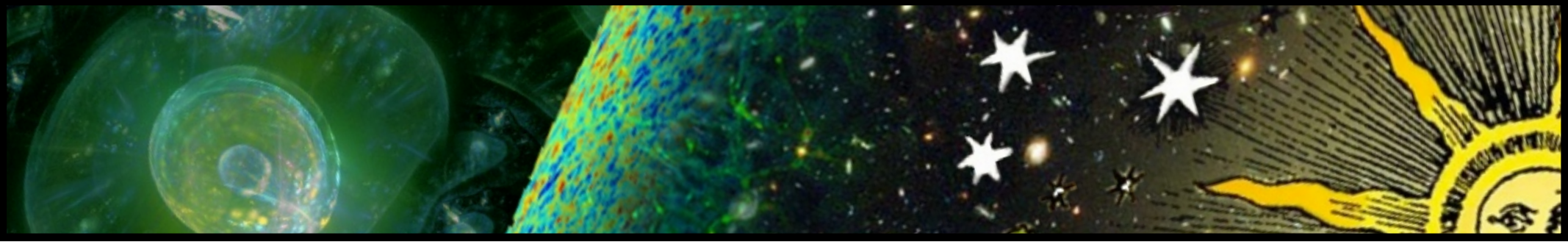
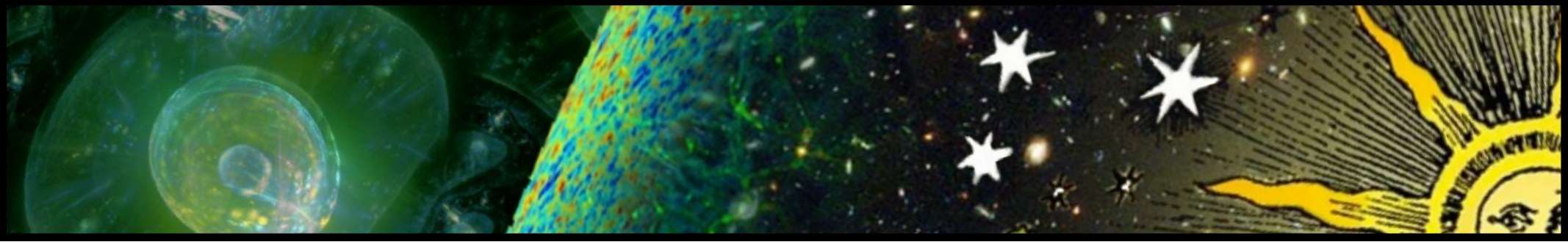


Towards fundamental physics from the cosmic microwave background

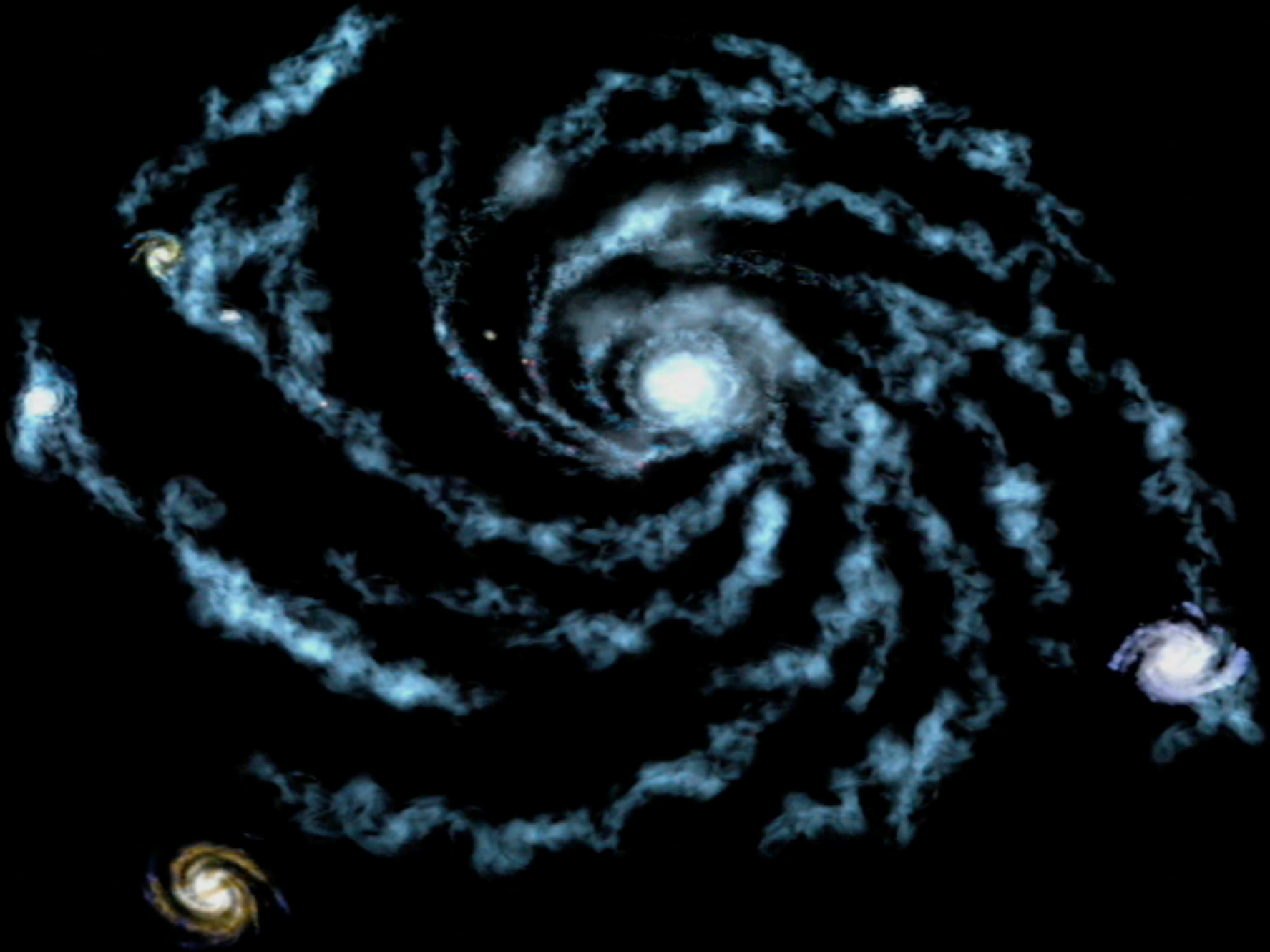
Hiranya V. Peiris
University College London

