A Century of Cosmology

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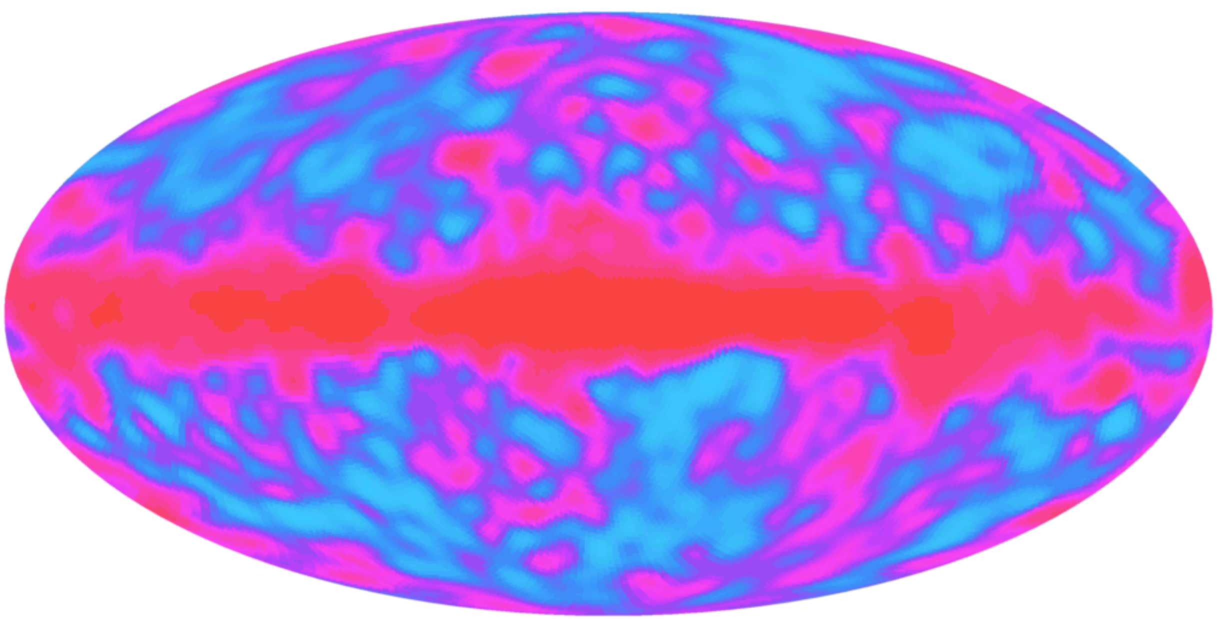
7 November 2005

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.”



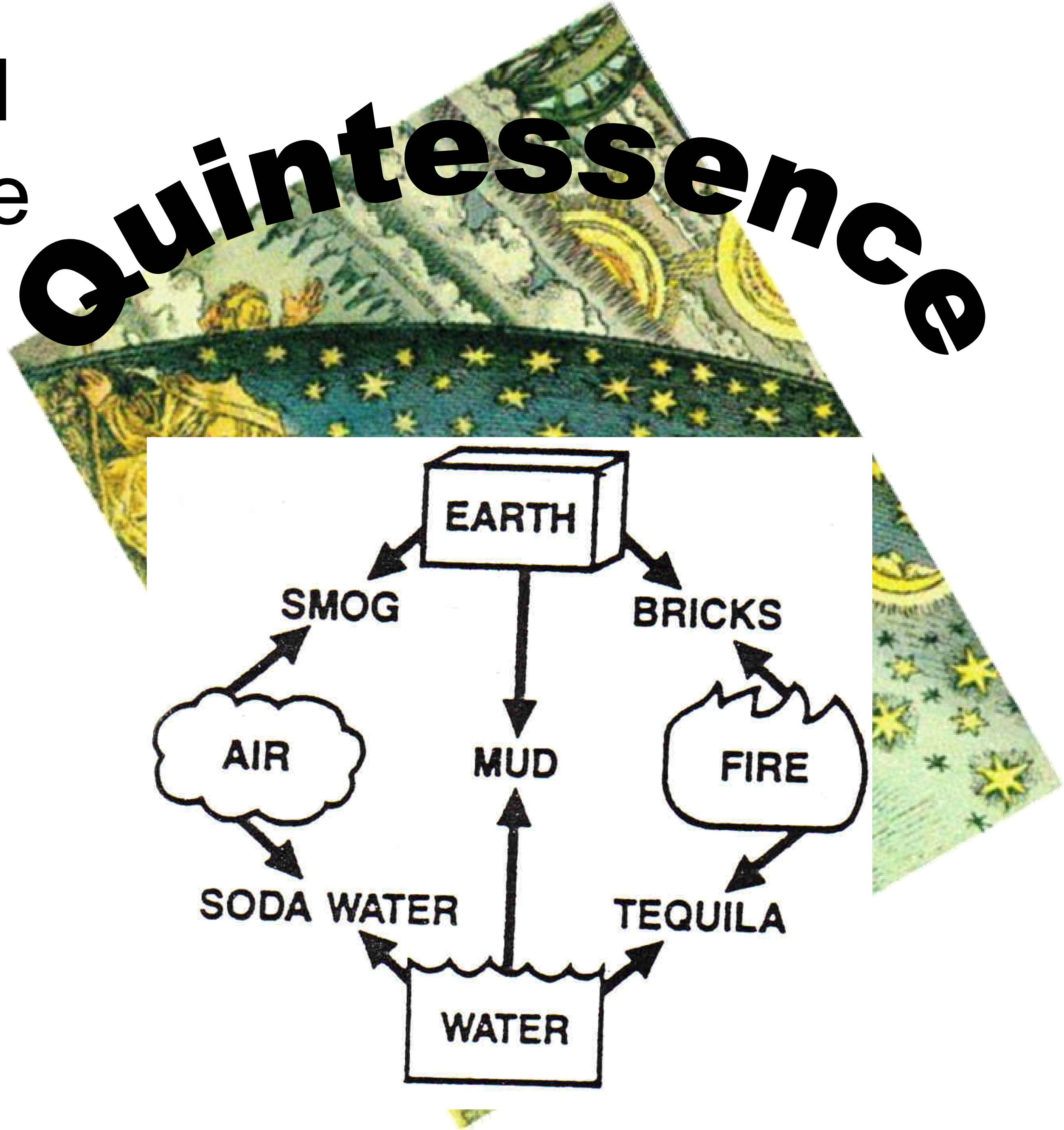
But really, what have we learned since 1905?

- 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

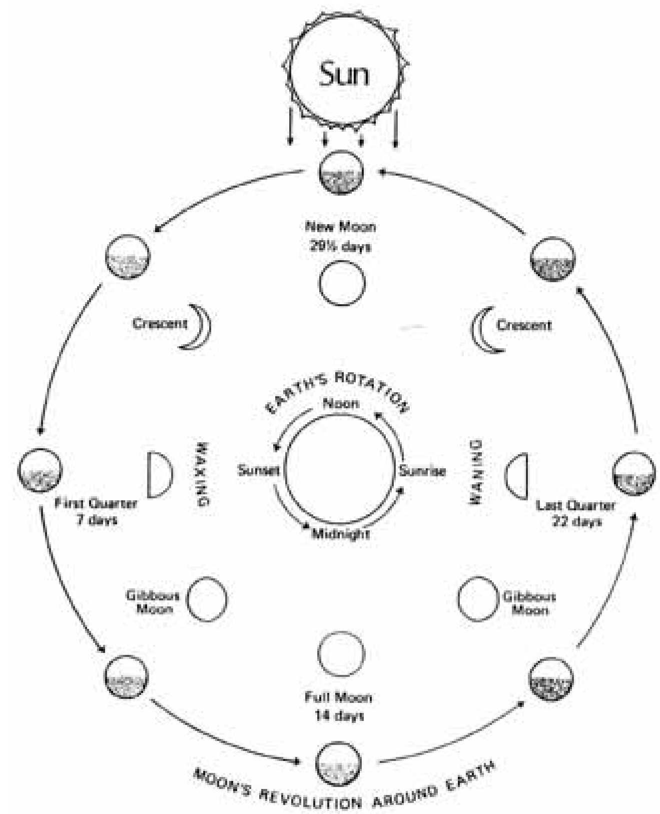
- We can’t do experiments on the Universe.
- We can’t change the initial conditions and see what happens.
- But we can observe what is the Universe is like.
- And we can study what past, present and future conditions of the Universe are compatible with our observations and the same laws of physics that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

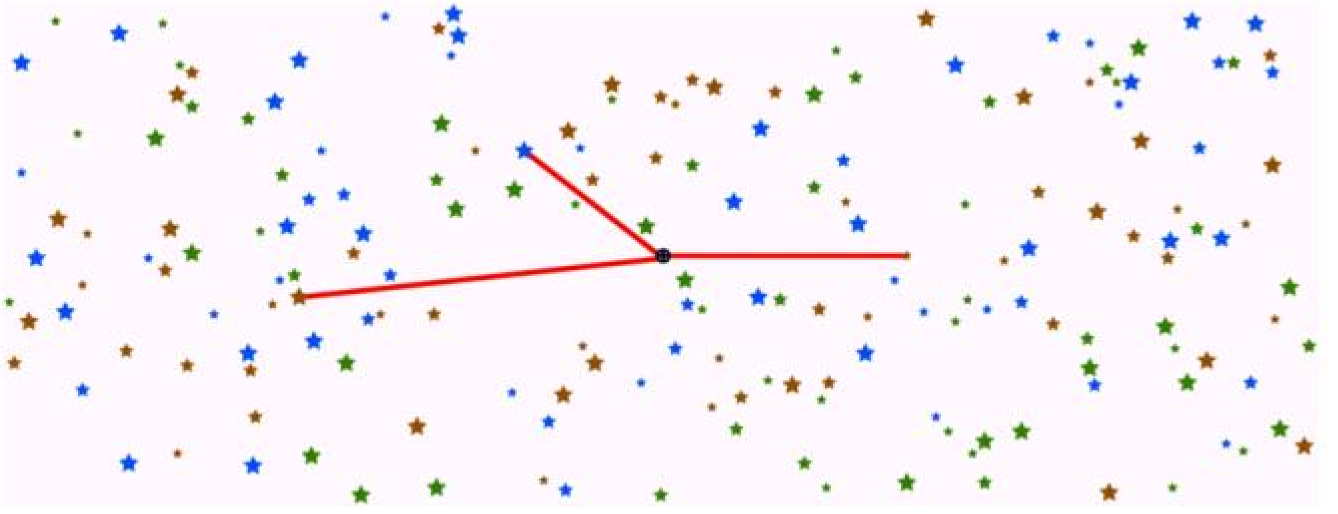
Two and a half Facts

Peter Scheuer (1963): “There are only two & a half facts in cosmology:

1) The sky is dark at night.
2) The galaxies are receding from each other as expected in a uniform expansion.
3) The contents of the Universe have probably changed as the Universe grows older.”

Only One Fact in 1917

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

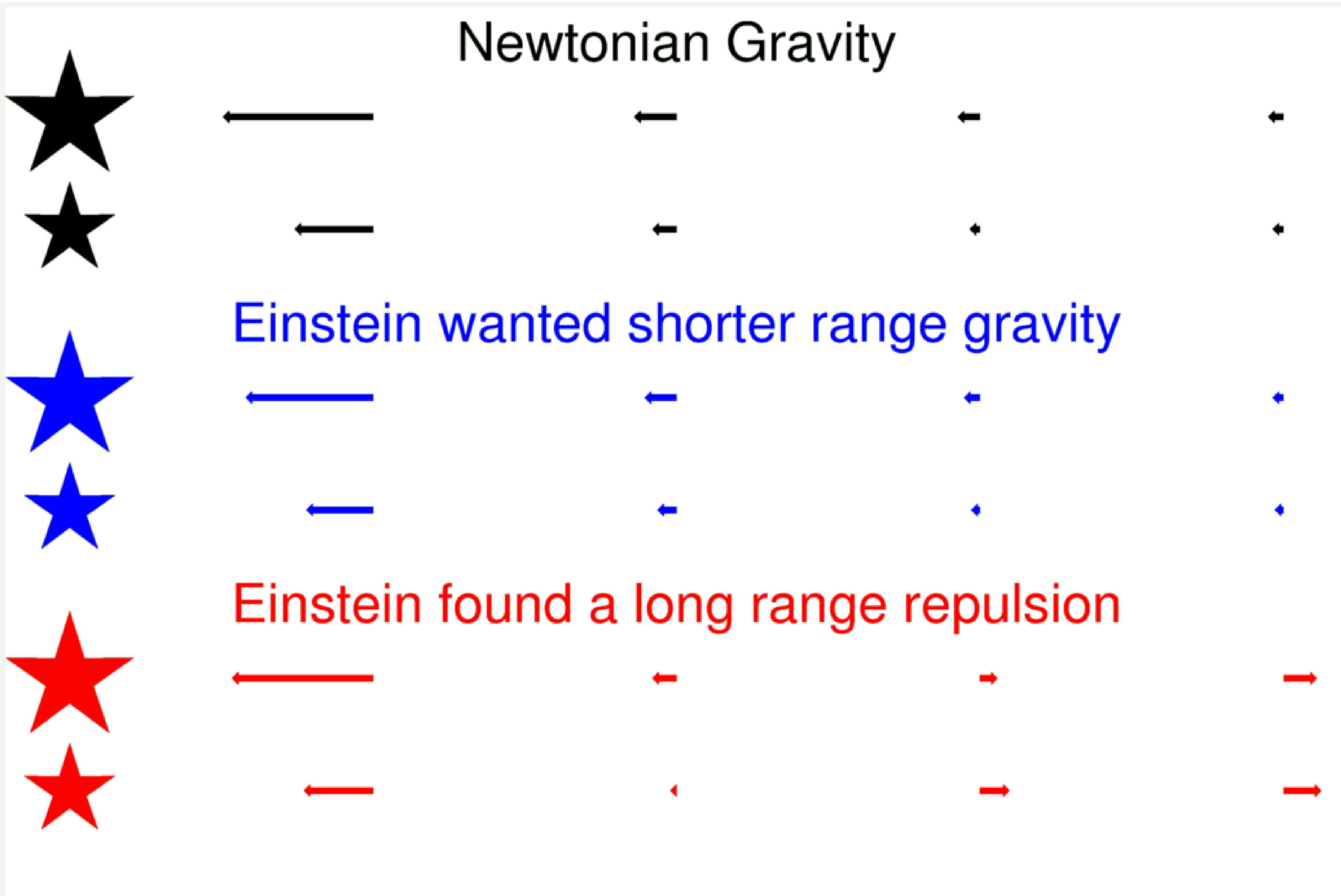


In a homogeneous unchanging Universe every line of sight will end on a star. So why is the night sky not as bright as the surface of a star? The Cosmic Infrared Background is what remains after this Olbers' paradox is resolved.

