Planck and the Microwave Background

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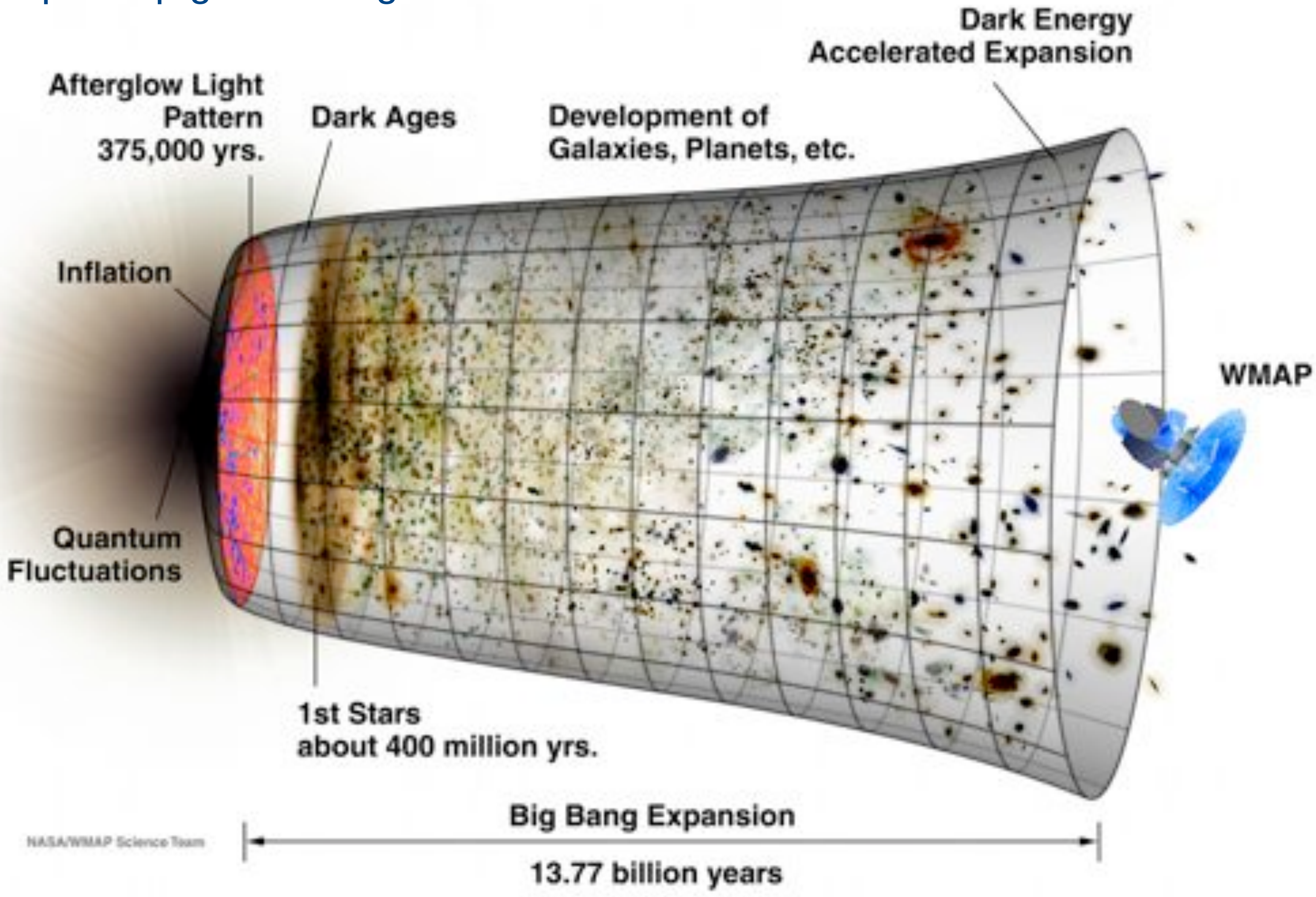
Outline

- The Microwave Background
- The Planck Satellite
- Inflation and Planck & BICEP2
- “Cross-Correlations”
- What's to Come?

Visualize the Evolution of the Universe

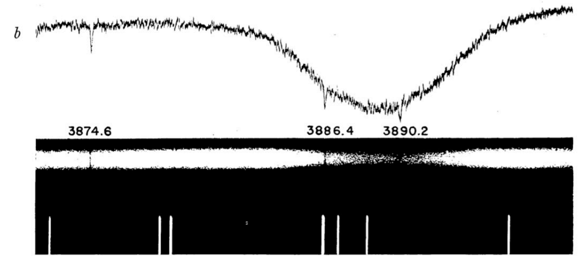
http://map.gsfc.nasa.gov/media/060915/index.html

The microwave background light we see today was created “just after” the Big Bang (400k yr)



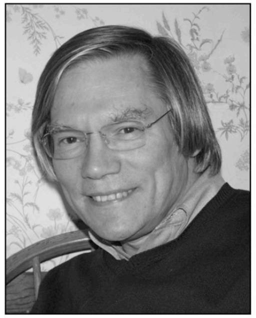
As such, it is a “baby picture” of the early Universe. By studying it, we hope to understand it's birth.

A History of the CMB in One Slide

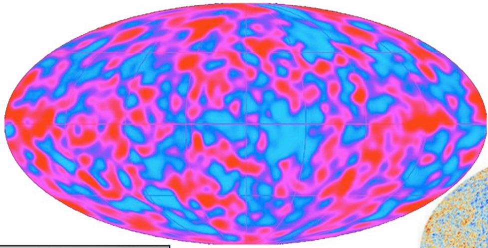


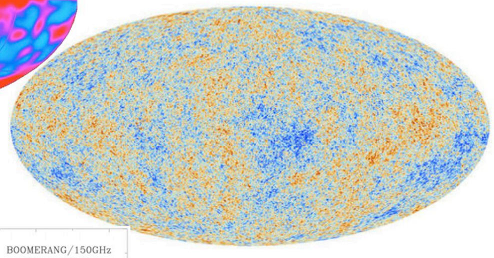
INTERSTELLAR LINES
a) α Cygni showing interstellar H and K superposed upon stellar lines; b) ζ Ophiuchi, positive reproduction of stellar and comparison spectra, with photometric tracings. Two lines of *CH* are shown, λ 3886 and λ 3890; also λ 3874.6 and a trace of λ 3874.0, both probably *CN*.

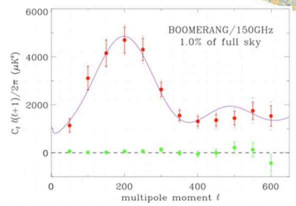
Alexei Starobinsky
b. 1948

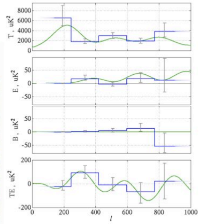


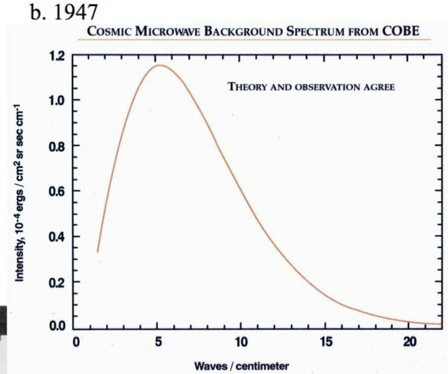
Alan Guth
b. 1947

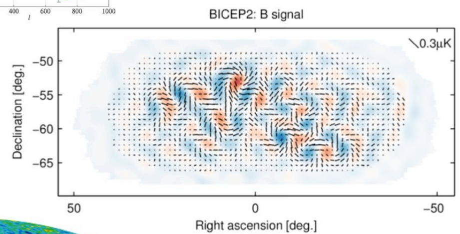




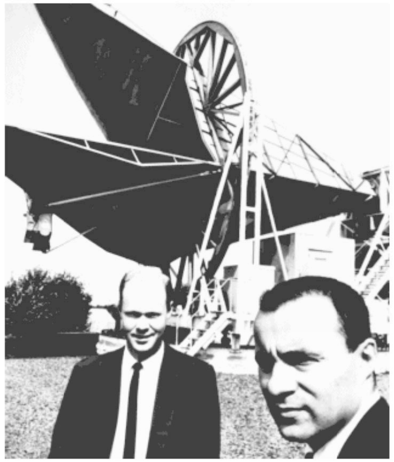


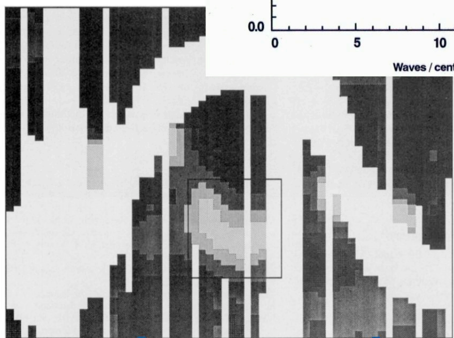


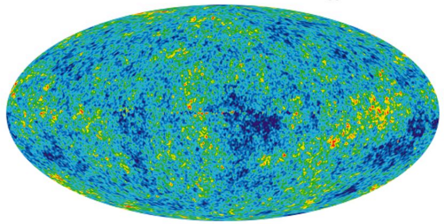


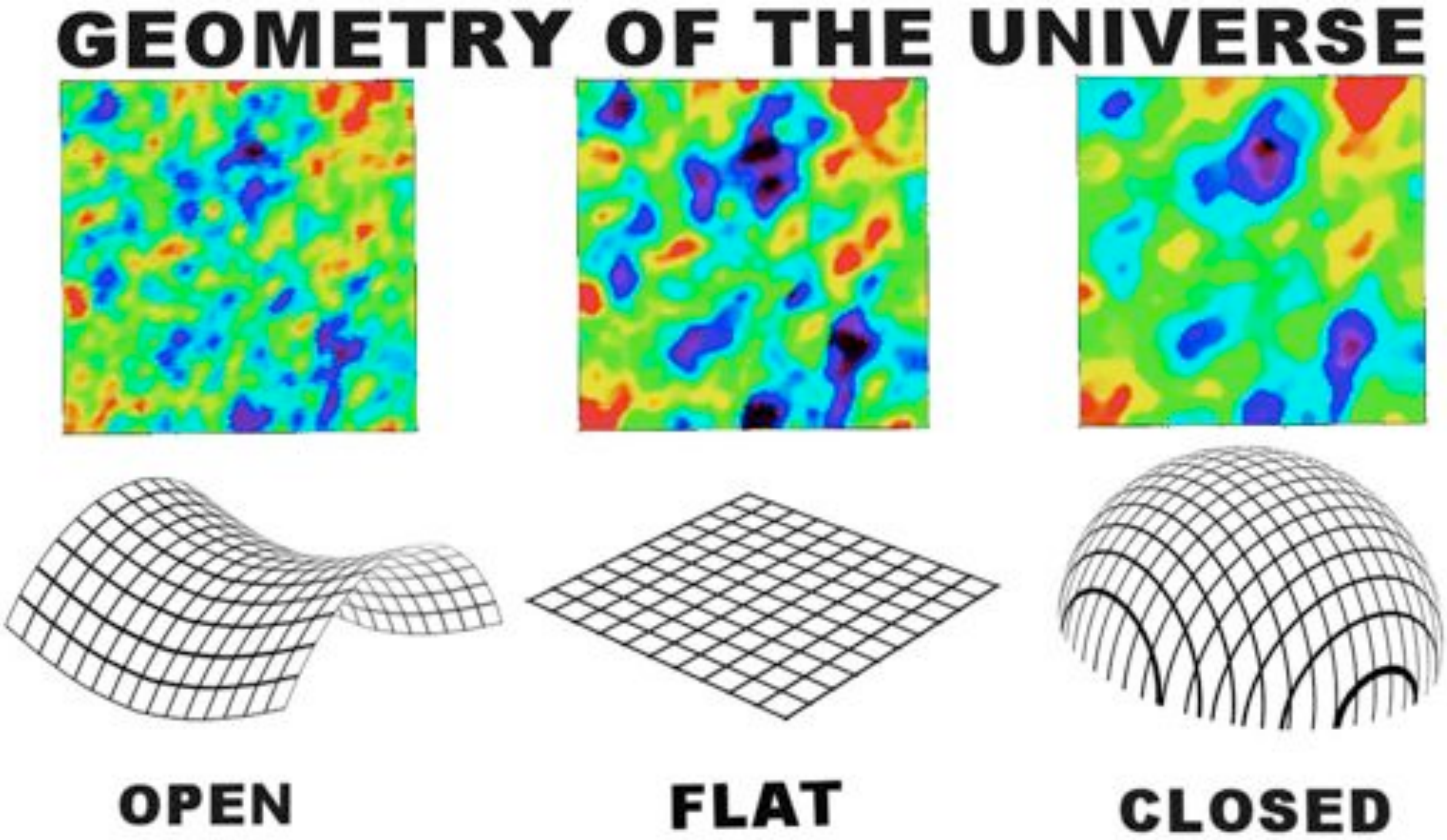


With apologies to most of the field for omissions...





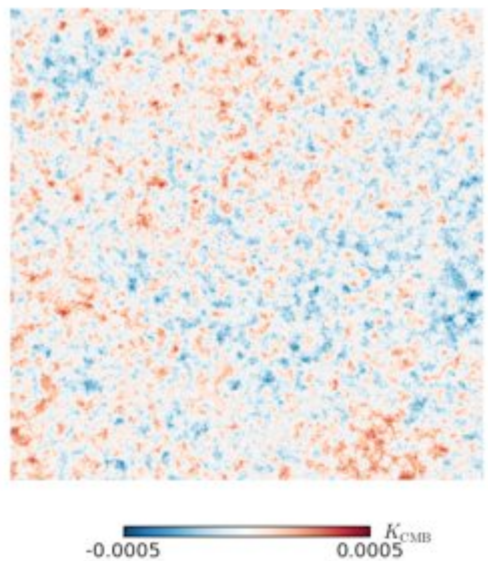




- Smaller characteristic scales indicate a closed Universe
- Larger characteristic scales indicate an open Universe

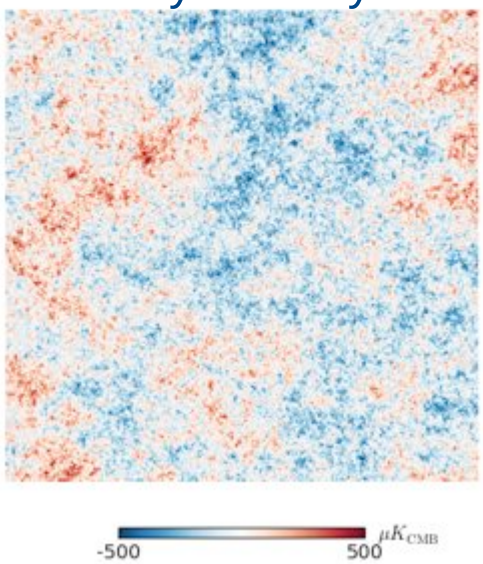
The Constituents of the Universe

Planck

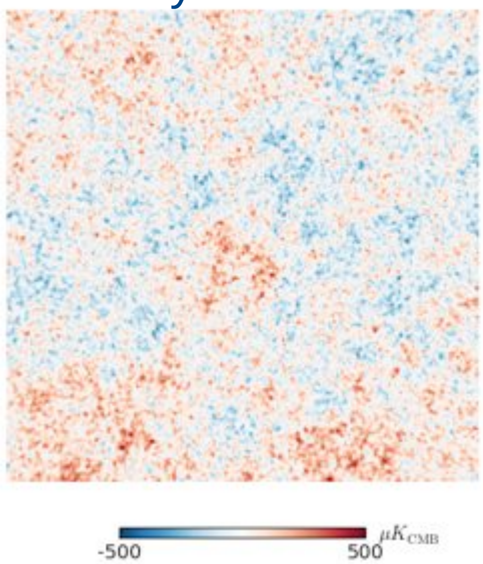


The real data resemble simulations with “normal” matter, cold dark matter and a cosmological constant more than they do simulations missing any of these three components.

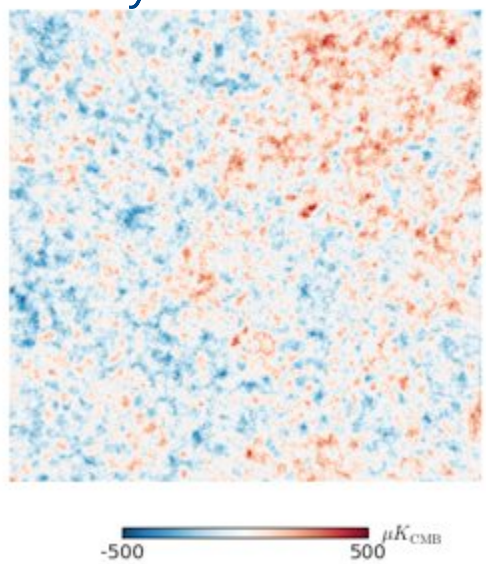
Baryons only



Baryons+CDM



Baryons+CDM+Λ



The CMB and Ω

Hu & Dodelson (2002)

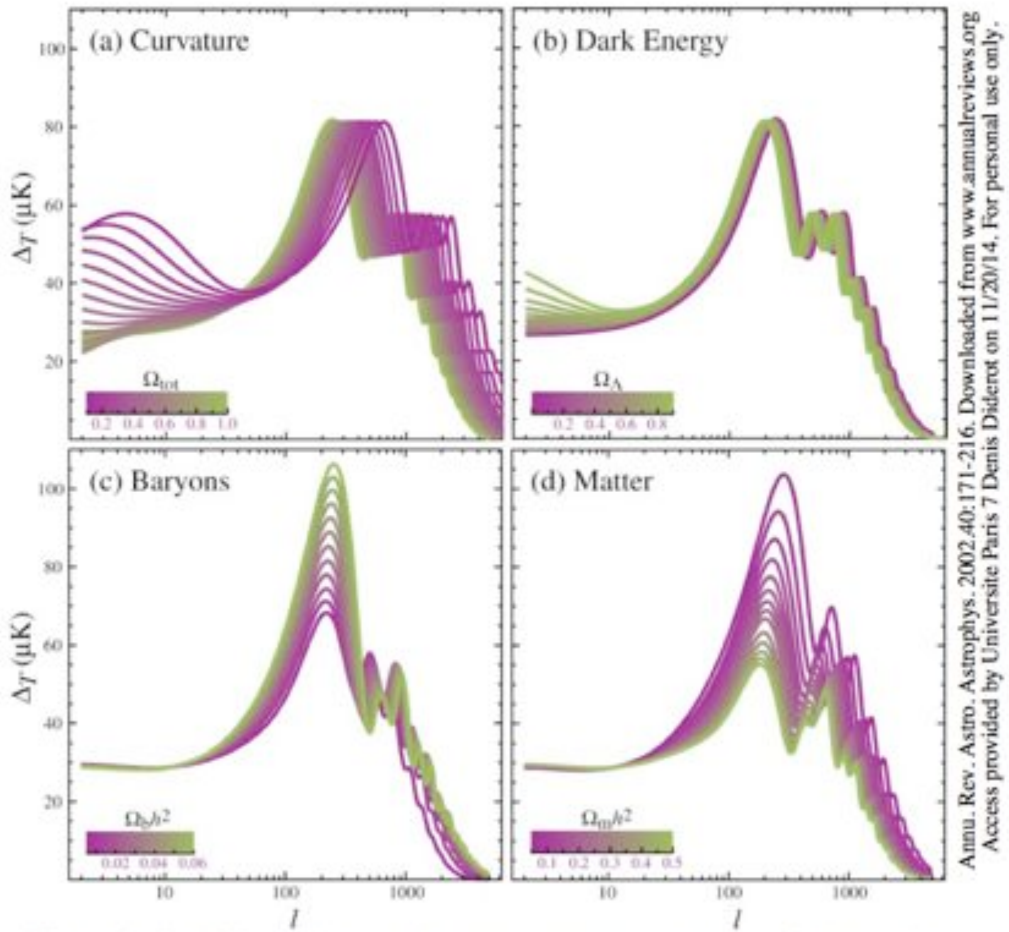
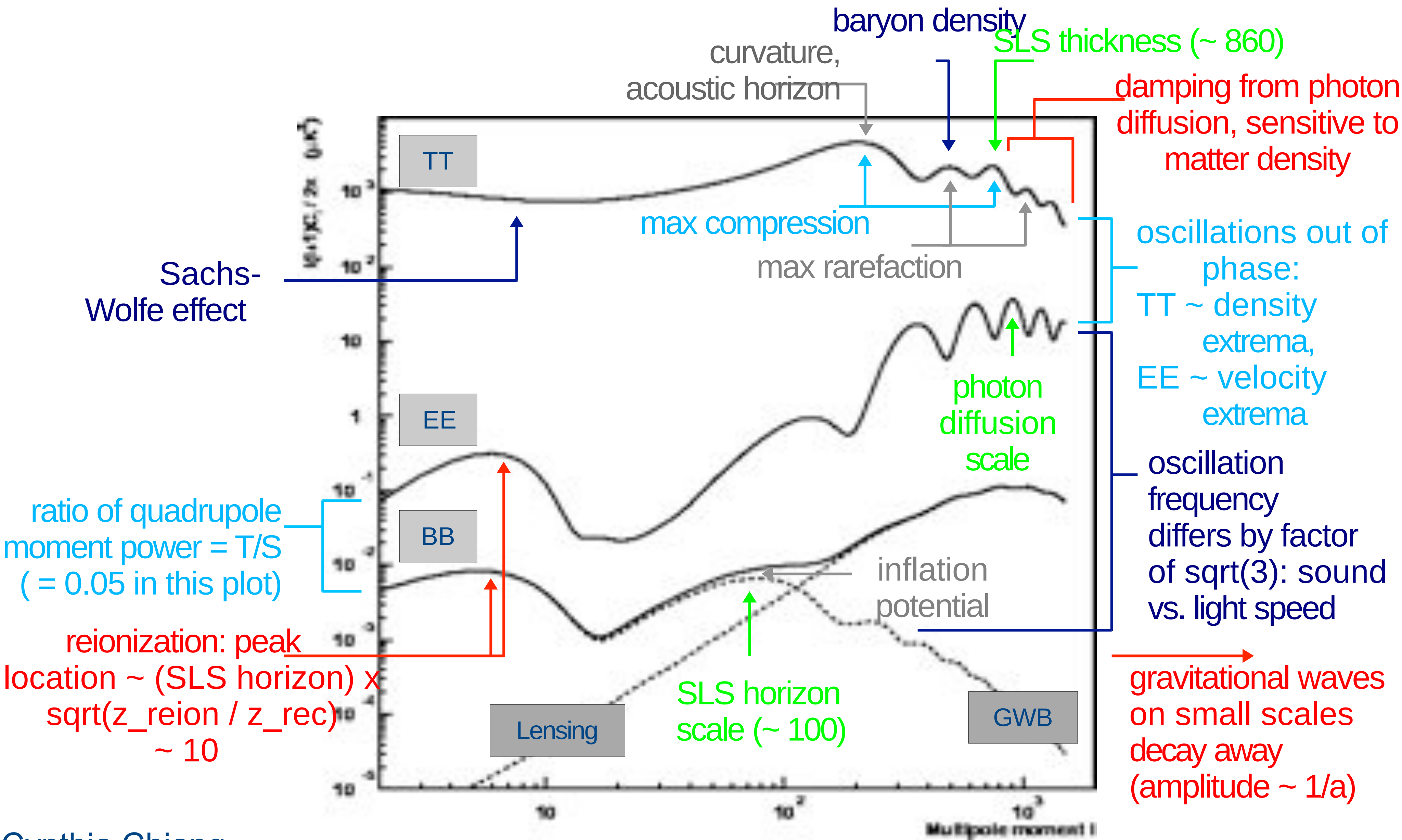


Figure 4 Sensitivity of the acoustic temperature spectrum to four fundamental cosmological parameters. (*a*) The curvature as quantified by Ω_{tot}. (*b*) The dark energy as quantified by the cosmological constant Ω_Λ ($w_\Lambda = -1$). (*c*) The physical baryon density $\Omega_b h^2$. (*d*) The physical matter density $\Omega_m h^2$. All are varied around a fiducial model of $\Omega_{tot} = 1$, $\Omega_\Lambda = 0.65$, $\Omega_b h^2 = 0.02$, $\Omega_m h^2 = 0.147$, $n = 1$, $z_{ri} = 0$, $E_i = 0$.

