Imperial College London

Planck launch, 14 May 2009
ESA Spaceport, French Guyana

The CMB

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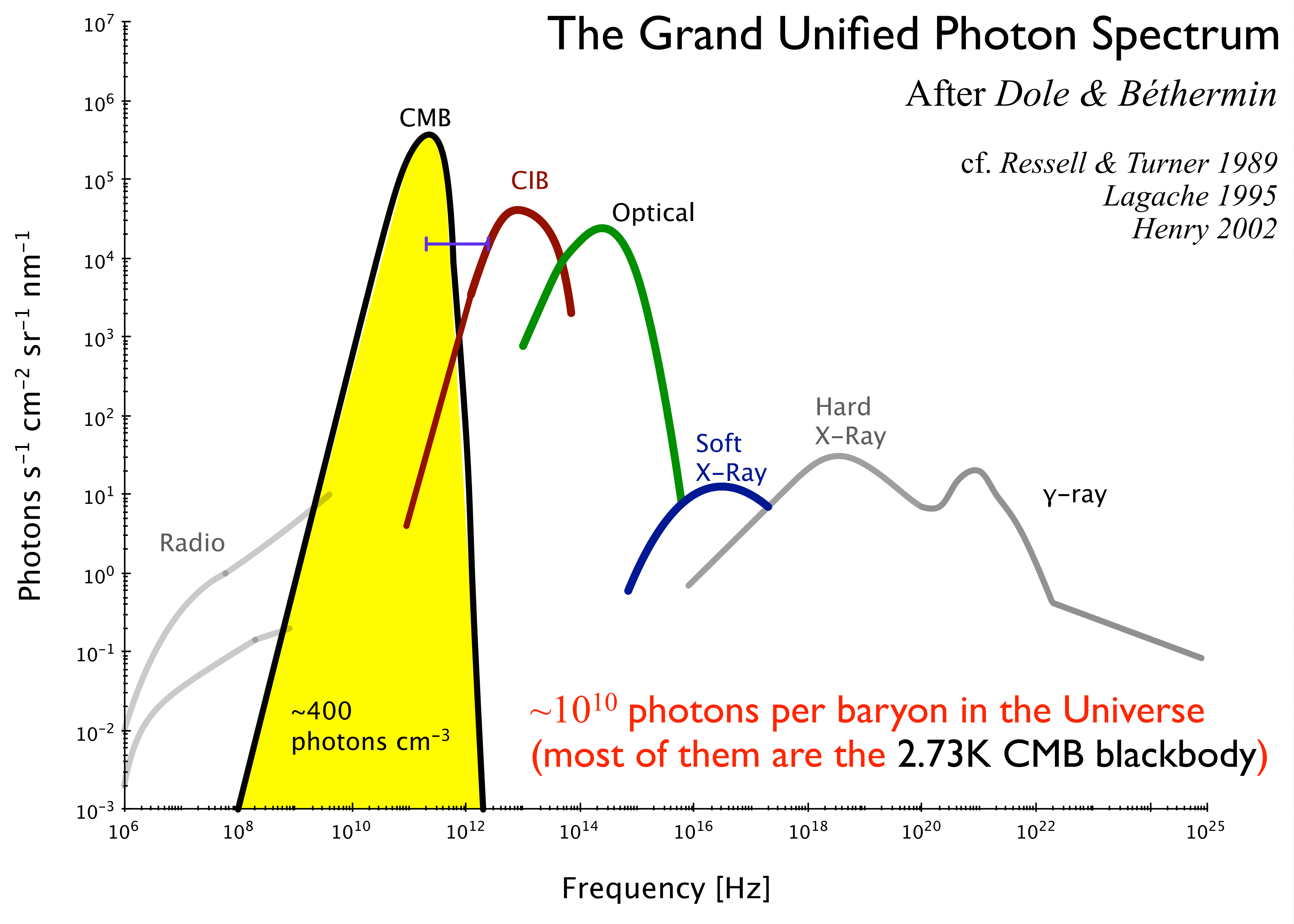
TIARA Winter School
AS/NTU, Taipei
February 2014

Outline

- What is the CMB?
  - Why is it the best cosmological probe (so far)?
  - What can we learn from it?
- State of the art
  - Planck — CMB intensity
    - primary fluctuations and lensing
  - Suborbital experiments
    - polarization – lensing
- The future:
  - highly sensitive polarization measurements from Planck and suborbital experiments

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

Light from the Universe



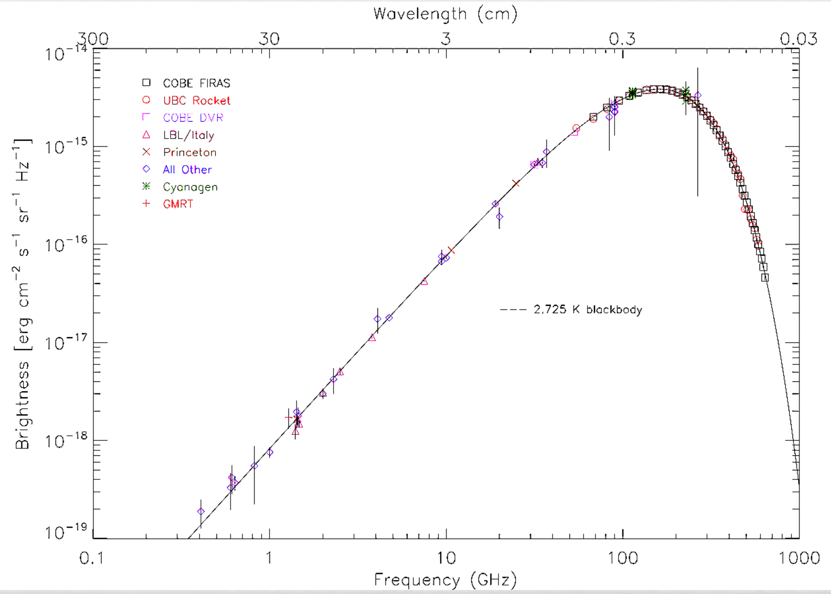
A standard cosmological model?

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

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*)

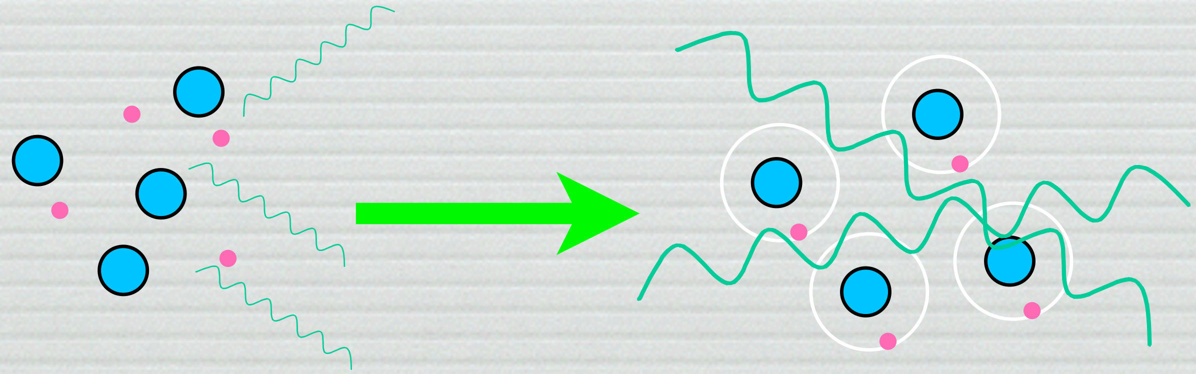


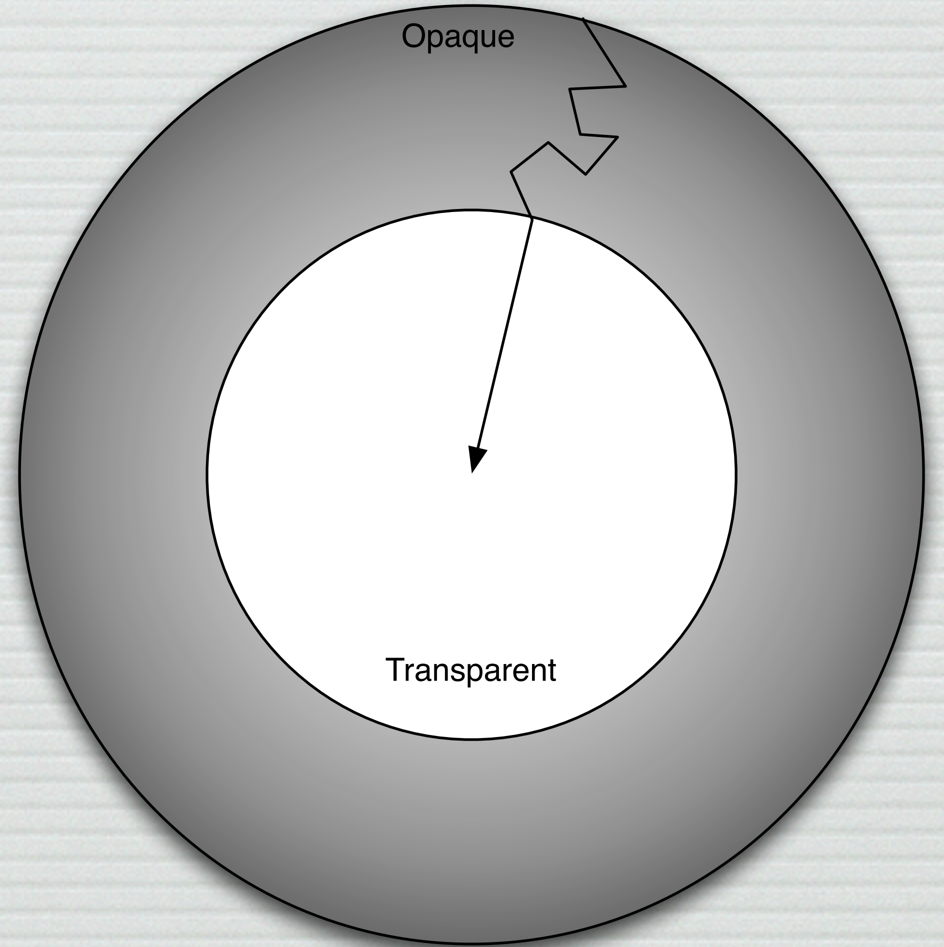
- Parameters:
  - density of radiation Ω_r, baryons Ω_b, dark matter Ω_c, dark energy Ω_Λ
  - Age t_0, expansion rate H_0
  - Curvature: Ω_k (=0?)

Also fluctuations—departures from uniformity—needed to form structure

Evidence & Observations: Cosmic Microwave Background

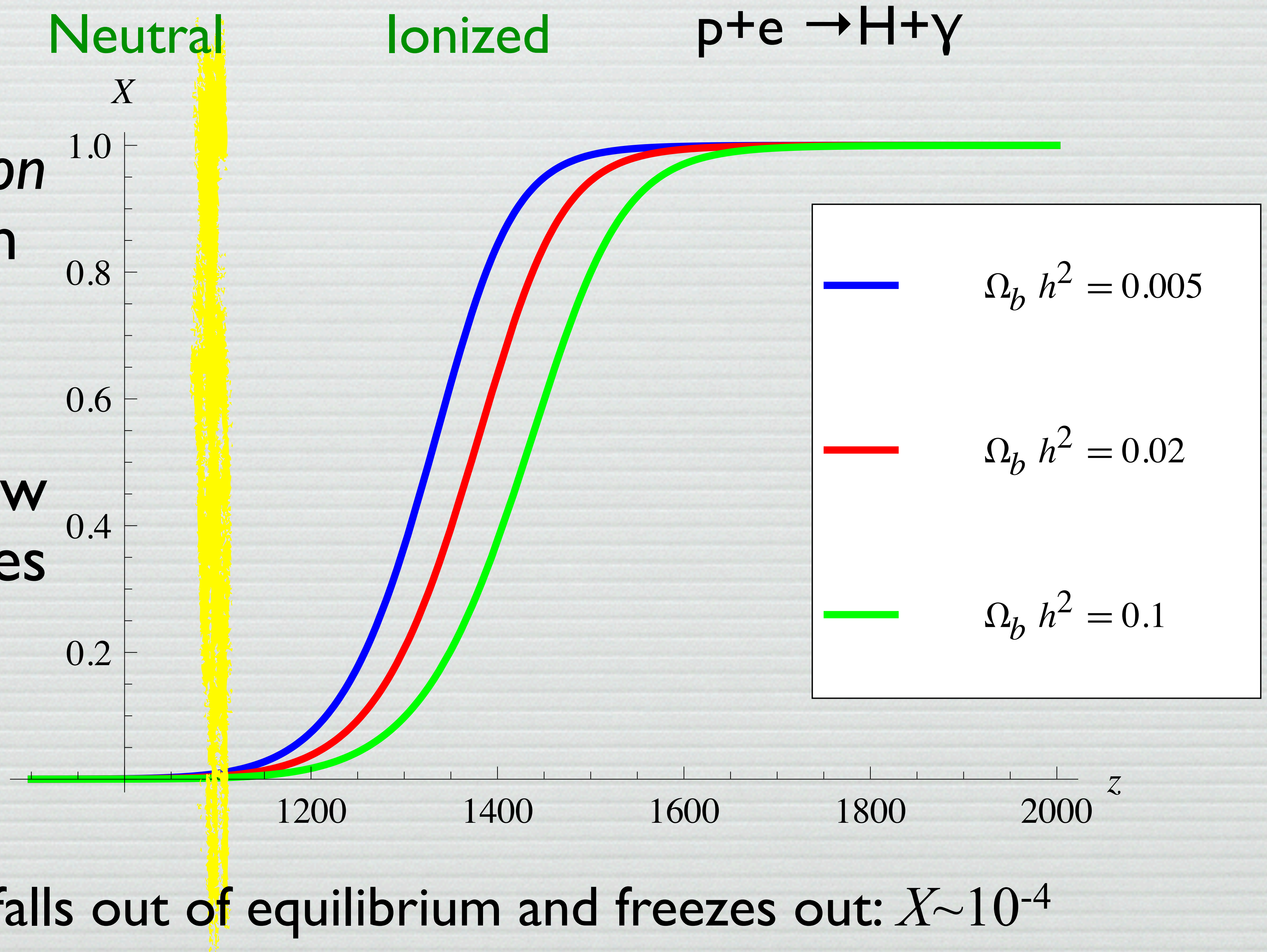
- 400,000 years after the Big Bang, the temperature of the Universe was T~3,000 K
- Hot enough to keep hydrogen atoms *ionized* until this time
  - ***proton + electron → Hydrogen + photon*** **[$p^+ + e^- \rightarrow H + \gamma$]**
  - ***charged plasma → neutral gas***
    - depends on *entropy* of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





Ionization fraction: Equilibrium

- large value of $\eta = n_b/n_\gamma \cong 10^{-9}$ key to "delay" to $kT \sim 0.6\text{eV} \ll 13.6$ eV
- Solve *Saha Equation* equilibrium ioniz'n balance
- really should follow many levels, species

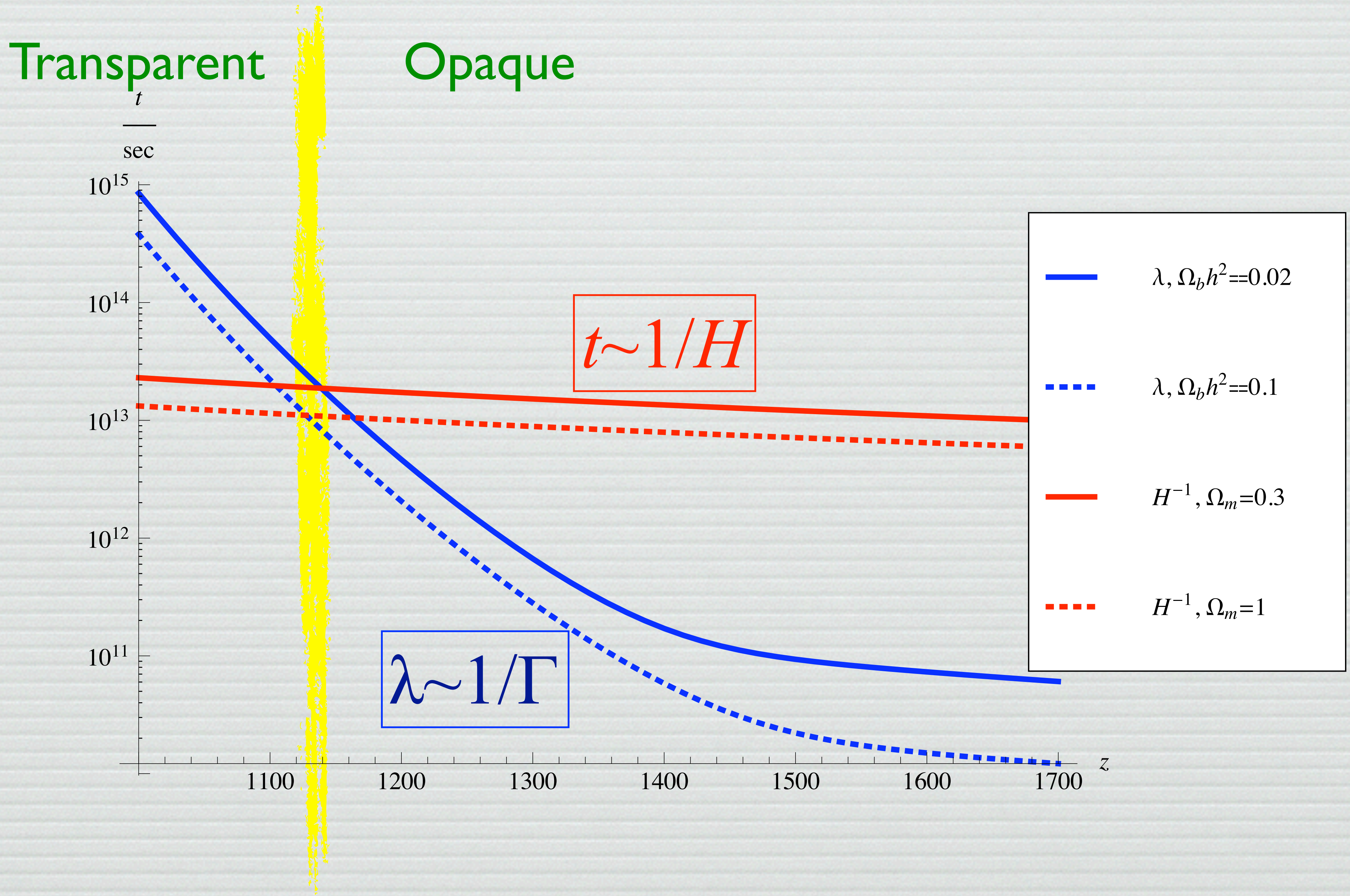


Not shown: interaction falls out of equilibrium and freezes out: $X \sim 10^{-4}$

Photon Decoupling

- Freeze-out when Γ<H

e+γ →e+γ

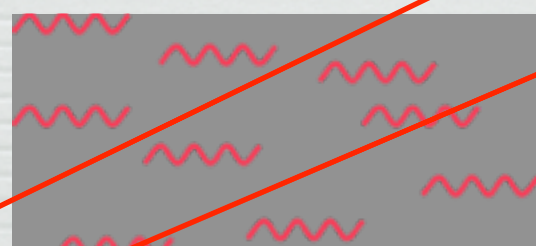


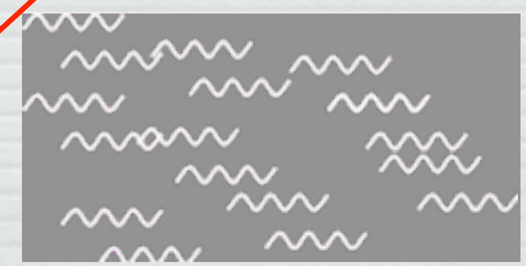
What affects the CMB temperature?

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

- Initial temperature (density) of the photons

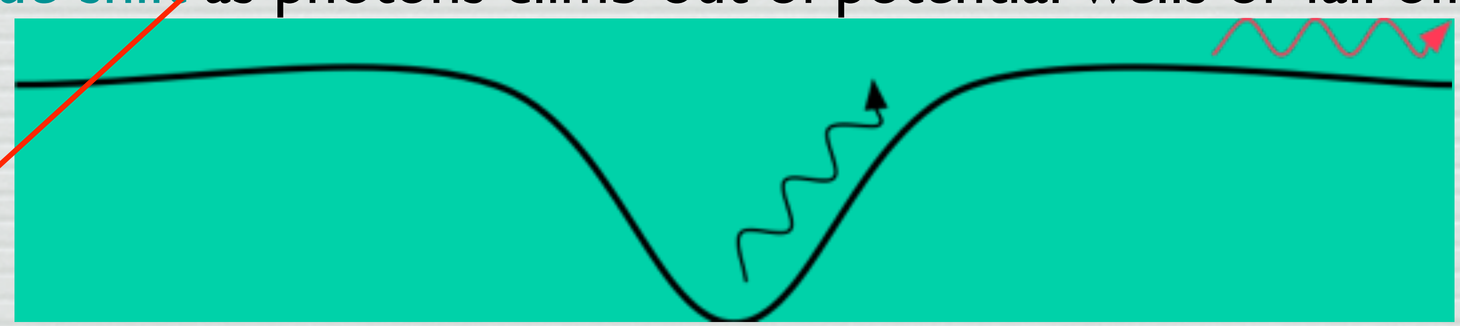
Cooler





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 ⇒ 10^{-5} fluctuations

The horizon at last scattering

- Particle (light) horizon at last scattering, corresponding to about 1° on the sky
  - $d_A = D/\theta = a_e r_e = a_o r_e (a_e/a_o) = a_o r_e/(1+z)$ for $D = d_H$
  - so $\theta = D/d_A$
- But fluctuations in the CMB are *sound waves*, so

$$d_{\rm sound} = \frac{1}{H_0(1+z)} \int_z^\infty \frac{dz' \; c_s}{E(z')}$$

for $c_s \simeq c/\sqrt{3}$ (mostly radiation):

- $d_{\rm sound} \simeq d_H/\sqrt{3}$

Large scales: the Sachs-Wolfe effect

- Outside the horizon (greater than a degree)
  - velocity term is negligible
  - metric (potential) term looks like

$$\int_{\rm rec}^{t_0} dt\,\dot{\phi} \simeq \phi_{\rm rec} - \phi_0$$

  - $\phi \simeq$ const for linear evolution in a flat MD universe
  - Further, the *potential* is related to the *density* term, so

$$\frac{\Delta T}{T} = \phi_{\rm rec} - \frac{2}{3}\phi_{\rm rec} = \frac{1}{3}\phi_{\rm rec}$$

- "Integrated Sachs-Wolfe effect" occurs when ϕ varies (e.g., nonlinear evolution, Λ, changing eq. of state)

Oscillations in primordial plasma: Acoustic Peaks

- Before recombination, a tightly-coupled plasma of matter (p, e) and photons
- Primordial/inflationary perturbations on all scales–can only collapse when in causal contact
- Pressure determined by mix of baryons and radiation ($\sim 10^{10}$ photons/baryon!): baryon "doping" lowers c_s from $1/\sqrt{3}$.
- Higher Ω_b decreases rebound force; lowers 2nd peak relative to first
- At smaller scales, imperfect coupling between baryons and photons — Silk damping

The CMB transfer function

$$C_\ell = \int P_i(k) T_\ell^2(k)\, dk$$

- compare density spectrum: $P(k) = P_i(k)T^2(k)$
- The transfer function depends on the "cosmological parameters". For example:
  - matter density—determines sound speed in baryon/photon fluid
  - curvature—determines angular-diameter distance to horizon

- Actually solve Boltzmann Equation over thickness of Last-Scattering surface – e.g., `CMBFAST, CAMB`

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:

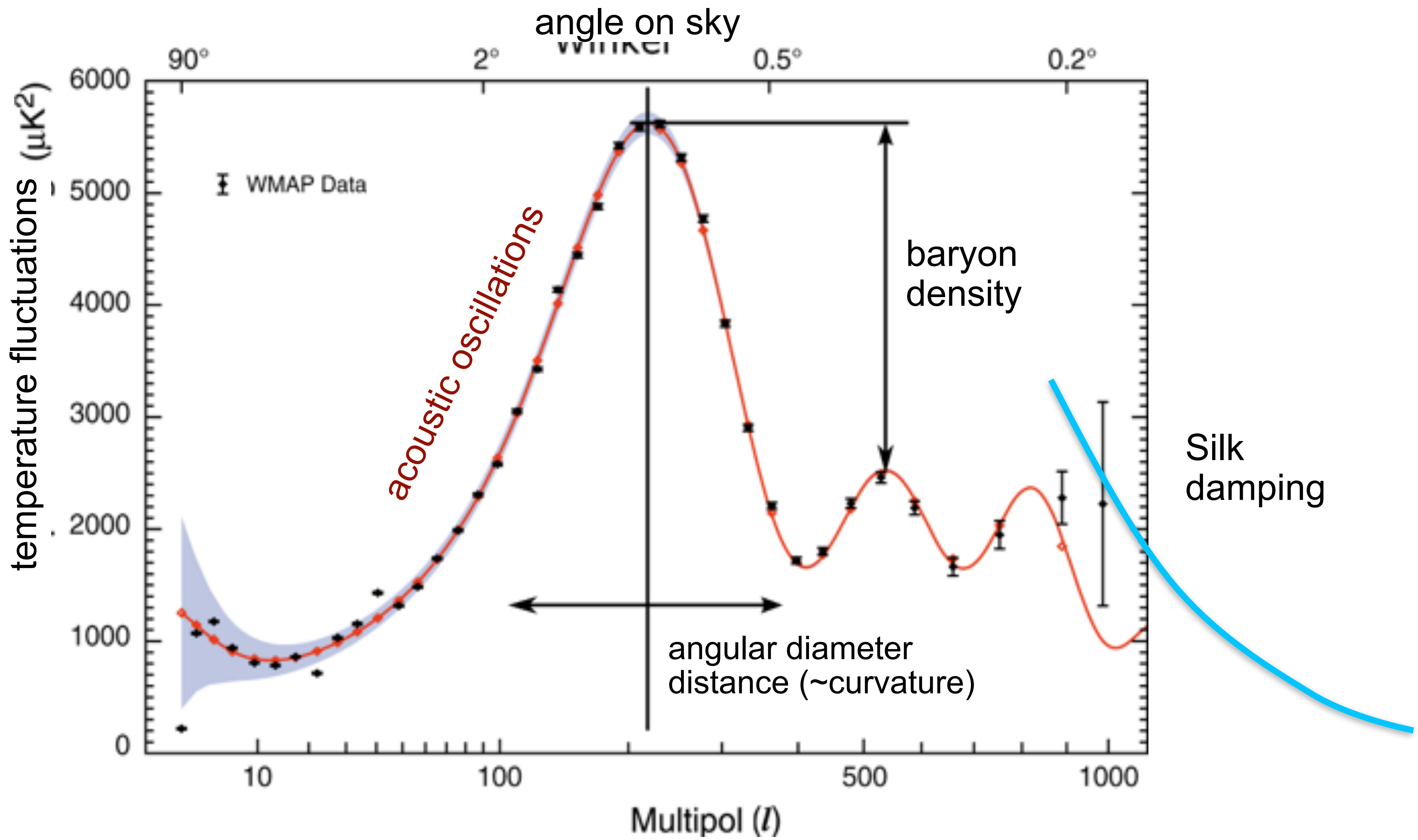
$$\langle a^*_{\ell m} a_{\ell' m'} \rangle = \delta_{\ell \ell'} \delta_{m m'} \, C_\ell$$

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

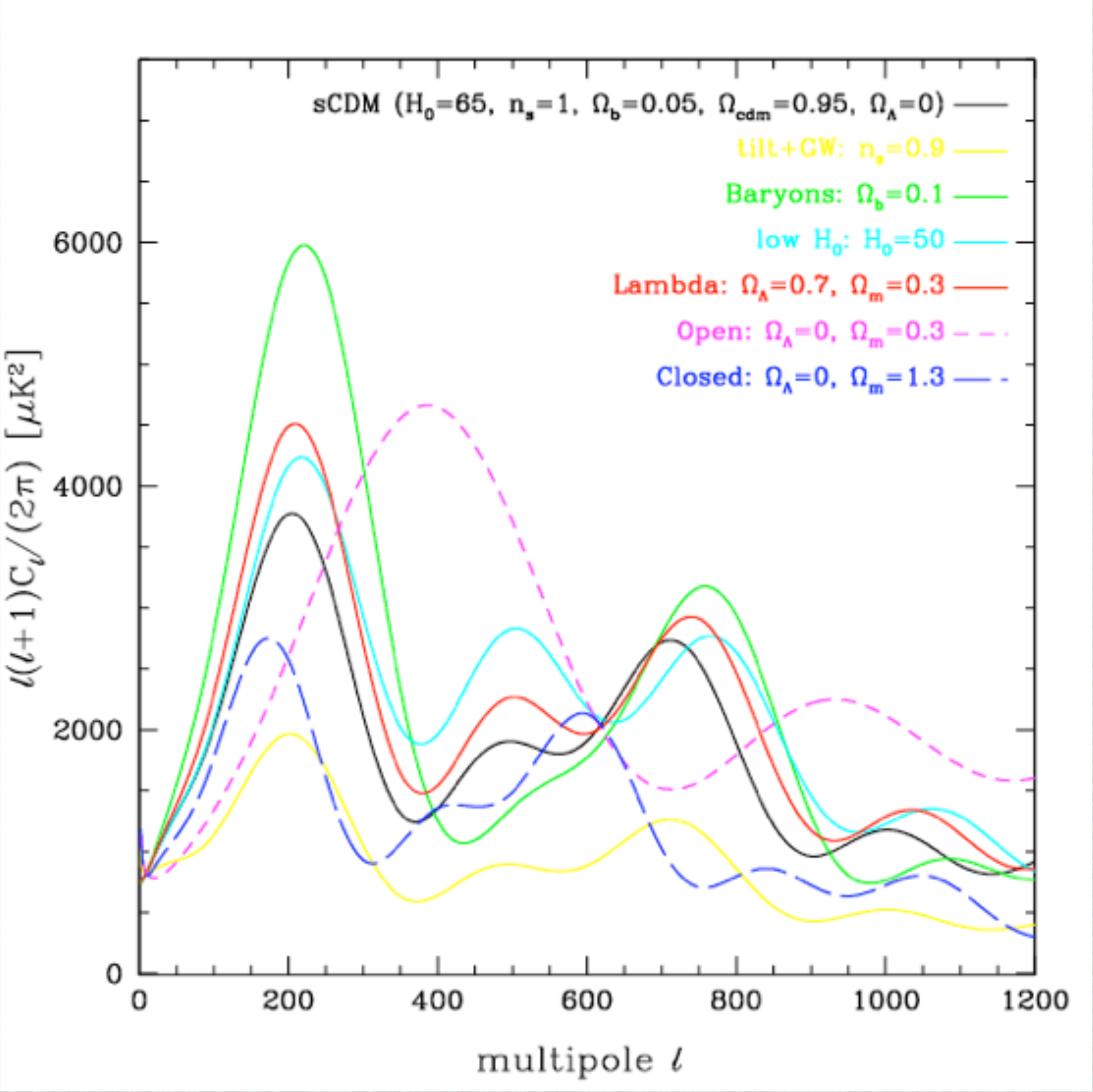
For a **Gaussian** theory, C_ℓ completely determines the statistics of the temperature.