General Relativity & Cosmology

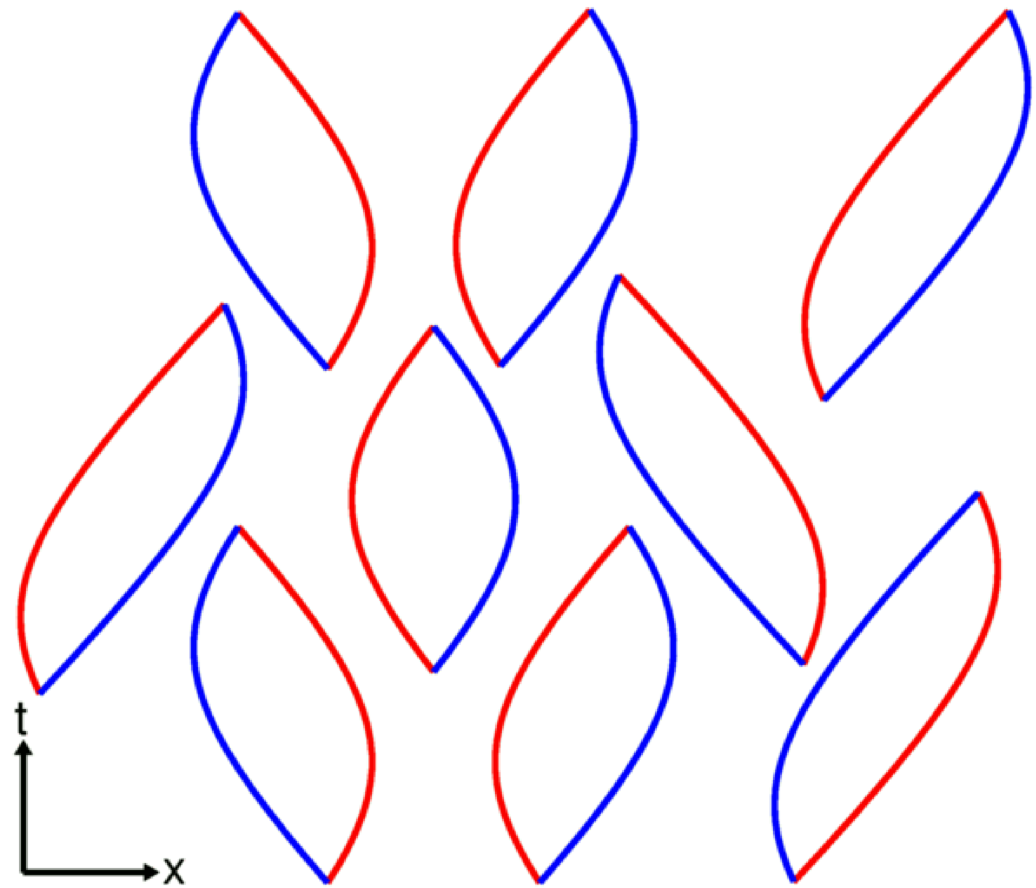
- General relativity allows a consistent calculation of the effects of gravity in a uniform distribution of galaxies that fills the entire Universe.
- But Einstein thought the Universe was static, and a static uniform distribution of galaxies that filled the entire Universe would be unstable to collapsing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

Effect of Λ term was unexpected

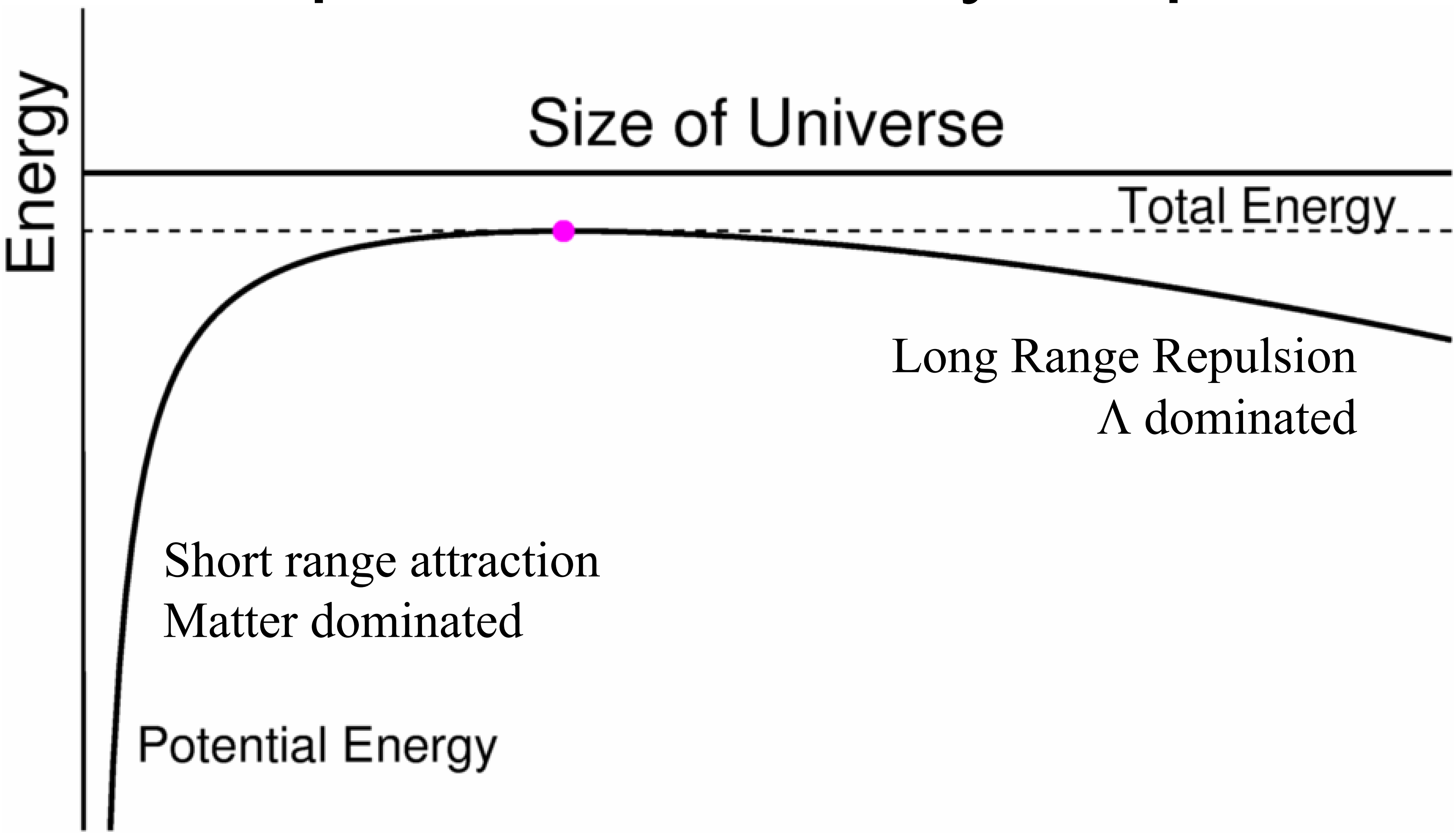


Source of Cosmological Constant

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



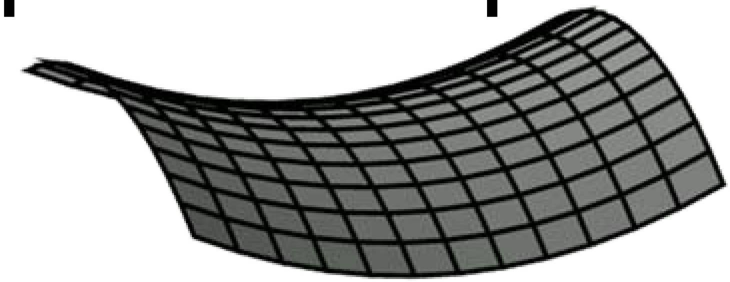
Represent Force by Slope



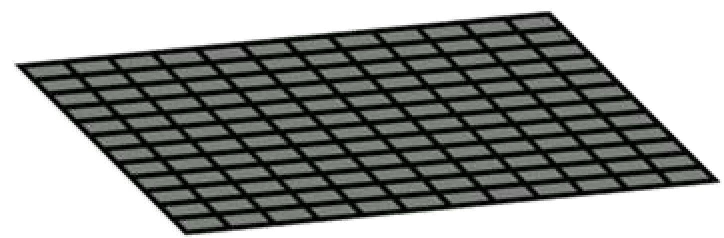
- This is quite a good analogy for cosmological models.

Total Energy implies Shape

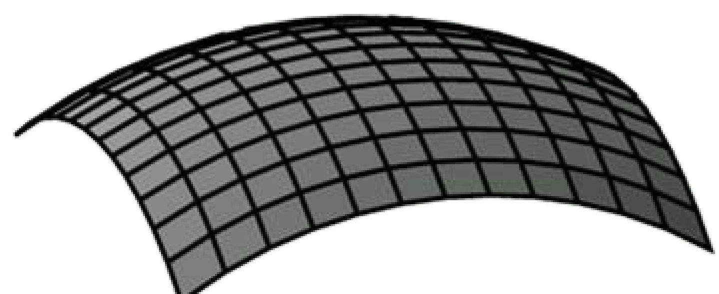
- Total Energy > 0
  - Sum of angles < 180°
  - Negative curvature
  - Infinite



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

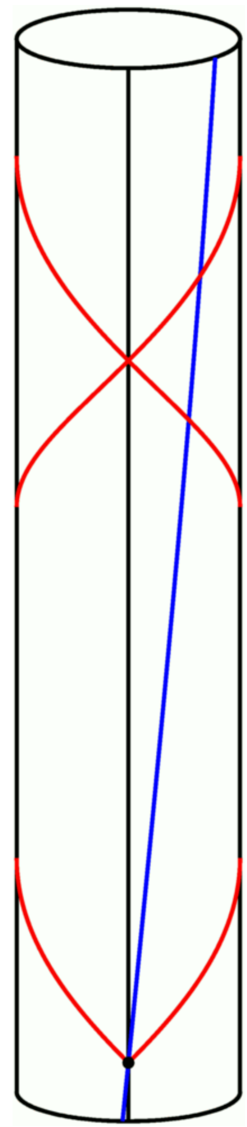


- Total Energy < 0
  - Sum of angles > 180°
  - Positive curvature
  - Finite



Einstein's Static Universe

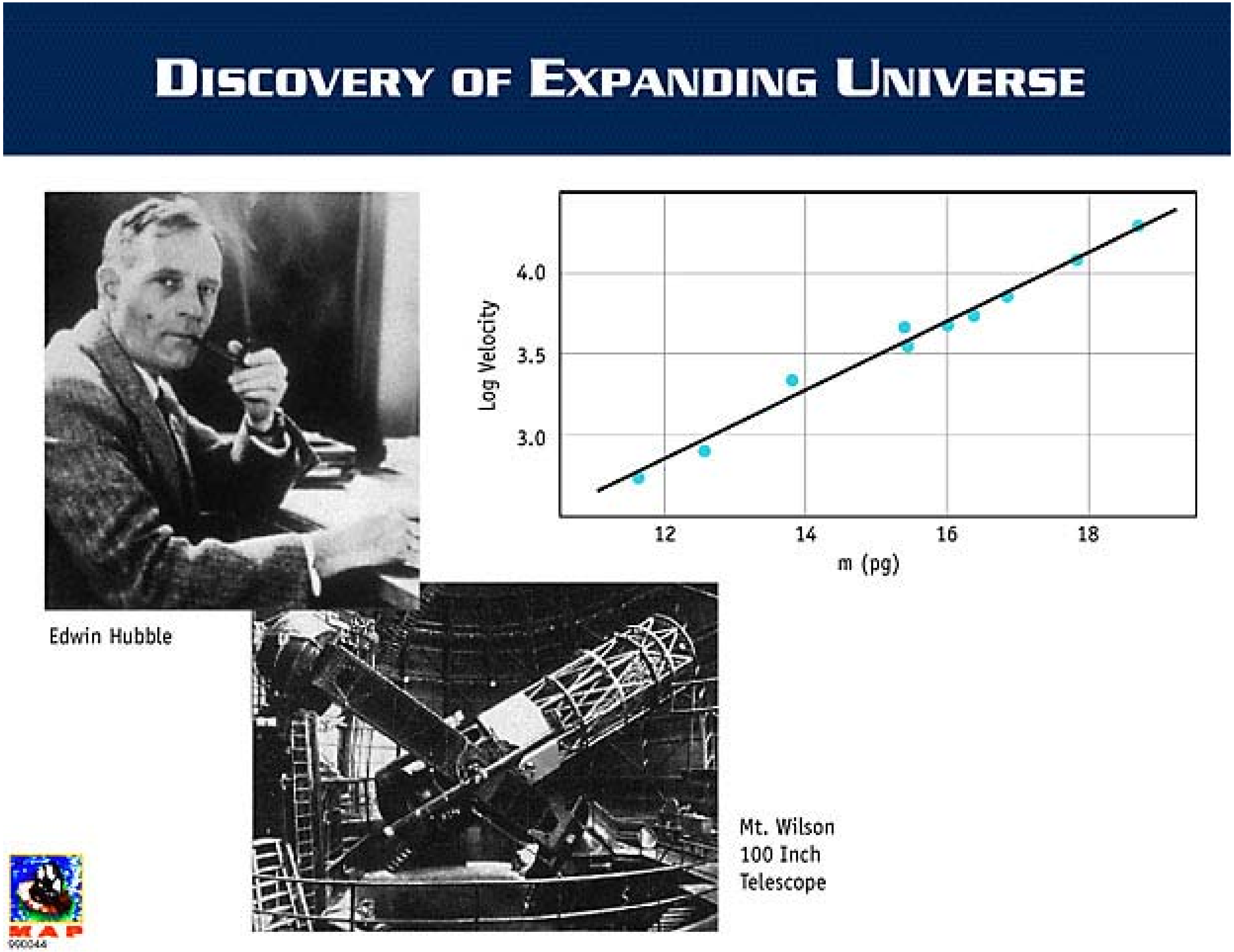
- Einstein made a static spherical model of the Universe.
- The diagram is a space-time diagram with time running up and a 1-D version of the 3-D sphere [a circle] for space.



In this space-time diagram there are two observers with different velocities. One observer sees the circumnavigating light rays return at the same time, while the other does not.