- All else remaining constant:
  - The first peak position measures the total Ω
  - The 1st and 2nd peak height difference measures baryon density (or electrons)
  - The amount of matter changes the amount of structure
  - Dark energy affects the largest scales

Many Different Effects Together



Cynthia Chiang

Degeneracies

Howlett et al. (2012);
http://arxiv.org/abs/arXiv:1201.3654

By minimizing $\chi^2_{\rm eff}$, we can find sets of parameters that give power spectra that are very close to the fiducial model. Example unlensed power spectra are shown in non-flat ΛCDM models in Fig. 1. In this case, the geometric degeneracy is within the two-dimensional space of Ω_Λ and h.

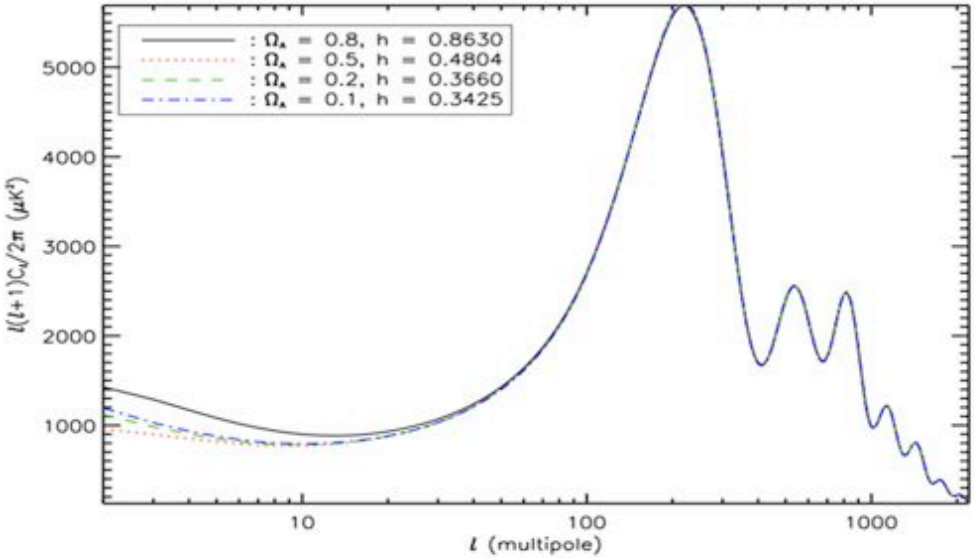


FIG. 1: CMB power spectrum obtained using CAMB for nearly degenerate geometries in non-flat ΛCDM models with no lensing (left) and the fractional differences from the fiducial-model spectrum (right). Both $\Omega_b h^2$ and $\Omega_c h^2$ were fixed to their fiducial values in all cases to preserve the pre-recombination physics. Low accuracy and values of 1 for `lSampleBoost`, `AccuracyBoost` and `lAccuracyBoost` were used for the calculations.

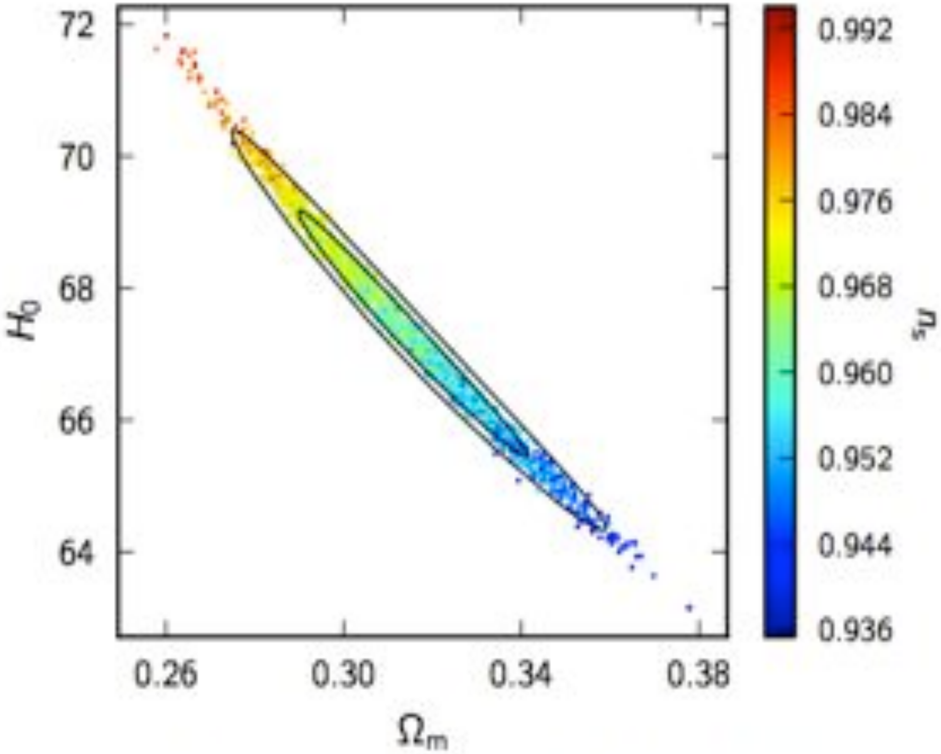
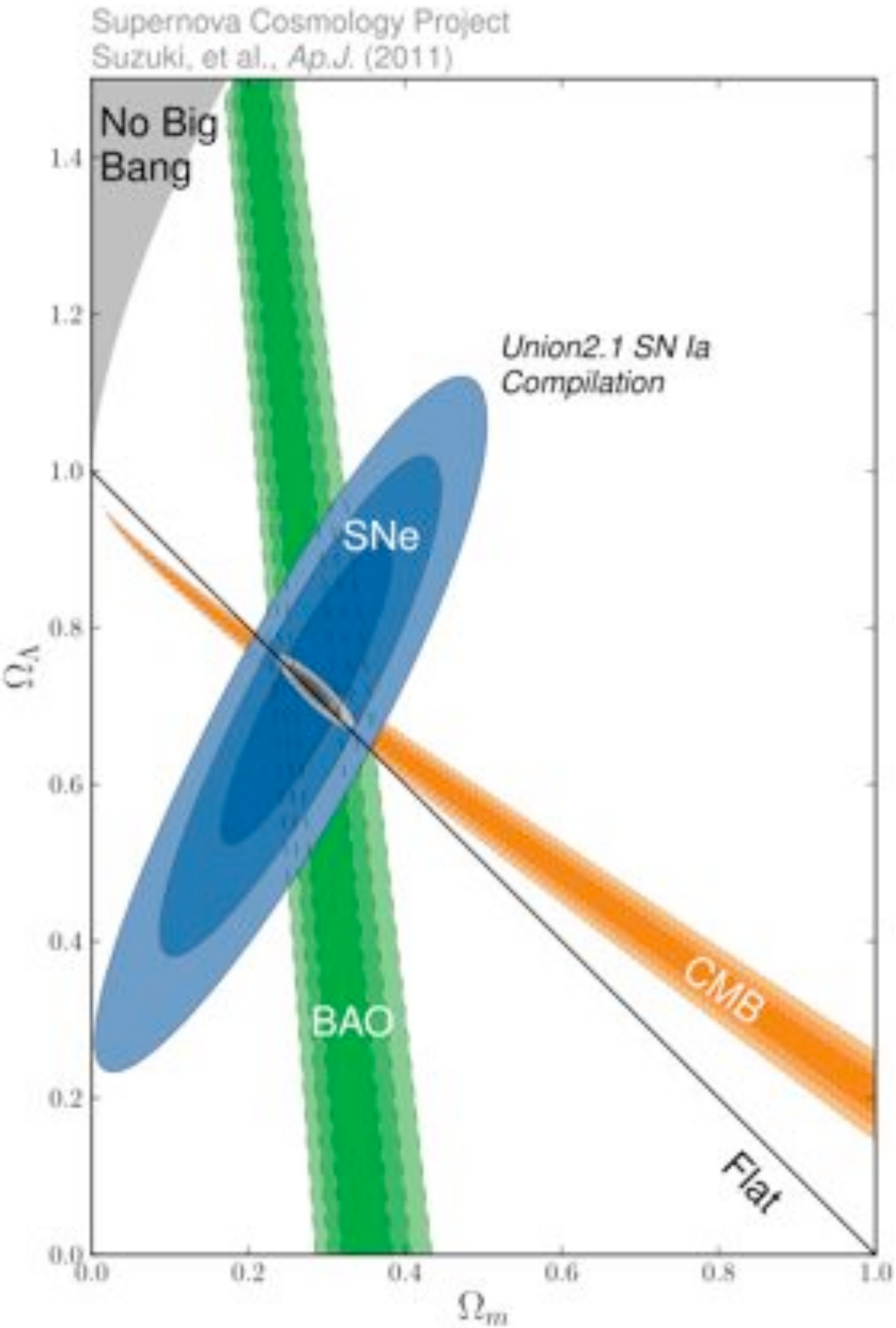


Fig. 3. Constraints in the Ω_m–H_0 plane. Points show samples from the *Planck*-only posterior, coloured by the corresponding value of the spectral index n_s. The contours (68% and 95%) show the improved constraint from *Planck*+lensing+WP. The degeneracy direction is significantly shortened by including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

Different sets of cosmological parameters can give us the same power spectrum (to within the error bars)

Matter, Dark Matter & Dark Energy



The CMB has helped consolidate dark matter and dark energy as real (though other probes sometimes provide somewhat more direct glimpses of their existence)

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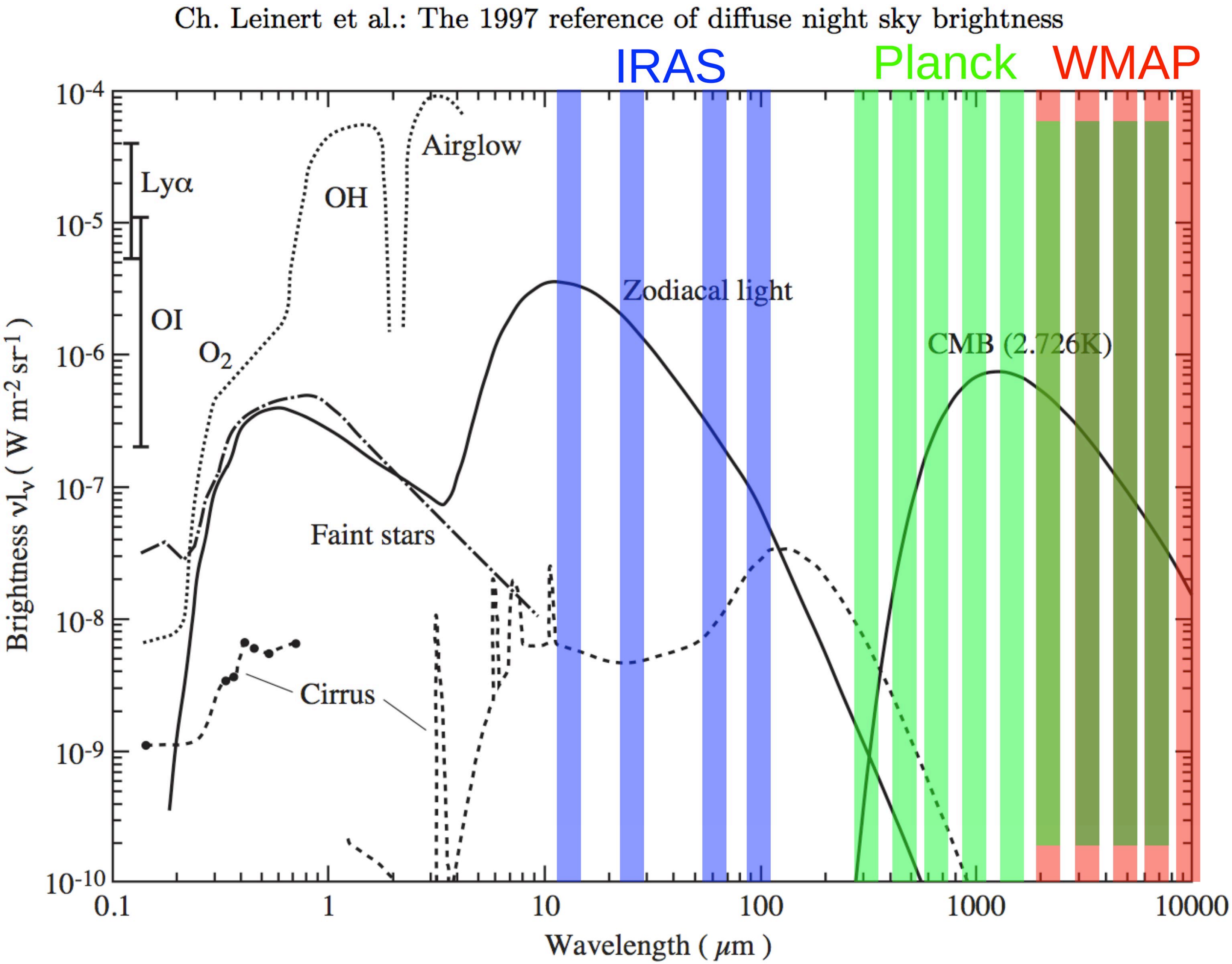
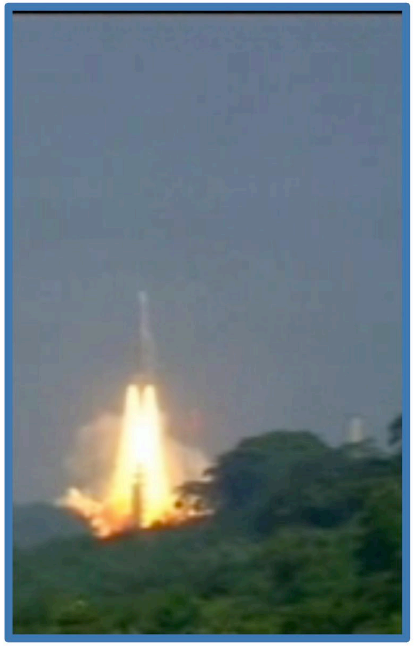
Frequency/wavelength coverage

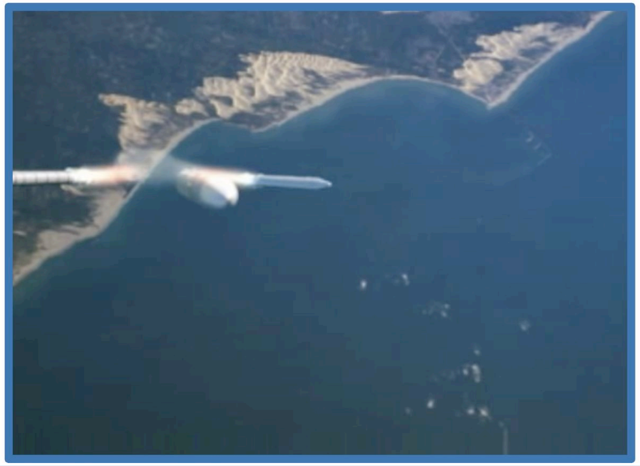


Planck fills the SubMM range, so in addition to CMB science, Planck will be able to say a lot about dust emission in our Galaxy and in others.

Launch, Orbit and Scanning

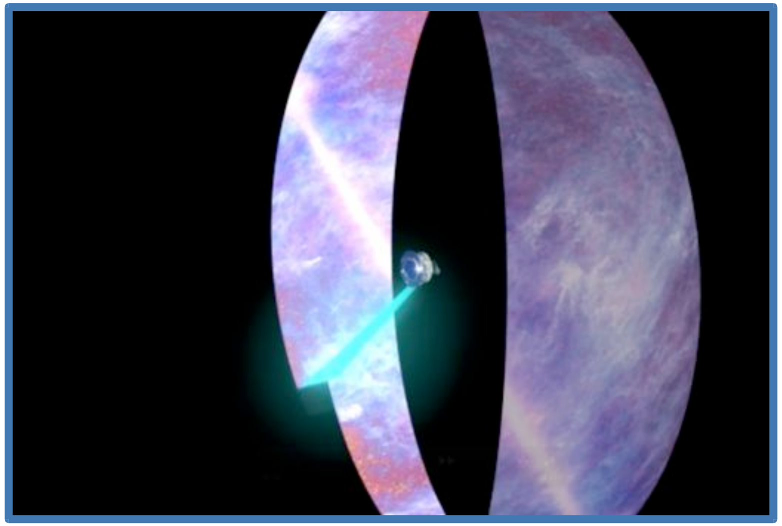


May 14, 2009 Launch with Herschel on an Ariane 5



Planck traveled the 1.5 million km to the second Sun-Earth Lagrange point in about three months

Scans full sky each ~6 months the sky in (almost) great circles.

