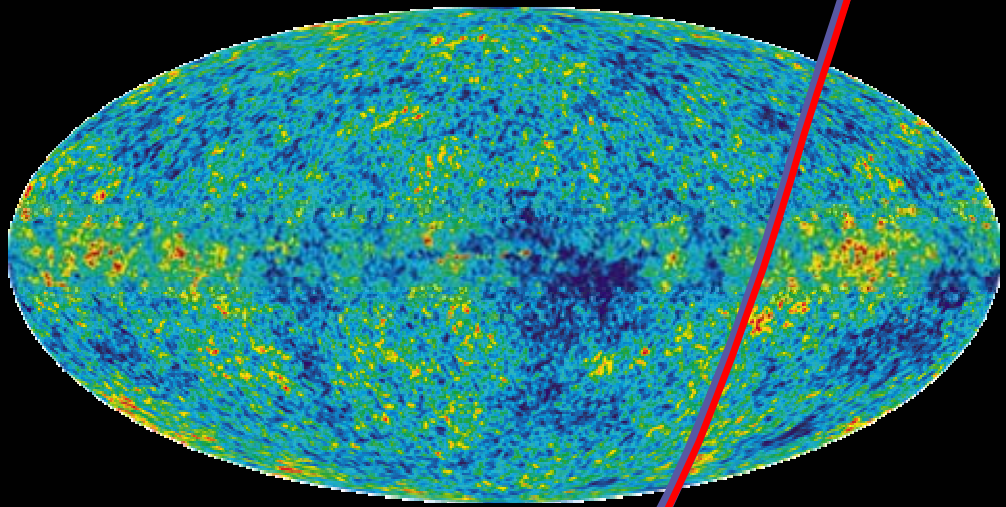
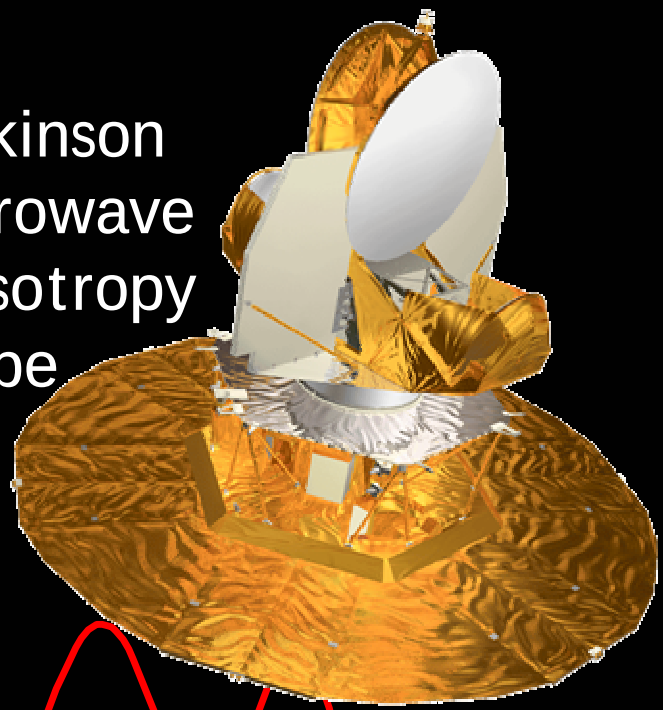
FIRST RESULTS FROM THE WMAP MISSION



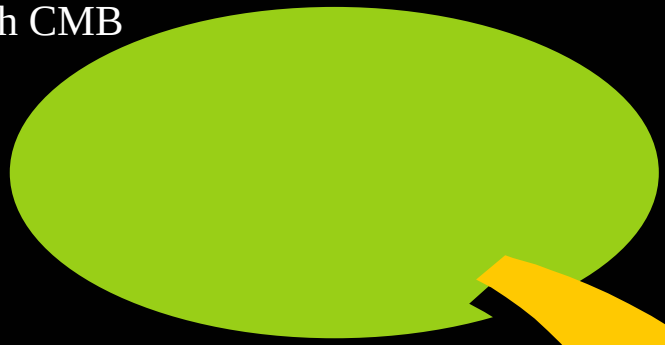
Wilkinson
Microwave
Anisotropy
Probe



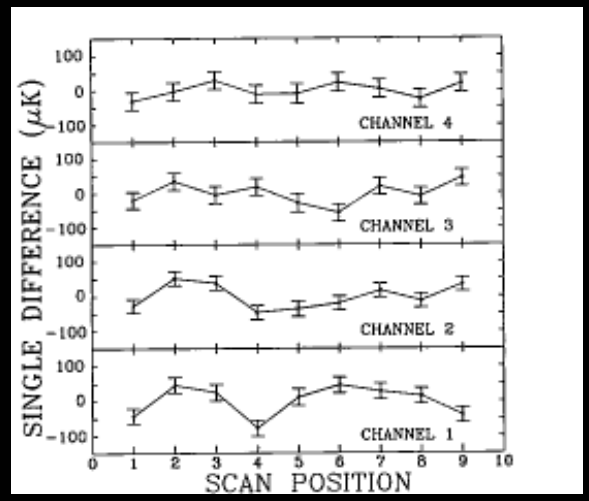
Al Kogut
Goddard Space Flight Center

1980's: Cosmology in Crisis?

Smooth CMB

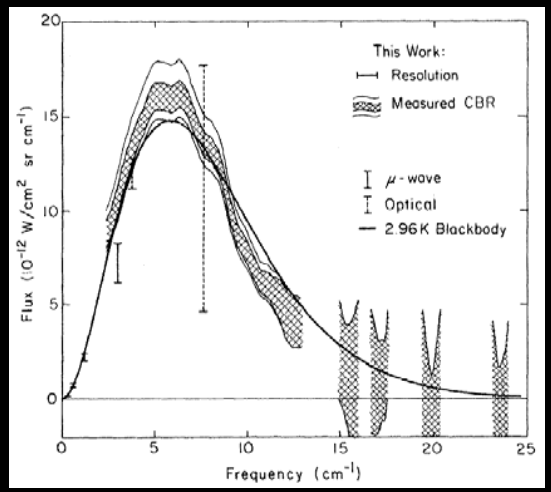


???



No sign of predicted anisotropy

???



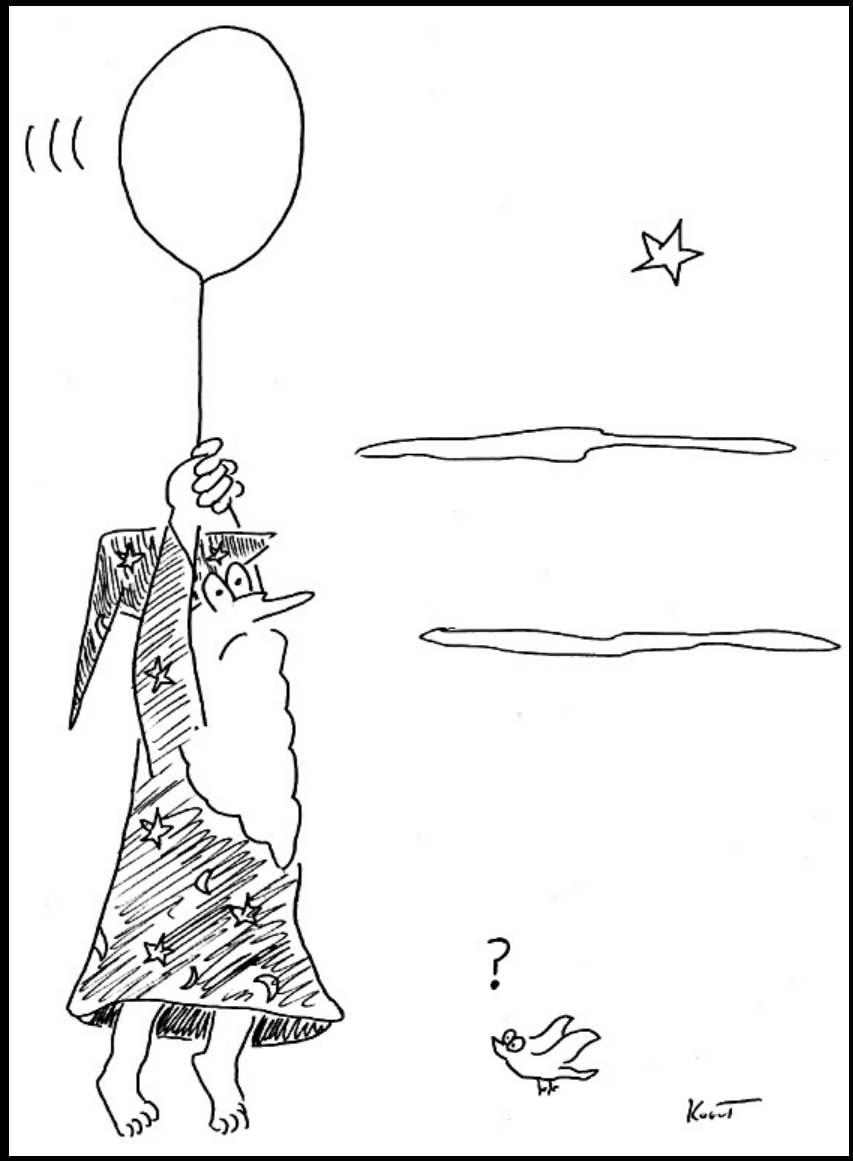
Hints of non-blackbody spectra

?

Clumpy Galaxies

The Problem With Ground-Based Cosmology

Balloons Have Problems, Too ...



… But In Space, You Can Let It All Hang Out

COSMIC BACKGROUND EXPLORER (COBE)

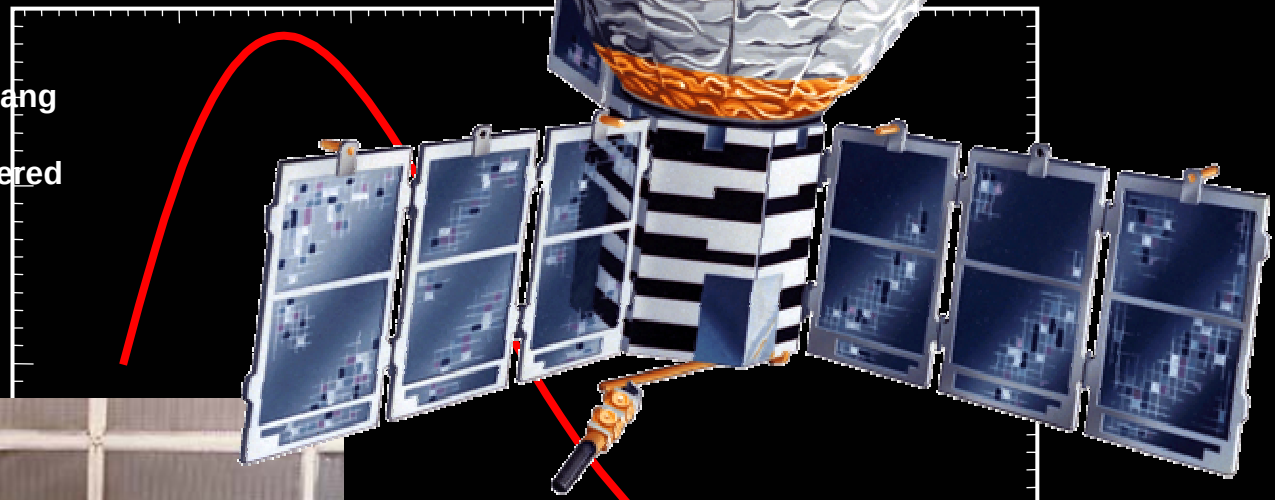
1974 COBE proposed
Spacecraft & all 3 instruments built at Goddard

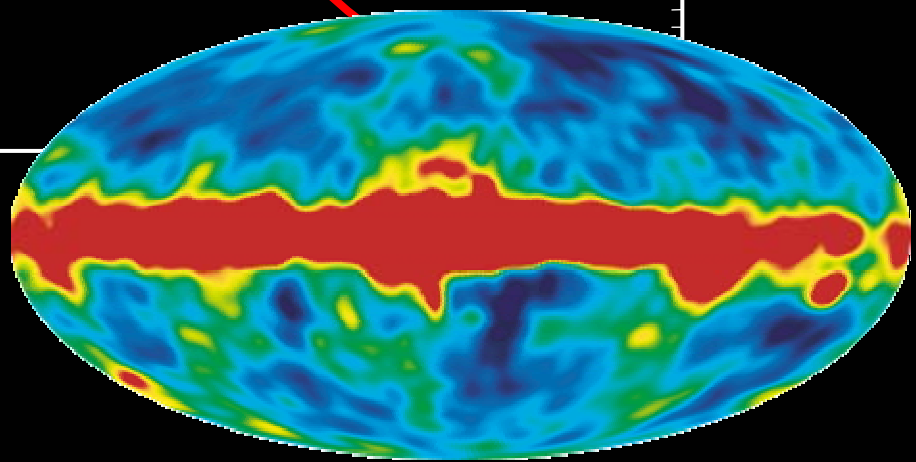
1989 COBE Launched

1990 Spectrum confirms Hot Big Bang

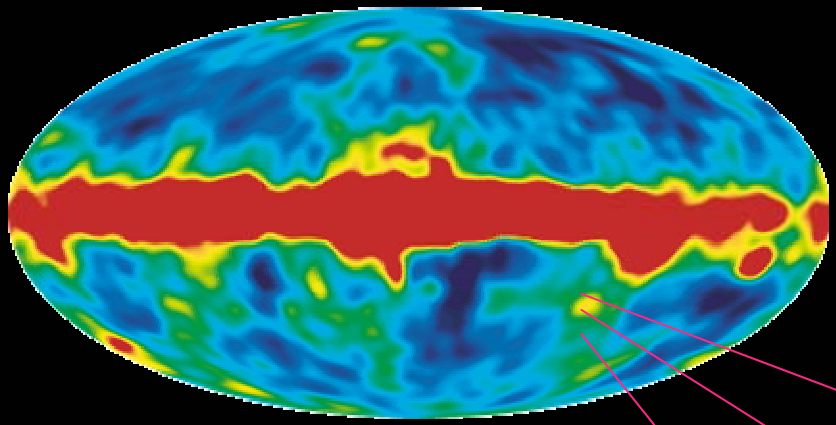
1992 Primordial anisotropy discovered

Confirms gravity + seeds as source of structure





Motivation for WMAP



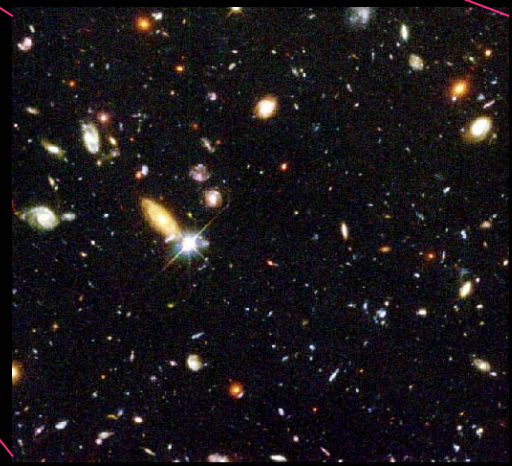
Cold Dark Matter Models:

Open? Closed?

Dark matter?

Dark Energy?

THEORY



Being close but wrong might mean that we are close,
But might equally well mean that we are wrong.
-- Ed Turner

Wilkinson Microwave Anisotropy Probe

Science Team

GODDARD

Charles Bennett (P.I.)
Robert Hill
Gary Hinshaw
Al Kogut
Michele Limon
Nils Odegard
Janet Weiland
Edward Wollack

PRINCETON U.

Chris Barnes
Norman Jarosik
Eiichiro Komatsu
Micheal Nolta
Lyman Page
Hiranya Peiris
David Spergel
Licia Verde

U. CHICAGO

Stephan Meyer

U. BRIT COLUMBIA

Mark Halpern

UCLA

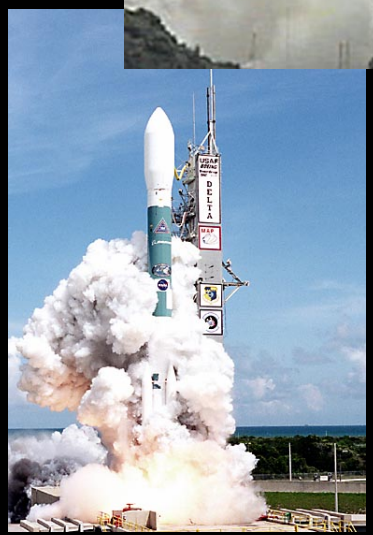
Edward Wright

BROWN U.

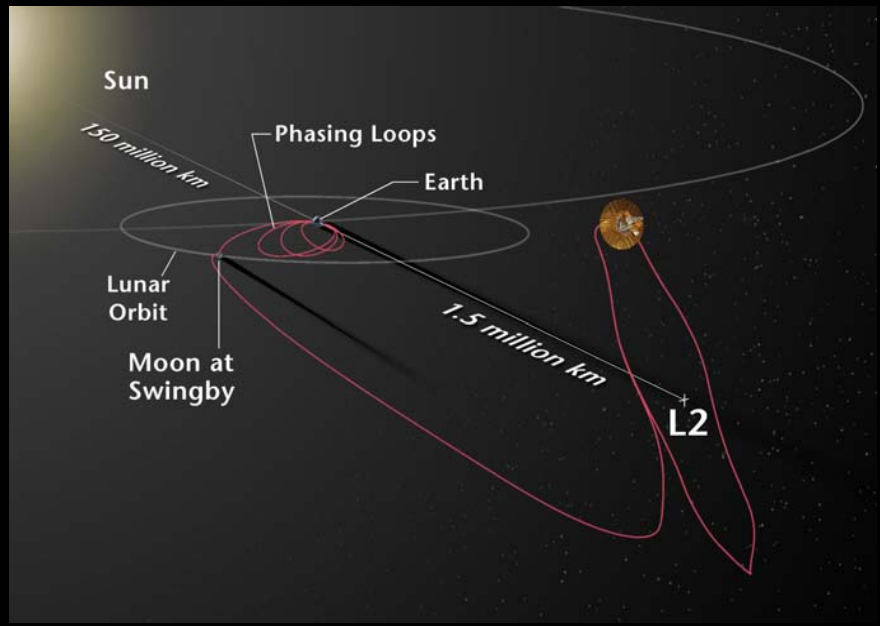
Greg Tucker

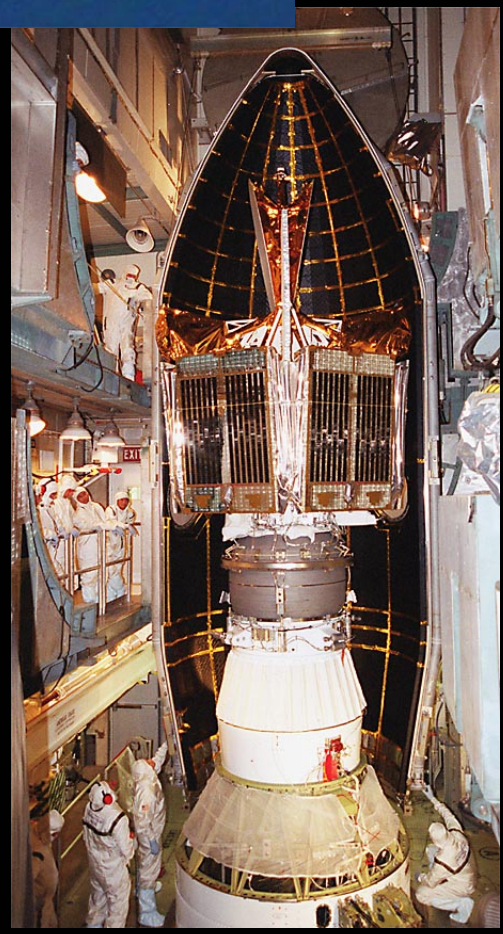
Prof. David T. Wilkinson
1935 - 2002

WMAP Launch



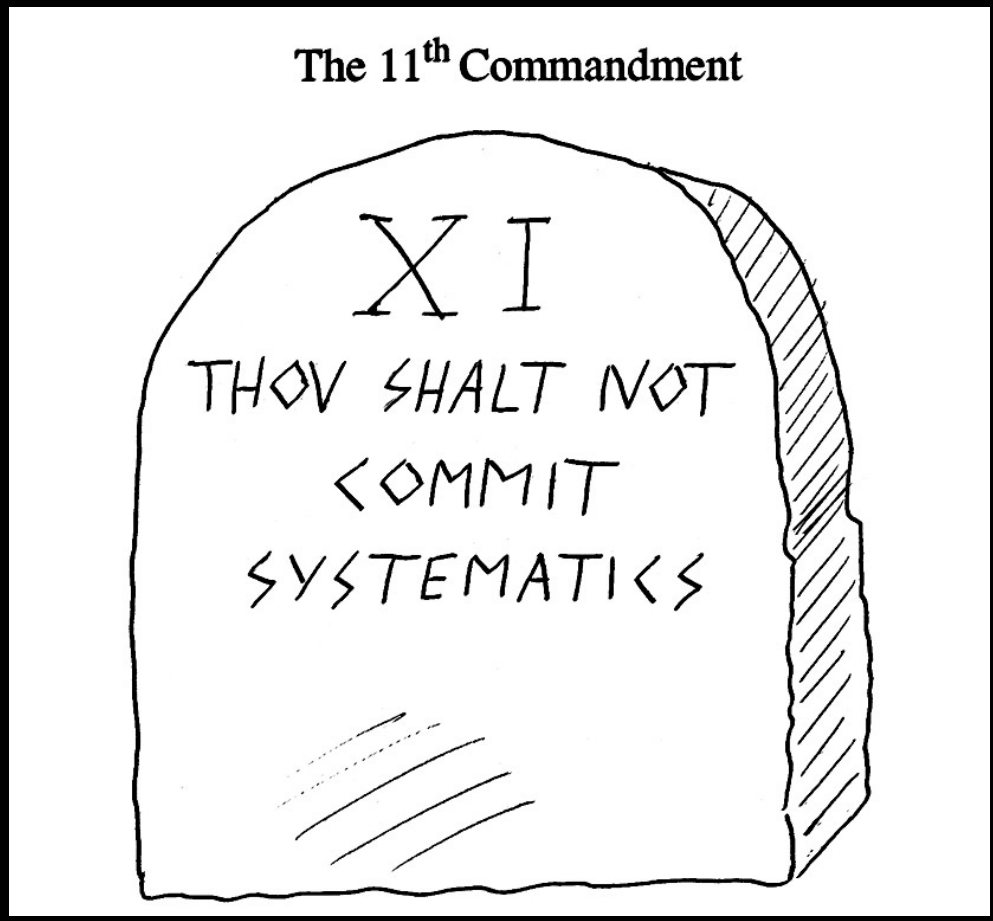
Launch June 30, 2001
3-Month Cruise to L2



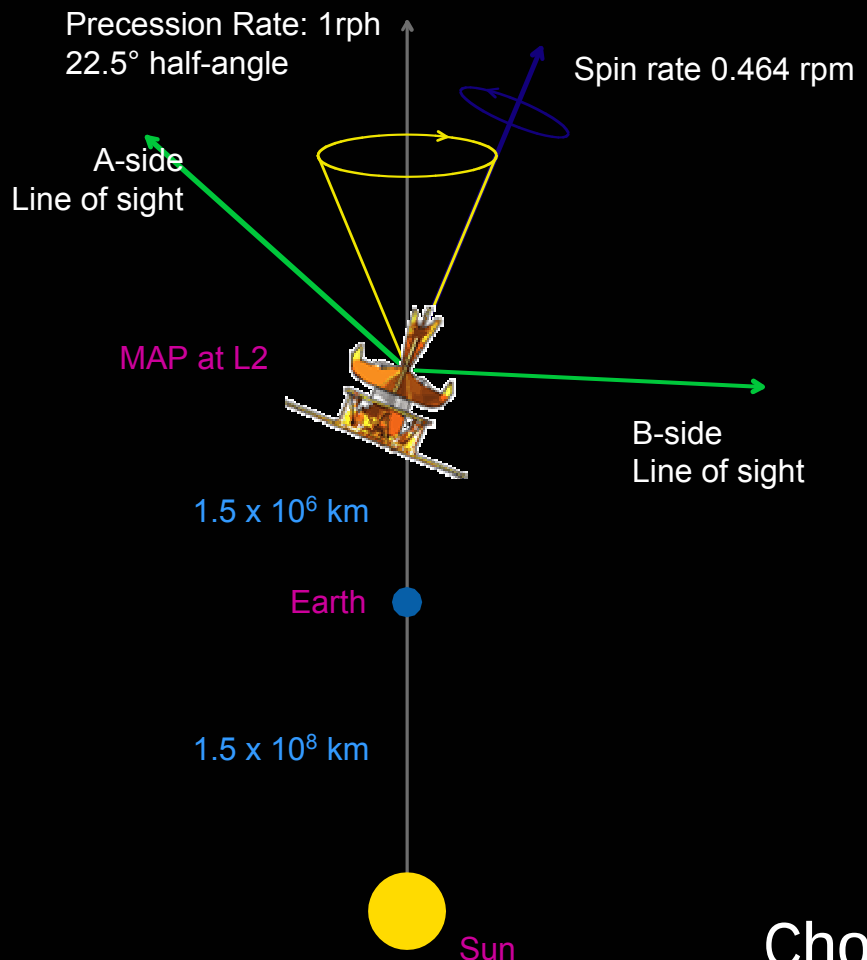


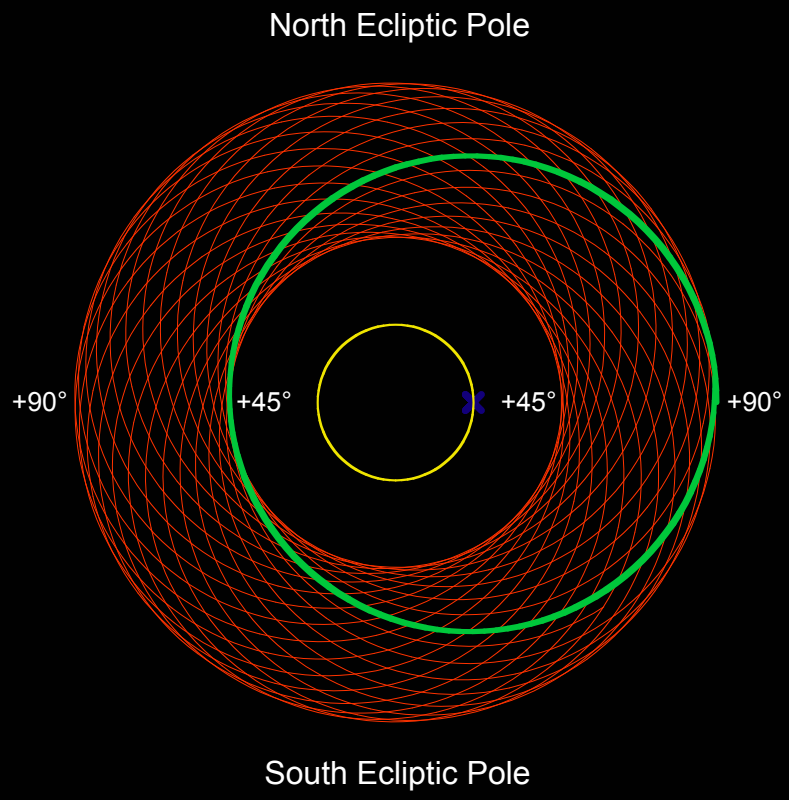
WMAP Design Strategy

- Differential Optics
- Multiple Frequencies
- Multiple Channels
- Interleaved Scan Pattern
- Stable Calibration
- L2 Orbit Far From Earth



