What’s New in Cosmology

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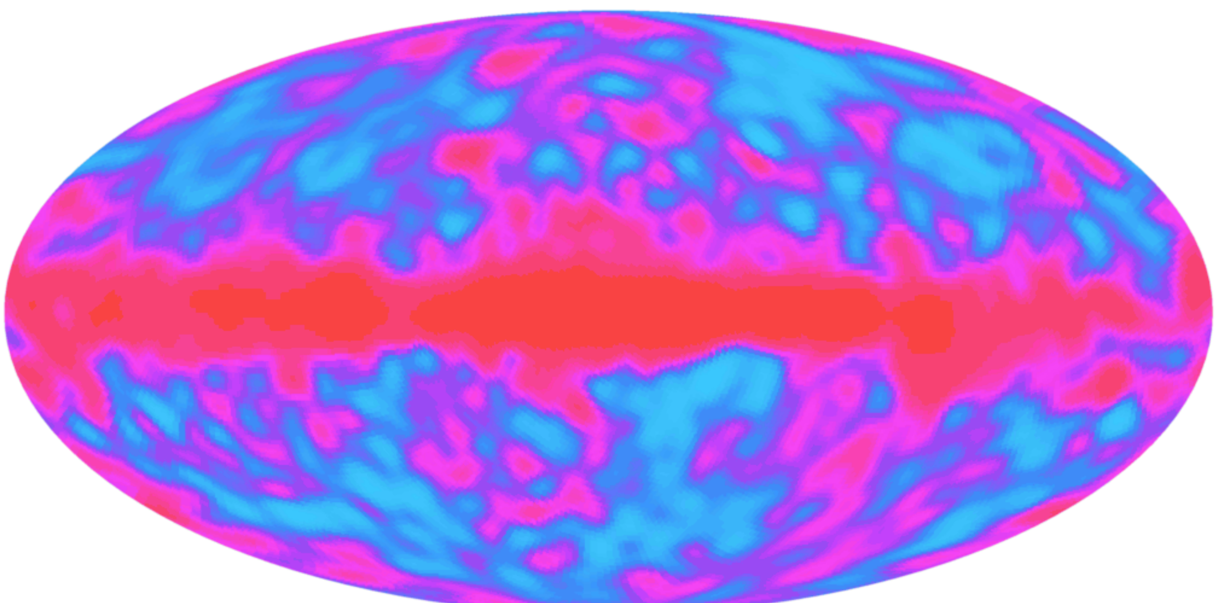
UCLA
10 November 2006

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.”

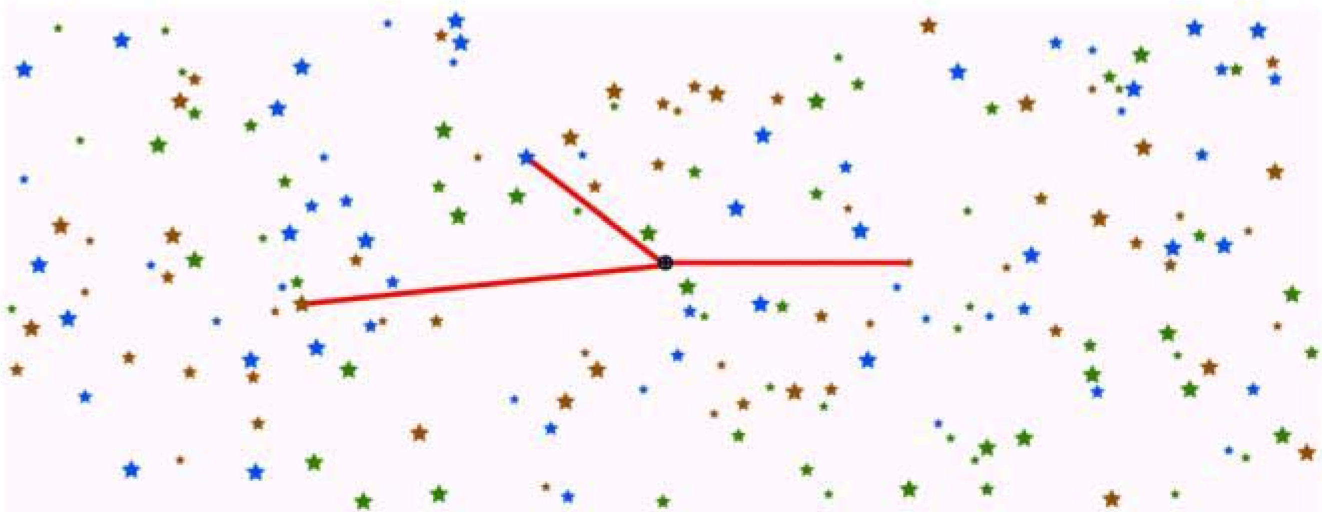


But really, what have we learned since 1906?

- Expansion of the Universe in 1929
- The Universe is homogeneous & isotropic.
- Dark matter in 1932
- Cosmic Microwave Background in 1964
- Accelerating Expansion in 1998

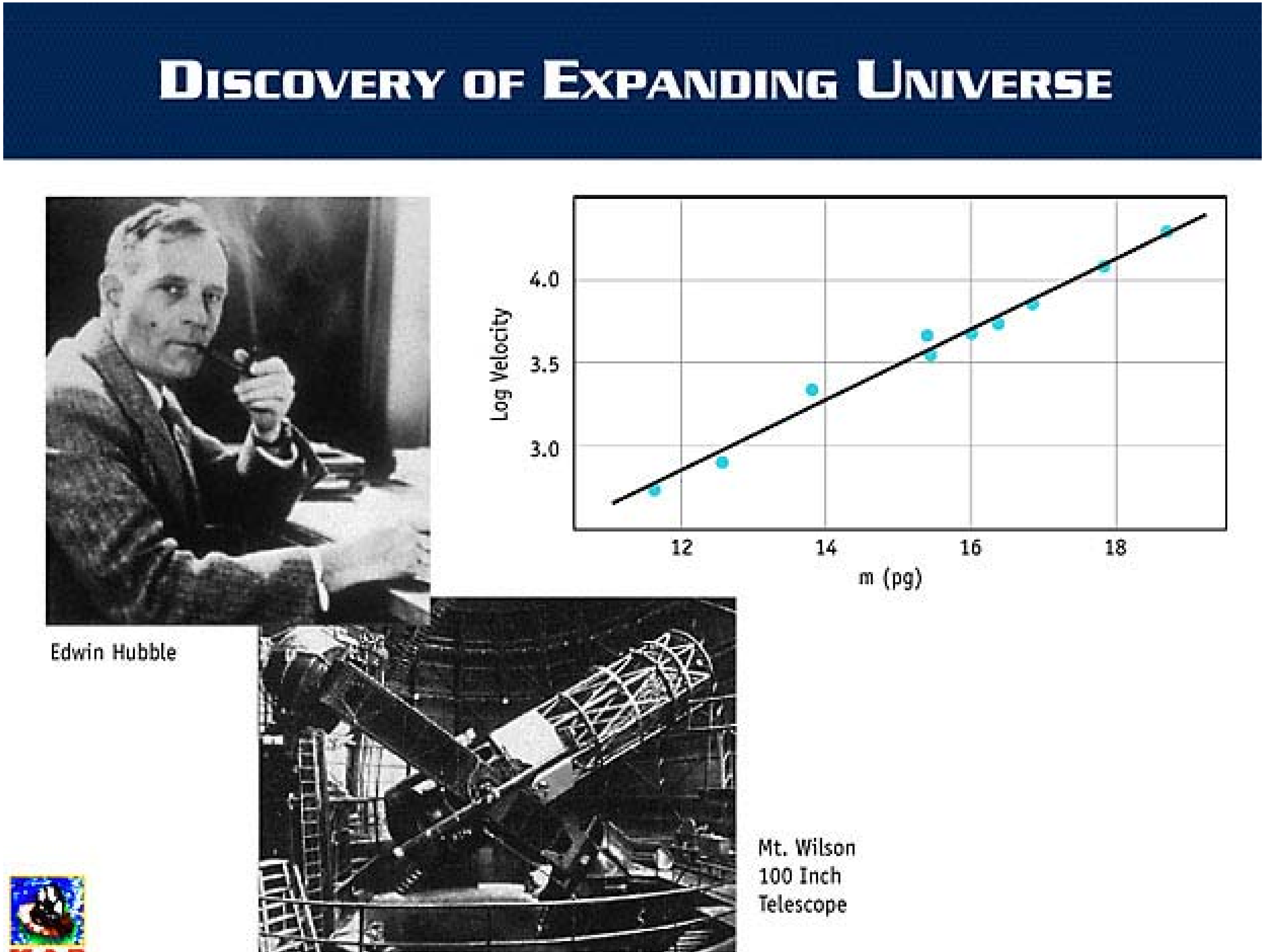
Only One Fact in 1917

1) The sky is dark at night. And Einstein ignored it.



In a homogeneous unchanging Universe every line of sight will end on a star. So why is the night sky not as bright as the surface of a star? The Cosmic Infrared Background is what remains after this Olbers' paradox is resolved.

New Data


DISCOVERY OF EXPANDING UNIVERSE
Log Velocity
4.0
3.5
3.0
12
14
16
18
m (pg)
Edwin Hubble
Mt. Wilson
100 Inch
Telescope

On the CN non-discovery

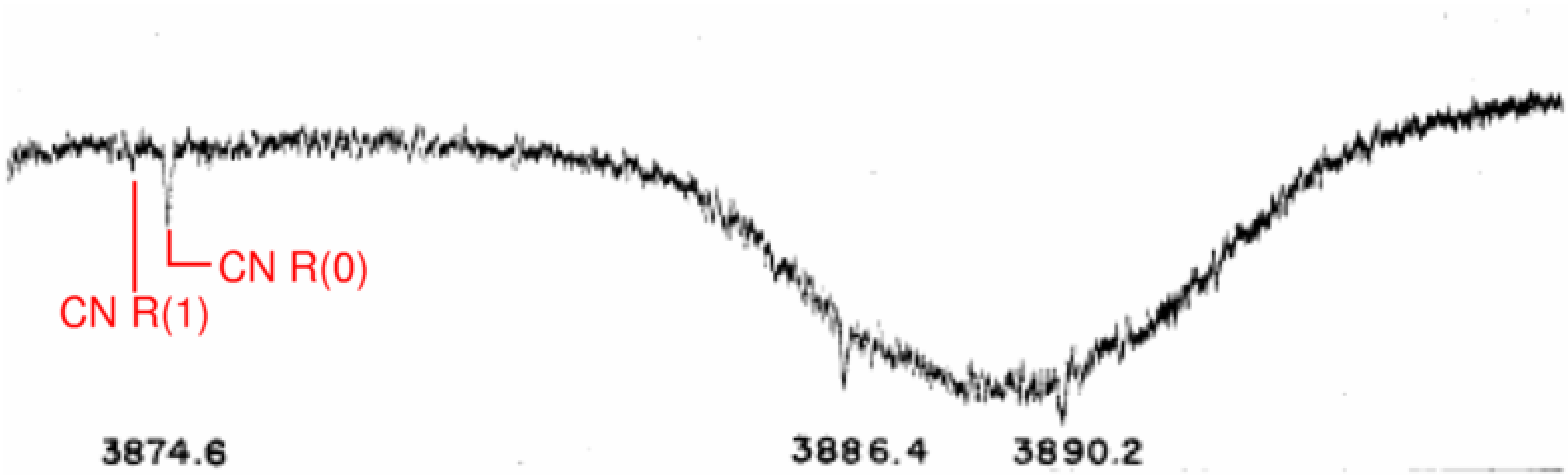


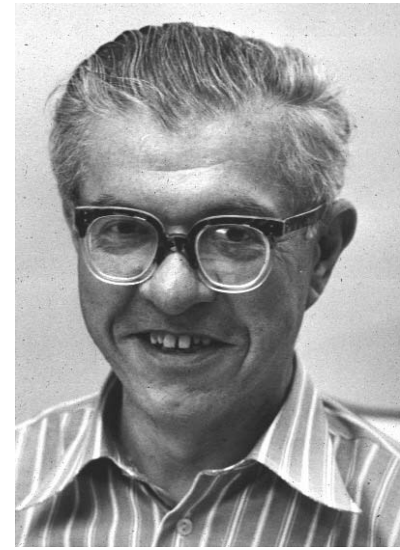
Plate 3 of Adams (1941, ApJ, 93, 11-23)

Herzberg (1950) in *Spectra of Diatomic Molecules*, p 496:

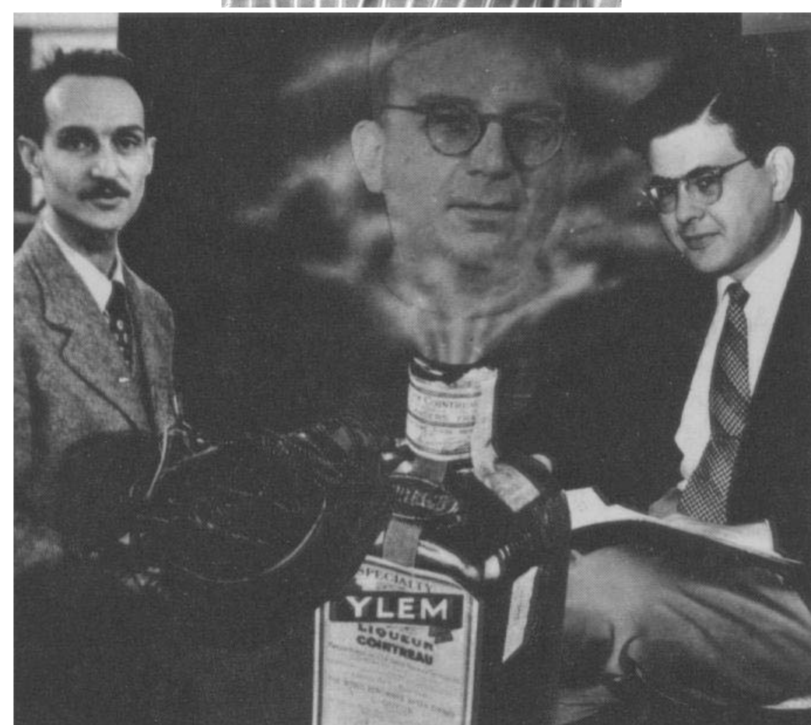
“From the intensity ratio of the lines with K=0 and K=1 a rotational temperature of 2.3^{o} K follows, which has of course only a **very restricted meaning**.”

There went Herzberg’s [second] Nobel Prize.

Fred Hoyle missed the Nobel Prize



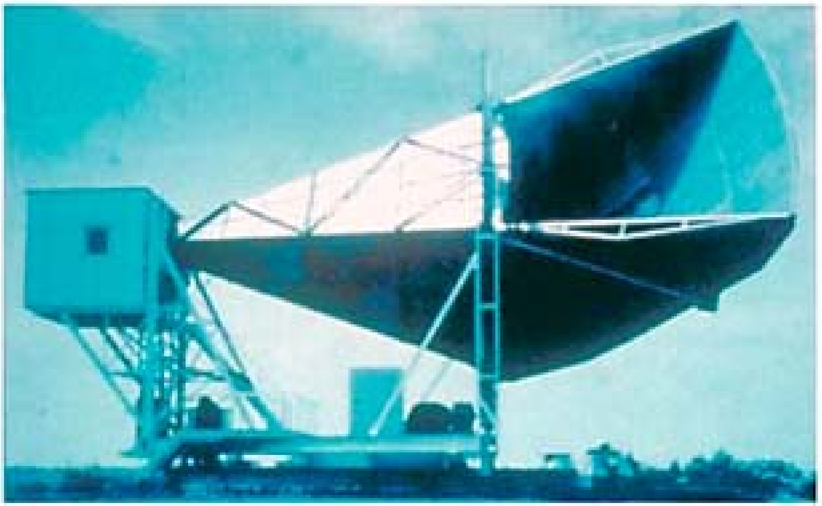
- Hoyle (1950), reviewing a book by Gamow & Critchfield: "[the Big Bang model] would lead to a temperature of the radiation at present maintained throughout the whole of space much greater than McKellar's determination for some regions within the Galaxy."
- This book implied T_o = 11 K. Gamow in 1956 Scientific American implied 6 K. Alpher & Herman explicitly gave 5 K or 1 K.
- Nobody followed this up!



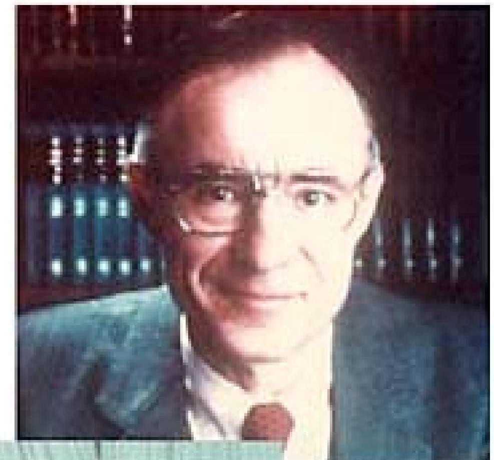
On Dicke's non-discovery

- Dicke et al. (1946) reported on war-time work done to see if K band radar was practical. The atmospheric absorption was low enough.
- $T_{sky} < 20$ K
- Dicke invented the differential radiometer for this work. This compares a source to a reference source. The switch used to connect the two sources alternately to the radiometer is called a *Dicke switch*.
- Dicke had all the tools needed to measure the 3 K CMB in 1945, but didn't look for the CMB until 1964 and got scooped.

Discovery of the Cosmic Microwave Background



Microwave Receiver

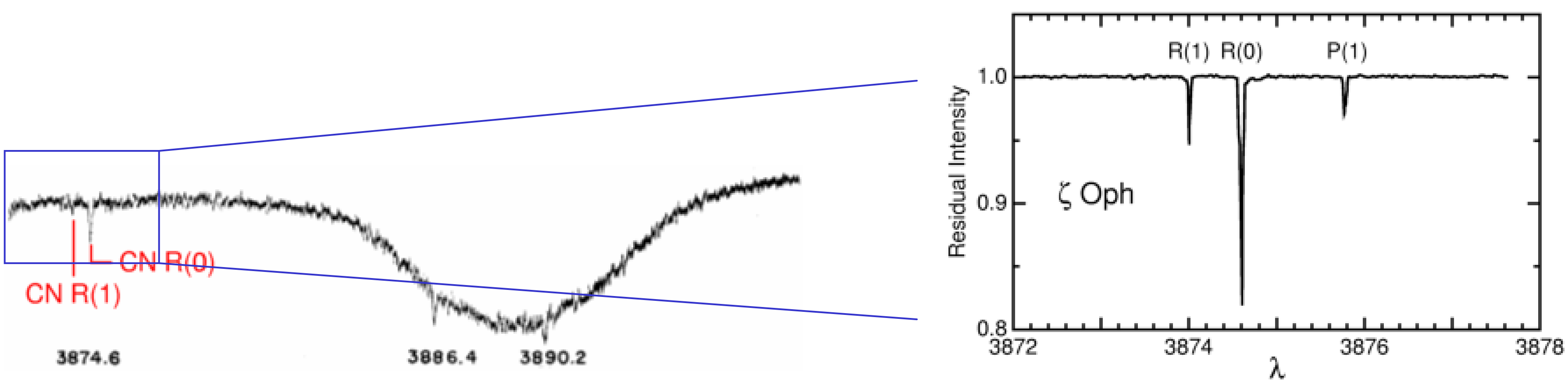


Arno Penzias

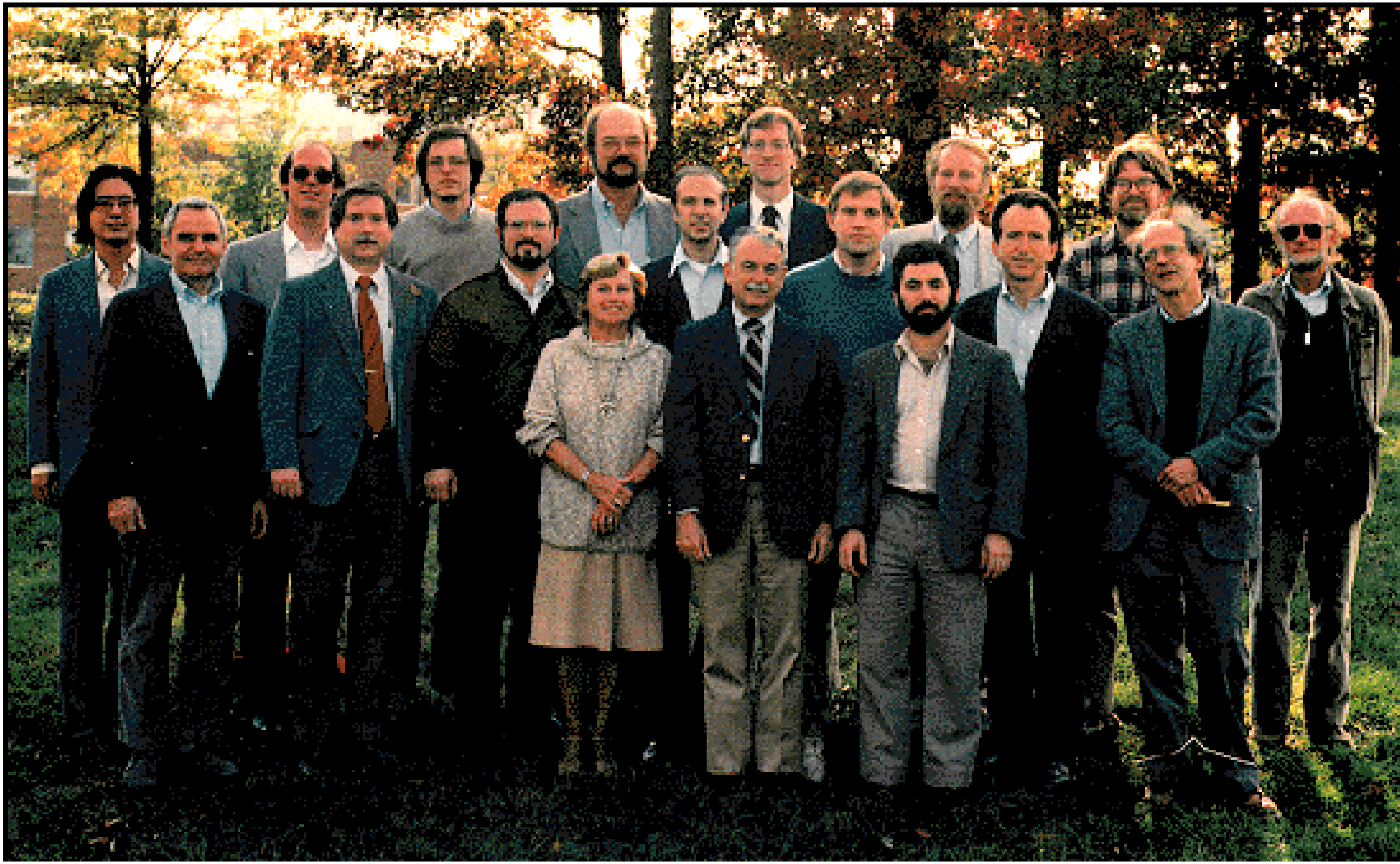
Robert Wilson

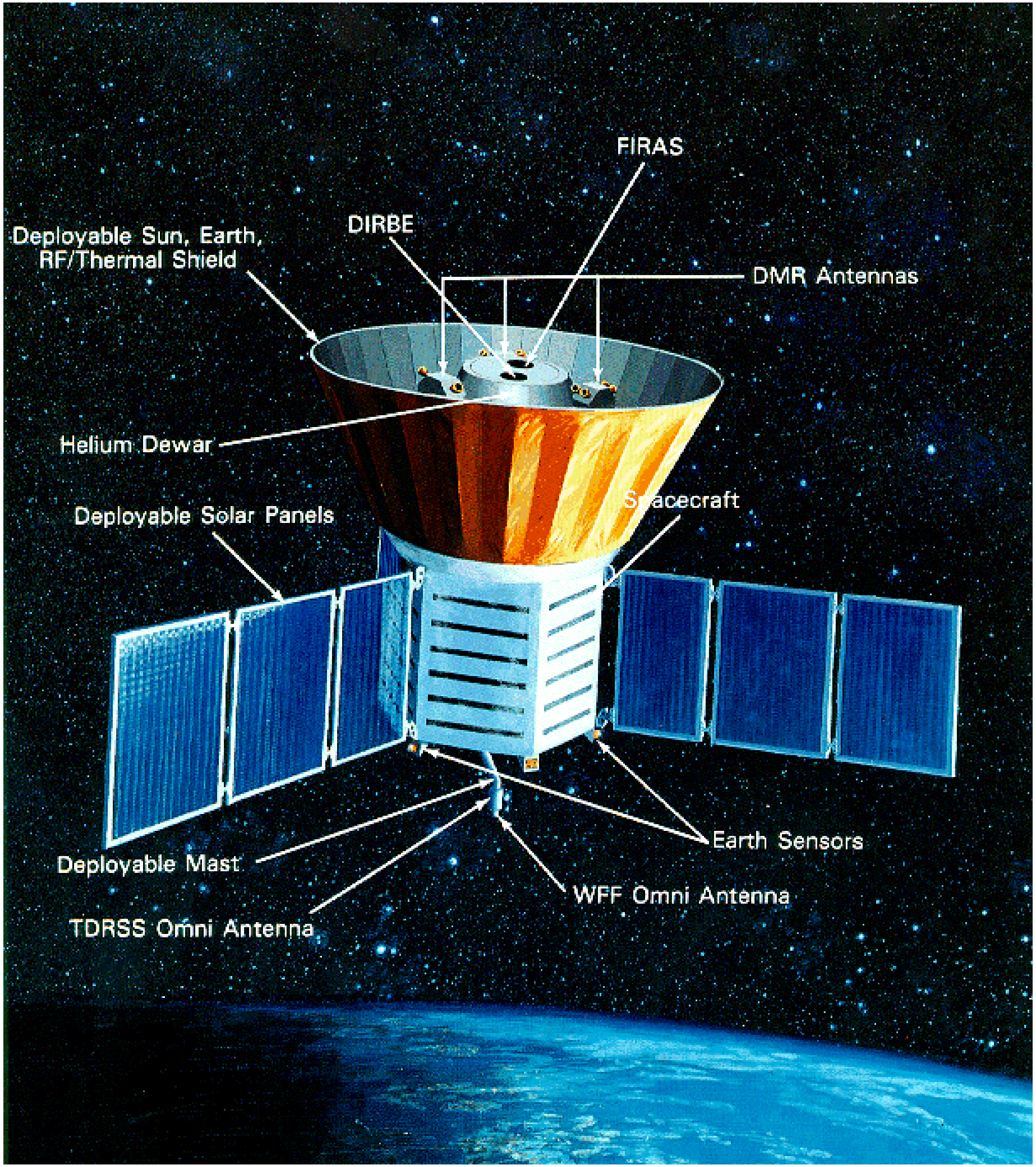
CN followup after Penzias & Wilson

- Reworking and reobserving the CN lines gave 2.78±0.10 K at 2.64 mm. (Thaddeus, 1972, ARAA, 10, 305-334)
- My PhD student Mary Beth Kaiser & ELW, 1990, T_{CMB} = 2.73±0.05 K (ζ Oph), 2.75±0.04 K (ζ Per)
- By 1993, 2.73±0.03 K (ζ Oph) [Roth, Meyer & Hawkins 1993]



