Observing the Origin of the Universe

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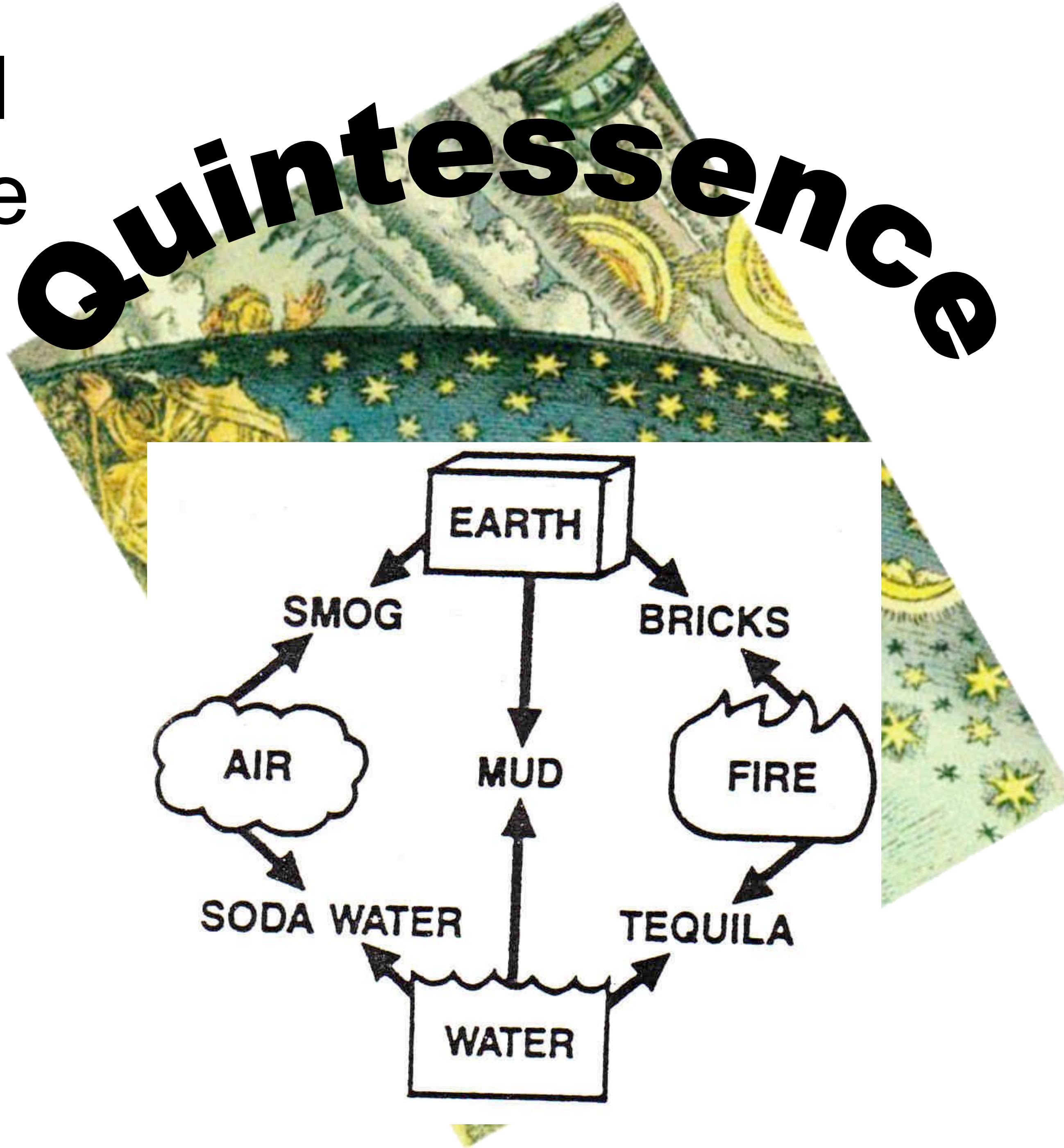
Old Style Cosmology

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.

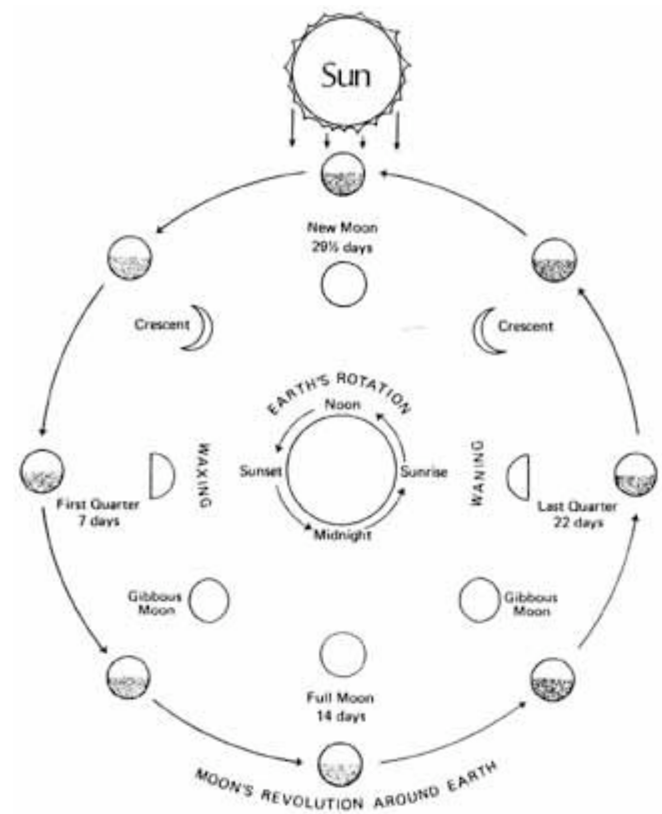
No special laws for the heavens

Quintessence



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.



