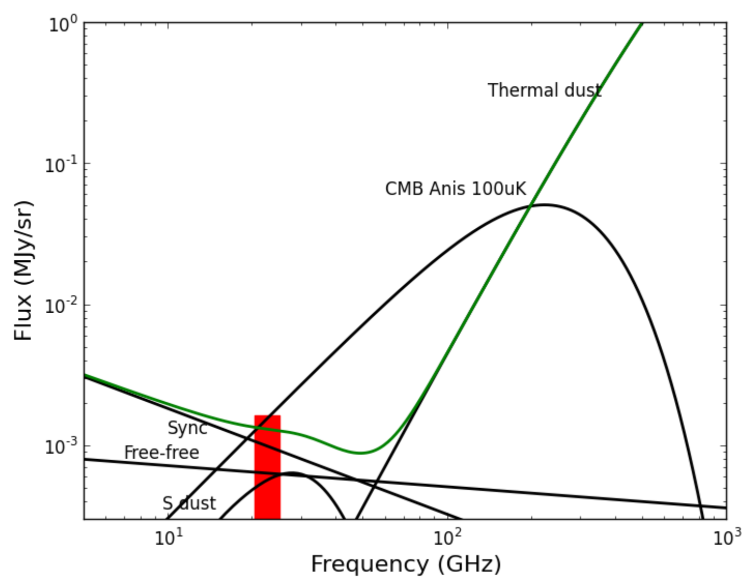
It can be reduced by proper preconditioning

It assumes 100% cpu (never achieved)

The microwave sky

Credits: Lyman Page





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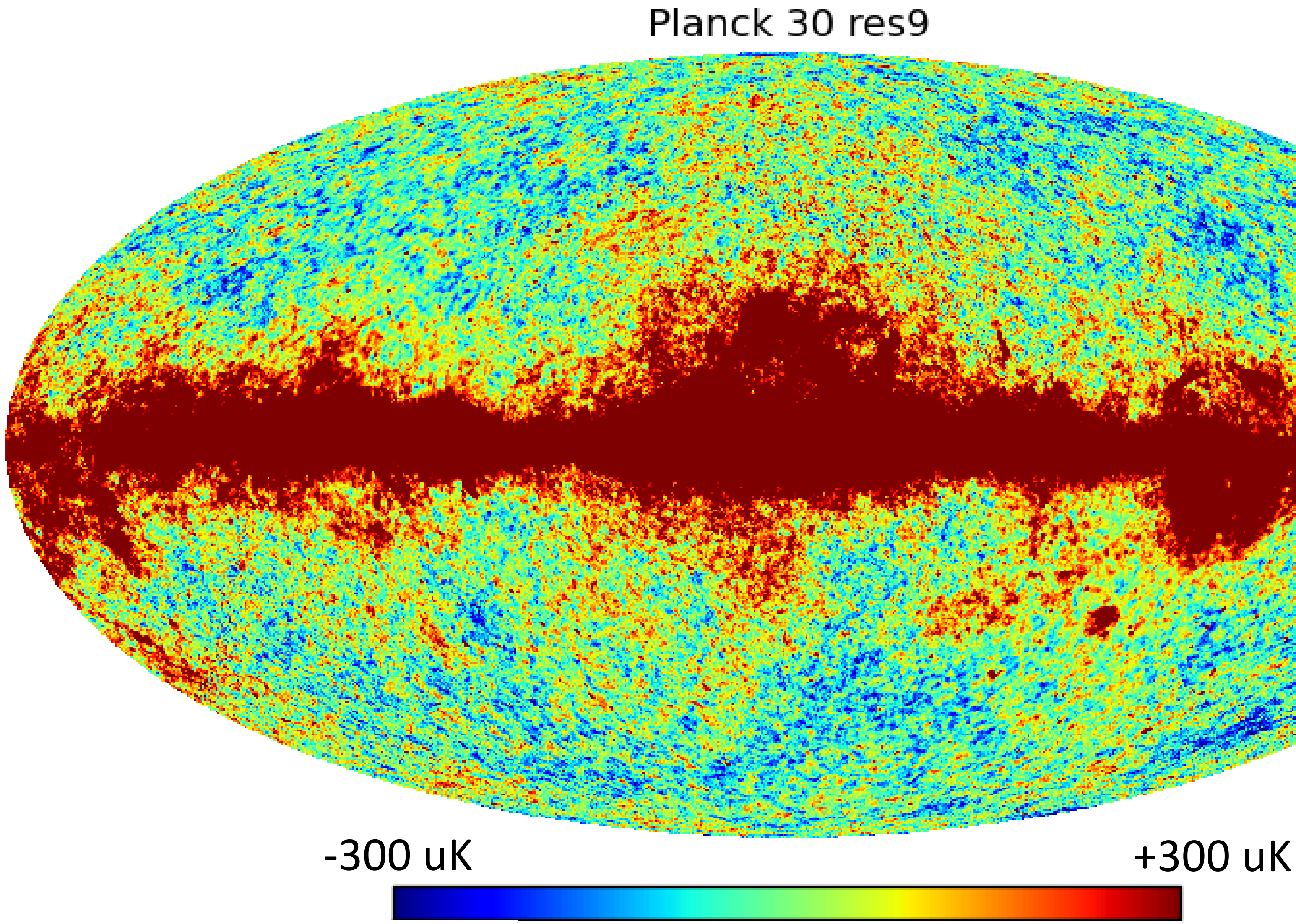

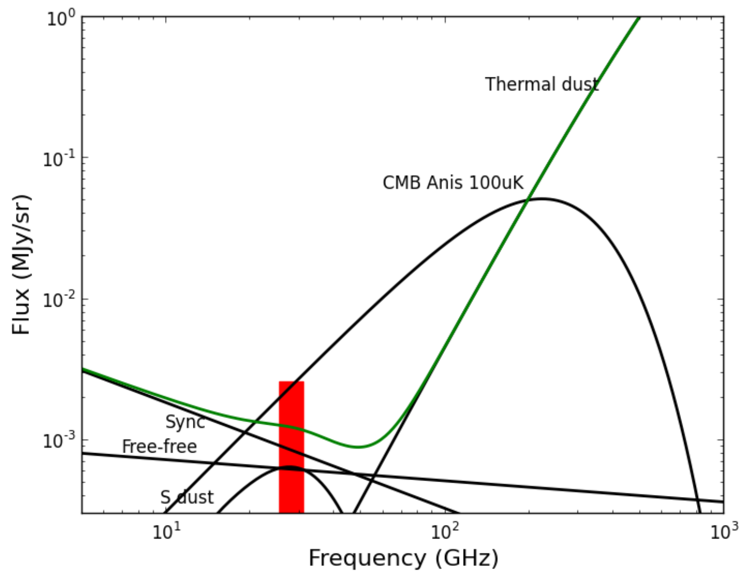

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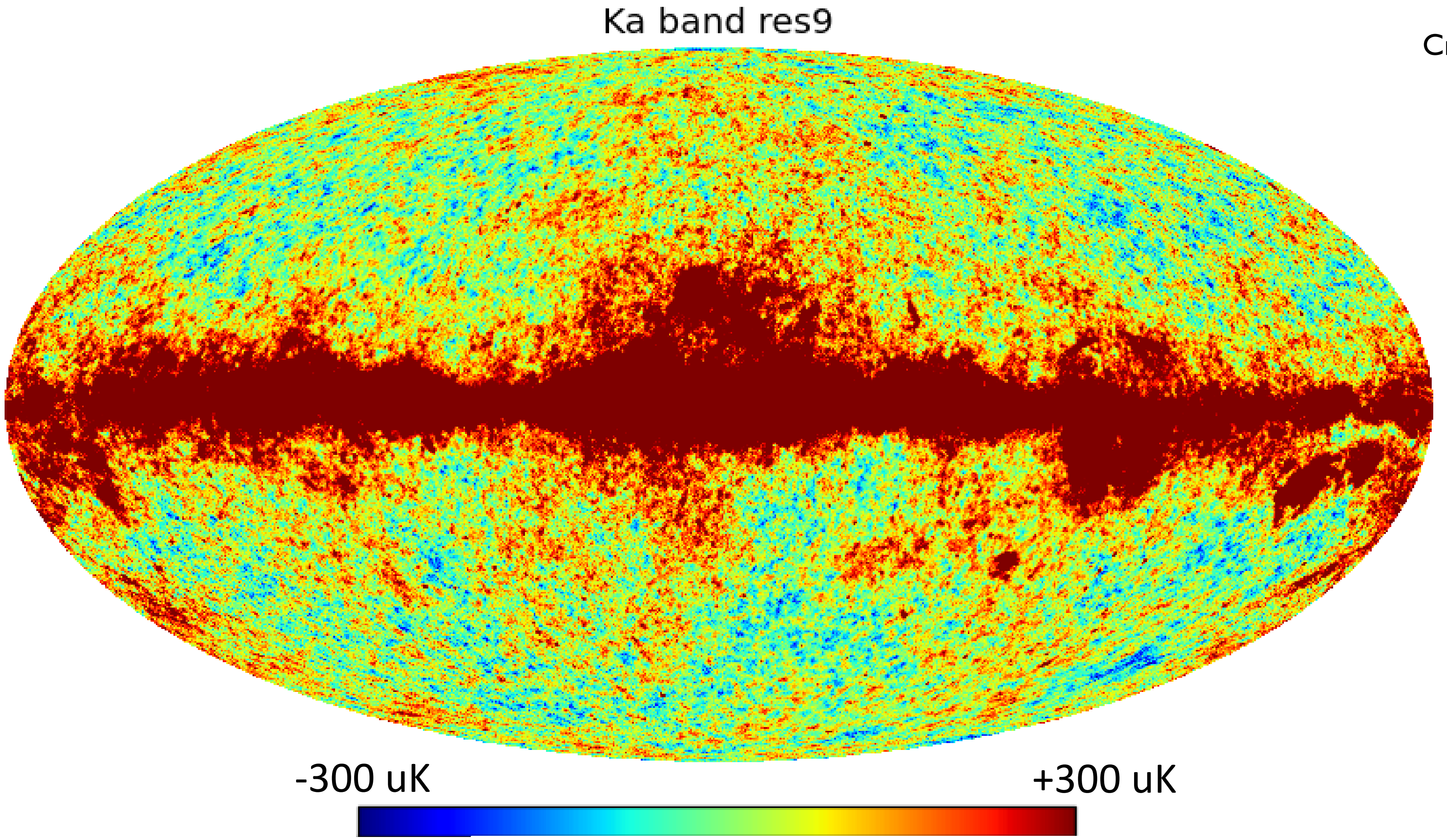

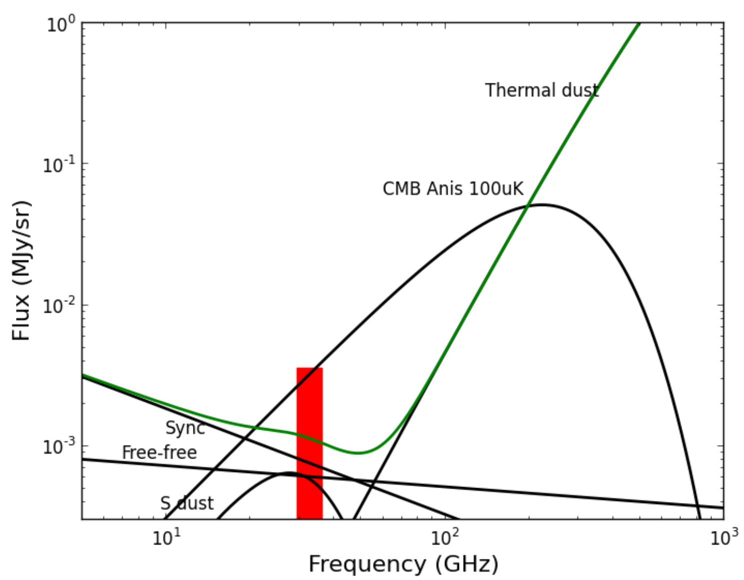

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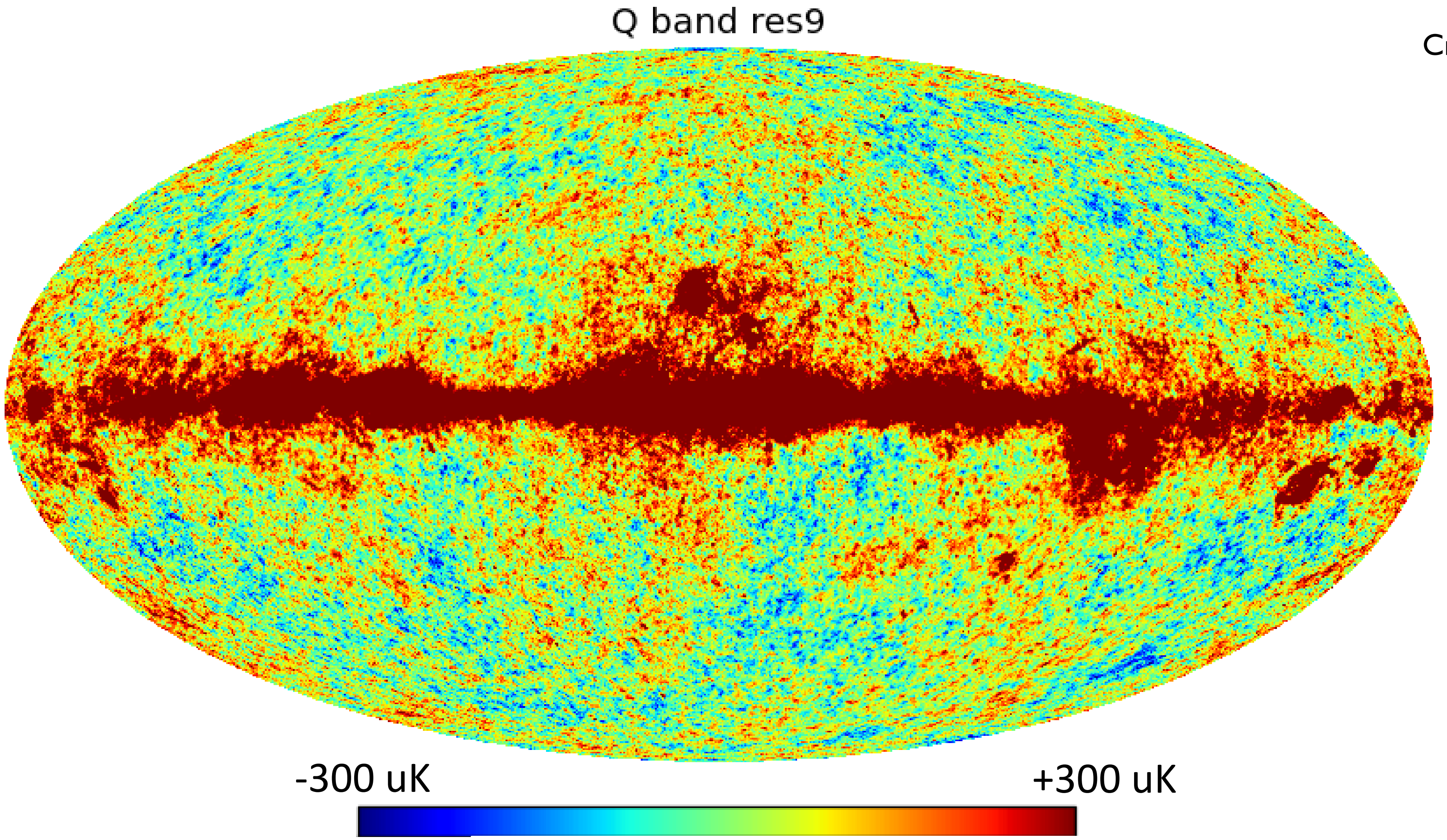

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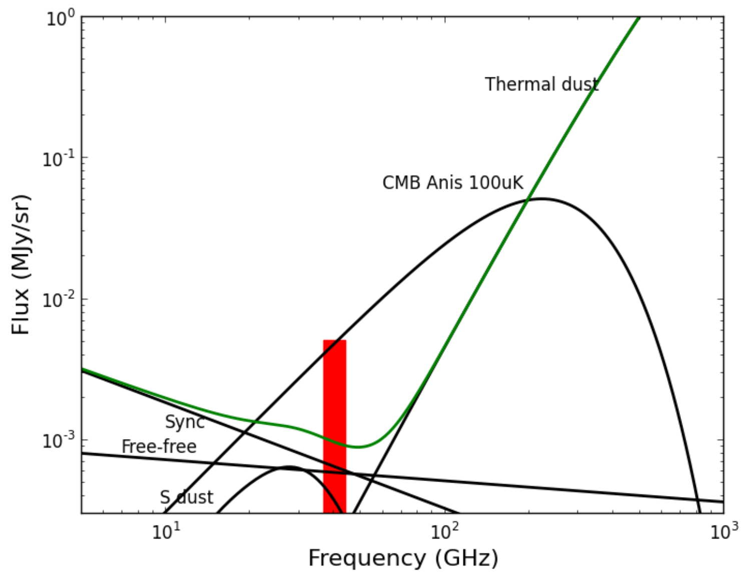

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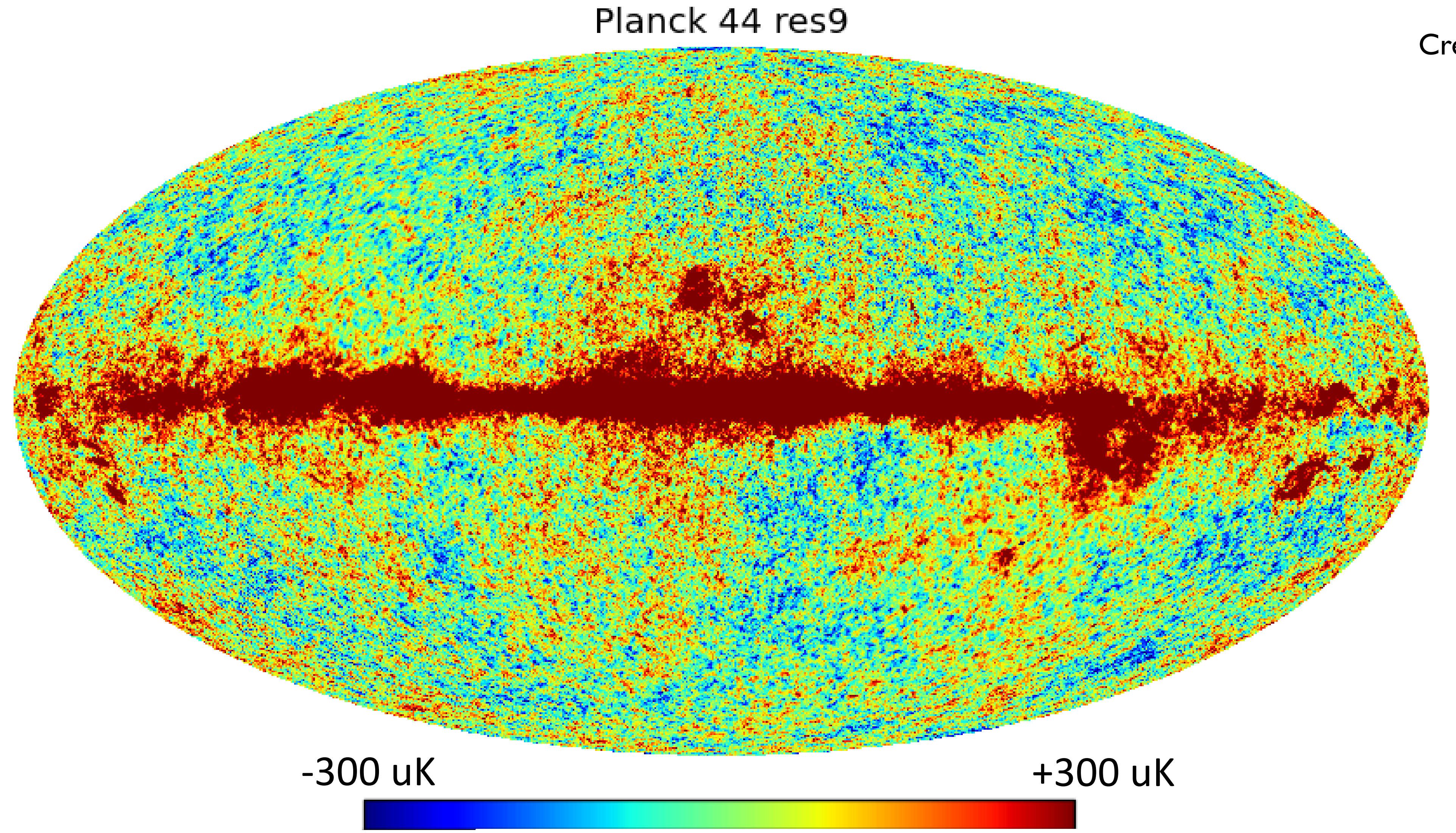

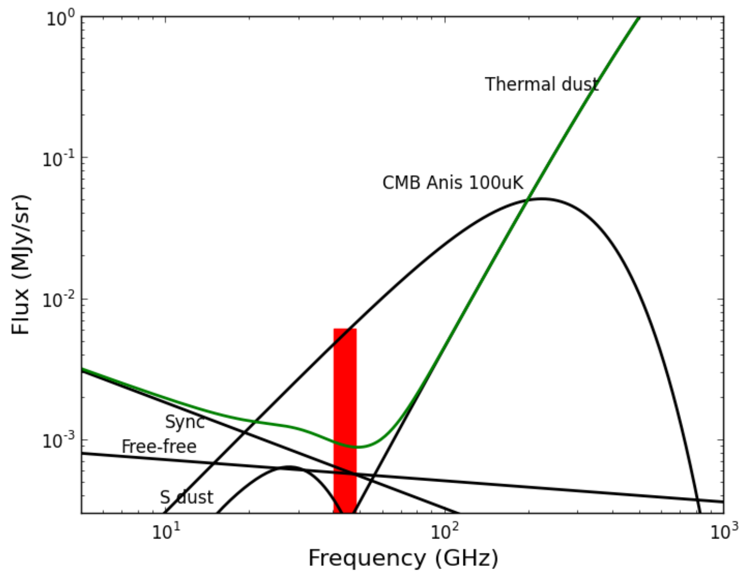

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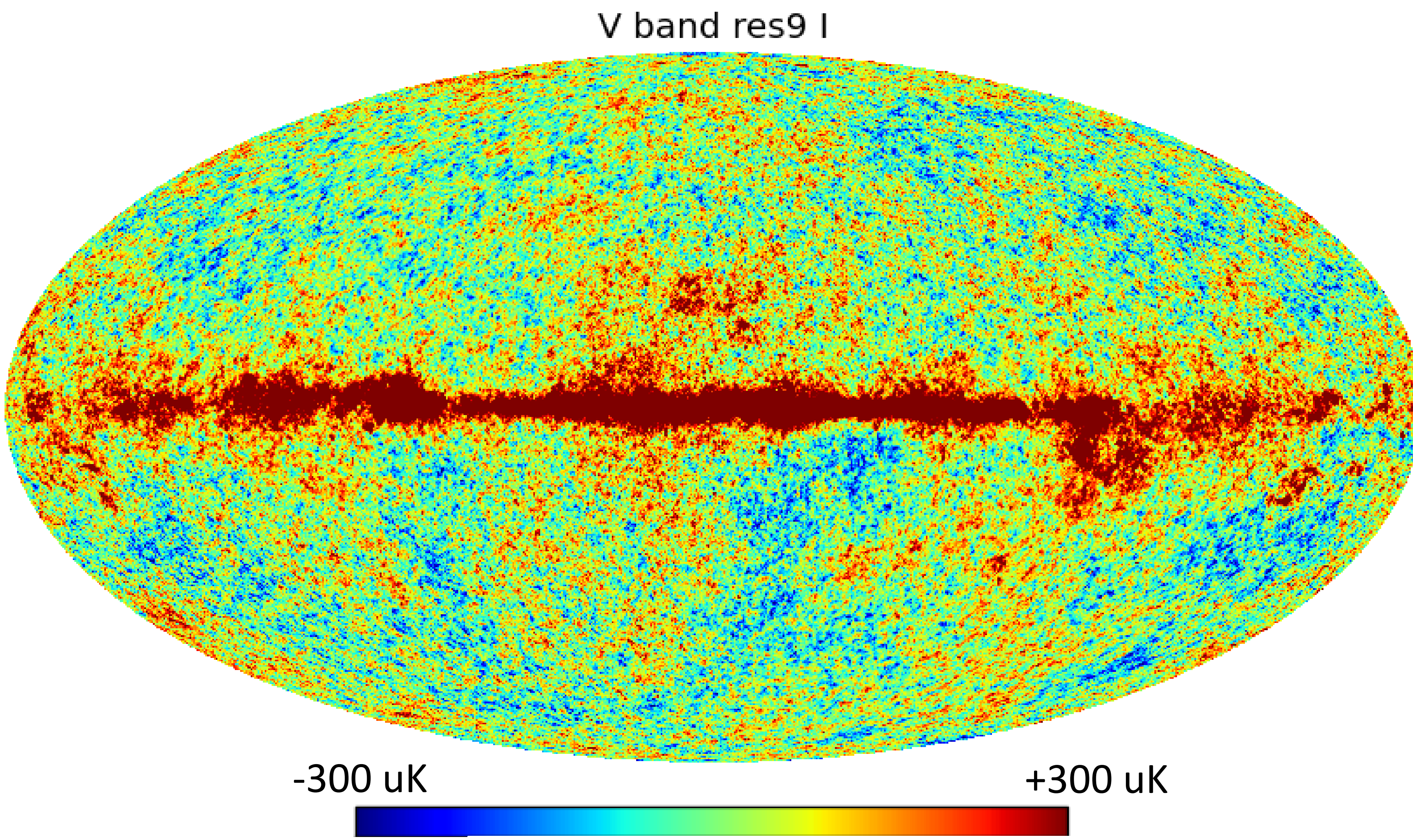

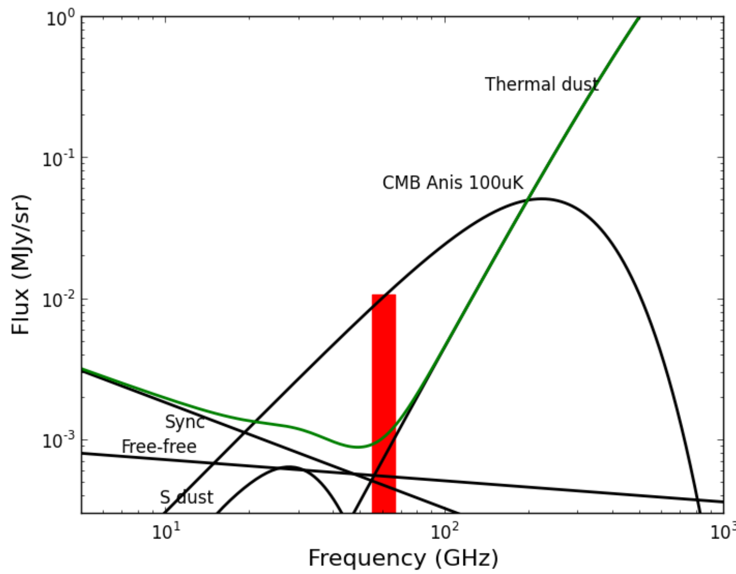

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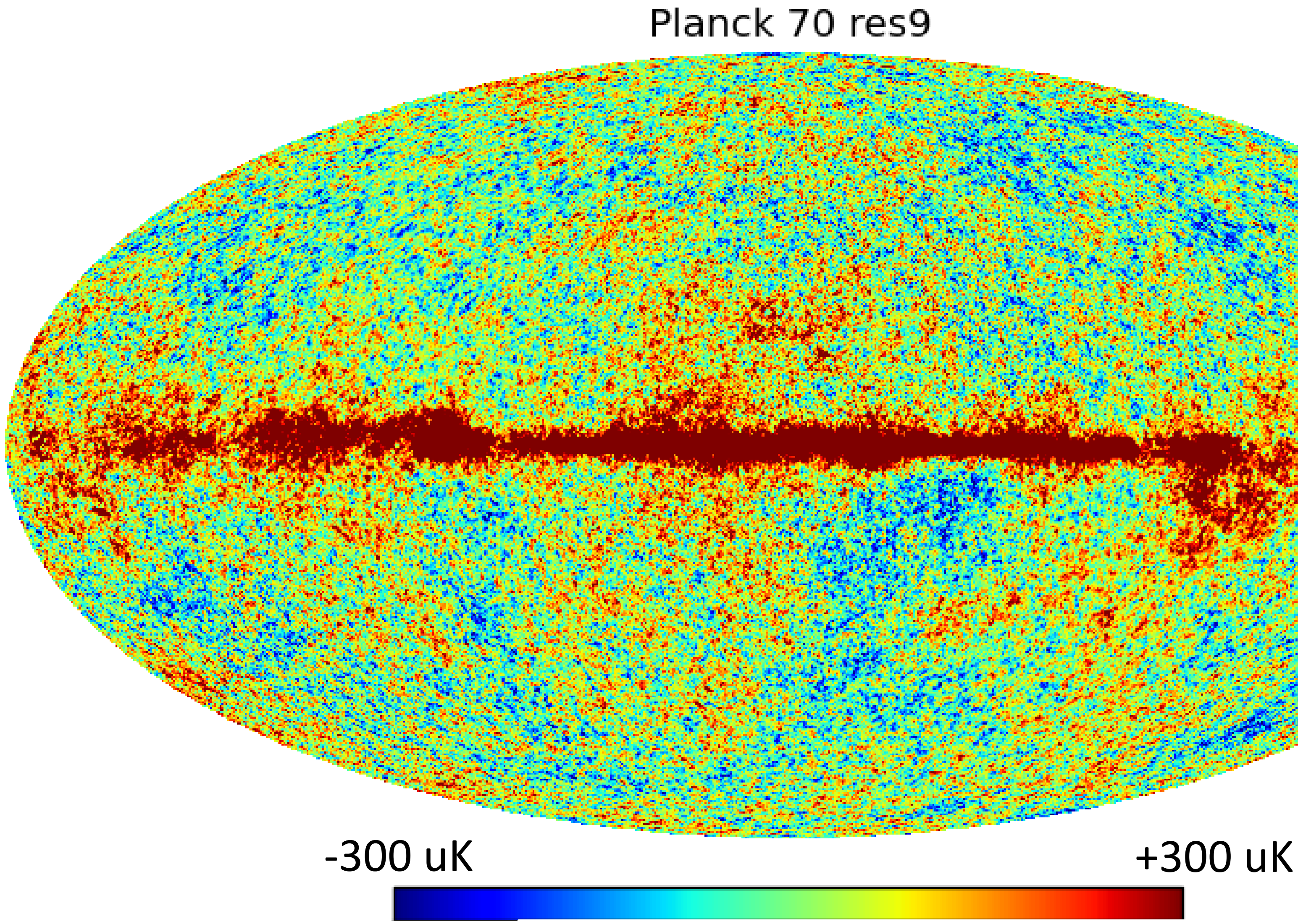

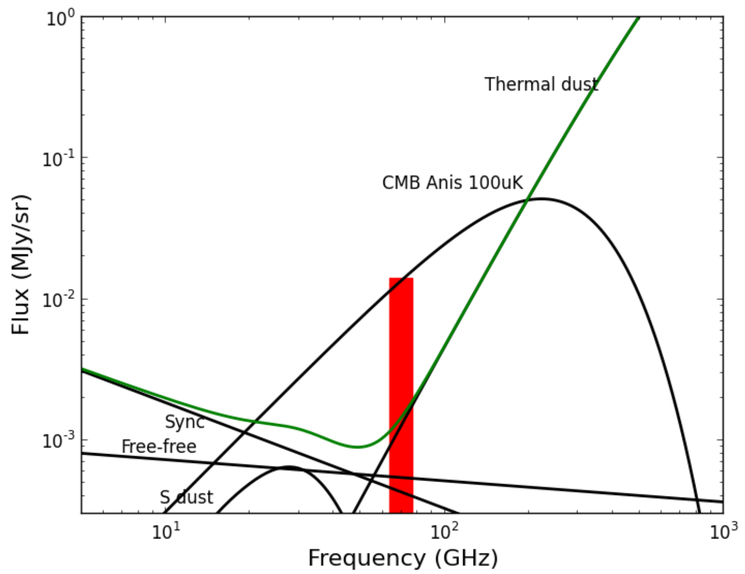

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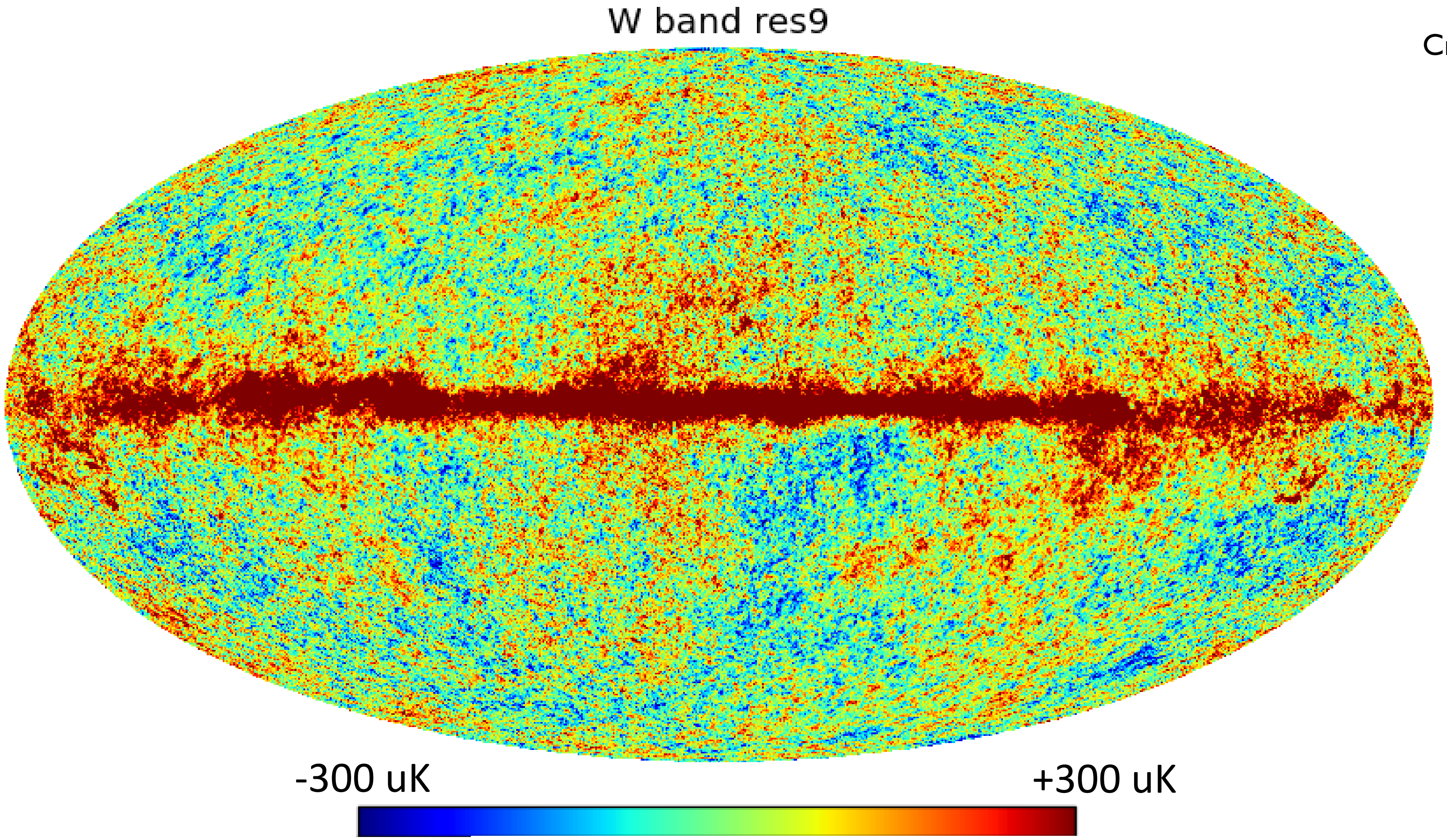

