Recent CMB Results

by

Ned Wright (UCLA)

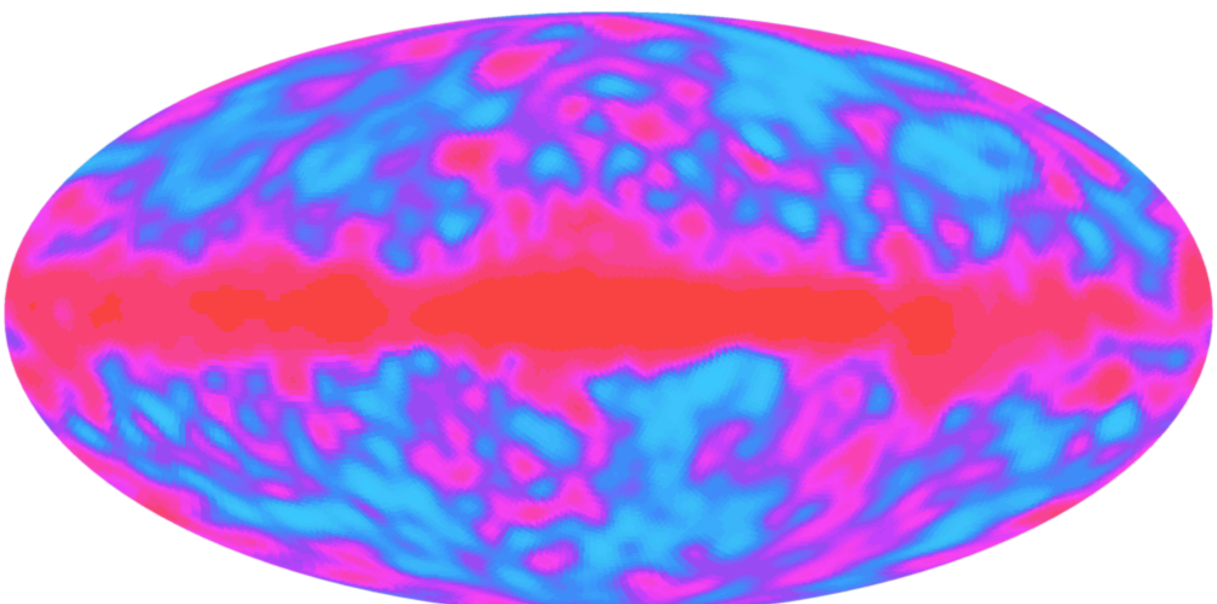
- http://www.astro.ucla.edu/~wright/intro.html
- http://www.astro.ucla.edu/~wright/cosmolog.htm
- http://www.astro.ucla.edu/~wright/CMB-DT.html
- http://map.gsfc.nasa.gov

A Big Media Splash in 1992:

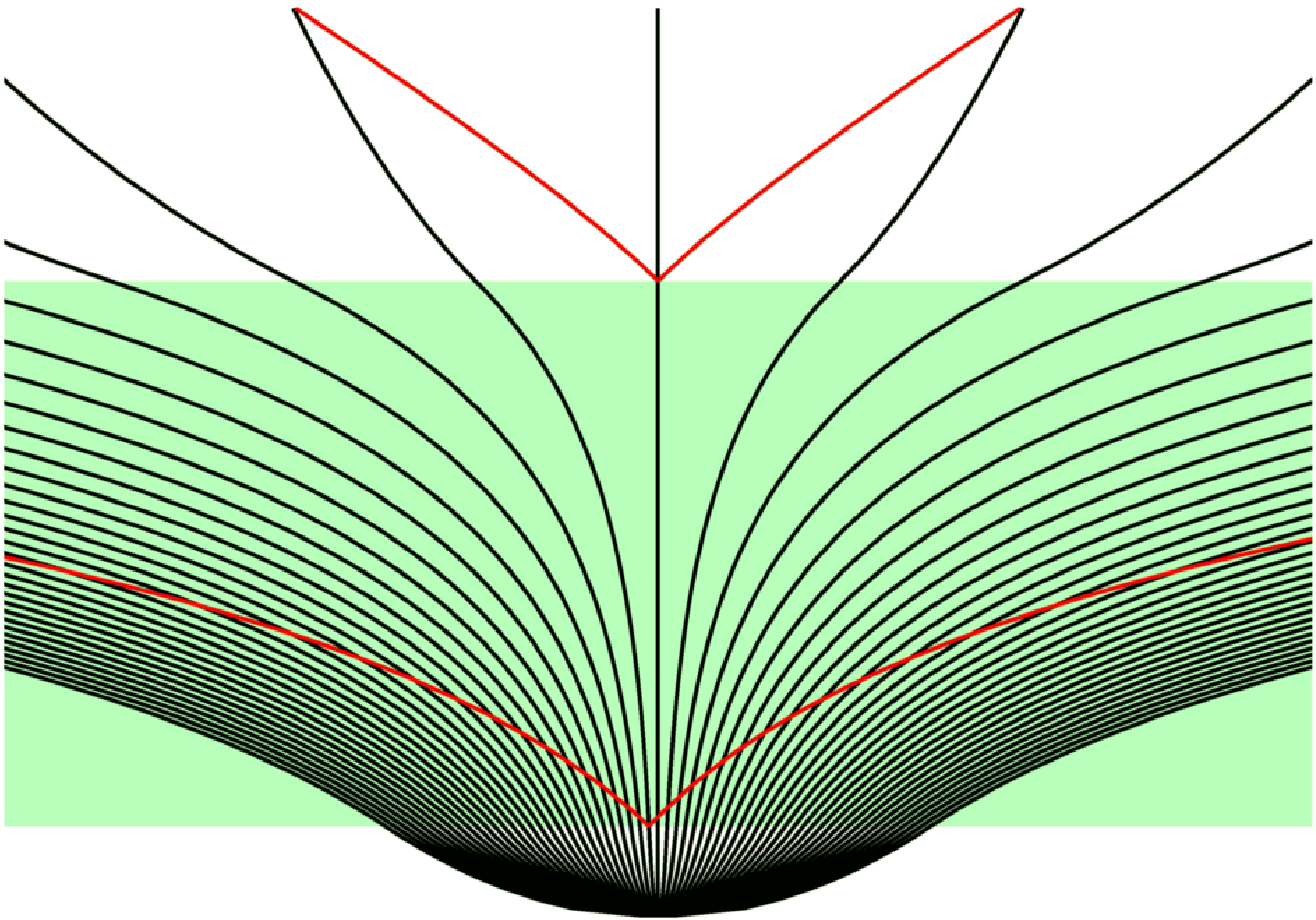
THE TIMES

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.”

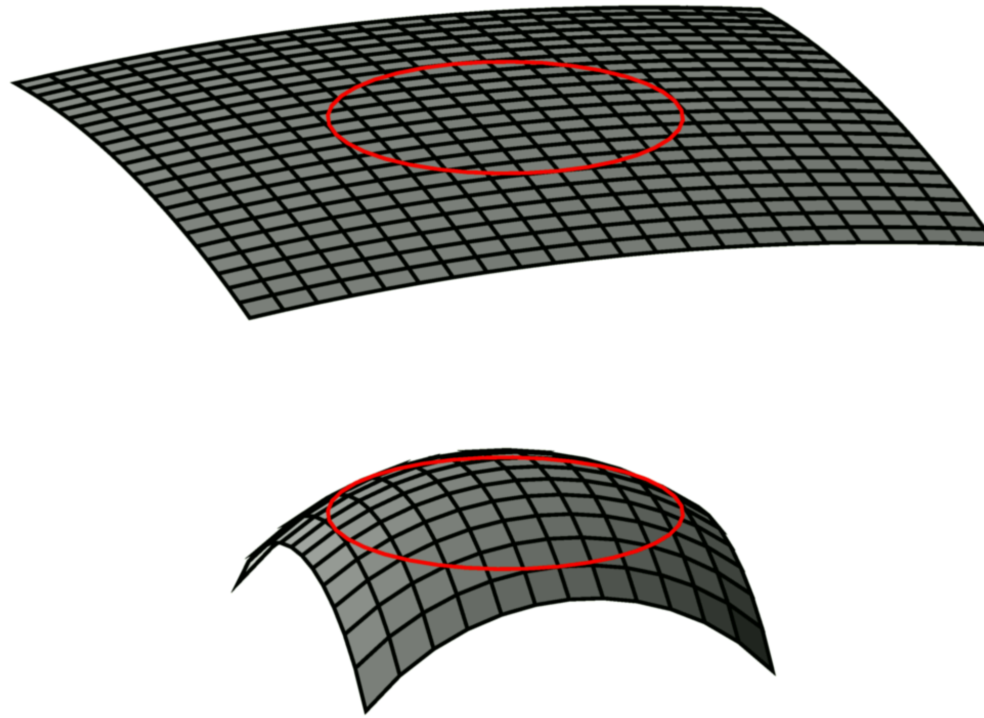


Large Λ & exponential growth during inflation



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.

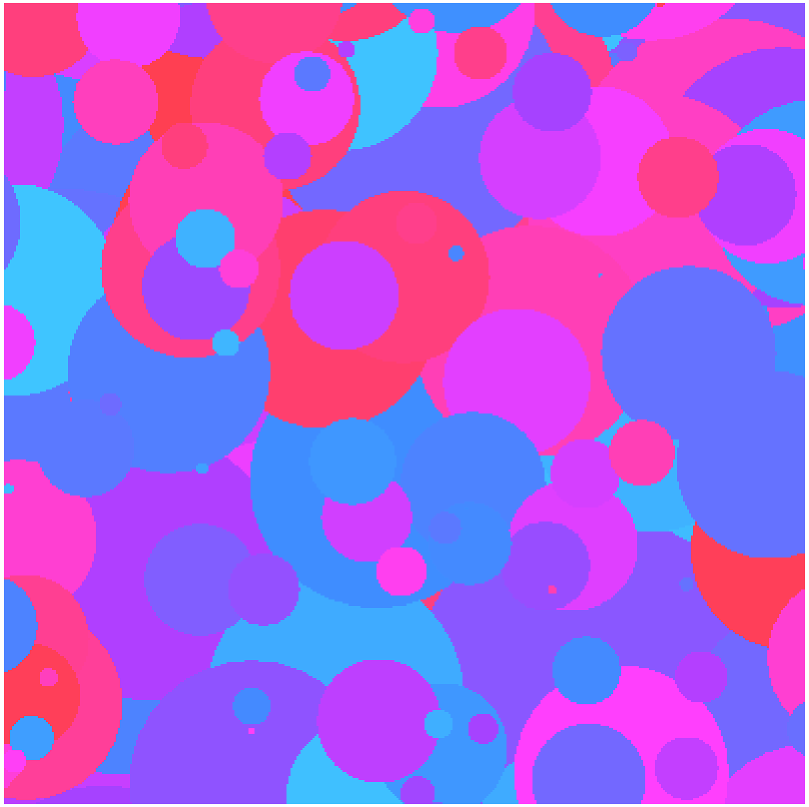


Inflationary Scenario

- The exponential growth during the period when there was a non-zero vacuum energy is called “inflation”.
- Inflation “postdicts” solutions to the flatness-oldness and horizon problems.
- It also solves the “monopole” problem.
- Does it predict anything that we can test?

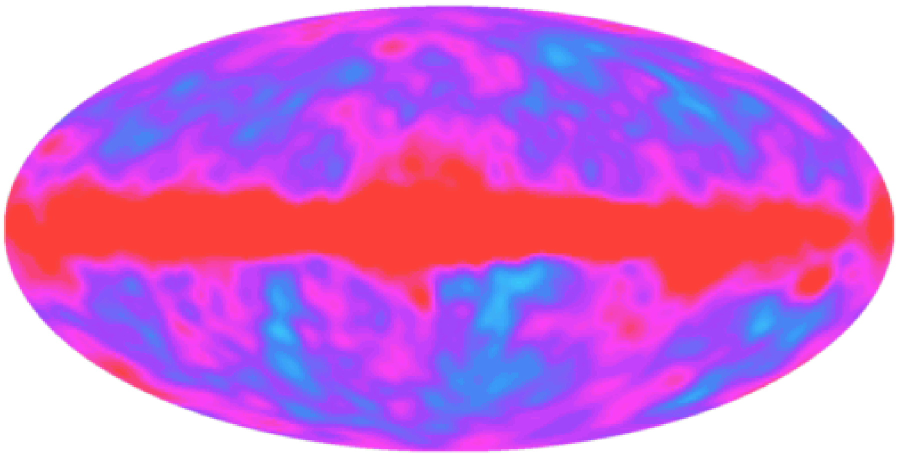
Quantum Fluctuations get Very Big

- QFs occur uniformly throughout space-time.
- Their future light-cones expand beyond the observable Universe.
- New QFs continue to add small-scale structure.

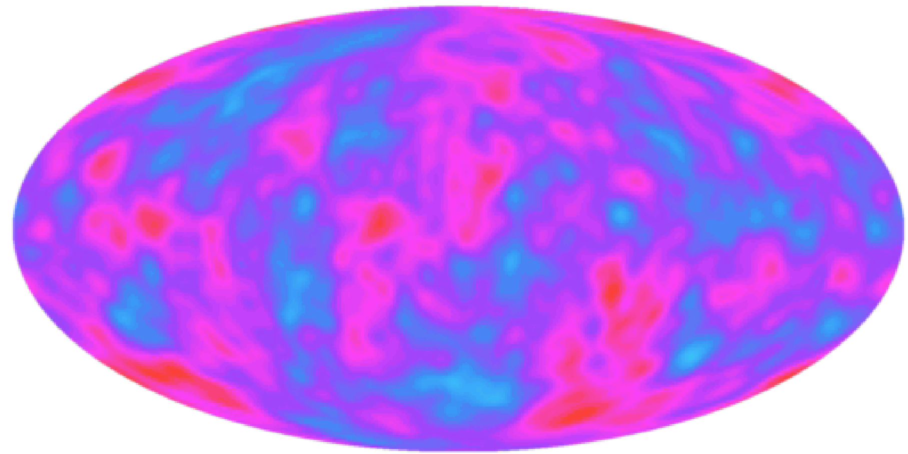


COBE DMR vs EPAS

COBE Data

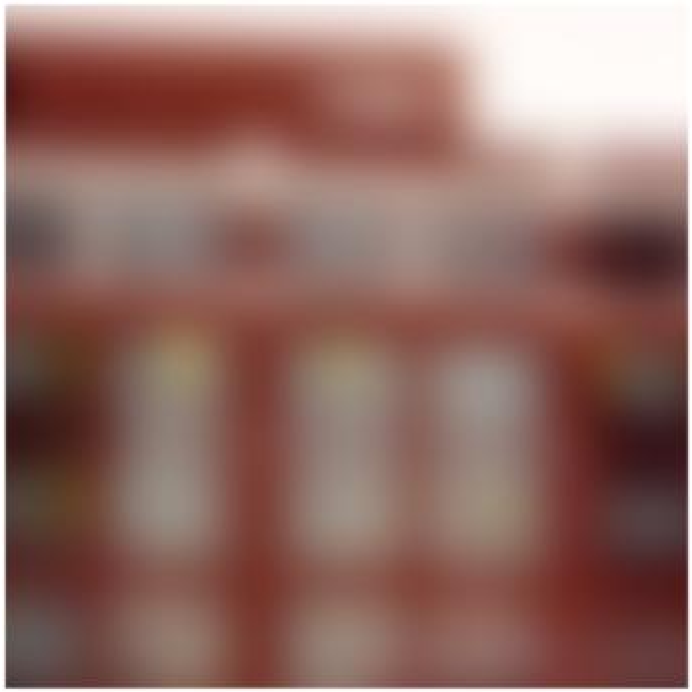


Equal Power on All Scales Model



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

COBE View was Blurry



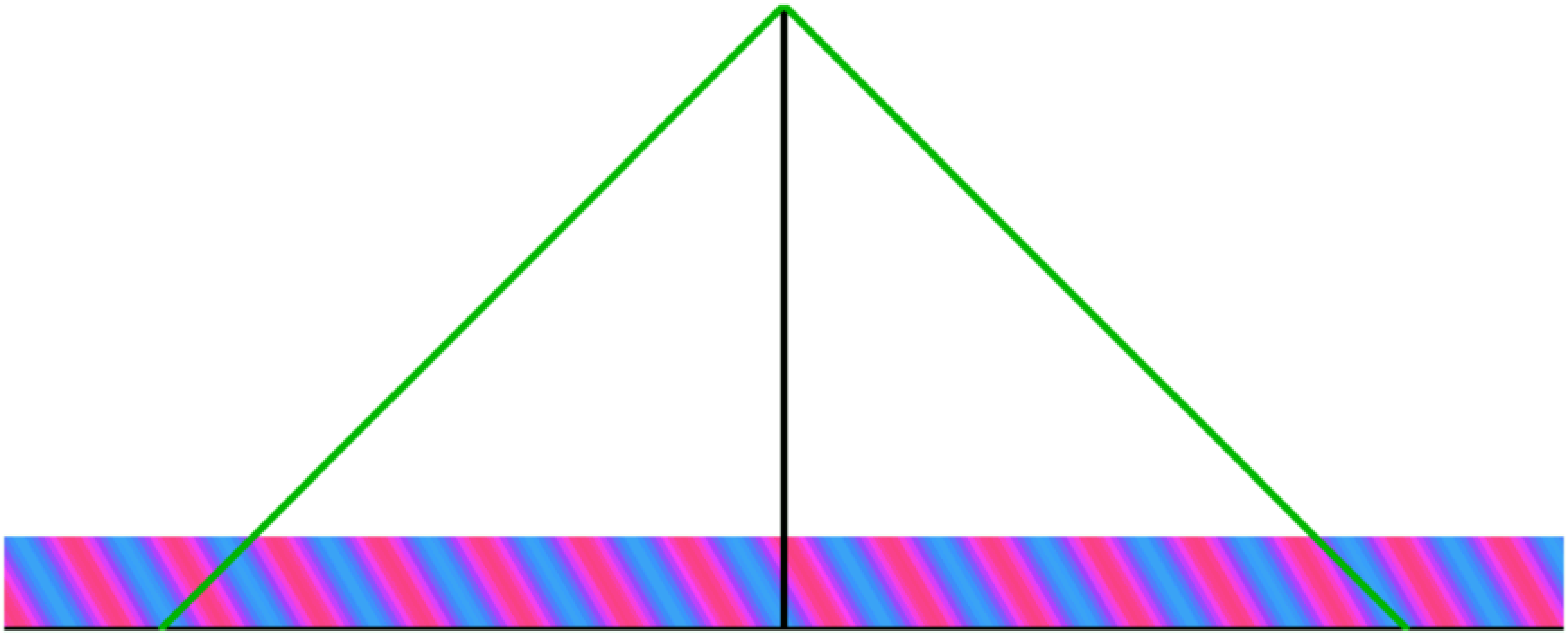
Sometimes higher resolution...