History of Cosmology

Era	Size of Universe	Age of Universe	Speed of light
Ancient	10^8 km	10^4 years	infinite
1900	10^{17} km	infinite	$3x10^5$ km/sec
Now	$>10^{23}$ km	13.7 Gyr	$3x10^5$ km/sec

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

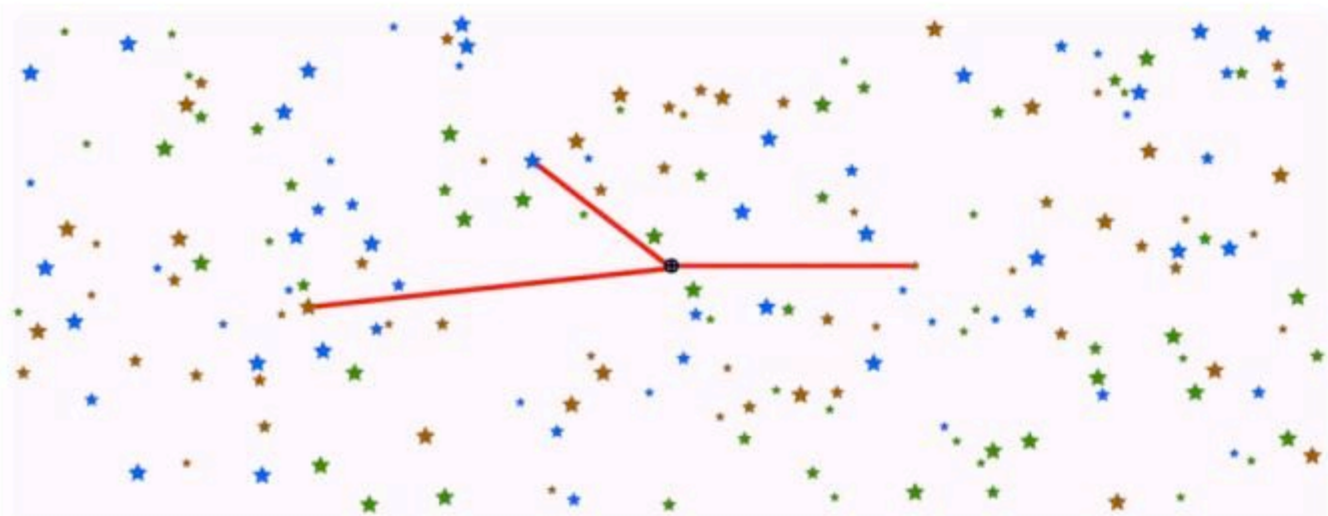
Two and a half Facts

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.

