CMB probes of the early universe: anisotropies and distortions

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Cosmology from Home

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Overview

1. CMB basics

2. CMB anisotropies

- What do we actually measure
- What do they tell us
- What type of models can we constrain

3. CMB distortions

- What could we measure
- What would they tell us
- What type of models could we constrain

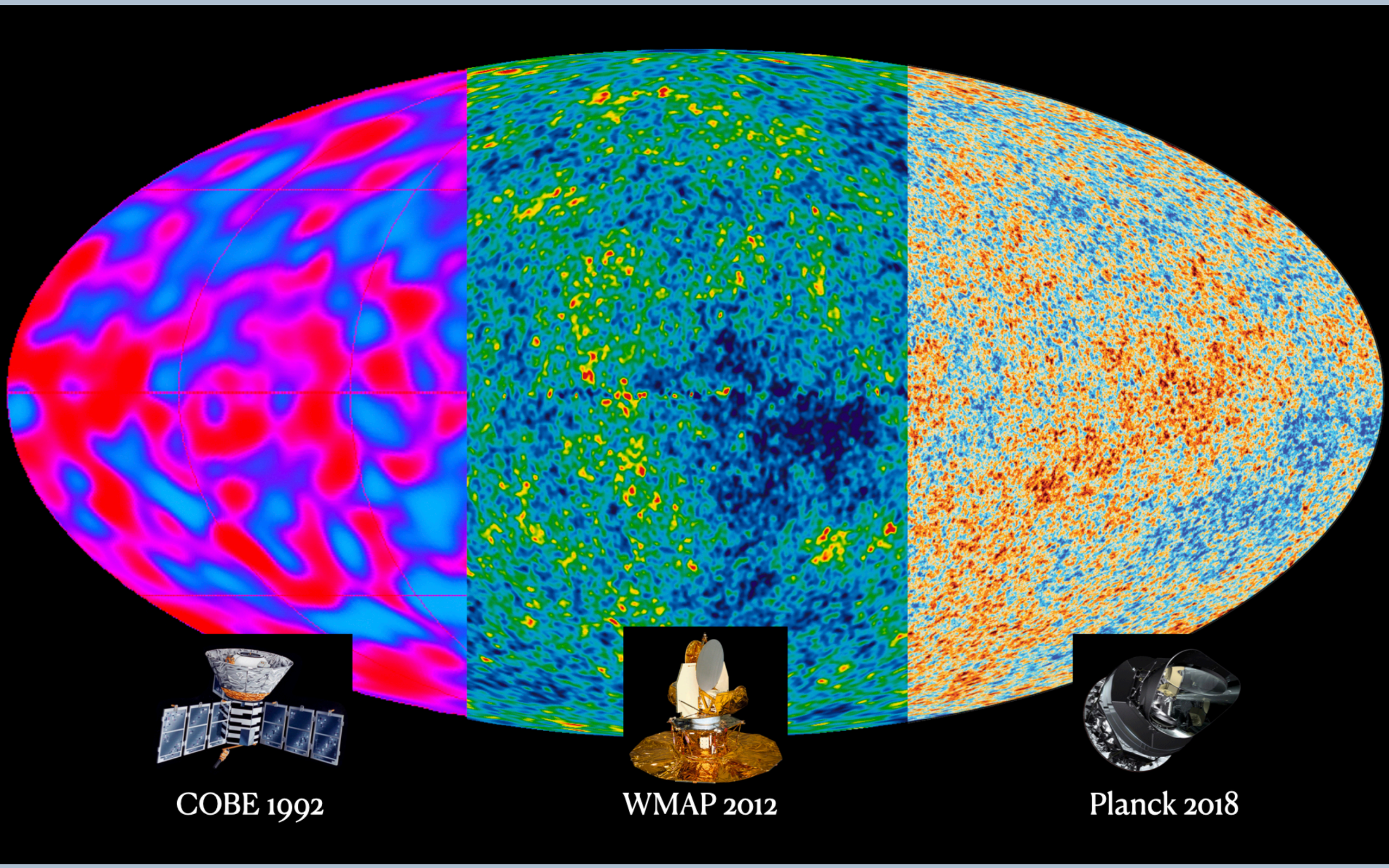
4. Summary and outlook

What is the CMB

- Early universe: photons in thermal equilibrium via Compton ($e^- + \gamma \rightarrow e^- + \gamma$) and Coulomb ($e^- + p \rightarrow e^- + p$) scattering
- At around $z \sim 1100$ $(T \sim 0.3\,\mathrm{eV})$ neutral hydrogen can form via $e^- + p \rightarrow H + \gamma$ reactions
- Free electron fraction drops sharply, Compton scattering becomes gradually more inefficient
- Photons decouple, producing the last scattering surface
- Cosmic microwave background with an average temperature of $T = 2.7255 \pm 0.0006\,\mathrm{K}$ with anisotropies only of $\Delta T/T \sim 10^{-5}$

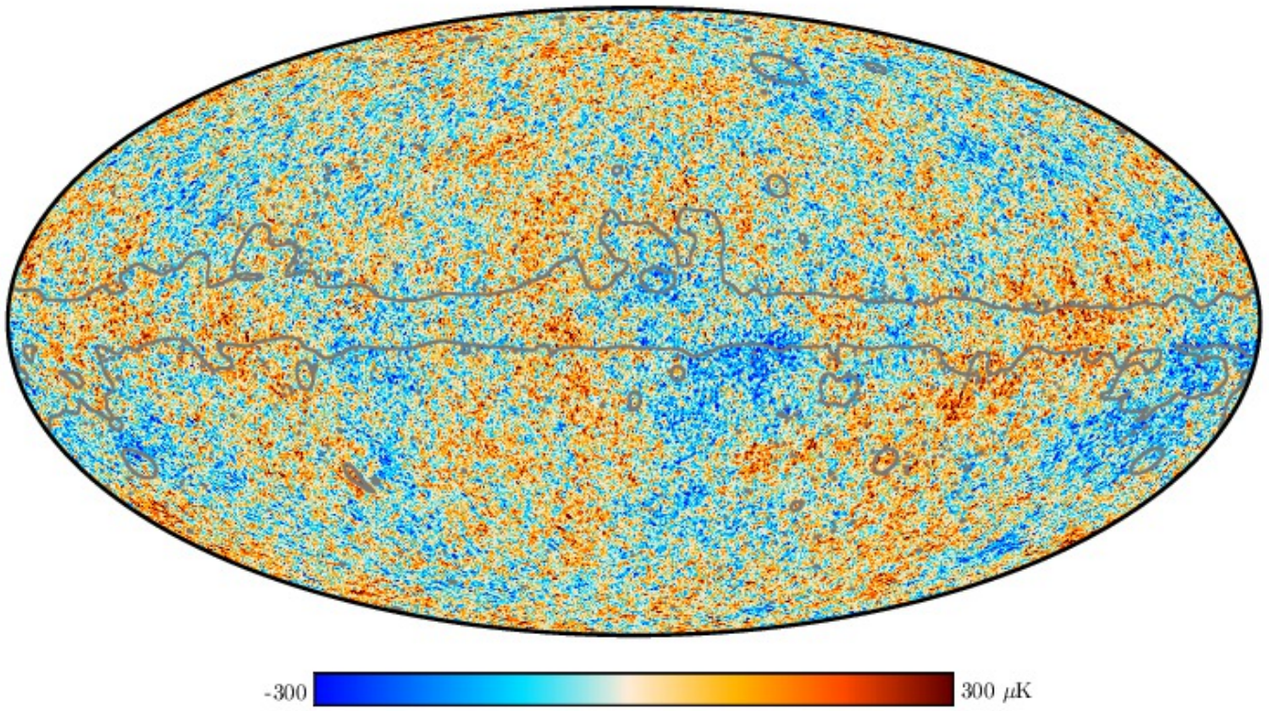
CMB Anisotropies

CMB measurements - the past

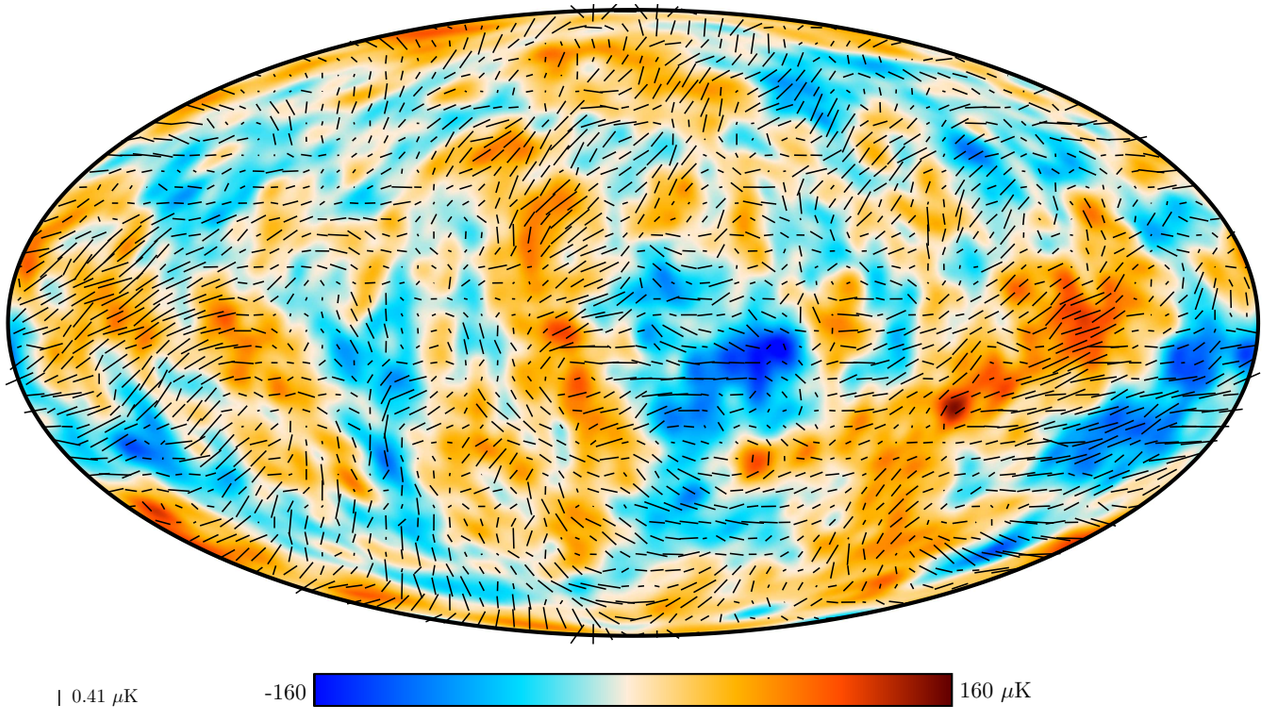


Fingerprint of the universe

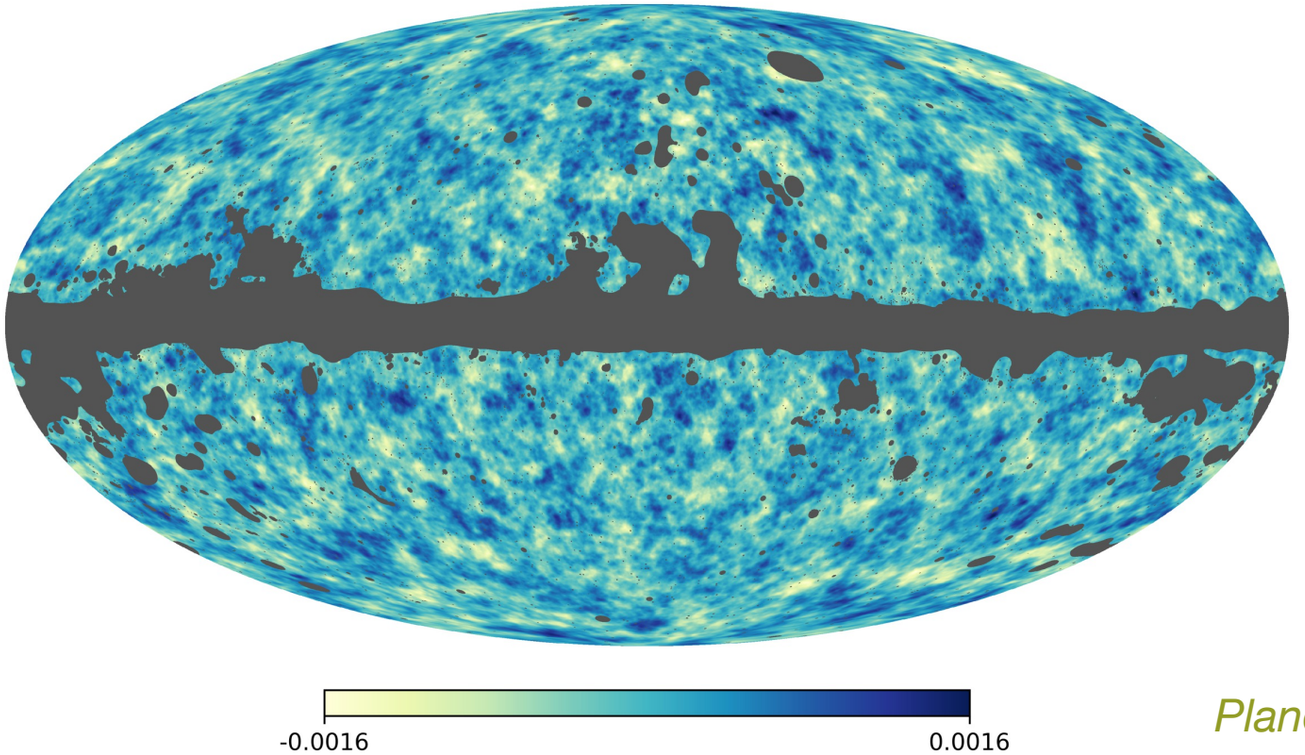
Temperature



E-mode Polarisation



Lensing



Planck Collaboration 1807.06205

Fingerprint of the universe

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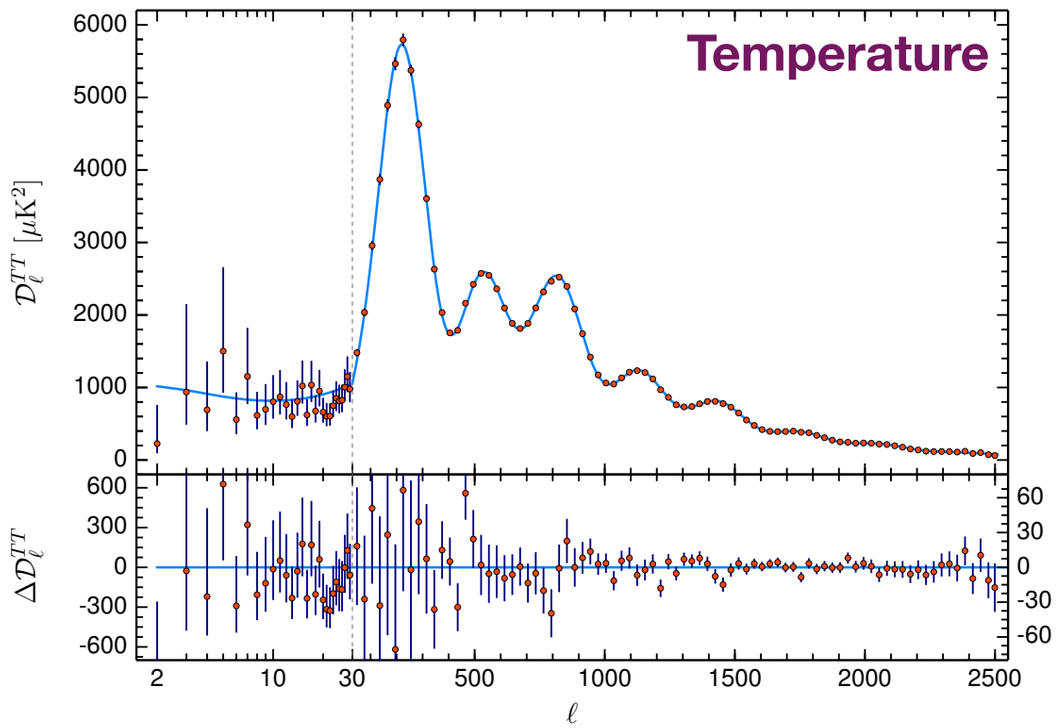

