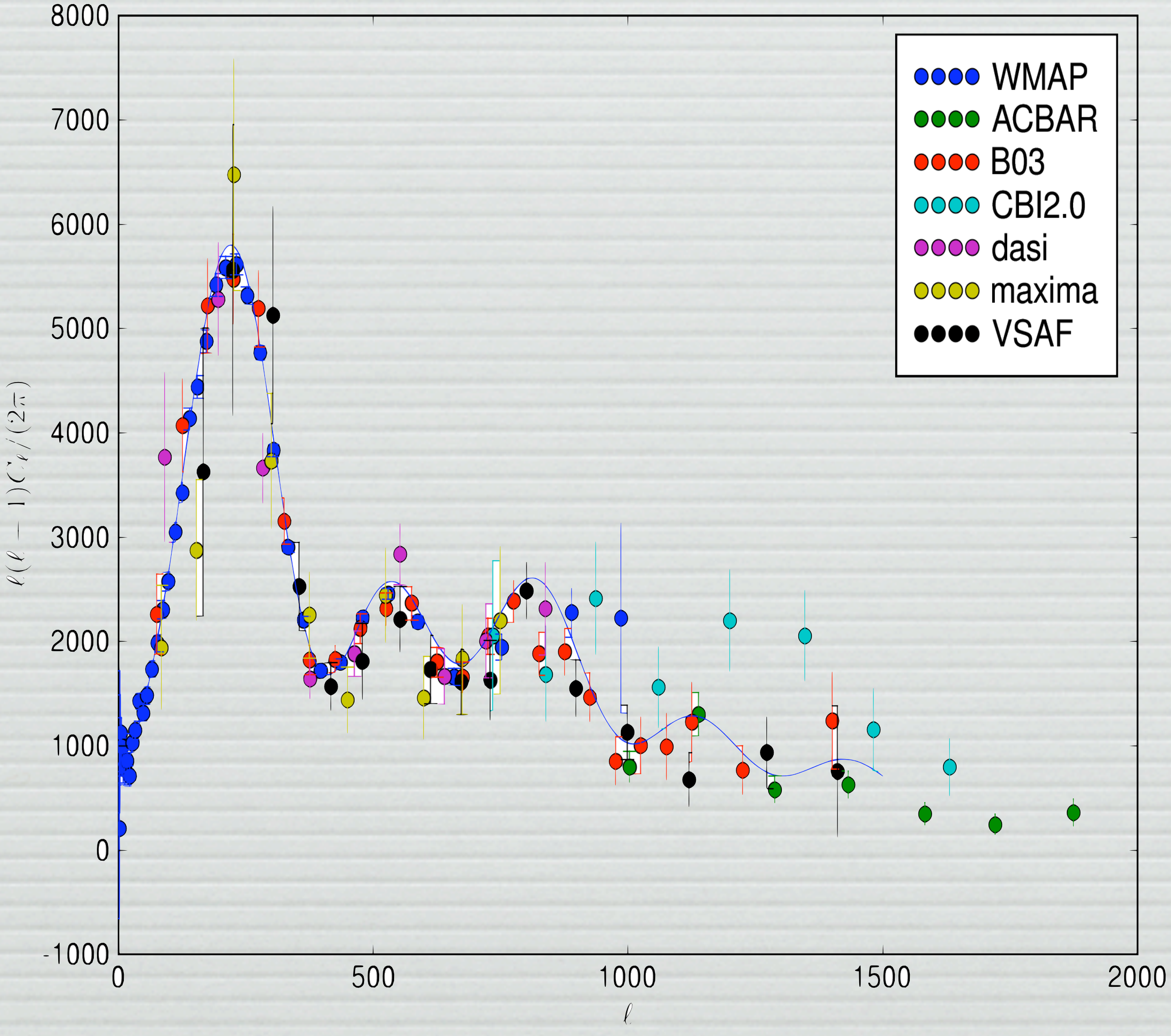
The Future of CMB Studies



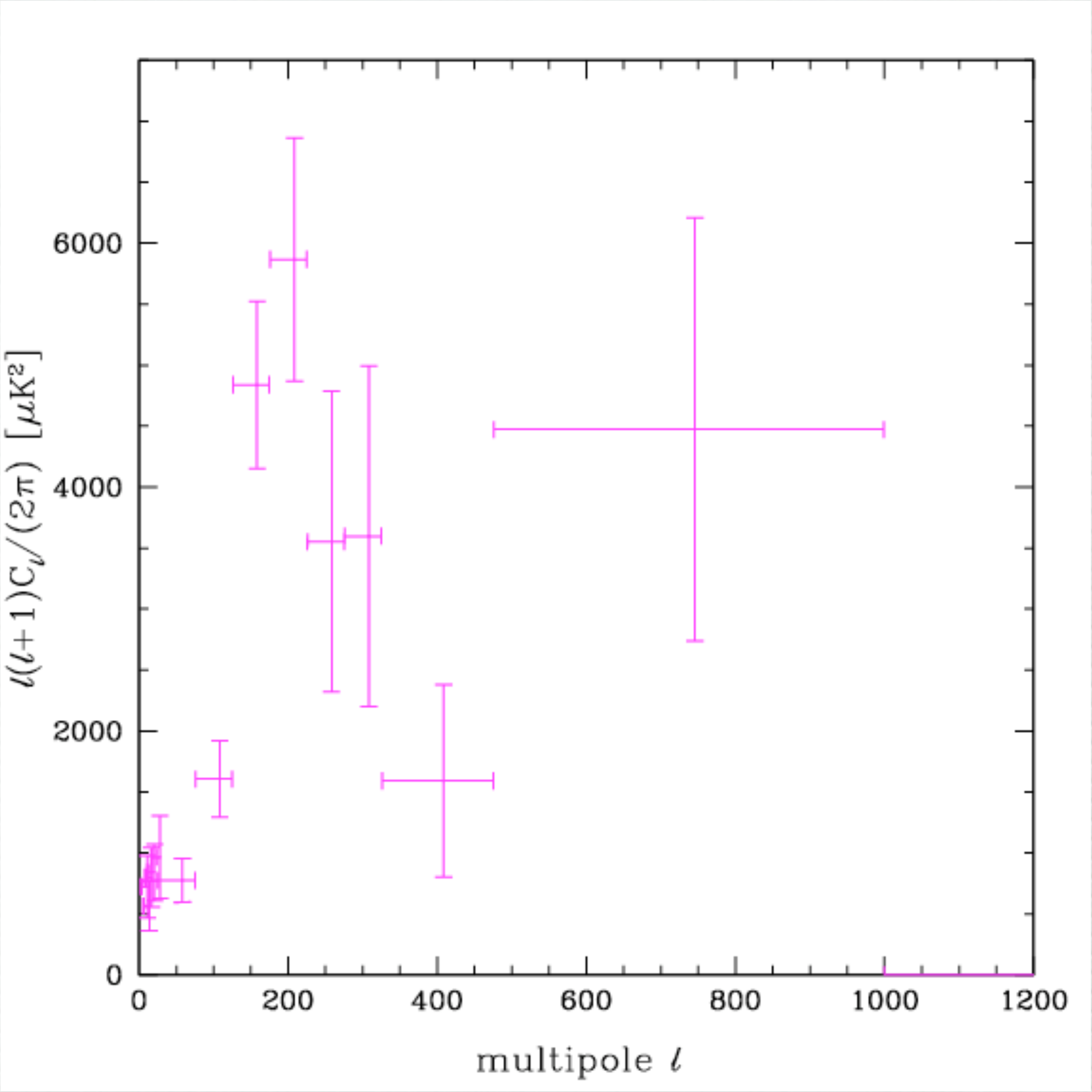
Andrew Jaffe

IUCAA, December 2007

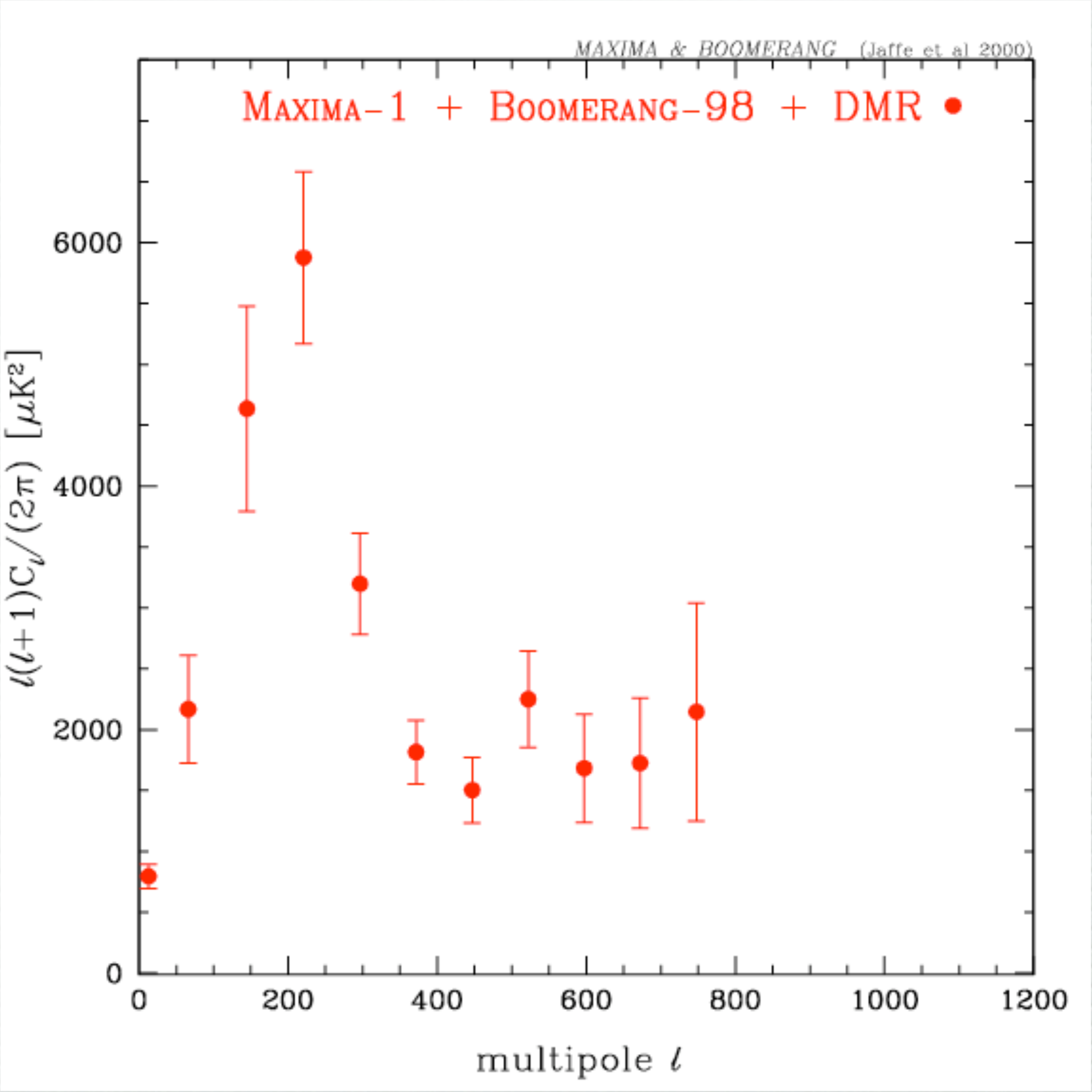
Outline

- Some recent history
- Linear evolution of scalar modes
  - Intensity, E-Mode polarization, l<1000
- Gravitational Radiation from the Early Universe
  - B-mode polarization, l<1000
- Clusters and the SZ effect (highly nonlinear scalar modes)
- Exotic physics
  - topology, anisotropy, parity violation
- Mildly nonlinear evolution
  - lensing, Ostriker-Vishniac effect
- Foregrounds
  - astrophysics in the microwave band
- Experiments: Planck, the next generation of suborbital telescopes, and beyond

February, 2000

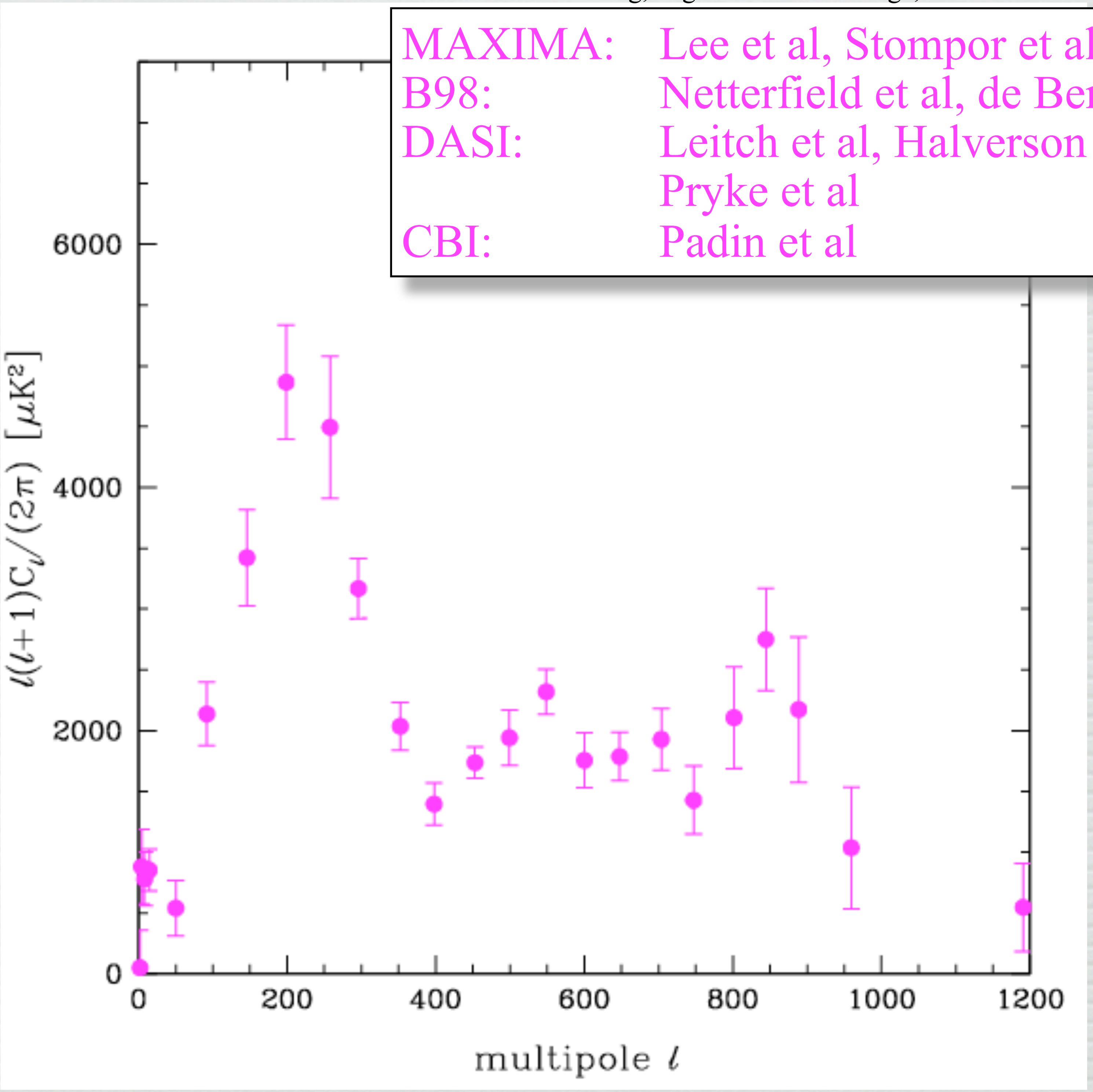


July, 2000


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]

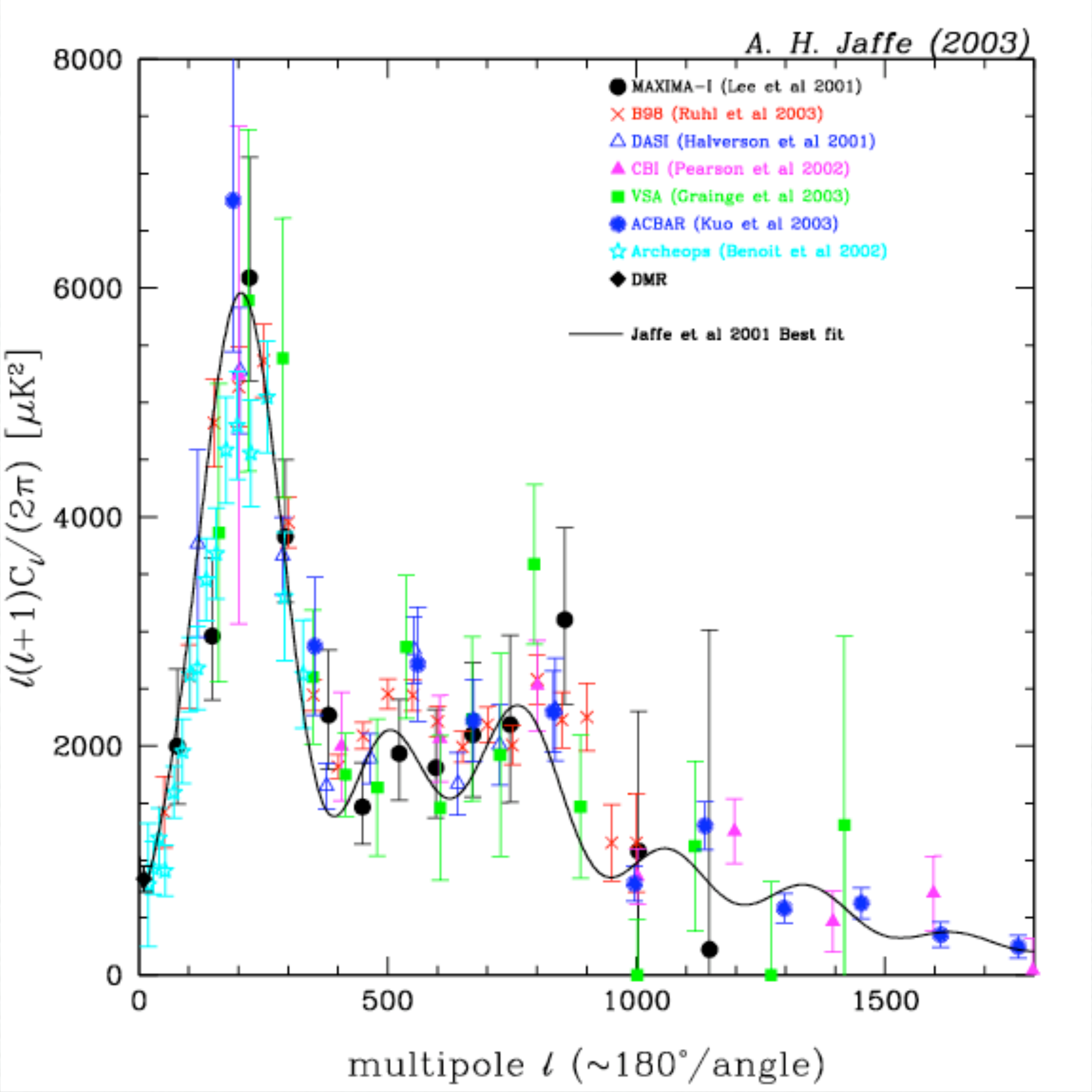
May, 2001

Wang, Tegmark & Zaldarriaga, 2001

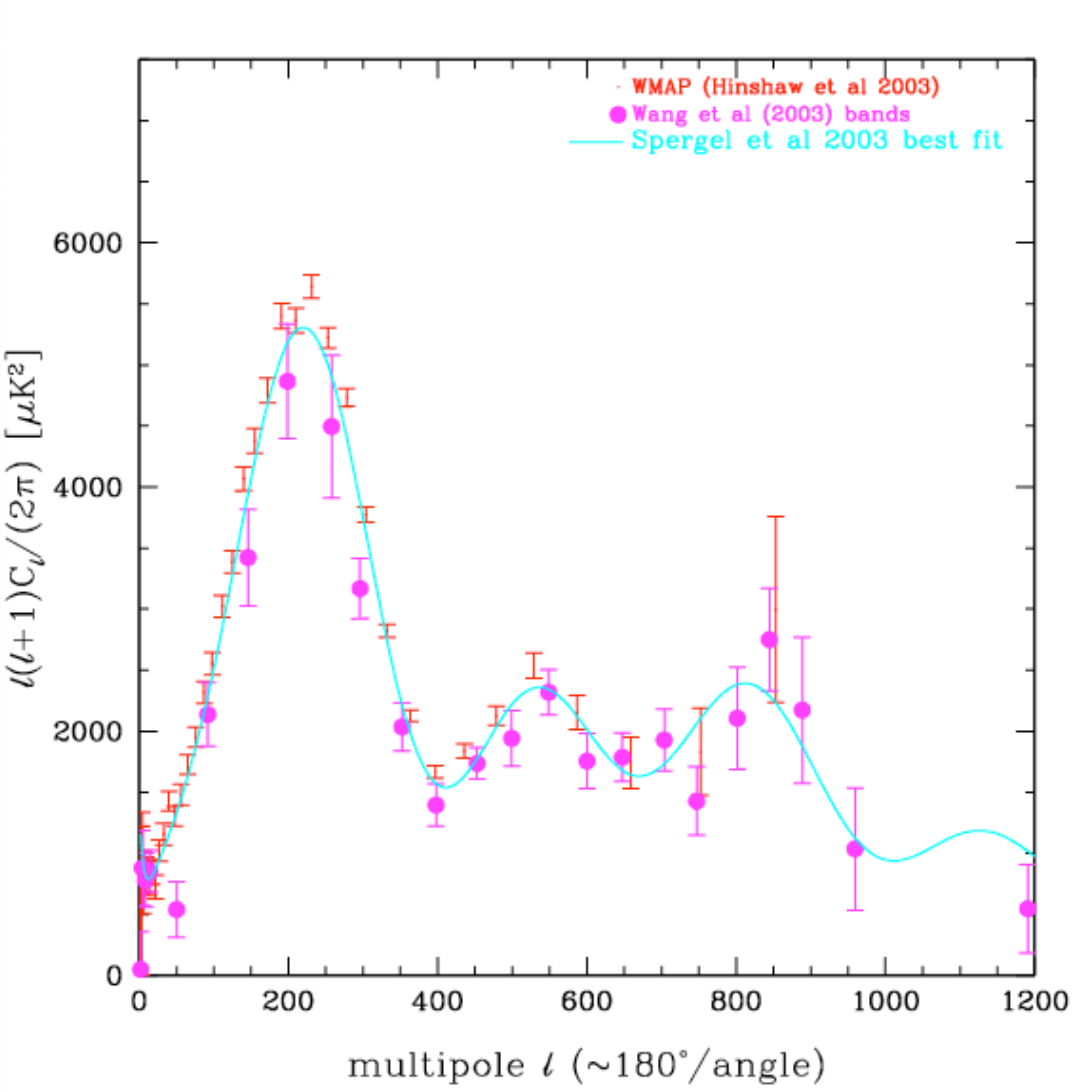


MAXIMA:	Lee et al, Stompor et al
B98:	Netterfield et al, de Bernardis et al
DASI:	Leitch et al, Halverson et al, Pryke et al
CBI:	Padin et al

January, 2003

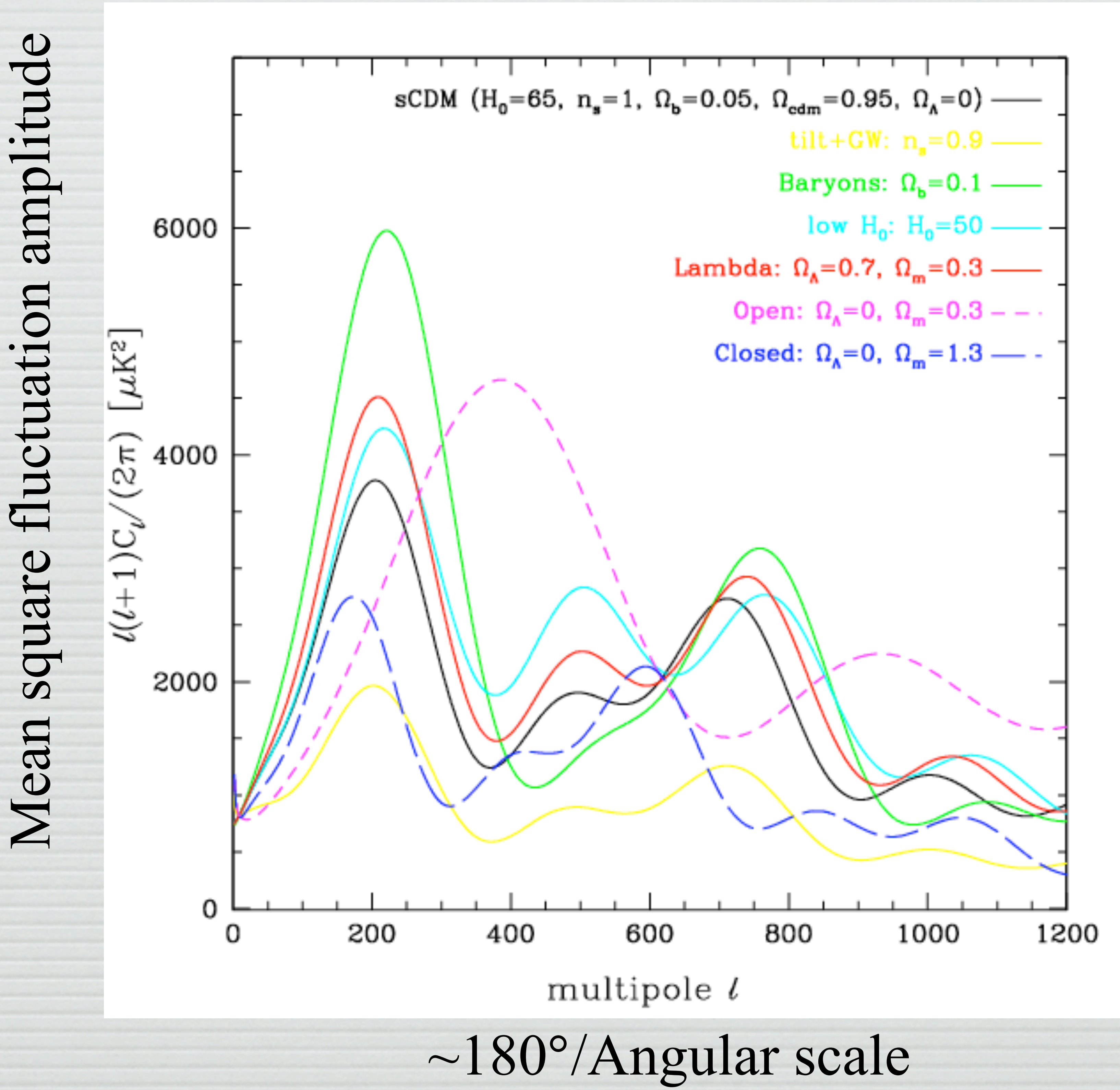


WMAP!



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)

Theoretical Predictions

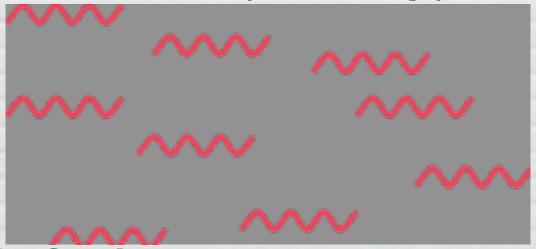


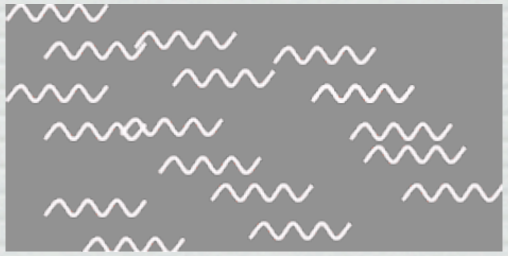
What affects the CMB temperature?

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

- Initial temperature (density) of the photons

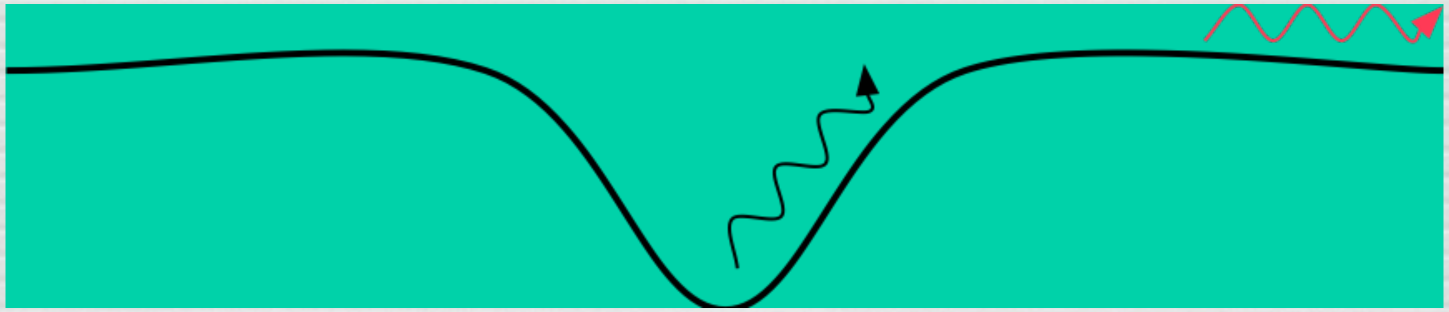
Cooler





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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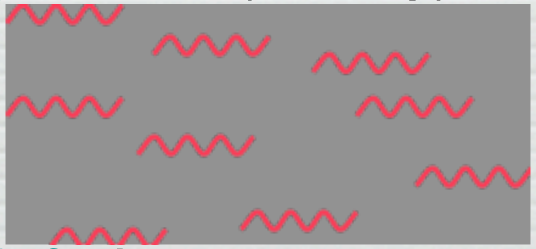

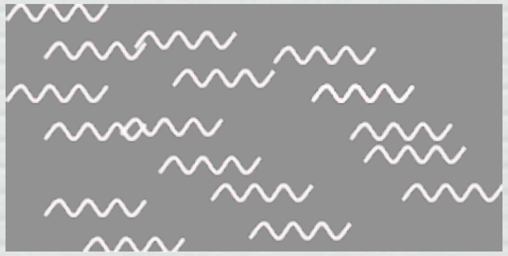

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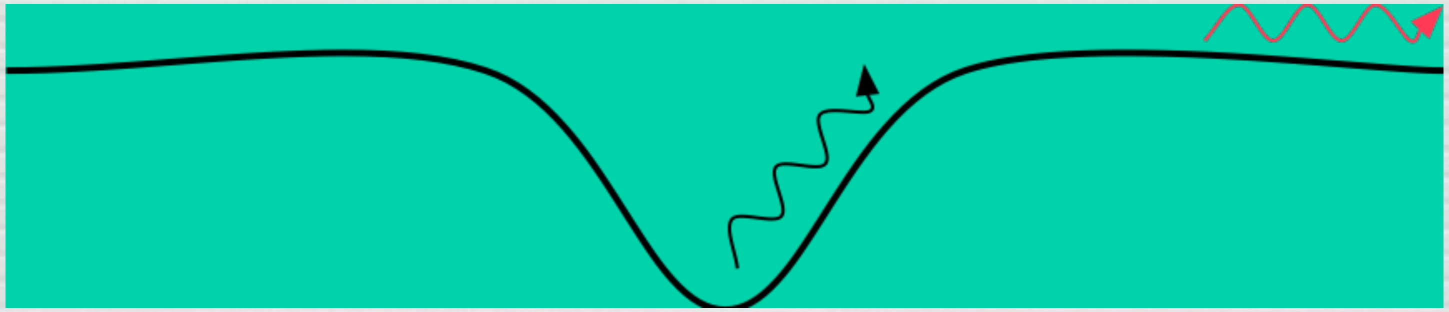

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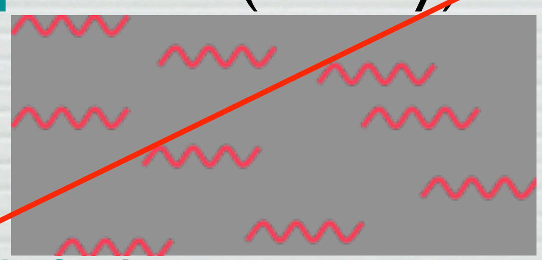

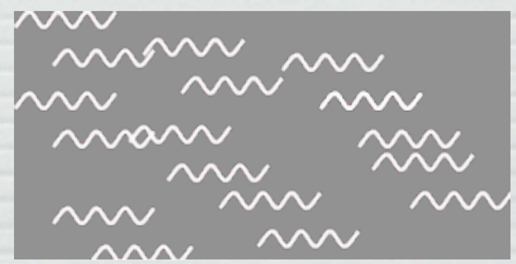

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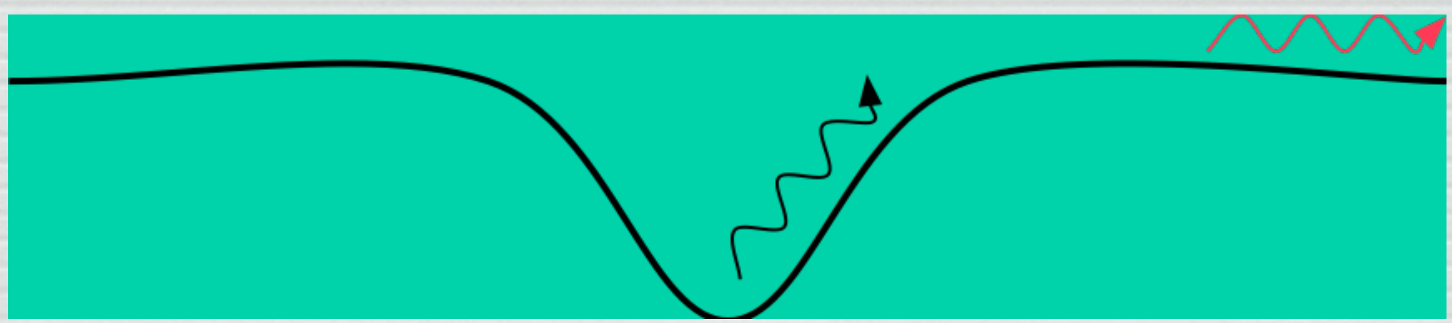

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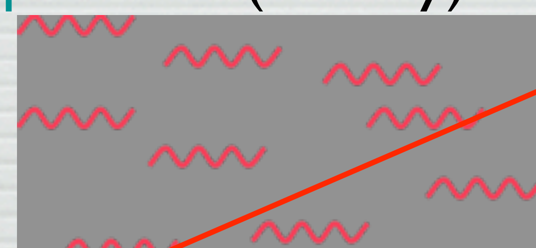

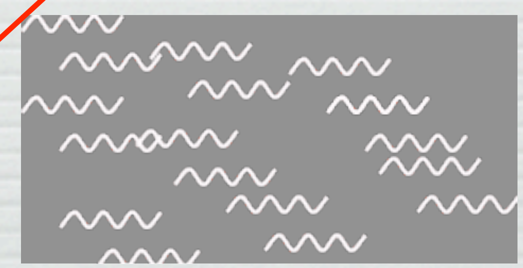

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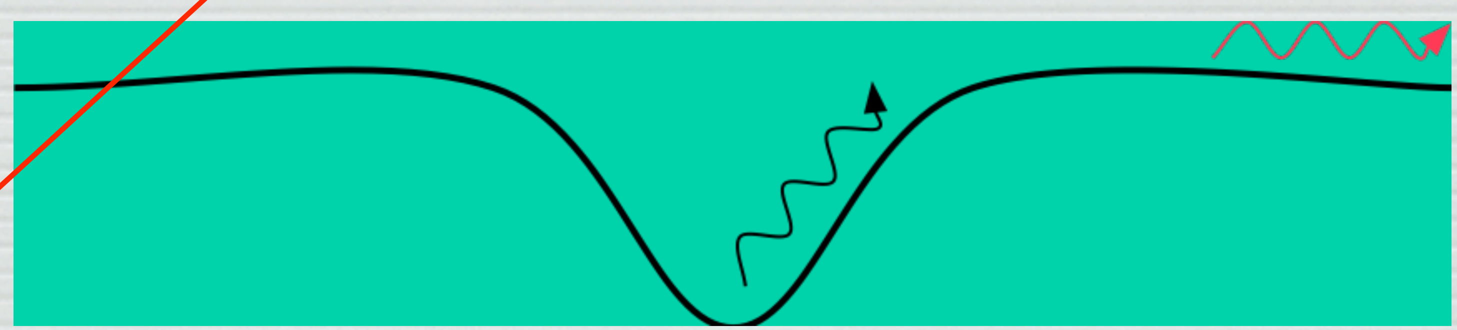