reveals the secret of the Universe

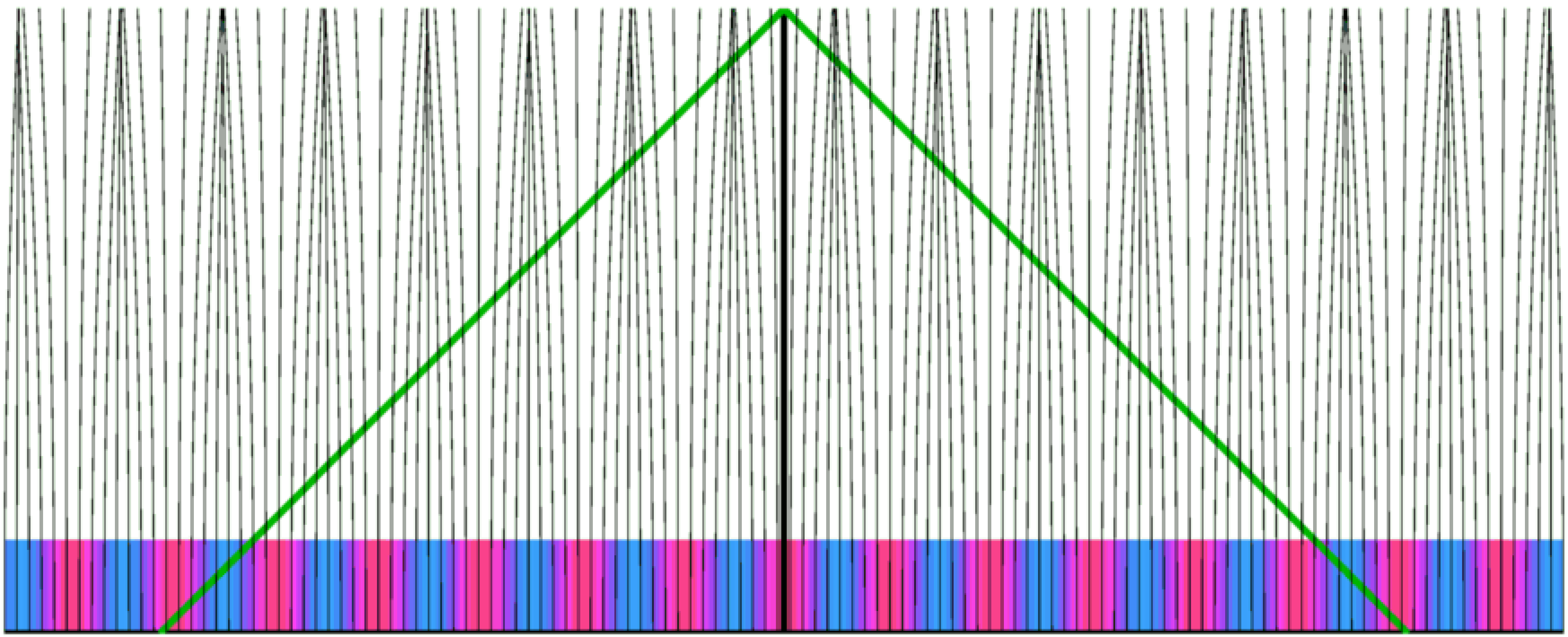
Two Fluids in the Early Universe

- 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

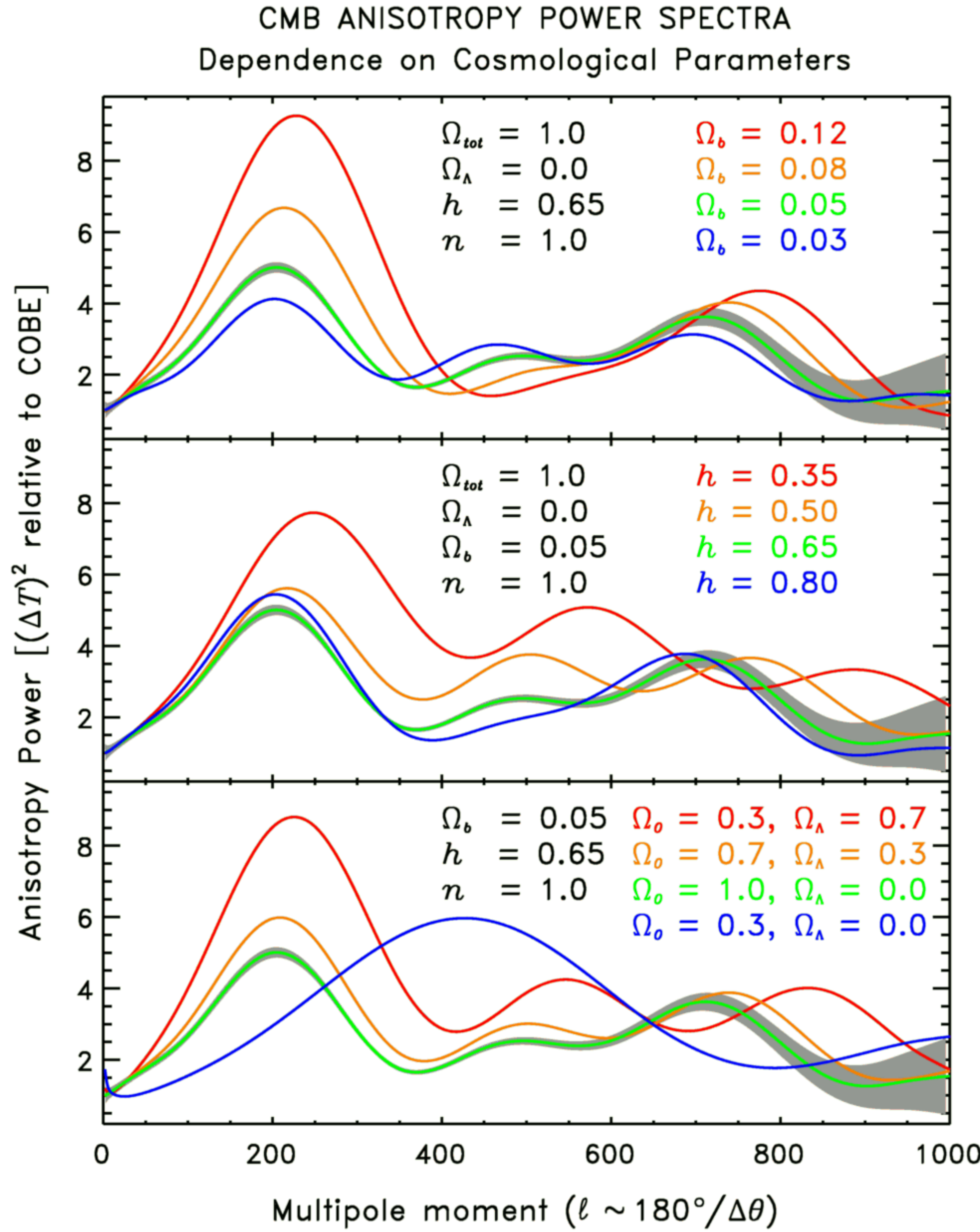


Interference at last scattering

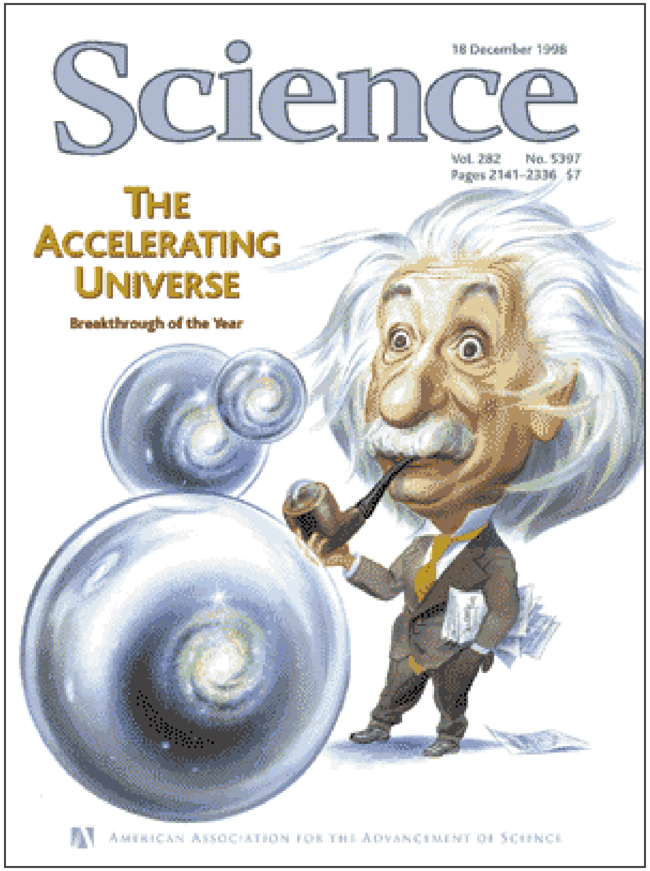
- For the wavelength illustrated [1/2 period between the Big Bang and recombination], the denser = hotter effect and potential well = cooler effect have gotten in phase.
- For larger wavelengths they are still out of phase at recombination.

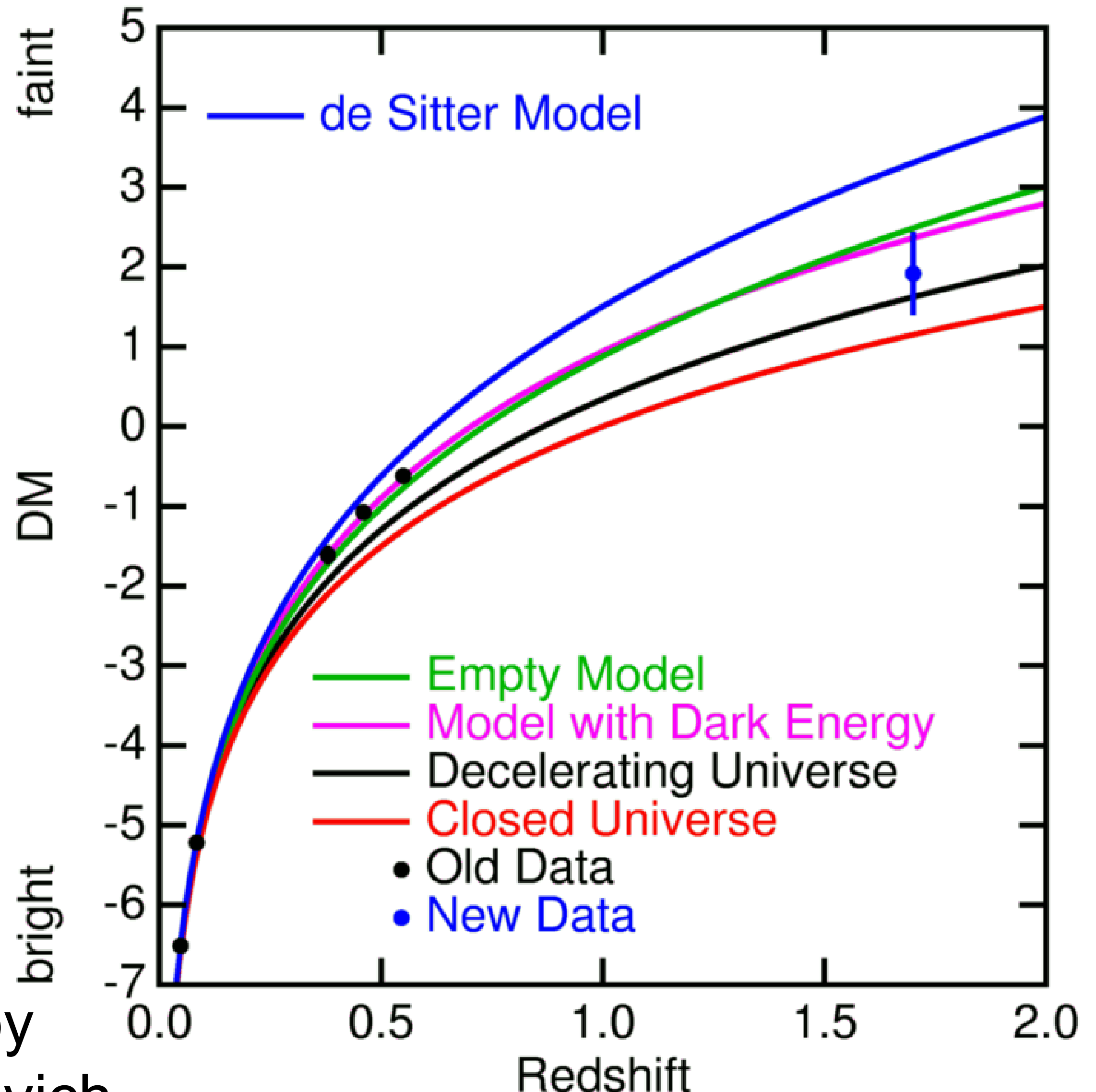
Many parameters to measure

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



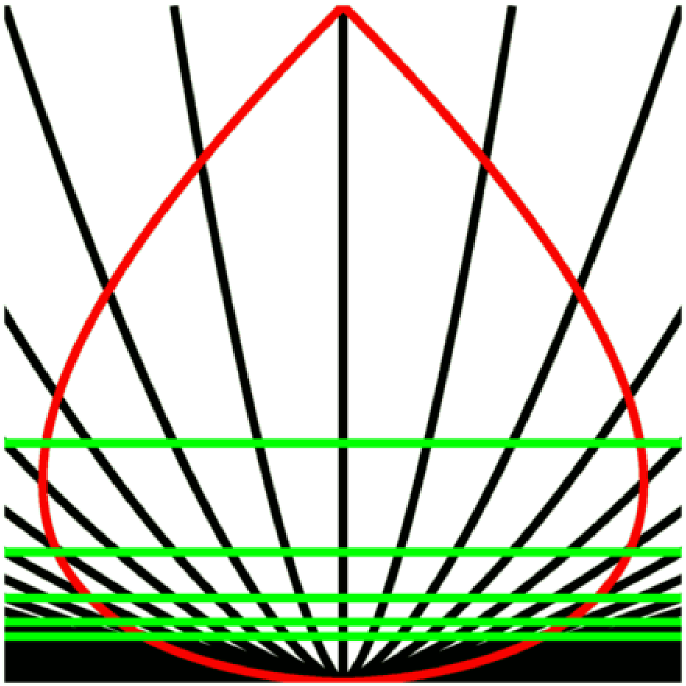
Accelerating Universe: 1998





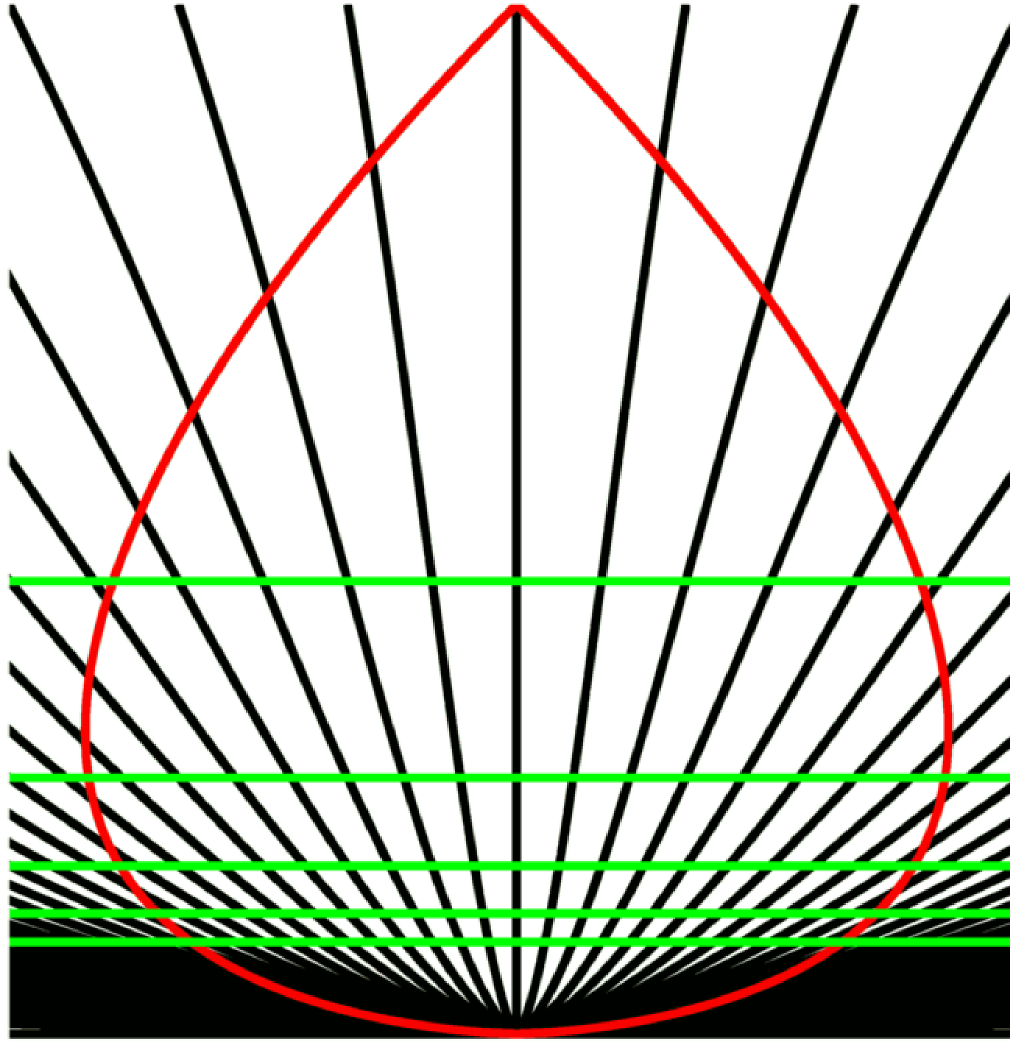
High z supernovae fainter than expected: see talks by Arlin Crotts & Peter Garnavich.