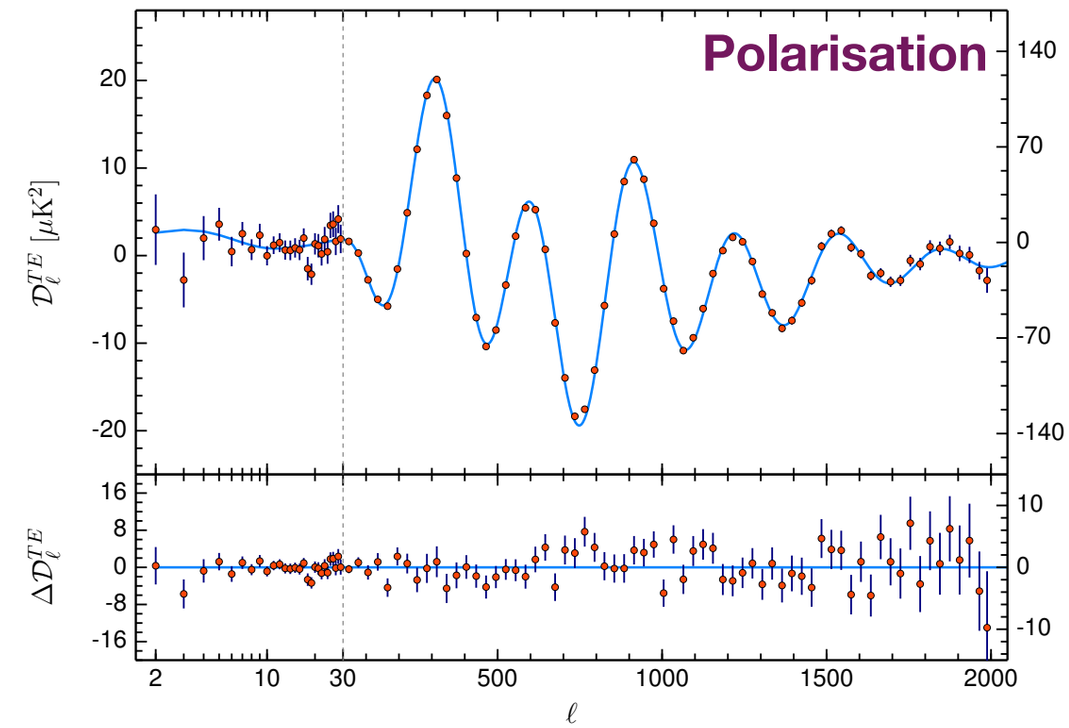

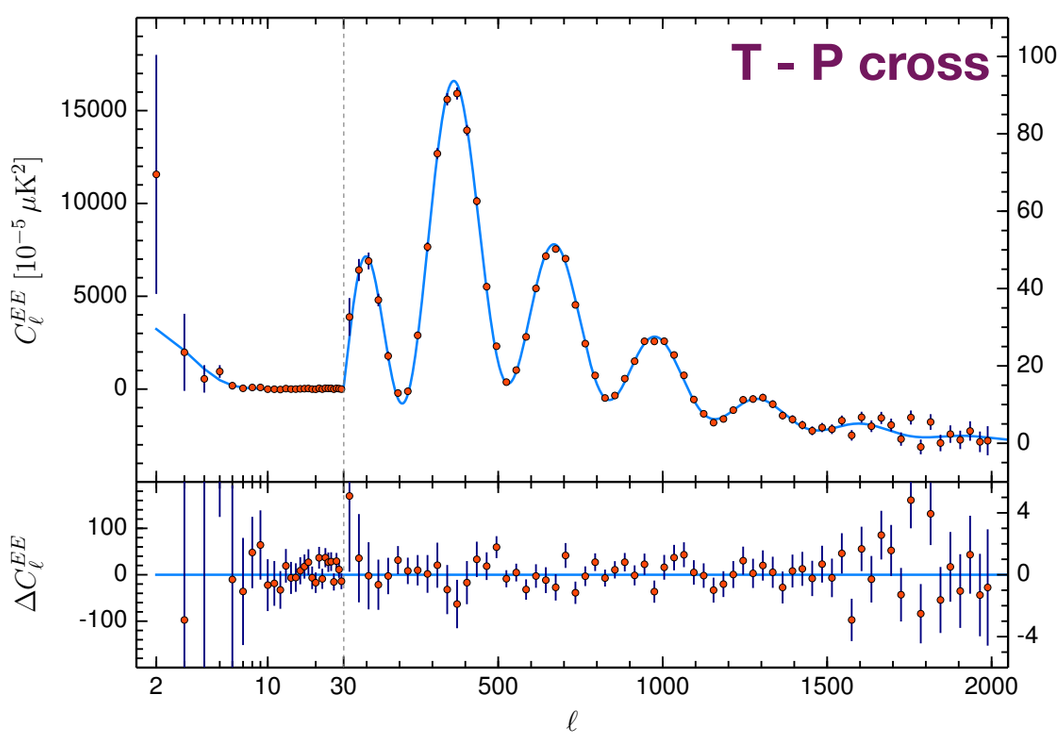

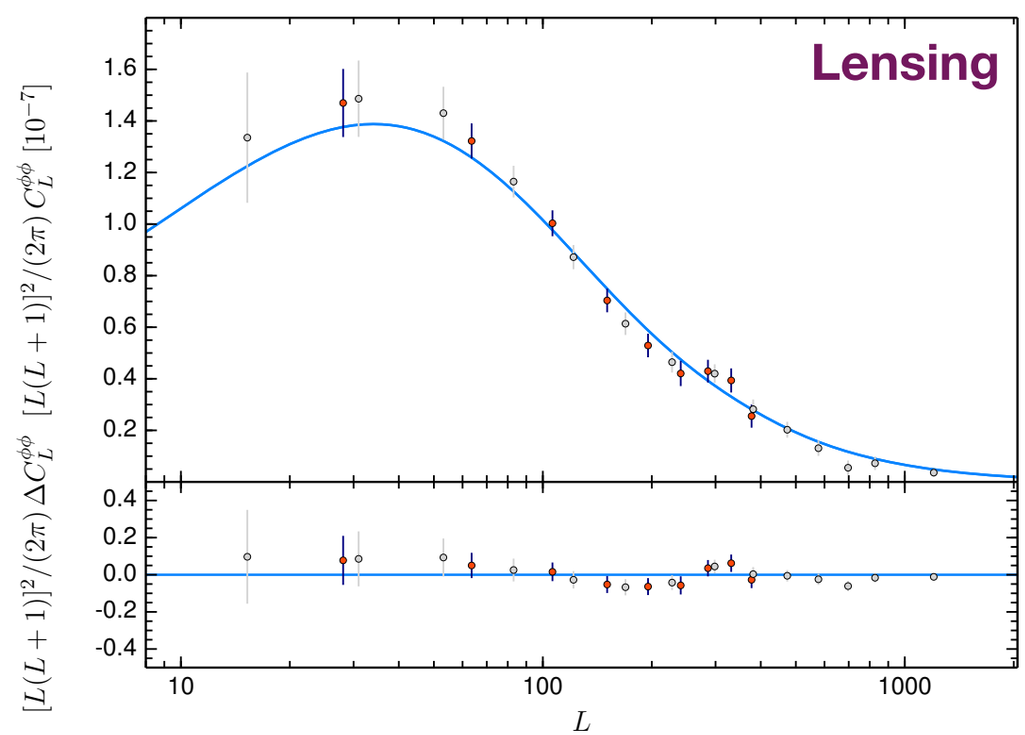

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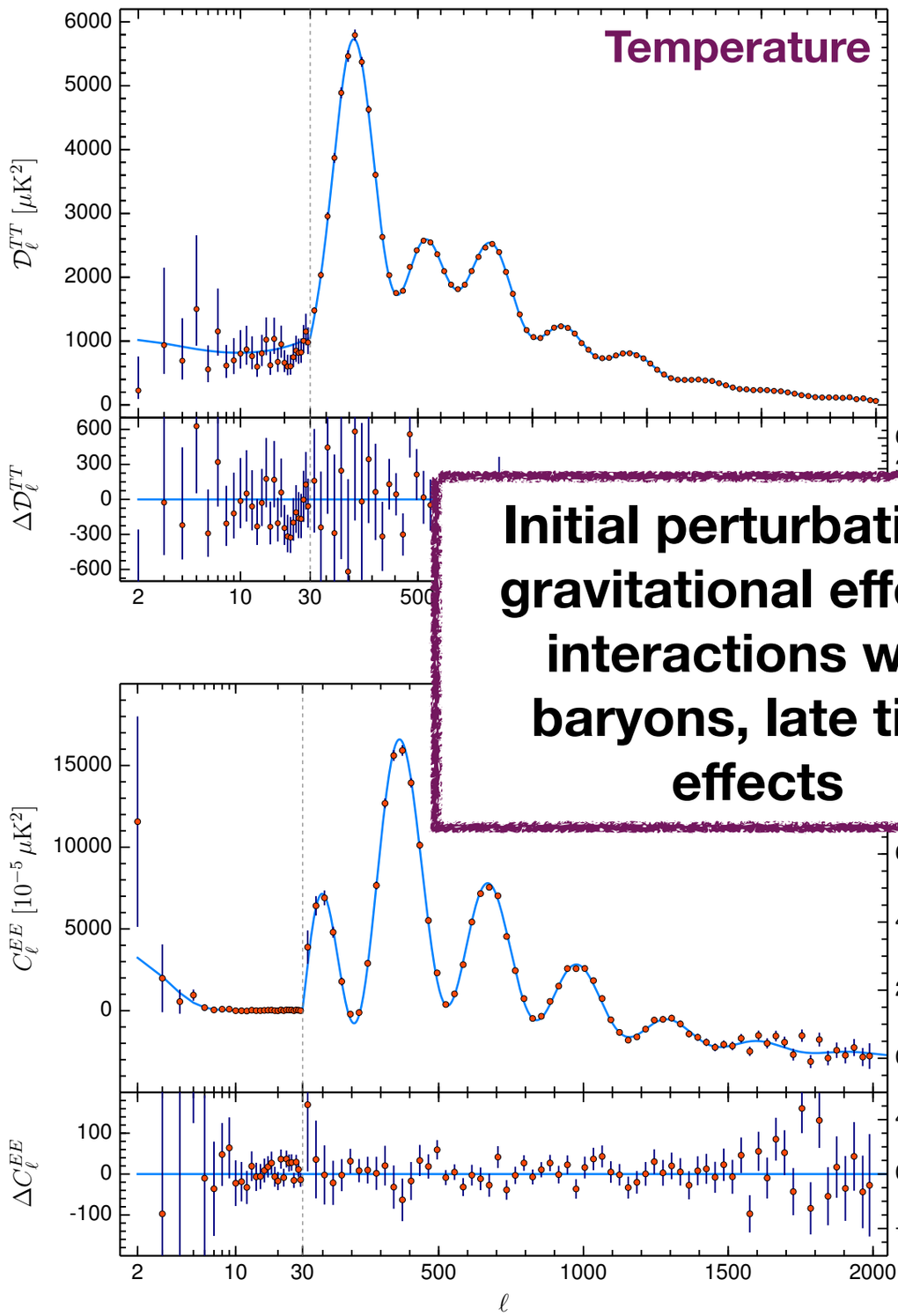

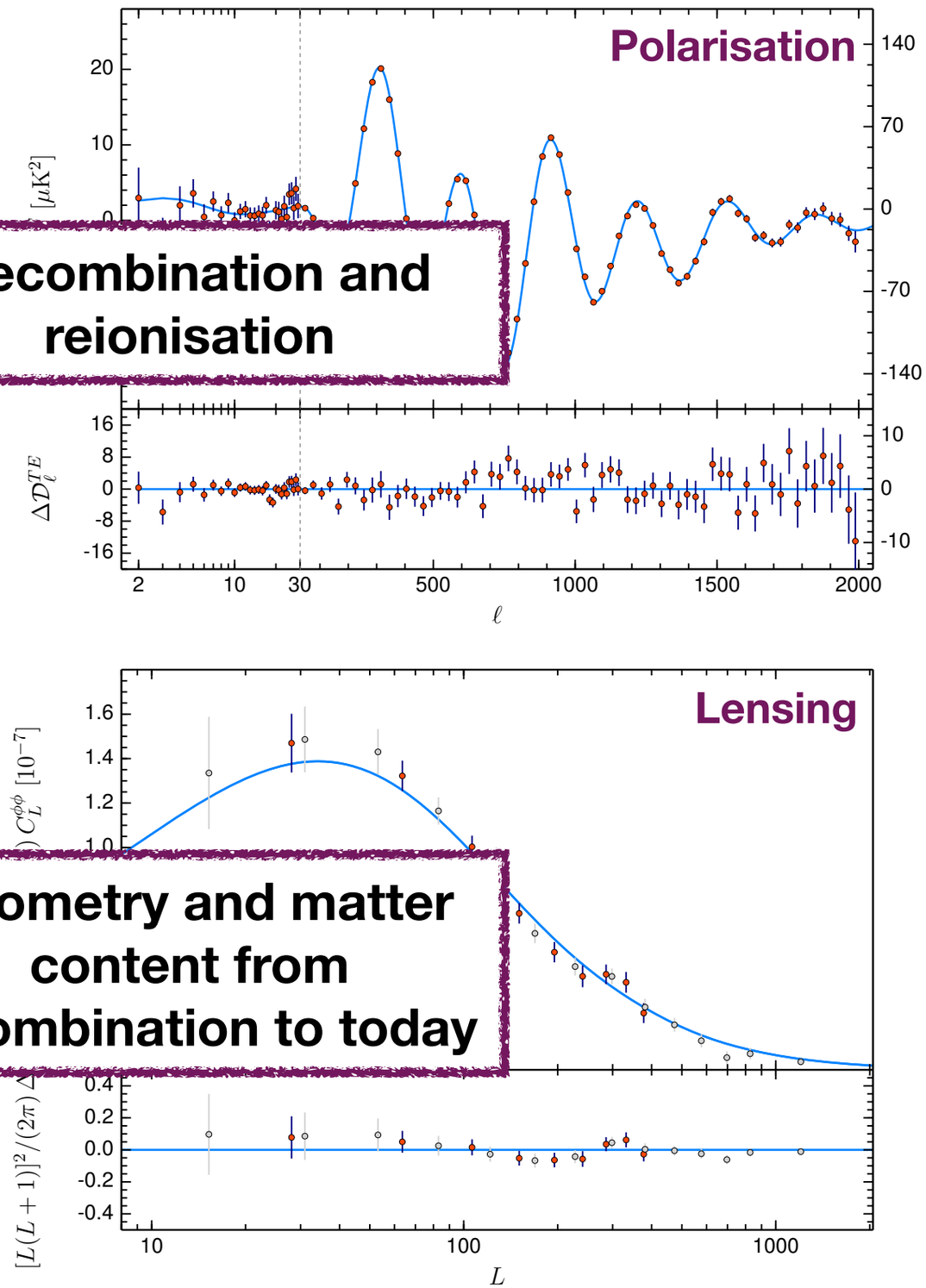

Initial perturbations, gravitational effects, interactions with baryons, late time effects

Recombination and reionisation

Geometry and matter content from recombination to today

Fingerprint of the universe

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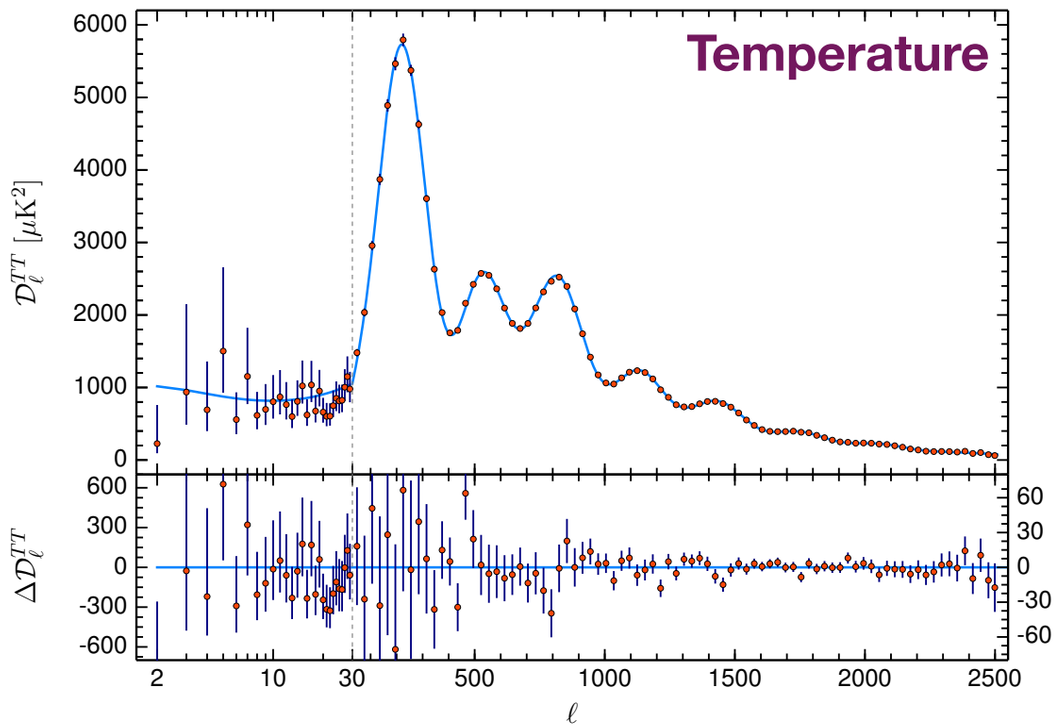