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Inflation

- 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,

Inflation Predicts

- Thermalized, uniform CMB
- Flat:
  - $\Omega_{\mathrm{tot}} = \Omega_{\mathrm{m}} + \Omega_{\Lambda} = 1$
- (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)

Perturbations from inflation

- Rapid expansion blows up quantum scales to astrophysical size:
  - weakly-coupled (~free) scalar field
    $\langle \phi(x)\phi(x')\rangle = F(x-x')$ (~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

(see Langlois review)

Fluctuations: Generation & Evolution

need more here

rdial fluctuations: $\frac{\delta\rho_0(\mathbf{r})}{\rho} \Leftrightarrow \delta_0(\mathbf{k})$

- e.g. inflation $\langle\delta_0^*(\mathbf{k})\delta_0(\mathbf{k})\rangle = (2\pi)^3 P_0(k) \propto k^{n_s}$ if $\mathbf{k} = \mathbf{k}'$
- QM microphysics
  - weakly-coupled (~free) scalar field
    〈φ(x)φ(x')〉 =F(x-x')
  - pre-inflationary white noise generates nearly scale-invariant superhorizon spectrum
- Linear evolution: $\delta(\boldsymbol{k}, t) = T(k, t)\ \delta(\boldsymbol{k})$
- $P(k, t) = T^2(k, t) P_0(k)$

Transfer function

- [local in k ⇒ convolution in space]
- CMB more complicated: mix k with $T_\ell(k)$

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

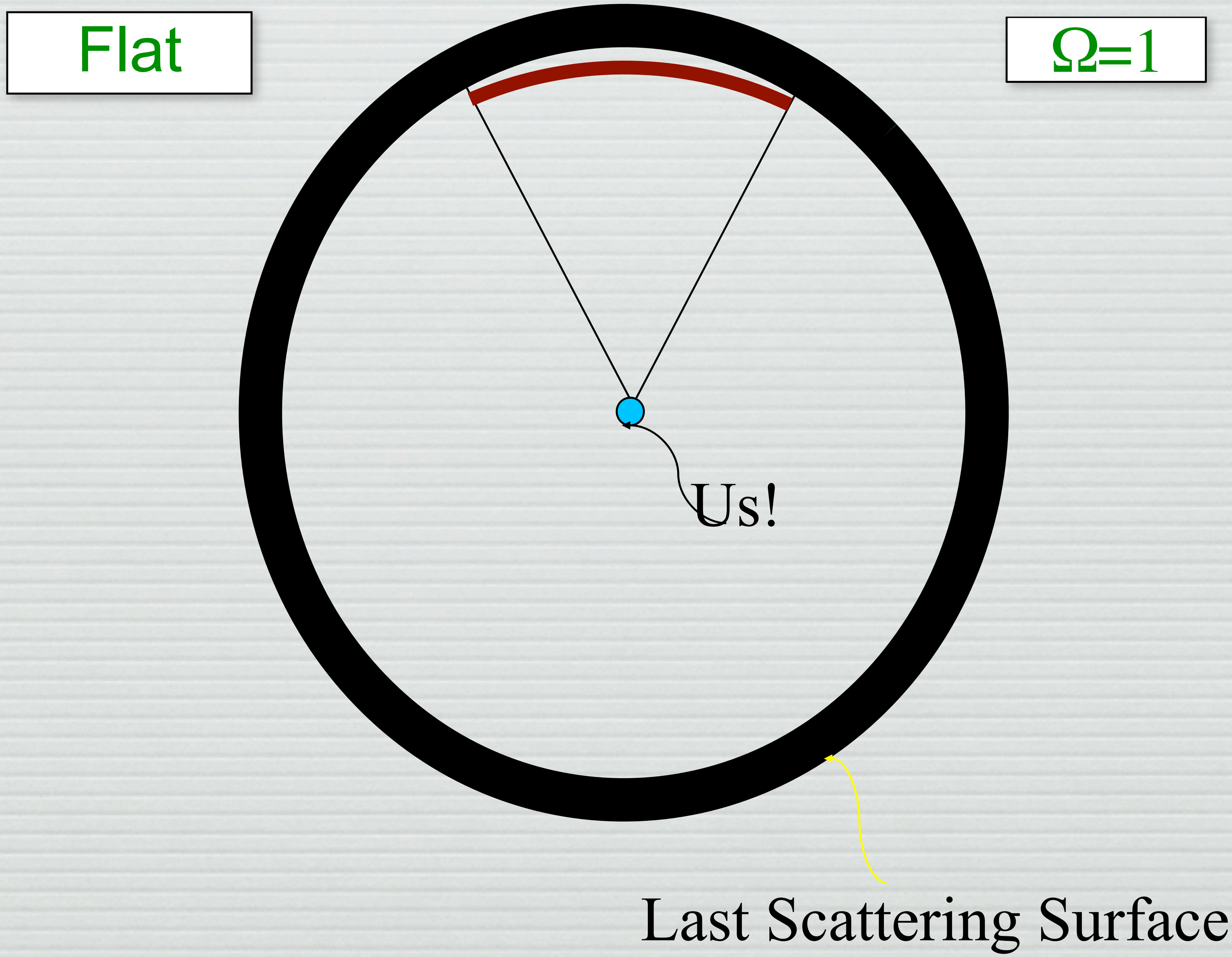
- Allows us to define the *power spectrum*, C_l

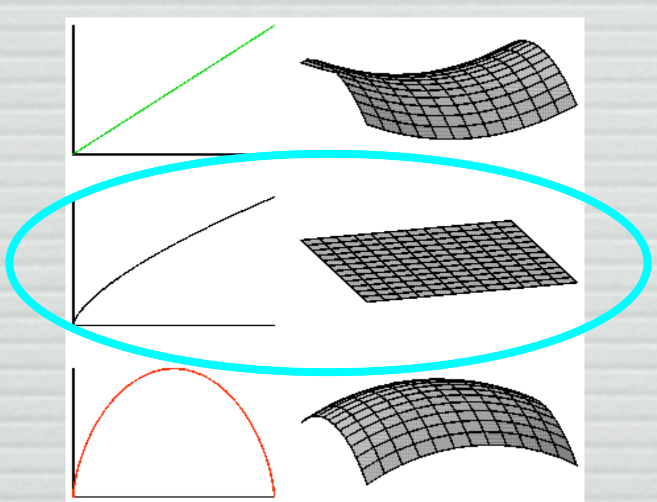
$$\langle a^*_{\ell m} a_{\ell' m'} \rangle = \delta_{\ell\ell'} \delta_{mm'} \; C_\ell$$

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

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

Measuring Curvature with the CMB





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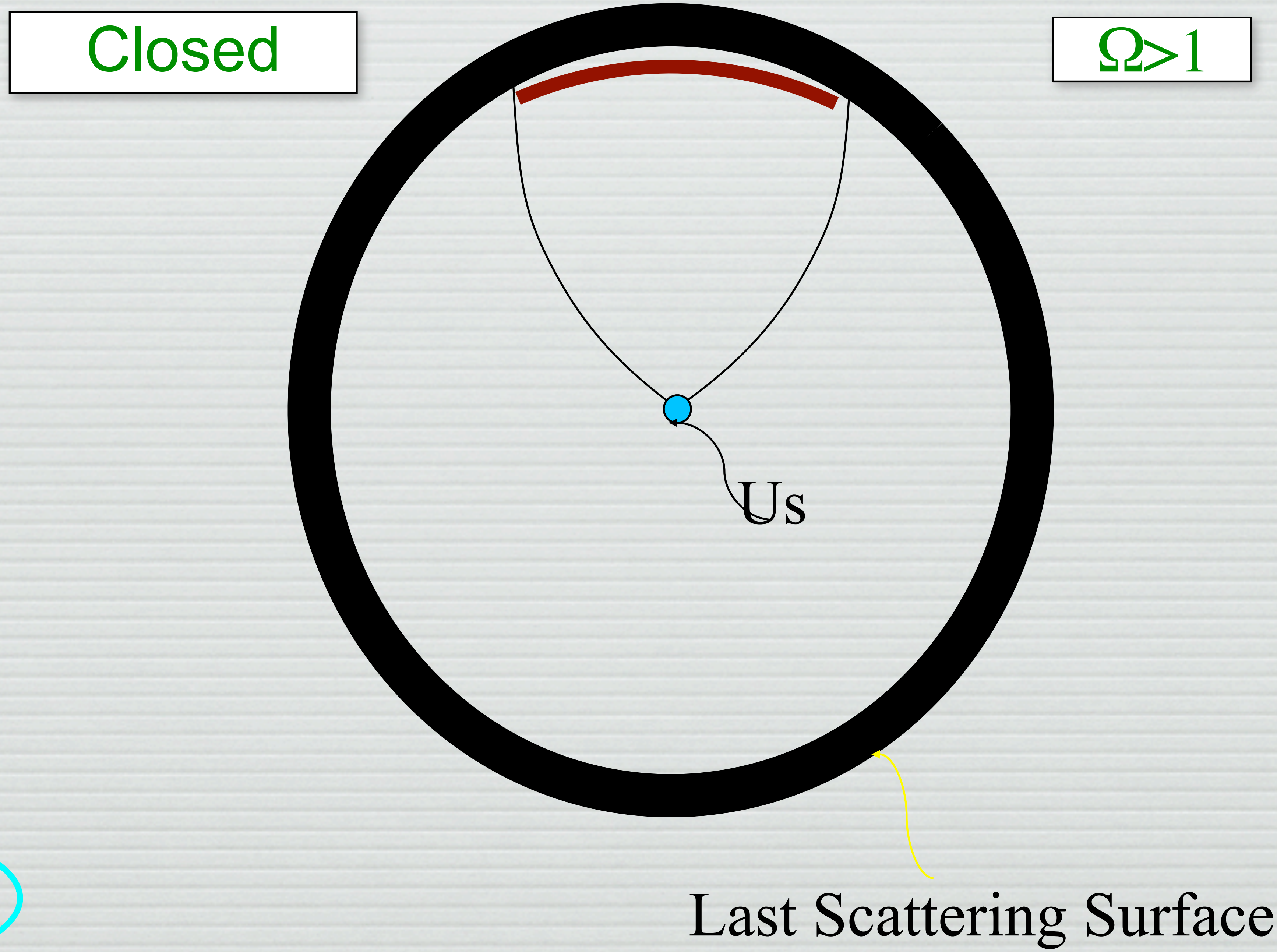
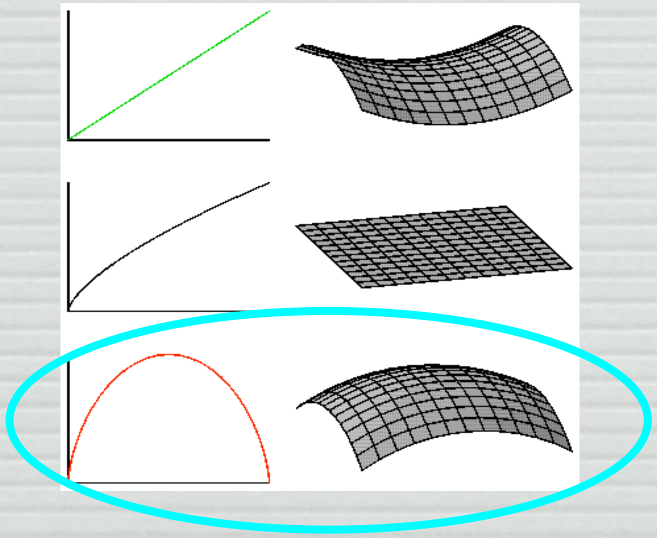
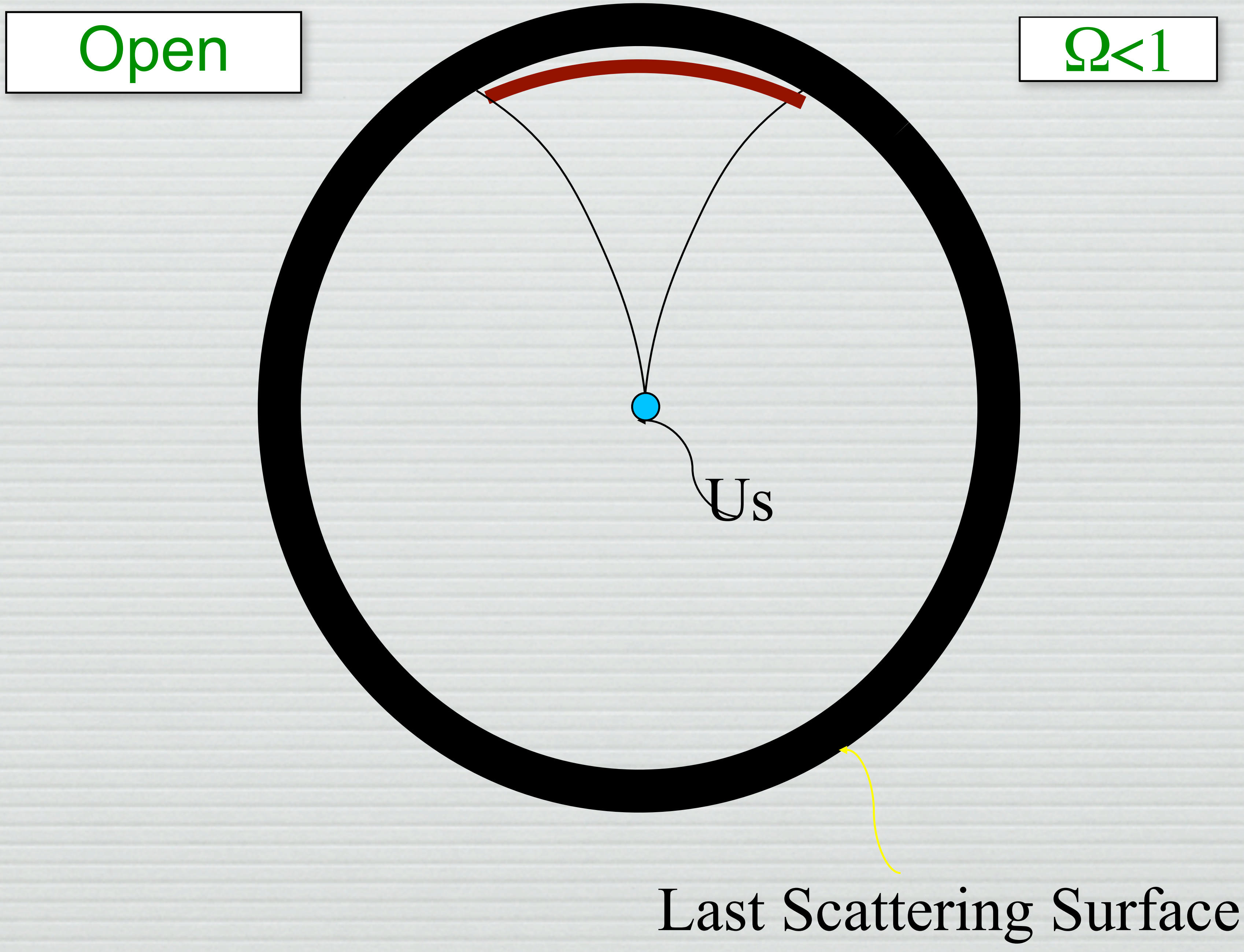
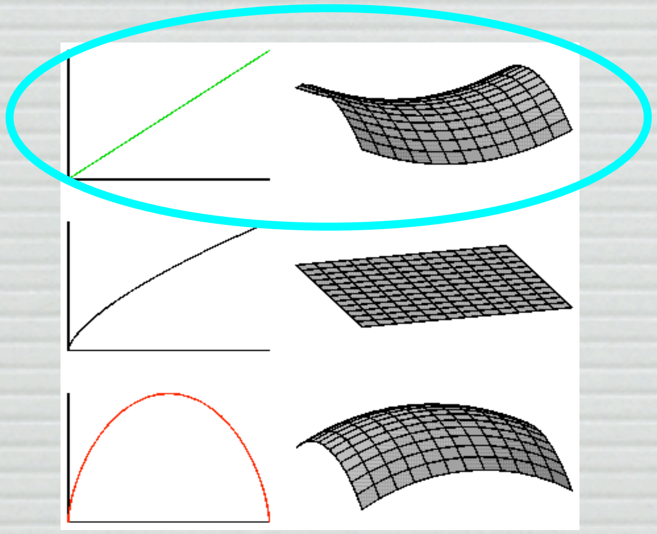
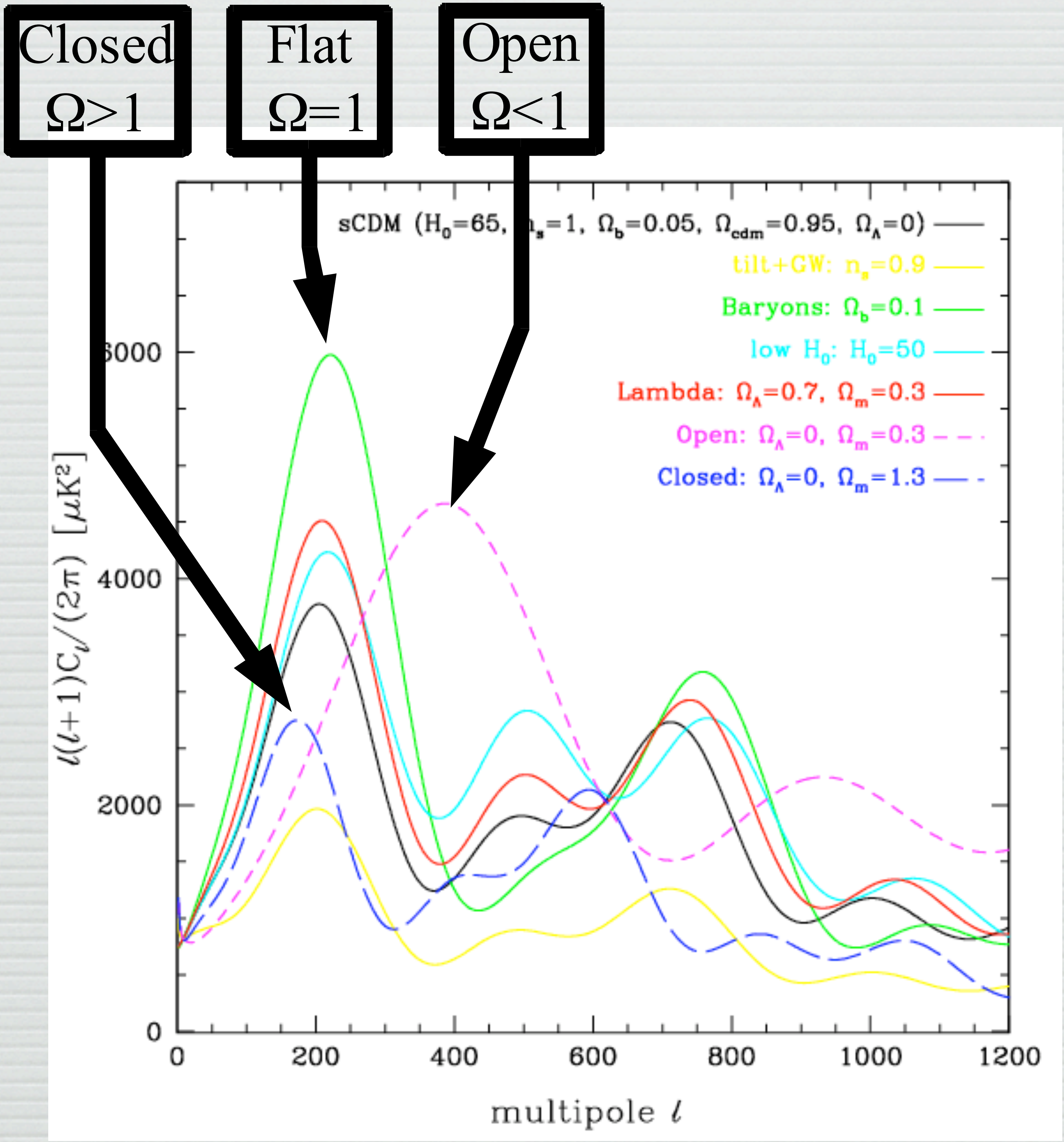




Measuring Curvature with the CMB



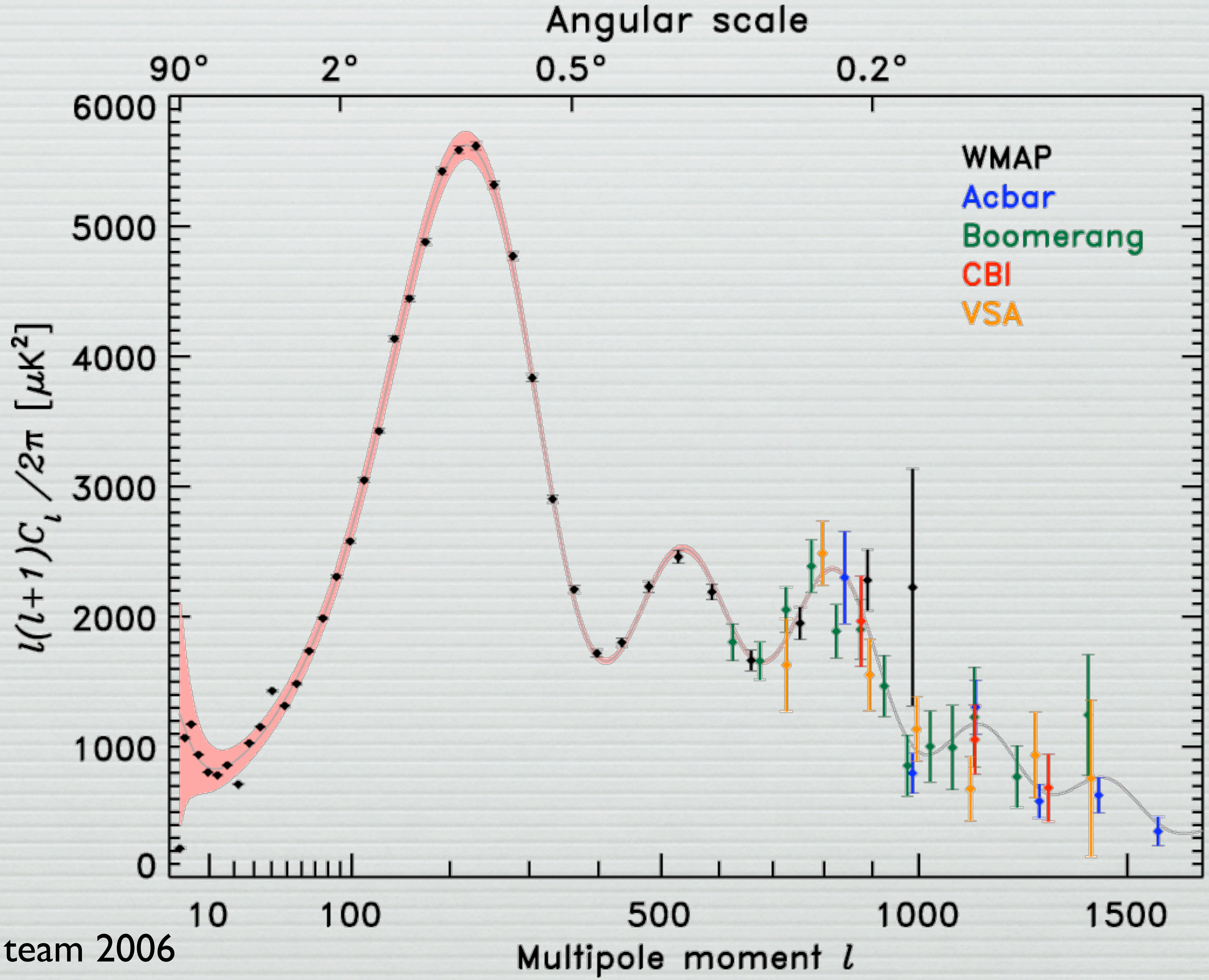




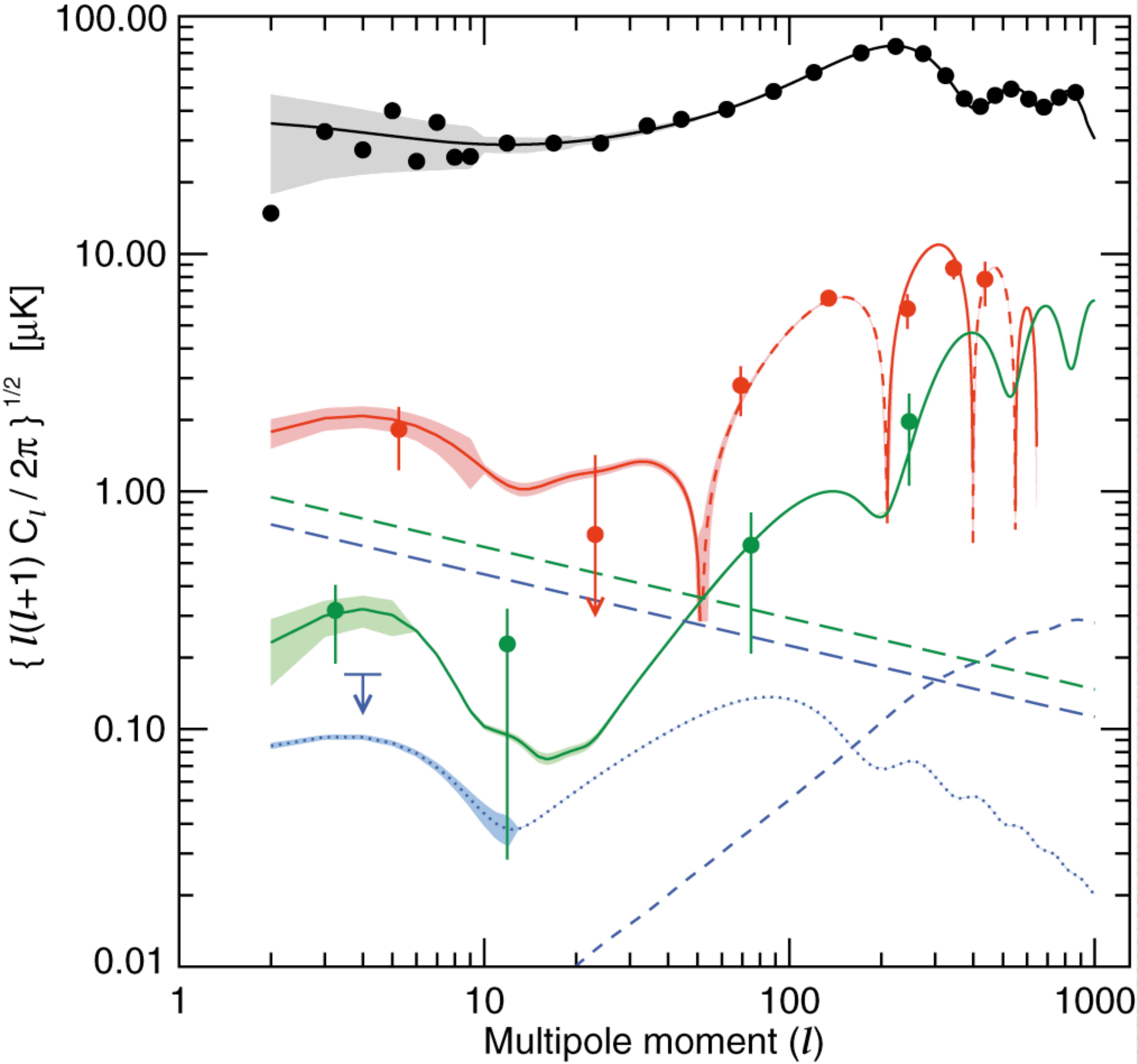
Closed
Ω>1
Flat
Ω=1
Open
Ω<1
sCDM (H0=65, ns=1, Ωb=0.05, Ωcdm=0.95, ΩΛ=0)
tilt+GW: ns=0.9
Baryons: Ωb=0.1
low H0: H0=50
Lambda: ΩΛ=0.7, Ωm=0.3
Open: ΩΛ=0, Ωm=0.3
Closed: ΩΛ=0, Ωm=1.3
6000
4000
2000
0
ℓ(ℓ+1)Cℓ/(2π) [μK²]
0
200
400
600
800
1000
1200
multipole ℓ

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



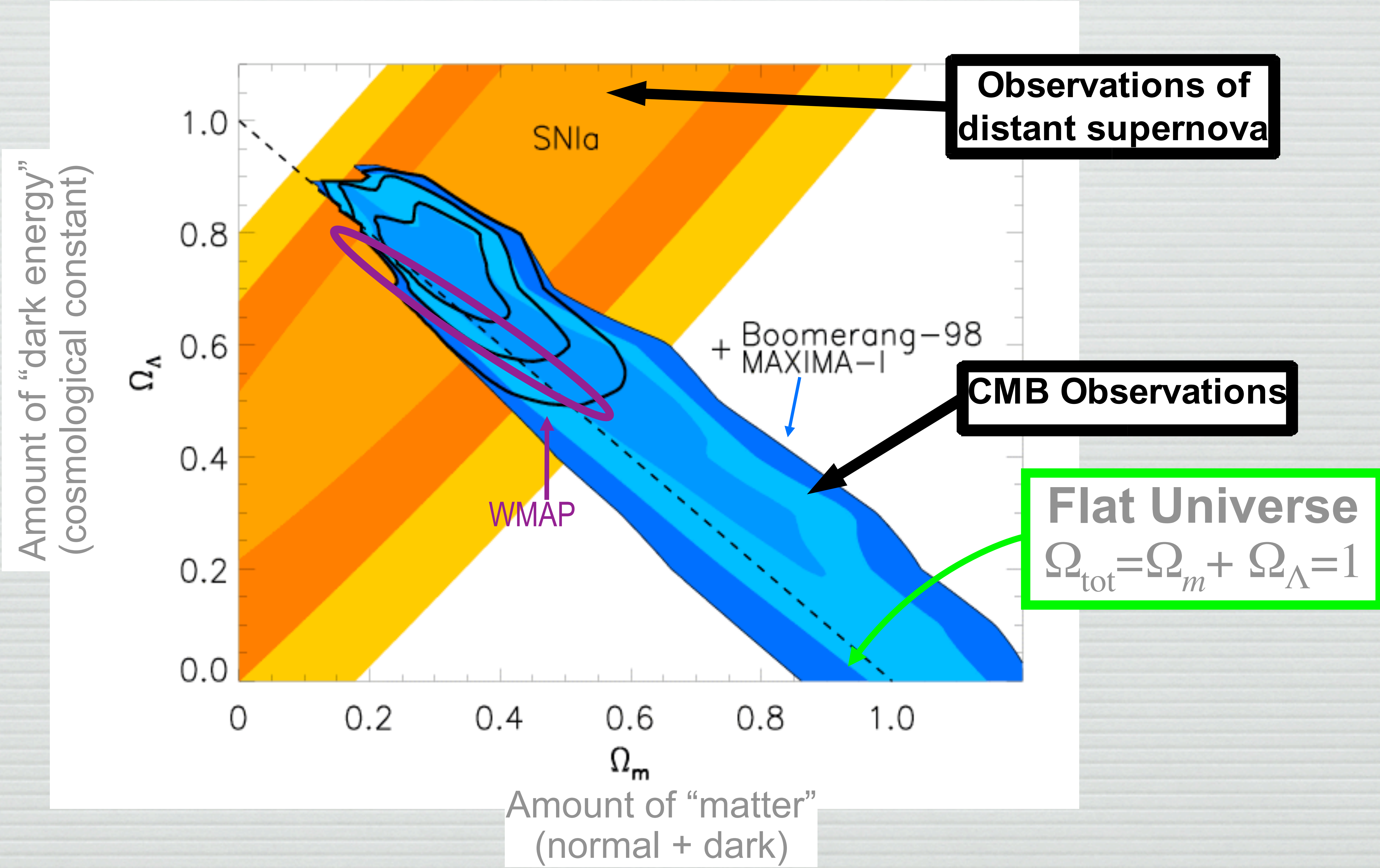
Temperature /Temperature

Temperature/ Polarization

Polarization / Polarization

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

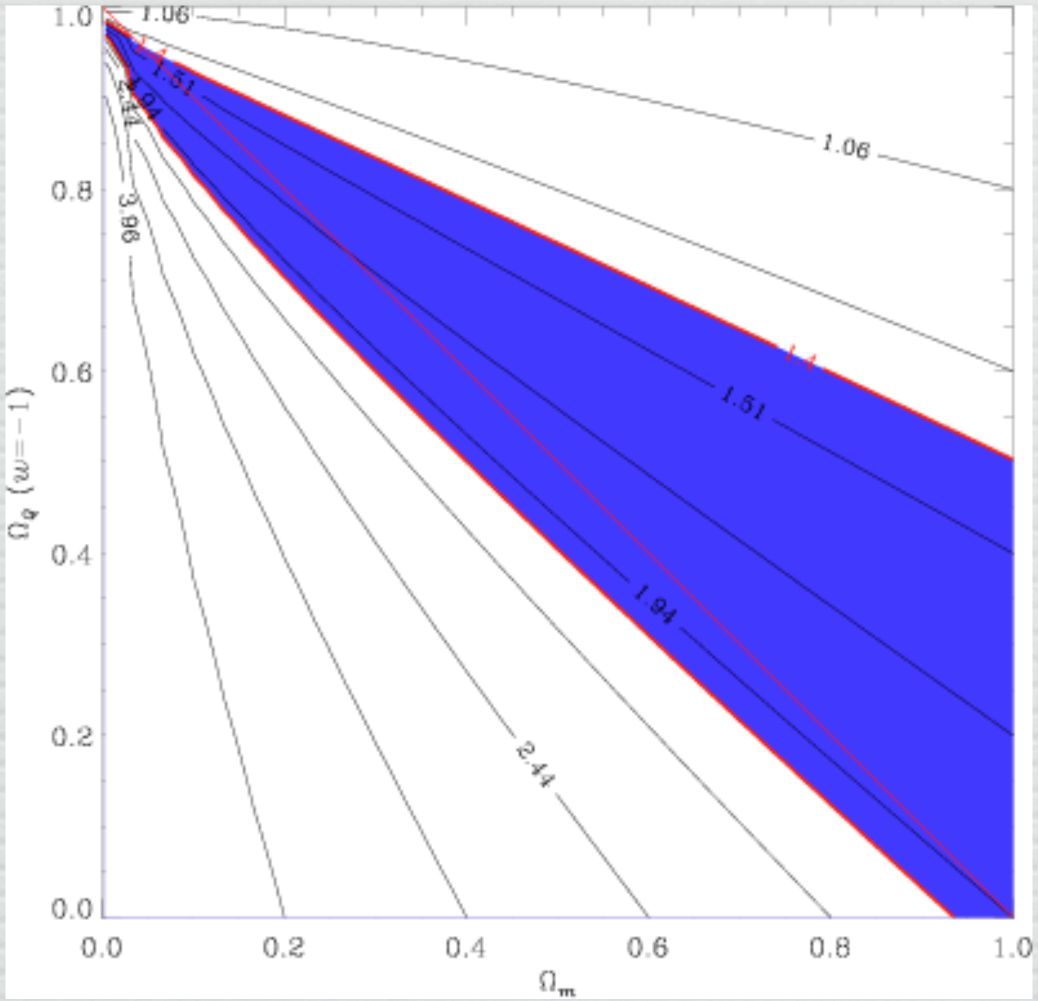
Measuring the geometry of the Universe

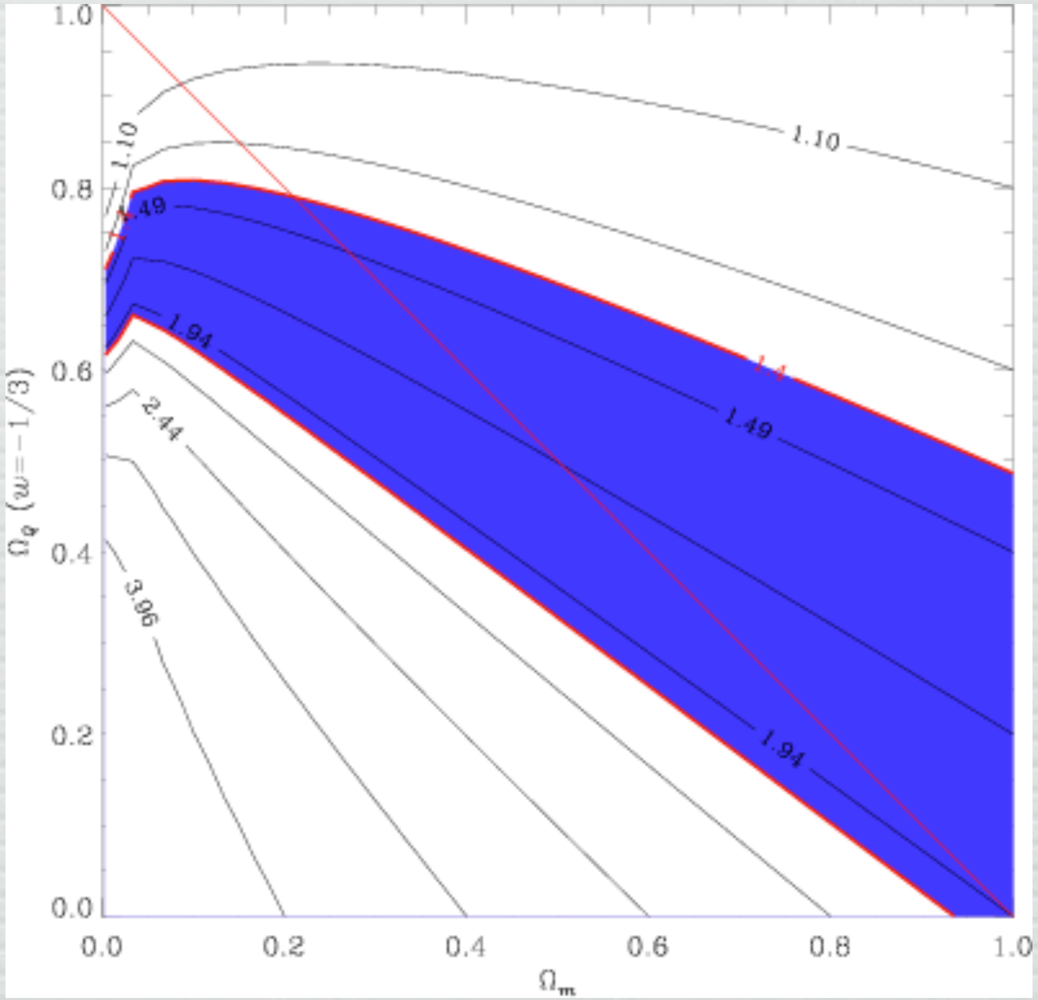


The CMB & Dark Energy

$W = -1$ (Λ)