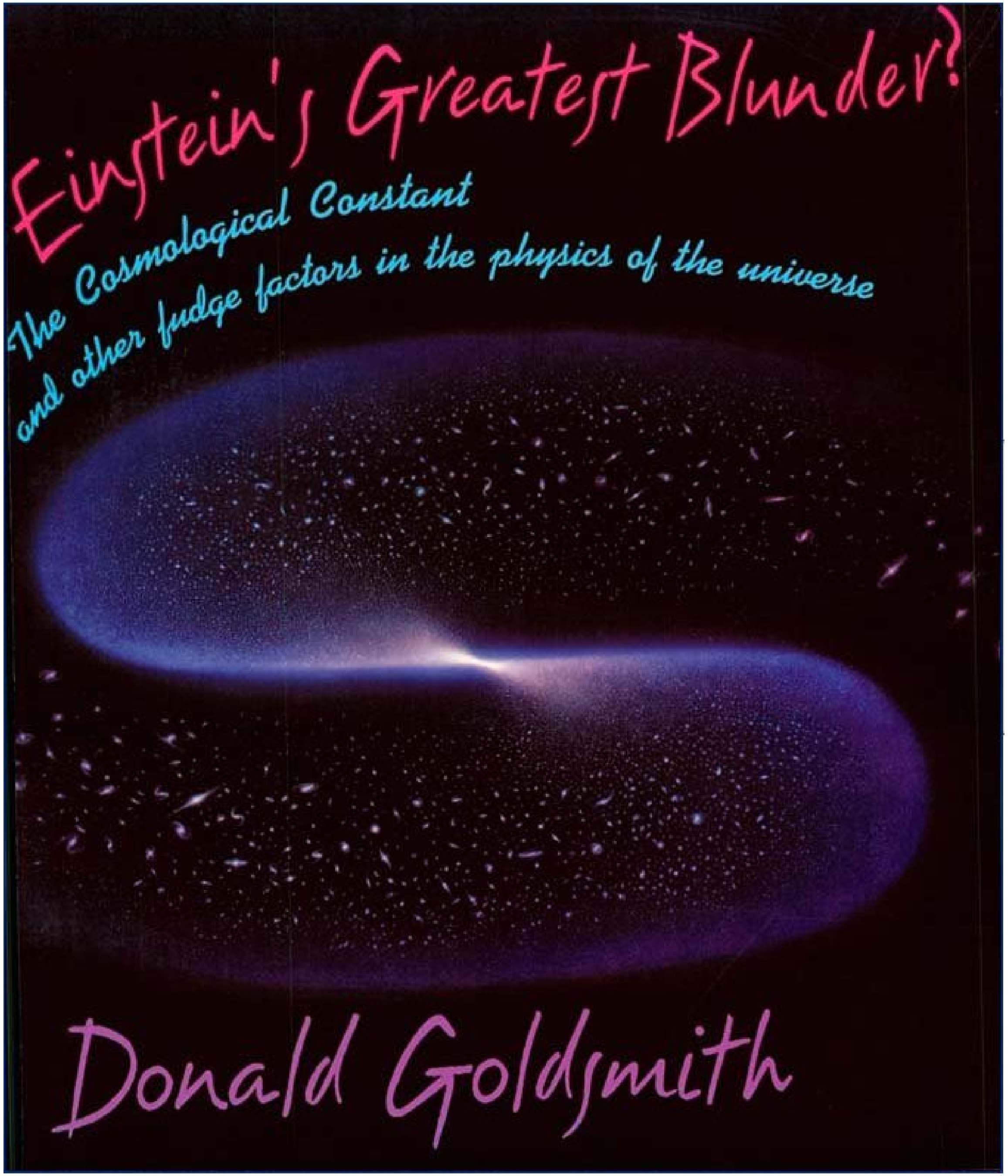
Velocity with respect to the Universe is easily measured.

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

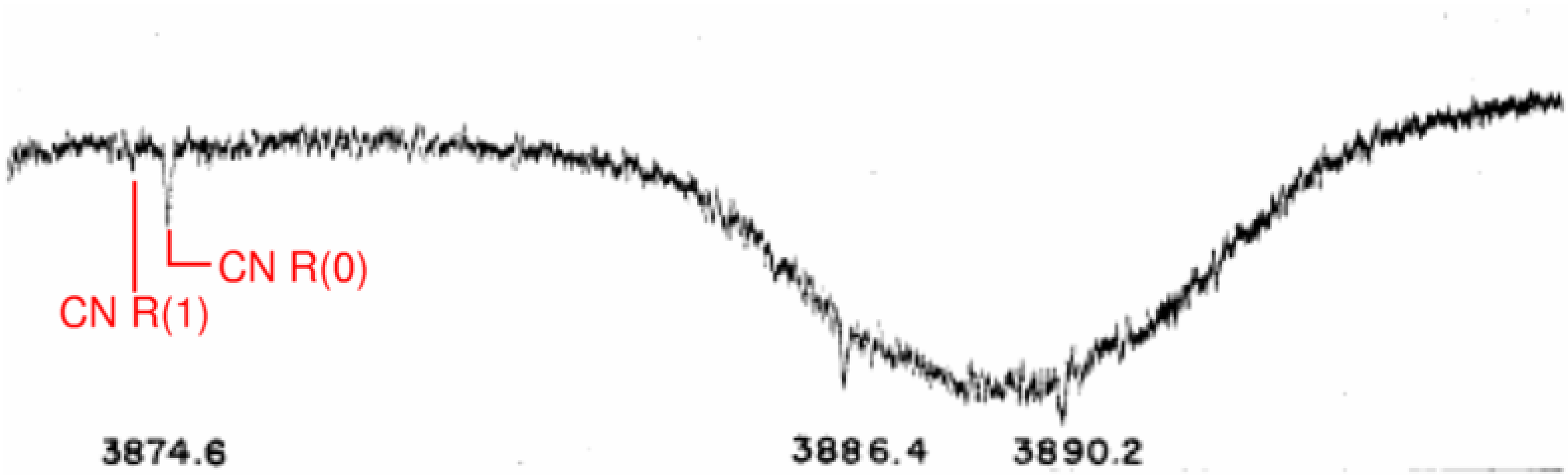


Plate 3 of Adams (1941, ApJ, 93, 11-23) reporting McKellar's work

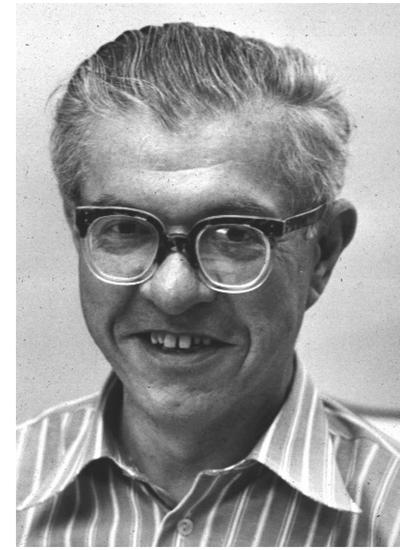
Herzberg (1950) in *Spectra of Diatomic Molecules*, p 496:

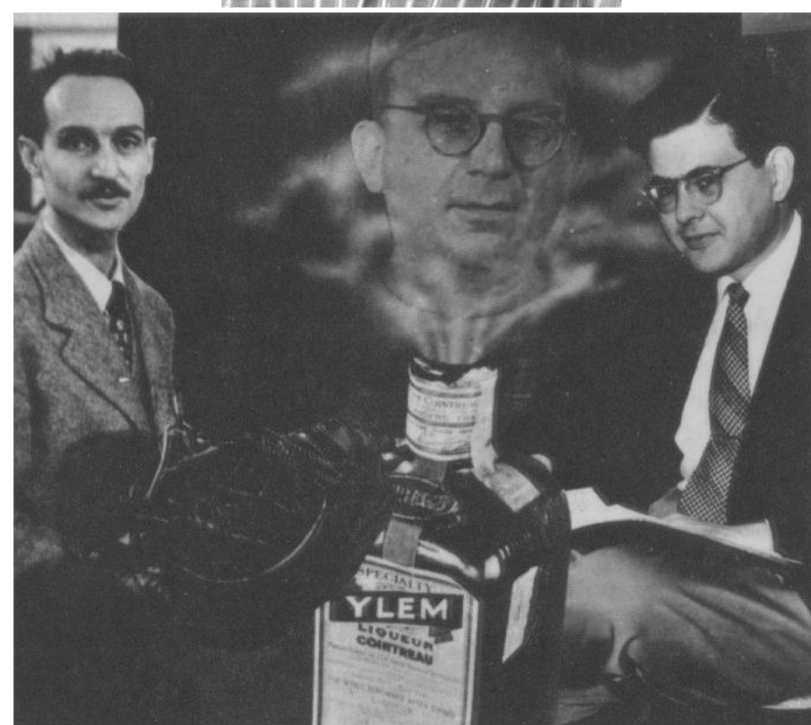
"From the intensity ratio of the lines with K=0 and K=1 a rotational temperature of 2.3^{o} K follows, which has of course only a **very restricted meaning**."

There went Herzberg's [second] Nobel Prize.

Fred Hoyle missed the Nobel Prize

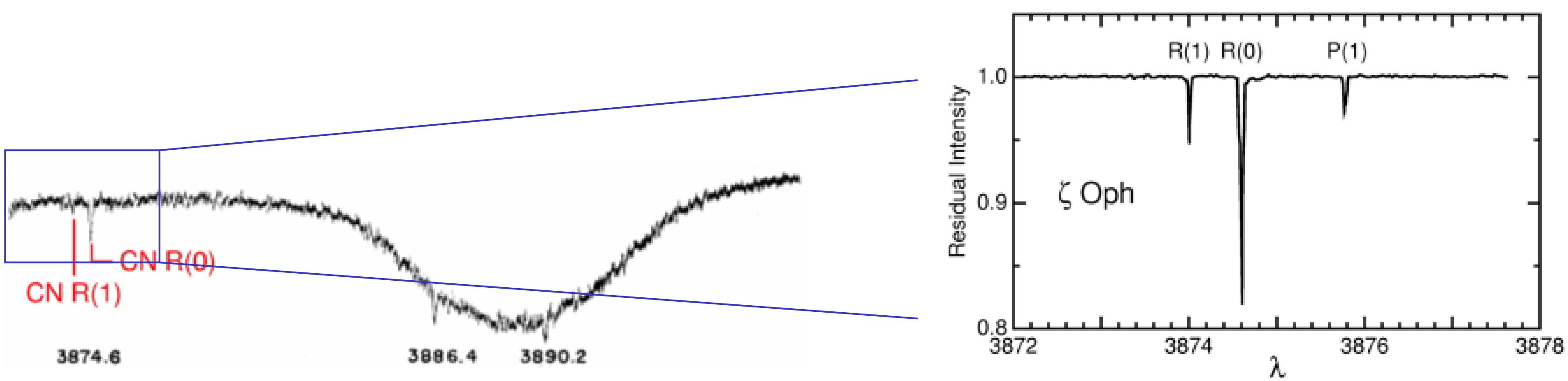
- Hoyle (1950, *The Observatory*, 70, 194), reviewing a book by Gamow & Critchfield: "[the Big Bang model] would lead to a temperature of the radiation at present maintained throughout the whole of space much greater than McKellar's determination for some regions within the Galaxy."
- This book implied 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!





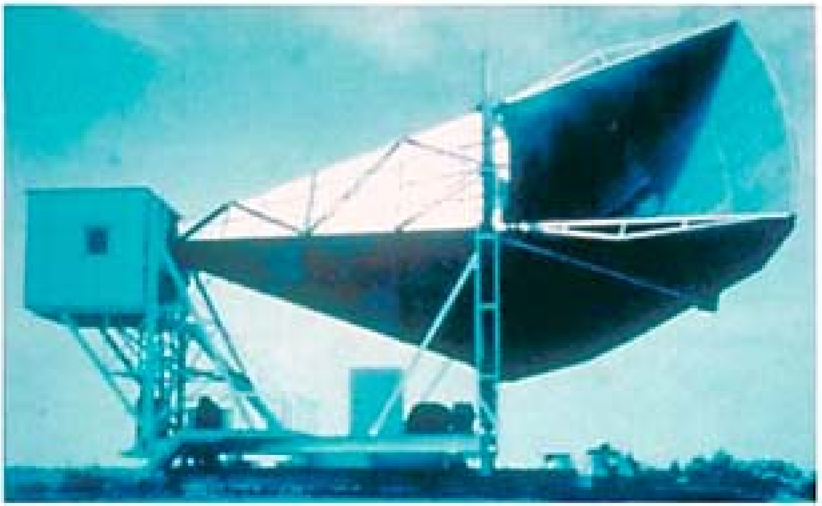
CN followup after Penzias & Wilson

- 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)

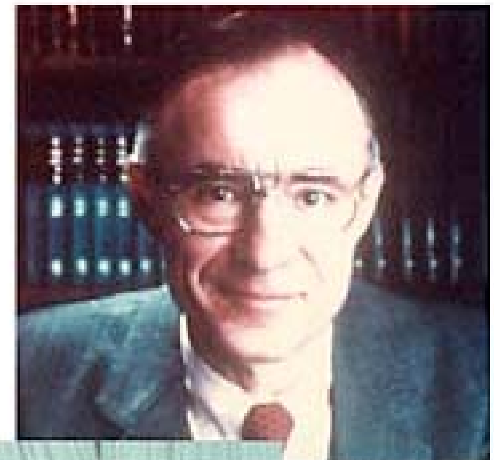


(UCLA PhD's) (advisor was Meyer)