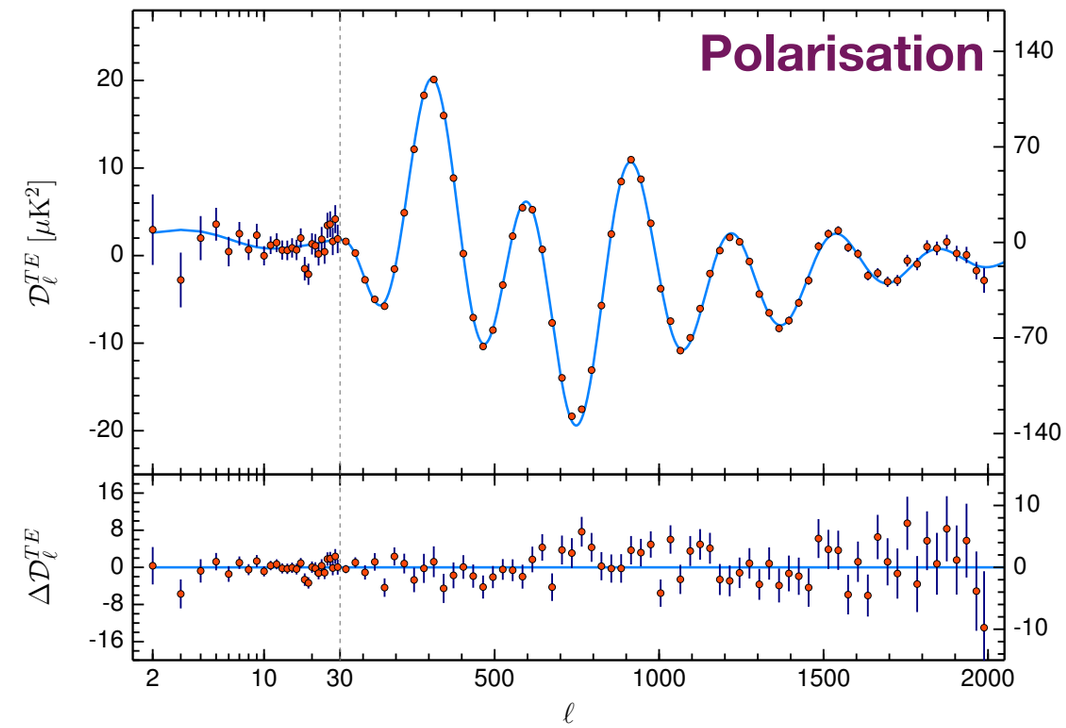

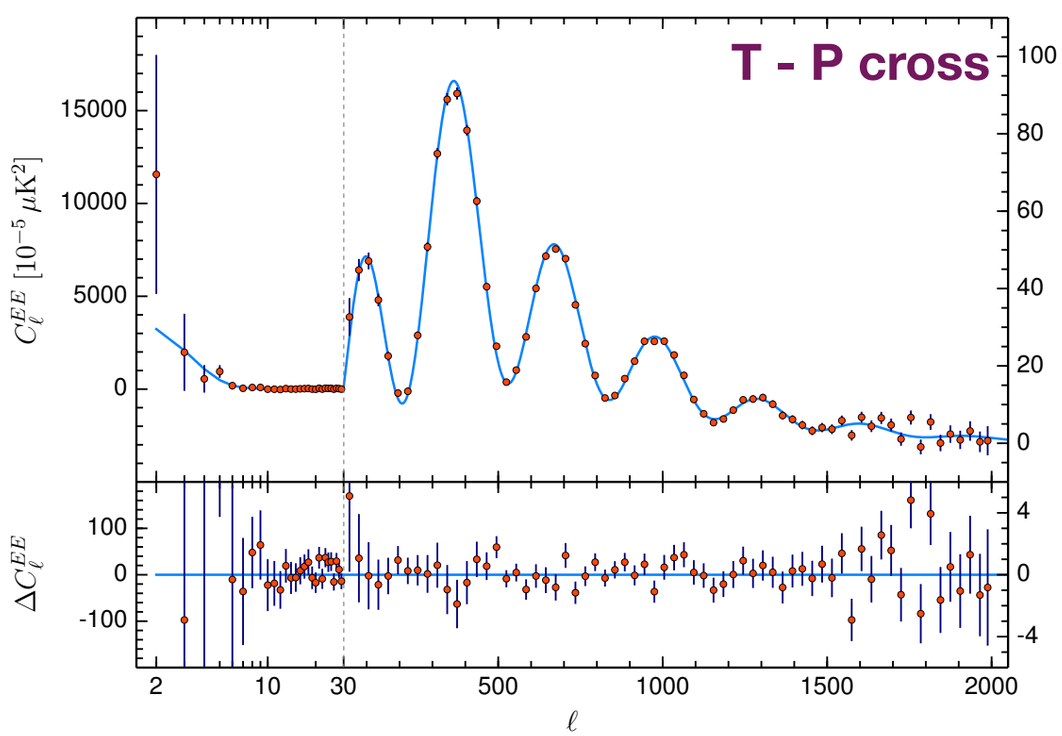

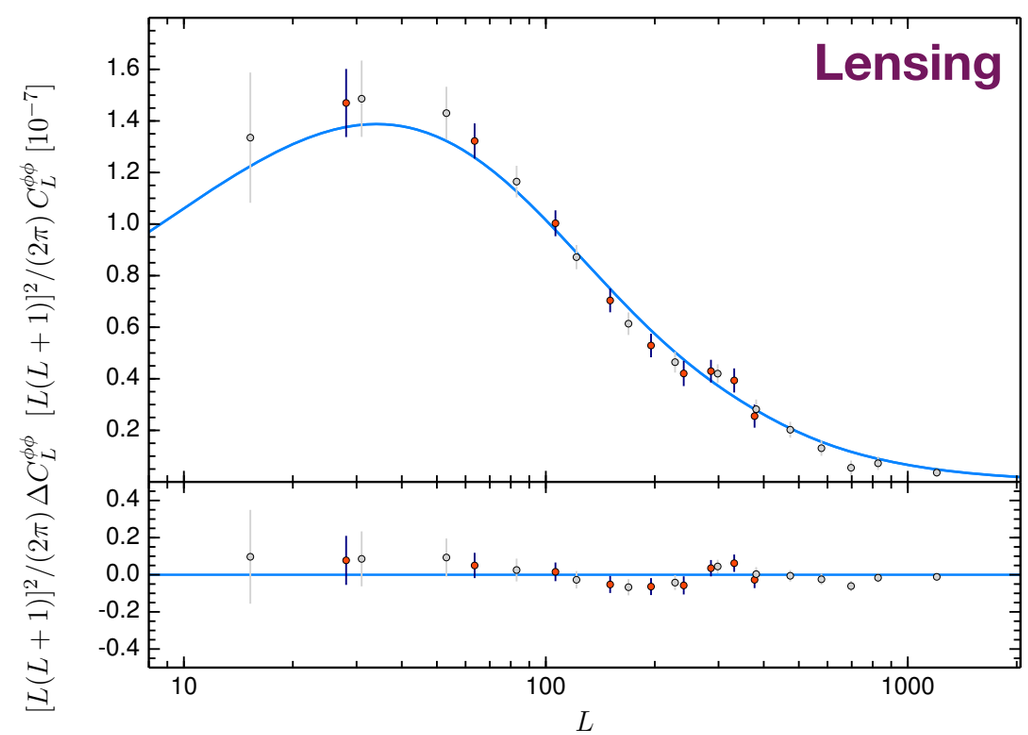

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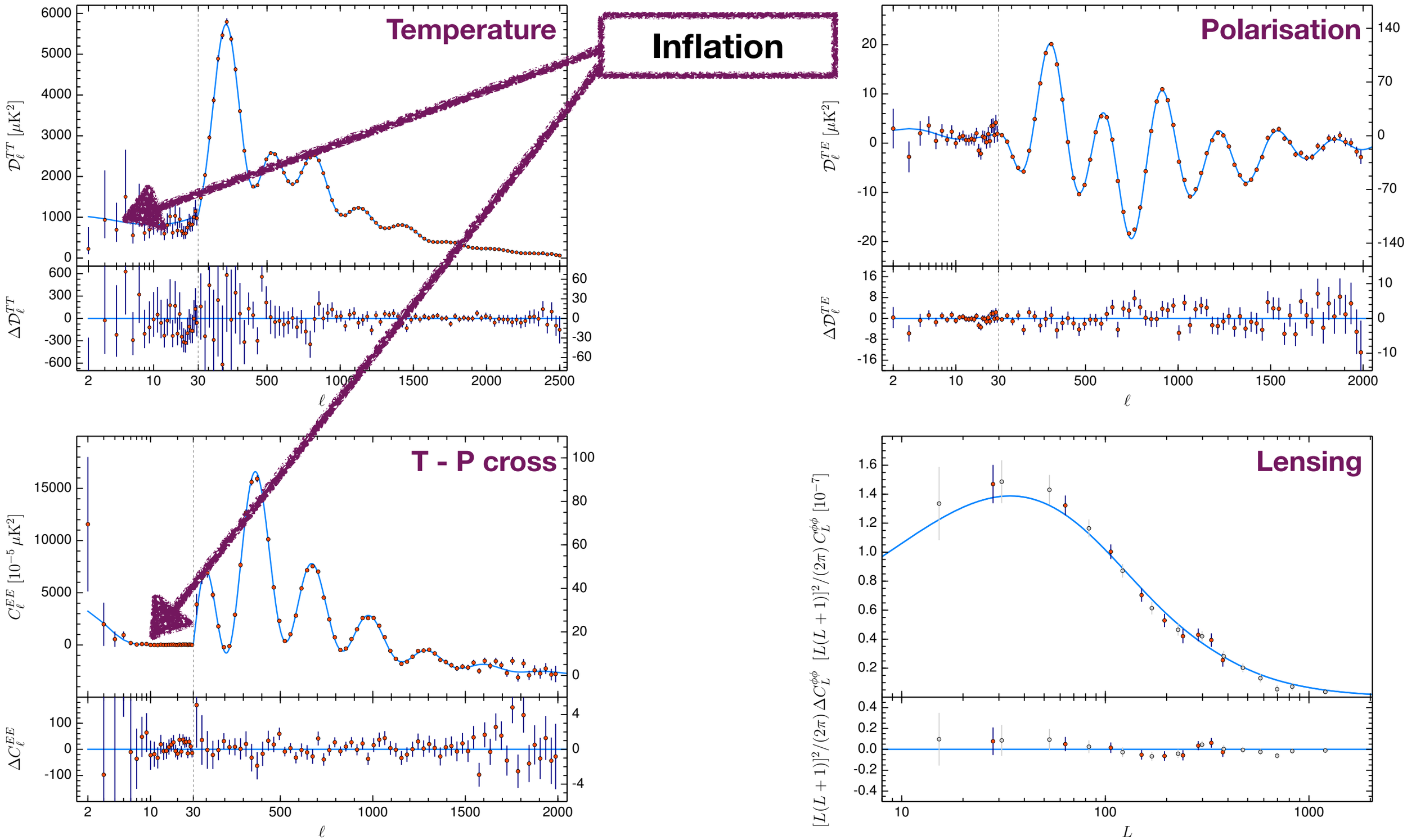

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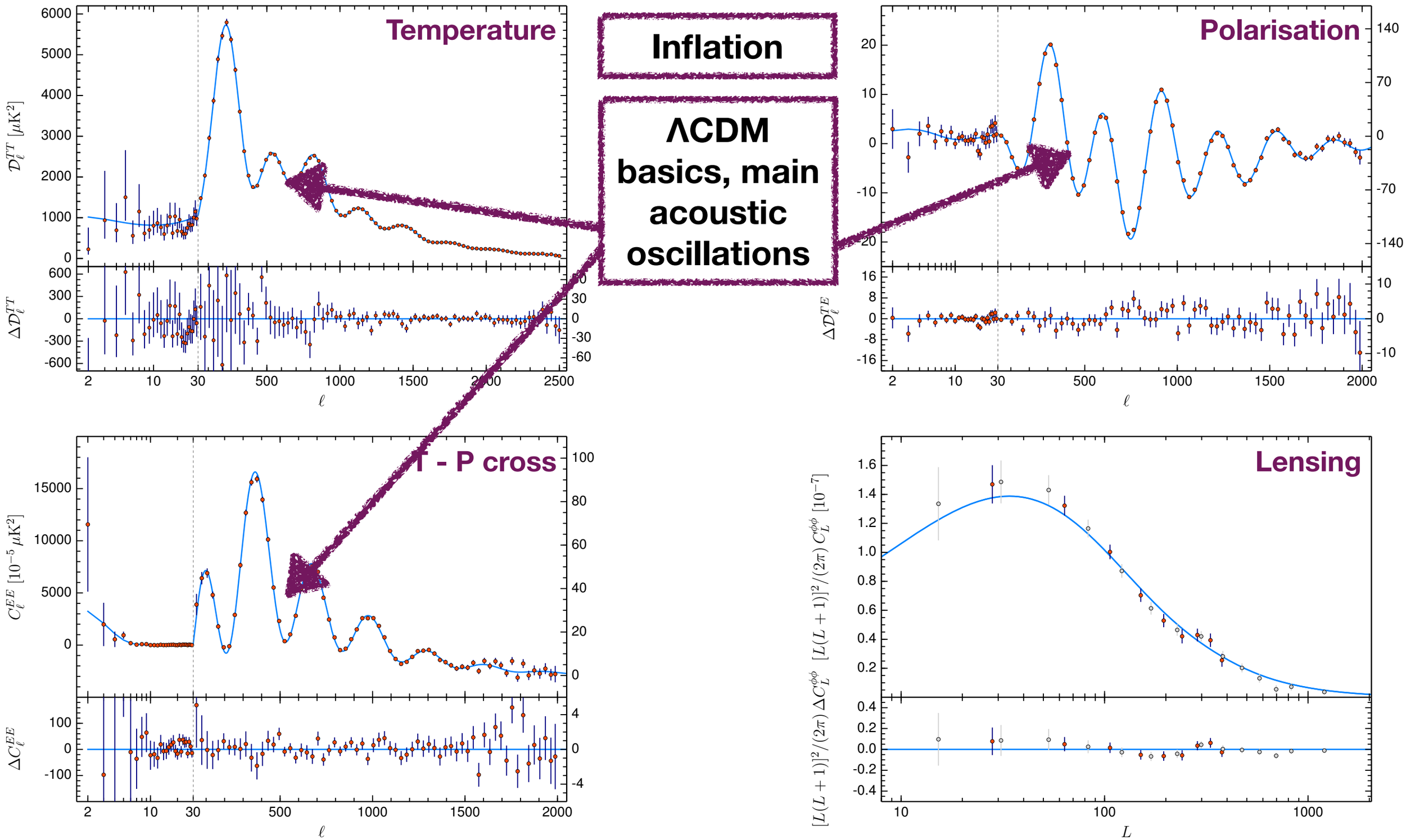

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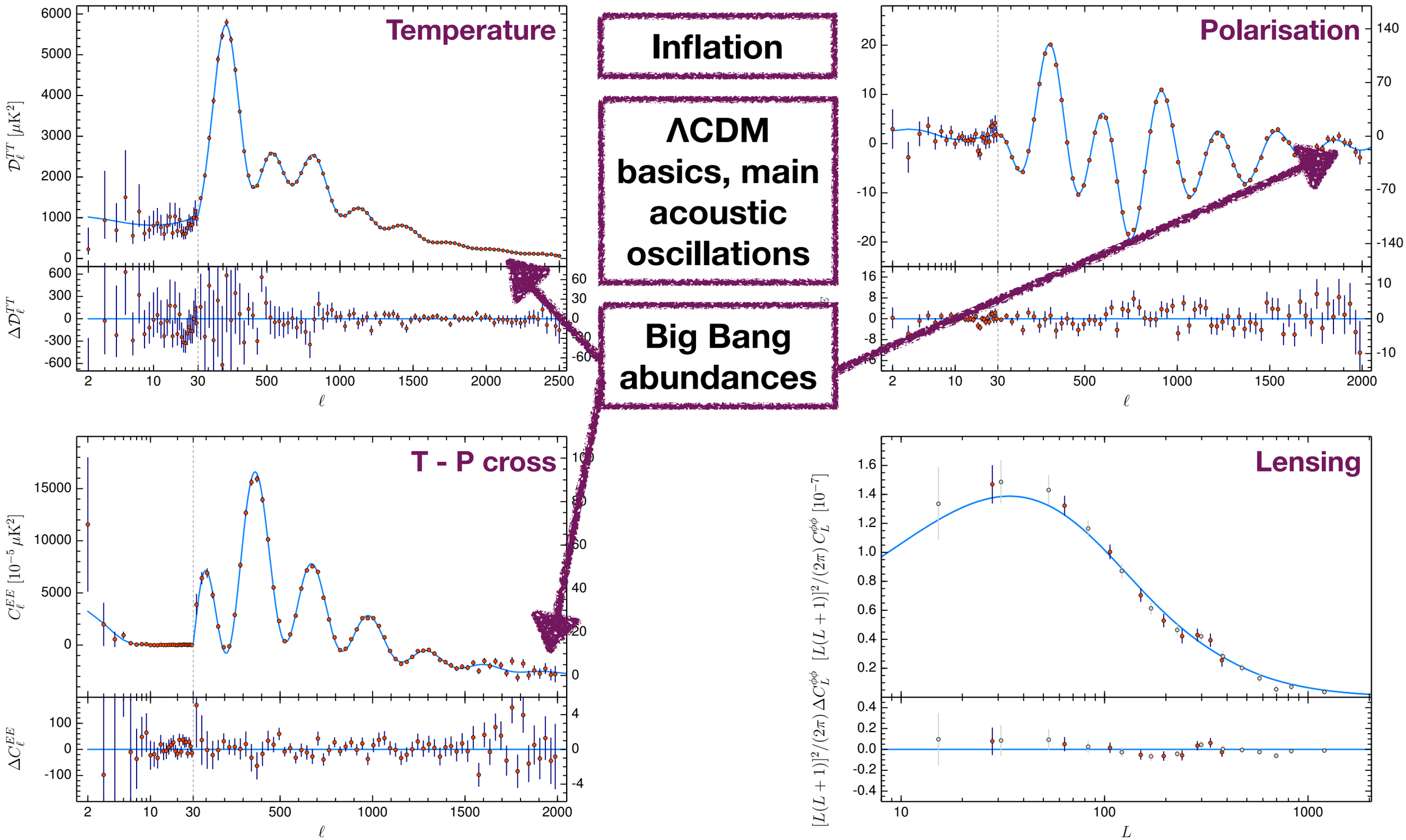