Acceleration causes Faintness



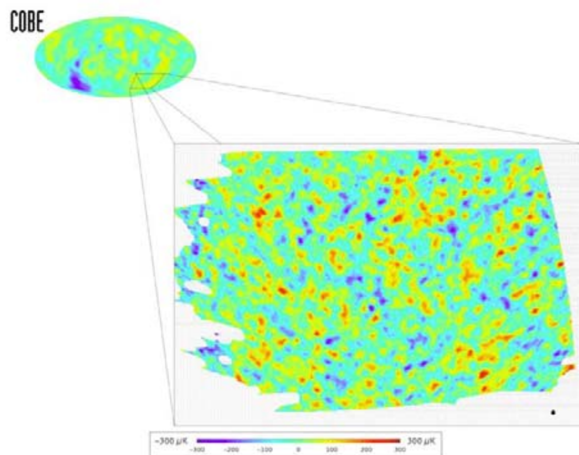
$\Omega = 1$

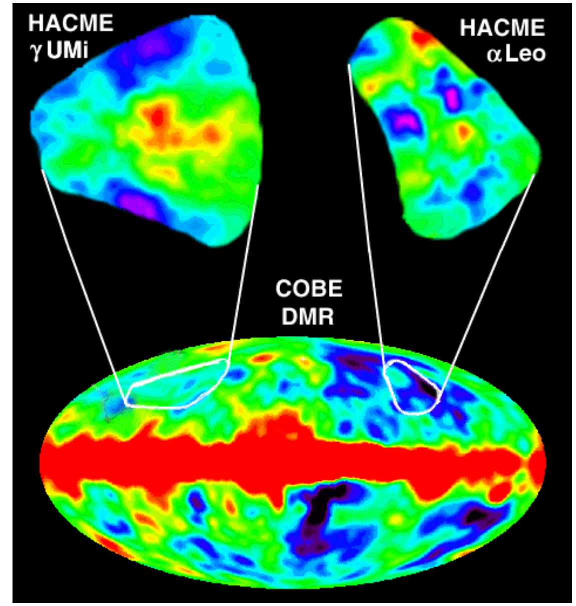
Without CC, Universe is younger, hence light travel time is smaller to any z, so SNe at z=1 are closer & thus brighter.

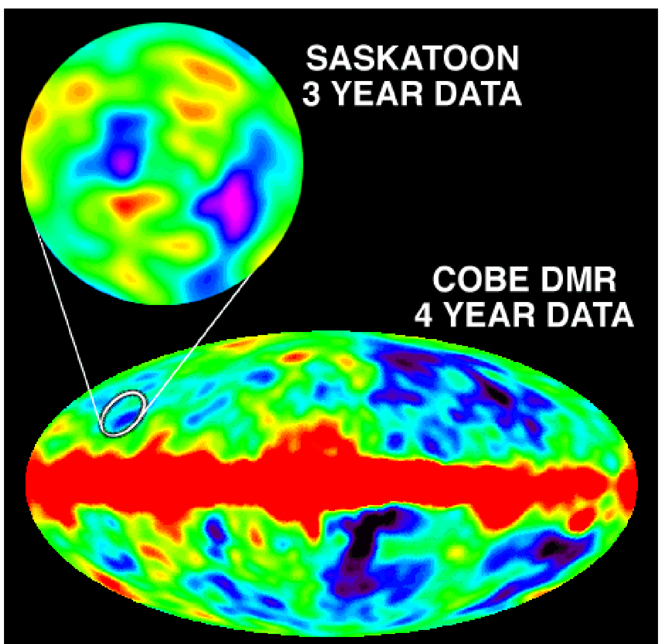


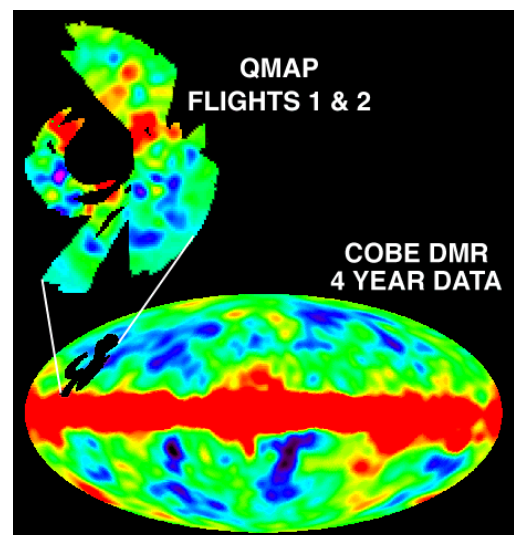
$\Omega = 0.25,\ \lambda = 0.75$

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

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

26-36 GHz

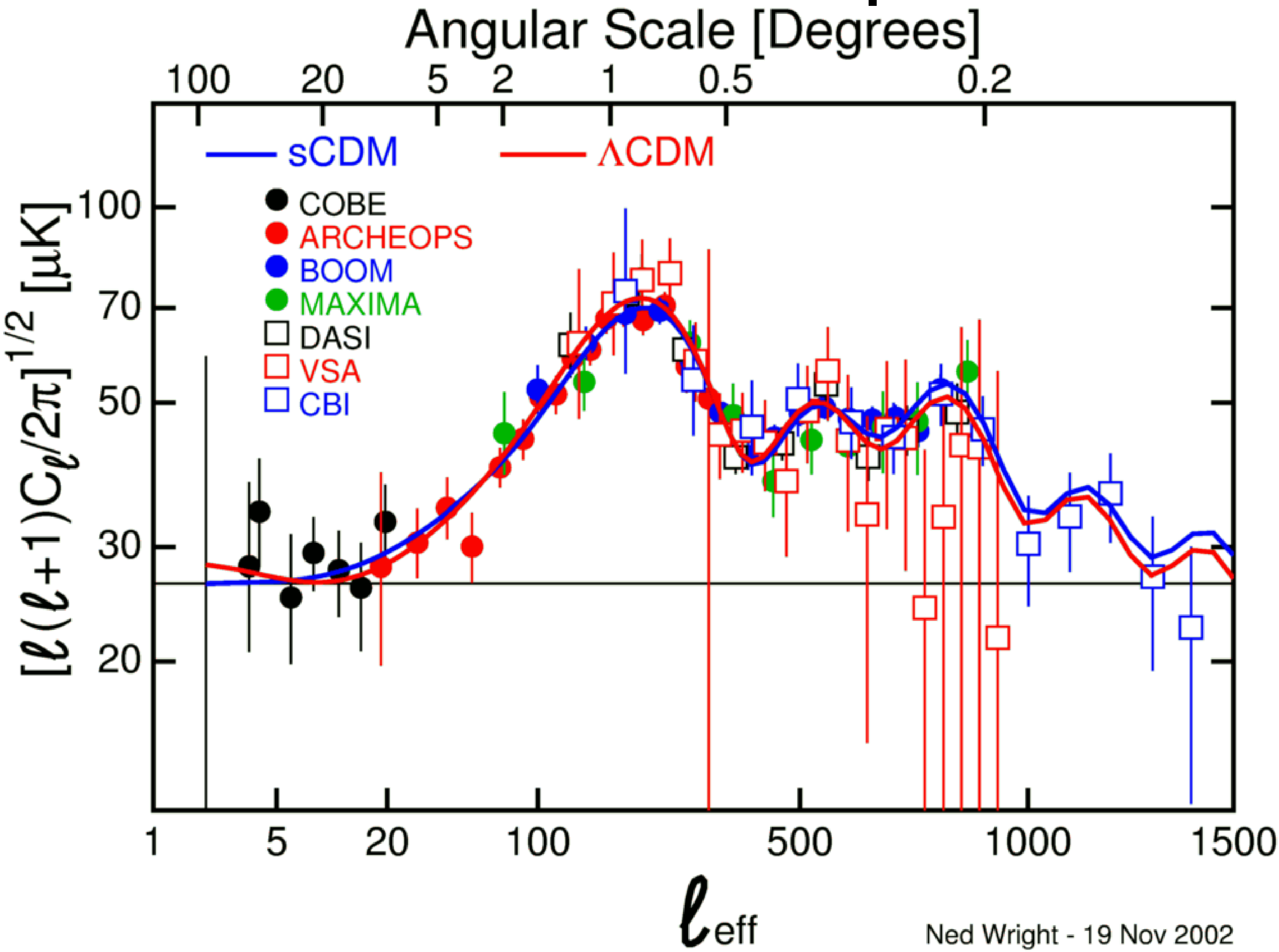
The Very Small Array

- 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

Cosmic Background Imager

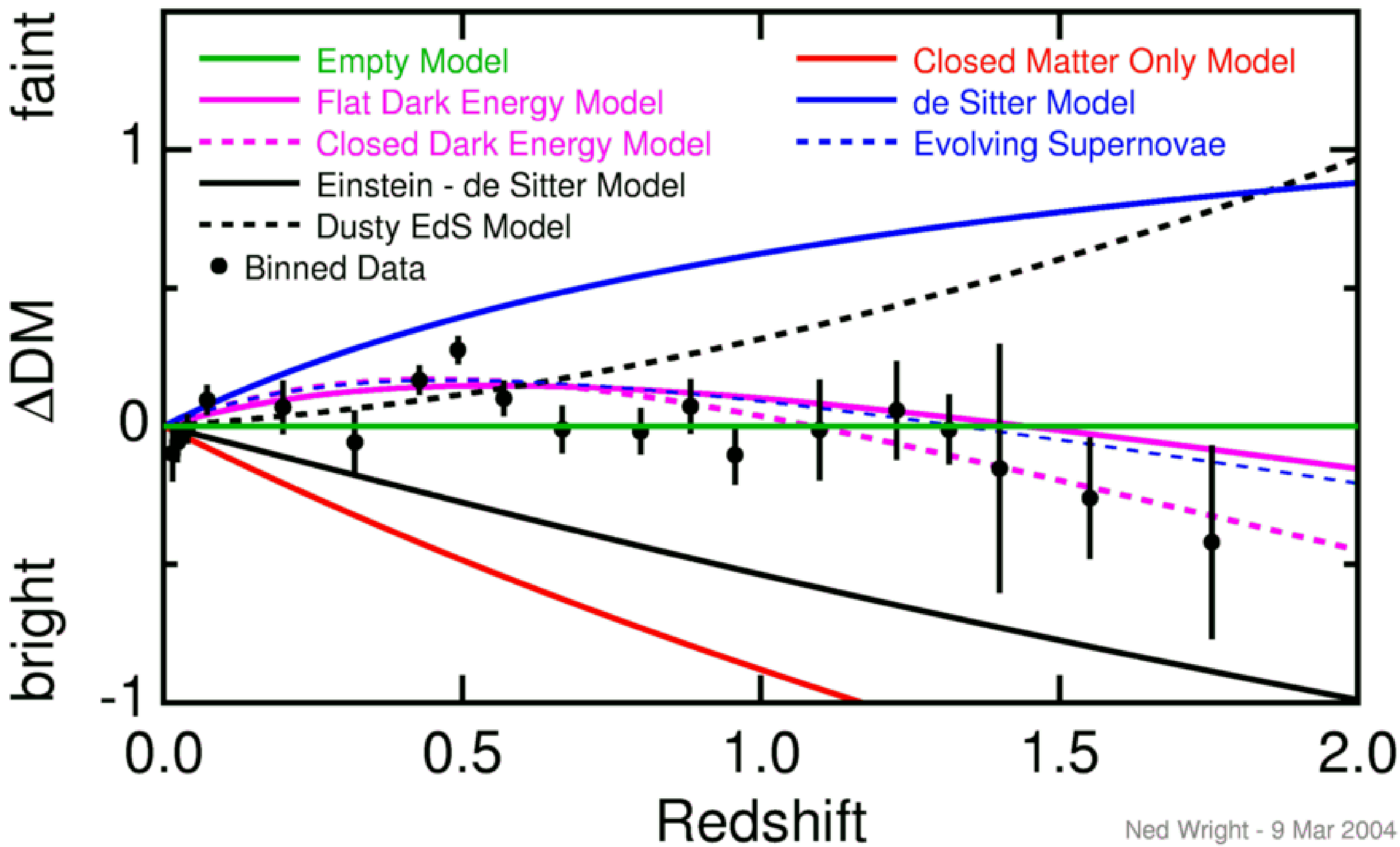
- Chile @ 5.08 km
- 13 antennae
- 26-36 GHz
- 10 GHz band
- 0.75^o FOV
- 0.075^o res
- Mosaic many FOV's together

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

Possible Systematic Errors in SNe

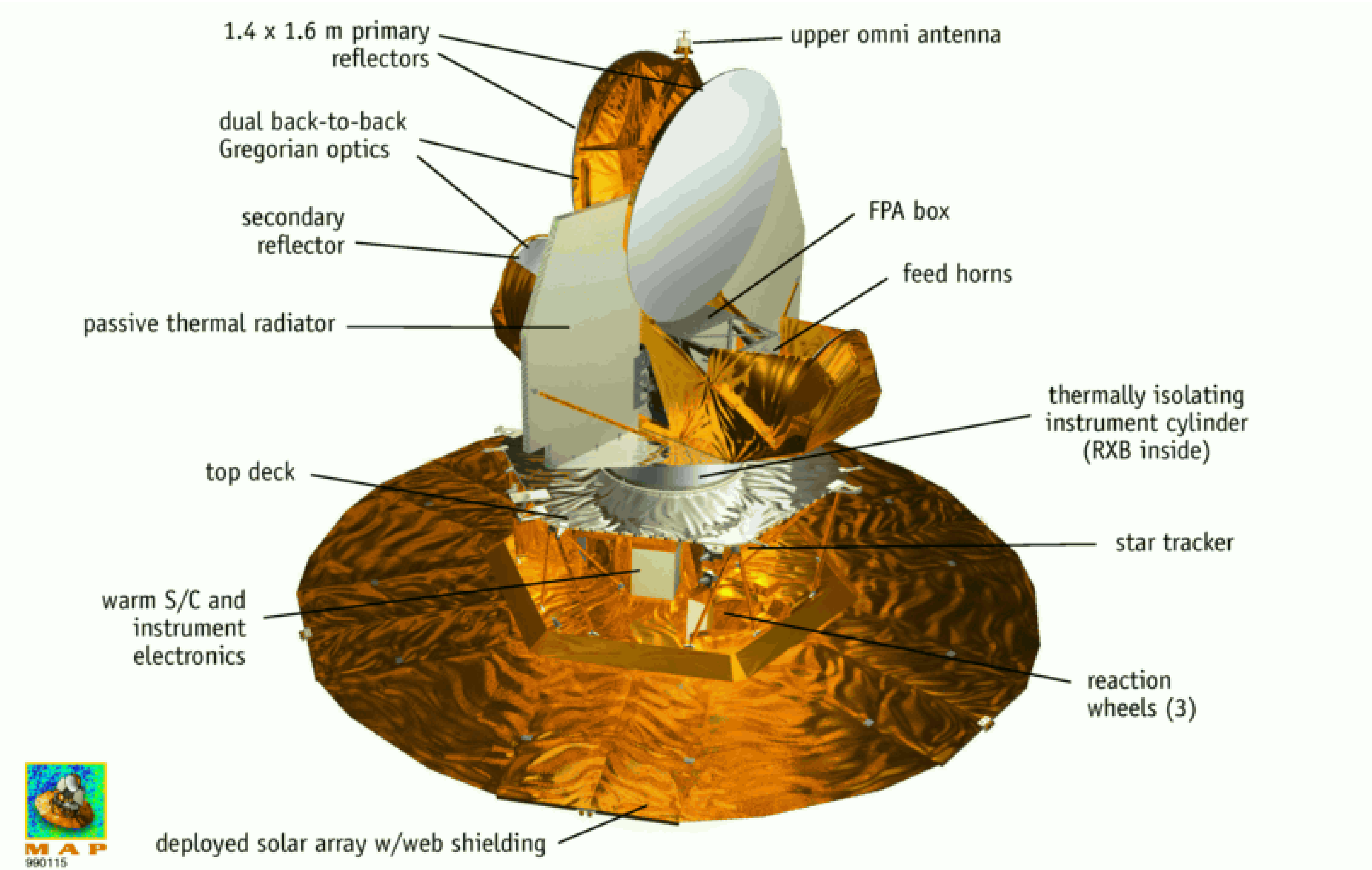


- Uniform comoving dust density is ruled out by highest z supernovae, but uniform physical density dust or exp(αt) evolution are better fits than ΛCDM.

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.

