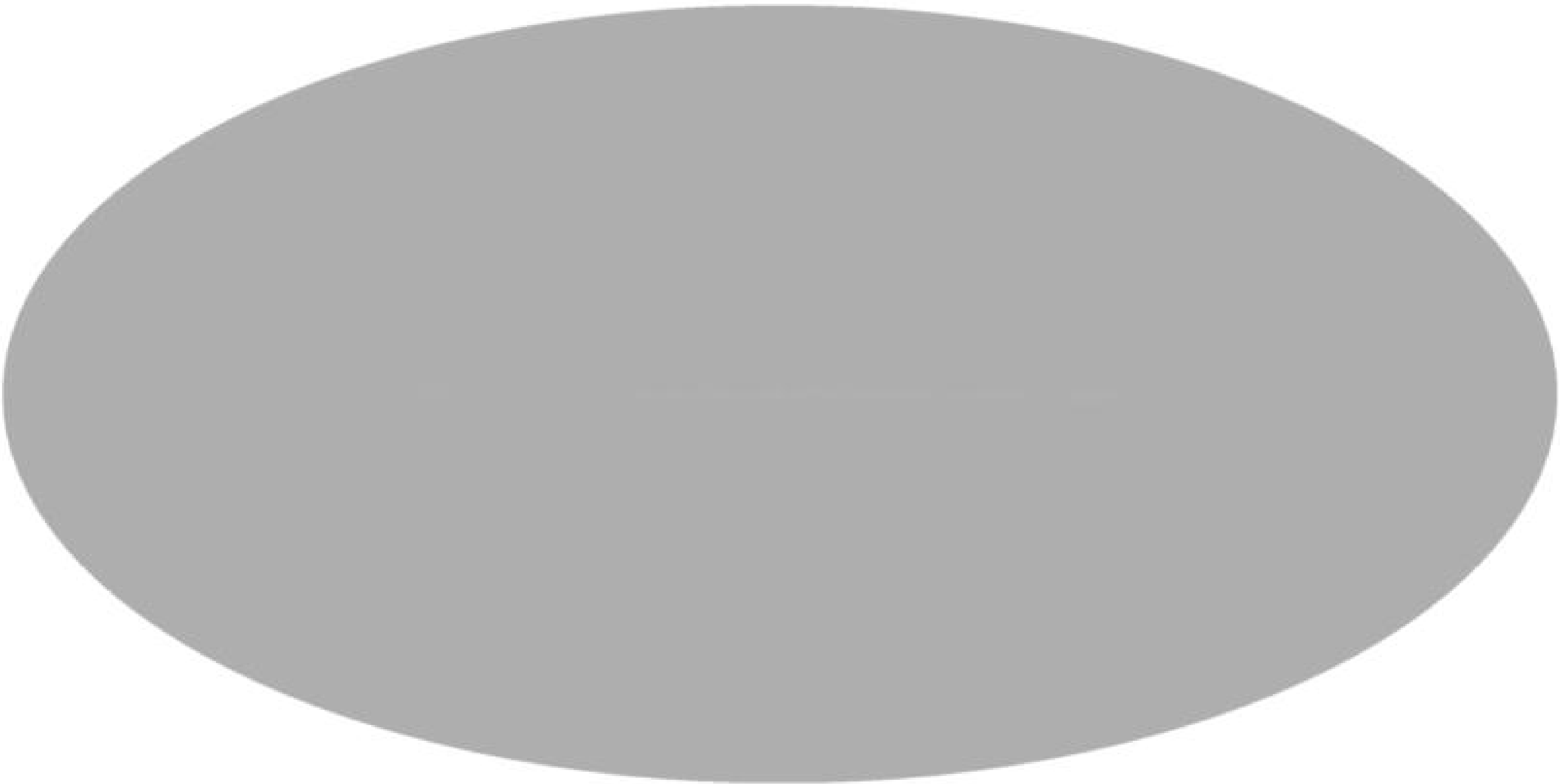
CMB Anisotropy

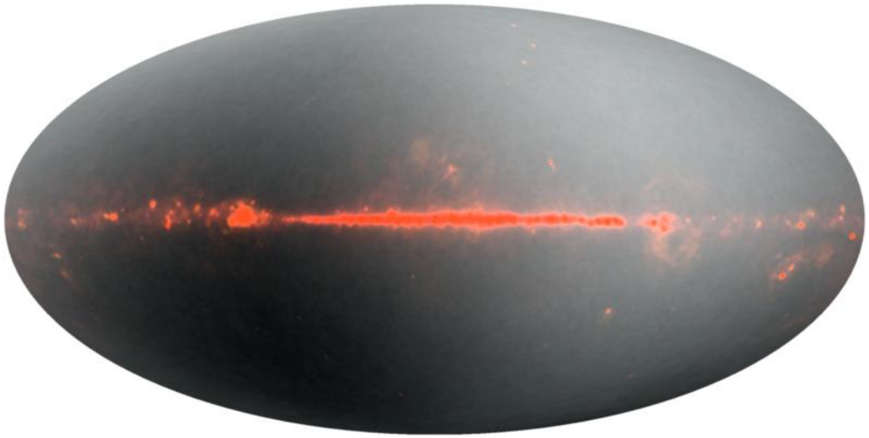
Ned Wright, UCLA

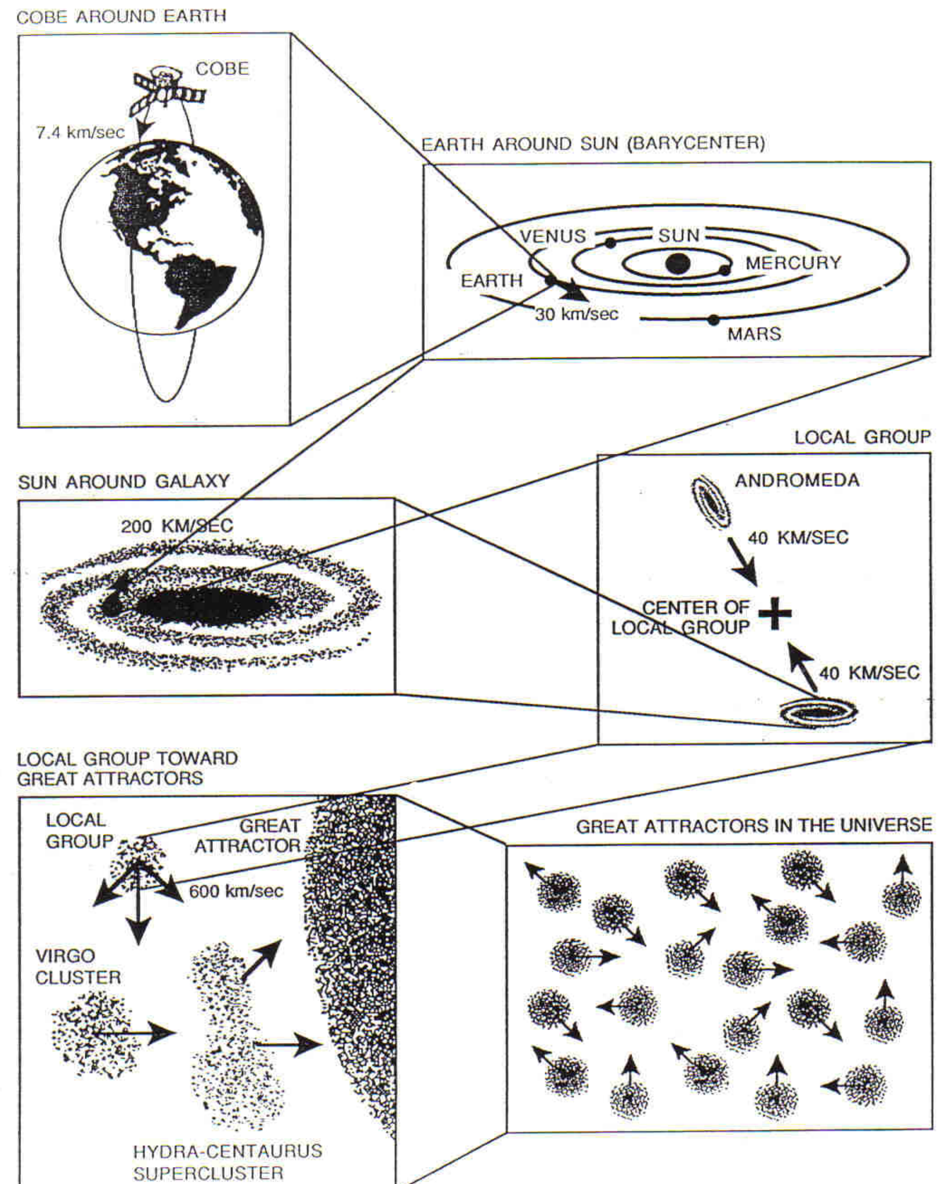
True Contrast CMB Sky



33, 41 & 94 GHz as RGB, 0-4 K scale

Enhanced Contrast:





- Conklin 1969 - 2σ
- Henry 1971 - 3σ
- Corey & Wilkinson 1976 - 4σ
- Smoot *et al.* 1977 - 6σ

Personal History: Anisotropy

rom: BONNIE::WRIGHT "Ned Wright - (213)825-5755" 17-AUG-19
91 19:18:36.02
To: 6938::CBSWG
CC: WRIGHT
Subj: DMR

COBE SWG only: 8/17/91

I have analyzed the preliminary 1 year DMR maps by making a linear combination to give a "no galaxy" map. The results are presented here, and are quite consistent with unbiased CDM. There is probably a real quadrupole in the data.

From: BONNIE::WRIGHT "Ned Wright - (213)825-5755" 6-OCT-1991 23:37:13.50
To: 6955::BENNETT
CC: WRIGHT
Subj: DMR

10/6/91

Chuck,

I have been working on the new 1 year maps. I include a bunch on analyses following this message. It looks like a 10 sigma detection of an Harrison-Zeldovich spectrum with an amplitude corresponding to a quadrupole of 15 microK. The "No Galaxy" map is noisier but agrees with the 53A+B.

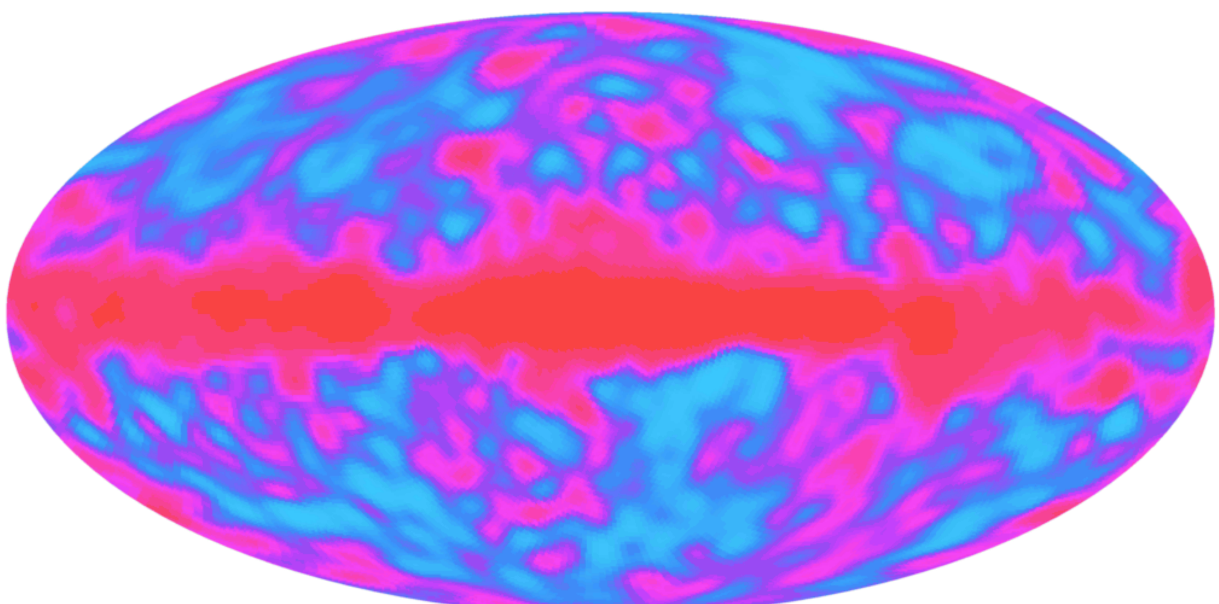
-Ned Wright-

A Big Media Splash in 1992:

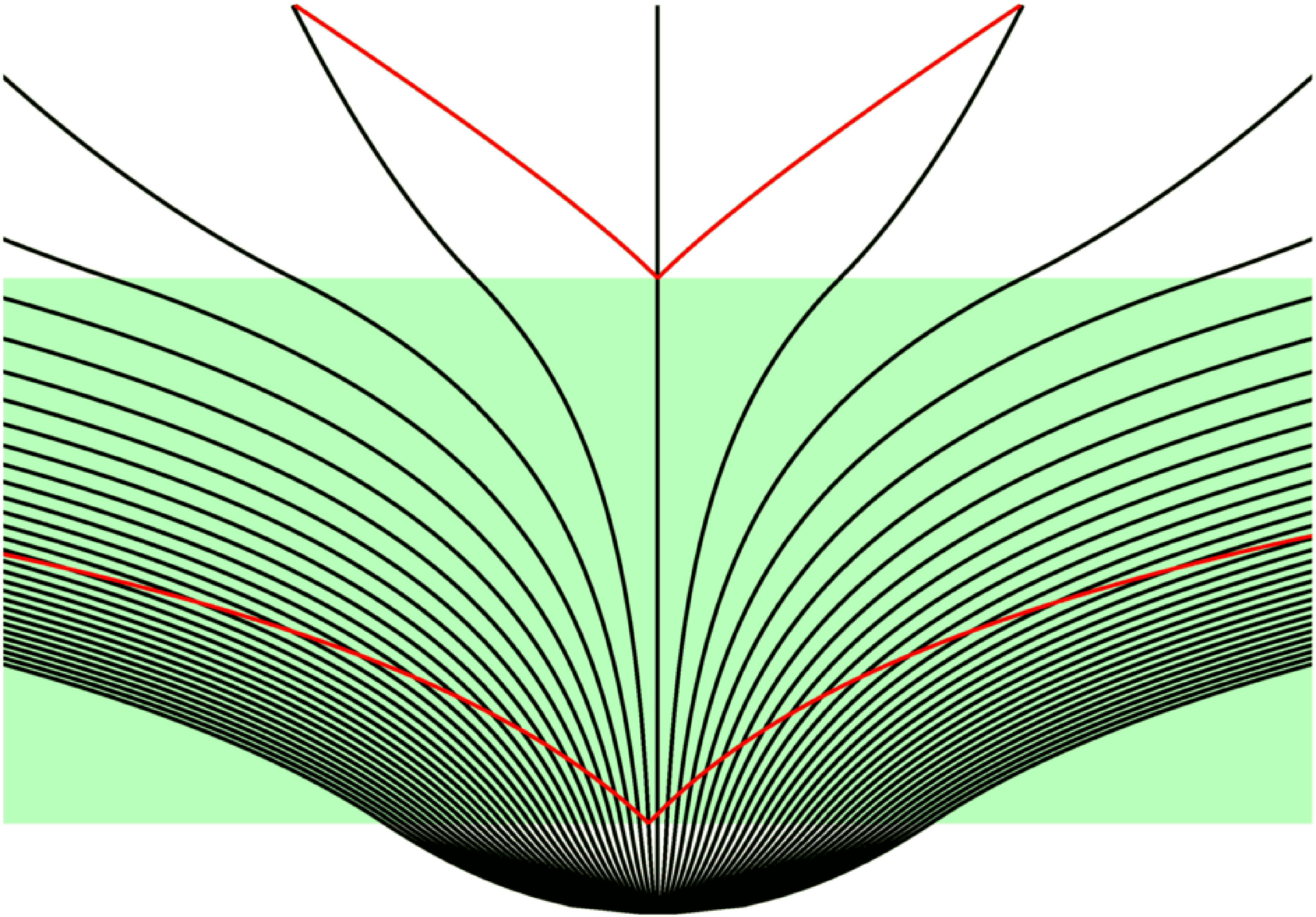
THE TIMES

25 April 1992

Prof. Stephen Hawking of Cambridge University, not usually noted for overstatement, said: “It is the discovery of the century, if not of all time.”

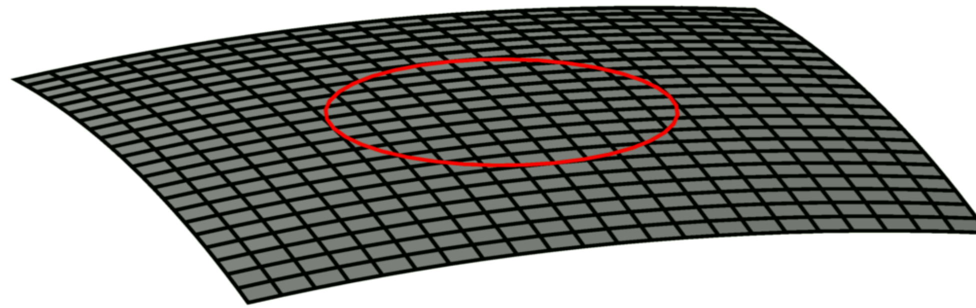


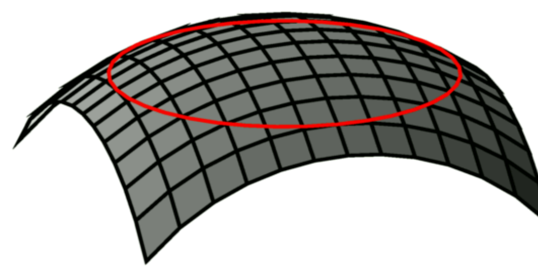
Inflation: Repulsion → exponential growth



Solving Horizon & Flatness-Oldness

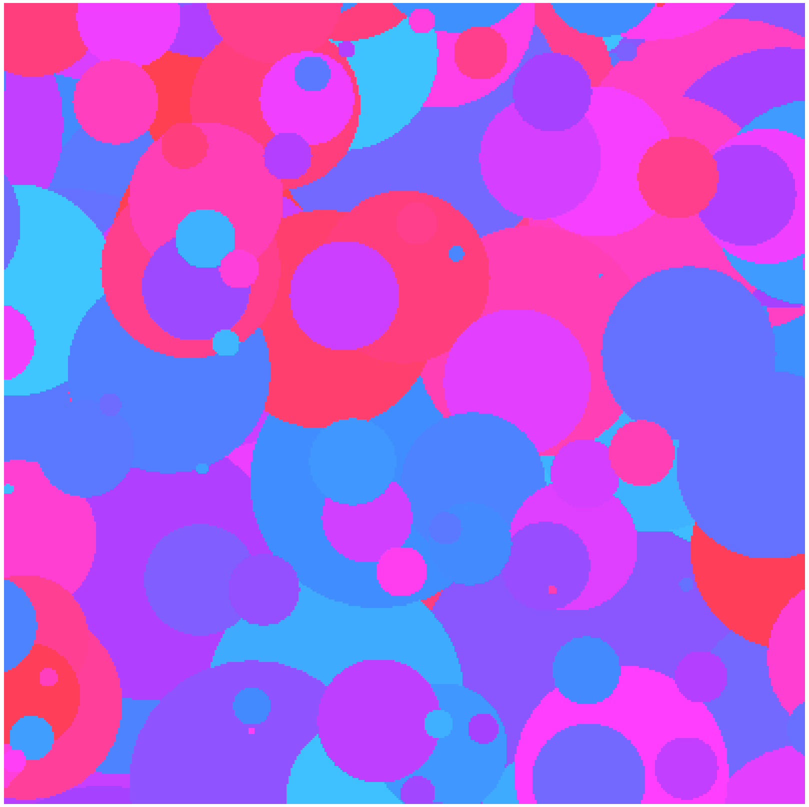
- A small patch grows to be bigger than the observable Universe. T=const is explained.
- Whatever the curvature of the patch may be, it will look flat. Density=critical is explained.





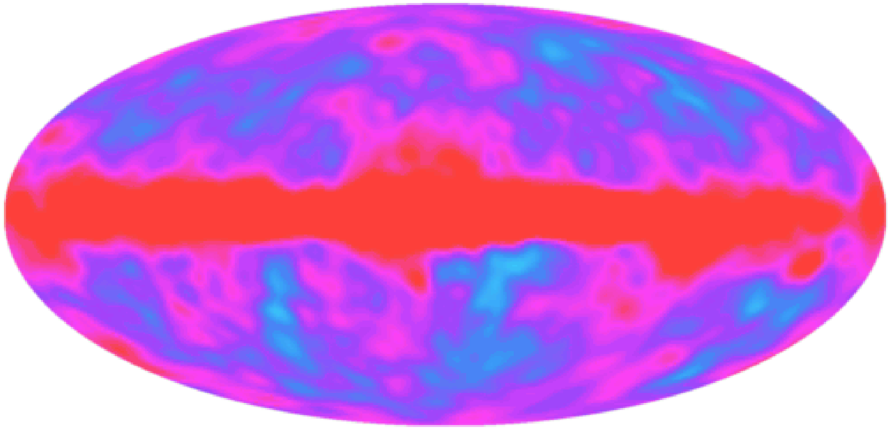
Animated View of Inflation

- Quantum fluctuations occur uniformly throughout space-time
- Future light cones have radii of (c/H)[exp(HΔt)-1]
- As small circles become large, new small circles are formed.
- Equal Power on All Scale - EPAS

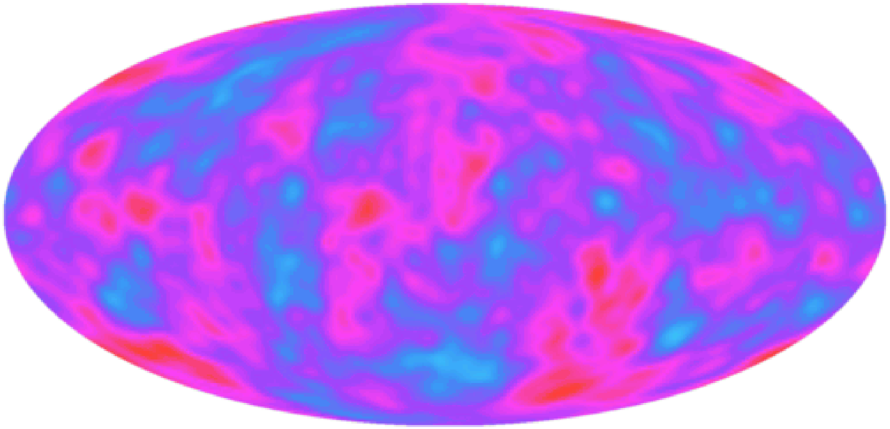


COBE DMR vs EPAS

COBE Data

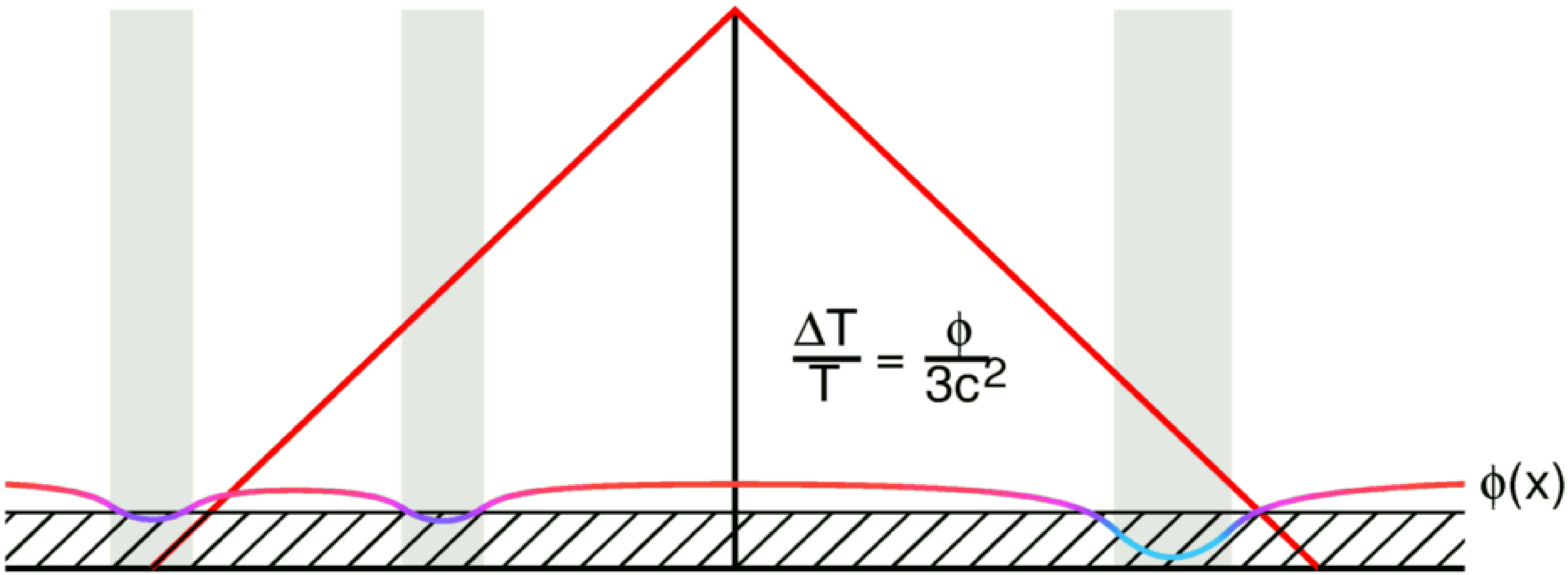


Equal Power on All Scales Model

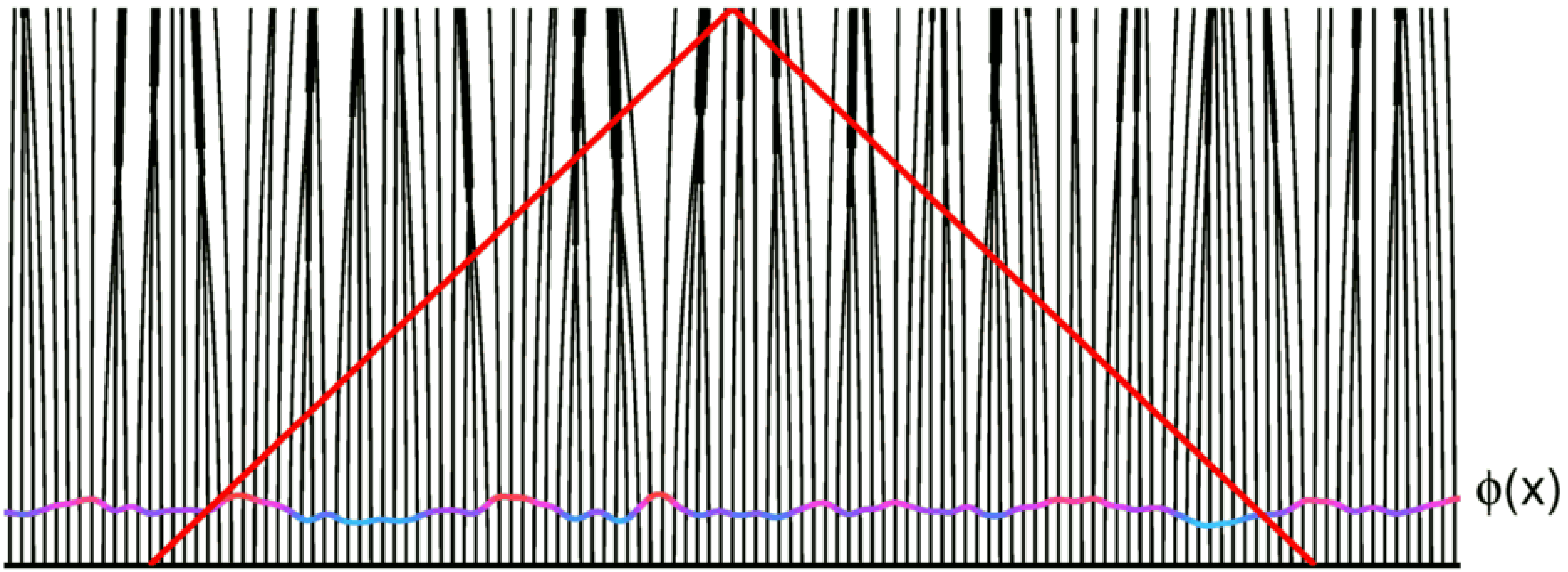


"Chi-by-eye" suggests that the "Equal Power on All Scales" prediction of inflation is correct.