Spin Precession and Sky Coverage



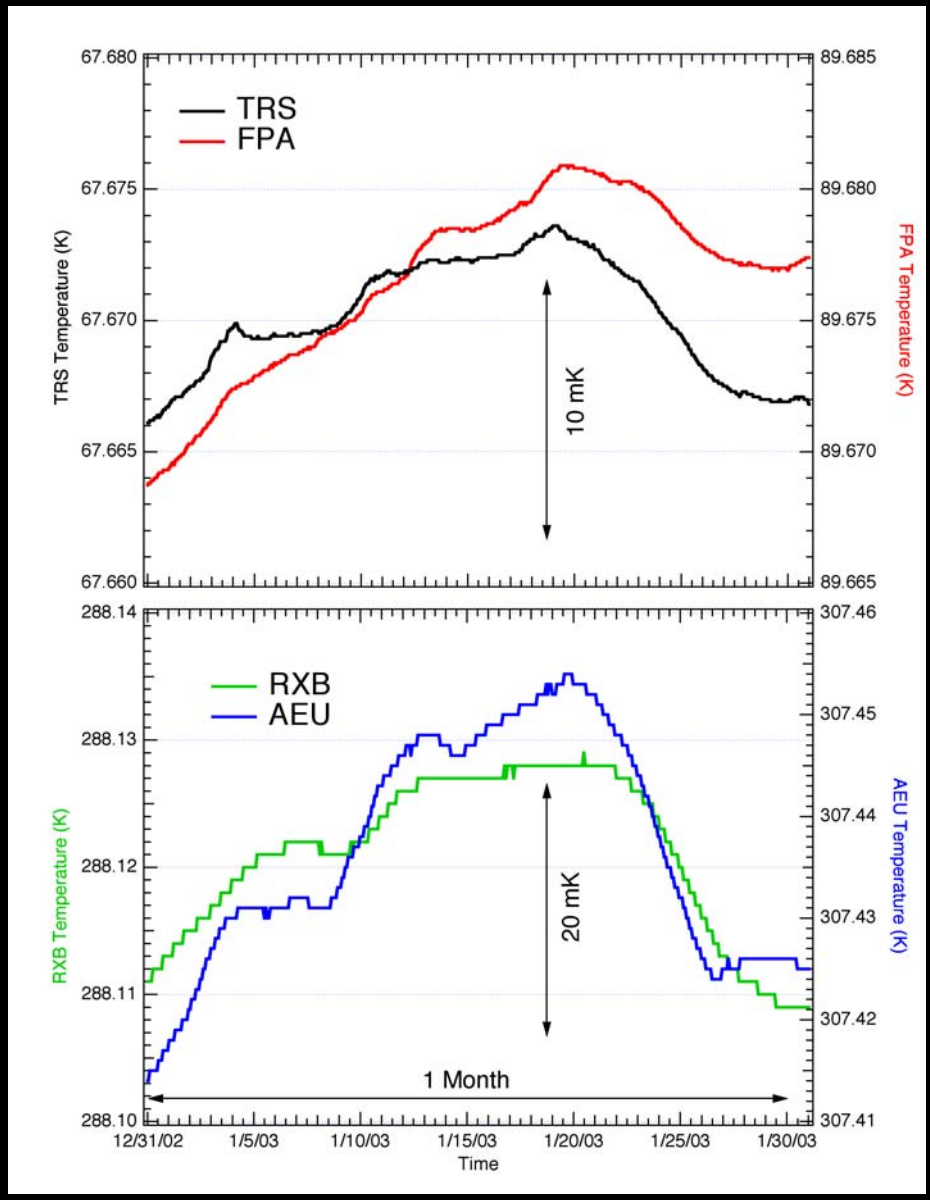


Chop at Multiple Time Scales

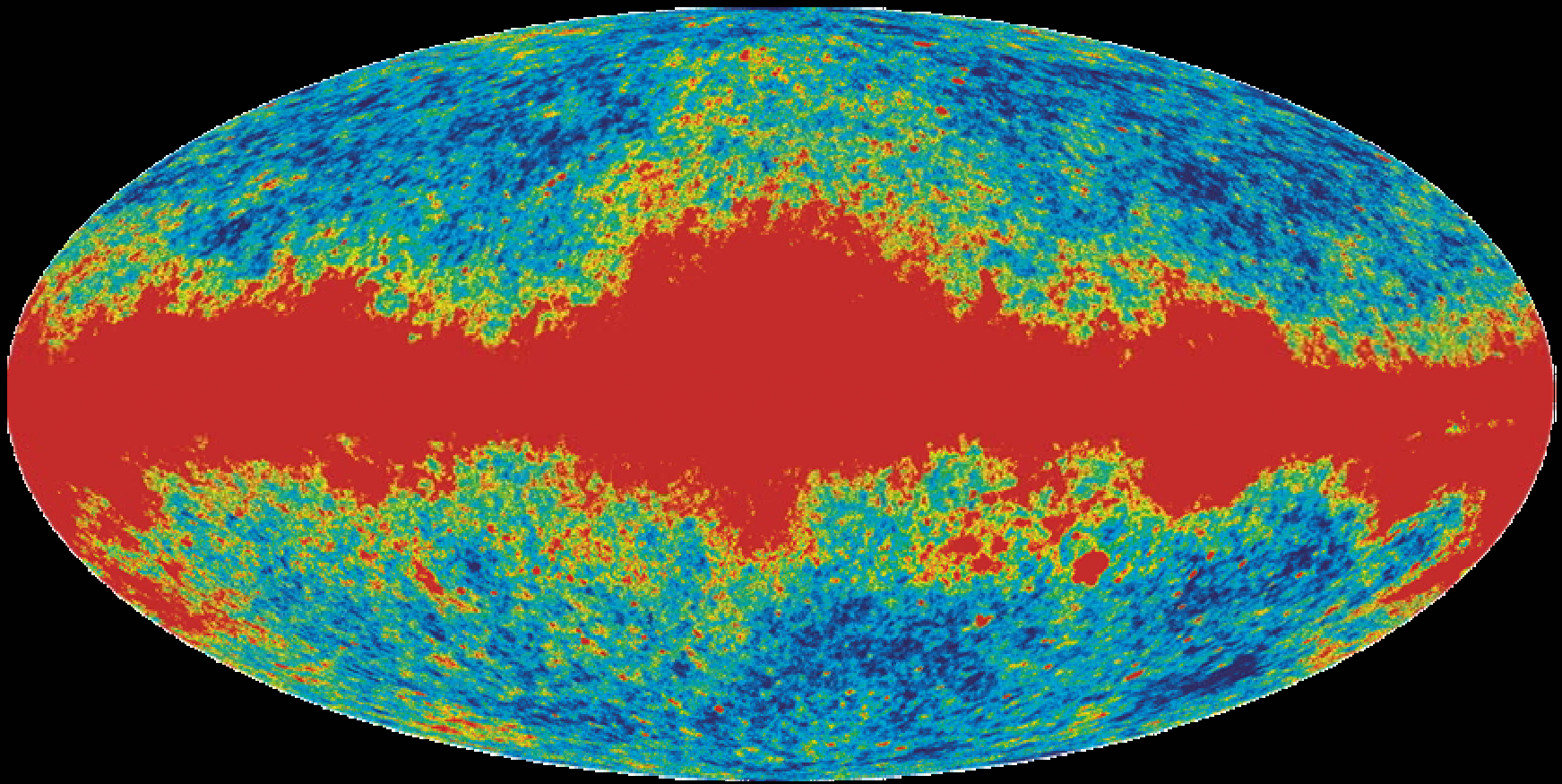
Switch: 0.4 ms Precession: 1 hr

Spin: 2 min Orbit: 1 yr

Ultra-Stable Observing Environment

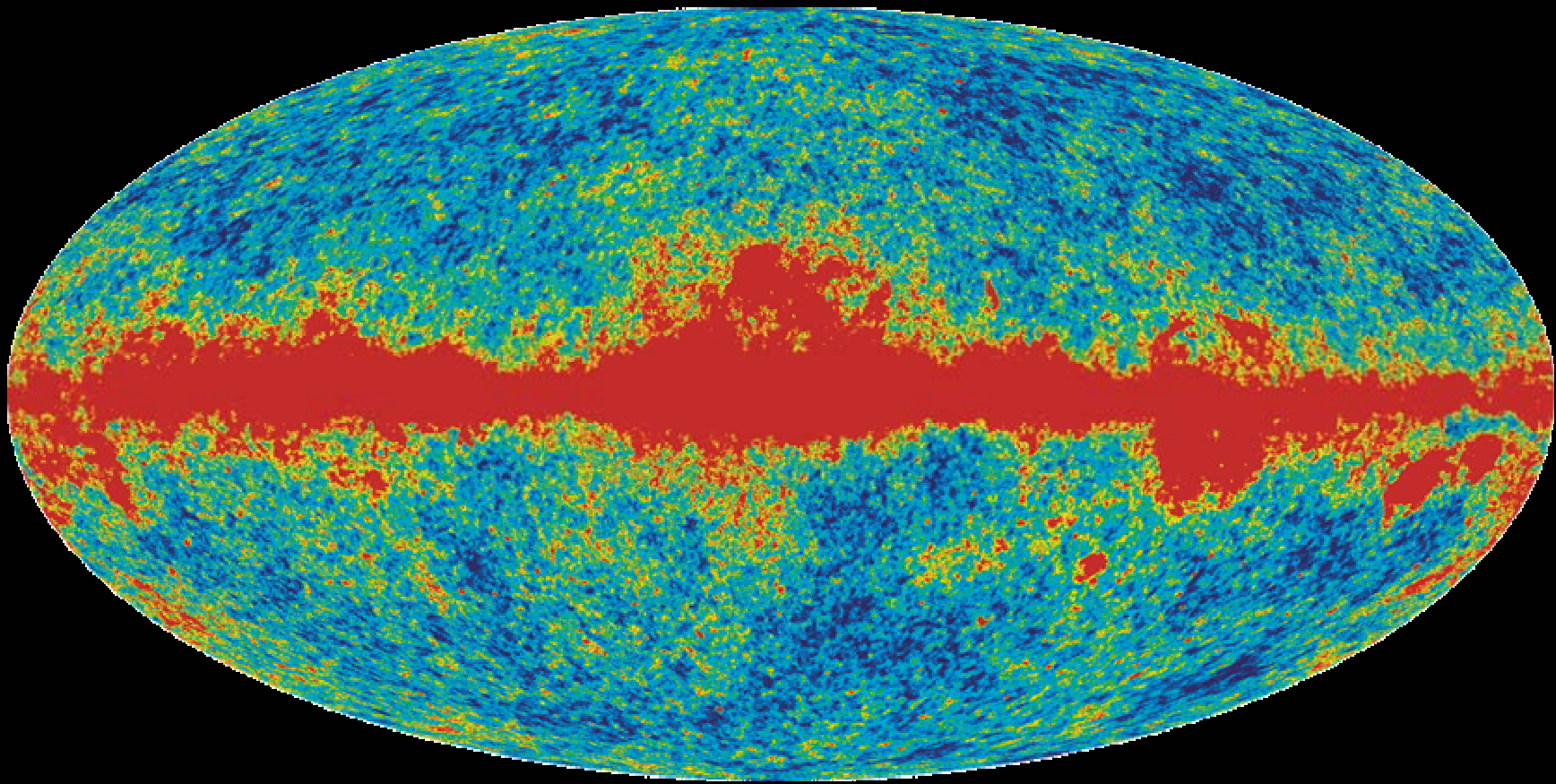


K Band (23 GHz)



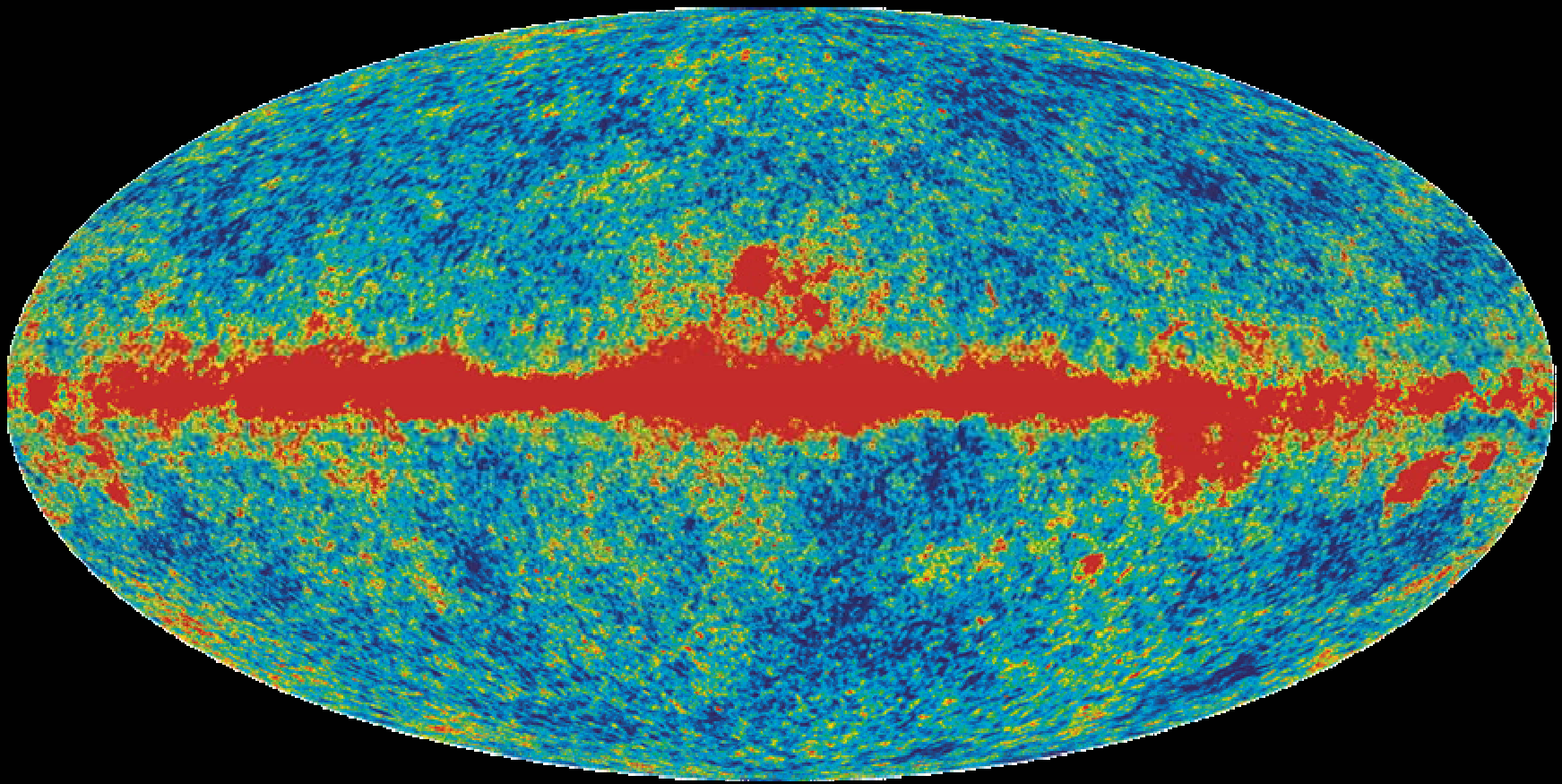
Bennett et al. (2003) ApJS, 148, 1

Ka Band (33 GHz)



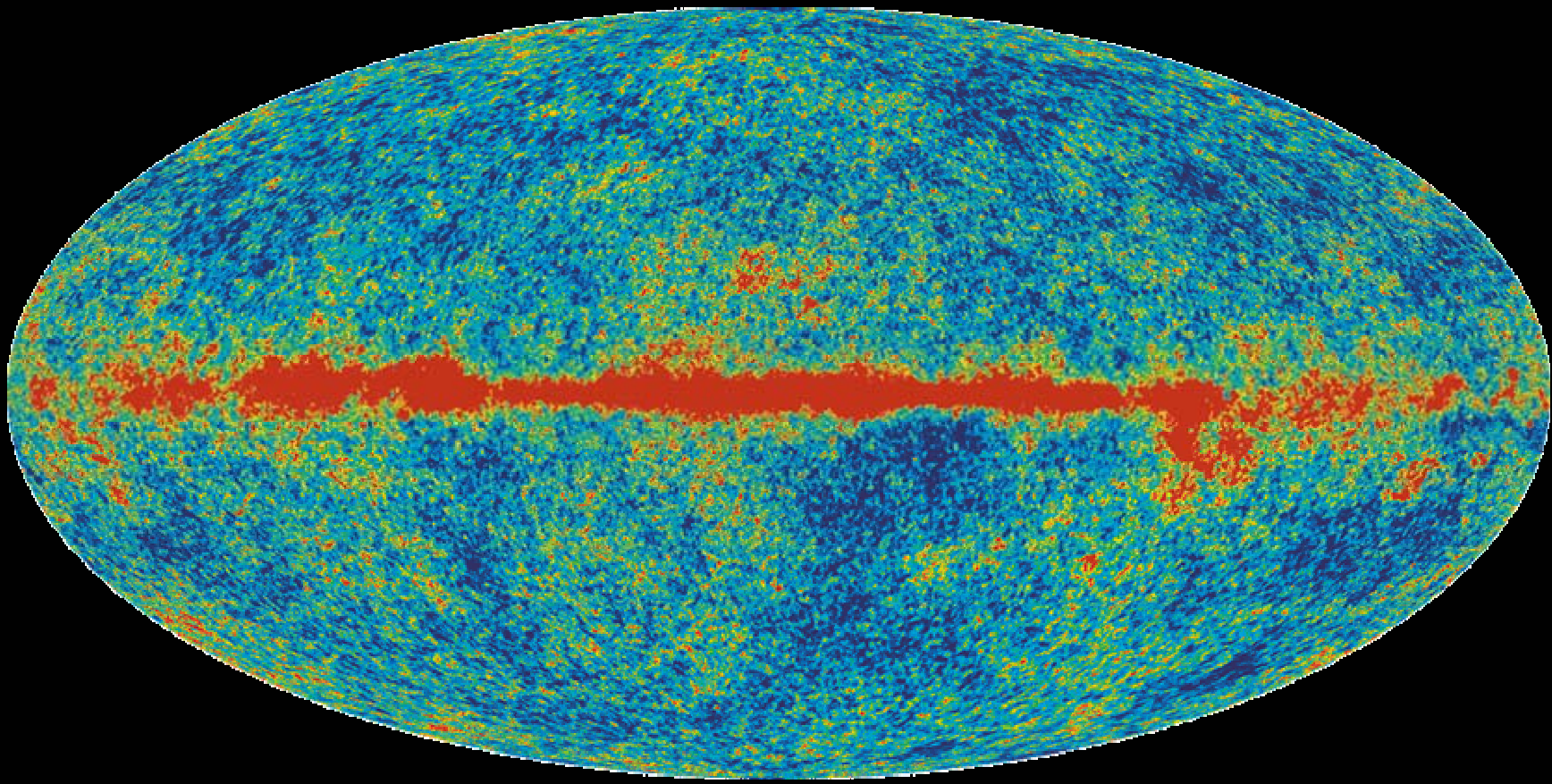
Bennett et al. (2003) ApJS, 148, 1

Q Band (41 GHz)



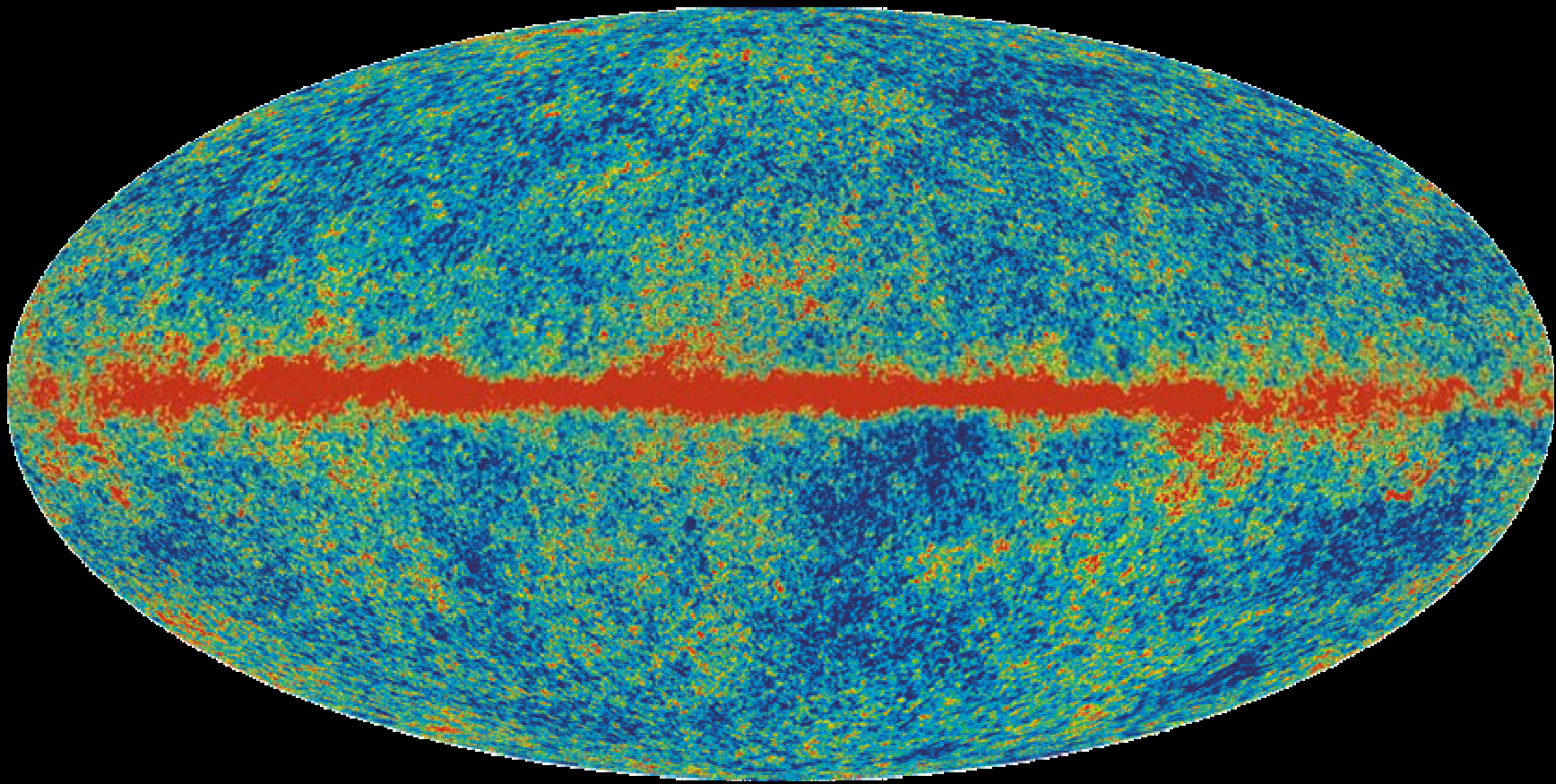
Bennett et al. (2003) ApJS, 148, 1

V Band (61 GHz)



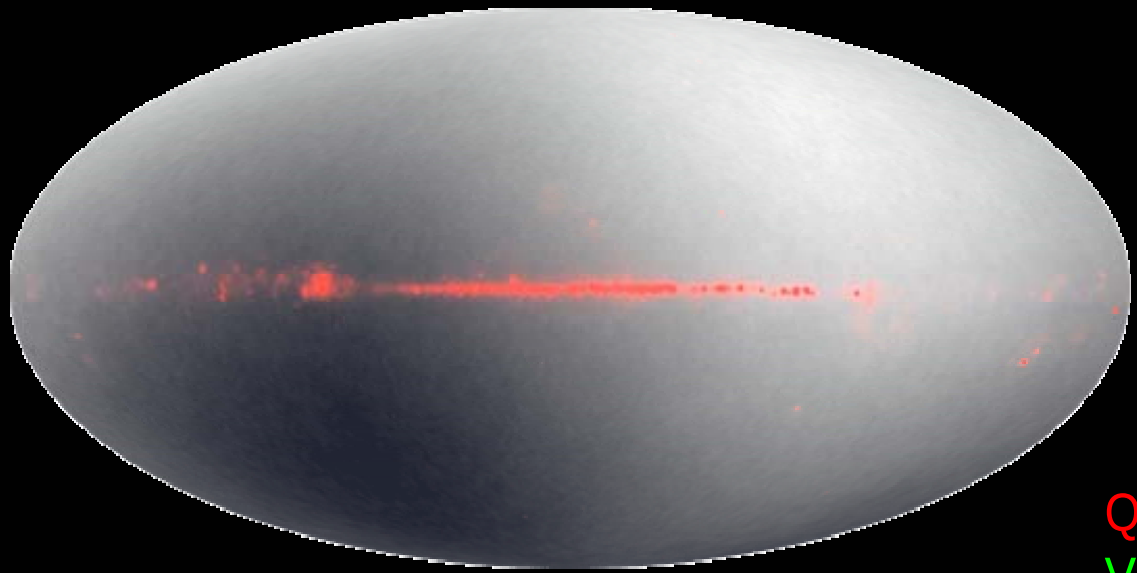
Bennett et al. (2003) ApJS, 148, 1

W Band (94 GHz)