A New Cosmology Satellite

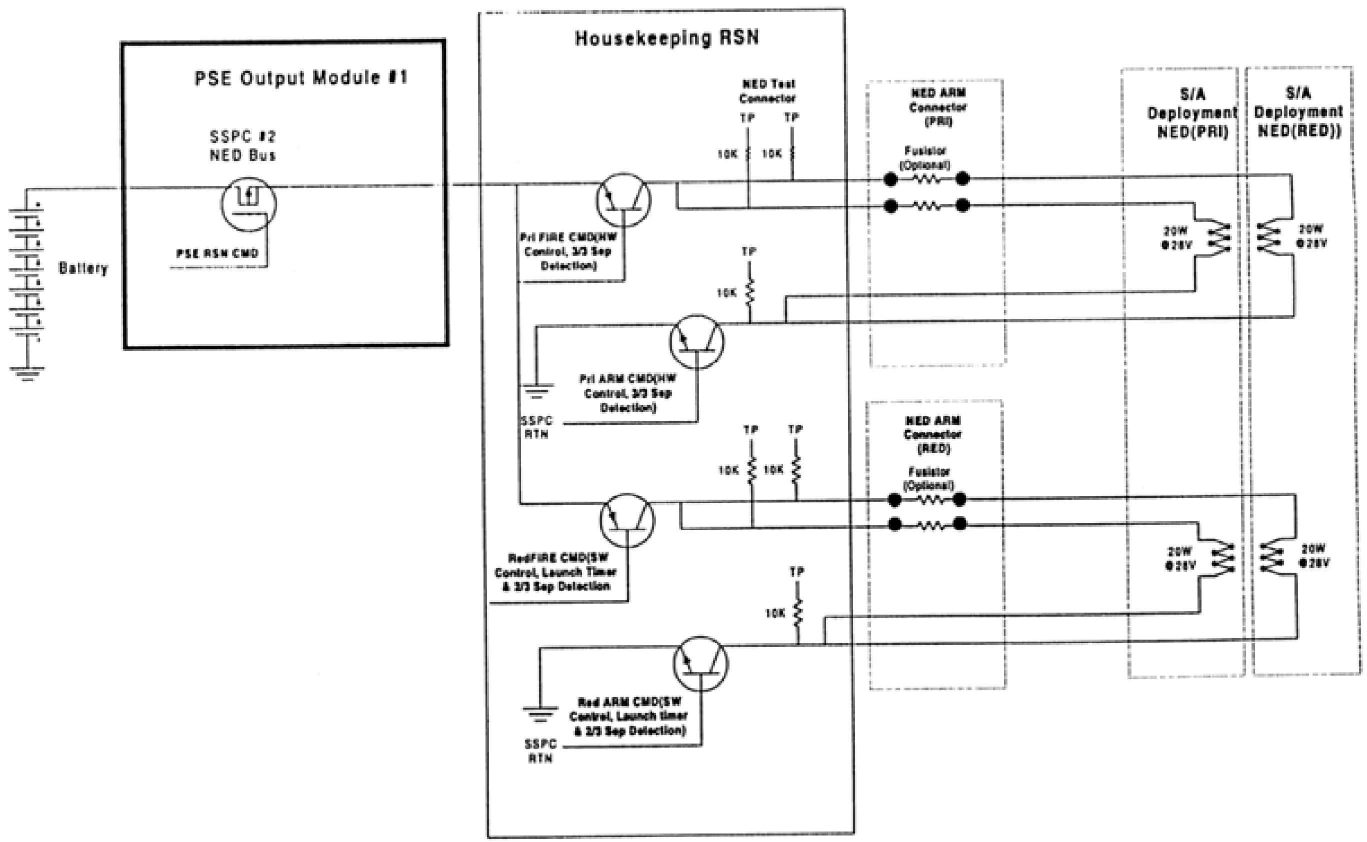


WMAP Science Working Group

WMAP Status on 30 Jun 2001

and WMAP has a NED Controller!

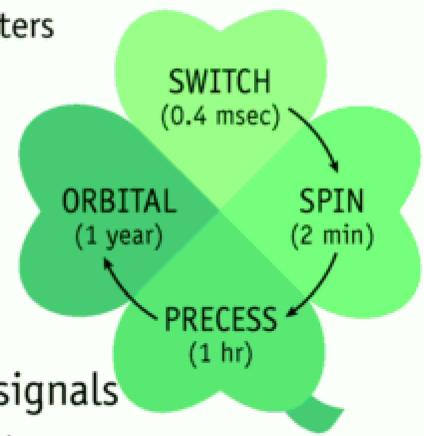
S/A Deployment NED Control



Systematic Error Control

SPIN-SYNCHRONOUS NON-SKY SIGNALS ARE THE LEADING CONCERN

- Minimize sensitivity of experiment to non-sky signals
  - –Minimize all observatory changes
    - L2 orbit; constant survey mode operations
    - minimize transmitter time; use make up heater
  - –Symmetric, rapidly switched, differential radiometers
  - –Rapid sky scanning (30% of sky per hour)

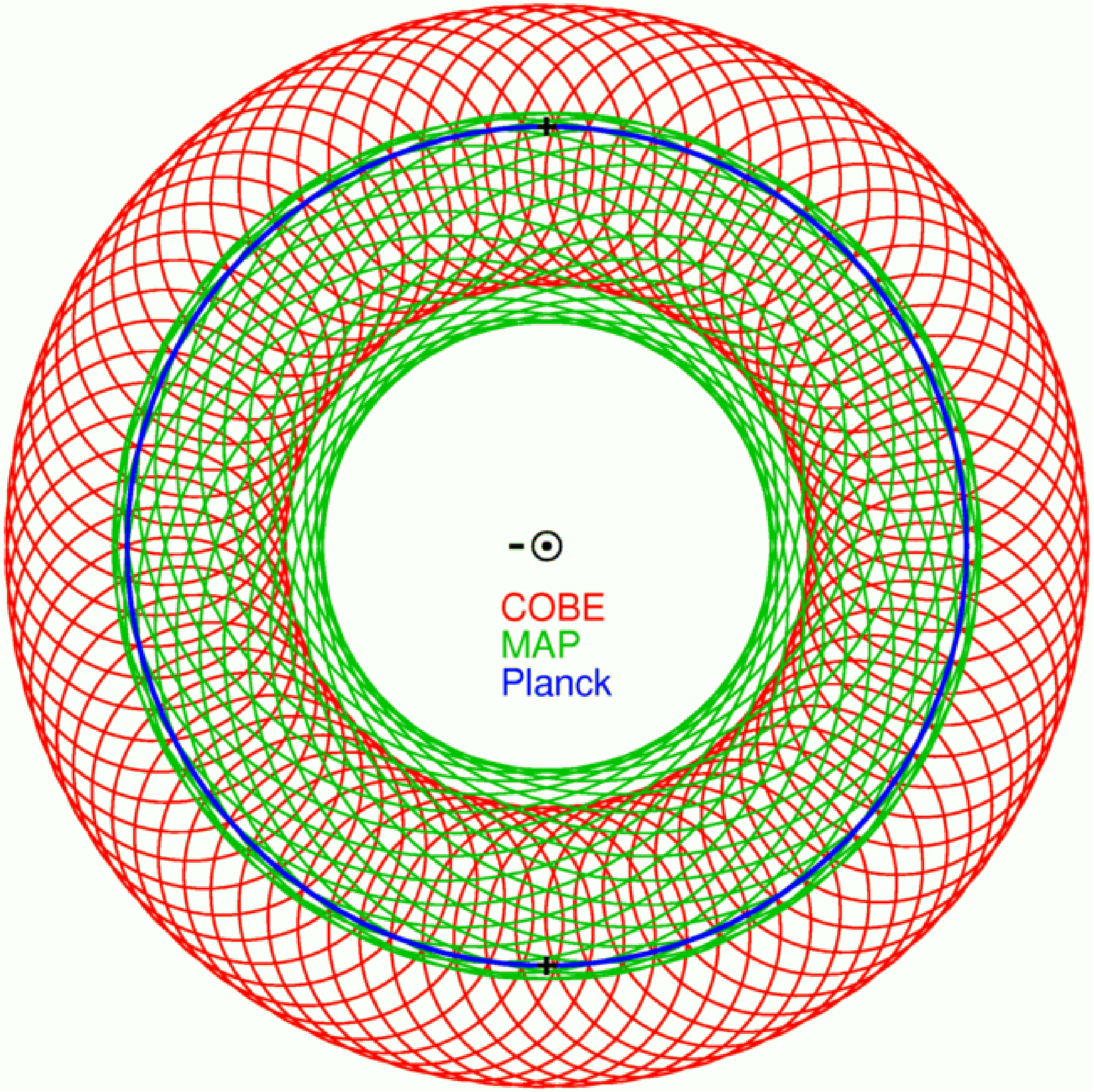


- Multiple modulation periods to isolate & identify systematic effects

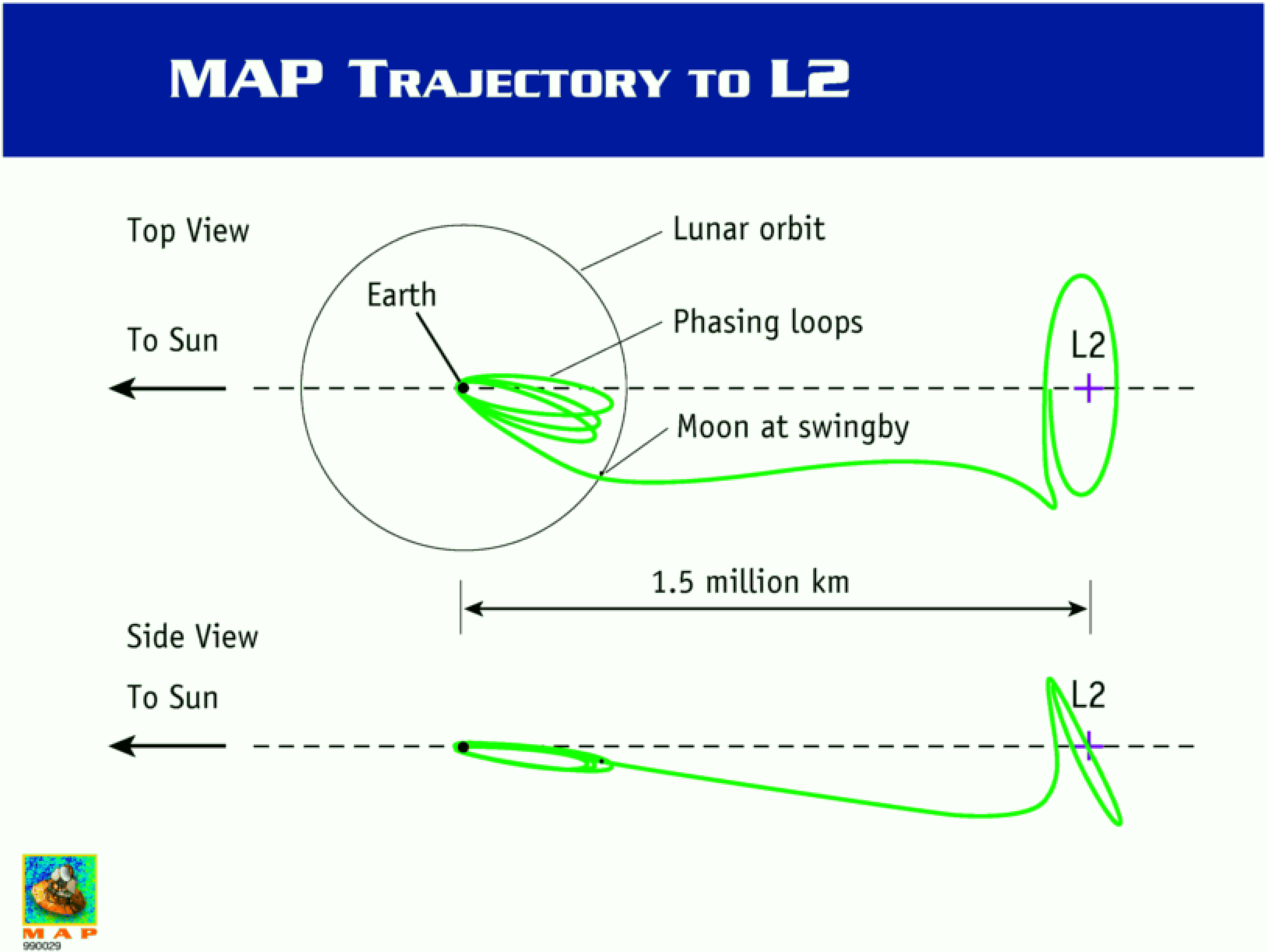
- Distinguish cosmic from non-cosmic sky signals
  - –5 frequencies to model and remove galactic signals
  - –Minimize stray diffracted signals from Earth, Sun, Moon
    - large edge taper; diffraction shielding
    - L2 orbit

MAP
990028a

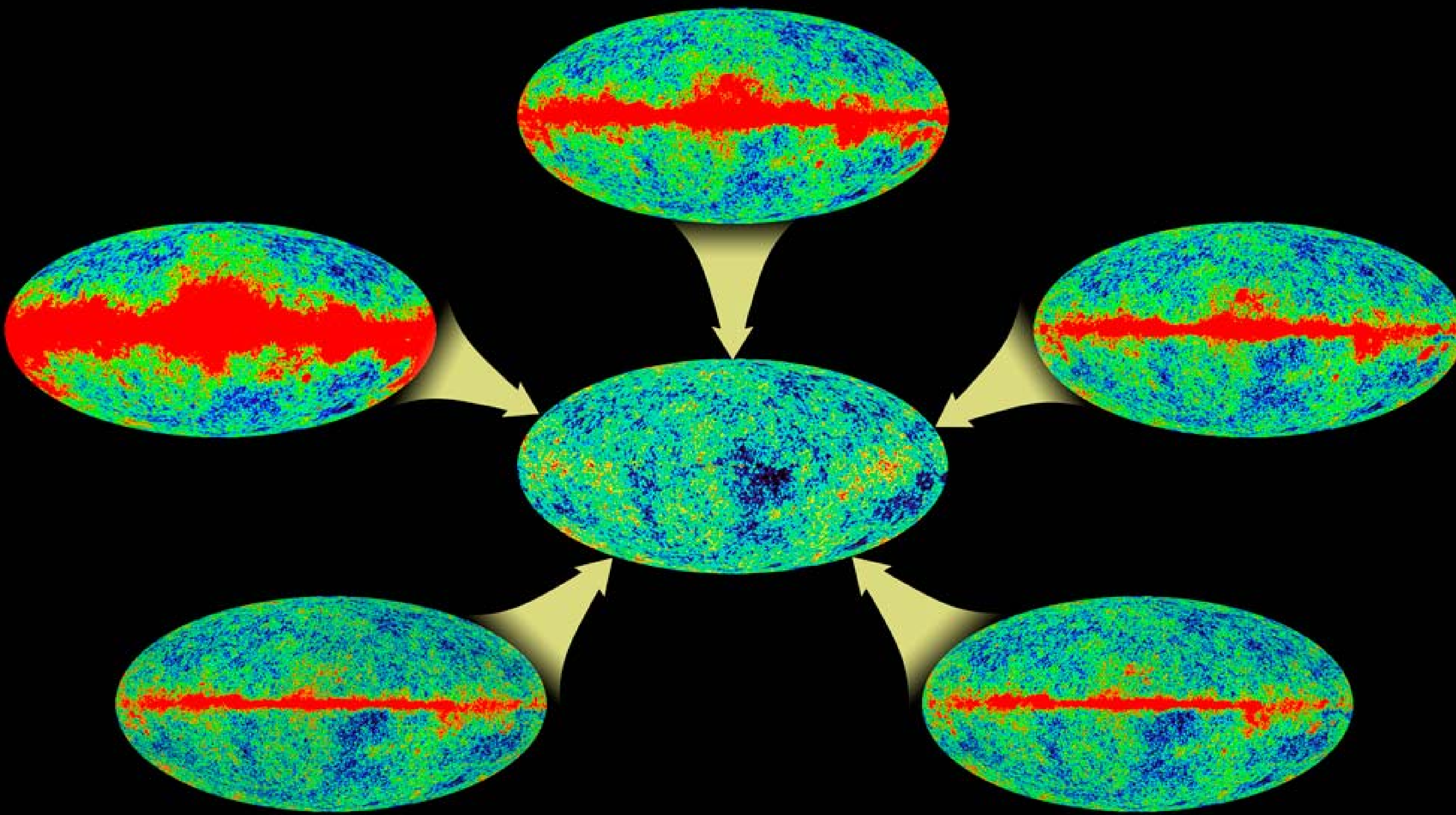
WMAP’s Scan Pattern like COBE’s



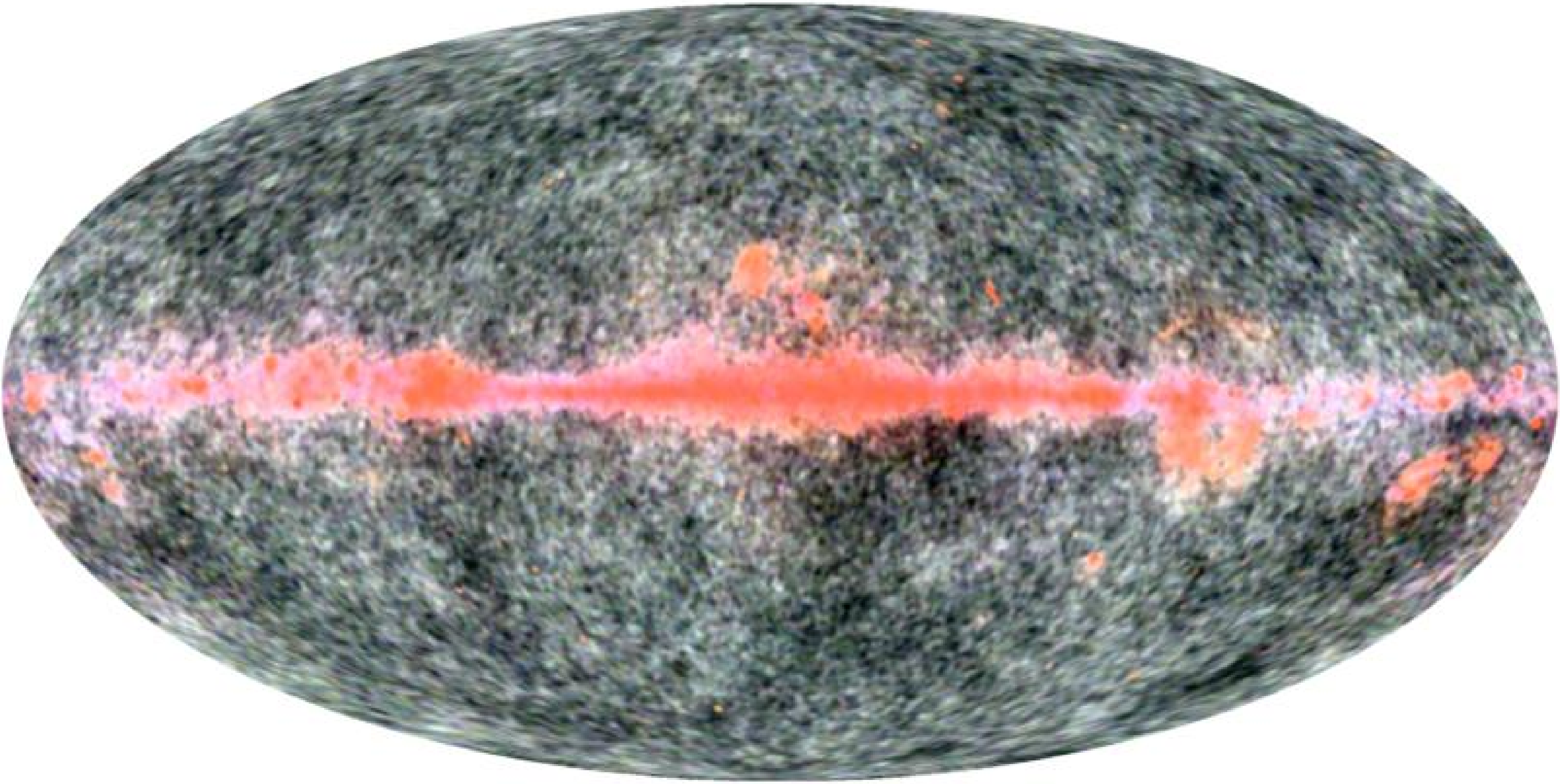
WMAP’s Orbit


MAP Trajectory to L2
Top View
Lunar orbit
Earth
Phasing loops
To Sun
L2
Moon at swingby
1.5 million km
Side View
To Sun
L2
MAP
990029