Inflation

ΛCDM basics, main acoustic oscillations

Big Bang abundances

Fingerprint of the universe

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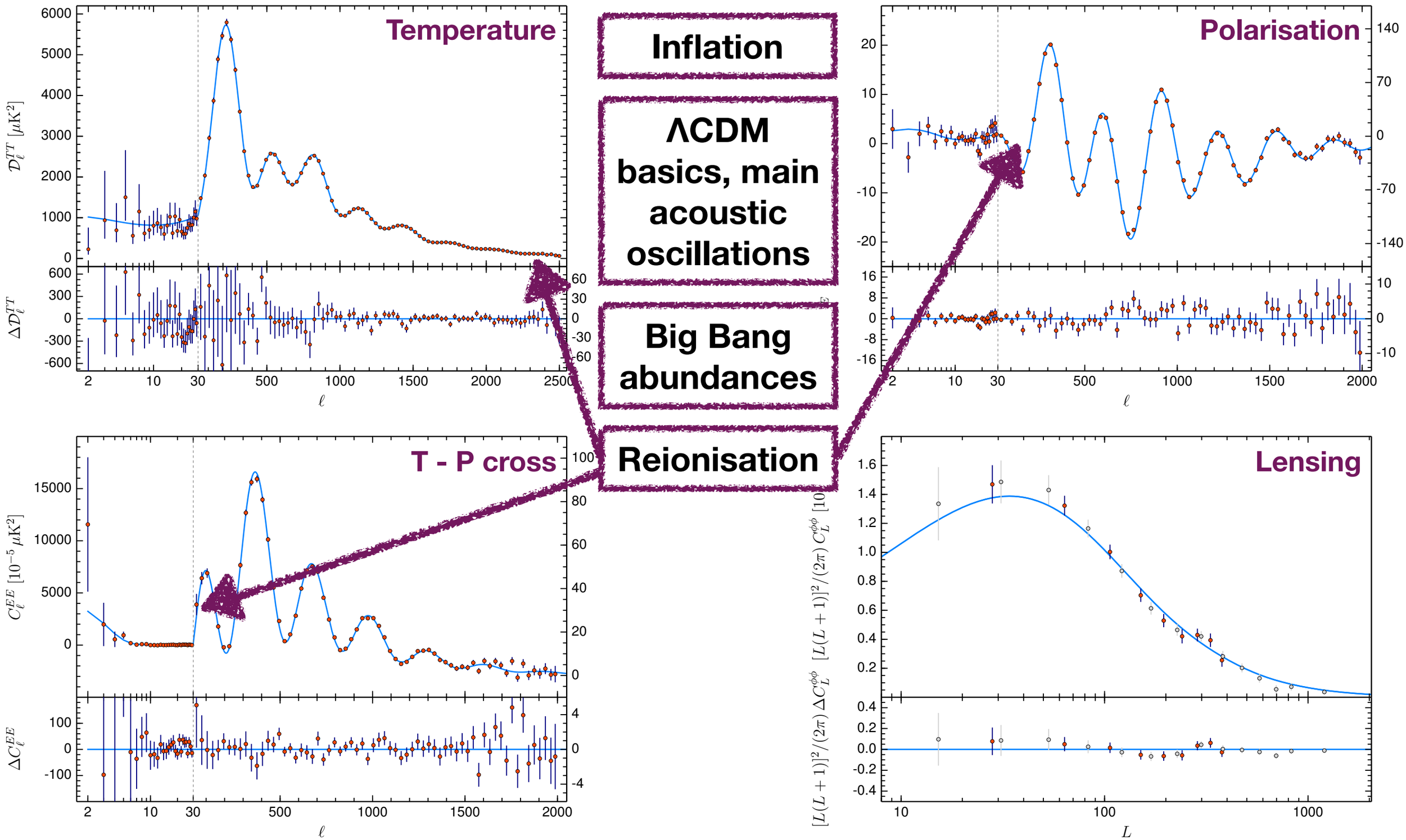

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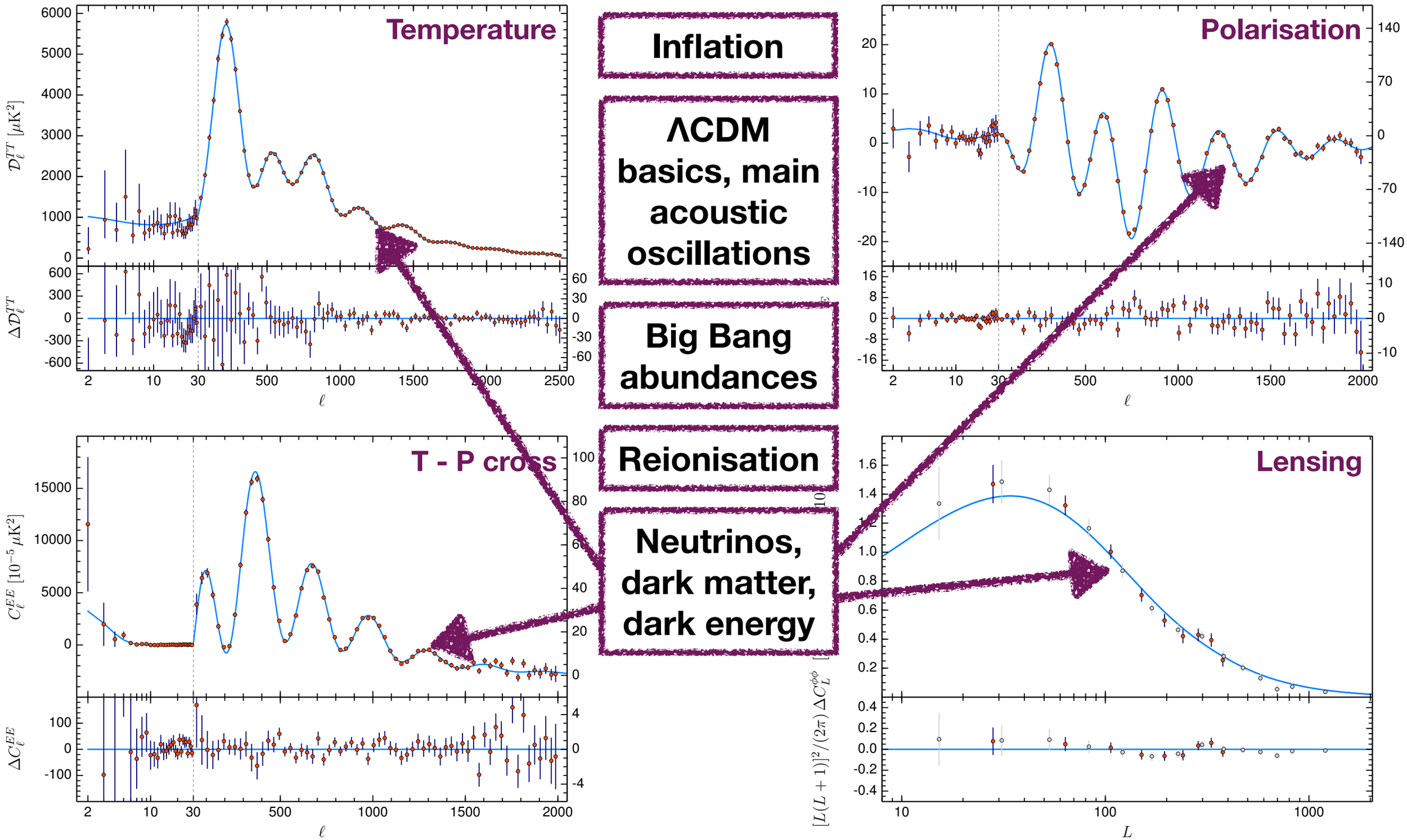

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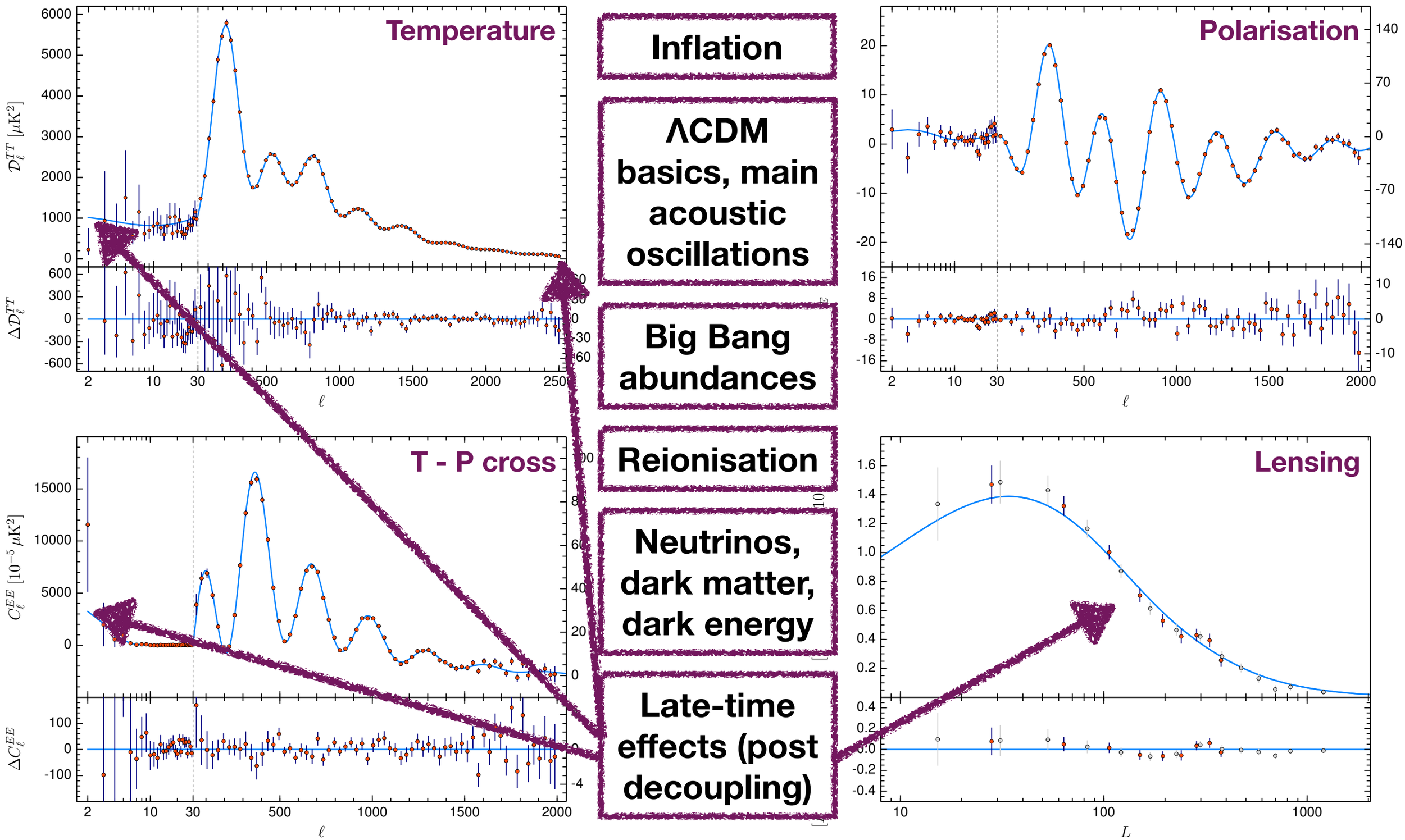

Temperature anisotropies

1. Peak scale: sound horizon ($\omega_{\rm b}$, $\omega_{\rm M}$) and angular diameter distance ($\Omega_\Lambda, \omega_{\rm M}$)
2. Odd/even peak amplitude ratio: gravity-pressure balance of photon-baryon fluid ($\omega_{\rm b}$)
3. Peak amplitude: expansion between radiation-matter equality and decoupling + EISW ($\omega_{\rm M}$)
4. Damping envelope: damping scale at decoupling ($\omega_{\rm M}$, $\omega_{\rm b}$) and angular diameter distance ($\Omega_\Lambda, \omega_{\rm M}$)
5. Global amplitude: amplitude of primordial power spectrum ($A_{\rm s}$)
6. Global tilt: tilt of primordial power spectrum ($n_{\rm s}$)
7. Additional plateau tilting: LISW (Ω_Λ)
8. Amplitude for $\ell \geq 40$: photon rescattering after reionisation ($\exp(-\tau_{\rm reio})$)

What the anisotropies tell us - ΛCDM

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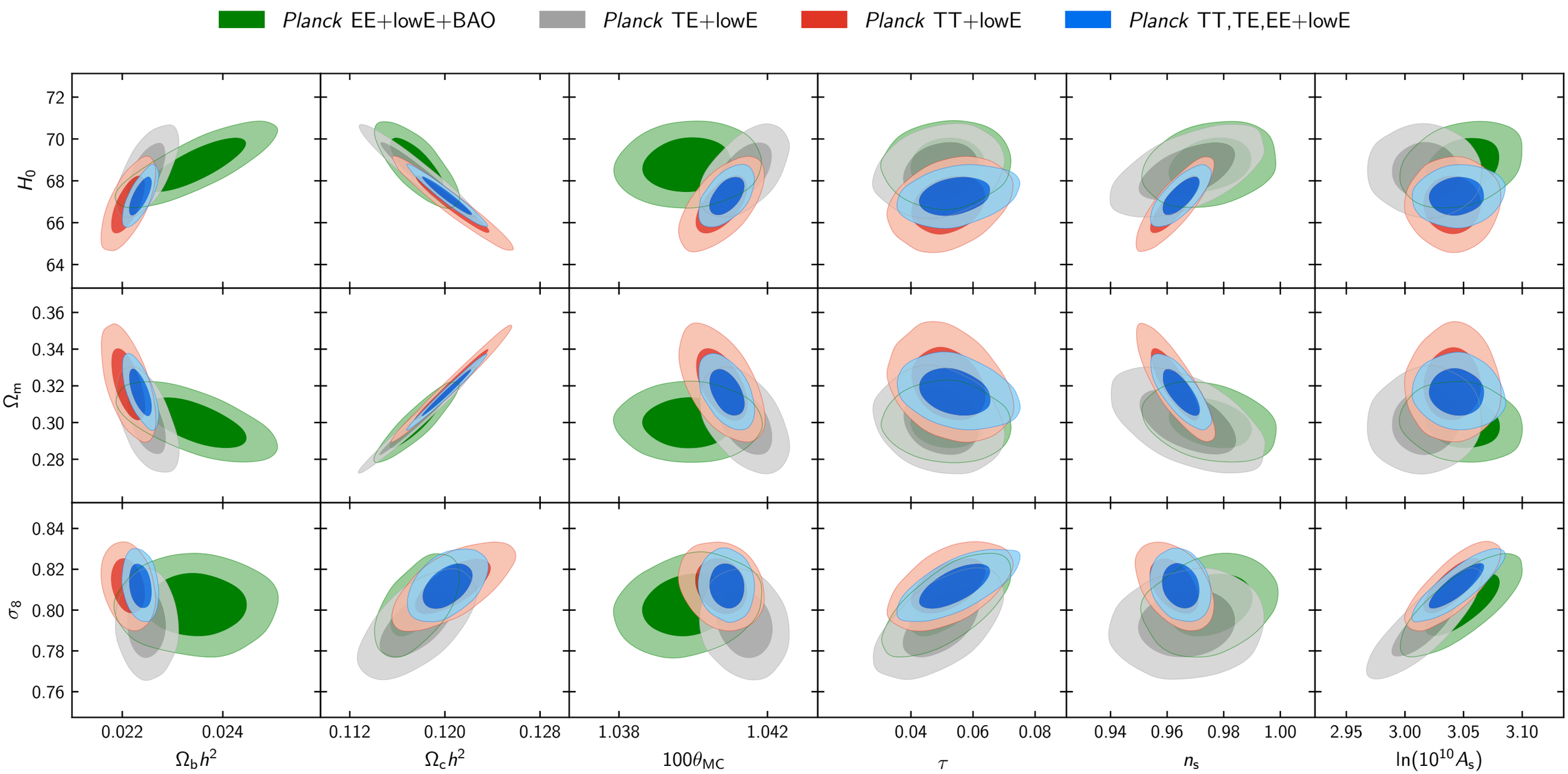
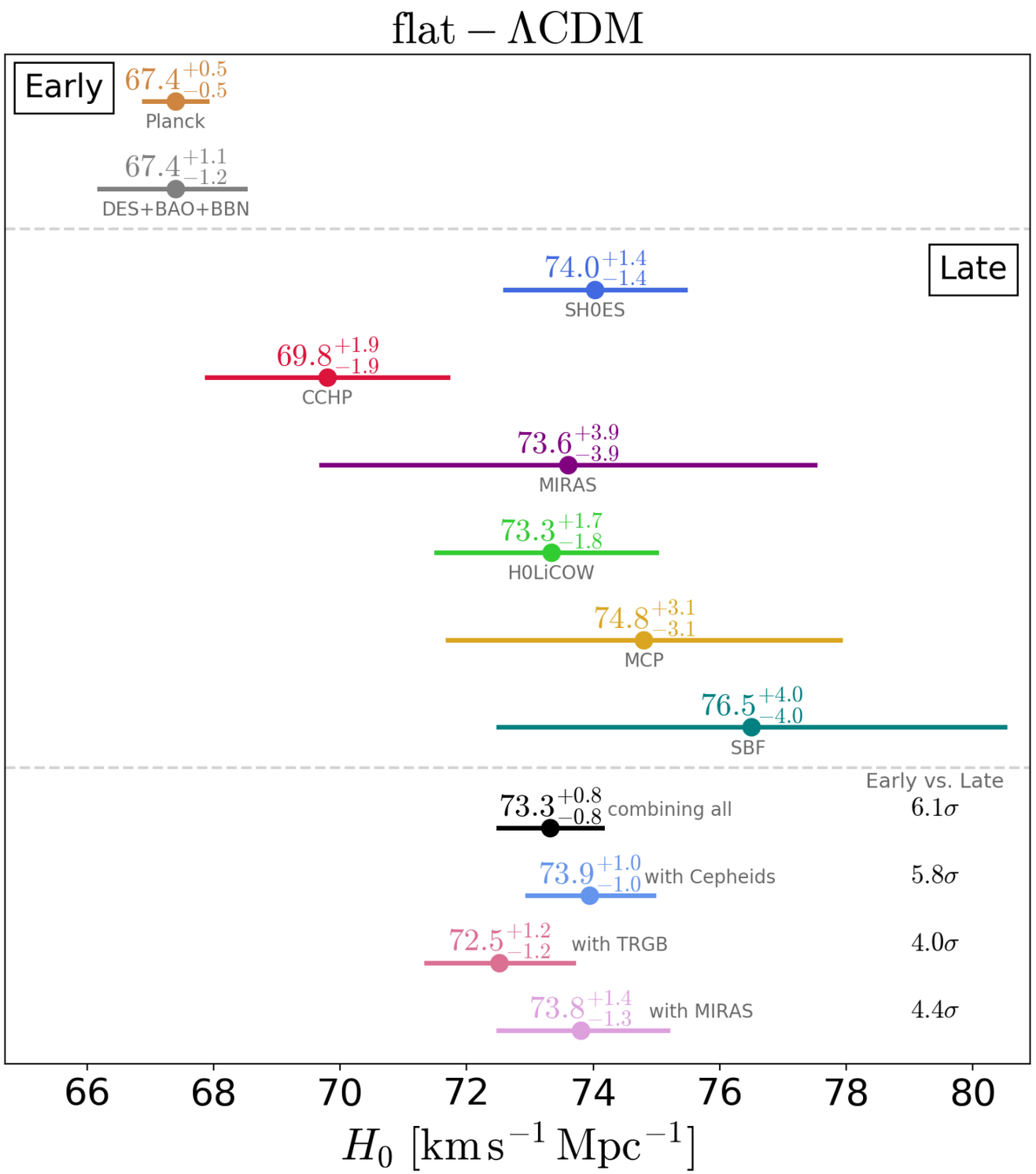


