What’s New in Cosmology

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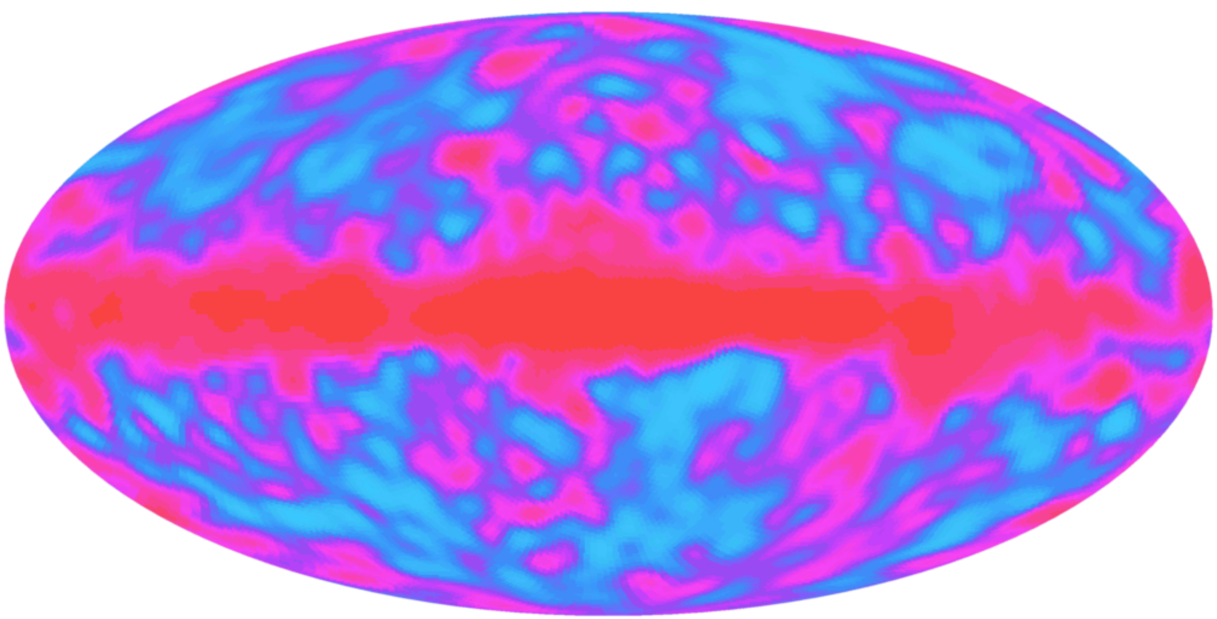
23 March 2006

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.”



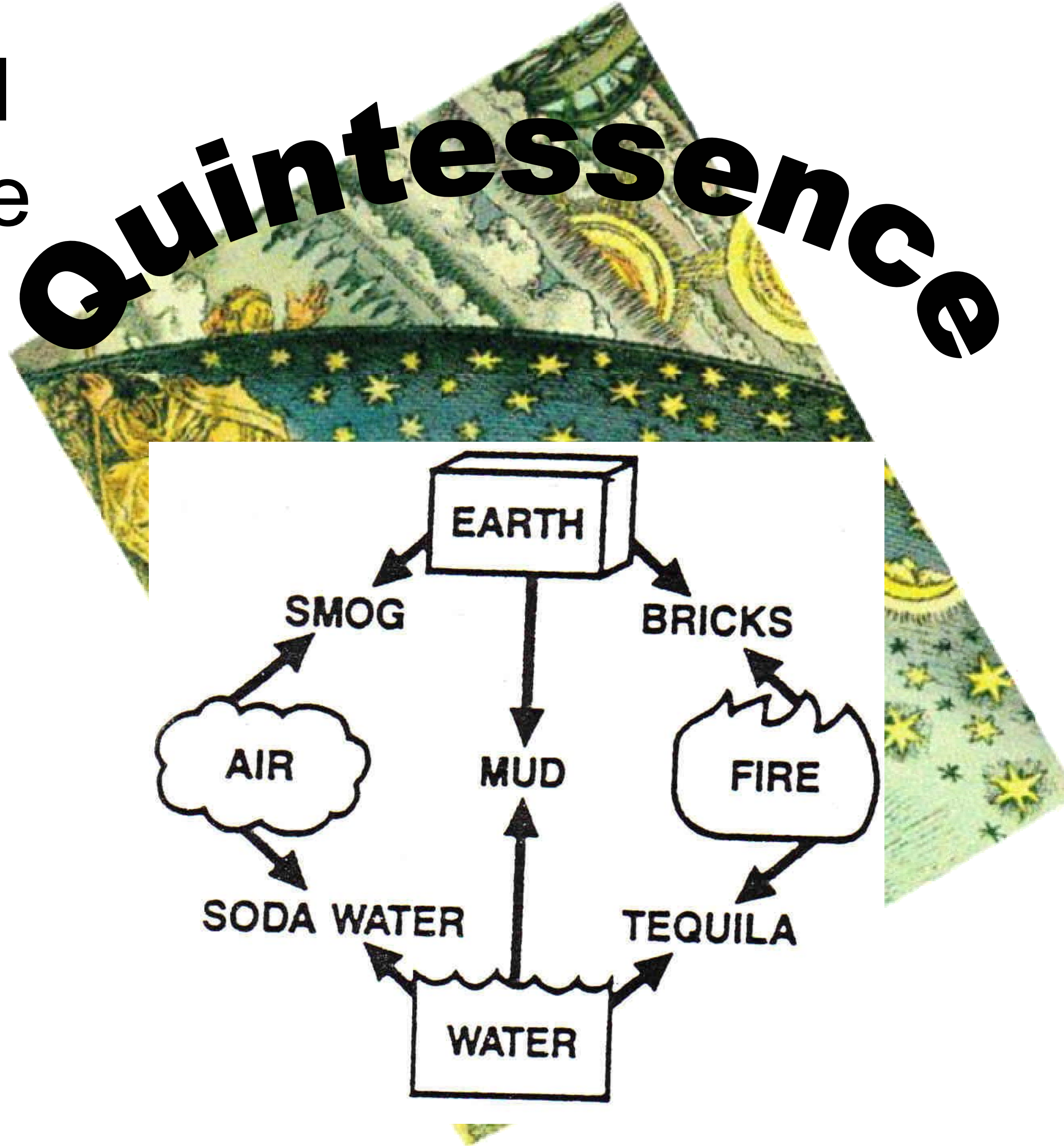
But really, what have we learned since 1906?

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

Cosmology is an Observational Science

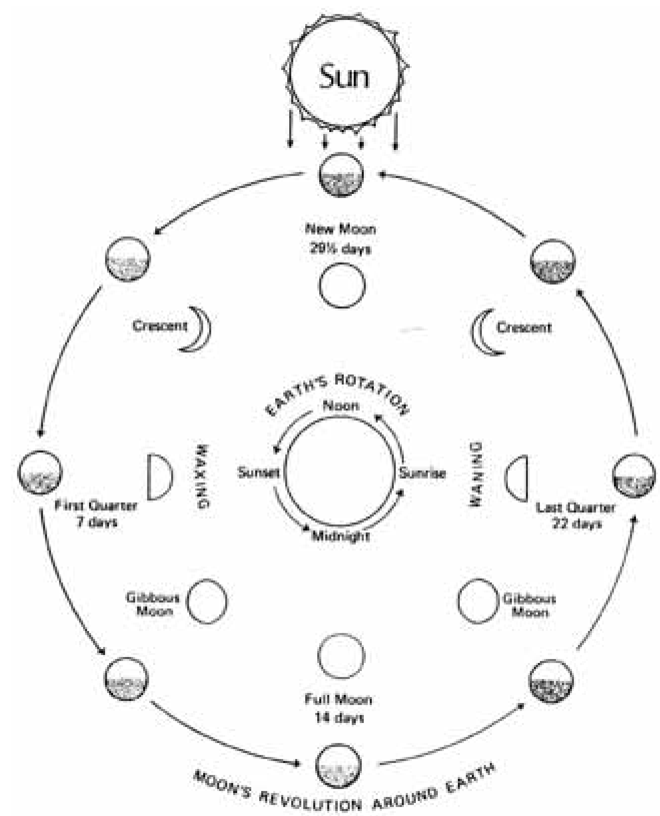
- We can’t do experiments on the Universe.
- We can’t change the initial conditions and see what happens.
- But we can observe what is the Universe is like.
- And we can study what past, present and future conditions of the Universe are compatible with our observations and the same laws of physics that apply in our laboratories.

No special laws for the heavens



Newton's Apple & the Moon

- Newton did not invent gravity to explain the apple's fall.
- Instead he realized that the same force law applied to the apple and to the Moon, which is always falling toward the Earth.



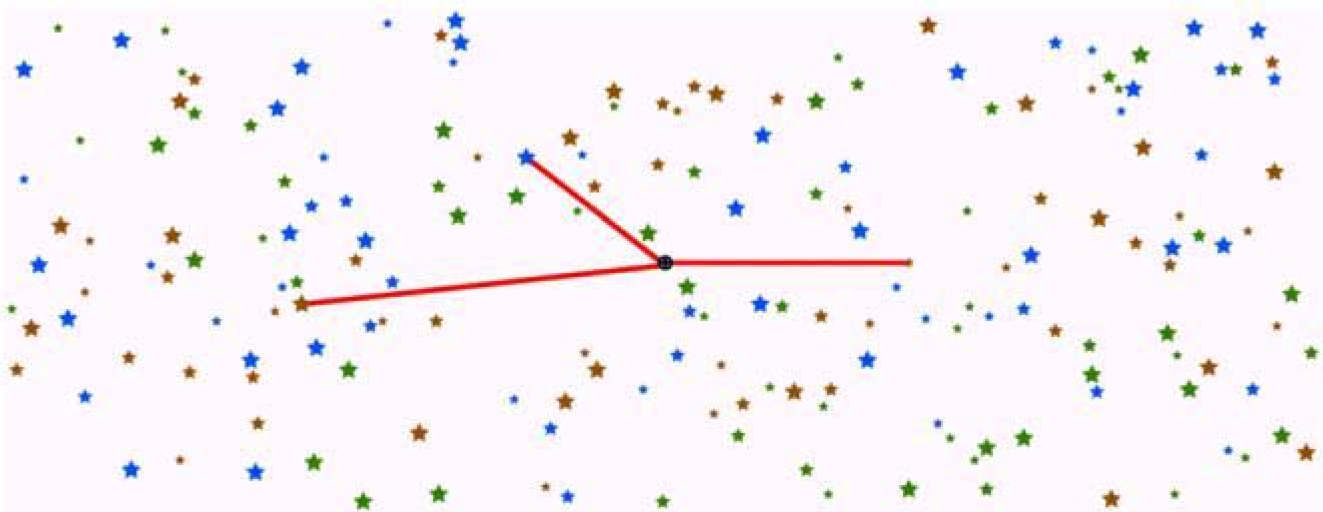
The Universe is dominated by gravity

- Einstein developed general relativity in 1915
- Gravity is the only long-range force without positive and negative charges, so it dominates the large scale structure of the Universe.
- Naturally Einstein created a general relativistic model for the Universe, based on what was known in 1917:

ALMOST NOTHING

Only One Fact in 1917

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

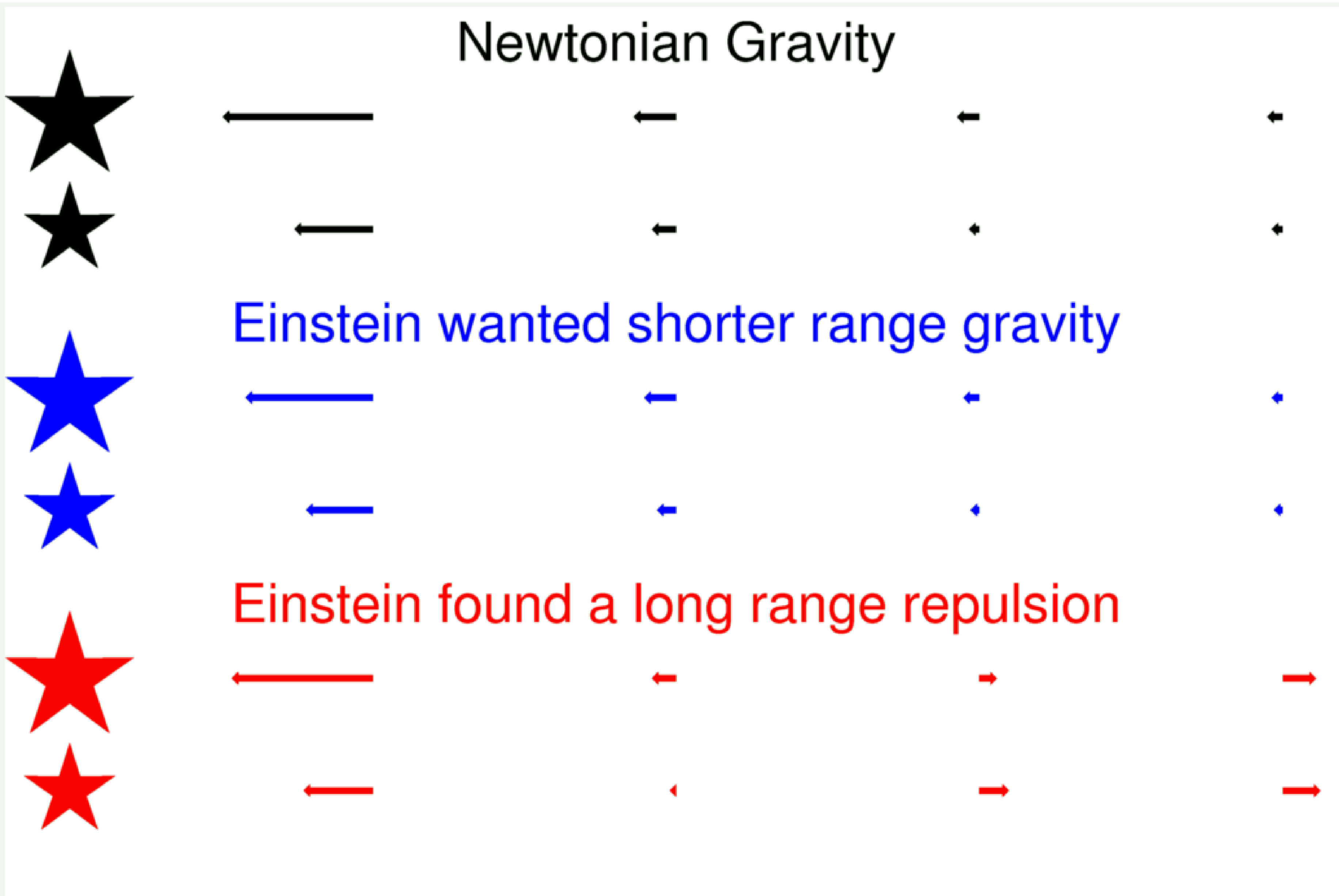


In a homogeneous unchanging Universe every line of sight will end on a star. So why is the night sky not as bright as the surface of a star? The Cosmic Infrared Background is what remains after this Olbers' paradox is resolved.

General Relativity & Cosmology

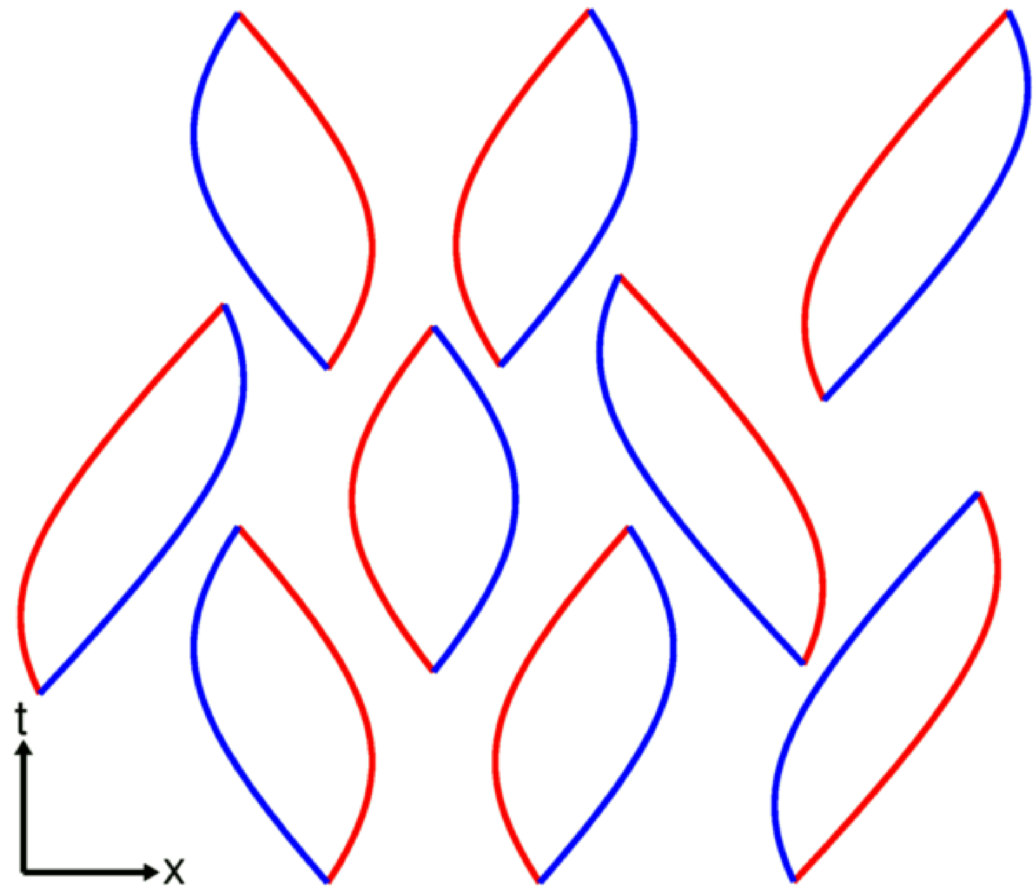
- General relativity allows a consistent calculation of the effects of gravity in a uniform distribution of galaxies that fills the entire Universe.
- But Einstein thought the Universe was static, and a static uniform distribution of galaxies that filled the entire Universe would be unstable to collapsing into clumps.
- So Einstein added a new constant to his equation for gravity: the cosmological constant, Λ.

Effect of Λ term was unexpected

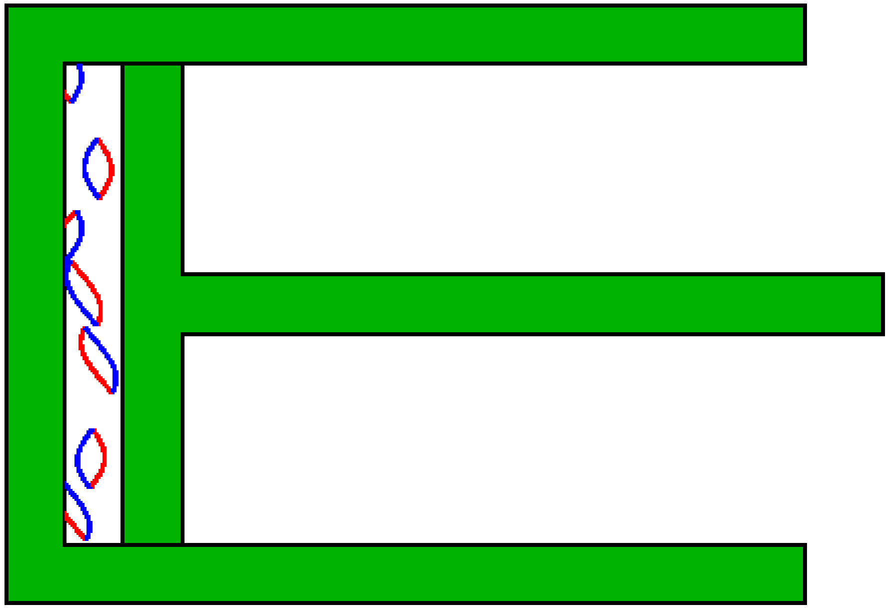


Source of Cosmological Constant

- A vacuum energy density is equivalent to Einstein's cosmological constant: Λ
- Quantum fluctuations could lead to a vacuum energy density.



Why $w = P/\rho_{vac}c^2$ should be -1



- Pulling out the piston creates new "vacuum" and energy $(\rho_{vac}c^2)dV$ has to be supplied.
- This requires a pressure that is $P = -(\rho_{vac}c^2)$

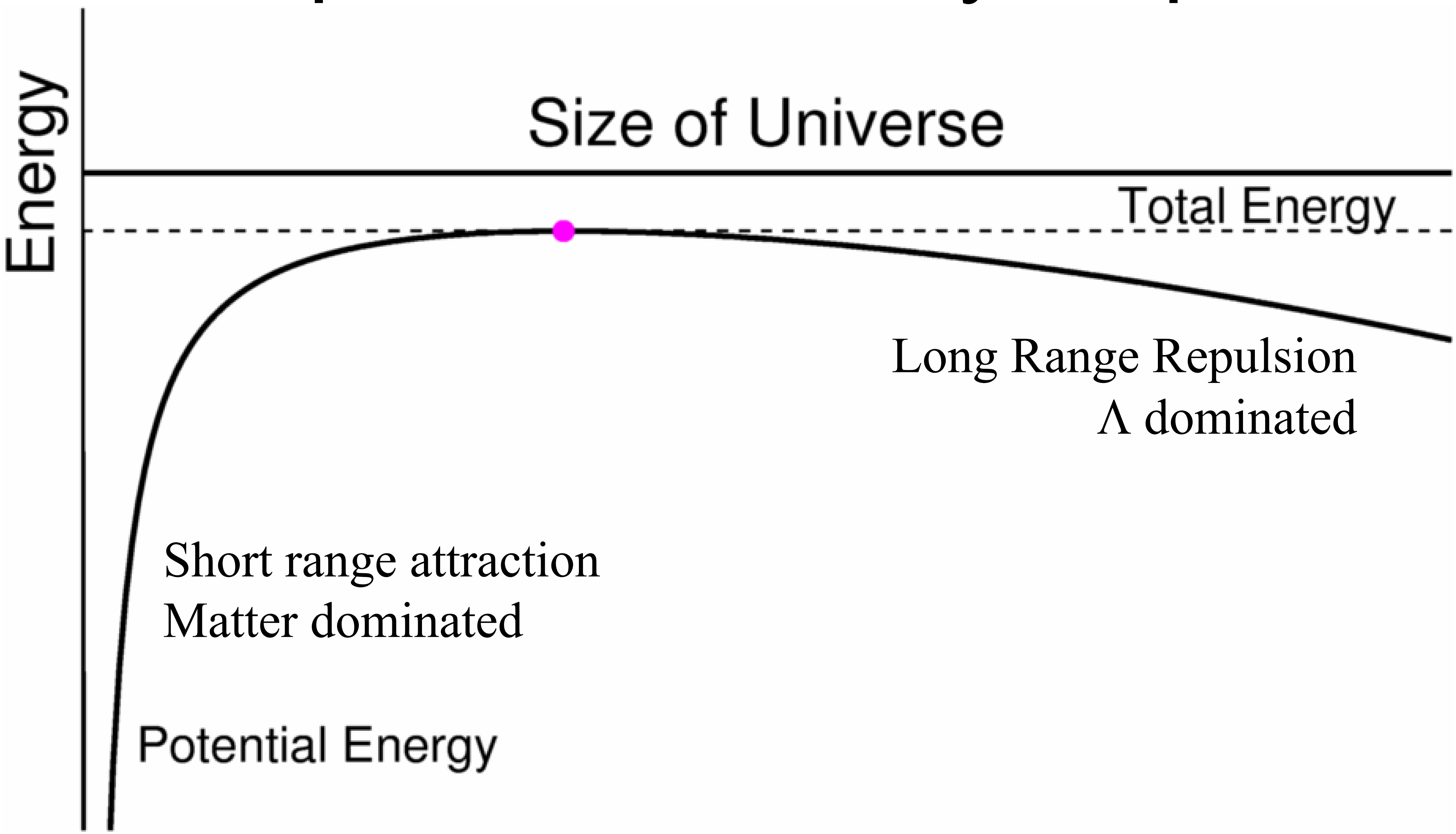
Details

Why the repulsive effect?

- In General Relativity energy has gravitational effects.
- A pressurized volume has energy, PV.
- Vacuum energy density must have a negative pressure.
- Net gravity from positive vacuum energy density plus negative pressure is repulsive.

