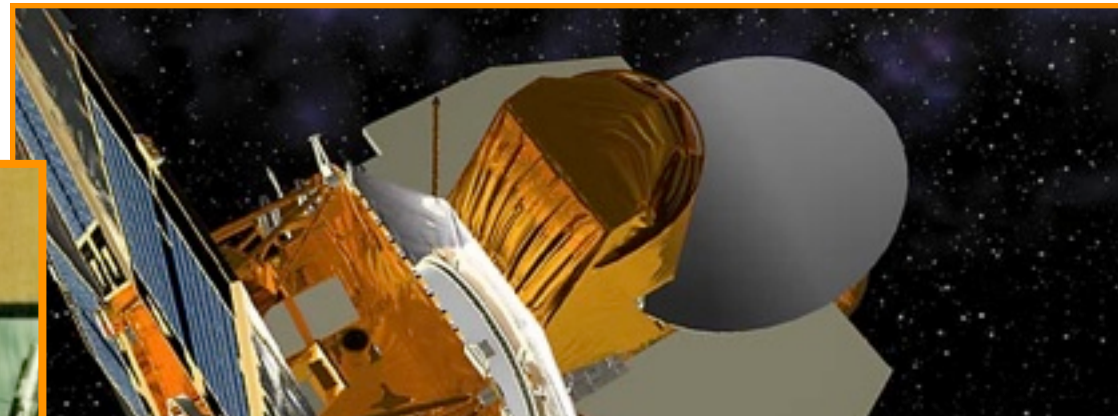
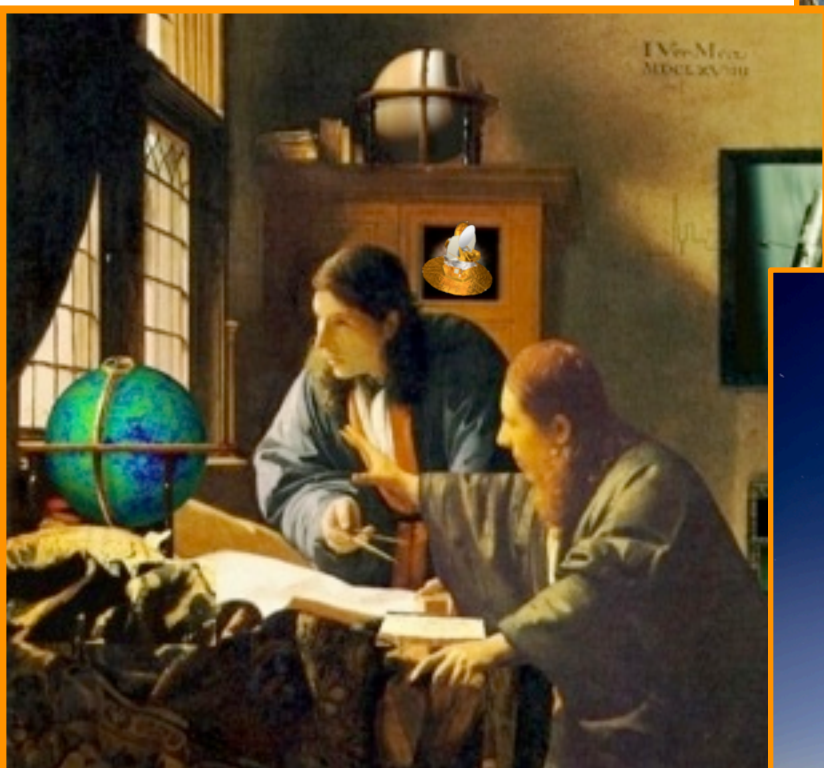
Observational Cosmology





Gary Hinshaw

14 January 2015   SFU – Testing Gravity 2015

1916: General Relativity

ALBERT EINSTEIN

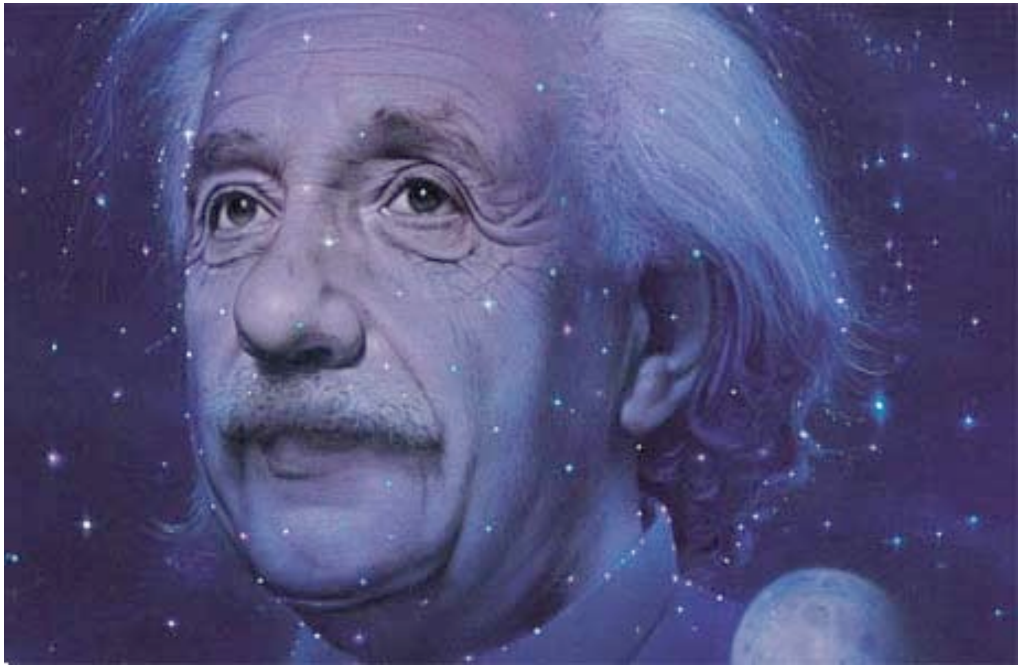
TIME MAGAZINE "PERSON OF THE CENTURY"

"Einstein's equations didn't have a solution that described a universe that was unchanging in time. … he fudged the equations by adding a term called the cosmological constant... The repulsive effect of the cosmological constant would balance the attractive effect of matter and allow for a universe that lasts for all time."

---Stephen Hawking

Einstein applied the General Theory of Relativity to the Universe as a whole:

- **Dynamic universe that expands and possibly contracts.**
- **Seemingly in conflict with belief that the universe was static.**



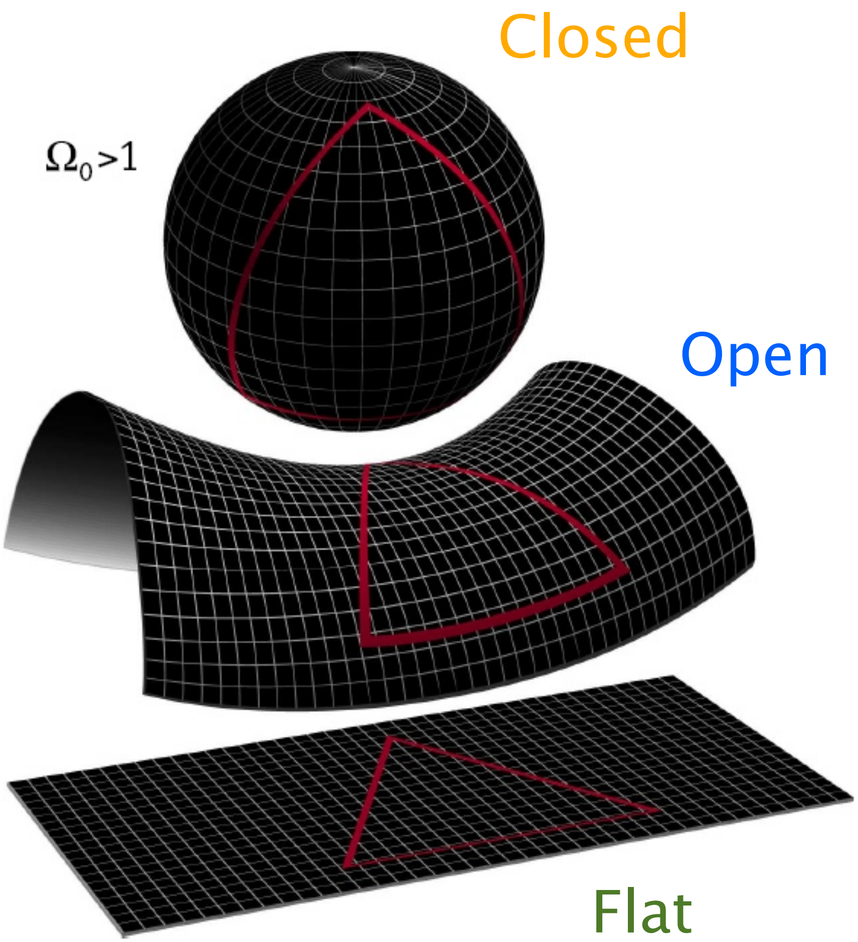
The Cosmological Principle (c. 1910's)

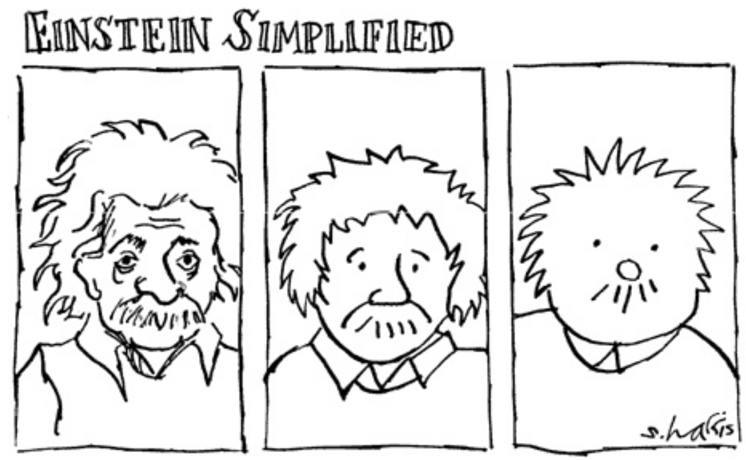
The universe is homogenous and isotropic

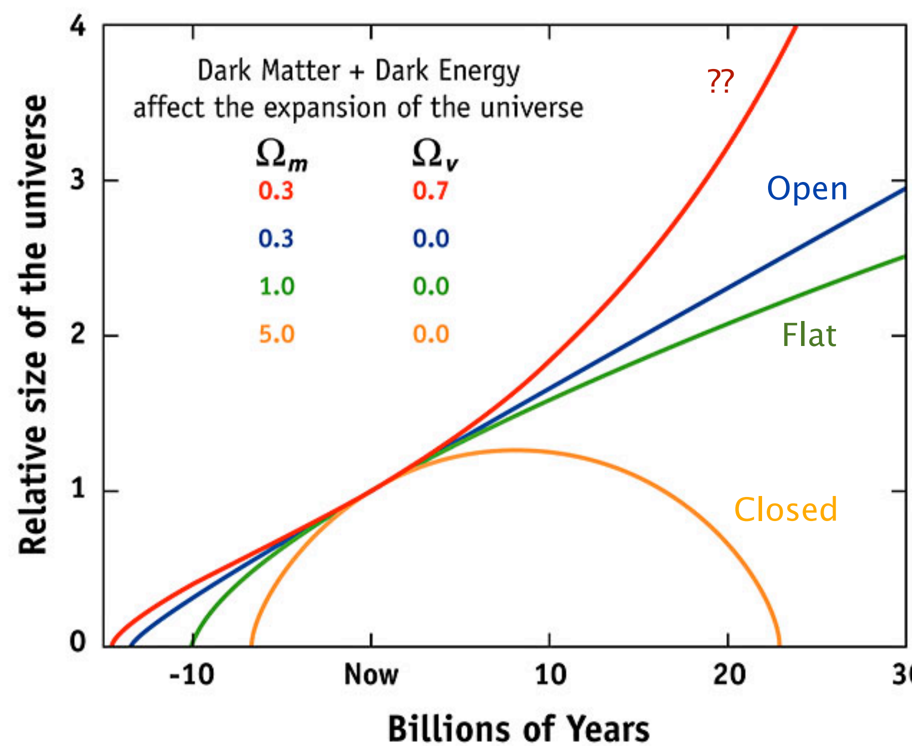
- **Homogenous** – it has the same average properties (e.g., temperature, density) everywhere in space.
- **Isotropic** – it has the same average properties in every direction.

If true, the Earth does not occupy a special place in the universe.

Cosmological Dynamics







Three Pillars of the Big Bang

Big Bang cosmology provides a fundamental test of gravity. It rests on three observational pillars:

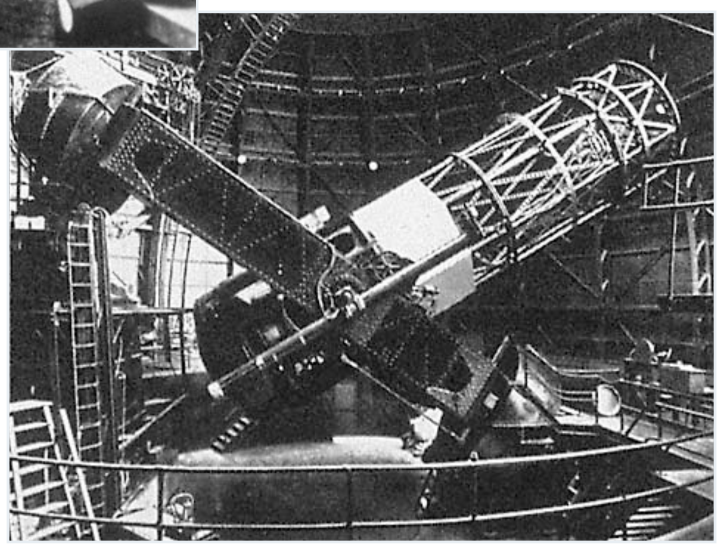
- **Hubble expansion**
- **Big Bang Nucleosynthesis (BBN)**
- **Cosmic Microwave Background (CMB)**

These are discussed in the following pages.

1929: The Expanding Universe

Edwin Hubble

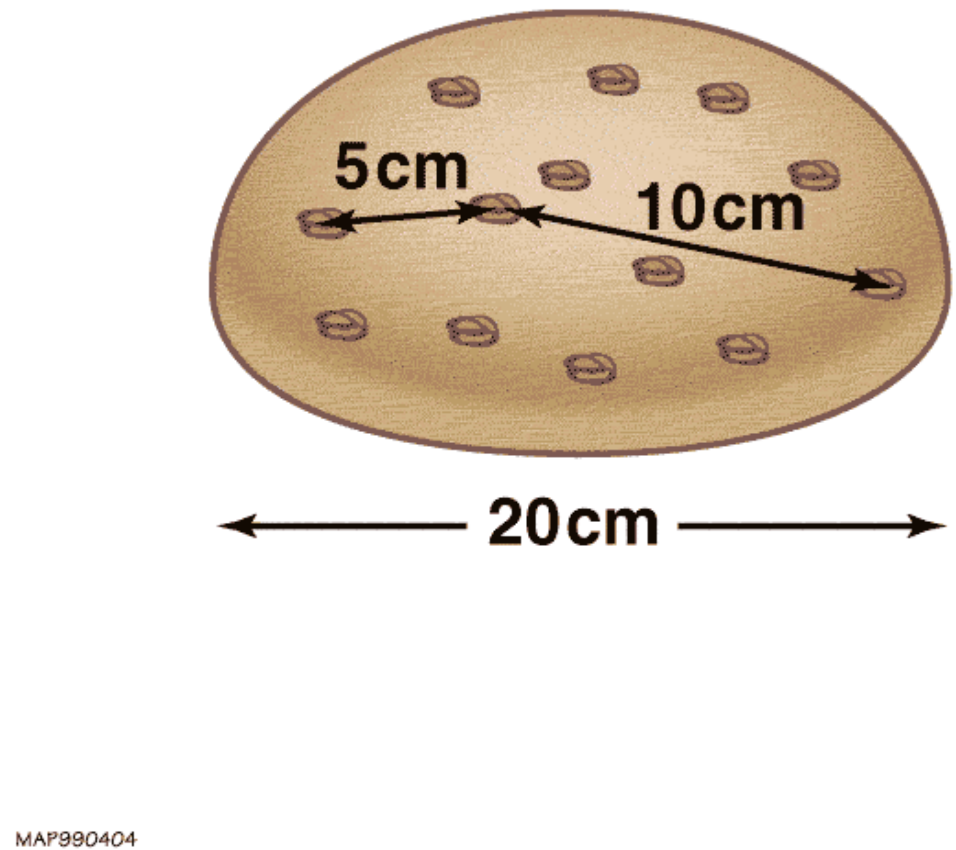
"...we know that we are reaching into space, farther and farther, until, with the faintest nebulae that can be detected with the greatest telescopes, we arrive at the frontier of the known universe."



Mt. Wilson 100 Inch Telescope

"..one of the most flabbergasting discoveries science has ever made." TIME noted, Hubble had evolved his theory "**by looking at the universe itself**."

Homogeneous Expansion: v = H d



An "observer" on any raisin would measure the same expansion law

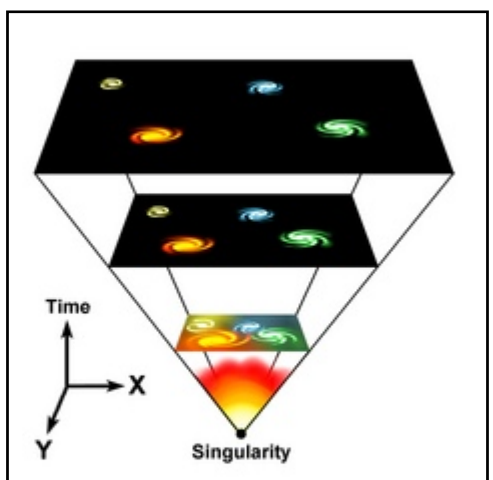
1940's: Big Bang Physics

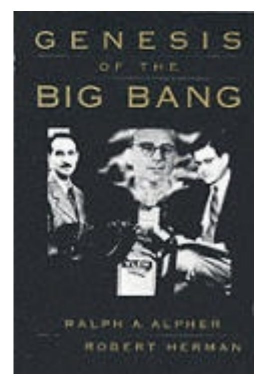
• Gamow (1946): Chemical elements might have been made in a hot early universe, stopping when expansion cools universe.

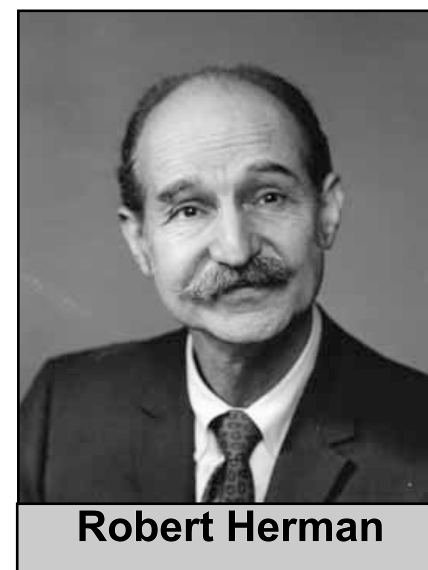
• Ralph Alpher (1946): Worked out the physics & found only the lightest chemical elements could have been made: D, He, Li, Be, B.

• Alpher, Bethe, Gamow (1948): Derives relative proportions of chemical elements in a hot expanding universe. [Bethe made no contribution whatsoever.]

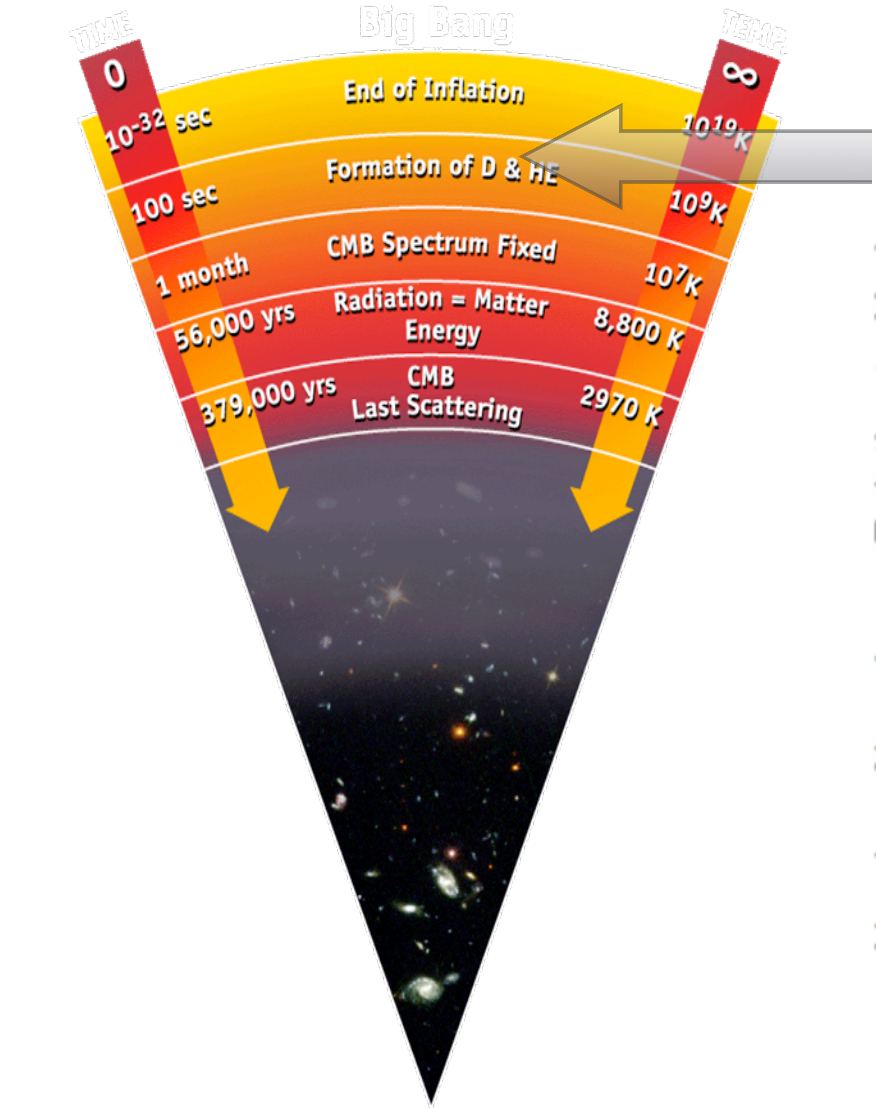
• Alpher & Herman (no input from Gamow): Calculated that the afterglow heat would make the temperature of the universe today about 5 Kelvin – a cosmic microwave background.

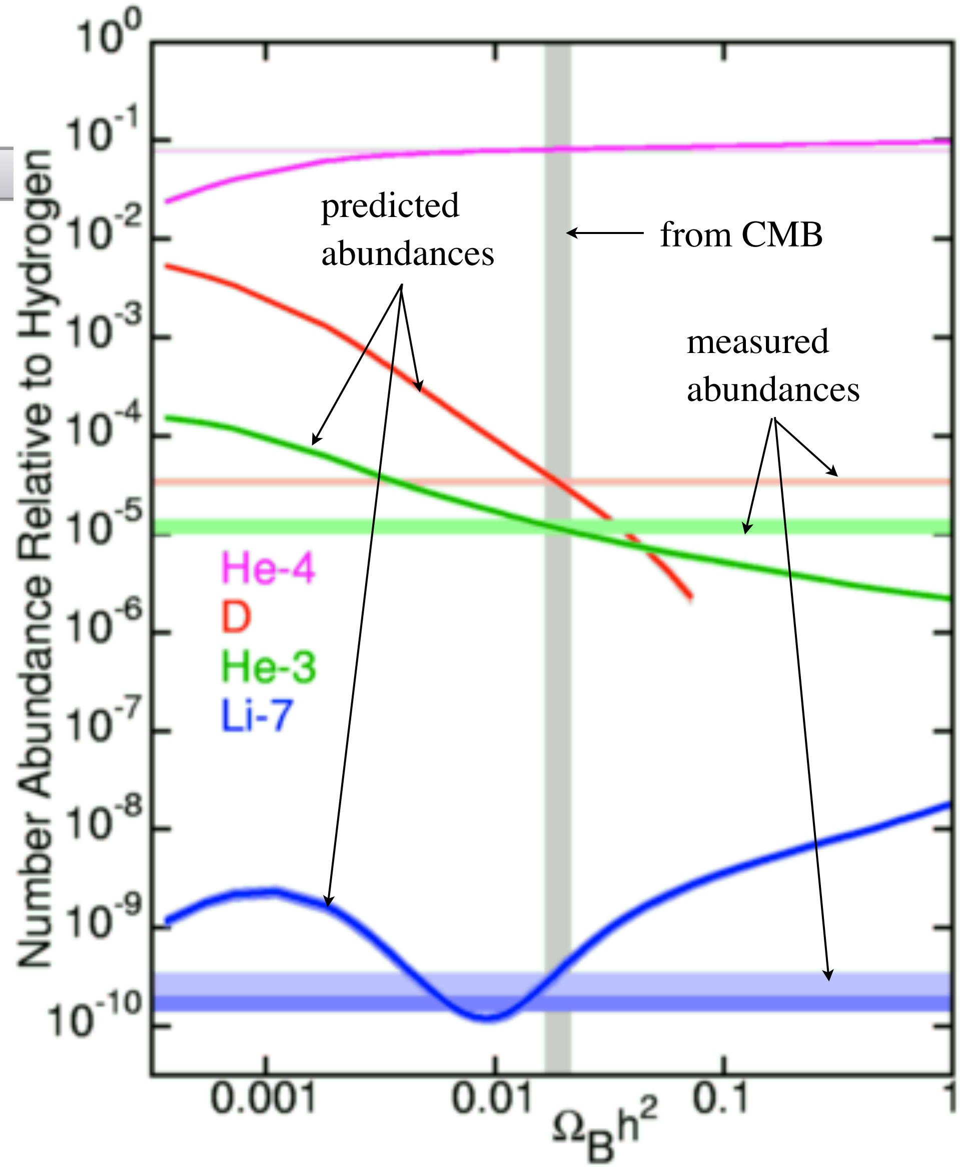




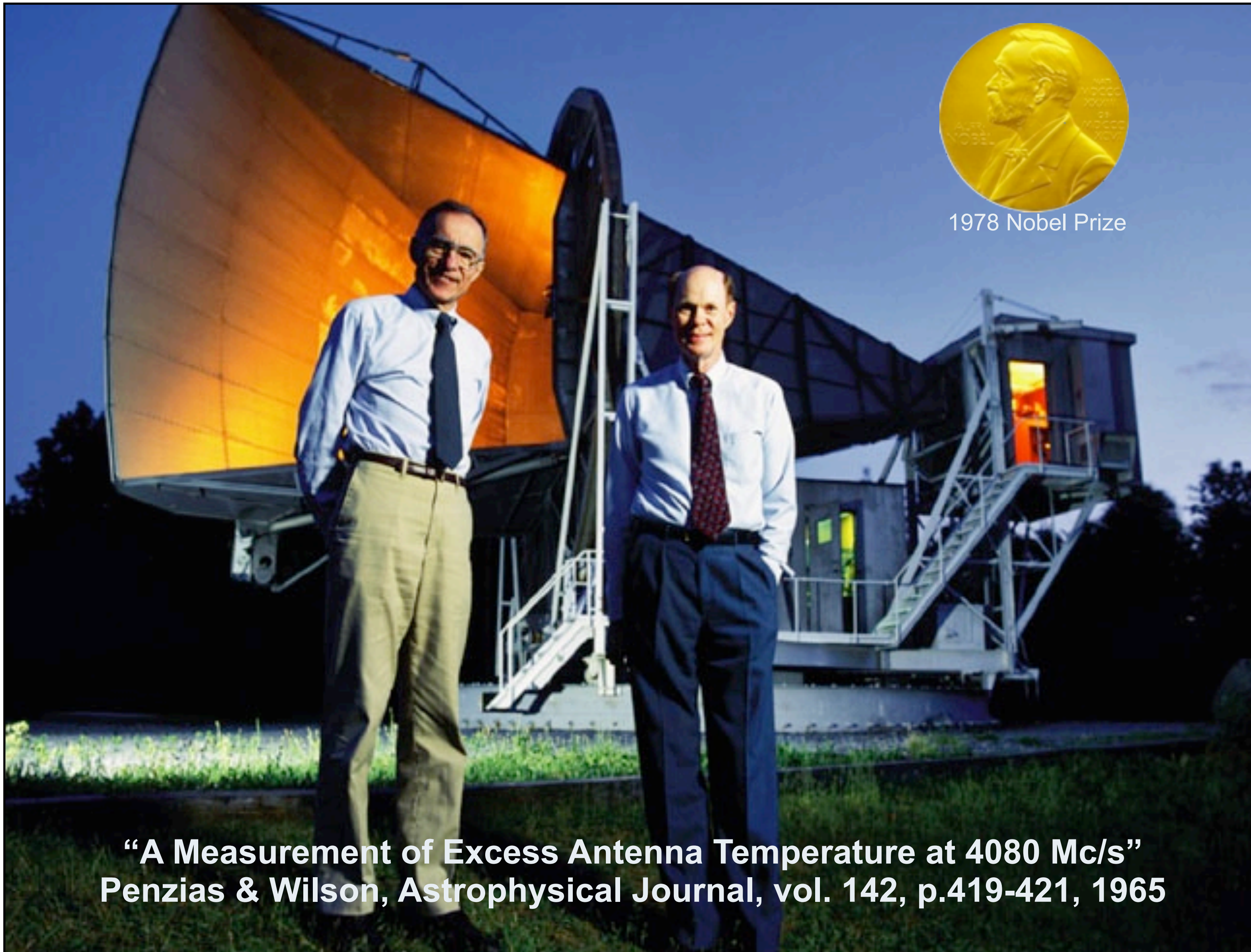


BBN Yields vs. Baryon Density





1964: Discovery of the CMB



COsmic Background Explorer (COBE)