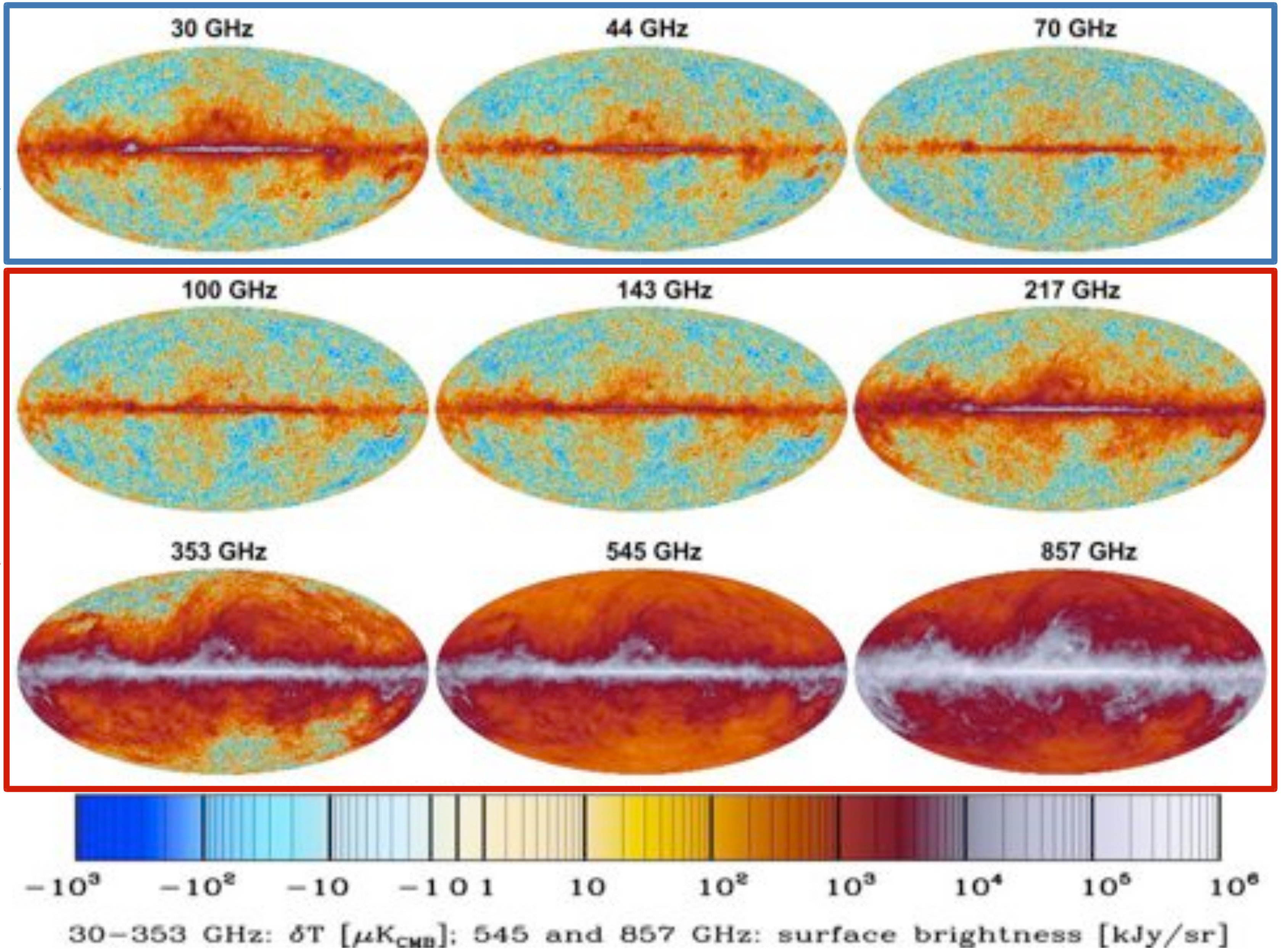


Planck Maps

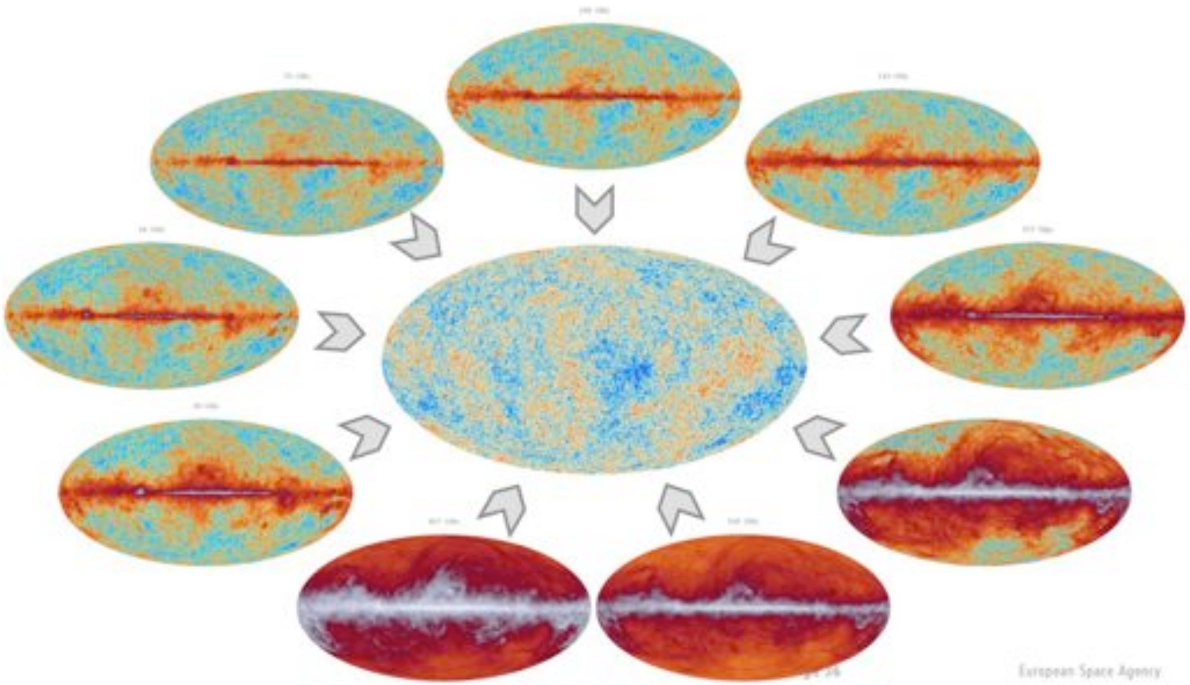
Planck has two instruments:

- LFI:
-- 30,
-- 44,
-- 70 GHz

- HFI
-- 100,
-- 143,
-- 217,
-- 353,
-- 545,
-- 857 GHz



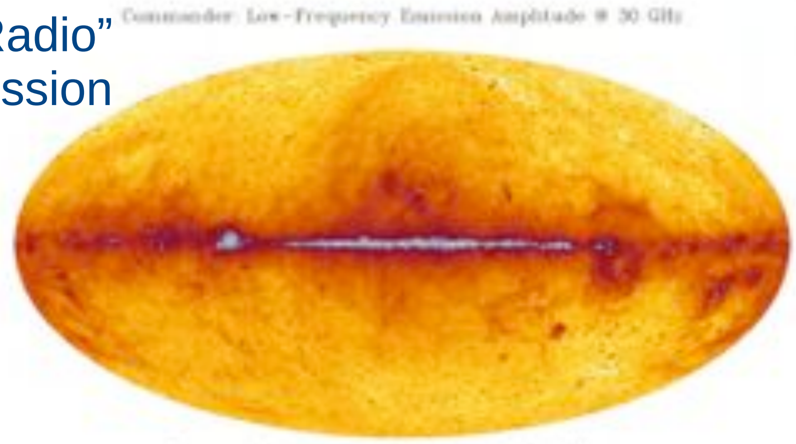
"Foregrounds"



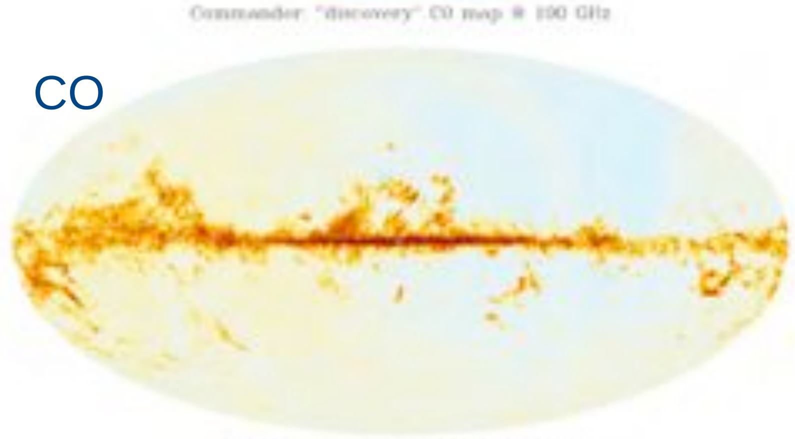
Combinations of the nine Planck channels allow us to separate the signals into CMB, CO, Dust and other components such as synchrotron, free-free and vibrational dust.

The Galactic Plane and point sources are usually masked for cosmological analyses.

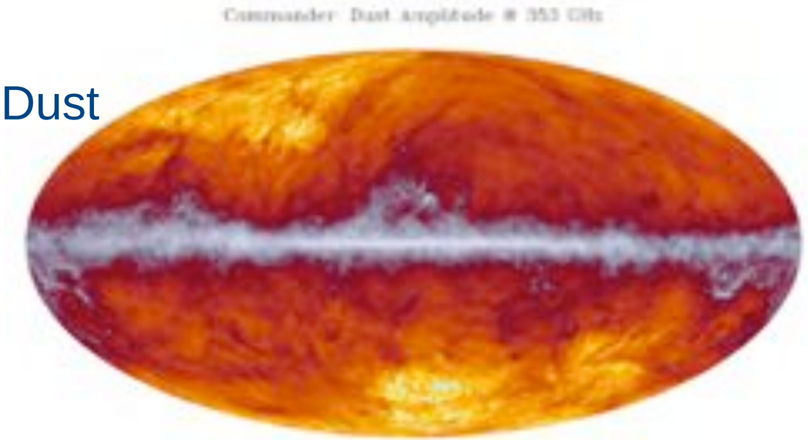
"Radio" Emission



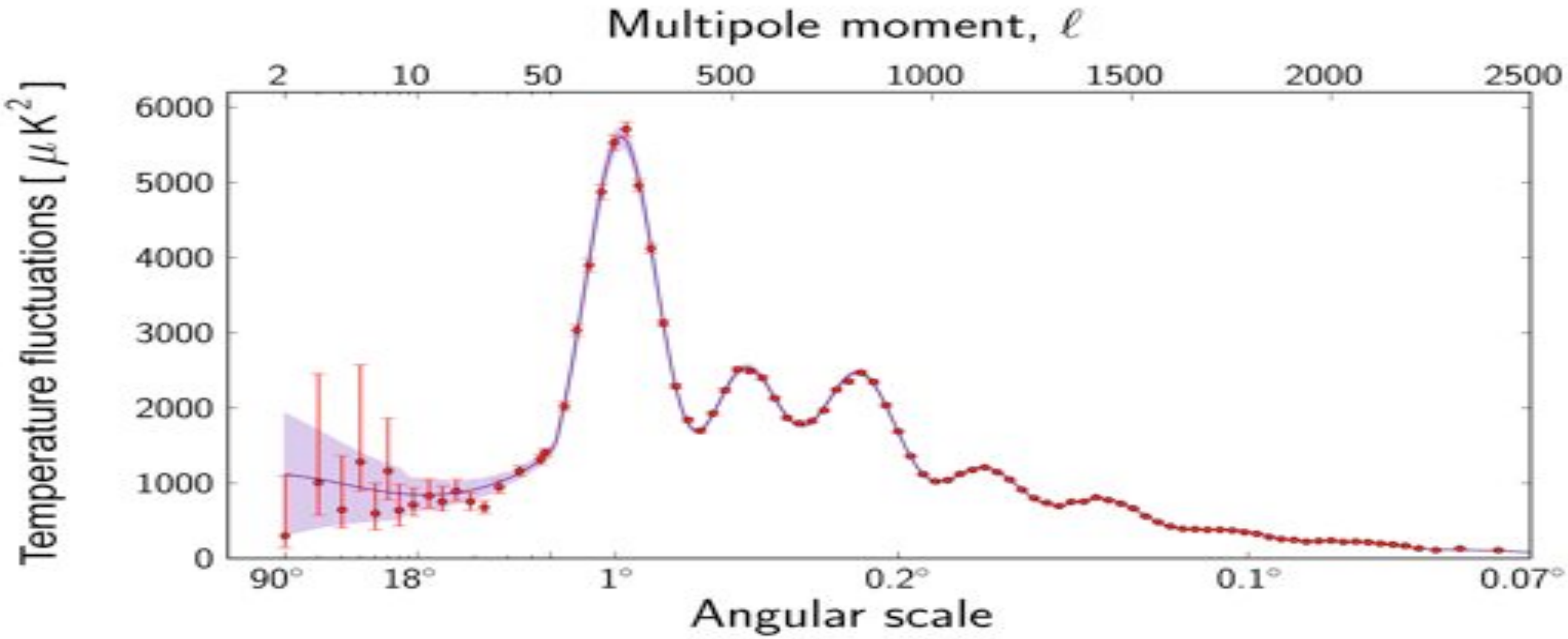
CO



Dust



Temperature & Polarization Spectra



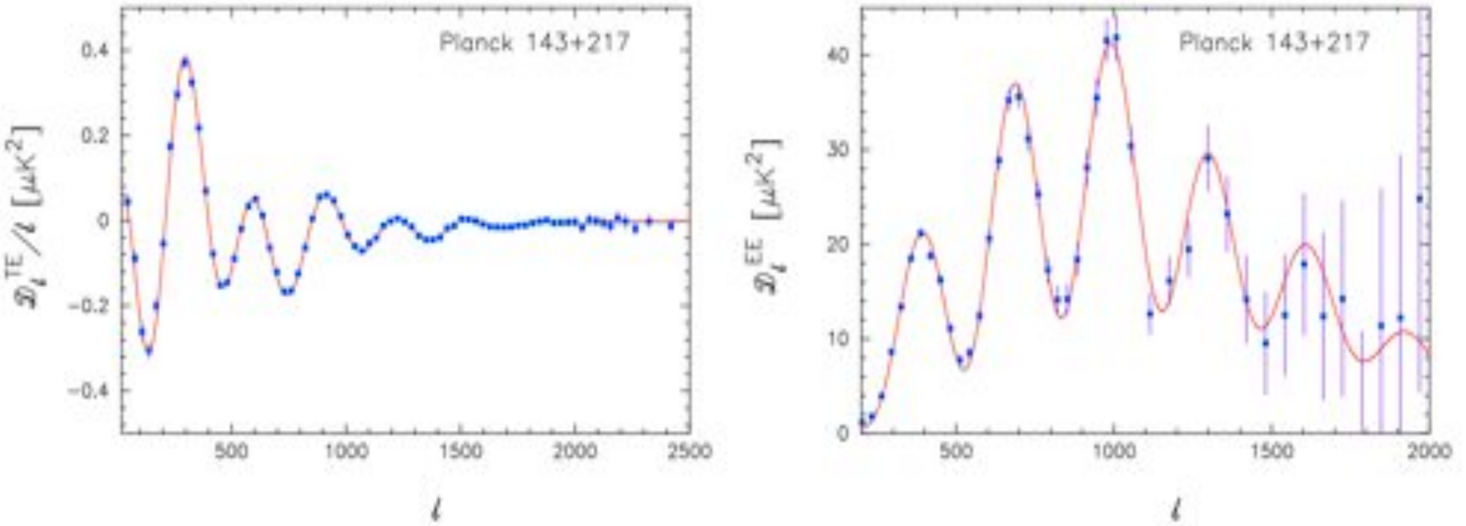
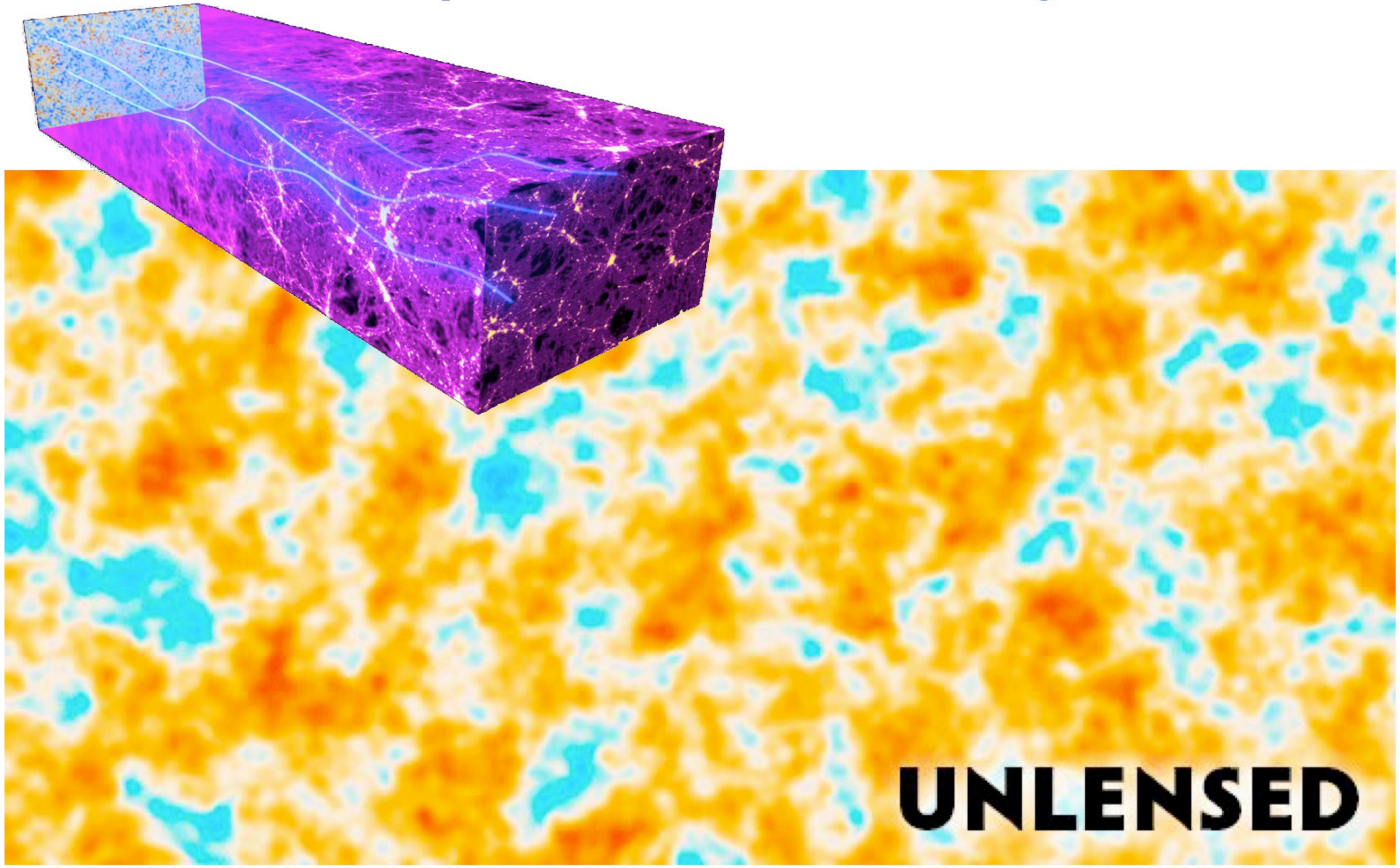
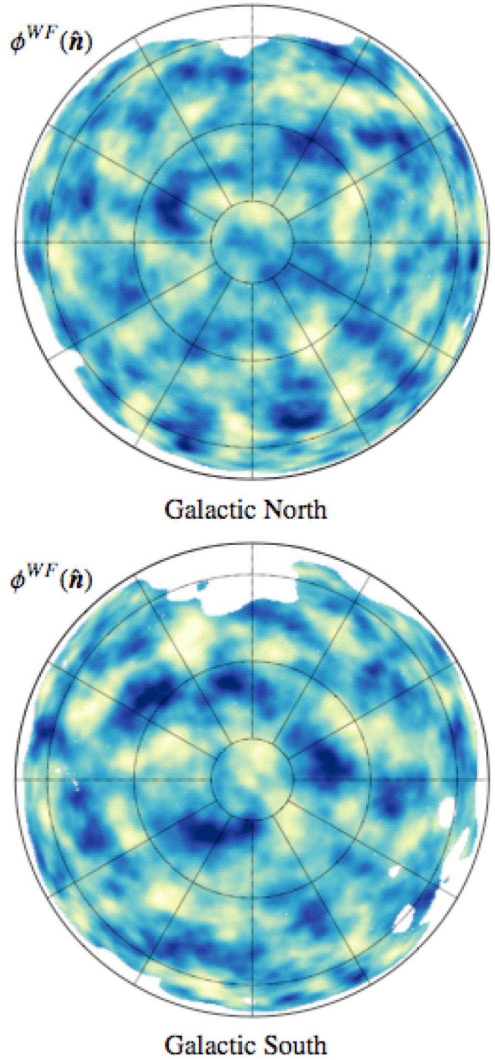


Fig. 11. *Planck TE* (left) and *EE* spectra (right) computed as described in the text. The red lines show the polarization spectra from the base ΛCDM *Planck*+WP+highL model, *which is fitted to the TT data only.*

Gravitational Lensing

- Mass between the last scattering surface and us lenses the CMB
- We use the deflections to infer the effective potential seen by the CMB





arXiv:1303.5078v1

Fig. 8. Wiener-filtered lensing potential estimate $\phi^{WF}_{LM} \equiv C^{\phi\phi}_{L}(\bar{\phi}_{LM} - \bar{\phi}^{MF}_{LM})$ for our MV reconstruction, in Galactic coordinates using orthographic projection. The reconstruction is bandpass filtered to $L \in [10, 2048]$. The *Planck* lens reconstruction has $S/N \leq 1$ for individual modes on all scales, so this map is noise dominated. Comparison between simulations of reconstructed and input ϕ in Fig. 4 show the expected level of visible correlation between our reconstruction and the true lensing potential.