$w = -1/3$ ("quintessence")

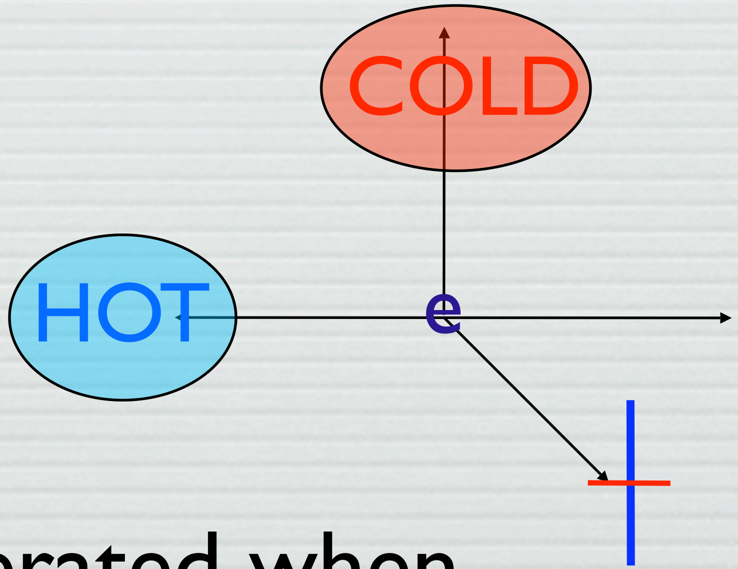




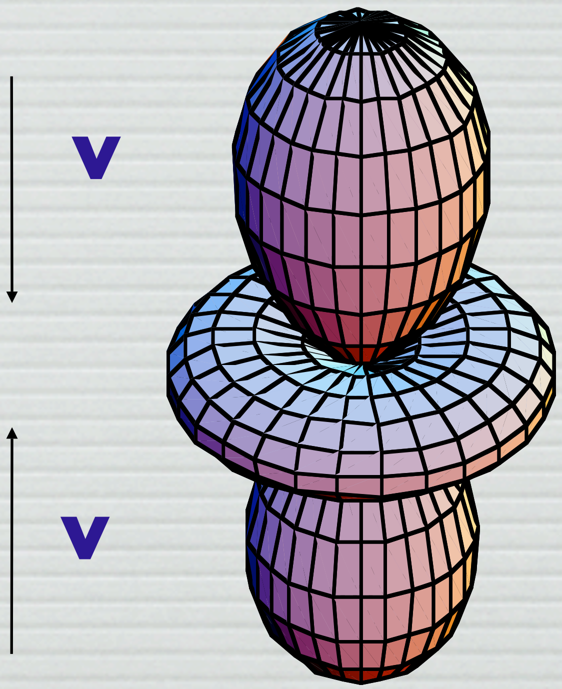
- CMB alone ~insensitive to equation of state

CMB Polarization: Generation

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



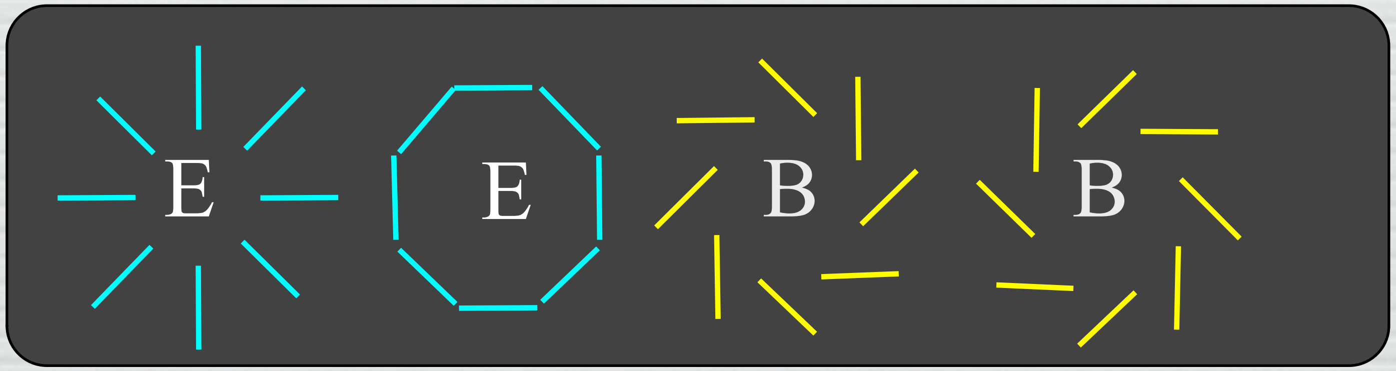
- Unlike intensity, only generated when ionization fraction, $0<x<1$ (*i*.e., during transition)



- Scalar perturbations: traces ~gradient of density (like velocity)

CMB Polarization: E/B Decomposition

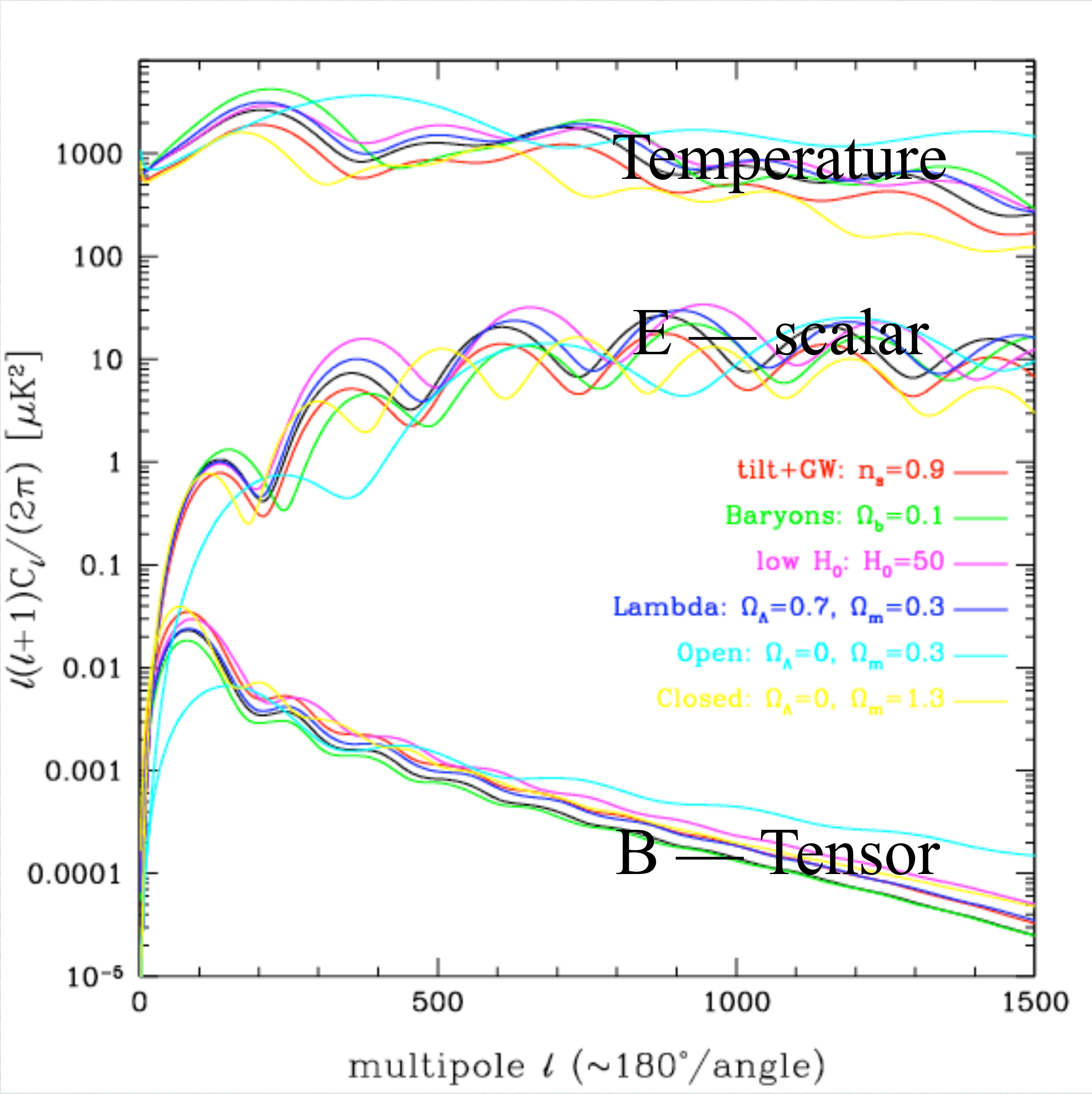
- 2-d (headless) vector field on a sphere
- Spin-2/tensor spherical harmonics
- grad/scalar/E + curl/pseudoscalar/B patterns



- NB. From polarization pattern ⇒ E/B decomposition requires integration: *non-local*
  - (data analysis problems)

Polarization from Gravitational Radiation

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



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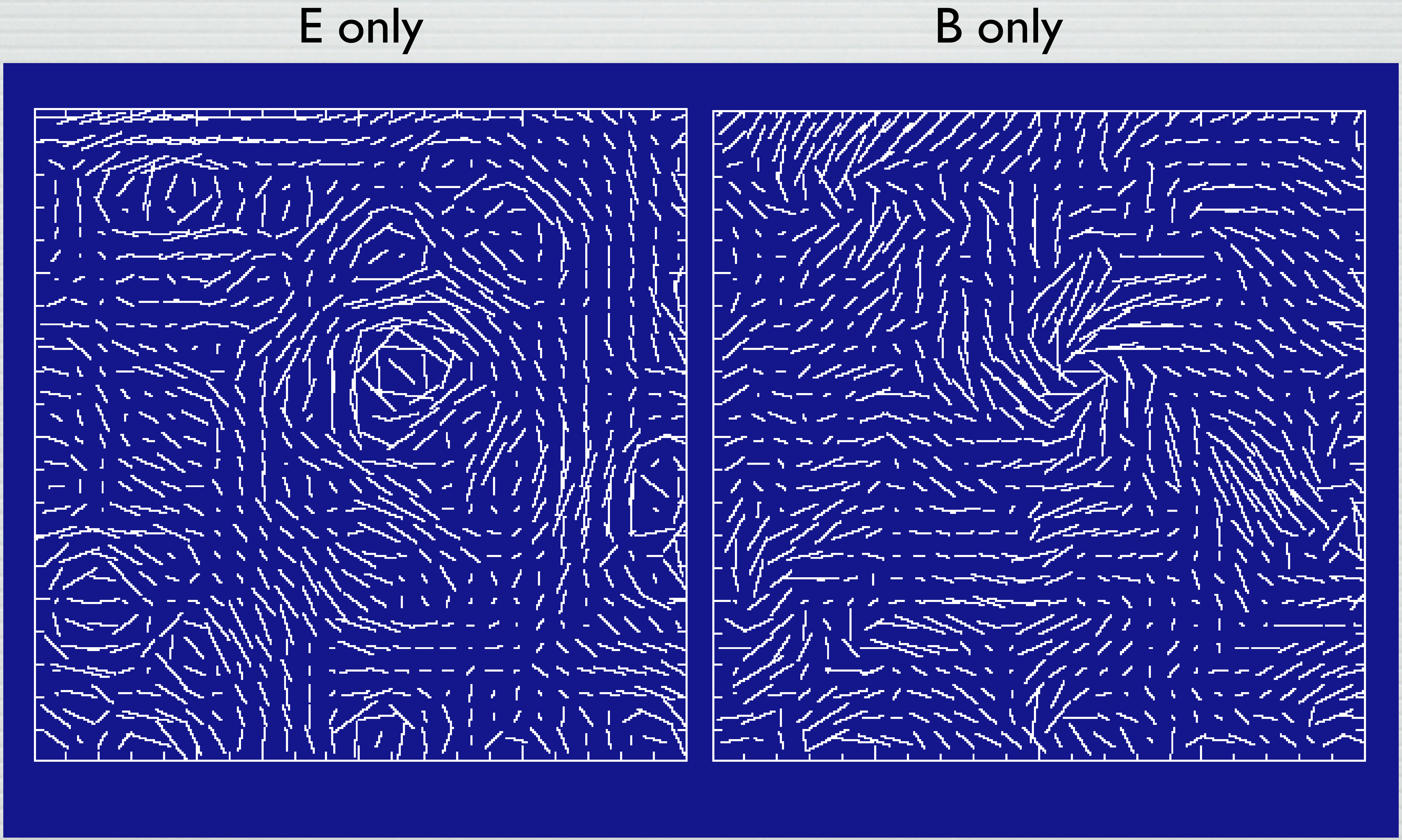


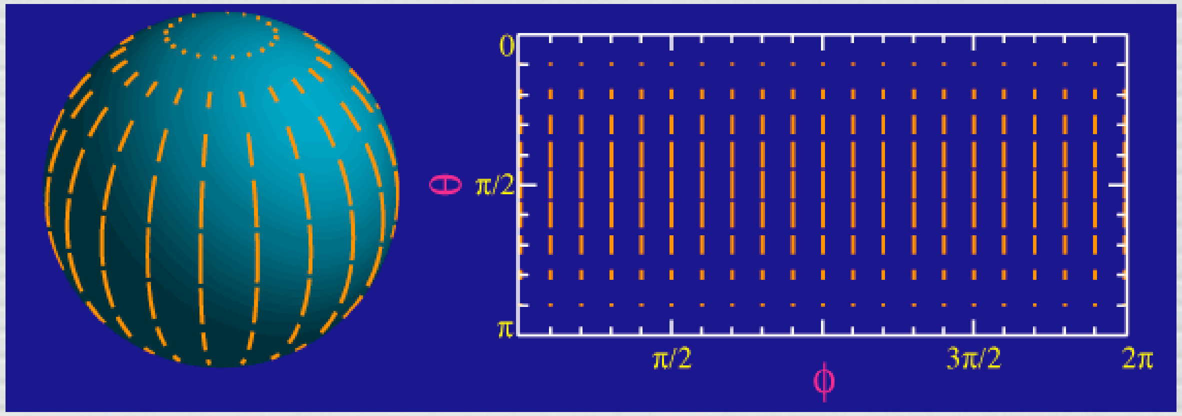
W. Hu

CMB Polarization: Spectra

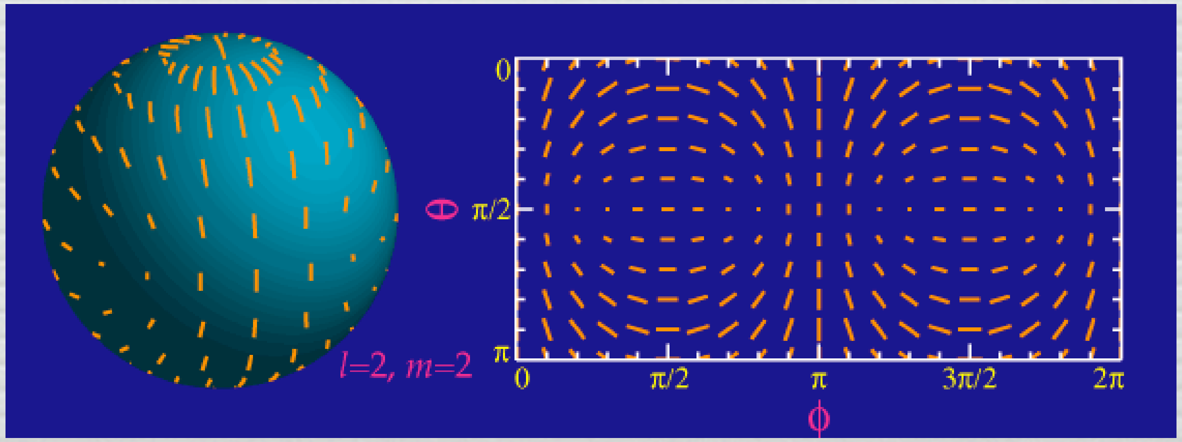
- $\langle EB \rangle = \langle TB \rangle = \langle \mathrm{scalar.pseudo} \rangle = 0$ by parity
- Density (scalar) plane waves
  ⇒ *aligned* quadrupole perturbations

  ⇒ *E* polarization

  (& $\langle TE \rangle$ correlation)



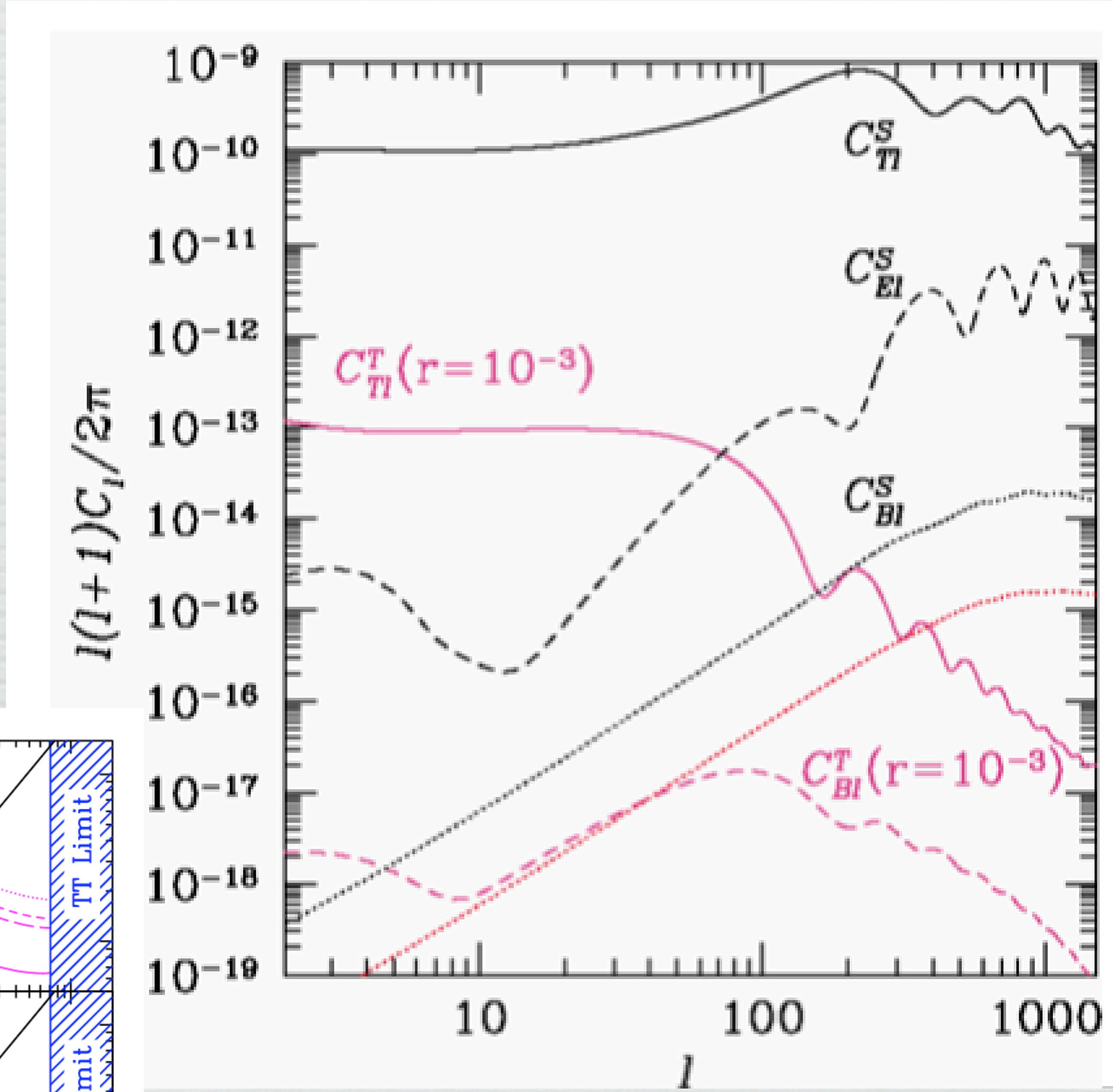
- Gravity (tensor) waves
  ⇒ *E* + *B* polarization

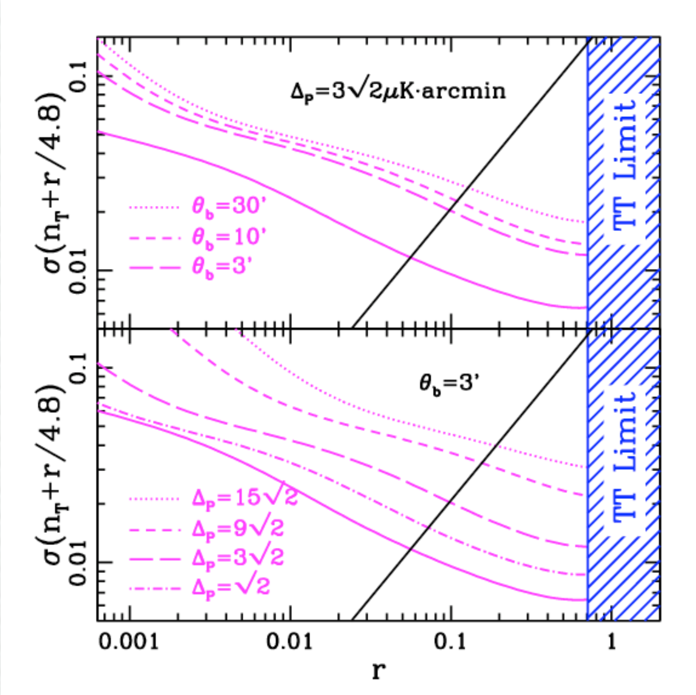


Diagrams courtesy W. Hu

Inflation, Gravitational Radiation and Polarization: Overview

- Energy scale of Inflation
  → amplitude of tensor fluct'ns
  → amplitude of B ($\propto V$)
  - detectable if $V > 10^{15}$ GeV
- Inflationary potential (slow roll)
  → scalar and tensor spectra
  $r > 10^{-5}$ detectable
  (but see e.g., Tucci et al 05)
- Consistency relations:
  e.g., $n_t = -r/8$
  - details accessible if $r > 0.01$
    [e.g., Song & Knox 2003]



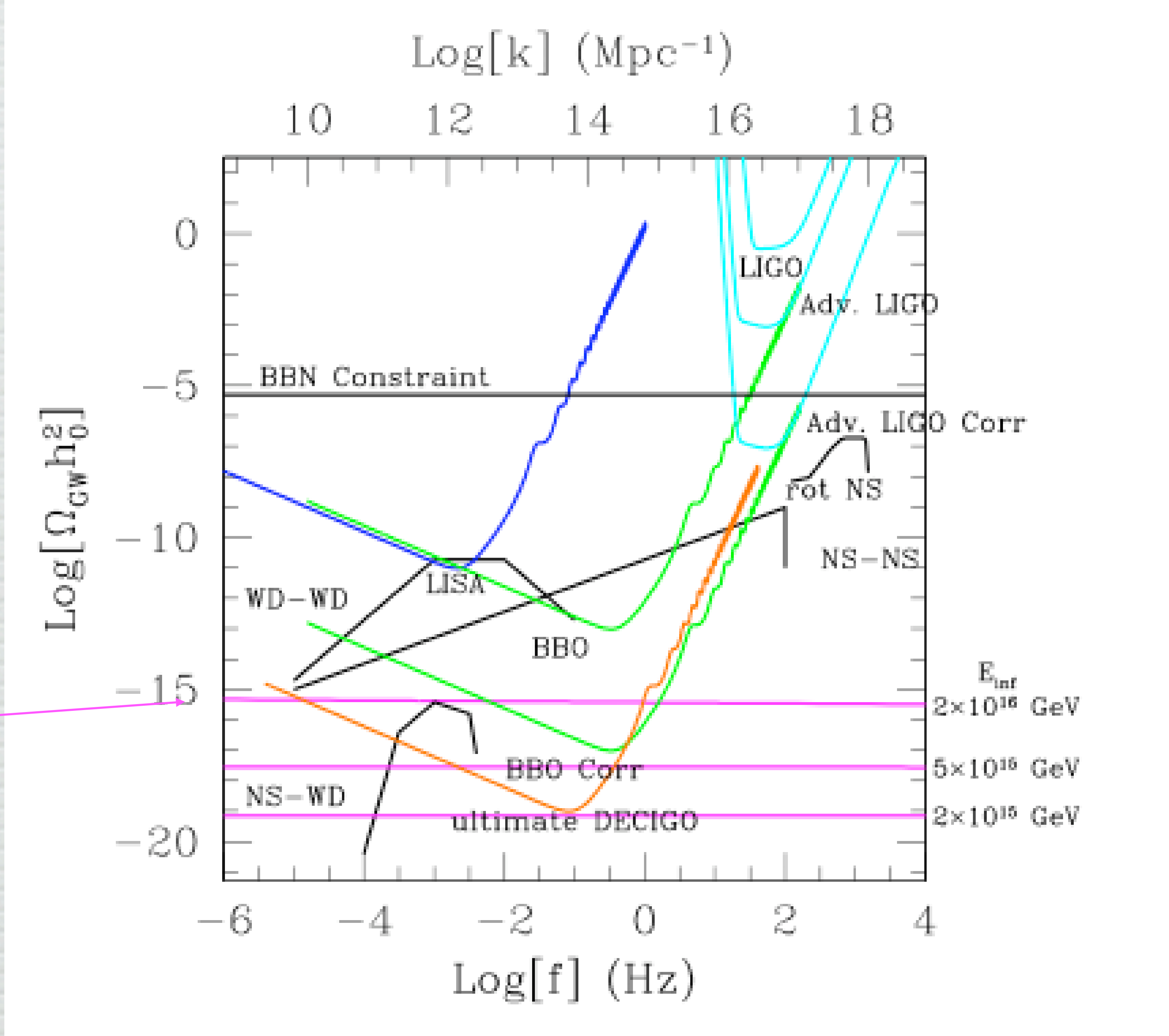


Gravitational Radiation from Inflation

- Gravitational radiation produced during inflation
  - same QM processes as density perturbations
- Characterized by ratio of amplitudes of tensor perturbation power (GWs) to scalar power (density), $r=T/S$
  - ⇒Energy scale of inflation: $V^{1/4}/M_{Pl} \approx 3\times 10^{-3} r^{1/4}$
  - In single-field, "slow-roll" models, *r* is further related to the scalar and tensor spectral indices:
  - $P_T(k) \propto k^{n_T}$ $P_S(k) \propto k^{1-n_s}$

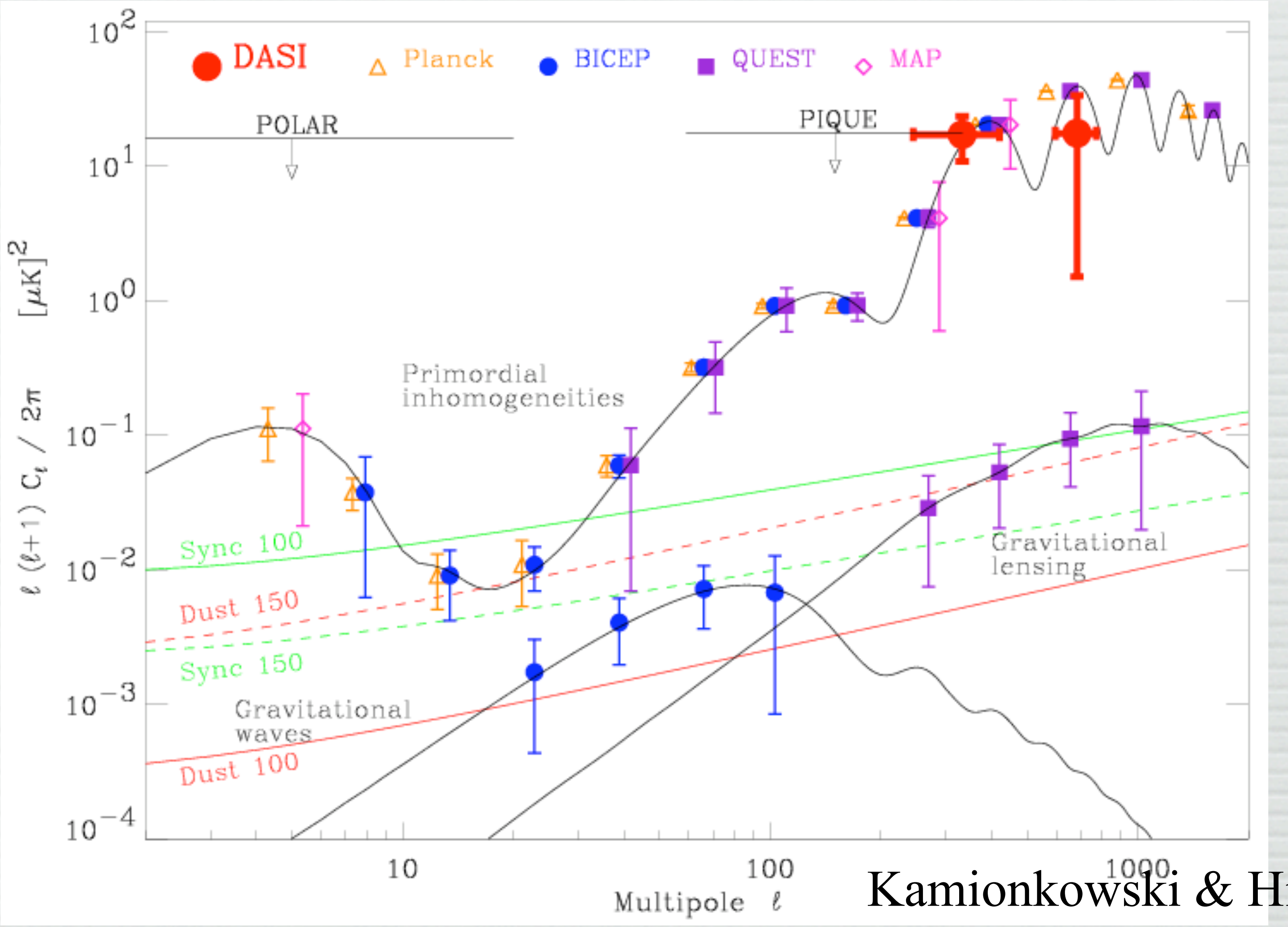
Gravitational Radiation from Inflation

Current CMB limit
(extrapolated from 10^{-16} Hz!)



Cooray 04

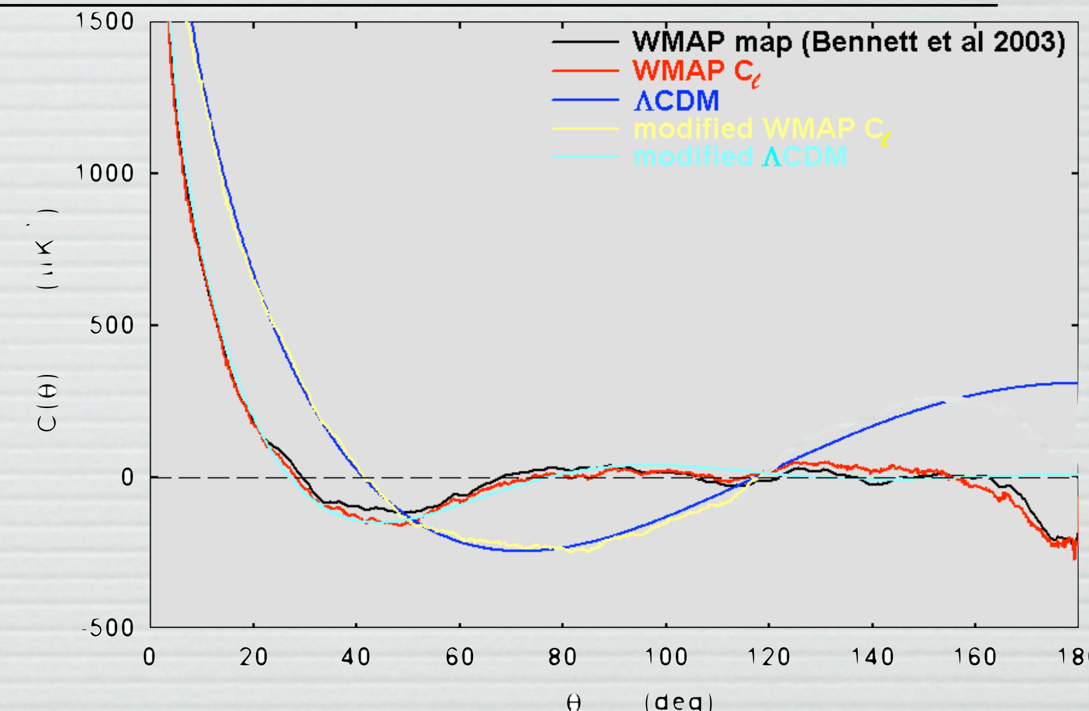
Further in the future?