Physics of the CMB power spectrum

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



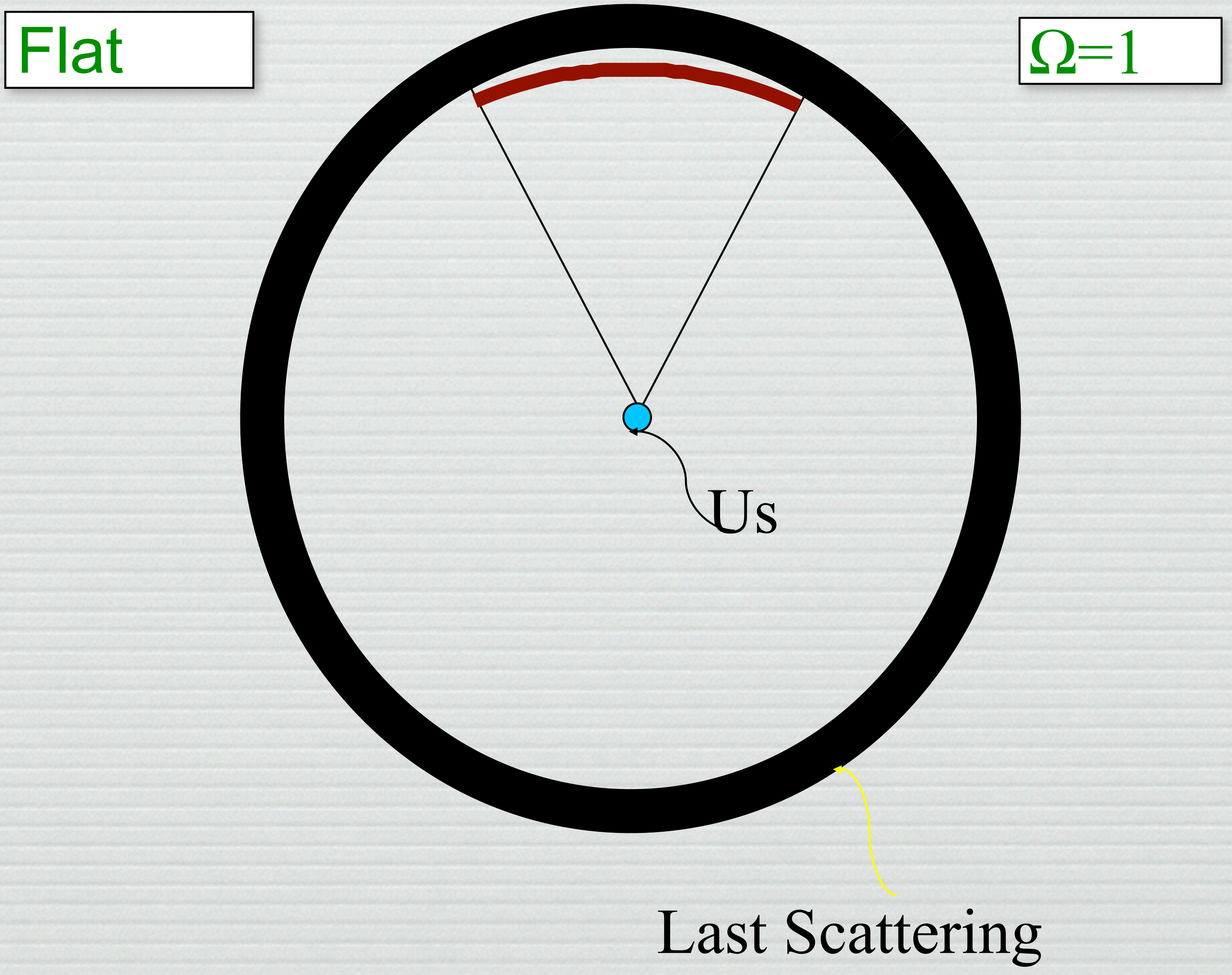
Theoretical Predictions

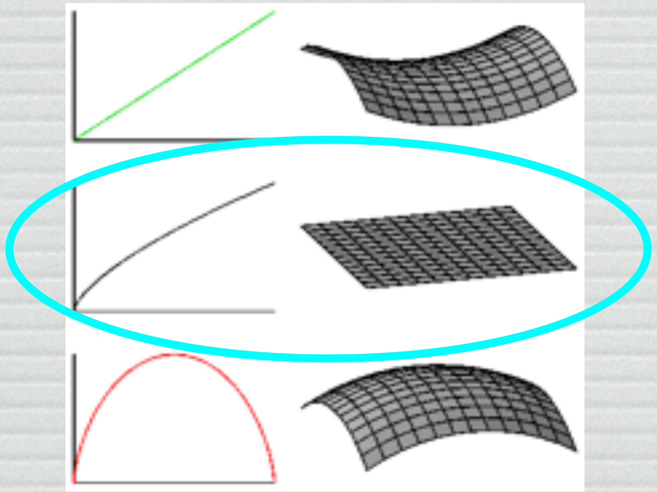


Mean square fluctuation amplitude

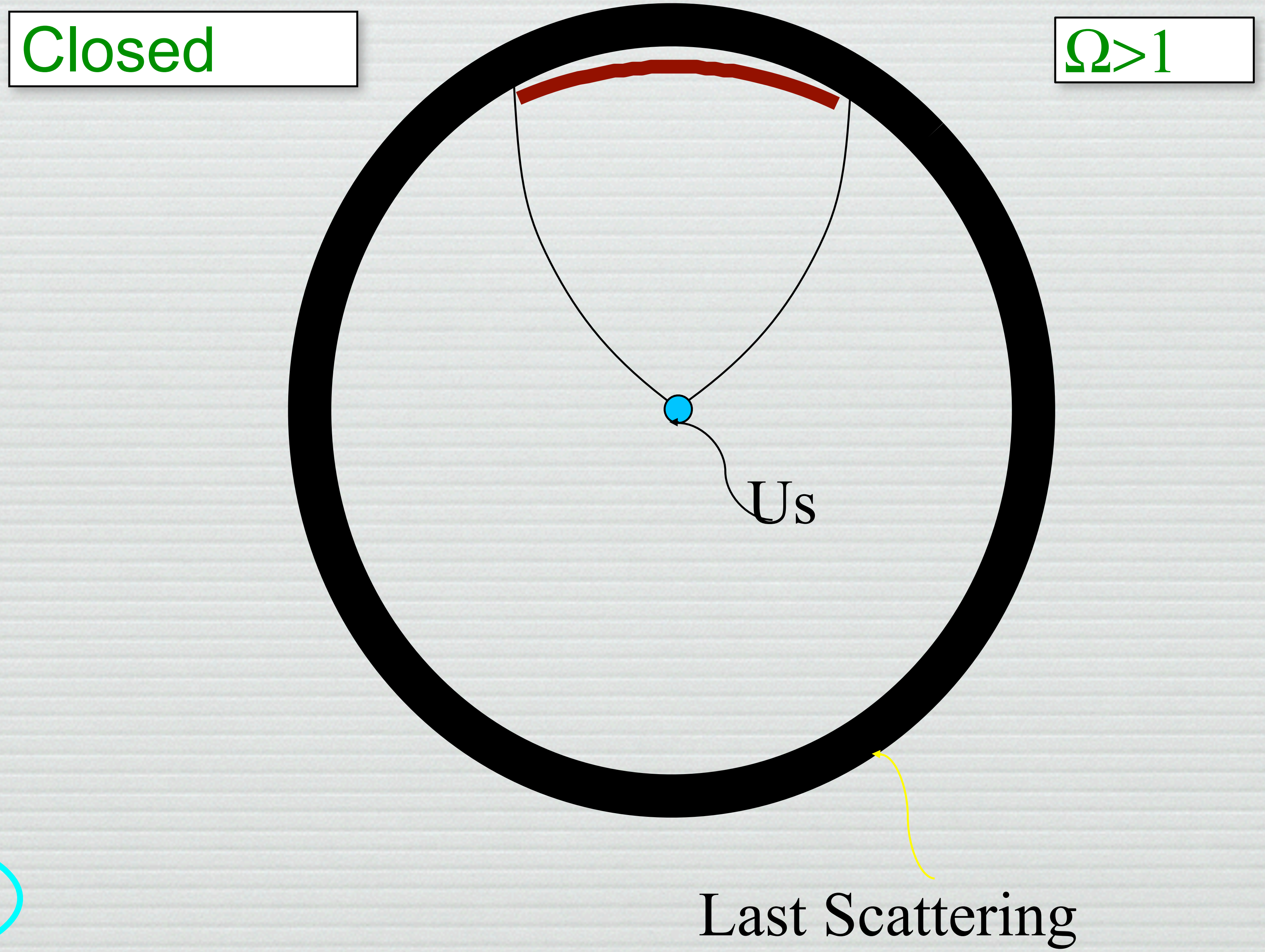
~180°/Angular scale

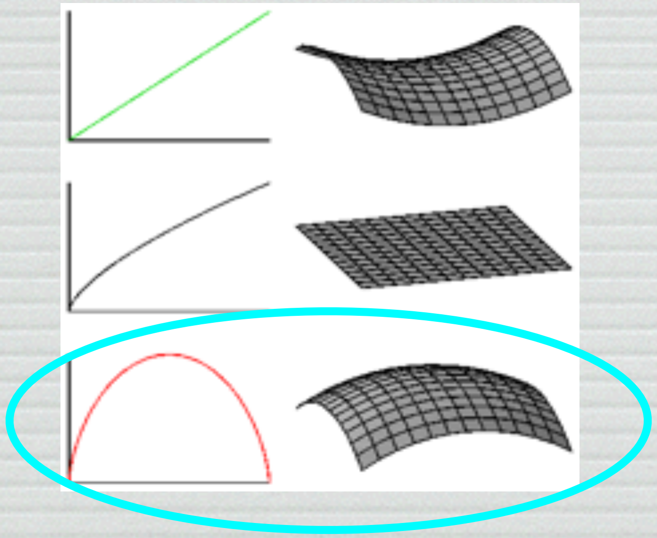
Measuring Curvature with the CMB





Measuring Curvature with the CMB

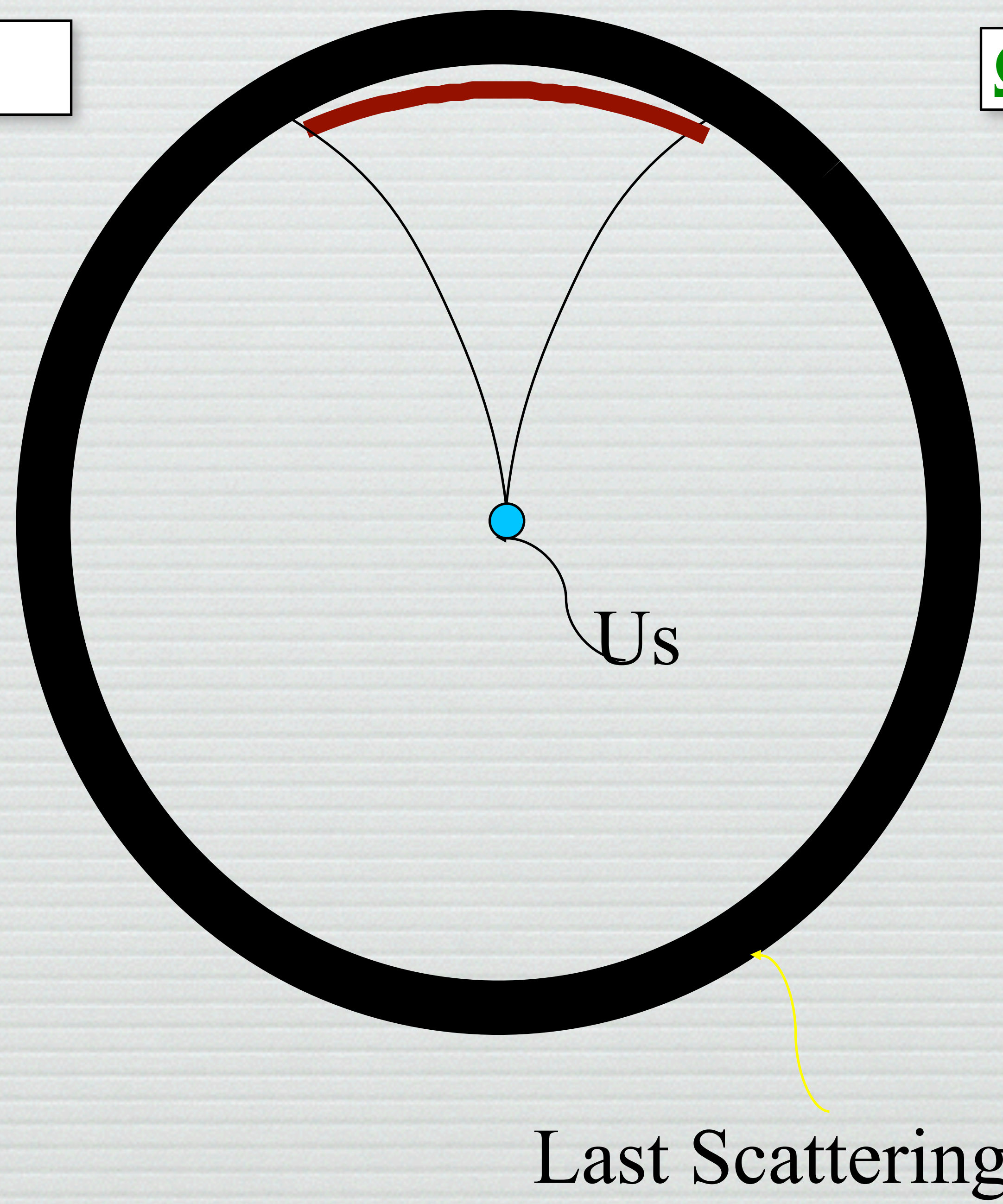


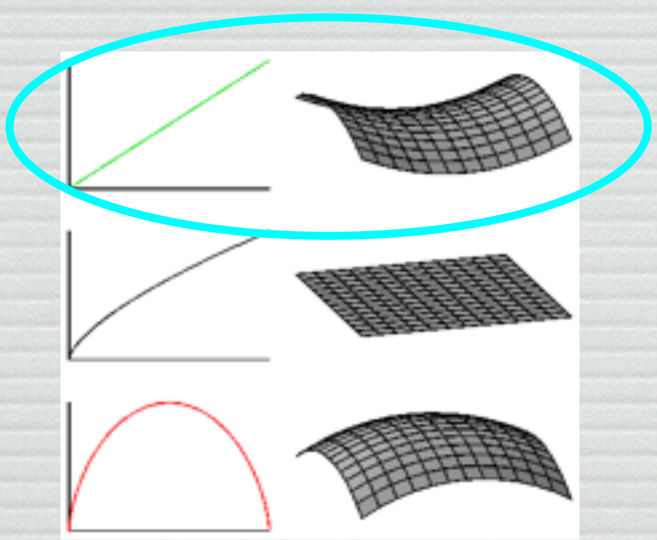


Measuring Curvature with the CMB

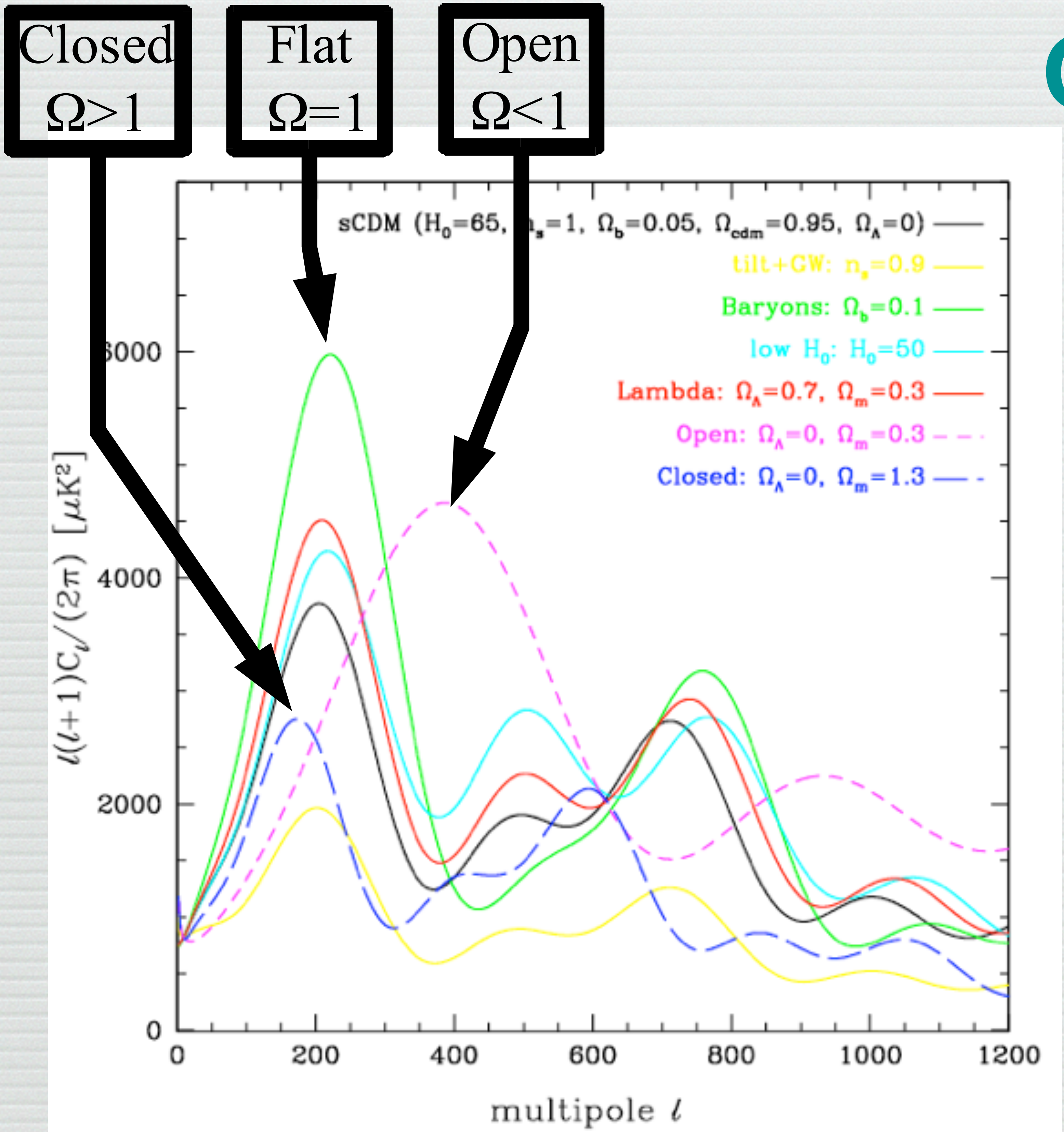
Open

$\Omega<1$





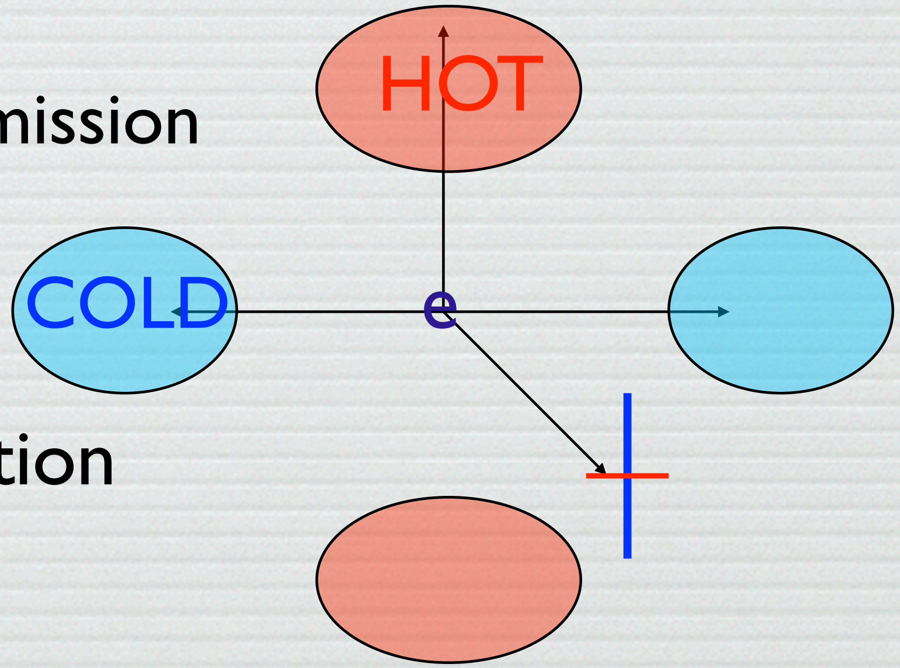
CMB Power Spectrum



- Model CMB as a 2d stationary Gaussian Random Field on the sphere
- Motivated by physics, confirmed by observation
  - (linear transform of underlying 3d process)

CMB Polarization: Generation

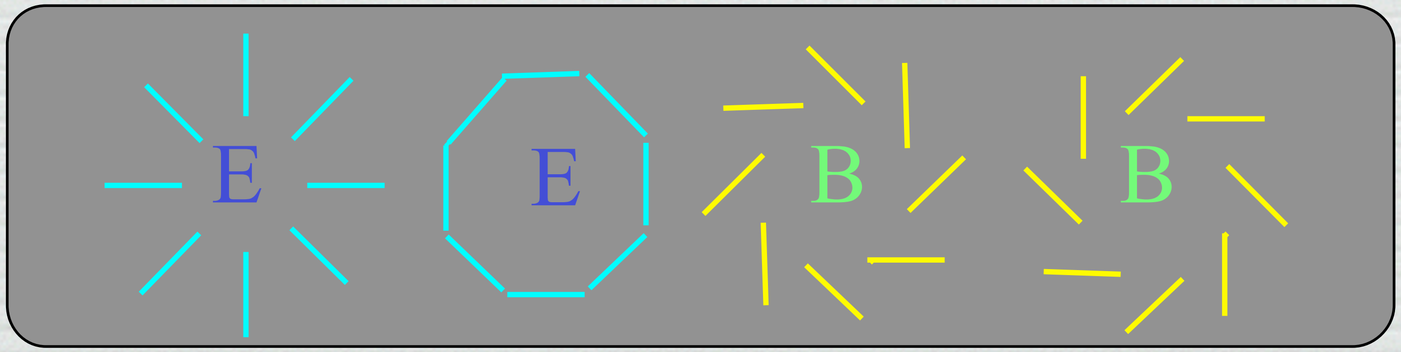
- Ionized plasma + quadrupole radiation field:
  - Thomson scattering ⇒ [linearly] polarized emission



- Unlike intensity, only generated when ionization fraction, $0<x<1$ (*i.e.*, during transition)
- *Scalar* perturbations: traces ~gradient of velocity
  - same initial conditions as temperature and density fluctuations
- *Tensor* perturbations: independent of density fluctuations
  - +,× patterns of quadrupoles (impossible to form via linear scalar perturbations)
  - at last-scattering, from primordial background of gravitational radiation, *predicted by inflation* (*cf. Senatore's lectures*)

CMB Polarization: E/B Decomposition

- 2-d (headless) vector field on a sphere
- Spin-2/tensor spherical harmonics
- grad/scalar/E + curl/pseudoscalar/B patterns



- NB. From polarization pattern ⇒ E/B decomposition requires integration (*non-local*) or differentiation (*noisy)*
  - *Lewis et al; Bunn et al; Smith & Zaldarriaga; Grain et al; Bowyer & AJ; …*
  - (data analysis problems)

Seljak & Zaldarriaga

Polarization: math

- Scalar and tensor modes are isotropic, parity-symmetric fields on the sky.
- T is a scalar, E is the "gradient" of a scalar, B is the "curl" of a pseudoscalar

$$Q(\hat{n}) = -\frac{1}{2}\sum_{lm}\left(a^E_{lm}\left[{}_2Y_{lm}(\hat{n}) + {}_{-2}Y_{lm}(\hat{n})\right] + ia^B_{lm}\left[{}_2Y_{lm}(\hat{n}) - {}_{-2}Y_{lm}(\hat{n})\right]\right)$$

$$U(\hat{n}) = -\frac{1}{2}\sum_{lm}\left(a^B_{lm}\left[{}_2Y_{lm}(\hat{n}) + {}_{-2}Y_{lm}(\hat{n})\right] + ia^E_{lm}\left[{}_2Y_{lm}(\hat{n}) - {}_{-2}Y_{lm}(\hat{n})\right]\right)$$

$$e(\hat{n}) = \sum_{lm}\sqrt{\frac{(l-2)!}{(l+2)!}}a^E_{lm}Y_{lm}(\hat{n}) \qquad b(\hat{n}) = \sum_{lm}\sqrt{\frac{(l-2)!}{(l+2)!}}a^B_{lm}Y_{lm}(\hat{n})$$

$$\nabla^4 e = -\frac{1}{2}[\bar{\eth}^2(Q+iU) + \eth^2(Q-iU)] \qquad \nabla^4 b = \frac{i}{2}[\bar{\eth}^2(Q+iU) - \eth^2(Q-iU)]$$

  - expect $\langle \mathrm{EB}\rangle = \langle \mathrm{TB}\rangle = 0$
  - try to measure $\langle \mathrm{TT}\rangle$, $\langle \mathrm{BB}\rangle$, $\langle \mathrm{EE}\rangle$, $\langle \mathrm{TE}\rangle$

CMB Signals from inflation

- Want to probe inflaton potential V(φ)
- Induce scalar and tensor power spectra
  - Observables:
    - temperature and polarization CMB spectra
    - functionally linear relationships

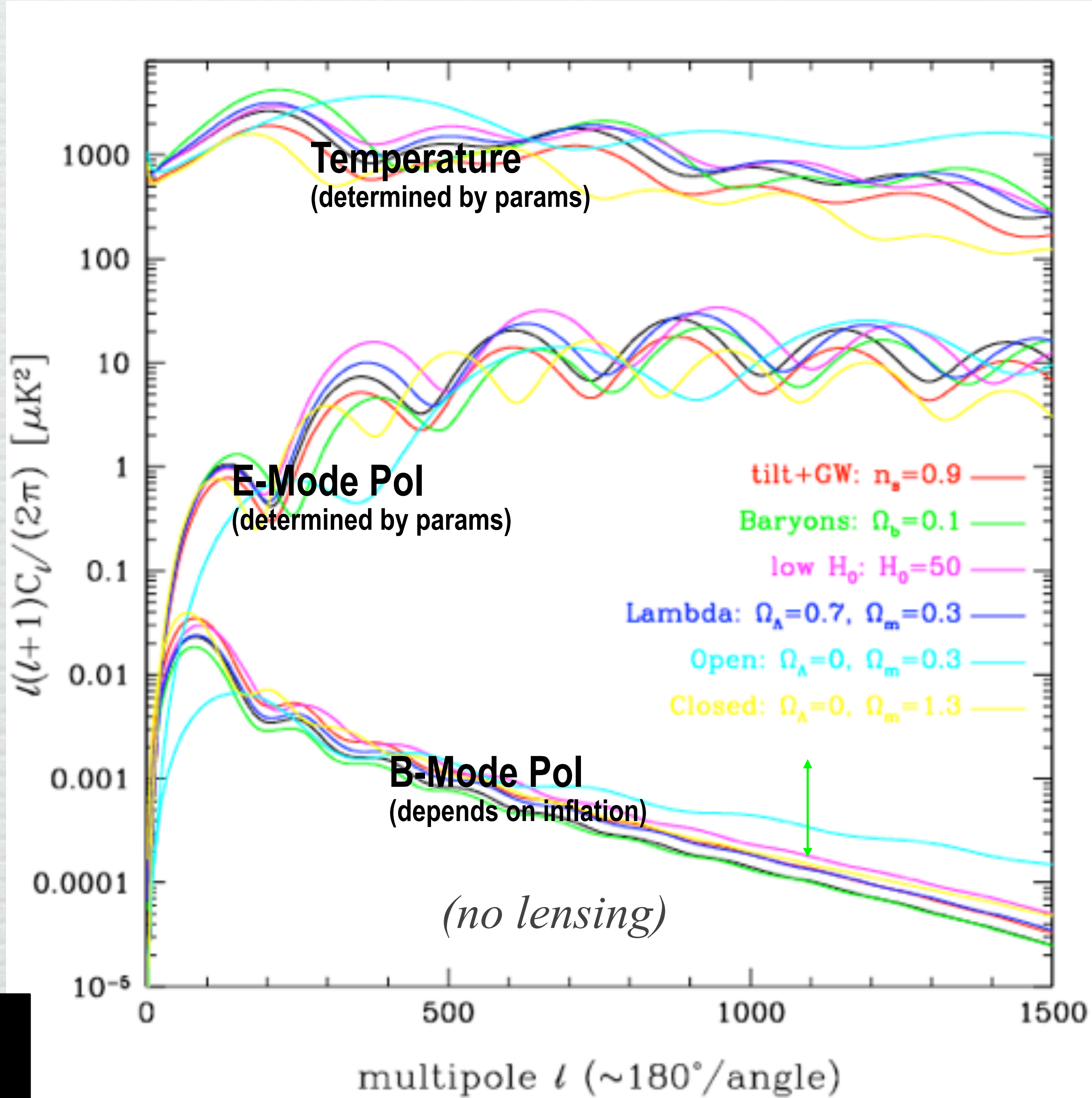
$$C_\ell^{BB} = \int dk\, T_\ell^{hB}(k) P_h(k)$$

