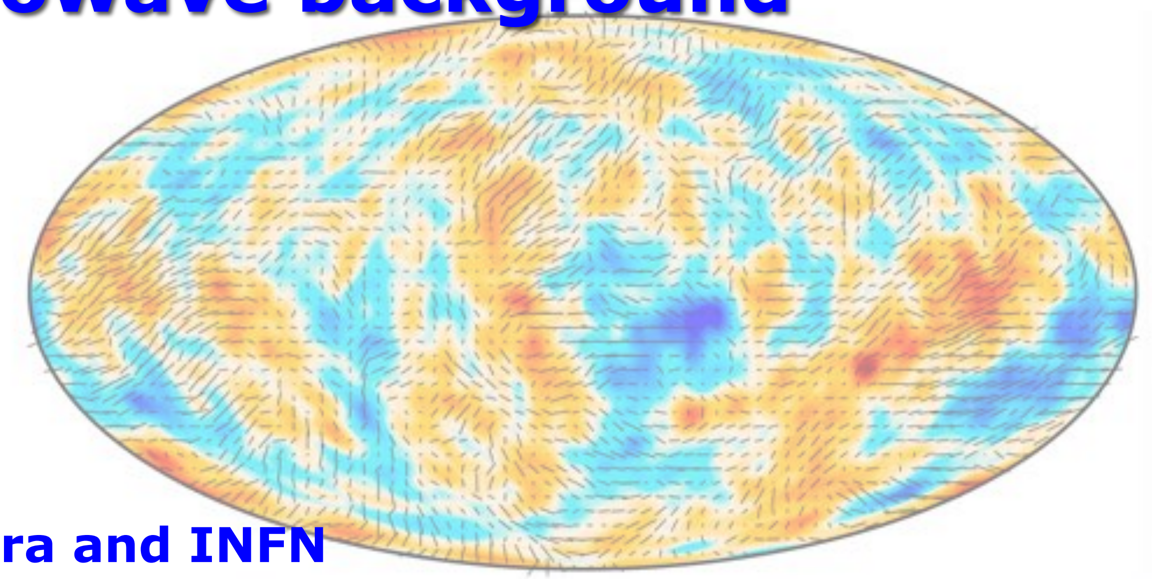
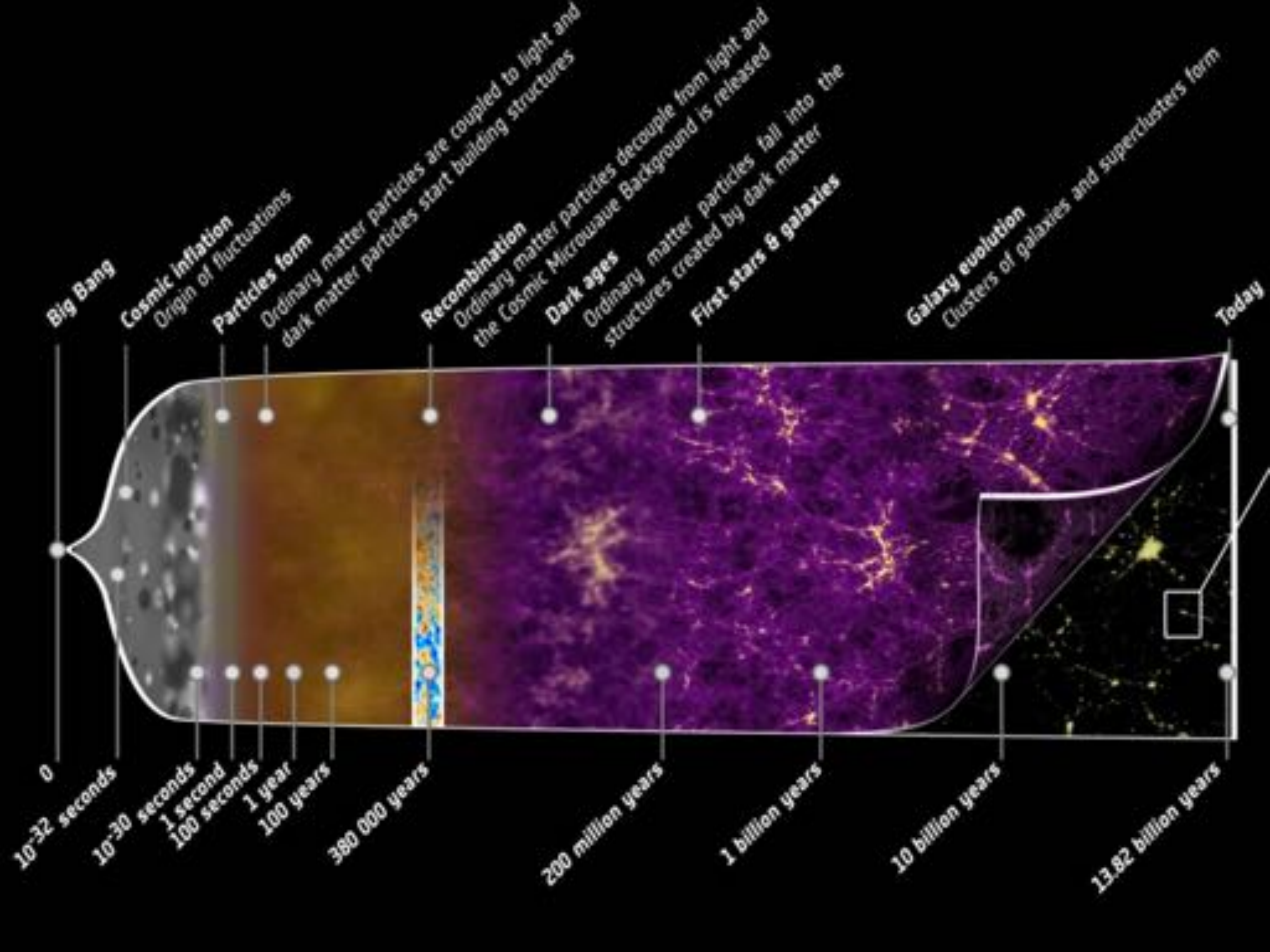
Exploring the early Universe through the cosmic microwave background



Paolo Natoli

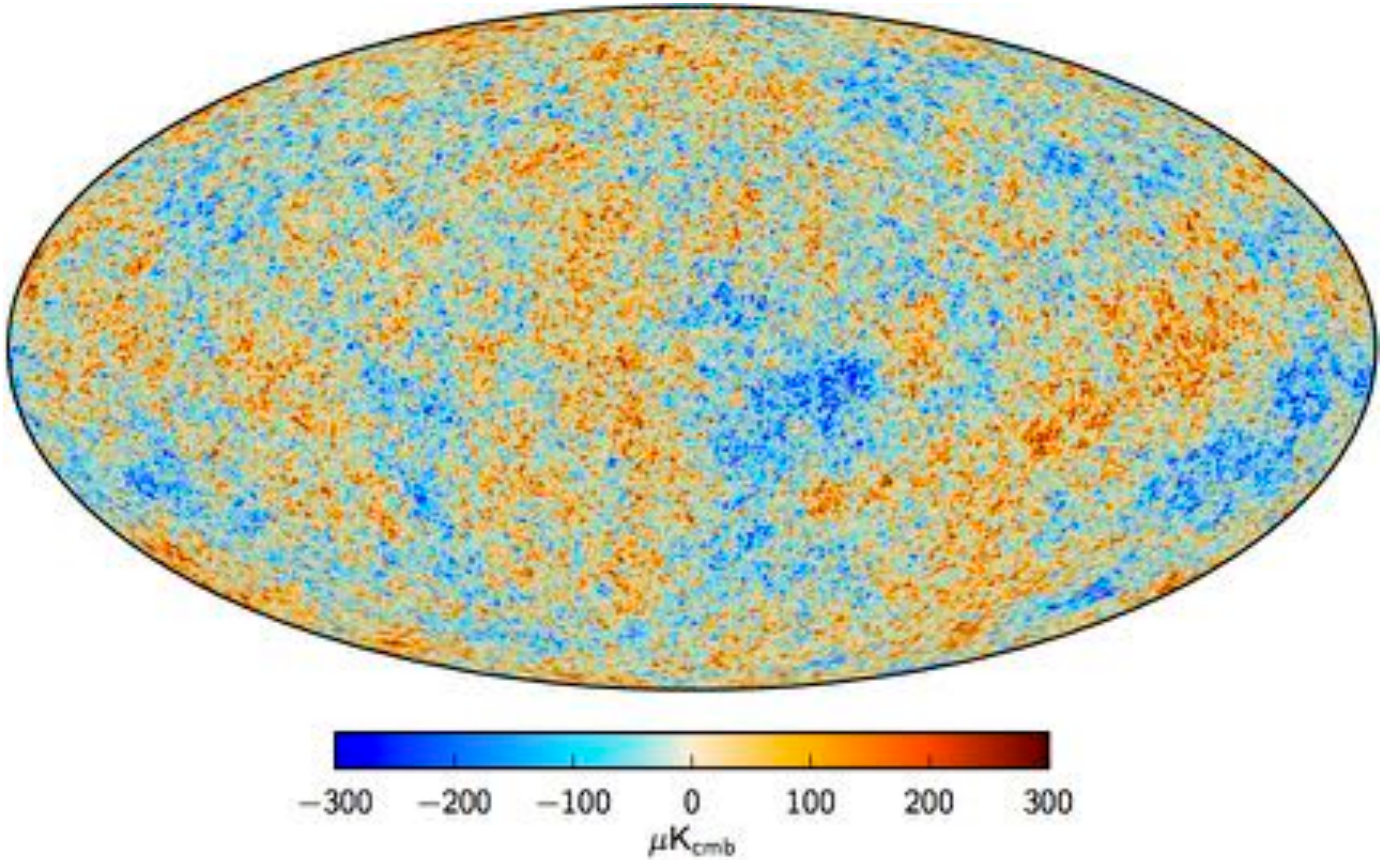
Università di Ferrara and INFN

Torino, 17 October 2019



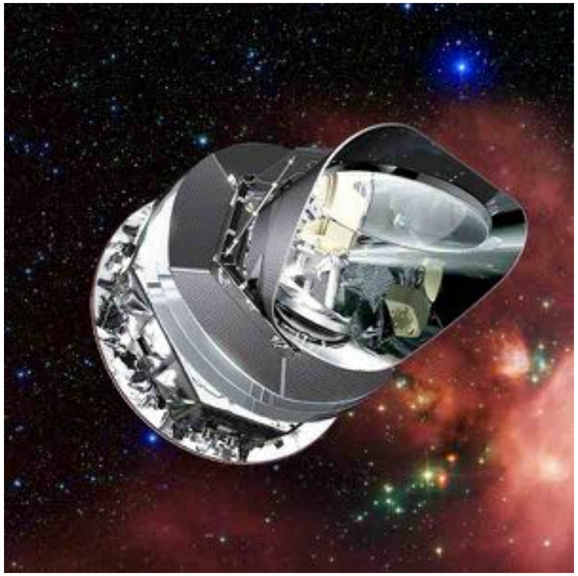
Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10^-32 seconds
10^-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

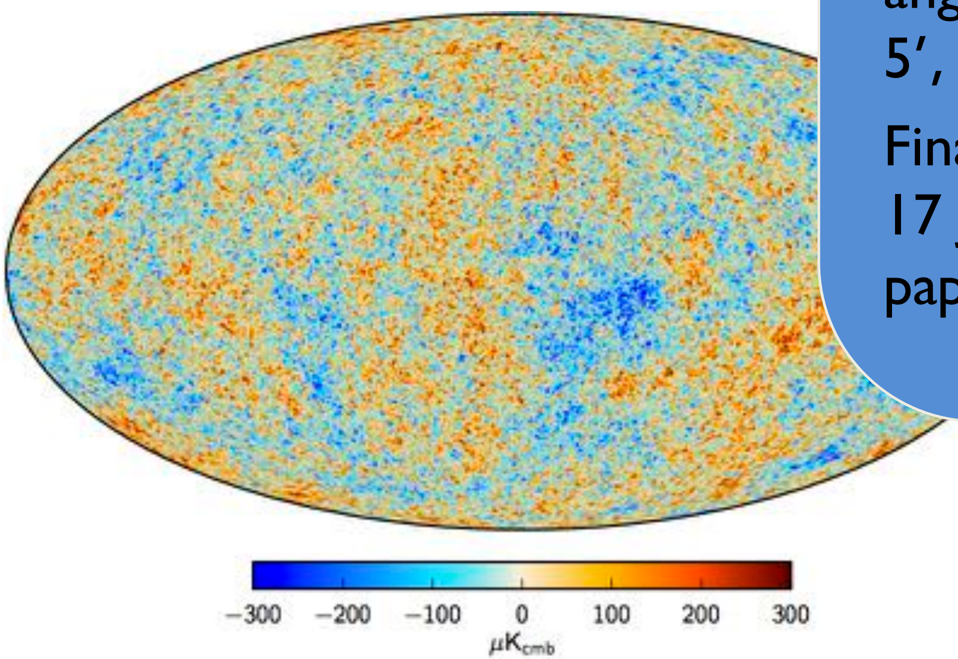
THE COSMIC MICROWAVE BACKGROUND



The CMB tiny (~ 10^{-5}) temperature (and polarization) anisotropies encode a wealth of cosmological information.

The Planck Satellite





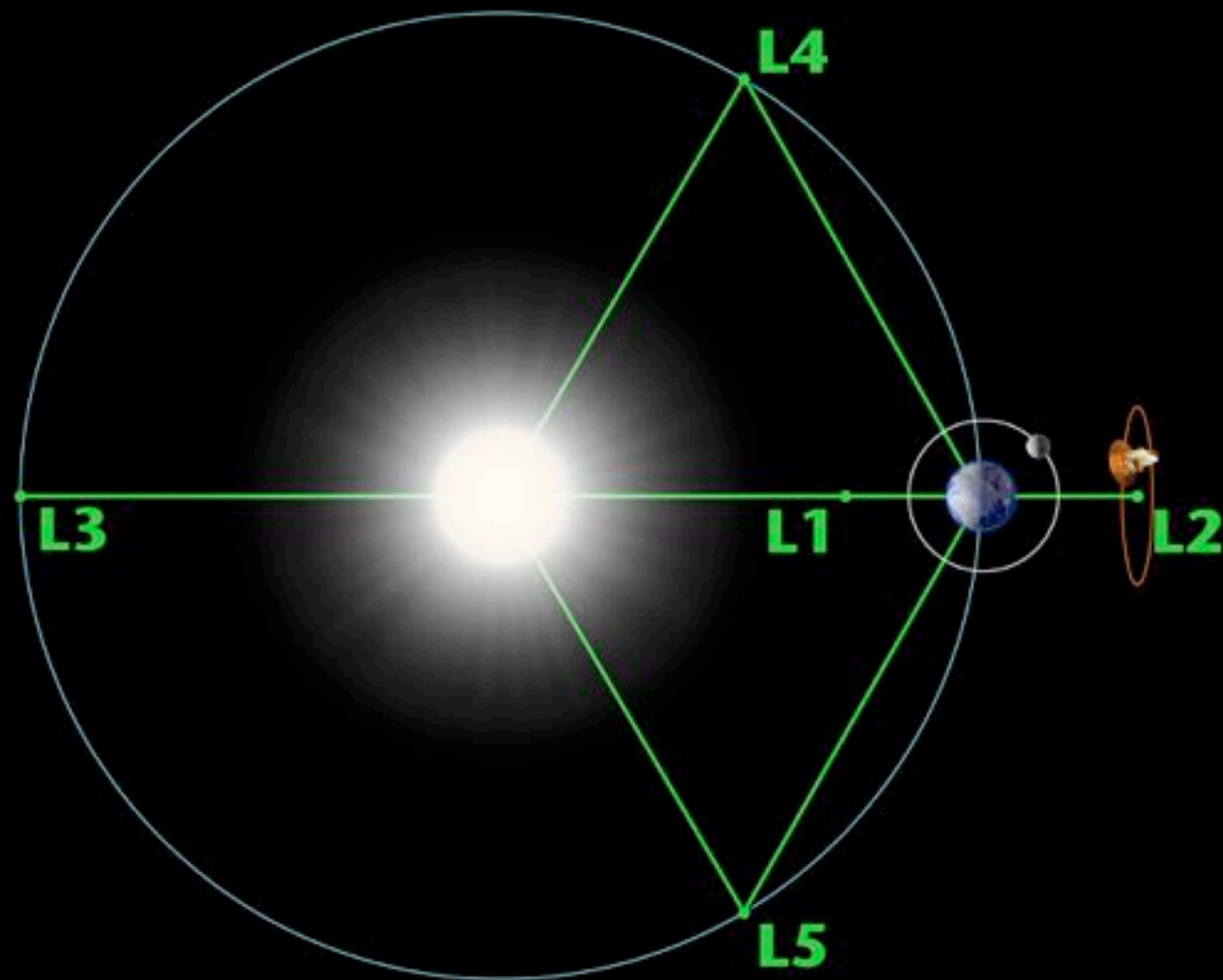
Planck is the 3rd generation ESA satellite devoted to CMB

Ultimate characterization of the temperature anisotropies

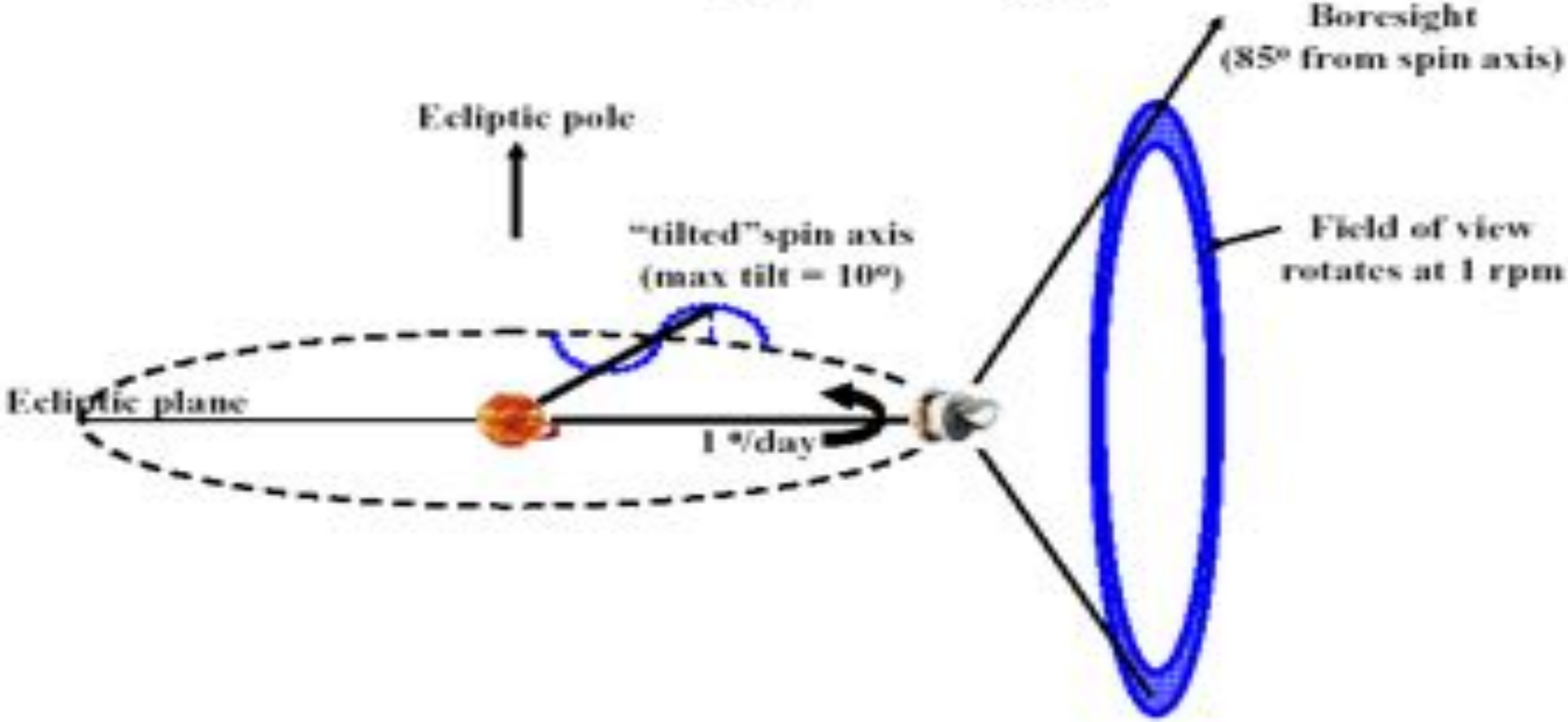
74 detectors (radiometers and bolometers) in 9 frequency bands from 30 to 857 GHz

angular resolution between 30' and 5', $\Delta T/T \sim 2 \times 10^{-6}$

Final (legacy) release took place on 17 July 2018, for data and (most) papers.

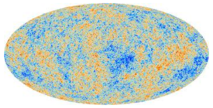

L4
L3
L1
L2
L5

Observing strategy



The Planck Collaboration

May 2009: Launched from Kourou

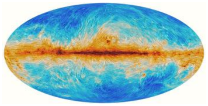


Mar 2013: Data Release and Cosmology Results
Nominal Mission Temperature data

32 papers

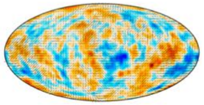
Oct 2013: Planck 'Shut Down'

52 papers / intermediate results



Feb 2015: Data Release and Cosmology Results
Full Mission Temperature and (preliminary) Polarization data

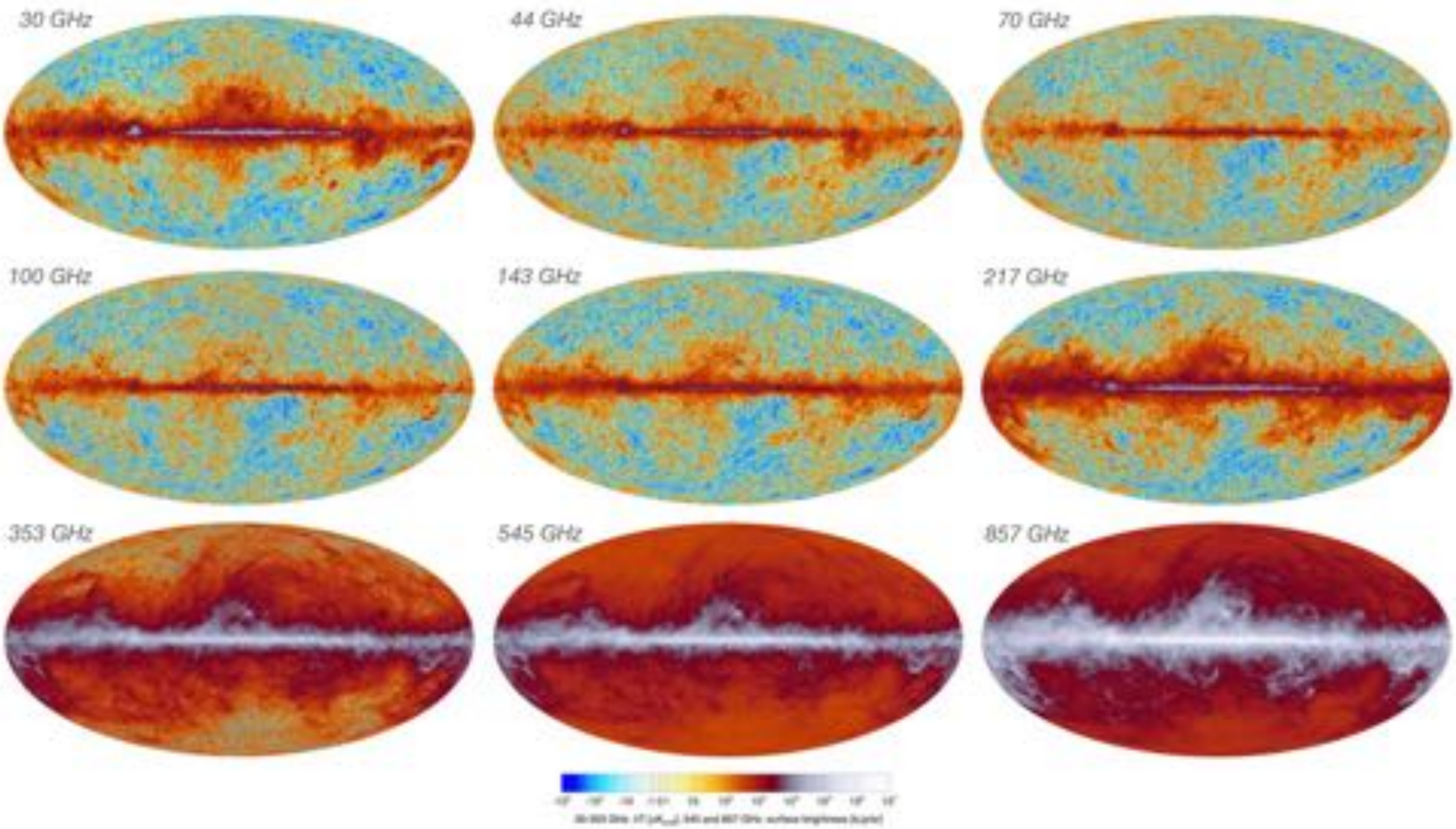
28 papers



Jul 2018: Legacy Data & Paper Release

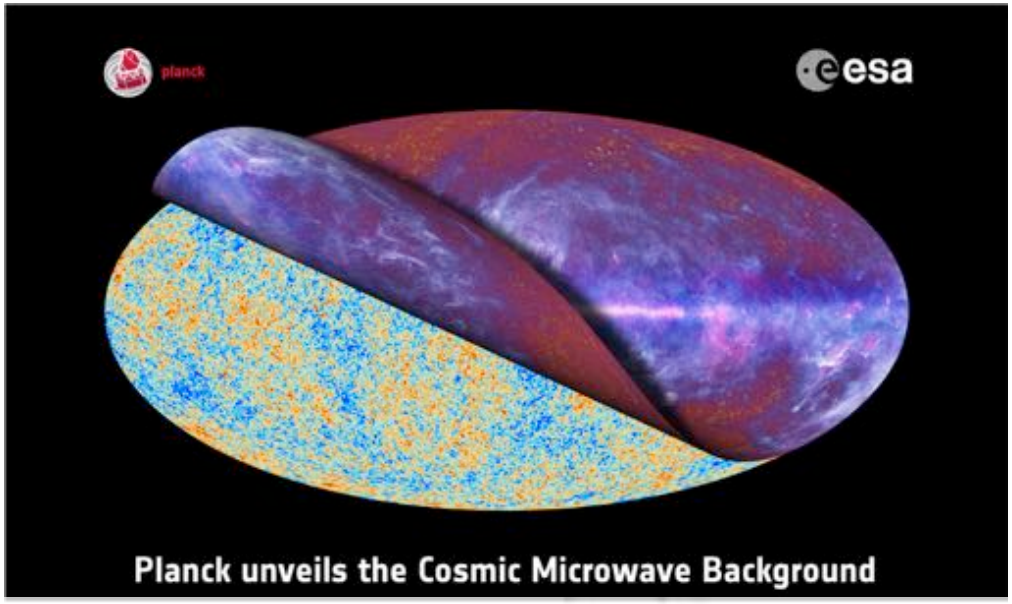
9 papers (+3 to appear soon)

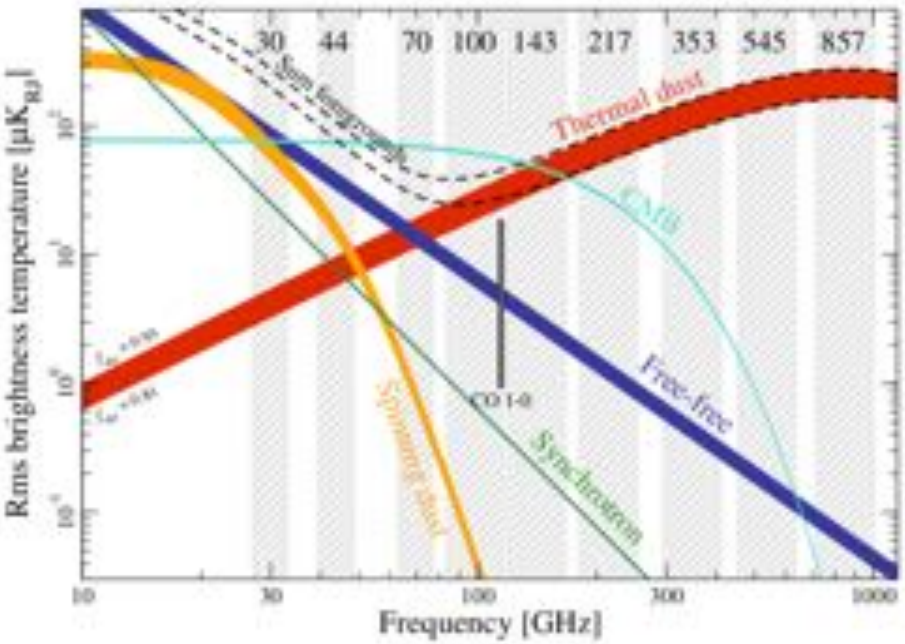
THE TEMPERATURE SKY AS SEEN BY PLANCK 2018