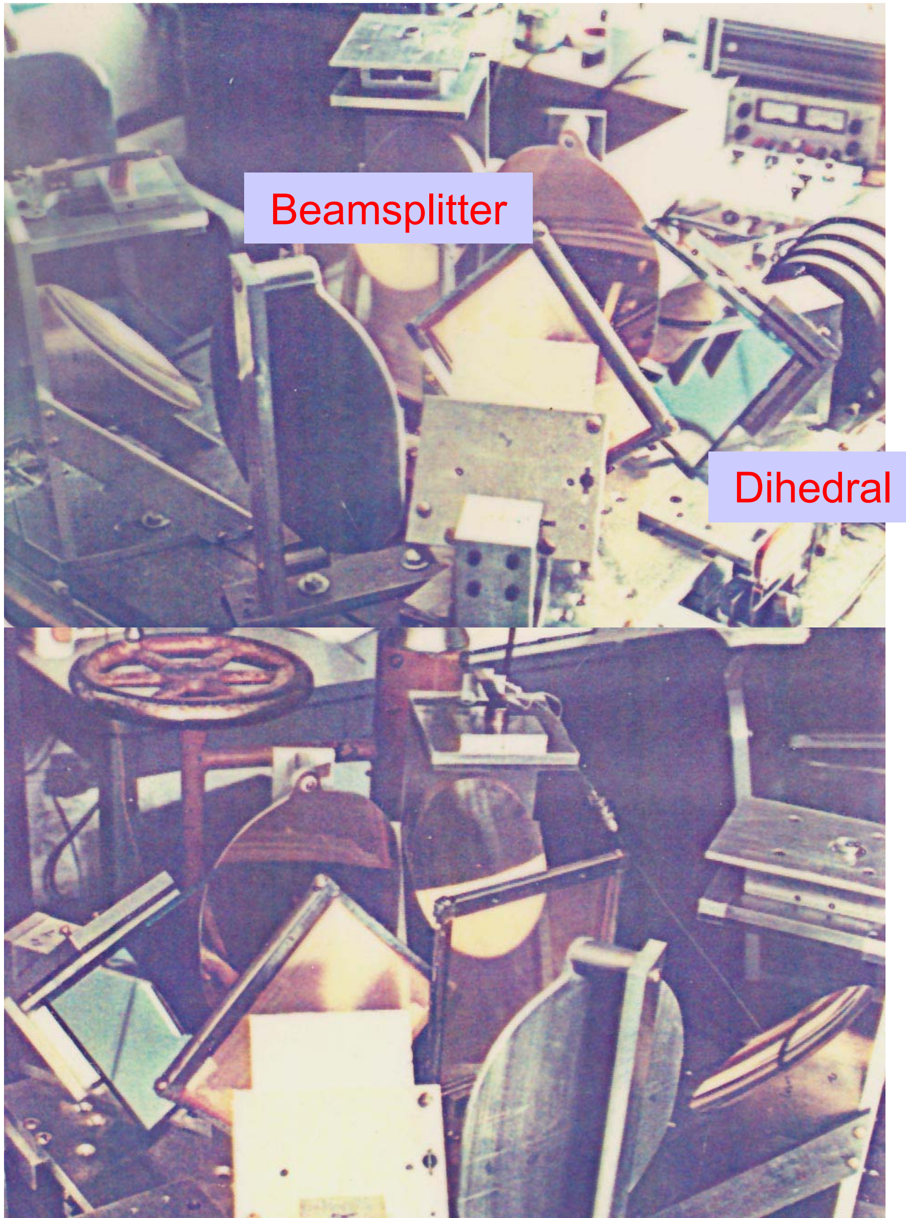
COBE Science Working Group

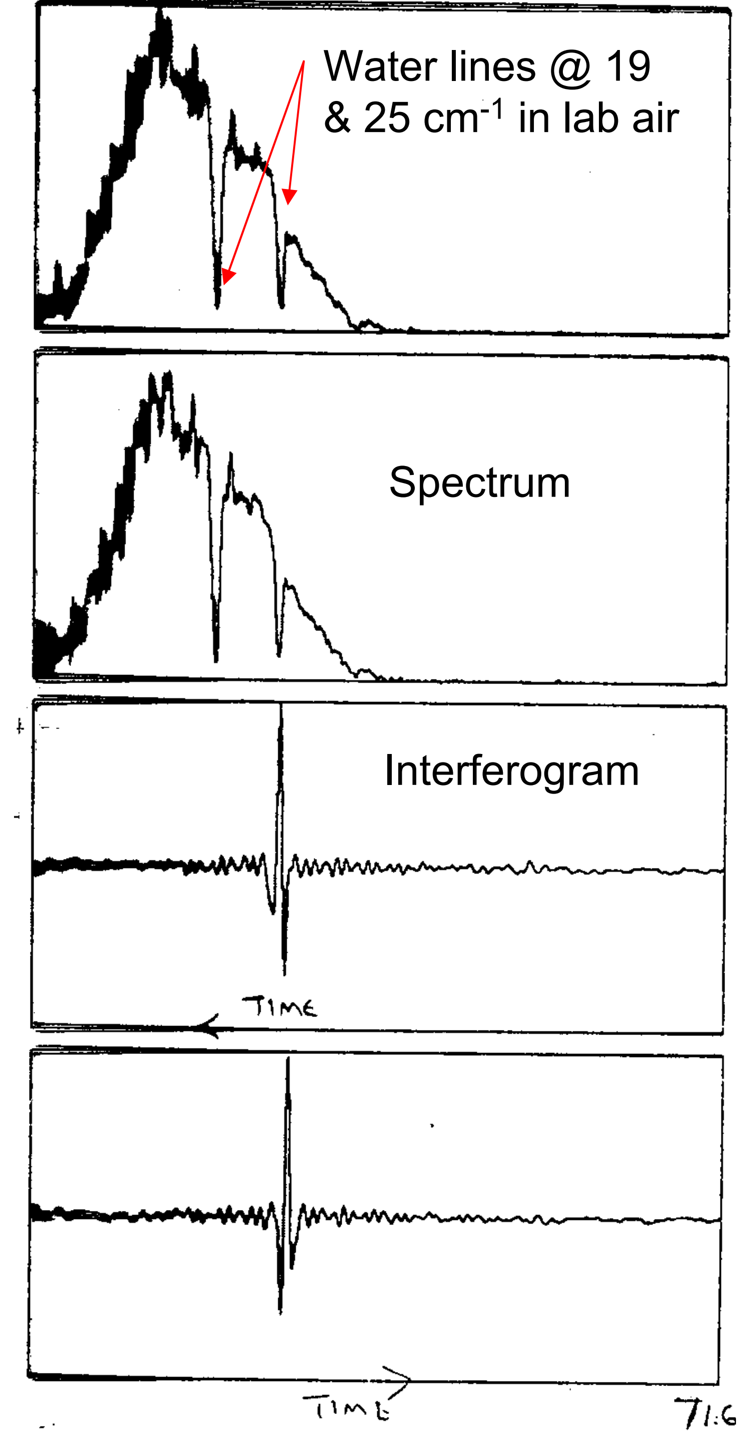




FIRAS
DIRBE
Deployable Sun, Earth,
RF/Thermal Shield
DMR Antennas
Helium Dewar
Spacecraft
Deployable Solar Panels
Earth Sensors
Deployable Mast
WFF Omni Antenna
TDRSS Omni Antenna

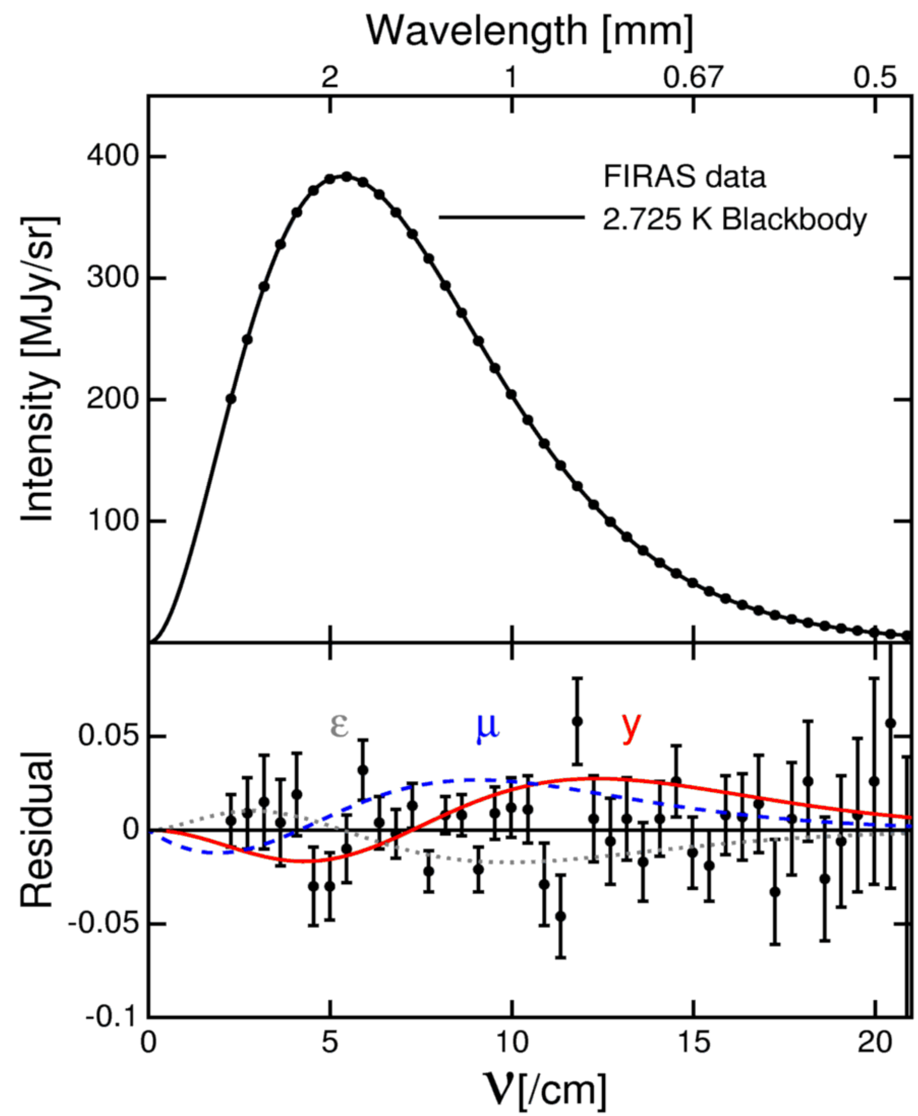
Personal History: my FIRAS breadboard at MIT



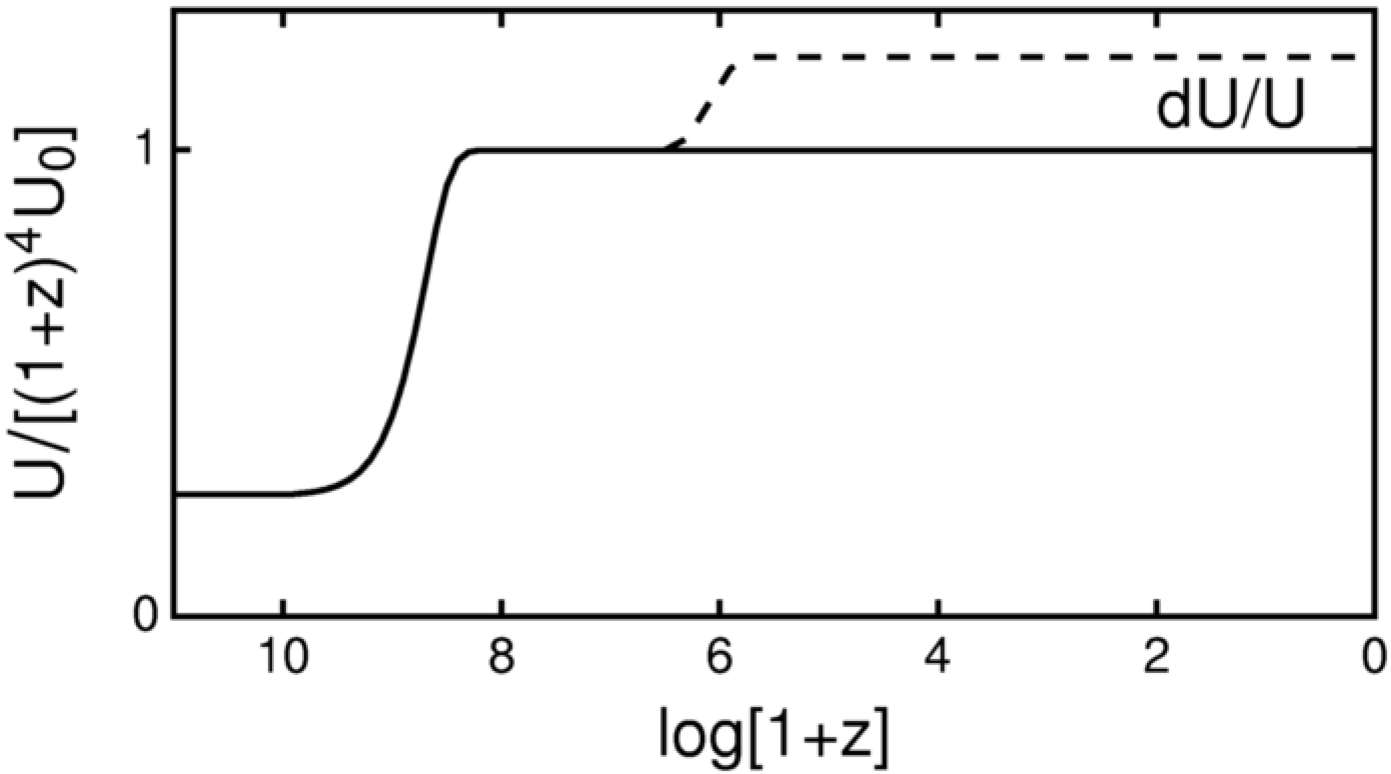


FIRAS Final Spectrum

- SZ Effect $\propto$ $y = N_e \sigma_T k T_e / m_e c^2$ $< 15\times10^{-6}$
- Bose-Einstein $\mu < 9\times10^{-5}$
- Energy from hot electrons into CMB < 60 parts per million

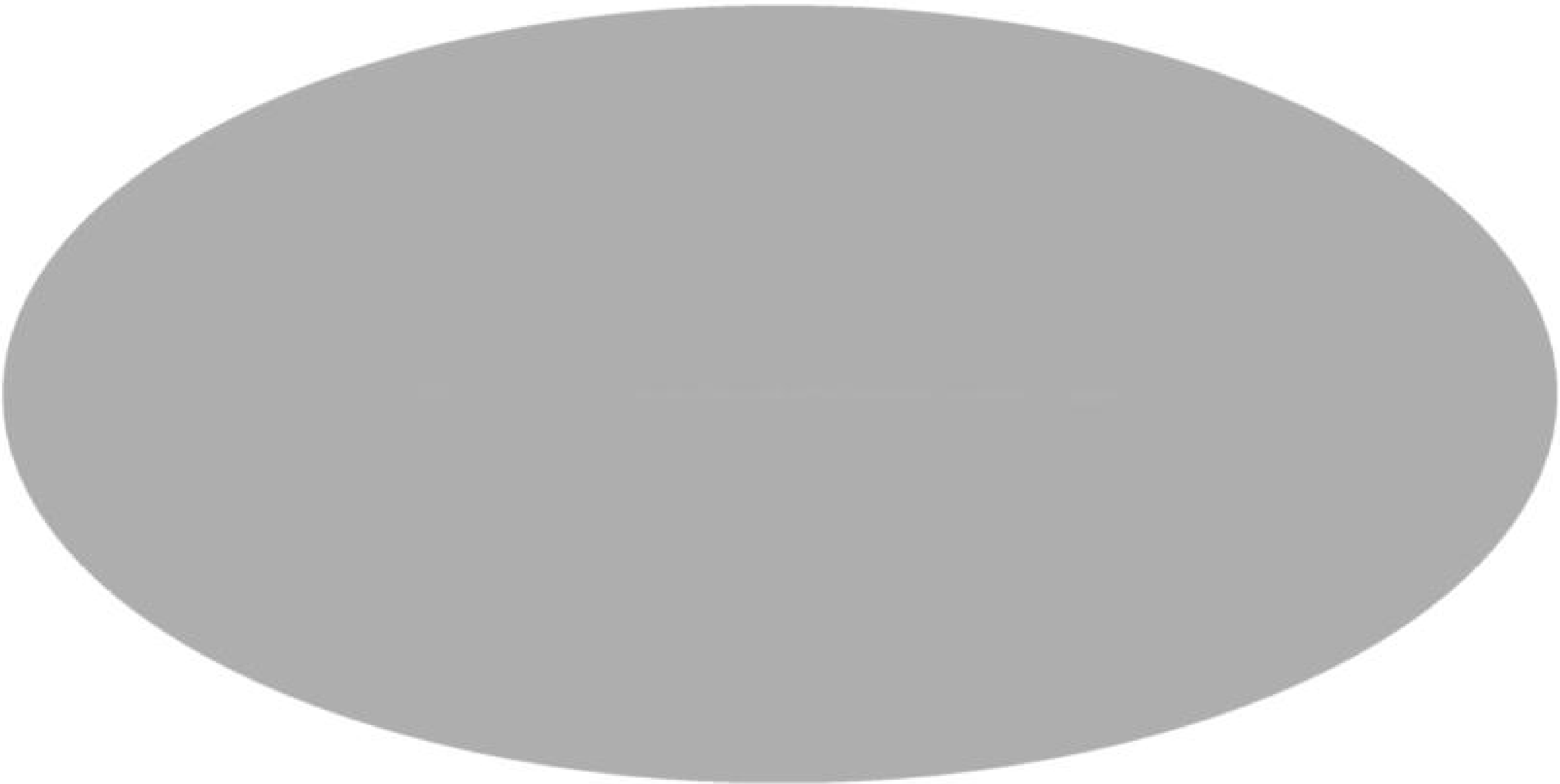


Expected change in U



The big change at $z = 10^9$ is when the electron-positron pair plasma annihilated. Any dU/U at $z < 2 \times 10^6$ is limited to $dU/U < 6 \times 10^{-5}$.

True Contrast CMB Sky

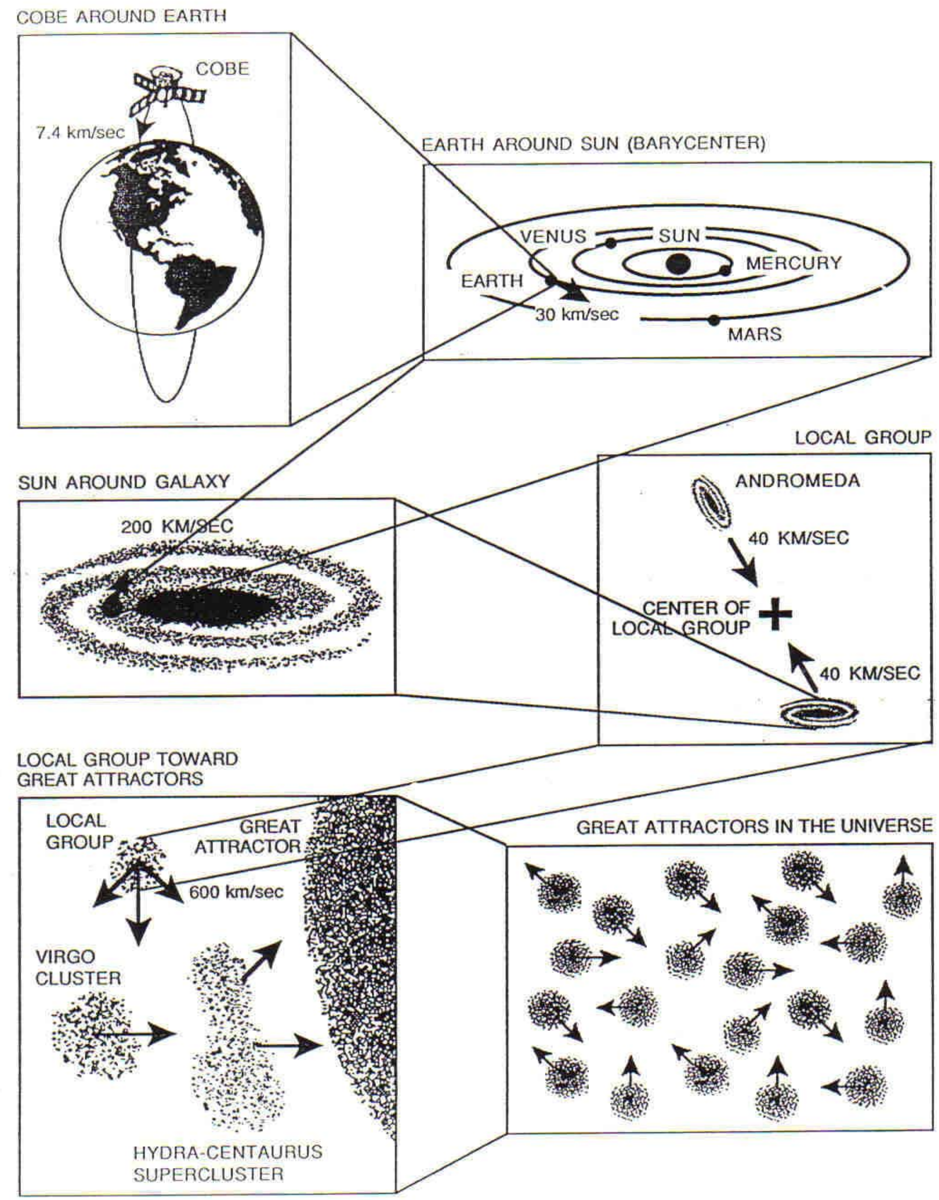


33, 41 & 94 GHz as RGB, 0-4 K scale

Enhanced Contrast:

- Conklin 1969 - 2σ
- Henry 1971 - 3σ
- Corey & Wilkinson - 4σ
- Smoot *et al.* 1977 - 6σ
- Vss = 369$\pm$2 km/s

VELOCITY COMPONENTS OF THE OBSERVED CMB DIPOLE



Personal History: Anisotropy

rom: BONNIE::WRIGHT "Ned Wright - (213)825-5755" 17-AUG-1991 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-

My October 1991 Paper

Probable Detection of Cosmic Anisotropy by the Cosmic Background Explorer (COBE) [1]

by

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2) NASA Goddard Space Flight Center, Code 685, Greenbelt MD 20771
3) Univ. Space Research Assoc., Code 610.3, NASA/GSFC, Greenbelt MD 20771
4) General Sciences Corporation, Code 685, NASA/GSFC, Greenbelt MD 20771
5) ST Systems Corporation, 4400 Forbes Blvd., Lanham MD 20706
6) Jet Propulsion Laboratory, Pasadena CA 91109
7) UCSB Physics Dept., Santa Barbara CA 93106

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ABSTRACT

The Differential Microwave Radiometers (DMR) experiment on the COsmic Background Explorer (COBE) has seen a statistically significant anisotropy in the 2.73 K background radiation. The RMS amplitude of the sky, smoothed with a 10° beam, is 32 ± 4 μK after the dipole is removed. The RMS quadrupole is 13 ± 2 μK in the region with galactic latitude $|b| > 20°$. A scale-invariant or Harrison-Zeldovich spectrum is consistent with these values, and the best fitting amplitude for this spectrum gives an expected RMS quadrupole of 17 ± 1.2 (statistical) $\pm$ 5 (systematic), where the dominant systematic uncertainty is galactic flux. This anisotropy seen by COBE is consistent with an unbiased cold dark matter model, with $H_{\circ} = 50$, $\Omega_B = 0.1$, and $\Omega_{CDM} = 0.9$, which predicts an RMS quadrupole of 16 μK.

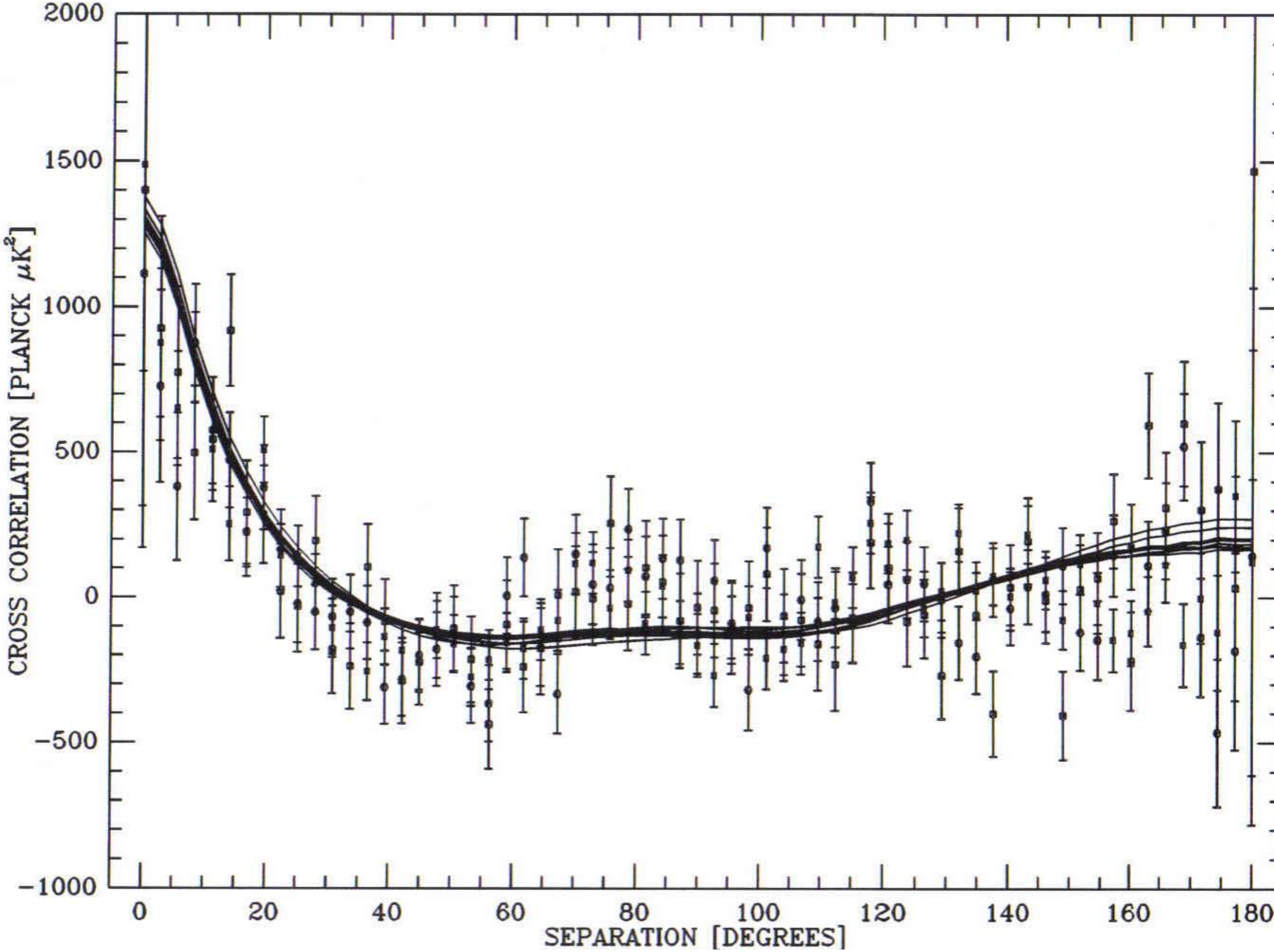
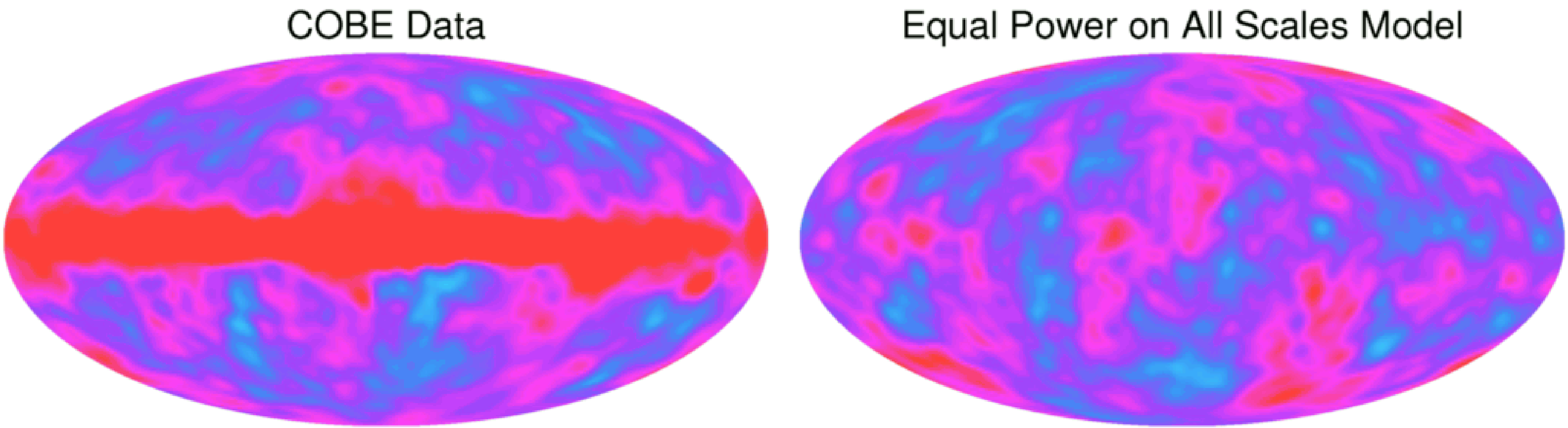


Figure 3: Cross-correlations for $|b| > 30°$ between the 53A & 53B (filled squares), 53A & 90B (filled circles), and the 53B & 90B (open squares), plus Monte Carlo predictions for a scale invariant spectrum with an expected quadrupole amplitude of 17 μK

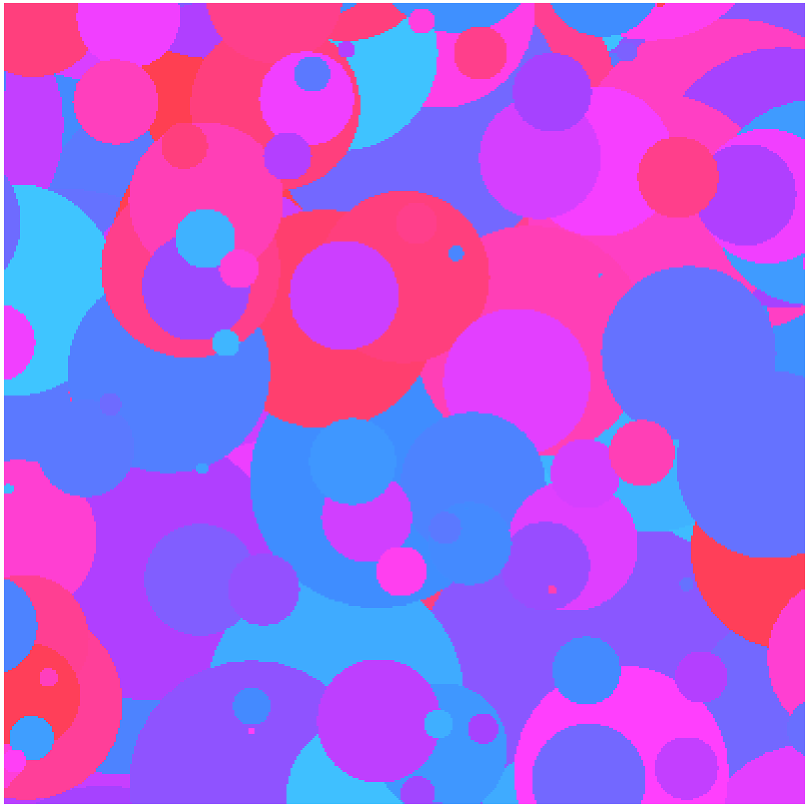
COBE DMR vs EPAS



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

Animated View of Inflation

- Quantum fluctuations occur uniformly throughout space-time.
- Future light cones of fluctuations grow making big circles but new fluctuations continuously replenish the small circles.
- Result is Equal Power on All Scales (EPAS).