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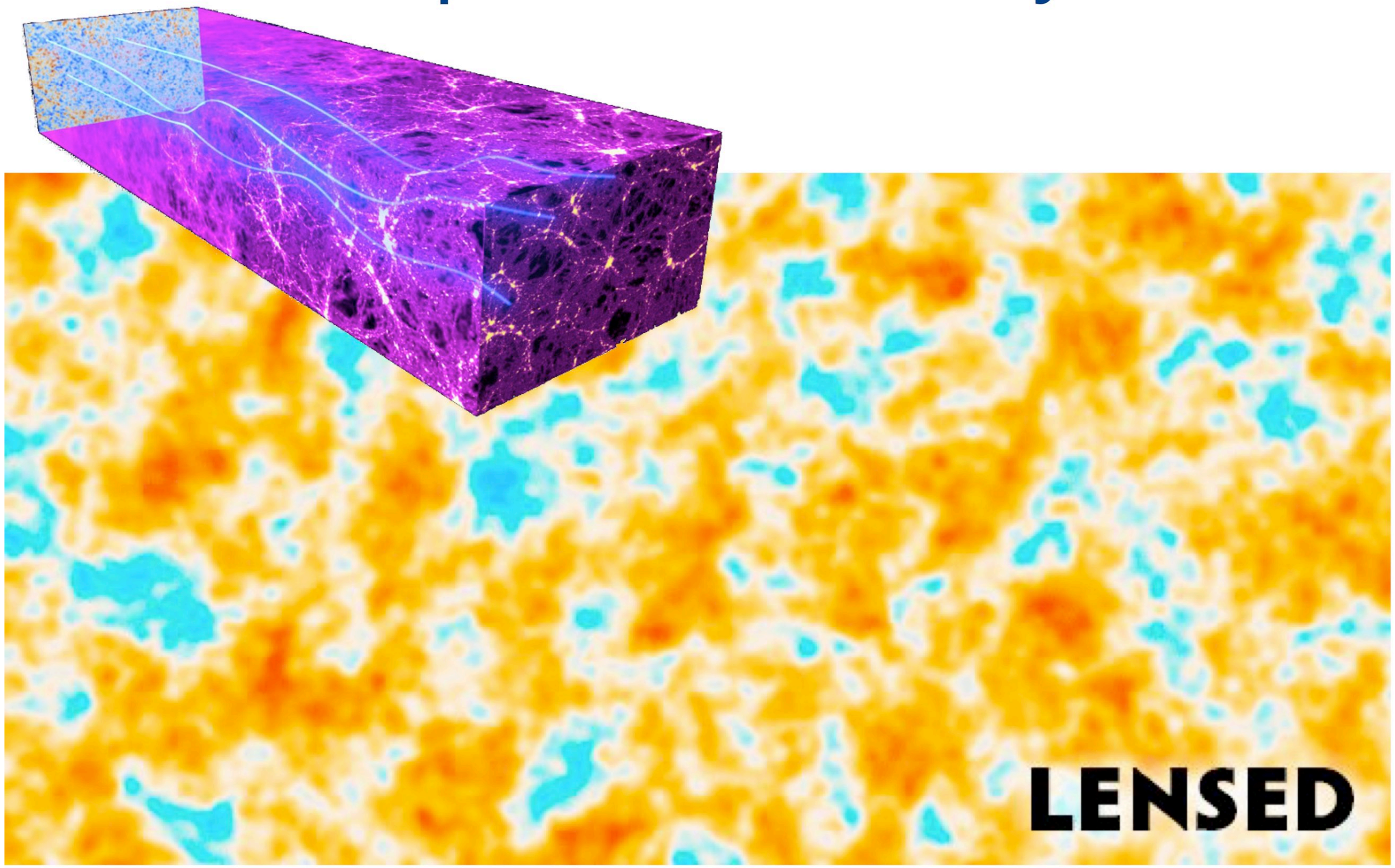

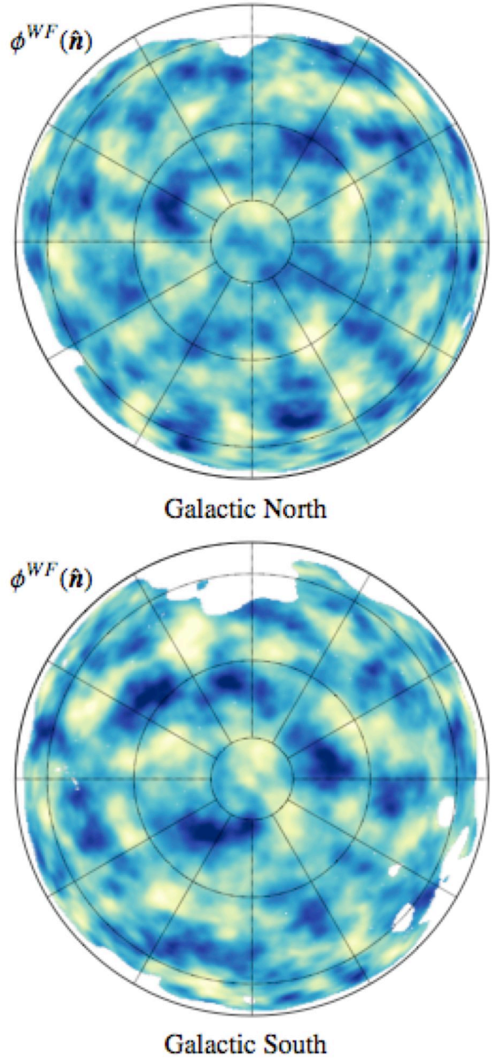

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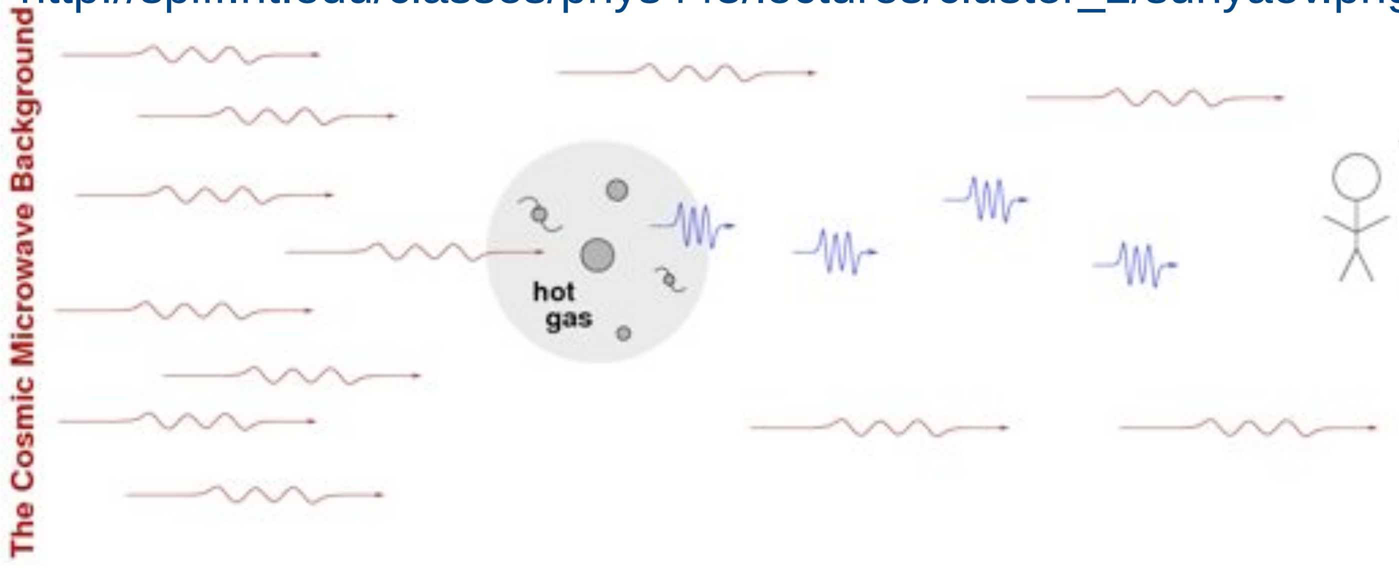
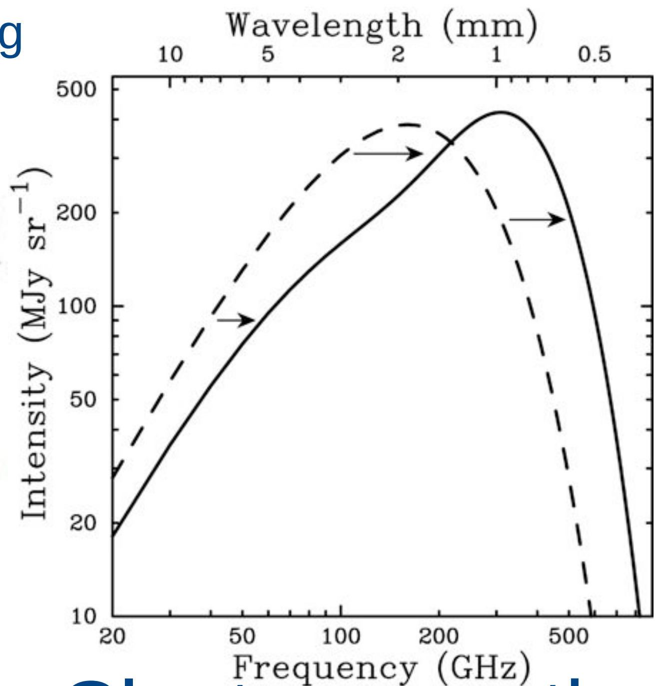
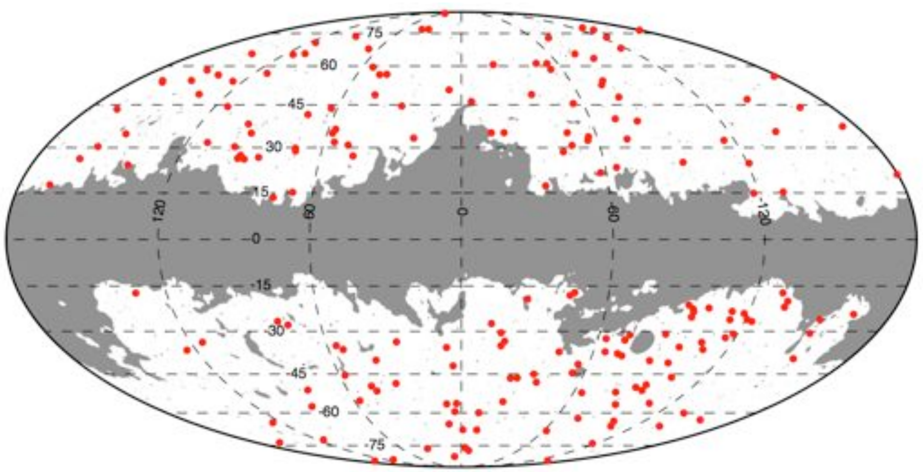
arXiv:1303.5078v1

The Sunyaev-Zeldovich Effect

http://spiff.rit.edu/classes/phys443/lectures/cluster_2/sunyaev.png

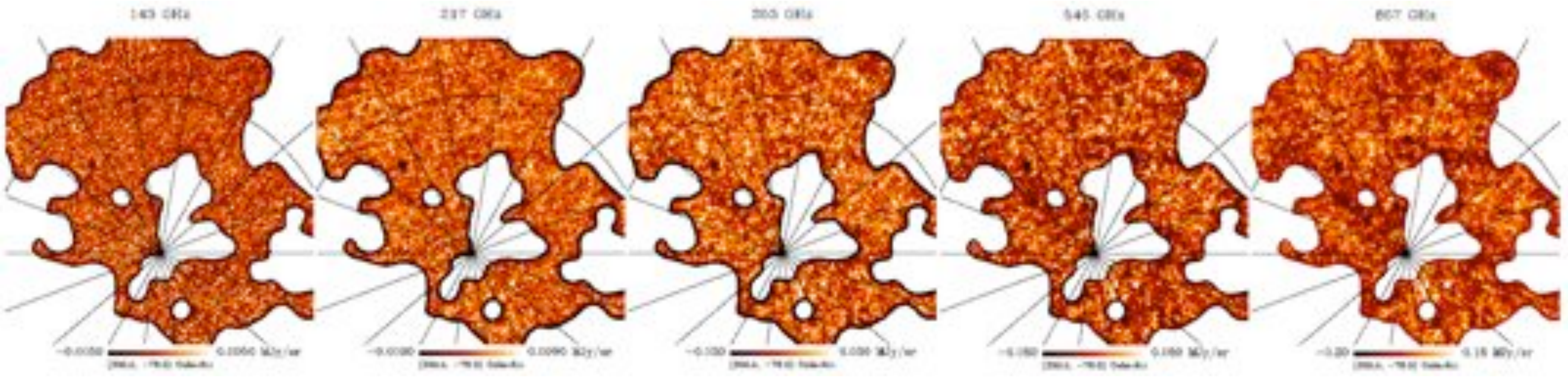






Galaxy Clusters are the largest known gravitationally bound structures in the Universe. Comparing the SZ effect and the CMB teaches about cosmology and clusters.

Cosmic Infrared Background



- Dominates the extragalactic sky in the higher Planck frequencies
- Has a spectrum similar to Galactic dust
- Tracer of star formation, much of it around z~2.
- Represents material at higher redshifts than many catalogs
- arXiv:1309.0382v1

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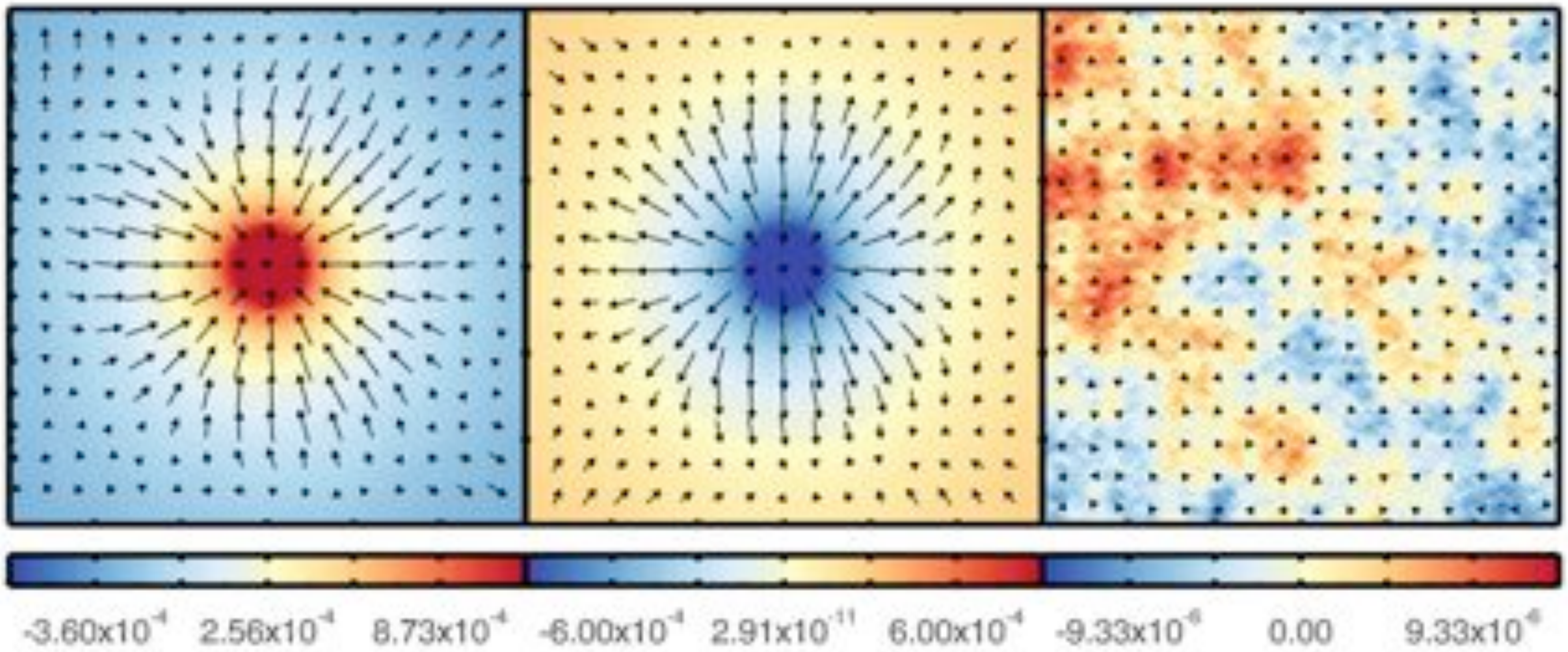
CIB × Lensing Potential

- The CIB is the remnant of star formation, much around z~2
- This material lenses the CMB
- A cross-correlation shows this:

- Correlations can also be done with your favorite catalog of sources, or other tracers of mass

545 GHz × Φ



ArXiv: 1303.5078v1

Lensing Correlations with the SZ Effect

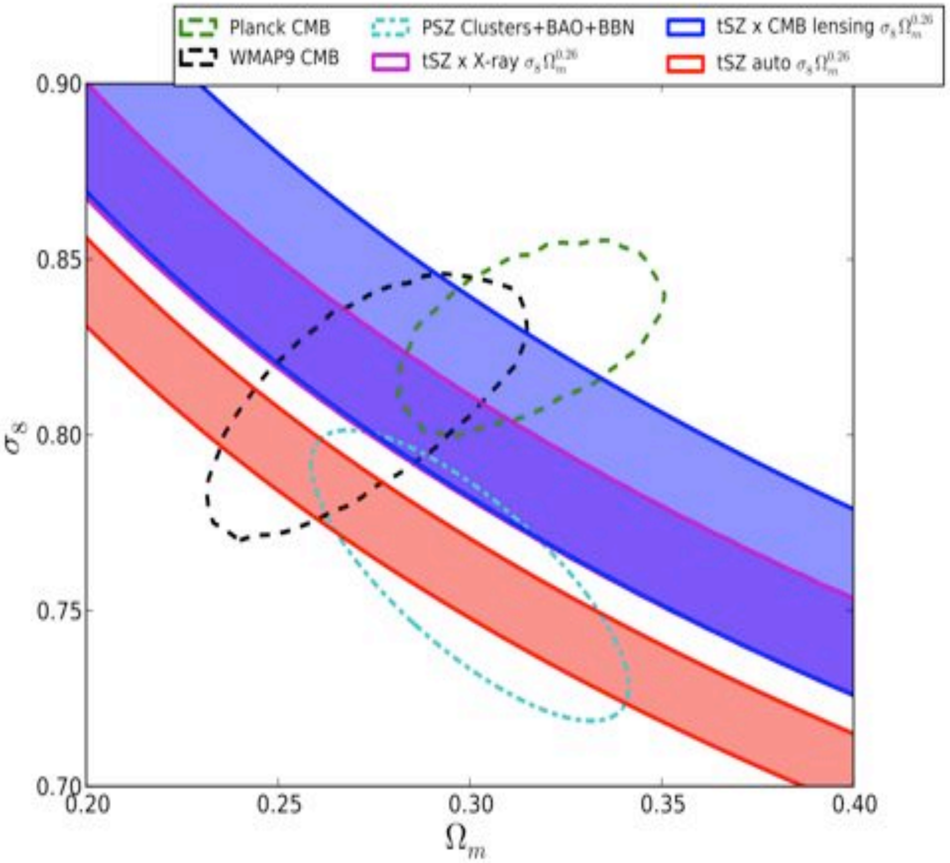


FIG. 16: Constraints on σ_8 and Ω_m from the tSZ – CMB lensing cross-power spectrum measurement presented in this work (blue shaded), the tSZ auto-power spectrum measurement from [44] re-analyzed in this work (red shaded), the Planck+WMAP polarization CMB analysis [3] (green dashed), WMAP9 CMB analysis [1] (black dashed), number counts of Planck tSZ clusters [12] (cyan dashed), and a recent cross-correlation of tSZ signal from Planck and WMAP with an X-ray "δ"-map based on ROSAT data [67] (magenta shaded). All contours shown are 68% confidence intervals only (for visual clarity). See the text for further discussion.

Hill & Spergel, 2014
http://arxiv.org/abs/1312.4525

- Both the SZ and lensing effects are "trace" large-scale structure in the Universe.
- Comparing (and cross-correlating) the two allows us to understand both the basic constituents of the Universe, and the astrophysics behind "structure formation"

SPT/Herschel Polarization Lensing

- Using an SPT E-Mode map and a Herschel map of the CIB, the predicted what B-Modes should be there and found a correlation.
- This is analogous to what Planck did using maps of temperature lensing and its own 545 GHz channel

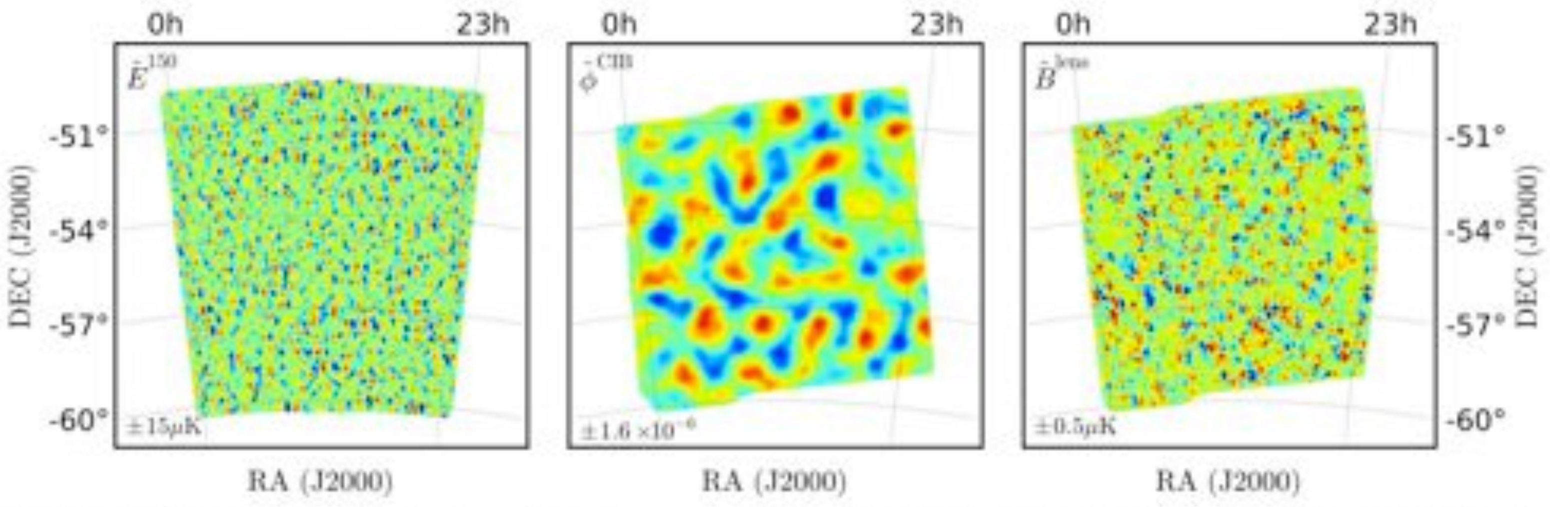
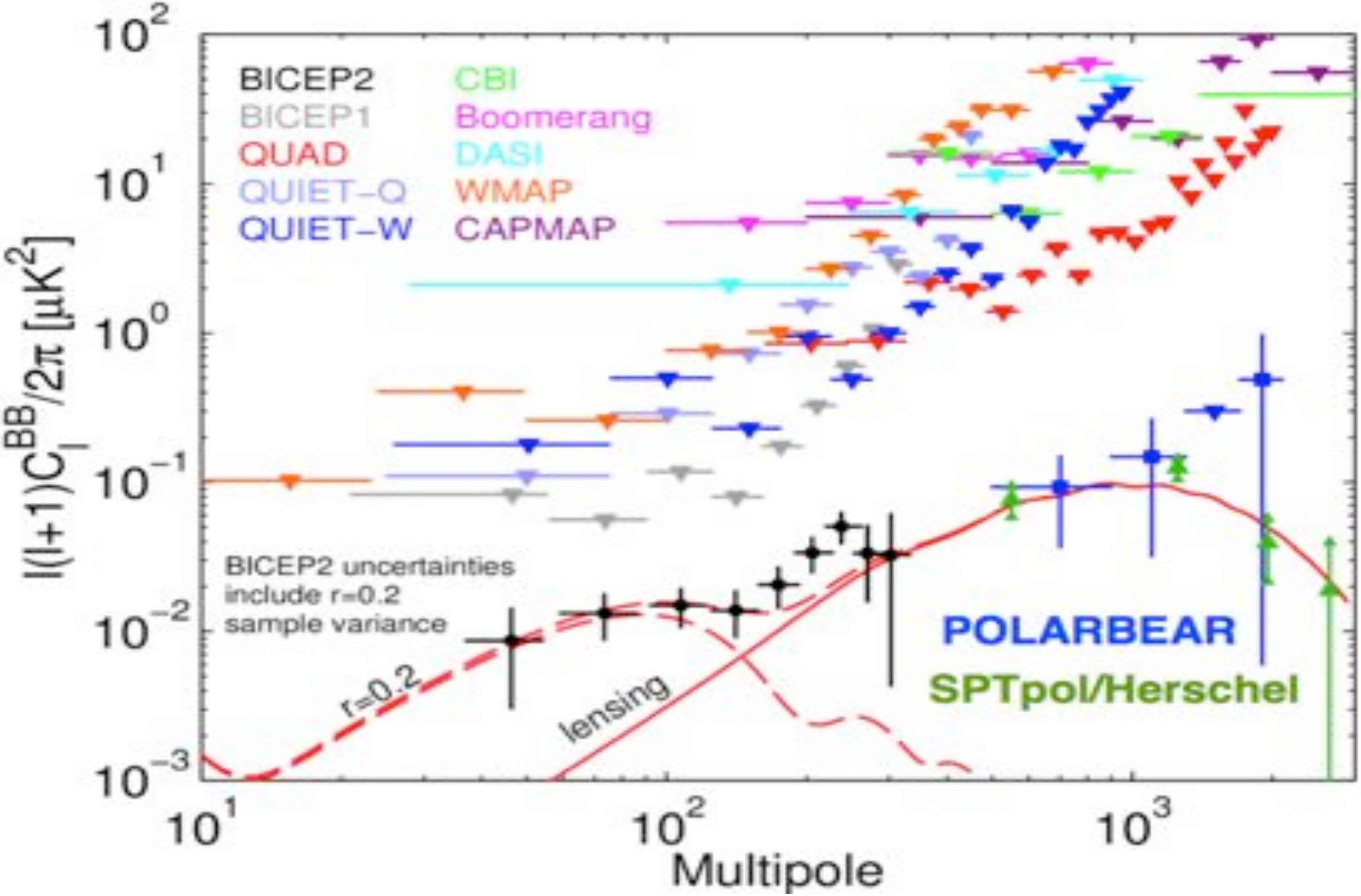


FIG. 1: Left: Wiener-filtered E-mode polarization measured by SPTpol at 150 GHz. Center: Wiener-filtered CMB lensing potential inferred from CIB fluctuations measured by *Herschel* at 500 μm. Right: gravitational lensing B-mode estimate synthesized using Eq. (1). The lower left corner of each panel indicates the blue(-)/red(+) color scale.

