Imperial College London

Planck Probes the Standard Model(s)

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New Directions in Theoretical Physics

Edinburgh

January 2014

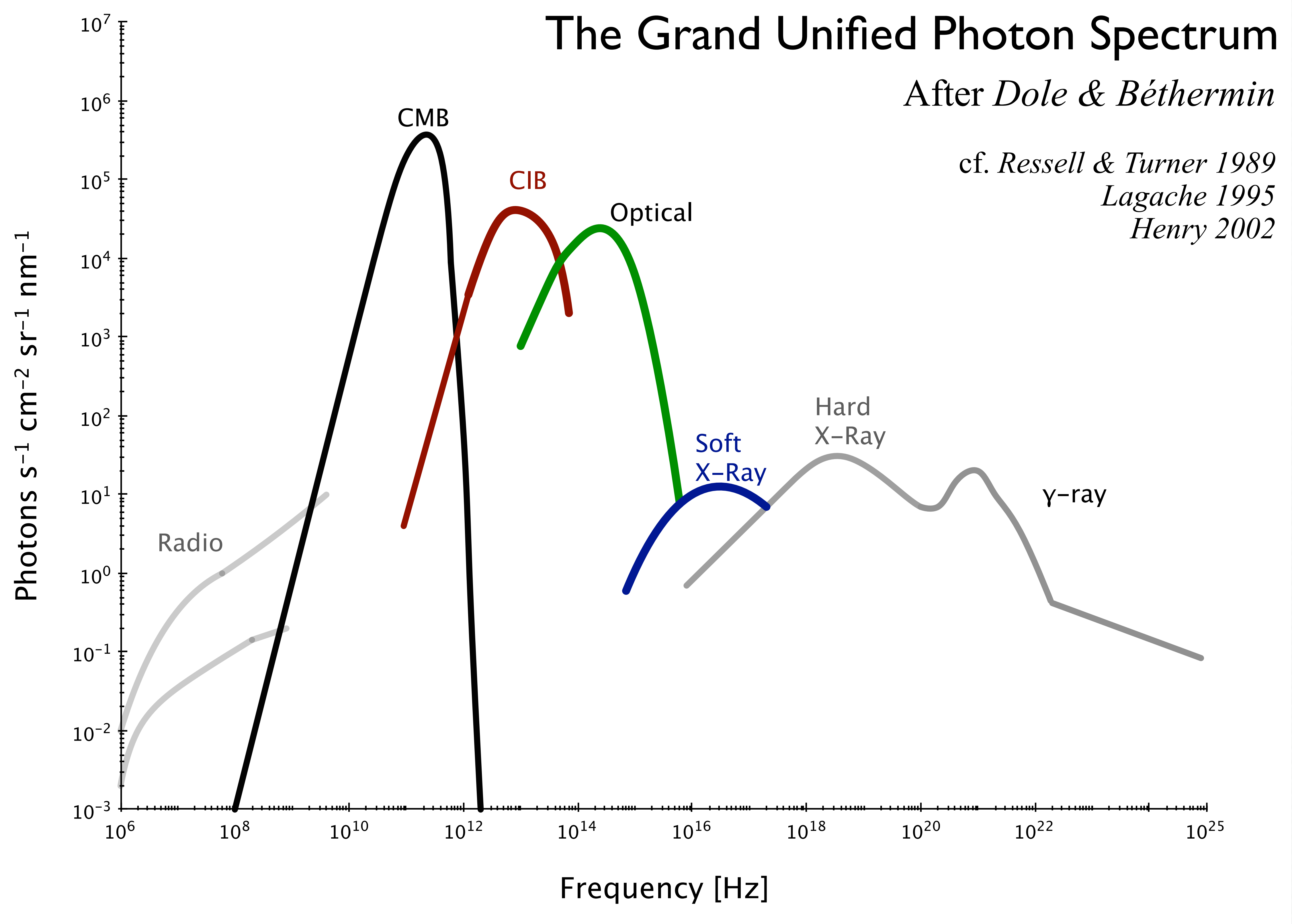
This talk based on data and ~30 papers released March 2013 by the 400-person Planck Collaboration

The Planck Mission

- Why the CMB?
- Why *Planck*?
- The *Planck* Mission:
  - Hardware & Analysis
- Highlights from *Planck*:
  - ~30 papers and many GB of data released March 2013
  - Cosmology, astrophysics, the structure of space & time
  - A simple, standard model? Or anomalies and inconsistencies?
  - data and papers available at ESA's *Planck* Legacy Archive Archive (and NASA's LAMBDA)

Planck launch, 14 May 2009, ESA Spaceport, French Guyana

Light from the Universe



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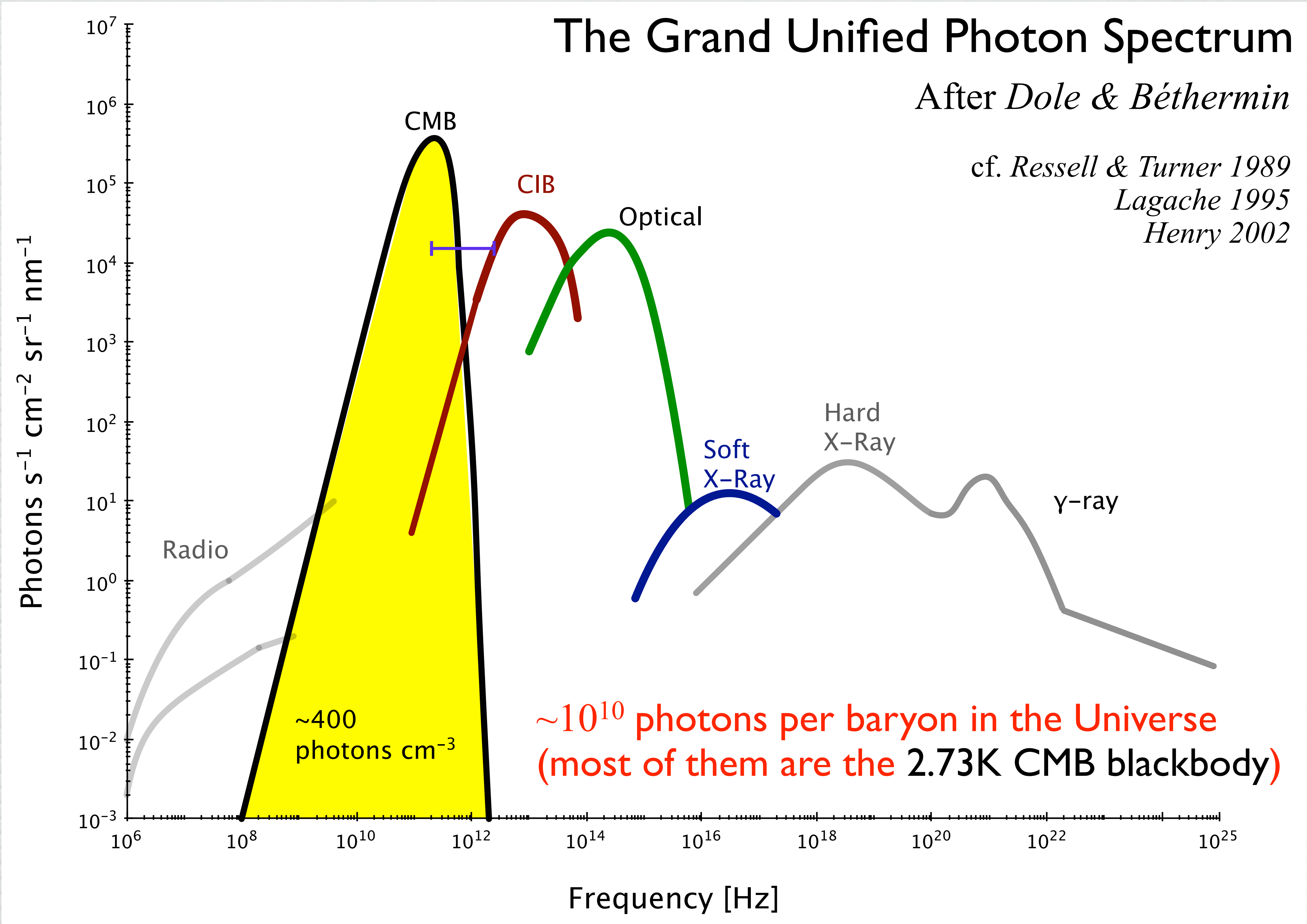
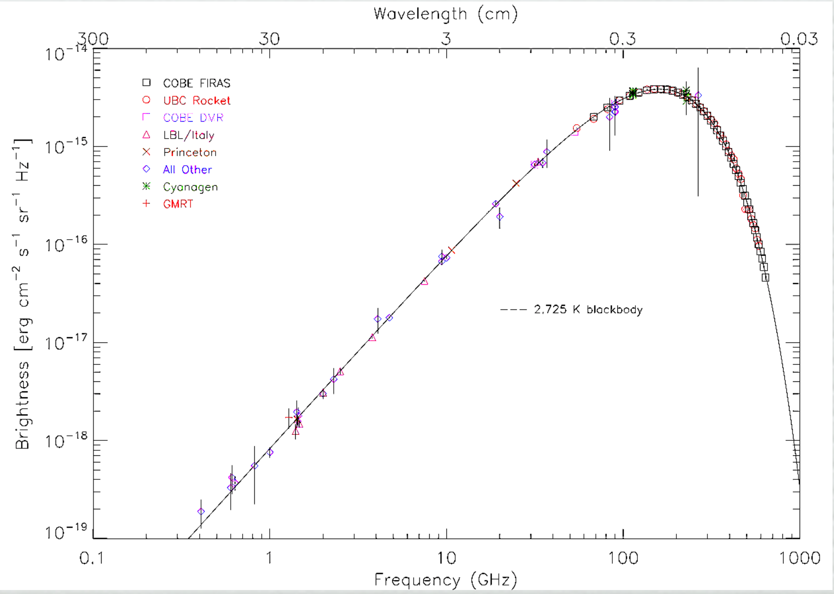


A standard cosmological model?

$$ds^2 = c^2dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2d\theta^2 + r^2\sin^2\theta\, d\phi^2\right]$$

Relativity

- *Predictions*:
  ("pillars of the Big Bang")
  - Expansion (Hubble)
- Hot big bang
  - Light element abundances (BBN)
  - Recombination (CMB)

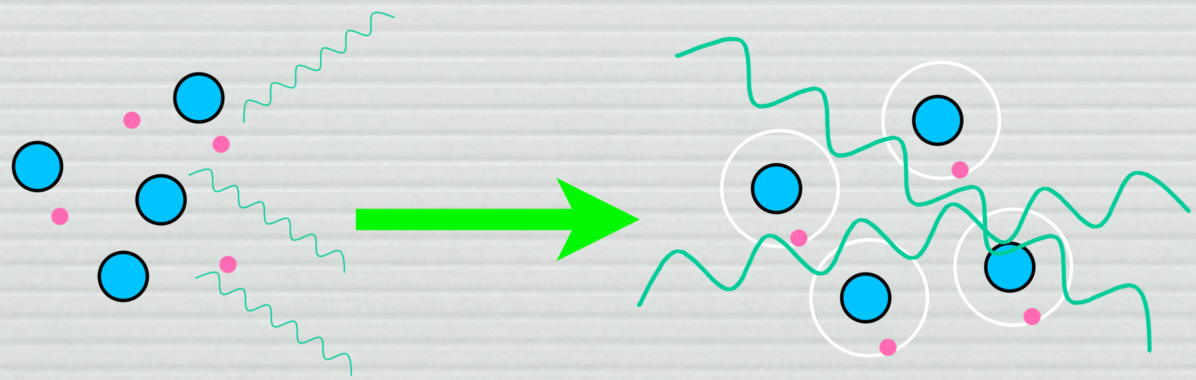


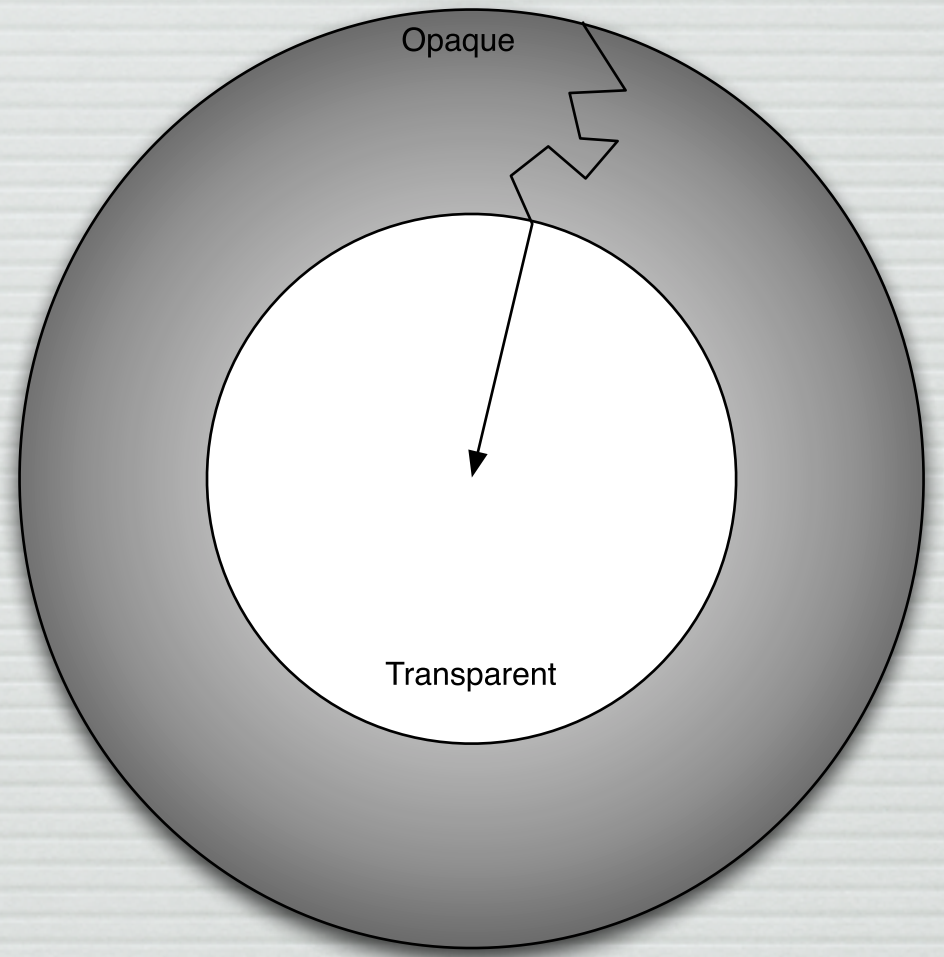
- The Hot Big Bang:
  - Expansion, cooling from a hot, dense early state
  - radiation $\Rightarrow$ matter (*baryogenesis*)
  - quarks $\Rightarrow$ protons & neutrons
  - protons & neutrons $\Rightarrow$ nuclei
    (*Big Bang Nucleosynthesis — BBN*)
  - nuclei & electrons $\Rightarrow$ atoms (*Cosmic Microwave Background — CMB*)
- Parameters:
  - density of radiation Ω_r, baryons Ω_b, dark matter Ω_c, dark energy Ω_Λ
  - Age t_0, expansion rate H_0
  - Curvature: Ω_k (=0?)

Also fluctuations—departures from uniformity—needed to form structure

Evidence & Observations: Cosmic Microwave Background

- 400,000 years after the Big Bang, the temperature of the Universe was $T \sim 3{,}000$ K
- Hot enough to keep hydrogen atoms *ionized* until this time
  - ***proton + electron → Hydrogen +*** *photon* [$p^+ + e^- \rightarrow H + \gamma$]
  - ***charged plasma → neutral gas***
    - depends on *entropy* of the Universe
- Photons (light) can't travel far in the presence of charged particles
  - ***Opaque → transparent***



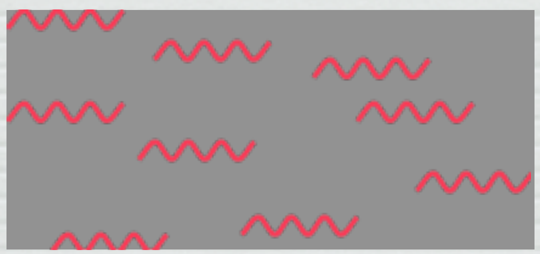


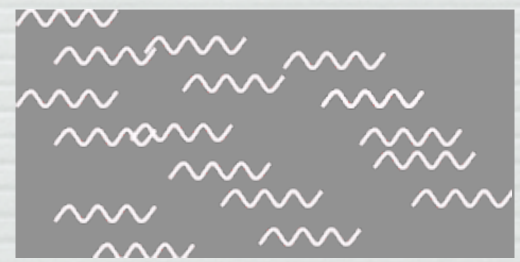
What affects the CMB temperature?

$$\frac{\Delta T}{T}(\hat{\boldsymbol{x}}) \simeq \frac{1}{4}\frac{\delta\rho_\gamma}{\rho_\gamma} + \boldsymbol{v}\cdot\hat{\boldsymbol{x}} + \int_{\eta_{rec}}^{\eta_0} d\eta\, \dot{h}_{ij}\hat{x}_i\hat{x}_j$$

- Initial temperature (density) of the photons

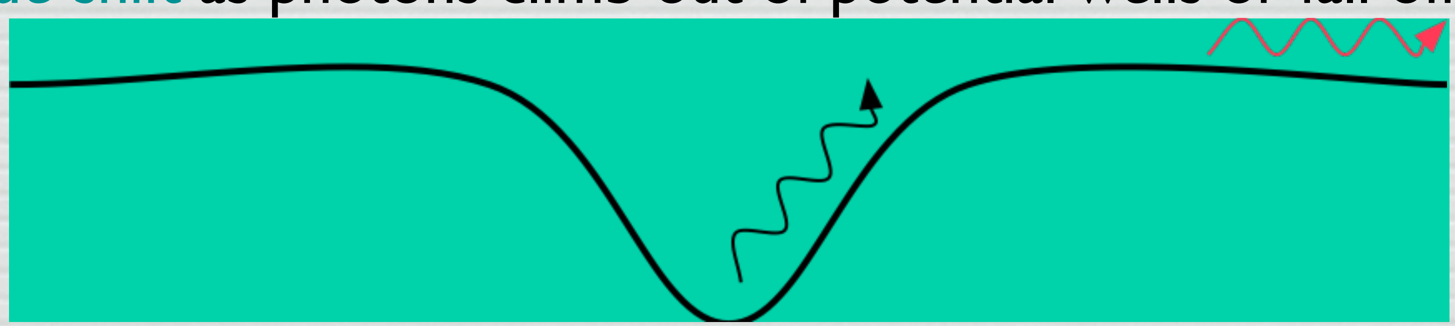
Cooler





Hotter

- Doppler shift due to movement of baryon-photon plasma
- Gravitational red/blue-shift as photons climb out of potential wells or fall off of underdensities



- Photon path from LSS to today
- All linked by initial conditions $\Rightarrow 10^{-5}$ fluctuations

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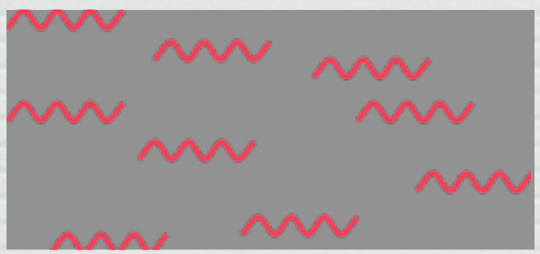

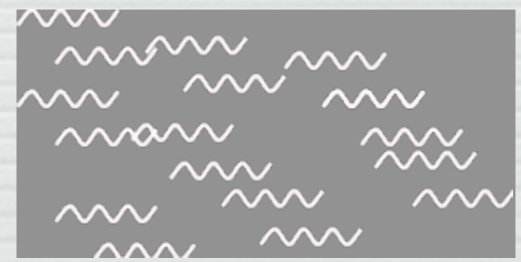

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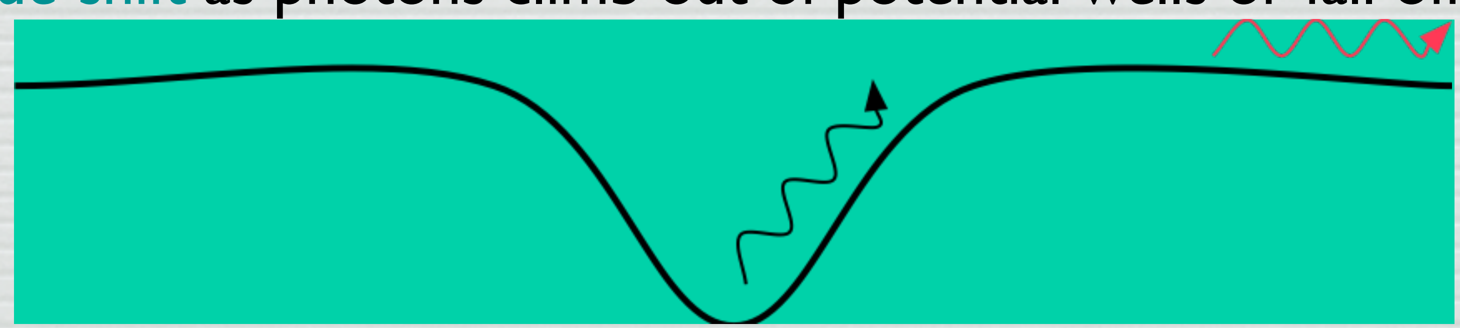