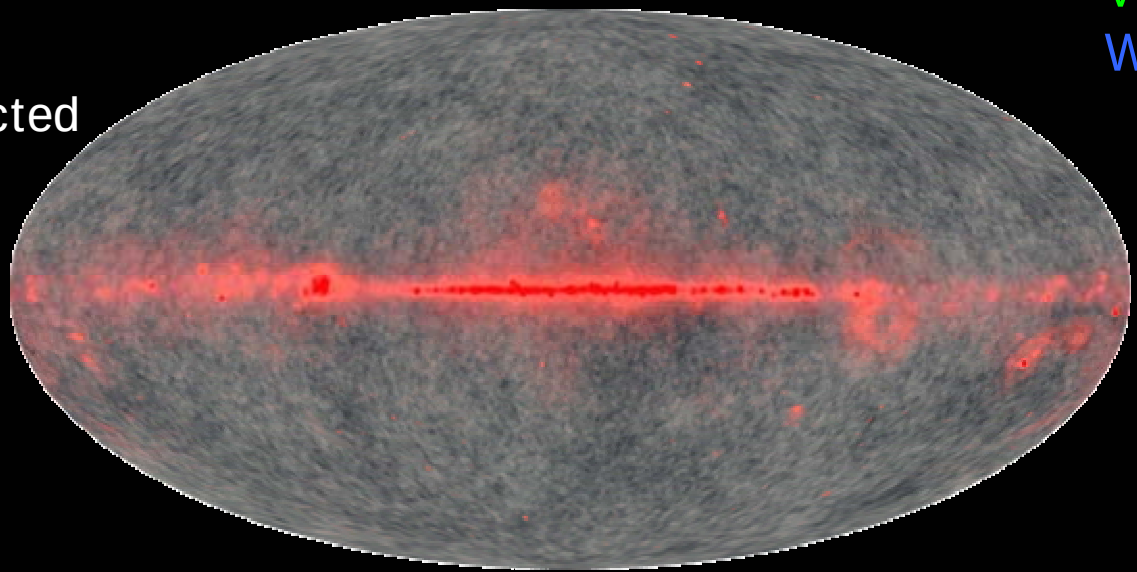
Bennett et al. (2003) ApJS, 148, 1

3-Color Maps



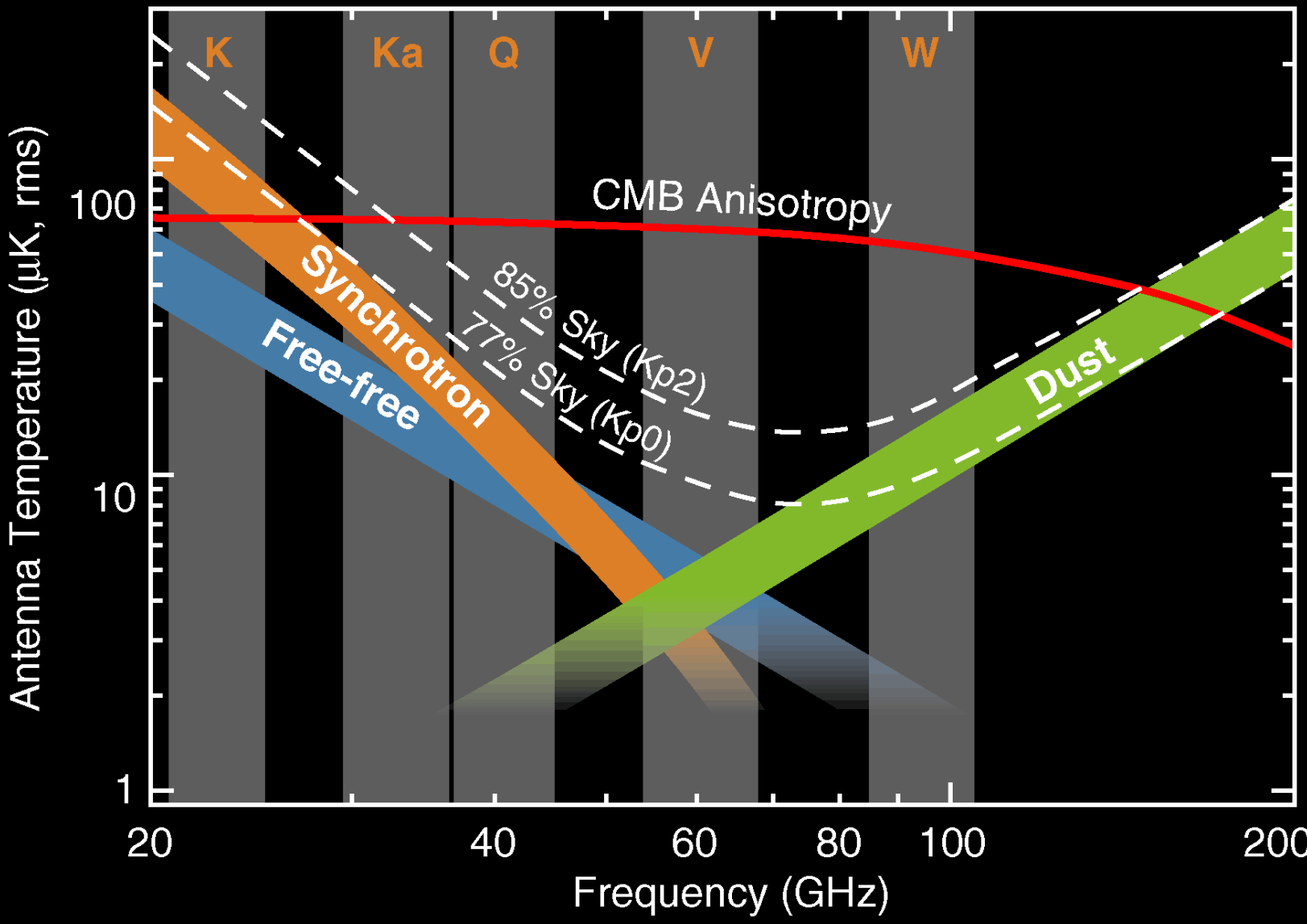
Q band
V band
W band

Dipole- subtracted



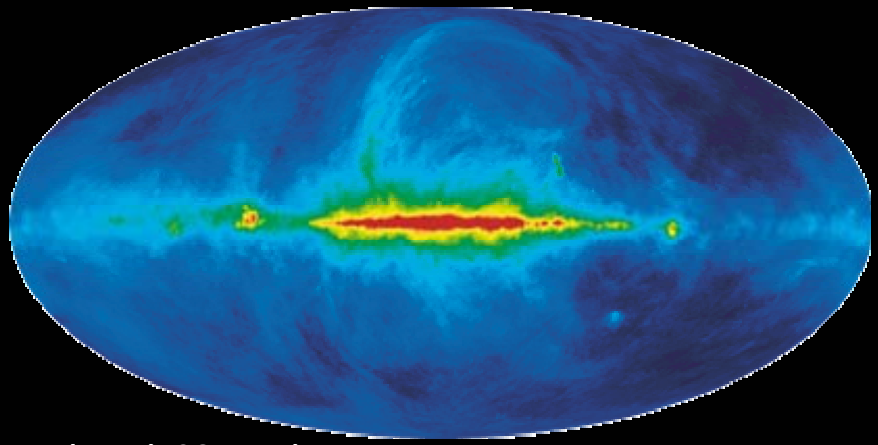
Bennett et al. (2003) ApJS, 148, 1

Foreground Spectra



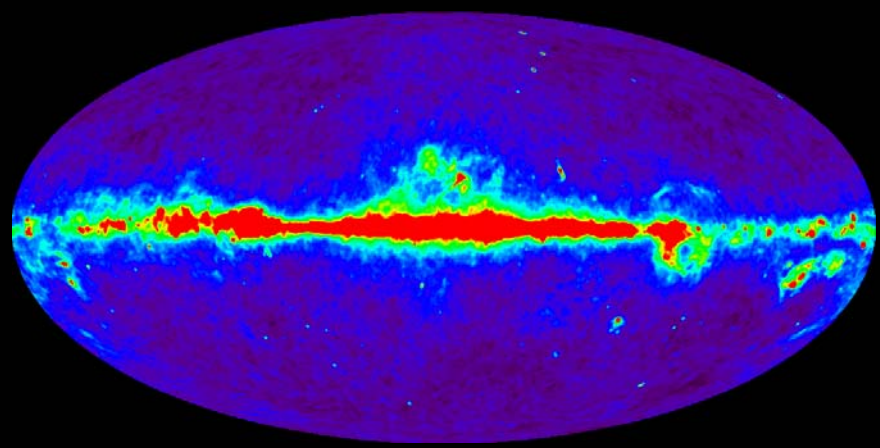
Bennett et al. (2003) ApJS, 148, 97

Synchrotron Foreground Emission



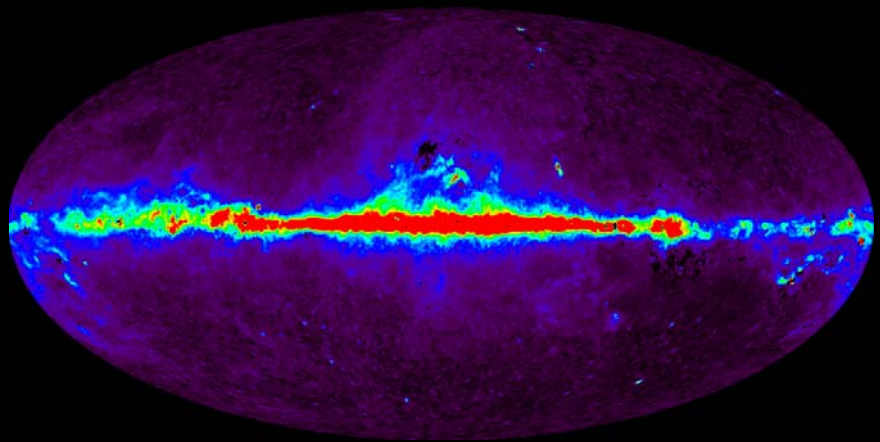
Haslam (408 MHz)

10 Temperature (K) 250



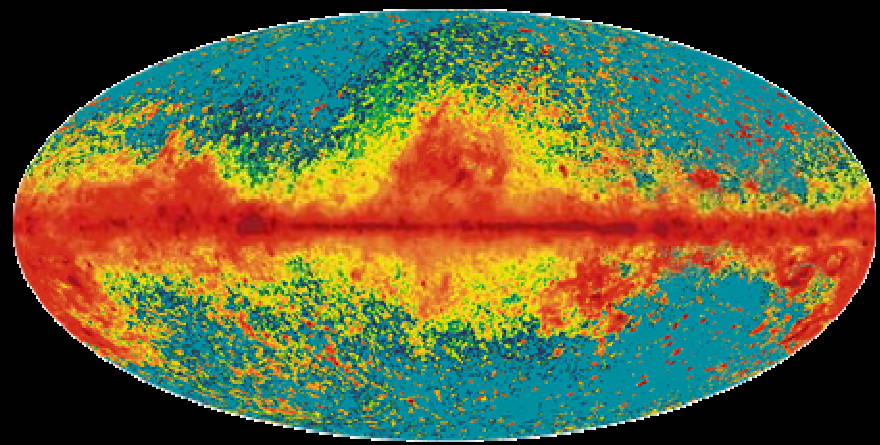
WMAP K-Band Data (23 GHz)

-0.3 Temperature (mK) +3



WMAP Synchrotron Model (23 GHz)

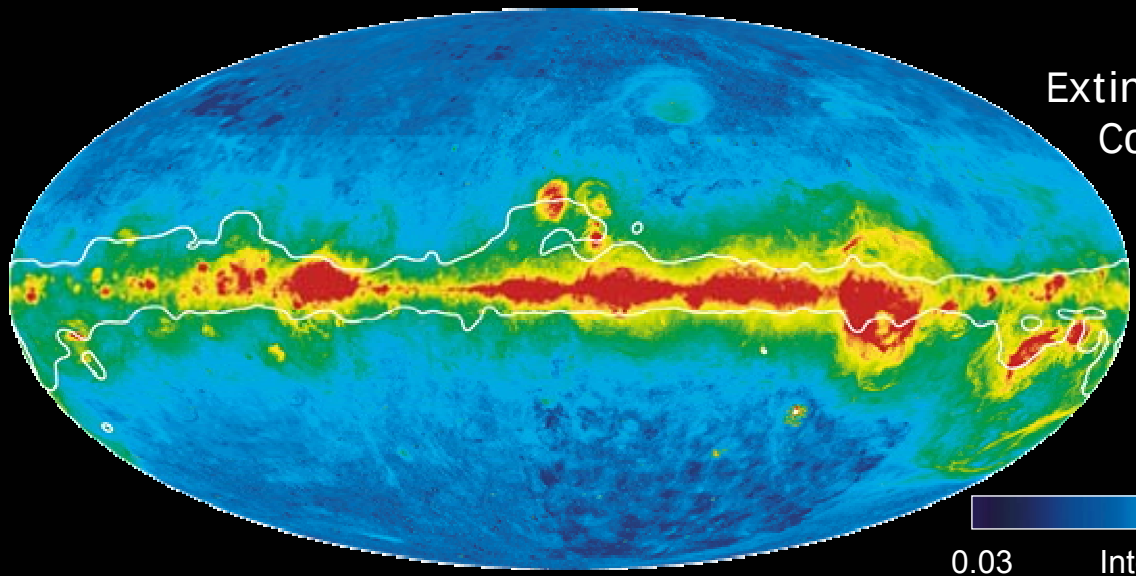
0 Temperature (mK) +3



Spectral Index of β(408 MHz, 23 GHz)

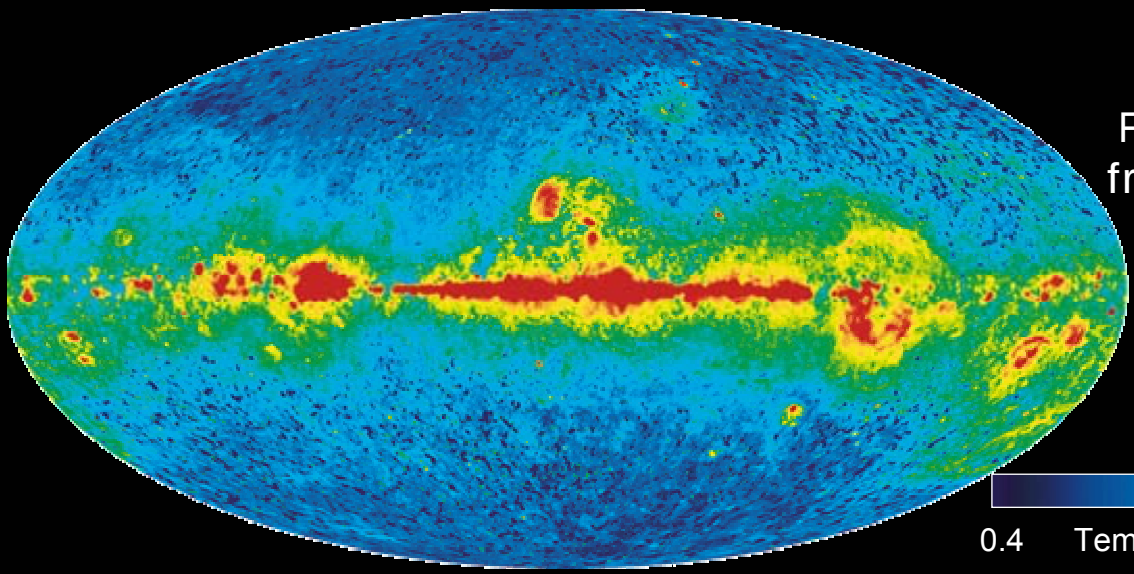
-3.4 β(408 MHz, 23 GHz) -2.3

Free-Free Foreground Emission



Extinction
Corrected
Hα (White Line: τ=1)

0.03 Intensity (R) 160

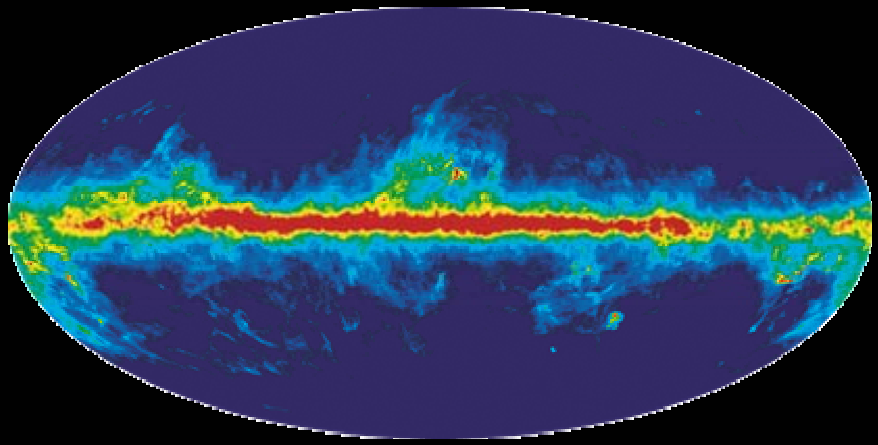


Free-free
from WMAP
at K band

0.4 Temperature (μK) 1,860

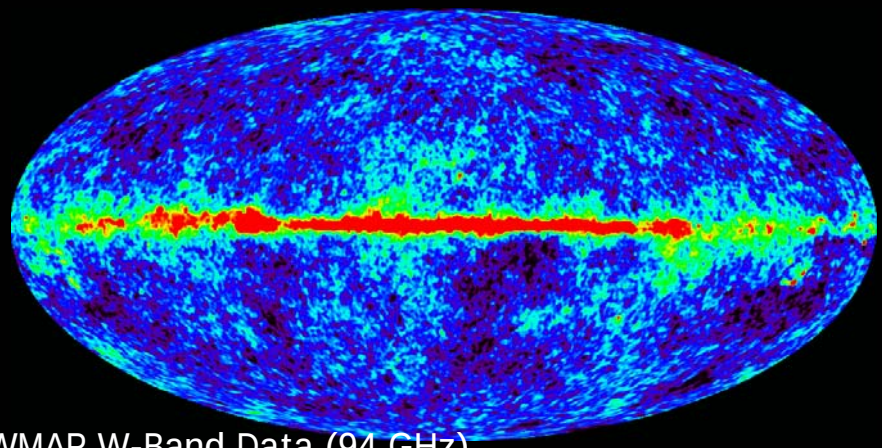
Bennett et al. (2003) ApJS, 148, 97

Dust Foreground Emission



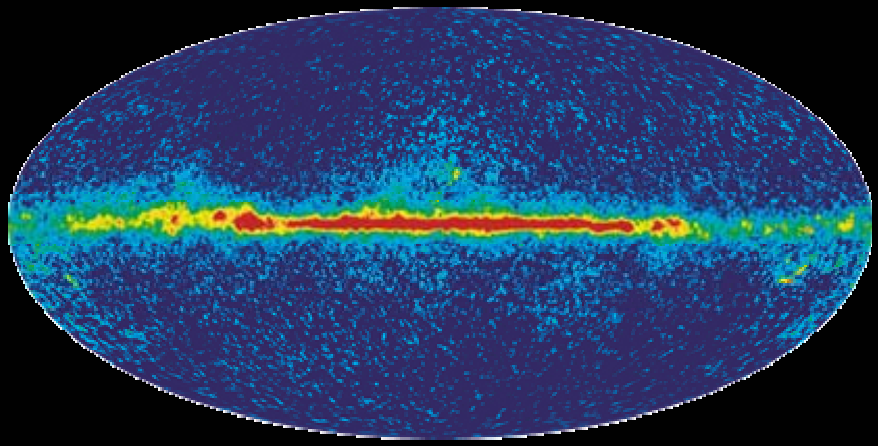
FDS Model 8 at W band (94 GHz)

15 Temperature (μK) 400



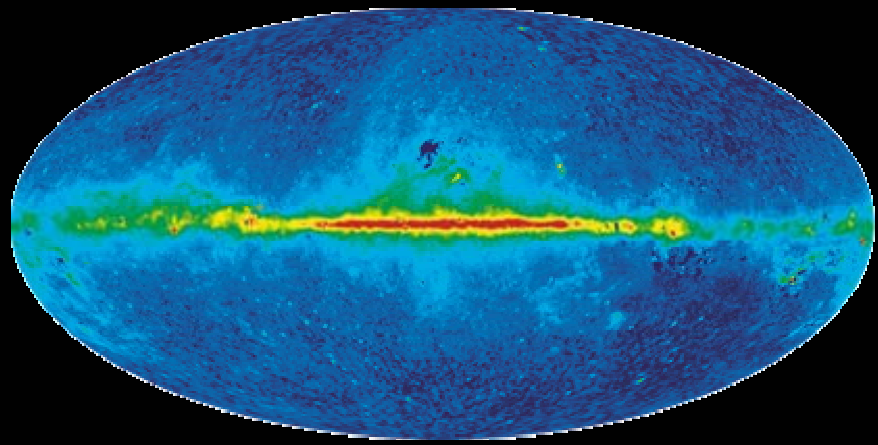
WMAP W-Band Data (94 GHz)

-100 Temperature (μK) 400



WMAP Dust Model (94 GHz)

15 Temperature (μK) 400

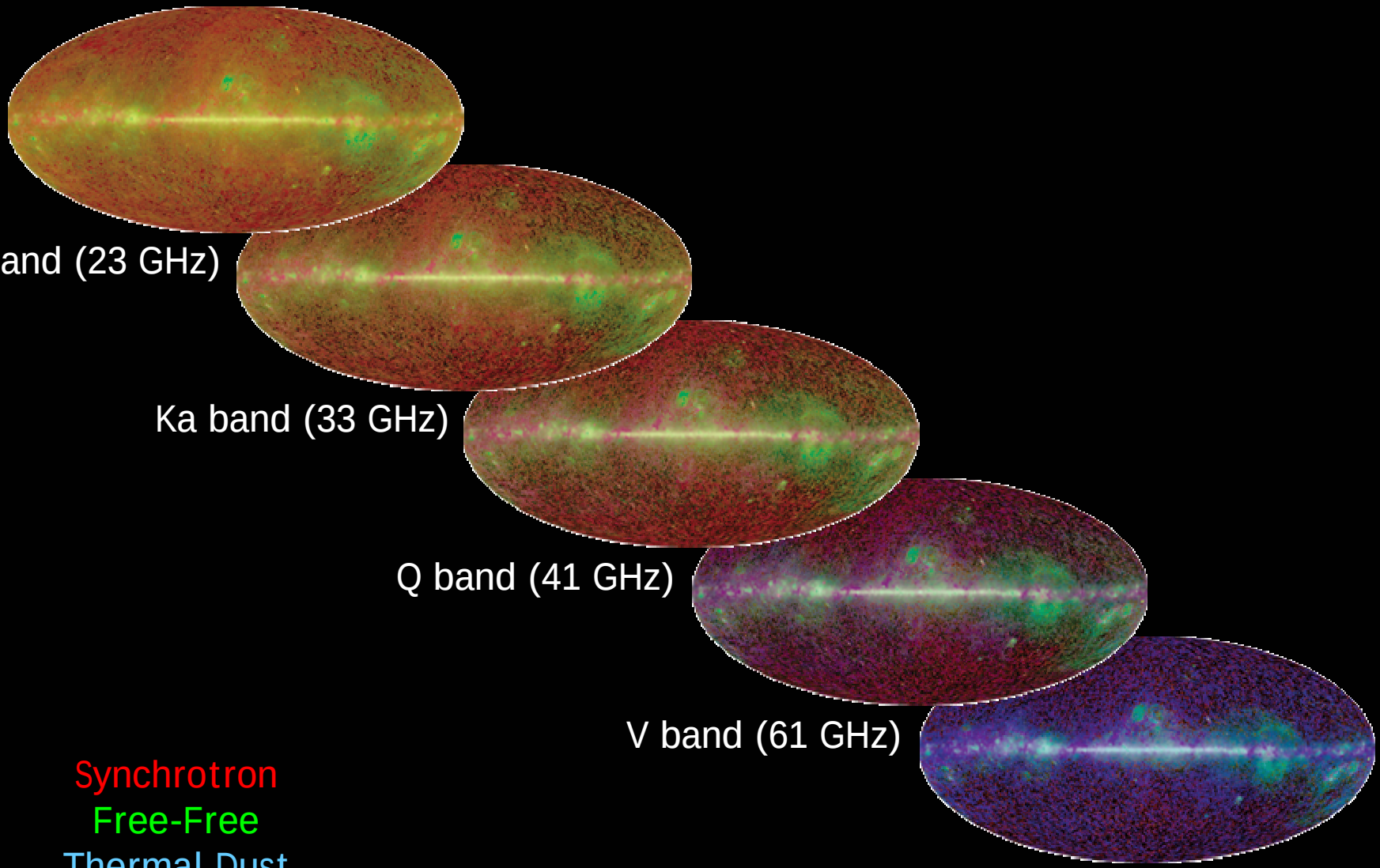


WMAP Synchrotron Model (23GHz)