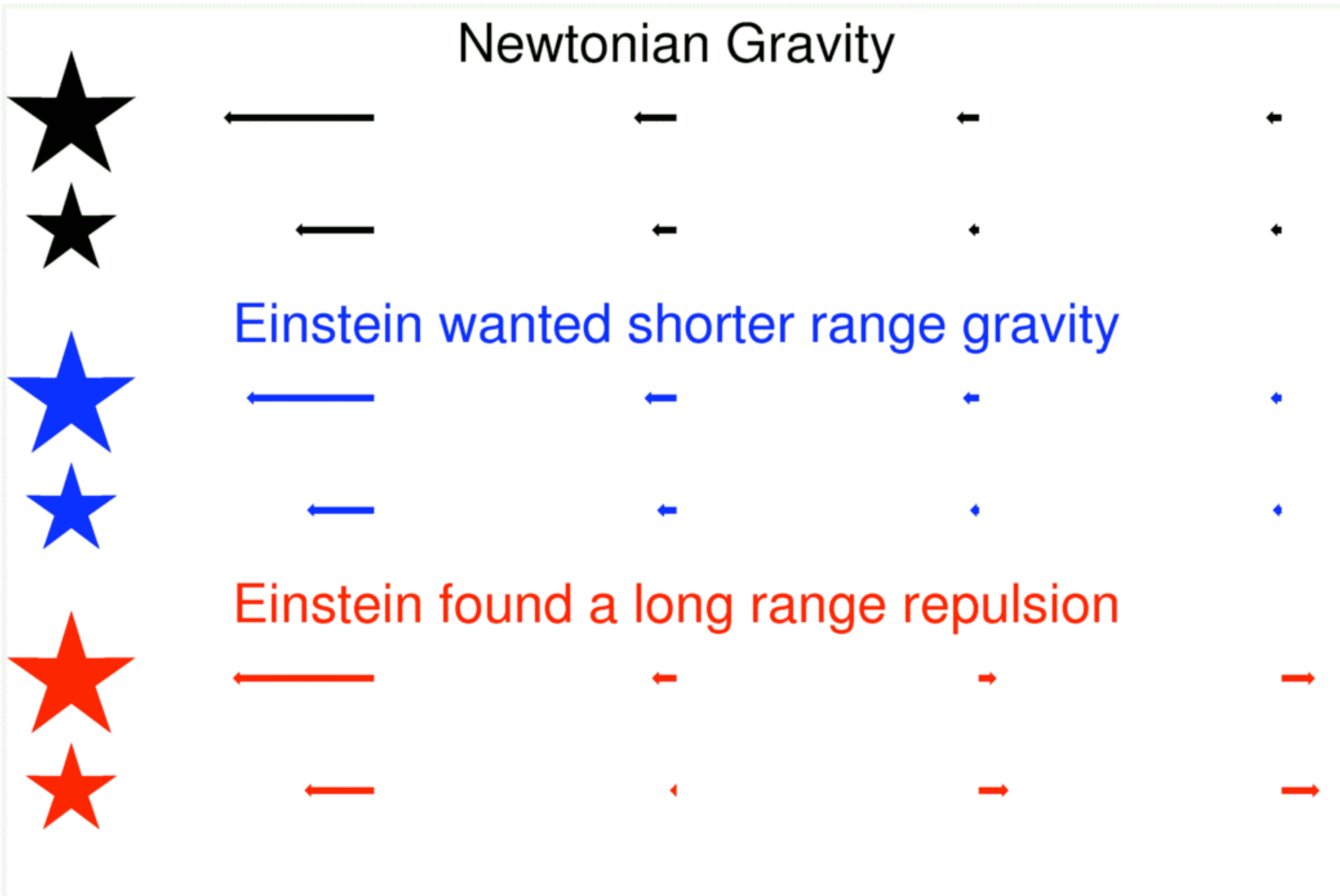


In a homogeneous unchanging Universe every line of sight will end on a star. So why is the night sky not as bright as the surface of a star? The Cosmic Infrared Background is what remains after this Olbers' paradox is resolved.

General Relativity & Cosmology

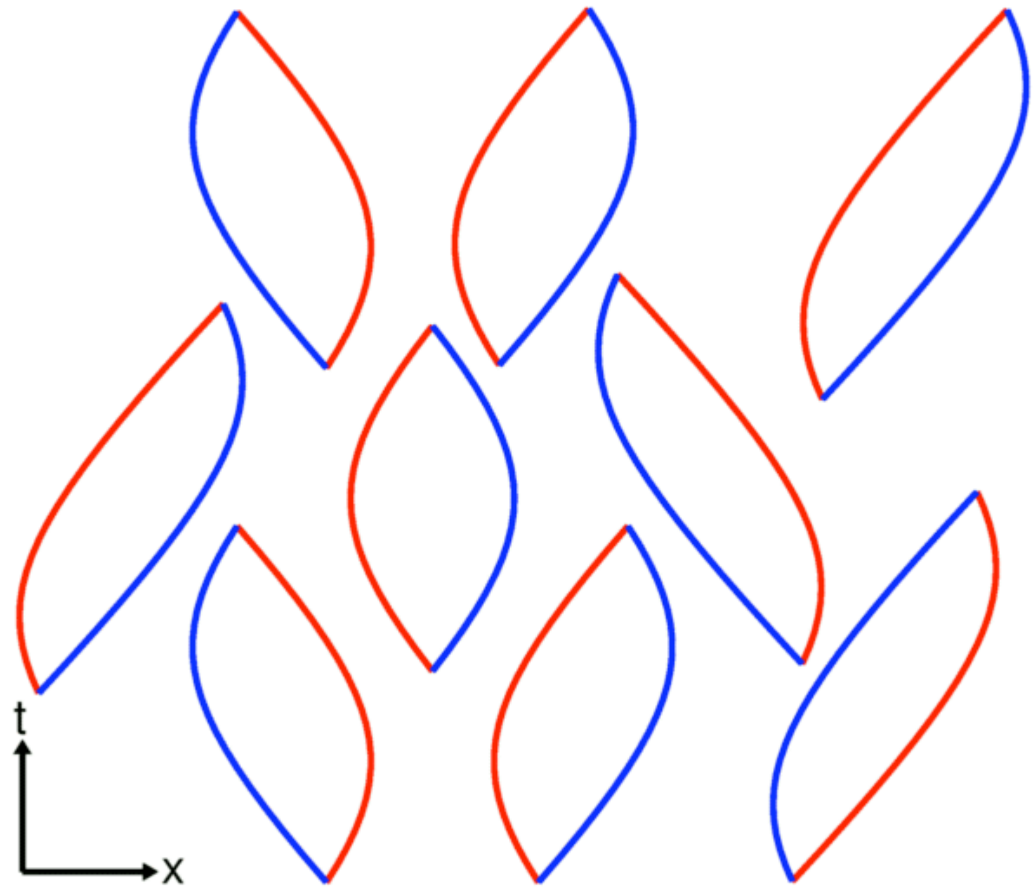
- General relativity allows a consistent calculation of the effects of gravity in a uniform distribution of galaxies that fills the entire Universe.
- But Einstein thought the Universe was static, and a static uniform distribution of galaxies that filled the entire Universe would be unstable to collapsing 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