Combination to remove foreground

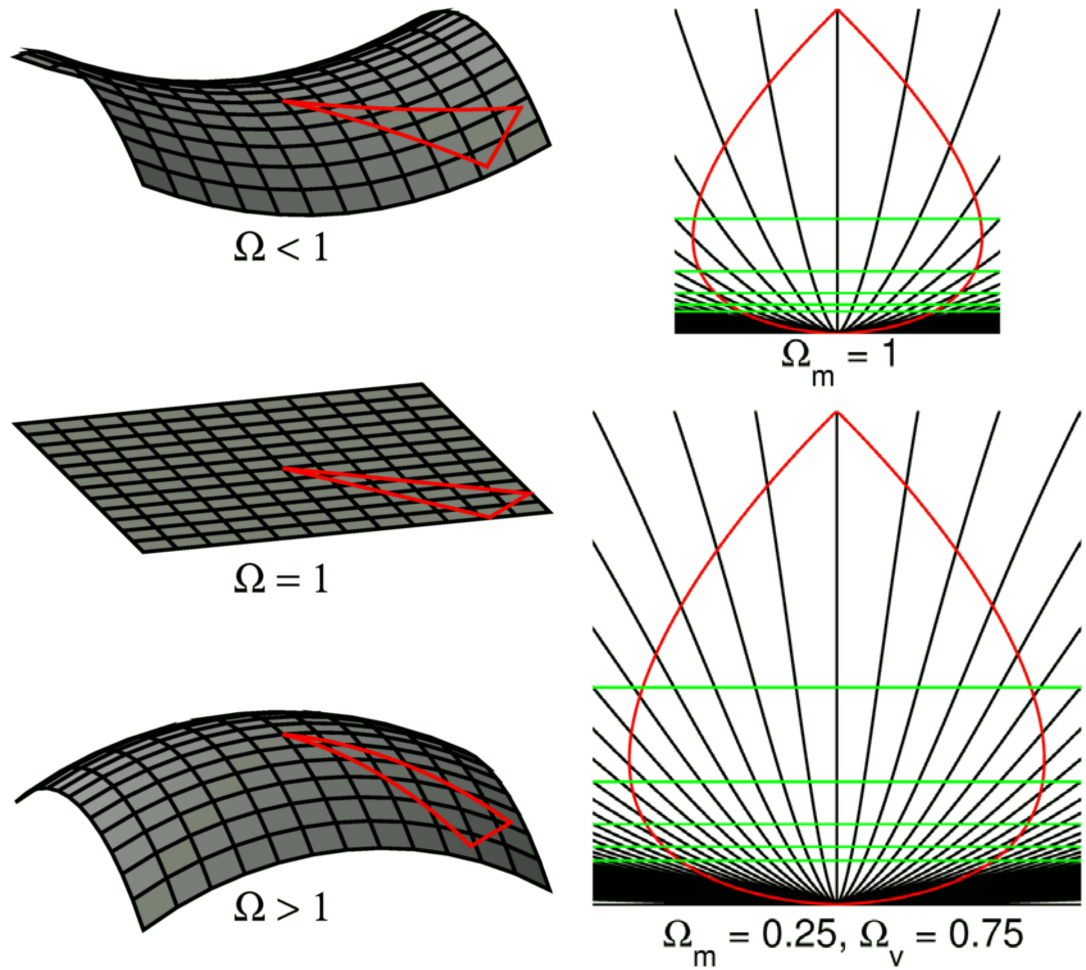


QVW as RGB

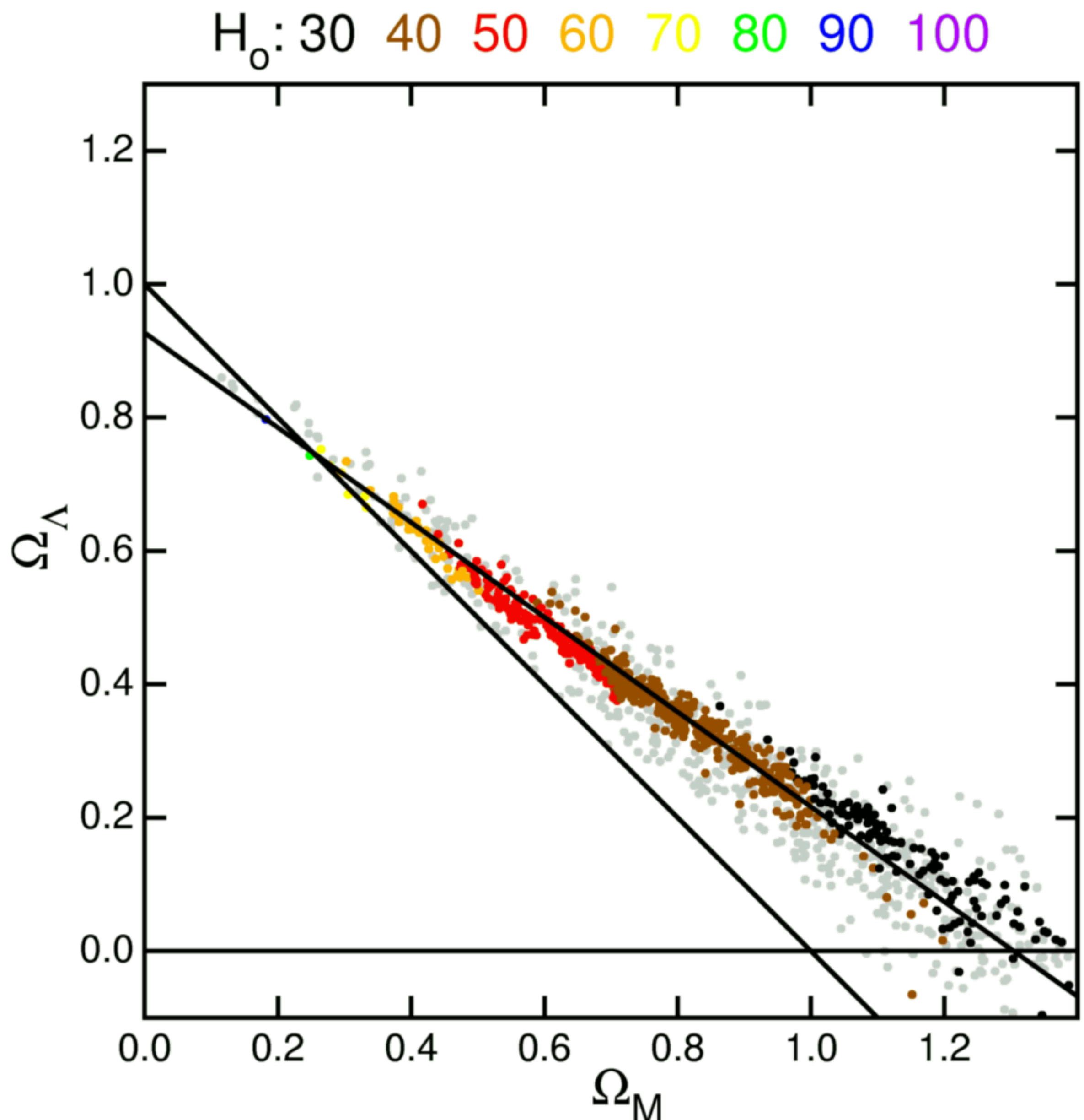


Effects on Peak Position: l_{pk}

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



With WMAP replacing COBE



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}.

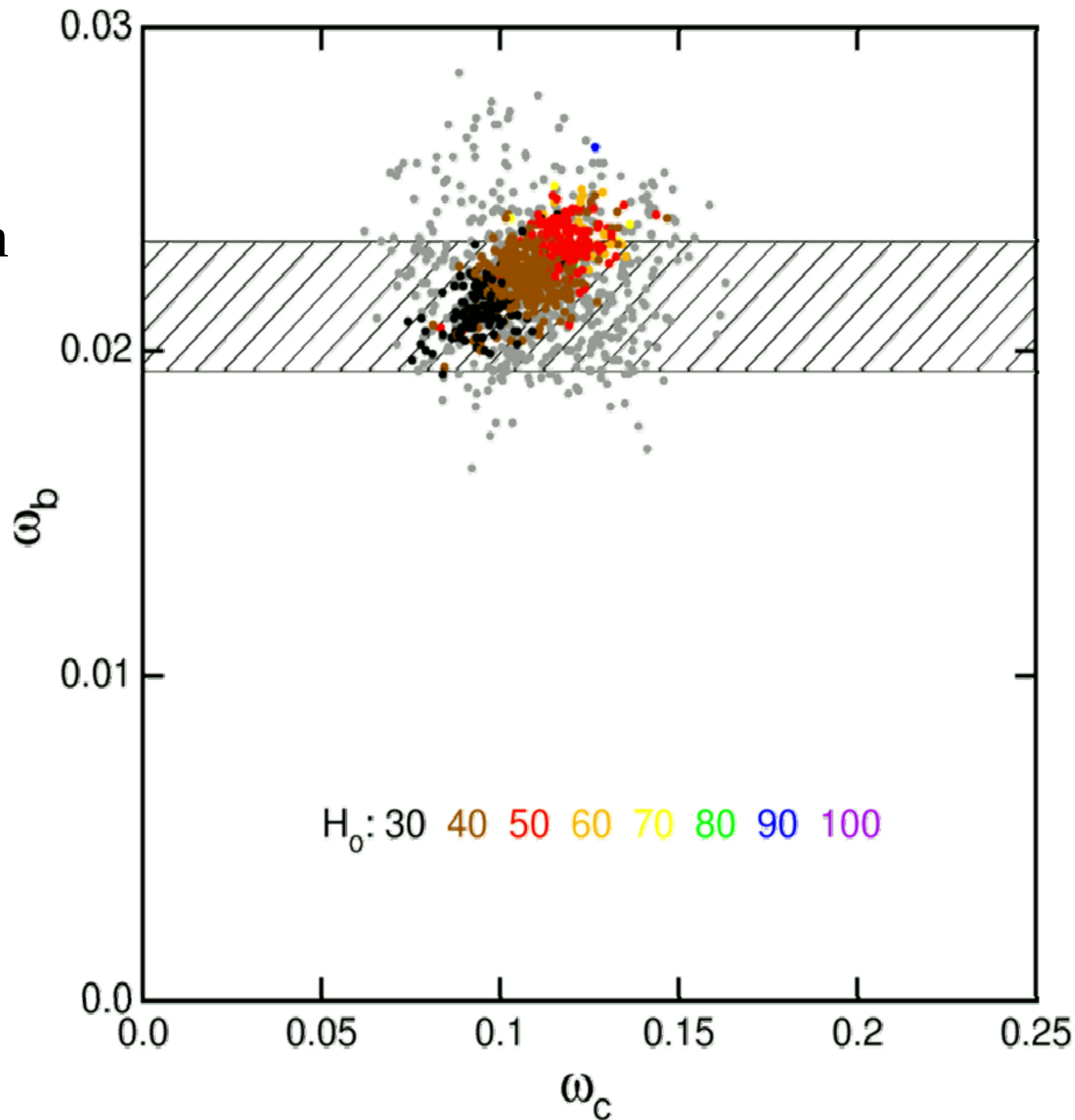
	CMB only	CMB+SNe	CMB+H_o	All
Pre-WMAP	1.18(11)	1.04(4)	1.02(3)	1.02(2)
With WMAP	1.16(9)	1.04(3)	1.03(3)	1.02(2)

Info from peak & trough heights

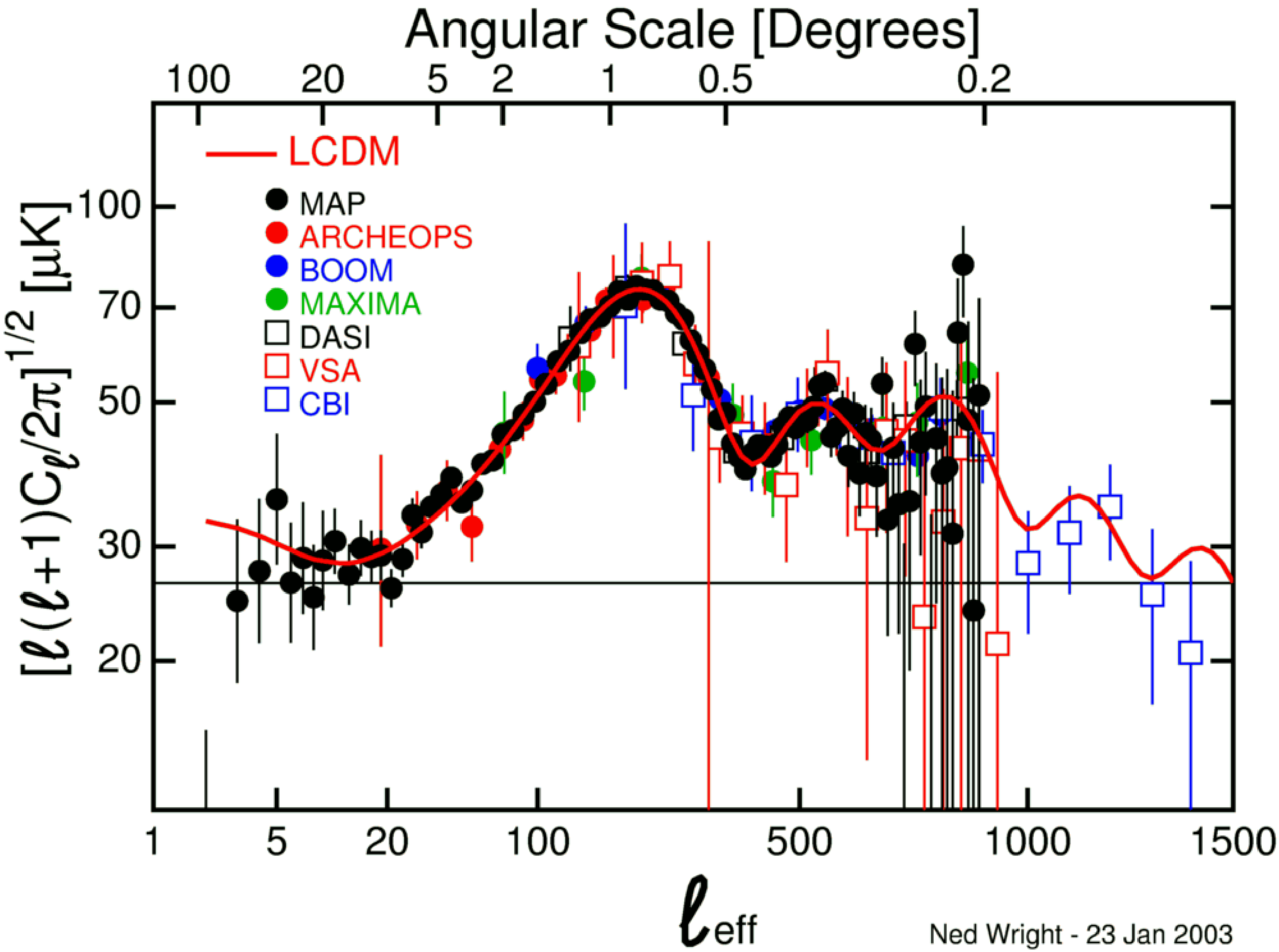
- Overall Amplitude of the perturbations
  - Agrees with large scale structure if almost all the dark matter is COLD dark matter
- Primordial power spectrum power law spectral index: $n = 0.99 \pm 0.04$ without running index.
  - EPAS inflationary prediction is $n = 1$
- Baryon/photon and DM/baryon density ratios
  - $\rho_b = 0.42$ yoctograms/m^3 $= 0.42\times10^{-30}$ gm/cc
  - $\rho_{cdm} = 2.1$ yg/m^3 [$\omega \equiv \Omega h^2 = \rho/\{18.8 \text{ yg/m}^3\}$]