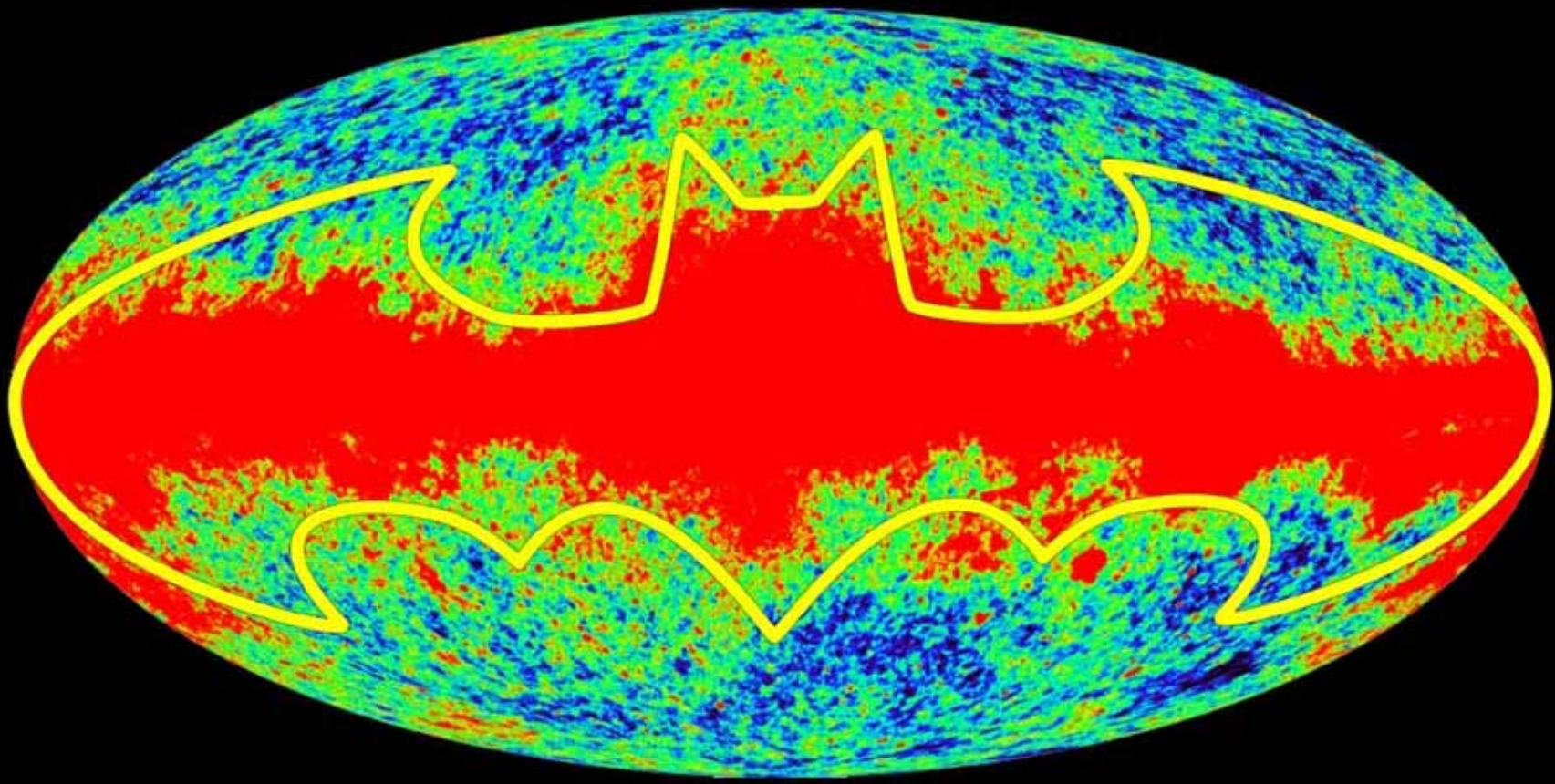
30 Temperature (μK) 10,000

at K band

3-Color Foregrounds

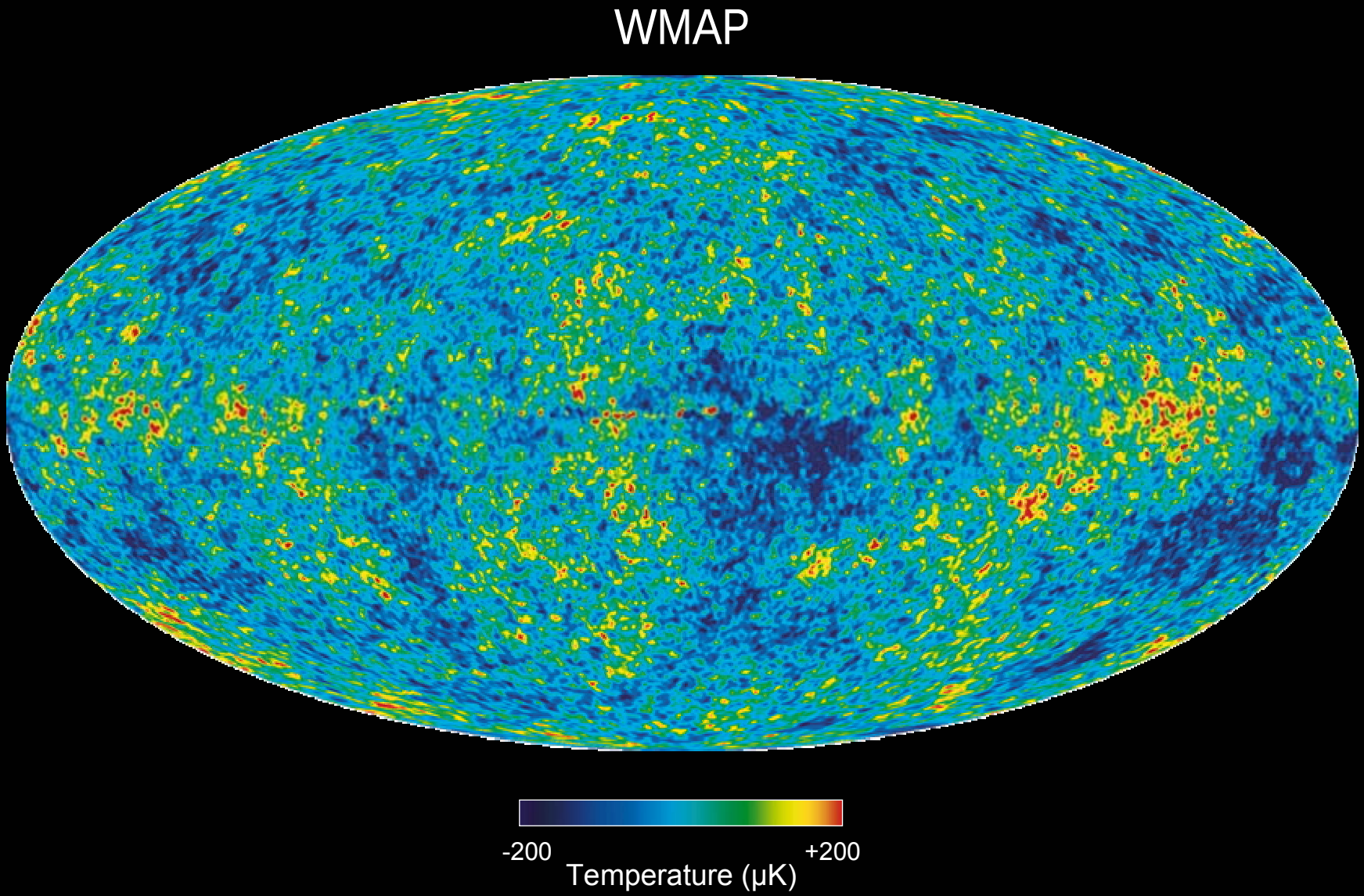


Best Fit Galactic Model



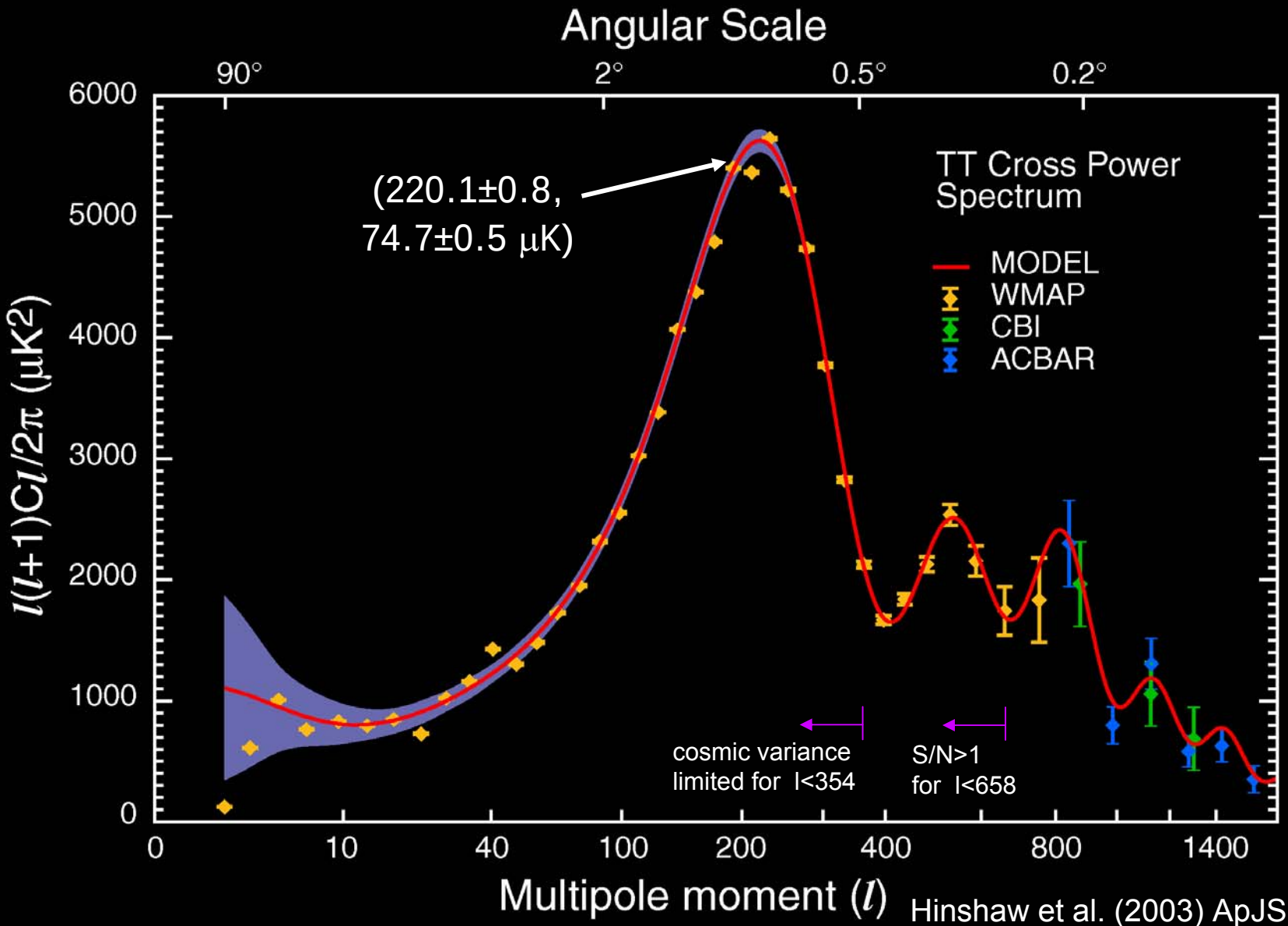
Stephane Coutu, Journal of Batty Results

Internal Linear Combination CMB



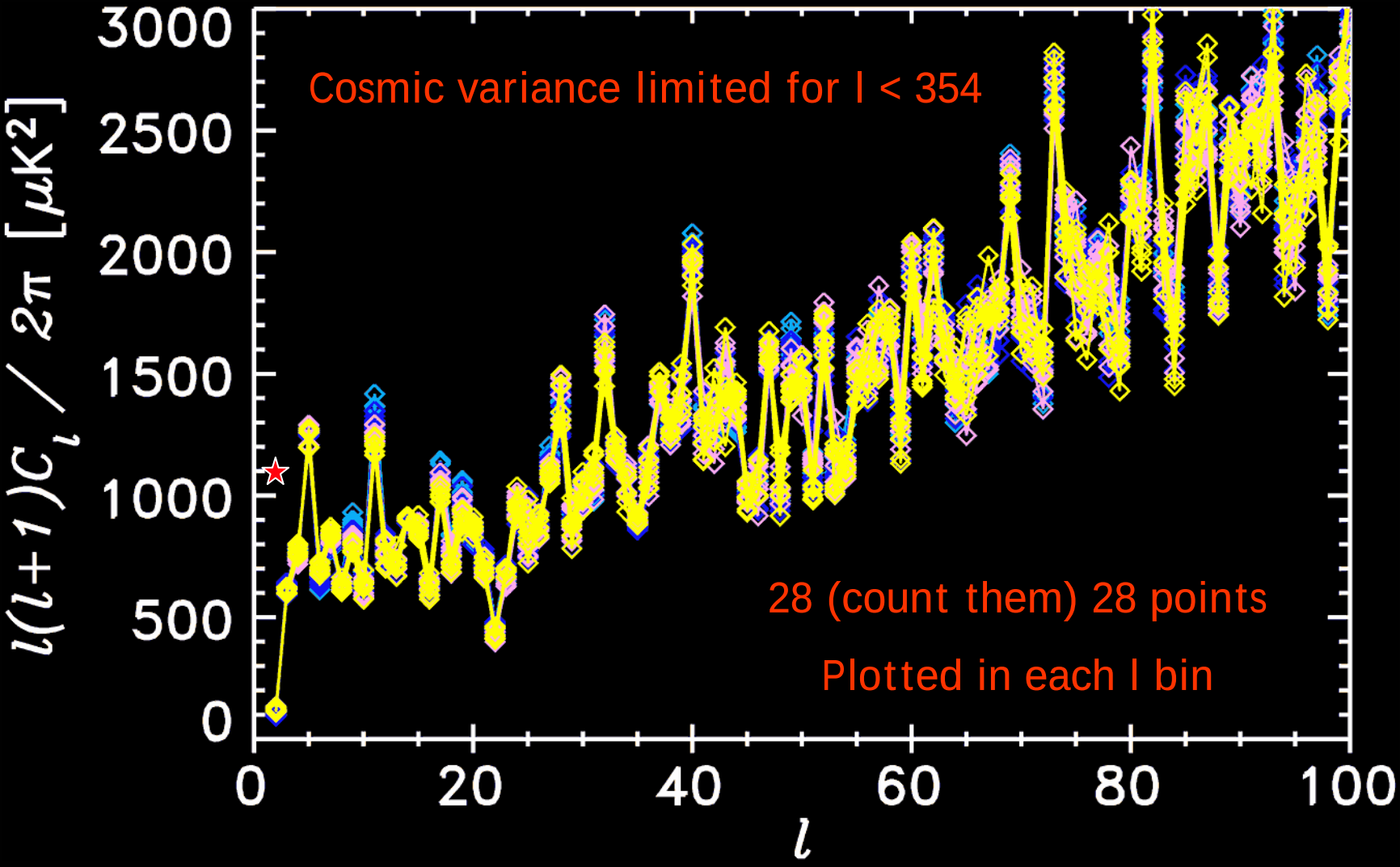
Bennett et al. (2003) ApJS, 148, 1

Power Spectrum



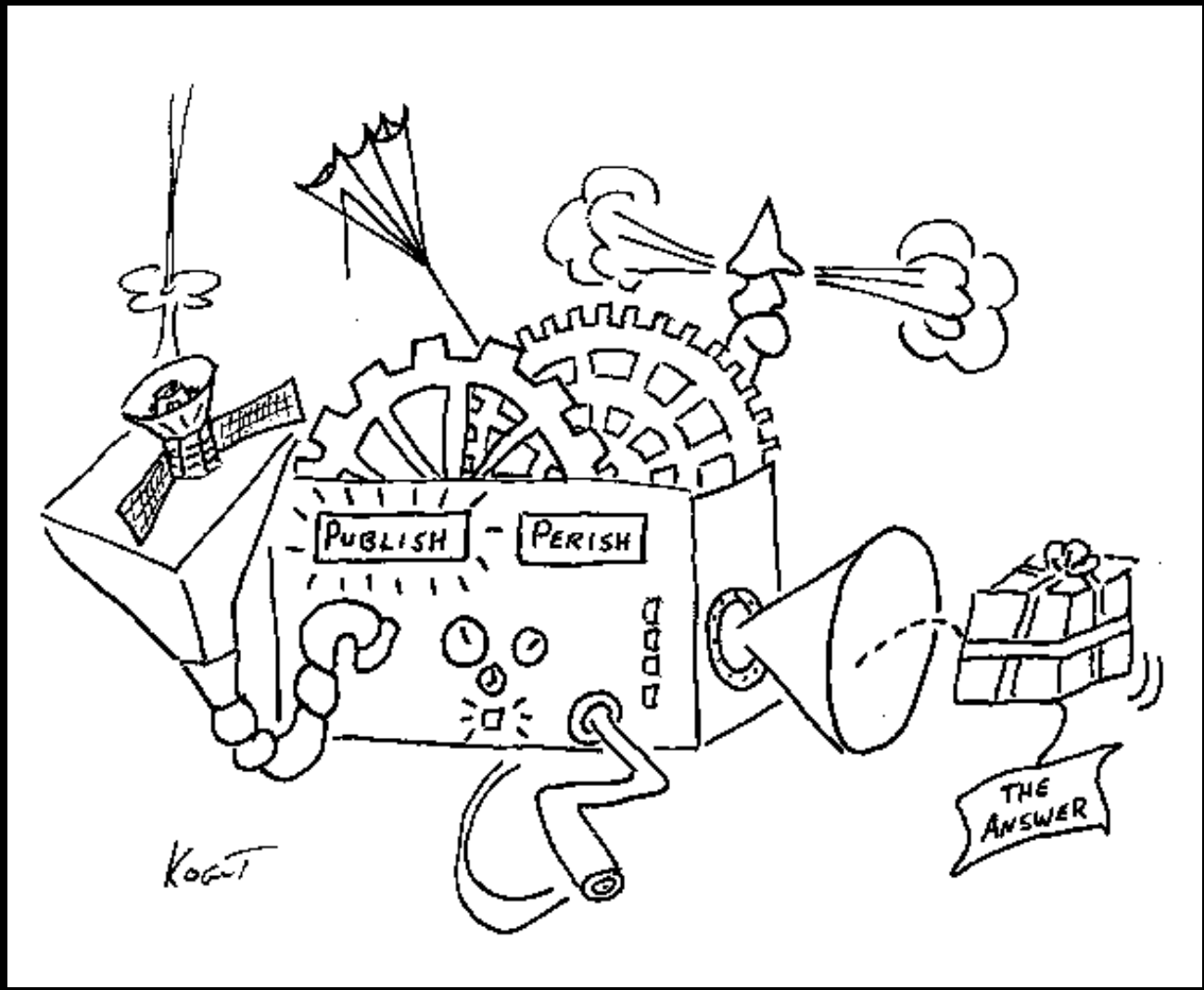
Hinshaw et al. (2003) ApJS, 148, 135
Bennett et al. (2003) ApJS, 148, 1

Unbinned Low-l Power Spectrum



Hinshaw et al. (2003) ApJS, 148, 135

A Cosmological Sampler ...



BIG BANG

- Age 13.7±0.2 Gyr

- Expansion rate $H_0 = 71^{+4}_{-3}$ km/s/Mpc

  [72±3±7 km/s/Mpc HST Freedman et al. (2001)]