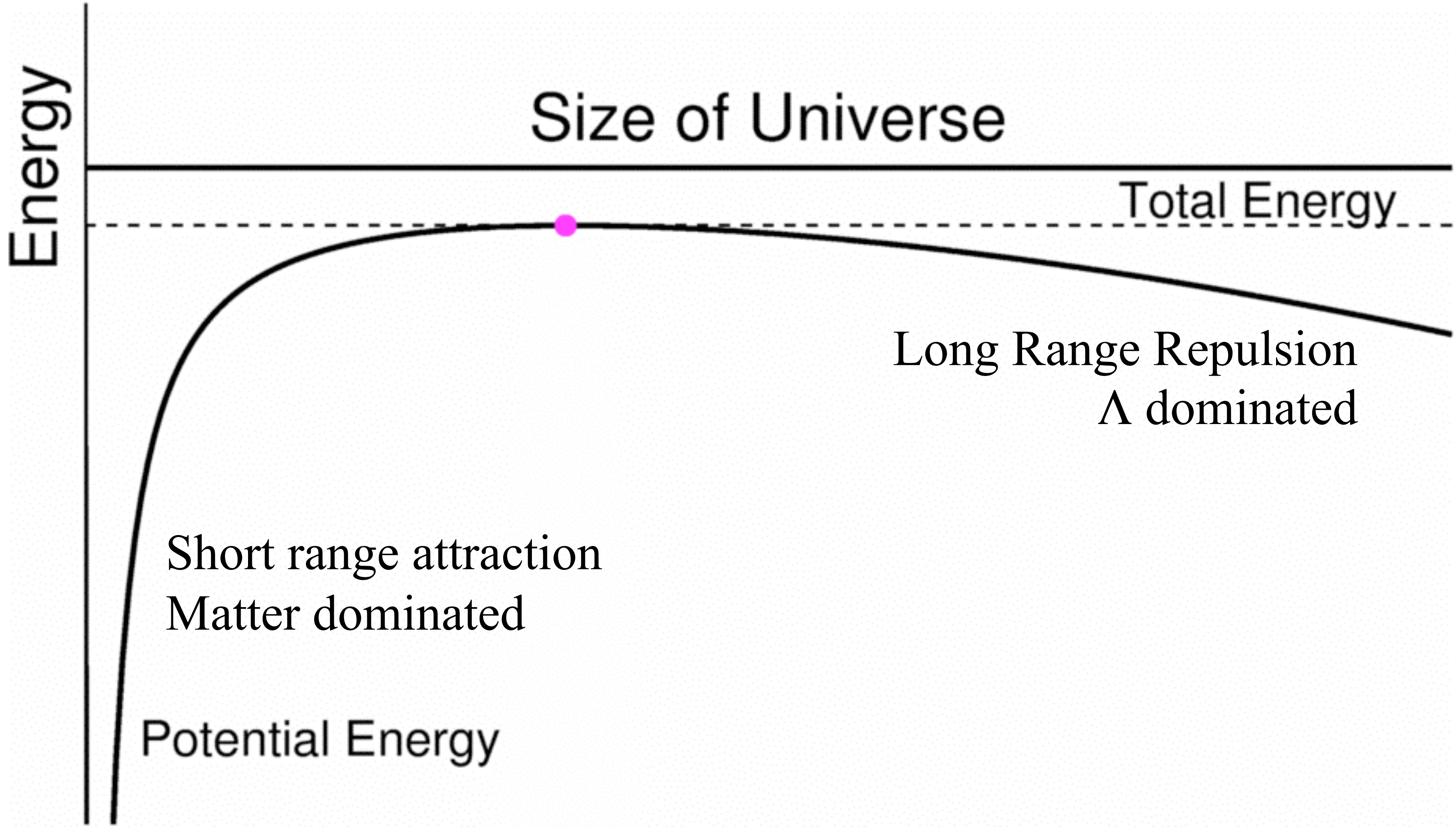
- A vacuum energy density is equivalent to Einstein's cosmological constant: Λ
- Quantum fluctuations could lead to a vacuum energy density.



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, $P = -\rho c^2$.
- If $P = -\rho c^2$ the stress-energy tensor of the vacuum is Lorentz invariant so you cannot measure your velocity relative to the vacuum.
- Net gravity from positive vacuum energy density plus negative pressure is repulsive.

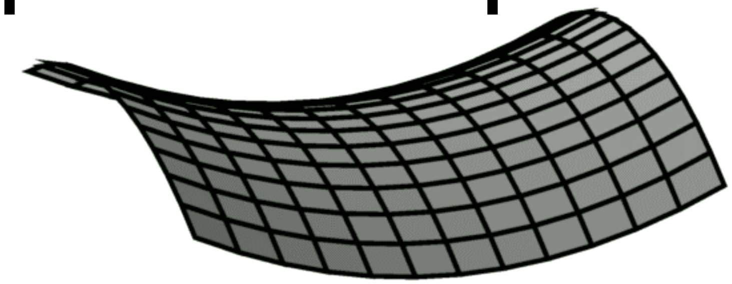
Represent Force by Slope



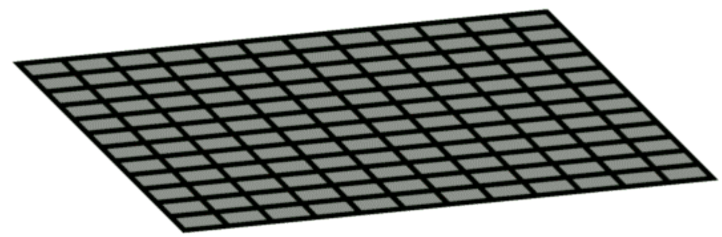
- This is quite a good analogy for cosmological models.