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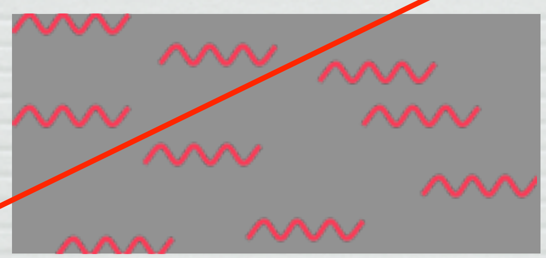

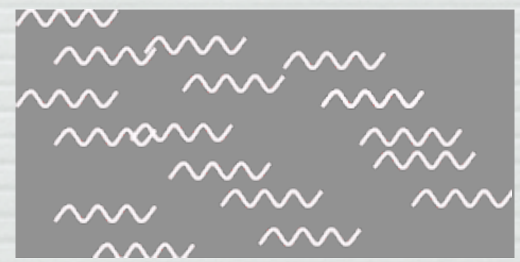

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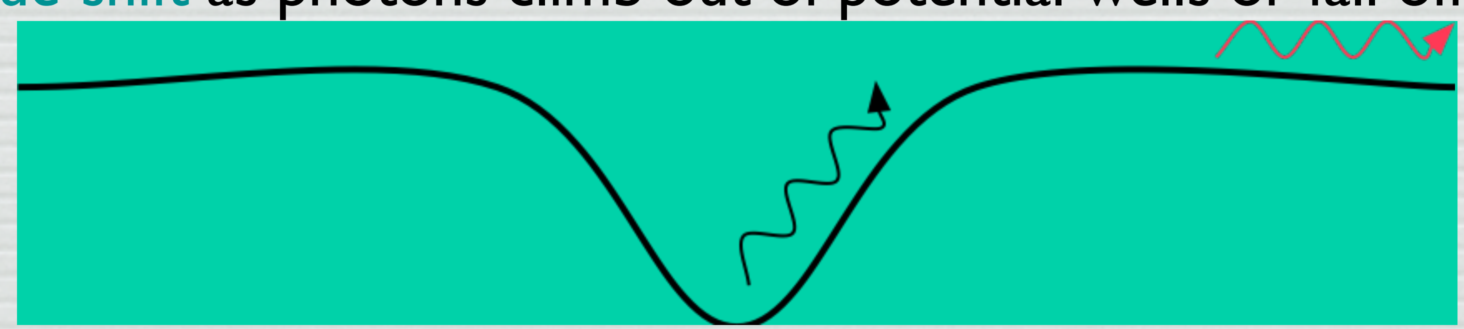

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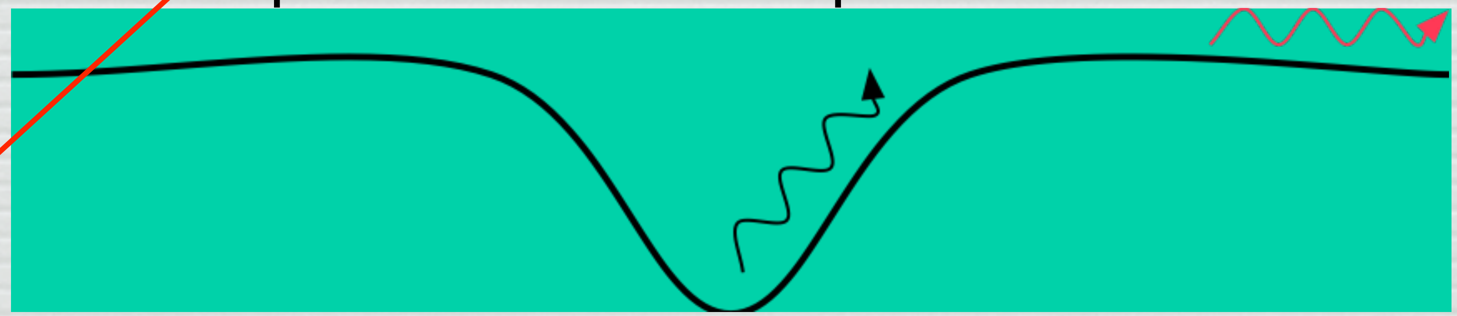

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CMB Statistics

z~1300: p+e→H & Universe becomes transparent.

$$\frac{T(\hat{x}) - \bar{T}}{\bar{T}} \equiv \frac{\Delta T}{T}(\hat{x}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{x})$$

i.e., Fourier Transform, but on a sphere

Determined by **temperature**, **velocity** and **metric** on the last scattering surface.

Power Spectrum:

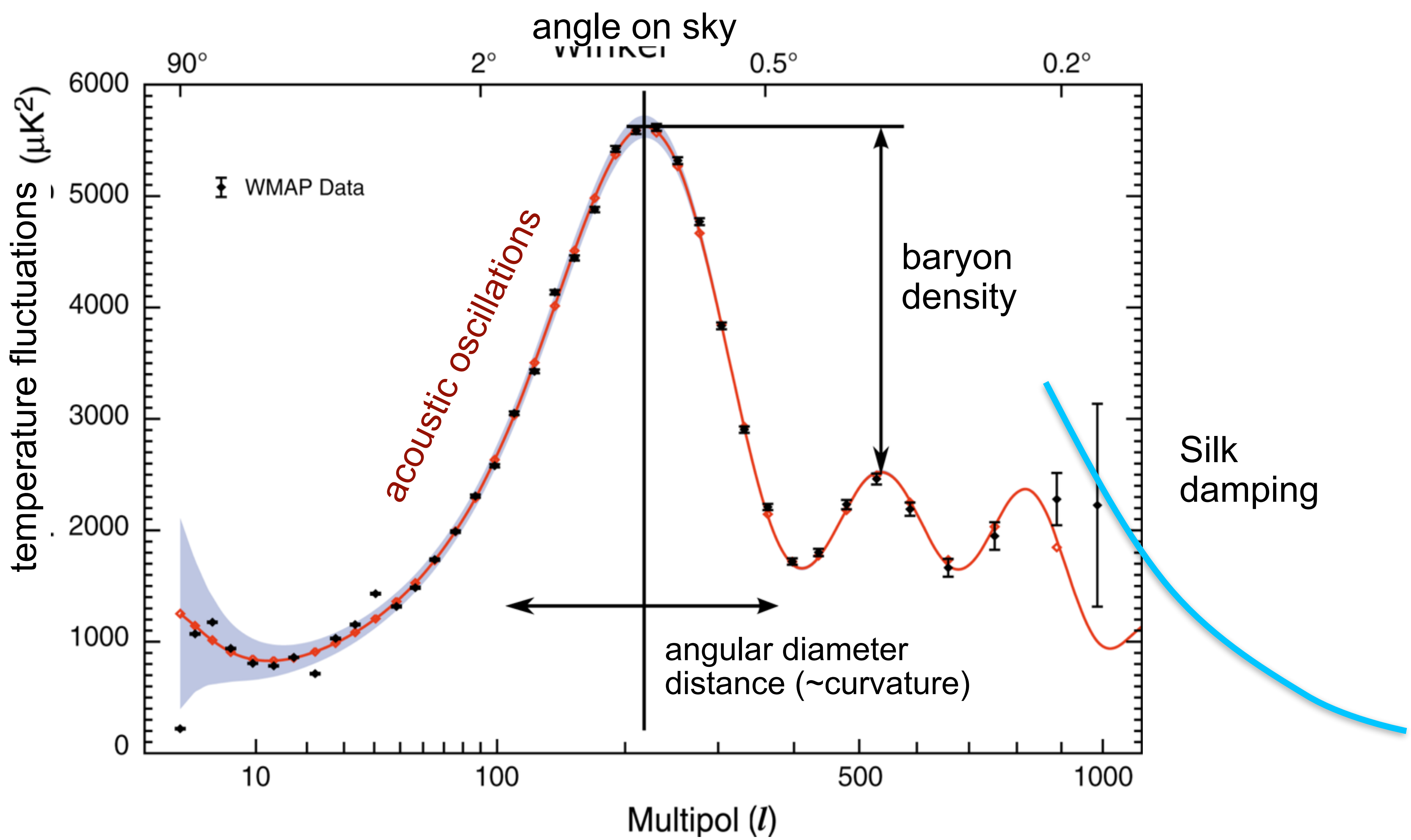
$$\langle a^*_{\ell m} a_{\ell' m'} \rangle = \delta_{\ell\ell'} \delta_{mm'}\, C_\ell$$

Multipole ℓ ~ angular scale $180°/\ell$

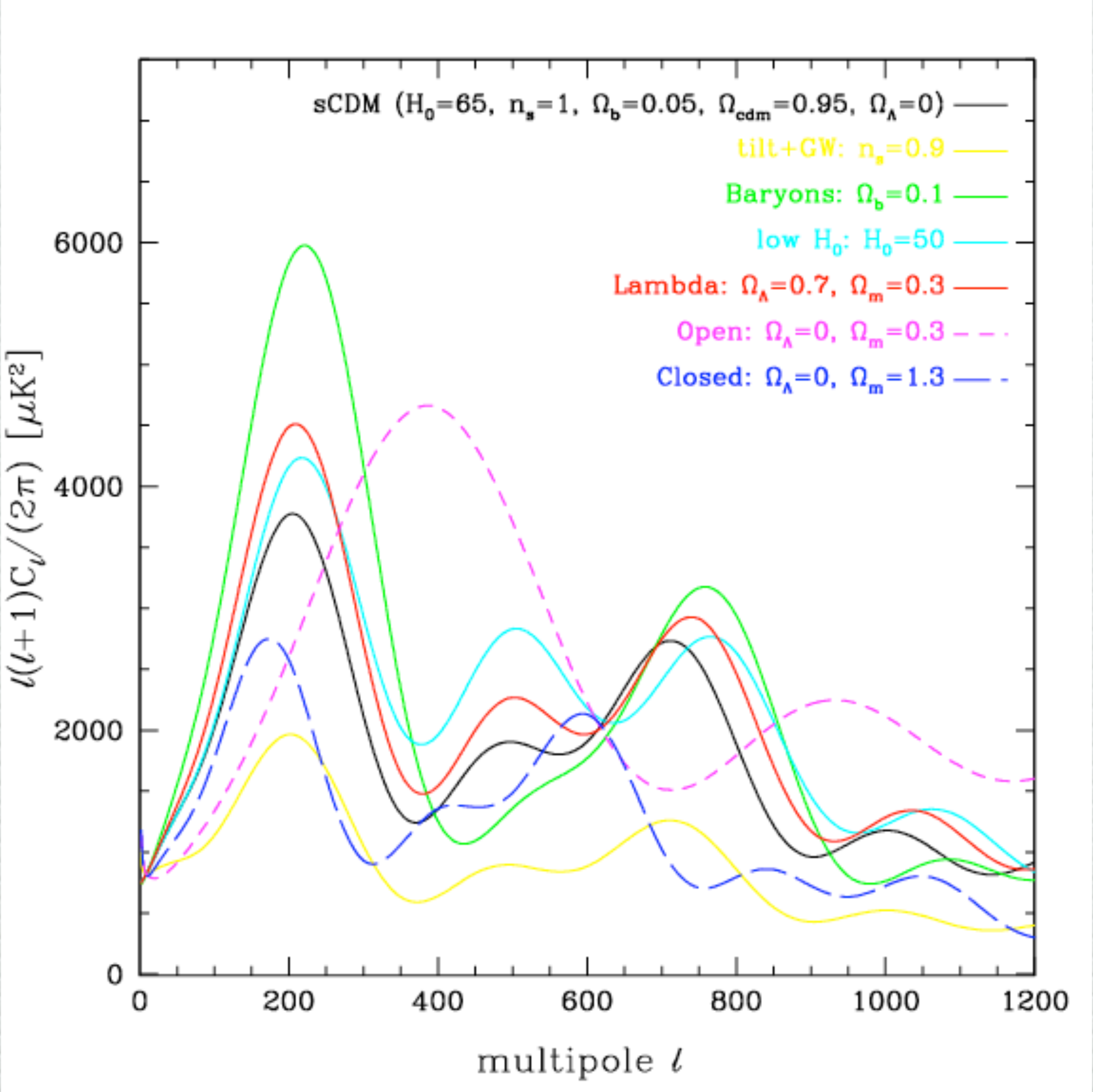
For a **Gaussian** theory, C_ℓ completely determines the statistics of the temperature.

Physics of the CMB power spectrum

Gravity + plasma physics modulates initial spectrum of fluctuations (from, e.g., inflation)



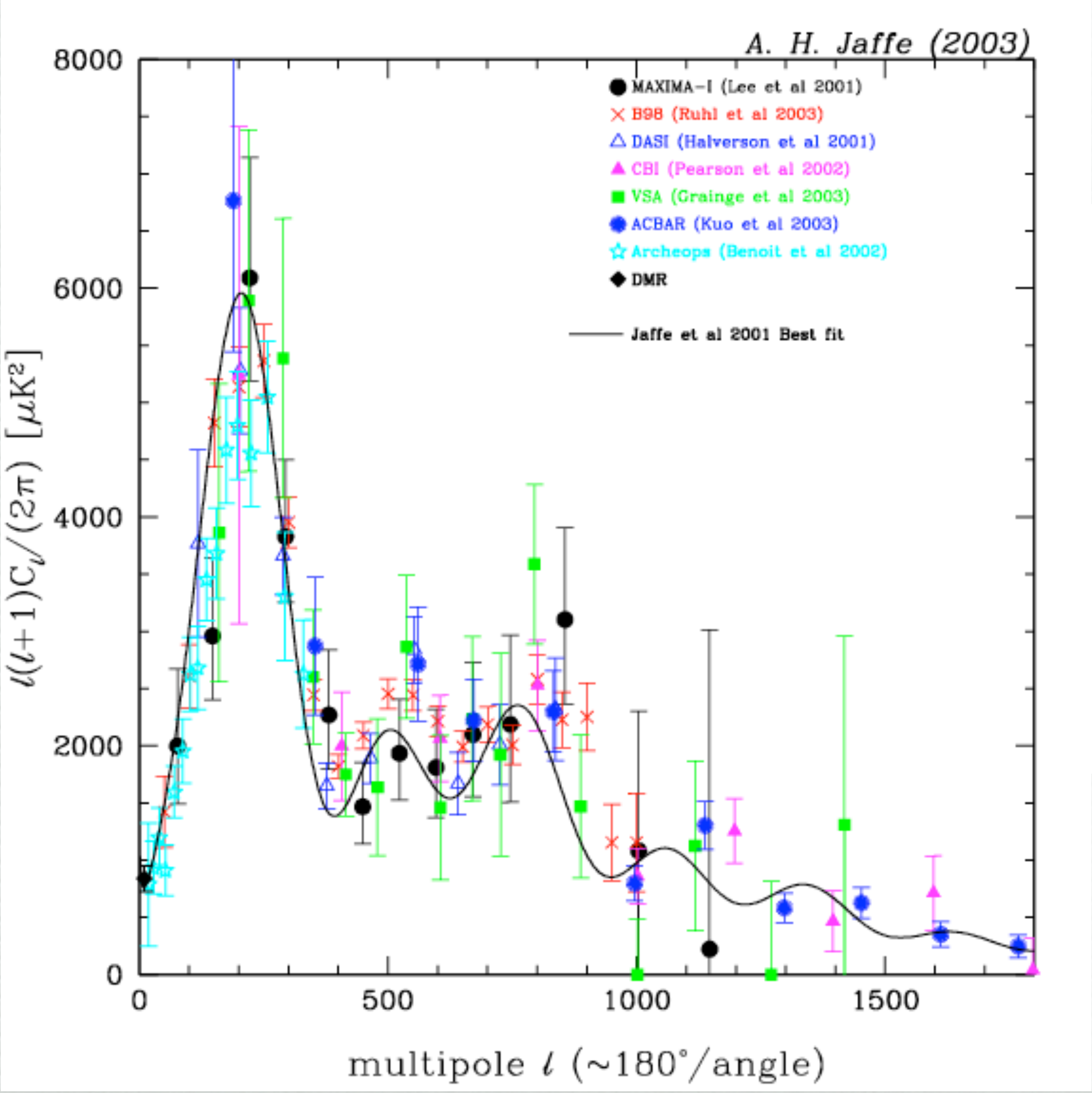
Theoretical Predictions

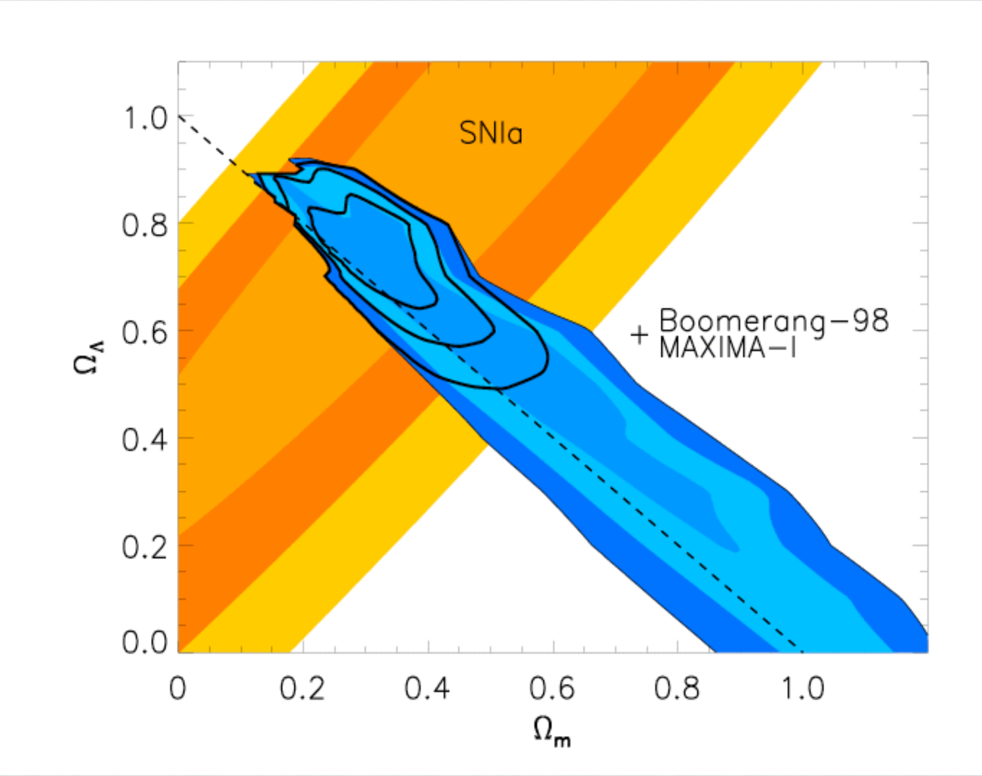


Mean square fluctuation amplitude

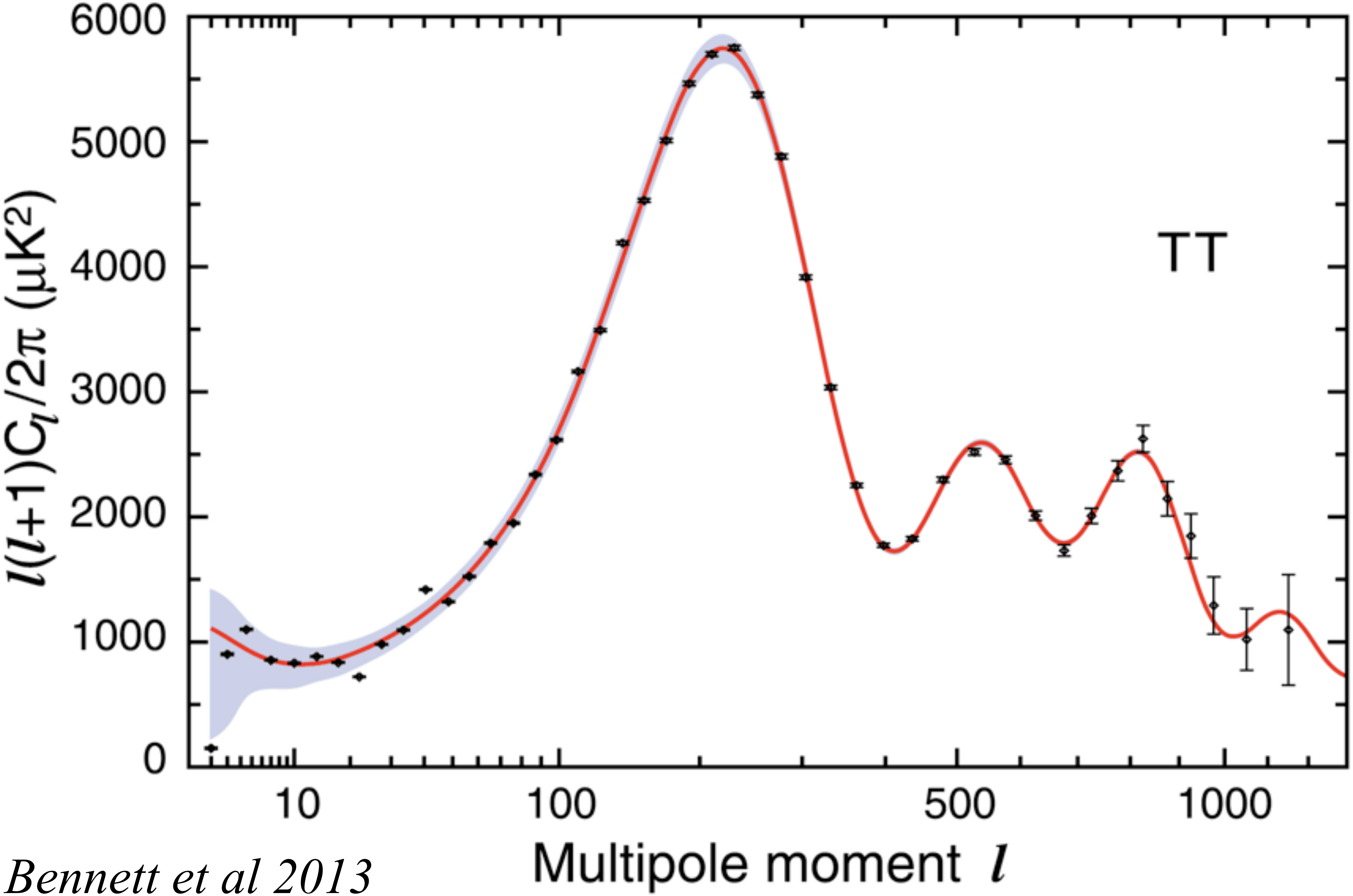
~180°/Angular scale

January, 2003





WMAP (2003-2012)