European Research Council
IDEAS



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

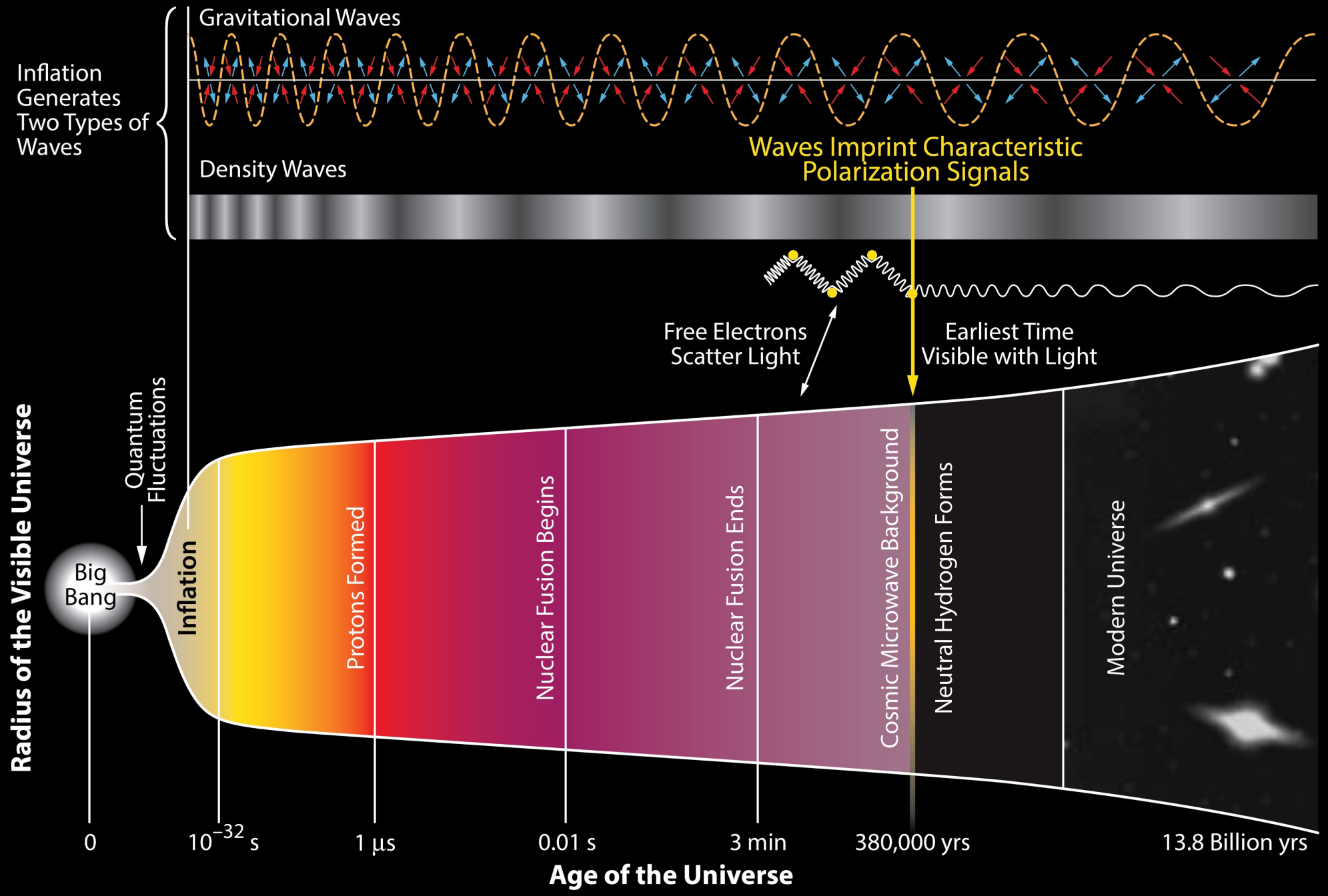
paraphrasing H. Shapley



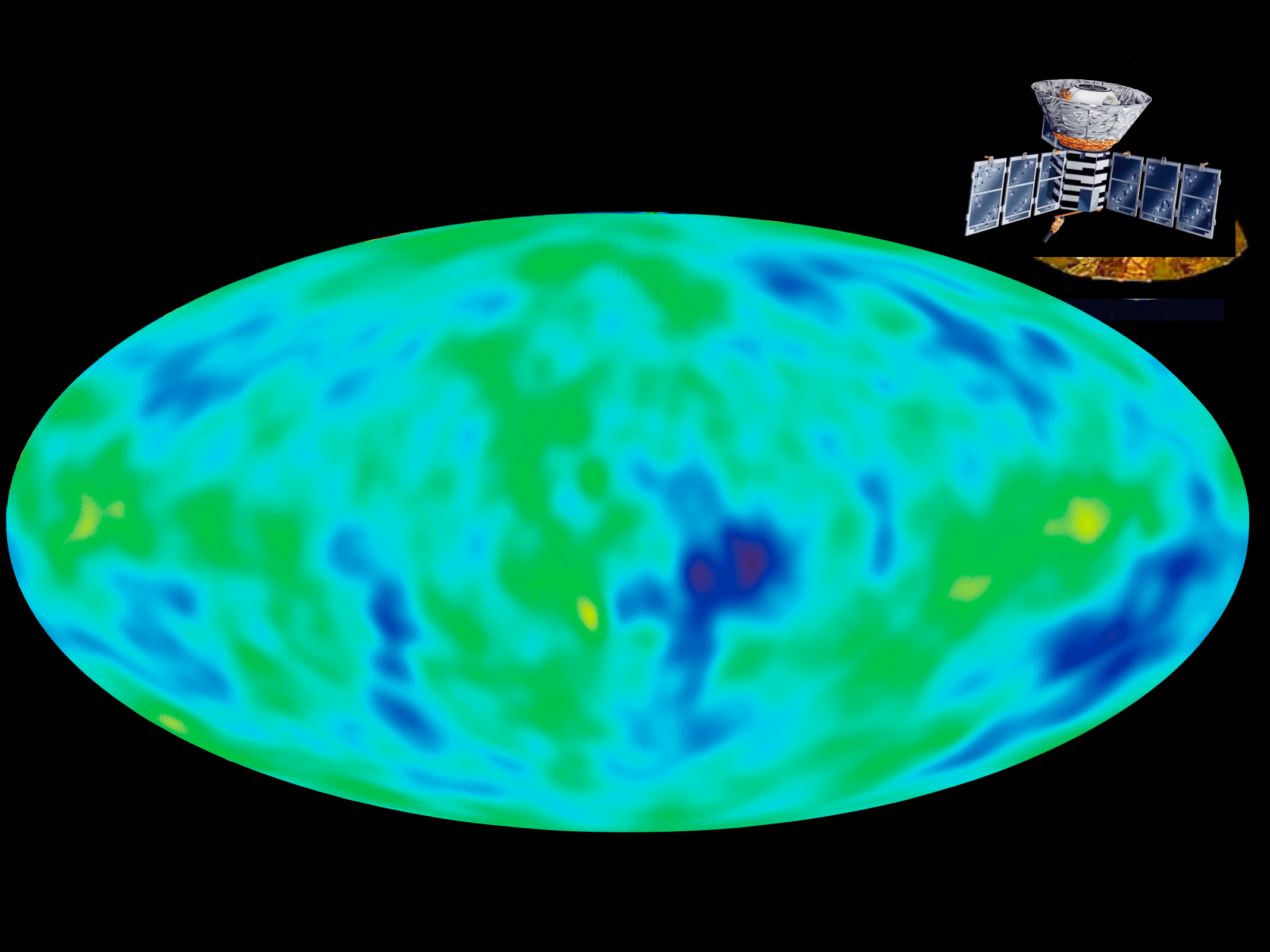
CREDIT: NASA / WMAP SCIENCE TEAM

CREDIT: NASA / WMAP SCIENCE TEAM

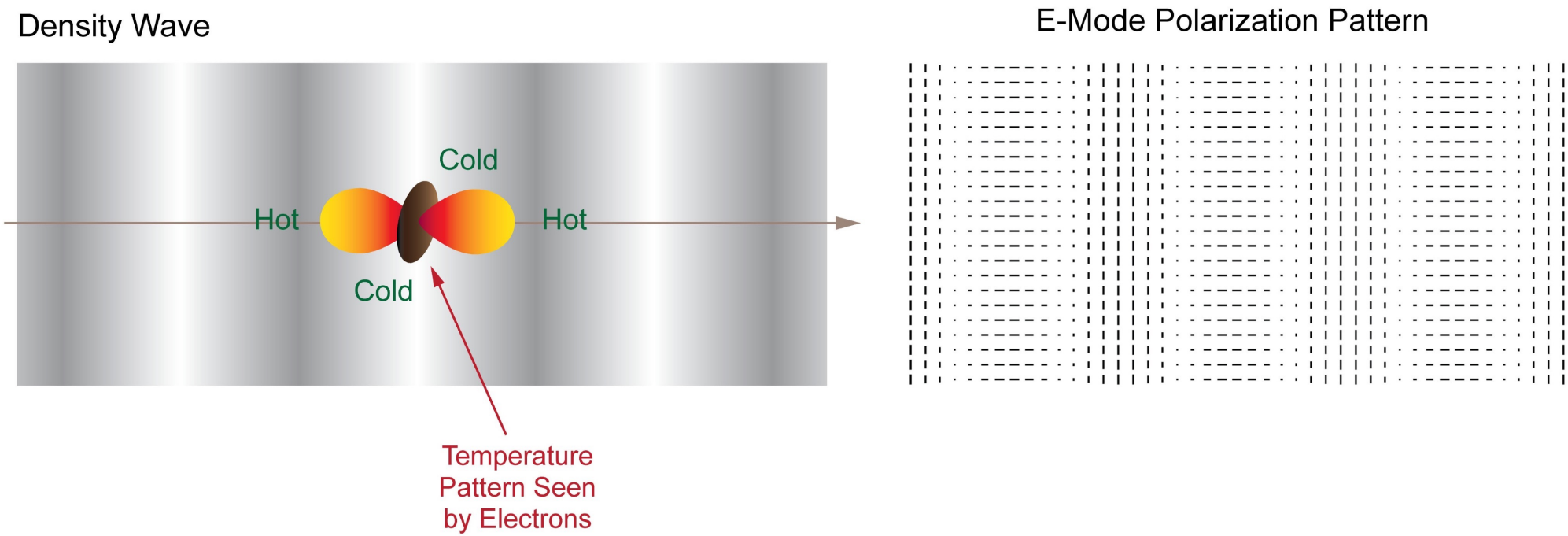
History of the Universe



CREDIT: BICEP / KECK COLLABORATIONS



Temperature quadrupole at surface of last scattering creates polarisation…



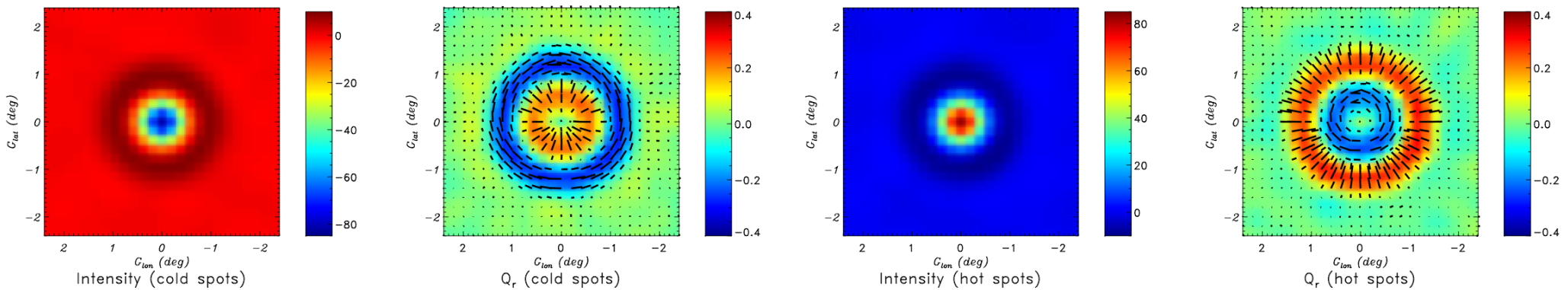
CREDIT: BICEP / KECK COLLABORATIONS

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

Measurement

Cold spot **Hot spot**

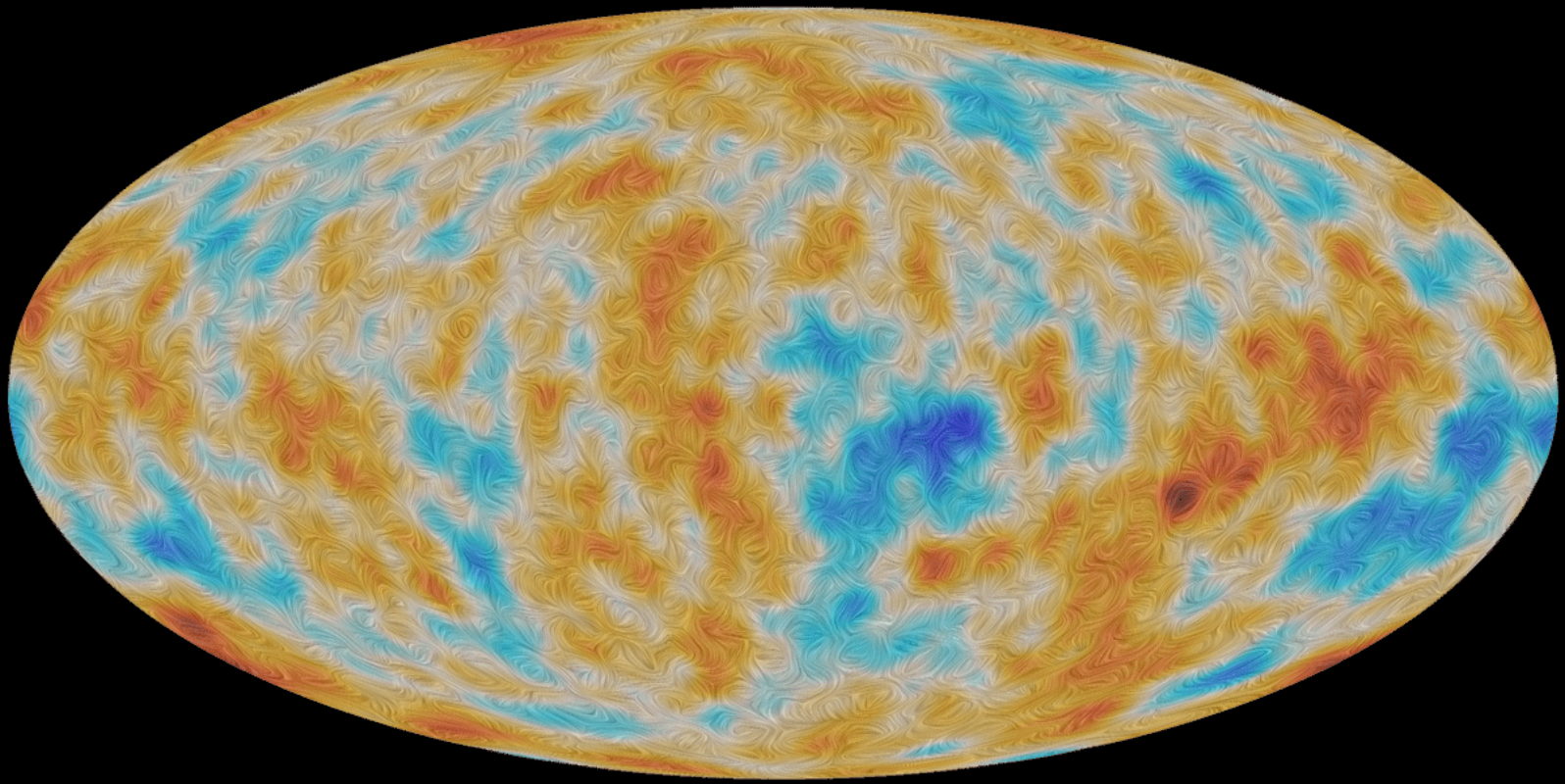
I *Q* *I* *Q*



Cold spot **Hot spot**

Theory prediction

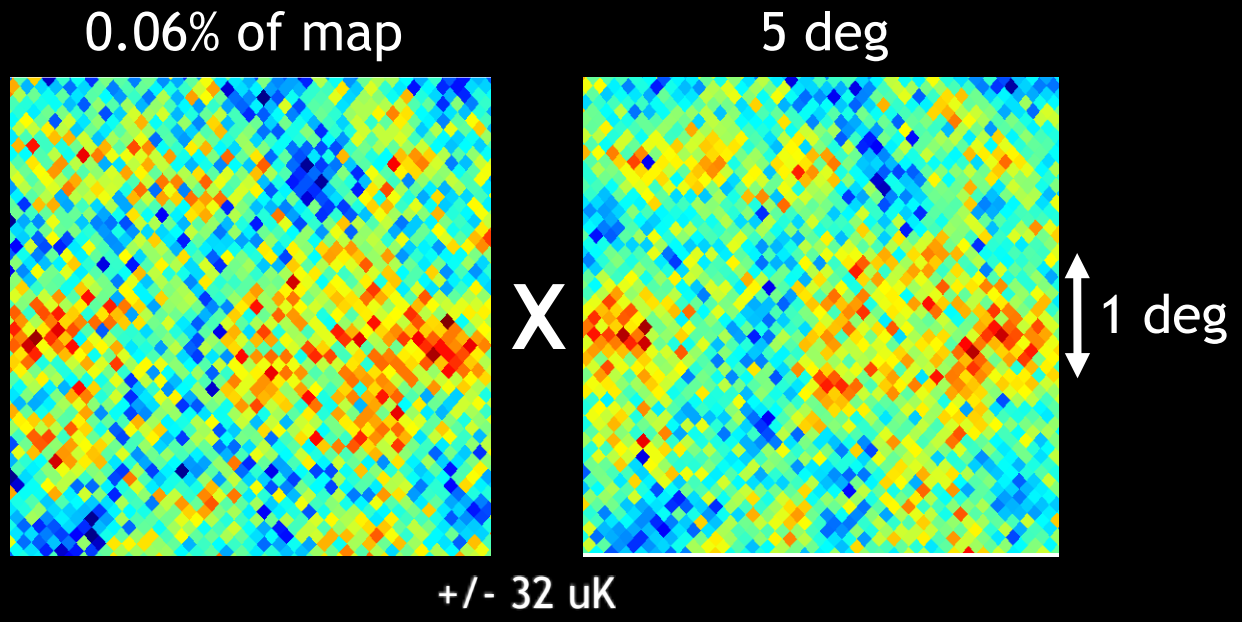
Planck Collaboration (2013)