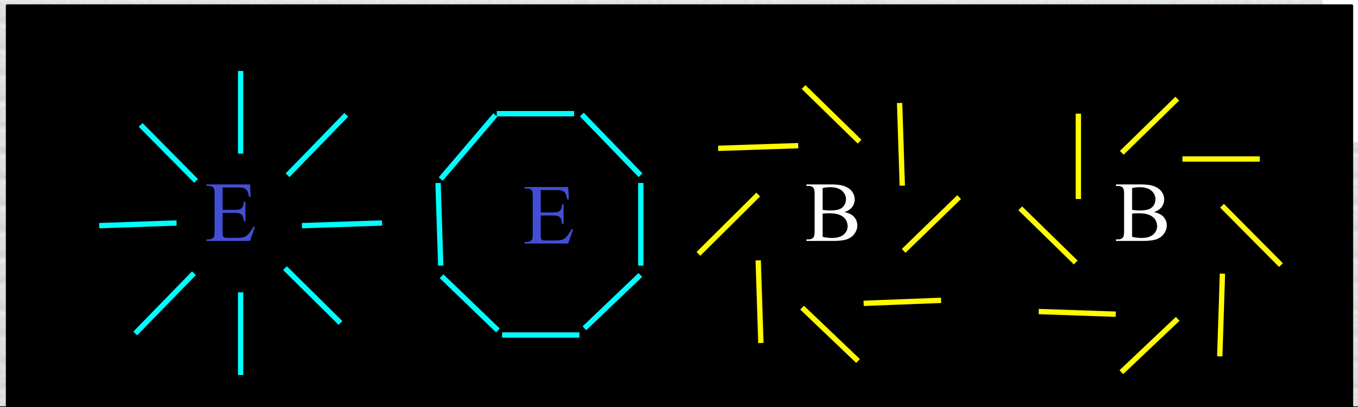
$$C_\ell^{TT} = \int dk\, \left[T_\ell^{hT}(k) P_h(k) + T_\ell^{RT}(k) P_R(k)\right]$$

    - Transfer functions T depend on cosmological parameters
    - Amplitude (r=T/S) and shape (n_s, n_T) of the spectra probe the inflaton potential
- Non-gaussianity:
  - specific inflationary models ⇒ departures from Gaussianity
  - e.g., f_{NL}~1 (in reach of Planck, but not [yet] detected)

The Polarization of the CMB

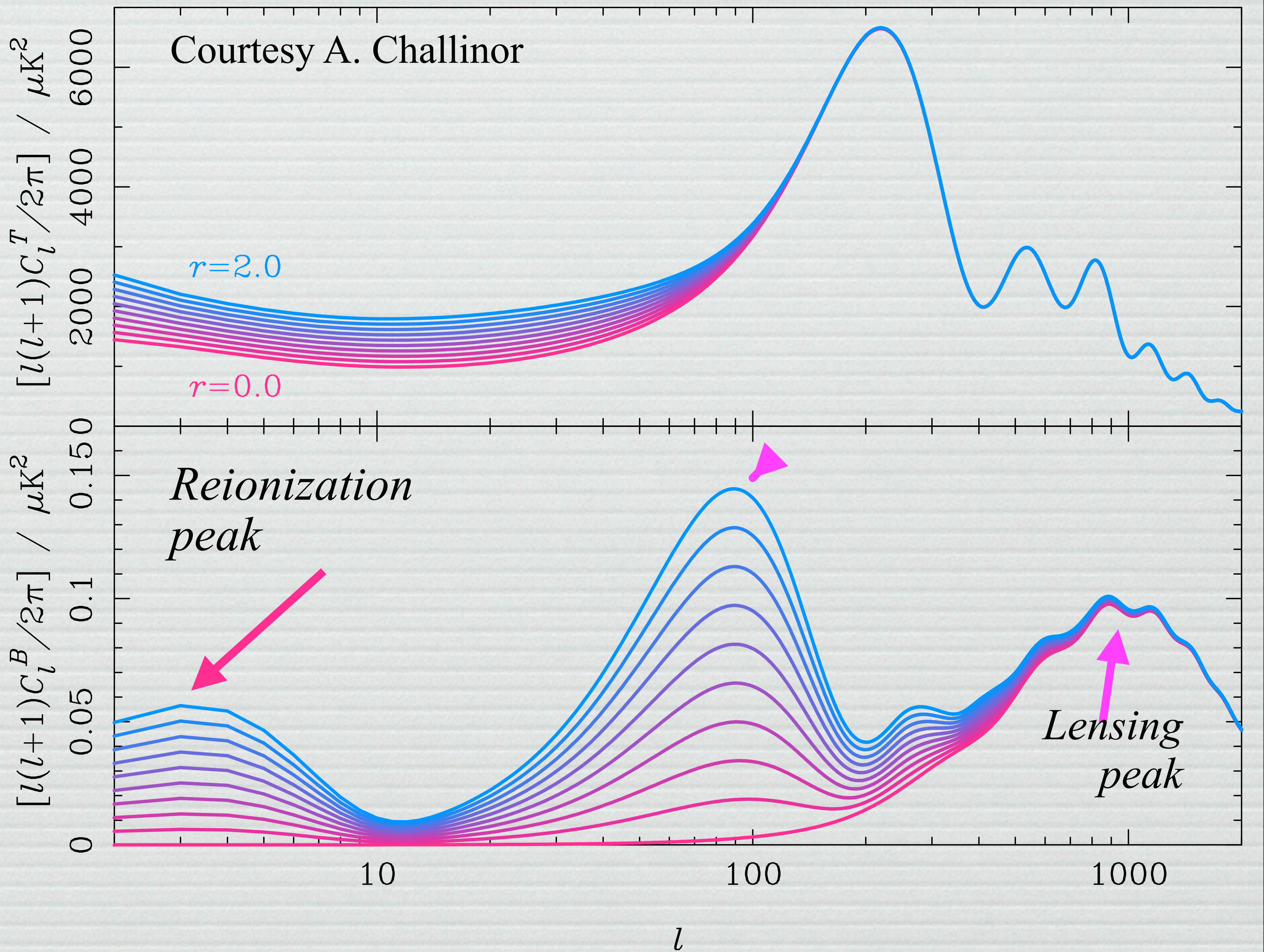
- Anisotropic radiation field at last scattering → polarization
  - "Grad" or *E* mode
  - Breaks degeneracies
  - New parameters:
    - reionization
- "Curl" or *B* sensitive to gravity waves
  - "Smoking gun" of inflation?
  - Very low amplitude
- Need better handle on systematics, and...
- Polarized foregrounds?





Gravitational Radiation & CMB

- Last scattering: "direct" effect of tensor modes (primordial GWs) on the primordial plasma
  - inflationary potential
- dominated by *lensing of E* ⇒ *B* for ℓ≳200

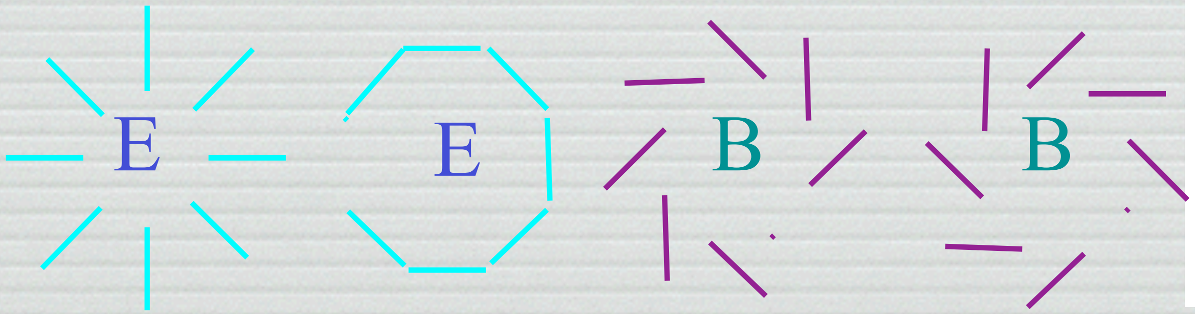


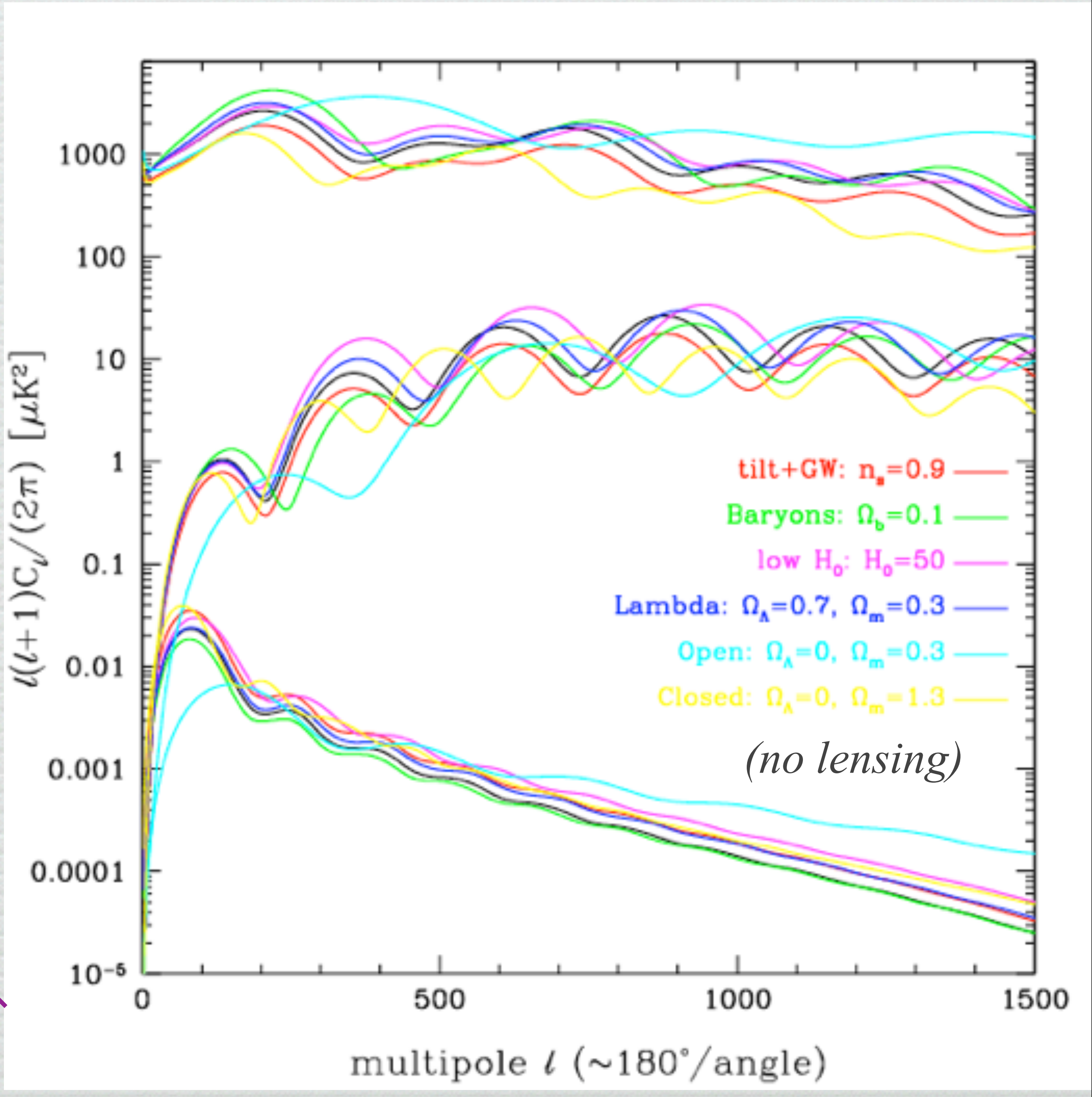
  - sensitive to $m_\nu \lesssim 0.06$eV
    - (i.e., hot dark matter)
- Reionization peak ℓ≲20
  - need ~full-sky. Difficult for single suborbital experiments
- *Limits depend on full set of parameters*

Suborbital experiments target ℓ~100 peak: require order-of-magnitude increase in sensitivity over Planck

Polarization from Gravitational Radiation

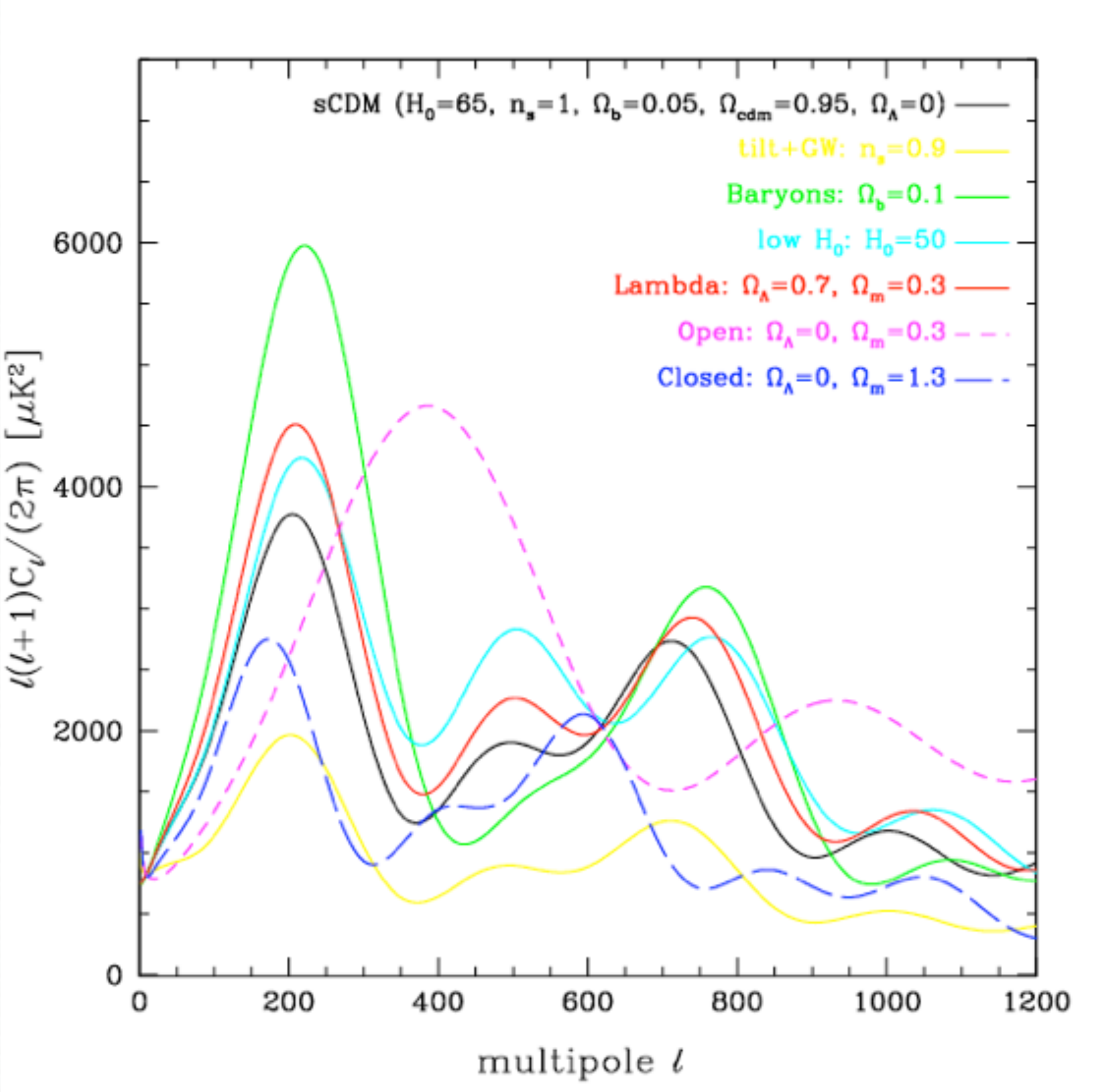
- Causal physics — scattering in baryon-photon plasma — same as intensity, E-mode polarization
  - Specific predictions given primordial P(k) + parameters





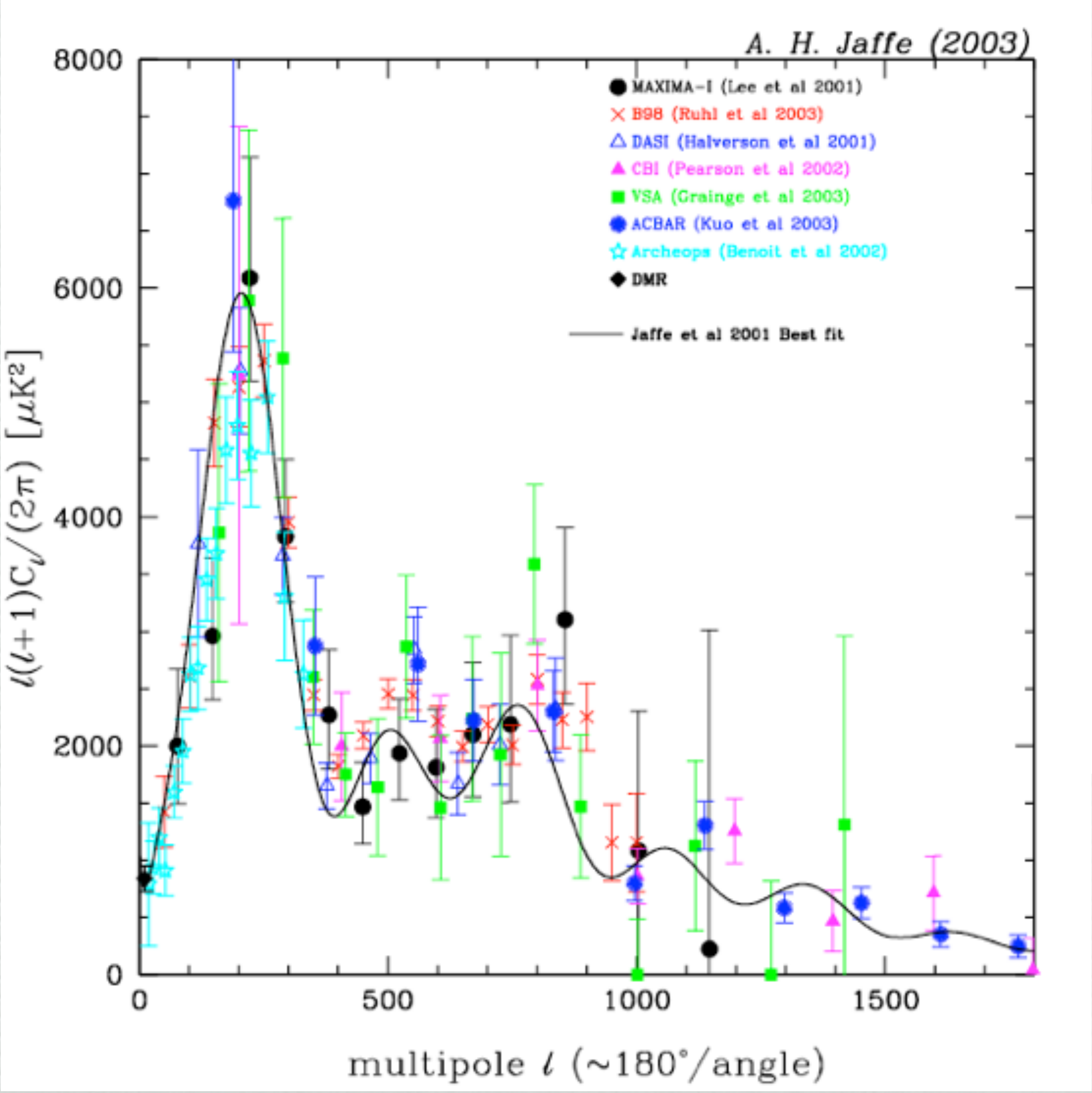
Theoretical Predictions

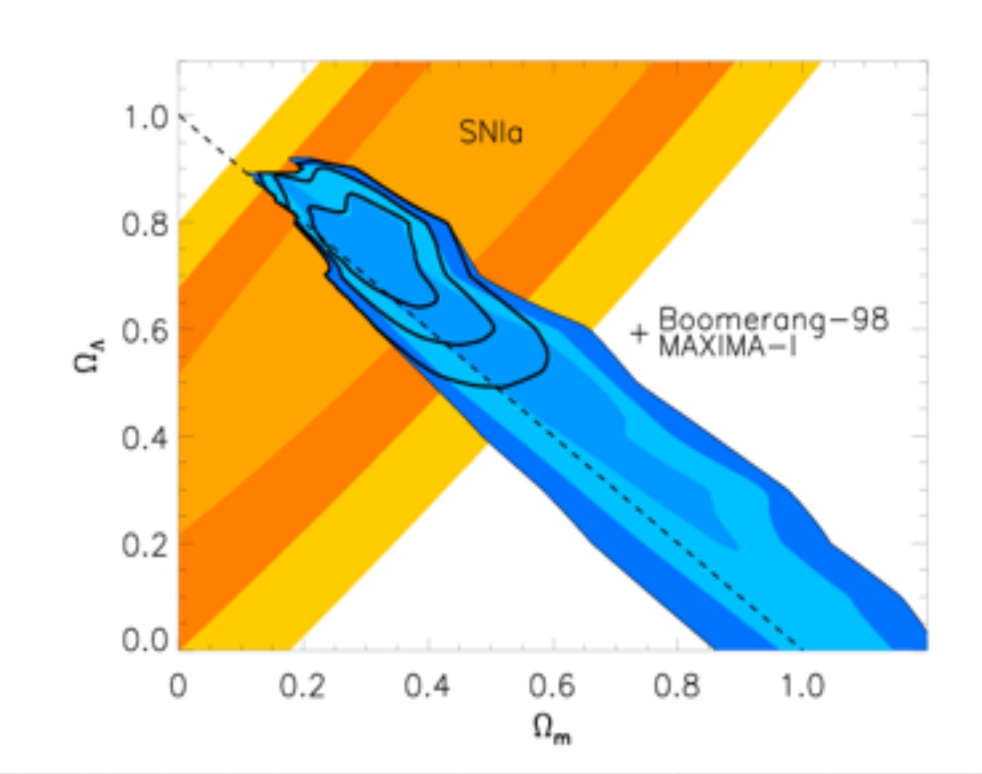
Mean square fluctuation amplitude



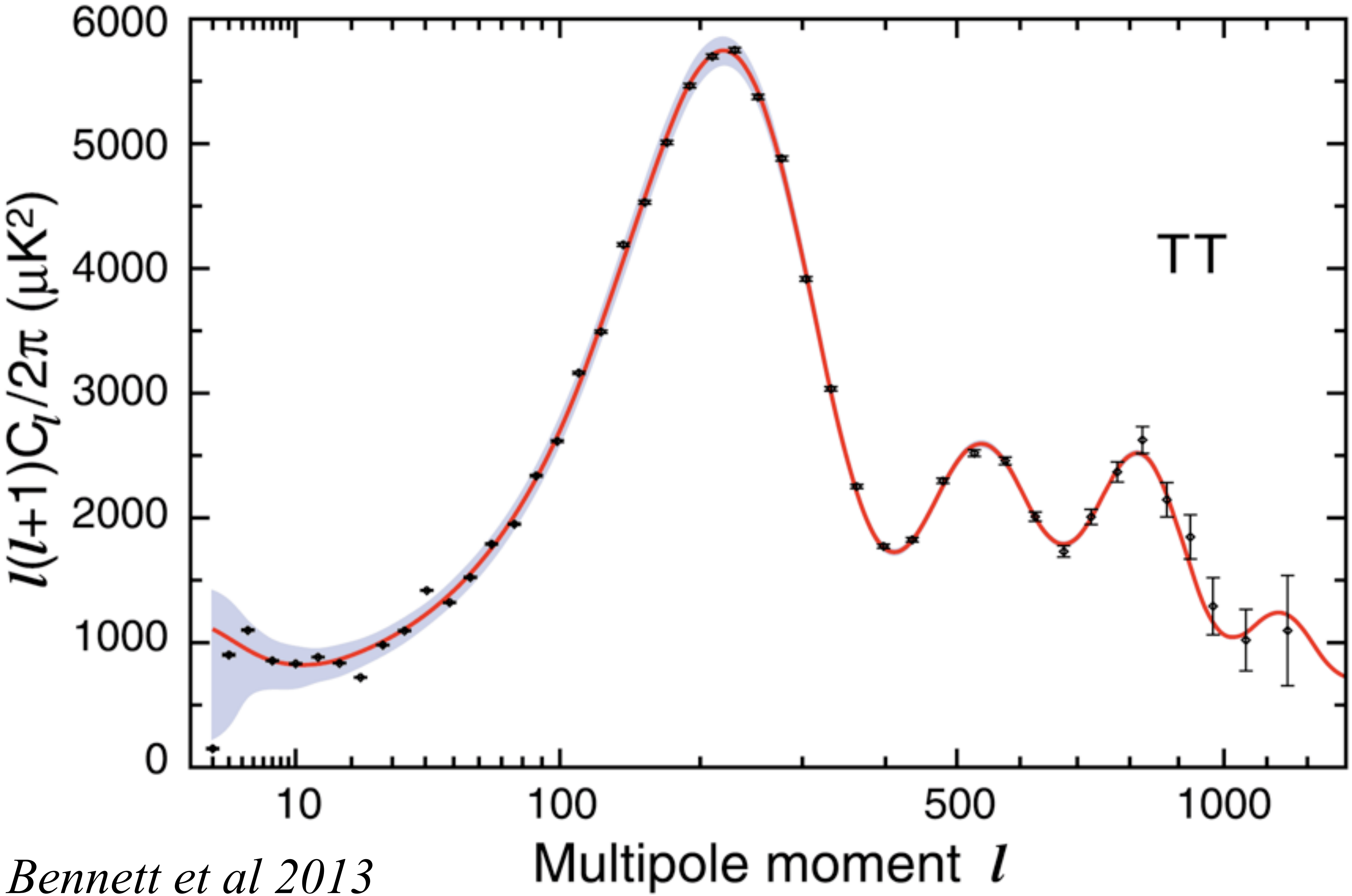
~180°/Angular scale

January, 2003





WMAP (2003-2012)



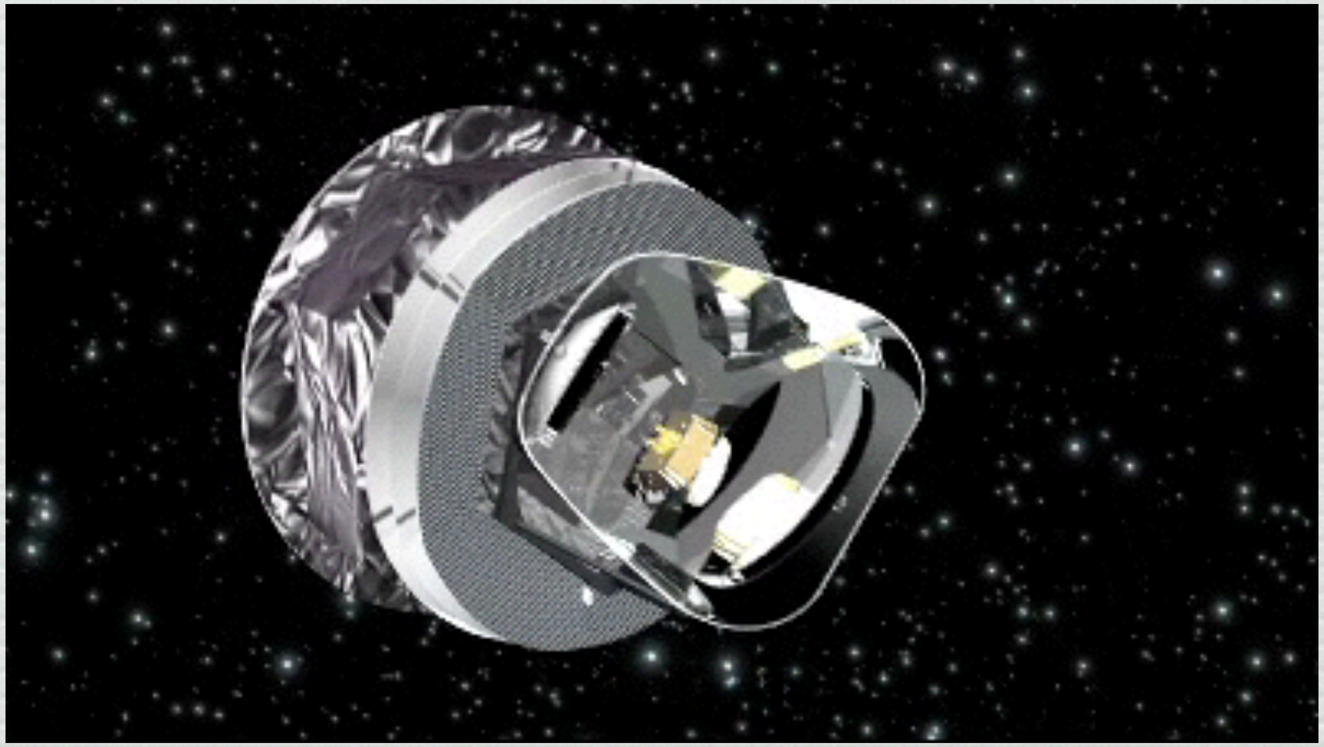
Bennett et al 2013

Planck: Launched 2009

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

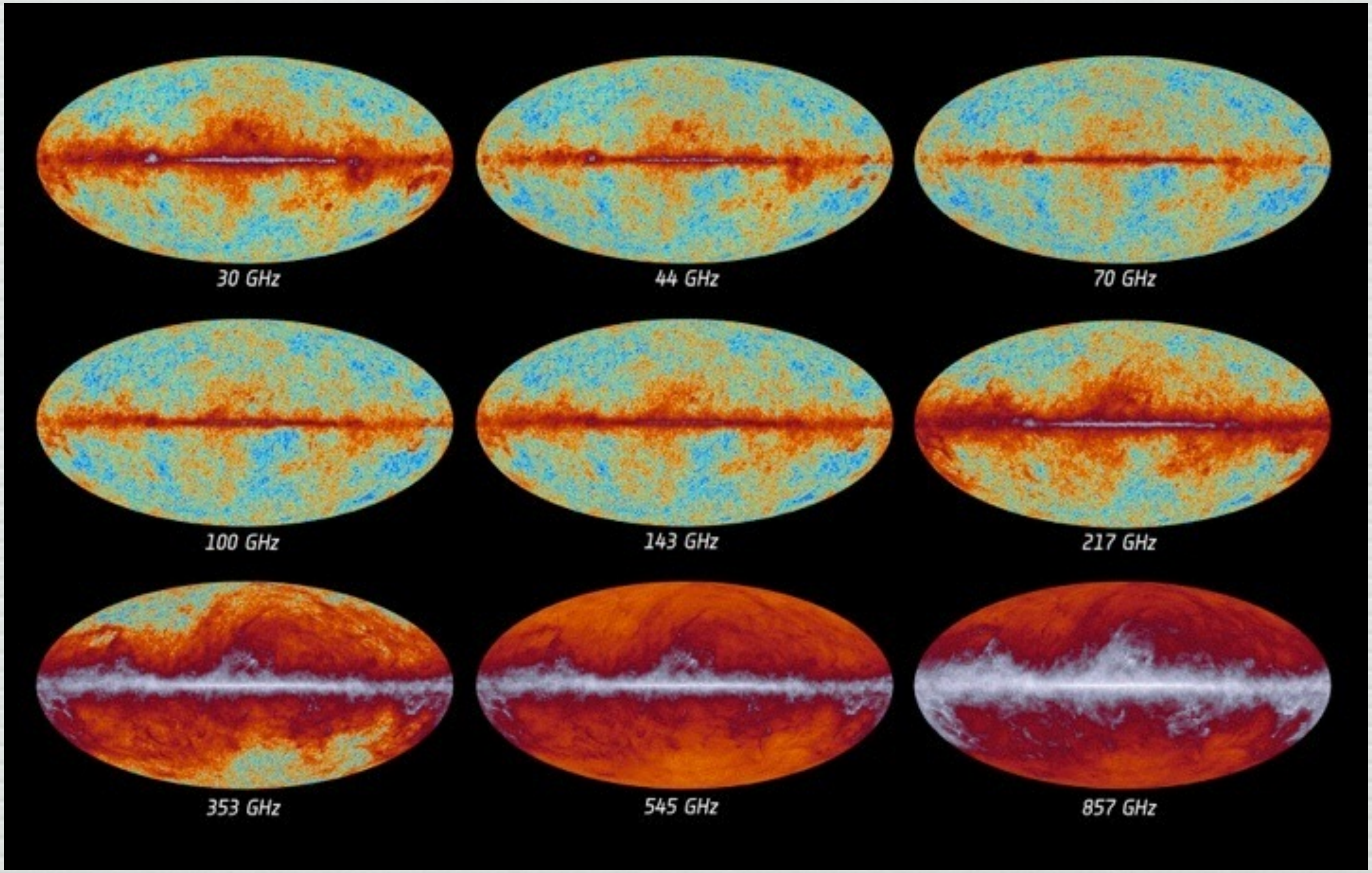
Planck launch, 14 May 2009

Planck in orbit (animation)