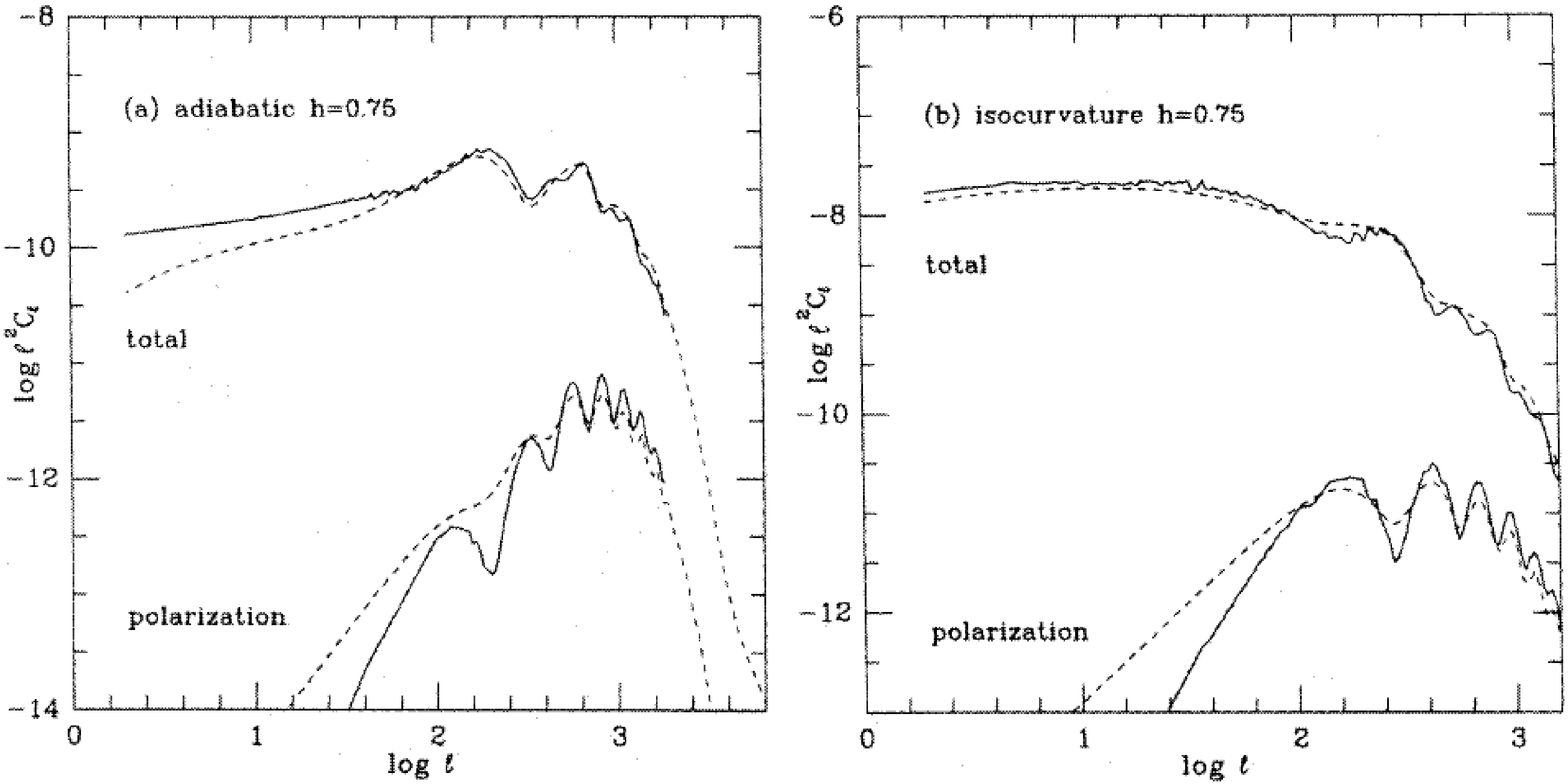
Sachs-Wolfe Effect



Measured Δϕ Leads to Structure



Prediction of Doppler Peaks:

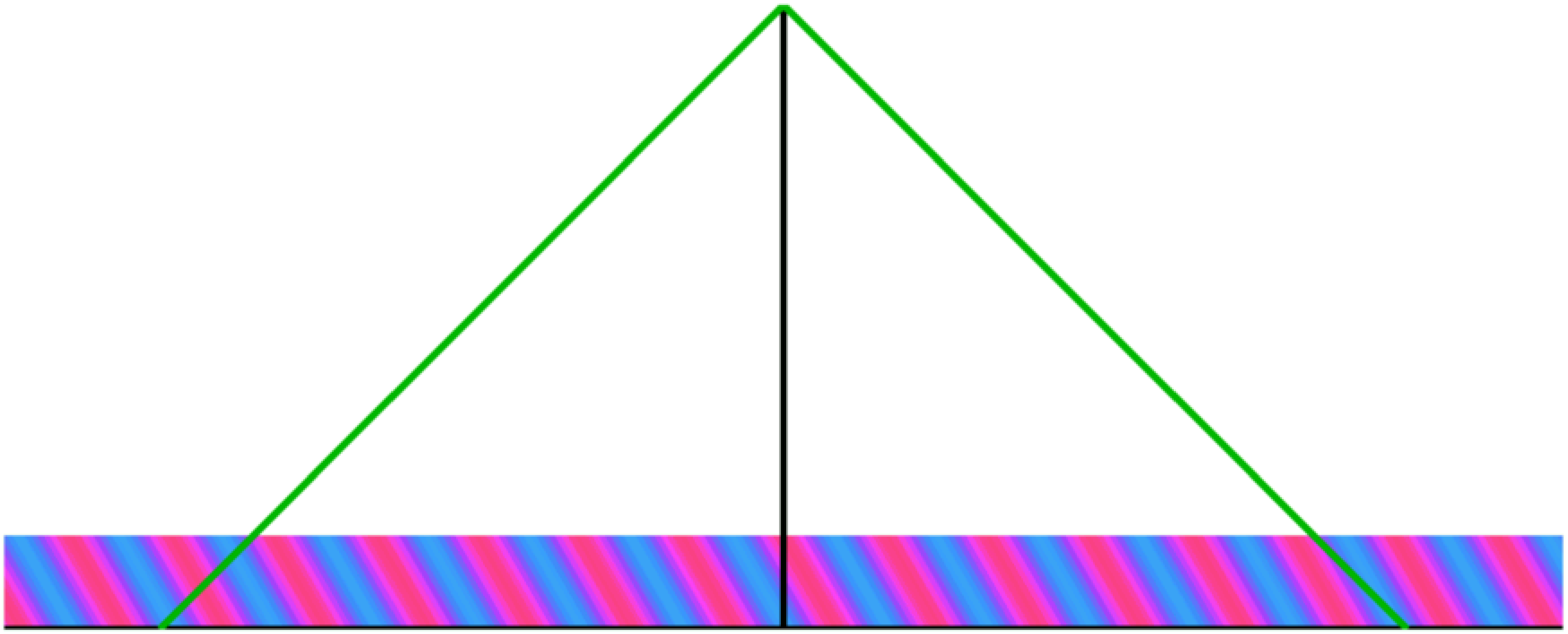


From Bond & Efstathiou, 1987, MNRAS, 226, 655-687

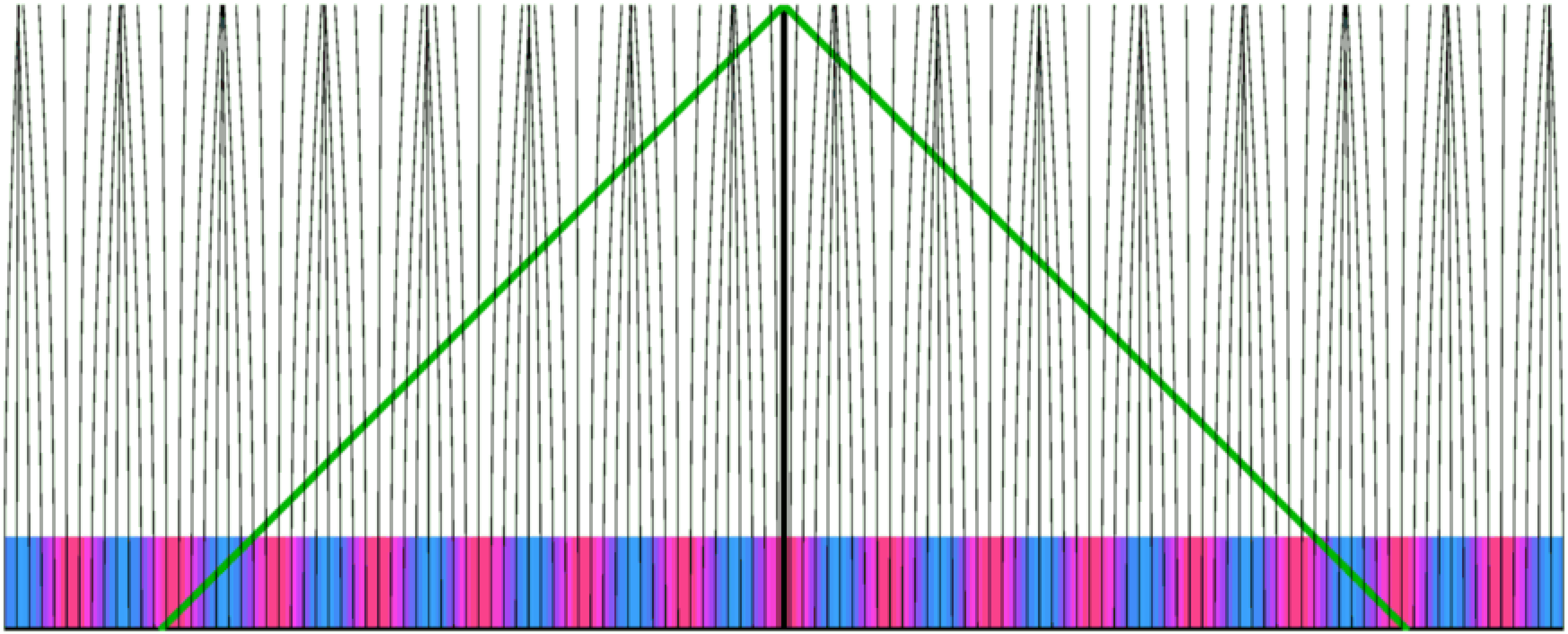
Two Fluids in the Early Universe

- Most of the mass is dark matter
  - 80-90% of the density
  - Zero pressure
  - Sound speed is zero
- The baryon-photon fluid
  - baryons are protons & neutrons = all ordinary matter
  - energy density of the photons is bigger than c^2 times the density of baryons
  - Pressure of photons = $u/3 = (1/3)\rho\, c^2$
  - Sound speed is about $c/\sqrt{3}$ = 170,000 km/sec

Traveling Sound Wave: $c_s = c/\sqrt{3}$



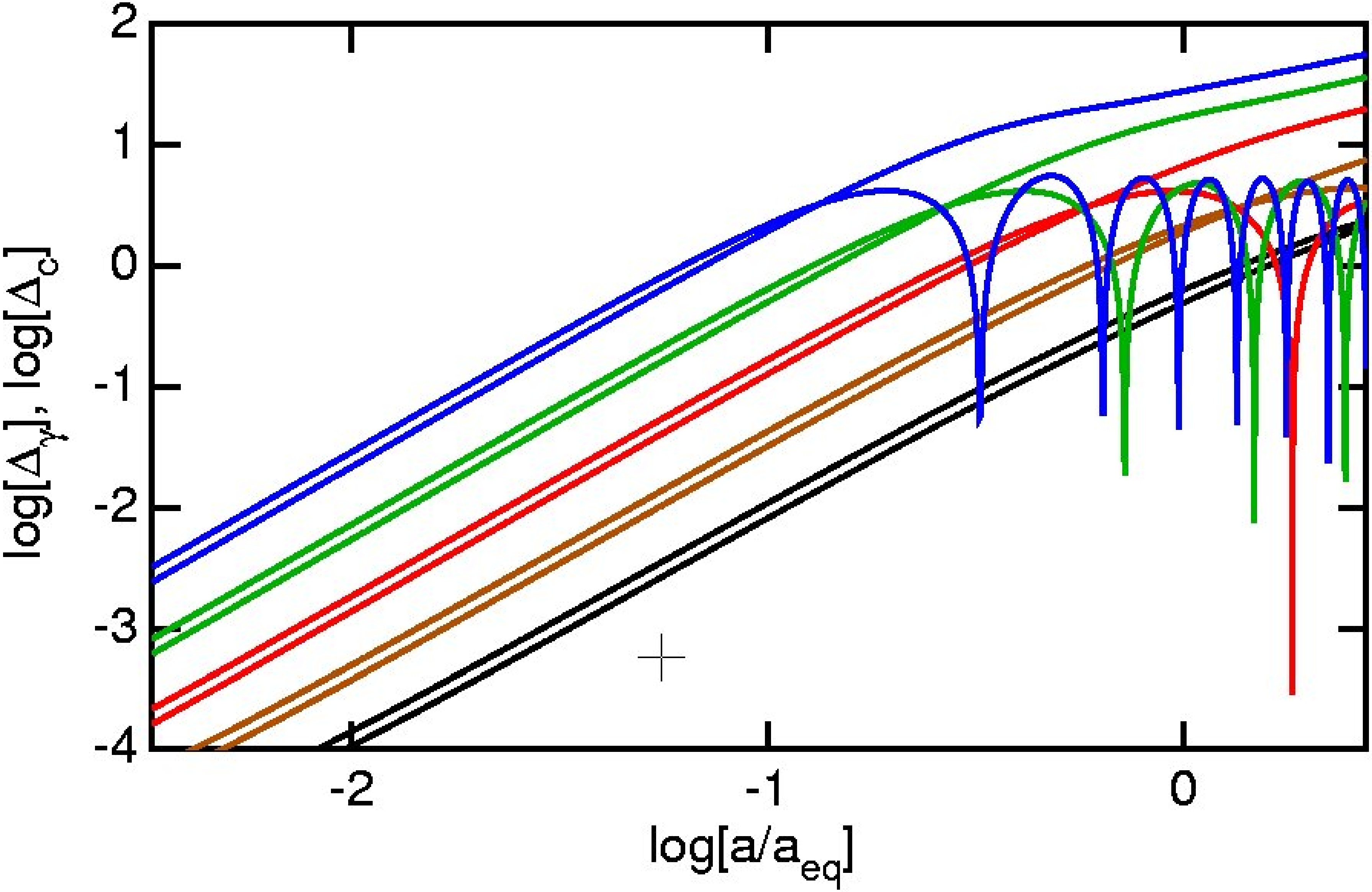
Stay at home Dark Matter



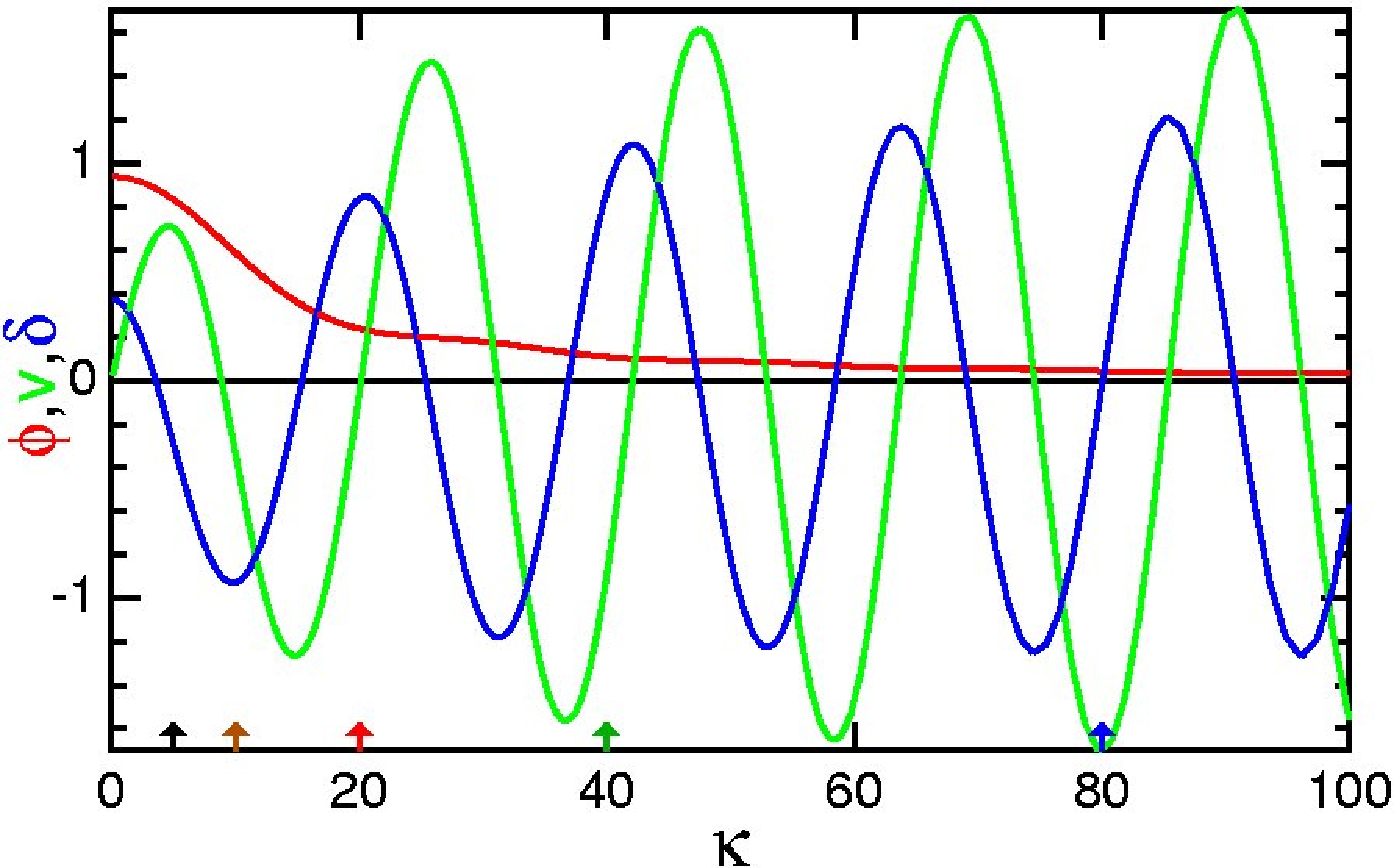
Interference at last scattering

- For the wavelength illustrated [1/2 period between the Big Bang and recombination], the denser = hotter effect and potential well = cooler effect have gotten in phase.
- For larger wavelengths they are out of phase at recombination:

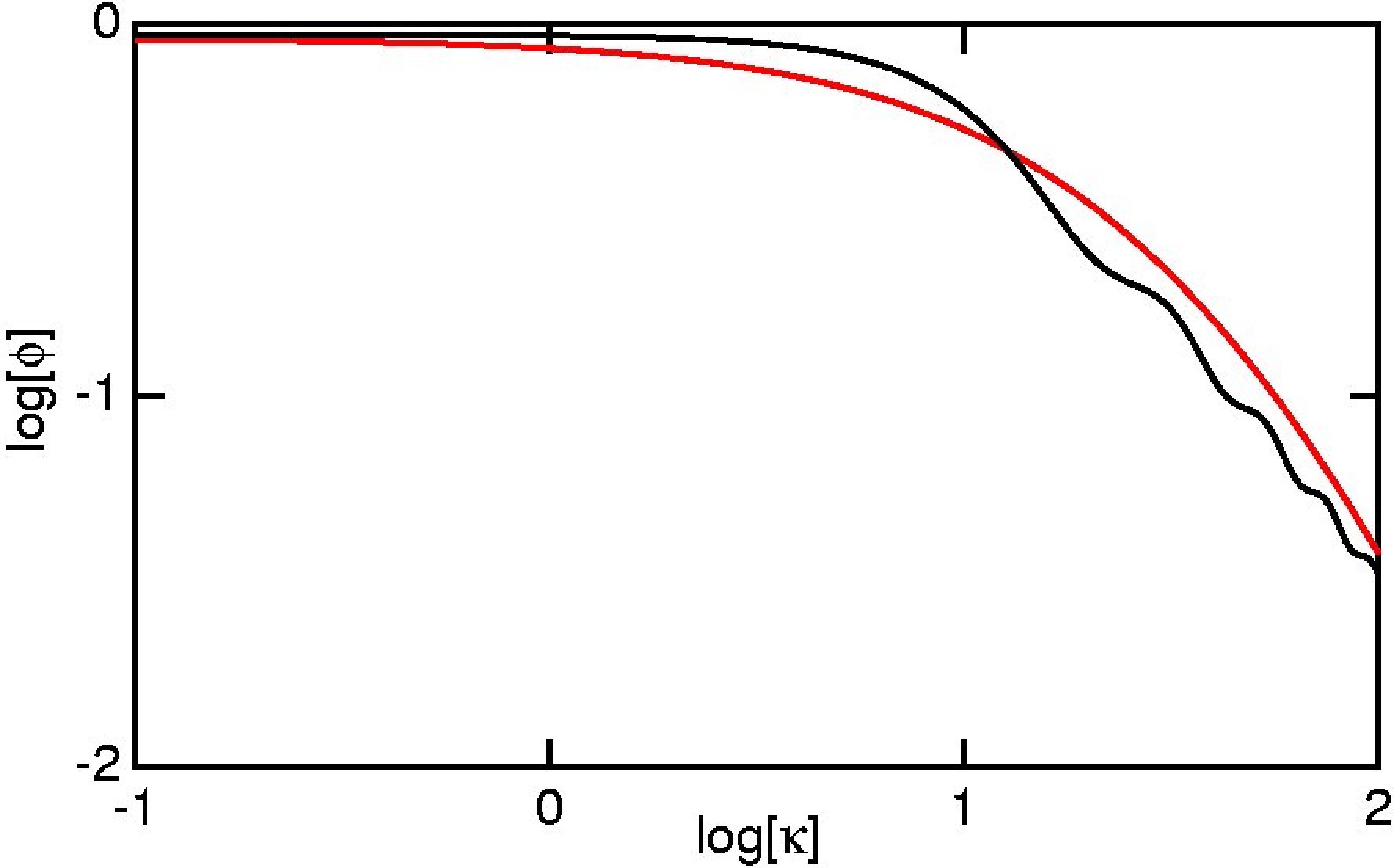
Density contrast vs a(t)