CREDIT: ESA / PLANCK

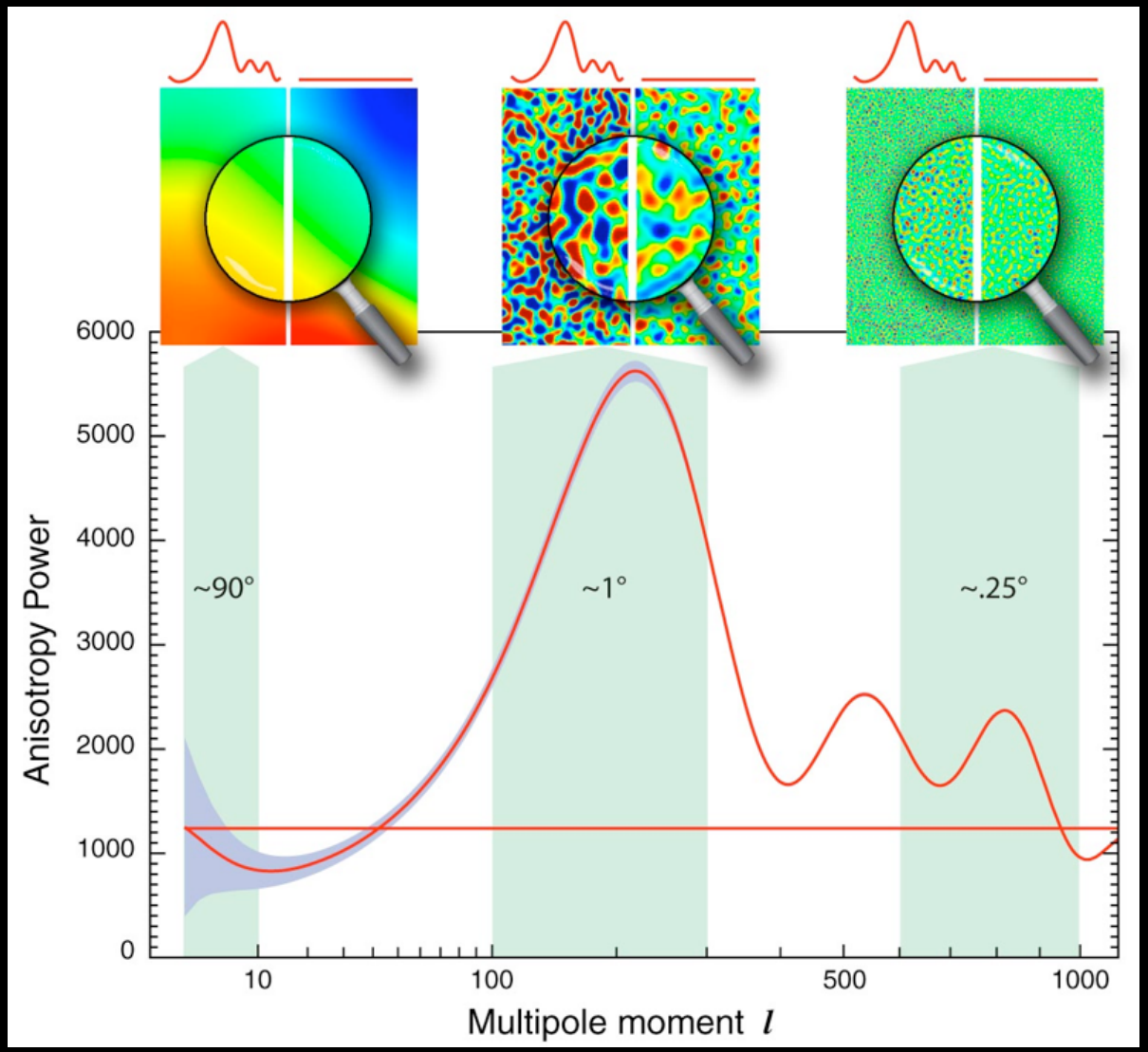
Compress the CMB map to study cosmology

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



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

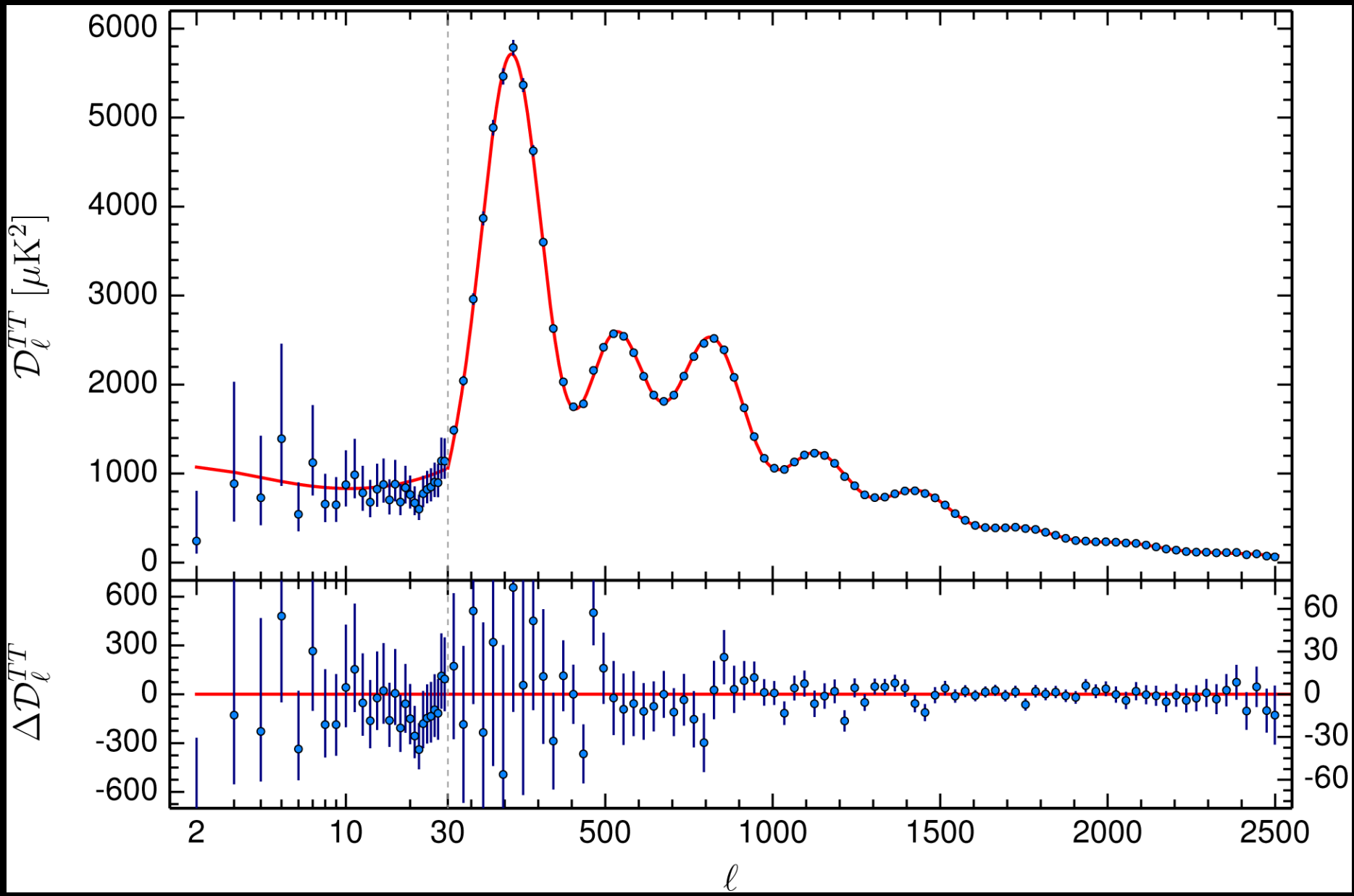
Sound waves on the sky



larger scales ⟷ smaller scales

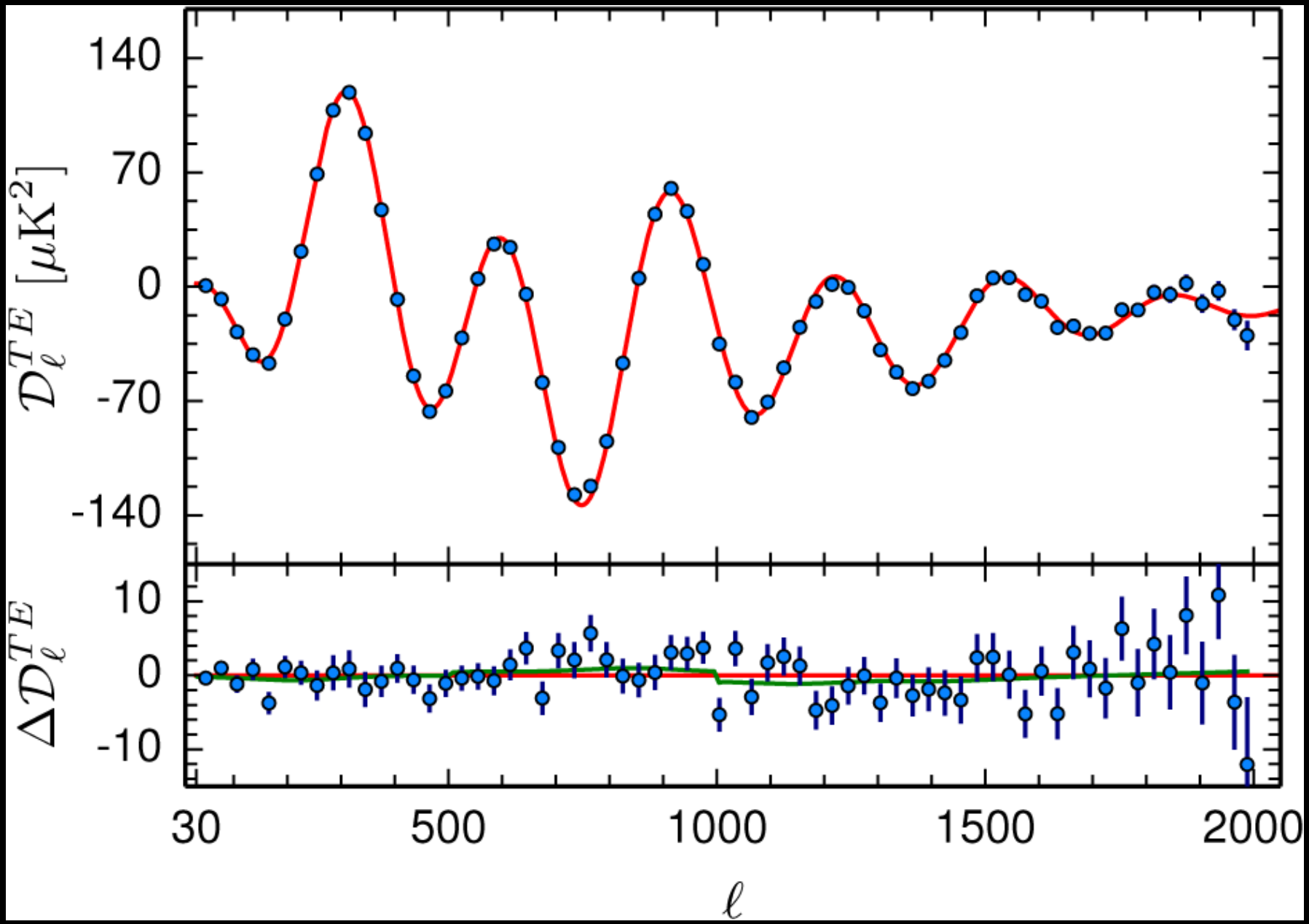
CREDIT: NASA / WMAP SCIENCE TEAM

Planck 2015 Temperature



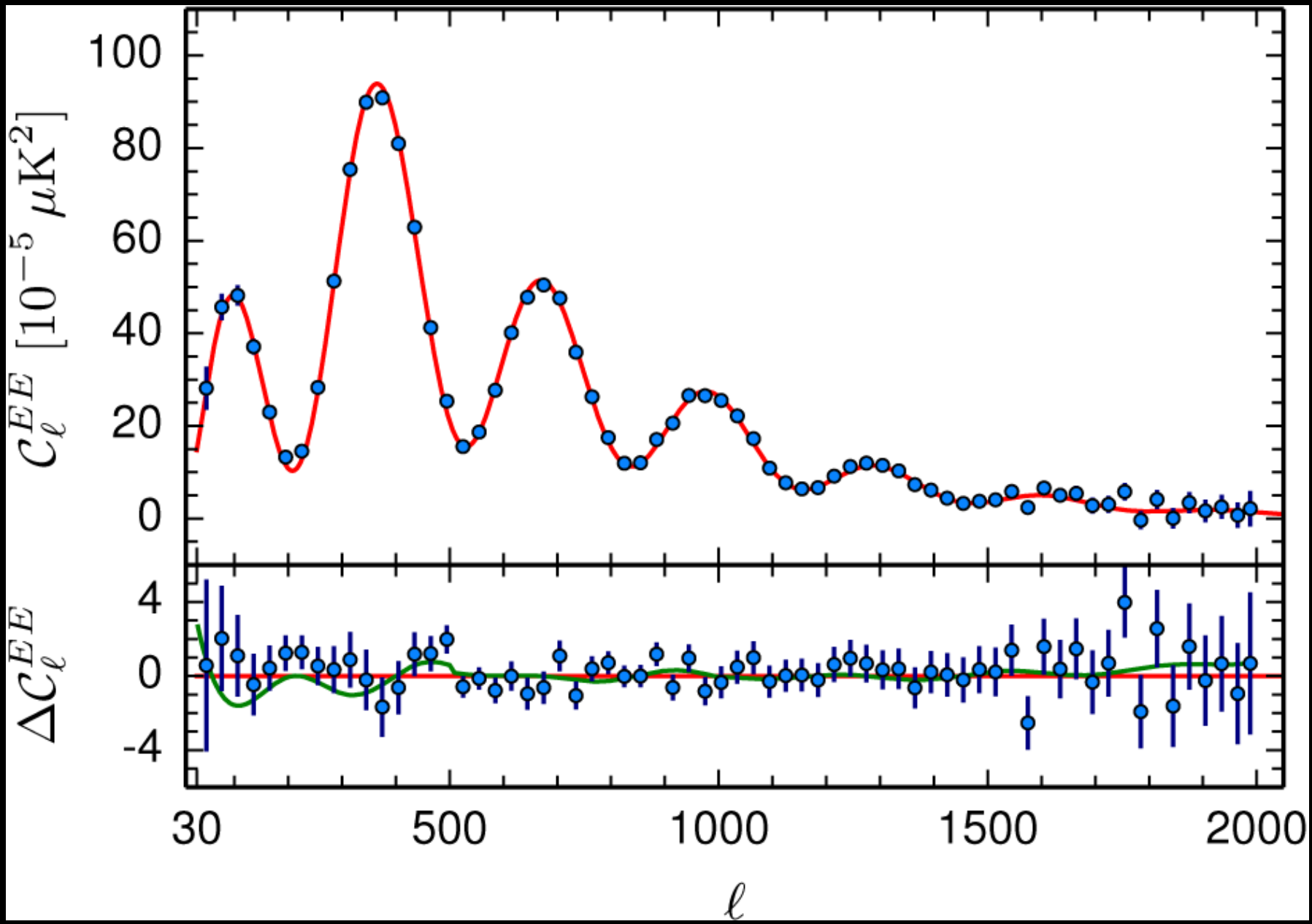
Credit: Planck Collaboration

Planck 2015 TE Polarization



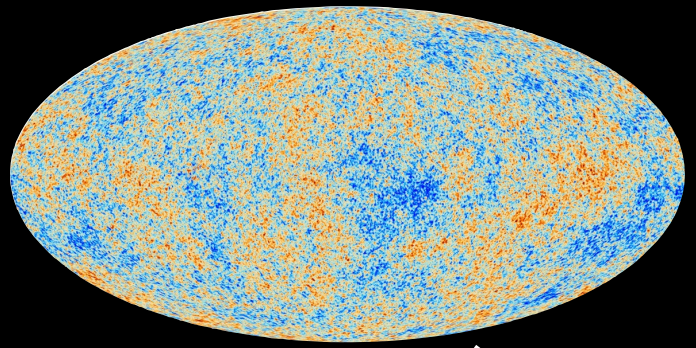
Credit: Planck Collaboration

Planck 2015 EE Polarization

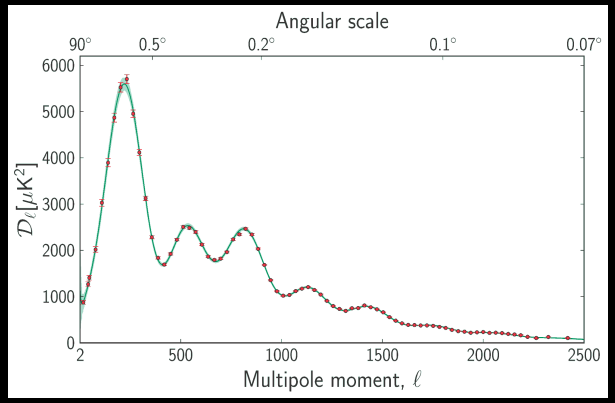


Credit: Planck Collaboration

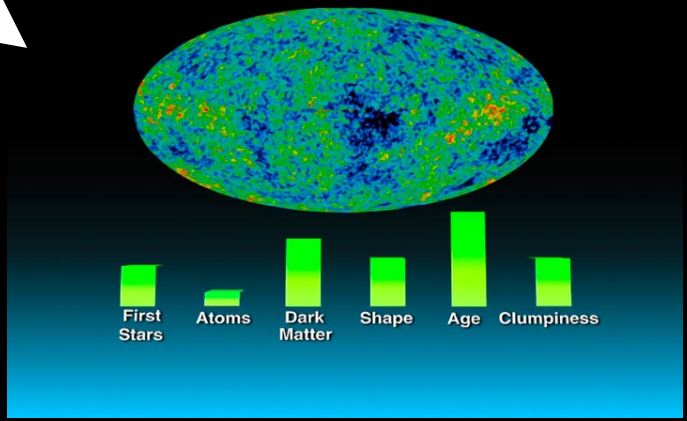
Radical data compression!



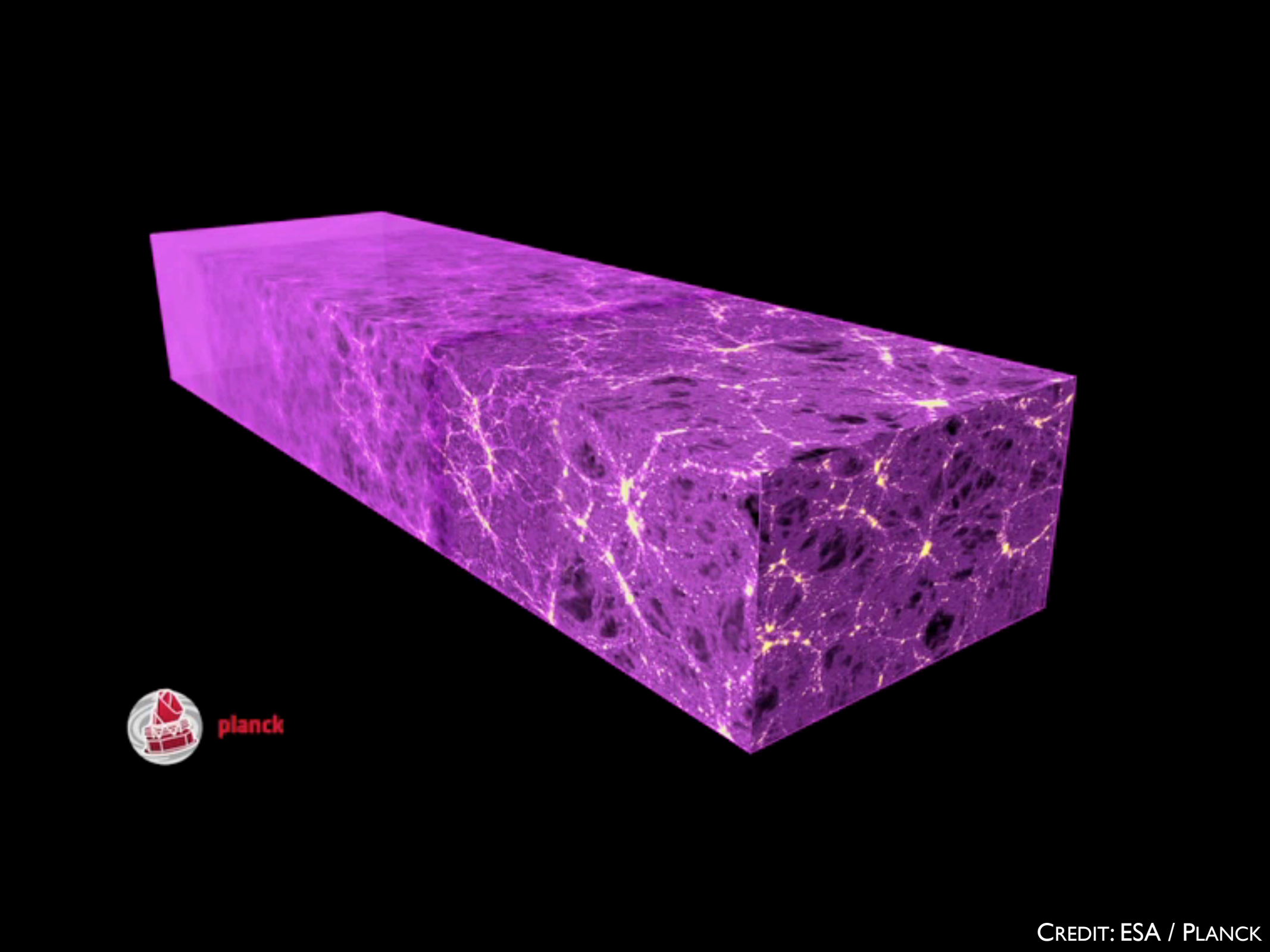
50 million pixels...



