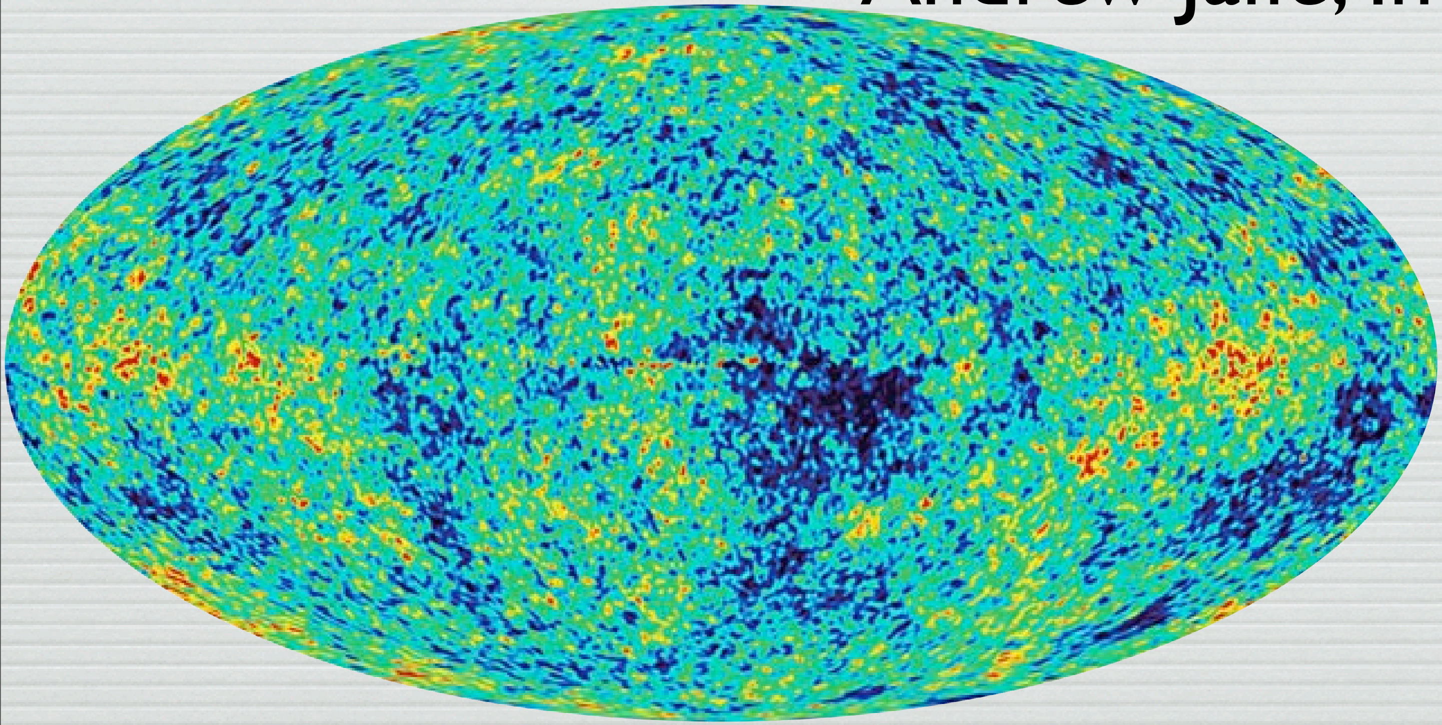
The CMB: Cosmology, Topology & Probability

Andrew Jaffe, Imperial College



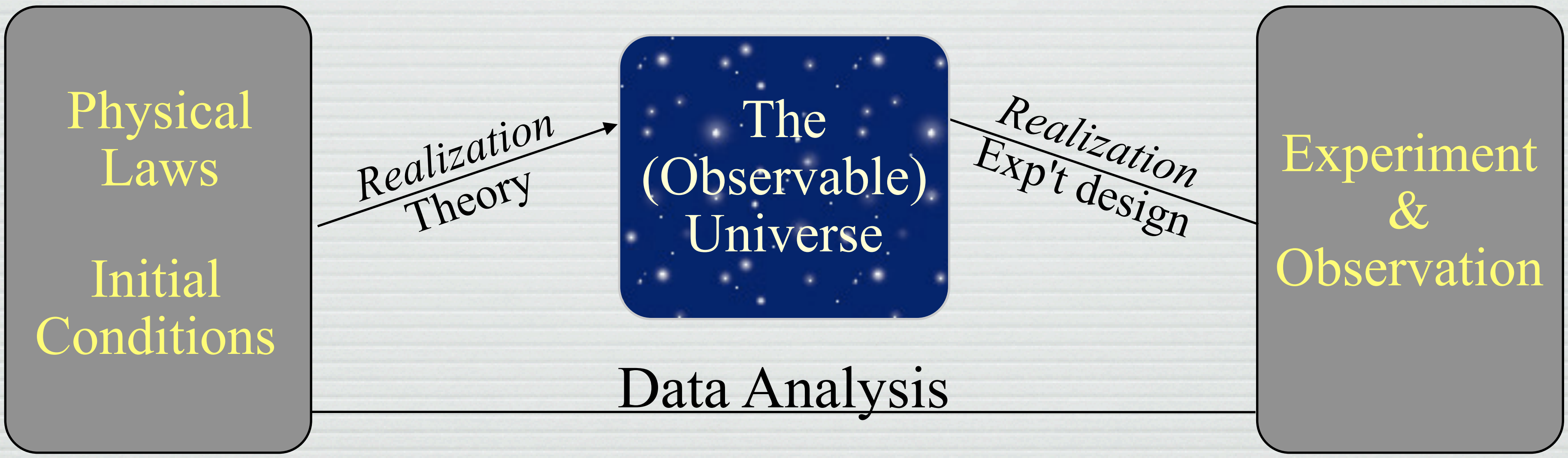
Edinburgh

March 2007

Road map

- The physics of the CMB (Cosmic Microwave Background)
- CMB Observations
  - Cosmological parameters
  - The topology of the Universe
- Future experiments & the background gravitational radiation
- … philosophical excursions…
  - probability
  - the anxxxrxpxc principle

Statistical Cosmology



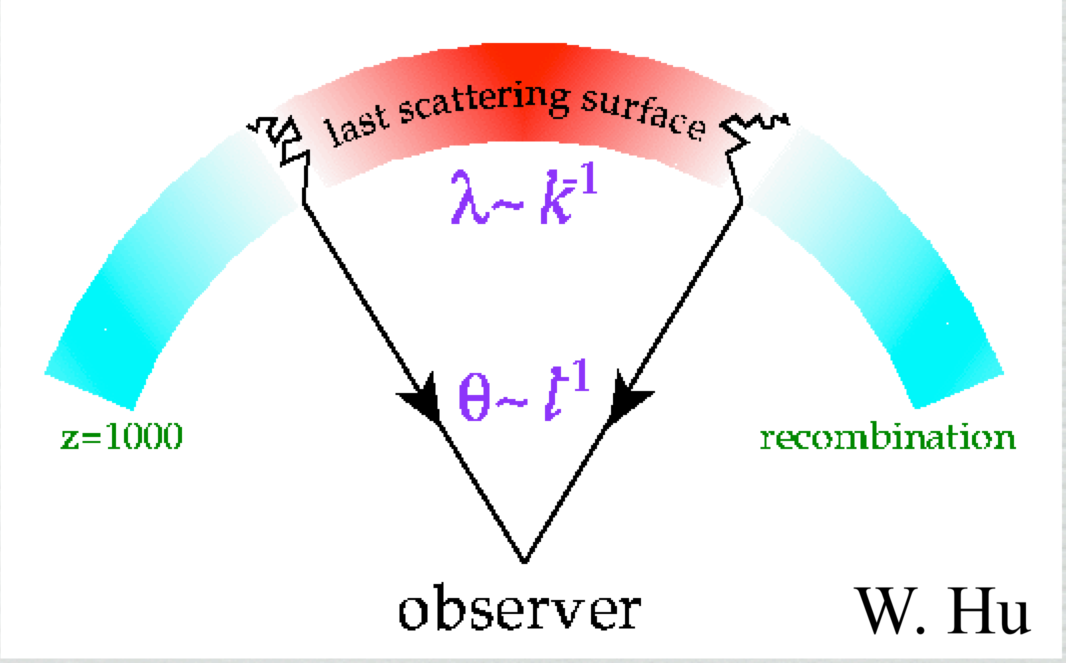
- 21st C. cosmology:
  - Redshift surveys
  - CMB (Cosmic Microwave Background)
  - Weak lensing
  - ...

The Physics of the CMB

- As Universe cools, p+e → H, when
  kT=0.3 eV~13.6 eV [400,000 yrs]
  - "last scattering" ~ "recombination"

- Rapid transition
  - $p^+ + e^- \rightarrow H$
    ionized → *neutral*
    opaque → *transparent*

- Penzias & Wilson 1964
  (+ Dicke, Peebles, Roll & Wilkinson)
- COBE/DMR (Mather & Smoot)

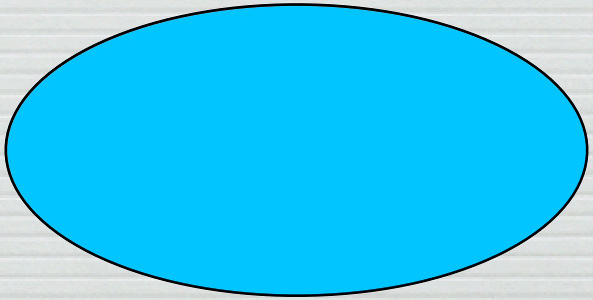


Cosmological Horizons

- Physics works at the speed of light:
- No "causal influence" from more than
  - Horizon distance

    d_H = (age of universe) × (speed of *light*)

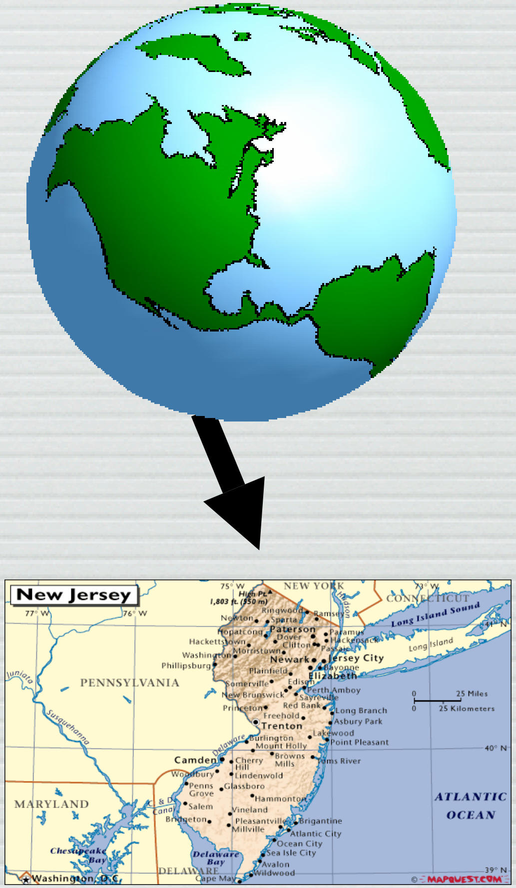
    Oscillations in primordial plasma (*sound* waves)
  - [Sound] horizon at LSS ~1°
  - In the standard big bang, the *horizon always grows*
  - But here's what Penzias & Wilson saw:
    - T = 3K, ~constant over sky



How did everything get to be the same temperature????

Inflation

- Expand the universe by a factor $>>10^{30}$ at $t\sim10^{-30}$ sec.
  - $a \propto e^{Ht}$
- Makes the universe flat ($\Omega=1$)
- Puts it all into "causal contact" (so the CMB can be isotropic)
- Generates perturbations that become galaxies, clusters, etc.
- But: no way yet to choose among specific models within particle physics, string theory,



Perturbations from inflation

- Rapid expansion blows up quantum scales to astrophysical size:
  - weakly-coupled (~free) scalar field
    $\langle\varphi(x)\varphi(x')\rangle = F(x-x')$ (~Gaussian)
  - quantum fluctuations become "frozen in", generating
  - scalar (density/curvature) fluctuations, and
  - tensor (gravitational radiation) fluctuations
    - +/X polarization — handedness — curl-like pattern in CMB photon polarization

Inflation Predicts

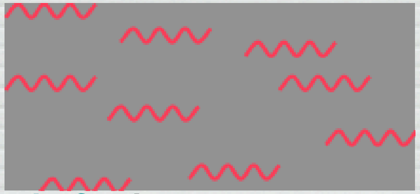
- Thermalized, uniform CMB
- Flat:
  - $\Omega_{tot} = \Omega_m + \Omega_\Lambda = 1$
- (Approximately) *scale-invariant* + *adiabatic* initial spectrum of density fluctuations
  - $P(k) \propto k^{n_s}, n_s \approx 1$
- Gravitational radiation
  - (Need CMB polarization to detect)
- Corollaries
  - Dark baryons, dark matter
- Caveats
  - Open inflation
  - Quintessence
  - Isocurvature fluctuations
  - Trace defects

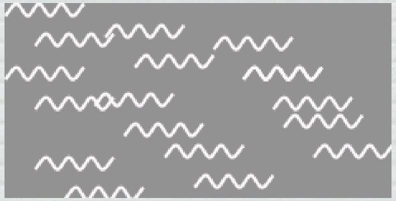
What affects the CMB temperature?

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

- Initial temperature (density) of the photons

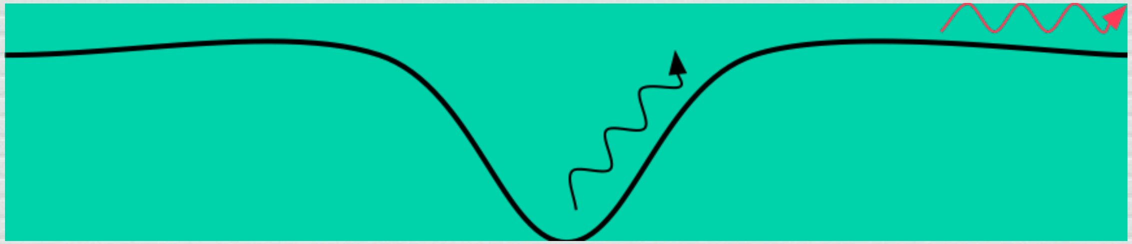
Cooler





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

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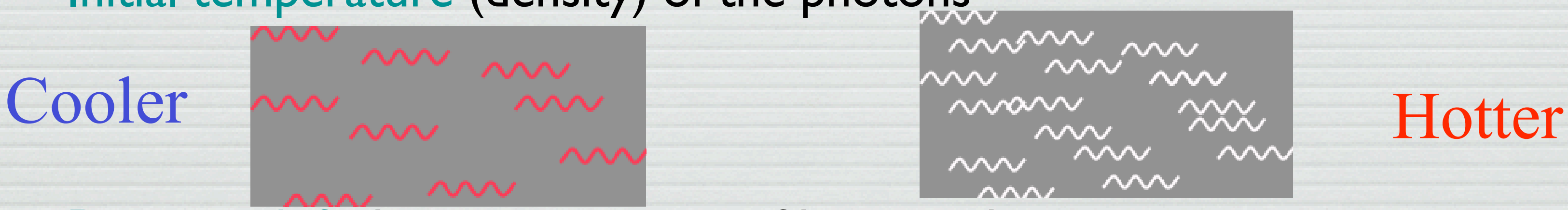

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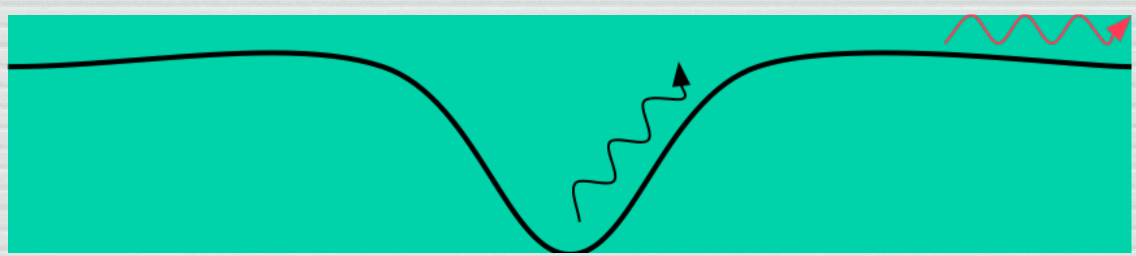

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What affects the CMB temperature?

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

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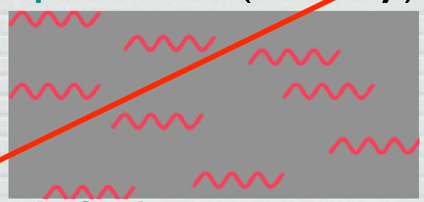

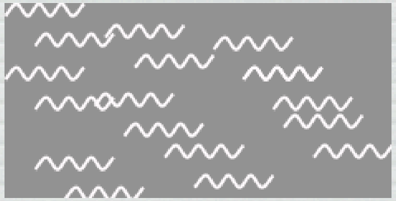

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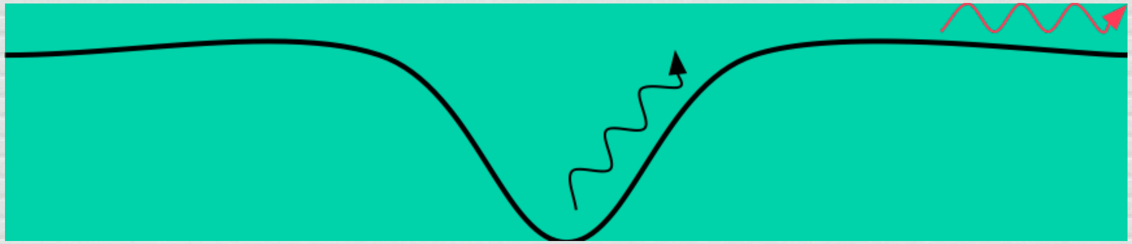

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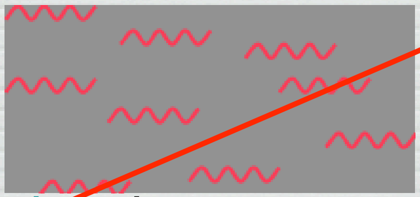
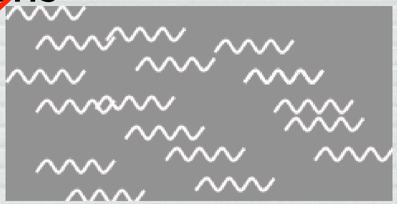
Cooler   Hotter

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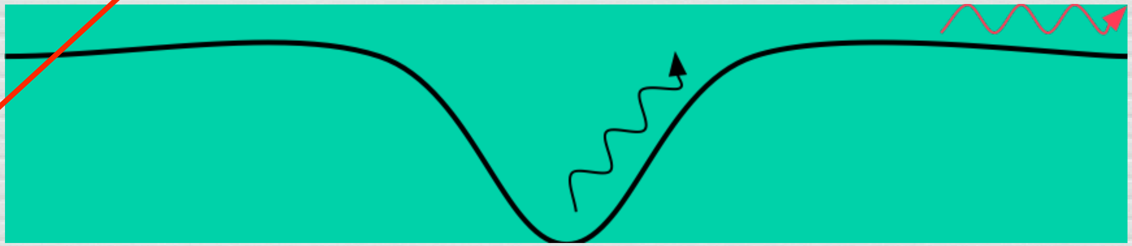


- Photon path from LSS to today
- All linked by initial conditions ⇒ 10^{-5} fluctuations

Describing the (CMB) Universe

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

"Fourier transform" on a sphere

- Allows us to define the *power spectrum*, C_l

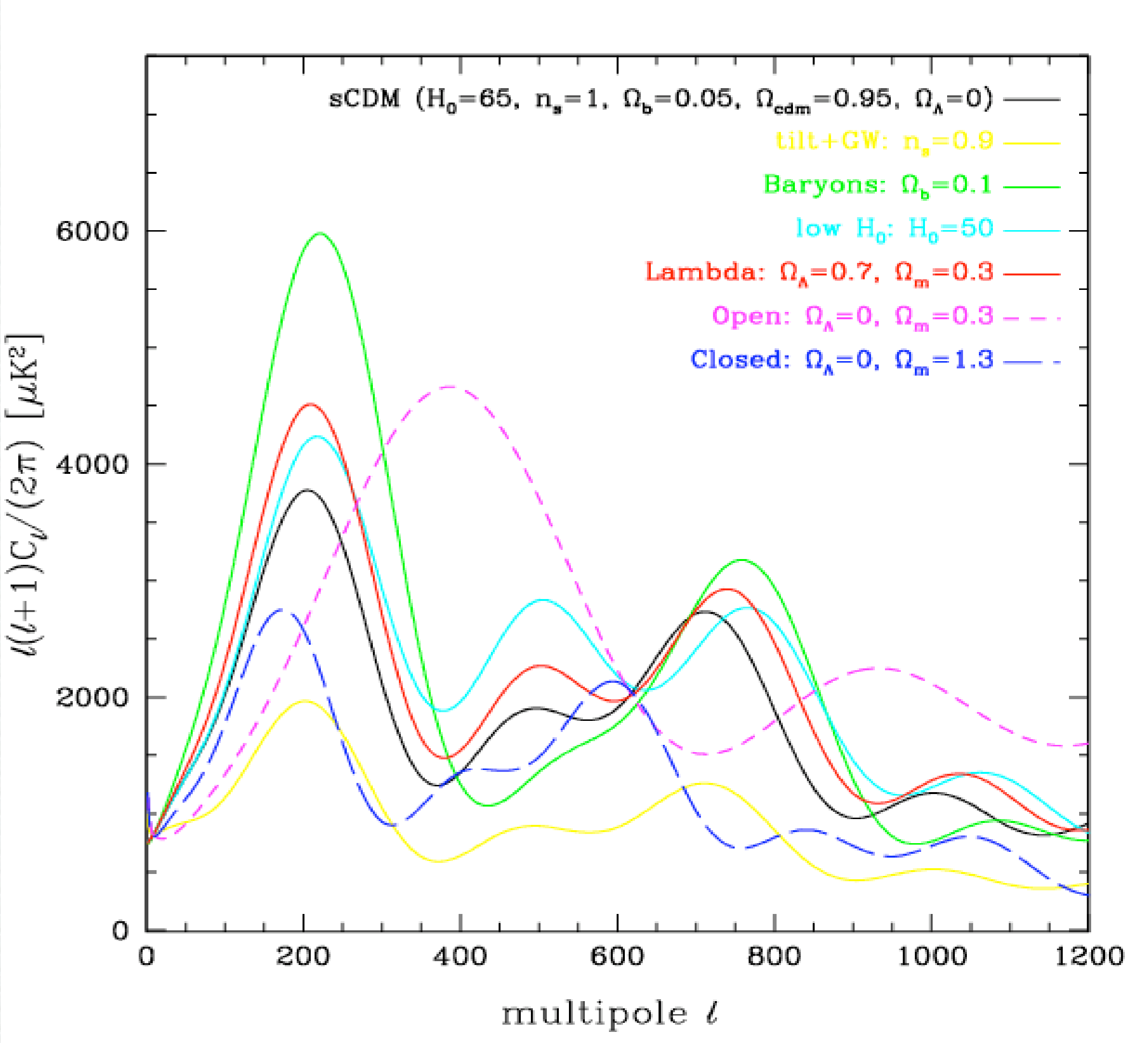
$$\langle a^*_{\ell m} a_{\ell' m'} \rangle = \delta_{\ell\ell'} \delta_{mm'} \; C_\ell$$

  - Assumes *isotropy* (no absolute orientation)
  - If we also assume *Gaussianity* (e.g., inflation):

$$P(a_{\ell m}|C_\ell) = \frac{1}{\sqrt{2\pi C_\ell}} \exp\left(-\frac{1}{2} \frac{|a_{\ell m}|^2}{C_\ell} \right)$$