Details

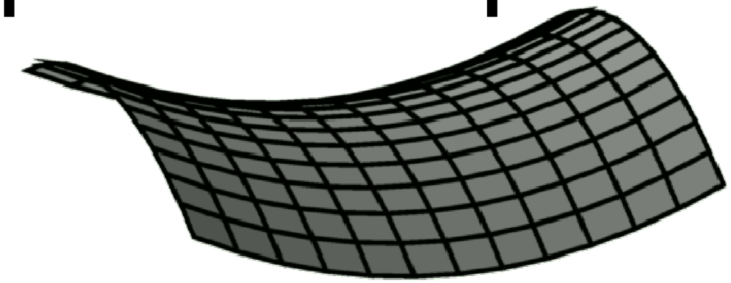
Represent Force by Slope



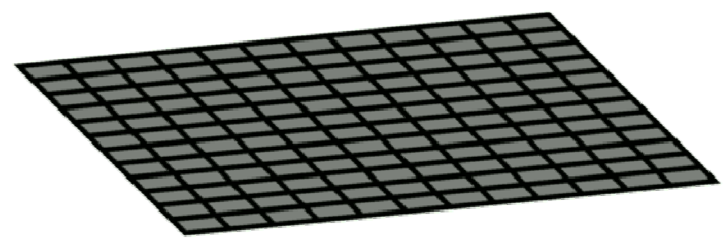
- This is quite a good analogy for cosmological models.

Total Energy implies Shape

- Total Energy > 0
  - Sum of angles < 180^o
  - Negative curvature
  - Infinite



- Total Energy = 0
  - Sum of angles = 180^o
  - No curvature
  - Infinite



- Total Energy < 0
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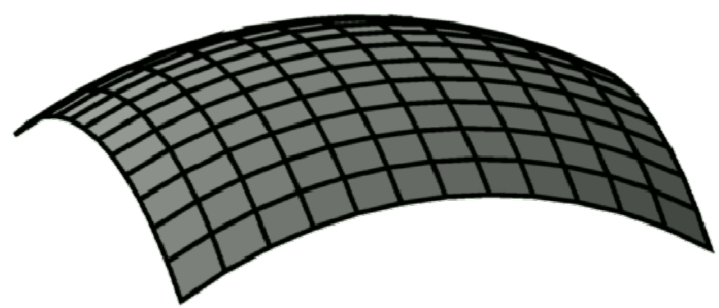
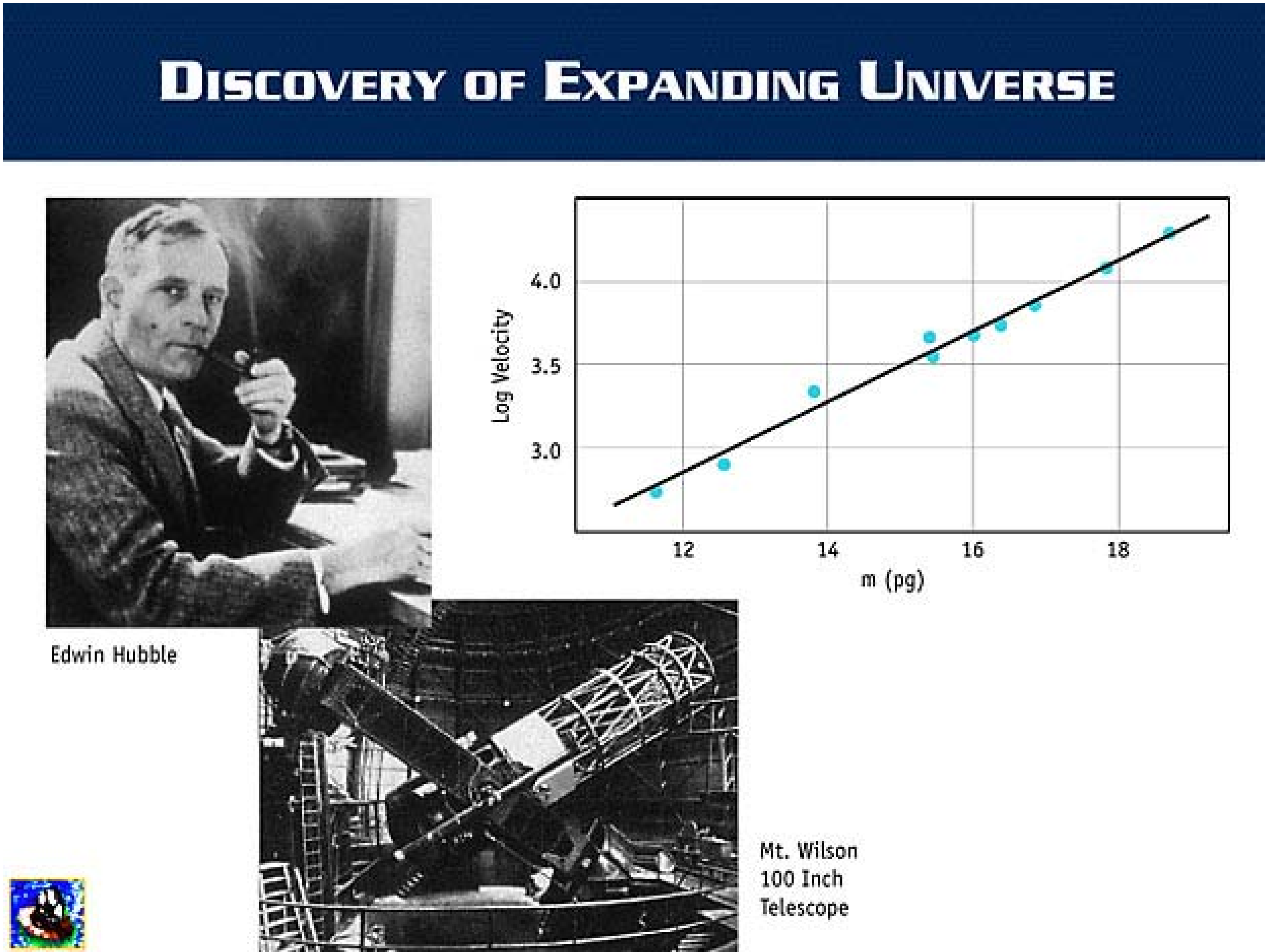
  - Finite

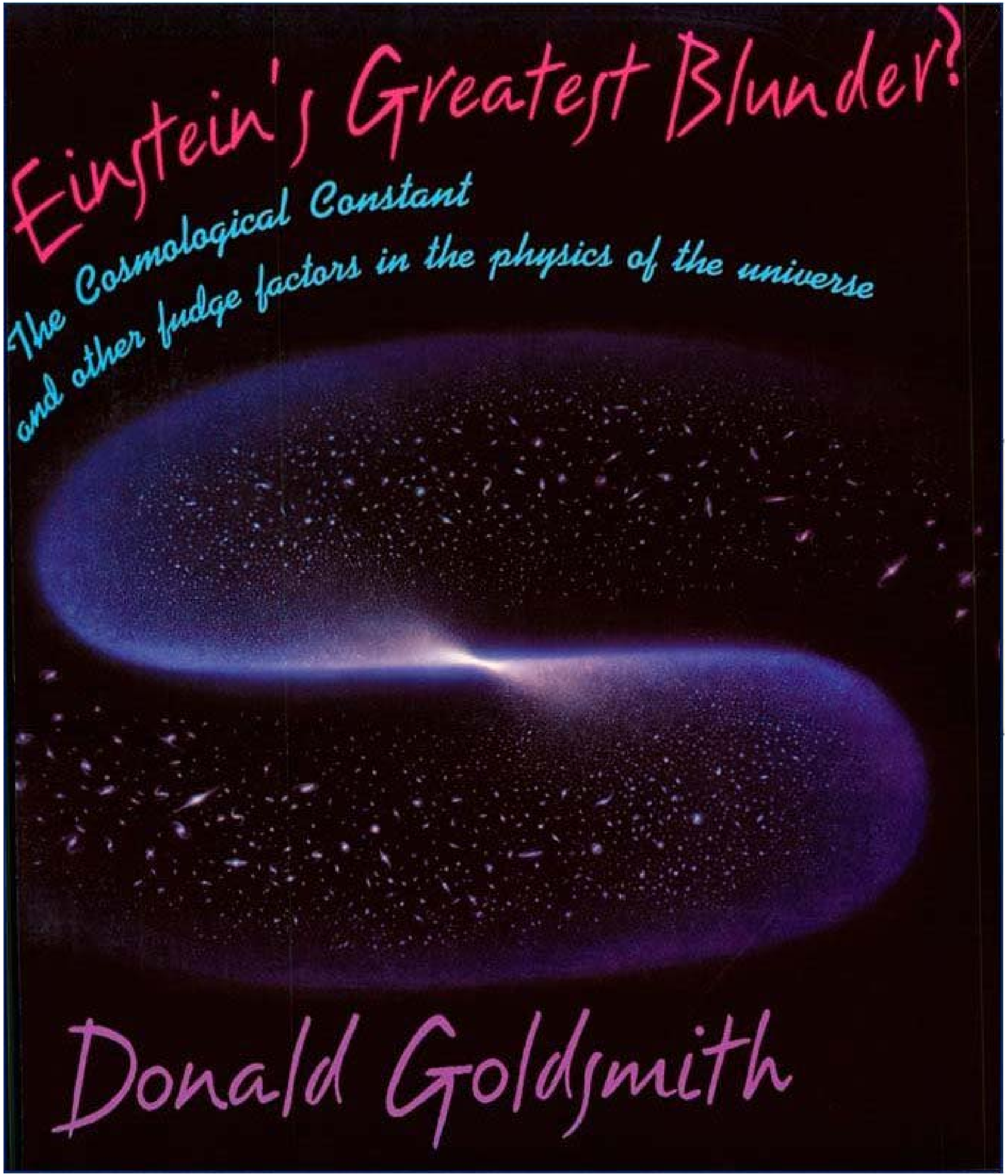


New Data


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
MAP

Λ Was Demoted

- Expanding models with or without matter and/or Λ are possible.
- But matter is needed – we are here.
- Λ was not needed so it was deprecated.



CN non-discovery of the CMB

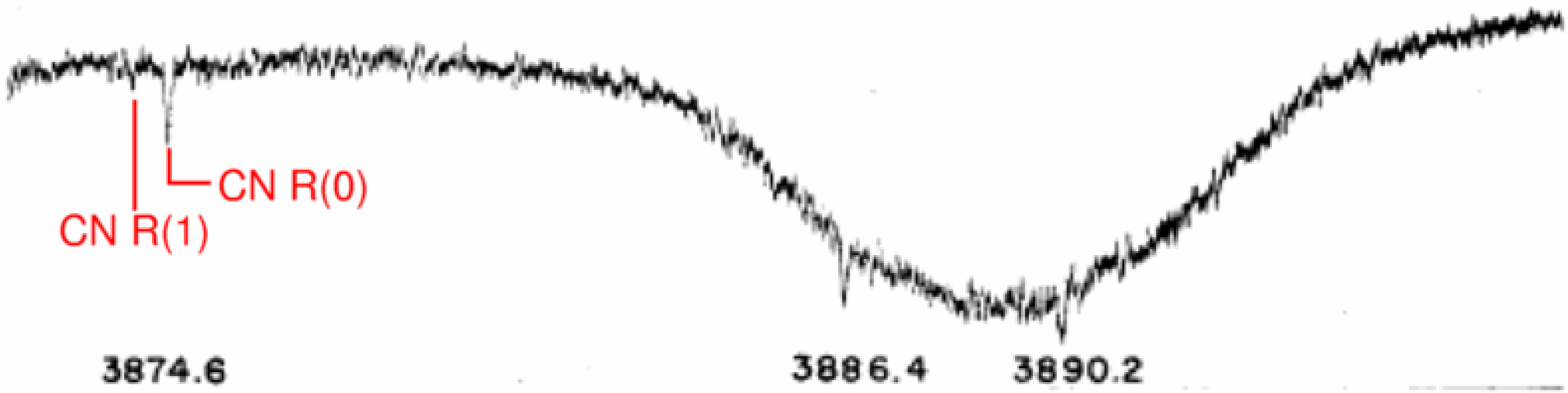


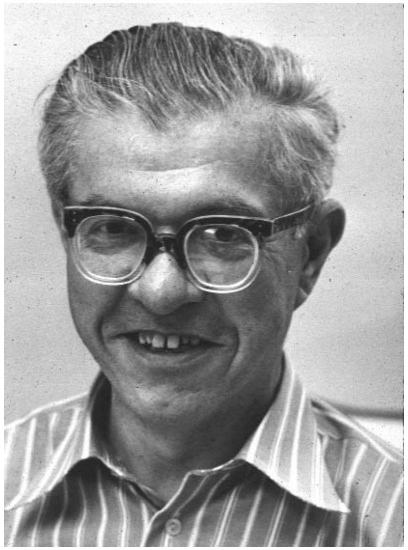
Plate 3 of Adams (1941, ApJ, 93, 11-23) reporting McKellar's work

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**."

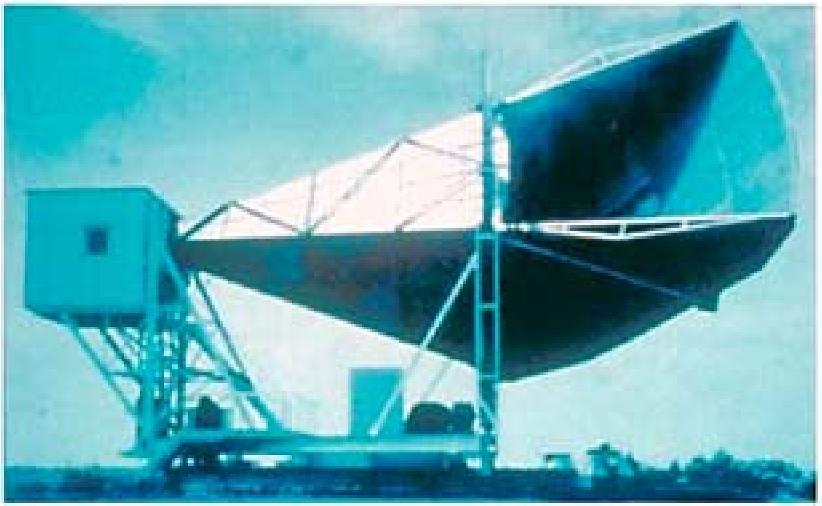
There went Herzberg's [second] Nobel Prize.

Fred Hoyle missed the Nobel Prize

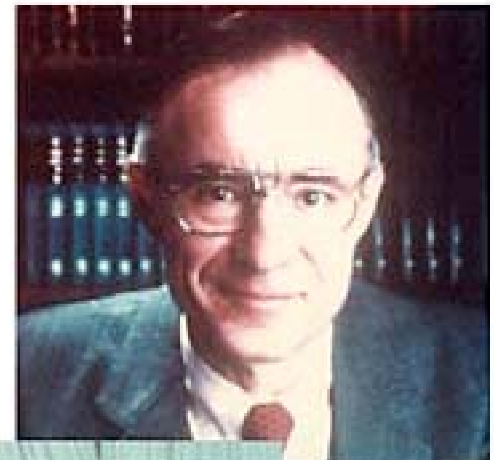


- Hoyle (1950, *The Observatory*, 70, 194), reviewing a book by Gamow & Critchfield: “[the Big Bang model] would lead to a temperature of the radiation at present maintained throughout the whole of space much greater than McKellar's determination for some regions within the Galaxy.”
- This book implied T_o = 11 K. Gamow in 1956 *Scientific American* implied 6 K. But Alpher & Herman explicitly gave 5 K or 1 K in the *Physical Review*.
- Nobody followed this up!

Discovery of the Cosmic Microwave Background



Microwave Receiver

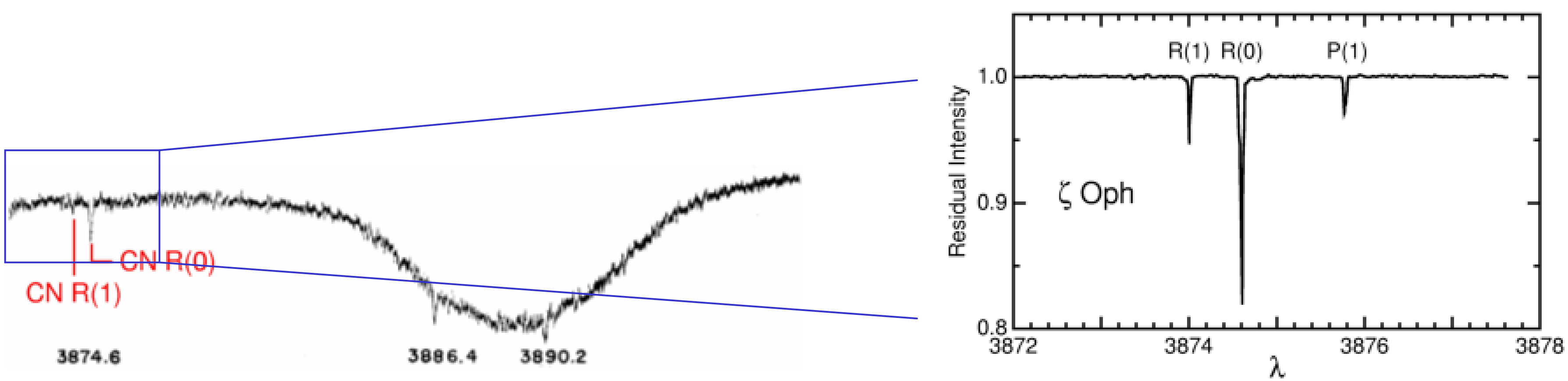


Arno Penzias

Robert Wilson

CN followup after Penzias & Wilson

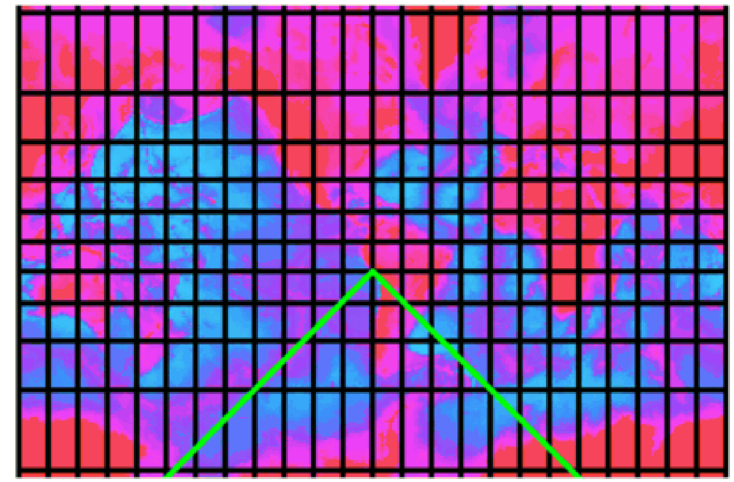
- Reworking and reobserving the CN lines gave 2.78±0.10 K at 2.64 mm. (Thaddeus, 1972, ARAA, 10, 305-334)
- By 1993, 2.73±0.03 K (Roth, Meyer & Hawkins 1993)

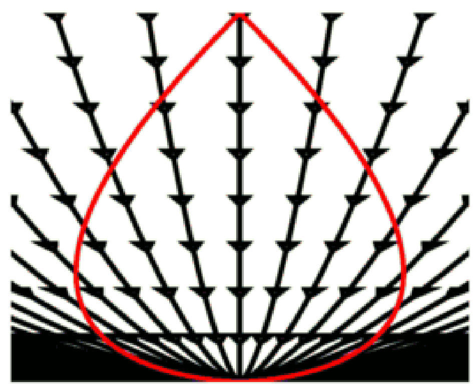


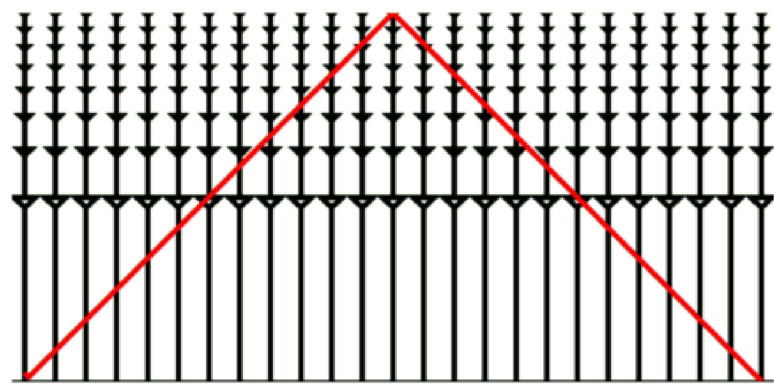
(UCLA PhD's) (advisor was Meyer)

“Normal” vs Conformal ST Diagram

- Constant SE course is a curve on the globe but a straight line on the conformal Mercator map.
- Constant speed-of-light is a curve on the “normal” space-time diagram but a straight line on the conformal diagram.

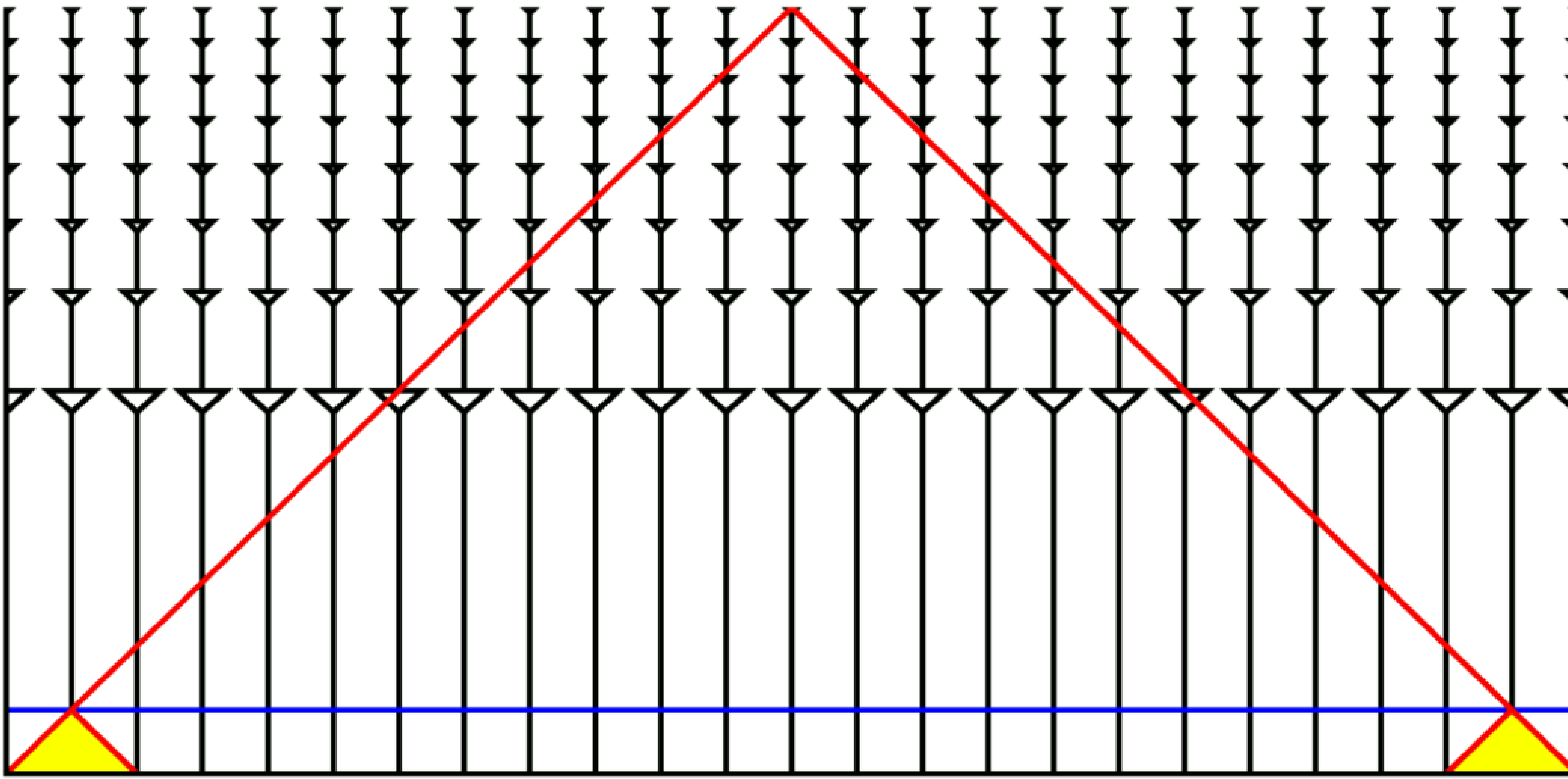




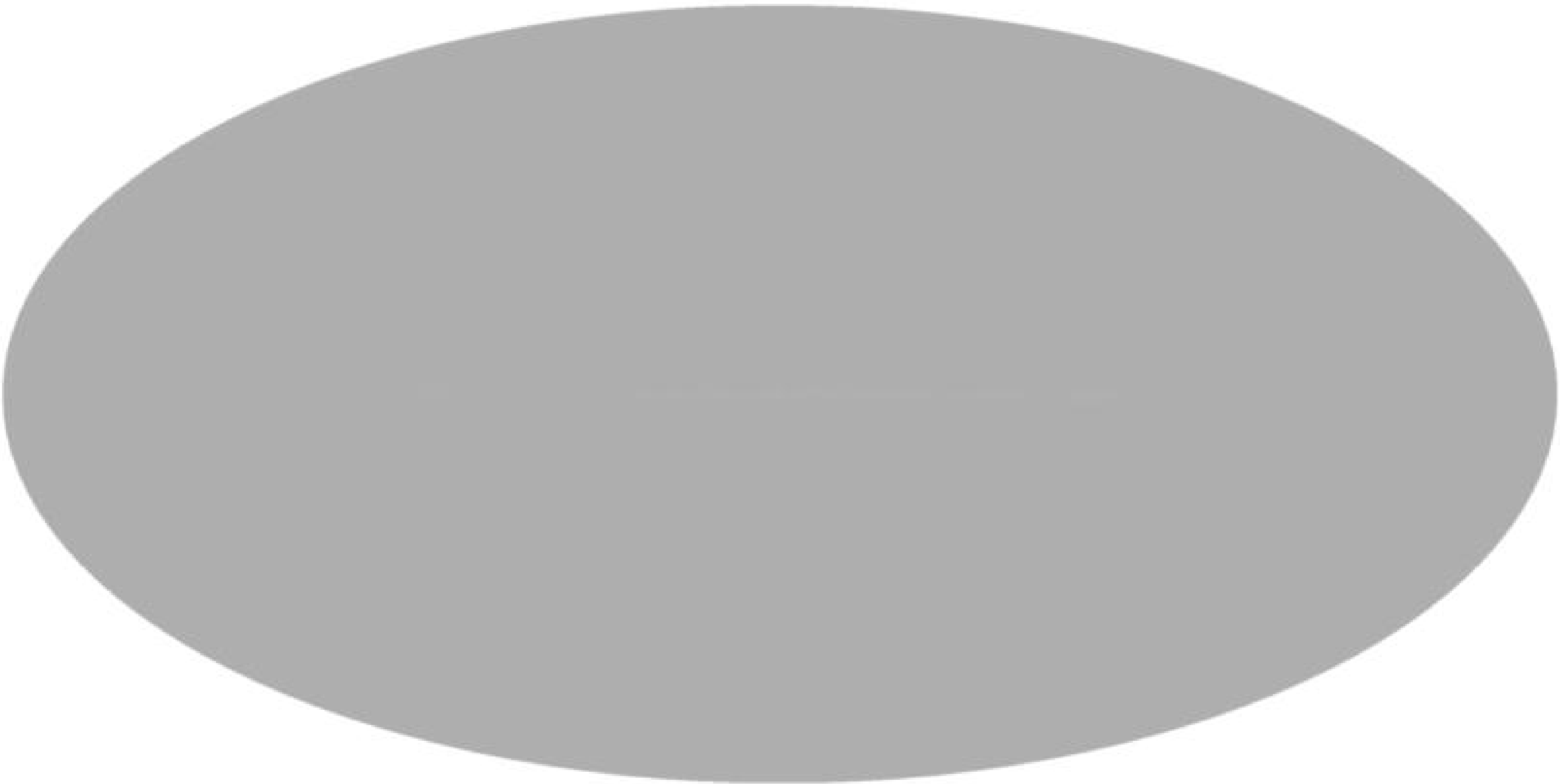


Horizon Problem

Regions seen on left and right of sky can only be influenced by the yellow areas in their past lightcones. These are disjoint, so why is the CMB T the same in both?