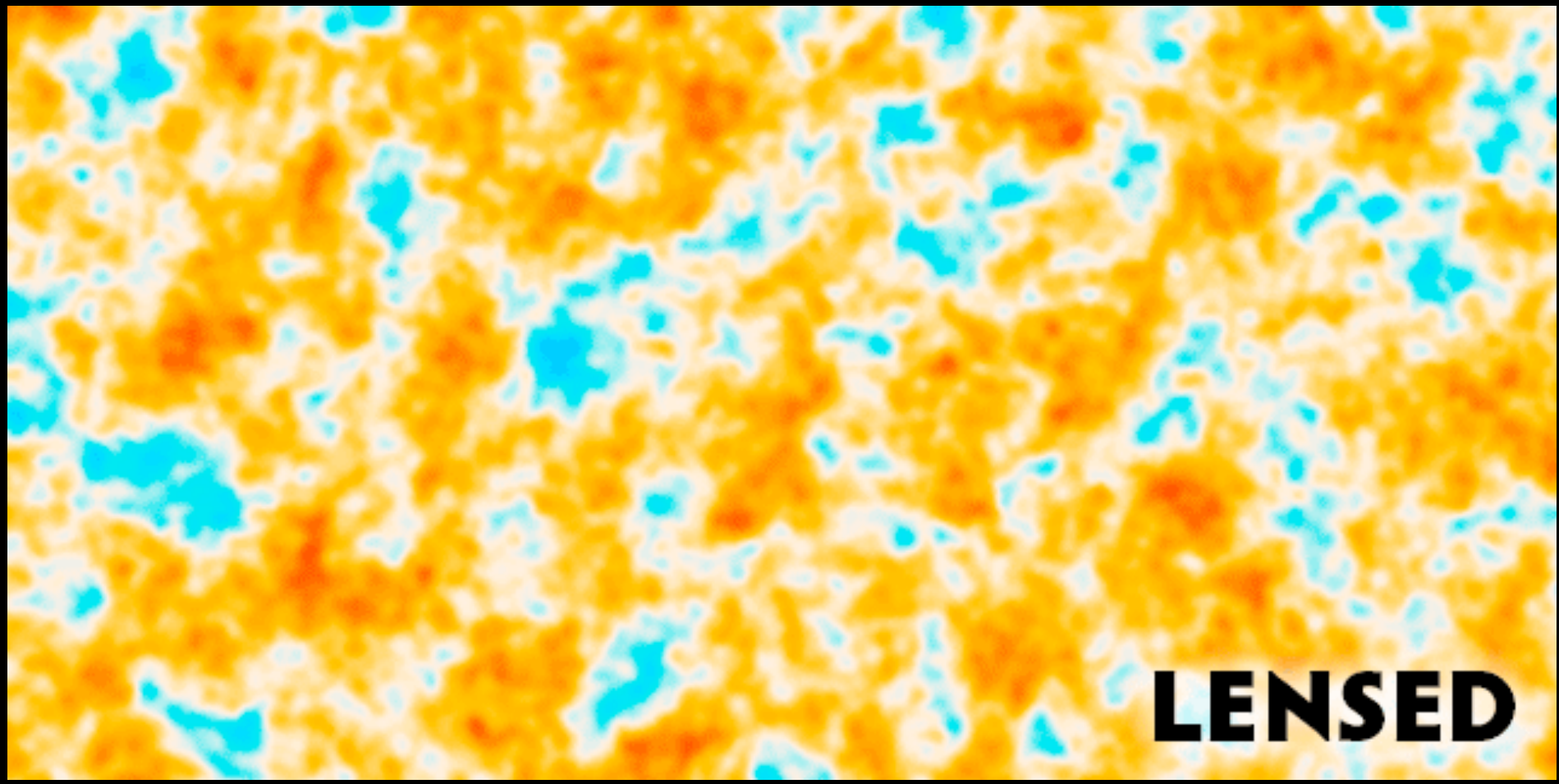
2500 multipoles...



six cosmological parameters!



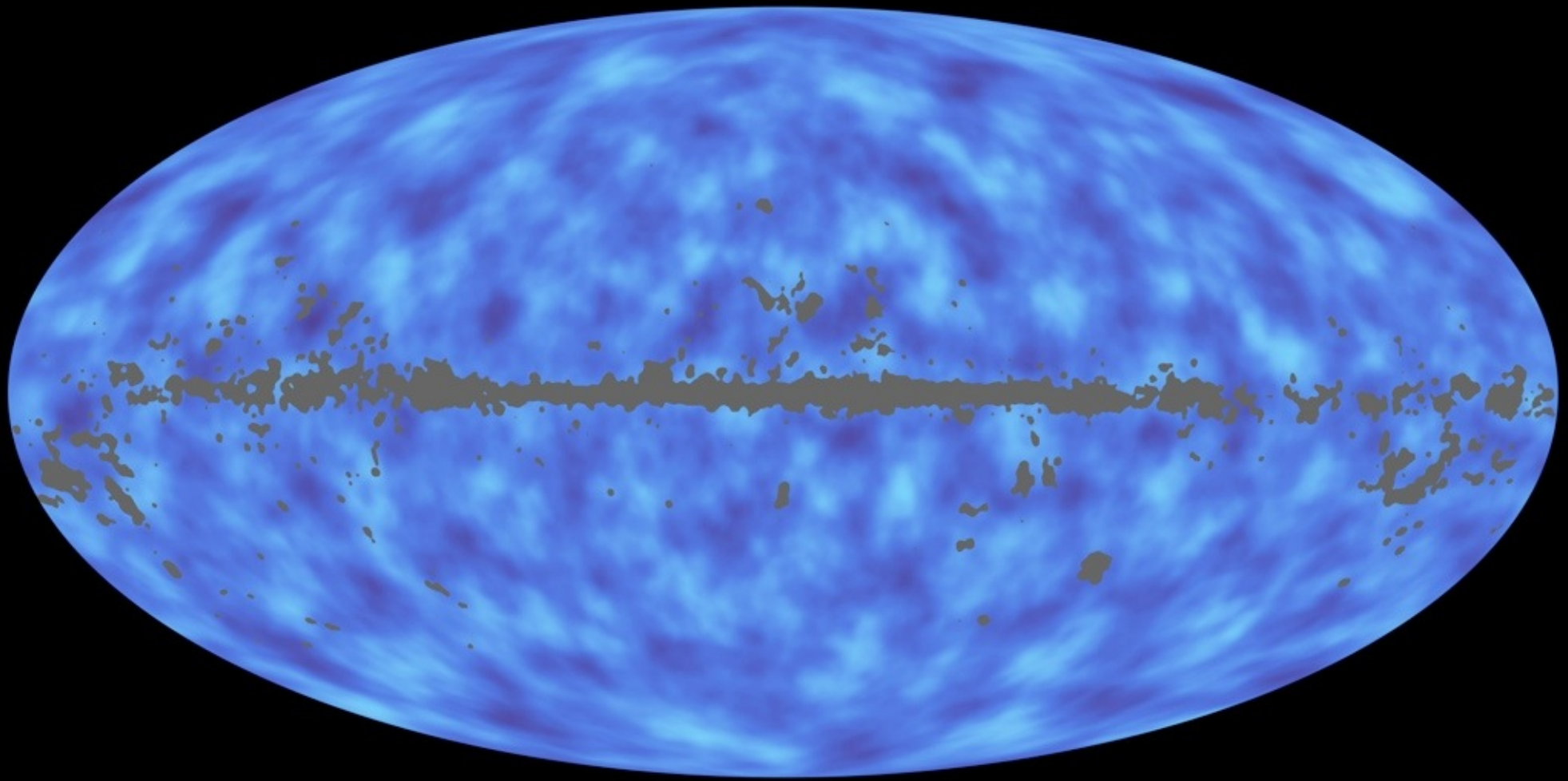
CREDIT: ESA / PLANCK



Deflections are ~ 2 arcmin

CREDIT: ESA / PLANCK

CMB lensing potential reconstruction

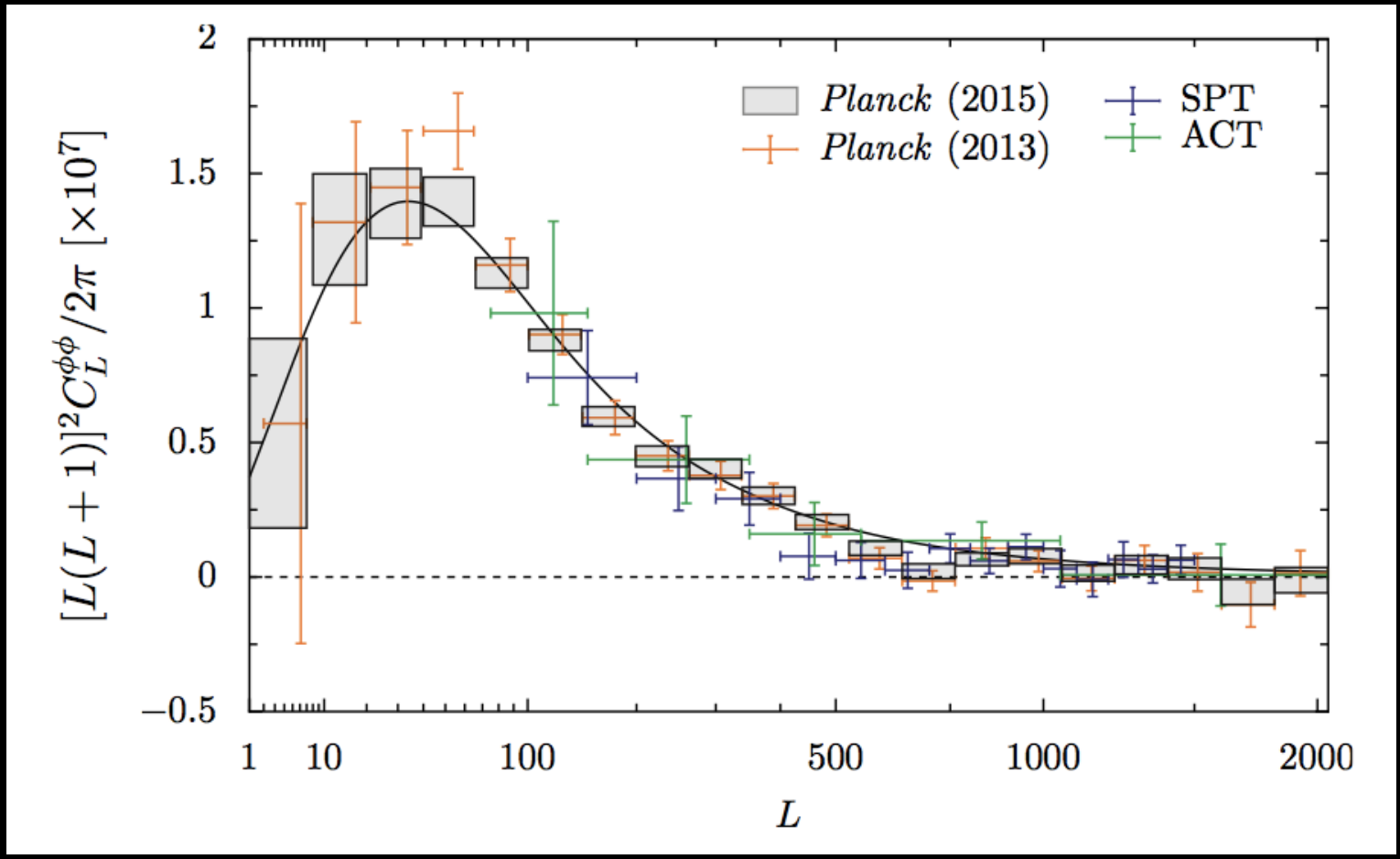


Credit: Planck Collaboration

CMB lensing potential power spectrum

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

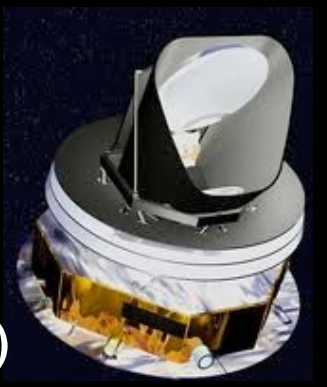
breaks parameter degeneracies from primary CMB alone; new window on growth of cosmic structure



