The Dark Universe: Cosmology

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IOP HEPP/APP 2010

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The Dark Universe: Cosmology in 2010 and beyond

- A Standard Cosmological Model & its Parameters?
  - Inflation, Dark Energy
- Measurements at low and medium redshift: galaxies
  - oscillations in the baryons: characteristic scales and the growth of structure
- Measurements at high redshift: the CMB
  - Confirming the paradigm, measuring parameters
  - beyond: gravitational radiation
- Areas of discomfort?...

Do we have a standard cosmological model?

- Flat Universe
- Dark Matter
- Acceleration

Lots of unseen stuff…

- Inflation
- Dark Energy

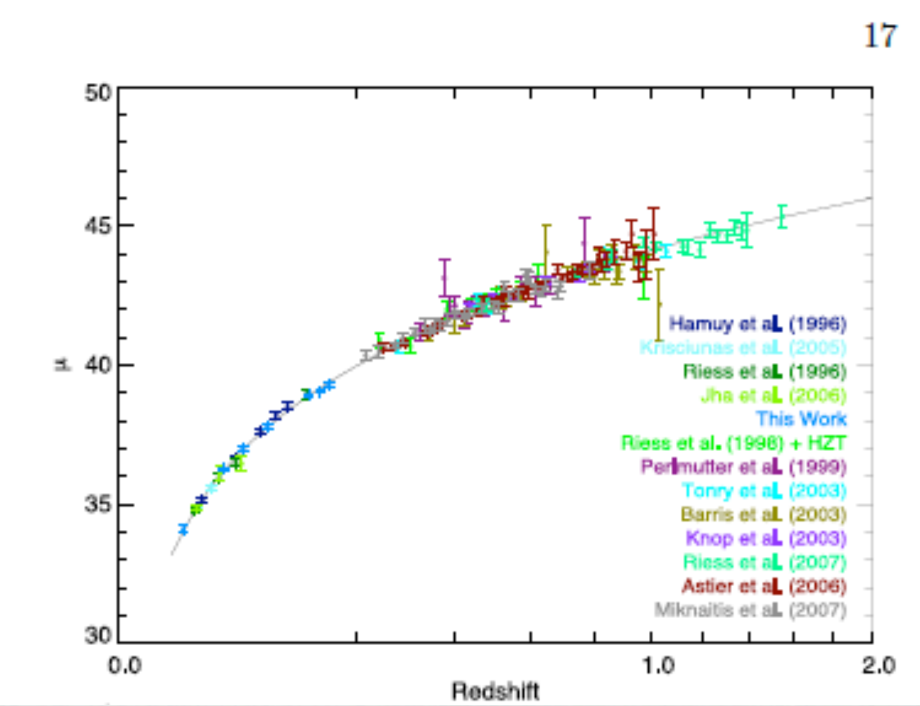
… with strange properties

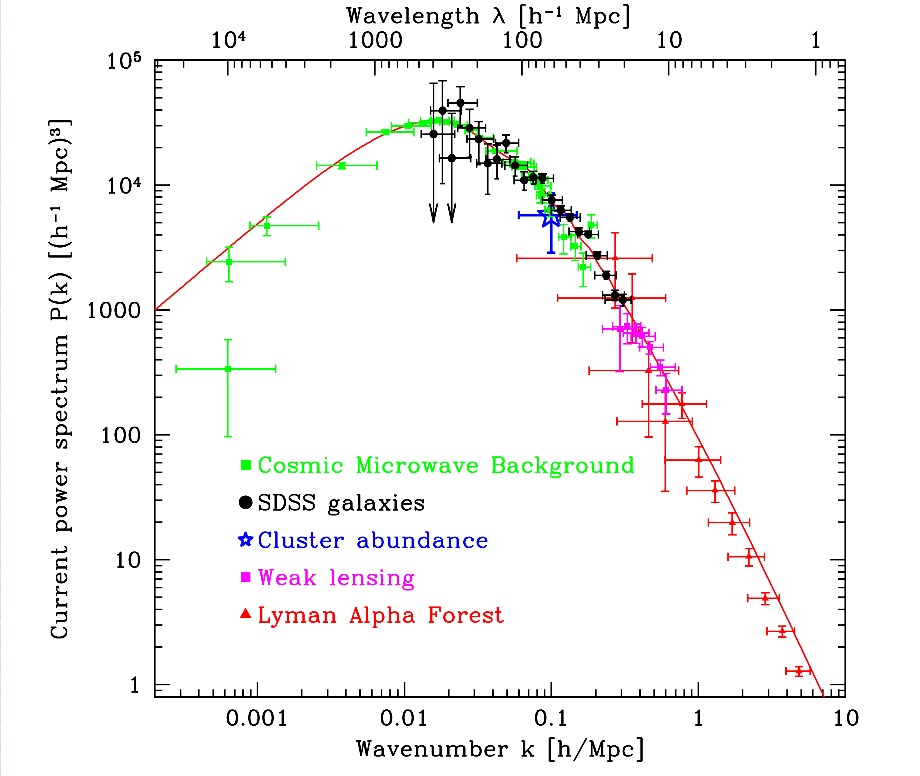
- Parameters
  - depend in detail on data and model

	Flat ΛCDM	Curved ΛCDM
Ω_{tot}	1	1.005±0.006
Ω_m	0.278±0.015	0.282±0.016
Ω_Λ	0.72±0.015	0.72±0.016
H_0	69.9±1.3 km/s/Mpc	68.5±2.0 km/s/Mpc

Measuring cosmological parameters

- The Hubble Diagram M(z)
  - Local: H_0
  - Distant: acceleration (q_0)
    - densities Ω_i
- Power spectra
  - Galaxies
  - CMB
  - Weak lensing
  - Velocities,
    cluster abundances, ...





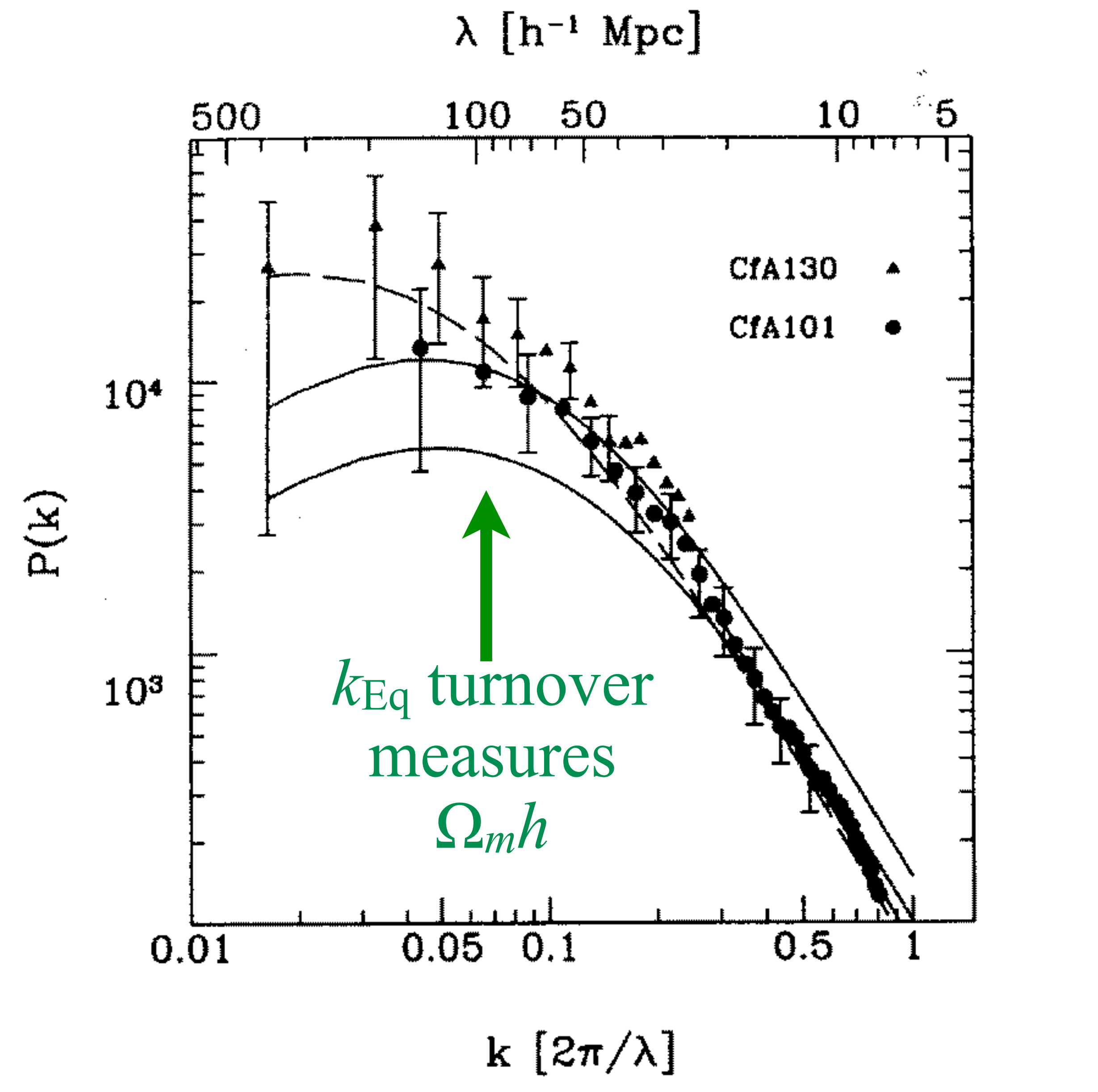
Statistical Cosmology

- Surveys as a cosmological tool ⇒ Power Spectra
- Initial conditions ⇒ Primordial spectrum
- Present day ⇒ processed power spectrum
- Linked via Transfer functions
  - for each kind of "power" measurement P_i
    - e.g., CMB C_ℓ, Galaxy spectrum $P(k)$

$$P_i = \int dk\, T_i^2(k) P_\varphi(k)$$

  - P_φ: primordial spectrum (of potential fluctuations)
  - $T_i(k)$ depends on the cosmological parameters

Power Spectrum of galaxies P(k)



- Old school: overall shape
- Growth of structure differs in early (radiation) and late (matter) epochs
  - turnover at $k_{eq} \propto H_{eq} \propto \Omega_m H_0$

2dF $\Omega_m = 0.27 \pm 0.06$

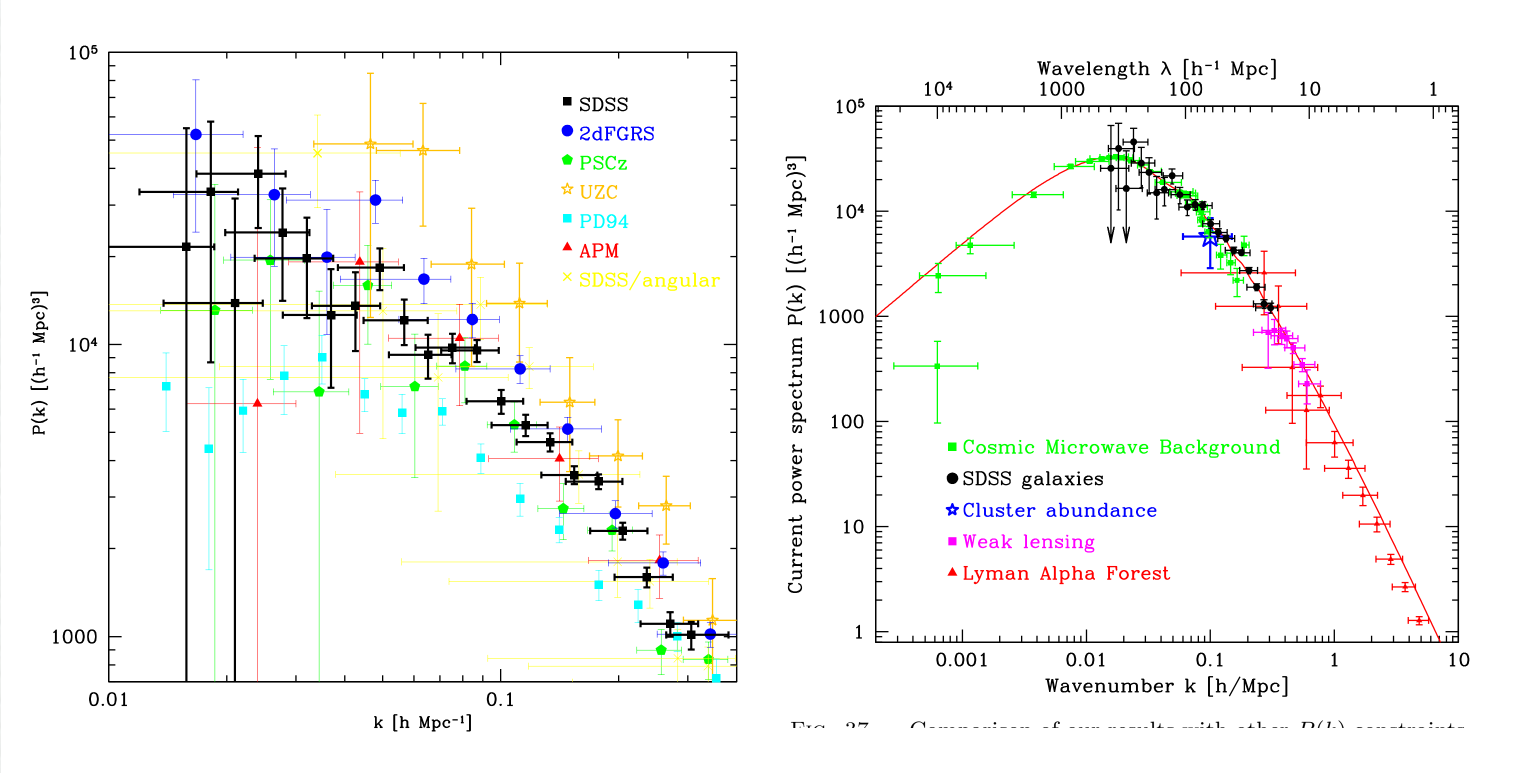
SDSS $\Omega_m = 0.30 \pm 0.03$

But now we can see detailed structure in $P(k)$

CfA survey

Observations

- Big complication in practice: *bias*
  - we observe galaxy numbers, not mass
  - Model: $$\frac{\delta n}{n} = b\frac{\delta \rho}{\rho}$$
    - should be good on large scales…
  - Expect to see overall power-law behaviour with superposed oscillations -- sound waves.