Power Spectrum of fluctuations

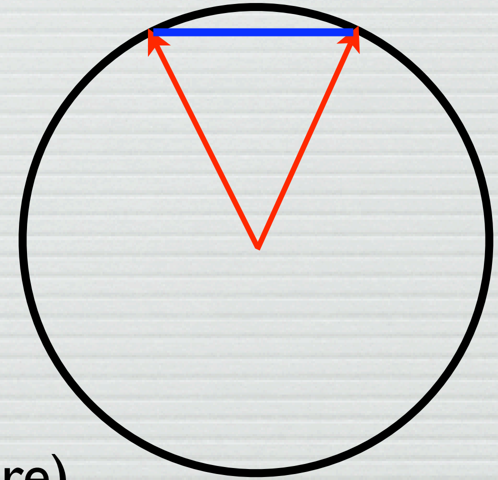
Mean square fluctuation



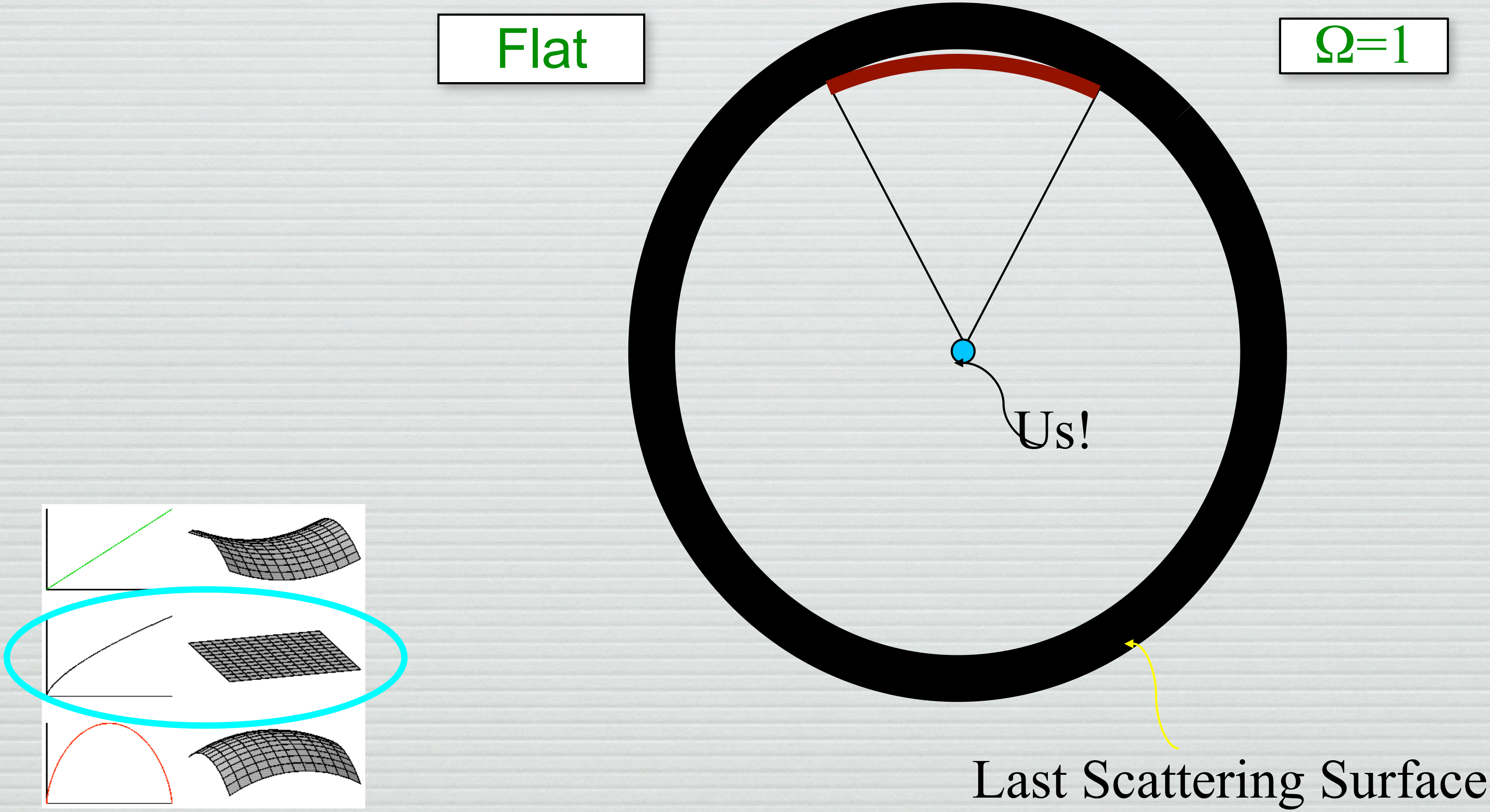
~180°/Angular Scale

CMB Fluctuations

- Sound Horizon at last-scattering surface is a standard ruler (degree-scale fluctuations)
  - angular diameter distance at z≈1300,
    Constrains ratio of
    - "sound horizon" at LSS, to
      - (matter content)
    - angular-diameter distance to LSS
      - (curvature, matter, quintessence: total curvature)
  - (approximately) constrains $\Omega_m + \Omega_{\Lambda/Q}$ $(=1 - \Omega_k)$
    - "geometrical degeneracy"



Measuring Curvature with the CMB



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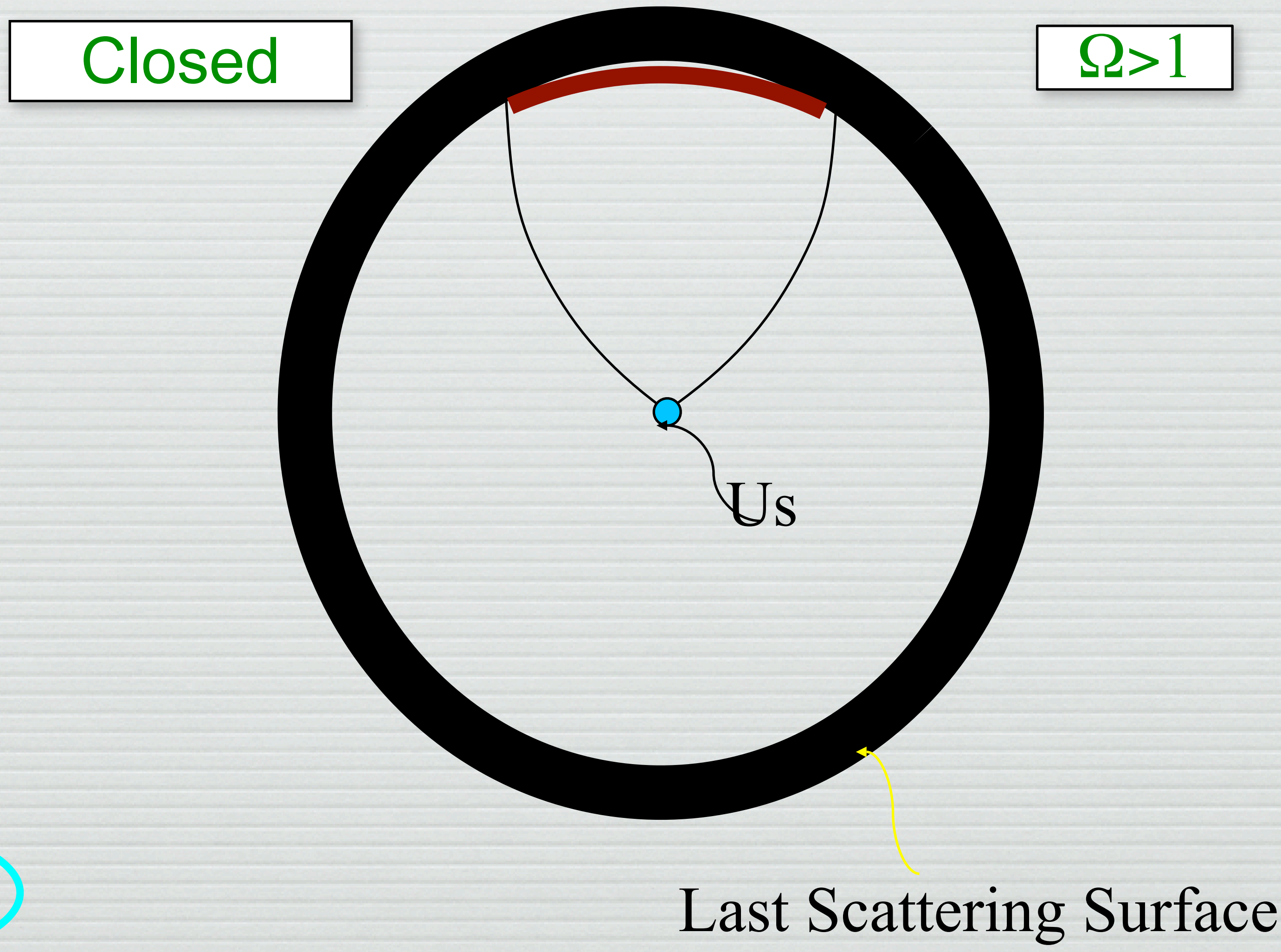

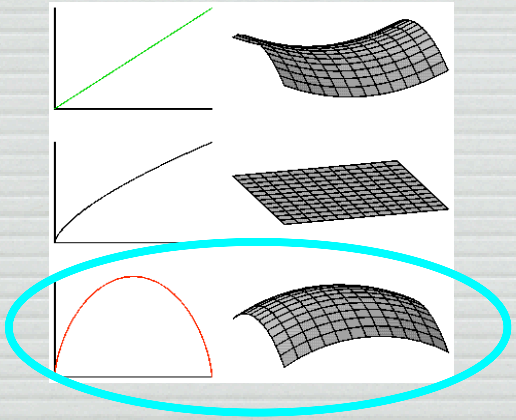

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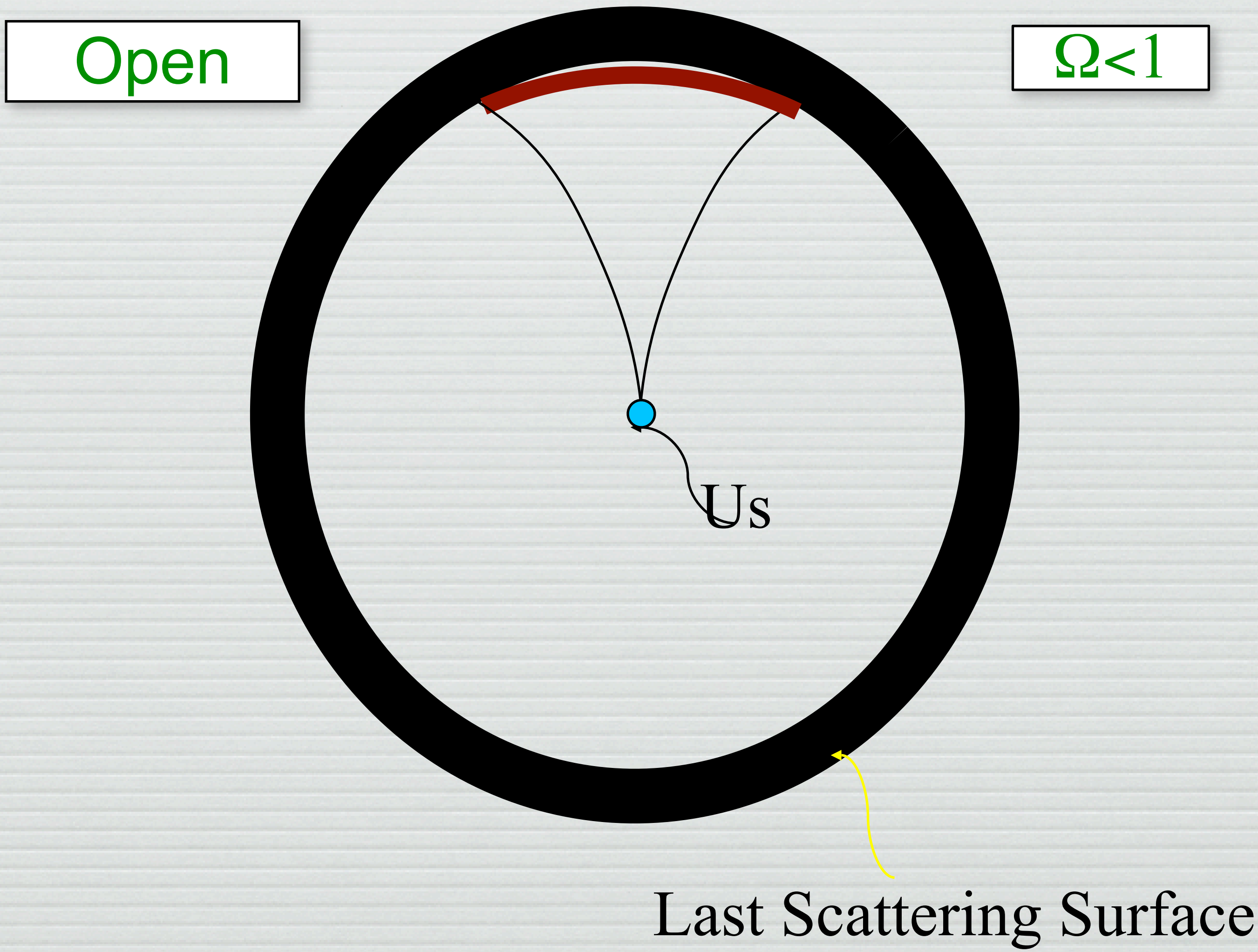
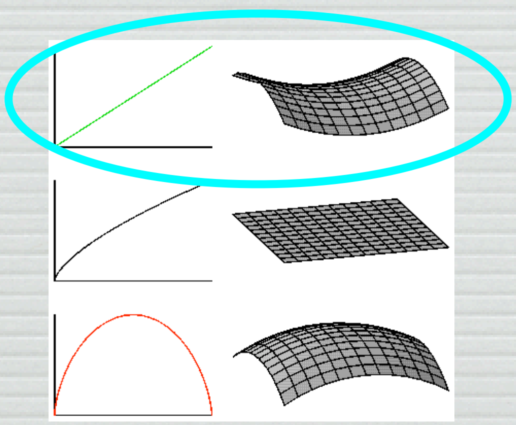
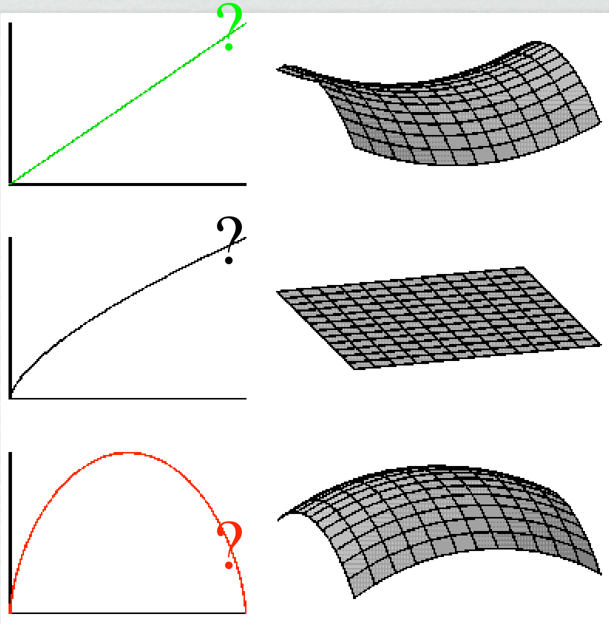


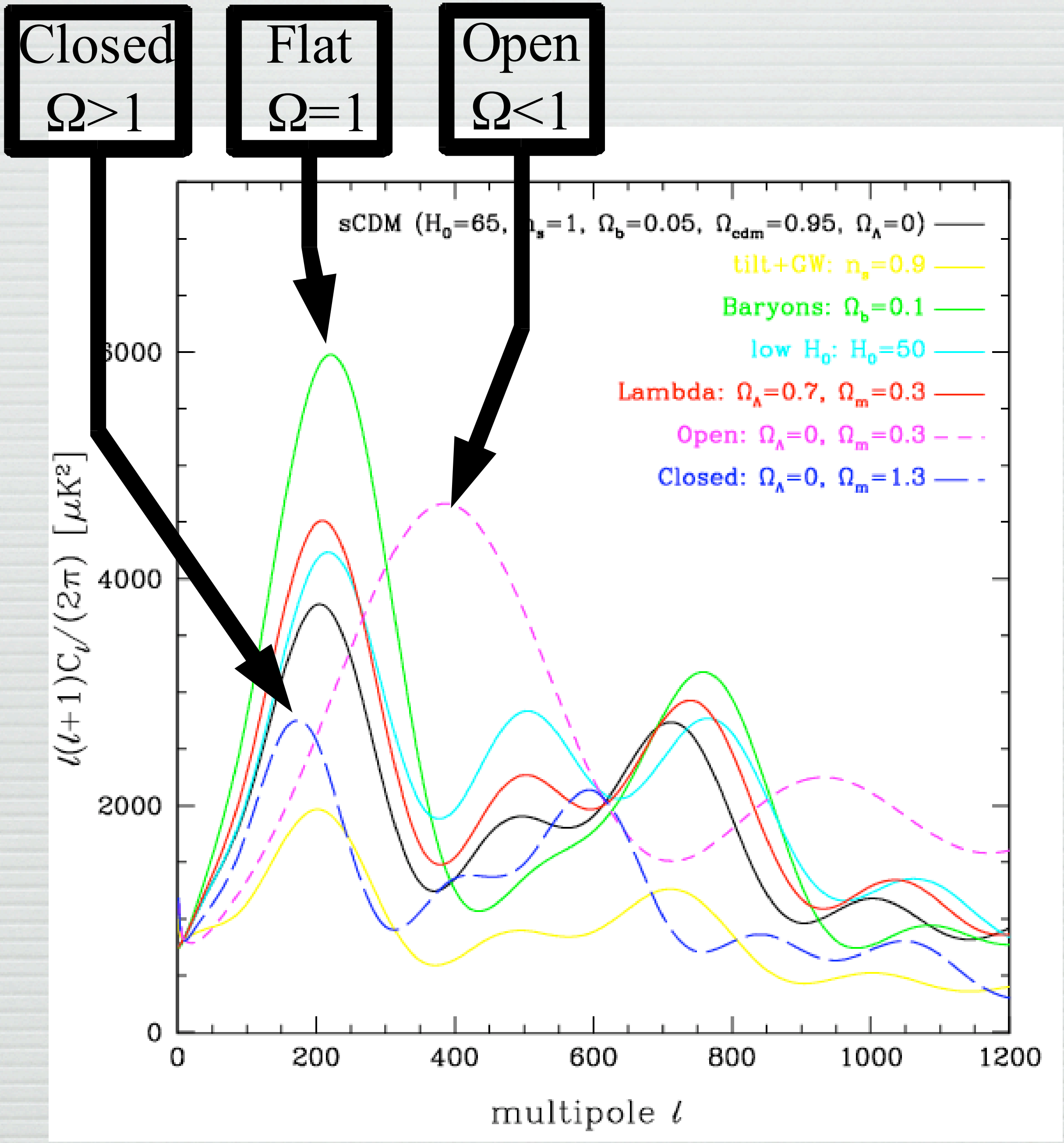


Fluctuations & Geometry

- Total density determines geometry – but geometry doesn't determine the fate of the Universe if we allow a cosmological constant (or quintessence)

$$\Omega \begin{cases} <1 & \text{open} \\ =1 & \text{flat} \\ >1 & \text{closed} \end{cases}$$

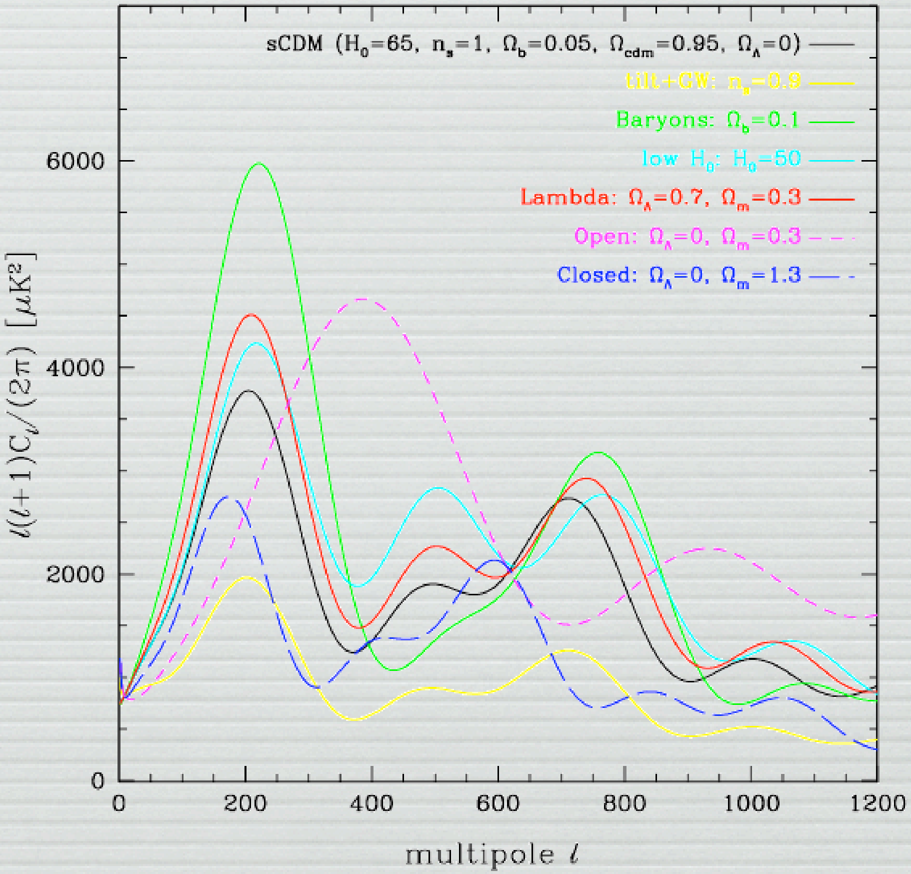




Closed $\Omega>1$
Flat $\Omega=1$
Open $\Omega<1$
sCDM (H_0=65, n_s=1, Ω_b=0.05, Ω_{cdm}=0.95, Ω_Λ=0)
tilt+GW: n_s=0.9
Baryons: Ω_b=0.1
low H_0: H_0=50
Lambda: Ω_Λ=0.7, Ω_m=0.3
Open: Ω_Λ=0, Ω_m=0.3
Closed: Ω_Λ=0, Ω_m=1.3
$\ell(\ell+1)C_\ell/(2\pi)$ [μK^2]
0
2000
4000
6000
0
200
400
600
800
1000
1200
multipole ℓ

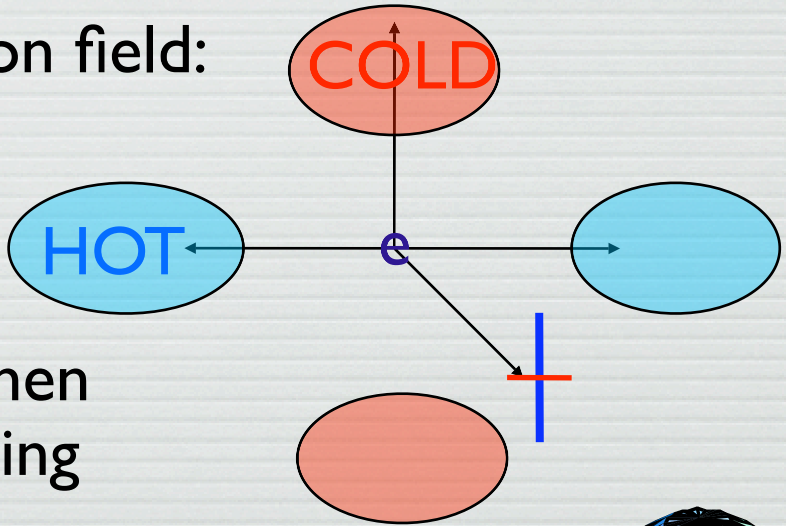
Oscillations in the primordial plasma: The Acoustic Peaks