Discovery of the Cosmic Microwave Background



Microwave Receiver



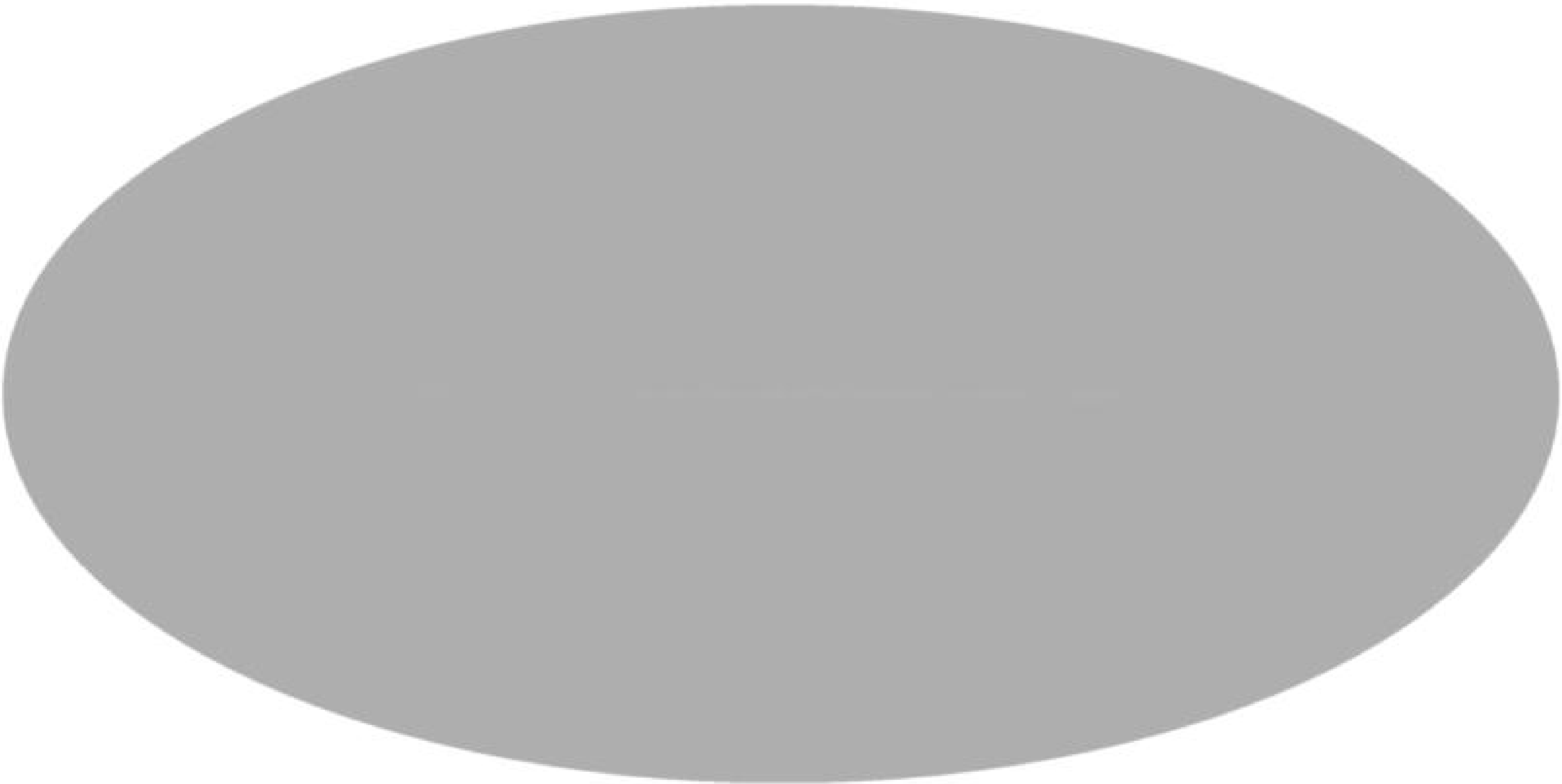
Arno Penzias

Robert Wilson

CMB Disproved the Steady State

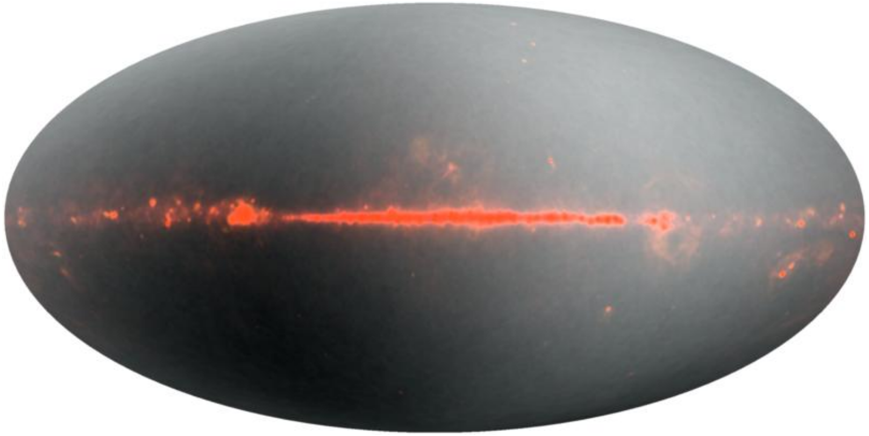
- A blackbody spectrum comes from an opaque, isothermal source.
- The Universe now is transparent, not opaque.
- The Universe now has a wide range of temperatures.
- Therefore, the Universe must have evolved from an opaque, isothermal state into its present condition, which contradicts the Steady State hypothesis.

True Contrast CMB Sky



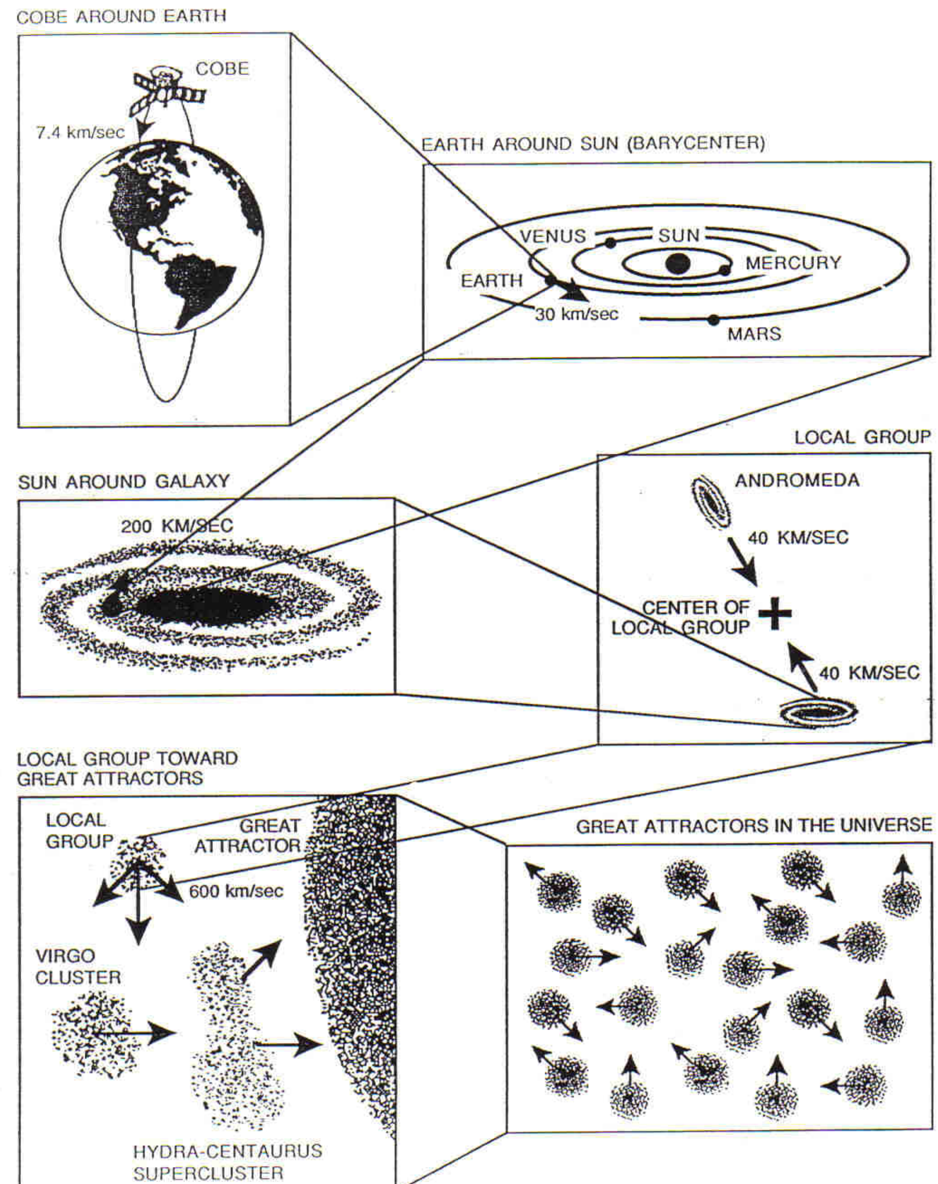
33, 41 & 94 GHz as RGB, 0-4 K scale

Enhanced Contrast:

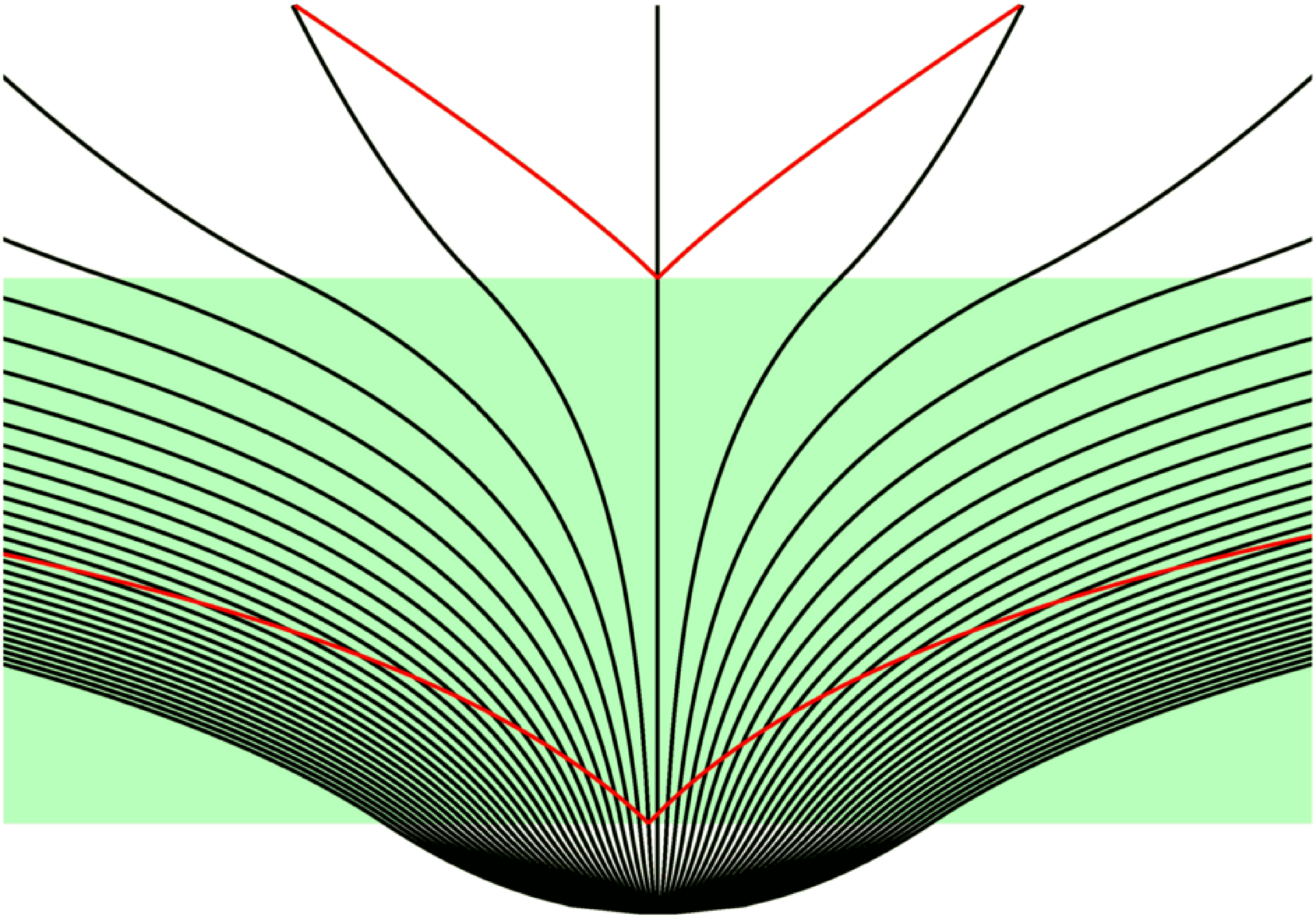


- Conklin 1969 - 2σ
- Henry 1971 - 3σ
- Corey & Wilkinson - 4σ
- Smoot *et al.* 1977 - 6σ
- Vss = 368$\pm$2 km/s

VELOCITY COMPONENTS OF THE OBSERVED CMB DIPOLE

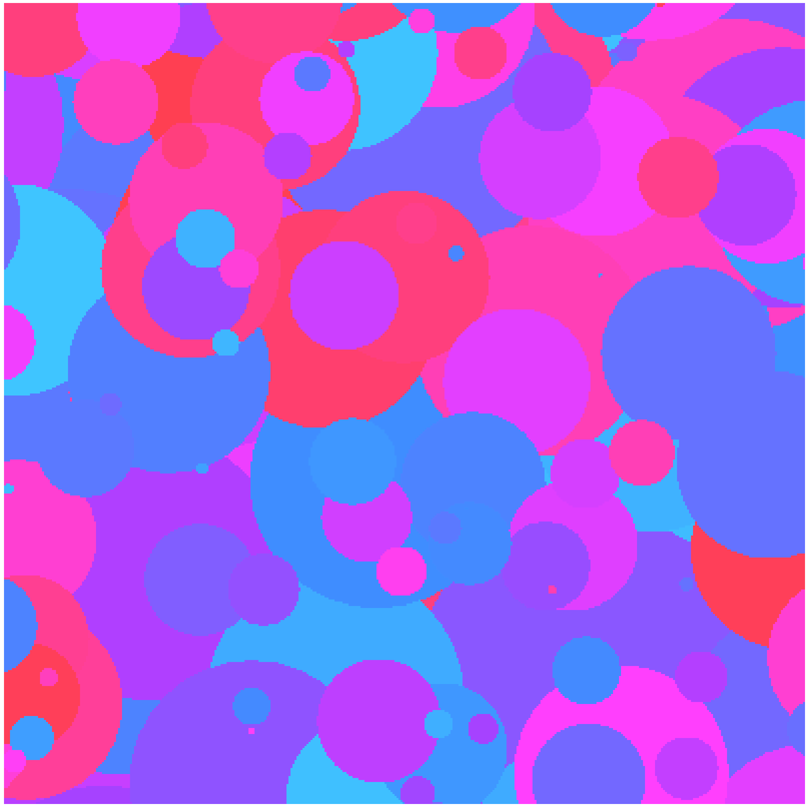


Inflation: Large Λ during an early phase



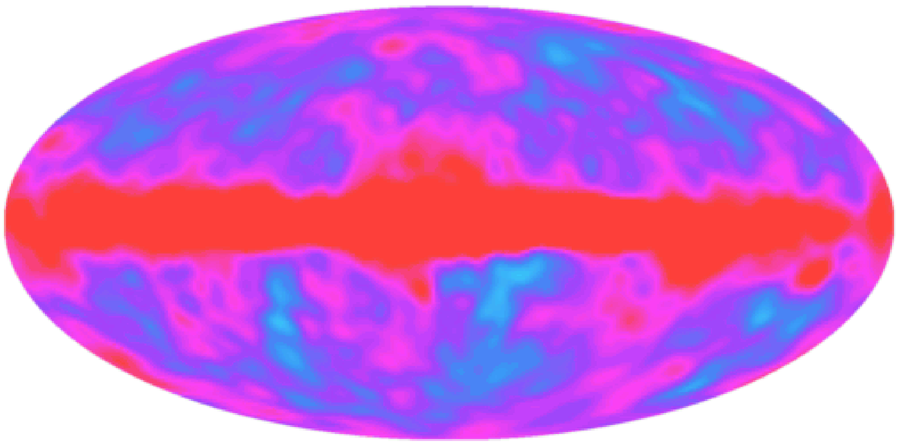
Animated View of Inflation

- 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).