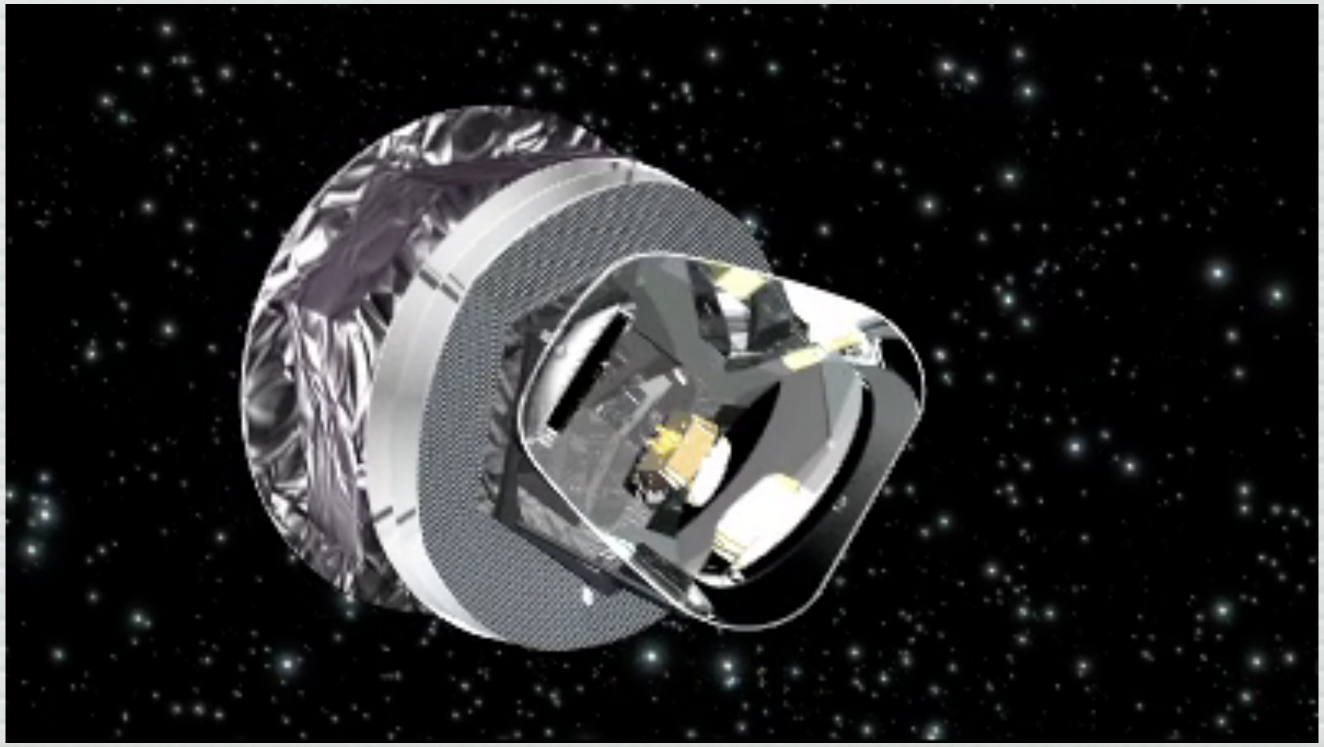
Bennett et al 2013

Planck: Launched 2009

- Nominal mission: 14 Months
  (extended ~2x, plus a "warm extension" for LFI)

Planck launch, 14 May 2009

Planck in orbit (animation)



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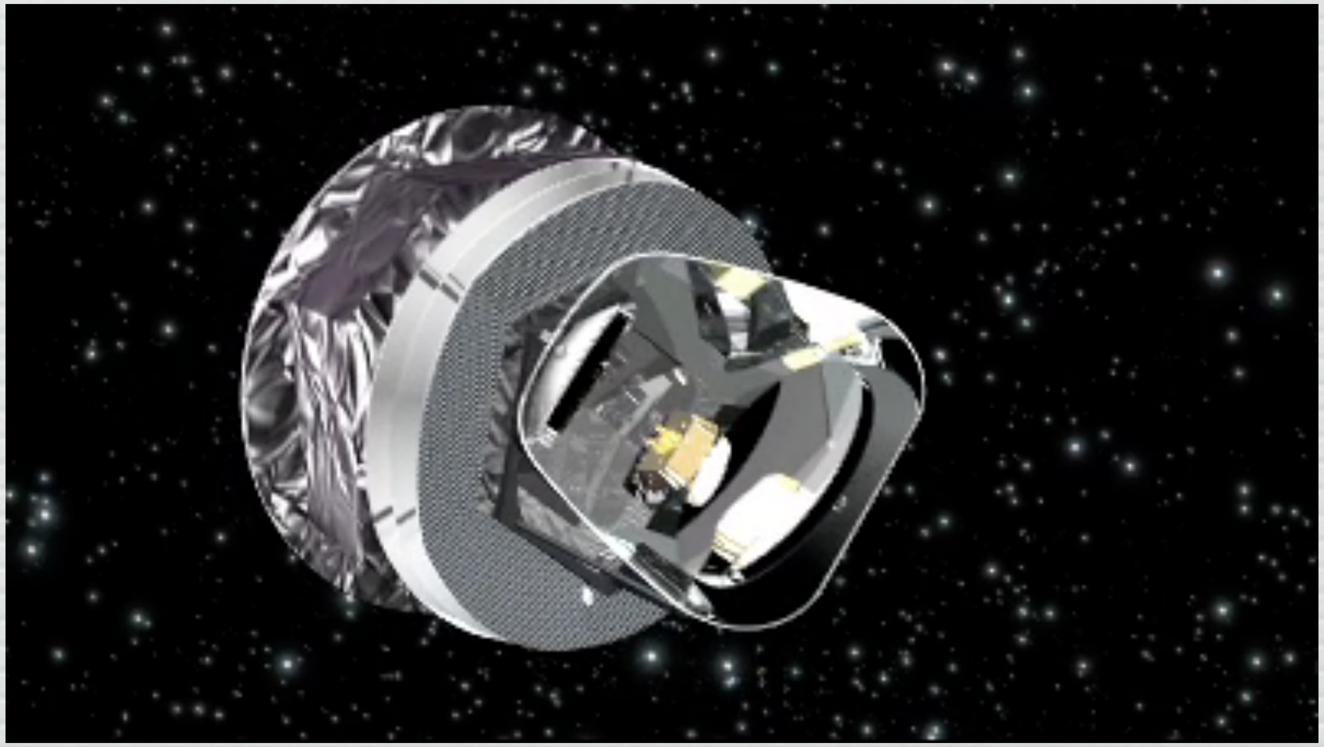
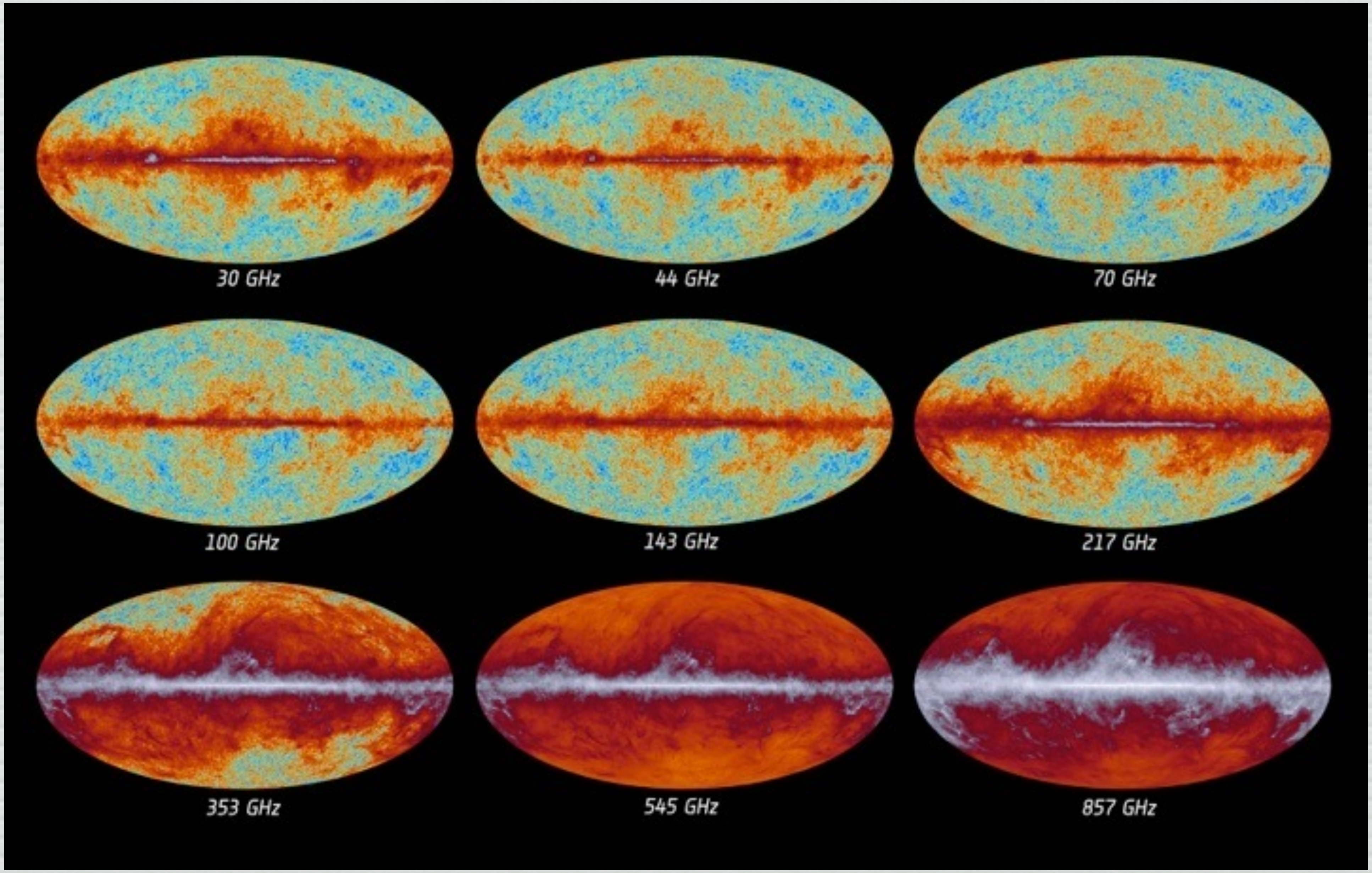


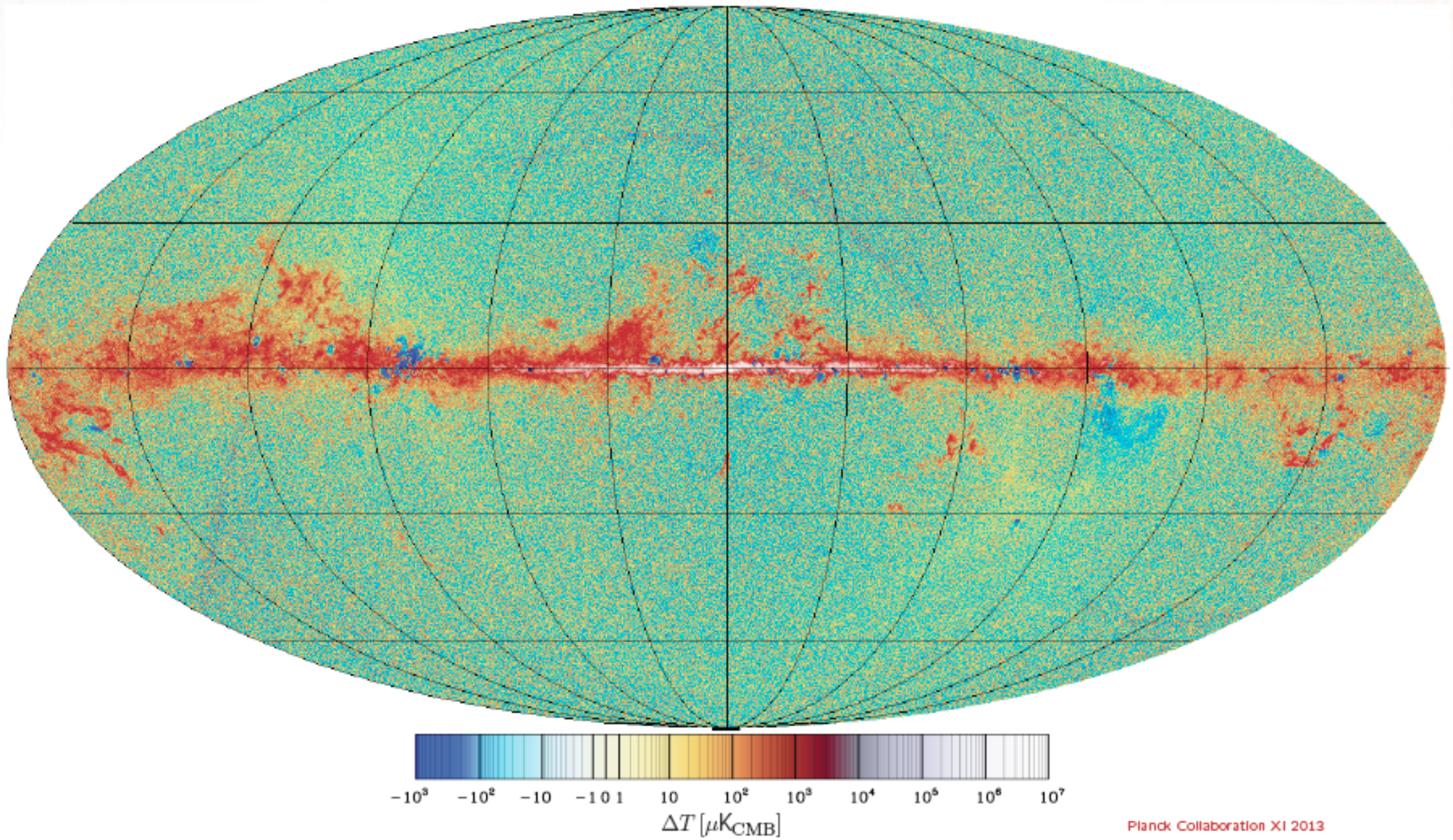
Frequency Maps

- Raw data: ~500 trillion samples over 15 months
- Maps: ~50 million pixels over 9 frequencies



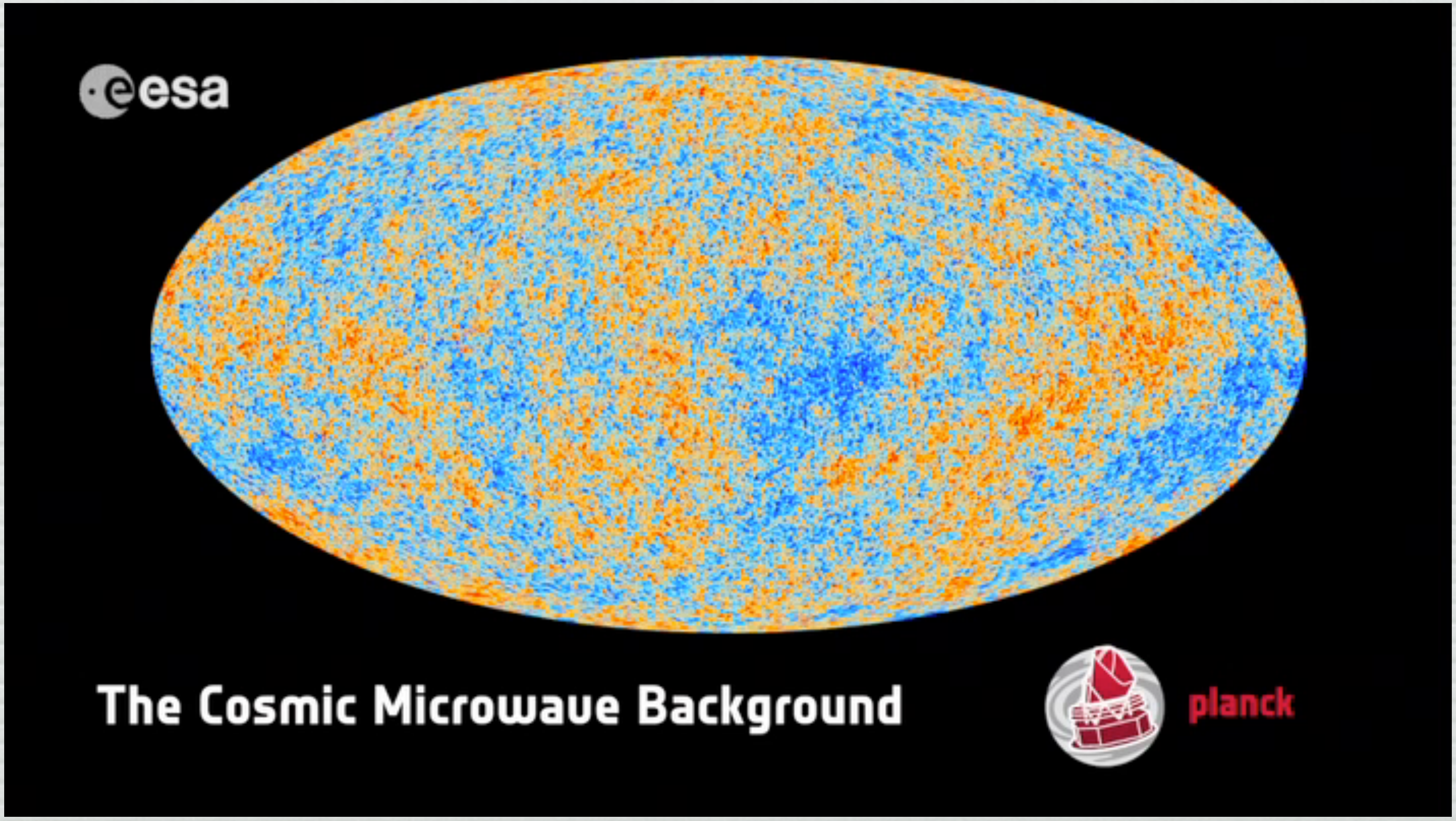
Map consistency

- 100 GHz – 70 GHz. Red is mostly CO, blue is mostly free-free. CMB is gone!