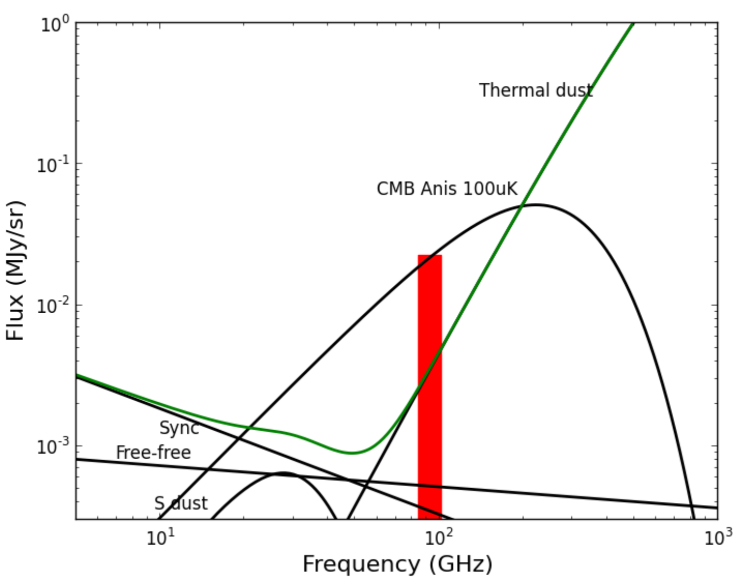

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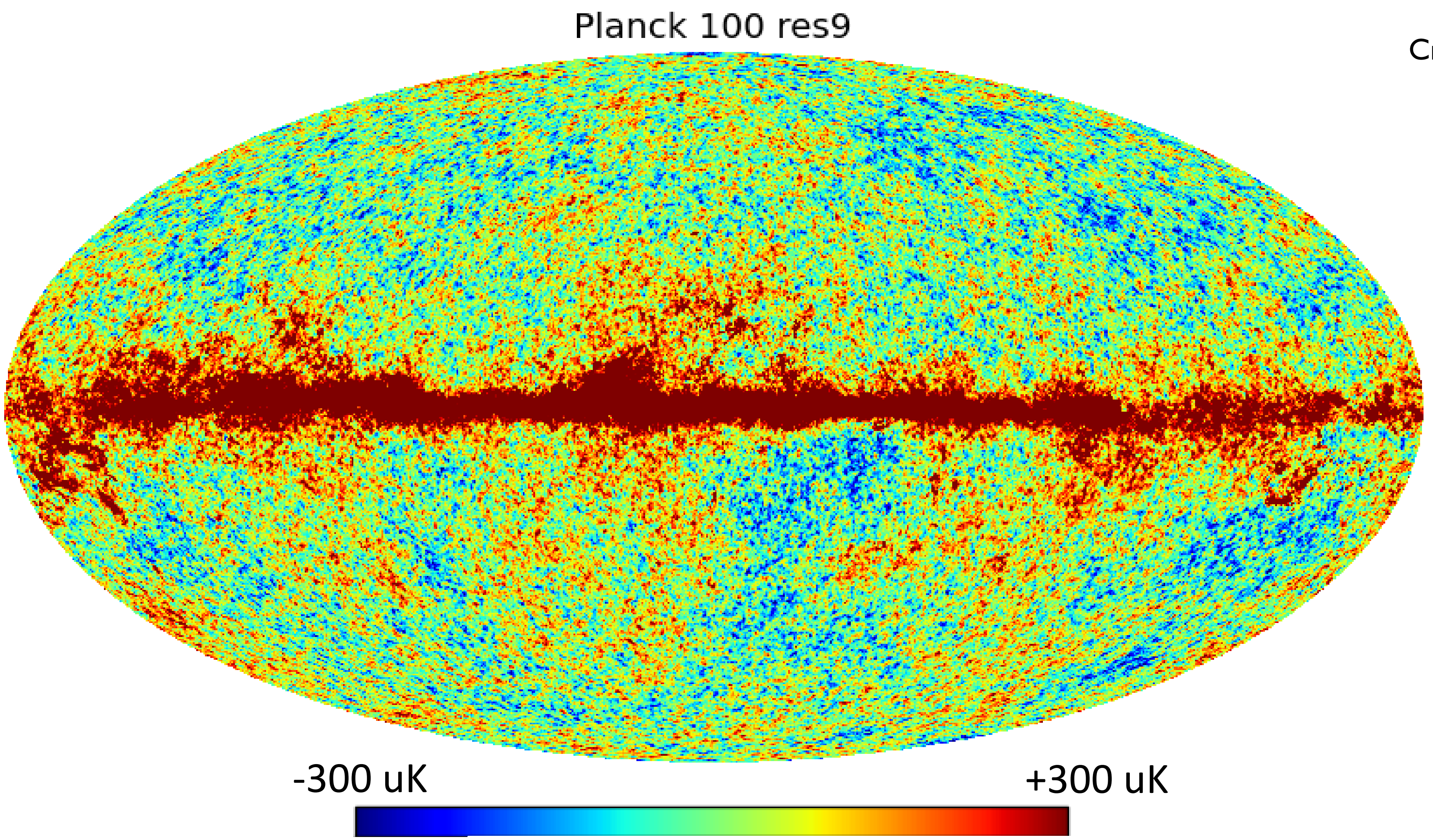

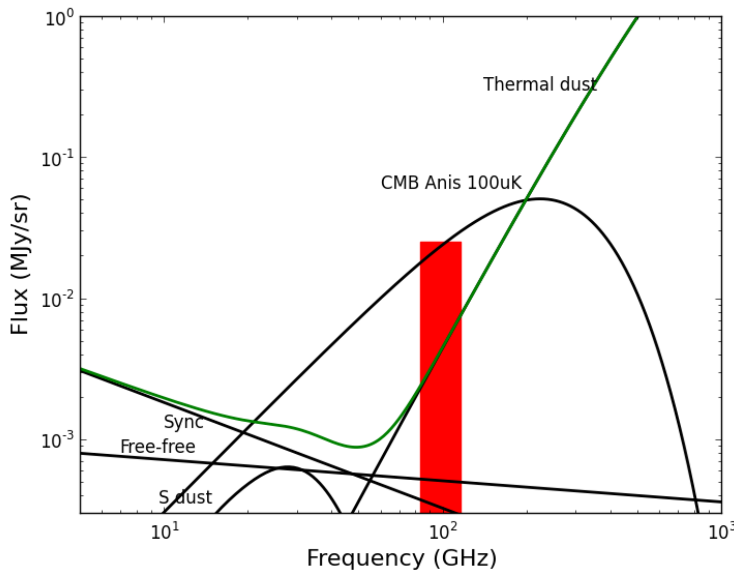

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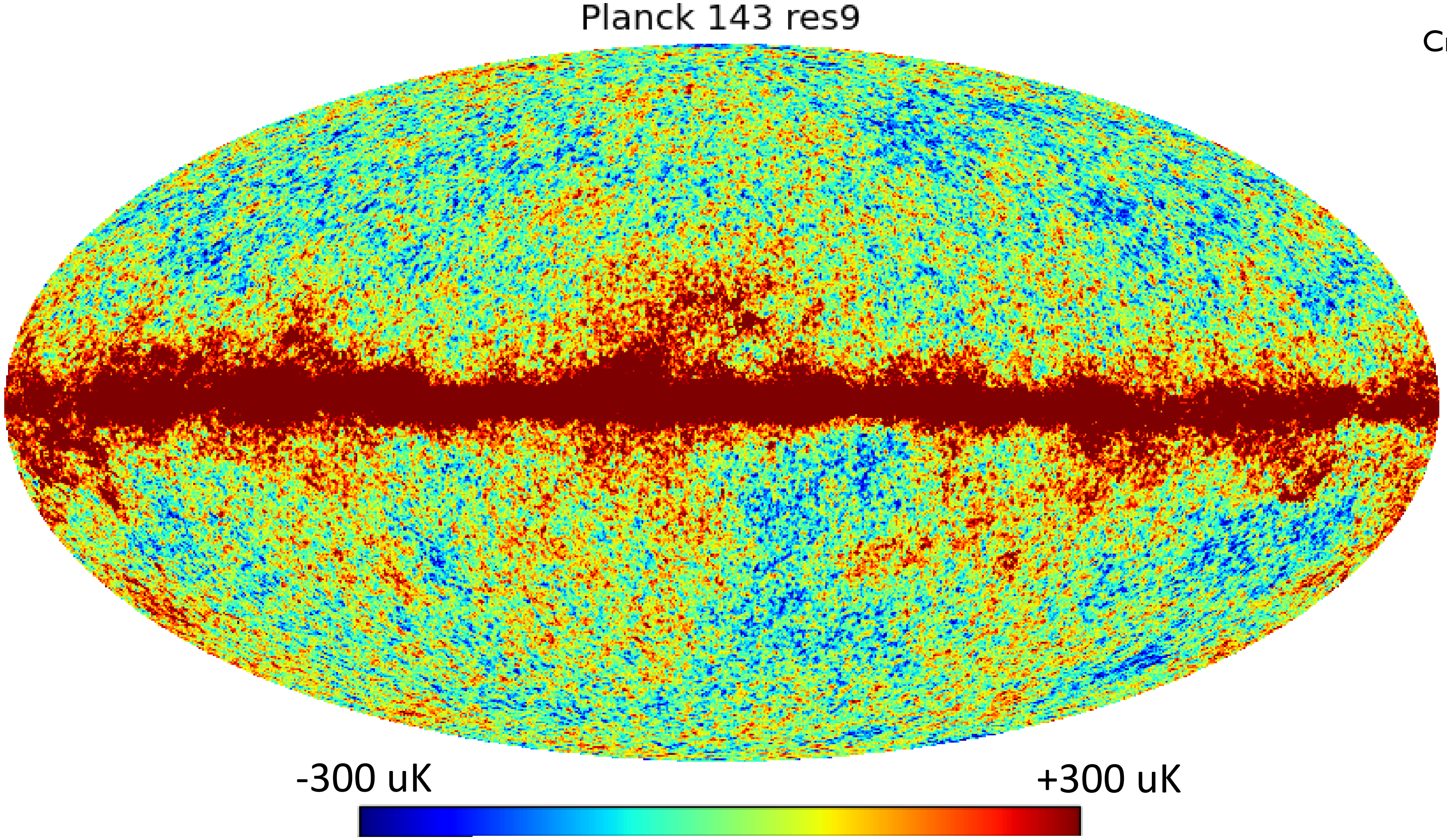

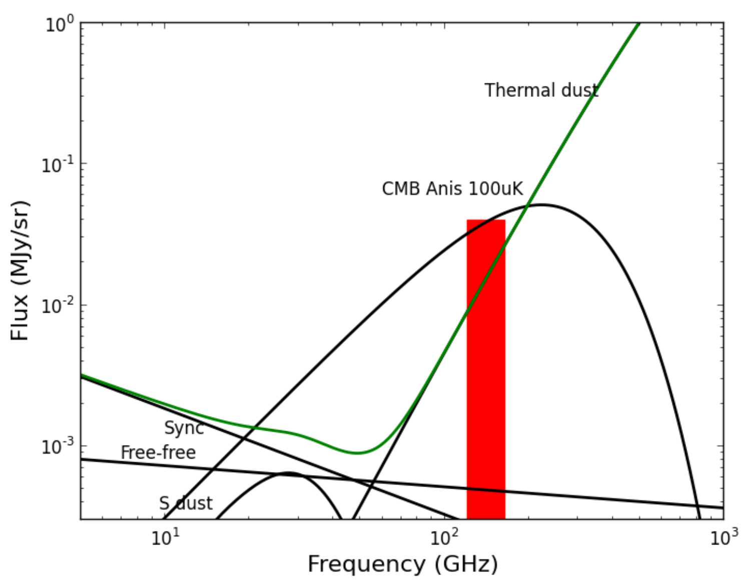

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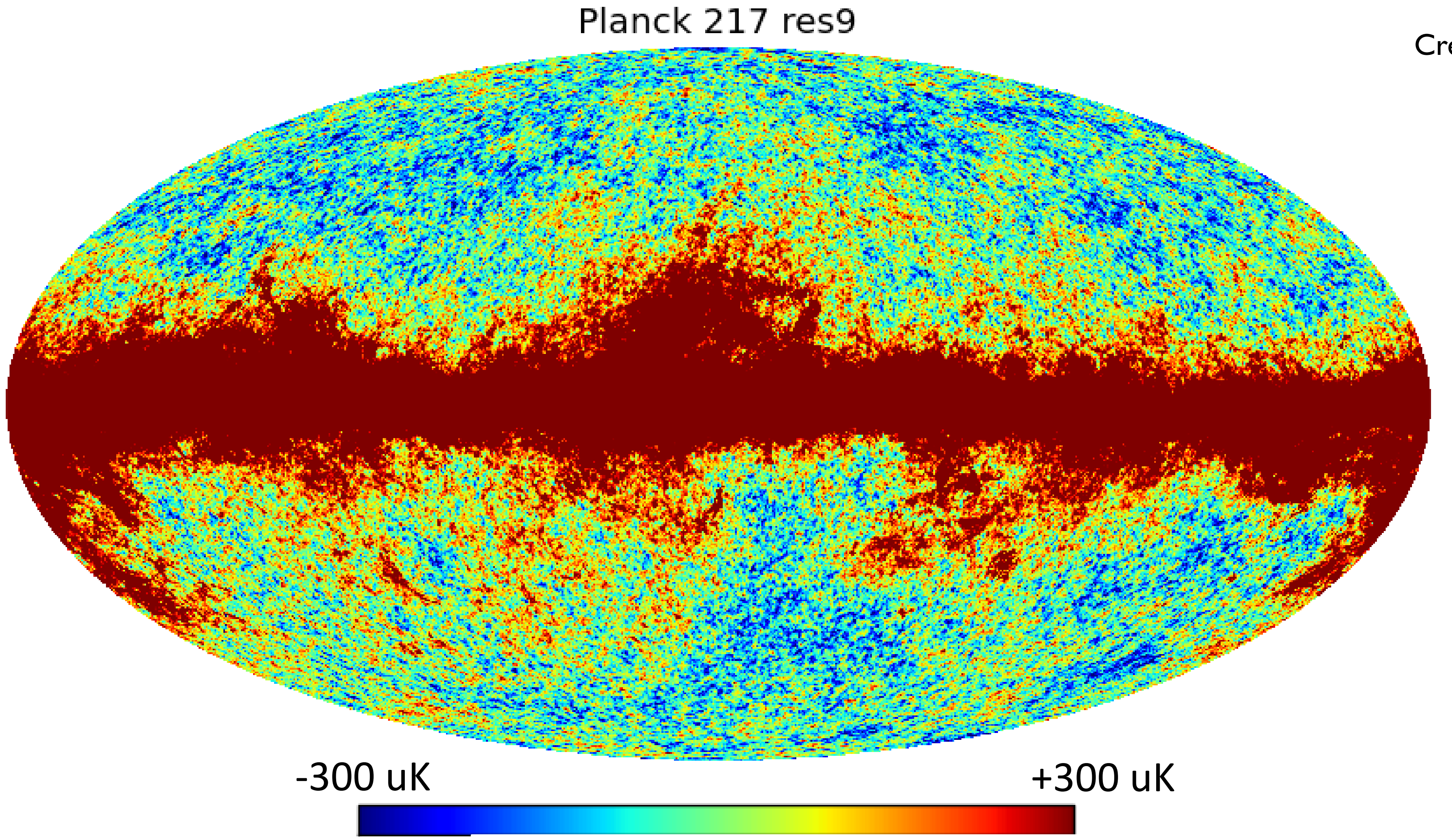

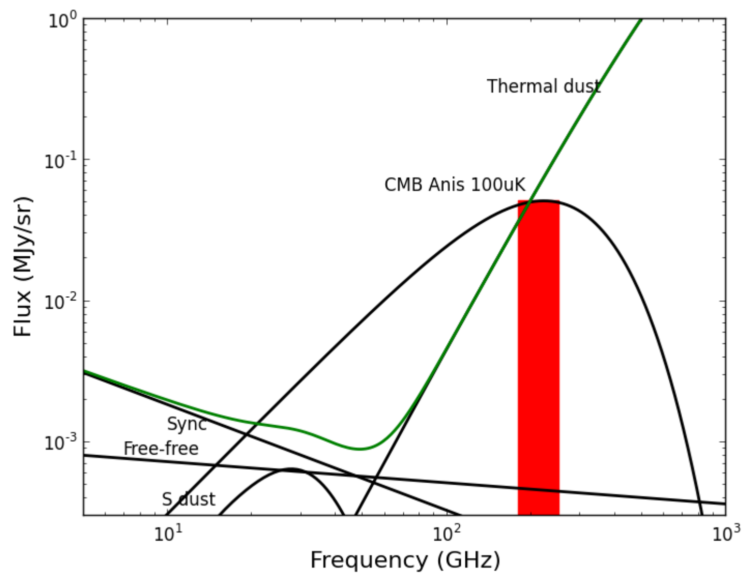

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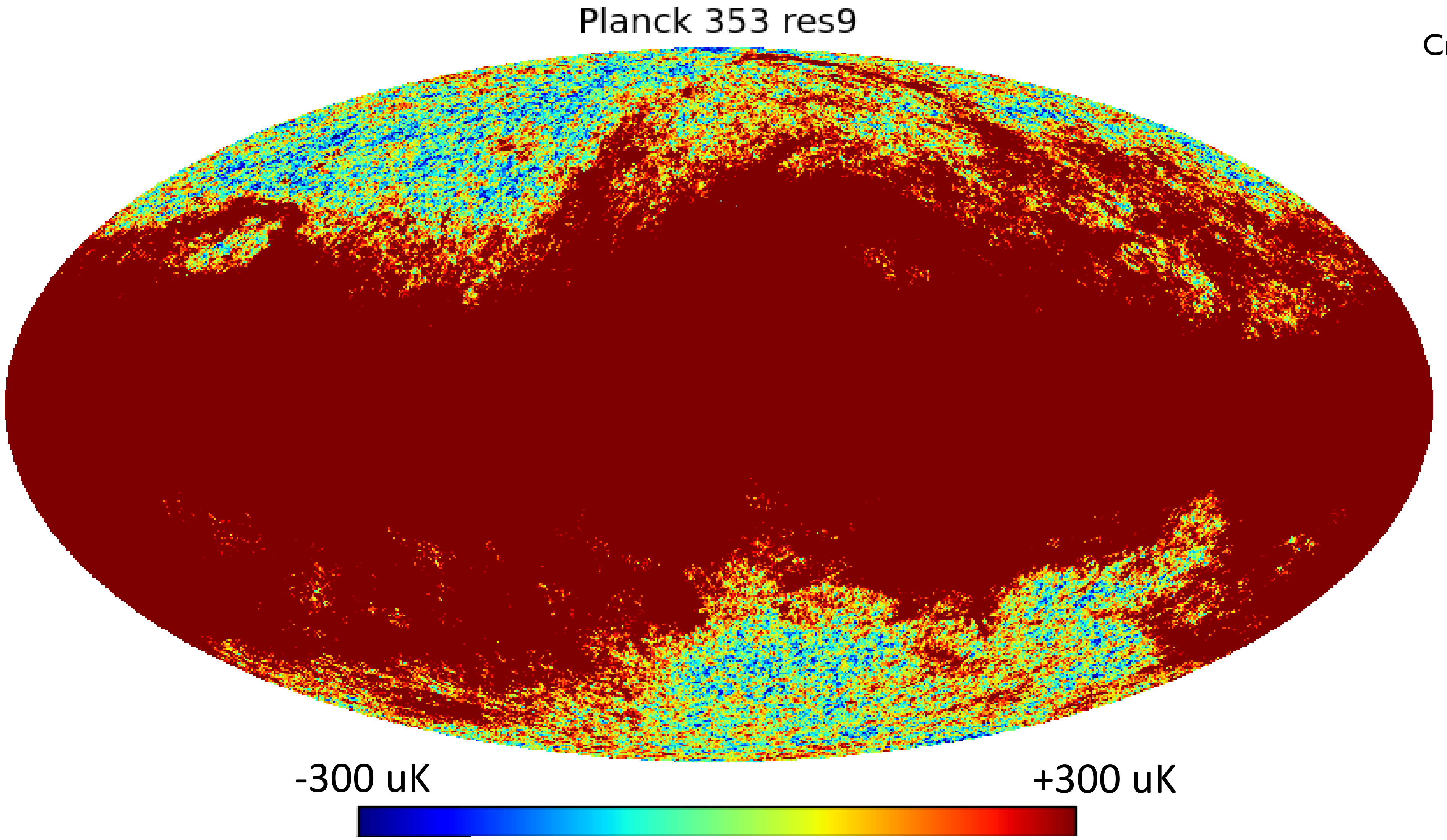
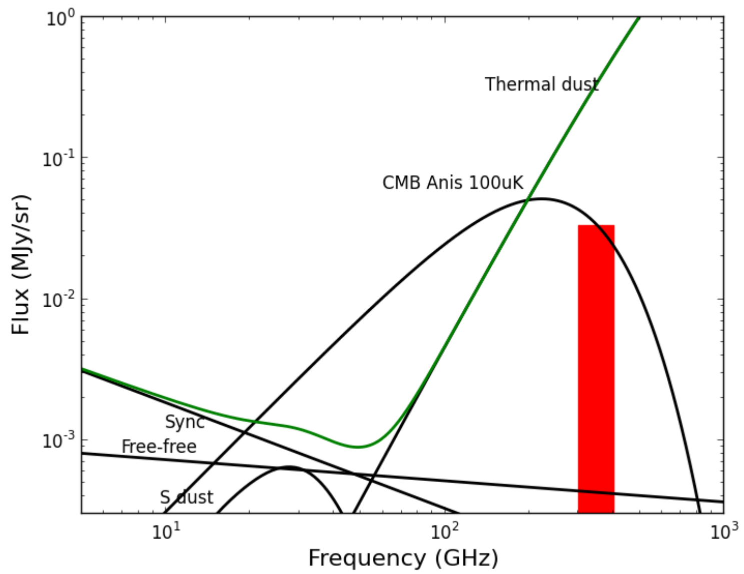


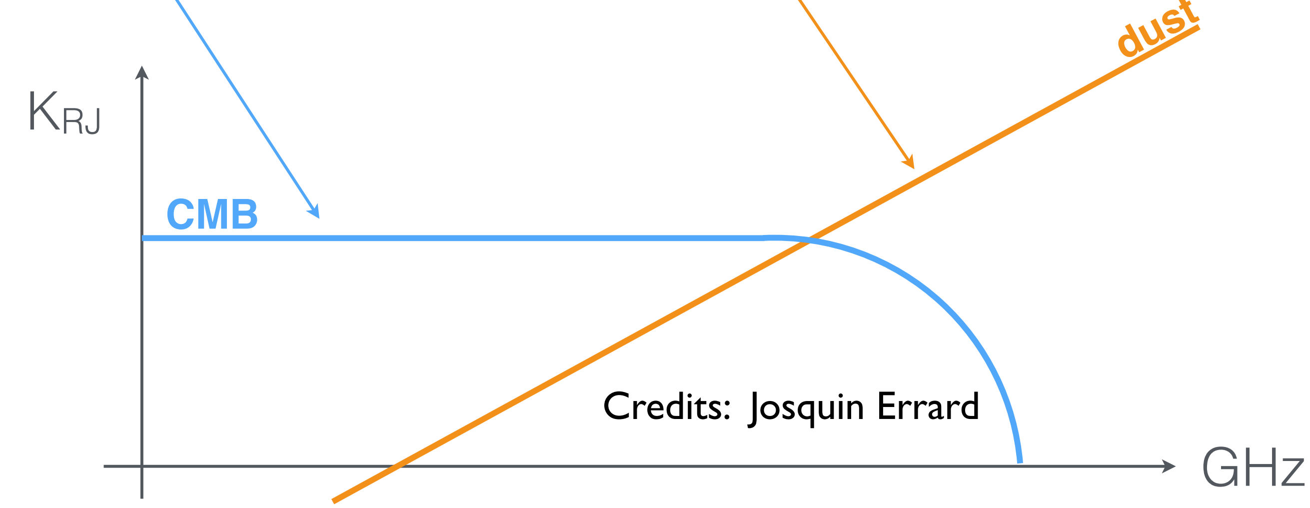


Component separation principle

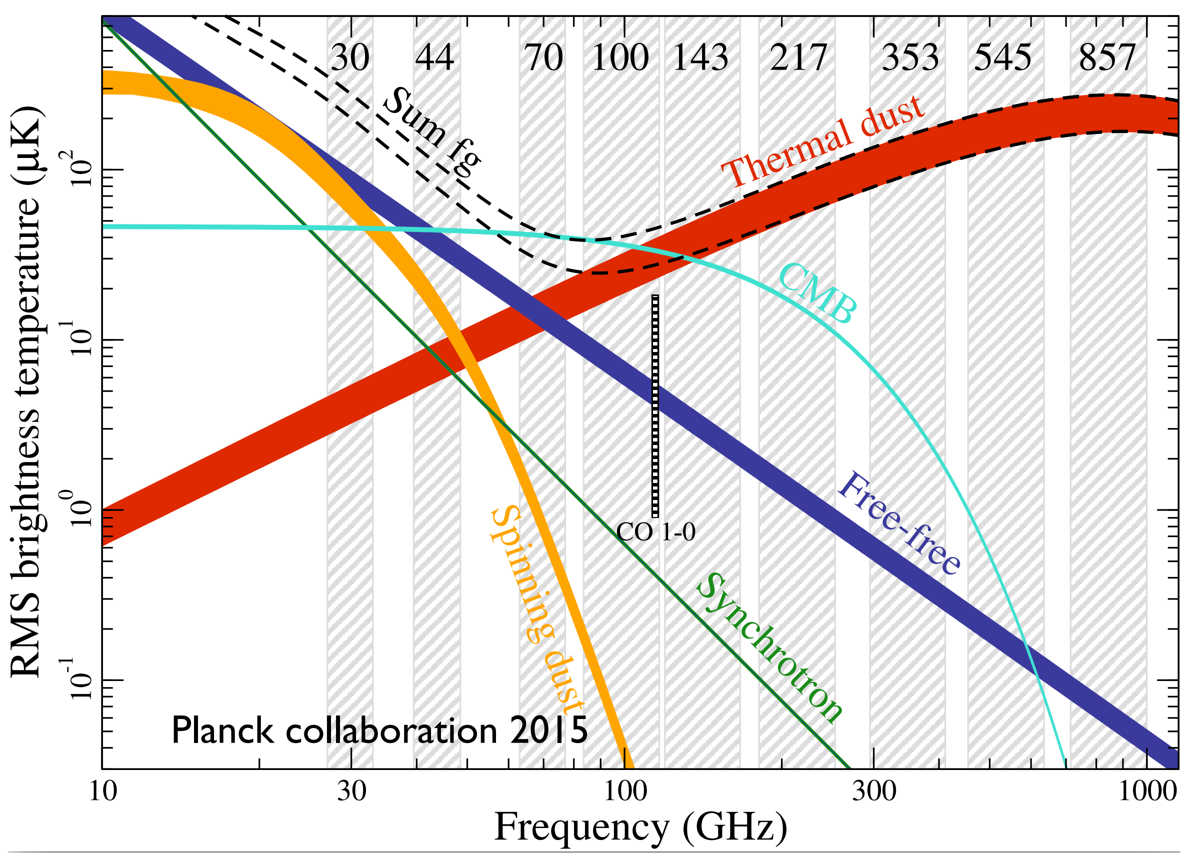
- How to disentangle CMB and foregrounds?
- Different emission laws, different scaling with frequency

$$a_{cmb} = \frac{(\nu/k_BT)^2 \exp(\nu/k_BT)}{(\exp(\nu/k_BT)-1)^2}$$

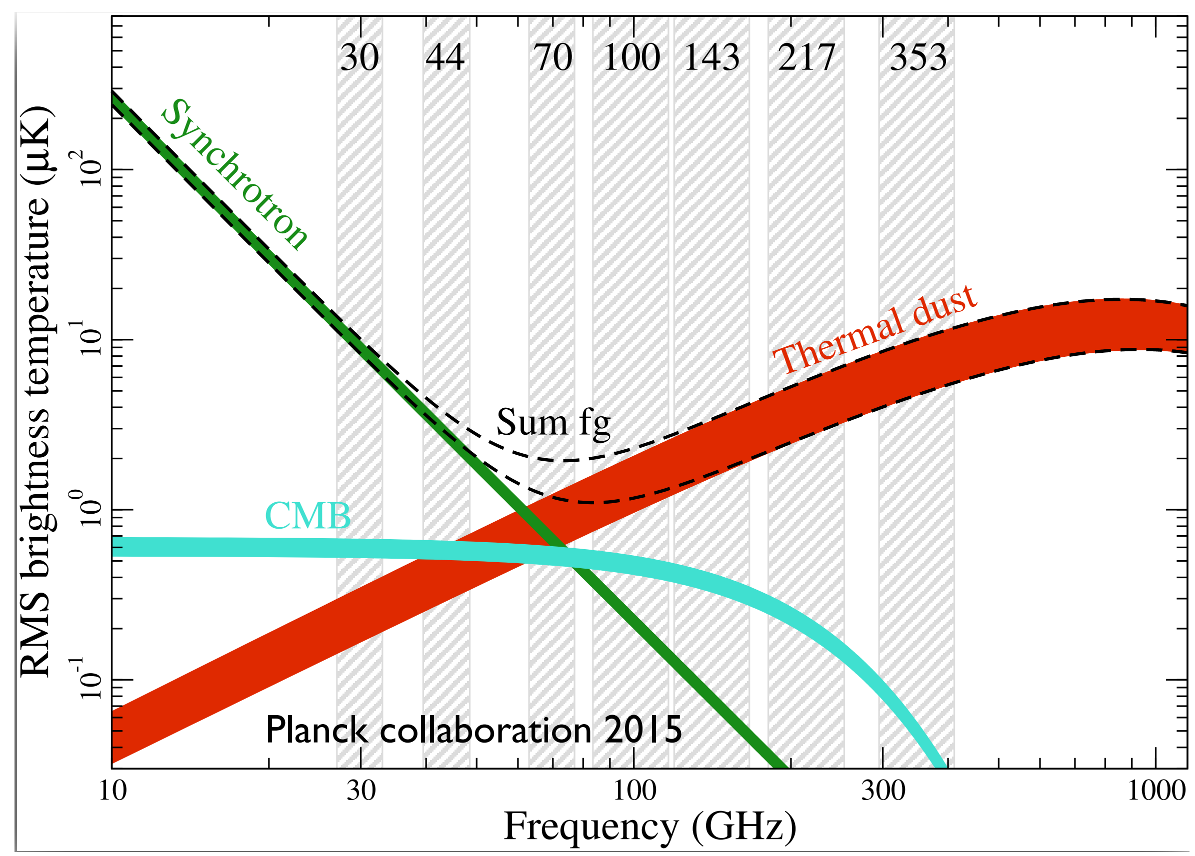
$$a_{dust}(\nu,\nu_{ref}) = \left(\frac{\nu}{\nu_{ref}}\right)^{\beta_d+1} \frac{\exp\frac{h\nu_{ref}}{kT_d}-1}{\exp\frac{h\nu}{kT_d}-1}$$