1974 COBE proposed
Spacecraft & all 3 instruments built at Goddard

1989 COBE Launched from Vandenberg AFB

FIRAS - measures CMB frequency spectrum

DMR - searches for CMB anisotropy

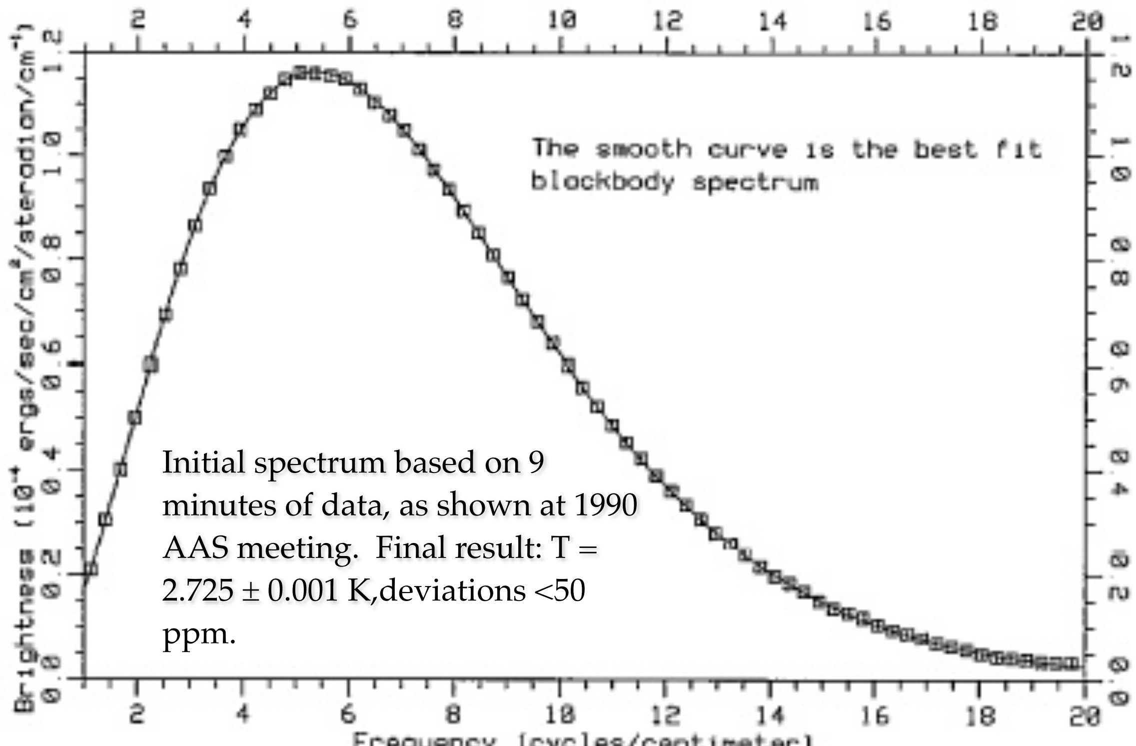
1990: Blackbody Spectrum of the CMB

A PRELIMINARY MEASUREMENT OF THE COSMIC MICROWAVE BACKGROUND SPECTRUM BY THE *COSMIC BACKGROUND EXPLORER* (*COBE*)[1] SATELLITE

J. C. MATHER,[2] E. S. CHENG,[2] R. E. EPLEE, JR., [3] R. B. ISAACMAN,[3] S. S. MEYER,[4] R. A. SHAFER,[2] R. WEISS,[4] E. L. WRIGHT,[5] C. L. BENNETT, N. W. BOGGESS,[2] E. DWEK,[2] S. GULKIS,[6] M. G. HAUSER,[2] M. JANSSEN,[6] T. KELSALL,[2] P. M. LUBIN,[7] S. H. MOSELEY, JR.,[2] T. L. MURDOCK,[8] R. F. SILVERBERG,[2] G. F. SMOOT,[9] AND D. T. WILKINSON[10]

THE ASTROPHYSICAL JOURNAL, 354:L37-40, 1990

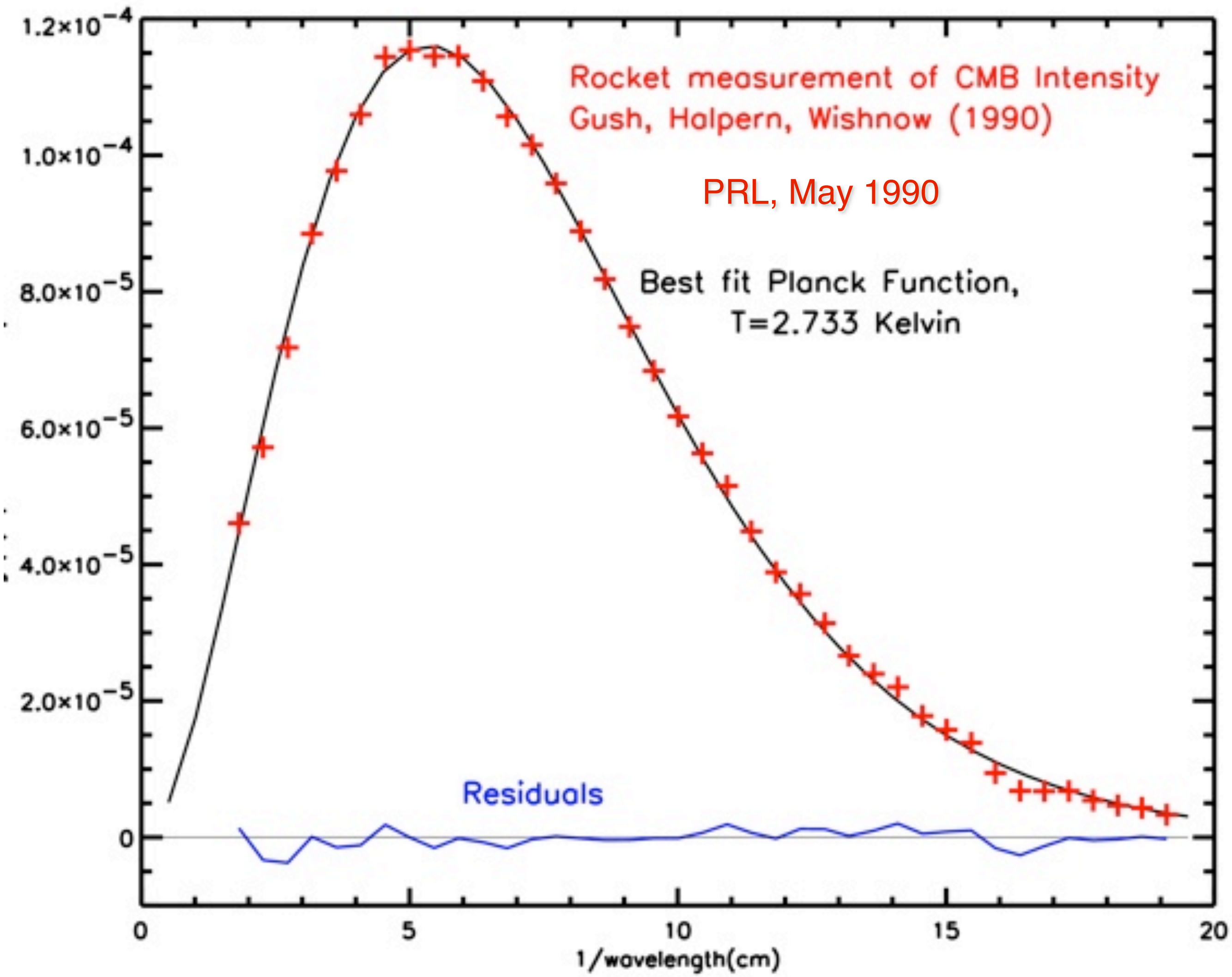
2006



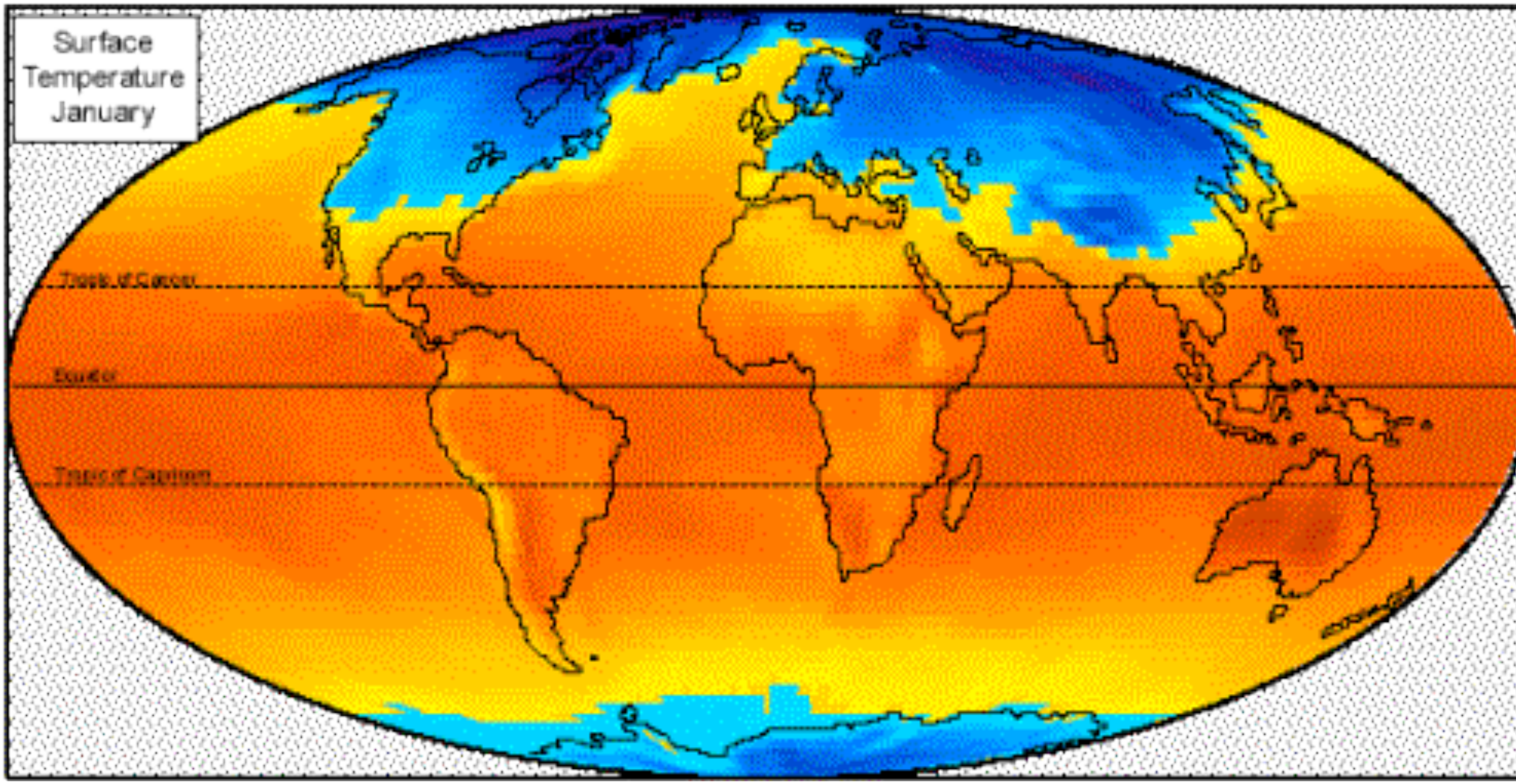
Initial spectrum based on 9 minutes of data, as shown at 1990 AAS meeting. Final result: T = 2.725 ± 0.001 K,deviations <50 ppm.

A crucial test of Big Bang cosmology.

1990: Gush, Halpern & Wishnow

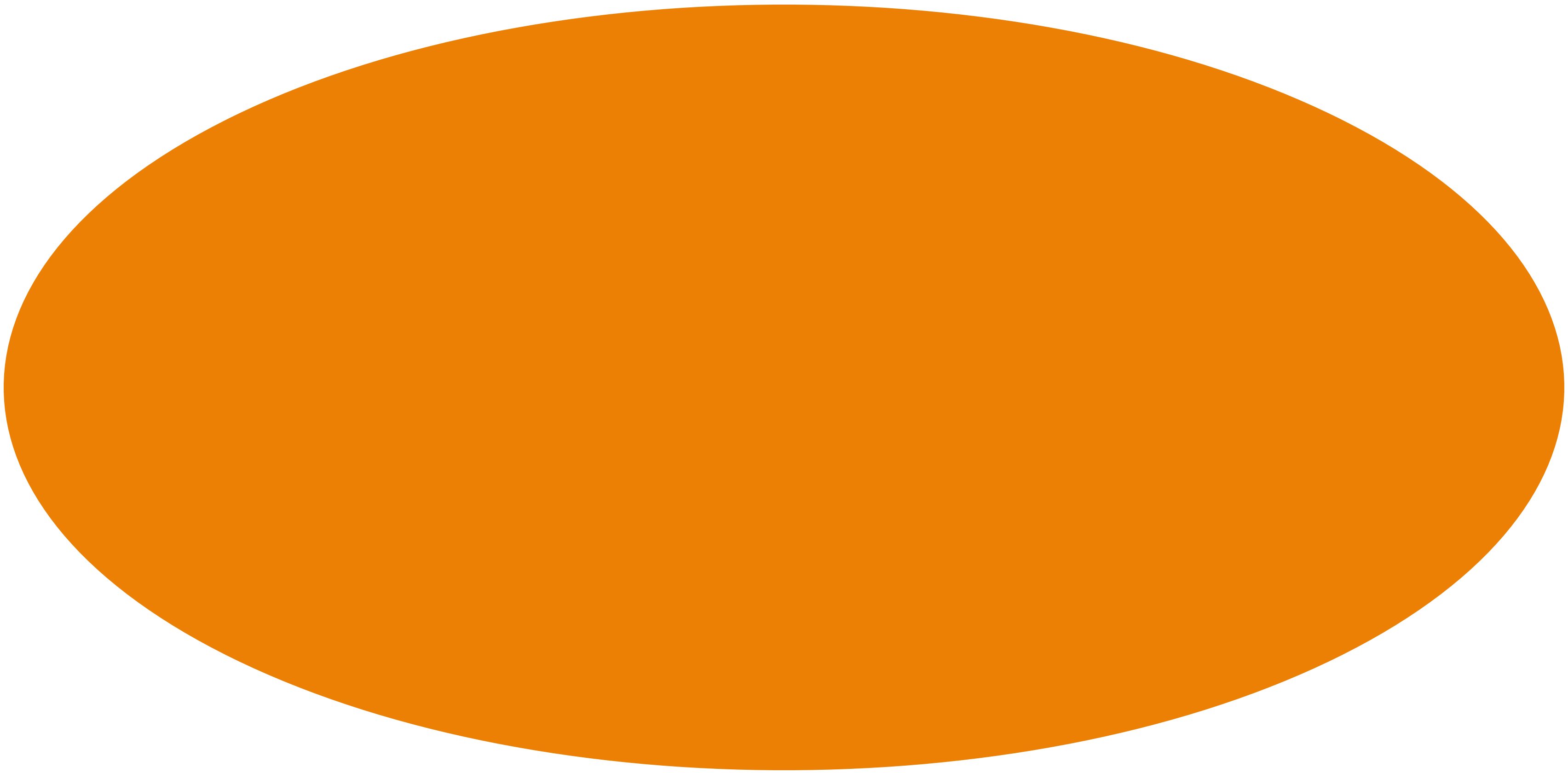


Mapping the CMB Temperature



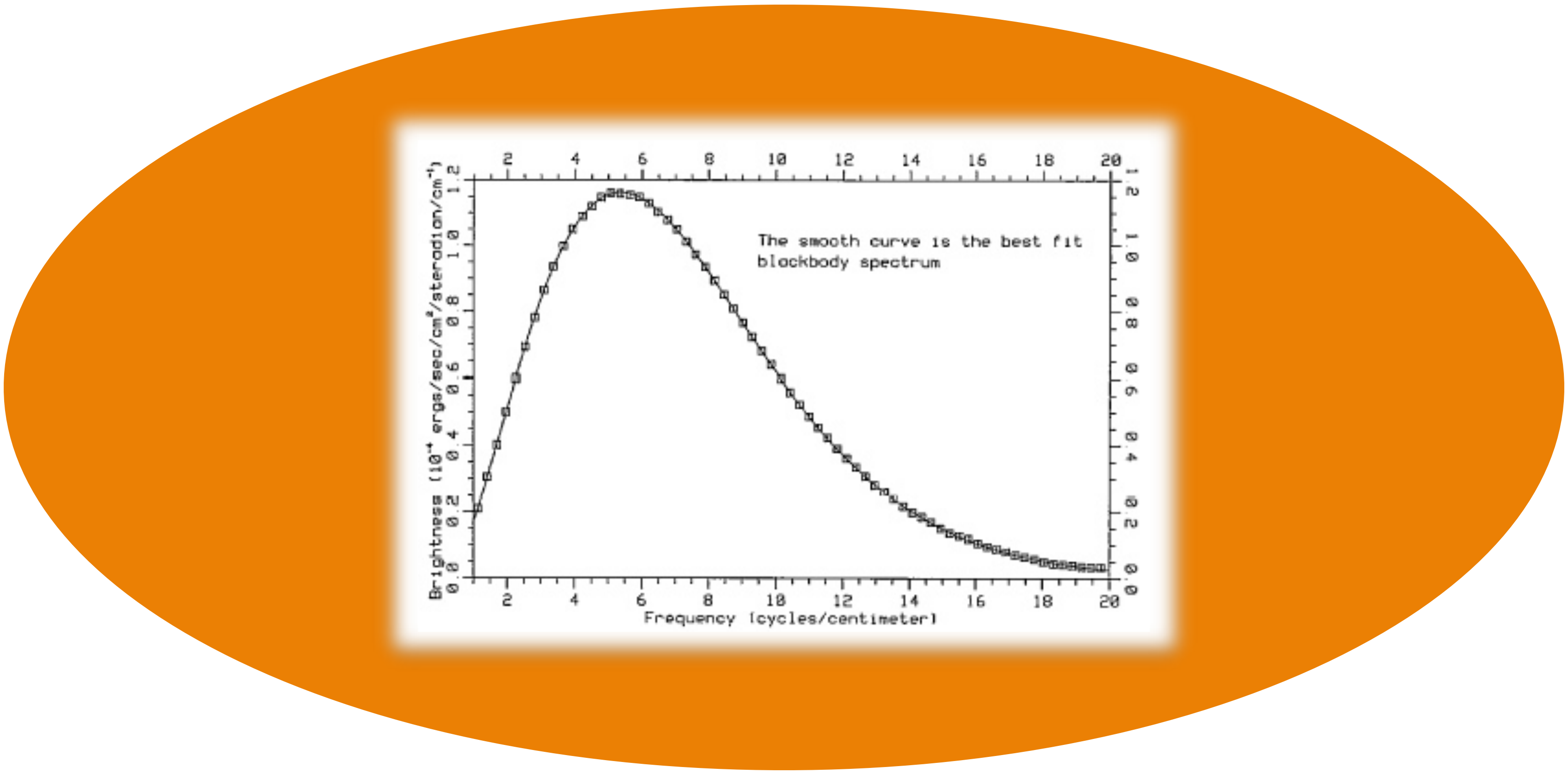
COBE-DMR was designed to measure brightness variations (anisotropy) across the sky - analogous to temperature variations across the surface of the Earth.

1990: COBE Limits on CMB Anisotropy



Preliminary results from COBE-DMR showed there was no significant variation in the CMB brightness across the sky (aside from the dipole anisotropy, due to our motion relative to the CMB rest frame).

The Early Universe

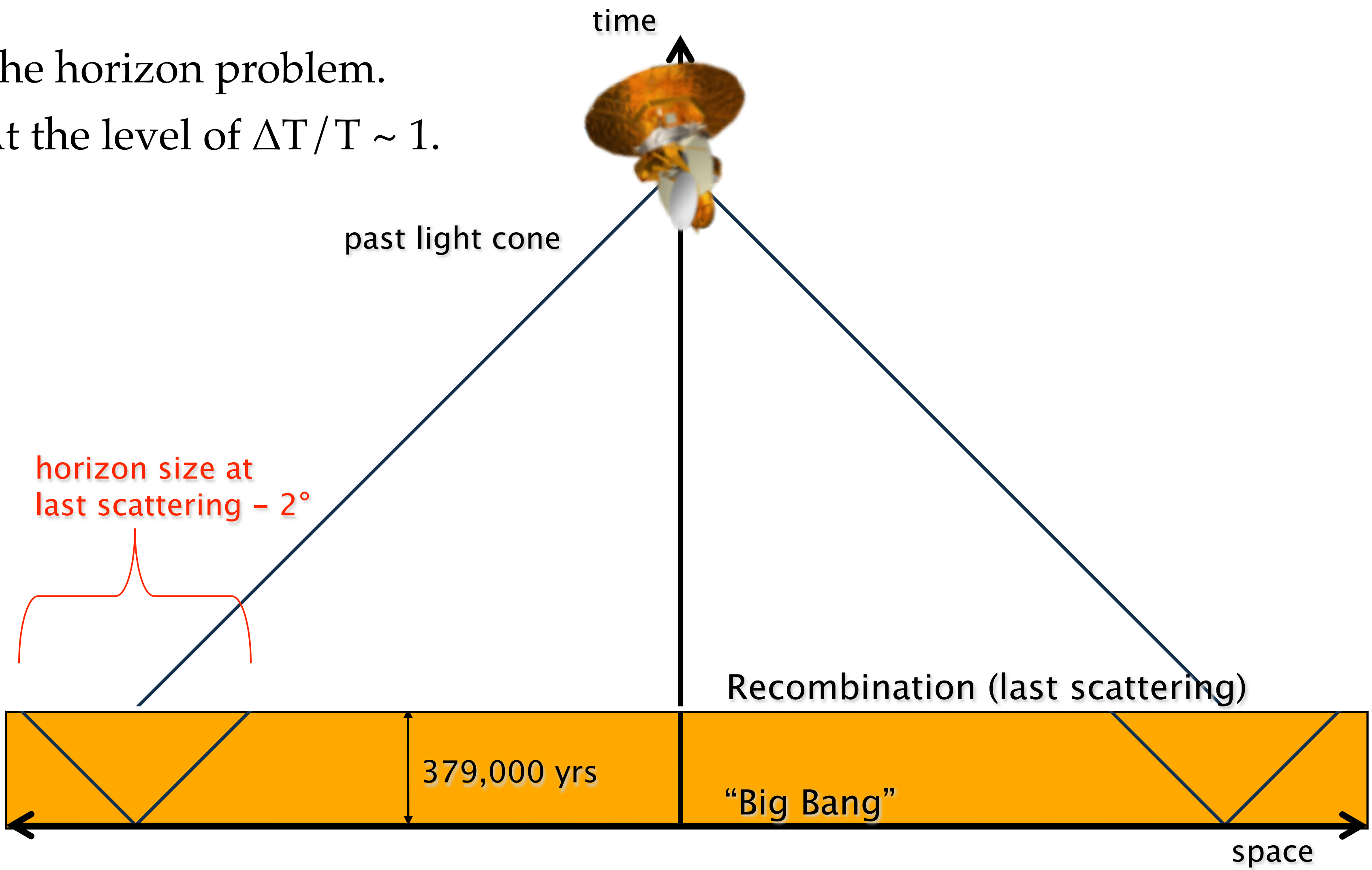


At the time of recombination (t=379,000 yr) the universe is filled with warm gas (T~3000 K) in thermal equilibrium. There is no discernible structure.

Questions Raised by Isotropy – I

The horizon problem.

At the level of $\Delta T/T \sim 1$.

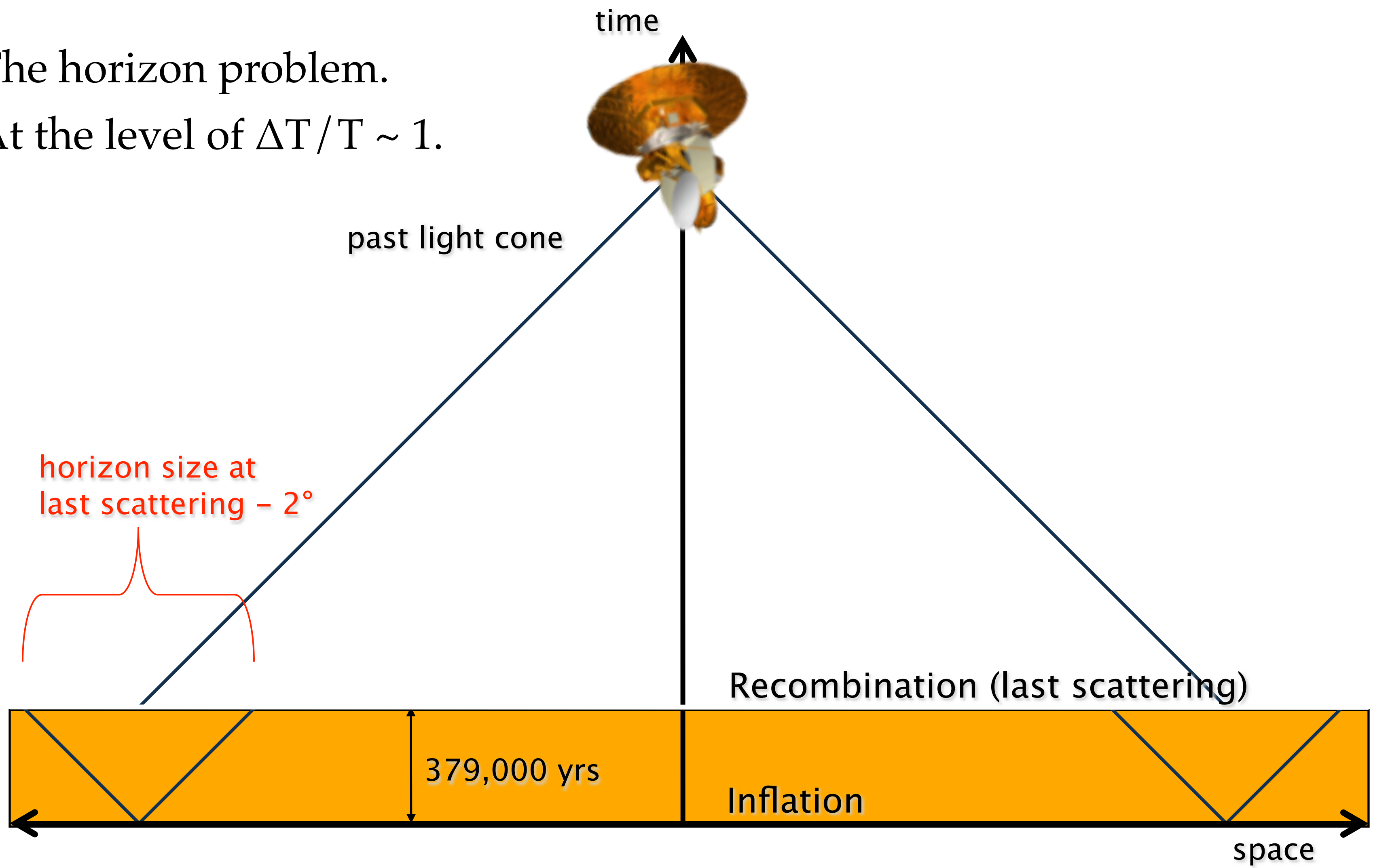


Why is the last scattering surface so isotropic?

Questions Raised by Isotropy – I

The horizon problem.