B-Mode Measurements



Stolen from Jeff Filippini; https://indico.cern.ch/event/296546/session/1/contribution/5

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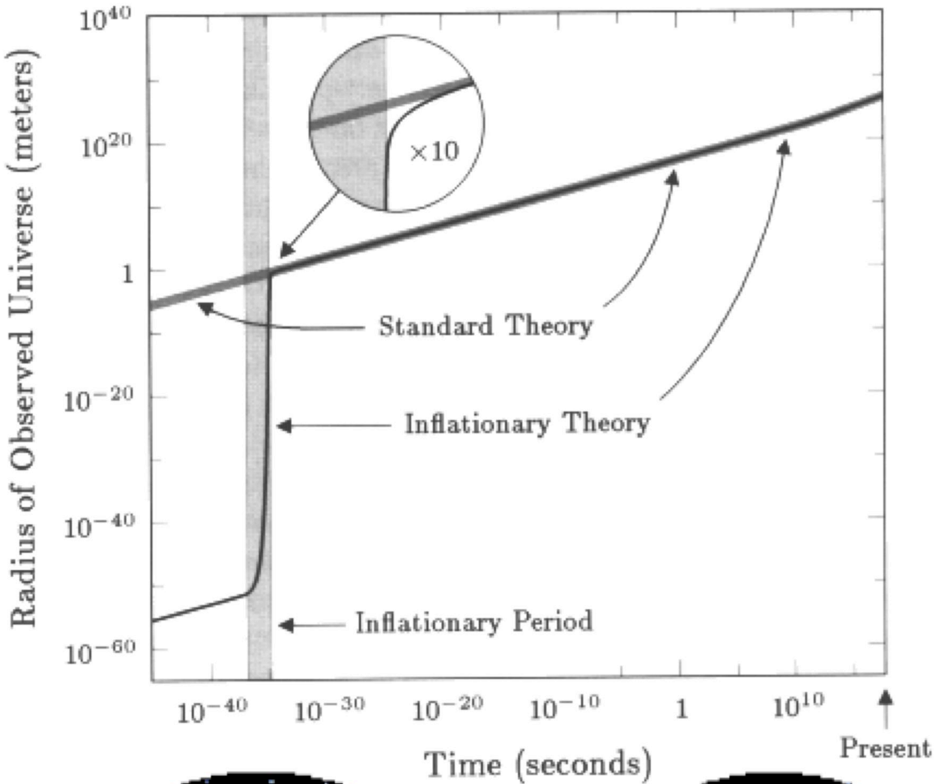
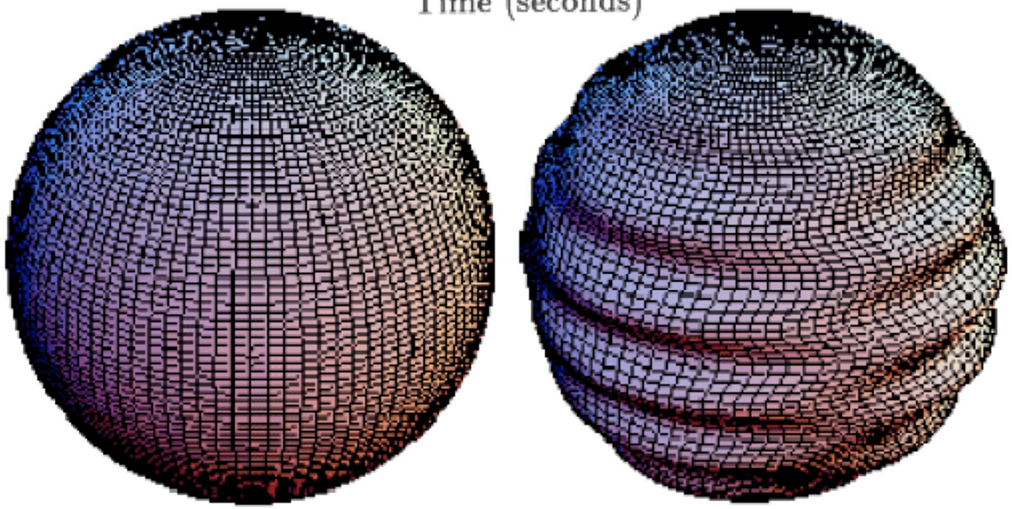
Inflation

Period of *very* fast expansion

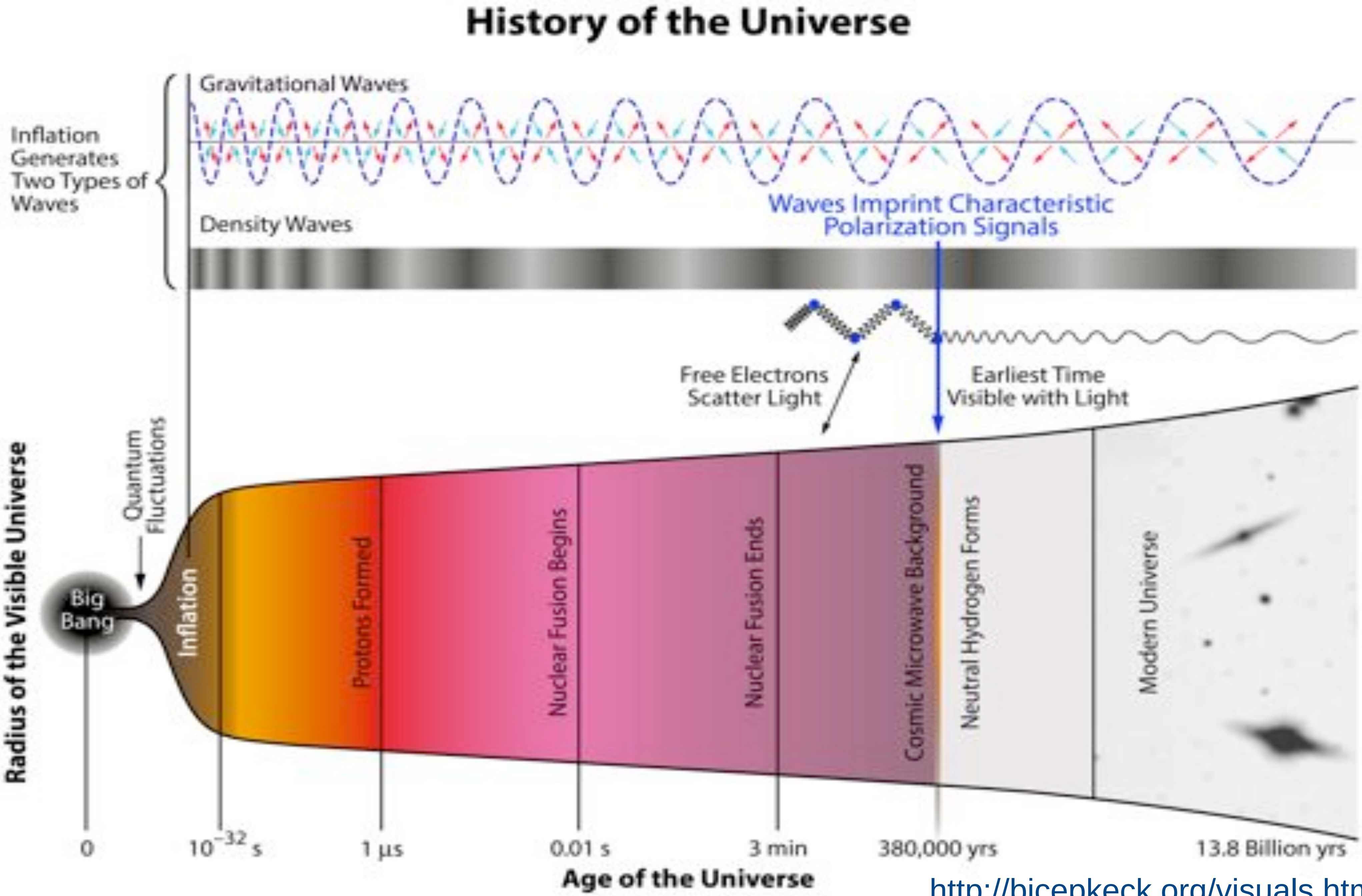
Solves monopole, flatness and horizon problems

Implies gravitational waves, but they may be vanishingly small.





Relic Gravitational Waves – B-Modes



http://bicepkeck.org/visuals.html

Inflation

- $n_s = 0.9603 \pm 0.0073$

arXiv:1303.5082

- Tensor-to-scalar ratio: $r < 0.11$
  - With polarization, we hope to be able to reduce this

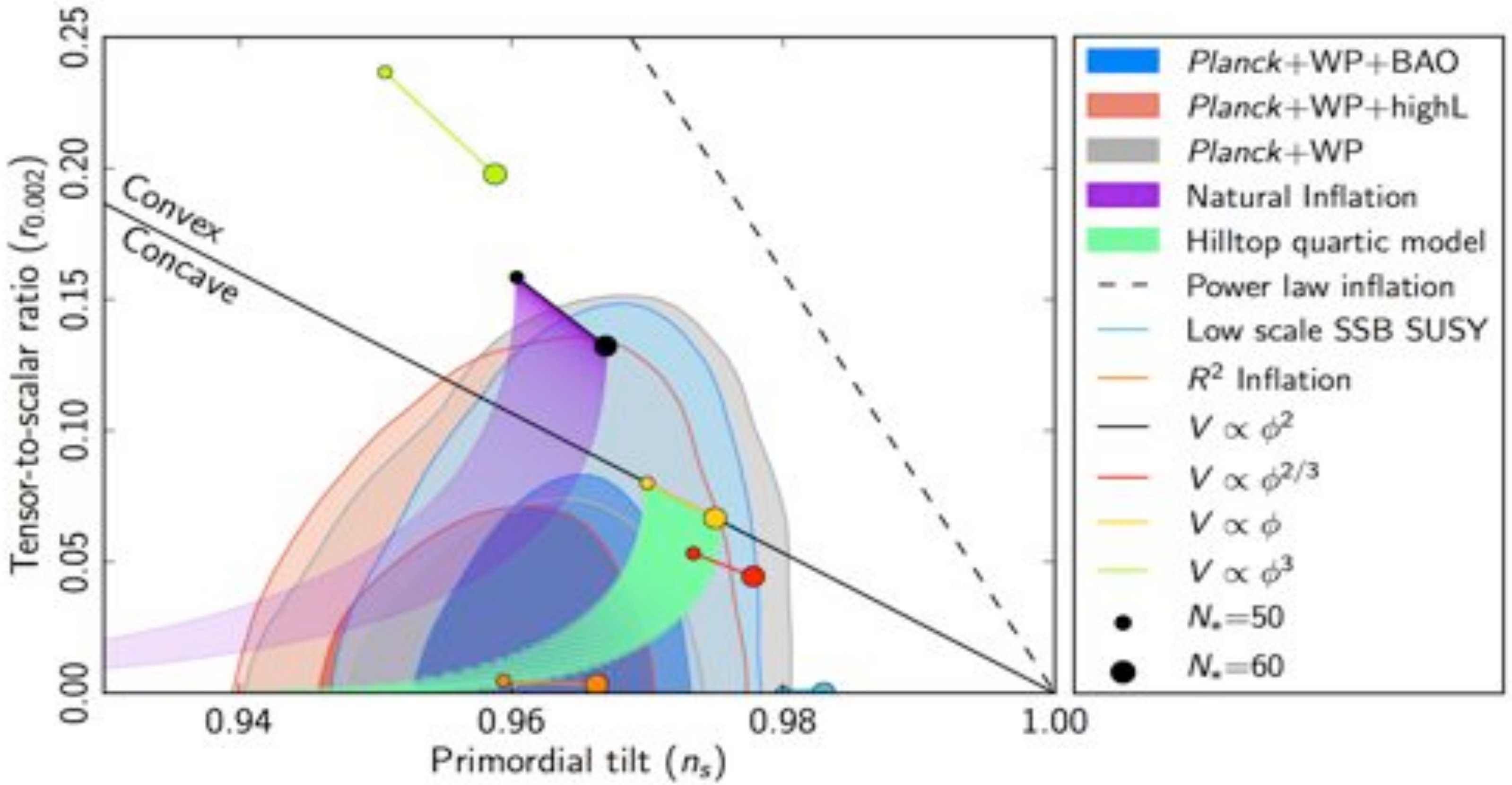
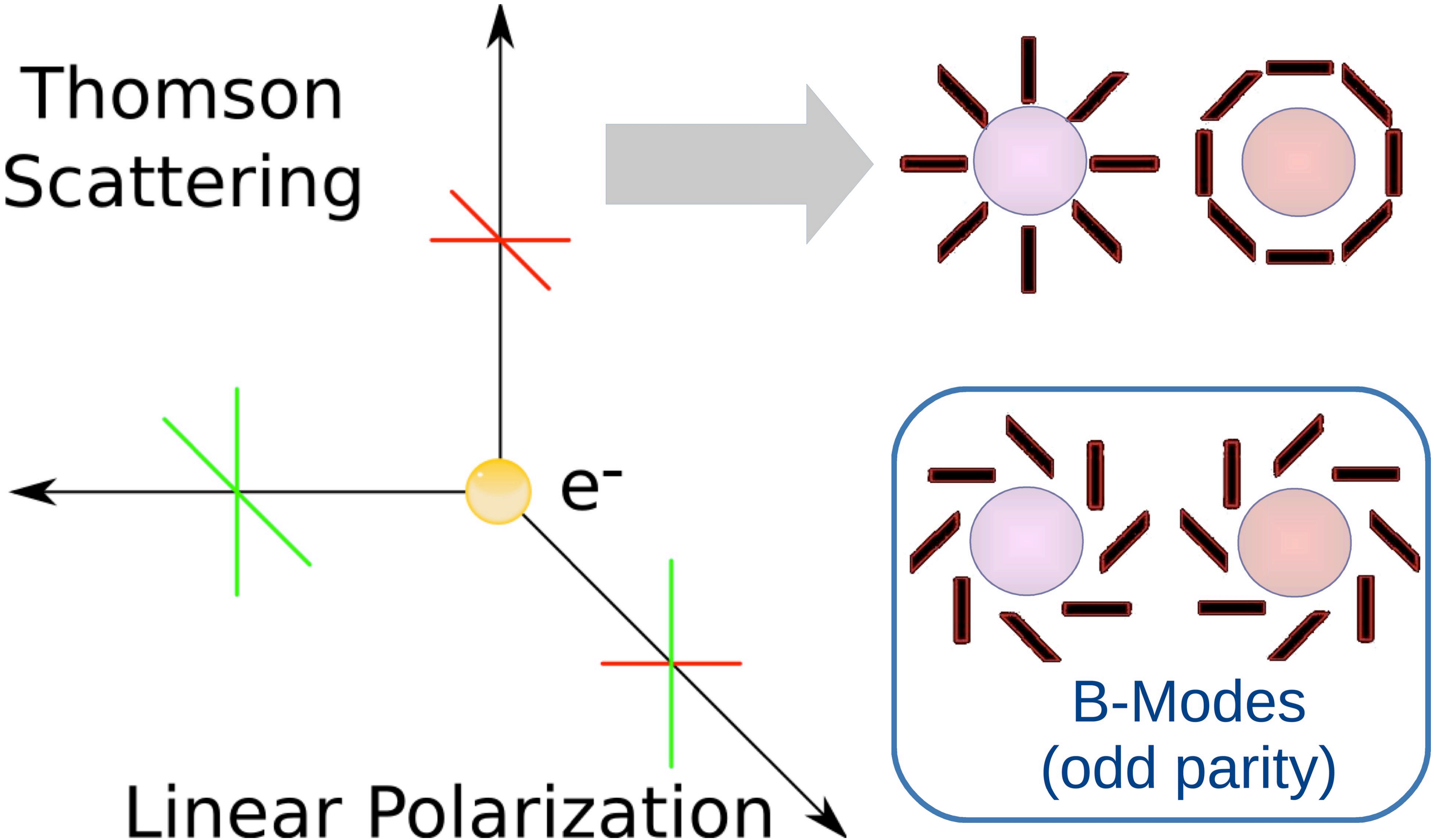
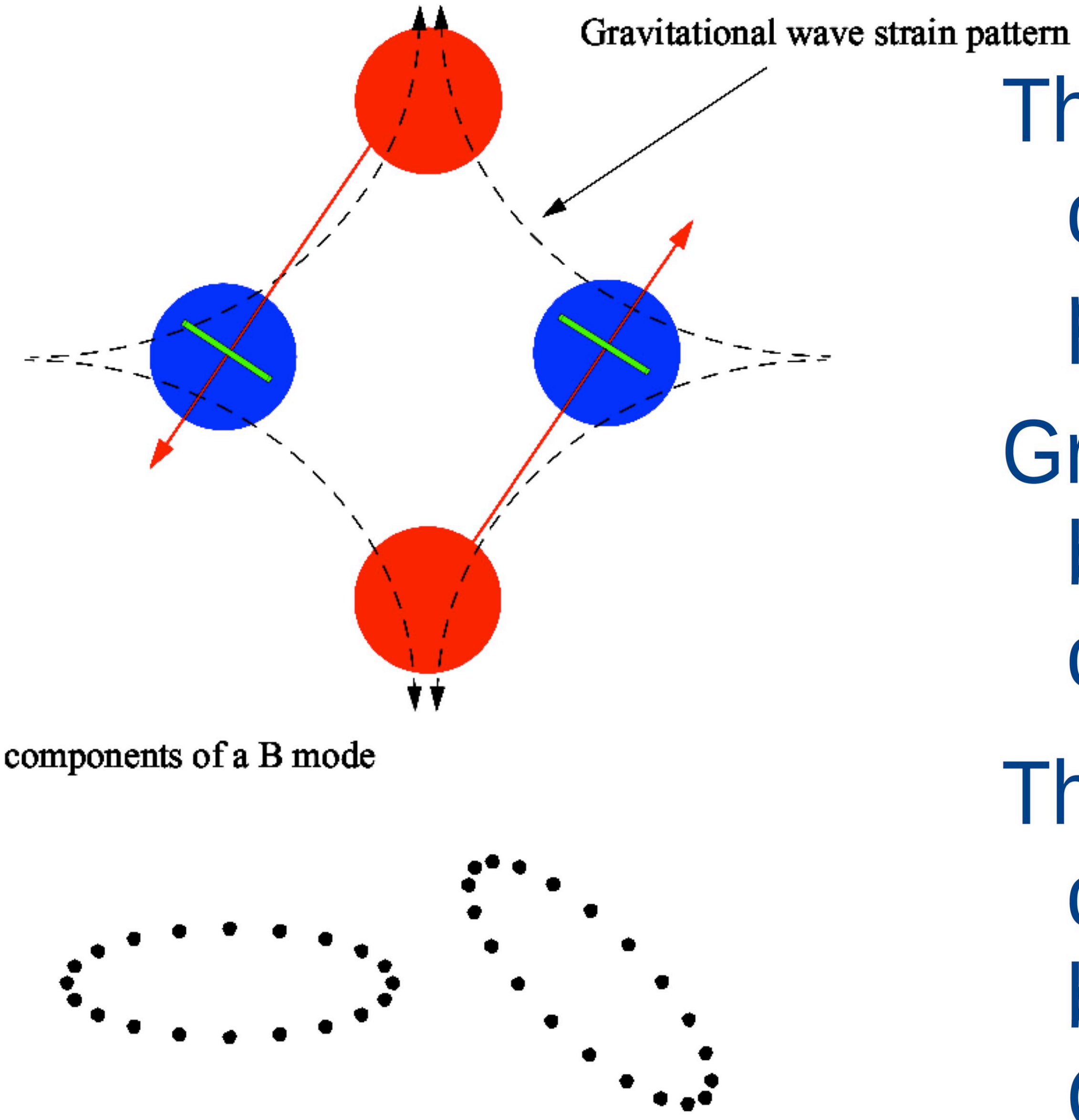


Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared to the theoretical predictions of selected inflationary models.