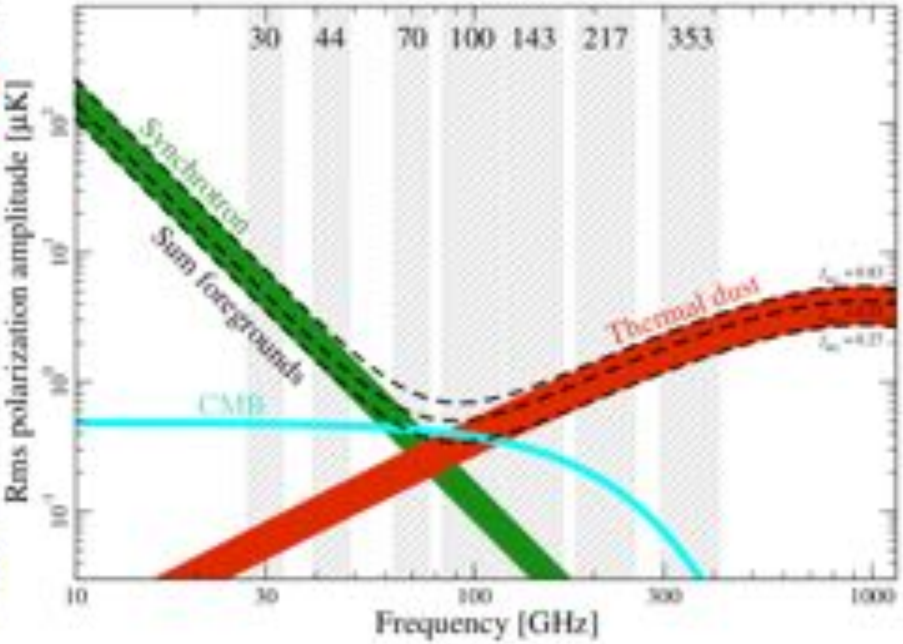


UNVEILING THE CMB SKY

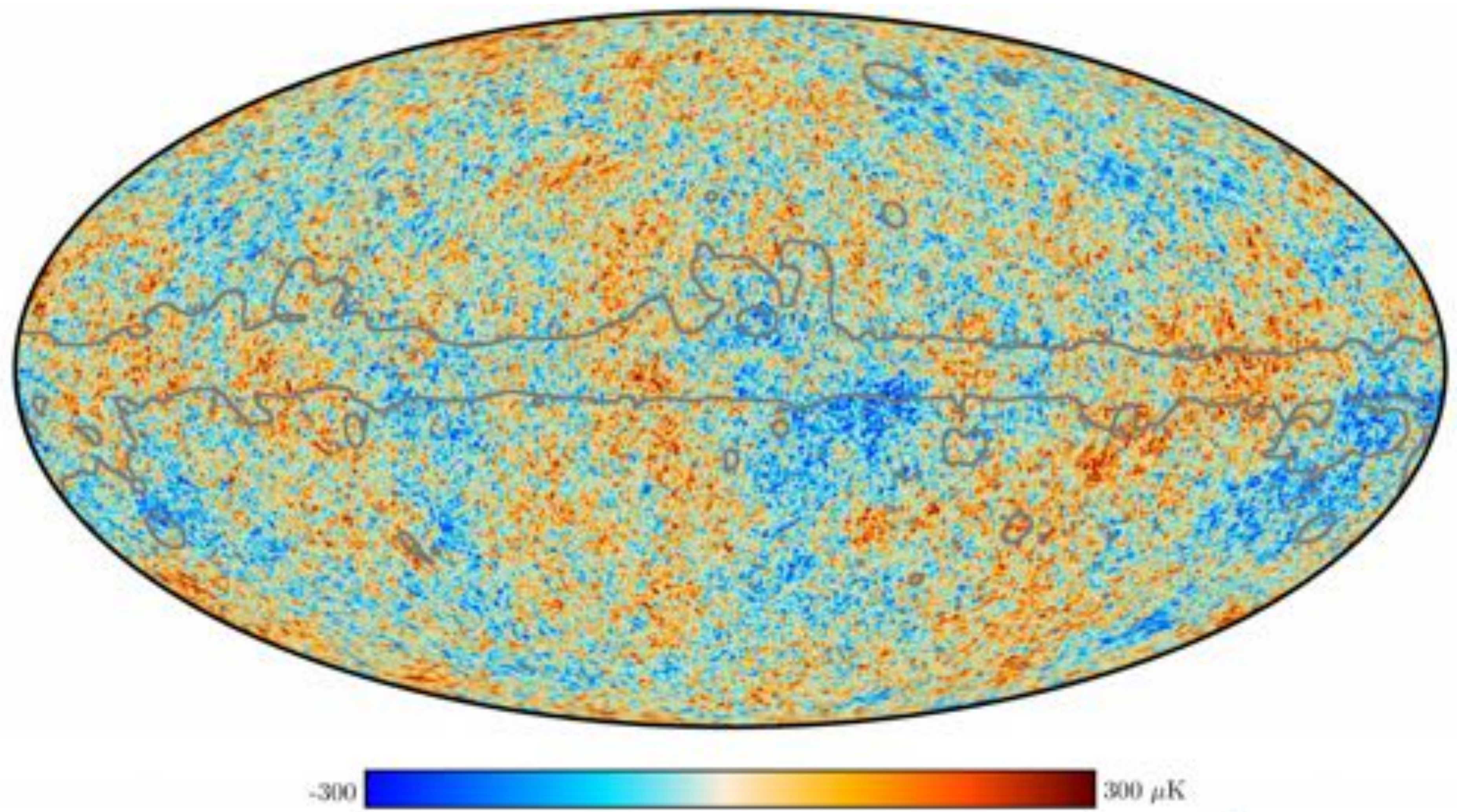
The *ultimate* measurement of the CMB temperature anisotropy field



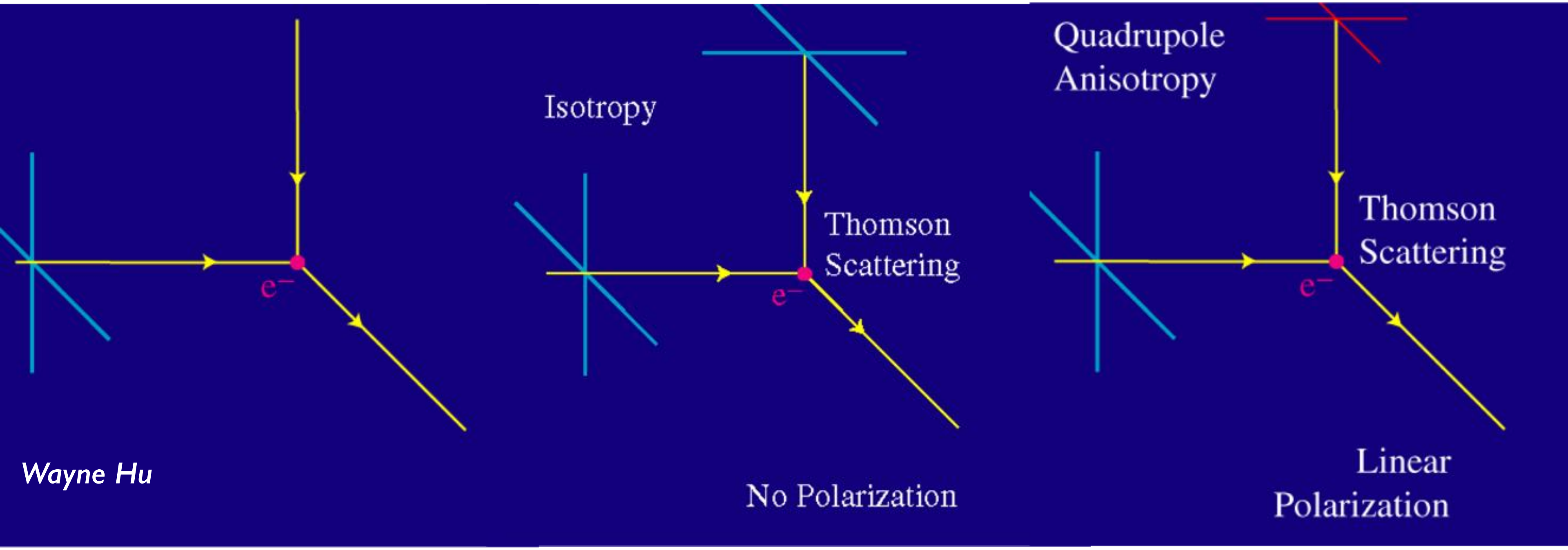




PLANCK: TEMPERATURE ANISOTROPIES

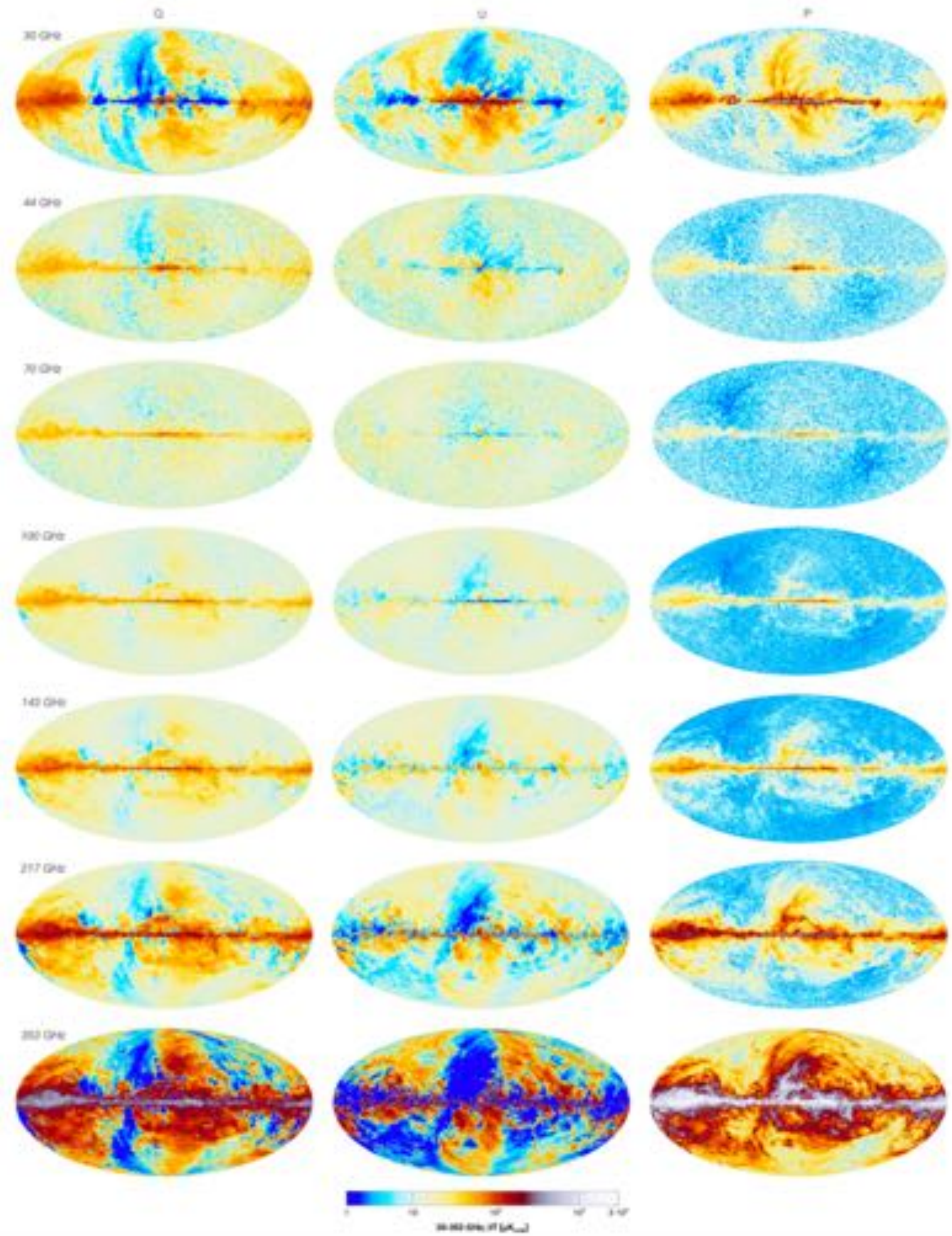


The CMB is linearly polarized



- The Thomson scattering cross section depends on photon polarization: $\frac{d\sigma_T}{d\Omega} \propto |\hat{\varepsilon} \cdot \hat{\varepsilon}'|^2$
- CMB polarization is created *only* by a local temperature **quadrupole** anisotropy. This is generated only when the photon diffusion length grows enough to reveal higher order moments in the brightness distribution (e.g. at recombination)

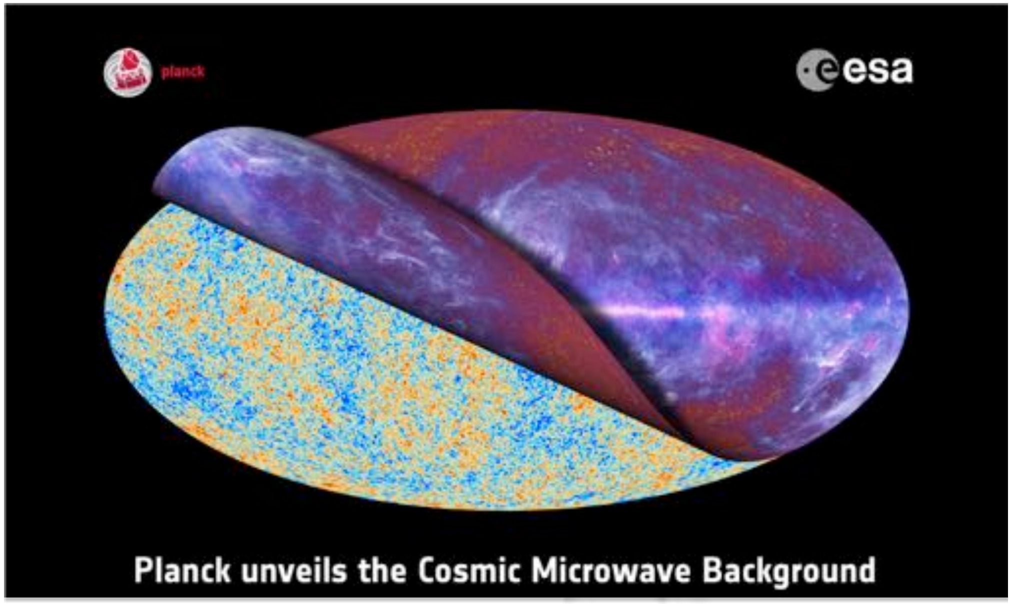
THE POLARIZATION SKY AS SEEN BY PLANCK 2018

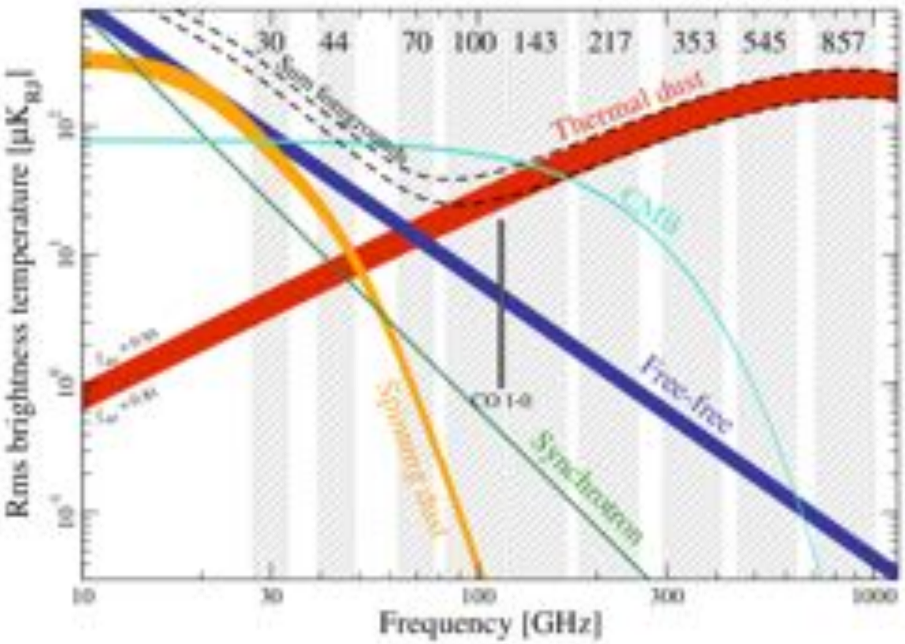


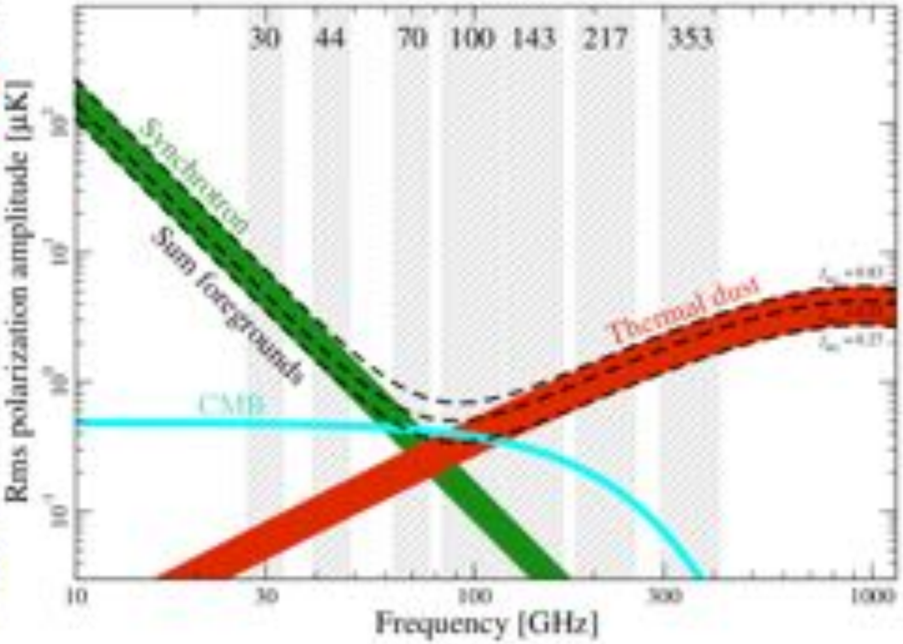
Significant reduction of large scale polarization systematics in 2018