Mather & Smoot win the 2006 Physics Nobel prize

A Scientist's [Junk] Mail

"you may have already won the Nobel Prize…"

Cartoon in American Scientist, v86, p492

COBE View of CMB was Blurry

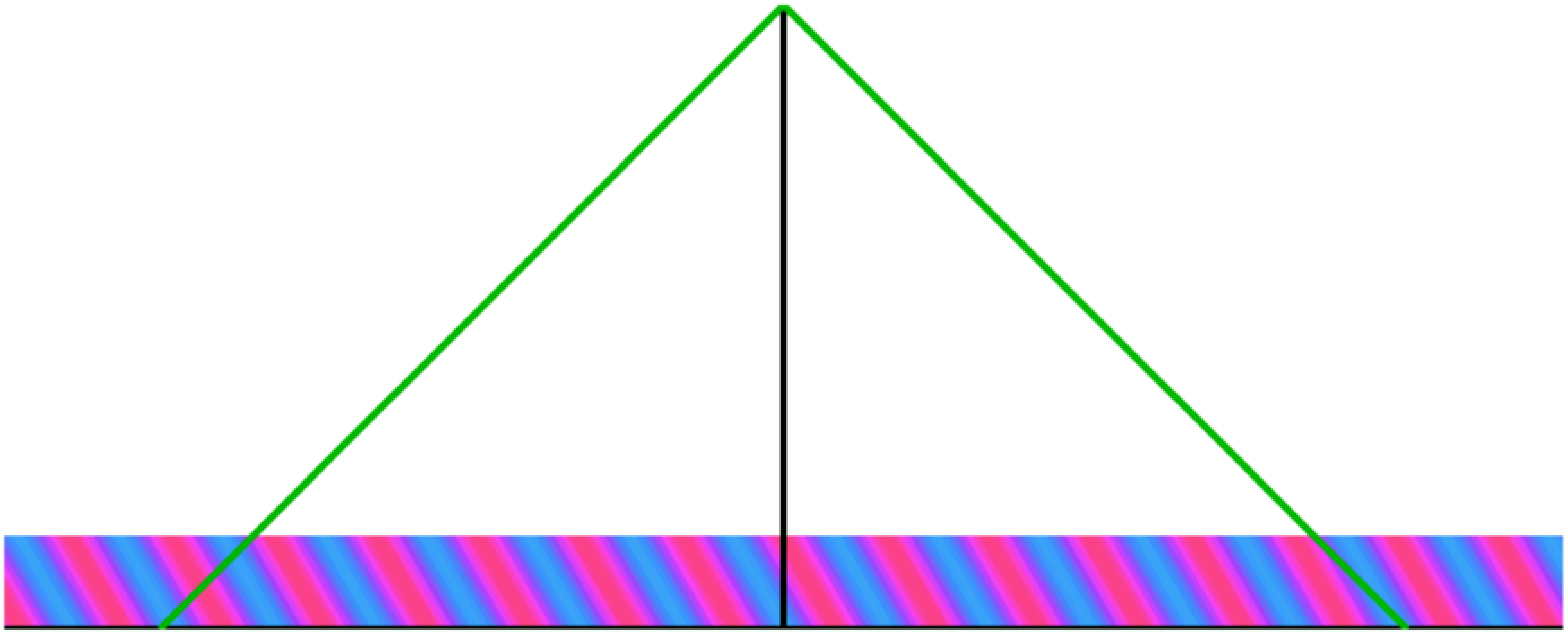
Sometimes higher
resolution...

reveals the secret
of the Universe

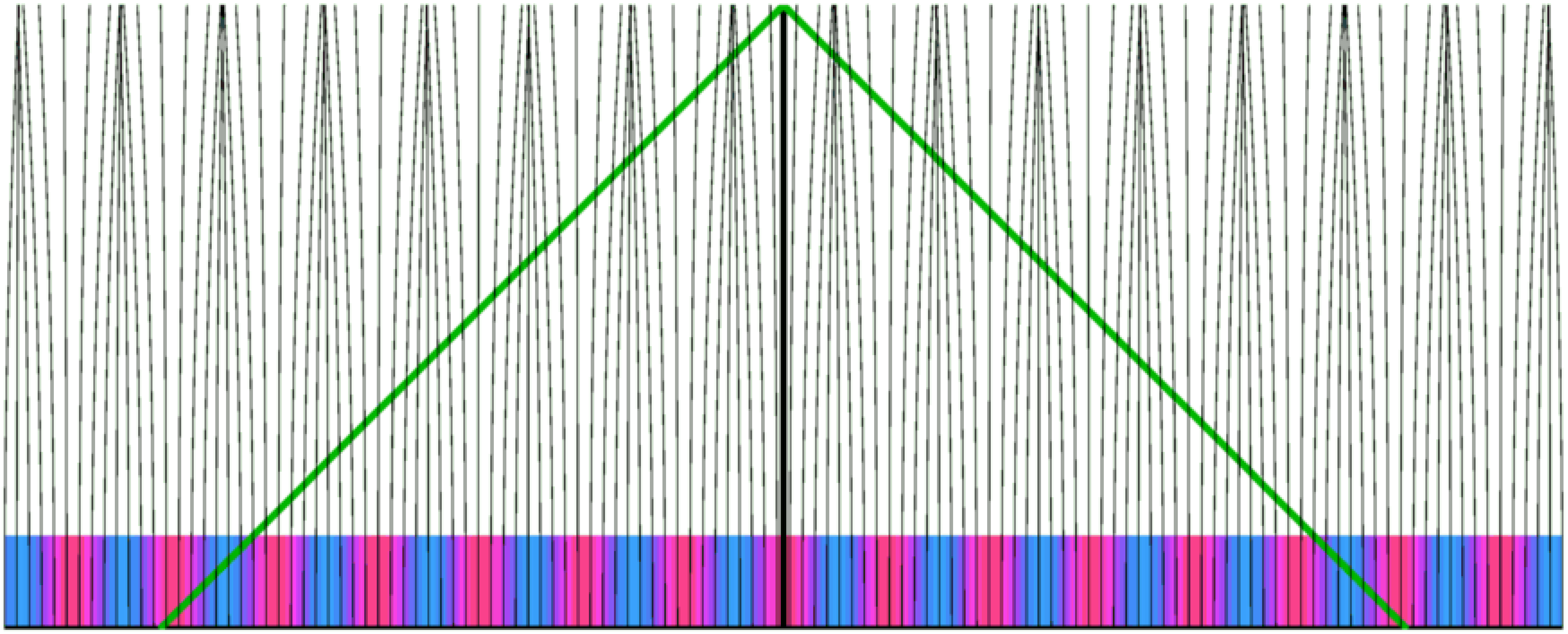
Two Fluids in the Early Universe

- 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 mass 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

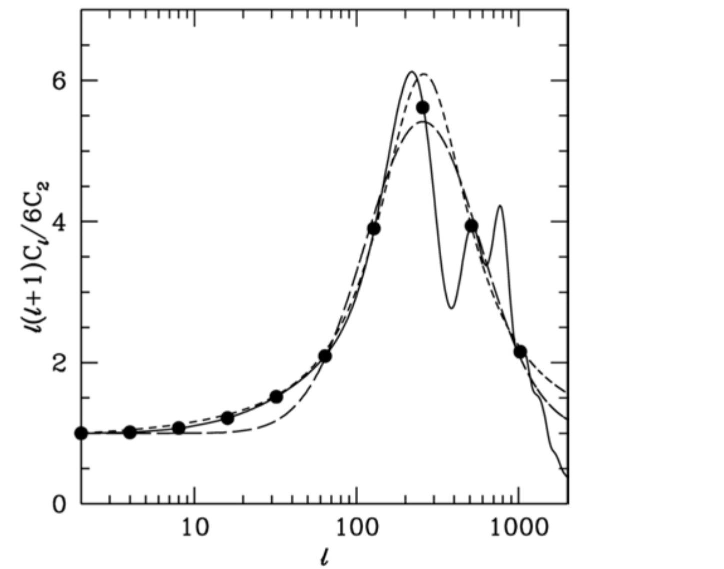
- For the wavelength illustrated [1/2 period between the Big Bang and recombination], the denser = hotter effect and potential well = cooler effect have gotten in phase.
- For larger wavelengths they are still out of phase at recombination.

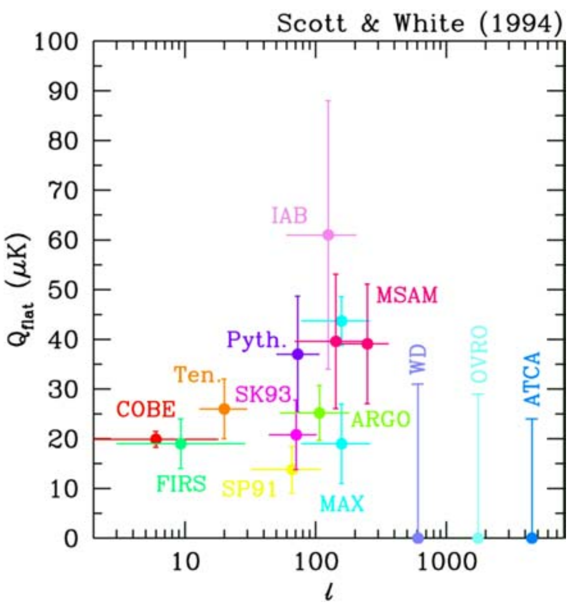
Some definitions

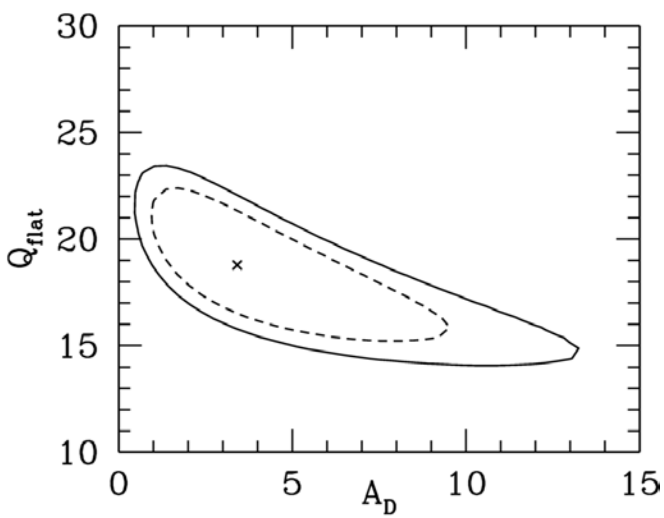
- $T(l,b) = T_o + \Delta T_d \cos\theta + \Sigma\, a_{lm} Y^{lm}(l,b)$
- $C_l = \langle| a_{lm}|^2\rangle$
- Baryon density $\omega_b = \Omega_b h^2$ or the density relative to the critical density for $H_o = 100$ which is 18.8×10^{-30} grams/cm^3 or 18.8 yoctograms per cubic meter in SI.
- Cold Dark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

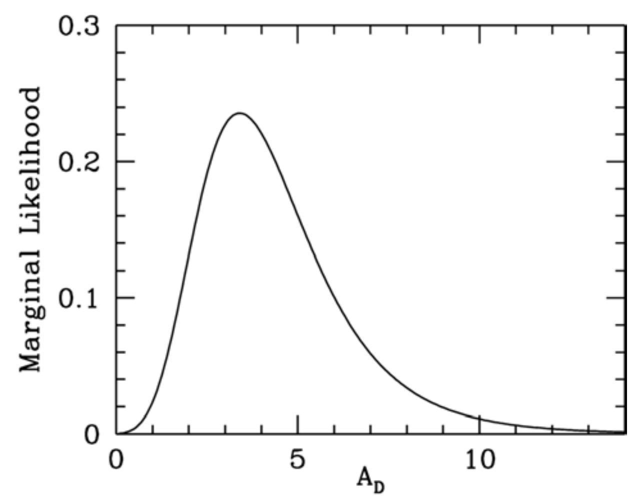
Observations pour in after COBE

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





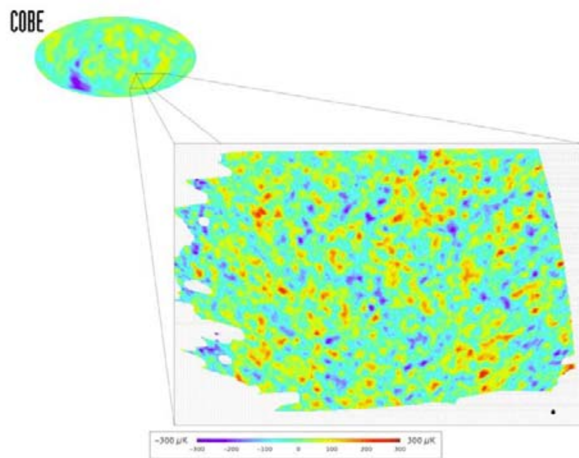


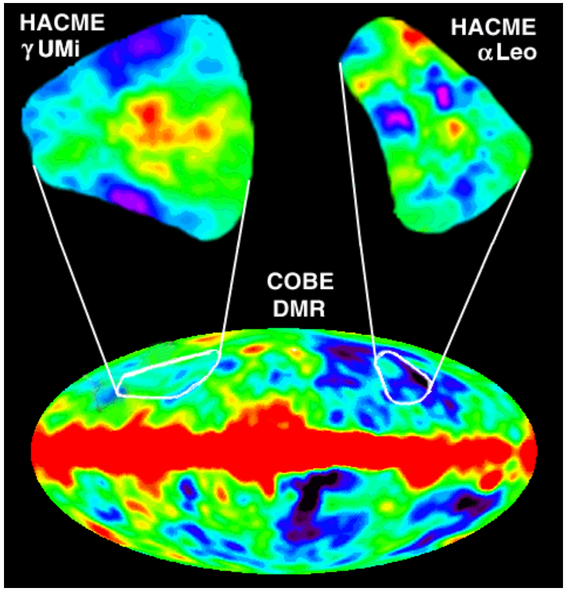


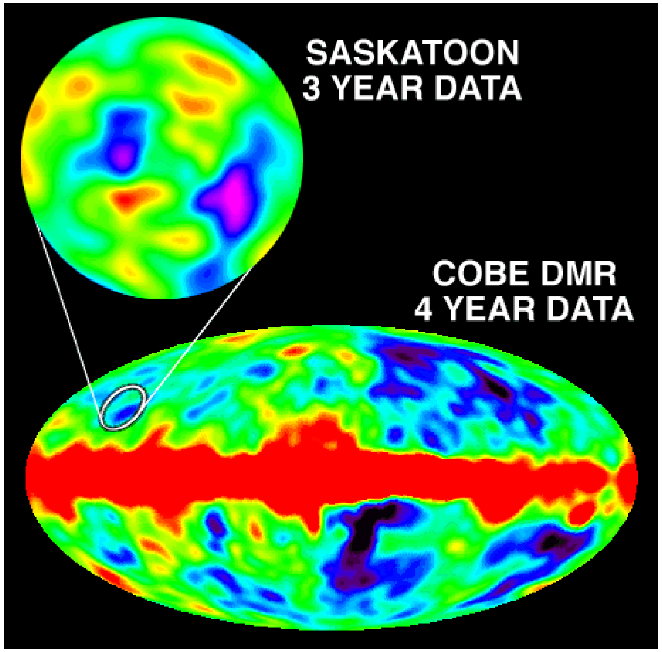
Observations since 1994

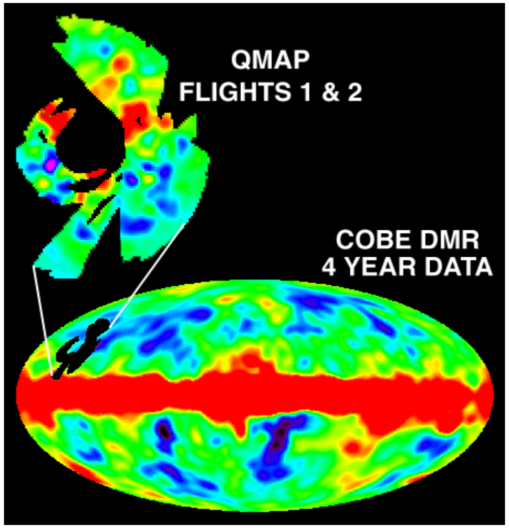
- More Saskatoon
- QDMAP – Saskatoon on a balloon
- TOCO – Saskatoon on a truck (Mobile Anisotropy Telescope) in Chile + D band (150 GHz channel)
- BOOMERanG
- MAXIMA
- DASI
- CBI

Smaller Scale Experiments



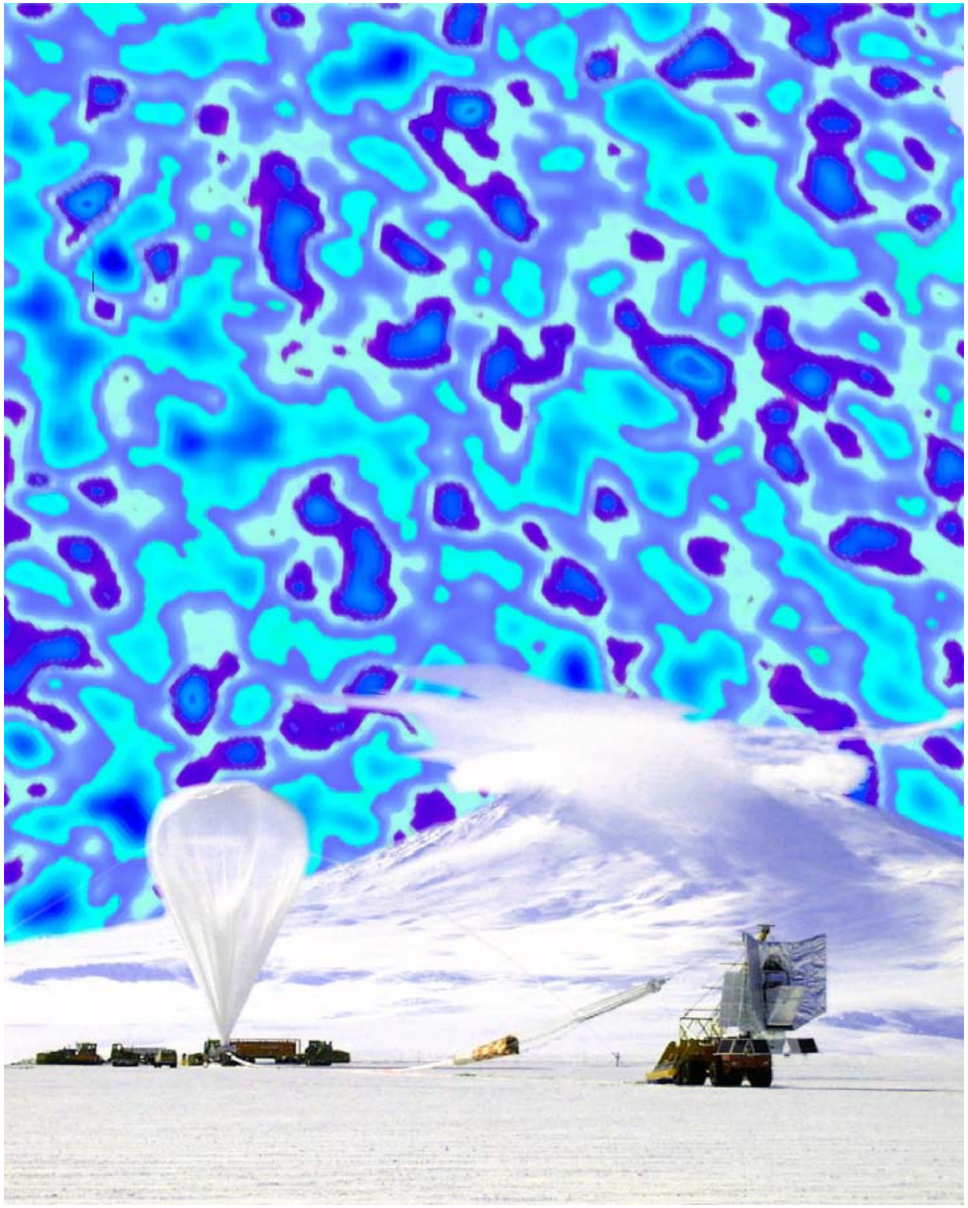






BOOMERanG

- 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)

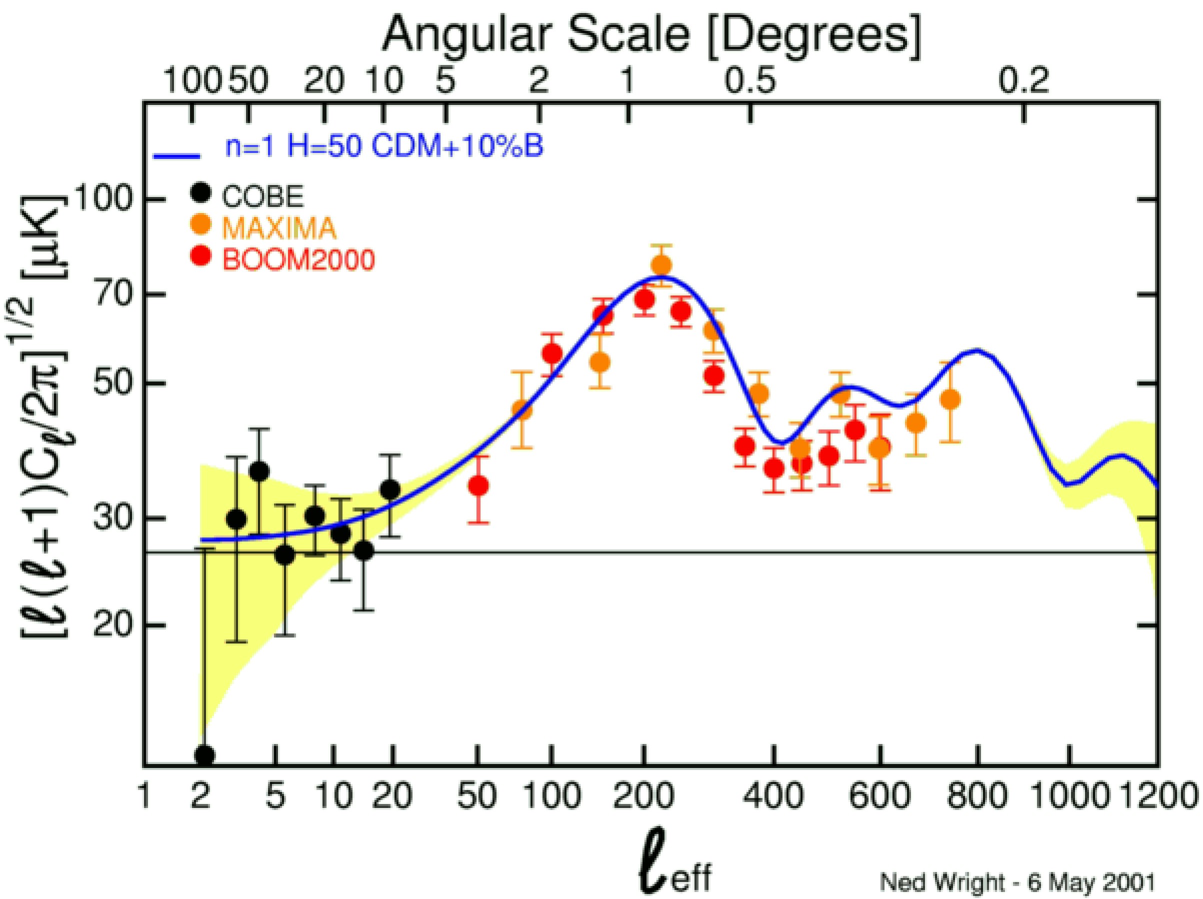


DASI:Degree Angular Scale Interferometer

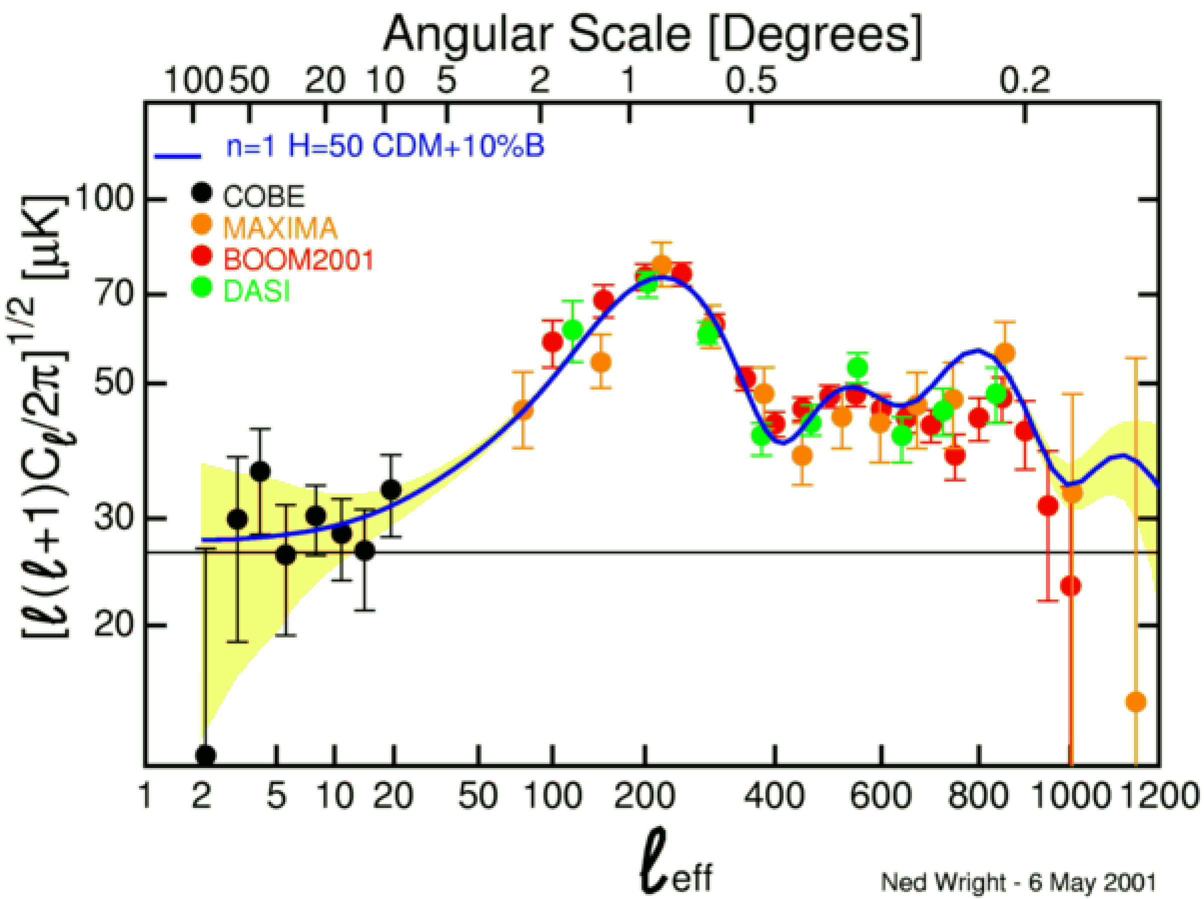
At the South Pole where it's very cold & dry