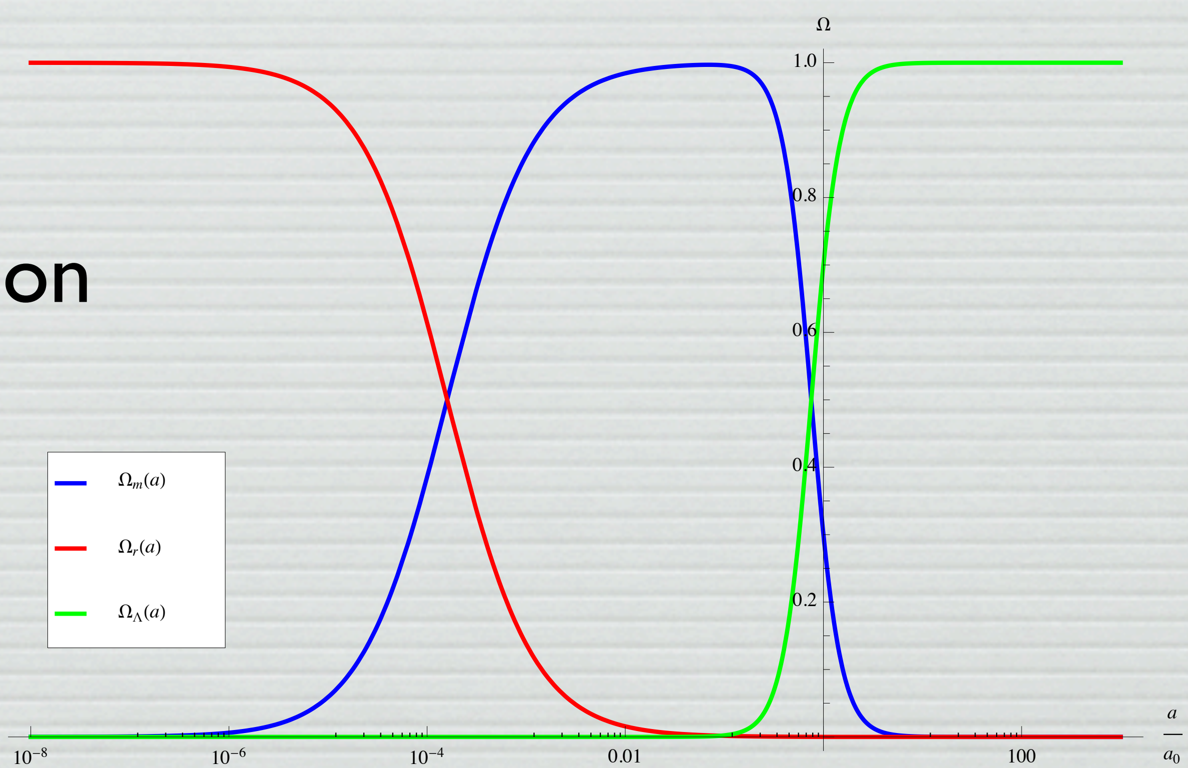
Sloan Digital Sky Survey
Tegmark et al '03

Inflation

- Early period of accelerated expansion, followed by reheating into radiation-dominated Universe of standard model particles
  - Predicts flat ✓, smooth ✓, hot big-bang ✓ Universe
  - usually realized by slowly-rolling scalar field, $V \approx \rho \approx -p$
    - "chaotic inflation" & questions of the correct measure for initial conditions
  - density perturbations via quantum fluctuations (cf. Hawking radiation)
    - Scale-invariant: $n_s \approx 1$ ✓
    - Gaussian (described by power spectrum) ✓
    - Adiabatic (perturbation to all species) ✓
  - Also predicts background of gravitational radiation
    - Amplitude depends on epoch of inflation
    - (possibly) observable in CMB polarization (not yet)

The Accelerating Universe: Dark Energy

- Universe appears to be accelerating *again*, today
  - (no compelling models yet linking the two periods…)
- Dark energy affects
  - luminosity and angular diameter distances
    - objects further away than "expected"
  - the growth of structure
    - accelerated expansion counters gravitational attraction



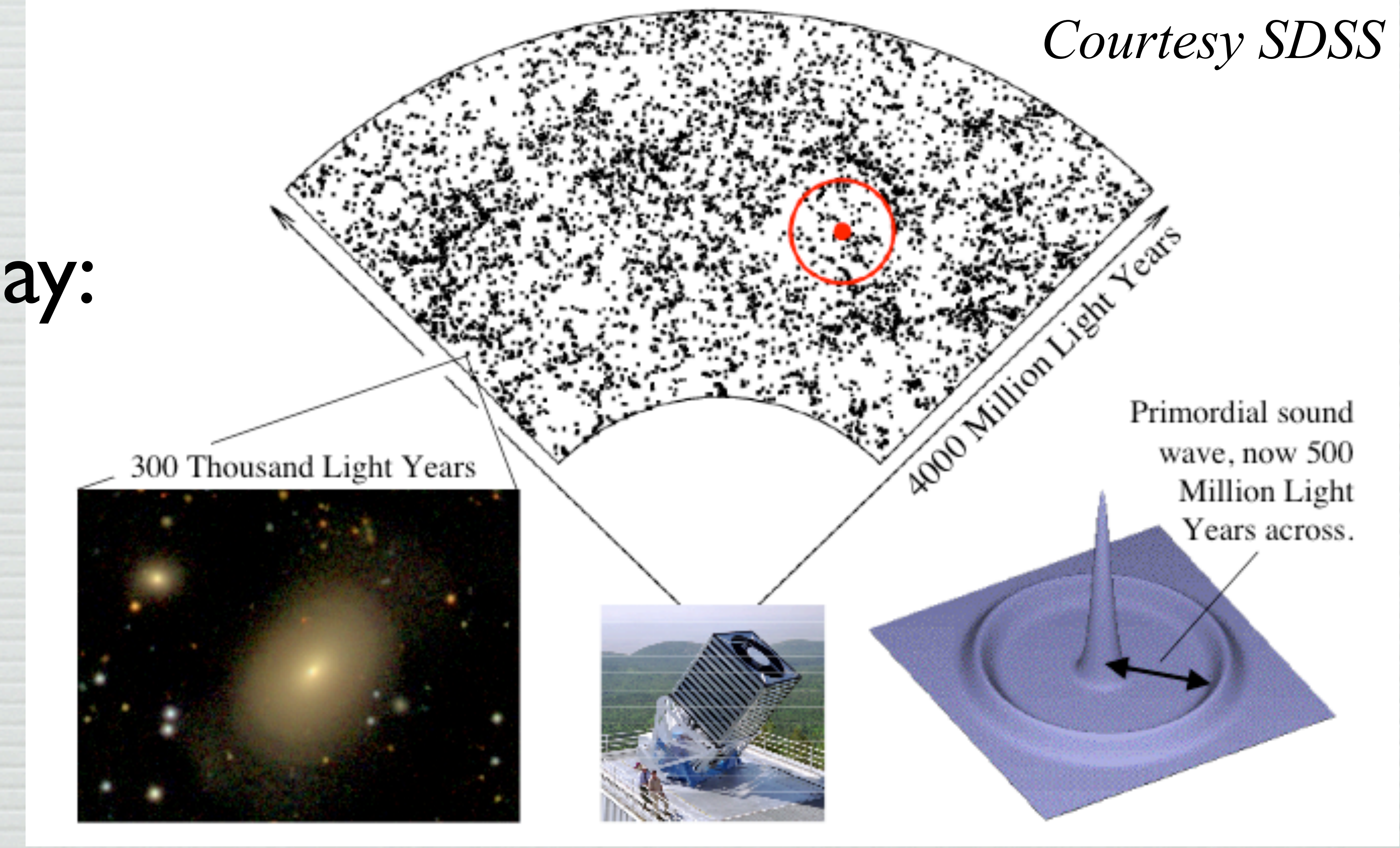
- In standard cosmologies, only since z~1
  - dark energy is only beginning to dominate today.

Dark Energy Models

- Scalar Field Models ($T_{\mu\nu}$)
  - like inflation, but need to delay to T~10K~1 meV (but no reheating…)
- Modified Gravity (lhs of Einstein Equation, $G_{\mu\nu}$)
  - e.g., change coupling in Einstein-Hilbert action — f(R) gravity
- Require equation of state
  - $w = p/\rho < -1/3$ (needed for acceleration)
  - (although $w \approx -1$ typical)

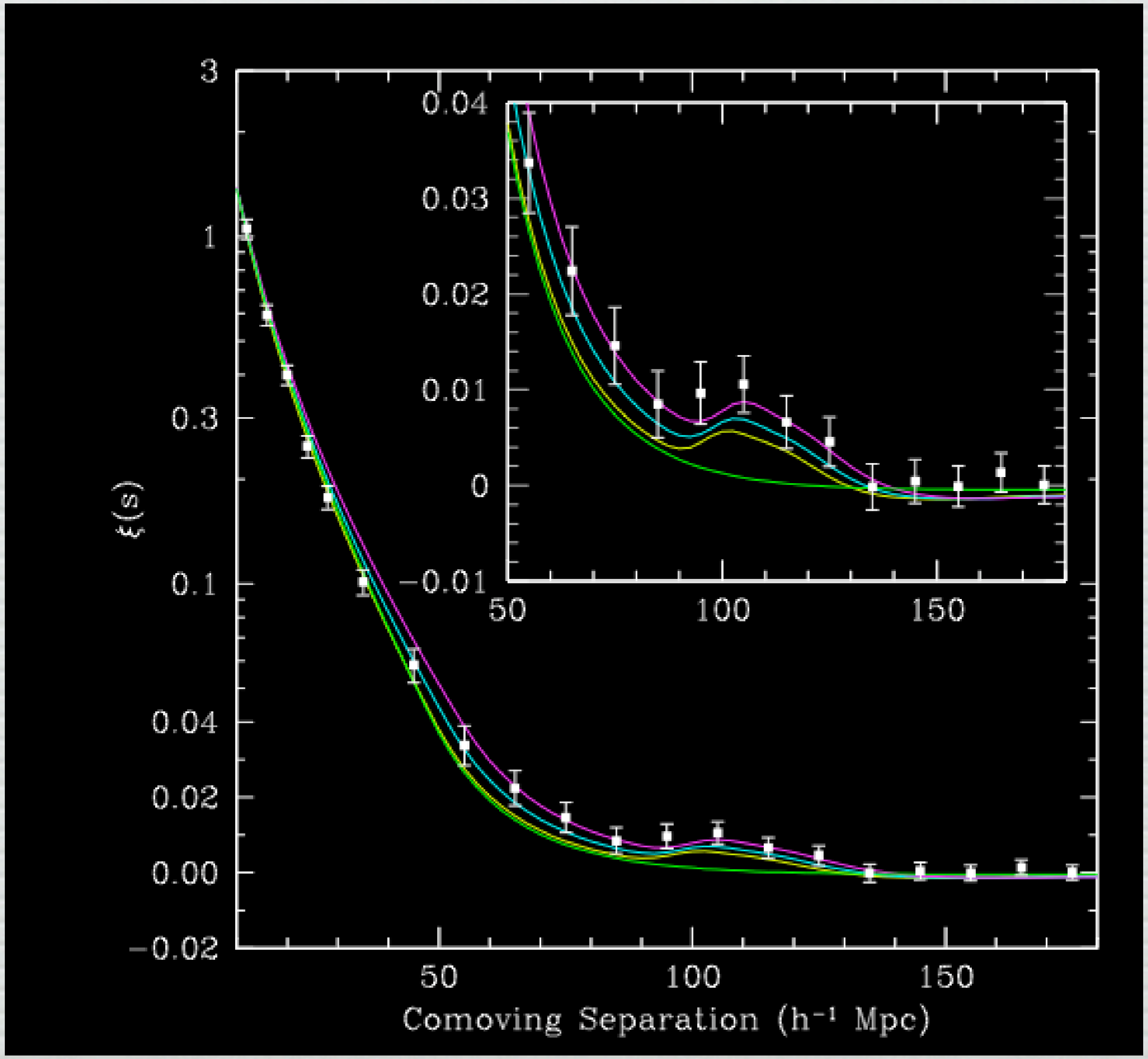
Probing the power spectrum: Baryon Oscillations

- At photon decoupling, early sound waves are trapped in the (now ~pressureless) baryons
  - characteristic scale ~$c_s\ t_{dec}$~100 Mpc
- Direct view
  - CMB
- Evolution to today:
  - BAOs from P(k)



Baryon Acoustic Oscillations

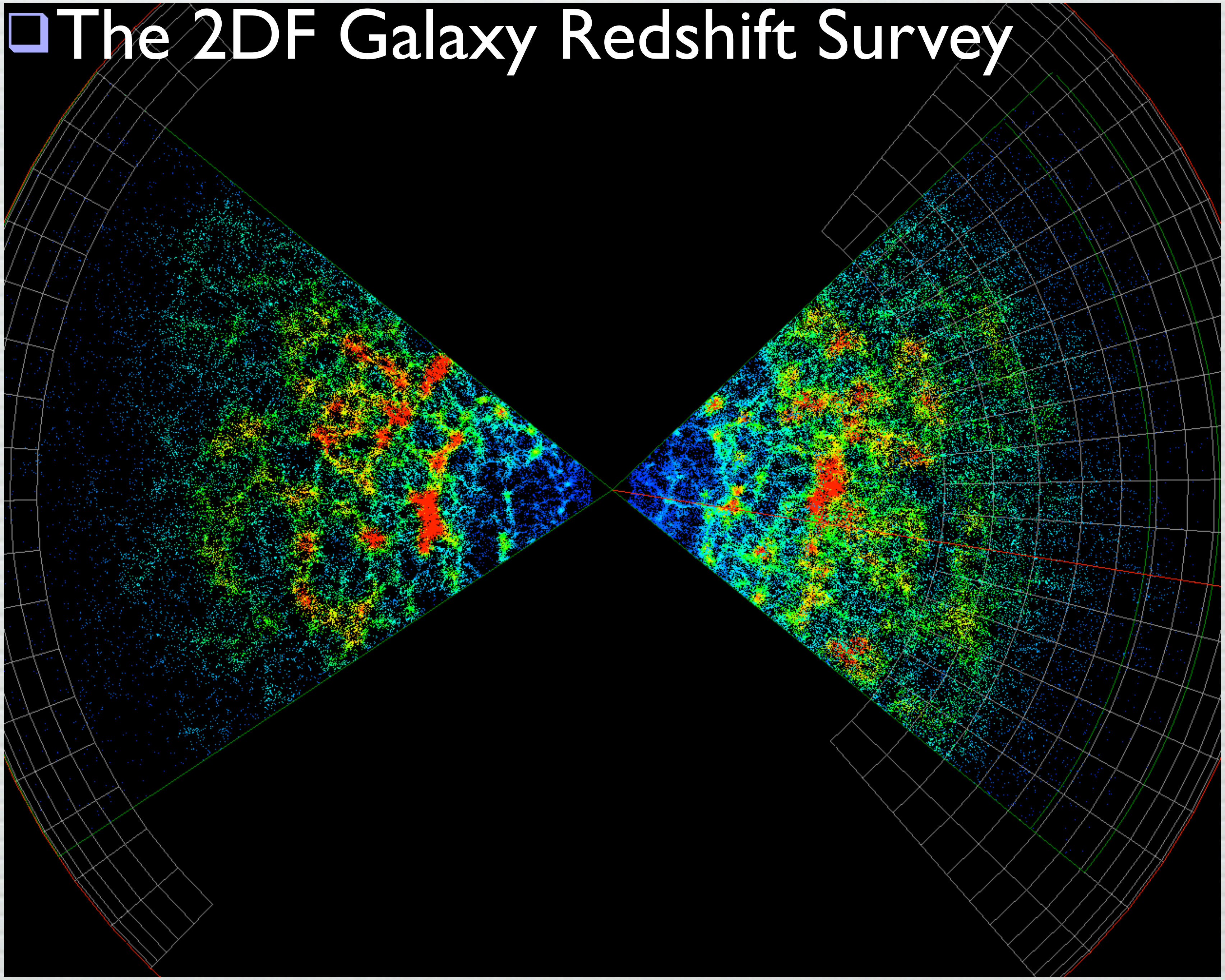
- See peak in correlations at ~100 Mpc corresponding to sound-wave propagation