UNVEILING THE CMB SKY

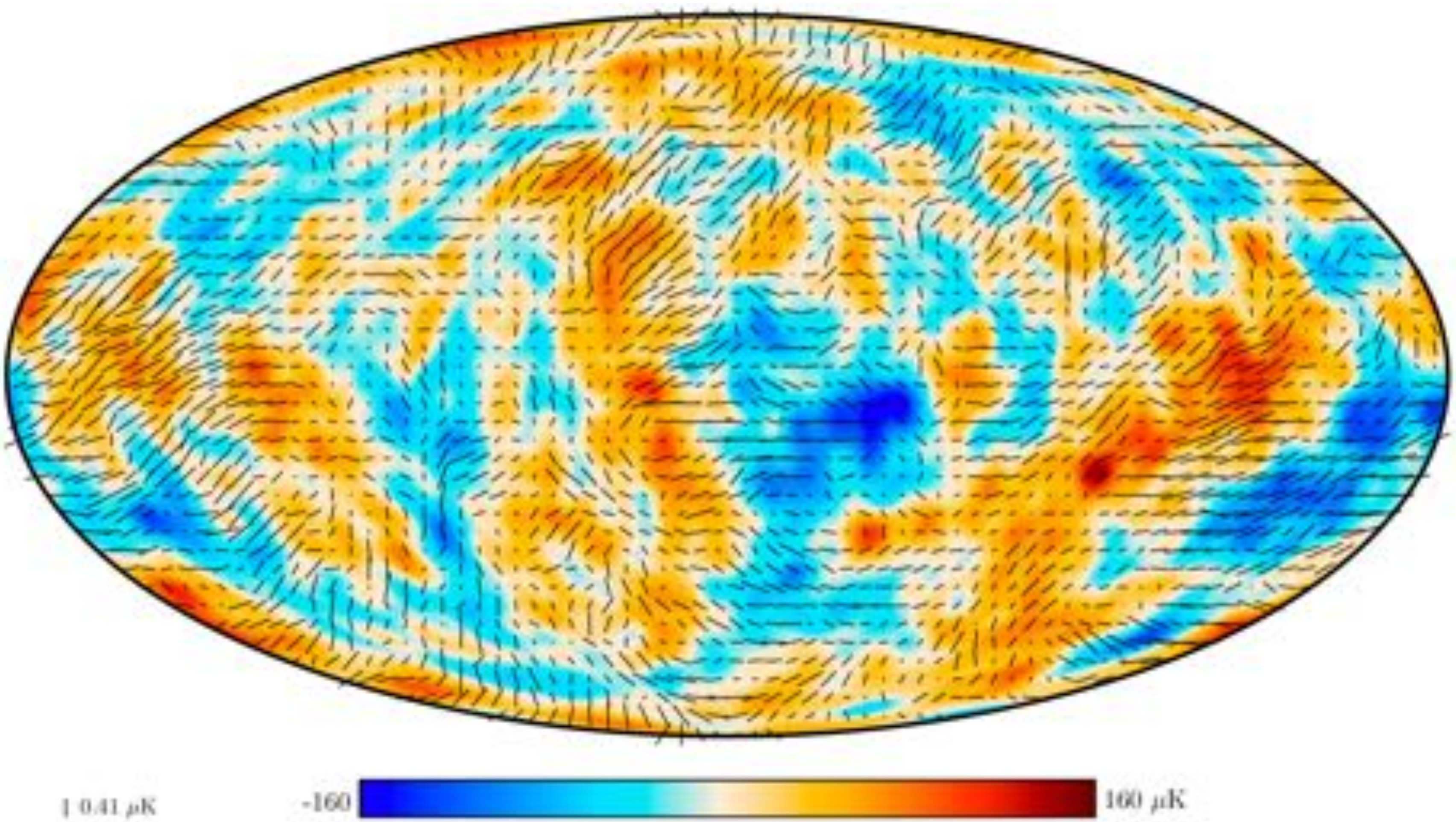
A first attempt to all sky polarization





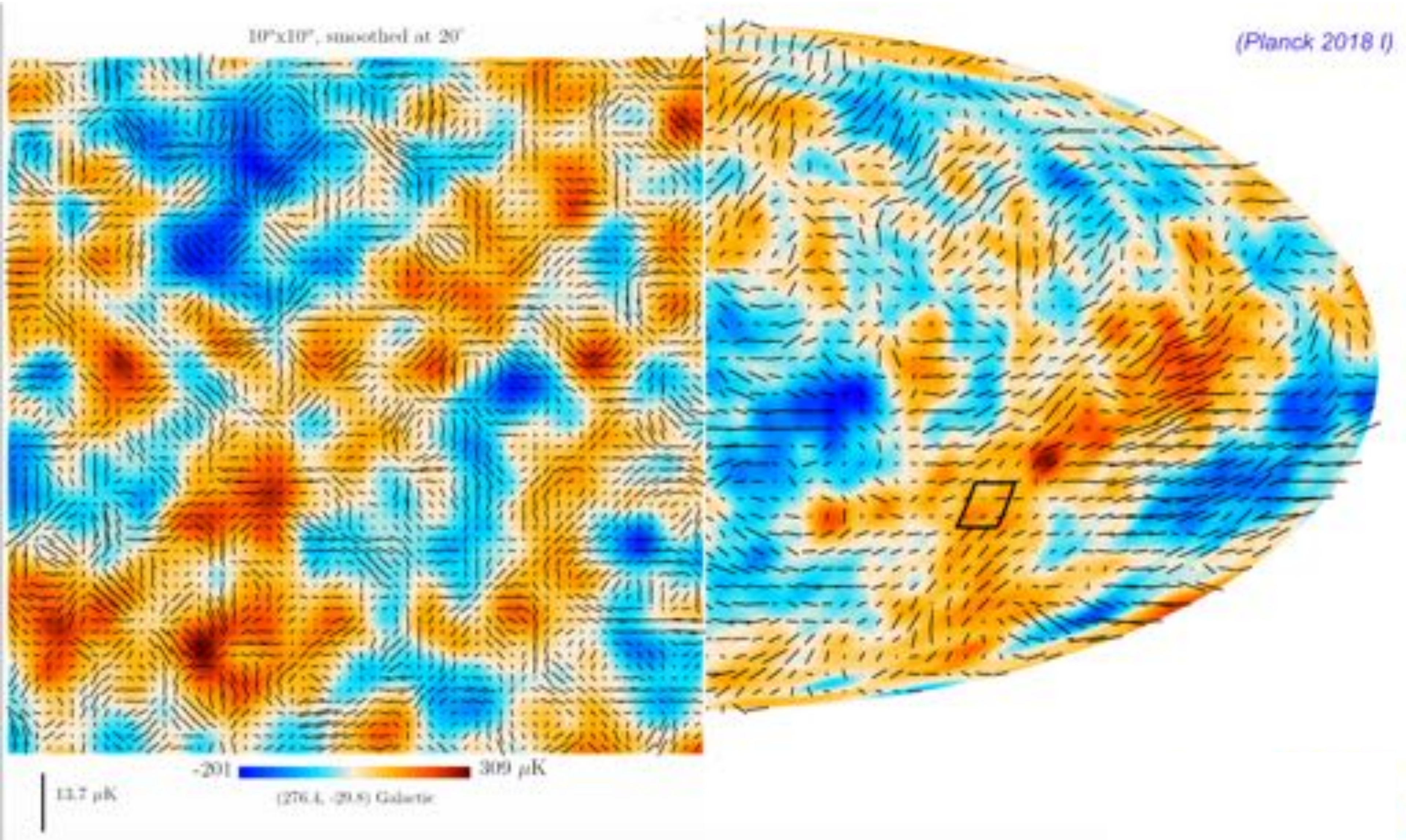


PLANCK: POLARIZATION ANISOTROPIES

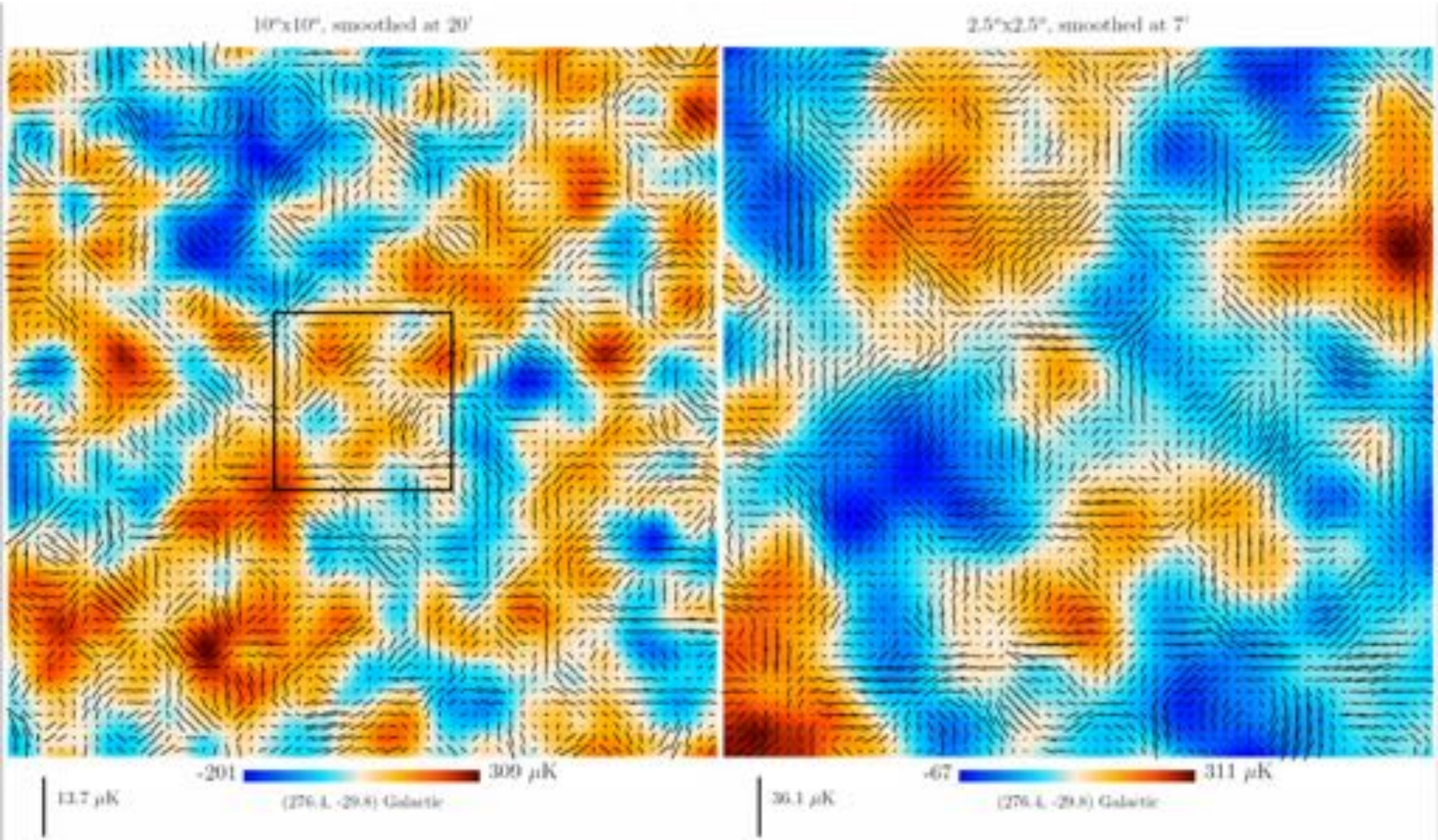


Temperature smoothed to 5 degrees

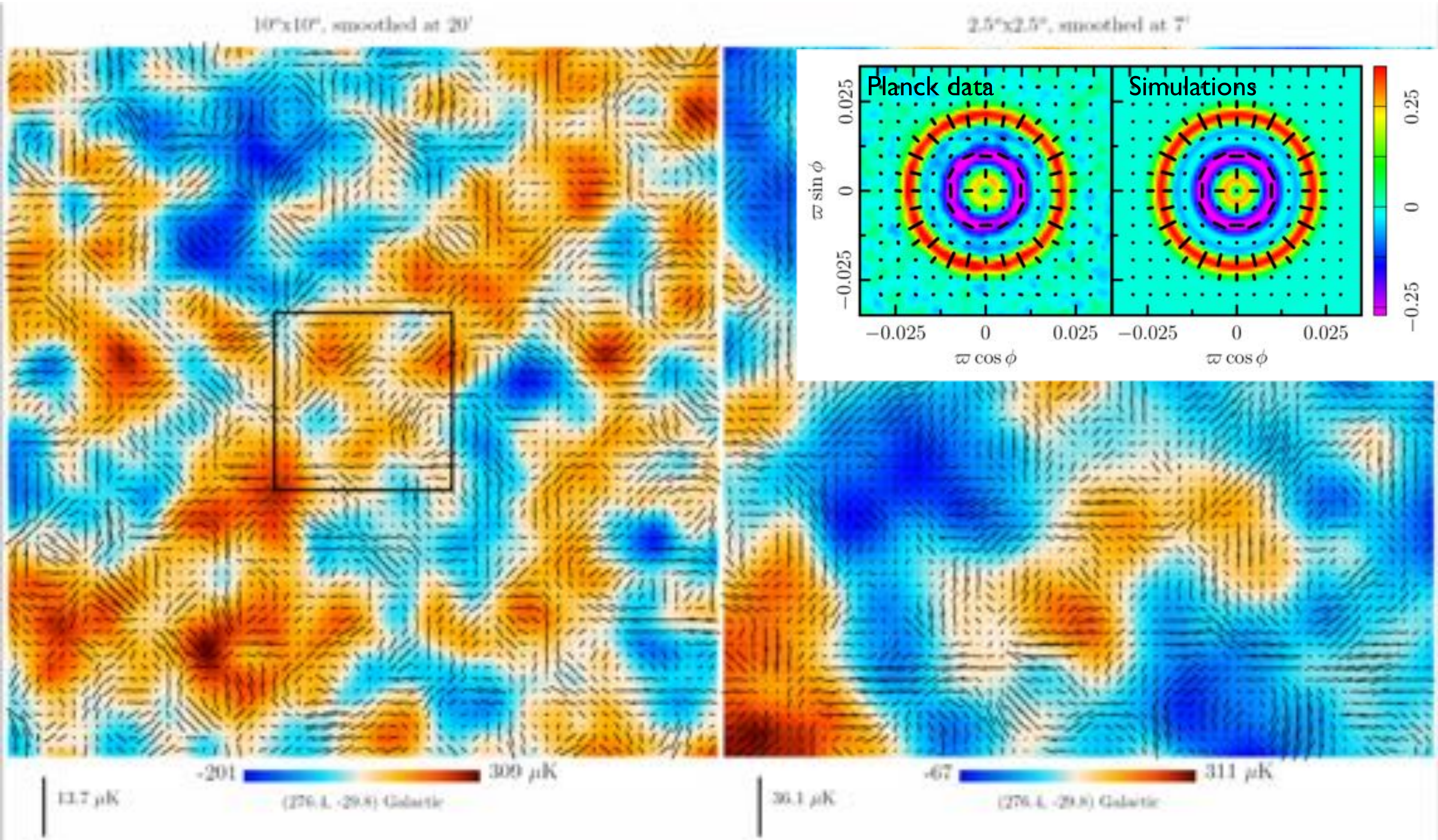
PLANCK: POLARIZATION ANISOTROPIES



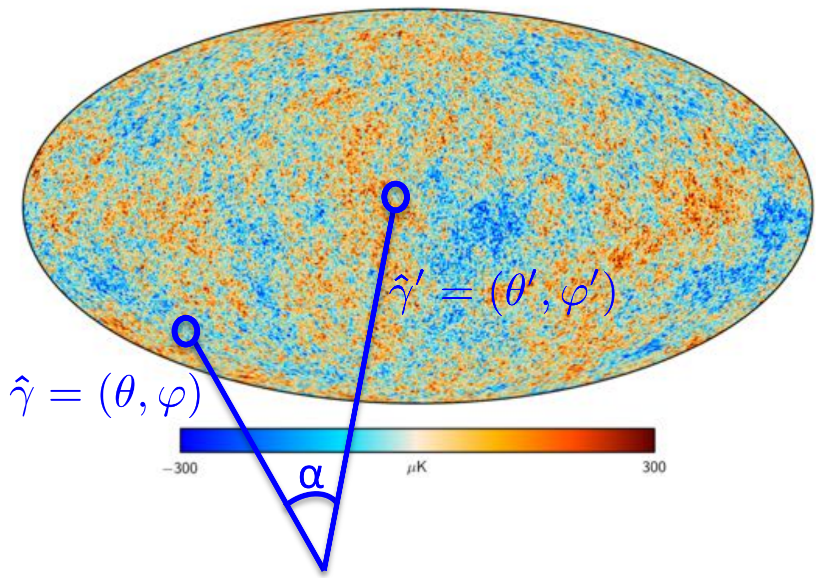
Planck: Polarization Anisotropies



PLANCK: POLARIZATION ANISOTROPIES



A STATISTICAL DESCRIPTION



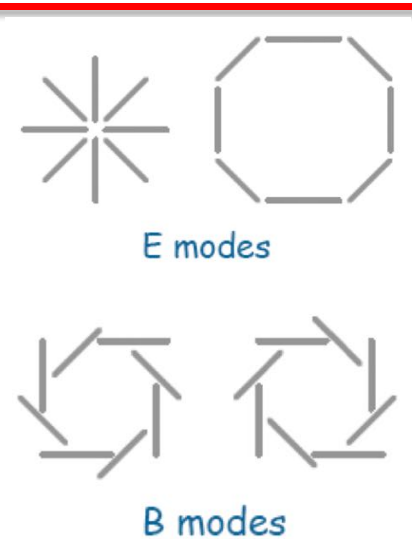
CORRELATION FUNCTIONS

$$\left\langle \frac{\Delta T}{T}(\vec{\gamma})\frac{\Delta T}{T}(\vec{\gamma}') \right\rangle$$ ← from Inflation

$$\left\langle \frac{\Delta T}{T}(\vec{\gamma})\frac{\Delta T}{T}(\vec{\gamma}')\frac{\Delta T}{T}(\vec{\gamma}'') \right\rangle$$

$$\left\langle \frac{\Delta T}{T}(\vec{\gamma})\frac{\Delta T}{T}(\vec{\gamma}')\frac{\Delta T}{T}(\vec{\gamma}'')\frac{\Delta T}{T}(\vec{\gamma}''') \right\rangle$$

...



POLARIZATION

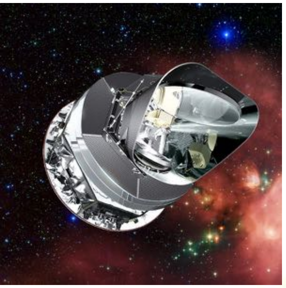
$$\mathbf{P}(\hat{\gamma}) = \nabla\mathbf{E} + \nabla \times \mathbf{B}$$

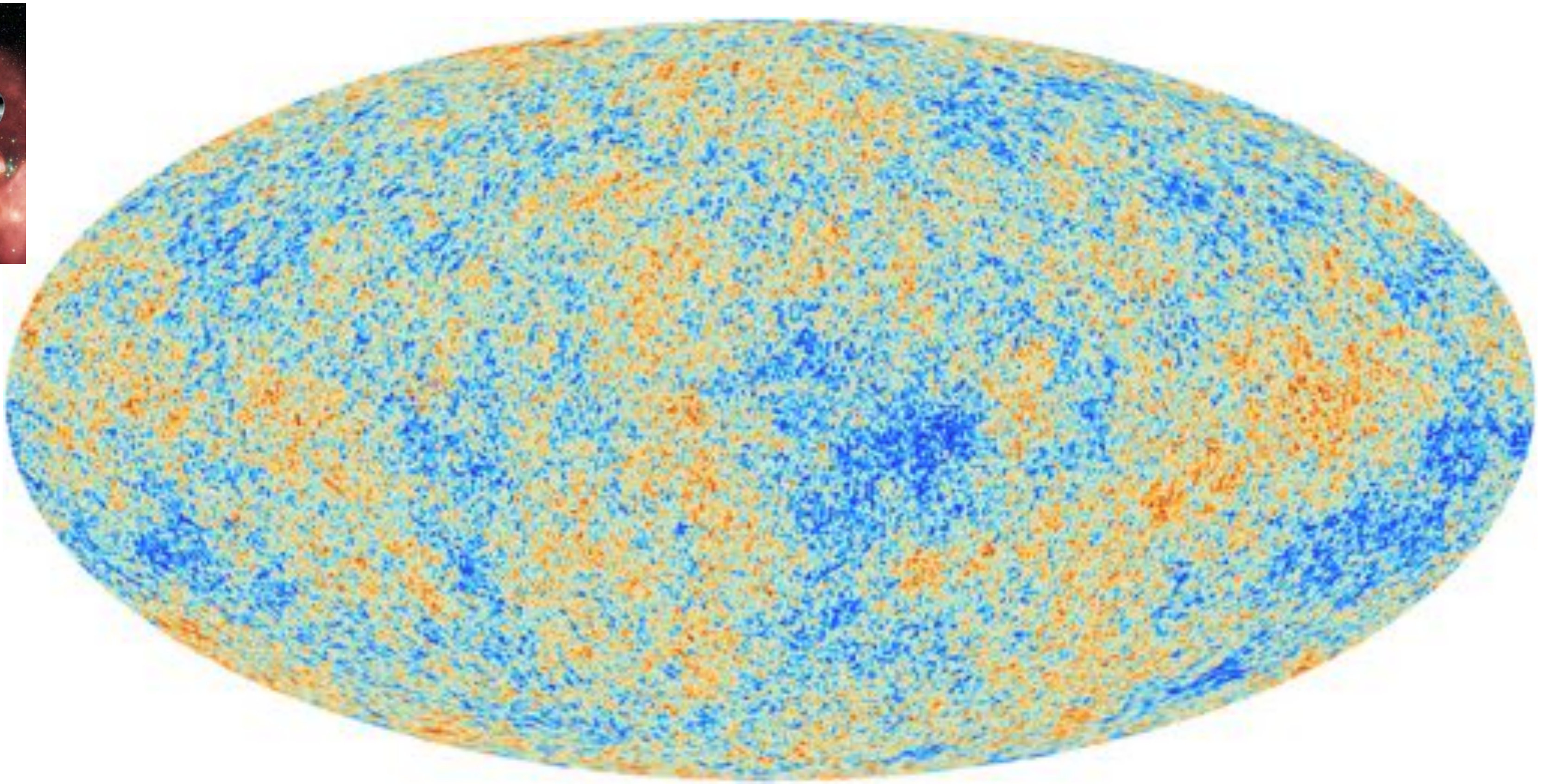
E-modes: even under parity

B-modes: odd under parity

Density perturbations -> E-modes

Gravitational Waves -> E- and B-modes

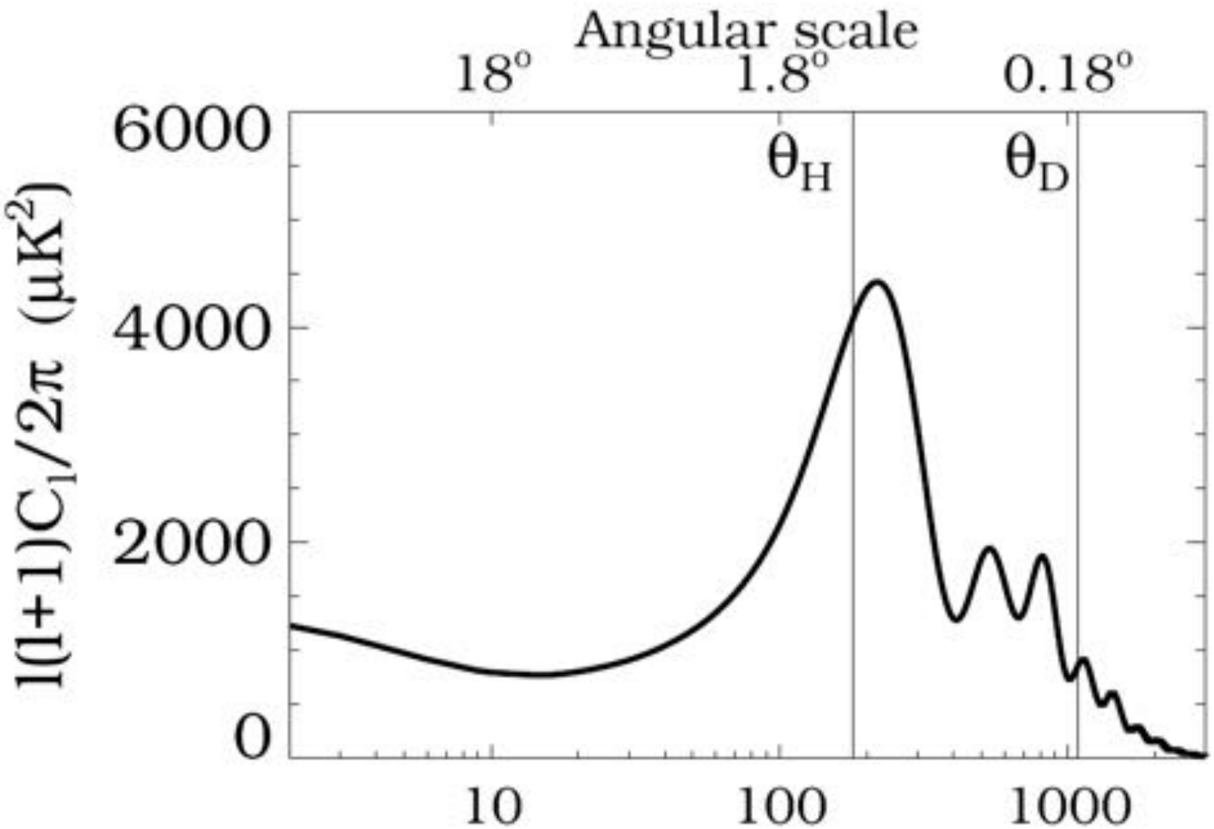




If the fluctuations are gaussian, all the statistical information in the map is encoded in the two point correlation function or in its harmonic transform, the angular power spectrum:

$$\Theta(\hat{n}) = \sum_{\ell=0}^{\ell=\infty} \sum_{m=-\ell}^{+\ell} a_{\ell m} Y_{\ell m}(\hat{n})$$

$$\left\langle a_{\ell m} a^{*}_{\ell' m'} \right\rangle = \delta_{\ell\ell'} \delta_{mm'} C_{\ell}$$

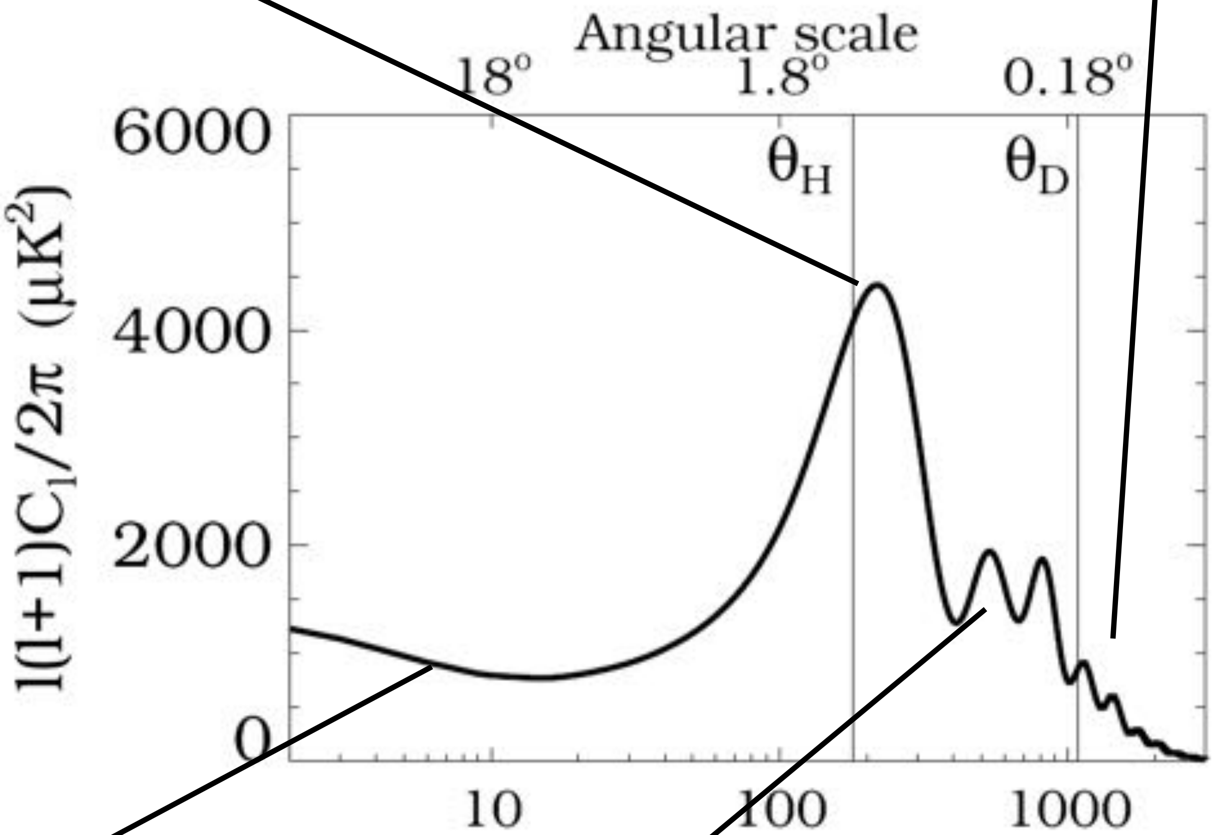


Angular scale
18°
1.8°
0.18°
6000
4000
2000
0
θH
θD
l(l+1)Cl/2π (μK²)
10
100
1000

Multipole l

spatial curvature
relative abundance of matter and radiation
distance to the last scattering surface
H_0, Ω_m, Ω_k

Photon diffusion length at recombination
Slope of the primordial spectrum
N_{eff}, Ω_b, Y_p, n_s



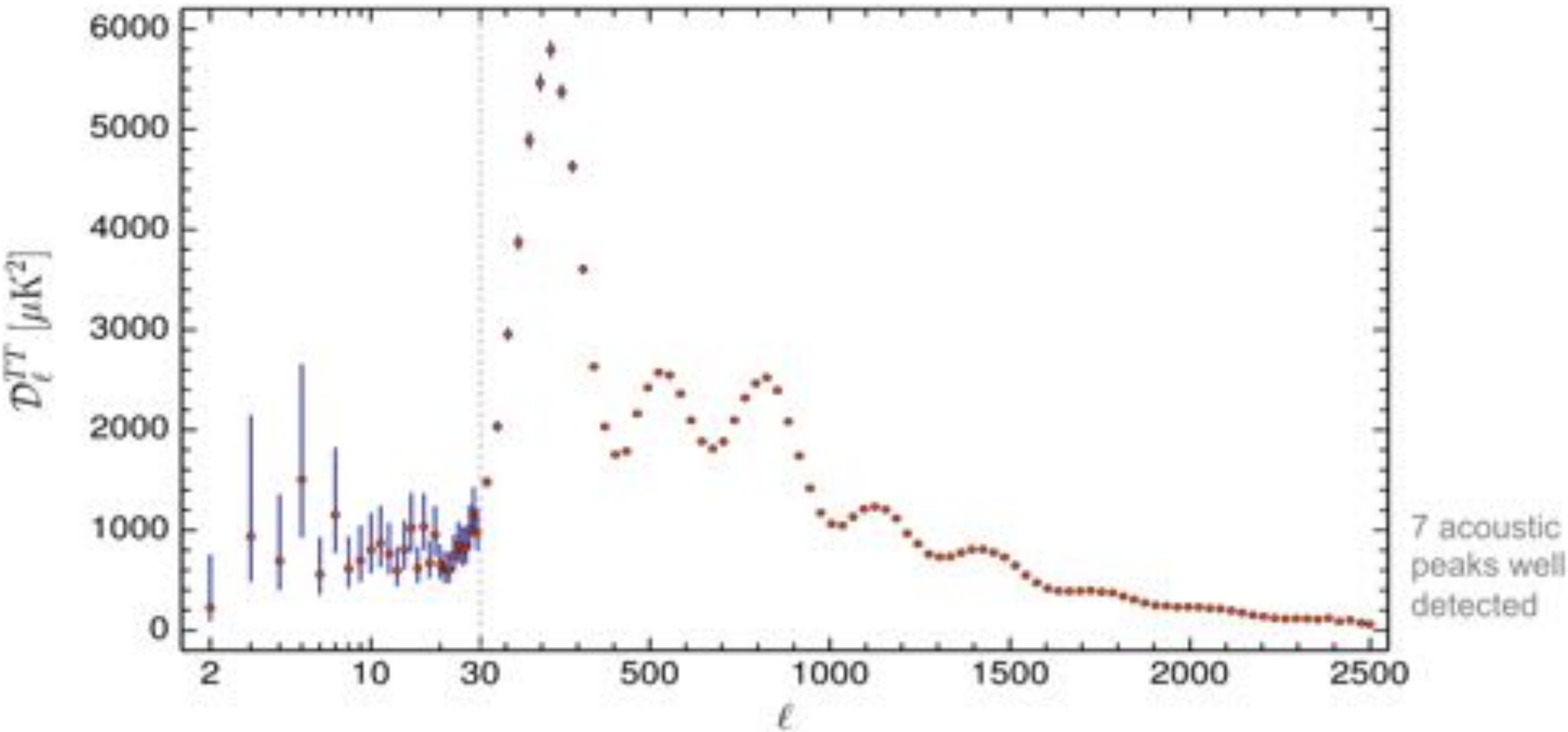
+ Overall power
$A_s e^{-2\tau}$

+ low-ell polarization (not shown)
Reionization history
τ

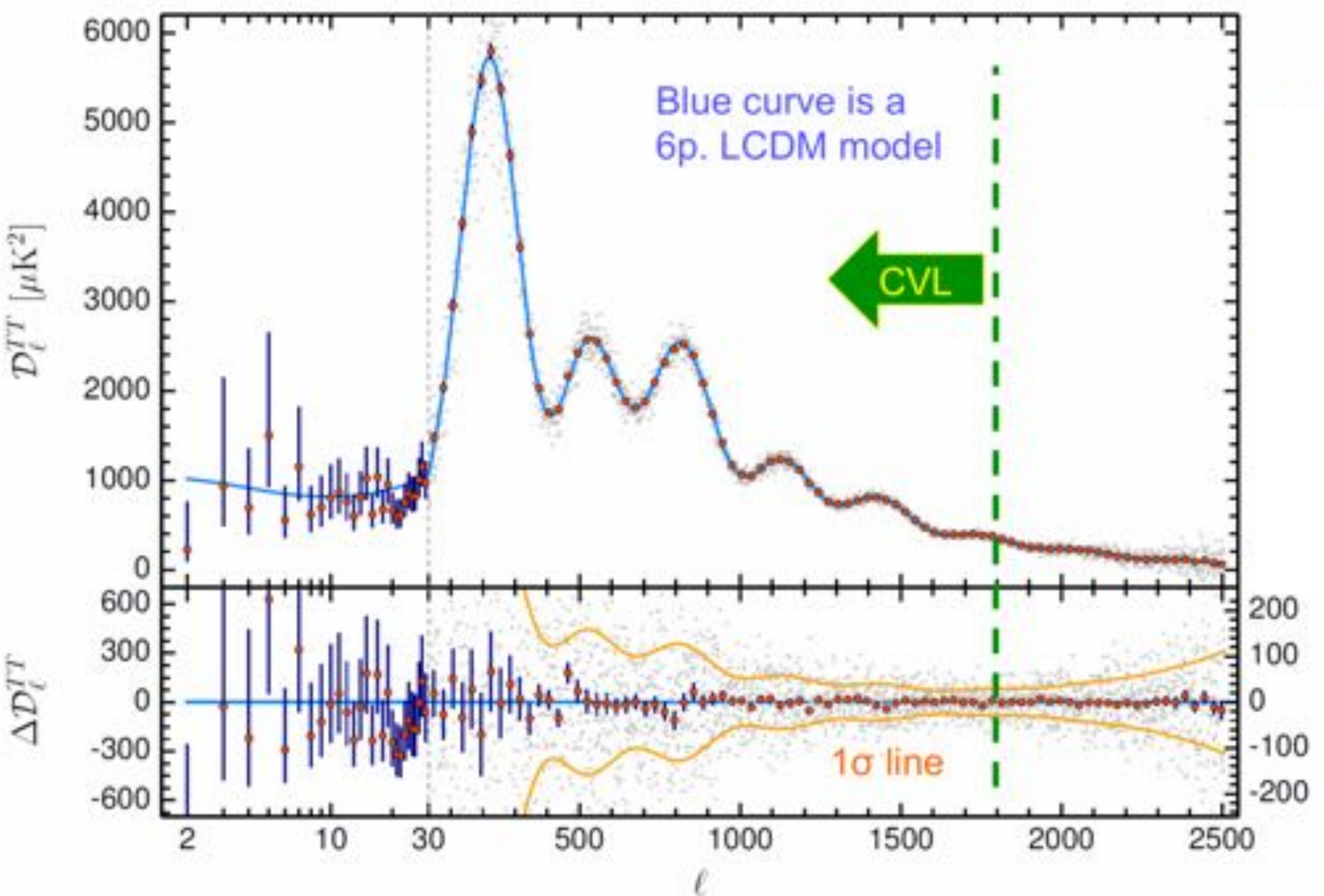
Primordial power spectrum
late time expansion
A_s, Ω_Λ