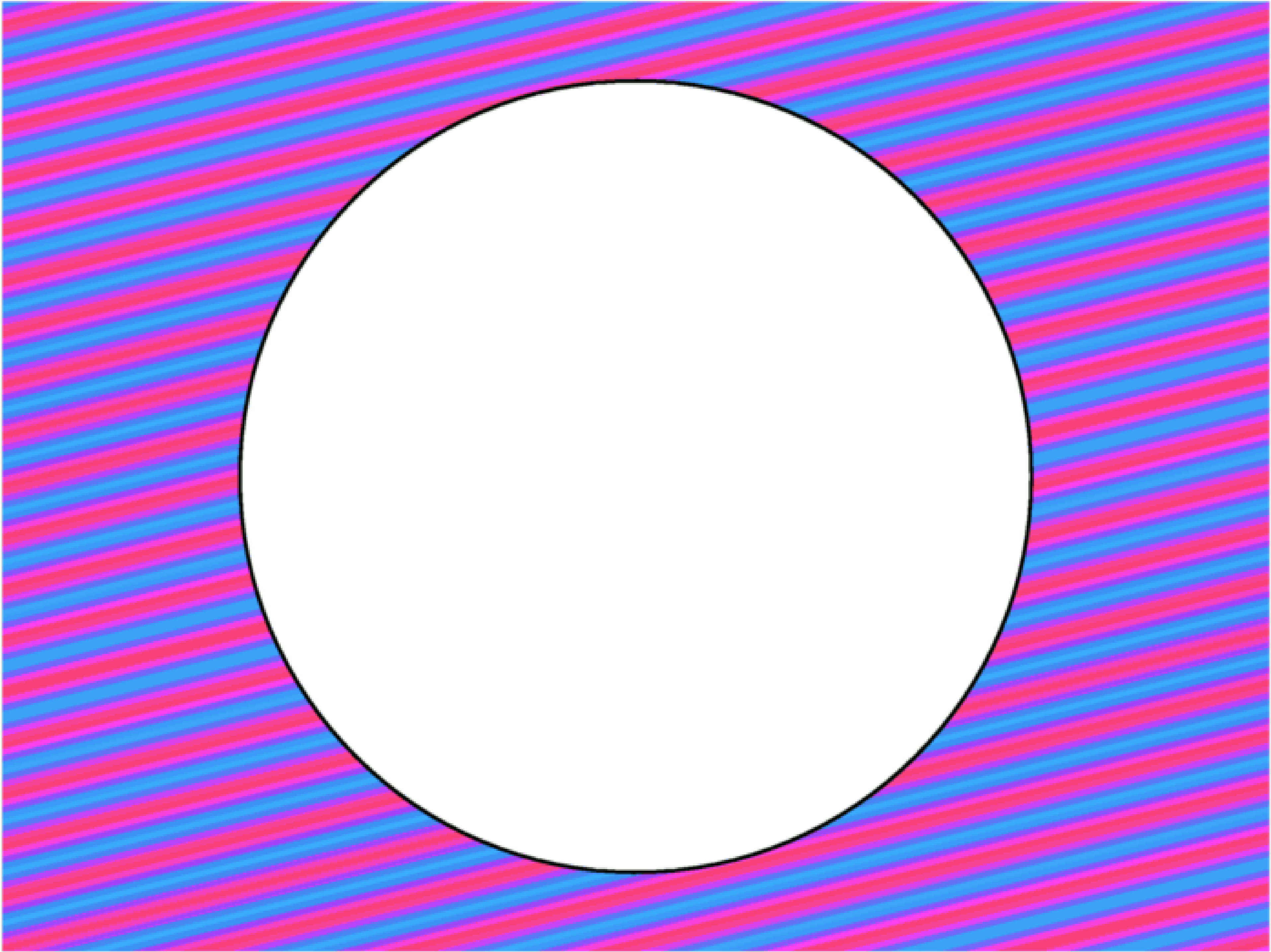
Contrast at last scattering vs κ



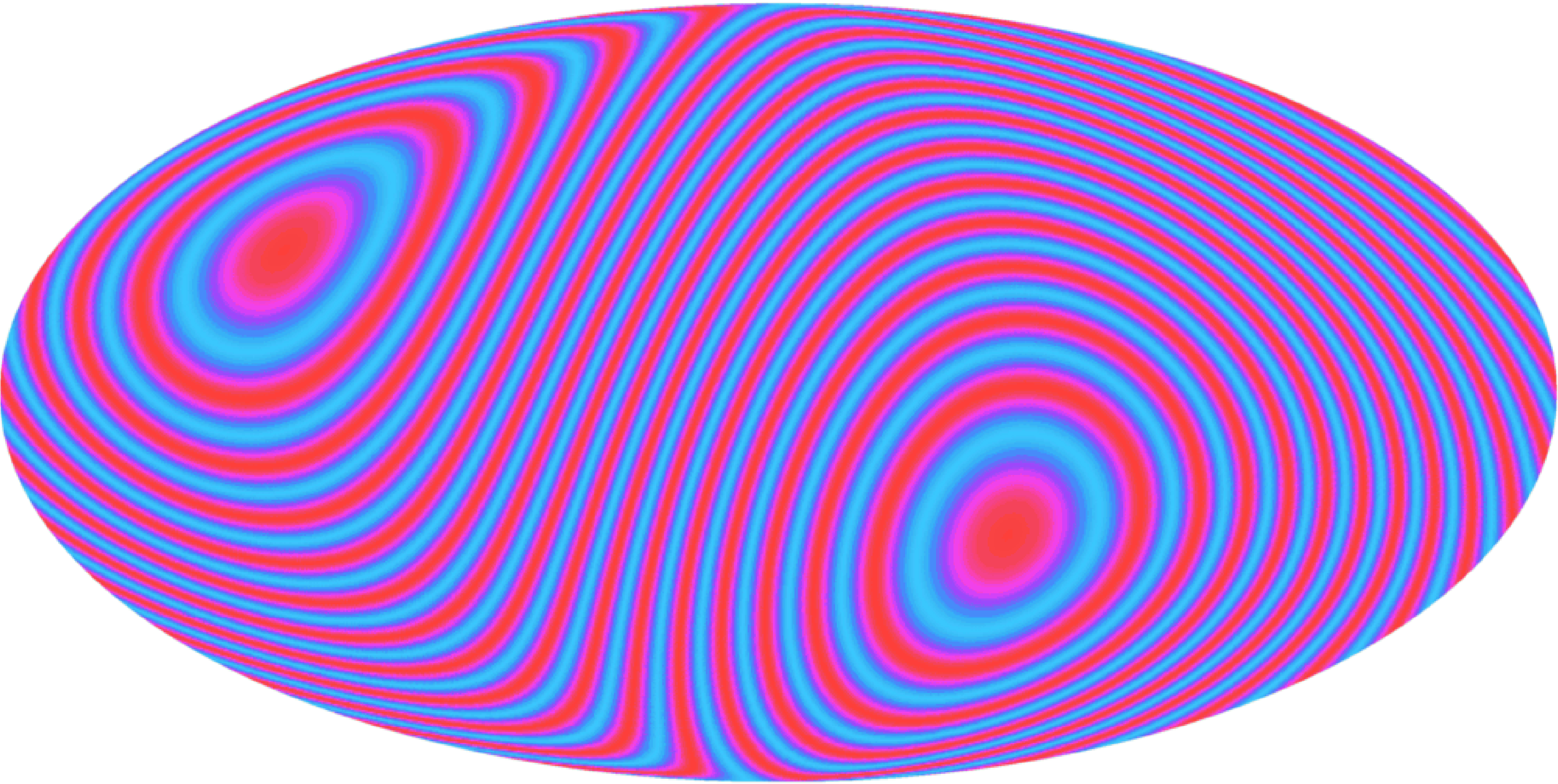
Potential survival vs κ



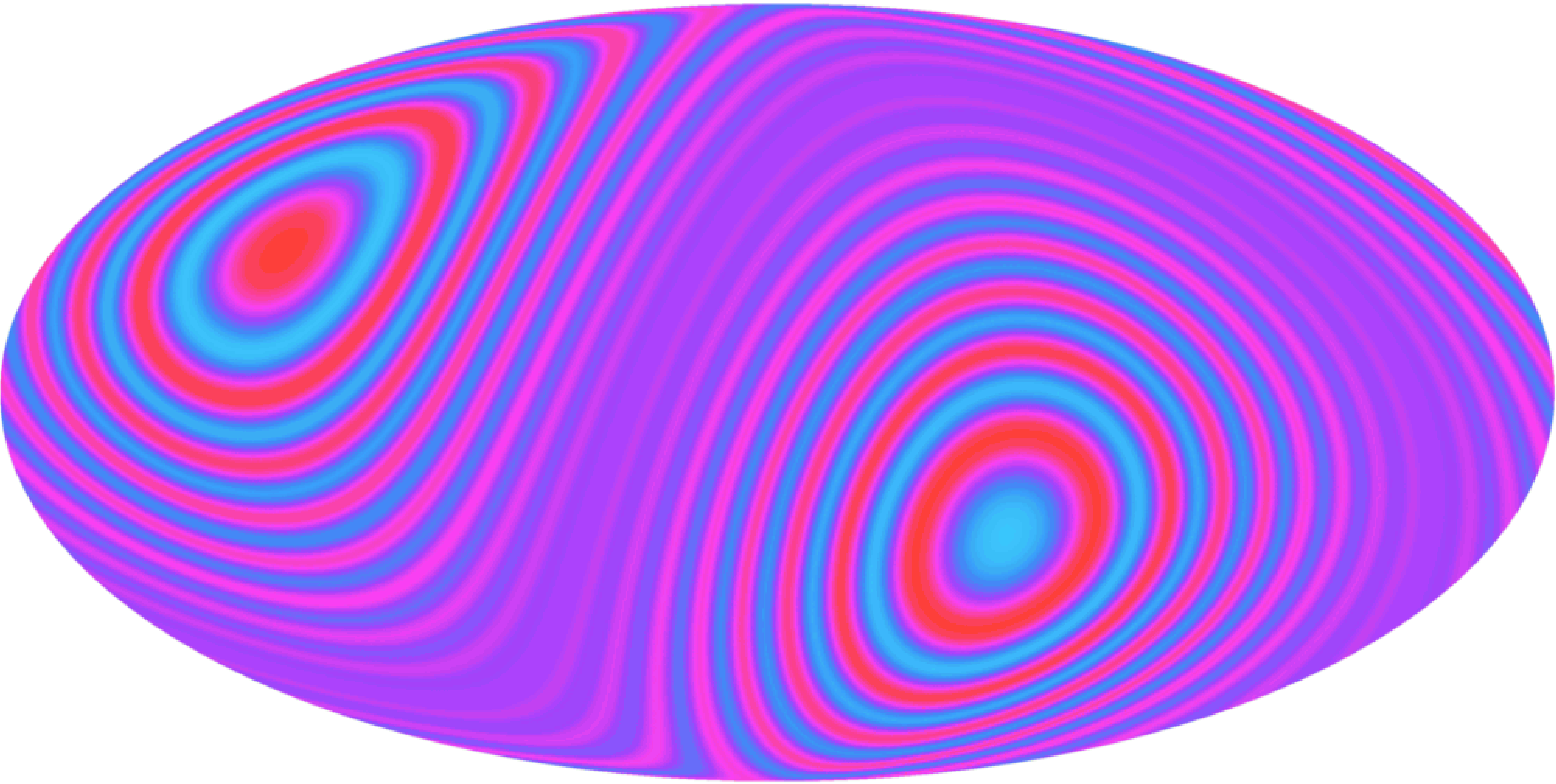
See Seljak, astro-ph/9406050, “Two-fluid approximation…”



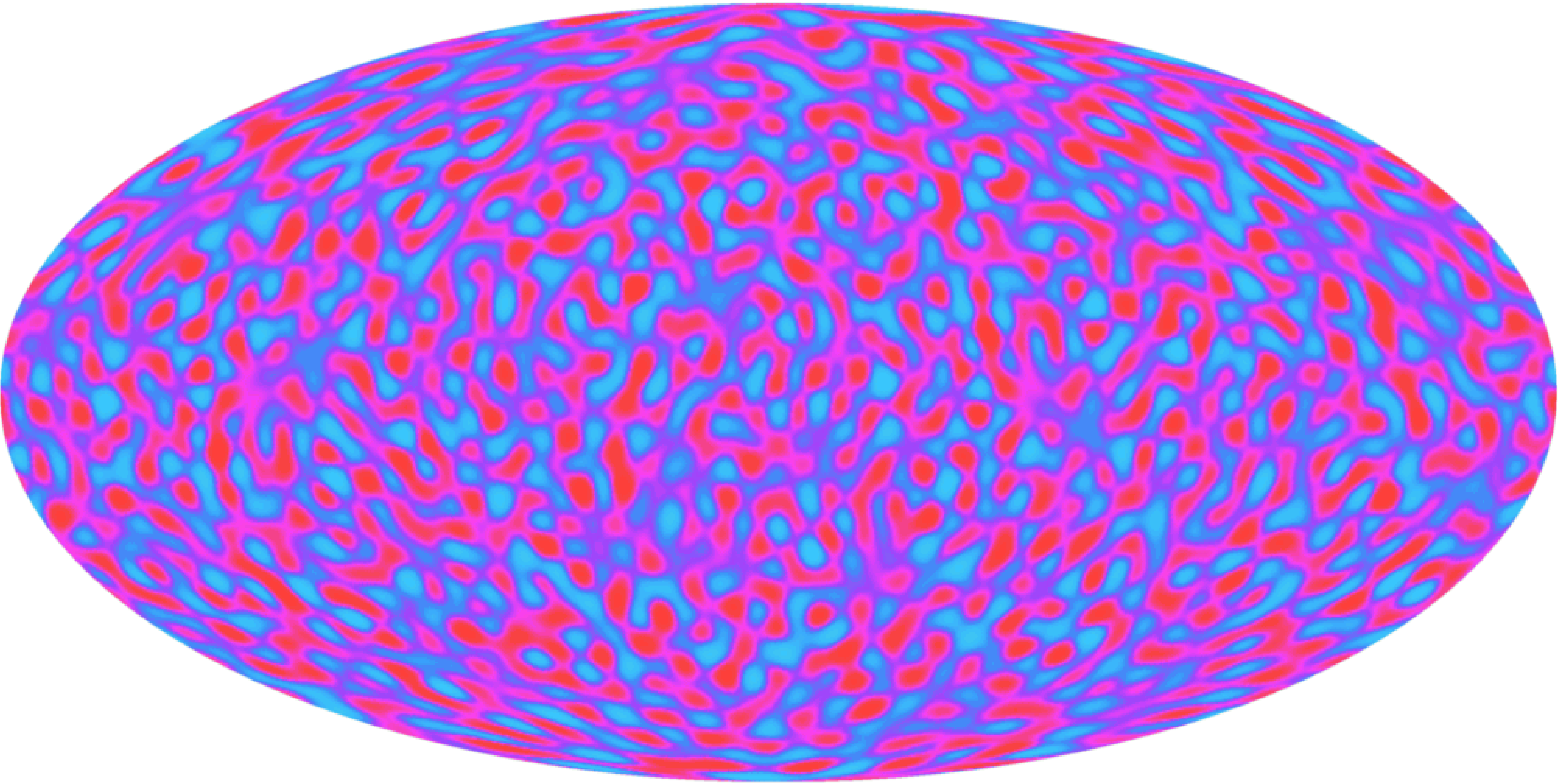
k*Rls = 50 plane wave



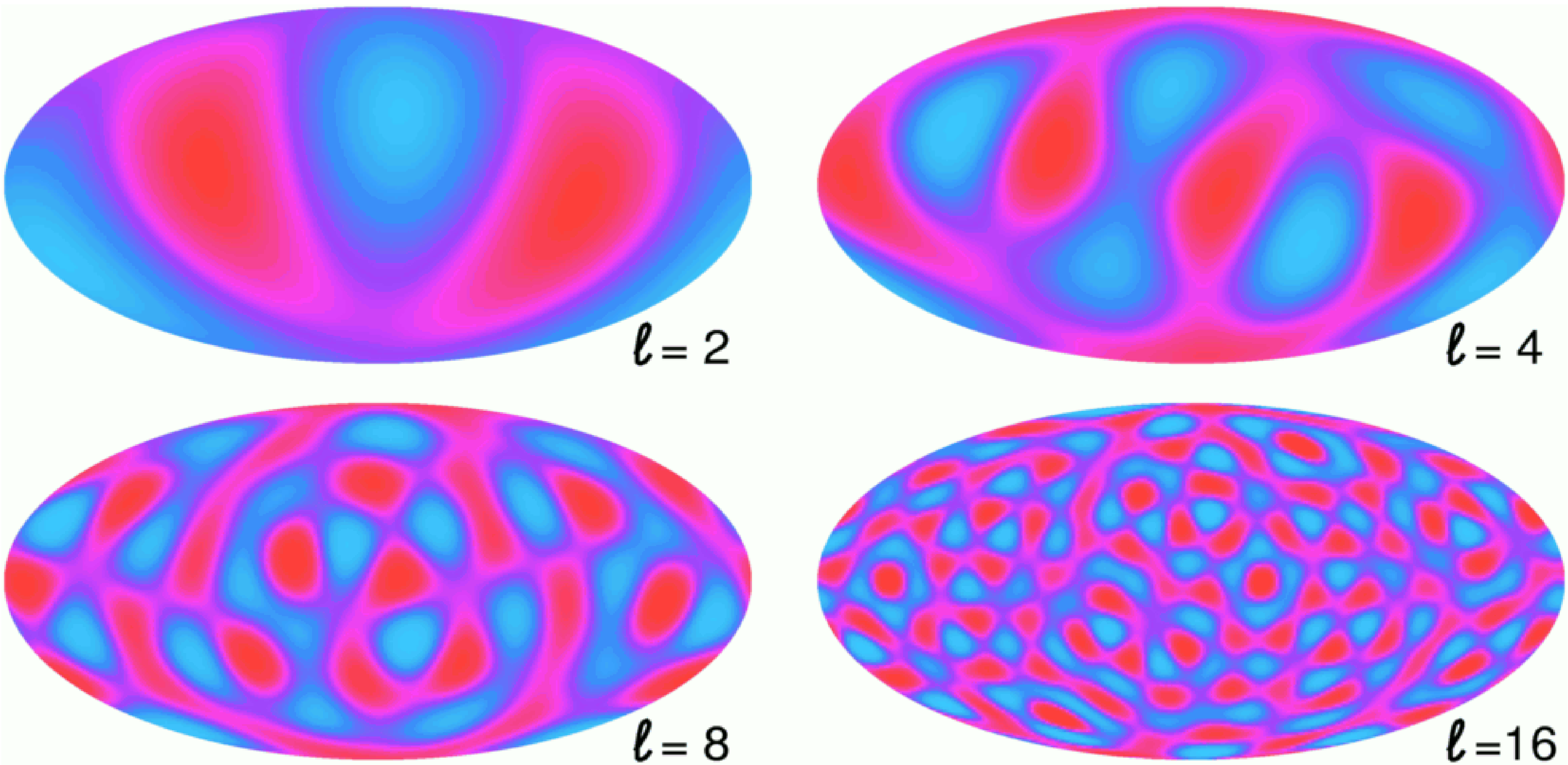
k=50 velocity term



99 k*Rls=50 plane waves

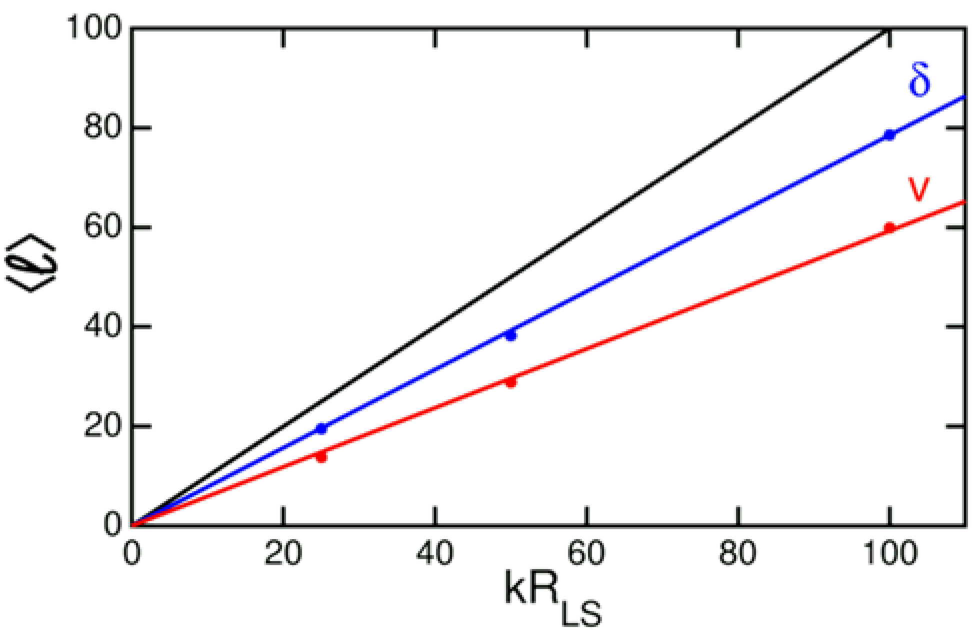


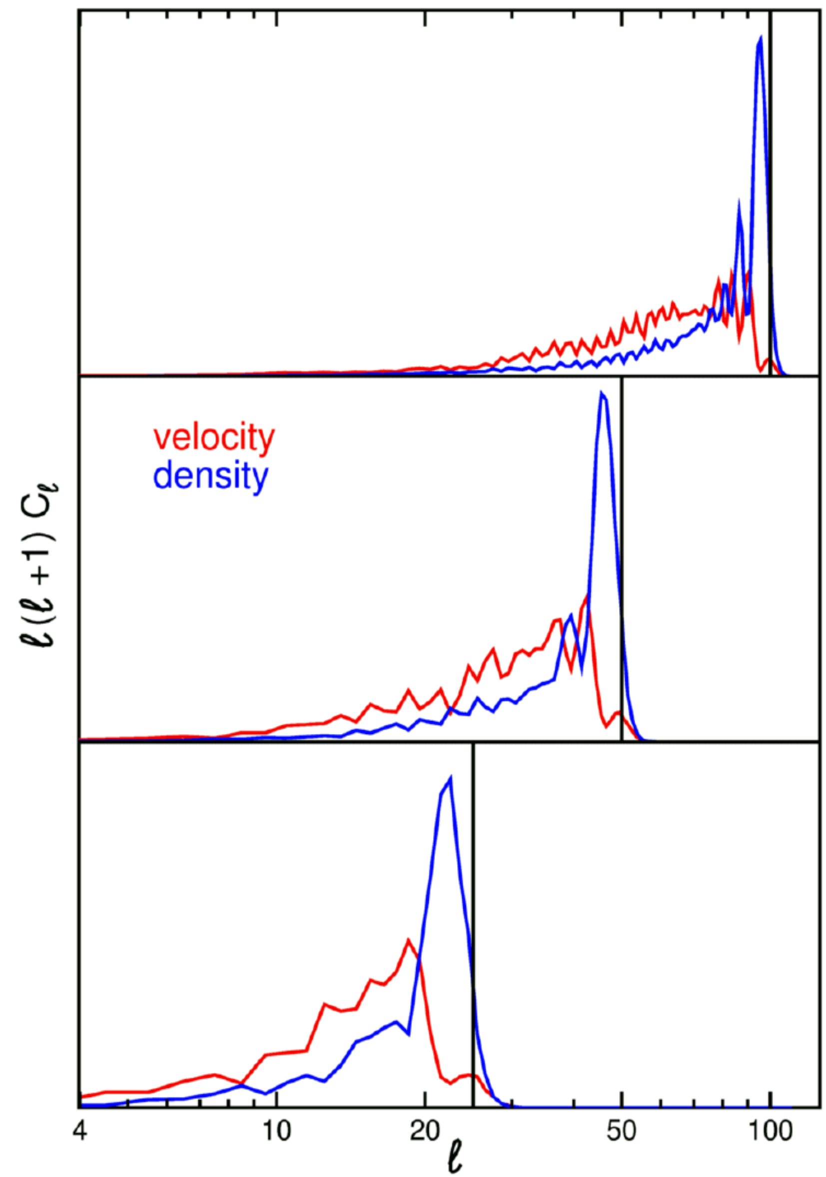
Spherical Harmonic Decomposition



Conversion from k to l

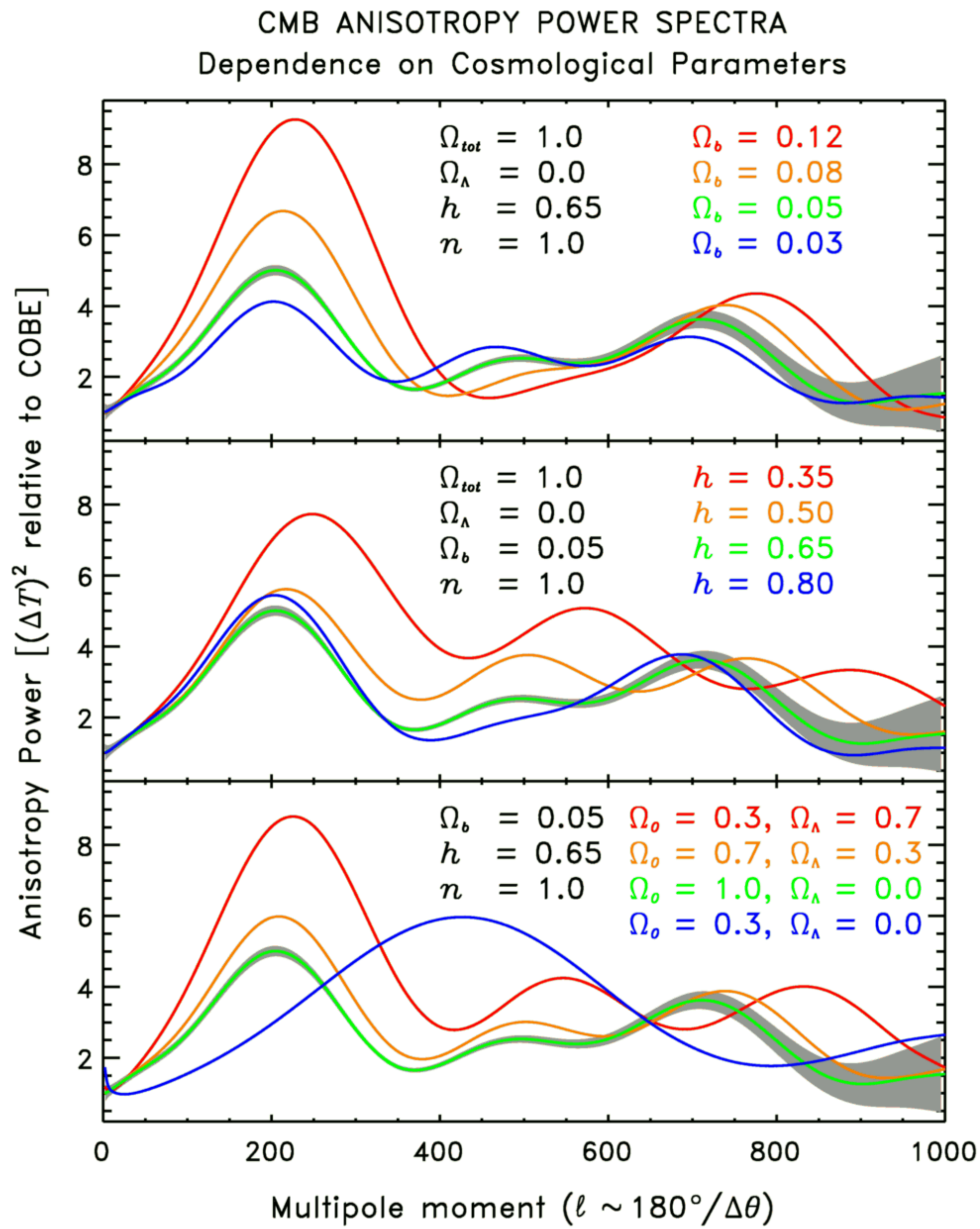
- Mean l is $(\pi/4)kR_{LS}$ for density effects, and $(3\pi/16)kR_{LS}$ for velocity effects
- Velocity effects give a broad spectrum in l and contribute little to the peaks in the angular power spectrum.





Many parameters to measure

Careful measurements of the power at various angular scales can determine the Hubble constant, the matter density, the baryon density, and the vacuum density.



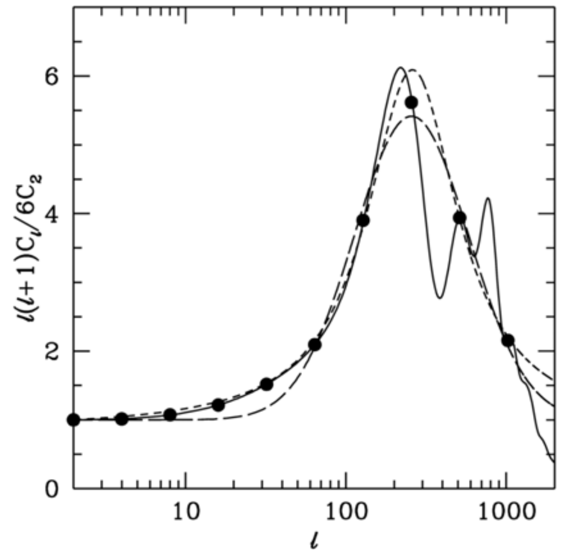
COBE View was Blurry

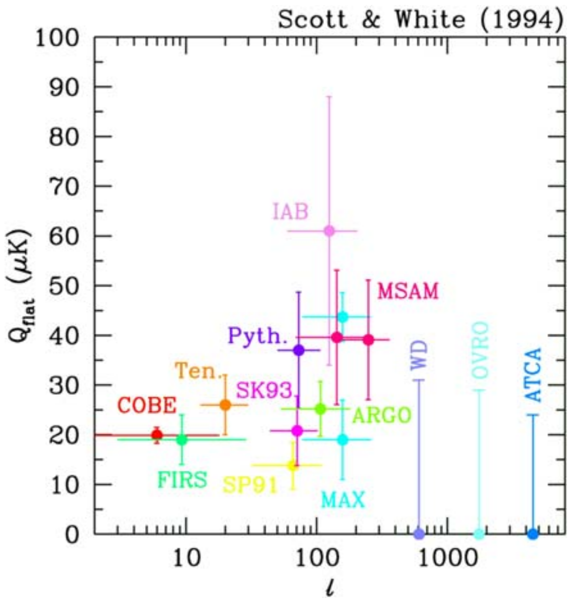
Sometimes higher resolution...