SDSS Galaxy Correlation function

BAOs from Redshift Surveys

- Also visible as bumps and wiggles in the power spectrum



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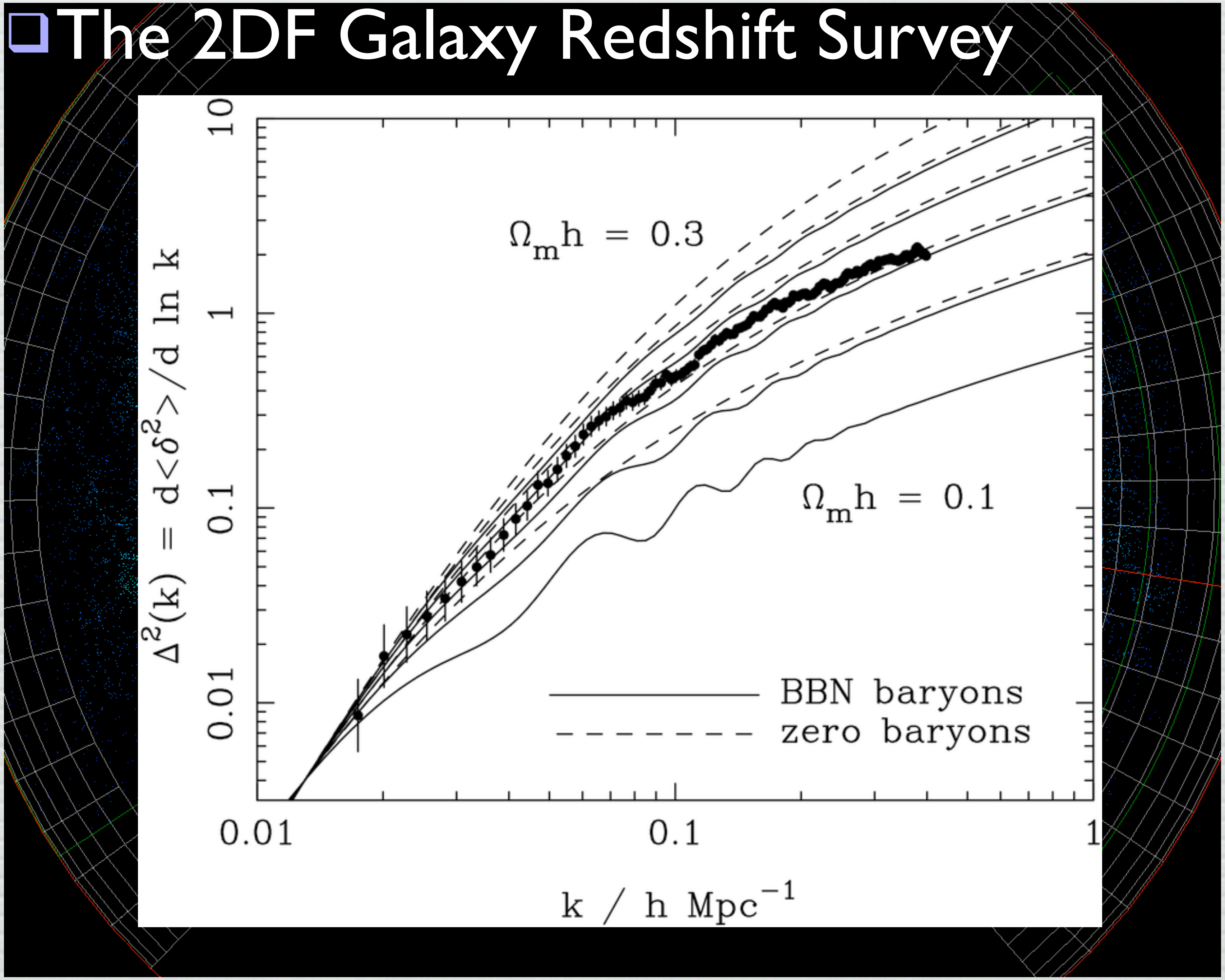
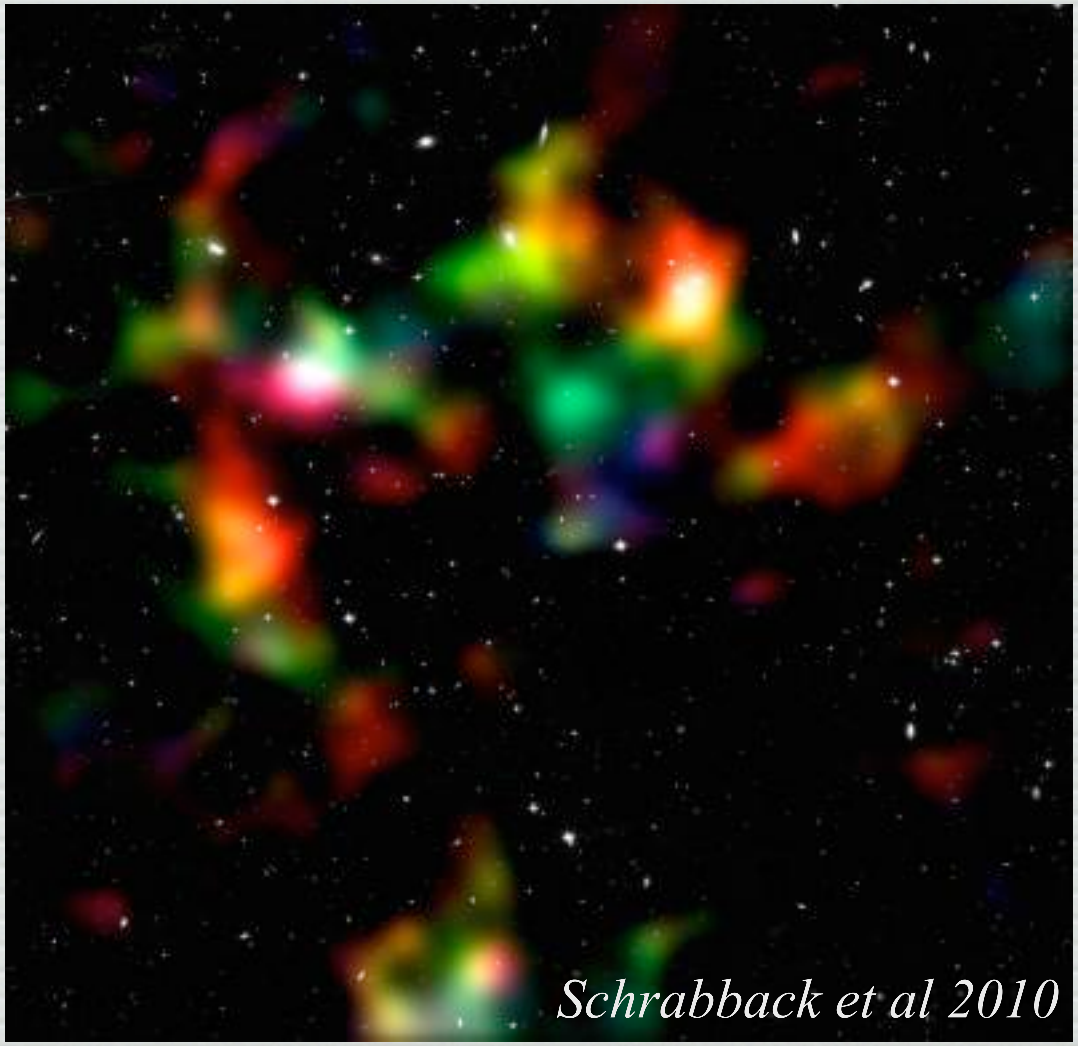


Exploring Dark Energy

- BAOs: characteristic comoving scale ~100 h^{-1} Mpc
  - Angular diameter distance $d_A(z)$
    - compare CMB peak $d_A(1,100)$
    - photometric redshift surveys
- Effect of dark energy on the growth of structure over time
    - weak lensing (also sensitive to d_A)
      - power spectra & transfer fn
- "Direct" measurements of the Hubble diagram $d(z)$
  - supernovae



Reconstructing the density field

Distant Galaxies and acceleration

- Going beyond z=0.1 to measure the shape of the Hubble diagram
  - Determining Ω:
  - SNae are dimmer than would be if $\Omega_\Lambda=0$
  - ⇒accelerating expansion
  -

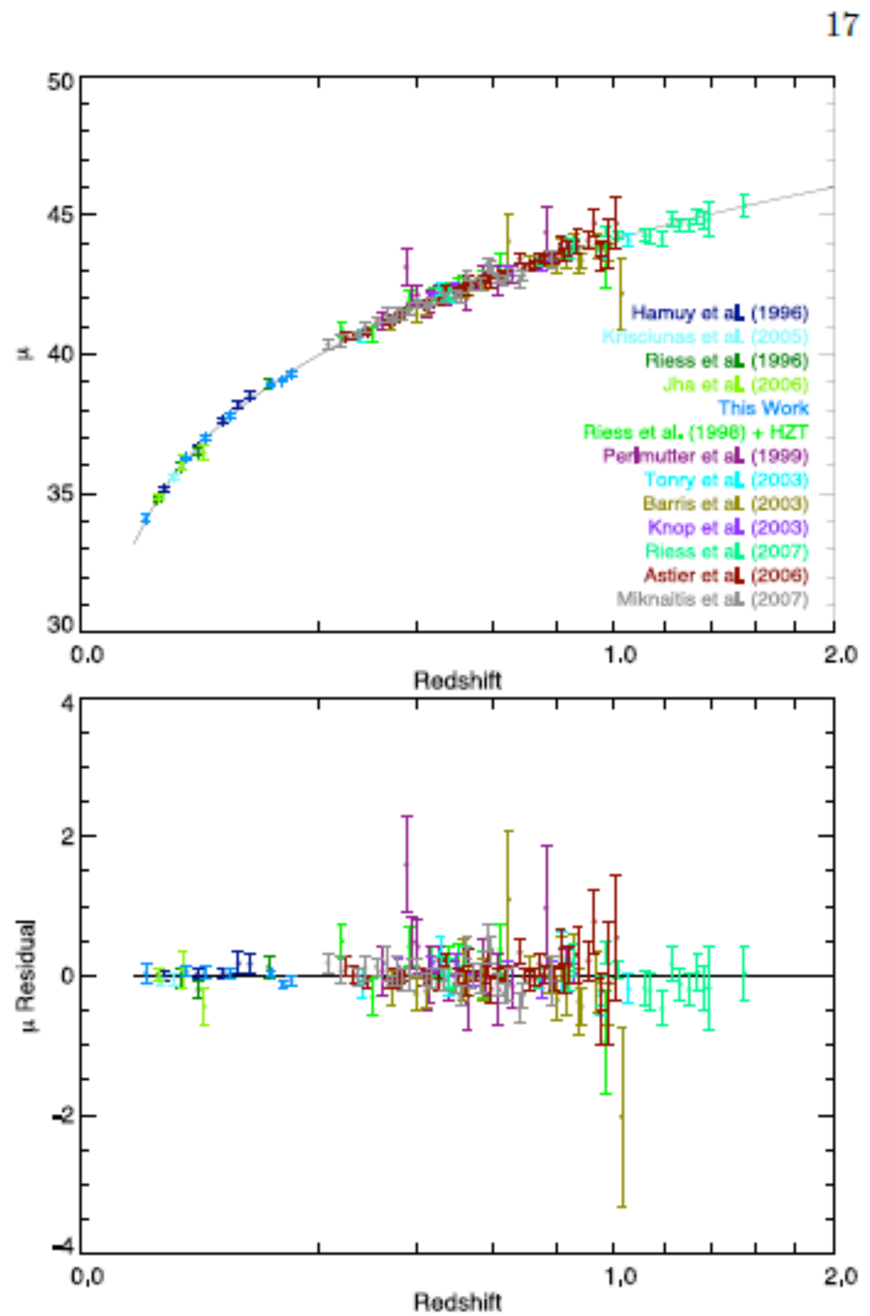


FIG. 10.— Top: Binned Hubble diagram (bin-size $\Delta z = 0.01$). Bottom: Binned residuals from the best fitting cosmology.

Kowalski et al 2008

Future surveys

- DES, BOSS (SDSS-III), WIGGLEZ
- Various combinations of
  - SN search
  - redshift surveys
  - weak lensing observations
  - cluster abundances

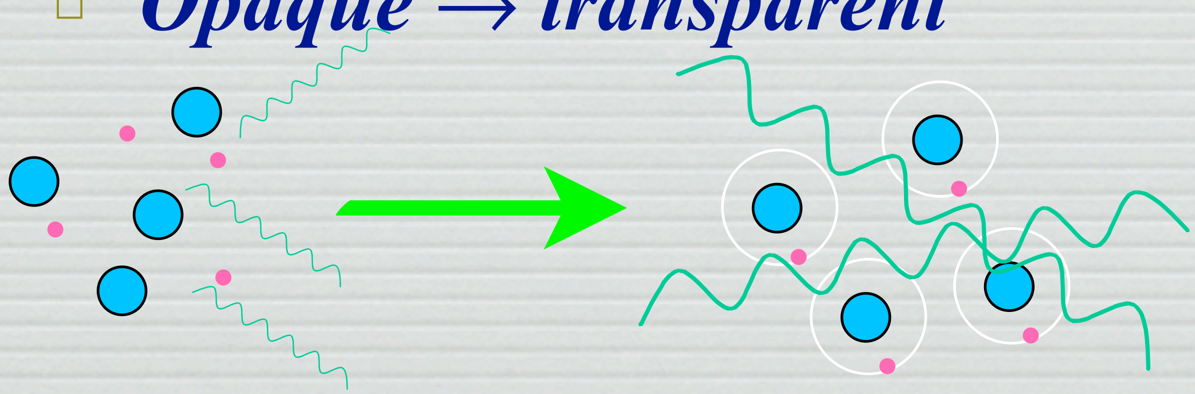
Detect ~10% deviations from $w = -1$

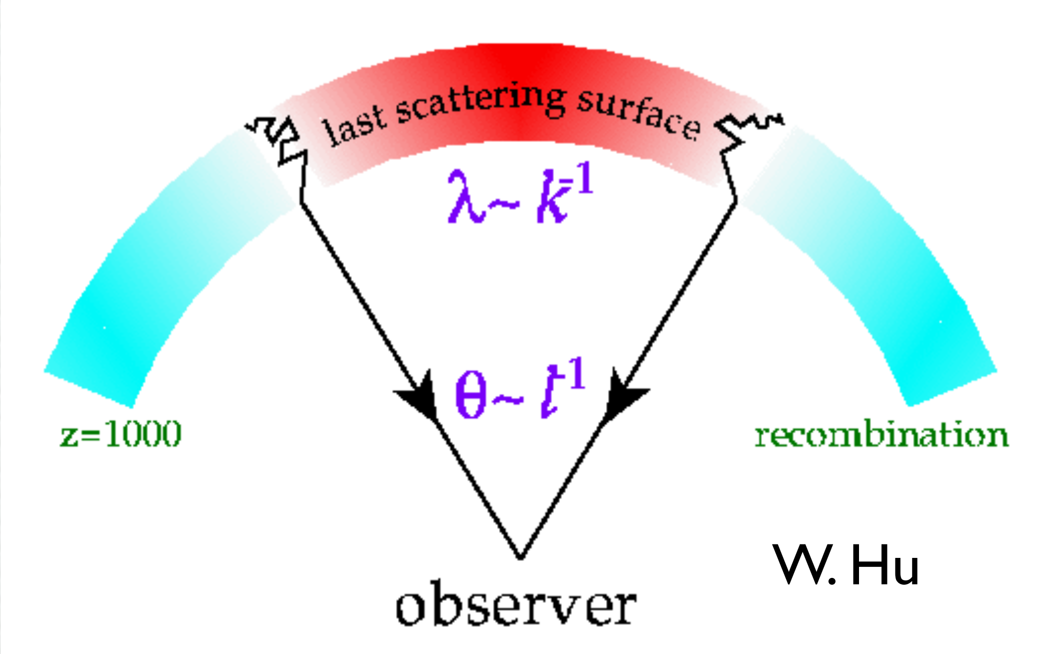
- Culminates with EUCLID/JEDAM/… satellite
  - goal: measure $w(z)$

- In very general models, $w(z)$ is degenerate with primordial spectrum, galaxy evolution, etc…

The Cosmic Microwave Background

- 400,000 years after the Big Bang, the temperature of the Universe was T~10,000 K
- Hot enough to keep hydrogen atoms *ionized* until this time
  - ***proton + electron → Hydrogen + photon*** [$p^+ + e^- \to H+\gamma$]
  - ***charged plasma → neutral gas***
- Photons (light) can't travel far in the presence of charged particles
  - ***Opaque → transparent***



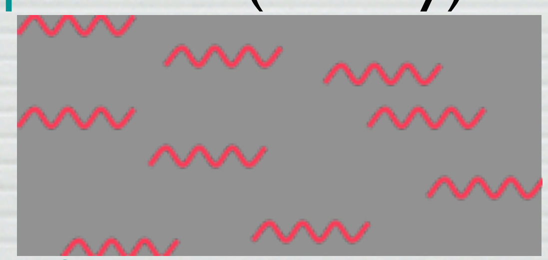


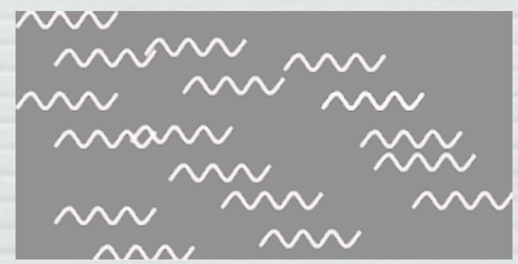
What affects the CMB temperature?