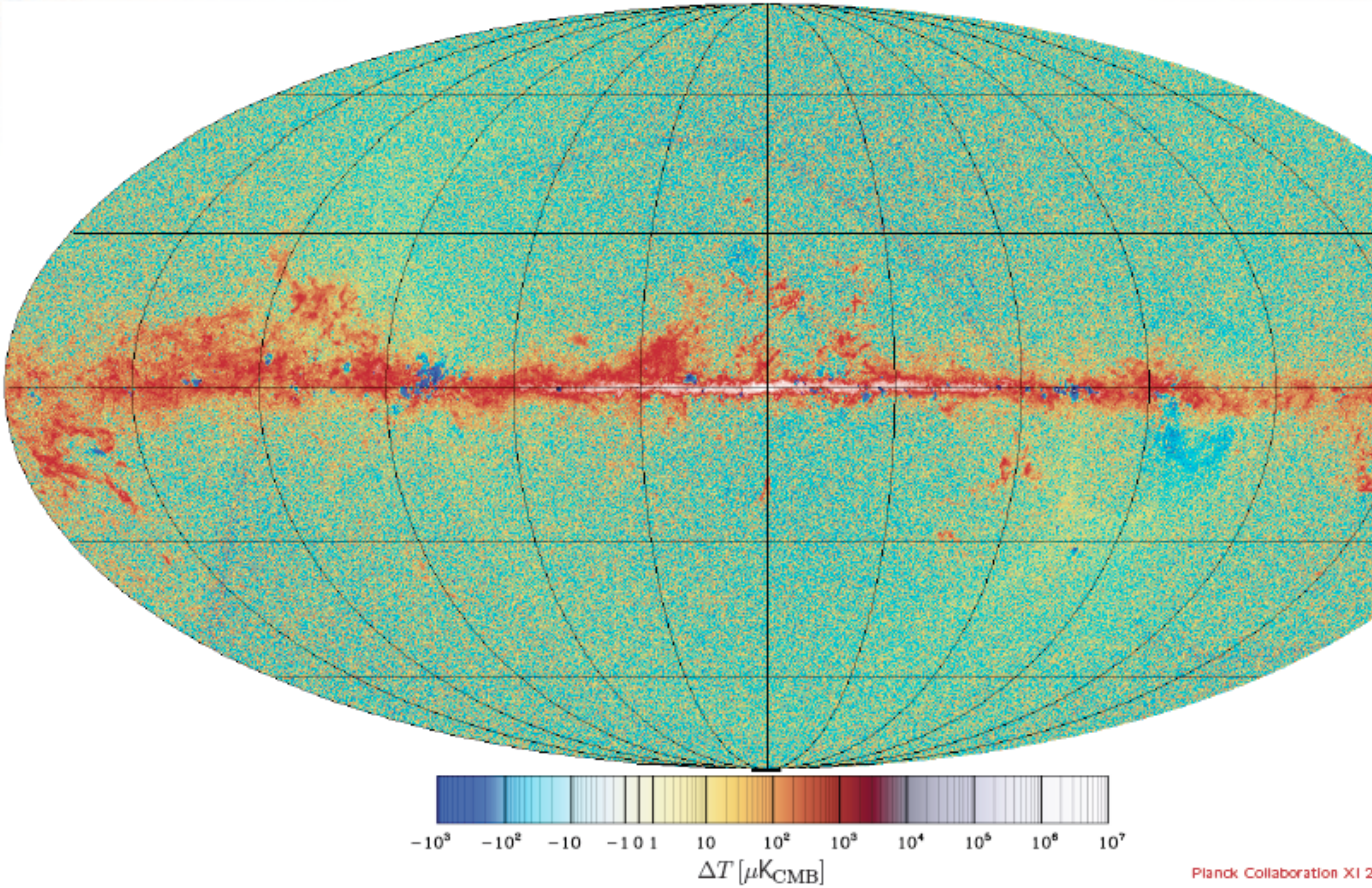
Frequency Maps

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



Map consistency

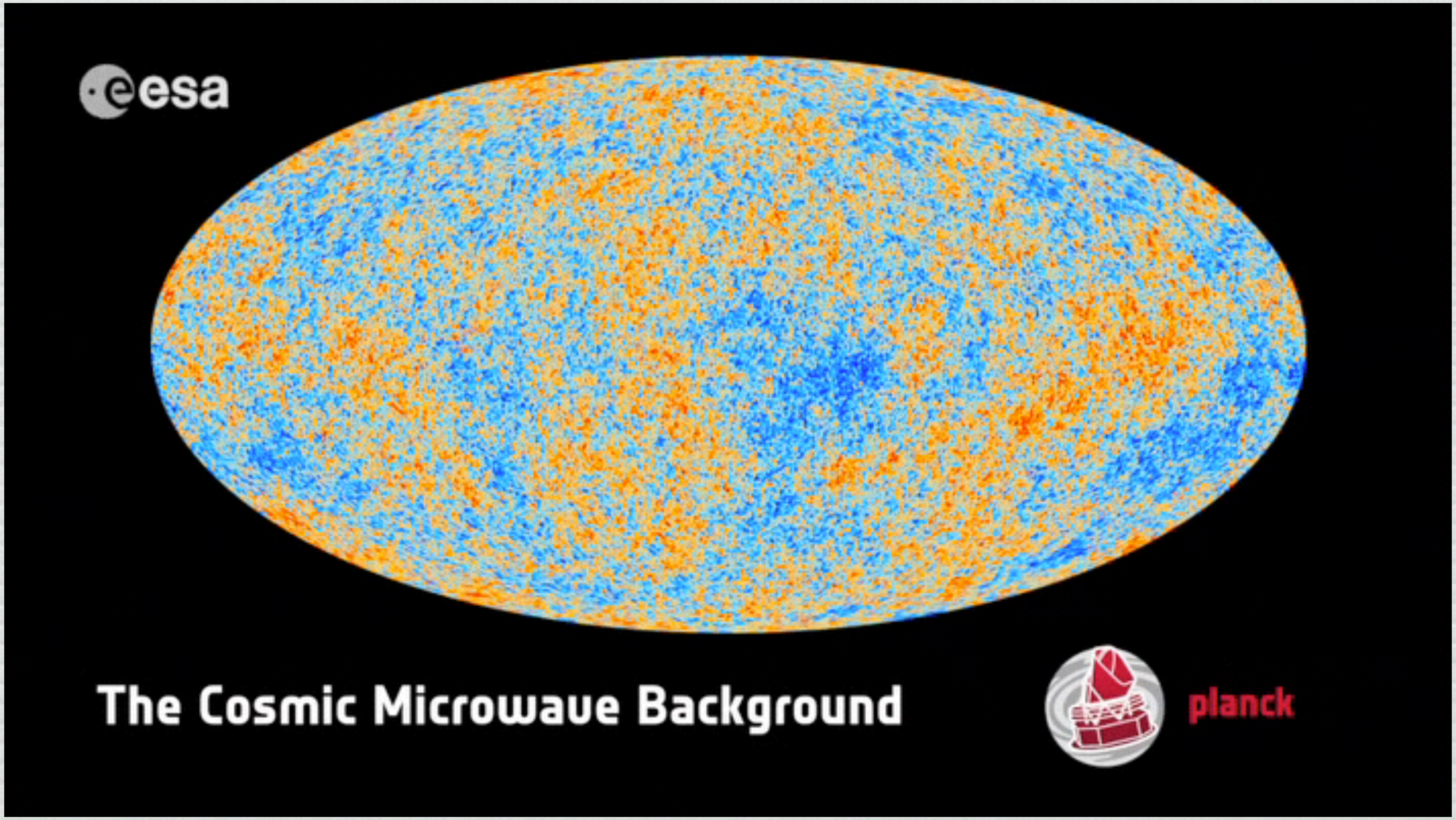
- 100 GHz – 70 GHz. Red is mostly CO, blue is mostly free-free. CMB is gone!



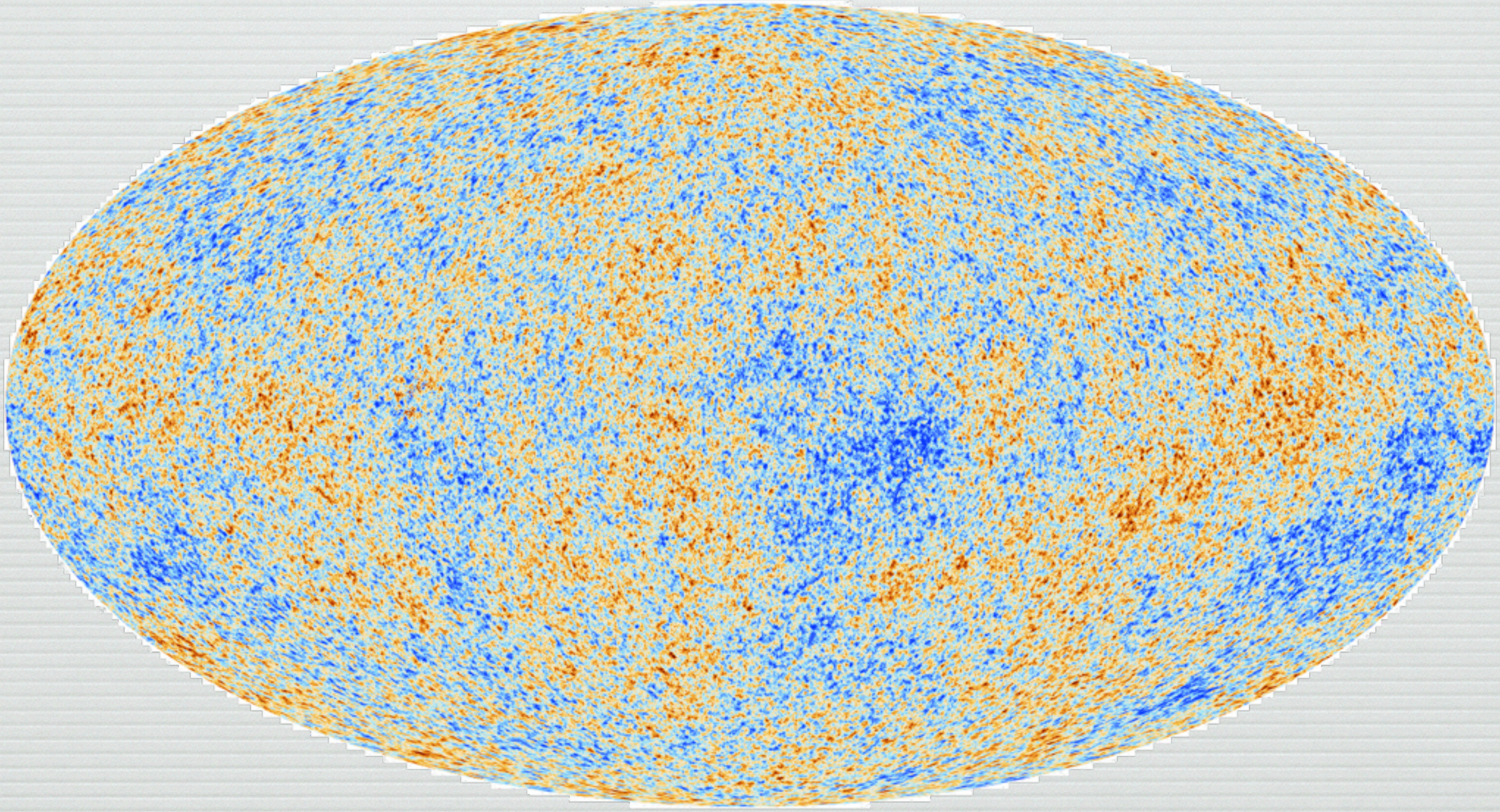
Planck Collaboration XI 2013

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

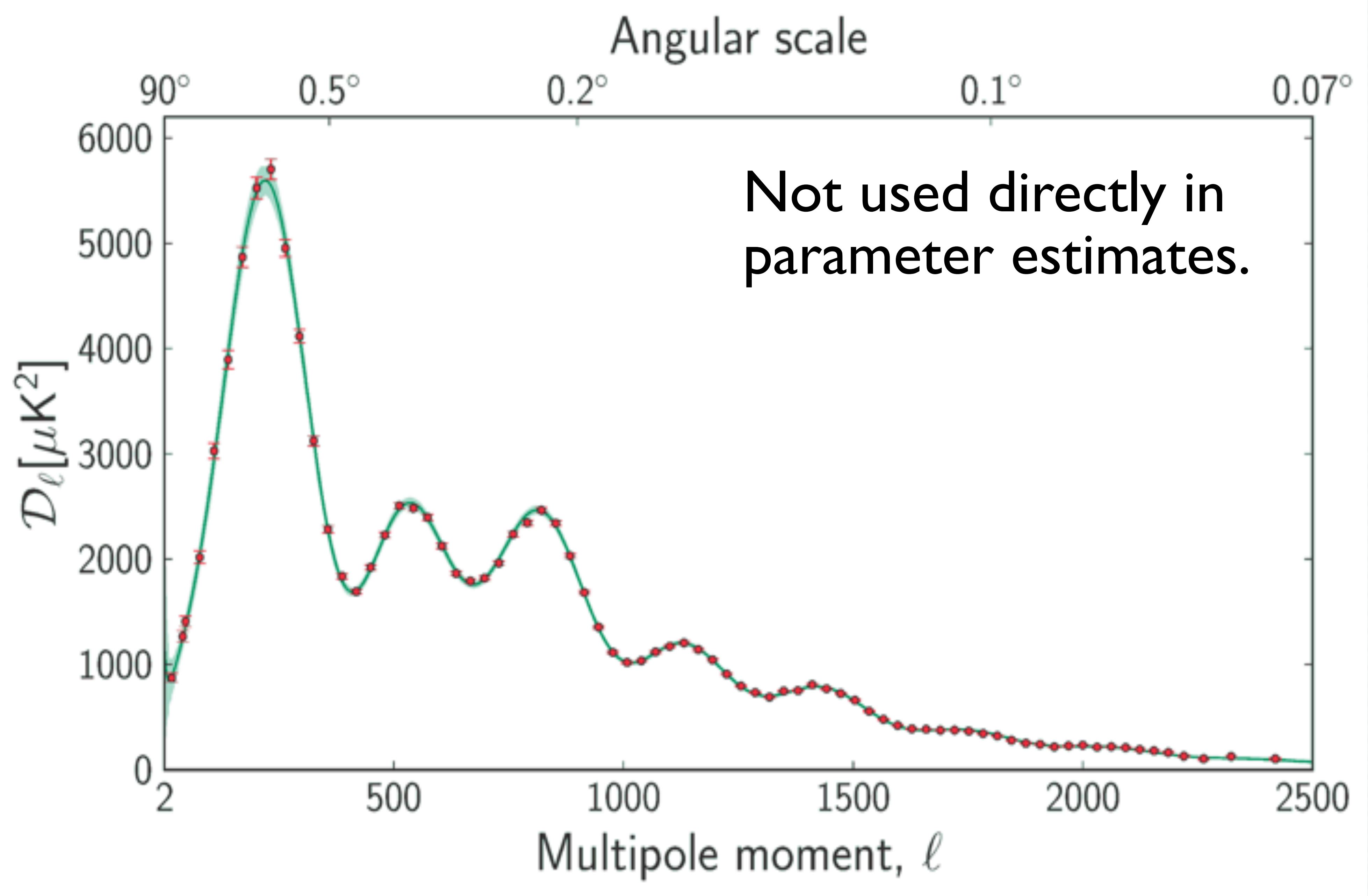


Planck (2013)



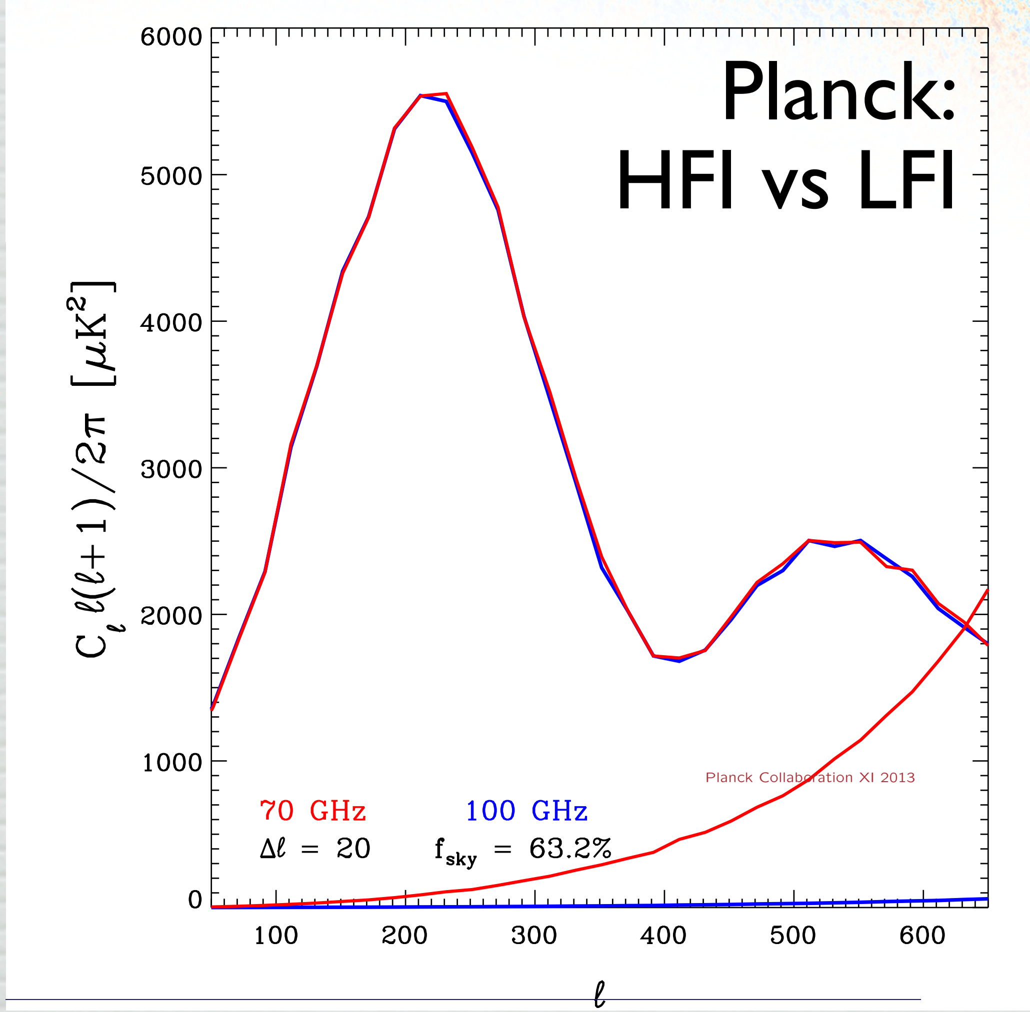
Planck (2013)

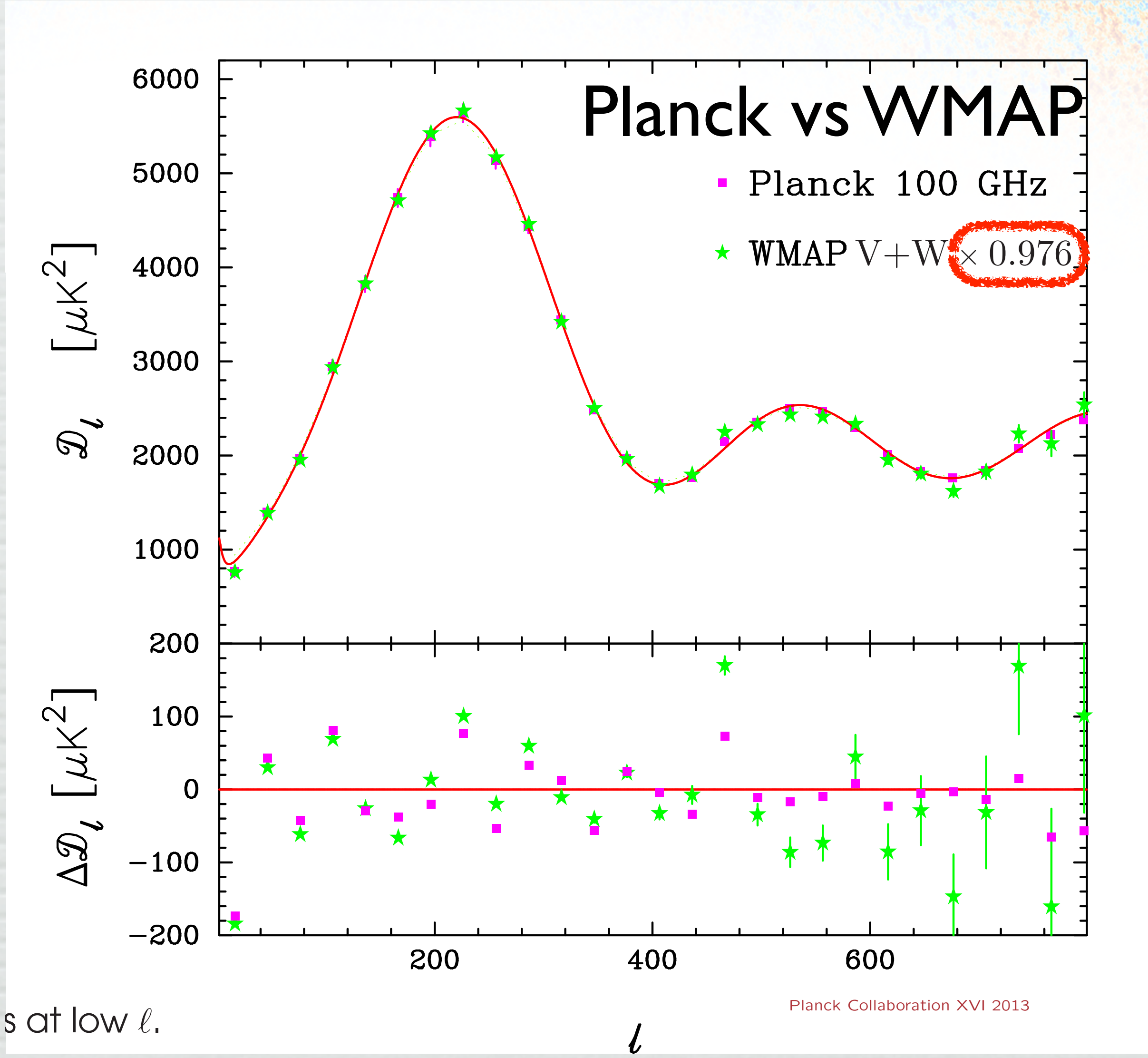
- From ~50 million pixels to ~2500 multipoles



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

Planck Collaboration: The *Planck* mission

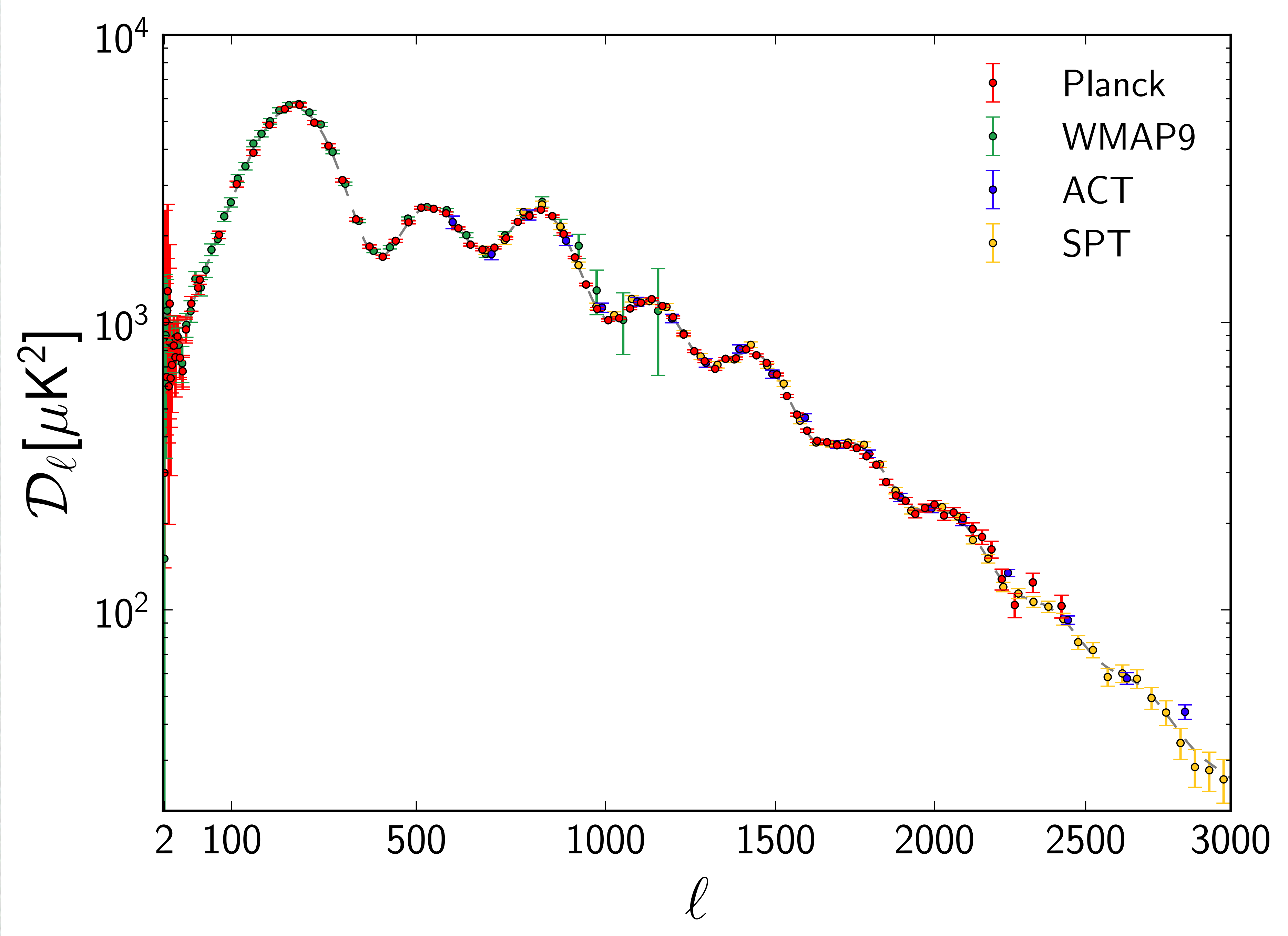


Fig. 25. Measured angular power spectra of *Planck*, WMAP9, ACT, and SPT. The model plotted is *Planck*'s best-fit model including *Planck* temperature, WMAP polarization, ACT, and SPT (the model is labelled [Planck+WP+HighL] in Planck Collaboration XVI (2013)). Error bars include cosmic variance. The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