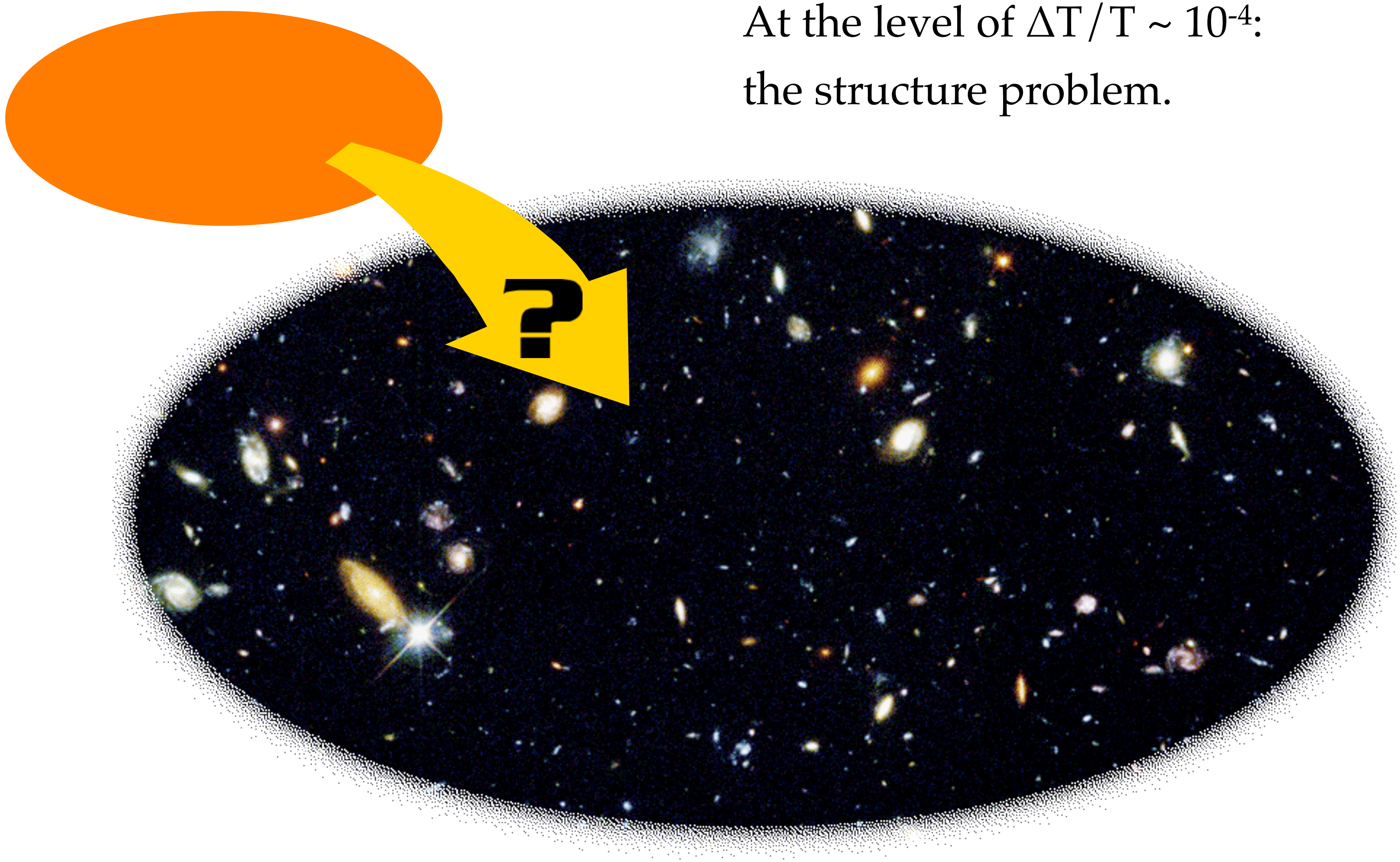
At the level of $\Delta T/T \sim 1$.



Inflation pushes the causal horizon outside our past light cone and "naturally" explains isotropy.

Questions Raised by Isotropy – II

At the level of $\Delta T/T \sim 10^{-4}$:
the structure problem.



Where is the precursor to observed cosmic structure?

1992: CMB Anisotropy Detected

STRUCTURE IN THE *COBE*[1] DIFFERENTIAL MICROWAVE RADIOMETER FIRST-YEAR MAPS

G. F. SMOOT,[2] C. L. BENNETT,[3] A. KOGUT,[4] E. L. WRIGHT,[5] J. AYMON,[2] N. W. BOGGESS,[3] E. S. CHENG,[3] G. DE AMICI,[2] S. GULKIS,[6] M. G. HAUSER,[3] G. HINSHAW,[4] P. D. JACKSON,[7] M. JANSSEN,[6] E. KAITA,[7] T. KELSALL,[3] P. KEEGSTRA,[7] C. LINEWEAVER,[2] K. LOEWENSTEIN,[7] P. LUBIN,[8] J. MATHER,[3] S. S. MEYER,[9] S. H. MOSELEY,[3] T. MURDOCK,[10] L. ROKKE,[7] R. F. SILVERBERG,[3] L. TENORIO,[2] R. WEISS,[9] AND D. T. WILKINSON[11]

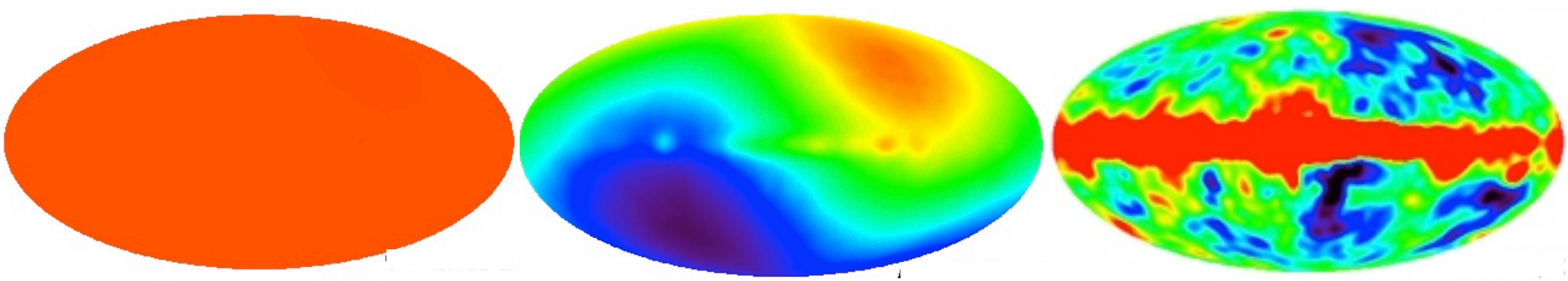
THE ASTROPHYSICAL JOURNAL, 396:L1-L5,

2006

"PRELIMINARY SEPARATION OF GALACTIC AND COSMIC MICROWAVE EMISSION…"
BENNETT ET AL, THE ASTROPHYSICAL JOURNAL, 396:L1-L5, 1992

"INTERPRETATION OF THE COSMIC MICROWAVE BACKGROUND RADIATION ANISOTROPY…"
WRIGHT ET AL, THE ASTROPHYSICAL JOURNAL, 396:L1-L5, 1992

"COBE DIFFERENTIAL MICROWAVE RADIOMETERS – PRELIMINARY SYSTEMATIC ERROR…"
KOGUT ET AL, THE ASTROPHYSICAL JOURNAL, 401, 1-18, 1992



First detection of temperature fluctuations (anisotropy): sets the scale of the signal – brighter than the Galactic foreground!

The Legacy of COBE

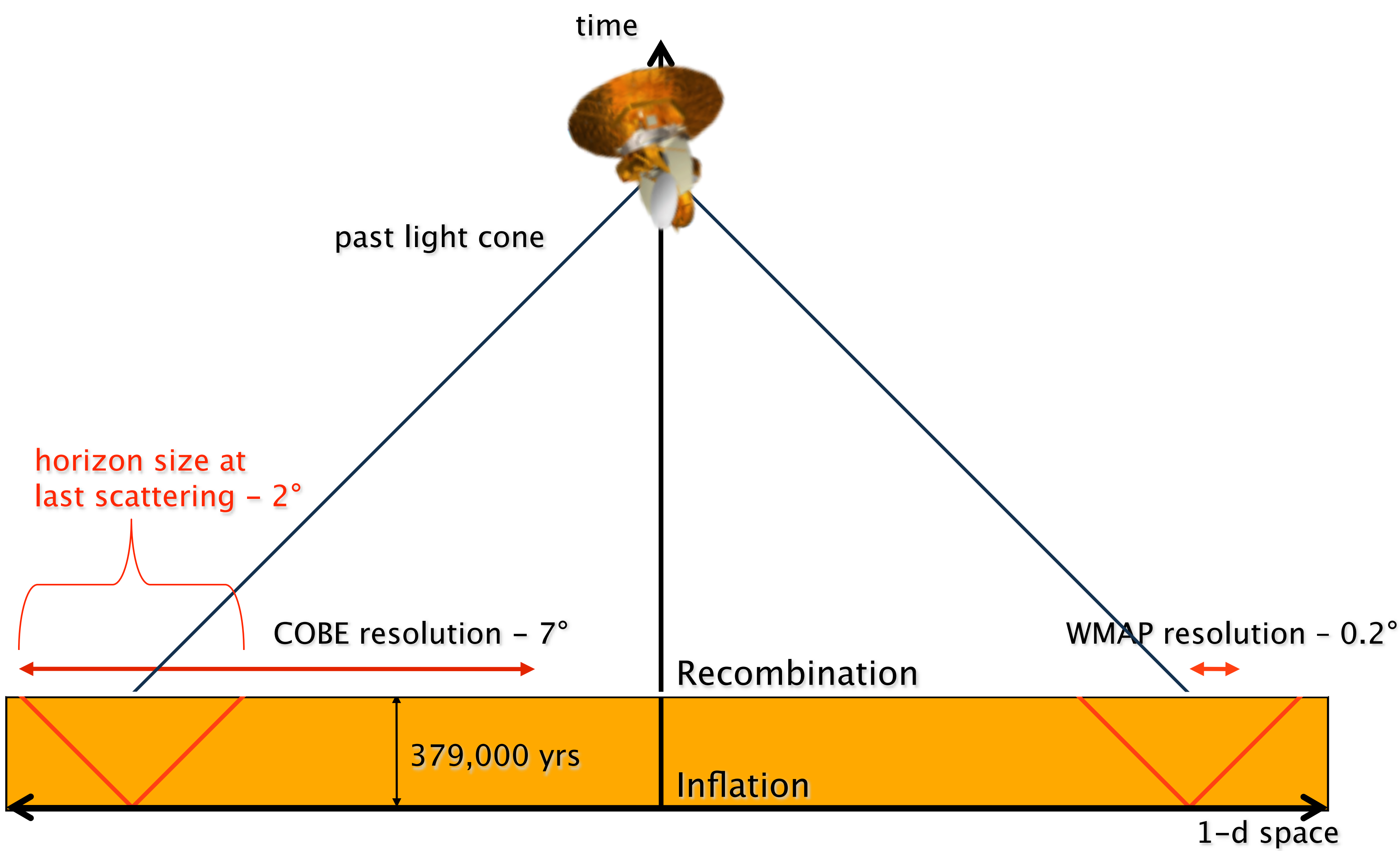
- **COBE-FIRAS** established that the CMB spectrum was blackbody to 50 ppm (quickly followed by the UBC rocket experiment).

  - Simplest interpretation: an optically thick plasma in thermal equilibrium that cooled, and became transparent, with the expansion of the universe.

- **COBE-DMR** was first to detected spatial fluctuations in the CMB brightness.

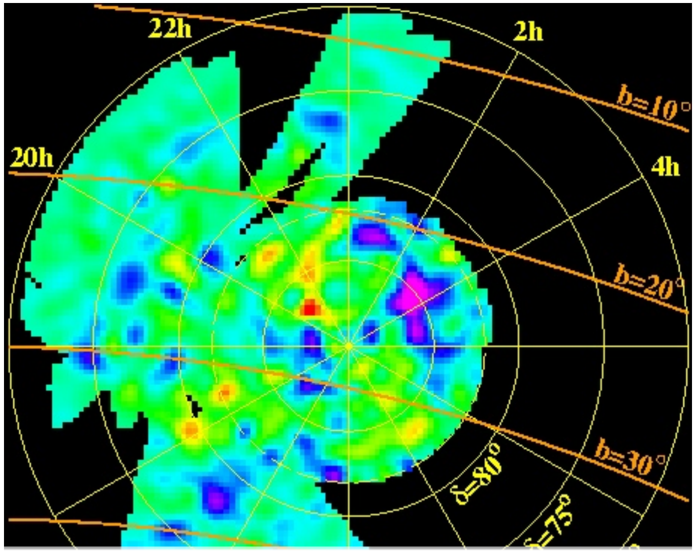
  - Establishes that anisotropy can be observed over the galactic emission.
  - Sets the overall scale for the precursor to large-scale structure: 10^{-5}.
  - Establishes that structure formation via gravitational instability is plausible, provided there is dark matter.

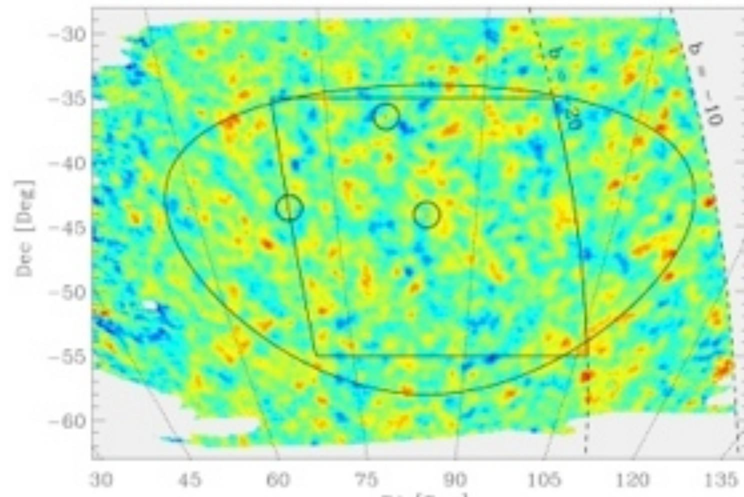
Post-COBE: Push for Higher Resolution

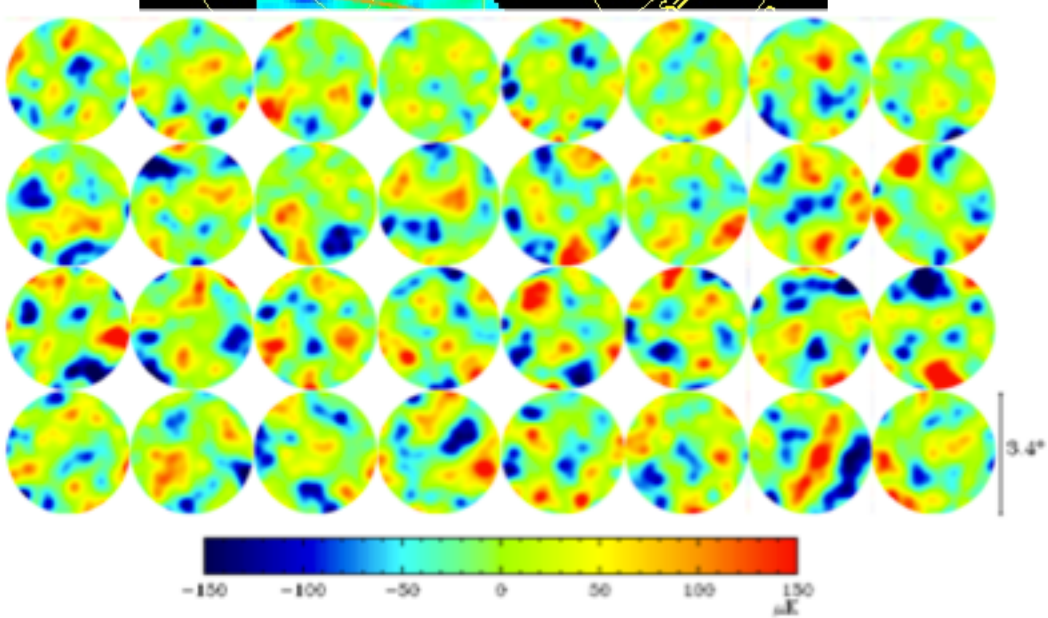


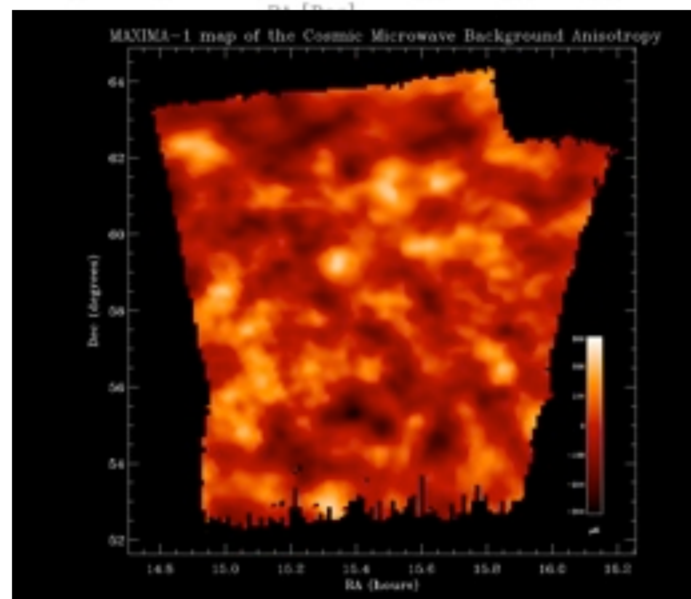
COBE does not probe causal (e.g. acoustic) effects that occur during the plasma epoch.

1990’s: A Decade of Rapid Progress!



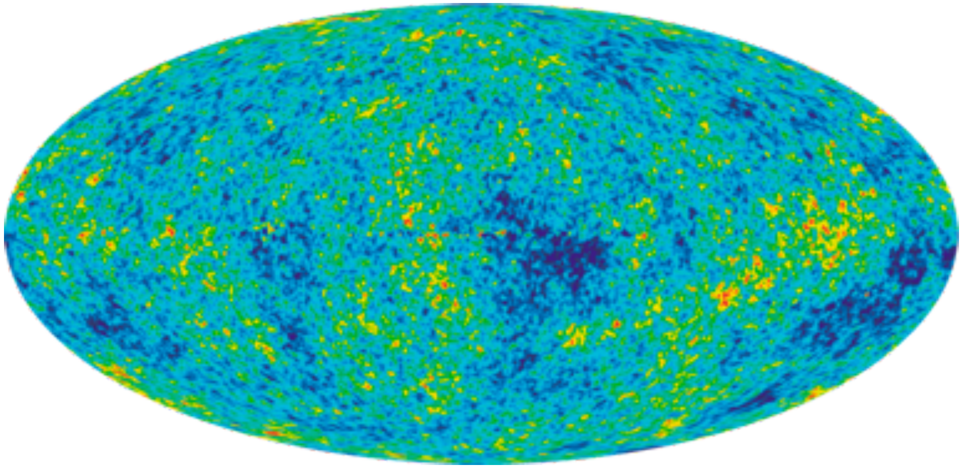




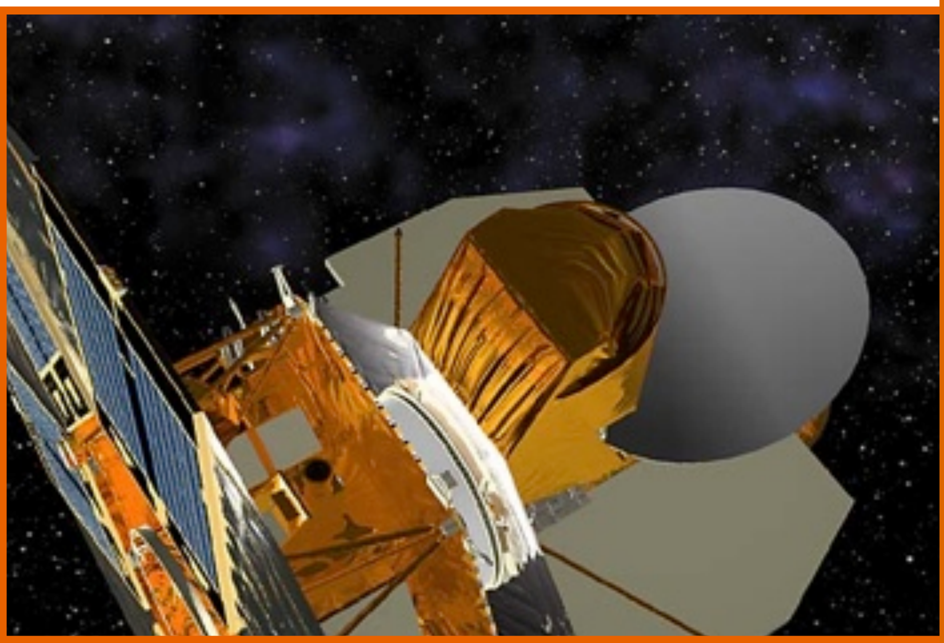


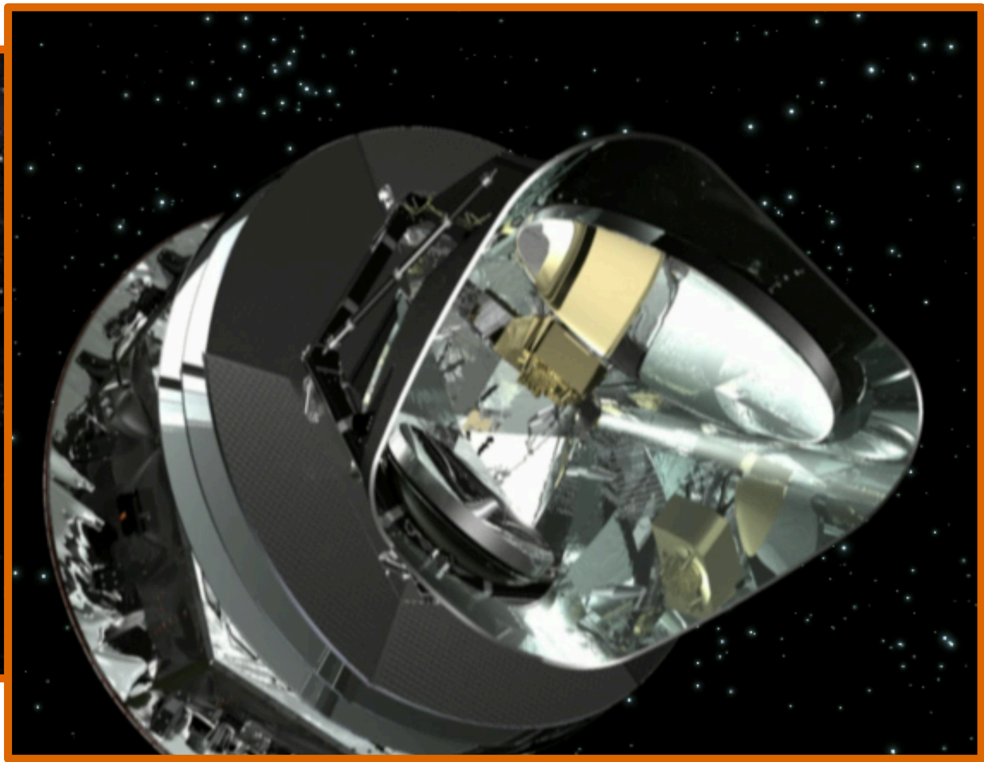
QMASK Boomerang
DASI Maxima

1995: MAP & Planck Missions Proposed



Stated purpose –
To make detailed full-sky maps of the CMB radiation anisotropy (temperature and polarization) with 0.1° (Planck) - 0.2° (MAP) angular resolution to constrain cosmological parameters.





WMAP's Differential Receivers*

10 "Differencing Assemblies"

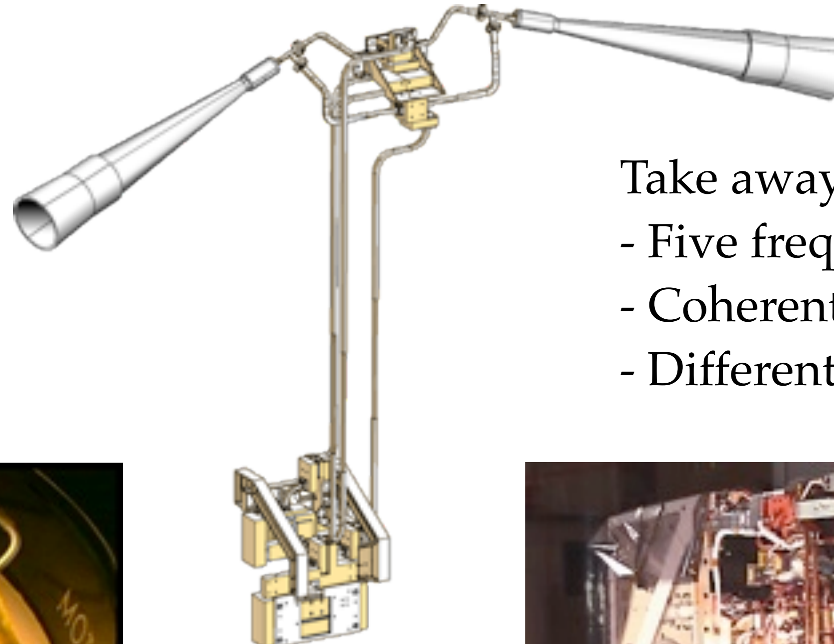
4 @ 94 GHz W–band

2 @ 61 GHz V–band

2 @ 41 GHz Q–band

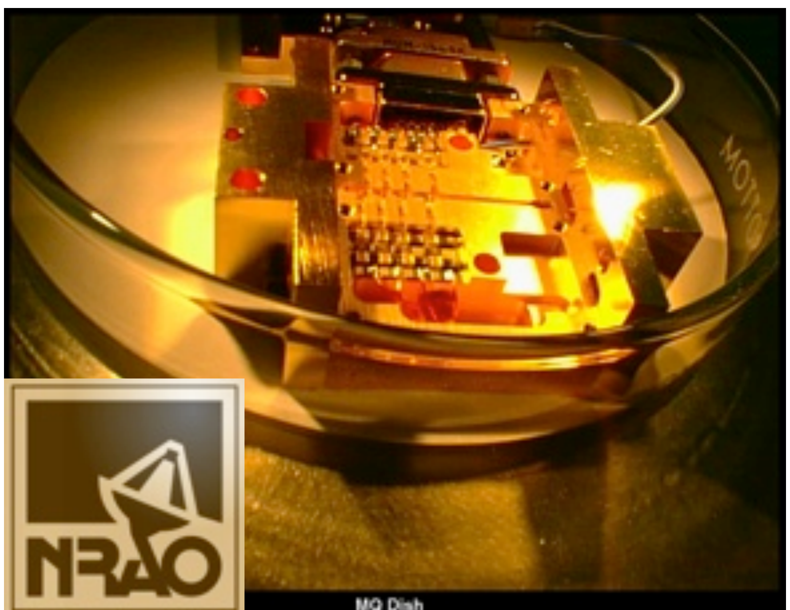
1 @ 33 GHz Ka–band

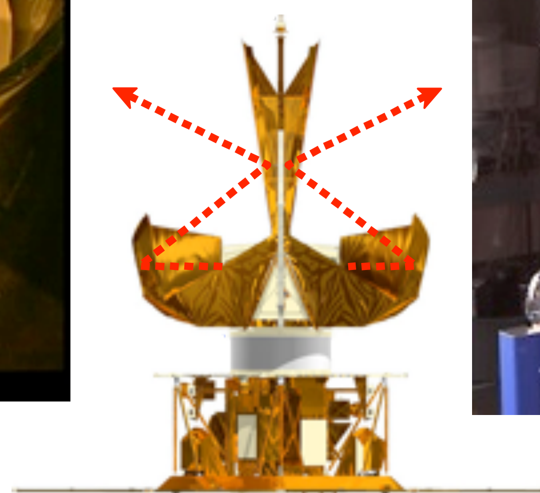
1 @ 23 GHz K–band

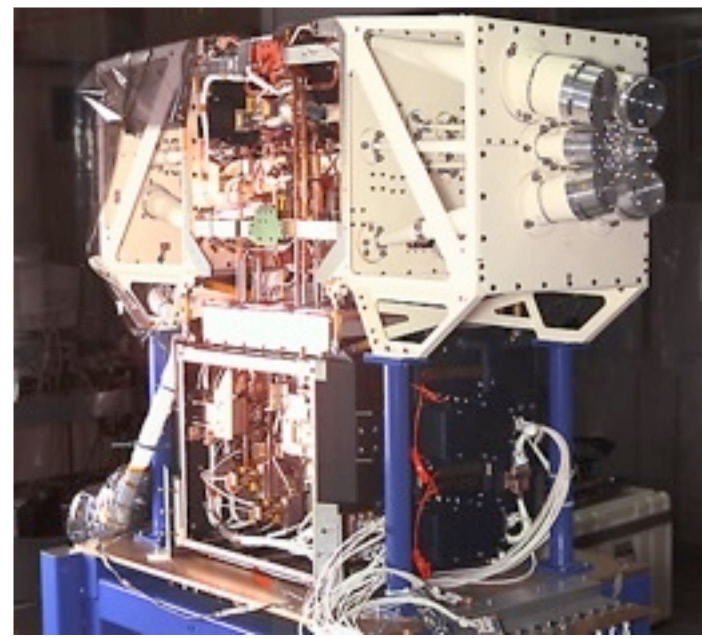


Take away:

- Five frequencies
- Coherent detection
- Differential (2-beam)