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

- Initial temperature (density) of the photons

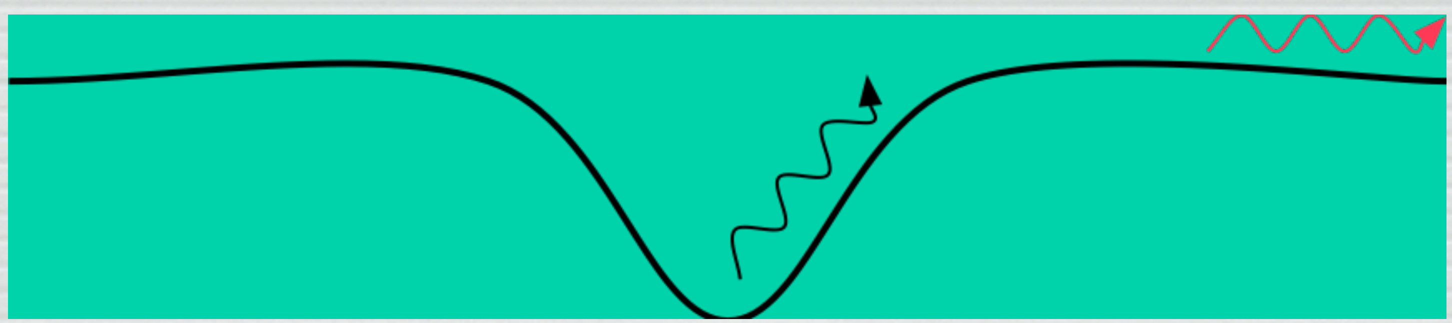
Cooler





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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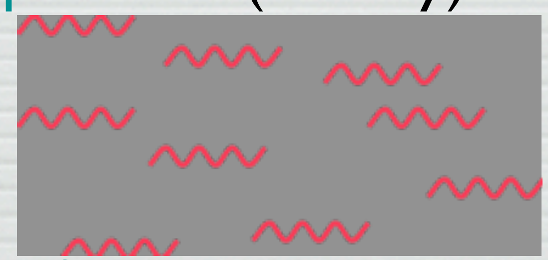
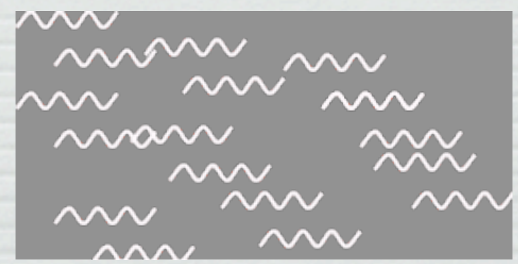
Cooler   Hotter

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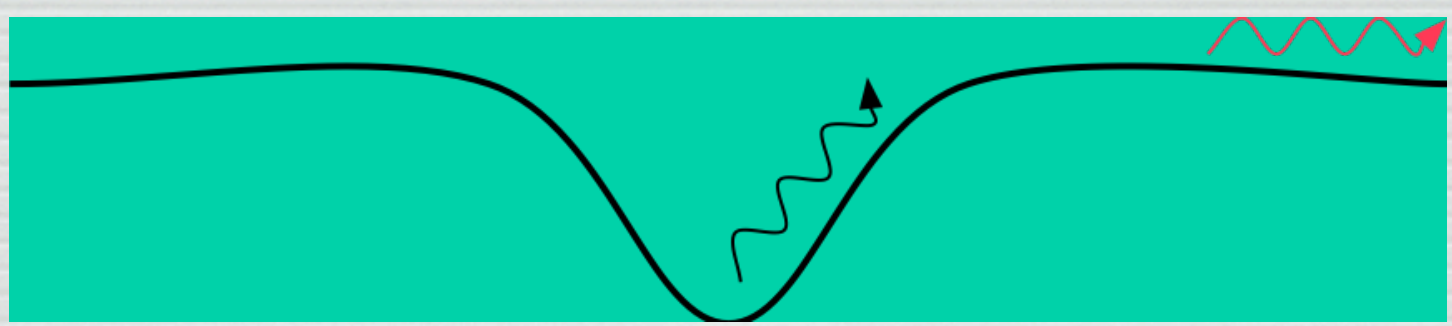

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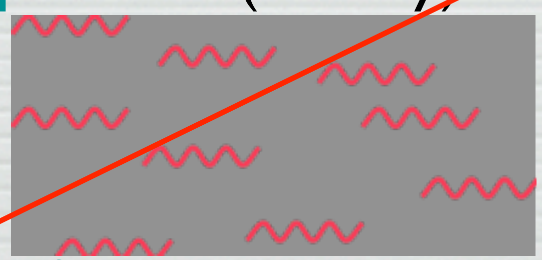

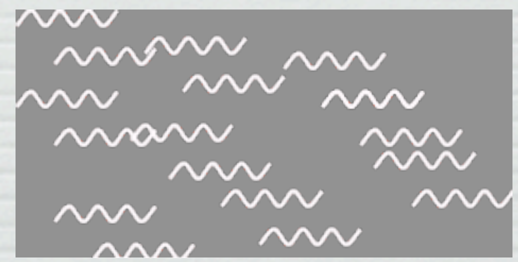

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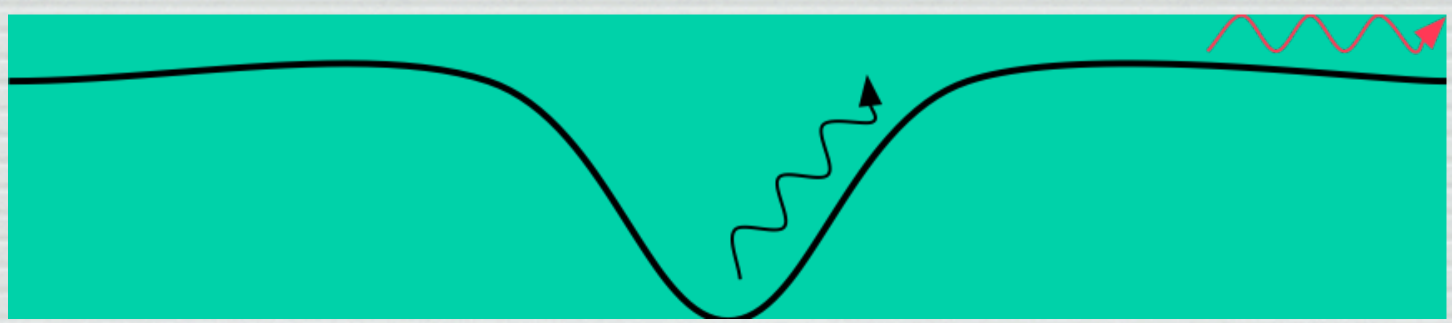

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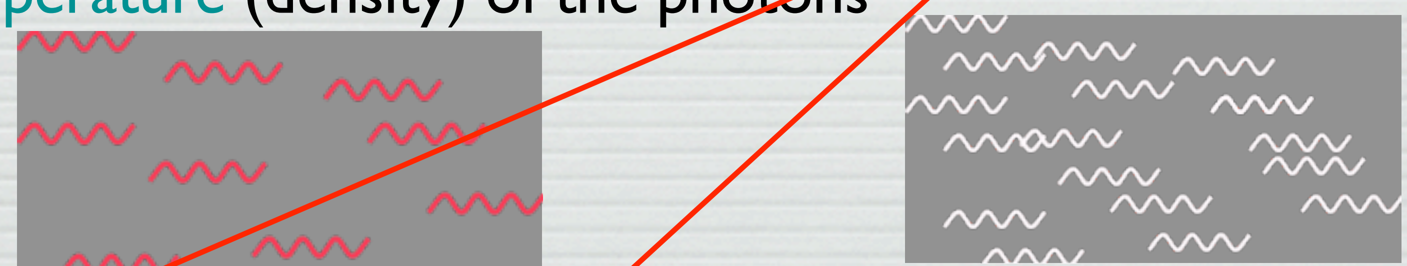

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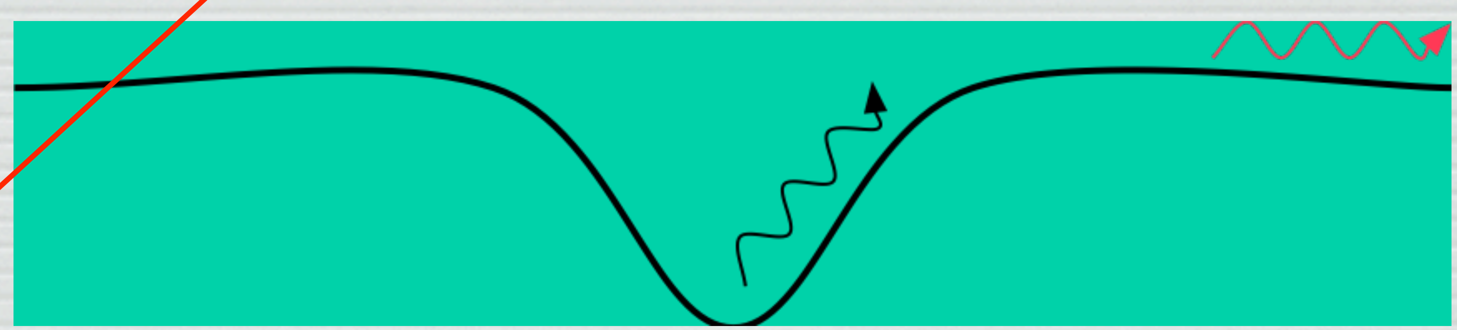

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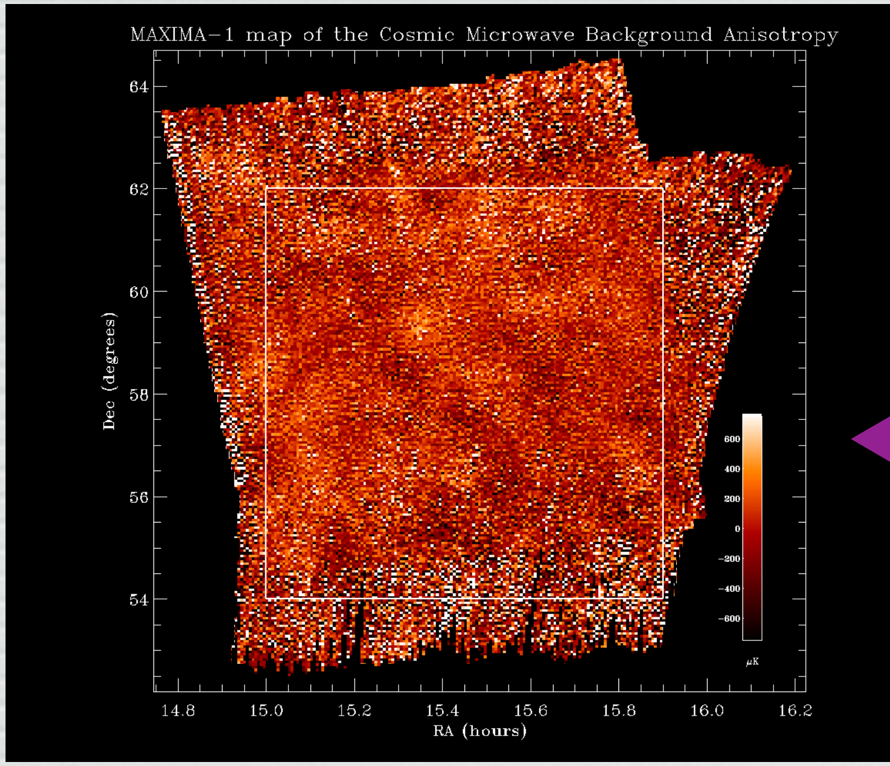
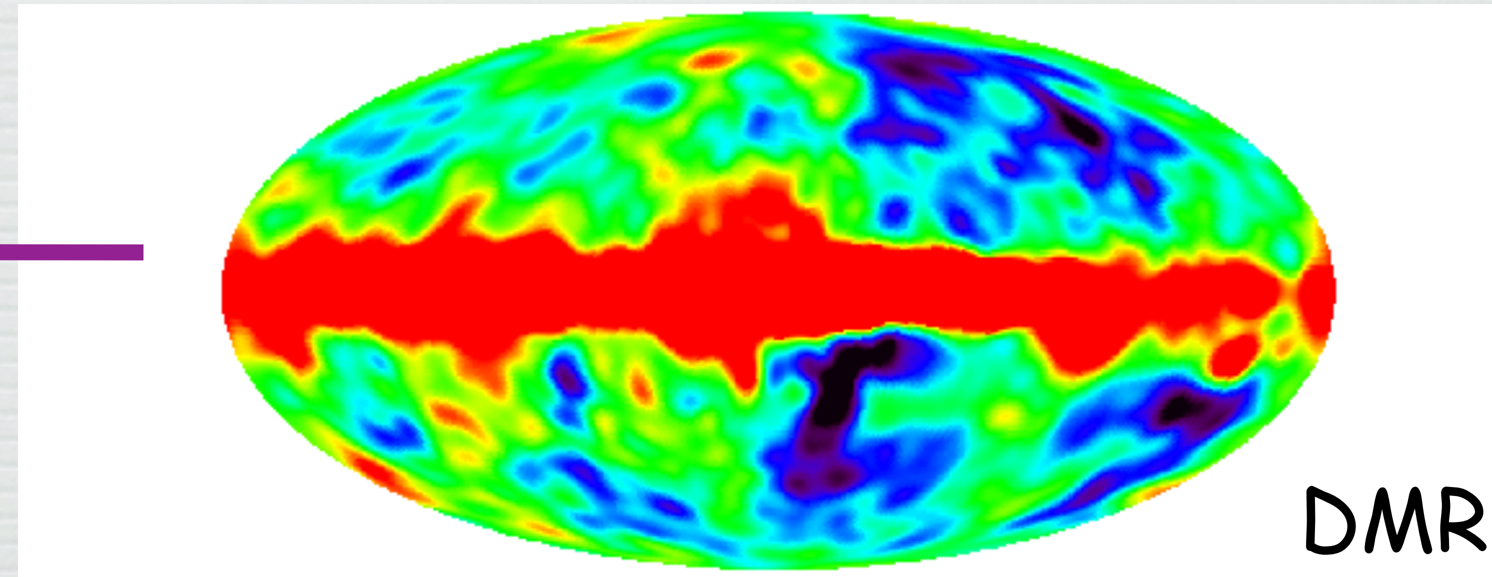
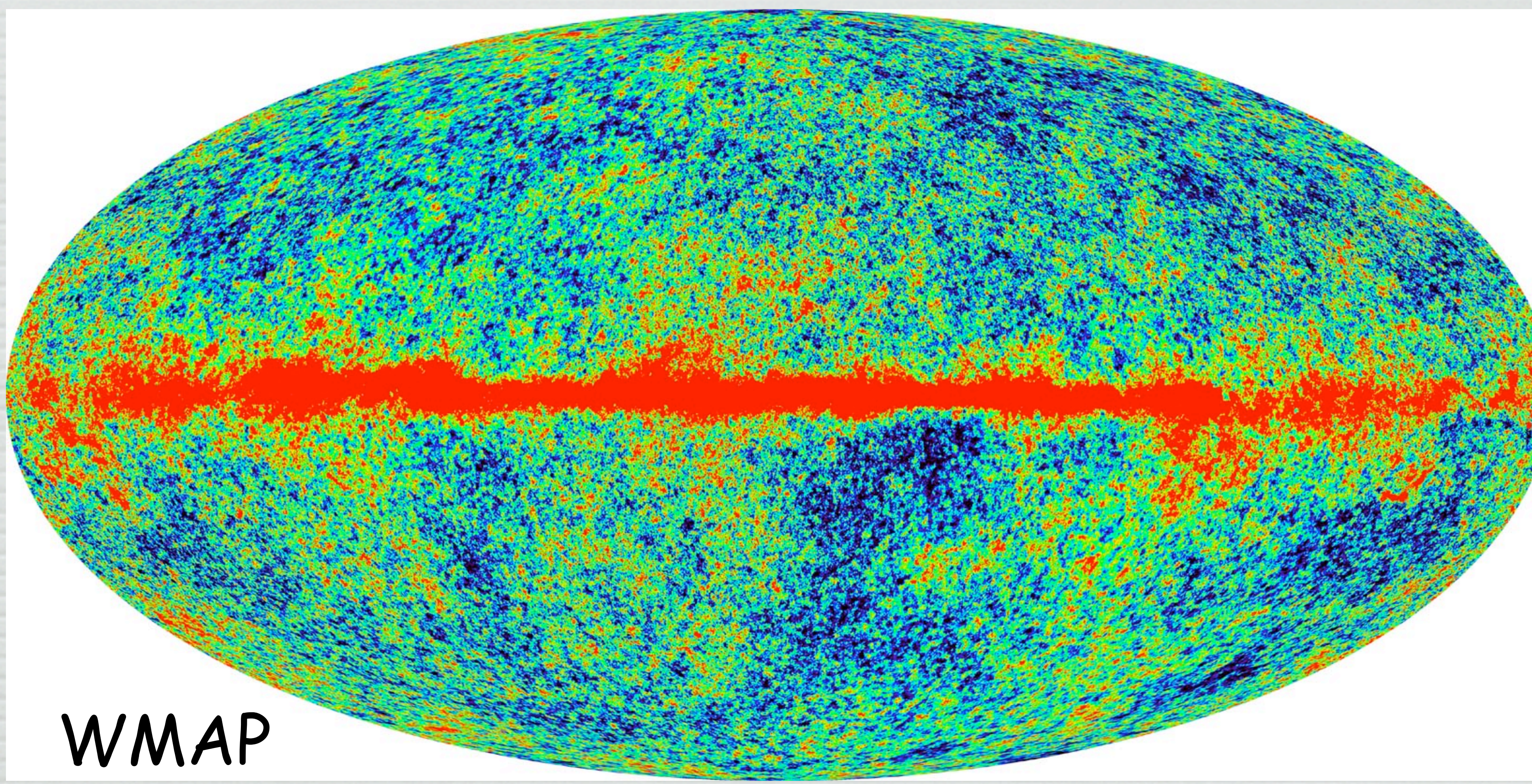
Maps of the Cosmos