Component Separation

- Emission at any frequency is the sum of the CMB and astrophysical sources along the line of sight.
- *Planck* observes in 9 bands over 30–850 GHz to disentangle cosmology from astrophysics



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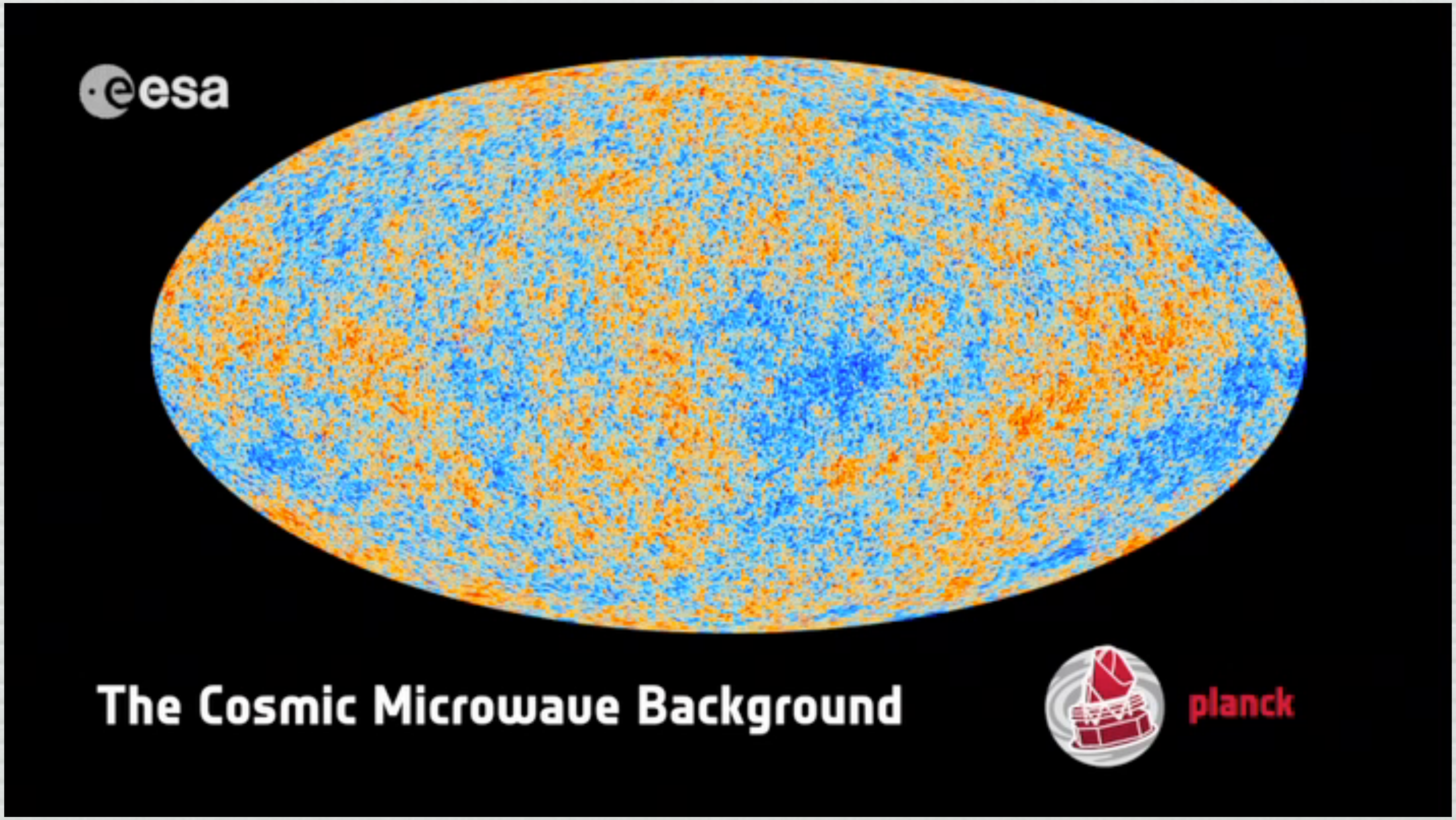
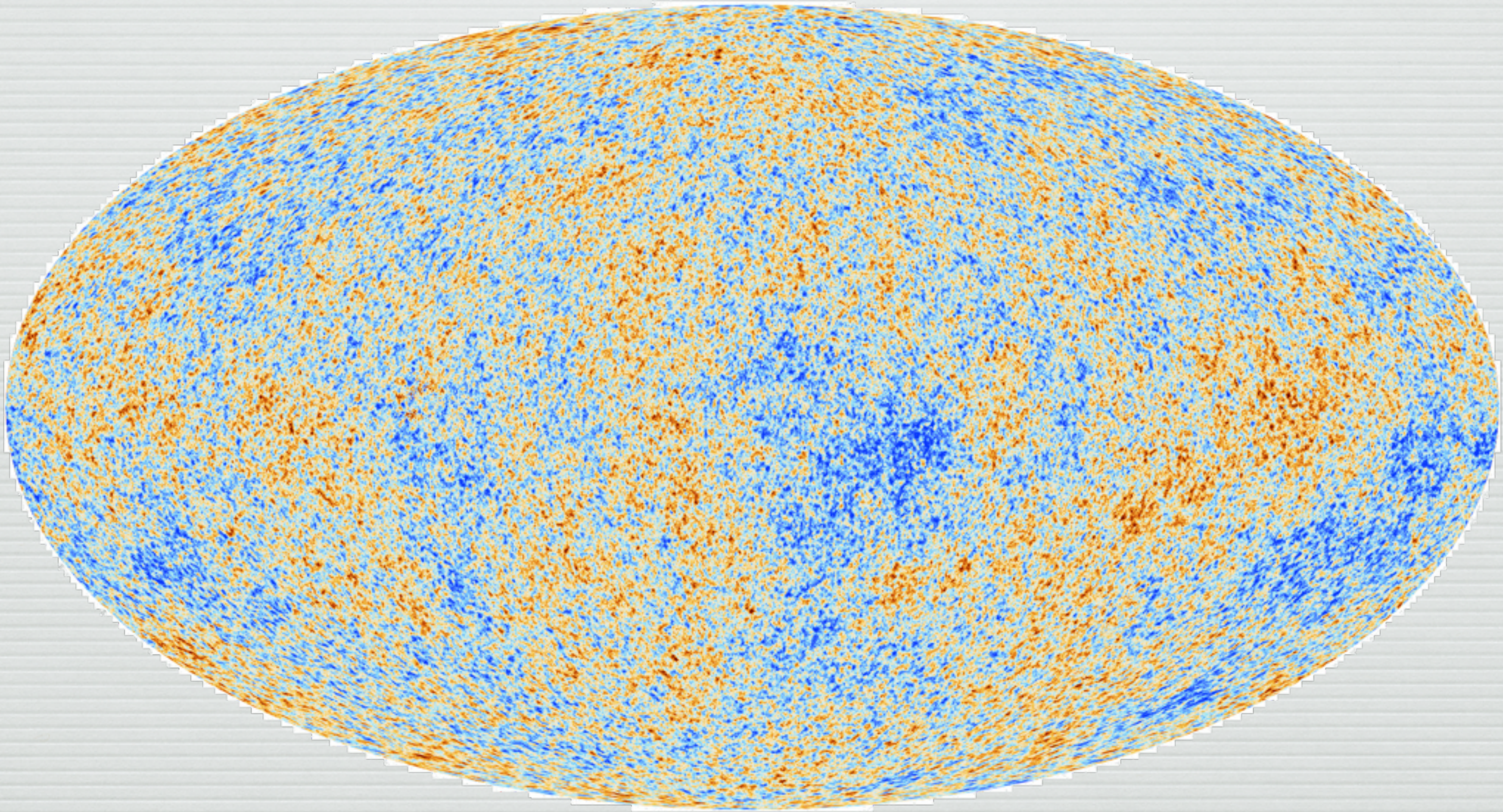
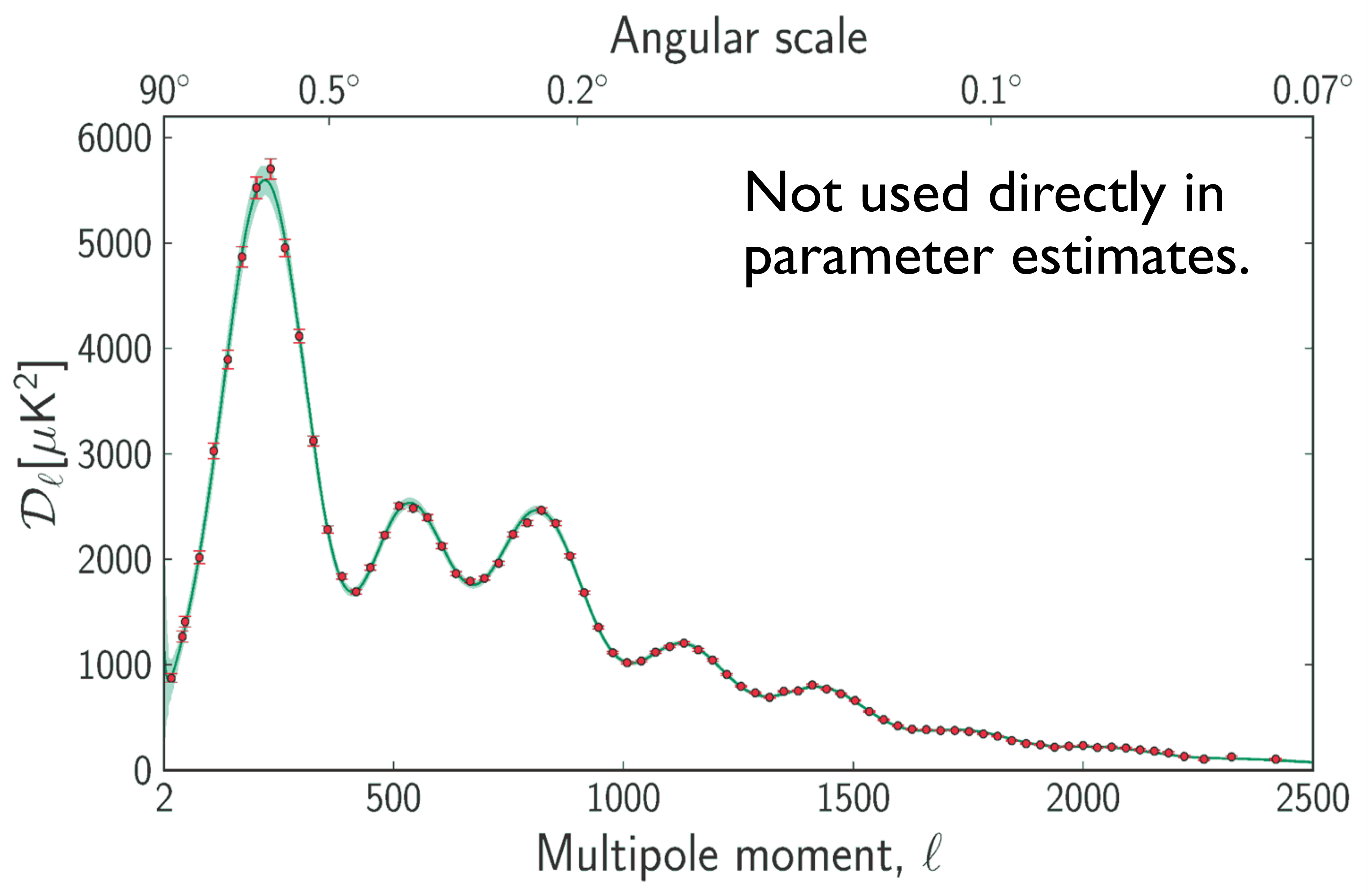


Planck (2013)



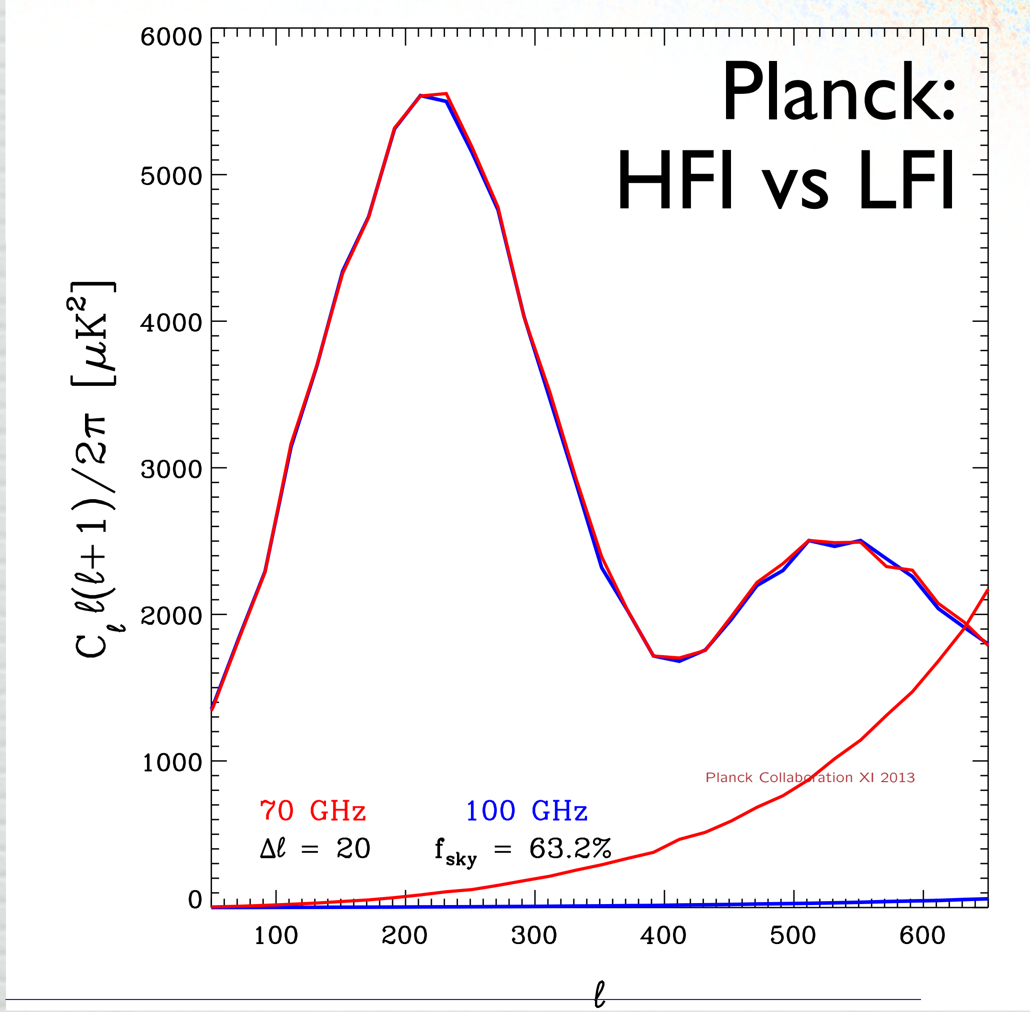
Planck (2013)

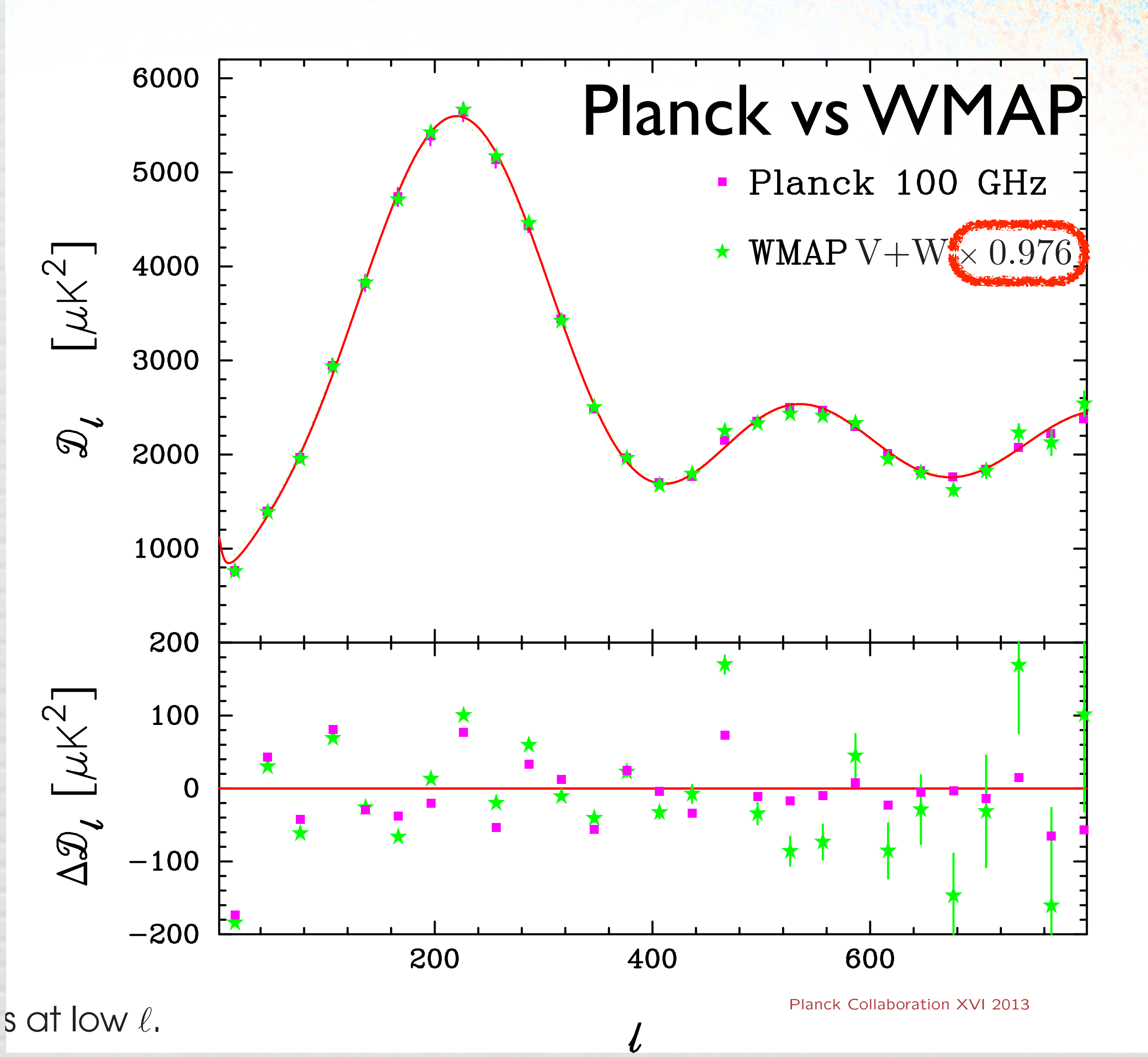
- From ~50 million pixels to ~2500 multipoles



Power spectrum consistency

- Excellent agreement between HFI & LFI
  - few x 0.1% through the first peak





- Evidence of a ~2.5% recalibration between WMAP & *Planck*?

Spectra

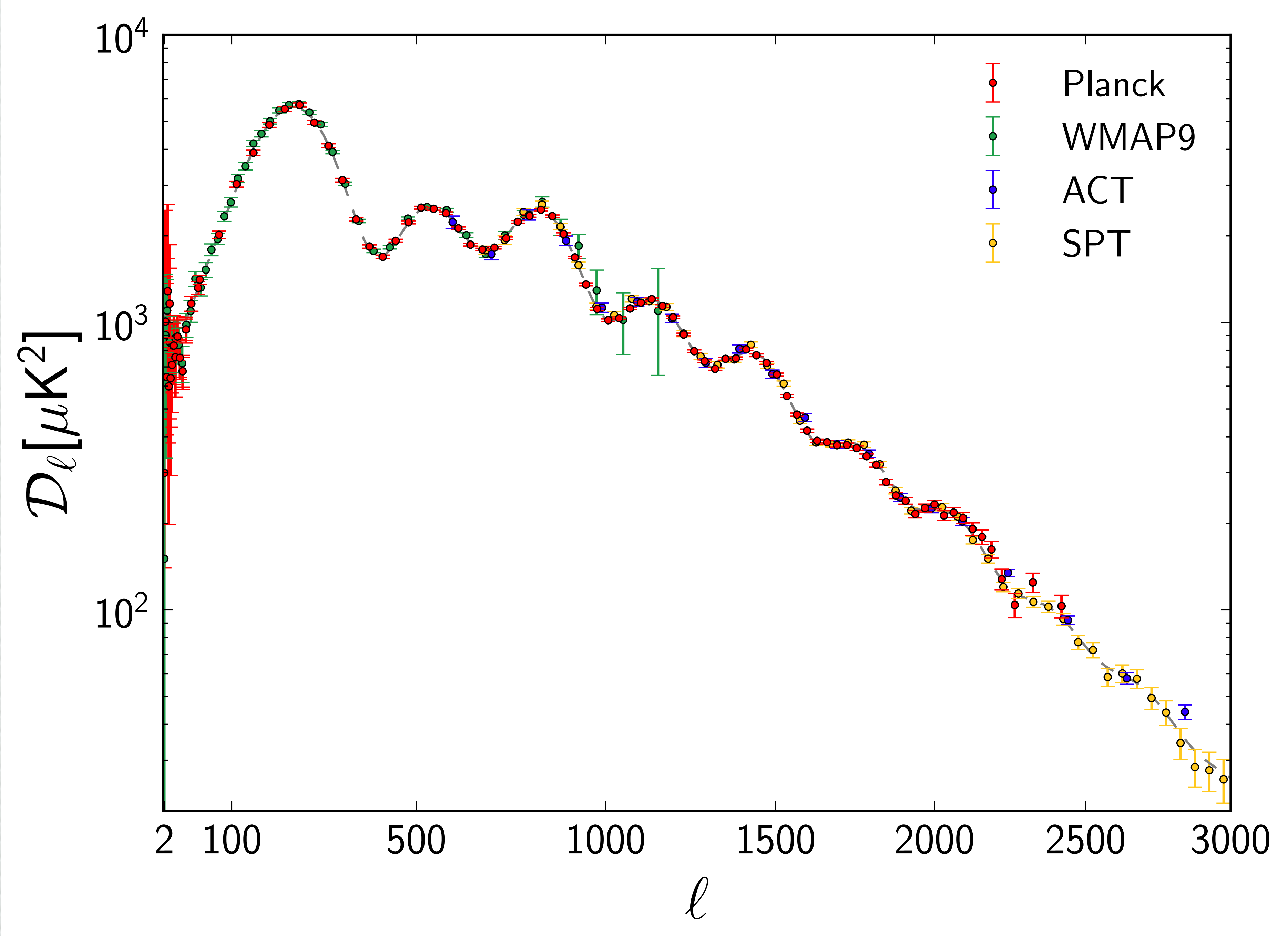


Fig. 25. Measured angular power spectra of *Planck*, WMAP9, ACT, and SPT. The model plotted is *Planck*'s best-fit model including *Planck* temperature, WMAP polarization, ACT, and SPT (the model is labelled [Planck+WP+HighL] in Planck Collaboration XVI (2013)). Error bars include cosmic variance. The horizontal axis is $\ell^{0.8}$.