Total Energy implies Shape

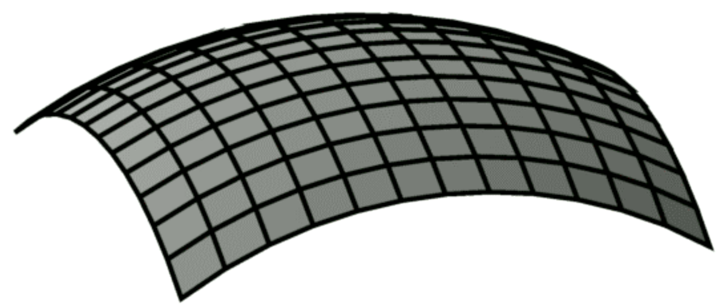
- Total Energy > 0
  - Sum of angles < 180^o
  - Negative curvature
  - Infinite



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

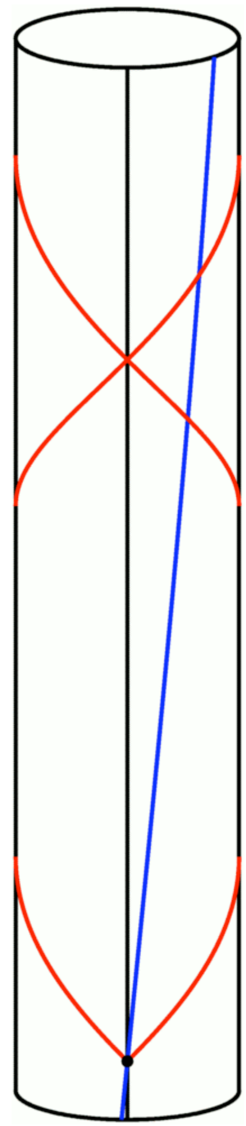


- Total Energy < 0
  - Sum of angles > 180^o
  - Positive curvature
  - Finite



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.



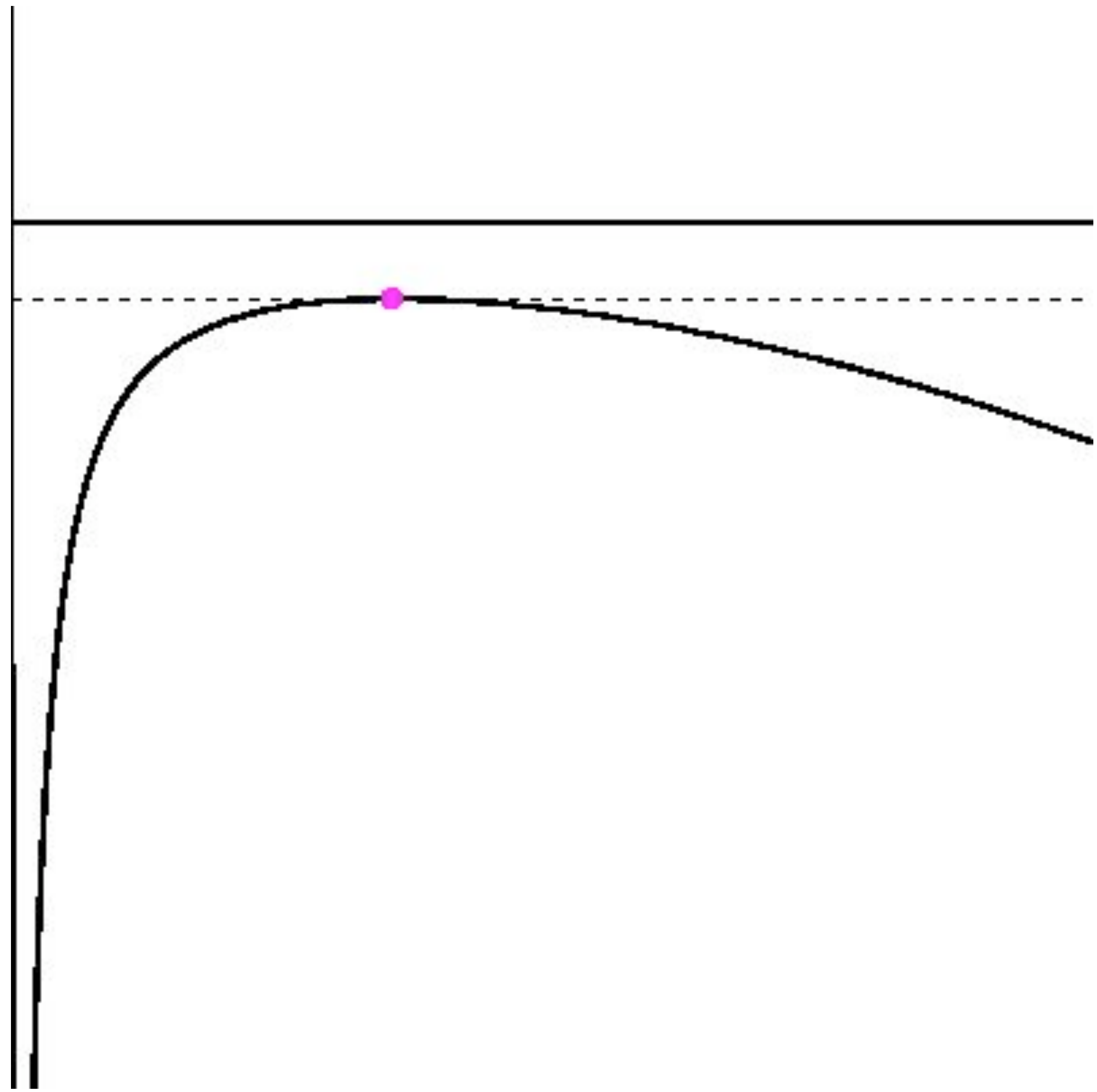
In this space-time diagram there are two observers with different velocities. One observer sees the circumnavigating light rays return at the same time, while the other does not.

Velocity with respect to the Universe is easily measured.