26-36 GHz

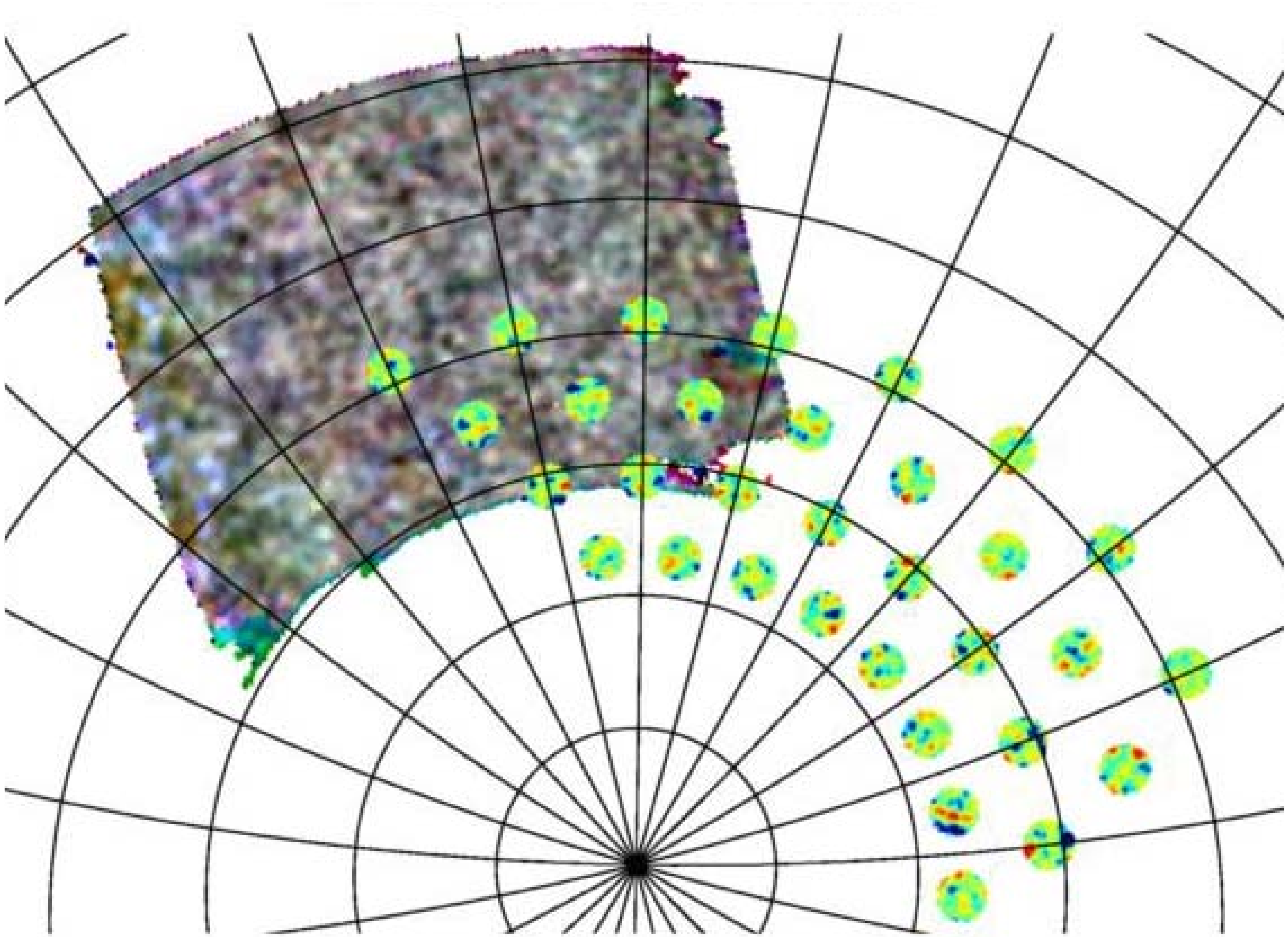
2000 Power Spectrum



2001 Power Spectrum



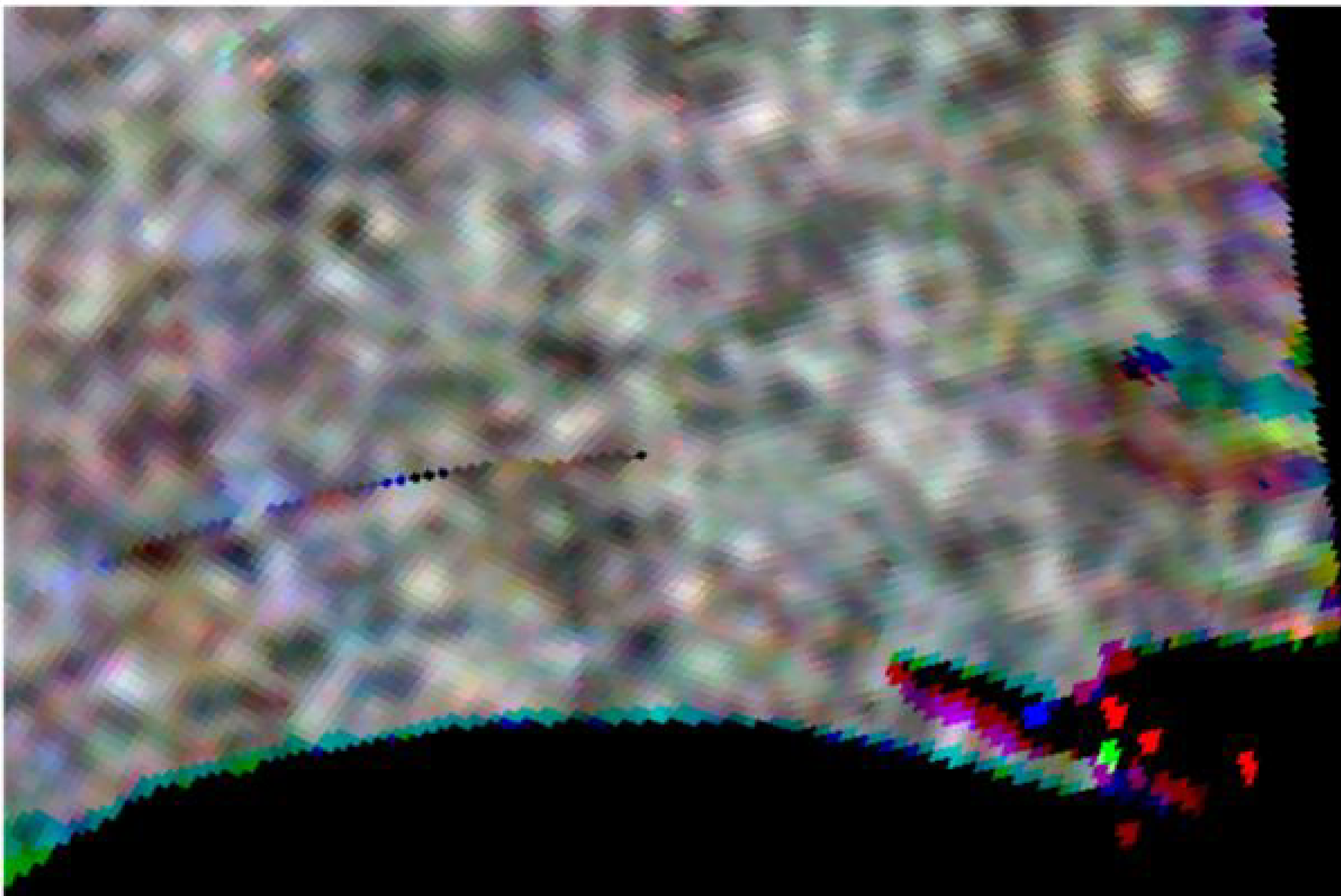
DASI on BOOMERanG



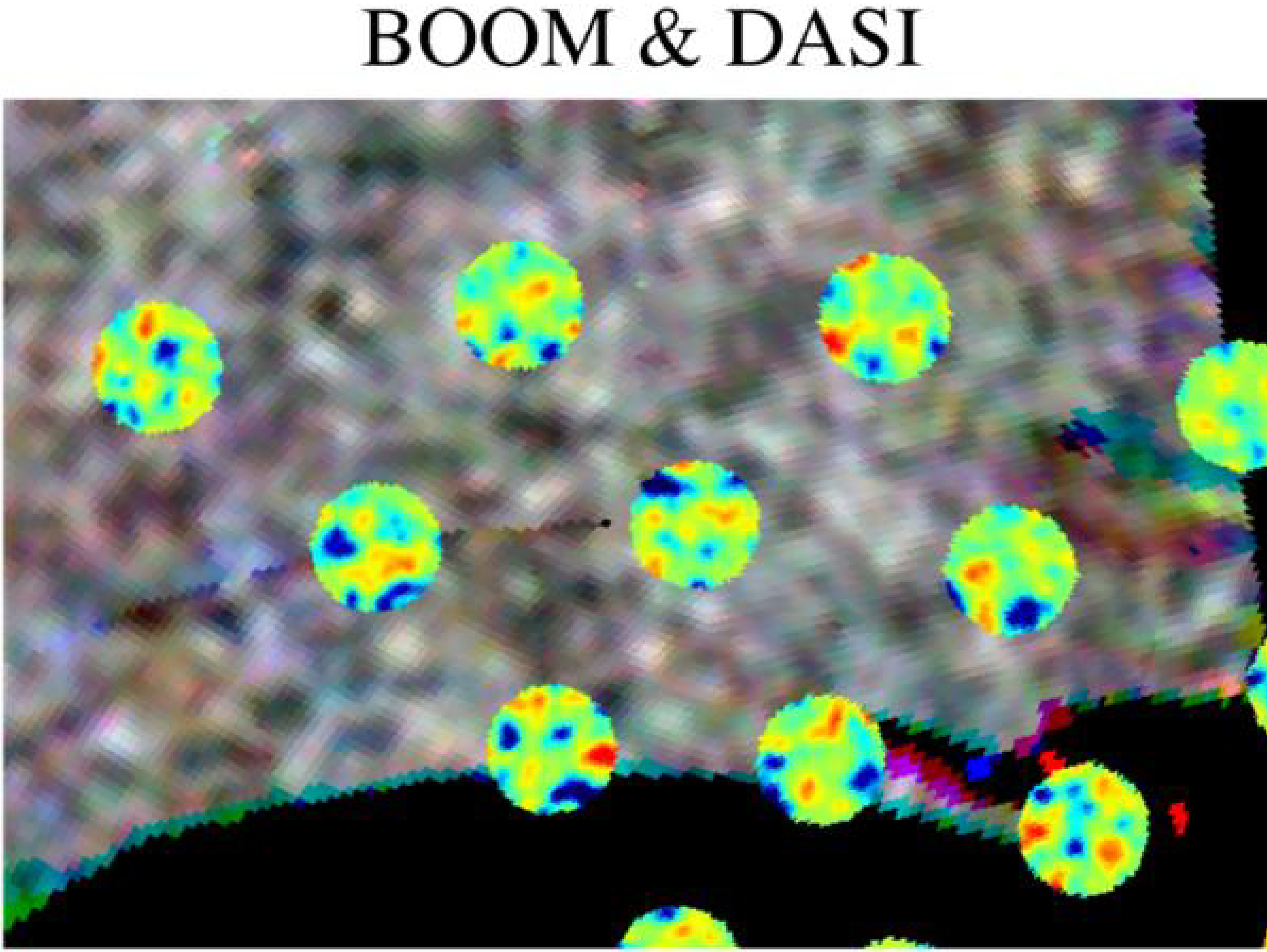
http://www.astro.ucla.edu/~wright/BOOMdat.html

Zoom in on BOOM-DASI Overlap

BOOM



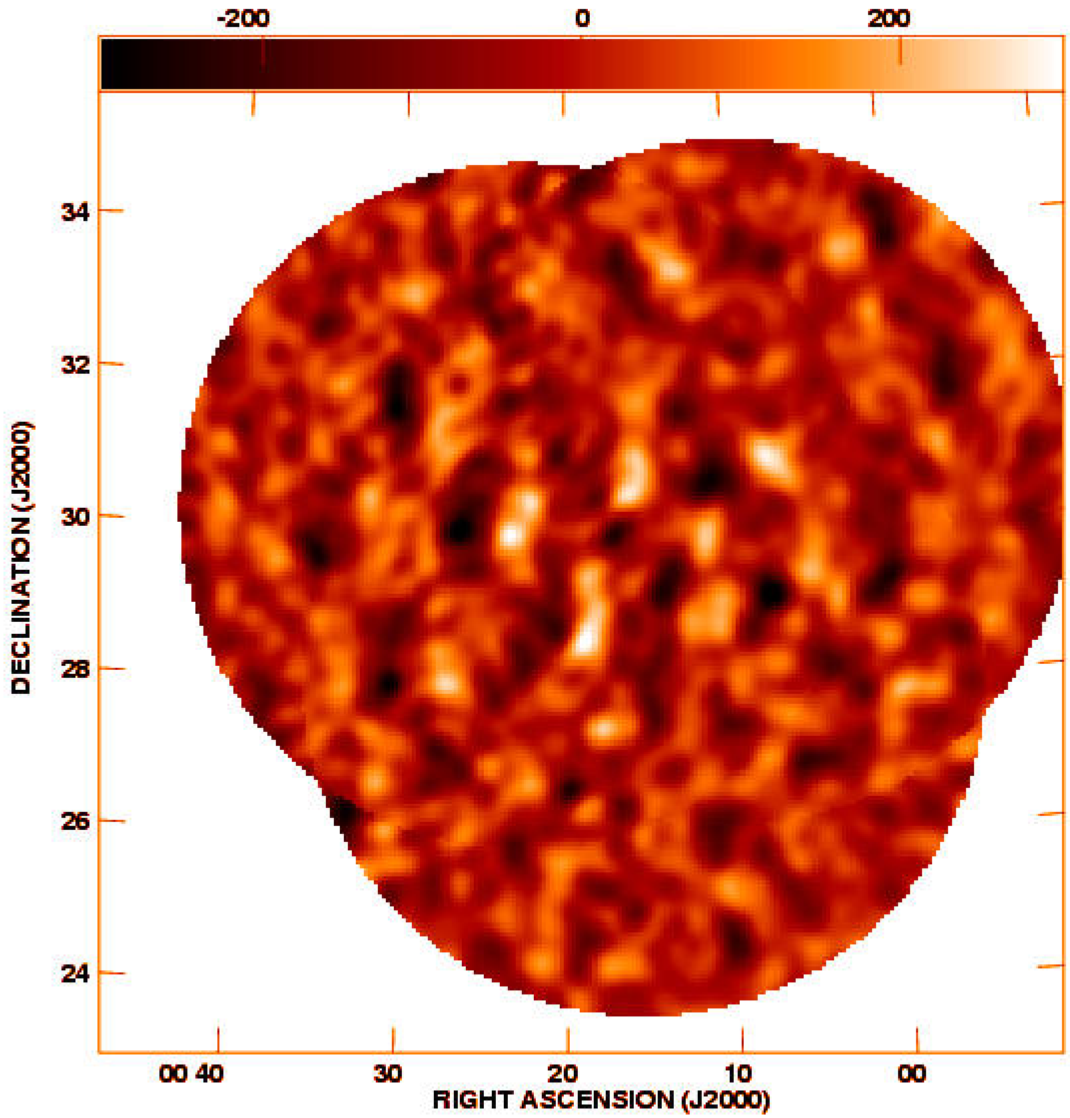
Overlay the DASI circles



The Very Small Array

- 14 antennae
- 4.5° or 2° FOV
- 0.5° or 0.2° res
- 26-36 GHz
- 1.5 GHz bandwidth
- Teide on Tenerife

VSA Sky Map

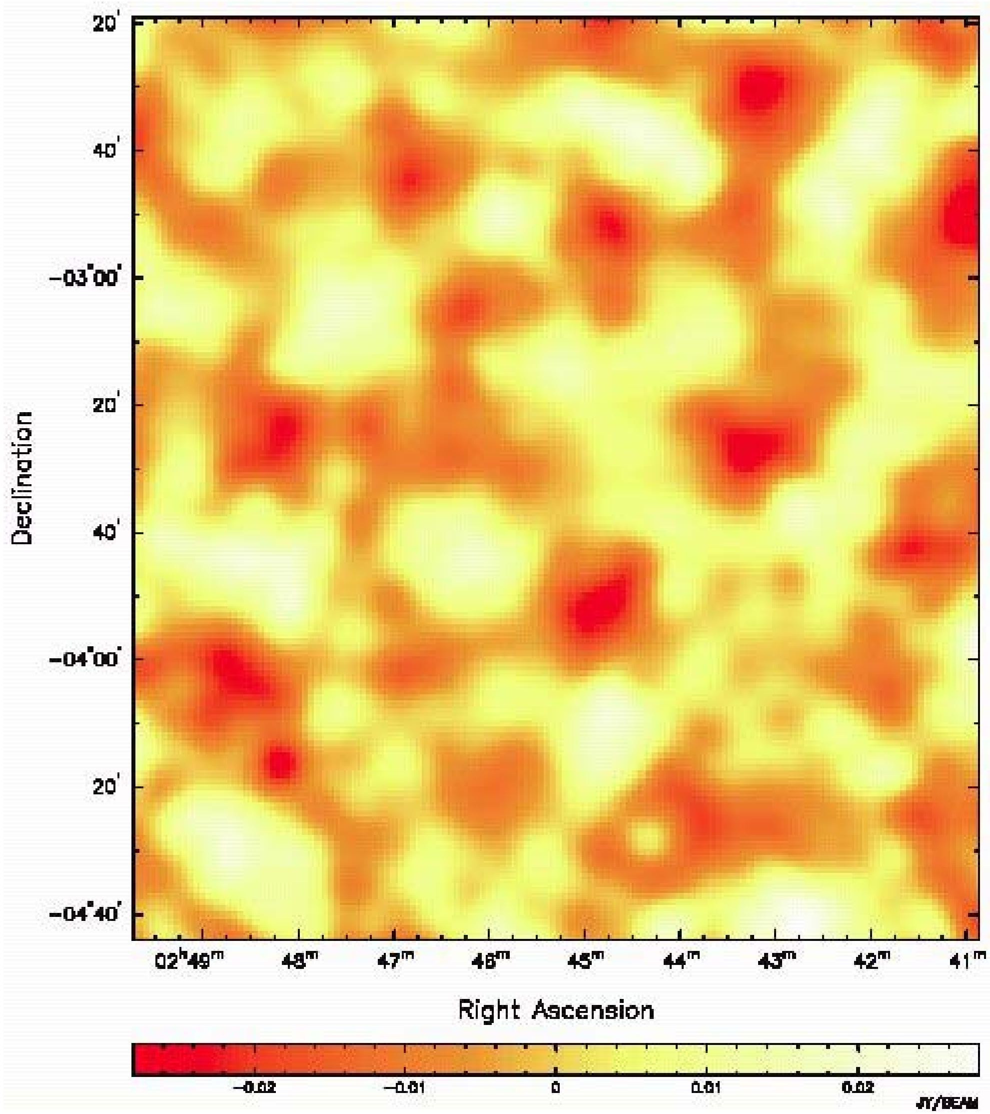


-200
0
200
34
32
30
28
26
24
DECLINATION (J2000)
00 40
30
20
10
00
RIGHT ASCENSION (J2000)

Cosmic Background Imager

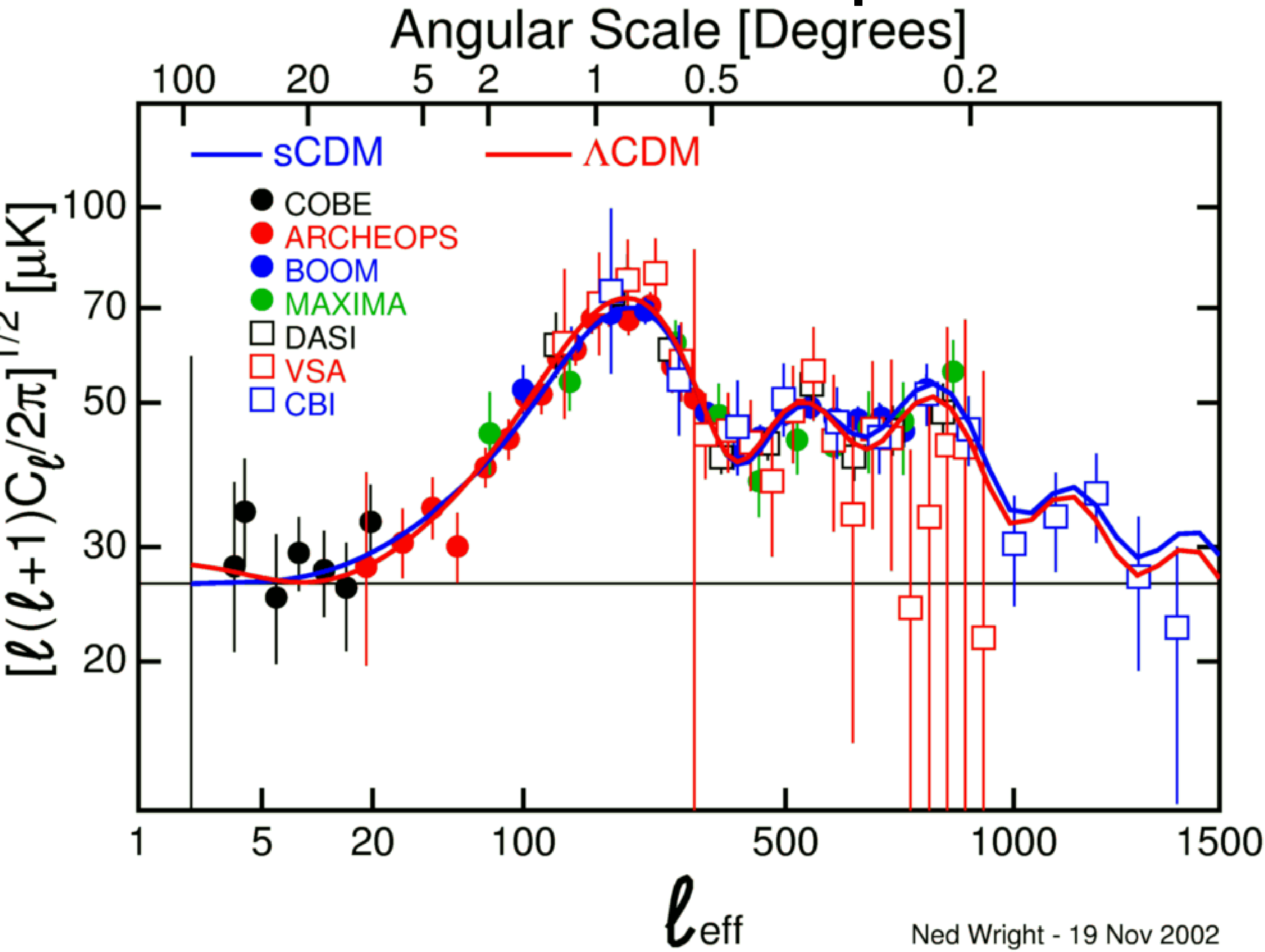
- Chile @ 5.08 km
- 13 antennae
- 26-36 GHz
- 10 GHz band
- 0.75° FOV
- 0.075° res
- Mosaic many FOV's together

CBI Map



Declination
20'
40'
−03°00'
20'
40'
−04°00'
20'
−04°40'
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

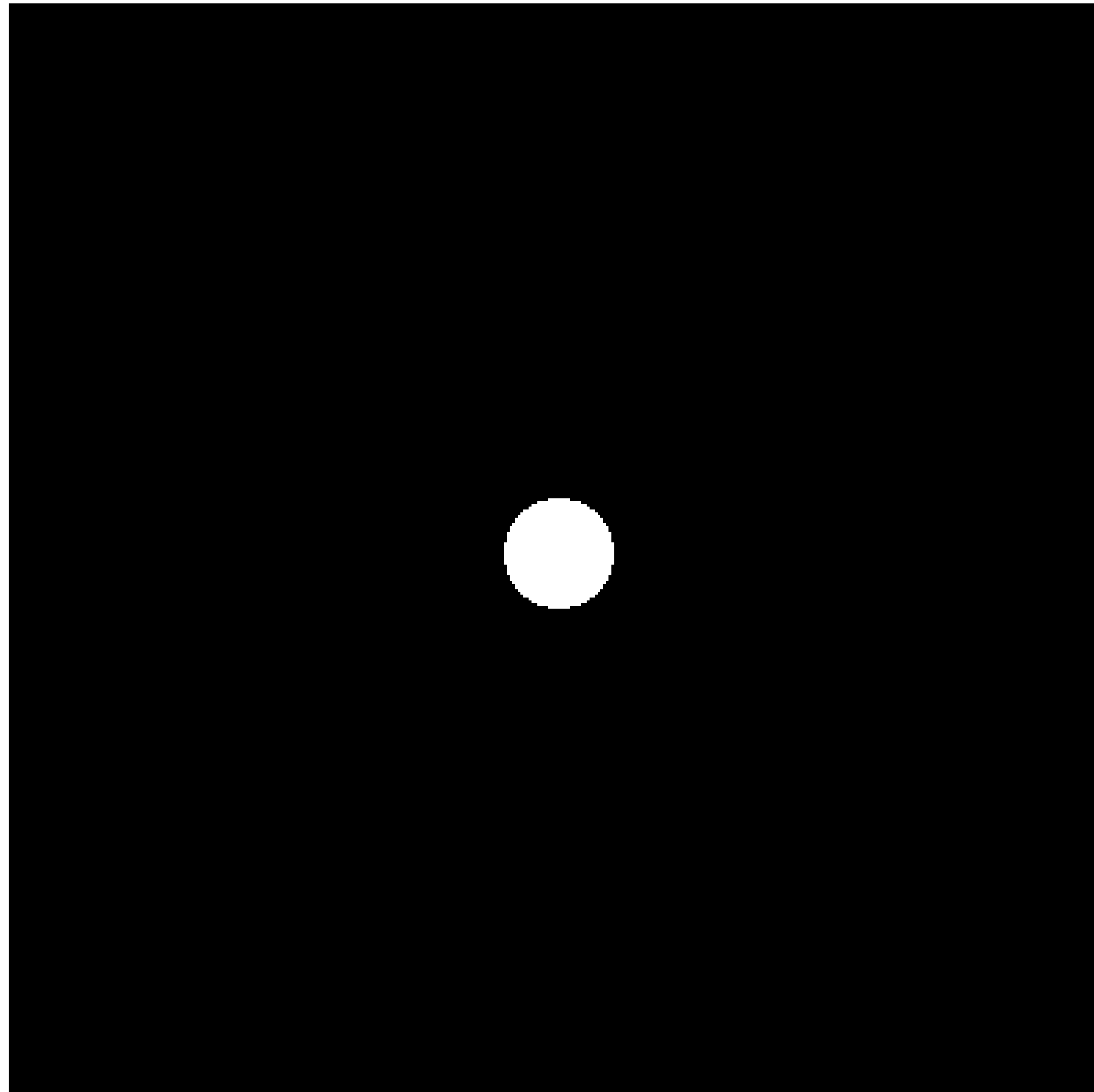
Calibration Uncertainties

- 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.