Polarization of the CMB



Grav. Waves Convert E Modes to B



Thomson scattering creates E-mode polarization

Gravitational Waves can break the symmetry and create B-modes

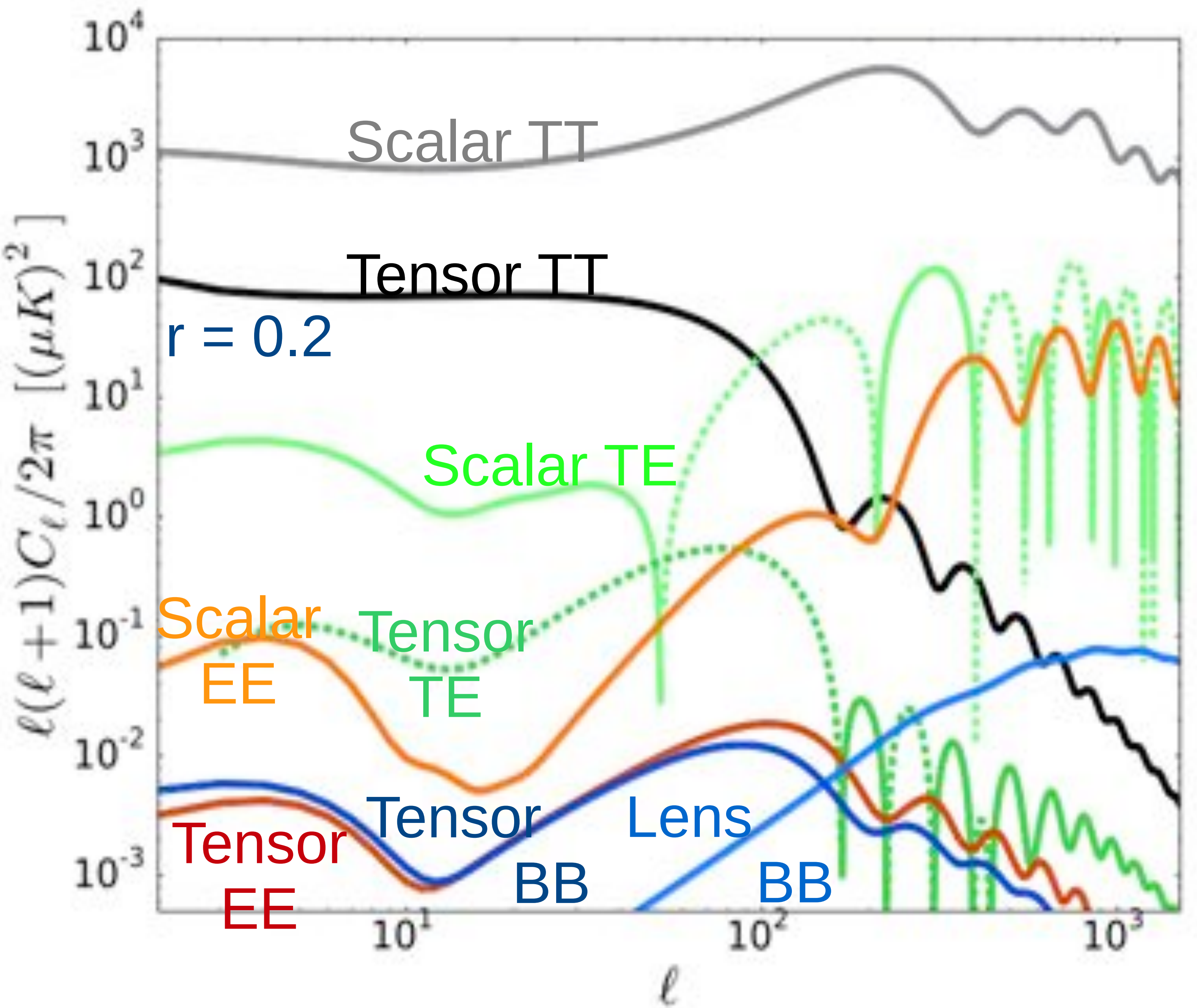
This is a very small effect compared to what has been measured with the CMB to date

Rai Weiss – 2005 CMB Task Force Update

Spectra Zoo

Scalar & Tensor TT, TE, EE & BB Spectra

'r' quantifies the fraction of power in tensors versus scalars



BICEP Saw r ~ 0.2

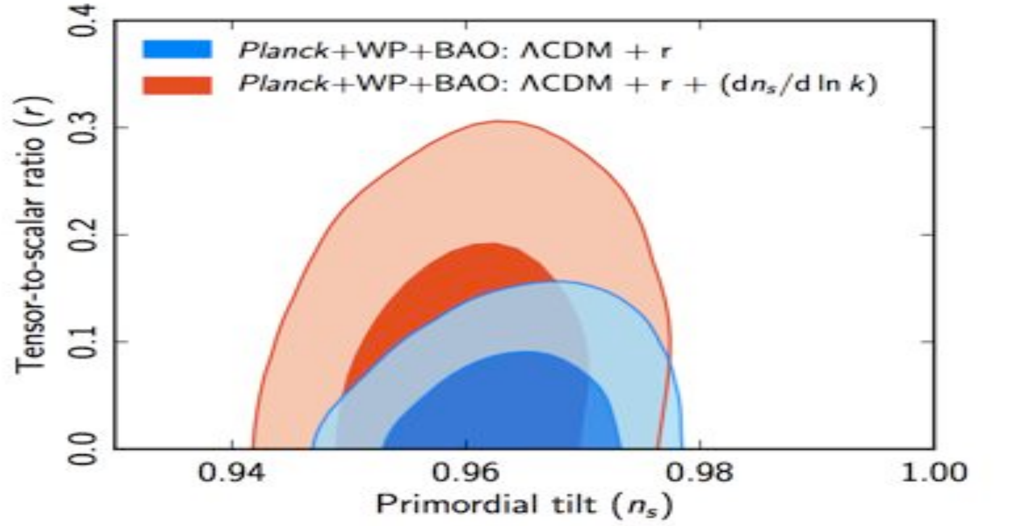
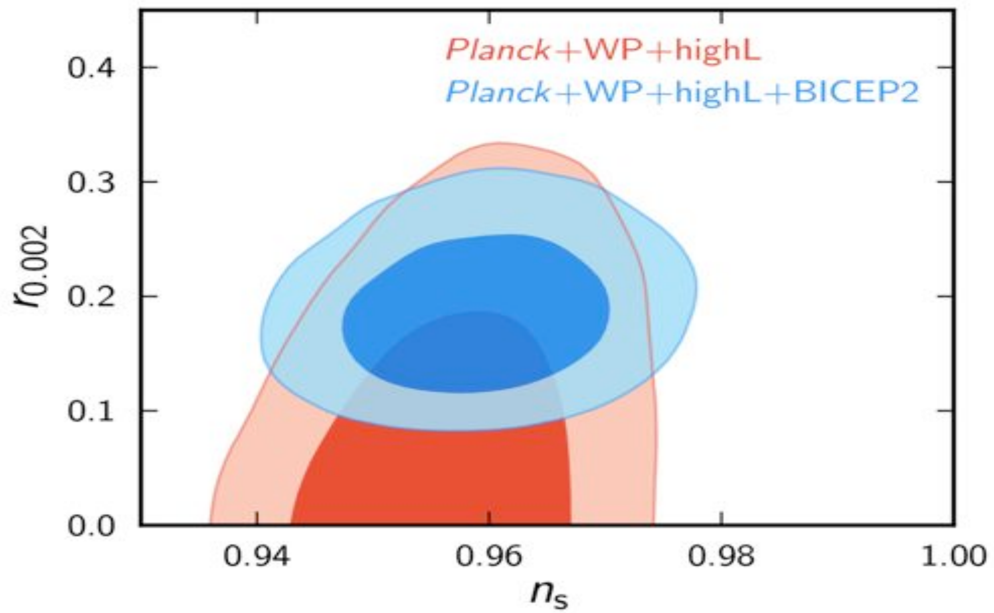


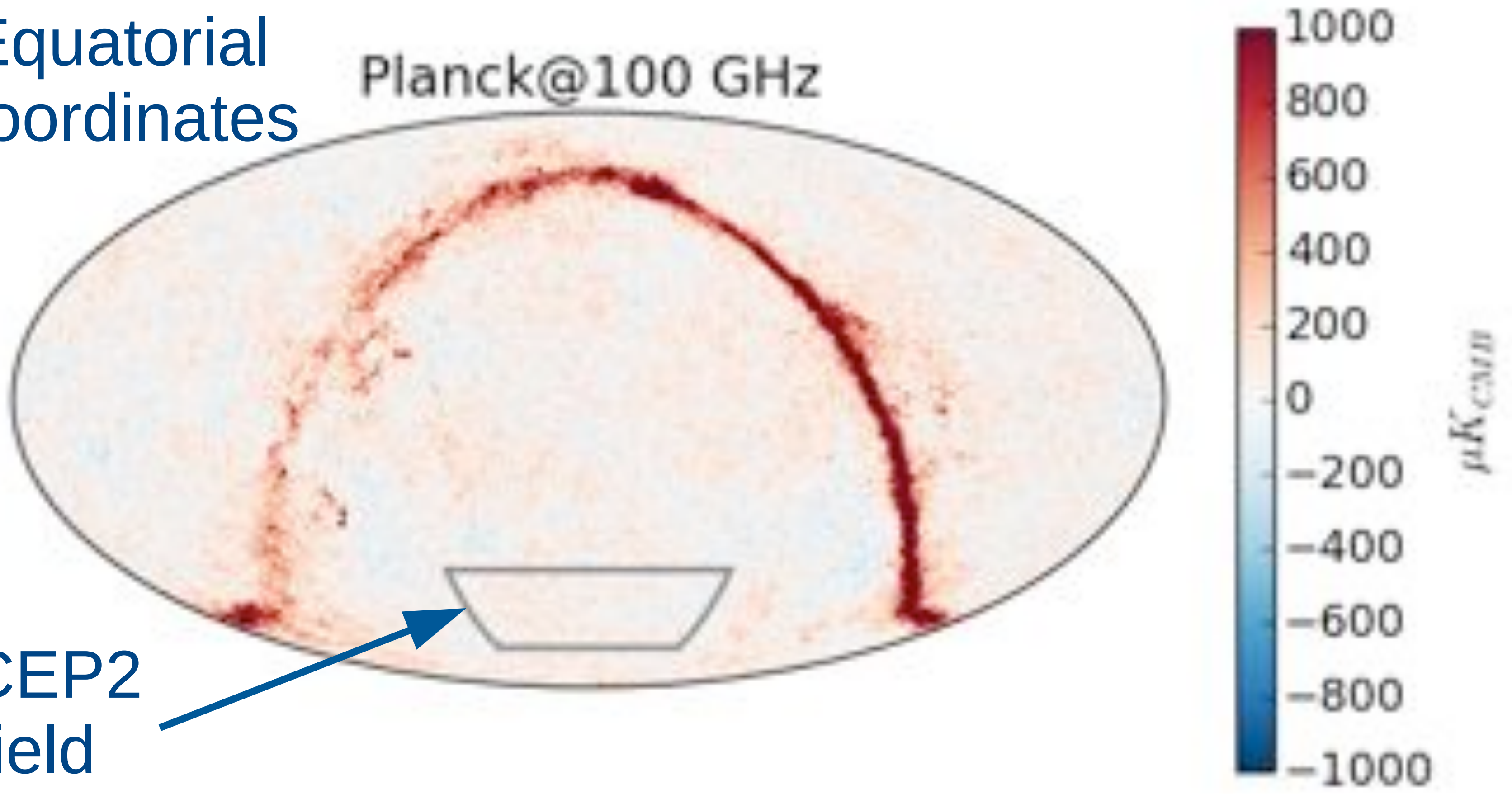
Fig. 4. Marginalized joint 68% and 95% CL regions for (r, n_s), using *Planck*+WP+BAO with and without a running spectral index.



- "... the fractional contribution of tensor modes is limited to r < 0.13 (95% CL)" -- *Nine-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Parameter Results (2012)*
- "Planck establishes an upper bound on the tensor-to-scalar ratio of r < 0.11 (95% CL)." -- *Planck 2013 results. XXII. Constraints on inflation*.
- "The observed B-mode power spectrum is well-fit by a lensed-LCDM + tensor theoretical model with tensor/scalar ratio $r=0.20^{+0.07}_{-0.05}$." -- *BICEP2 I: Detection of B-mode Polarization at Degree Angular Scales (2014)*
- We were looking for a needle in a haystack, but instead we found a crowbar. -- *Clem Pryke*

Planck 143 GHz Temperature Map

Equatorial Coordinates

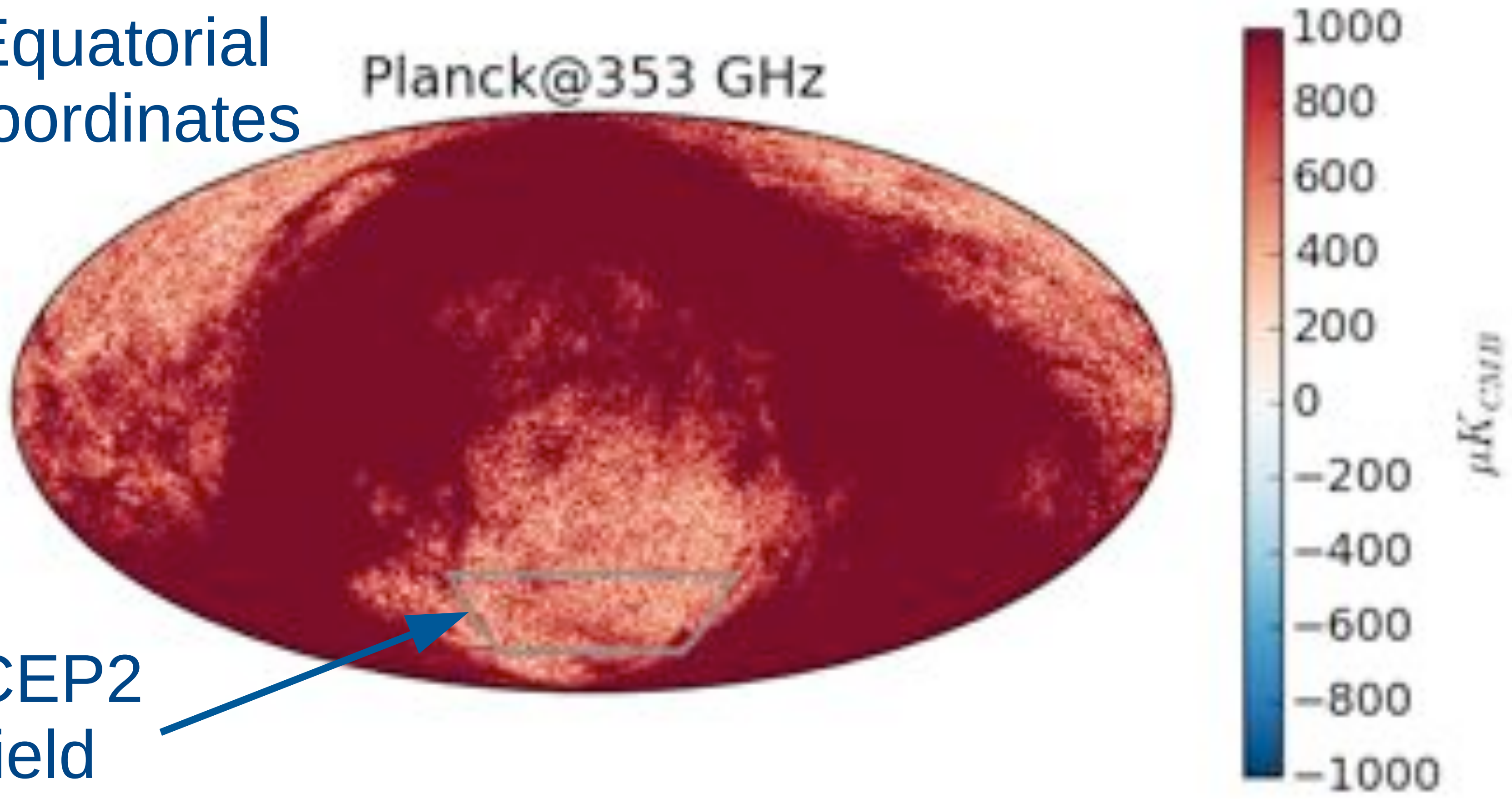


BICEP2 Field

This is a *temperature* map. Planck has not yet released full-sky polarization maps.

Planck 353 GHz Temperature Map

Equatorial Coordinates



BICEP2 Field

This is a *temperature* map. Planck has not yet released full-sky polarization maps.

What Planck is Working on Now

Stokes Q & U at 353 GHz from Planck

Planck collaboration: The Planck dust polarization sky

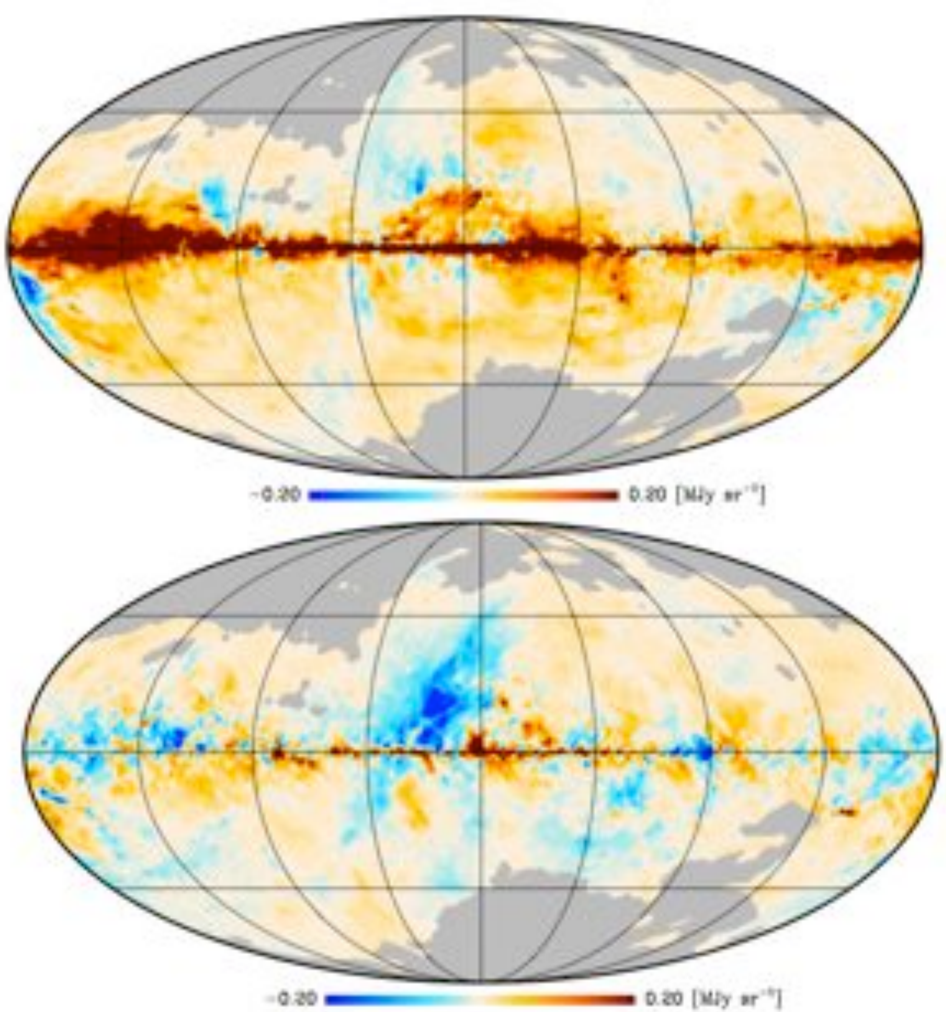
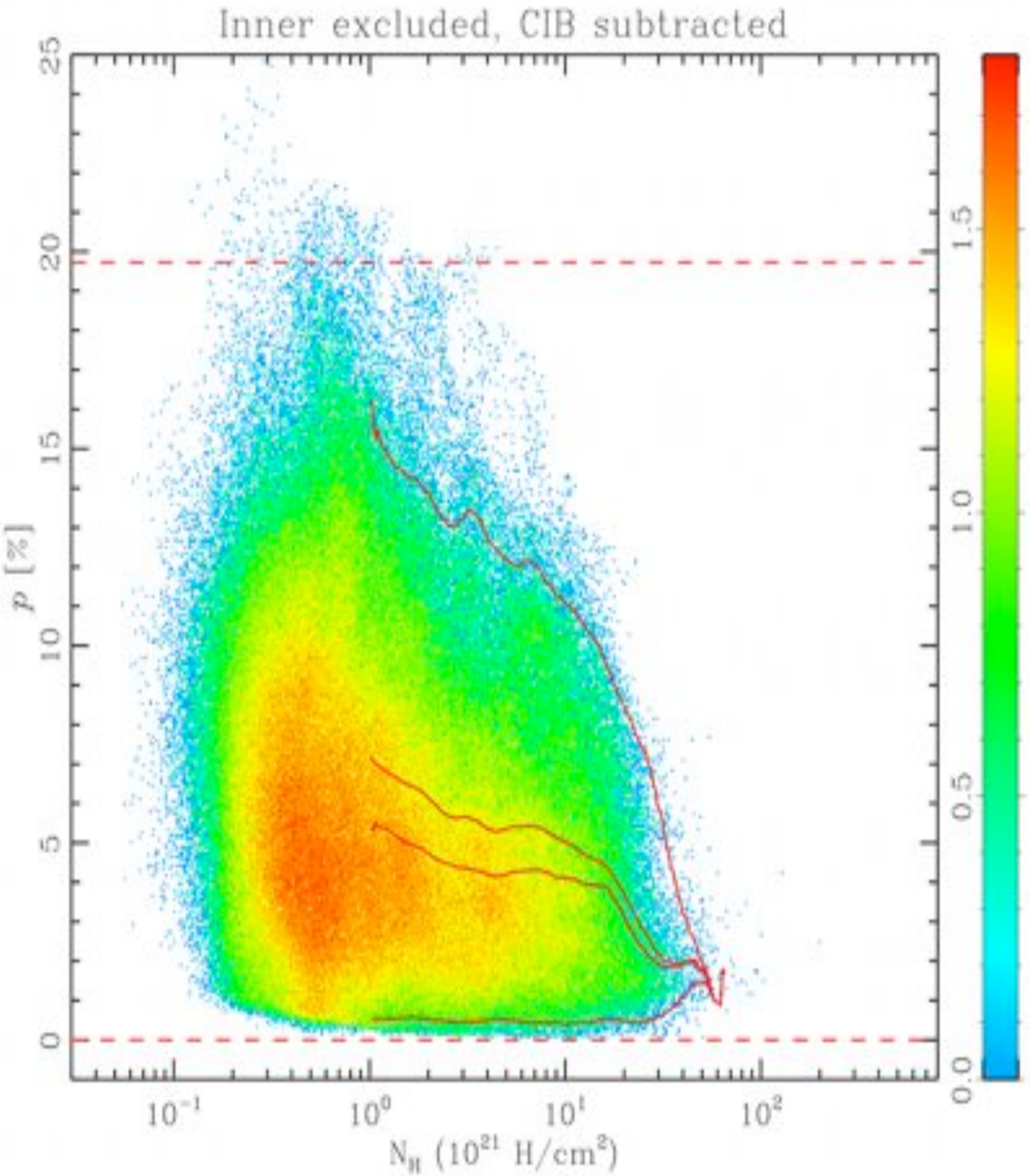