What the anisotropies tell us - ΛCDM

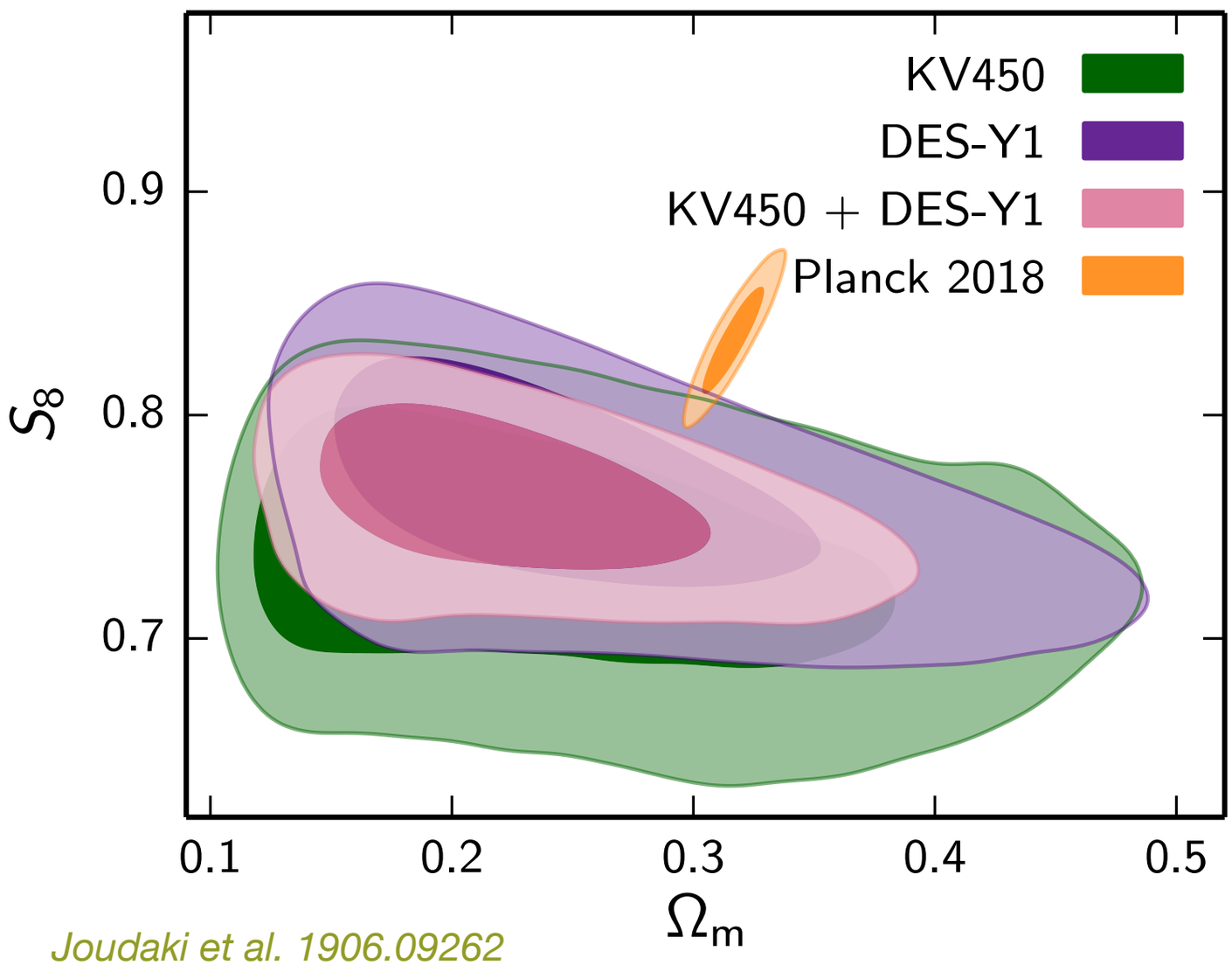


- H_0: expansion rate of the universe today
- Values measured by early-universe probes (CMB, BAO) differ from late-universe probes (supernovae, lensed quasars)
- Biggest hint of beyond-ΛCDM physics

Figure credit: V. Bonvin and A. Shahib, available at 1907.10625

What the anisotropies tell us - ΛCDM

- Clustering parameter S_8: measurement of the amplitude of the power spectrum on the scale of 8 Mpc/h, $S_8 \equiv \sigma_8\sqrt{\Omega_{\rm M}/0.3}$



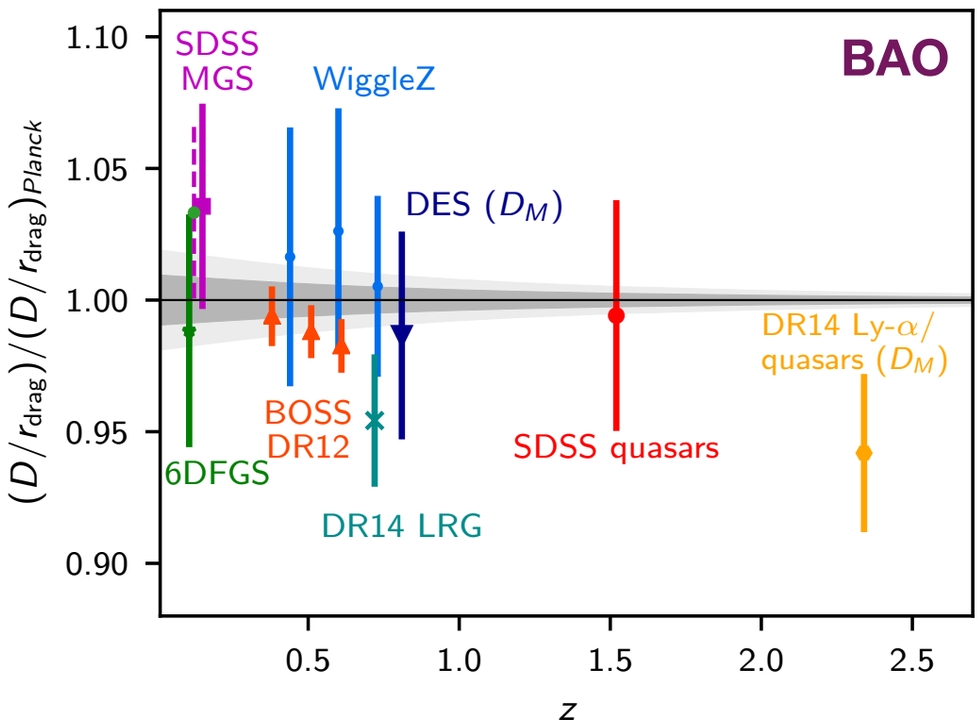
Joudaki et al. 1906.09262

- There is a $\sim 2.5\sigma$ tension between weak lensing and CMB measurements

- S_8 from Planck: $S_8 = 0.825 \pm 0.011$
  Planck Collaboration, 1807.06209

- S_8 from Kids + DES: $S_8 = 0.762 \pm 0.025$
  Joudaki et al. 1906.09262

What the anisotropies tell us - ΛCDM



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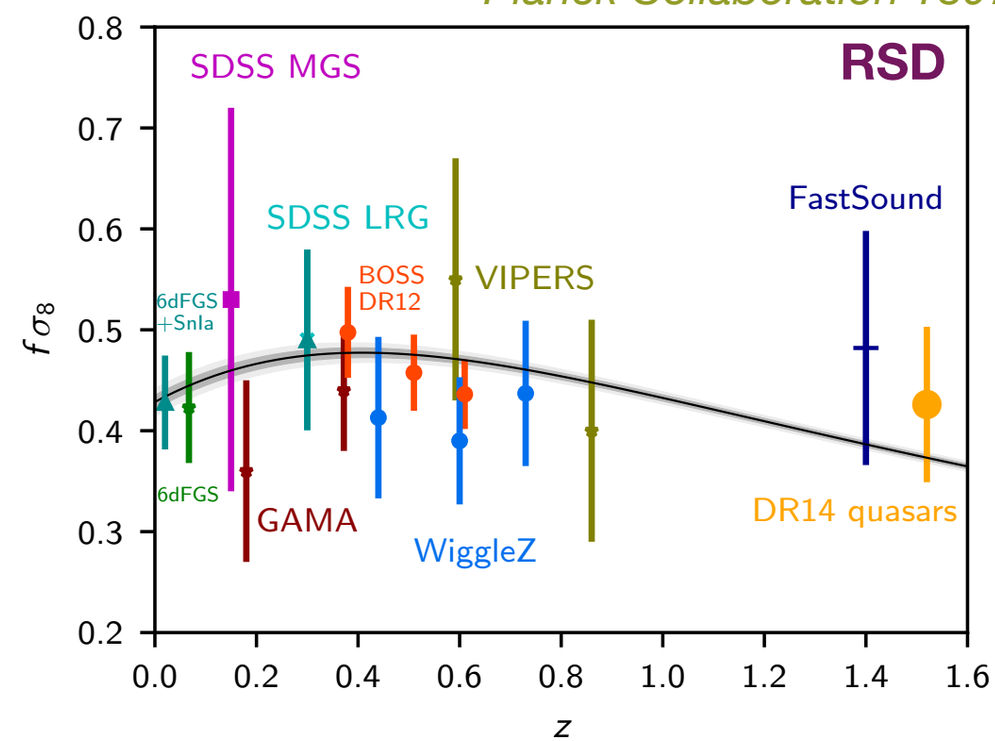
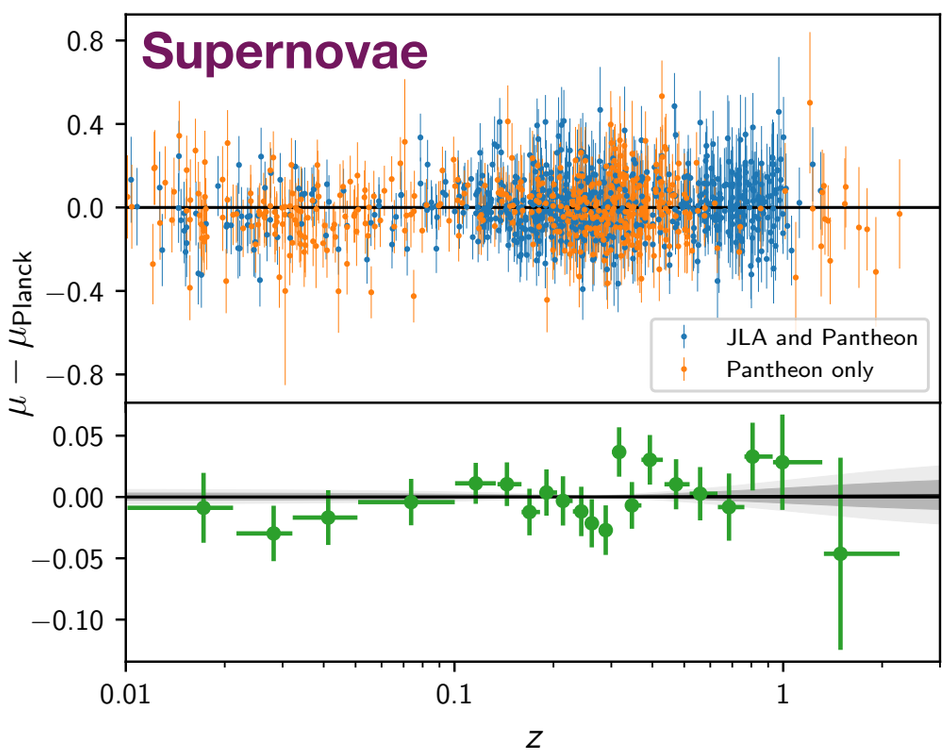
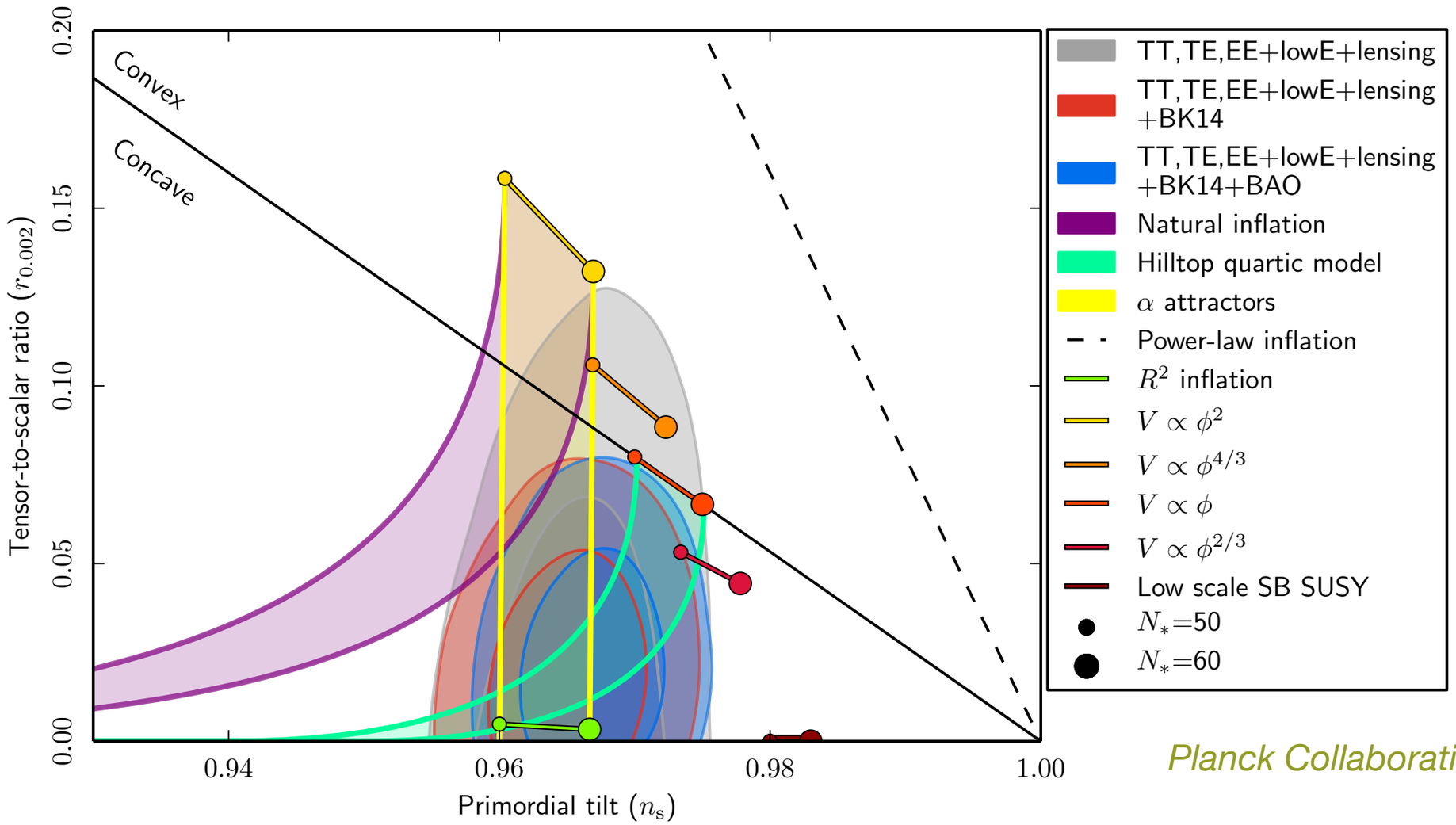