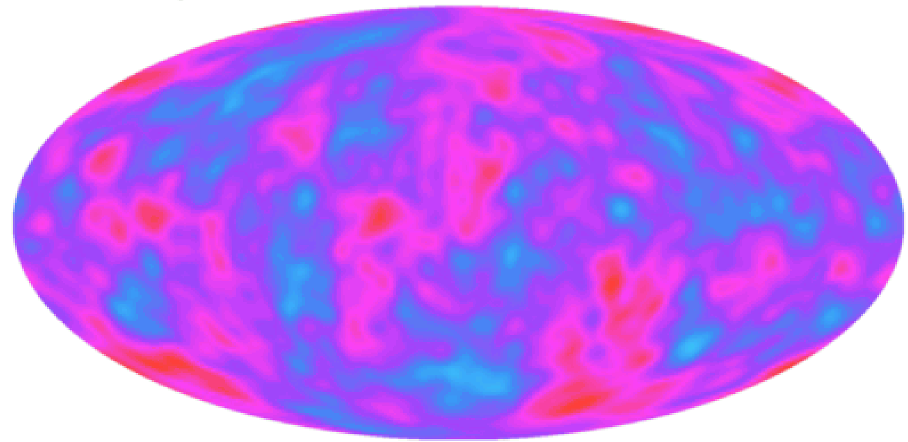


COBE DMR vs EPAS

COBE Data



Equal Power on All Scales Model



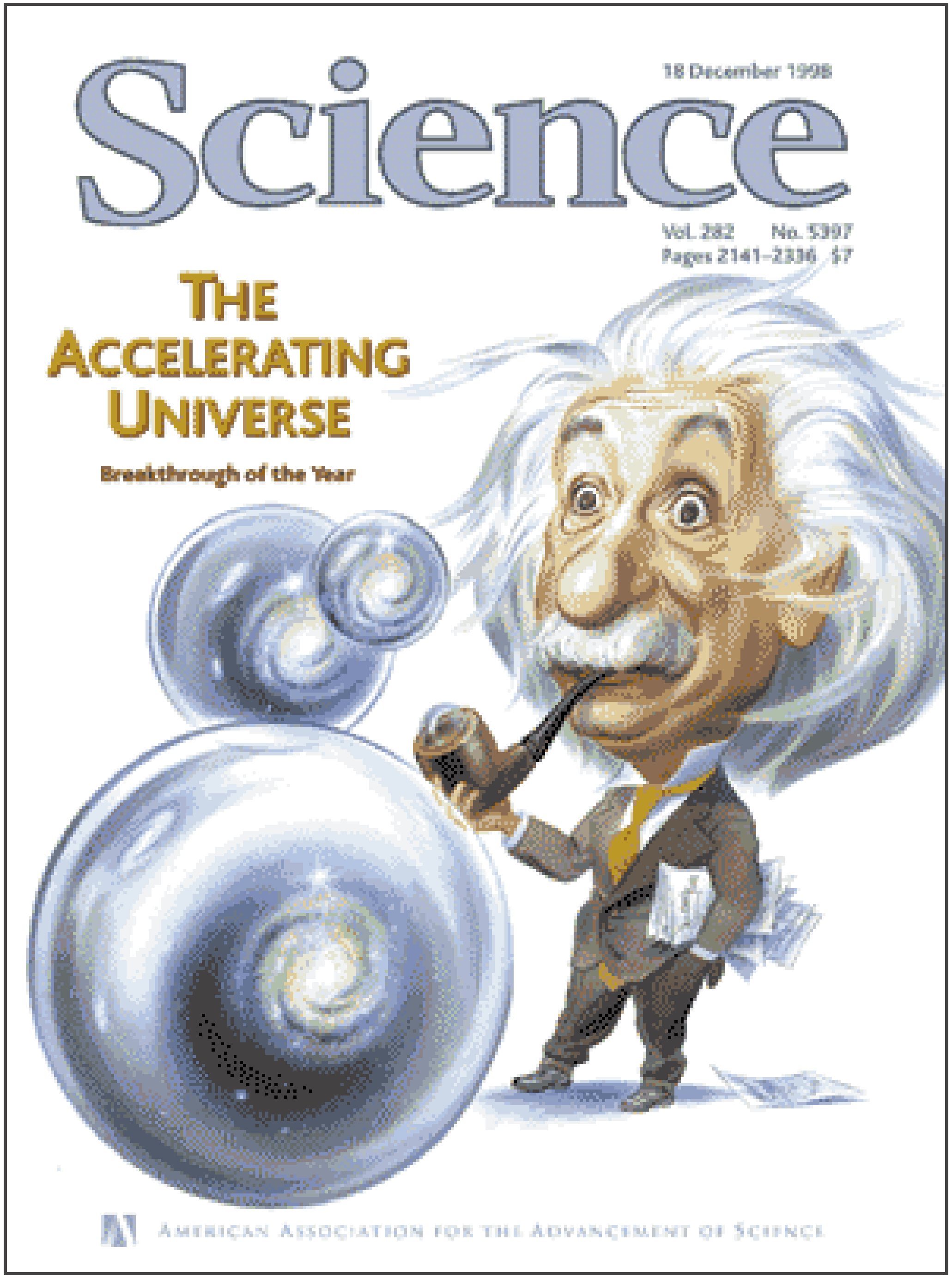
"Chi-by-eye" suggests that the "Equal Power on All Scales" prediction of inflation is correct.

Accelerating Universe: 1998

Distant (high z) supernovae fainter than expected.

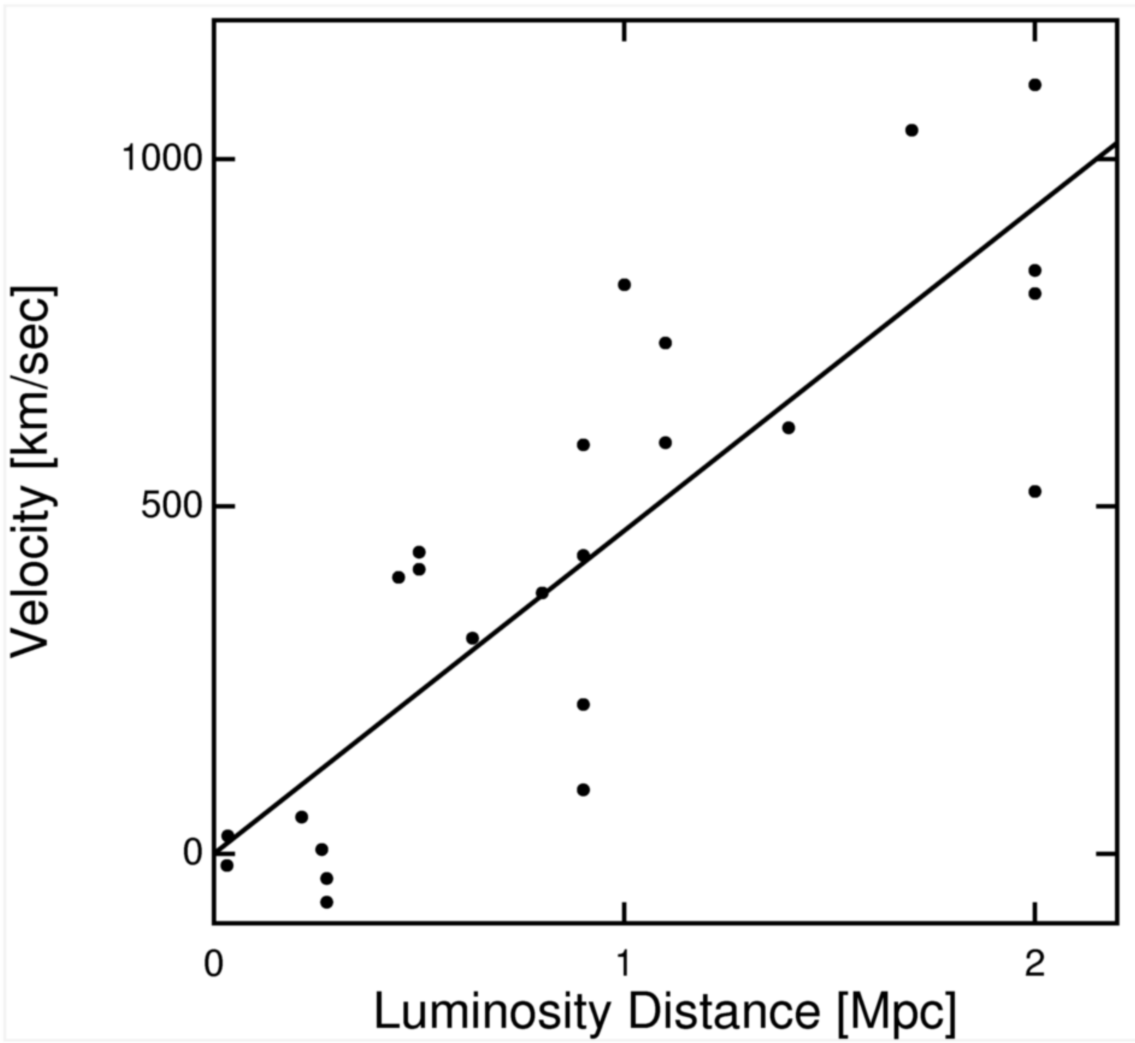
This was the AAAS discovery of the year in 1998.

Λ causes acceleration!

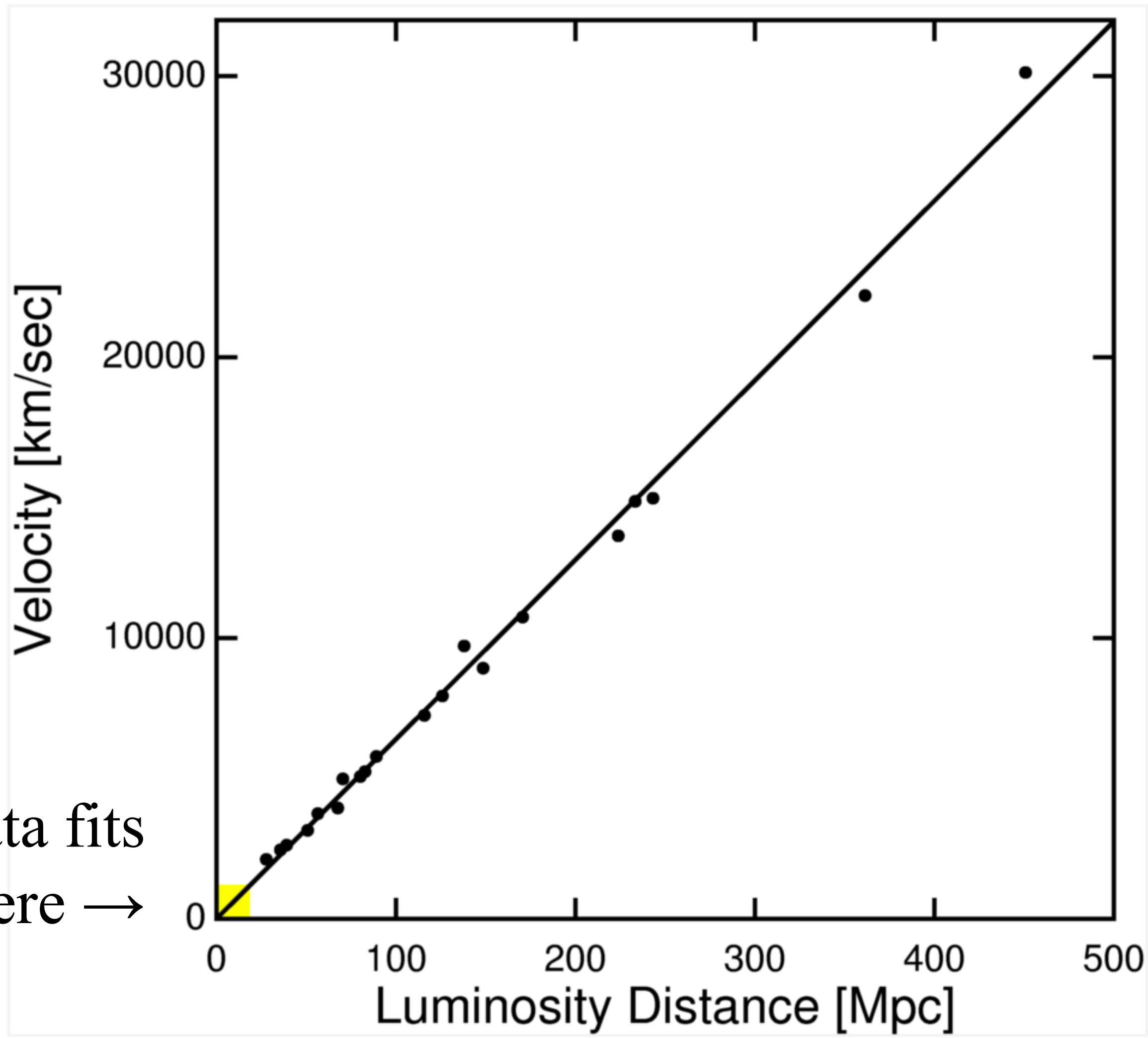


We recently learned how to read the "wattage" label on supernovae:

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

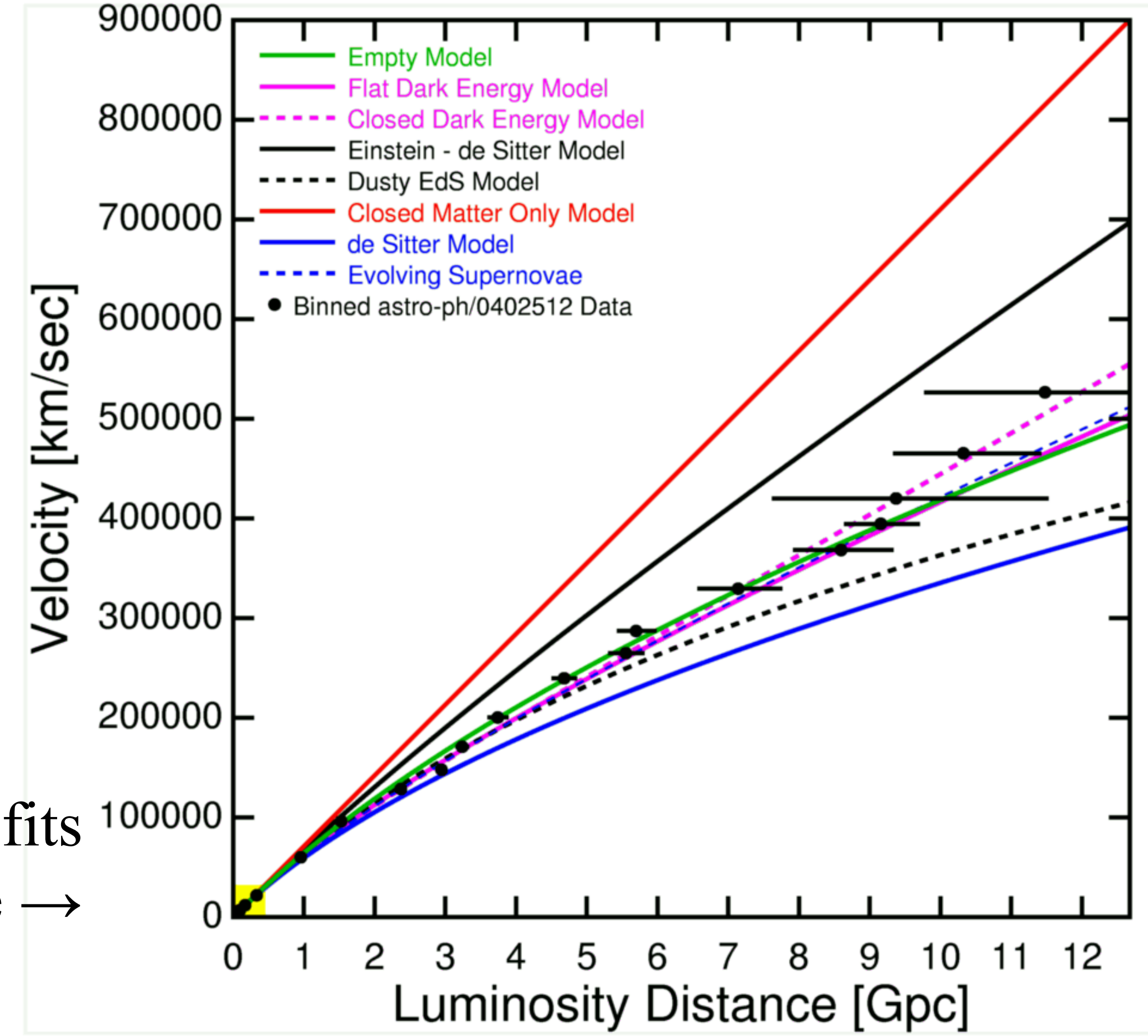


As a result, data on velocity vs distance is now much better! 1995



1929 data fits in here →

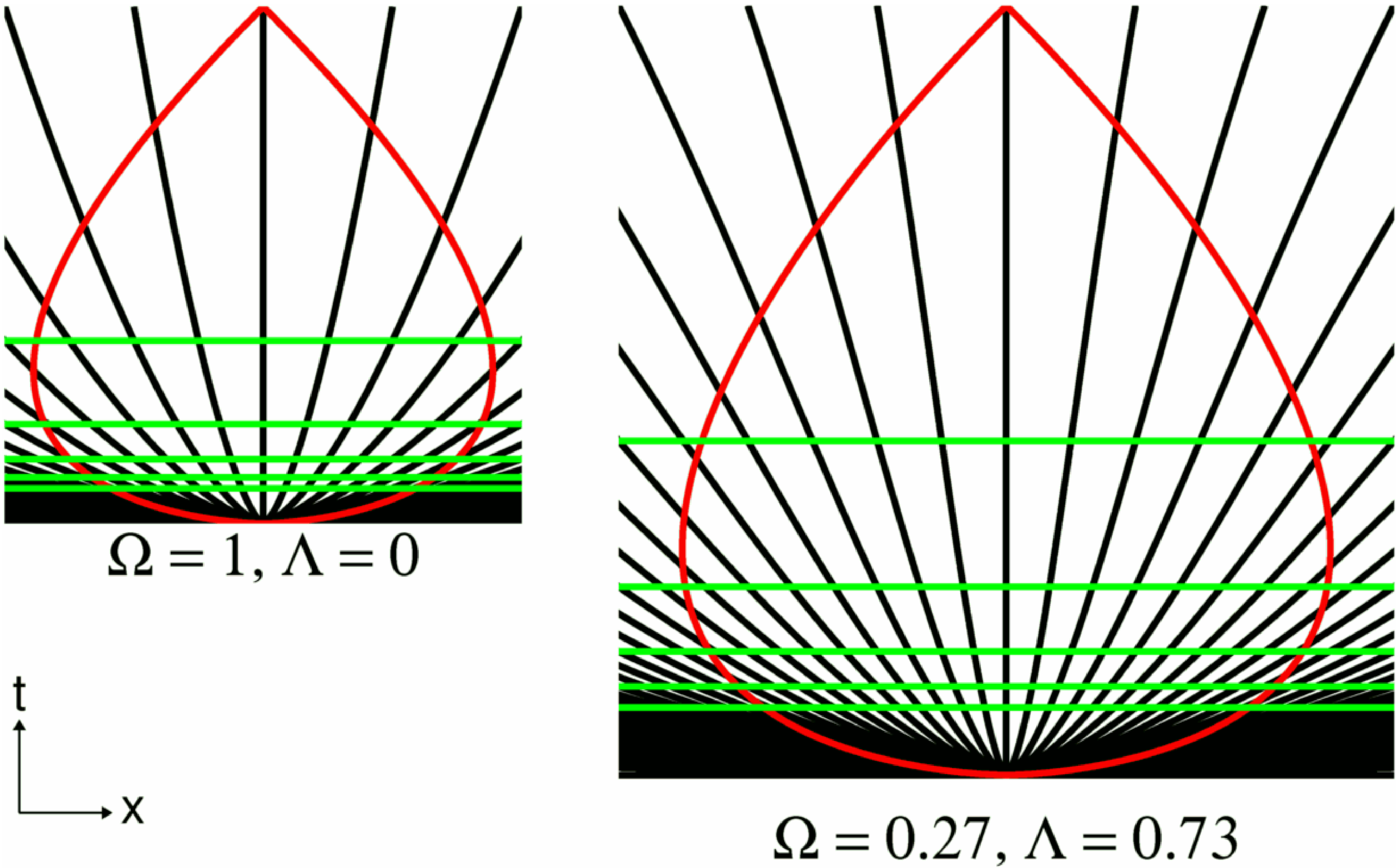
As a result, data on velocity vs distance is now much better! 2004



