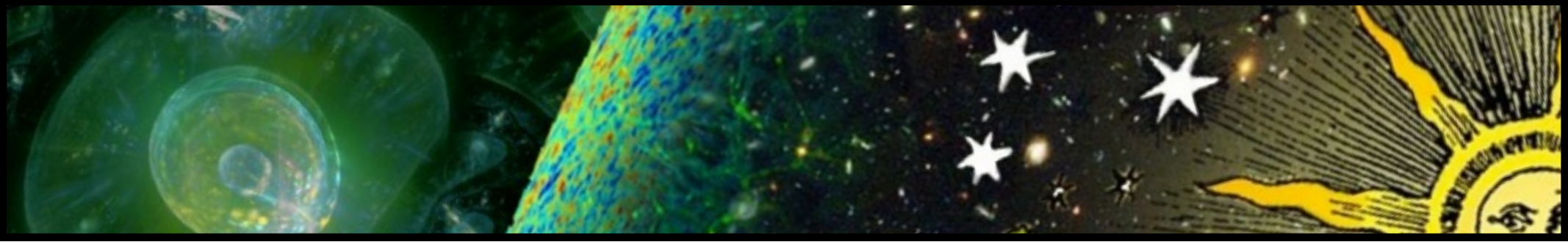


Towards fundamental physics from the cosmic microwave background

Hiranya V. Peiris
UCL and Stockholm

European Research Council

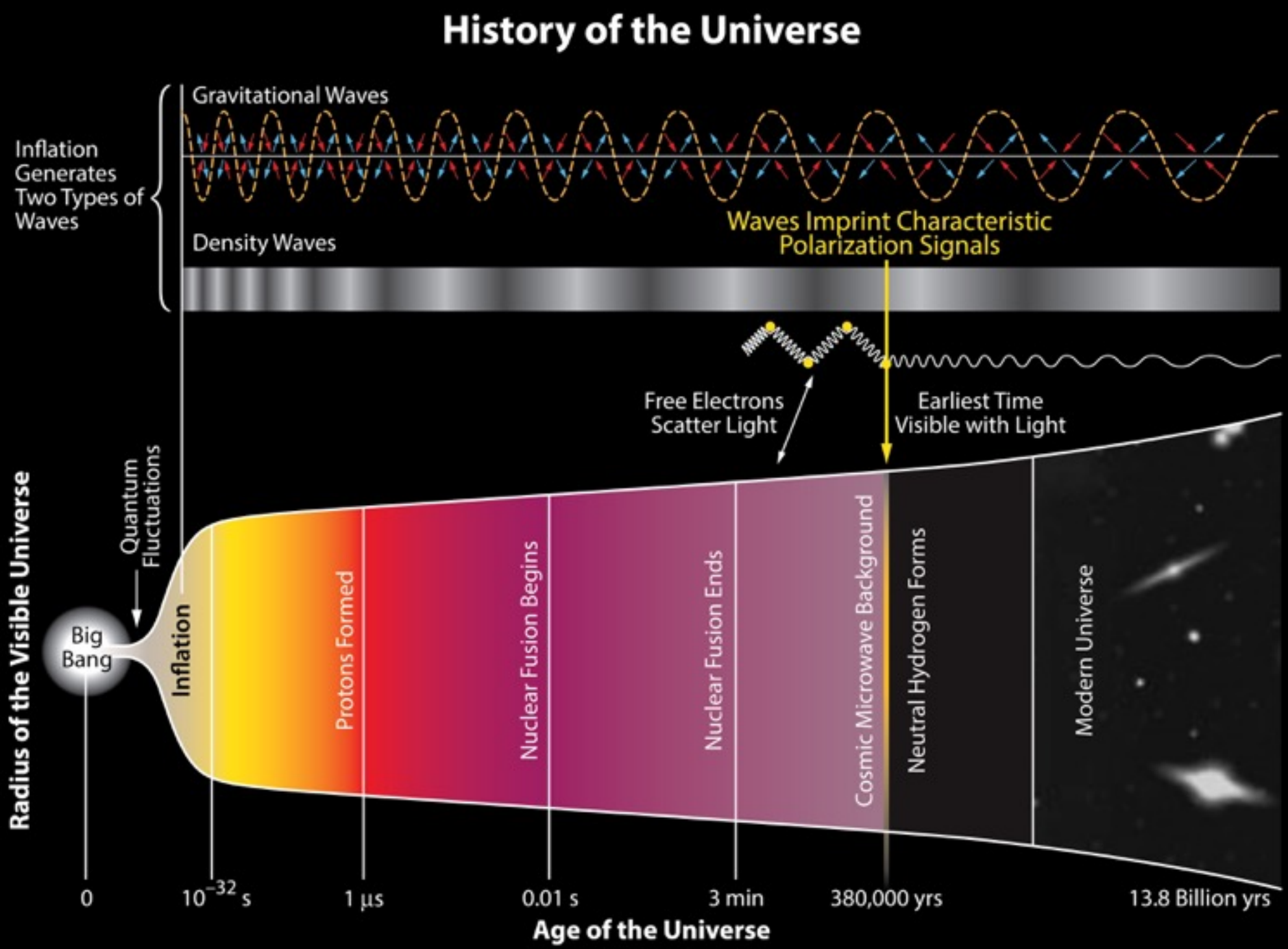
Oskar Klein centre

UCL

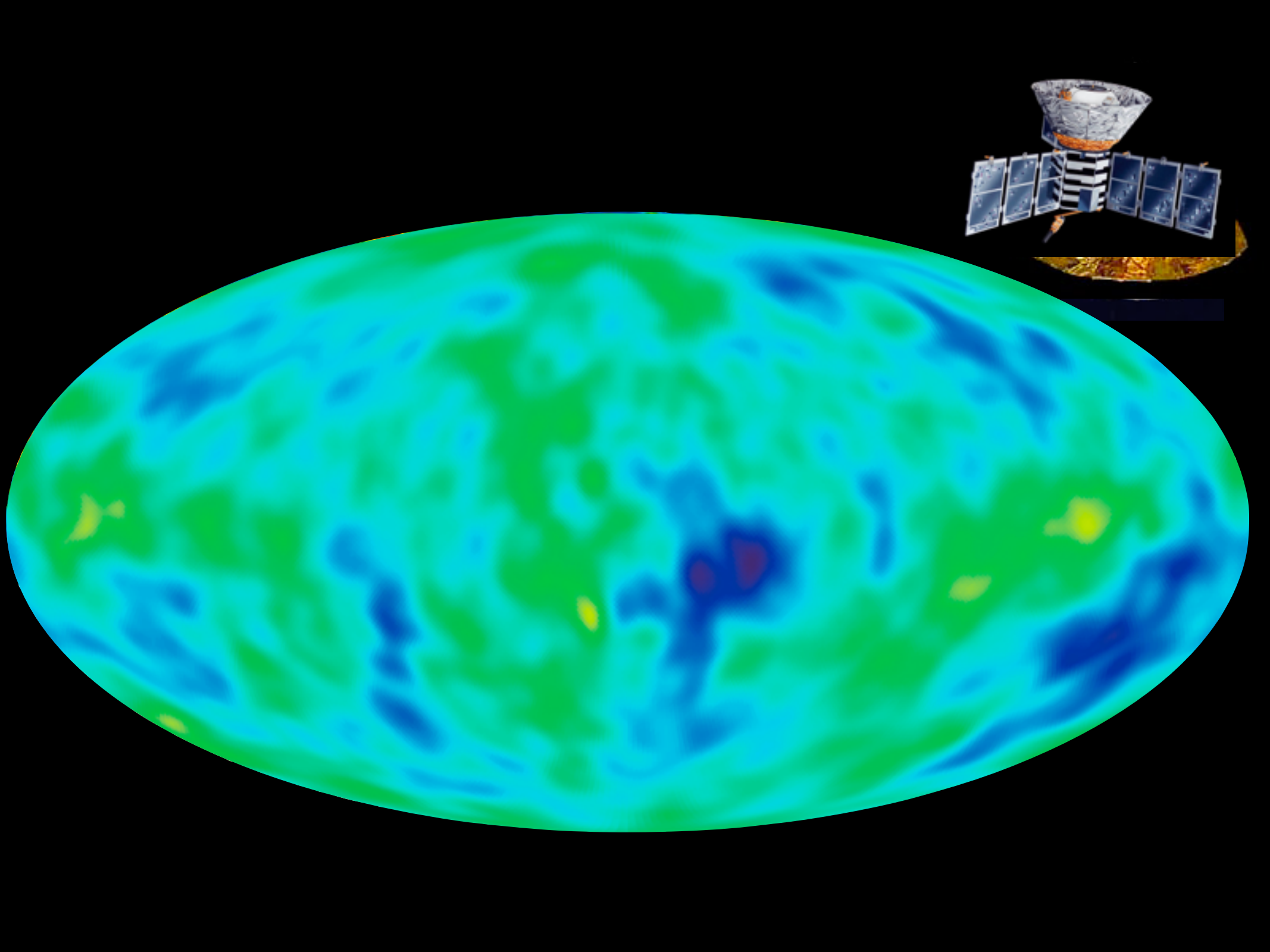
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

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

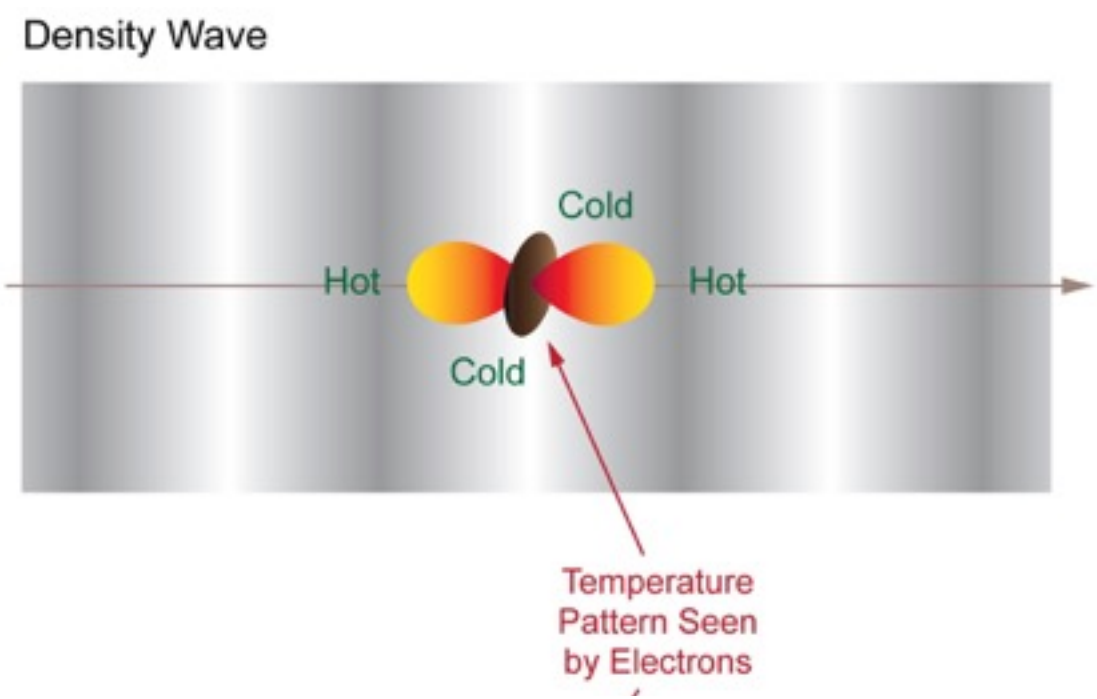
(Part of) the Planck team

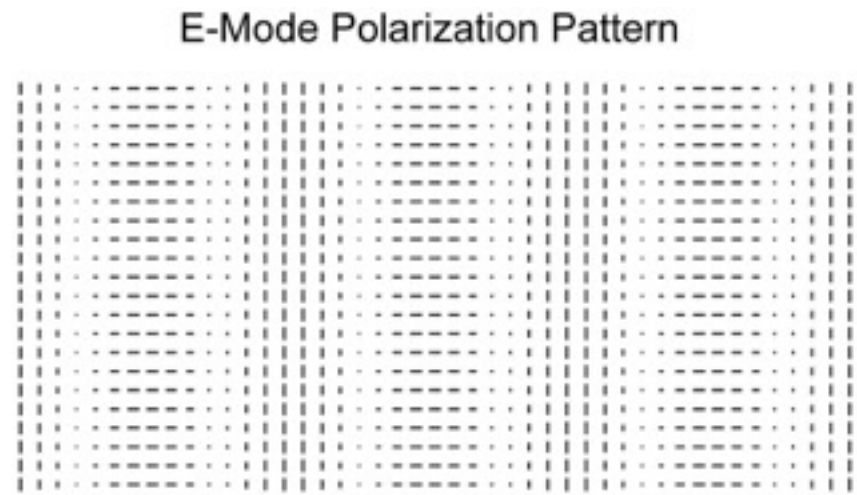


CREDIT: BICEP / KECK COLLABORATIONS



Temperature quadrupole at surface of last scattering creates polarisation…





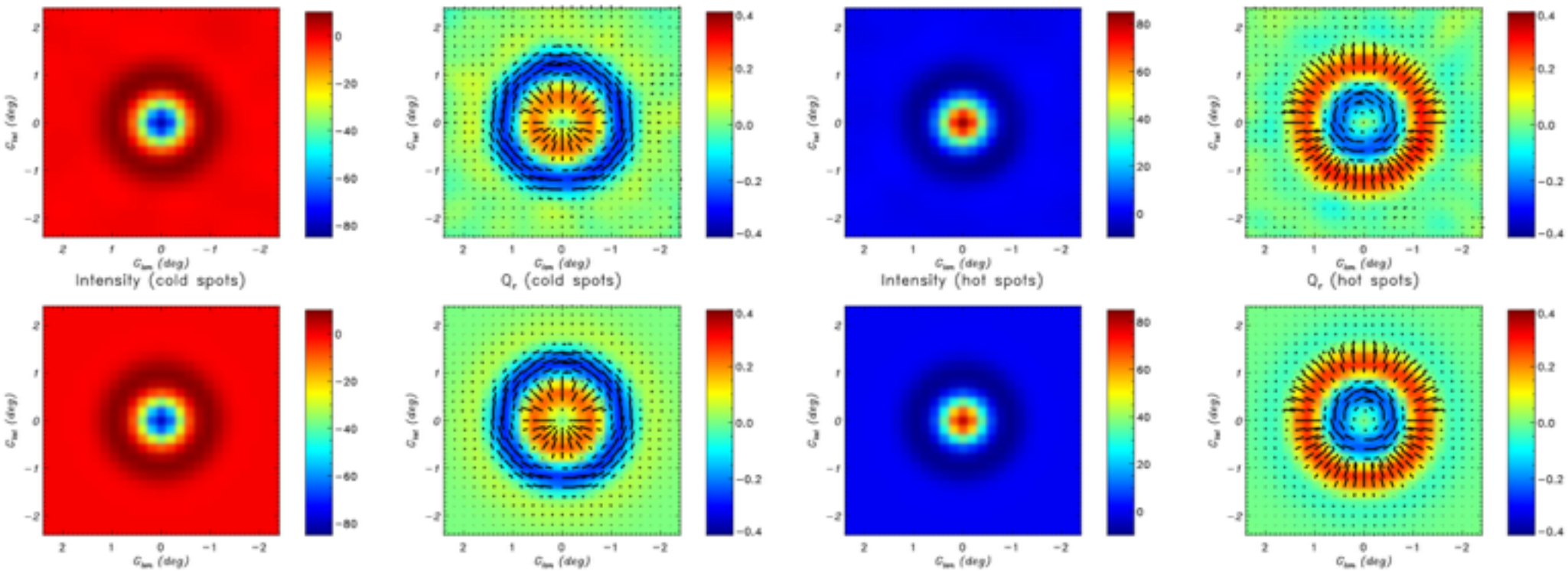
CREDIT: BICEP / KECK COLLABORATIONS

Radial (tangential) pattern around hot (cold) spots.

Measurement

Cold spot **Hot spot**

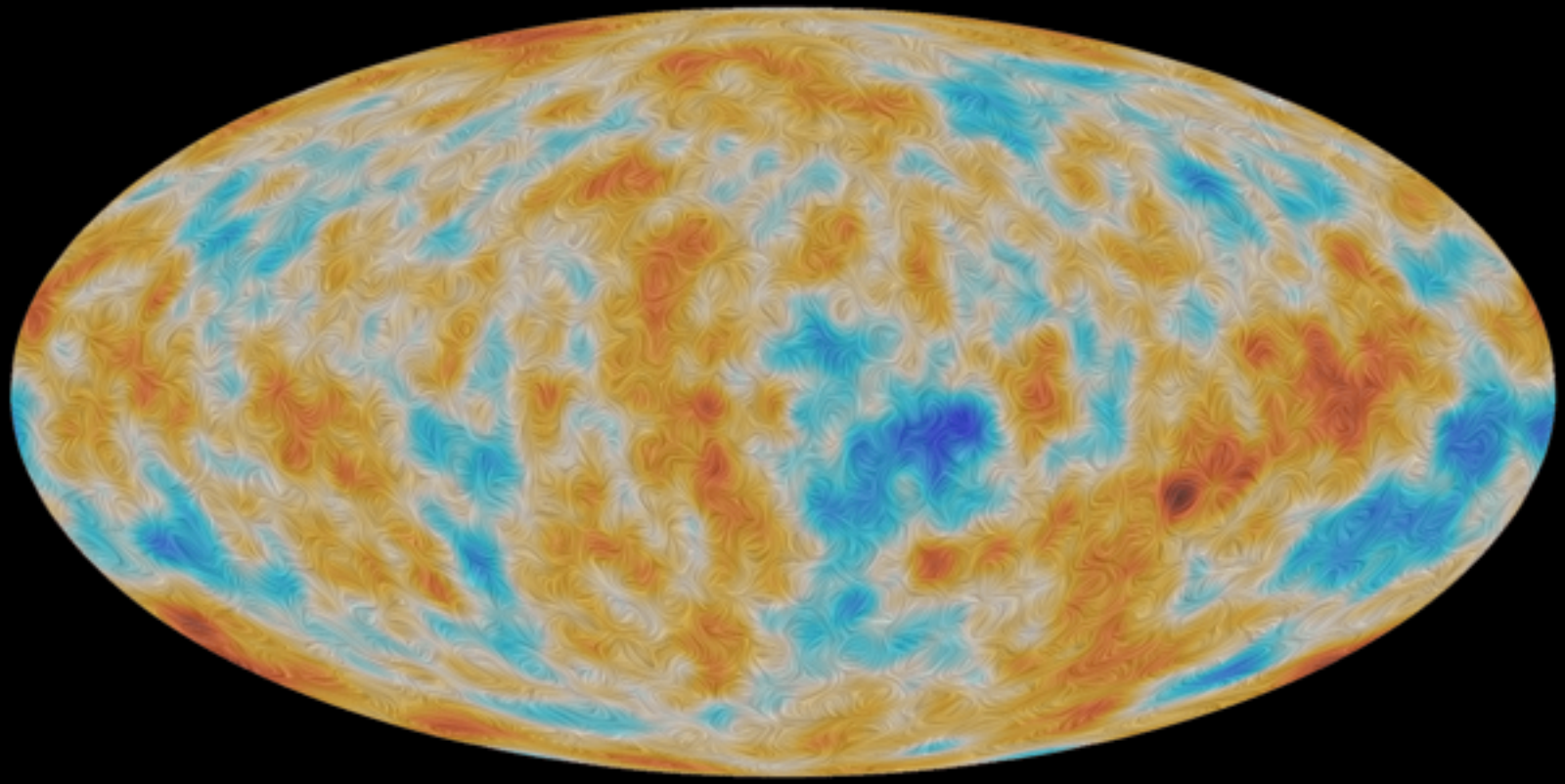
I *Q* *I* *Q*



Cold spot **Hot spot**

Theory prediction

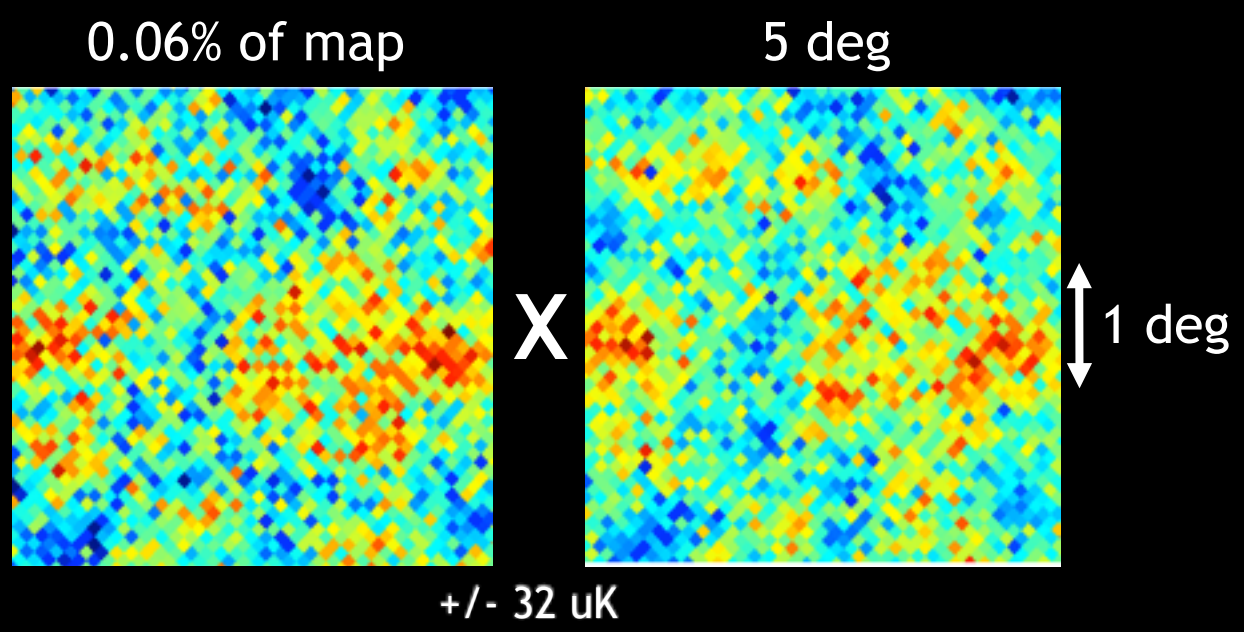
Planck Collaboration (2013)