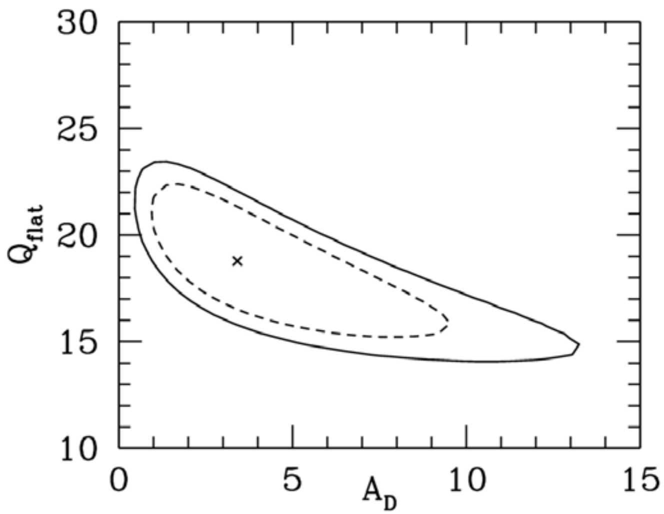
reveals the secret of the Universe

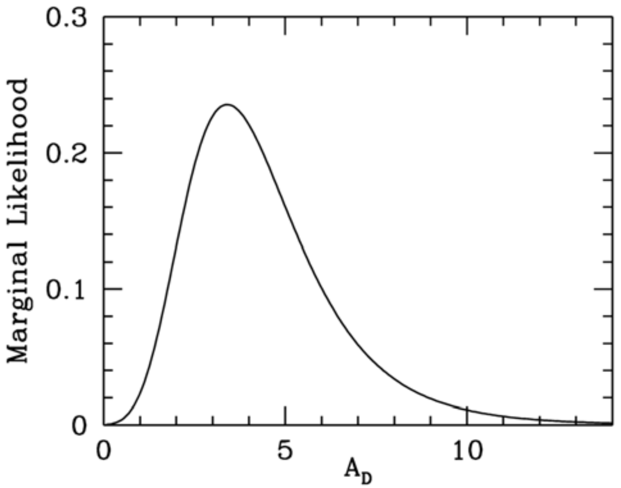
Observations pour in after COBE

- By 1994 Scott & White give > 95% confidence that the Doppler peaks are present: 9407073





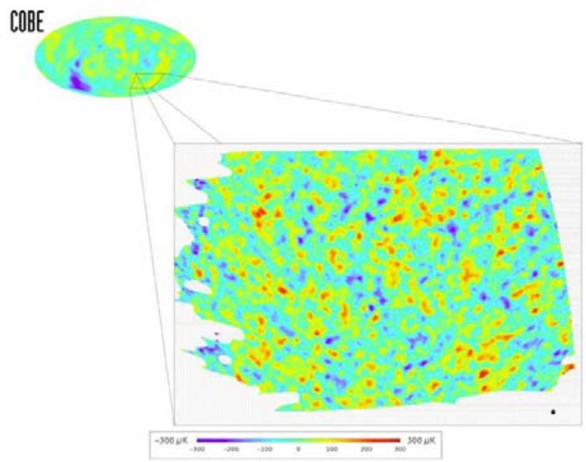


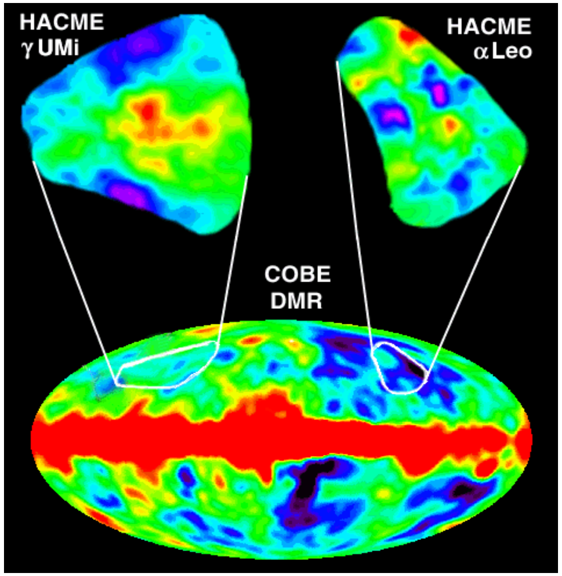


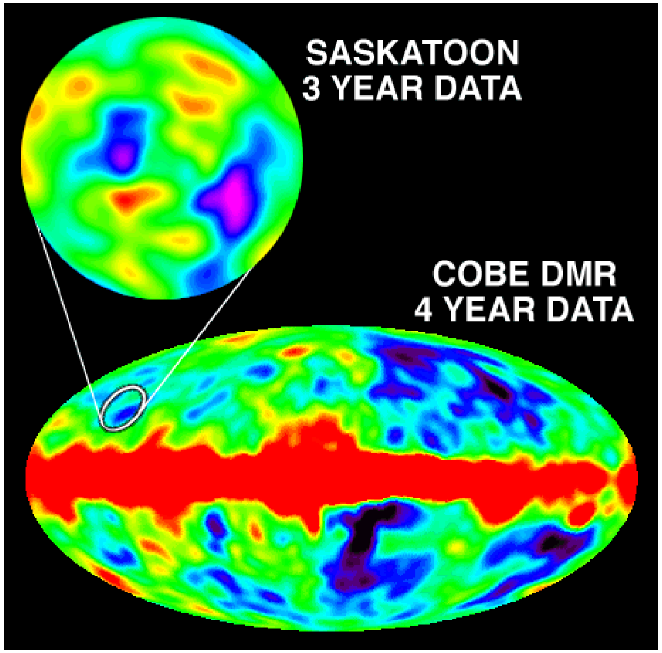
Observations since 1994

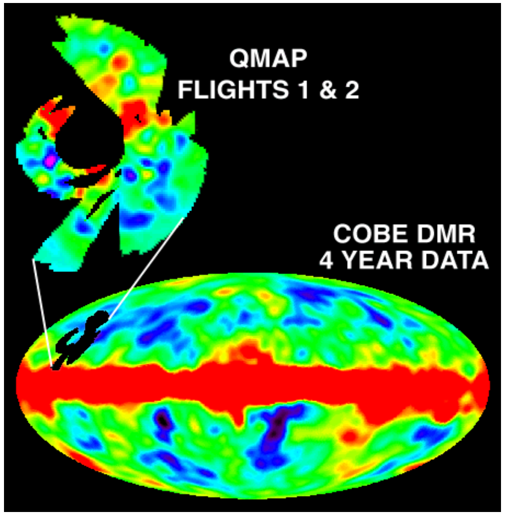
- More Saskatoon
- QDMAP – Saskatoon on a balloon
- TOCO – Saskatoon on a truck (Mobile Anisotropy Telescope) in Chile + D band (150 GHz channel)
- BOOMERanG
- MAXIMA
- DASI
- ARCHEOPS
- CBI

Smaller Scale Experiments









BOOMERanG

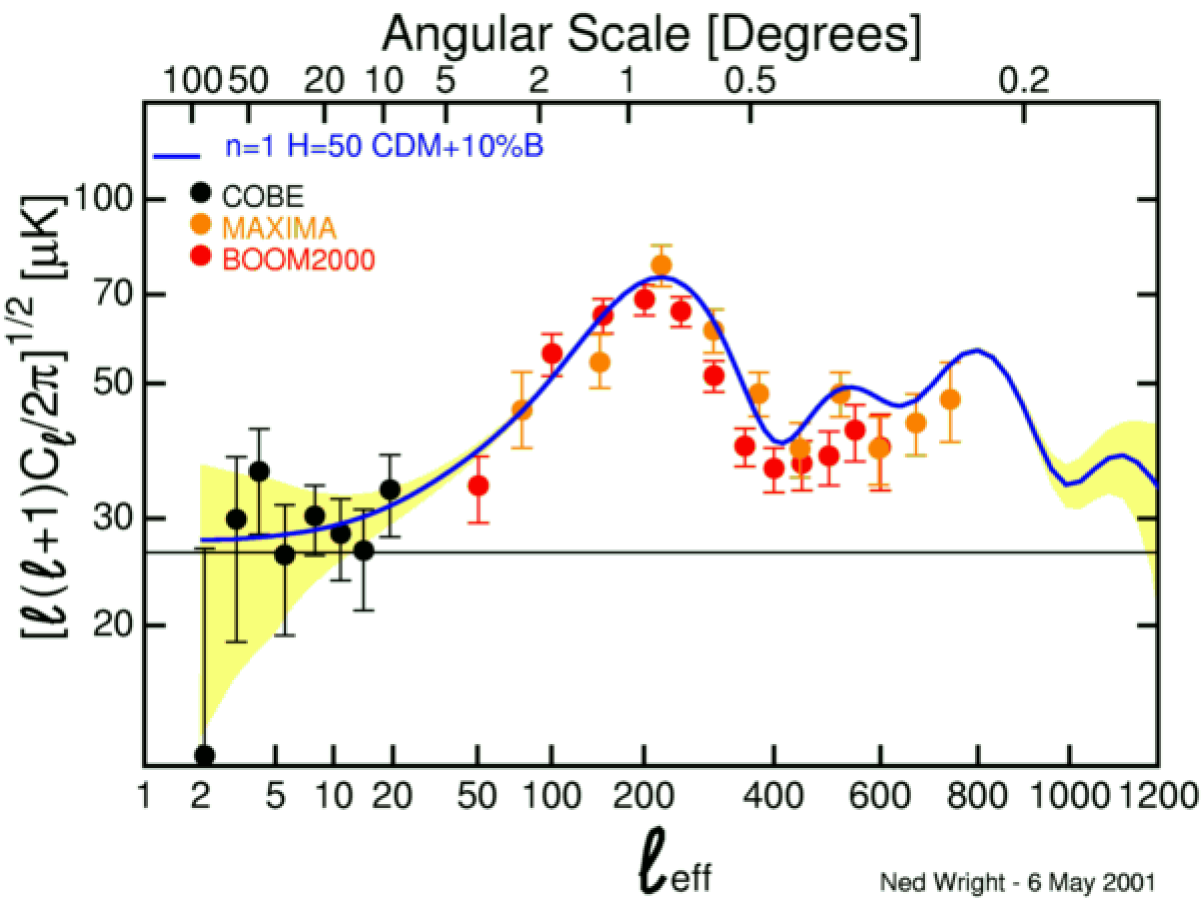
- First acoustic peak was well established and position known before BOOMERanG:
  - l_{pk} = 210±15 (L. Page, 2 Jan 2000)
- The Italian-American BOOMERanG balloon-borne experiment announced “the flat Universe” in April 2000:
  - l_{pk} = 197±6
- BOOMERanG was a big improvement in sky coverage and sensitivity, and thus reduced the first peak position uncertainty to about 3% (unfortunately 4σ off the true l_{pk} = 220)

DASI:Degree Angular Scale Interferometer

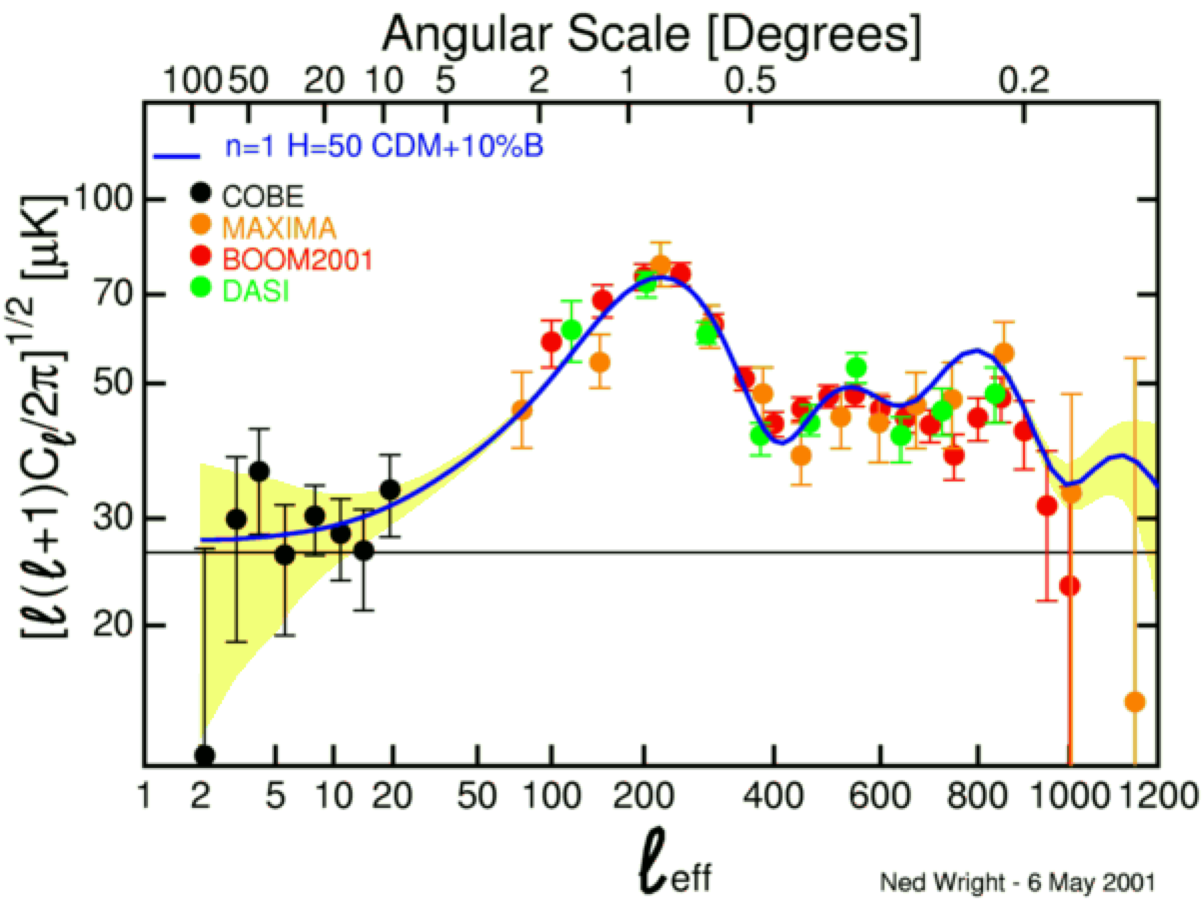
At the South Pole where it's very cold & dry

26-36 GHz

2000 Power Spectrum



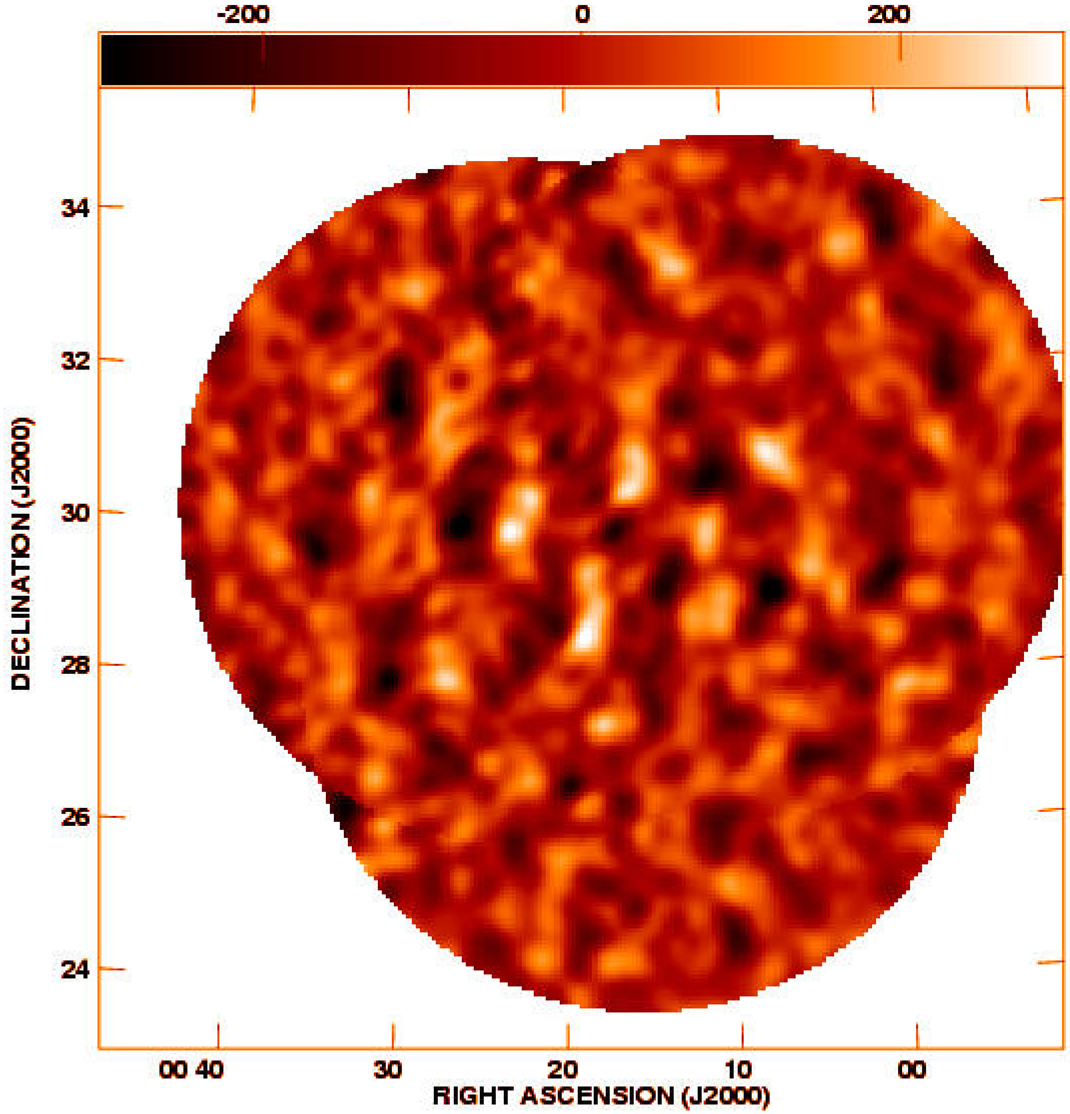
2001 Power Spectrum



The Very Small Array

- 14 antennae
- 4.5^{o} or 2^{o} FOV
- 0.5^{o} or 0.2^{o} res
- 26-36 GHz
- 1.5 GHz bandwidth
- Teide on Tenerife

VSA Sky Map

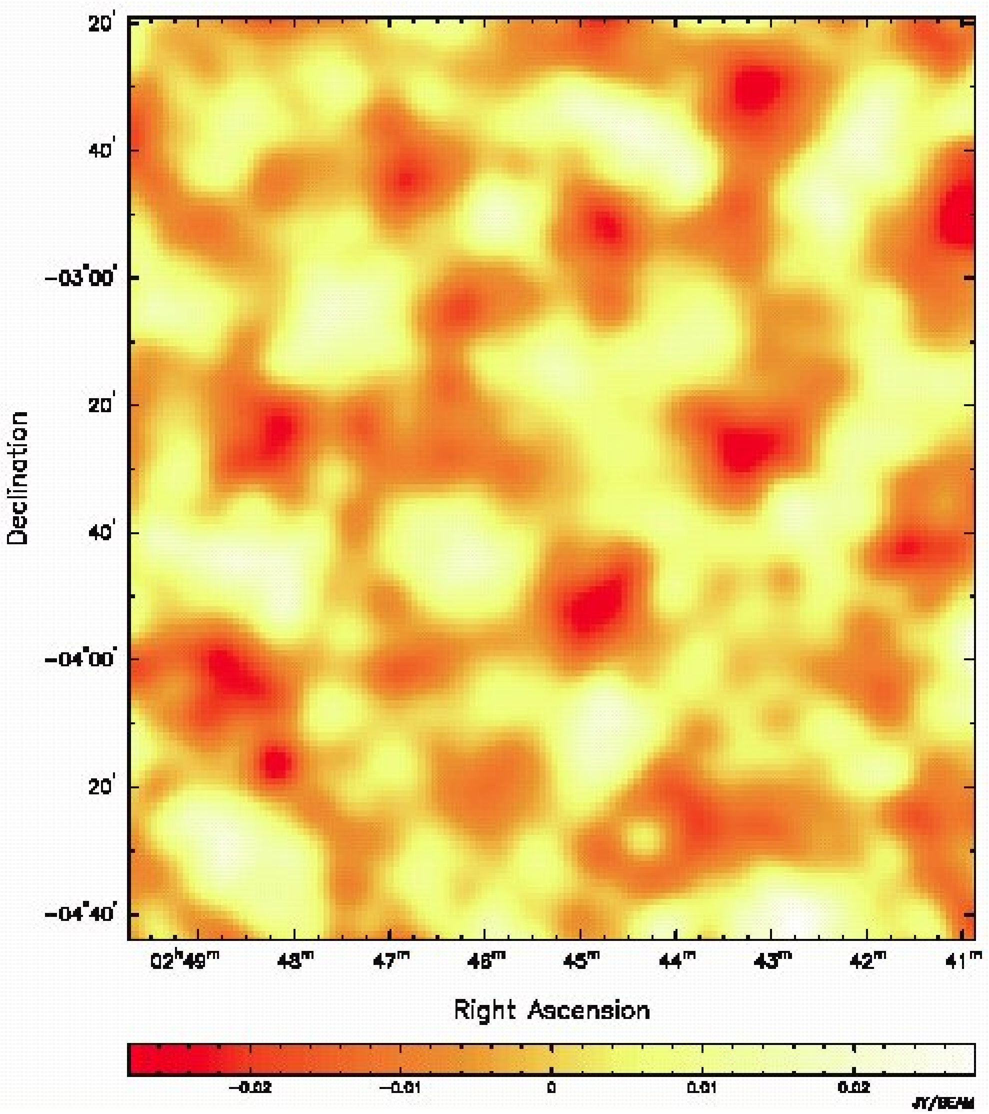


-200
0
200
DECLINATION (J2000)
34
32
30
28
26
24
00 40
30
20
10
00
RIGHT ASCENSION (J2000)

Cosmic Background Imager

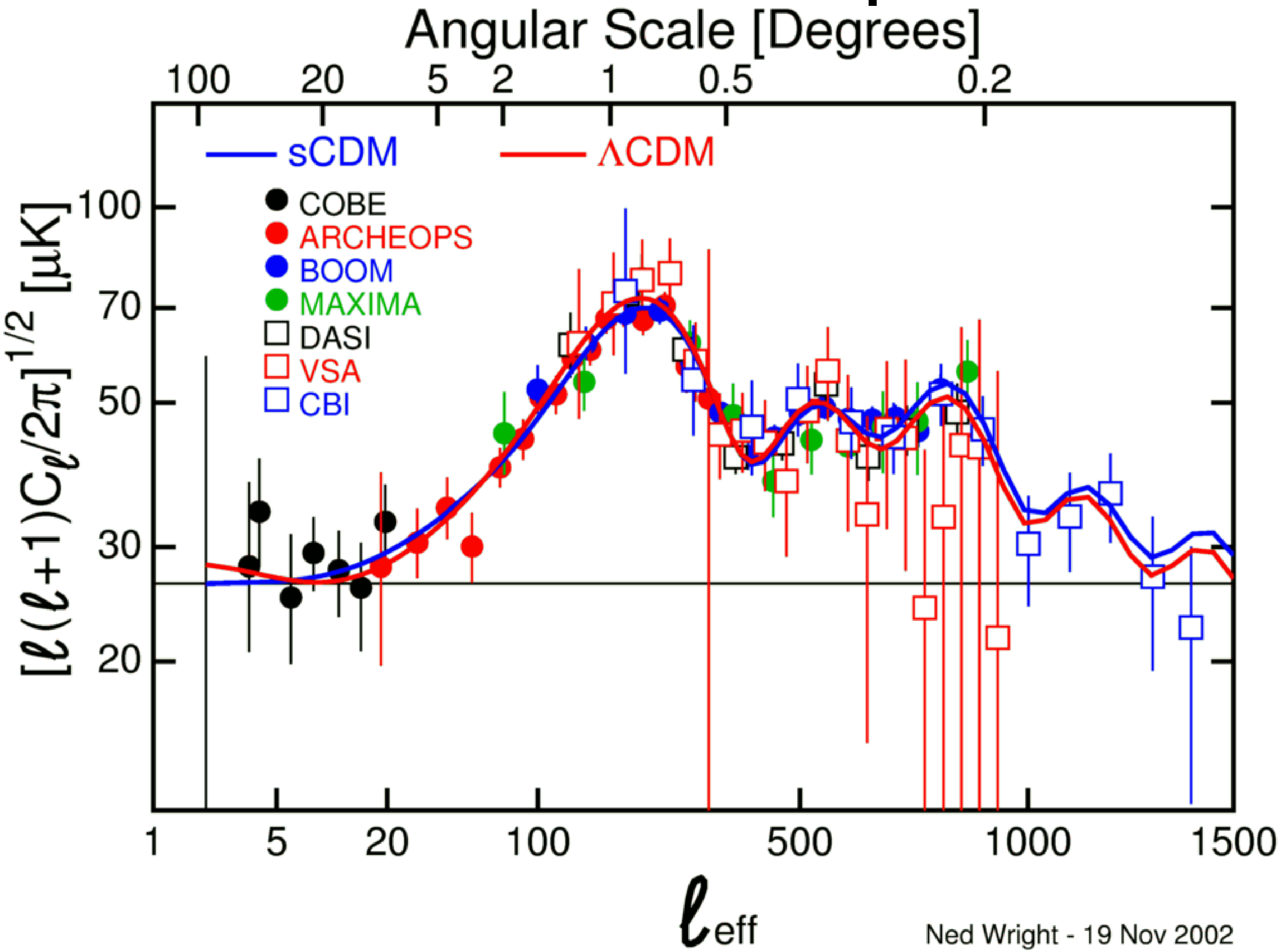
- Chile @ 5.08 km
- 13 antennae
- 26-36 GHz
- 10 GHz band
- 0.75^{o} FOV
- 0.075^{o} res
- Mosaic many FOV's together

CBI Map



20′
40′
−03°00′
20′
40′
−04°00′
20′
−04°40′
Declination
02h49m
48m
47m
46m
45m
44m
43m
42m
41m
Right Ascension
−0.02
−0.01
0
0.01
0.02
JY/BEAM

Pre-MAP Power Spectrum



Flat, n=1; ω_b = 0.021, ω_c = 0.196, H_o = 47; ω_b = 0.022, ω_c = 0.132, H_o = 68, Λ = 2/3

Some definitions

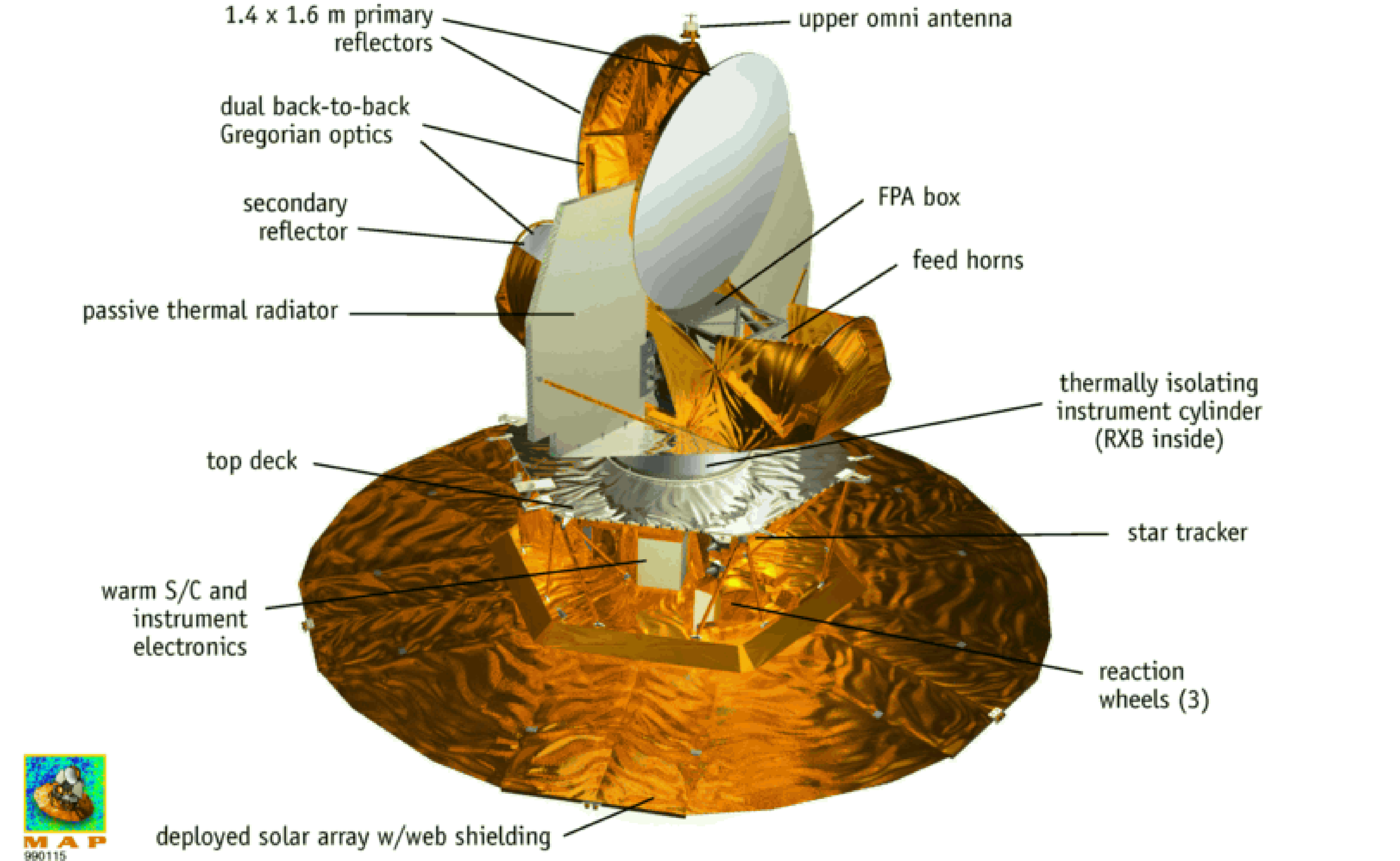
- $T(l,b) = T_o + \Delta T_d \cos\theta + \Sigma\, a_{lm} Y^{lm}(l,b)$
- $C_l = <| a_{lm}|^2>$
- Baryon density $\omega_b = \Omega_b h^2$ or the density relative to the critical density for $H_o = 100$ which is 18.8×10^{-30} grams/cm^3 or 18.8 yoctograms per cubic meter in SI.
- Cold Dark Matter density $\omega_c = \Omega_c h^2$
- Vacuum energy density $\Lambda = \Omega_\Lambda$ or energy density = $10.5\ \Omega_\Lambda h^2$ keV/cm^3

Calibration Uncertainties

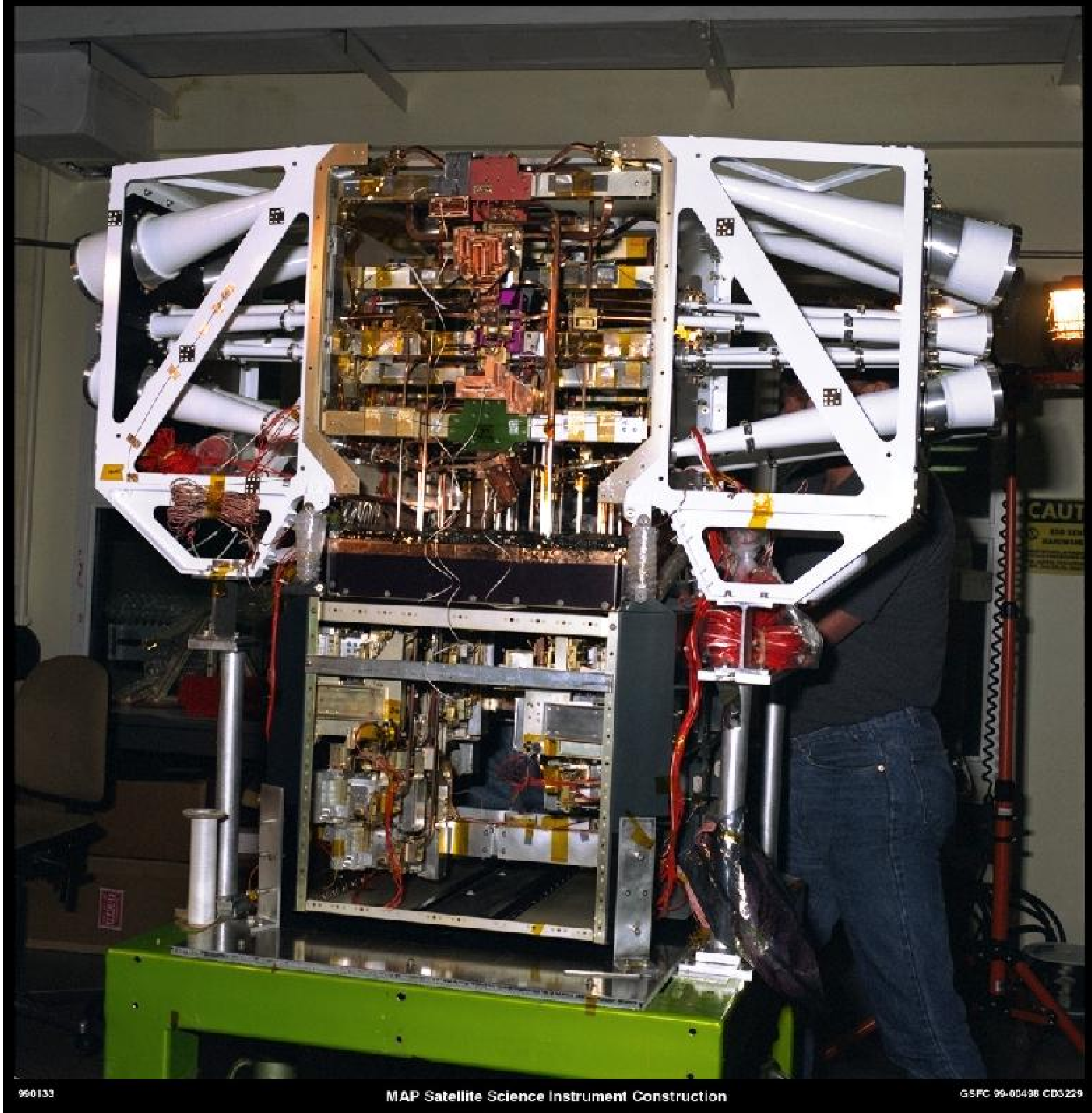
- Each experiment (except for COBE and later WMAP) has amplitude uncertainty of several percent that is correlated across all the data from that experiment.
- I have done fits and plots that solve separately for calibration adjustment "nuisance parameters" which are included in the χ^2 but not in the errorbars.
- Combining data from many experiments gives a "flexible" observed spectrum due to these calibration errors.