Cosmological Parameters

- *Planck* + WP

from 2500 points to ~6 parameters

  - *~directly measured*

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

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

$n_s = 0.960 \pm 0.007$

$\tau = 0.089 \pm 0.014$

$10^9 A_s = 2.20 \pm 0.06$

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

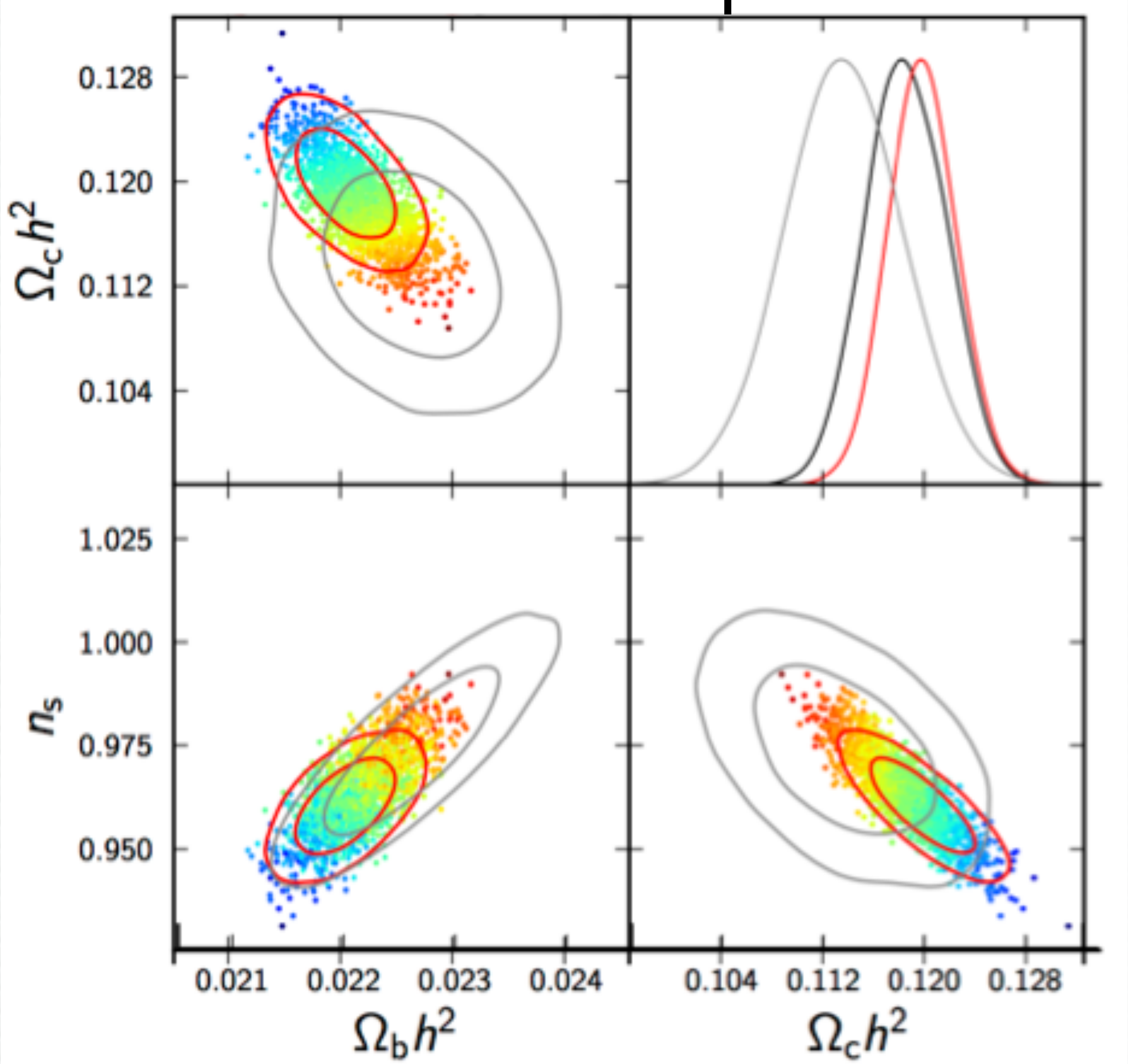
  - *derived (e.g.)*

$H_0 = 67.3 \pm 1.2$ 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]

Planck Params

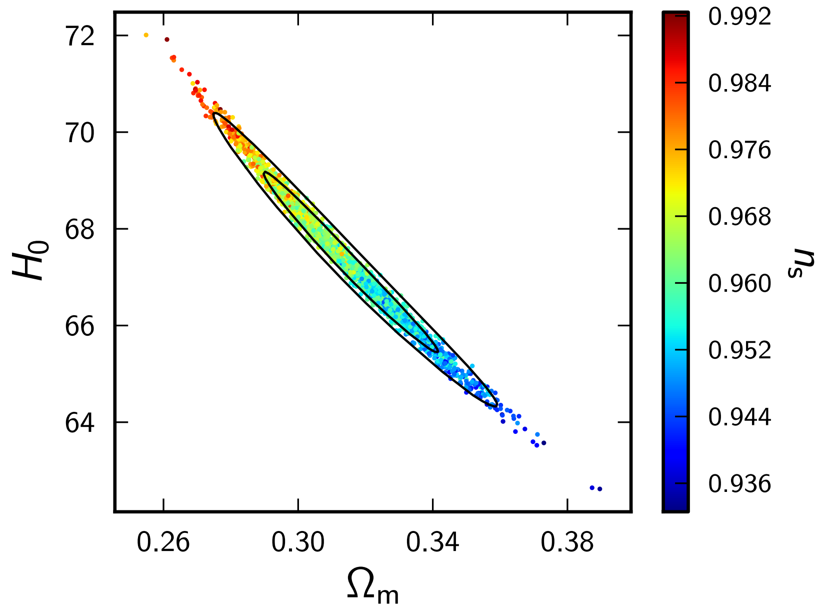


Fig. 3. Constraints in the Ω_m–H_0 plane. Points show samples from the *Planck*-only posterior, coloured by the corresponding value of the spectral index n_s. The contours (68% and 95%) show the improved constraint from *Planck*+lensing+WP. The degeneracy direction is significantly shortened by including WP, but the well-constrained direction of constant $\Omega_m h^3$ (set by the acoustic scale), is determined almost equally accurately from *Planck* alone.

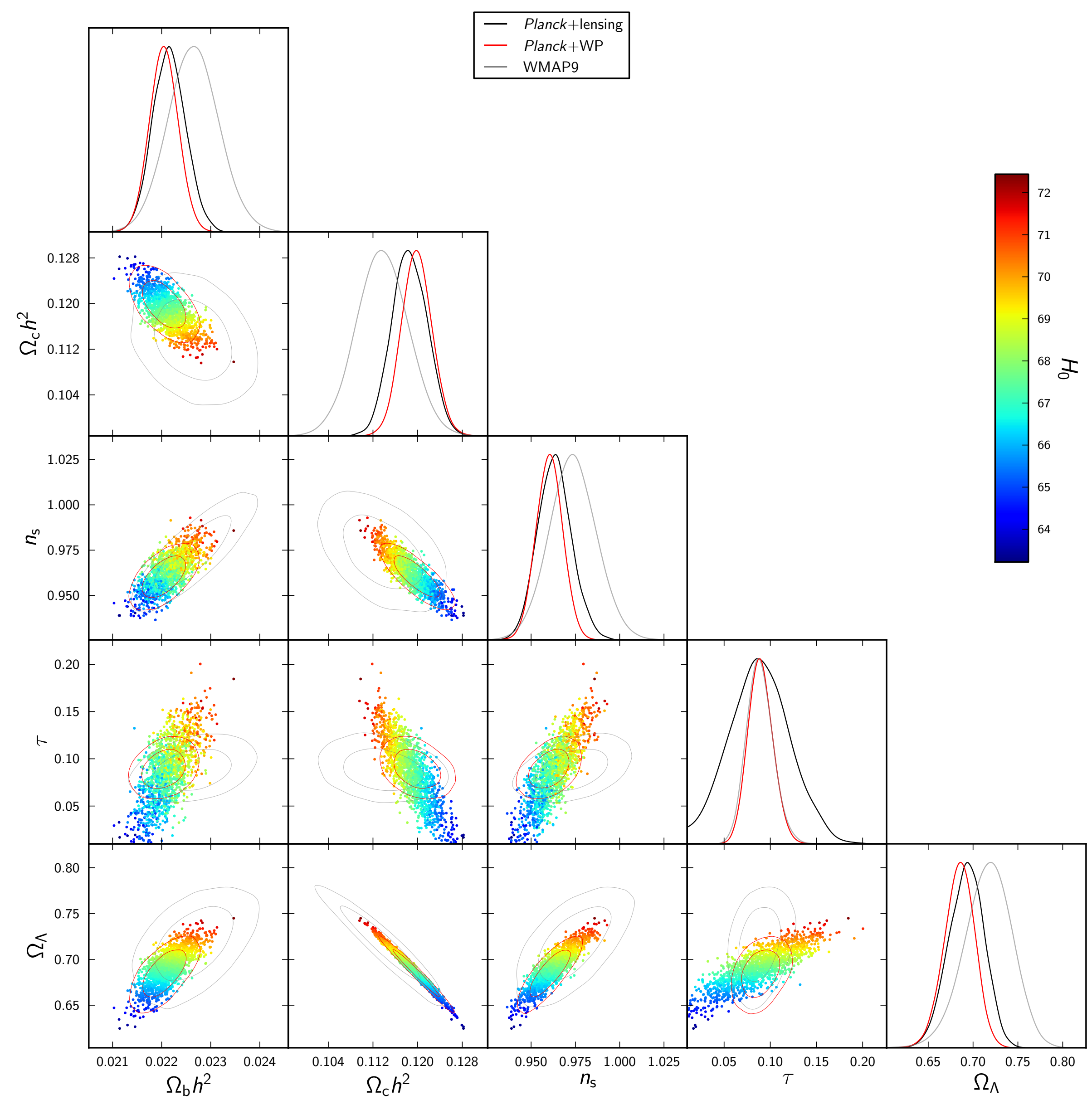
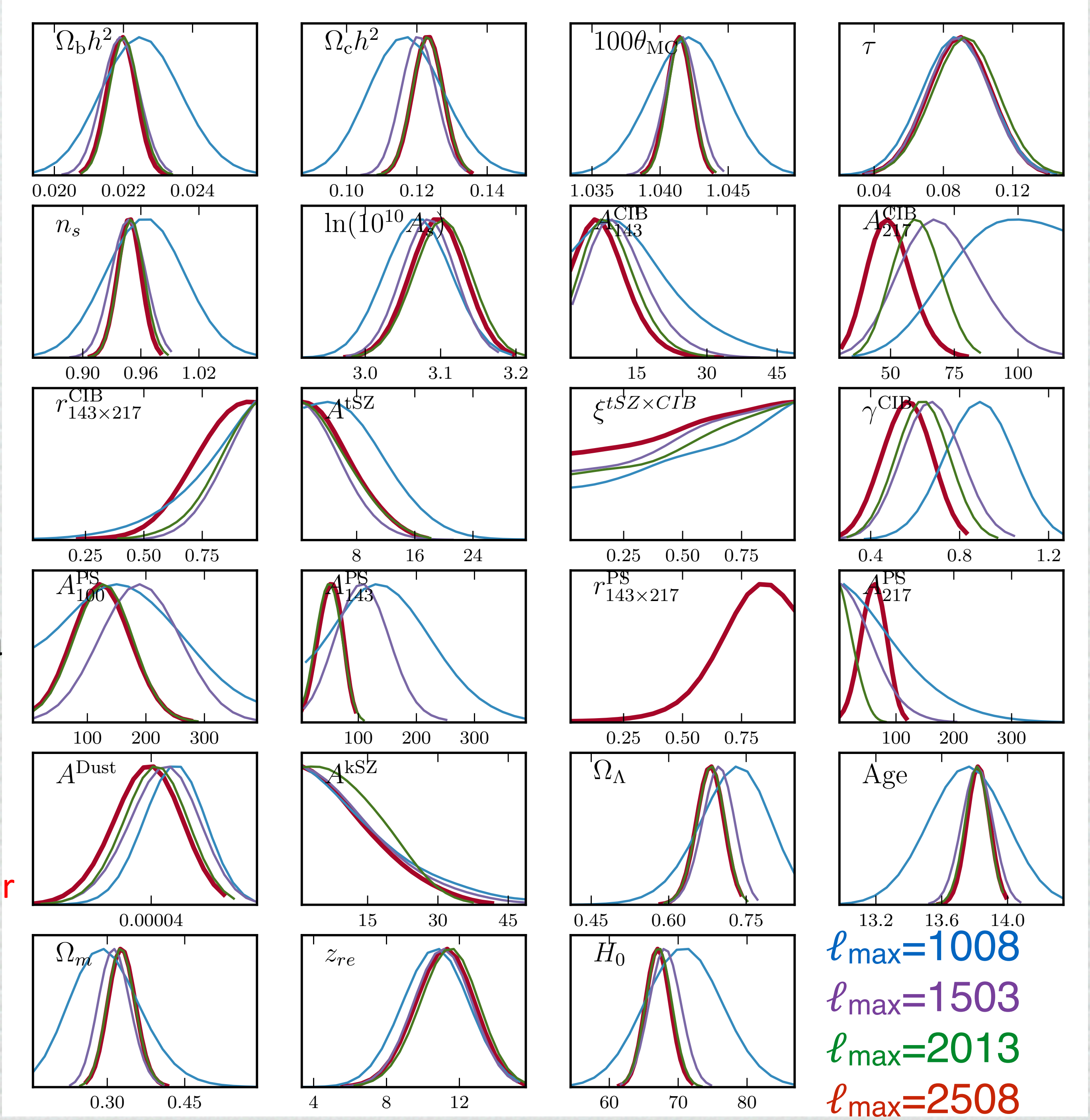


Fig. 2. Comparison of the base ΛCDM model parameters for *Planck*+lensing only (colour-coded samples), and the 68% and 95% constraint contours adding *WMAP* low-ℓ polarization (WP; red contours), compared to *WMAP*-9 (Bennett et al. 2012; grey contours).

Self-consistency of the parameters

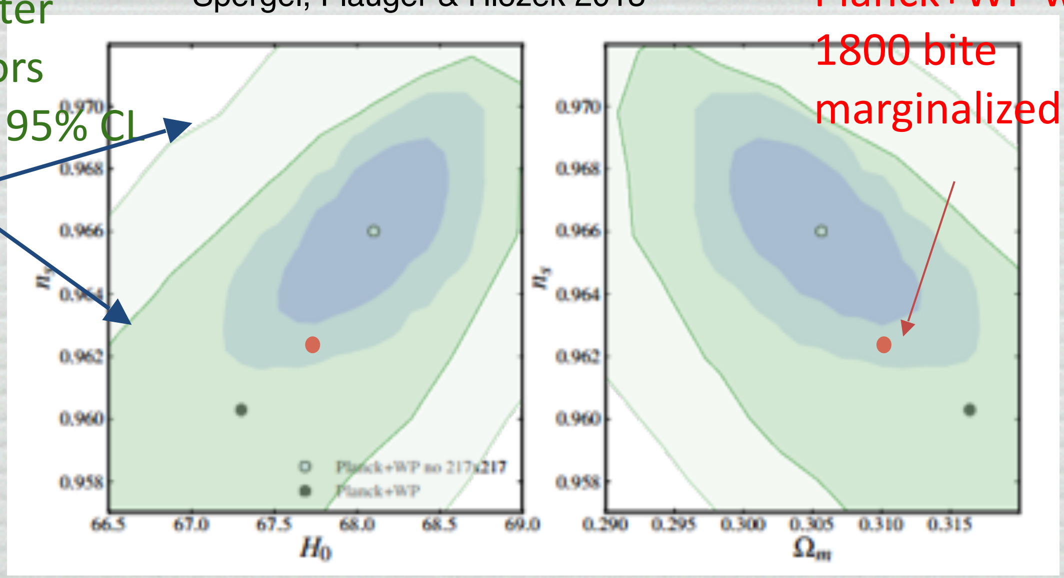
- Very weak dependence on which subset of *Planck* data is analysed.
- Robust to
  - changes in ℓ_{max}
    - e.g., ℓ~1800 cooler line
  - inclusion of channels
    - 217 GHz is a minor outlier, but inclusion affects parameters by a small fraction of a sigma



Planck+WP parameter posteriors @ 68 & 95% CL

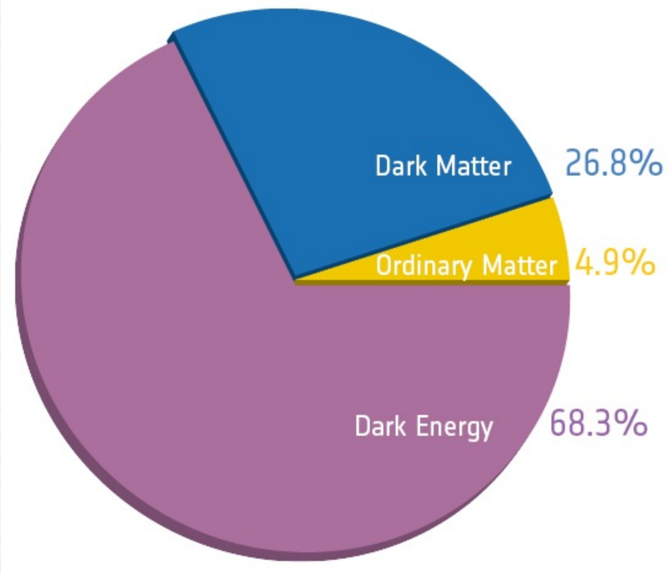
Spergel, Flauger & Hlozek 2013

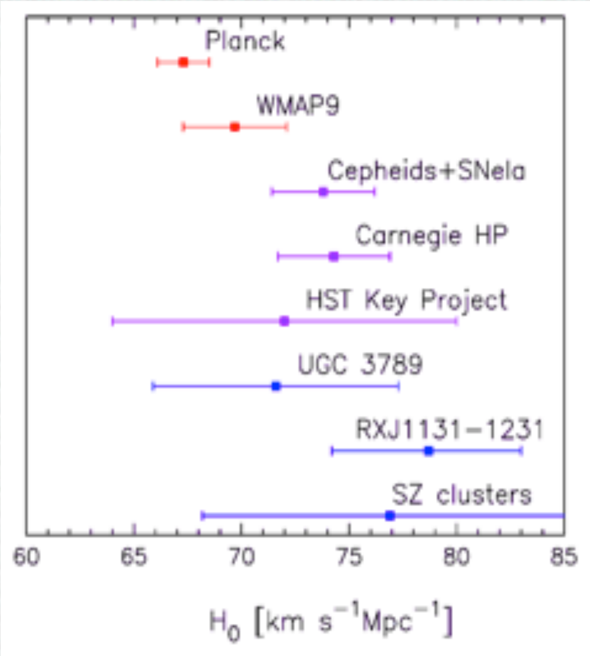
Planck+WP with 1800 bite marginalized over



The new old Universe

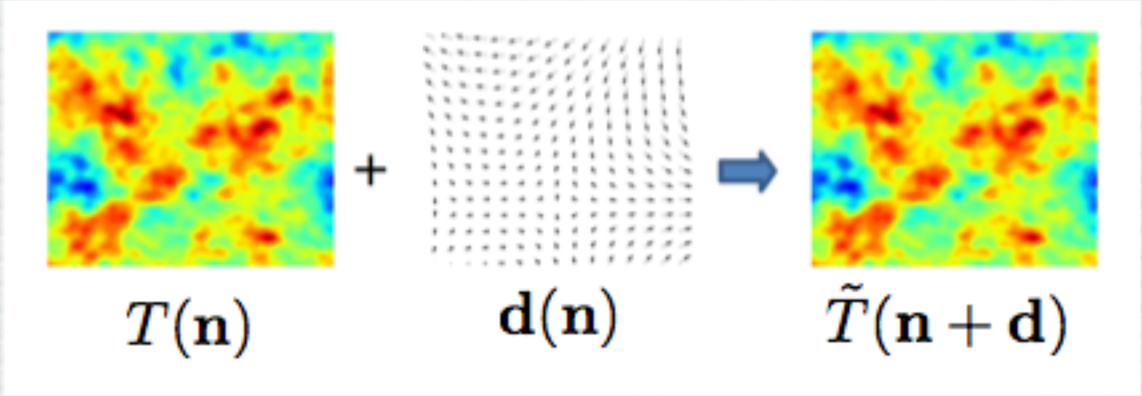
- Big picture: no qualitative changes
- Quantitatively:
  - Planck's higher resolution allows a better measurement of the damping physics at small scales
    - slightly slower expansion rate, slightly older universe
    - slightly less dark energy, more dark matter
  - Cosmological parameters not "directly measured" by *Planck*; details depend on the models considered ["priors"]
    - In particular, there are some tensions with other measurements of H_0





Gravitational lensing

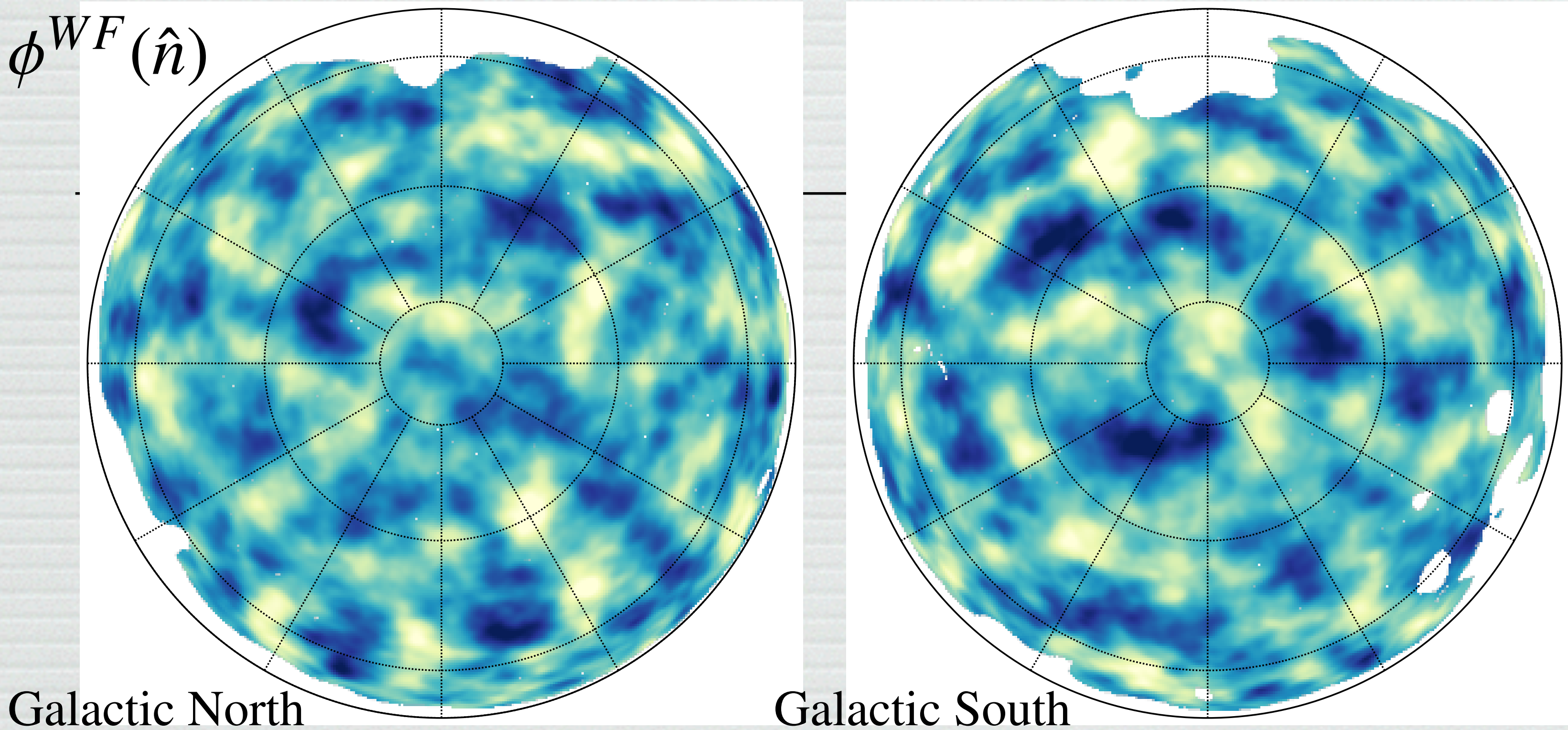
$$\frac{\ell^2}{4} C_\ell^{dd} = \int_0^{\eta_*} \mathrm{d}\eta \underbrace{W^2(\eta)}_{\text{geometry}} \underbrace{P\left(k = \frac{\ell + 1/2}{d_A(\eta)}, \eta\right)}_{\text{matter}}$$

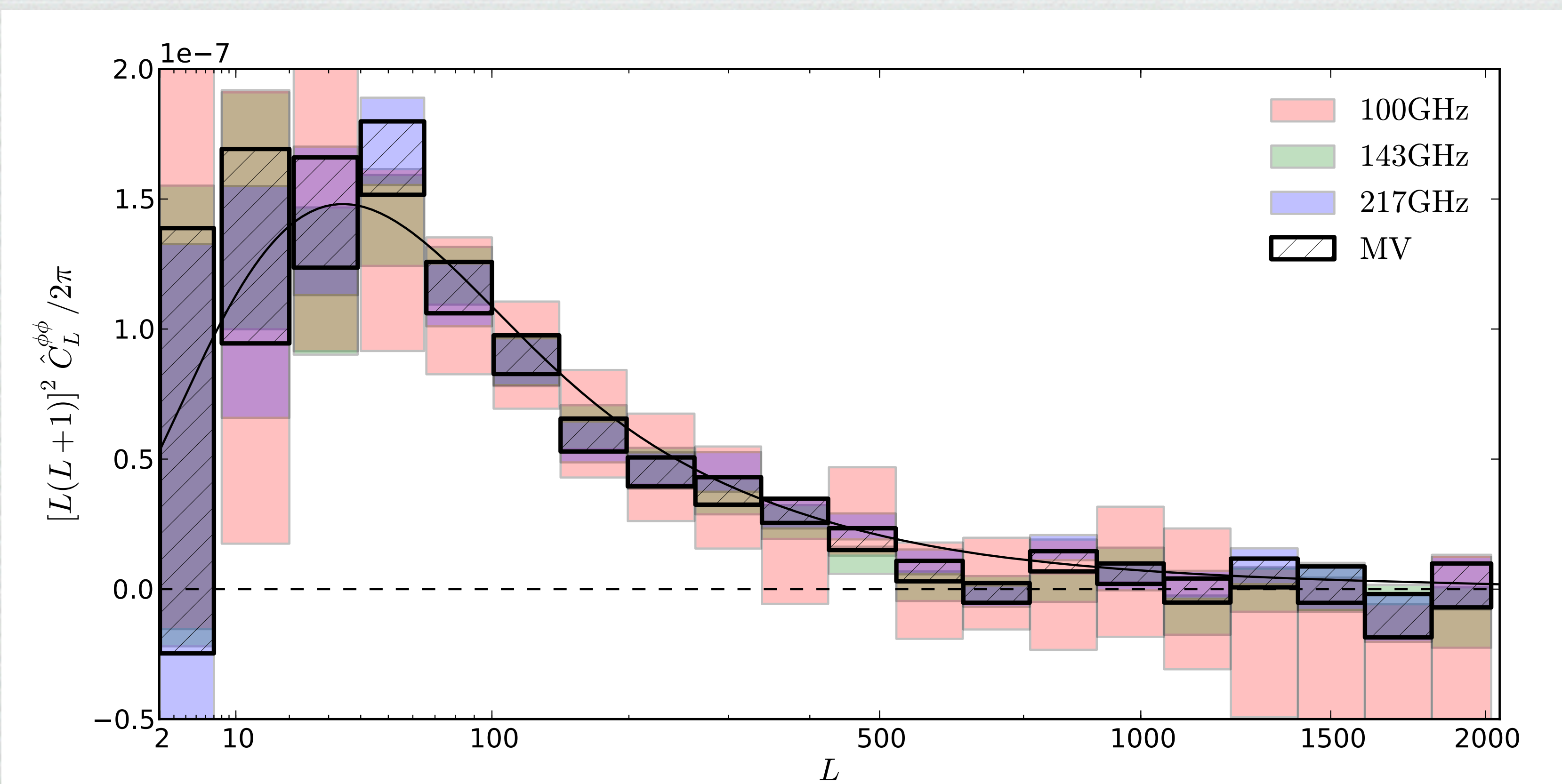


planck

- *Planck* observes lensing:
  - non-Gaussianity
  - on the power spectrum (smoothing)
  - correlations with the IR background

Lensing





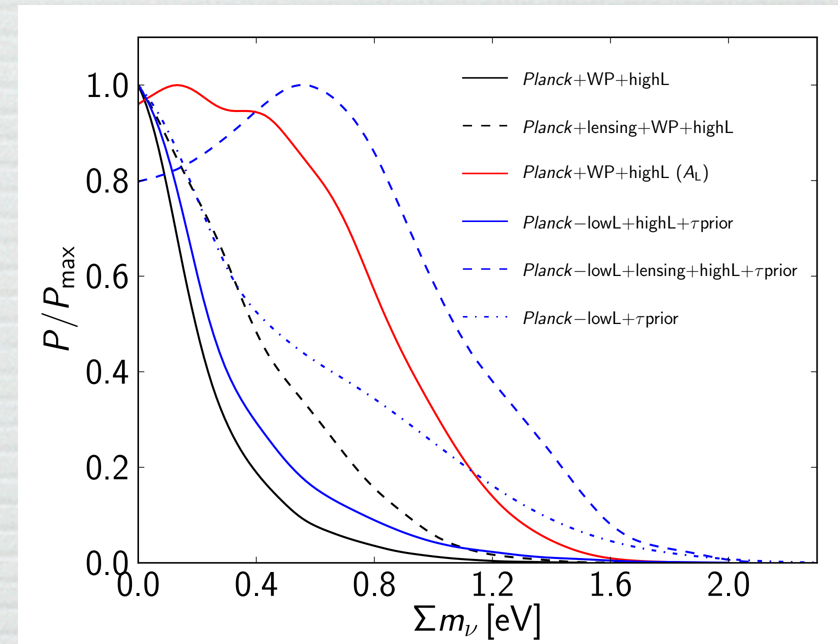


Fig. 26. Marginalized posterior distributions for $\sum m_\nu$ in flat models from CMB data. We show results for *Planck*+WP+highL without (solid black) and with (red) marginalization over $A_{\rm L}$, showing how the posterior is significantly broadened by removing the lensing information from the temperature anisotropy power spectrum. The effect of replacing the low-ℓ temperature and (*WMAP*) polarization data with a τ prior is shown in solid blue (*Planck*−lowL+highL+τprior) and of further removing the high-ℓ data in dot-dashed blue (*Planck*−lowL+τprior). We also show the result of including the lensing likelihood with *Planck*+WP+highL (dashed black) and *Planck*−lowL+highL+τprior (dashed blue).