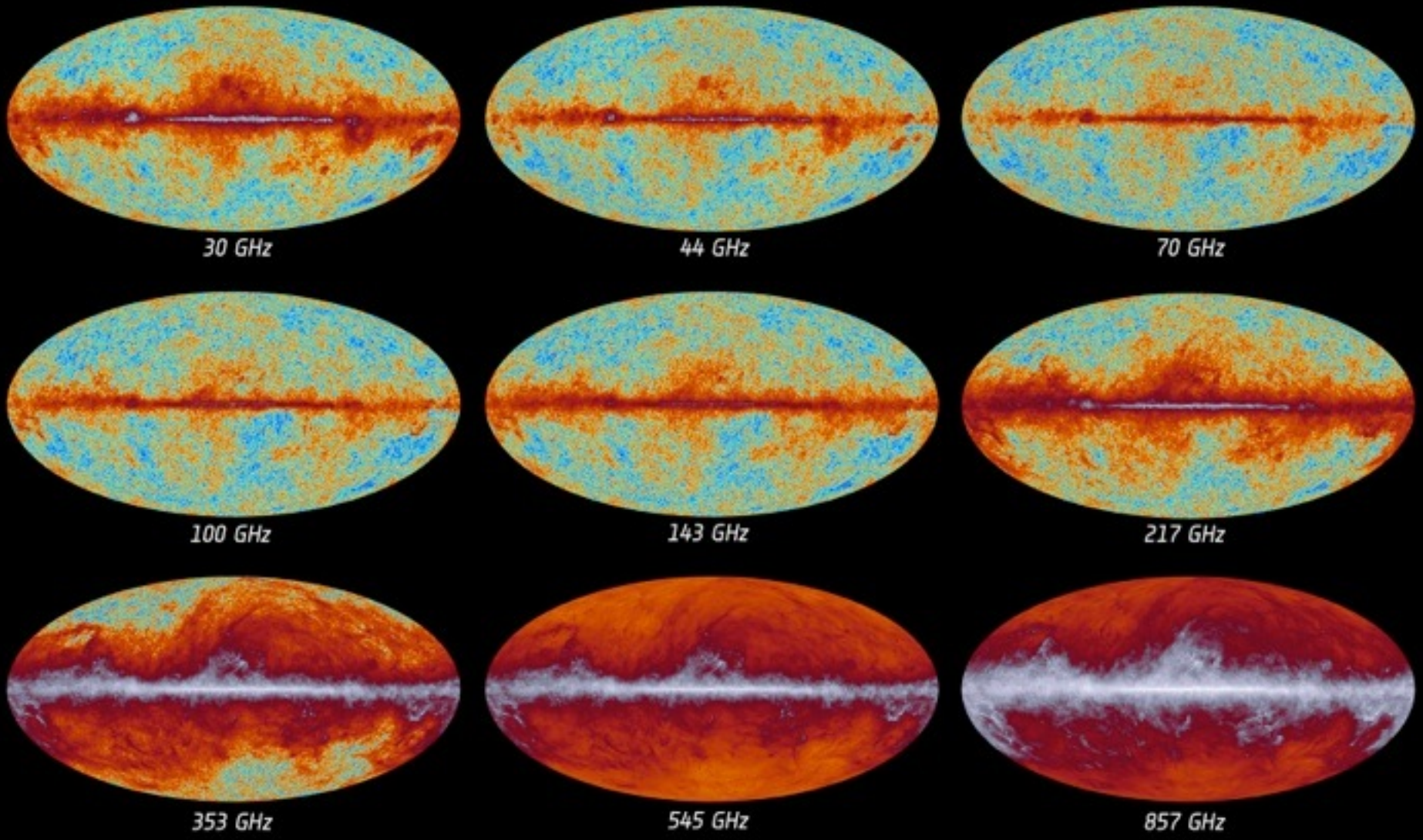
Credit: Planck Collaboration

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

Maps: *~50 million pixels over 9 frequencies*

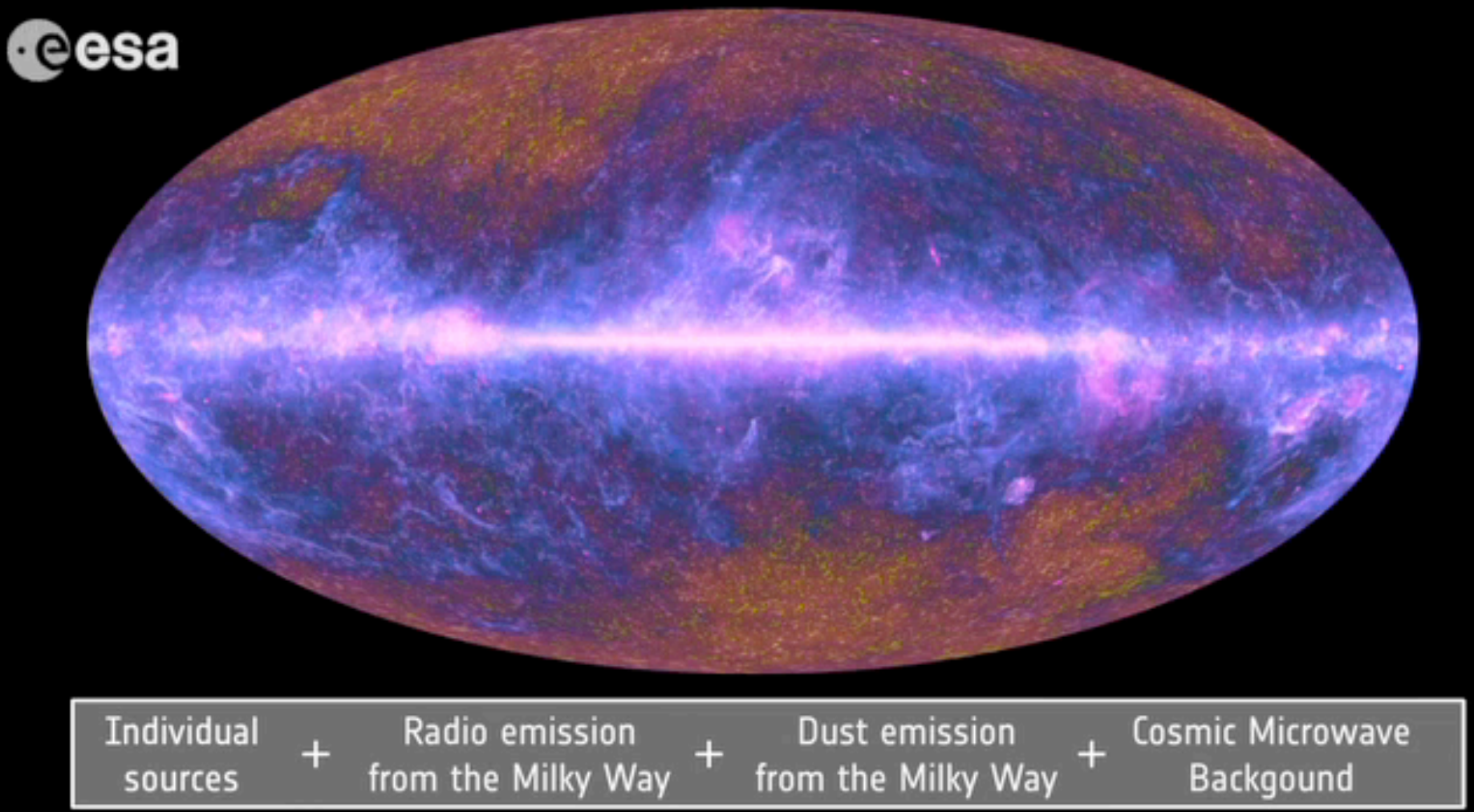


Planck (2015)



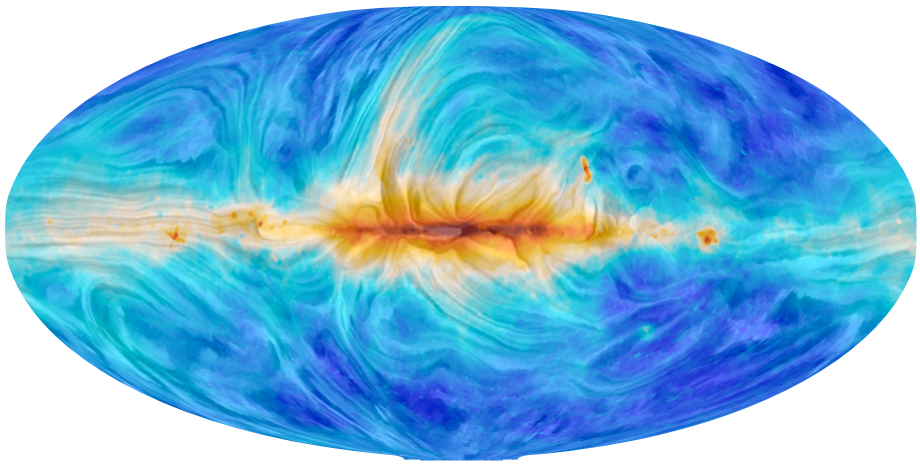
Emission at frequency = CMB + astrophysical sources along line of sight.

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

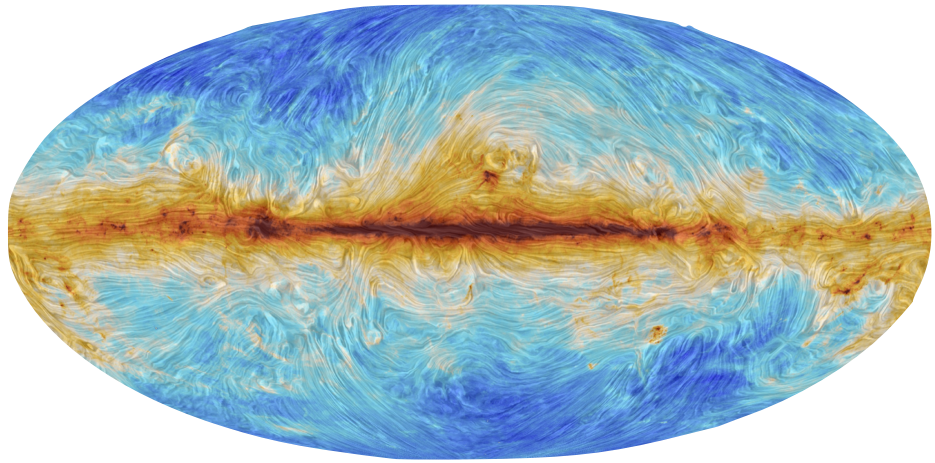


CREDIT: ESA / PLANCK

Just beginning to characterise polarised foregrounds



polarised
synchrotron



polarised
dust

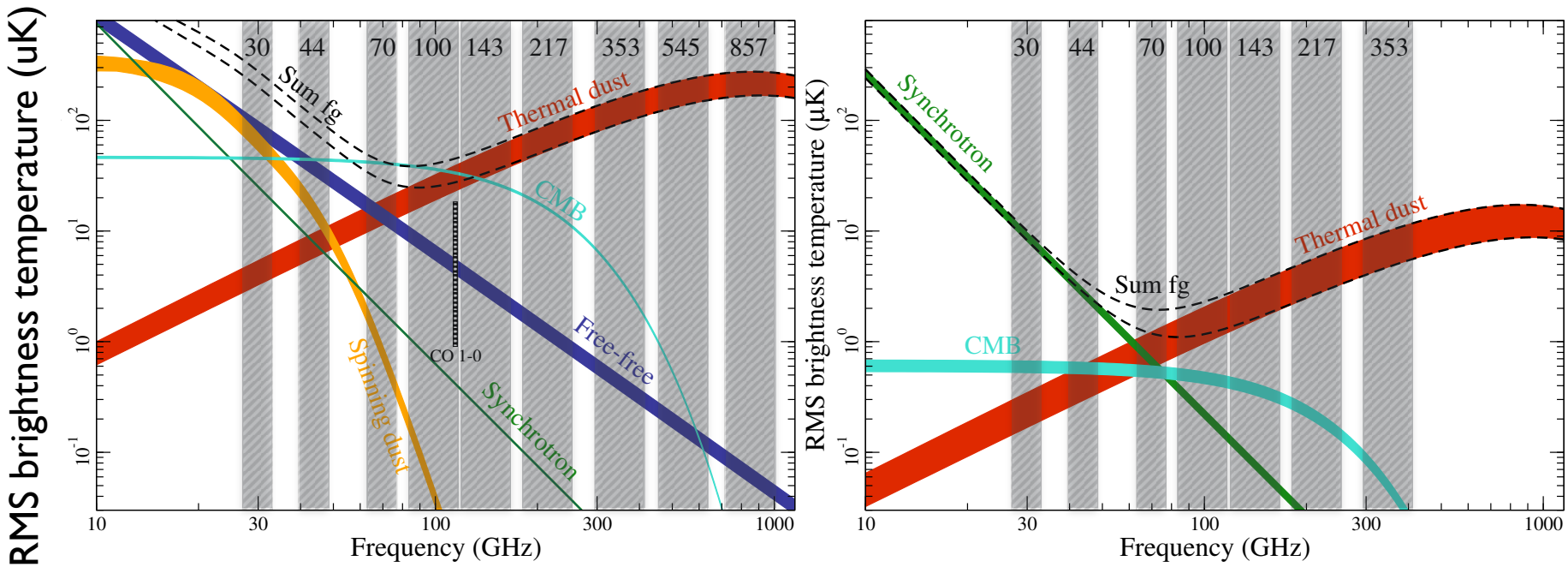
Polarised FG **complex & filamentary**

Planck Collaboration (2015)

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)