CREDIT: ESA / PLANCK

Compress the CMB map to study cosmology

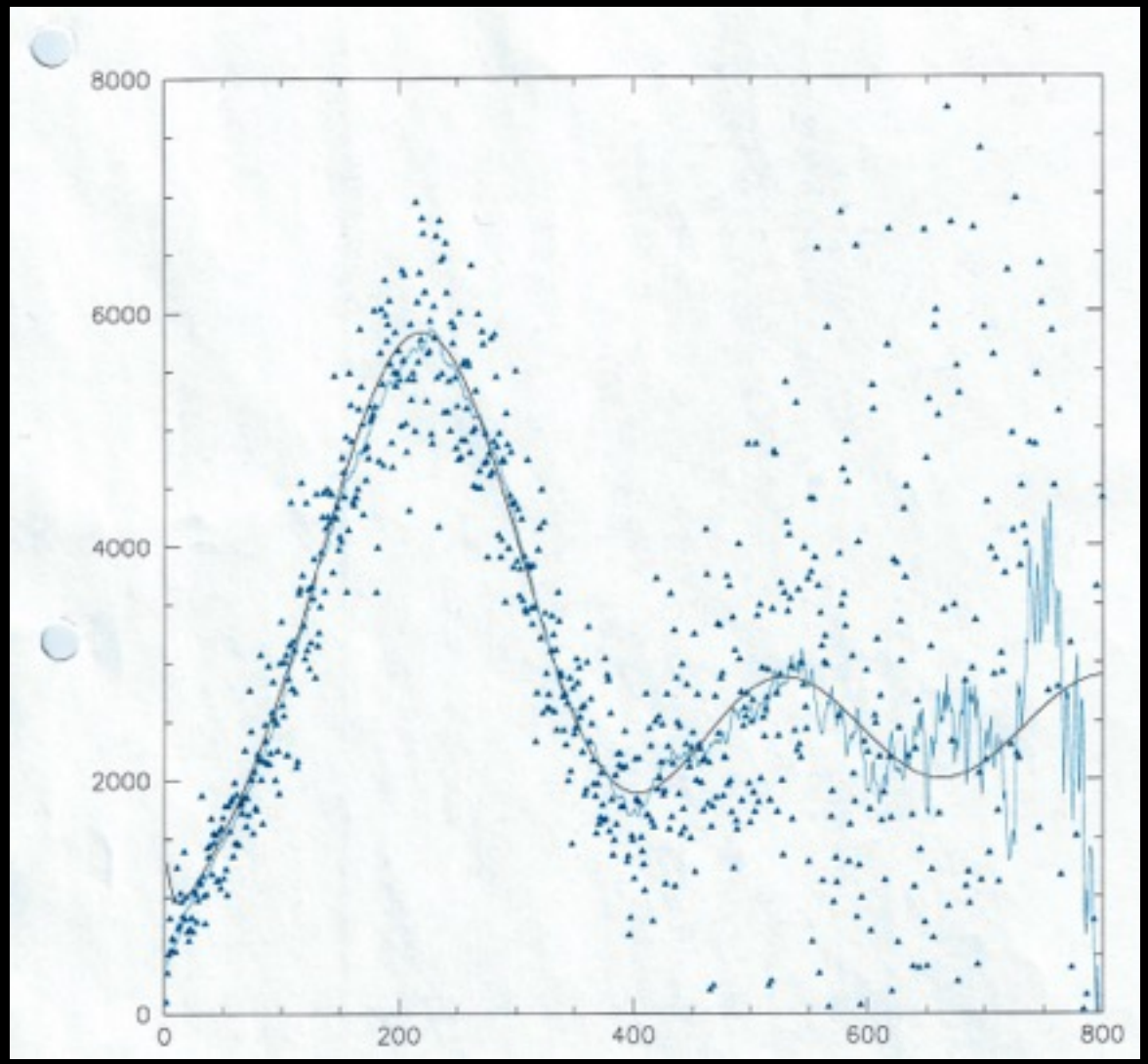
Express sky as: $$\delta T(\theta,\phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\phi)$$



Angular power spectrum $$C_l = \frac{1}{2\ell+1} \sum_m |a_{lm}|^2$$

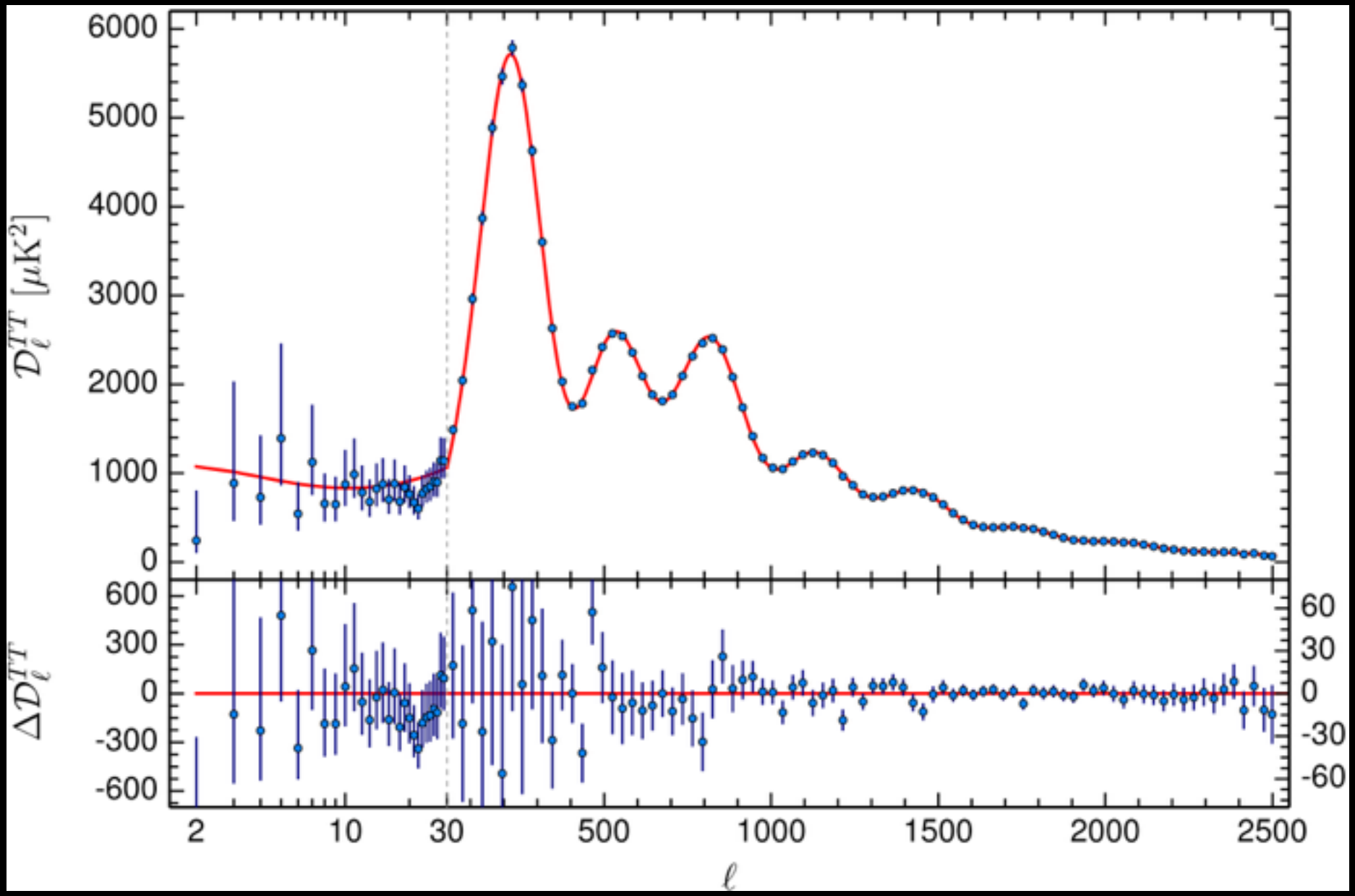
WMAP "first light" spectrum

power



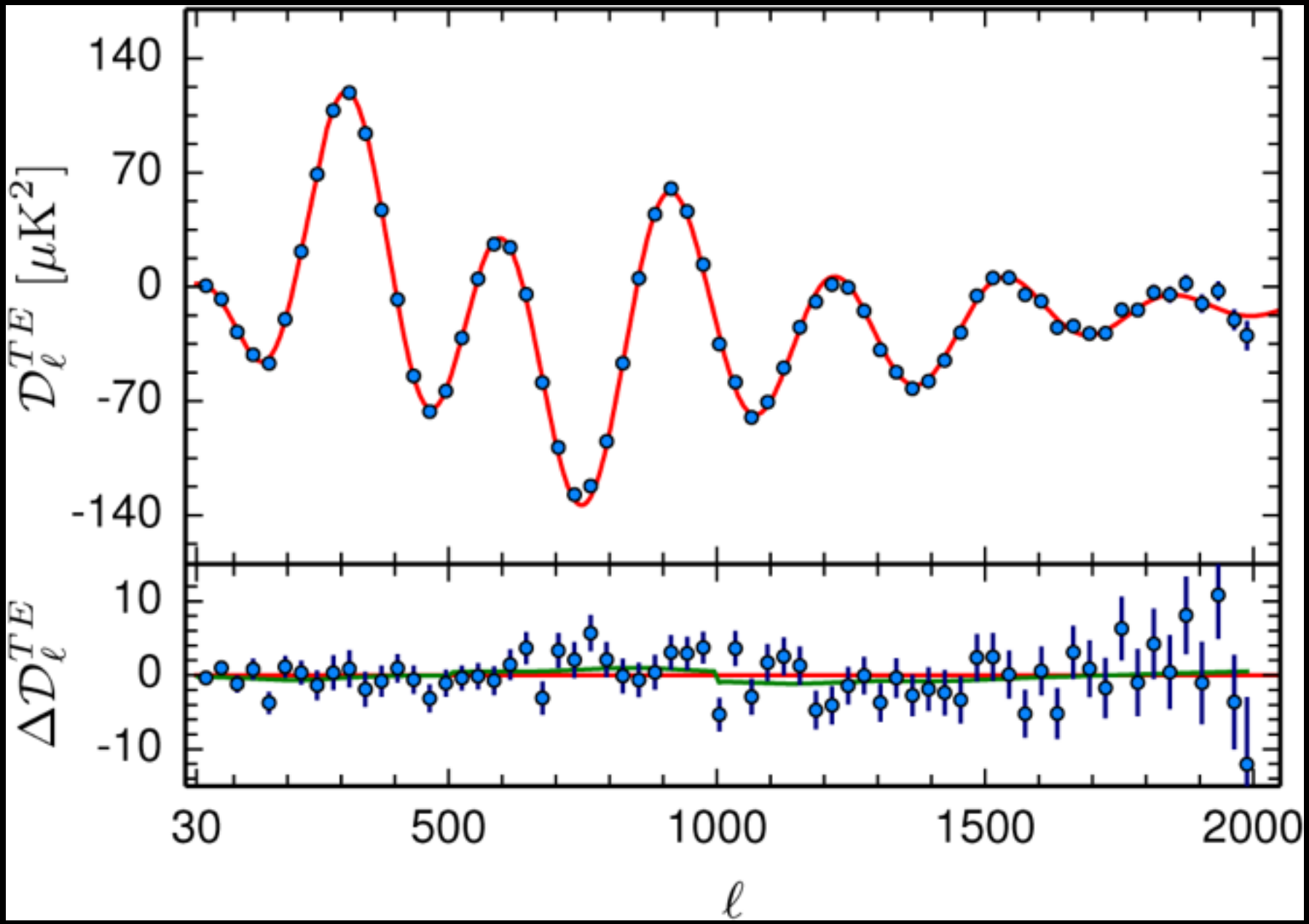
larger scales ⟷ smaller scales

Planck 2015 Temperature



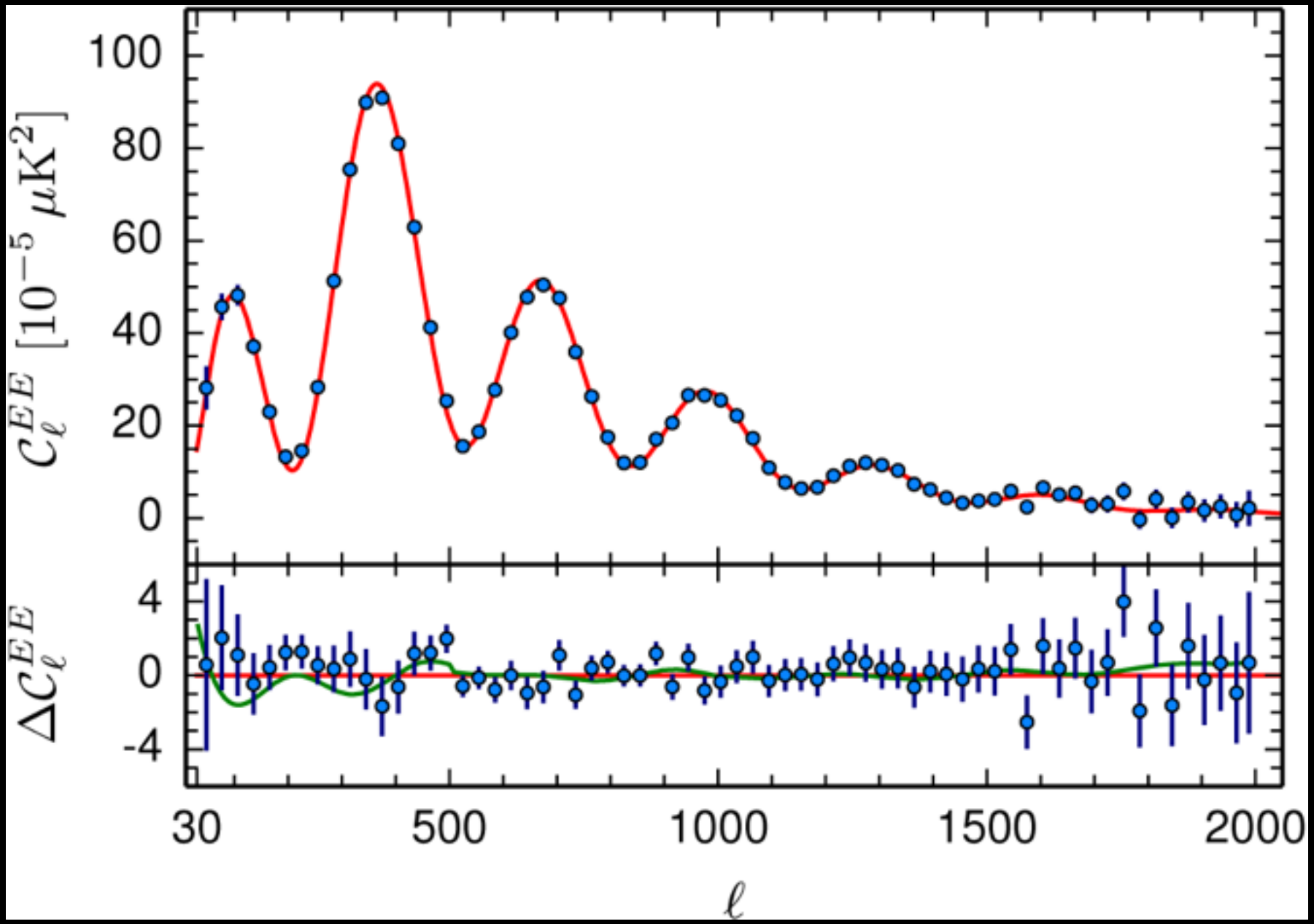
Credit: Planck Collaboration

Planck 2015 TE Polarization



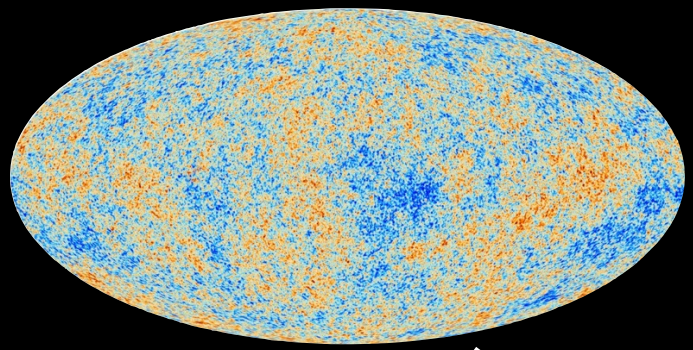
Credit: Planck Collaboration

Planck 2015 EE Polarization

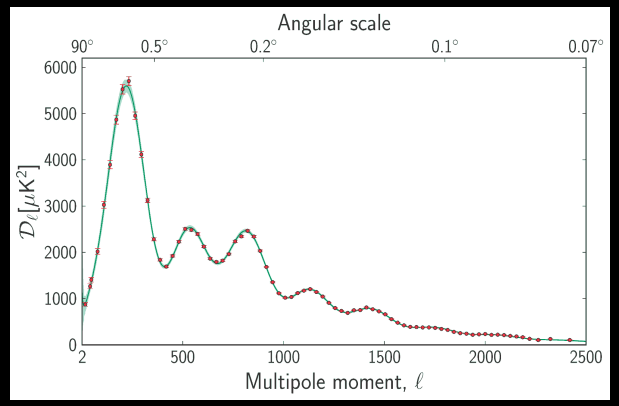


Credit: Planck Collaboration

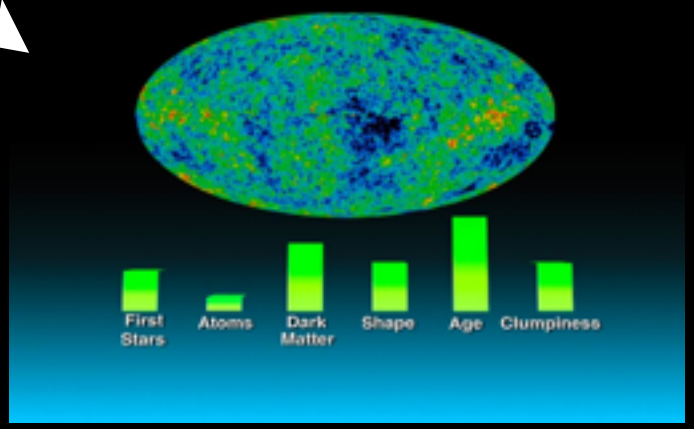
Radical data compression!



50 million pixels...



2500 multipoles...



six cosmological parameters!