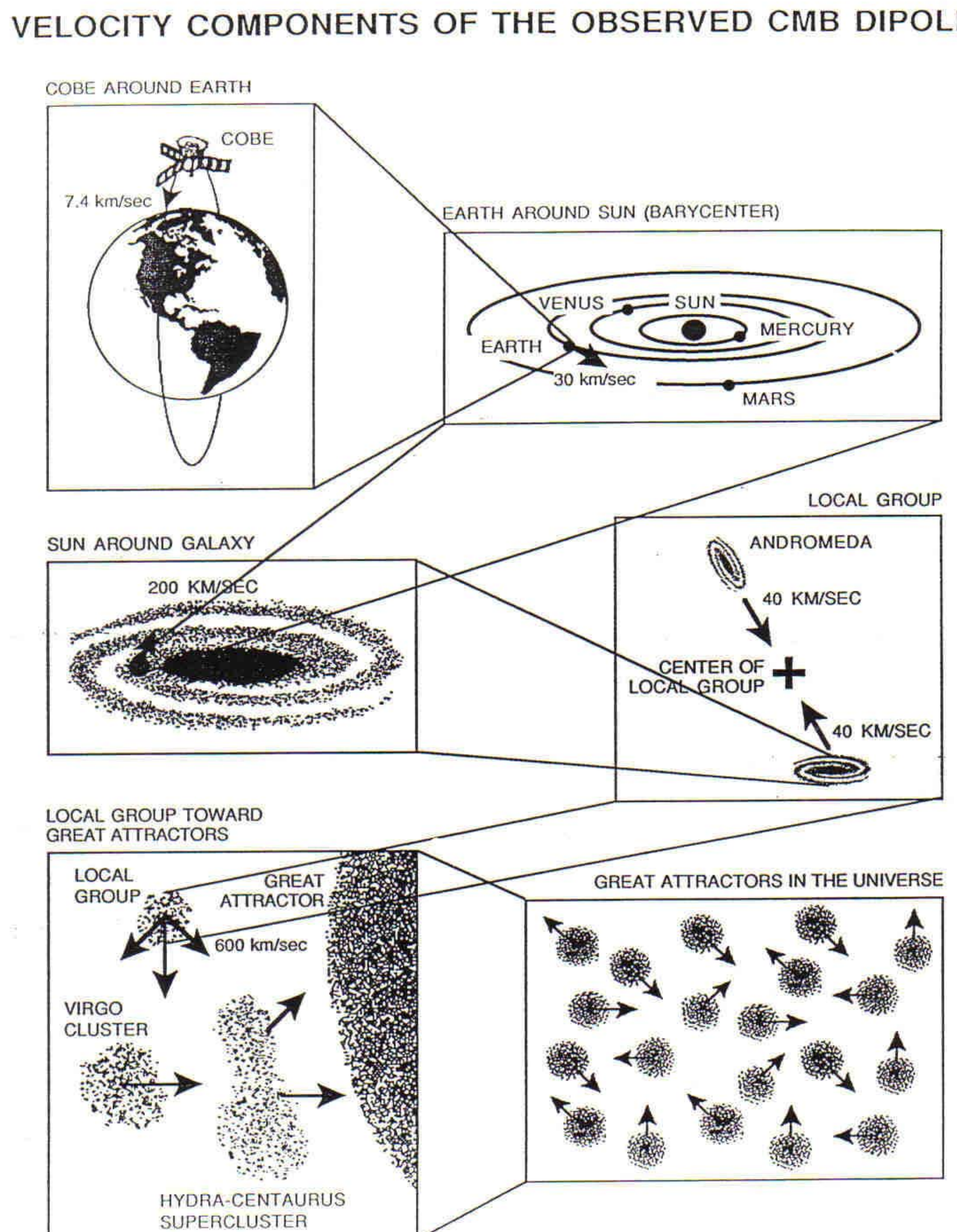


True Contrast CMB Sky



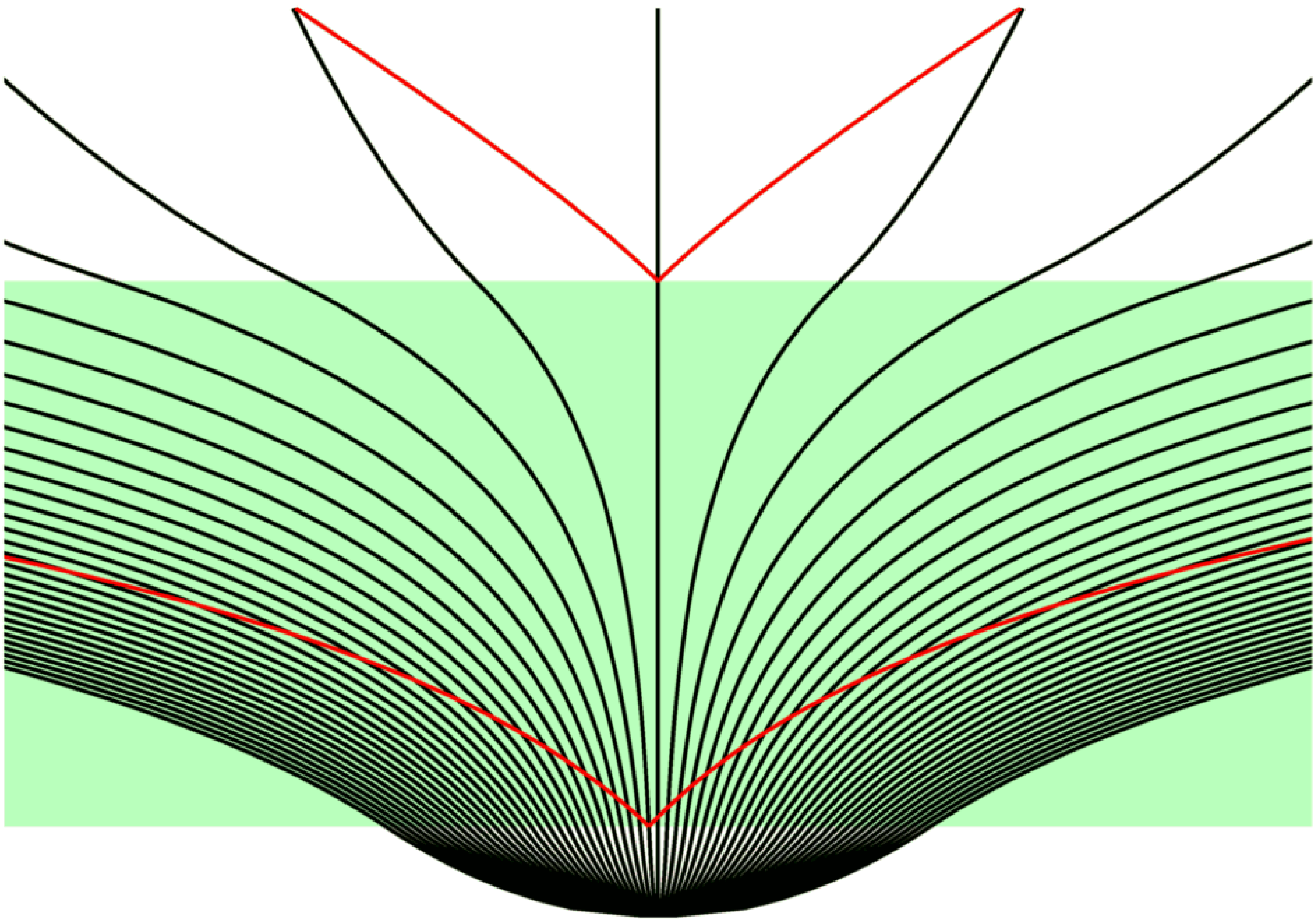
33, 41 & 94 GHz as RGB, 0-4 K scale

Enhanced Contrast:



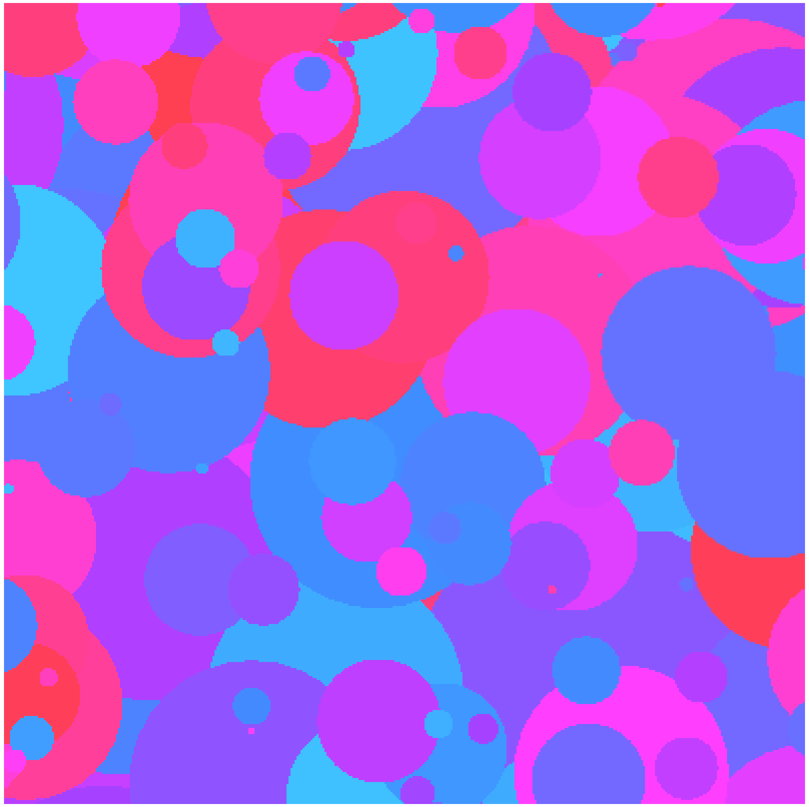
- Conklin 1969 - 2σ
- Henry 1971 - 3σ
- Corey & Wilkinson - 4σ
- Smoot *et al.* 1977 - 6σ
- Vss = 368$\pm$2 km/s

Inflation: Large Λ during an early phase

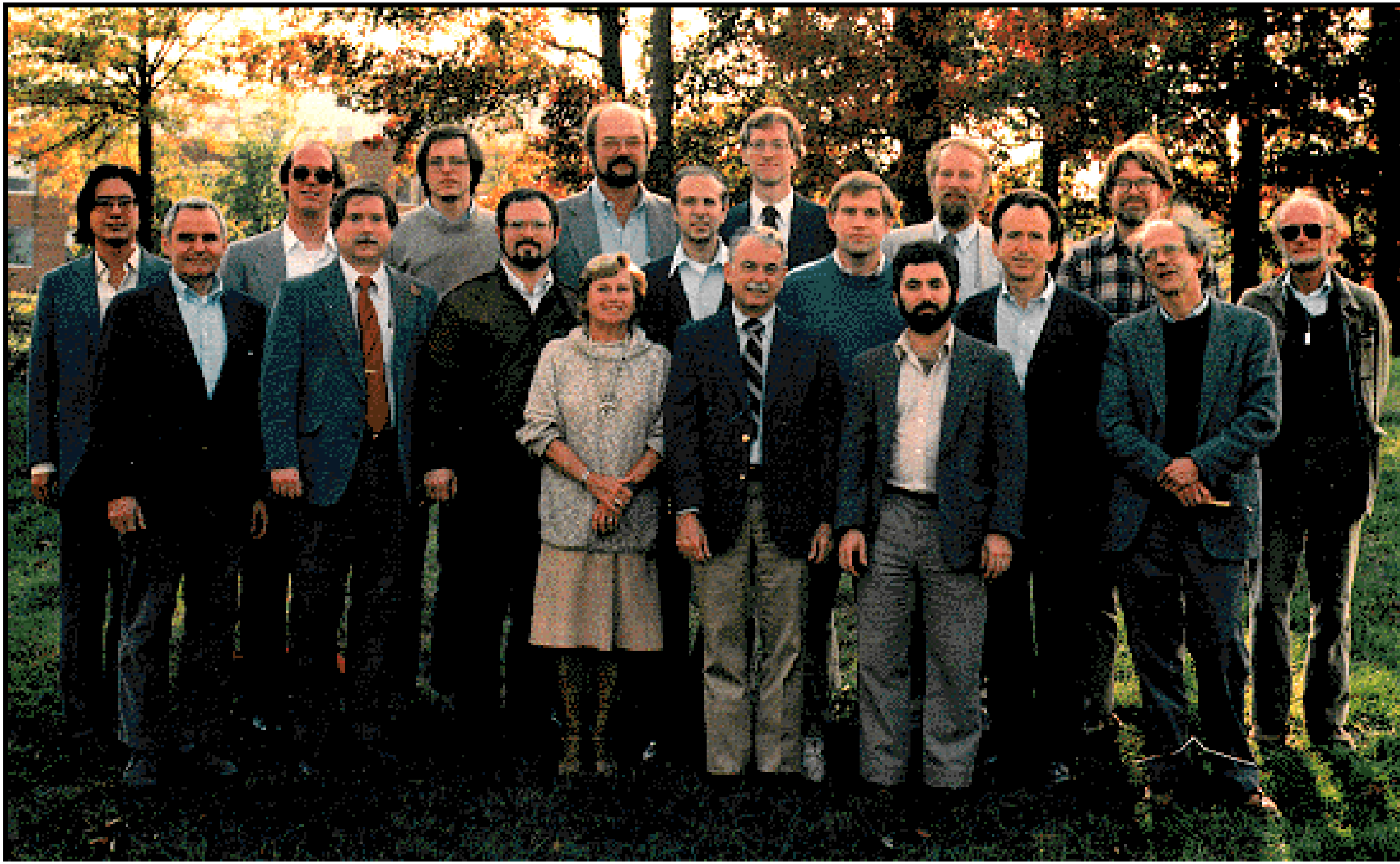


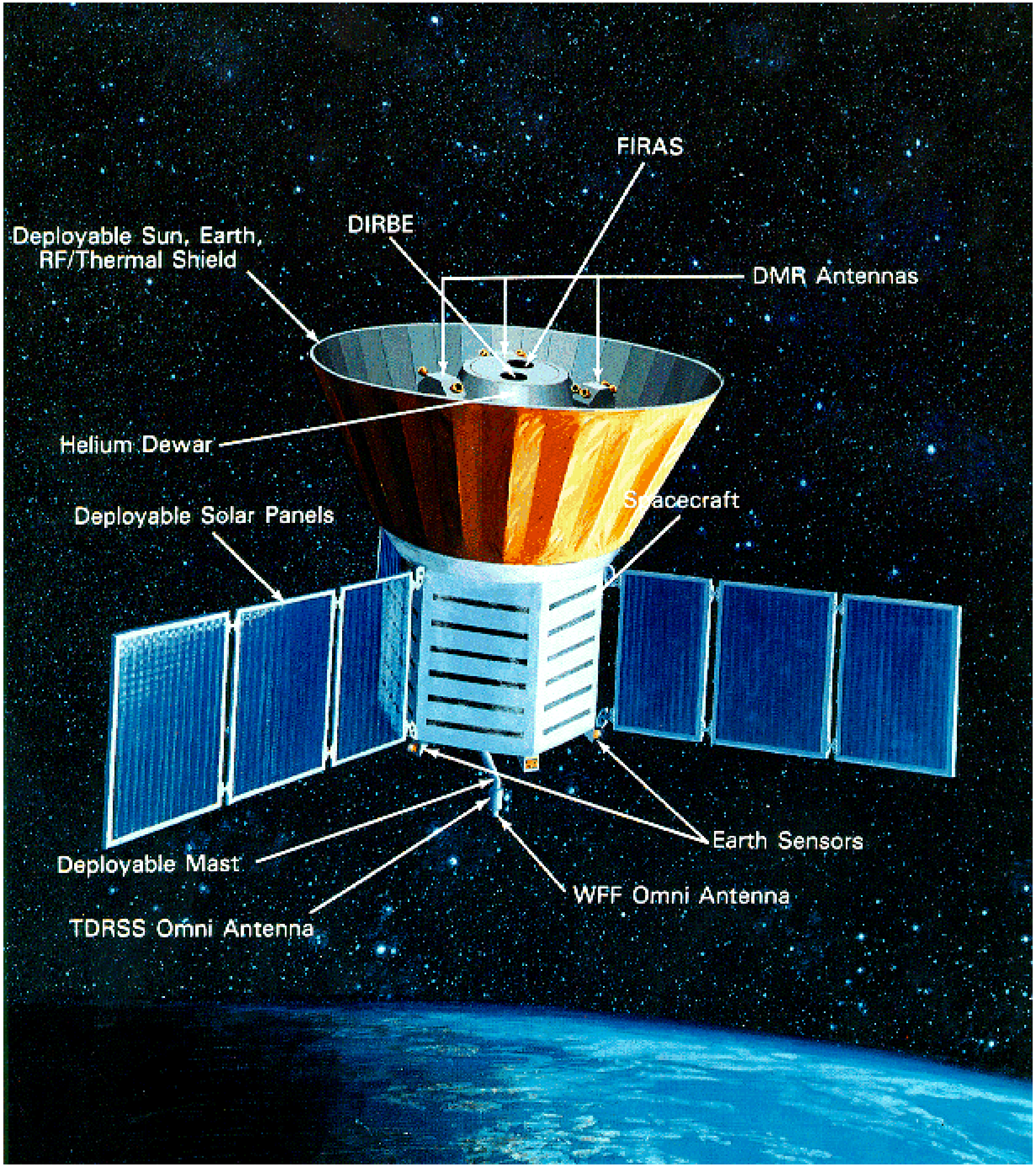
Animated View of Inflation

- 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).



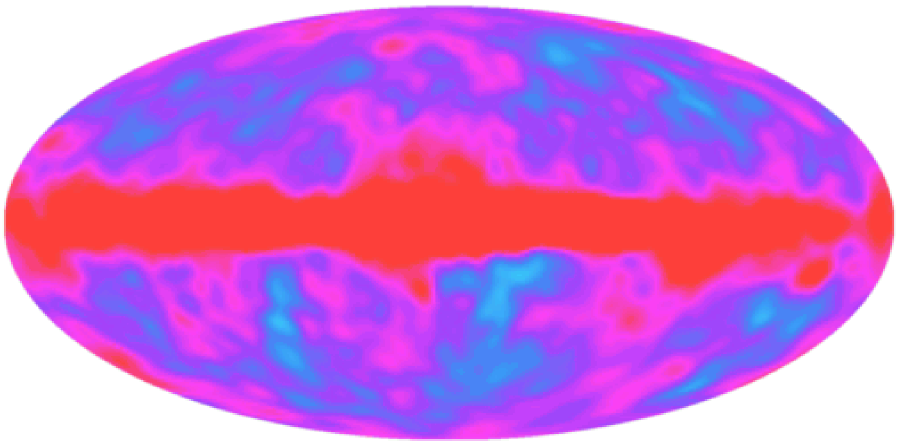
COBE Science Working Group



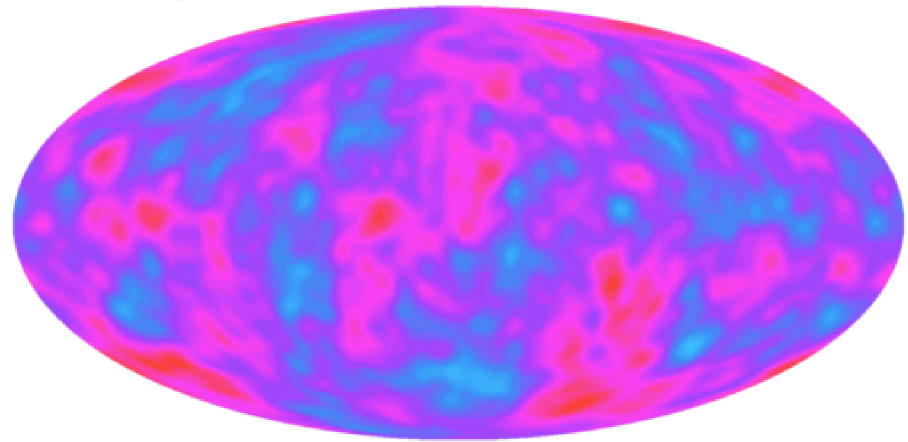

FIRAS
DIRBE
Deployable Sun, Earth, RF/Thermal Shield
DMR Antennas
Helium Dewar
Spacecraft
Deployable Solar Panels
Earth Sensors
Deployable Mast
WFF Omni Antenna
TDRSS Omni Antenna

COBE DMR vs EPAS

COBE Data



Equal Power on All Scales Model

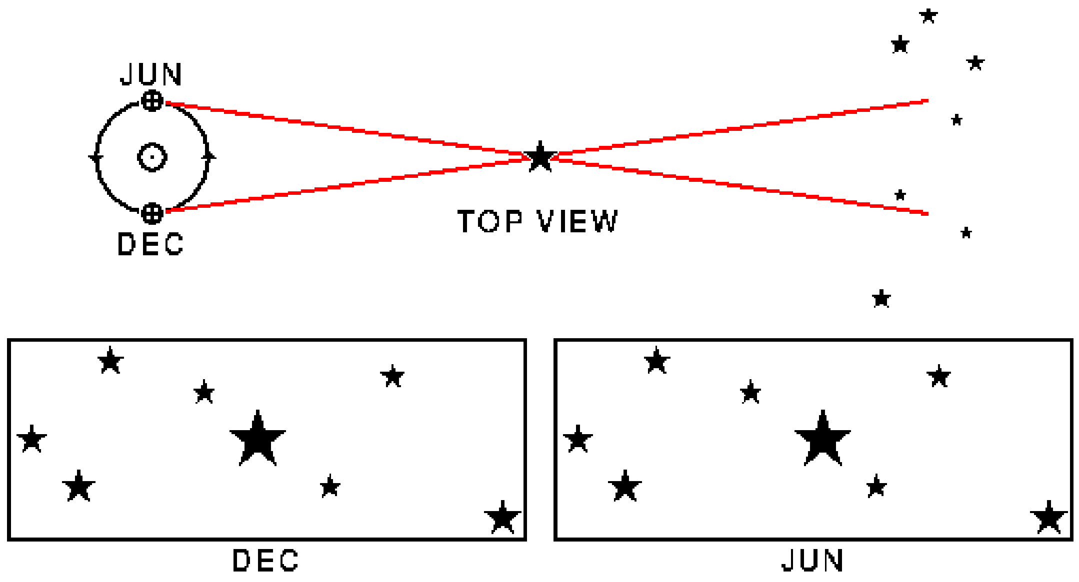


"Chi-by-eye" suggests that the "Equal Power on All Scales" prediction of inflation is correct.