Credits: Josquin Errard

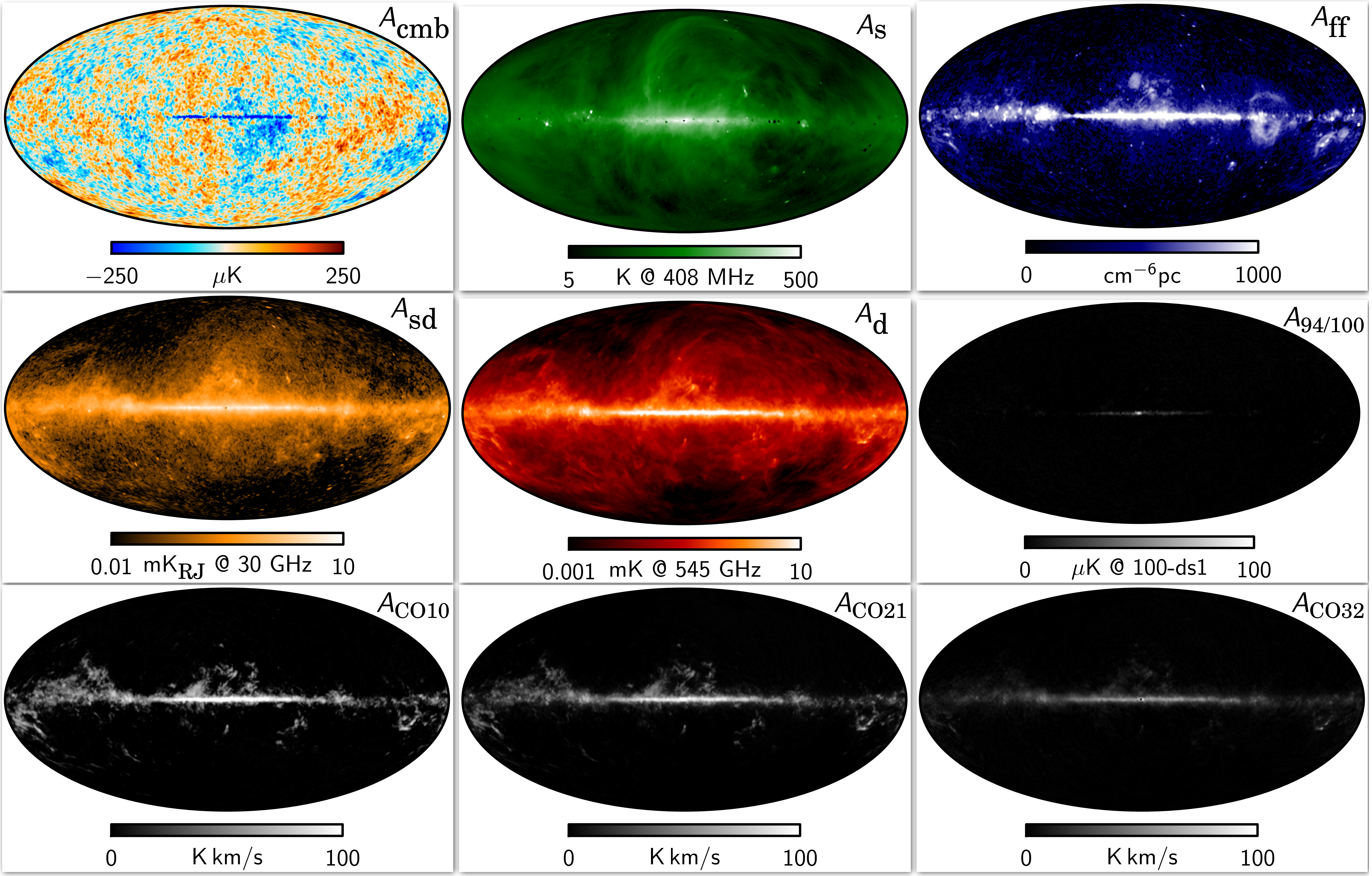


Planck collaboration 2015



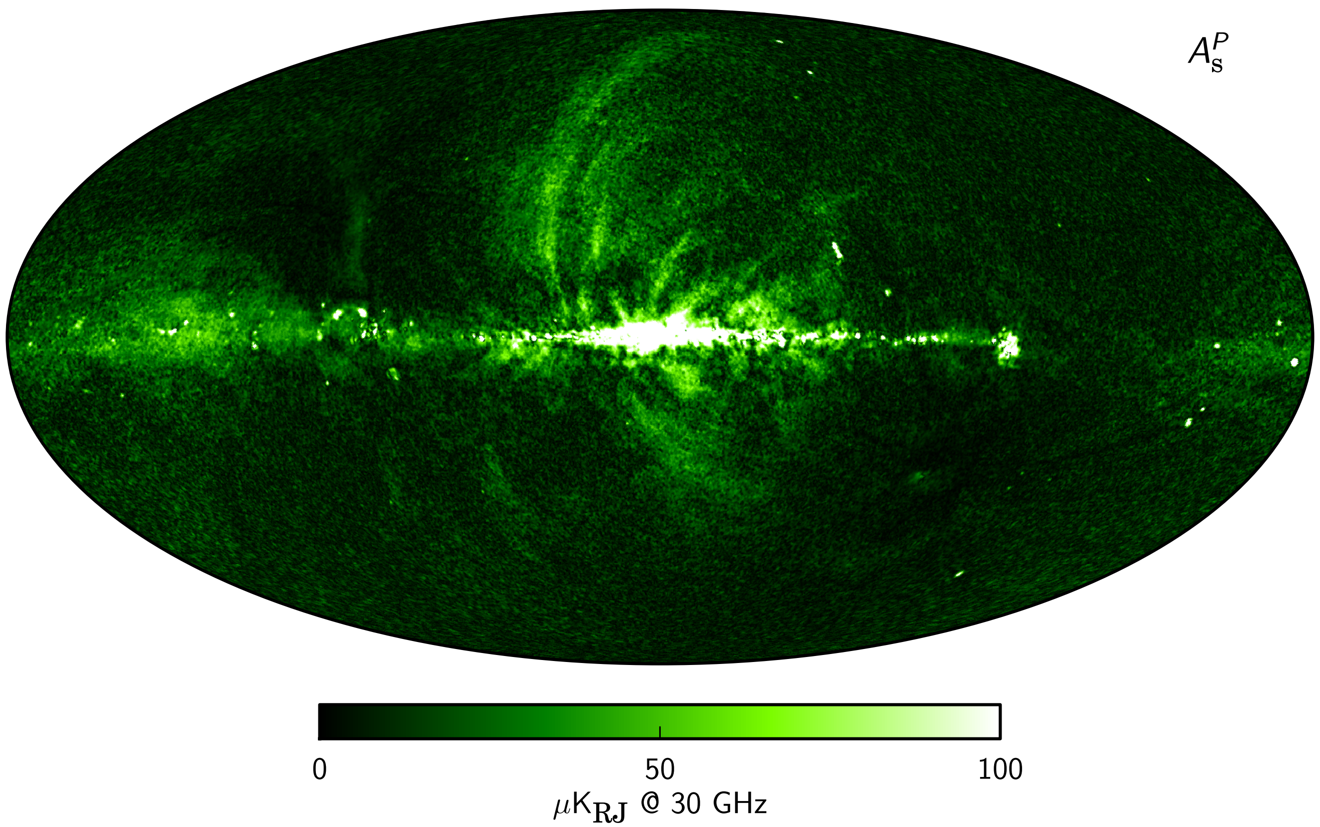
Planck collaboration 2015

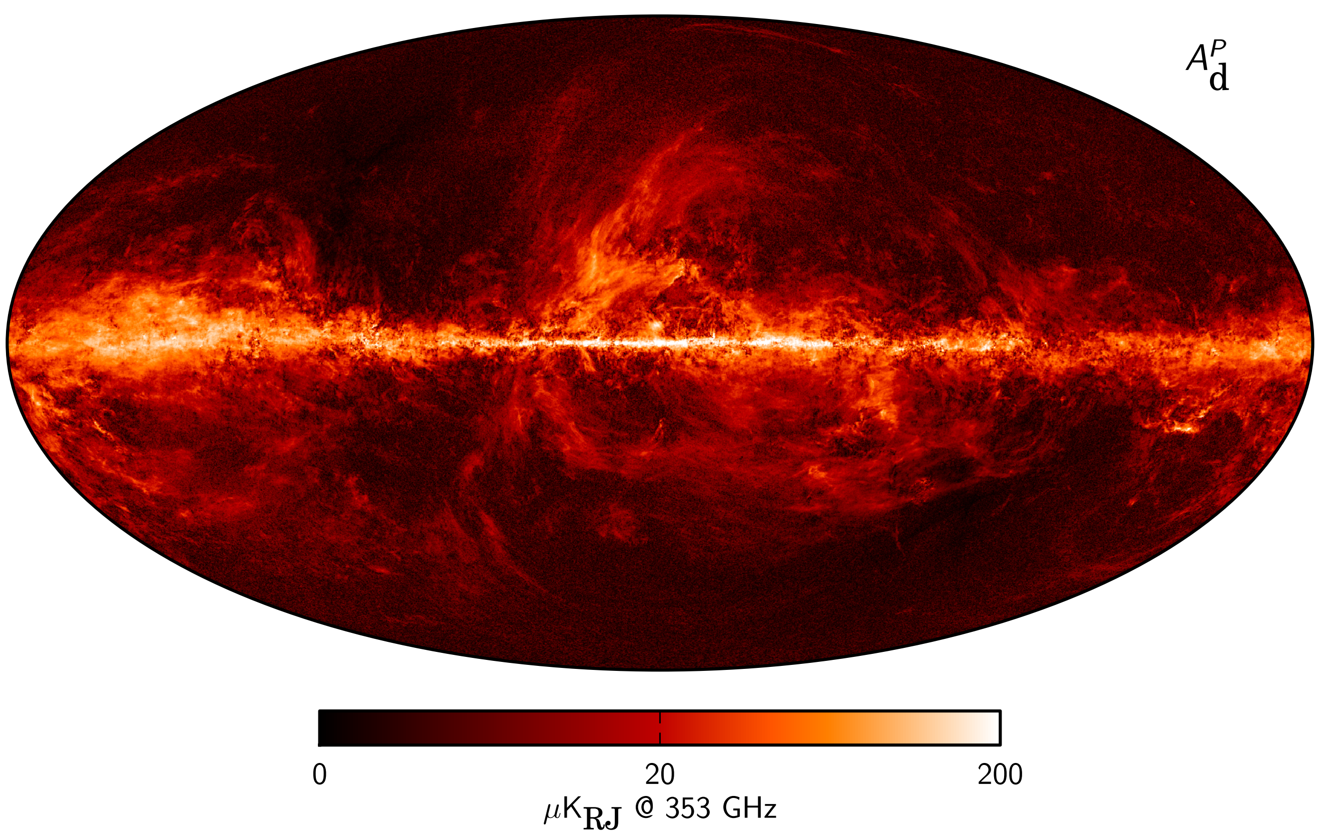
Snapshot of foregrounds



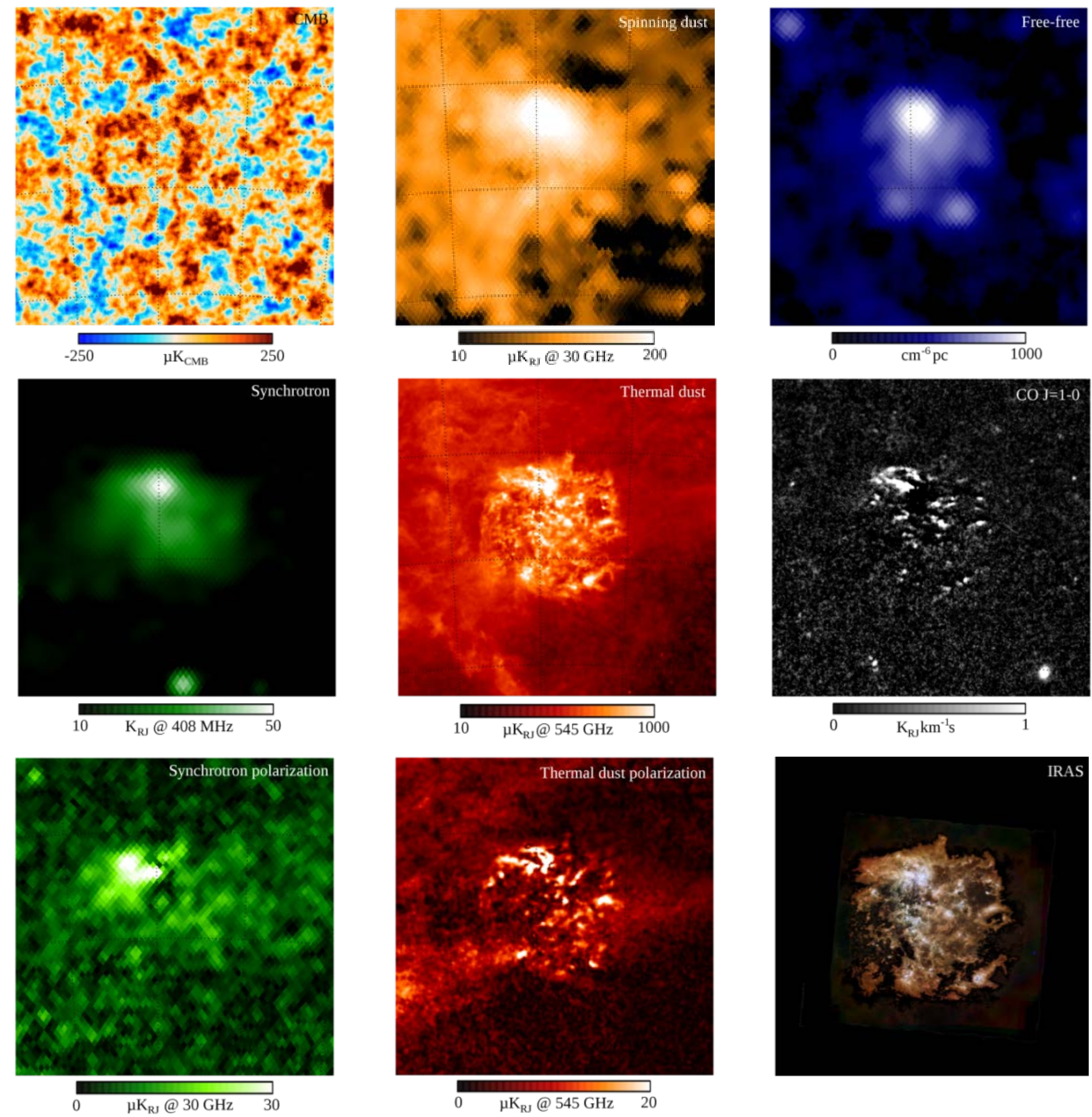
Planck collaboration 2015

Snapshot of polarized foregrounds





Planck collaboration 2015



Component separation: a concrete example

1- Component separation generalities

a map at a given frequency is a sum of cmb, dust and noise

(1) $$map(\nu) = a_{cmb}(\nu)s_{cmb} + a_{dust}(\nu)s_{dust} + n(\nu)$$

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for three frequency channels, using matrix form

(2) $$\begin{bmatrix} map(\nu_1) \\ map(\nu_2) \\ map(\nu_3) \end{bmatrix} = \mathbf{A}(\nu_1, \nu_2, \nu_3) \begin{bmatrix} s_{cmb} \\ s_{dust} \end{bmatrix} + \begin{bmatrix} n(\nu_1) \\ n(\nu_2) \\ n(\nu_3) \end{bmatrix}$$

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GLS solution

(3) $$\begin{bmatrix} s_{cmb} \\ s_{dust} \end{bmatrix} = \underbrace{\boxed{\left(\mathbf{A}^T\mathbf{N}^{-1}\mathbf{A}\right)^{-1}}}_{\tilde{\mathbf{N}}} \mathbf{A}^T\mathbf{N}^{-1} \begin{bmatrix} map(\nu_1) \\ map(\nu_2) \\ map(\nu_3) \end{bmatrix}$$

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Component separation is performed in two steps:
1- Estimation of the mixing matrix **A** — method specific
2- Solving the linear system (2), with **A** estimated above — general to any method

GLS solution

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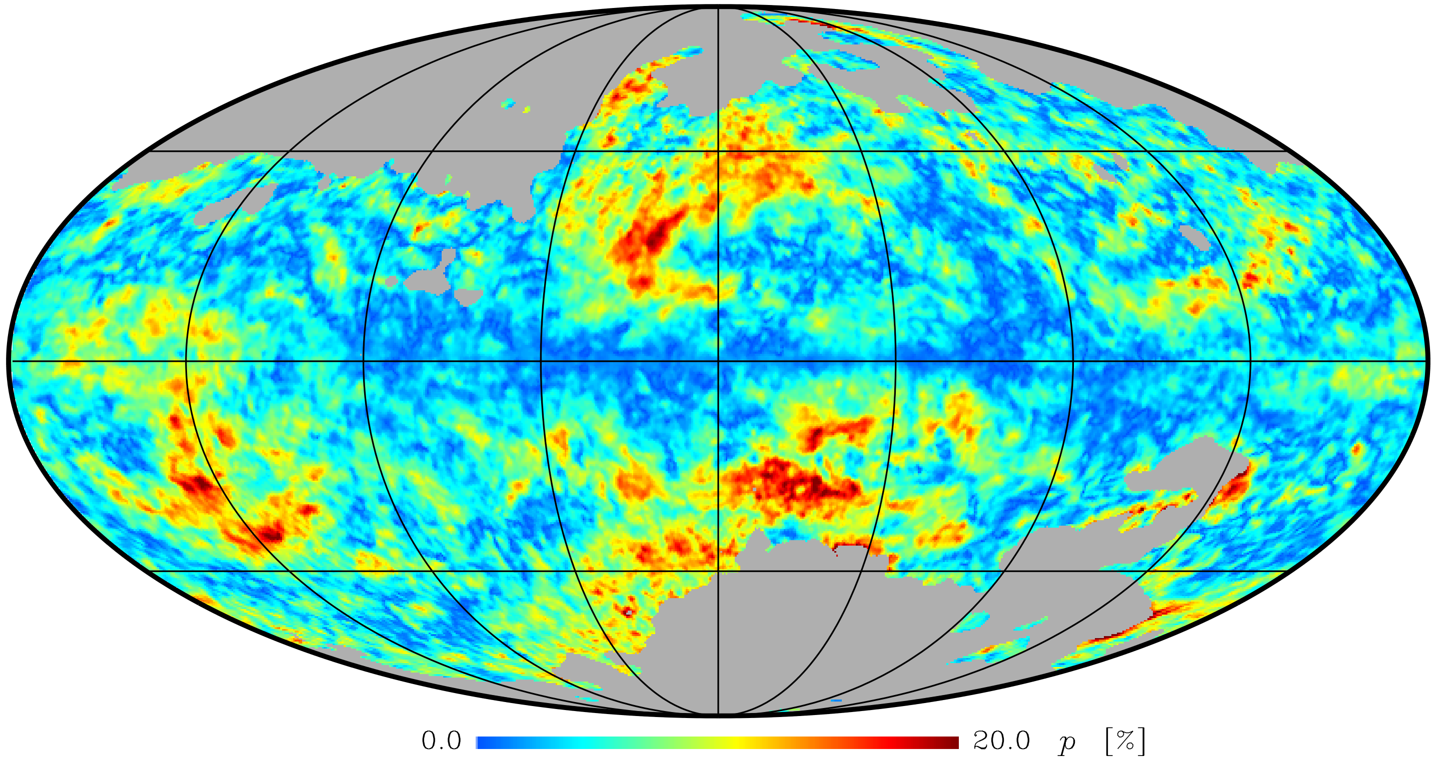
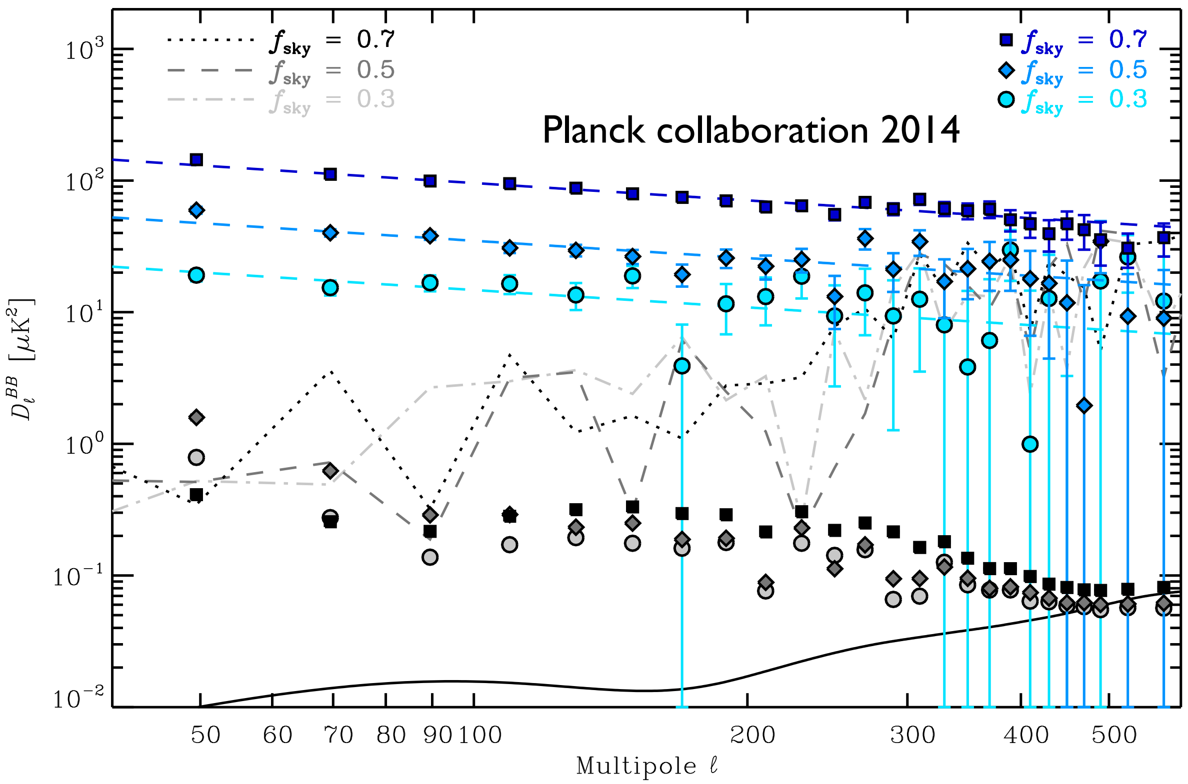
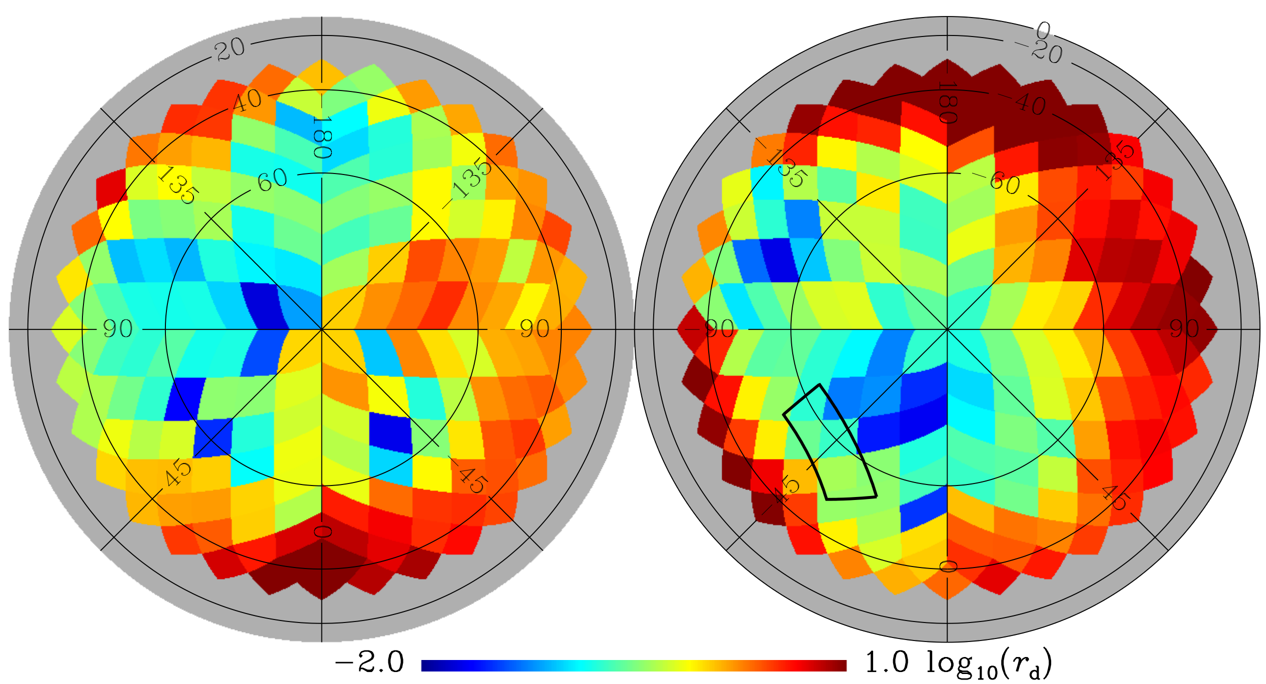
Planck foregrounds results

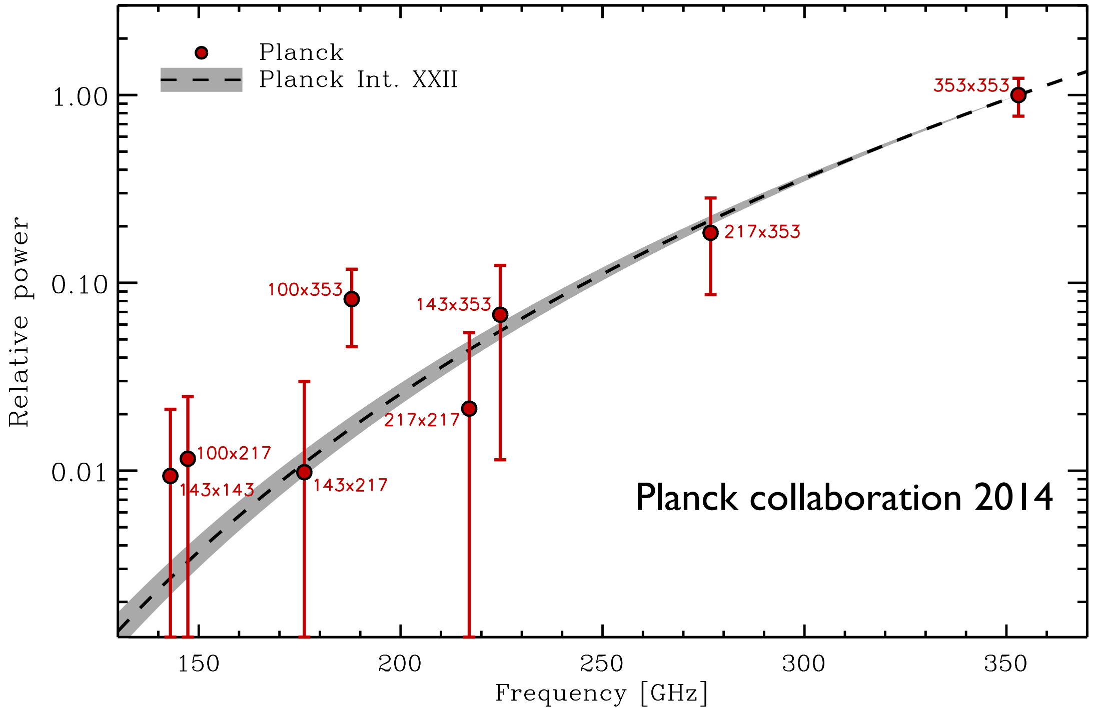
- First polarized survey at high-frequency: highly polarized dust far from the galactic center





Planck collaboration 2014





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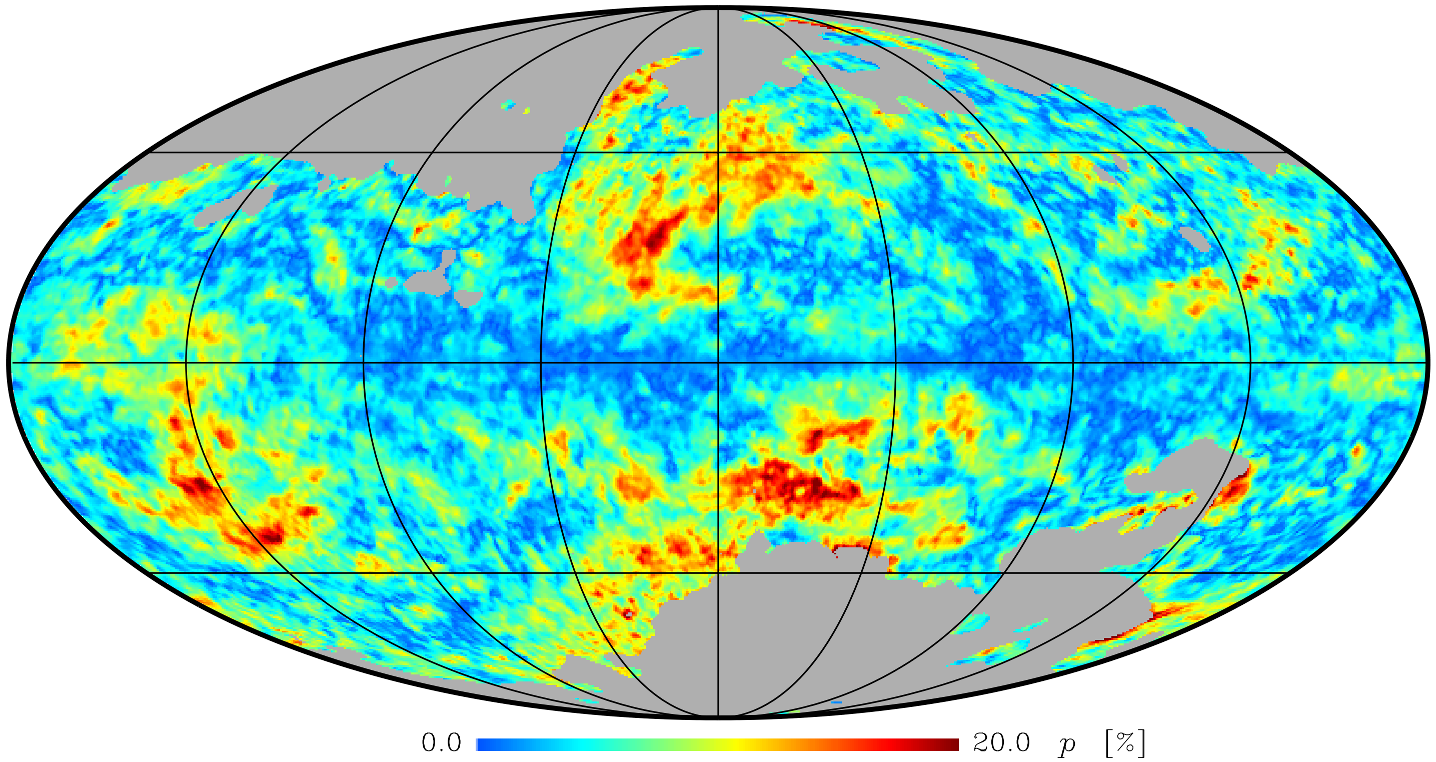
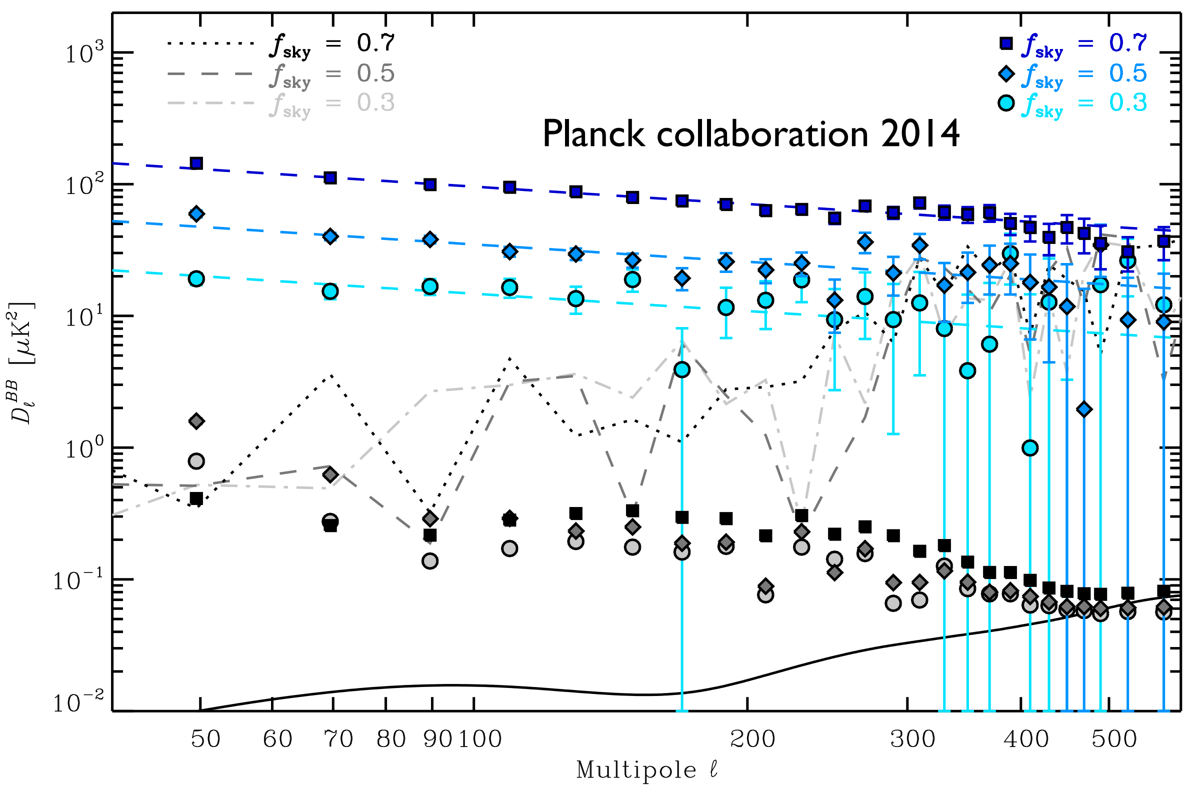
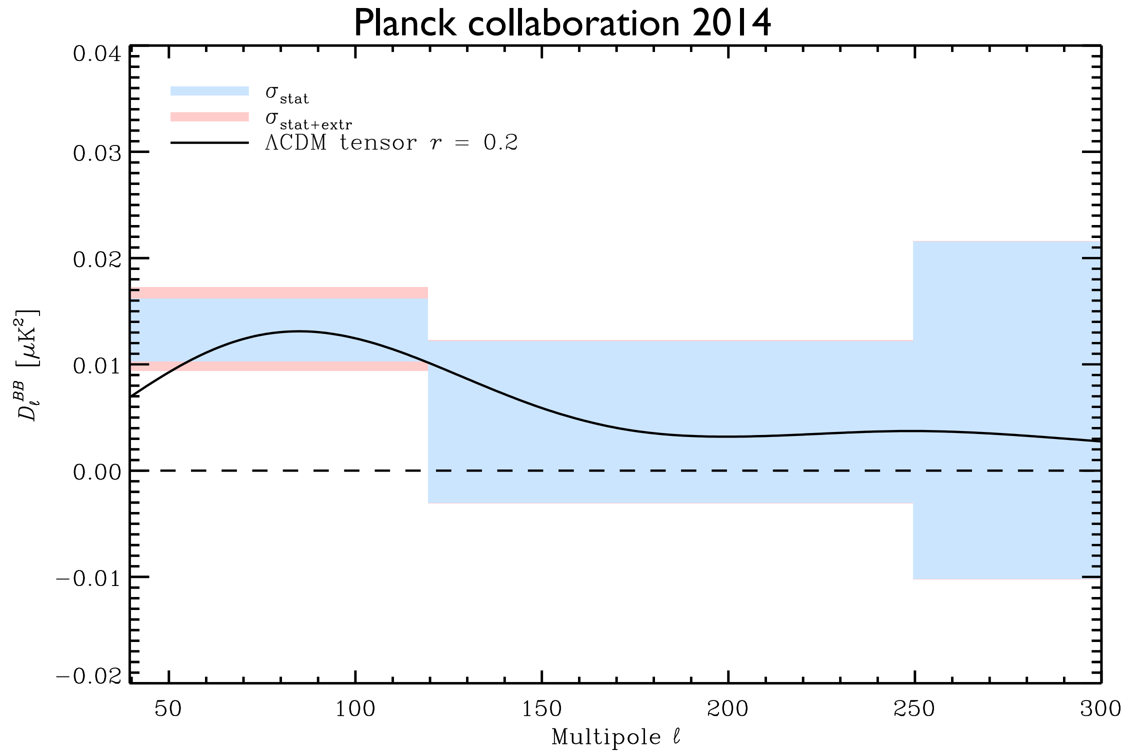
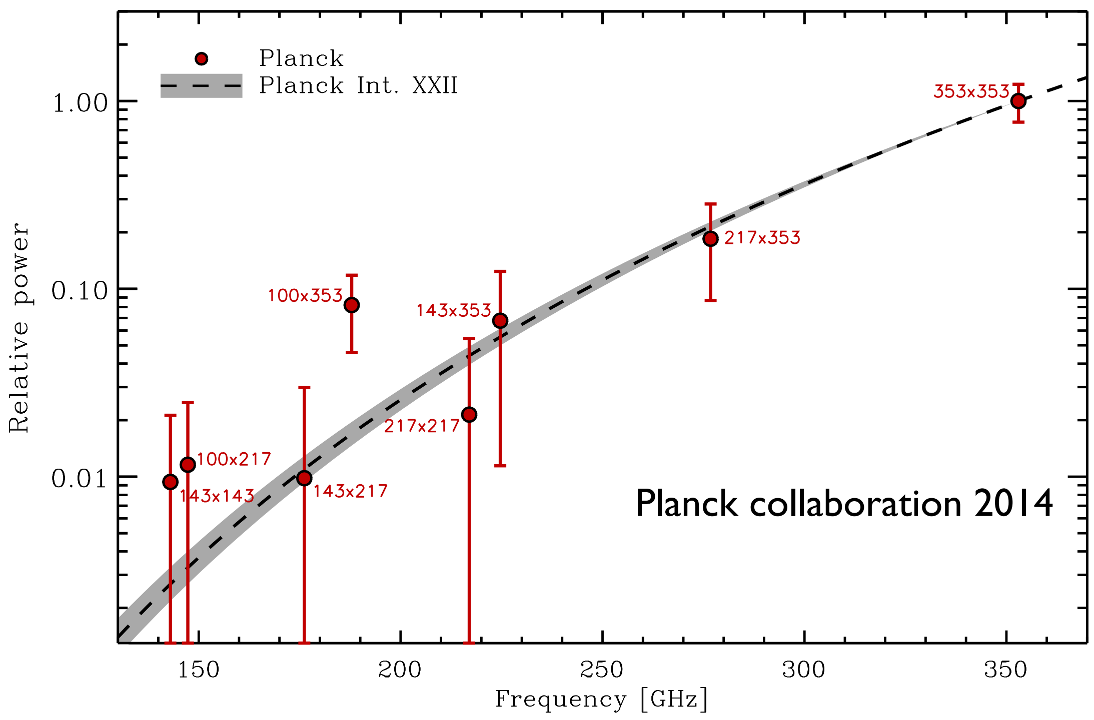