Planck data are remarkably consistent with many external datasets

What the anisotropies tell us - inflation



Planck Collaboration 1807.06211

- Planck found no clear evidence for deviations from standard single-field slow-roll inflation: no running, no features, no non-gaussianity or isocurvature modes
- Convex potentials such as $m^2\phi^2$ are not compatible with the latest data
- B-mode polarisation will push this further, but we have already come a long way

What the anisotropies tell us - inflation

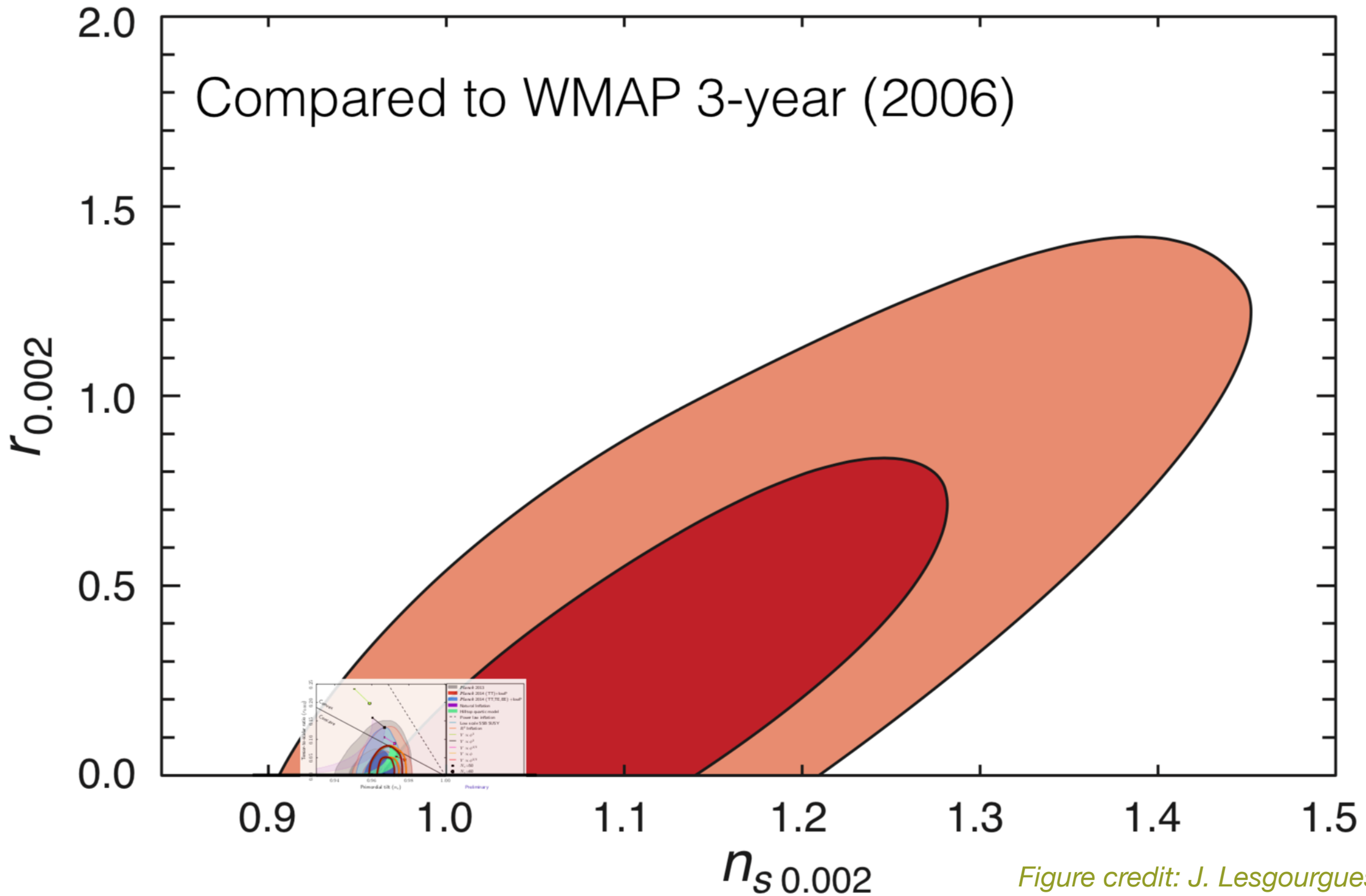


Figure credit: J. Lesgourgues

What the anisotropies tell us - relics

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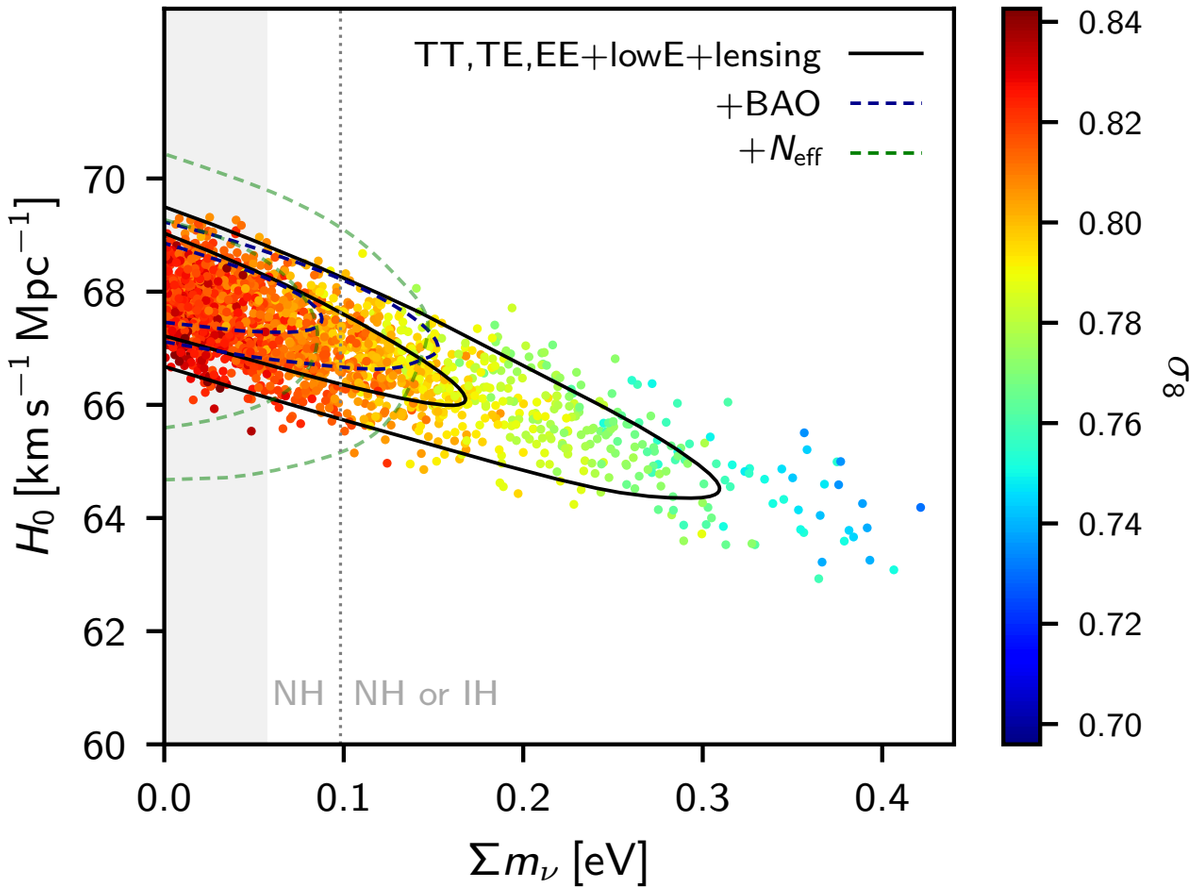

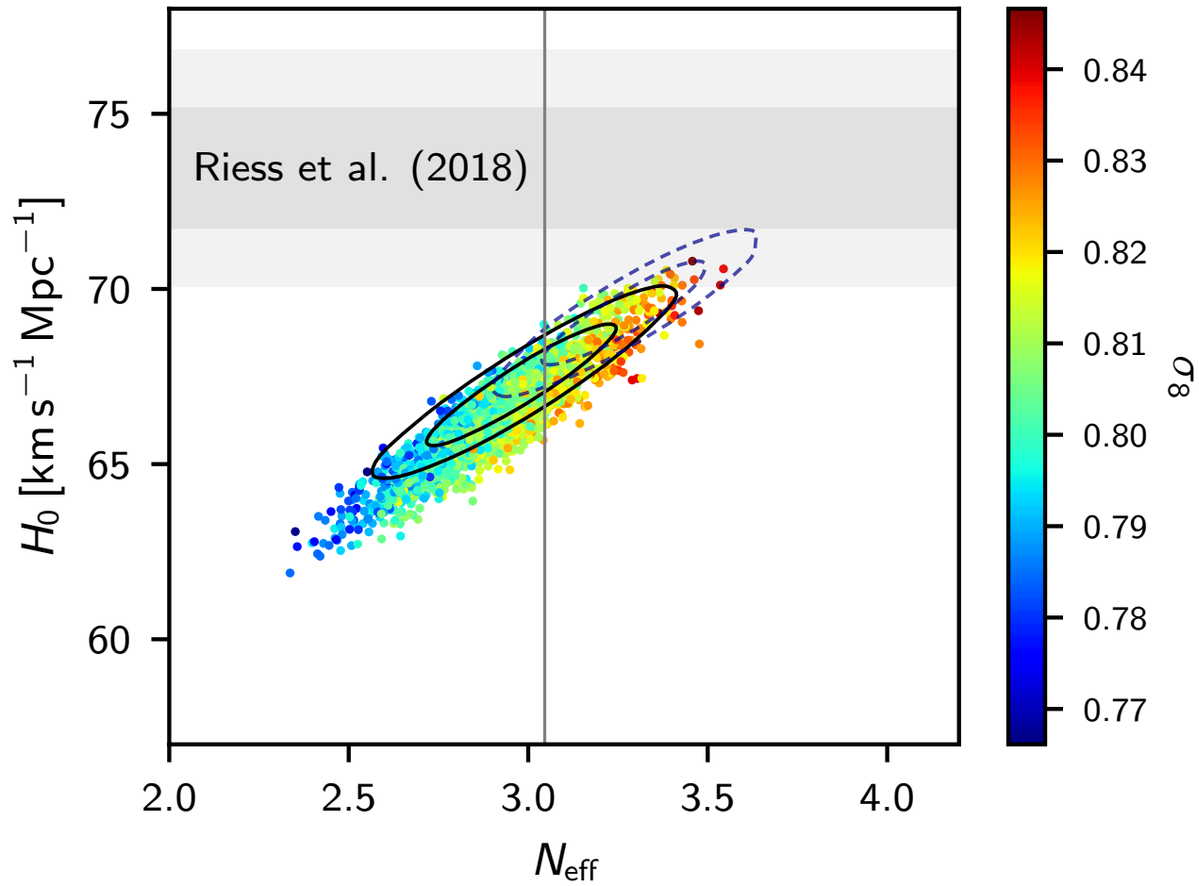

- Planck constrains $\Sigma m_\nu < 0.24\,\mathrm{eV}$
- With BAO $\Sigma m_\nu < 0.12\,\mathrm{eV}$
- Higher neutrino masses make H_0 tension worse

- Planck constrains $N_{\rm eff} = 2.89^{+0.36}_{-0.38}$
- Compatible with predicted value of $N_{\rm eff} = 3.044$
- More relativistic particles make S_8 tension worse

What the anisotropies tell us - DM

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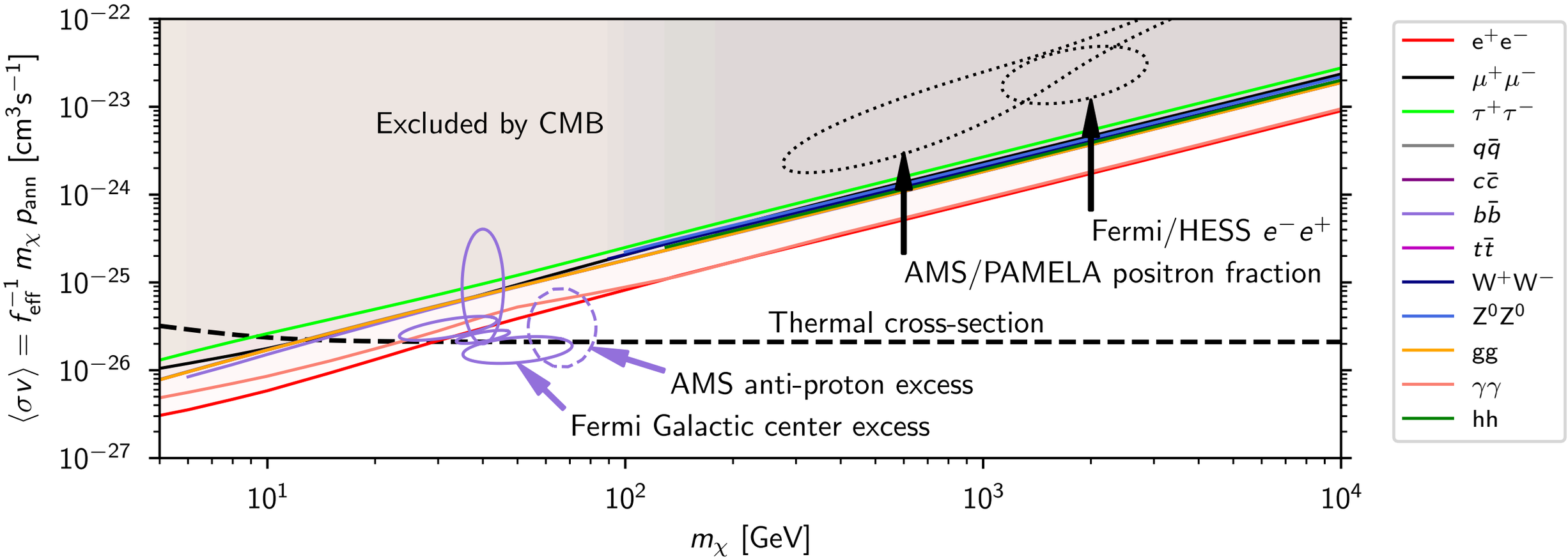
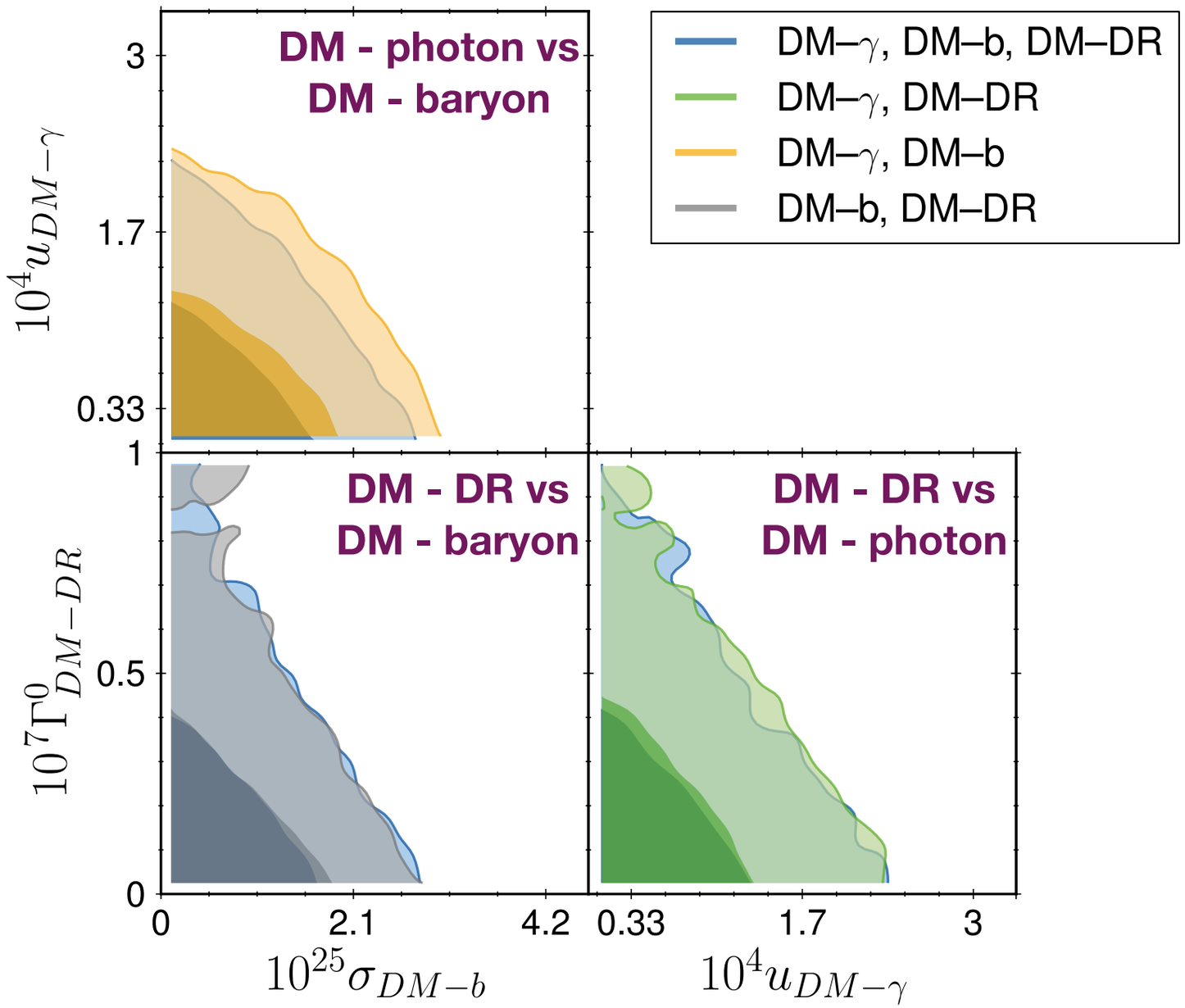