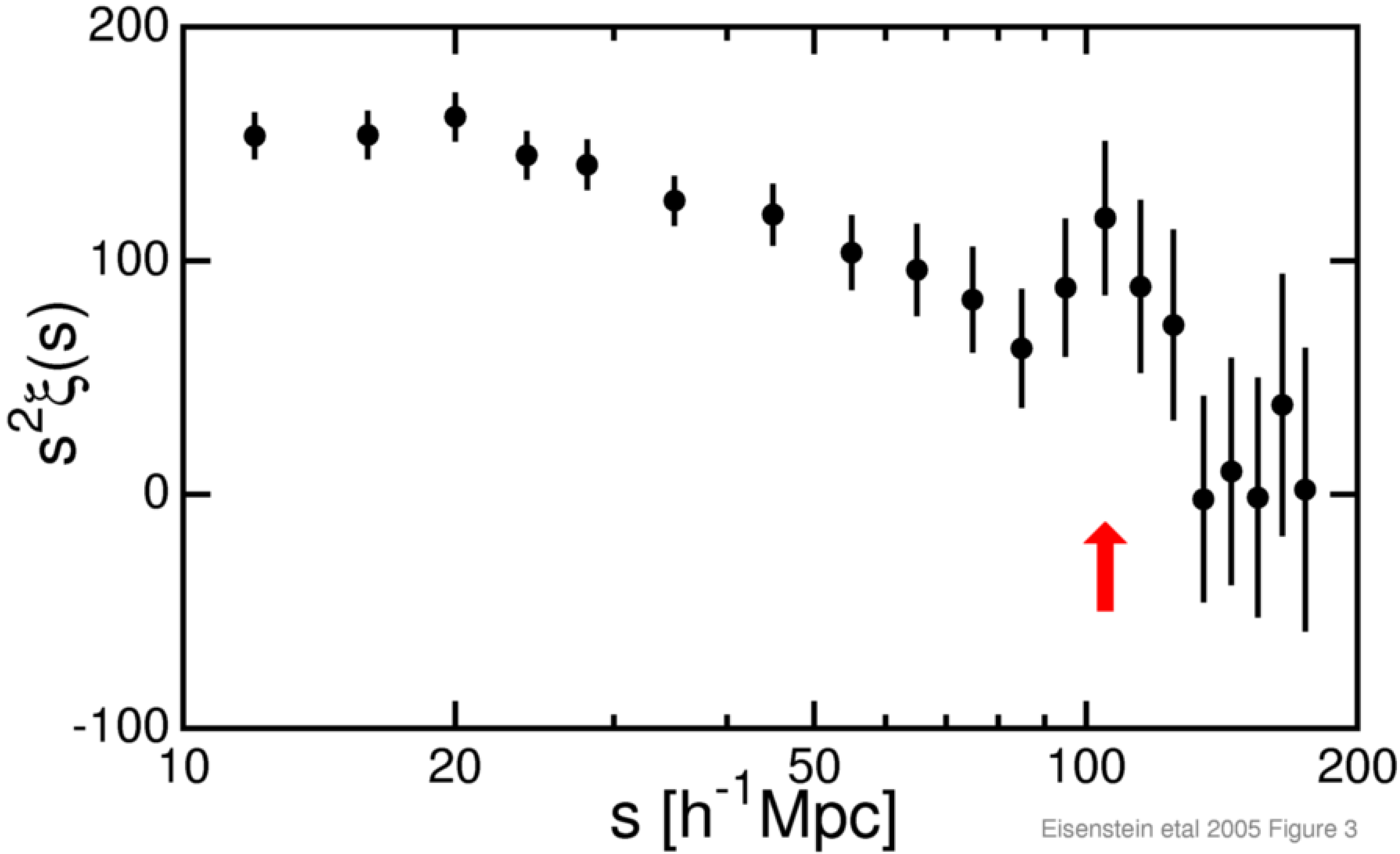
Spreading Sphere of Sound

The baryon-photon fluid spreads out in an expanding spherical shell surrounding the cold dark matter which does not move. After recombination, the Universe becomes transparent and the photons exit the shell, leaving a spherical density enhancement which should show up as a sharp feature in the 3D two-point correlation function at a radius equal to the distance sound could travel before recombination.

This is the same scale involved in the acoustic peaks of the CMB angular power spectrum.



Baryonic Oscillations in SDSS LRGs



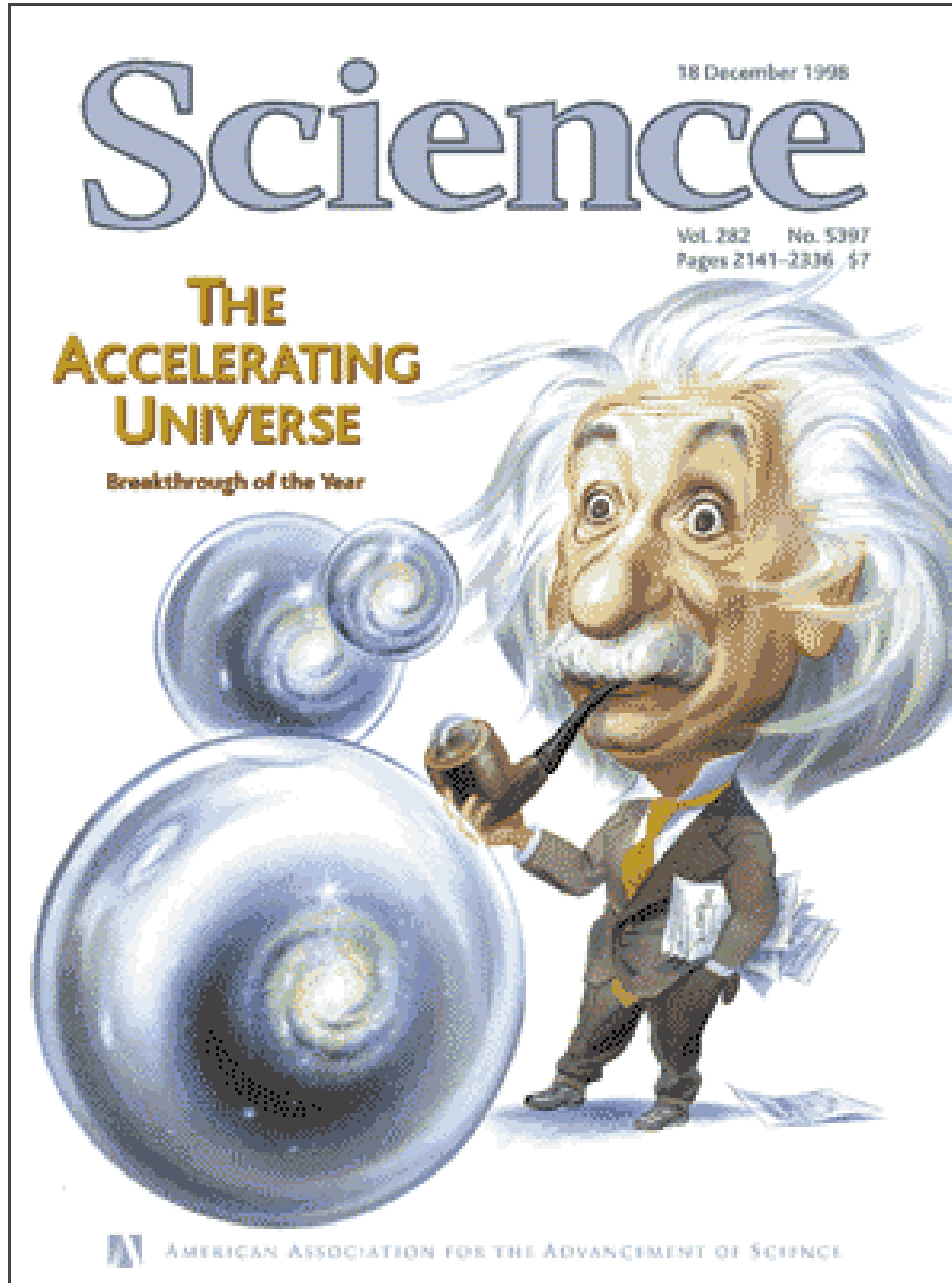
Eisenstein etal 2005 Figure 3

Accelerating Universe: 1998

Distant (high z) supernovae fainter than expected.

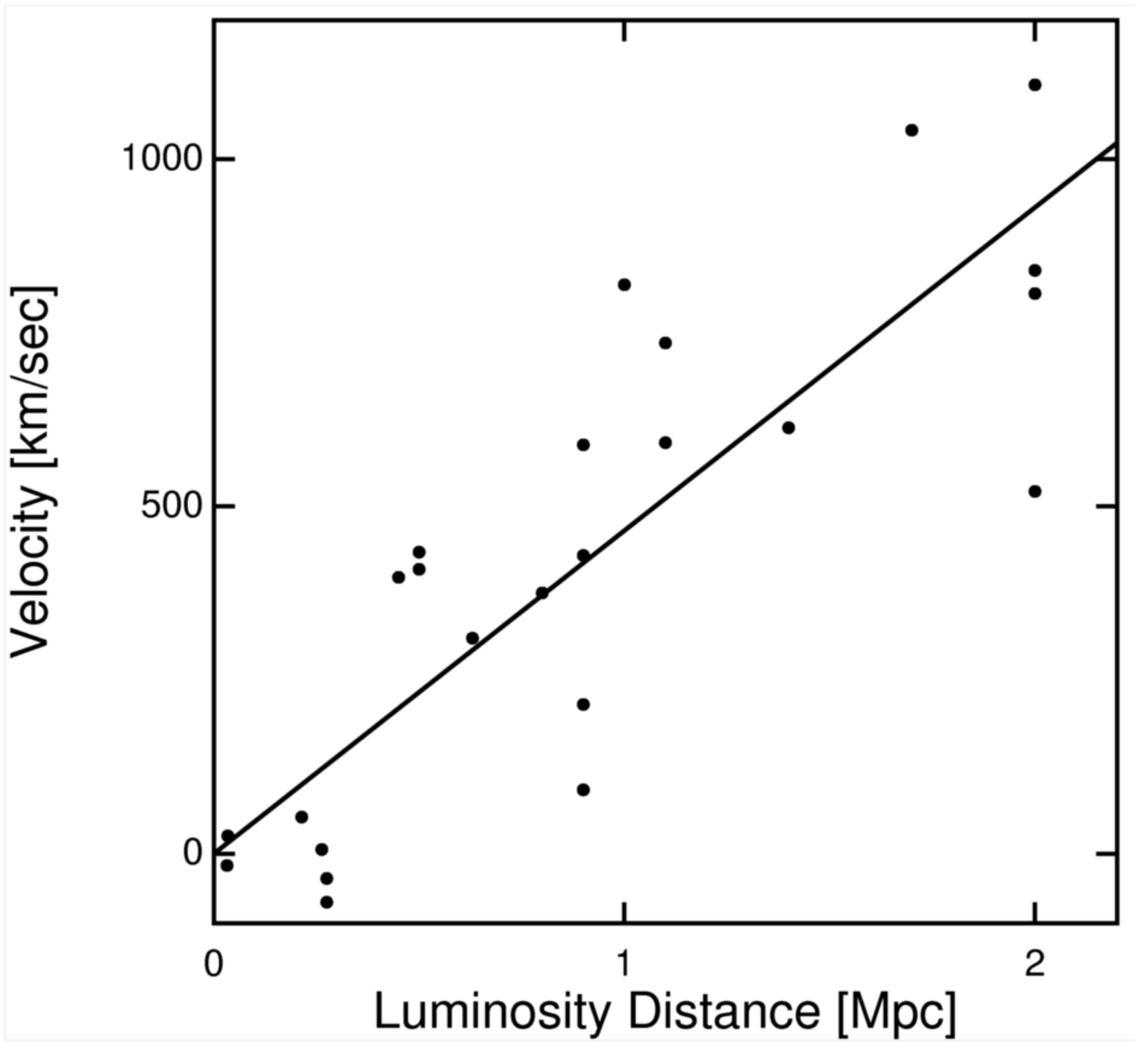
This was the AAAS discovery of the year in 1998.

Λ causes acceleration!

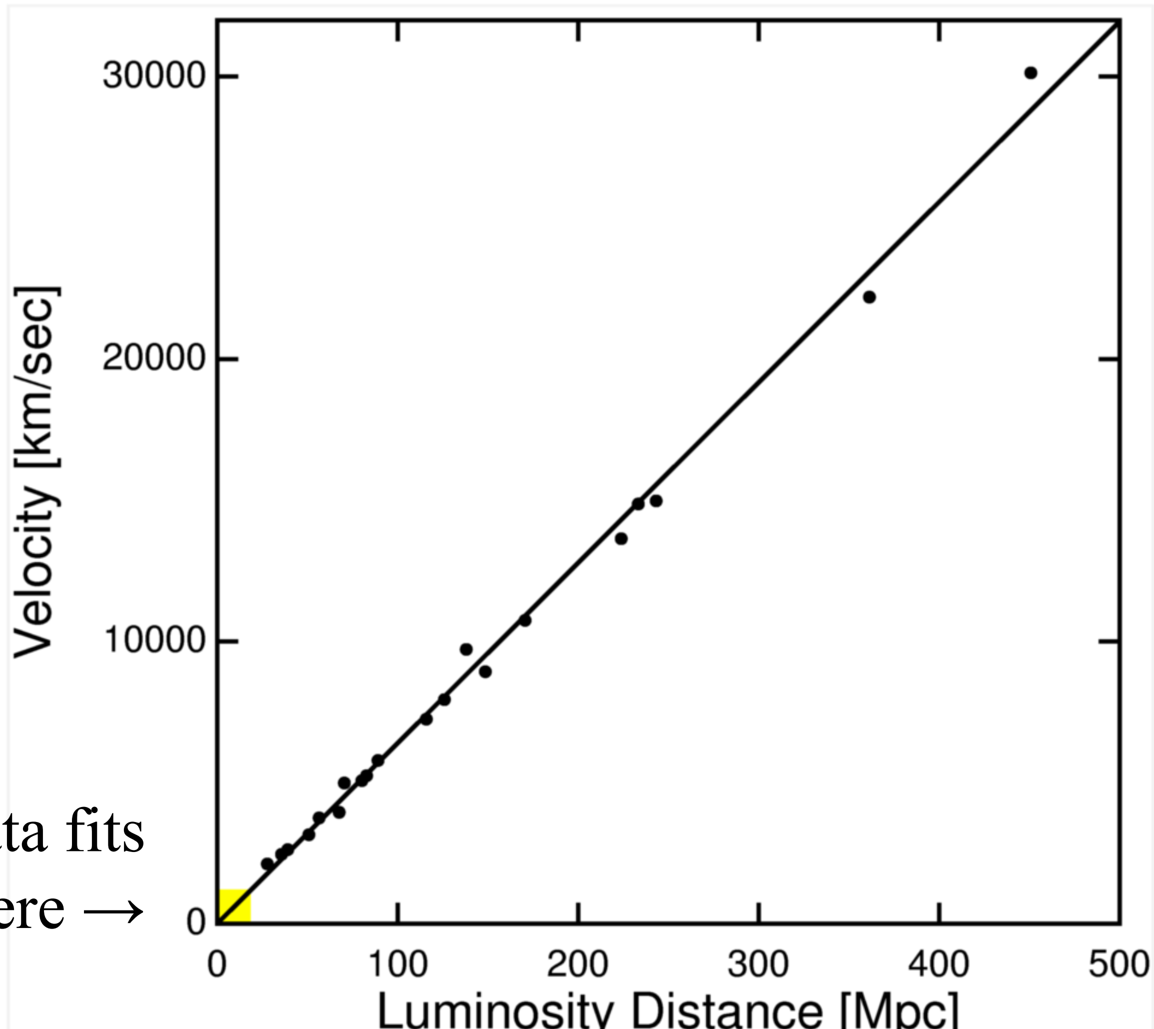


We recently learned how to read the "wattage" label on supernovae:

As a result, data on velocity vs distance is now much better! 1929

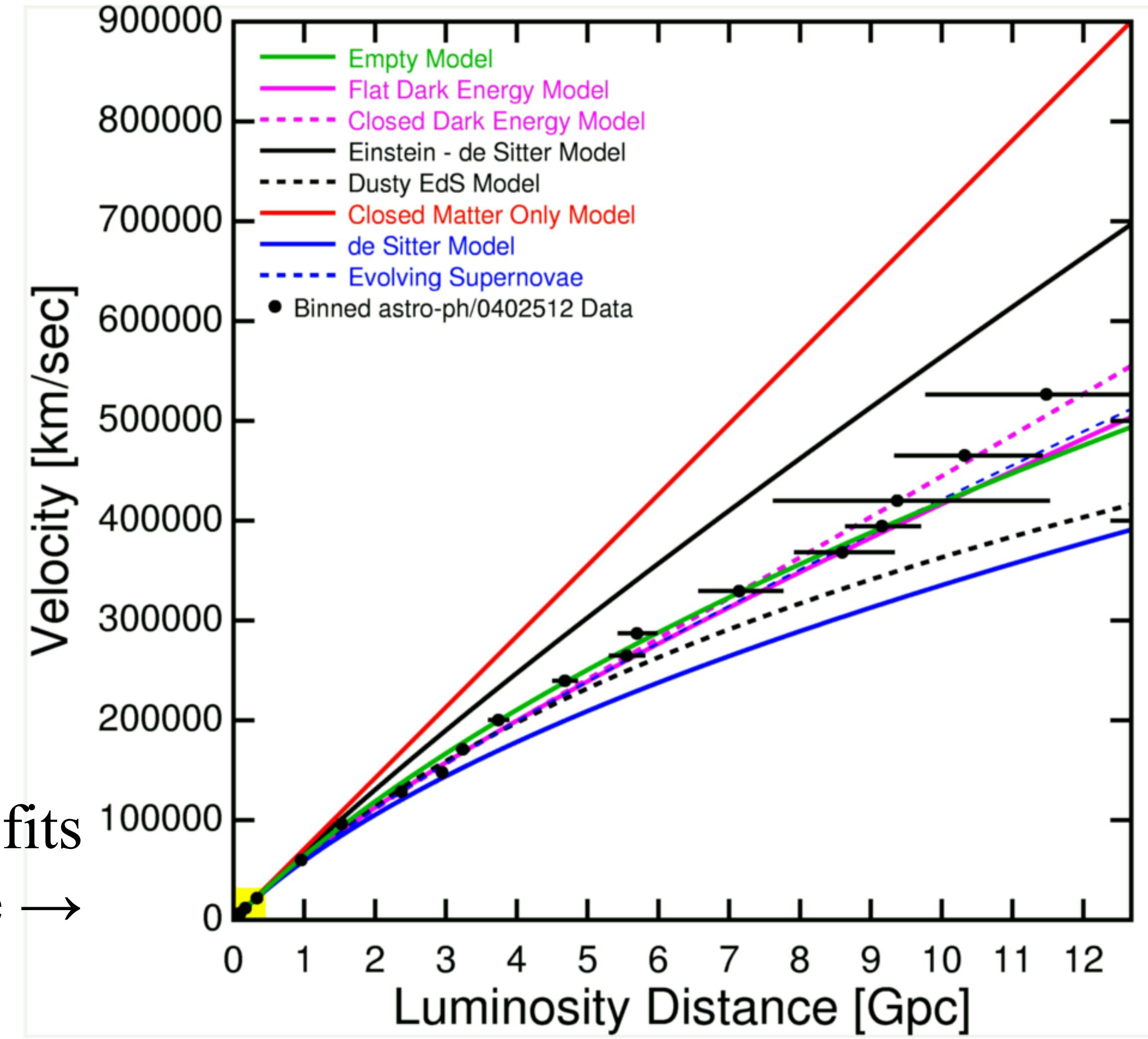


As a result, data on velocity vs distance is now much better! 1995



1929 data fits
in here →

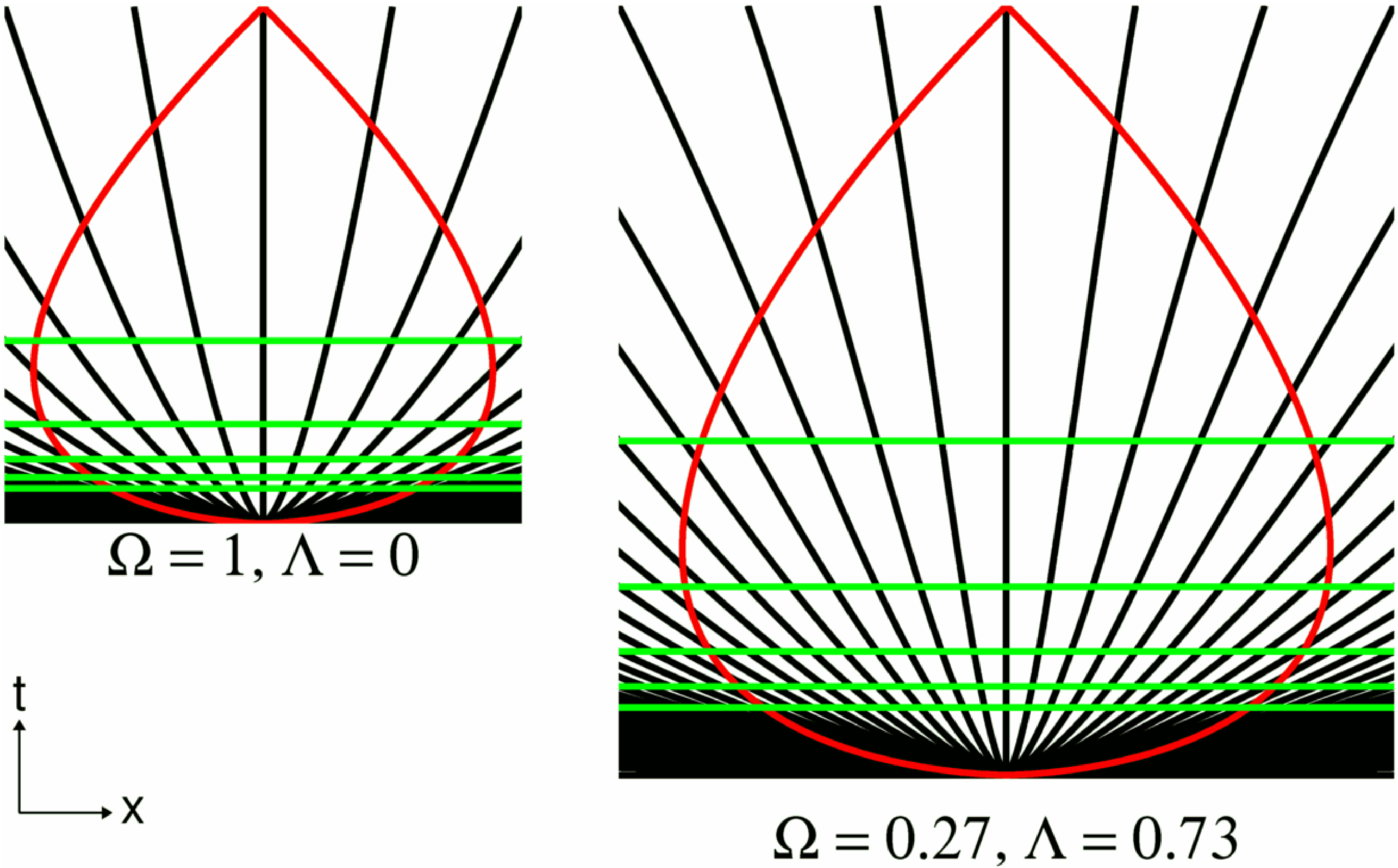
As a result, data on velocity vs distance is now much better! 2004