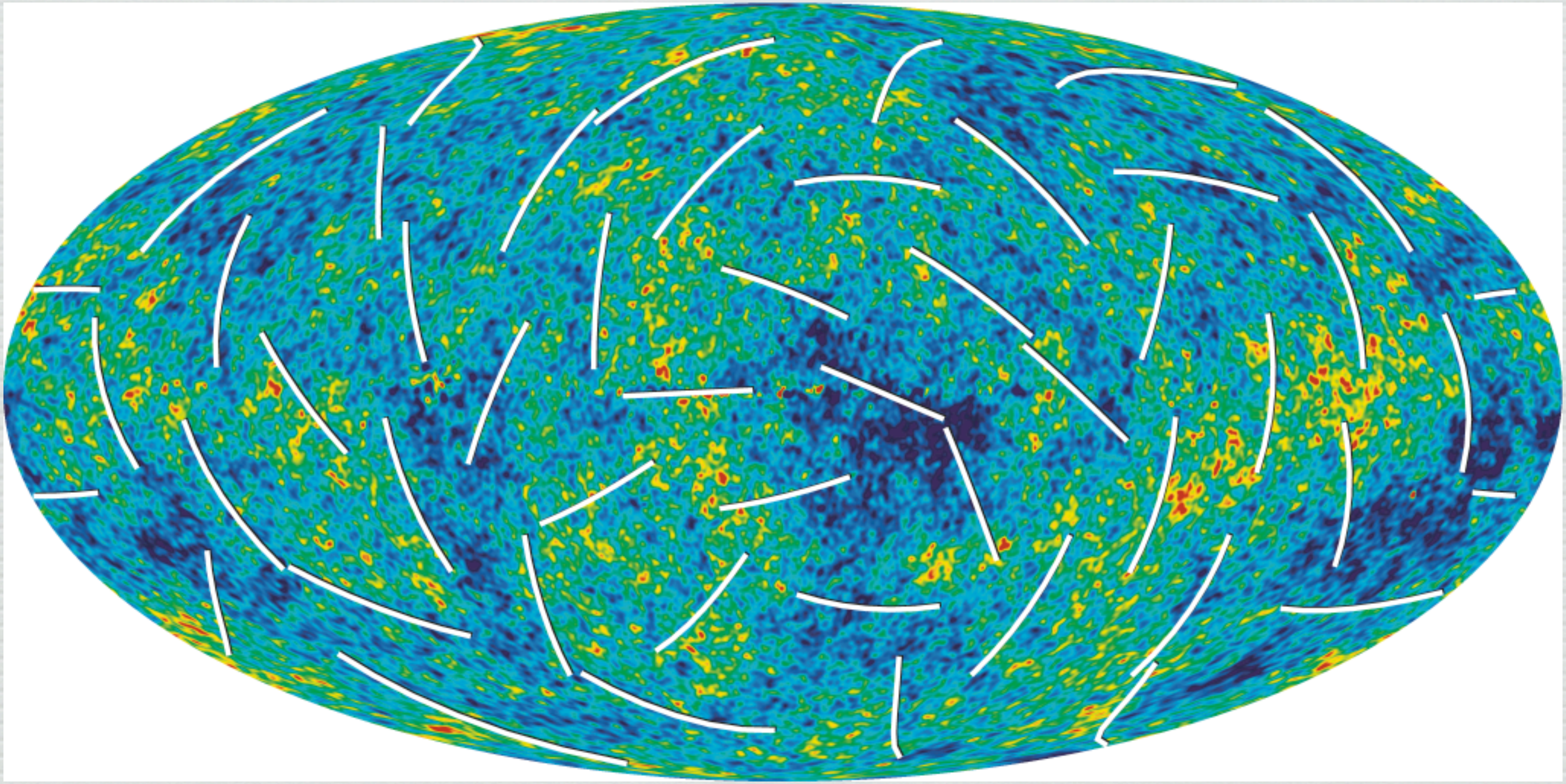


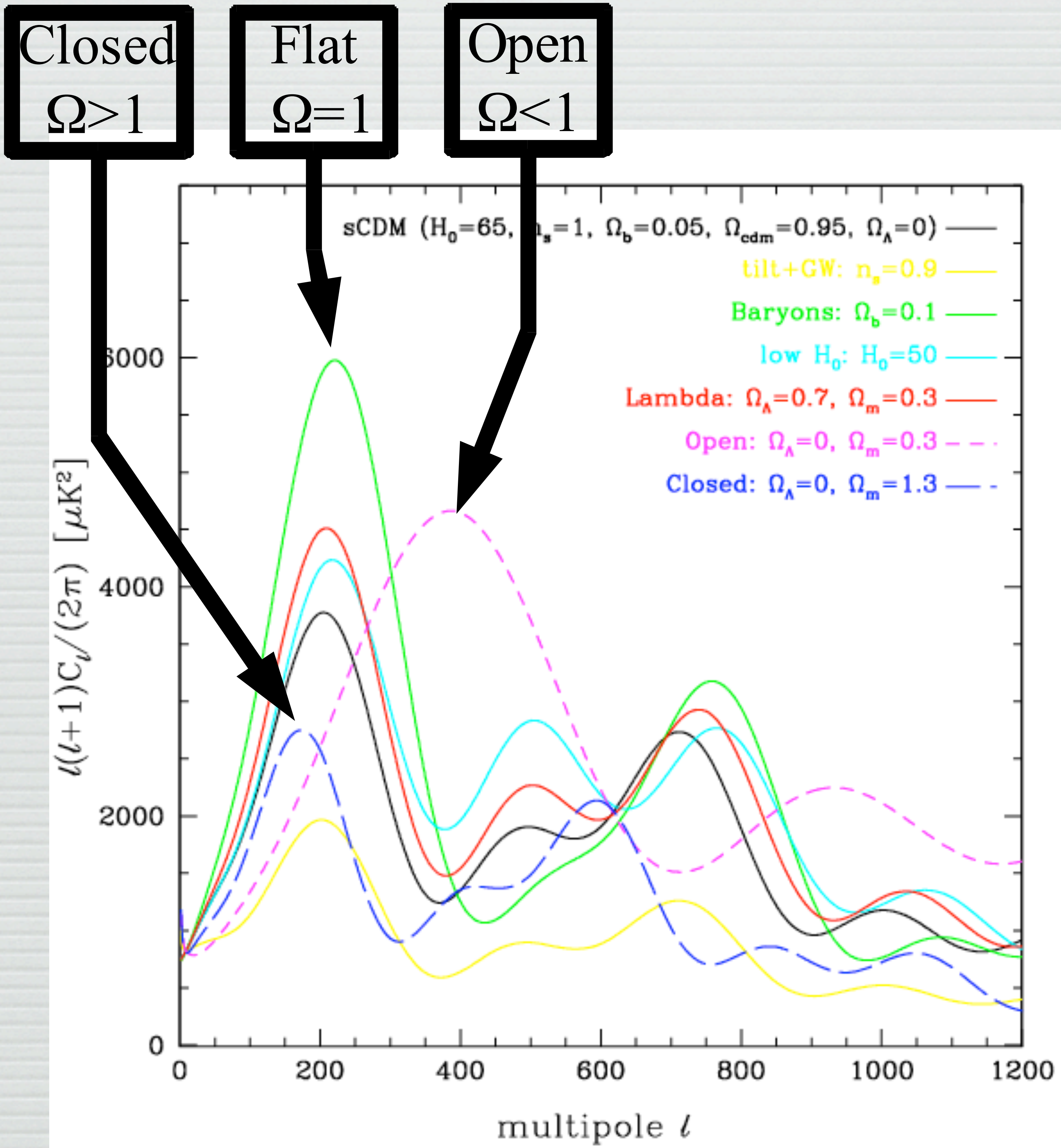
MAXIMA





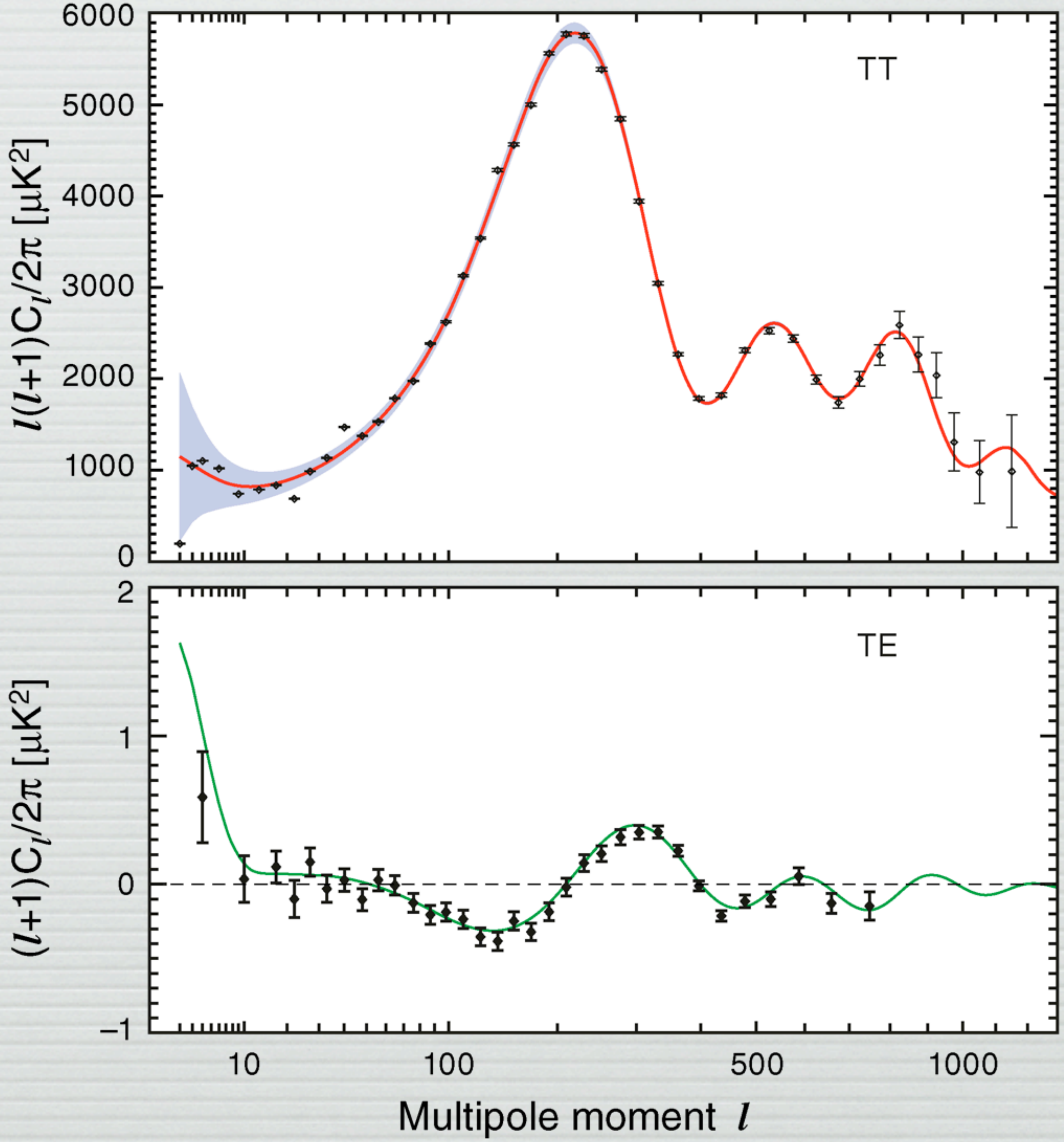
Temperature and polarization from WMAP





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
ℓ(ℓ+1)Cℓ/(2π) [μK²]
0
2000
4000
6000
0
200
400
600
800
1000
1200
multipole ℓ

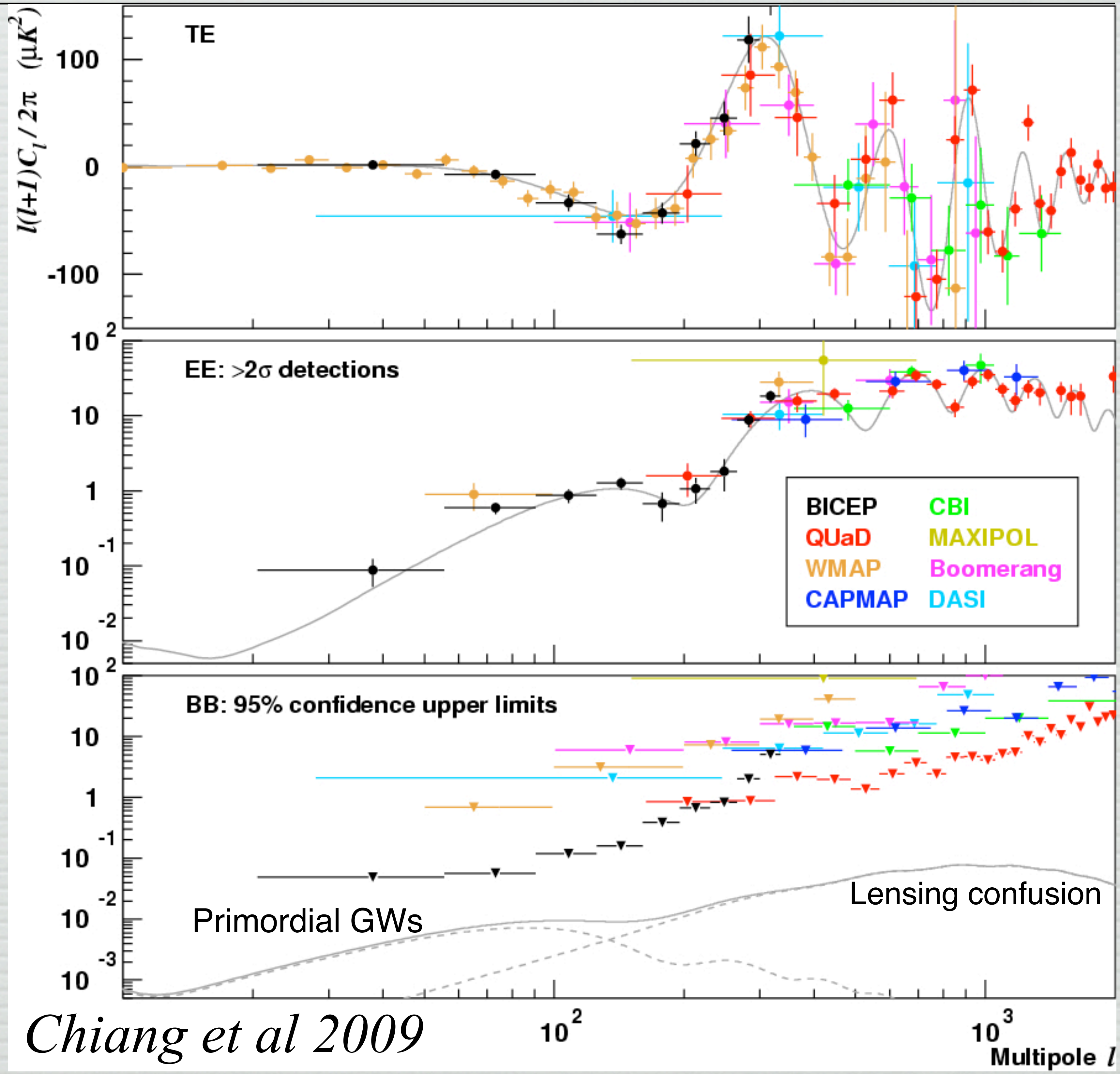
The CMB from WMAP: Temperature and Polarization