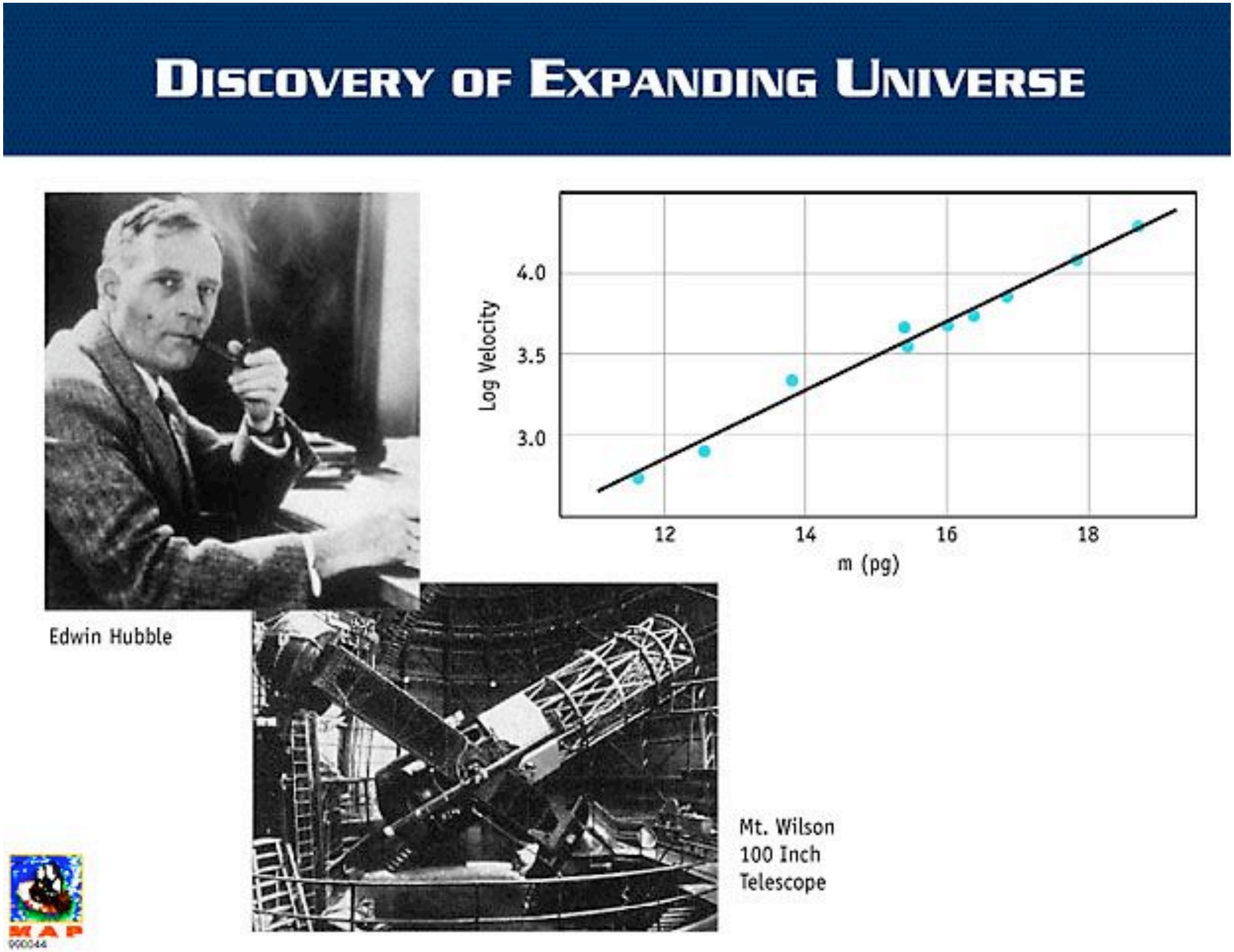
Other models based on GR

- Einstein had a very special combination of matter, Λ and total energy to give a static Universe. But this model is only metastable. If perturbed, it would either collapse or expand forever.
- de Sitter considered a model with no matter, only Λ. This model had an exponentially accelerating expansion.
- Friedmann considered models with matter that expanded from a singularity of infinite density.

Forces Balance Only at 1 Size



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

Hubble Law: v = HD

- Hubble found a recession velocity proportional to the distance.
  - Einstein static fails, de Sitter & Friedmann pass
- Hubble also found that the distribution of galaxies was homogeneous [the same in all places] and isotropic [the same in all directions].
  - Einstein static, de Sitter & Friedmann all pass