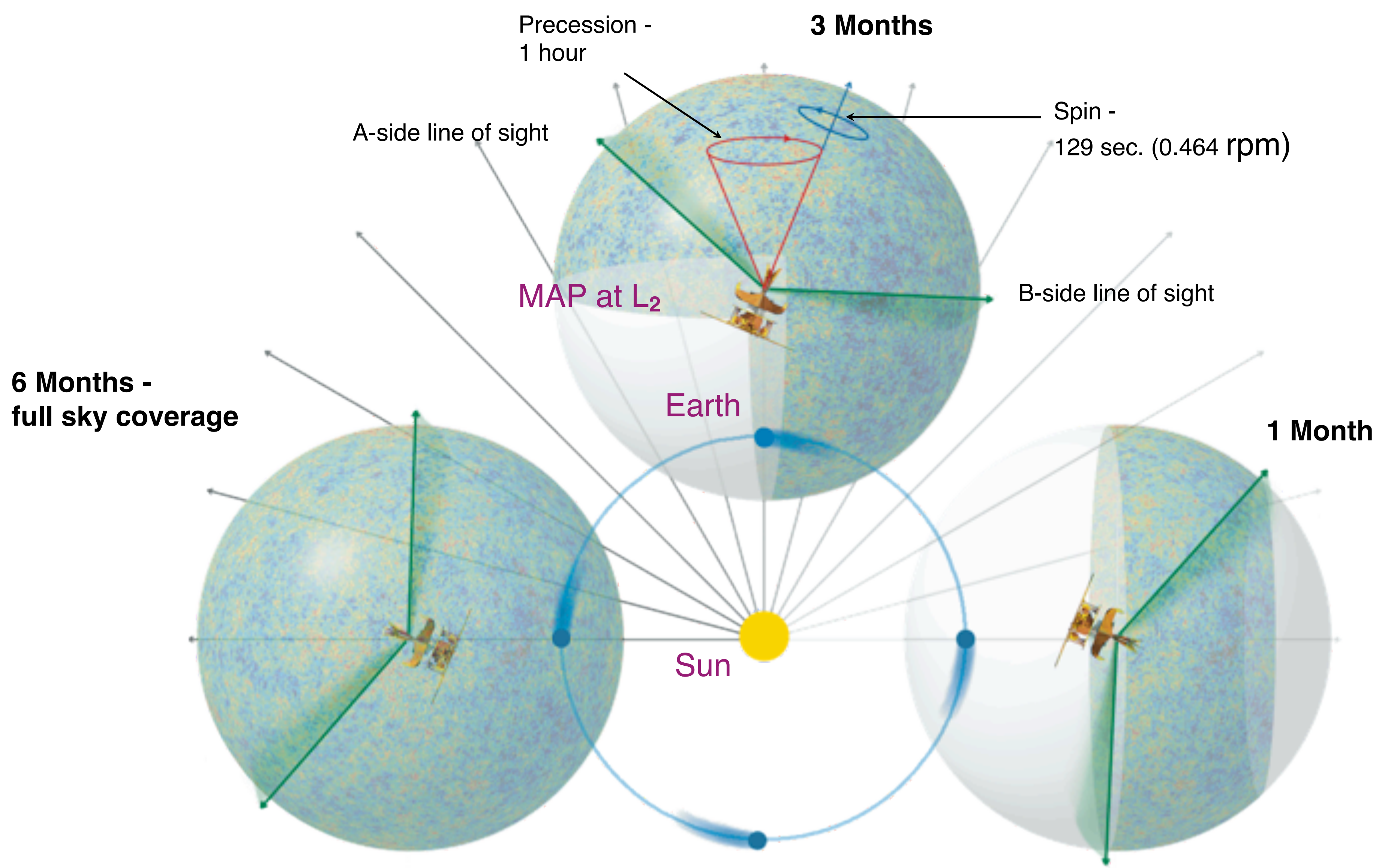




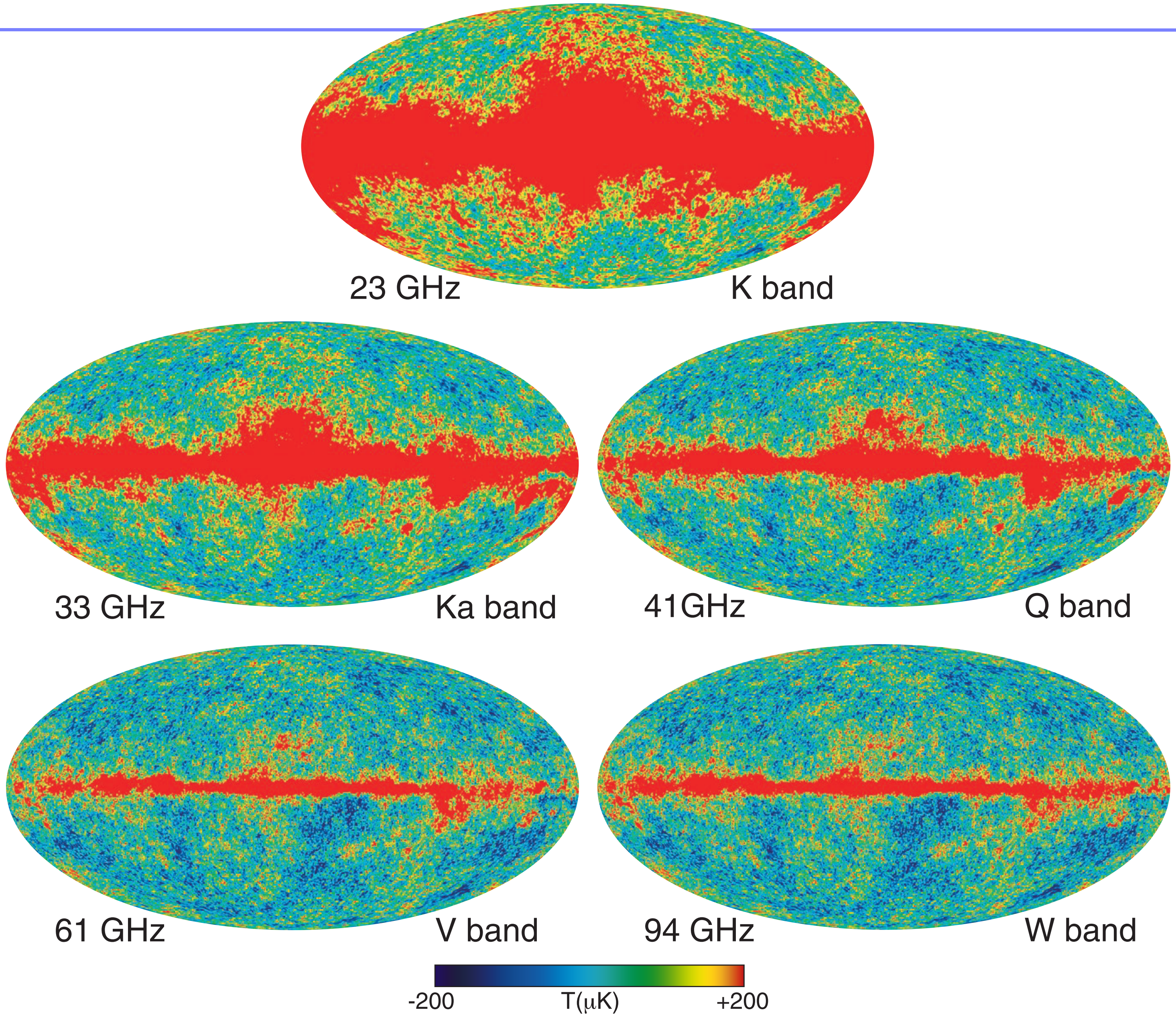


*based on amplifier design of M. Pospieszalski

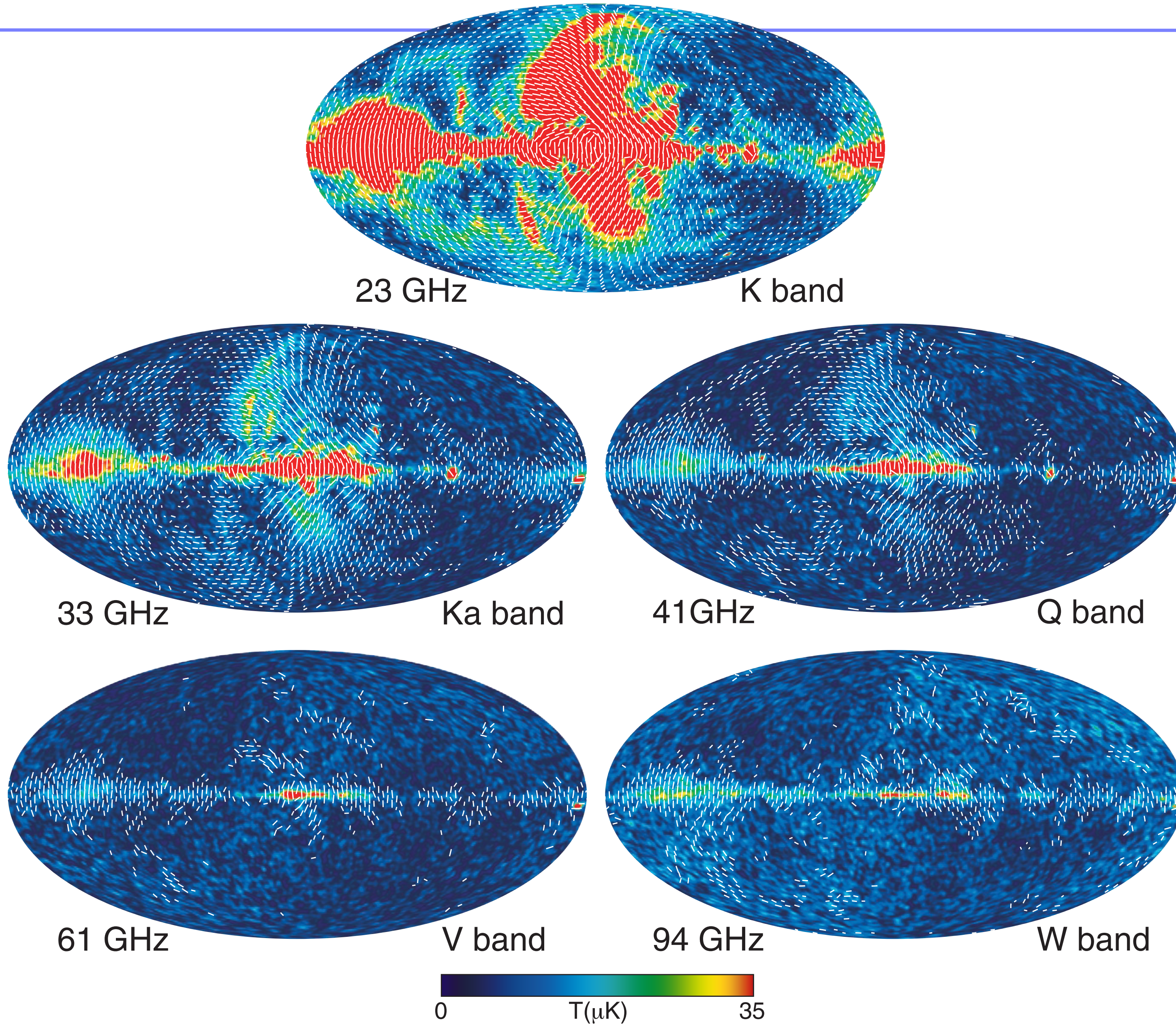
WMAP Scanning From L2



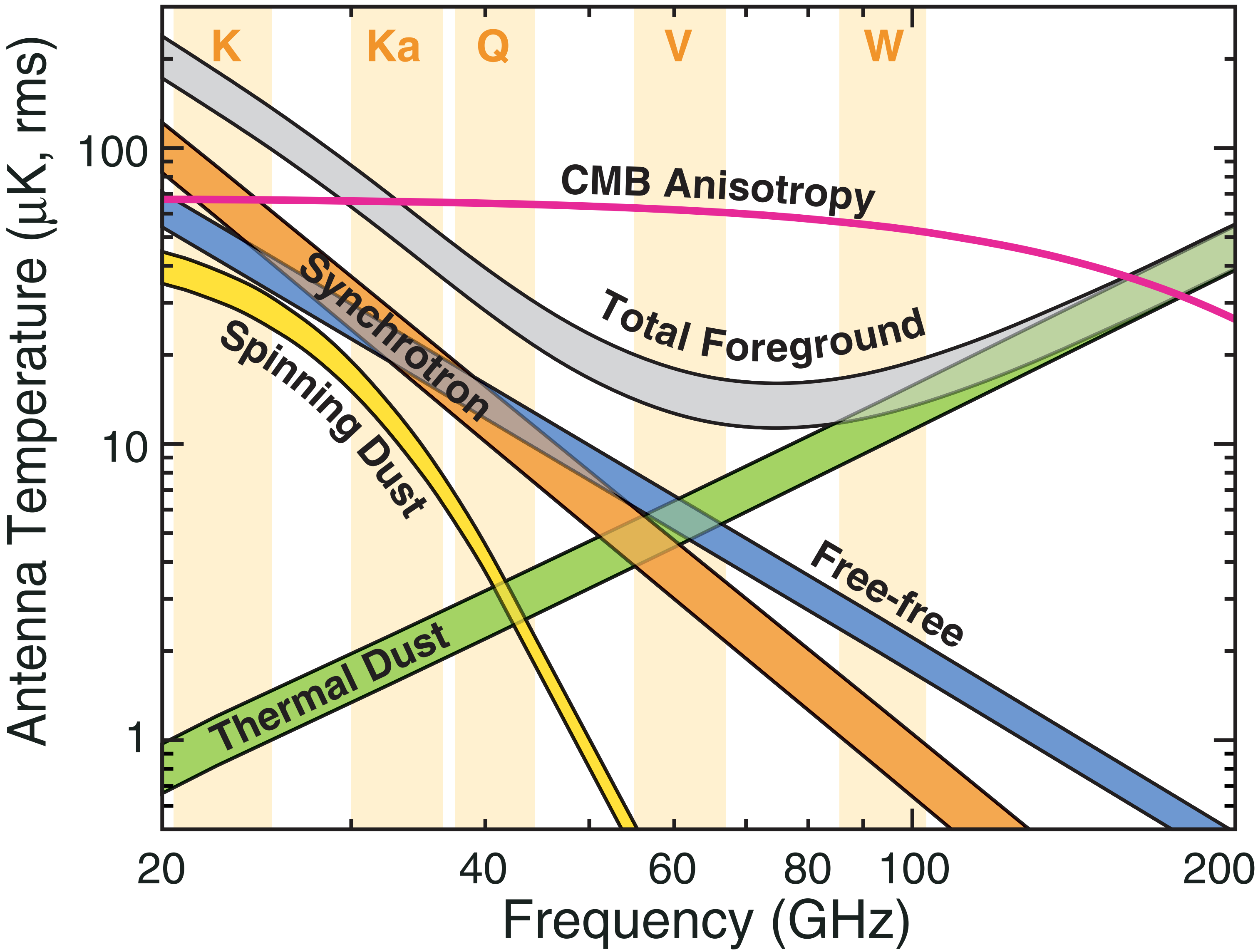
9-year WMAP Temperature Maps



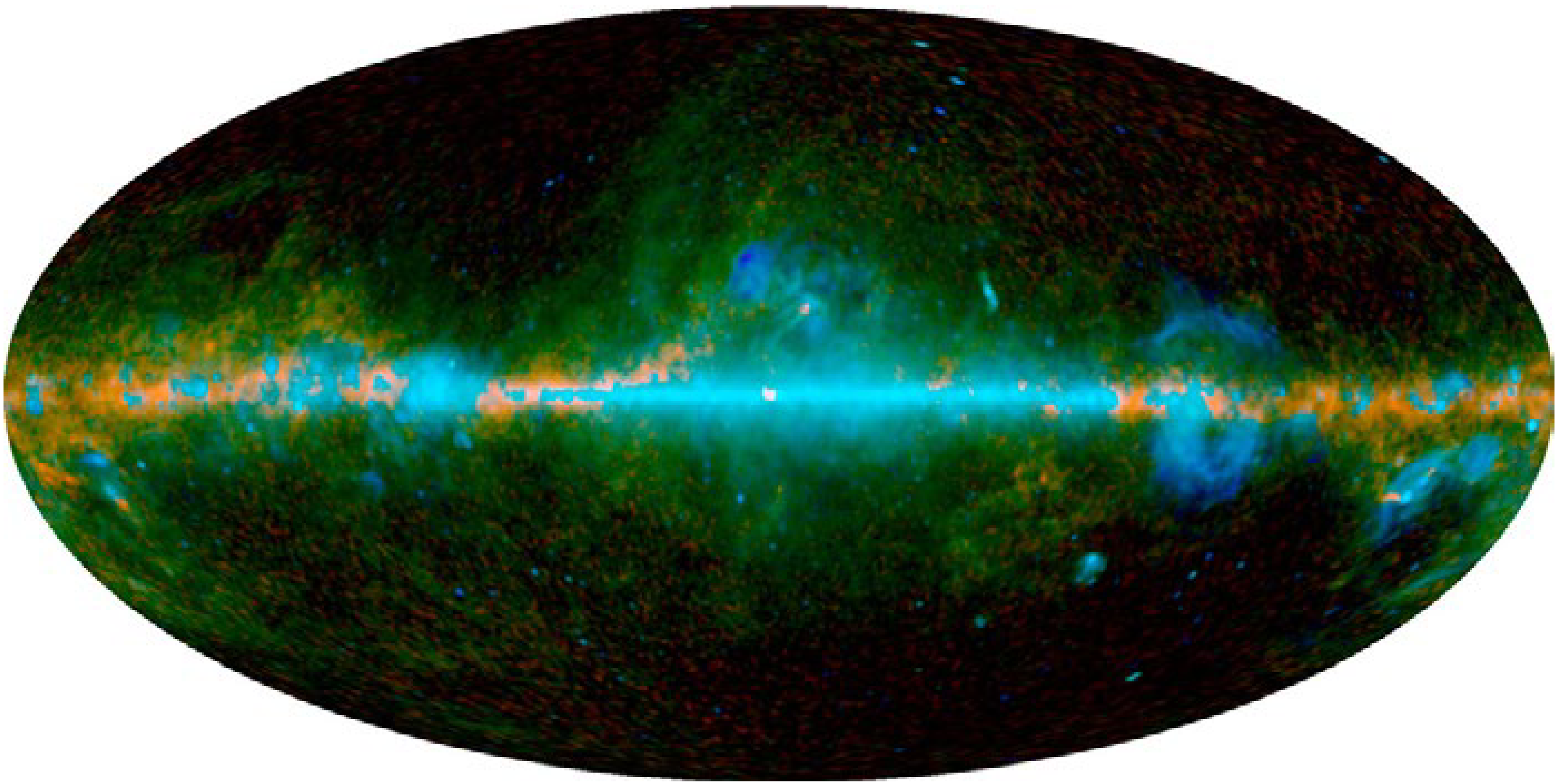
9-year WMAP Polarization Maps



Foreground Components

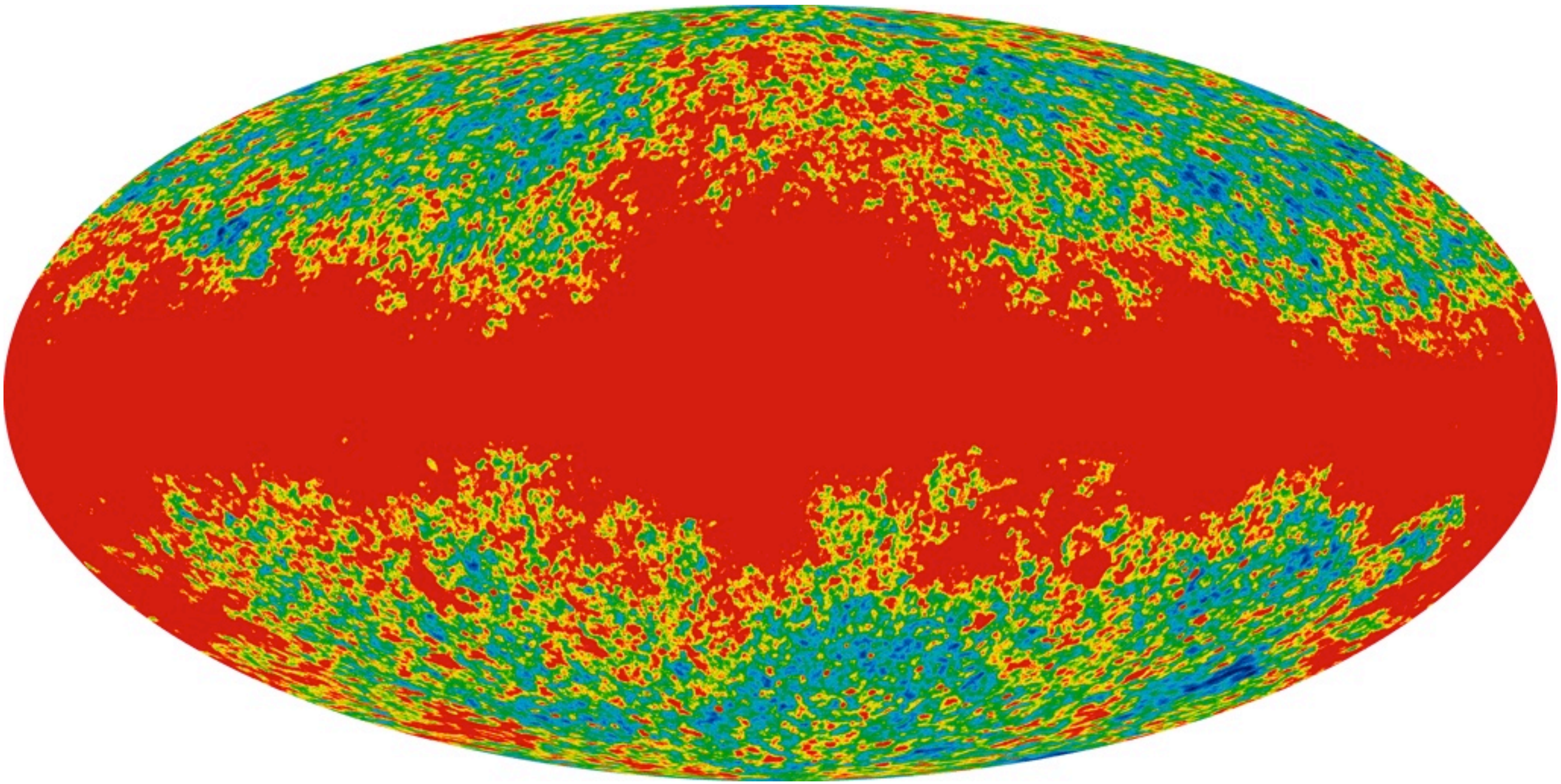


Galactic Emission, ~by Component

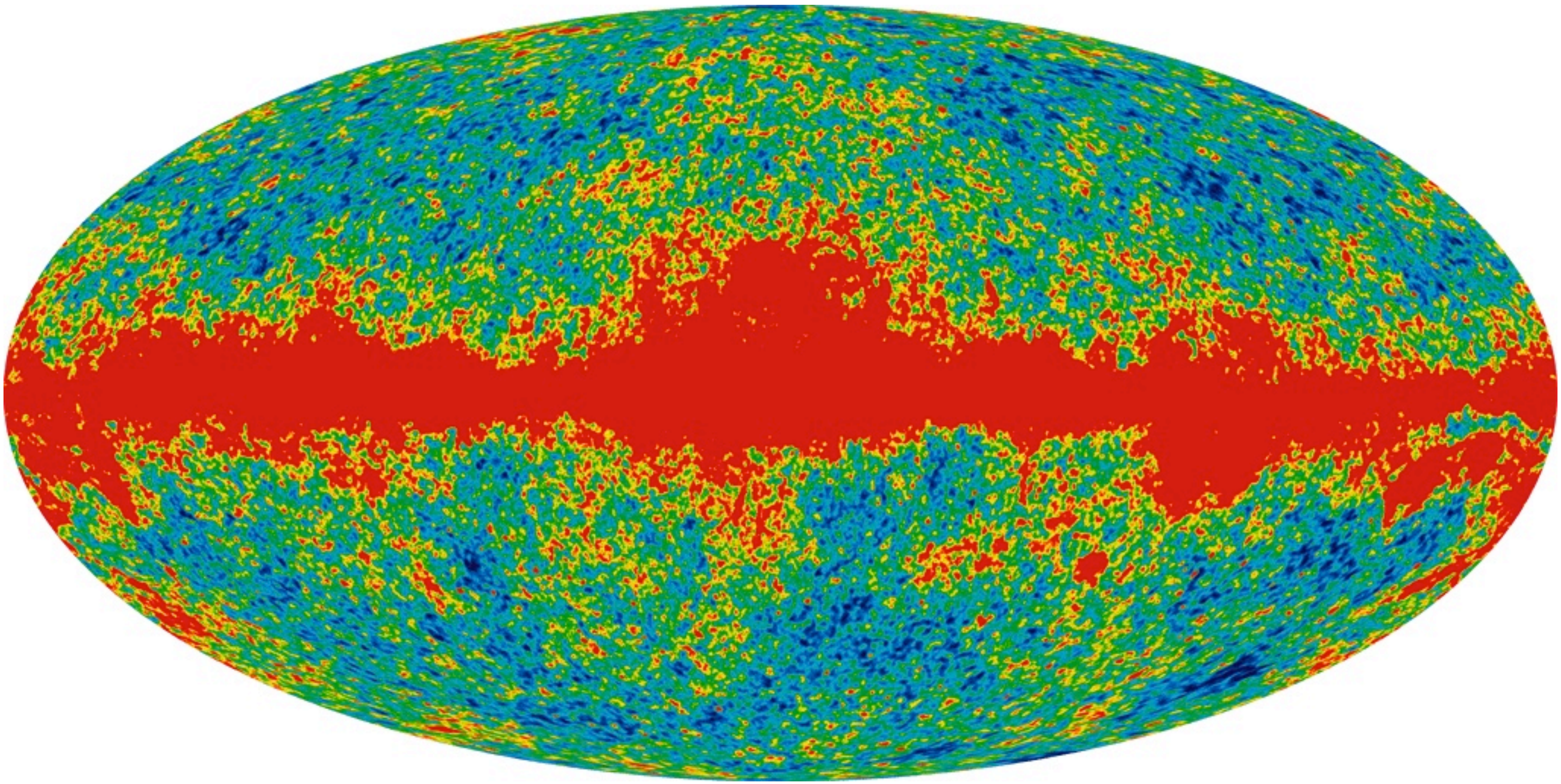


3-color image of three band difference maps, selected to highlight emission components.
Green: ~synchrotron/spinning dust; blue: ~free-free; orange: ~thermal dust.