Planck TT + lowP cosmological parameters

~directly measured

$\Omega_b h^2 = 0.02222 \pm 0.00023$

$\Omega_c h^2 = 0.1197 \pm 0.0022$

$n_s = 0.9655 \pm 0.0062$

$\tau = 0.078 \pm 0.019$

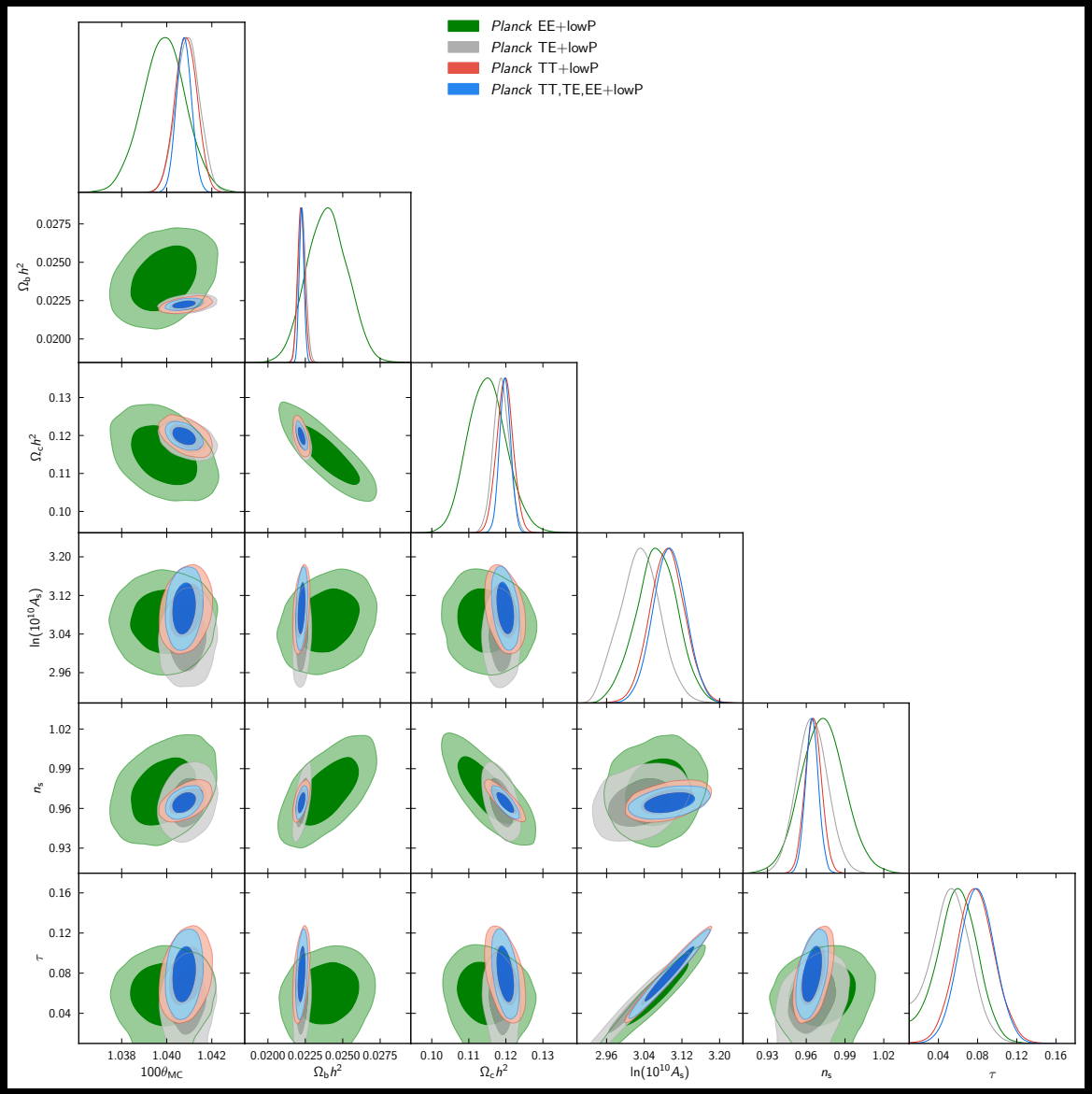
$\ln(10^{10} A_s) = 3.089 \pm 0.036$

derived

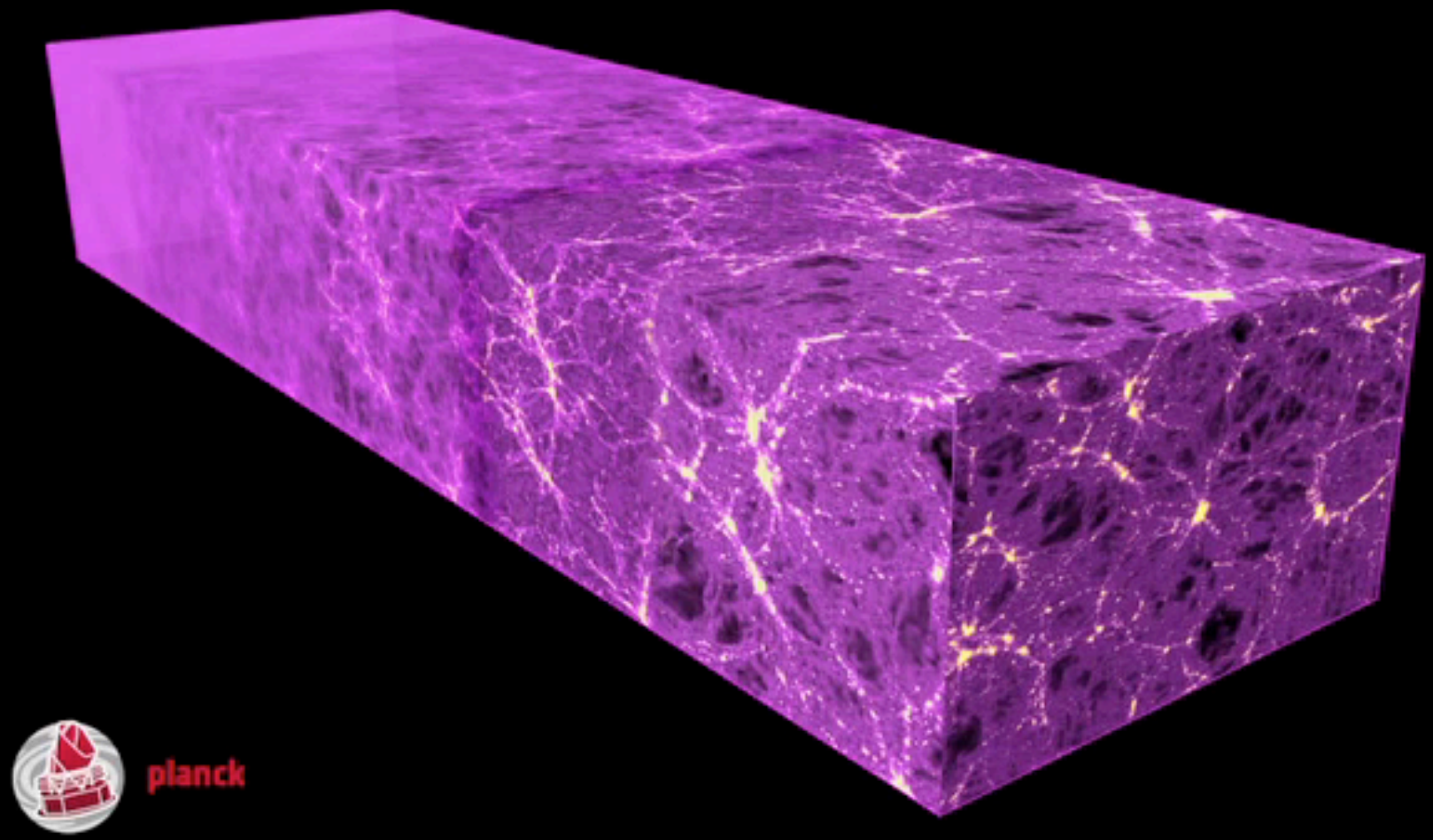
$H_0 = 67.31 \pm 0.96$ km/s/Mpc

$\Omega_\Lambda = 0.685 \pm 0.013$

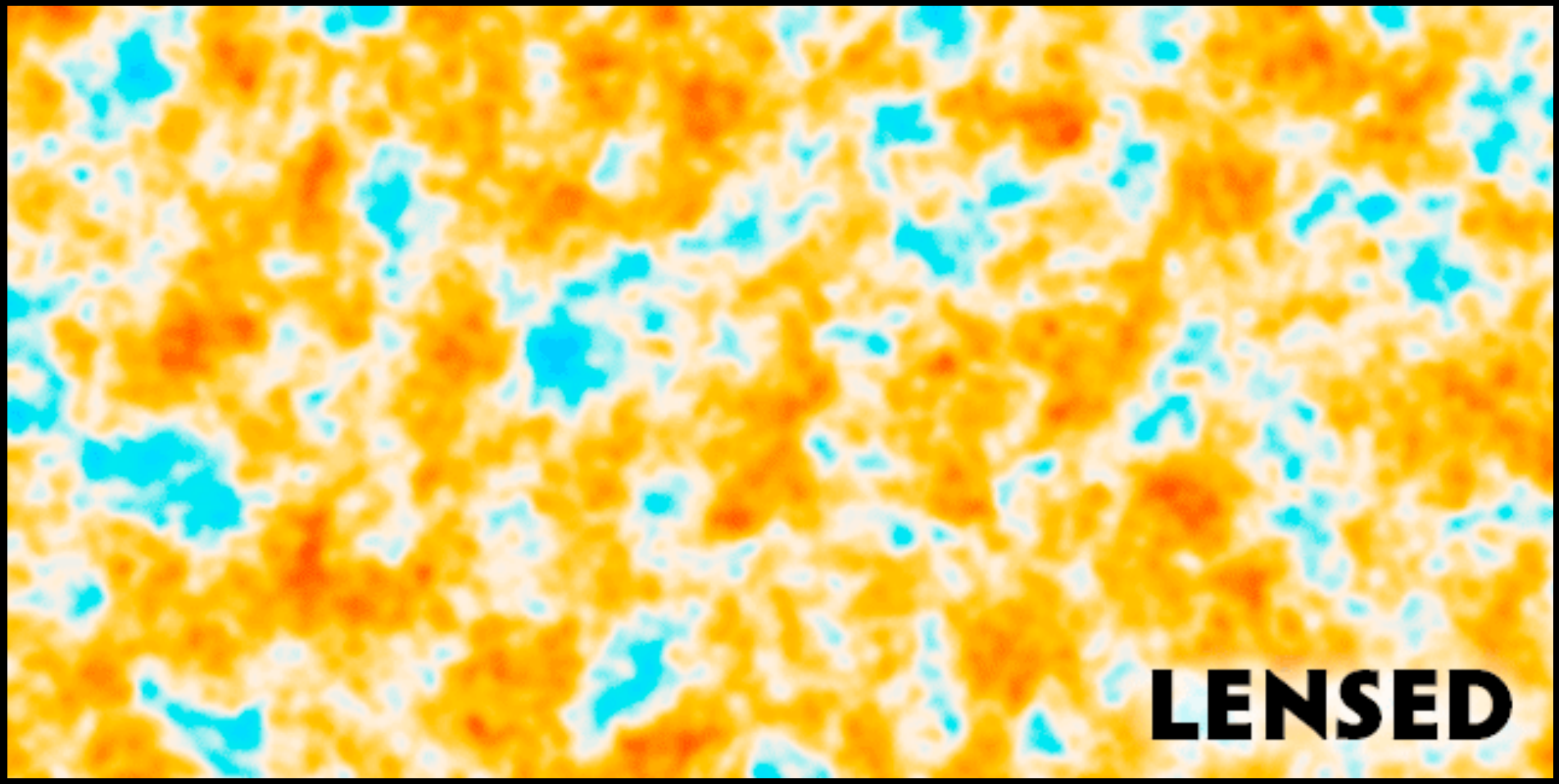
$\sigma_8 = 0.829 \pm 0.014$



Cosmological parameters not "directly measured"; details depend on models ["priors"]



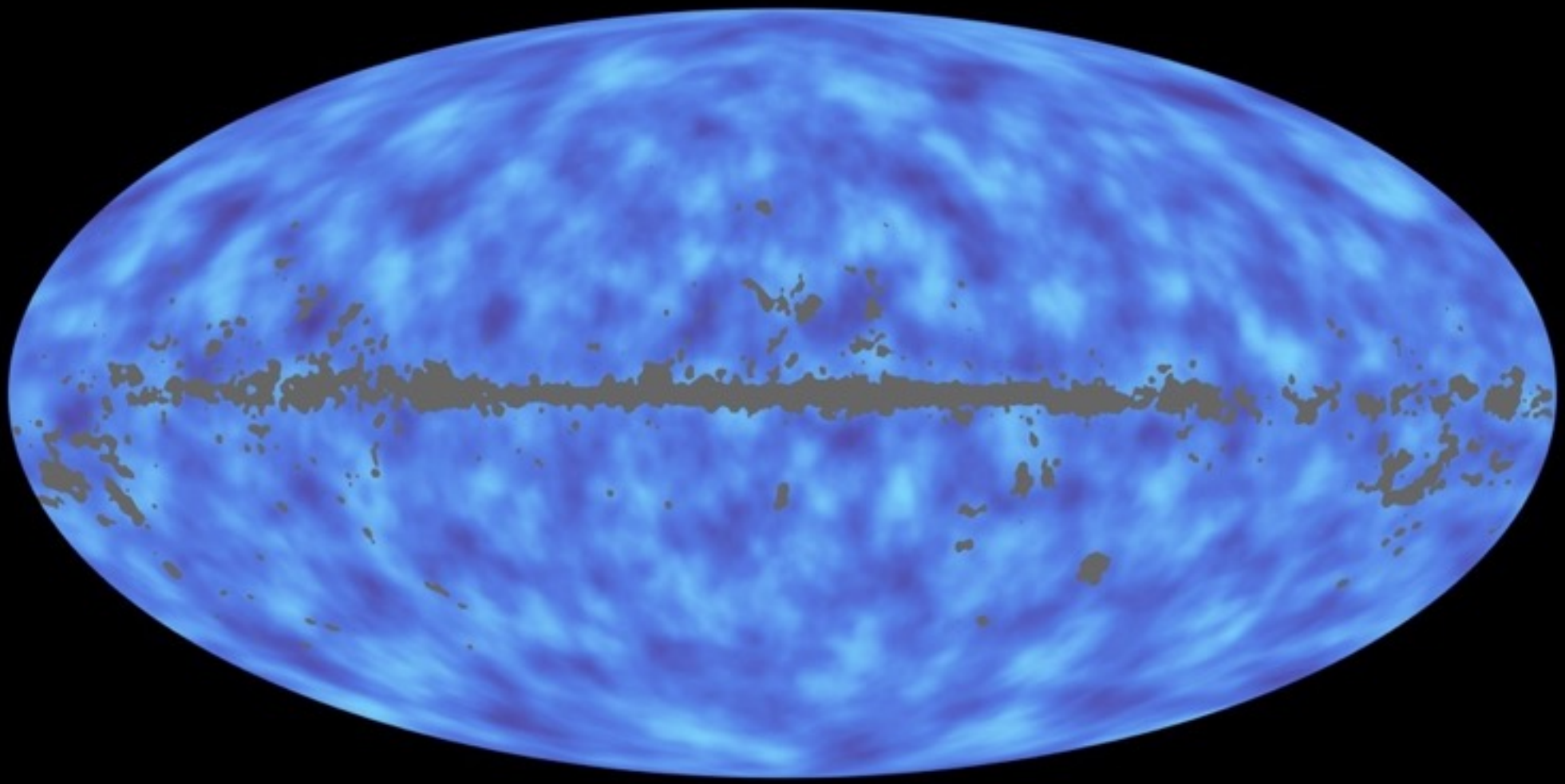
CREDIT: ESA / PLANCK



Deflections are ~ 2 arcmin

CREDIT: ESA / PLANCK

CMB lensing potential reconstruction

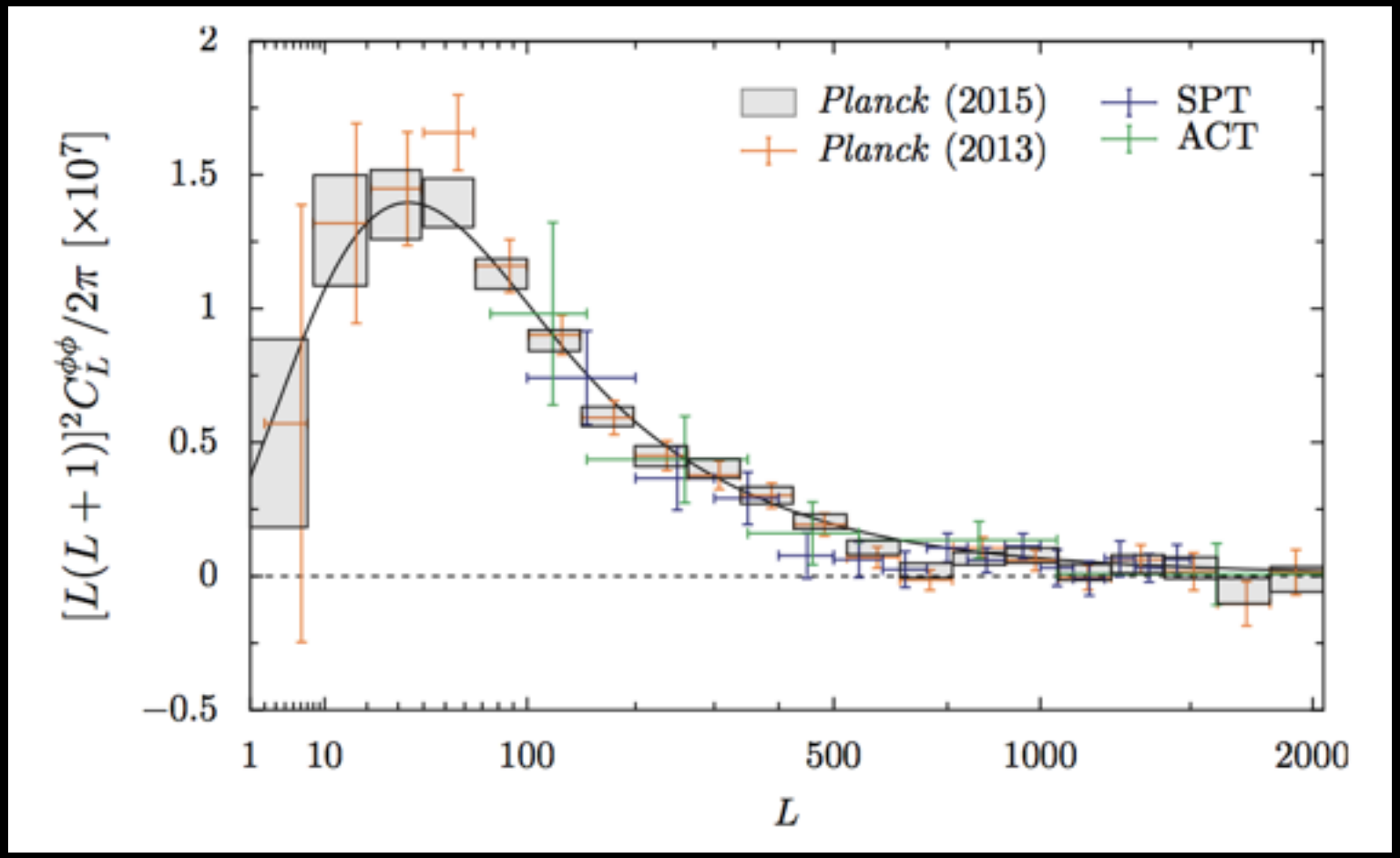


Credit: Planck Collaboration

CMB lensing potential power spectrum

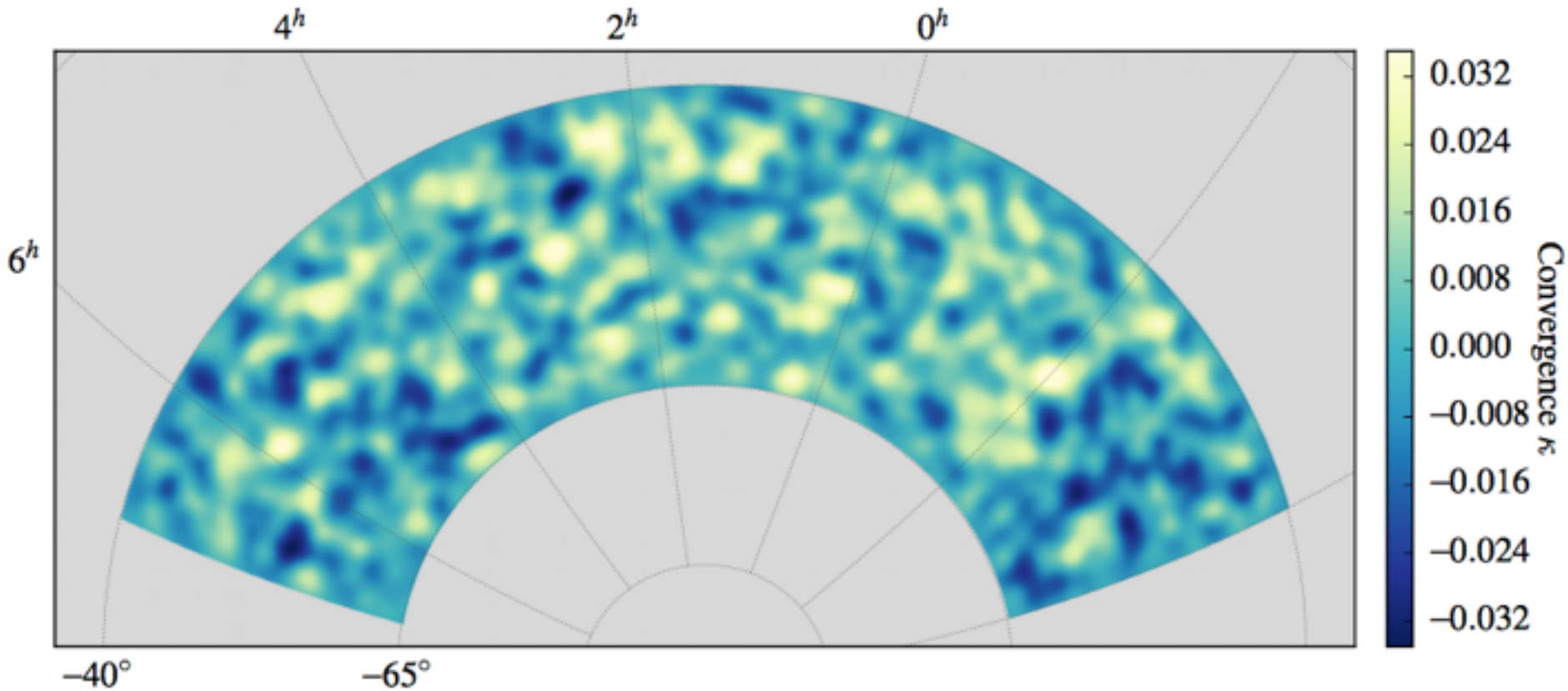
Detected at ~40σ (nearly doubled 2013 sensitivity):

breaks parameter degeneracies from primary CMB alone; new window on growth of cosmic structure



Credit: Planck Collaboration

CMB lensing potential reconstruction



2500 sq. deg. map of gravitational lensing potential projected along the line of sight

(South Pole Telescope 150 GHz + Planck 143 GHz)

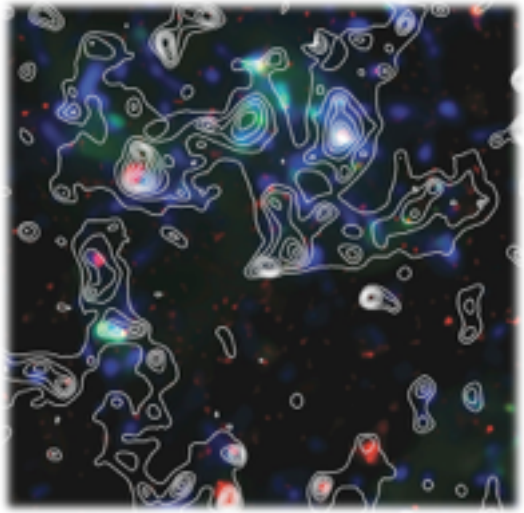
Omori et al (SPT Collaboration, 2017)

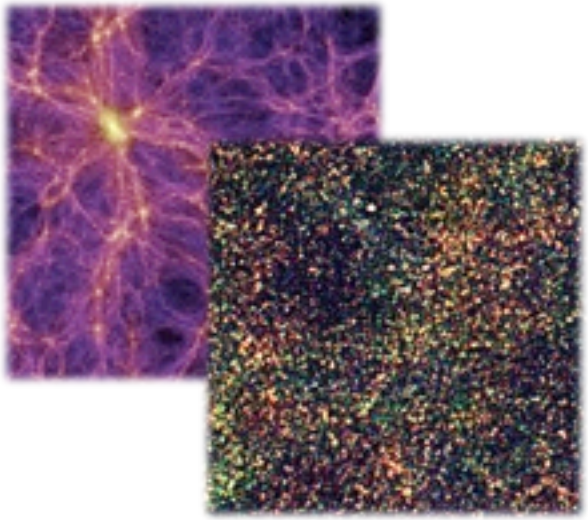
Cross-correlations with large-scale structure probes

- **Secondary CMB contributions**
  Integrated Sachs-Wolfe effect, thermal / kinetic Sunyaev-Zel'dovich effect, lensing, cosmic infrared background….