Cosmological Parameters

- *Planck* + WP

from 2500 points to ~6 parameters

  - *~directly measured*

$\Omega_b h^2 = 0.02205 \pm 0.00028$

$\Omega_c h^2 = 0.1199 \pm 0.0027$

$n_s = 0.960 \pm 0.007$

$\tau = 0.089 \pm 0.014$

$10^9 A_s = 2.20 \pm 0.06$

$100\,\theta_{MC} = 1.04131 \pm 0.00063$

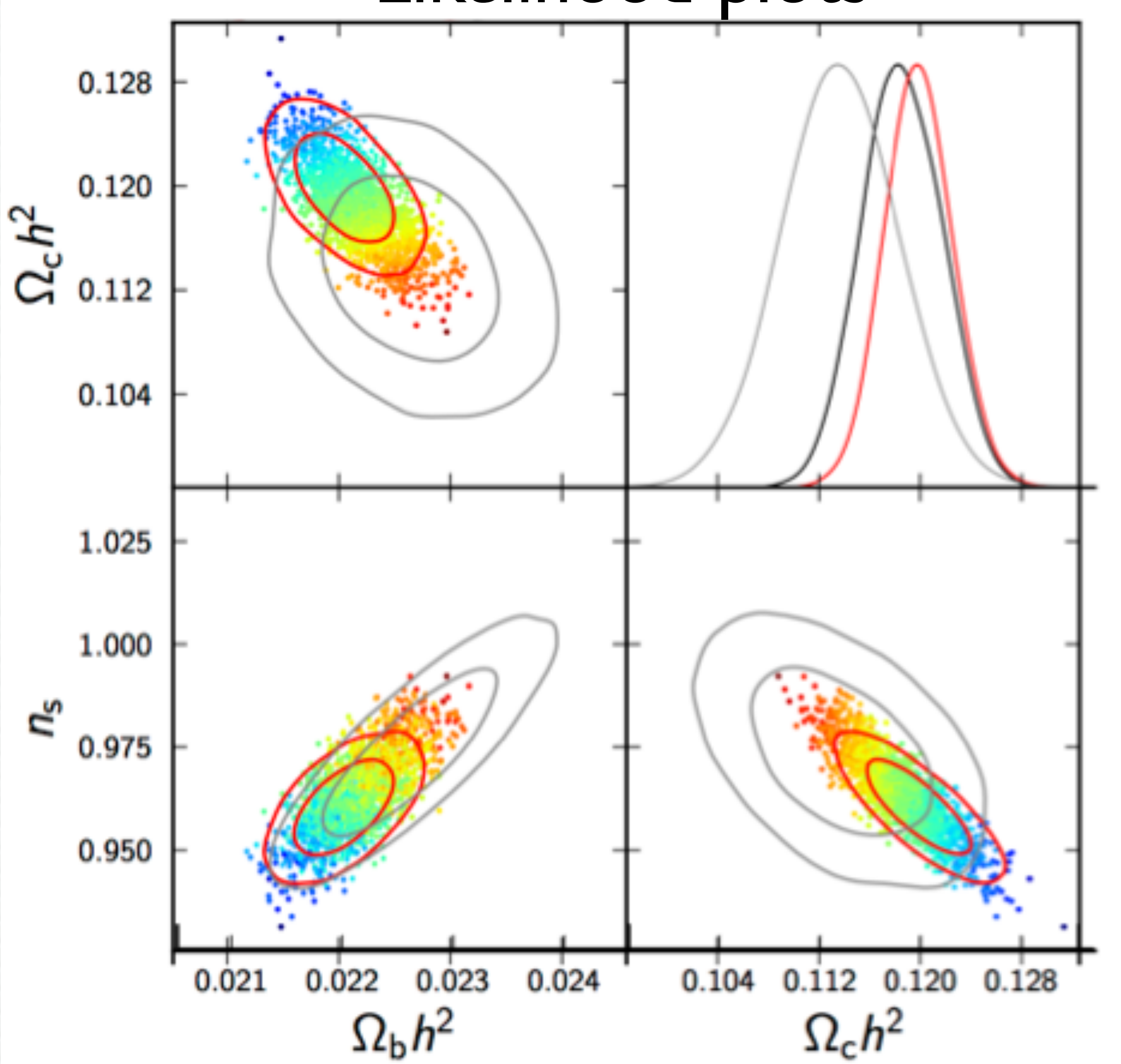
  - *derived (e.g.)*

$H_0 = 67.3 \pm 1.2$ km/s/Mpc

$\Omega_\Lambda = 0.685 \pm 0.017$

$\sigma_8 = 0.829 \pm 0.012$

Likelihood plots

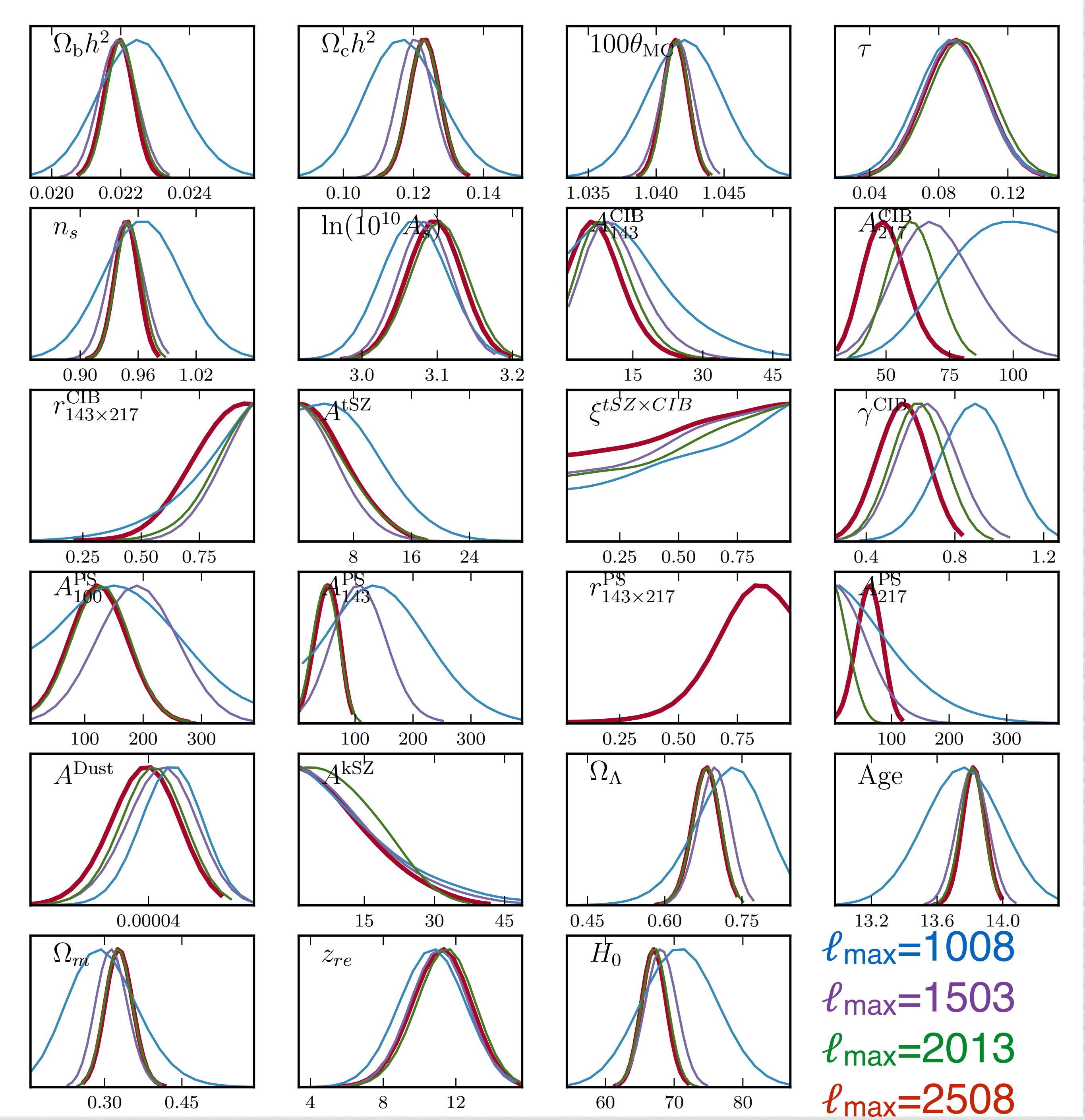


Samples: Planck+lensing; Red: Planck+WP; Grey: WMAP-9

  - $\Sigma m_\nu < 0.23$ eV (95%), $N_{\nu,\mathrm{eff}} = 3.30 \pm 0.27$ (68%) [with caveats]

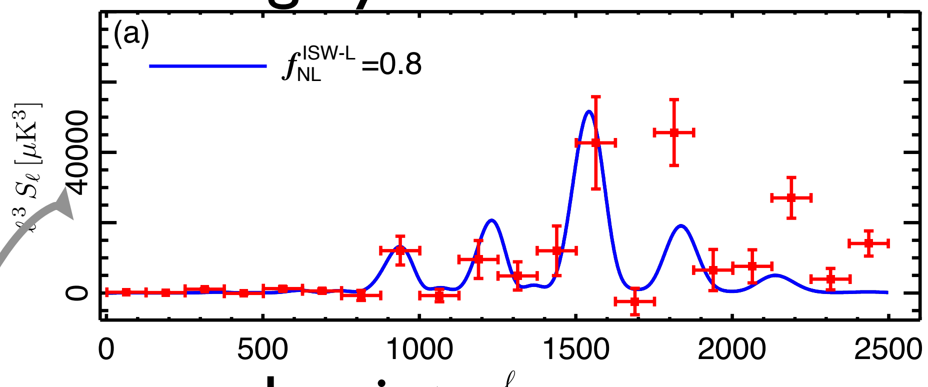
Self-consistency of the parameters

- Very weak dependence on which subset of *Planck* data is analysed.
- Robust to
  - changes in ℓ_{max}
    - e.g., ℓ~1800 cooler line
  - inclusion of channels
    - 217 GHz is a minor outlier, but inclusion affects parameters by a small fraction of a sigma

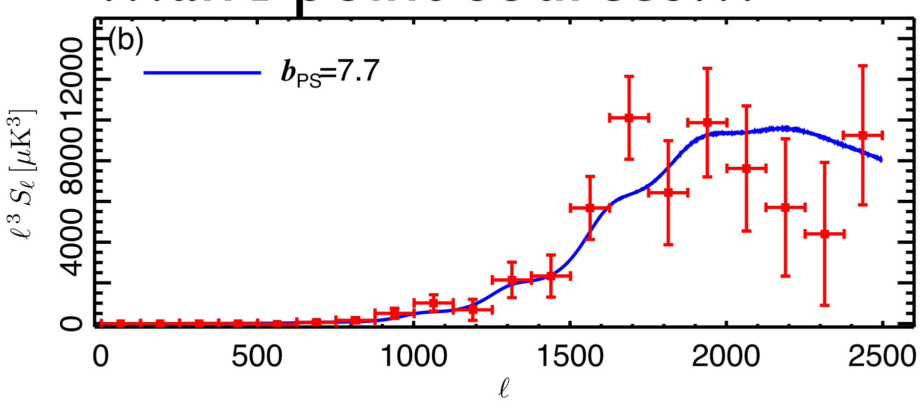


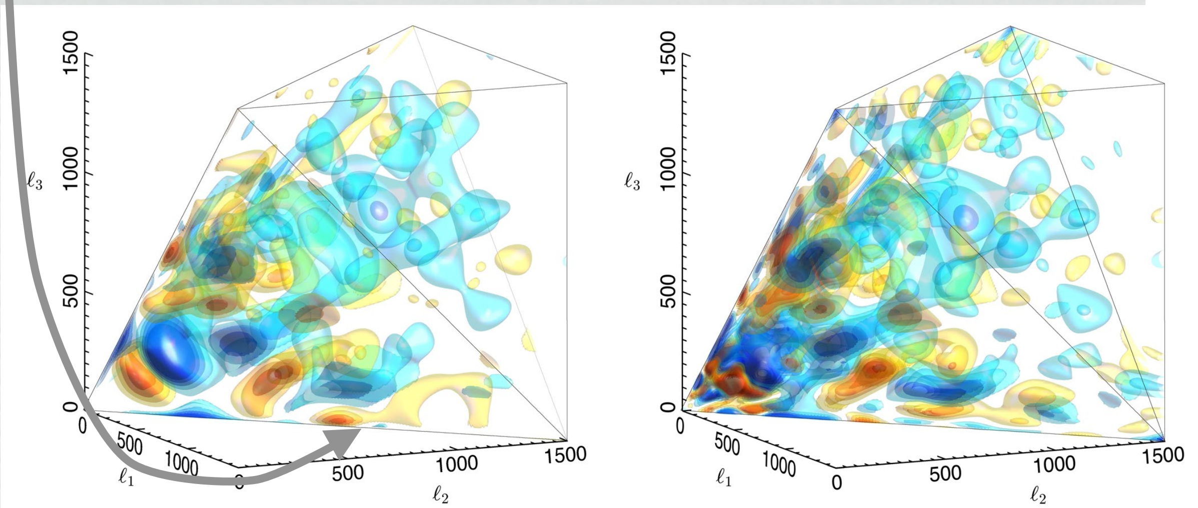
Non-Gaussianity

We see
lensing by cosmic structures

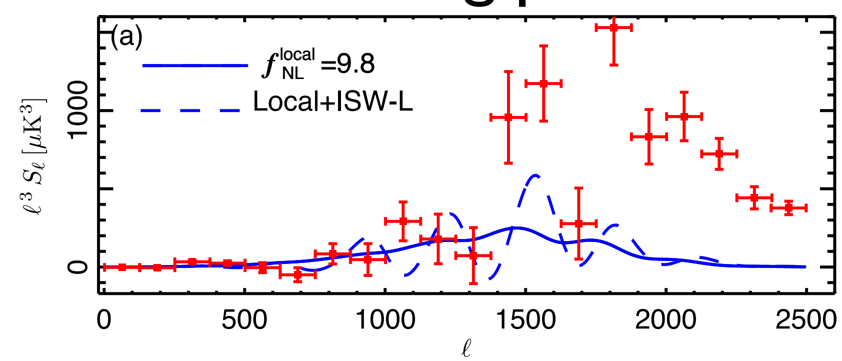


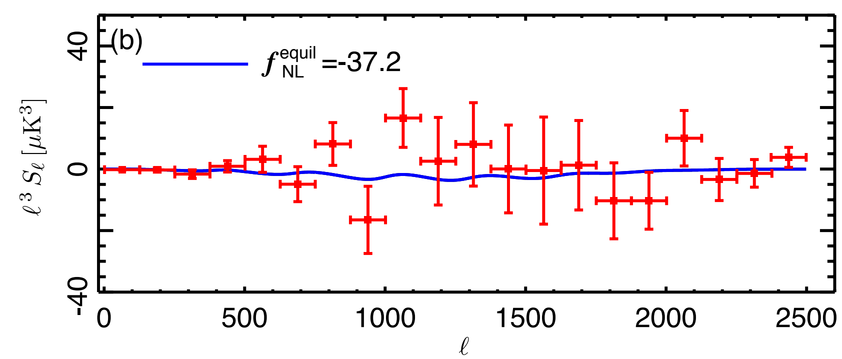
…and point sources…

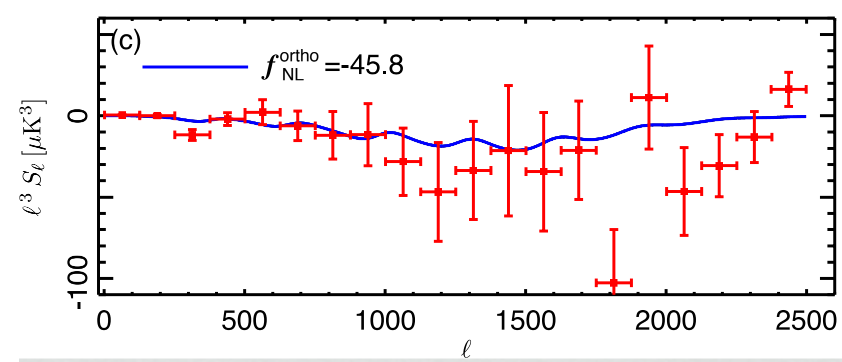


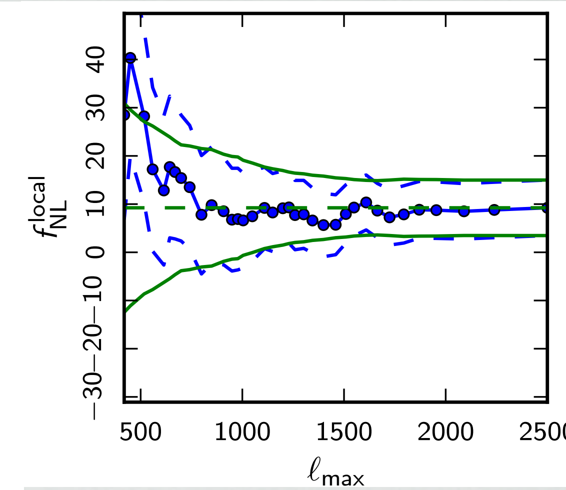


…but nothing primordial









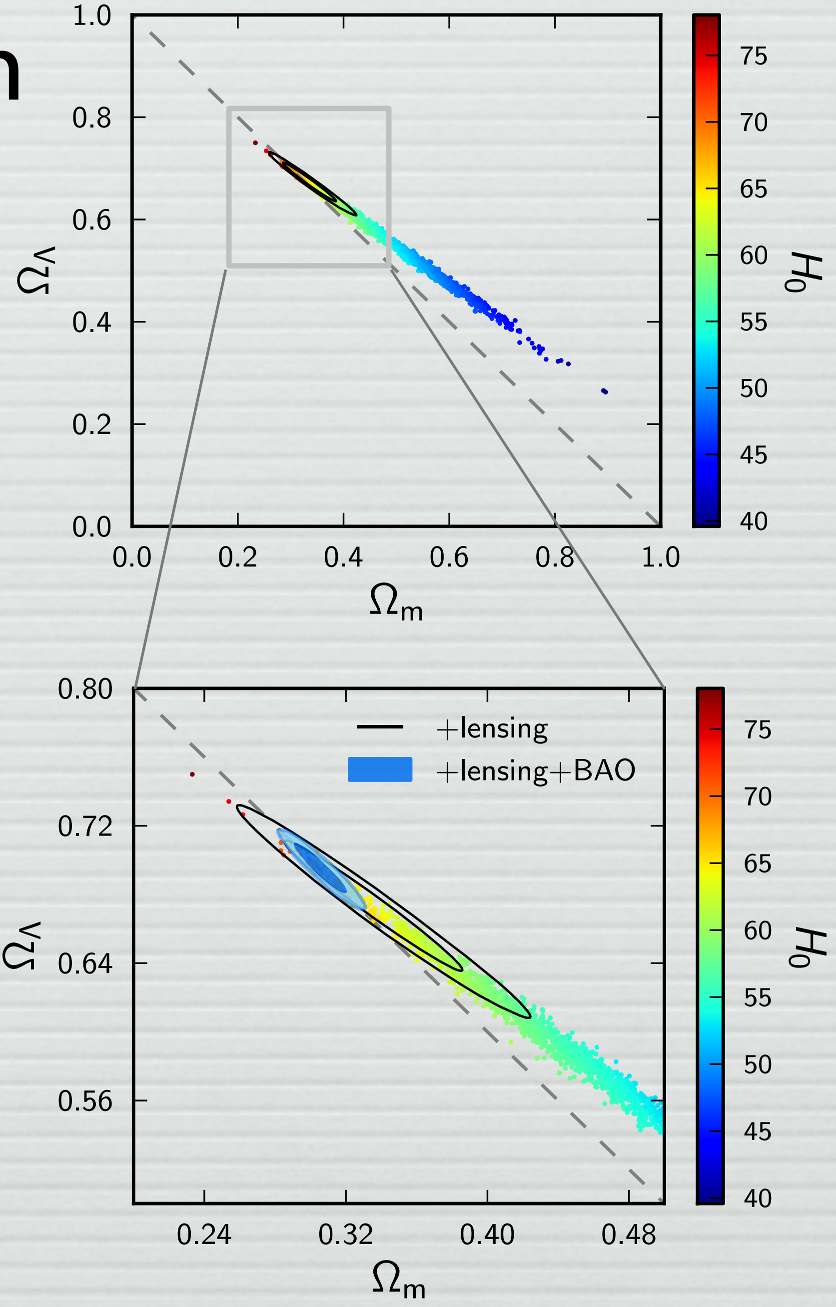
$$f_{\rm NL}^{\rm local} = 2.7 \pm 5.8$$
$$f_{\rm NL}^{\rm equil} = -42 \pm 75$$
$$f_{\rm NL}^{\rm ortho} = -25 \pm 39$$

Fundamental (?) Physics: Inflation

- Early period of exponential expansion
  - makes the Universe geometrically flat
    - Prediction: flat Universe (Ω_k=1) ✓
  - takes a "causally connected" region and makes it larger than the observable Universe
    - Prediction: nearly uniform temperature ✓
  - produces fluctuations (quantum randomness on astrophysical scales!)
    - slope of initial power spectrum $\Rightarrow$ shape of C_ℓ
    - Prediction: n_s a little less than 1 ✓
      - also: nearly Gaussian fluctuations ✓
    - Prediction: gravitational radiation background ?