Fig. 1. *Planck* 353 GHz polarization maps at 1° resolution. *Upper:* *Q* Stokes parameter map. *Lower:* *U* Stokes parameter map. The maps are shown with the same colour scale. High values are saturated to enhance mid-latitude structures. The values shown have been bias corrected as described in Sect. 2.3. These maps, as well as those in following figures, are shown in Galactic coordinates with the galactic center in the middle and longitude increasing to the left. The data is masked as described in Sect. 2.4.

arXiv:1405.0871v1 5 May 2014

- BICEP has more sensitivity than Planck in their field at 150 GHz
- But Galactic dust is much brighter at 353 GHz than at 150 GHz
- Planck finds that at 150 GHz, dust must be carefully addressed, even in the cleanest regions of the sky

Polarization vs. Optical Depth



arXiv:1405.0871v1 5 May 2014

- Historically, the CMB world has used a canonical 5% polarization figure for dust
- These are based on the only regions we could measure – bright regions
- Lower column-depth regions are less complicated, have less depolarization and so seem have higher polarization fraction

B-Mode Spectrum on the BICEP Field

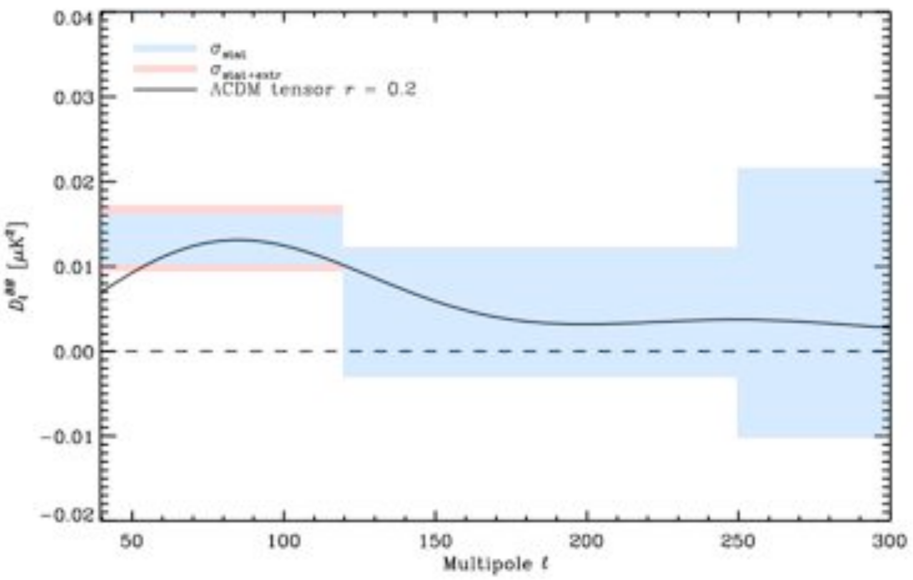


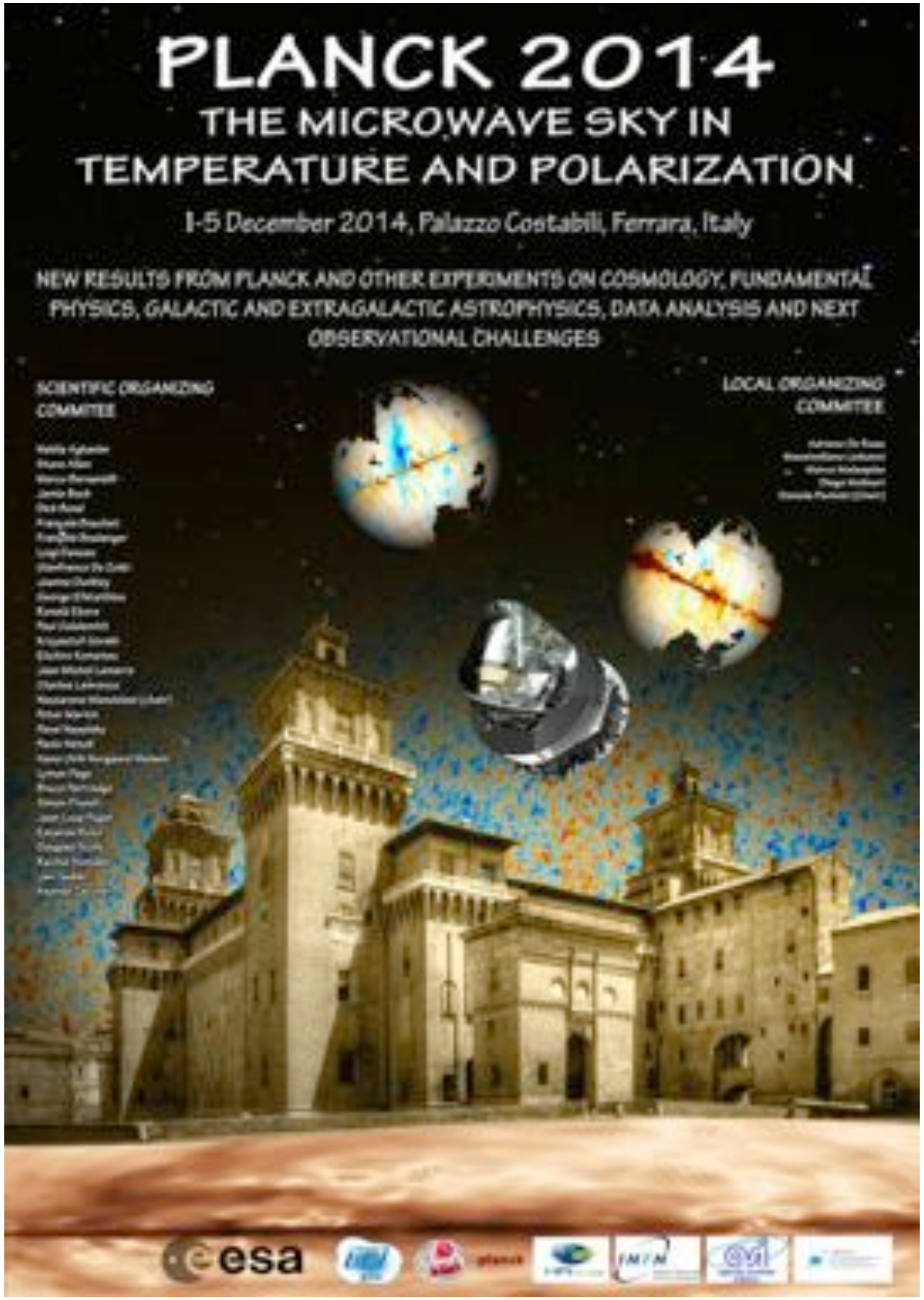
Fig. 9: *Planck* 353 GHz $\mathcal{D}_\ell^{BB}$ angular power spectrum computed on M_{B2} defined in Sect. 6.1 and extrapolated to 150 GHz (box centres). The shaded boxes represent the $\pm 1\,\sigma$ uncertainties: blue for the statistical uncertainties from noise; and red adding in quadrature the uncertainty from the extrapolation to 150 GHz. The *Planck* 2013 best-fit ΛCDM $\mathcal{D}_\ell^{BB}$ CMB model based on temperature anisotropies, with a tensor amplitude fixed at $r = 0.2$, is overplotted as a black line.

Blue: Statistical Uncertainty
Pink: 353-150 Extrapolation Uncertainty

Cross-Correlations between BICEP2 and Planck are happening now...

- Measured at 353 GHz and extrapolated to 150 GHz
- Note that there are only three bins here...
  - The first band is the most relevant to the primordial B-Modes...
- The filtering and processing that BICEP has actually done is not accounted for here.

Planck Polarization Progress



- Planck has released no CMB polarization data
  - A few papers have been written about polarization foregrounds, including implications for BICEP2 (which I will discuss)
- Most of the new polarization results will be shown at the Ferrara conference December 1-5
- But...

Planck's Status

- Not all Planck products will be ready by December 1st
- The release has therefore been postponed to December 22nd
  - LFI will deliver their polarization maps
  - “Foreground” maps will be delivered
- The “Cleaned” CMB map will be delivered Dec. 22nd, but will have the largest angular scales filtered or otherwise obfuscated.
- In addition, HFI will delay the release of the 100, 143 and 217 GHz polarization maps until the Spring of 2015.

Outline

- The Microwave Background
- The Planck Satellite
- Inflation and Planck & BICEP2
- “Cross-Correlations”
- What's to Come?

Near-Term Experiments

B-Mode Search Projects Underway

GroundBird **MuSE**

Ground-Based (Chile):

POLARBEAR: Polarization of Background Radiation

ACTPOL: Atacama Cosmology Telescope – Polarization

ABS: Atacama B-mode Search

CLASS: Cosmology Large Angular Scale Surveyor

Ground-Based (Antarctica):

SPTPOL: South Pole Telescope's polarization-sensitive camera

BICEP2: Background Imaging of Cosmic Extragalactic Polarization (and Keck Array)

QUBIC: Q&U Bolometric Interferometer for Cosmology

Ground-Based (Canary Islands):

QUIJOTE: Q-U-I JOint TEnerife

Balloon Experiments:

EBEX: E and B Experiment

SPIDER: Suborbital Polarimeter for Inflation

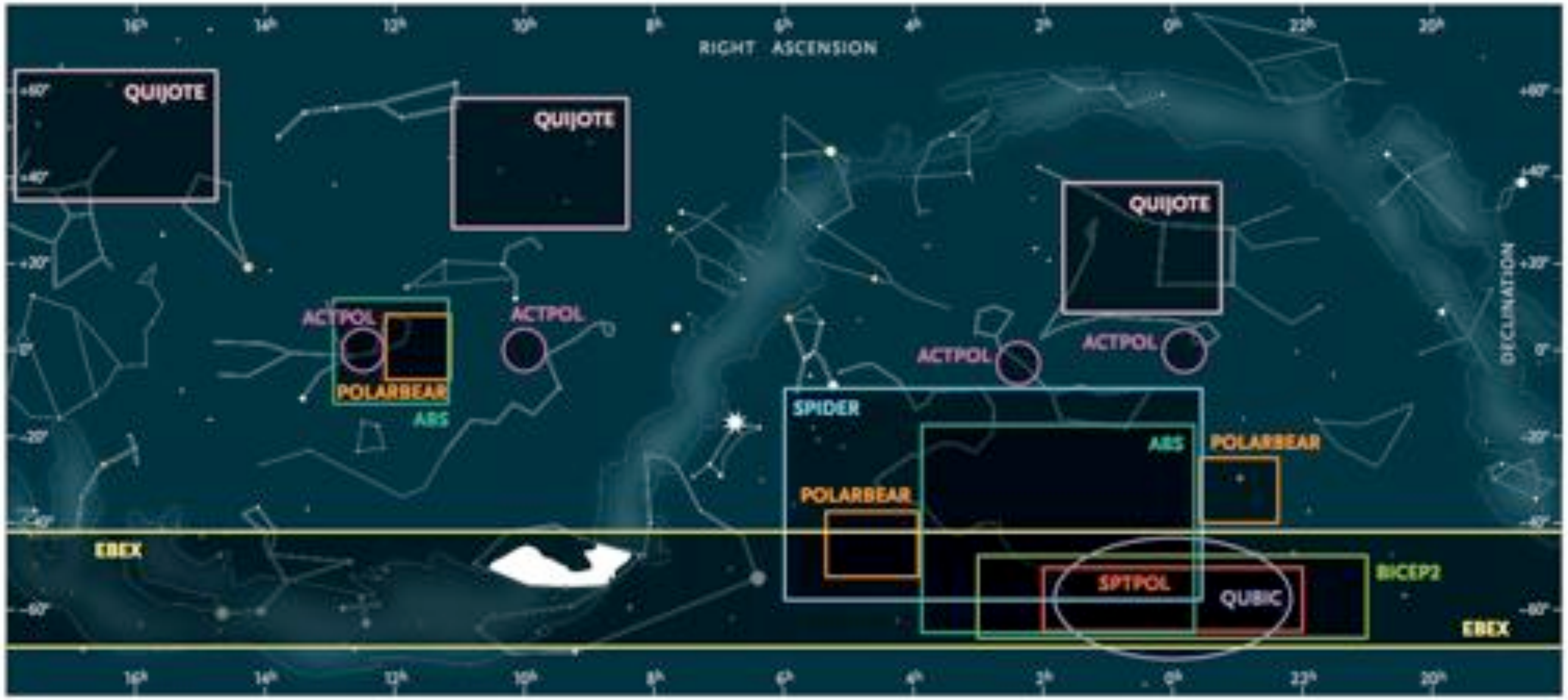
LSPE: Large-Scale Polarization Explorer

PIPER: Primordial Inflation Polarization Explorer

ESA Satellite Mission:

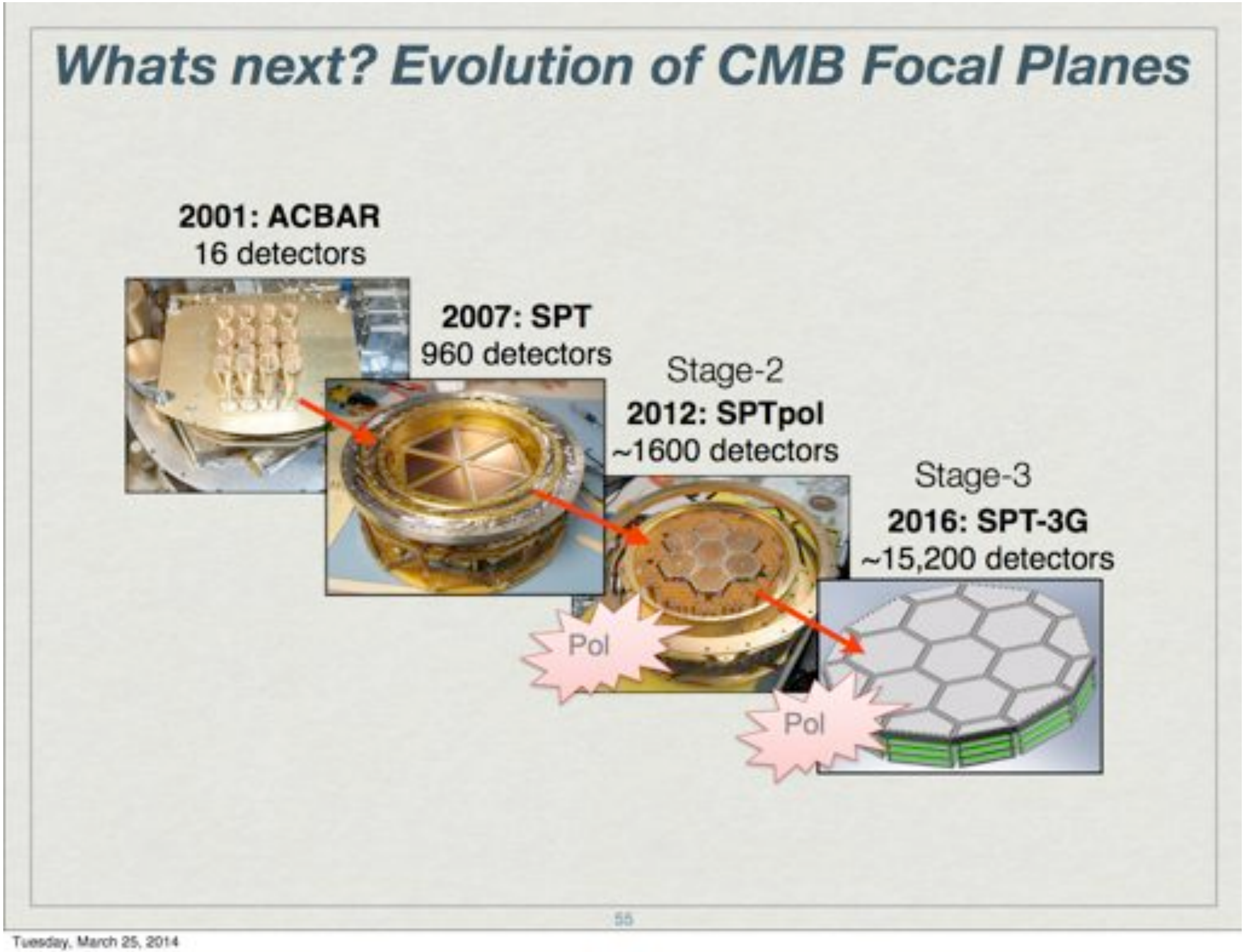
PLANCK

RACE TOWARD THE BIG BANG Several projects are currently hunting for the polarization signature of inflation. Shown below are the fields of view for active projects (except for Planck, which is all-sky). Fields are approximate and distorted by projection at high declinations.



SkyandTelescope.com October 2013 27

More and more detectors...



From Kyle Story's March, 2014 Moriond Cosmology Presentation

Ground-Based Plans

For reference, Planck/HFI has ~50 detectors

CMB timeline

O(100) detectors ==>

- 2009: $r < 0.7$ (BICEP) Chiang et al, 0906.1181

O(1000) detectors ==>

- 2013: $r \lesssim 0.1$ from Inflationary B-modes (BICEP 2) ?
- 2013: Stage II experiments detect lensing B-modes
- 2013-2016: Stage II experiments
  $\sigma(r)\sim0.03$, $\sigma(N_{eff})\sim0.1$, $\sigma(\Sigma m_\nu)\sim0.1$eV
- 2016-2020: Stage III experiments
  $\sigma(r)\sim0.01$, $\sigma(N_{eff})\sim0.06$, $\sigma(\Sigma m_\nu)\sim0.06$eV;

O(100000) detectors ==>

- 2020-2025: **Stage IV goal to reach**
  $\sigma(r) = 0.001$, $\sigma(N_{eff}) = 0.025$, $\sigma(\Sigma m_\nu) = 16$ meV

Taken from a pre-BICEP2 presentation by John Carlstrom
Note: 2**(15 years/1.5 year “Moore” doubling time) ~ 1000

Fig. 8: Best Parts of the Polarized Sky

- Value of BB spectrum at ℓ=80, normalized to a spectrum with r=1.
  - Deep red is r~10
  - Orange/red is r~1
  - Blue/cyan is r~0.1
  - Deep blue is r~0.01
- Computed from the 353 GHz data and extrapolated to 150 GHz using power law above