V = HD is the only good choice

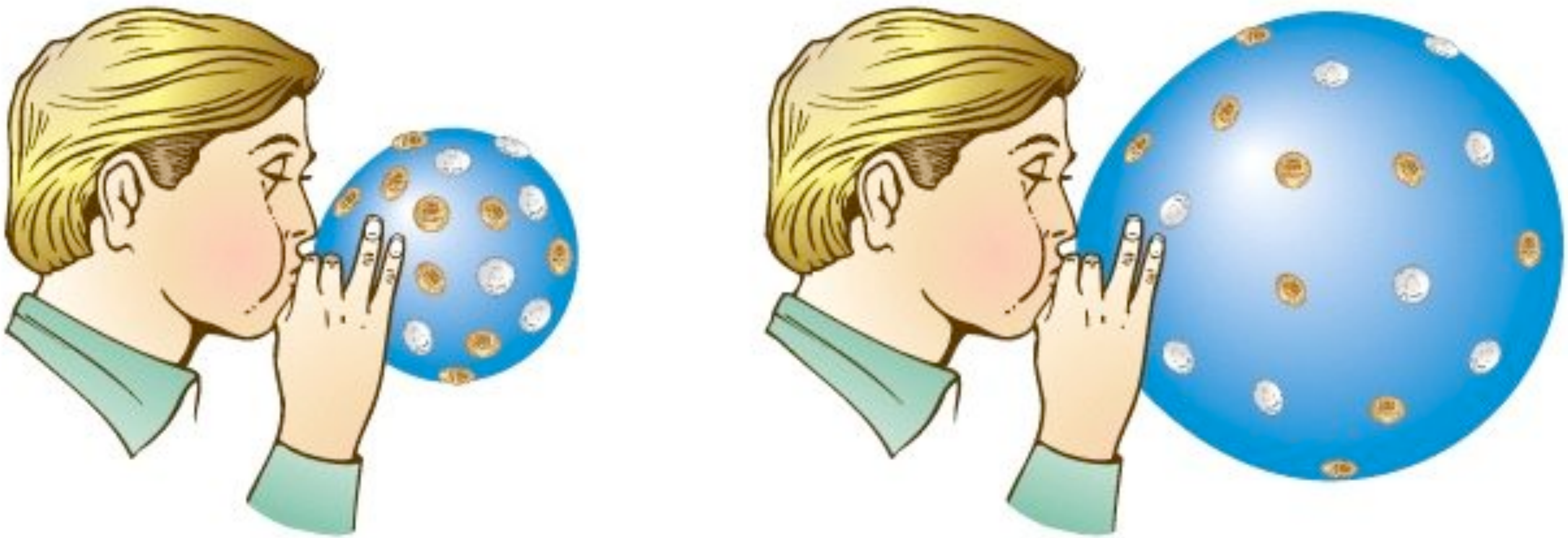
$V \propto D^0$ $V \propto D^1$ $V \propto D^2$

Without the Hubble law, the Universe would not stay homogeneous and isotropic as it expanded.

The Balloon Analogy

- Notes that the galaxies DO NOT expand!
- The number density of galaxies goes down.
- The number density of photons goes down.
- The photon energy goes down.