Results With WMAP

Note the new BBNS value from astro-ph/0302006

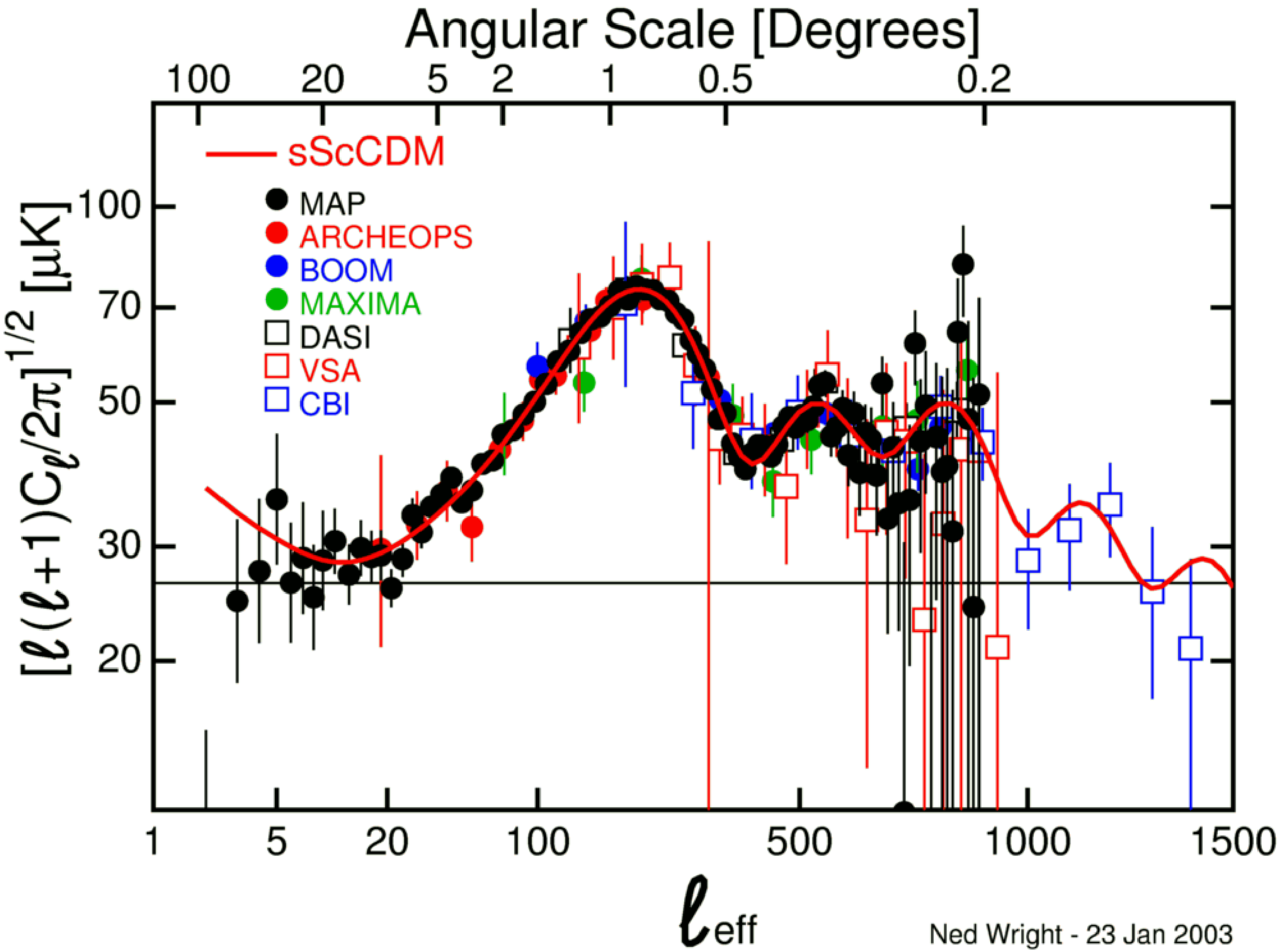


ΛCDM is a Good Fit



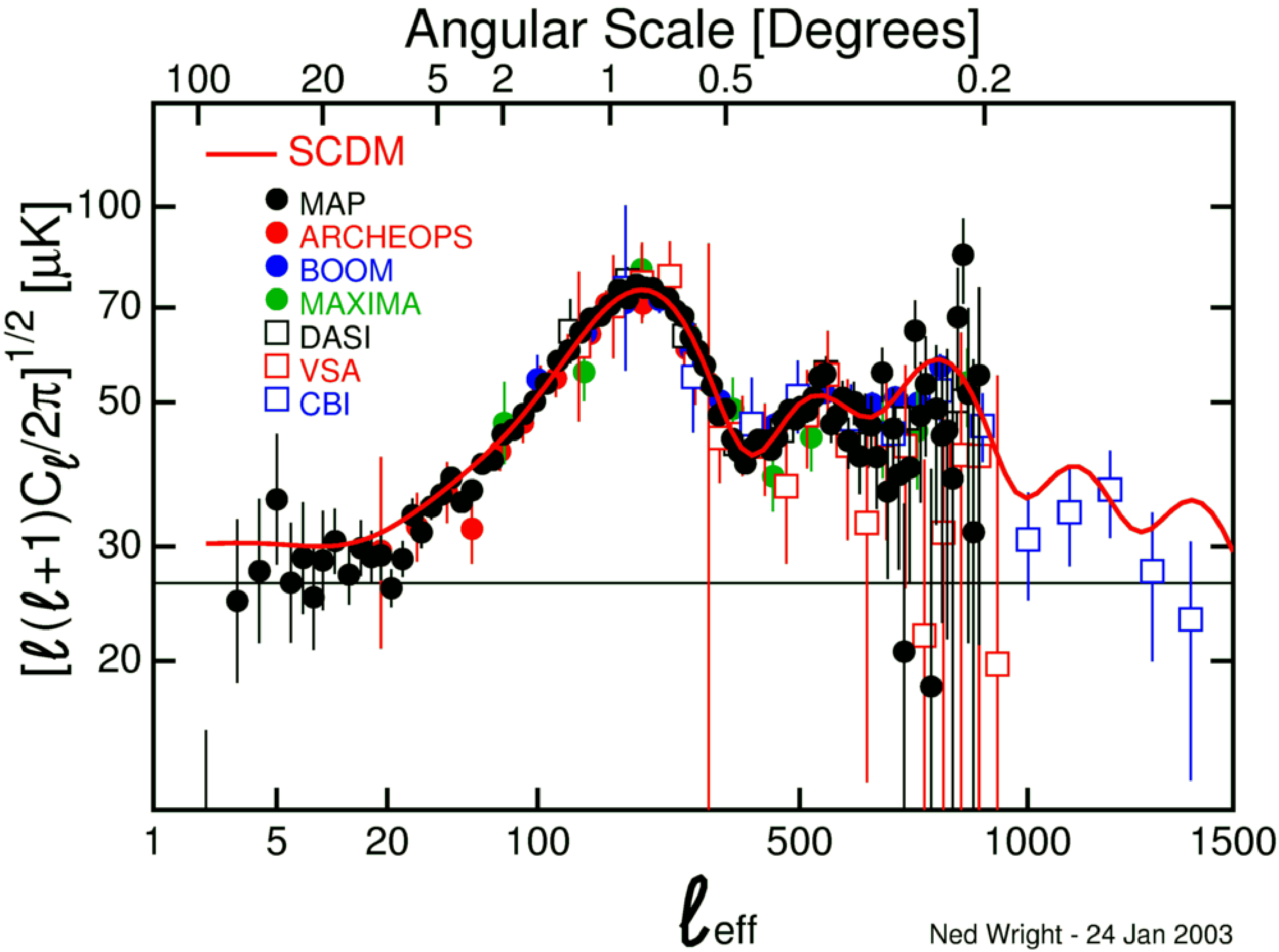
$H_o = 71$, $\Omega_\Lambda = 0.73$, $\Omega_b h^2 = 0.0224$, $\Omega_m h^2 = 0.135$, $\Omega_{tot} = 1$

Closed super-Sandage is a good fit



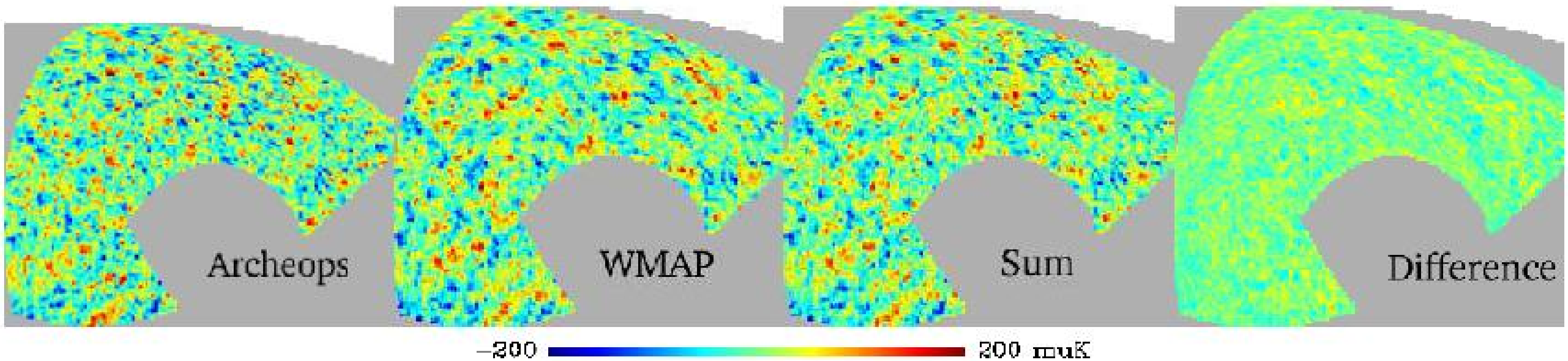
$H_o = 32$, $\Omega_\Lambda = 0$, $\Omega_b h^2 = 0.0232$, $\Omega_m h^2 = 0.139$, $\Omega_{tot} = 1.3$

Einstein – de Sitter Model Fails



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

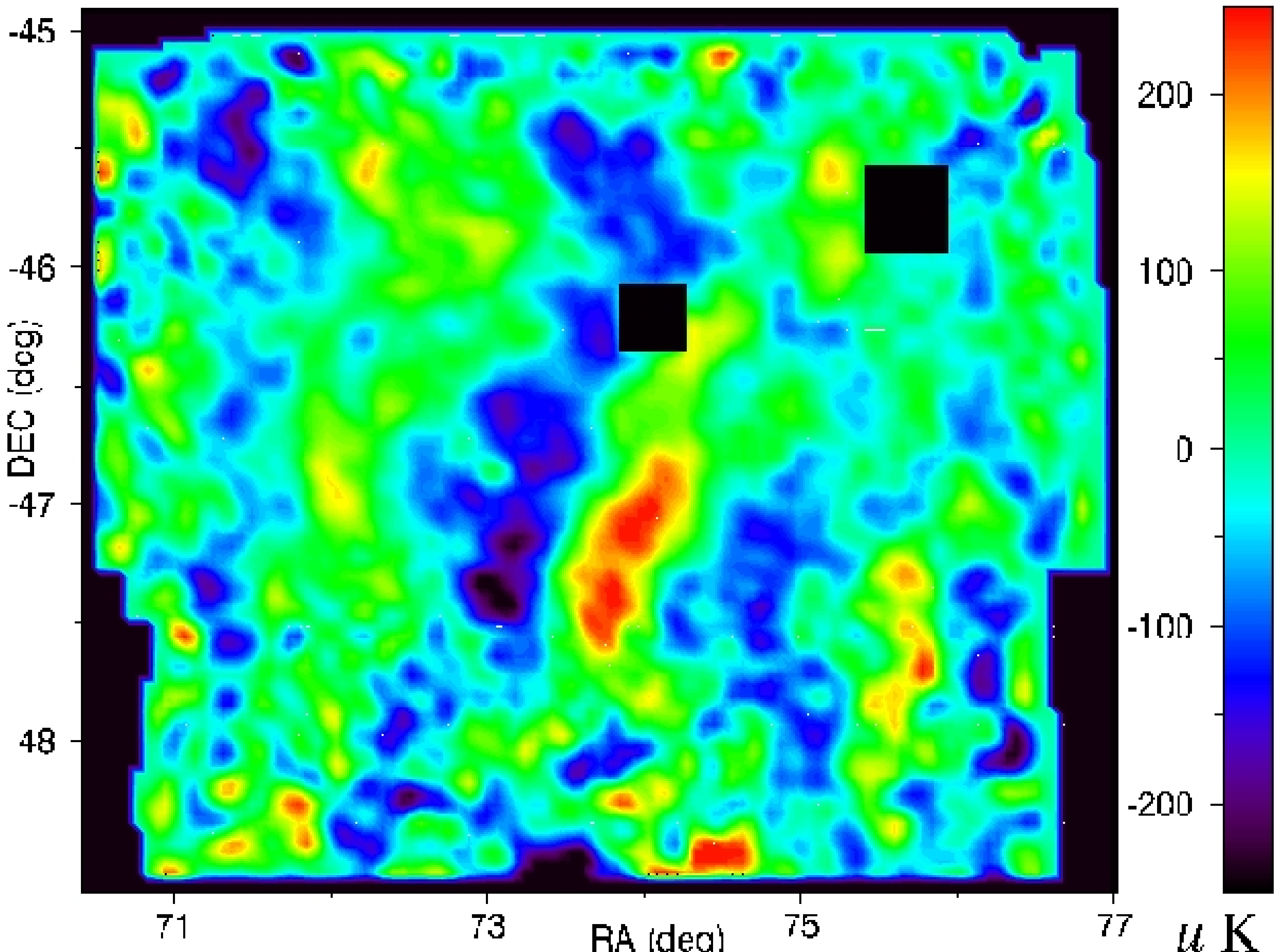
ARCHEOPS vs WMAP



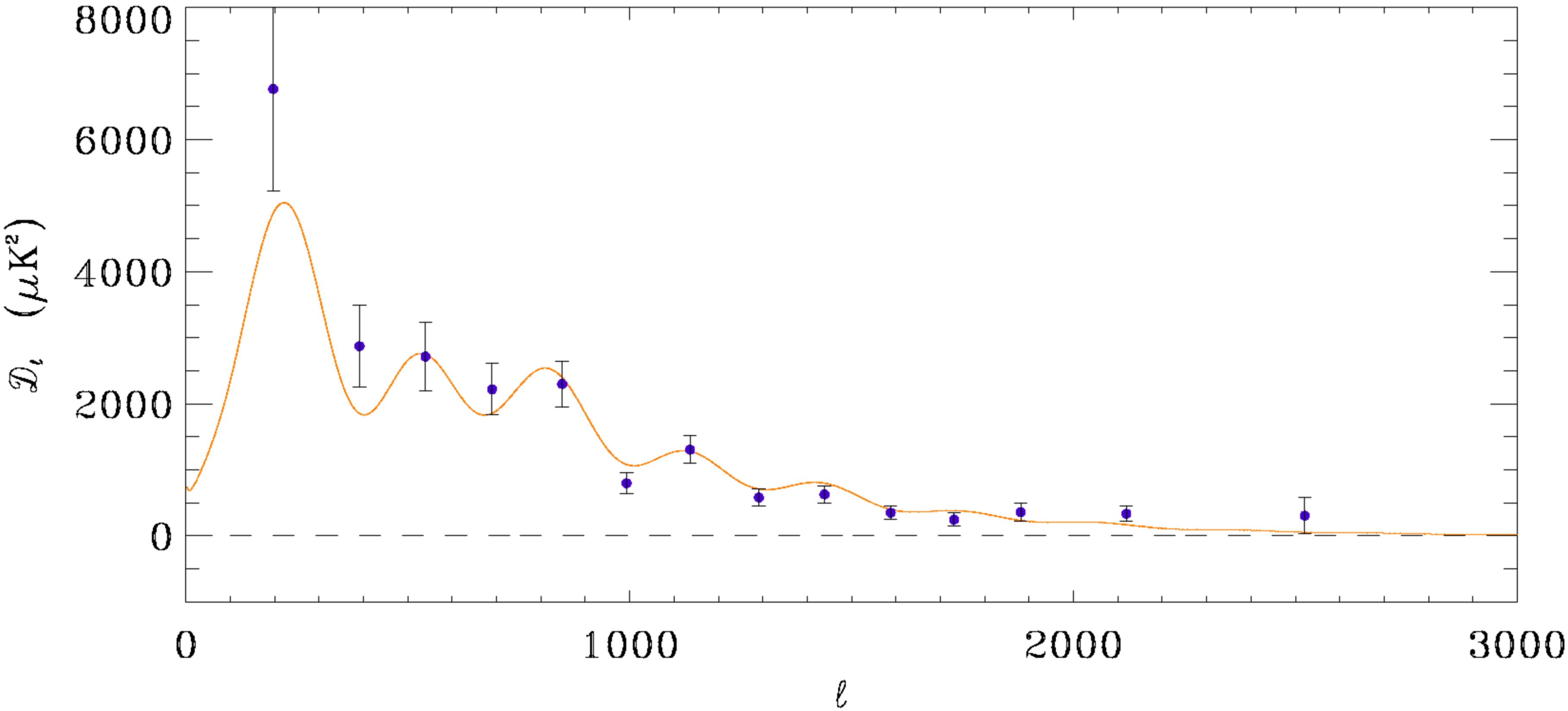
- ARCHEOPS observed same ΔT at 143 & 217 GHz.
- Also consistent with WMAP at 94 GHz.
- Therefore thermal Sunyaev-Zeldovich effect is insignificant at l < 500.