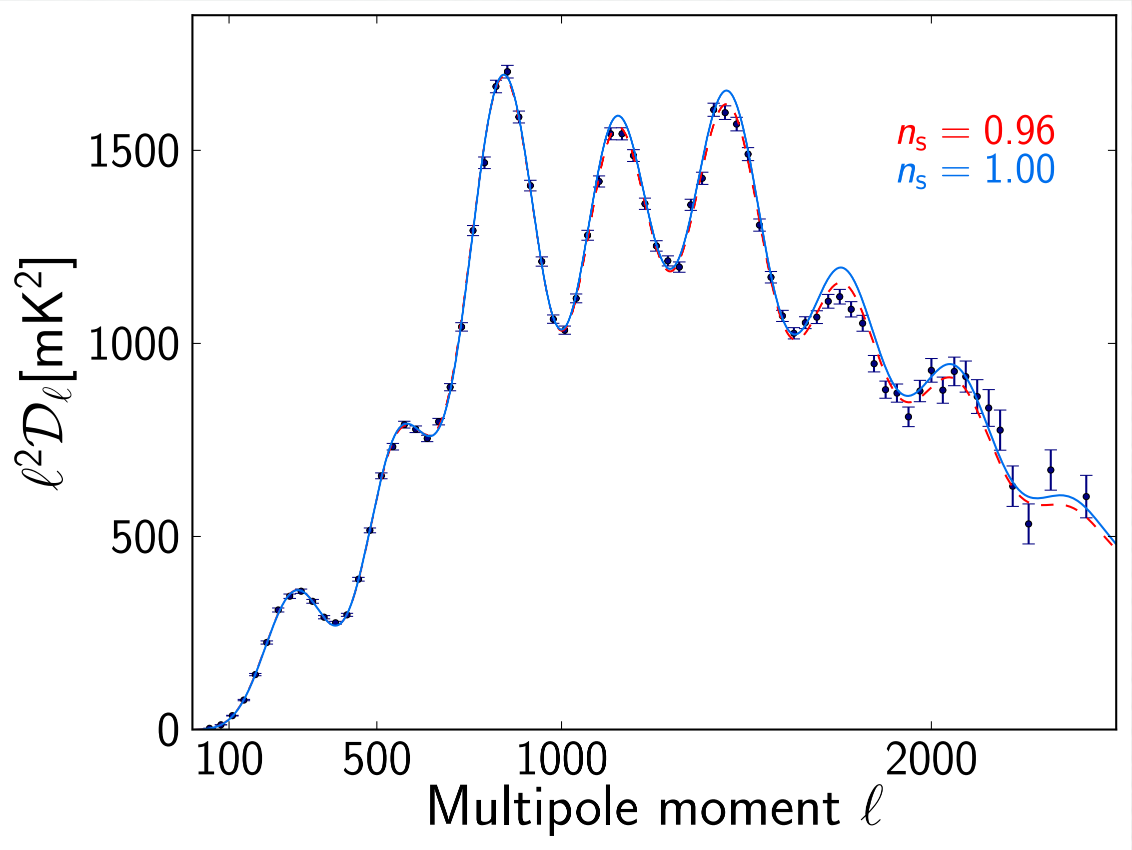
Inflation: Curvature from the CMB

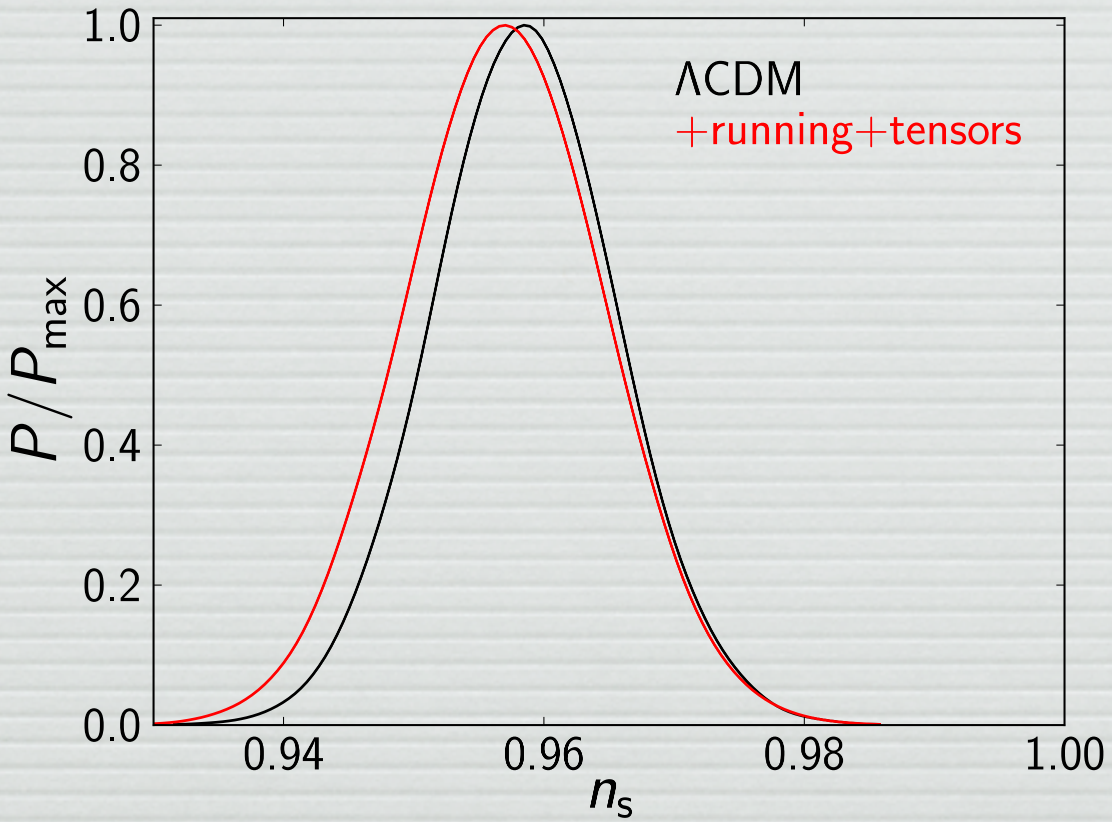
- With primary CMB alone, cannot determine both Ω_Λ & Ω_m (i.e., curvature)
- *Planck* measures curvature through *lensing*
  - more matter, less dark energy $\Rightarrow$ more lensing
    - distorts shape of power spectrum, smears out the small-scale peaks
    - boosts deflection power spectrum
      - about double at Ω_Λ=0
  - Even more well-determined when combined with other astrophysical data



Inflation: Primordial fluctuations

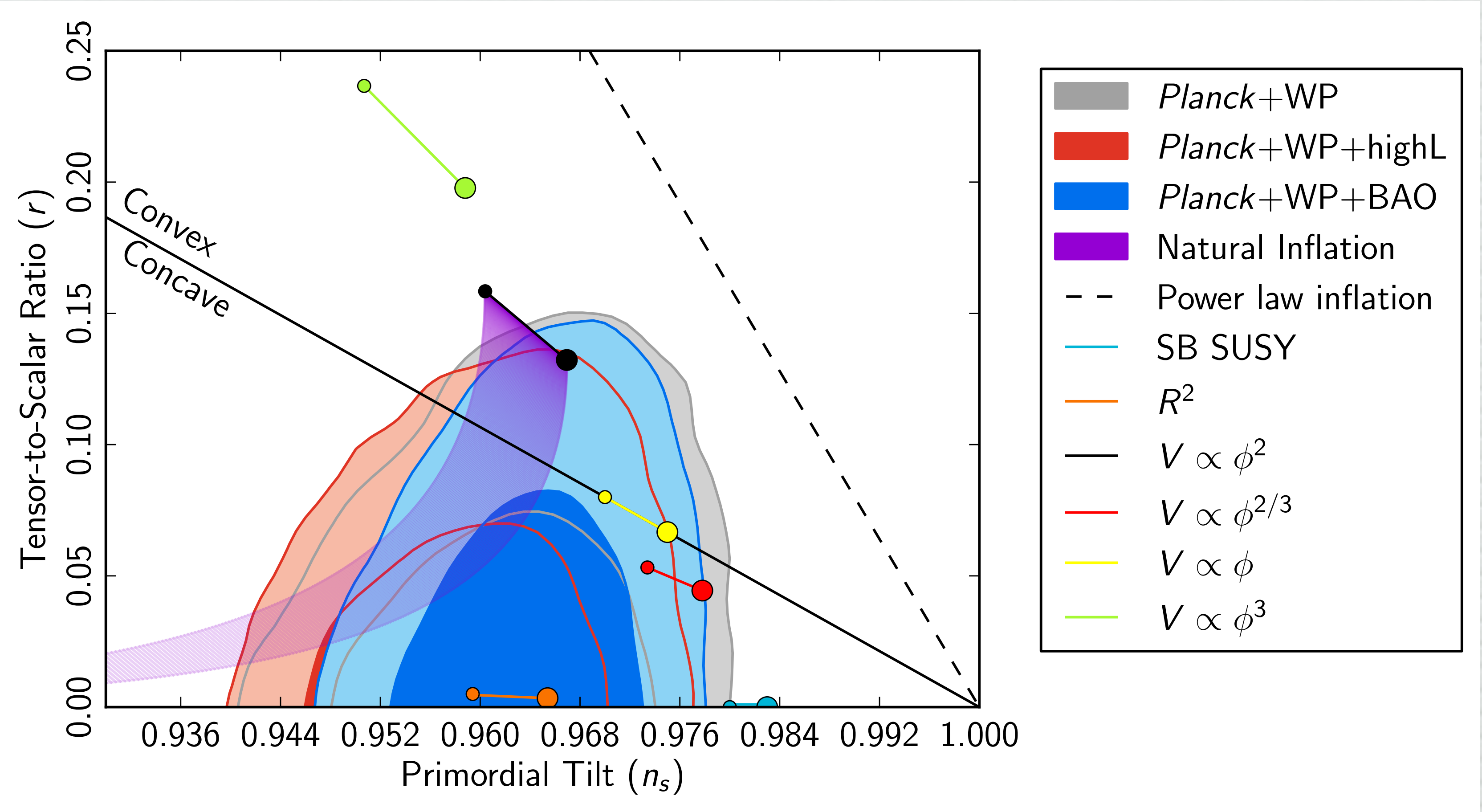
- $n_s = 0.960 \pm 0.007$
  - >5 sigma away from n_s=1





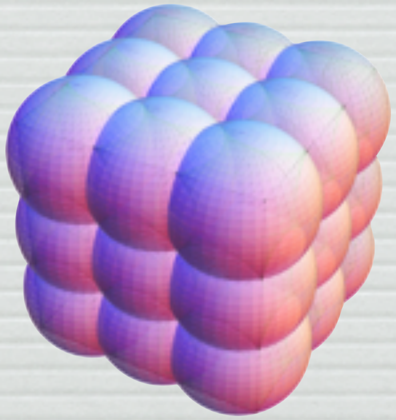
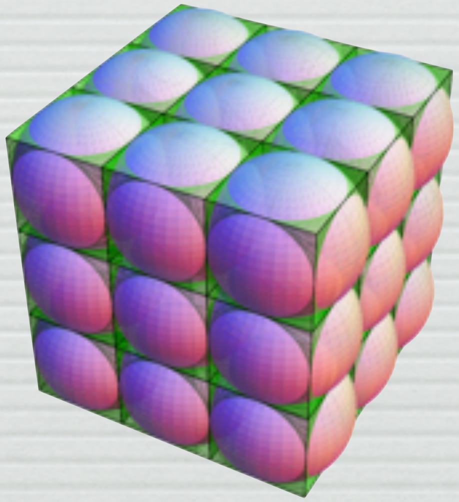
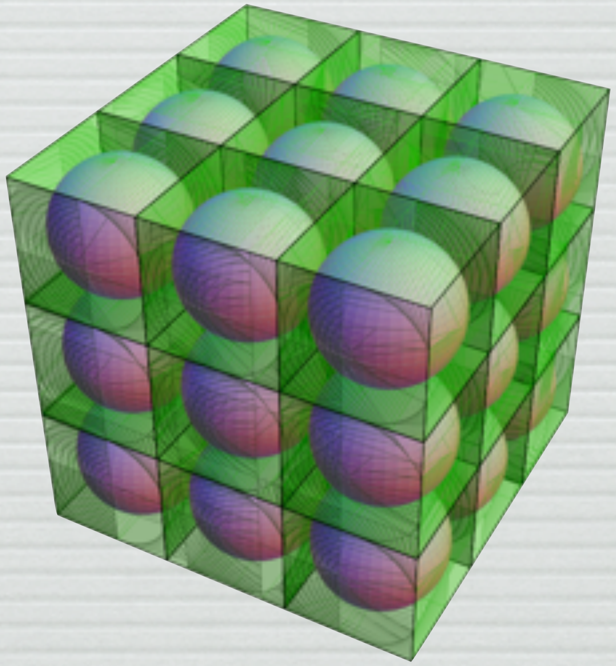
Inflation: Models

- Simplest models: scalar field φ w/very flat potential $V(\varphi)$
- *Planck* constrains specific models of inflation
- More information from the polarization of the CMB, which may observe the presence of gravitational waves in the early Universe:
  - next year's *Planck* data release
  - next-gen ground & balloon expts (e.g., PolarBear, EBEX, SPIDER,…)

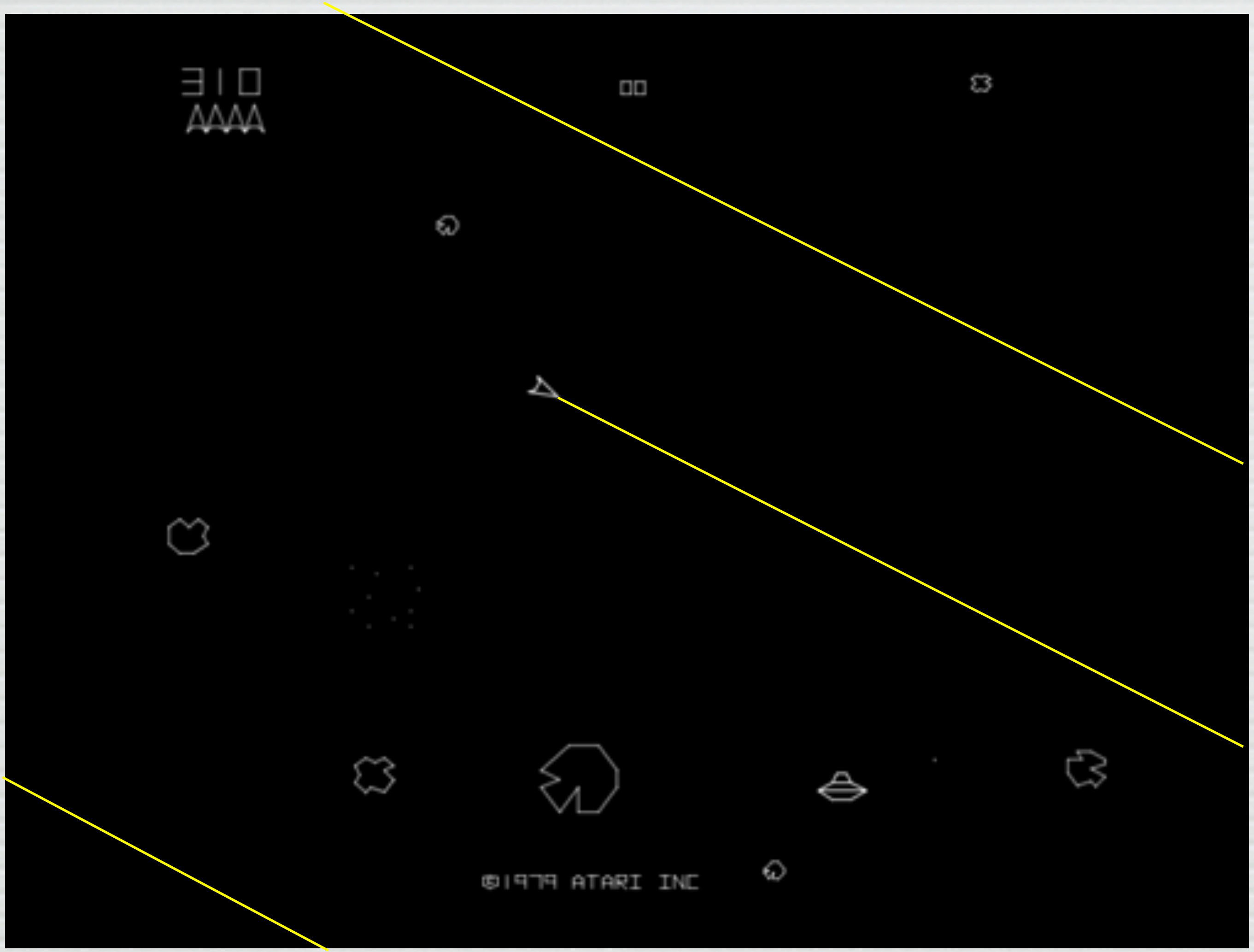


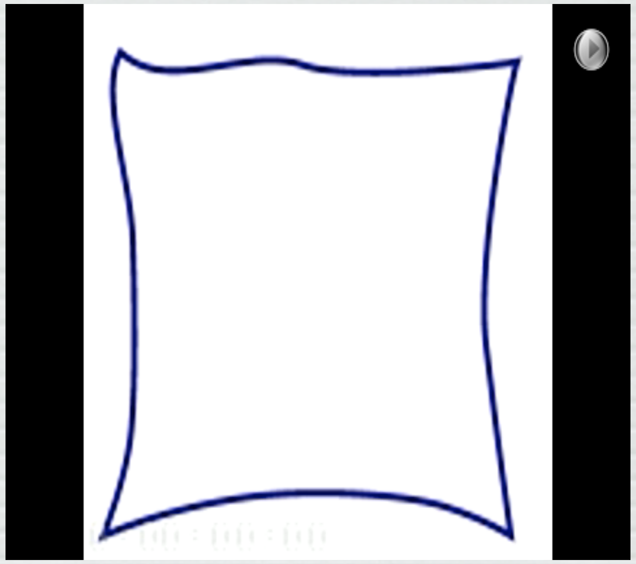
Fundamental Physics: The shape of the Universe

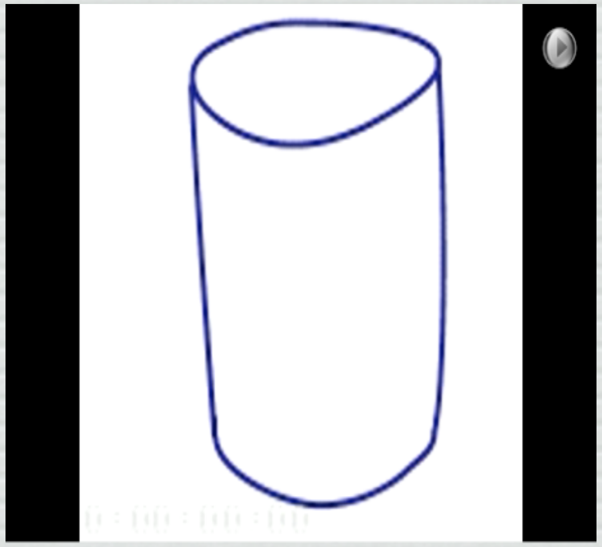
- General relativity determines the curvature of the Universe, but not its topology (holes and handles)
- Most theories of quantum gravity (and quantum cosmology) predict topological change on small scales and at early times.
- Does this have cosmological implications?
  - E.G., small universe $\Rightarrow$ fewer large-scale modes available $\Rightarrow$ low power on large scales?