1995 data fits in here →

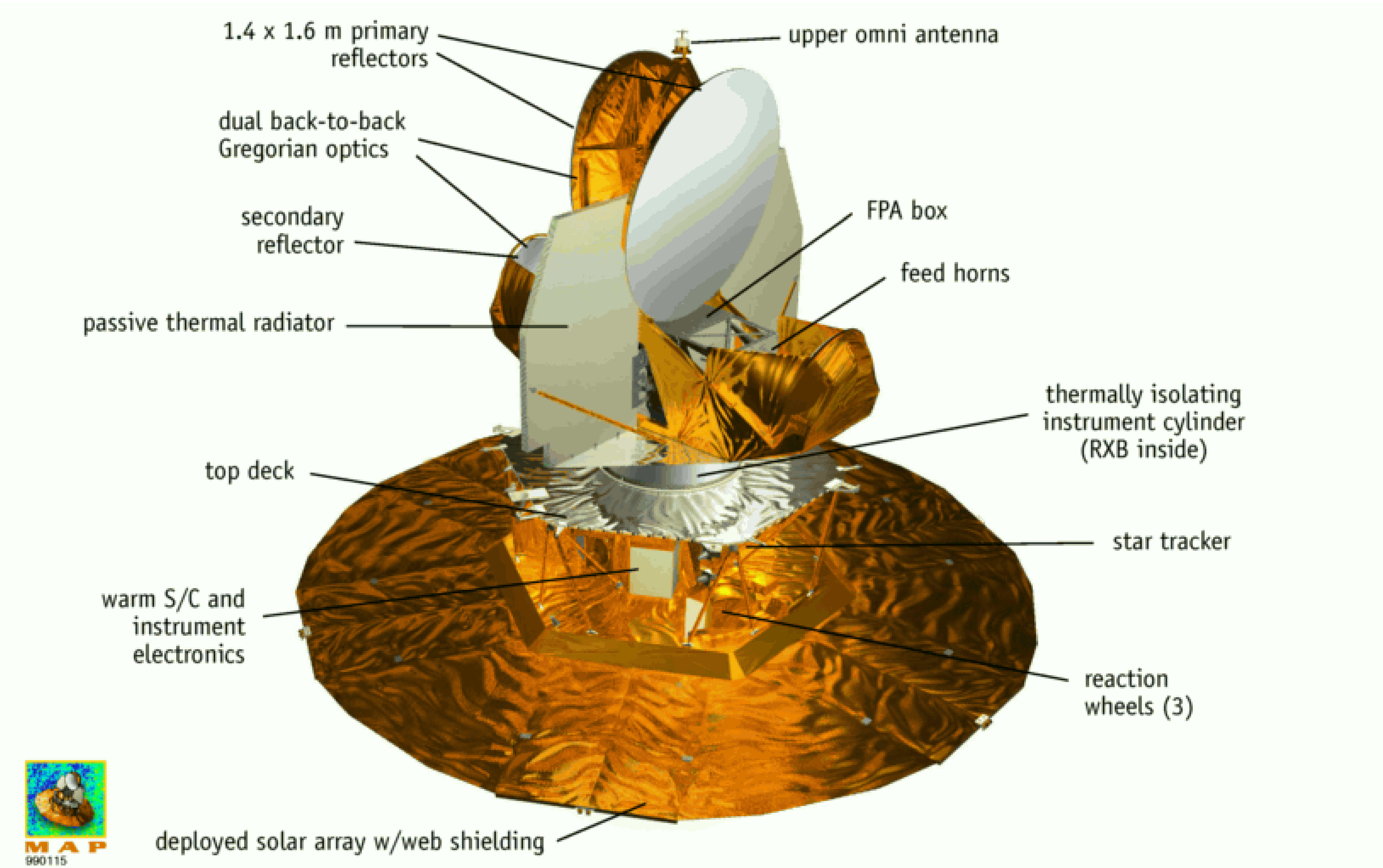
v = cz

Acceleration causes Faintness

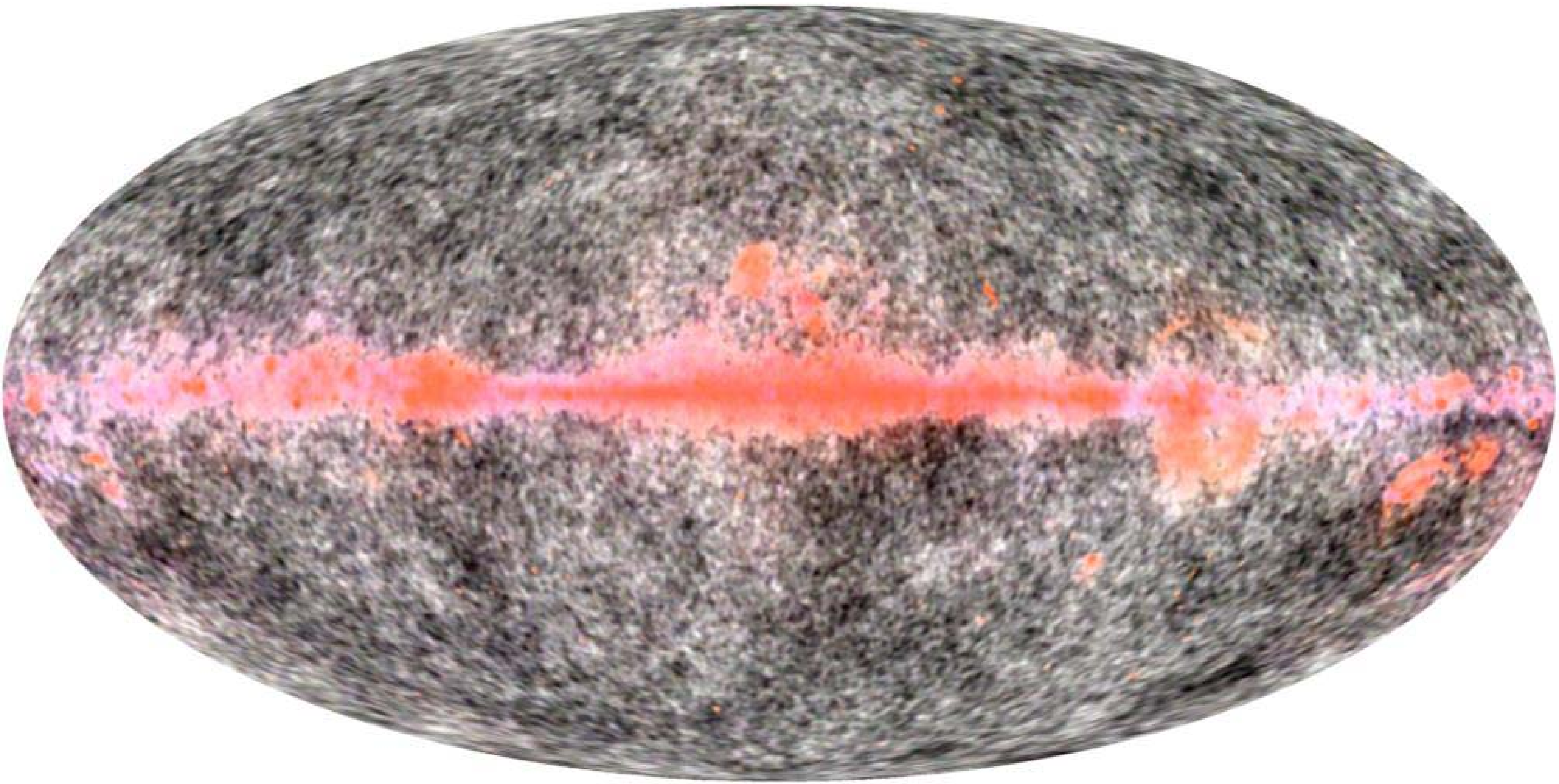


WMAP Science Working Group

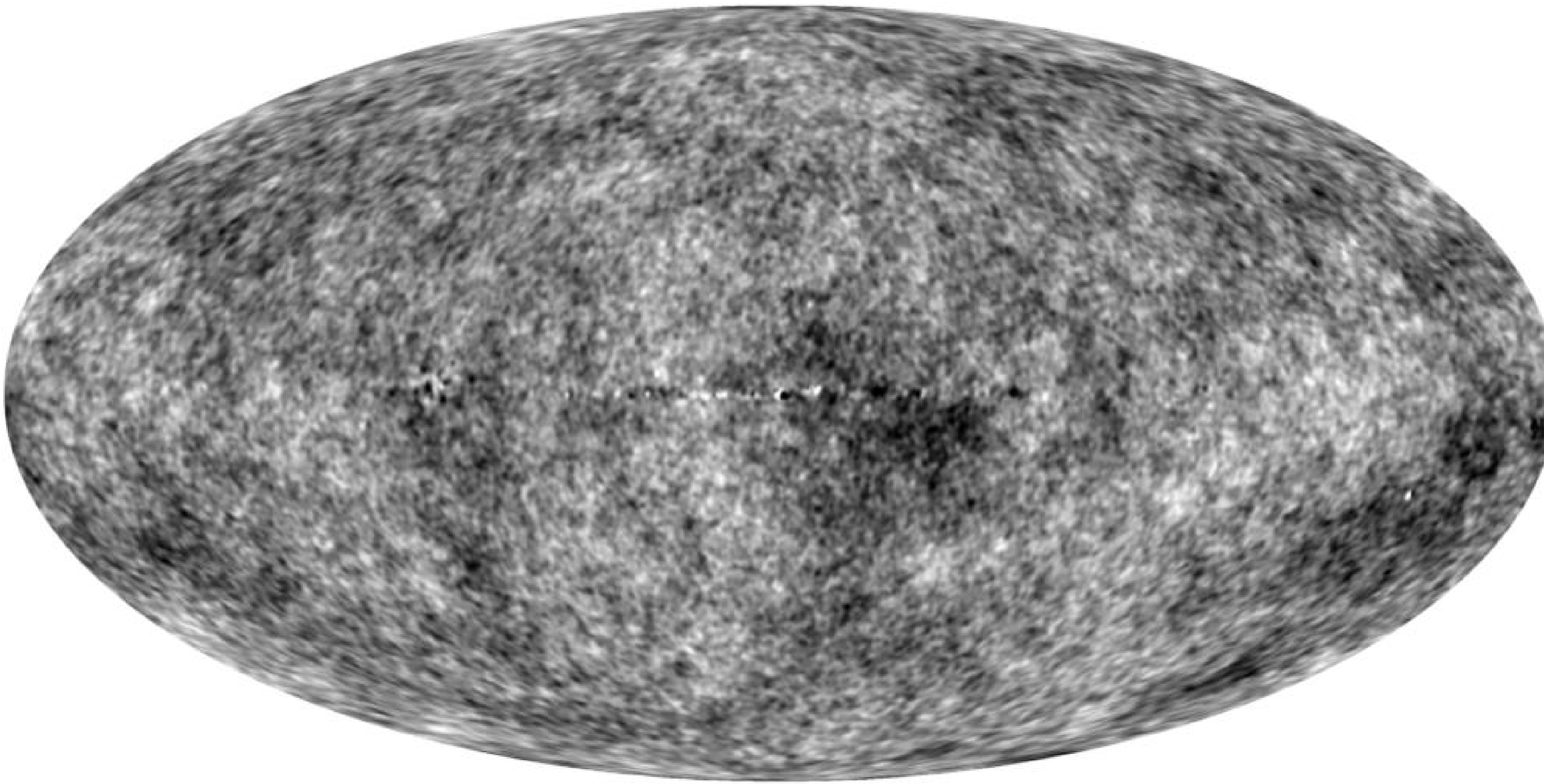
A New Cosmology Satellite



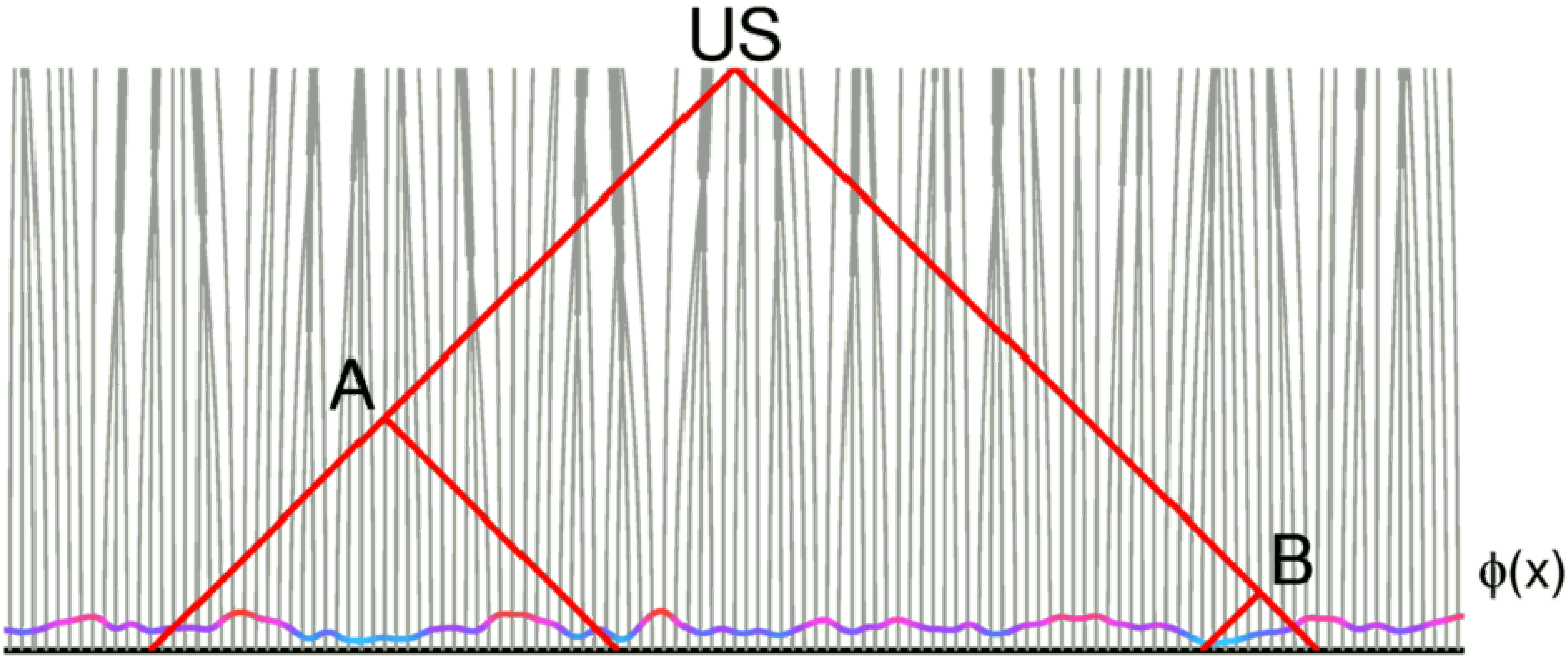
WMAP 41, 61 & 94 GHz Map



WMAP "No galaxy" ILC Map



Gravitational Potential $\rightarrow \Delta T$



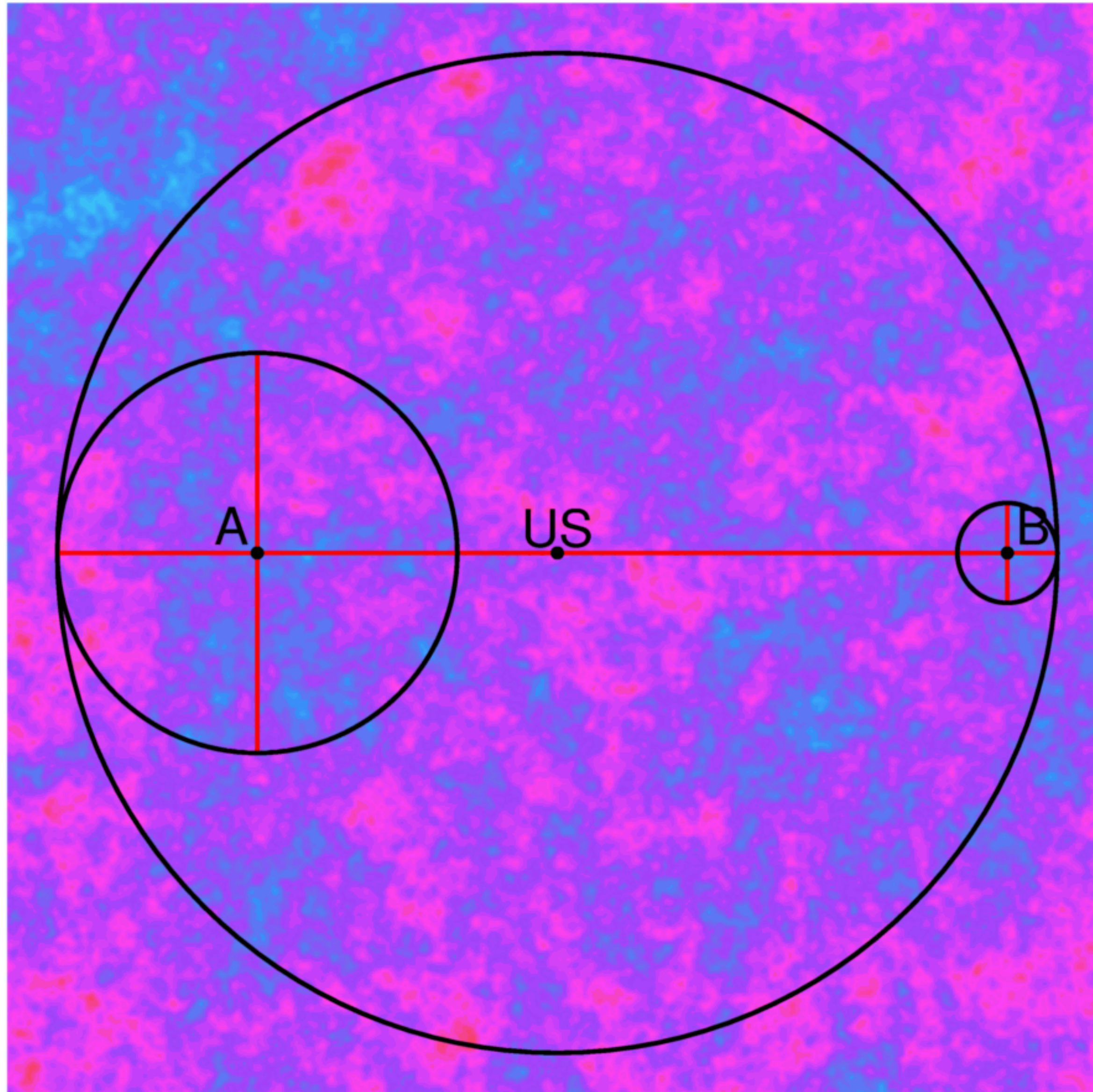
This potential also leads to large scale structure formation.

Reionization puts scatterers at A: many degree scale

Scatterers during recombination are at B: sub-degree scale

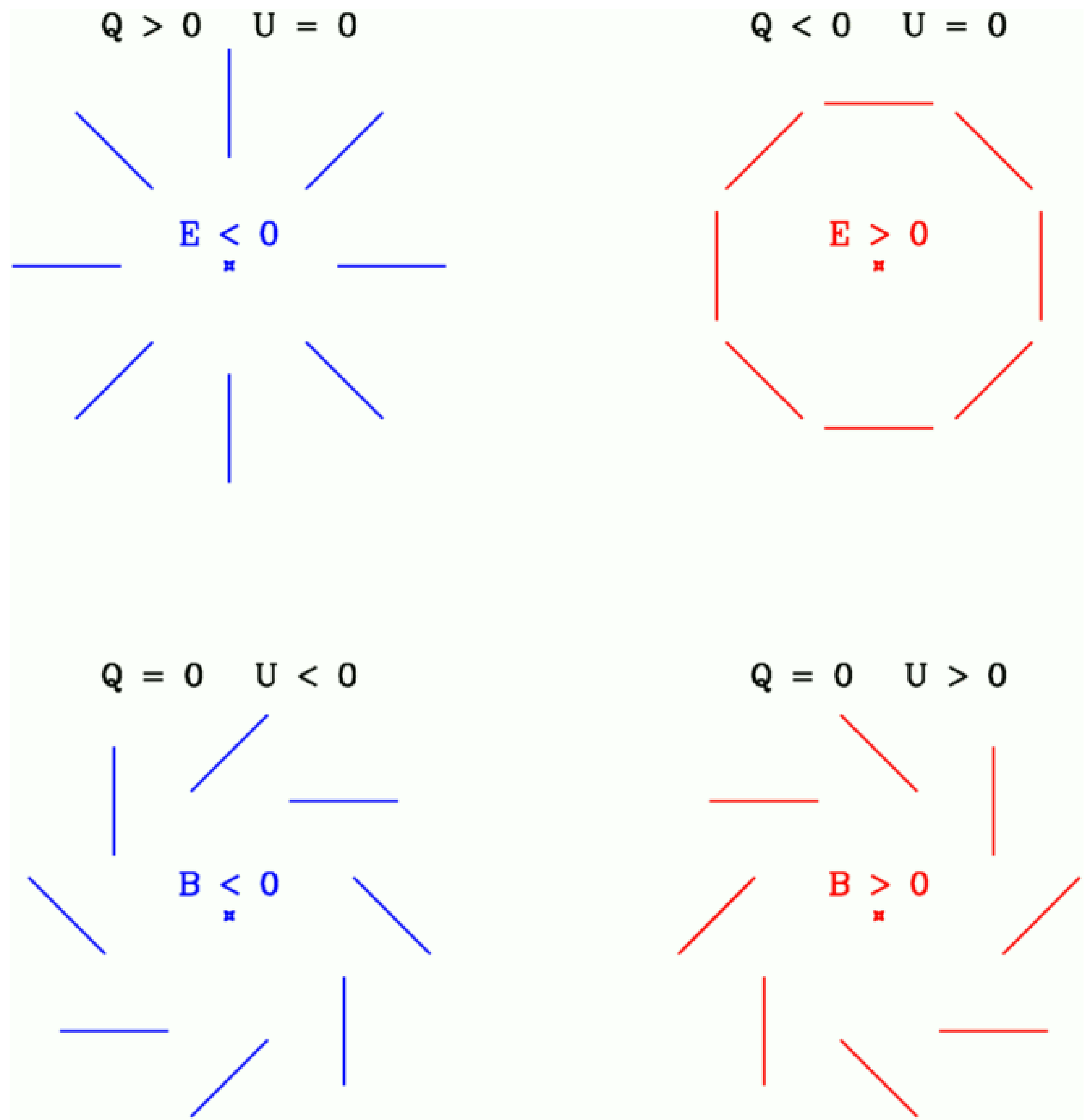
Top view of same S-T Diagram

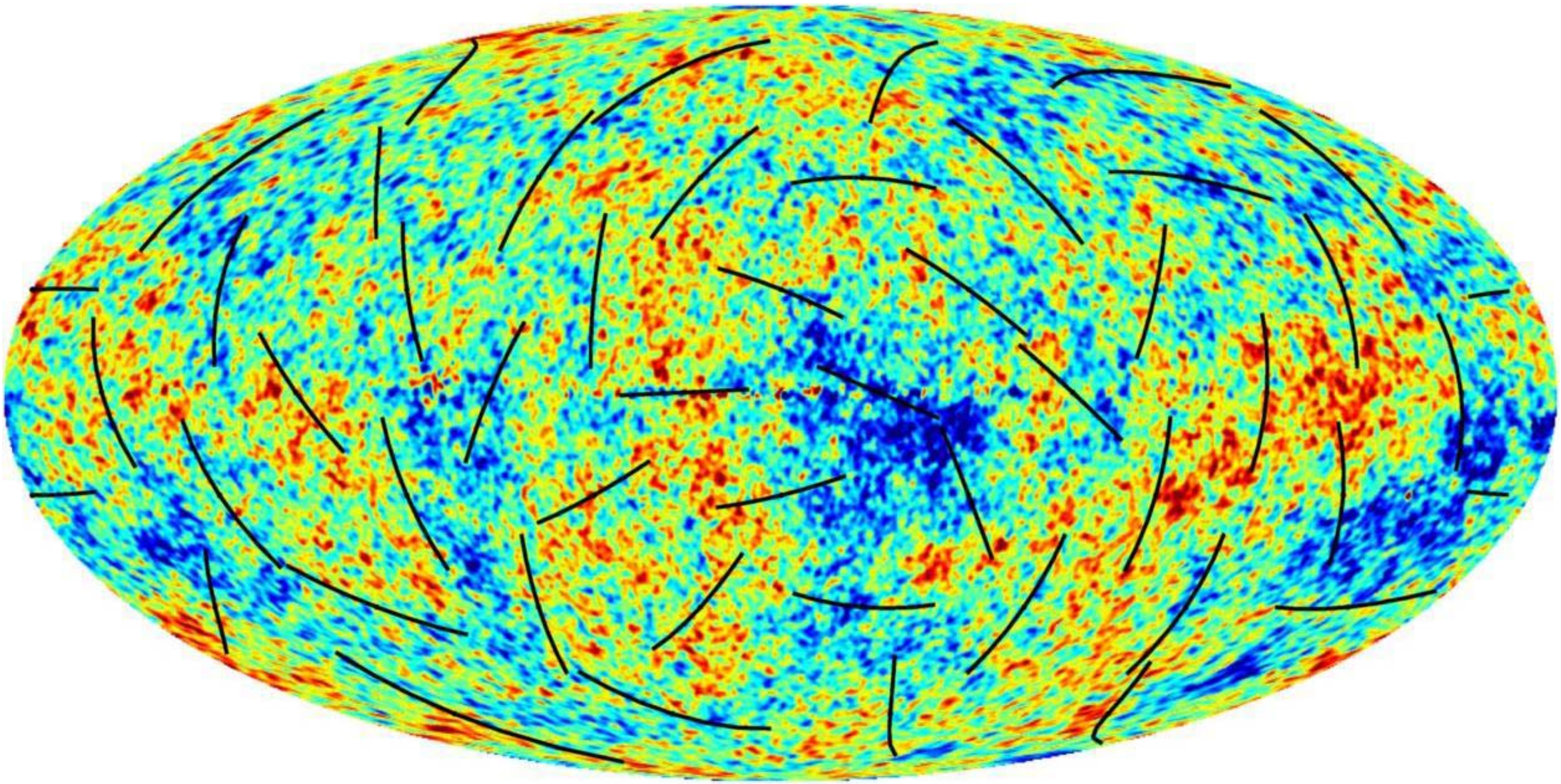
- Electrons at A or B see a somewhat different piece of the surface of last scattering than we do.
- If electrons at A or B see a quadrupole anisotropy then we get polarization.



Two kinds of pattern: E & B

- E modes are the gradient of a scalar.
- B modes are rotated 45 degrees.
- Only E modes are generated by electron scattering acting on density perturbations.





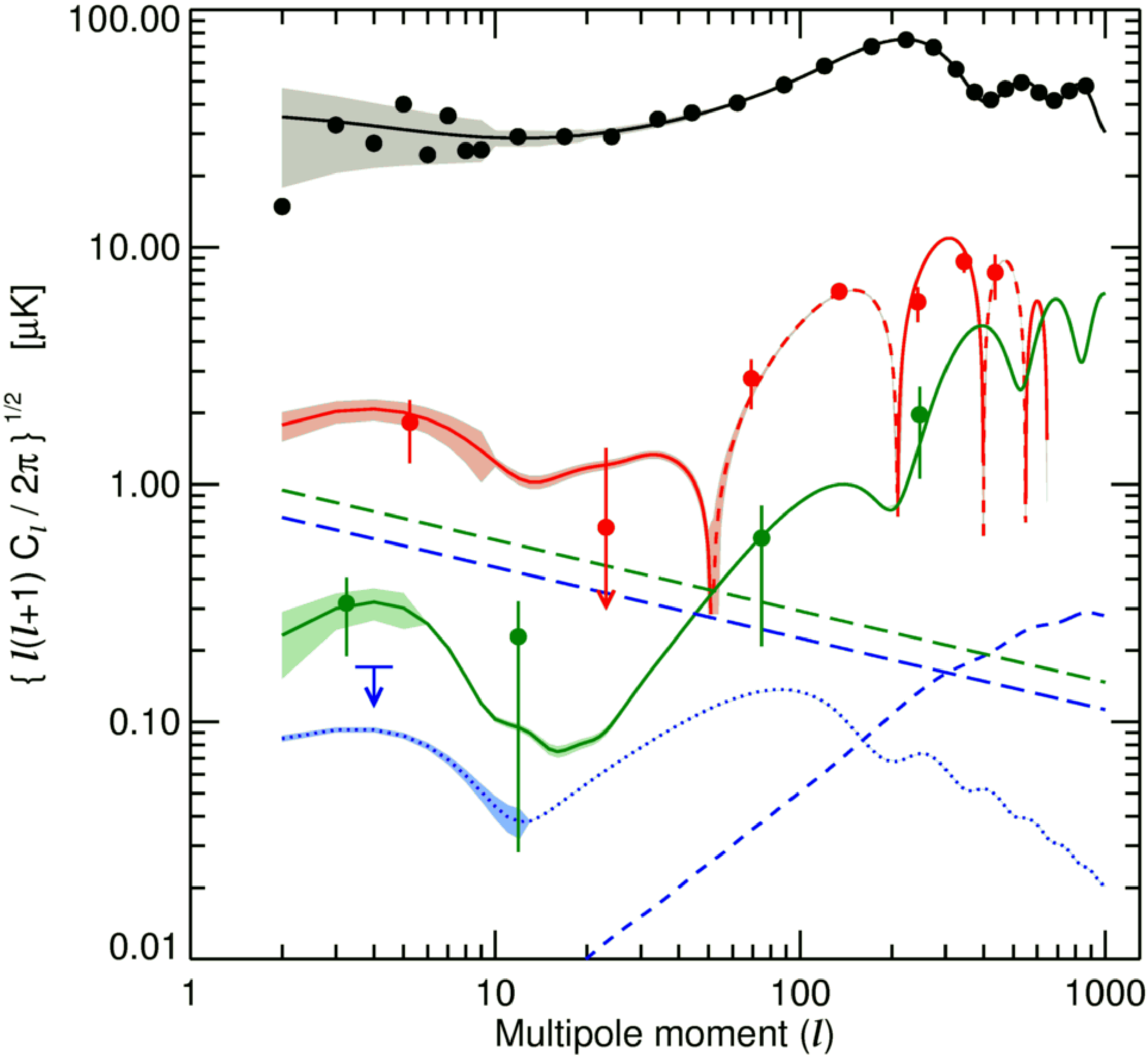
Final Results

$$\ell(\ell+1)C^{EE}_{\ell=<2-6>}/2\pi = 0.086 \pm 0.029\ (\mu K)^2$$

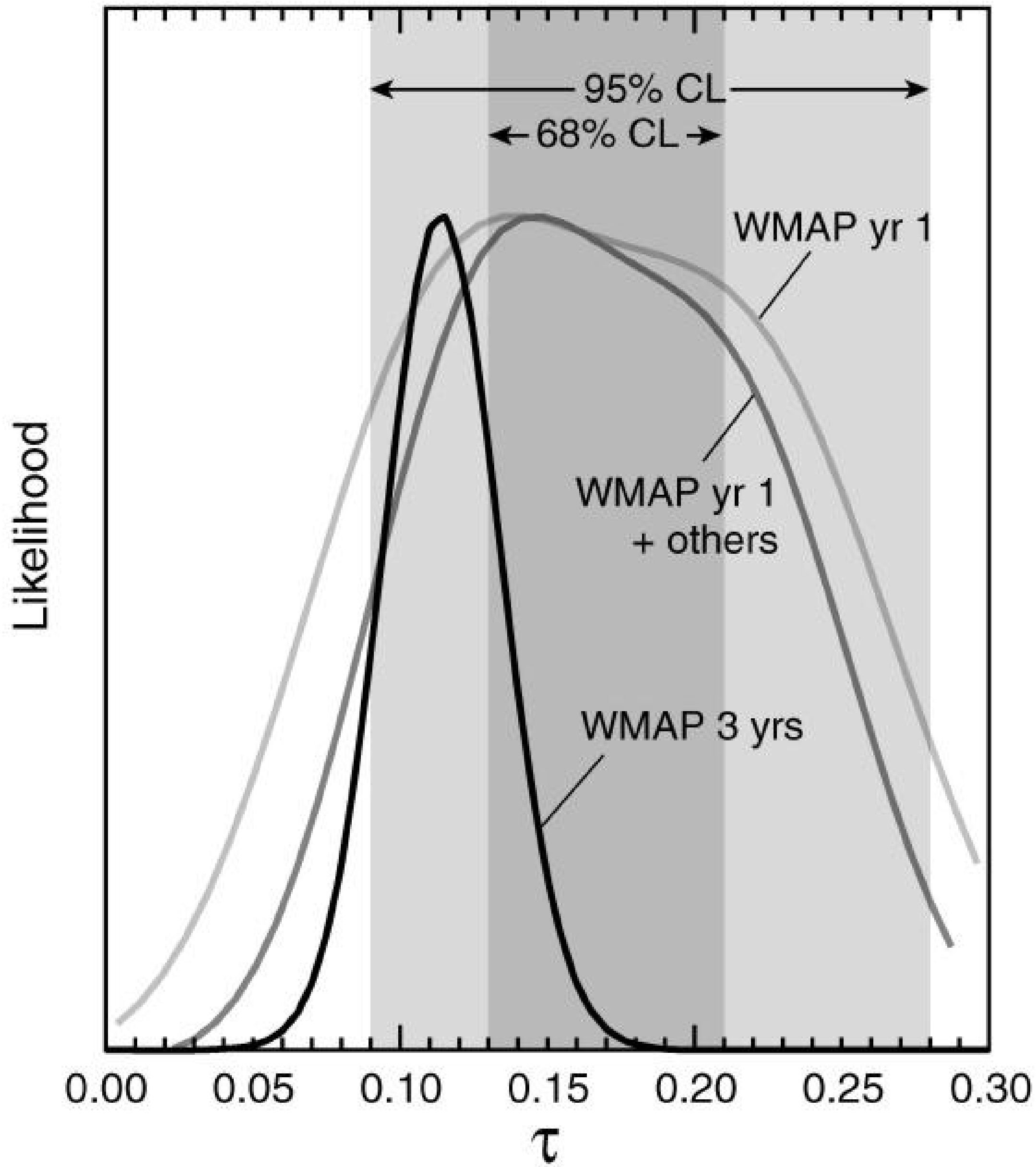
$$\ell(\ell+1)C^{BB}_{\ell=<2-6>}/2\pi = -0.04 \pm 0.03\ (\mu \mathrm{K})^2$$