Baryon abundance
Ω_b

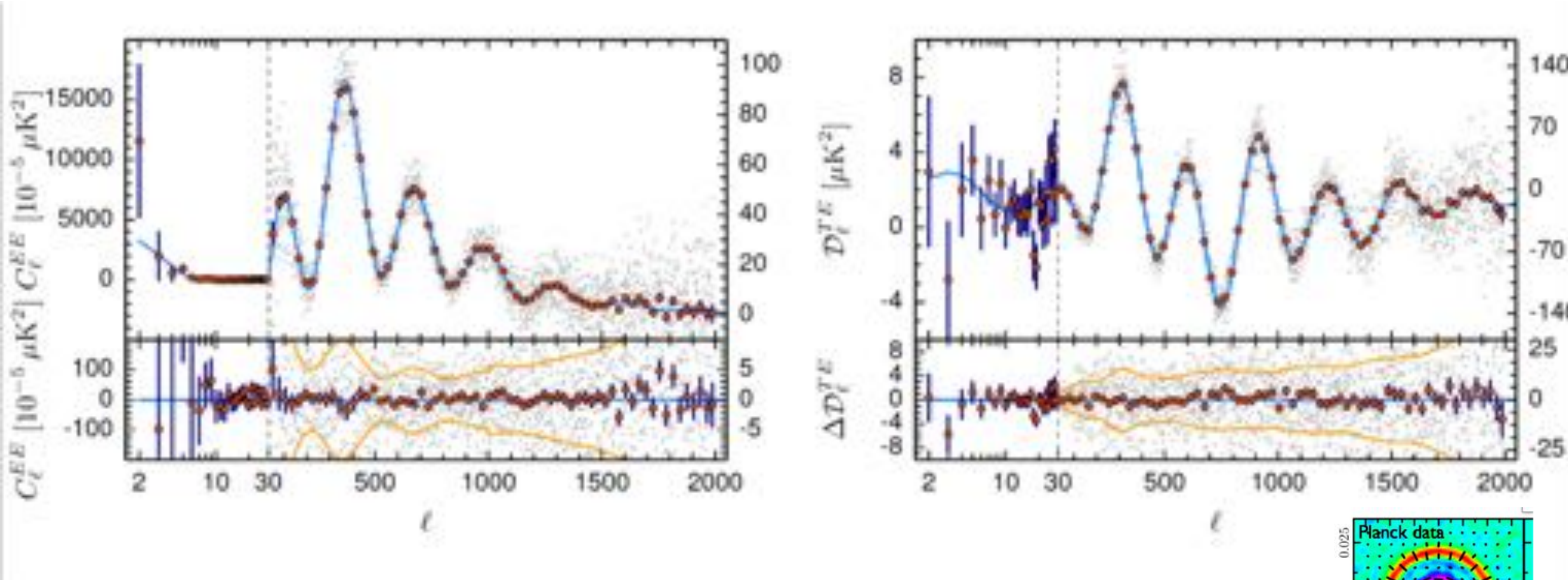
Planck 2018 TT power spectrum

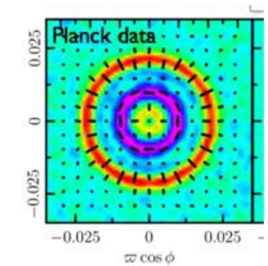


Planck 2018 TT power spectrum



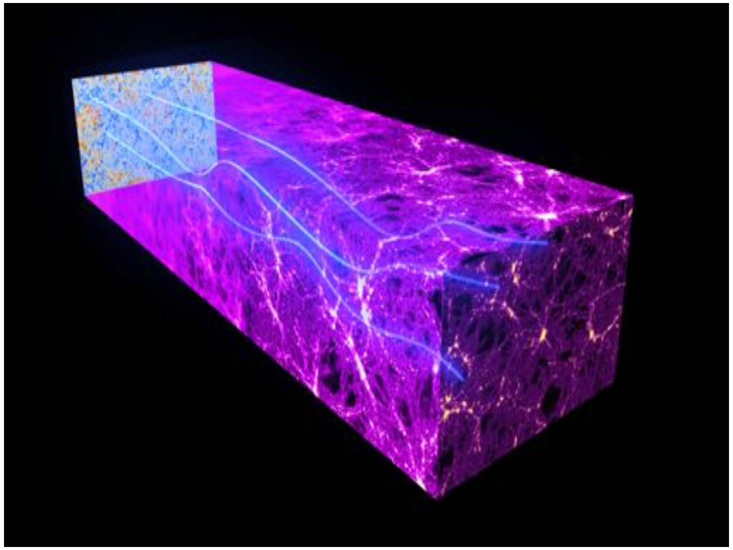
Planck 2018 TE, EE power spectra





Blue line is not a fit, but a prediction given the TT spectrum!

CMB is sensitive to the late-time density field, too….

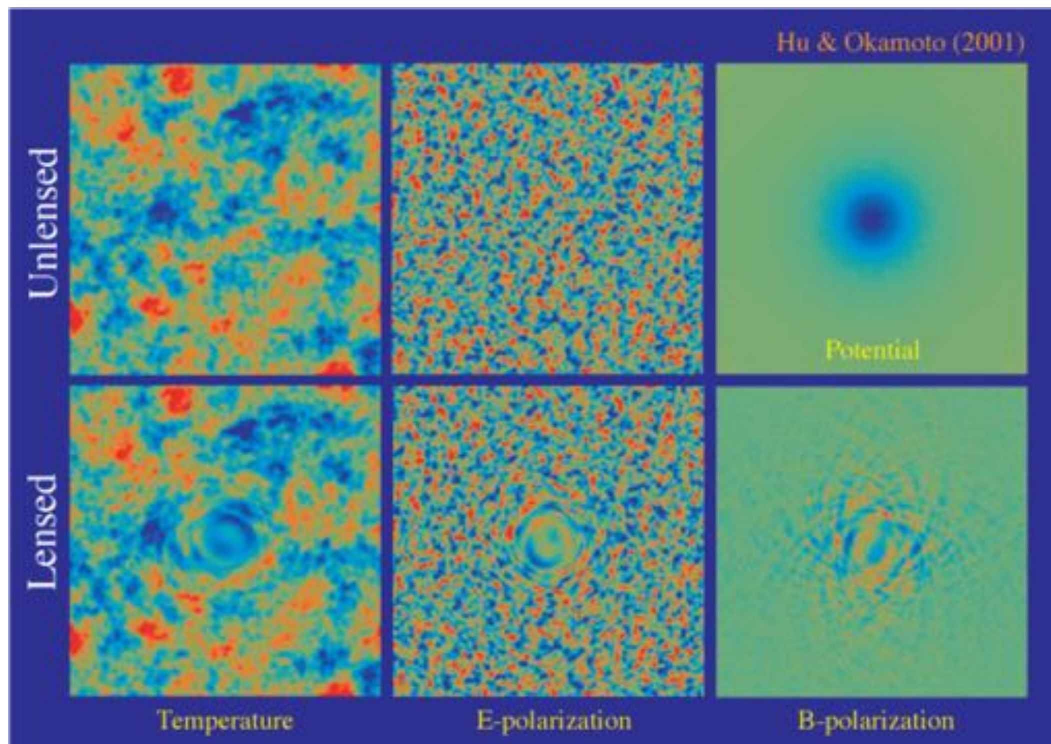


Line-of-sight integral of the gravitational potentials

$$\phi(\hat{n}) = -\int_0^{\chi_*} d\chi \frac{\chi_* - \chi}{\chi_* \chi} (\Phi + \Psi)$$

Deflection field

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



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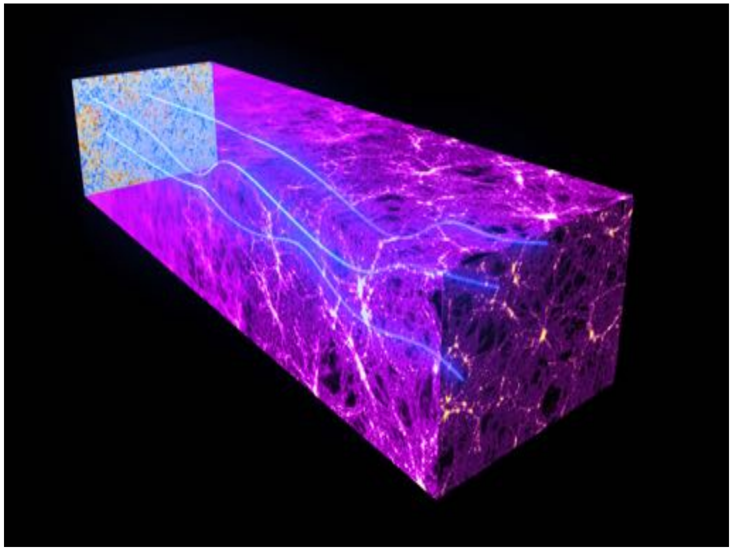

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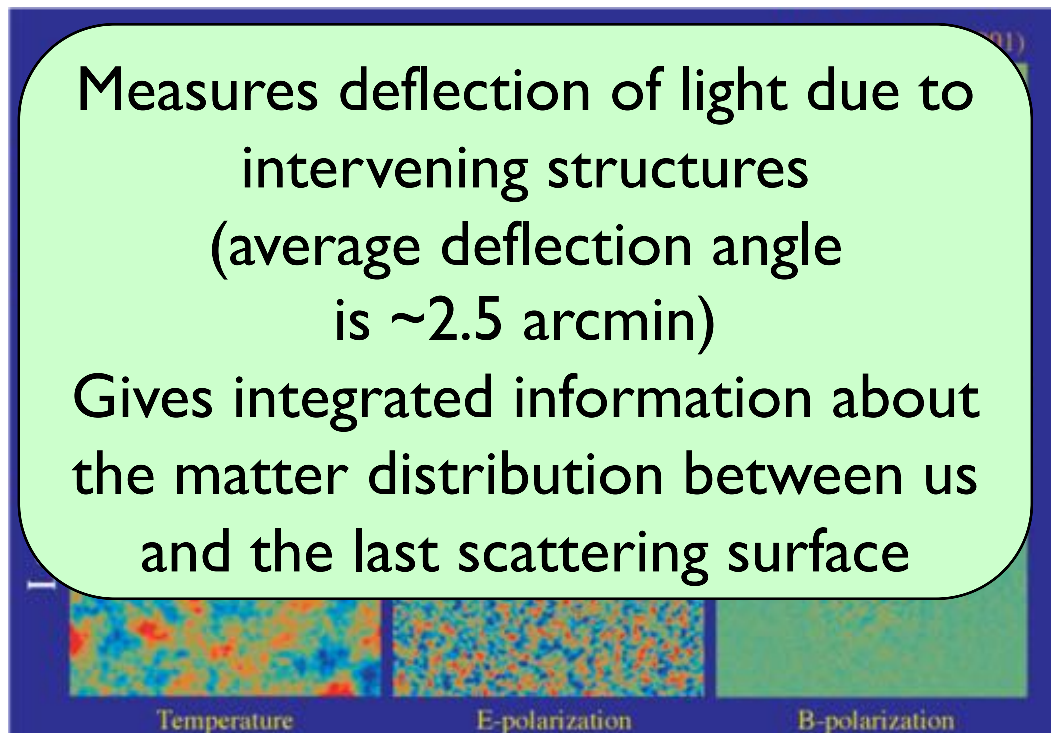
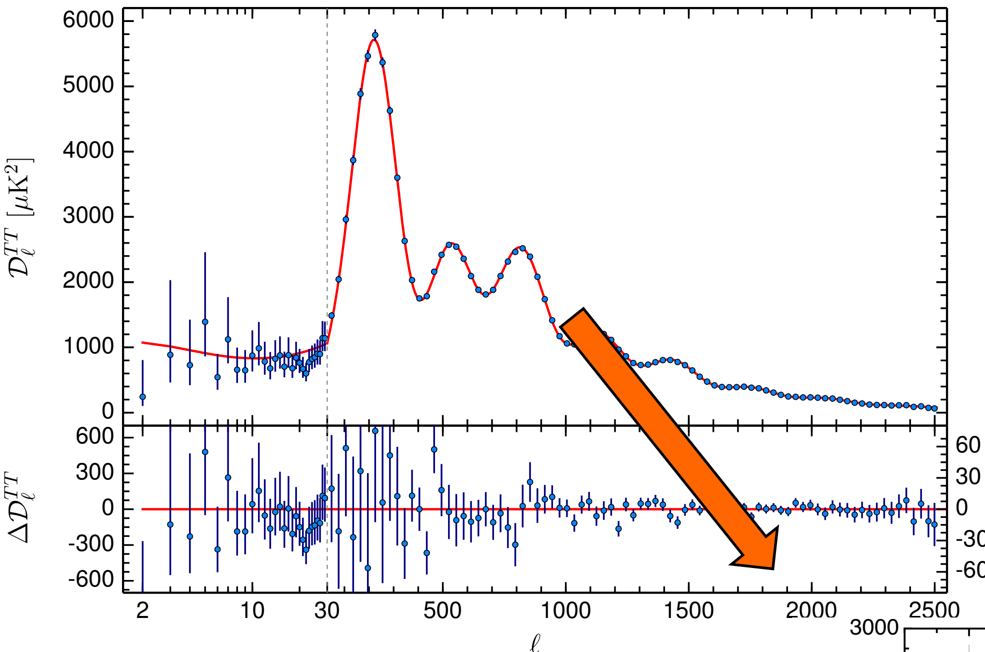
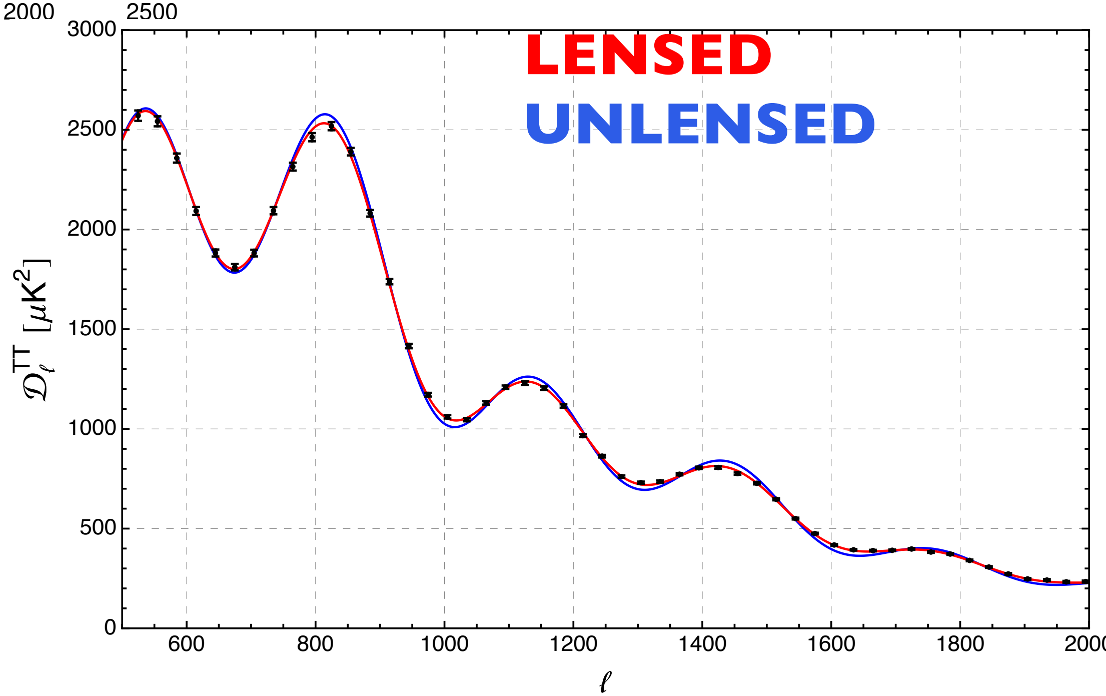


Measures deflection of light due to intervening structures
(average deflection angle is ~2.5 arcmin)
Gives integrated information about the matter distribution between us and the last scattering surface

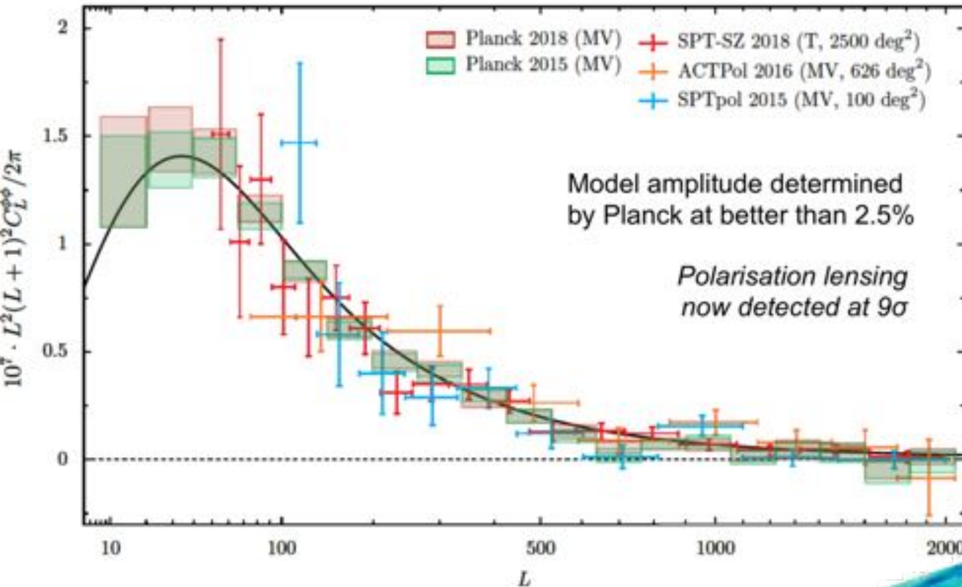


Lensing smooths the peaks of the CMB power spectrum…

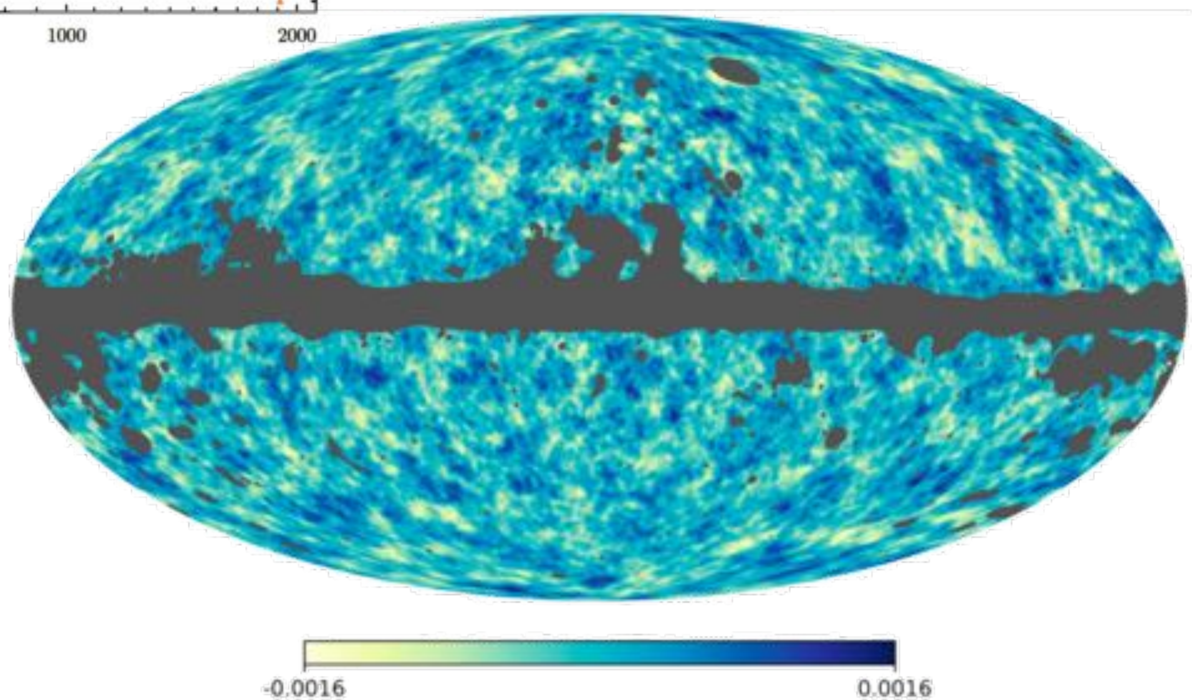
… and introduces non-gaussianities in the map (nonzero 4-point c.f.)



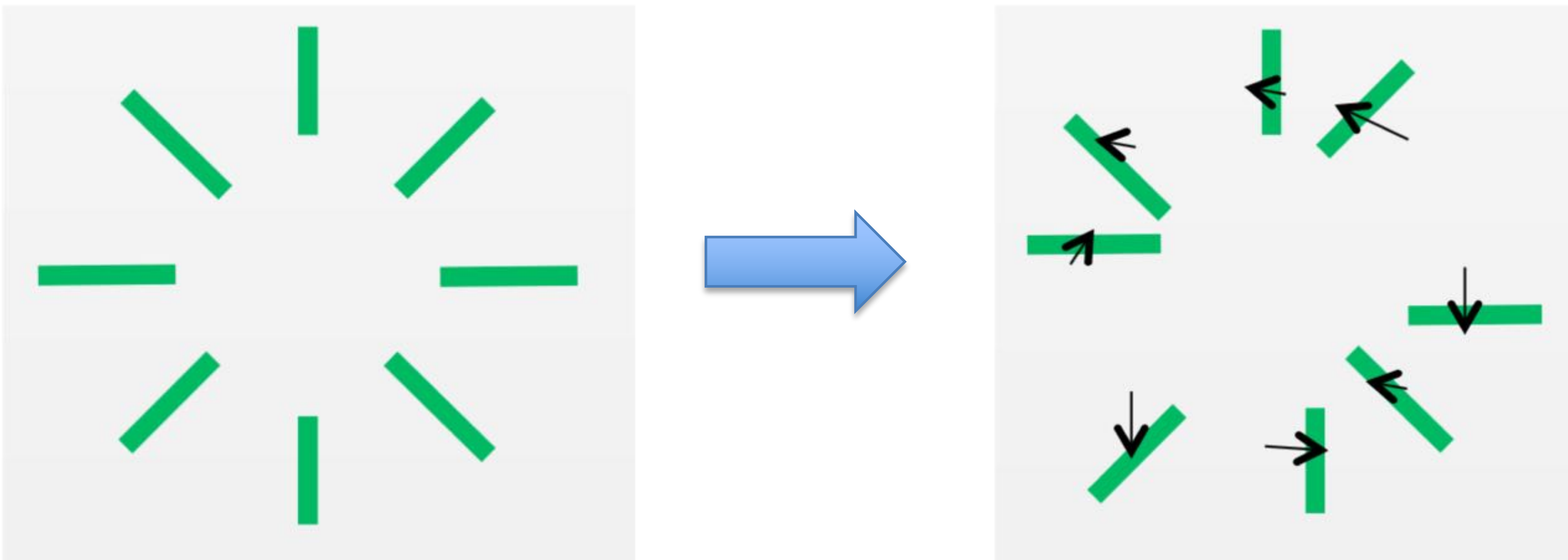
LENSING



Lensing potential estimated from the four-point correlation function

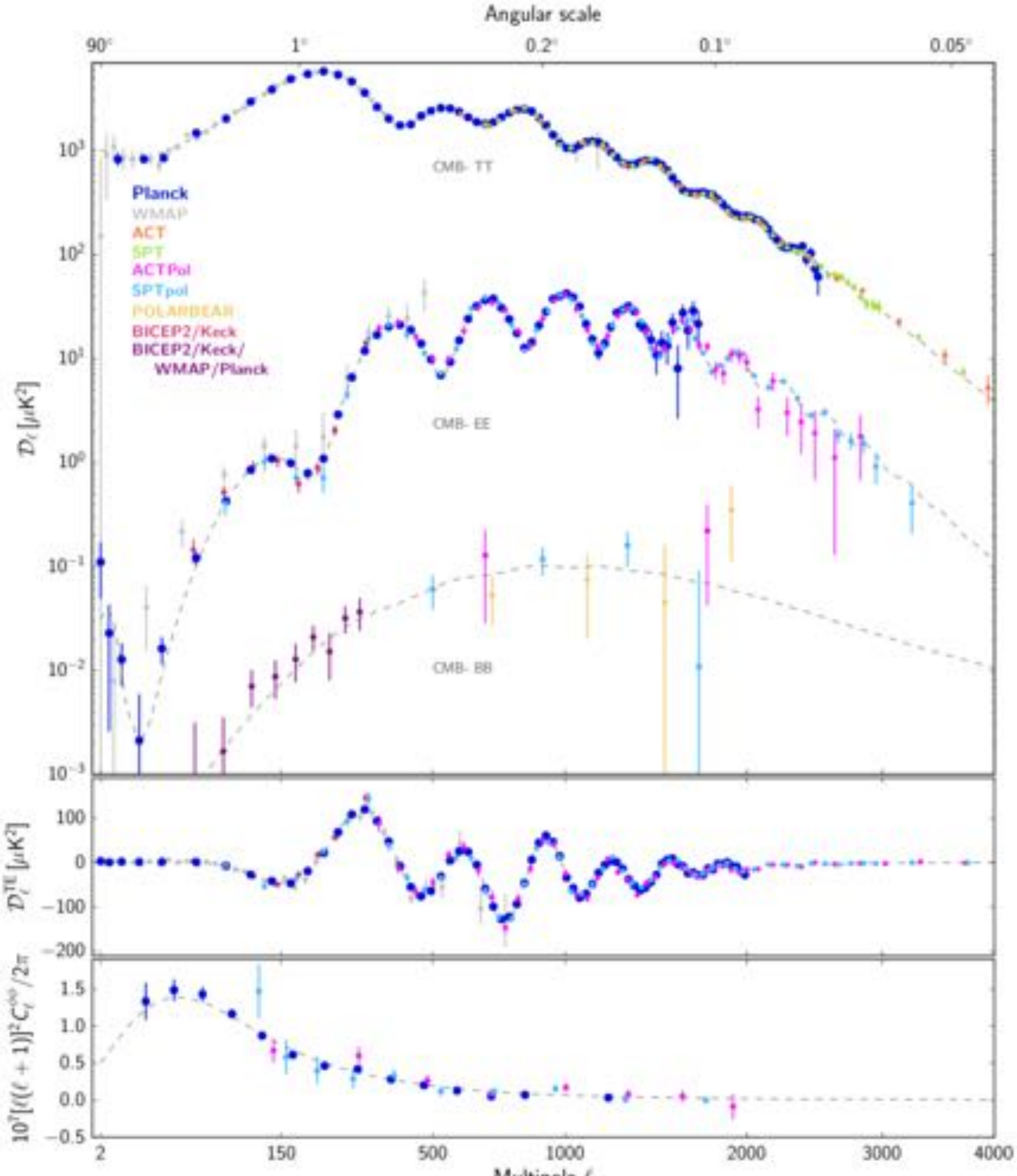


The role of lensing in polarization



Pure E mode

E -> B mixing (no longer parity even)



Angular scale
90°
1°
0.2°
0.1°
0.05°
CMB- TT
Planck
WMAP
ACT
SPT
ACTPol
SPTpol
POLARBEAR
BICEP2/Keck
BICEP2/Keck/
WMAP/Planck
CMB- EE
CMB- BB
$\mathcal{D}_\ell\ [\mu K^2]$
$\mathcal{D}_\ell^{TE}\ [\mu K^2]$
$10^7[\ell(\ell+1)]^2 C_\ell^{\phi\phi}/2\pi$
Multipole ℓ

ΛCDM 6 parameter fit

(Planck temperature, polarization and lensing)

		Mean	Stdev	Rel. err.
primary	$\Omega_b h^2$ Baryon density	0.02237	0.00015	0.007
	$\Omega_c h^2$ Dark matter density	0.1200	0.0012	0.01
	100θ CMB acoustic scale	1.04092	0.00031	0.0003
	τ Optical depth to reionization	0.0544	0.0073	0.13
	$\ln(A_s 10^{10})$ Primordial amolitude of perturbation	3.044	0.014	0.007
	n_s Primordial Scalar spectral index	0.9649	0.0042	0.004
derived	H_0 Hubble parameter today	67.36	0.54	0.008
	Ω_m Total matter density	0.3153	0.0073	0.023
	σ_8 Matter perturbation amplitude	0.8111	0.0060	0.007