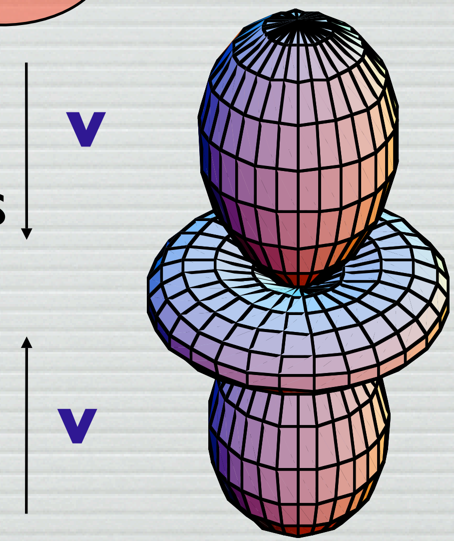
- Before recombination, a tightly-coupled plasma of matter (p, e) and photons
- Primordial/inflationary perturbations on all scales–can only collapse when in causal contact
- Pressure determined by mix of baryons and radiation ($\sim 10^{10}$ photons/baryon!): baryon "doping" lowers c_s from $1/\sqrt{3}$.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



CMB Polarization: Generation

- Ionized plasma + quadrupole radiation field:
  - Thomson scattering ⇒polarized emission
  - Unlike intensity, only generated when ionization fraction, $0<x<1$ (*i.e.*, during transition)





- Scalar perturbations — aligned quadrupoles: traces ~gradient of velocity
- Tensor perturbations: +,× patterns of quadrupoles (impossible to form via linear scalar perturbations)
  - same underlying physics as temperature perturbations

Learning from Data: Bayes' Theorem

$$P(H \mid DI) = \frac{P(H \mid I) P(D \mid HI)}{P(D \mid I)}$$

$$\text{Posterior} \propto \text{Prior} \times \text{Likelihood}$$

- Linking ontology (what is out there?) with epistemology (how do we know it?)
- Solves *Hume*'s problem of induction?
  - but all probabilities are (at least) conditional if not downright subjective:
  - science is about doing experiments and coming to agreement about the world (irrespective of your priors)

CMB Data

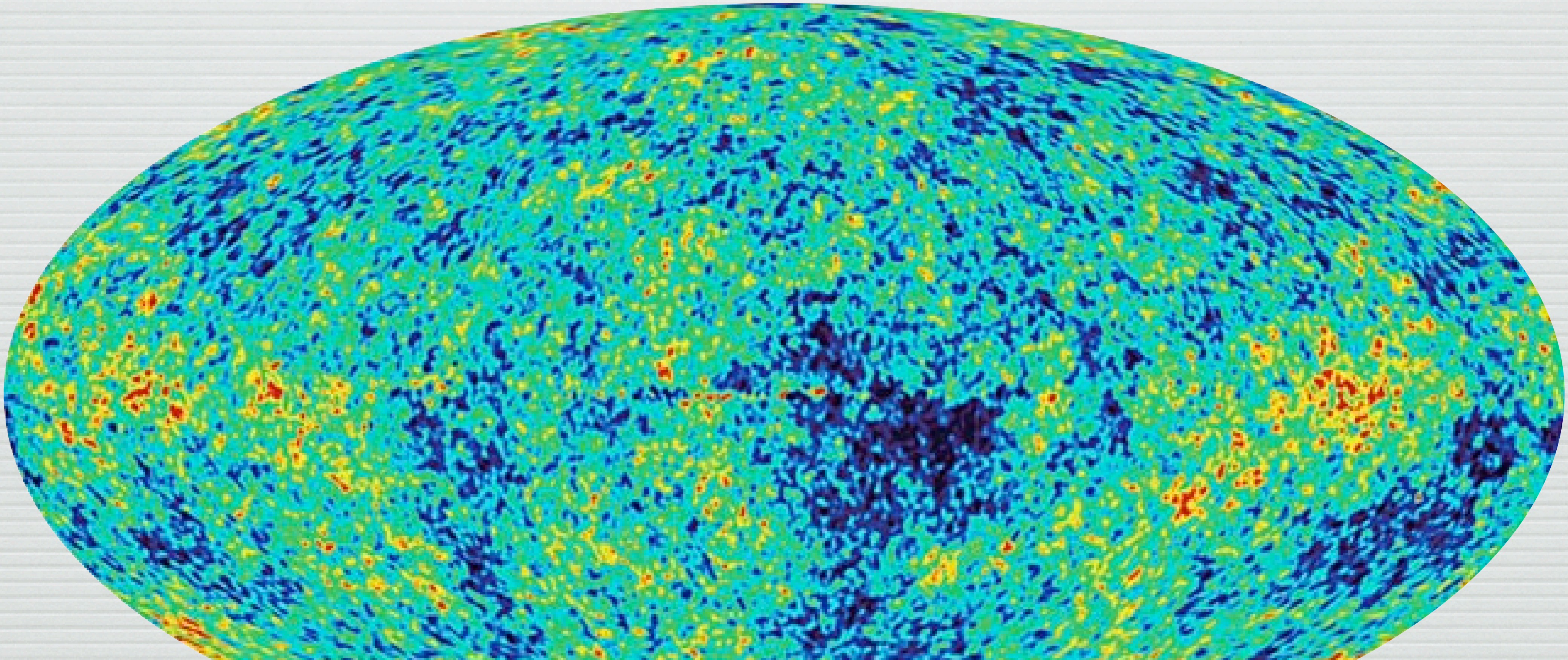
- data = signal + noise
- $d_t = \mathrm{A}_{tp} s_p + n_t$ w/ correlations:

$$\langle s_p s_{p'} \rangle = S_{pp'} = \sum_\ell \frac{2\ell+1}{4\pi} B_\ell^2 C_\ell$$ (scanning temperature experiments)

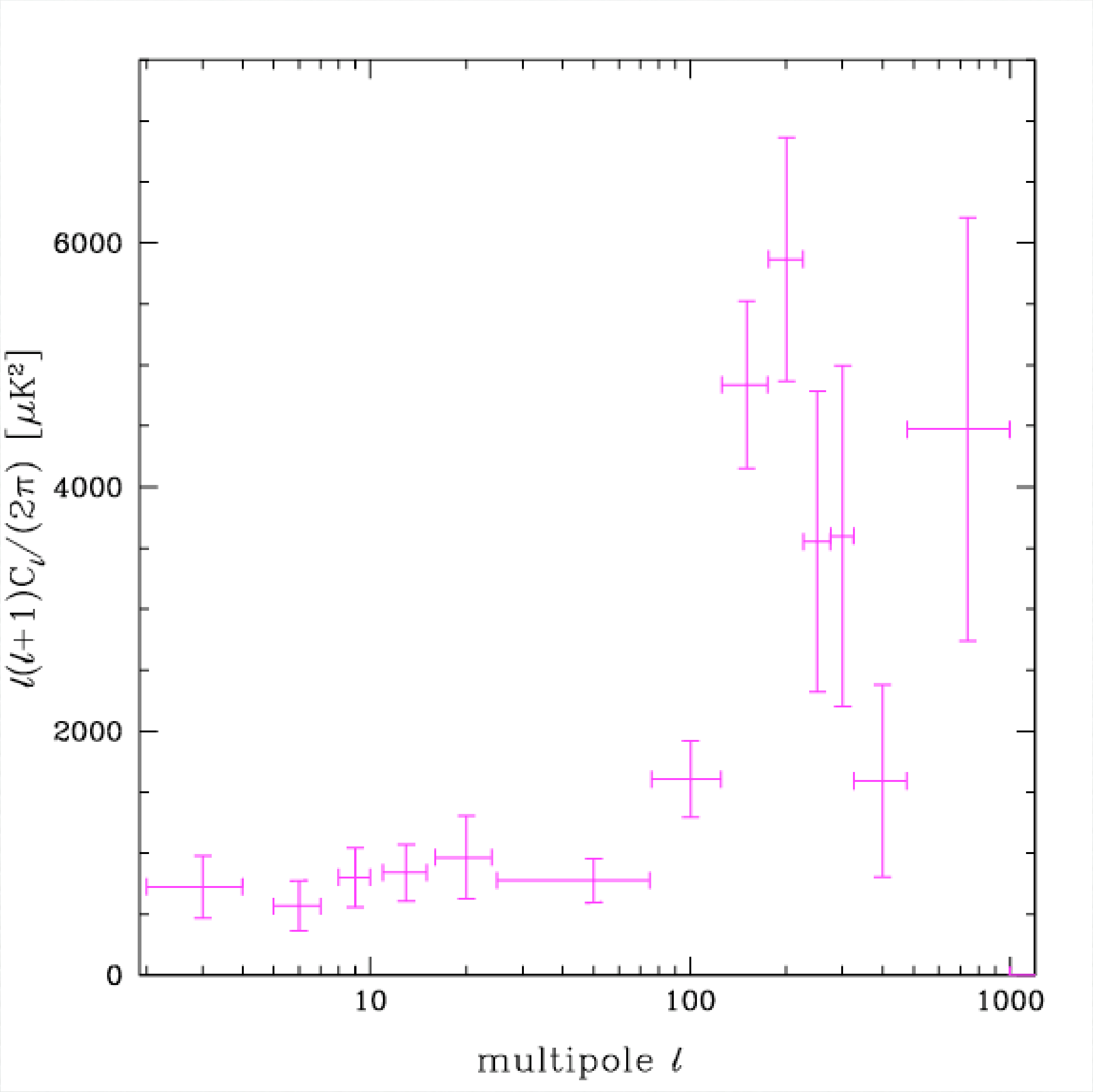
$$\langle n_t n_{t'} \rangle = N_{tt'} = N(t-t')$$

- Polarization: $S_{pp'}$ is linear combination of $C_l^{XX'}$
- Task: measure C_l and preserve *all* sky information for parameter estimation

$$P(d\,|\,SNI) = \frac{1}{|2\pi(S+N)|^{1/2}} \exp\left[-\tfrac{1}{2} d^T (S+N)^{-1} d\right]$$



February, 2000



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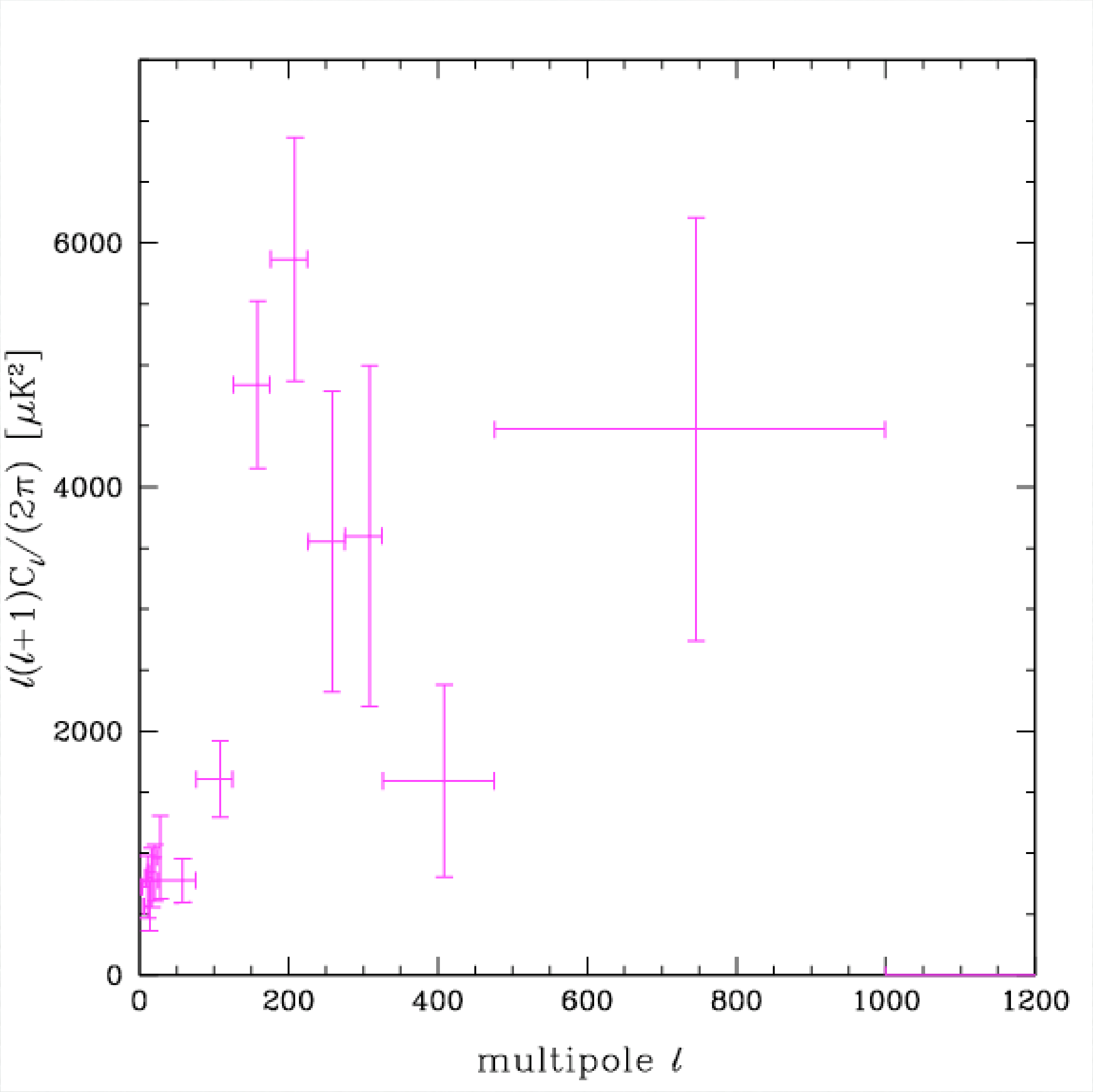
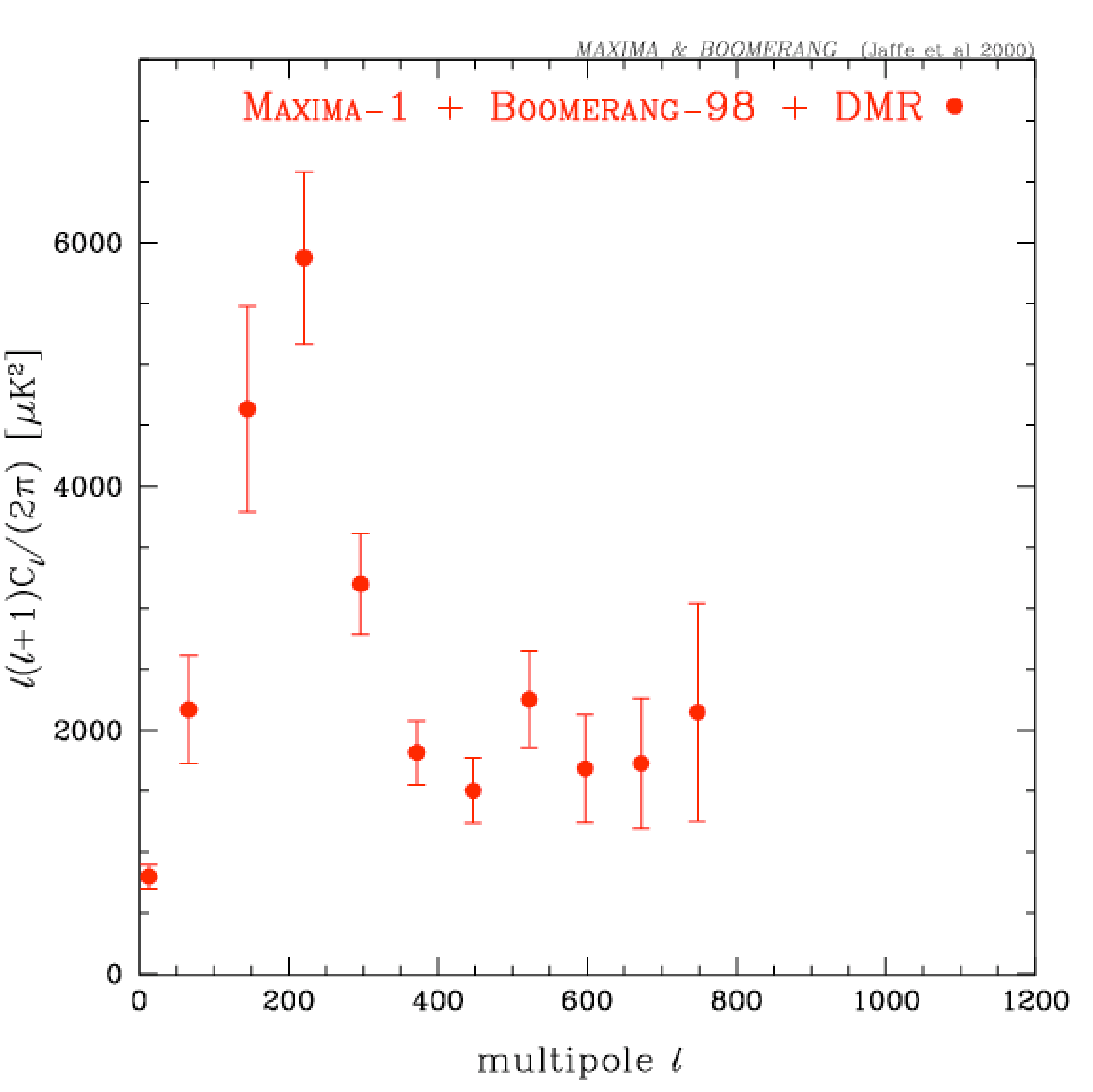
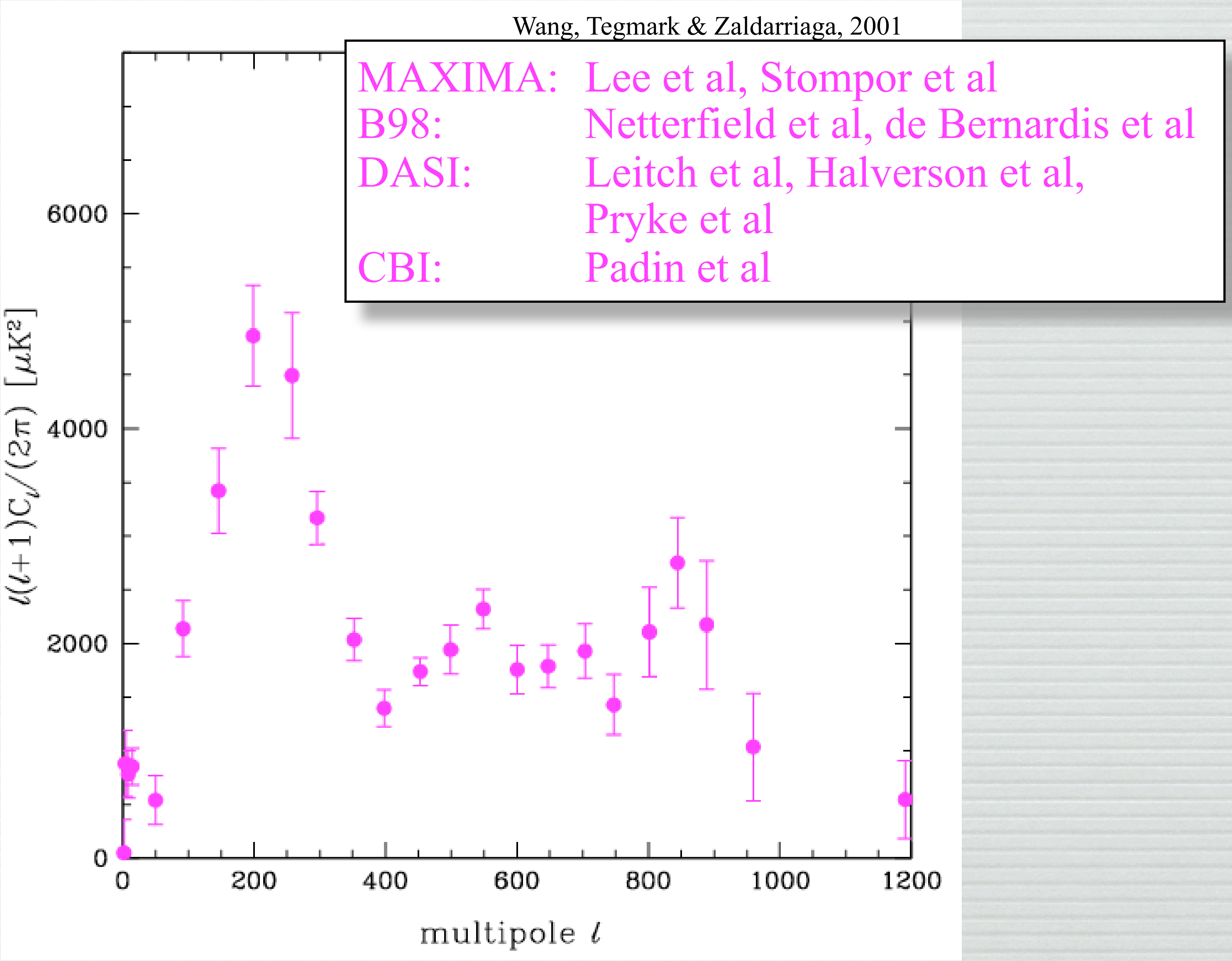


July, 2000



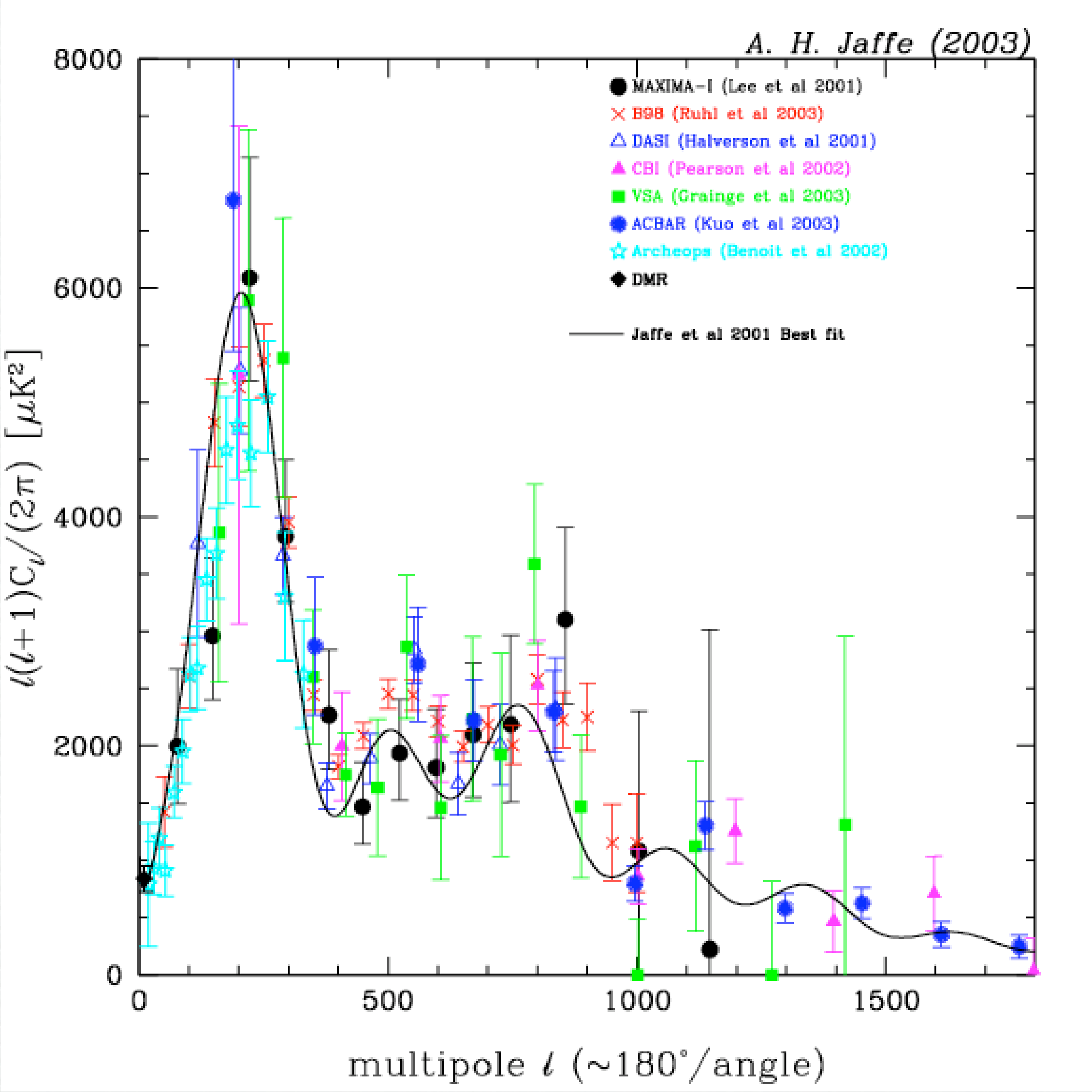
MAXIMA & BOOMERANG (Jaffe et al 2000)
MAXIMA-1 + BOOMERANG-98 + DMR
6000
4000
2000
0
0
200
400
600
800
1000
1200
multipole ℓ
ℓ(ℓ+1)C_ℓ/(2π) [μK²]