from Hamilton *et al.*, astro-ph/0310788

ACBAR: also at South Pole

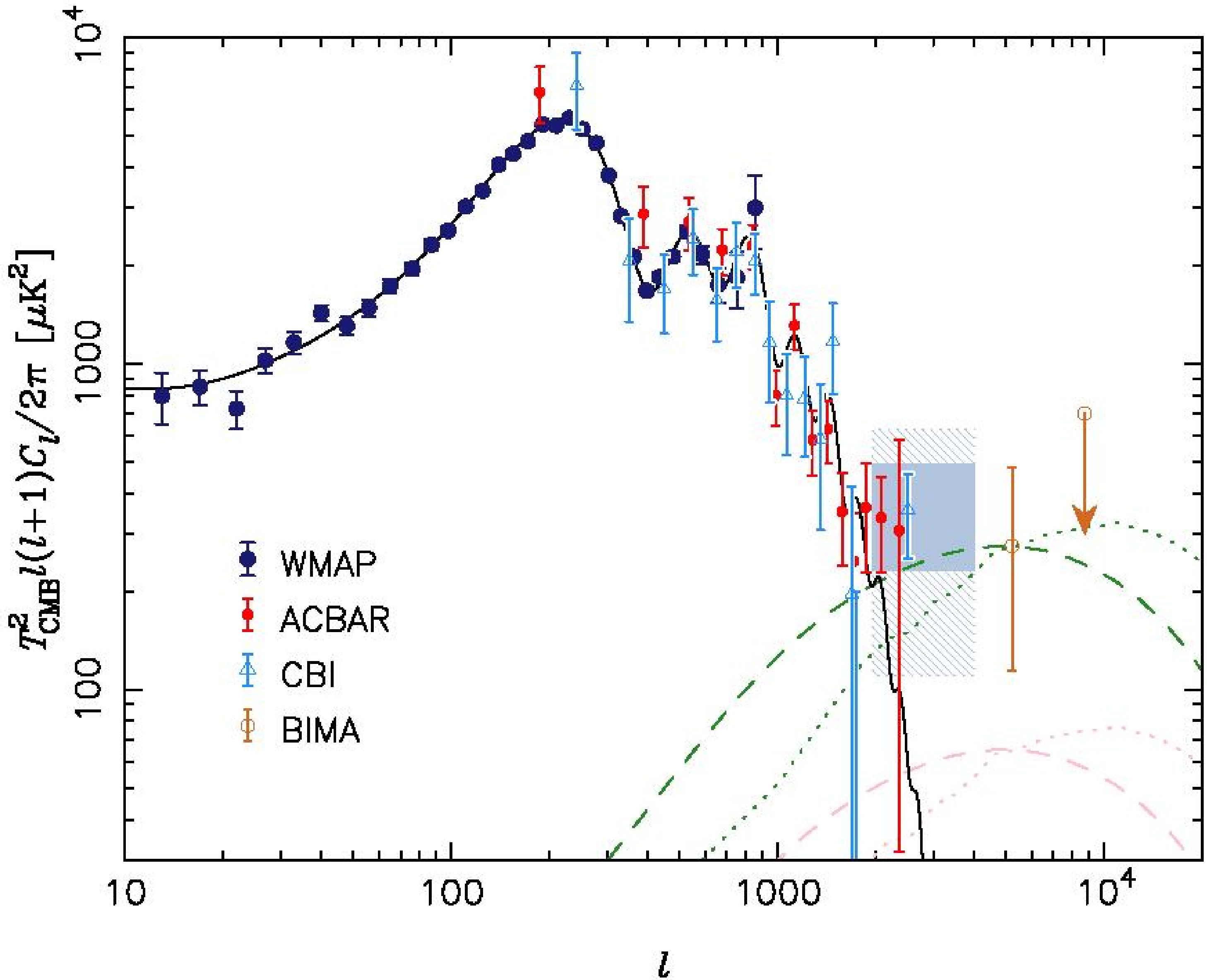


ACBAR Power Spectrum at 150 GHz



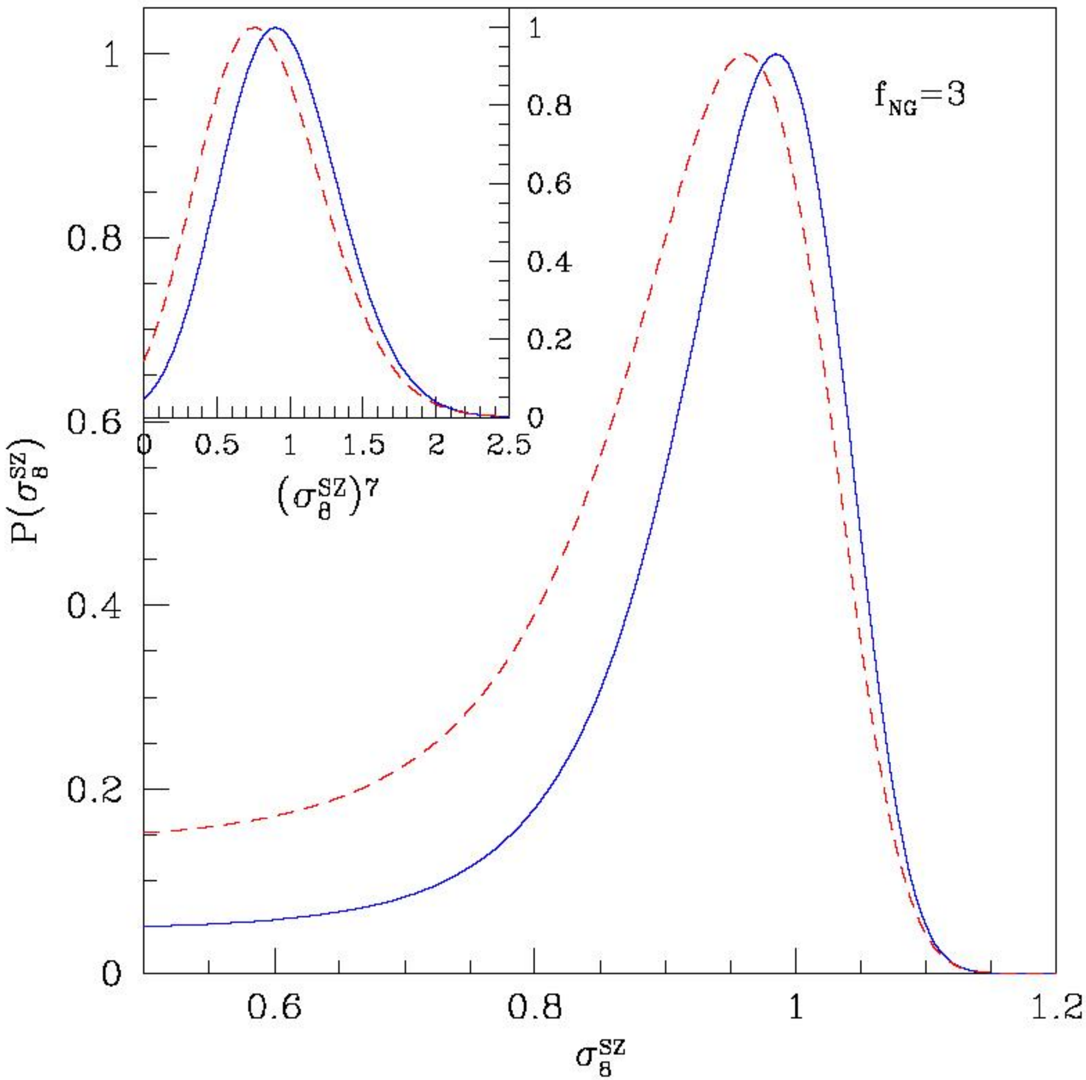
from Kuo *et al.*, astro-ph/0212289

Latest CBI High l Excess is Lower



If SZ, a high σ_8 is wanted

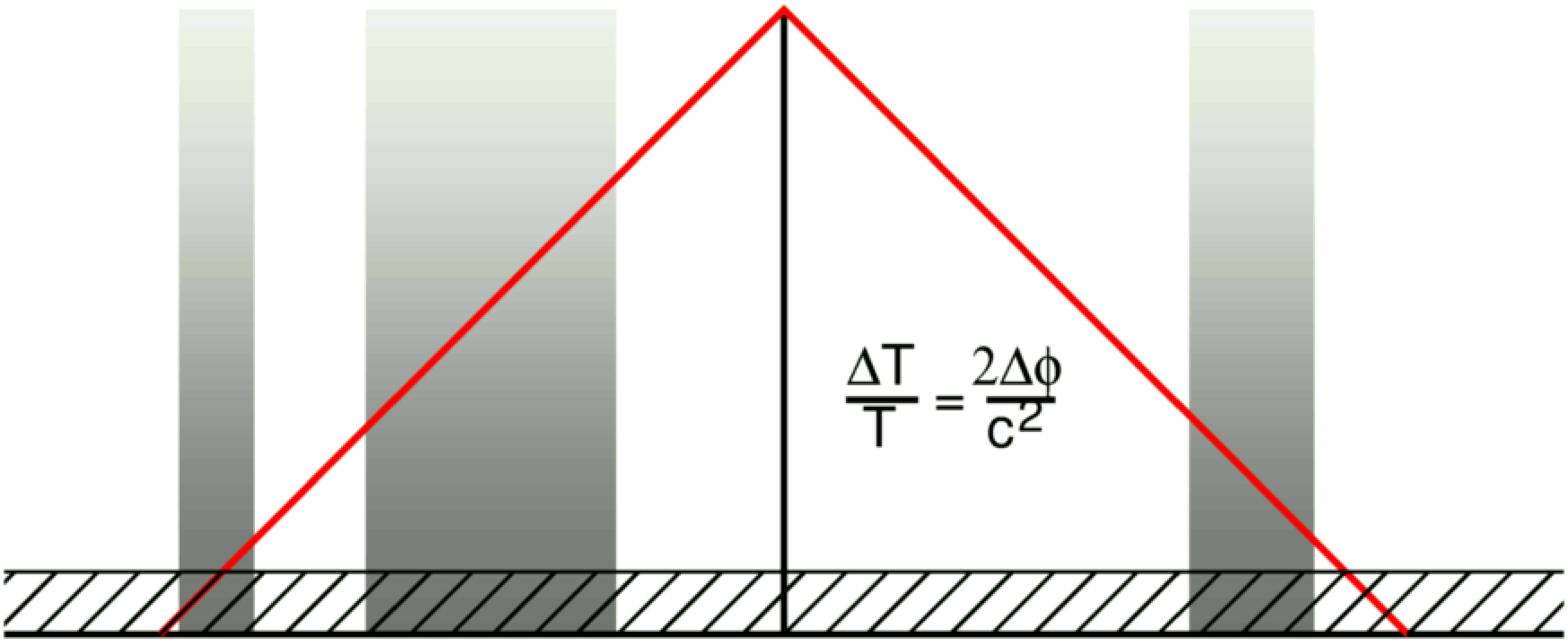
- CBI:ACBAR ratio is 1:1 but should be 4:1 for SZ. However the error bars allow an SZ model.
- Predicted SZ C_l is insignificant at l < 500.
- To have a high σ_8, a higher τ is wanted.



Latest Results

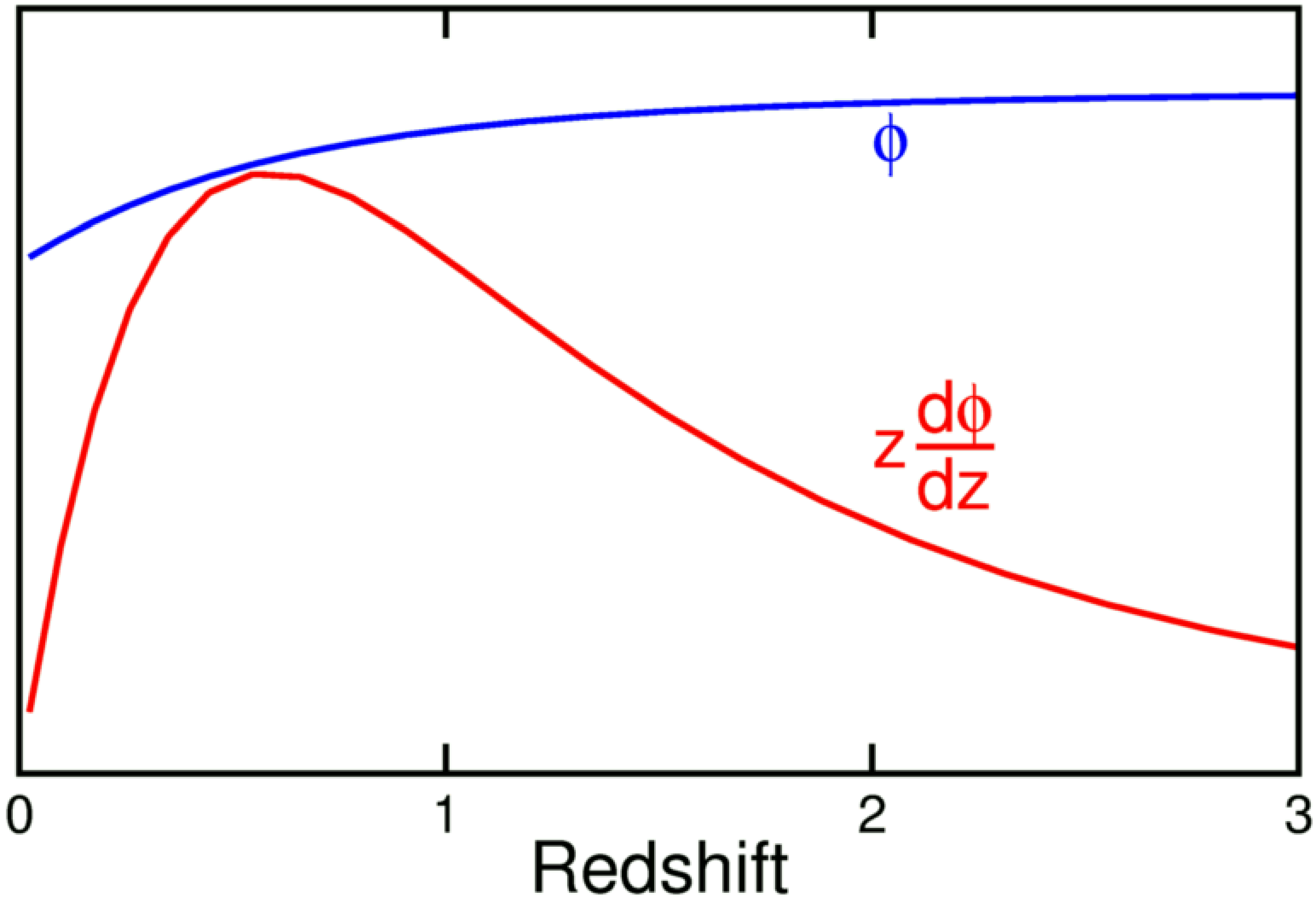
- BOOMERanG long duration 2003 flight, published 2.5 year later in summer 2005.
- Polarization sensitive bolometers.
- Power spectrum consistent with earlier results.
- Polarization consistent with electron scattering at recombination – see talk by Bruce Winstein.

Late ISW Effect: Another test for Λ



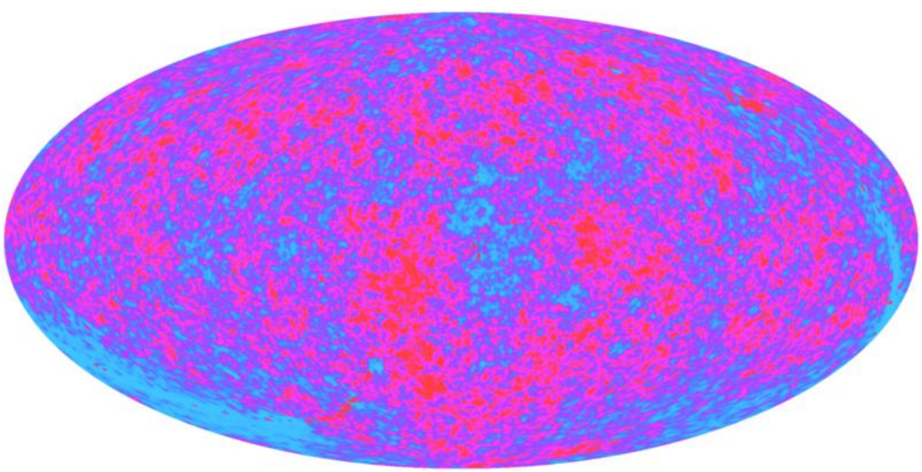
Potential only changes if $\Omega_m \neq 1$ (or in non-linear collapse, but that's another story [Rees-Sciama effect]).