Power spectrum estimation in real life

Problem with $\hat{C}_\ell = \sum_{m=-\ell}^{\ell} \frac{a^*_{\ell m} a_{\ell m}}{2\ell+1}$: a_{lm} are not available (partial sky coverage)

C_l is estimated by

- sampling the power of s along functions in the l subspace (the $\{Y_{lm}\}_{m\in\{-l\ldots l\}}$ functions)
- averaging (the expected power on each function is C_l)

In this case the functions are orthogonal but don't have to be

If a function f straddles multiple l subspaces, the expected power of s along f is a **(known) linear combination of C_l**

Define a pseudo-basis of such f functions: $\tilde{Y}_{\ell m}$ (any set!) and sample s along them. $\tilde{a}_{\ell m} \equiv \int \tilde{Y}^*_{\ell m} s \mathrm{d}\Omega$

$$\tilde{C}_\ell = \sum_{m=-\ell}^{\ell} \frac{\tilde{a}^*_{\ell m} \tilde{a}_{\ell m}}{2\ell+1}$$ Pseudo-power spectrum

$$\langle \tilde{C}_\ell \rangle = \sum_{\ell'} M_{\ell\ell'} C_{\ell'}$$

Compute and "invert" the M_{ll} and and you are done

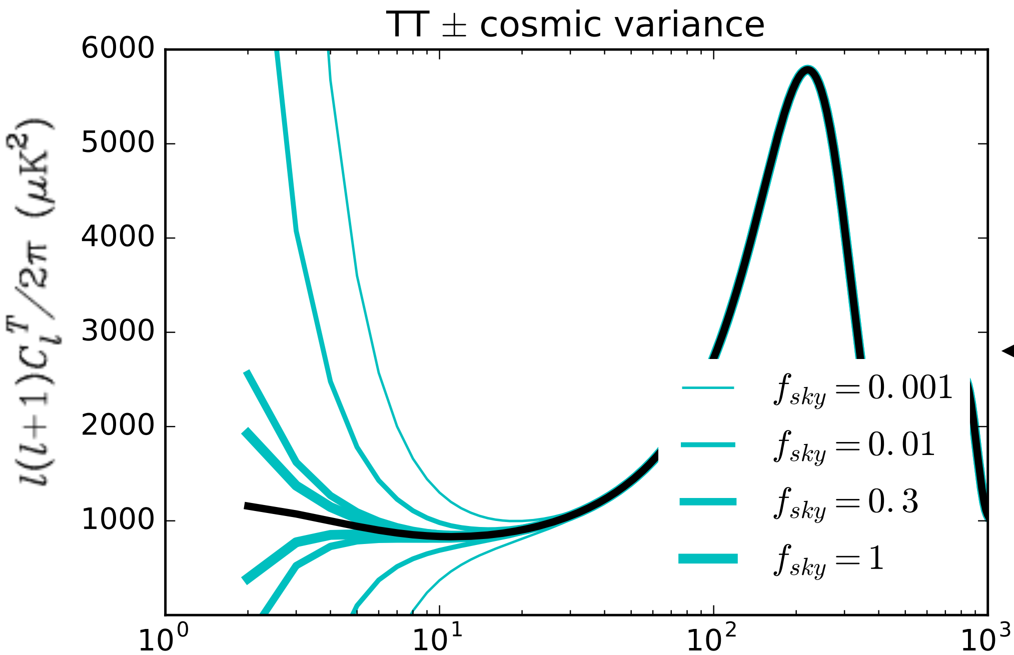
Notable example: $\tilde{Y}_{\ell m} \equiv W Y_{\ell m}$

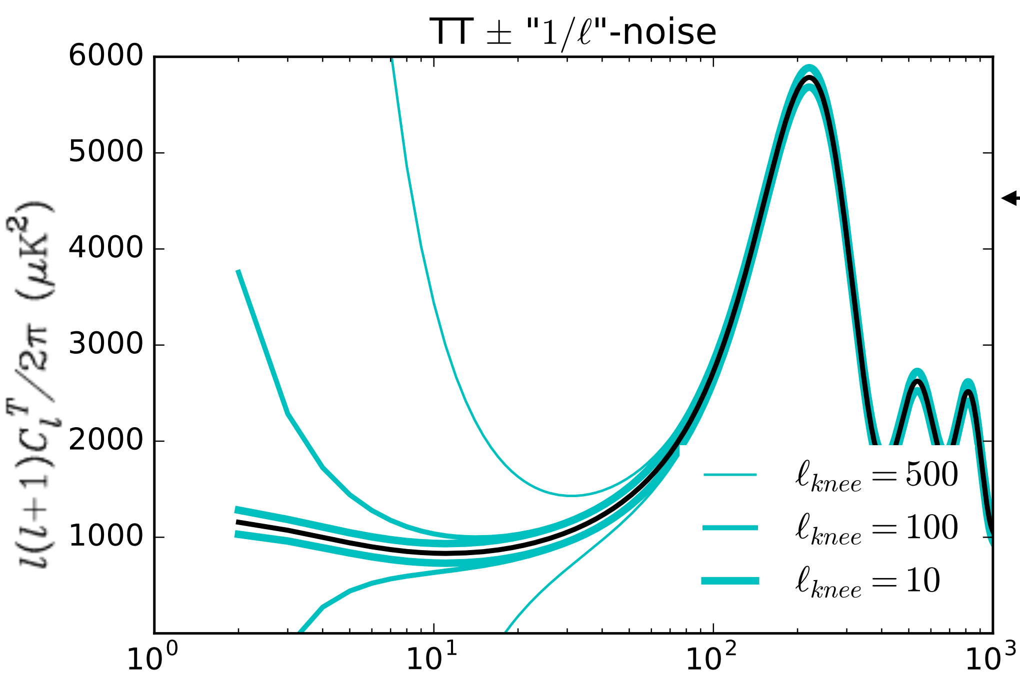
W is the inverse noise

- handle cut sky
- handle inhomogeneous coverage
- Computing the M_{ll} scales as $N_p^{3/2}$

Hauser and Peebles (1973), Hivon et al. (2002), Kogut et al. (2003)

Power spectrum estimates errors





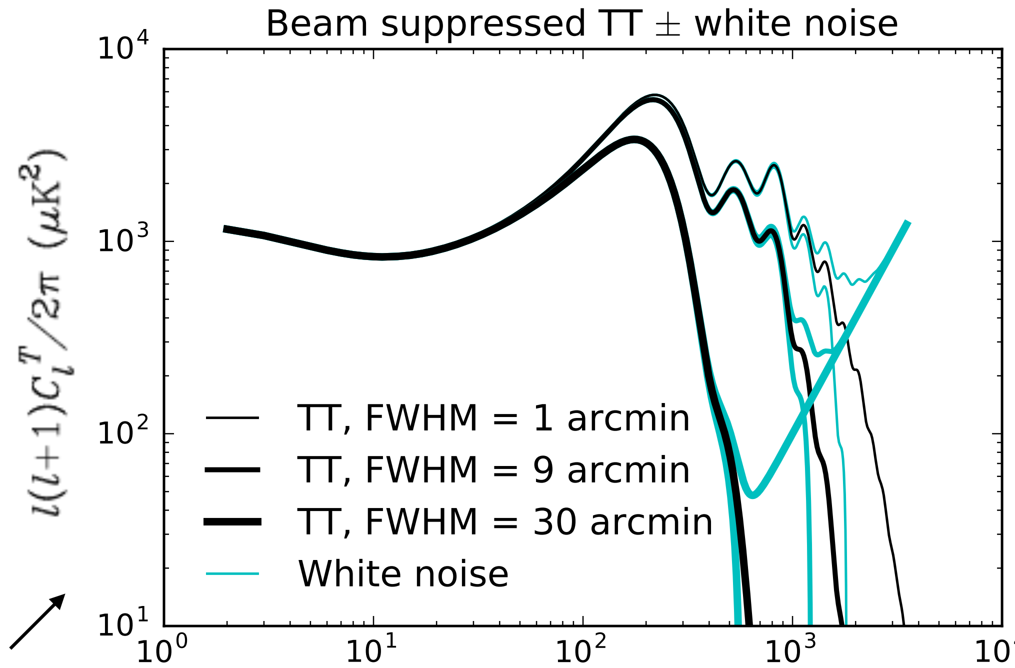
Large Scales

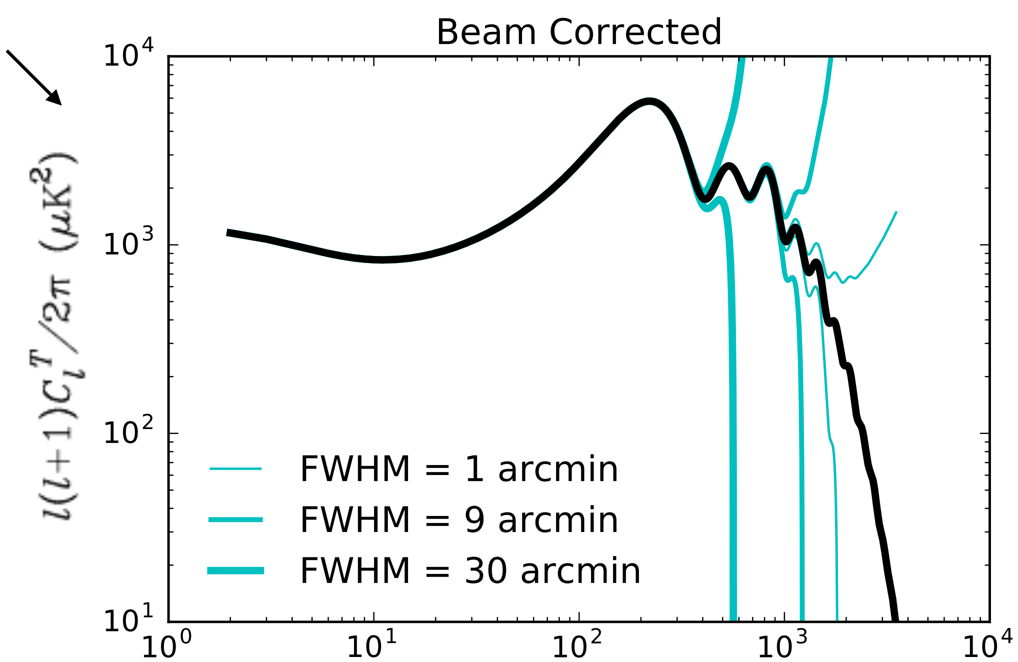
Cosmic variance

Correlated noise

Small Scales

White noise





Foregrounds

Galactic

Extra-galactic

Data analysis basics

- Scientific observations can be represented by a data vector **d** which can be a time series $\{t\}$ or temperature map of the sky $\{T\}$ or something else.
- Data have information about some physical process for which we have a theoretical model represented by a set of parameters i.e., parameter vector Θ.
- One of its example is a Gaussian process represented by two parameters i.e., the mean μ and the variance σ^2. The probability of obtaining data d given a theoretical (Gaussian model (μ, σ^2)) is given by:

$$P(d|\mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{1}{2}\frac{(d-\mu)^2}{\sigma^2}\right]$$

Data analysis basics - II

- Not all the inverse problems are solvable and in some cases we can easily find out why that is so.
- On the basis of whether the size N of the data vector $\mathbf{d}$ is larger, smaller or equal to the size M of the parameter vector Θ, there are three possibilities.
  - $N = M$: Unique solution is possible
  - $N > M$: Over constrained problem, χ^2 minimization, Unique solution
  - $N < M$: Under-constrained problem, ill posed problem, priors, regularization

  Note that in the above consideration we have assumed that all the data points are independent.
- One of the common methods to solve an inverse is to minimize a measure of misfit between the data and the theoretical model.

Maximum likelihood estimation

- The probability distribution $P(\Theta|\mathbf{d})$ (posterior) for model parameters Θ given data $\mathbf{d}$ can be related to the probability $P(\mathbf{d}|\Theta)$ (likelihood) of an experiment giving data $\mathbf{d}$ for model parameters Θ using the Bayes' theorem:

$$P(\Theta|\mathbf{d}) = \frac{P(\mathbf{d}|\Theta)P(\Theta)}{P(\mathbf{d})}$$

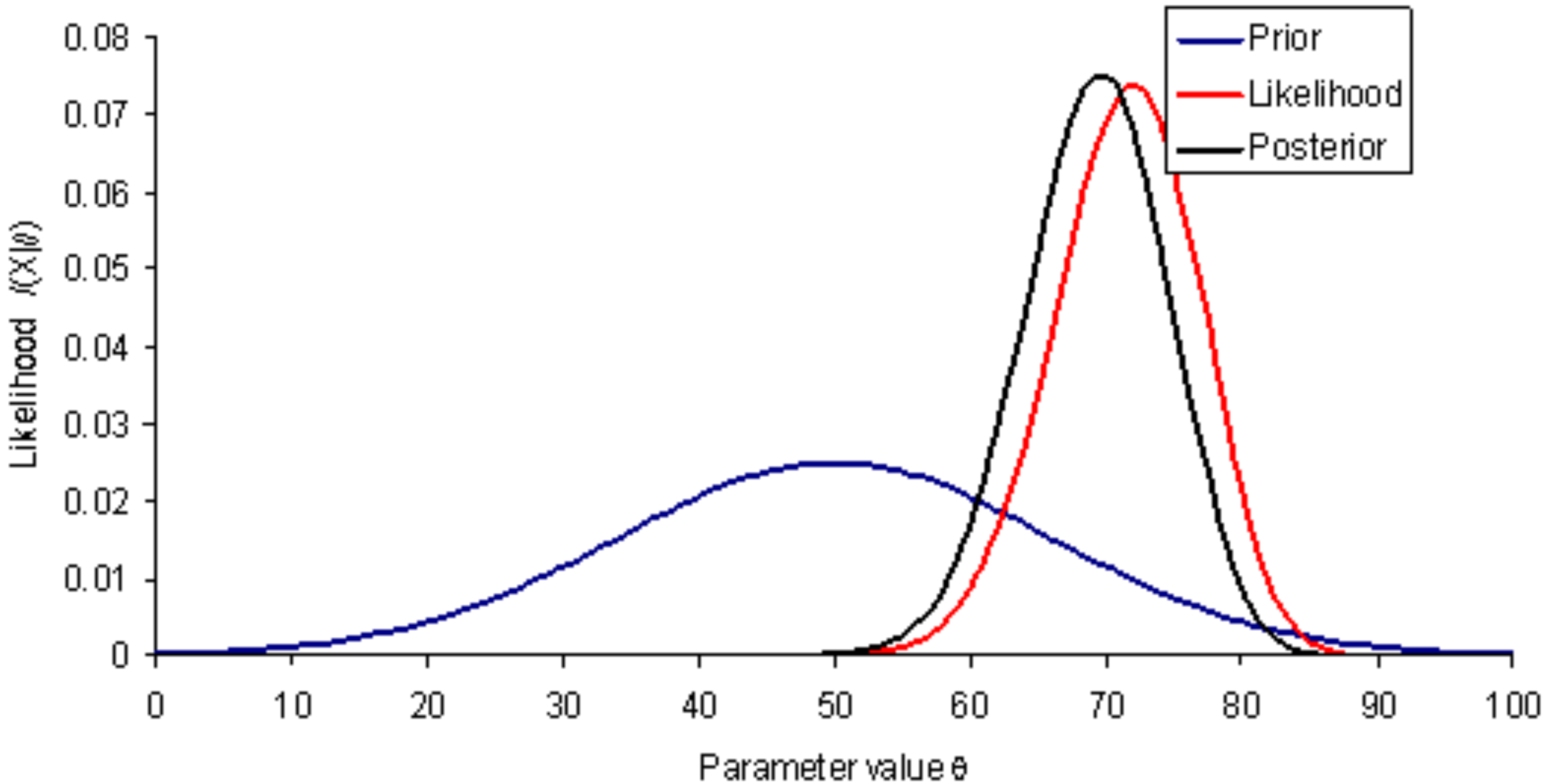
  where $P(\Theta)$ is called the prior and $P(\mathbf{d}) = \sum P(\mathbf{d}|\Theta)P(\Theta)$ is used for the normalization purpose.

- For the case of flat prior, posterior and likelihood are proportional:

$$P(\Theta|\mathbf{d}) = P(\mathbf{d}|\Theta) = L(\mathbf{d}|\Theta)$$

- In Bayesian formalism we can easily incorporate new data in analysis by considering the posterior of the old data as prior.

The role of the prior



Note that when likelihood/posterior is not Gaussian then the average value of the parameter $<\theta>$ may not coincide with the value of θ_0 at which the likelihood/posterior is maximum.

An efficient sampling: Markov Chains MC

- Once we have the probability distribution $P(\Theta|\mathbf{d})$ for model parameters Θ we can statistics of the parameters:

$$< \Theta >= \int \Theta d\Theta P(\Theta|\mathbf{d})$$

- In practice, before carrying out the above integral we find out the one dimensional probability distribution by marginalization over other parameters:

$$P(\theta_r) = \int d\theta_1 d\theta_2 ....d\theta_{r-1} d\theta_{r+1}...d\theta_M P(\theta_1, \theta_2, ...s\theta_M)$$

and

$$< \theta_r >= \int \theta_r d\theta_r P(\theta_r)$$

Maximum likelihood estimation

- Carrying out multi-dimensional integration is very expansive i.e., computational cost grows as $O(n^M)$ where n is the number of grid points along one direction and M is the dimensionality of the parameter space.
- If we can replace the multi-dimensional integration by summation over a finite number of points which represent the probability distribution function then computational cost becomes manageable.

$$< \Theta >= \int \Theta d\Theta P(\Theta|\mathbf{d}) = \frac{1}{N}\sum_{i=1}^{N} \Theta_i P(\Theta_i|\mathbf{d})$$

- Markov-Chain Monte Carlo sampling samples the likelihood function in such a way that there are more point in the region where the likelihood function has the large values and less where it has small values.

Basic idea of MCMC

- When we toss a coin n times then the outcome of the n^{th} toss does not depend on the outcome of any of the previous outcomes.
- In a Markov-Chain the probability of a random variable X_n to have value x_n at step n depends on the probability of the variable X_{n-1} to have the value x_{n-1} at step $n-1$.

$$P(X_N) = P(X_n, X_{n-1})P(X_{n-1})$$

  where $P(X_n, X_{n-1})$ is called the transition probability, transition kernel or proposal density.
- In most cases transition kernel is symmetric:

$$P(X_n, X_{n-1}) = P(X_{n-1}, X_n)$$

- The transition probability $P(X_n, X_{n-1})$ has the remarkable property that after an initial burn-in period it generates a sample which has the probability distribution $P(X)$.

CMB gaussian likelihood

- In terms of C_l the likelihood function can be written as:

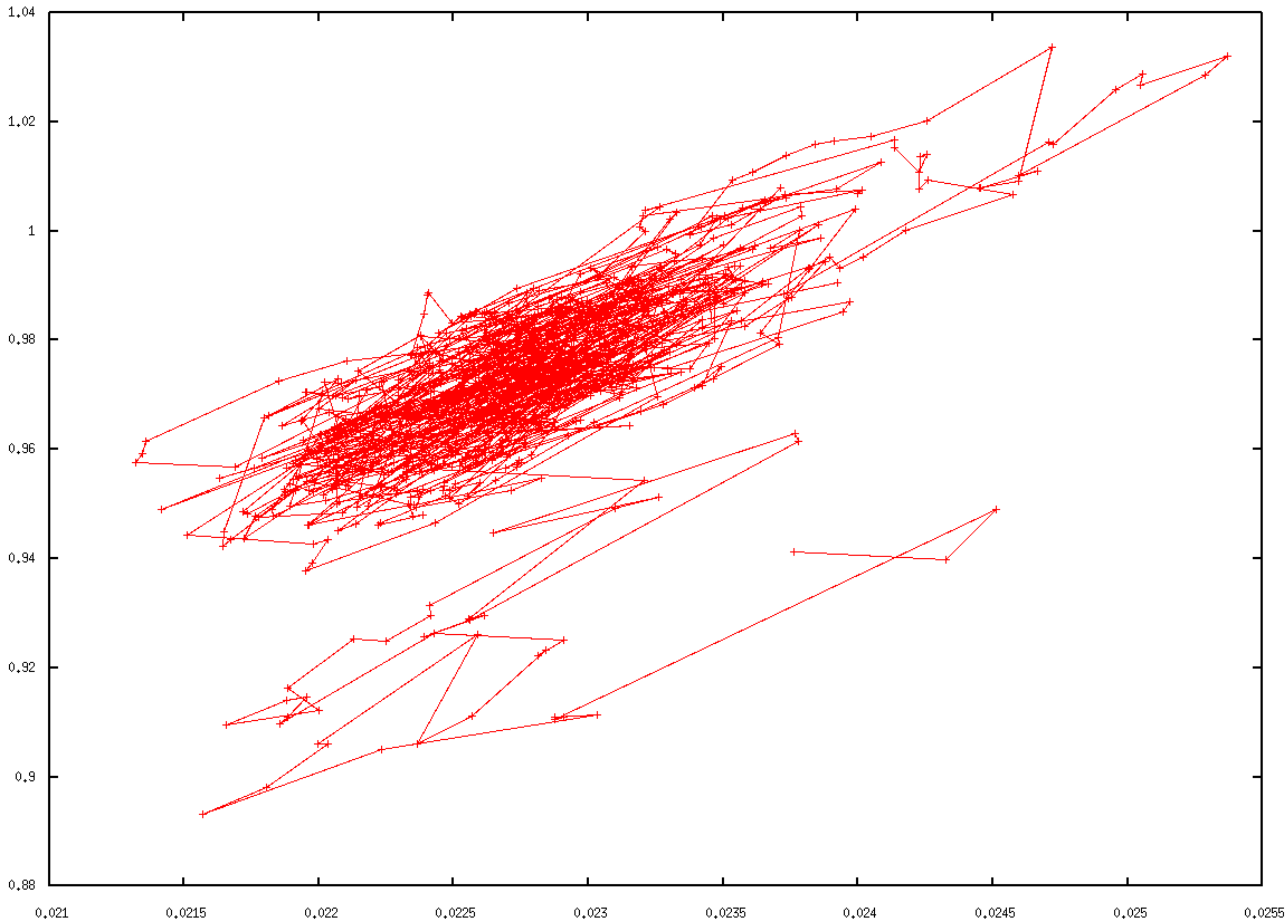
$$L(T|C_l) = \prod_{lm} \frac{1}{\sqrt{C_l}} \exp[-|a_{lm}|^2/(2C_l)]$$

- Since we observe only one sky so we cannot measure the power spectra directly, but instead form the rotationally invariant estimators, C_l, for full-sky CMB maps given by

$$\hat{C}_l = \frac{1}{2l+1} \sum_{m=-l}^{m=l} |a_{lm}|^2$$

$$\chi^2 = -2 \log L(\hat{C}_l|C_l) = \sum_l (2l+1) \left[\log\left(\frac{C_l}{\hat{C}_l}\right) + \frac{\hat{C}_l}{C_l} - 1 \right]$$

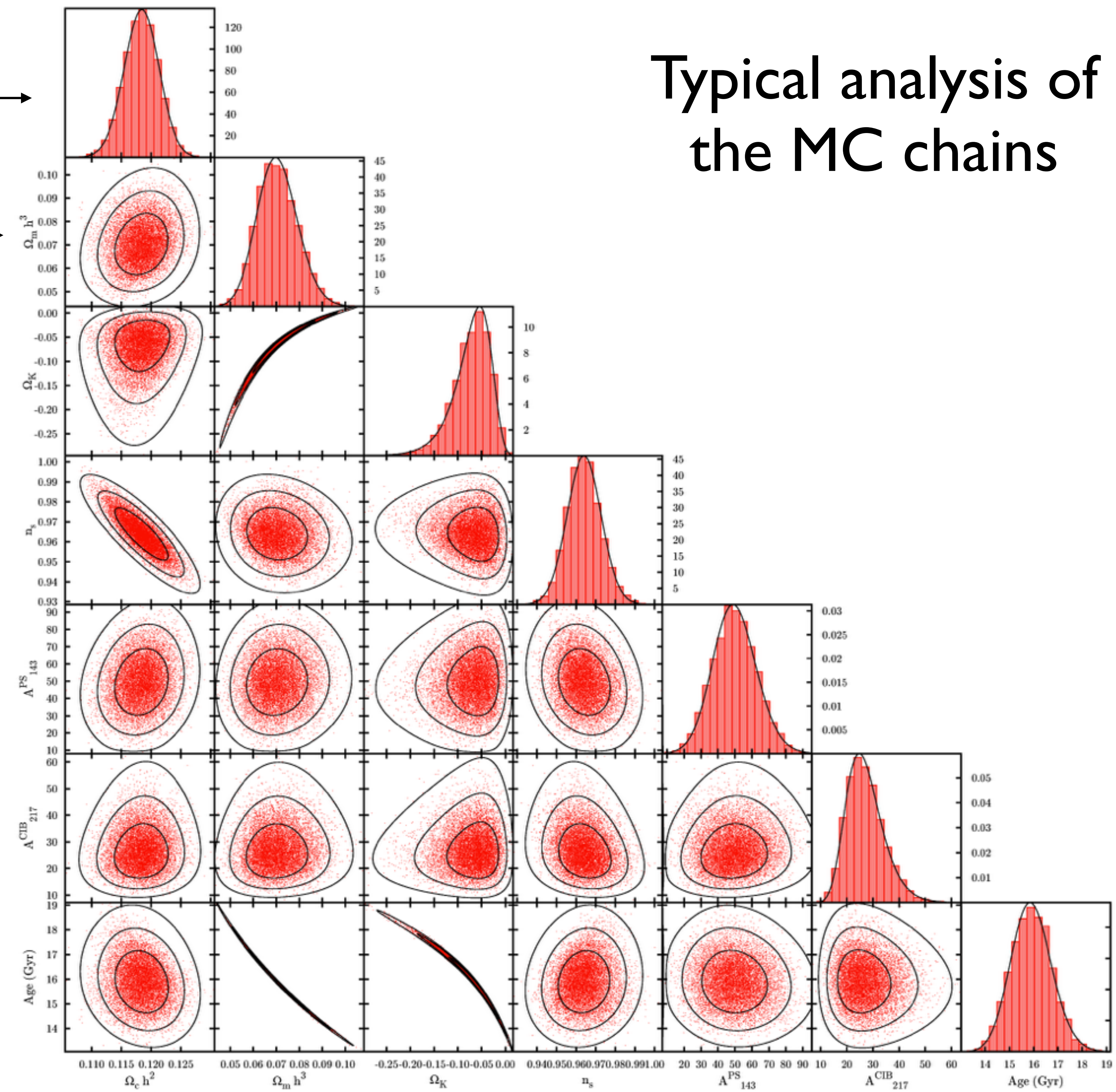
MCMC chain convergence



Typical analysis of the MC chains

1-D marginal distribution

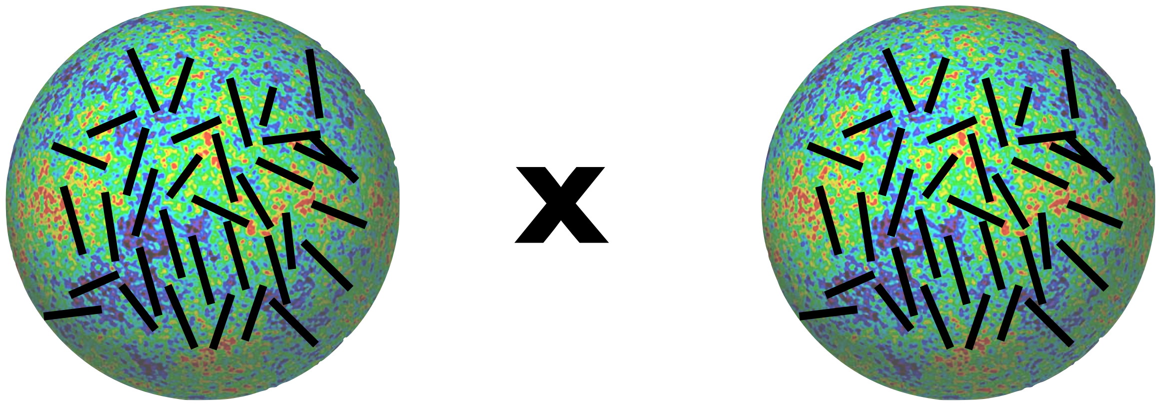
2-D marginal distribution



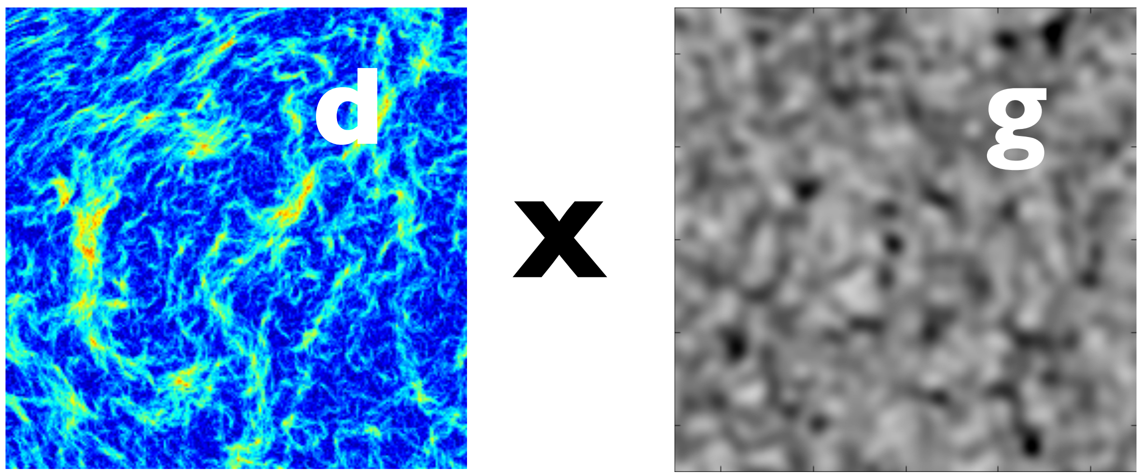
Schuhmann et al. (2016)

Current strategies to detect B-modes

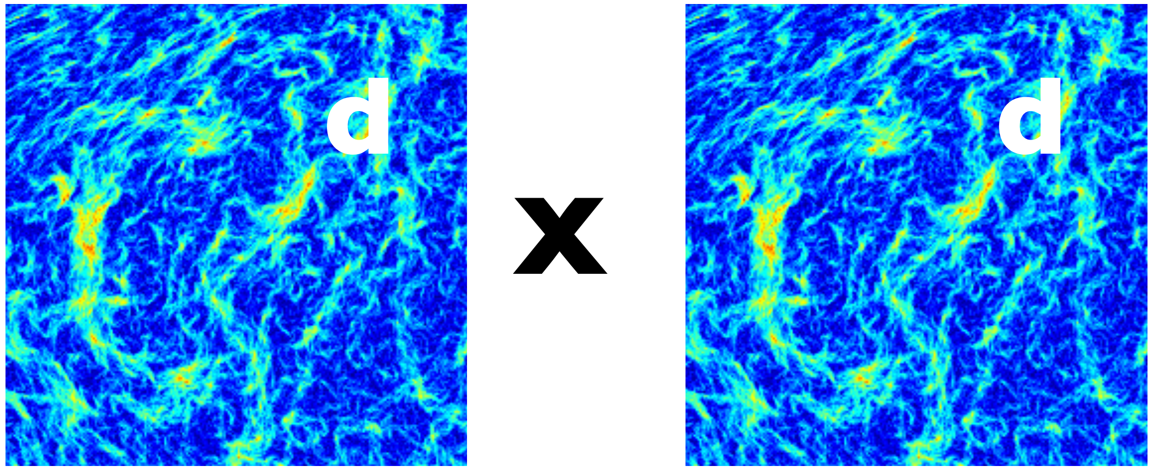
- 2-point correlation:
  CMB power spectrum



- 3-point correlation:
  CMB cross correlation with biased tracers of dark matter halos