- Geometry

  $\Omega_0 = 1.02 \pm 0.02$

- Baryon density

  $\Omega_b h^2 = 0.0224 \pm 0.0009$

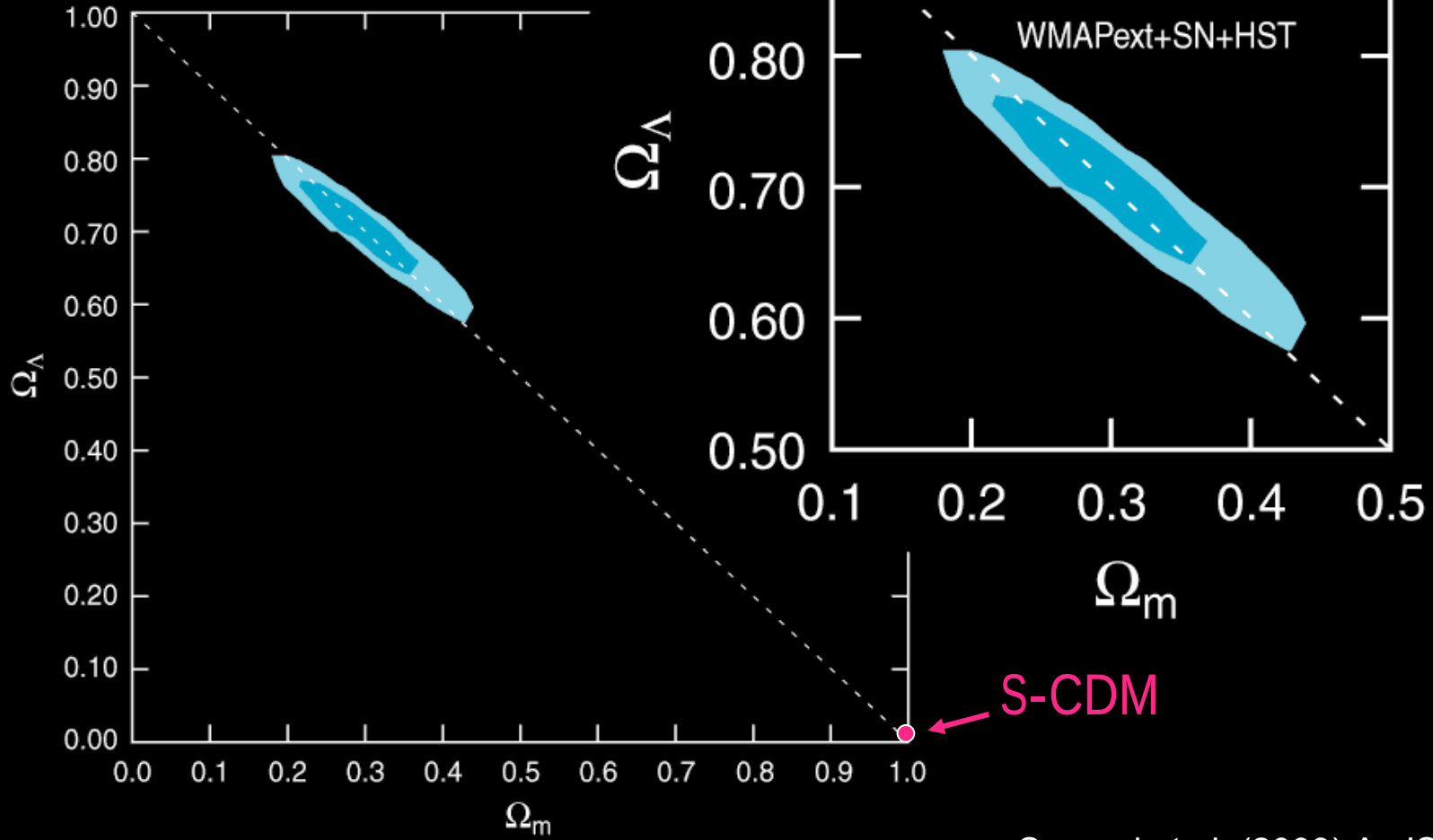
  $\Omega_b = 0.044 \pm 0.004$

Spergel et al. (2003) ApJS, 148, 175
Bennett et al. (2003) ApJS, 148, 1

Ω_Λ vs. Ω_m

$\Omega_\Lambda = 0.73 \pm 0.04$

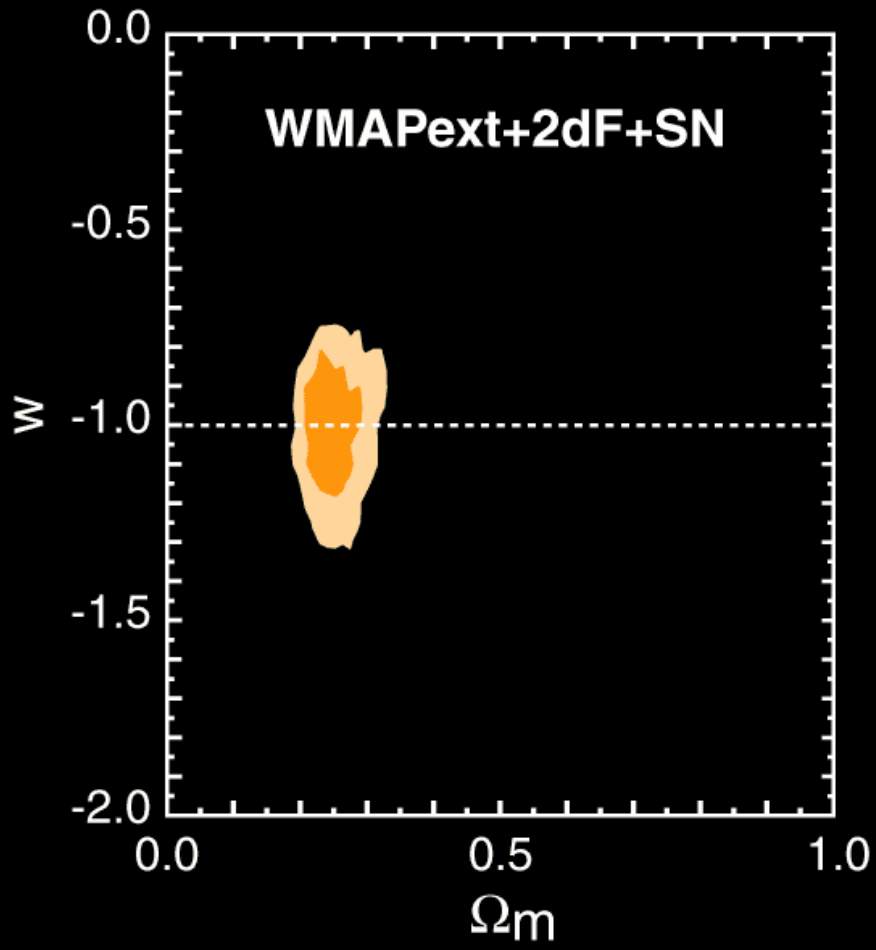
$\Omega_m = 0.27 \pm 0.04$

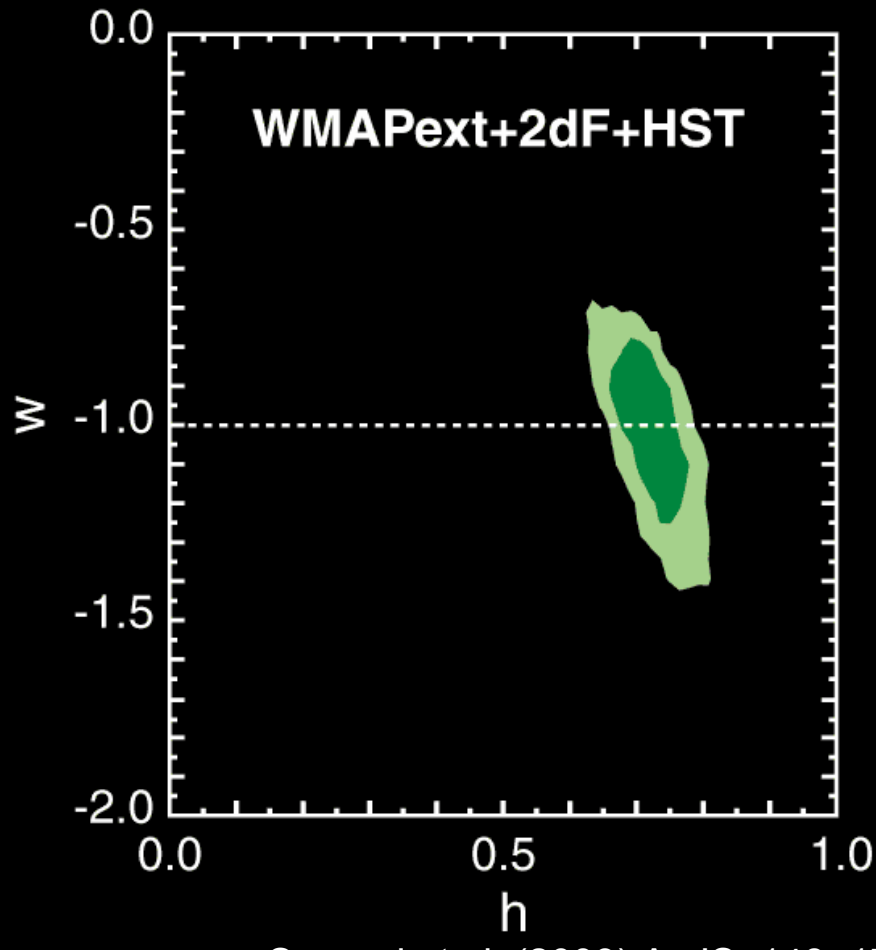


Spergel et al. (2003) ApJS, 148, 175

Constraints on Dark Energy

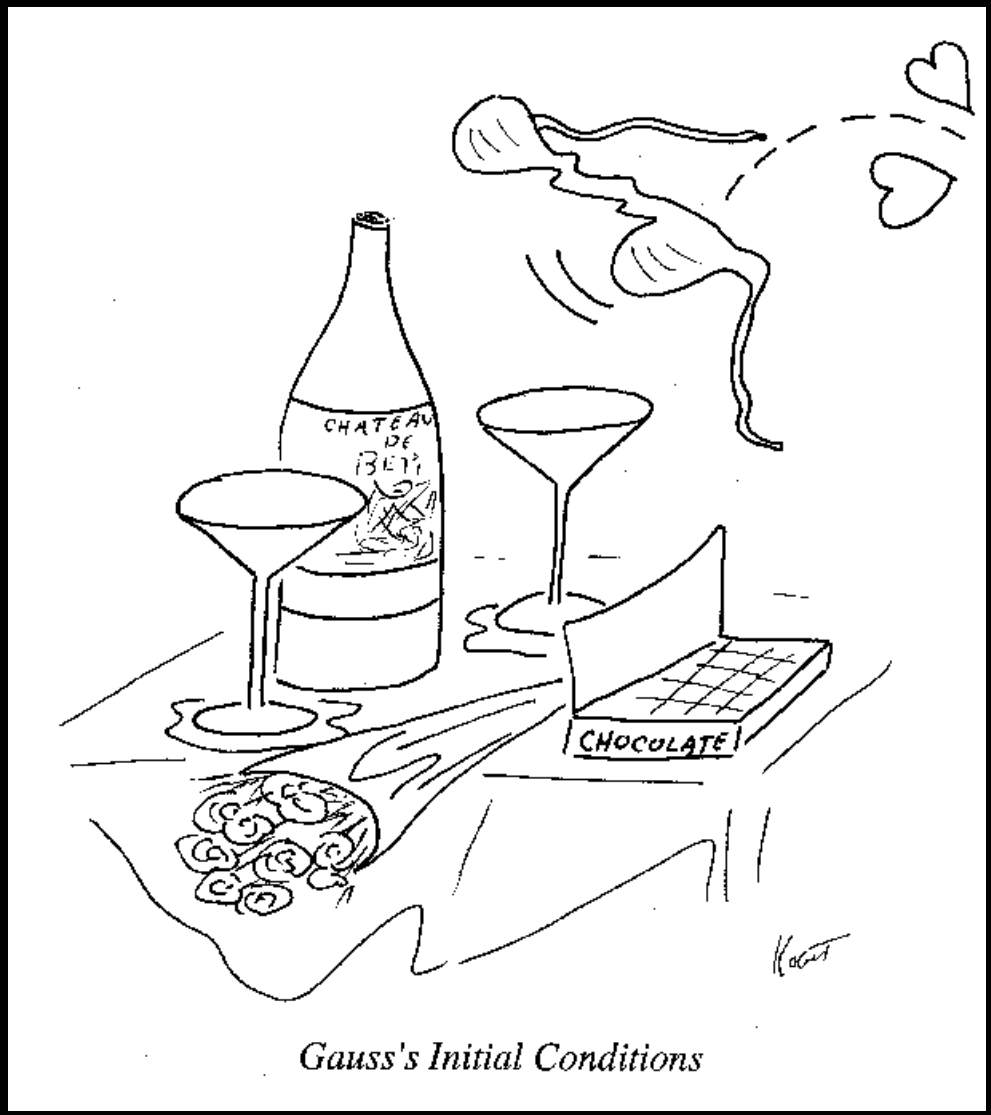
w = pressure (tension) / density
= $p/\rho c^2$
= -0.98 ± 0.12





Spergel et al. (2003) ApJS, 148, 175

Tests for Gaussianity



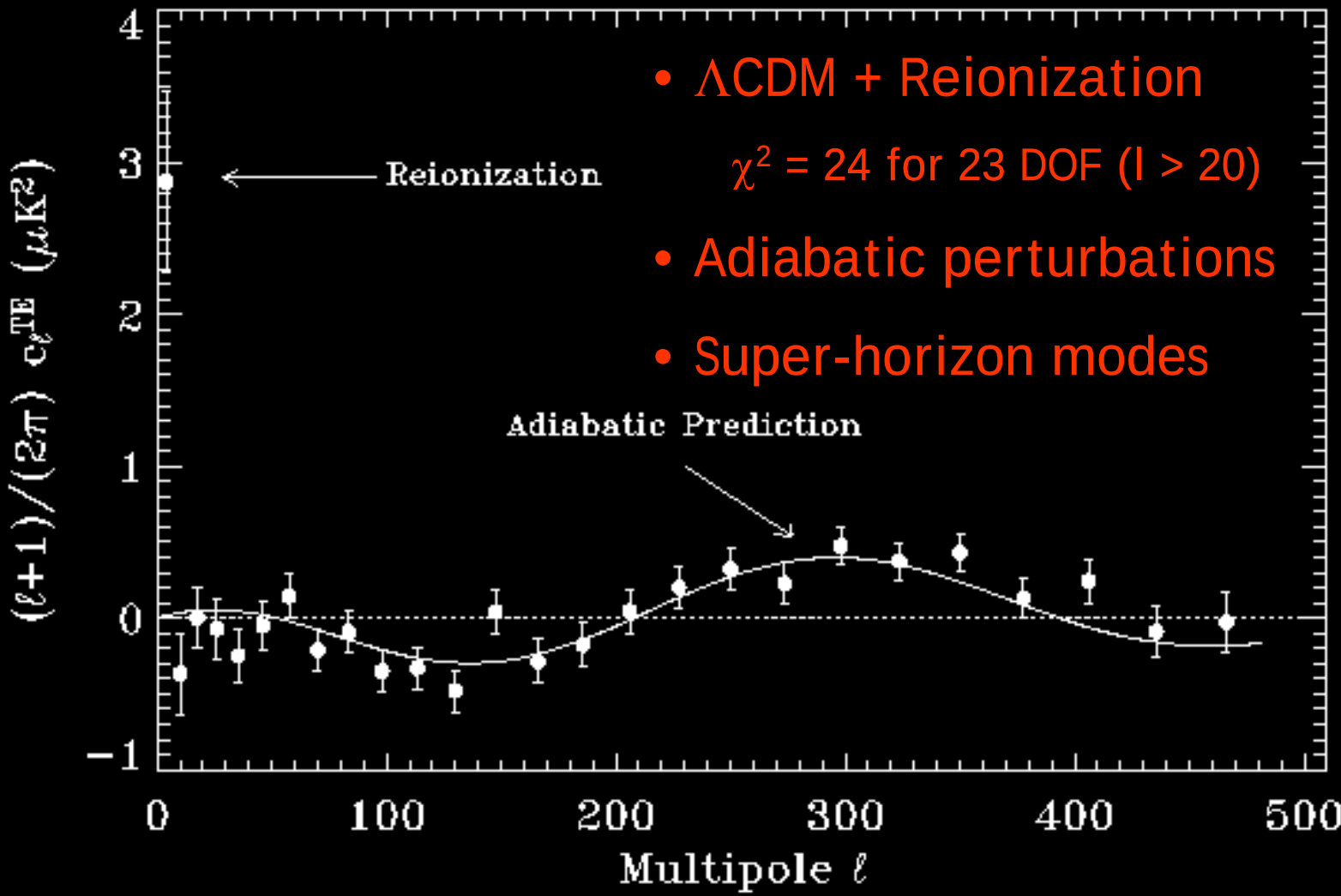
Gauss's Initial Conditions

Multiple Tests

- Pixel Space (Minkowski Functionals)
- Harmonic Transform (Bispectrum)
- Data compatible with Gaussian sims
- $-58 < f_{NL} < 134$ at 95% CL

Komatsu et al. (2003) ApJS, 148, 119

WMAP Polarization

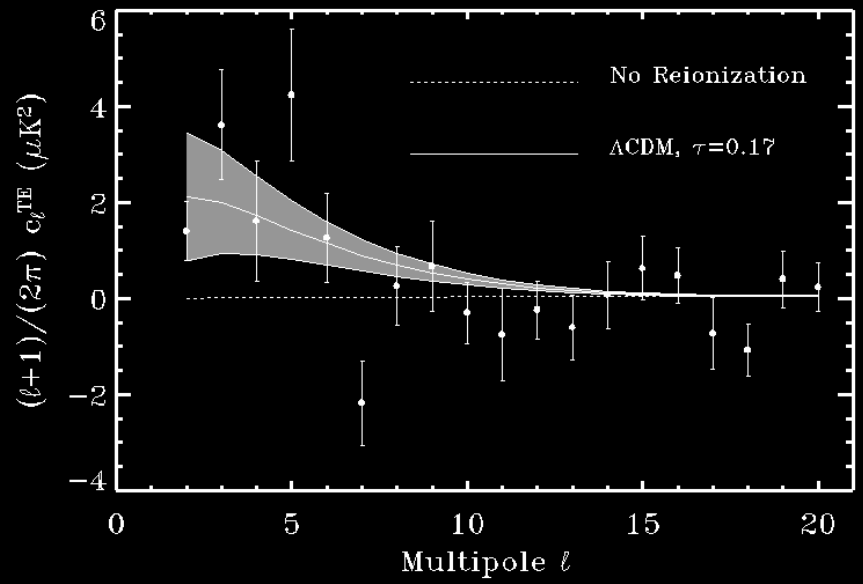


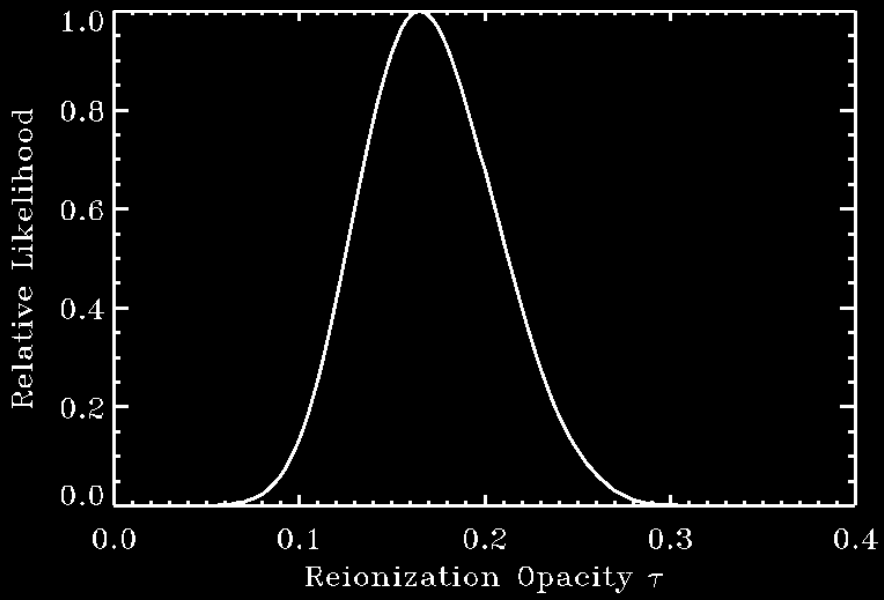
- ΛCDM + Reionization

  χ^2 = 24 for 23 DOF (l > 20)
- Adiabatic perturbations
- Super-horizon modes

Kogut et al. (2003) ApJS, 148, 161

WMAP and Reionization





Large Angular Scales (l < 10)

Suppress l>40 anisotropy by 30% (!)

Large Optical Depth

$\tau = 0.17 \pm 0.04$

$z_r = 20 \pm 10$

Complicated Ionization History

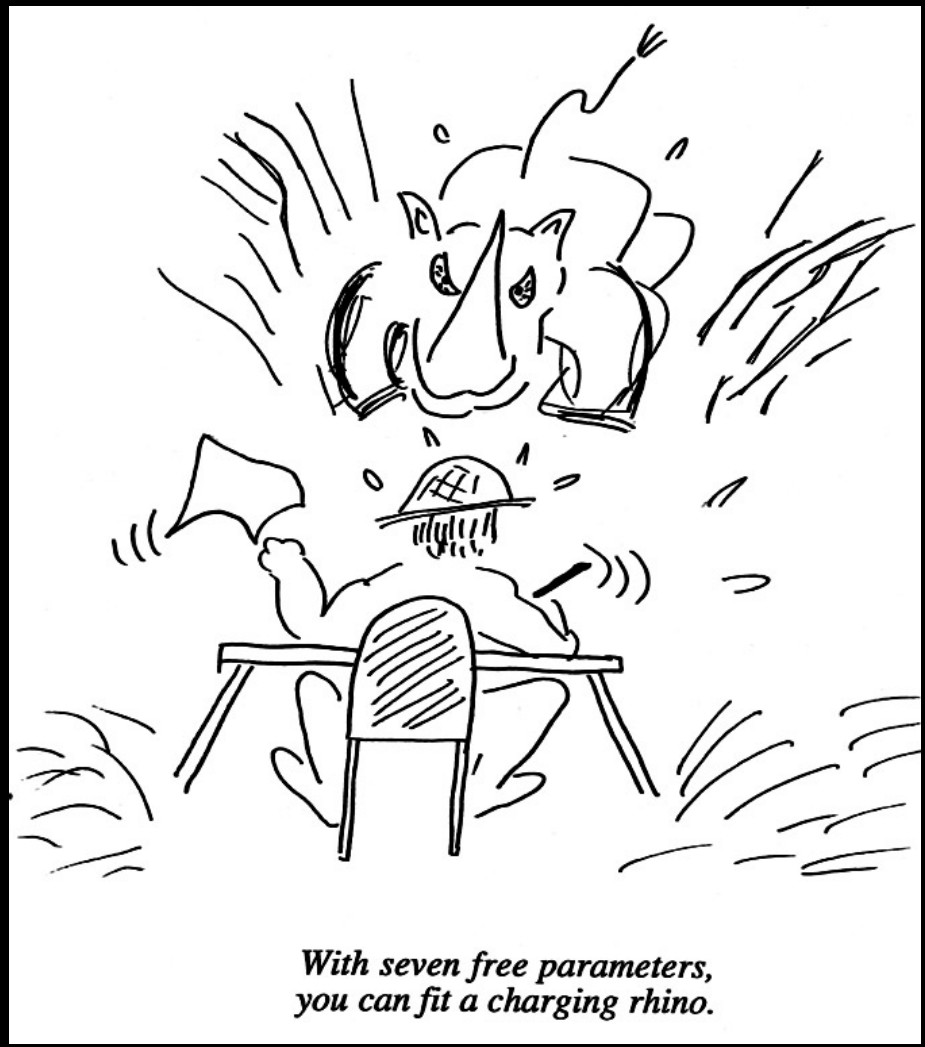
Kogut et al. (2003) ApJS, 148, 161

… Are We There Yet?

Consistent Cosmology From Multiple Measurements

Geometry	Ω	= 1.02 ± 0.02
Baryons	Ω_b	= 0.044 ± 0.004
Matter	Ω_m	= 0.27 ± 0.04
Dark Energy	Ω_Λ	= 0.73 ± 0.04
Eq of State	w	= -0.98 ± 0.12
Scalar Index	n	= 0.97 ± 0.03
Reionization	τ	= 0.17 ± 0.04

So cosmology is solved, right?



A Precise Quantification of Ignorance

Ω_Λ

Ω_b

Ω_c

What Is Dark Matter?

What Is Dark Energy?

Why Are They So Close?

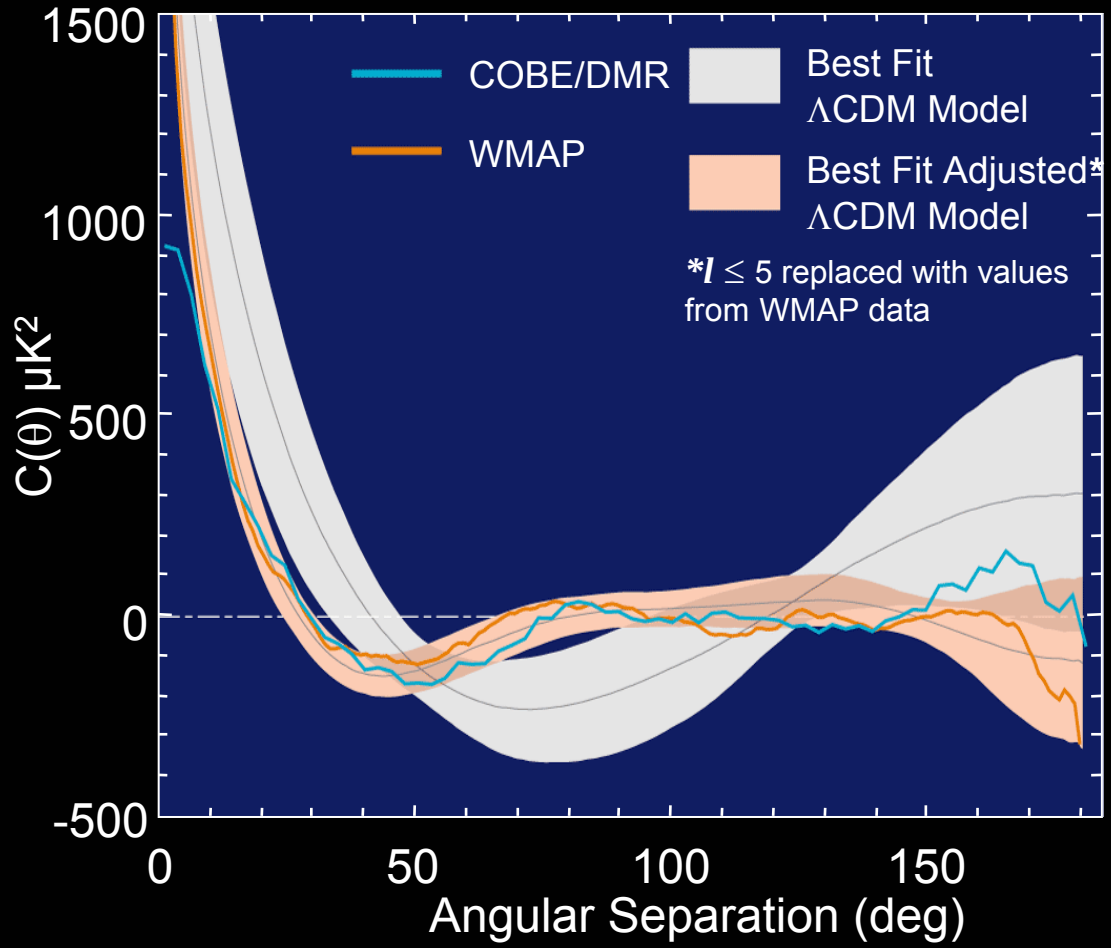
What Is The Dark Matter?

- Must be non-relativistic
  - Sorry, neutrino fans …
- Lightest supersymmetric particle
  - Minimal SUSY models have a stable lightest particle not yet seen
  - Estimated to be 150-400 GeV
  - LHC can probe this energy range, but even if it sees new particles (which would be exciting), it doesn't prove it is stable on a Hubble time scale
  - Need direct dark matter detection too
- Axion
  - Hypothetical elementary particle
  - Potential mechanism to suppress otherwise large CP violation in QCD
- Something Else?
  - MeV gauge boson?
  - Ghost of Christmas Past?

What Is The Dark Energy?

- Who knows!
- A **HUGE** problem for both cosmology and basic physics
- Basic physics:
  - Dark energy should be enormous, but clearly isn't
  - … so there must be some unknown reason why it is exactly zero
  - … but now it seems that isn't true either
  - … resort to the "A"-word?
- Possibilities
  - Cosmological constant (predicts $w=-1$)
  - Quintessence (universal, evolving scalar field) (any $w<-1/3$)
  - Leakage from compact extra dimensions
  - Extensions of GR

Hints of Something Else?



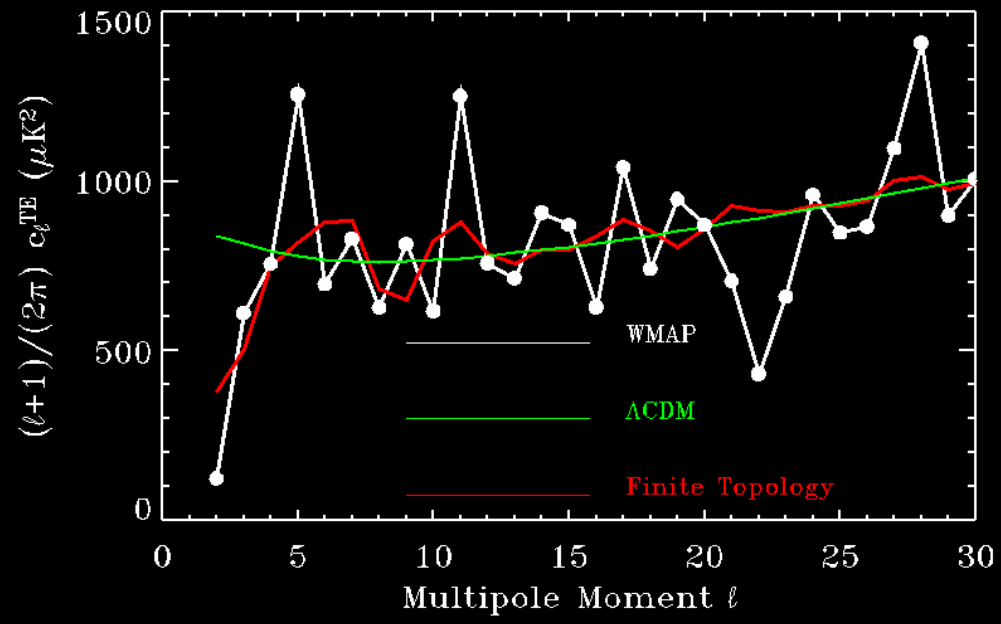
Anomalies at low l

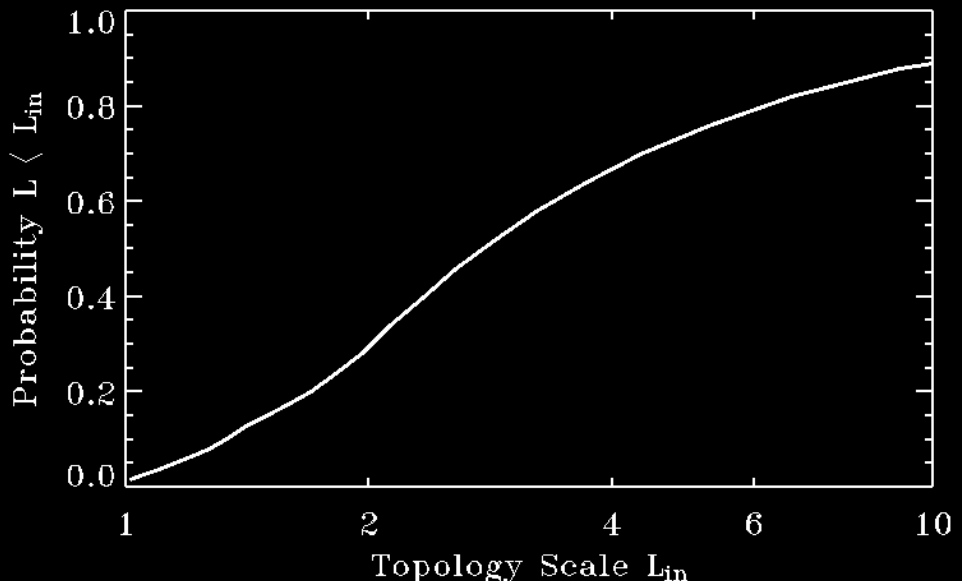
- Suppressed power
- Planarity
- Multipole Alignment

What Does It Mean?

- ΛCDM hits the lottery?
- Compact topology?