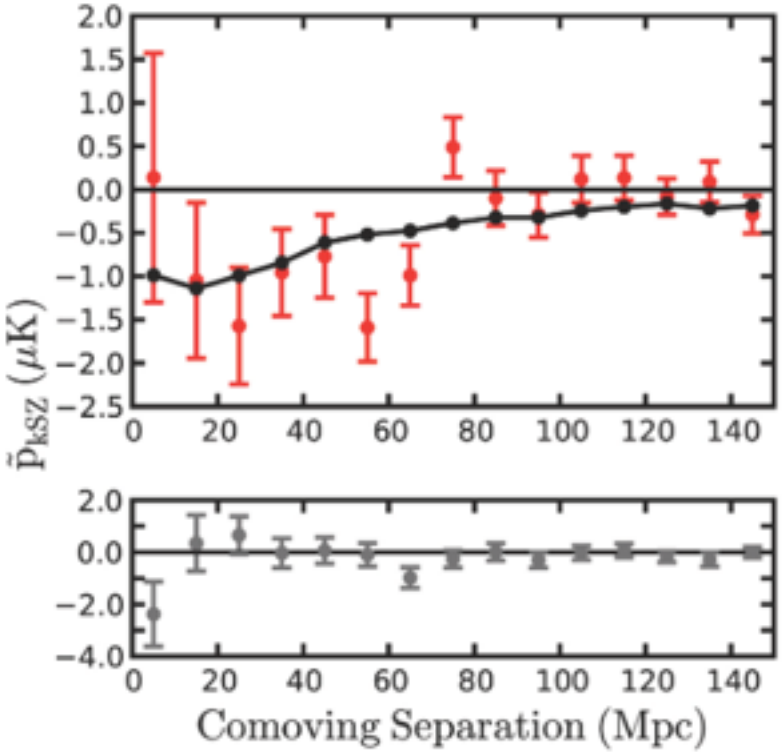
- **Cross-correlations** with non-CMB "tracers"
  Galaxy surveys, clusters, weak lensing mass maps, velocity reconstructions…

- Reveals **interplay of dark and light matter** in evolved universe
  Intracluster gas, "missing" baryons, star formation history, halo masses…

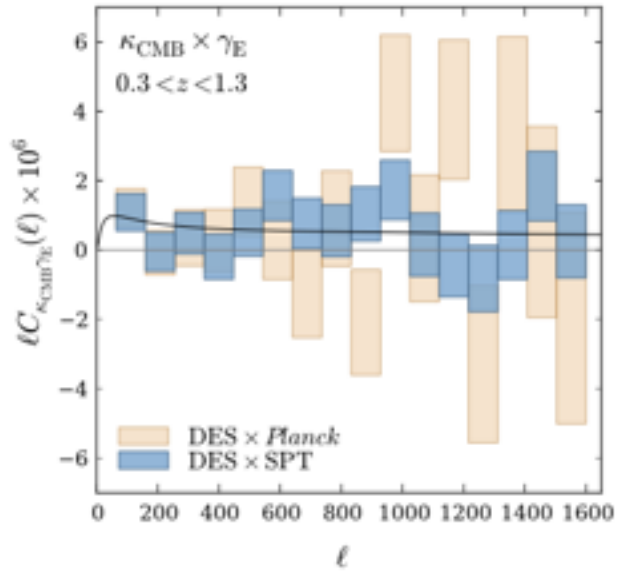




Cross-correlations with large-scale structure probes

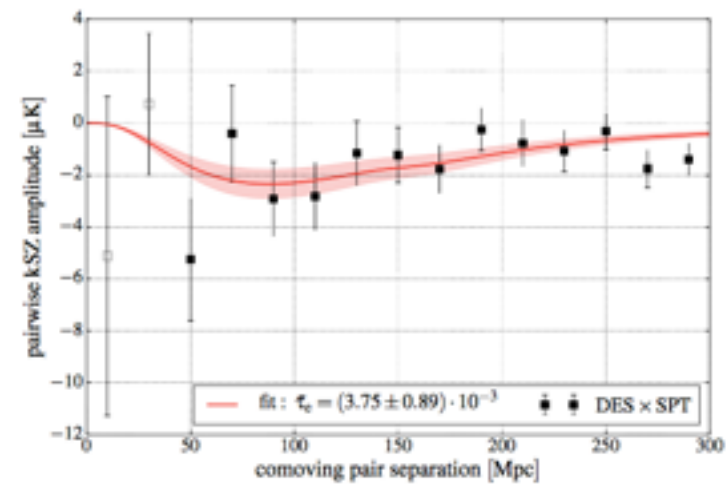


Original detection of kSZ
ACT x BOSS cluster positions
(Hand et al 2012)



WL x CMB lensing
DESxSPT, DESxPlanck
(Kirk et al 2015)

kSZ (4.2σ)
DES clusters x SPT-SZ
(Soergel et al 2016)

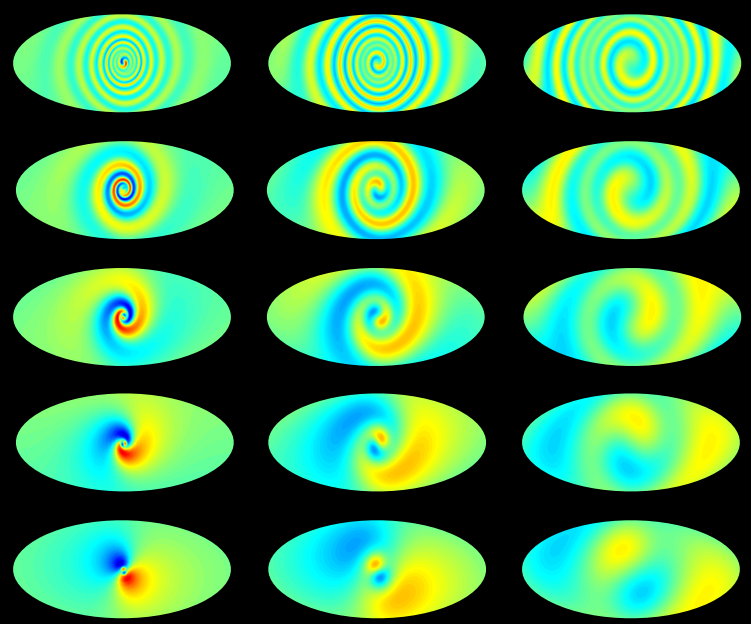


Hill, Spergel (2014), Van Waerbeke et al (2014), Ferraro et al (2016), Soergel et al (2016), Hill et al (2016), Schaan et al (2015), Planck Collaboration (XIX 2013, XXXVII 2015), Hand et al (2012), Harnois-Deraps et al (2016), Kirk et al. (2015), Liu, Hill (2015), Omori, Holder (2015), Ma et al (2015), Hand et al (2014), Serra et al (2014), Giannantonio et al (2015), Hurier et al (2017)

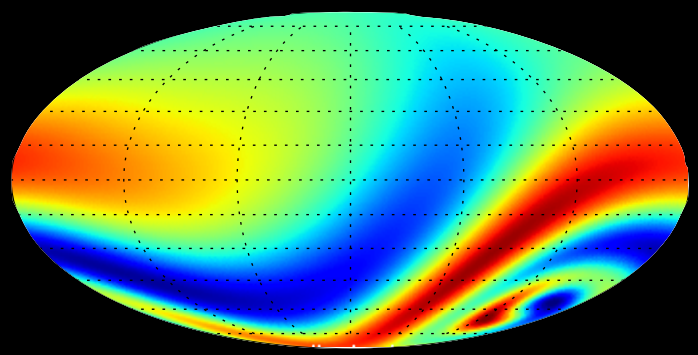
Geometry & Topology of the Universe

- Einstein's General Relativity explains local curvature of spacetime but doesn't tell us global geometry and topology of Universe.

- No evidence for non-trivial geometry or topology, tight constraints on models.



Simulated Bianchi CMB contributions



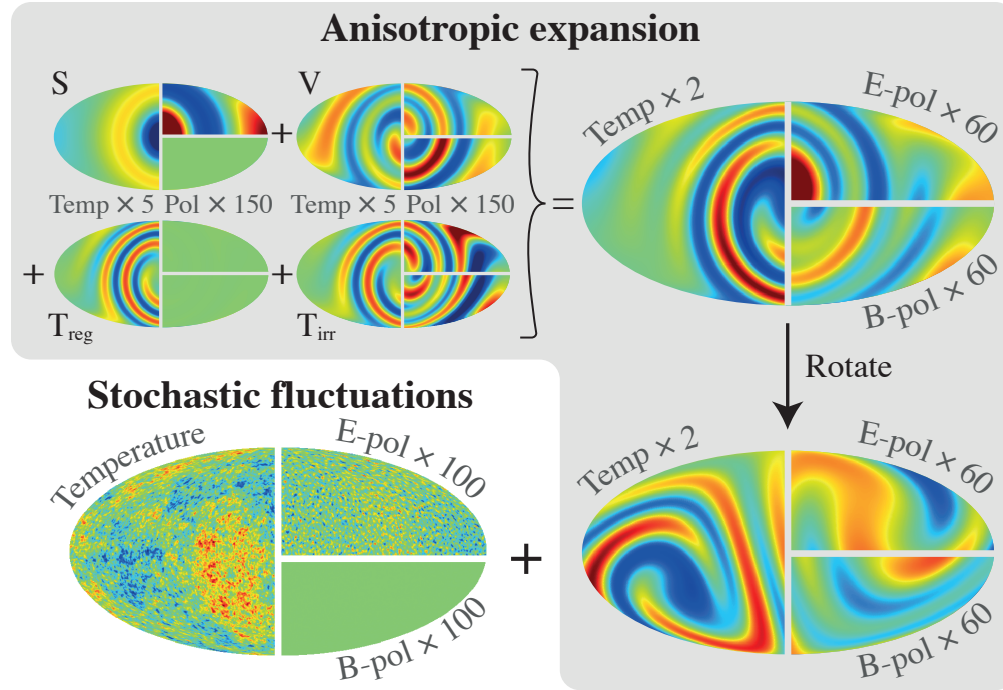
Best fit Bianchi component to Planck

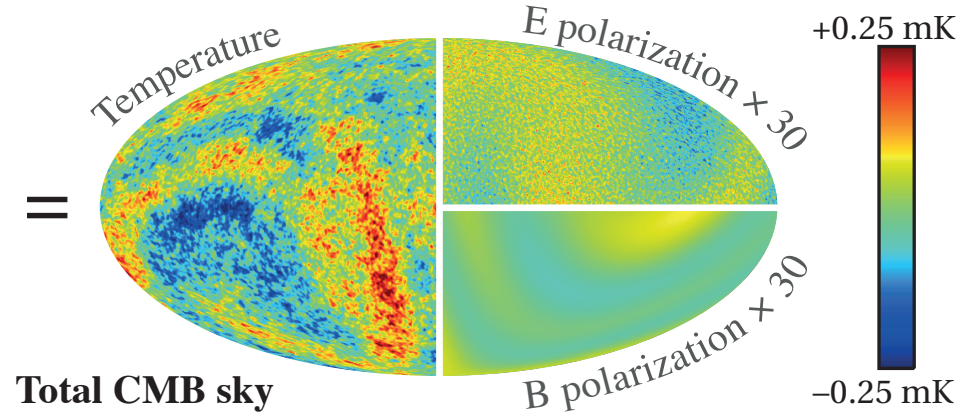
Planck Collaboration (2015)

How isotropic is the Universe?

- Tested full Bianchi freedom to conduct general test of isotropy.
- Highly constraining polarisation data used for the first time.
- Vectors:
  $(\sigma_V/H)_0 < 4.7 \times 10^{-11}$ *(95% CL)*

  Tensors: Collins and Hawking (1973)
  $(\sigma_T/H)_0 < 1.0 \times 10^{-6}$ *(95% CL)*
- Anisotropic expansion of the Universe disfavoured by 120,000:1.





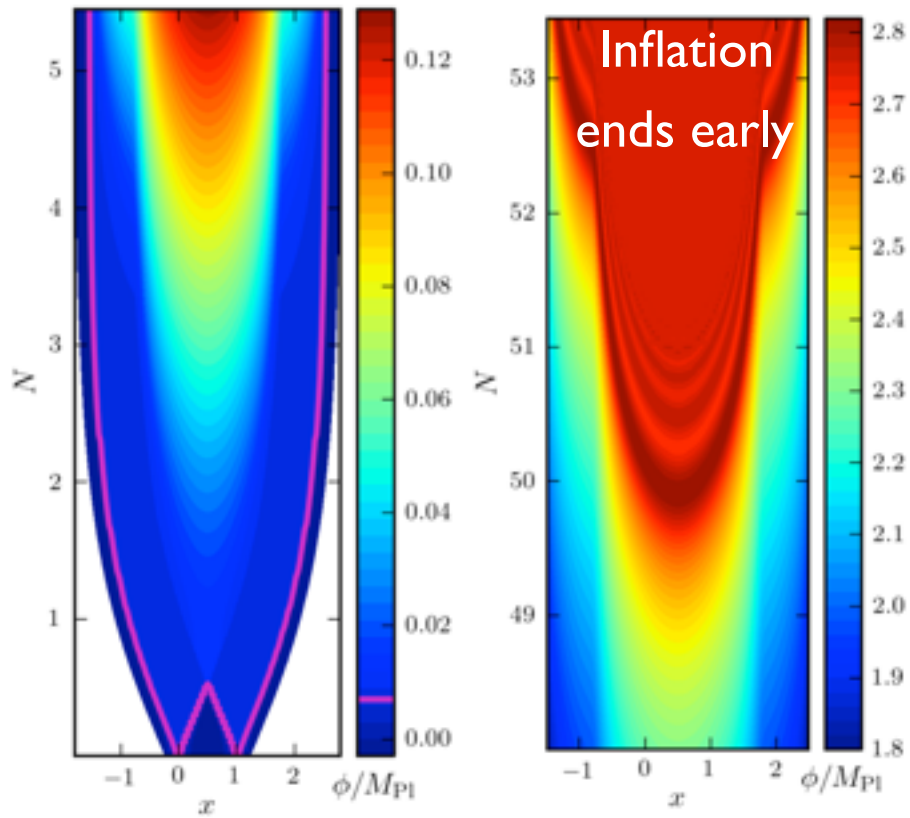
Saadeh, Feeney, Pontzen, Peiris, McEwen (PRL, 2016)

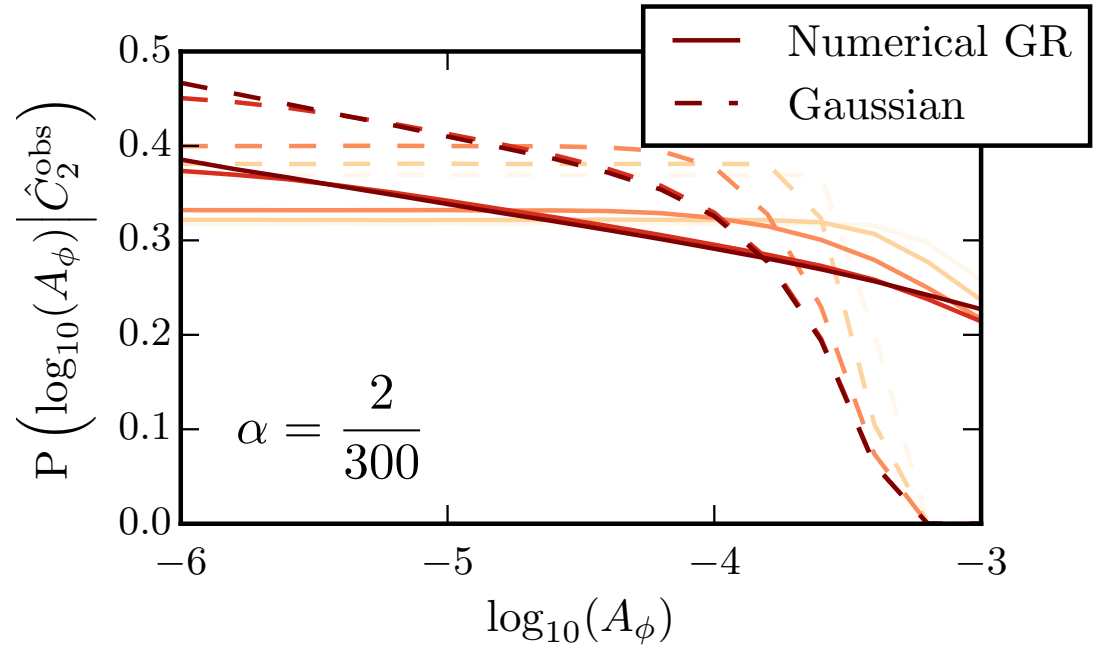
Inhomogeneous nonlinear (ultra)-large scale cosmology

- Dawn of **numerical relativity in cosmology**. CMB-related examples:

  Constraining ultra-large scale inhomogeneities with CMB quadrupole

  Testing eternal inflation with cosmic bubble collisions imprint on the CMB





ultra large scale structure amplitude

Bentivegna, Bruni (2016), Mertens, Giblin, Starkman (2016), East, Kleban, Linde, Senatore (2015)
Wainwright, Johnson, Peiris, Aguirre, Lehner, Leibling (2014), Johnson, Peiris, Lehner (2012)
Adamek, Daverio, Durrer, Kunz (2016), Braden, Johnson, Peiris, Aguirre (2016), GRChombo (2015)

H_0: Cosmological vs distance ladder measurements

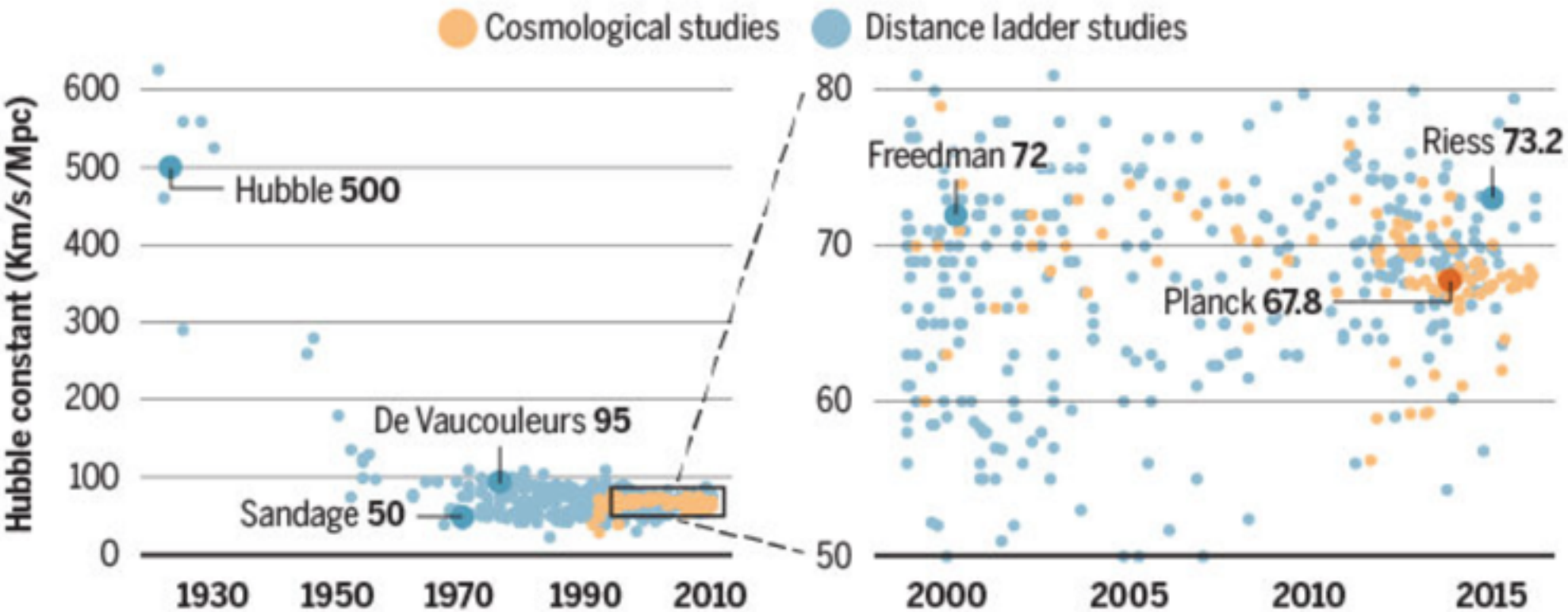
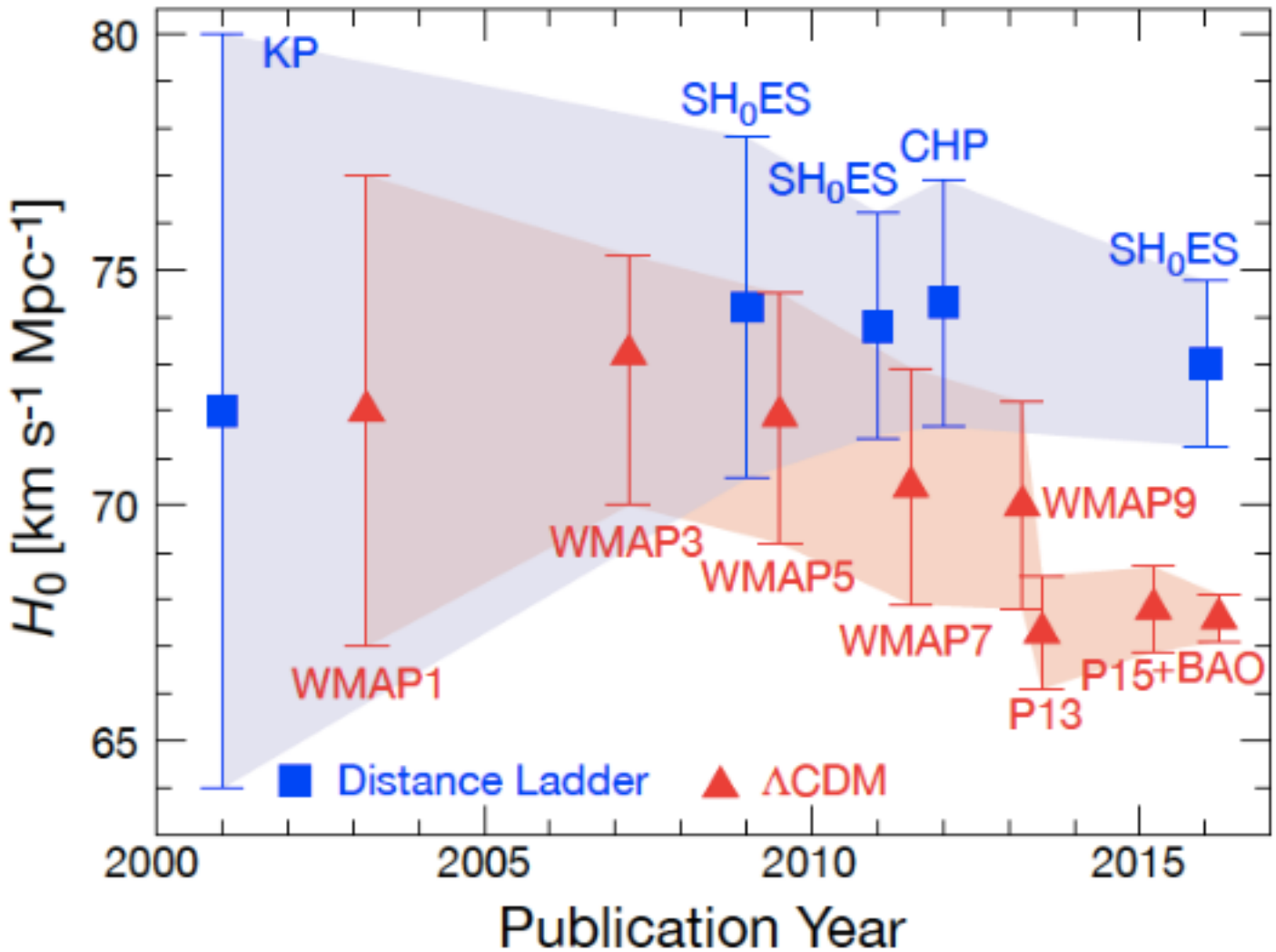


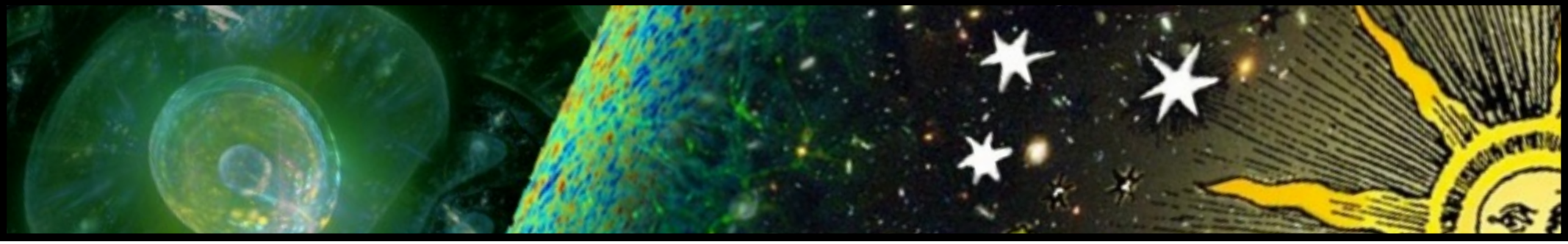
Figure: Science Magazine

Cosmic (in)consistency: real or "tension in a teapot"?