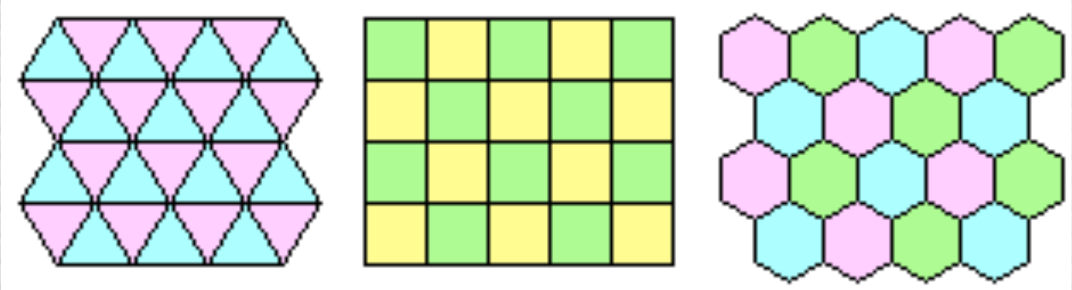




Topology in a flat "universe"





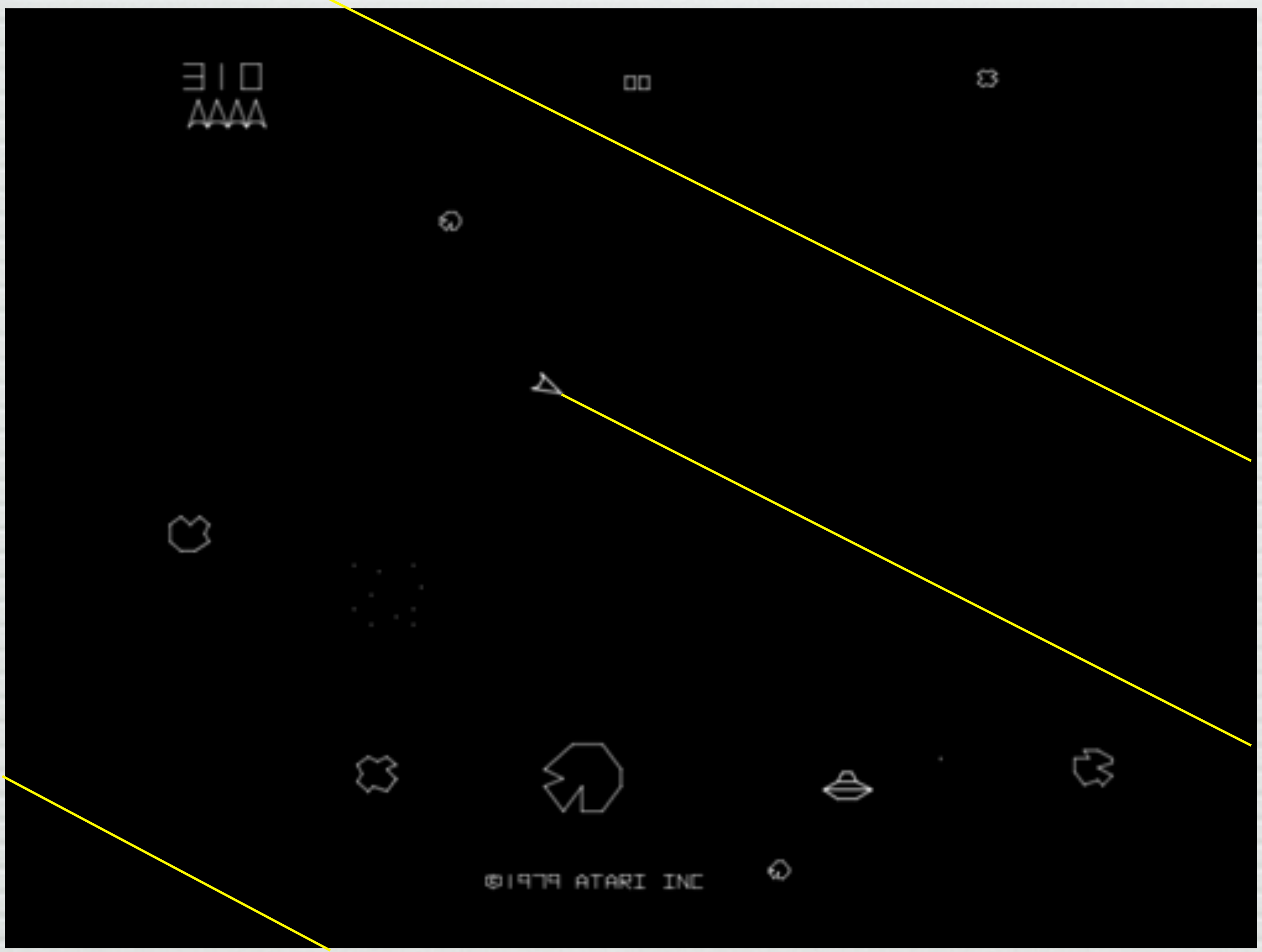


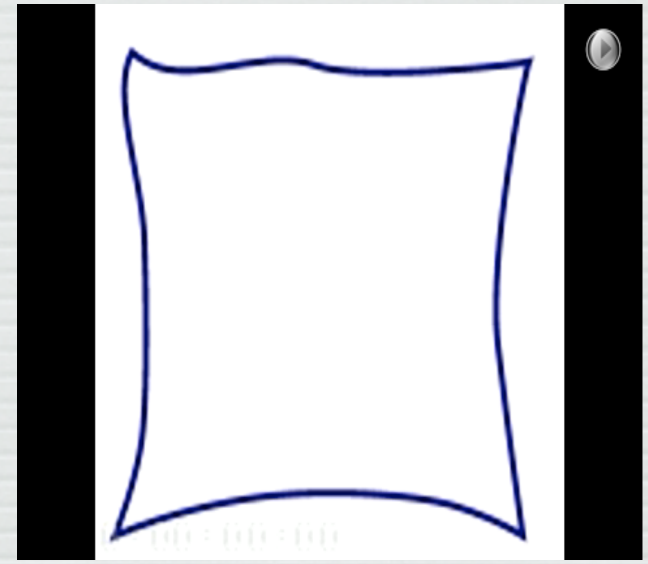


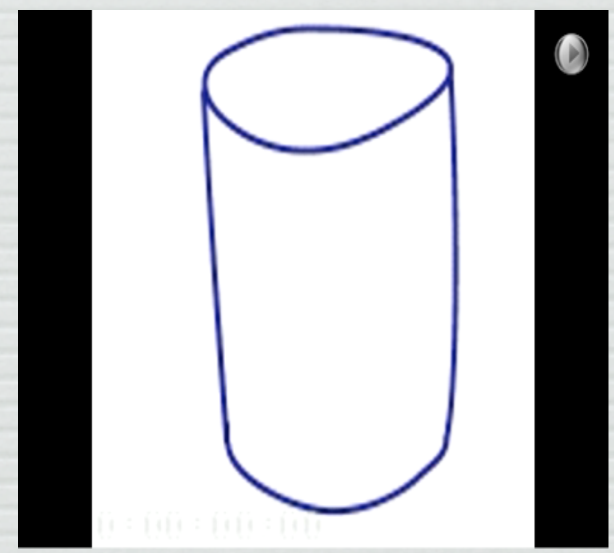
"tiling the plane"

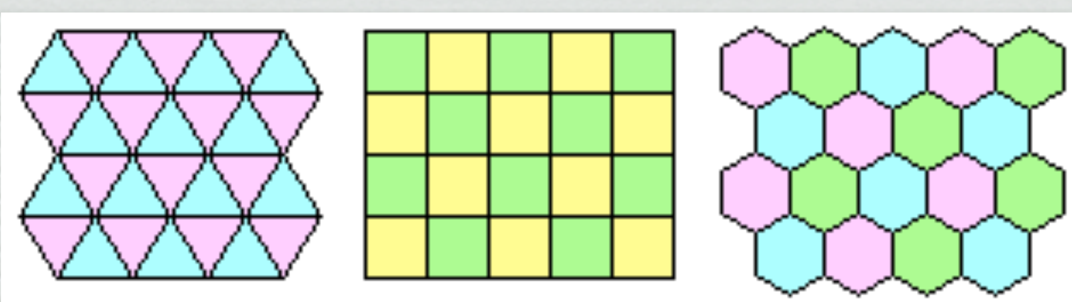
Don't *need* to "embed" the square to have a connected topology.

Topology in a flat “universe”









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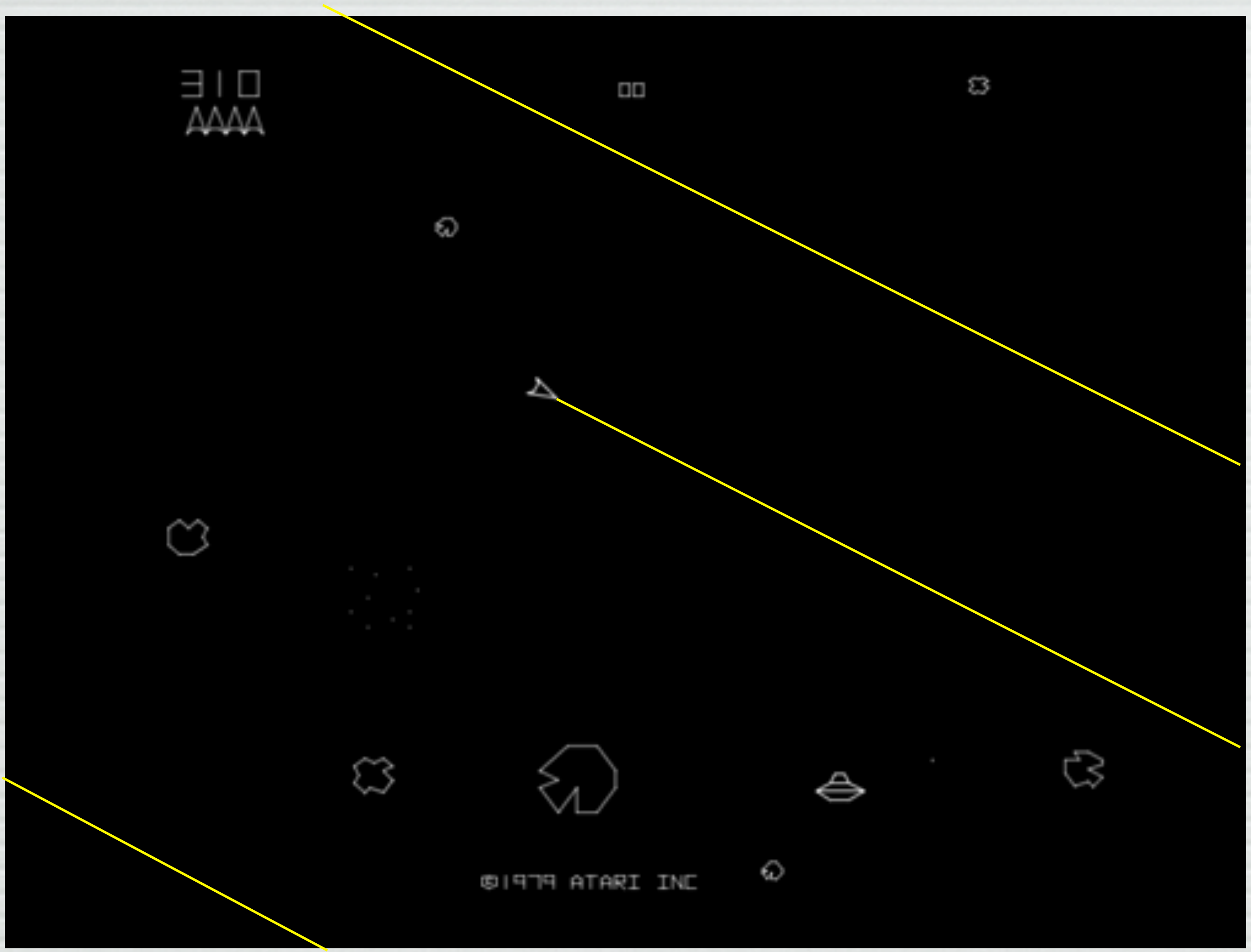

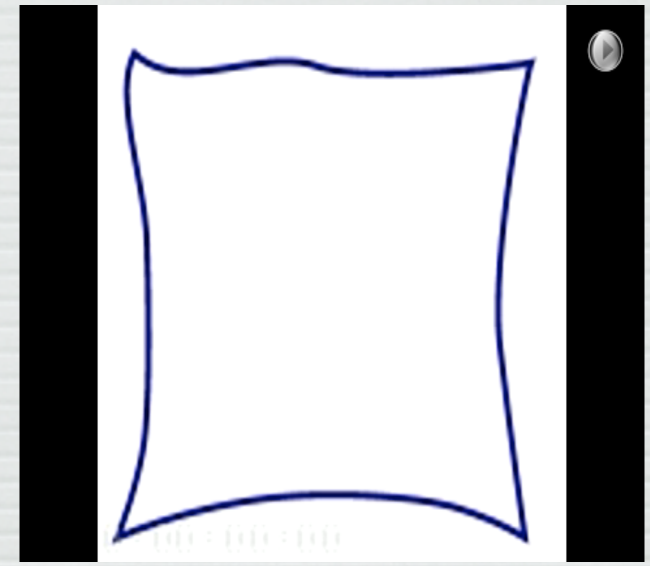

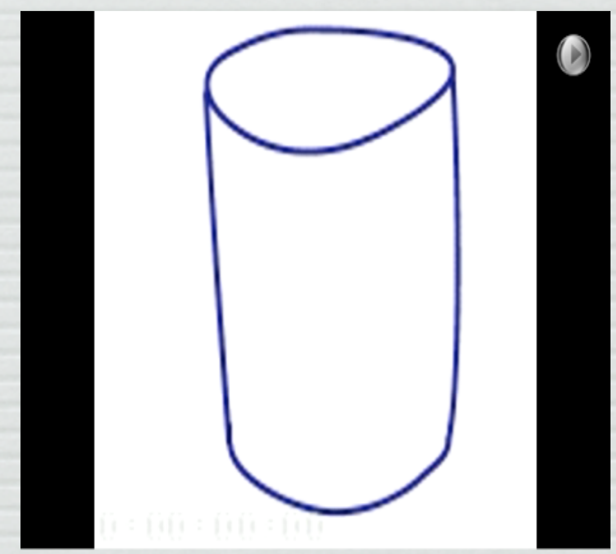

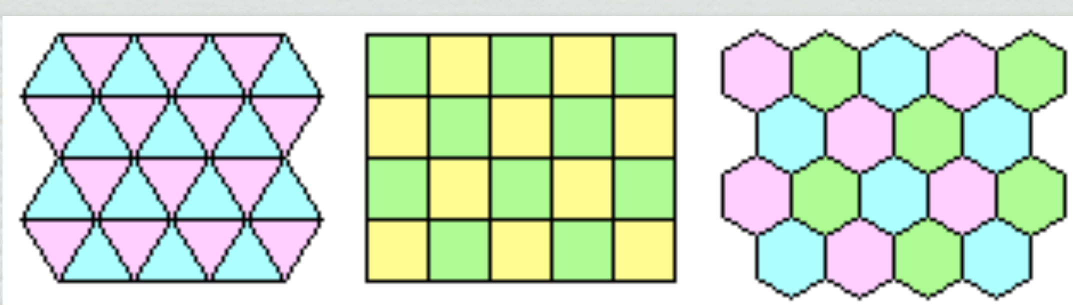

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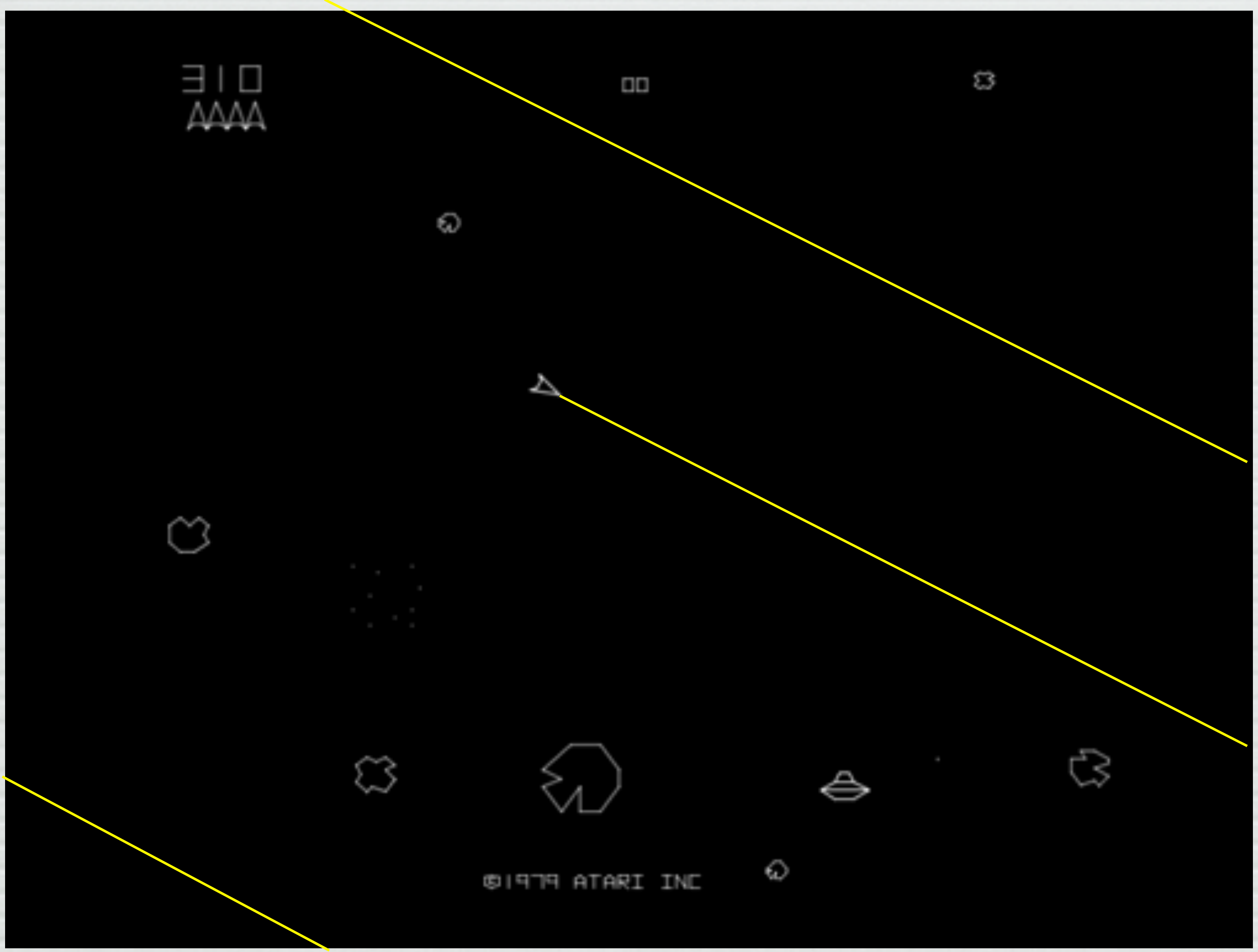