May, 2001

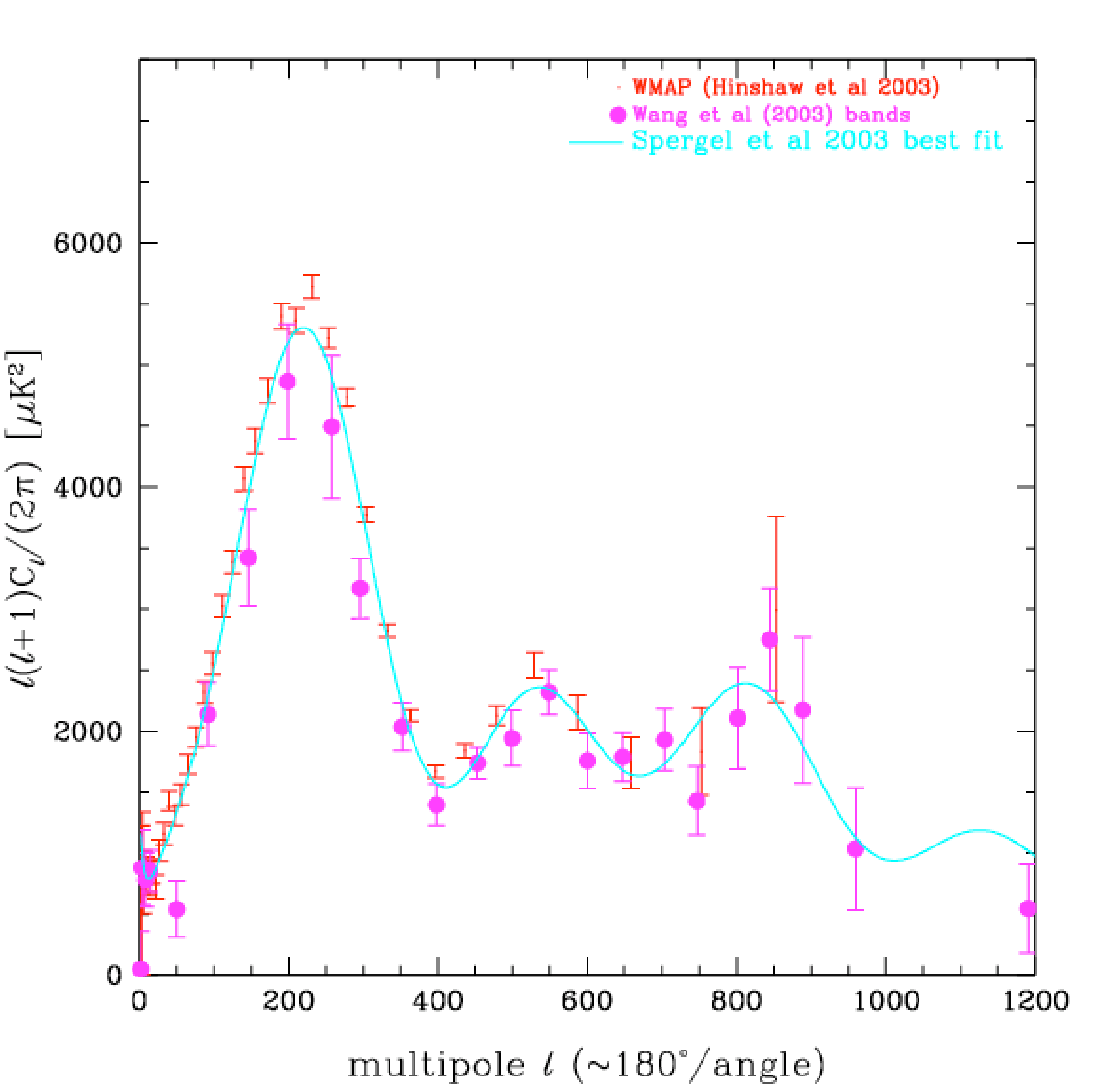


Wang, Tegmark & Zaldarriaga, 2001
MAXIMA: Lee et al, Stompor et al
B98: Netterfield et al, de Bernardis et al
DASI: Leitch et al, Halverson et al, Pryke et al
CBI: Padin et al
$\ell(\ell+1)C_\ell/(2\pi)$ [μK^2]
0
2000
4000
6000
0
200
400
600
800
1000
1200
multipole ℓ

January, 2003



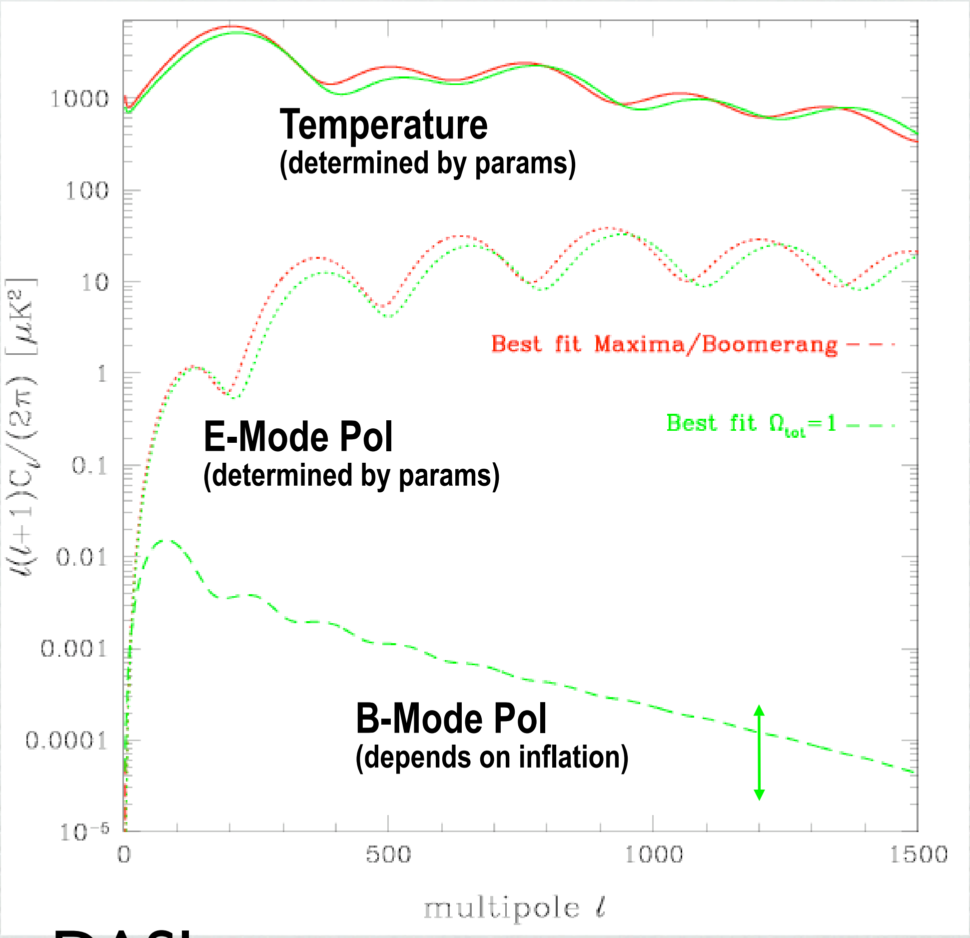
WMAP!



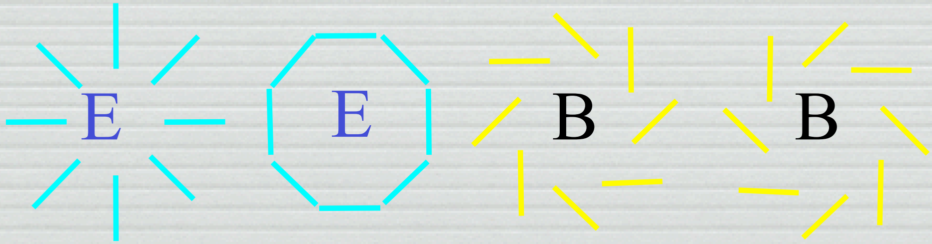
WMAP (Hinshaw et al 2003)
Wang et al (2003) bands
Spergel et al 2003 best fit
6000
4000
2000
0
0
200
400
600
800
1000
1200
ℓ(ℓ+1)C_ℓ/(2π) [μK²]
multipole ℓ (~180°/angle)

The Polarization of the CMB

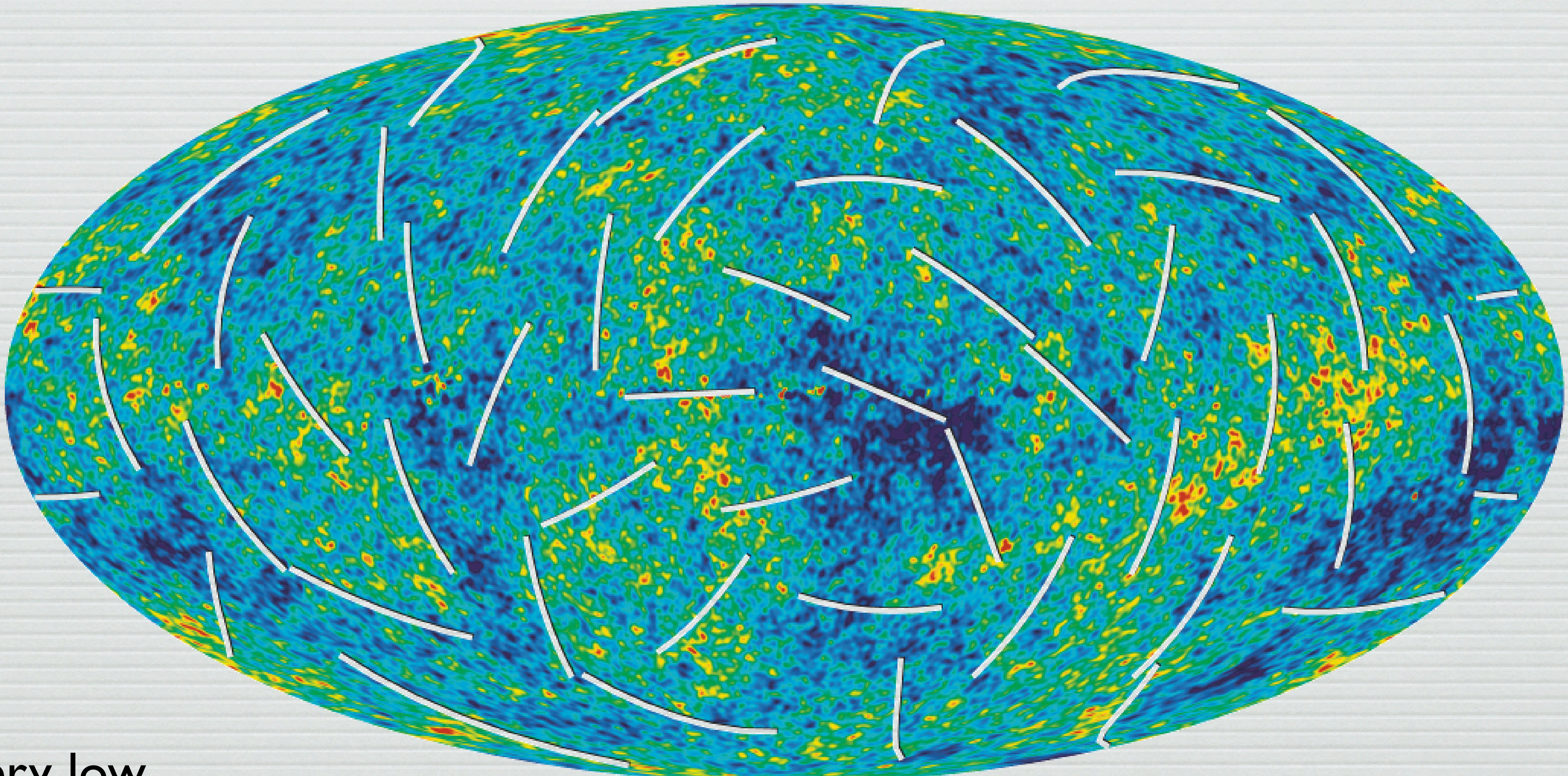
- Anisotropic radiation field at last scattering → polarization
  - "Grad" or *E* mode
  - Breaks degeneracies
  - New parameters:
    - reionization
- "Curl" or *B* sensitive to gravity waves
  - "Smoking gun" of inflation?
  - Very low amplitude
- Need better handle on systematics, and...
- Polarized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



DASI
MAXIPOL, B2K
MAP
Planck
Future satellites?



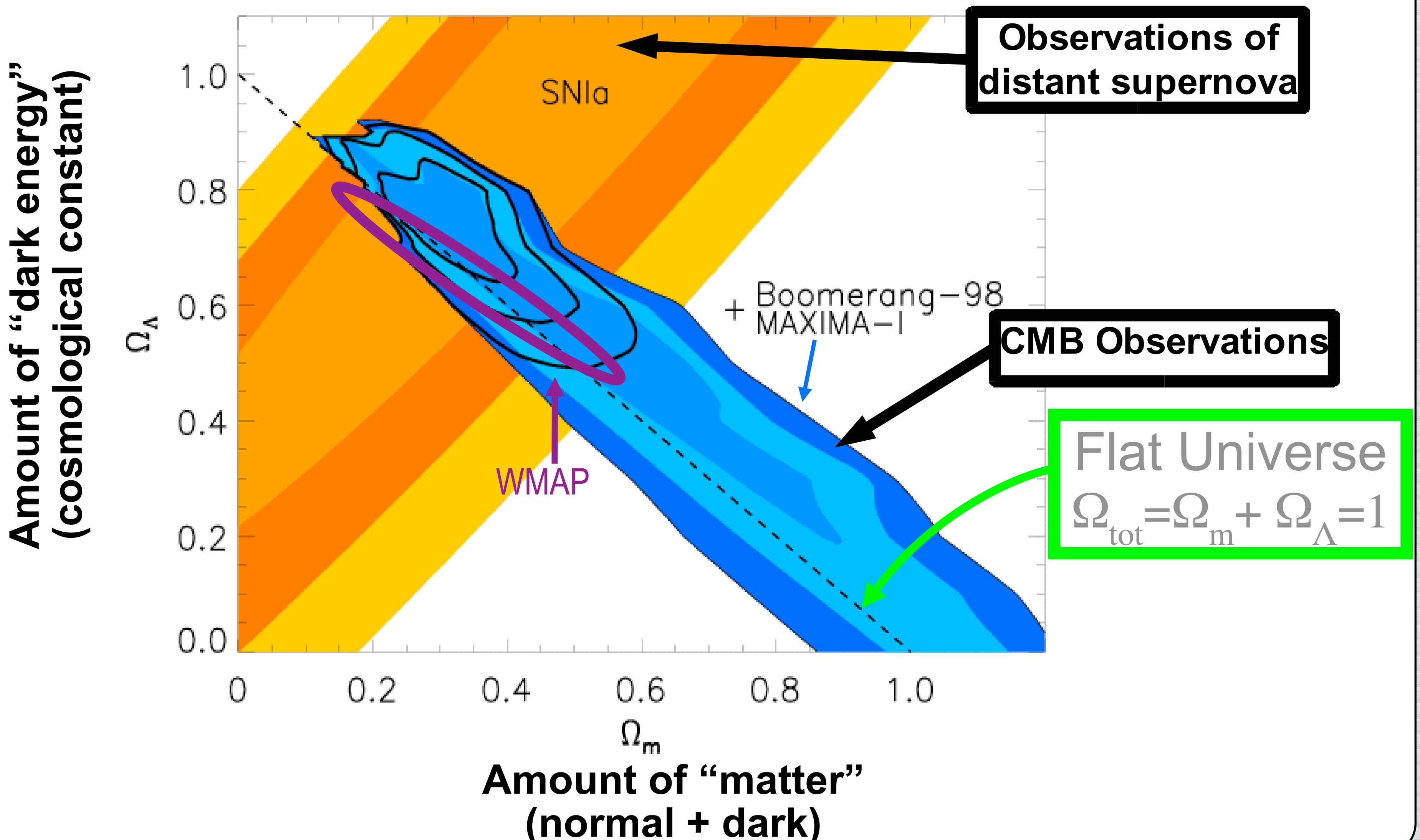
The CMB 2006: WMAP &c



Very low
Signal/“noise” on polarization —
dominated by foregrounds and systematic effects

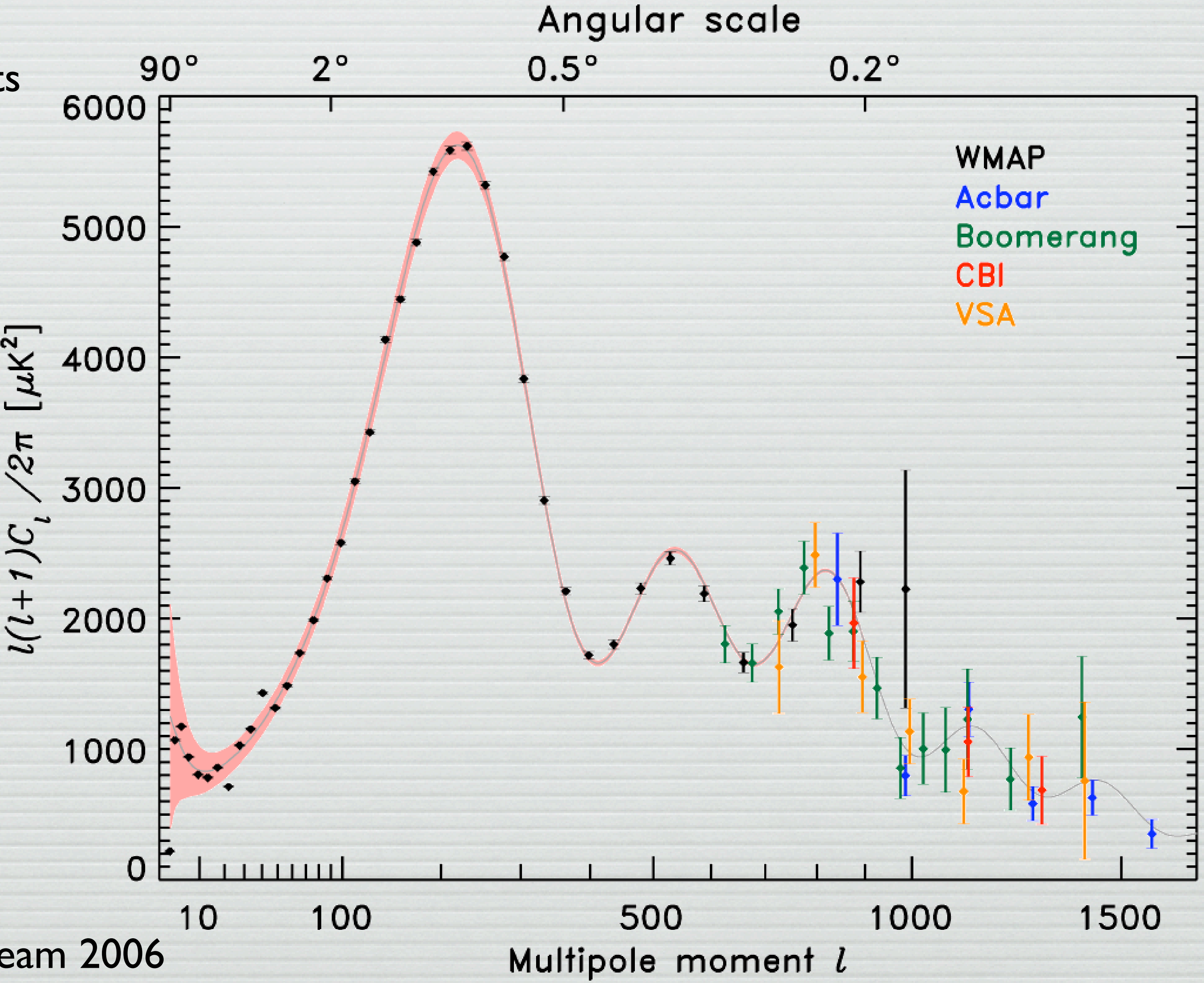
WMAP Science team 2006

Measuring the geometry of the Universe

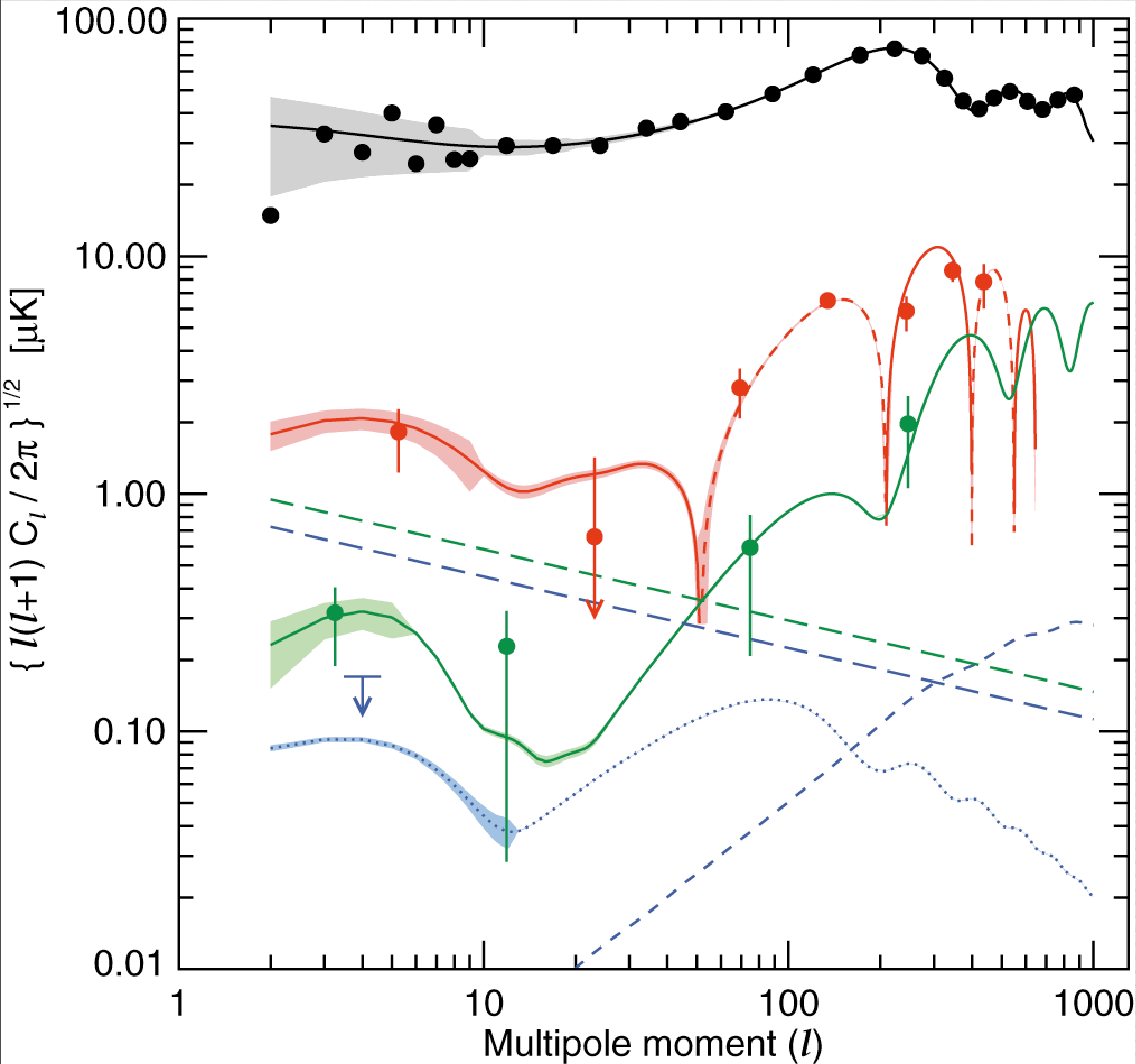


The CMB 2006: WMAP &c

- High-res experiments confirm and extend WMAP results
- see also recent MAXIPOL results
  - Wu et al, astro-ph/0611392
  - Johnson et al, astro-ph/0611394