WMAP Limits for Topology





Power Spectrum Suggestive of Compact Topology

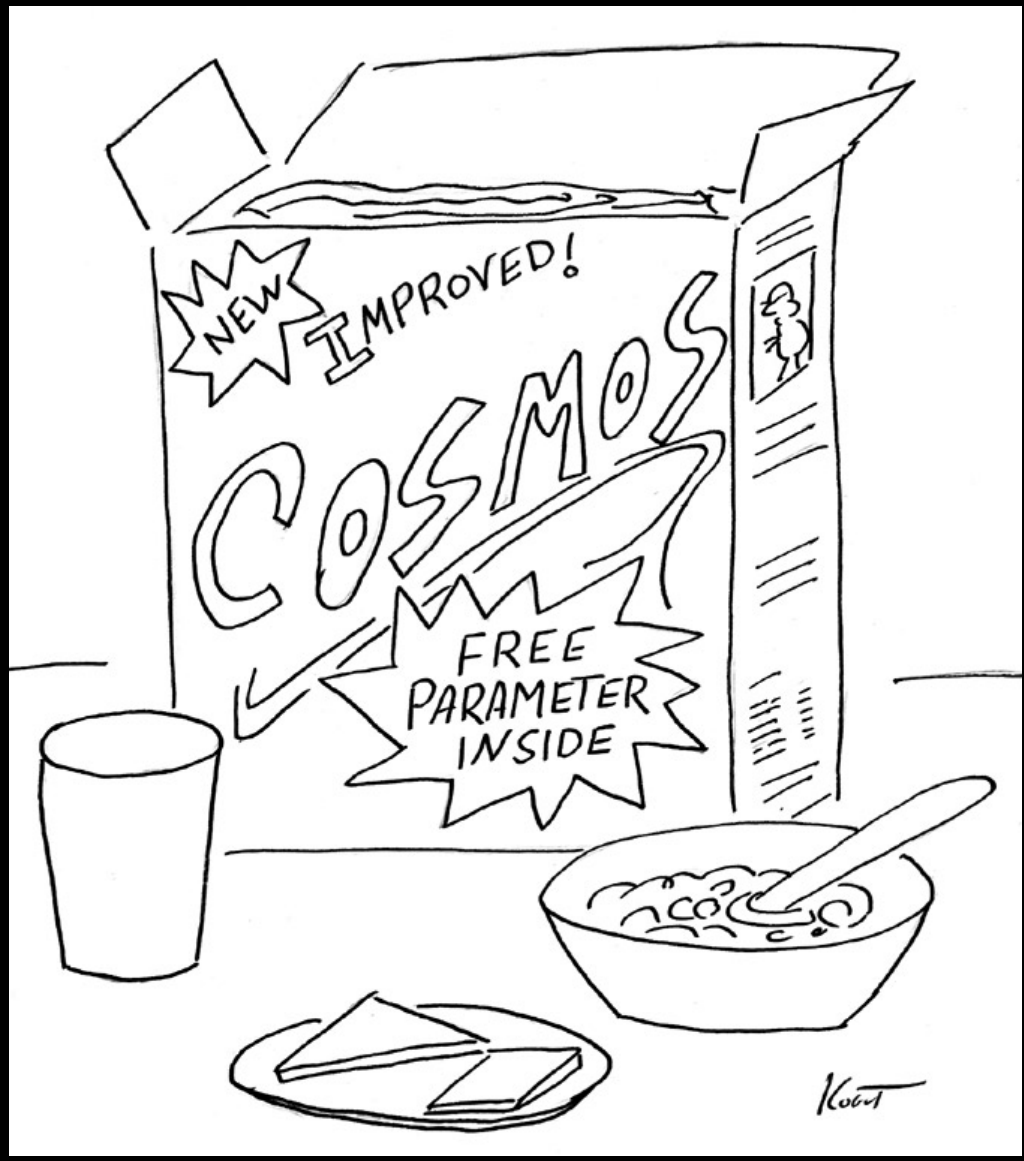
But …

- Matching Circles Not Found
- a_{lm} Correlations Not Found

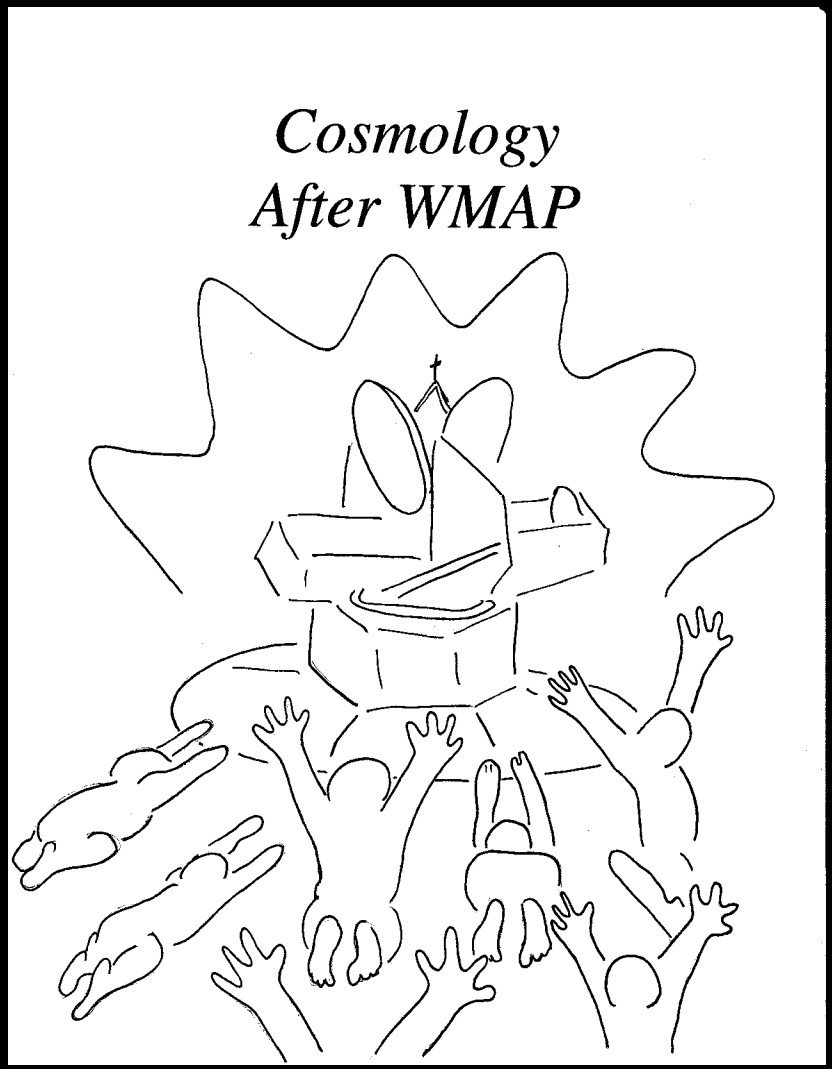
Scale L > 1.7 x Dist to LSS (95% CL)

Cornish et al. (2004), PRL, 92, 201302
Phillips & Kkogut (2004) ApJ, astro-ph/0404400

Breakfast of Theorists

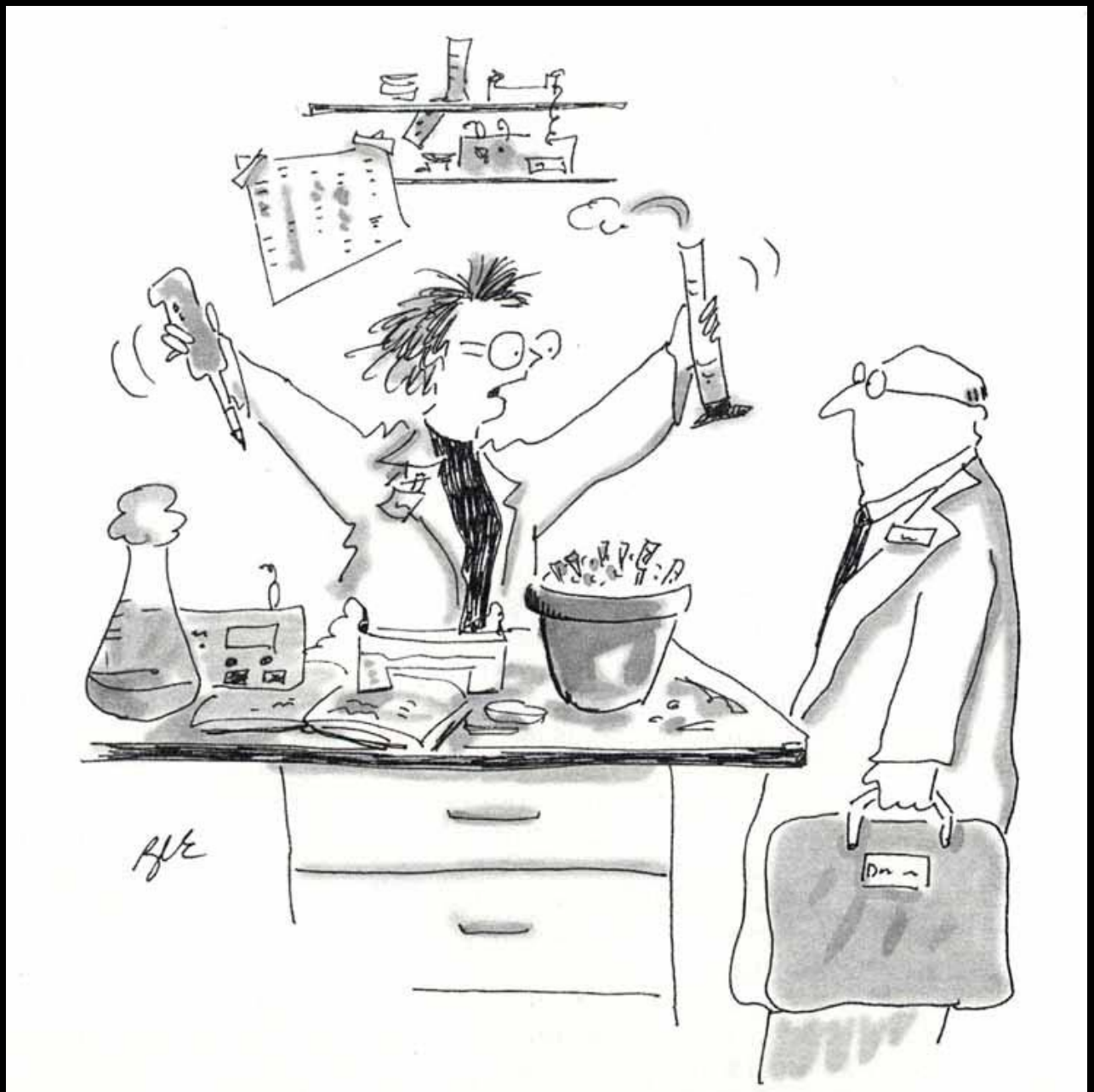


The Future …



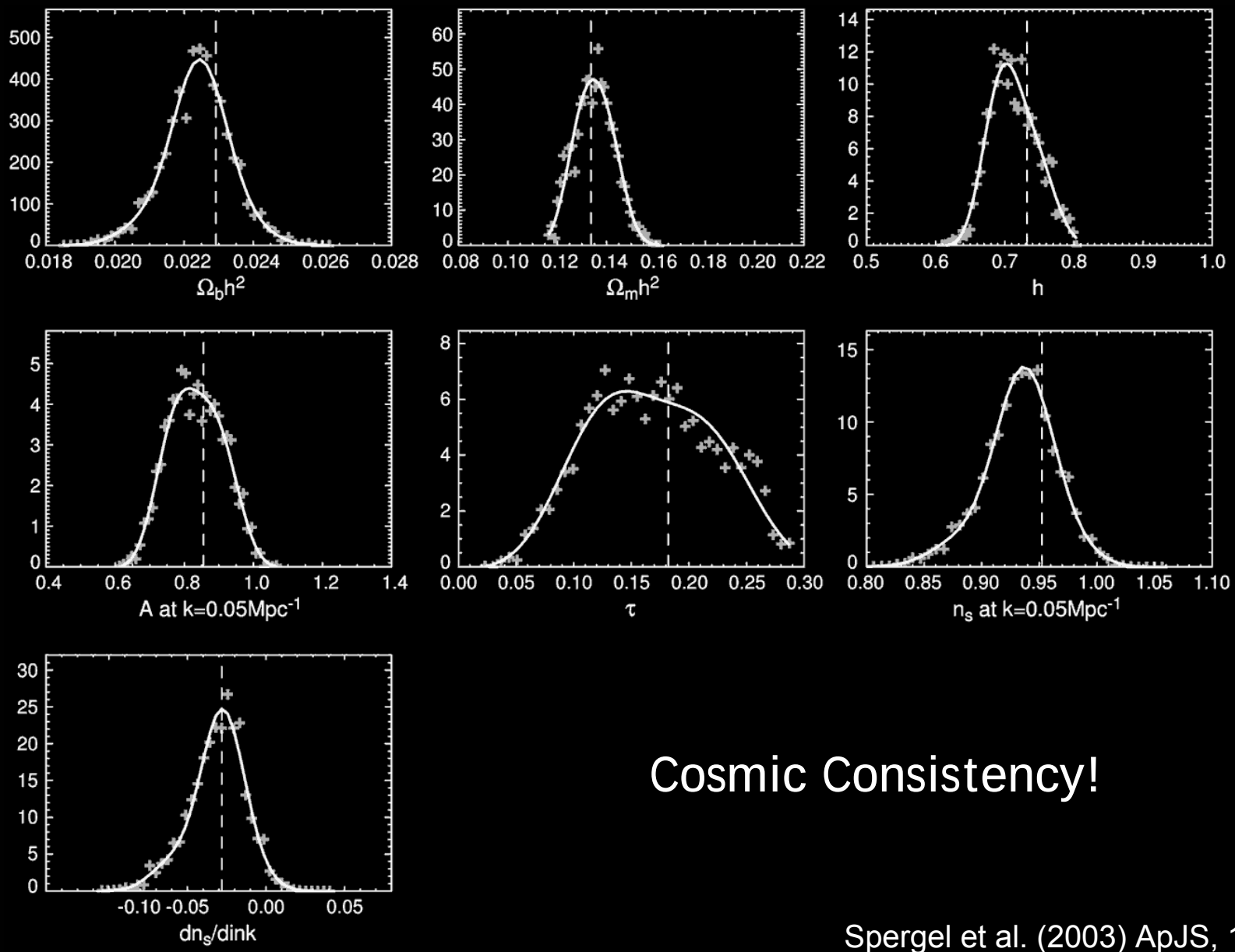
- WMAP continues to take data
  - Scheduled 4 years observations
  - Request for 8 years
- CMB Polarization
  - Over 20 current/planned measurements
  - Planck, Beyond Einstein Inflation Probe
- Data From Other Fields
  - Supernovae (NASA/DOE JDEM)
  - Galaxy Surveys
  - Lensing Surveys
  - Gravity waves (LIGO, LISA)
  - Particle Physics


THE END



"You can't keep running in here and demanding data every two years!"

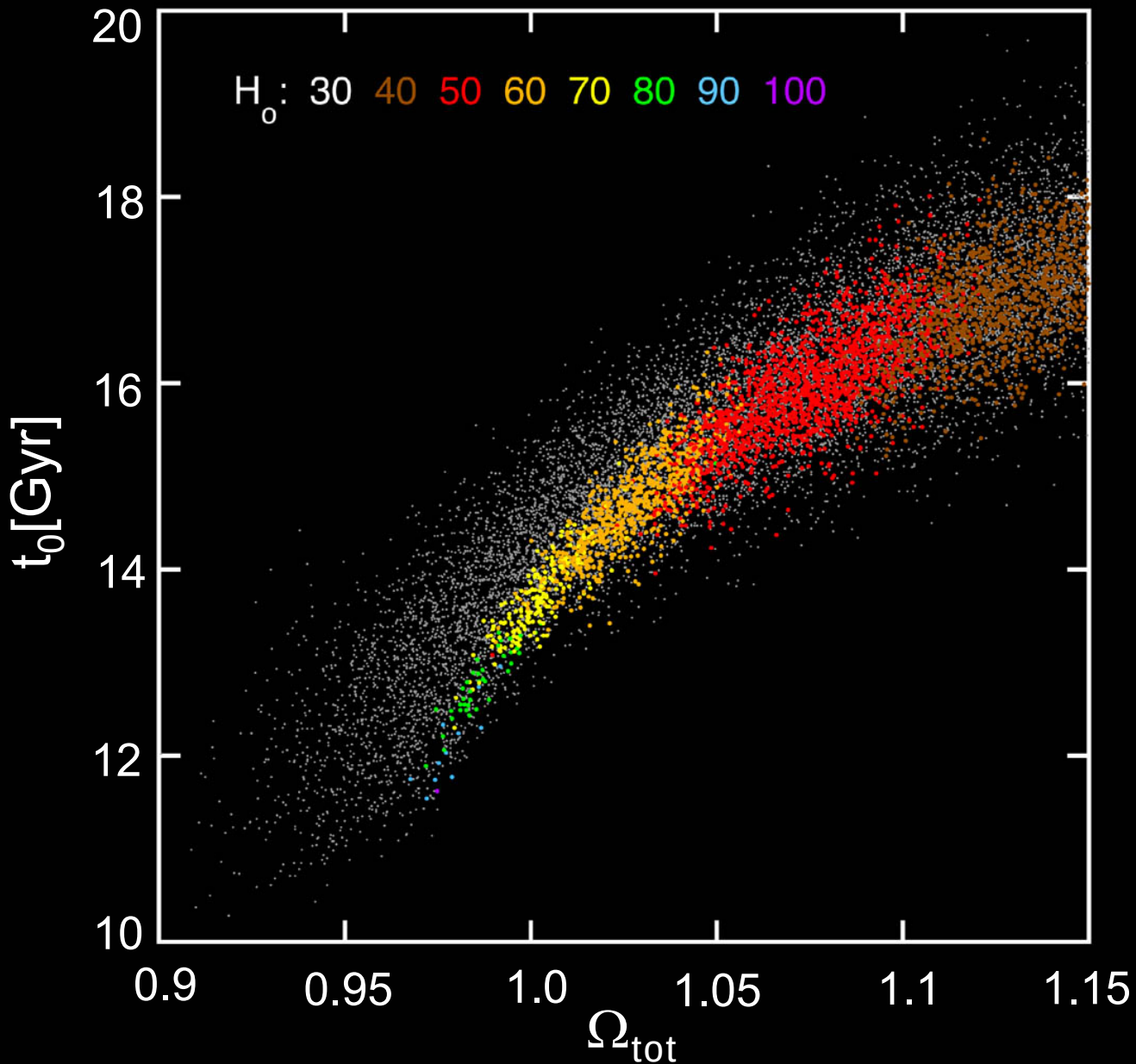
Parameter Likelihood Functions



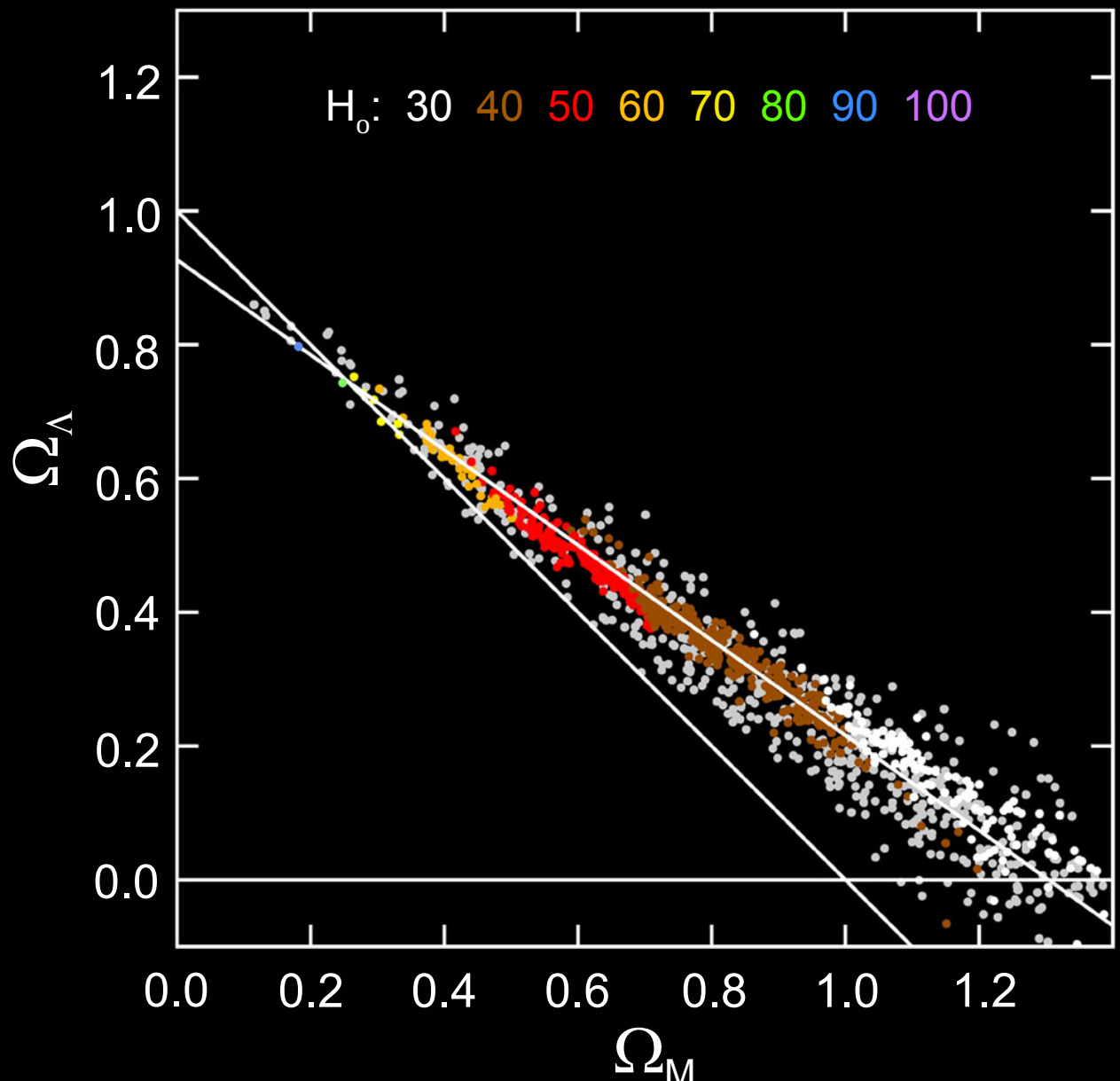
Cosmic Consistency!

Spergel et al. (2003) ApJS, 148, 175

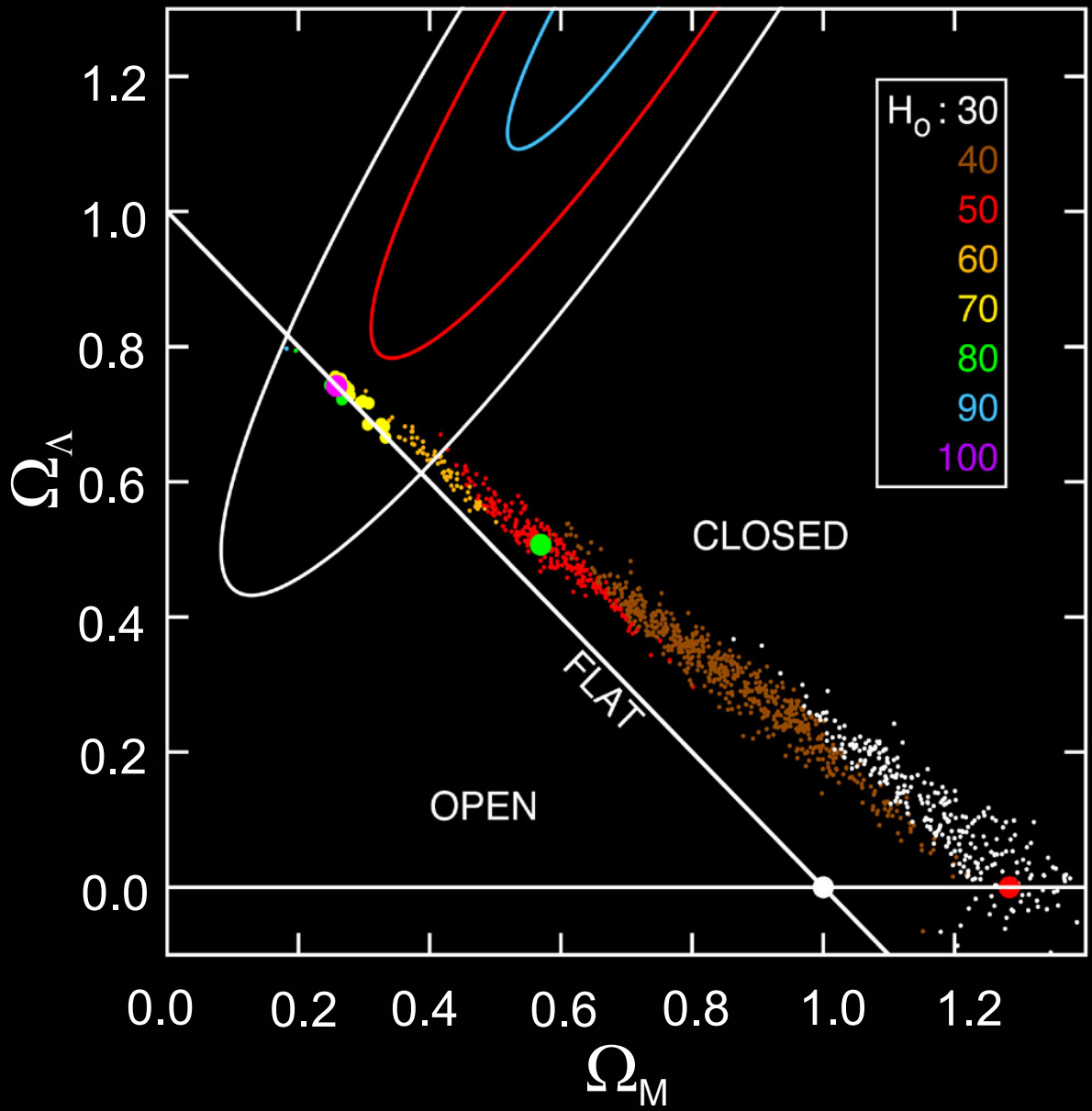
AGE OF THE UNIVERSE



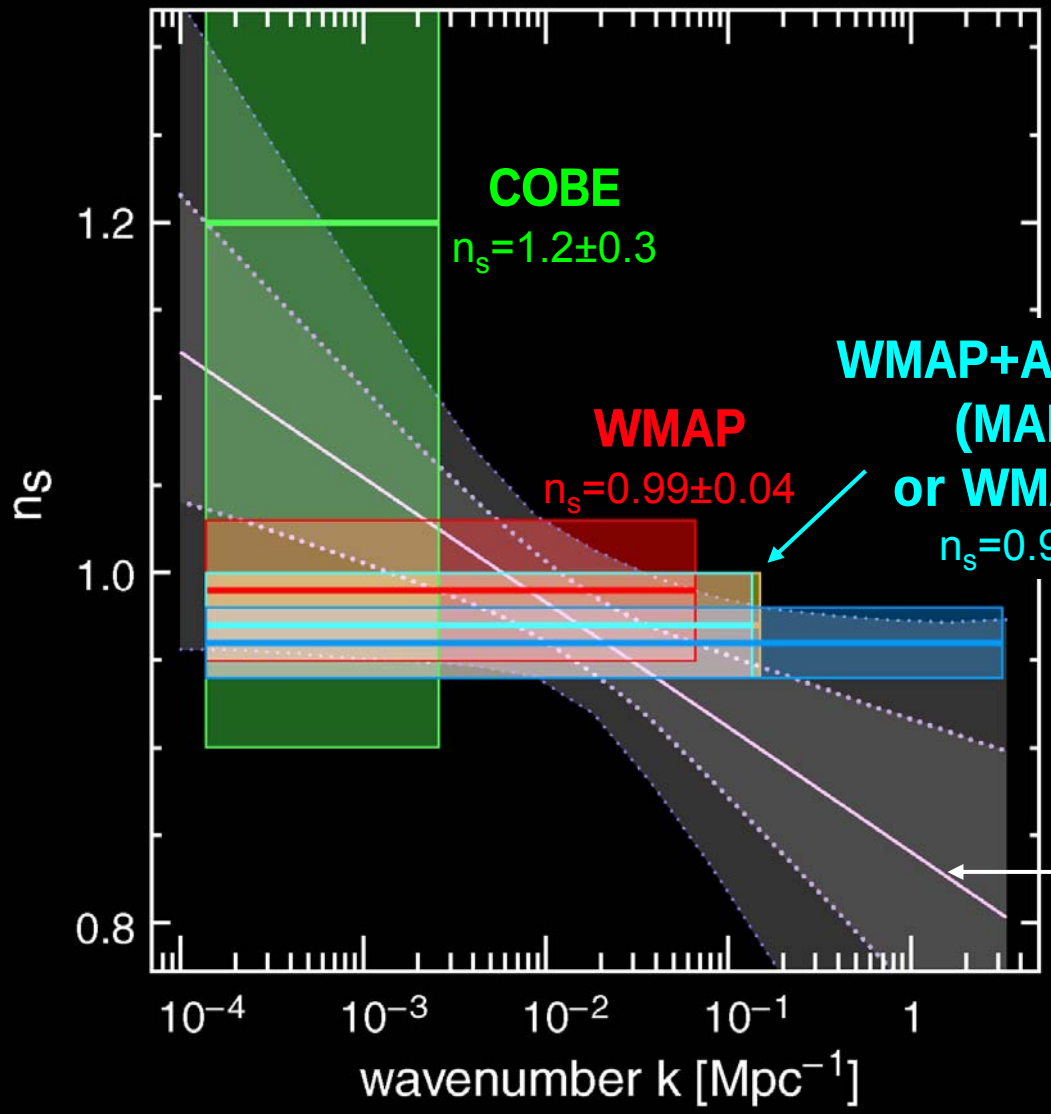
DARK ENERGY VS. MATTER



DARK ENERGY VS. MATTER



Inflation: A Running Spectral Index?