CMB Measurements: State of the Art

- Polarization

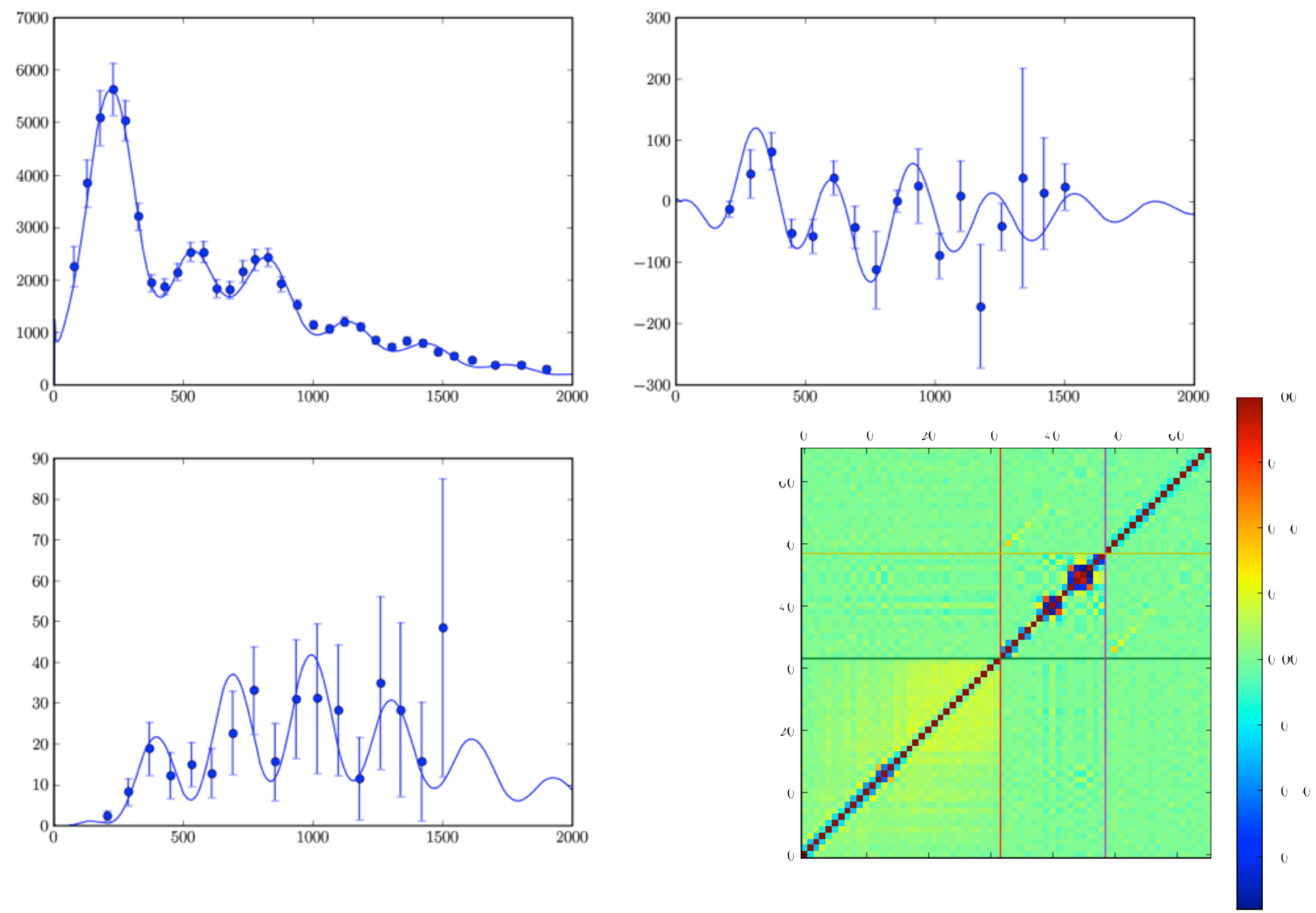
Polarization from Gravitational Radiation



Chiang et al 2009

The “unified” spectrum c. 2008

Contaldi & Jaffe



Planck: Launched on 14 May!

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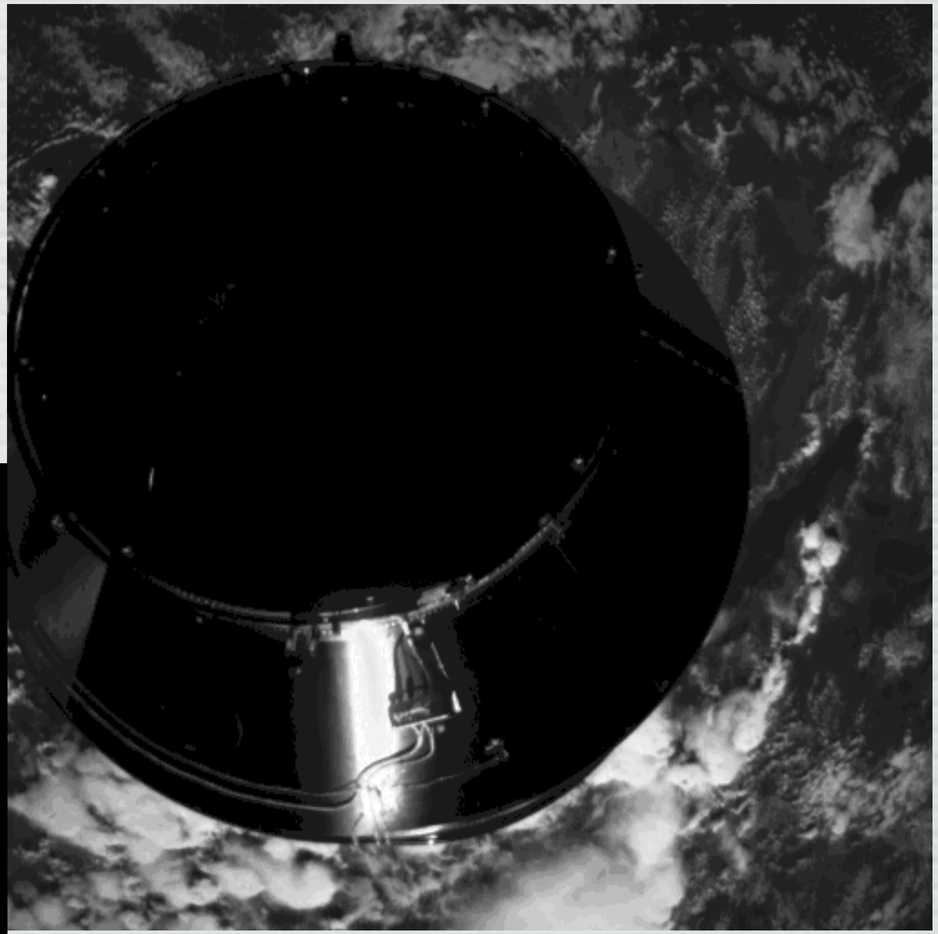
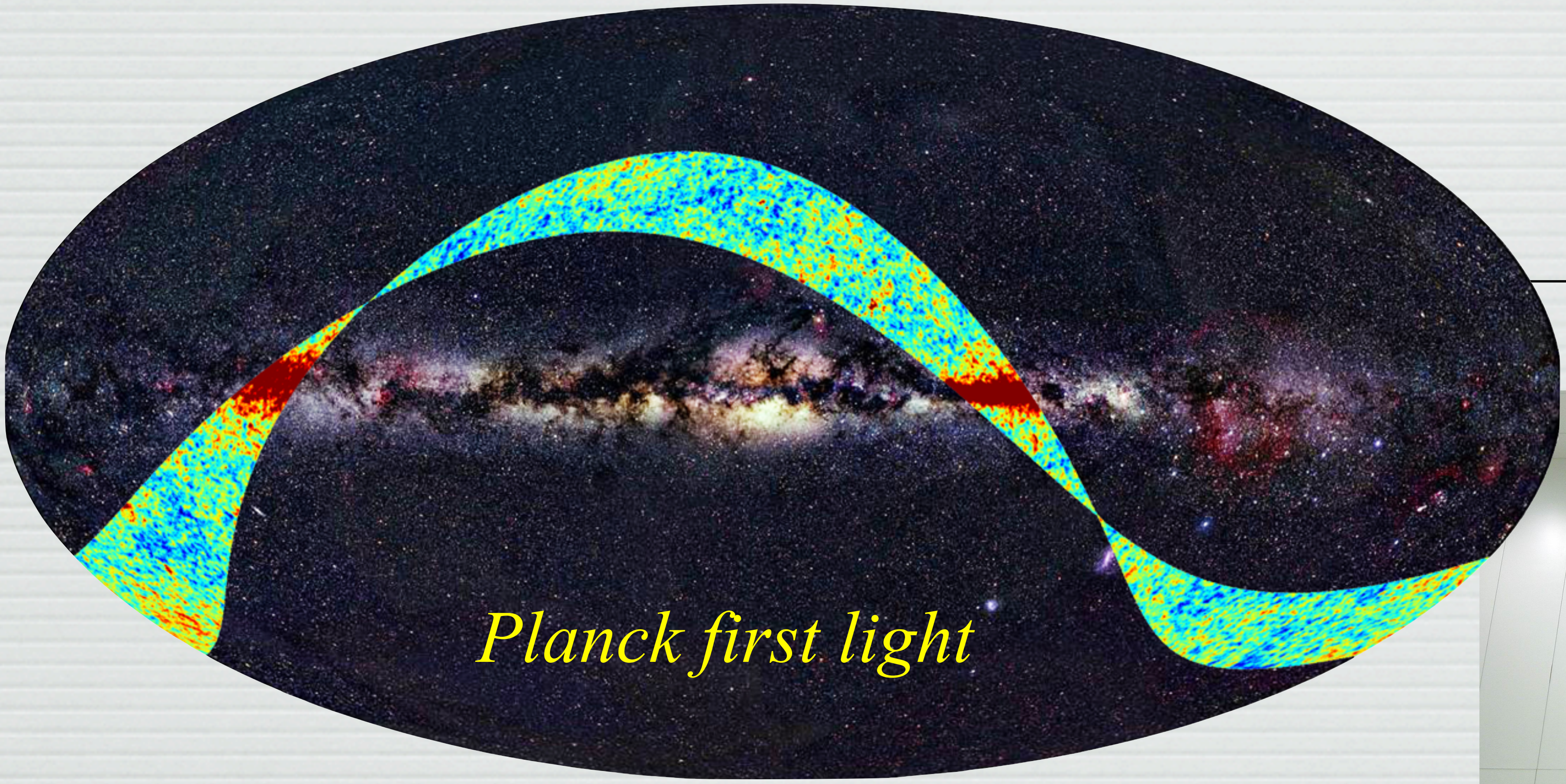
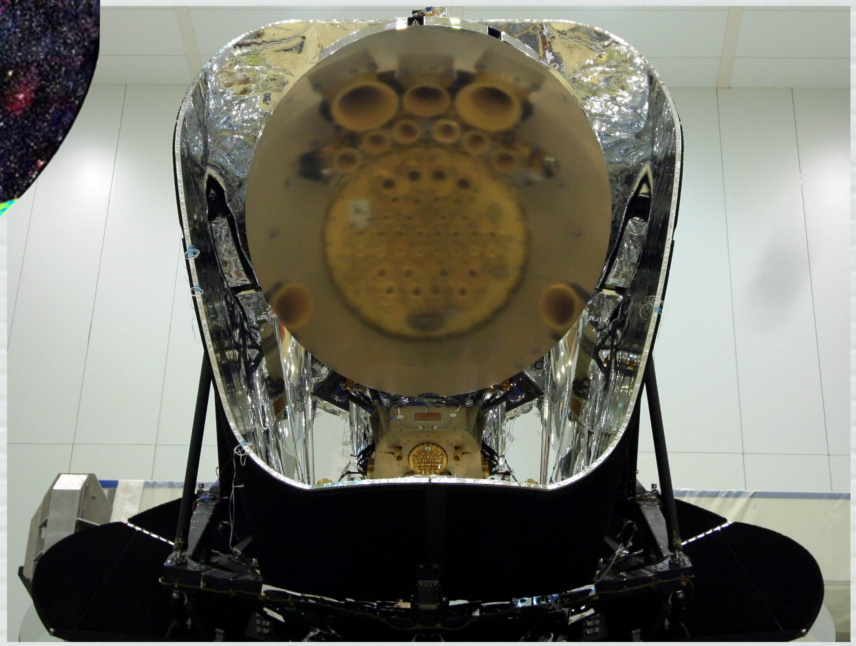
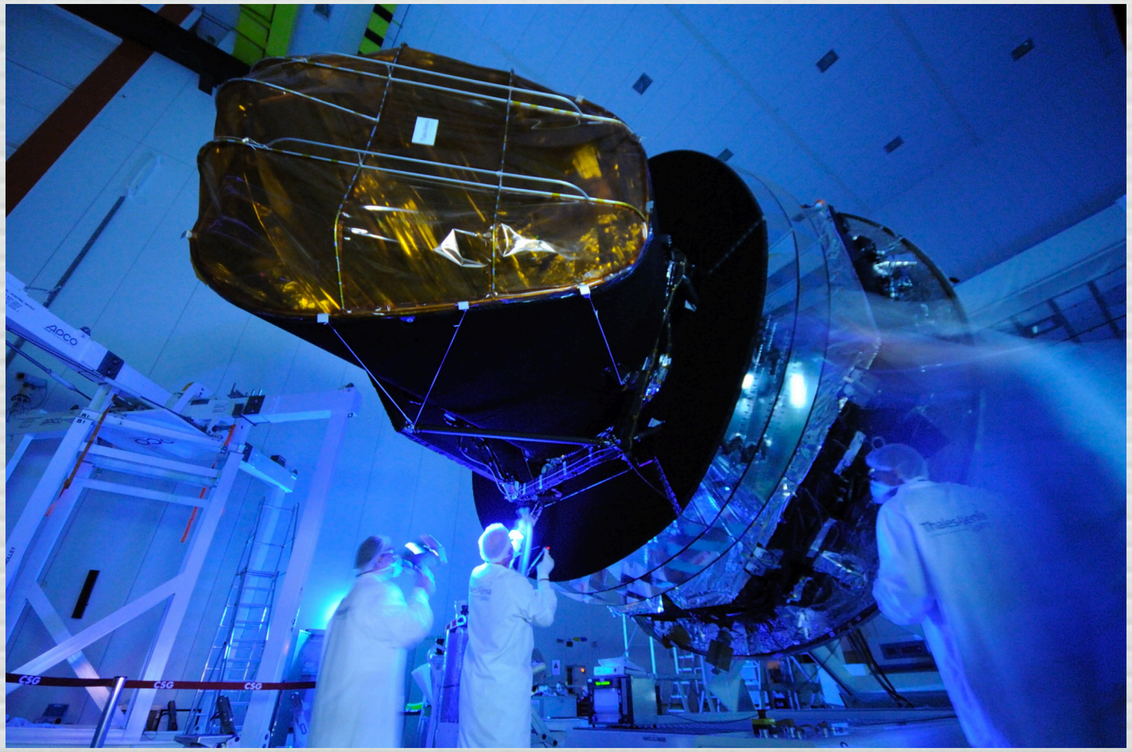


Planck


Planck first light

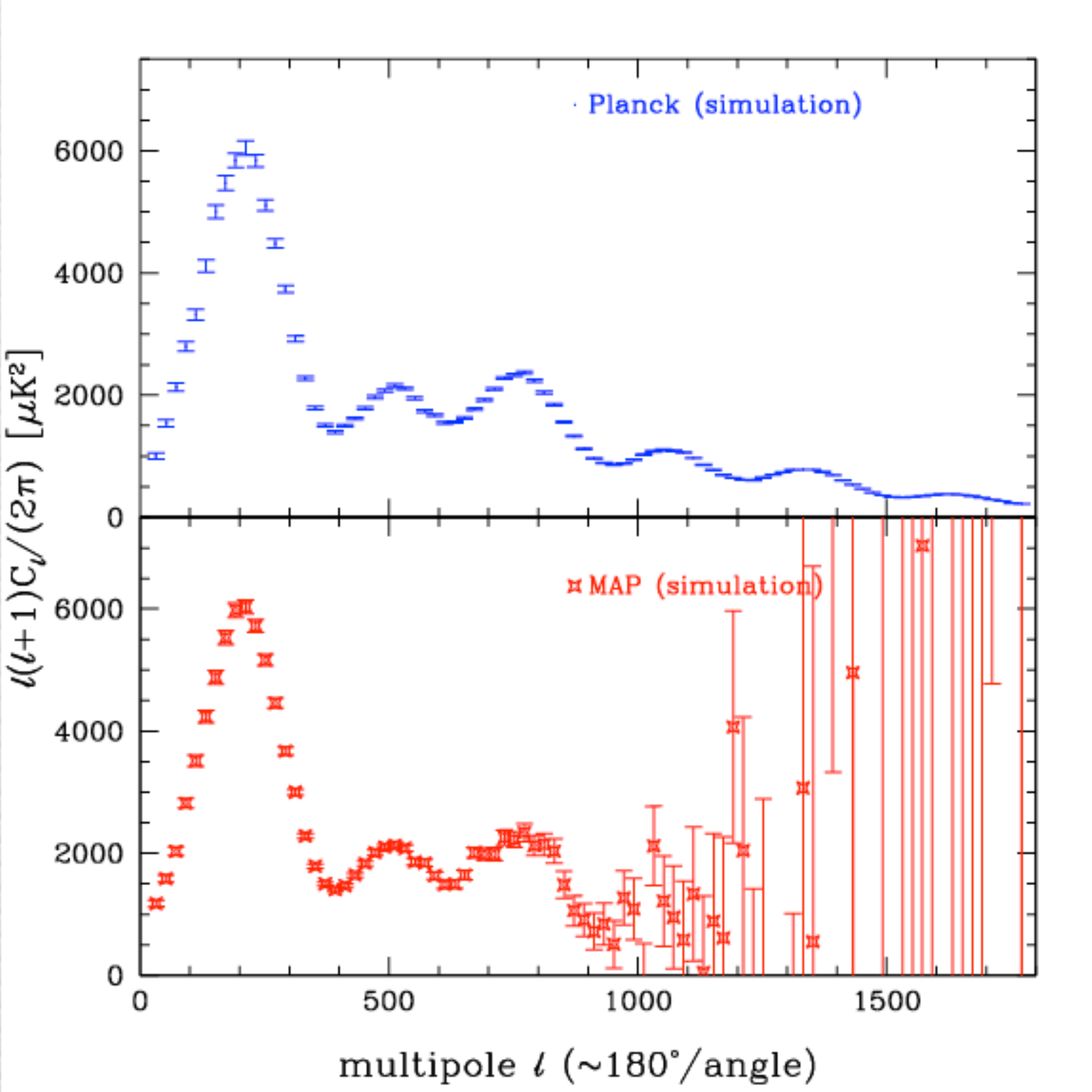





Planck as a telescope:
dust in the Milky Way galaxy

Future (soon) spectra

- Planck gets ~all of T, most of E
- Wide frequency coverage for "foreground" removal