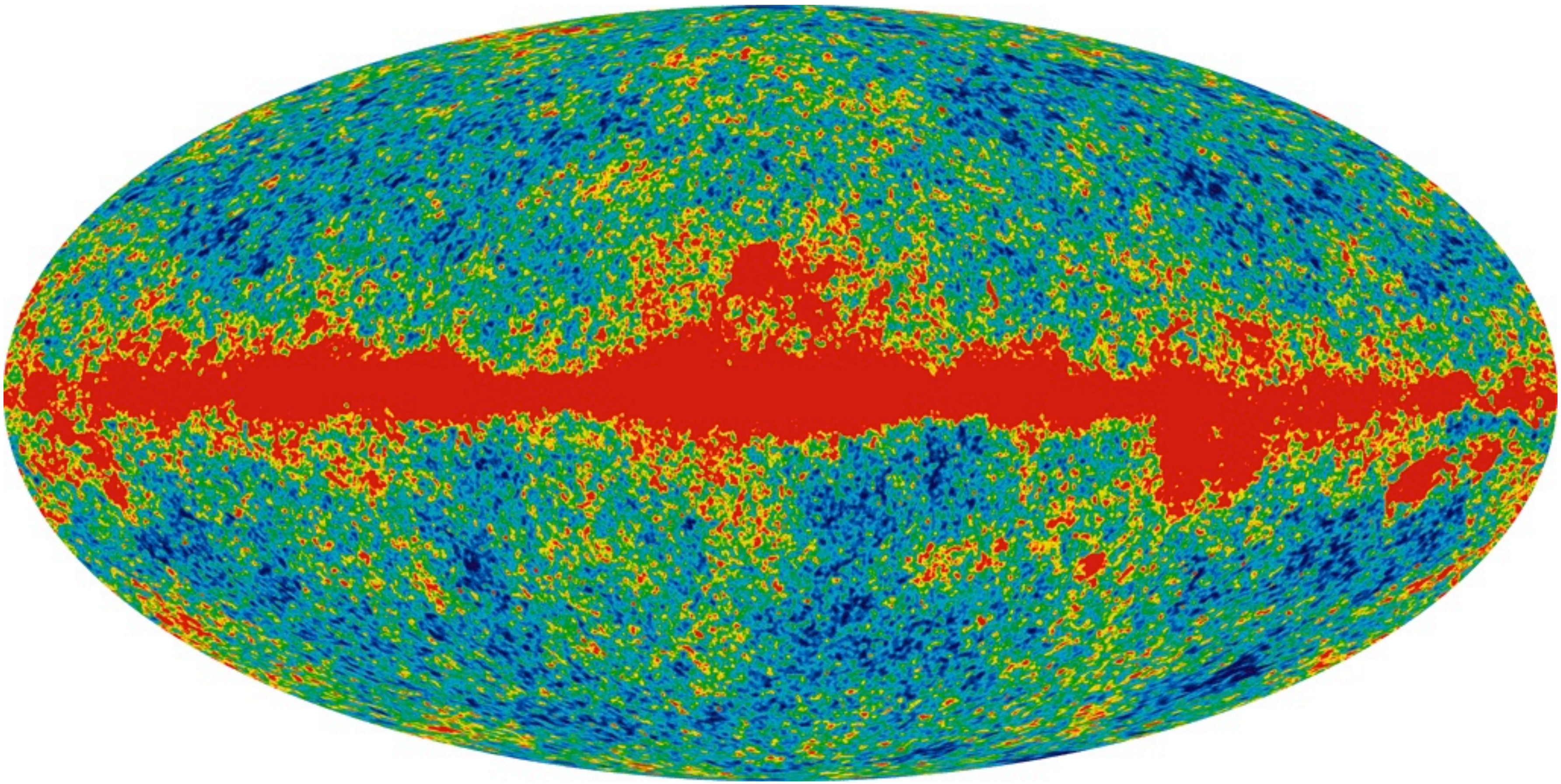
WMAP K Band Temperature, 23 GHz



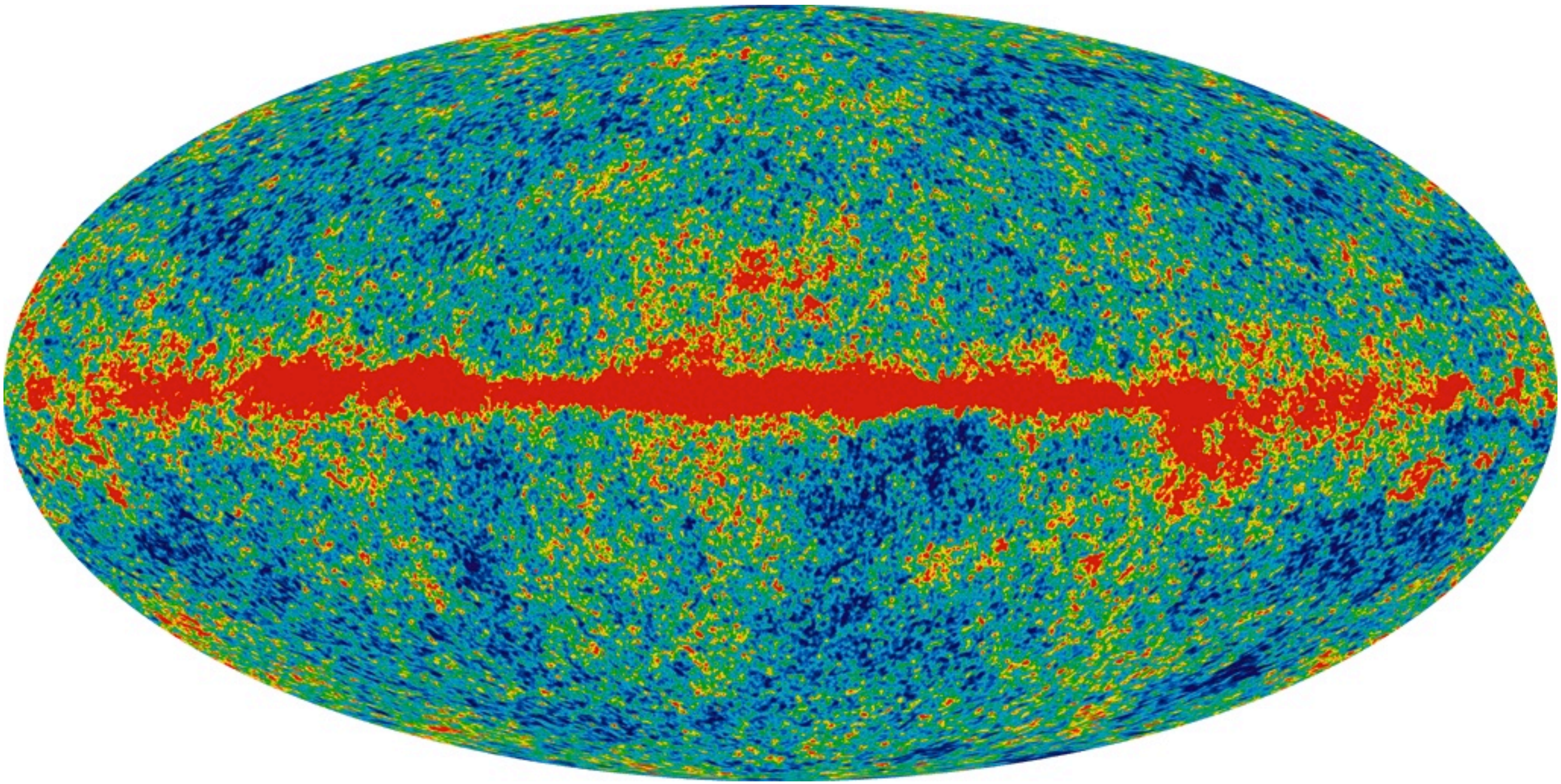
WMAP Ka Band Temperature, 33 GHz



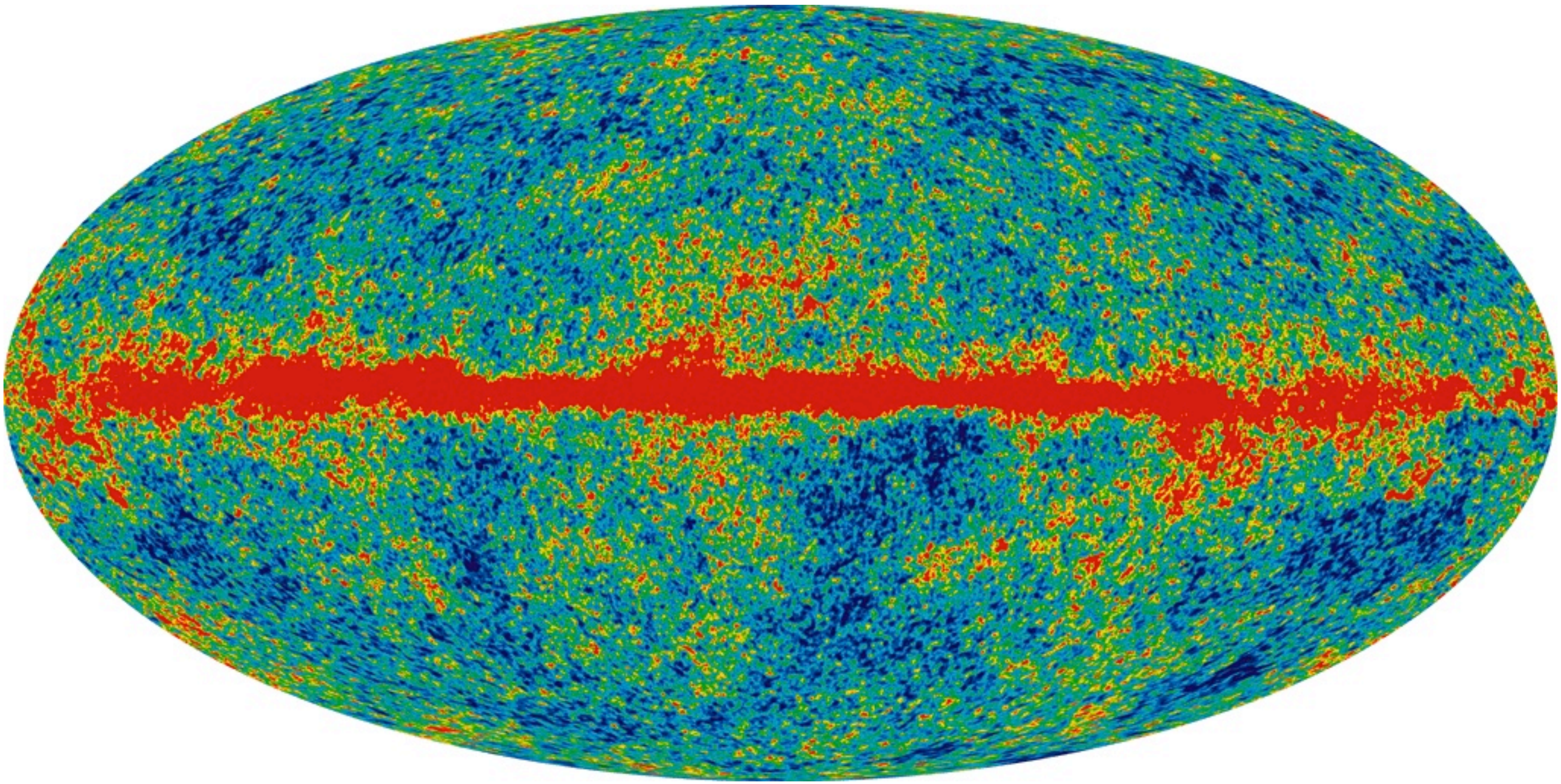
WMAP Q Band Temperature, 41 GHz



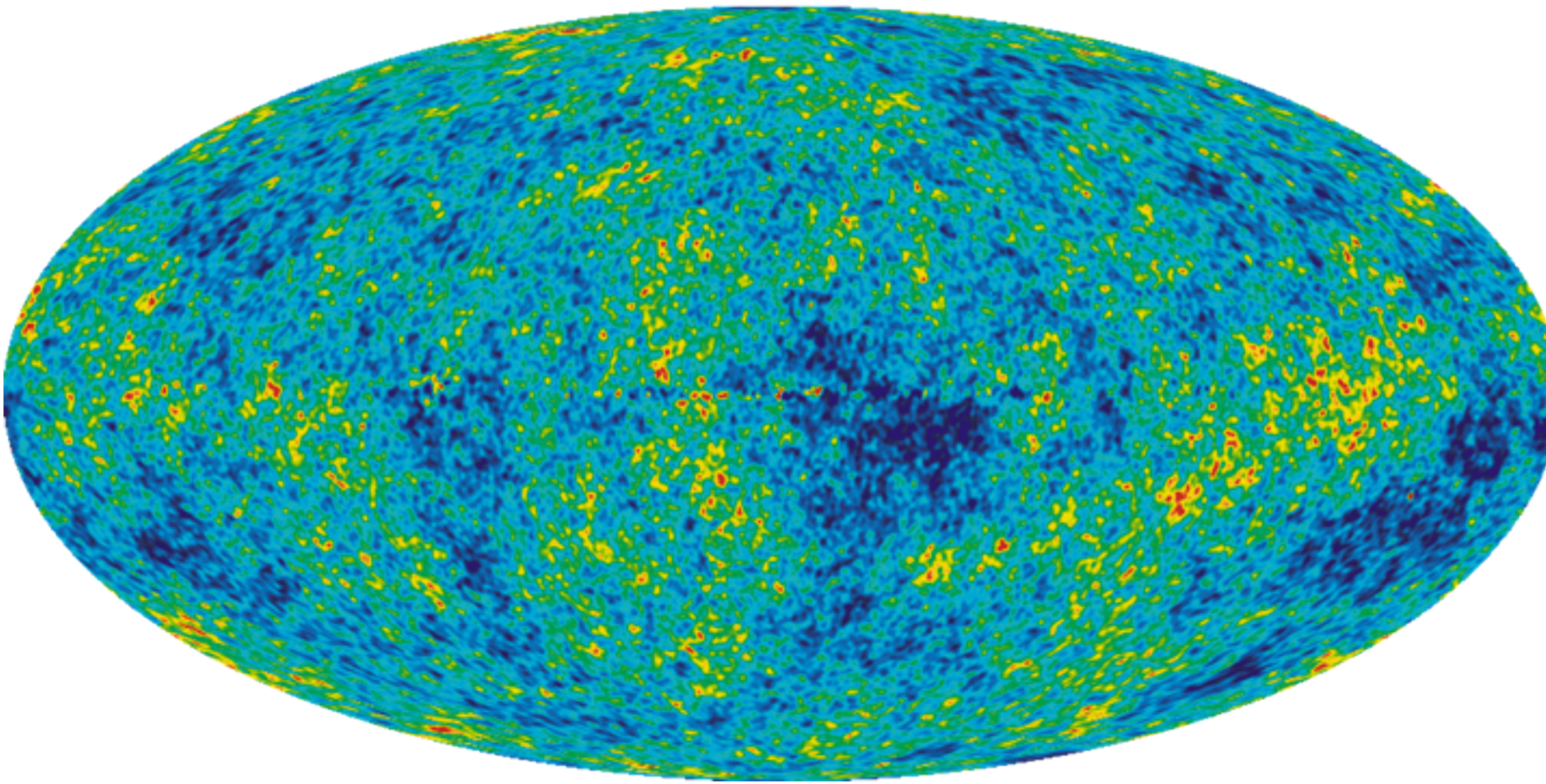
WMAP V Band Temperature, 61 GHz



WMAP W Band Temperature, 94 GHz

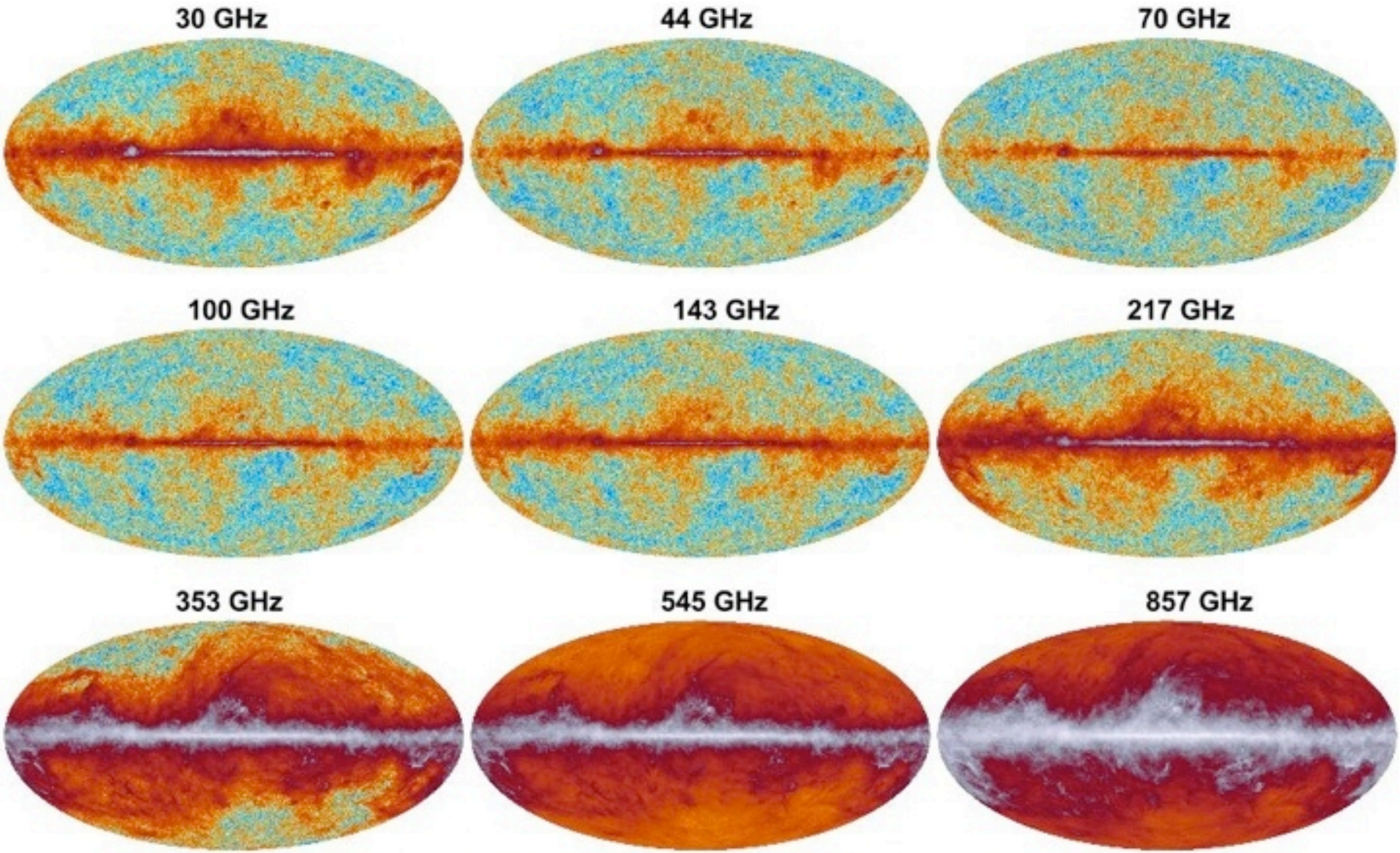


WMAP “ILC” Foreground-Cleaned Map

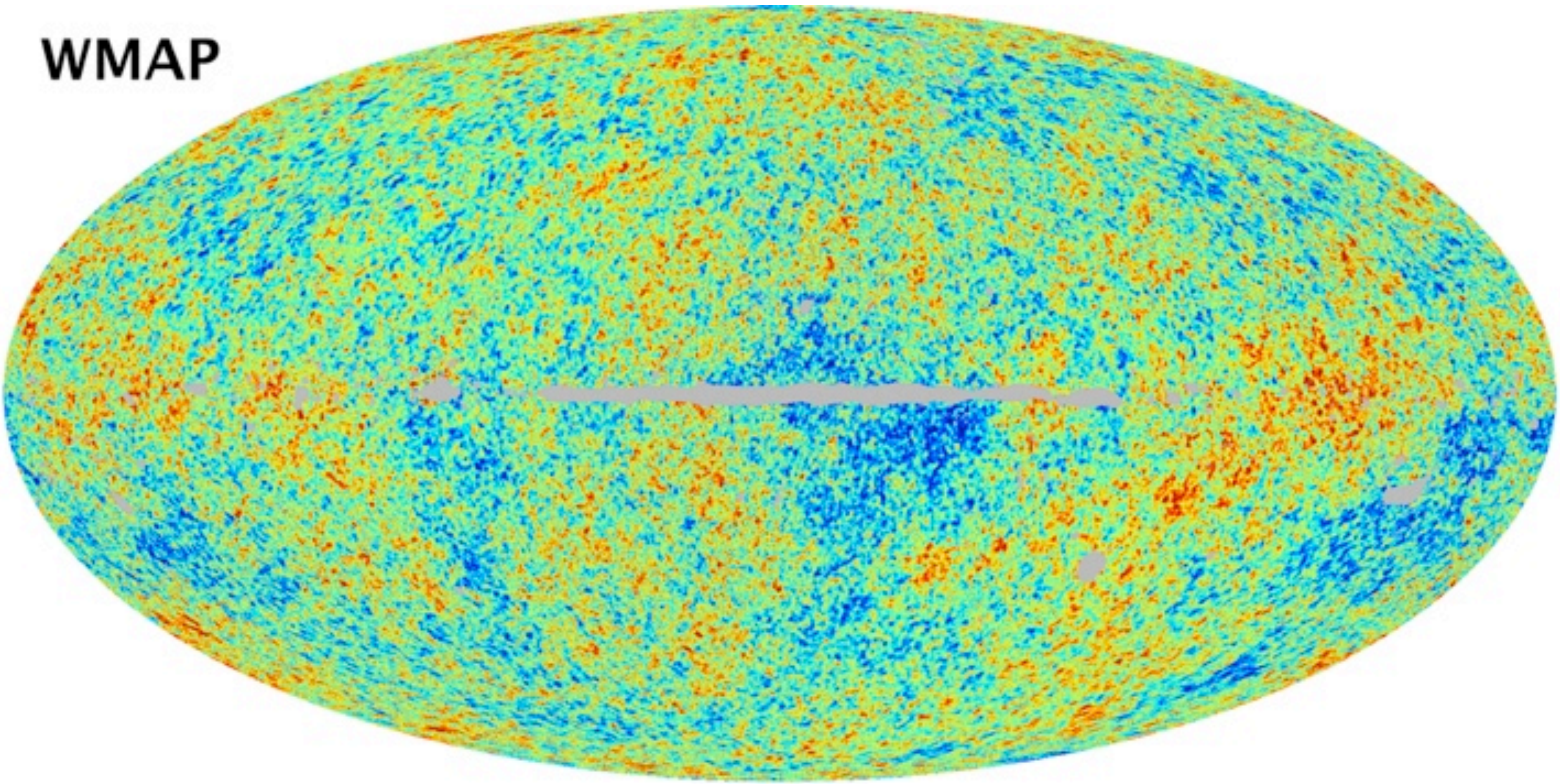


Minimum variance ILC: the internal linear combination (ILC) of frequency bands that minimizes the variance of the final map: $T = \sum_i w_i T_i$ with $\sum_i w_i = 1$.

Planck Full-Sky Maps: 9 Frequencies

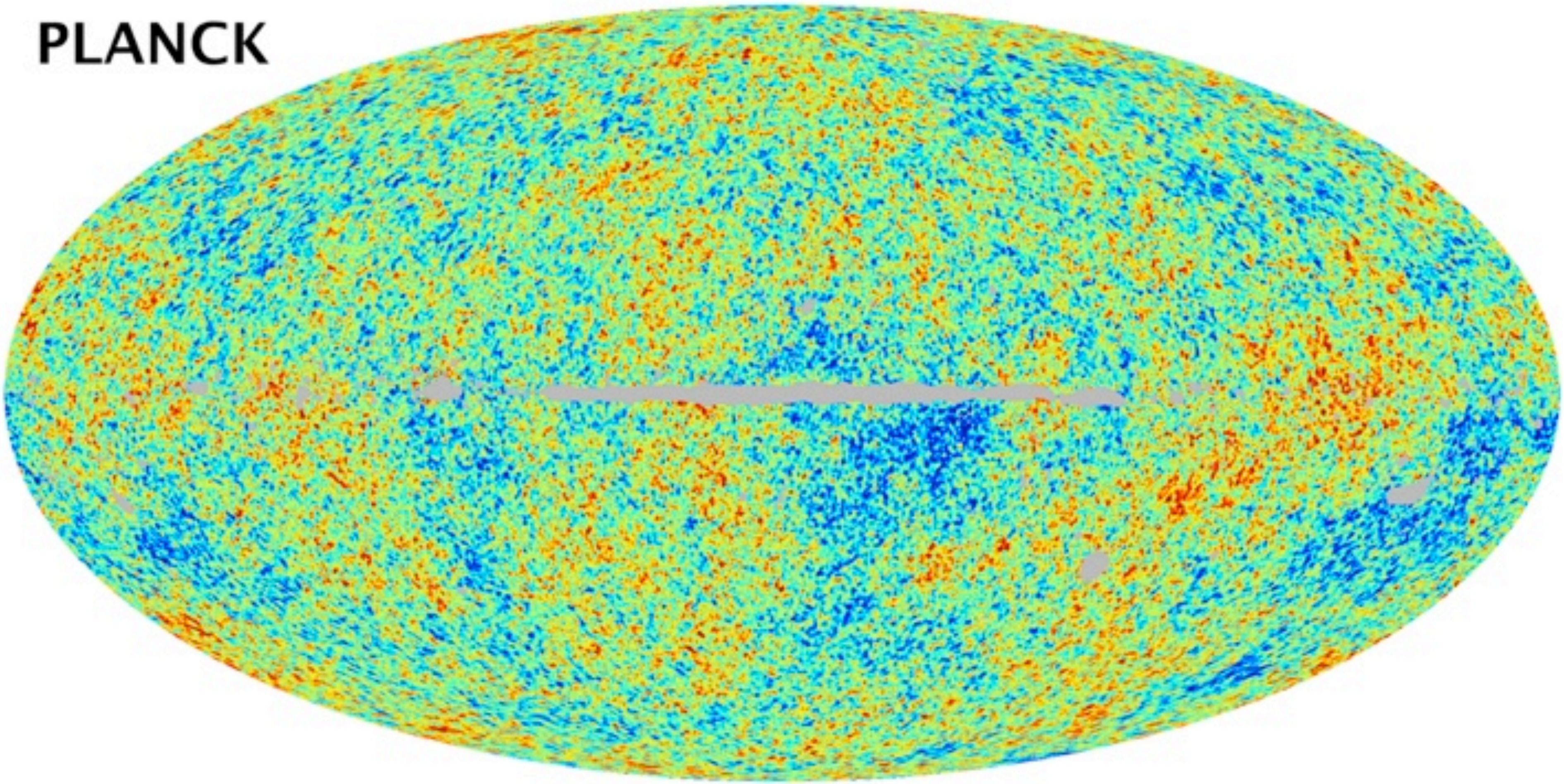


WMAP/Planck Sky Map Comparison



Cleaned with Planck 353 GHz dust map and low-frequency templates. 12′ resolution.

WMAP/Planck Sky Map Comparison

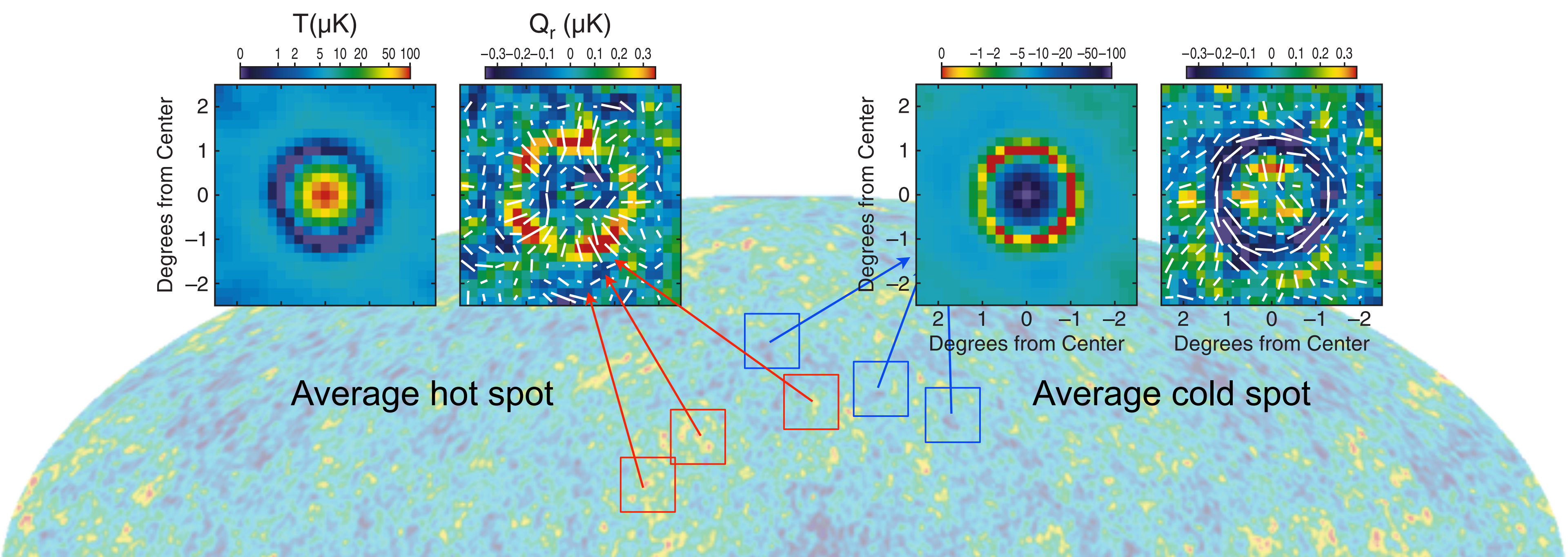


Planck/SMICA map, 5′ resolution.