- Dark matter annihilations could affect the CMB via energy injections
- Assuming WIMPs, CMB bounds are competitive with and complementary to indirect DM searches
- Polarisation spectrum provides the most stringent CMB bounds

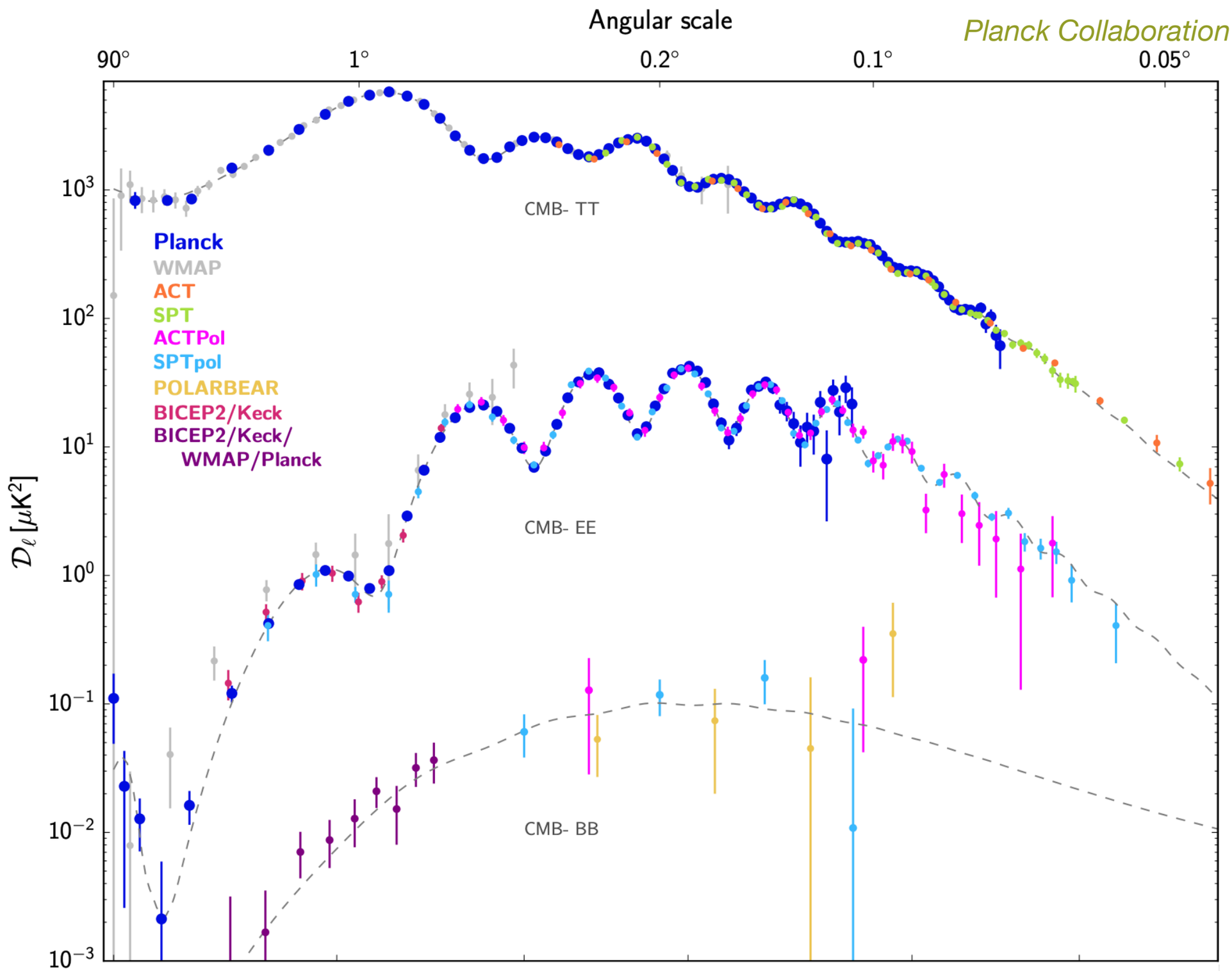
What the anisotropies tell us - DM

*Becker, **DCH**, et al. 2010.04074*

- Planck data find no evidence for interacting dark matter
- Single, double and triple interacting models with DR, photons, or baryons are tightly constrained
- Improved polarisation data is expected to constrain these models further



CMB measurements - the future



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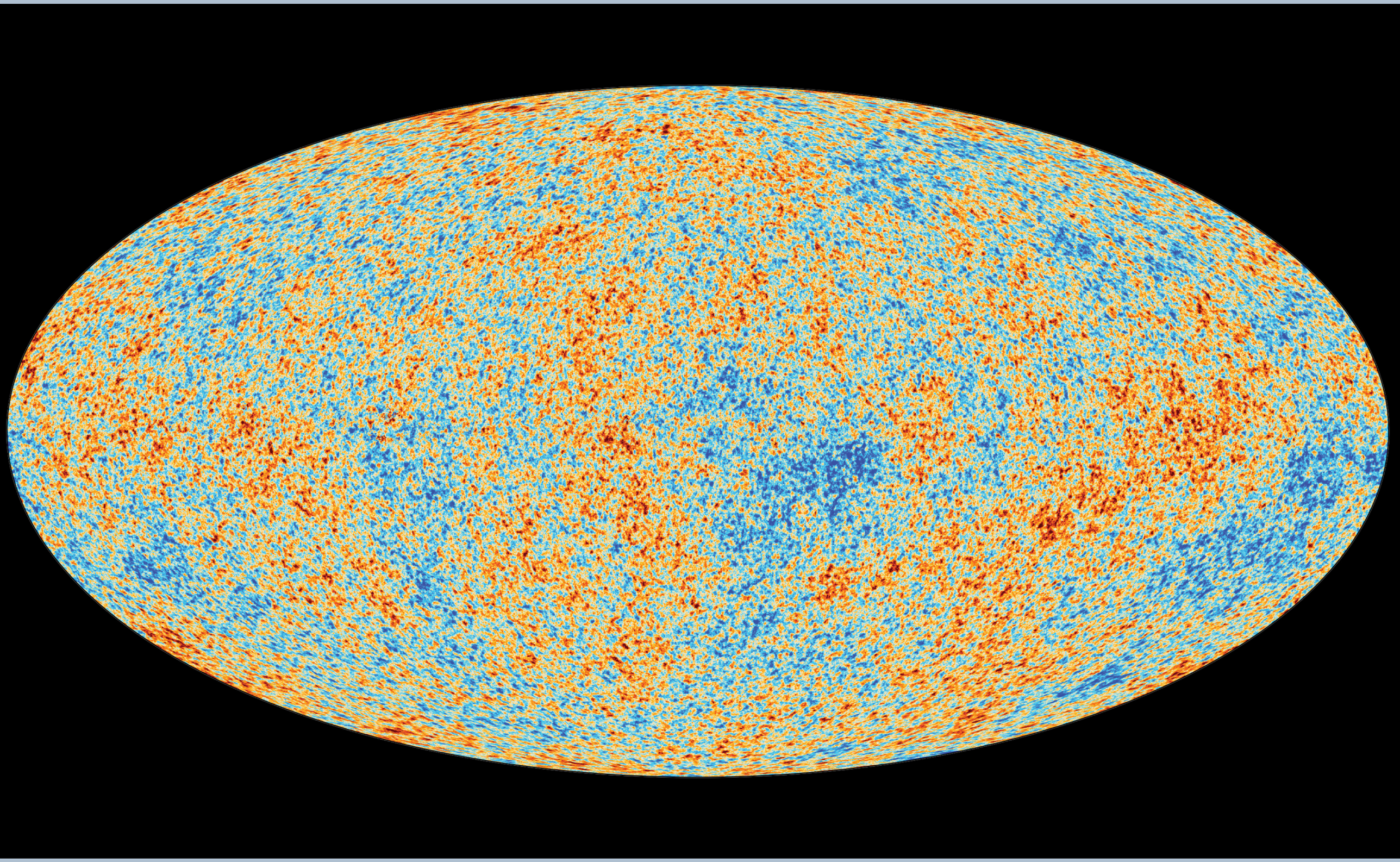
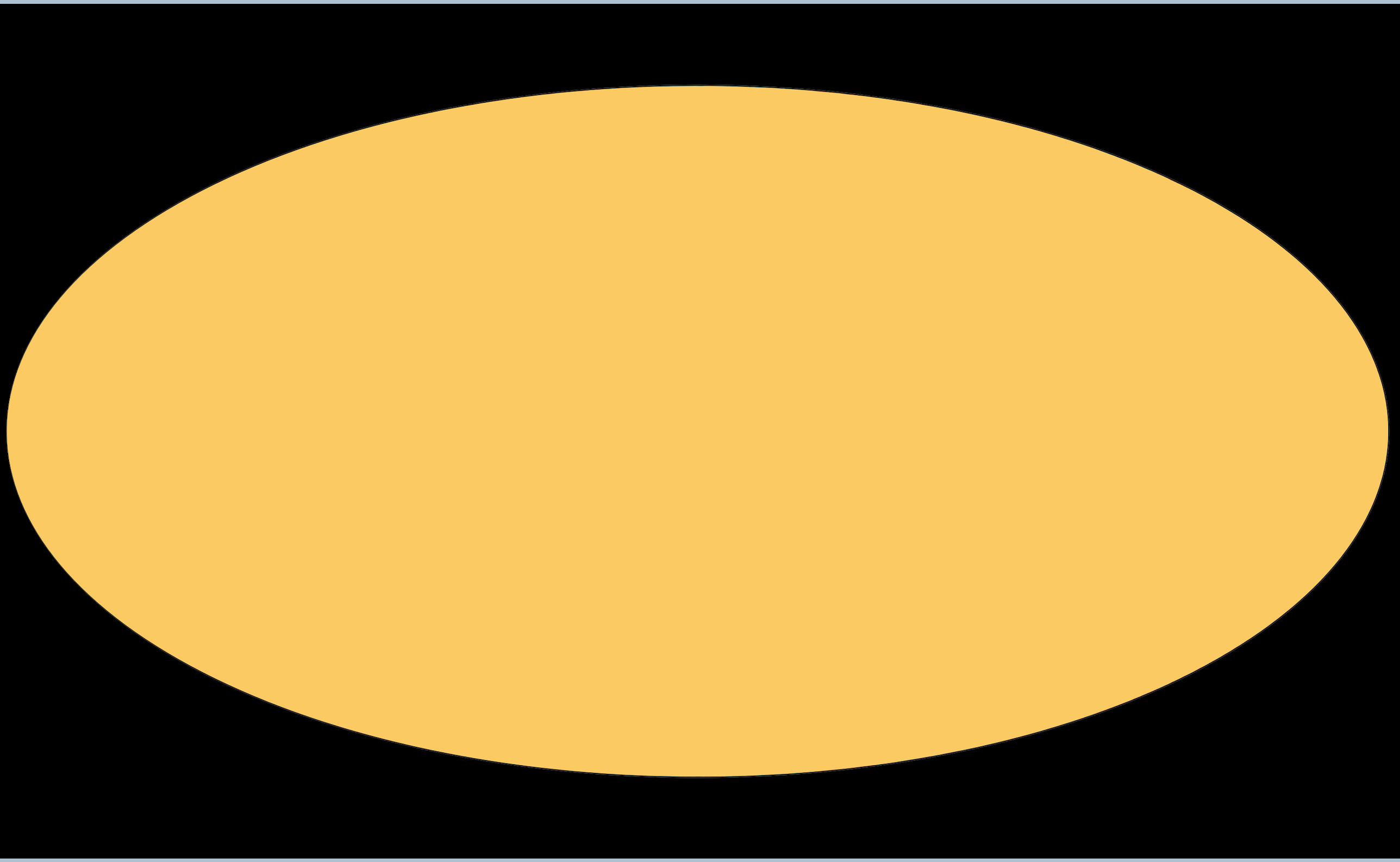
CMB Distortions

What are distortions



What are distortions



What are distortions

- The CMB is an *almost perfect* black body
- There are small distortions caused by the inefficiency of scattering and number-changing processes
- These spectral distortions are sensitive to energy injections
- As the primordial spectral distortion signal is frozen at decoupling, they provide a unique window into the early universe
- Distortions can present as a temperature shift, a Compton-like distortion (y), or a chemical potential distortion (μ)

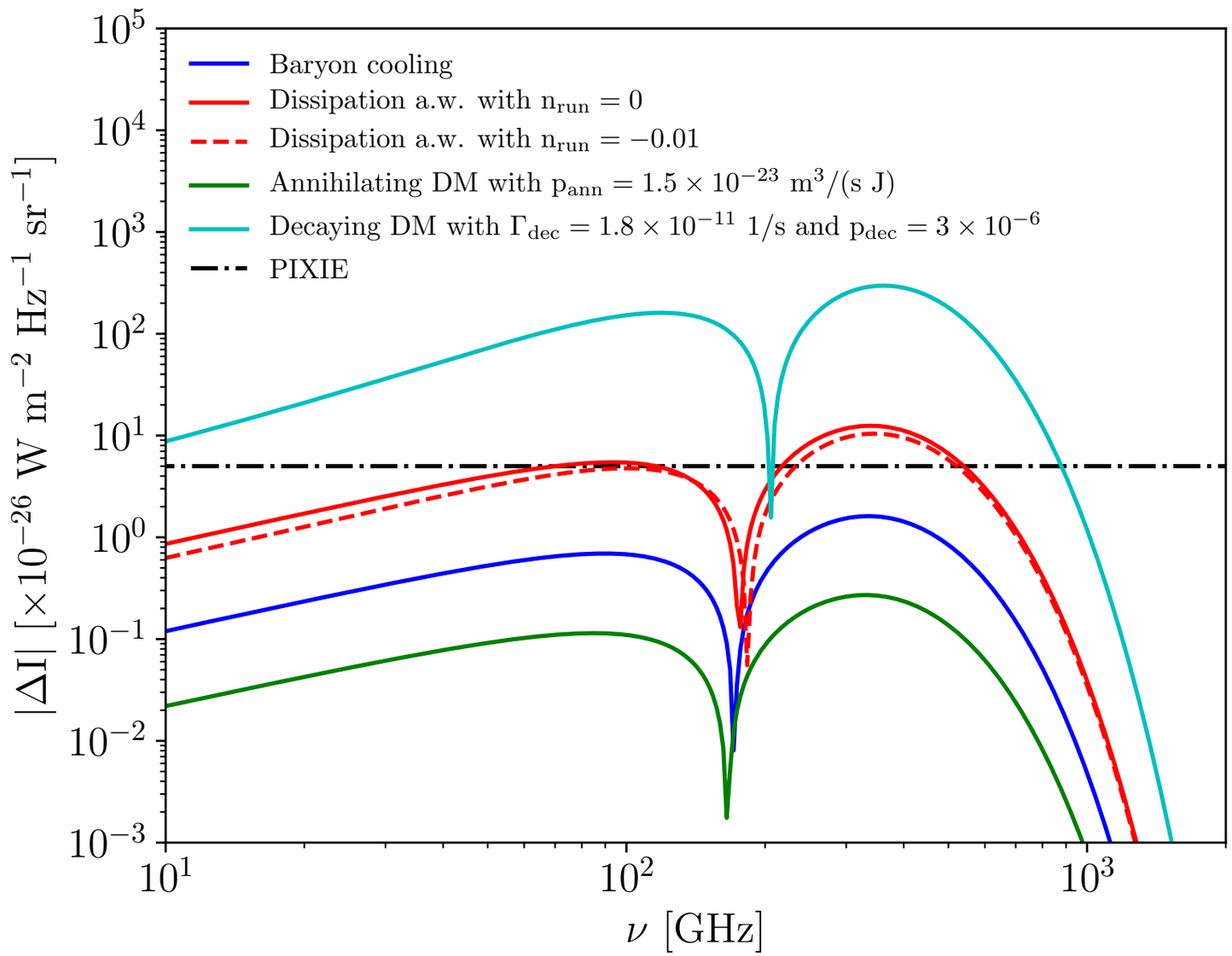
Sources of distortions

- Spectral distortions are caused by both standard (ΛCDM) and exotic processes: they are a unique test of our standard model
- Within ΛCDM (not exhaustive) $\mu\,, y \sim 10^{-8}$:
  - Adiabatic cooling of electrons and baryons
  - Dissipation of acoustic waves
  - Sunyaev-Zeldovich effect
- Exotic scenarios (not exhaustive) $\mu\,, y \sim 10^{-9}$:
  - Various inflationary models
  - Dark matter: annihilation, decay, interaction
  - PBH abundance and evaporation