Kamionkowski & Hivon 2003

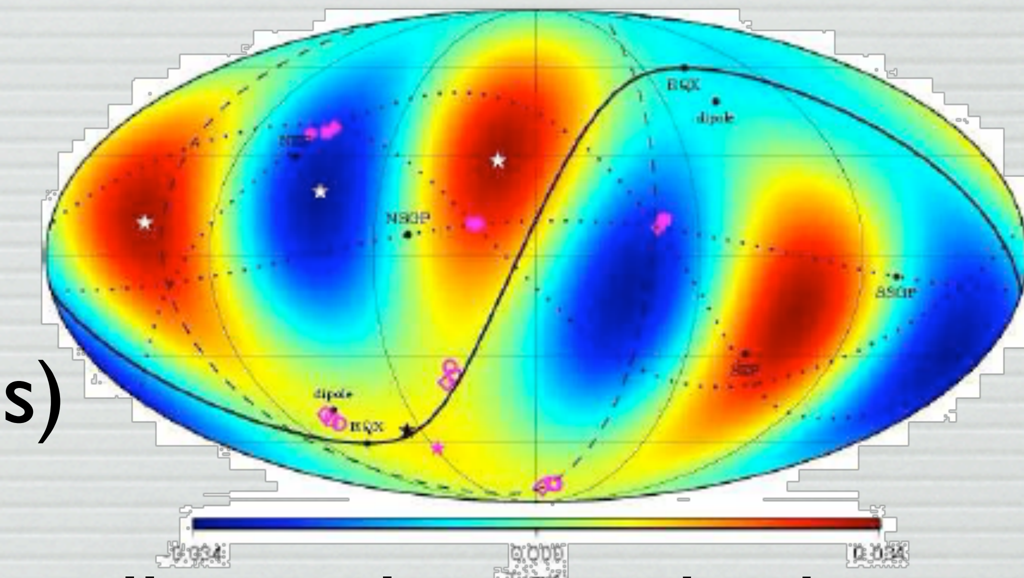
- Primordial Gravitational Radiation (e.g., from Inflation) generates B (Curl) modes; scalar (density) fluctuations only generate E (grad) modes
- Crucial foreground signal from gravitational lensing via intervening structure: generates B modes, masks GW signal

Anisotropy (from topology?)



8 C.J. Copi, D. Huterer, D.J. Schwarz and G.D. Starkman

- Low power at large scales?
- 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)
  - Possible apparent non-Gaussianity
- Effects only present at large scales – at smaller scales standard ΛCDM power spectrum recovered
- (Luminet et al "Soccer Ball" [Dodecahedron/Poincaré] universe?)

Anisotropy (from topology?)

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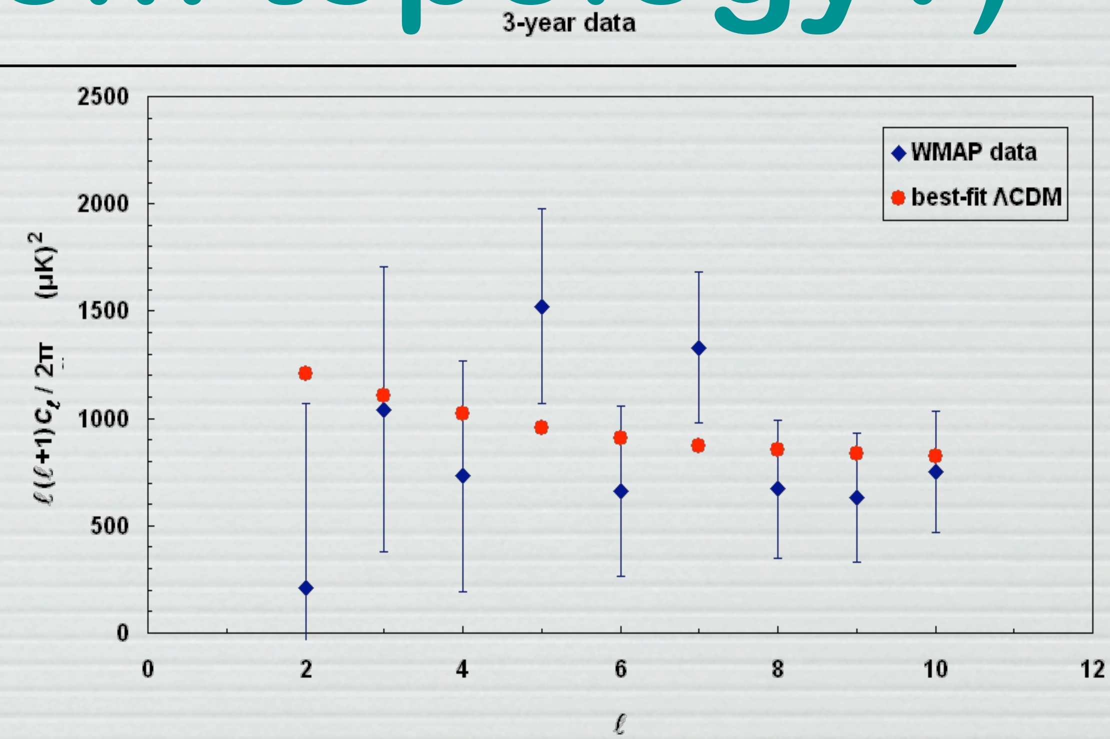
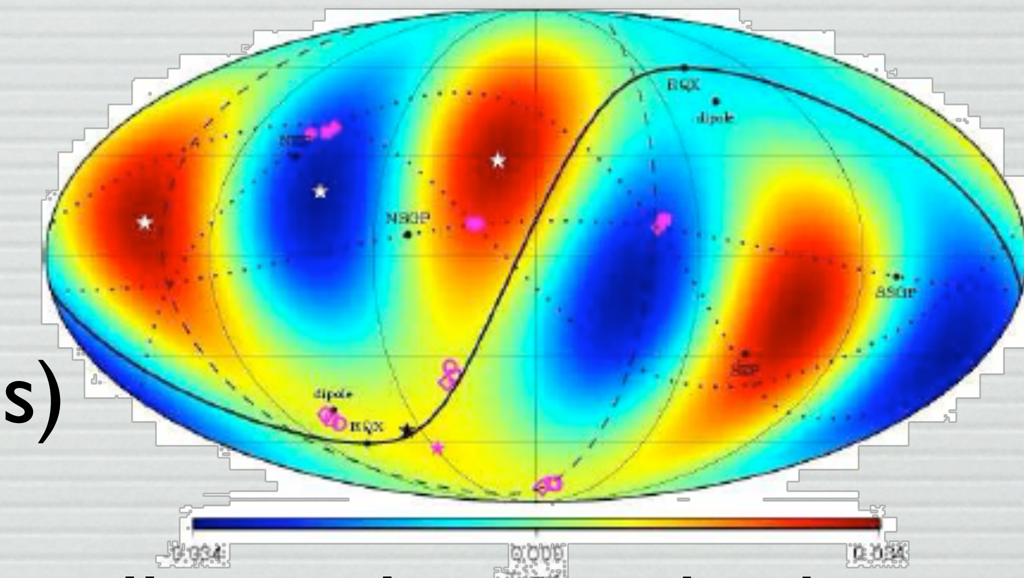
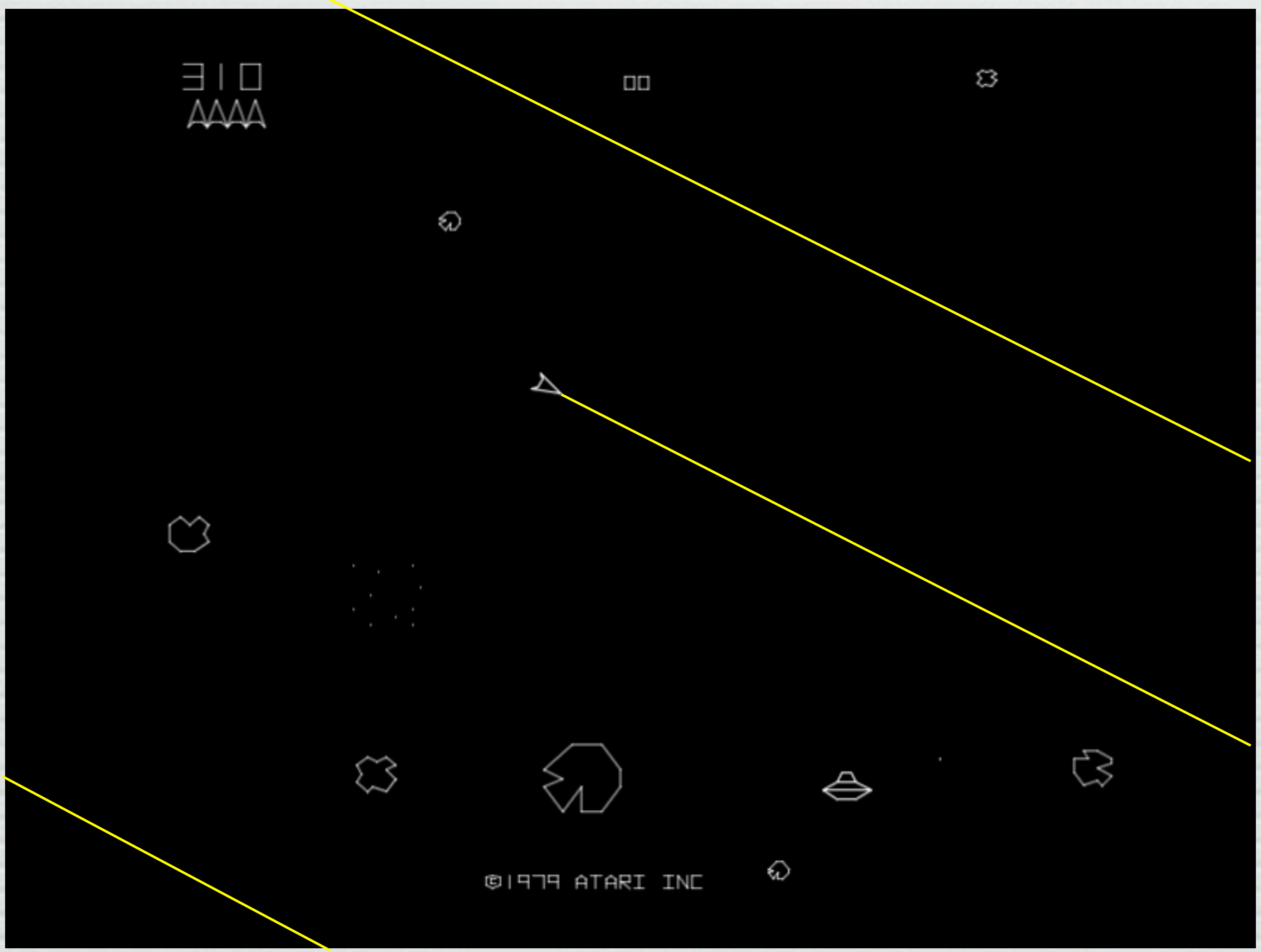


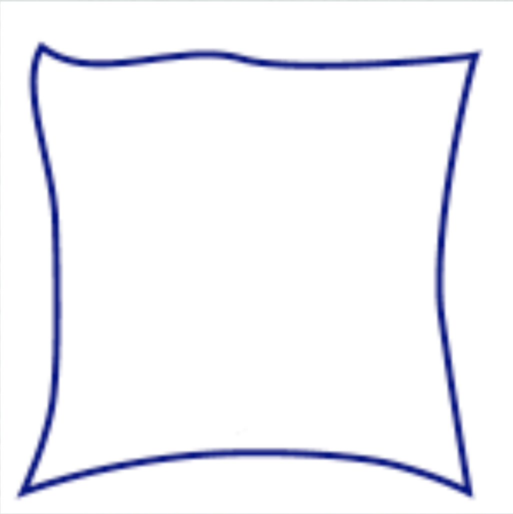
8 C.J. Copi, D. Huterer, D.J. Schwarz and G.D. Starkman

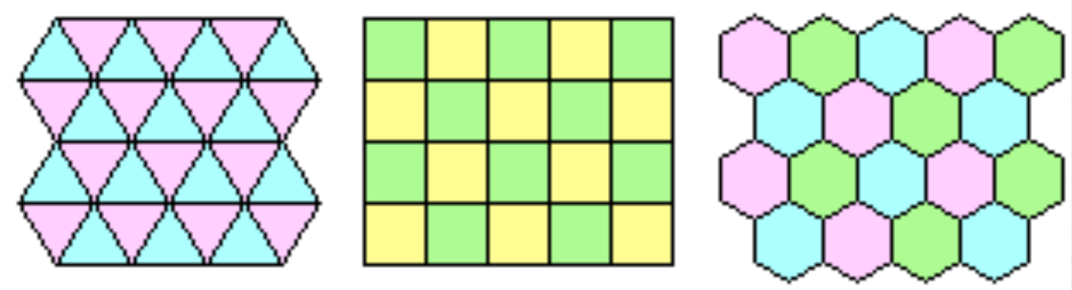


- Intrinsic anisotropy (orientable manifolds)
  - Possible apparent non-Gaussianity
- Effects only present at large scales – at smaller scales standard ΛCDM power spectrum recovered
- (Luminet et al "Soccer Ball" [Dodecahedron/Poincaré] universe?)

Topology in a flat "universe"







"tiling the plane"

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

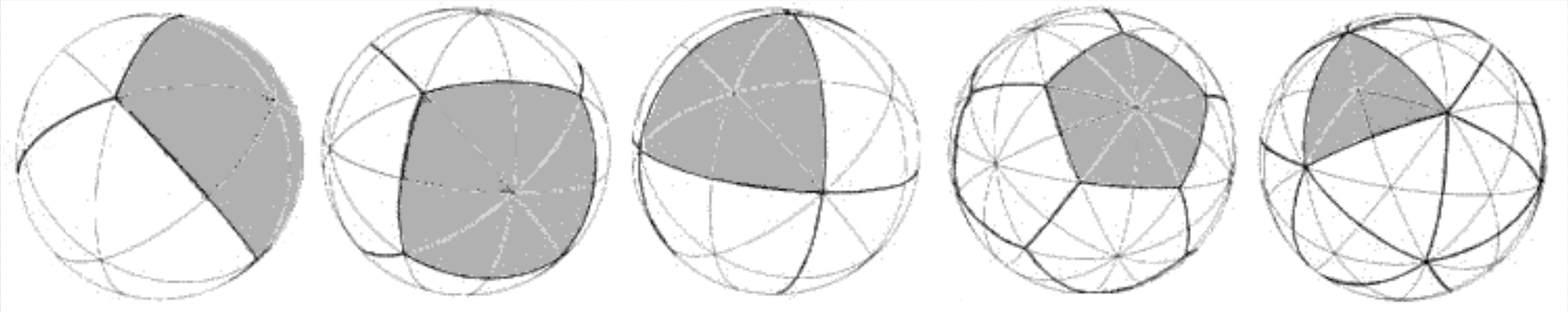
Geometry and Topology

- 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").

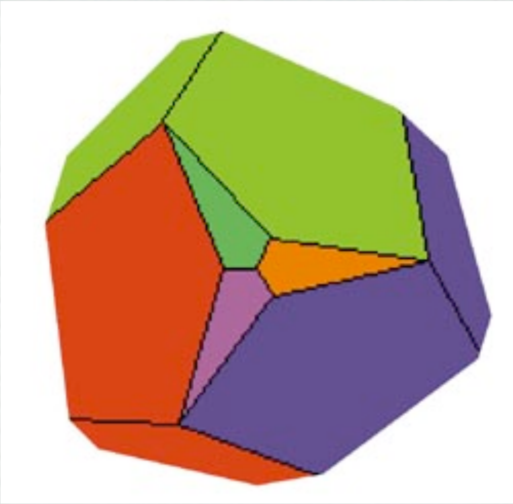
Topology + geometry



- Tile the 2-sphere with different fundamental domains

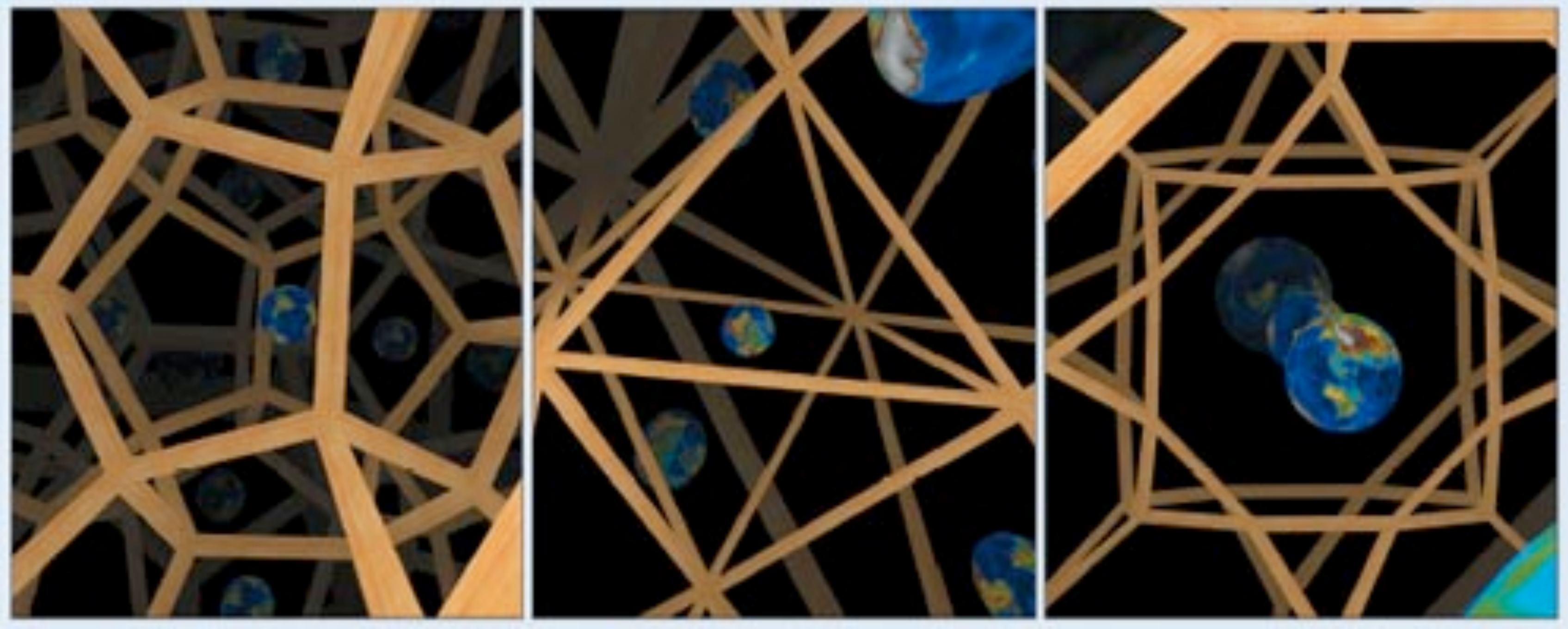
- Can also tile an open (hyperbolic) universe
  - (Souradeep et al)

http://www.sciencenews.org/pages/sn_arc98/2_21_98/bob1.htm



Topology in 3-d

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



Model Comparison

- Model posteriors: marginalize over all parameters

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

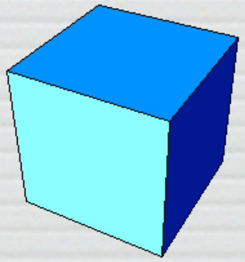
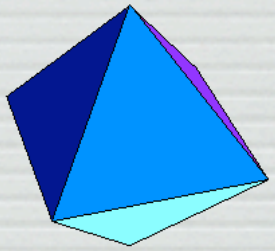
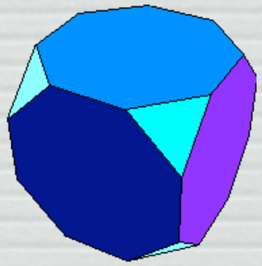
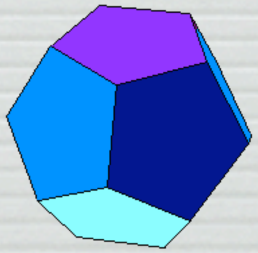
$$\frac{P(m|DI)}{P(n|DI)} = \underbrace{\frac{P(m|I)}{P(n|I)}}\ \underbrace{\frac{P(D|I_m)}{P(D|I_n)}}$$

depends on prior Information for whole model

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

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

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
$Y_{\beta \ell m}$	$Y^s_\beta = \sum_{\ell=0}^{\beta-1} \sum_{m=-\ell}^{\ell} \xi^s_{\beta\ell m} Y_{\beta\ell m}$
$a_{\ell m} = i^\ell \int d\beta\, \beta^2 \sqrt{P(\beta)}\Delta_\ell(\beta)\varepsilon_{\beta\ell m}$	$a_{\ell m} \propto \sum_\beta \sqrt{P(\beta)}\Delta_\ell(\beta) \sum \xi^s_{\beta\ell m}\varepsilon_{ks}$
$\langle a_{\ell m} a_{\ell' m'} \rangle = C_\ell \delta_{\ell\ell'}\delta_{mm'}$	$\langle a_{\ell m} a_{\ell' m'} \rangle = C^{\ell' m'}_{\ell m}$ $\quad C_\ell \equiv \sum_m C^{\ell m}_{\ell m}$

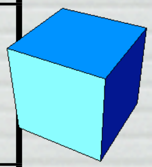
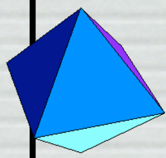
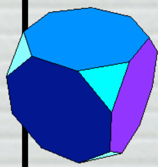
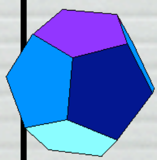
Model Comparison

- 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

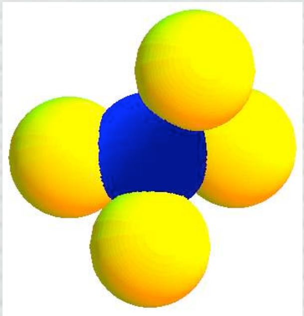
- This is a topology-specific test (cf. "circles-in-the-sky" which purports to be more generic)
  - Difficult (impossible?) to test when (topology scale)>>(Hubble scale)

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	$\ll 1$

Anisotropy & non-Gaussianity: the future

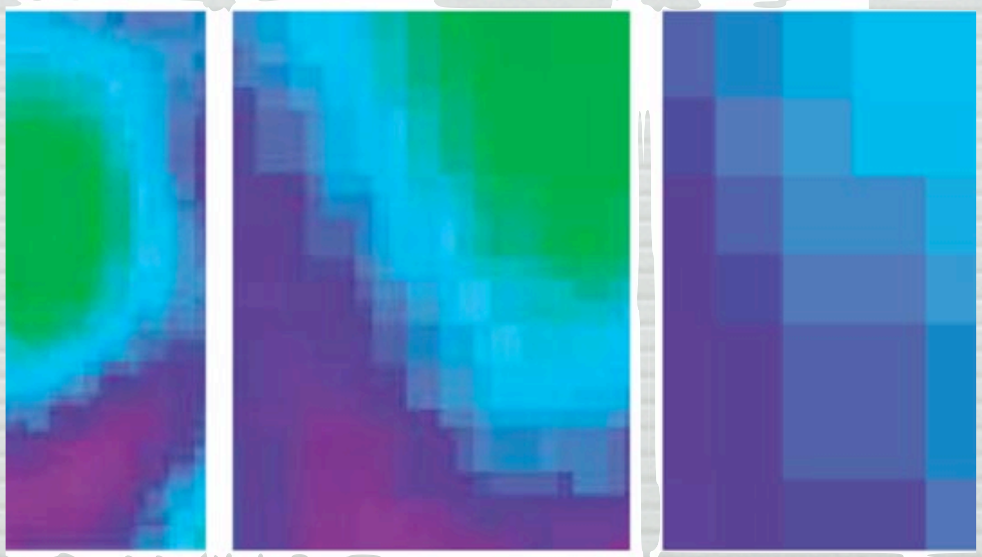
- Limits on *specific topologies* via marginalization
  - Next: expand to *polarization* predictions
- Generic topologies harder to find
  - infinitely-large parameter space...
  - non-Bayes techniques e.g., "Circles-in-the-sky"



- Generalize to search for anisotropy
  - e.g. Hajian & Souradeep
  - Specific models: Bianchi (T. Jaffe et al)
- ... and non-Gaussianity
  - e.g., f_{NL} parameterizes higher-order contributions
    - expect f_{NL} ~1, ultimately sensitive to f_{NL} ~few (?)
    - (& see new work from Yadav & Wandelt for better detection methods?)

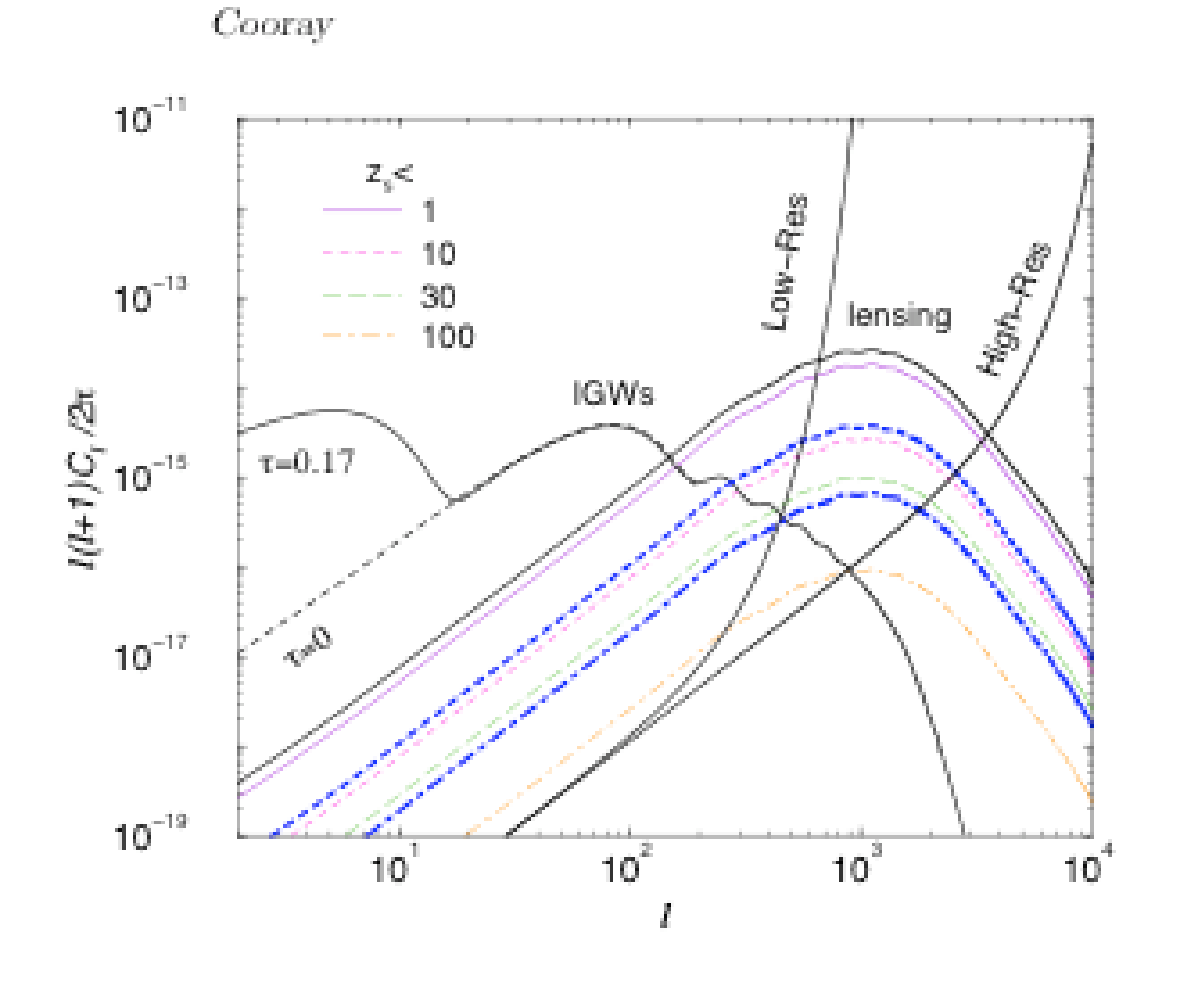
really exotic physics

- Parity violation in the early universe
  - helicity induces EB, TB correllations
  - (Kahniashvili; Alexander)
- holography: information quantization (Hogan)
  - discrete spacetime
  - AdS-CFT correspondence and information bounds
  - 10^{120} bits in observable Universe back to Planck epoch
    - inflation could reduce this to 10^{10}!!



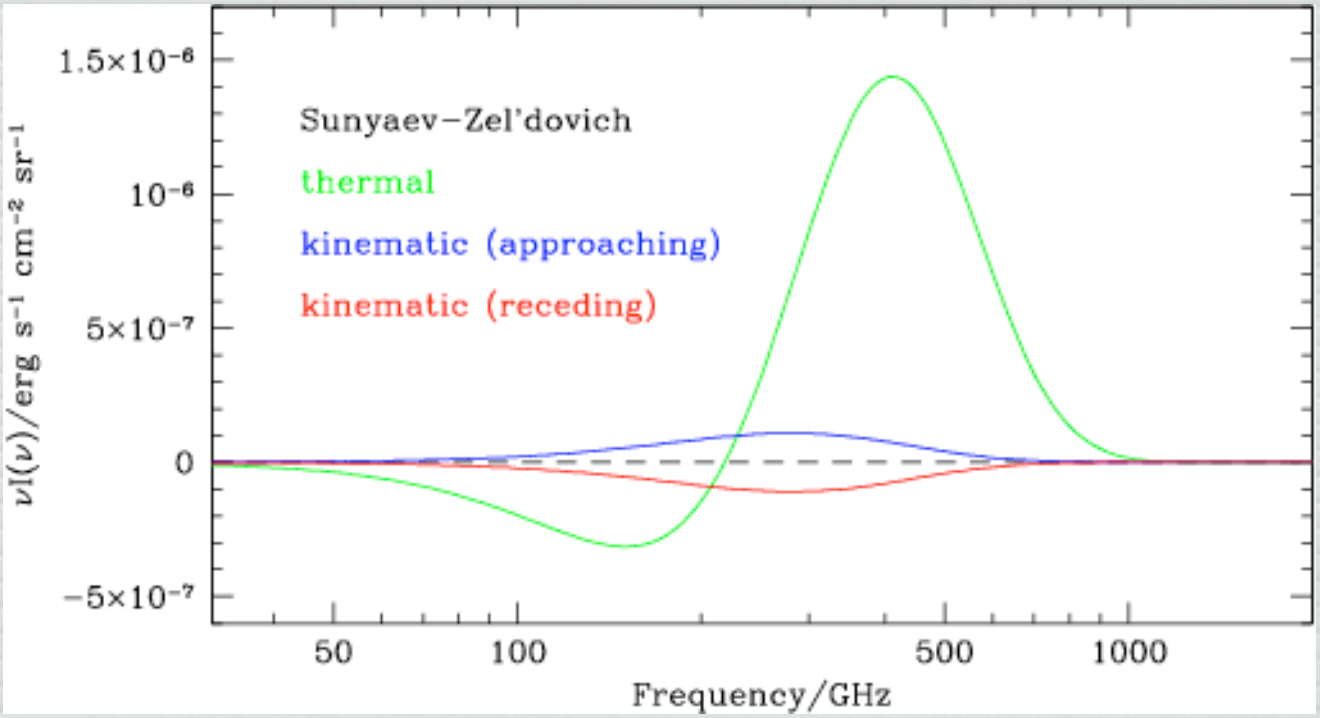
Confusion from gravitational lensing

- Can clean with detailed knowledge of projected density along line of sight to LSS (Lewis; Knox & Song)



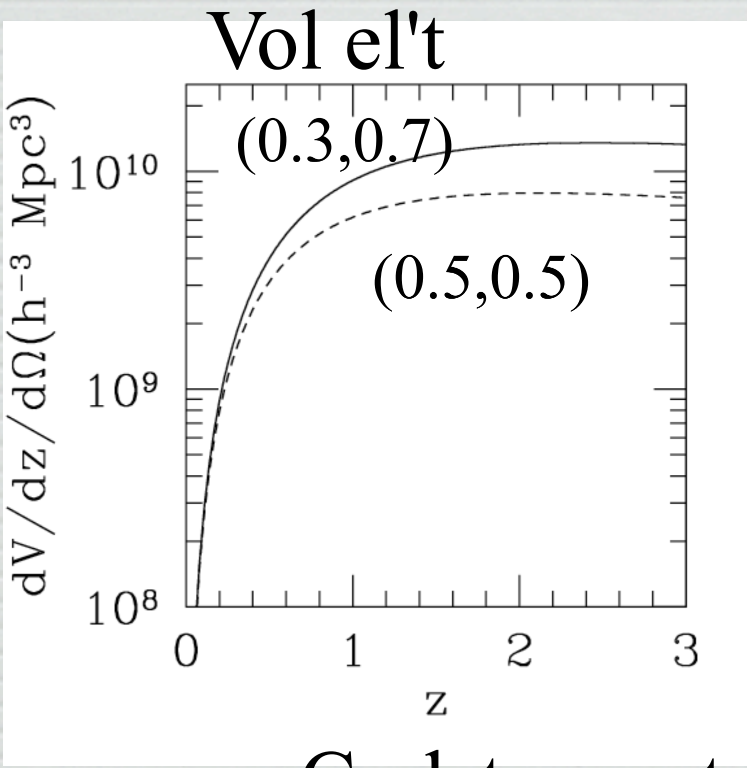
Clusters and SZ

- Cluster distances: Hubble Diagram
  - SZ decrement [$\int n_e$] & X-Ray Temp [$\int n_e^2$] : size → Distance Indicator
- Cluster Baryon fraction
  - (SZ gas mass) / (X-Ray or Lensing: total mass) → Ω_b/Ω_m
- Cluster density: growth of structure
- Predictions:
  - Press-Schechter (++)
  - primordial P(k) & cosmological parameters ⇒ number density of mass peaks (i.e., clusters, galaxies, ...)