ΛCDM 6 parameter fit
(Planck temperature, polarization and lensing)

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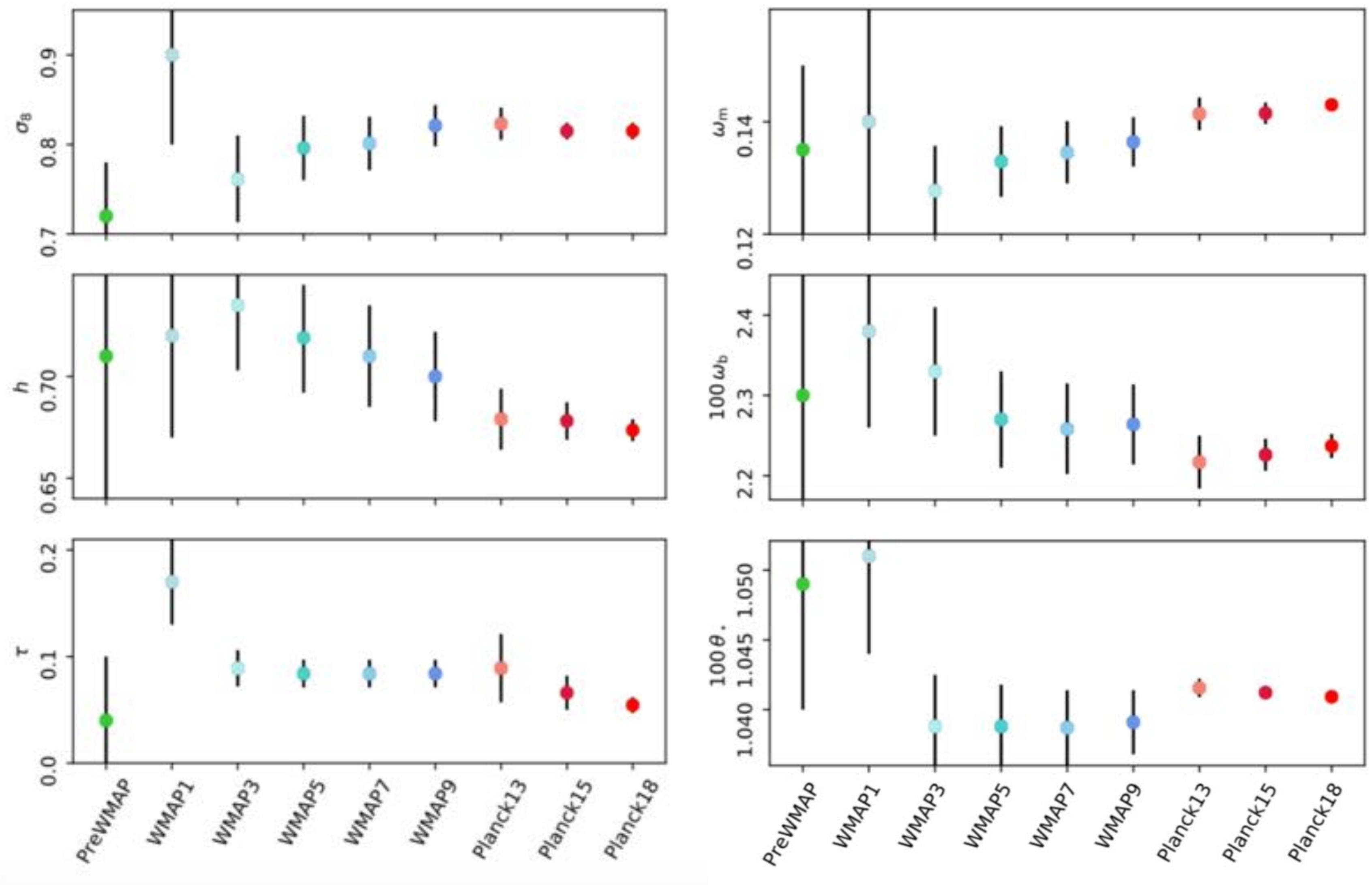
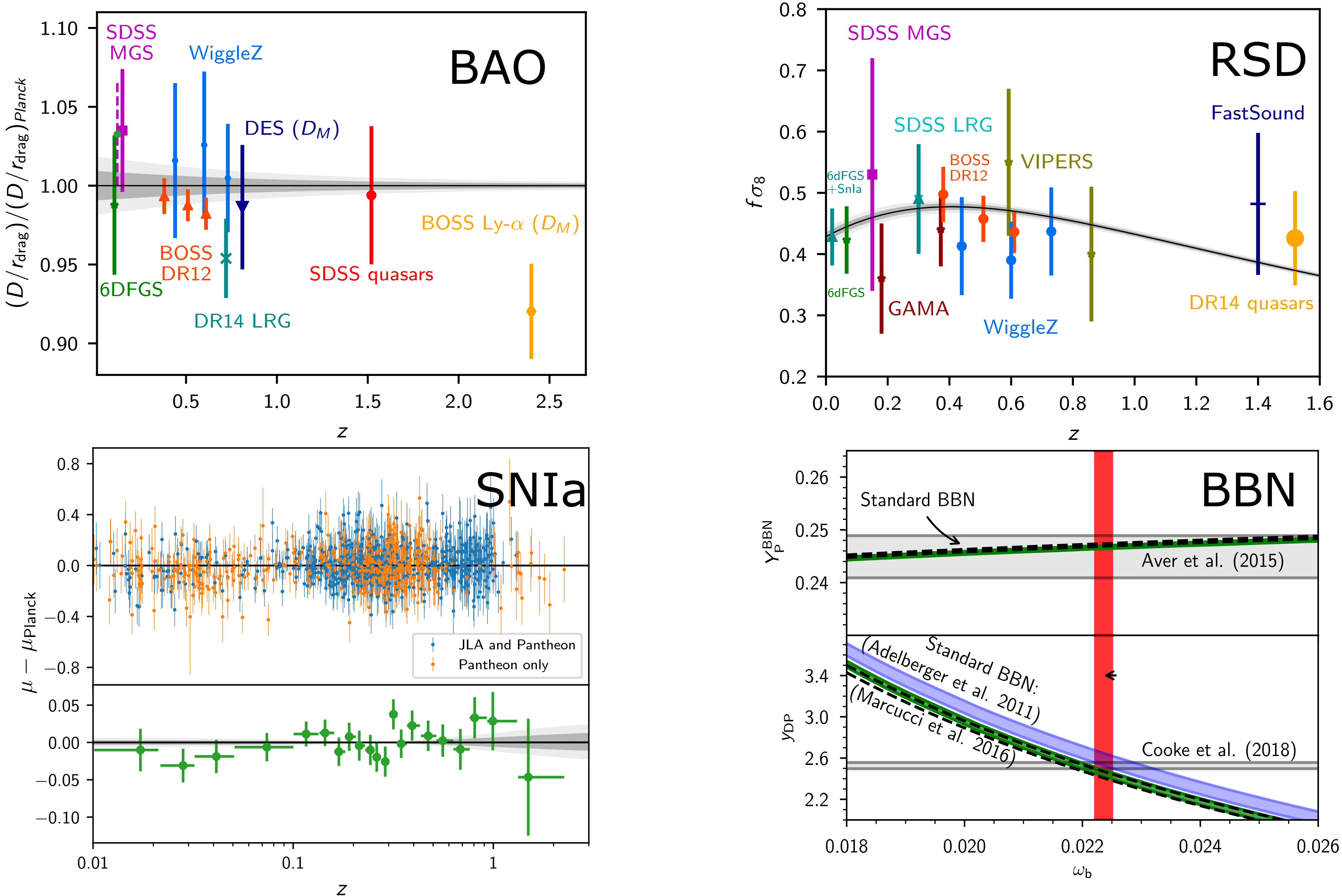
Highlights:

1. Best determination of H_0 to date (indirect, in strong tension with direct measurements)
2. Scalar spectral index is now 8 σ away from 1 (a signature of inflation). Even in extended
3. Optical depth t greatly improved after taming of large-angle polarization systematics. Still, at 13% relative error, by far the worst parameter determined from CMB

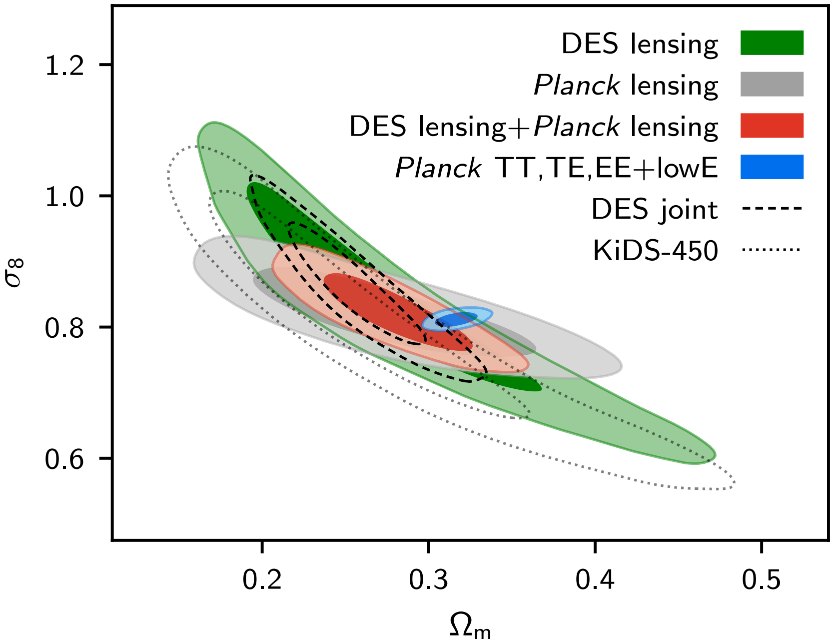
Improvement in parameter accuracy



Consistency with other datasets



...And tensions with others



Mild tension with DES year 1 results

$$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$$

DES Joint

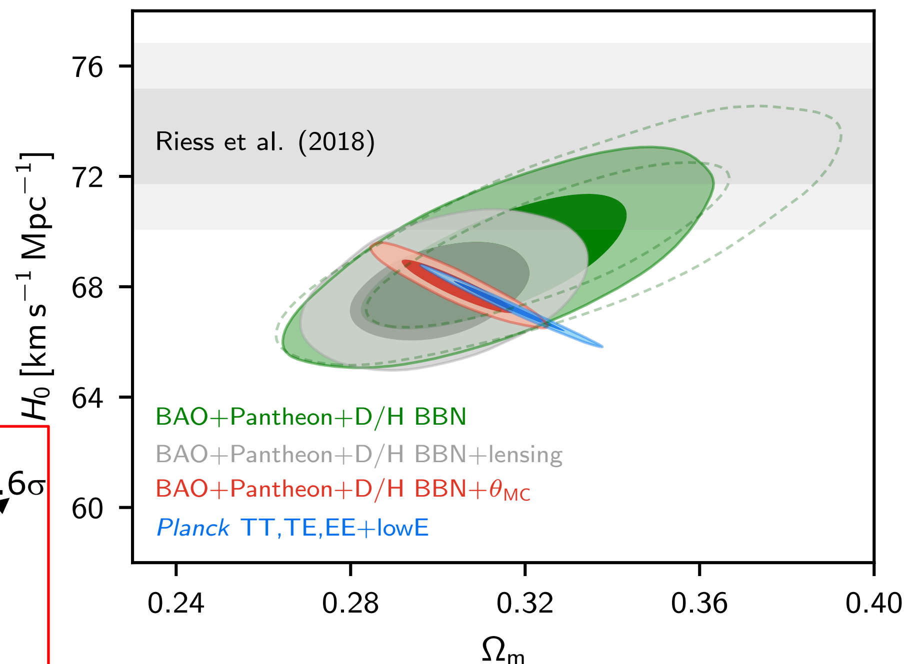
$S_8 \equiv 0.792 \pm 0.024$

$\Omega_m = 0.257^{+0.023}_{-0.031}$

Planck TTTEE+lowE+lensing

$S_8 = 0.832 \pm 0.013$

$\Omega_m = 0.315 \pm 0.007.$



Strong tension with H_0 distance ladder measurements.

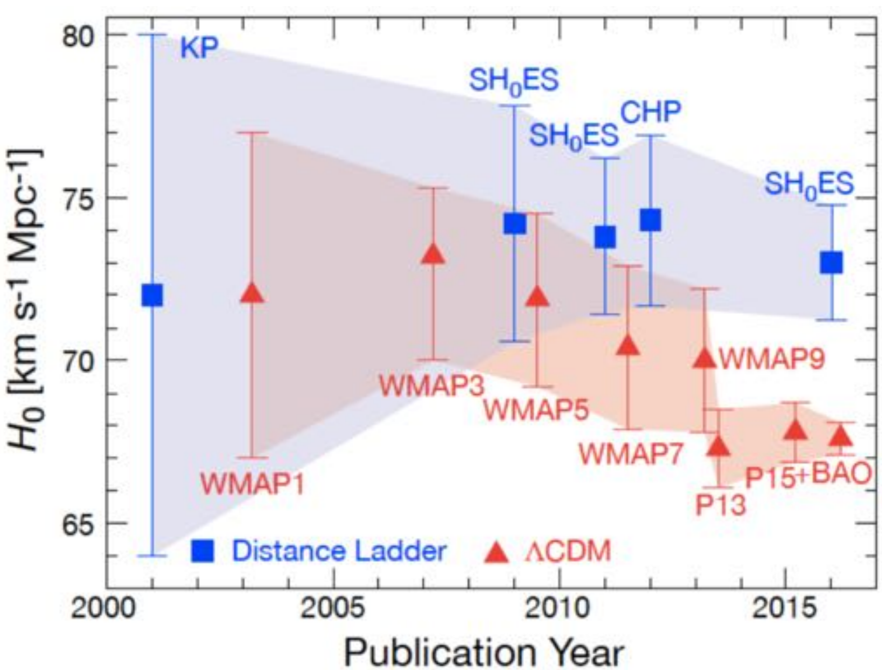
H_0= 67.36±0.54 km/s/Mpc Planck ΛCDM
H_0= 73.5 ±1.6 km/s/Mpc SH0ES (Riess+ 18)

} 3.6σ

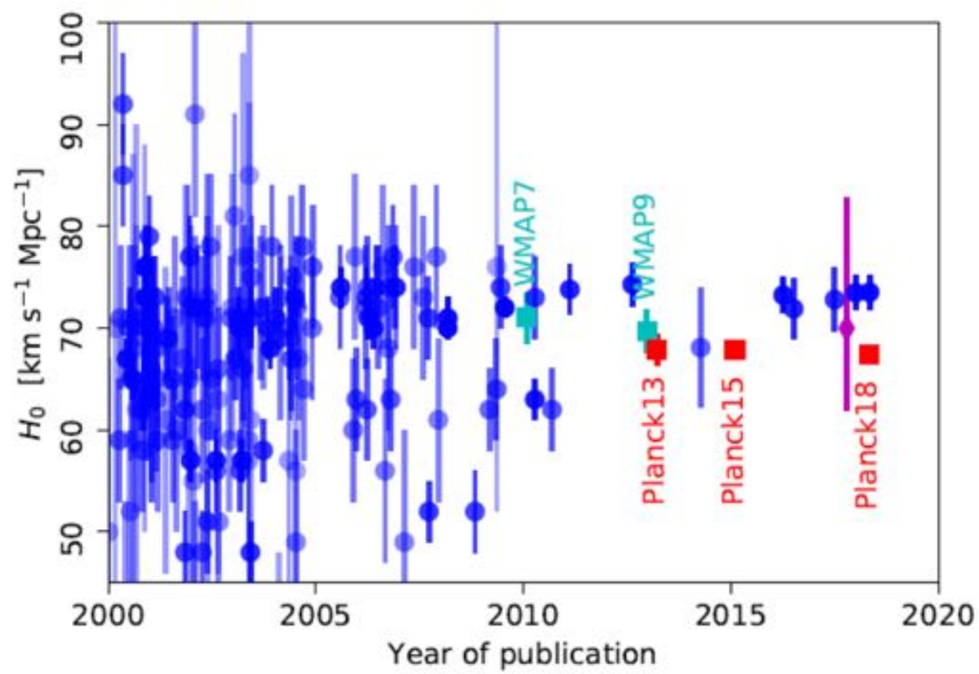
Inverse distance ladder:
H_0= 67.9 ± 1.3 km/s/Mpc BAO+D/H+CMB lensing

Now approaching 5σ, RIess+ 2019

H_0 MEASUREMENTS IN RECENT YEARS



W. Freedmann Nat. Astr. 1 2017



ΛCDM 6 parameter fit + extensions (where surprises might hide)

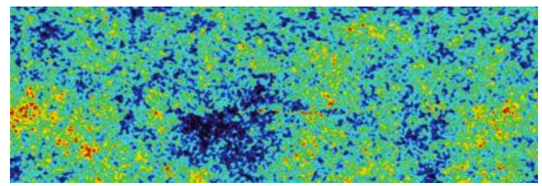
- Tensor modes, i.e. primordial gravitational waves, $r = A_T/A_s$
- Running spectral index $dn_s/d\ln k$
- Primordial non Gaussianity f_{NL}
- Non adiabatic (isocurvature) primordial perturbations
- Dark energy equation of state, w
- Spatial curvature $\Omega_k = 1 - \Omega_m - \Omega_\Lambda$
- Neutrino masses $\Sigma\, m_\nu$
- Number of relativistic species N_{eff}
- …

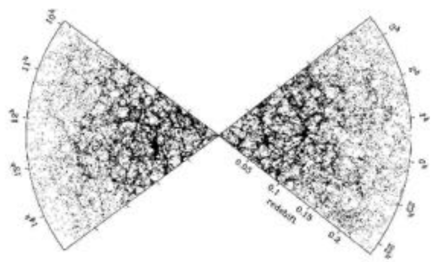
Line element:

$$d\ell^2 = a^2(t)[1 + 2\zeta(\mathbf{x}, t)][\delta_{ij} + h_{ij}(\mathbf{x}, t)]dx^i dx^j$$

ζ

scalar mode



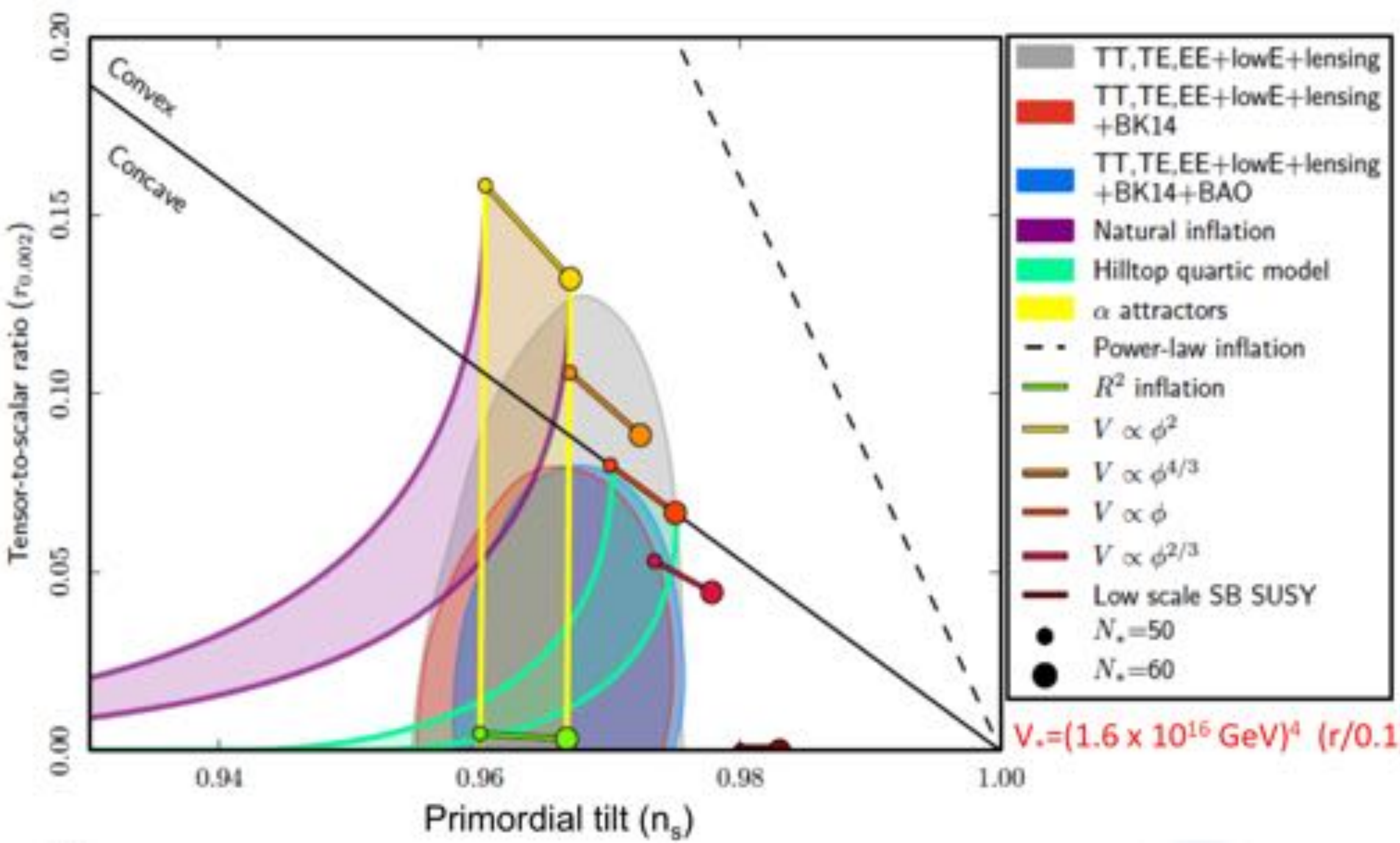


Fluctuation have quantum origin, boosted by inflation. Ultra-long gravitational waves (also stretched by inflation) are just another kind of fluctuations

h_{ij}

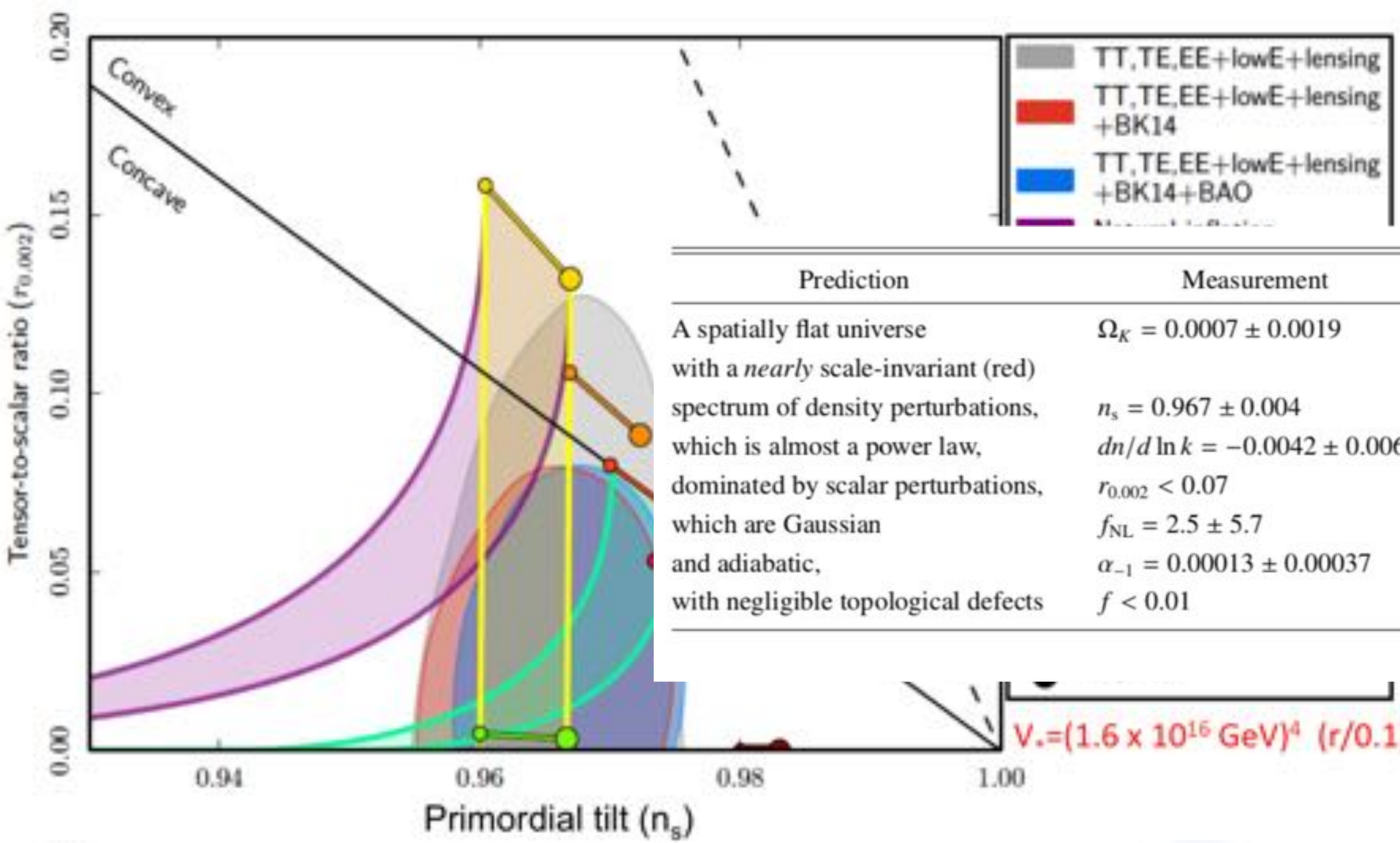
tensor mode

Constraints for tensor perturbations



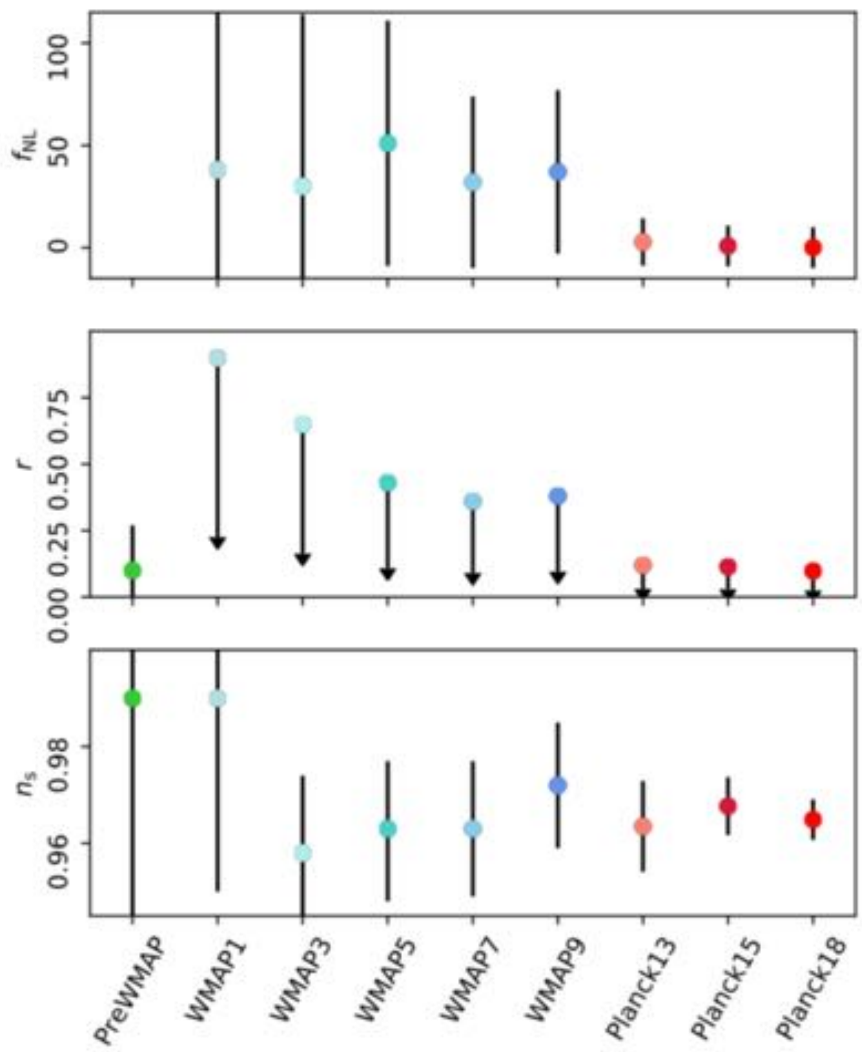
$V_* = (1.6 \times 10^{16}\ \text{GeV})^4\ (r/0.1)$