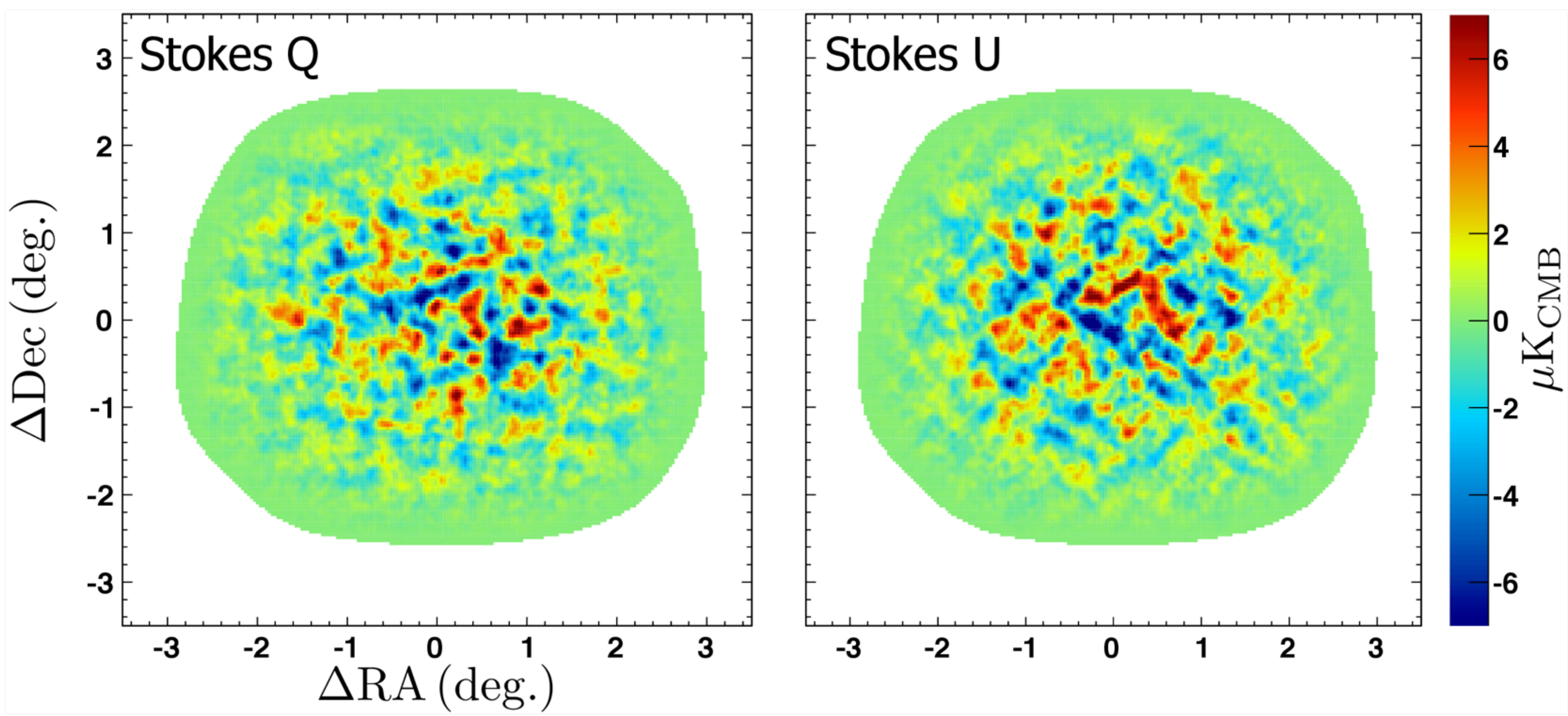


- 4-point correlation: lensing reconstruction with polarization

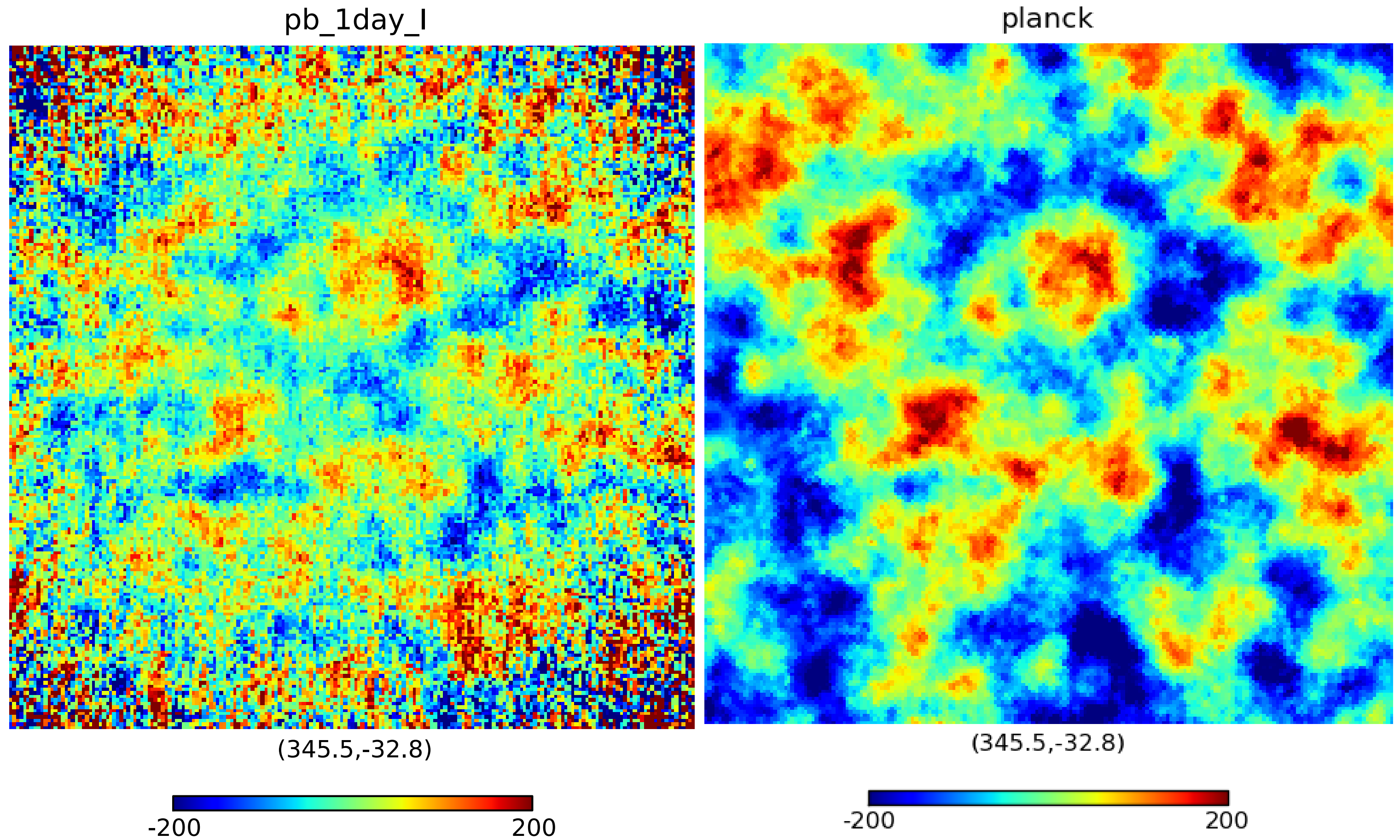


Ground-based sensitivity: POLARBEAR example

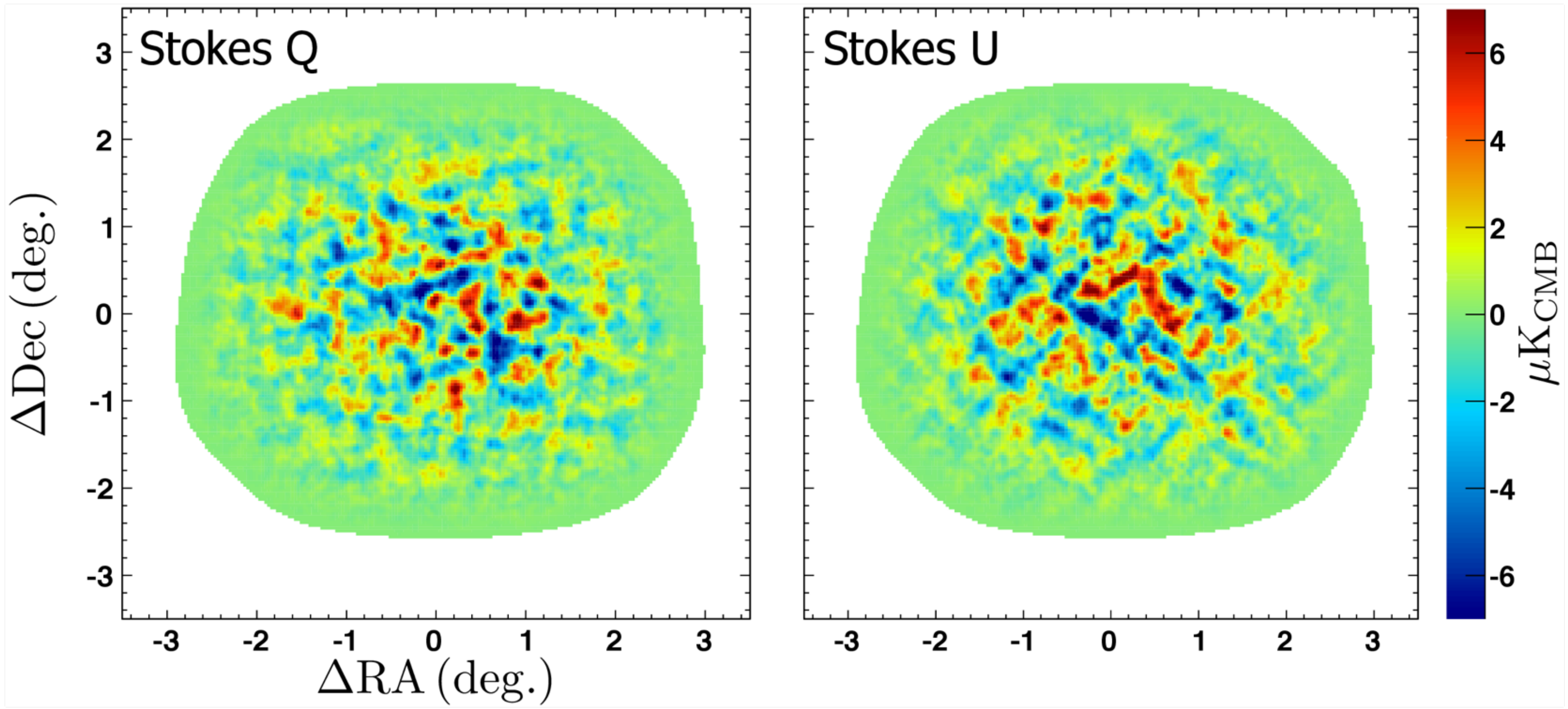
POLARBEAR collaboration 2014



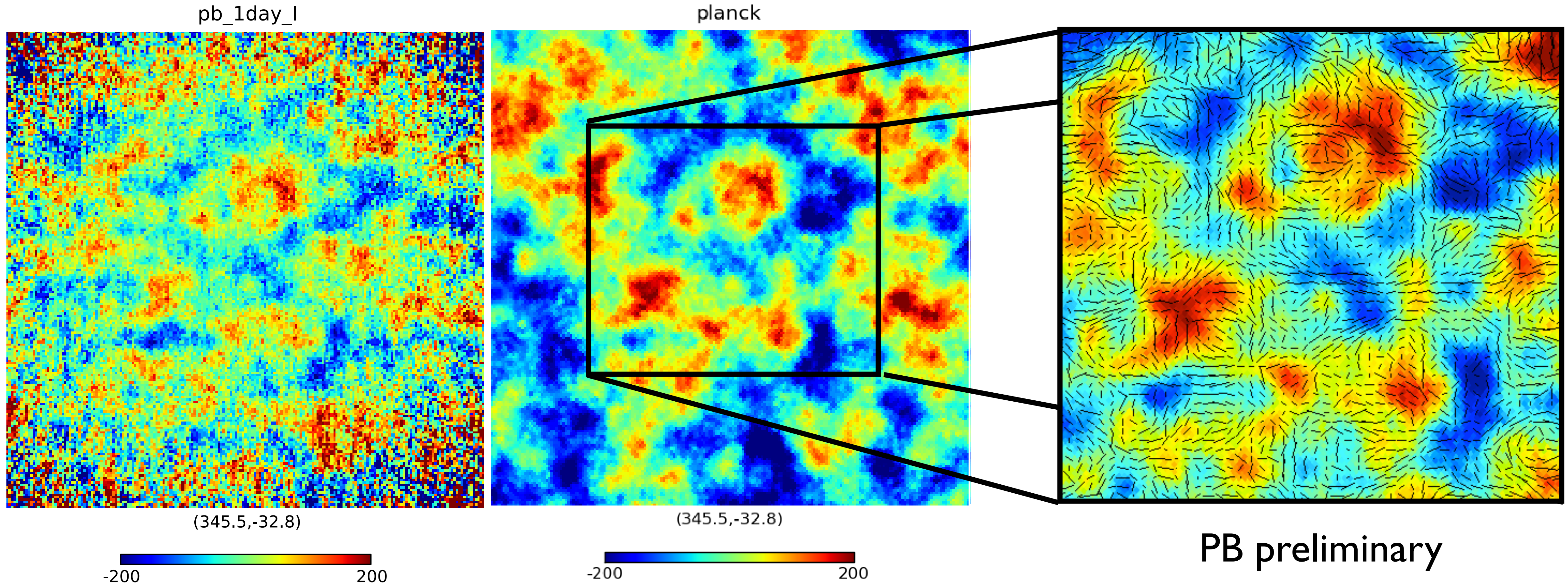
Ground-based sensitivity: POLARBEAR example



POLARBEAR collaboration 2014

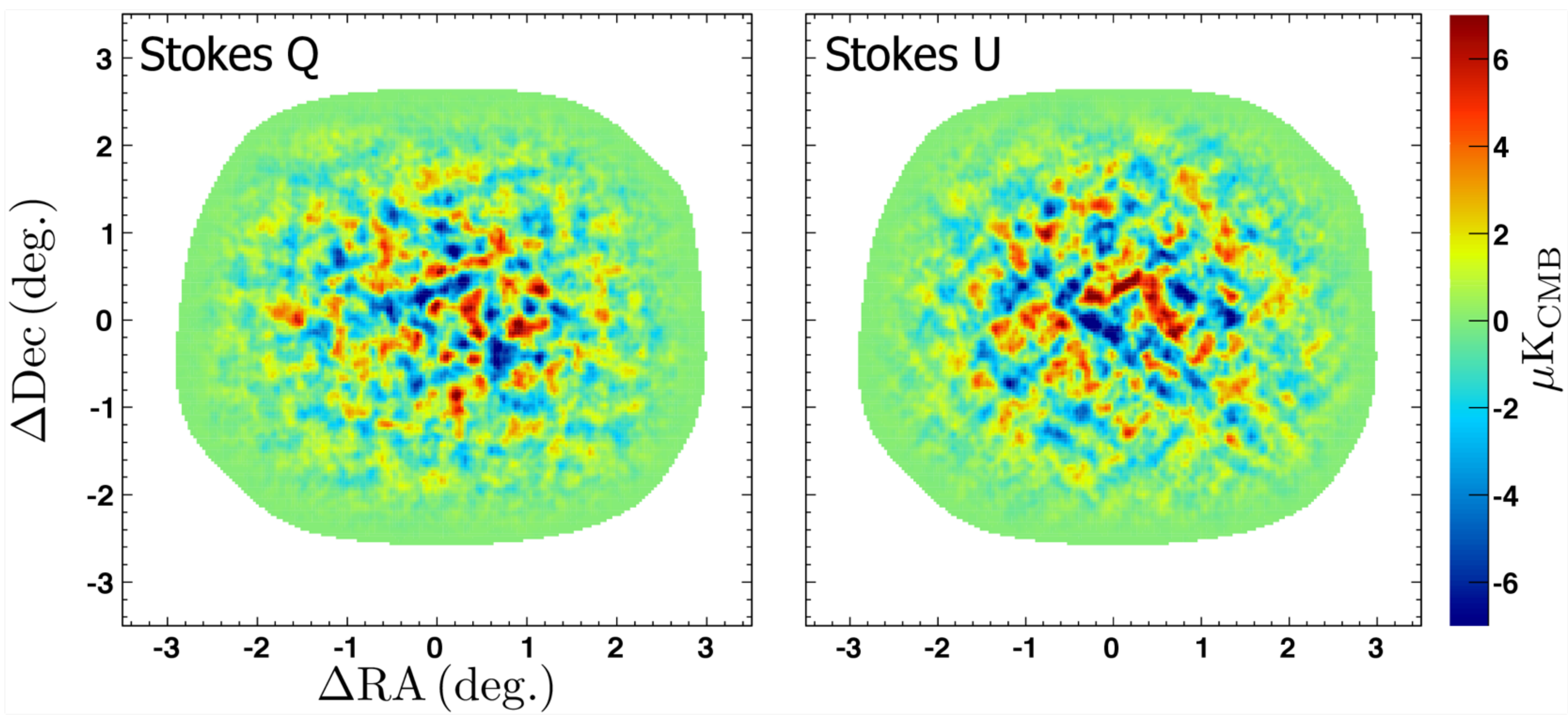


Ground-based sensitivity: POLARBEAR example



PB preliminary

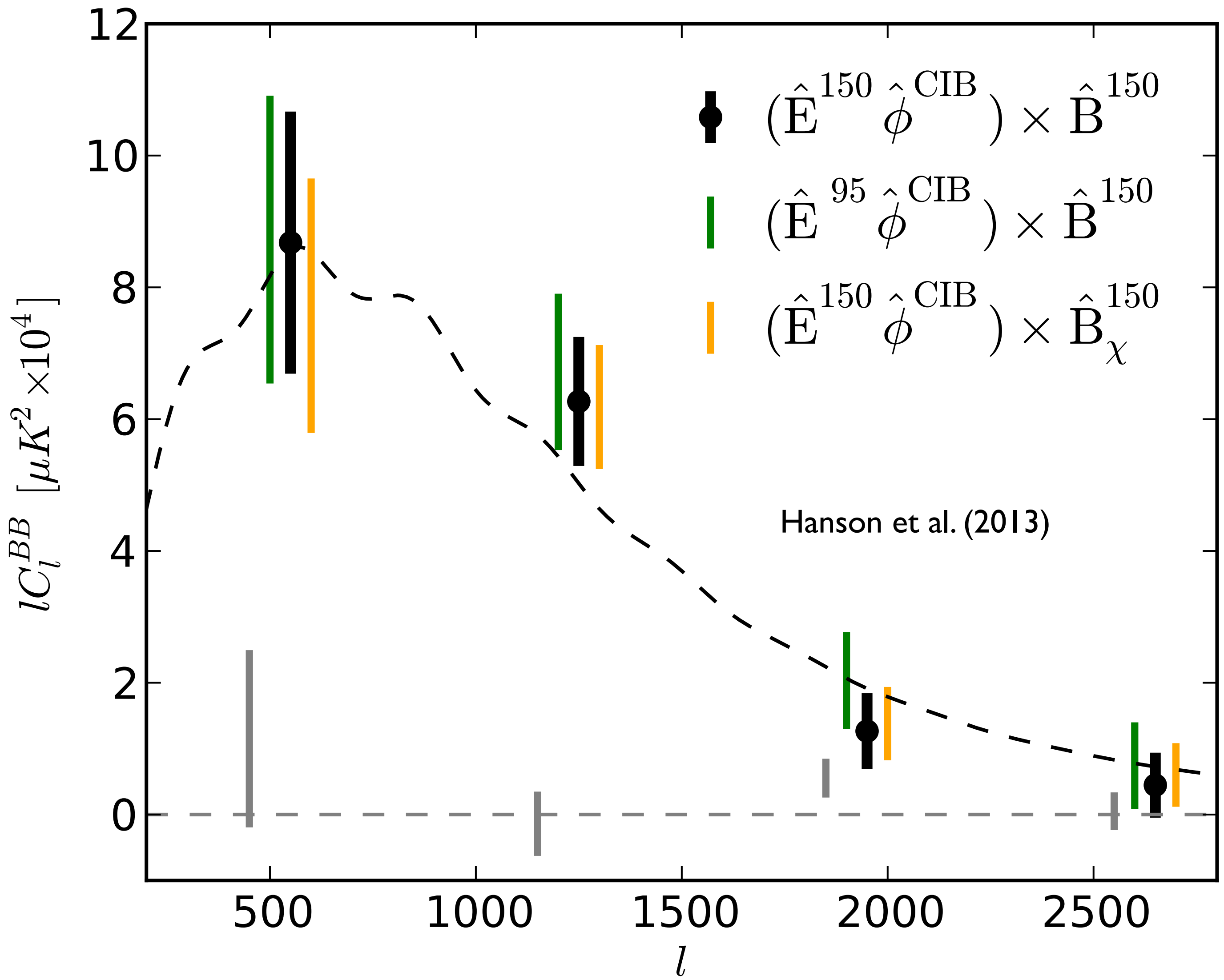
POLARBEAR collaboration 2014

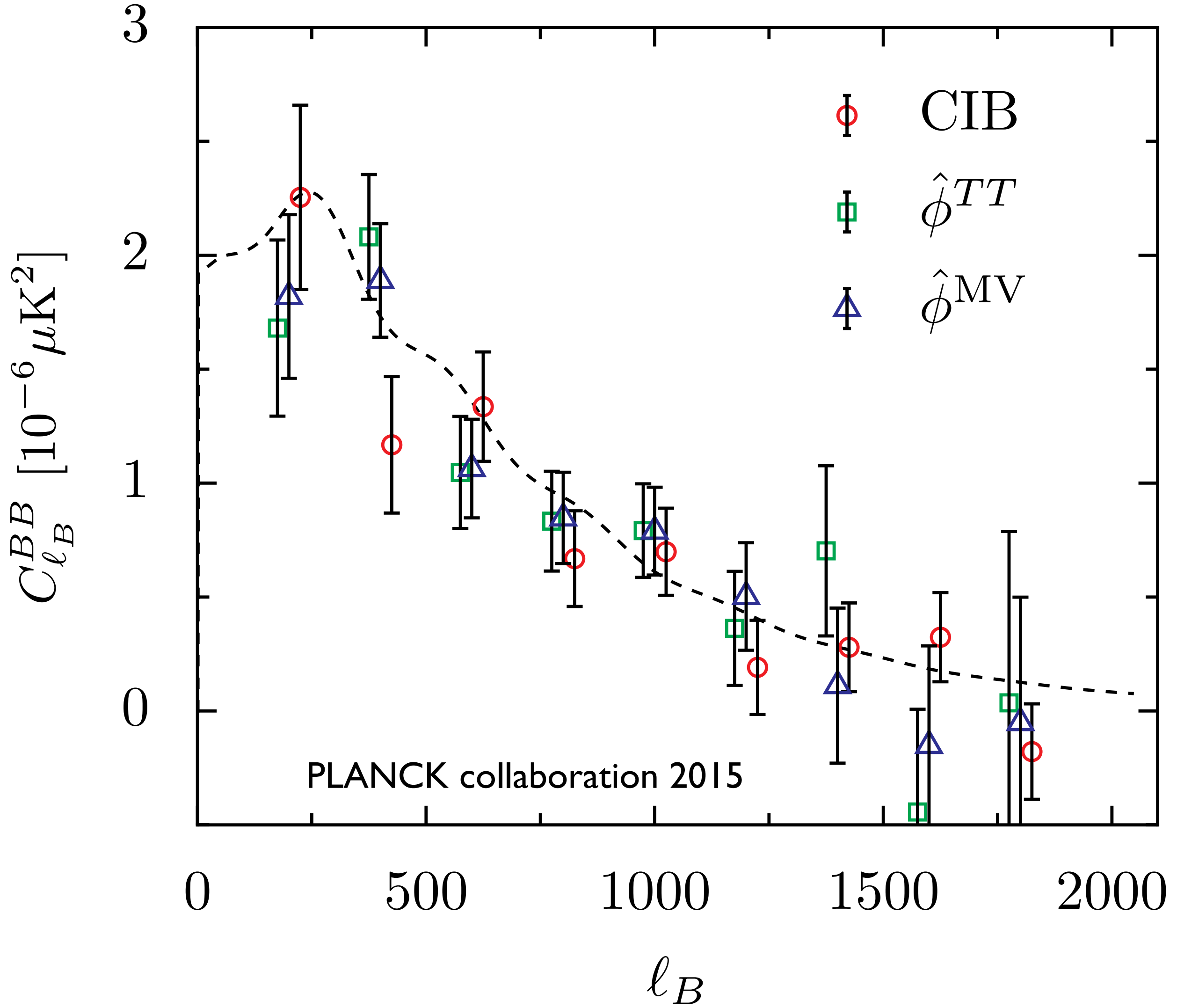


SPTpol: B-modes through cross-correlation

- Cosmic infrared background and lensing potential are correlated
- Idea: construct a noisy template of lensing B-modes and correlate with my observed B-modes hidden within noise

$$B^{\text{lens}}(\vec{l}_B) = \int d^2\vec{l_E} \int d^2\vec{l_\phi} W^\phi(\vec{l}_E, \vec{l}_B, \vec{l}_\phi) E(\vec{l}_E)\phi(\vec{l}_\phi)$$





Lensing reconstruction with polarization data

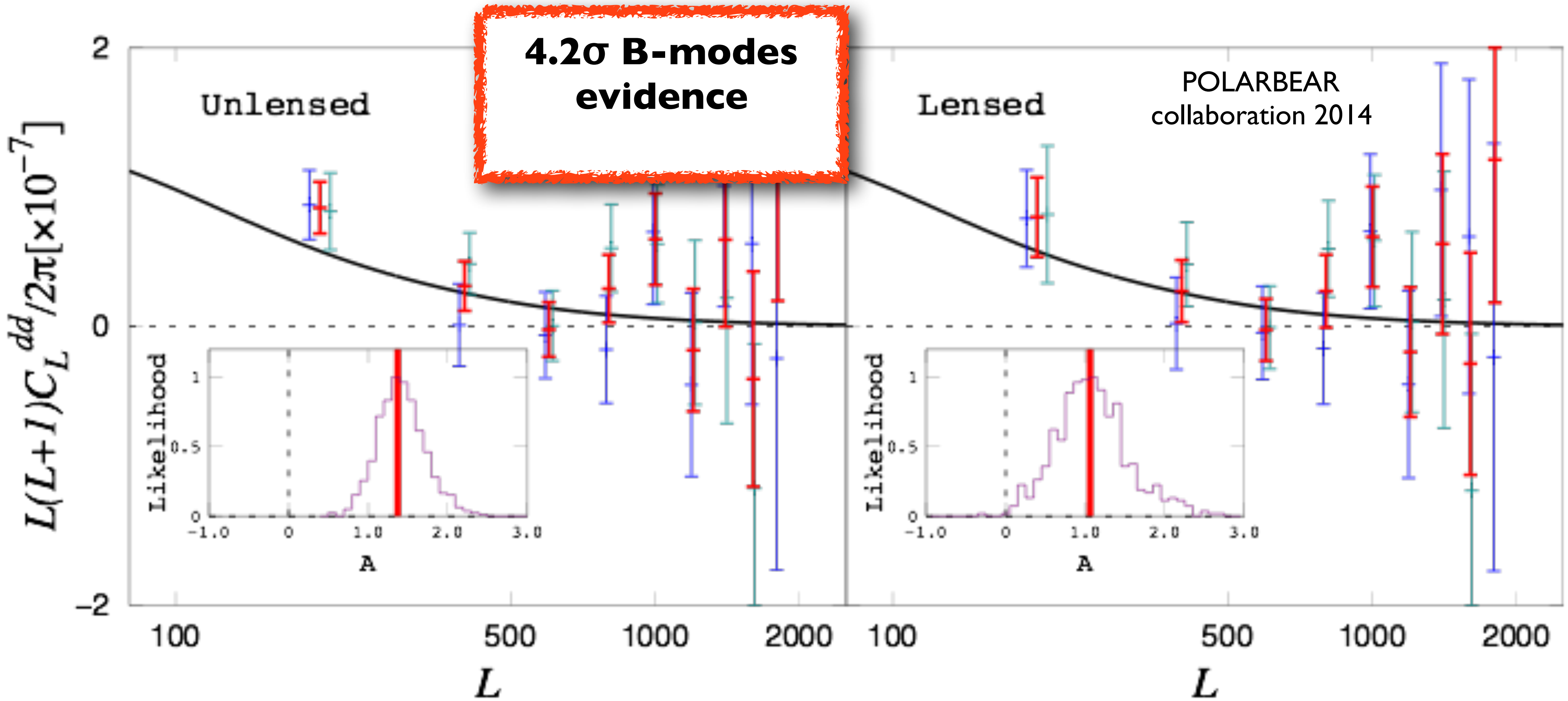
- Clean reconstruction of the deflection field from CMB polarization

$$d_{EB}(\mathbf{L}) = \frac{A_{EB}(L)}{L}\int \frac{d^2\mathbf{l}}{(2\pi)^2}E(\mathbf{l})B(\mathbf{l}')\frac{\tilde{C}_l^{EE}\mathbf{L}\cdot\mathbf{l}}{C_l^{EE}C_{l'}^{BB}}\sin 2\phi_{\mathbf{l}\mathbf{l}'}$$

$$\boldsymbol{d} = \nabla\phi$$

$$d_{EE}(\mathbf{L}) = \frac{A_{EE}(L)}{L}\int \frac{d^2\mathbf{l}}{(2\pi)^2}E(\mathbf{l})E(\mathbf{l}')\frac{\tilde{C}_l^{EE}\mathbf{L}\cdot\mathbf{l}}{C_l^{EE}C_{l'}^{EE}}\cos 2\phi_{\mathbf{l}\mathbf{l}'}$$

- Detection of lensing of CMB polarization from CMB alone

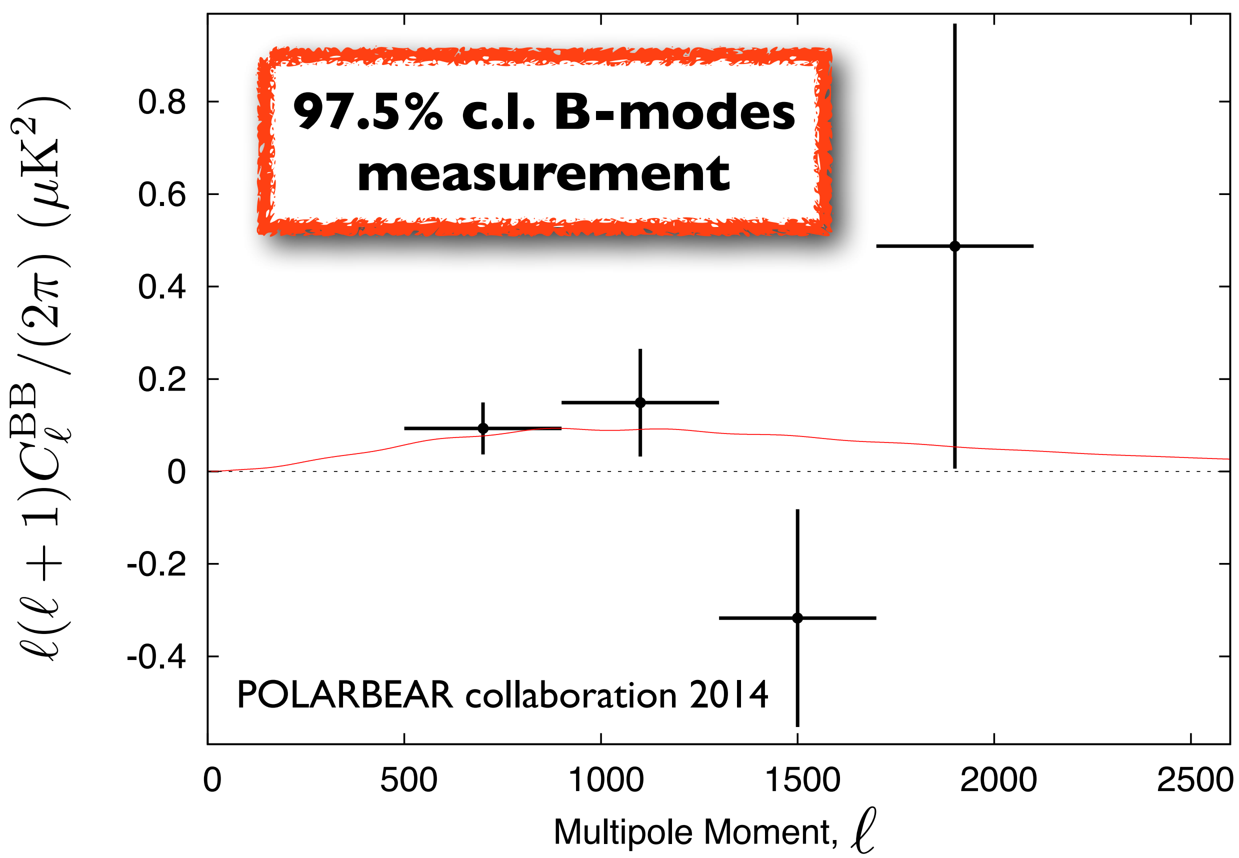


POLARBEAR direct B-modes measurement

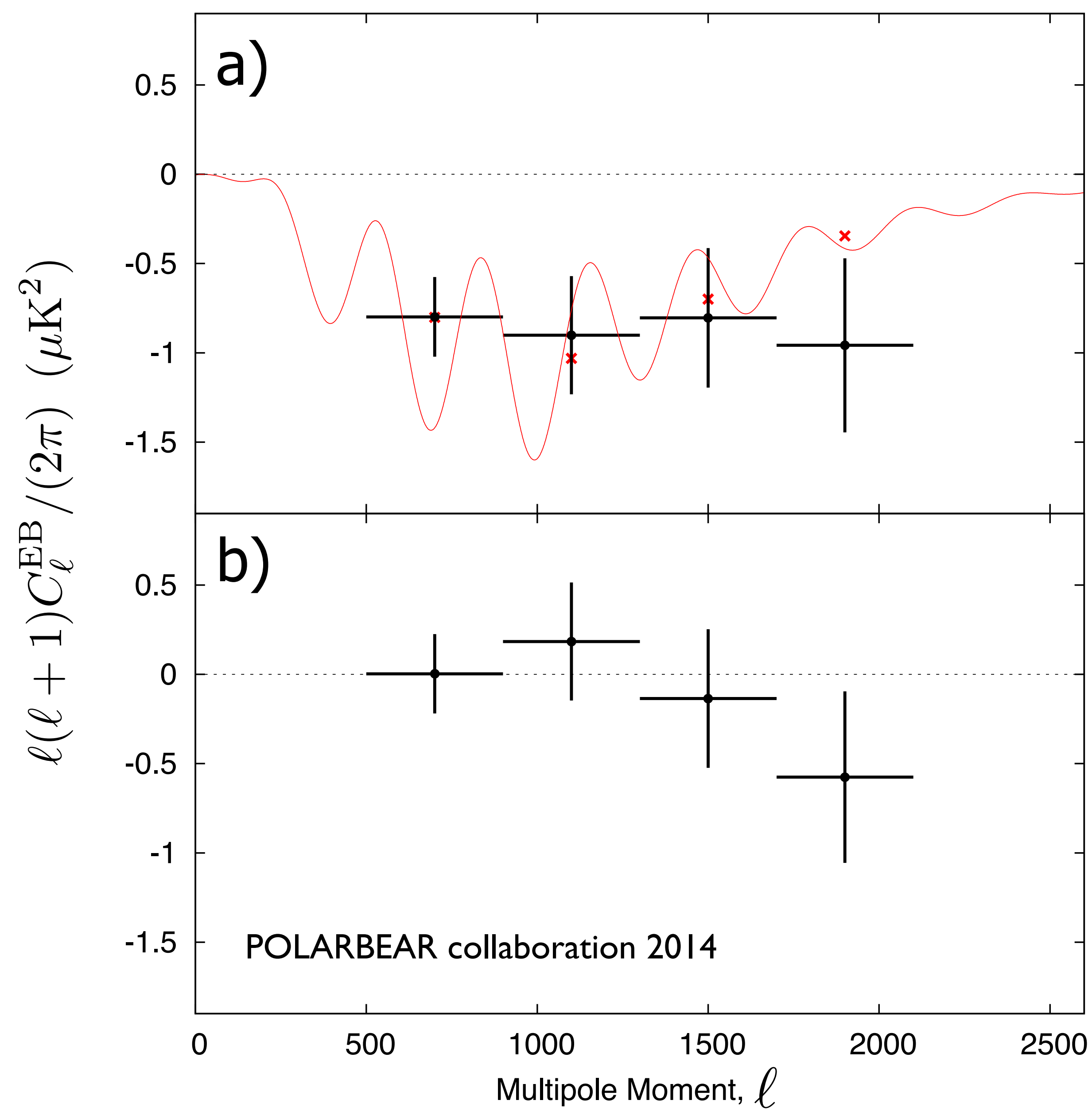
- First evidence for B-modes power spectrum (ApJ 2014)

$$A_{BB} = 1.12 \pm 0.61(\mathrm{stat})^{+0.04}_{-0.10}(\mathrm{sys}) \pm 0.07(\mathrm{multi})$$