non-Gaussianity: f_{NL}

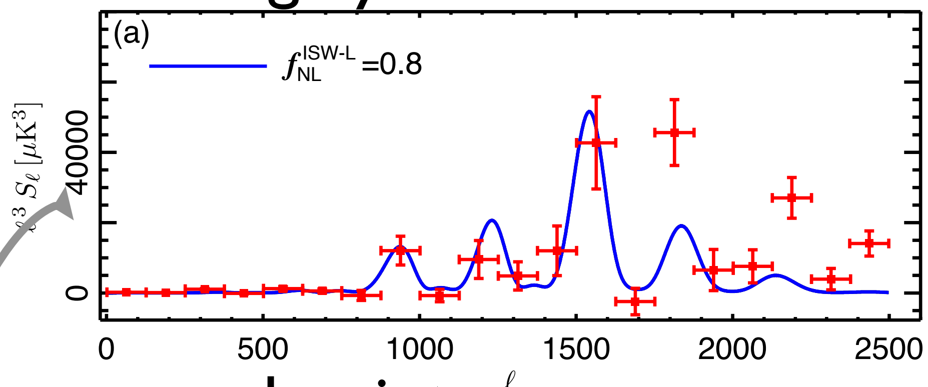
- Heuristically $\phi = \phi_G + f_{\rm NL}(\phi_G^2 - \langle\phi_G^2\rangle)$
  for a Gaussian ϕ_G (e.g., multi-field inflation)
  - This is the (spatially) local model for non-Gaussianity
  - Induces specific 3-d correlations

    $$\langle\phi\phi\phi\rangle \sim 3 f_{\rm NL}\left(\langle\phi_G\phi_G\phi_G\phi_G\rangle - \langle\phi_G\phi_G\rangle\langle\phi_G\phi_G\rangle\right) + O(f_{\rm NL}^2)$$
    $$\sim 6 f_{\rm NL}\langle\phi_G\phi_G\rangle\langle\phi_G\phi_G\rangle + O(f_{\rm NL}^2)$$

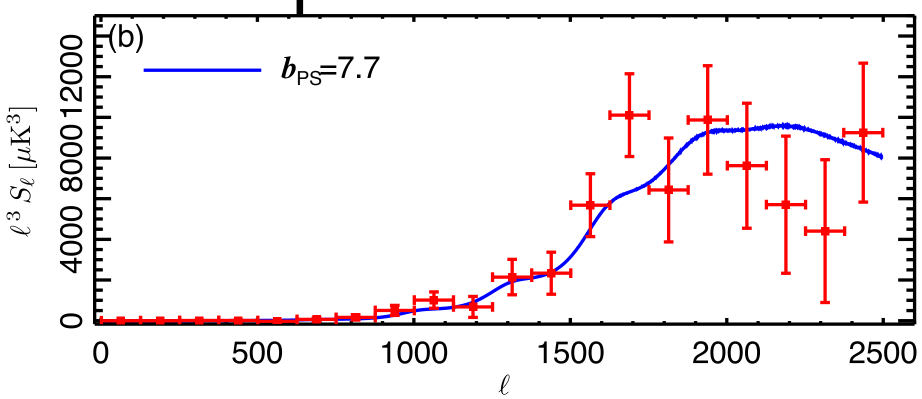
    and hence 2-d correlations in the CMB
  - Corresponds to Fourier bispectrum $B(k_1, k_2, k_3)$ which peaks in squeezed case $k_1 \ll k_2 \simeq k_3$
    - modulate small-scale structure by large-scale modes
      - cf. galaxy bias
  - More generally, consider other shapes (e.g., equilateral) motivated by specific theories

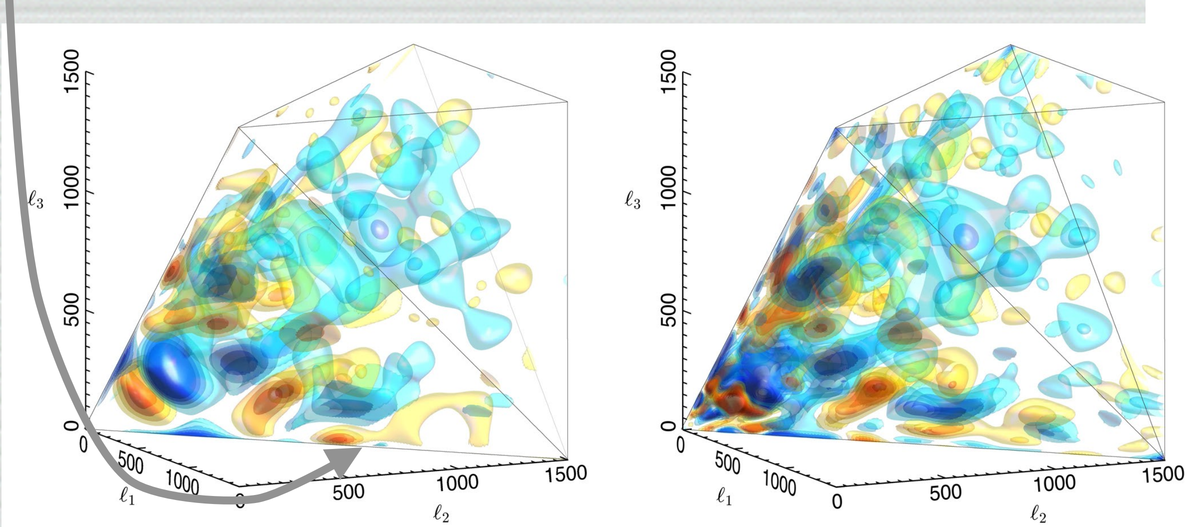
Non-Gaussianity

We see
lensing by cosmic structures

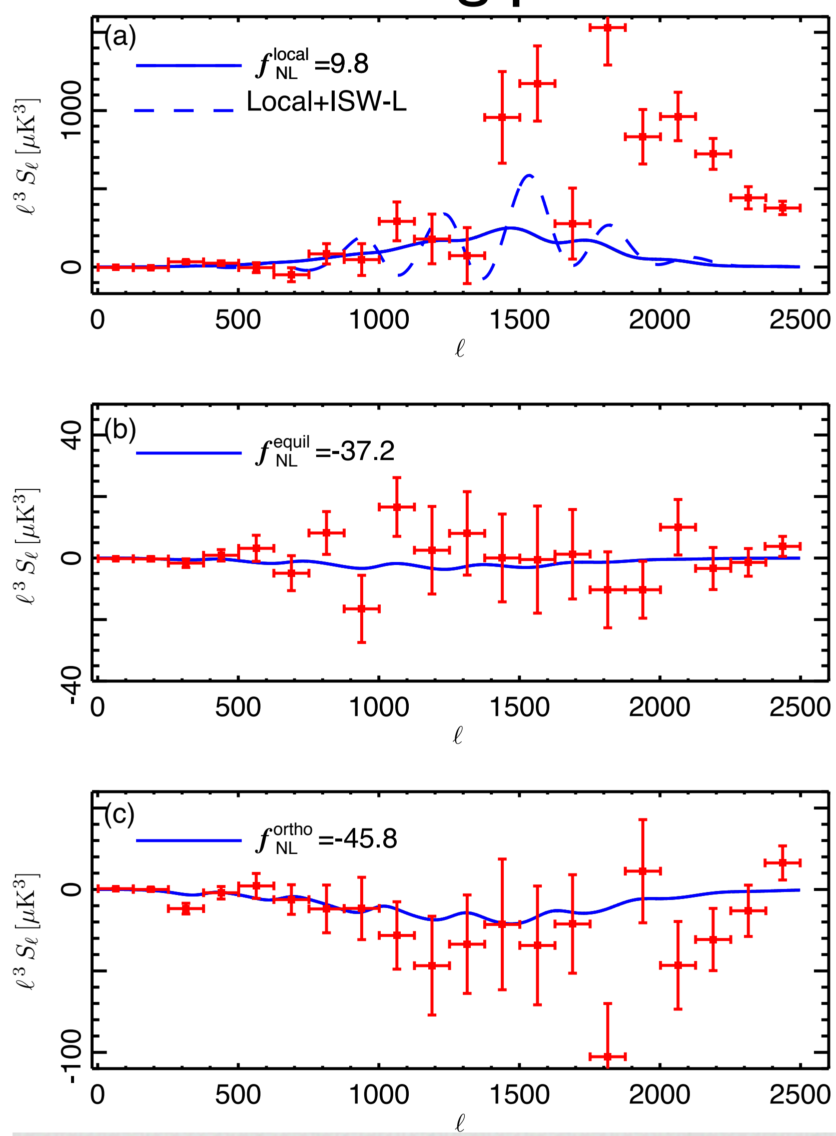


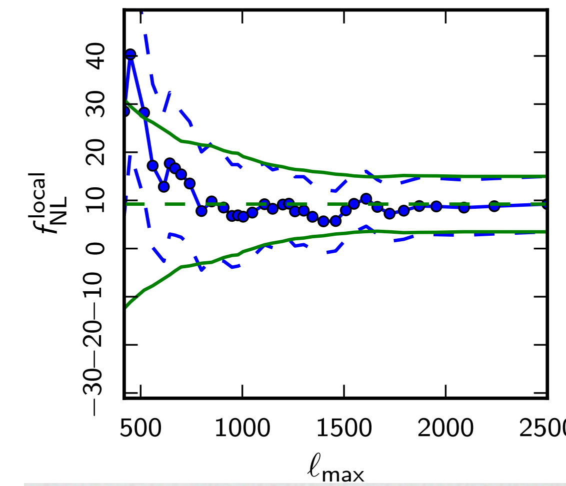
…and point sources…





…but nothing primordial





$$f_{NL}^{local} = 2.7 \pm 5.8$$

$$f_{NL}^{equil} = -42 \pm 75$$

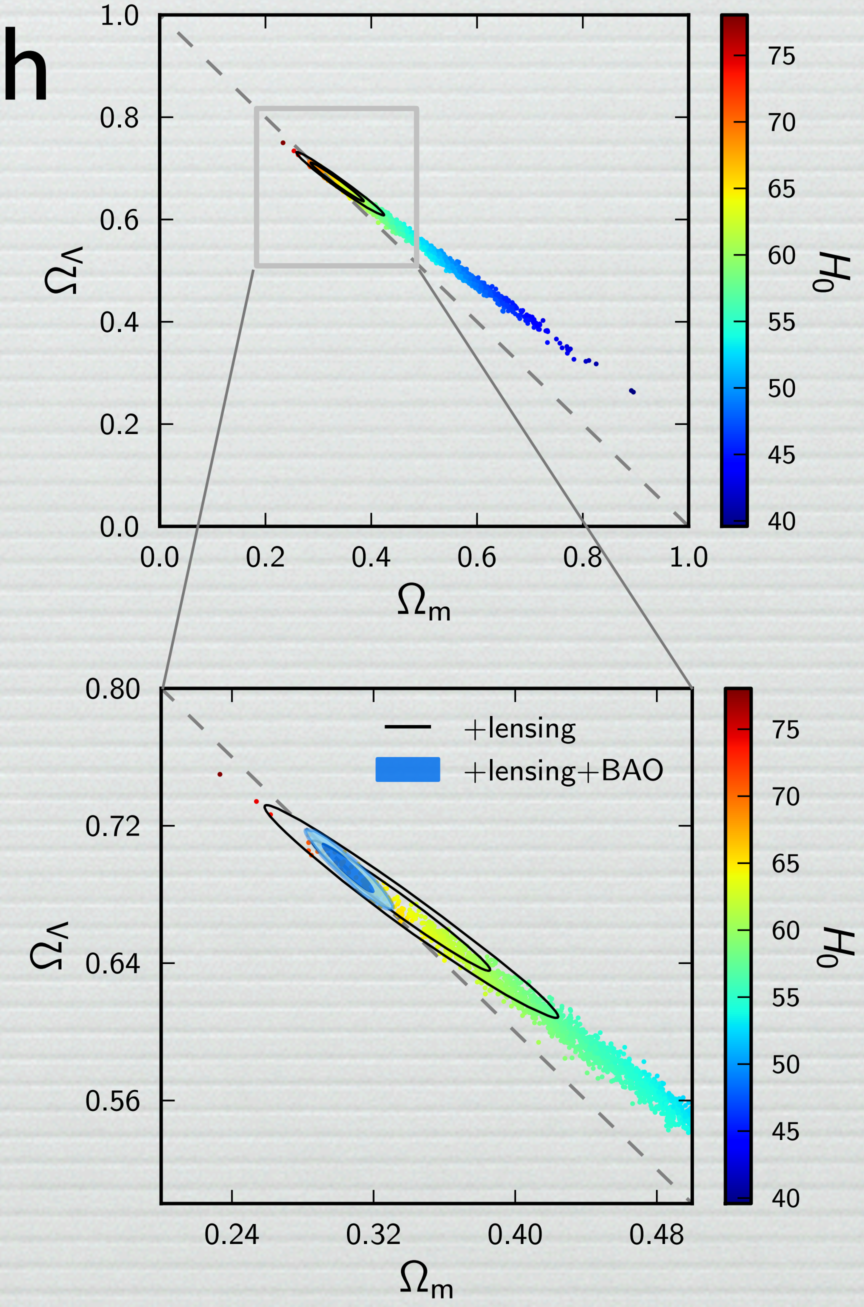
$$f_{NL}^{ortho} = -25 \pm 39$$

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 ⇒ shape of C_ℓ
    - Prediction: n_s a little less than 1 ✓
      - also: nearly Gaussian fluctuations ✓
    - Prediction: gravitational radiation background ?

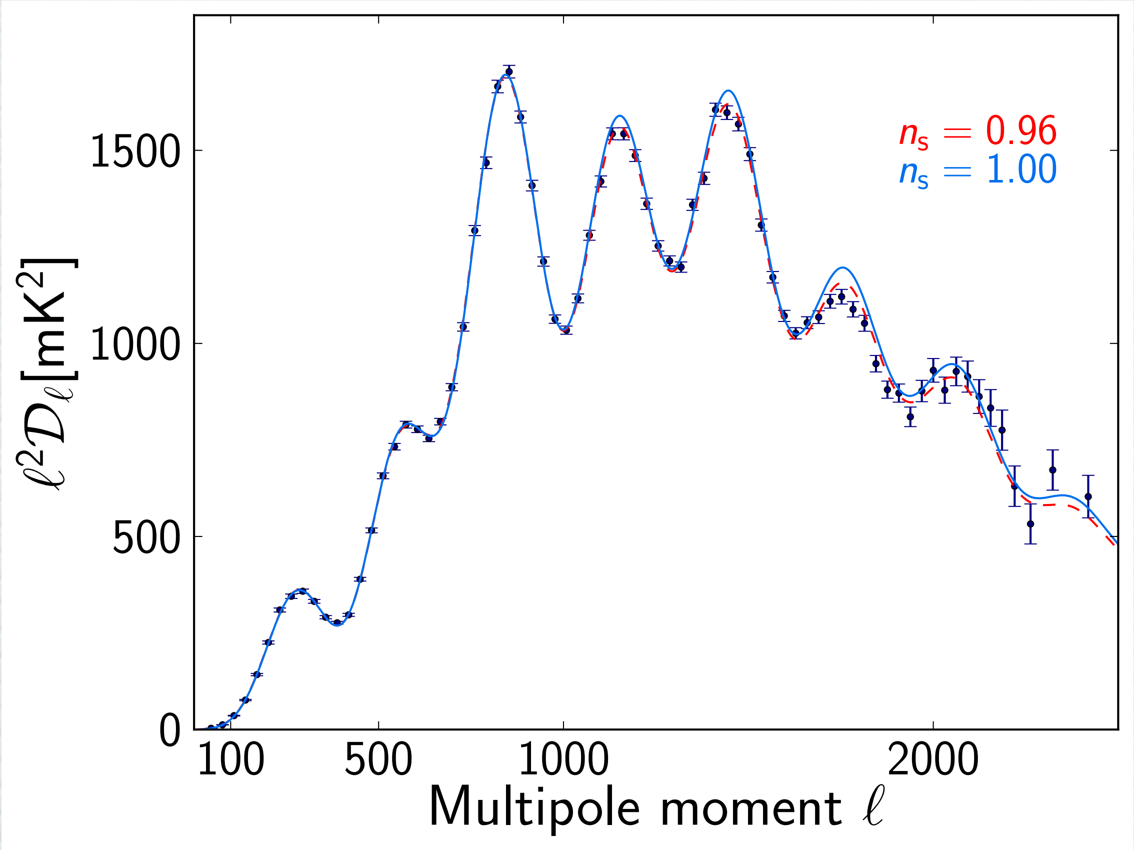
Inflation: Curvature from the CMB

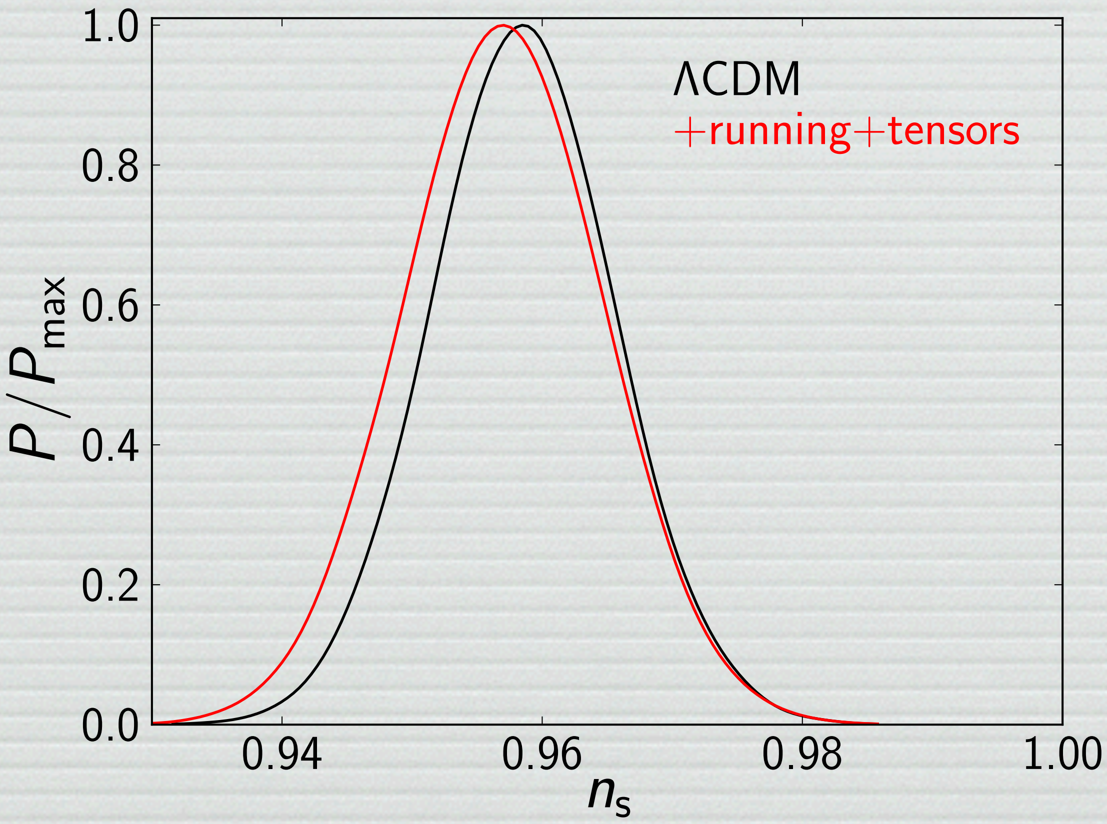
- With primary CMB alone, cannot determine both Ω_Λ & Ω_m (i.e., curvature)
- *Planck* measures curvature through *lensing*
  - more matter, less dark energy $\Rightarrow$ more lensing
    - distorts shape of power spectrum, smears out the small-scale peaks
    - boosts deflection power spectrum
   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



Inflation: Primordial fluctuations

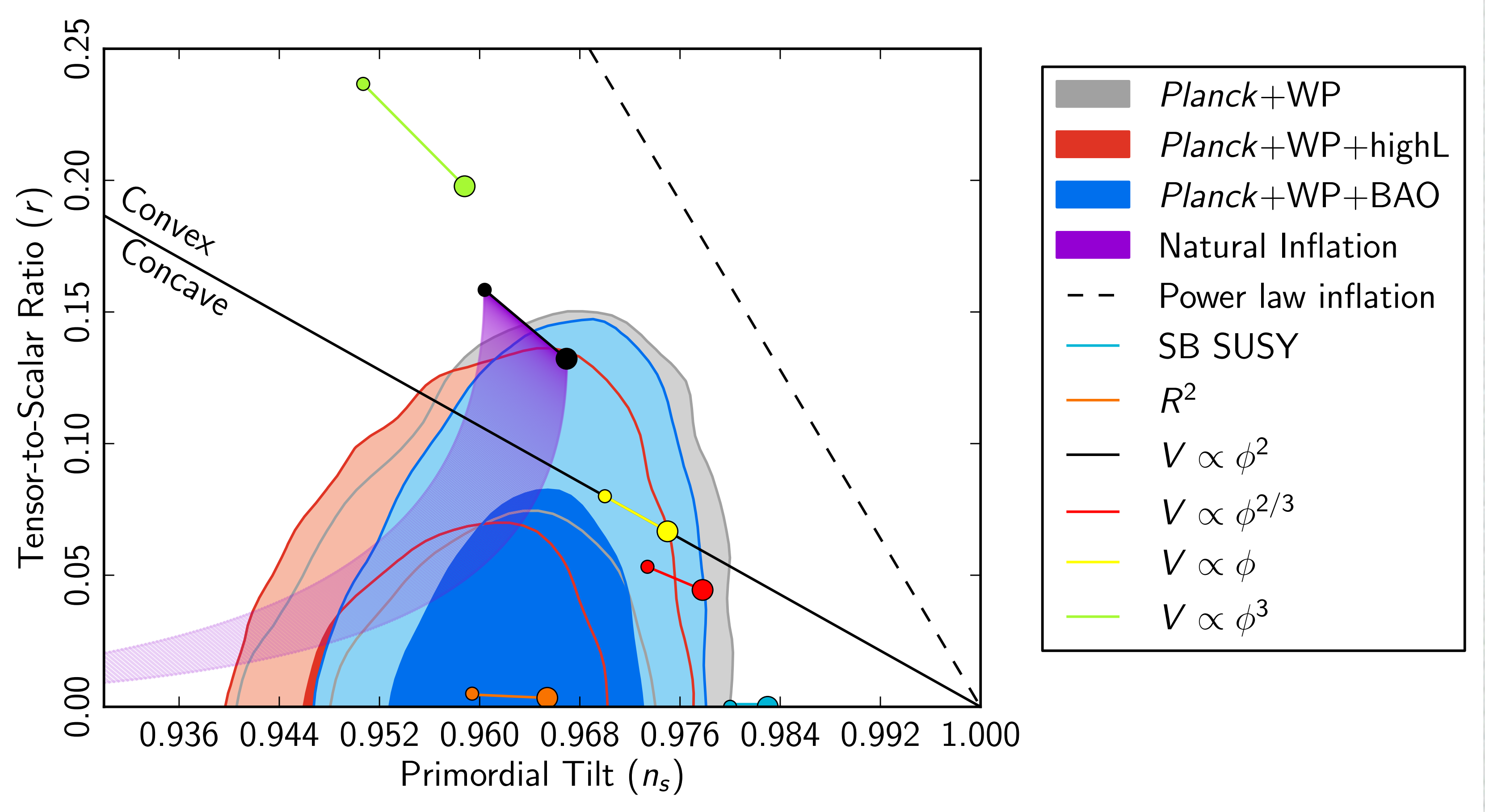
- $n_s = 0.960 \pm 0.007$
  - >5 sigma away from n_s=1





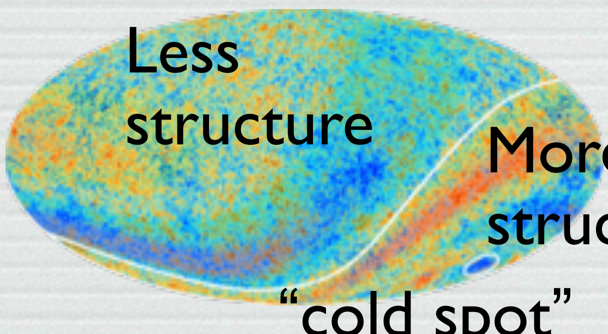
Inflation: Models

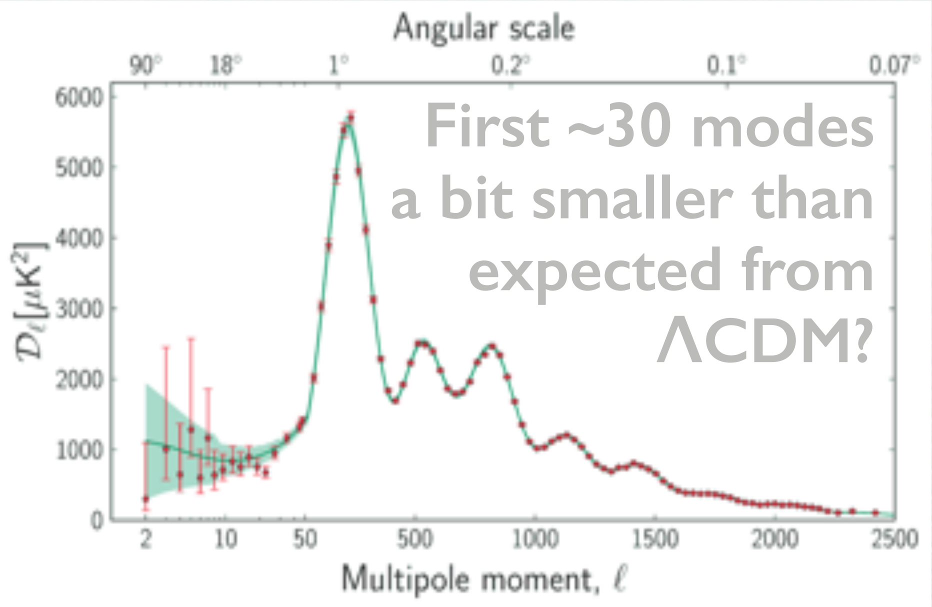
- Simplest models: scalar field φ w/very flat potential *V*(φ)
- *Planck* constrains specific models of inflation
- More information from the polarization of the CMB, which may observe the presence of gravitational waves in the early Universe:
  - next year's *Planck* data release
  - next-gen ground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



Consistency of Planck data

- Do the data fit the model?

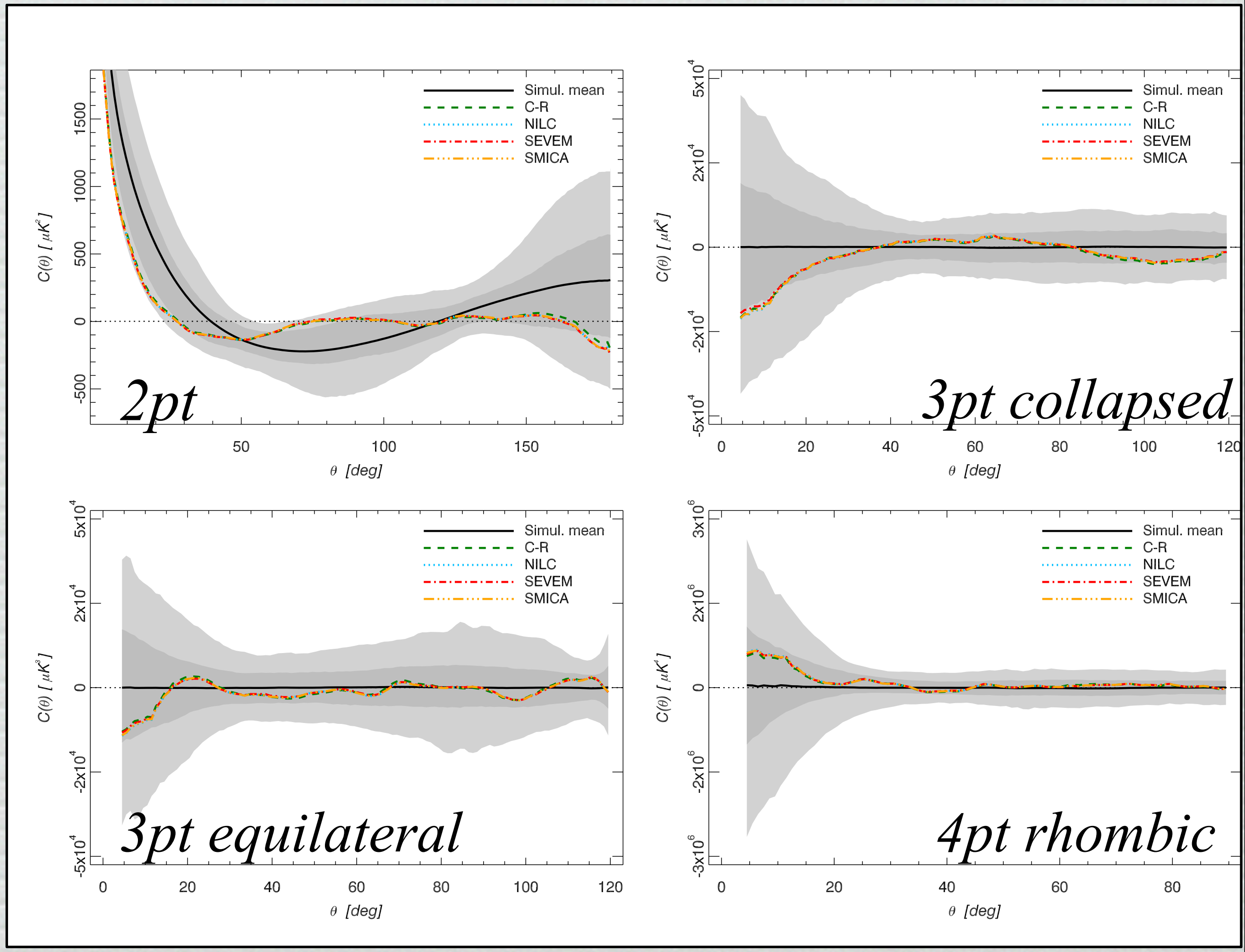


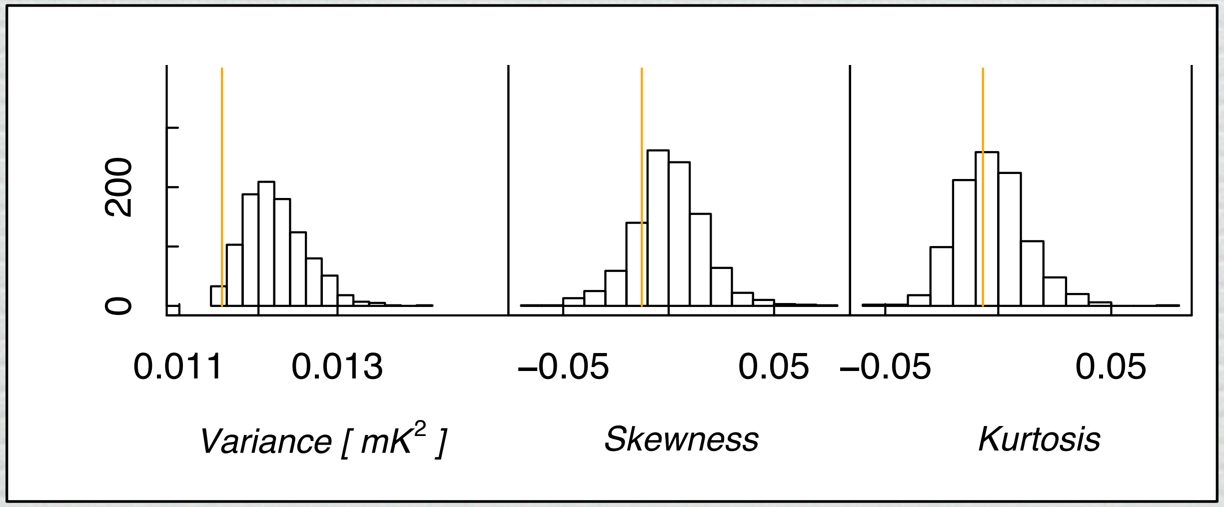


- Do different data agree?
  - within *Planck* ΔT/T: see above for self-consistency of maps, spectra, parameters
  - between *Planck* methods
    - lensing: direct measurement of lensing amplitude ~ 1.2 vs 1.0
    - clusters: lower Ω_m, σ_8
      - at face value, can be [only partially] ameliorated with 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*?