EE only: $\tau = 0.10 \pm 0.03$

TT, TE & EE: $\tau = 0.09 \pm 0.03$

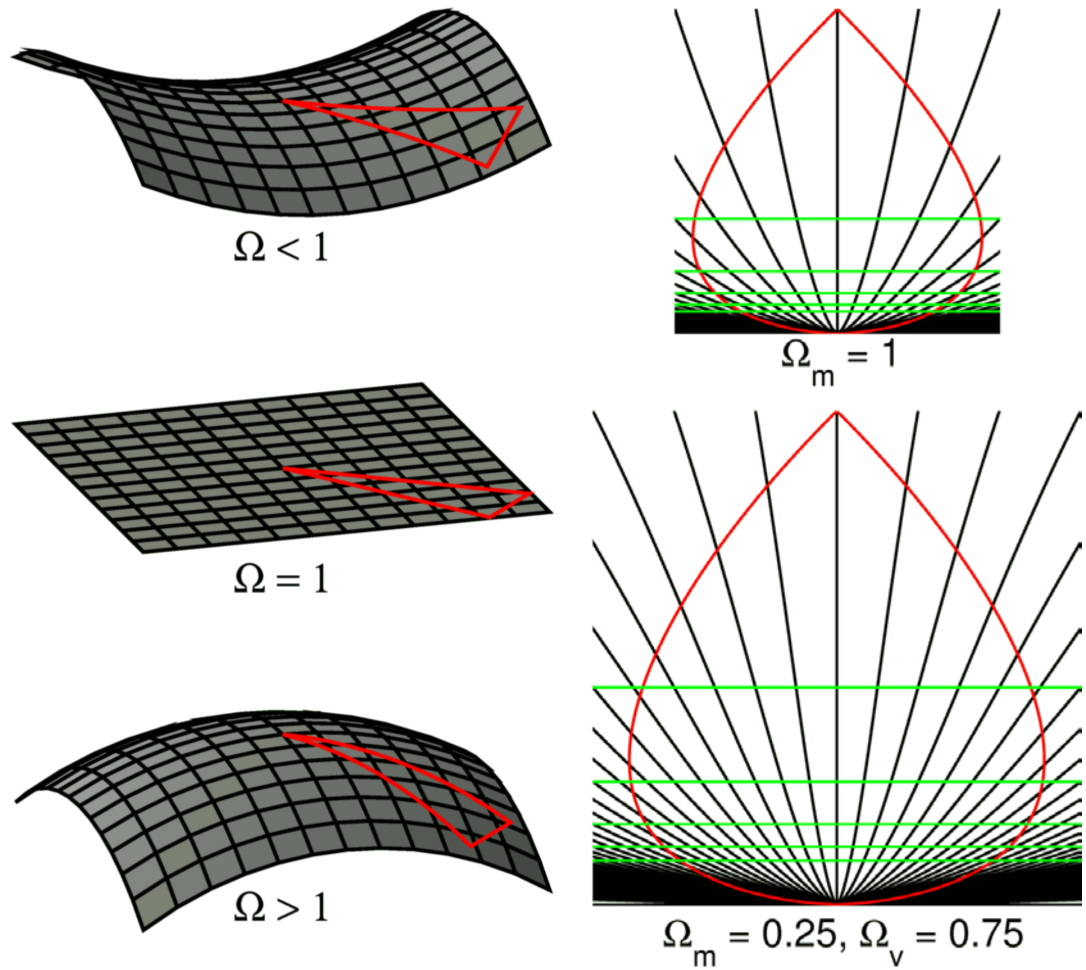

100.00
10.00
1.00
0.10
0.01
1
10
100
1000
Multipole moment (l)
{ l(l+1) C_l / 2π } ^1/2 [μK]

Comparison to Previous TE

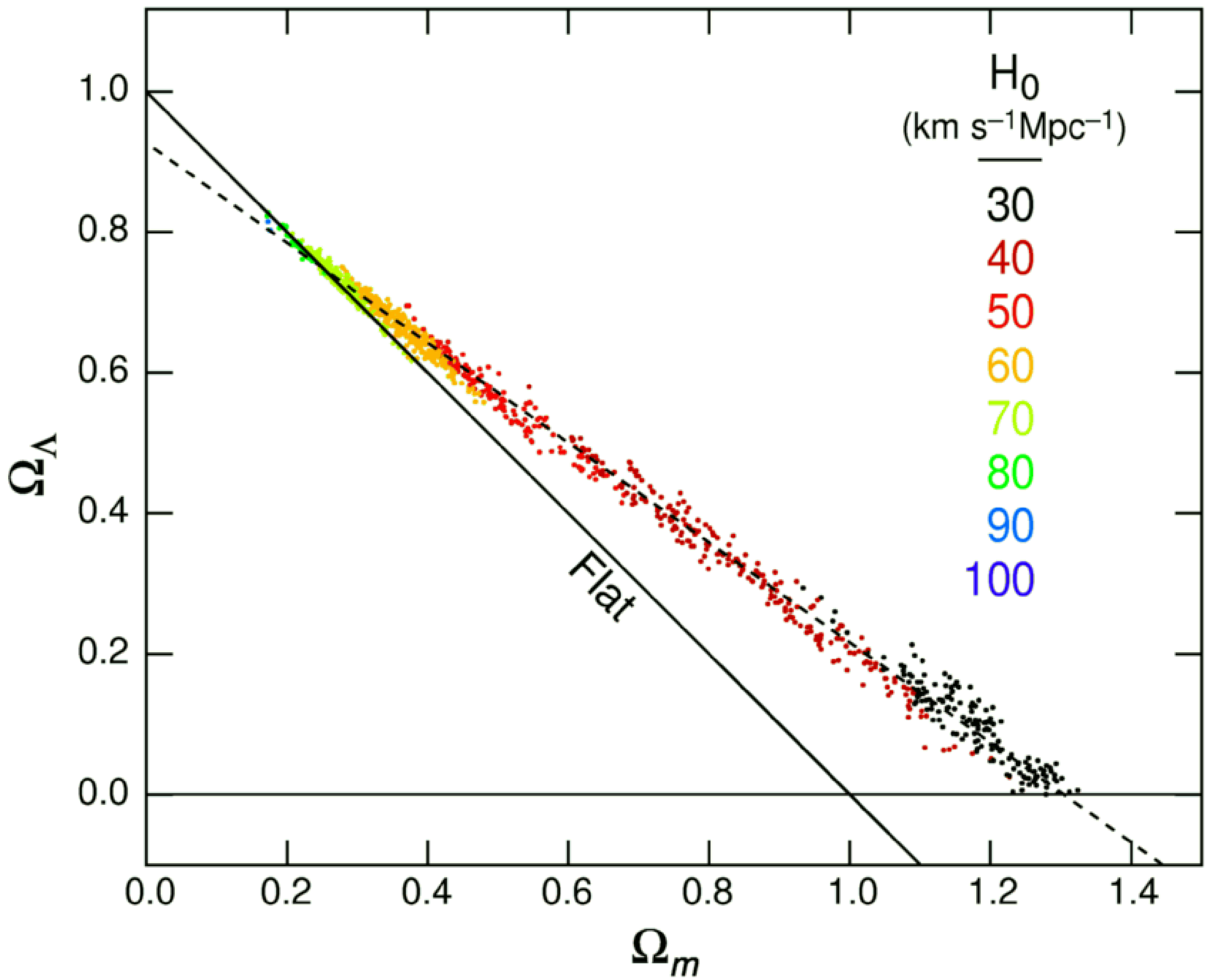


Effects on Peak Position: l_{pk}

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

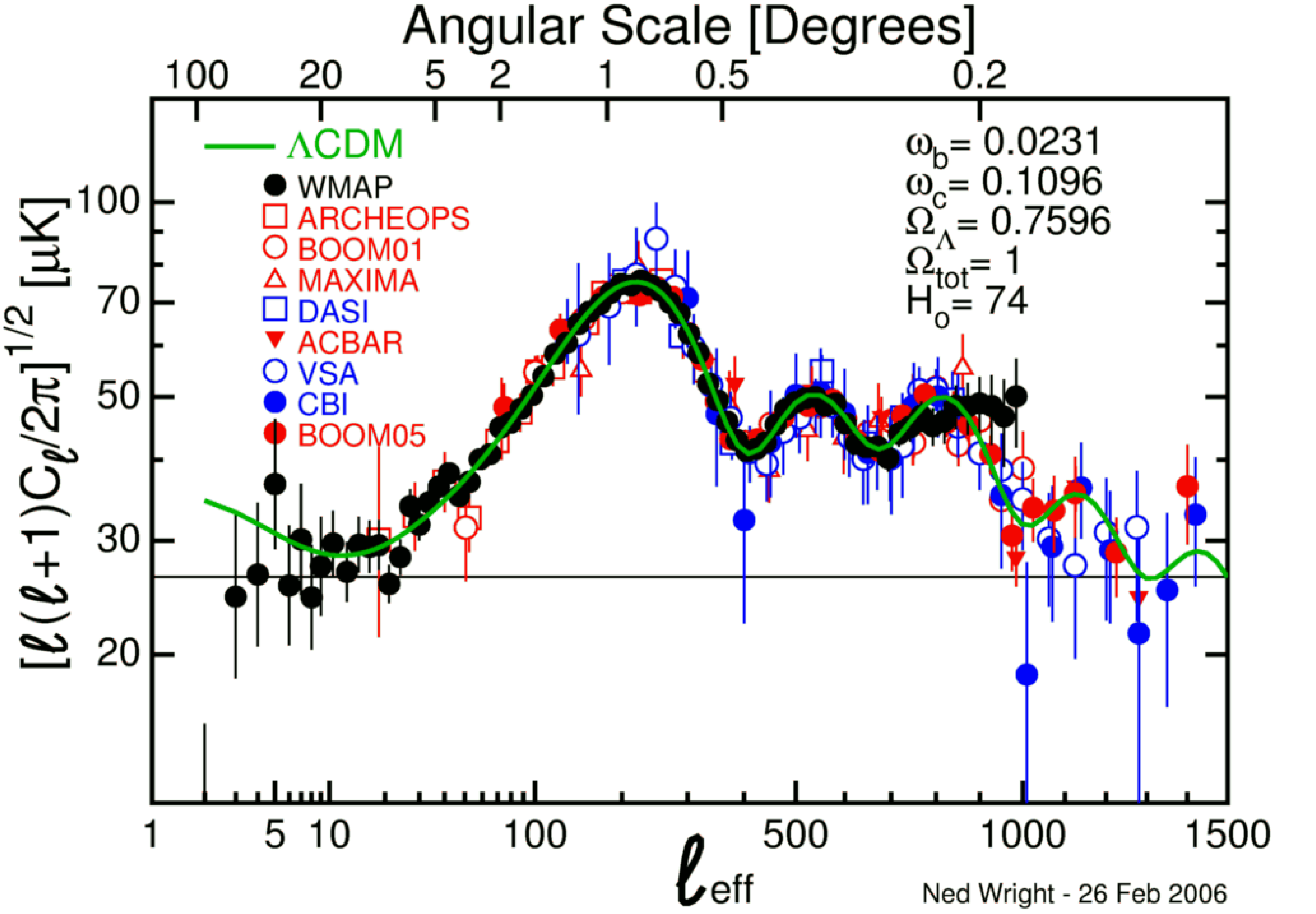


The CMB does not imply flatness

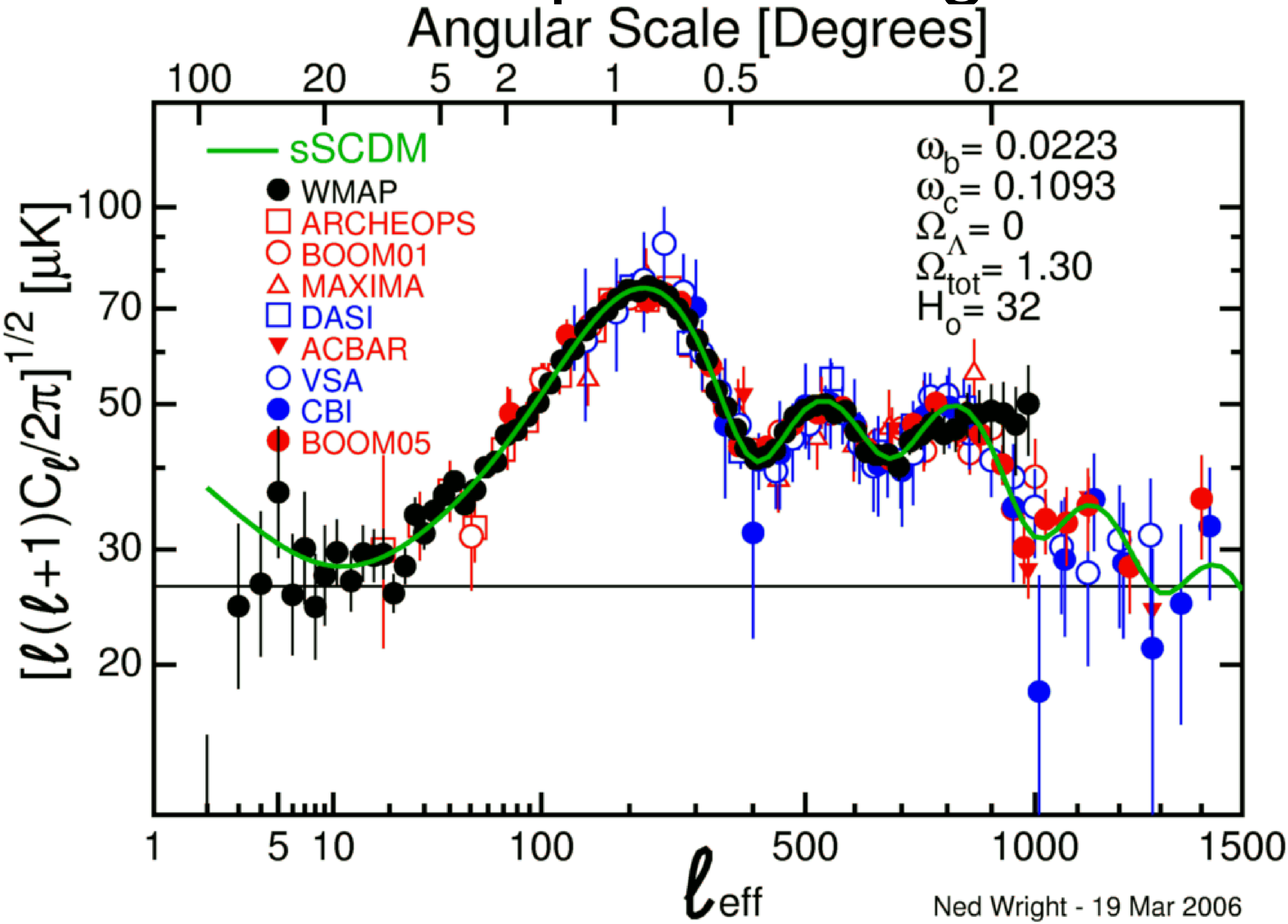


- But CMB + H_o (or other data) do imply flatness.

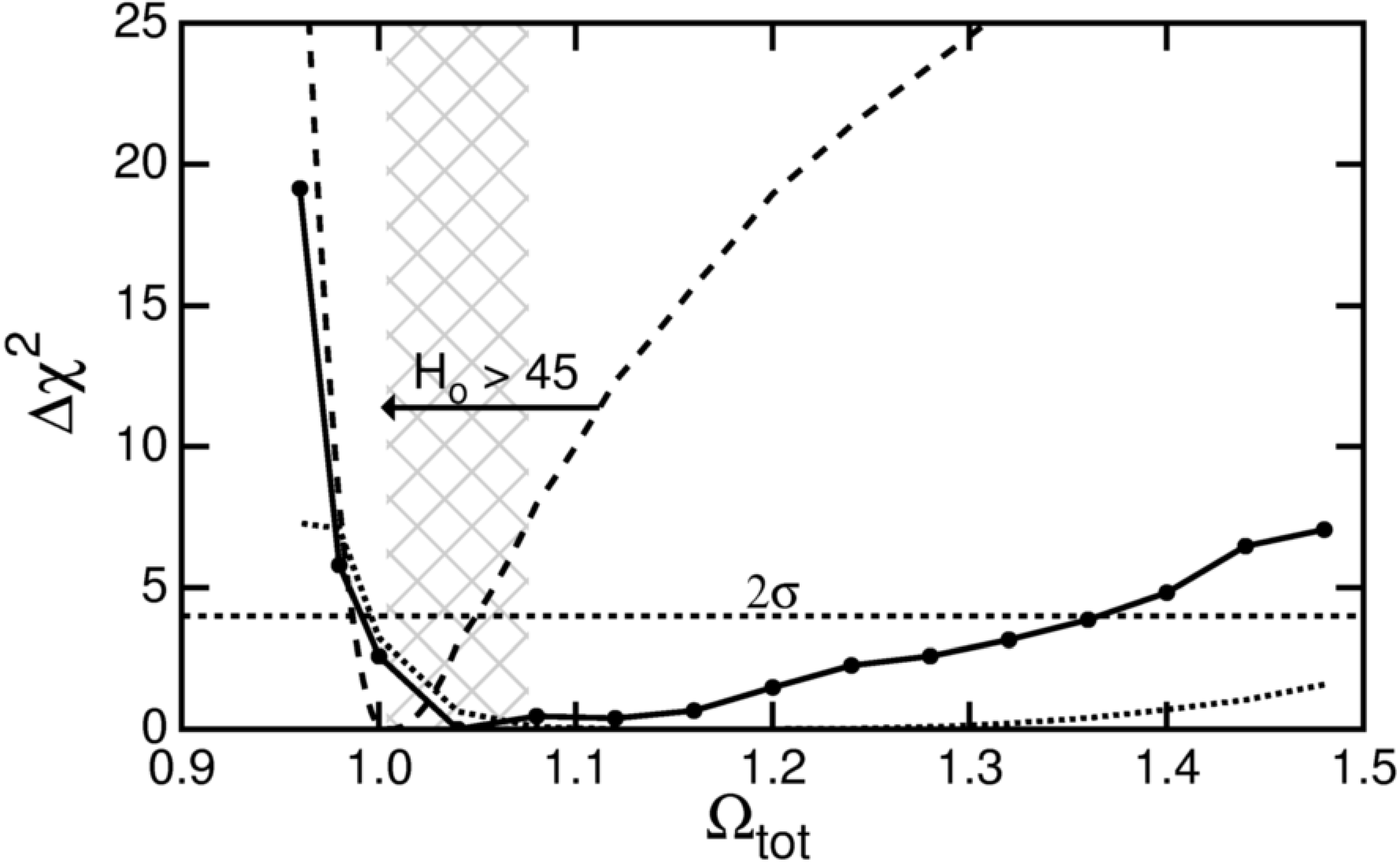
ΛCDM is a Good Fit



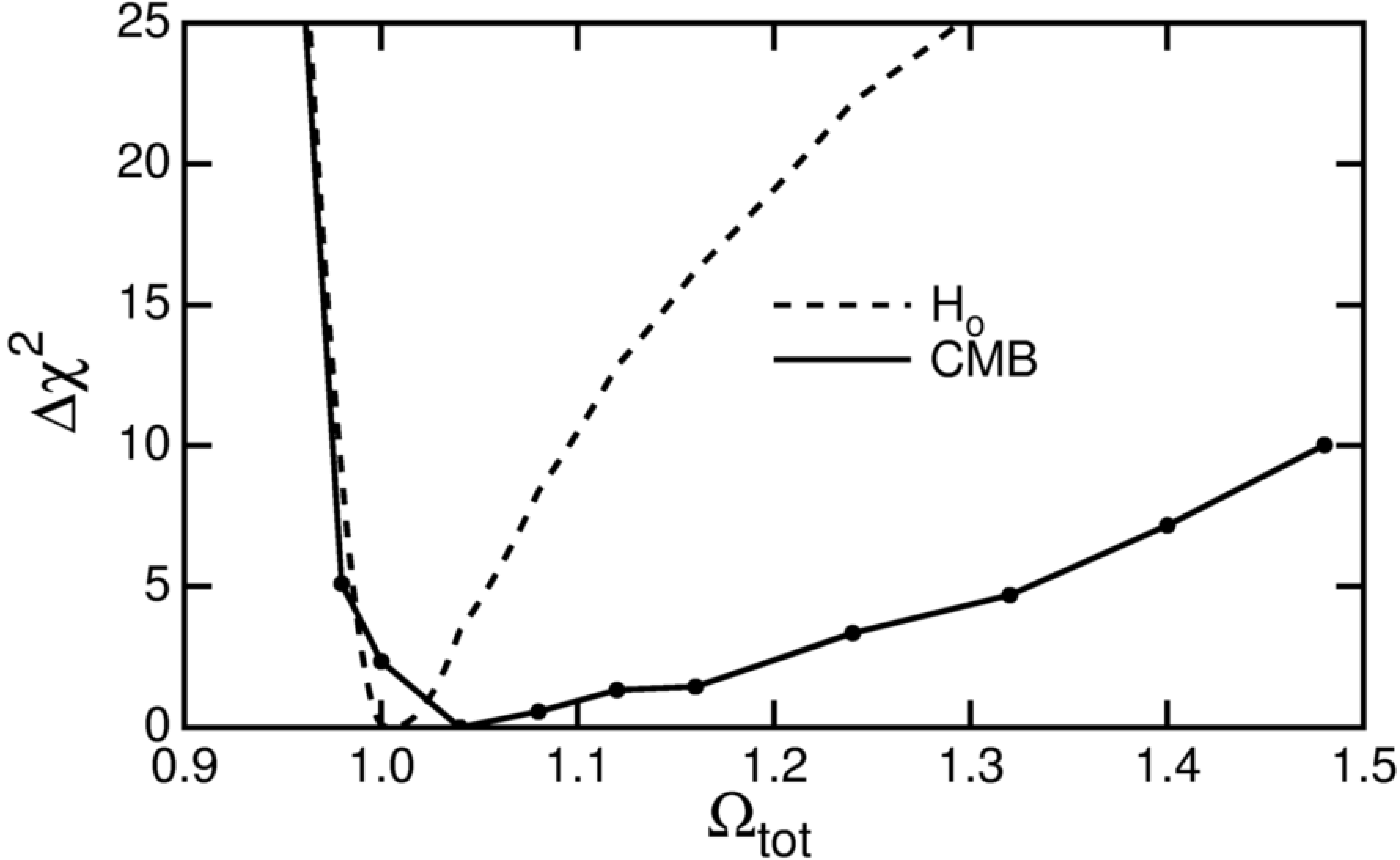
So is "super Sandage"



Minimum χ^2 vs Ω_{tot}: 1year



Minimum χ^2 vs Ω_{tot}: 3year



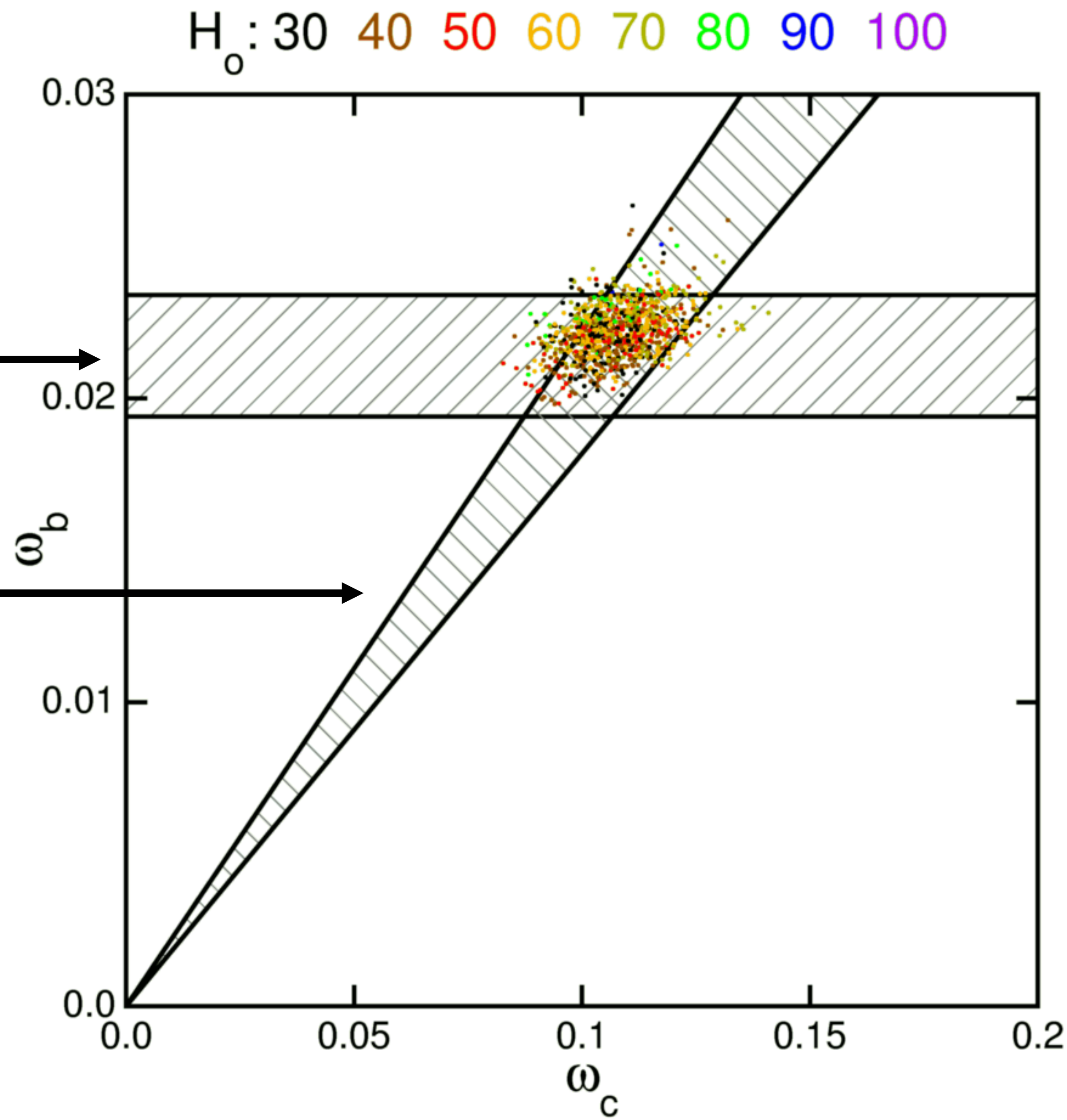
Info from peak & trough heights

- Overall Amplitude of the perturbations
  - Agrees with large scale structure if almost all the dark matter is COLD dark matter
- Primordial power spectrum power law spectral index: $n = 0.951 \pm 0.017$ without running index.
  - EPAS inflationary prediction is $n = 1$
- Baryon/photon and DM/baryon density ratios
  - $\rho_b = 0.42$ yoctograms/m^3 = 0.42×10^{-30} gm/cc
  - $\rho_{cdm} = 1.9$ yg/m^3 [$\omega \equiv \Omega h^2 = \rho/\{18.8 \text{ yg/m}^3\}$]

Baryon & CDM densities

BBNS value

5:1 Ratio



Is Λ really a *CONSTANT*?

- The large Λ during inflation went away.
- Will the small Λ driving the accelerating expansion go away too? Is it the same now as it was 5 billion years ago?
- If $w \neq -1$ then the dark energy density changes.
- In order to find out, NASA and the US Department of Energy want to build JDEM, the Joint Dark Energy Mission, but JDEM funding is in danger.
- I am on the JDEM Science Definition Team.