Cluster abundances

- Clusters – very massive
- tail of Mass distribution
- numbers exponentially sensitive to details
  (Press-Schechter formalism and extensions)



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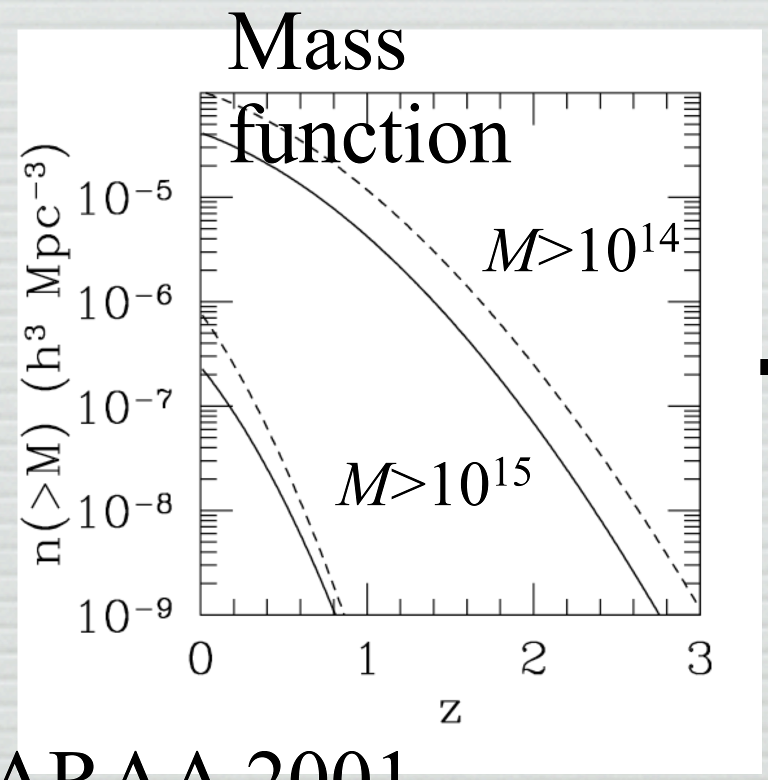
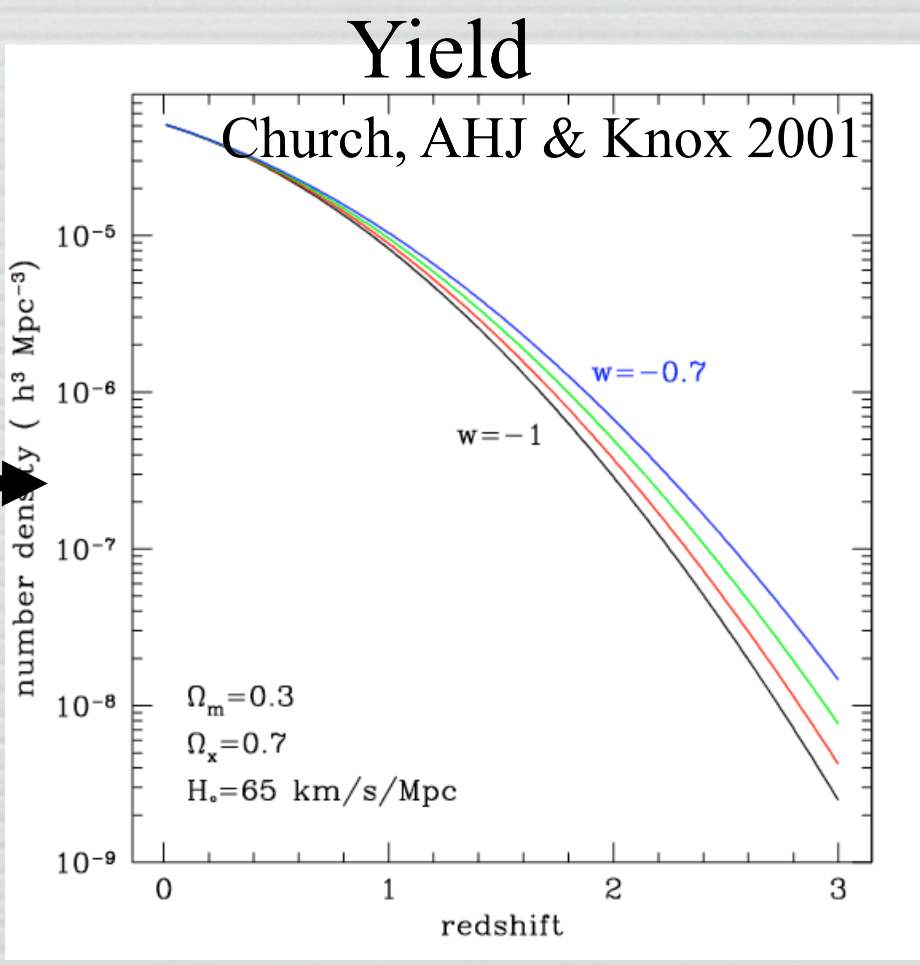


Carlstrom et al ARAA 2001

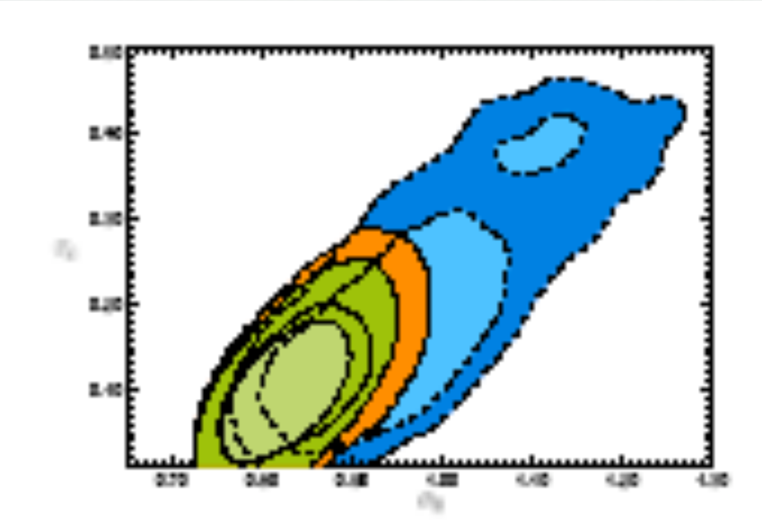
→



Polarization and reionization

- Universe [astrophysically] ionized again today
  - Damps primary oscillations: $\Delta T \rightarrow \Delta T\, e^{-\tau}$
  - Generates "second-order" perturbations at very small scales
    - Ostriker-Vishniac (1") / Sunyaev-Zel'dovich (Clusters)
  - New surface of 'last' scattering:
    - low *l* structure dominates *polarization*

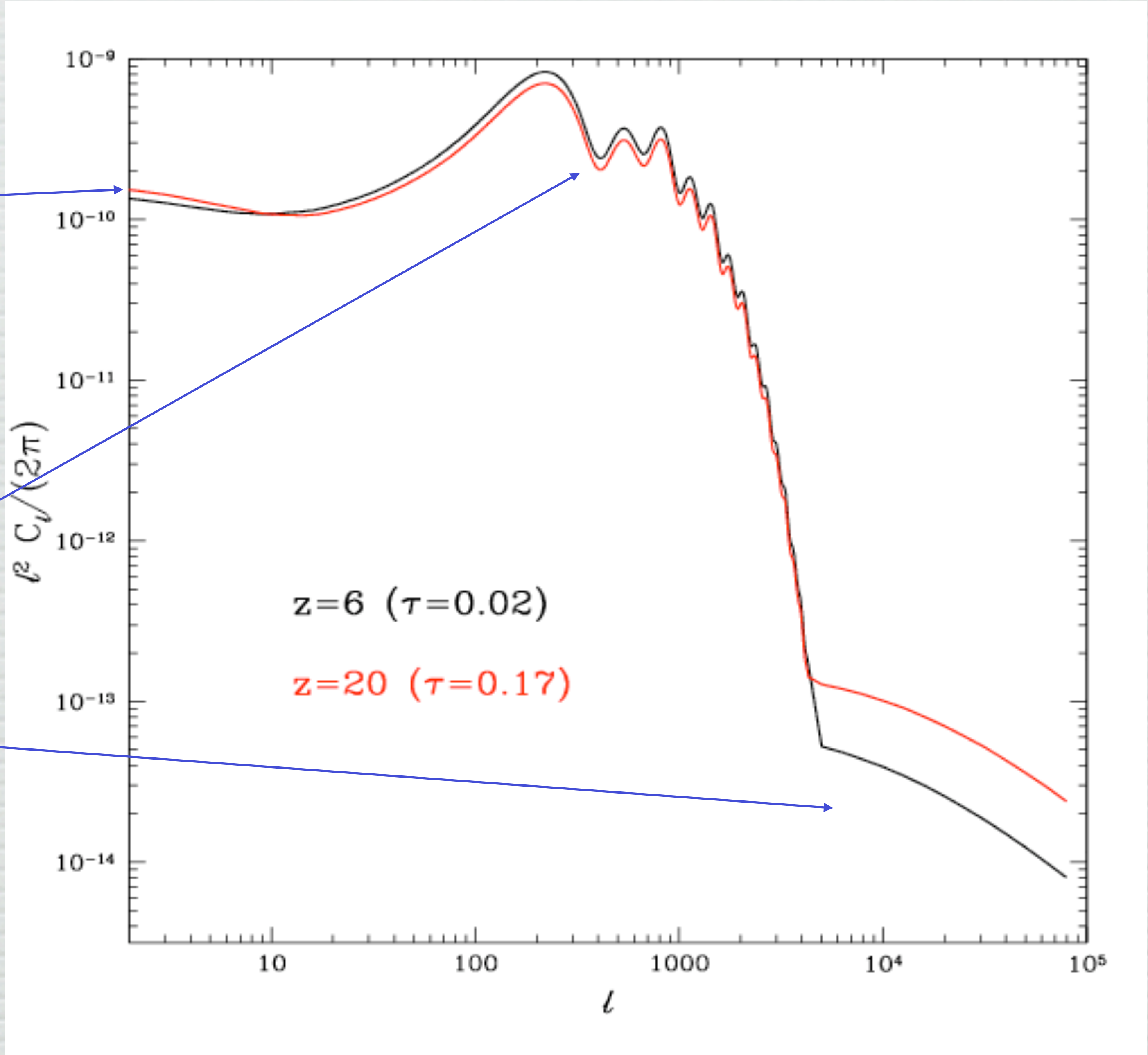
- WMAP: τ=0.17±0.06 $\rightarrow z_r$ = 20±5
  - all very prior-dependent:
    degenerate with n, running, …



Reionization and the CMB

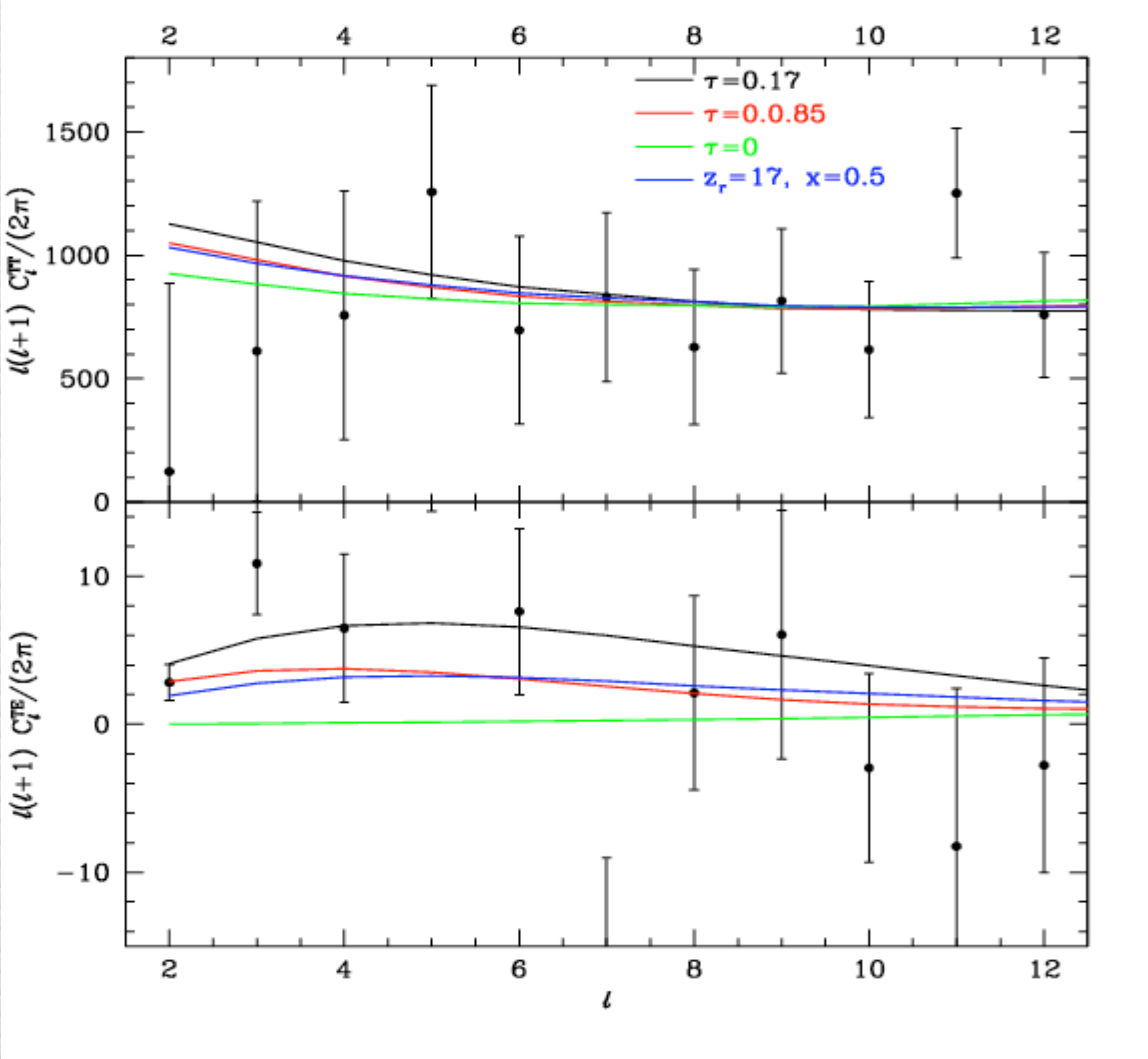
CMB/free electron
Thomson scattering

- Large scales: secondary scattering peak
  - Esp. polarization
- Intermediate scales: $e^{-\tau}$ damping
- Small scales: secondary effects coupling density & ionization (OV, SZ)
  - Esp temperature



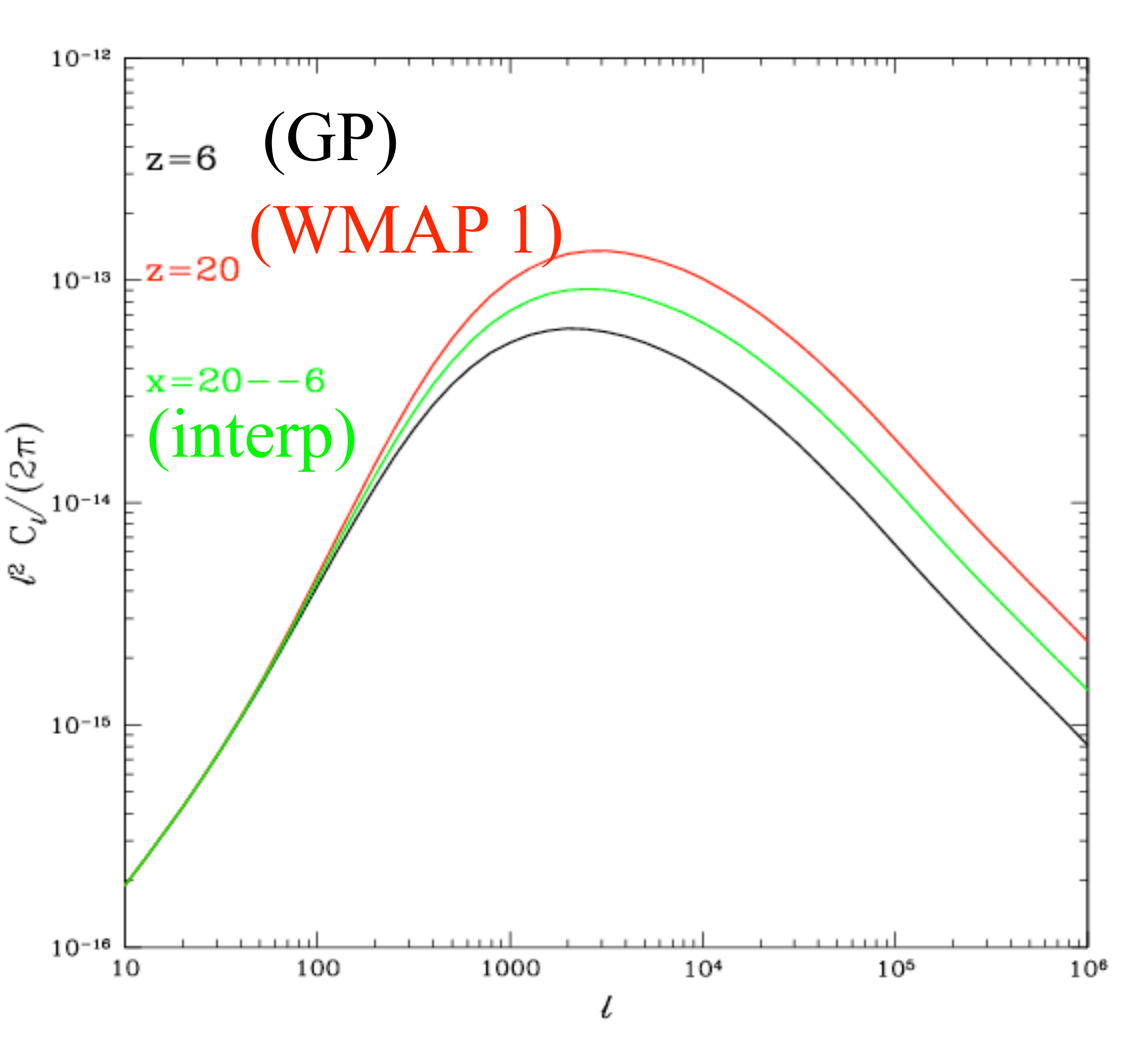
Large scales

- Generates new surface of "last" scattering
- Mild dependence on full ionization history, $x_e(z)$
  - z_{ri} shifts peak
  - e.g., Kaplinghat et al '04; Colombo '04 — Planck can distinguish x_e=1.0, 0.6



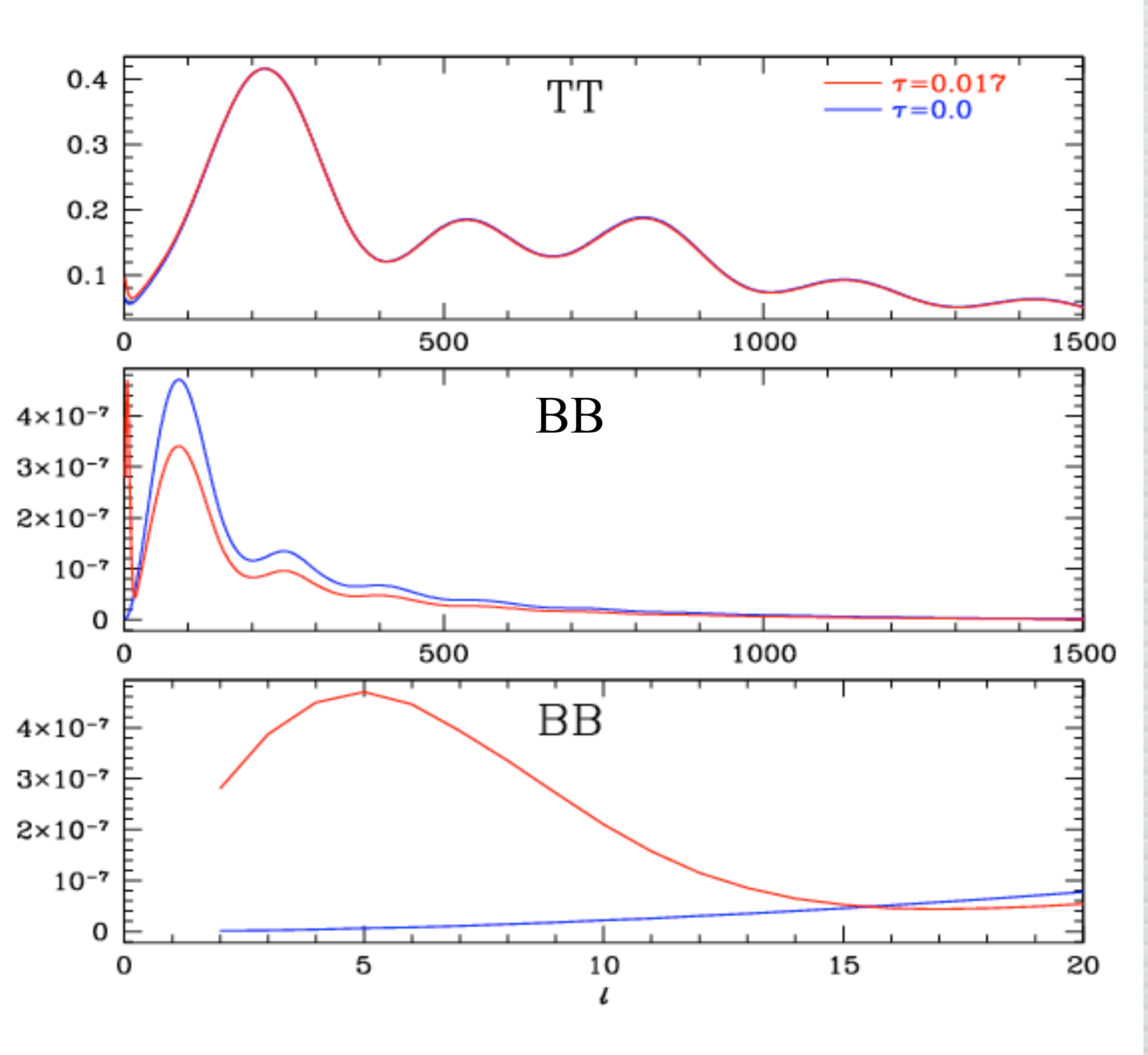
The Ostriker-Vishniac effect

- Dependence on the ionization history
  - (mostly optical depth, but some structure based on details — esp. in nonlinear regime)



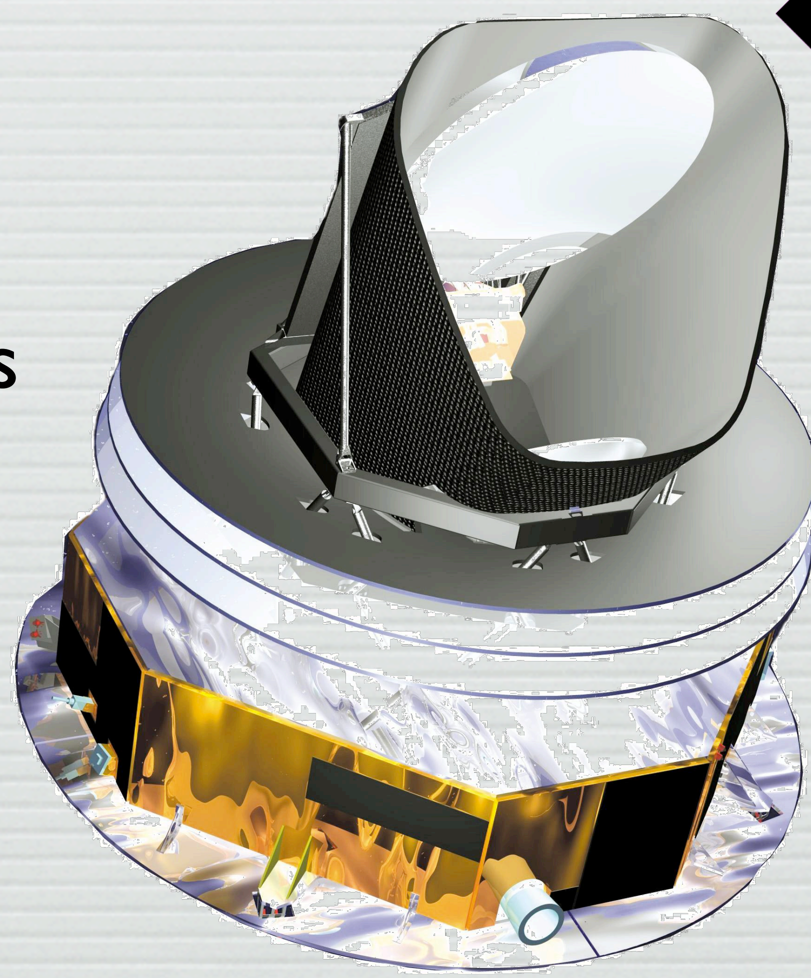
The uses of reionization

- Large scale: Reionization "amplifies" effects of primordial tensor spectrum
  - (new, nearby, scattering surface)
- Large increase in total BB power:
  - $r>0.01$ ($\tau=0.0$) vs $r>10^{-4}$ ($\tau=0.2$) detectable
- Small & medium scales: Cross-correlation analyses (e.g., ISW/SZ)



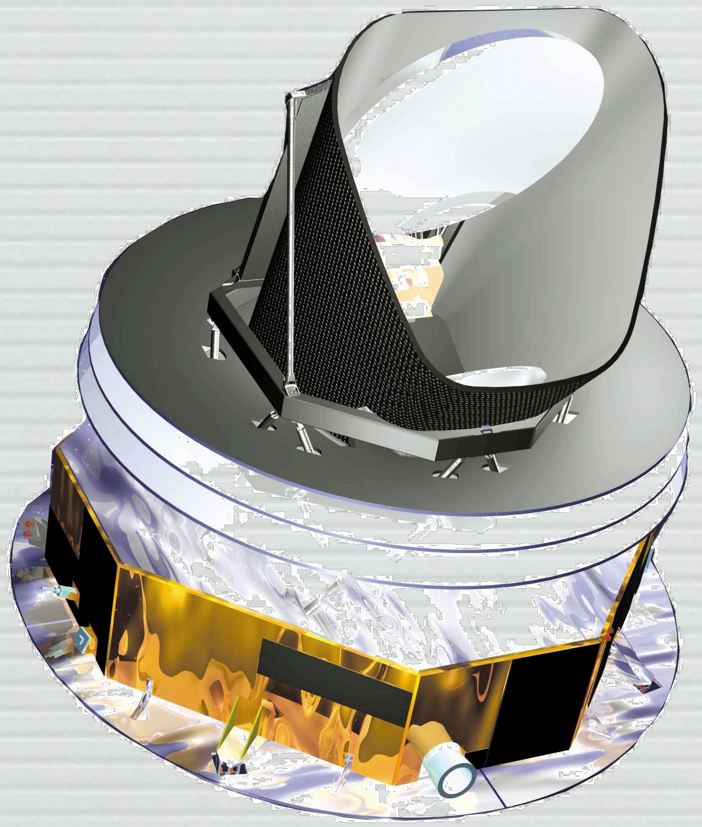
Prospects for Planck

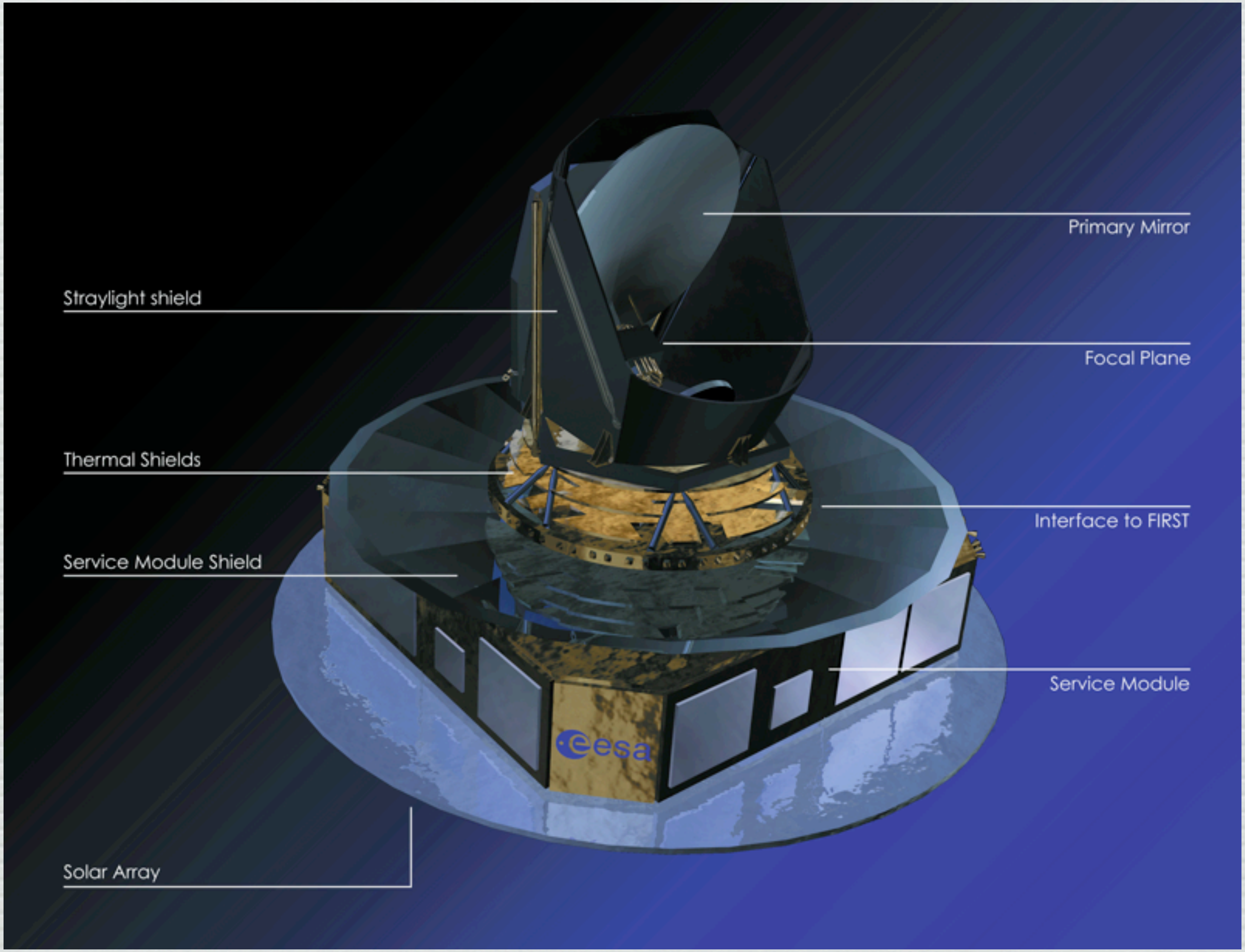
- The Instrument(s)
  - 30 - 850 GHz, resolution 30’ - 4’
- Science
  - ~150 defined papers/projects
  - Cosmology
  - Extragalactic Astrophysics
  - Galactic Astrophysics
  - Solar System
- Beyond Planck

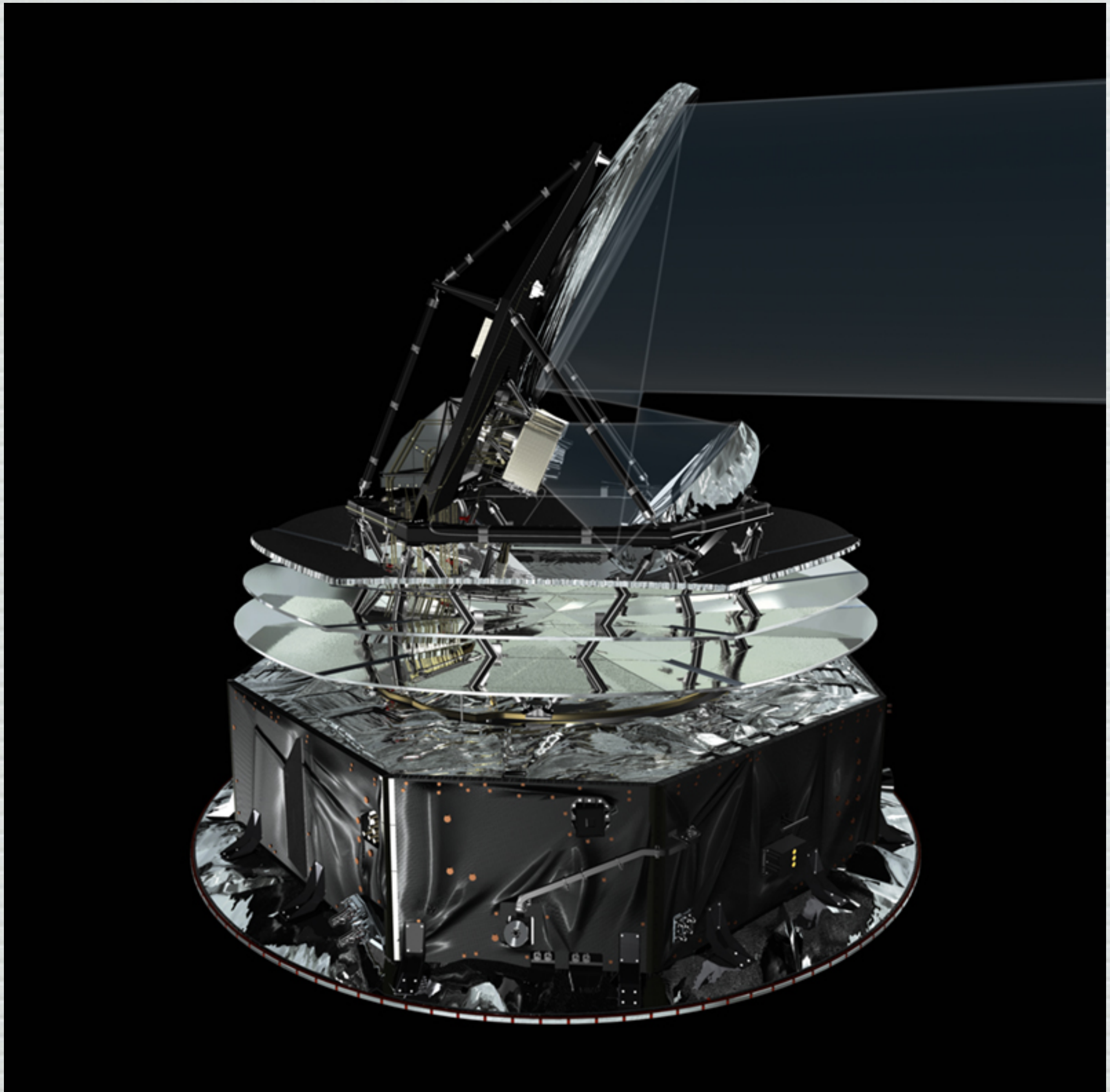


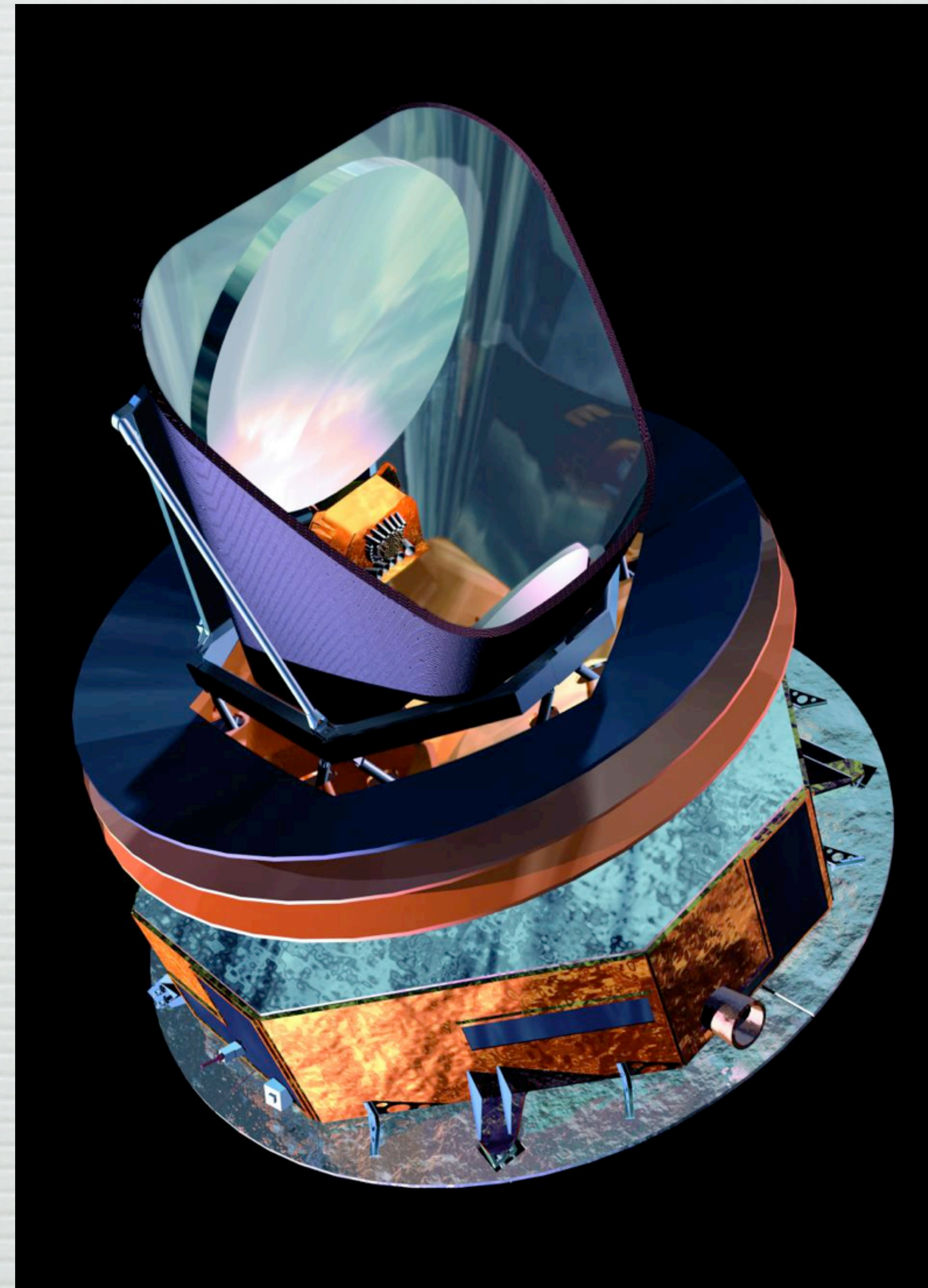
- *The Scientific Programme of Planck*
  - http://www.rssd.esa.int/index.php?project=Planck
  - arXiv:astro-ph/06040