WMAP Science team 2006



Temperature
/Temperature

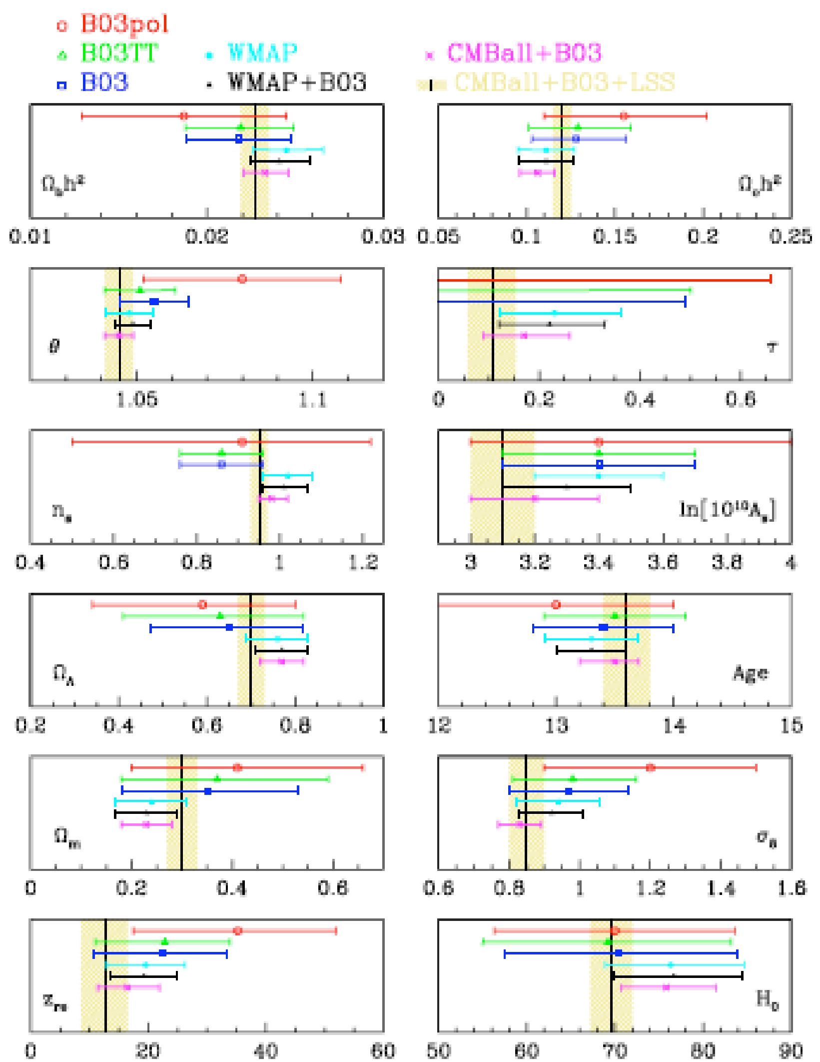
Temperature
/Polarization

Polarization
/Polarization

Polarization consistent with and extended by DASI, BOOMERaNG, &c.

Priors and Parameters

MacTavish et al.



VSA: Rebolo et al 2004

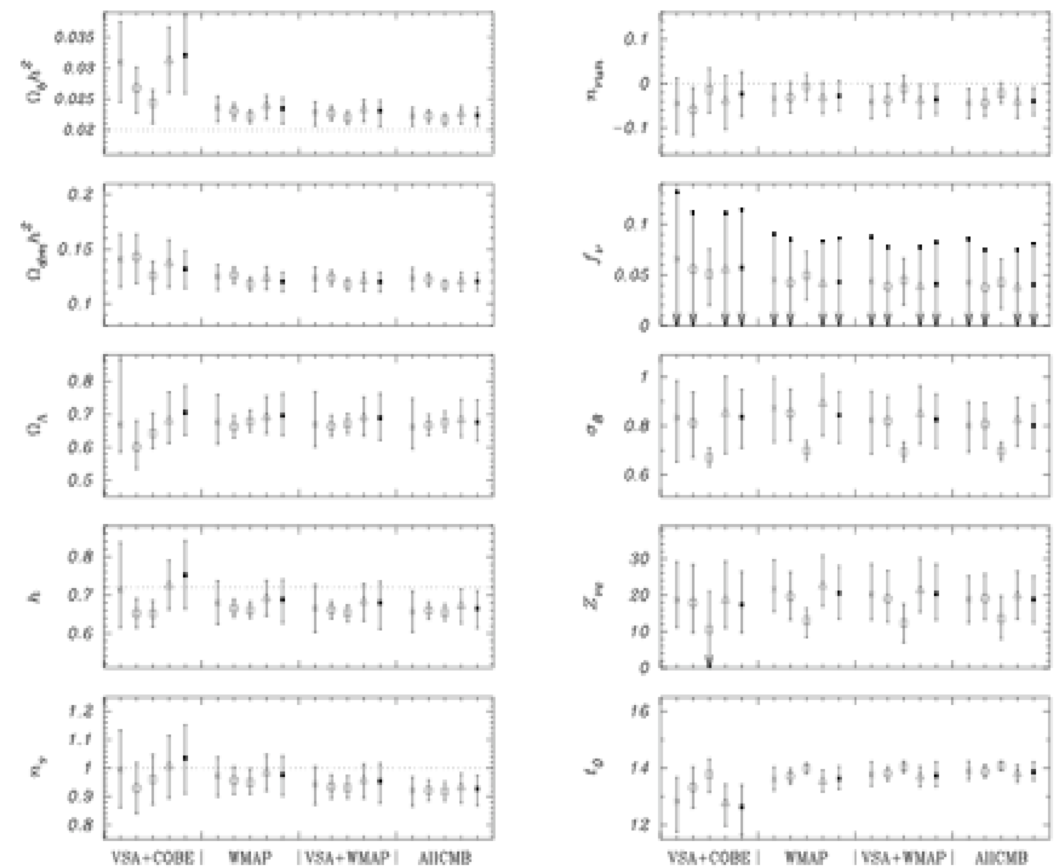


Figure 6. Estimates for cosmological parameters in the flat ΛCDM running spectral index model, extended to include f_ν. Four CMB data sets are considered and, for each data set, four determinations are plotted, corresponding to different combinations of external priors. From left to right the external priors are: 2dF; 2dF+f_{gas}; 2dF+f_{gas}+XLF; 2dF+HST and 2dF+CS. The points indicate the median of the corresponding marginal distributions. The error bars denote 68% confidence limits. If a distribution peaks at zero then the 95% upper limit is shown. The horizontal dashed lines plotted in some of the panels indicate BBN values for $\Omega_b h^2$, the value of h given by the HST key project, the Harrison-Zel'dovich value of the spectral index of fluctuations and a zero value for the running index.

Cosmological Parameters

- *Detailed* parameter estimates depend upon
  - Data considered
  - Theoretical context
    - (I.e., prior information)
- General picture ~robust (at least w/in *nearly**-scale-invariant, moderately expanding FRW models)
- *inflationary prediction, but requires large-scale polarization and "lever arm" *between* different experiments.

Table 5: ΛCDM Model: Joint Likelihoods

Parameter	WMAP Only	WMAP +CBI+VSA	WMAP+ACBAR +BOOMERanG	WMAP + 2dFGRS
$100\Omega_b h^2$	$2.233^{+0.072}_{-0.091}$	$2.203^{+0.072}_{-0.090}$	$2.228^{+0.066}_{-0.082}$	$2.223^{+0.066}_{-0.083}$
$\Omega_m h^2$	$0.1268^{+0.0073}_{-0.0128}$	$0.1238^{+0.0066}_{-0.0118}$	$0.1271^{+0.0070}_{-0.0128}$	$0.1262^{+0.0050}_{-0.0103}$
h	$0.734^{+0.028}_{-0.038}$	$0.738^{+0.028}_{-0.037}$	$0.733^{+0.030}_{-0.038}$	$0.732^{+0.018}_{-0.025}$
A	$0.801^{+0.043}_{-0.054}$	$0.798^{+0.047}_{-0.057}$	$0.801^{+0.048}_{-0.056}$	$0.799^{+0.042}_{-0.051}$
τ	$0.088^{+0.028}_{-0.034}$	$0.084^{+0.031}_{-0.038}$	$0.084^{+0.027}_{-0.034}$	$0.083^{+0.027}_{-0.031}$
n_s	$0.951^{+0.015}_{-0.019}$	$0.945^{+0.015}_{-0.019}$	$0.949^{+0.015}_{-0.019}$	$0.948^{+0.014}_{-0.018}$
σ_8	$0.744^{+0.050}_{-0.060}$	$0.722^{+0.044}_{-0.056}$	$0.742^{+0.045}_{-0.057}$	$0.737^{+0.033}_{-0.045}$
Ω_m	$0.238^{+0.027}_{-0.045}$	$0.229^{+0.026}_{-0.042}$	$0.239^{+0.025}_{-0.046}$	$0.236^{+0.016}_{-0.029}$

Table 6: ΛCDM Model

Parameter	WMAP+ SDSS	WMAP+ LRG	WMAP+ SNLS	WMAP + SN Gold	WMAP+ CFHTLS
$100\Omega_b h^2$	$2.233^{+0.062}_{-0.086}$	$2.242^{+0.062}_{-0.084}$	$2.233^{+0.069}_{-0.088}$	$2.227^{+0.065}_{-0.082}$	$2.247^{+0.064}_{-0.082}$
$\Omega_m h^2$	$0.1329^{+0.0057}_{-0.0109}$	$0.1337^{+0.0047}_{-0.0098}$	$0.1295^{+0.0055}_{-0.0106}$	$0.1349^{+0.0054}_{-0.0106}$	$0.1410^{+0.0042}_{-0.0094}$
h	$0.709^{+0.024}_{-0.032}$	$0.709^{+0.016}_{-0.023}$	$0.723^{+0.021}_{-0.030}$	$0.701^{+0.020}_{-0.026}$	$0.686^{+0.017}_{-0.024}$
A	$0.813^{+0.042}_{-0.052}$	$0.816^{+0.042}_{-0.049}$	$0.808^{+0.044}_{-0.051}$	$0.827^{+0.045}_{-0.053}$	$0.852^{+0.036}_{-0.047}$
τ	$0.079^{+0.029}_{-0.032}$	$0.082^{+0.028}_{-0.033}$	$0.085^{+0.028}_{-0.032}$	$0.079^{+0.028}_{-0.034}$	$0.088^{+0.021}_{-0.031}$
n_s	$0.948^{+0.015}_{-0.018}$	$0.951^{+0.014}_{-0.018}$	$0.950^{+0.015}_{-0.019}$	$0.946^{+0.015}_{-0.019}$	$0.950^{+0.015}_{-0.019}$
σ_8	$0.772^{+0.036}_{-0.048}$	$0.781^{+0.032}_{-0.045}$	$0.758^{+0.038}_{-0.052}$	$0.784^{+0.035}_{-0.049}$	$0.826^{+0.023}_{-0.035}$
Ω_m	$0.266^{+0.025}_{-0.040}$	$0.267^{+0.017}_{-0.029}$	$0.249^{+0.023}_{-0.034}$	$0.276^{+0.022}_{-0.036}$	$0.301^{+0.018}_{-0.031}$

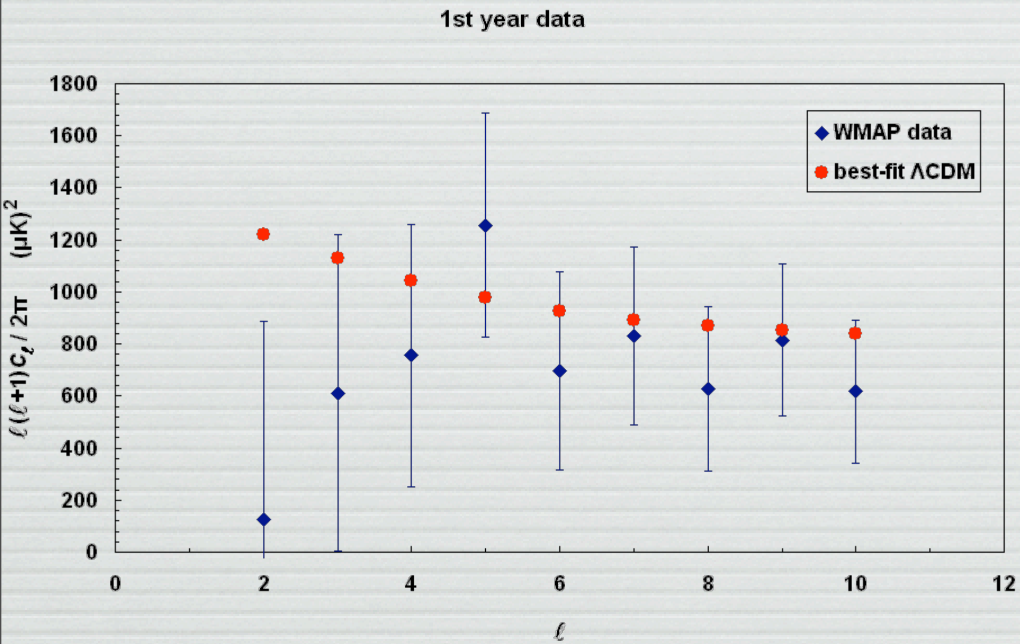
WMAP Science team 2006

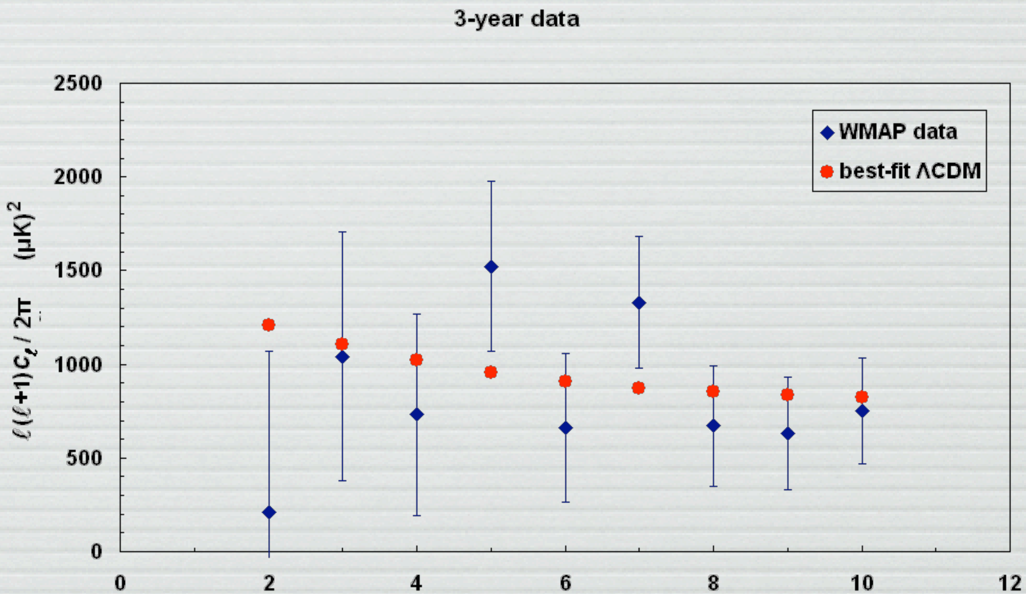
Cosmological Parameters c. 2007

- Big picture: consistent with inflation
  - Flat Universe
  - nearly-scale-invariant fluctuations
  - adiabatic, gaussian fluctuations
  - 5% Baryons, 25% dark matter, 70% dark energy
  - consistency with “direct” measurements of expansion rate (H_0) and baryon density (BBN)

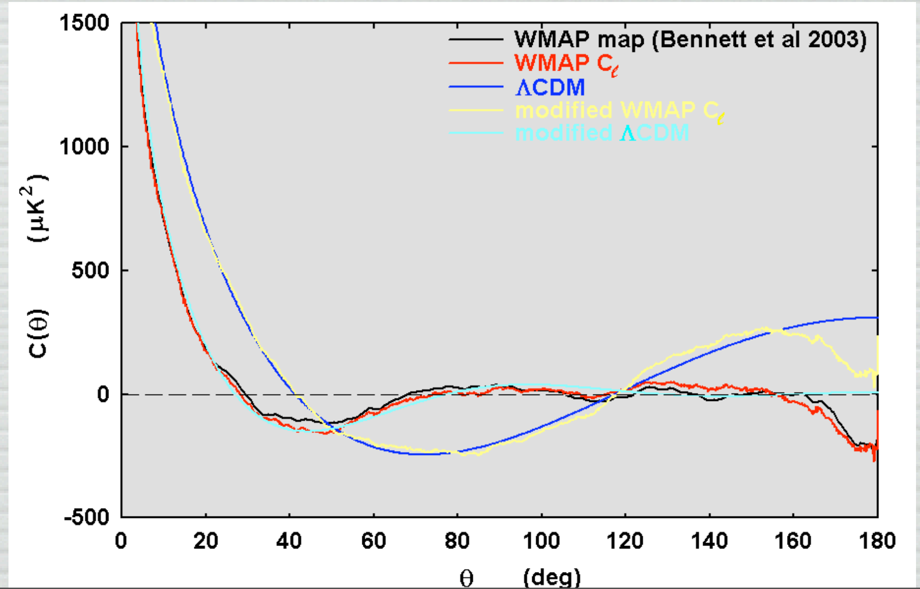
  - requires external data for measurements of all parameters
  - details depend on priors
  - no “evidence” for physics beyond the standard model?

First hints of a problem: Large-scale CMB power





- Efstathiou; Contaldi et al; de Oliveira-Costa, Tegmark, Hamilton; Copi et al; Land, Magueijo, …
- (Originally noticed in COBE/ DMR)



Model Comparison

- Model posteriors: marginalize over all parameters

$$\text{evidence}: \quad P(D|I_m) = \int P(\theta|I_m)P(D|\theta I_m)d\theta$$

$$\frac{P(m|DI)}{P(n|DI)} = \frac{P(m|I)}{P(n|I)}\frac{P(D|I_m)}{P(D|I_n)}$$

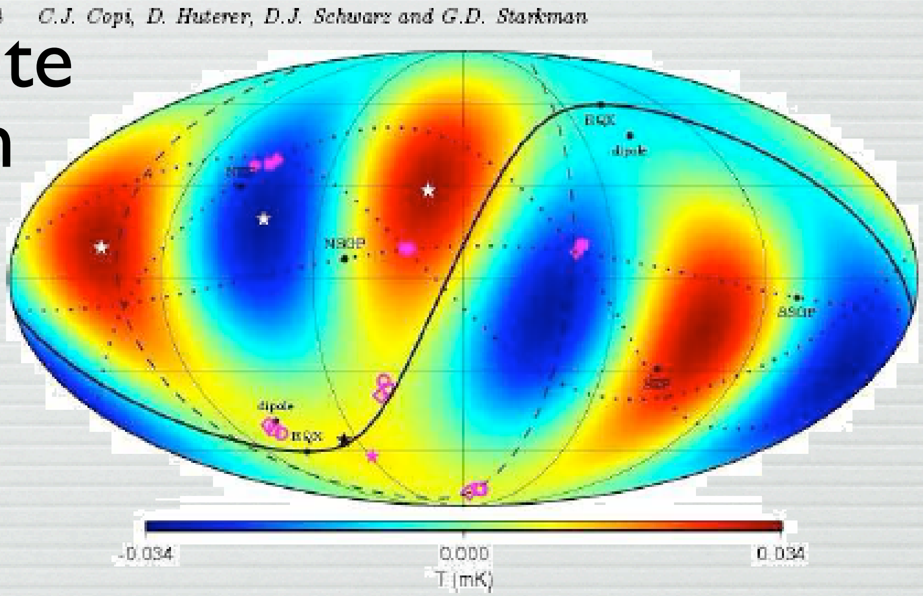
depends on prior Information for whole model

Bayes factor (B_{mn}) : model likelihoods ("evidence") depend on experimental information and parameter priors

$$\text{model } m \text{ favoured by}: \quad \nu\sigma = \sqrt{2|\ln B_{mn}|}$$

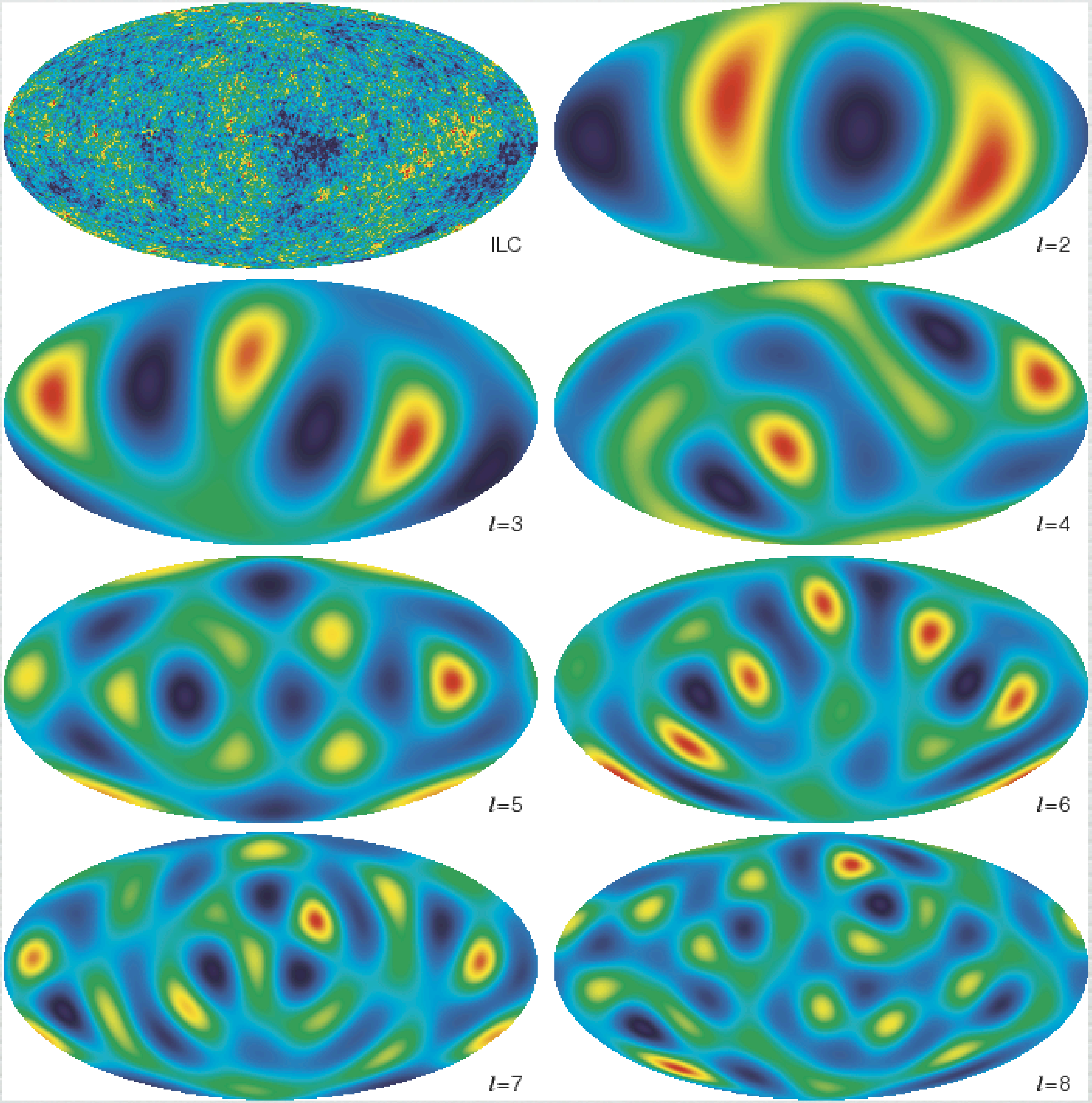
Anisotropy (from topology?)