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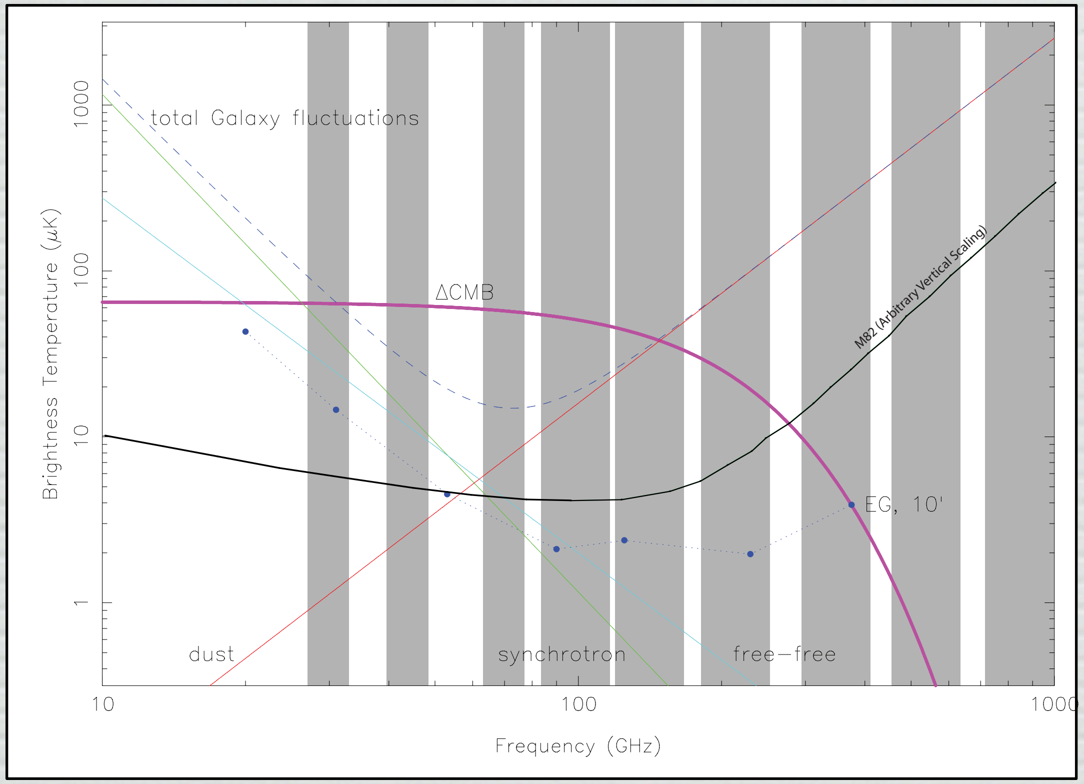

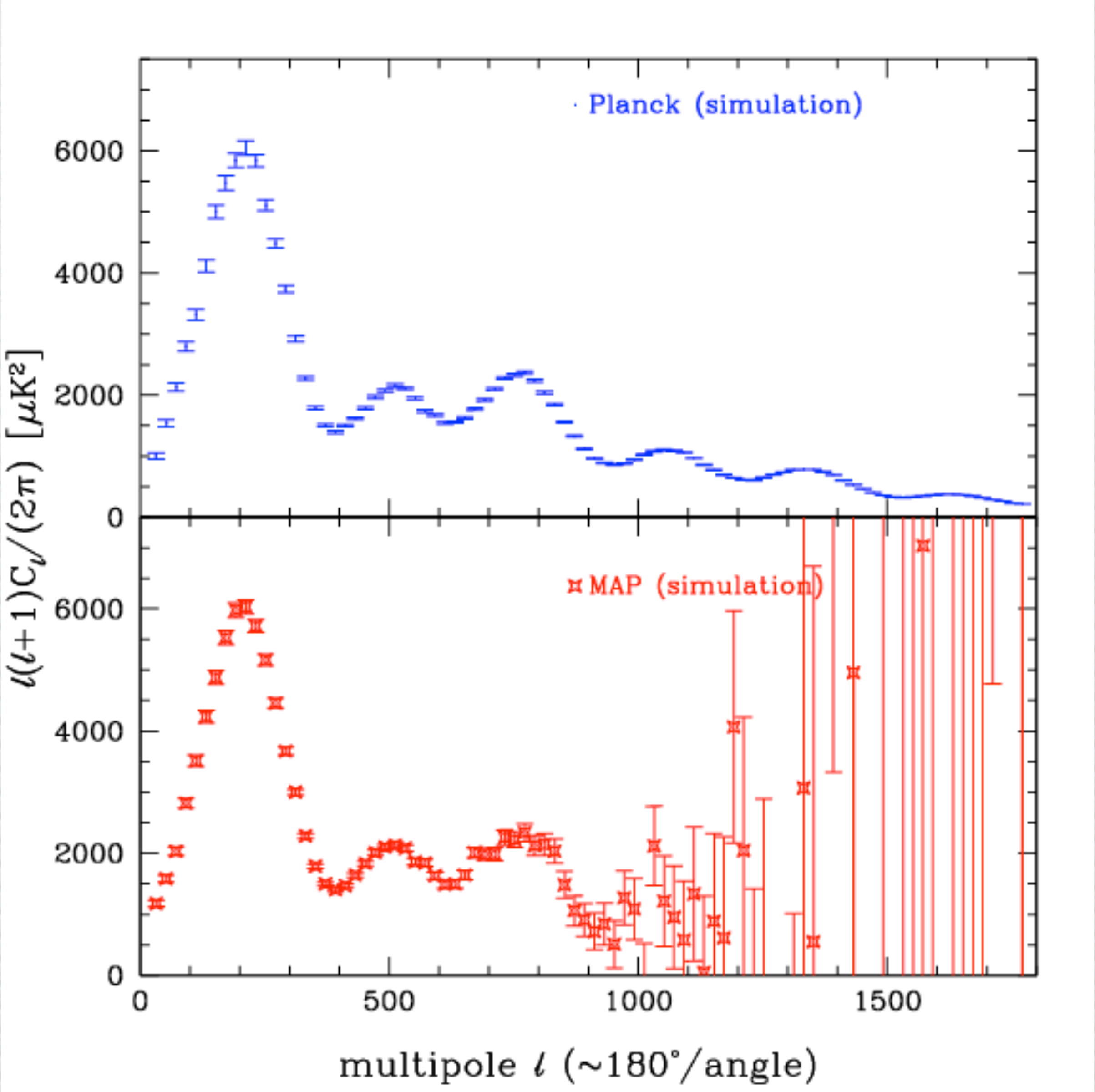

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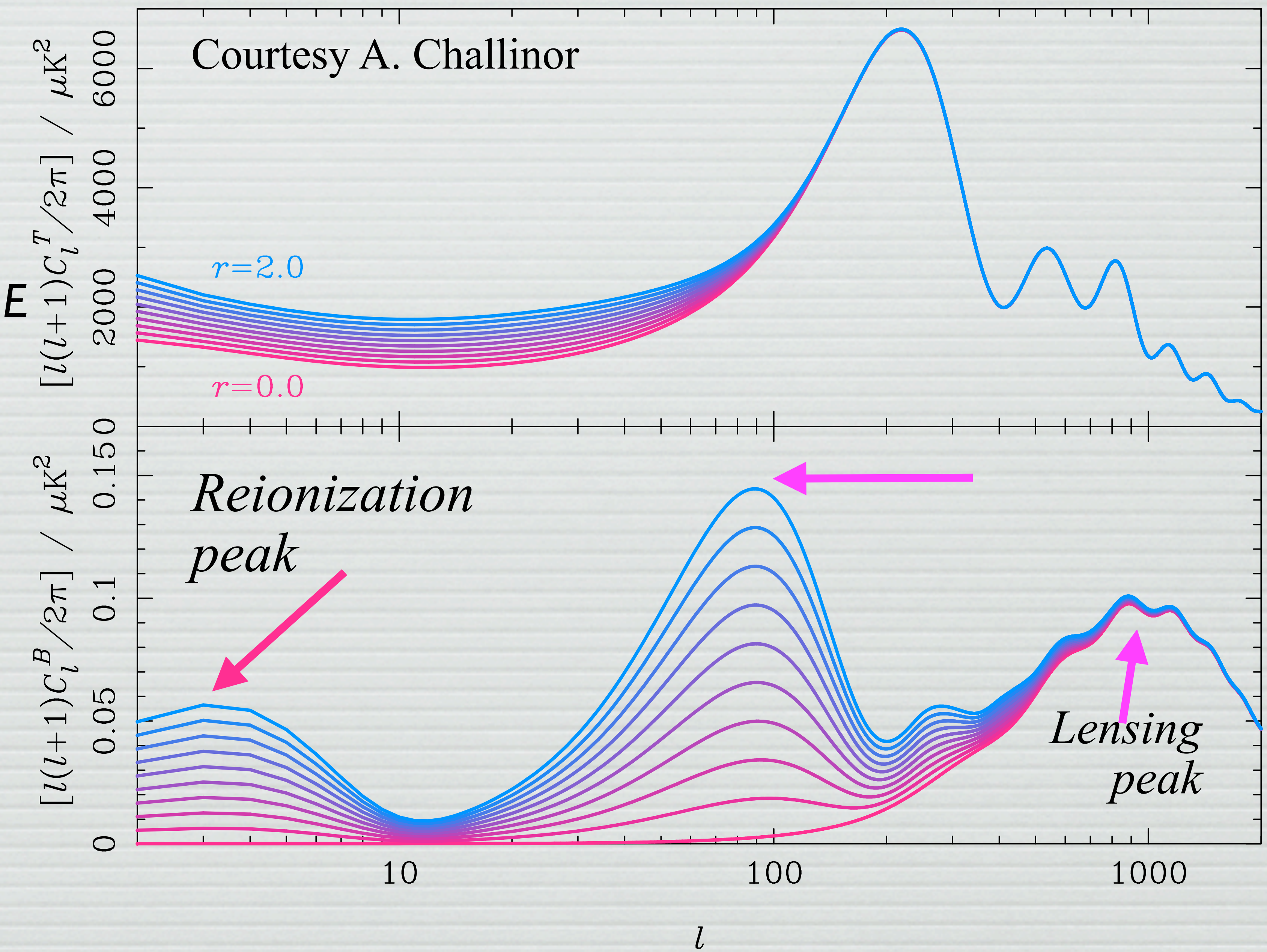
Gravitational Radiation & CMB

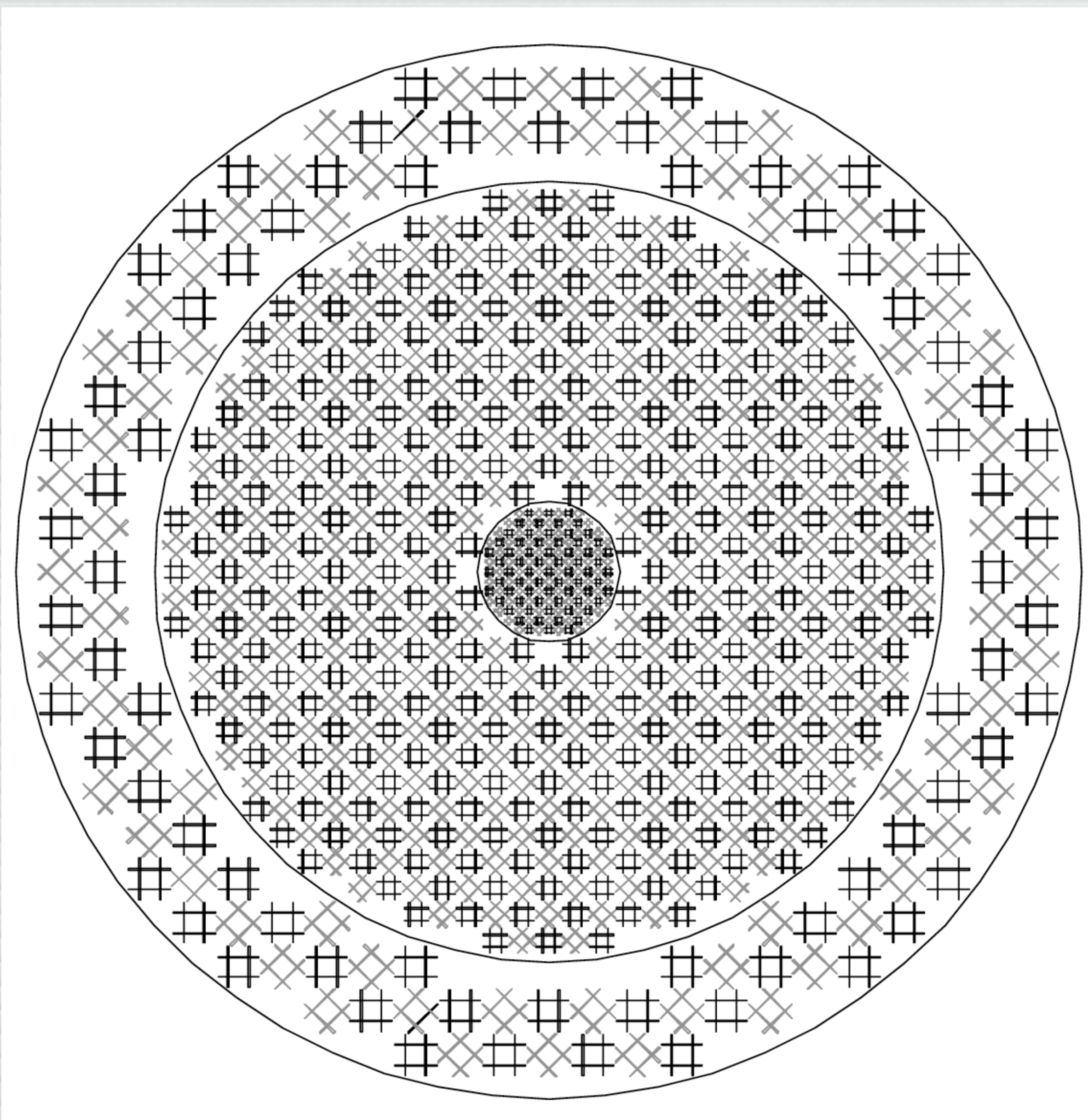
- Last scattering: "direct" effect of tensor modes on the primordial plasma
  - dominated by *lensing of E* ⇒ *B* for $\ell \gtrsim 100$
    - cleaning?
- Reionization peak $\ell \lesssim 20$
  - need ~full-sky. Difficult for single suborbital experiments
- *Limits depend on full set of parameters*