Planck Surveyor (2008++)





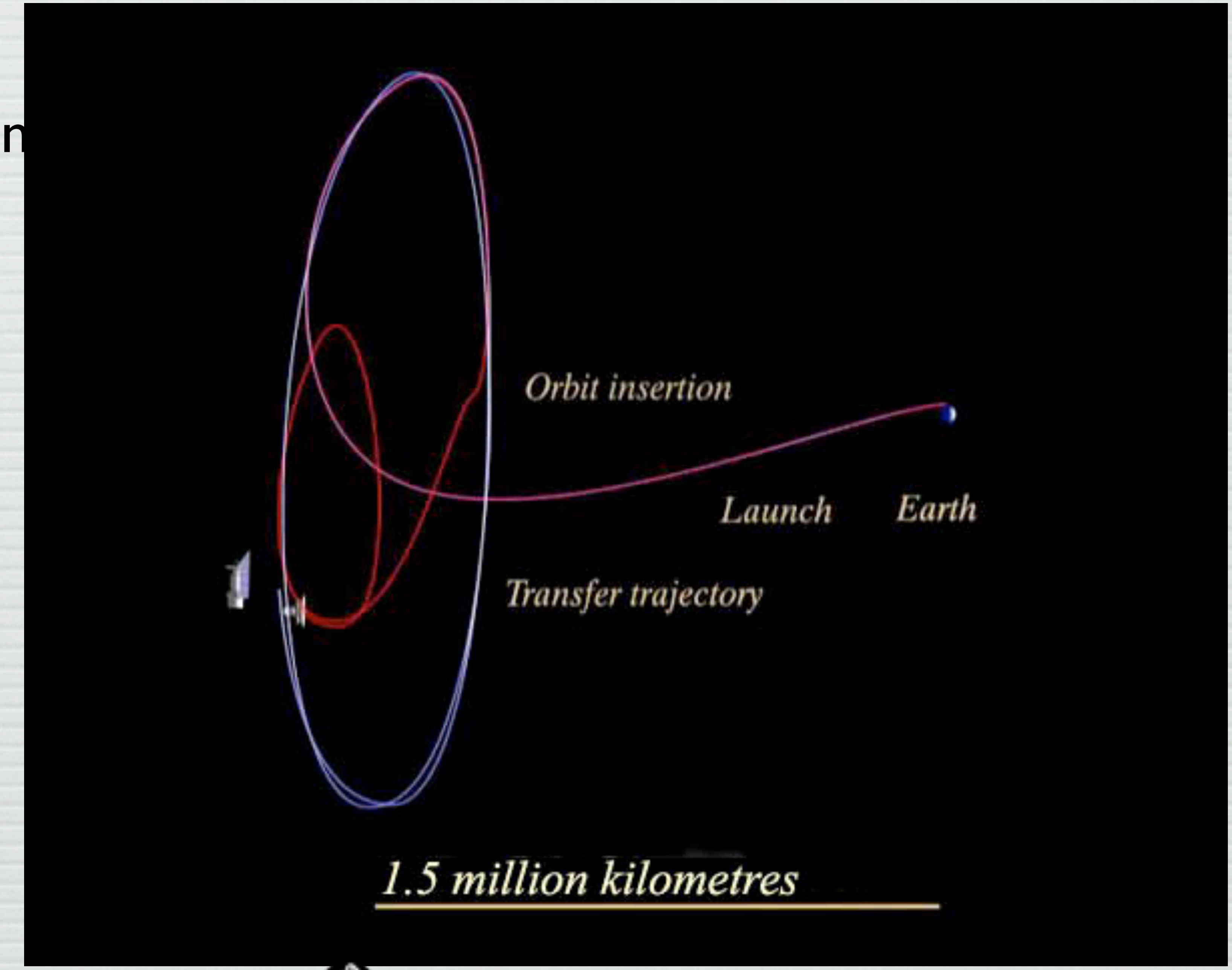




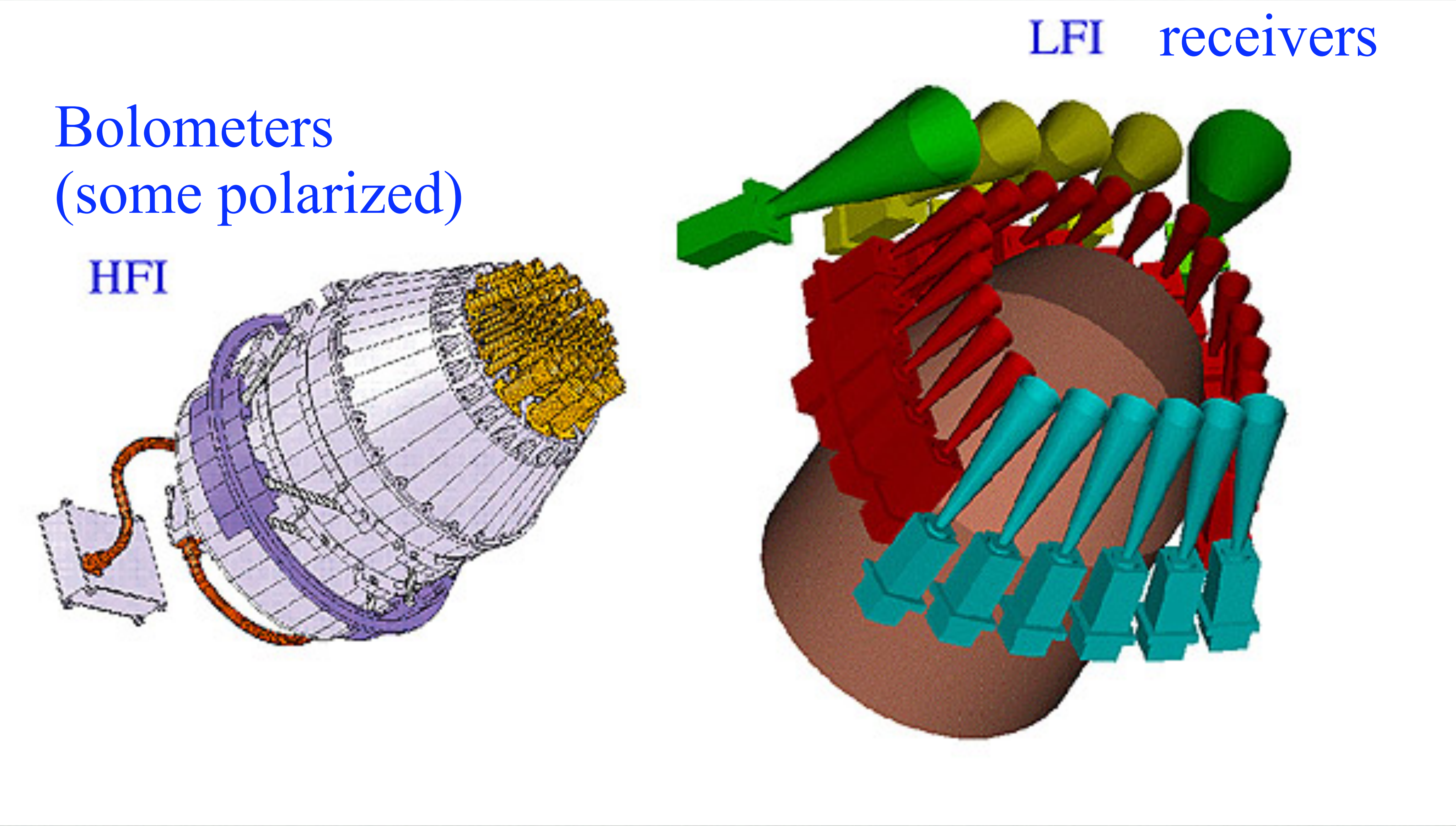
Planck's orbit & schedule

- L2 orbit
- minimize and localize sun moon, earth emission
- ~7-month full-sky scan
  - (nominal mission 2 scans)

  - mid-late 2008 launch
  - 2-4 month to L2
  - PV phase
  - 2 * 7 month scan
  - proprietary period



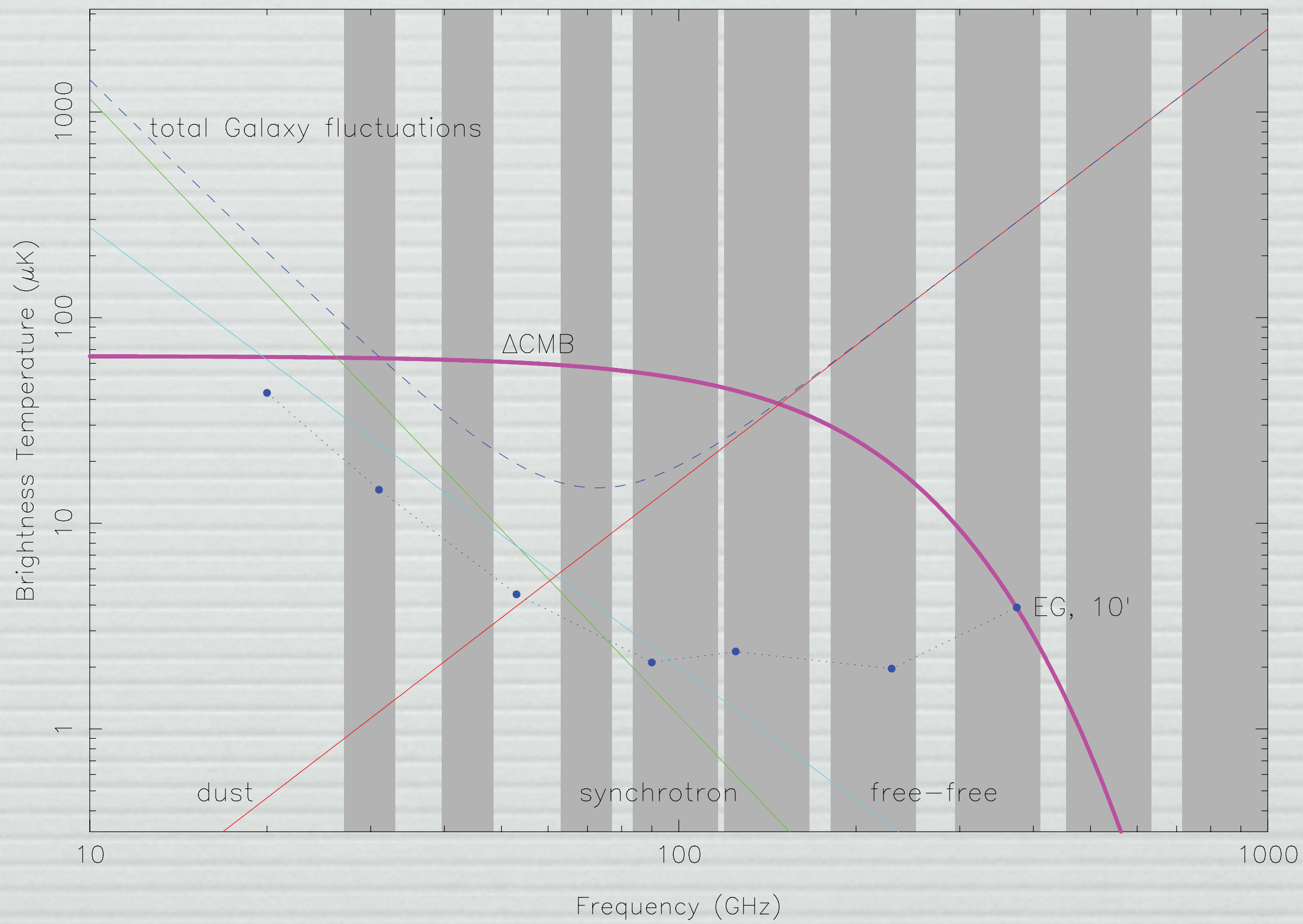
The Planck Instruments



The Planck bands

Instrument Characteristic	LFI			HFI					
Detector Technology	HEMT arrays			Bolometer arrays					
Center Frequency [GHz]	30	44	70	100	143	217	353	545	857
Bandwidth ($\Delta\nu/\nu$)	0.2	0.2	0.2	0.33	0.33	0.33	0.33	0.33	0.33
Angular Resolution (arcmin)	33	24	14	10	7.1	5.0	5.0	5.0	5.0
$\Delta T/T$ per pixel (Stokes I)[a]	2.0	2.7	4.7	2.5	2.2	4.8	14.7	147	6700
$\Delta T/T$ per pixel (Stokes Q & U)[a]	2.8	3.9	6.7	4.0	4.2	9.8	29.8	. . .	. . .

[a] Goal (in μK/K) for 14 months integration, 1σ, for square pixels whose sides are given in the row "Angular Resolution".



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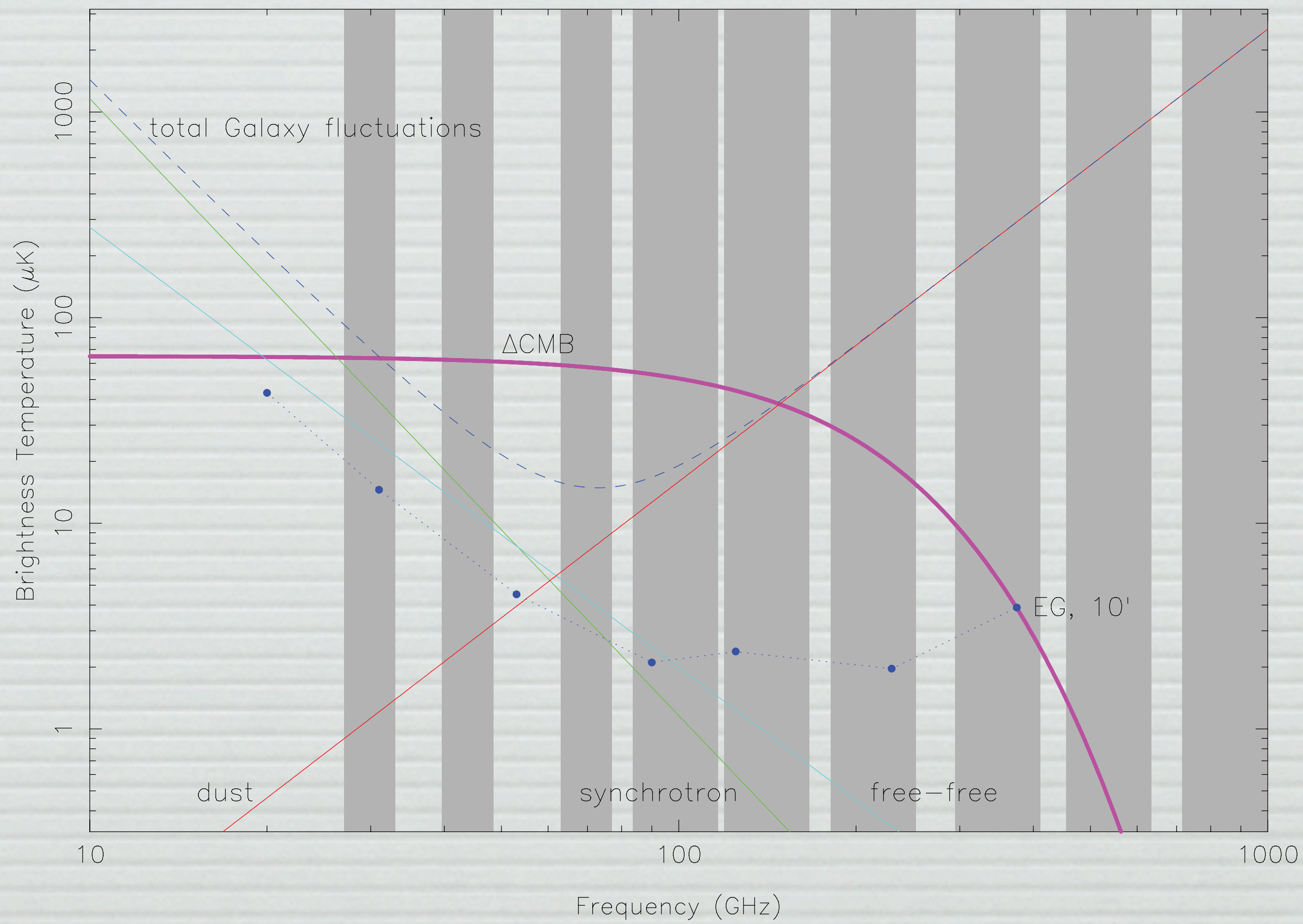
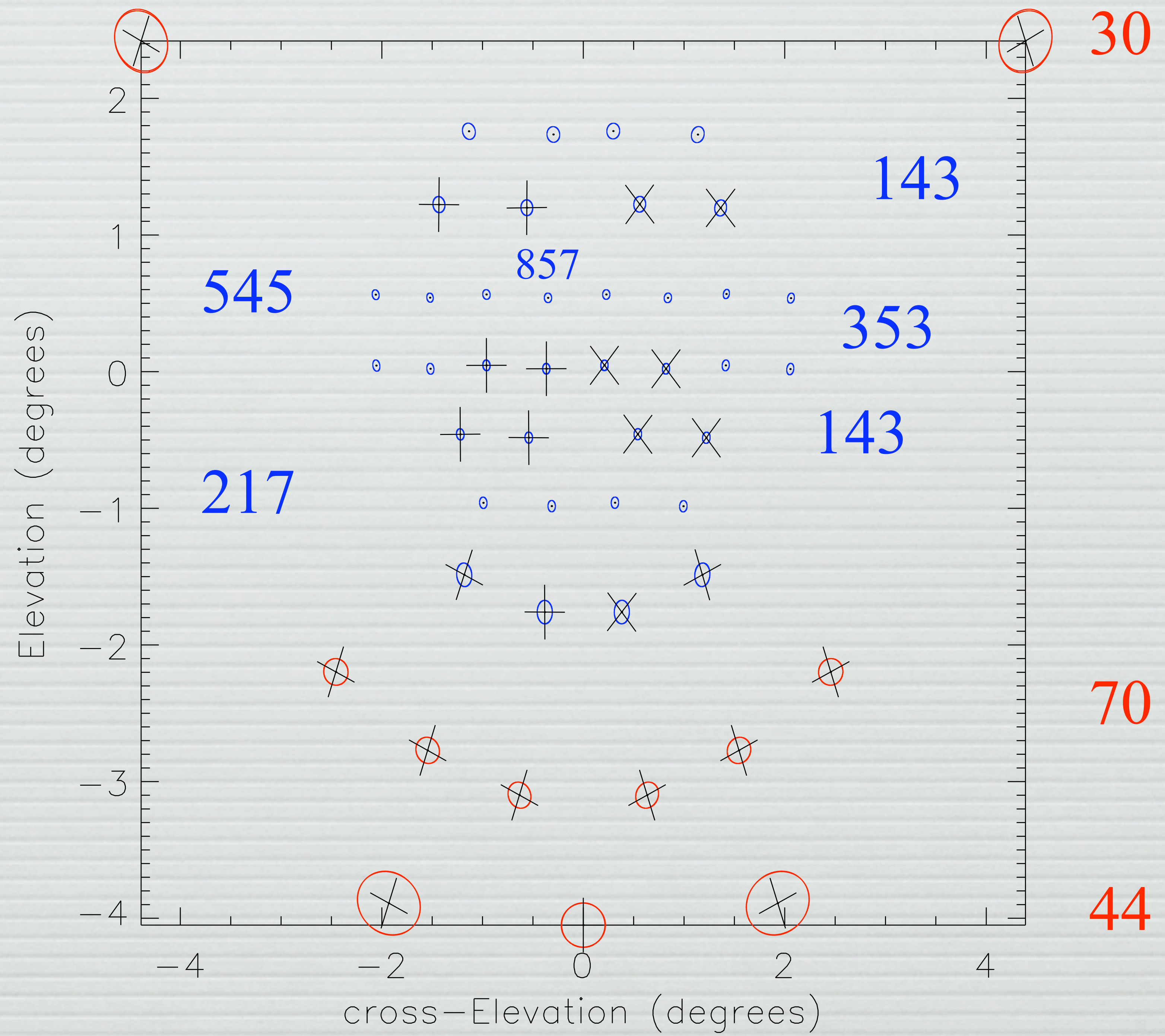
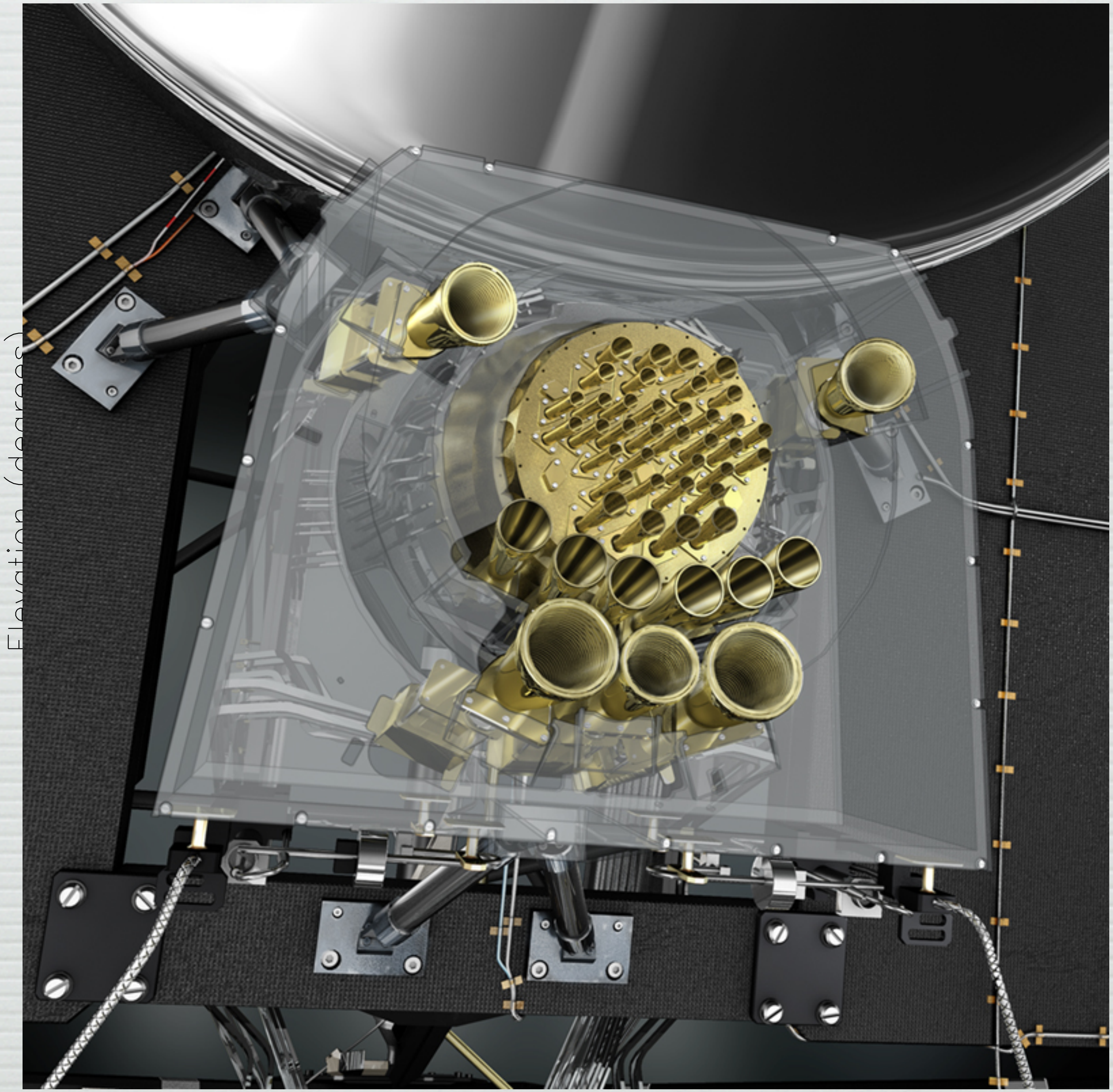


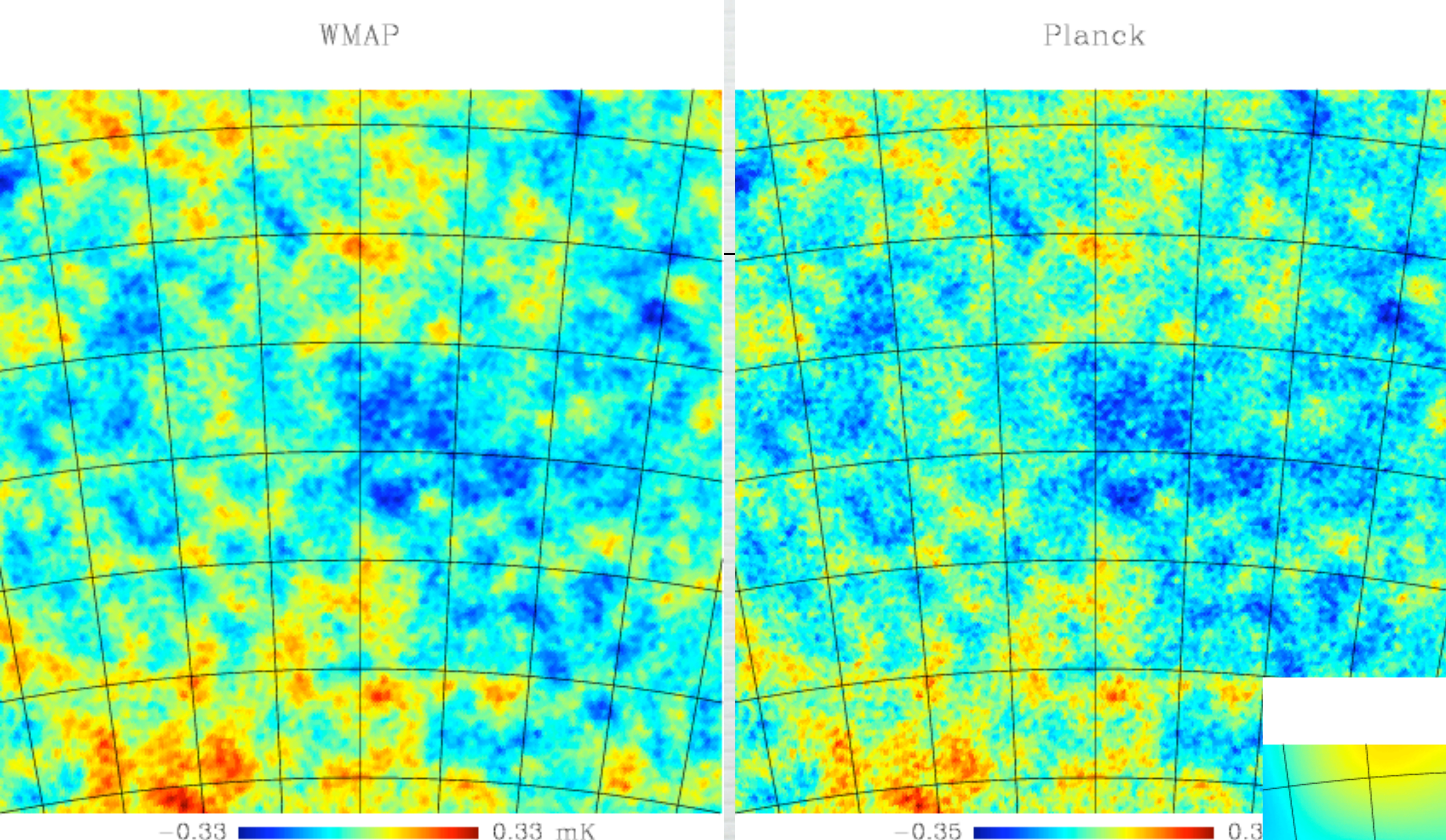
The Planck Focal Plane

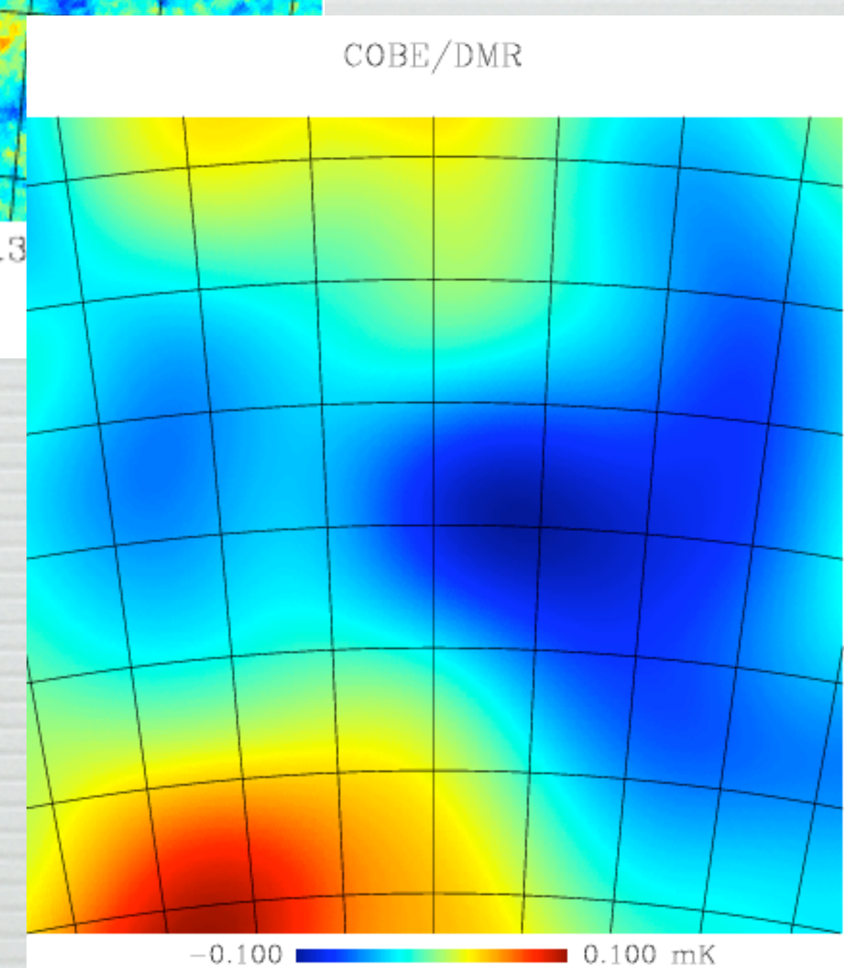


The Planck Focal Plane

Elevation (degrees)





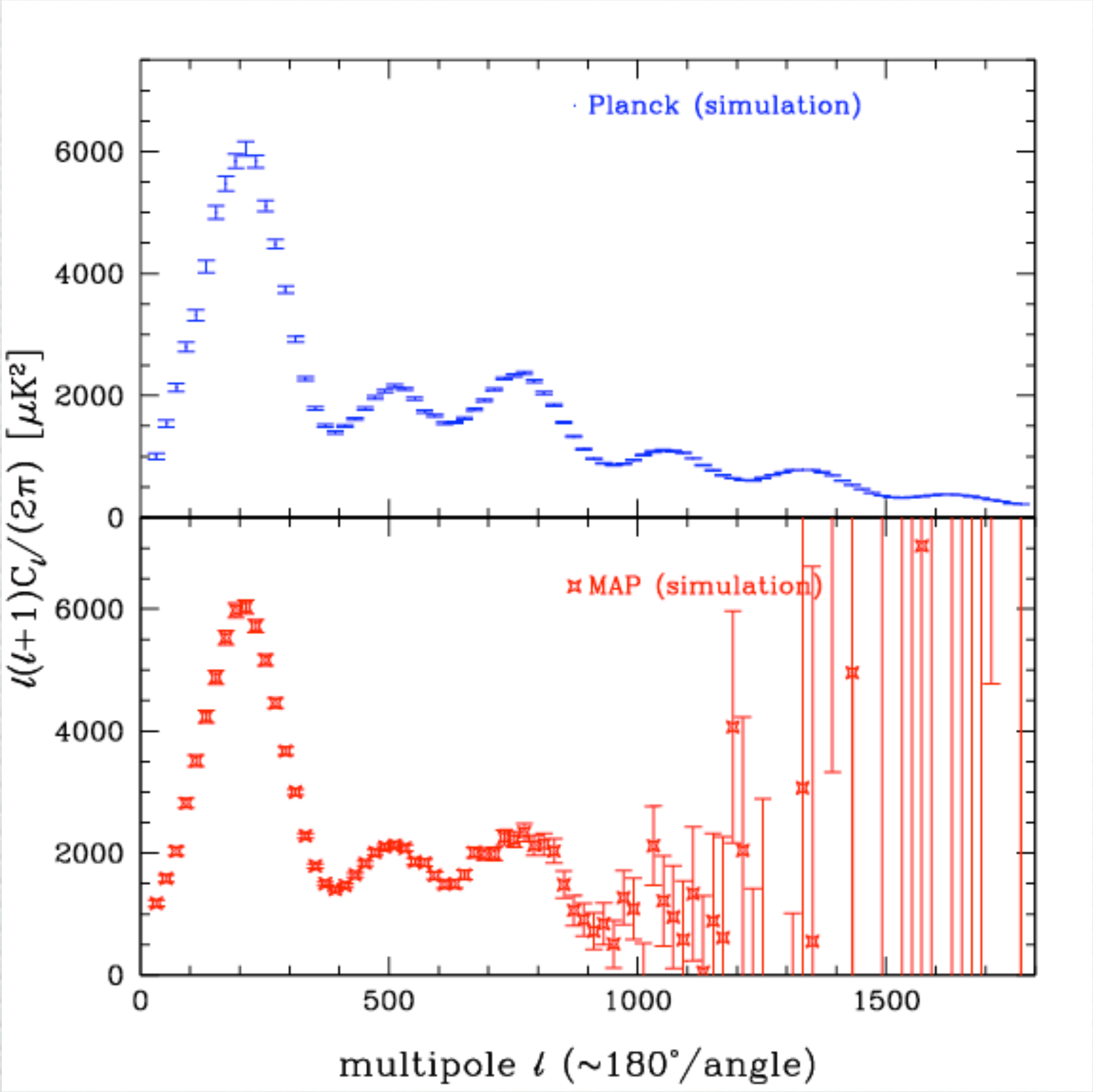


Planck Surveyor will get ~all the (T) information that the CMB has to give us!