- Polarization angle self-calibration from detected EB power (~1deg)

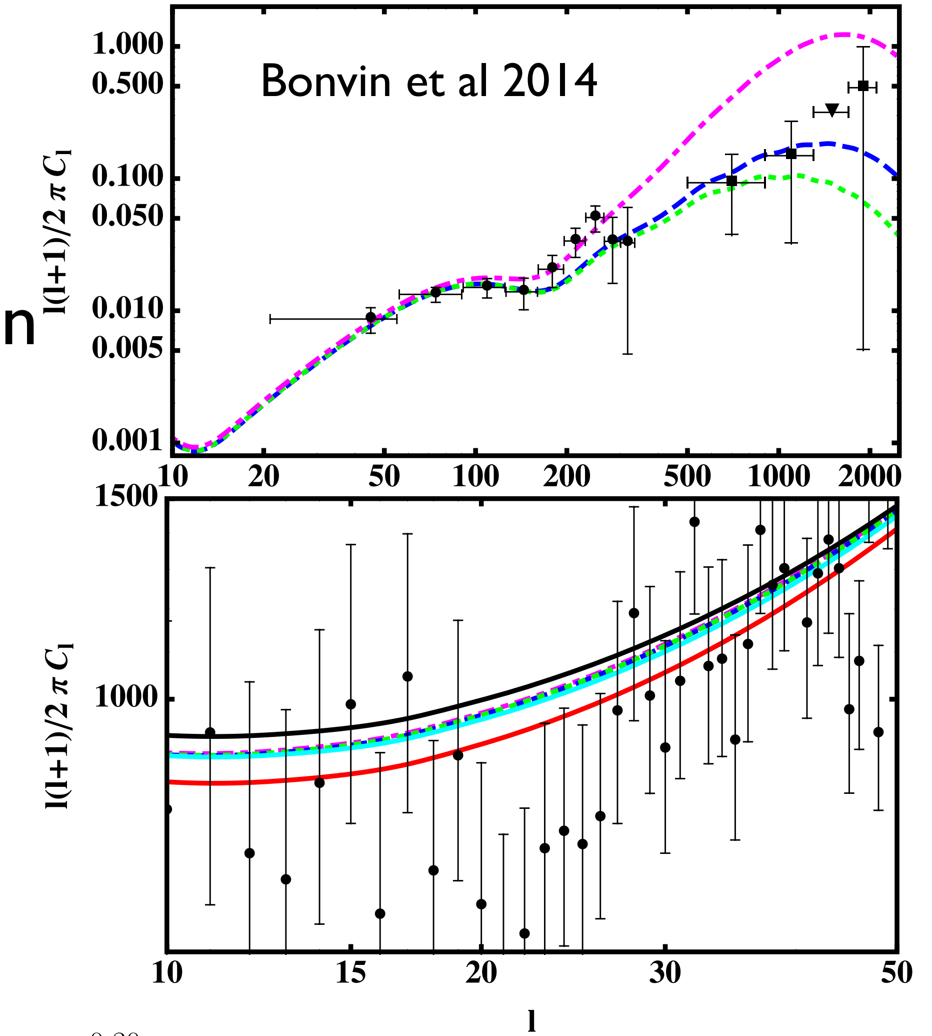


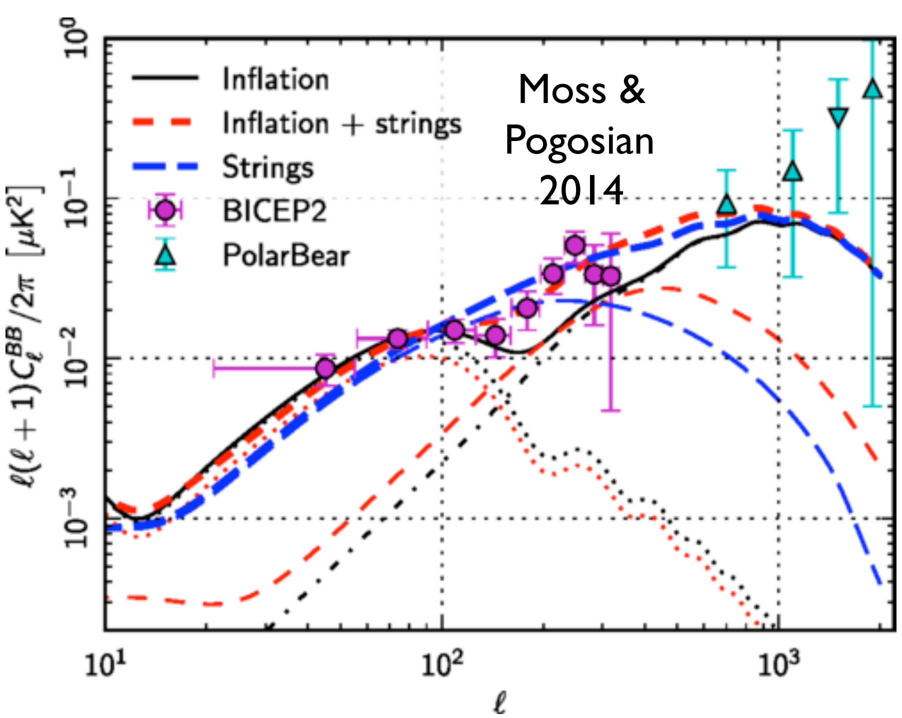
$$
\begin{aligned}
C_\ell^{EE} &= \sin^2(2\Delta\psi)\tilde{C}_\ell^{BB} + \cos^2(2\Delta\psi)\tilde{C}_\ell^{EE} \\
C_\ell^{EB} &= \frac{1}{2}\sin(4\Delta\psi)(\tilde{C}_\ell^{BB} - \tilde{C}_\ell^{EE}) \\
C_\ell^{TB} &= -\sin(2\Delta\psi)\tilde{C}_\ell^{TE} \\
C_\ell^{BB} &= \cos^2(2\Delta\psi)\tilde{C}_\ell^{BB} + \sin^2(2\Delta\psi)\tilde{C}_\ell^{EE}
\end{aligned}
$$

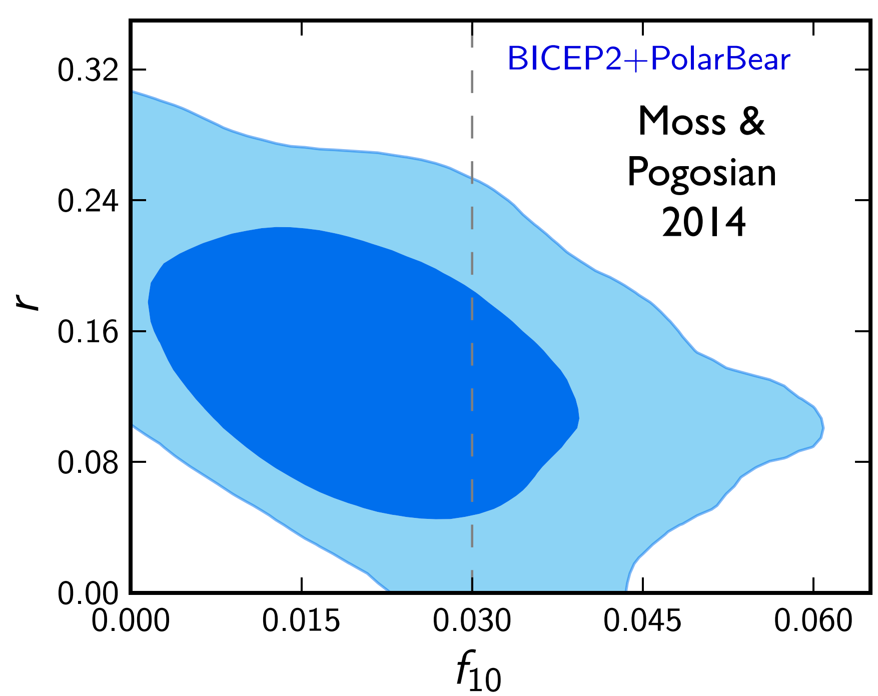


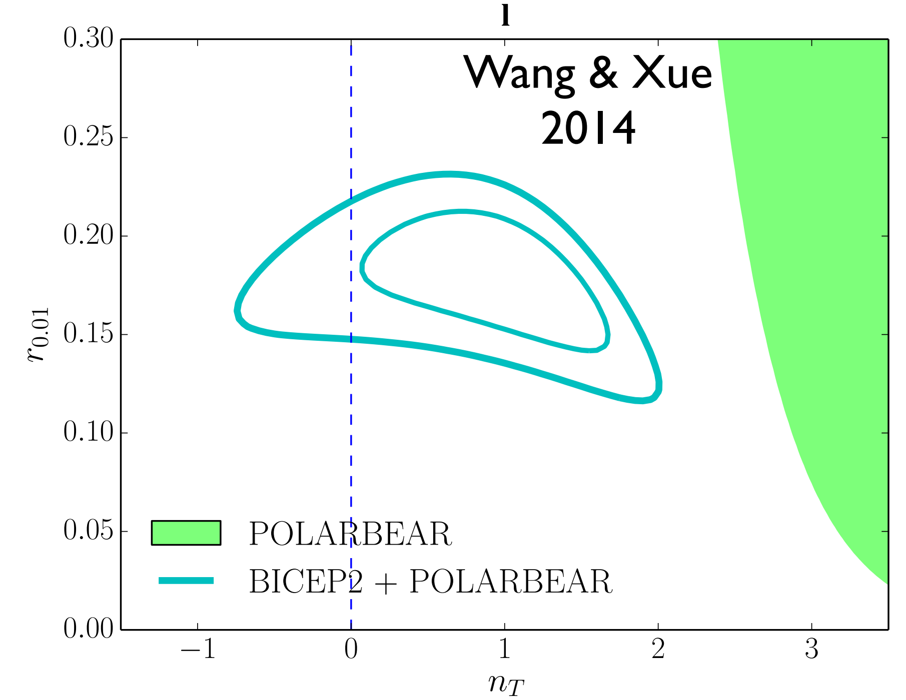
Cosmological constraints with B-modes

- Constraints on inflationary magnetogenesis: compatible with lower r and blue tensor spectra
- Cosmic defects / vector plus tensor modes can explain data but rule out local strings
- Alternatives to inflation can be tightly constrained:
  - string gas cosmology with blue tensor spectrum
  - slow roll or null energy condition violation etc....

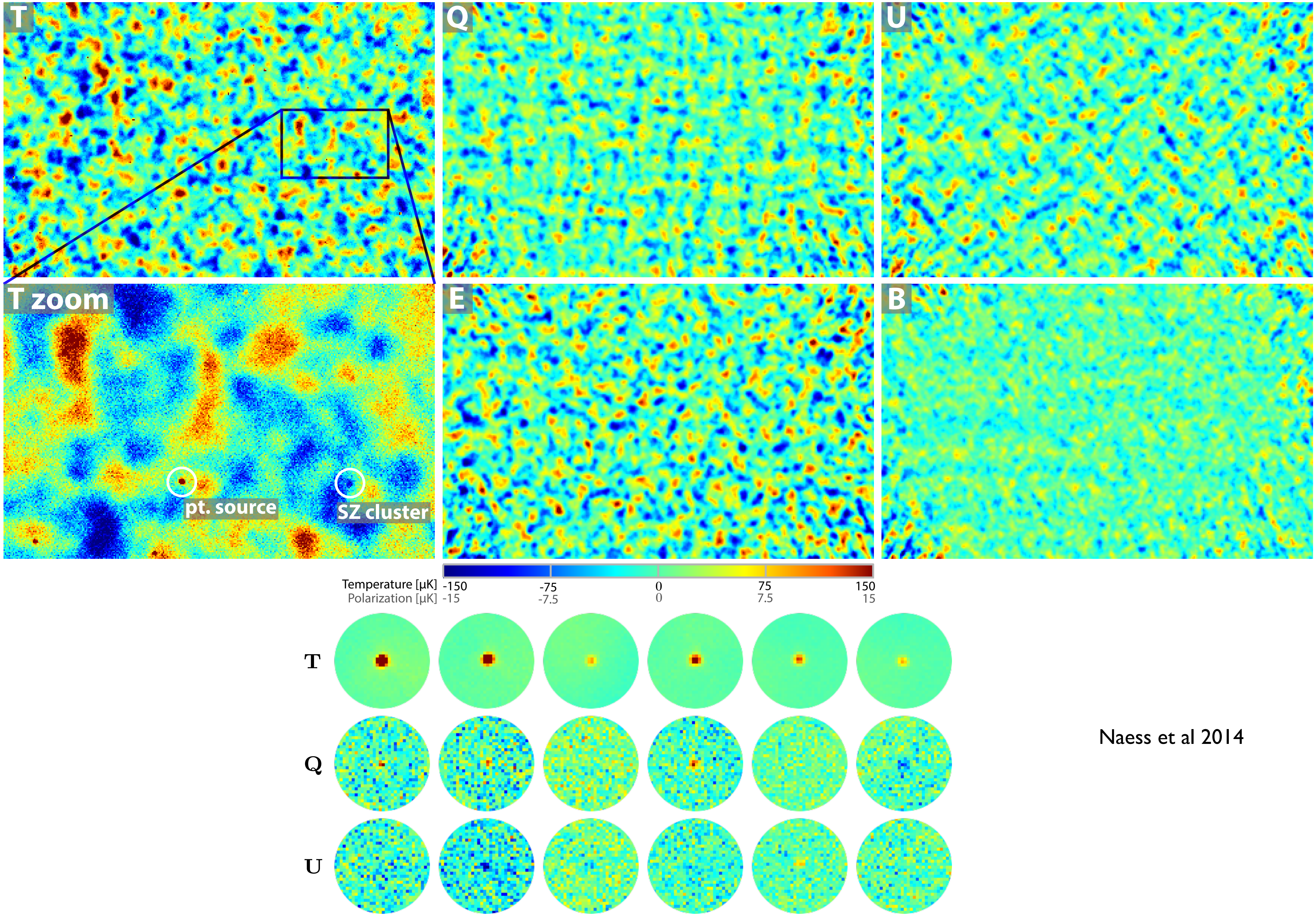








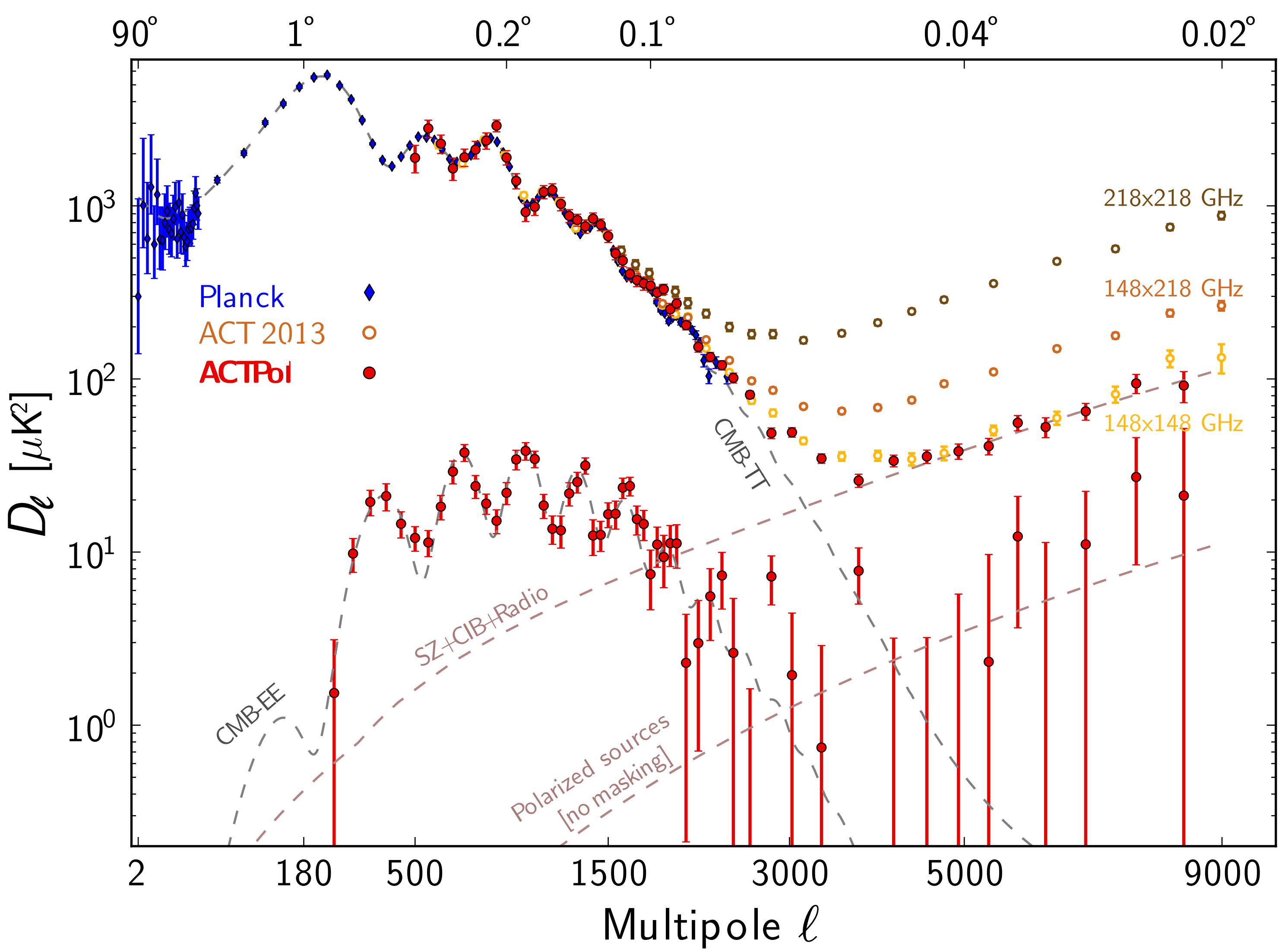
ACTpol results I (148 GHz)

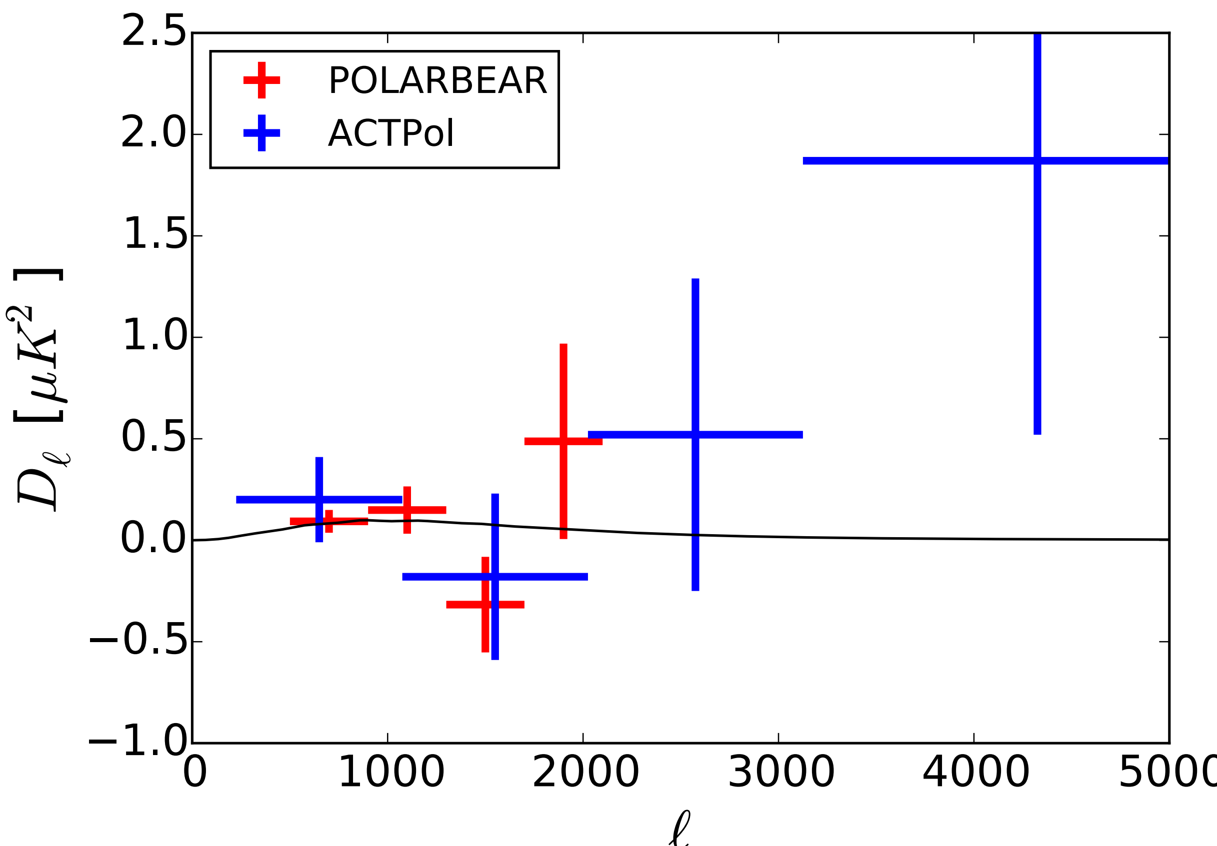


Naess et al 2014

ACTpol results II (148GHz)

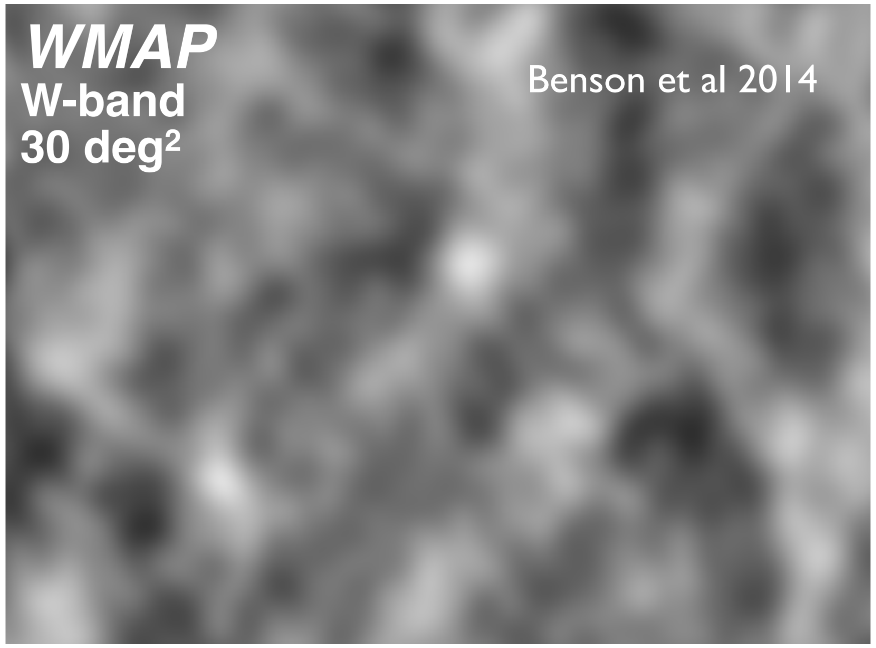
- High resolution allows constraining diffuse polarized emission from astrophysical sources
- No B-modes constraints reported yet





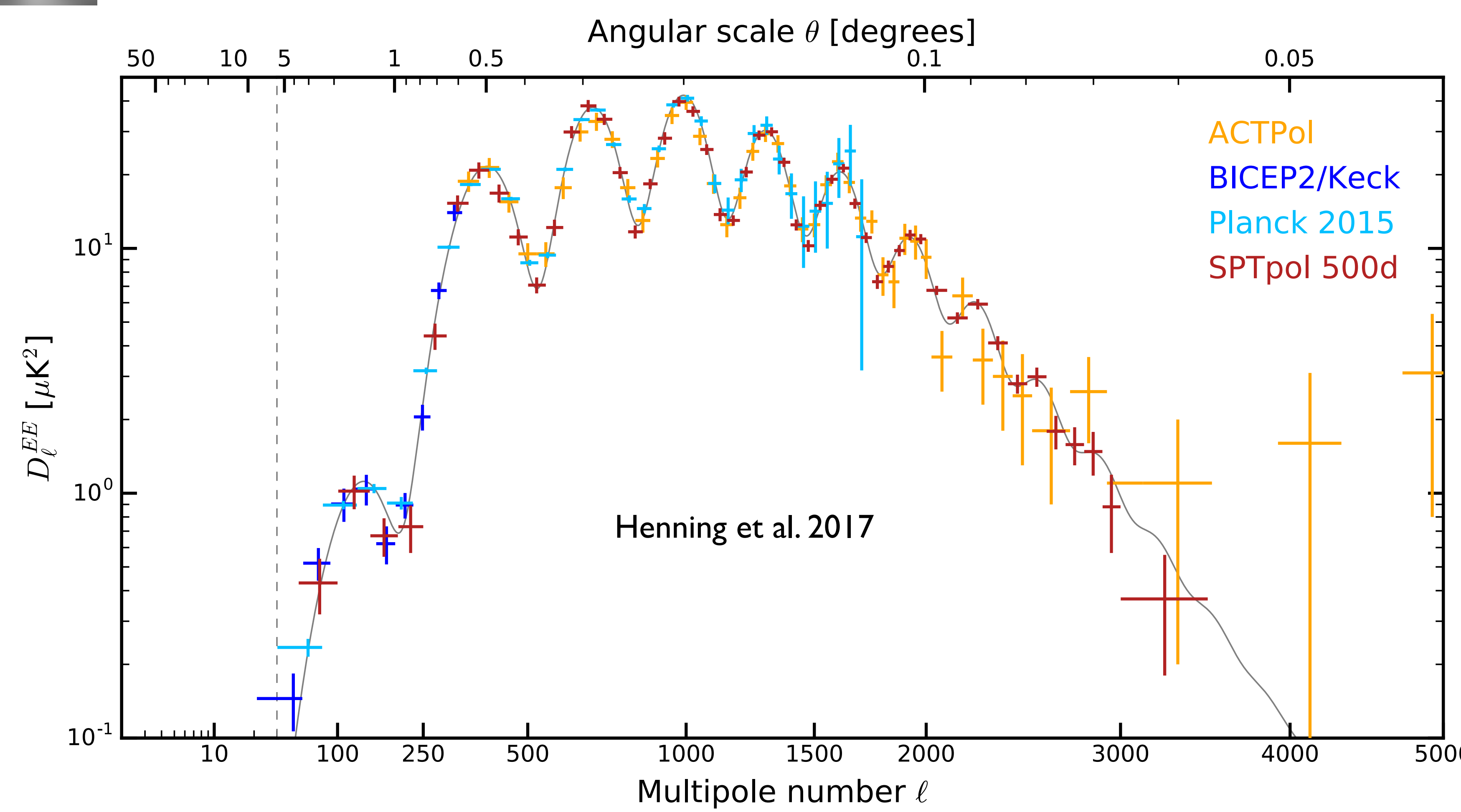
Naess et al 2014

SPTpol results

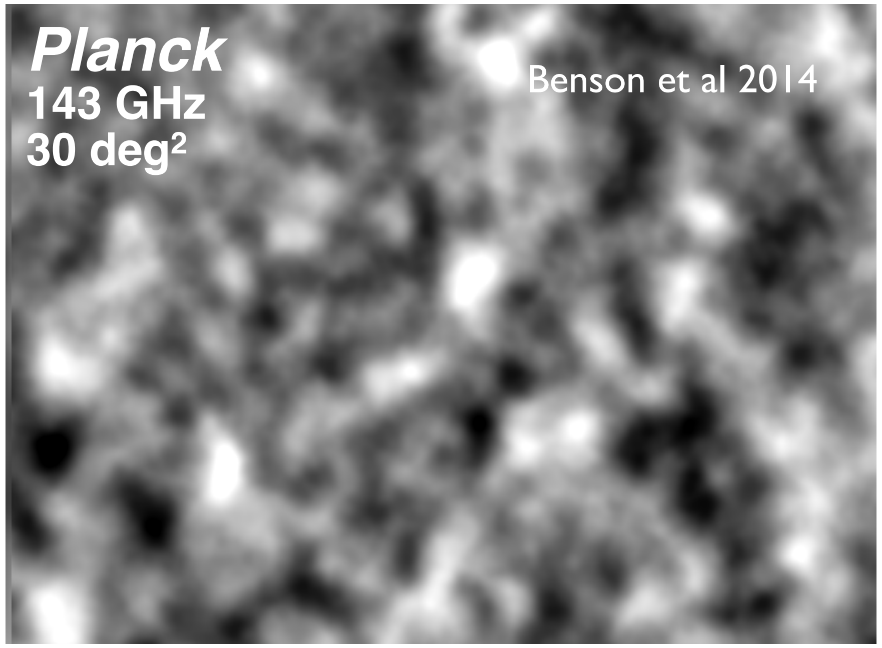


- Highest resolution among current experiment (1arcmin)
- Cluster science together with CMB science
- No direct B-modes measurement reported