Systematics? astrophysics? (new) physics?

Freedman (2017) adapted from Beaton et al (2016)



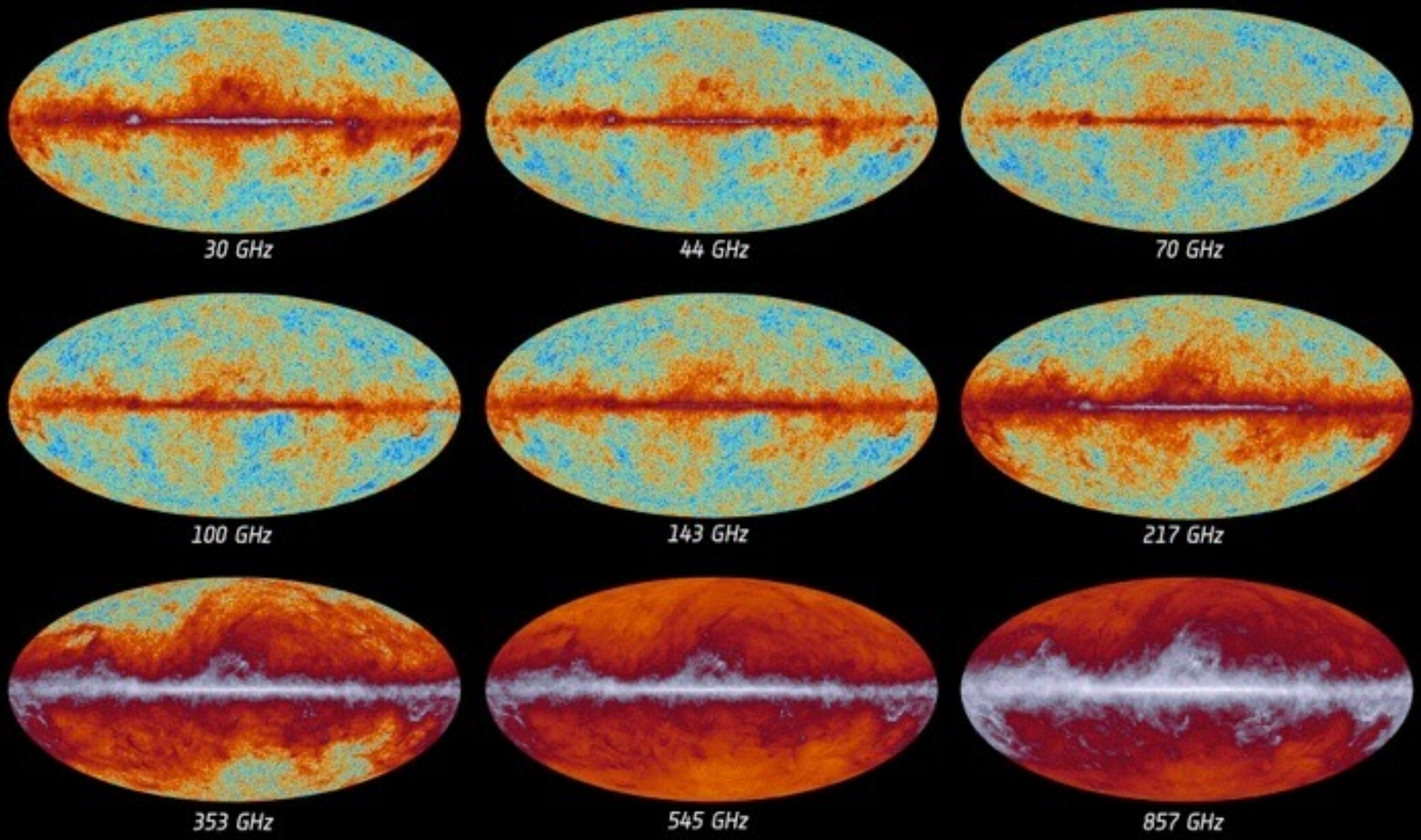
"No one trusts a model except the person who wrote it;
everyone trusts an observation, except the person who made it".

paraphrasing H. Shapley

Raw data: *~quadrillion samples over 29 months (HFI), 50 months (LFI)*

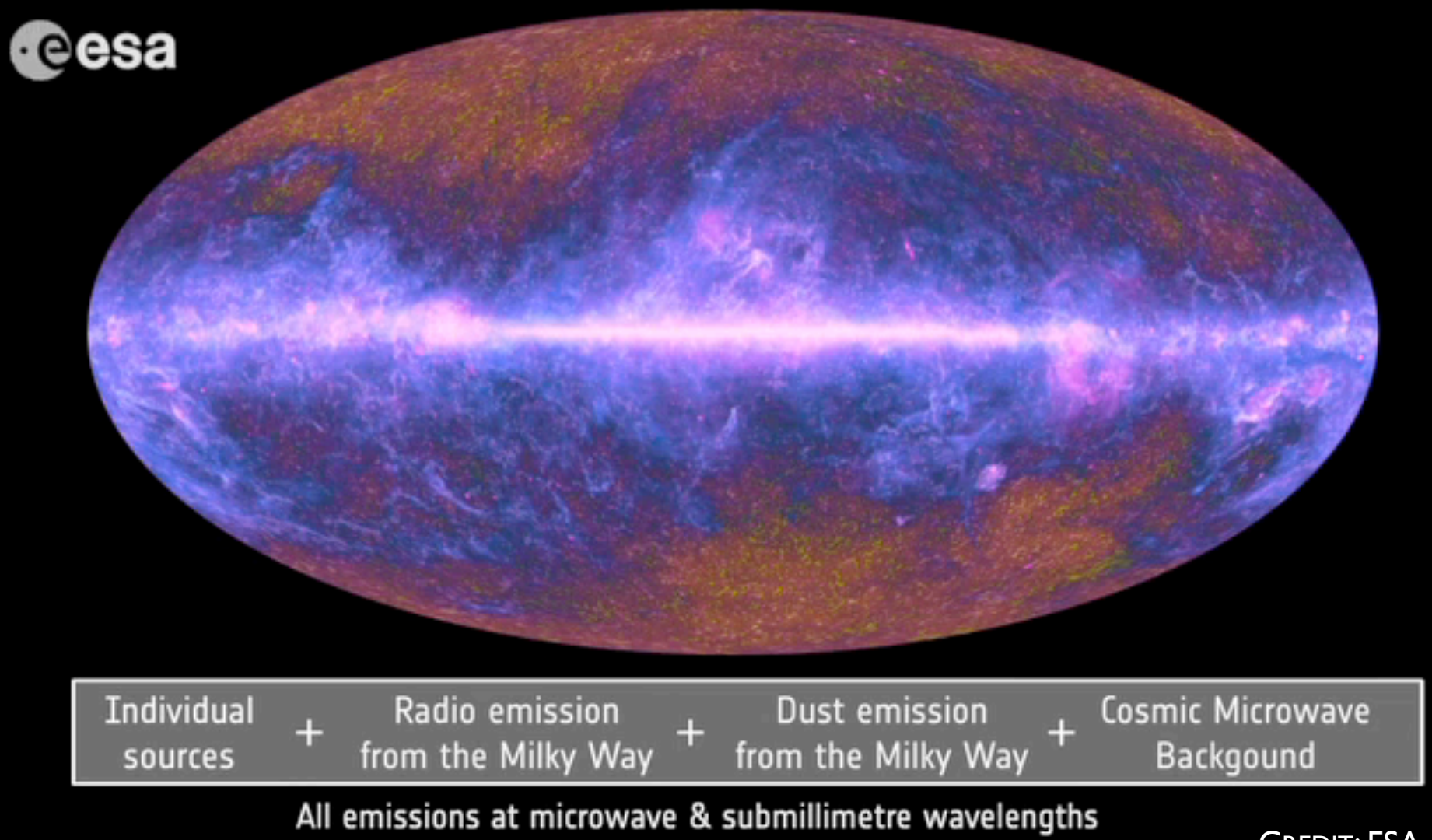
Maps: *~50 million pixels over 9 frequencies*

Planck (2015)



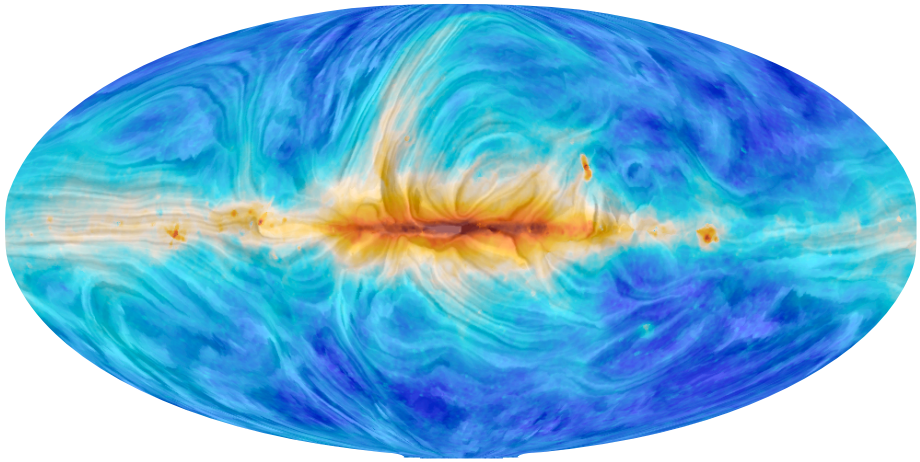
Emission at frequency = CMB + astrophysical sources along line of sight.

Planck observes in 9 bands over 30–850 GHz to disentangle cosmology from astrophysics

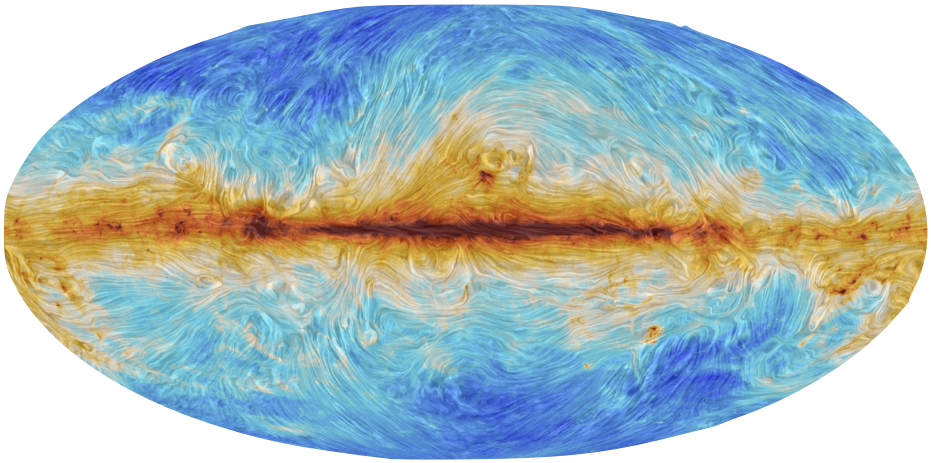


CREDIT: ESA / PLANCK

Just beginning to characterise polarised foregrounds



polarised
synchrotron



polarised
dust

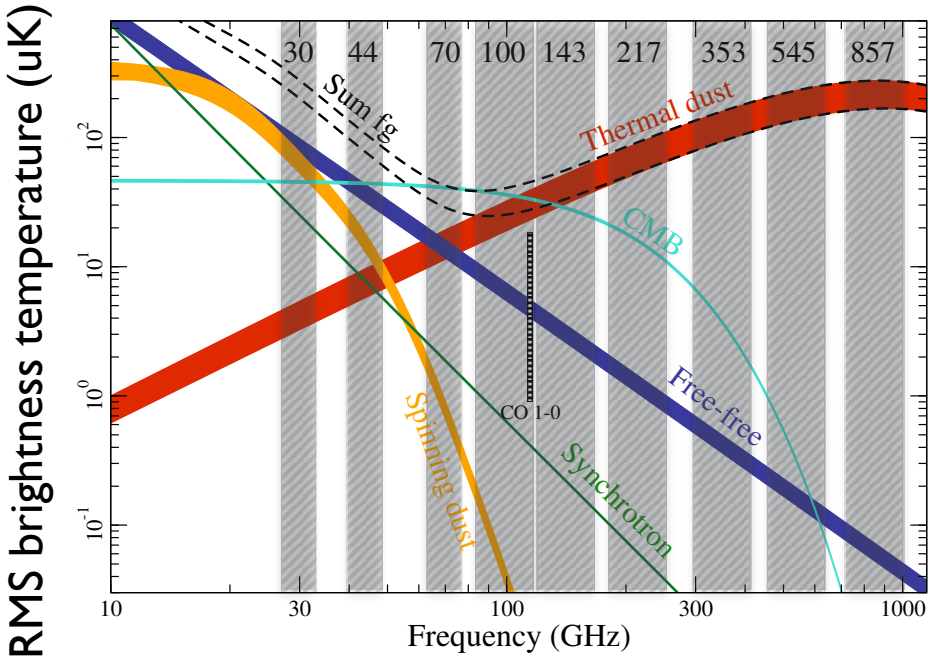
Polarised FG **complex & filamentary**

Planck Collaboration (2015), Planck intermediate results. XLIV. (2016)

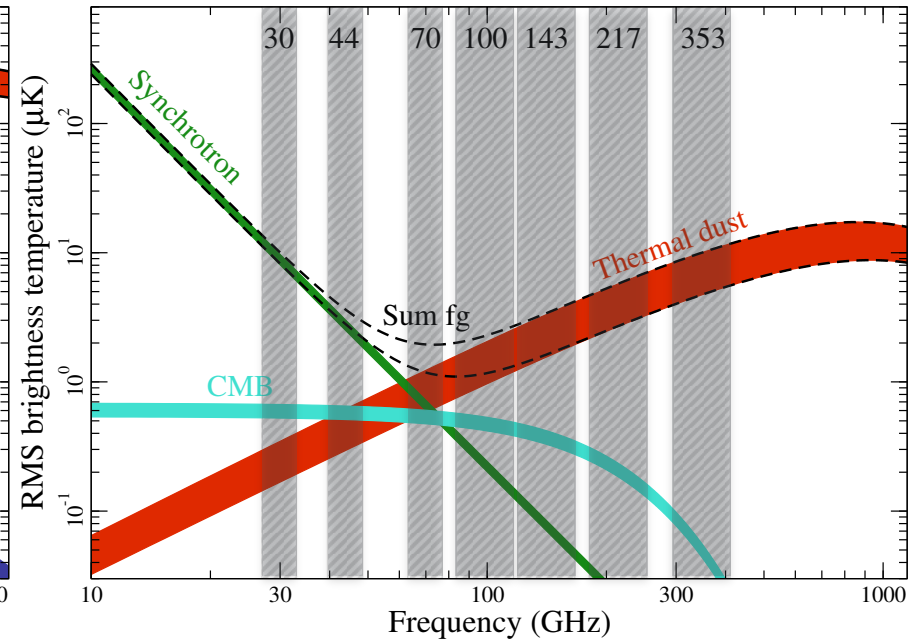
Frequency dependence of Galactic foregrounds

CMB obscured by astrophysical foregrounds at all frequencies

Orders of magnitude worse for polarisation



Temperature



Polarisation

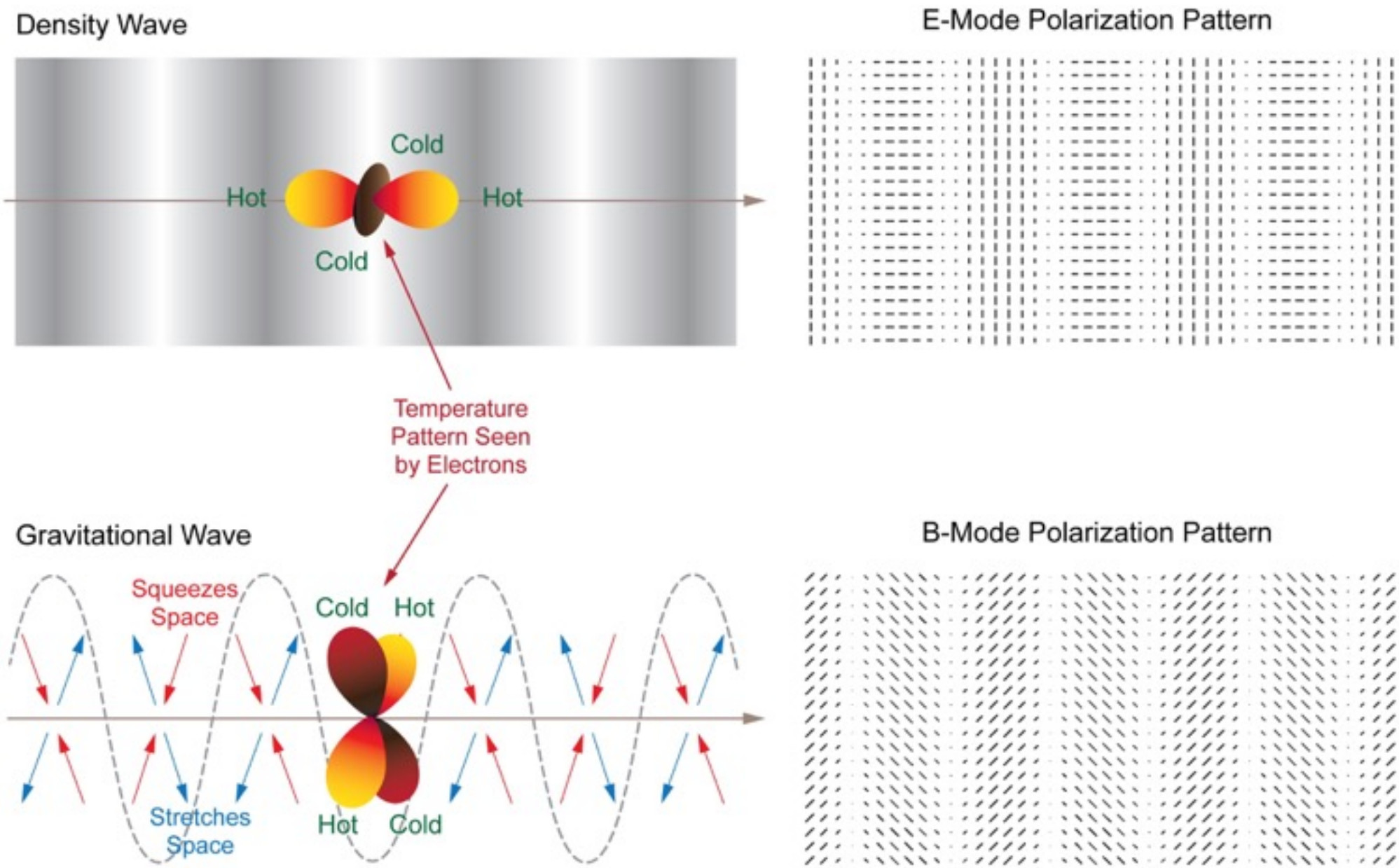
Planck Collaboration

What do we know about cosmic initial conditions?

- Background:
  - Spatial flatness (tested at <1% level!)

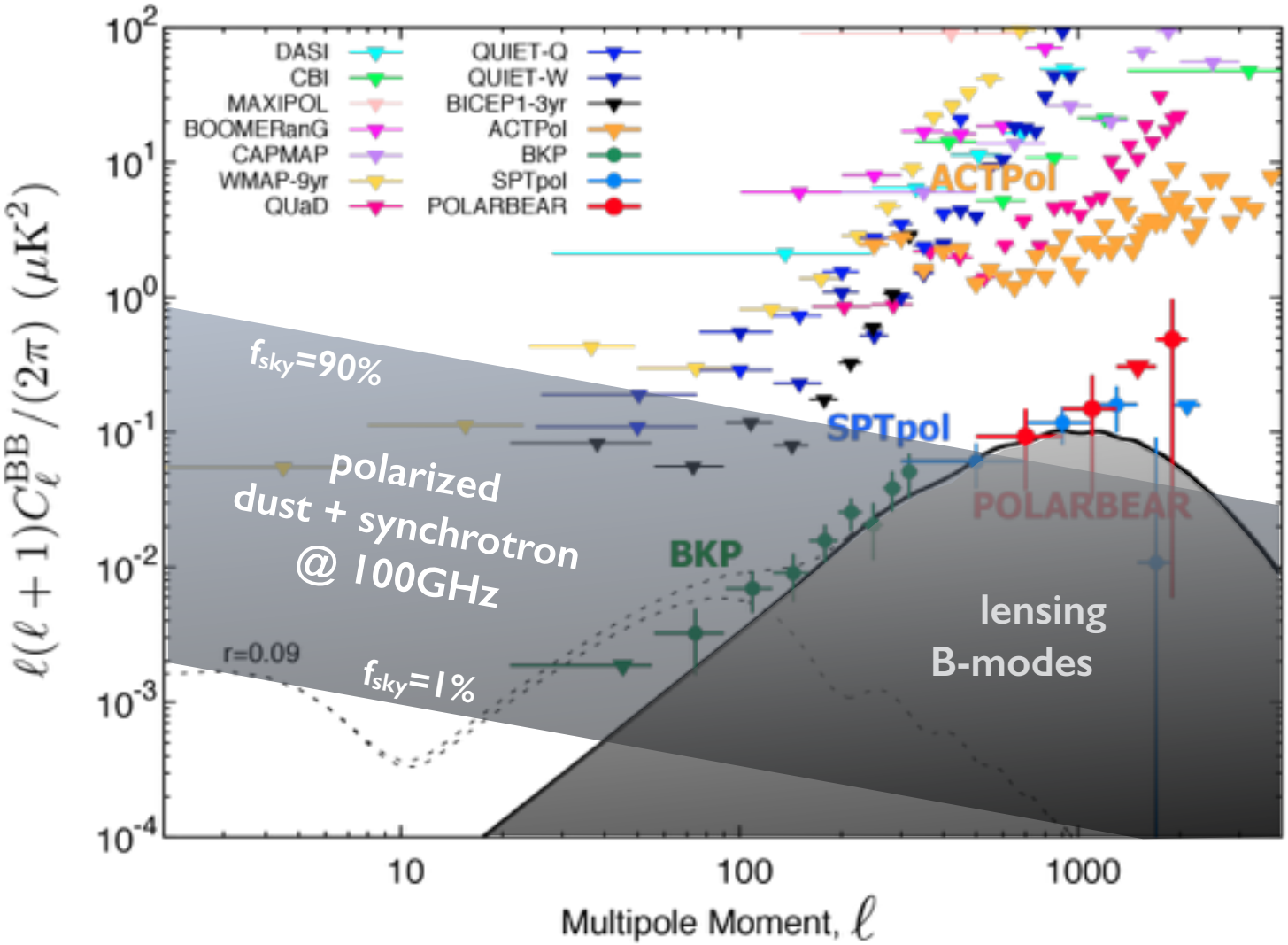
- Perturbations:
  - scalar fluctuations in the CMB temperature
    - ✓ nearly but not exactly scale-invariant (>5σ!)
    - ✓ approximately Gaussian (at the 10^{-4} level!)
    - ✓ Adiabatic fluctuations
    - ✓ Superhorizon perturbations
  - ? primordial tensor fluctuations (stochastic gravitational waves)

Gravitational waves also create polarisation…. lensing creates *B*-mode polarisation from *E*-mode polarisation even if no tensors.