Testing assumptions

- We have been calculating the posterior $P(\Omega_b h^2, \Omega_c h^2, \theta_{MC}, \tau, n_s, A_s \mid \text{Planck}, I)$
- Background information "I"
  - (testable) assumptions:
    - LCDM in general
    - gaussianity, isotropy (+lensing)
    - by some measures, it obeys these assumptions very well



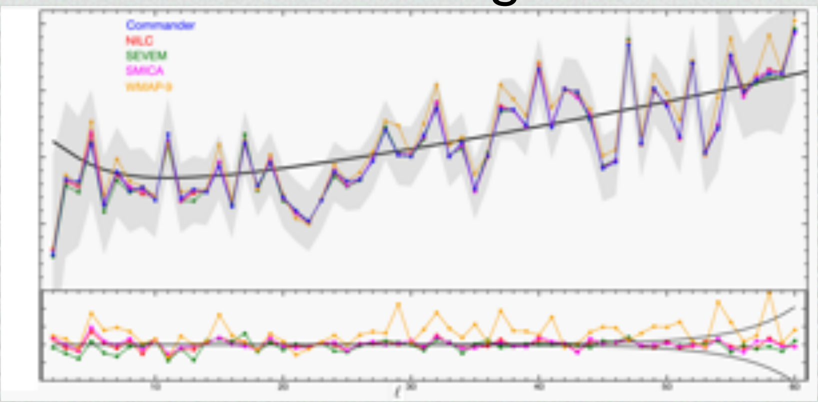


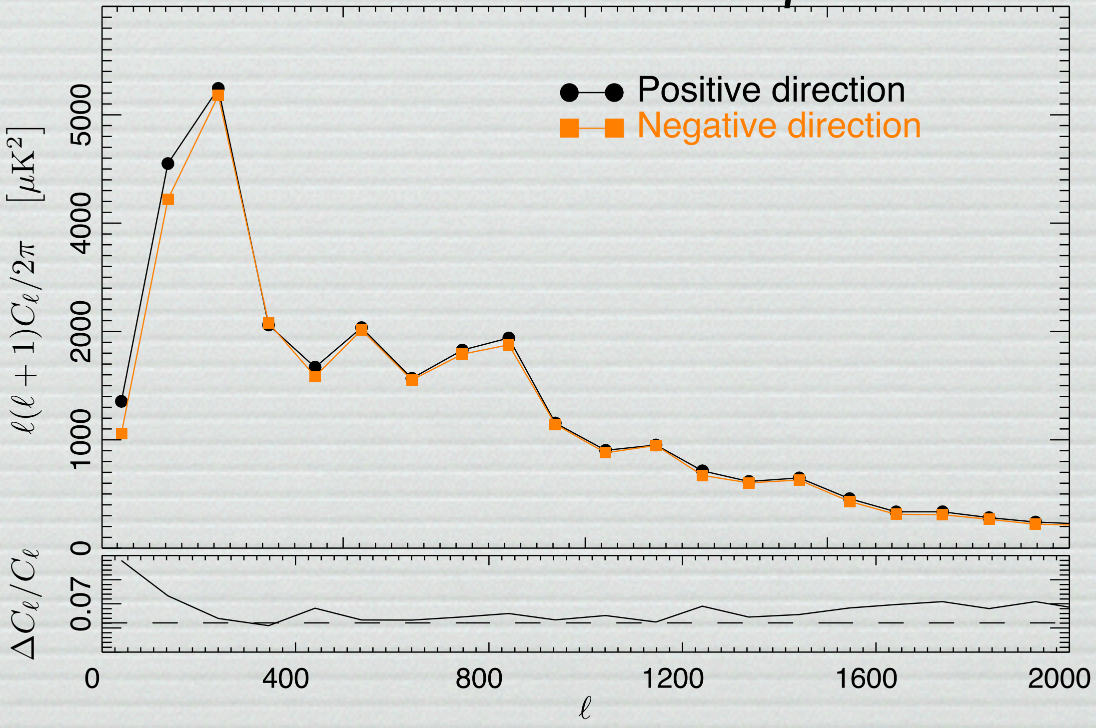
Large-scale anisotropy

- Hemispherical differences: how can we arrange anisotropy on the scale of the horizon?
  - initial conditions: anisotropic inflation?
  - the large-scale structure of spacetime
    - change the geometry: Bianchi
      - homogeneous + anisotropic spacetimes
    - change the topology

Small (but statistically significant) difference between the power in the hemispheres

Overall low power at large scales



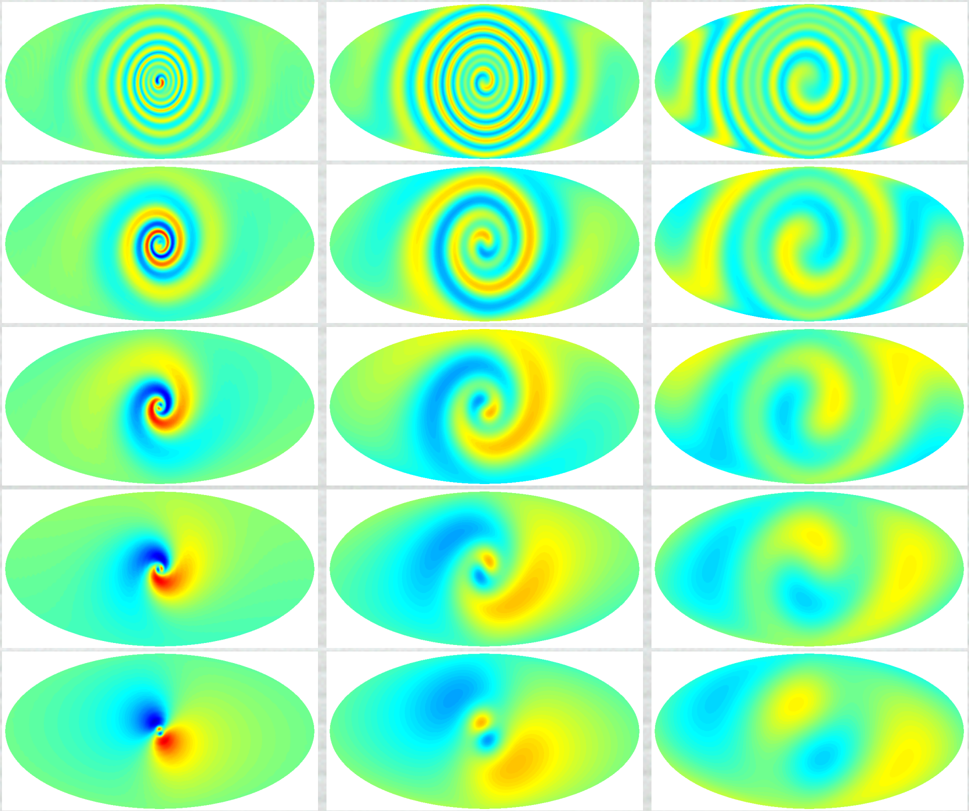


Bianchi Models

- Homogeneous, anisotropic spaces
- VII$_h$: global shear and rotation
  - parameter h relates vorticity ω_i to shear σ_{ij}, Ω_{tot}

$$\left(\frac{\omega}{H}\right)_0 = \frac{(1+h)^{1/2}(1+9h)^{1/2}}{6h}\frac{1-\Omega_{\rm tot}}{\Omega_{\rm tot}}\sqrt{\left(\frac{\sigma_{12}}{H}\right)_0^2+\left(\frac{\sigma_{13}}{H}\right)_0^2}$$

- Focusing induces specific pattern of temperature anisotropy on large scales
- Full likelihood calculation (Gaussian added to deterministic template)
  - consistent cosmology very low likelihood



Bianchi Models

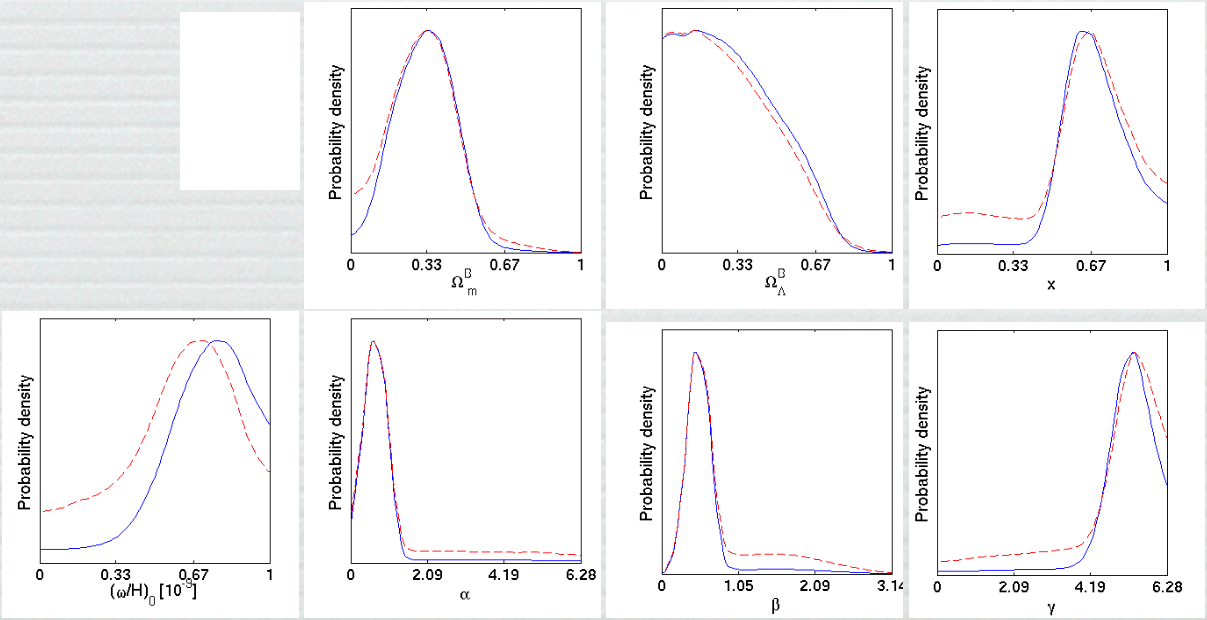
Flat-decoupled

Bianchi Parameter	SMICA		SEVEM	
	MAP	Mean	MAP	Mean
Ω_m^B	0.38	0.32 ± 0.12	0.35	0.31 ± 0.15
Ω_Λ^B	0.20	0.31 ± 0.20	0.22	0.30 ± 0.20
x	0.63	0.67 ± 0.16	0.66	0.62 ± 0.23
$(\omega/H)_0$	8.8×10^{-10}	$(7.1 \pm 1.9) \times 10^{-10}$	9.4×10^{-10}	$(5.9 \pm 2.4) \times 10^{-10}$
α	38.8°	51.3° ± 47.9°	40.5°	77.4° ± 80.3°
β	28.2°	33.7° ± 19.7°	28.4°	45.6° ± 32.7°
γ	309.2°	292.2° ± 51.9°	317.0°	271.5° ± 80.7°

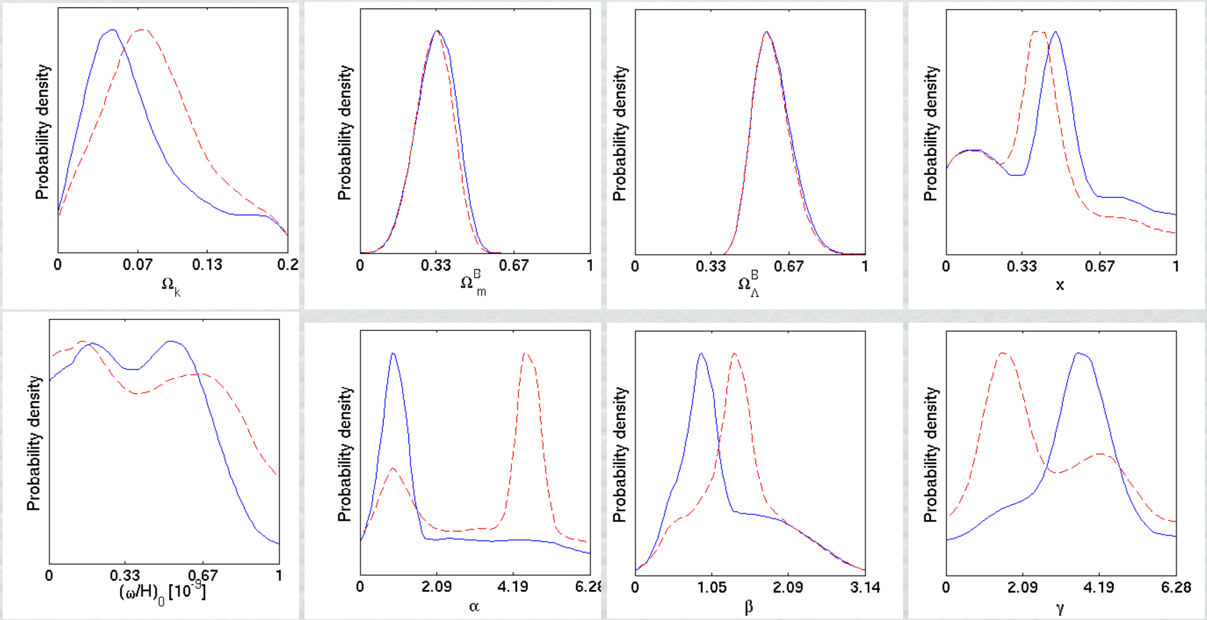
Open-coupled

Bianchi Parameter	SMICA		SEVEM	
	MAP	Mean	MAP	Mean
Ω_k	0.05	0.07 ± 0.05	0.09	0.08 ± 0.04
Ω_m^B	0.41	0.33 ± 0.07	0.41	0.32 ± 0.07
Ω_Λ^B	0.55	0.60 ± 0.07	0.50	0.59 ± 0.07
x	0.46	0.44 ± 0.24	0.38	0.39 ± 0.22
$(\omega/H)_0$	5.9×10^{-10}	$(4.0 \pm 2.4) \times 10^{-10}$	9.3×10^{-10}	$(4.5 \pm 2.8) \times 10^{-10}$
α	57.4°	122.5° ± 96.0°	264.1°	188.6° ± 98.7°
β	54.1°	70.8° ± 35.5°	79.6°	81.1° ± 31.7°
γ	202.6°	193.5° ± 77.4°	90.6°	160.4° ± 91.1°

Flat-coupled: $\omega_0/H_0 < 8.1 \times 10^{-10}$ (95%)

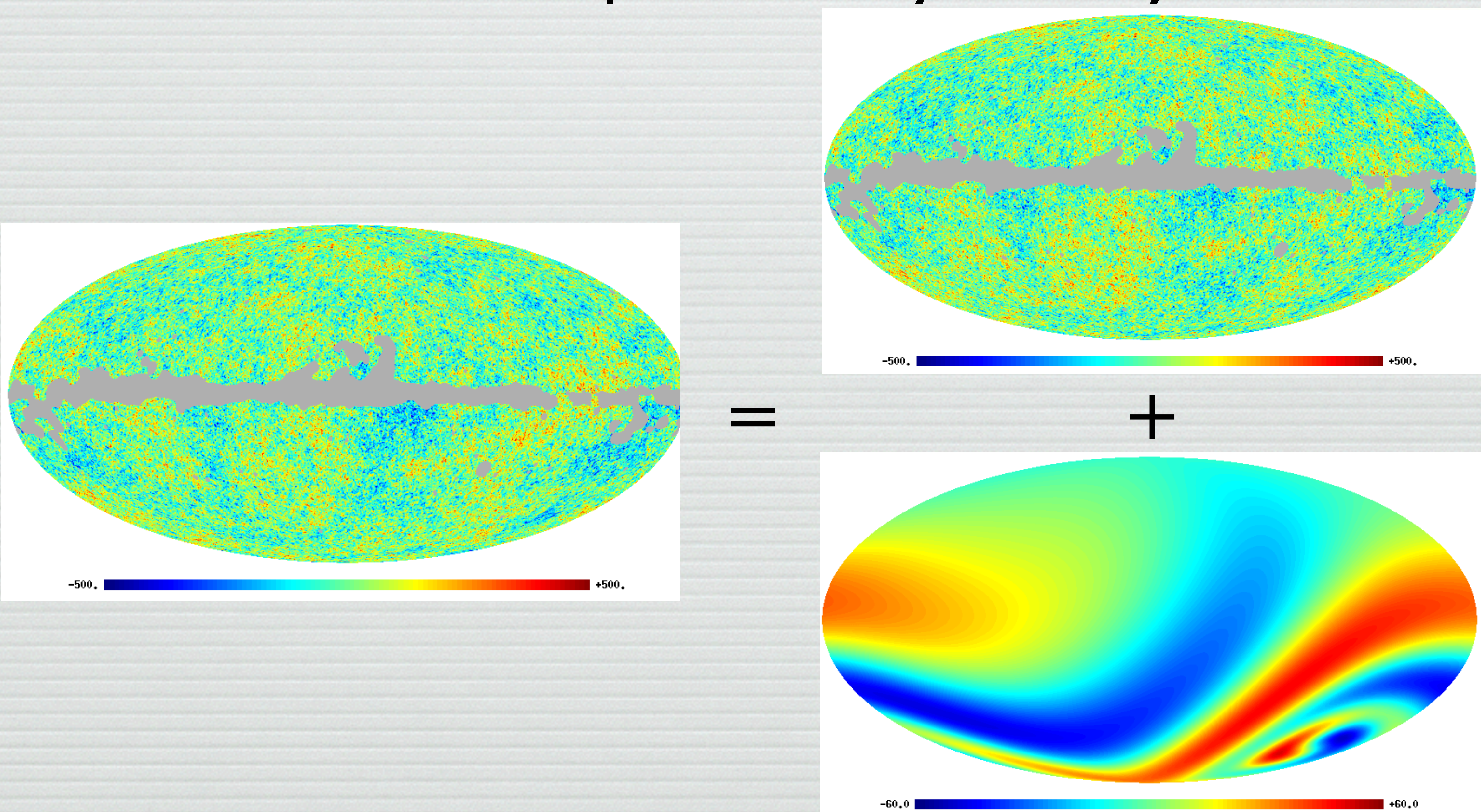


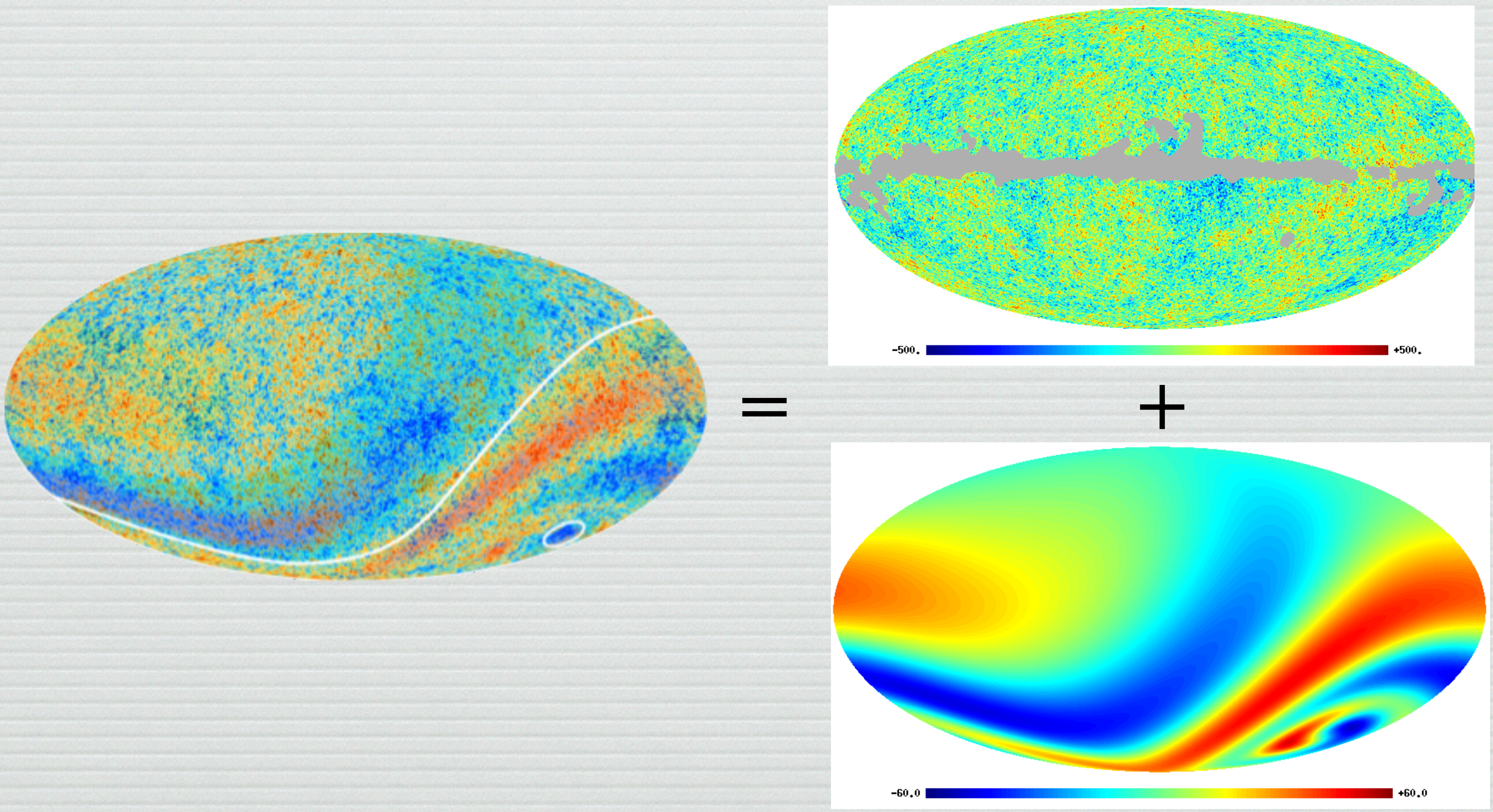
(**a**) Flat-decoupled-Bianchi model.



(**b**) Open-coupled-Bianchi model.

- The Bianchi VII_h uncoupled "model" accounts for much of the hemispherical asymmetry

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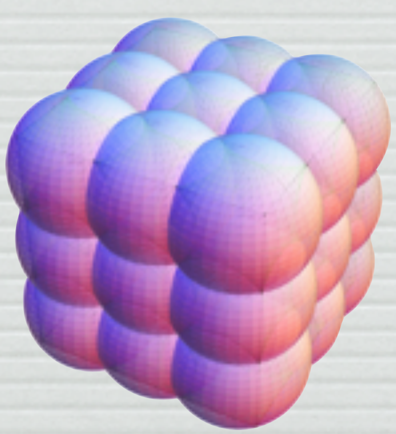
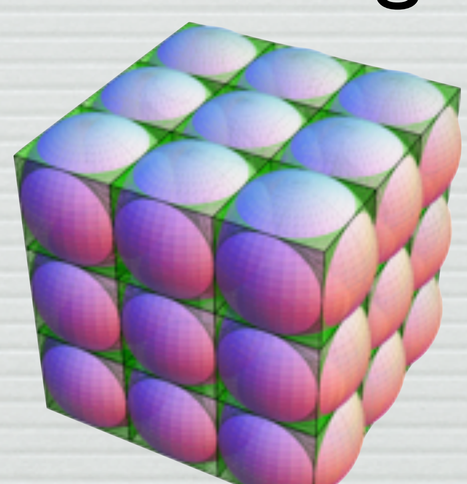
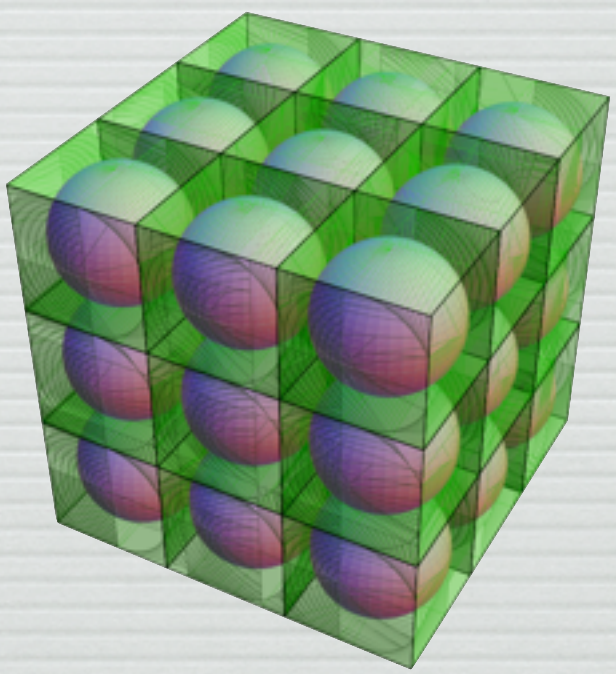
Fundamental Physics: The shape of the Universe

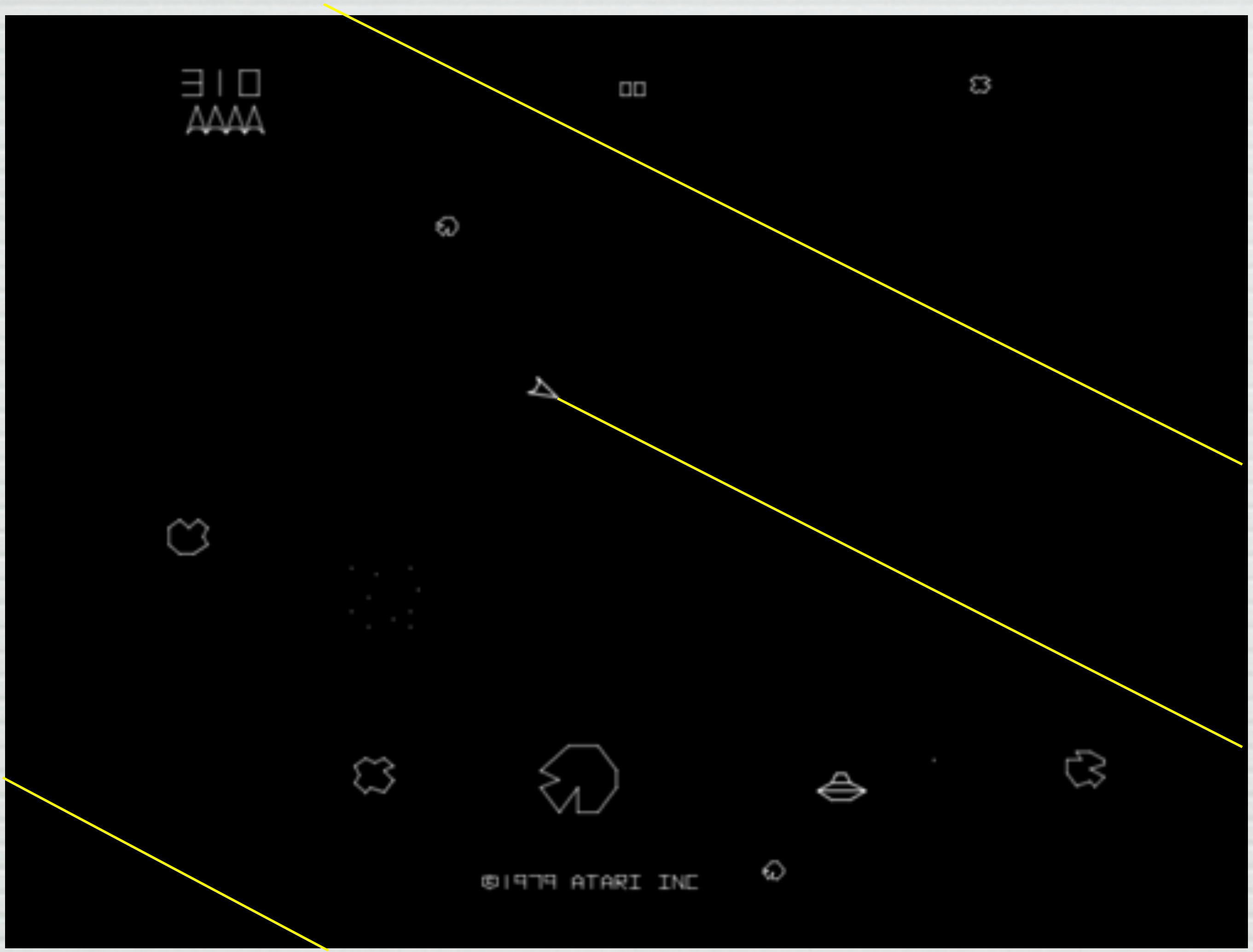
- General relativity determines the curvature of the Universe, but not its topology (holes and handles)
- Most theories of quantum gravity (and quantum cosmology) predict topological change on small scales and at early times.
- Does this have cosmological implications?
  - E.G., small universe ⇒ fewer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