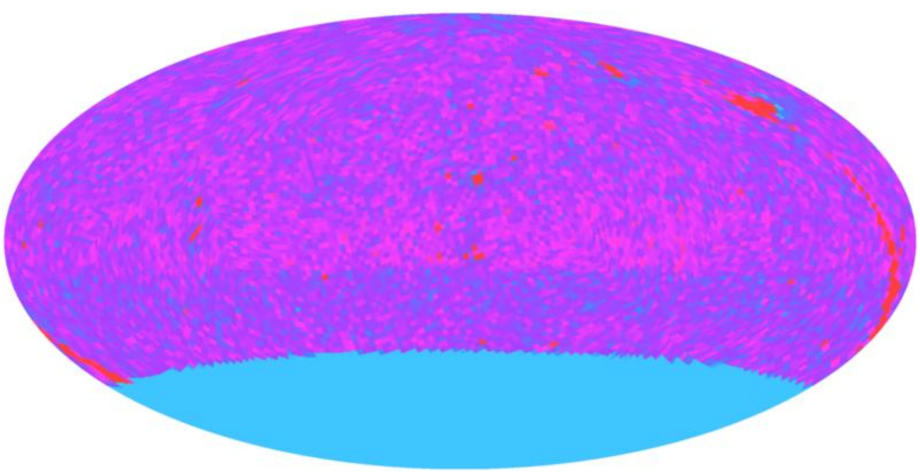
Potential decays at $z \approx 0.6$



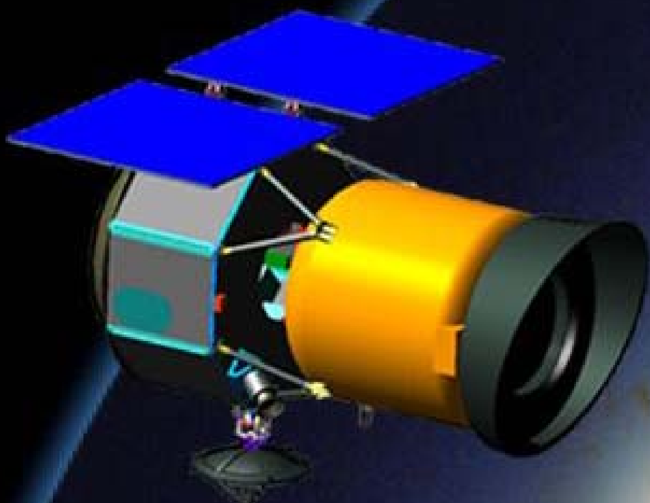
CMB-LSS correlation seen by WMAP

- This late ISW effect occurs on our past light cone so the ΔT we see is due to structures we also see.
- Correlation between WMAP and LSS seen by:
  - Boughn & Crittenden (astro-ph/0305001) at 2.75σ with hard X-ray background and 2.25σ with NVSS
  - Nolta et al. (astro-ph/0305097) at 2σ with NVSS
  - Ashfordi et al (astro-ph/0308260) at 2.5σ with 2MASS





Wide-field Infrared Survey Explorer



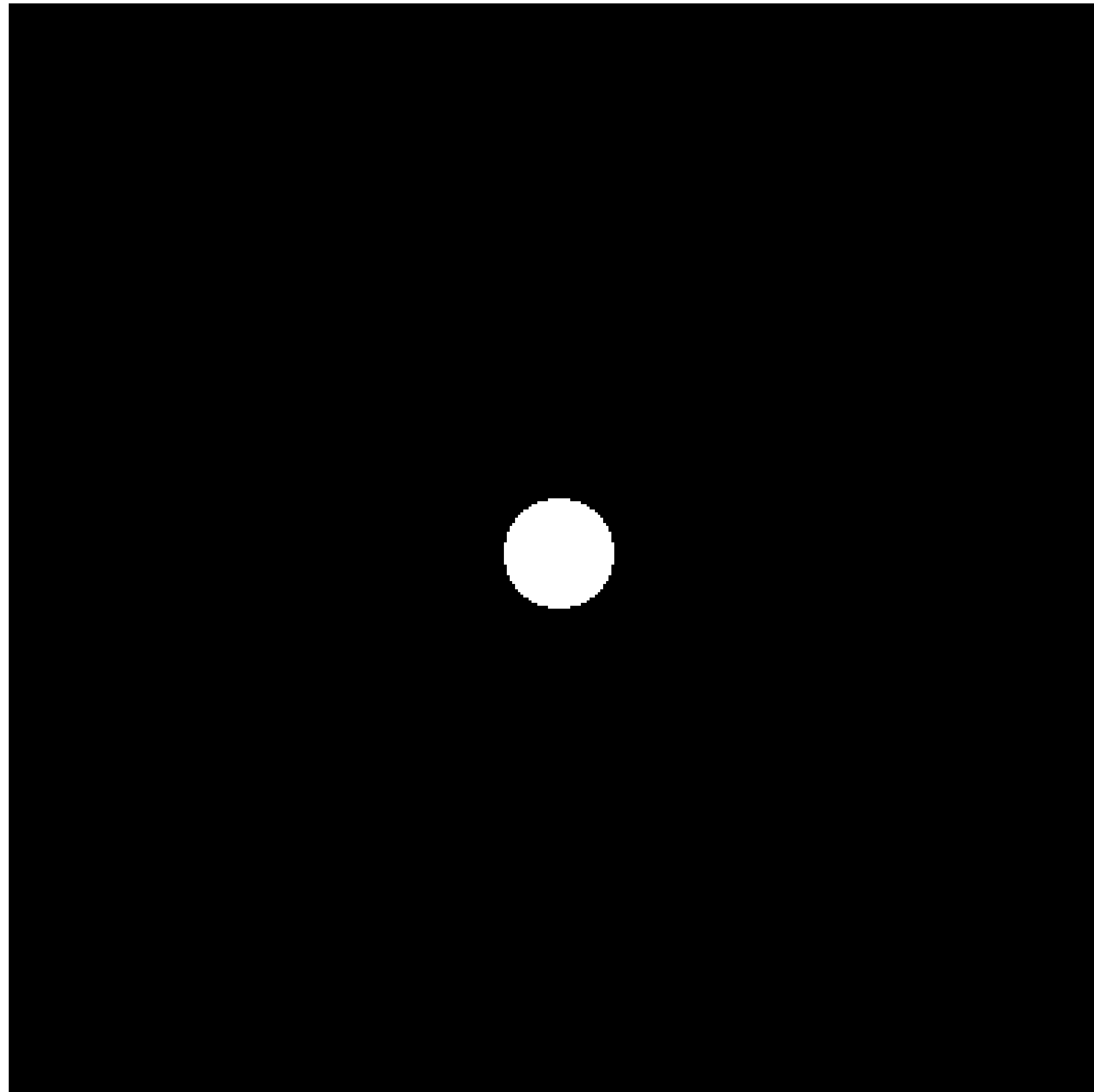
I am the PI on a MIDEX called WISE, an all-sky survey in 4 bands from 3.3 to 23 μm. WISE will find and study the closest stars to the Sun, the most luminous galaxies in the Universe, and also map the large-scale structure out to redshift z=1, covering the era when the late ISW effect should be generated.

WISE will fly in 2009.

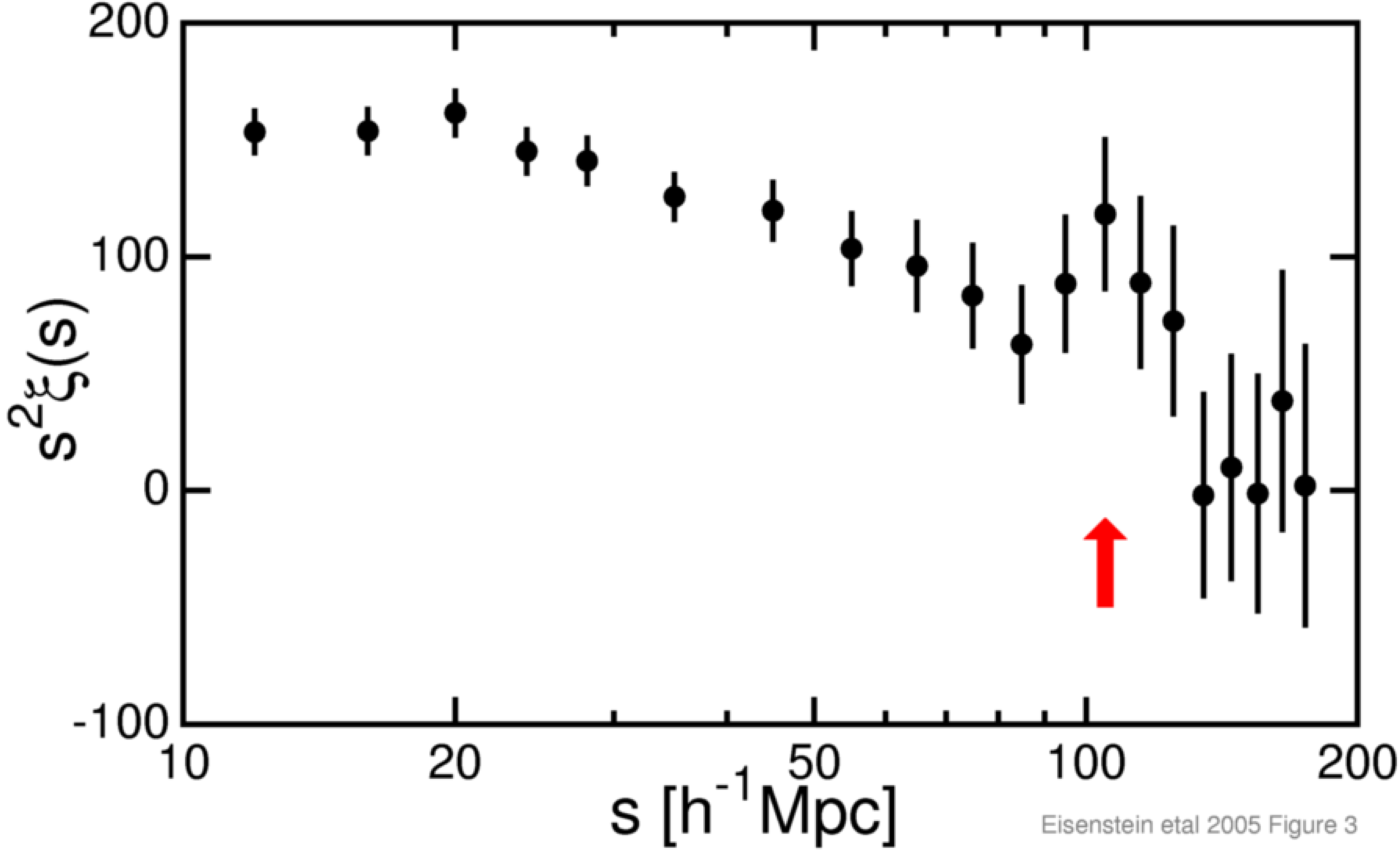
Spreading Sphere of Sound

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.

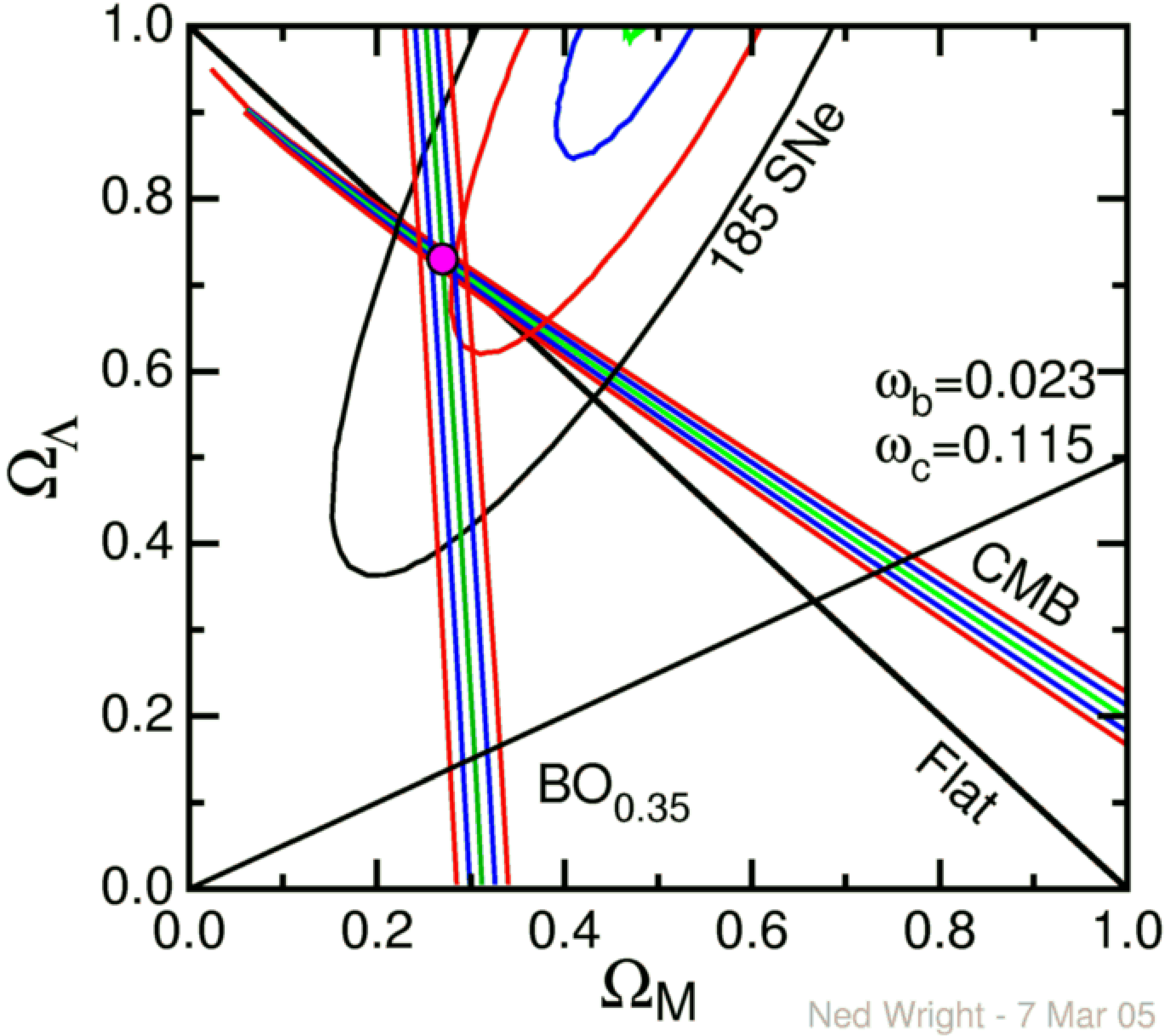


Baryonic Oscillations in SDSS LRGs



Eisenstein etal 2005 Figure 3

Implications for Ω_M, Ω_Λ



The Three Simplicities

- $\Lambda = 0$ but this probably is not correct.
- $\Omega_{tot} = 1$ due to inflation.
- w = -1 if there is dark energy.
  - Note that if w = -1, the dark energy is Lorentz invariant, but if w ≠ -1 observers can measure their velocity with respect to the dark energy so it has to be a dynamical thing that will react to inhomogeneities in the Universe. Thus w will be a function of space *and time*, not a function of redshift w(z).

We should prove flatness.

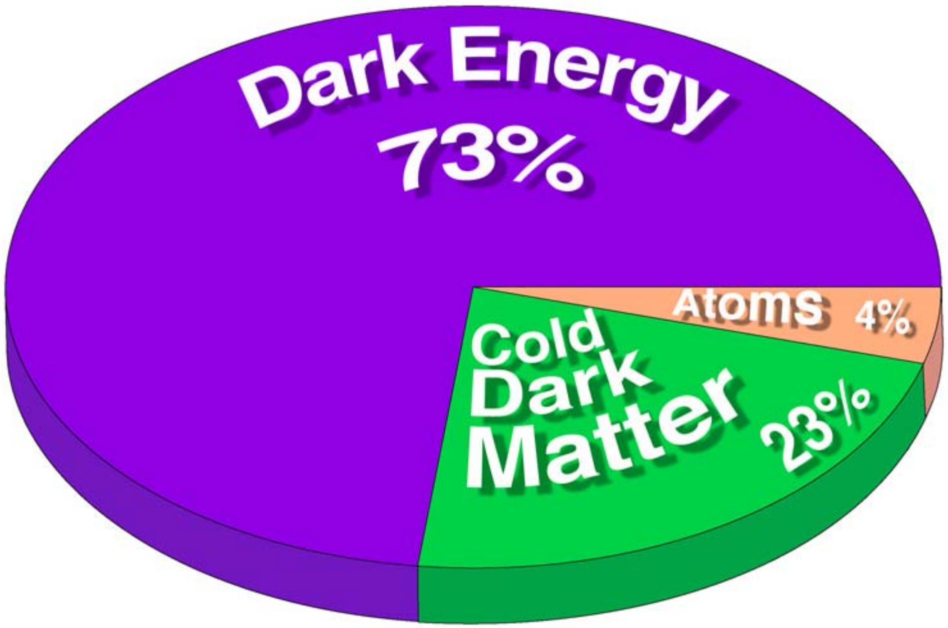
- The success of the flat model with w = -1 can not be used to justify assuming flatness when trying to find w and w’.
- Certainly Ω_{tot} = 1 is simpler, but
  - Ω_X = 0 is simpler, no CDM is simpler & w = -1 is simpler
- But the model consistent with both the CMB and SNe data moves as w is varied, and is most consistent with the Hubble constant from the HST Key Project when w is close to -1. So w can be measured ***using all data combined*** but be suspicious of priors on Ω_{tot} or Ω_M.

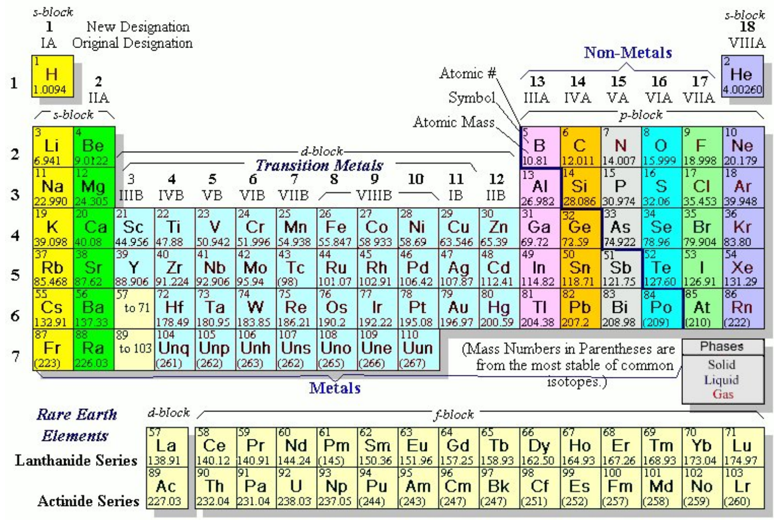
Search for Two Numbers?

- Allan Sandage in 1970 was searching for H_o and q_o.
- Now we are searching for w and w' but H_o and q_o have not been chiseled into a stone tablet by God (or by Sandage).
- We still need to measure H_o, Ω_M and Ω_V 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.

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





Conclude: Big Cosmic News of 2003


"All the News That's Fit to Print"

The New York Times

Late Edition

NEW YORK, WEDNESDAY, FEBRUARY 12, 2003

ONE DOLLAR

Greenspan Throws Cold Water On Bush Arguments for Tax Cut

Budget Deficits Do Matter, Fed Chairman Says

TOP U.S. OFFICIALS PRESS CASE LINKING IRAQ TO AL QAEDA

C.I.A. CHIEF CLOSES RANKS

Powell Cites New Tape Said to Be of Bin Laden as Sign of Baghdad 'Partnership'

Tapes of Shuttle's Descent Show Dawning of Disaster

France Offering Plan to Expand Iraq Arms Hunt

Congress Agrees to Bar Pentagon From Terror Watch of Americans

INSIDE

BEST IN SHOW

Kerry Blue Terrier Is Leader of the Pack

Robben Island Journal

With Vivid Palette, Mandela Depicts the Jailhouse Years

Cosmos Sits for Early Portrait, Gives Up Secrets

- A flat ΛCDM model gives a good fit to CMB, SNe, H_o, late ISW, baryon oscillation, and age data.
- This model is 13.7±0.2 Gyr old.
- More than 95% of this model is "dark energy" [or "smooth tension"] and cold dark matter. Finding the nature of these dark components gives cosmologists plenty to work on.