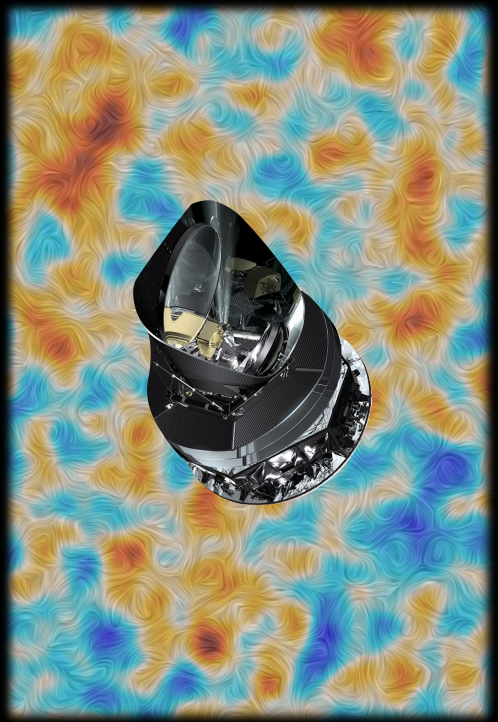
Gravitational Wave Periods

Milliseconds

Minutes to Hours

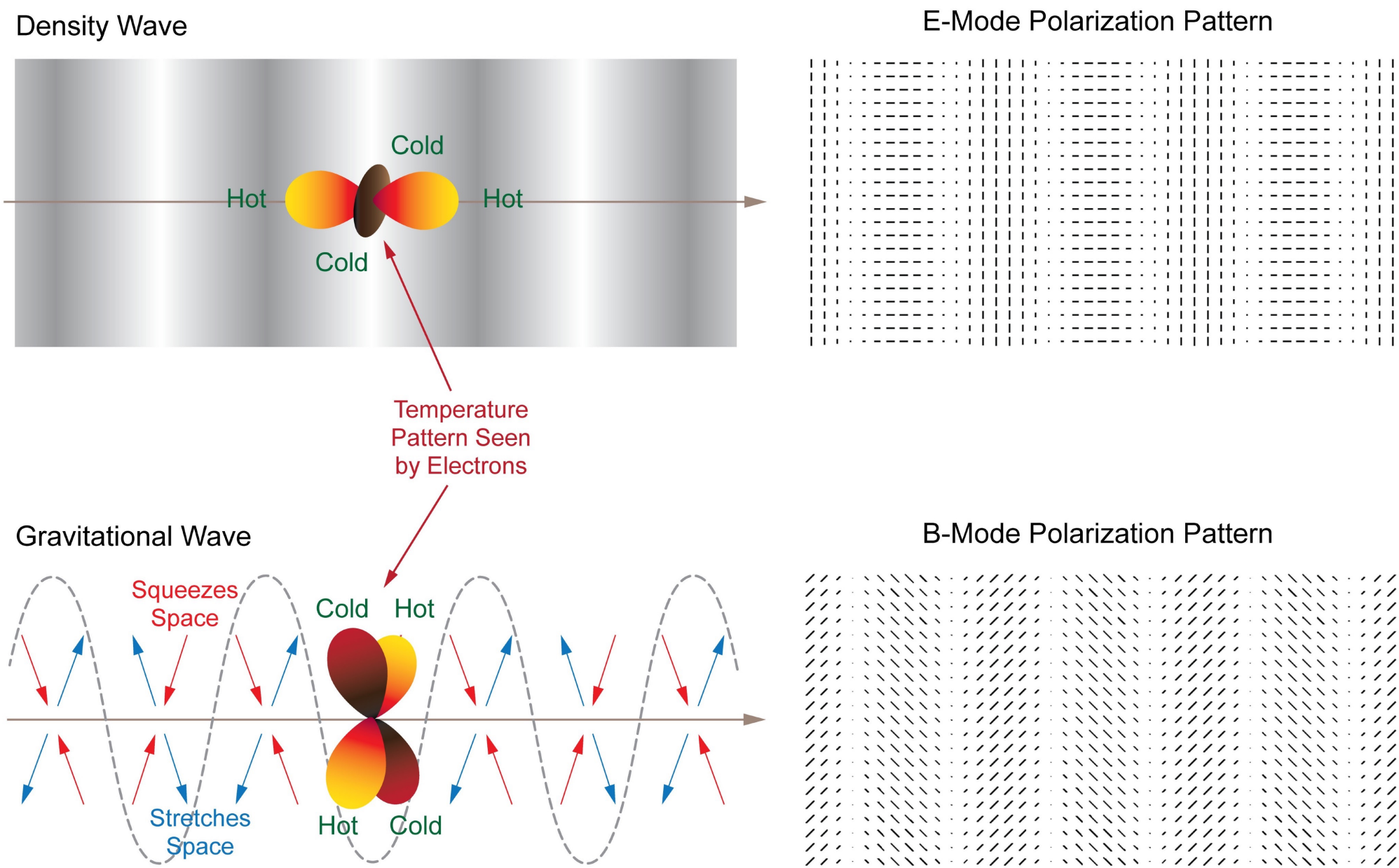
Years to Decades

Billions of Years



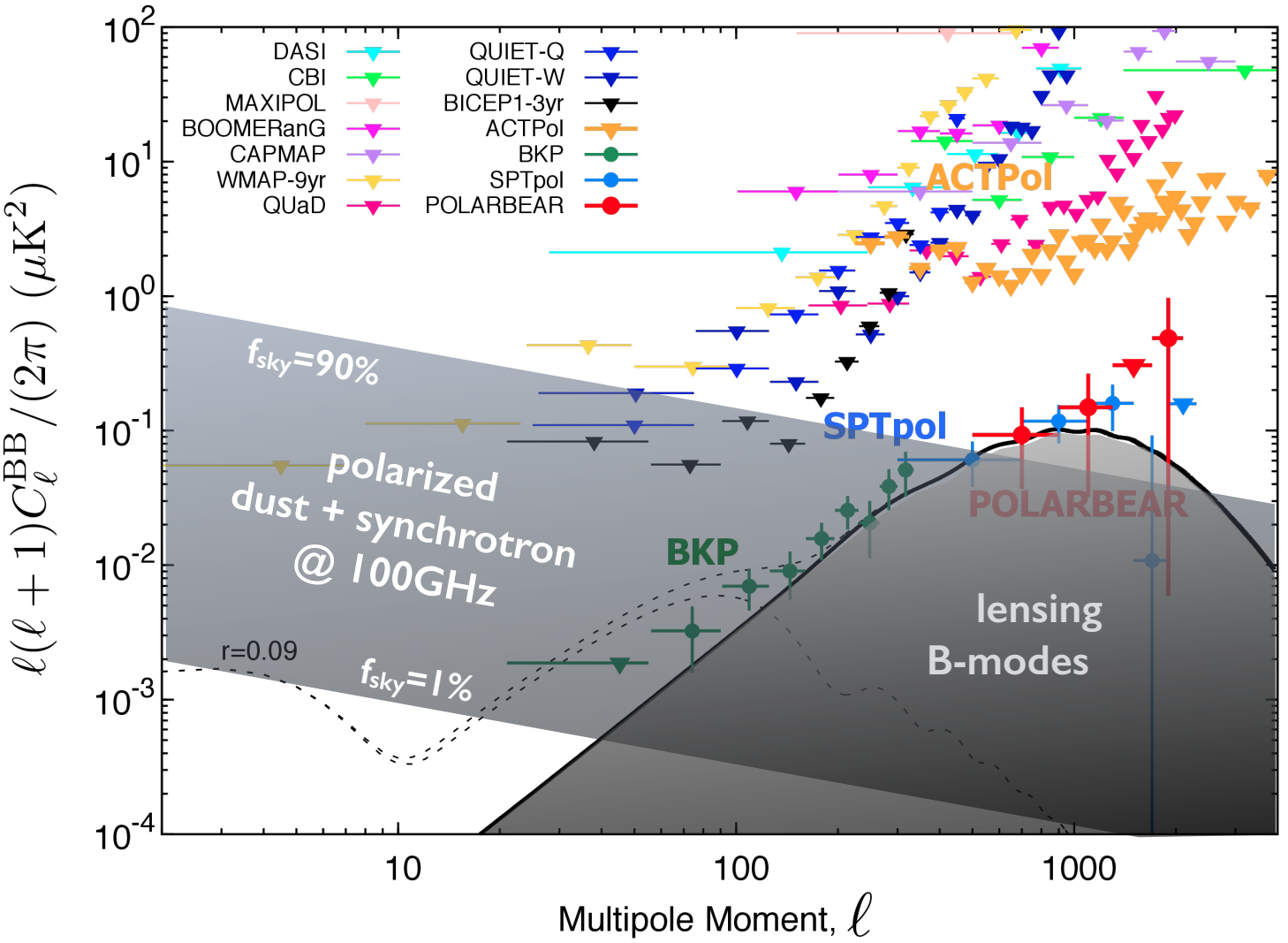
CREDIT: LIGO / KIP THORNE

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**)

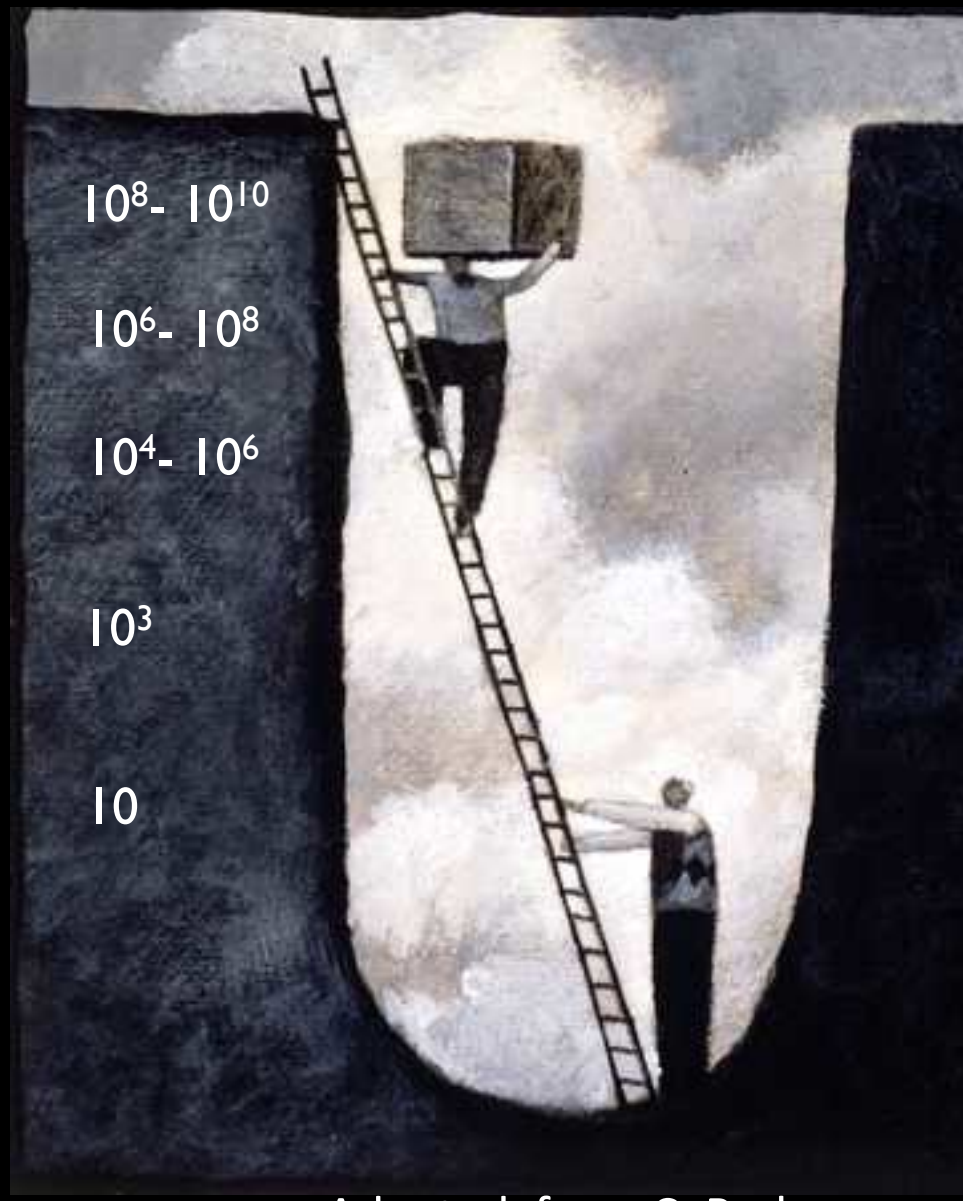
BICEP/Keck Array 95 GHz (2015)
r<0.09 (95%)

Josquin Errard

The challenge

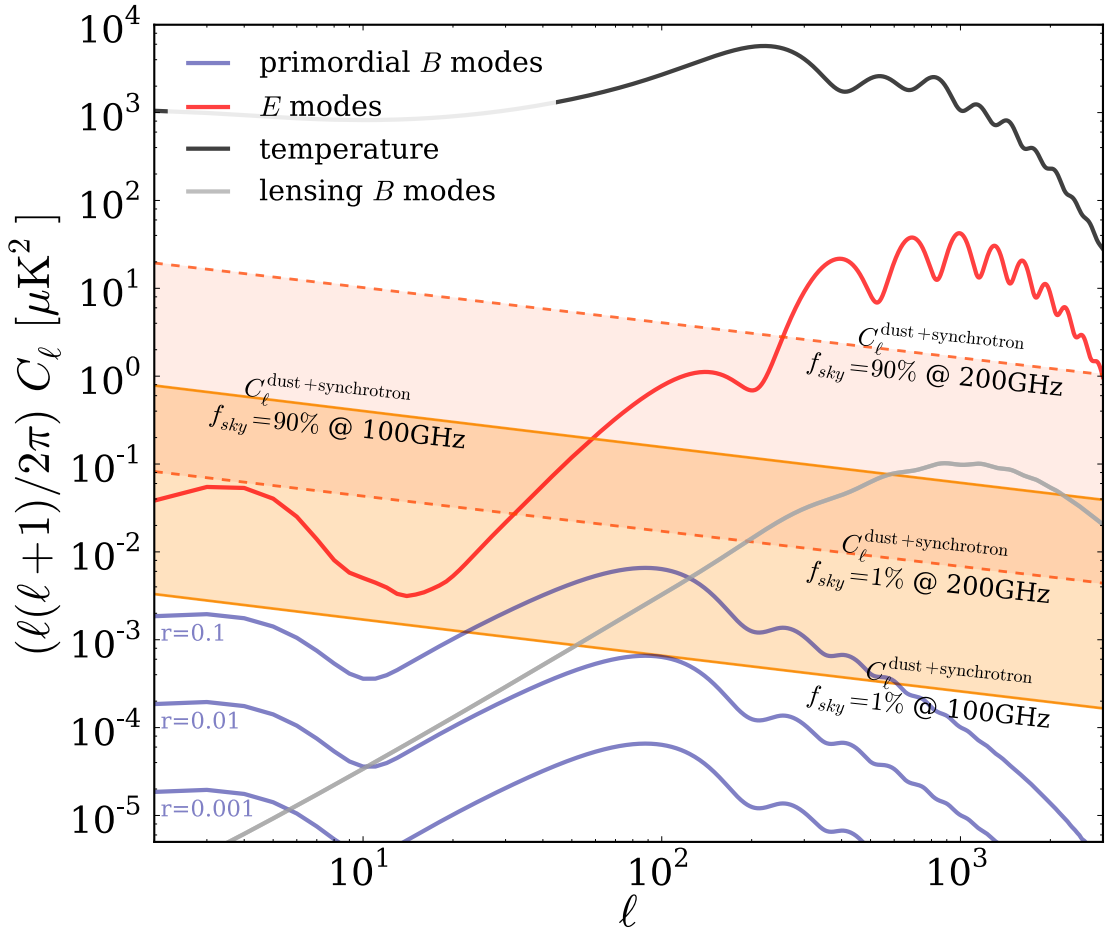
Typical degree-scale brightness fluctuations (150GHz)

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 (1509.06770)

Robust CMB polarisation forecasts

- *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, COrE+, LiteBIRD, PIXIE, Stage IV, …

Time to revisit forecasts!