Measuring the CMB distortions

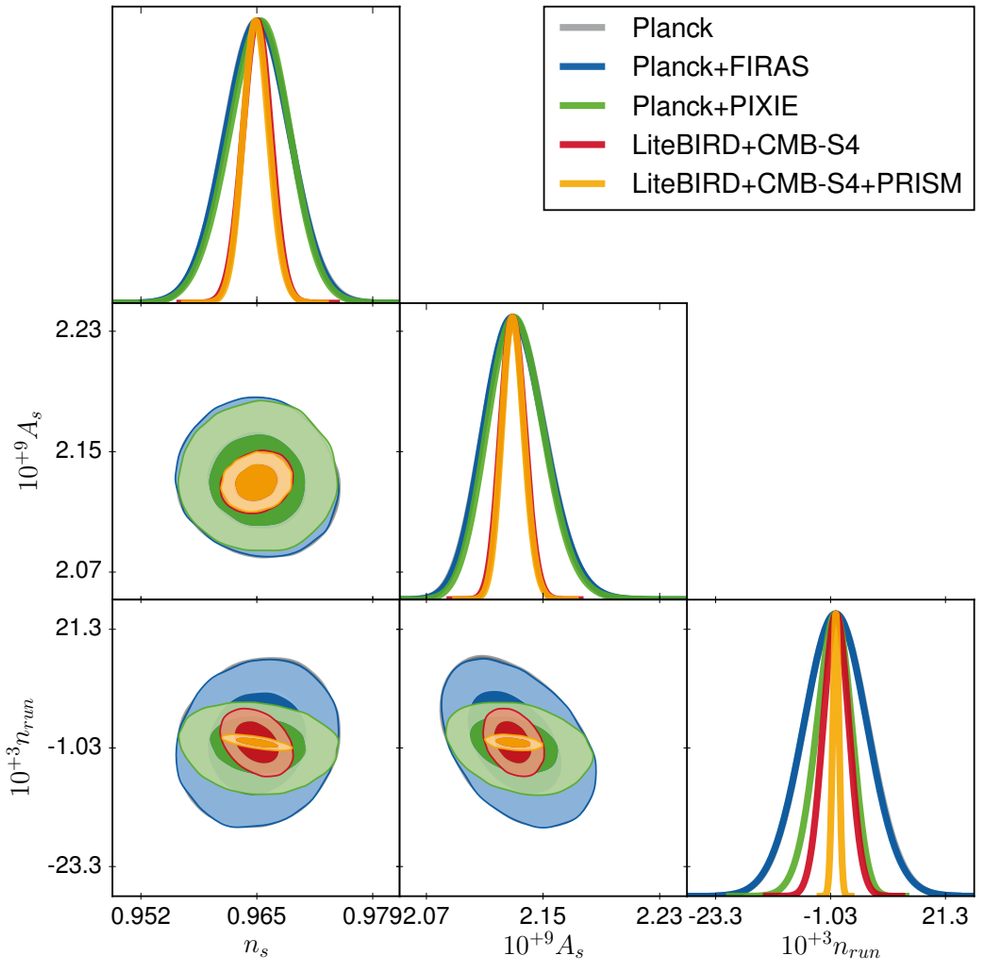
*Lucca, Schöneberg, **DCH**, et al. 1910.04619*

- Current bound is from COBE/FIRAS (1996): $\mu\,, y < 10^{-5}$
- Several proposed missions: PIXIE ($\delta\mu \sim 10^{-8}$), PRISM ($\delta\mu \sim 10^{-9}$), Voyage 2050 ($\delta\mu \sim 10^{-10}$)
- Foregrounds are a problem: low-frequency measurements from the ground are required

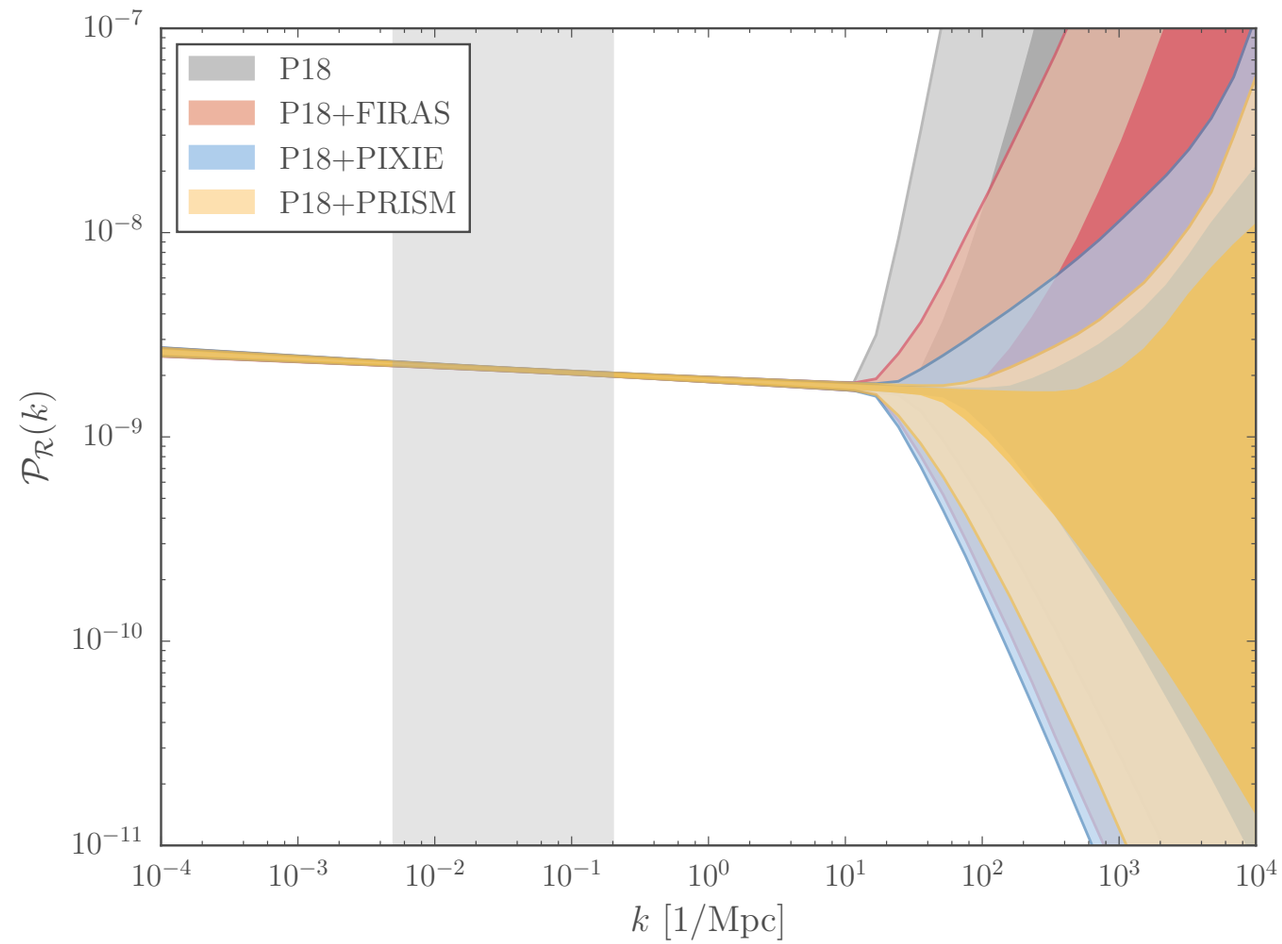


What the distortions tell us - inflation

*Lucca, Schöneberg, **DCH**, et al. 1910.04619*



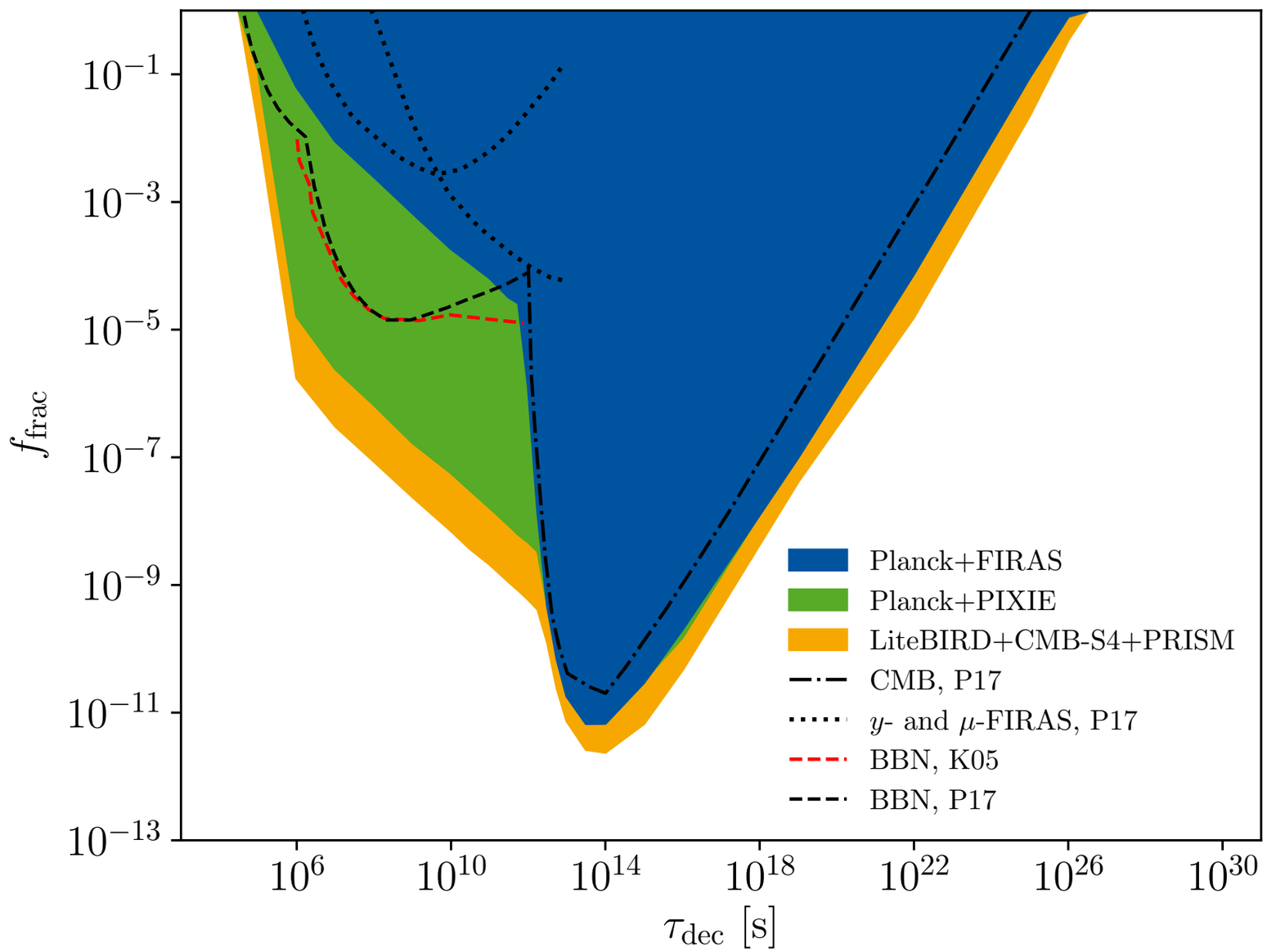
*Schöneberg, Lucca, **DCH** 2010.07814*



- Spectral distortions can constrain many inflationary models
- We can probe the shape of the primordial power spectrum, extending our lever arm to $k \sim 10^4\,\mathrm{Mpc}^{-1}$
- Can also probe some of the parameter space of PBH production

What the distortions tell us - DM

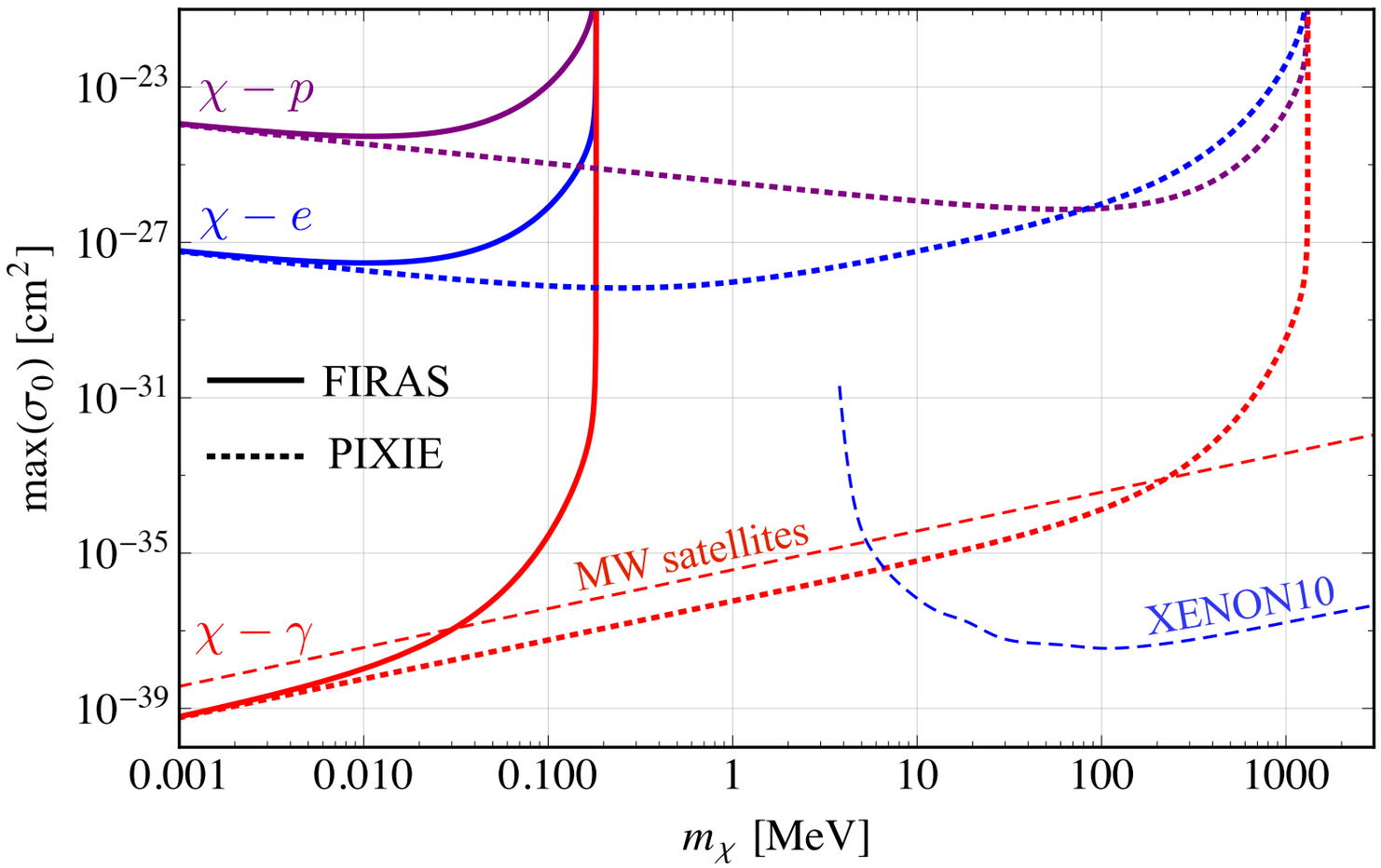
*Lucca, Schöneberg, **DCH**, et al. 1910.04619*



- Energy injection history depends on the lifetime of the decaying DM particle
- CMB anisotropy and distortion constraints are disentangled
- In some regions spectral distortions can improve bounds by 3-4 orders of magnitude wrt other probes

What the distortions tell us - DM

Ali-Haïmoud, et al. 1506.04745



- Dark matter interactions can be probed through adiabatic cooling effect
- Competitive bounds on interactions with photons, electrons, or protons
- Allows to probe lower-mass regions than anisotropies

Summary

- The CMB contains a treasure-trove of information for the early universe
- Different CMB spectra are in remarkable agreement, but some tensions with other datasets remain
- Latest Planck data find no evidence for extensions to ΛCDM
- Spectral distortions provide an excellent test of ΛCDM and could constrain many extended models
- The CMB still has a lot more to tell us: better E-mode polarisation, B-mode polarisation, spectral distortions

Thank you for your attention

I am happy to answer questions on slack and in the discussion session!