WMAP Science Working Group

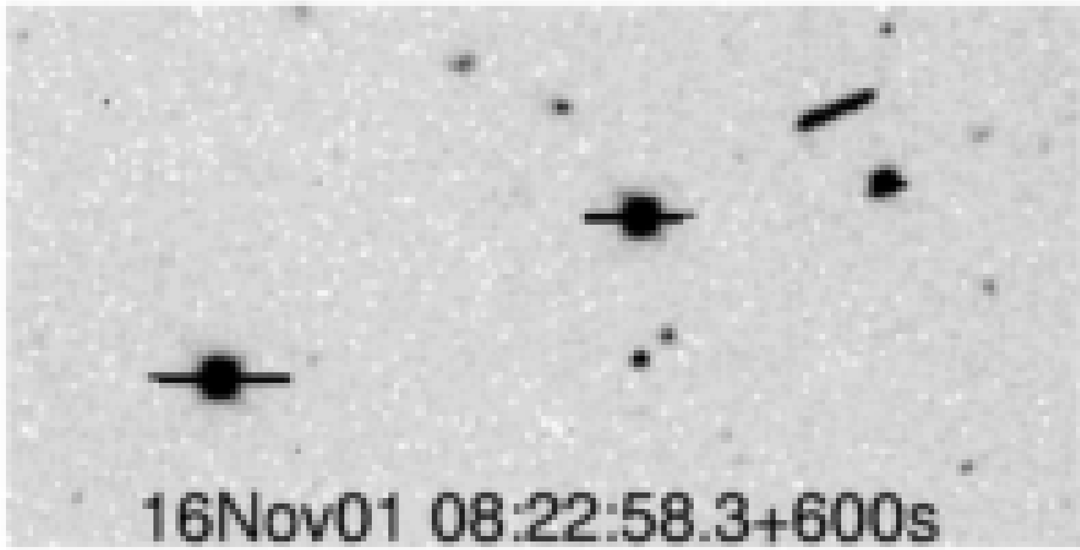
MAP Observatory



The MAP RF plumbing is very complex with 10 horns per side, 20 DA’s, 40 amplifier chains.

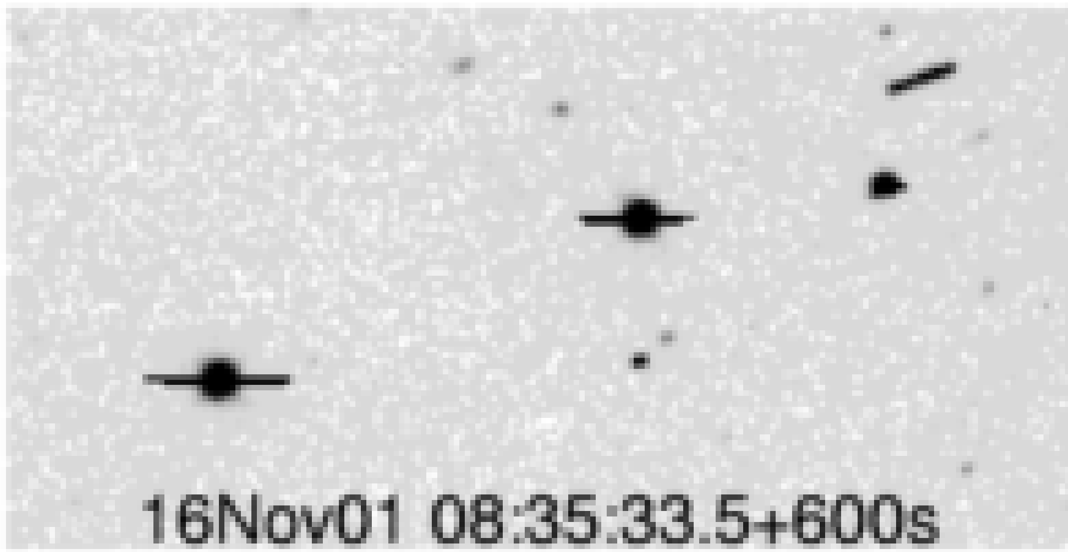


Seeing WMAP at L2



- You need a pretty big telescope.
- These pictures were taken on 16 Nov 2001 with the KPNO 4m by Ian Dell'Antonio
- The 3 stars are mag 15.2, 15.4 & 17.3
- FOV is 115" wide.

Seeing WMAP at L2



- You need a pretty big telescope.
- These pictures were taken on 16 Nov 2001 with the KPNO 4m by Ian Dell'Antonio
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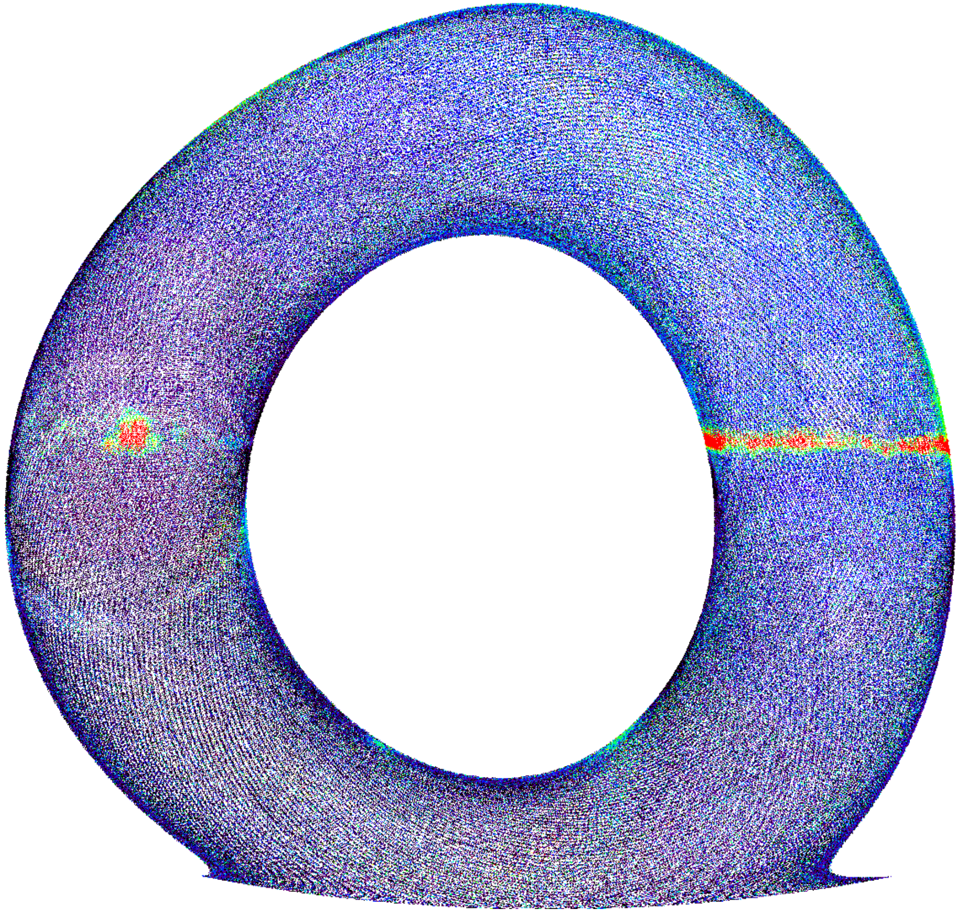
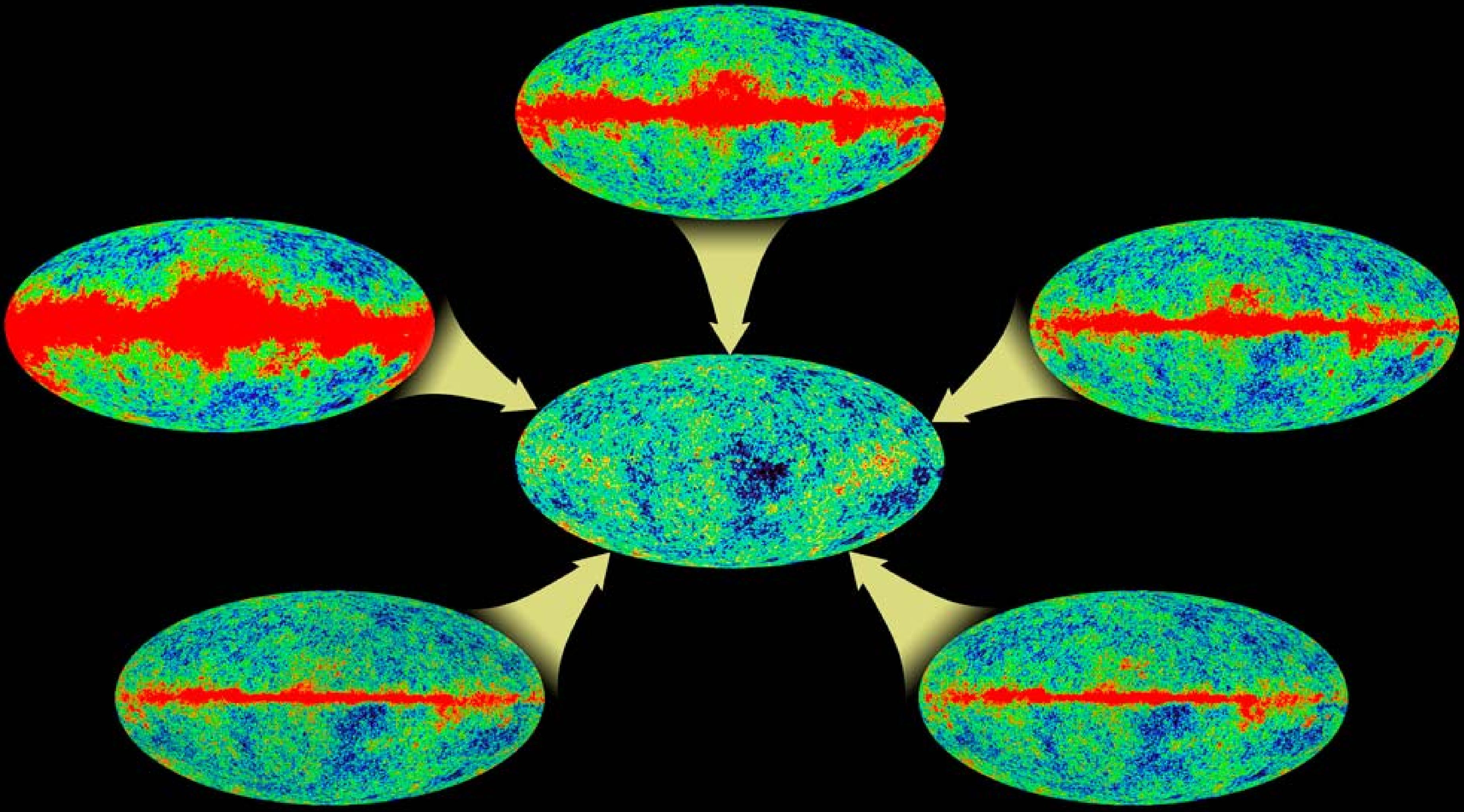
- FOV is 115" wide.