Astronomical Quantities:

Astronomical Quantities:

- 1 parsec means a parallax of 1 arc-second
- Hence it is 206265 astronomical units or 3.085678×10^{18} cm or 3.26 light-years

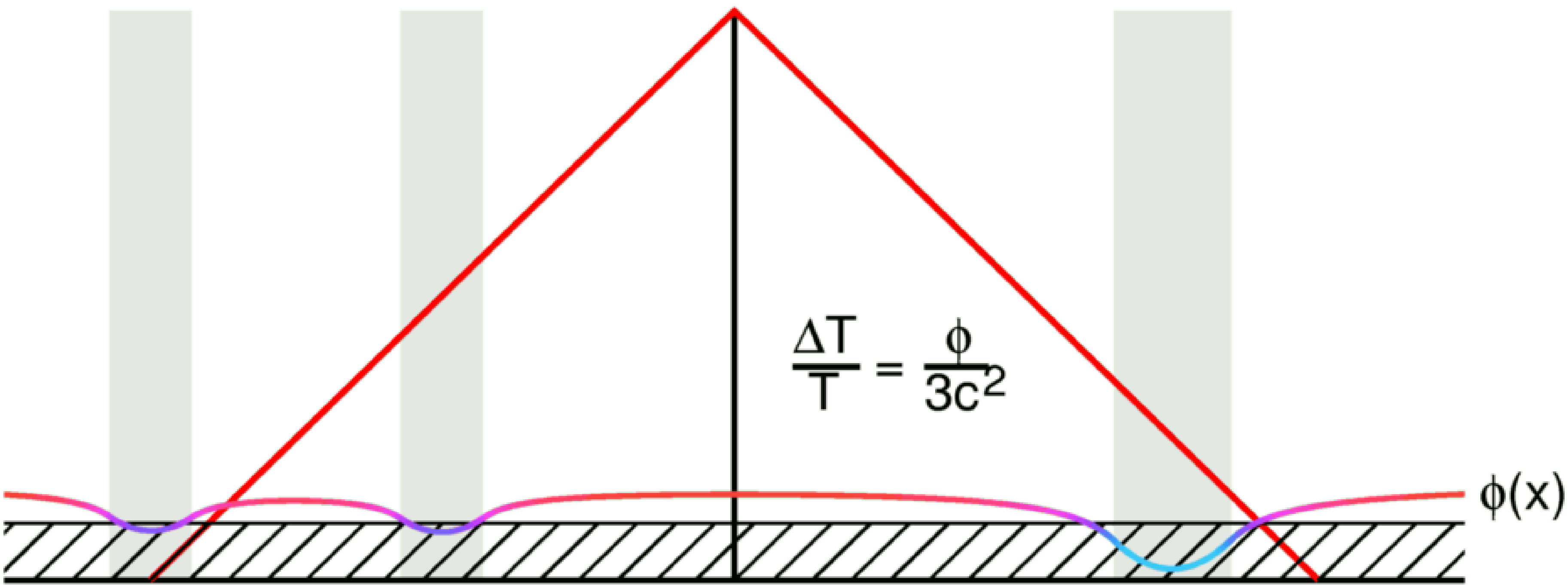


DEFINITIONS & DERIVATIONS

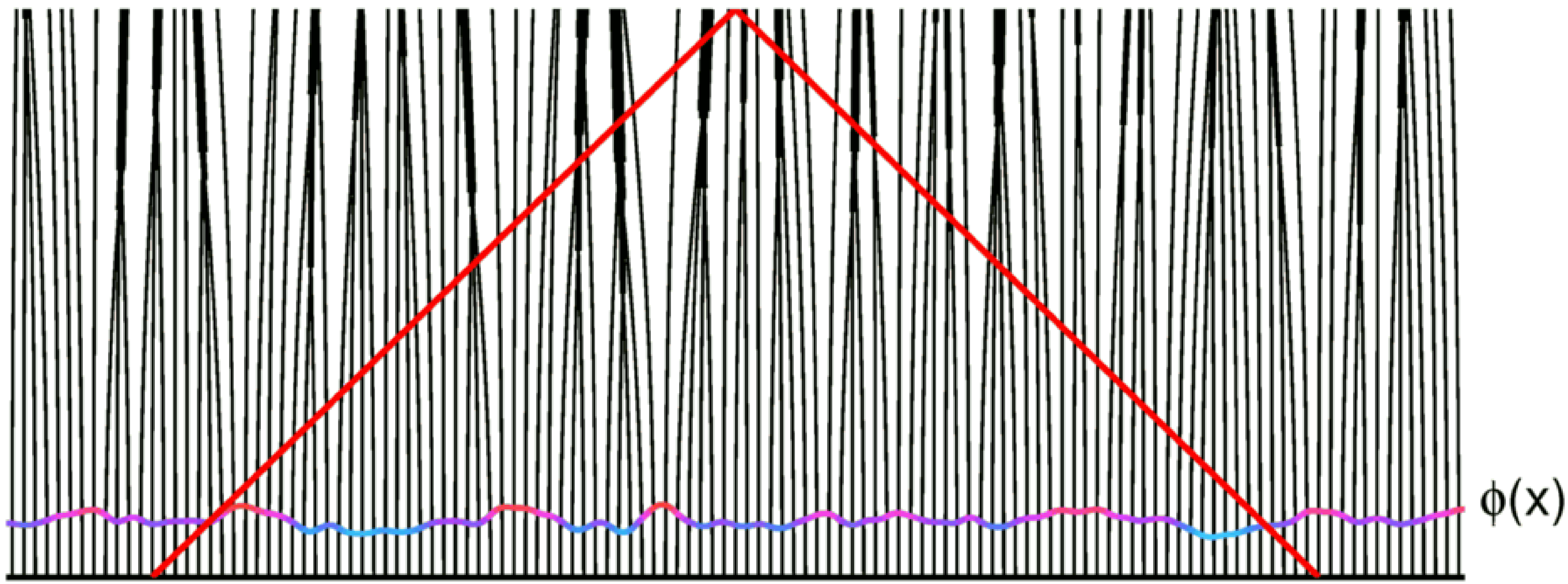
- $t_\circ$: the age of the Universe.
- $a(t)$: the scale factor. $D_{AB}(t) = a(t)D_{AB}(t_\circ)$.
  - $a(t_\circ) = 1$.
  - $a(0) = 0$ and $t = 0$ at the Big Bang.
- $H(t) = \dot{a}/a$, and $H_\circ = H(t_\circ)$. $h = H_\circ/(100\ \mathrm{km/sec/Mpc})$.
- Hubble velocity $v = d(D_{AB}(t))/dt = H(t)D_{AB}(t)$ exactly.
- If $v = HD = v_{esc} = \sqrt{2GM(r < D)/D}$
  then $\rho = \rho_{crit} = 3H^2/(8\pi G)$, the critical density.
- $\Omega = \rho/\rho_{crit}$ $\qquad\omega = \Omega h^2 = \rho/(18.8\ \mathrm{yoctograms/m^3})$.

Details

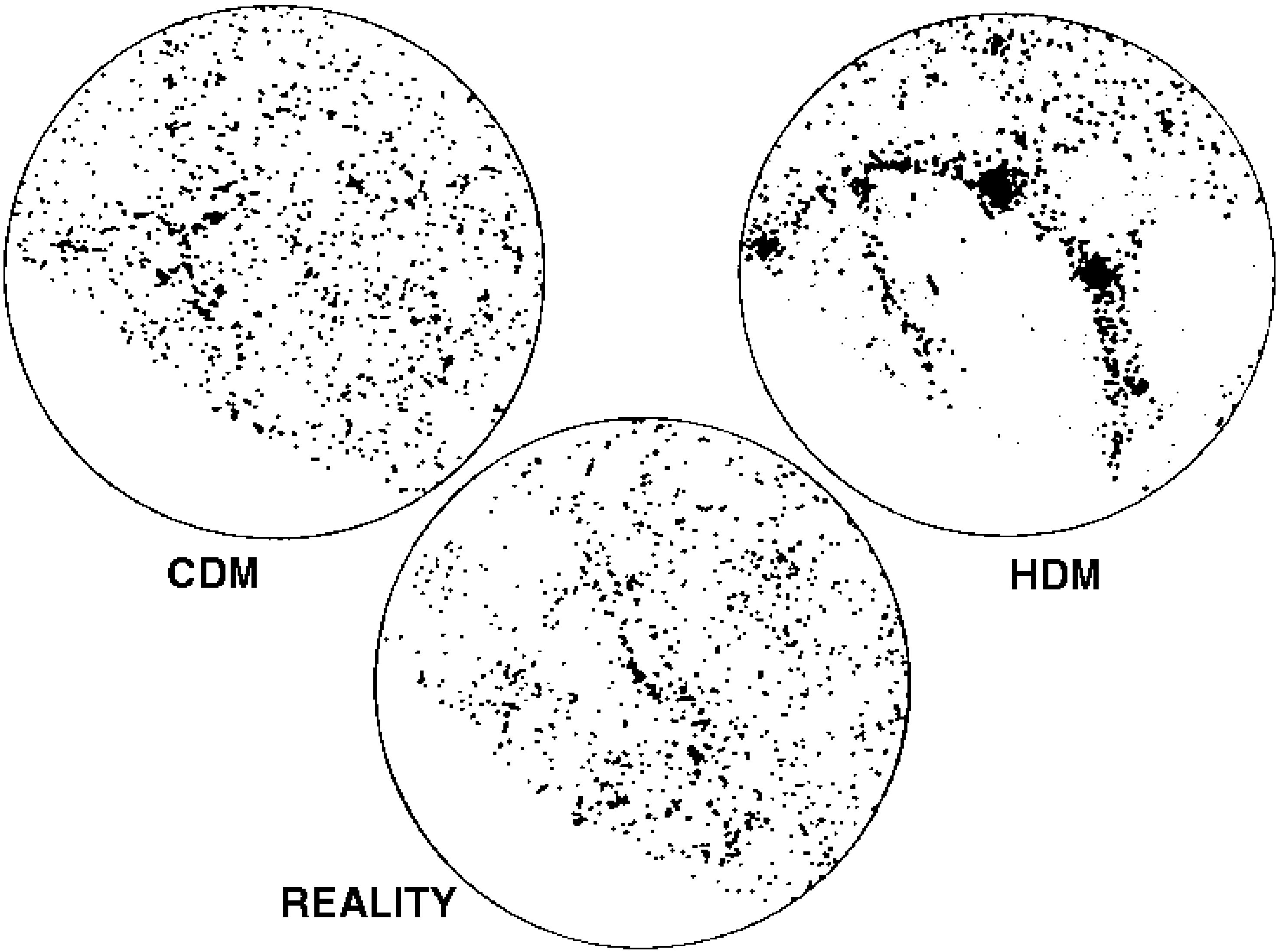
Sachs-Wolfe Effect



Measured $\Delta\phi$ Leads to Structure



Need Cold Dark Matter

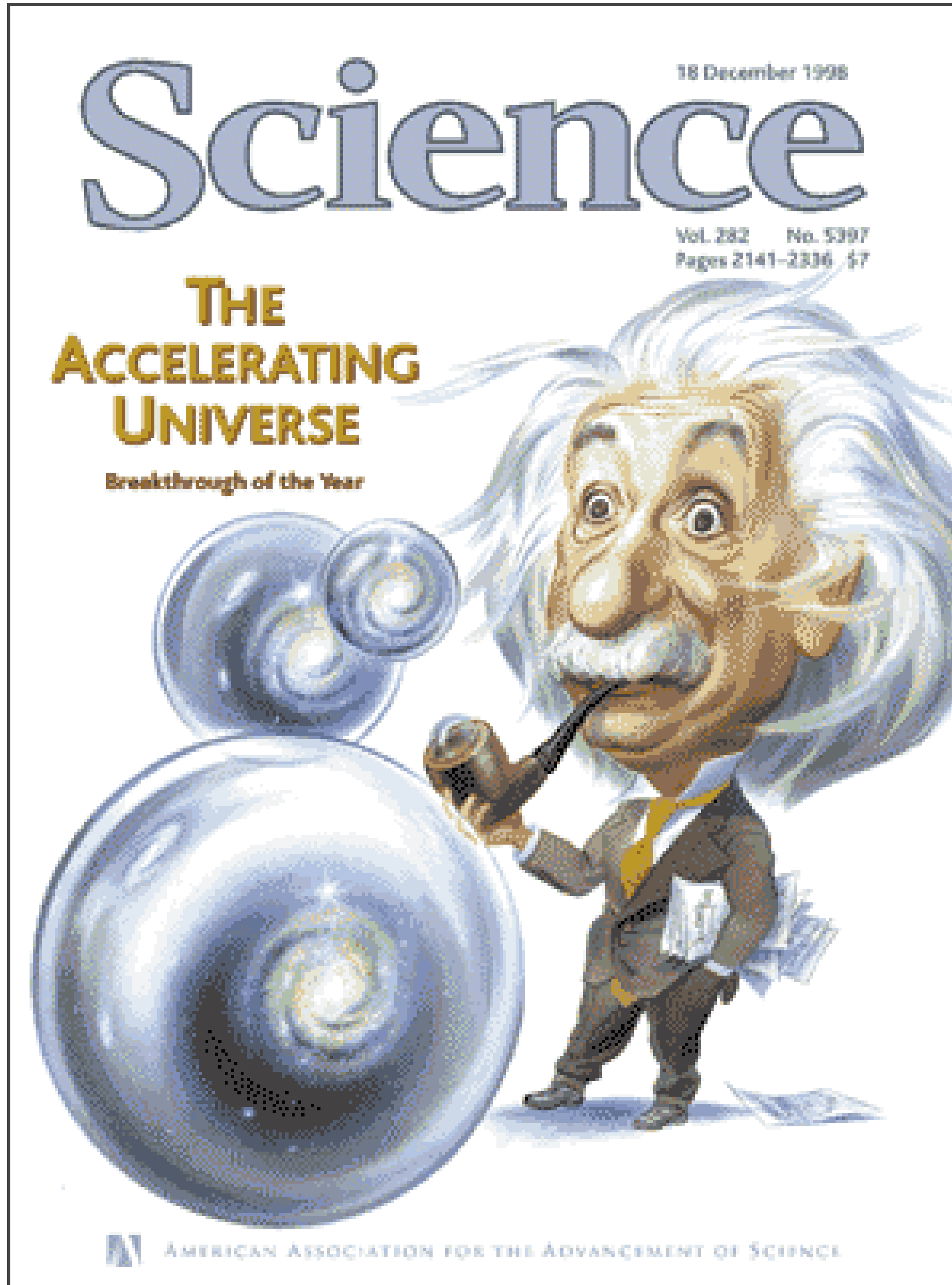


Accelerating Universe: 1998

Distant (high z) supernovae fainter than expected.

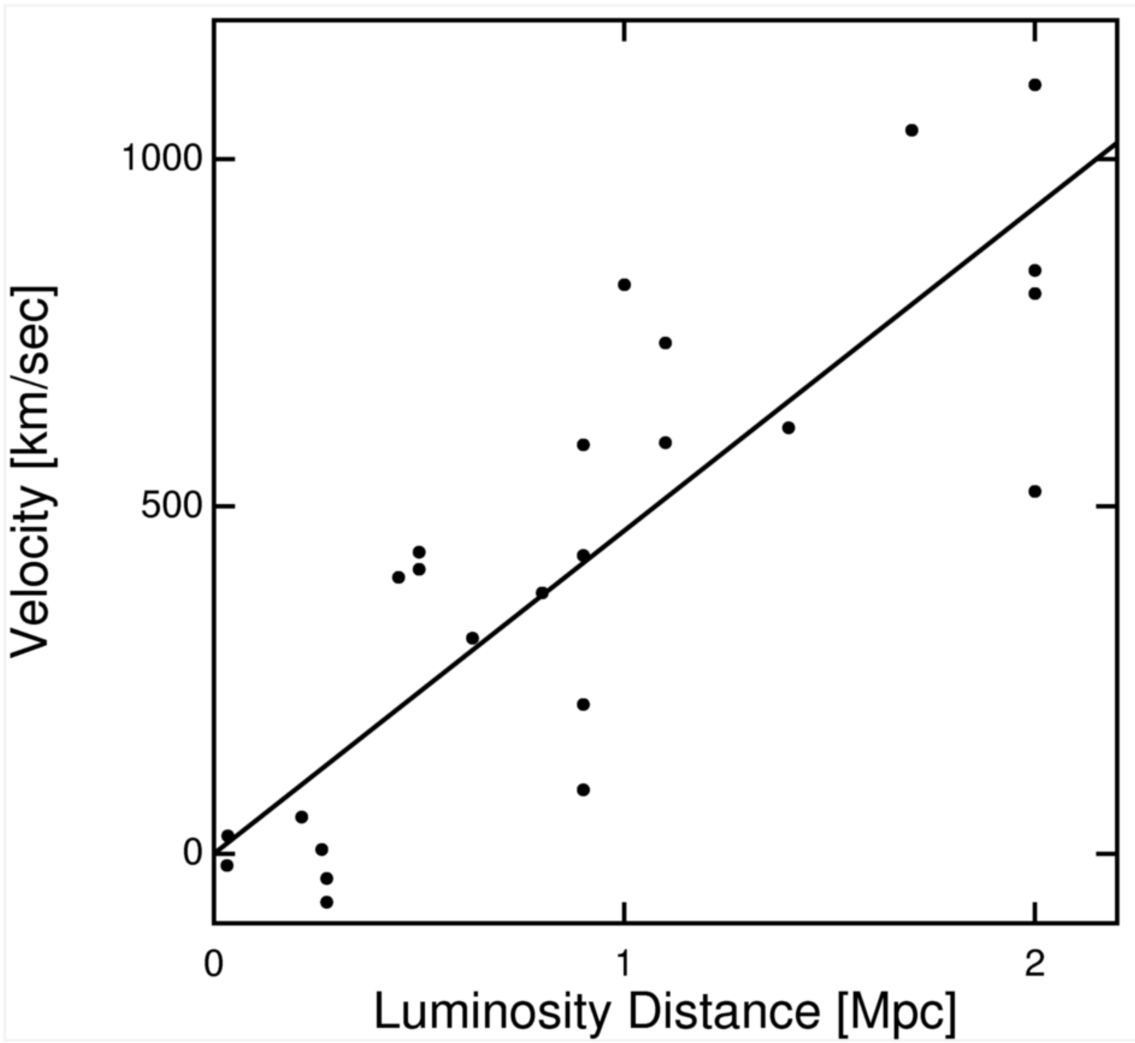
This was the AAAS discovery of the year in 1998.

Λ causes acceleration!



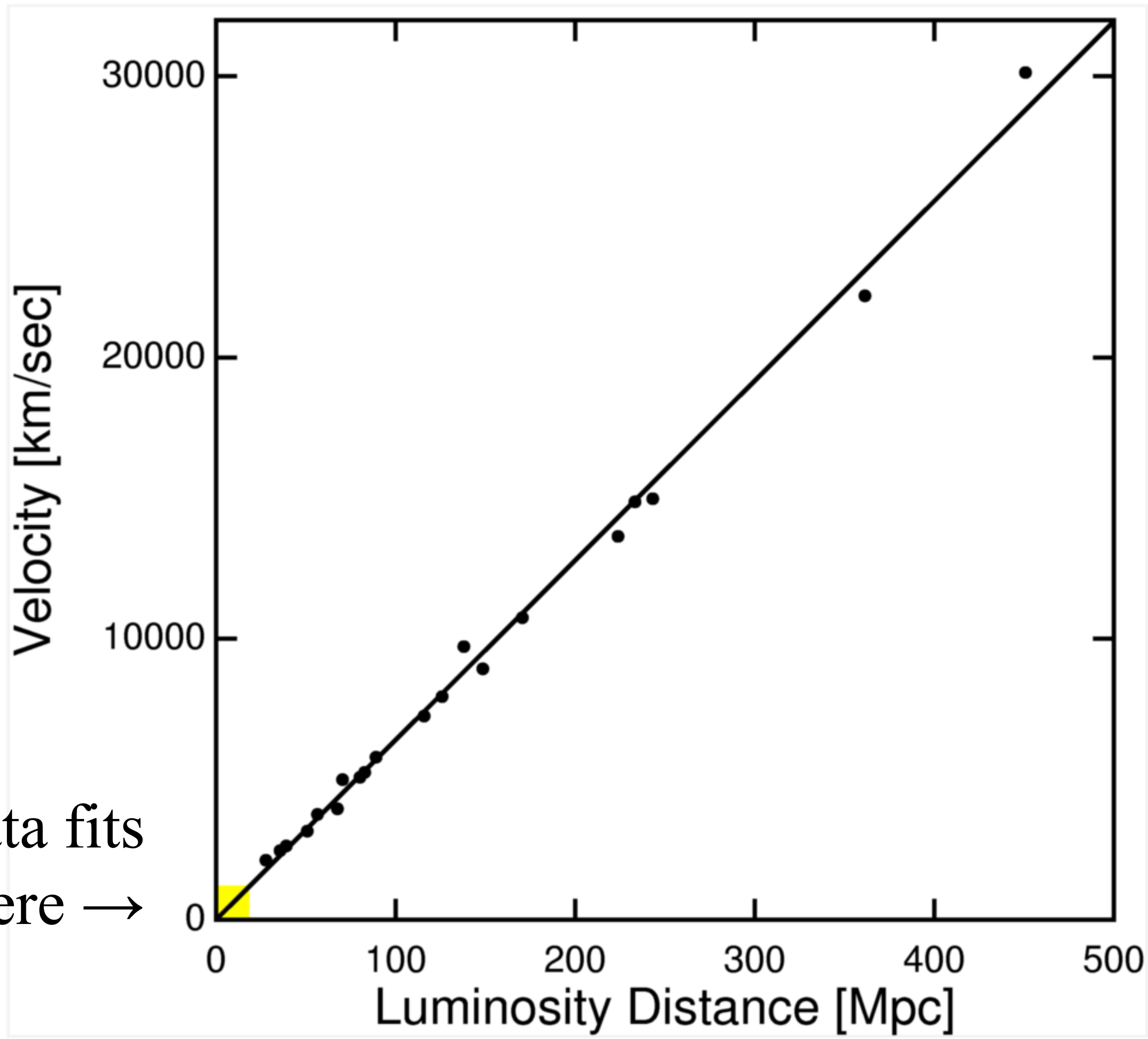
We recently learned how to read the “wattage” label on supernovae:

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

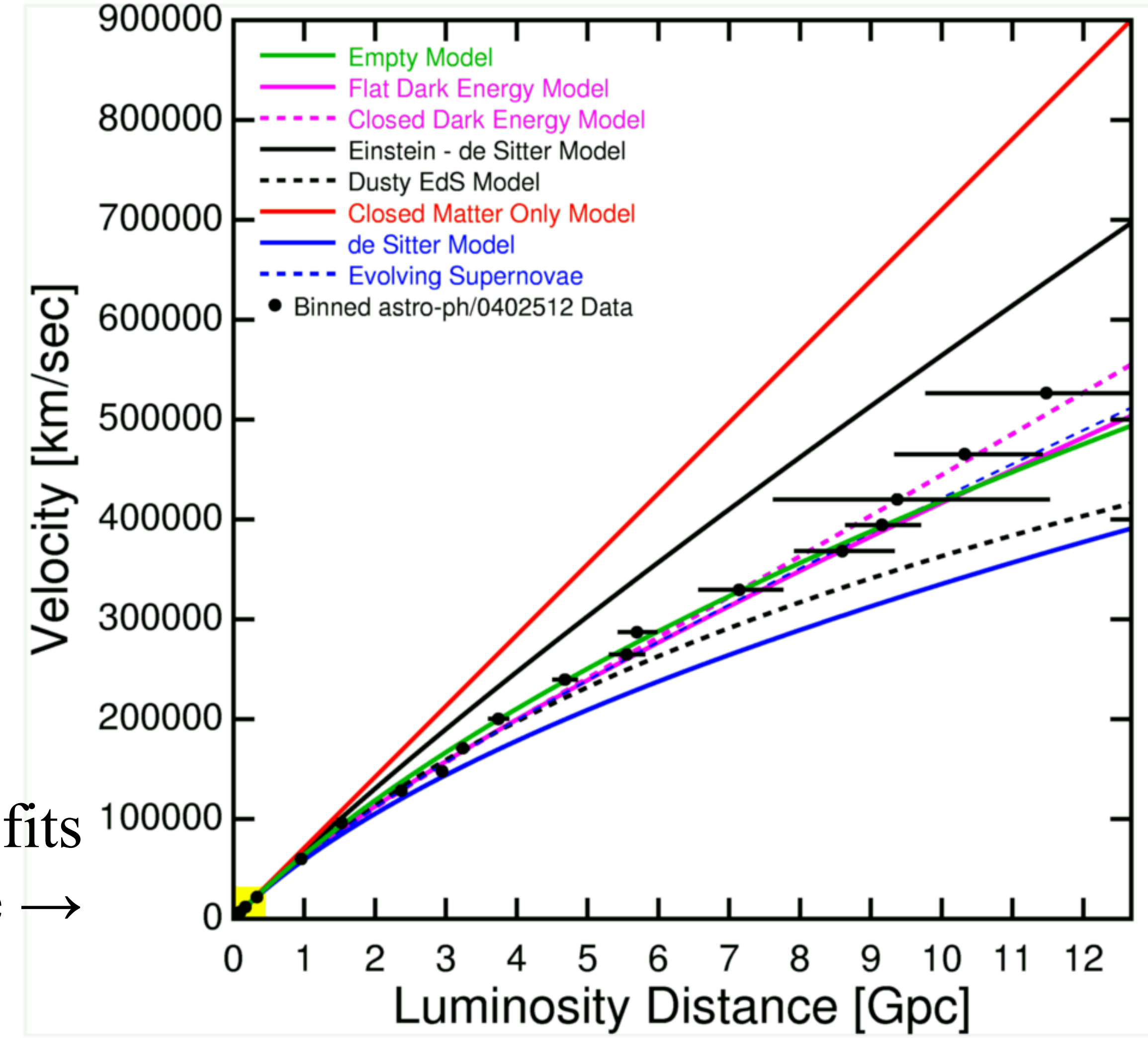


As a result, data on velocity vs distance is now much better! 1995

1929 data fits in here →



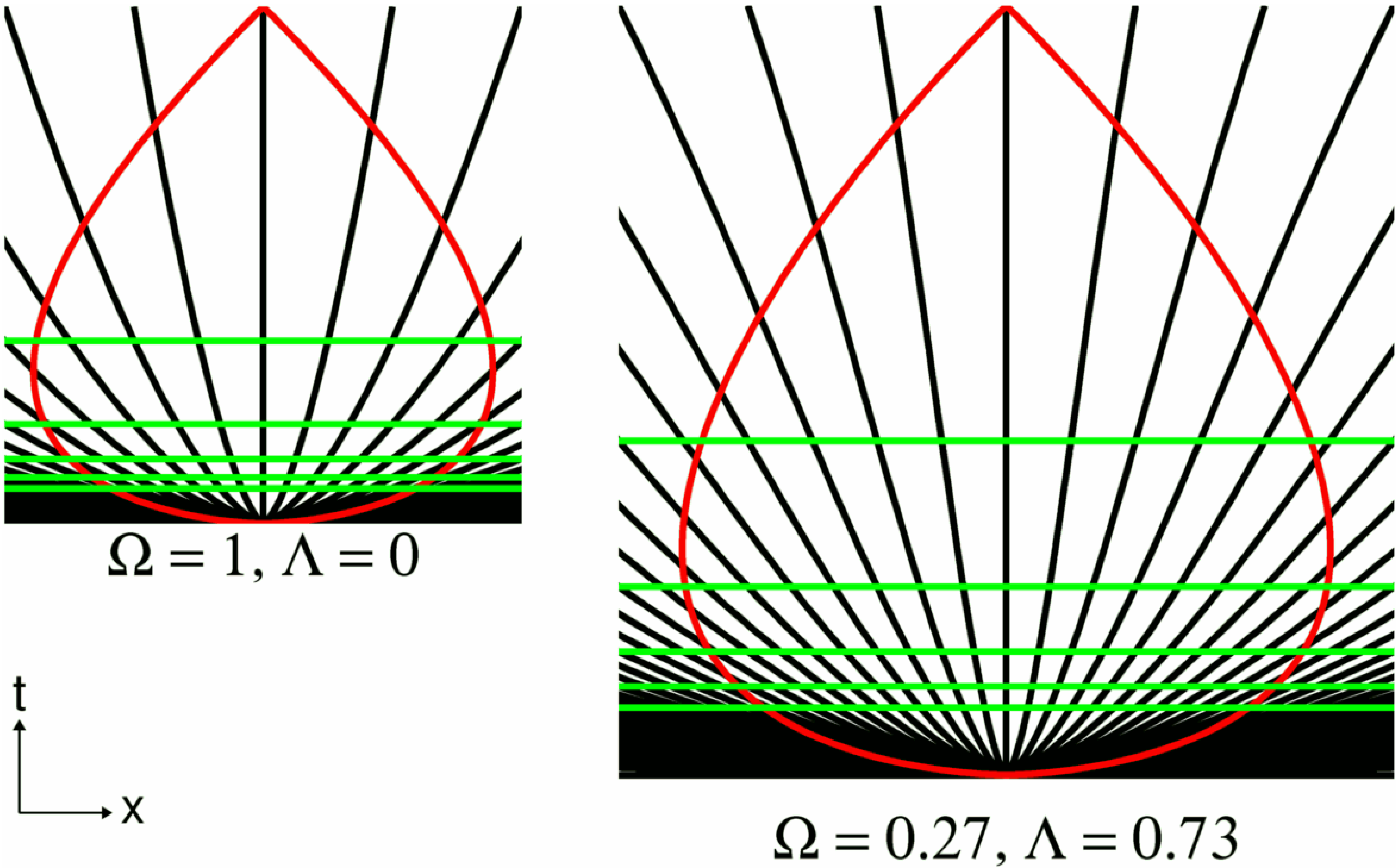
As a result, data on velocity vs distance is now much better! 2004



1995 data fits in here →

v = cz

Acceleration causes Faintness



COBE View of CMB was Blurry

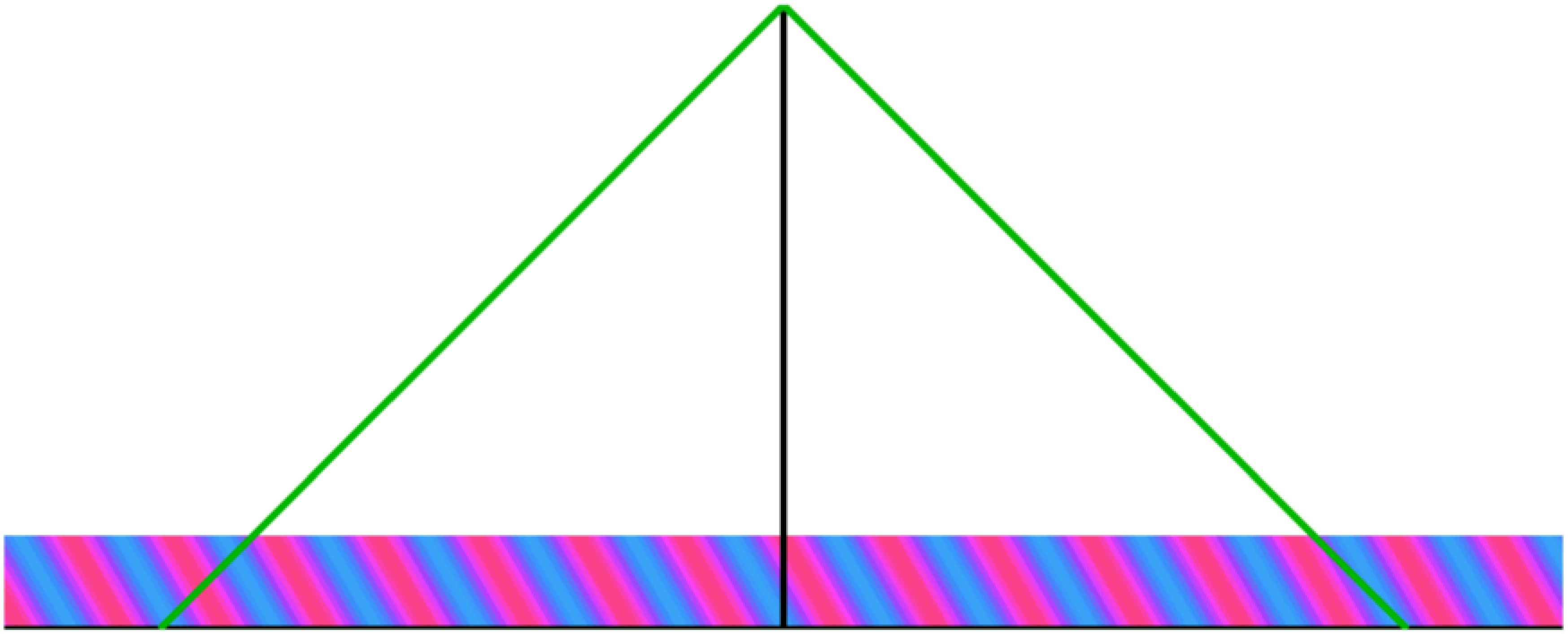
Sometimes higher resolution...

reveals the secret of the Universe

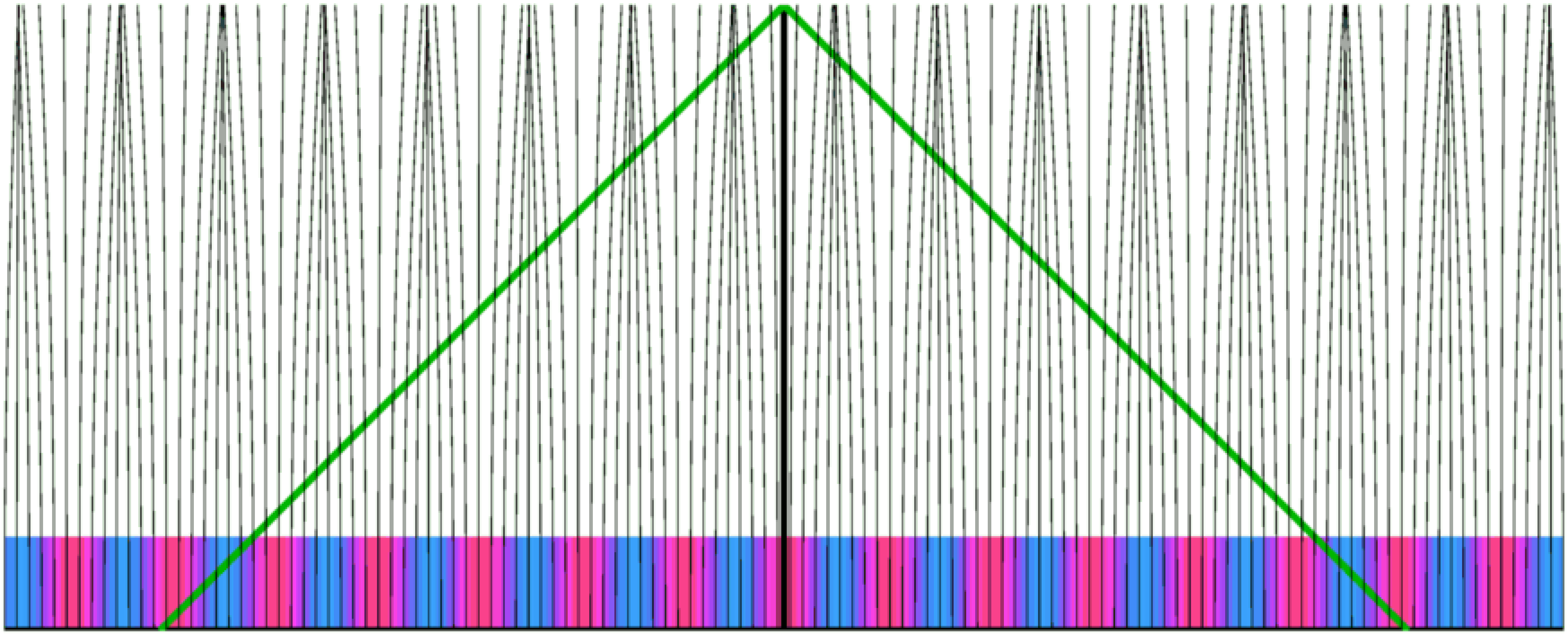
Two Fluids in the Early Universe

- 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



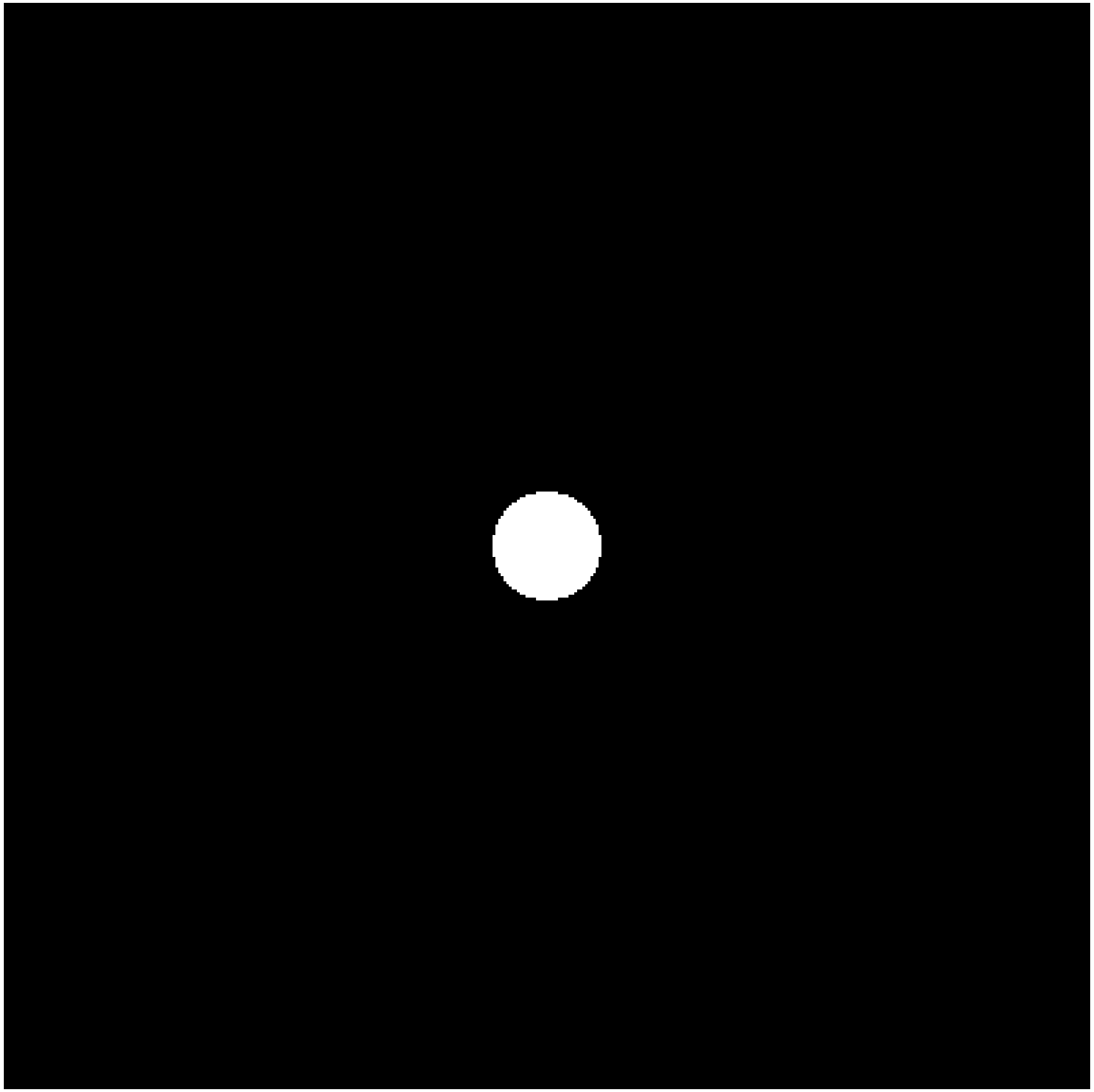
Interference at last scattering

- 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.

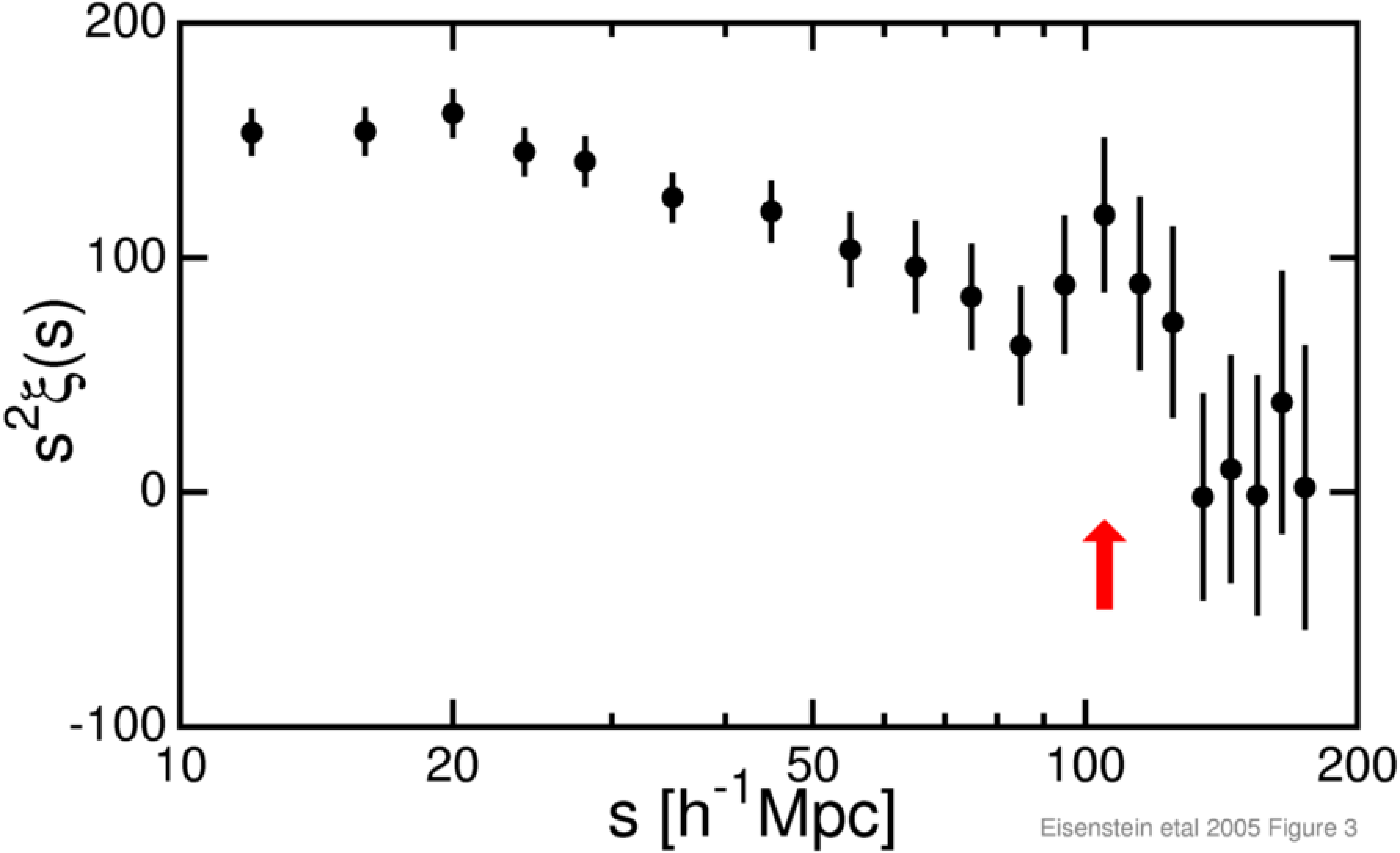
Spreading Sphere of Sound

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.