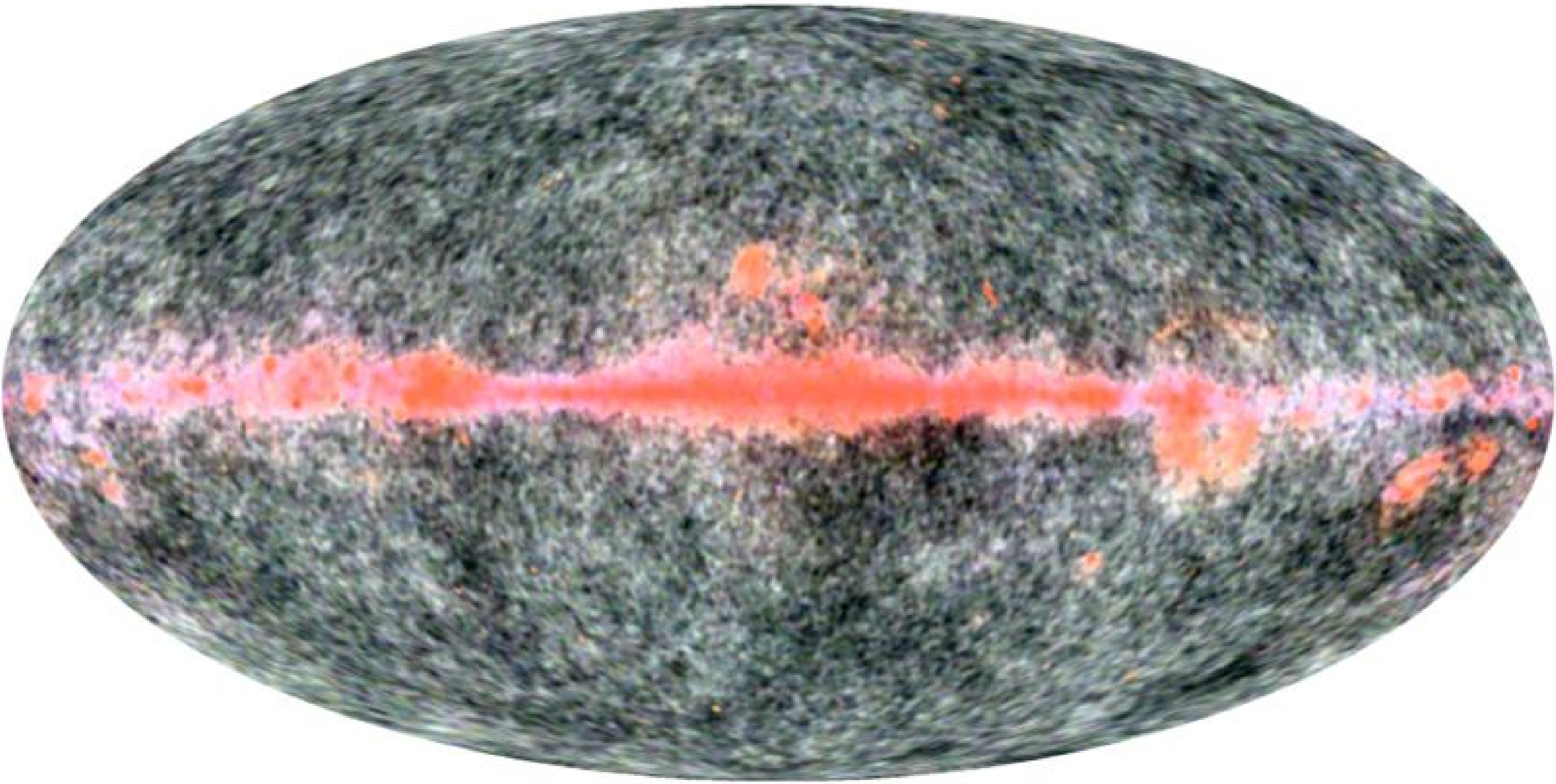
1995 data fits in here →

v = cz

Acceleration causes Faintness



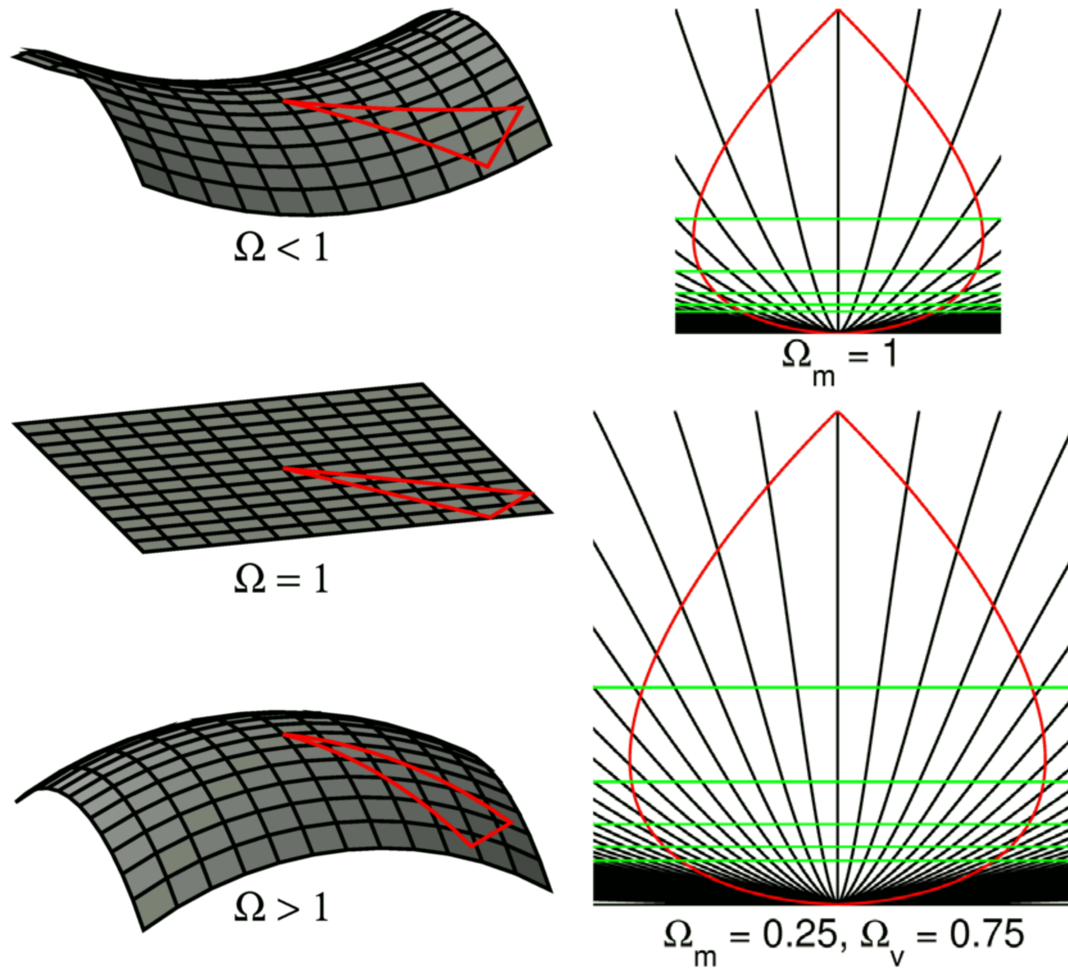
WMAP QVW as RGB



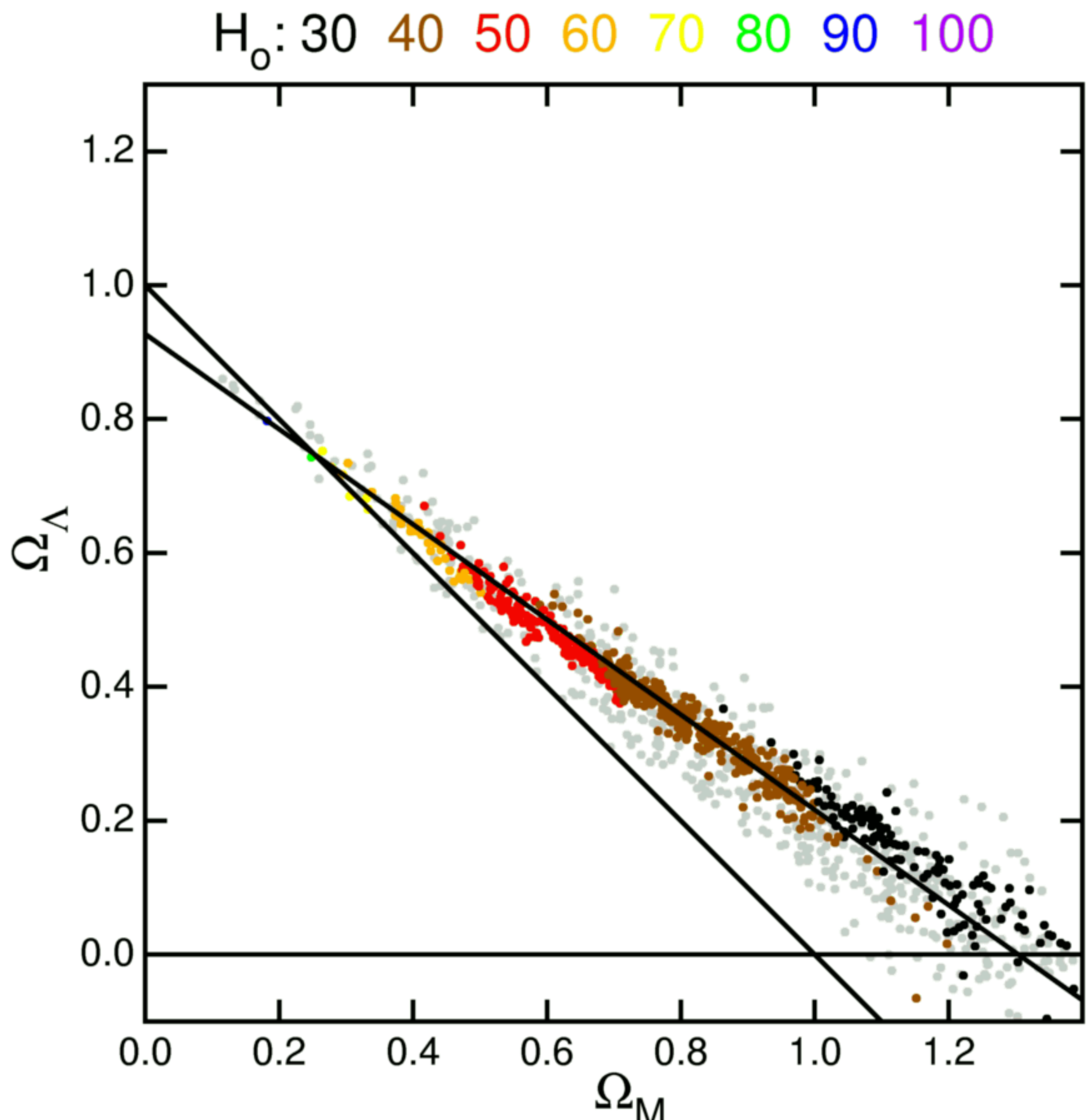
Note the characteristic spot size away from Milky Way: $l_{pk} \approx 180/\theta$

Effects on Peak Position: l_{pk}

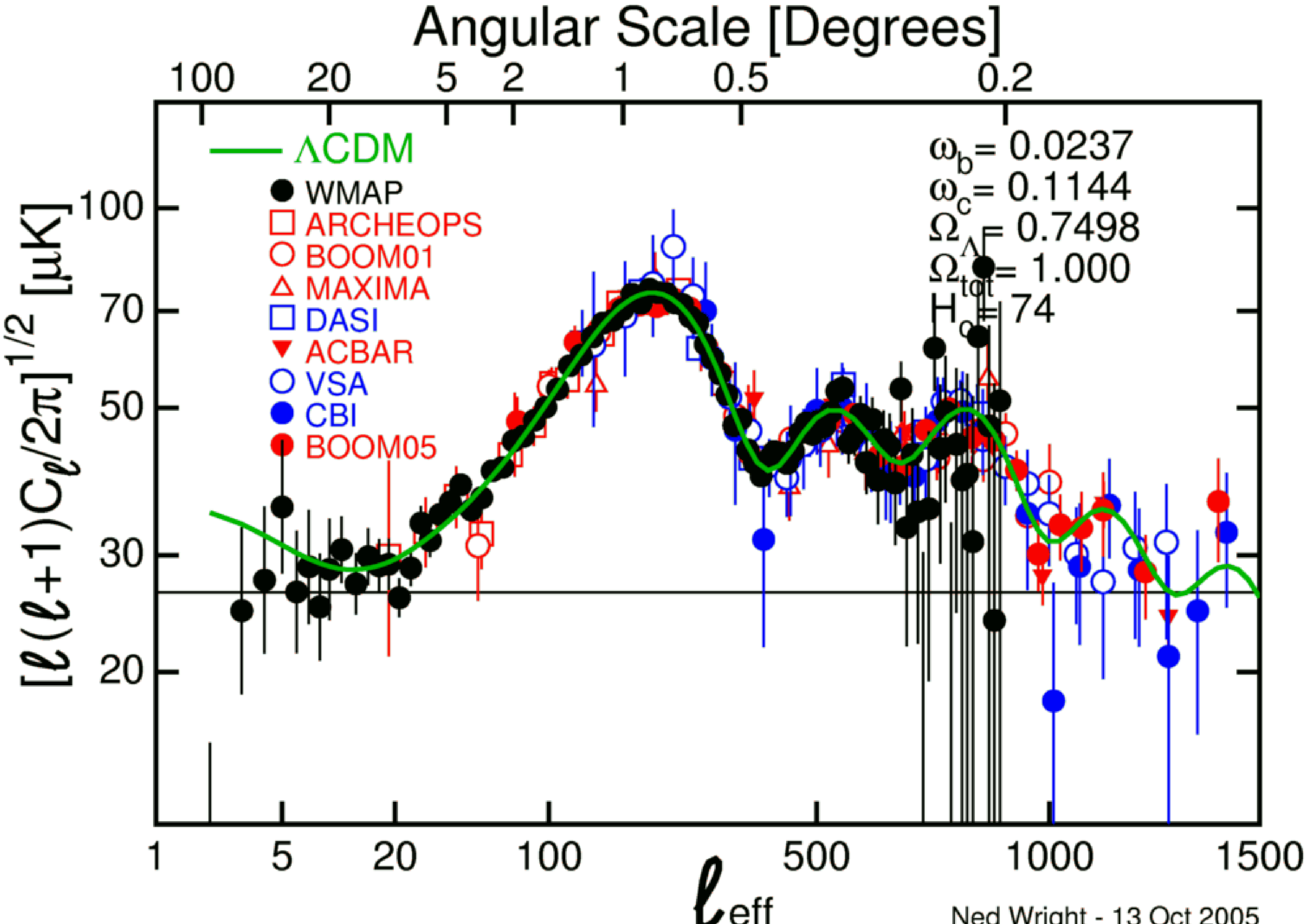
- Open or vacuum dominated Universes give larger distance to last scattering surface
- High matter density gives smaller wavelength



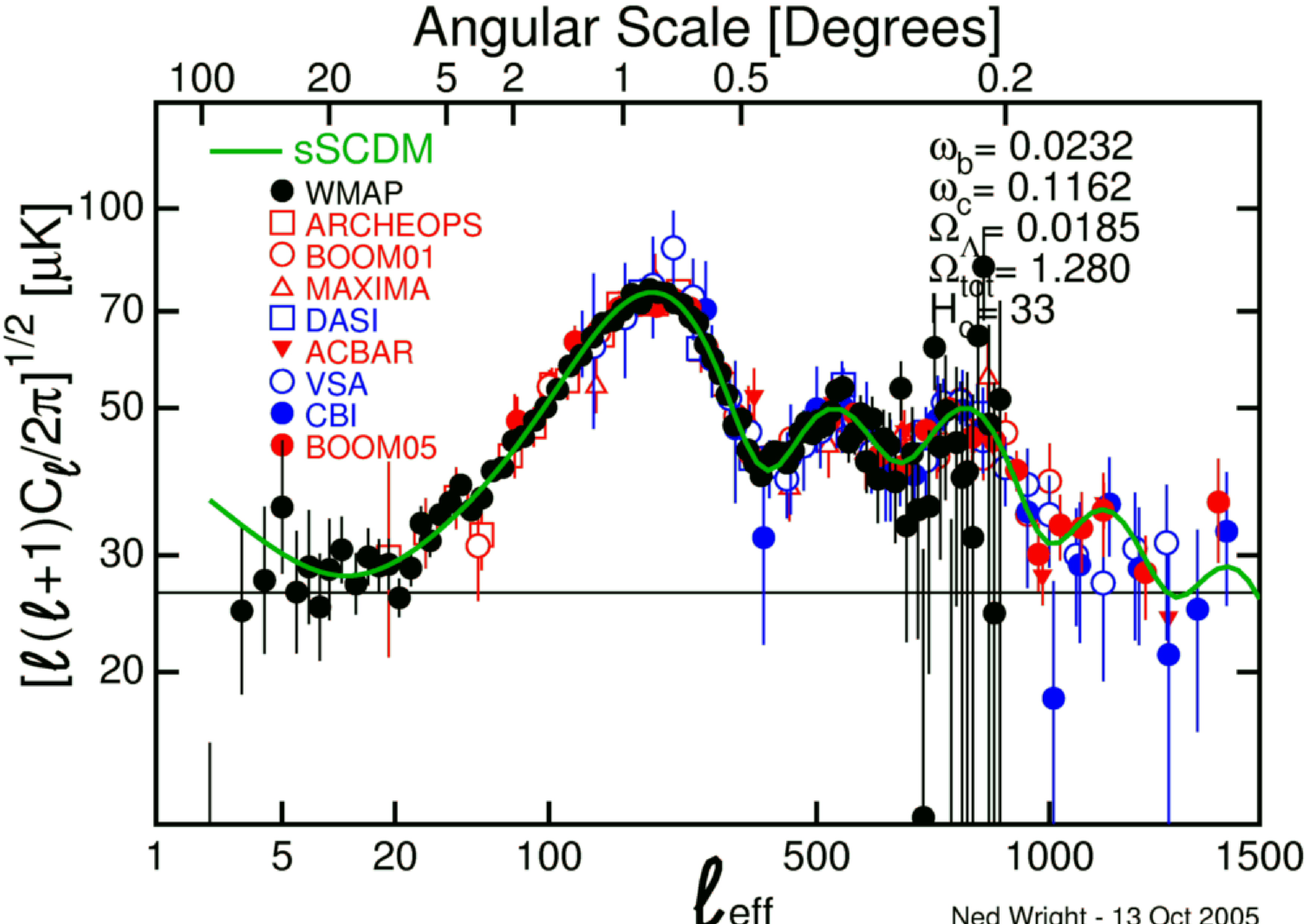
Results With WMAP



ΛCDM is a Good Fit



So is "super Sandage"



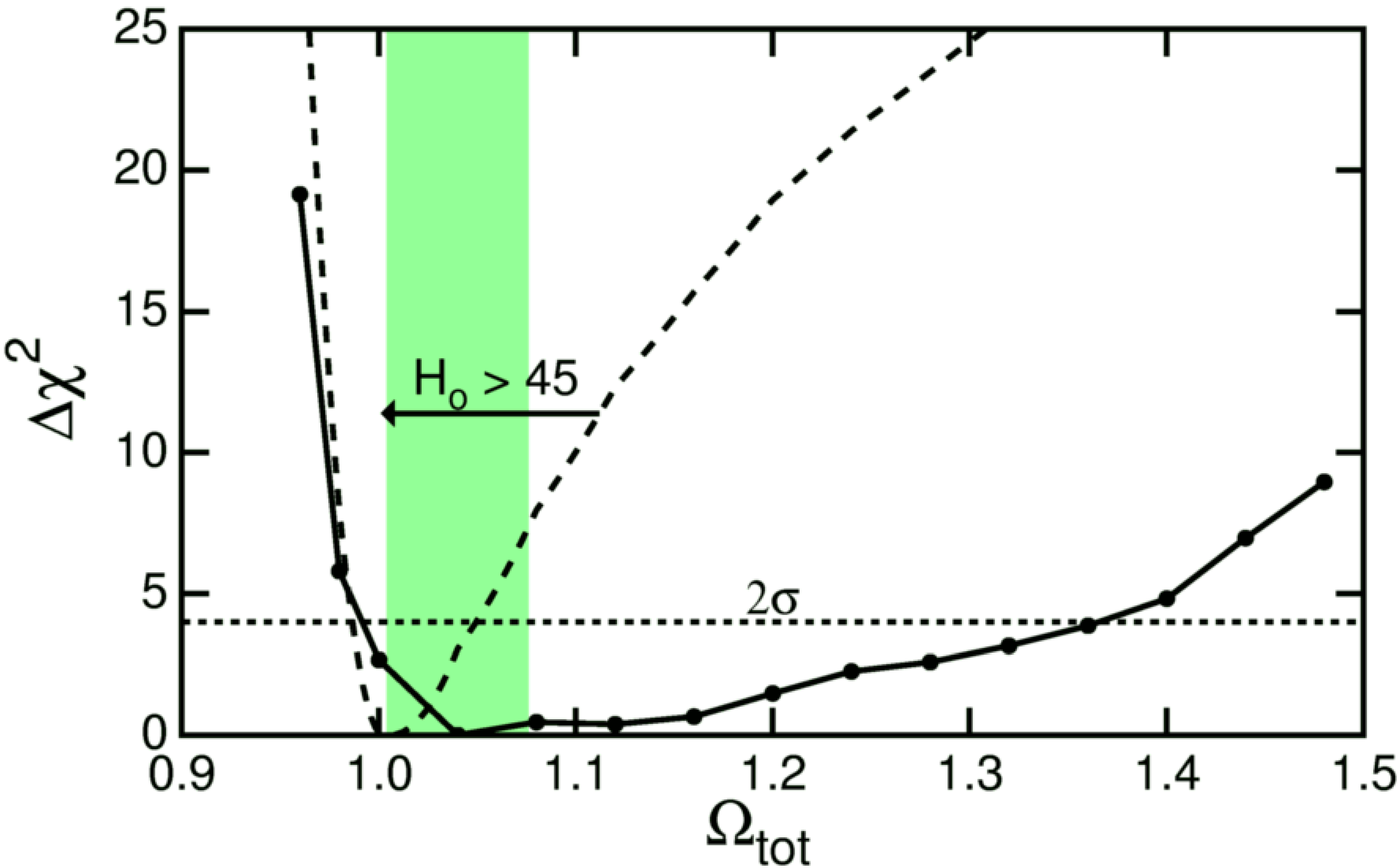
Is the Universe Really Flat?