CREDIT: BICEP / KECK COLLABORATIONS

CMB polarisation status



A Measurement of the Cosmic Microwave Background B-Mode Polarization Power Spectrum at Sub-degree Scales with POLARBEAR
The POLARBEAR Collaboration
The Astrophysical Journal (**2014**)

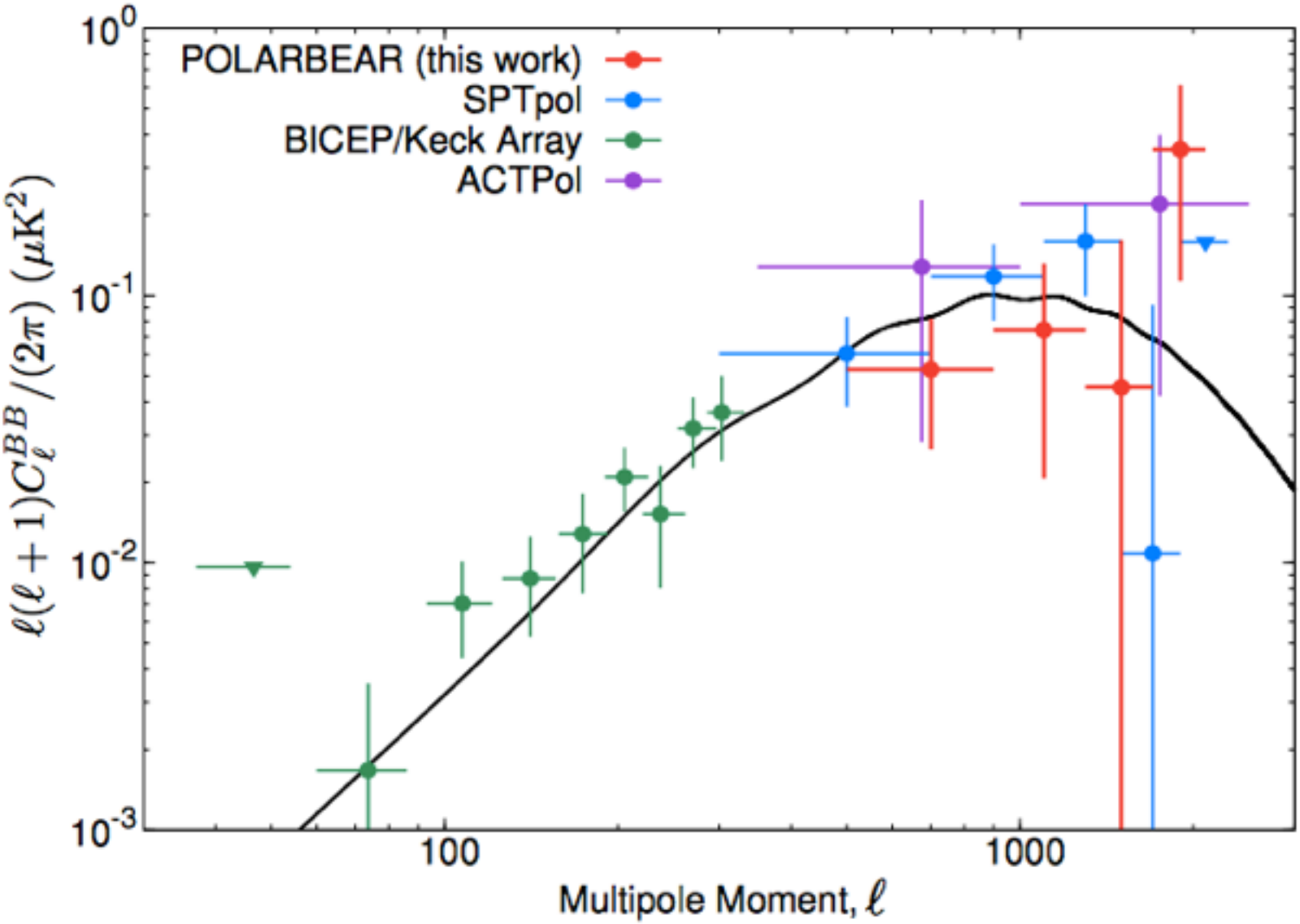
Measurements of Sub-degree B-mode Polarization in the Cosmic Microwave Background from 100 Square Degrees of SPTpol Data
R. Keisler et al.
The Astrophysical Journal, (**2015**)

Joint Analysis of BICEP 2 / Keck Array and Planck Data
P. Ade et al.
Physical Review Letters (**2015**)

BICEP/Keck Array 95 GHz (2015)
r<0.09 (95%)

Yuji Chinone / Josquin Errard

CMB polarisation status



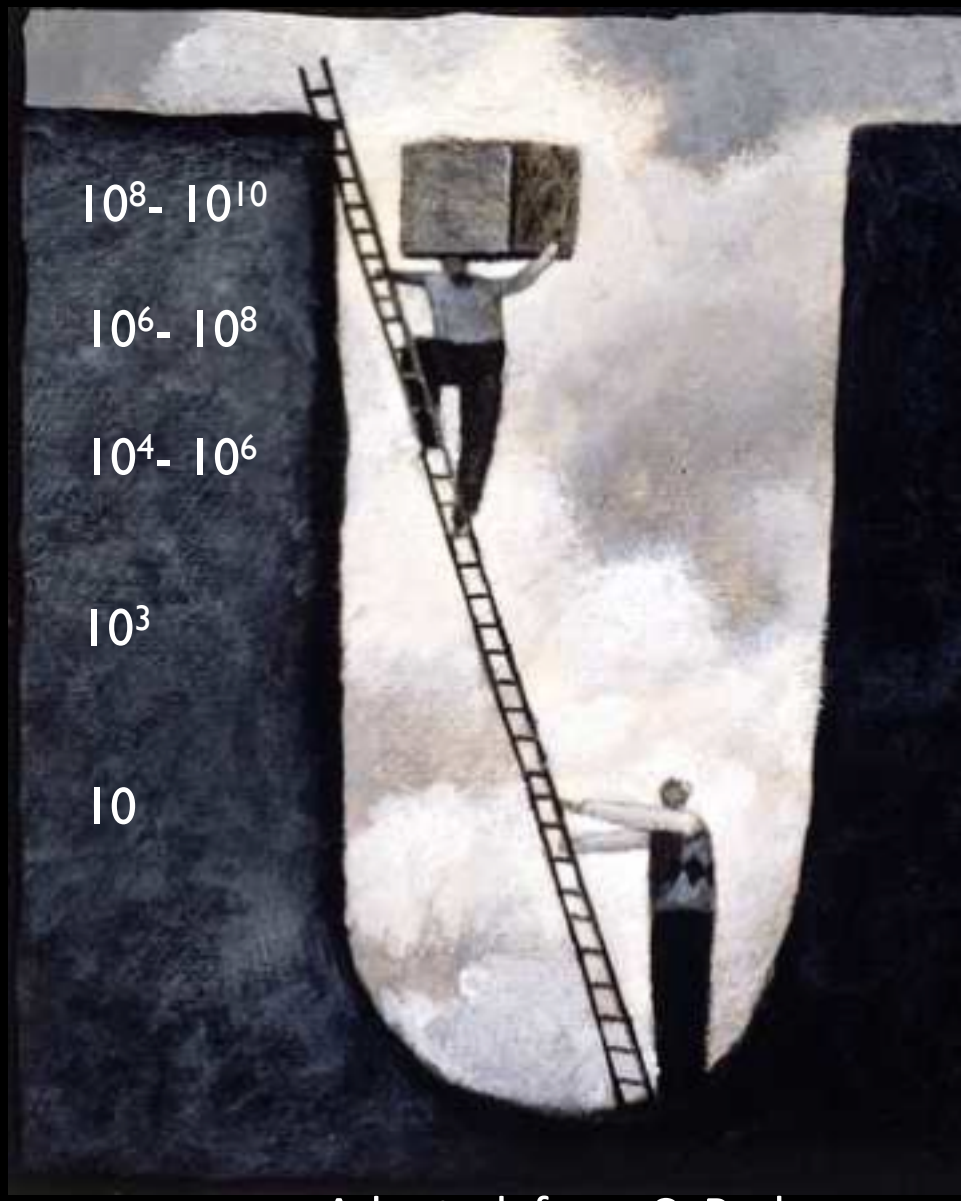
PolarBear Collaboration (2017)

The challenge

Typical degree-scale brightness fluctuations (150GHz)

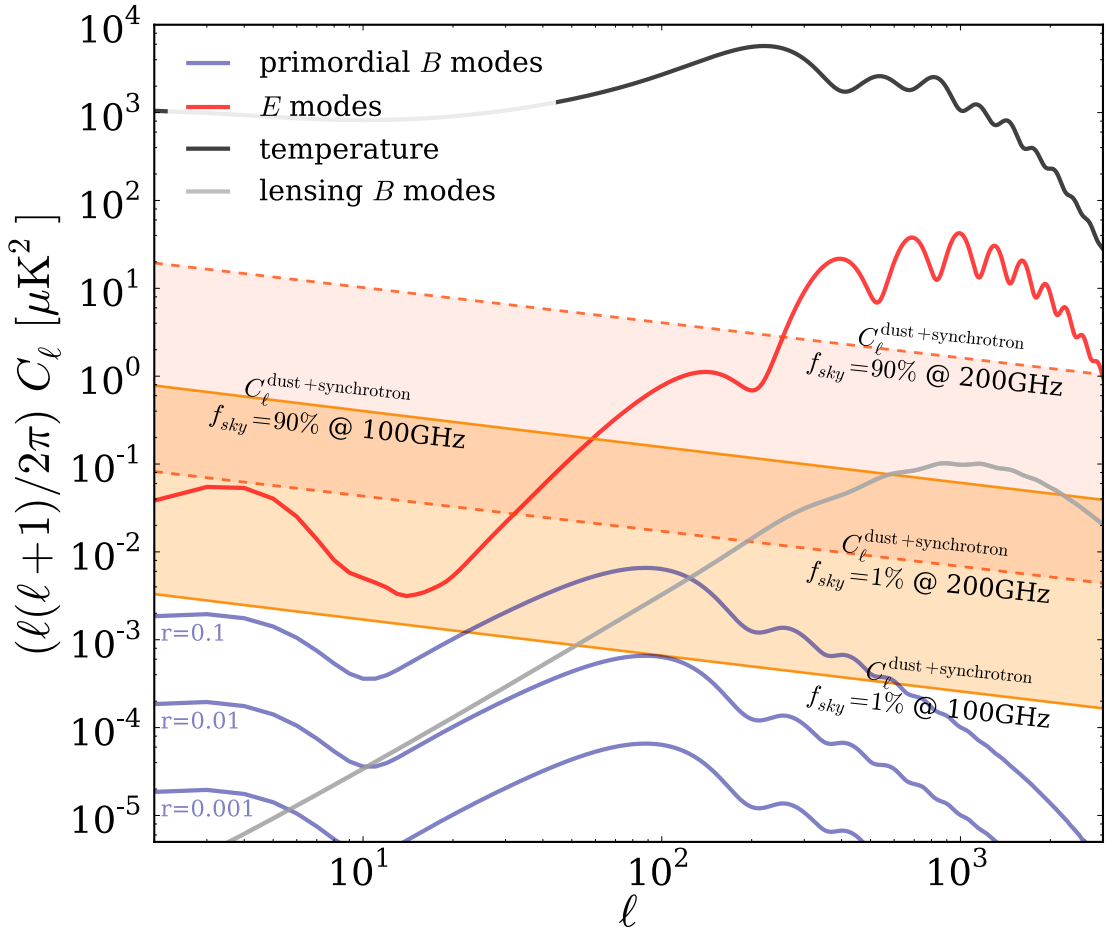
T → P

Ground, Telescope mount etc	3-300 K
Atmosphere	30 mK - 3 K
Galaxy	0.3-30mK
CMB T anisotropies	30μK
Lensing B modes (at arcmin)	300 nK
r=0.01 B-modes	30 nK
noise you want to reach	<10 nK



Adapted from C. Pryke

Polarisation is not going to be easy.



- Planck/BICEP2/Keck: polarised dust and/or synchrotron important at all Galactic latitudes (1502.00612, 1502.01588)

- Lensing additional "foreground" for tensors

Errard, Feeney (joint first authors), Peiris, Jaffe (JCAP, 2016)

Designing next generation polarisation experiments

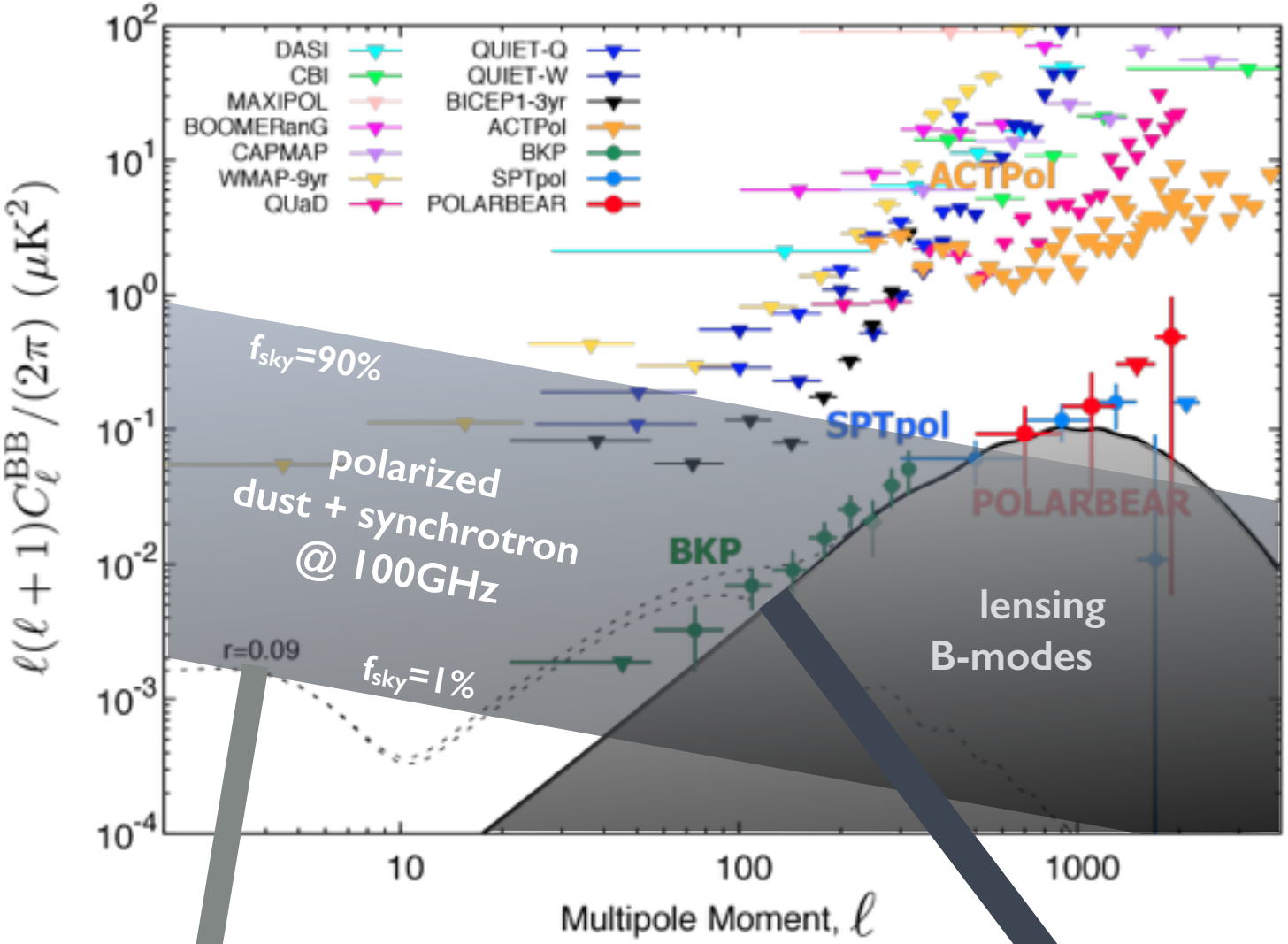
- ***Degree-scale B-modes: inflation***

- ***Arc-minute scale B-modes: gravitational lensing***

  – *late-time physics: sum of neutrino masses*
  – *geometry: break geometric degeneracy, measure curvature*

- ***EE and TE more constraining than TT (Galli+ 1403.5271)***

- ***Huge investment!***
  AdvACTPol, BICEP3, CLASS, Simons Array, SPT-3G, EBEX10K, PIPER, SPIDER, Simons Observatory, COrE+, LiteBIRD, PIXIE, Stage IV, …



A Measurement of the Cosmic Microwave Background B-Mode Polarization Power Spectrum at Sub-degree Scales with POLARBEAR
The POLARBEAR Collaboration
The Astrophysical Journal (**2014**)

Measurements of Sub-degree B-mode Polarization in the Cosmic Microwave Background from 100 Square Degrees of SPTpol Data
R. Keisler et al.
The Astrophysical Journal, (**2015**)

Joint Analysis of BICEP 2 / Keck Array and Planck Data
P. Ade et al.
Physical Review Letters (**2015**)

BICEP/Keck Array 95 GHz (2015)
r<0.09 (95%)

foregrounds cleaning

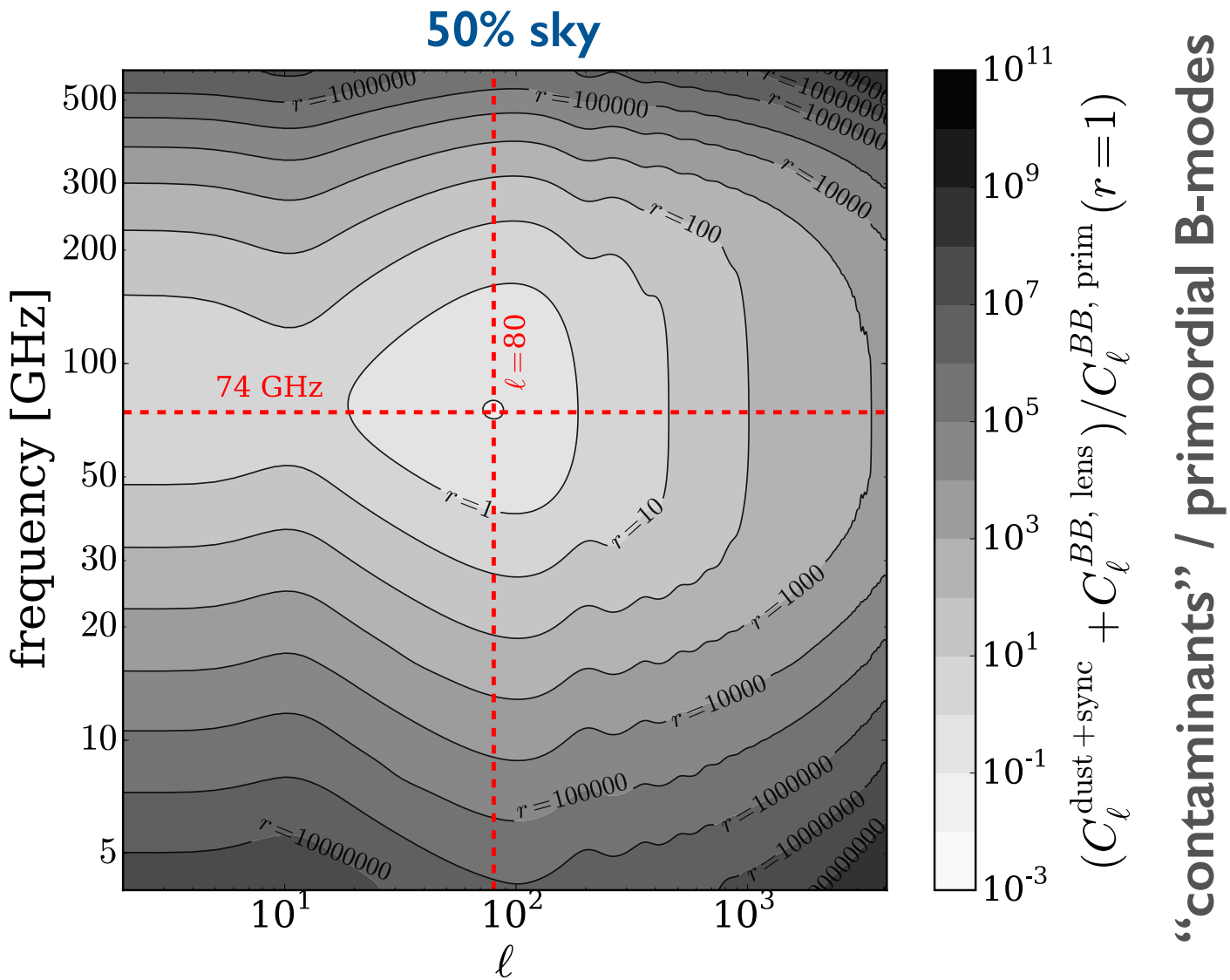
[Stompor et al (2009),
Stivoli et al (2010)
Errard et al (2011+2012)]

delensing

[Seljak & Hirata (2004),
Smith et al (2012),
Sherwin & Schmittfull (2015)]

Yuji Chinone / Josquin Errard

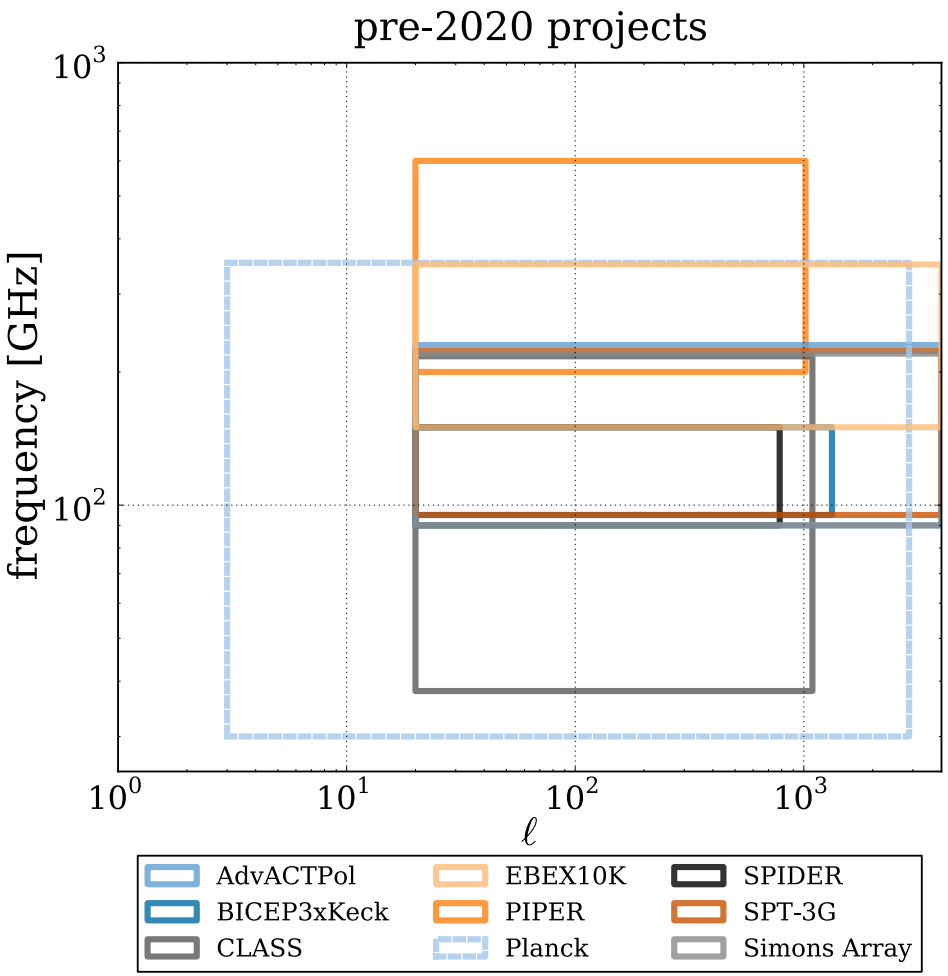
Polarisation is not going to be easy.