Cosmological Analysis –

Baryon Acoustic Oscillations (BAO) in the CMB

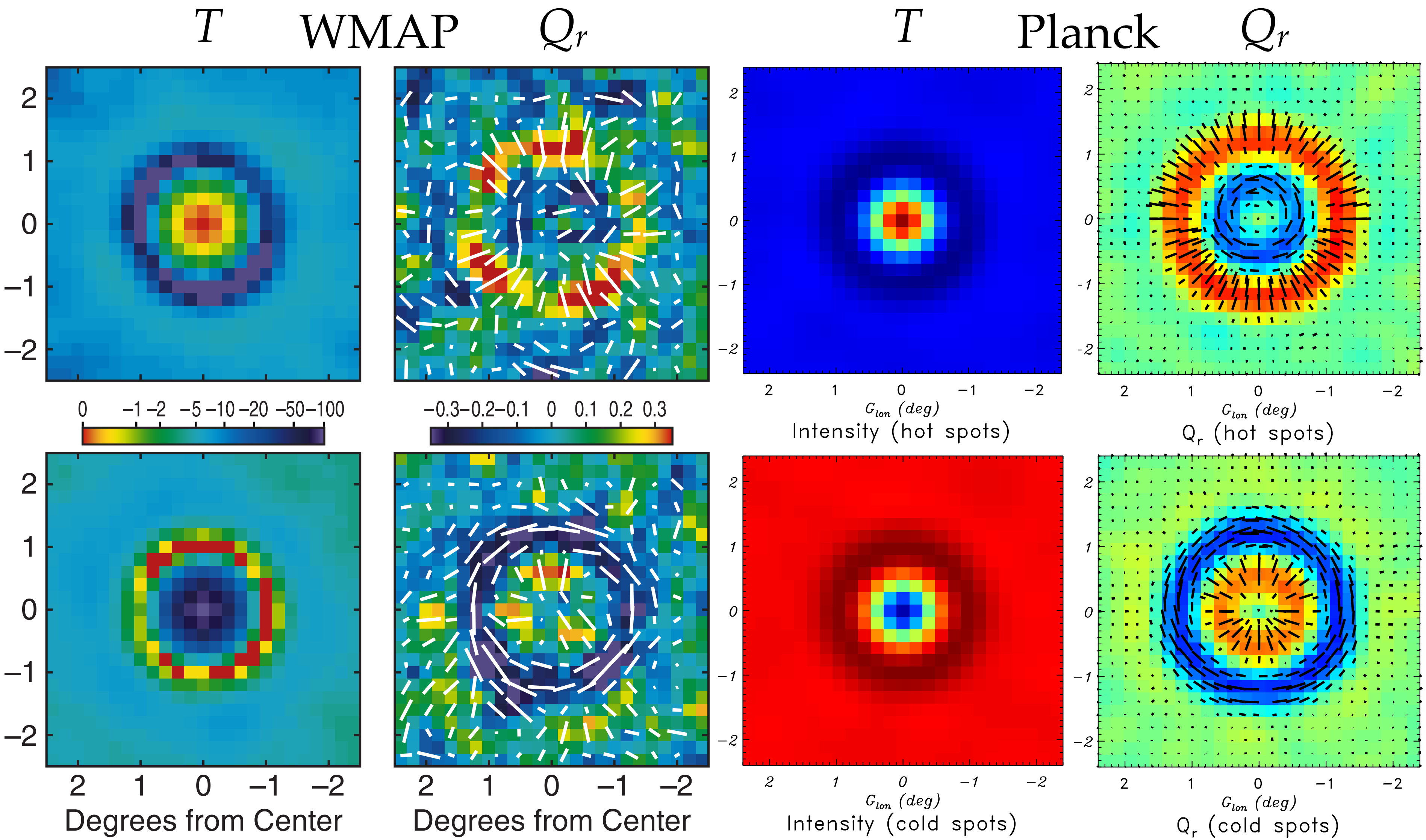
Acoustic Oscillations in the CMB



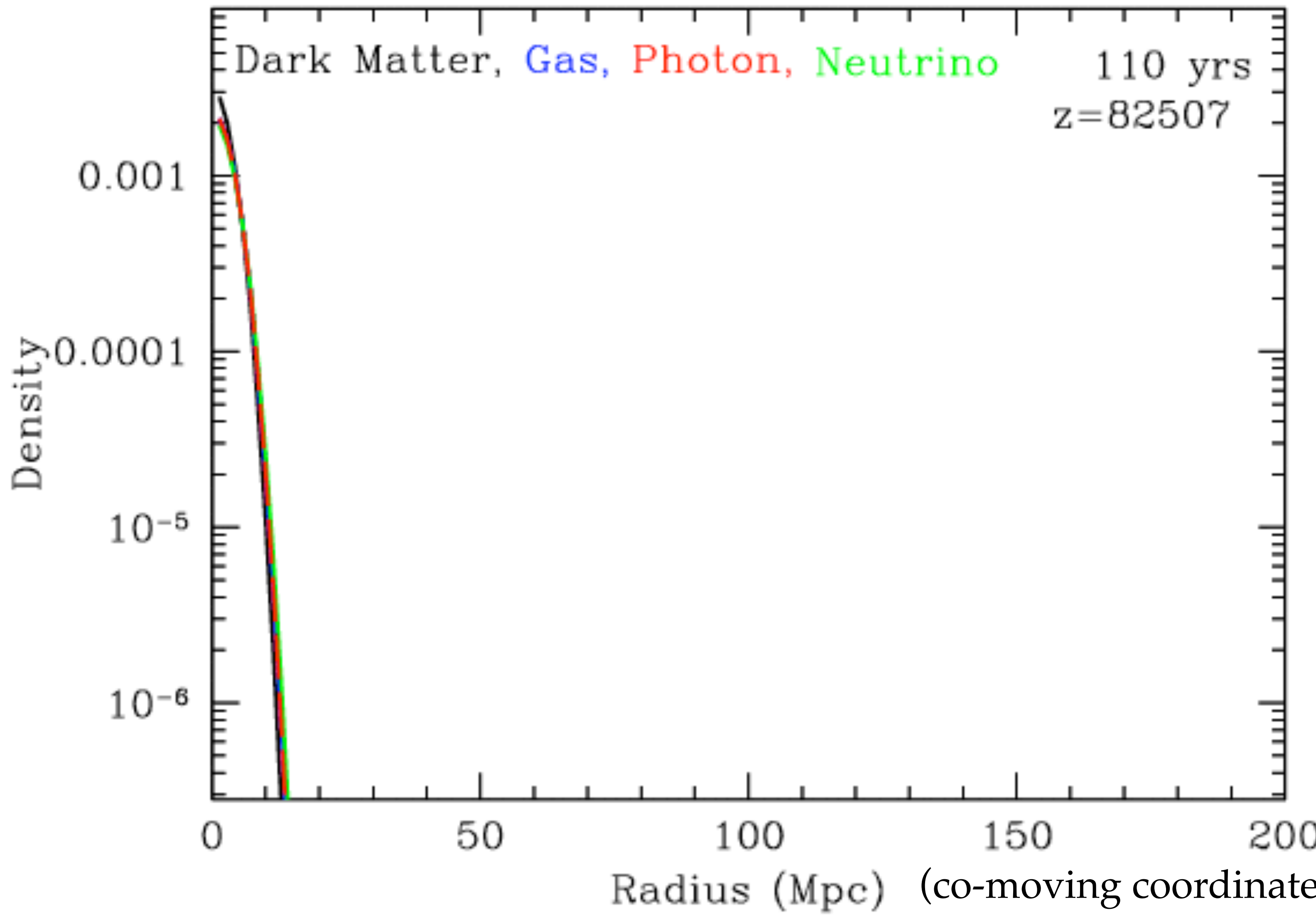
Temperature – the imprint of BAO is visible in the co-added degree-scale hot (left) & cold (right) spots.

Polarization – The expected radial/tangential polarization pattern around these extrema, due to Thompson scattering is clearly seen.

BAO in the CMB – WMAP & Planck



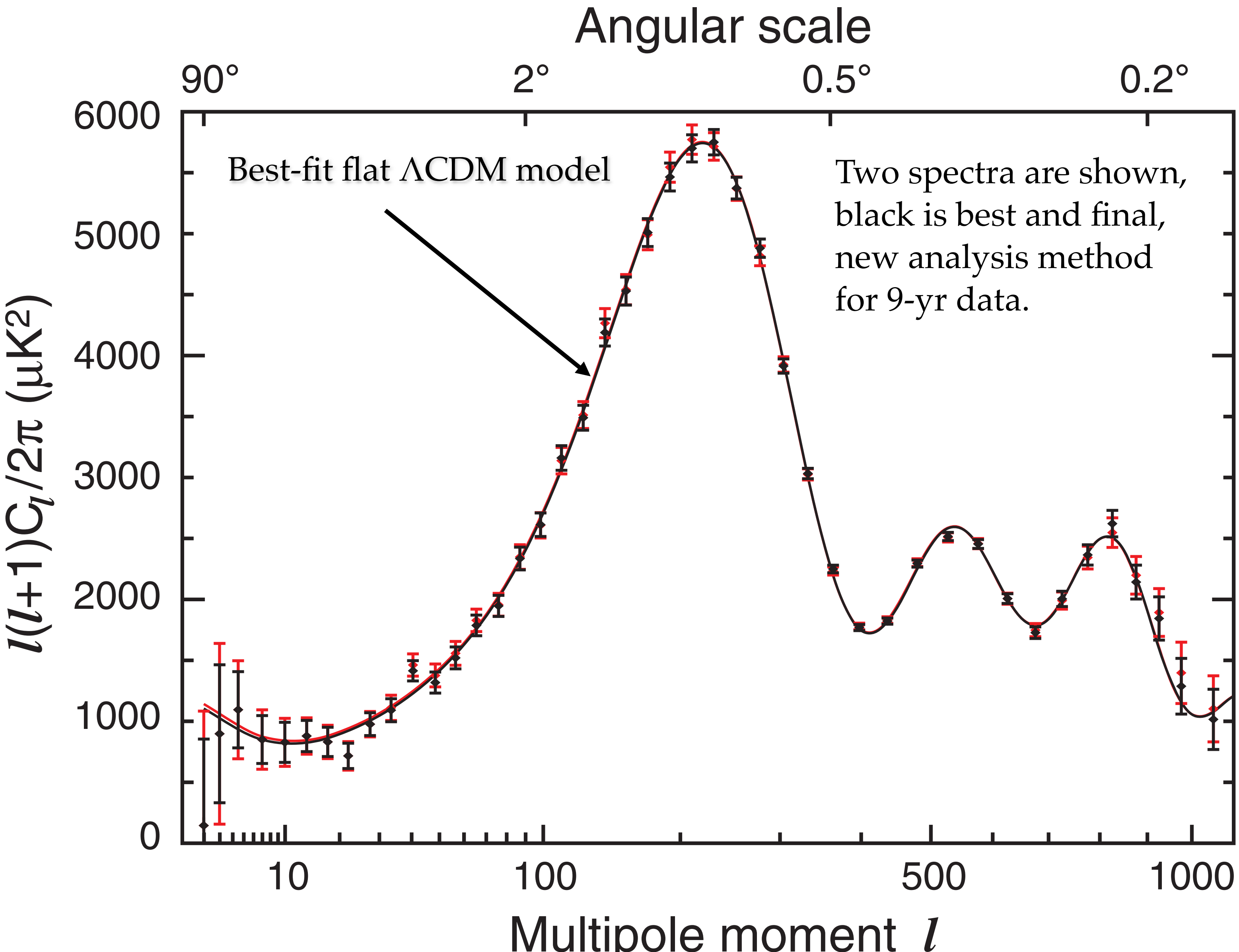
BAO, the Movie: Evolution of a Peak



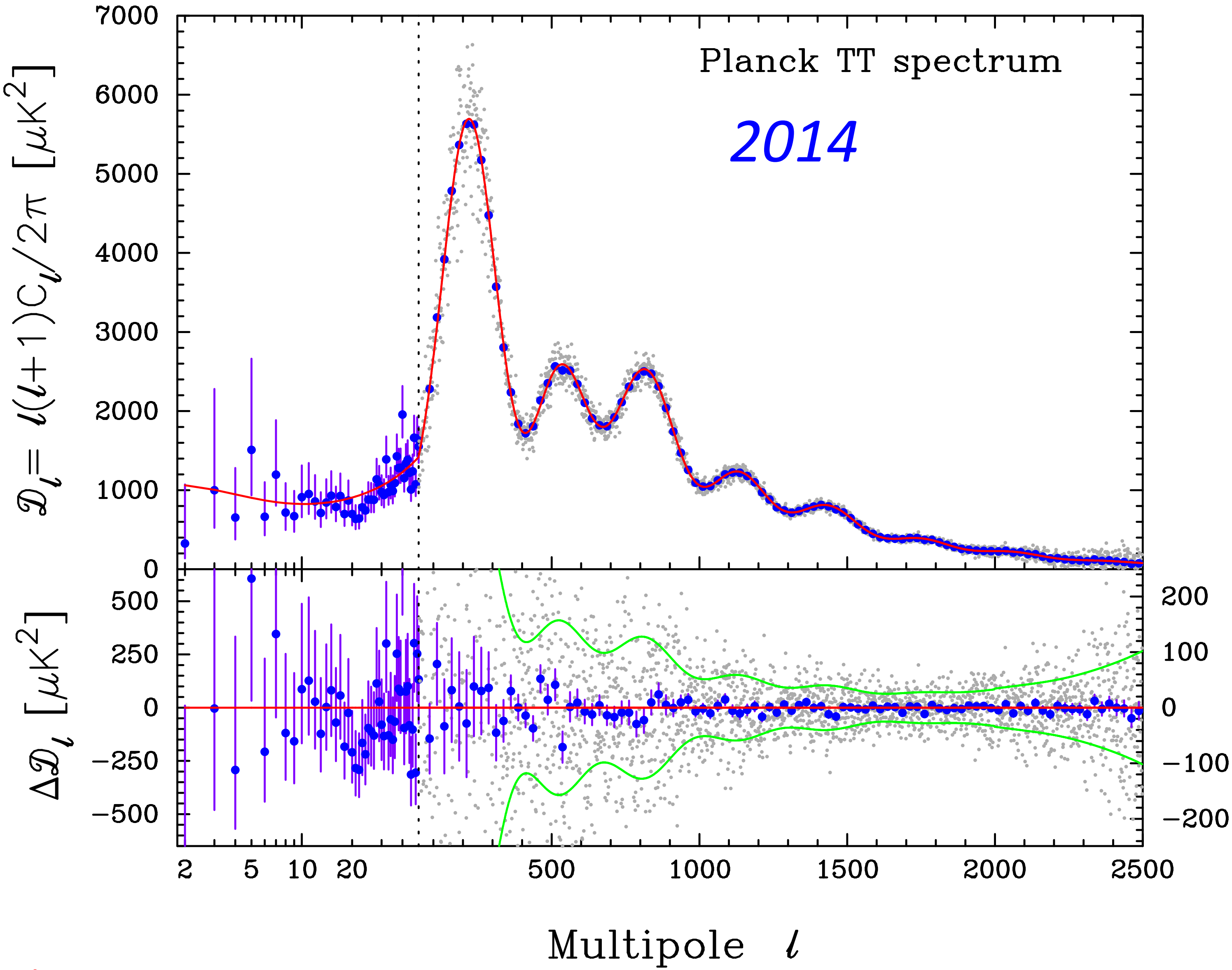
(co-moving coordinates)

Credit: SDSS Collaboration

The 9-Year WMAP Power Spectrum

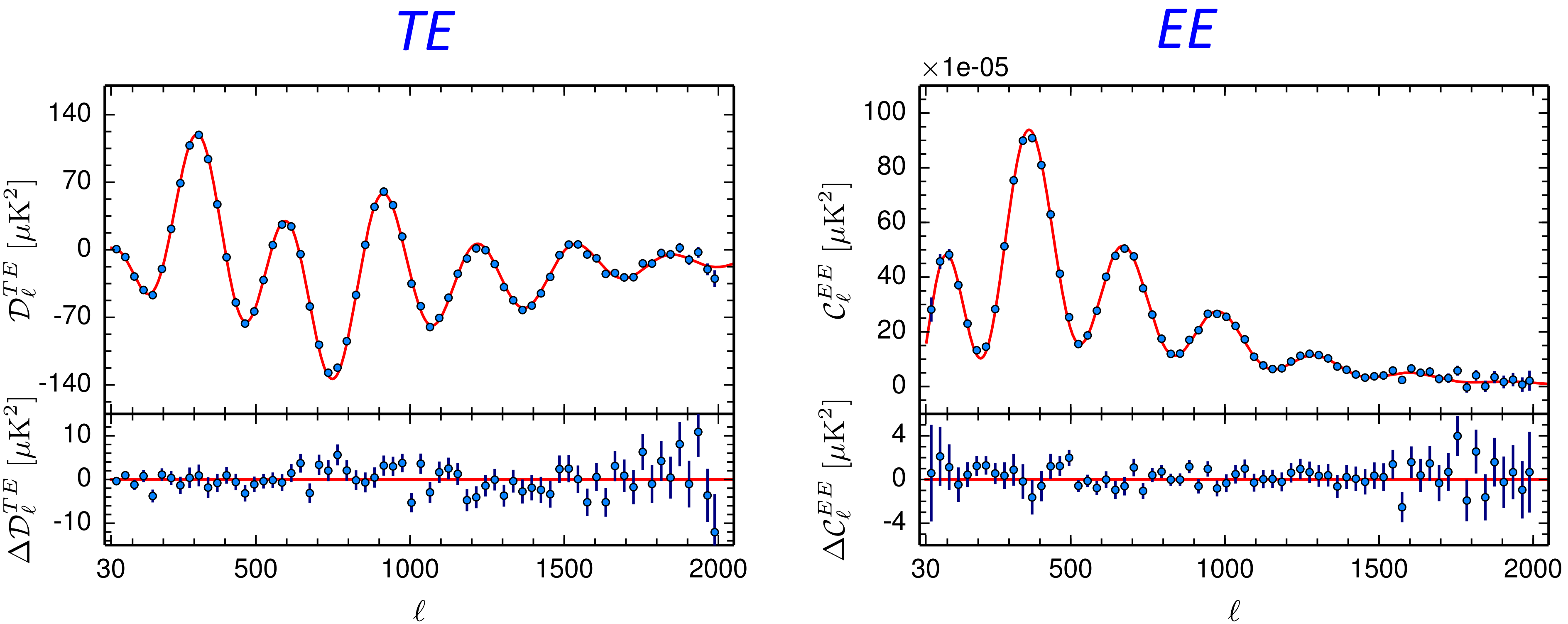


Planck 2014 Power Spectrum



preliminary *Efstathiou et al. 2014*

Planck 2014 Polarization Spectra



preliminary *Efstathiou et al. 2014*

WMAP Cosmological Parameters

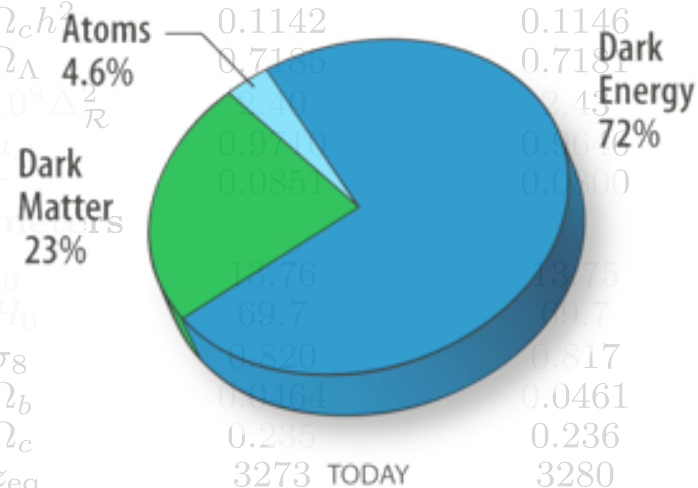
Hinshaw et al., arXiv/1212.5226

TABLE 2
Maximum Likelihood ΛCDM Parameters[a]

Parameter	Symbol	*WMAP* data	Combined data[b]
Fit ΛCDM parameters			
Physical baryon density	$\Omega_b h^2$	0.02256	0.02240
Physical cold dark matter density	$\Omega_c h^2$	0.1142	0.1146
Dark energy density ($w = -1$)	Ω_Λ	0.7185	0.7181
Curvature perturbations, $k_0 = 0.002$ Mpc^{-1}	$10^9 \Delta^2_{\mathcal{R}}$	2.40	2.43
Scalar spectral index	n_s	0.9710	0.9646
Reionization optical depth	τ	0.0851	0.0800
Derived parameters			
Age of the universe (Gyr)	t_0	13.76	13.75
Hubble parameter, $H_0 = 100h$ km/s/Mpc	H_0	69.7	69.7
Density fluctuations @ $8h^{-1}$ Mpc	σ_8	0.820	0.817
Baryon density/critical density	Ω_b	0.0464	0.0461
Cold dark matter density/critical density	Ω_c	0.235	0.236
Redshift of matter-radiation equality	z_{eq}	3273	3280
Redshift of reionization	z_{reion}	10.36	9.97

[a] The maximum-likelihood ΛCDM parameters for use in simulations. Mean parameter values, with marginalized uncertainties, are reported in Table 4.
[b] "Combined data" refers to *WMAP*+eCMB+BAO+H_0.

ΛCDM: the model everyone loves to hate...



This gives most-likely model parameters for "vanilla" 6-parameter ΛCDM model. Stay tuned for errors and goodness of fit.

WMAP Cosmological Parameters

Hinshaw et al., arXiv/1212.5226

TABLE 4
Six-Parameter ΛCDM Fit; *WMAP* plus External Data[a]

Parameter	*WMAP*	+eCMB	+eCMB+BAO	+eCMB+H_0	+eCMB+BAO+H_0
Fit parameters					
$\Omega_b h^2$	0.02264 ± 0.00050	0.02229 ± 0.00037	0.02211 ± 0.00034	0.02244 ± 0.00035	0.02223 ± 0.00033
$\Omega_c h^2$	0.1138 ± 0.0045	0.1126 ± 0.0035	0.1162 ± 0.0020	0.1106 ± 0.0030	0.1153 ± 0.0019
Ω_Λ	0.721 ± 0.025	0.728 ± 0.019	0.707 ± 0.010	0.740 ± 0.015	$0.7135^{+0.0095}_{-0.0096}$
$10^9 \Delta^2_{\mathcal{R}}$	2.41 ± 0.10	2.430 ± 0.084	$2.484^{+0.073}_{-0.072}$	$2.396^{+0.079}_{-0.078}$	2.464 ± 0.072
n_s	0.972 ± 0.013	0.9646 ± 0.0098	$0.9579^{+0.0081}_{-0.0082}$	$0.9690^{+0.0091}_{-0.0090}$	0.9608 ± 0.0080
τ	0.089 ± 0.014	0.084 ± 0.013	$0.079^{+0.011}_{-0.012}$	0.087 ± 0.013	0.081 ± 0.012
Derived parameters					
t_0 (Gyr)	13.74 ± 0.11	13.742 ± 0.077	13.800 ± 0.061	13.702 ± 0.069	13.772 ± 0.059
H_0 (km/s/Mpc)	70.0 ± 2.2	70.5 ± 1.6	68.76 ± 0.84	71.6 ± 1.4	69.32 ± 0.80
σ_8	0.821 ± 0.023	0.810 ± 0.017	$0.822^{+0.013}_{-0.014}$	0.803 ± 0.016	$0.820^{+0.013}_{-0.014}$
Ω_b	0.0463 ± 0.0024	0.0449 ± 0.0018	0.04678 ± 0.00098	0.0438 ± 0.0015	0.04628 ± 0.00093
Ω_c	0.233 ± 0.023	0.227 ± 0.017	0.2460 ± 0.0094	0.216 ± 0.014	$0.2402^{+0.0088}_{-0.0087}$
$z_{\rm eq}$	3265^{+106}_{-105}	3230 ± 81	3312 ± 48	3184 ± 70	3293 ± 47
$z_{\rm reion}$	10.6 ± 1.1	10.3 ± 1.1	10.0 ± 1.0	10.5 ± 1.1	10.1 ± 1.0

[a] ΛCDM model fit to *WMAP* nine-year data combined with a progression of external data sets.

Marginalized parameter constraints with 68% CL uncertainties.
The 6-d volume of allowable parameter space is 68,000 times smaller than pre-WMAP.

χ^2 of high-l power spectrum is 1200/1168 d.o.f. with 25% PTE. The low-l polarization data has a somewhat high χ^2 (PTE < ~1%), possibly from residual foregrounds.

Planck 2014 Cosmological Parameters

Parameter	TT	TT,TE,EE
$\Omega_b h^2$	0.02222±0.00023	0.02224±0.00015
$\Omega_c h^2$	0.1199±0.0022	0.1199±0.0014
$100\theta_*$	1.04086±0.00048	1.04073±0.00032
τ	0.078±0.019	0.079±0.017
n_s	0.9652±0.0062	0.9639±0.0047
H_0	67.3±1.0	67.6 ± 0.6 (+BAO)
Ω_m	0.316±0.014	0.316±0.009
σ_8	0.830±0.015	0.831±0.013
z_{re}	9.9±1.9	10.7±1.7

…but beware there are still low level systematics in the polarization spectra

preliminary *Efstathiou et al. 2014*

The Legacy of WMAP & Planck

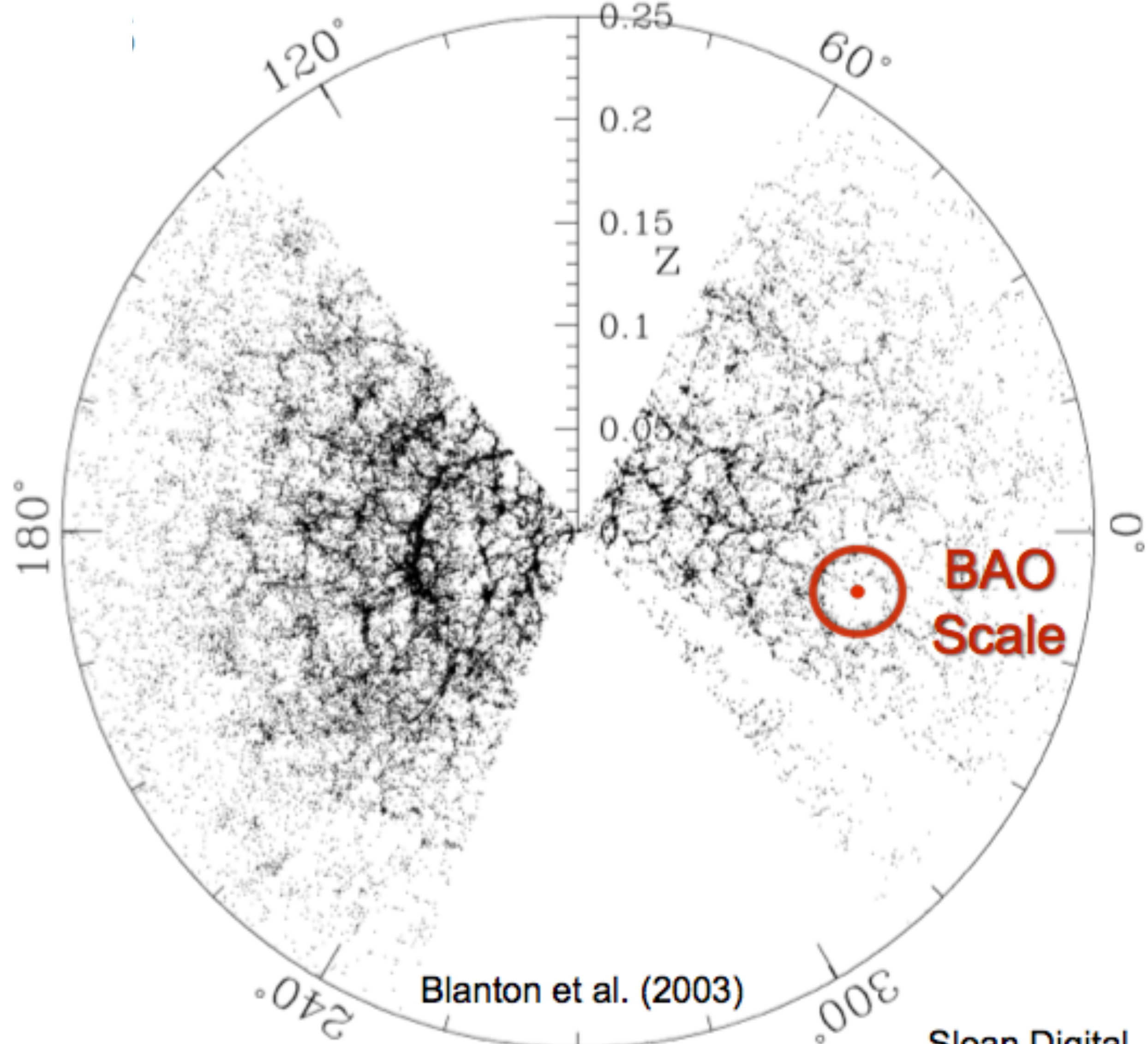
The "vanilla" 6-parameter ΛCDM model is a remarkably good fit to both the WMAP & Planck data.

A detailed analysis of the consistency between WMAP9 & Planck 2013 showed that the ΛCDM parameters had small but significant differences. There are some calibration changes in Planck 2014 that will reduce the discrepancy somewhat, but the details are TBD.

Probing extensions to ΛCDM –
CMB + complementary data sets

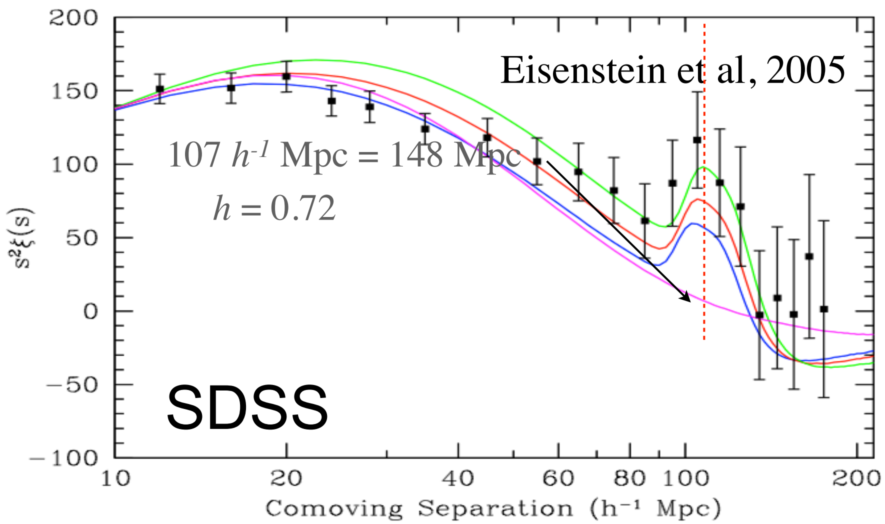
BAO in Galaxy Redshift Surveys

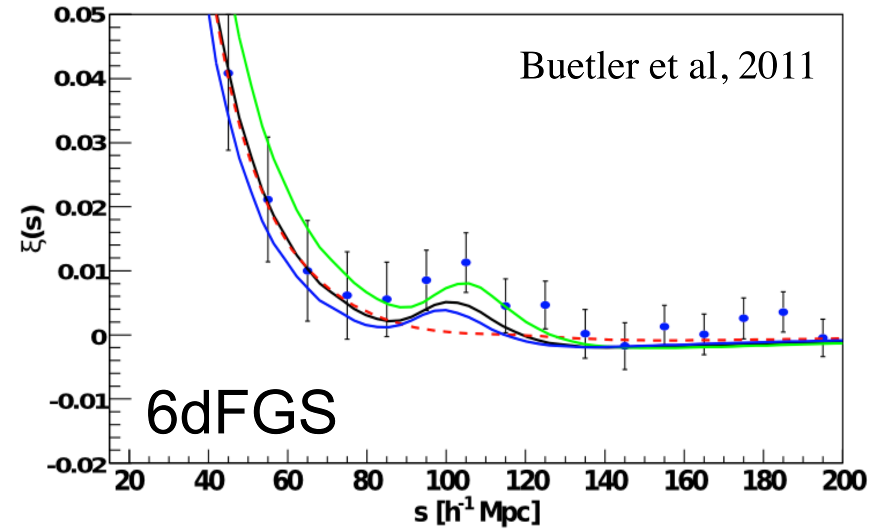
The BAO scale schematically superposed on the SDSS galaxy distribution.