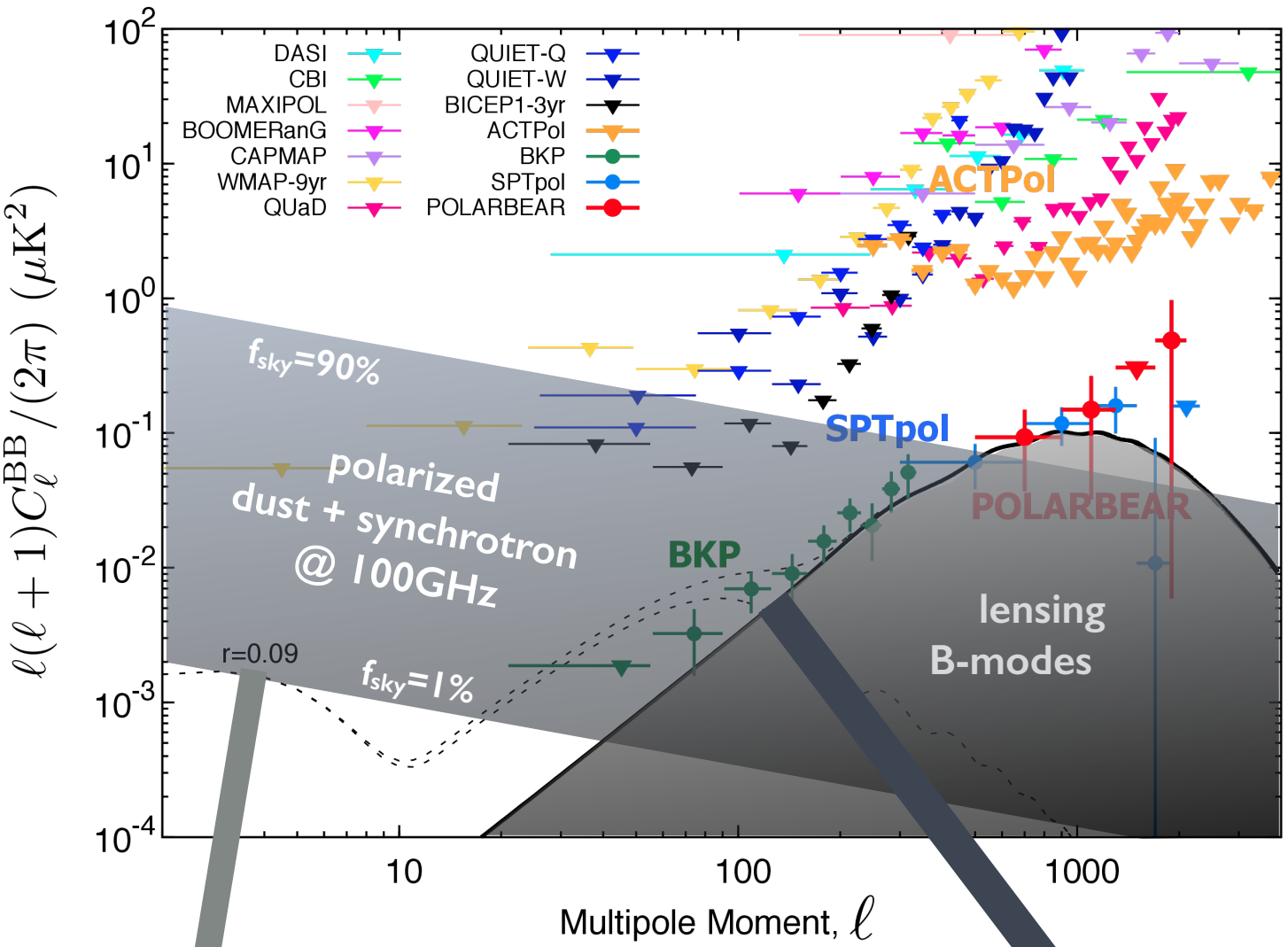
Josquin Errard

- latest foreground information *(e.g. Planck Collaboration 1502.01588)*
- propagate component-separation uncertainties through delensing to forecast

Stephen Feeney

- Can we find **synergy** between different experiments?
- Released as online tool: *http://turkey.lbl.gov*

Errard, Feeney (joint first authors), Peiris, Jaffe (1509.06770)



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

foregrounds cleaning

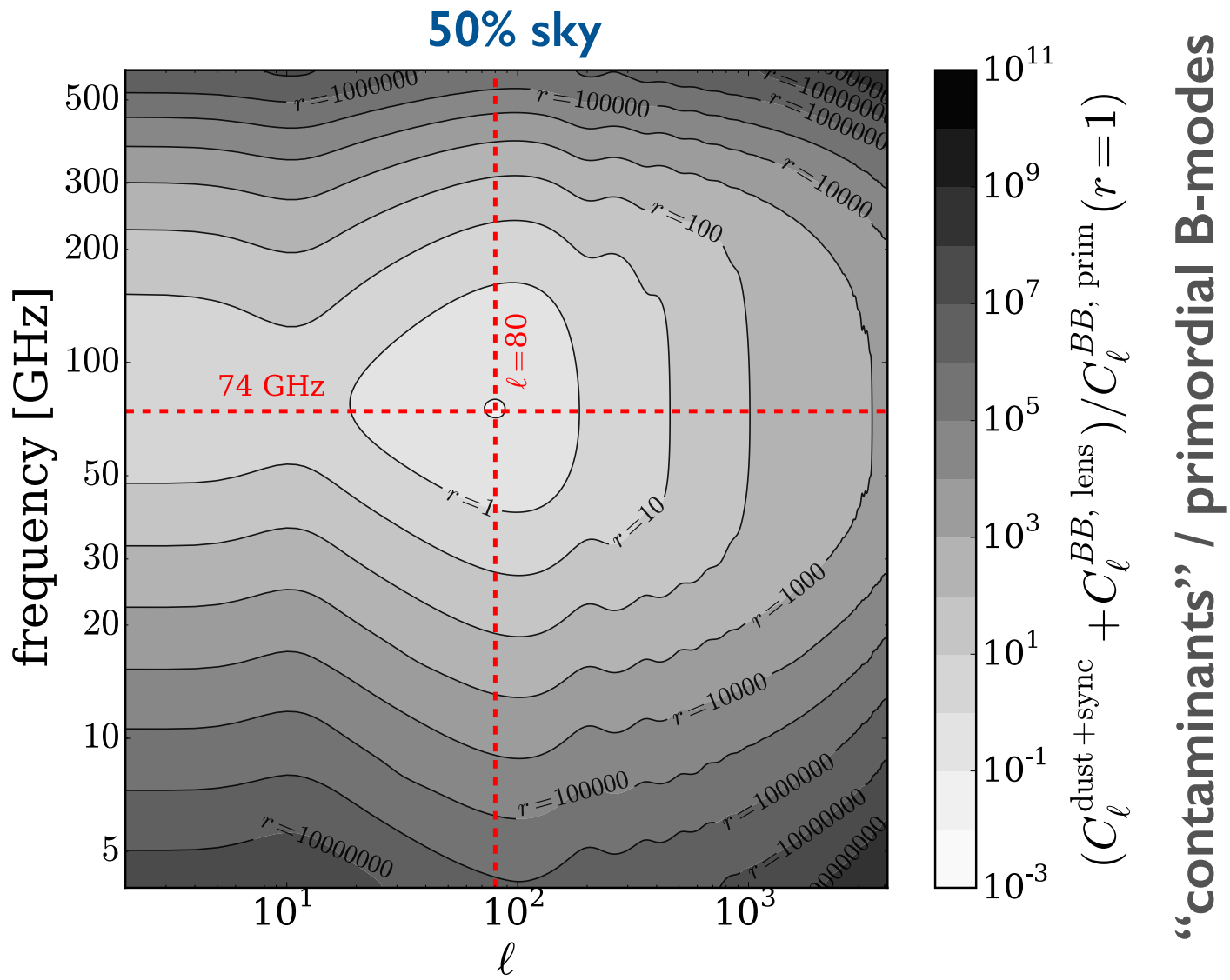
[Stompor et al (2009),
Stivoli et al (2010)
Errard et al (2011+2012)]

delensing

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

Josquin Errard

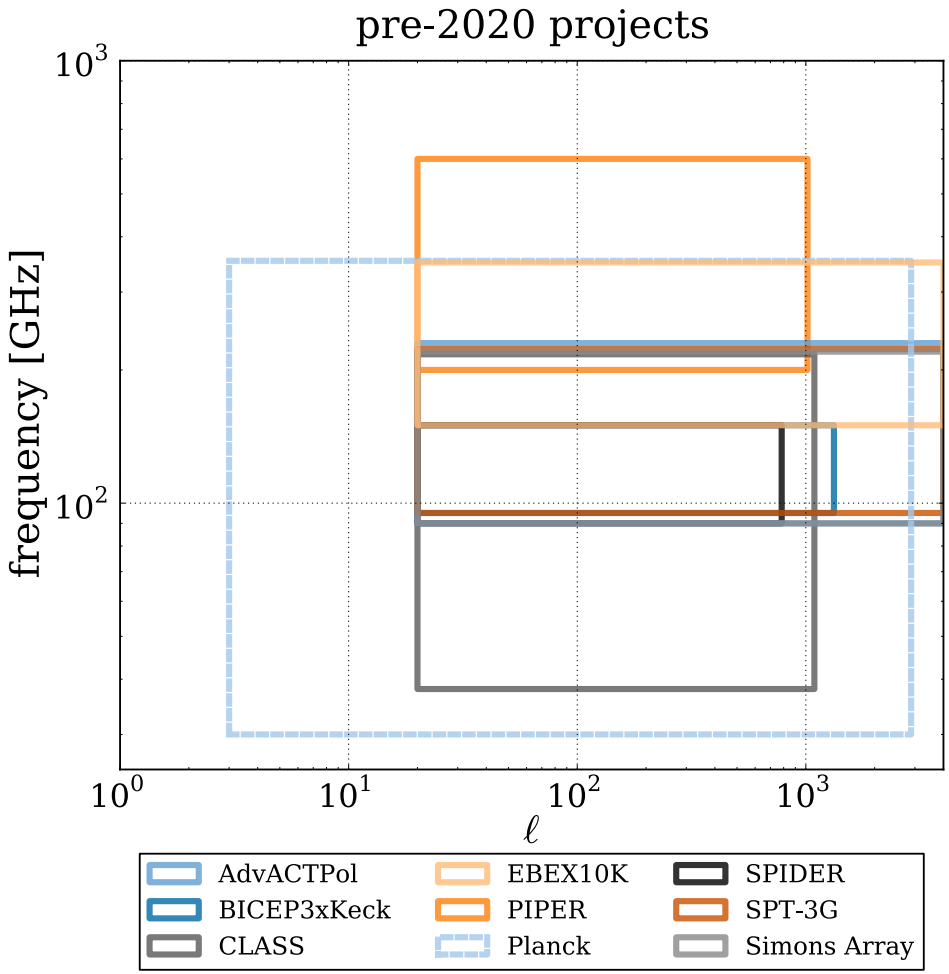
Polarisation is not going to be easy.

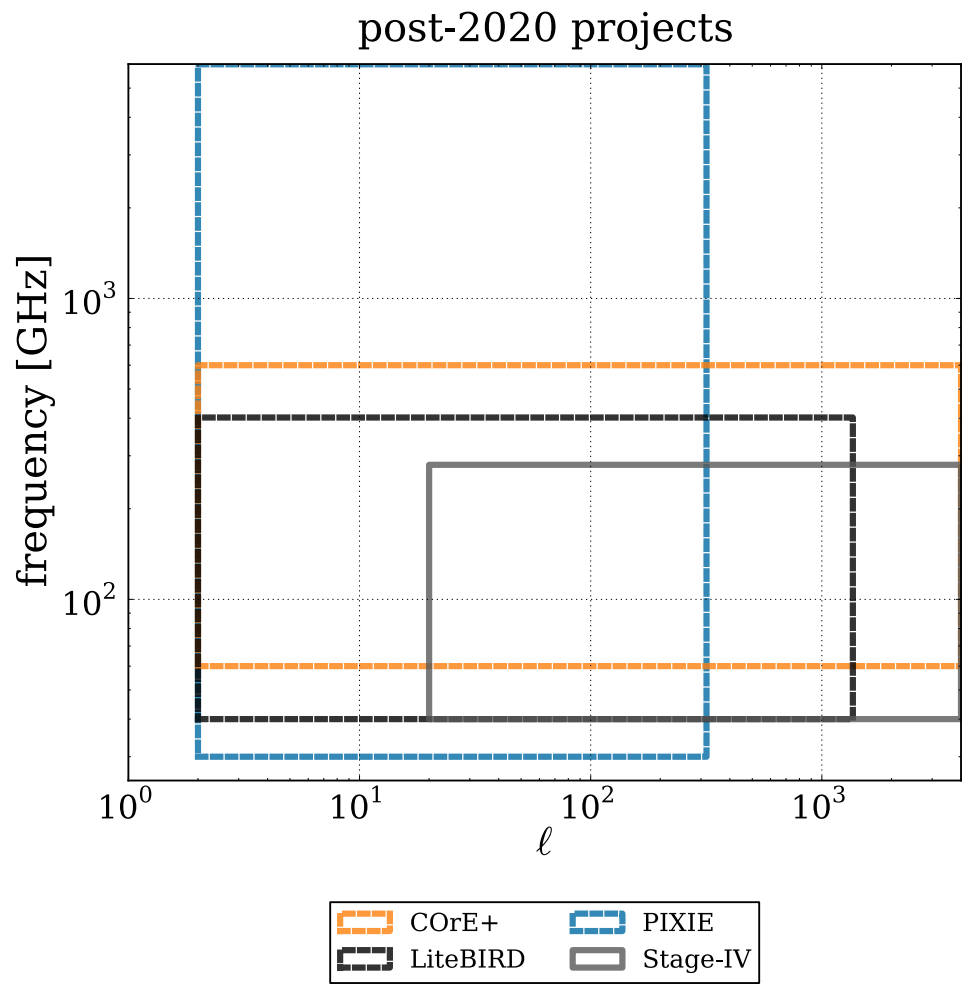


- Half-sky minimum for tensors: $\ell \sim 80$, 75 GHz

Errard, Feeney (joint first authors), Peiris, Jaffe (1509.06770)

Experiments

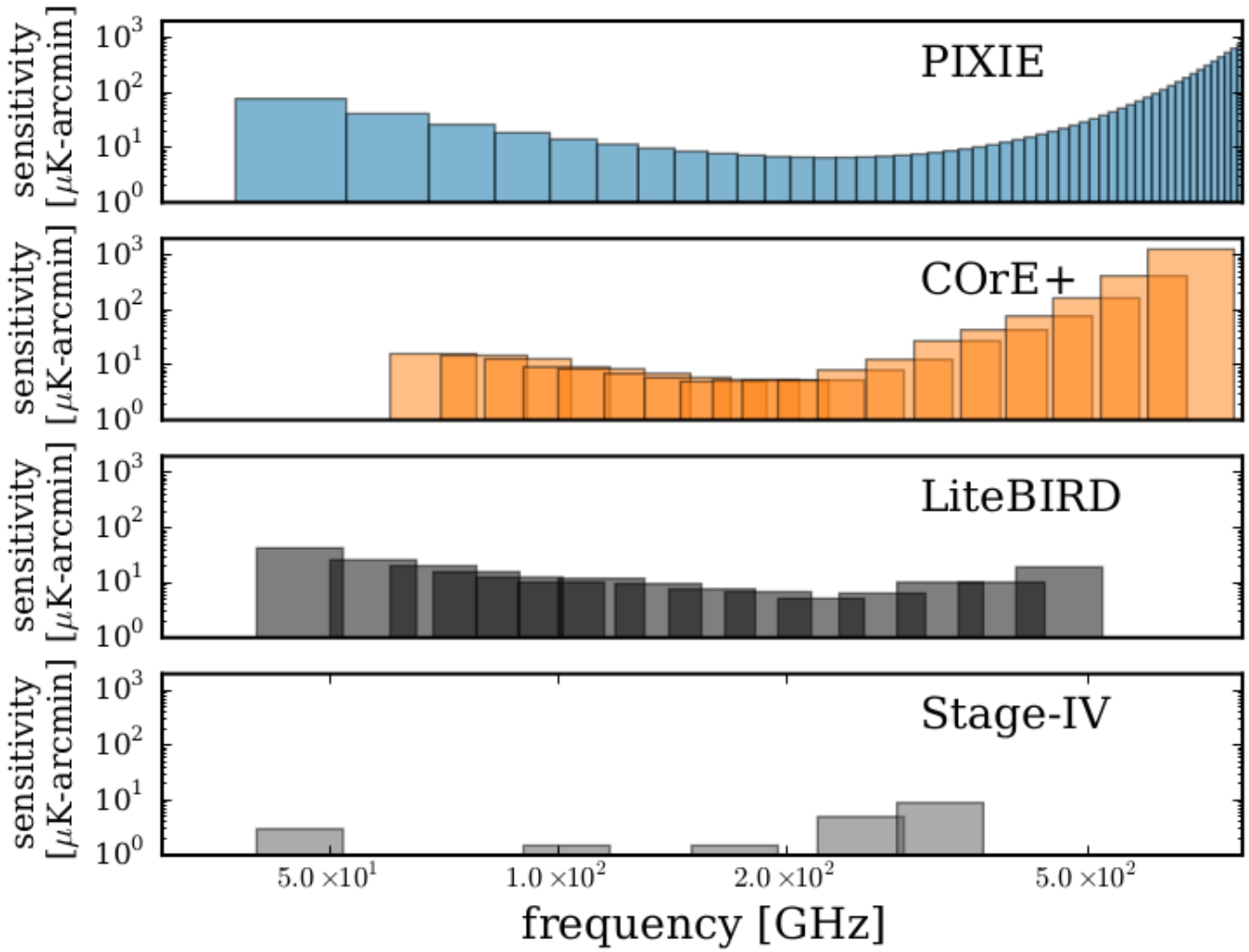




- Frequency bands, polarisation noise, beams and fsky
- Pre-2020 all crossed with Planck