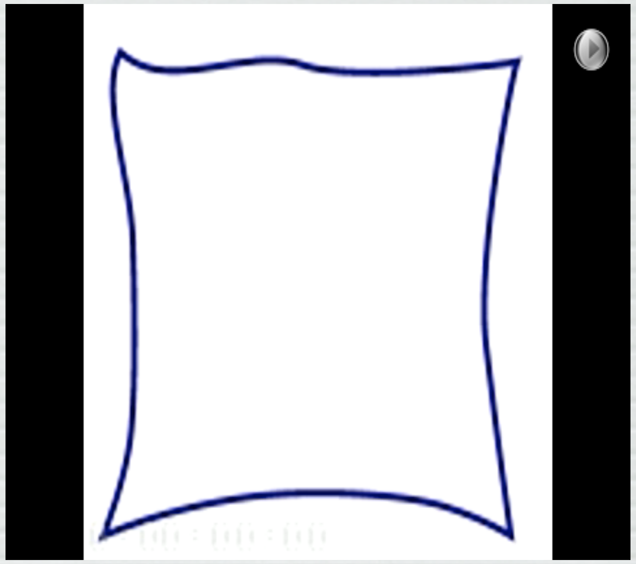

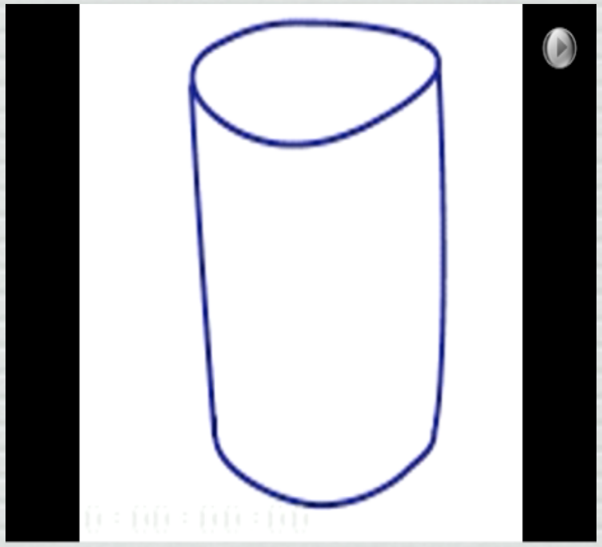

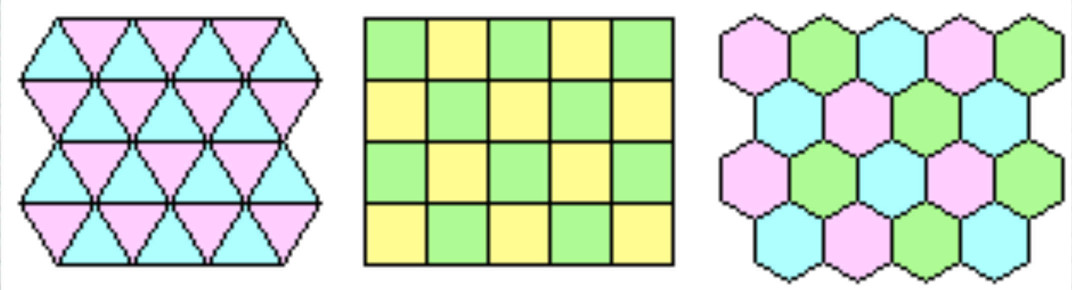

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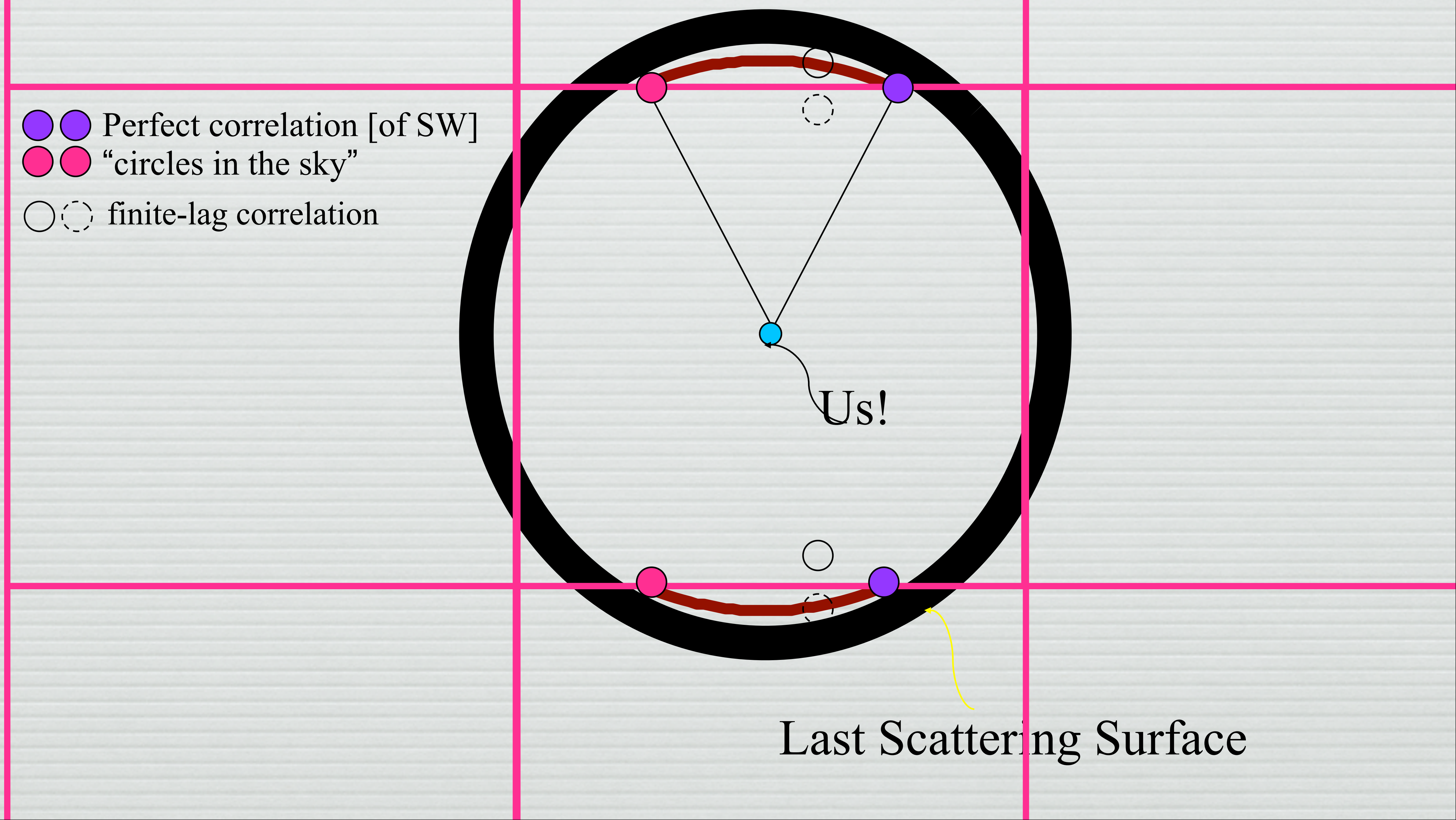
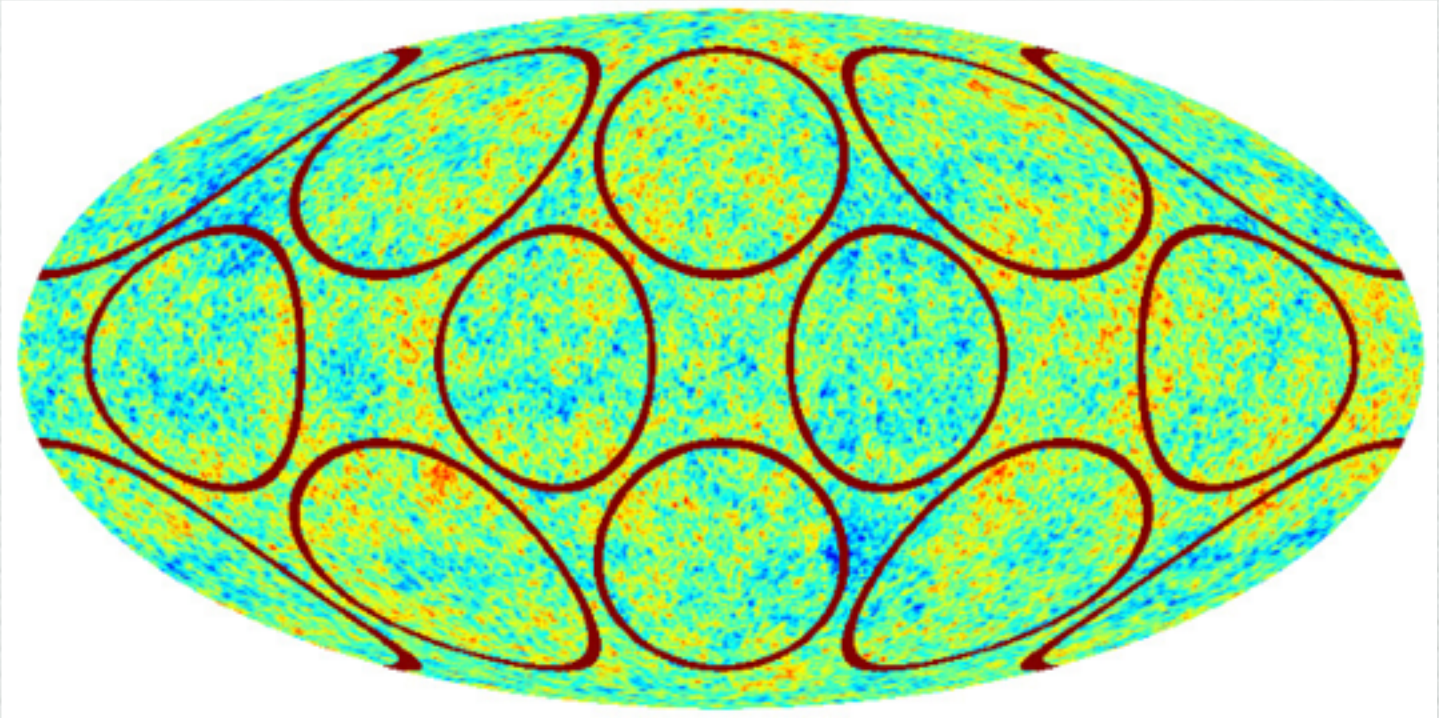
Measuring Topology with the CMB



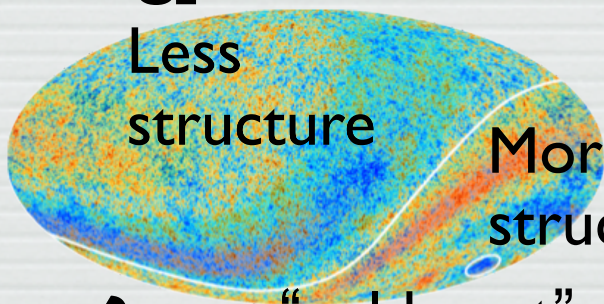
Topology from Planck

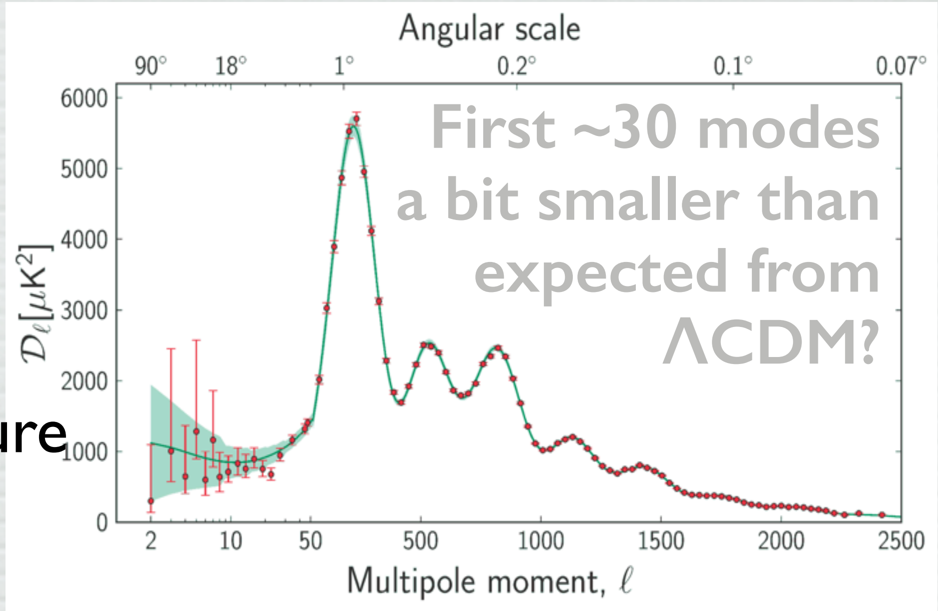


- "Matched circles" in a simulated Universe:
- When *topological scale ≲ Horizon scale*, induce anisotropic correlations (and suppress power) on large scales
- More powerful (Bayesian) methods take advantage of full correlation structure
- Alas, not found… but we limit the size of the "fundamental cube" to be greater than the size of the surface we observe with the CMB:
  - side $L \gtrsim 26$ Gpc (85 billion light years!)

Consistency of Planck data

- Do the data fit the model?
  - looks a little like a [wrong] Bianchi univ.

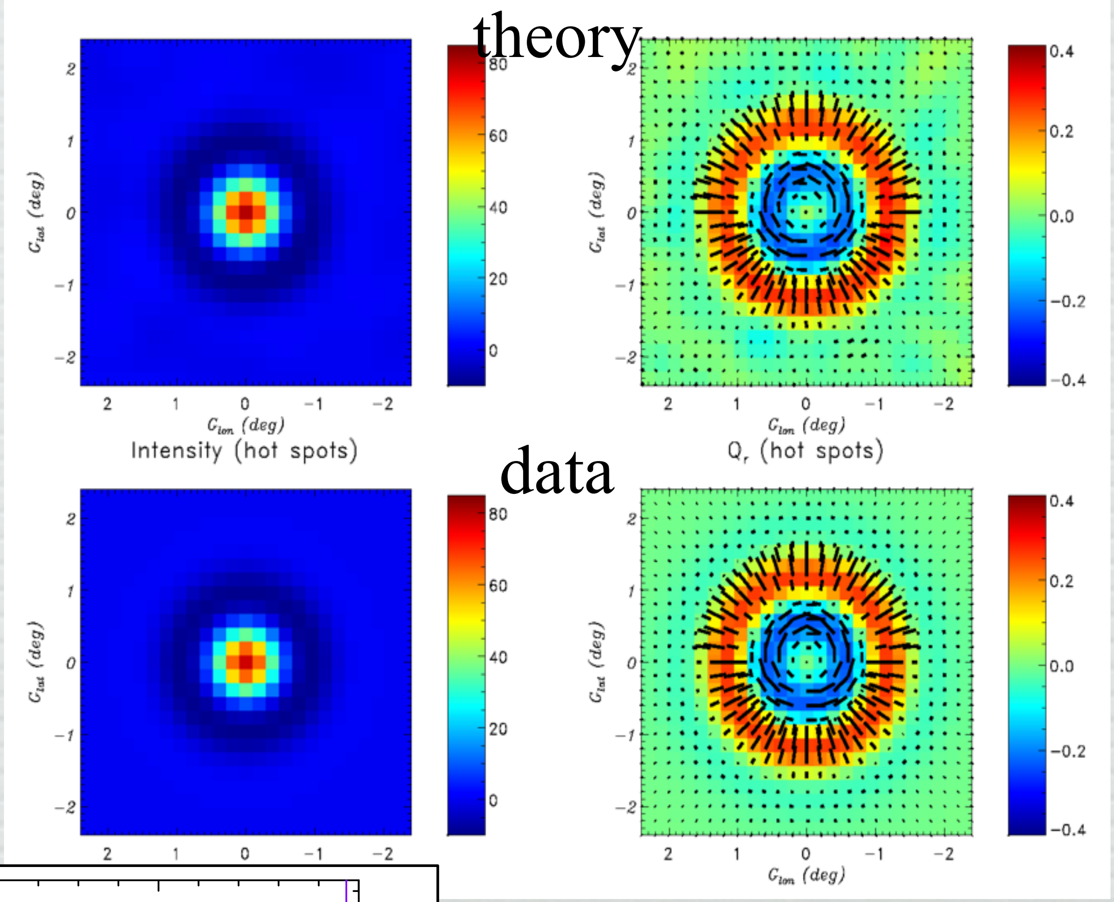




- Do different data agree?
  - within *Planck* ΔT/T: see above for self-consistency of maps, spectra, parameters
  - between *Planck* methods
    - lensing: direct measurement of lensing amplitude ~ 1.2 vs 1.0
    - clusters: lower Ω_m, σ_8
      - at face value, can be [only partially] ameliorated with neutrinos
      - but strong dependence on cluster modelling (e.g., hydrostatic bias)
  - Parameter details: e.g., CMB measurements of H_0 a few σ low vs cosmic distance ladder
    - astrophysical measurements seem to be coming down *a posteriori*?

Planck 2014-

- Next up: twice as much intensity data (30 vs 15 months) and polarization.
- Preview: at small/intermediate scales, polarization and intensity correlation exactly as predicted by theory.



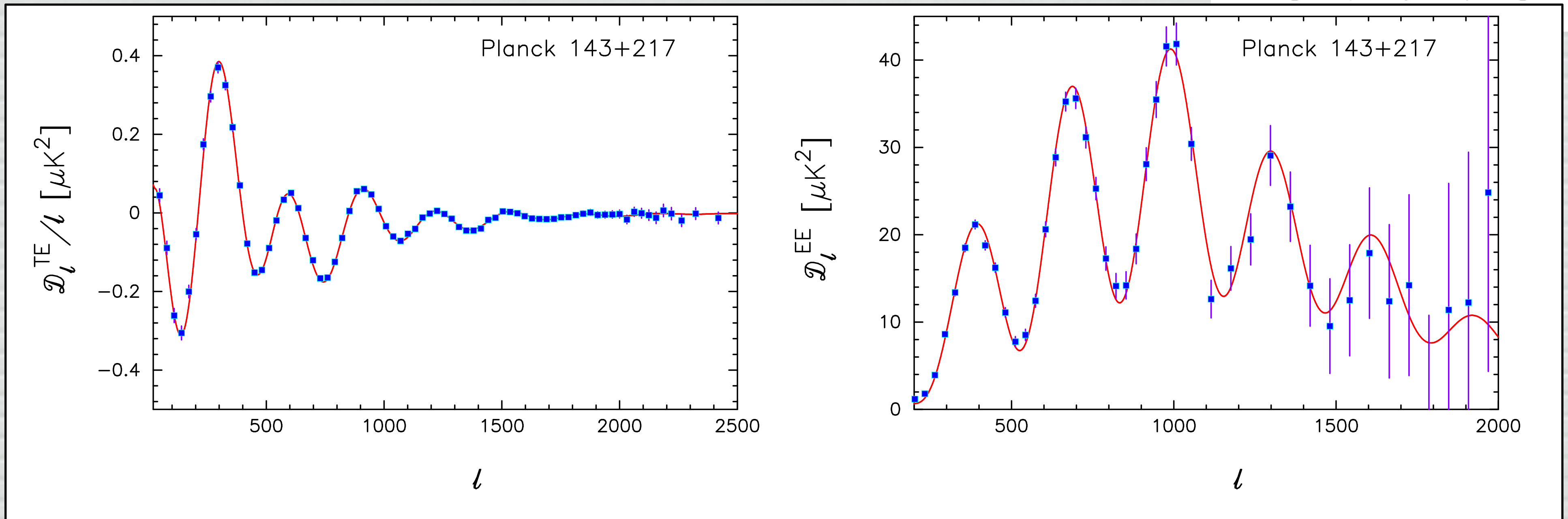
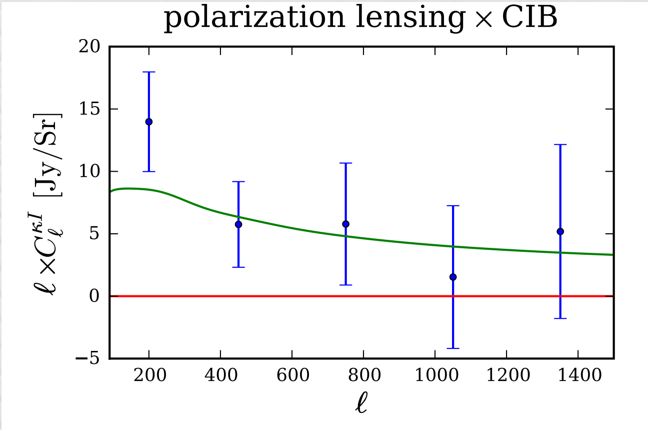


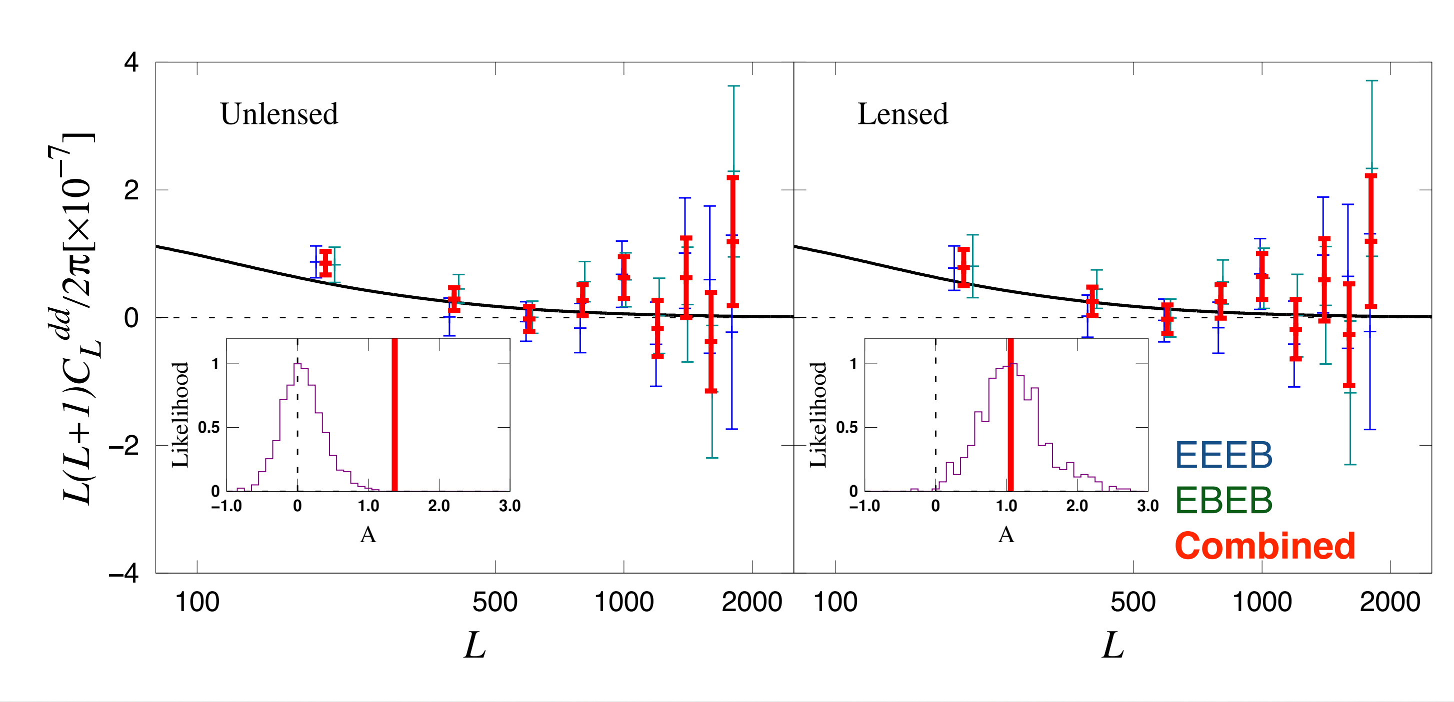
Fig. 11. *Planck TE* (left) and *EE* spectra (right) computed as described in the text. The red lines show the polarization spectra from the base ΛCDM *Planck*+WP+highL model, *which is fitted to the TT data only*.

Post-Planck

- Polarization: Starting to get the first results from kilo-pixel CMB detector arrays — sufficient to detect lensing conversion of E→B
  - Cross-correlation with large-scale structure (SPTPol: Hanson et al; ACT: Hand etal; Polarbear)



  - ⟨EEEB⟩ & ⟨EBEB⟩ (Polarbear)
  - Still no detection of primordial B modes (gravitational radiation)



Conclusions

- *Planck* data support a standard ΛCDM cosmology
  - flat FRW
  - perturbations:
    - nearly scale-invariant adiabatic
    - Gaussian + linear & nonlinear evolution
  - Λ-like acceleration

inflation?

- Some anomalies/inconsistencies remain (as might be expected)
- More data in 2014-15 from *Planck* and other experiments
  - especially polarization