COSMOLOGY: A SEARCH FOR TWO NUMBERS

Precision measurements of the rate of expansion and the deceleration of the universe may soon provide a major test of cosmological models

ALLAN R. SANDAGE

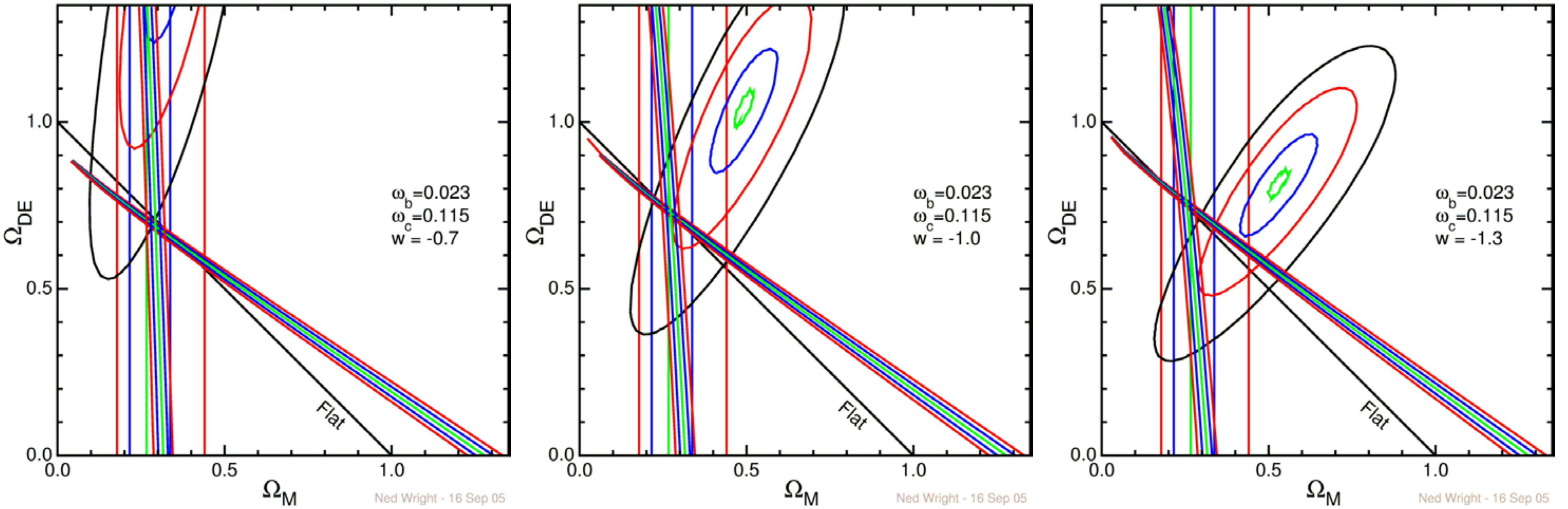
- Allan Sandage in Feb 1970 *Physics Today* was searching for H_o [80 km/sec/Mpc $\pm$ 50%] and q_o [1.2 $\pm$ 0.4].

Search for Two Numbers?

- Now we are searching for $w=P/\rho c^2$ and dw/dz but H_o and Ω_{tot} have not been chiseled into a stone tablet by God or Guth.
- We still need to measure H_o, Ω_M and Ω_Λ while we search for w and w'.
- A majority of theoretical analyses of w and w' on astro-ph use unreasonable priors and thus obtain unreasonable results.

If $w = -1$, then flat ΛCDM is a good fit to all the data. If $\Omega = 1$, then $w = -1$ is a good fit to all the data.

Can we say anything about w?



- Pretty good mutual agreement of 4 datasets (CMB, SNe, H_o & Baryon oscillations) for w = -1 and Ω_{tot} =1.
- This agreement is slowly lost as w moves away from -1.

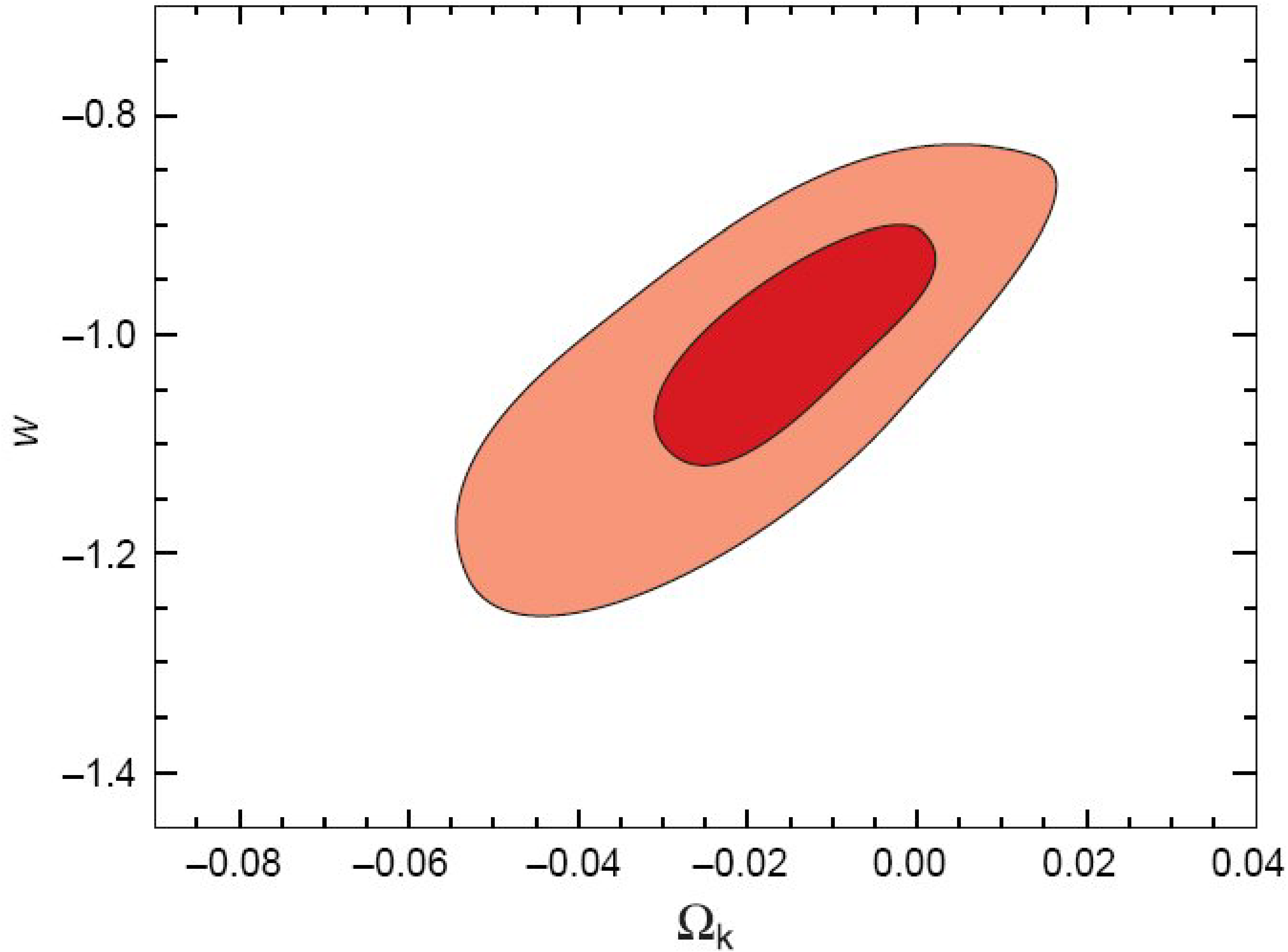
Non-flat Dark Energy Fitting!

CMB,

SNe,

SDSS P(k) & BAO,

2dFGRS



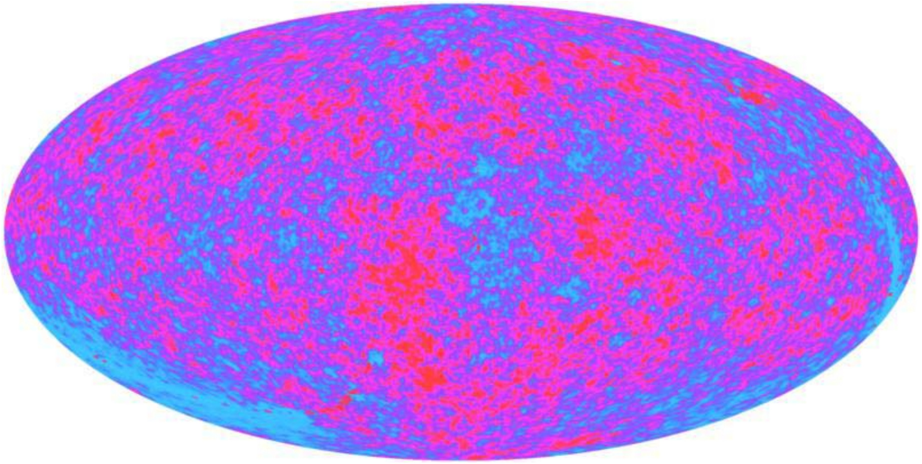
- $\Omega_k = 0$, w = -1 is OK: -0.93 > w > -1.14

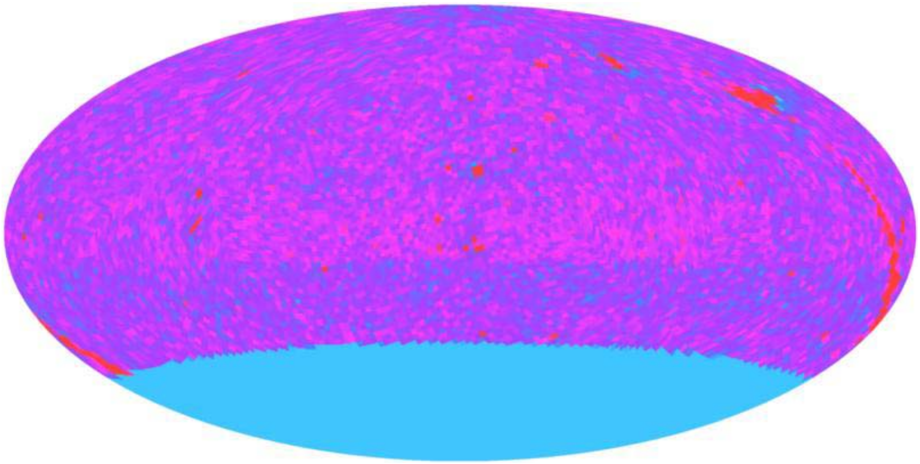
Same Laws of Physics?

- The cosmological constant Λ is present in space and also in our laboratory.
- But its effects in the laboratory are too small to measure. This is not the best situation.
- Astrophysicists are very eager to confirm the existence of Λ by every possible method.
- Currently there are several independent methods that all agree on the existence of Λ.

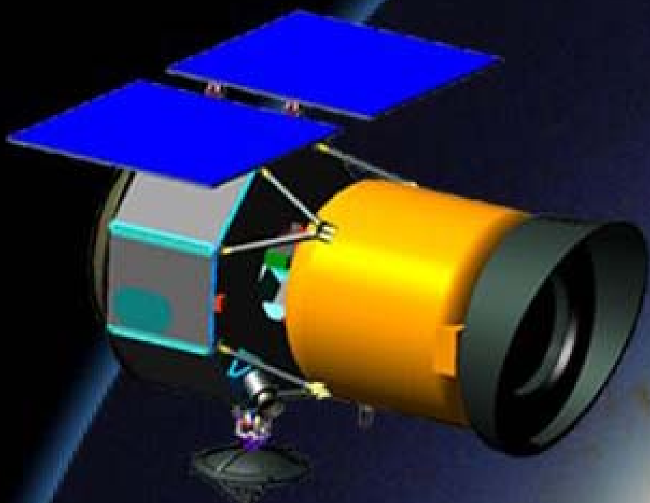
Λ Confirmed by CMB & IR maps

- The late Integrated Sachs-Wolfe effect occurs on our past light cone so the CMB ΔT we see is due to structures we also see.
- Correlation between WMAP and large-scale structure seen by:
  - Boughn & Crittenden at 99.7% confidence with hard X-ray background
  - Nolta *et al.* at 98% confidence with the NRAO VLA Sky Survey
  - Afshordi *et al.* at 99.4% with the 2MASS 2 micron all sky survey





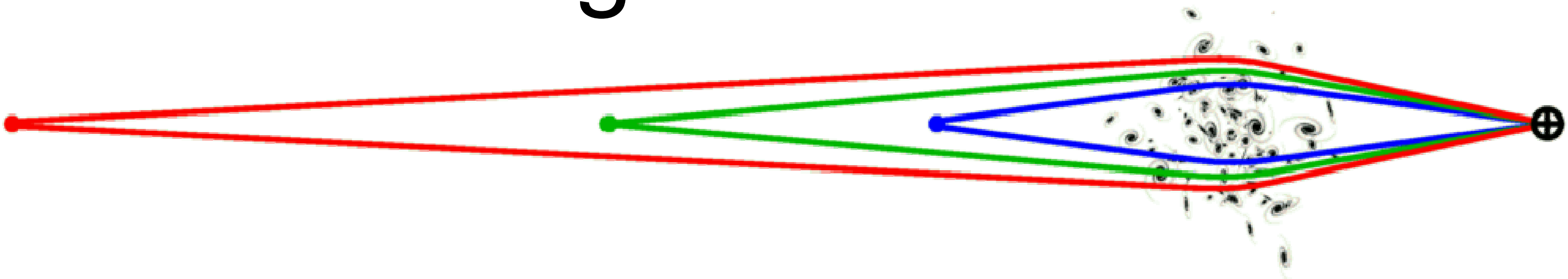
WIDE-FIELD INFRARED SURVEY EXPLORER



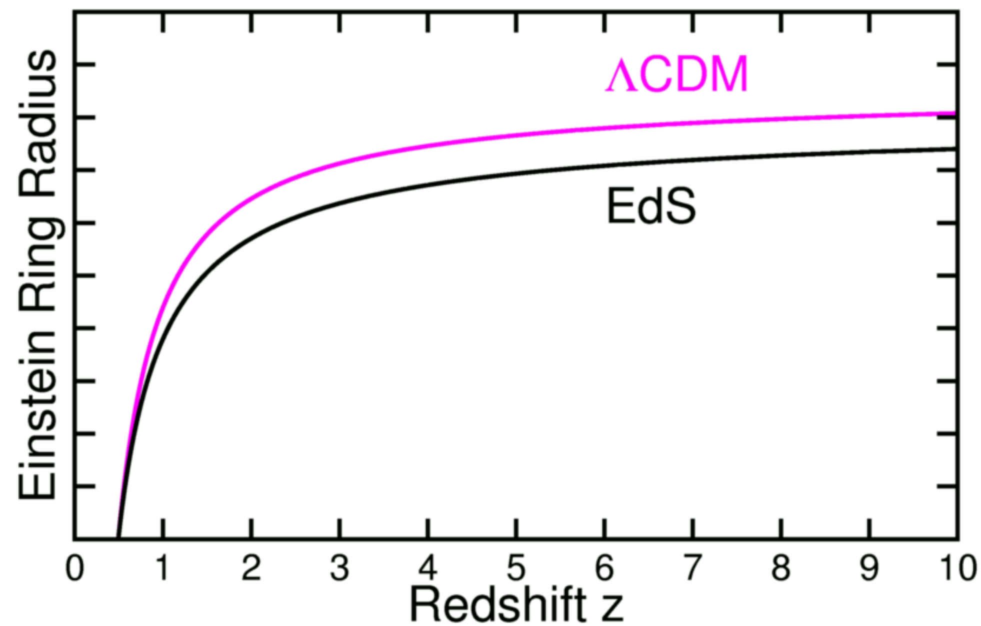
I am the PI on a MIDEX called WISE, an all-sky survey in 4 bands from 3.3 to 23 μm. WISE will find and study the closest stars to the Sun, the most luminous galaxies in the Universe, and also map the large-scale structure out to redshift z=1, covering the era when the late ISW effect should be generated.

WISE will fly in 2009, if funding is assured, but NASA needs $$$.

Einstein Ring Radius vs Distance

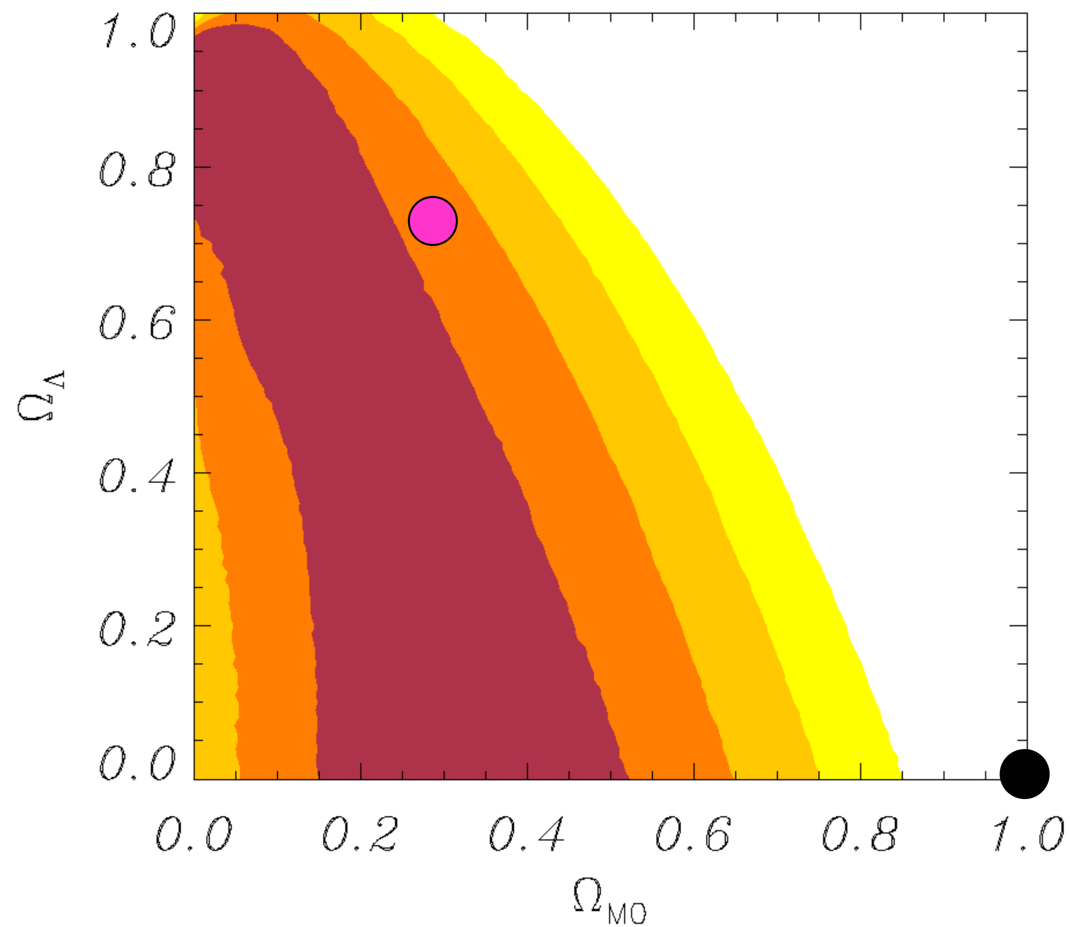


- Radius depends on distance.
- Distance depends on redshift and the geometry of the Universe.



Can be used to measure Universe

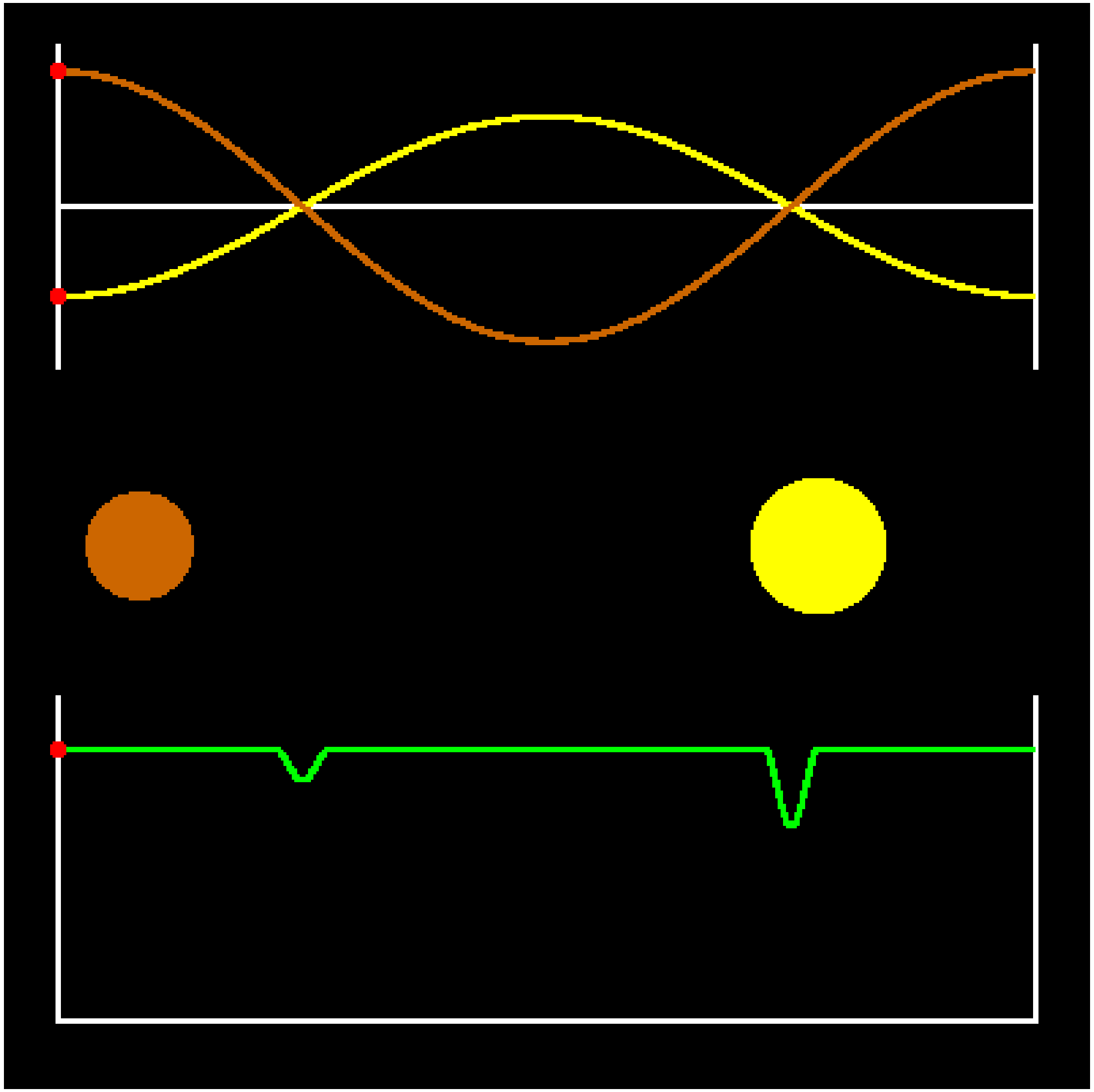
- 4 arcs with well-known redshifts in Abell 2218.
- These arc radii agree more-or-less with the accelerating Universe from SNe.



Soucail et al., 2004, astro-ph/0402658

DIRECT: $H_o = 61 \pm 4$(?!)

- Double-lined spectroscopic eclipsing binary in M33.
- Δv and period give orbit size in meters.
- Eclipse duration gives star size over orbit size.
- Flux and color give angular size.
- Distance in meters follows.
- Albedo uncertainty not included and probably dominant.

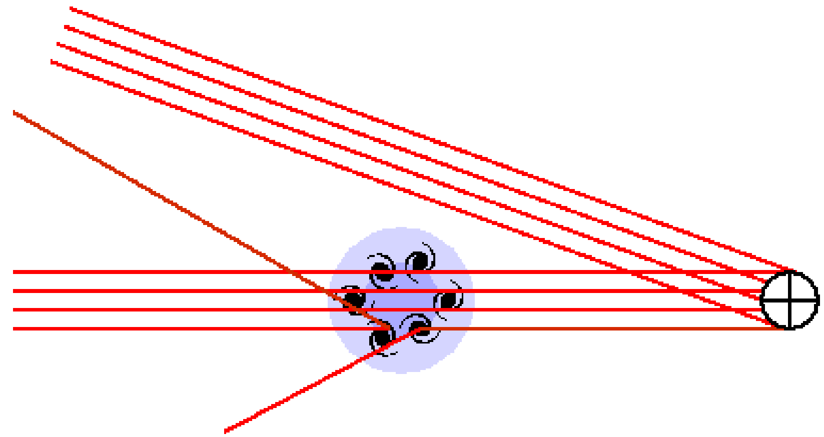


Bonanos et al., astro-ph/0606279

Cepheids in NGC 4258

- Circumnuclear disk of masers.
- Angular radius, proper motion and radial velocity range give distance in meters.
- Cepheid recalibration gives
  - $H_o = 74 \pm 3_{stat} \pm 6_{sys}$ km/s/Mpc.
- Macri et al., astro-ph/0608211
- Now 61 vs 74 is considered newsworthy.
  - Much better than the old 50 vs 100 Hubble wars.

SZ effect in Clusters of Galaxies



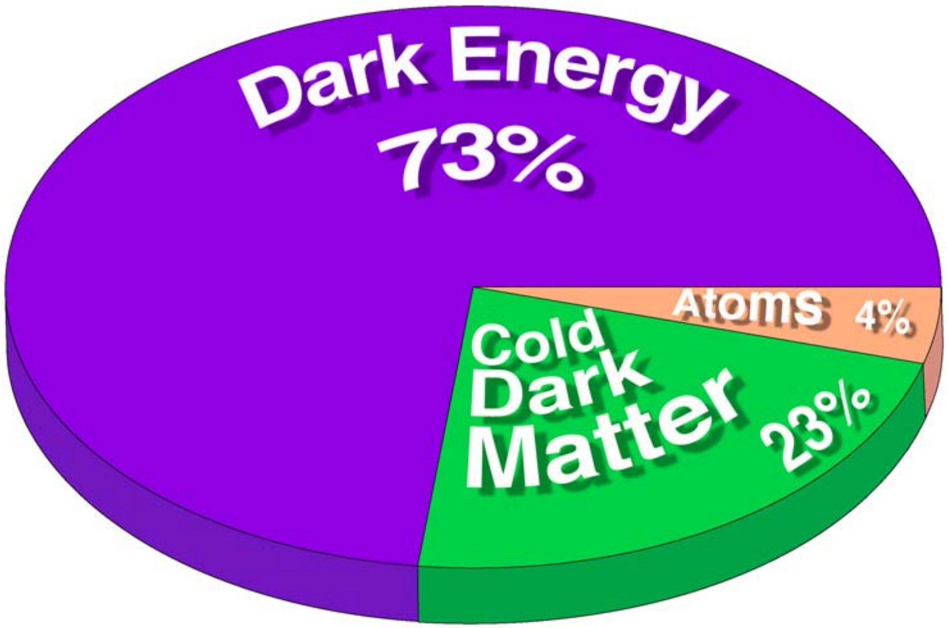
- X-rays give T_e, θ, and n_e^2R.
- SZ effect gives $T_e n_e R$.
- $(SZ)^2/I_x f(T_e)$ gives R.
- R/θ gives distance in meters.
- $H_o = 76.9{+3.9}{-3.4}_{stat}{+10.0}{-8.0}_{sys}$ km/s/Mpc

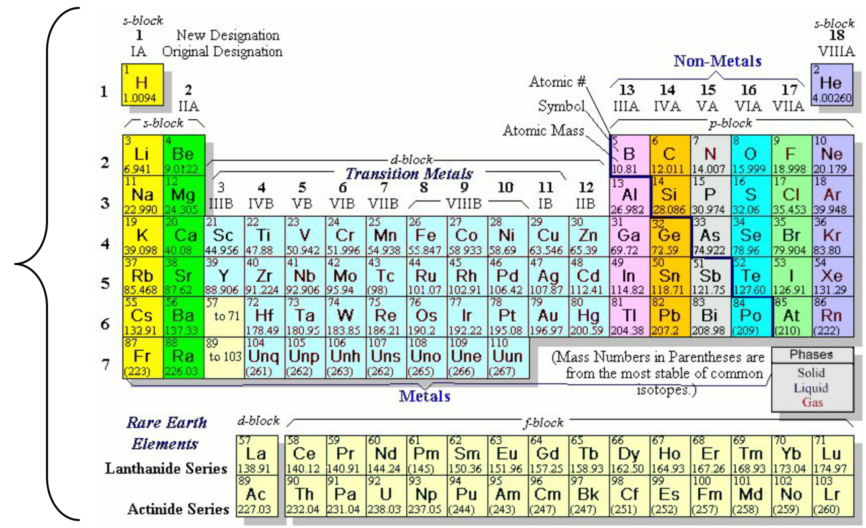
Bonamente etal, astro-ph/0512349

Something really funny

- A Sydney Harris cartoon: Cosmology Marches On
  - A caveman asks: “Where the hell does it does it all come from?” while looking at the sky.
  - A modern astronomer asks “Where the hell does it does it all come from?” while sitting at a desk ignoring his telescope.
- Nothing really funny
  - Now we ask “Where the hell does it does Λ come from?”

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





Conclusion: A Century of Progress

- From 1 fact in 1906 to hundreds of facts now.
- From the unnecessary introduction of Λ in 1917 to strong evidence for dark energy now.
  - Supernova D_L vs z.
  - CMB & Ho, CMB & SNe, CMB & LSS Γ, CMB & baryon oscillations, multiple arcs in A2218, CMB & LSS late integrated Sachs-Wolfe effect.
- A simple 6 parameter ΛCDM model fits all of these facts remarkably well.
- But are we ignoring something? Are the new “CN lines” out there?