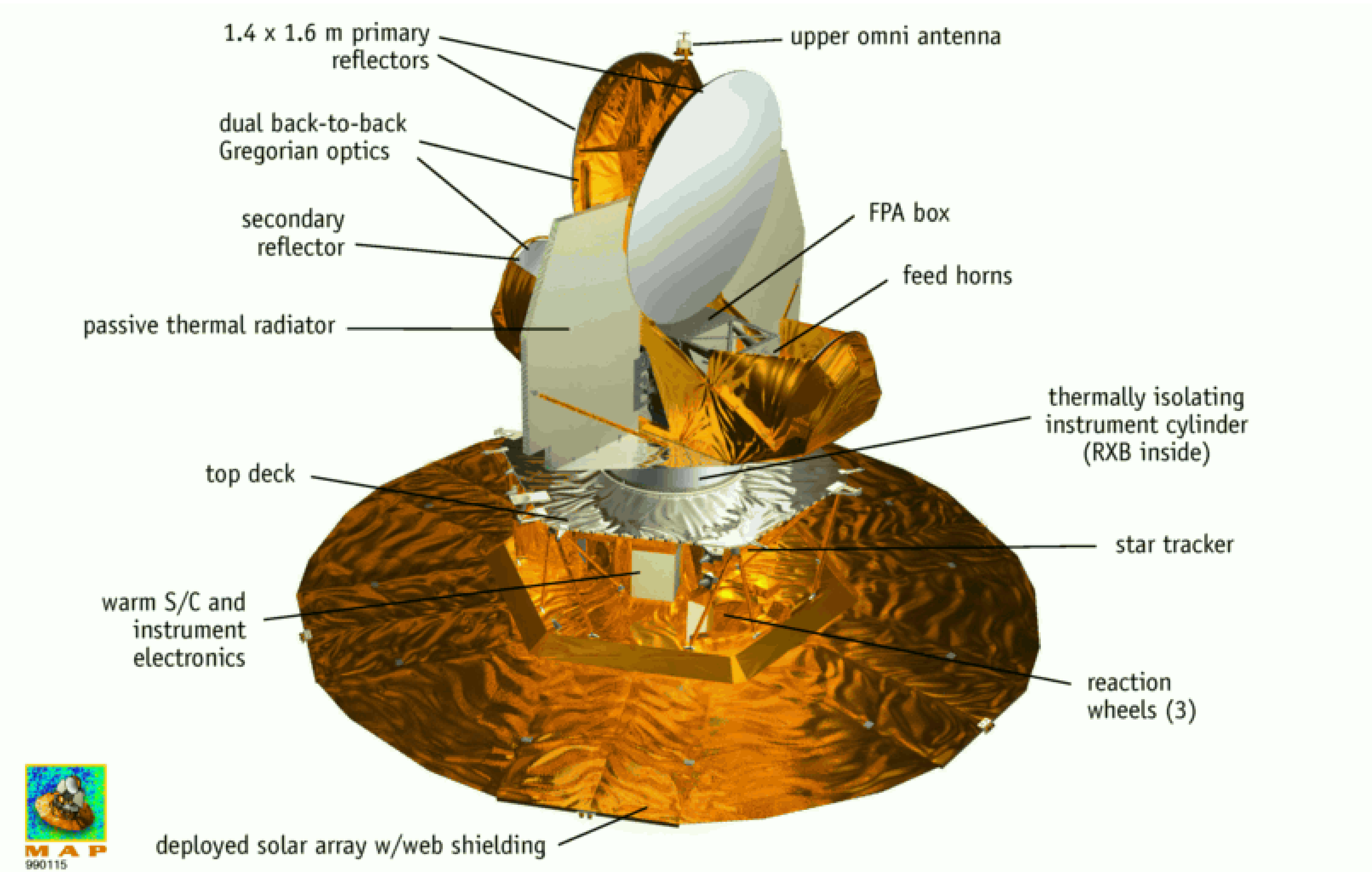


Baryonic Oscillations in SDSS LRGs

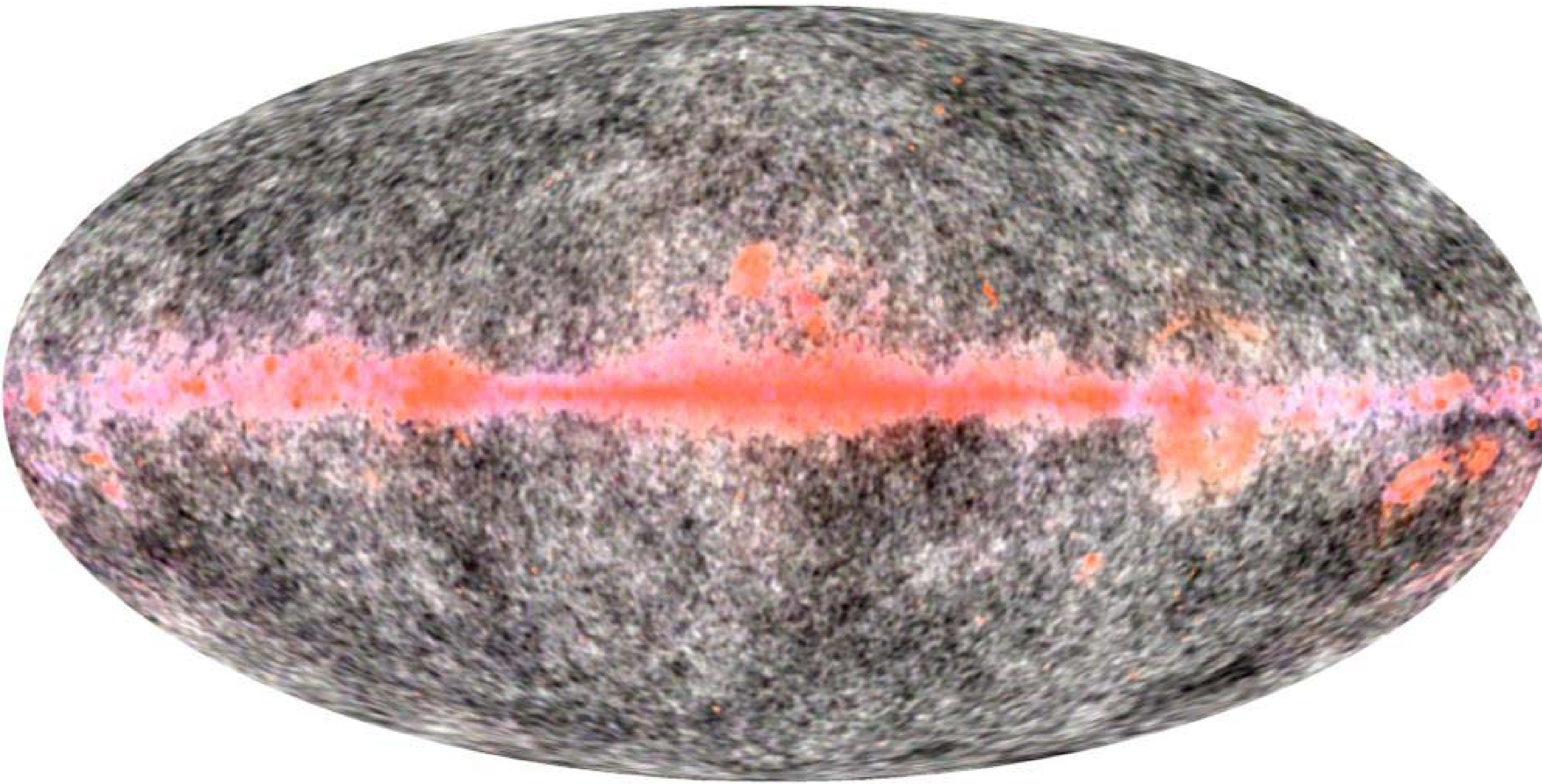


WMAP Science Working Group

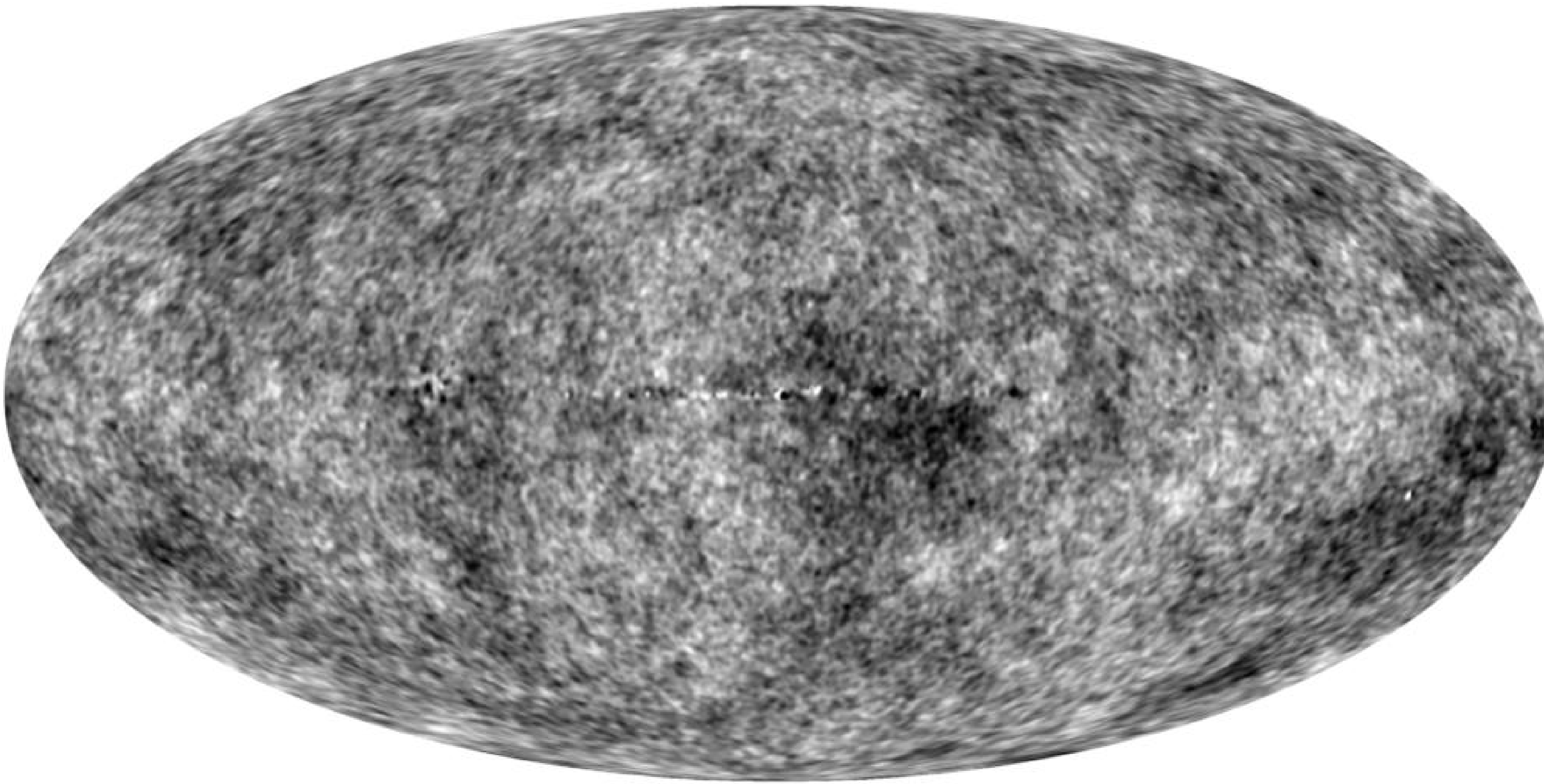
A New Cosmology Satellite



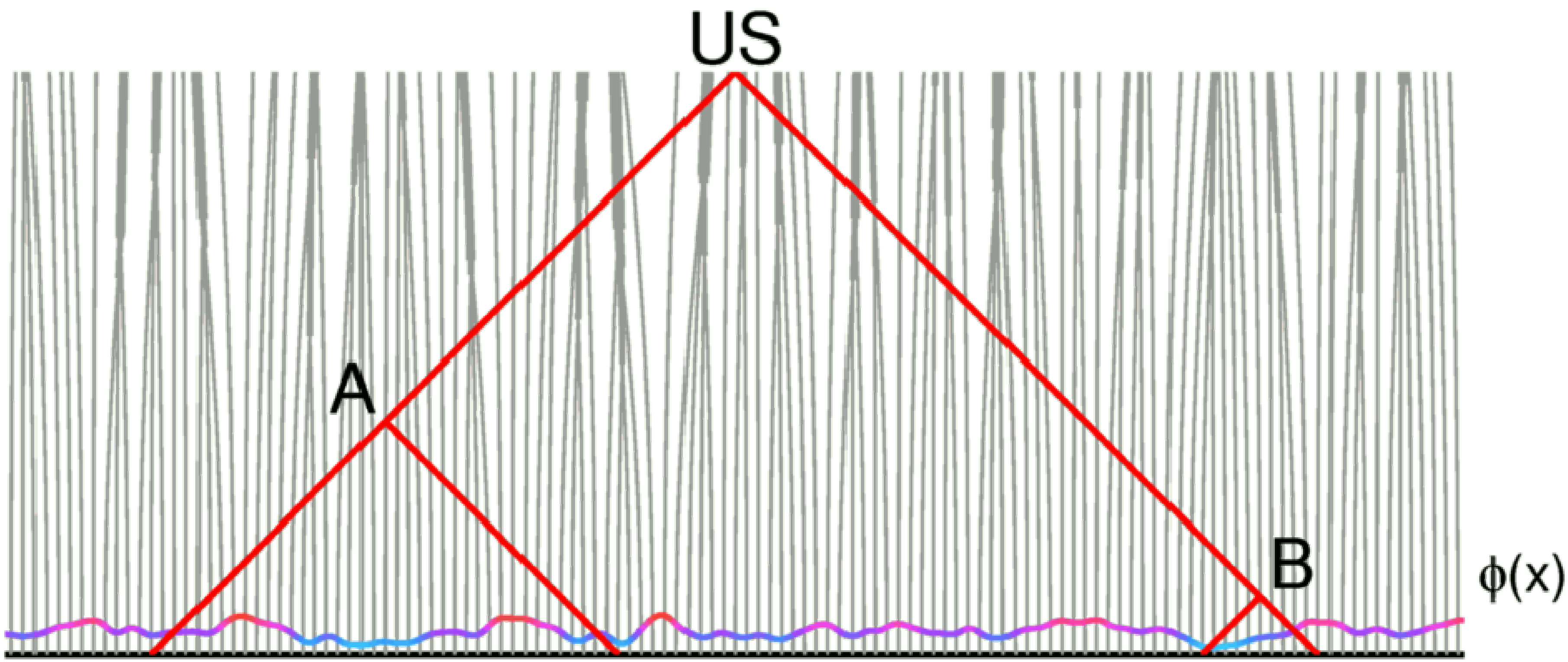
WMAP 41, 61 & 94 GHz Map



WMAP “No galaxy” ILC Map



Gravitational Potential $\rightarrow \Delta T$



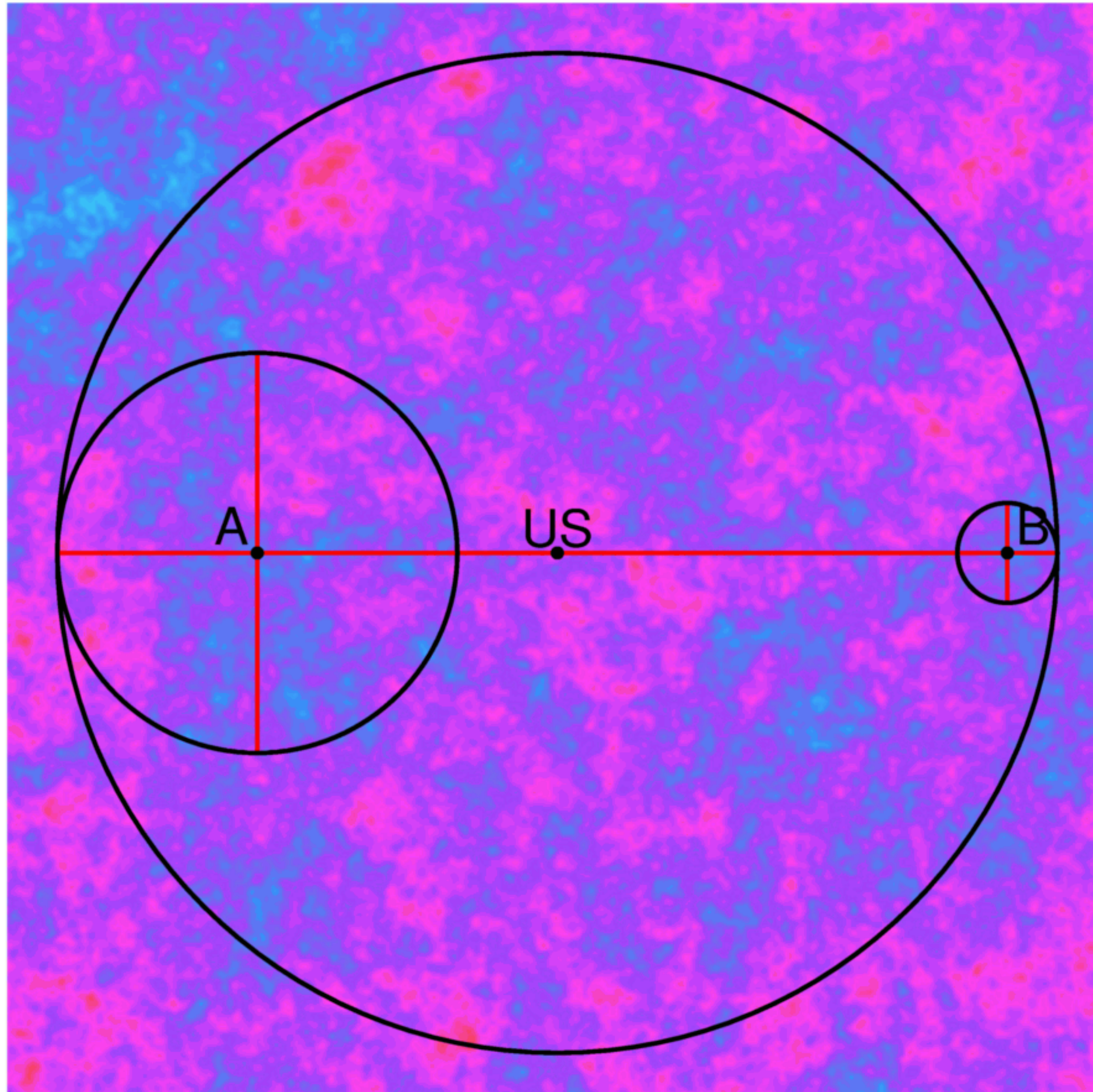
This potential also leads to large scale structure formation.

Reionization puts scatterers at A: many degree scale

Scatterers during recombination are at B: sub-degree scale

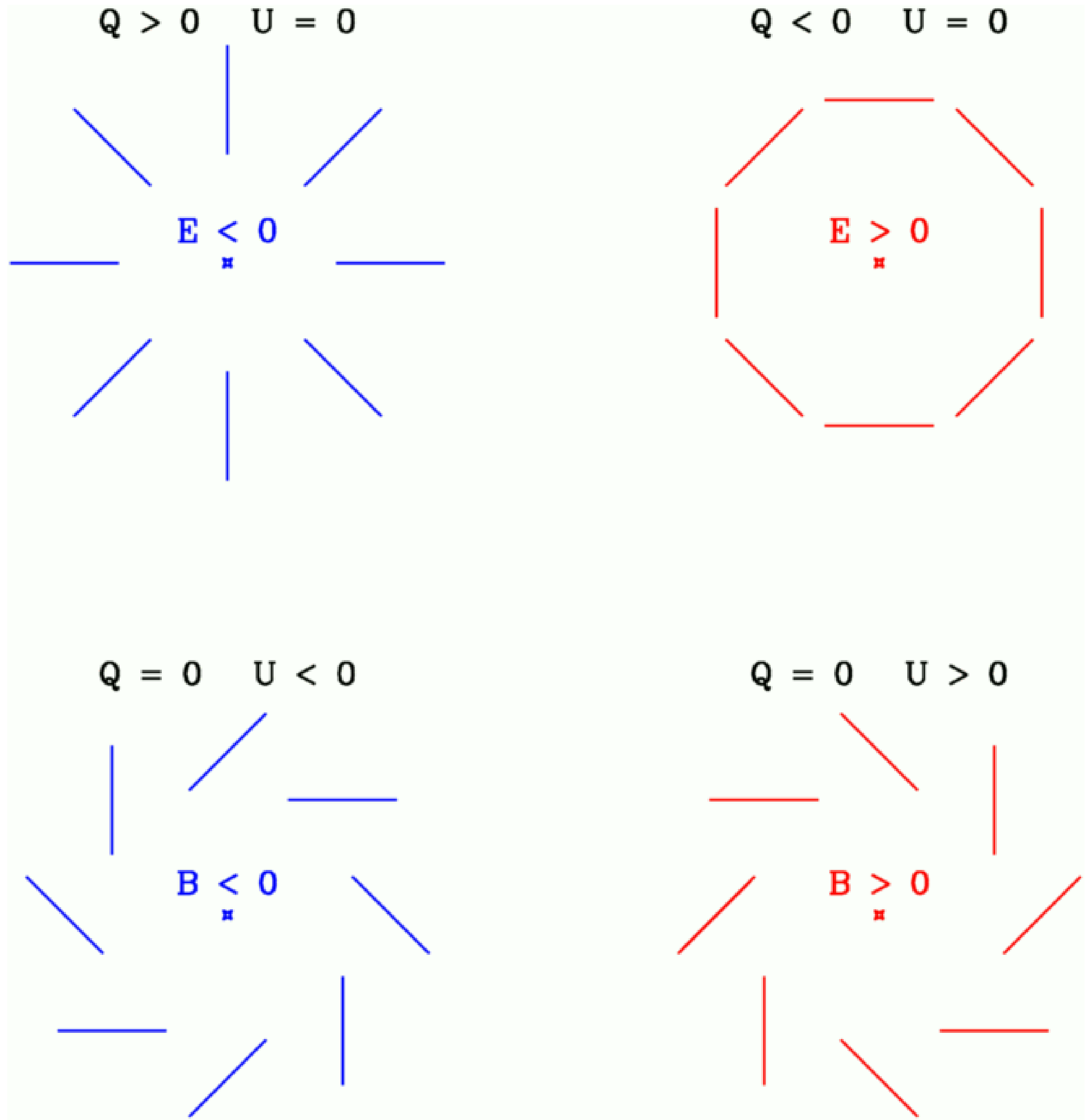
Top view of same S-T Diagram

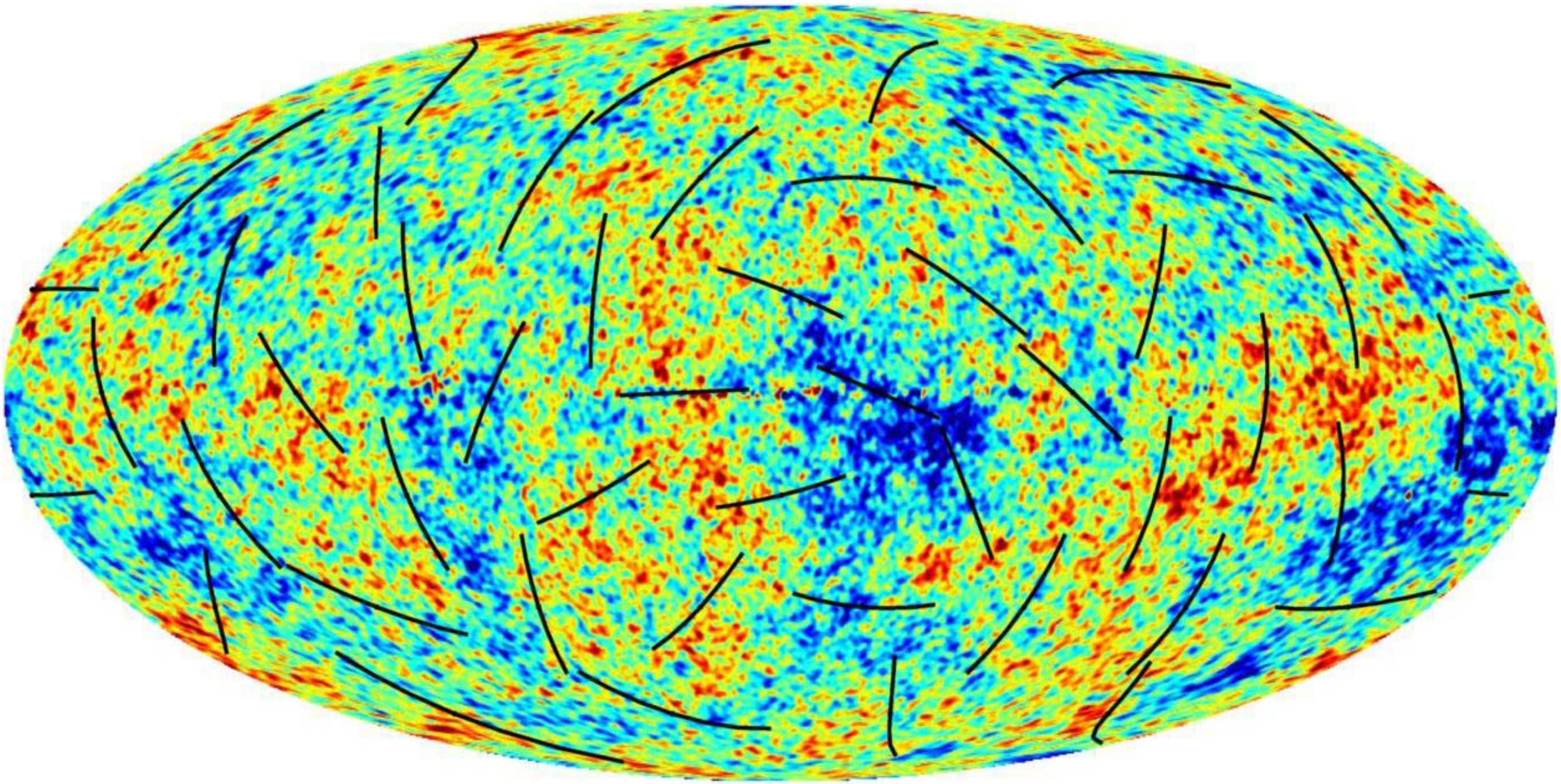
- Electrons at A or B see a somewhat different piece of the surface of last scattering than we do.
- If electrons at A or B see a quadrupole anisotropy then we get polarization.



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.