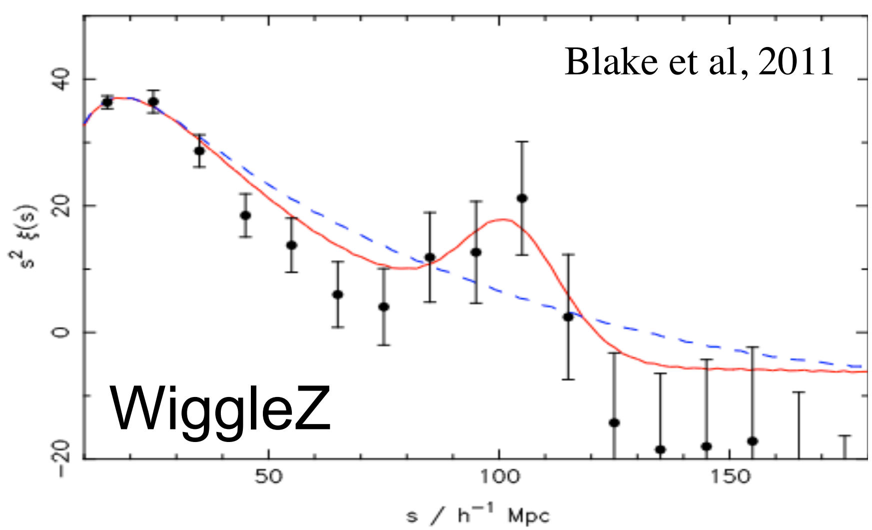


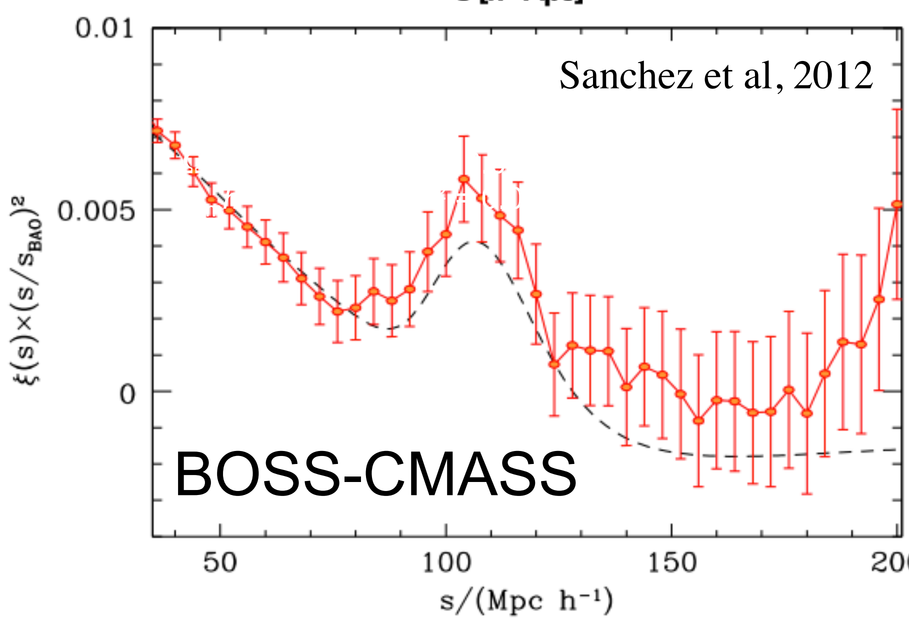
Sloan Digital
Sky Survey (SDSS)

BAO Detections in Galaxy Surveys





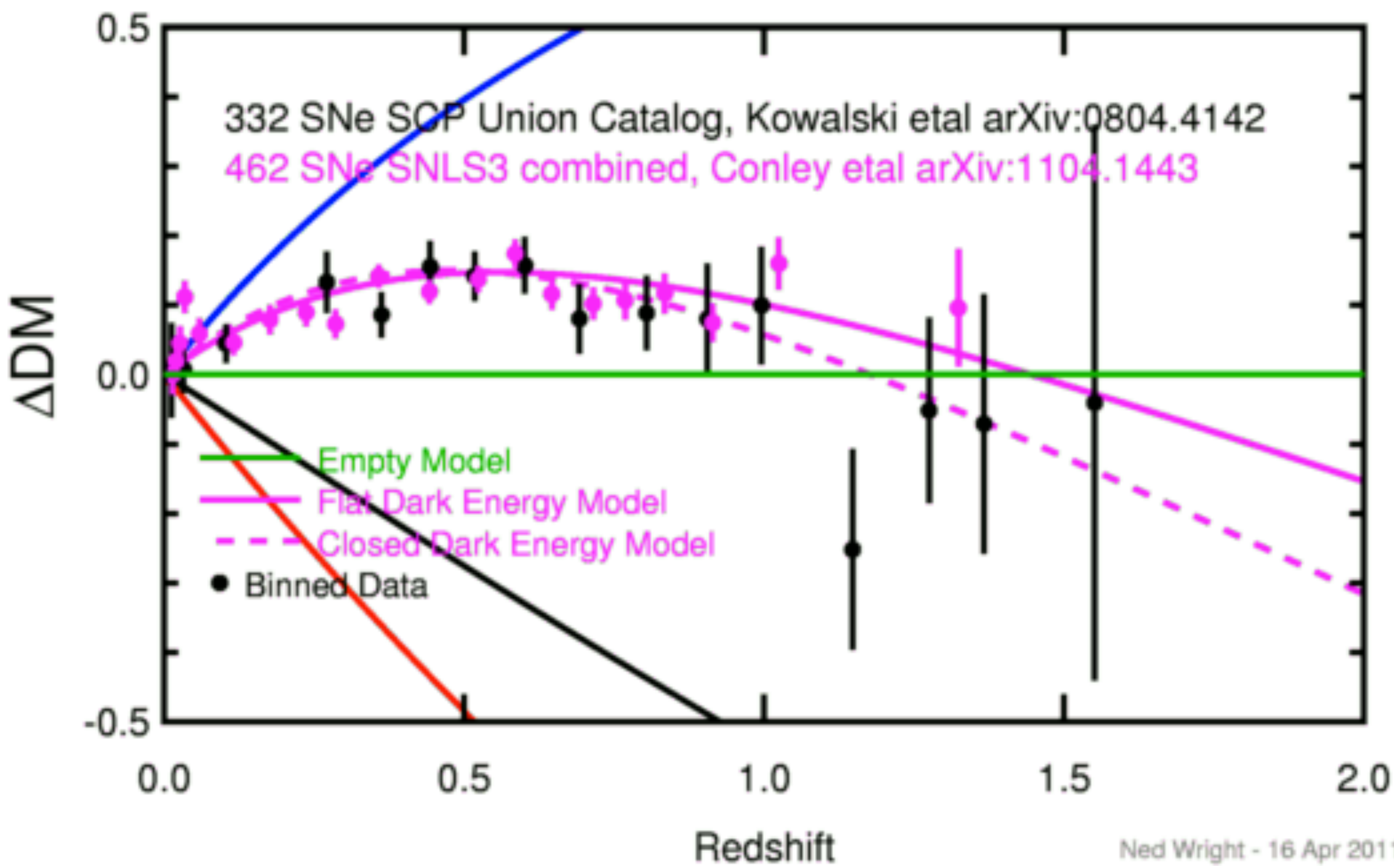




BAO now detected in galaxy redshift surveys from $0.1 < z < 0.8$.

Supernovae Distances & Local Distances

Supernovae distances



Distance ladder

Riess (2014) use revised classical distance ladder techniques to find: $H_0 = 73.0 \pm 2.4$ km/s/Mpc

Tension With H_0

- Riess (2014) used revised classical distance ladder techniques to find:

$$H_0 = 73.0 \pm 2.4 \ \text{km/s/Mpc}$$

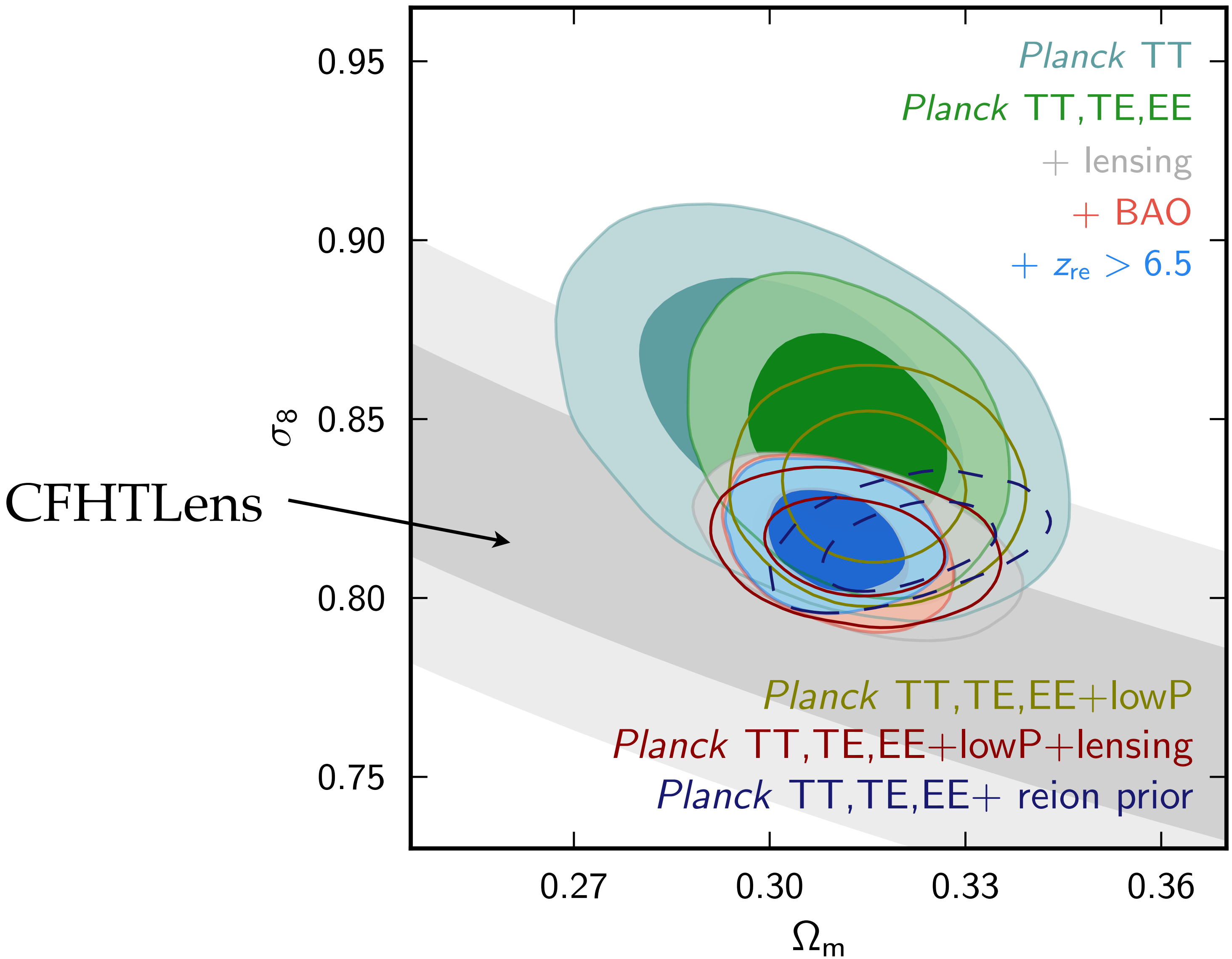
- Planck 2014:

$$H_0 = 67.6 \pm 0.6 \ \text{km/s/Mpc}$$

Efstathiou et al. 2014

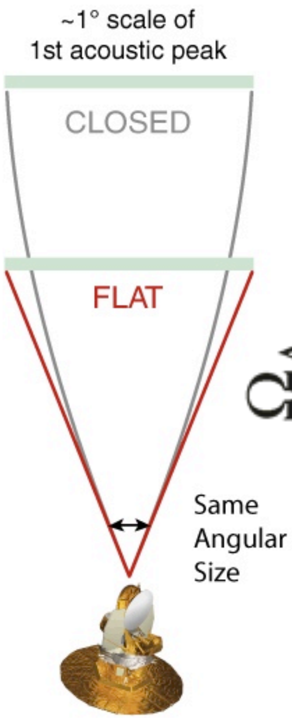
- Tension at the 2.5-sigma level. Important?

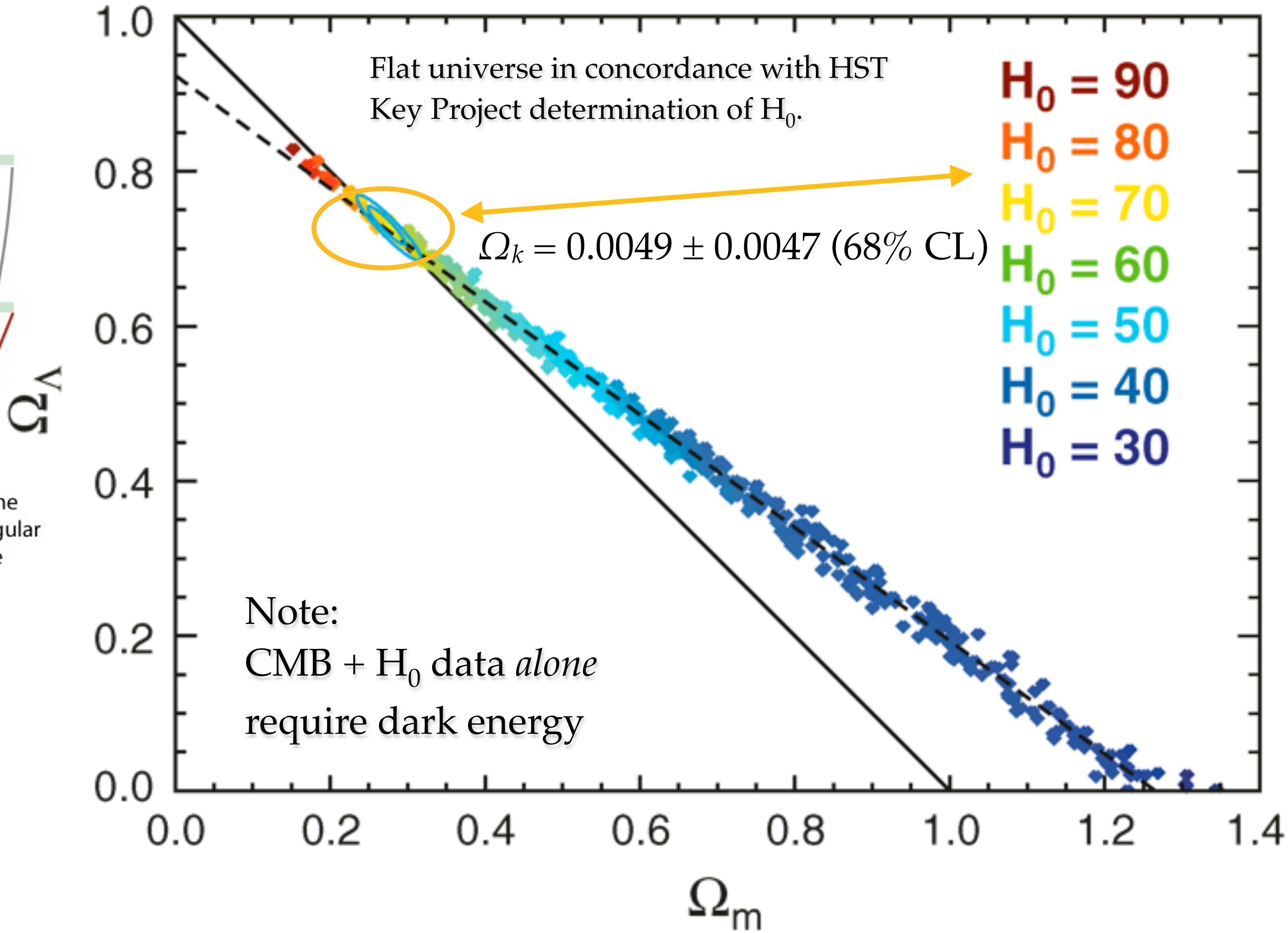
Tension Between Planck & CFHTLens



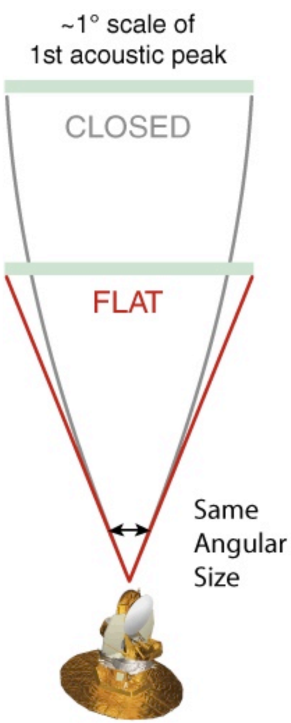
preliminary *Efstathiou et al. 2014*

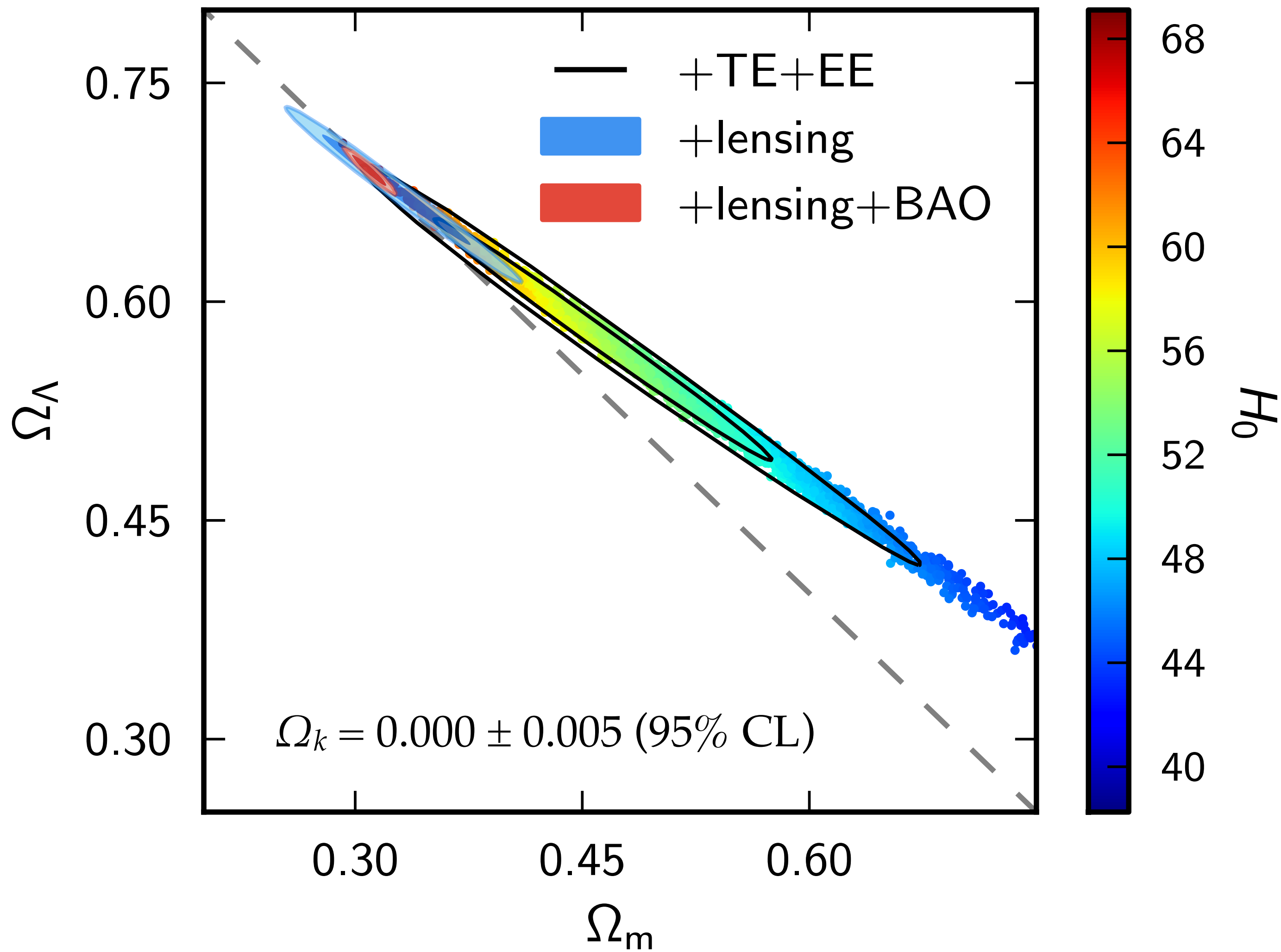
Testing Assumptions: Flatness/WMAP





Testing Assumptions: Flatness/Planck



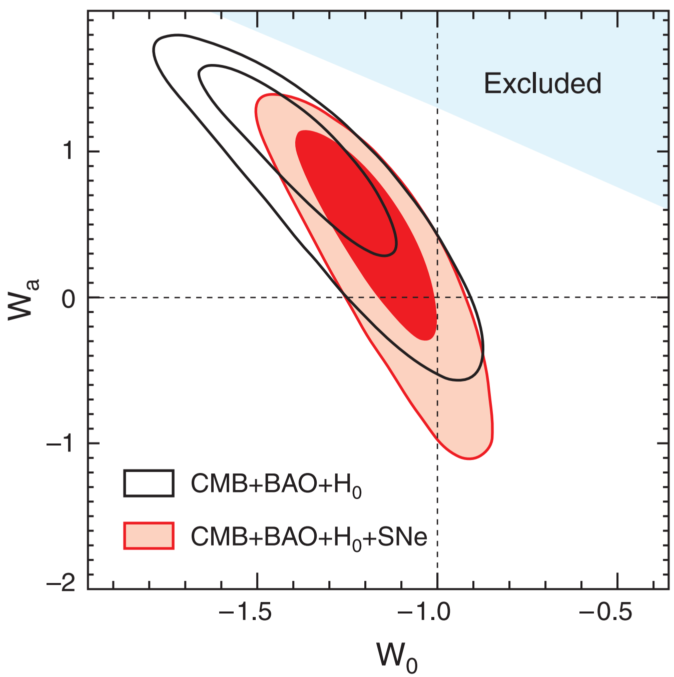


preliminary *Efstathiou et al. 2014*

Testing Assumptions: Dark Energy/WMAP

TABLE 10
Dark energy constraints[a]

Parameter	*WMAP*	+eCMB	+eCMB+BAO+H_0	+eCMB+BAO+H_0+SNe
Constant equation of state; flat universe				
w	$-1.71 < w < -0.34$ (95% CL)	$-1.07^{+0.38}_{-0.41}$	$-1.073^{+0.090}_{-0.089}$	$-1.037^{+0.071}_{-0.070}$
Constant equation of state; non-flat universe				
w	> -2.1 (95% CL)	$\cdots$	-1.19 ± 0.12	-1.077 ± 0.072
Ω_k	$-0.052^{+0.051}_{-0.054}$	$\cdots$	$-0.0072^{+0.0042}_{-0.0043}$	-0.0065 ± 0.0040
Non-constant equation of state; flat universe				
w_0	$\cdots$	$\cdots$	-1.34 ± 0.18	$-1.17^{+0.13}_{-0.12}$
w_a	$\cdots$	$\cdots$	0.85 ± 0.47[b]	$0.35^{+0.50}_{-0.49}$



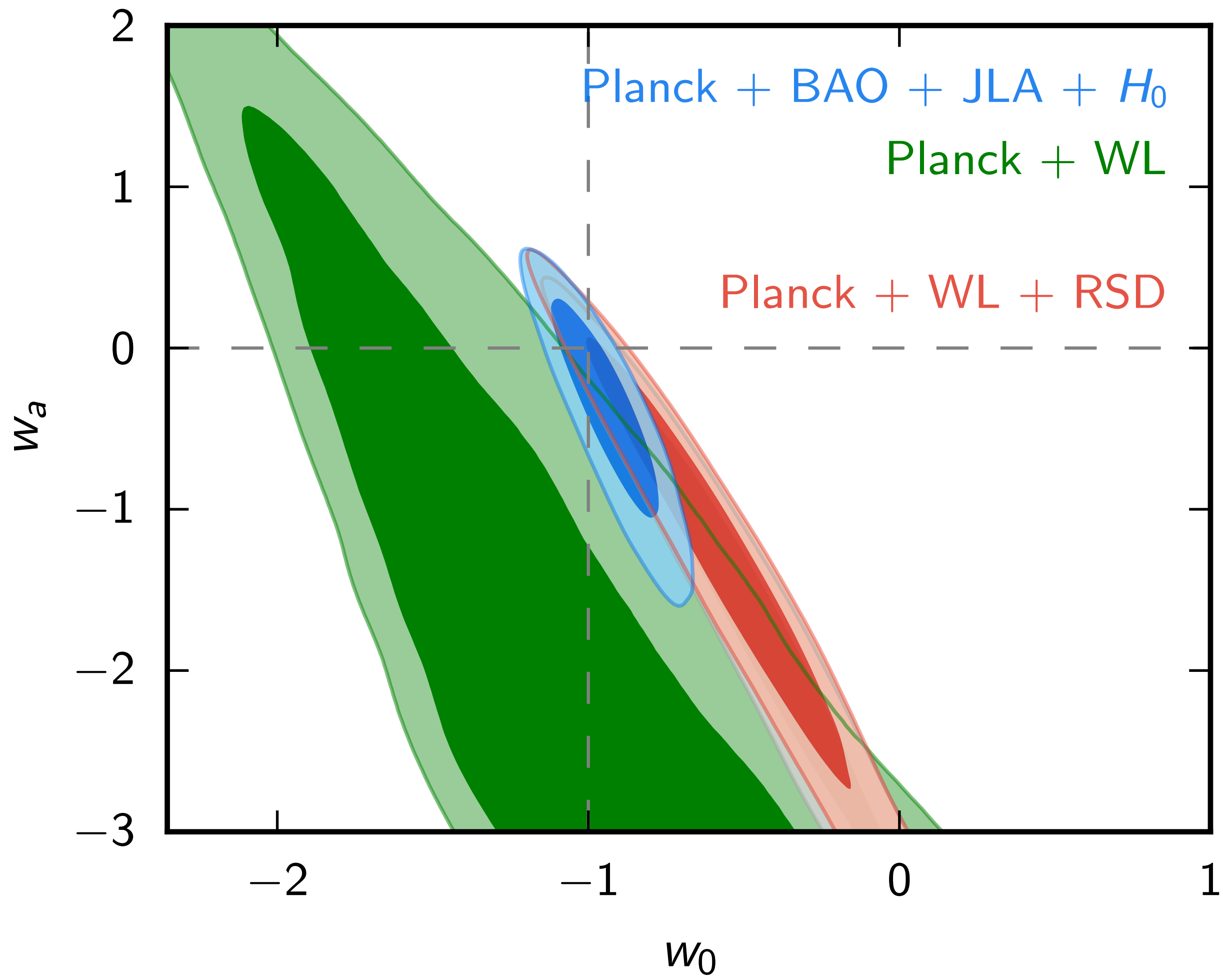
Meaningful constraints require very accurate low redshift distance measurements, *d(z)*.

All constraints consistent with Λ ($w = -1$).

Constraints on *w(z)* still weak (*left*) – more data needed, e.g., EUCLID, CHIME.

Testing Assumptions: Dark Energy/Planck

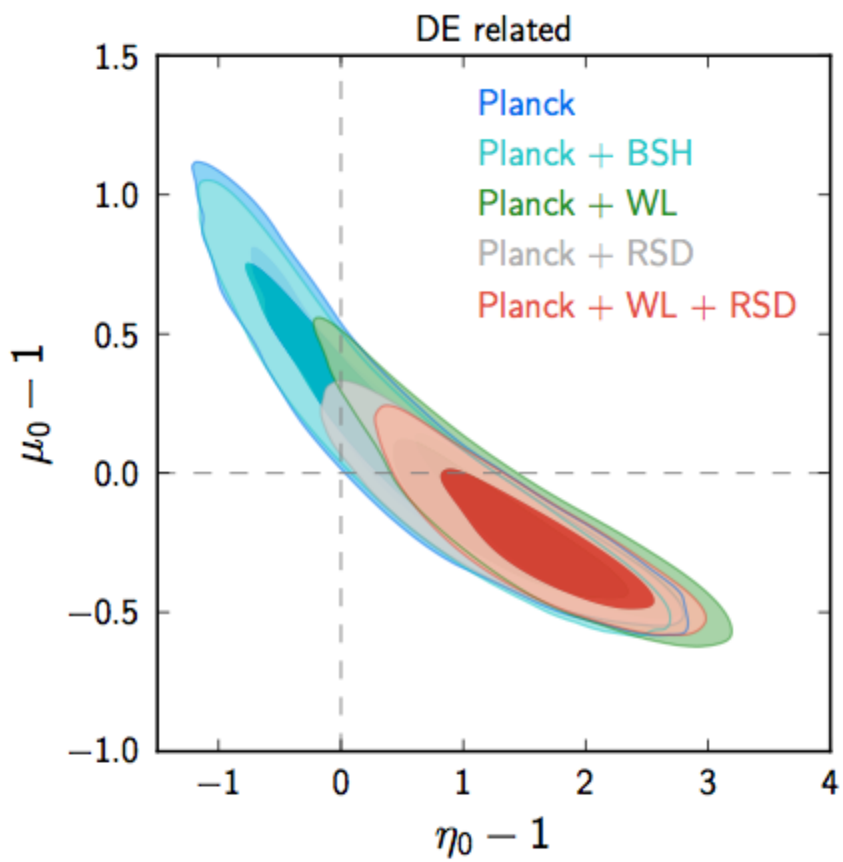
$$w(a) = w_0 + (1-a)w_a$$



preliminary *Efstathiou et al. 2014*

Testing Modified Gravity with Planck

Modified gravity: μ modifies gravitational potential, η is the ratio of the potentials Φ and Ψ.