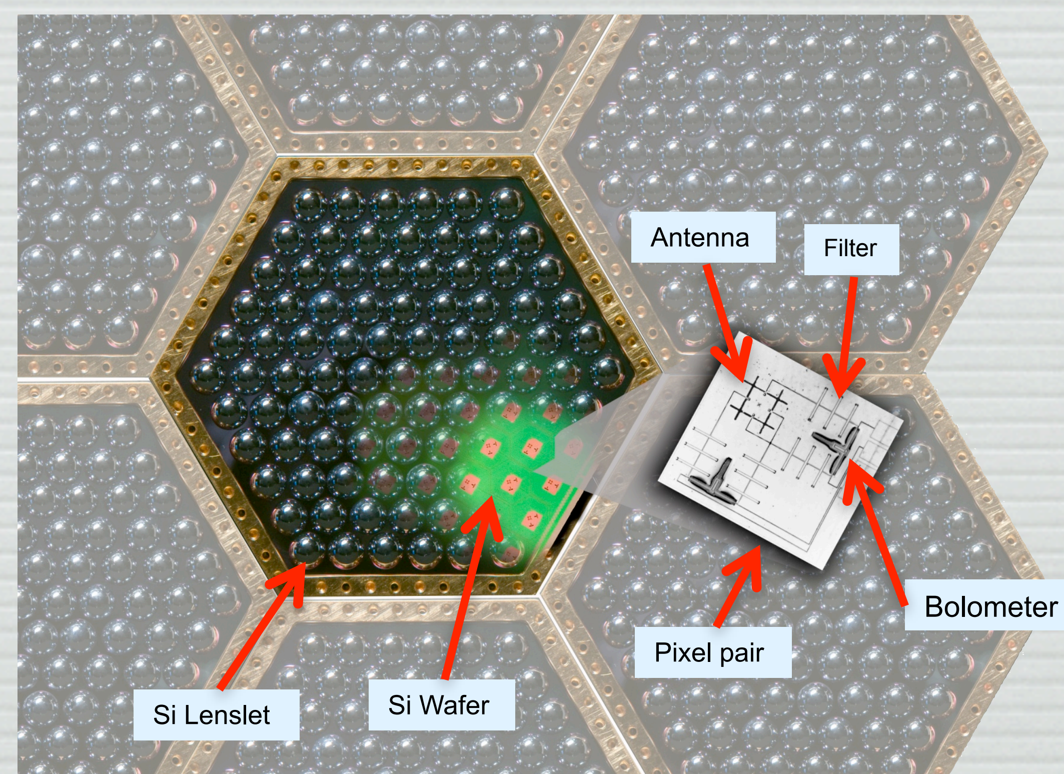
Suborbital experiments target ℓ~100 peak: require order-of-magnitude increase in sensitivity over Planck

Beyond Planck: New Technologies

- PolarBear - AT Lee (Berkeley)

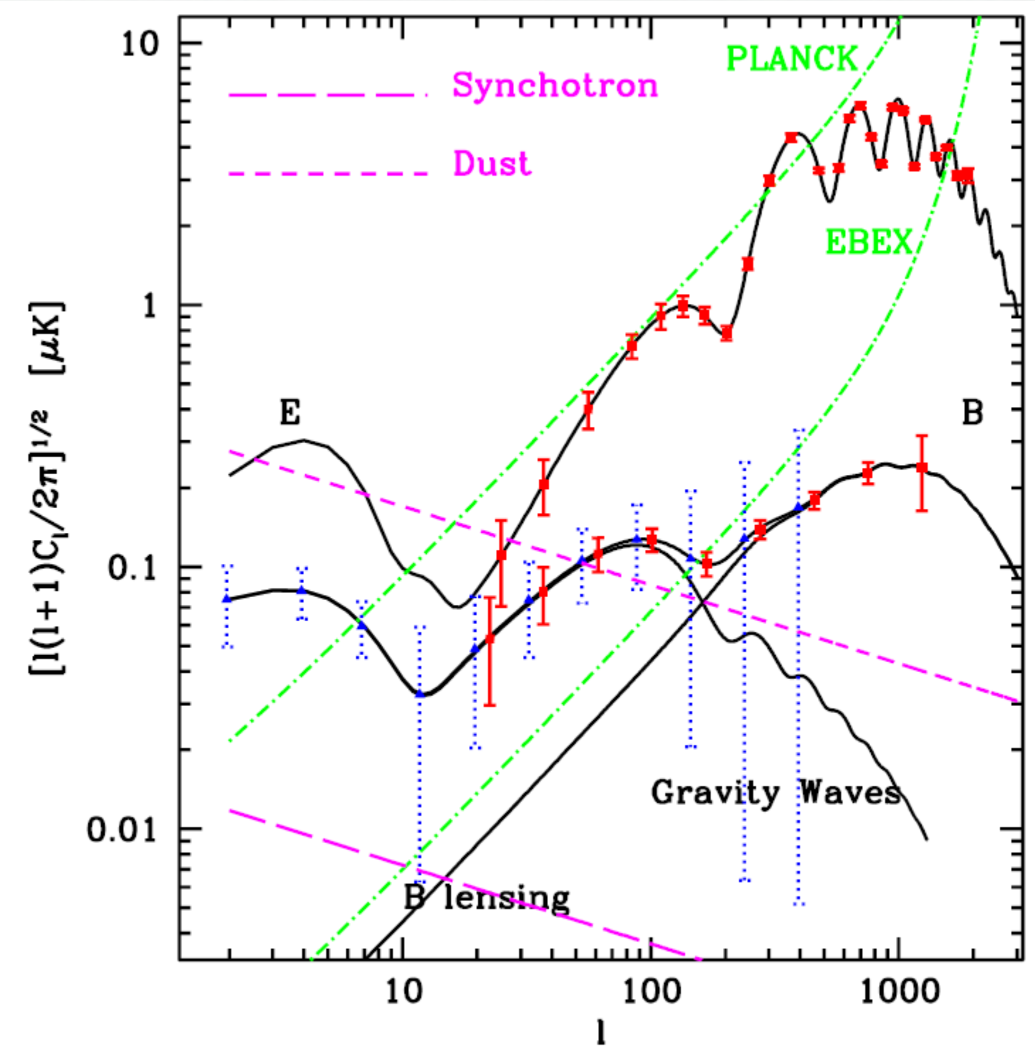


- Antenna-coupled bolometers
- ~900 pixels @ 150 GHz, 3000 bolometers
- Full use of useful 150 GHz Field-of-view
- New challenges: 1000s of bolometers (central limit theorem to the rescue????)



EBEX

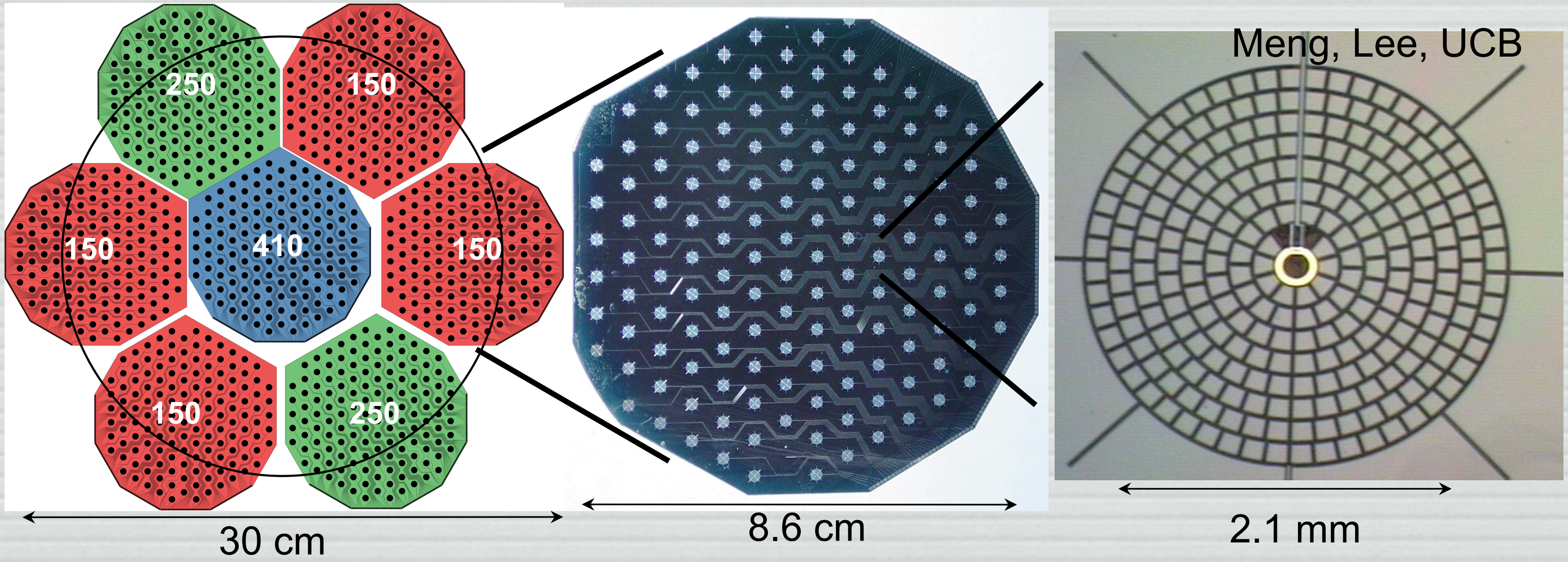
From individual bespoke detectors to 1,500 fabricated en masse



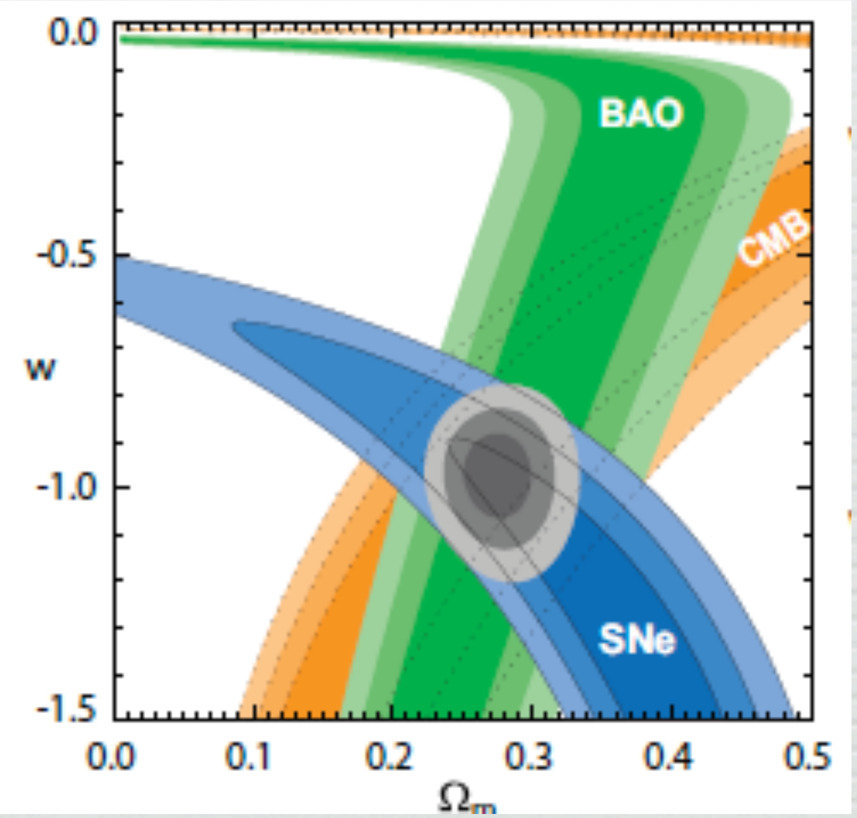
738 element array

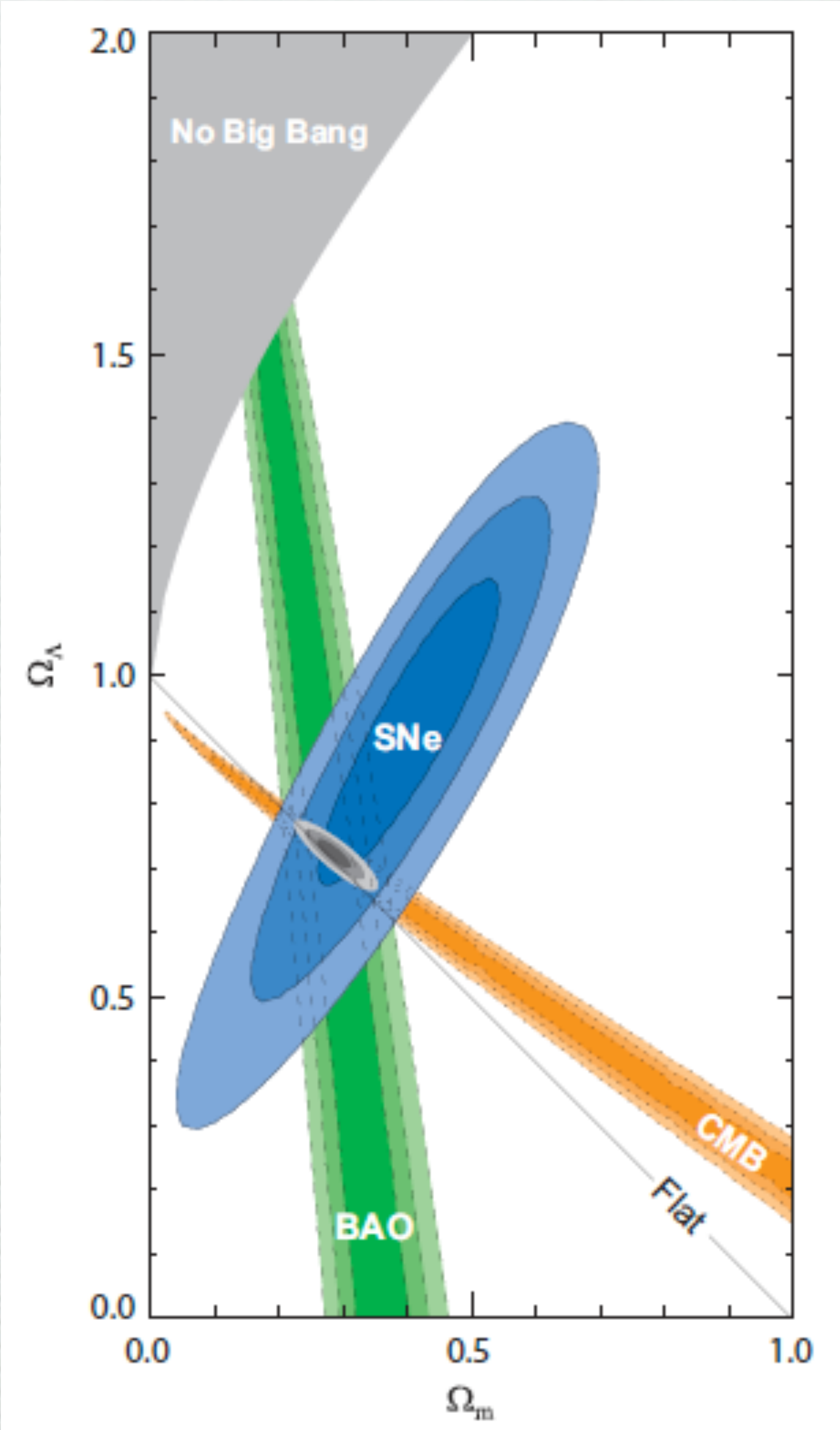
139 element decagon

Single TES



Our strange Universe: geometry & equation of state

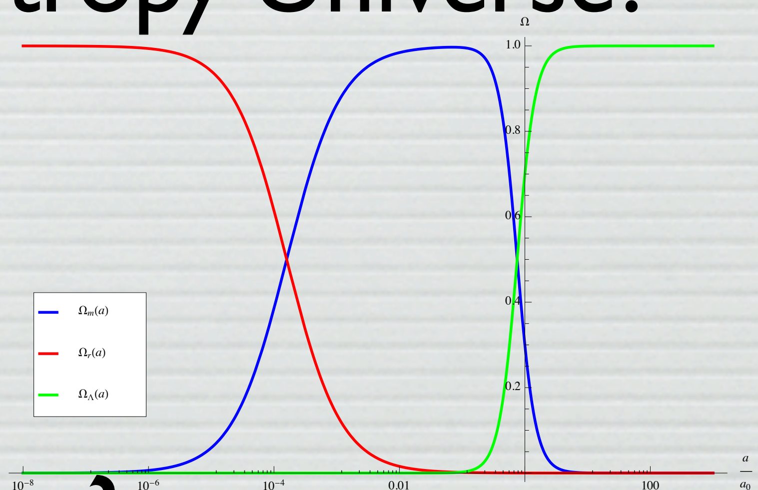




Kowalski et al 2008

Open Questions

- Fundamental Theories for Inflation, Dark Energy
  - Would naively expect $\rho_\Lambda \sim M_{\rm Pl}^4 \Rightarrow$ predict $\Omega_\Lambda \sim 10^{122} \gg 0.7$
  - pre-Inflation: do we live in a low-entropy Universe?
- Why now? $\Omega_\Lambda \sim \Omega_m \sim \Omega_{tot} \sim 1$
  - do we *need* anthropic arguments to solve these puzzles?



- CMB “anomalies”: low-ℓ anisotropy?
- Is the simplest ΛCDM model sufficient?
  - Or: hot dark matter? isocurvature fluctuations? complicated initial conditions? varying *w*? non-trivial topology?

Conclusions

- ΛCDM fits present data extremely well
- Next-generation experiments may measure free parameters
  - Scale of inflationary potential
  - variation of equation of state
- … and may close *some* open questions
  - but we will need to revitalize the inner-space/outer-space connection to answer them all