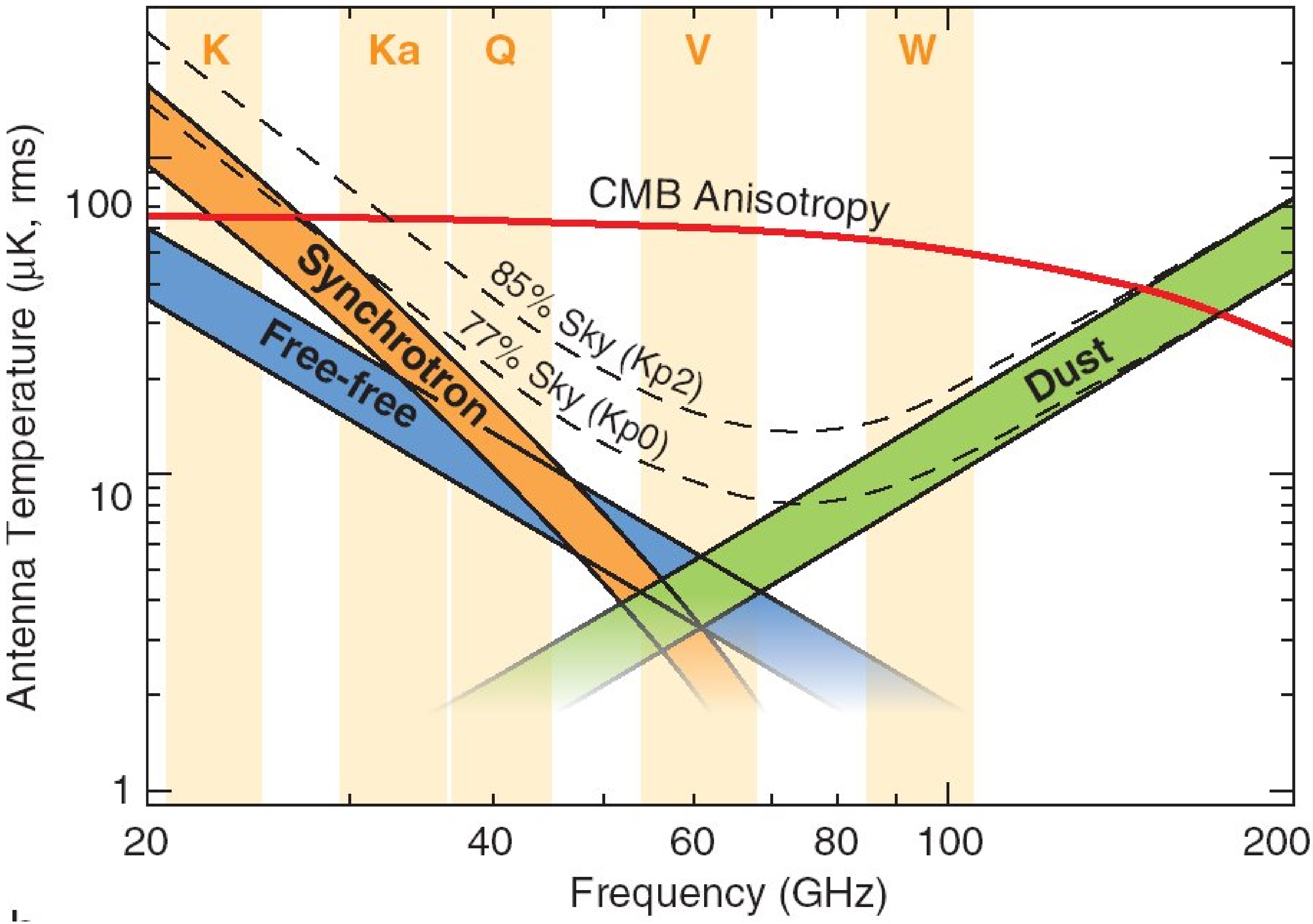
First map from WMAP, day 01186



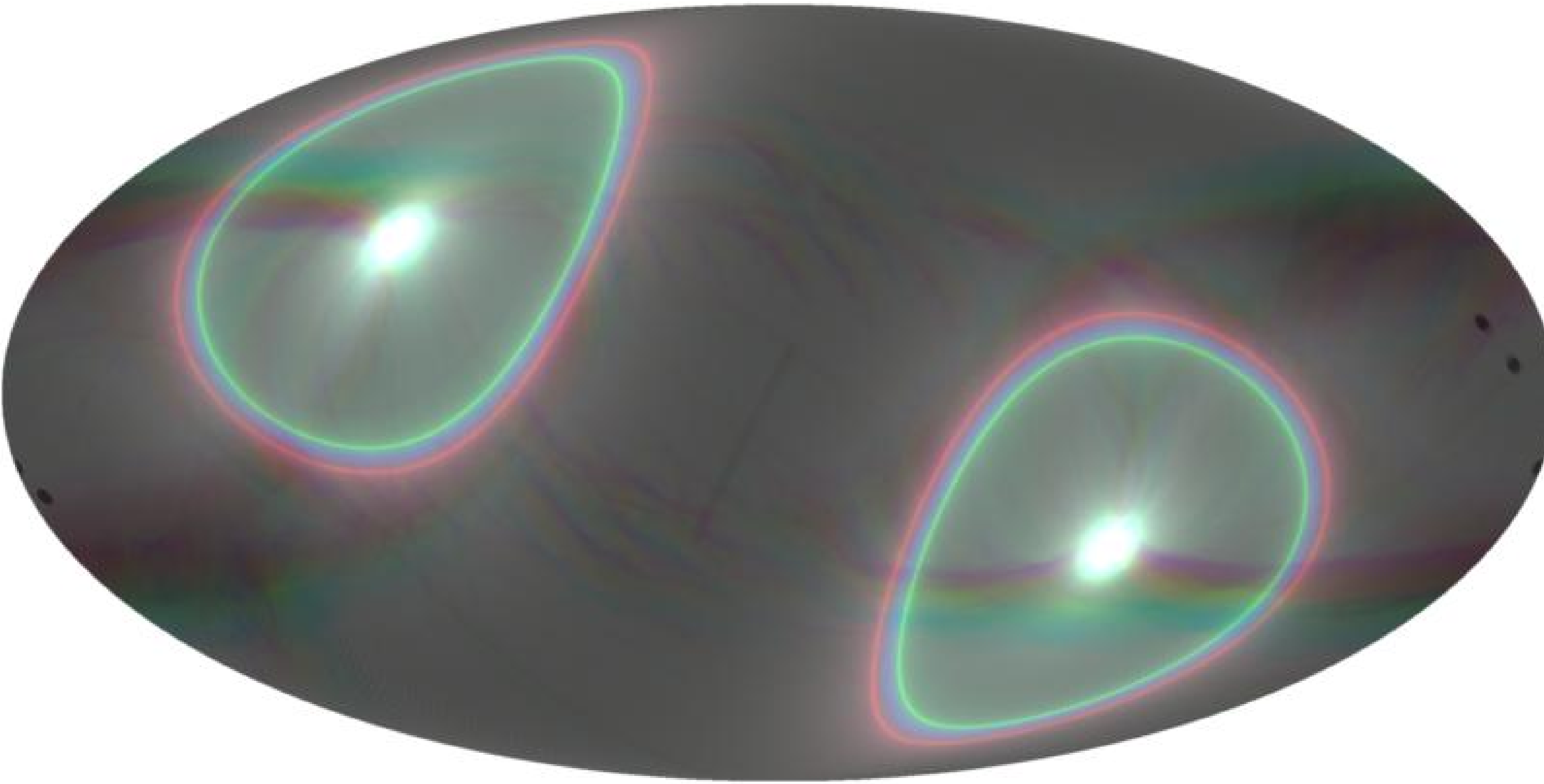
Combination to remove foreground



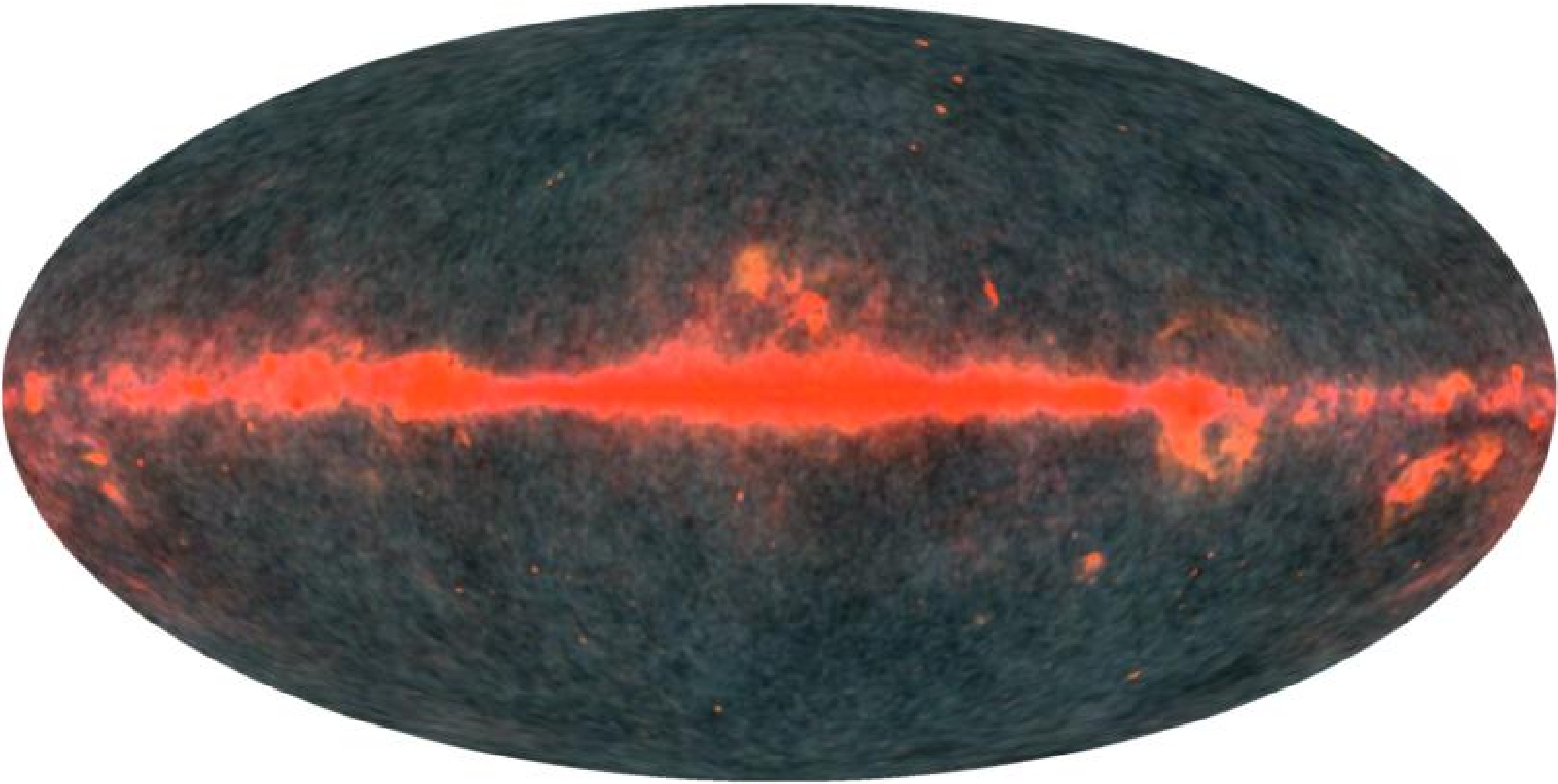
Foreground vs CMB Power



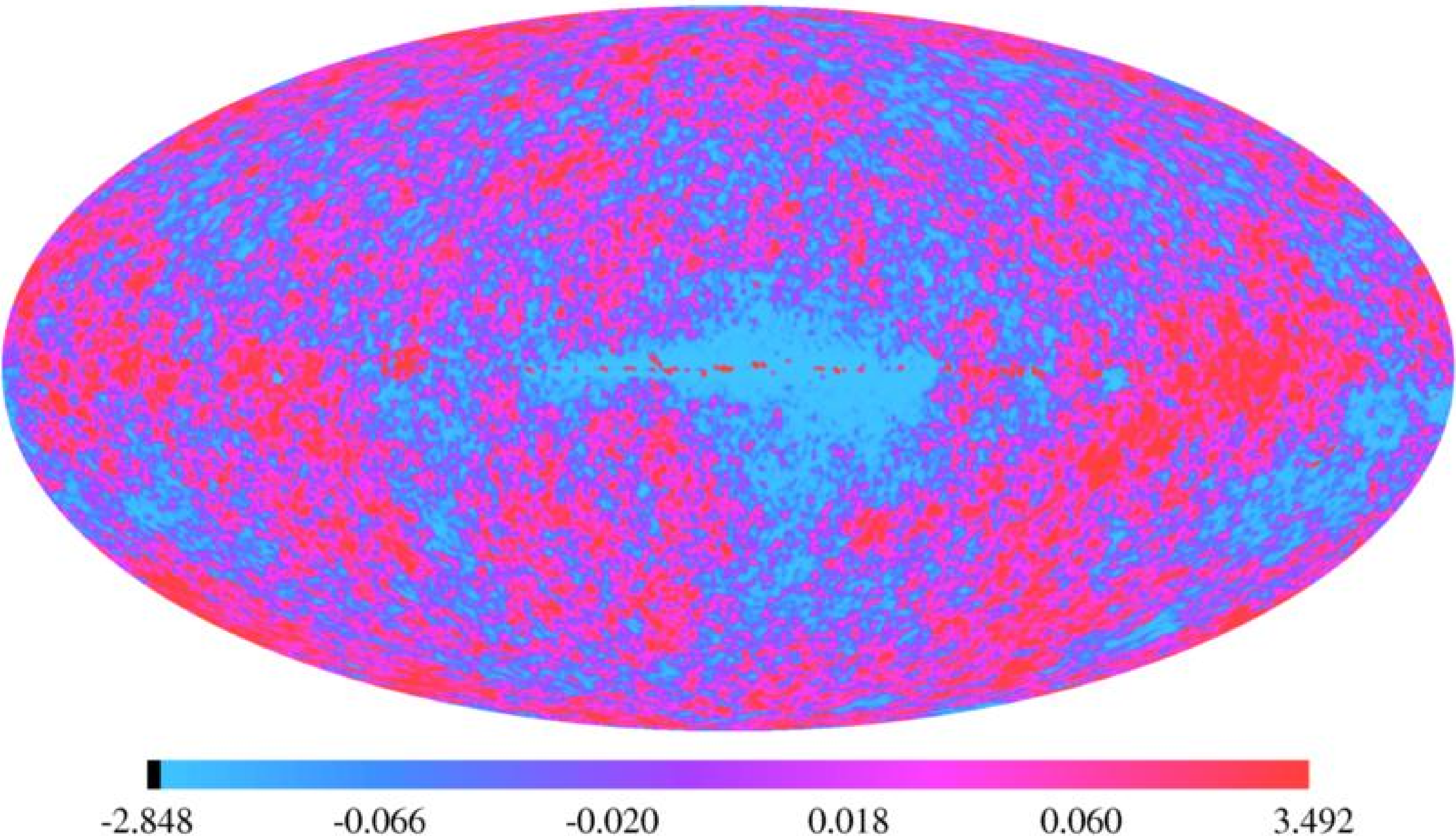
Nobs for K, Q & W



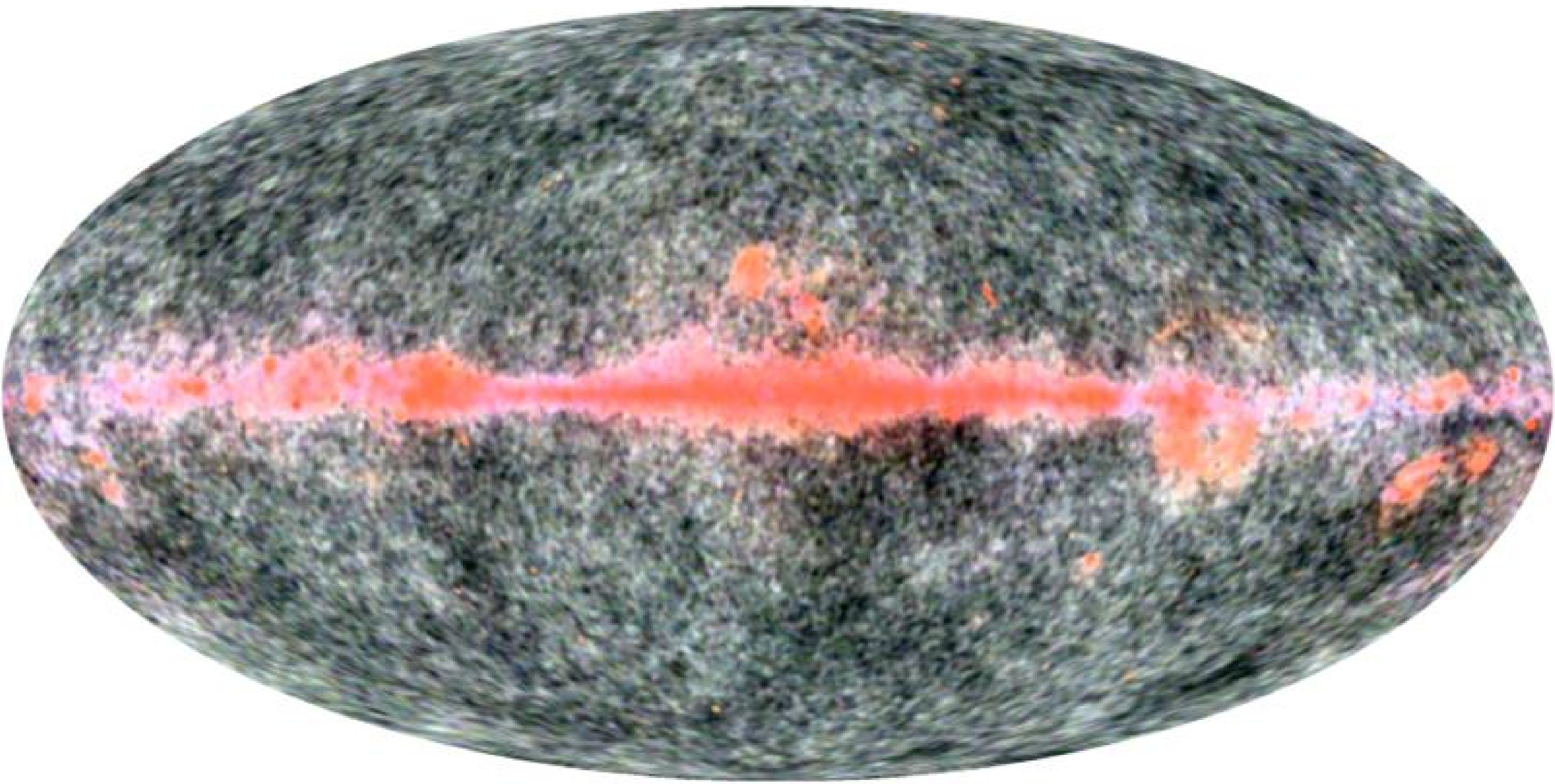
Remove v_{SS}, 2000x contrast



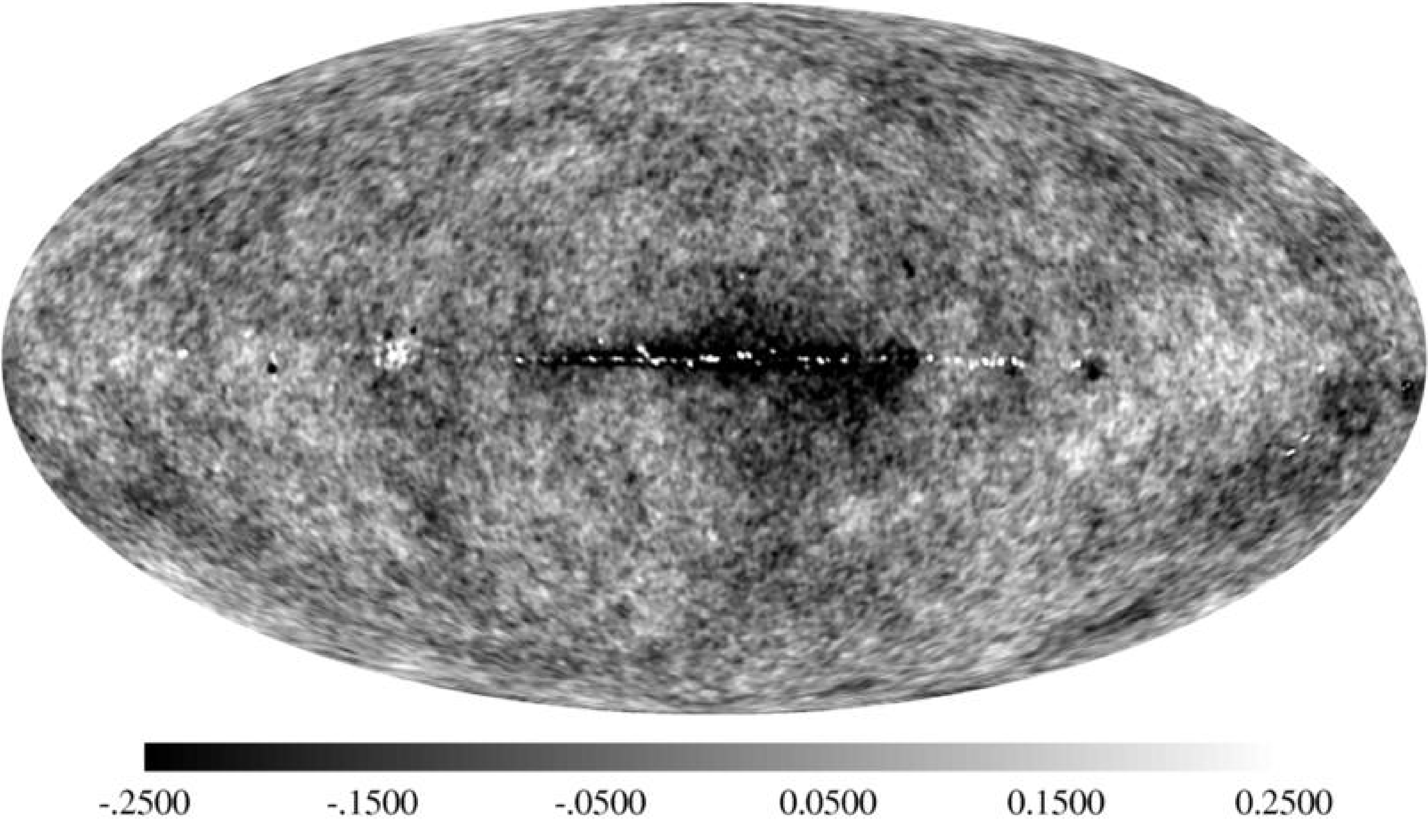
Remove Galaxy, 19000x Contrast



QVW as RGB

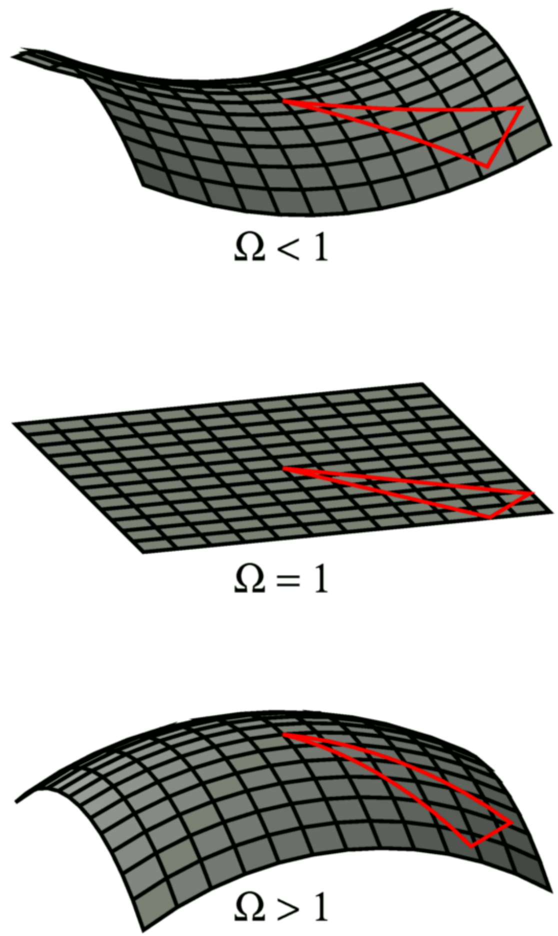


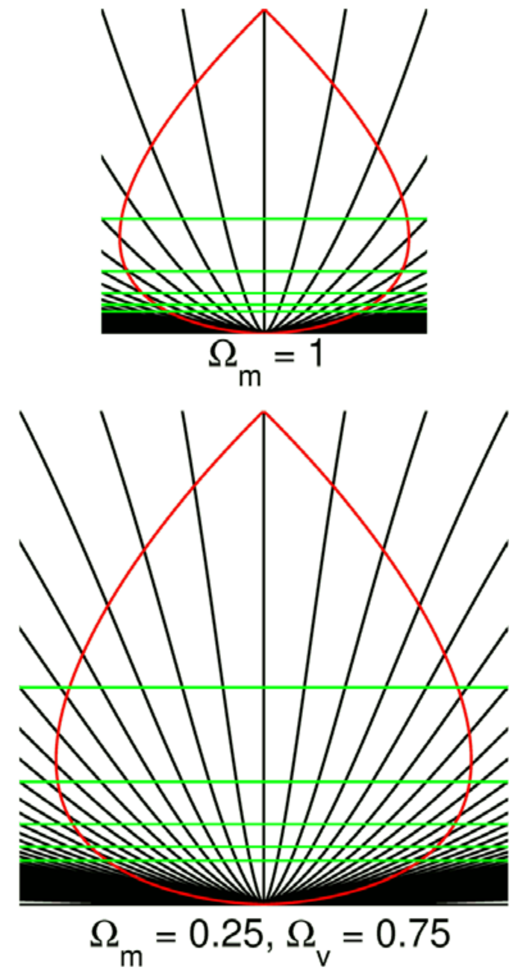
No Galaxy on same scale



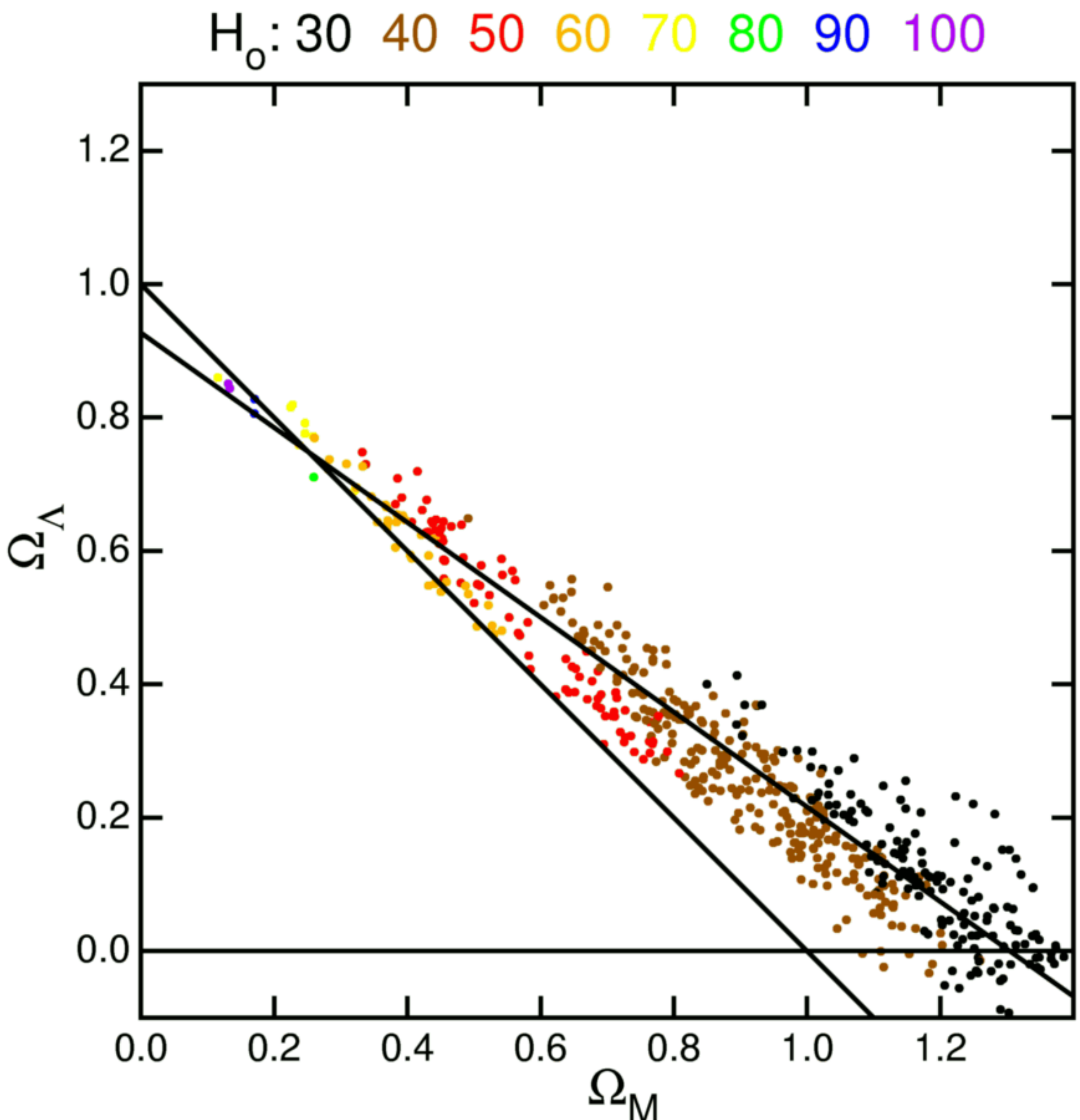
Effects on Peak Position: l_{pk}

- + Open or vacuum dominated Universes give larger distance to last scattering surface
- + High matter density gives smaller wavelength

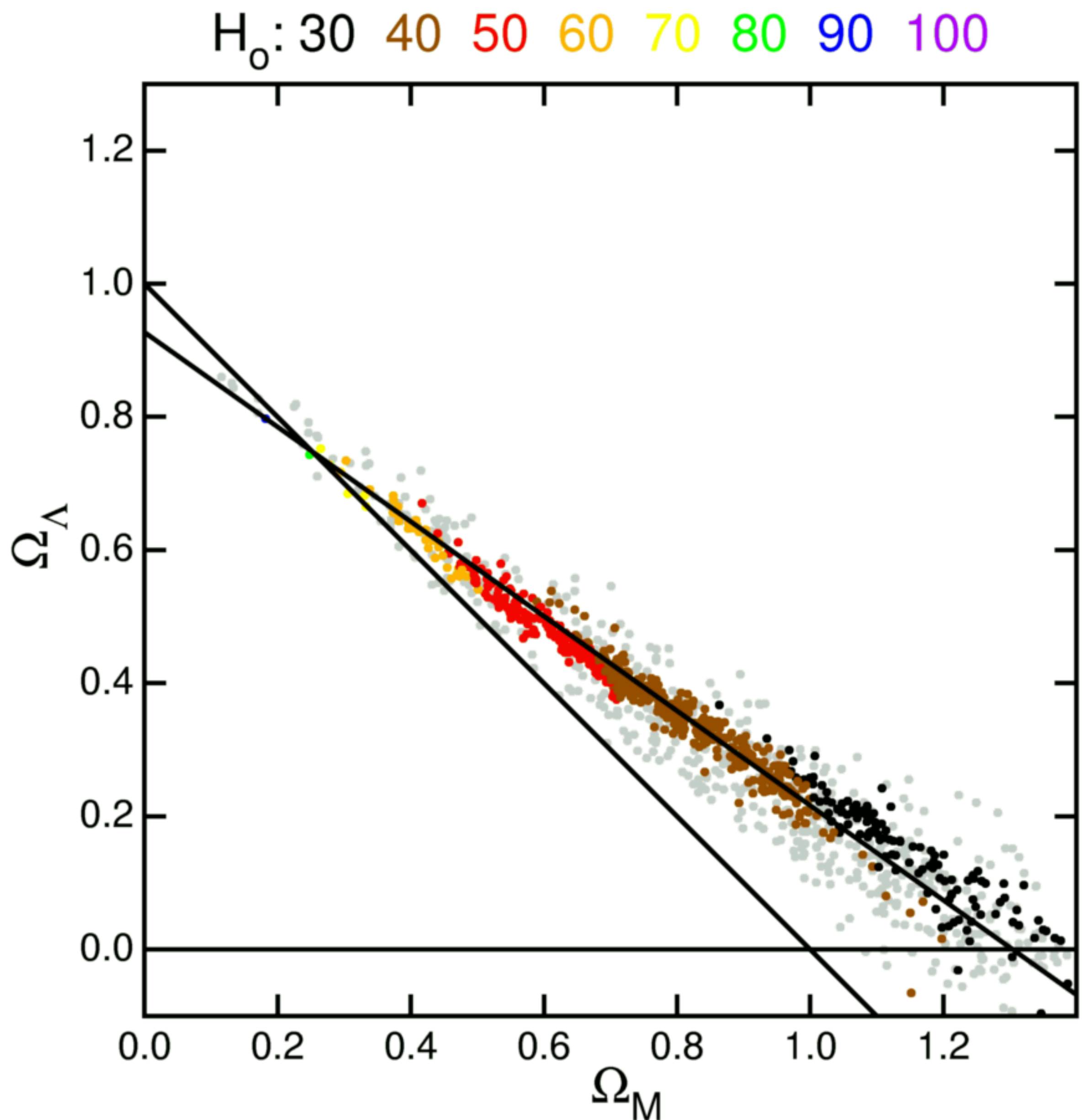




What We Have Learned: pre-WMAP



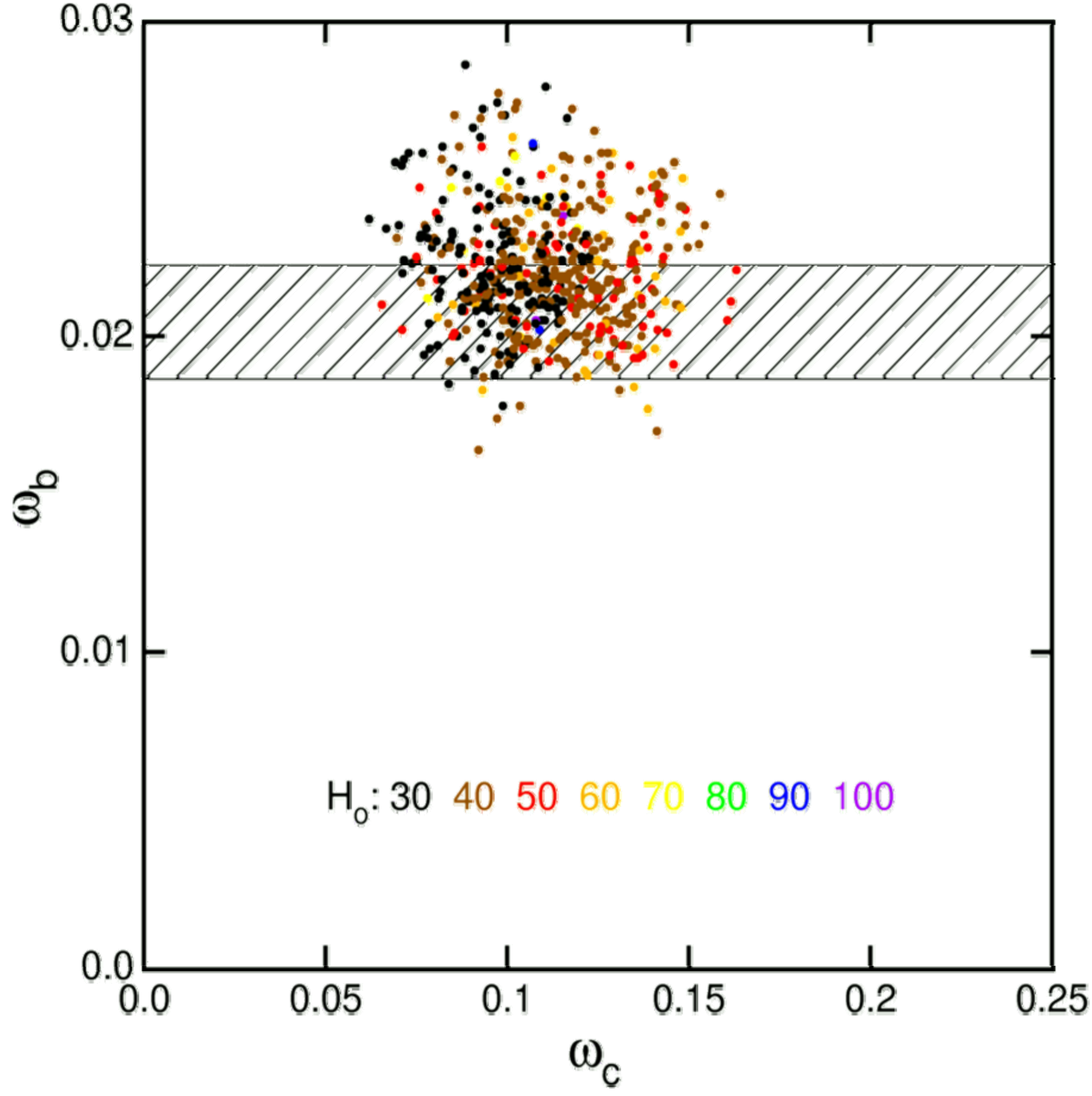
With WMAP replacing COBE



Info from peak & trough heights

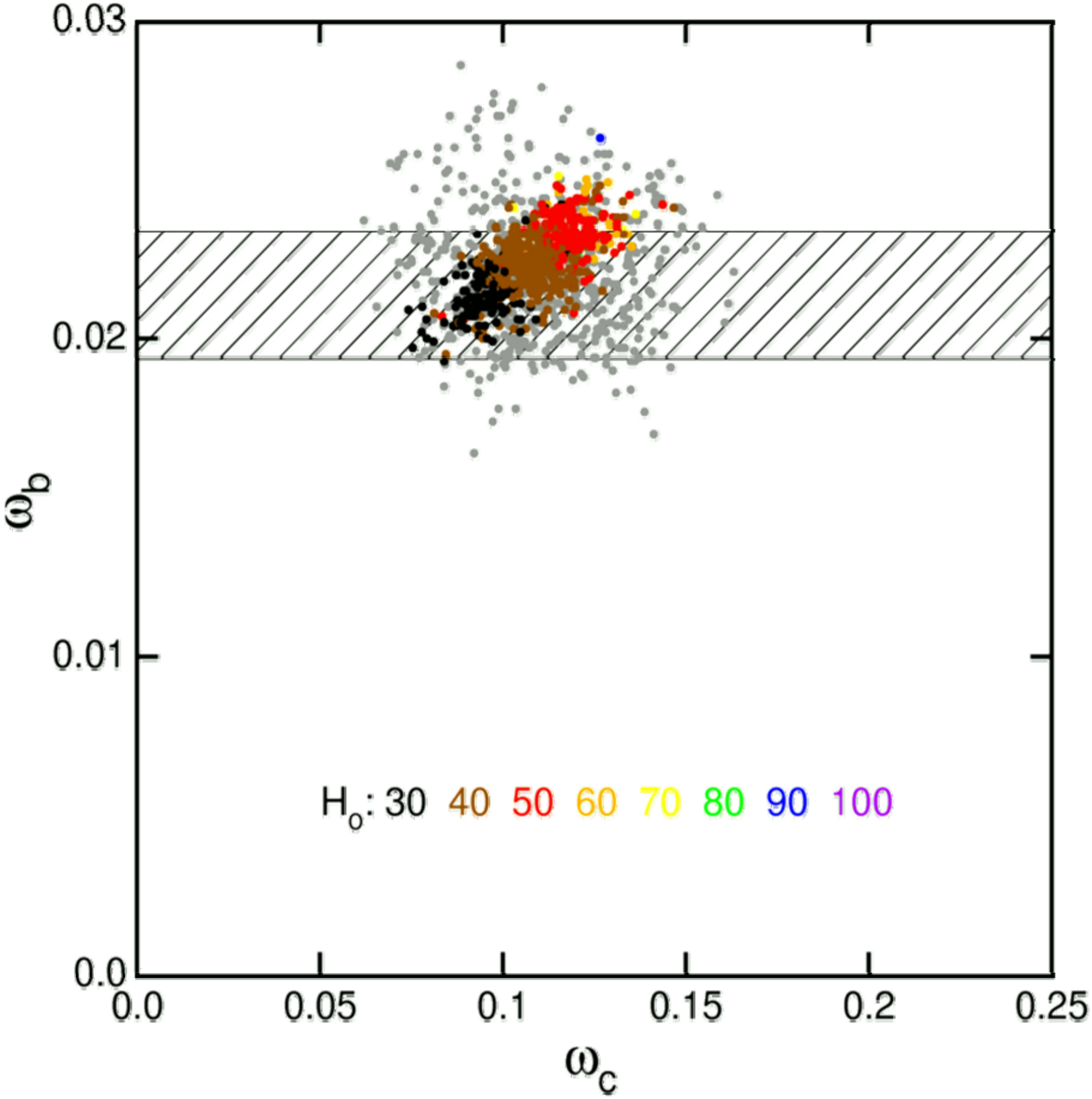
- Overall Amplitude of the perturbations
  - Agrees with large scale structure if sum of neutrino masses is < 0.7 eV
- Primordial power spectrum power law spectral index: $n = 0.99 \pm 0.04$ without running index.
  - Agrees with inflationary prediction
- Baryon/photon and DM/baryon density ratios
  - $\rho_b = 0.42$ yoctograms/m^3 = 0.42×10^{-30} gm/cc
  - $\rho_{cdm} = 2.1$ yg/m^3 [$\omega \equiv \Omega h^2 = \rho/\{18.8 \text{ yg/m}^3\}$]