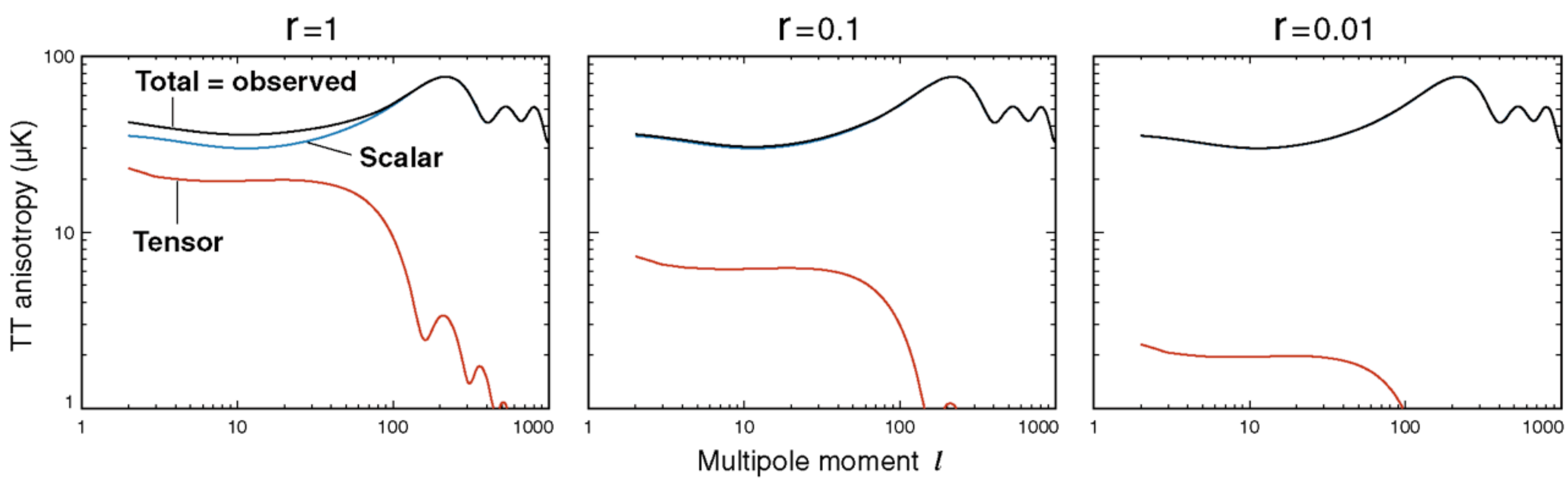
preliminary *Efstathiou et al. 2014*

Inflation and Gravity Waves – I

- Inflation predicts two forms of fluctuations:
- Scalar modes (density perturbations) with slope n_s:
    - generate CMB anisotropy and lead to structure formation
- Tensor modes (gravity waves) with slope n_t:
    - generate CMB anisotropy but do not contribute to structure formation
- Gravity wave amplitude, r, proportional to energy scale of inflation:

$$\boxed{r^{1/4} \propto \frac{V_\phi^{1/4}}{m_{pl}} = \frac{E_{\rm infl}}{3.3\times10^{16}\,{\rm GeV}} \quad \text{with} \quad r \equiv \frac{P(k_0)_{tensor}}{P(k_0)_{scalar}}}$$

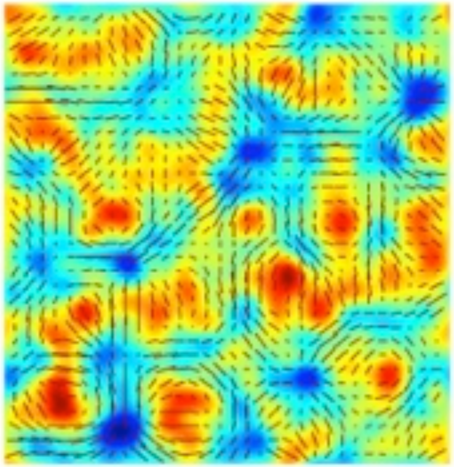
- Both types of fluctuations contribute to CMB temperature anisotropy:

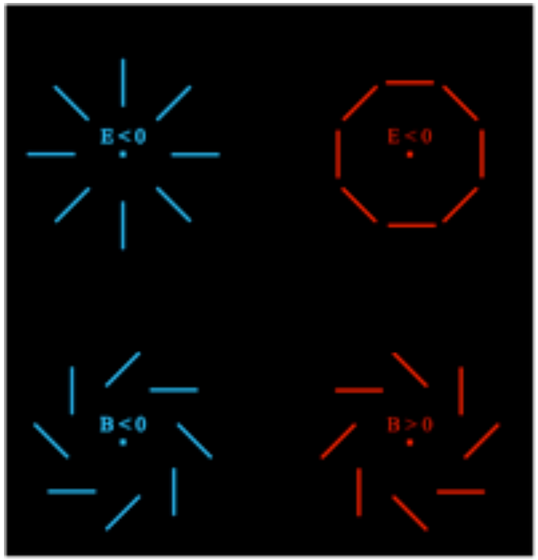


Inflation and Gravity Waves – II

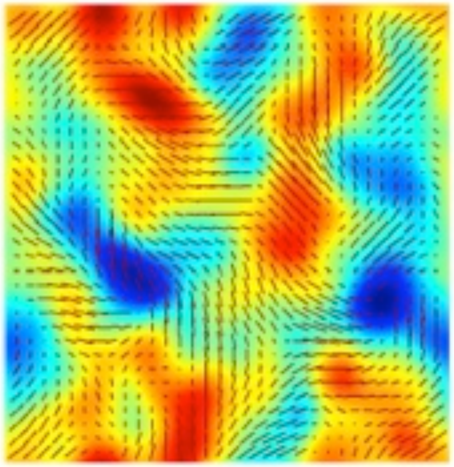
- Both types of fluctuations contribute to CMB polarization anisotropy:
  - Scalar modes produce only "E-mode" polarization patterns, by symmetry
  - Tensor modes produce both "E-mode" and "B-mode" polarization patterns (see below)
- The observation of B-mode polarization uniquely separates scalar and tensor modes from inflation and measures the energy scale of inflation.
- *Only* known probe of physics at E ~ 10^{16} GeV… *12 orders of magnitude higher than planned accelerators.*

E – scalar+tensor

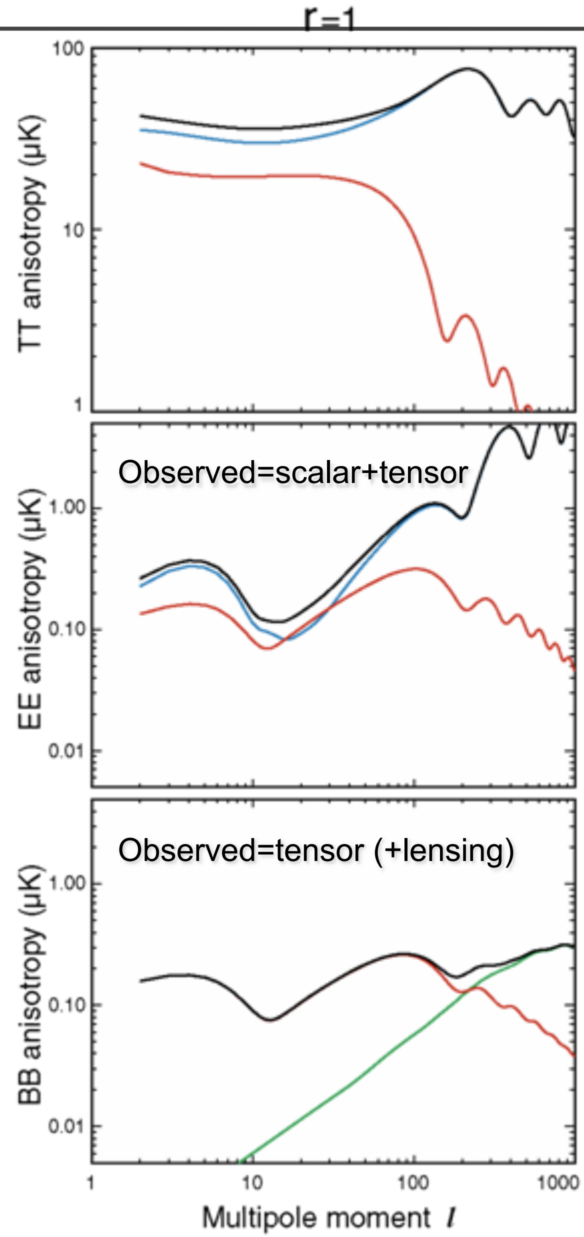




B – tensor only



Predicted Polarization Spectra, r=1.0

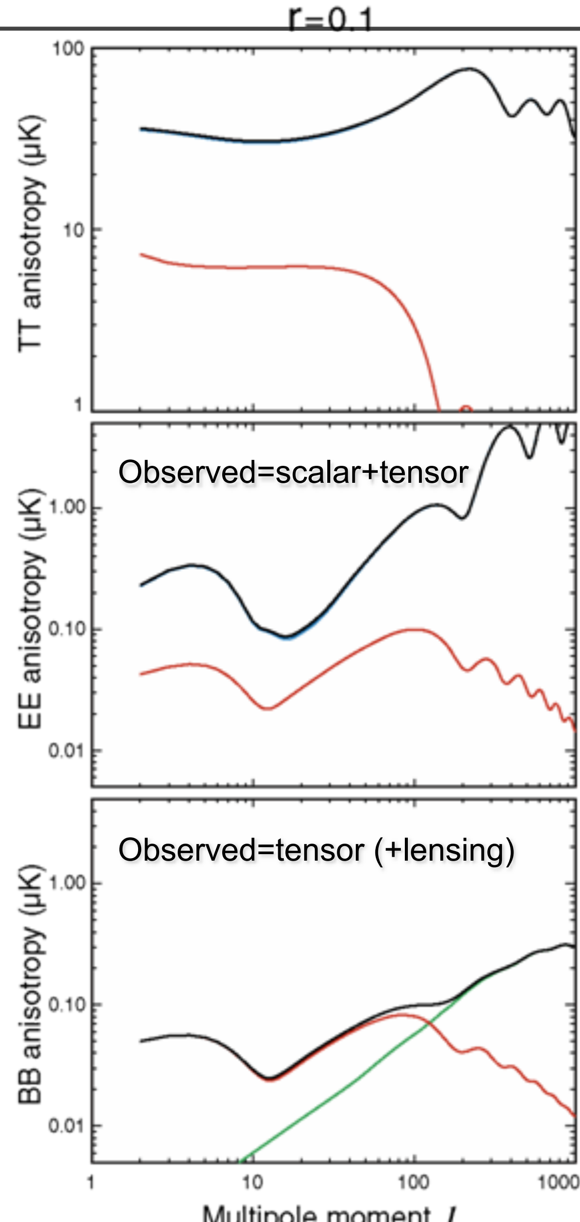


Temperature spectrum
(as before)

E-mode polarization spectrum,
scalar (blue) & tensor (red) terms

B-mode polarization spectrum,
tensor (red) & gravitational lensing (green)
terms

Predicted Polarization Spectra, r=0.1

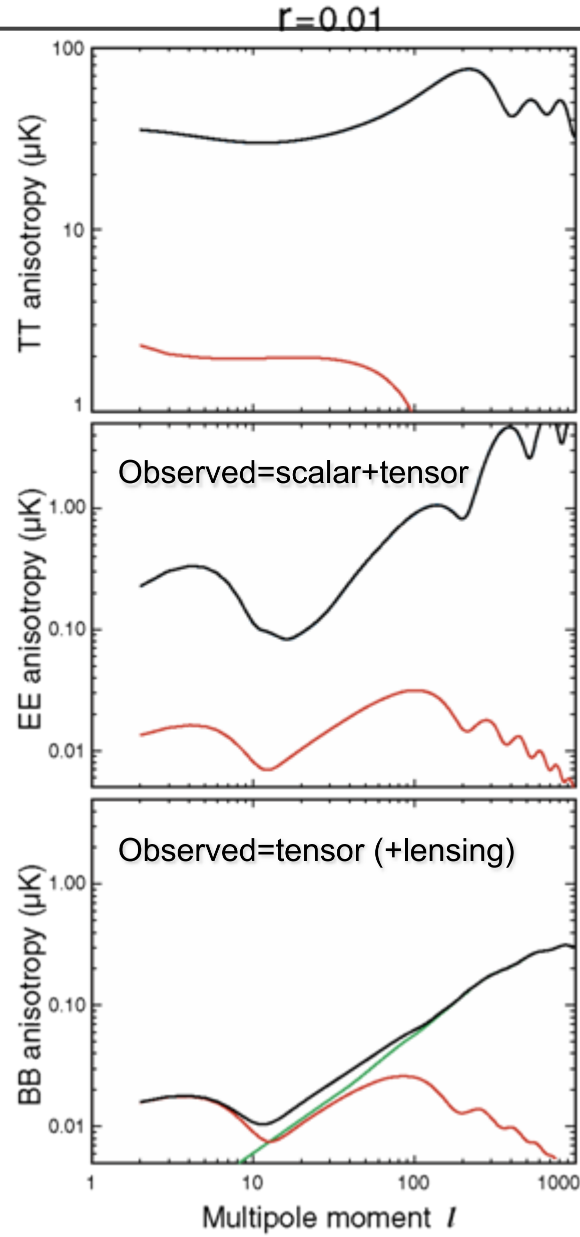


Temperature spectrum
(as before)

E-mode polarization spectrum,
scalar (blue) & tensor (red) terms

B-mode polarization spectrum,
tensor (red) & gravitational lensing (green)
terms

Predicted Polarization Spectra, r=0.01

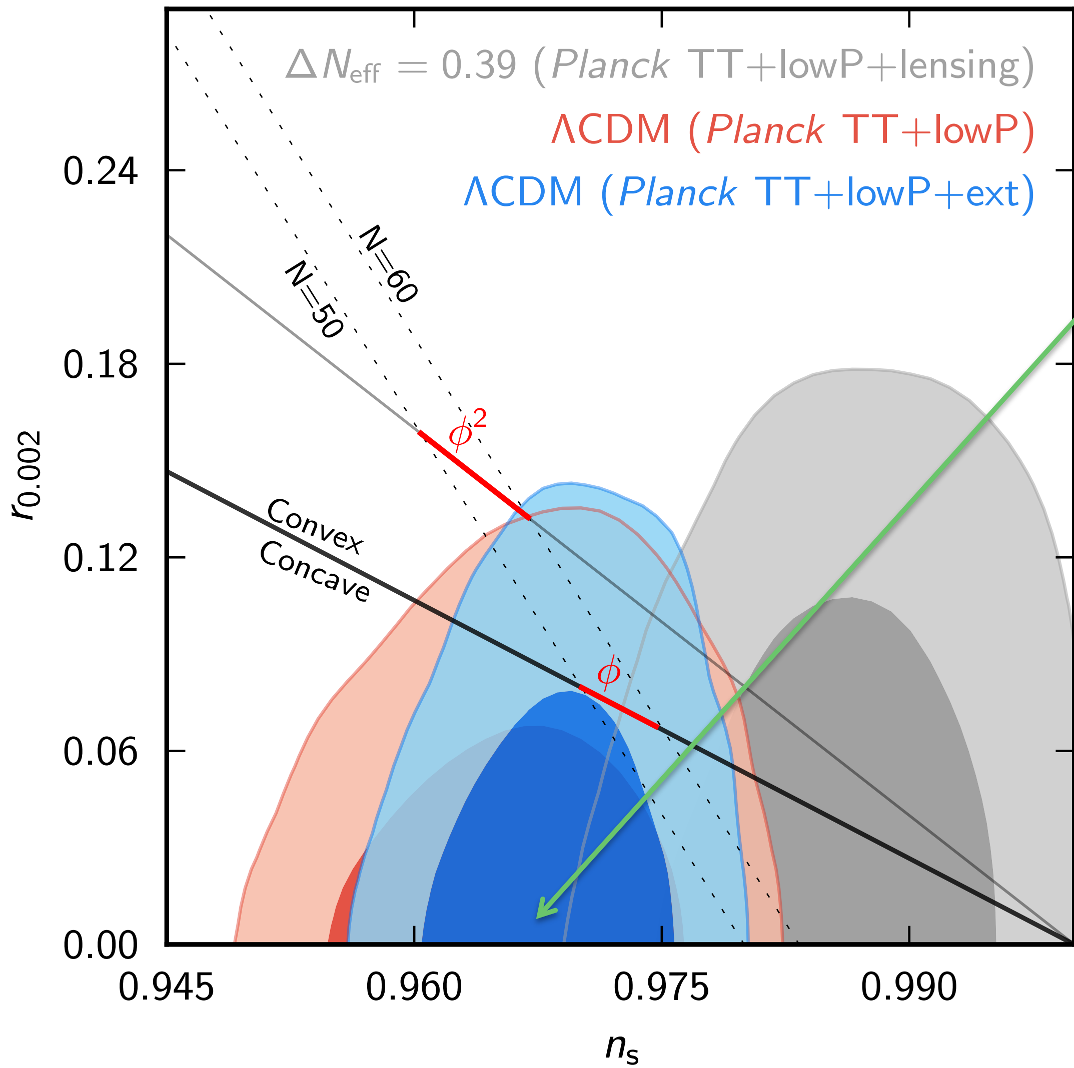


Temperature spectrum
(as before)

E-mode polarization spectrum,
scalar (blue) & tensor (red) terms

B-mode polarization spectrum,
tensor (red) & gravitational lensing (green)
terms

Planck Limits on Inflation Parameters



preliminary *Efstathiou et al. 2014*

Starobinsky (R^2) inflation

$n_s \approx 1 - 2/N \approx 0.967$

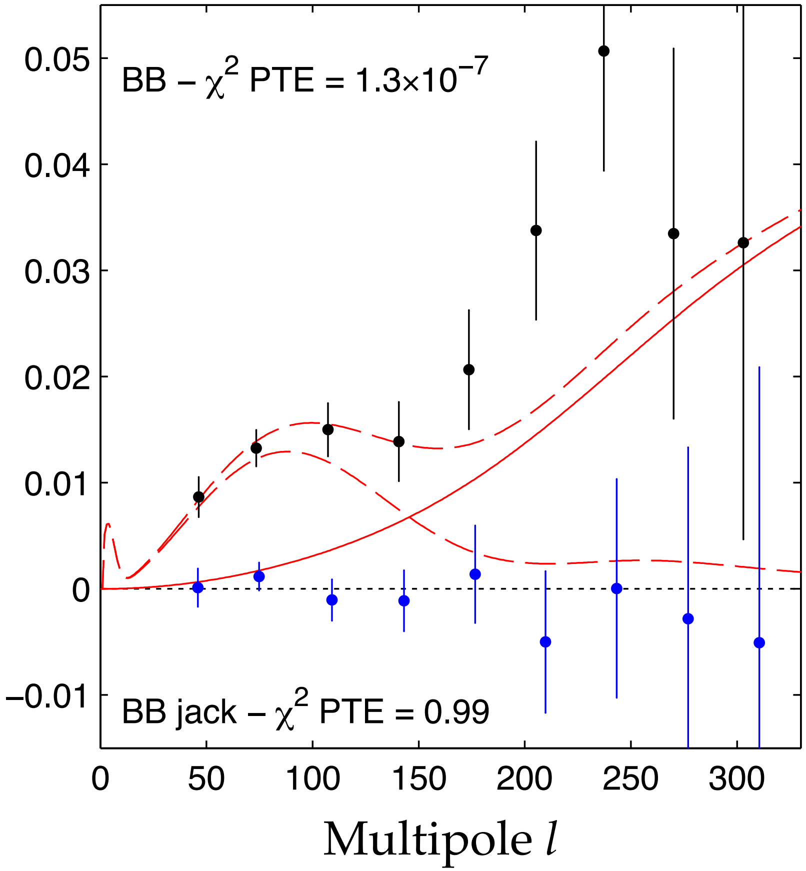
$r \approx 12/N^2 \approx 0.0033$

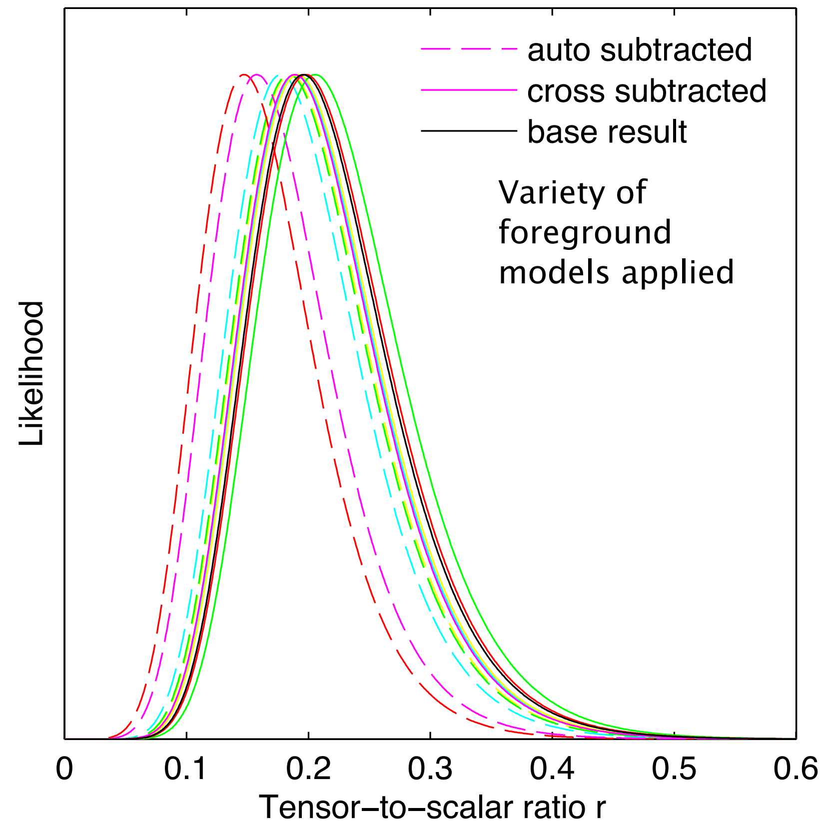
$dn_s/d\ln k \approx -2/N^2 \approx -0.0006$

…… but, there is plenty of room at the top

(and to the side!)

BICEP2 – Polarization @ 150 GHz





The BICEP2 team reports detection of B-mode polarization (right) and argues that it *cannot* be explained by foreground emission from synchrotron or dust (right).

Big surprise: $r \approx 0.2$, higher than the limit reported by WMAP & Planck: ($r < 0.12$).

Planck & BICEP2 – I

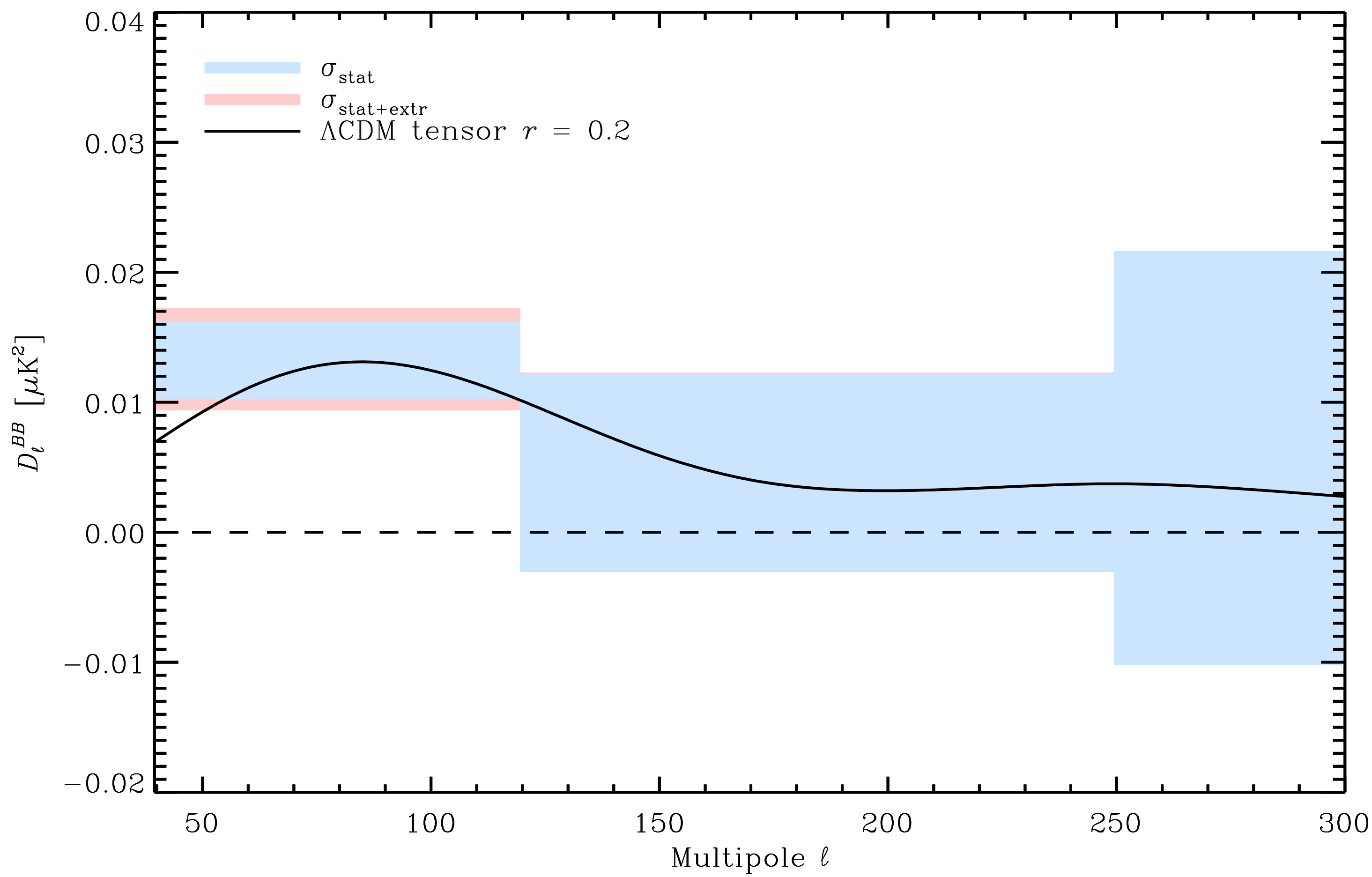
Planck intermediate results. XXX. The angular power spectrum of polarized dust emission at intermediate and high Galactic latitudes

Galactic latitudes with low dust column densities. We show that even in the faintest dust-emitting regions there are no "clean" windows in the sky where primordial CMB B-mode polarization measurements could be made without subtraction of foreground emission. Finally, we investigate the level of dust polarization in the specific field recently targeted by the BICEP2 experiment. Extrapolation of the *Planck* 353 GHz data to 150 GHz gives a dust power $\mathcal{D}_\ell^{BB} \equiv \ell(\ell+1)C_\ell^{BB}/(2\pi)$ of $1.32 \times 10^{-2}\,\mu\mathrm{K}^2_{\mathrm{CMB}}$ over the multipole range of the primordial recombination bump ($40 < \ell < 120$); the statistical uncertainty is $\pm 0.29 \times 10^{-2}\,\mu\mathrm{K}^2_{\mathrm{CMB}}$ and there is an additional uncertainty $(+0.28, -0.24) \times 10^{-2}\,\mu\mathrm{K}^2_{\mathrm{CMB}}$ from the extrapolation. This level is the same magnitude as reported by BICEP2 over this ℓ range, which highlights the need for assessment of the polarized dust signal even in the cleanest windows of the sky. The present uncertainties are large and will be reduced through an ongoing, joint analysis of the *Planck* and BICEP2 data sets.

"...We show that even in the faintest dust-emitting regions there are no "clean" windows in the sky where primordial CMB B-mode polarization measurements could be made without subtraction of foreground emission."

"...This level is the same magnitude as reported by BICEP2 over this l range, which highlights the need for assessment of the polarized dust signal even in the cleanest windows of the sky. "

Planck & BICEP2 – II



Blue boxes - 353 GHz BB dust spectrum extrapolated to 150 GHz (BICEP2 band) with 1σ uncertainties (pink includes systematic errors). Black curve is an r=0.2 ΛCDM model spectrum....

Future Observations

CMB experiments (not exhaustive!):

BICEP/Keck, SPIDER, ABS, CLASS - large-scale polarization, B-mode.

SPT 3G, Advanced ACT ("stage IV") - high resolution temperature & polarization.

LiteBIRD, CoRE, PIXIE - large-scale polarization from space.

Large-scale structure (weak lensing, BAO, and/or SNe):

EUCLID, WFIRST - WL, BAO (SNe?) from space

LSST - ground-based large-scale structure (and more). Weak lensing.

DESI - galaxy redshift survey (BAO).

CHIME - 21 cm large-scale structure (BAO).

Conclusions

ΛCDM is in remarkably solid shape

Some mild tensions exist between data sets, e.g. H_0 (CMB vs. distance ladder) and σ_8 (CMB vs. low-redshift probes).

Hints of tensors are tantalizing. More progress expected soon.

Many probes of dark energy (vis large-scale structure) are underway.

Depending on nature's whims, fundamental progress may be difficult!


COSMOLOGY MARCHES ON
Where did it all come from?
Where did it all come from?
s. harris

The End