Benson et al 2014



SPTpol results



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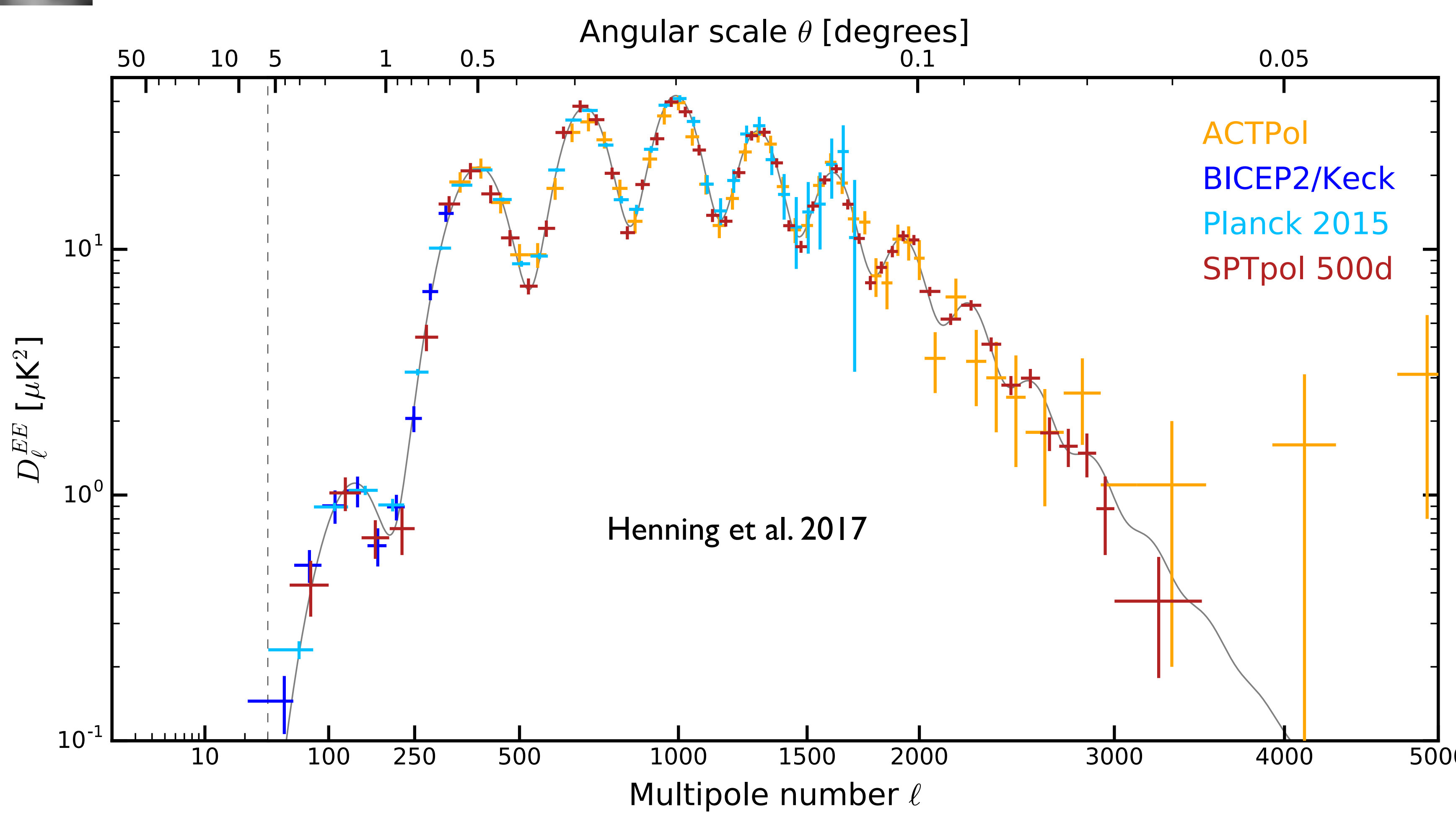
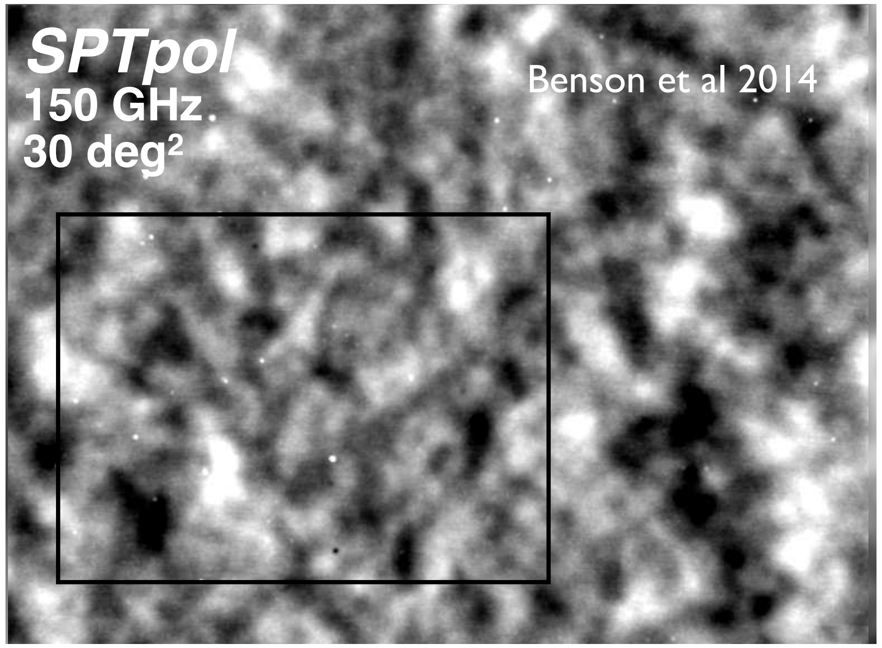
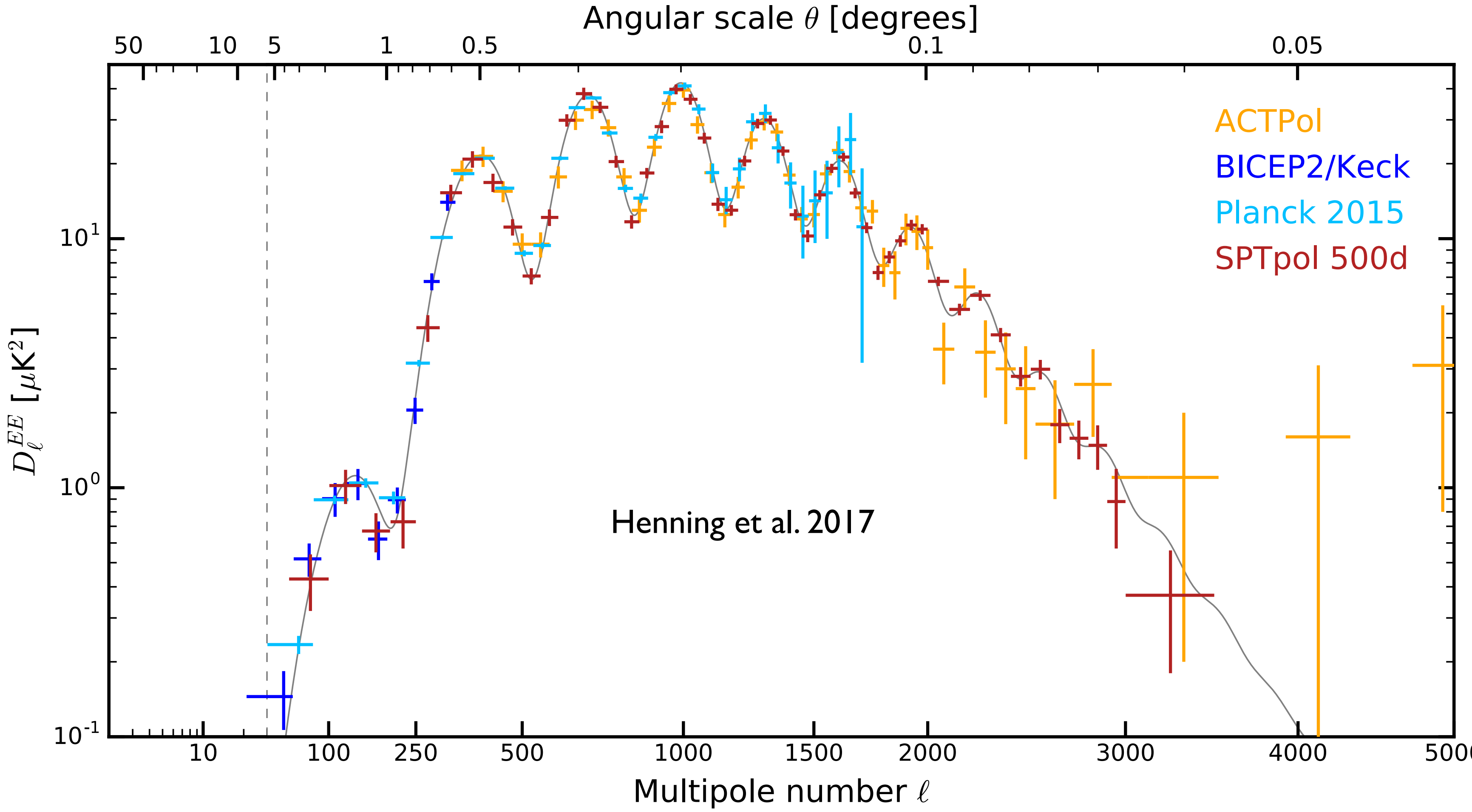
Benson et al 2014



SPTpol results



Benson et al 2014



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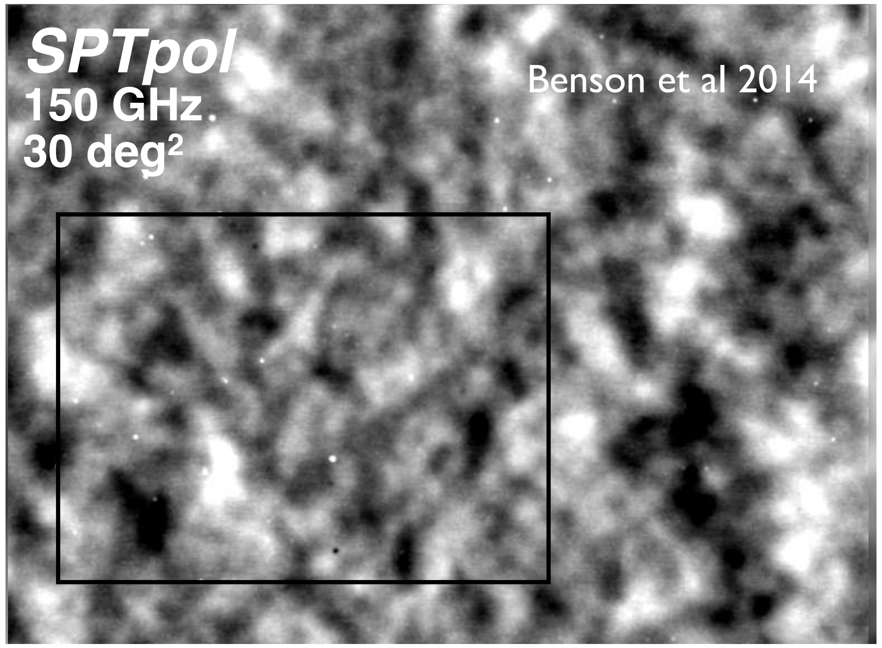

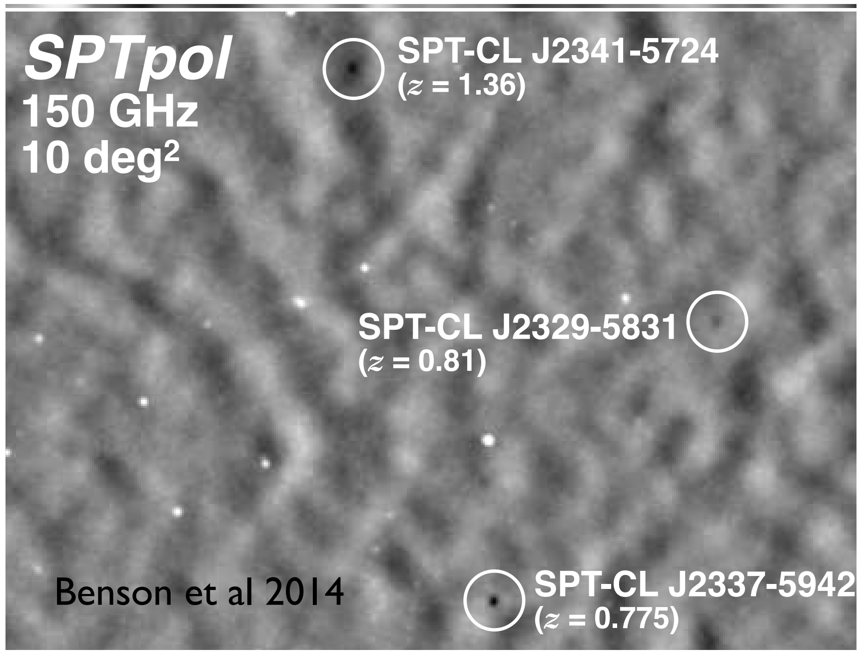

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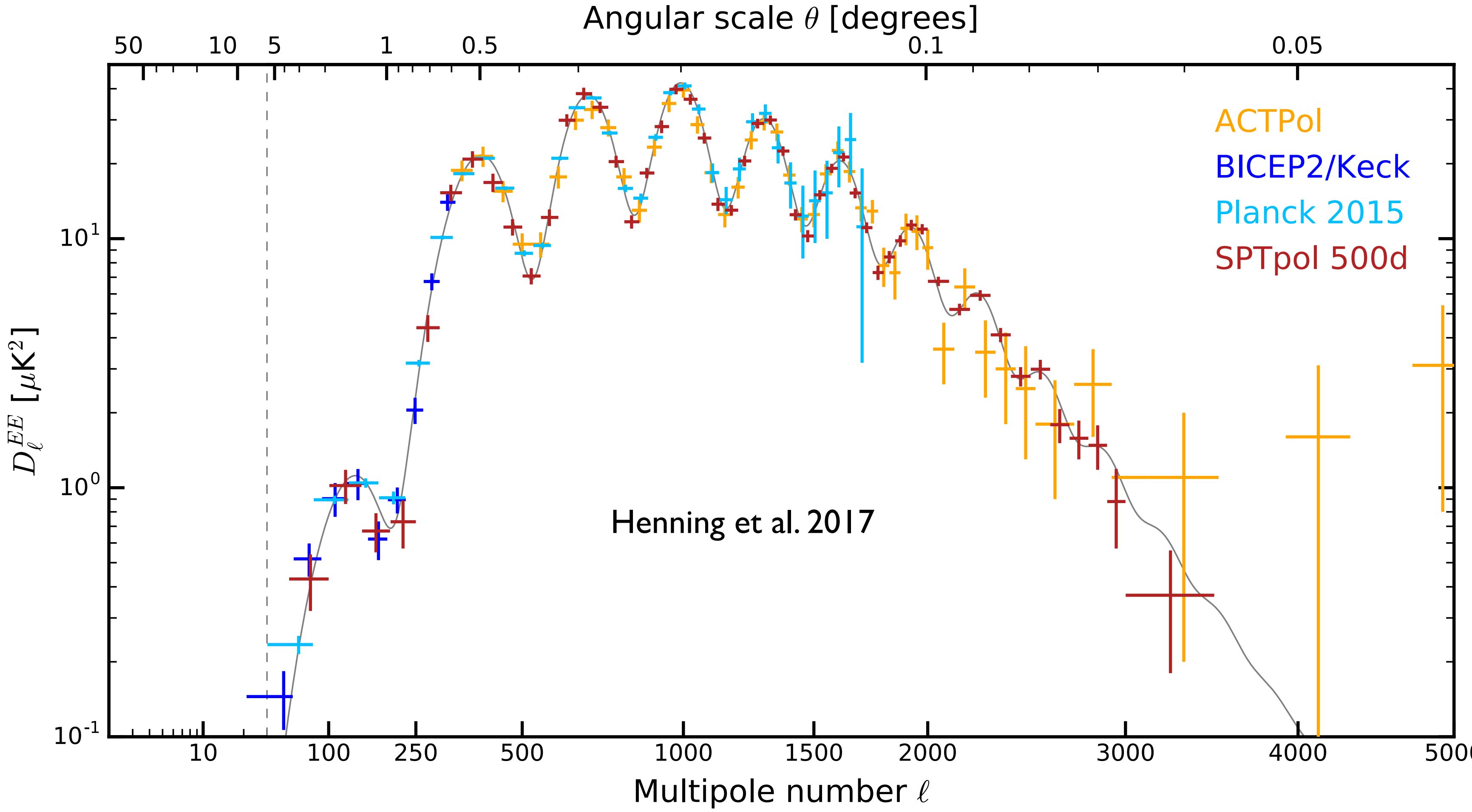
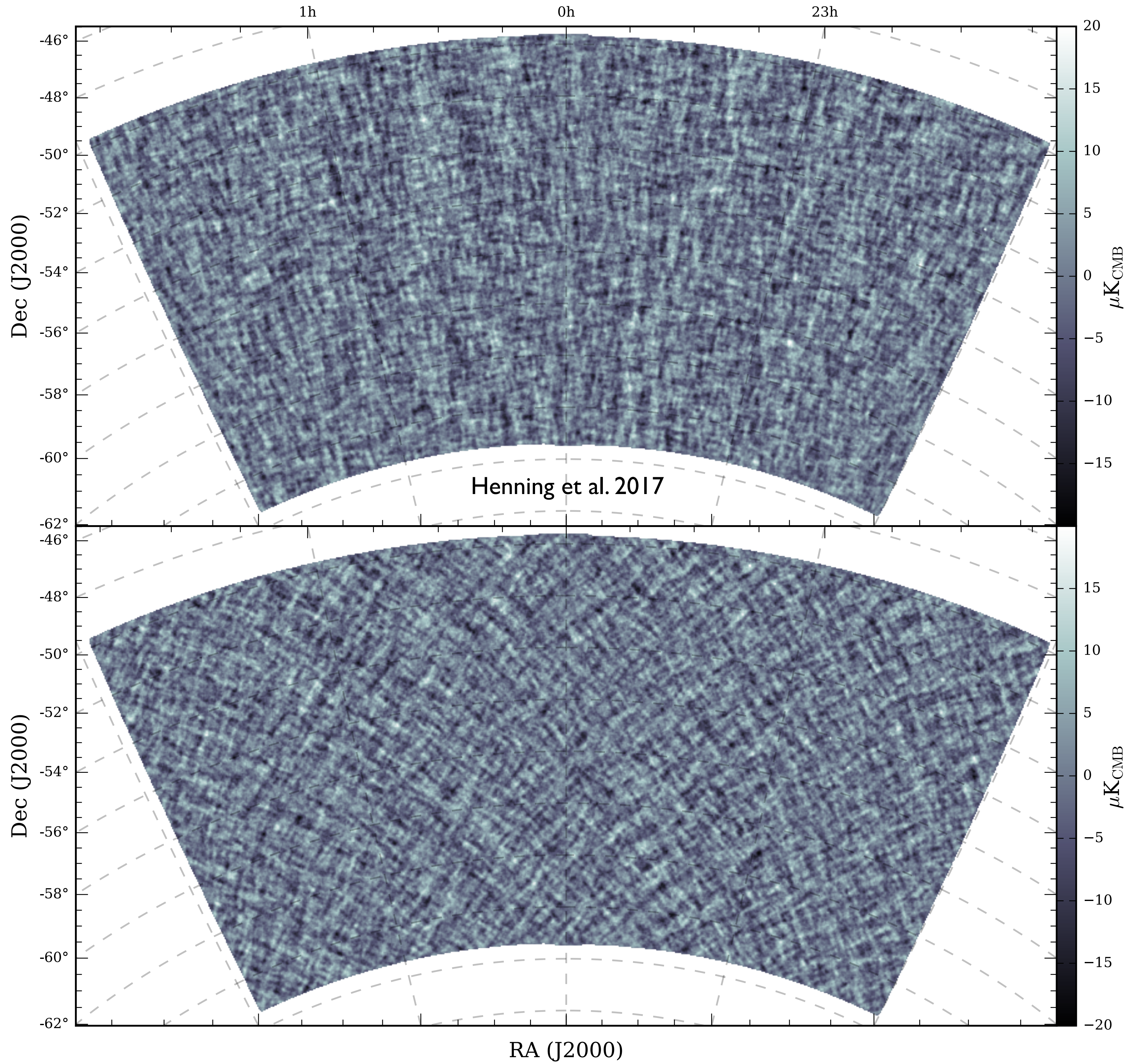
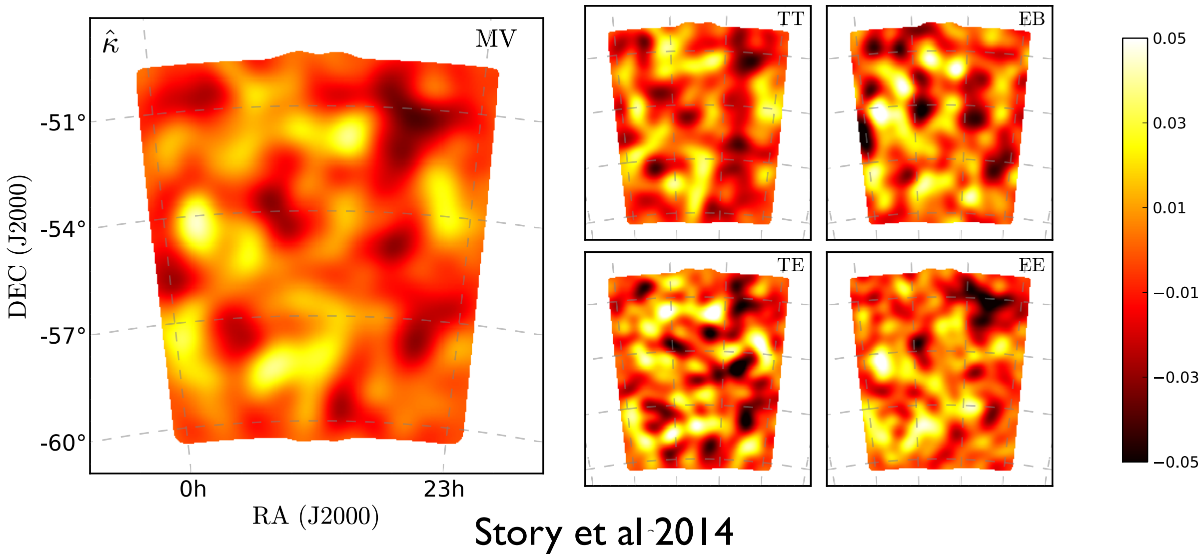


SPTpol maps 2017

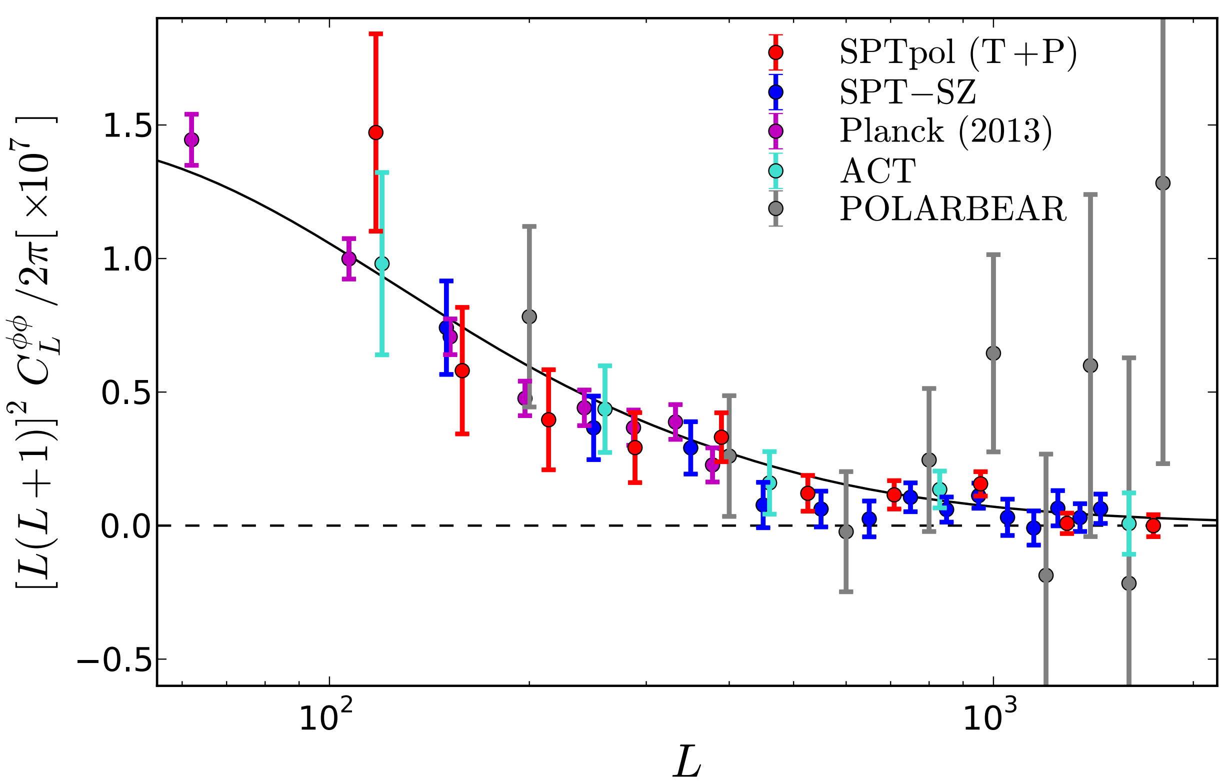


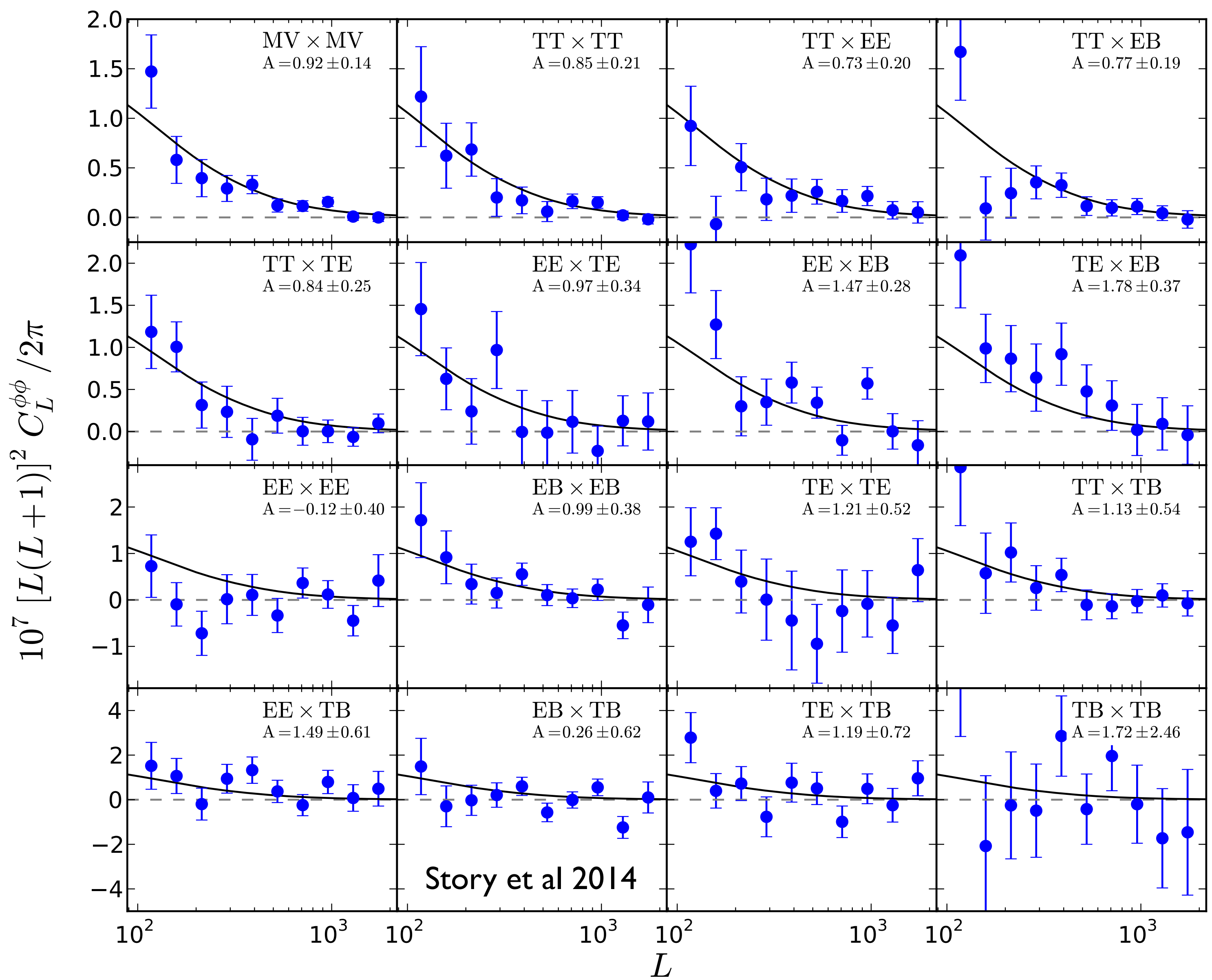
SPTpol lensing results

- Lensing reconstruction with polarization (still dominated by temperature sensitivity)



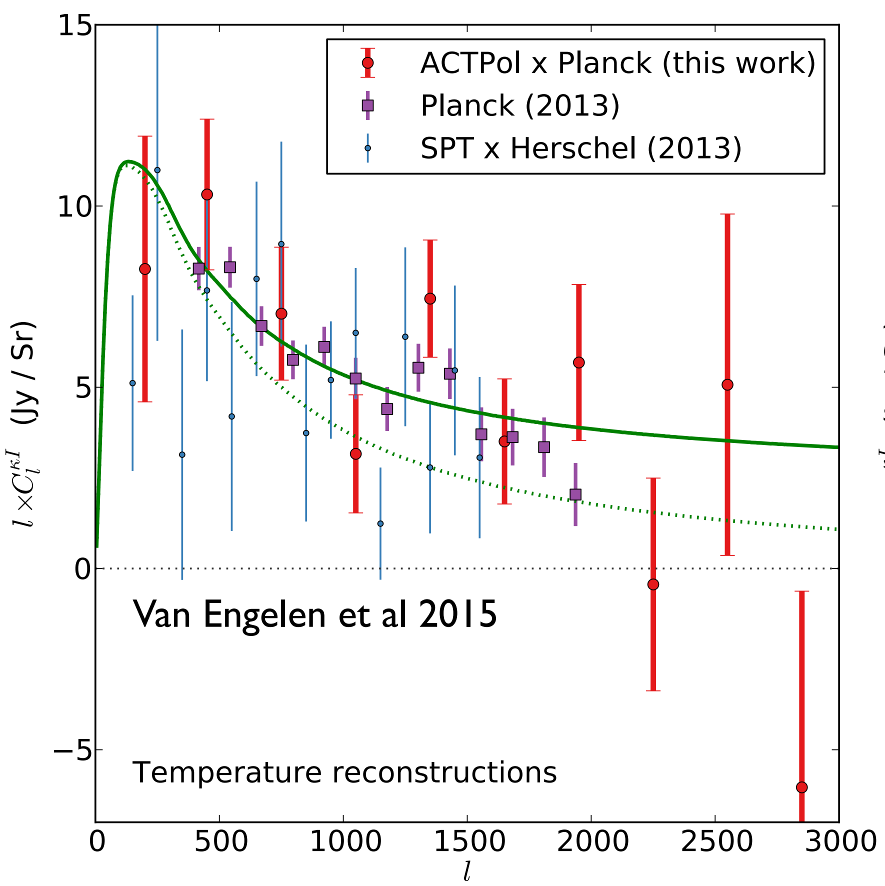
Story et al 2014

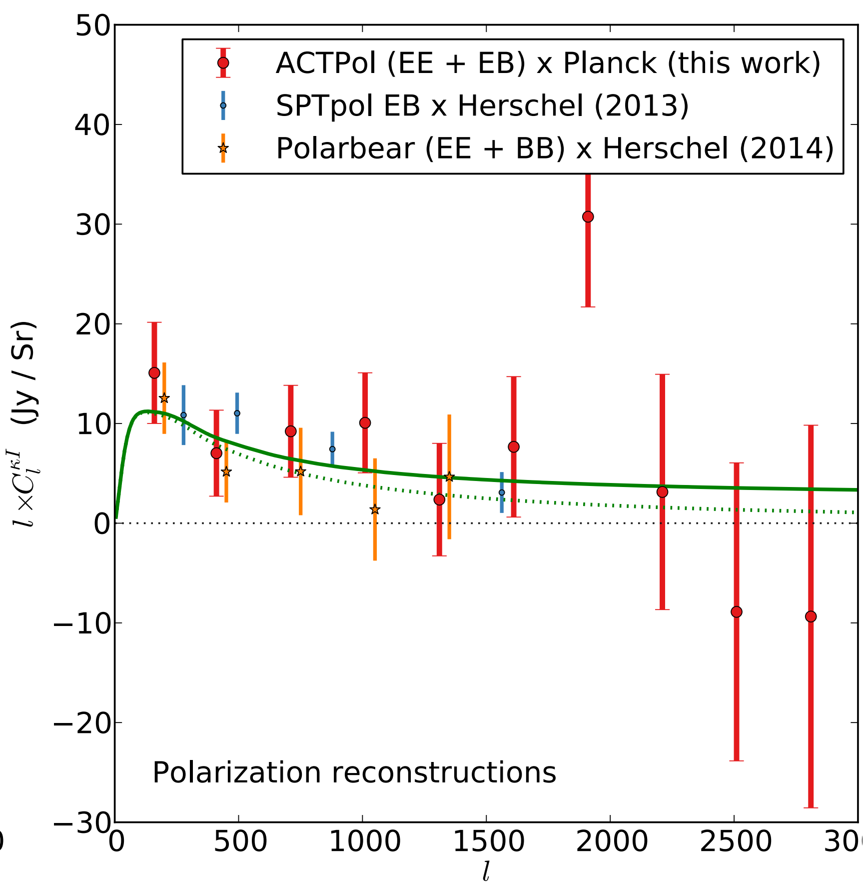


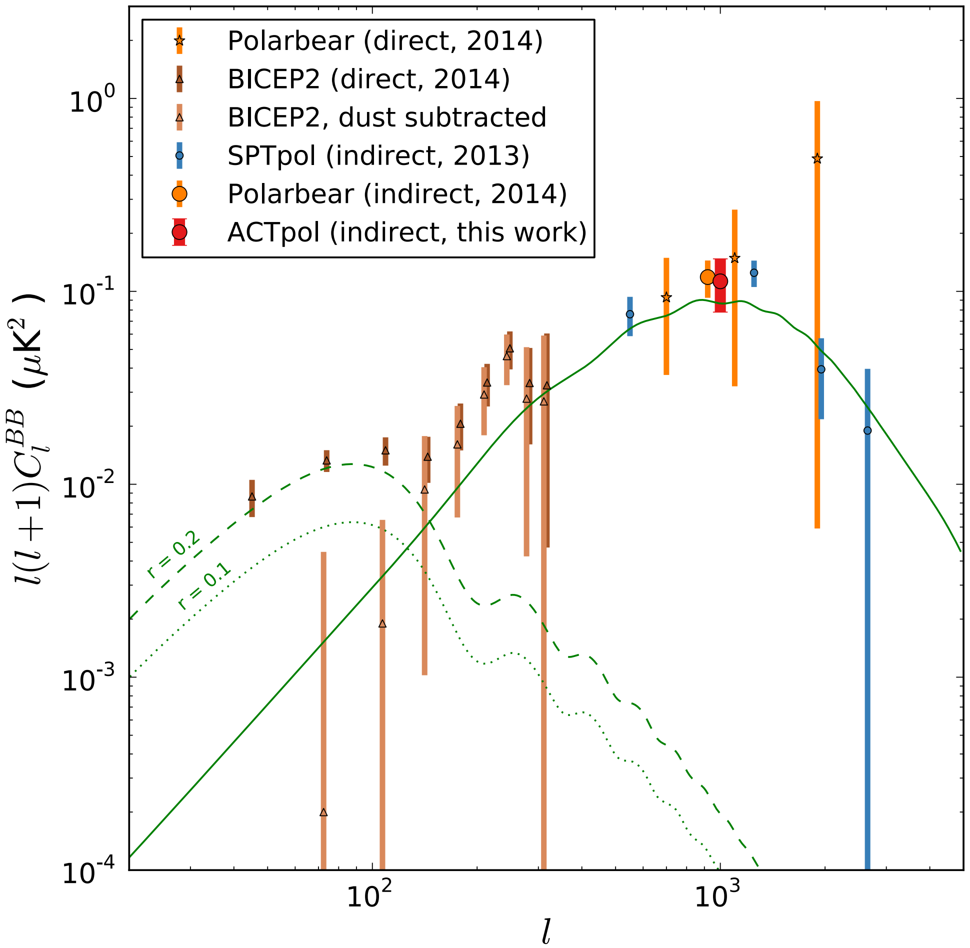


ACTpol lensing results

- Lensing reconstruction using temperature and polarization
- Cross-correlation with Planck CIB at small angular scales, additional constraints for CIB model at small angular scales
- Indirect constraints of lensing B-modes consistent with POLARBEAR and SPTpol results