“Best” Cosmological Parameters Pg. 1

Description	Symbol	Value	+ uncertainty	- uncertainty
Total density	Ω_{tot}	1.02	0.02	0.02
Equation of state of quintessence	w	< -0.78	95% CL	—
Dark energy density	Ω_Λ	0.73	0.04	0.04
Baryon density	$\Omega_b h^2$	0.0224	0.0009	0.0009
Baryon density	Ω_b	0.044	0.004	0.004
Baryon density (cm^{-3})	n_b	2.5×10^{-7}	0.1×10^{-7}	0.1×10^{-7}
Matter density	$\Omega_m h^2$	0.135	0.008	0.009
Matter density	Ω_m	0.27	0.04	0.04
Light neutrino density	$\Omega_\nu h^2$	< 0.0076	95% CL	—
CMB temperature (K)[a]	T_{cmb}	2.725	0.002	0.002
CMB photon density (cm^{-3})[b]	n_γ	410.4	0.9	0.9
Baryon-to-photon ratio	η	6.1×10^{-10}	0.3×10^{-10}	0.2×10^{-10}
Baryon-to-matter ratio	$\Omega_b \Omega_m^{-1}$	0.17	0.01	0.01
Fluctuation amplitude in $8h^{-1}$ Mpc spheres	σ_8	0.84	0.04	0.04
Low-z cluster abundance scaling	$\sigma_8 \Omega_m^{0.5}$	0.44	0.04	0.05
Power spectrum normalization (at $k_0 = 0.05$ Mpc^{-1})[c]	A	0.833	0.086	0.083
Scalar spectral index (at $k_0 = 0.05$ Mpc^{-1})[c]	n_s	0.93	0.03	0.03

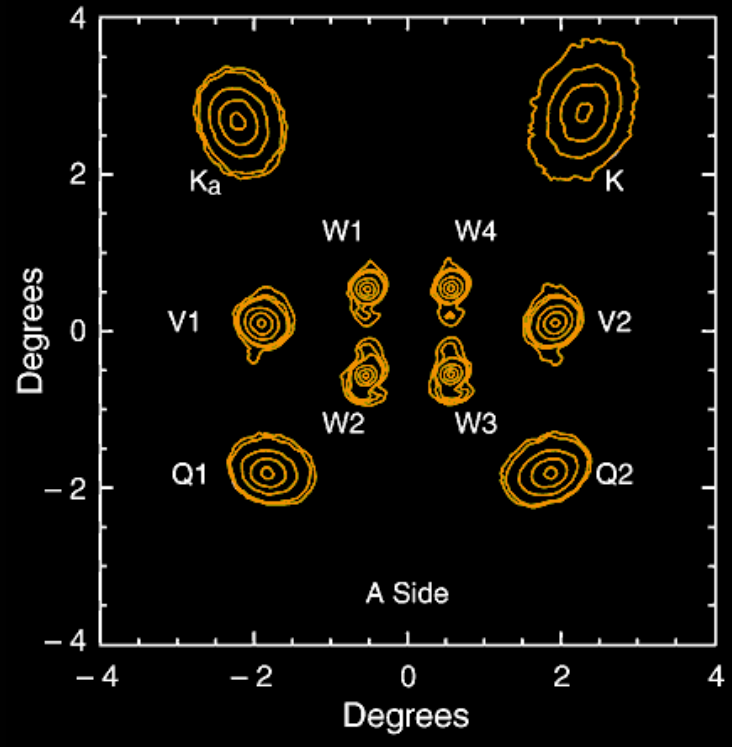
[a]from *COBE* (Mather et al. 1999) [b]derived from *COBE* (Mather et al. 1999) [c]$l_{eff} \approx 700$

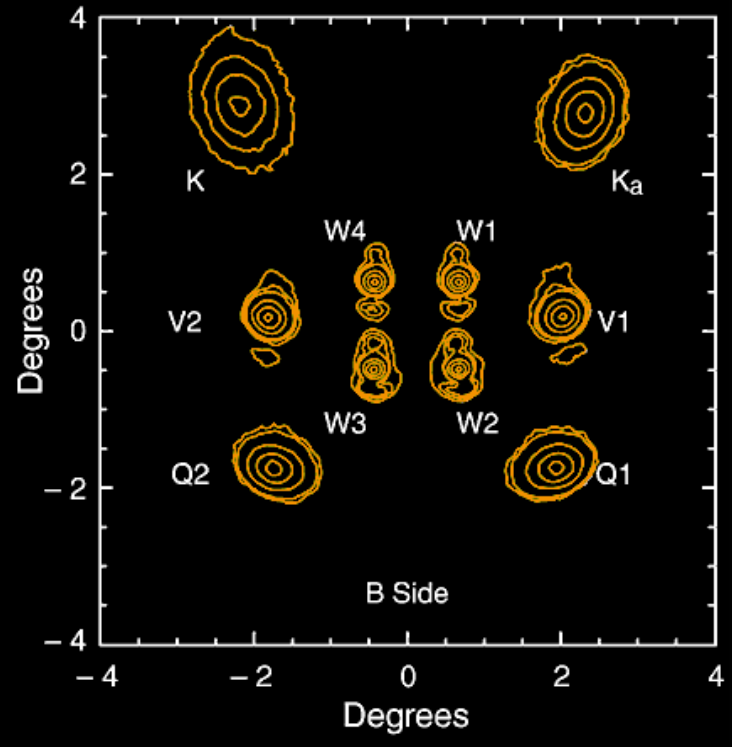
“Best” Cosmological Parameters Pg. 2

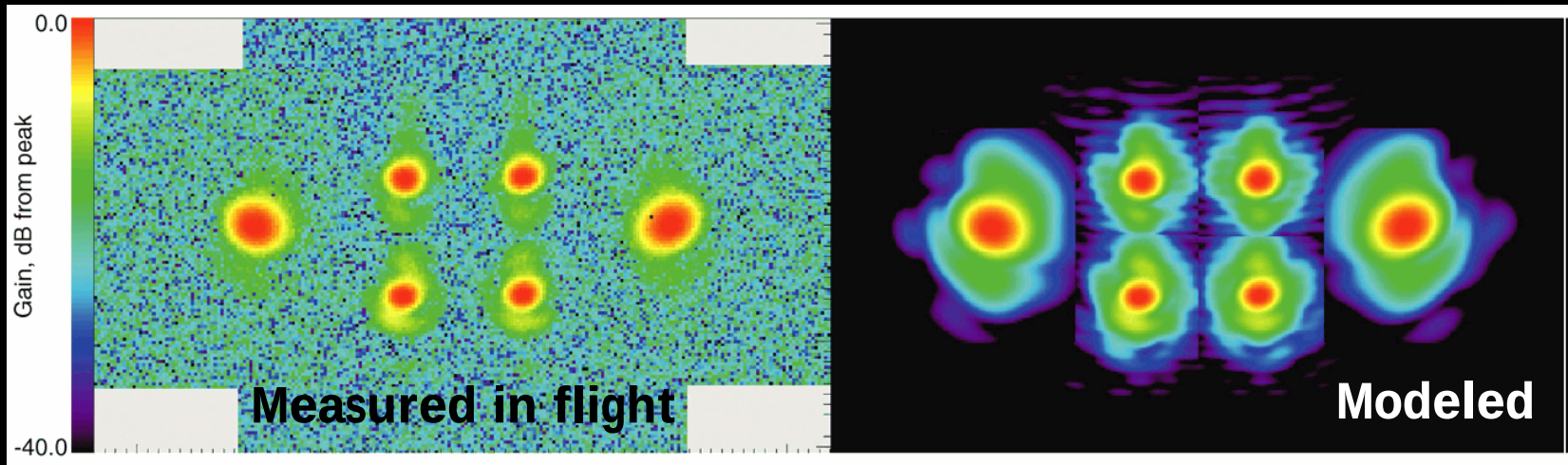
Description	Symbol	Value	+ uncertainty	- uncertainty
Running index slope (at $k_0 = 0.05$ Mpc^{-1})[c]	$dn_s/d\ln k$	–0.031	0.016	0.018
Tensor-to-scalar ratio (at $k_0 = 0.002$ Mpc^{-1})	r	< 0.90	95% CL	—
Redshift of decoupling	z_{dec}	1089	1	1
Thickness of decoupling (FWHM)	Δz_{dec}	195	2	2
Hubble constant	h	0.71	0.04	0.03
Age of universe (Gyr)	t_0	13.7	0.2	0.2
Age at decoupling (kyr)	t_{dec}	379	8	7
Age at reionization (Myr, 95% CL))	t_r	180	220	80
Decoupling time interval (kyr)	Δt_{dec}	118	3	2
Redshift of matter-energy equality	z_{eq}	3233	194	210
Reionization optical depth	τ	0.17	0.04	0.04
Redshift of reionization (95% CL)	z_r	20	10	9
Sound horizon at decoupling (°)	θ_A	0.598	0.002	0.002
Angular size distance (Gpc)	d_A	14.0	0.2	0.3
Acoustic scale[d]	ℓ_A	301	1	1
Sound horizon at decoupling (Mpc)[d]	r_s	147	2	2

[c] $l_{eff} \approx 700$ [d] $\ell_A \equiv \pi\theta_A^{-1}$ $\theta_A \equiv r_s\, d_a^{-1}$

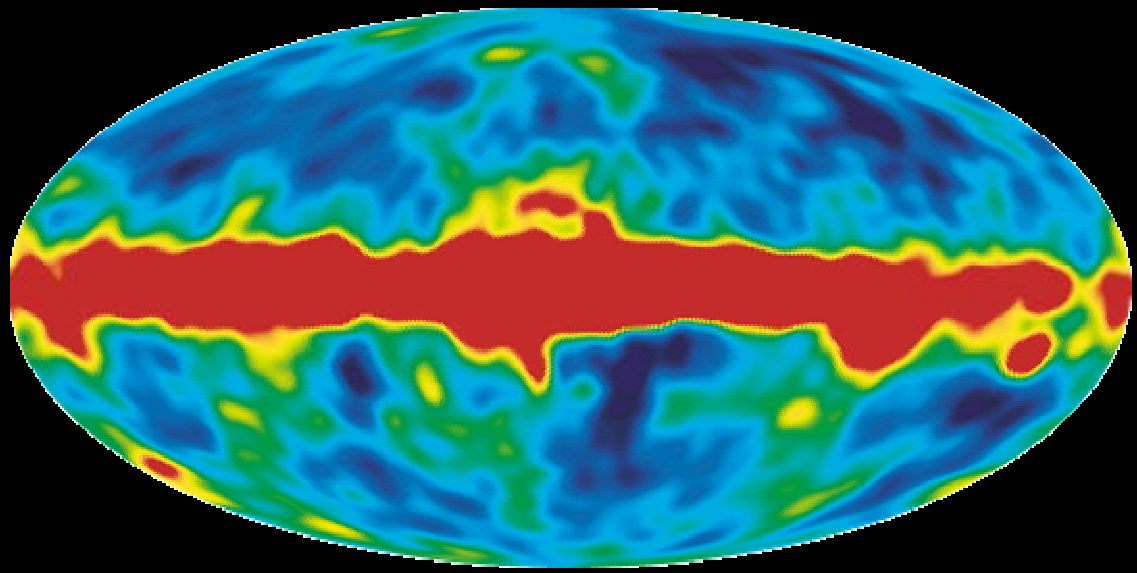
Jupiter Beam Maps







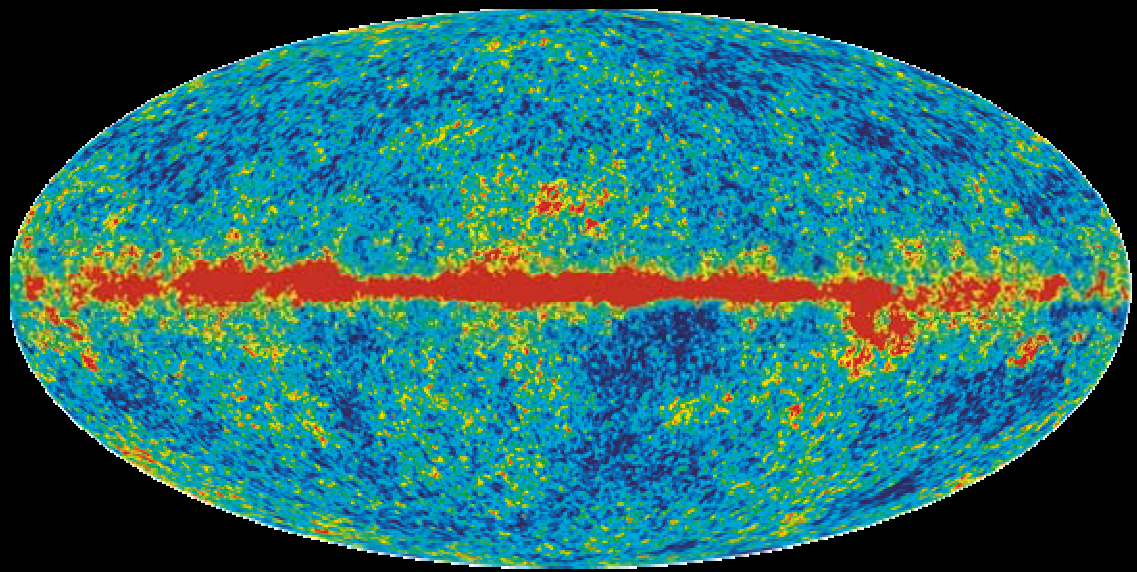
COBE-WMAP Comparison



COBE

-200 +200

Temperature (μK)



WMAP

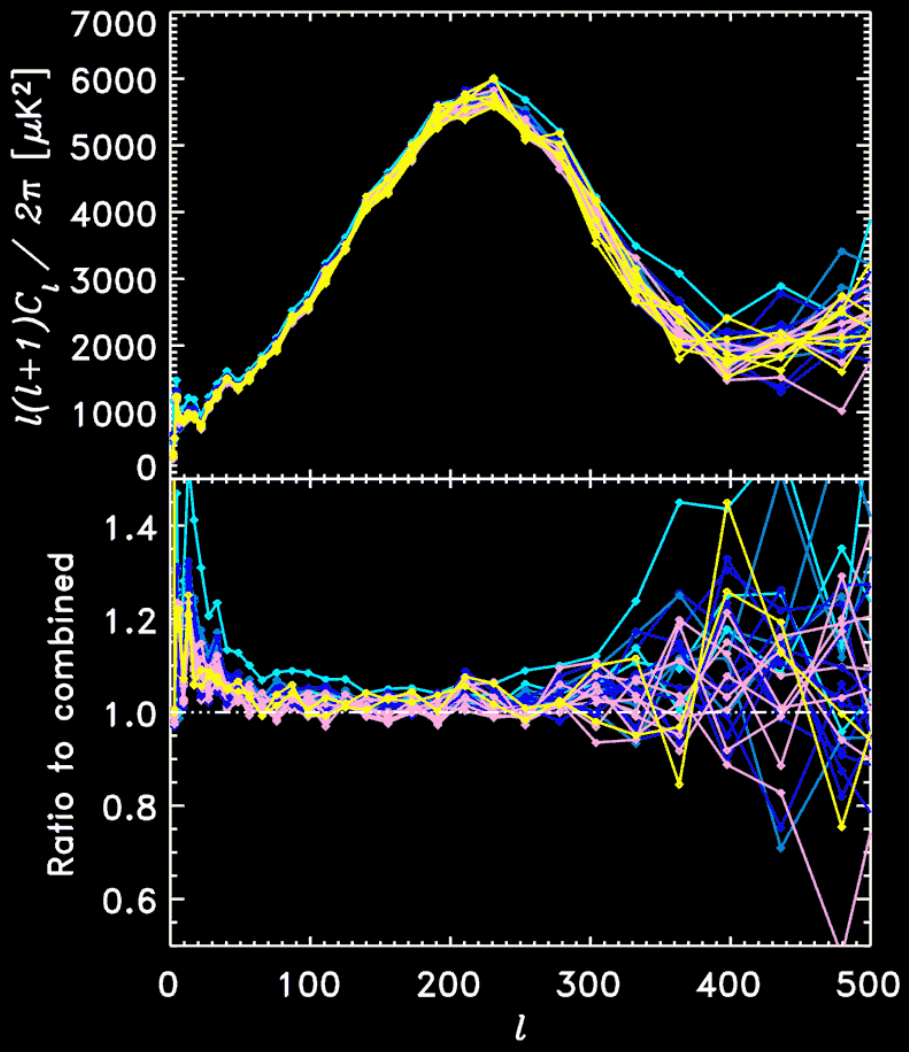
-200 +200

Temperature (μK)