- Problem becomes more acute beyond the power spectrum
- Multi-connected topology?
- Finite universe
  - Cutoff at large scales induces power deficit
  - In closed universe cutoff determined by curvature alone



- Intrinsic anisotropy (orientable manifolds)
  - Þ Possible apparent non-Gaussianity

- Effects only present at large scales – at smaller scales standard ΛCDM power spectrum recovered



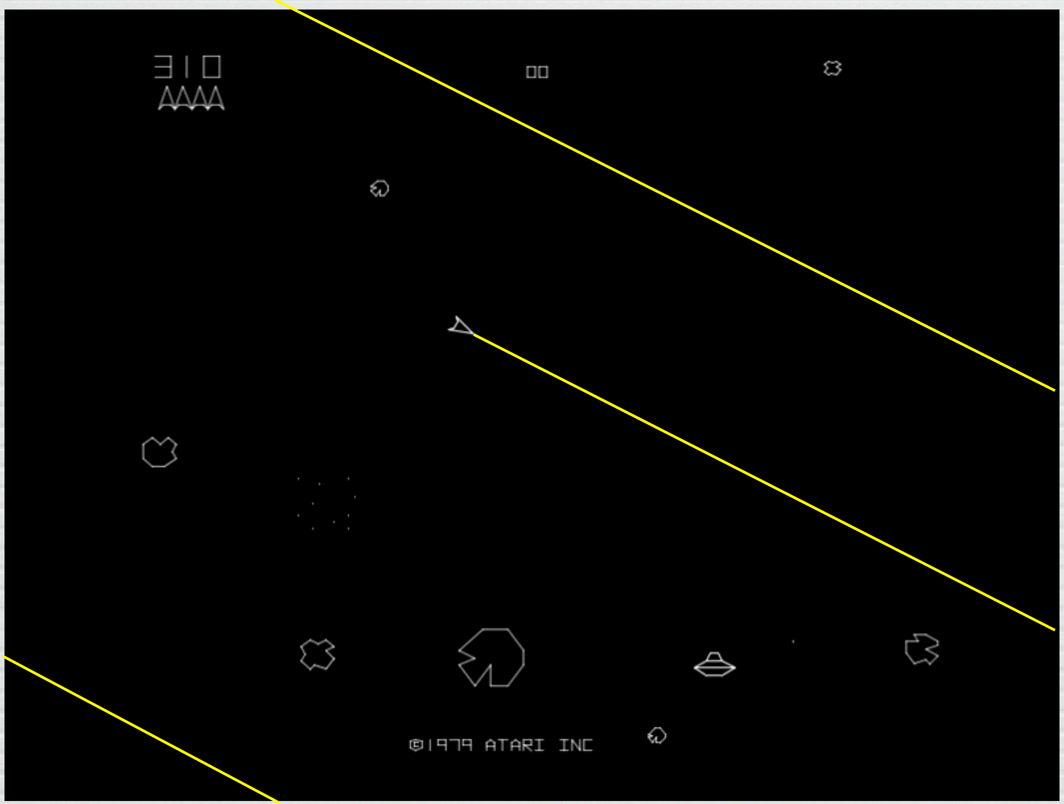
ILC
l=2
l=3
l=4
l=5
l=6
l=7
l=8

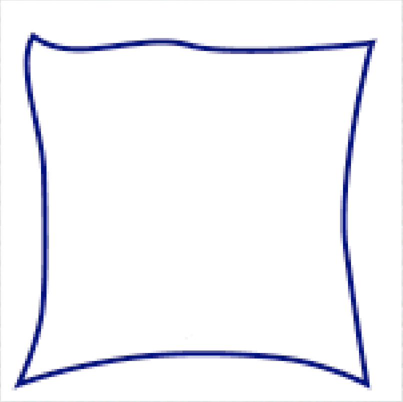
Geometry and Topology

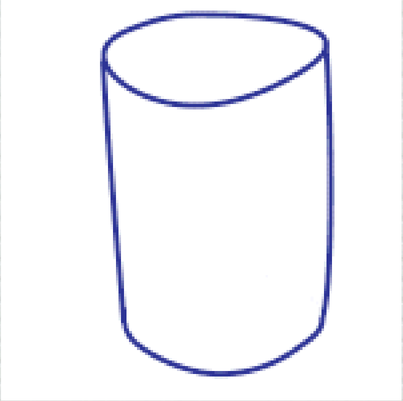
- GR links mass-energy with curvature (geometry)
- Topology determined in early Universe?
- "Topology scale" > H_0^{-1} (Hubble Scale)
  - Can't see the back of our head!
- Infinitely many multiply-connected topologies…

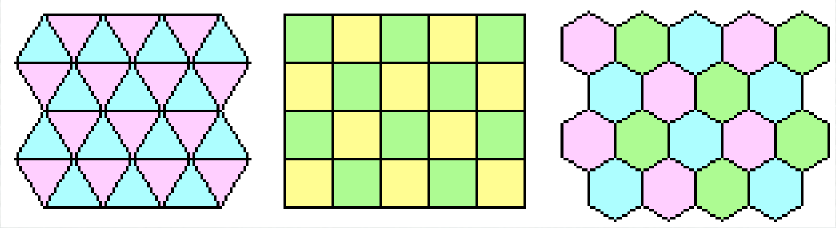
  Closed (3-sphere) universes:
  - finite number of [well-proportioned] tilings
  - *topology scale linked to curvature scale* (one fewer "coincidence").

Topology in a flat "universe"





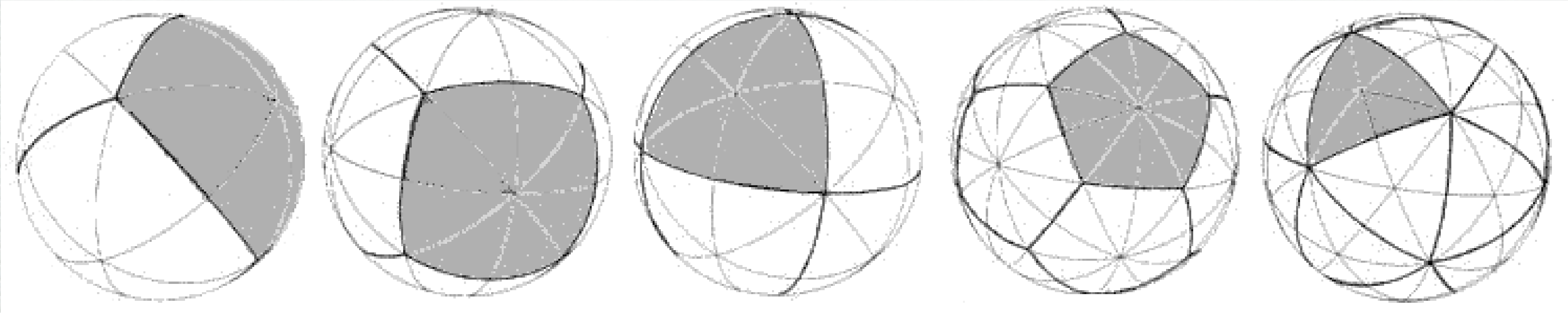




"tiling the plane"

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

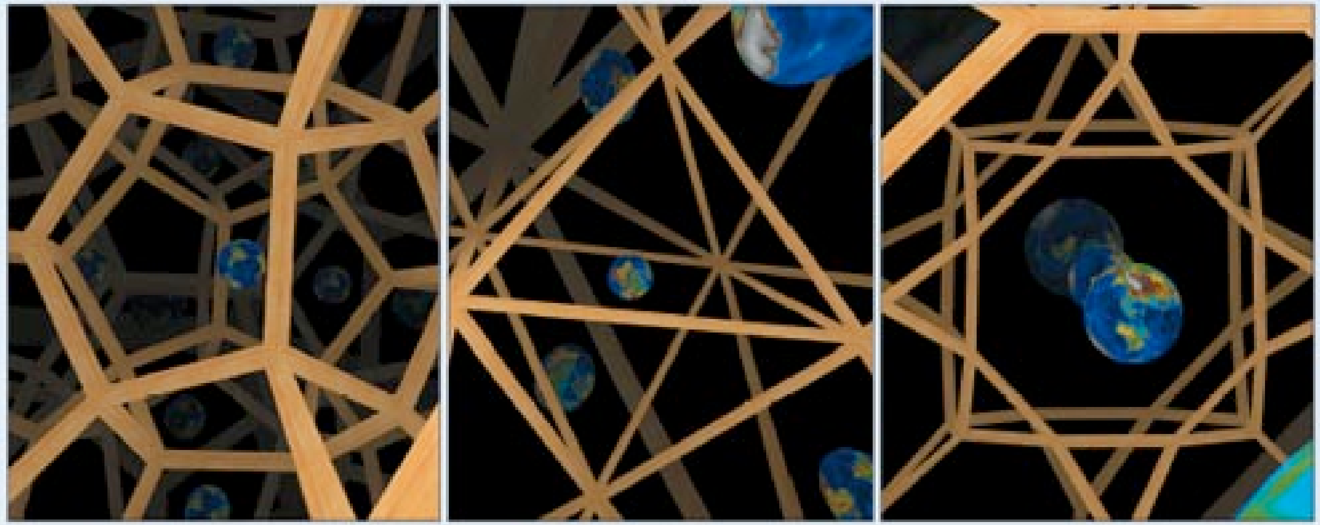
Topology + geometry



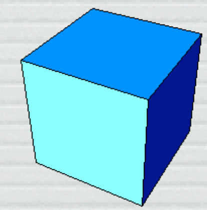
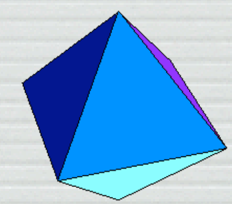
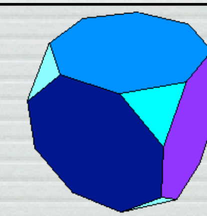
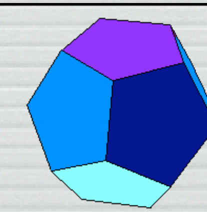
- Tile the 2-sphere with different fundamental domains

Topology in 3-d

- Flat space: infinitely many possibilities
- Curved space: fundamental domains are constrained by geometry (Thurston, Weeks)



Multiply-connected Spherical Topologies

Space	Fundamental group	Order	Elements	F.P.
Quaternionic	Binary Dihedral	8	order 2 rotations about 2 perpendicular axes	
Octahedral	Binary Tetrahedral	24	symmetries of r. tetrahedron	
Truncated Cube	Binary Octahedral	48	symmetries of r. octahedron	
Poincaré	Binary Icosahedral	120	symmetries of r. icosahedron	

Effects of non-trivial topology

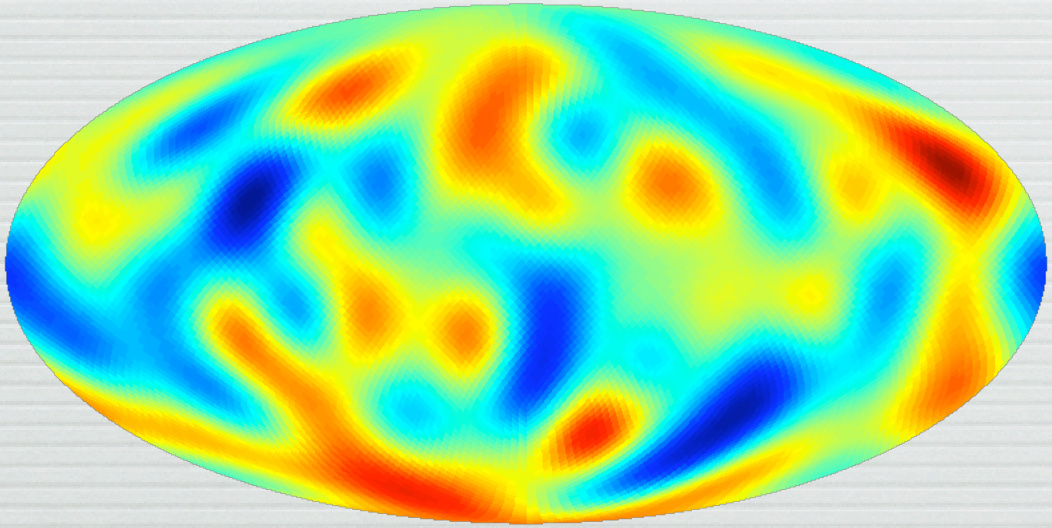
- Orientability of manifolds
- breakdown of global isotropy
  - apparent non-Gaussianity in the CMB
- Finite size of fundamental domains
  - Fewer wavenumbers

Niarchou & Jaffe 07

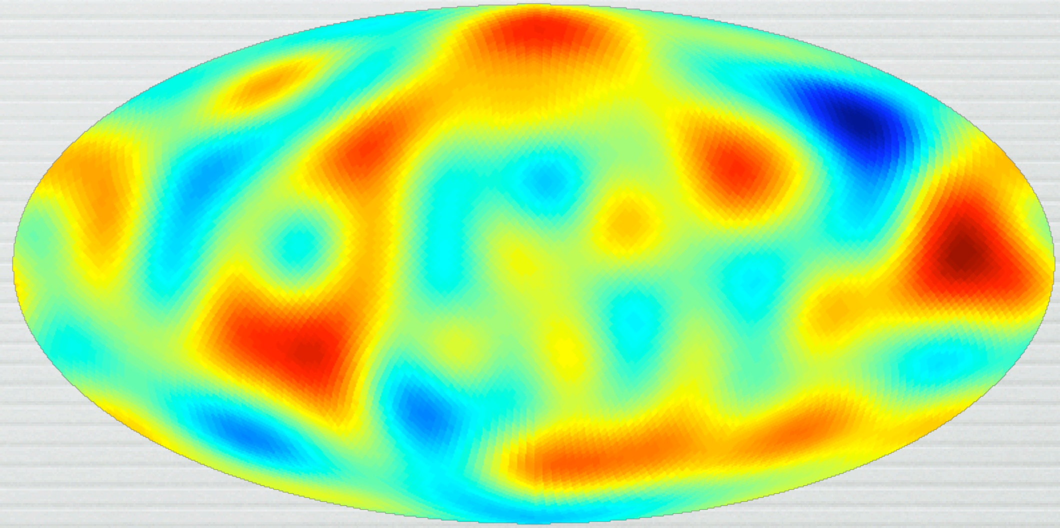
simply connected	multi-connected
$Y_{\beta \ell m}$	$Y_\beta^s = \sum_{\ell=0}^{\beta-1} \sum_{m=-\ell}^{\ell} \xi_{\beta\ell m}^s Y_{\beta\ell m}$
$a_{\ell m} = i^\ell \int d\beta\, \beta^2 \sqrt{P(\beta)} \Delta_\ell(\beta) \varepsilon_{\beta\ell m}$	$a_{\ell m} \propto \sum_\beta \sqrt{P(\beta)} \Delta_\ell(\beta) \sum \xi_{\beta\ell m}^s \varepsilon_{ks}$
$\langle a_{\ell m} a_{\ell' m'} \rangle = C_\ell \delta_{\ell\ell'} \delta_{mm'}$	$\langle a_{\ell m} a_{\ell' m'} \rangle = C_{\ell m}^{\ell' m'}$ $\qquad C_\ell \equiv \sum_m C_{\ell m}^{\ell m}$

Simulated Maps (Ω_k = - 0.063)

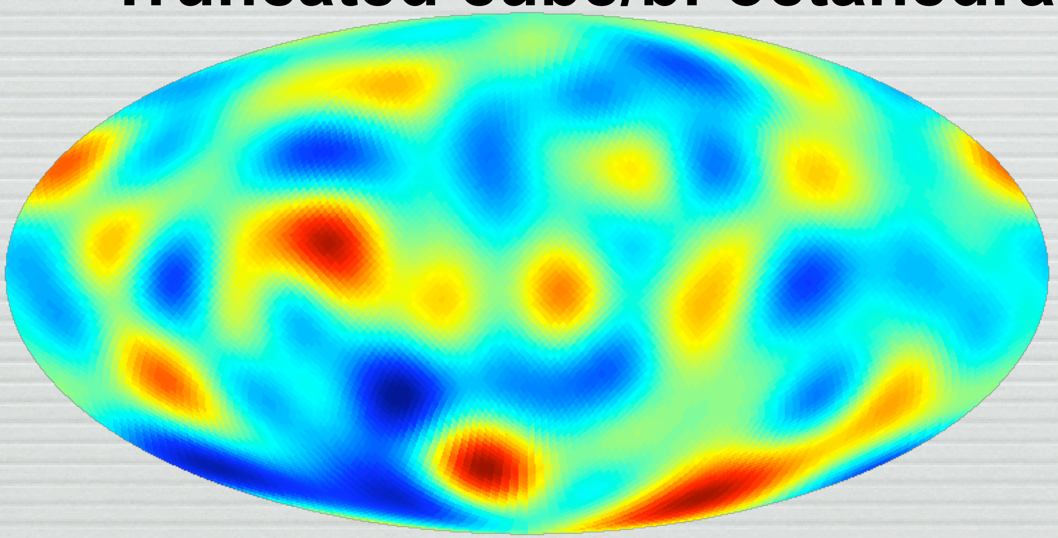
Quaternionic/bi-dehedral



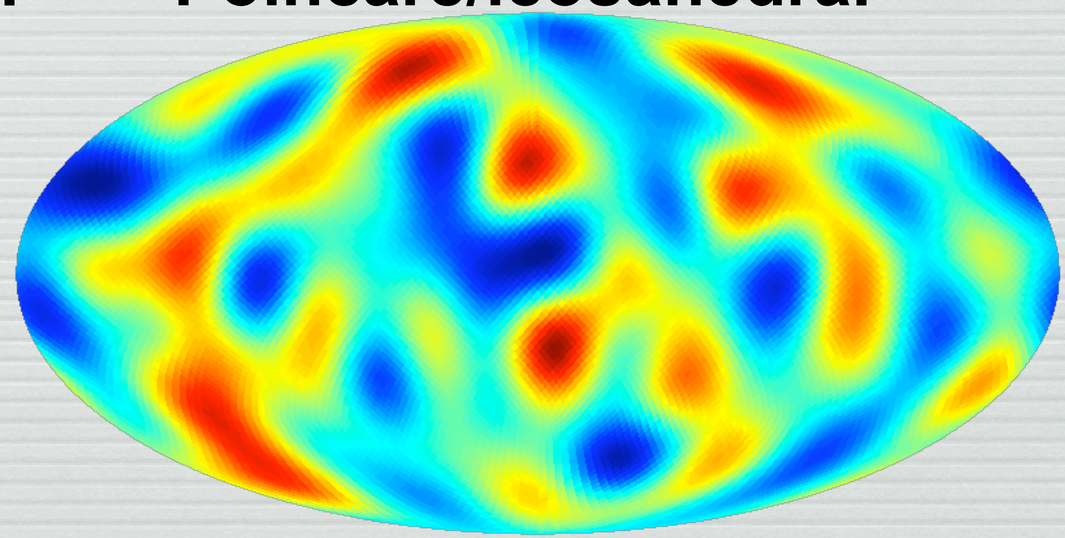
Octahedral/bi-tetrahedral



Truncated cube/bi-octahedral

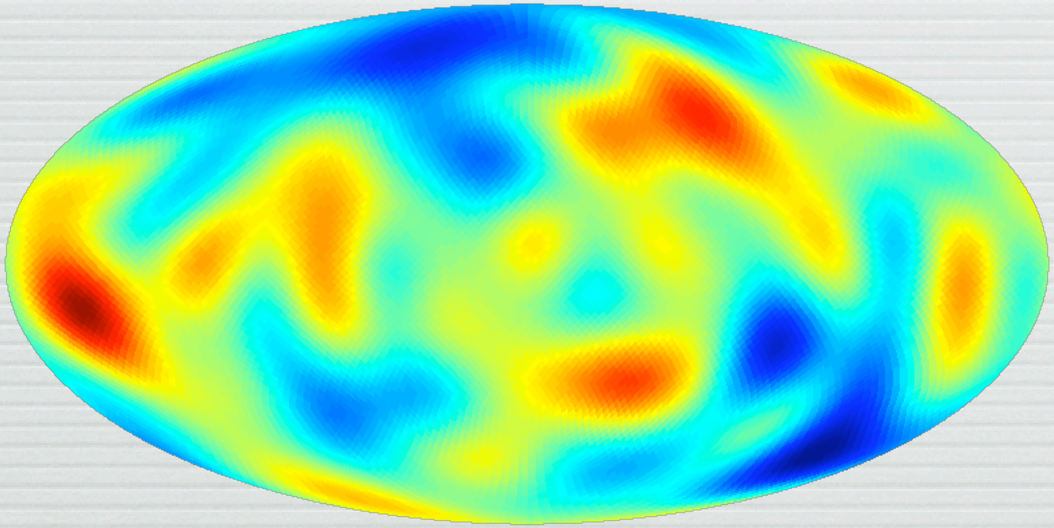


Poincaré/icosahedral

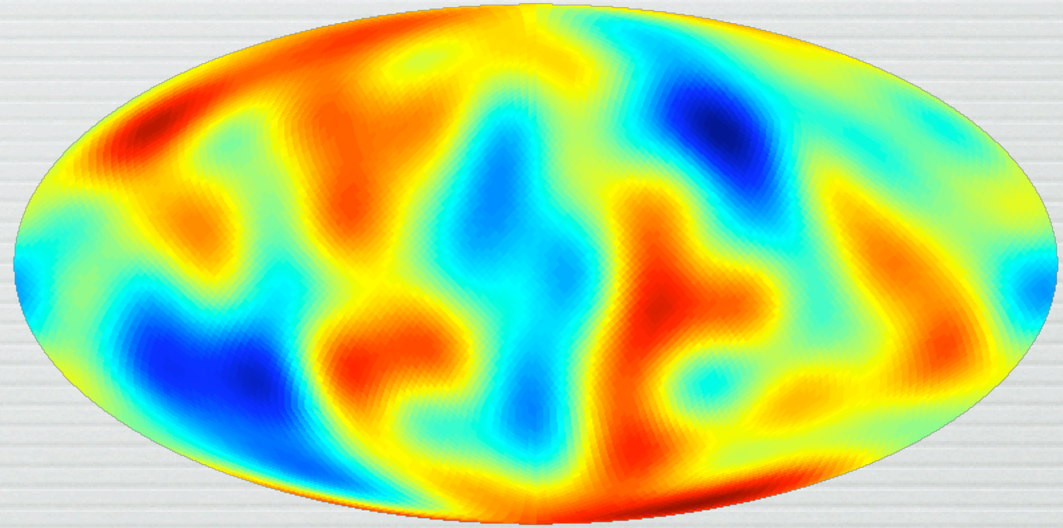


Simulated Maps ($\Omega_k = -0.017$)