Constraints for tensor perturbations

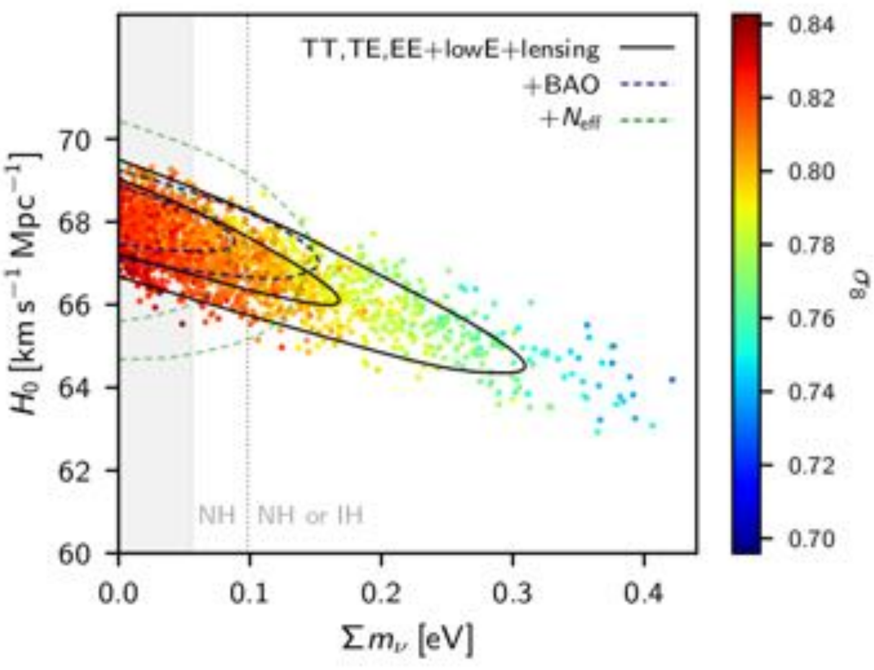


Prediction	Measurement
A spatially flat universe	$\Omega_K = 0.0007 \pm 0.0019$
with a *nearly* scale-invariant (red)	
spectrum of density perturbations,	$n_s = 0.967 \pm 0.004$
which is almost a power law,	$dn/d\ln k = -0.0042 \pm 0.0067$
dominated by scalar perturbations,	$r_{0.002} < 0.07$
which are Gaussian	$f_{NL} = 2.5 \pm 5.7$
and adiabatic,	$\alpha_{-1} = 0.00013 \pm 0.00037$
with negligible topological defects	$f < 0.01$

Improvement in inflationary parameters



Neutrino legacy of Planck: $\Sigma\, m_\nu$

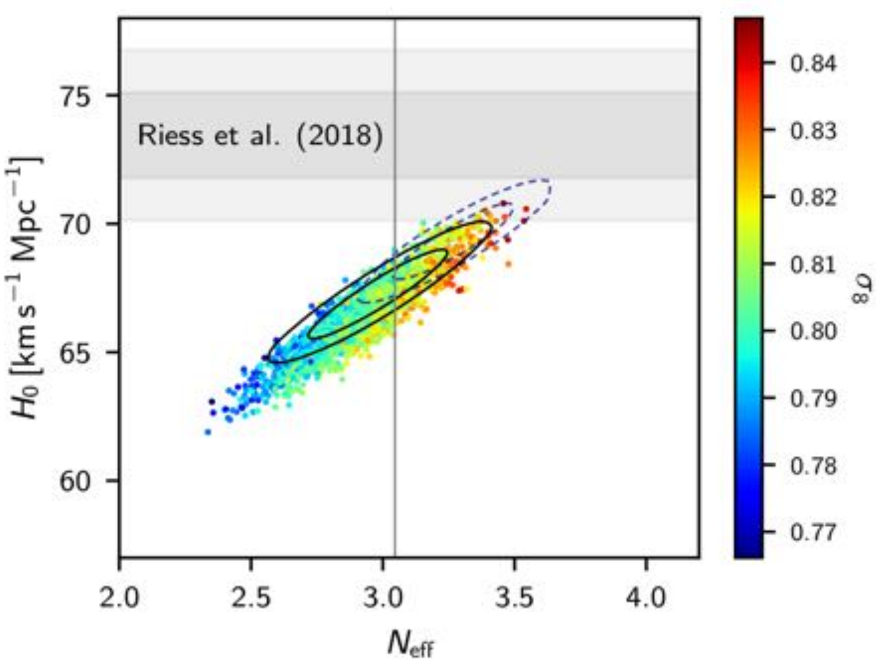


- Tightest constraint from a single experiment
- First constraint exploiting the information encoded in the CMB weak lensing
- One order of magnitude better than present kinematic constraints, already at the same level than future expectations for KATRIN
- The combined limits from Planck and large scale structure probes are starting to corner the inverted hierarchy scenario

$m_\nu < 0.44$ eV (95%CL, TT + lowE + lensing)

$m_\nu < 0.13$ eV (95% CL, TT+lowE+lensing+BAO)

Neutrino legacy of Planck: Neff



$$N_{eff} = 3.00^{+0.57}_{-0.53}$$ (95% CL, TT+lowE)

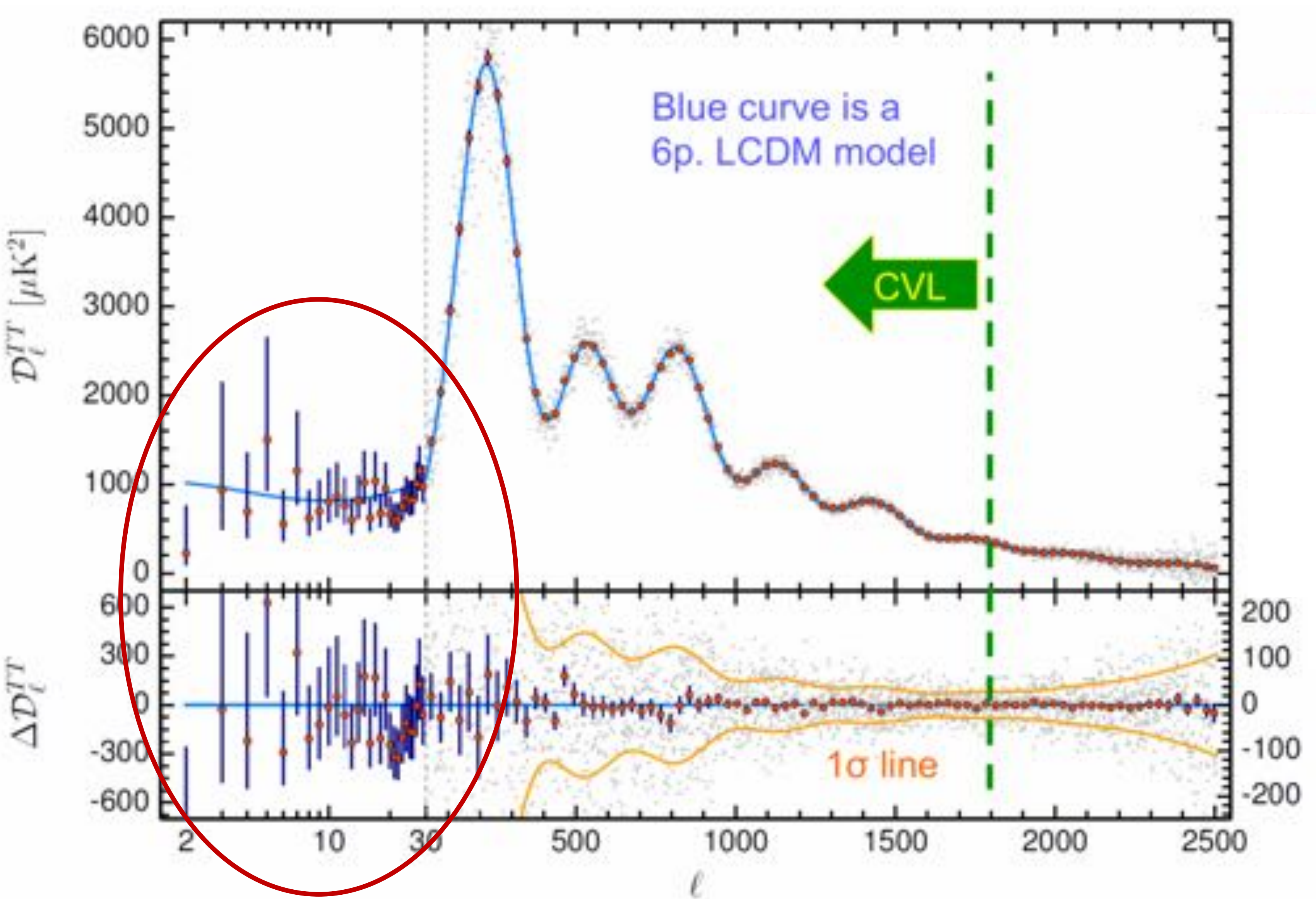
$$N_{eff} = 3.11^{+0.44}_{-0.43}$$ (95% CL, TT+lowE+lensing+BAO)

- Effective number of relativistic species is consistent with the standard expectation $N_{eff} = 3.046$
- Data are consistent with these relativistic species behaving as free-streaming neutrinos – a strong indication that they are indeed the SM neutrinos!
- A fourth thermalized species (N_{eff}=4) is excluded at 3.5 to 6 σ, depending on the dataset
- A light sterile neutrino species is allowed if not thermalized. Still, the sterile neutrino interpretation of the short-baseline anomalies is excluded by Planck

Anomalies in the CMB field

- At large angles, the CMB field is known to exhibit anomalies:
  - Lack of power
  - Hemispherical asymmetry
  - Even-odd asymmetry
  - And others…
- For temperature, Planck has reached cosmic variance. For polarization, there is much room for improvement.

Planck 2018 TT power spectrum



Nearly scale-invariance of the large-scale perturbations is a prediction of single-field, slow-roll inflation.

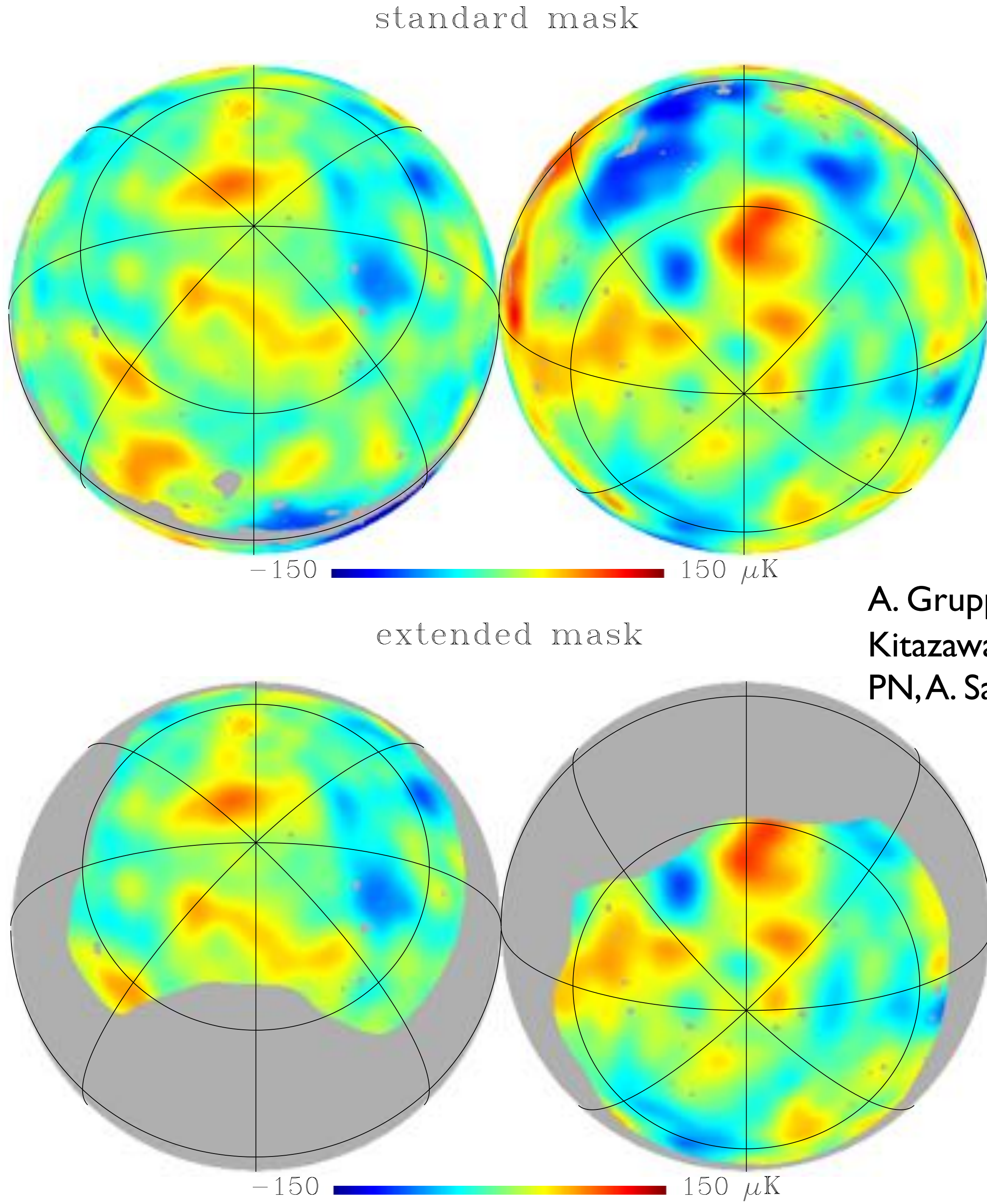
Transition from a pre-inflationary "fast-roll" phase to slow-roll would suppress power in the primordial spectrum. This arises naturally in a stringy-inspired inflation scenario.

Are we seeing relics of a decelerating inflaton?

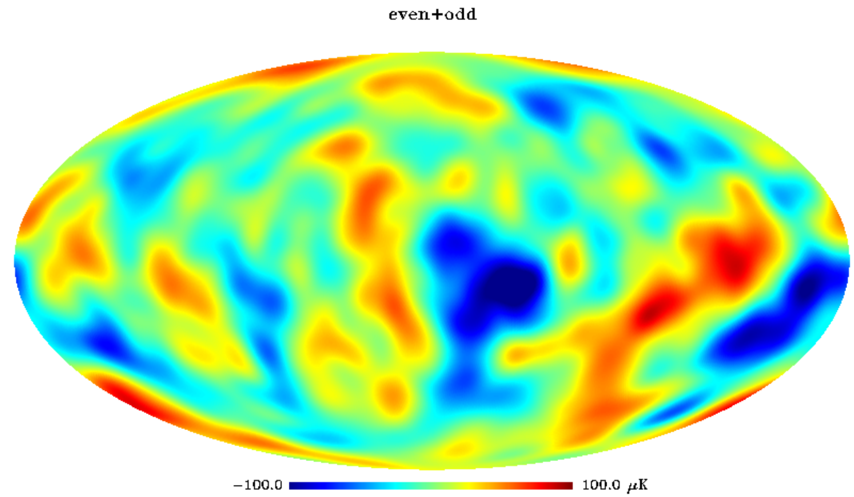
$$P(k) \sim \frac{k^3}{\left[k^2 + \Delta^2\right]^{2 - \frac{n_S}{2}}}$$

See e.g. Contaldi, Peloso, Kofman, Linde (2003); Destri, de Vega, Sanchez (2010); Dudas, Kitazawa, Patil, Sagnotti (2012); Kitazawa, Sagnotti (2014)

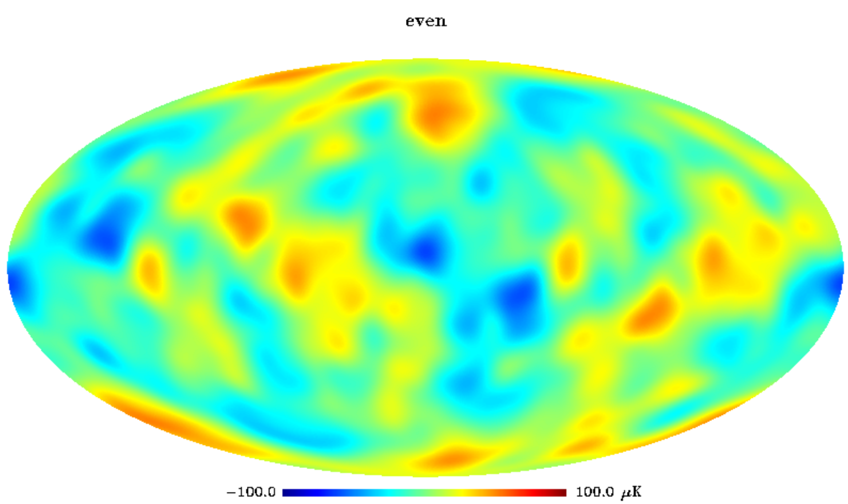
~ scale that enters the horizon at the onset of slow roll

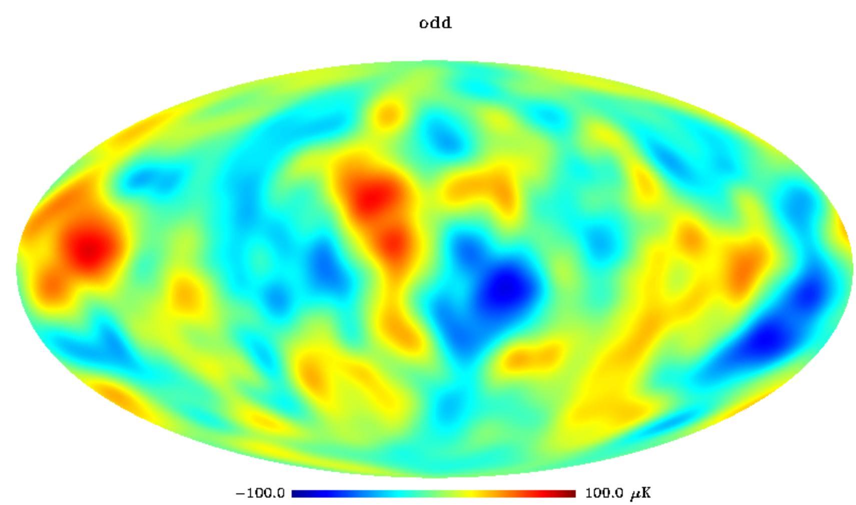


A. Gruppuso, N. Kitazawa, N. Mandolesi, PN, A. Sagnotti 2017



Planck 2015 data

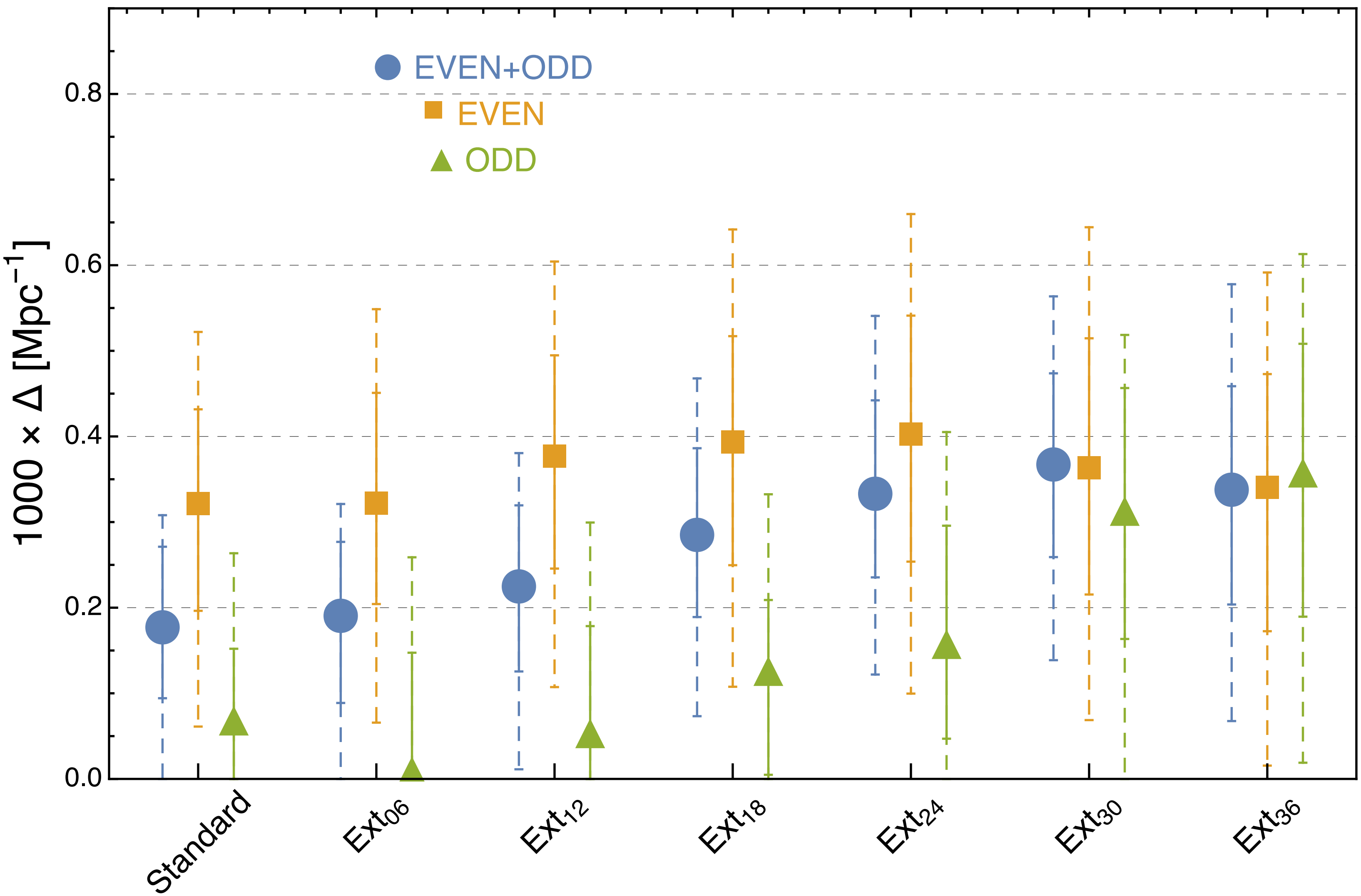




$$\left(\frac{\delta T}{T}(\hat{n})\right)_{\pm} \equiv \frac{1}{2}\left[\frac{\delta T}{T}(\hat{n}) \pm \frac{\delta T}{T}(-\hat{n})\right]$$

A. Gruppuso, N. Kitazawa, M. Lattanzi, N. Mandolesi, PN, A. Sagnotti 2017

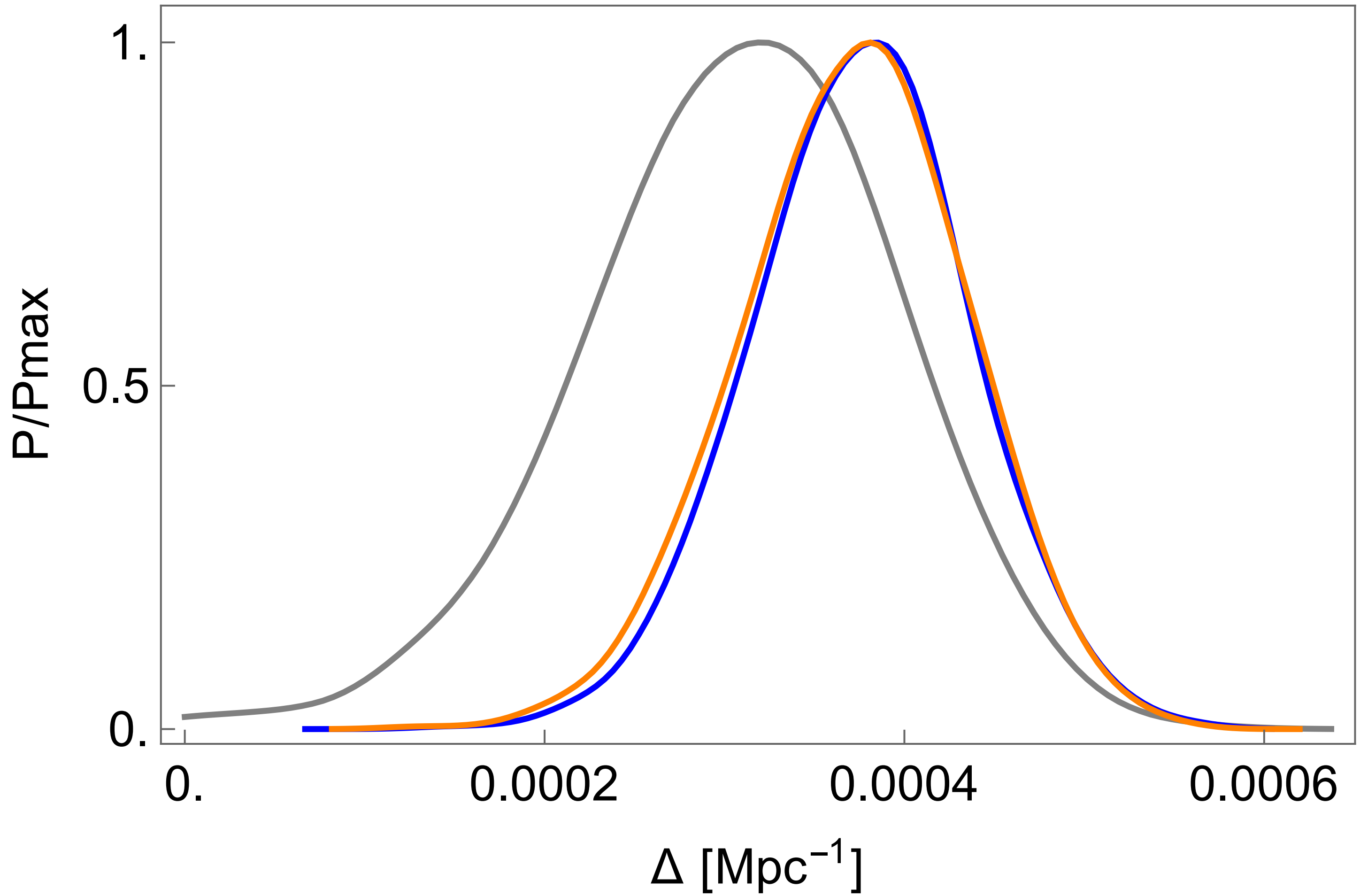
Constraints on Δ from Planck 2015



A. Gruppuso, N. Kitazawa, M. Lattanzi, N. Mandolesi, PN, A. Sagnotti 2017

- The even multipoles are consistently lower than the LCDM expectation, independently on the galactic masking
- The odd multipoles are consistent with the LCDM expectation for the smaller masks (more sky). In larger masks (less sky), they are consistent with the even multipoles (and then have low power)
- The power at large scales is concentrated around the galactic plane, in the odd multipoles
- 3.16σ detection of Δ in the Ext30 mask