Pre-WMAP densities

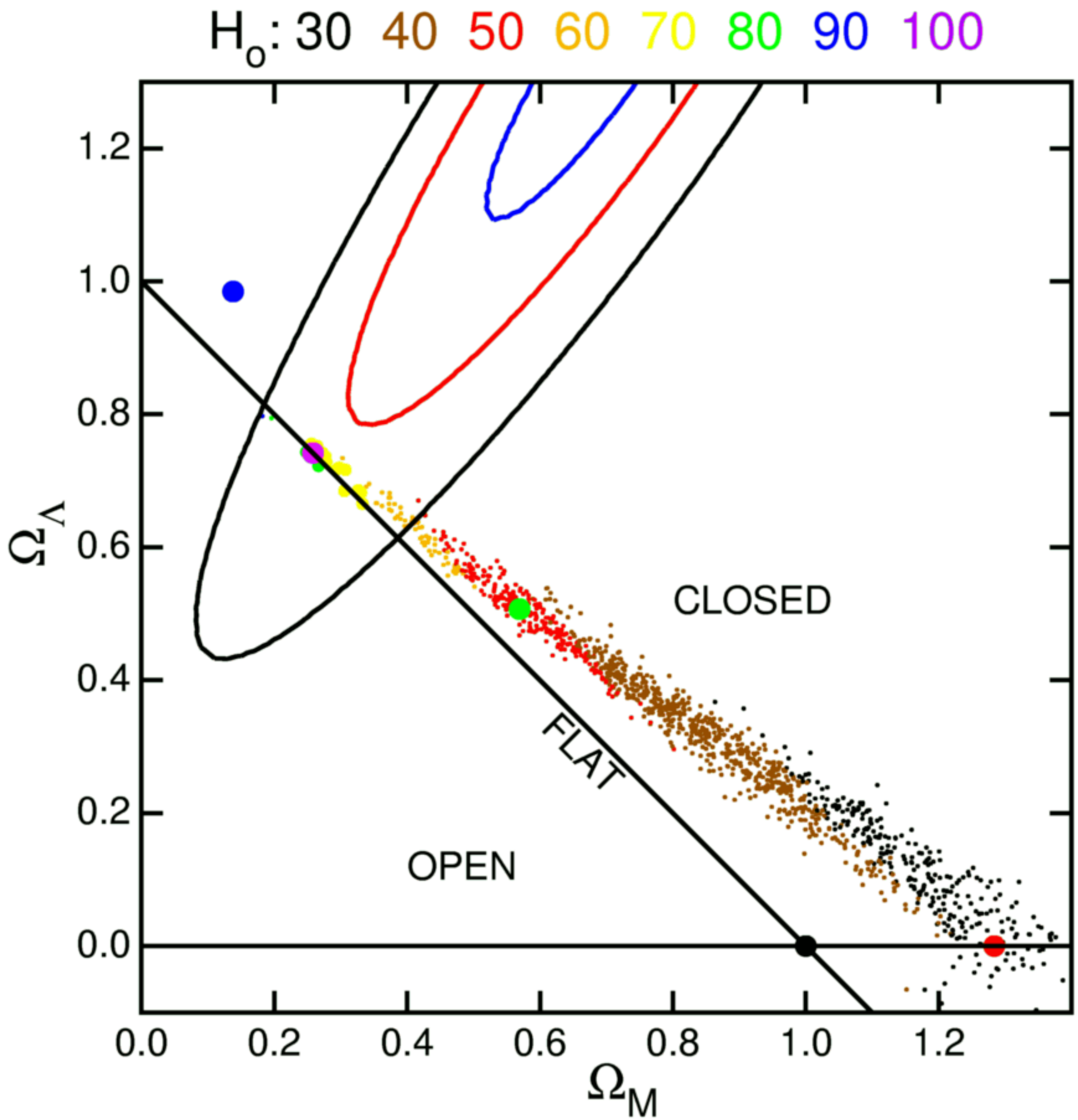


With WMAP replacing COBE

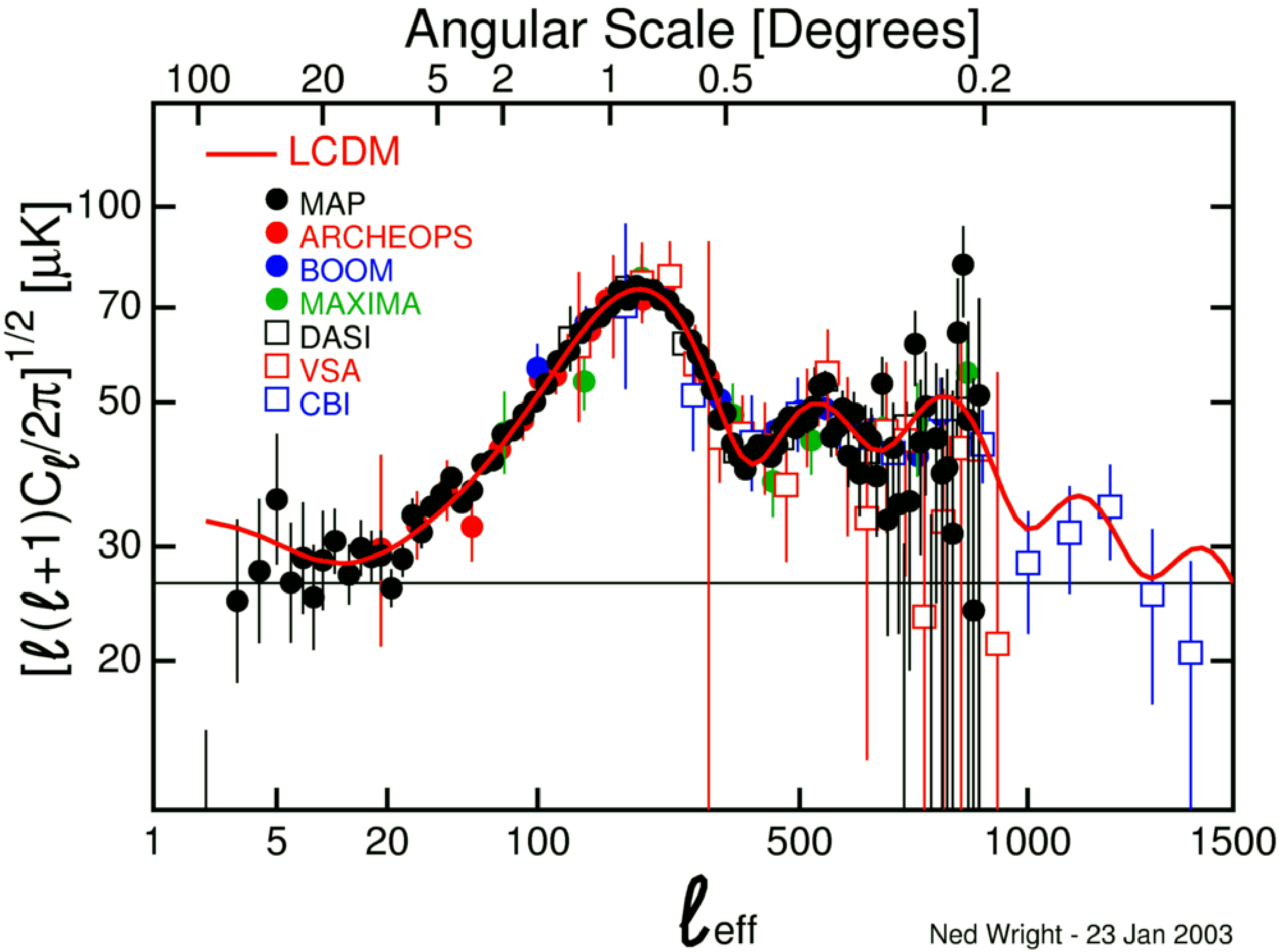
Note the new BBNS value from astro-ph/0302006



Key to Models

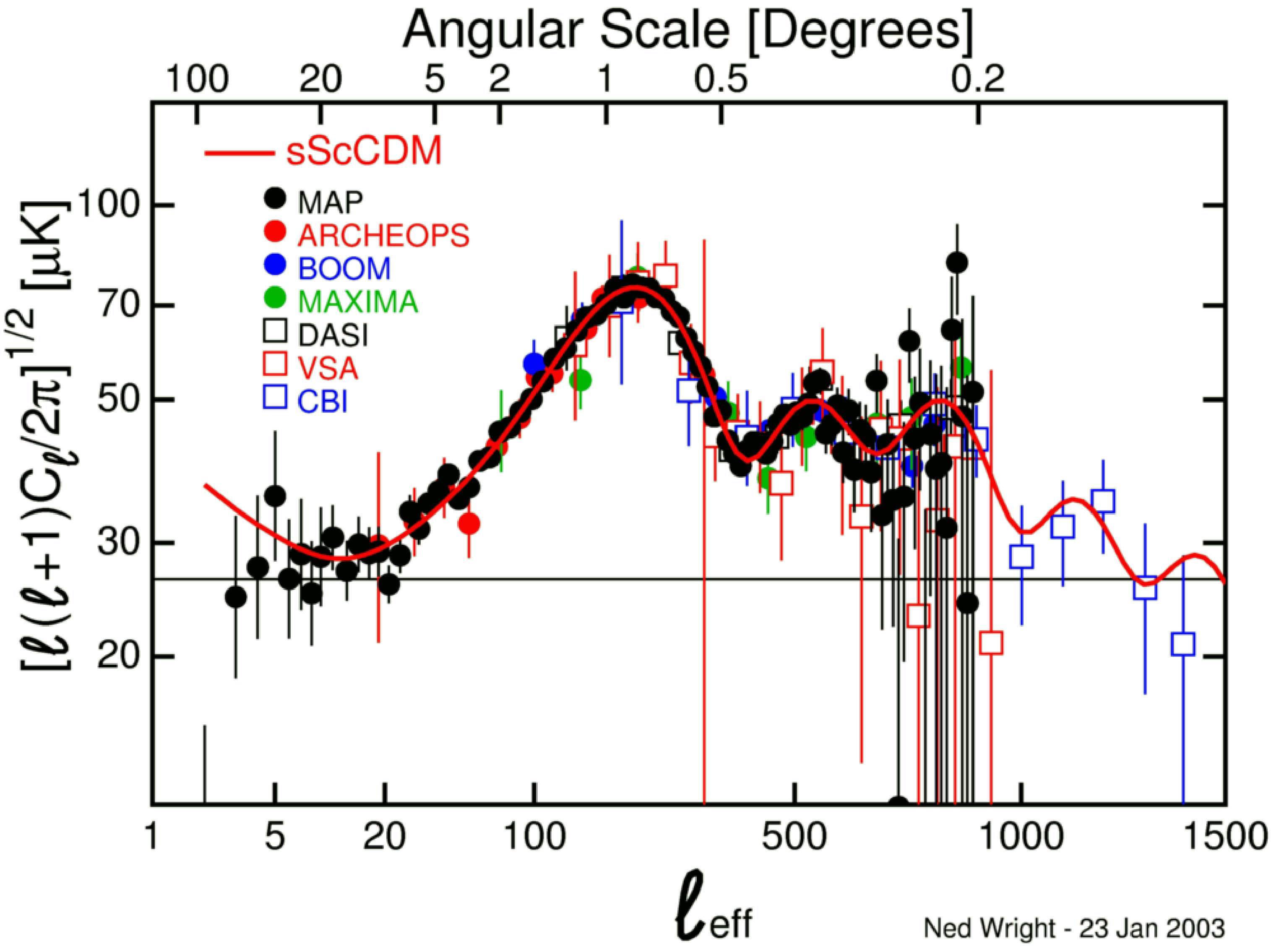


ΛCDM is a Good Fit



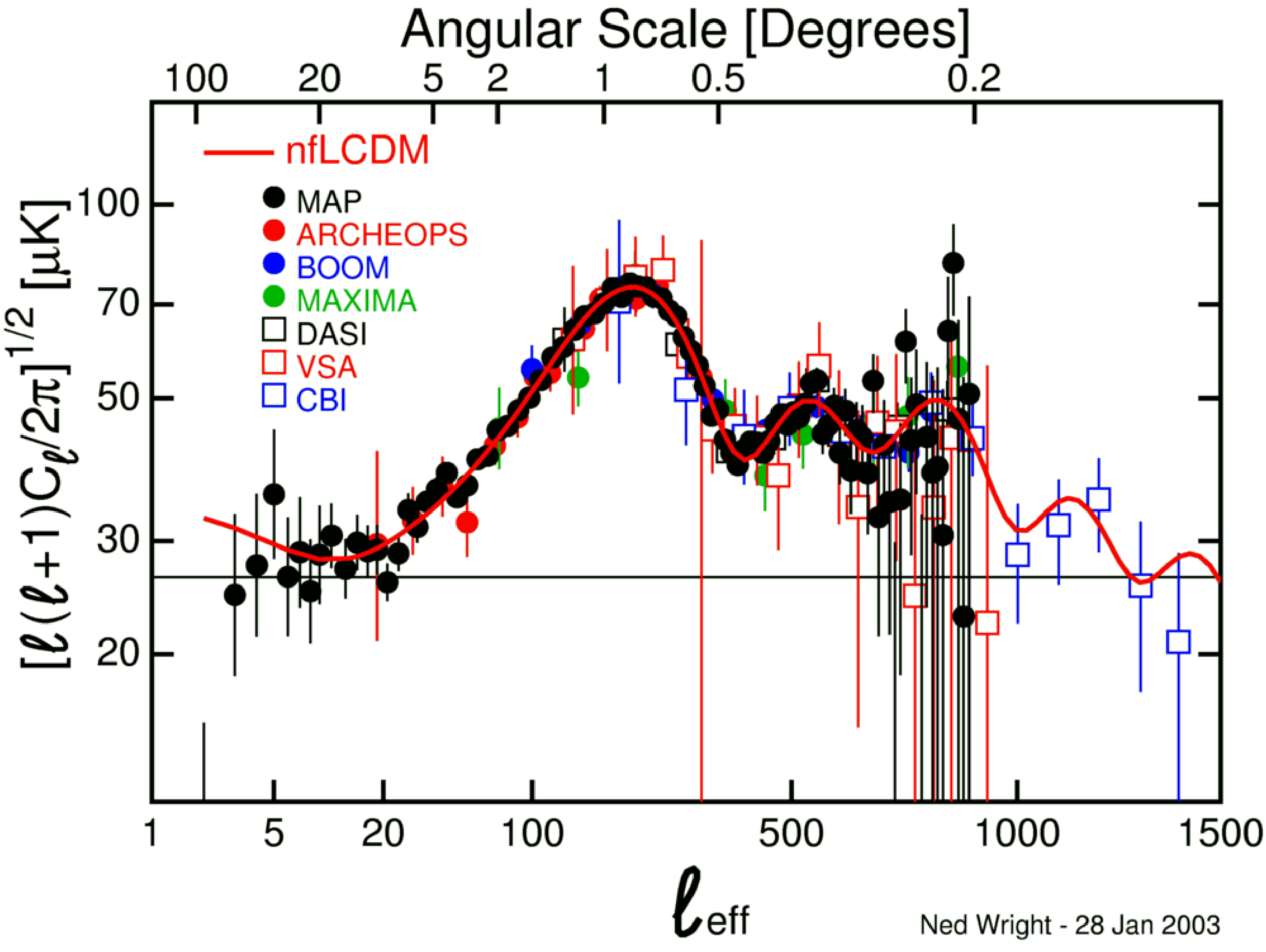
$H_o = 71$, $\Omega_\Lambda = 0.73$, $\Omega_b h^2 = 0.0224$, $\Omega_m h^2 = 0.135$, $\Omega_{tot} = 1$

Super-Sandage is Closed



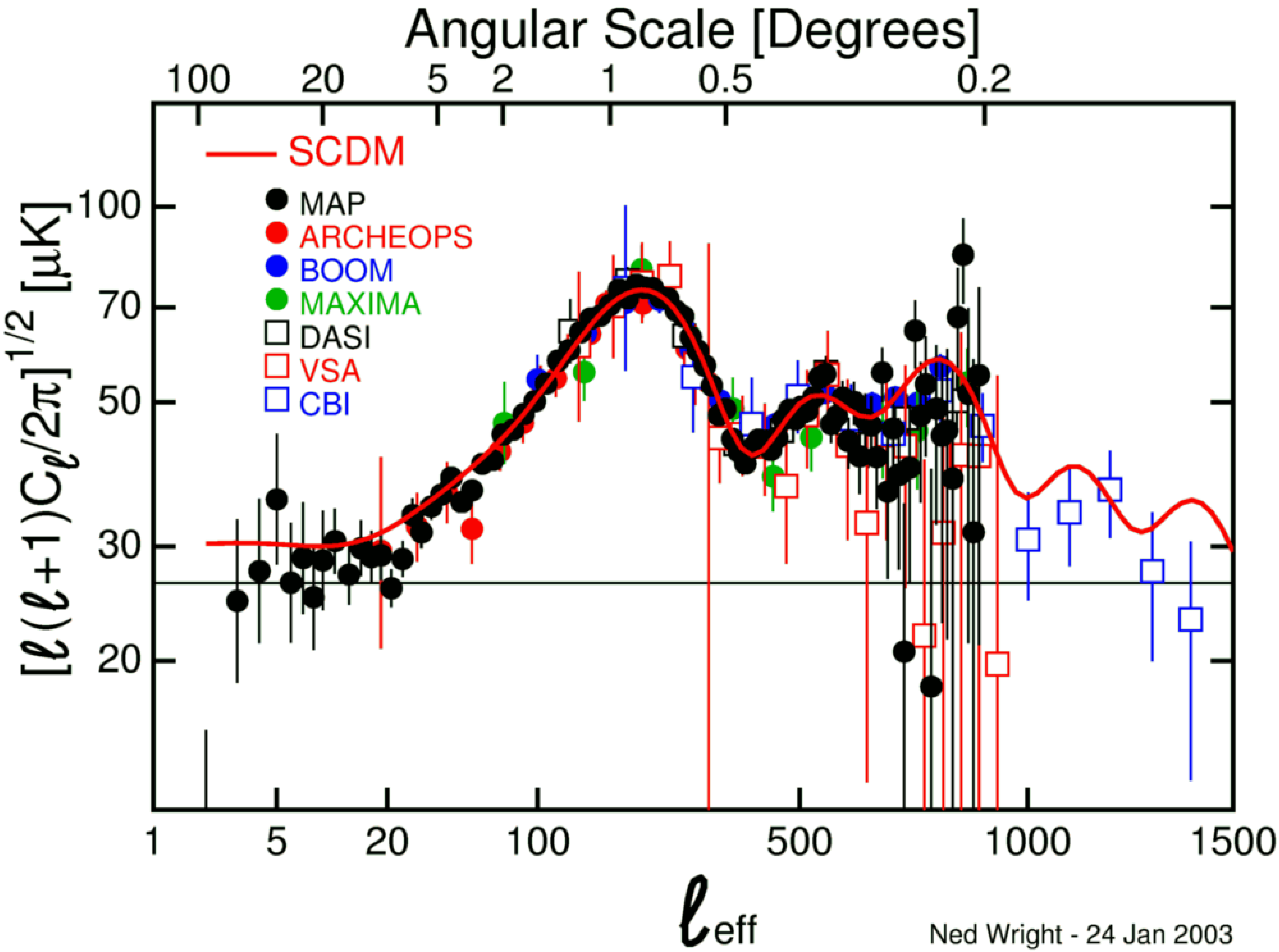
$H_o = 32,\ \Omega_\Lambda = 0,\ \Omega_b h^2 = 0.0232,\ \Omega_m h^2 = 0.139,\ \Omega_{tot} = 1.3$

Best Fit: Two Many Tooth Fairies



$H_o = 50$, $\Omega_\Lambda = 0.51$, $\Omega_b h^2 = 0.0233$, $\Omega_m h^2 = 0.141$, $\Omega_{tot} = 1.08$

Einstein – de Sitter Model Fails



$H_o = 50, \Omega_\Lambda = 0, \Omega_b h^2 = 0.0236, \Omega_m h^2 = 0.25, \Omega_{tot} = 1$

Can this model be saved?

- Einstein – de Sitter fails because it is off the "degeneracy line".
- To get the peak positions right the densities have to be pushed out of the "sweet spot".
- As a result the amplitude, especially at low l, is wrong. An 8σ discrepancy on C_l
- Blanchard et al. astro-ph/0304237 fix this with a broken power law primordial P(k). They use a mixed dark matter approach to get the Large Scale Structure right.
- Their EdS model is still 3σ off on H_o and 10σ off on the accelerating Universe data from supernovae.

Is the Universe Really Flat?

- CMB data alone give some limits but adding H_o and SNe priors gives much better limits.
- Replacing COBE by WMAP does not dramatically change the limits on Ω_{tot}.

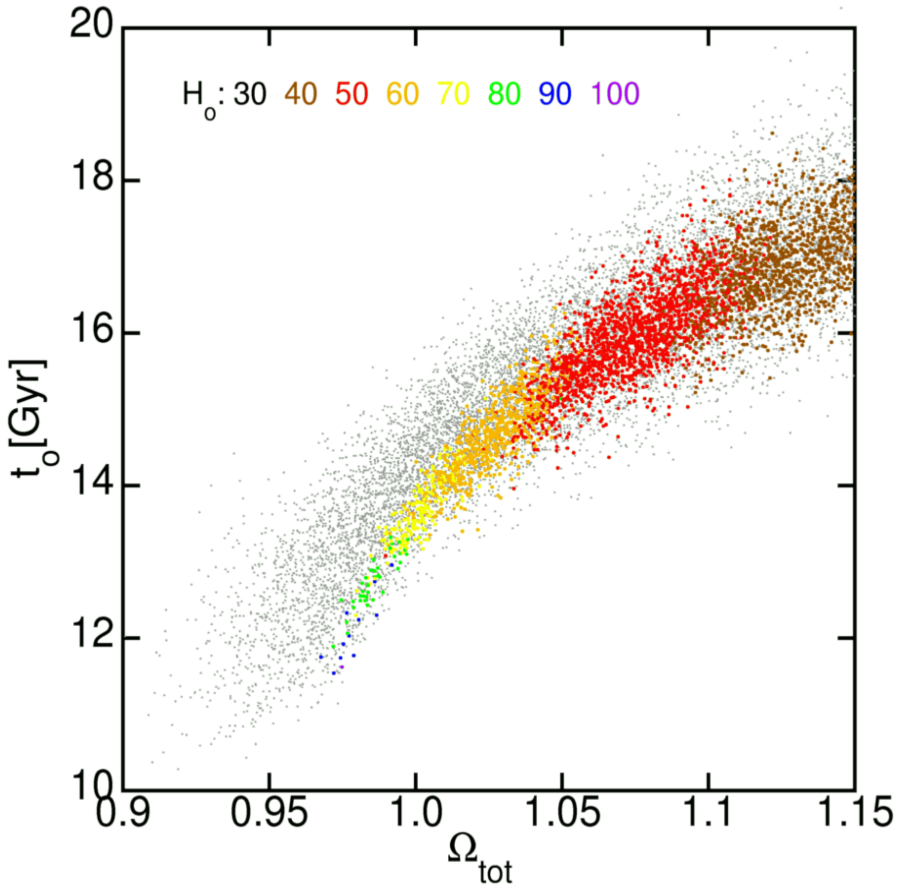
	CMB only	CMB+SNe	CMB+H_o	All
Pre-WMAP	1.18(11)	1.04(4)	1.02(3)	1.02(2)
With WMAP	1.16(9)	1.04(3)	1.03(3)	1.02(2)

More Restrictions on Models

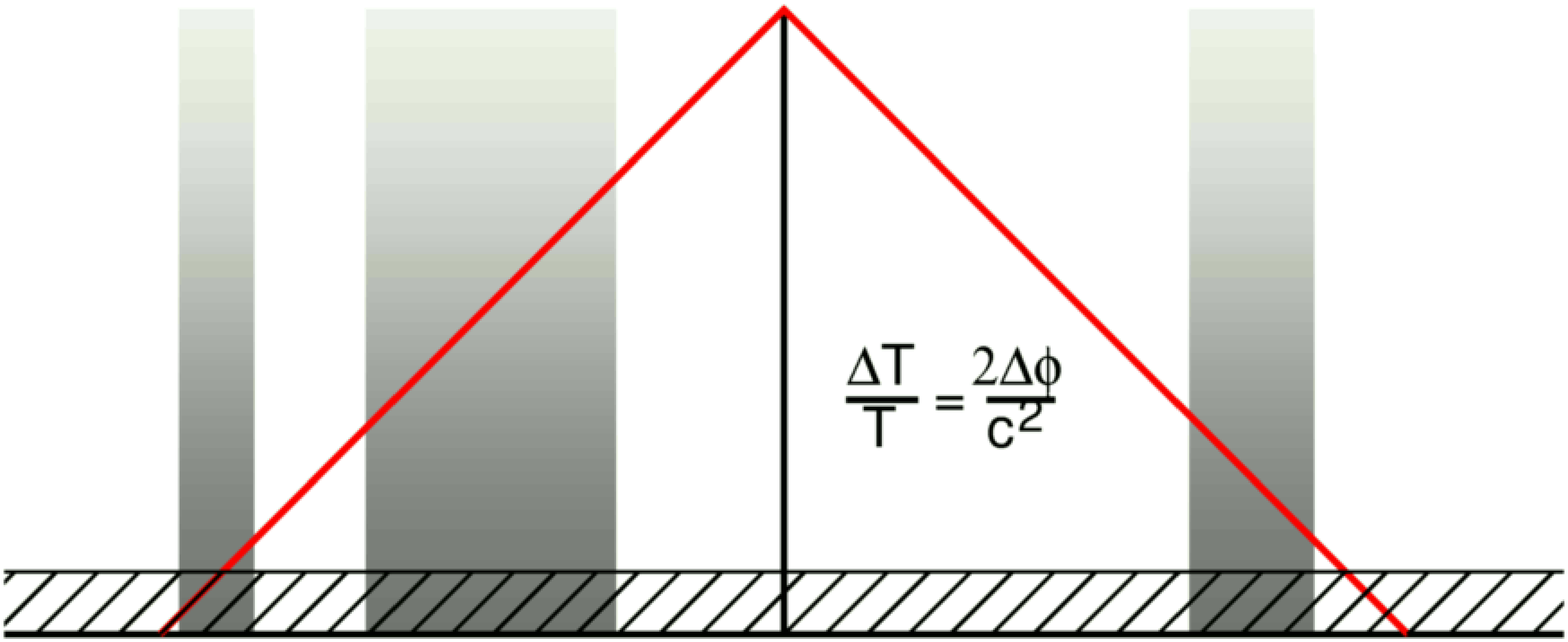
- Quintessence is restricted: $w = P/\rho c^2 \leq -0.78$ in the dark energy
- Neutrino masses add up to less than 0.7 eV
  - $\Delta P(k)/P = -8\ \Omega_\nu / \Omega_m$ (Hu et al. astro-ph/9712057)
  - So this limit, about 7% of the CDM density, gives a 50% reduction in small-scale power

Going Flat Out with LSS & Lyα

- Assuming a flat, Ω_{tot} = 1, Universe gives:
  - H_o = 71 ± 3.5 km/s/Mpc
  - t_o = 13.7 ± 0.2 Gyr
  - Ω_Λ = 0.73 ± 0.04
  - $\Omega_b h^2$ = 0.0224 ± 0.001 or 0.25 baryons/m^3
  - $\Omega_m h^2$ = 0.135 ± 0.009 or 2.54 yoctograms/m^3
  - σ_8 = 0.84 ± 0.04