Errard, Feeney (joint first authors), Peiris, Jaffe (1509.06770)

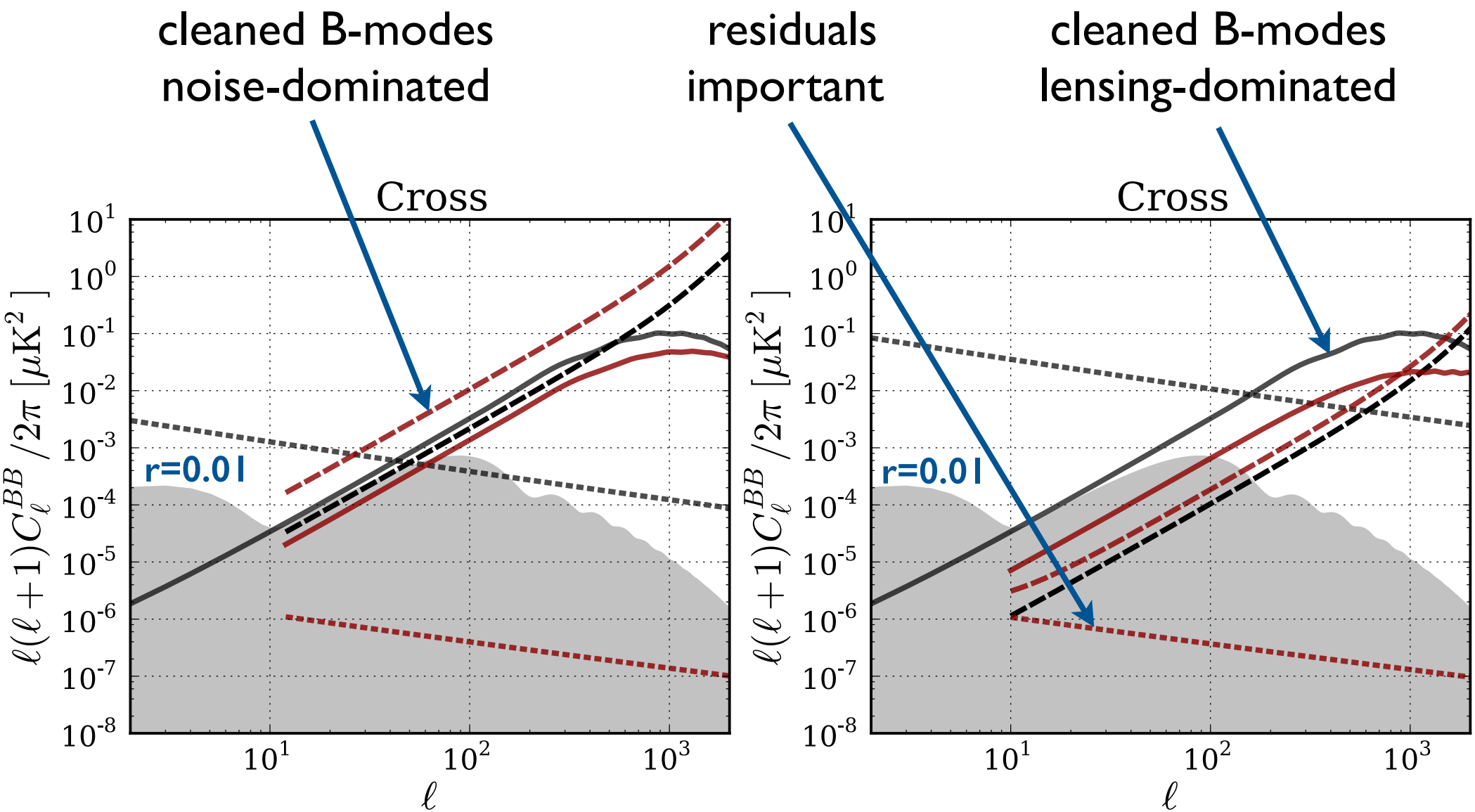
Experiments (post-2020 examples)



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

Errard, Feeney (joint first authors), Peiris, Jaffe (1509.06770)

Foregrounds: selected real experiments

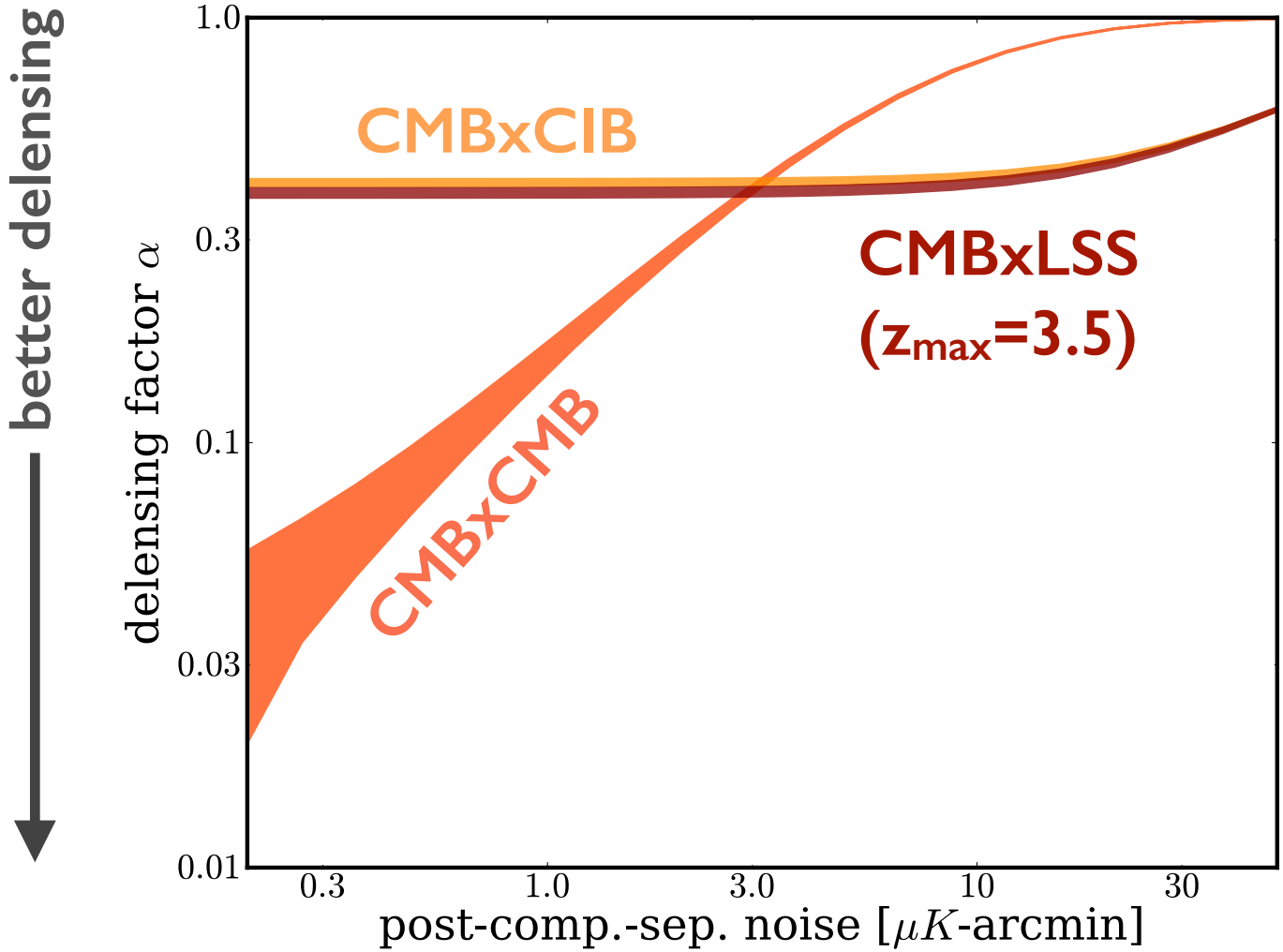


Pre-2020: ground x balloon

Post-2020: ground x satellite

Errard, Feeney (joint first authors), Peiris, Jaffe (1509.06770)

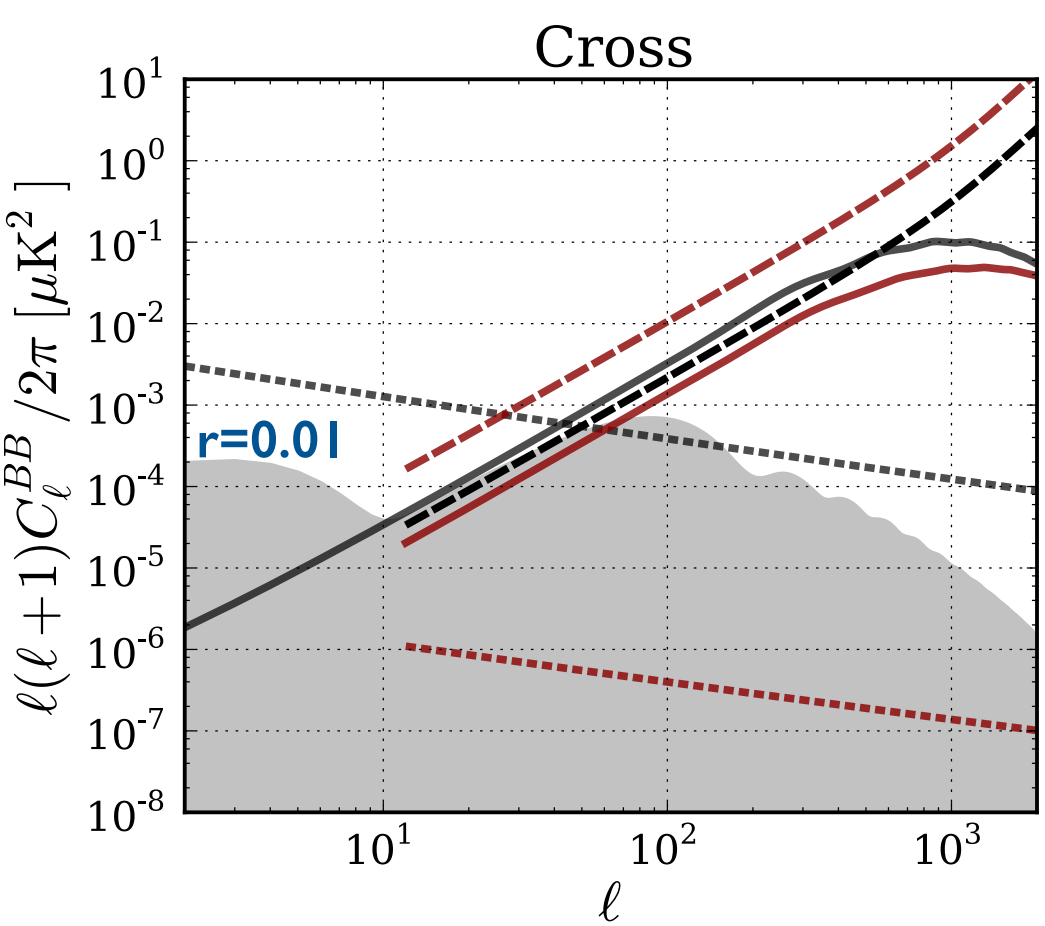
Delensing: toy experiment



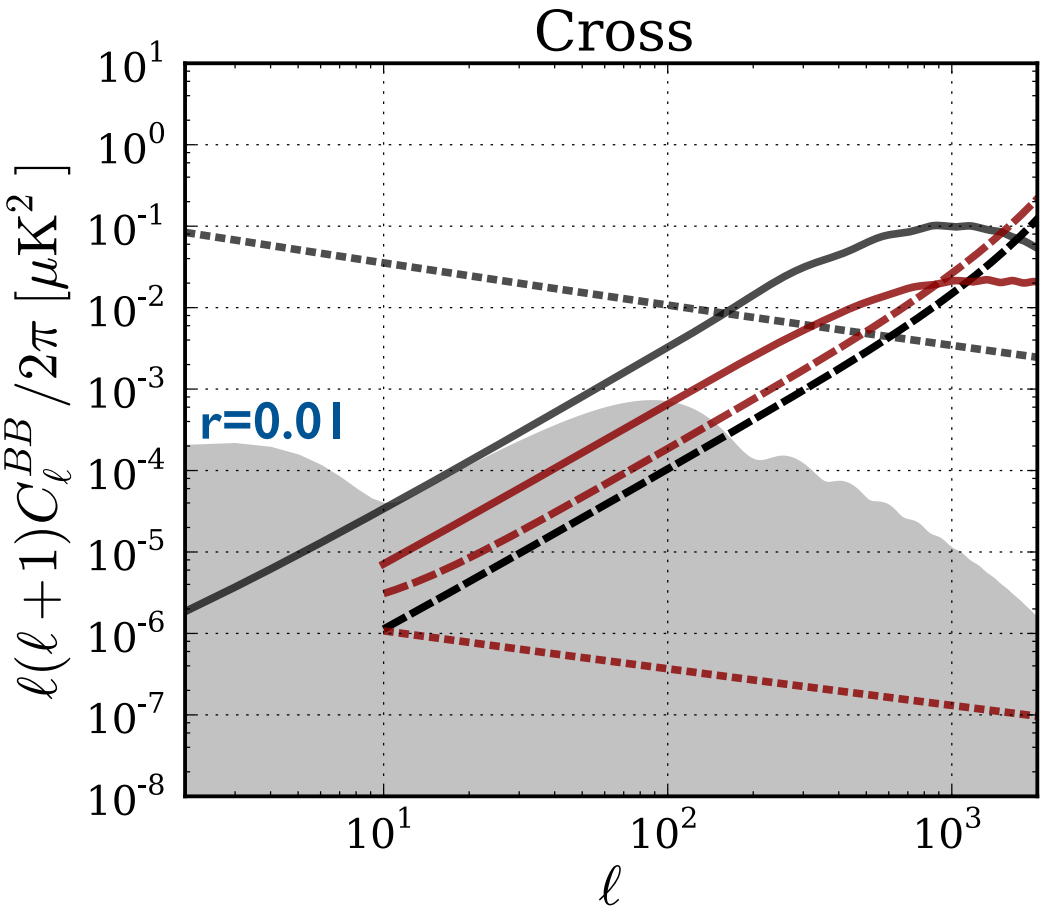
- 3' beam, 0.01 < f_{sky} < 1.0 (f_{sky} floor without delensing)
- CIB/LSS better for noisy expts; CMB delenses to zero if noiseless.

Errard, Feeney (joint first authors), Peiris, Jaffe (1509.06770)

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 (1509.06770)

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 (1509.06770)

Summary

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

  Transition between precision and accuracy