Forecasted constraints on Δ from future experiments



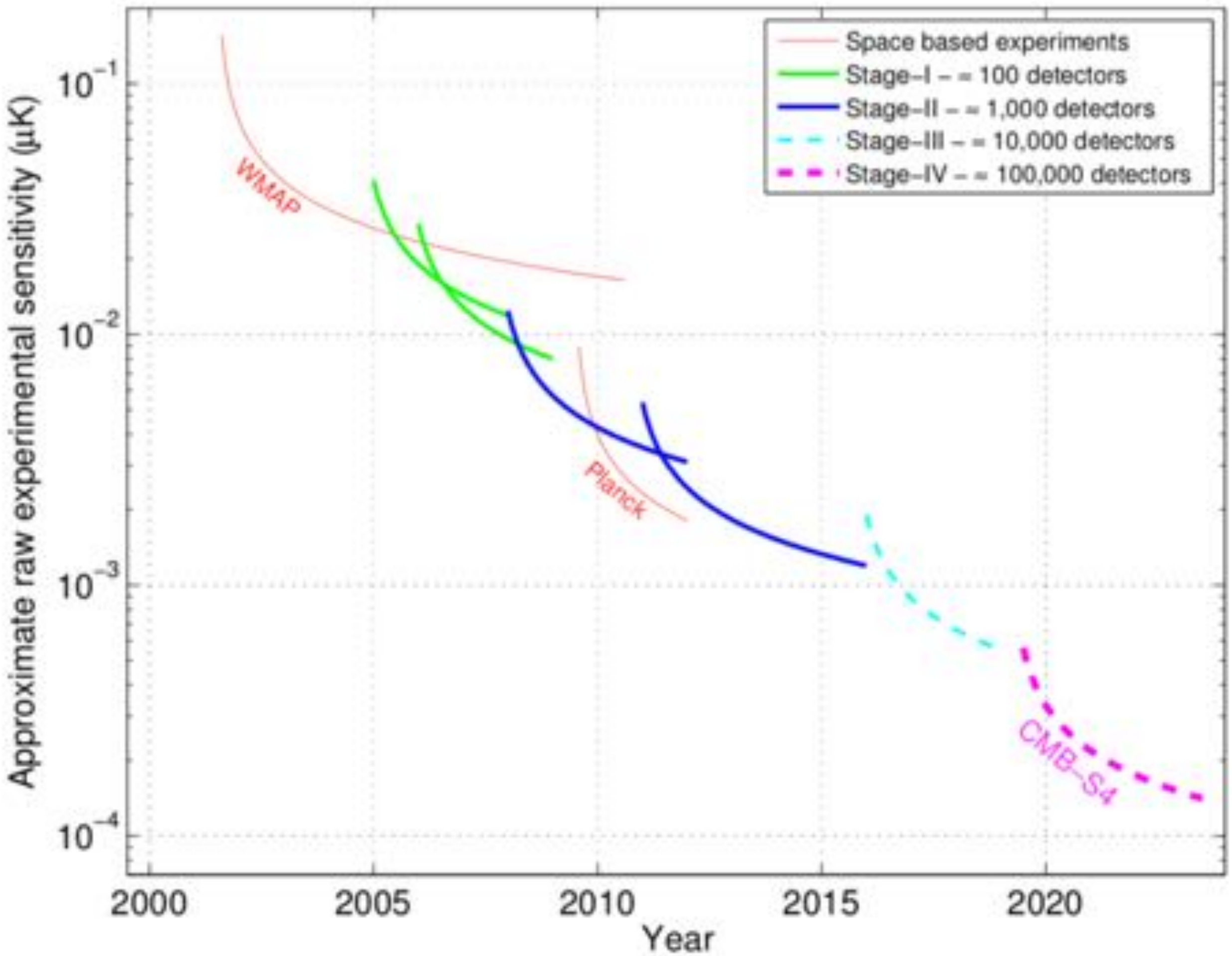
Grey: Planck-like noise, standard masking

Orange: Ideal experiment large-scale polarization, ext30 mask

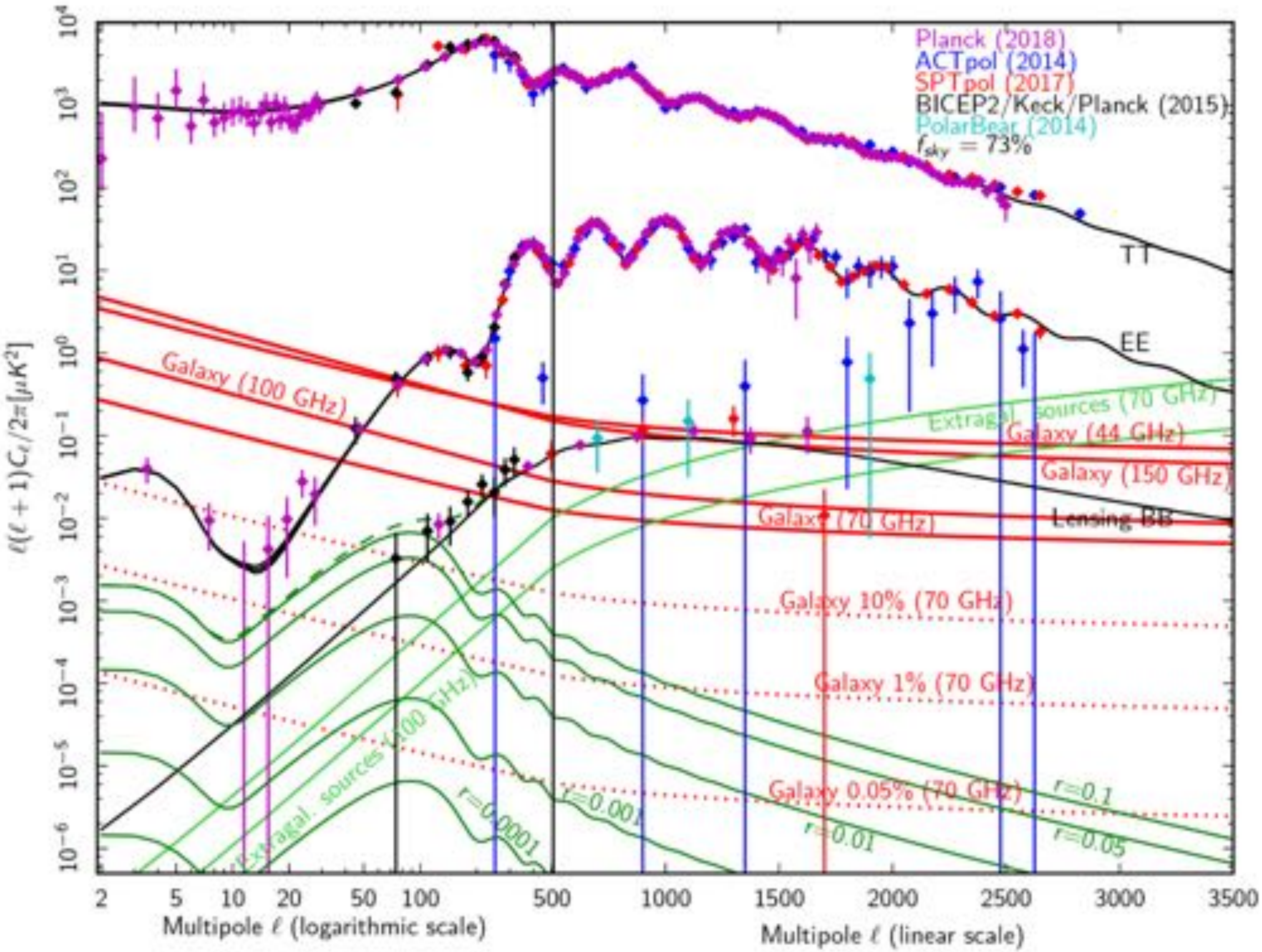
Blue: As orange, but full sky

THE FUTURE OF CMB OBSERVATIONS

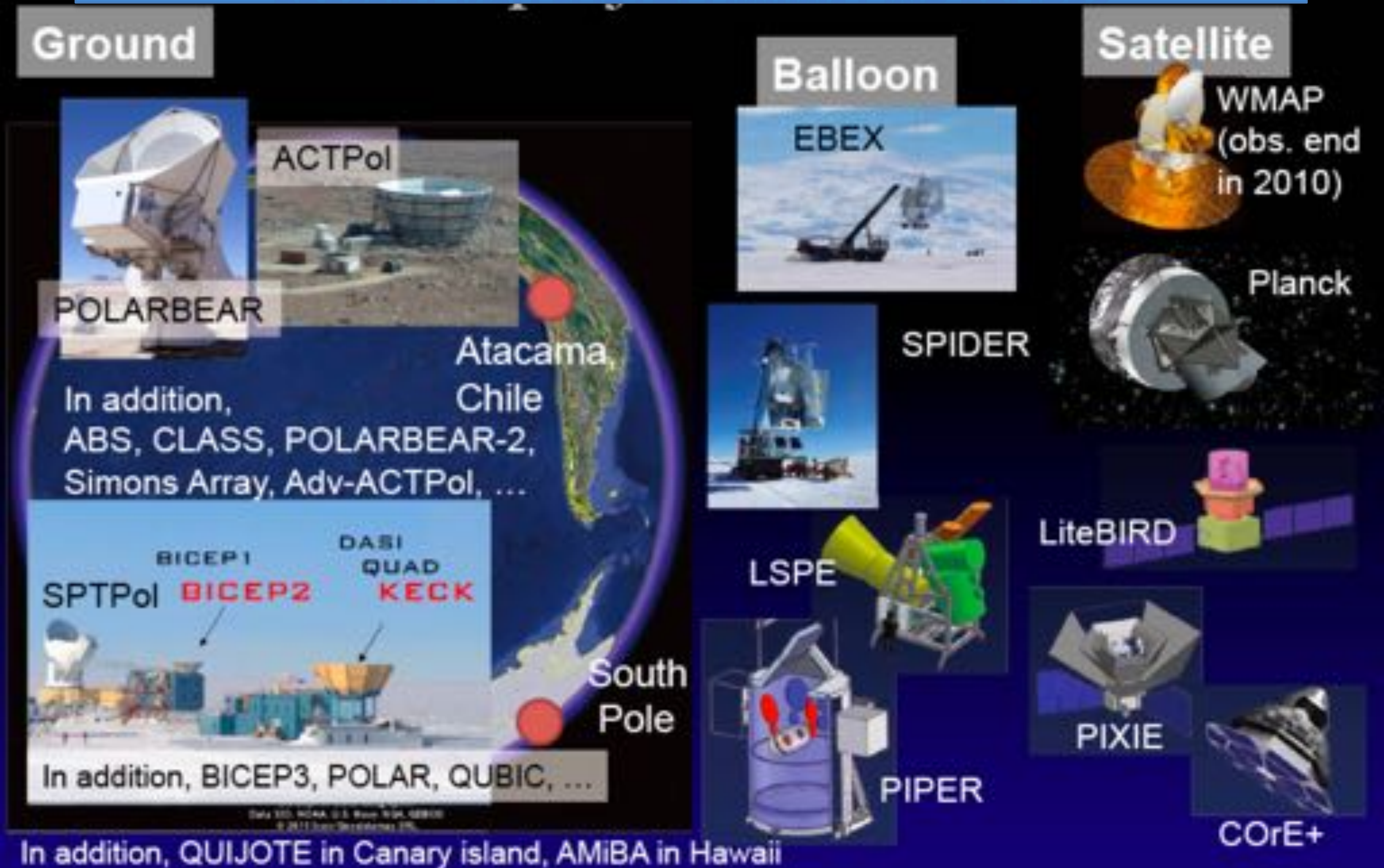
A Matter of sensitivity?



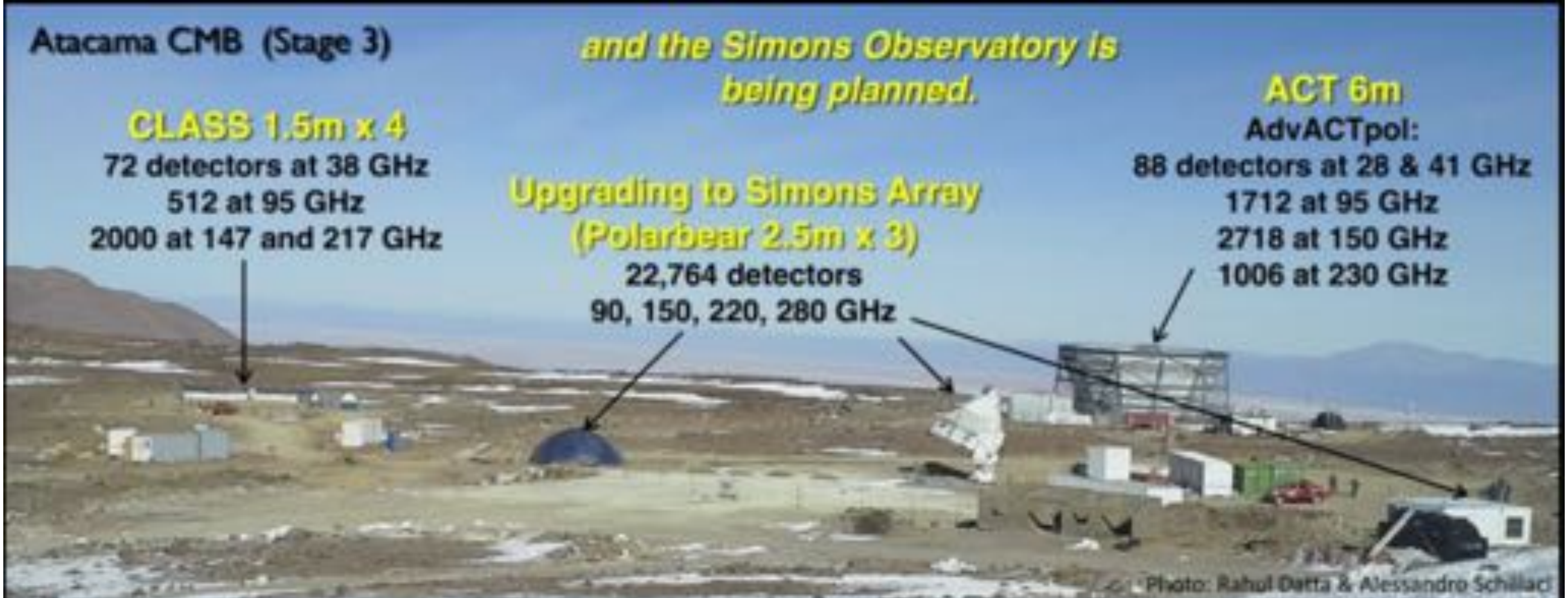
Well, not only….

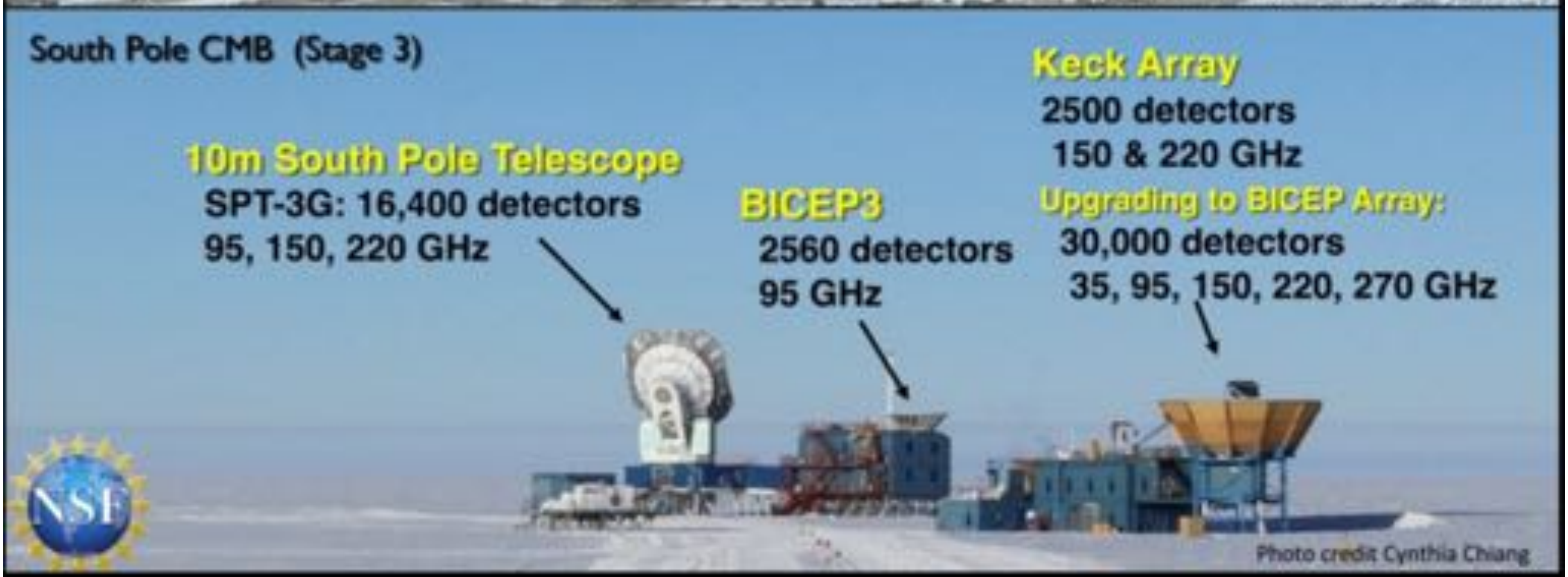


PRESENT AND FORTHCOMING CMB PROBES



PRESENT AND FORTHCOMING CMB PROBES


Atacama CMB (Stage 3)
and the Simons Observatory is being planned.
CLASS 1.5m x 4
72 detectors at 38 GHz
512 at 95 GHz
2000 at 147 and 217 GHz
Upgrading to Simons Array
(Polarbear 2.5m x 3)
22,764 detectors
90, 150, 220, 280 GHz
ACT 6m
AdvACTpol:
88 detectors at 28 & 41 GHz
1712 at 95 GHz
2718 at 150 GHz
1006 at 230 GHz
Photo: Rahul Datta & Alessandro Schillaci


South Pole CMB (Stage 3)
Keck Array
2500 detectors
150 & 220 GHz
Upgrading to BICEP Array:
30,000 detectors
35, 95, 150, 220, 270 GHz
10m South Pole Telescope
SPT-3G: 16,400 detectors
95, 150, 220 GHz
BICEP3
2560 detectors
95 GHz
NSF
Photo credit Cynthia Chiang

LSPE

the Large-Scale Polarization Explorer

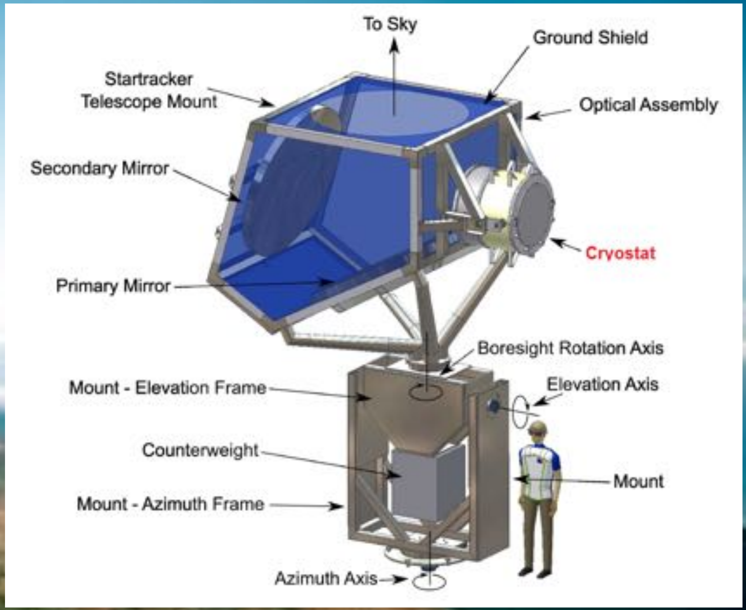
MILANO
GENOVA
PISA
FERRARA
ROMA 1
ROMA 2

[1] This slide and following five courtesy LSPE PIs M. Bersanelli and P. de Bernardis

LSPE in a nutshell

- The Large-Scale Polarization Explorer is an experiment to measure the polarization of the Cosmic Microwave Background at large angular scales
- Frequency coverage: 40 – 250 GHz (5 channels, 2 instruments: STRIP & SWIPE)
- Angular resolution: around 1^{o} FWHM
- Sky coverage: 20-25% of the sky
- Current collaboration: Sapienza, UNIMI, UNIMIB, IASFBO-INAF, IFAC-CNR, Uni.Cardiff, Uni.Manchester, INFN-GE, INFN-PI, INFN-RM1, INFN-RM2, INFN-FE
- PI: P. de Bernardis (Sapienza), M. Bersanelli (UniMI), F. Gatti (INFN)
- Combined sensitivity: 10 μK arcmin

LSPE/STRIP

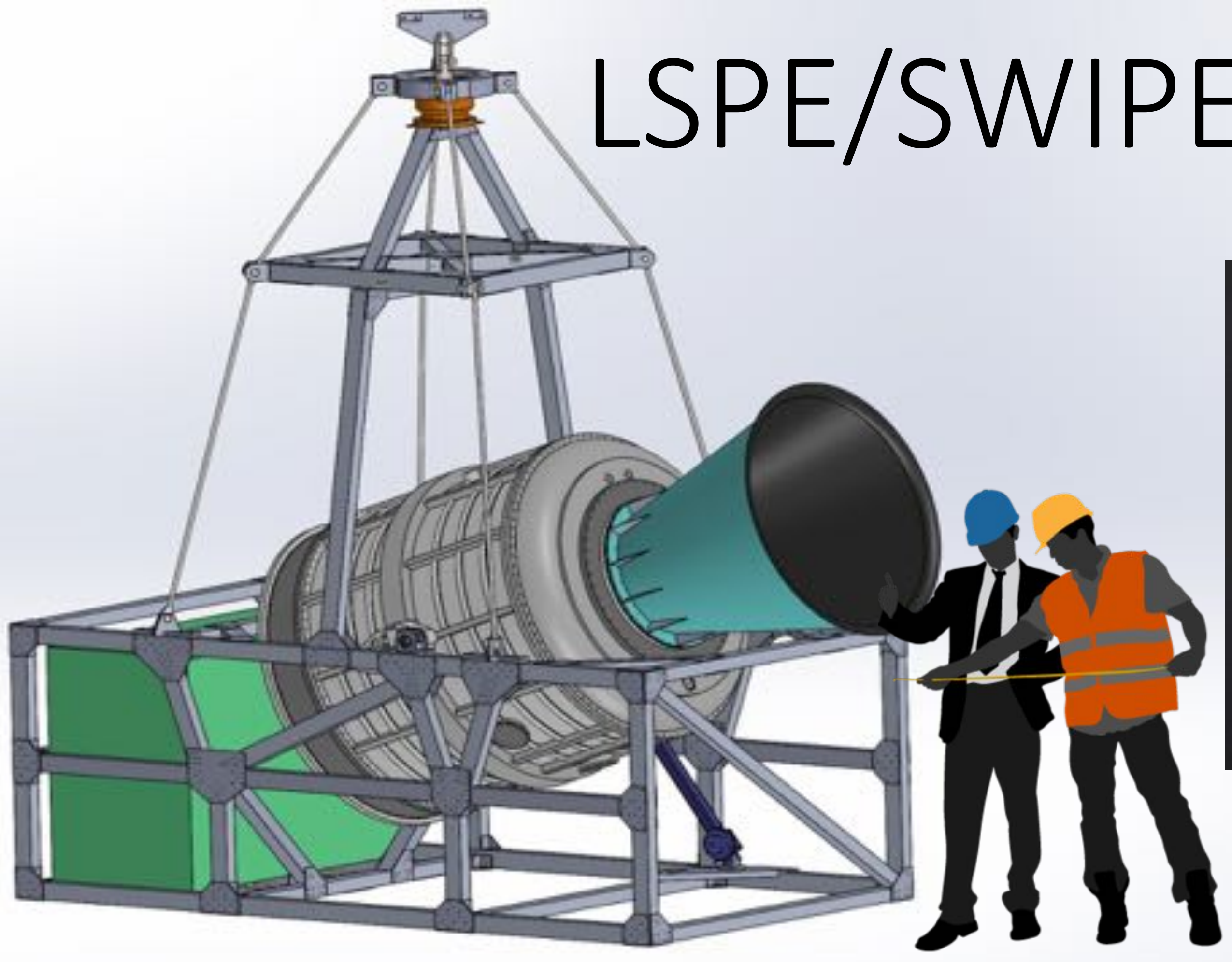


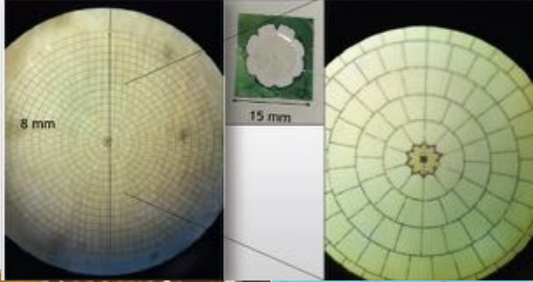
STRIP telescope)

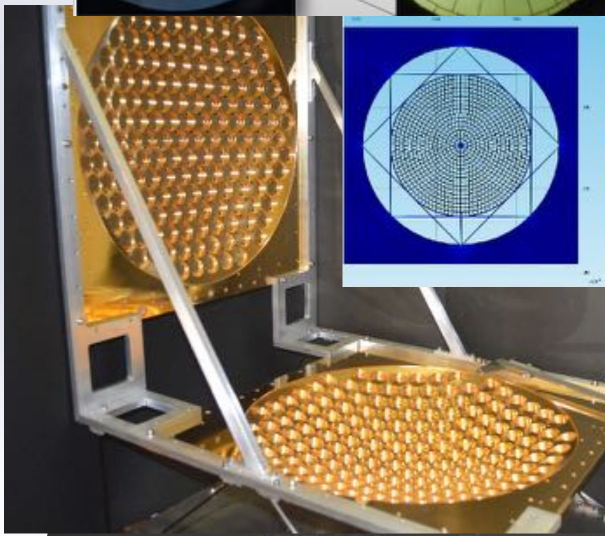
STRIP 44GHz polarimeters arrays)

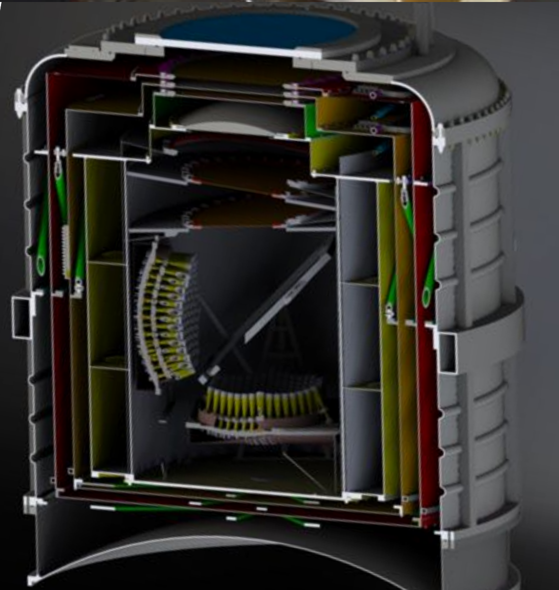
STRIP observing site : Tenerife)