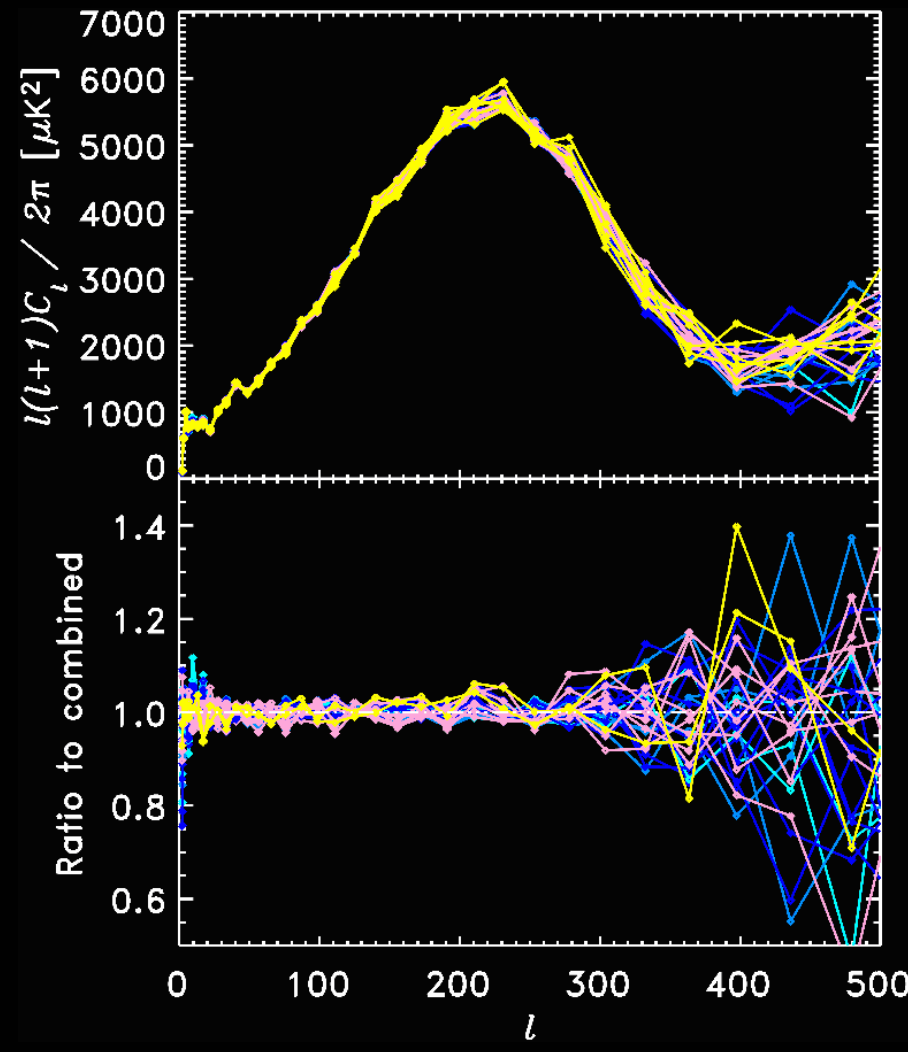
Bennett et al. (2003) ApJS, 148, 1

Power Spectrum

Before Galactic Subtraction

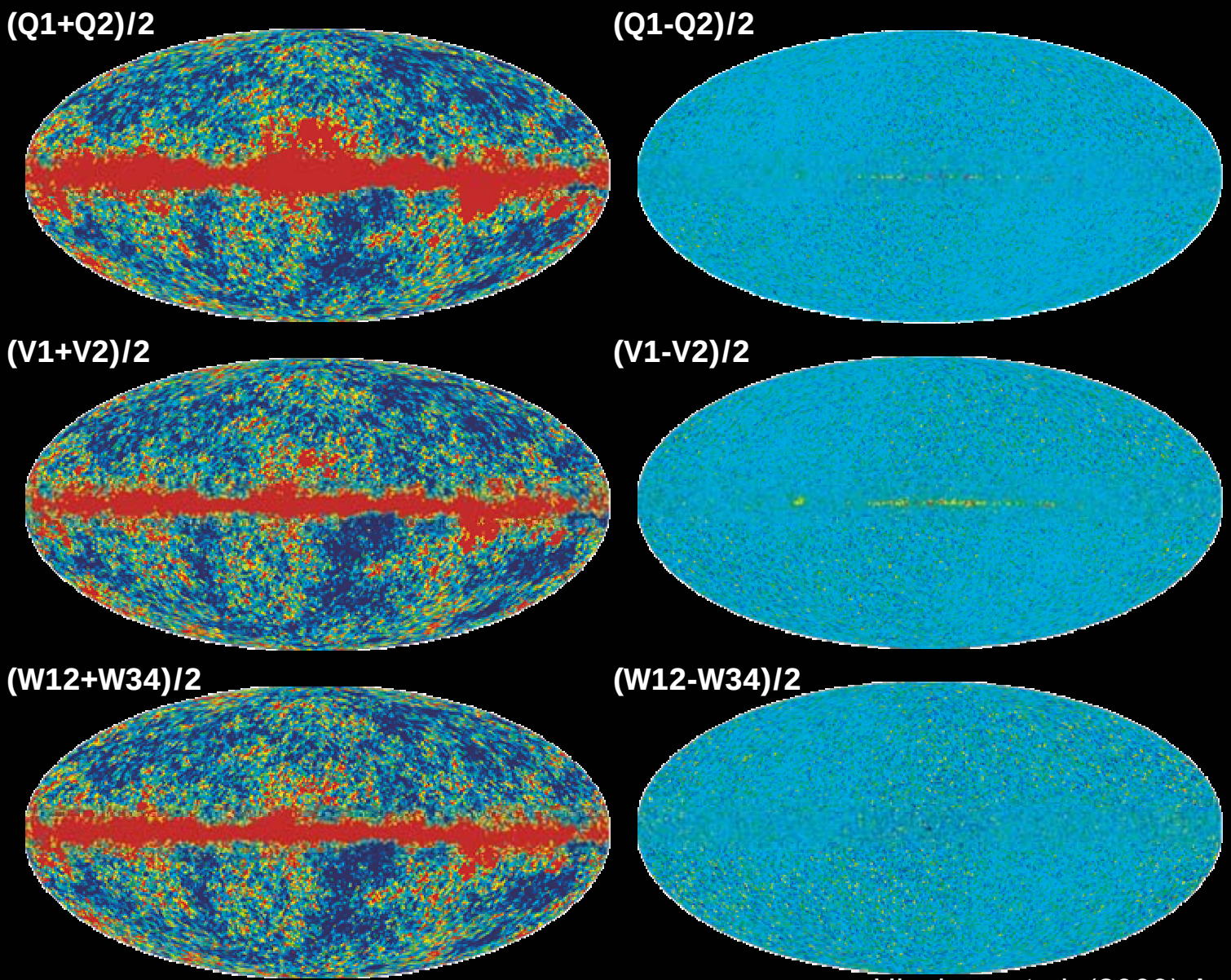


After Galactic Subtraction



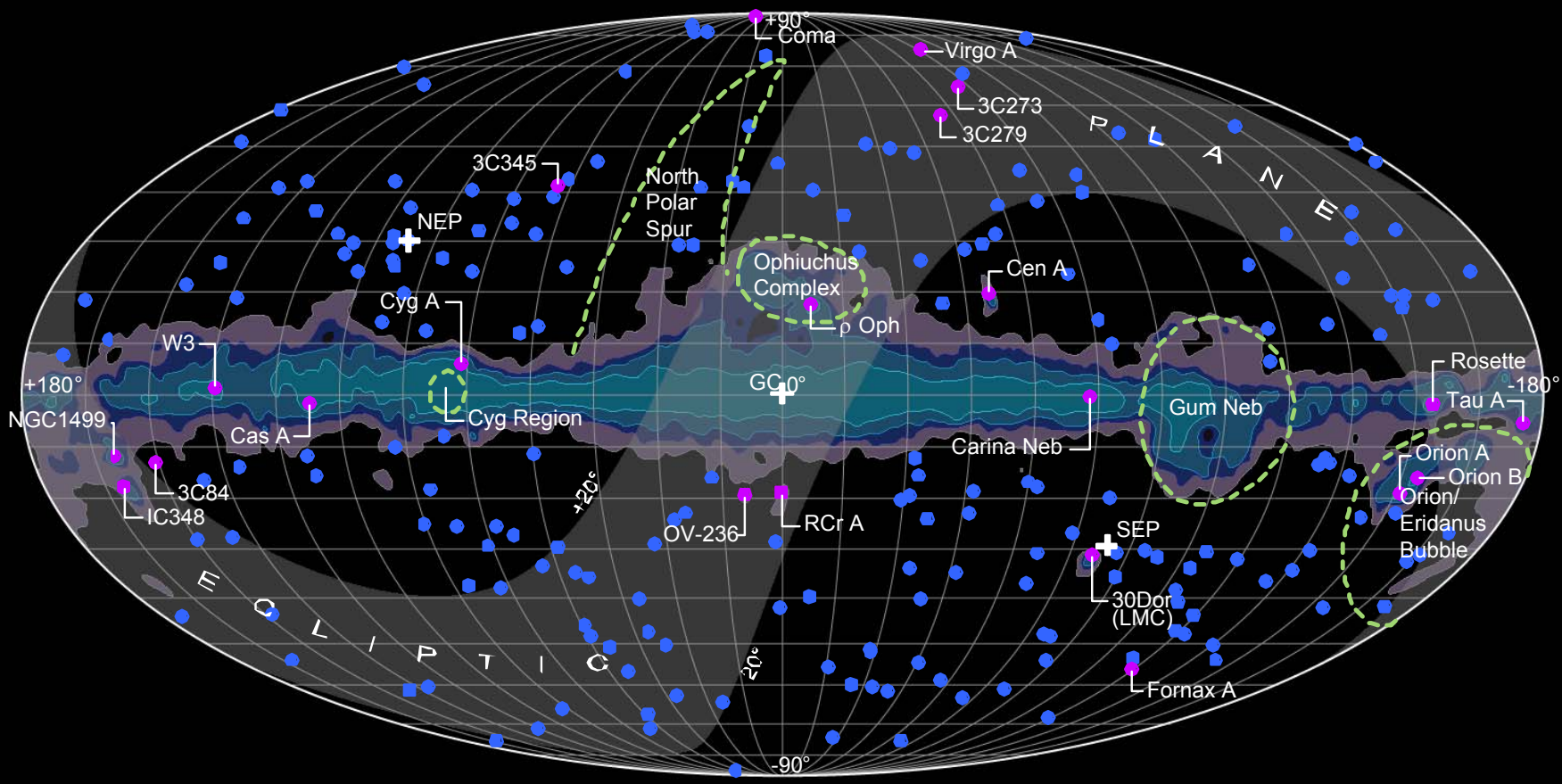
Hinshaw et al. (2003) ApJS, 148, 135

Systematic Error Cross-Checks



Hinshaw et al. (2003) ApJS, 148, 63

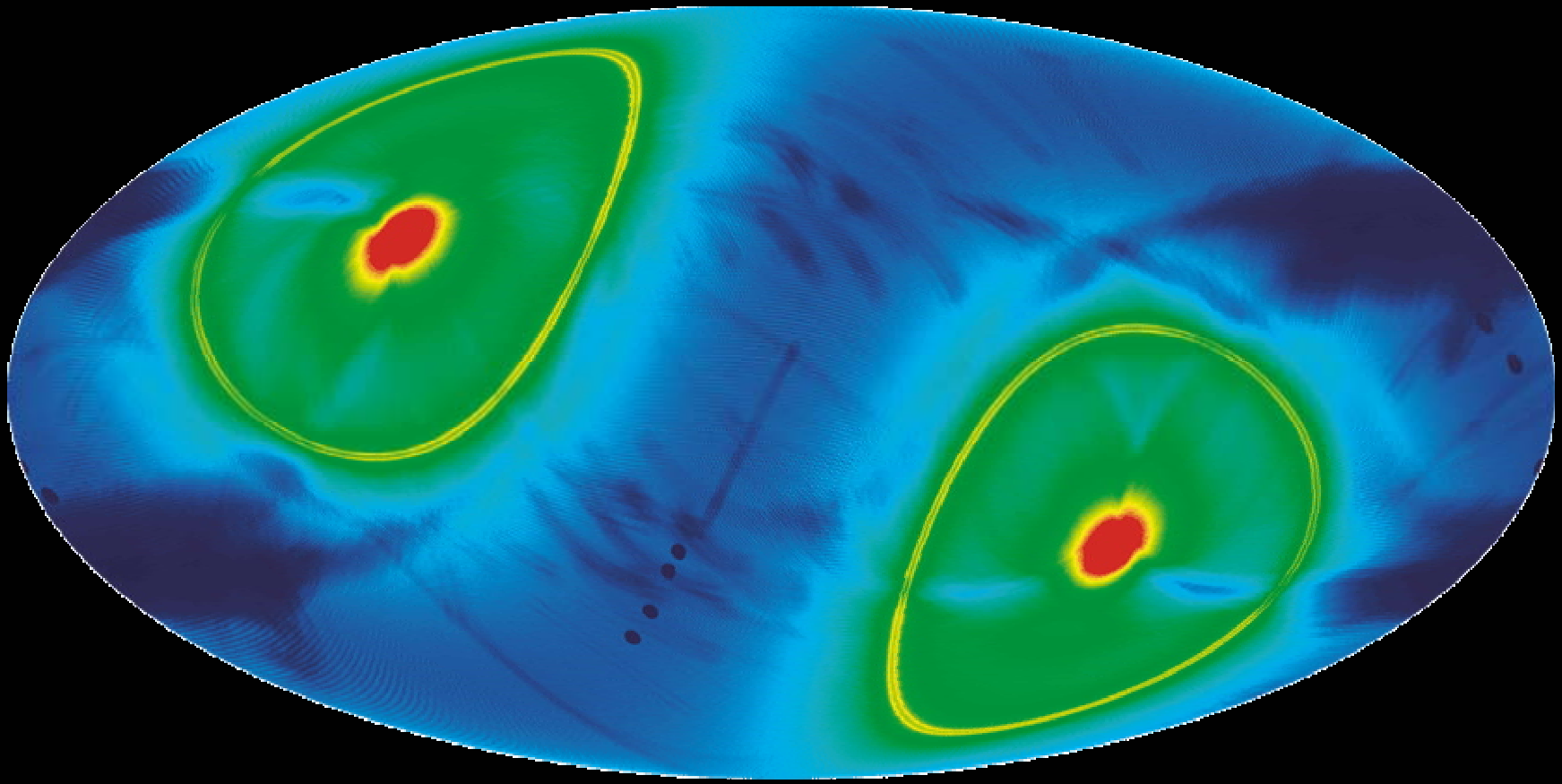
Full Sky Guide

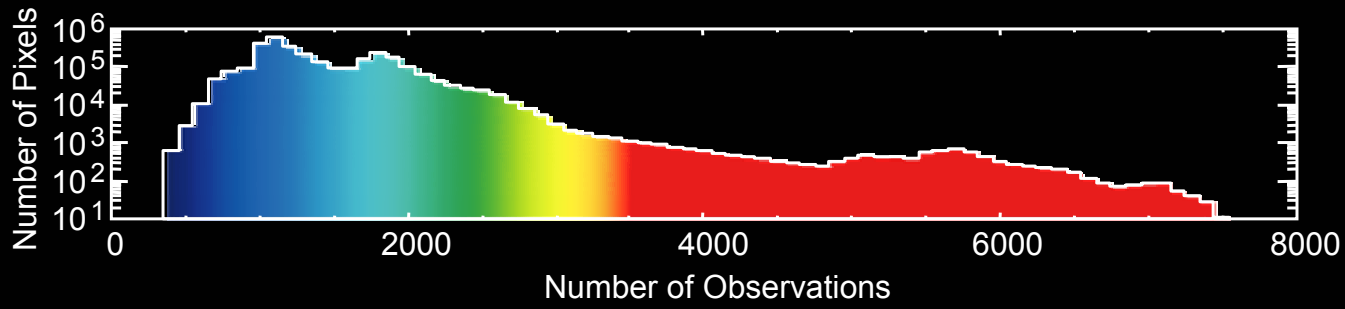


● WMAP-detected point sources (● brightest)

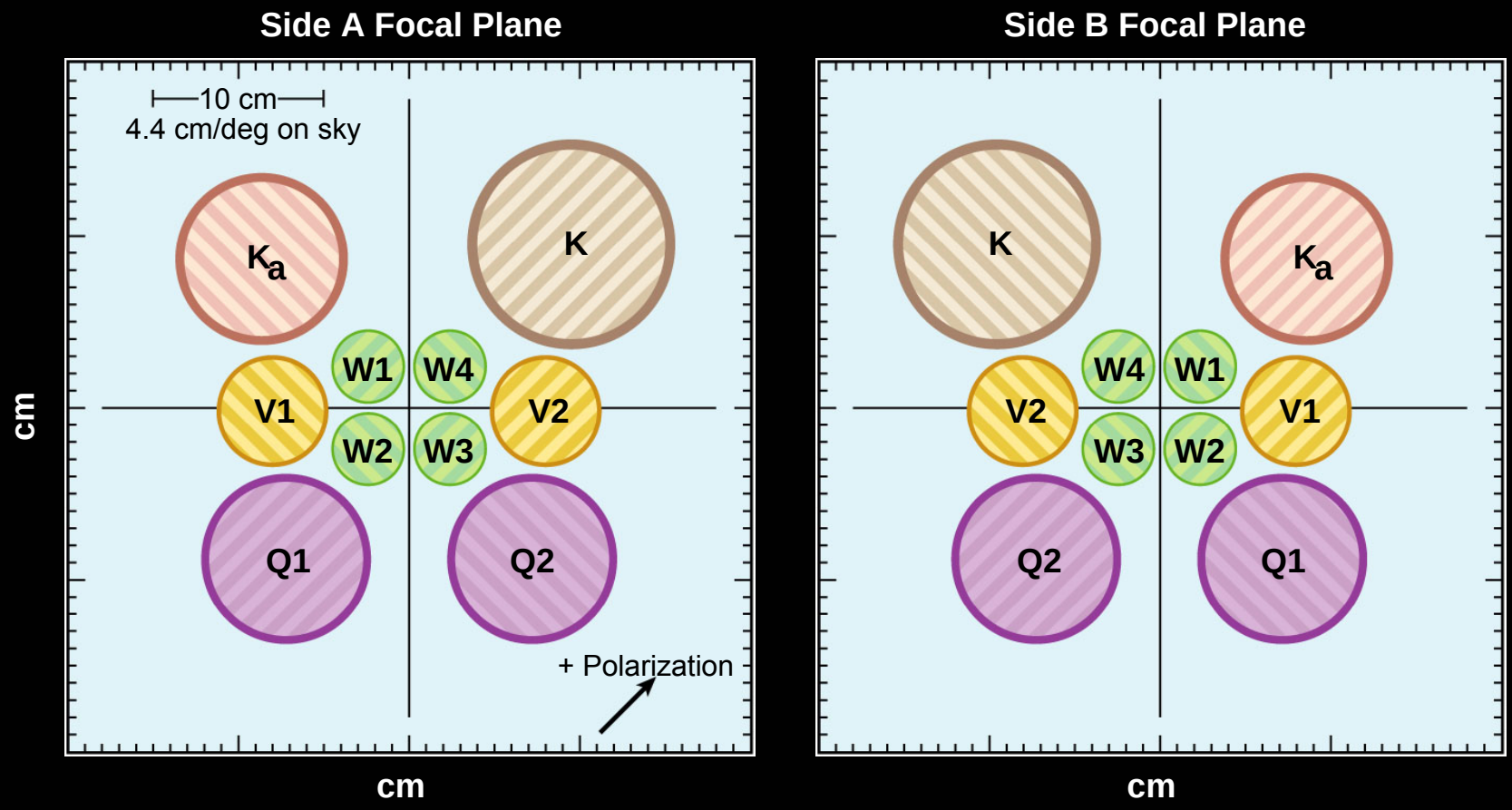
Bennett et al. (2003) ApJS, 148, 1

Number of Observations/Pixel





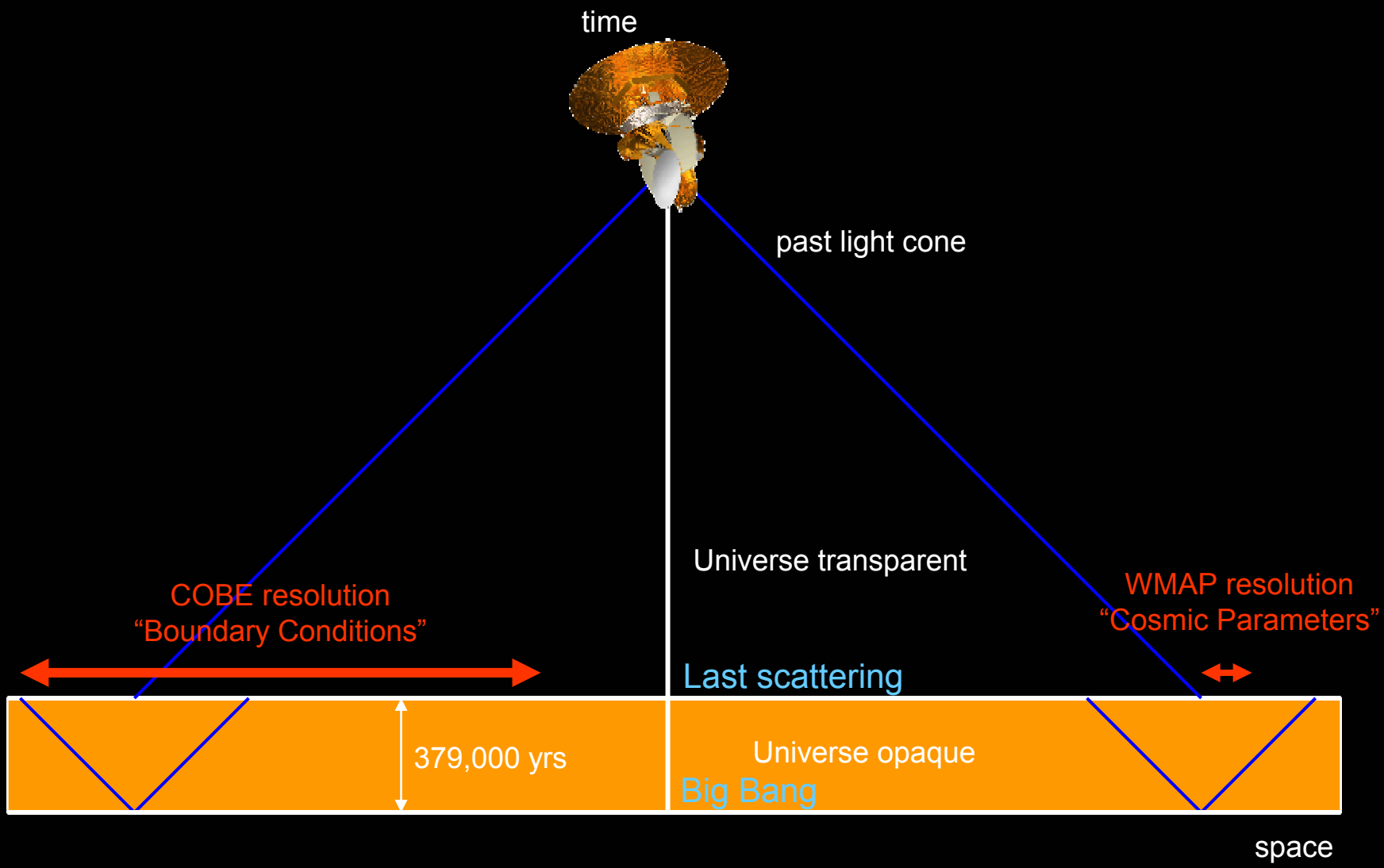
Feed Horn Arrangement in Focal Plane



- View looking at feeds from secondary
- Side A is +y direction, Side B is -y direction
- E-plane polarization shown for longitudinal OMT port (radiometer side 1)

Space-time of CMB Physics

(NOT to scale)

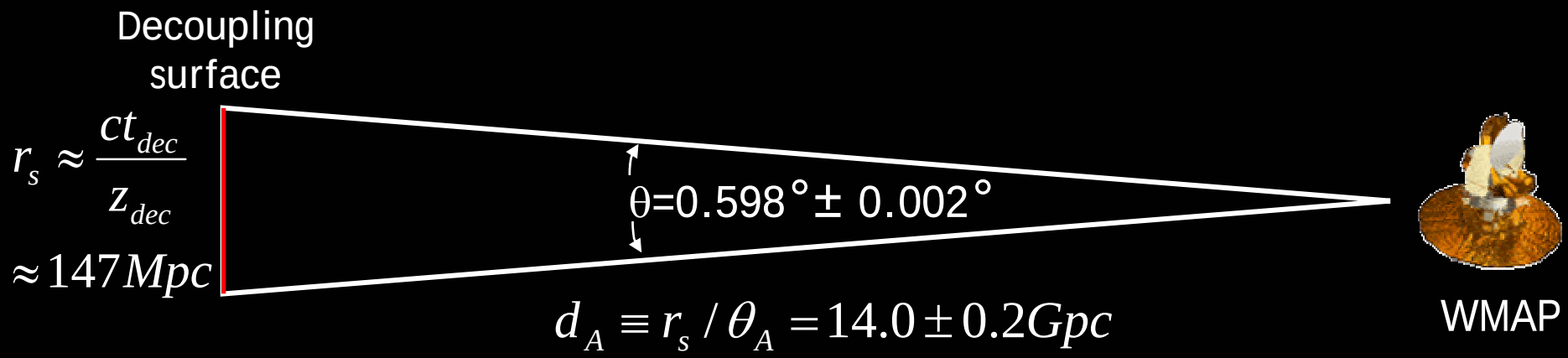


Viewing the Decoupling Surface

- Ratio of heights of 1st and 2nd peaks gives baryon density:

$$\Omega_b h^2 = 0.0224 \pm 0.0009$$

- Baryon density determines $t_{dec} = 379^{+8}_{-7}$ kyrs, $z_{dec} = 1089 \pm 1$
- Sound horizon ~ct_{dec} (size of blobs)



LEGACY ARCHIVE FOR MICROWAVE BACKGROUND DATA ANALYSIS

"One Stop Shopping for CMB Researchers"

LAMBDA Highlights

Data Products
- WMAP
- COBE
- Relikt
- IRAS
- SWAS

CMB Related Data
- Space Experiments
- Suborbital
- Foreground
- LSS Links

CMB Toolbox
- CMBFAST
- HEALPix
- Coordinate Conv.
- more...

Outreach
- News & Updates
- Latest CMB Papers

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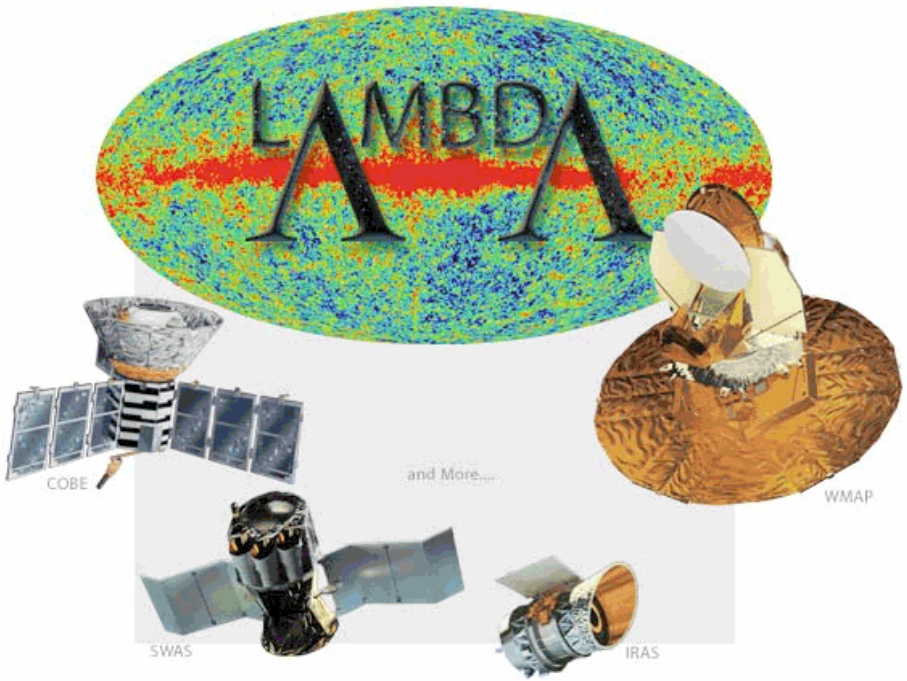


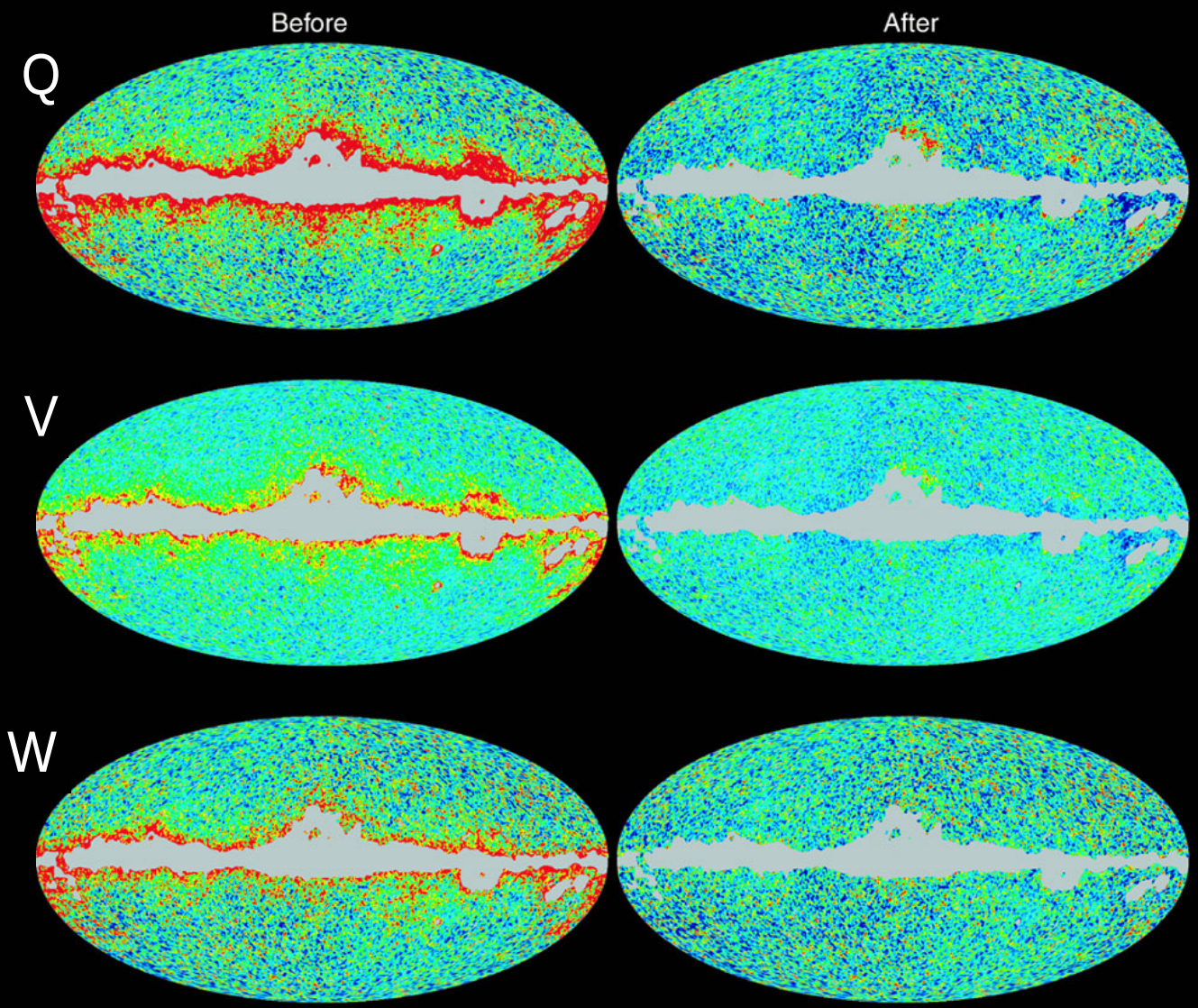
http://lambda.gsfc.nasa.gov

Research QuickLinks

Other Archives	IPAC, MAST, HEASARC, CDS, NED, NSSDC, NVO
Theory Sites	Banday, Berkeley, CPAC, Hu, MAP, Scott, Tegmark, TAC, White, Wright
Experimental Sites	ACBAR, APACHE, Archeops, ATCA, BAM, BOOMERanG, CAT, CBI, CG, DASI, more...
Journals	astro-ph, AASTeX, ADS, ApJ, ArXive, Blackwell Science, MNRAS, New Astronomy, more...
Useful Links	Encyc. of Astronomy & Astrophysics, Physical Constants, Reference Desk, more...
NASA Community	NASA, ARC, DFRC, GRC, GSFC, JPL, JSC, KSC, LRC, MSFC, SSC, WFF, OSS, more...

Page updated: Monday, 02-10-2003

Foreground Template Removal



Bennett et al. (2003) ApJS, 148, 97

CMB Anisotropy Power Spectra

Dependence on Cosmological Parameters