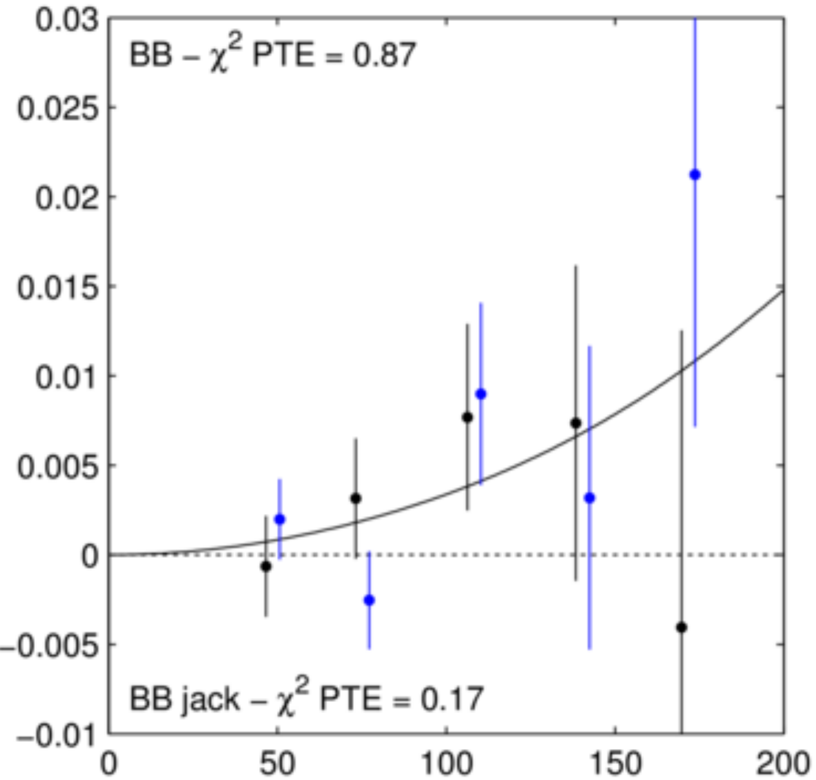




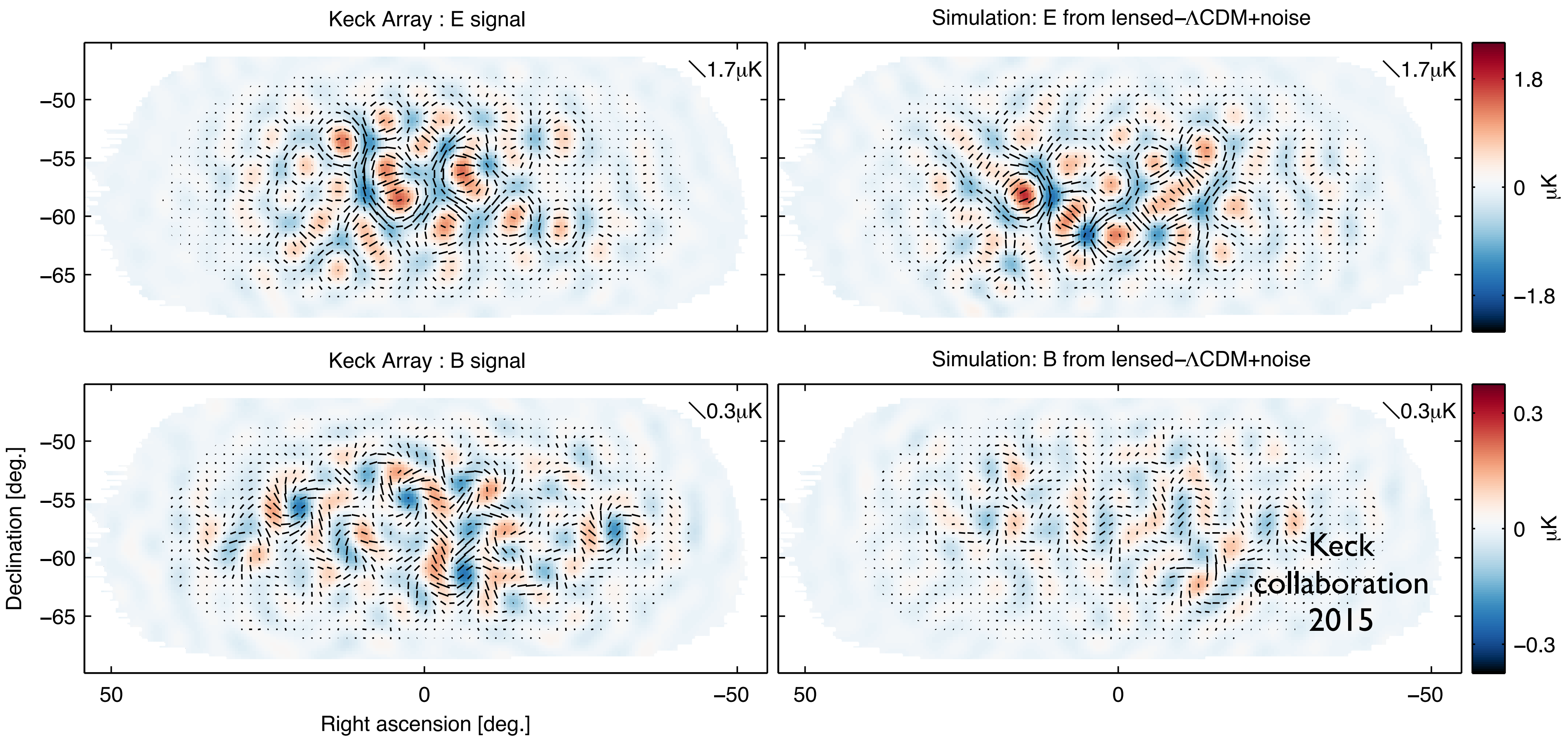


BICEP2/Keck

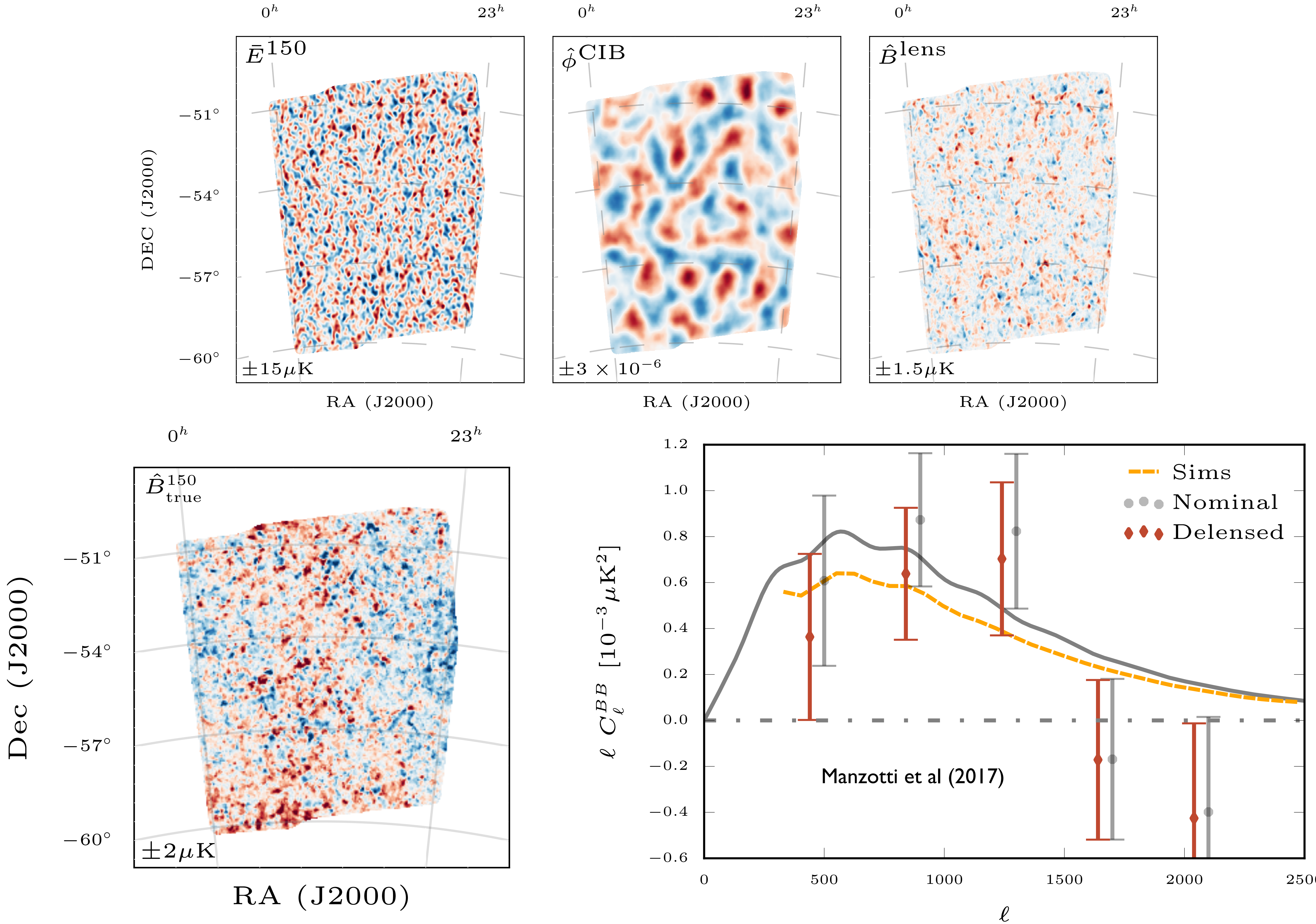
- Dedicated to large scale polarization, series of subsequent upgrades (BICEP1, 2, Keck, 3)
- Reported evidence of B-modes at first interpreted by primordial GW r=0.2



BICEP2/Keck collaboration 2017

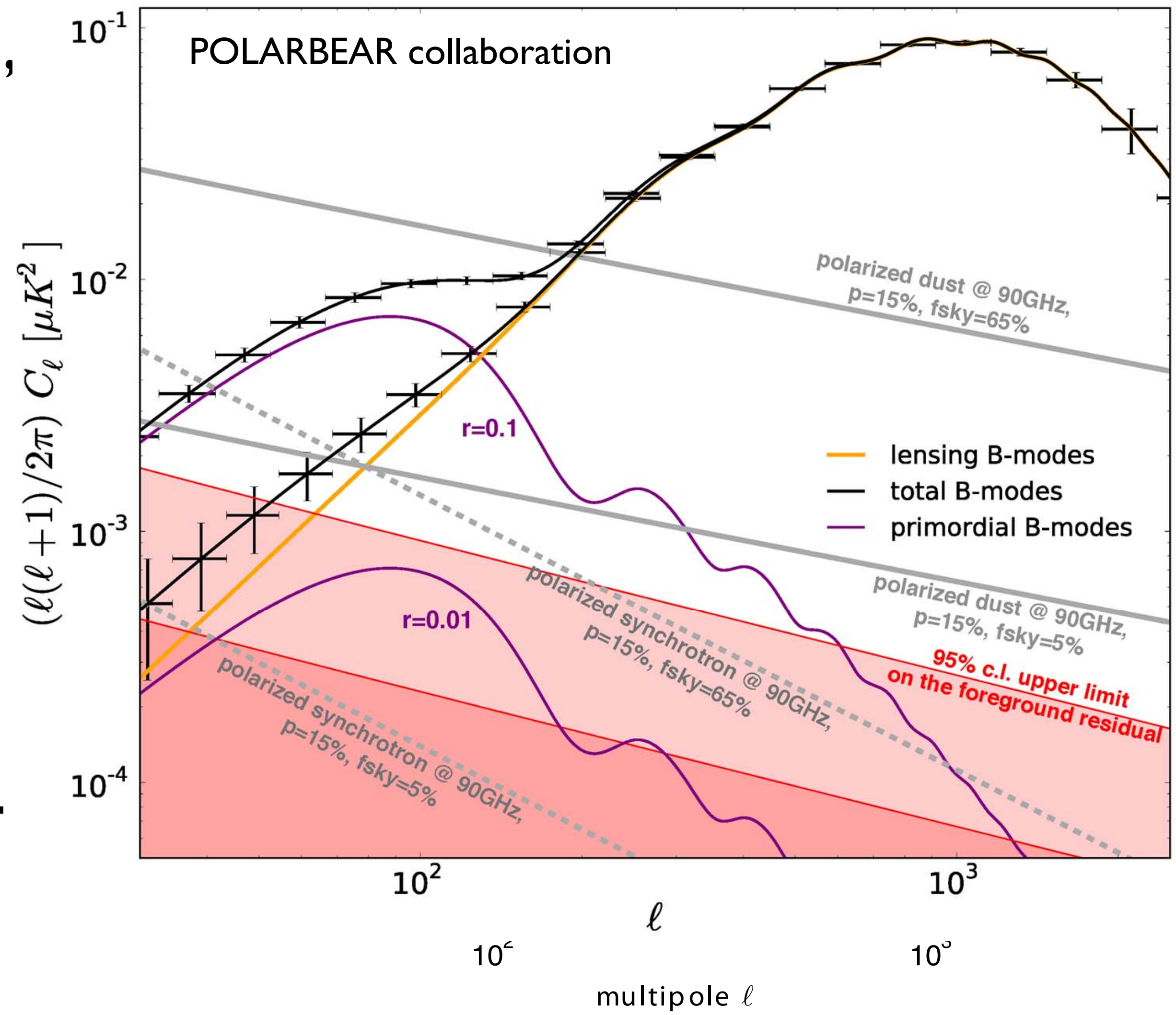


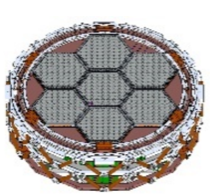
B-modes delensing



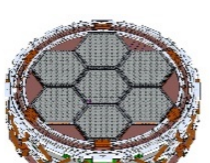
The future of ground-based CMB experiment

- Multichroic pixels receivers: 7,588 detectors, 95/150 GHz e.g. for POLARBEAR-2
- Simons Array by 2018: 3 telescopes, 22,764 detectors, 95/150/220 GHz and high resolution (similar, AdvACTpol, SPT3G)
- High sensitivity B-modes characterization on all angular scales
- 500.000 detectors telescope network CMB-S4

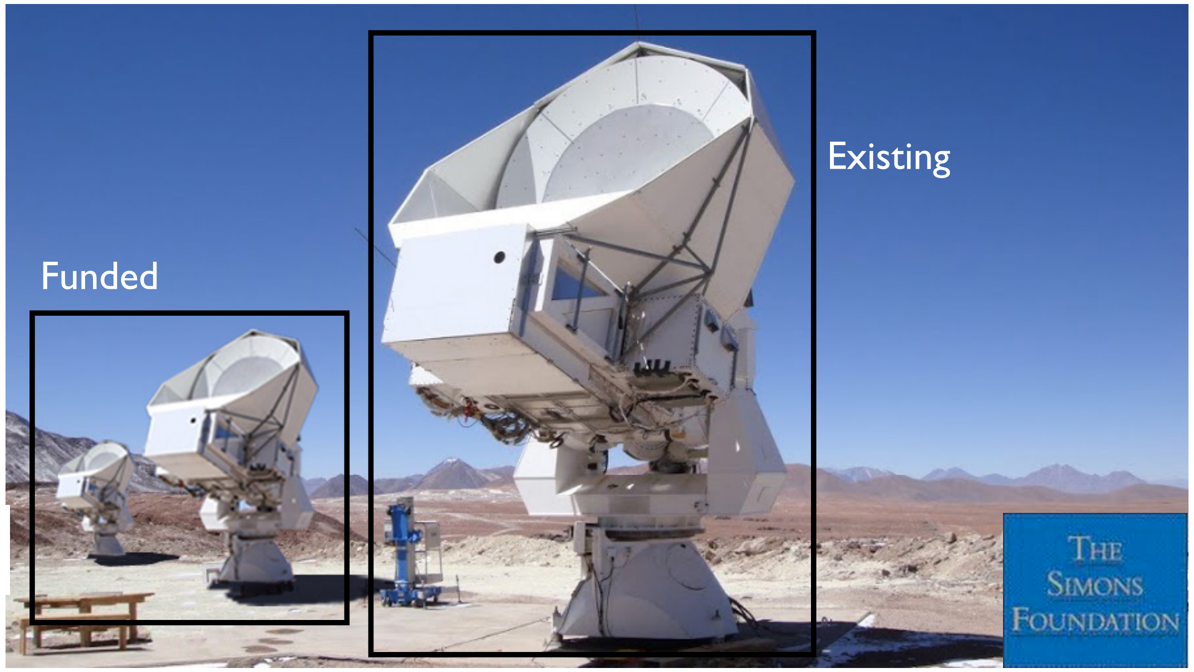


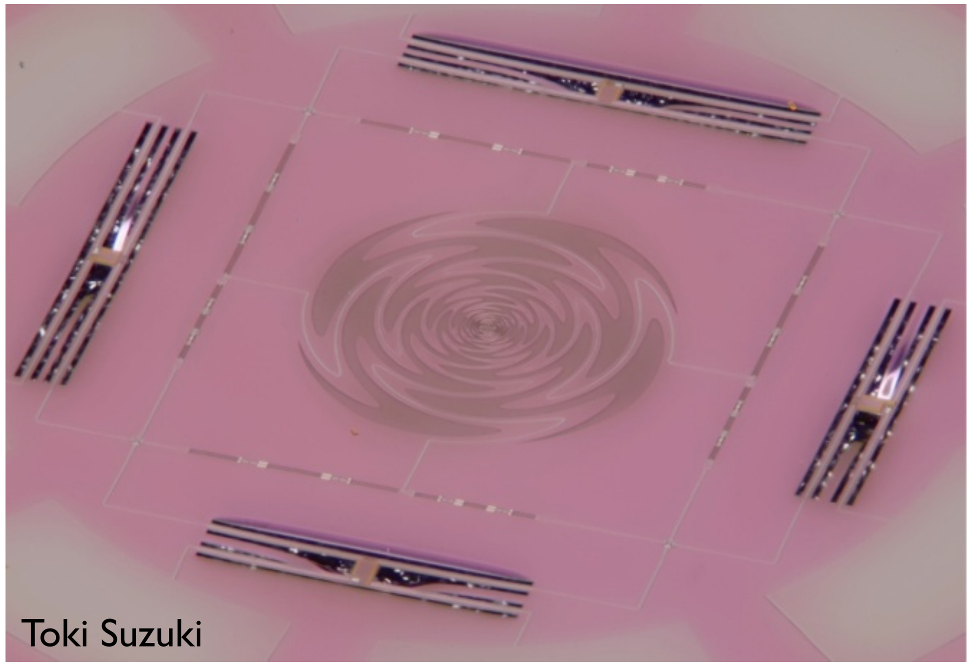
2x 

95/150

1x 

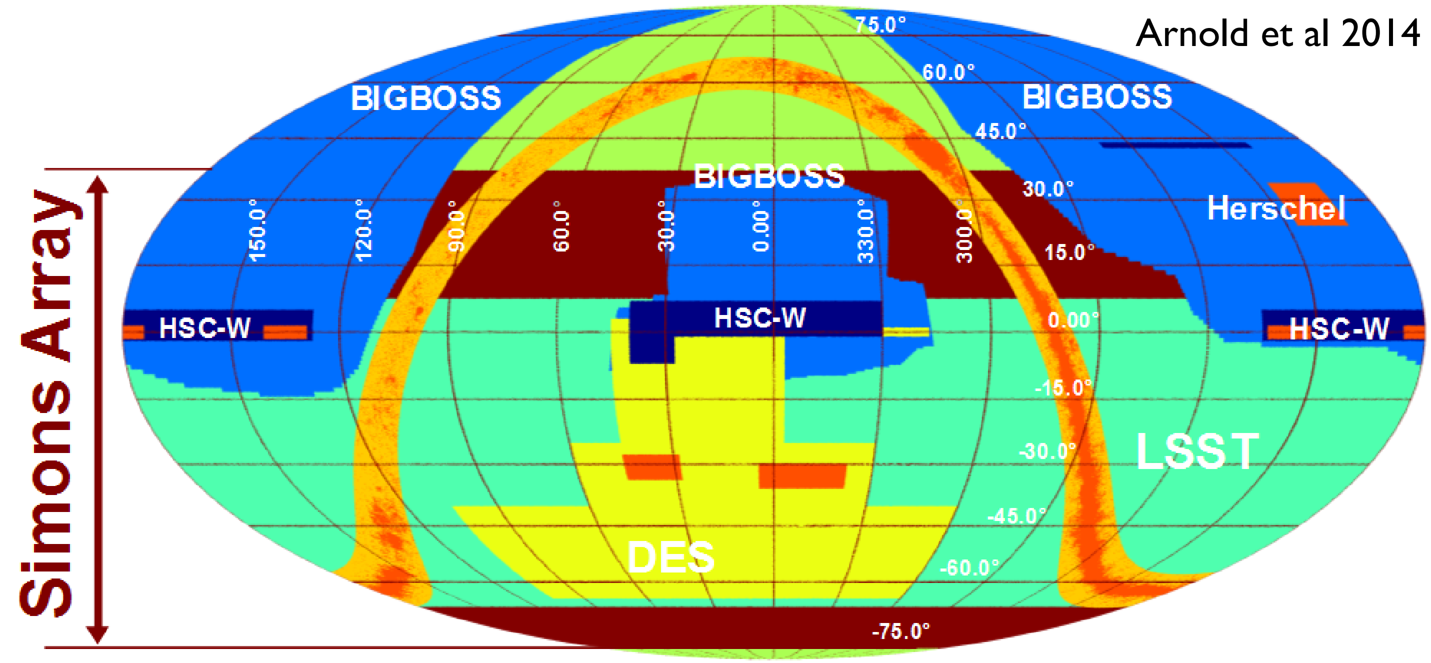
150/220

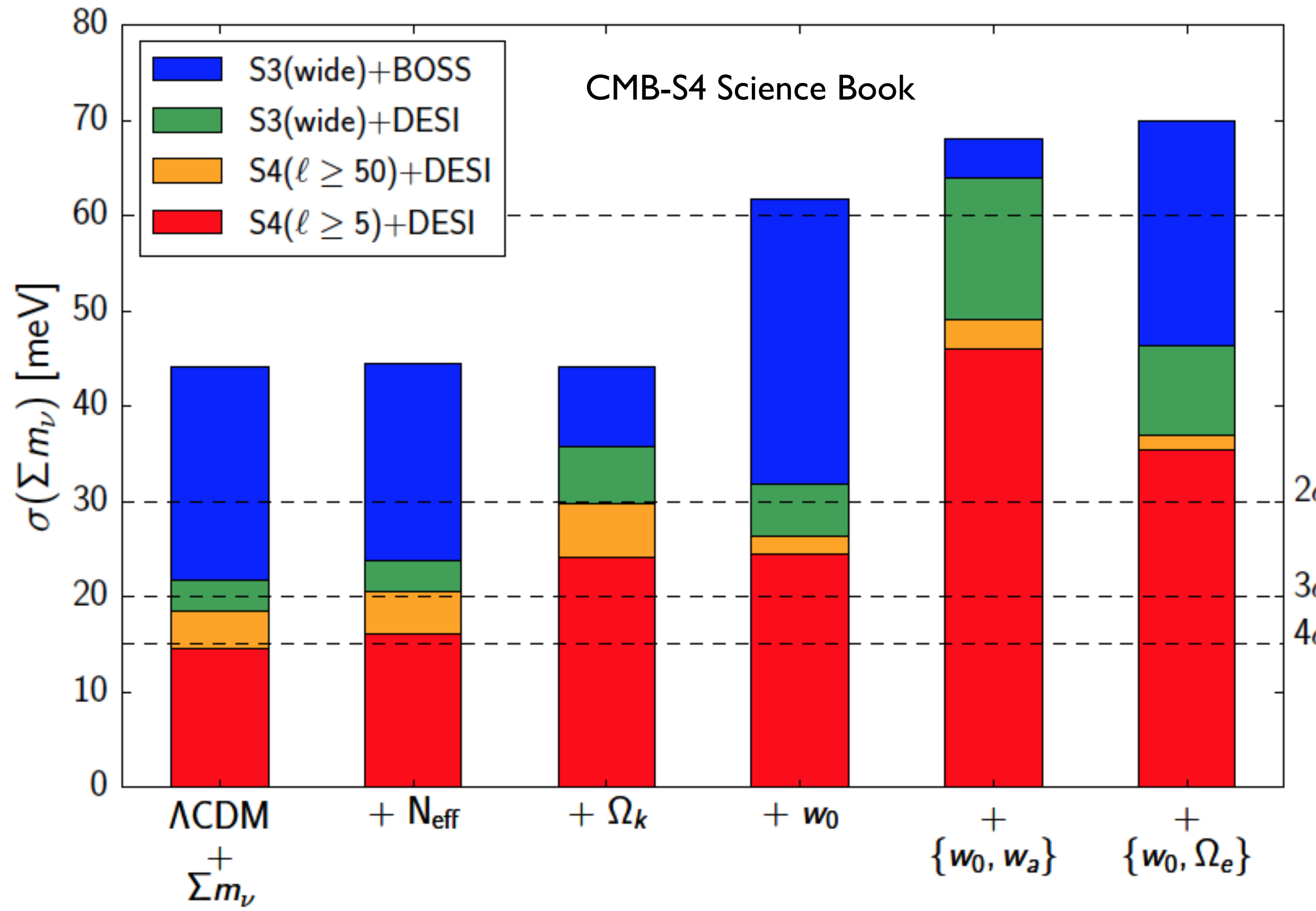




Towards "Stage 4" experiment

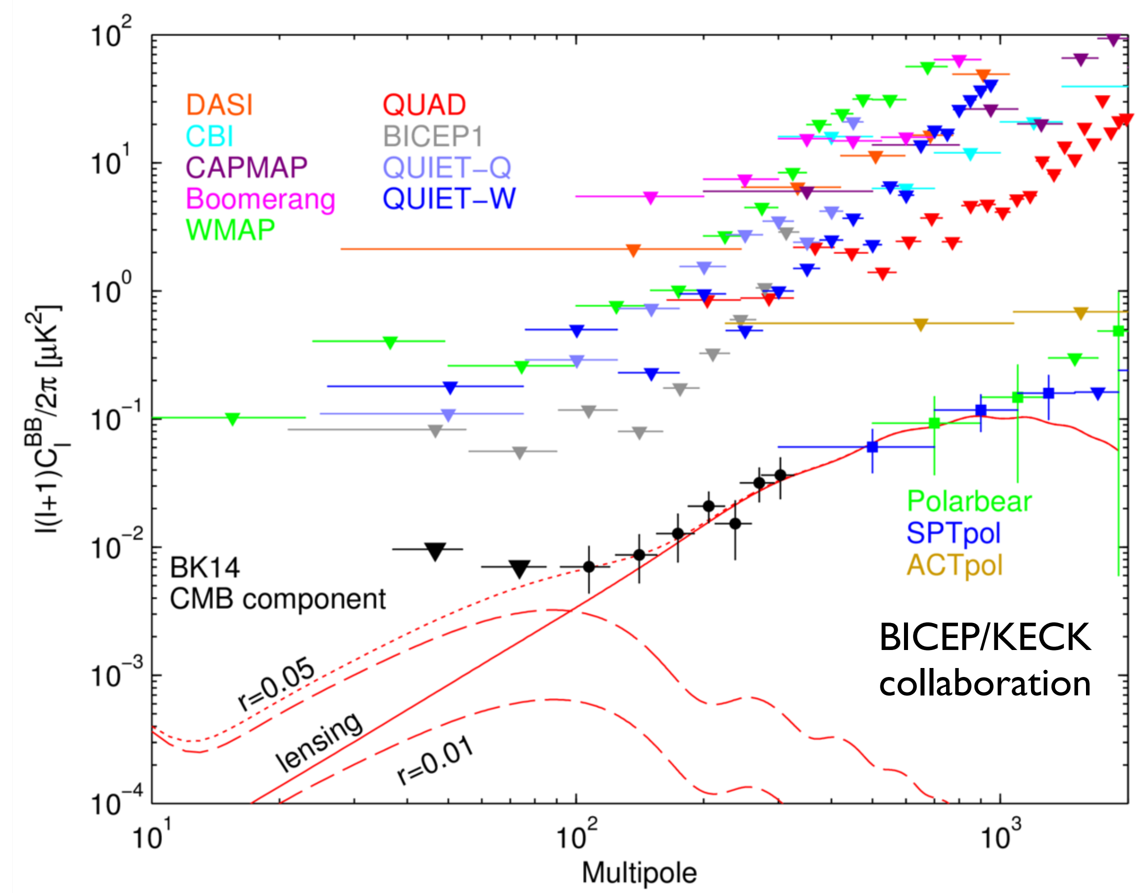
- Large sky, overlap with other astrophysical surveys for cross-correlation studies
- Constrain neutrino mass hierarchy,
  galaxy mass bias, dark energy....
- 1% error constraints on r with internal delensing capabilities
- Cosmic birefringence, primordial magnetic fields...

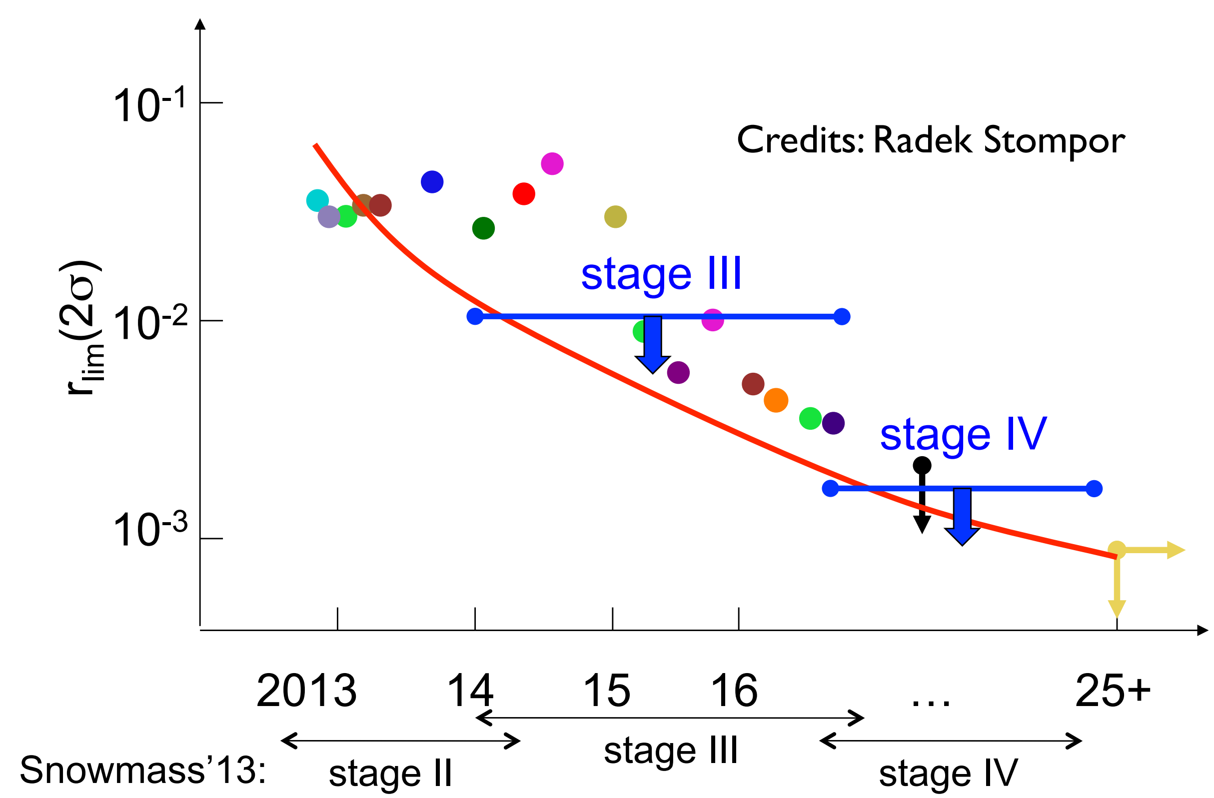




Conclusions

- CMB is one of the most accurate method available to constrain cosmology (both primordial and intermediate epochs)
- CMB field IS NOT dead: the B-modes era will be dominated by suborbital experiments for the next years to come
- Cross correlation: among the most active area of research nowadays (both LSS and primordial science)
- Early universe constraints will face dramatic improvement in few years
- Foreground (galactic and extragalactic) crucial for experimental success





Towards Simons Observatory and CMB-S4

Some material courtesy of Silvia Galli, Davide Poletti, Jayanti Prasad, Josquin Errard

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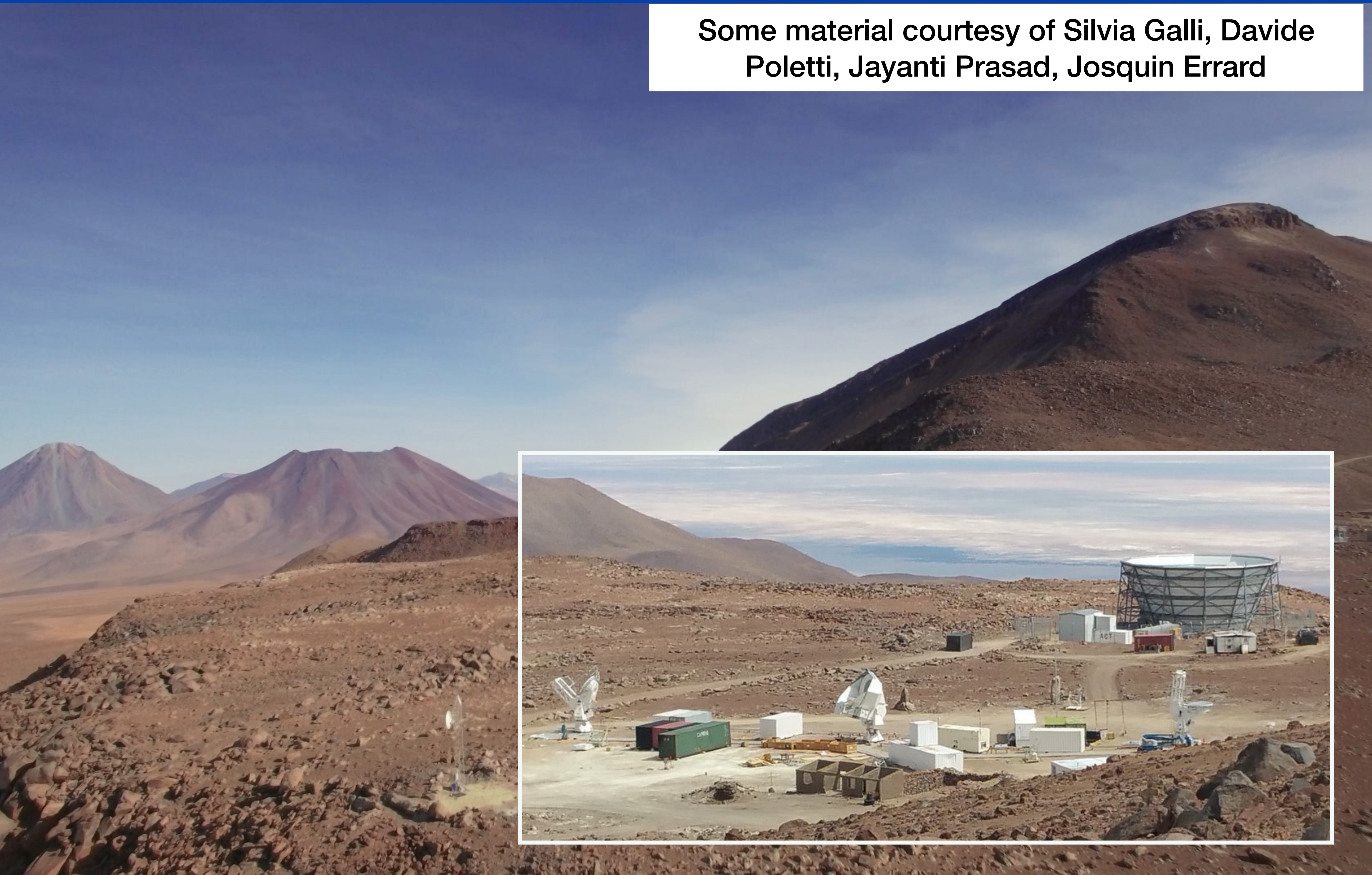

Towards Simons Observatory and CMB-S4

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