Planck will also get a better of the "polarization" of the CMB: probes movement of matter in the early universe and *Gravity Waves – from inflation???*

"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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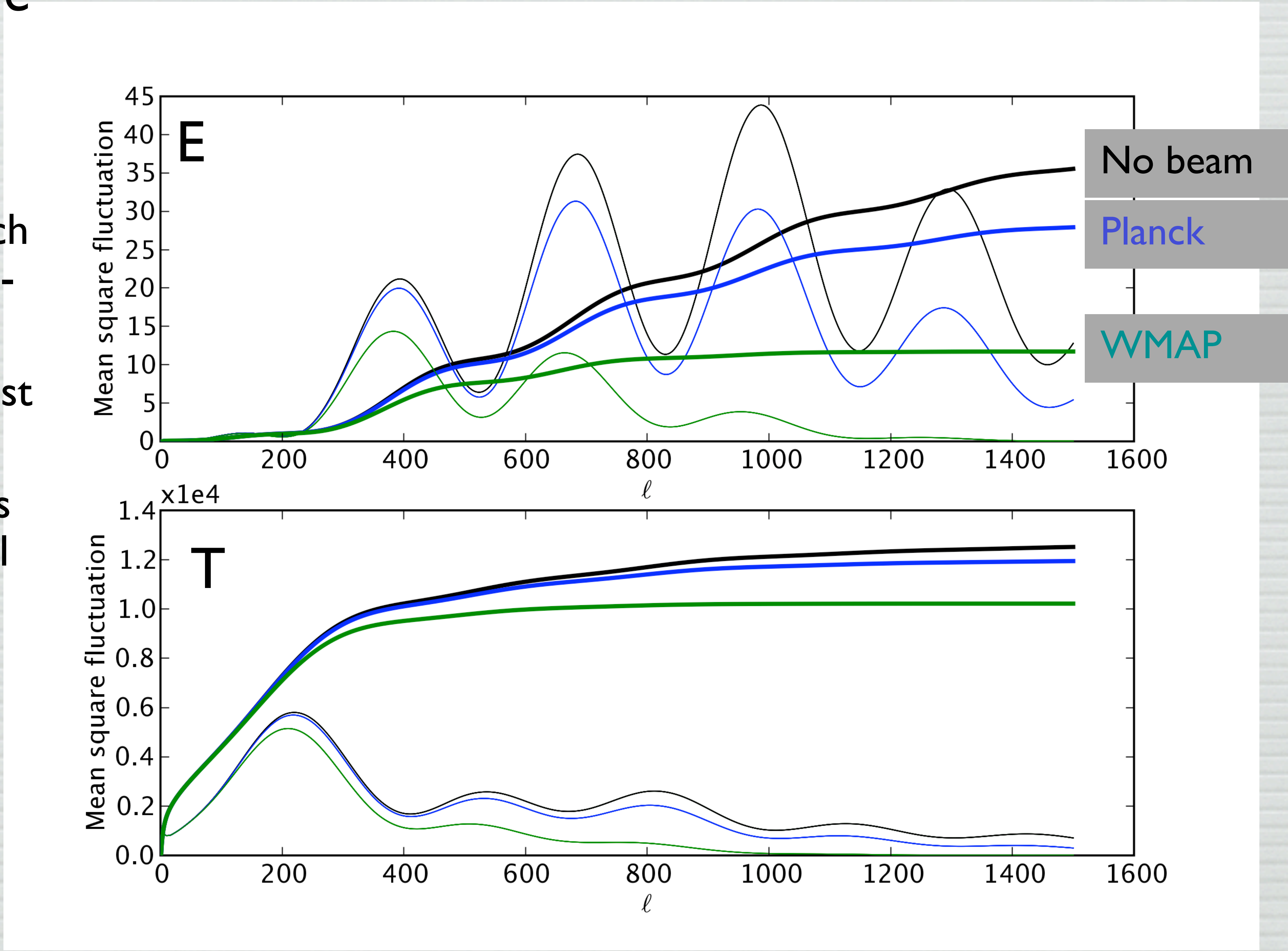


Cosmological Parameters from Planck

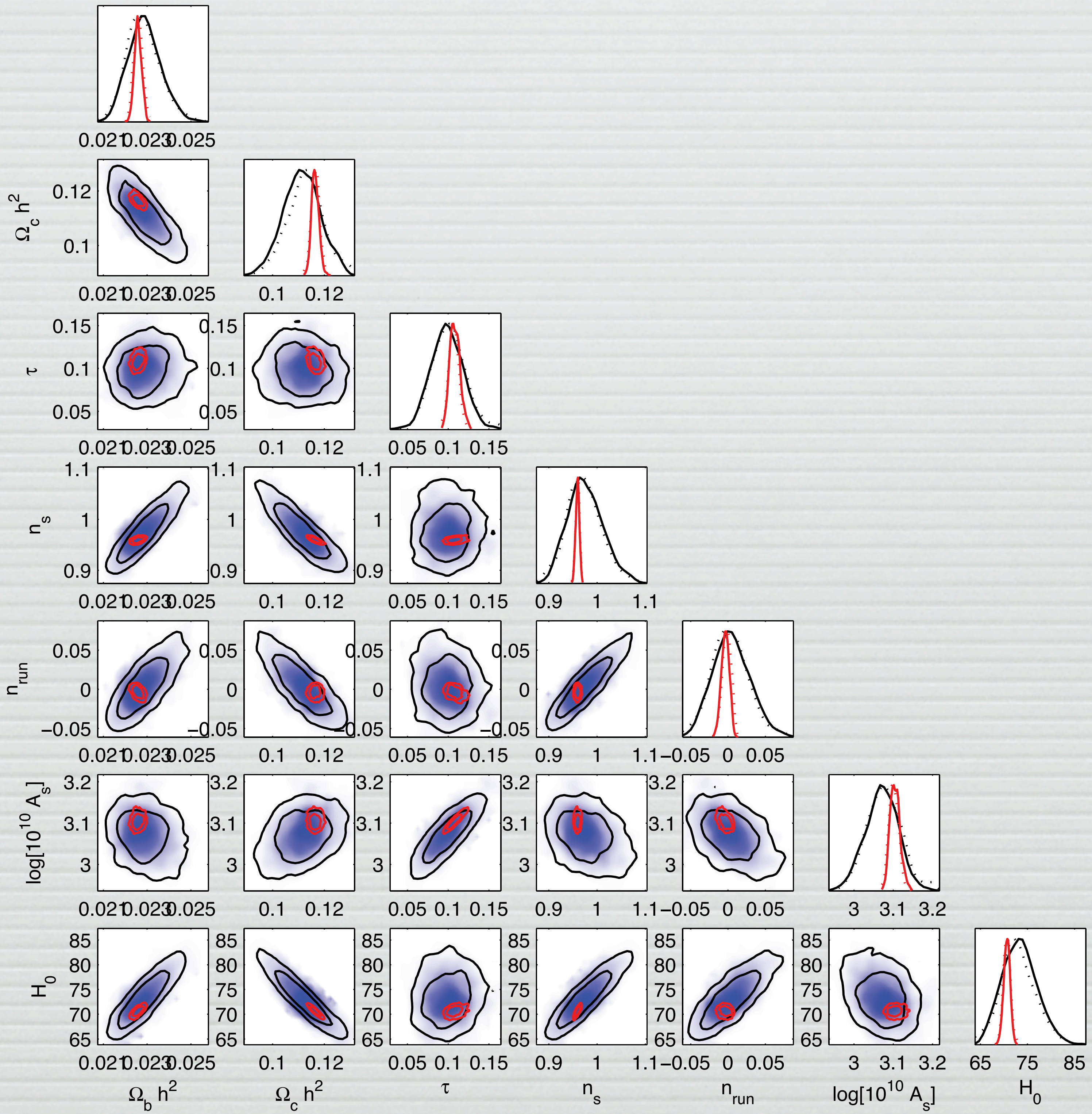
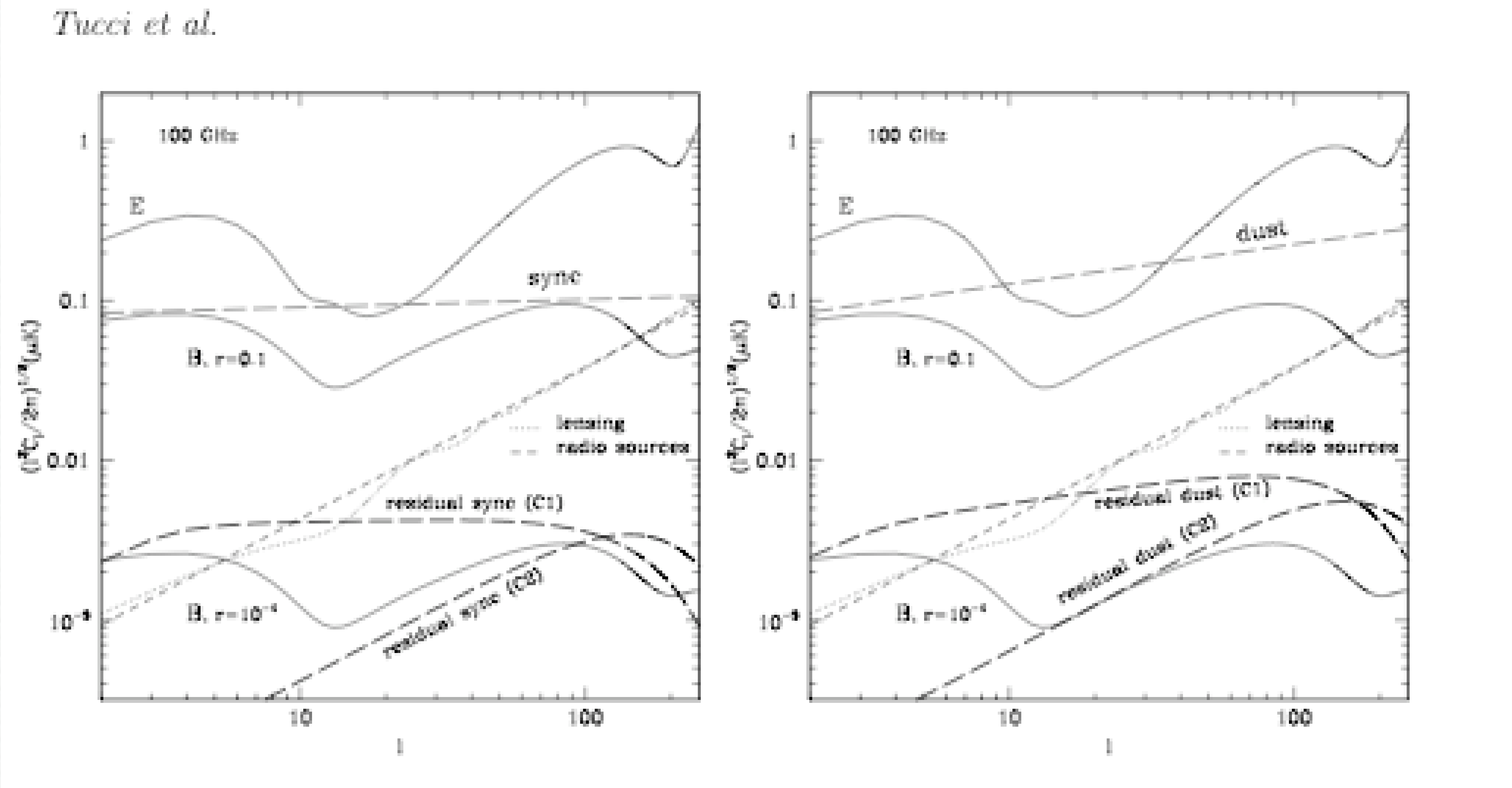


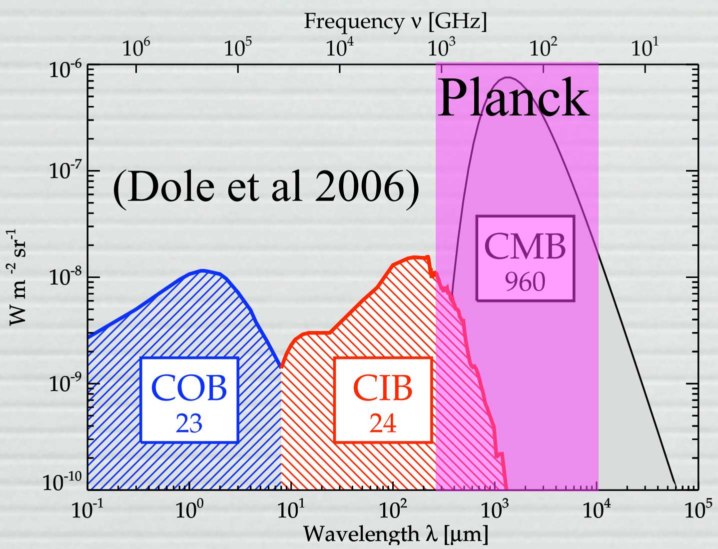
FIG 2.18.—Forecasts of 1 and 2σ contour regions for various cosmological parameters when the spectral index is allowed to run. Blue contours show forecasts for *WMAP* after 4 years of observation and red contours show results for *Planck* after 1 year of observations. The curves show marginalized posterior distributions for each parameter.

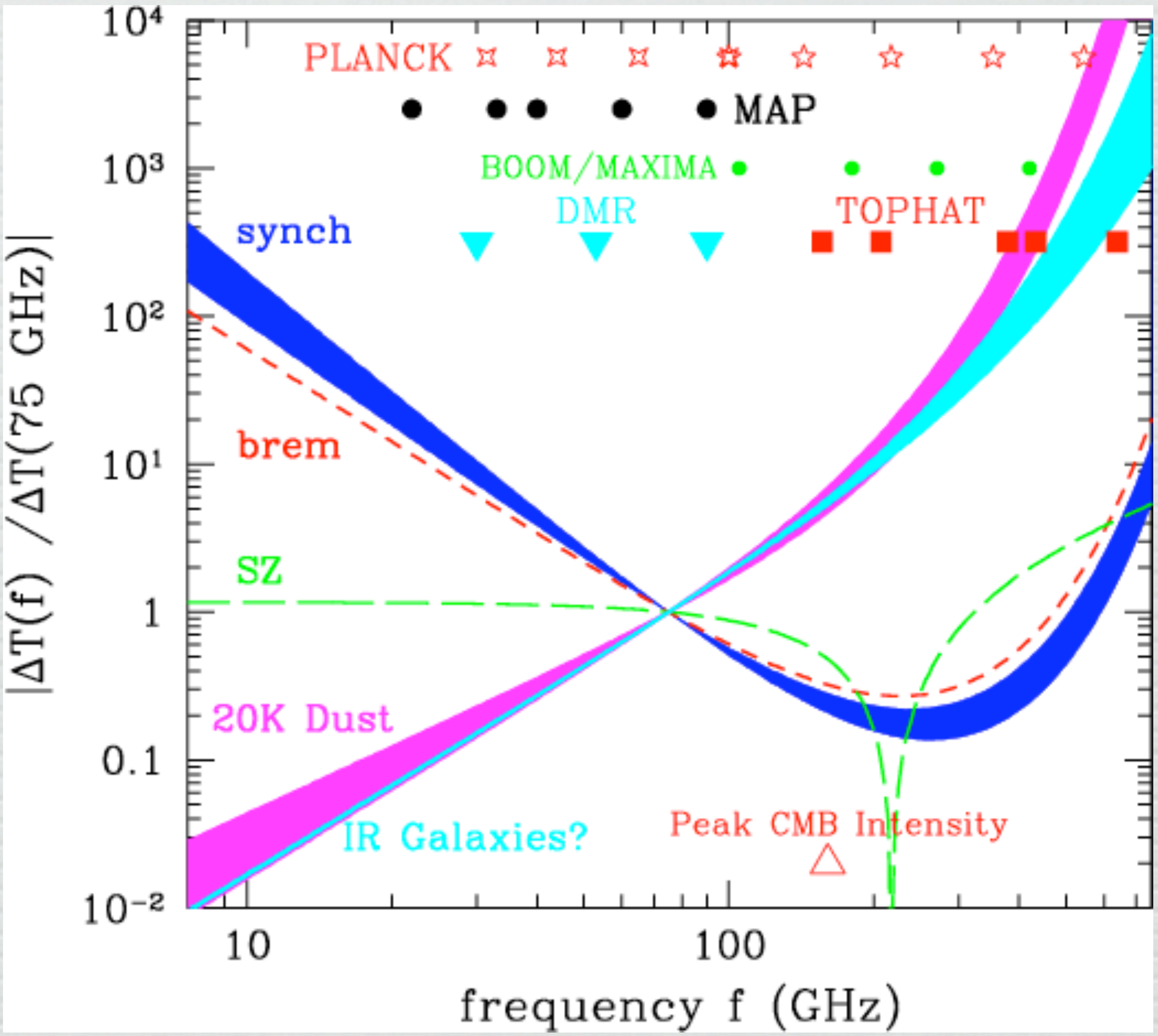
B-mode foregrounds

- Astrophysical foregrounds
  - Contamination amplitudes E~B

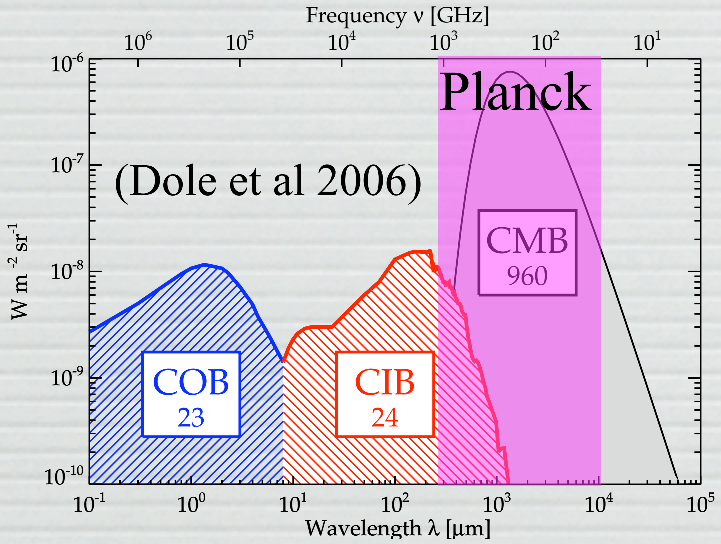


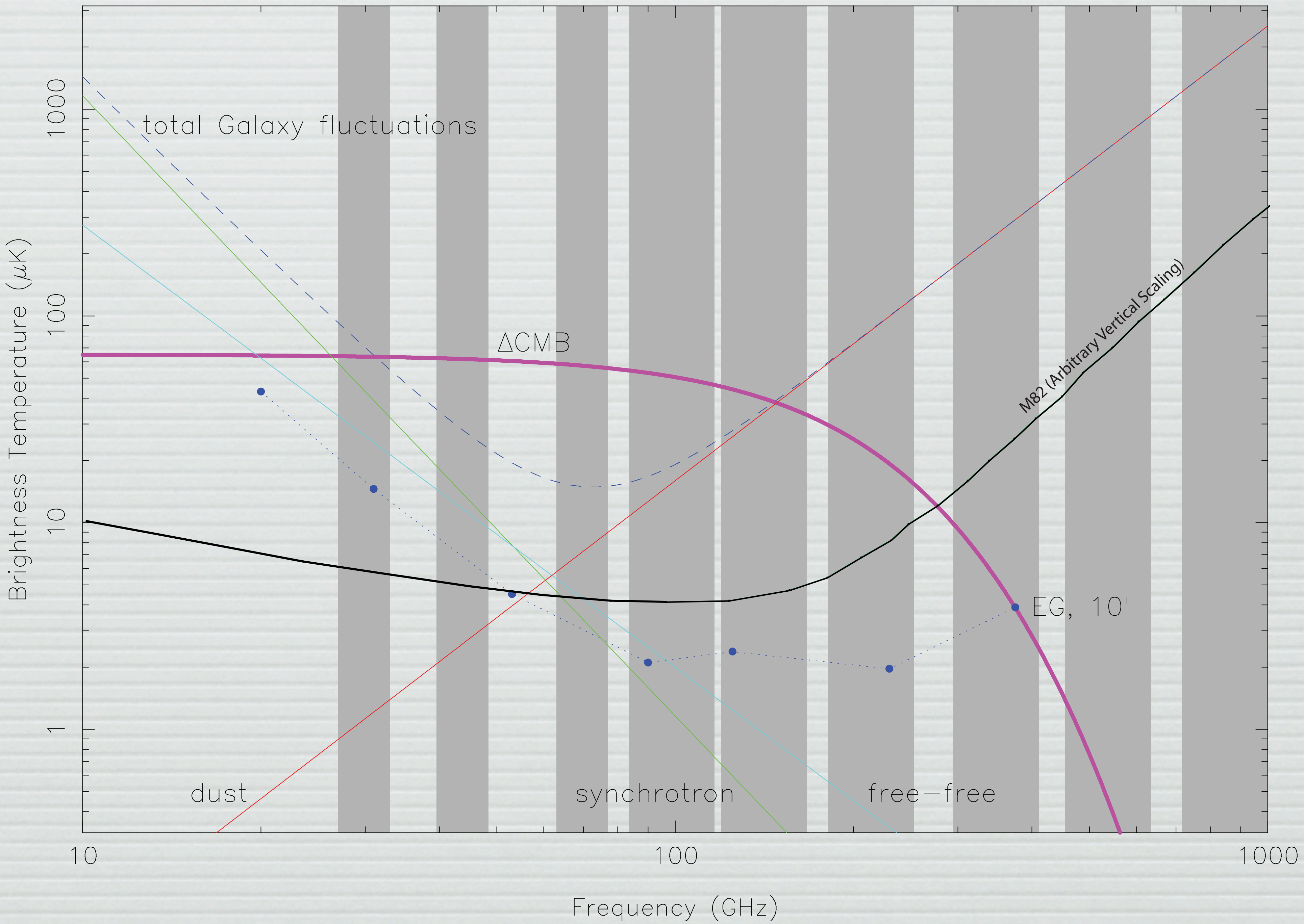
Astrophysics from 30-850 GHz



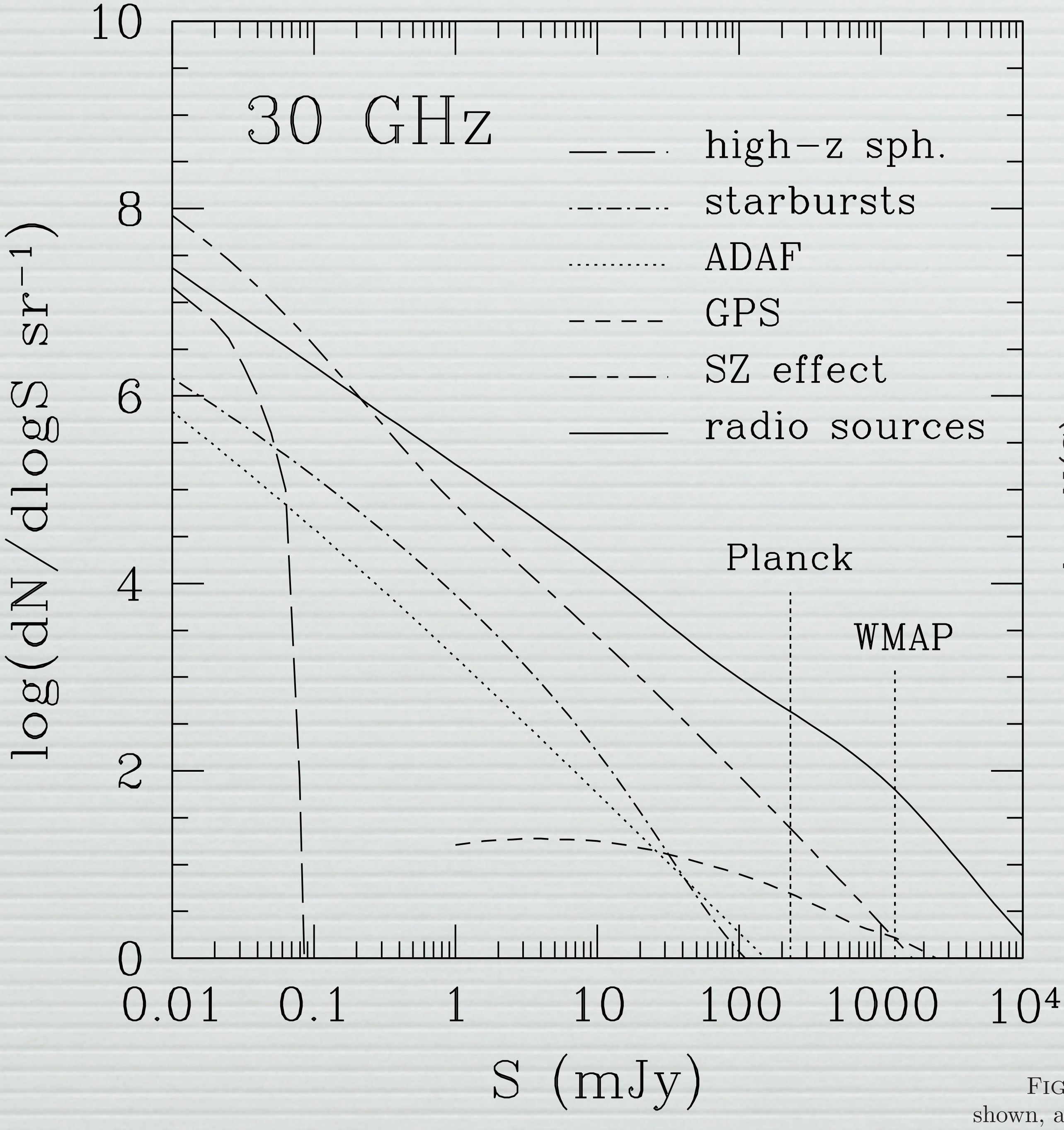


Astrophysics from 30-850 GHz





Source counts



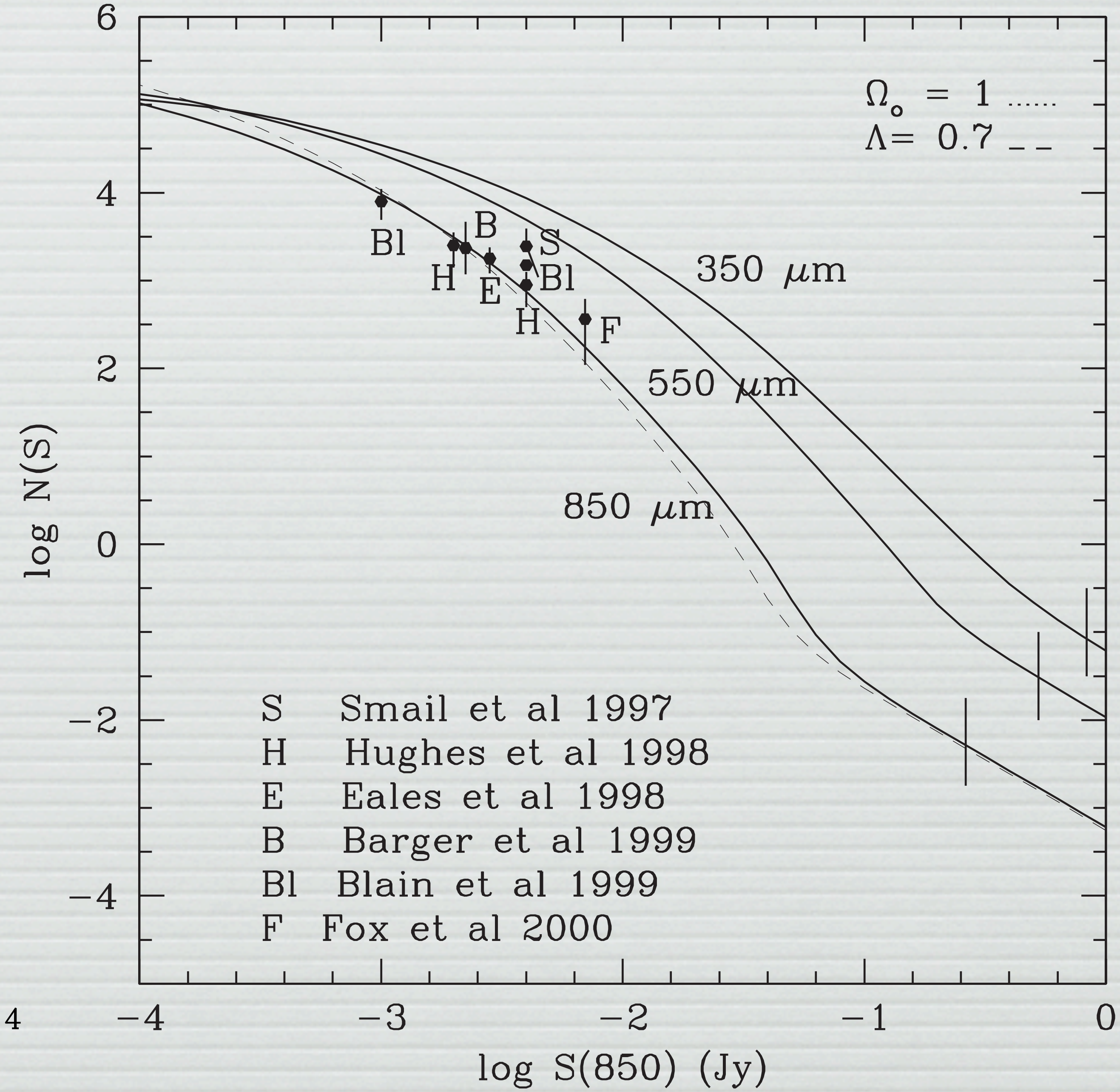
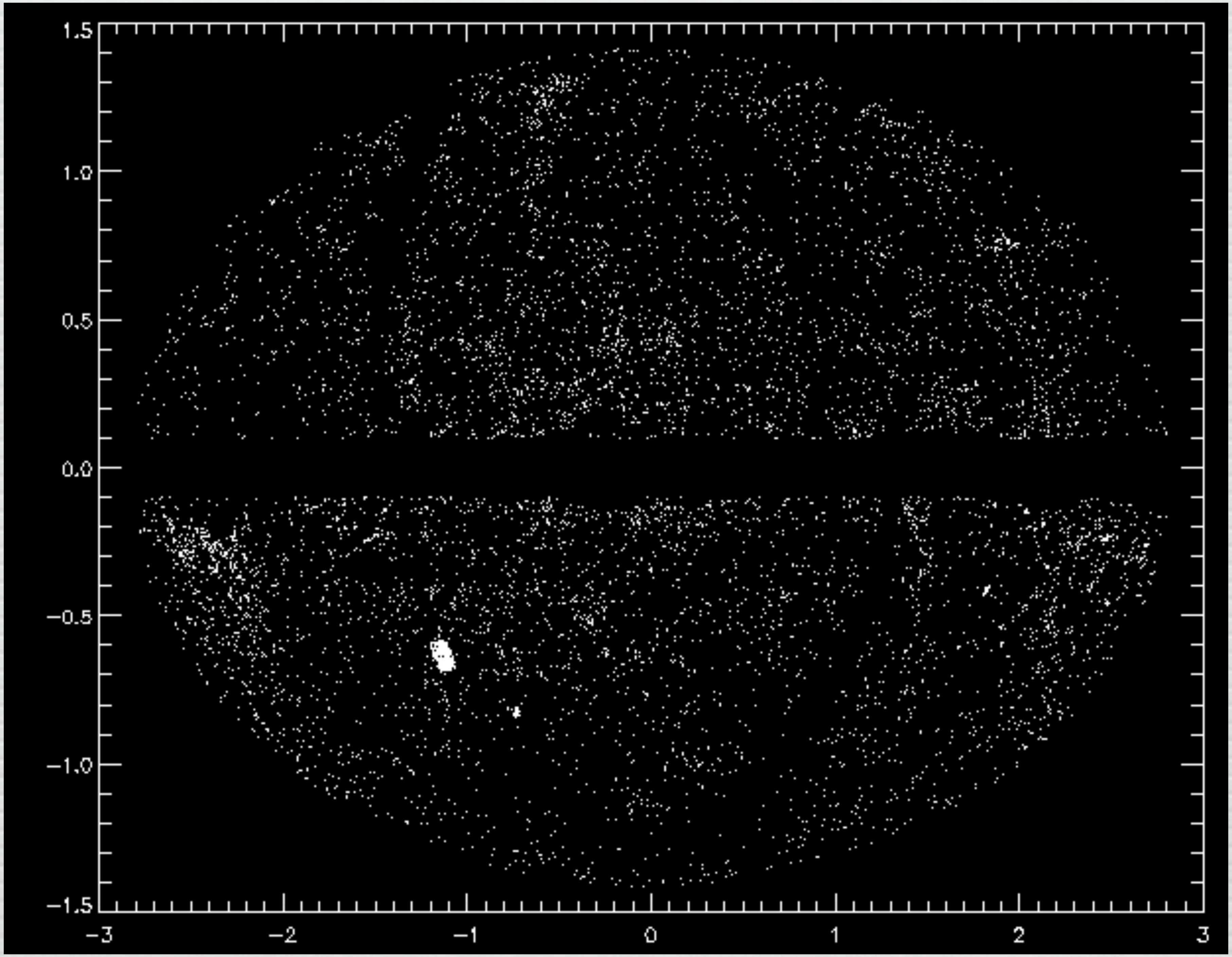


FIG 4.11.— Predicted counts at 350, 550 and 850 μm (Rowan-Robinson 2001). Observed counts at 850 μm are shown, and the *Planck* sensitivity is indicated by the vertical bars.

Planck point sources

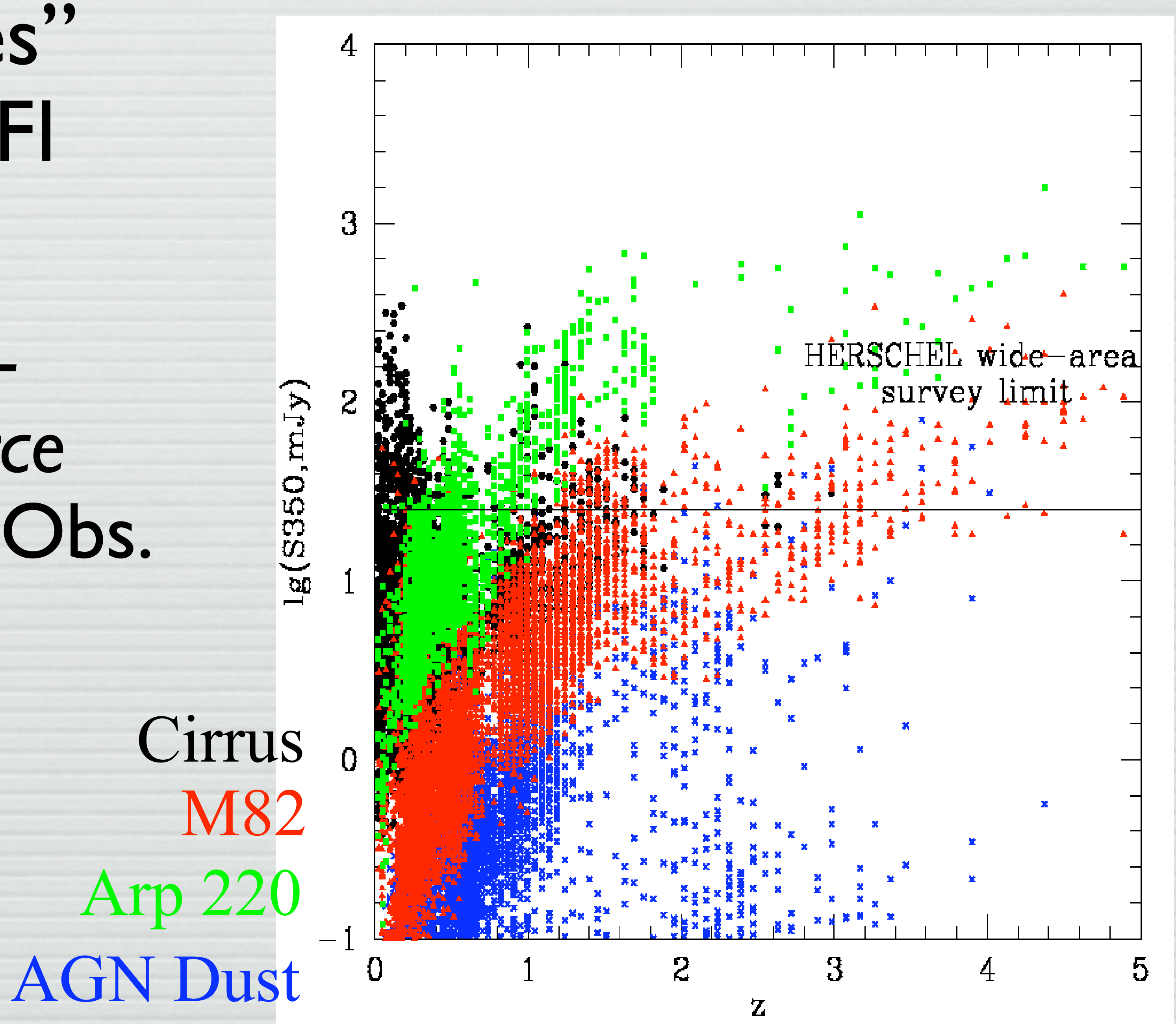
- 857 GHz predictions, S>0.5 Jy (6sigma)
- ~8000 sources



Courtesy D Clements

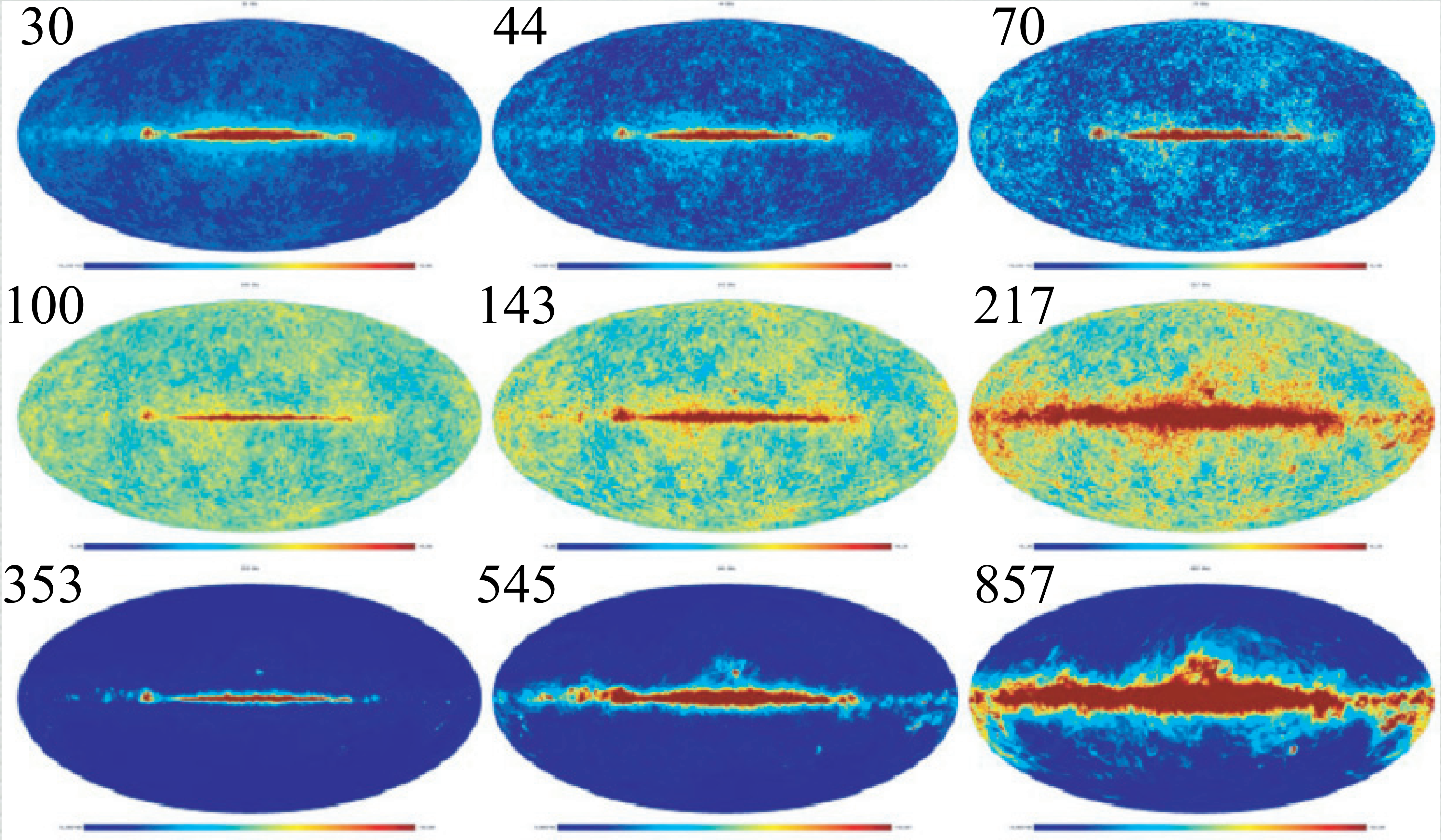
Planck and Herschel

- >8000 "dusty galaxies" z>1 detectable by HFI
- Input to Herschel
  - Planck provides *Early-Release Compact Source Catalog* for Herschel Obs.