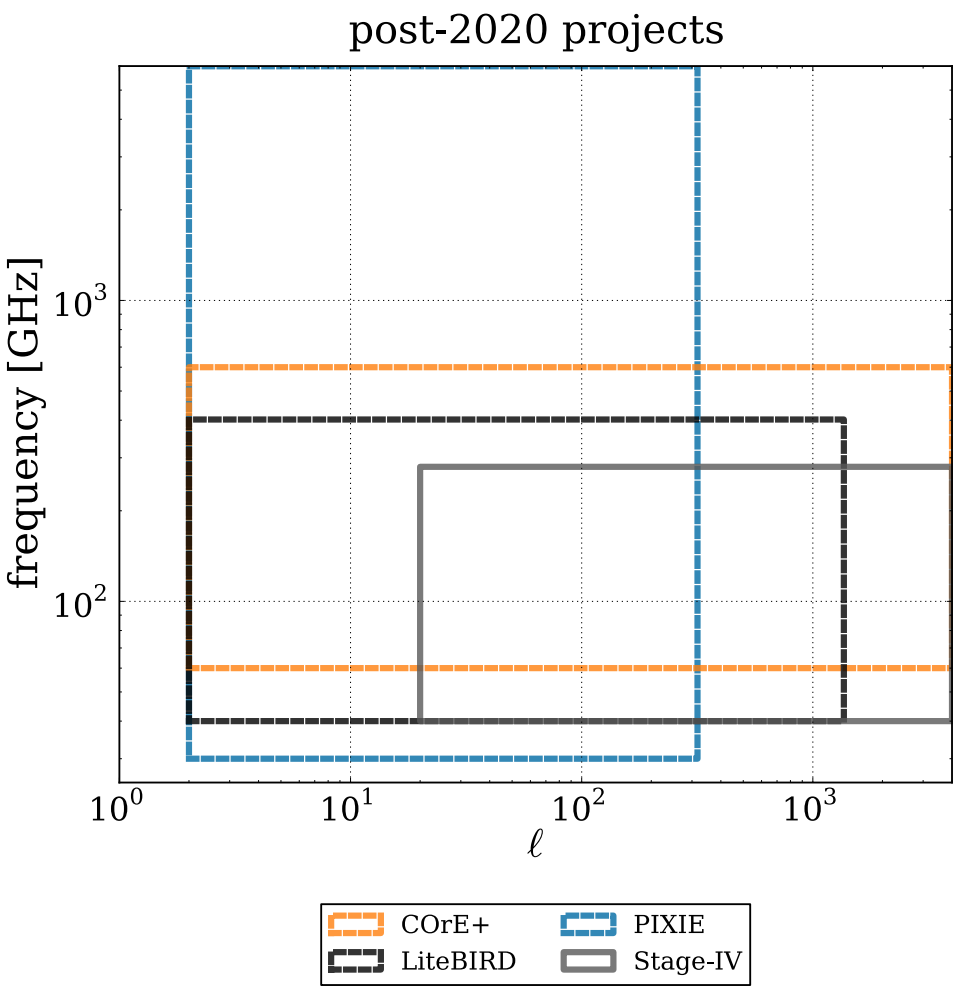


- Half-sky minimum for tensors: $\ell \sim 80$, 75 GHz

Errard, Feeney (joint first authors), Peiris, Jaffe (JCAP, 2016)

Experiments

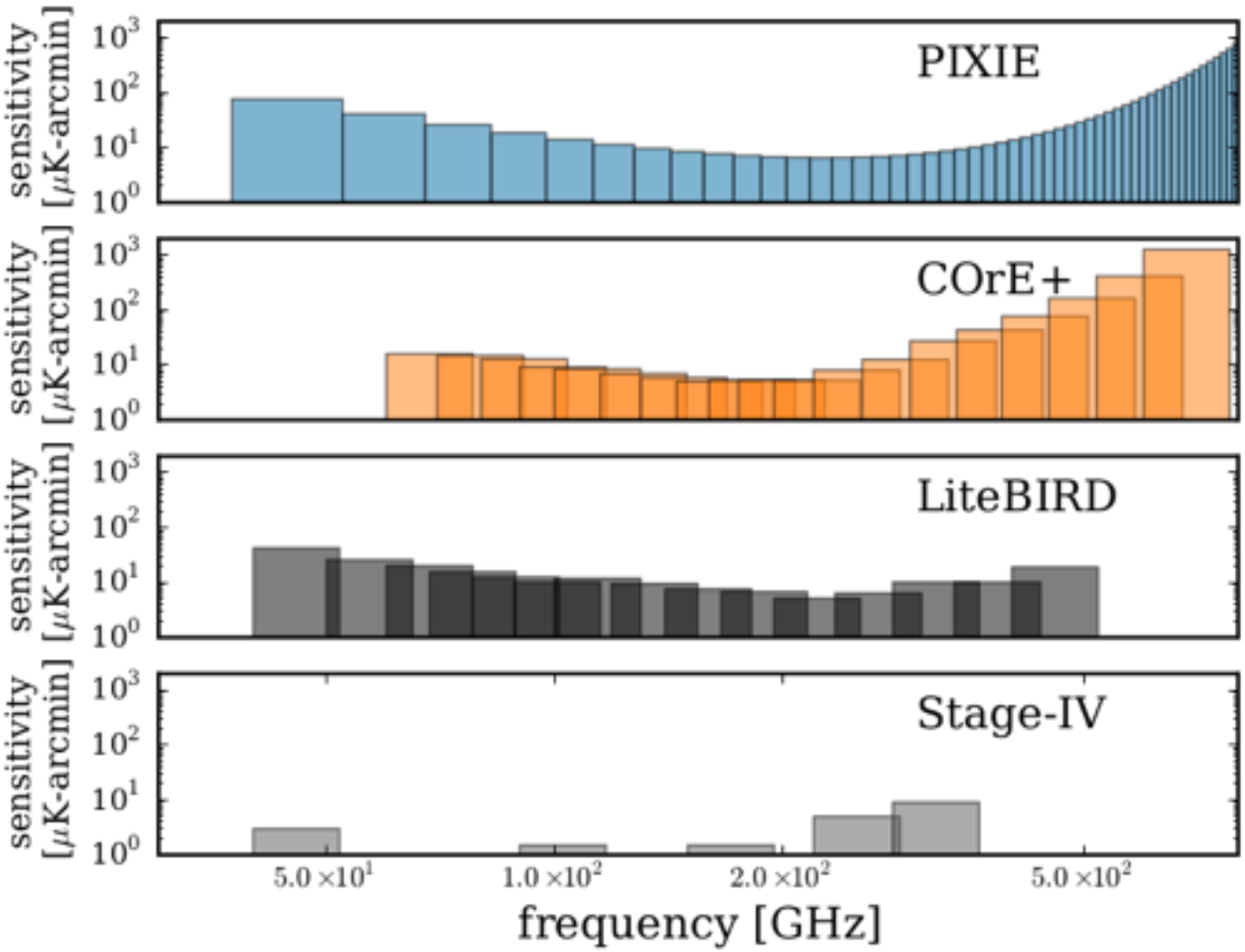




- Frequency bands, polarisation noise, beams and fsky
- Pre-2020 all crossed with Planck

Errard, Feeney (joint first authors), Peiris, Jaffe (JCAP, 2016)

Experiments (post-2020 examples)



- Frequency bands, polarisation noise, beams and fsky
- Pre-2020 all crossed with Planck

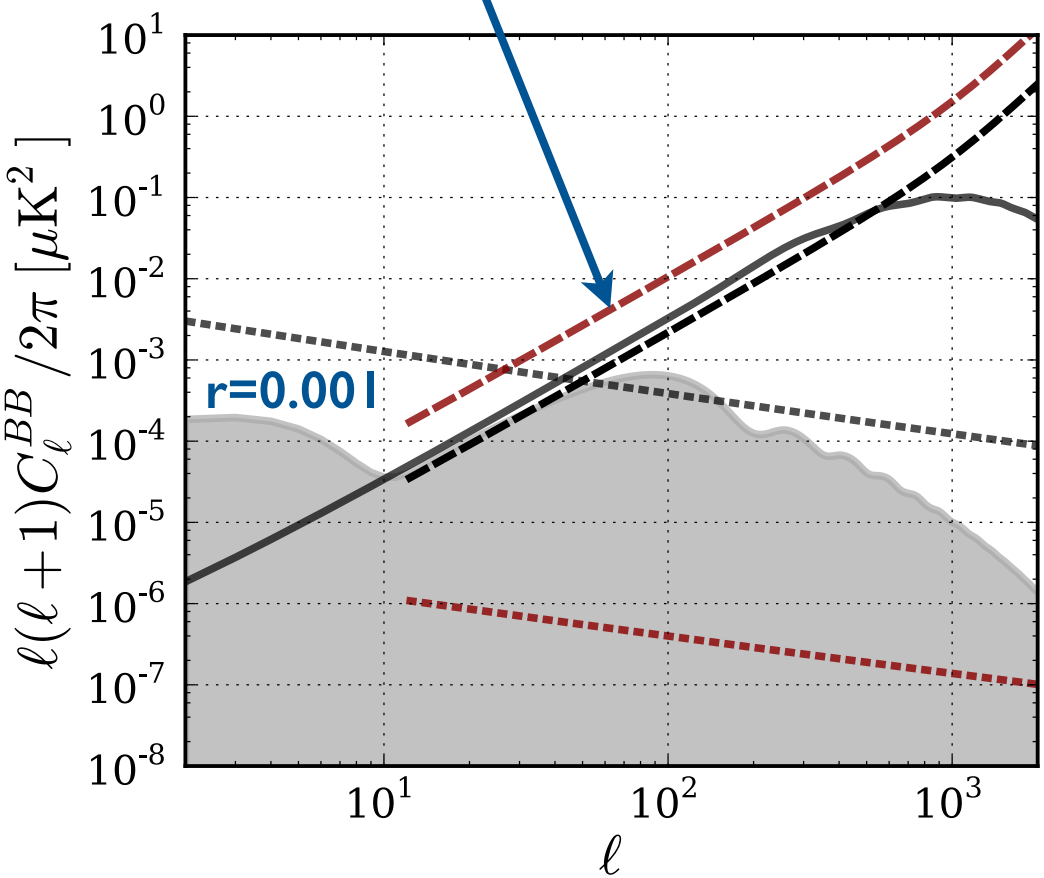
Errard, Feeney (joint first authors), Peiris, Jaffe (JCAP, 2016)

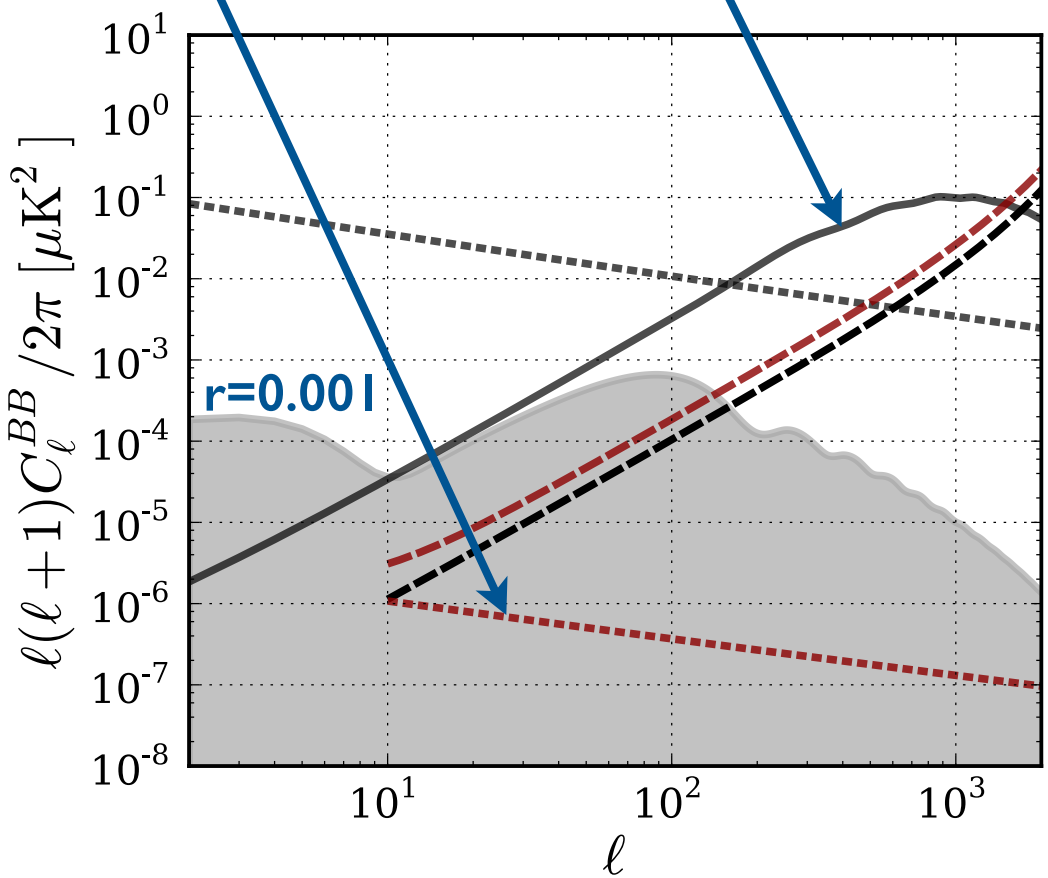
Foregrounds: selected real experiments

cleaned B-modes
noise-dominated

residuals
important

cleaned B-modes
lensing-dominated



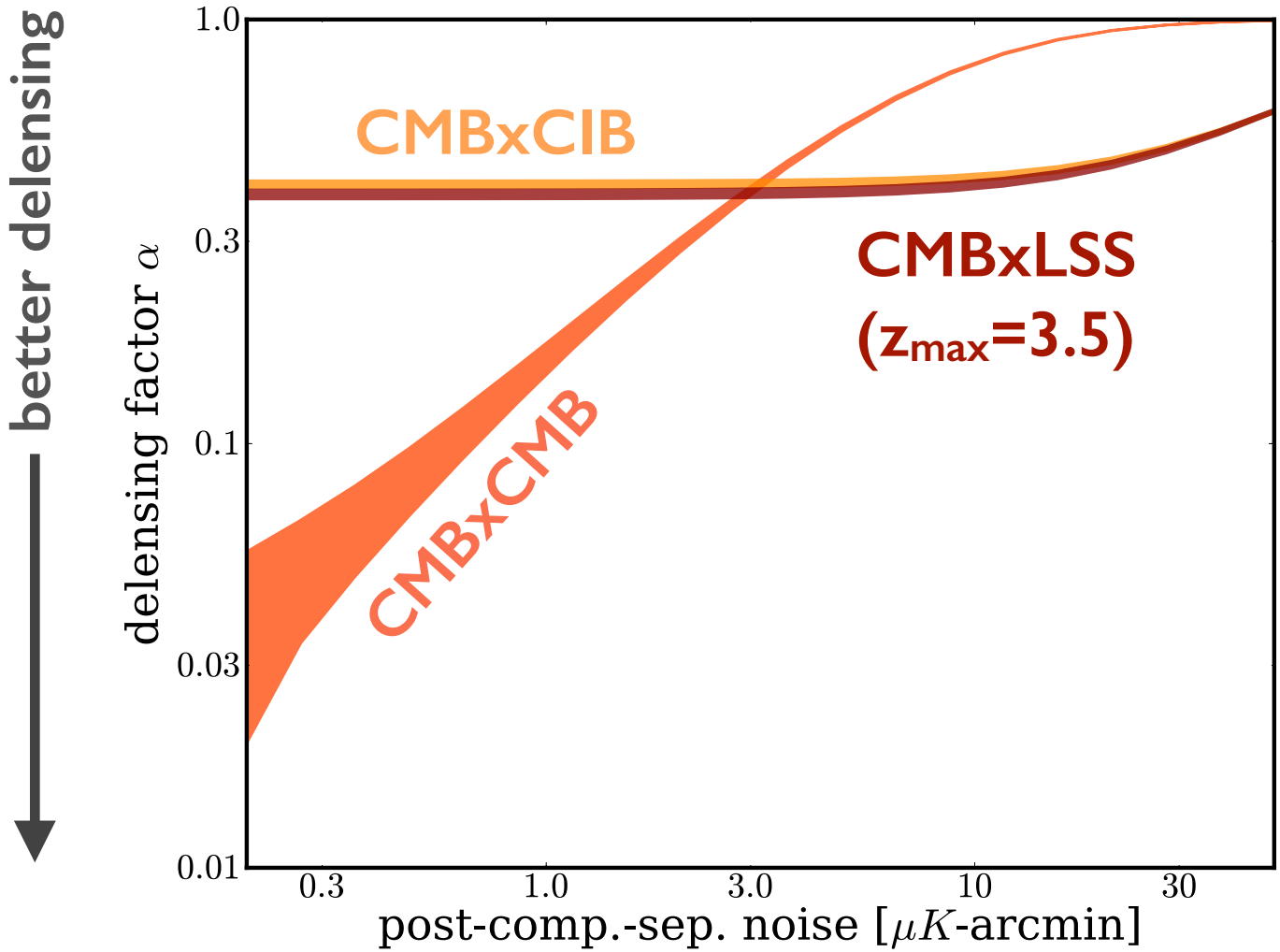


Pre-2020: ground x balloon

Post-2020: ground x satellite

Errard, Feeney (joint first authors), Peiris, Jaffe (JCAP, 2016)