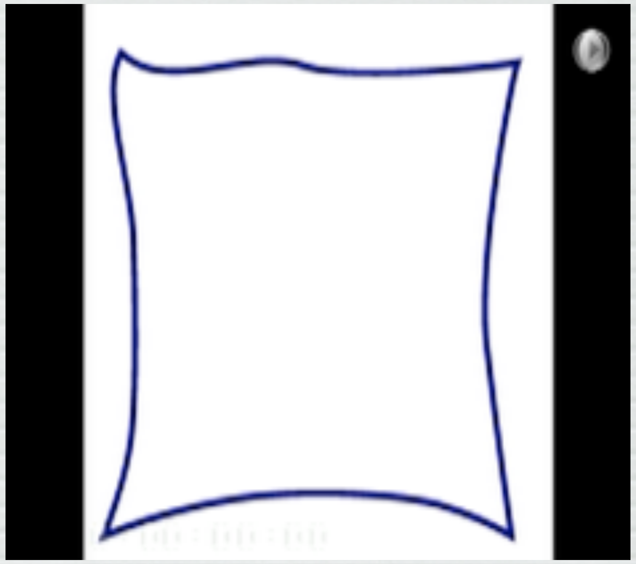


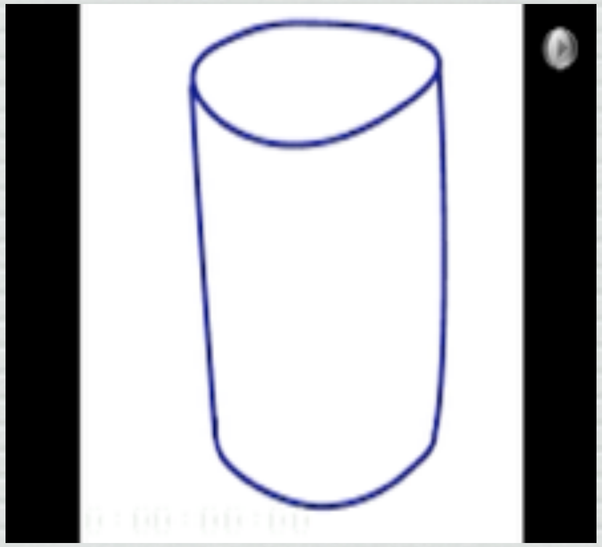


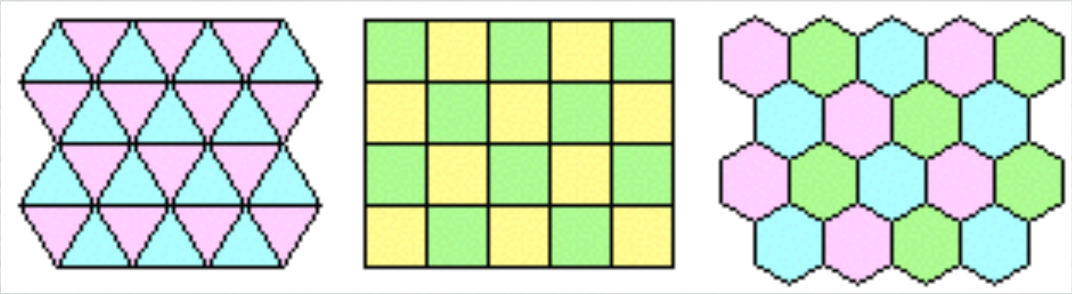


Topology in a flat "universe"





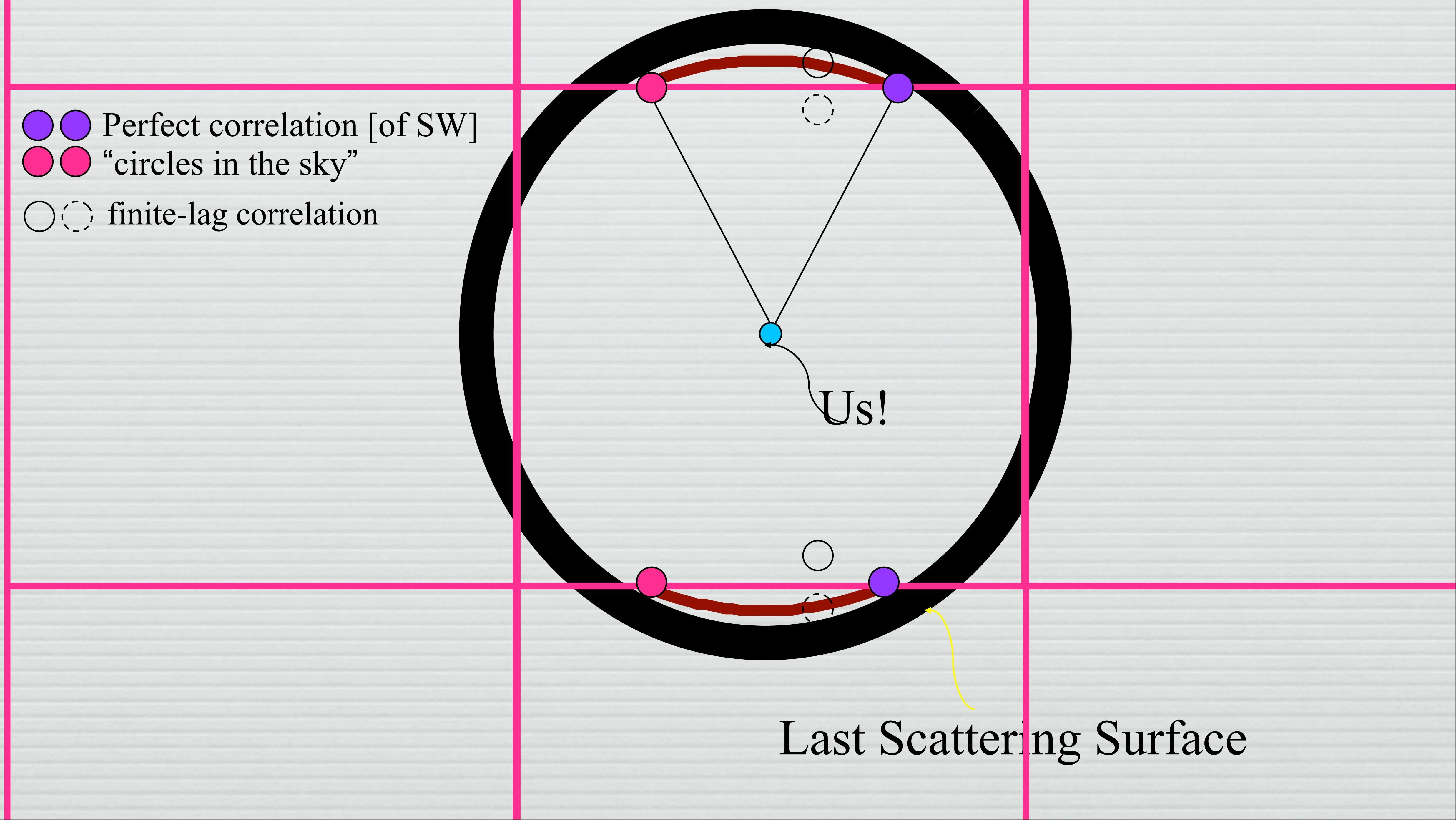




"tiling the plane"

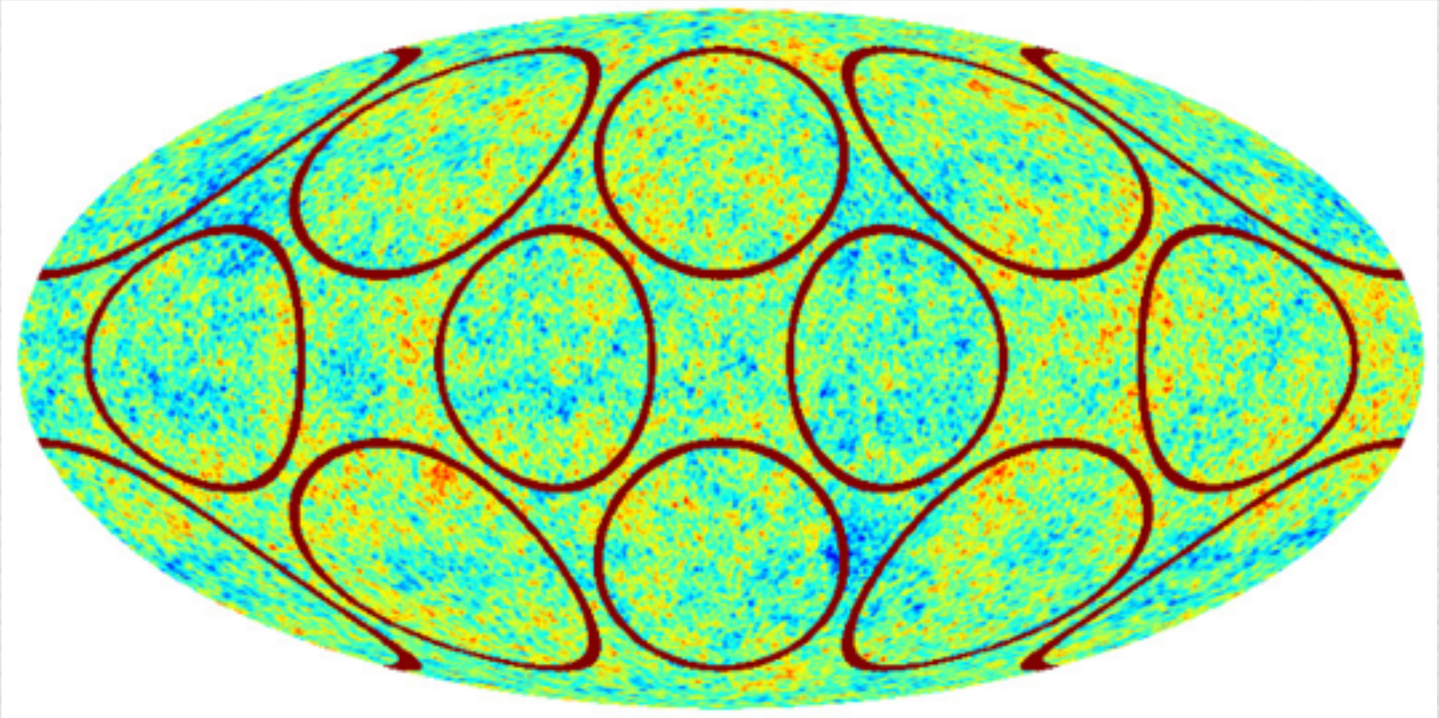
Don't *need* to "embed" the square to have a connected topology.

Measuring Topology with the CMB



Topology from Planck

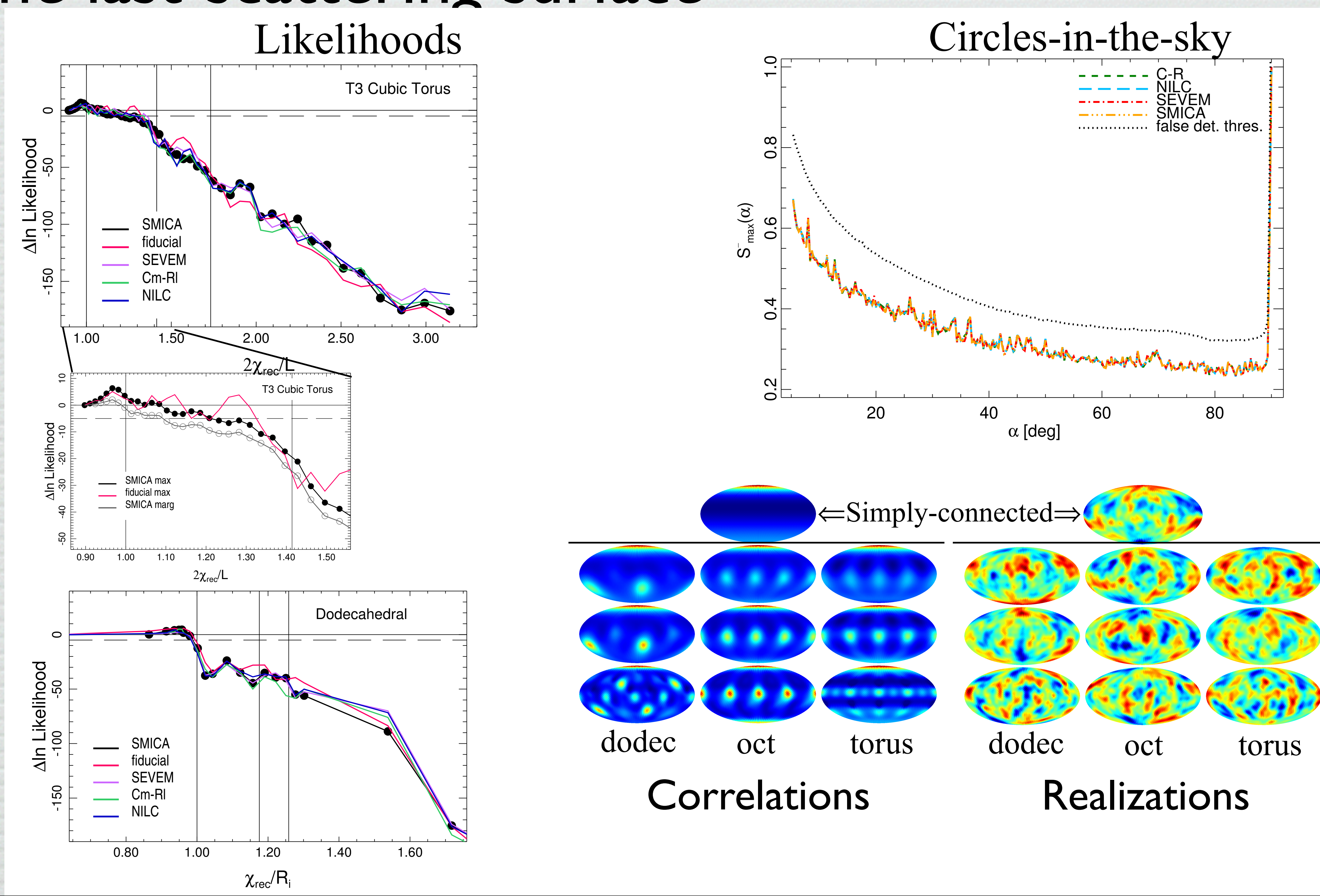
- “Matched circles” in a simulated Universe:



- 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!)

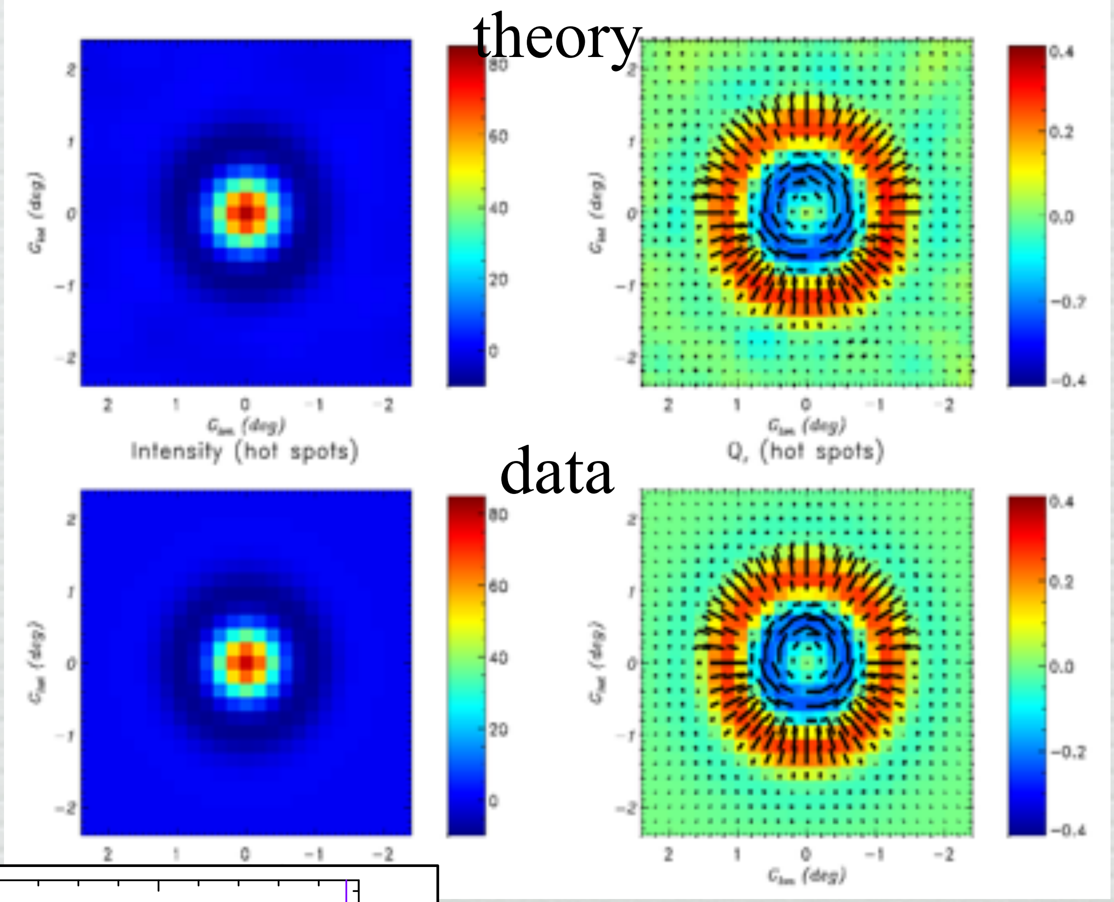
Topology: results

- No strong evidence for topology on the scale of the last-scattering surface



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.



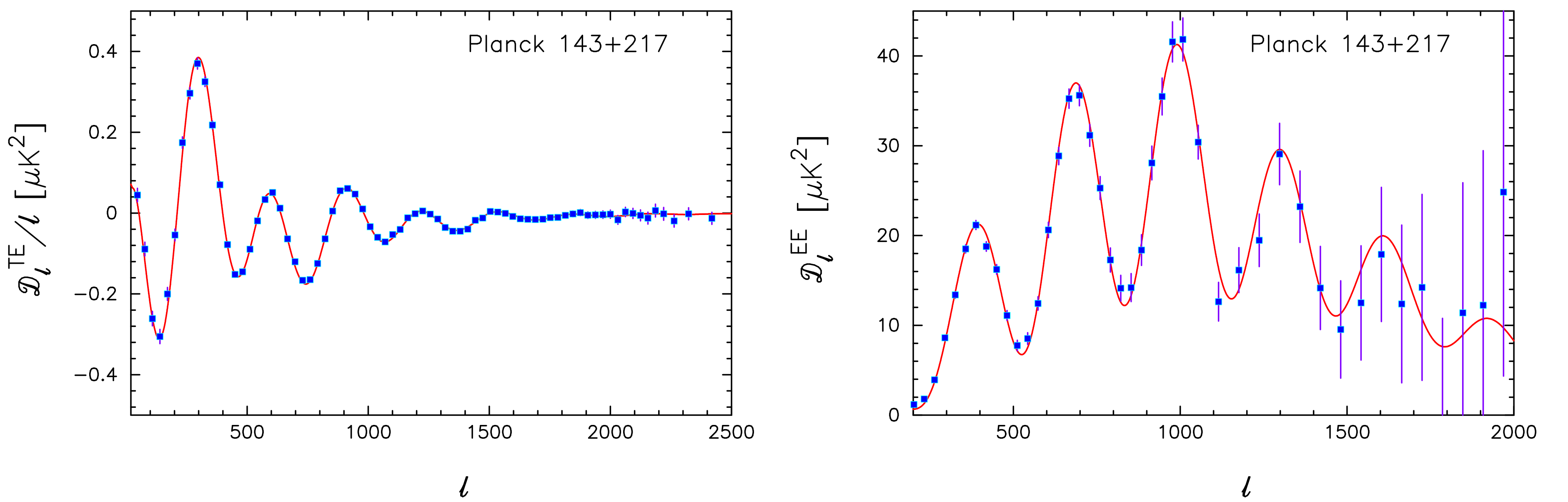
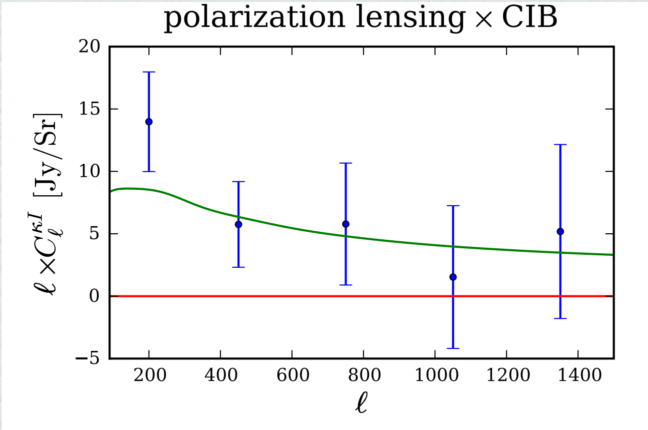


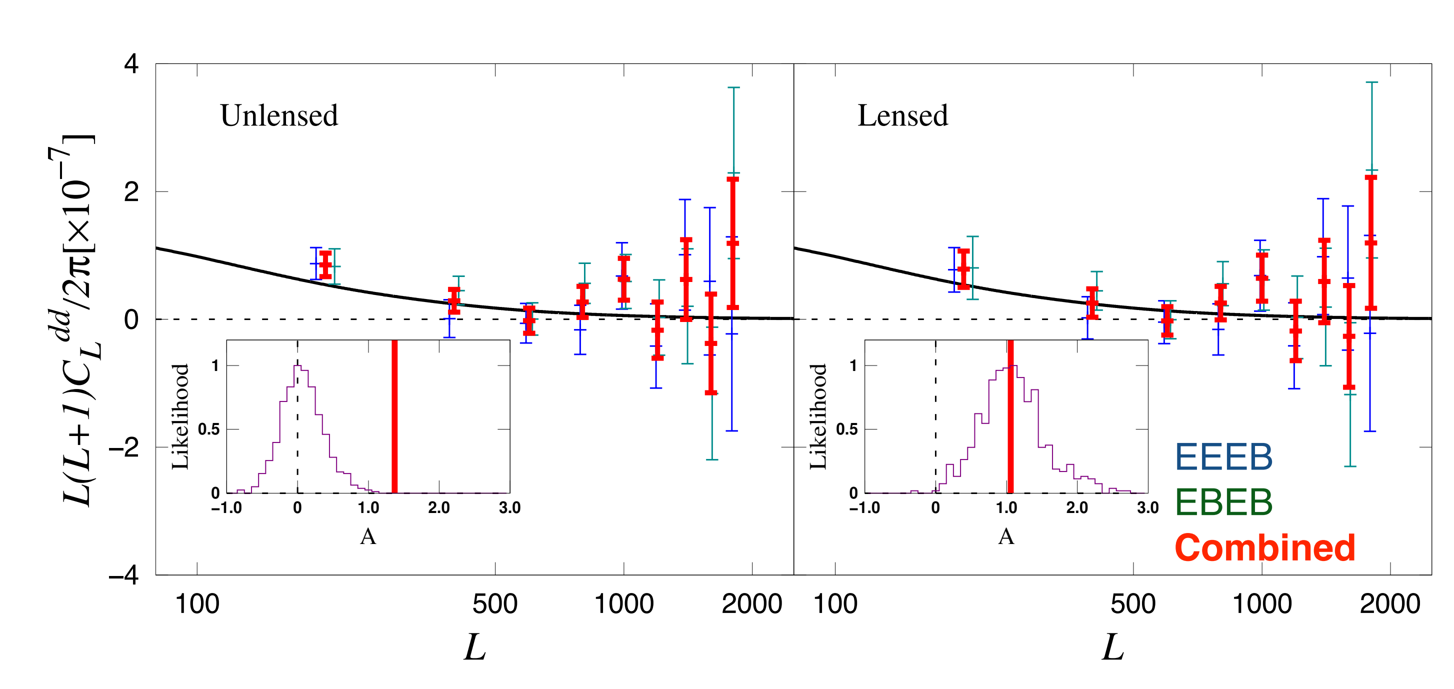
Fig. 11. *Planck TE* (left) and *EE* spectra (right) computed as described in the text. The red lines show the polarization spectra from the base ΛCDM *Planck*+WP+highL model, *which is fitted to the TT data only*.

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 et al; Polarbear)



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



Hanson et al, *SPTPOL,* arXiv:1307.5830

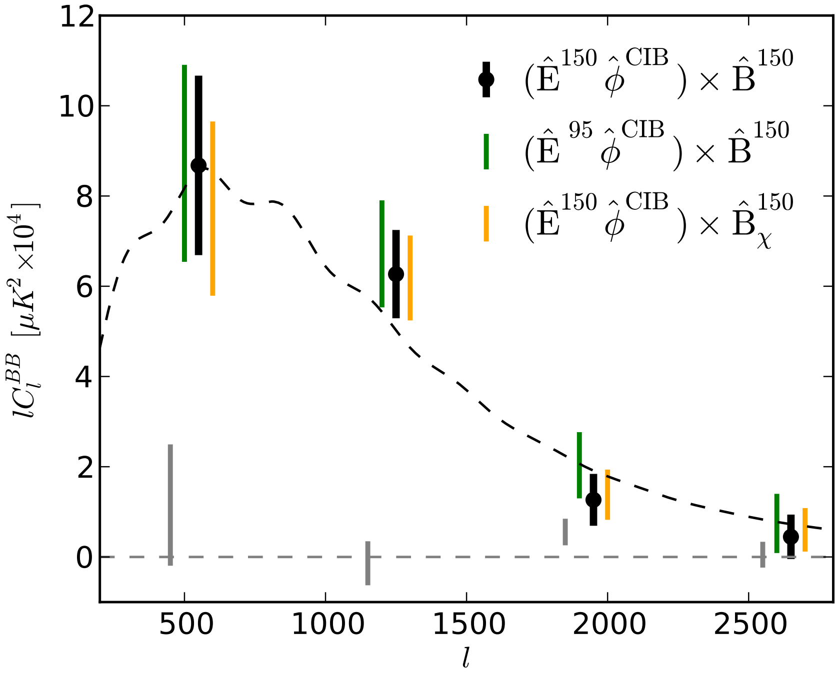


FIG. 2: (Black, center bars): Cross-correlation of the lensing B modes measured by SPTpol at 150 GHz with lensing B modes inferred from CIB fluctuations measured by *Herschel* and E modes measured by SPTpol at 150 GHz; as shown in Fig. 1. (Green, left-offset bars): Same as black, but using E modes measured at 95 GHz, testing both foreground contamination and instrumental systematics. (Orange, right-offset bars): Same as black, but with B modes obtained using the χ_B procedure described in the text rather than our fiducial Wiener filter. (Gray bars): Curl-mode null test as described in the text. (Dashed black curve): Lensing B-mode power spectrum in the fiducial cosmological model.

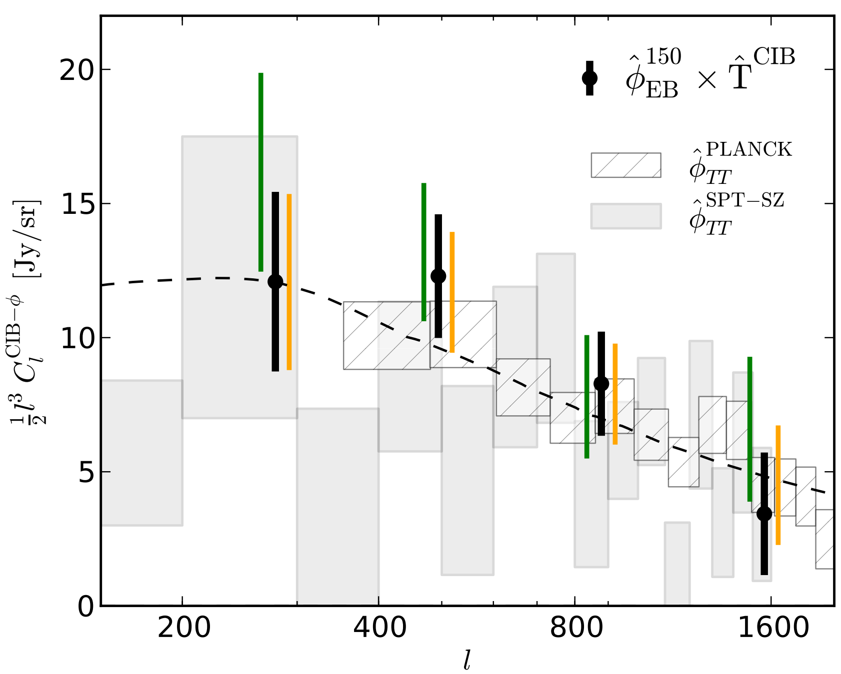


FIG. 3: "Lensing view" of the $EB\phi$ correlation plotted in Fig. 2, in which we cross-correlate an EB lens reconstruction from SPTpol data with CIB intensity fluctuations measured by *Herschel*. Left green, center black, and right orange bars are as described in Fig. 2. Previous analyses using temperature-based lens reconstruction from *Planck* [26] and SPT-SZ [22] are shown with boxes. The results of [26] are at a nominal wavelength of 550 μm, which we scale to 500 μm with a factor of 1.22 [37]. The dashed black curve gives our fiducial model for $C_l^{CIB\text{-}\phi}$ as described in the text.

Conclusions

- *Planck* data support a standard ΛCDM cosmology
  - flat FRW
  - perturbations:
    - nearly scale-invariant adiabatic
    - Gaussian + linear & nonlinear evolution
  - } inflation?
  - Λ-like acceleration
- Some anomalies/inconsistencies remain (as might be expected)
- More data in 2014-15 from *Planck* and other experiments
  - especially polarization

Extra Stuff

- Lensing
- Neutrinos
- Bianchi

Particle physics with the whole Universe

- Neutrinos are very light ⇒ act like radiation
  - affect expansion rate at early times
  - affect growth of structure at late times
- Still relativistic at recombination
- Improved limit from lensing: more mass = less lensing
  - $\Sigma m_\nu < 0.66$ eV (95%, *Planck*+WP+highL)
  - $\Sigma m_\nu < 0.23$ eV (+BAO)
  - However, adding *Planck* lensing spectrum *increases* limit to <0.85 eV.
  - $N_{eff} = 3.36 \pm 0.34$ (68%, *Planck*+WP+highL)
  - $N_{eff} = 3.30 \pm 0.27$ (+BAO)
- With nominal cluster mass bias, SZ cluster counts prefer non-zero neutrino mass (~0.5 eV).