Quaternionic/bi-dehedral



Octahedral/bi-tetrahedral



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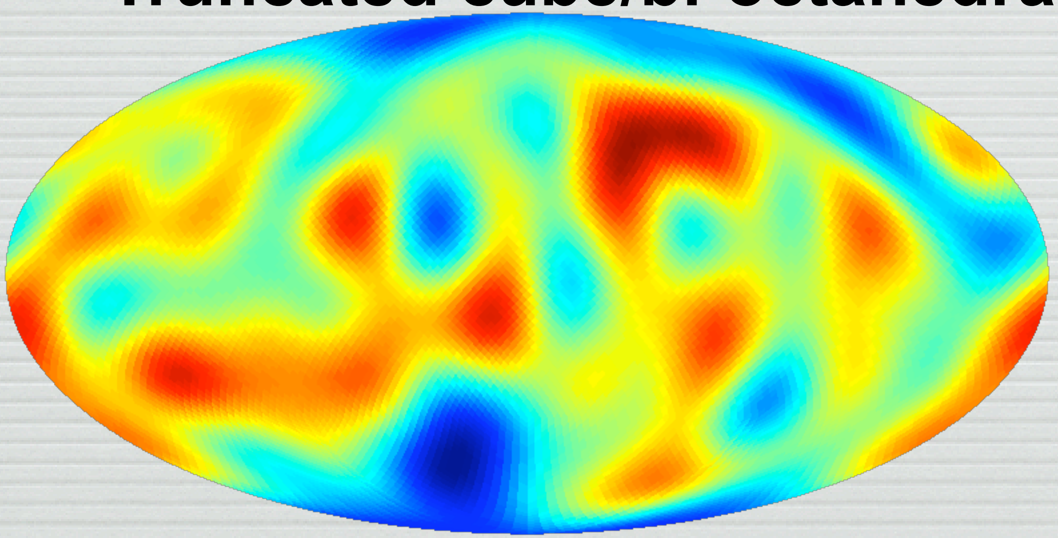
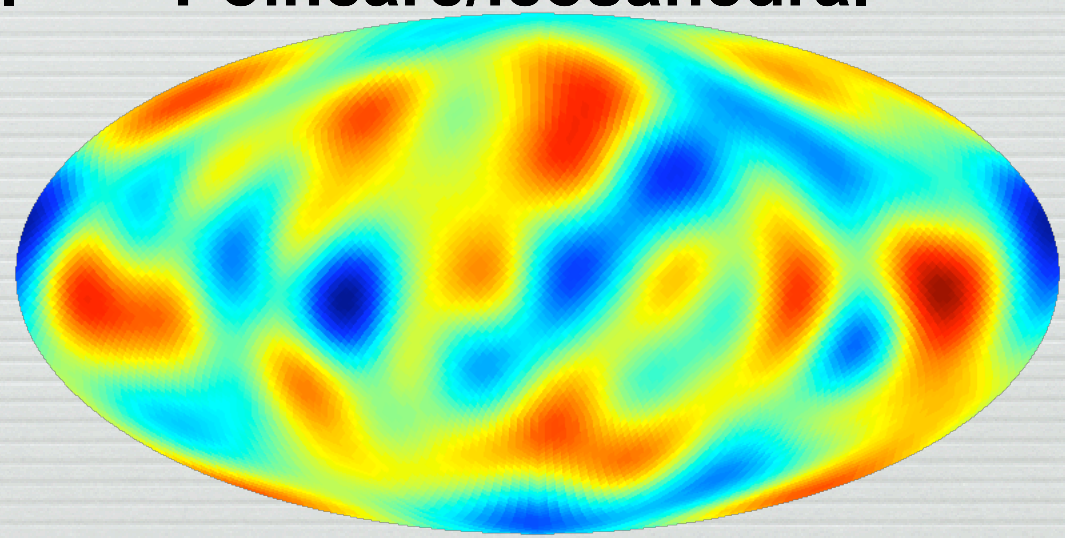
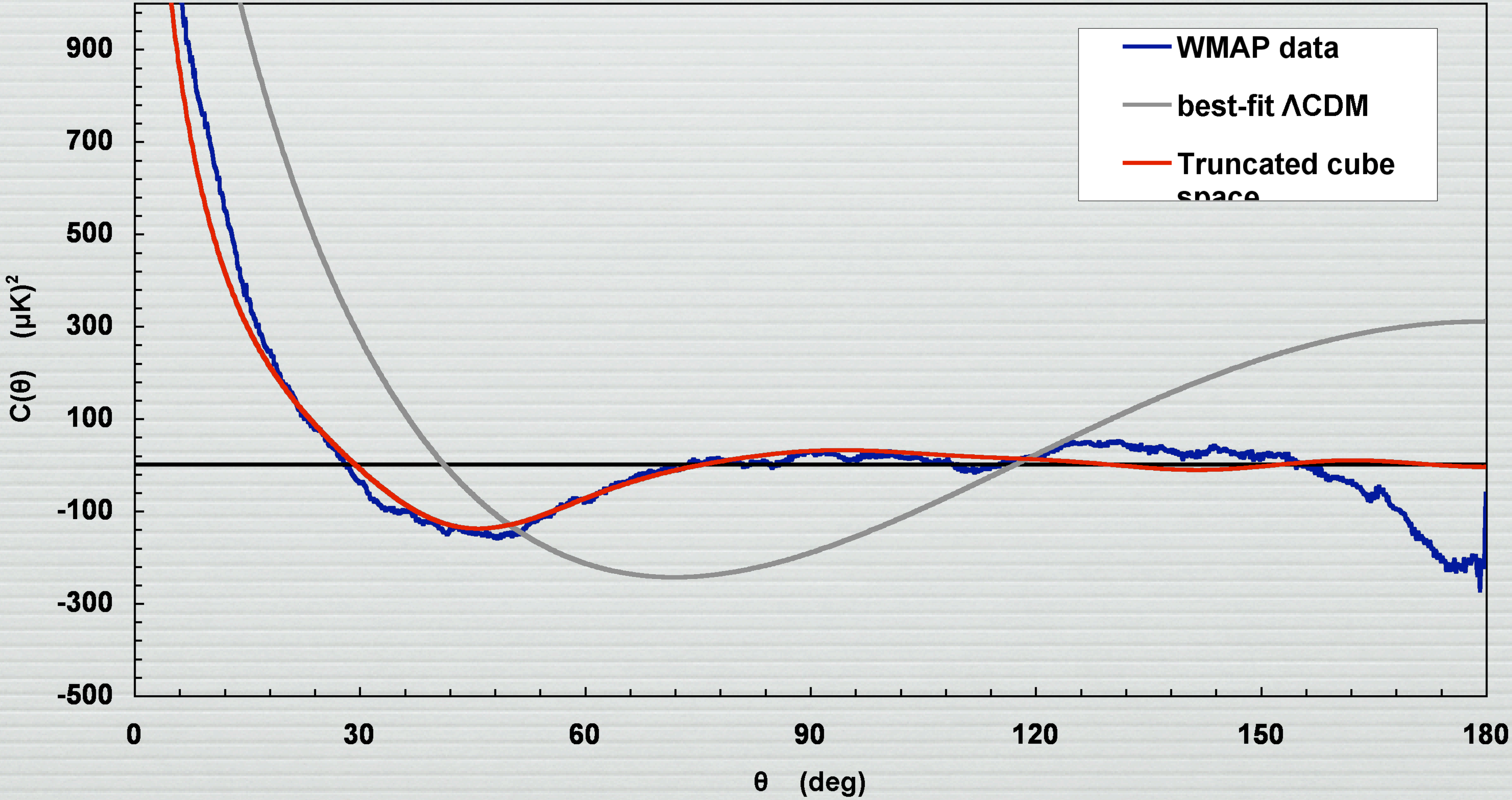


Poincaré/icosahedral



Truncated cube space / $H_0 = 52$



Bayesian topology

- Power spectrum: likelihood code by WMAP team (accounting for correlations among ℓ's)

- Full correlation matrix:

$$P(a \mid C) = \frac{1}{\sqrt{2\pi |C|}} \exp\left(-\frac{1}{2} a^t C^{-1} a \right)$$

$C = C_{\ell \ell' mm'} = C$(cosmology, topology)

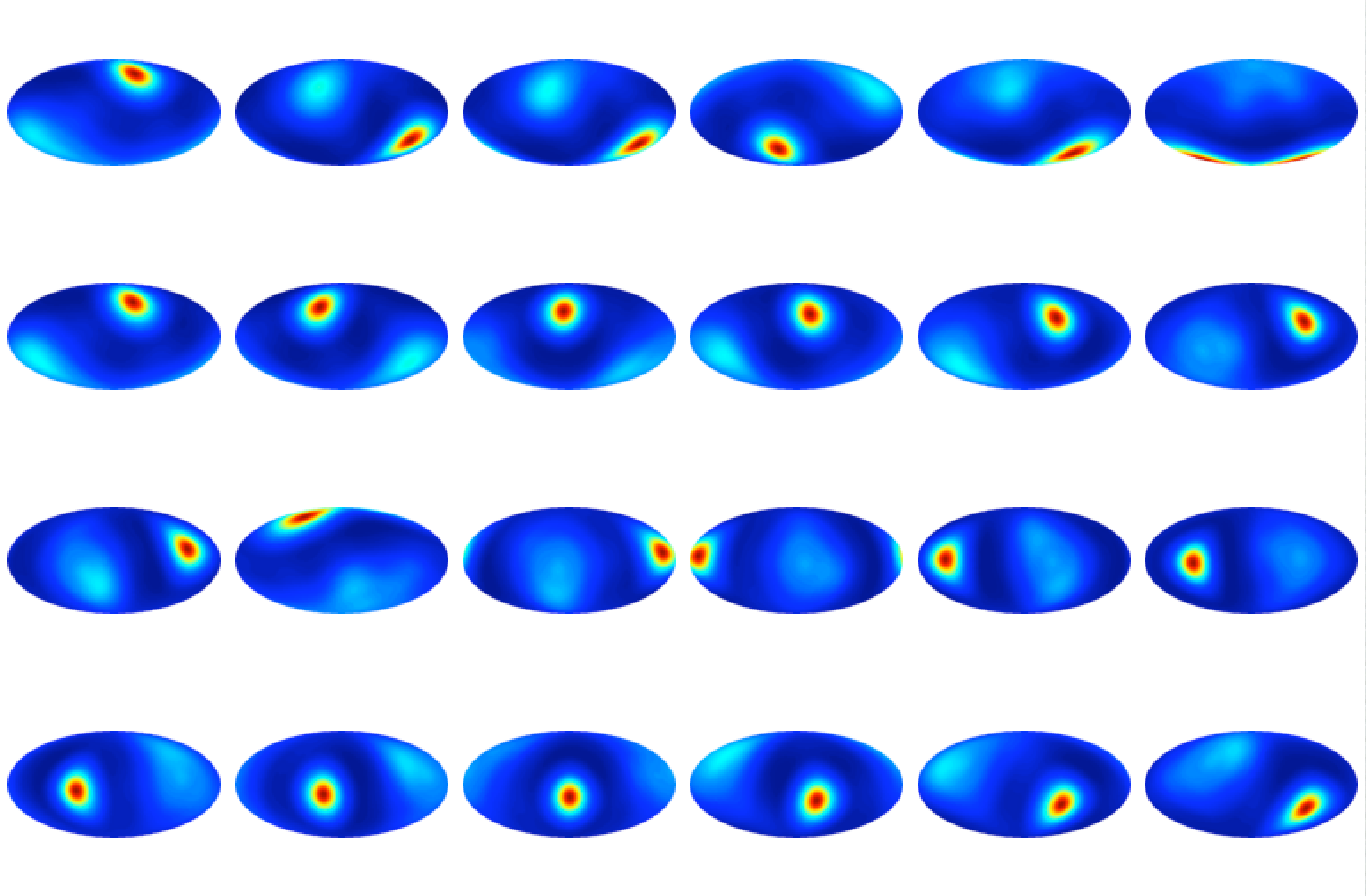
$a = a_{\ell m}$ from ILC

(Noise irrelevant on scales of interest)

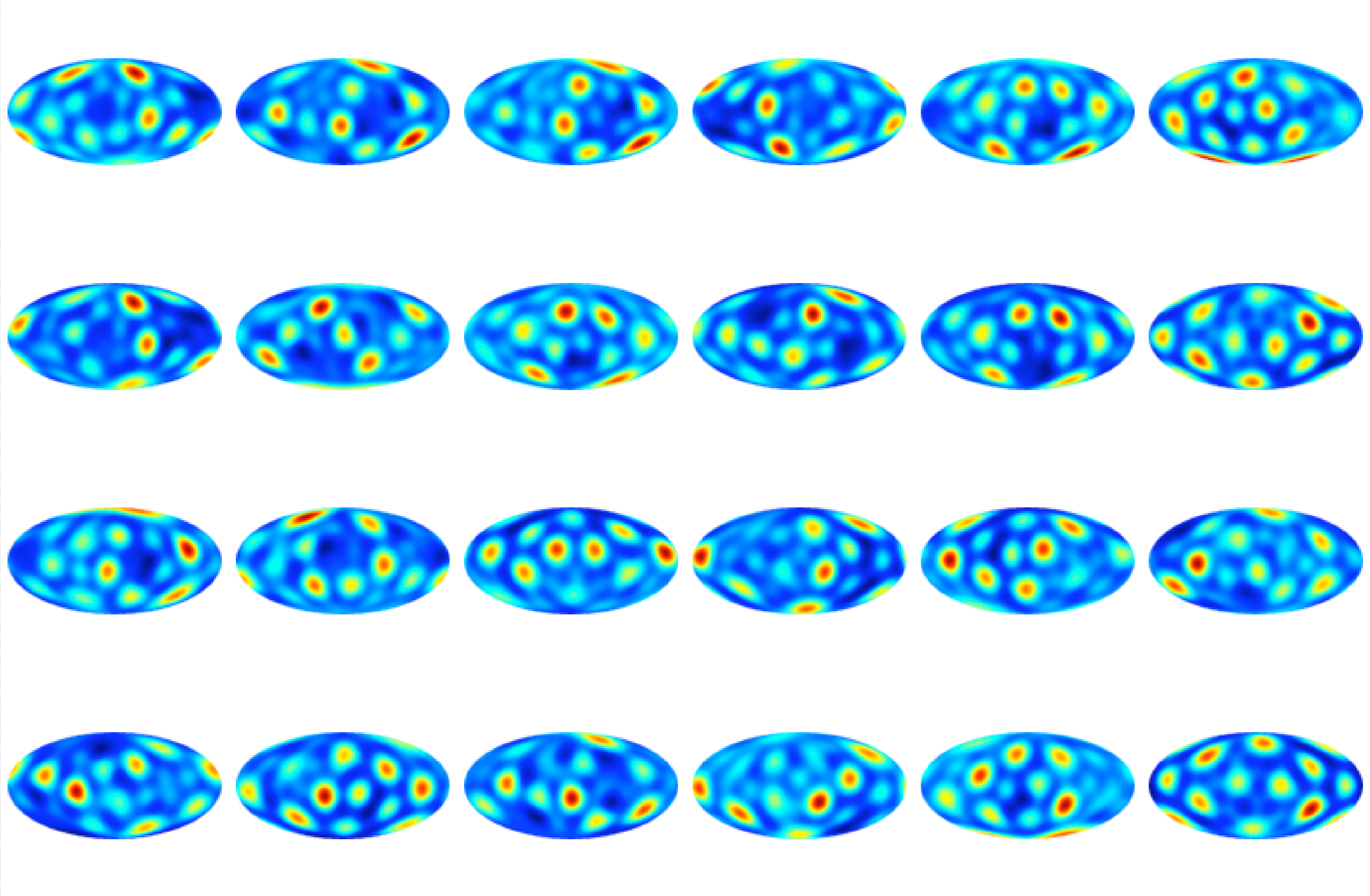
Suppressed power ⇒ stronger correlations

Pixel correlations

- Octahedral: h=0.64, Ω_k = - 0.017



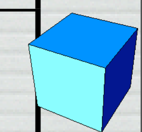
- Poincaré: h=0.52, Ω_k = - 0.063

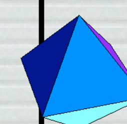


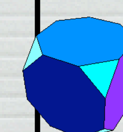
Model Comparison

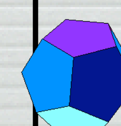
- WMAP 3-yr data
  - significant diffs from 1yr, e.g., octupole
  - First-year low ***power*** favors "small" fundamental domain to lower quadrupole (smooth low-l "decay")
- Details depend on "priors":
  - esp. H_0 for C_ℓ odds
- This is a topology-specific test (cf. "circles-in-the-sky" which purports to be more generic)
  - Difficult (impossible?) to test when (topology scale)>>(Hubble

Model	Odds: C_ℓ alone	Odds: $C_{\ell m \ell' m'}$
Simply-connected	1	1
Quaternionic	0.07	0.04
Octahedral	0.32	0.005
Truncated Cube	0.14	0.0003
Poincaré	0.04	$\ll 1$



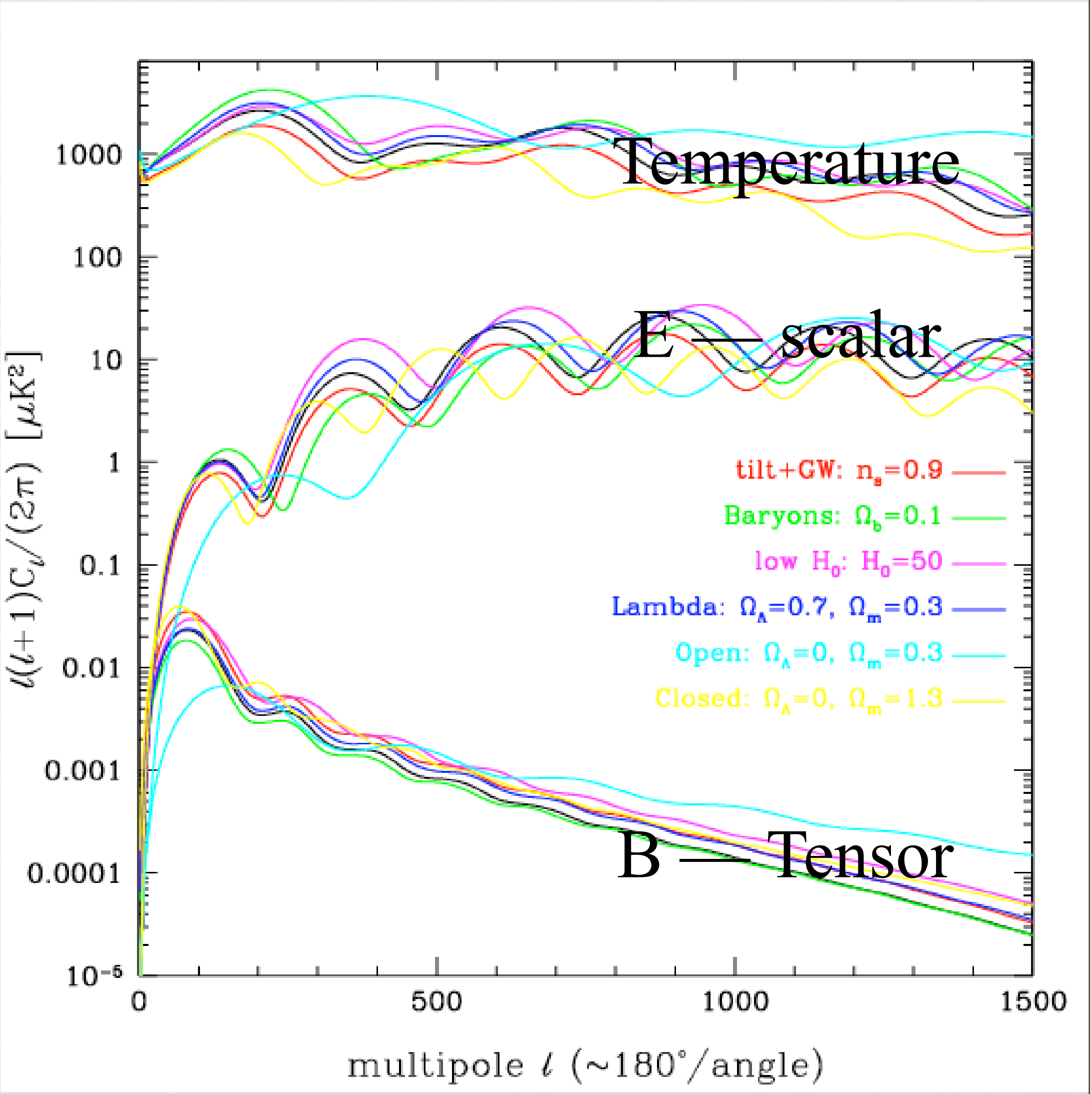




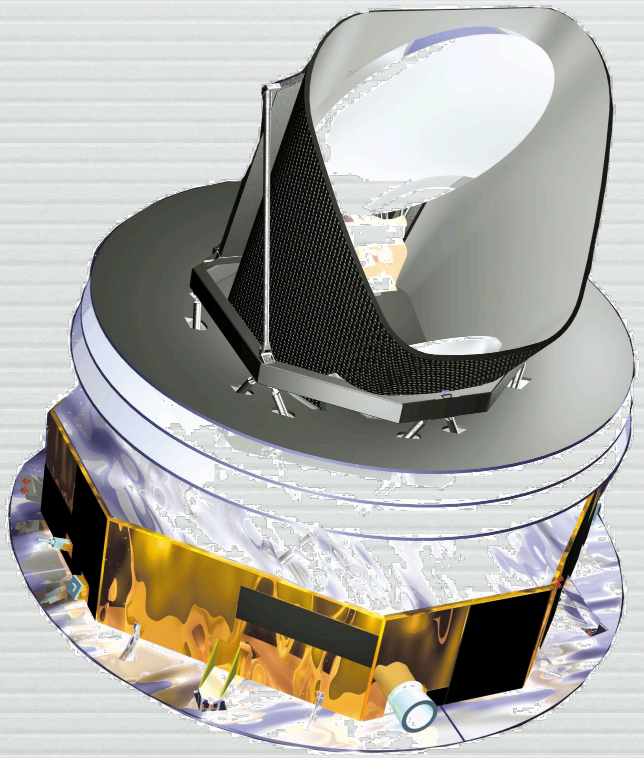


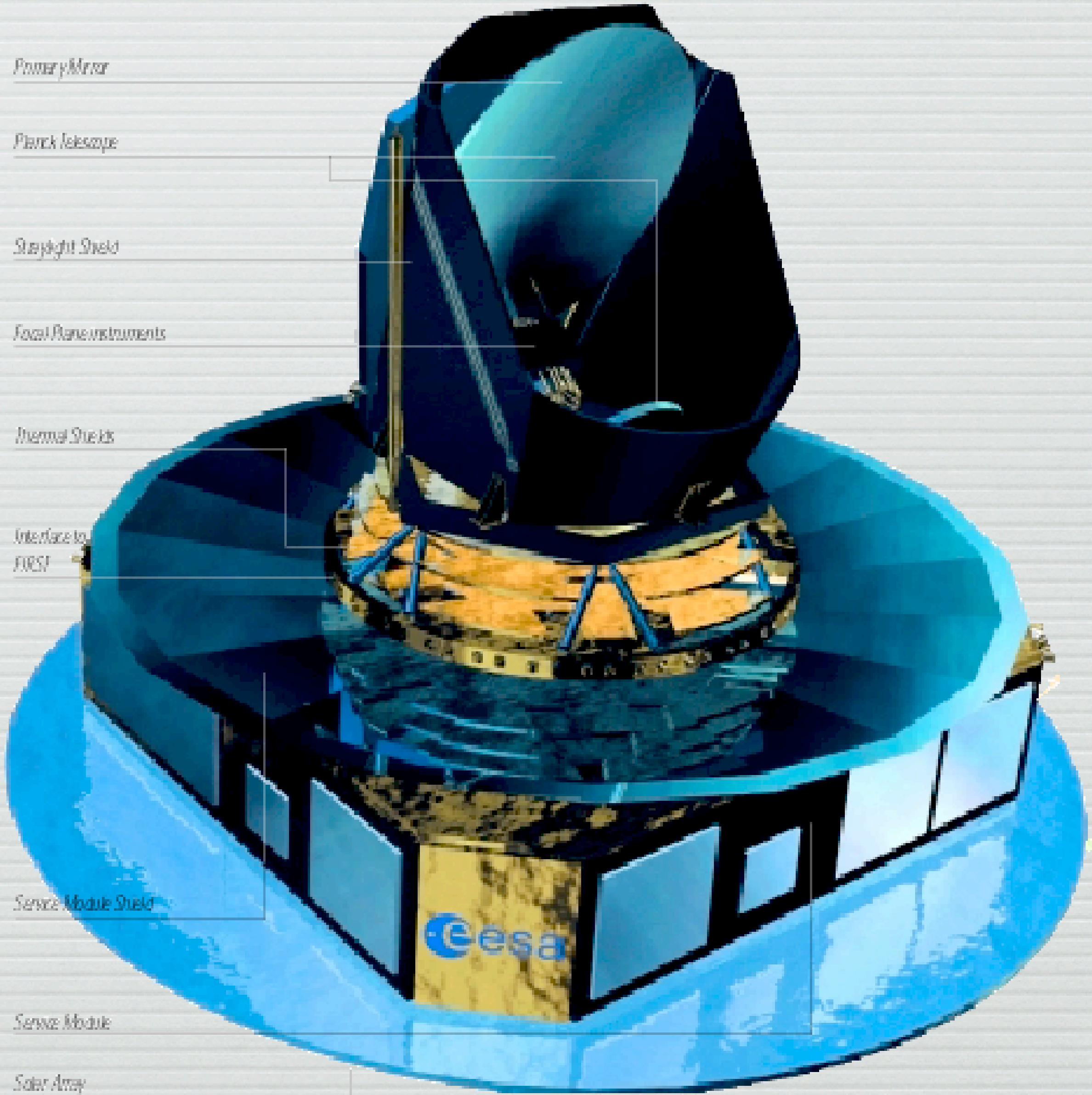
Polarization from Gravitational Radiation