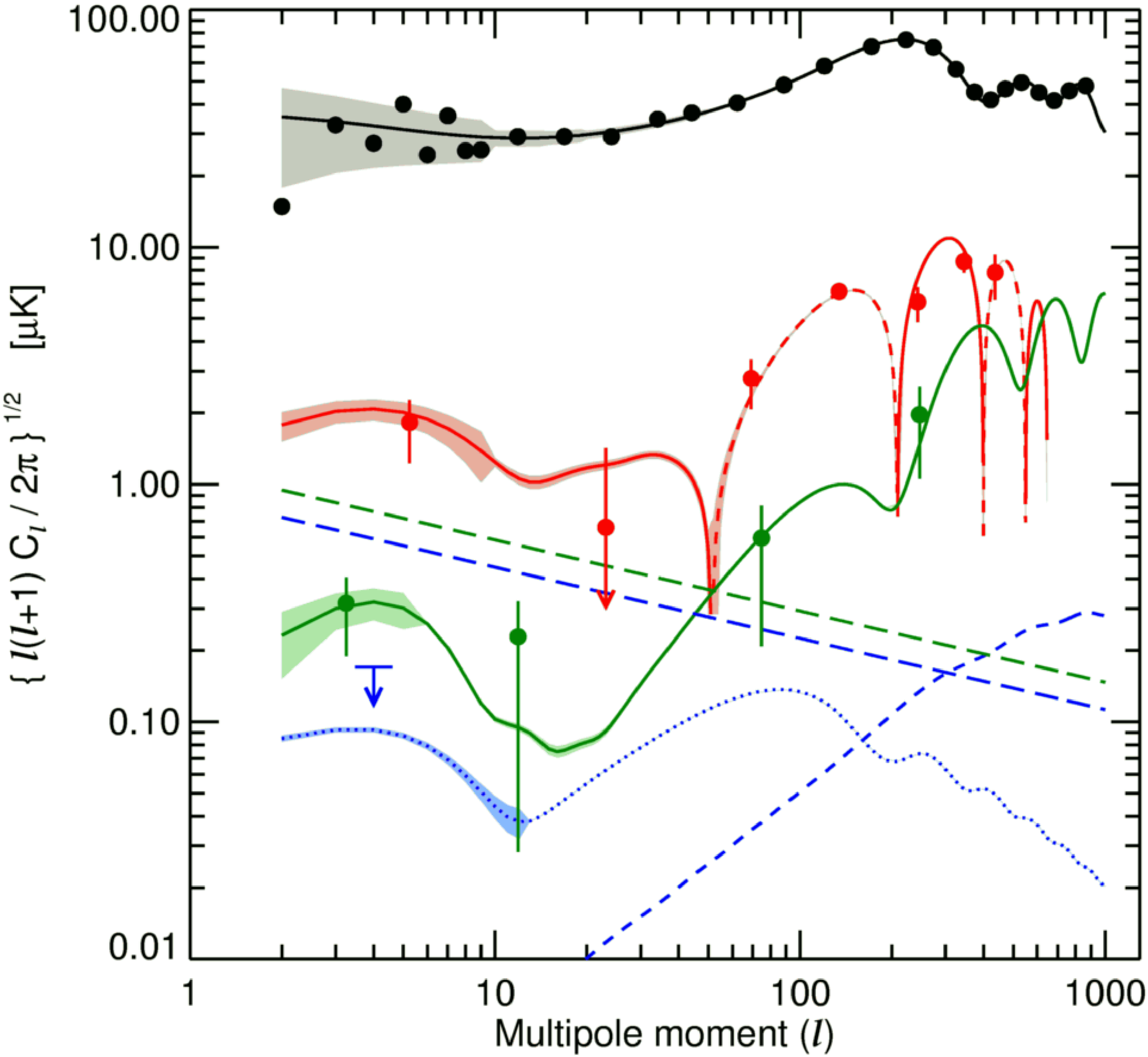
Final Results

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

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

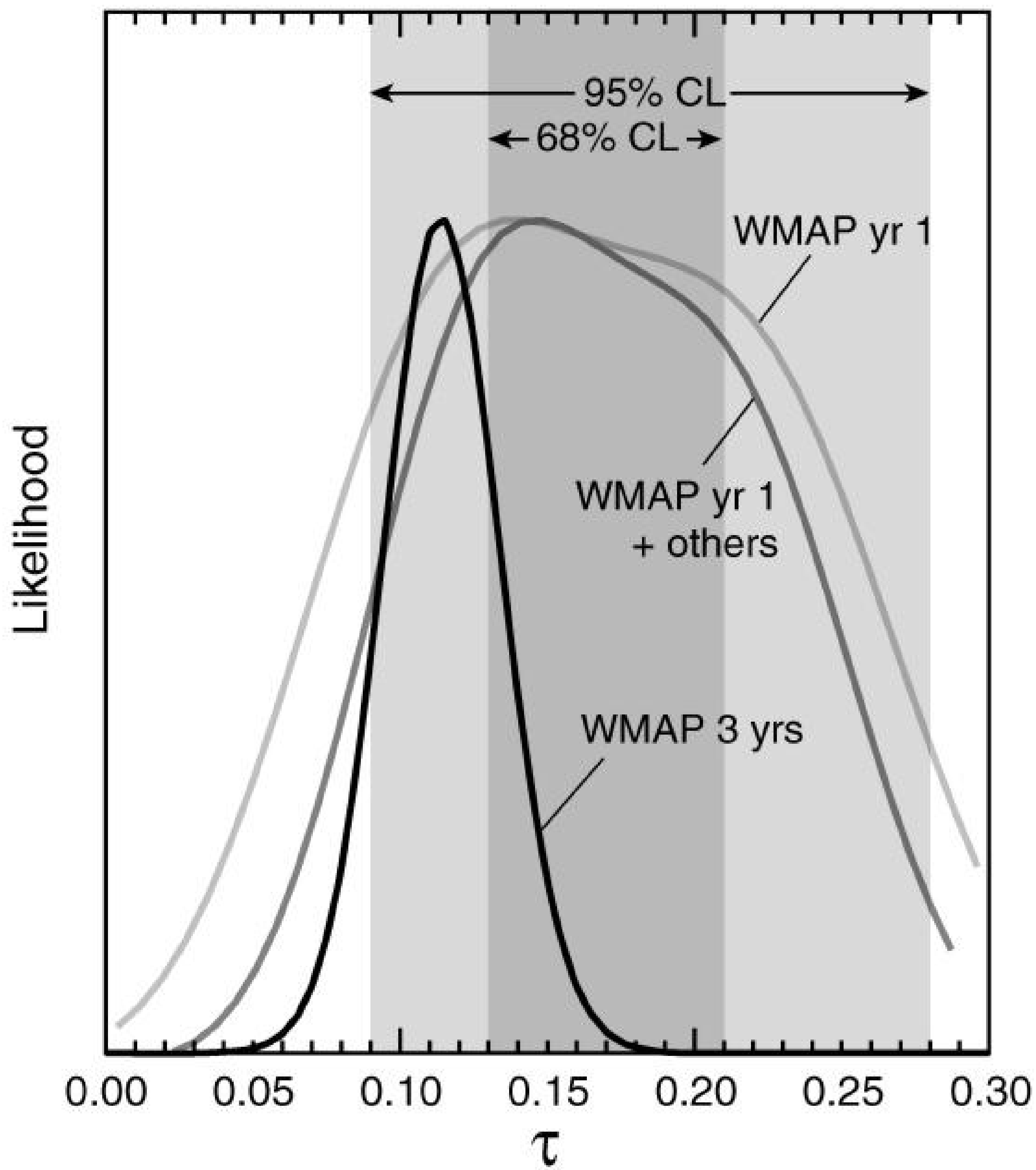
EE only: $\tau = 0.10 \pm 0.03$

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



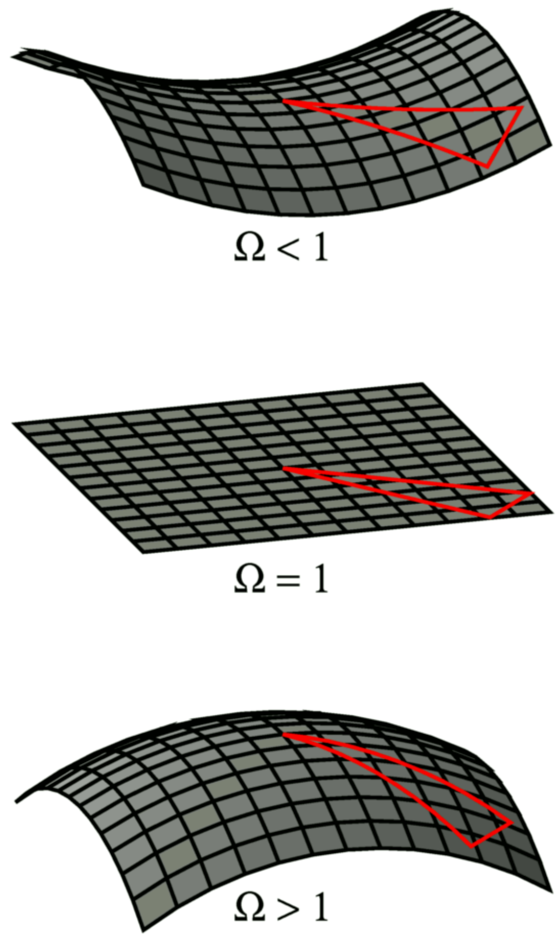
100.00
10.00
1.00
0.10
0.01
1
10
100
1000
Multipole moment (l)
{ l(l+1) C_l / 2π }^1/2 [μK]

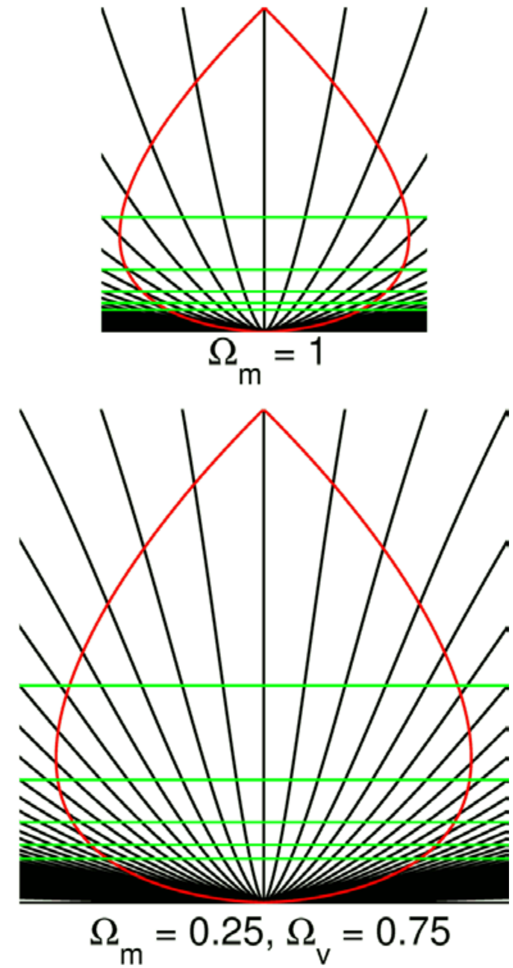
Comparison to Previous TE



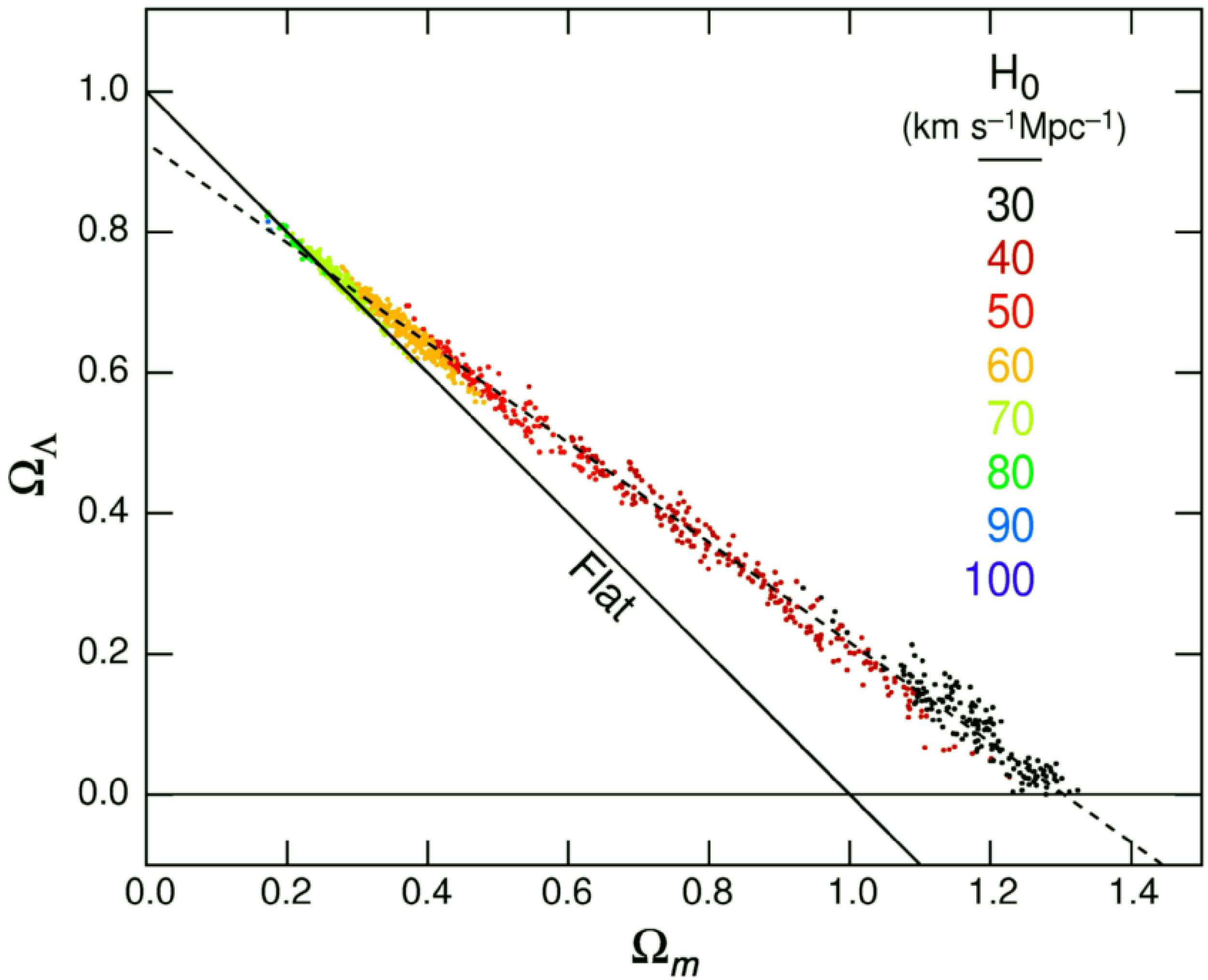
Effects on Peak Position: l_{pk}

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



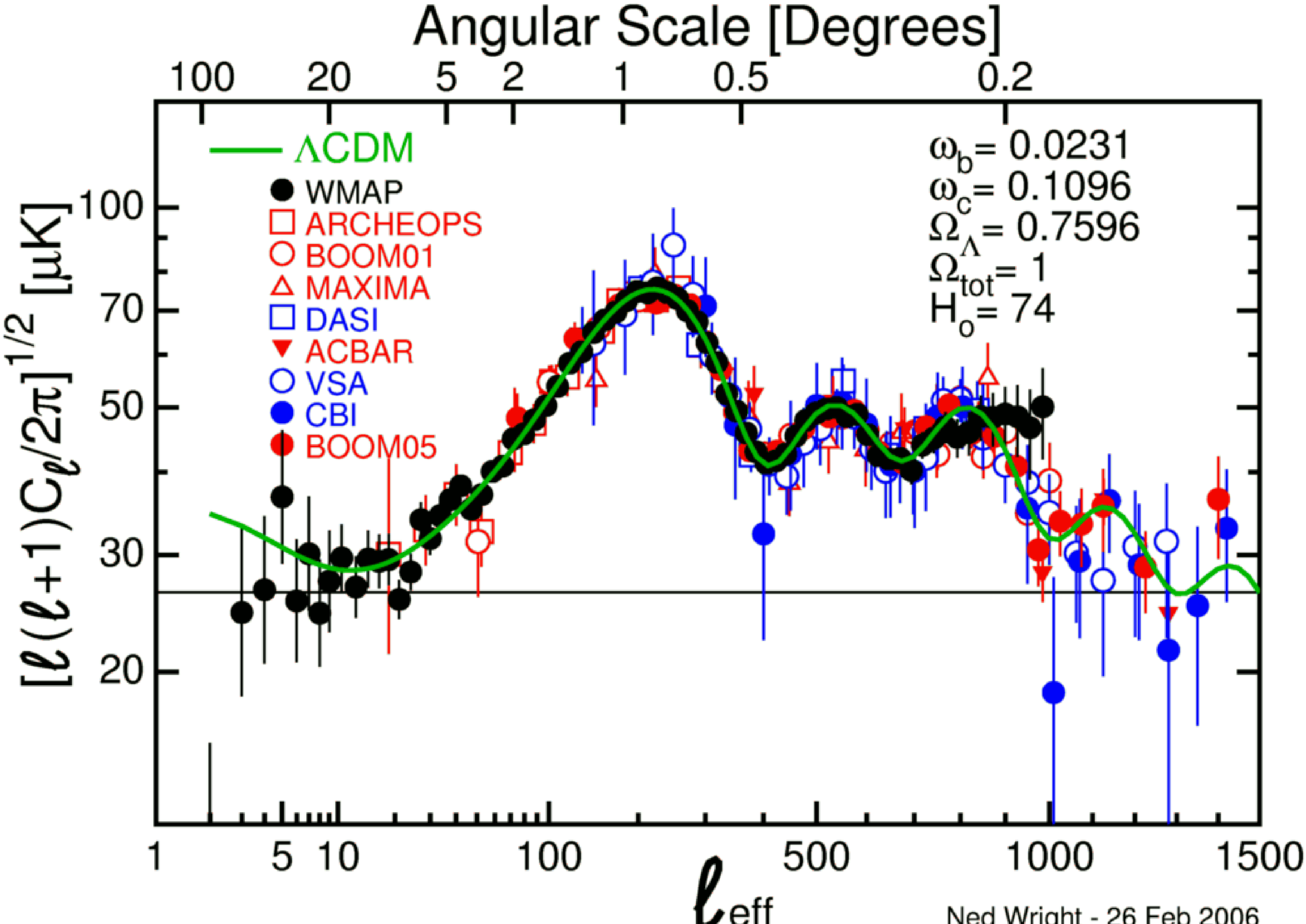


The CMB does not imply flatness

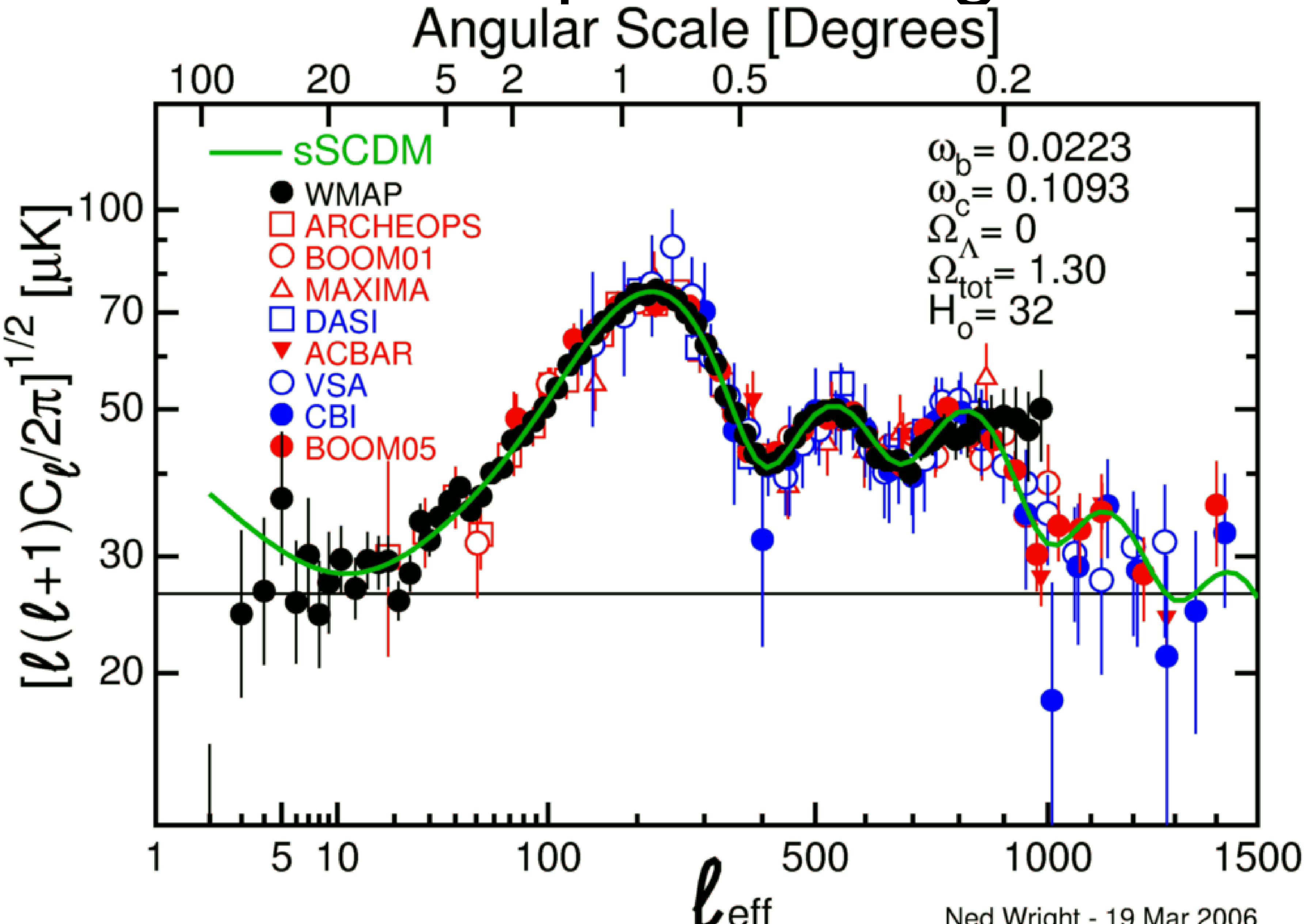


- But CMB + H_o (or other data) do imply flatness.

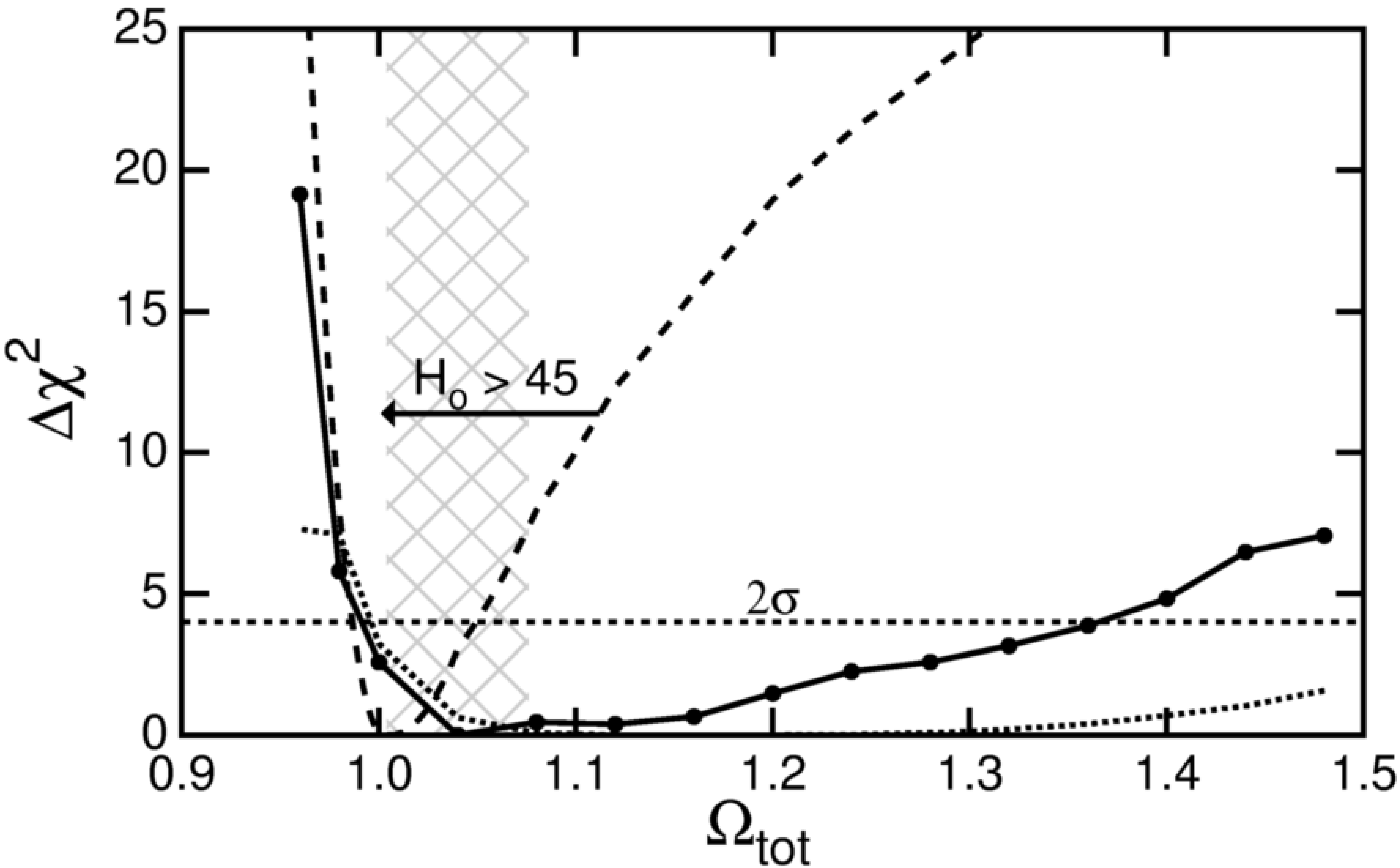
ΛCDM is a Good Fit



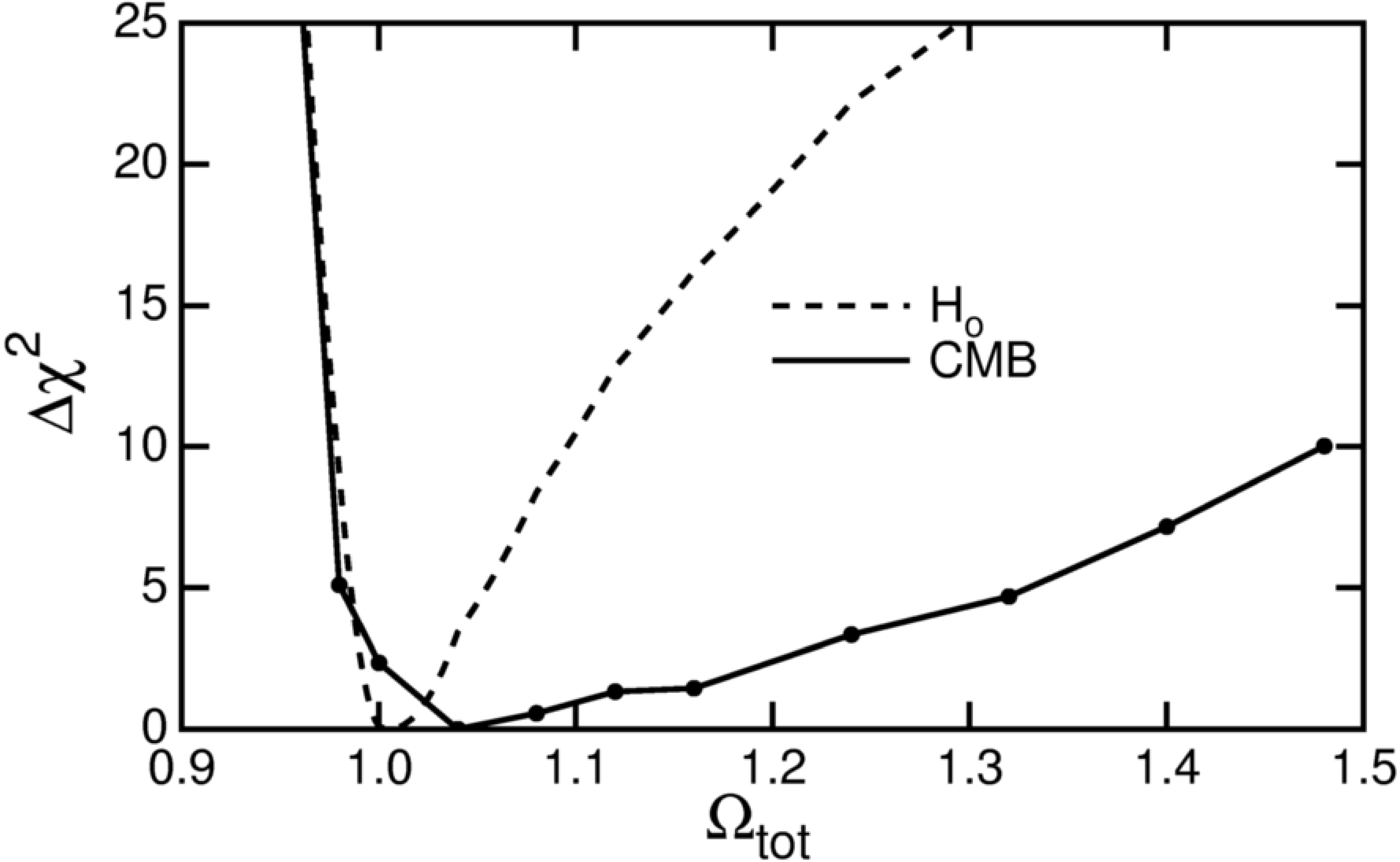
So is "super Sandage"