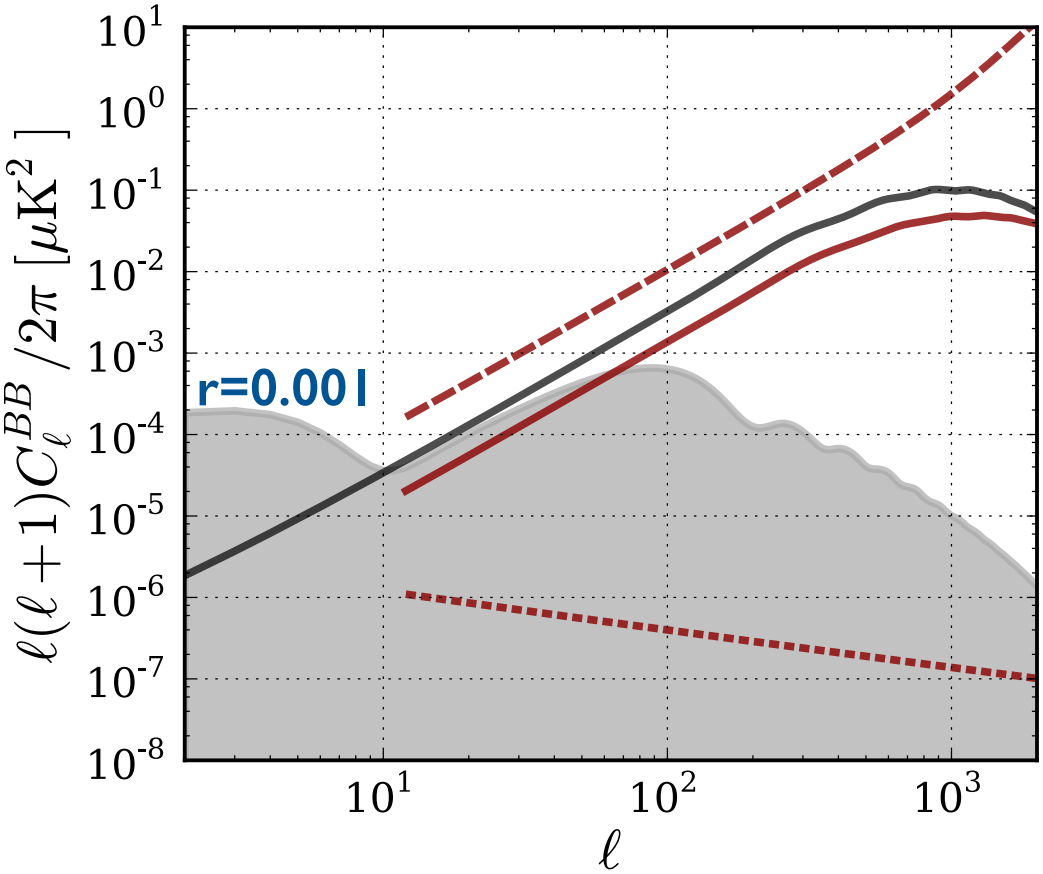
Delensing: toy experiment

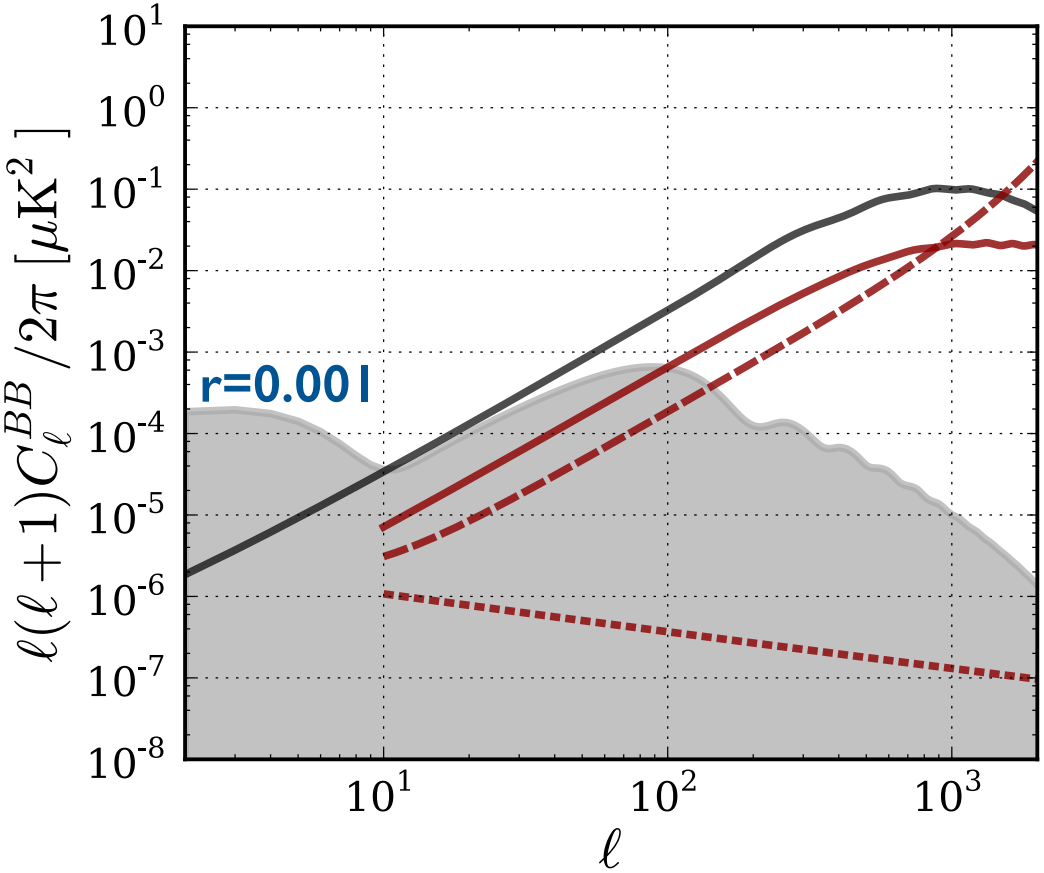


- 3' beam, 0.01 < f_{sky} < 1.0 (f_{sky} floor without delensing)
- CIB/LSS better for noisy expts; CMB delenses to zero if noiseless.

Errard, Feeney (joint first authors), Peiris, Jaffe (JCAP 2016)

Delensing: selected real experiments



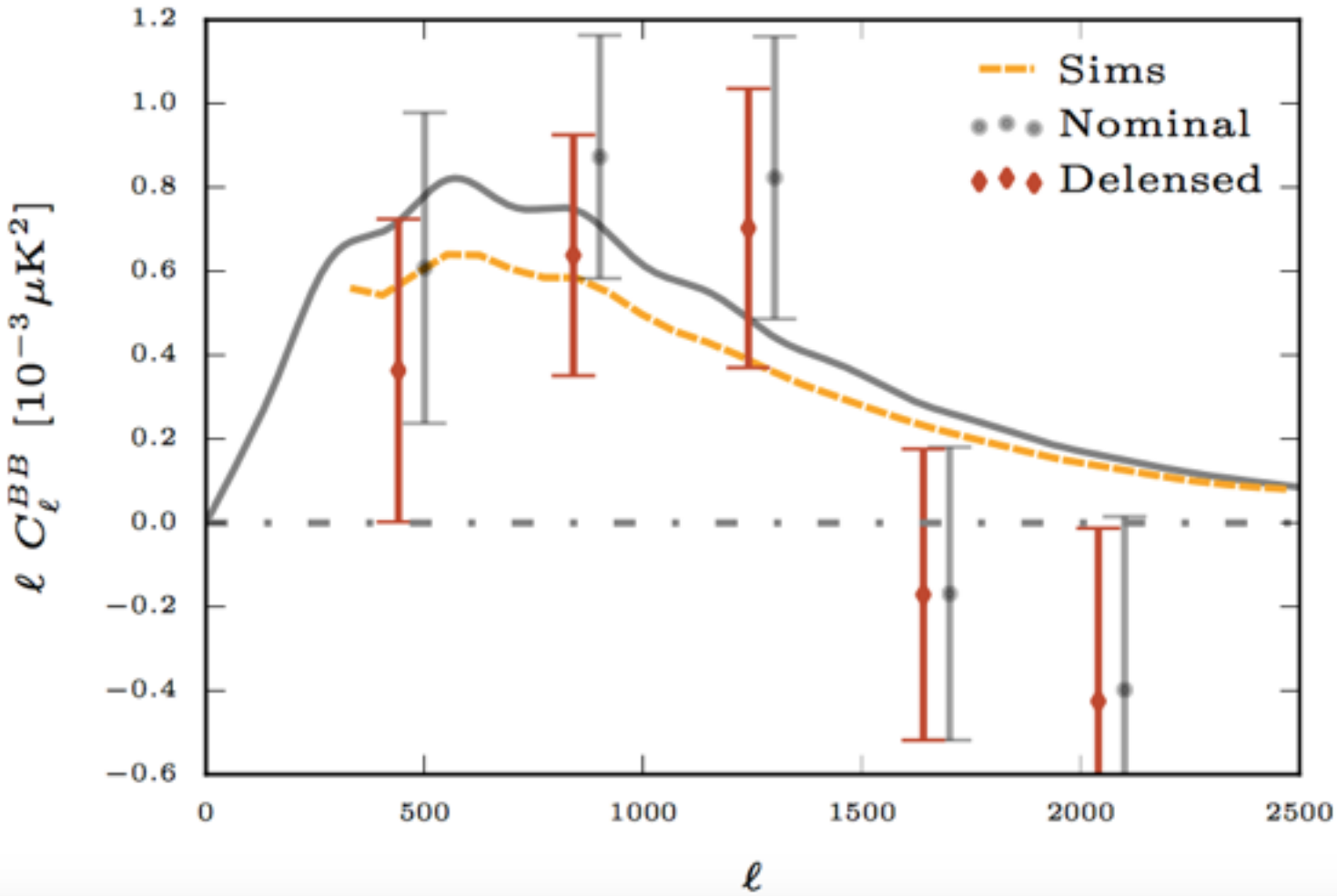


Pre-2020: ground x balloon
CIB delensing

Post-2020: ground x satellite
CMB delensing

Errard, Feeney (joint first authors), Peiris, Jaffe (JCAP, 2016)

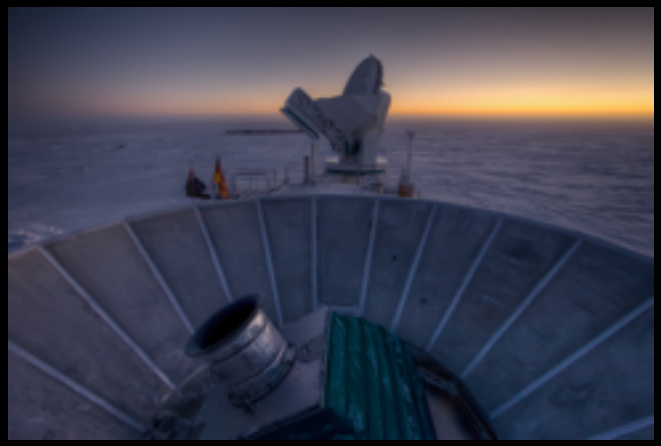
B-mode delensing demonstration



SPT-pol and Herschel 500 micron CIB map
(28% reduction; efficiency limited by noise in lensing potential map)

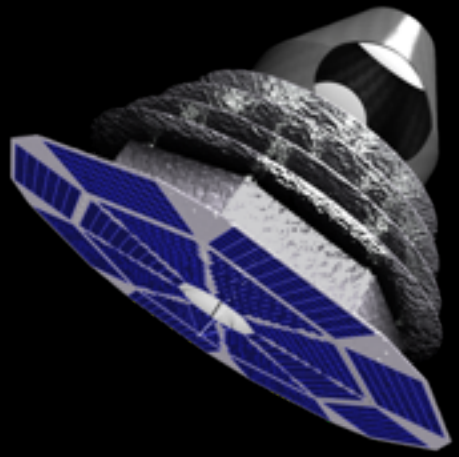
Manzotti et al (2017)

CMB at commercial aircraft altitudes?



ground

balloon



satellite

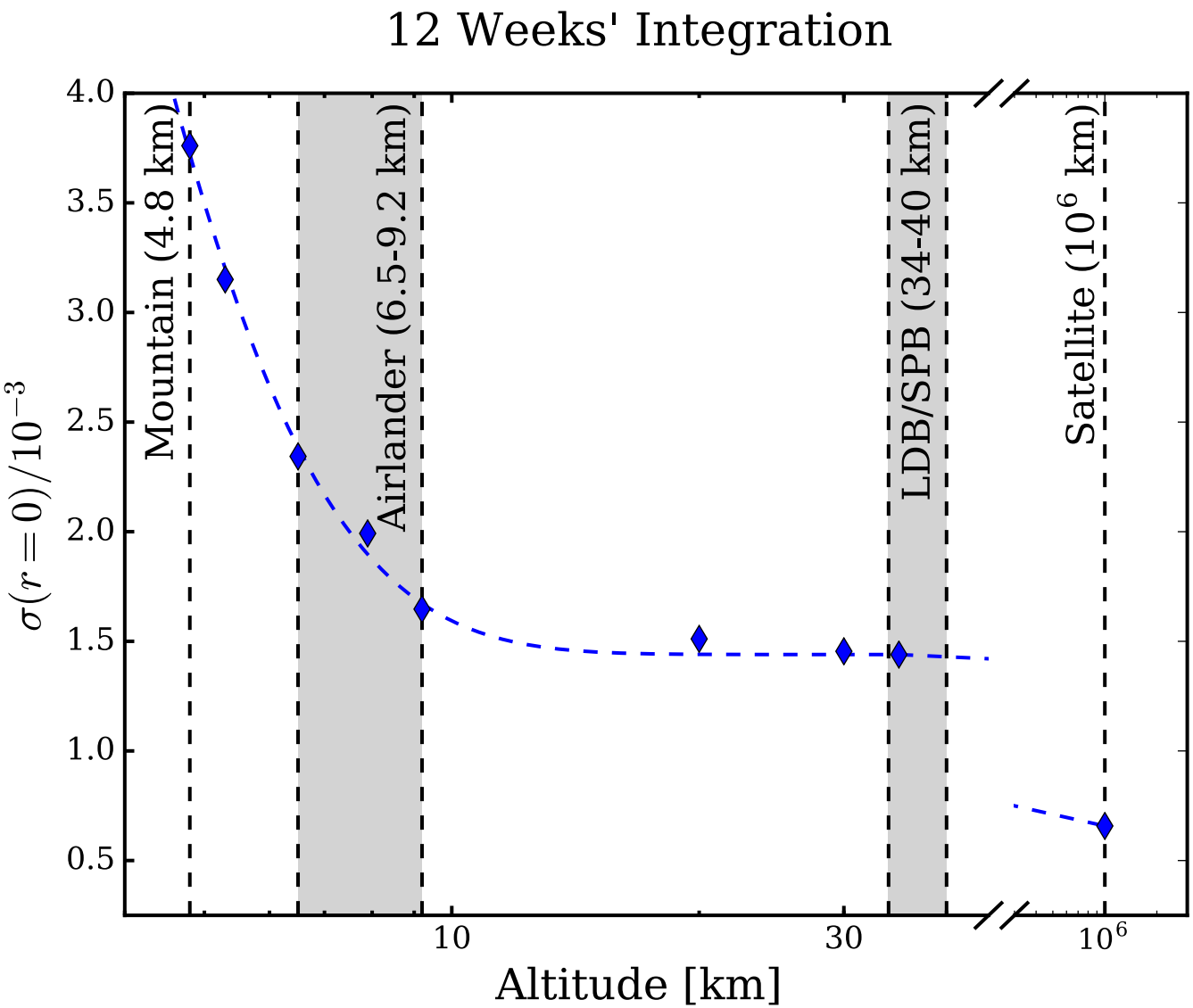
Airlander (Hybrid Air Vehicles)
(300 ft megablimp) ??

10 km flight altitude

3 week flights

2.5T payload

Up, up and away!



- half-sky, 10,000 detectors distributed equally @ [40, 94, 150, 220, 270, 350] GHz, synch+dust cleaning, no delensing

Feeney, Gudmundsson, Peiris, Errard, Verde (2017, MNRAS Letters)

Cosmological Highlights

Pre-2020:

- **inflation:**
  - $\sigma(r=0.001) \sim 0.003$
  - $\sigma(n_t) \sim 0.2$ $(r = 0.1)$

- **neutrinos:**
  - $\sigma(M_\nu) \sim 60$ meV

    CMBxCIB deflection estimate

Post-2020:

- **inflation:**
  - $\sigma(r=0.001) \sim 2 \times 10^{-4}$

    5-σ measurement (<80% delensing)
  - $\sigma(n_t) \sim 0.03$ $(r = 0.1)$

- **neutrinos:**
  - $\sigma(M_\nu) \sim 30$ meV

    (normal vs inverted hierarchies…)
  - $\sigma(N_{eff}) \sim 0.024$

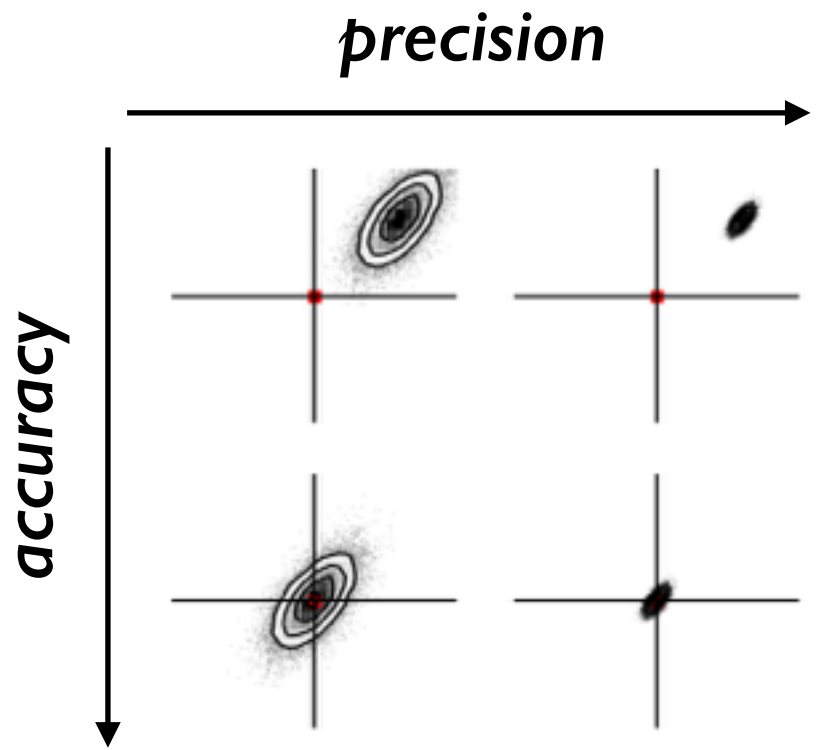
    (thermal history 1 sec after Big Bang!)

Errard, Feeney (joint first authors), Peiris, Jaffe (JCAP, 2016)

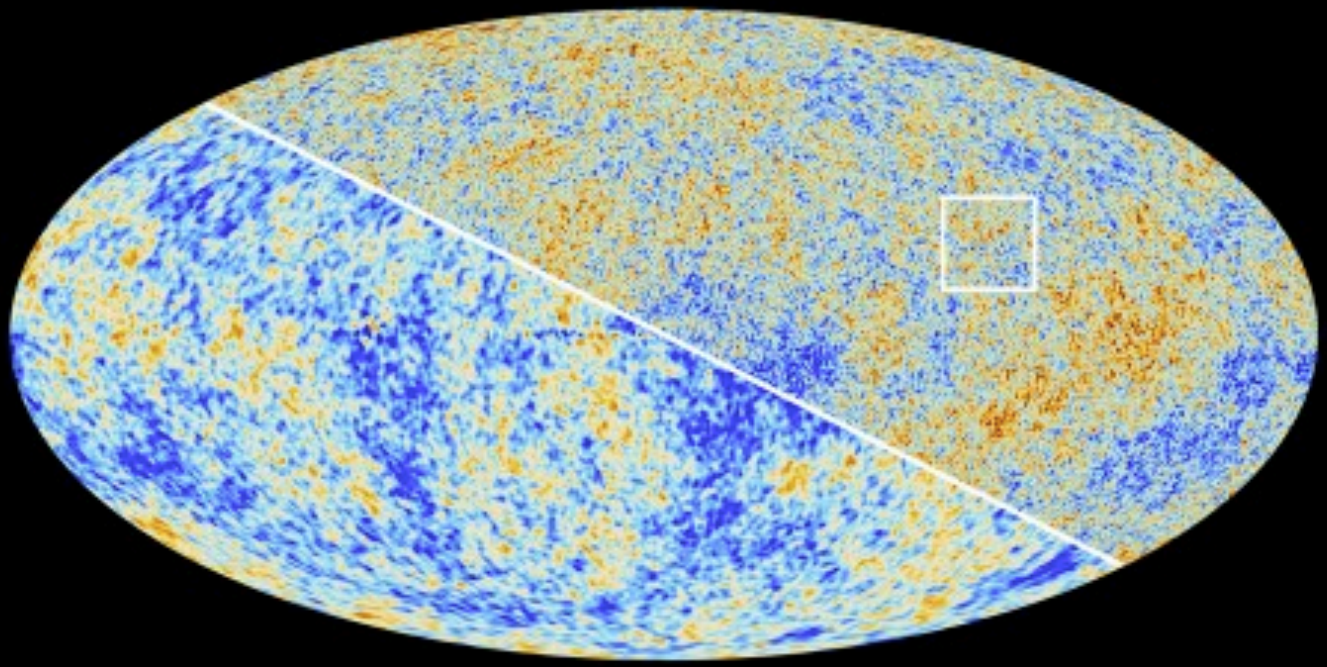
Summary

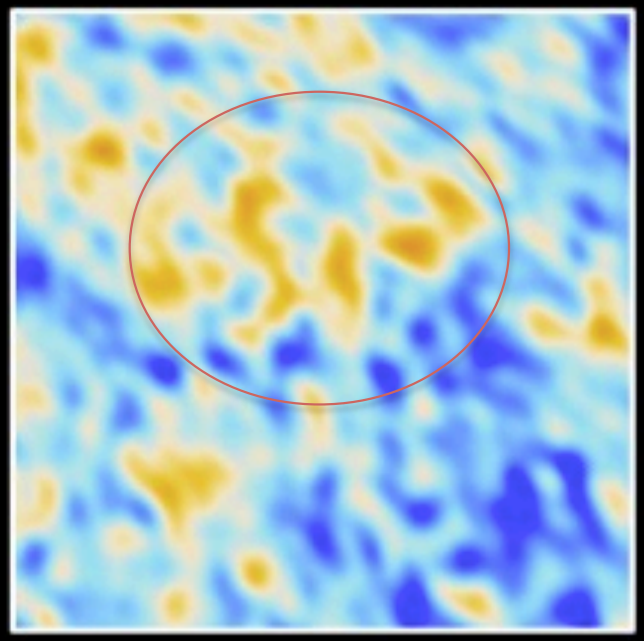
- ***Next generation CMB surveys: discovery potential for new physics if systematics under control***

  Transition between precision and accuracy

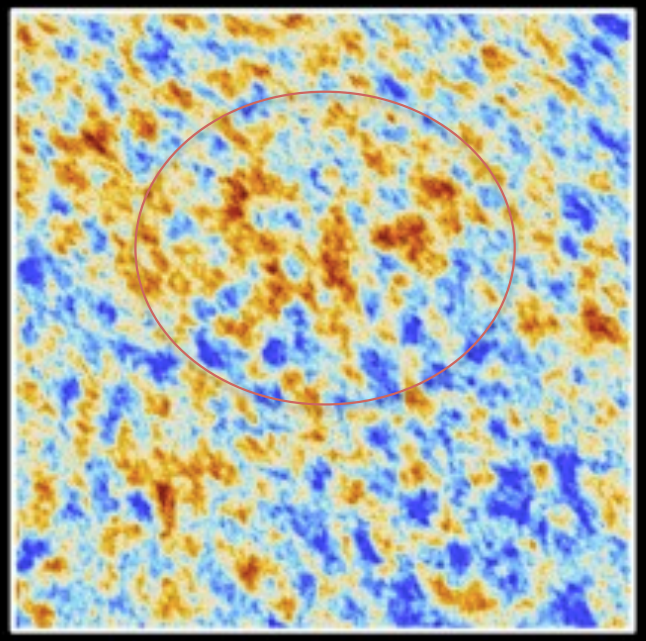


The Cosmic Microwave Background as seen by Planck and WMAP





WMAP



Planck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