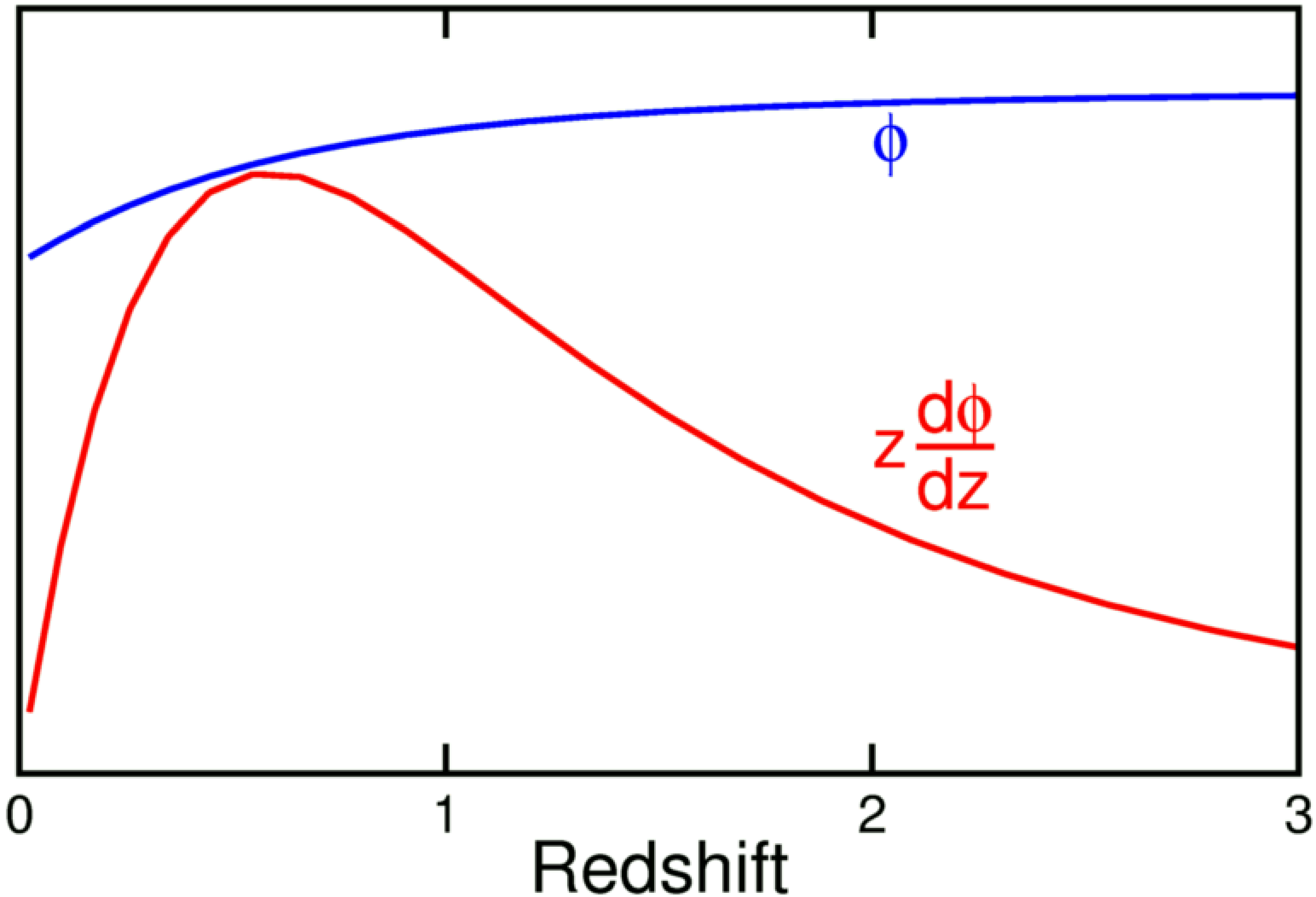


Late ISW Effect



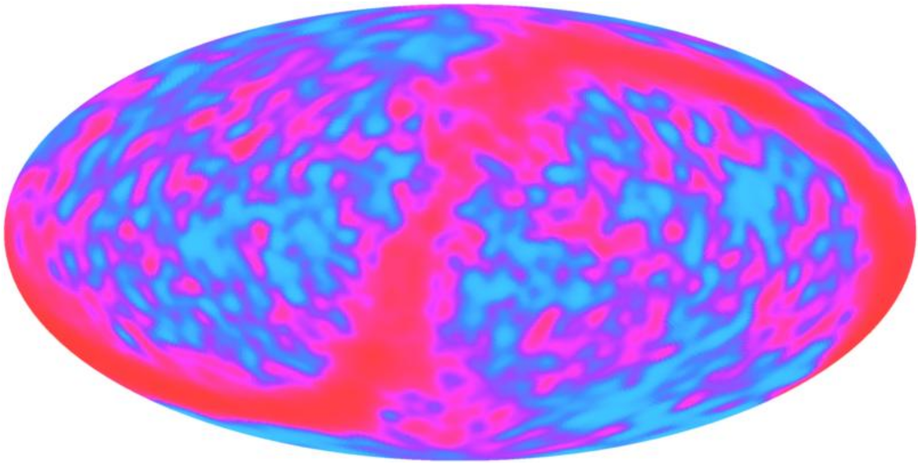
Potential only changes if $\Omega_m \neq 1$ (or in non-linear collapse, but that's another story [Rees-Sciama effect]).

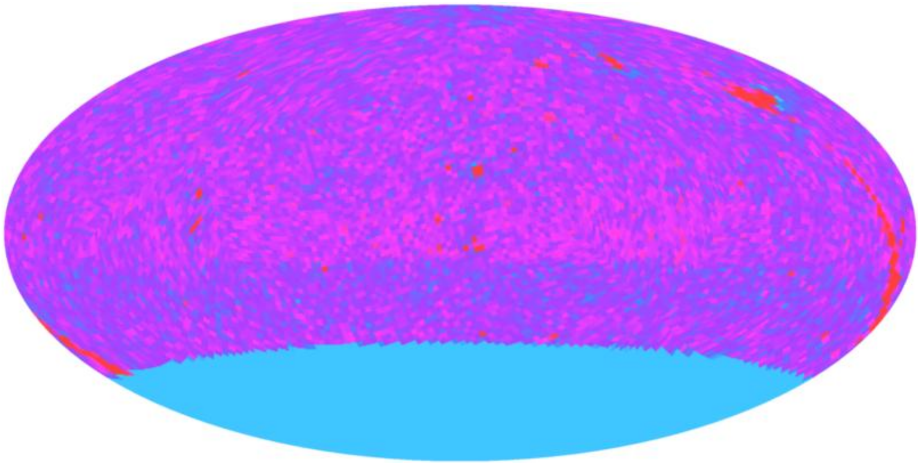
Potential decays at $z \approx 0.6$



Correlated with Observed LSS

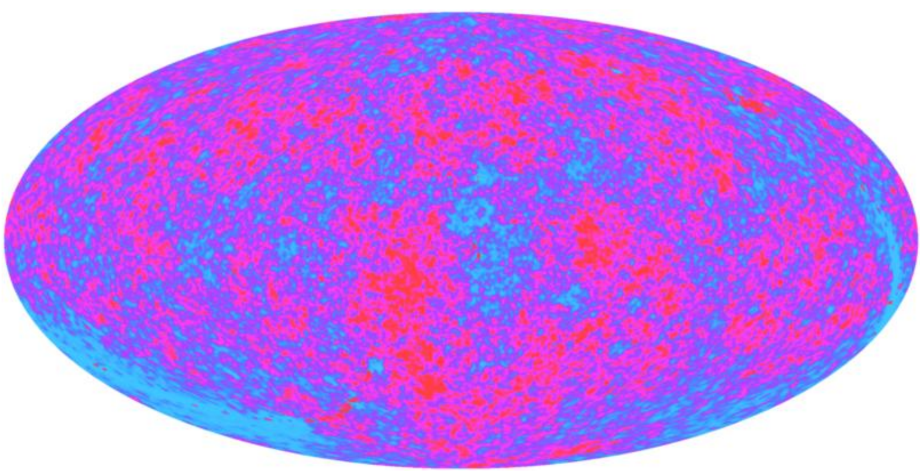
- This late ISW effect occurs on our past light cone so the ΔT we see is due to structures we also see.
- Search for correlation between LSS at z=0.6 and the CMB anisotropy: see Boughn & Crittenden, astro-ph/0111281
  - Expected 0.035 cross-correlation between NVSS sources and COBE DMR
  - observed -0.003 ± 0.025

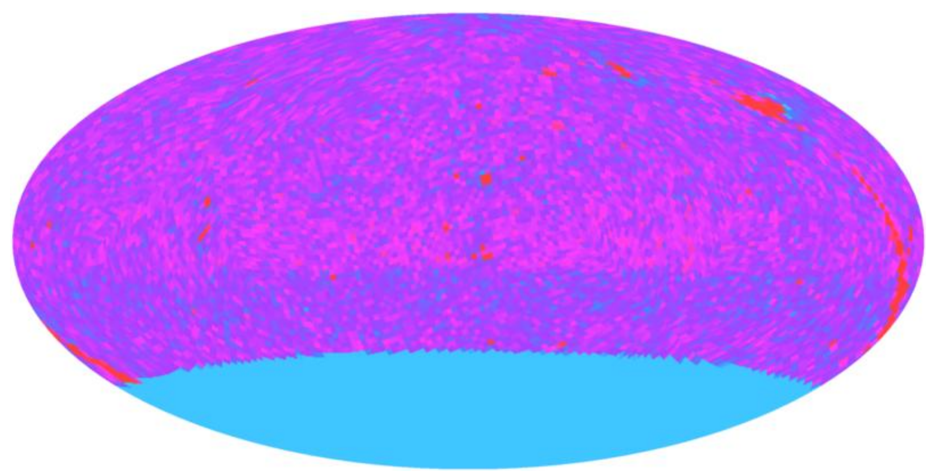




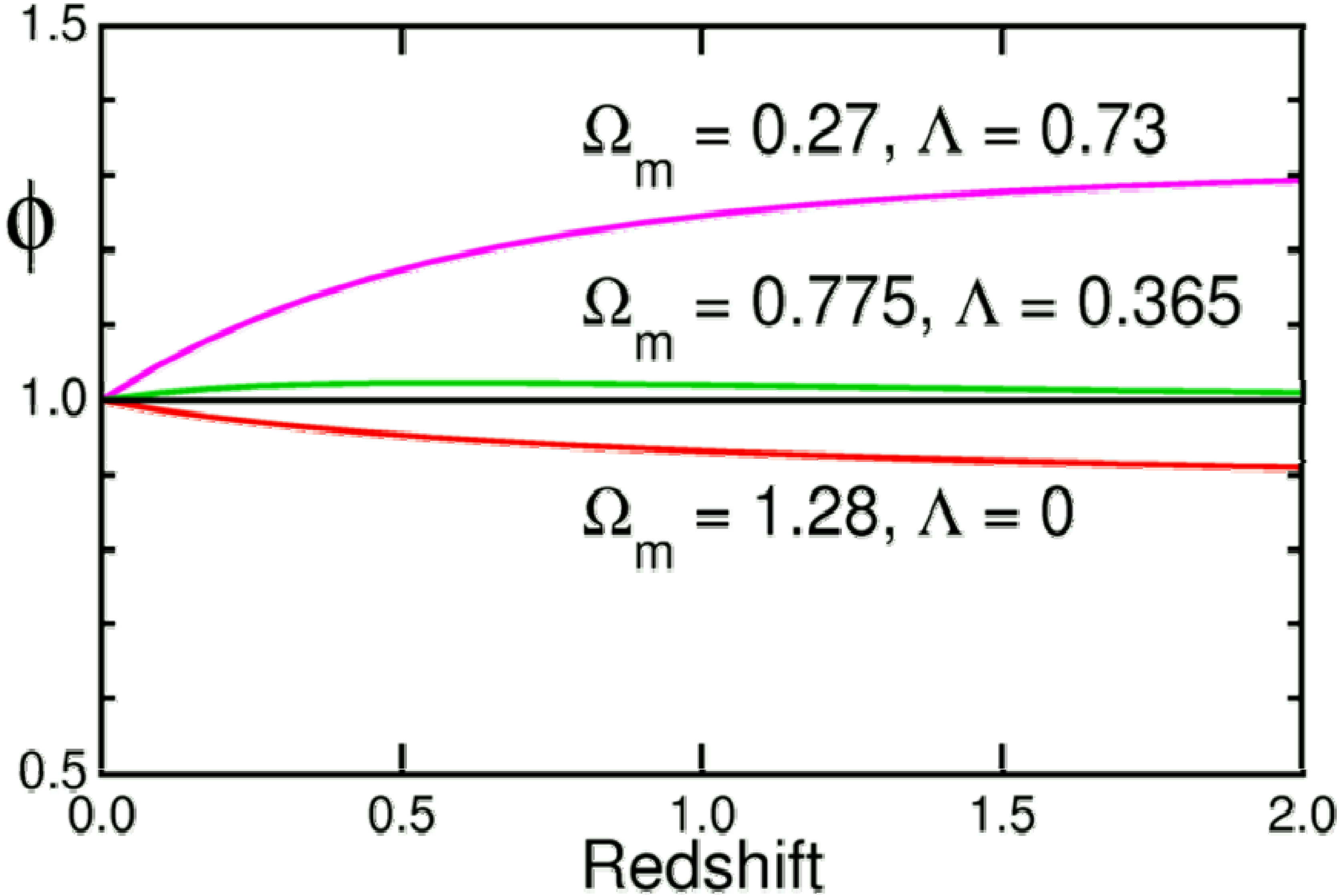
Correlation is seen with WMAP

- Correlation between WMAP and LSS seen by:
  - Boughn & Crittenden (astro-ph/0305001) at 2.75σ with hard Xray background and 2.25σ with NVSS
  - Nolta et al. (astro-ph/0305097) at 2σ with NVSS





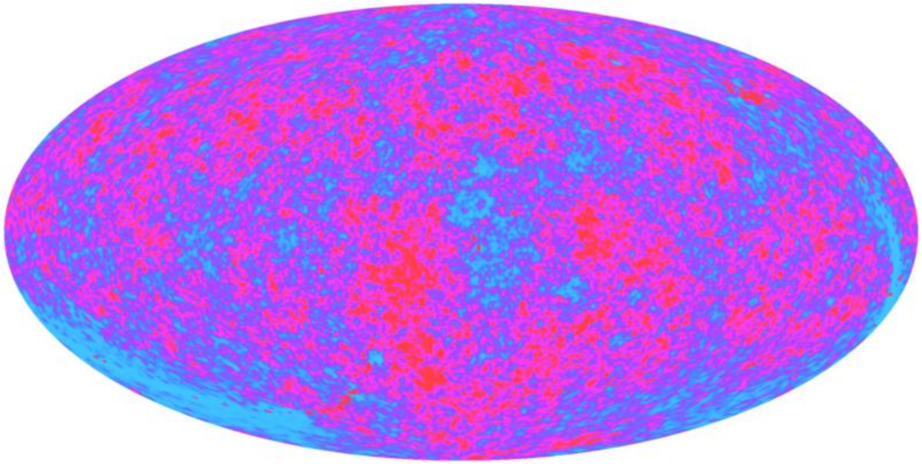
ΛCDM is OK, sSCDM fails at 3σ

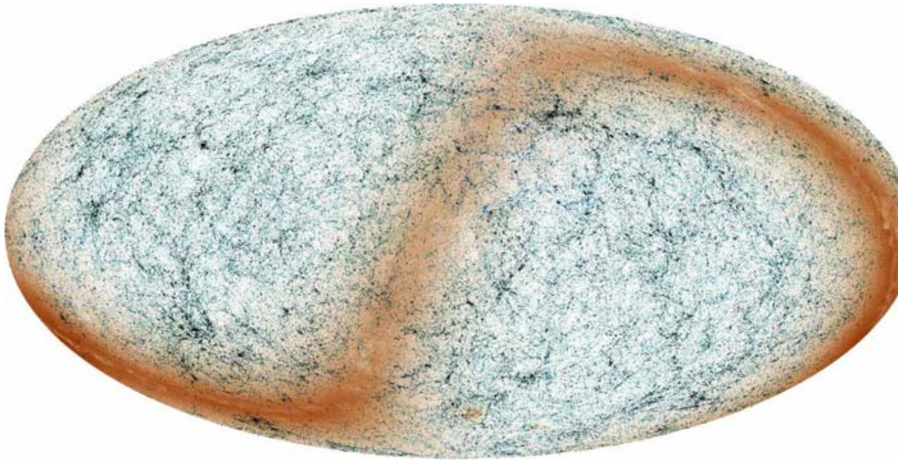


Possible Improvements?

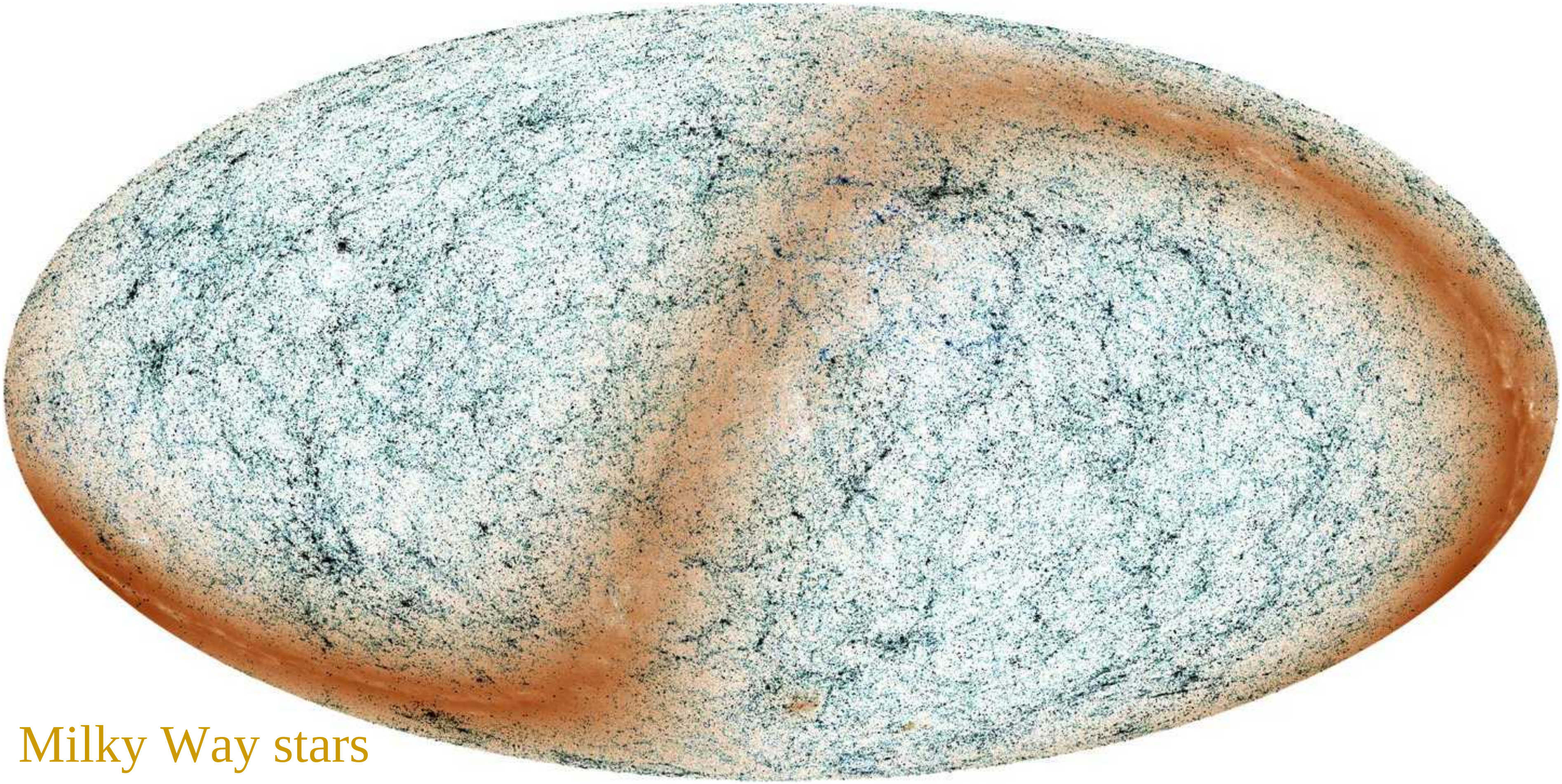
✓Less noisy and higher resolution CMB data.

- Use a better tracer of LSS. IR surveys trace old stars and thus are close to a mass survey.

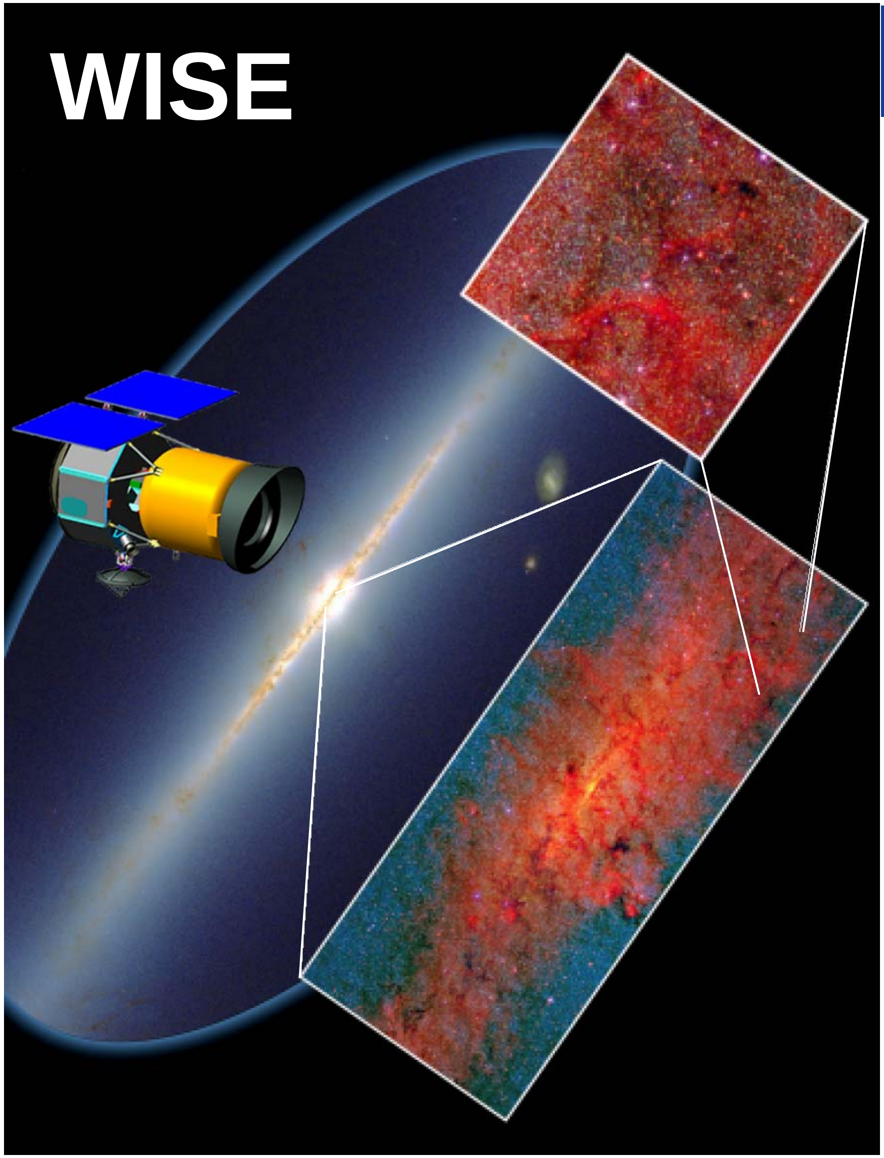




2MASS Galaxies at $z \approx 0.15$



To get a deeper sample, use:



WIDE-FIELD INFRARED SURVEY EXPLORER

WISE will provide an all-sky survey from 3 to 23 µm with three orders of magnitude better sensitivity than IRAS. The survey will help search for the origins of planets, stars, and galaxies and will be a valuable precursor for JWST.

WISE will

- *Find the most luminous galaxies in the Universe.*
- *Find the closest stars to the sun.*
- *Detect most main belt asteroids larger then 3km.*

Mission Overview

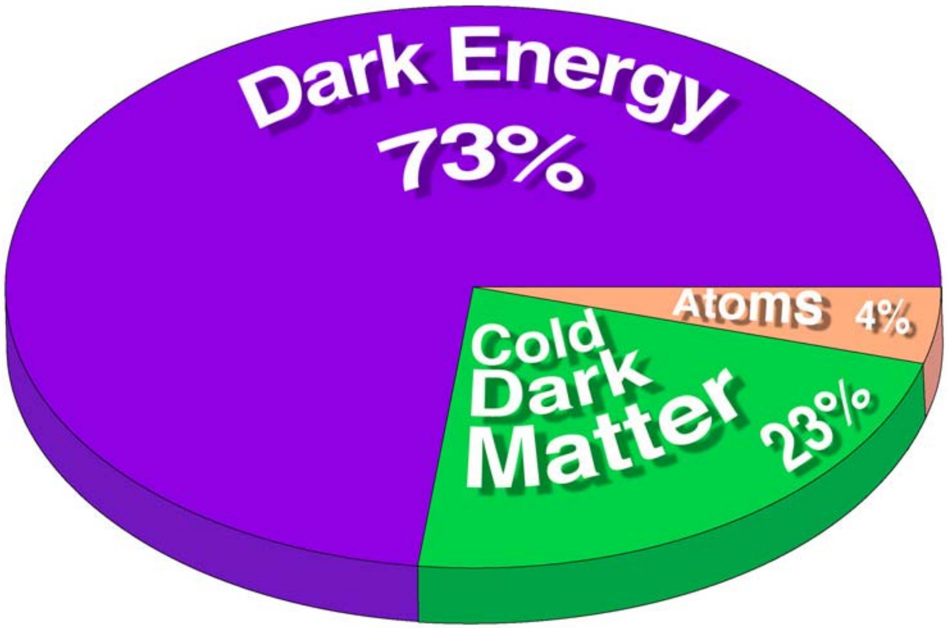
- *Circular 500-km Sun-synchronous orbit.*
- *7-month mission including a 1-month checkout.*
- *Four 1024^2 focal plane arrays.*
- *40-cm telescope cooled by a two-stage solid-hydrogen cryostat.*
- *Scan mirror to stabilize the line-of-sight while the spacecraft scans the sky.*

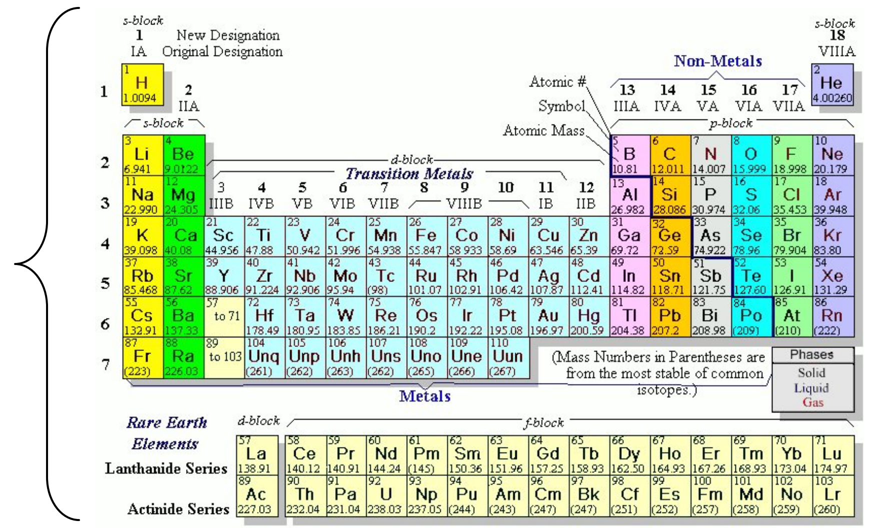
NASA UCLA SDL USU SSG, Inc. Rockwell Scientific Orbital DRS Technologies Ball Lockheed Martin JPL

“Nothing” really funny

- Where the hell does it all come from?
- And where does the vacuum energy come from?
- Why 3.9 keV/cc?

We (and all of chemistry) are a small minority in the Universe.





CONCLUSION

- The basic ΛCDM model for the Big Bang with inflation is confirmed:
  - The baryon density is measured to an accuracy of 4% from the CMB and agrees with the value from BBNS (9% accuracy) to within 5%.
  - Flat model fit only to CMB data matches the Hubble constant, supernova and large scale structure data.
  - Age of the Universe in a flat ΛCDM model is 13.7 ± 0.2 Gyr
- Get more information at http://map.gsfc.nasa.gov

WMAP Status

- At L2, having completed of 4th full year of observations.
- Approved for an extended mission of 8 years total at L2 if the spacecraft and instrument continue to work and we ever get the polarization data out.
- WMAP has already greatly exceeded the “minimum space mission” goal discussed at Snowmass in 1994 of measuring the anisotropy to the cosmic variance limit for all scales larger than a degree.
- More integration will greatly improve the SNR on polarization and l’s up to 1000.