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



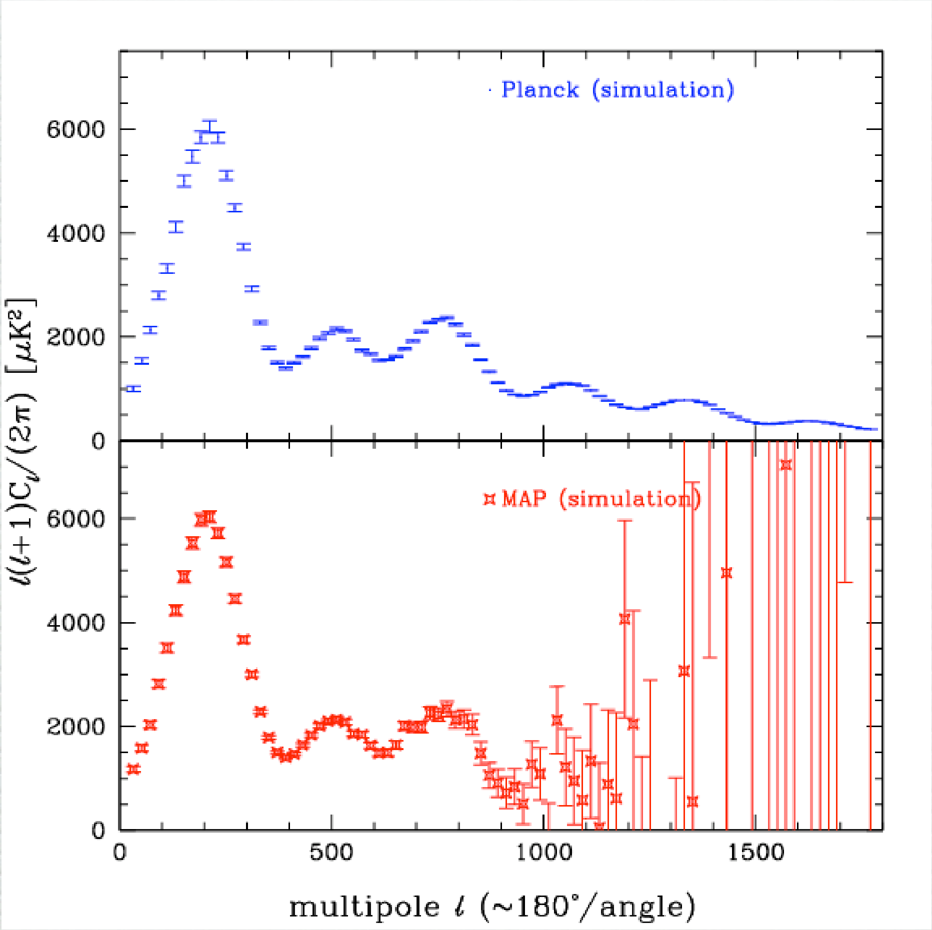
Planck Surveyor (2008++)





“Because it’s there”

- Heavy lines: cumulative fluctuation power in high S/N regime
  - Much more to be seen (esp E polarization, which isn’t dominated by large-scale fluctuations)
  - Planck gets ~all of T, most of E
  - But what about B Modes (inflationary gravitational radiation)?



“Because it’s there”

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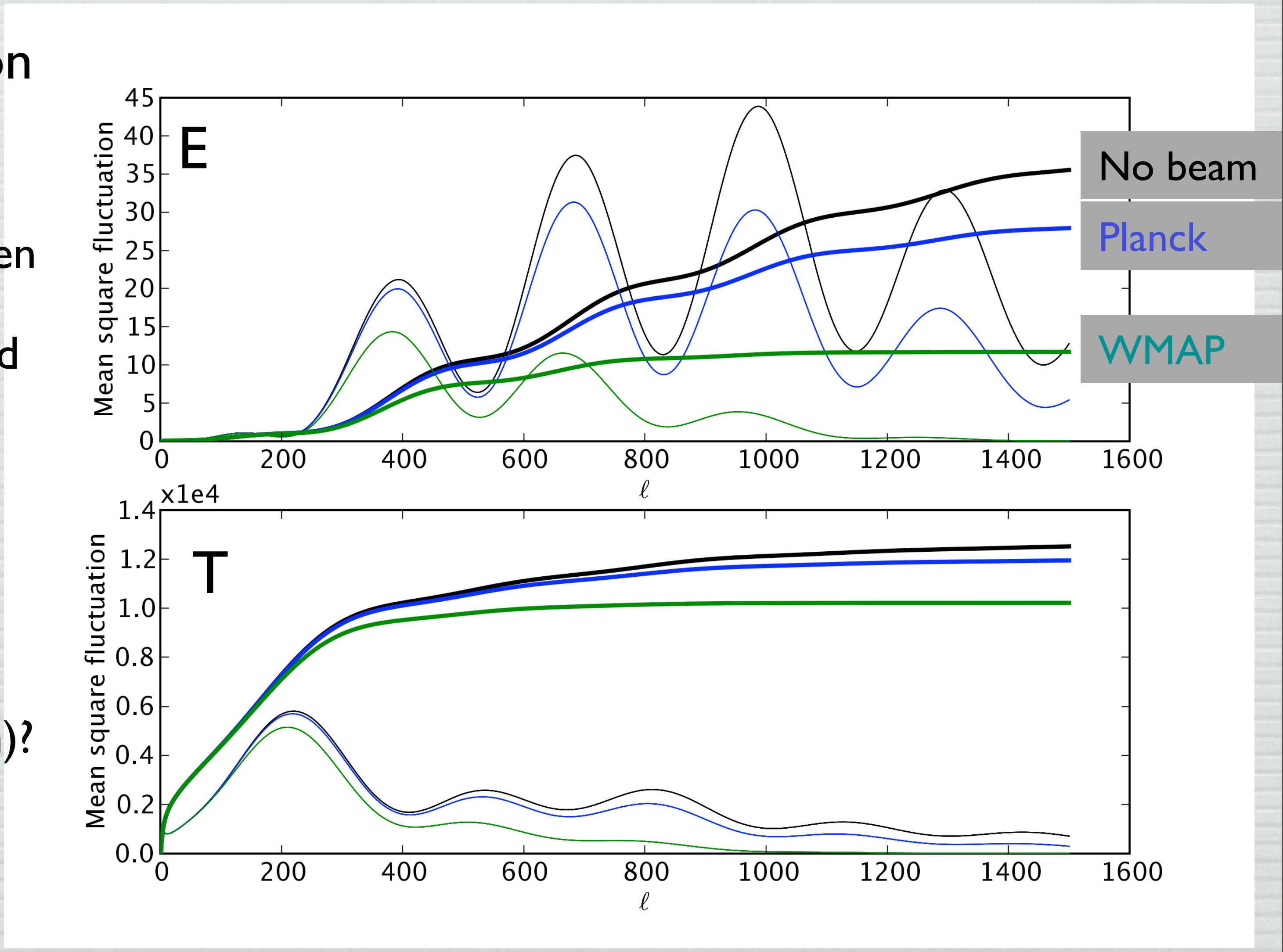
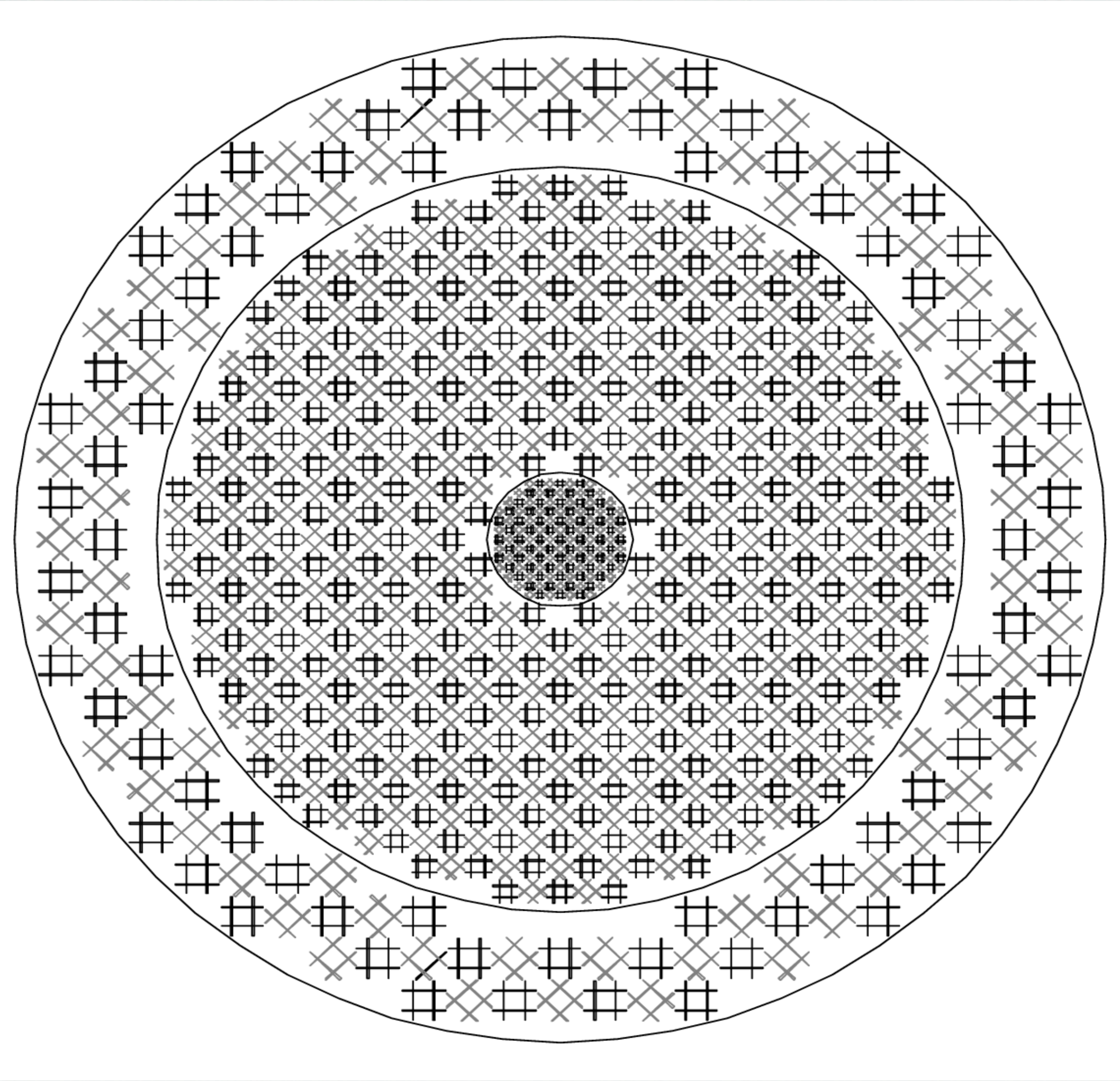
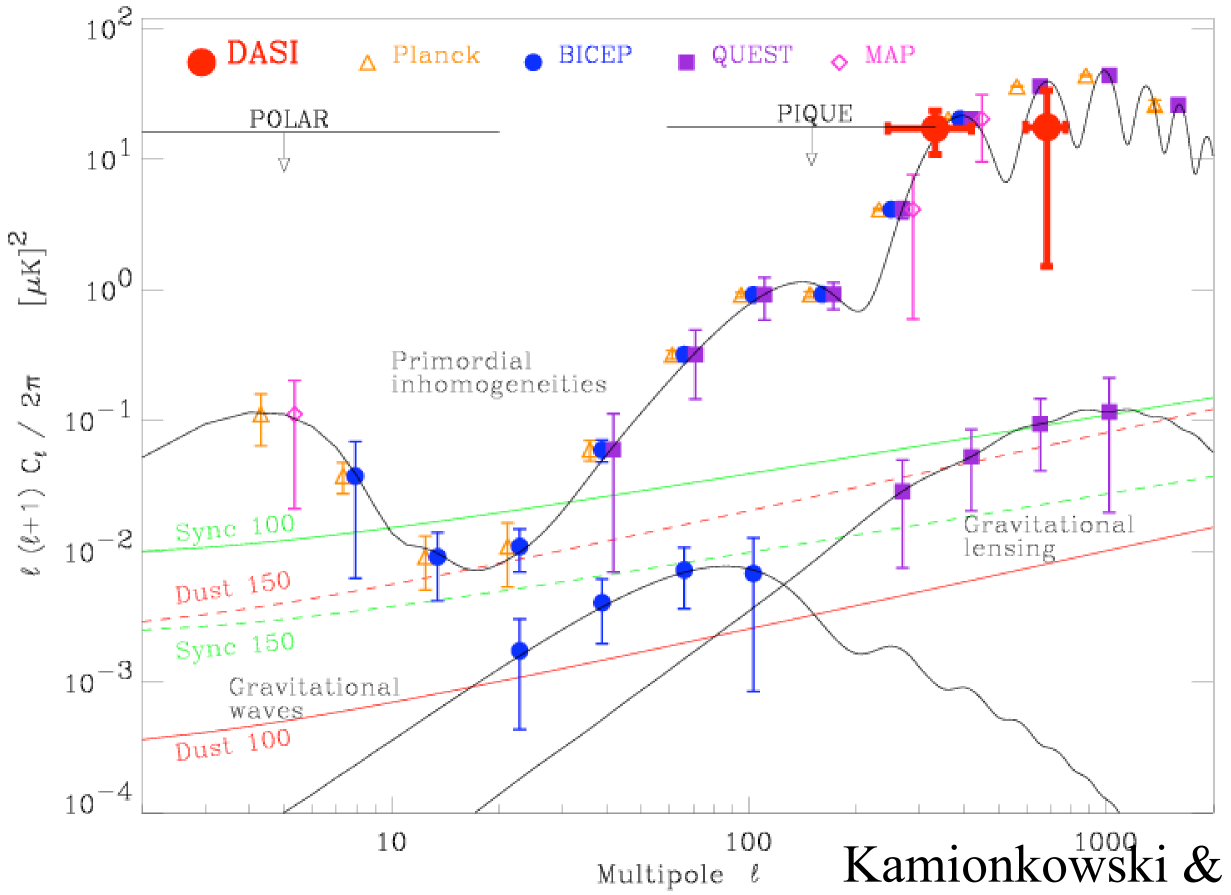


New Technologies



- PolarBear: AT Lee (Berkeley)
  - Antenna-coupled bolometers
  - 900 pixels @ 150 GHz, 3000 bolometers
  - Full use of useful 150 GHz Field-of-view

Further in the future?

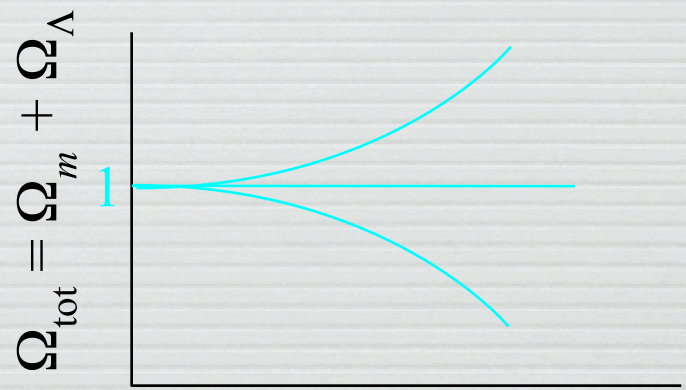


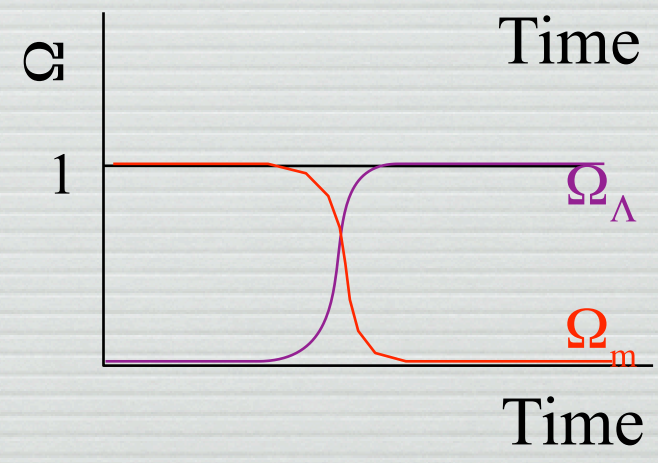
Kamionkowski & Hivon 2003

- Primordial Gravitational Radiation (e.g., from Inflation) generates B (Curl) modes; scalar (density) fluctuations only generate E (grad) modes
- Crucial foreground signal from gravitational lensing via intervening structure: generates B modes, masks GW signal

Unanswered questions

- Cosmic coincidences (Dicke/Peebles):
  - Why $\Omega_m \sim \Omega_\Lambda \sim 1$ today??
    - A very special time!
- Inflation can set $\Omega_{tot} = \Omega_m + \Omega_\Lambda = 1$ [*i*.e., flat]
- But simplest "theories" predict $\Omega_\Lambda \sim (m_{Pl}/L_{Pl}^3)/\rho_{crit} \sim 10^{120}$!!!
  - String theory? Quintessence?
    - More fossils yet to be uncovered…

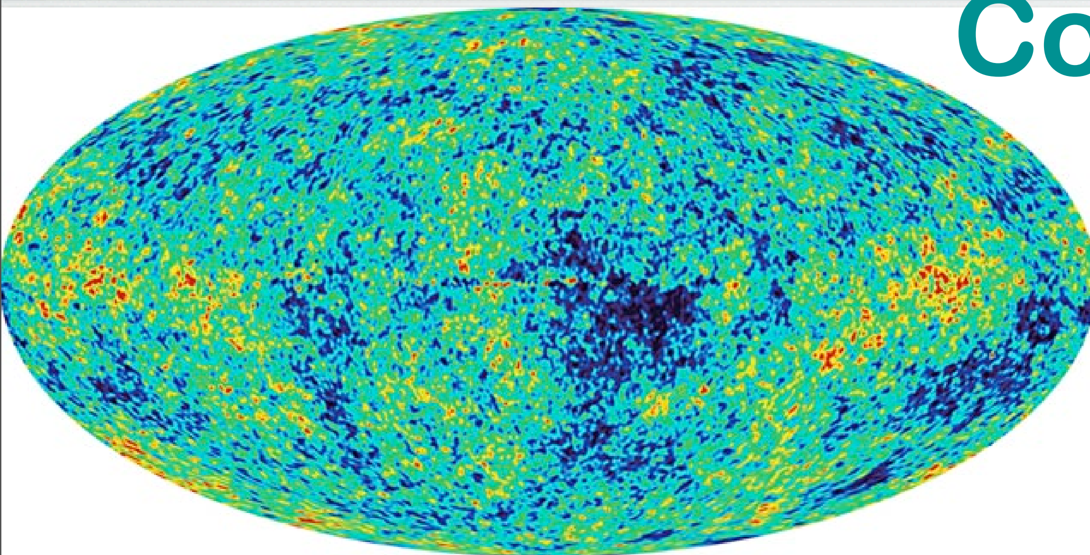


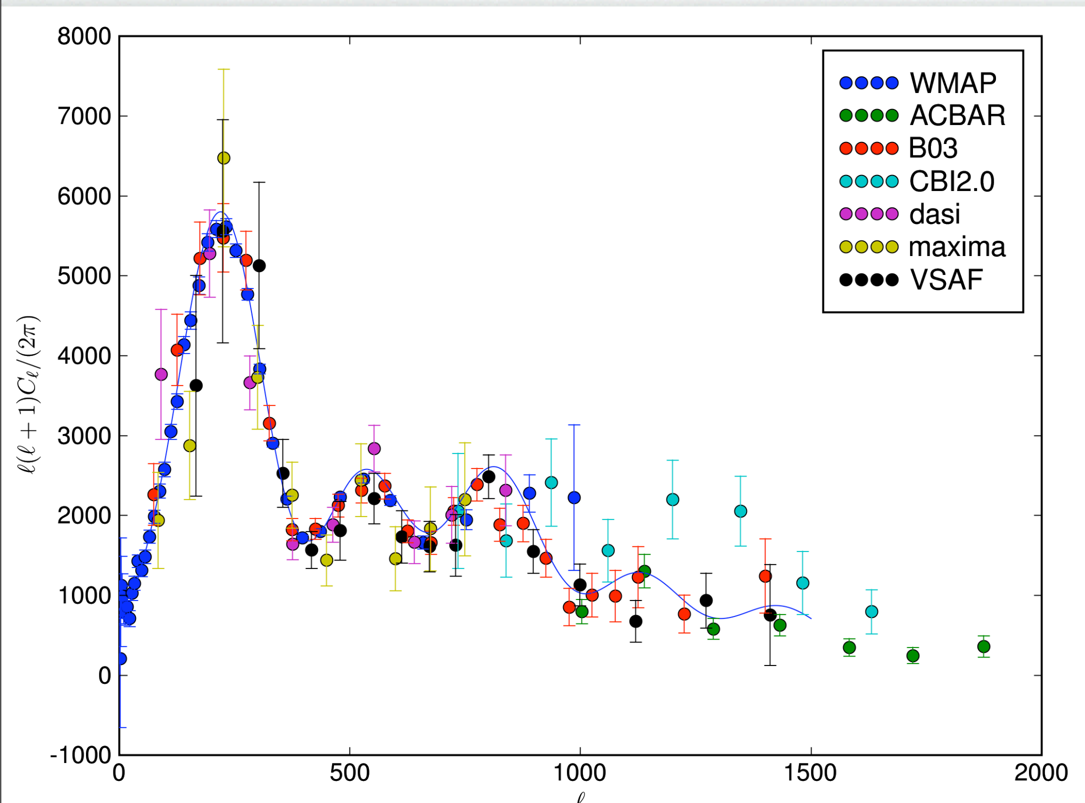


Can we go further?

- Doomed to phenomenology?
- Or can we ask "why?"
- Back to conditional probabilities
  - the string landscape: 10^{100} vacua, each with its own physical laws
    - happy to measure one part in 10^{100}
  - in an infinite universe, is *everything* possible?
    - brains-in-vats, the Matrix, Boltzmann brains...
  - Do we need a get-out clause? (Davies' "life principle")
  - Condition on being Carbon-based beings on earth-like planets with sun-like stars? (Lineweaver & Egan 07)

Cosmology c. 2006





- The Hot Big Bang
- Flat Universe
- Dark Matter

Parameters measured to 2-3 decimal places!

- Cosmological Acceleration
- Adiabatic Initial conditions

- Inflation
- Dark Energy
- Gravitational radiation