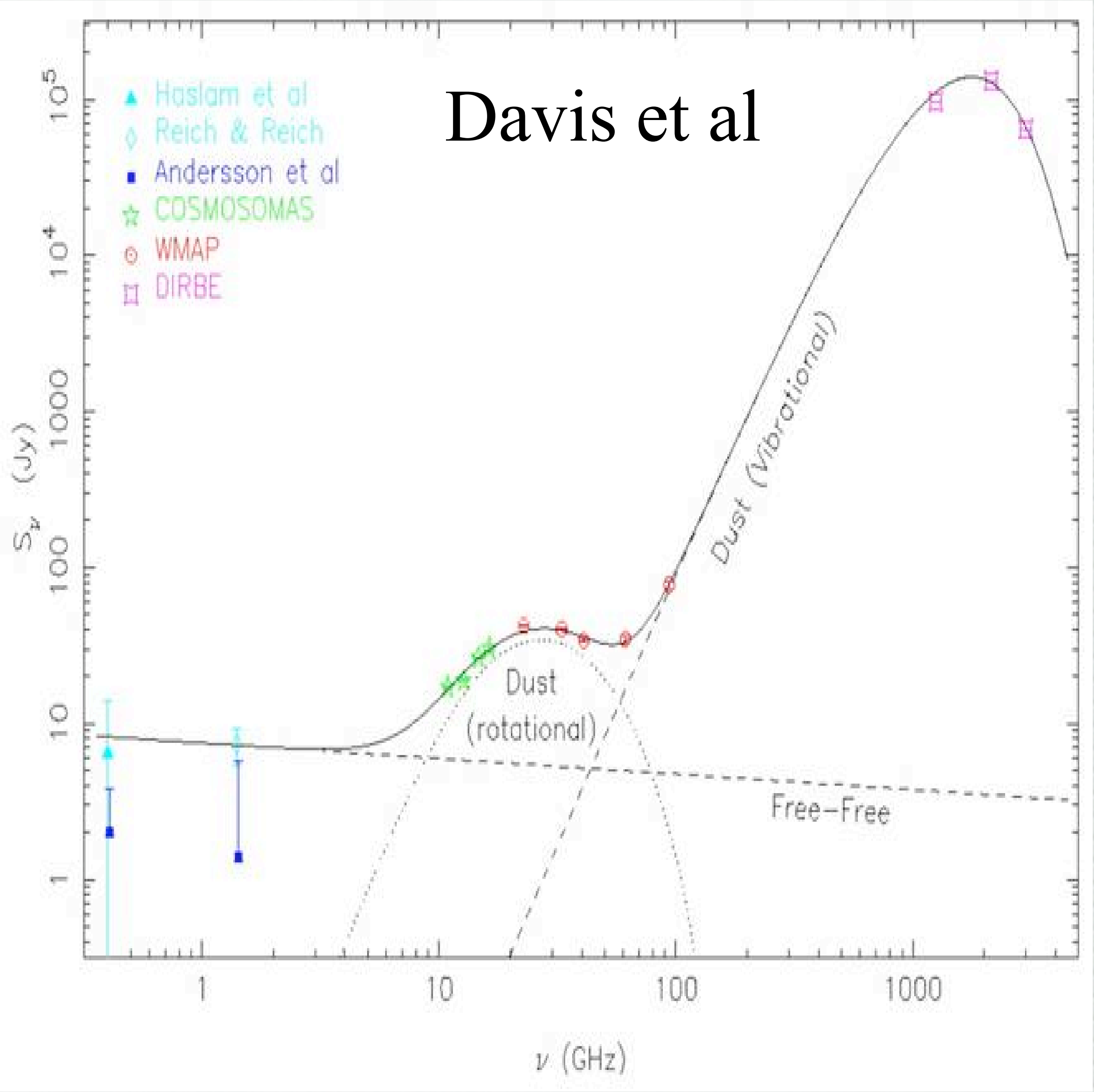
857 GHz flux predictions (MRR)

Galactic Astrophysics: Diffuse foregrounds



Anomalous emission?

- 10-20 GHz bump
- first noticed in CMB
  - Kogut et al. 1996; de Oliveira-Costa et al. 1997; Leitch et al. 1997
- models
  - Spinning dust?
  - Unexpected distrib of grain sizes?
- Polarization signal?



Stellar and Solar System Astrophysics

- Moving objects (comets)
- Zodiacal emission
  - detectable in timestream: short periods and seasonal variation due to L2 orbit
- Stellar:
  - PN
  - SNR

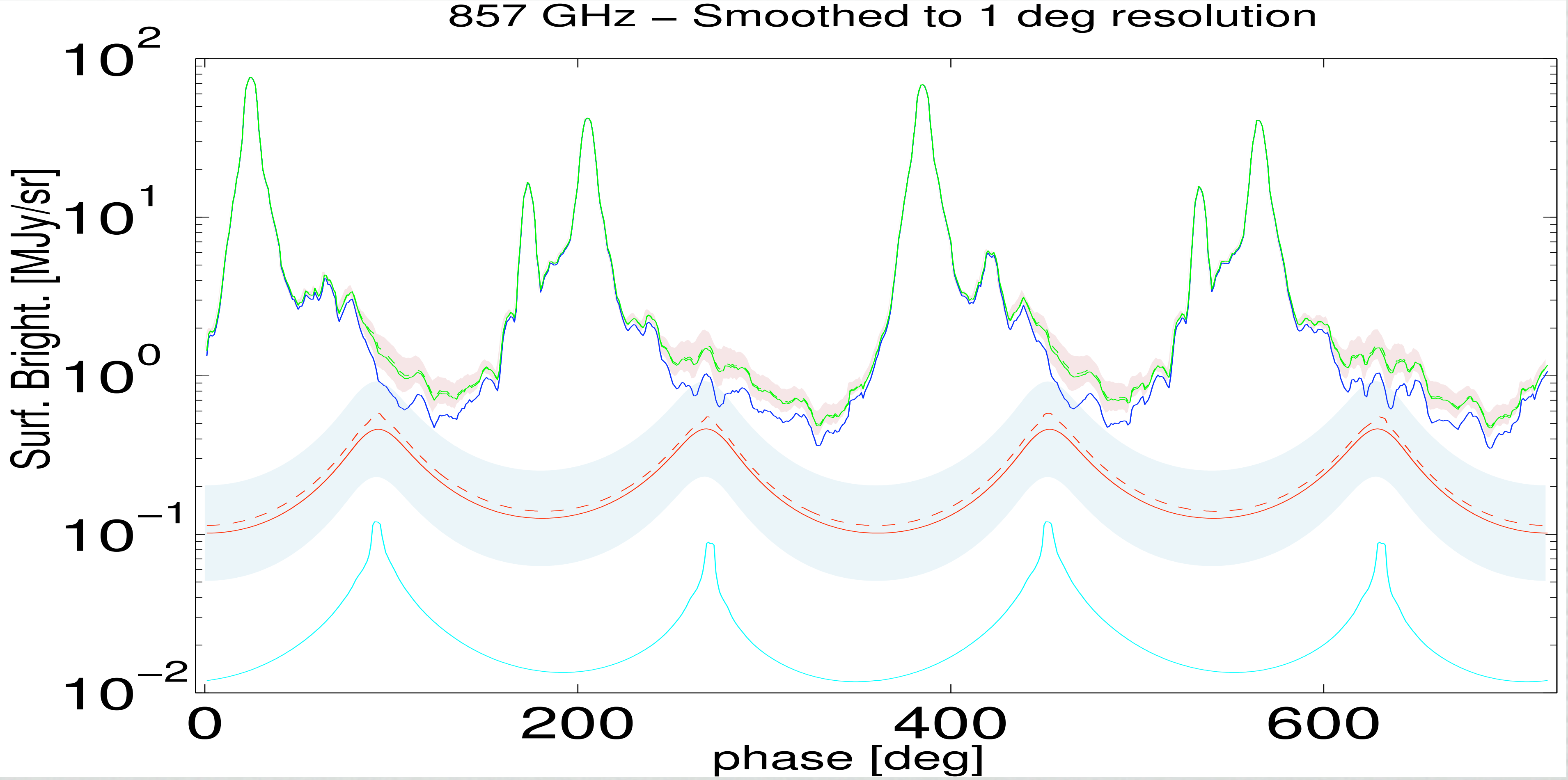
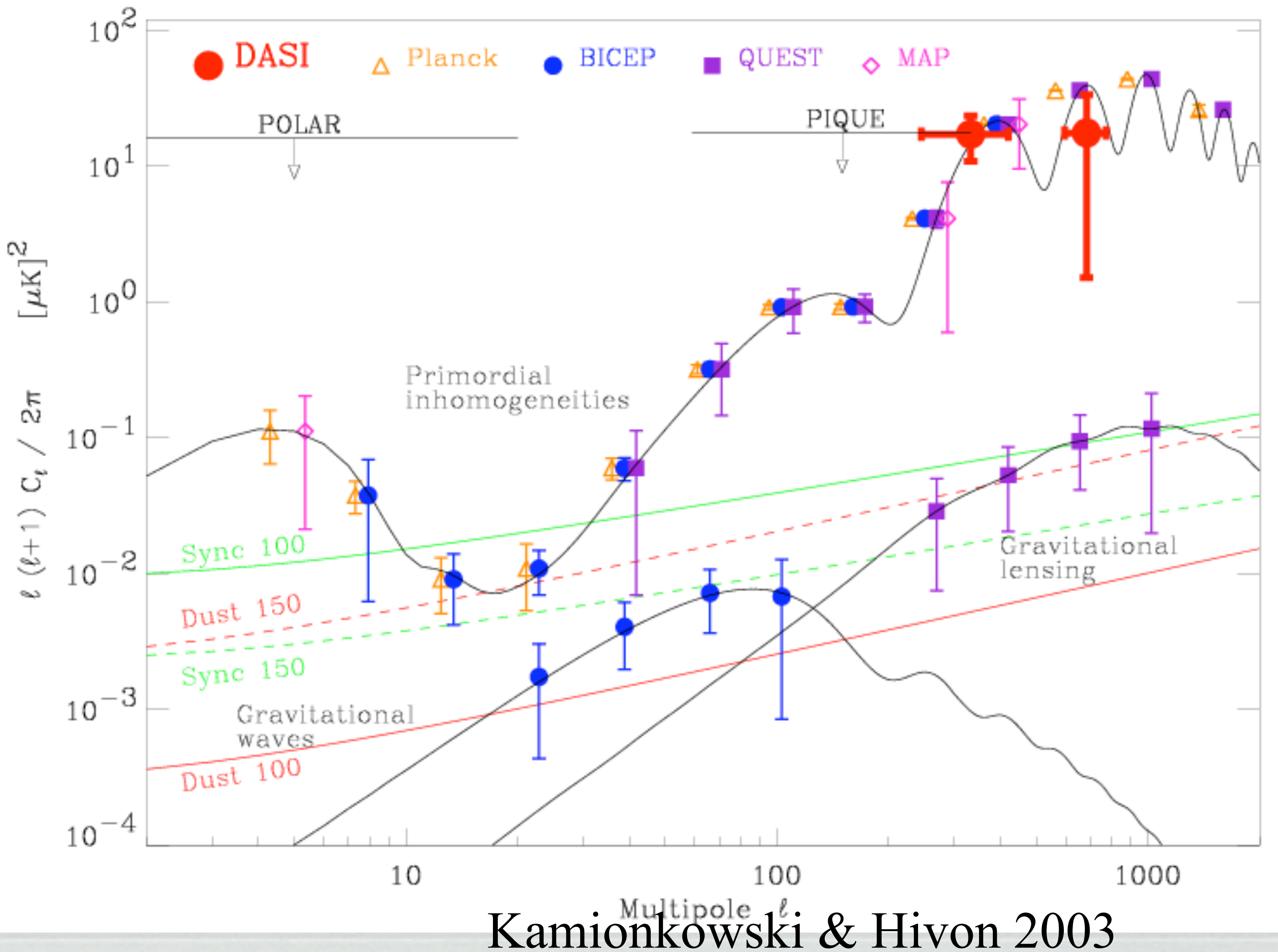


Fig.1 - ZLE in TOIs

Beyond Planck

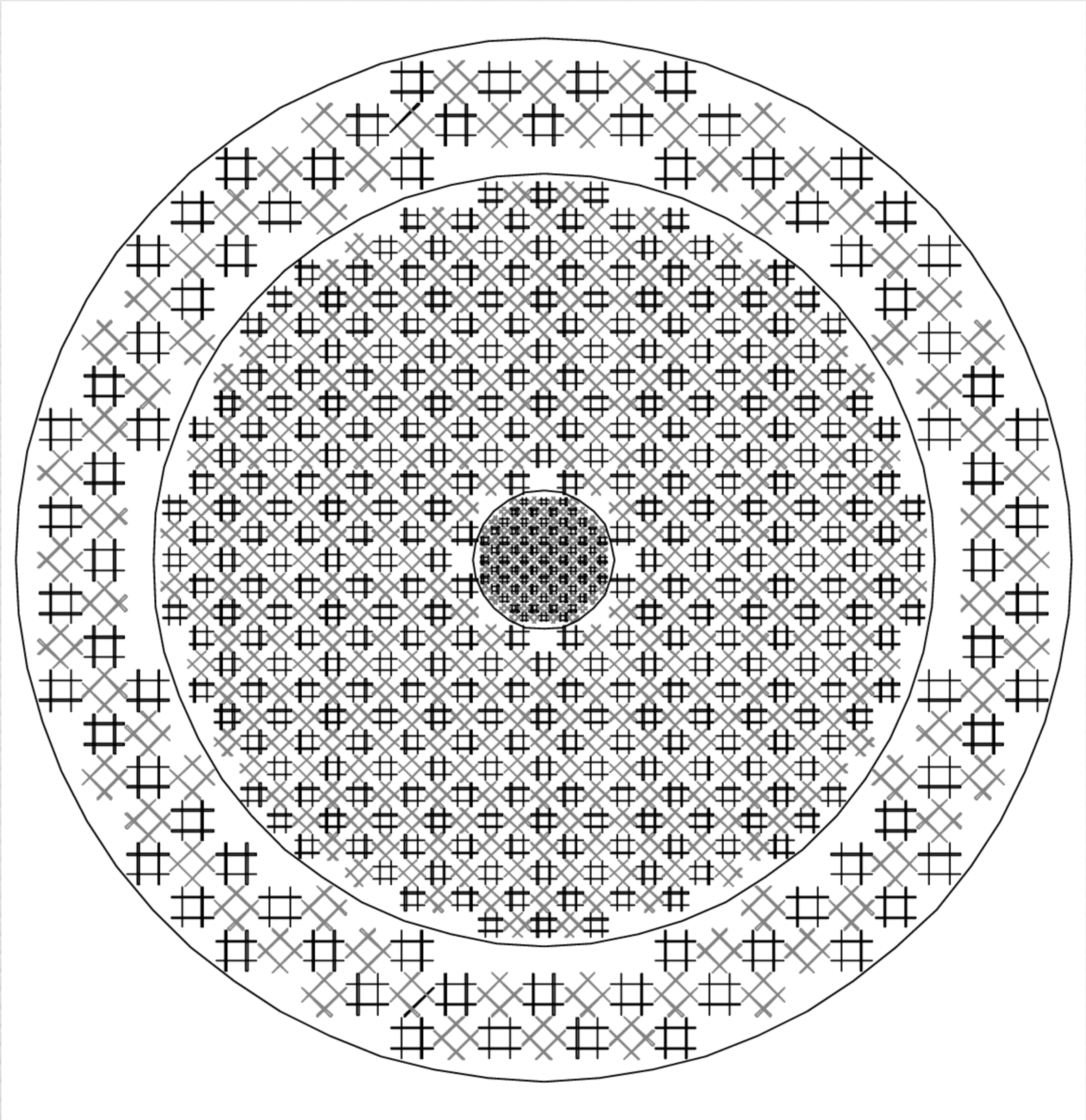
- Next generation of ground/ balloon experiments targets Gravitational waves (B polarization)
  - PolarBear
  - SPIDER
  - Eventually need ~full sky: e.g., ***ESA BPol***



Kamionkowski & Hivon 2003

- Crucial foreground signal from gravitational lensing via intervening structure: generates B modes, masks GW signal
- Astrophysical Foregrounds likely to be dominant $\ell \lesssim 200$

New Technologies

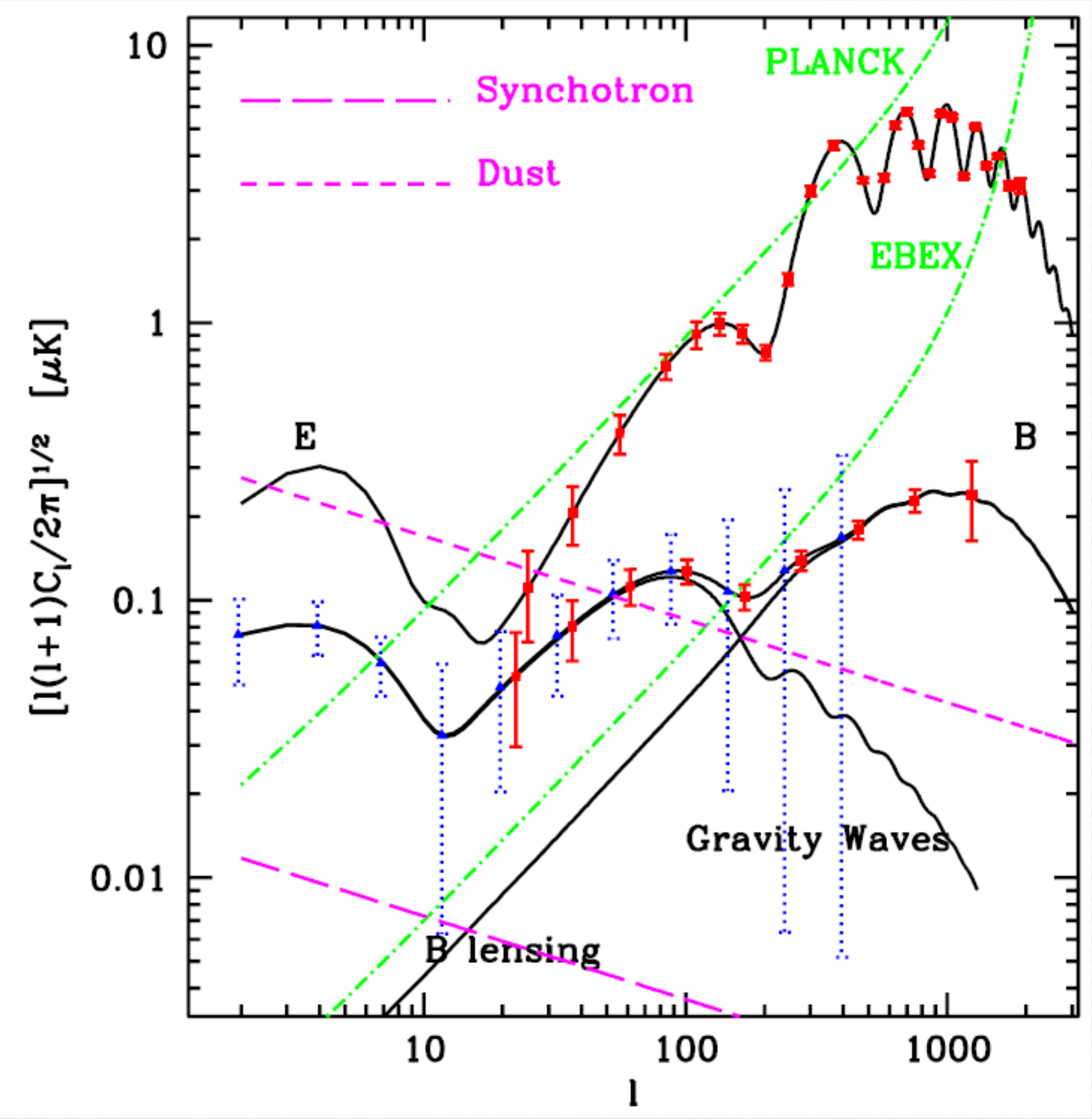


- PolarBear: AT Lee (Berkeley)
  - Antenna-coupled bolometers
  - 900 pixels @ 150 GHz, 3000 bolometers
  - Full use of useful 150 GHz Field-of-view
  - New challenges: 1000s of bolometers (central limit theorem to the rescue????)

Design Principles

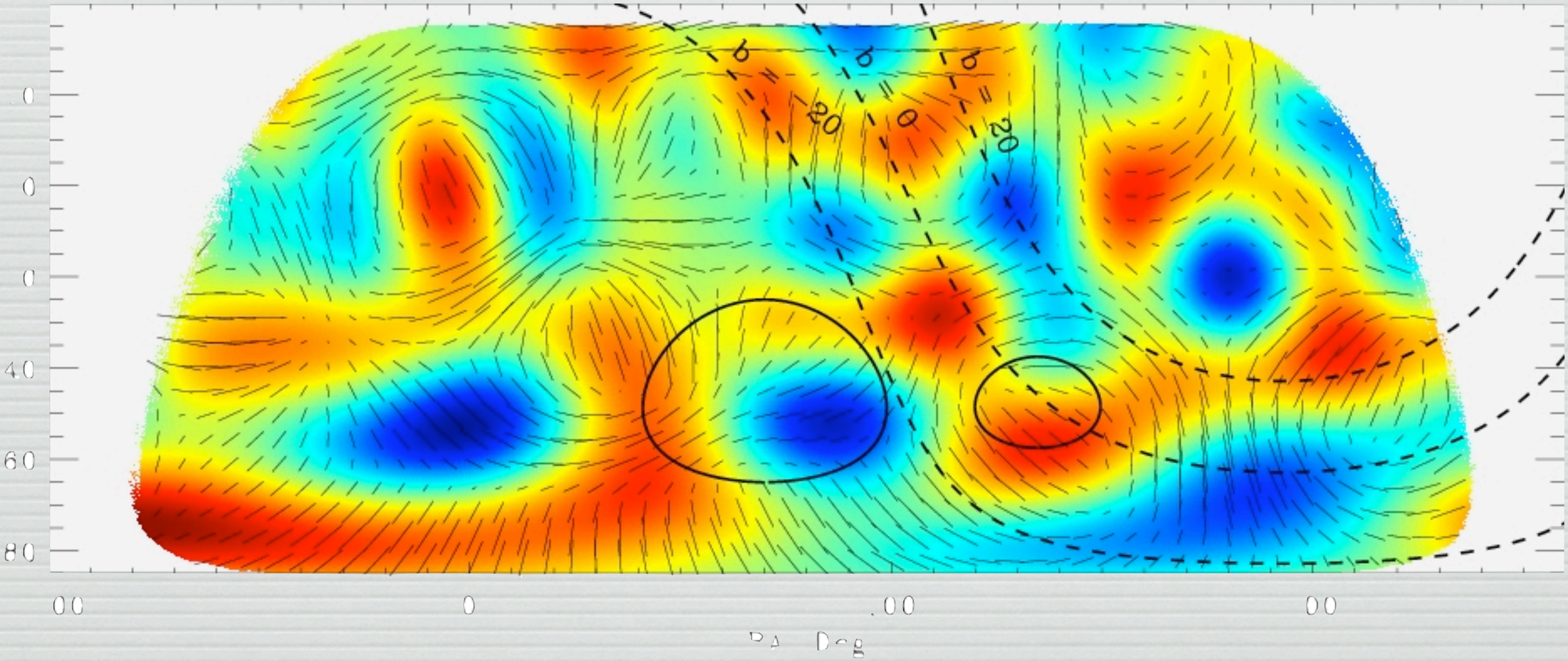
- Search for CMB B modes

- $\ell < 20$ from satellite; concentrate on $20 < \ell < 1500$
- Deal with only one foreground
- Use balloon to get firm handle on dust foreground
- Detect B lensing signal: ~x5 stronger than dust
- Provide strong rejection of polarimetric systematics
- Use available technologies where practical



SPIDER

- SPIDER (Caltech, CITA, Imperial -- Antarctic Balloon)
  - optimized for large scales



Future CMB Polarization Anisotropy Instruments (Ground-Based Only)

Currently operating or already have data in hand

- CAPMAP (HEMT) – N. Hemisphere (New Jersey, USA)
  - Princeton, Chicago, Miami, JPL
- DASI (HEMT – Interferometer) – S. Hemisphere (South Pole)
  - Chicago, Caltech, JPL
- CBI (HEMT – Interferometer) – S. Hemisphere (Atacama Desert, Chile)
  - Caltech, Chicago, JPL

Upcoming – tens of detectors

- QUEST (bolometer) – S. Hemisphere (South Pole)
  - Stanford, Cardiff, Chicago, Caltech, JPL, IPAC
- BICEP (bolometers) – S. Hemisphere (South Pole)
  - Caltech, JPL, Cardiff, San Diego
- AMIBA (HEMTs)
  - ASIAA, Physics Department of National Taiwan University, ATNF

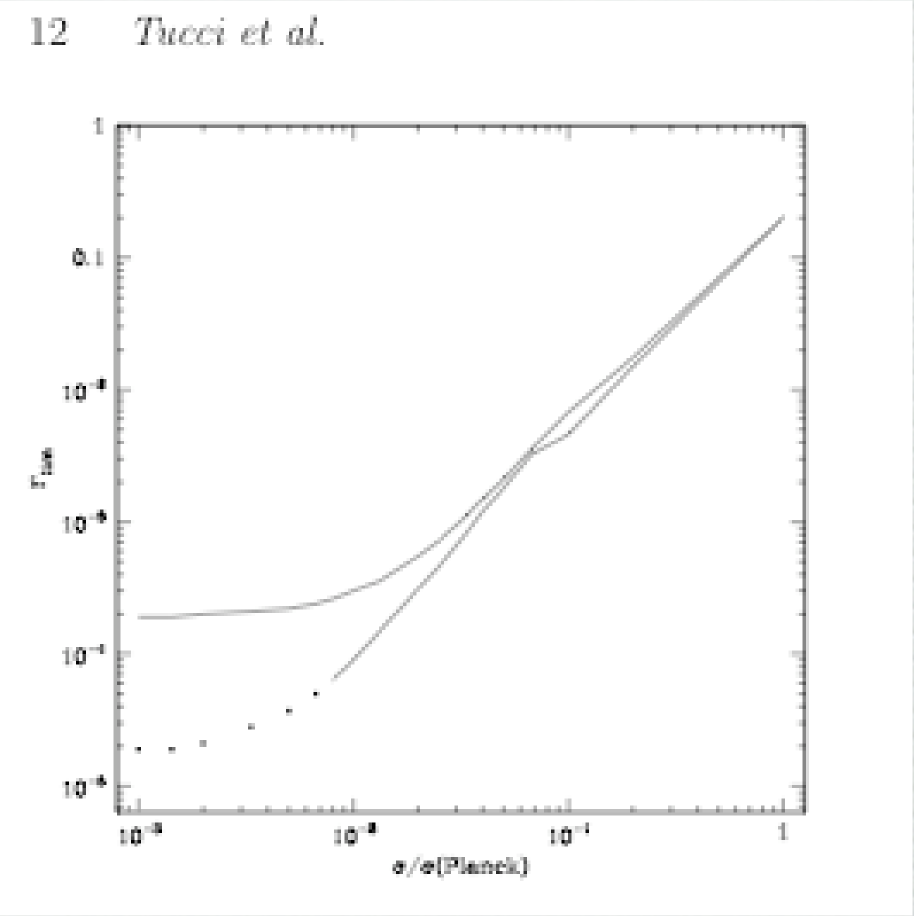
Upcoming – hundreds to thousands of detectors

- QUIET (HEMTs) – S. Hemisphere (Atacama Desert, Chile)
  - Caltech, Chicago, Columbia, JPL, Miami, Princeton, Berkeley, Harvard, GSFC
- PolarBear (bolometers) – N. Hemisphere (White Mountain, CA)
  - Berkeley, ?
- clover (bolometers) S. Hemisphere (Dome C, Antarctica)
  - Cardiff, Cavendish Astrophysics Group

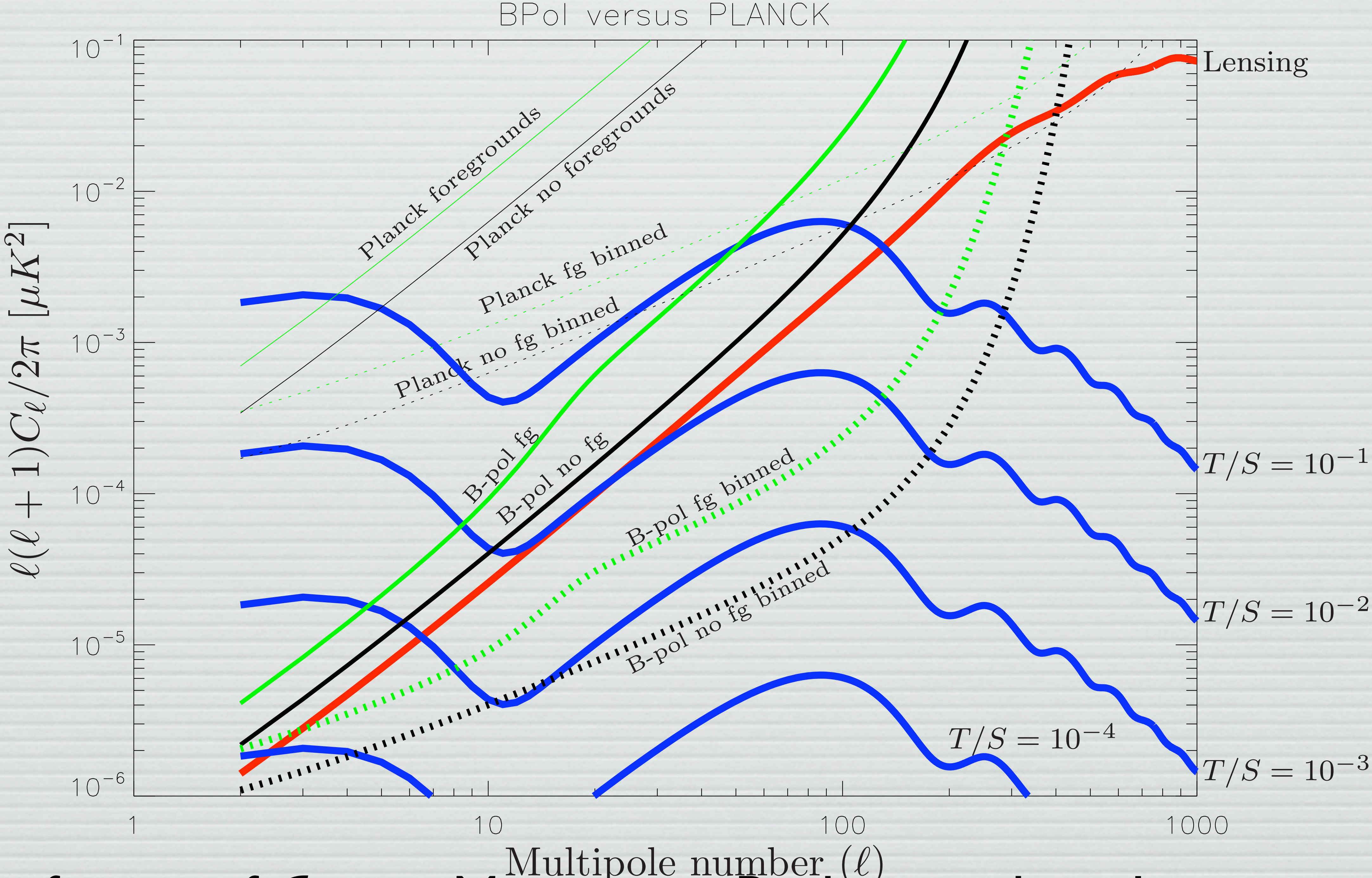
Courtesy A. Miller

Ultimate limits?

- Astrophysical foregrounds:
  - Multifrequency experiments for astrophysical foregrounds
- Lensing signal:
  - Large-scale structure cross-correlations
  - non-Gaussian extraction



Beyond Planck from Space: BPol



- The future of *Cosmic* Microwave Background exploration is likely foreground-limited.

Challenges for the future

- Polarized Forgrounds
- Getting around the lensing signal
  - cross-correlation?
- New systematic problems
  - intensity/polarization and Q/U leakage
- Data analysis
  - combine thousands of maps (with thousands of different beams) and some correlated noise?
  - central limit theorem is our friend?
  - (lots of technical stuff about optimality, Bayesian estimation, etc.)
  - non-Gaussianity

The future of CMB Studies

- Closes cosmological loopholes
  - qualitatively determine the background cosmogony
- Opens astrophysics from cm to sub-mm
- Next: high-sensitivity measurements of polarization (B-mode)
  - suborbital experiments (QUAD, CIOVER, SPIDER, PolarBear)
  - Cosmic Vision: BPol
- All of these require active collaboration with other wavelengths, techniques, theorists, data-analysts