Minimum χ^2 vs Ω_{tot}: 1year



Minimum χ^2 vs Ω_{tot}: 3year



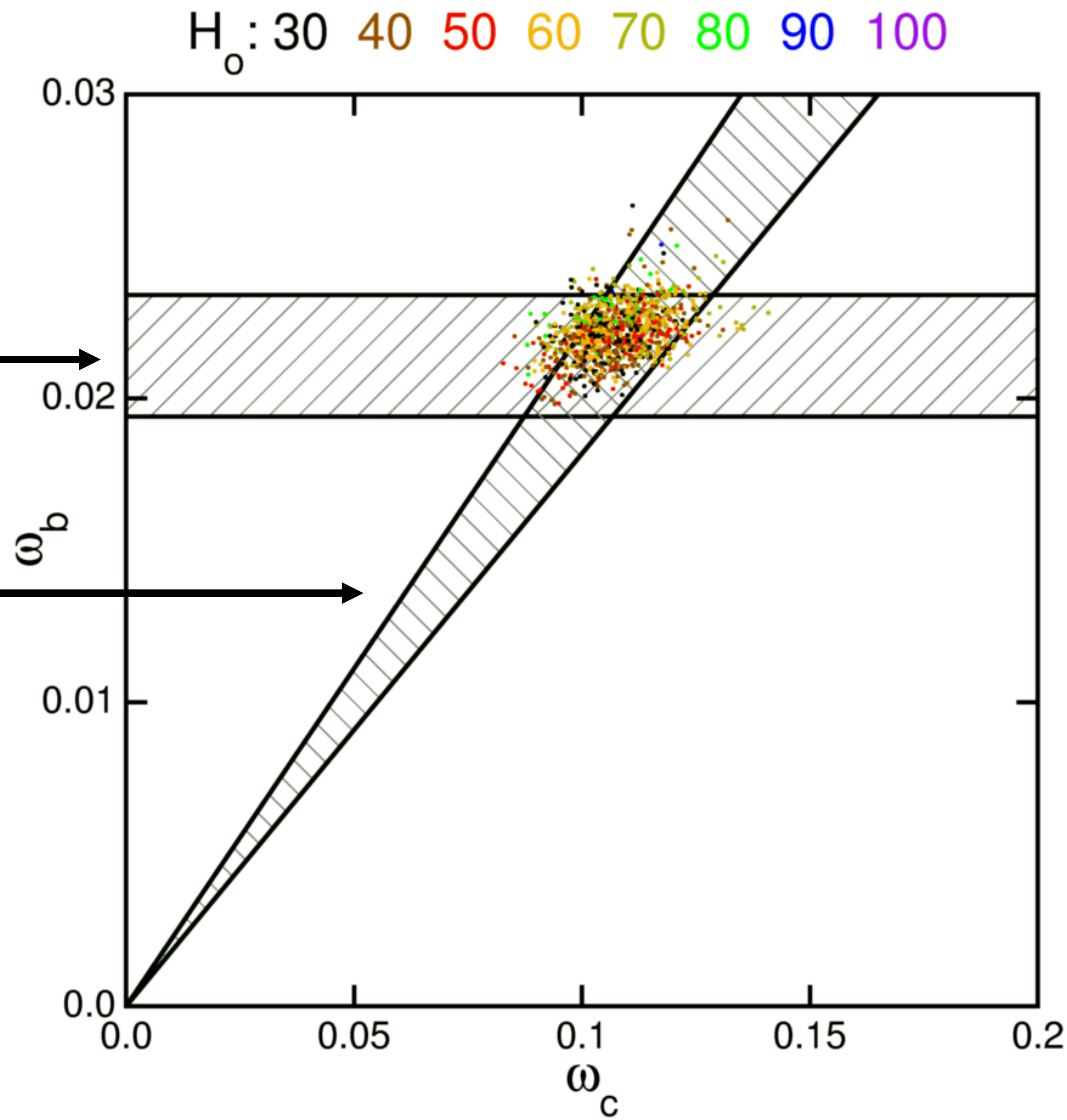
Info from peak & trough heights

- 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

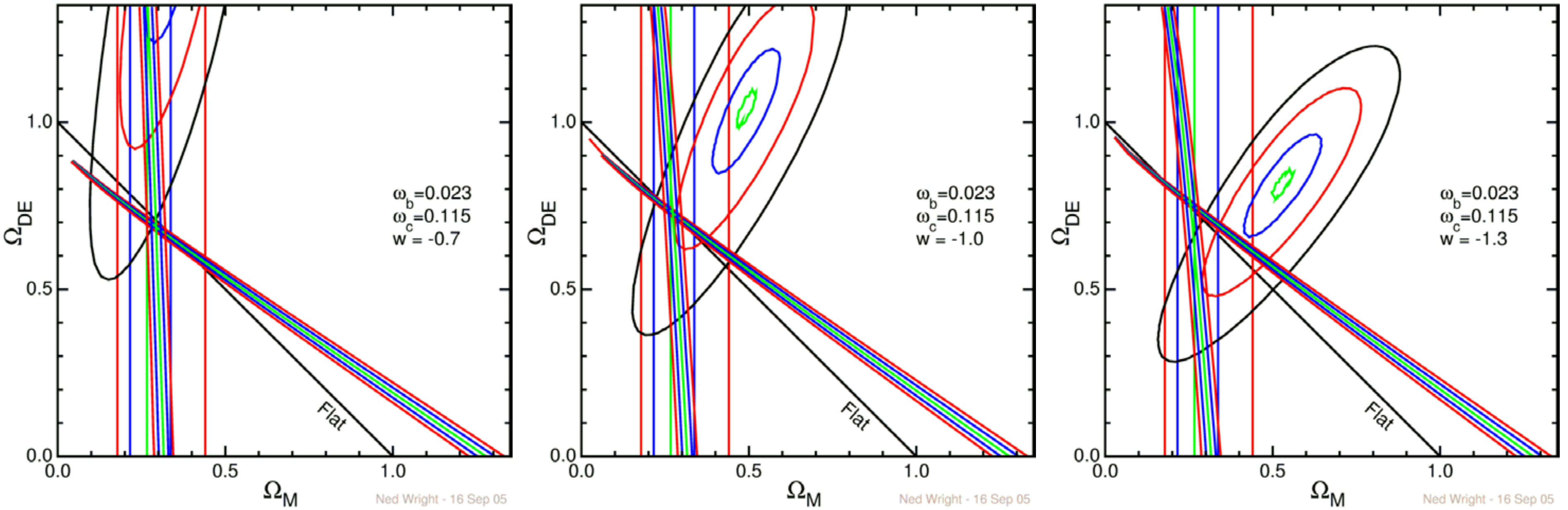
- Allan Sandage in Feb 1970 *Physics Today* was searching for H_o [80 km/sec/Mpc $\pm$ 50%] and q_o [1.2 $\pm$ 0.4].

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.

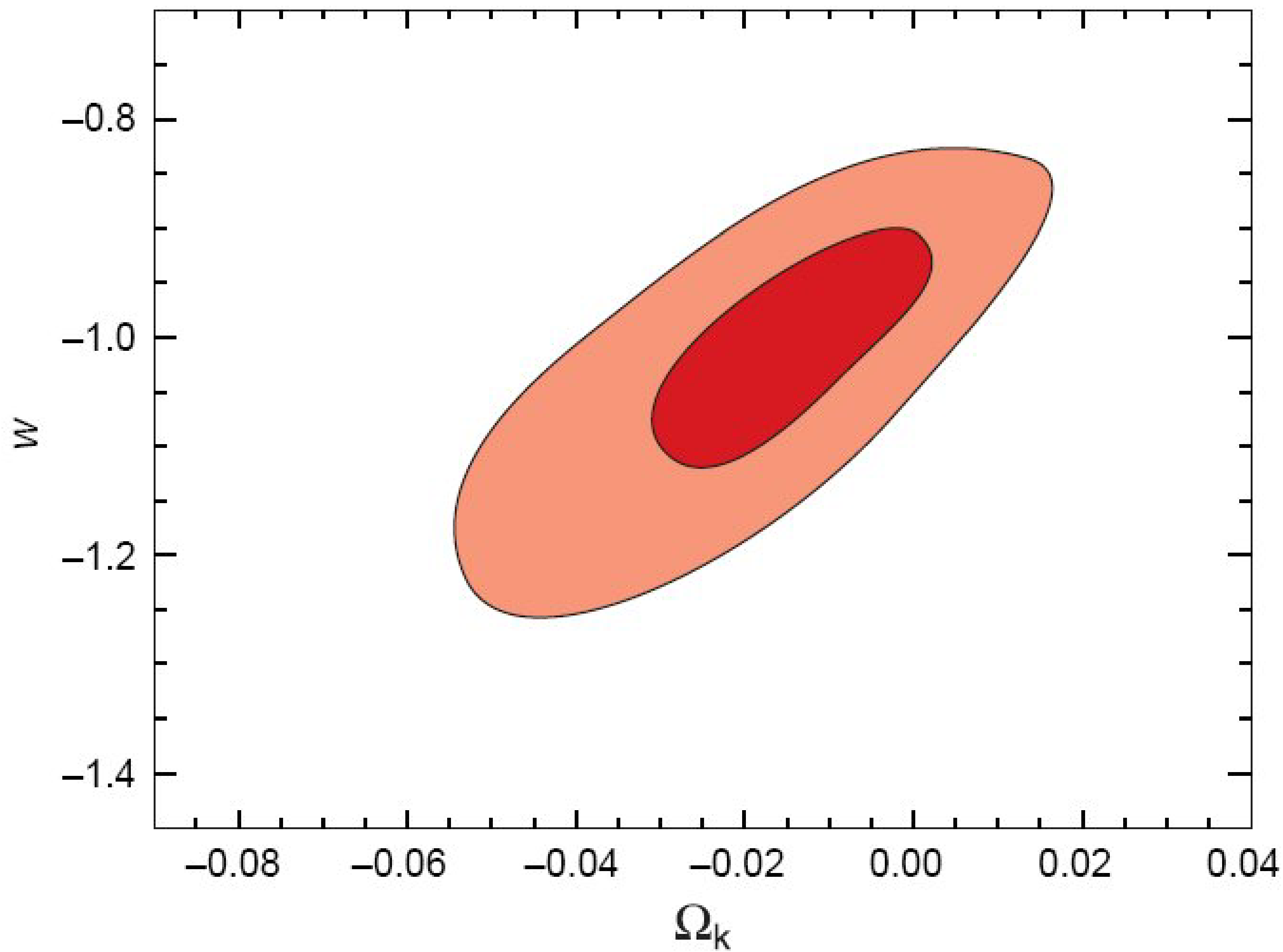
Non-flat Dark Energy Fitting!

CMB,

SNe,

SDSS P(k)
& BAO,

2dFGRS



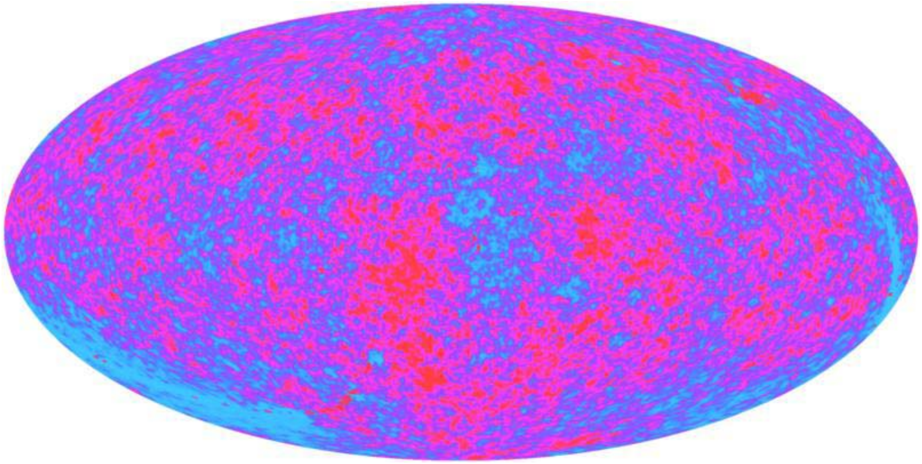
- $\Omega_k = 0$, w = -1 is OK: -0.93 > w > -1.14

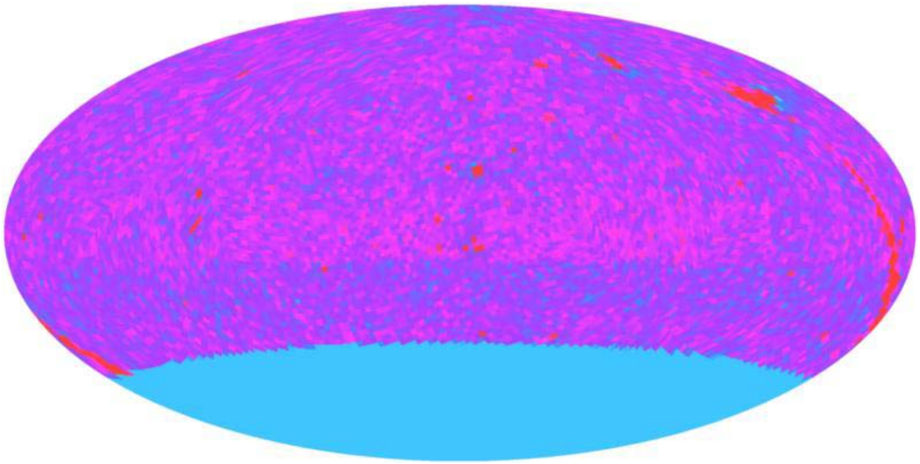
Same Laws of Physics?

- 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.

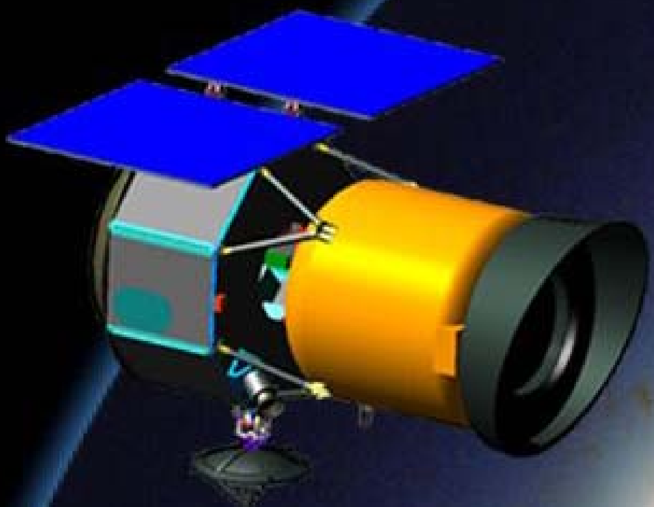
Λ Confirmed by CMB & IR maps

- 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

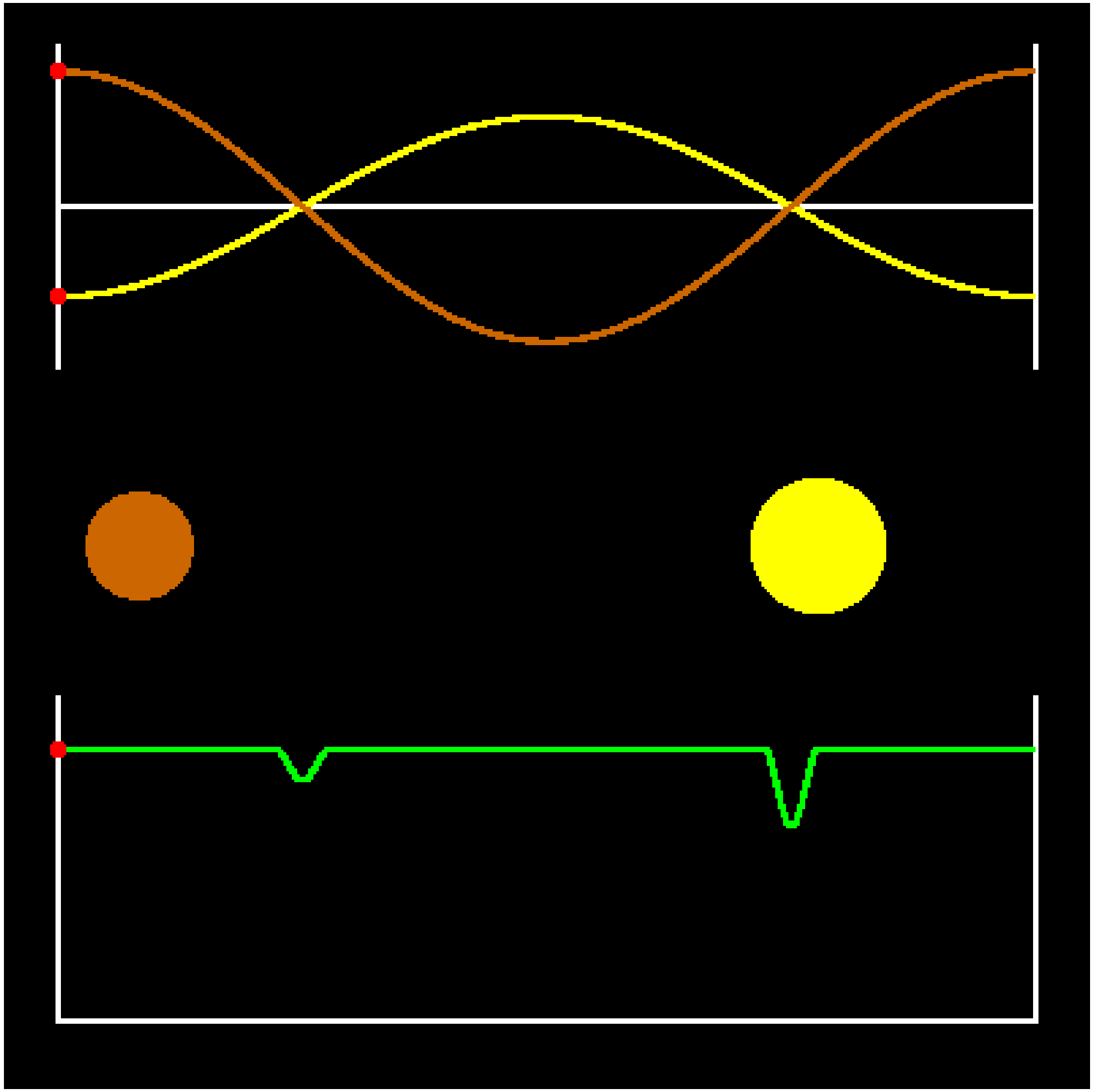


I am the PI on a MIDEX called WISE, an all-sky survey in 4 bands from 3.3 to 23 μm. WISE will find and study the closest stars to the Sun, the most luminous galaxies in the Universe, and also map the large-scale structure out to redshift z=1, covering the era when the late ISW effect should be generated.

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

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.

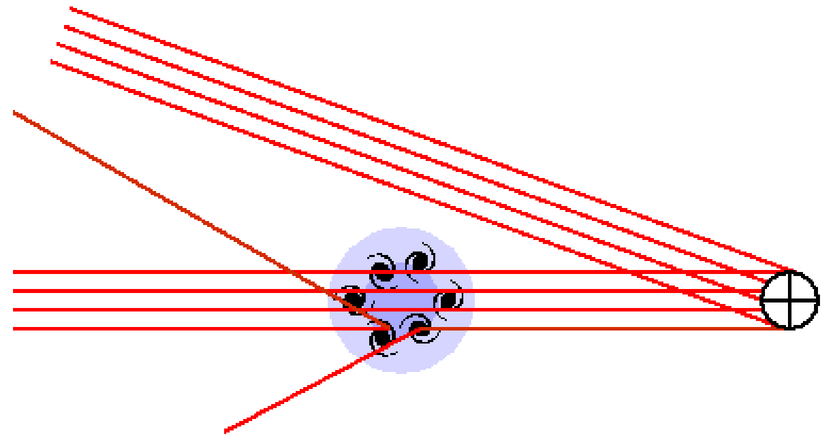


Bonanos et al., astro-ph/0606279

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



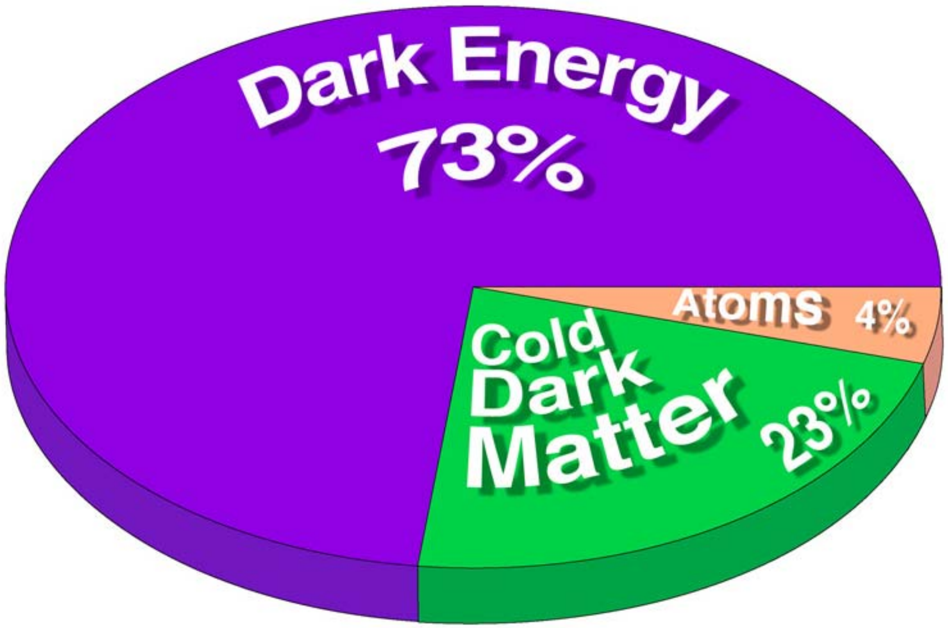
- X-rays give T_e, θ, and $n_e^2 R$.
- SZ effect gives $T_e n_e R$.
- $(SZ)^2 / I_x f(T_e)$ gives R.
- R/θ gives distance in meters.
- $H_o = 76.9{+3.9}{-3.4}_{stat}{+10.0}{-8.0}_{sys}$ km/s/Mpc

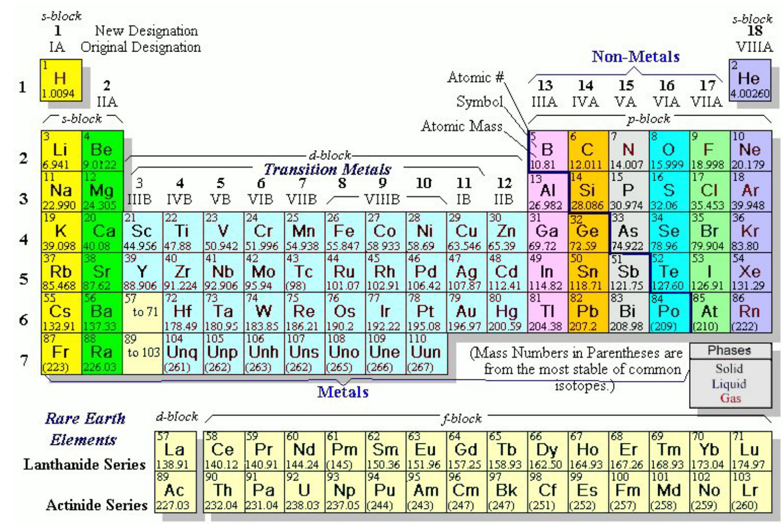
Bonamente etal, astro-ph/0512349

“Nothing” really funny

- Sydney Harris cartoon
  - Cosmology marches on
    - Where the hell did it all come from?
    - Where the hell did 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?