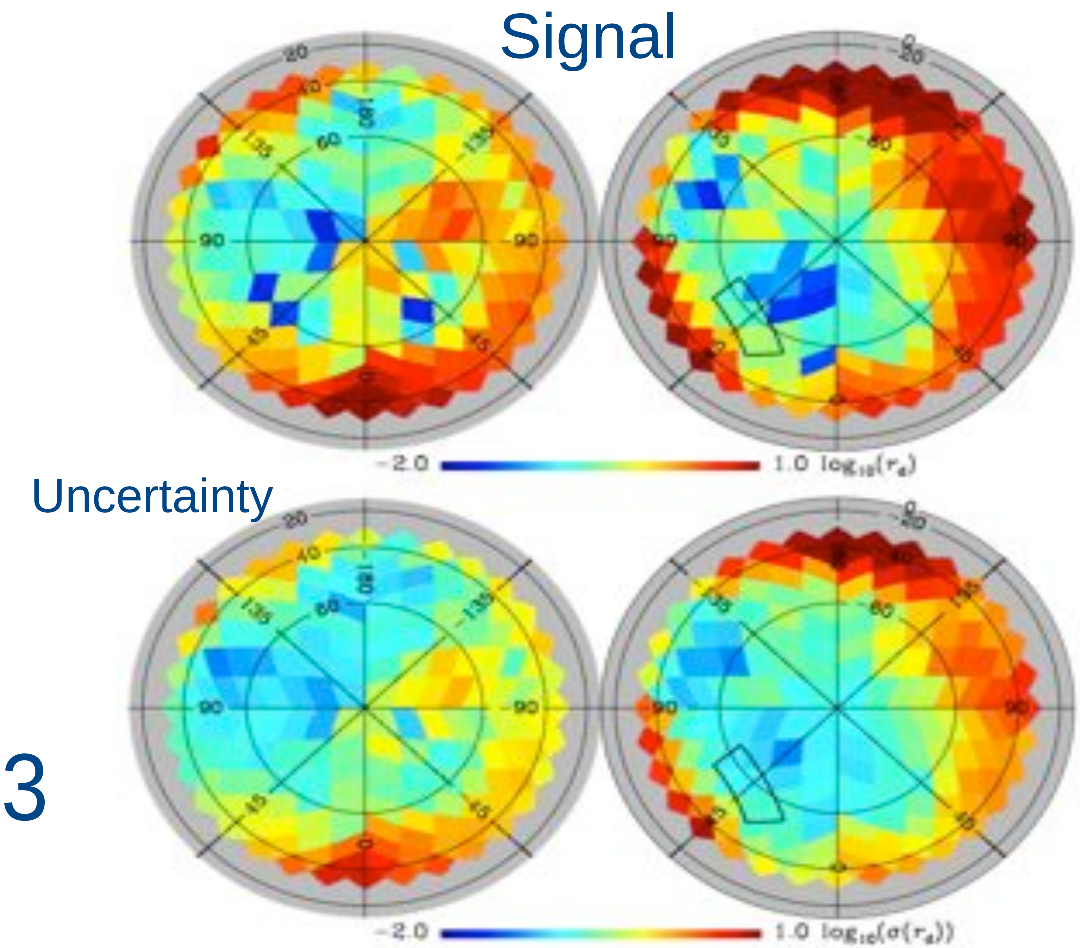
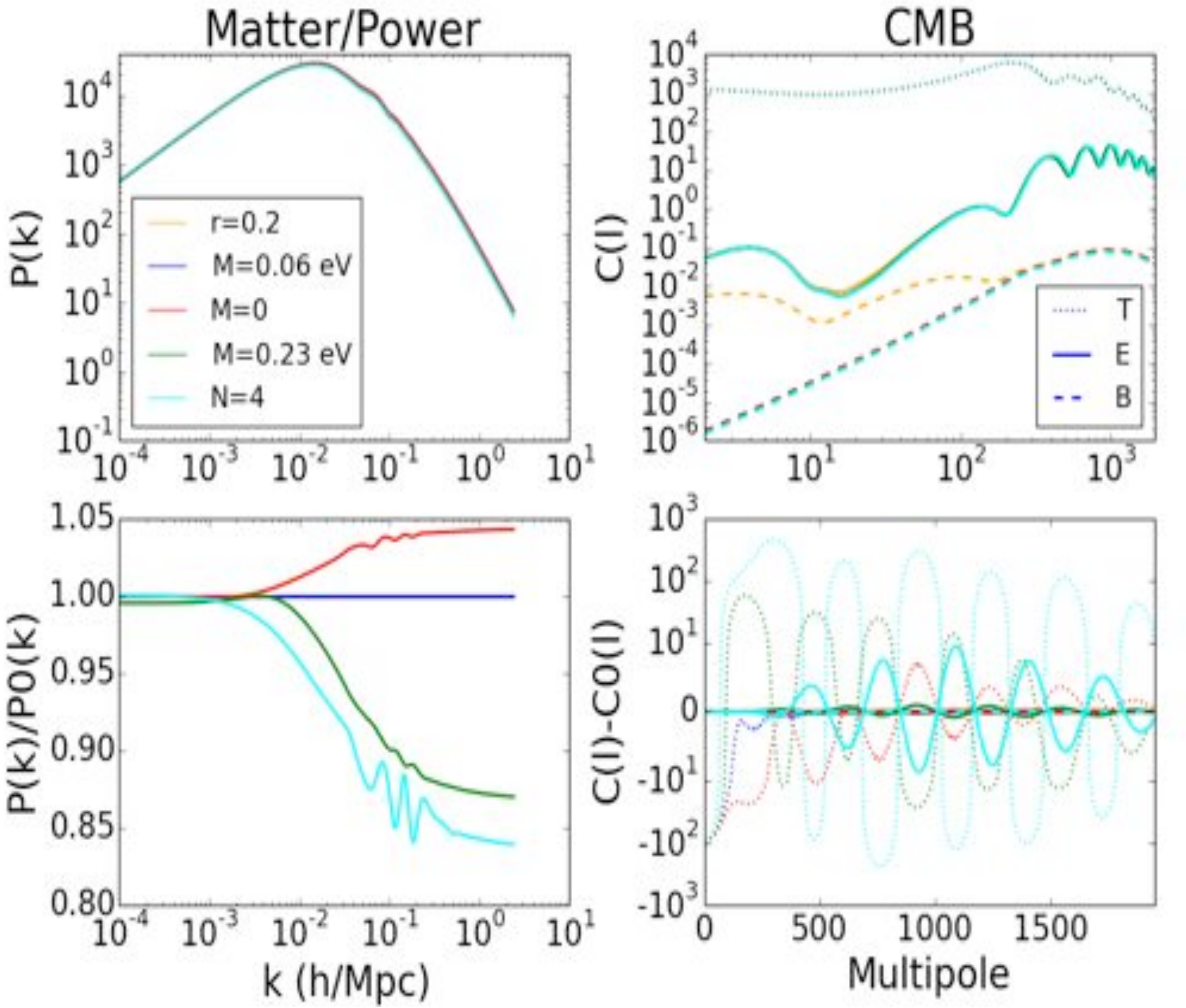


Fig. 8: *Top*: map in orthographic projection of the 150 GHz $\mathcal{D}_\ell^{BB}$ amplitudes at $\ell = 80$, computed from the *Planck* 353 GHz data, extrapolated to 150 GHz, and normalized by the CMB expectation for tensor-to-scalar ratio $r = 1$. The colours represent the estimated contamination from dust in r_d units (see details in Sect. 5.3). The logarithm of the absolute value of r_d for a 400 deg^2 patch is presented in the pixel on which the patch is centred. As described in Sect. 3.3.2, the patches overlap and so their properties are not independent. The northern (southern) Galactic hemisphere is on the left (right). The thick black contour outlines the approximate BICEP2 deep-field region (see Sect. 6). *Bottom*: associated uncertainty, $\sigma(r_d)$.

Neutrinos & the CMB

In addition to the Early Sachs-Wolfe Effect, neutrinos change “small”-scale structure through free-streaming, which is visible through weak gravitational lensing



Neutrino Limits from Polar. Lensing

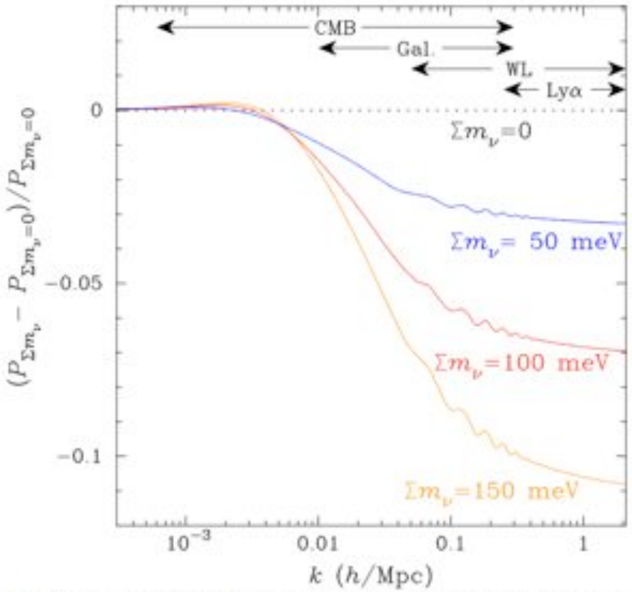


Figure 1. *Fractional change in the matter density power spectrum as a function of comoving wavenumber k for different values of $\sum m_\nu$. Neutrino mass suppresses the power spectrum due to free streaming below the matter-radiation equality scale. The shape of the suppression is highly characteristic and precision observations over a range of scales can measure the sum of neutrino masses (here assumed all to be in a single mass eigenstate). Also shown are the approximate ranges of experimental sensitivity in the power spectrum for representative probes: the cosmic microwave background (CMB), galaxy surveys (Gal.), weak lensing of galaxies (WL), and the Lyman-alpha forest (Lyα). The CMB lensing power spectrum involves (an integral over) this same power spectrum, and so is also sensitive to neutrino mass.*

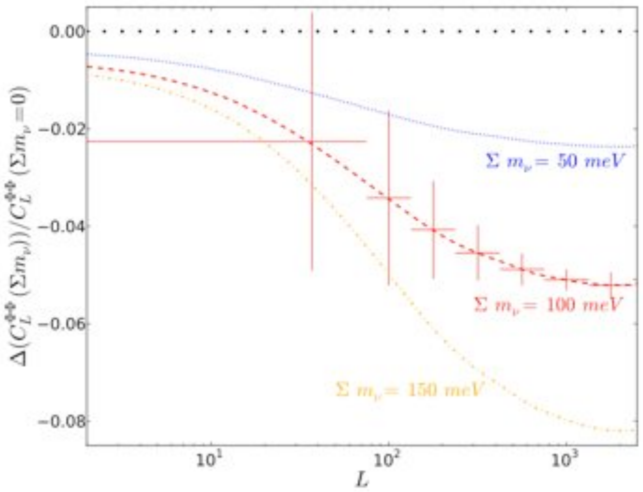


Figure 5. *The effect of massive neutrinos on the CMB lensing potential power spectrum $C_L^{\Phi\Phi}$. The fractional change in $C_L^{\Phi\Phi}$ for a given value of $\sum m_\nu$ is shown relative to the case for zero neutrino mass. Projected constraints on $C_L^{\Phi\Phi}$ for a Stage-IV CMB experiment are shown for $\sum m_\nu = 100$ meV. Here we have approximated all of the neutrino mass to be in one mass eigenstate and fixed the total matter density $\Omega_m h^2$ and H_0. The 1σ constraint for $\sum m_\nu$ is approximately 45 meV for lensing alone and drops to 16 meV when combined with other probes.*

- Neutrinos suppress structure; This changes CMB lensing
- By measuring lensing we measure N_{eff} & Σm_ν

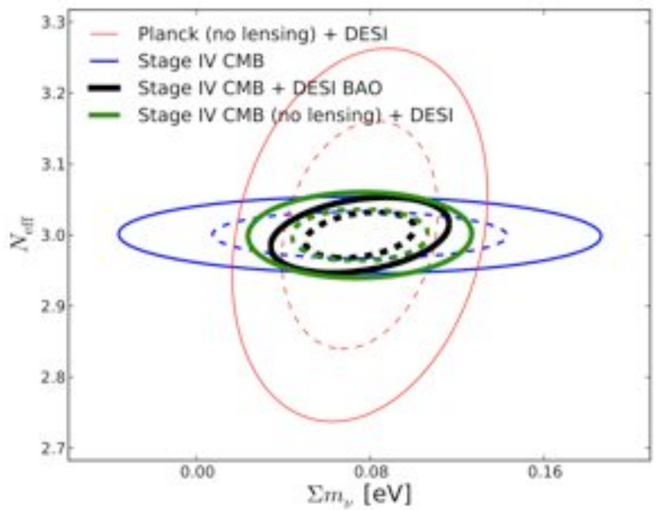
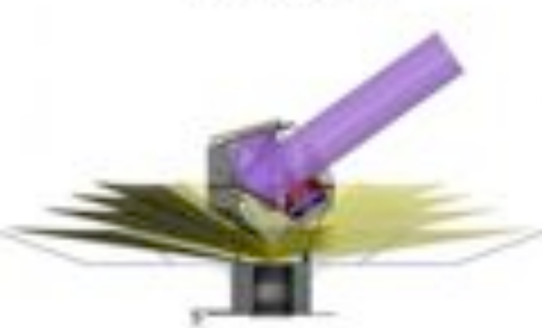


Figure 4. *The same as Figure 3, but showing forecasts in the Σm_ν - $N_{\rm eff}$ plane for a model including the effective number of neutrino species as a free parameter. A Stage-IV CMB experiment will not be able to distinguish between the standard model value of $N_{\rm eff} = 3.046$ and the integer value of 3 at high statistical significance, but it will indicate a preference for one over the other at the ∼ 2 σ level.*

CMB Mission Concepts in the Current Environment

EPIC-IM	PRISM	LITEBIRD	PIXIE
			

Can we fit a CMB concept into a ~$220M Explorer cost cap?

Any concept seems very cost challenged at this cap

L2 concepts have a high launch cost

Will the science community accept a single-purpose satellite designed to discover inflationary B-modes?

In the US, the answer from Decadal planning exercise is clearly "No"

We need a detection from the ground first to justify a satellite for full characterization

What about an absolute spectrum instrument?

Absolute spectrum science is interesting and should be considered in its own right

No heritage for polarization measurements is worrisome

Is there a window for a large CMB mission?

Not in the US this decade. We'll see how PRISM fares in Europe.

- Stolen from J. Bock; see: http://www-conf.kek.jp/cmb/2013/

CMB Mission Concepts in the Current Environment

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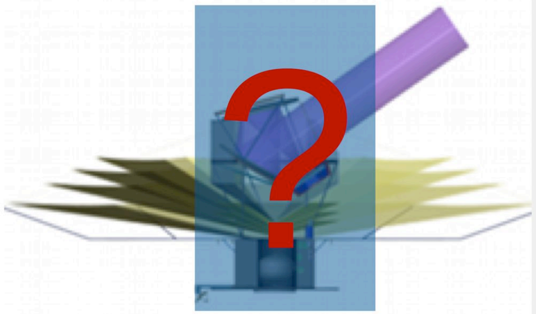
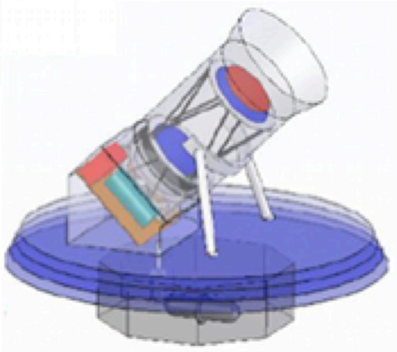
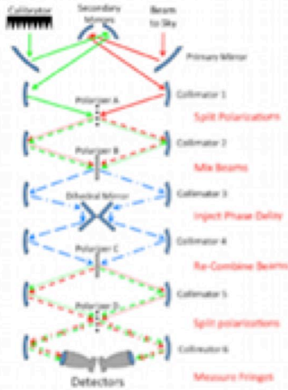


LITEBIRD



PIXIE



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Secondary Science: Dark Matter

PIXIE: Blackbody distortion from dark matter decay or annihilation

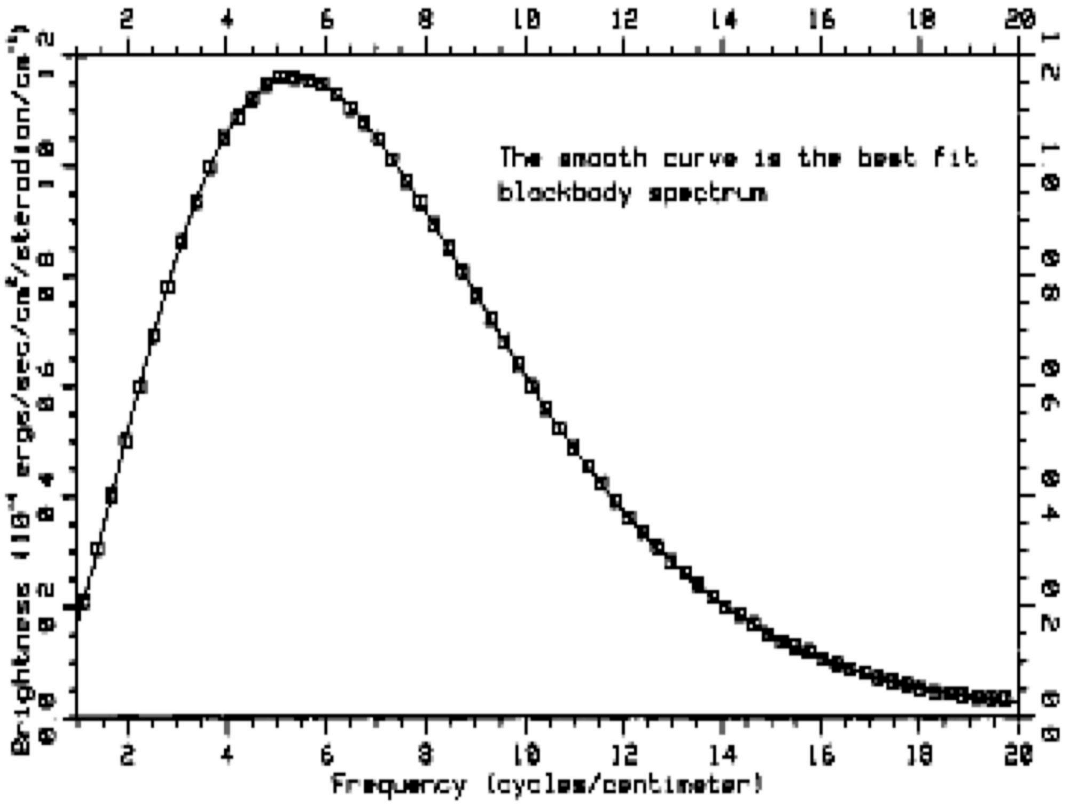


FIG. 2.—Preliminary spectrum of the cosmic microwave background from the FIRAS instrument at the north Galactic pole, compared to a blackbody. Boxes are measured points and show size of assumed 1% error band. The units for the vertical axis are 10^{-4} ergs s^{-1} cm^{-2} sr^{-1} cm.

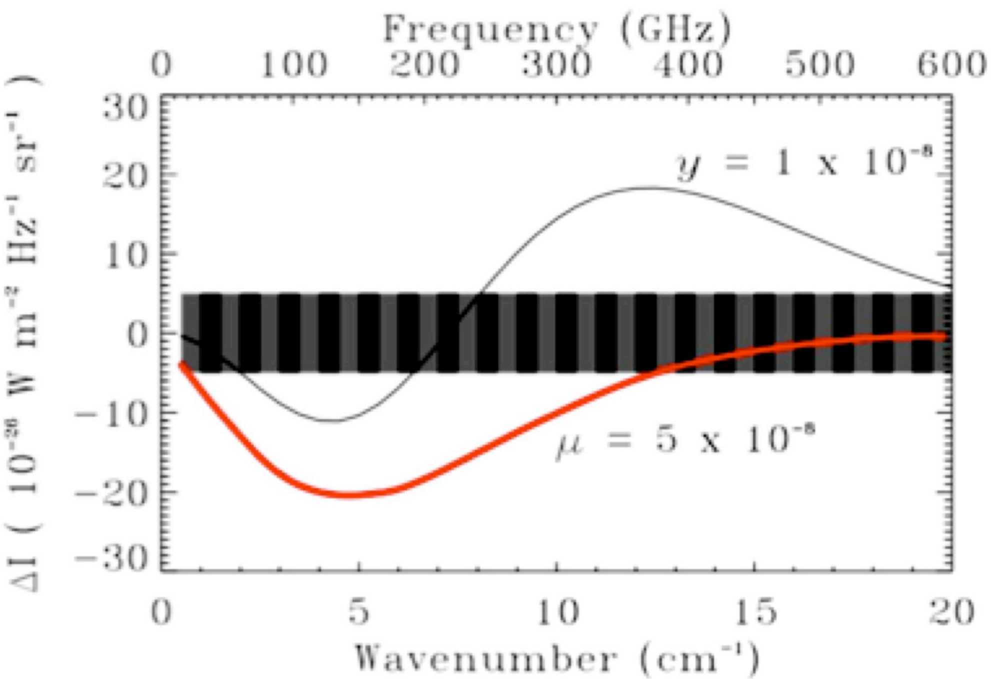
Test of gravitino dark matter

Energy release at $10^6 < z < 10^8$

Chemical potential $\mu = 1.4 \frac{\Delta E}{E}$

Energy release $\Delta E \sim \Omega_{DM} \Gamma \Delta m$

Distort CMB from blackbody spectrum

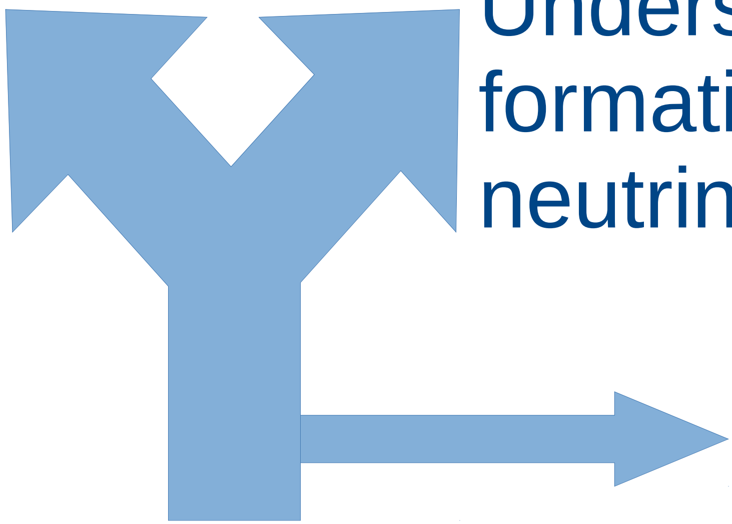


McDonald et al 2001
de Vega & Sanchez 2010
Feng 2010

Will the CMB Field Split/Change?

"Primordial" CMB:
E.g., Polarized B-Modes. Traditionally "aligned" with fundamental physics. May soon become even much more dependent on "Galactic" astronomy to remove polarized foregrounds.

"Late" CMB:
Use the CMB not as a probe of the early Universe, but as a well-understood tool to probe astro- and particle-physics. E.g. Understand cluster formation and/or neutrino masses.



Spectrum?

CMB Now

Thank you

Acknowledgments

We acknowledge the use of the Legacy Archive for Microwave Background Data Analysis (LAMBDA). Support for LAMBDA is provided by the NASA Office of Space Science.

Some of the work here is from the Planck scientific collaboration. Planck is an ESA project with instruments funded by ESA member states (in particular the PI countries: France and Italy), and with special contributions from Denmark and NASA (USA).

Some plots here were made using CAMB and some using CMBFast.

Some plots here were made using HEALPix (healpix.jpl.nasa.gov)