LSPE/SWIPE





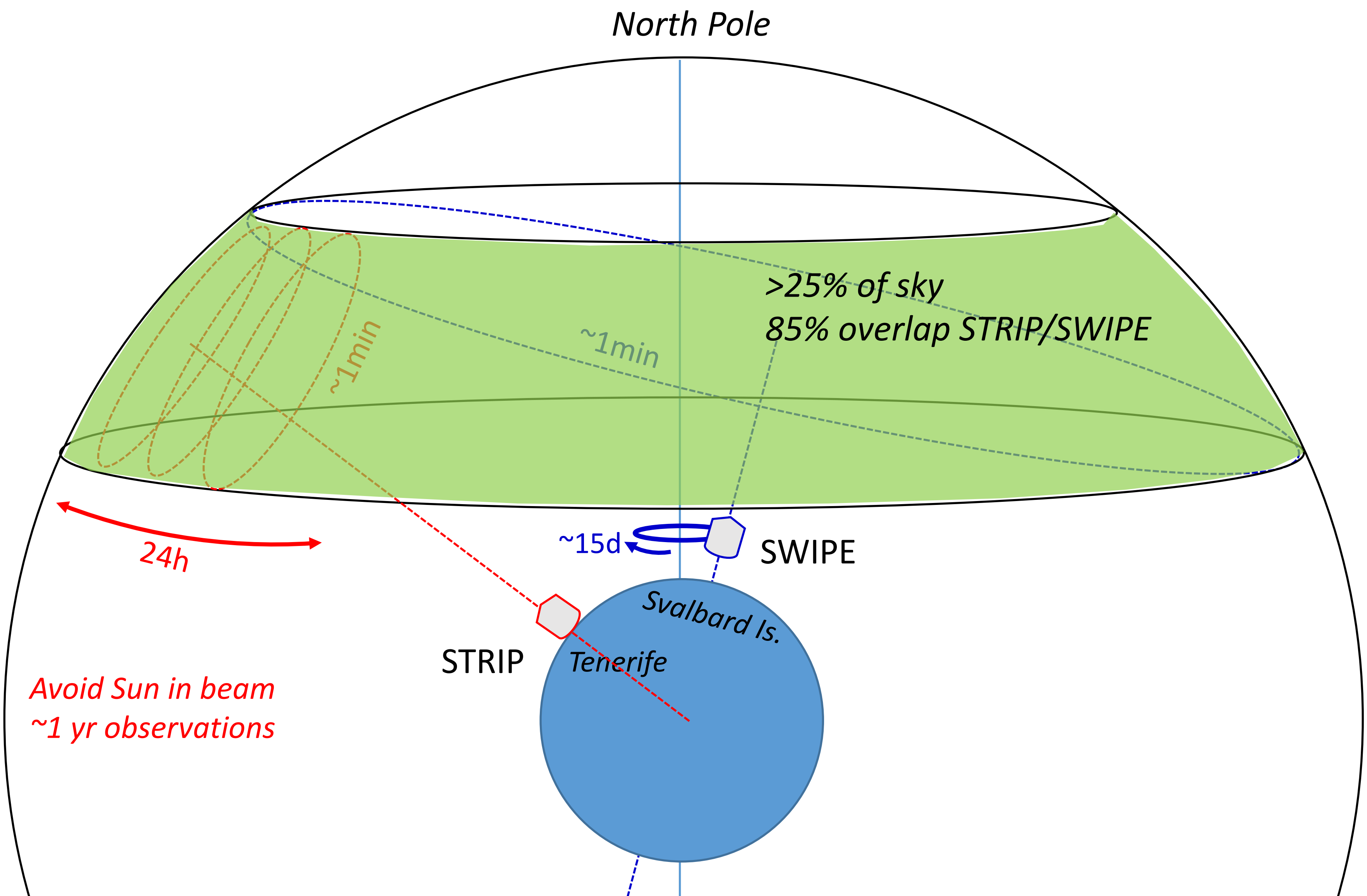




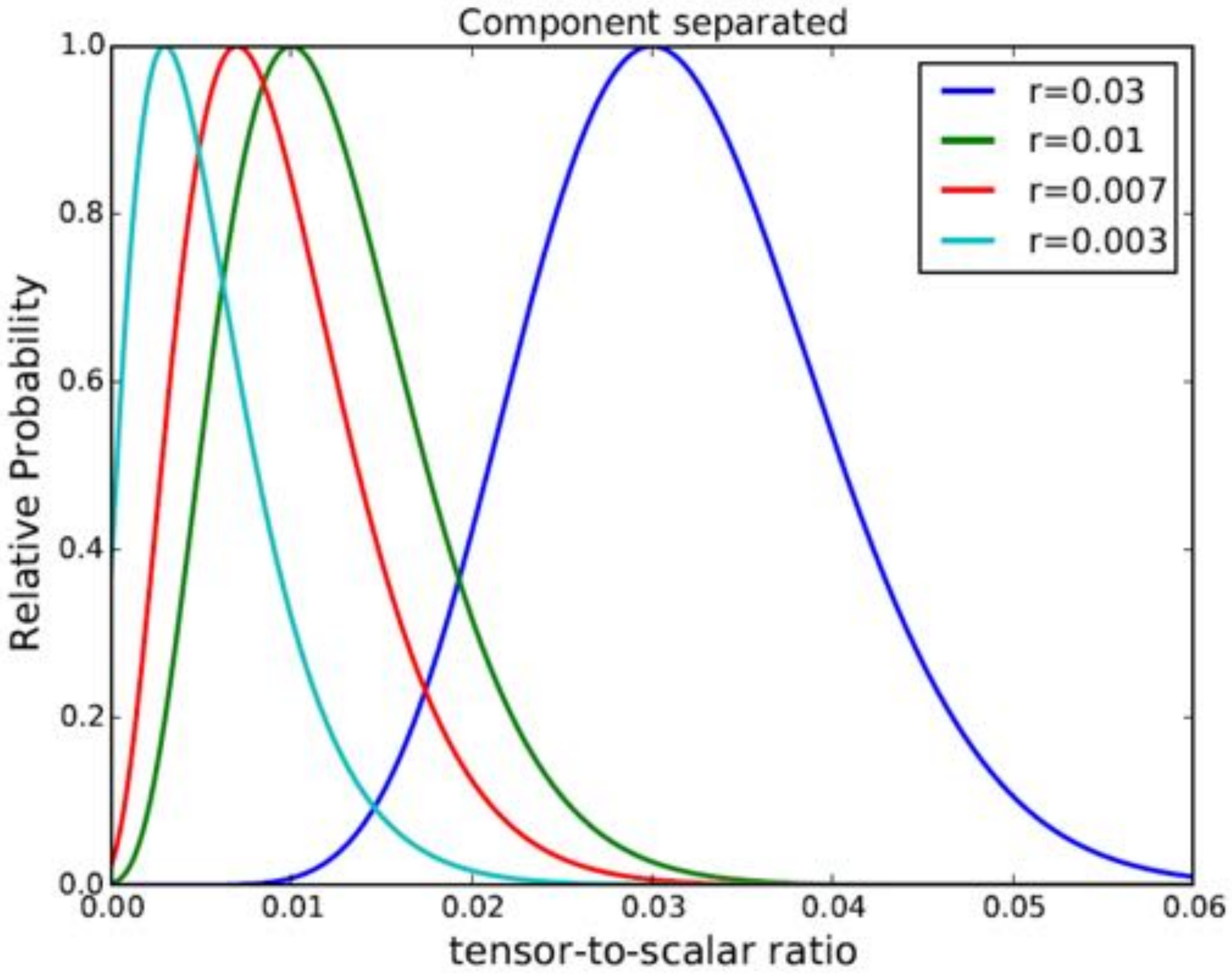
The SWIPE instrument (120-250 GHz) uses:

- *a spinning stratospheric balloon payload* to avoid atmospheric noise, flying *long-duration, in the polar night* to avoid diffracted solar pickup
- a *polarization modulator* to achieve high stability
- Large arrays of multimode bolometers for high sensitivity (8800 radiation modes)

LSPE
Scanning strategy concept



Performance Forecast



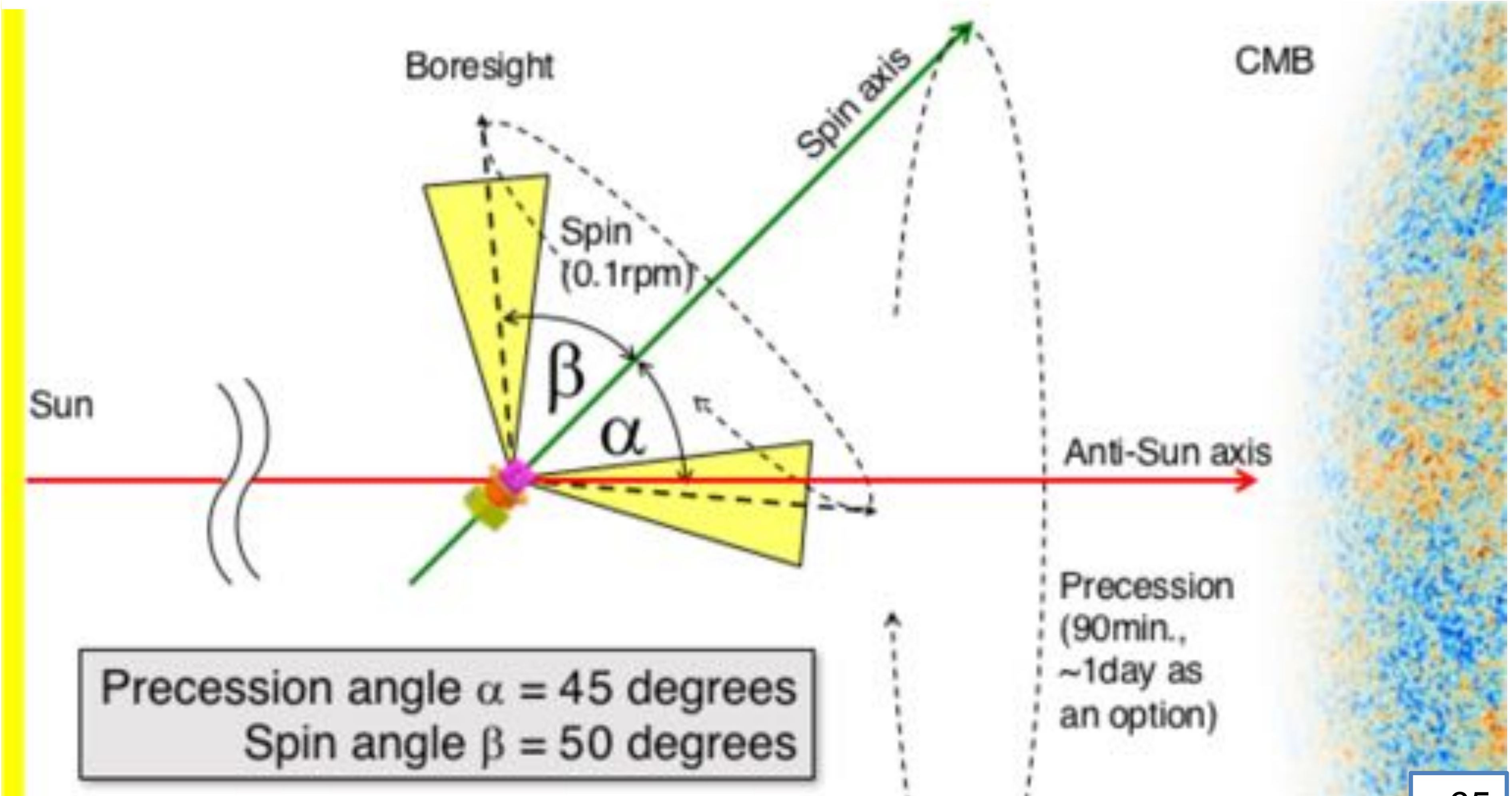
LiteBIRD

A JAXA lead post Planck space mission for CMB polarization, with participation from US and Europe

This slide and following six courtesy LiteBIRD PI M. Hazumi

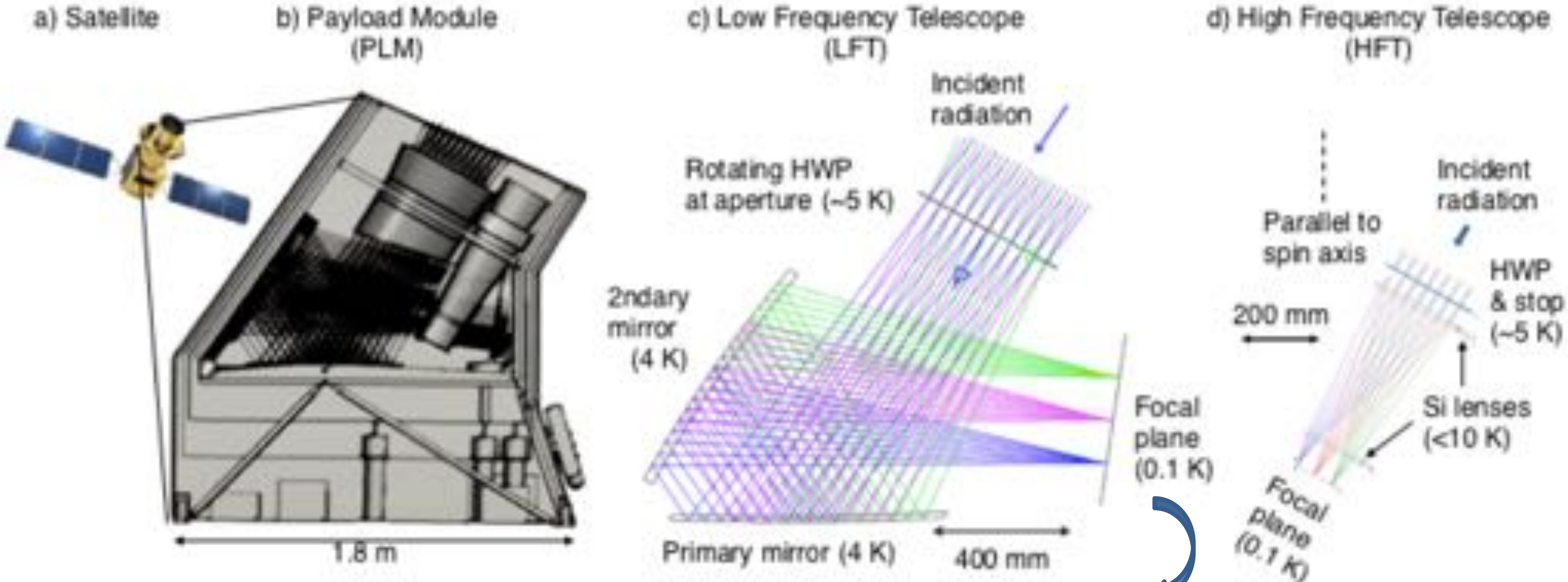
Scan Strategy

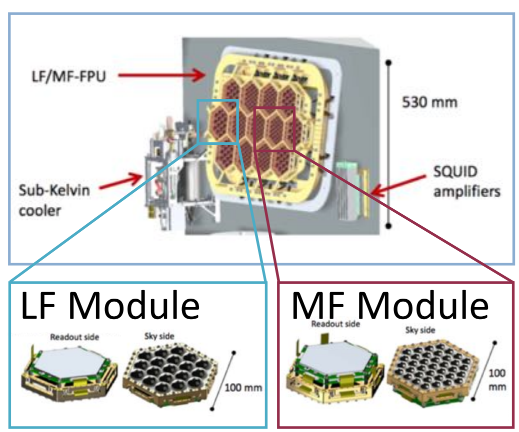
Orbit: L2 Lissajous

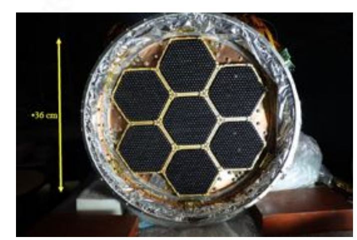


Payload Module

Phase-A1 2016 Baseline



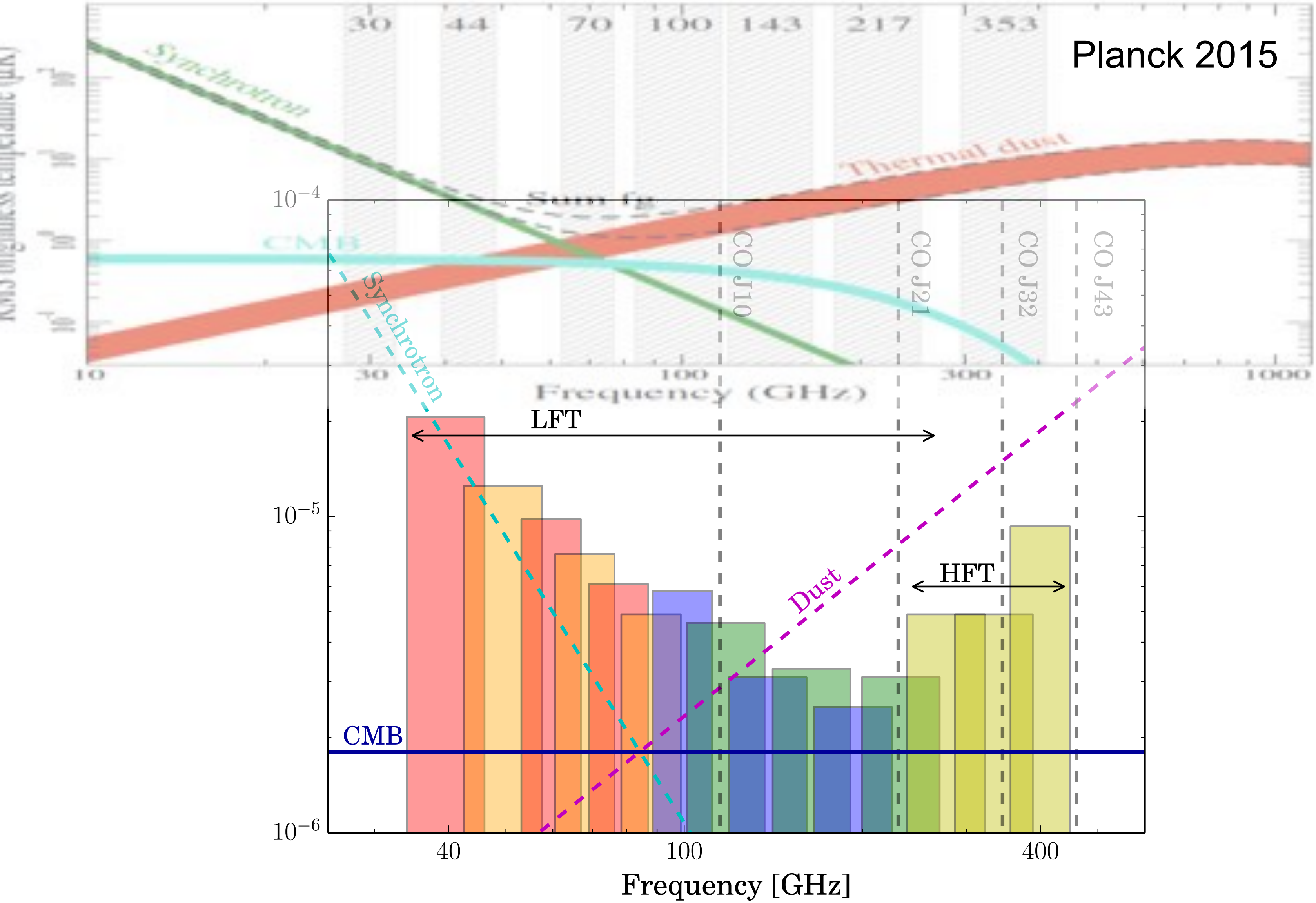




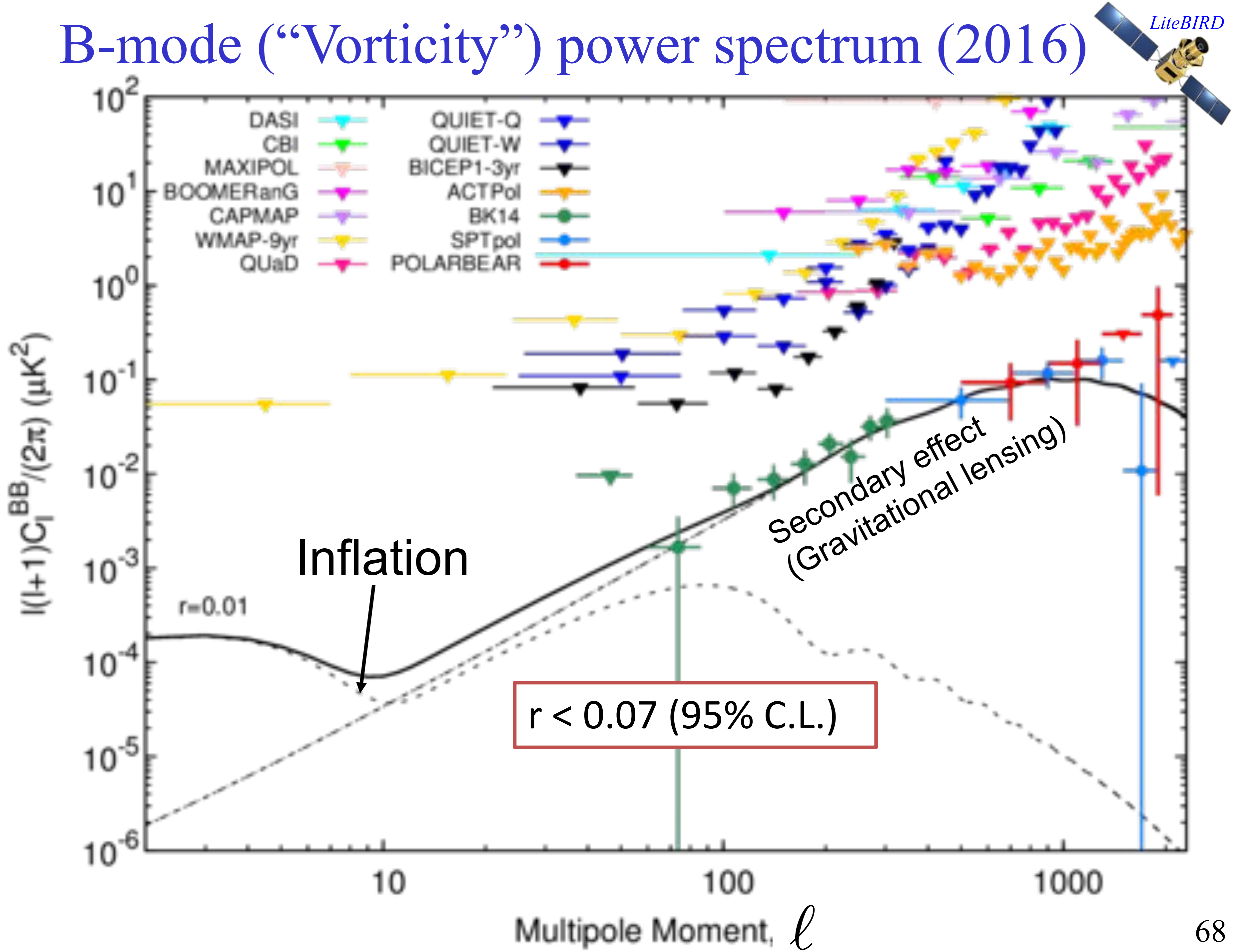
POLARBEAR-2 focal plane as a proof of principle

- TES arrays
- Polarization modulators
- LFT + HFT
- 0.1 cooling system (ST/JT/ADR)

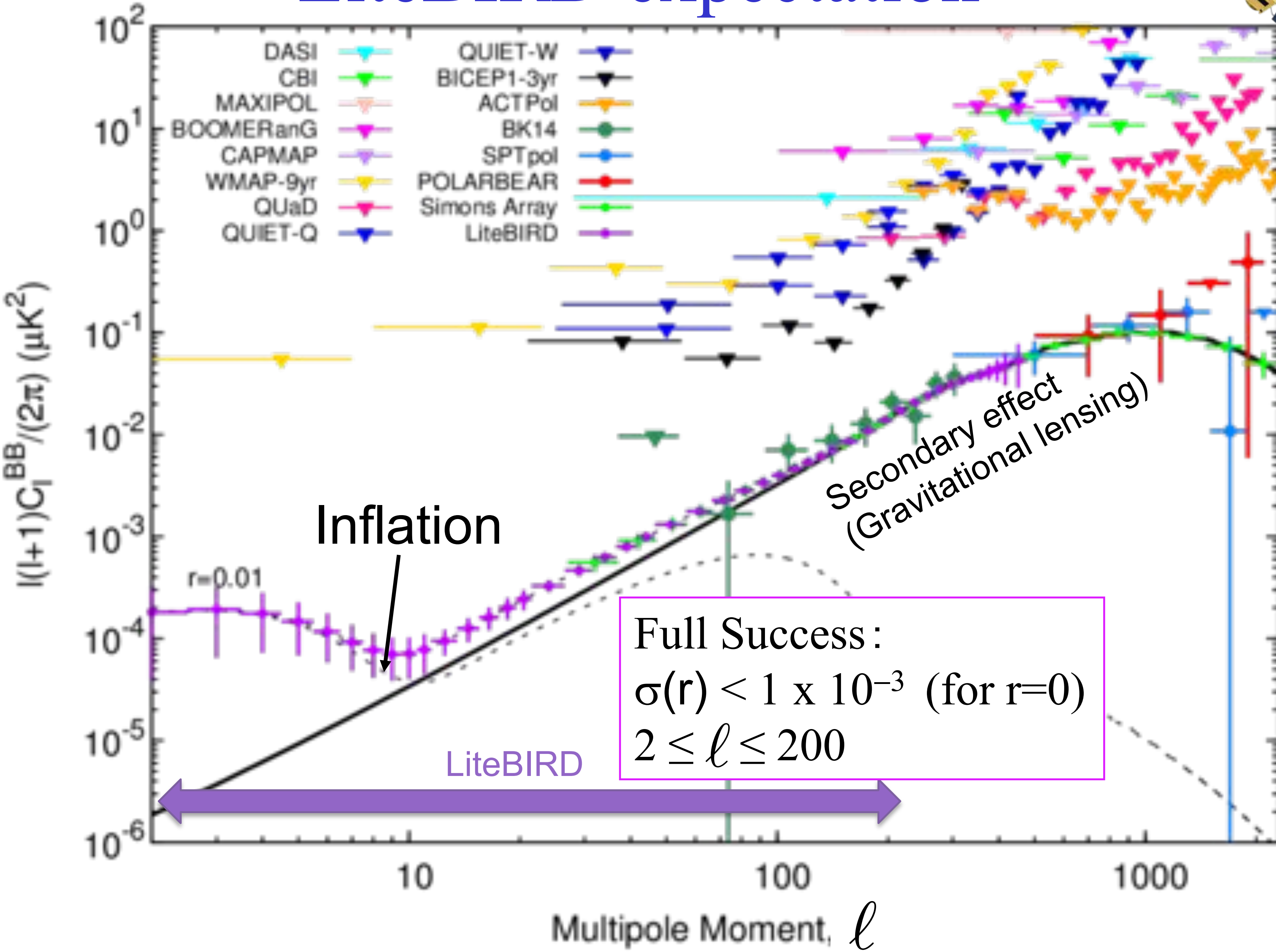
LiteBIRD: 15 Frequency Bands (Phase-A1 2016 Baseline)



B-mode (“Vorticity”) power spectrum (2016)



LiteBIRD expectation



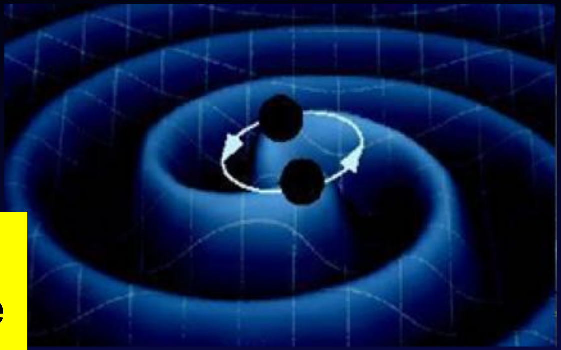
Full Success :
$\sigma(r) < 1 \times 10^{-3}$ (for r=0)
$2 \leq \ell \leq 200$

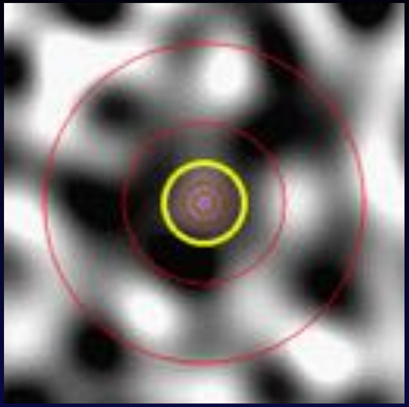
Big leap from LIGO to LiteBIRD

within Einstein's theory of general relativity

beyond Einstein

The 2017 Nobel Prize in Physics





LIGO: gravitational waves with classical origin

LiteBIRD: gravitational waves with quantum origin

Conclusions

- Planck has delivered its final (legacy) release
- It has provided the ultimate (cosmic variance limited) measurement of CMB anisotropy
- … But just opened the door of CMB polarization (which Planck was never designed to measure, by the way)
- It has fulfilled its promise of measuring the fundamental cosmological parameters to percent accuracy
- ...and brought remarkable constraints on particle physics parameters as well, excluding a fourth fully thermalized neutrino and constraining the total neutrino masses in the 100 meV range.
- Has measured well one relevant inflationary parameter, the primordial spectral index, allowing constraints on the inflationary paridigm
- Yet has uncovered several tensions with astrophysical measurements, which may or may not hint at new physics.
- Intrinsic anomalies do exist in the large-angle CMB field, which may also be a tracer of something hitherto unseen.
- If these tension/anomalies are really hinting at new physics, its signature in the CMB is scant. Accurate measurements are needed to pin down the issue.
- Primordial gravitational waves remain unseen.
- To exploit the wealth of information that still is in the CMB, we need to cope with the extraordinary complexity of the sky. This can be credibly done only with a future space mission.

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.