- 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)

- Adding baryon oscillation peak: $\Omega_{tot} = 1.01 \pm 0.01$

One BOOMERanG Claim is Wrong



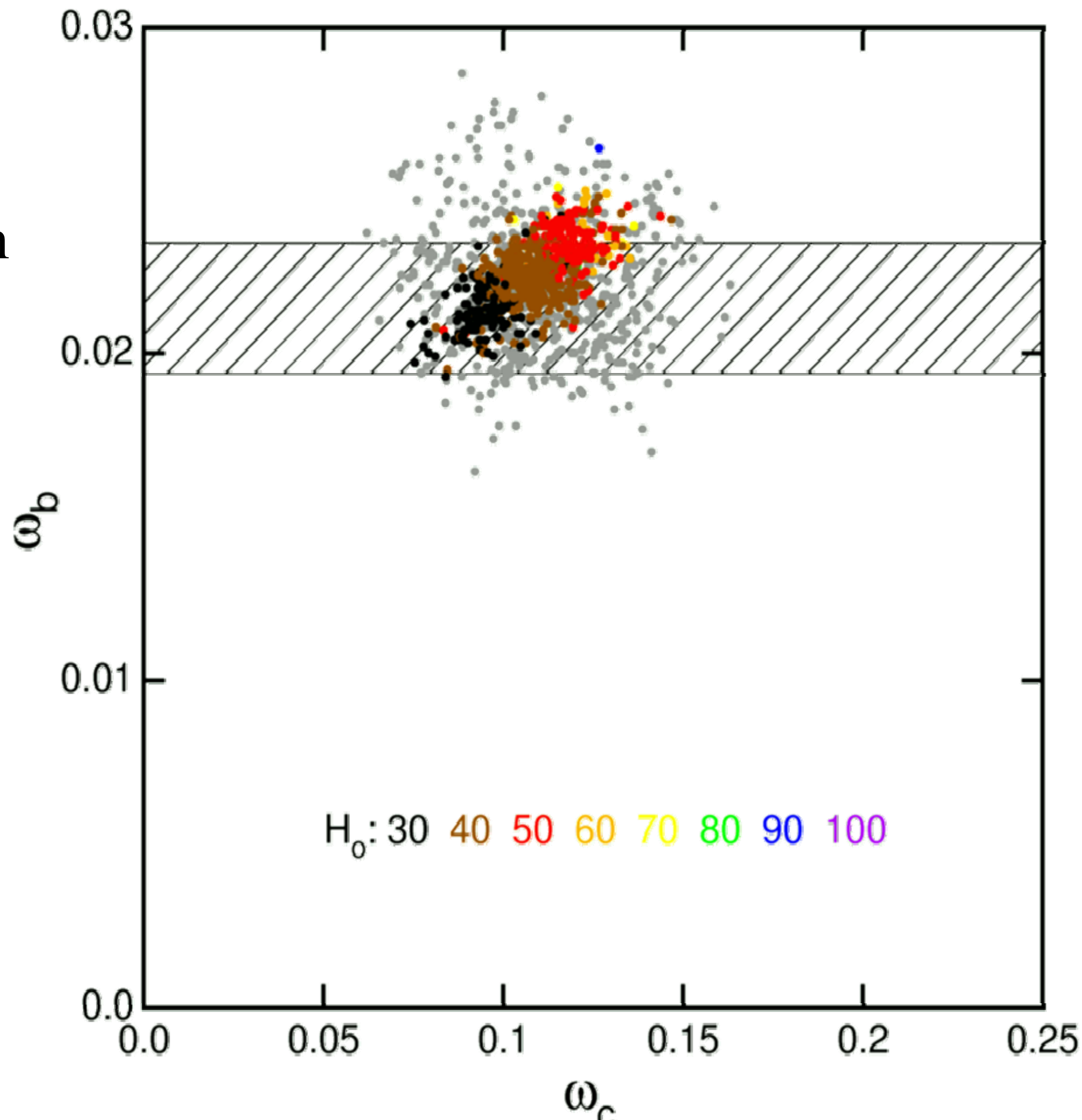
- MacTavish et al. (2005) *CMB only*: $1 < \Omega_{tot} < 1.08$

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 = 0.42×10^{-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

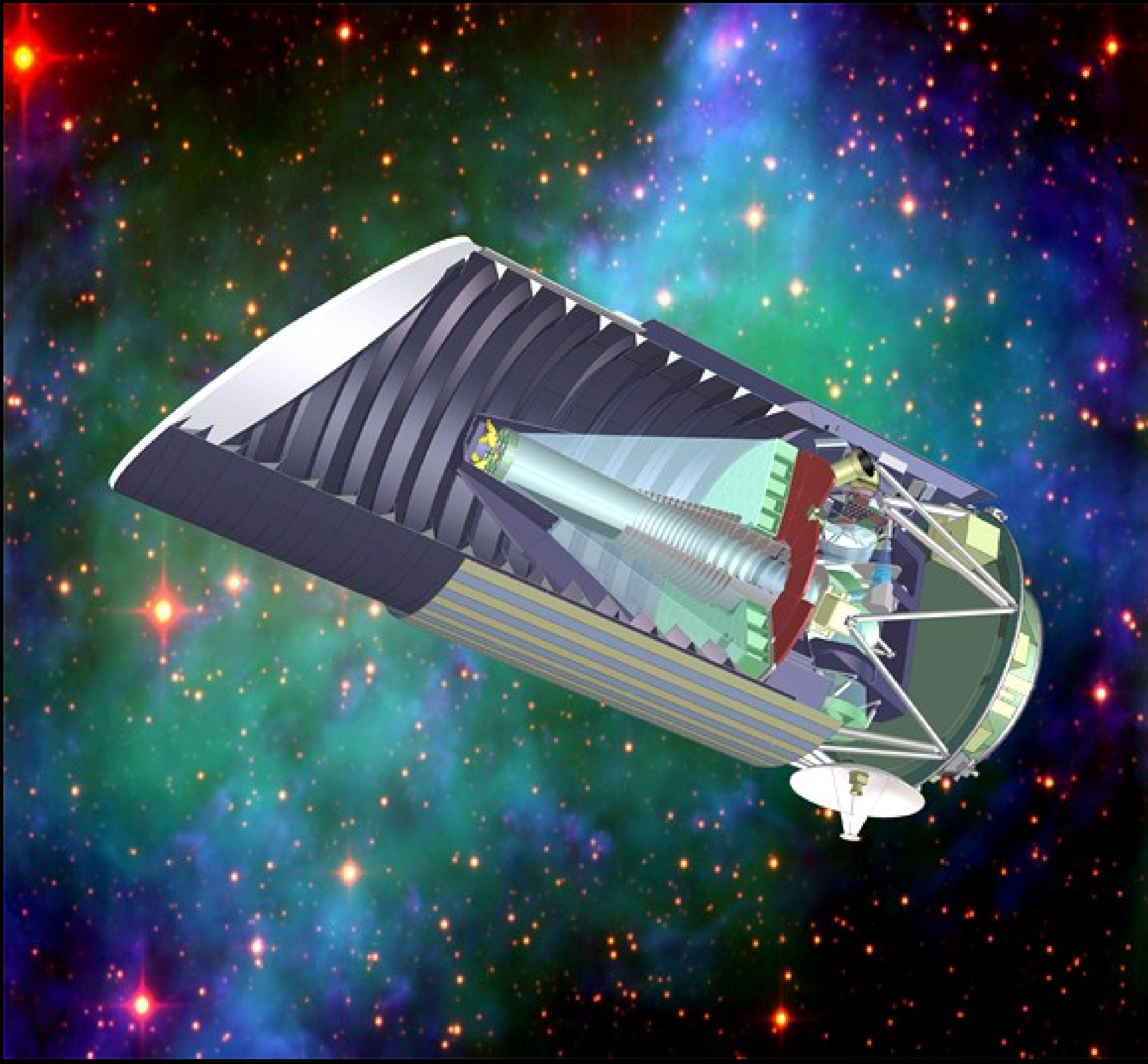


Is Λ really a *CONSTANT*?

- 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?
- In order to find out, NASA and the Department of Energy want to build JDEM, the Joint Dark Energy Mission.
- Several groups are proposing JDEM concepts.
- I am on the JDEM Science Definition Team.

JDEM in 10 years?

NASA needs $$$

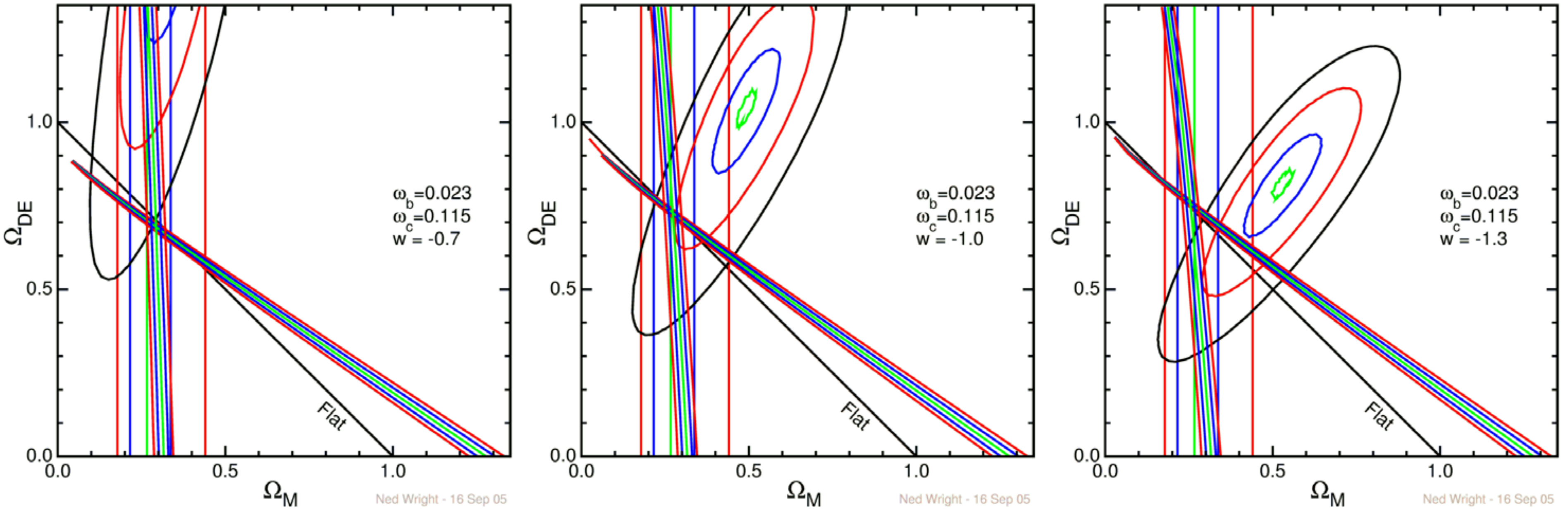


Search for Two Numbers?

- 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].
- 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?



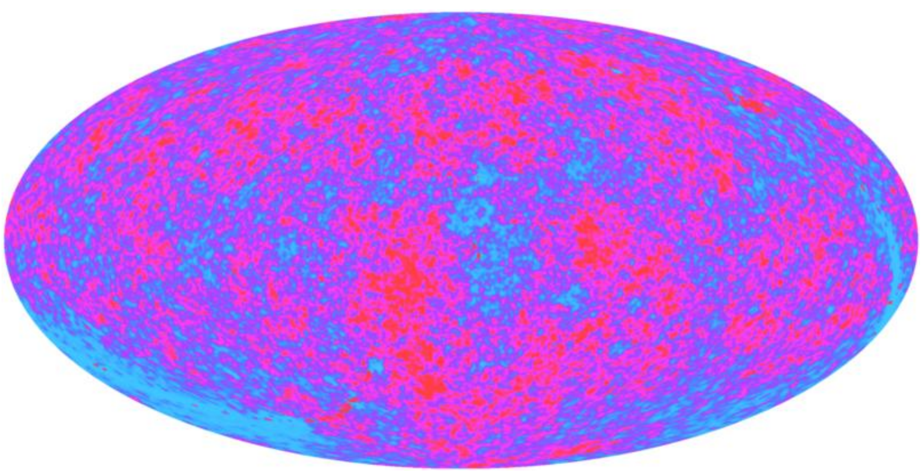
- Pretty good mutual agreement of 4 datasets (CMB, SNe, H_o & Baryon oscillations) for w = -1 and Ω_{tot} =1.
- This agreement is slowly lost as w moves away from -1.

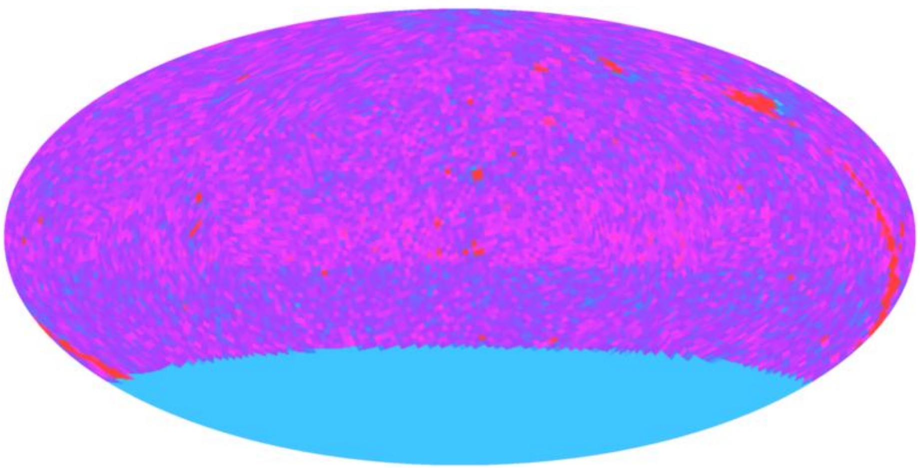
Same Laws of Physics?

- 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.

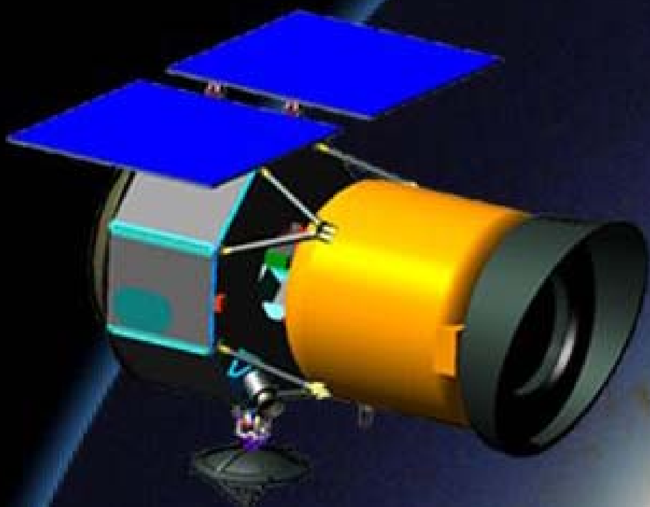
Λ Confirmed by CMB & IR maps

- 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.

Conclusion: A Century of Progress

- From 1 fact in 1905 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 5 parameter ΛCDM model fits all of these facts remarkably well.
- But are we ignoring something? Are the new "CN lines" out there?