Glue coins to the balloon

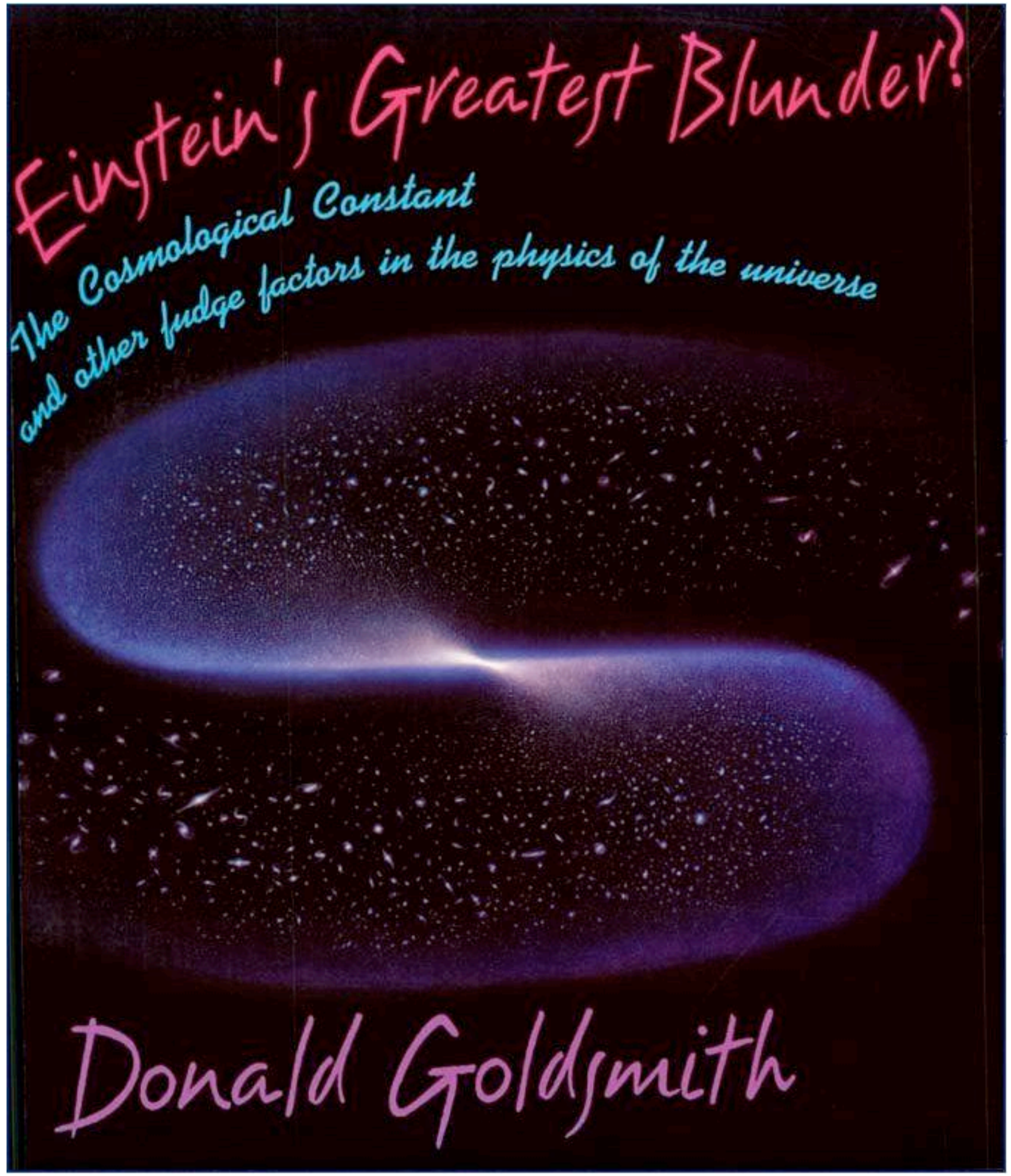


Models vs Olbers Paradox

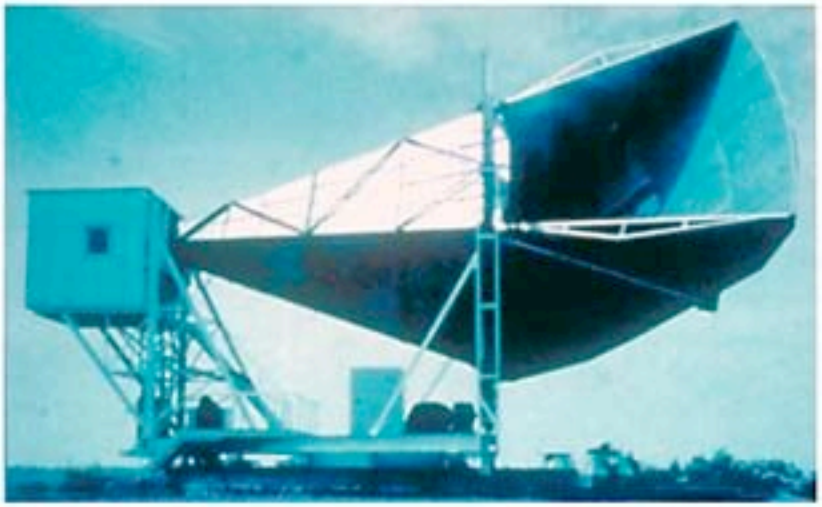
- A static Universe filled with light-emitting stars cannot be static. It will fill up with photons and gradually get brighter.
- Einstein's static model will fill up with light until the night sky is as bright as the surface of a star.
- Expanding de Sitter & Friedmann models are consistent with a dark night sky.

Λ Was Demoted

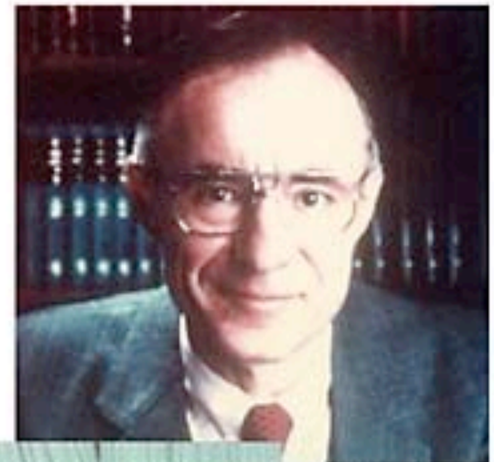
- Expanding models with or without matter and/or Λ are possible.
- But matter is needed – we are here.
- Λ was not needed so it was deprecated.



Discovery of the Cosmic Microwave Background



Microwave Receiver



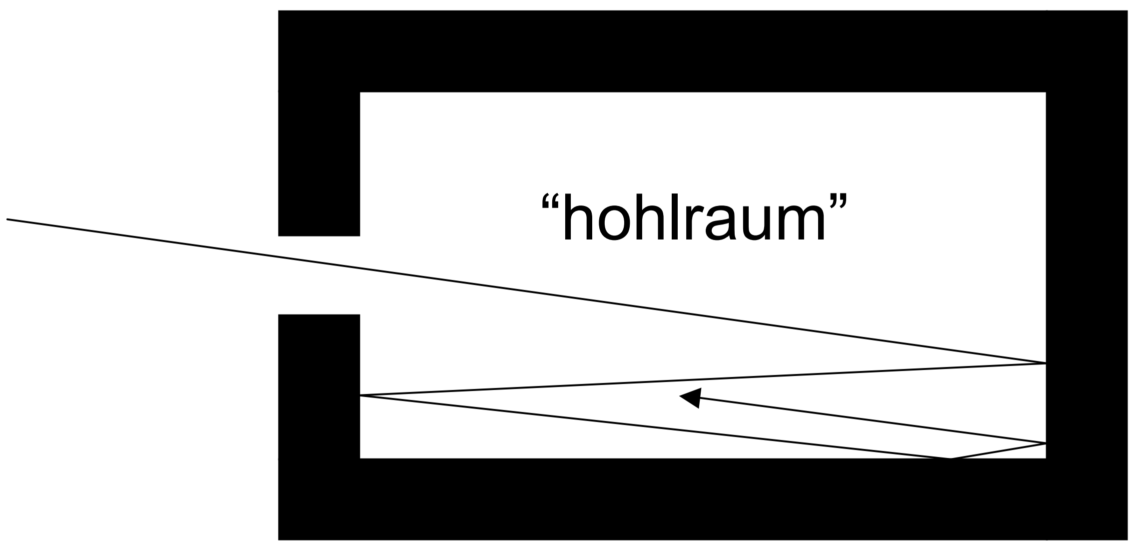
Arno Penzias

Robert Wilson

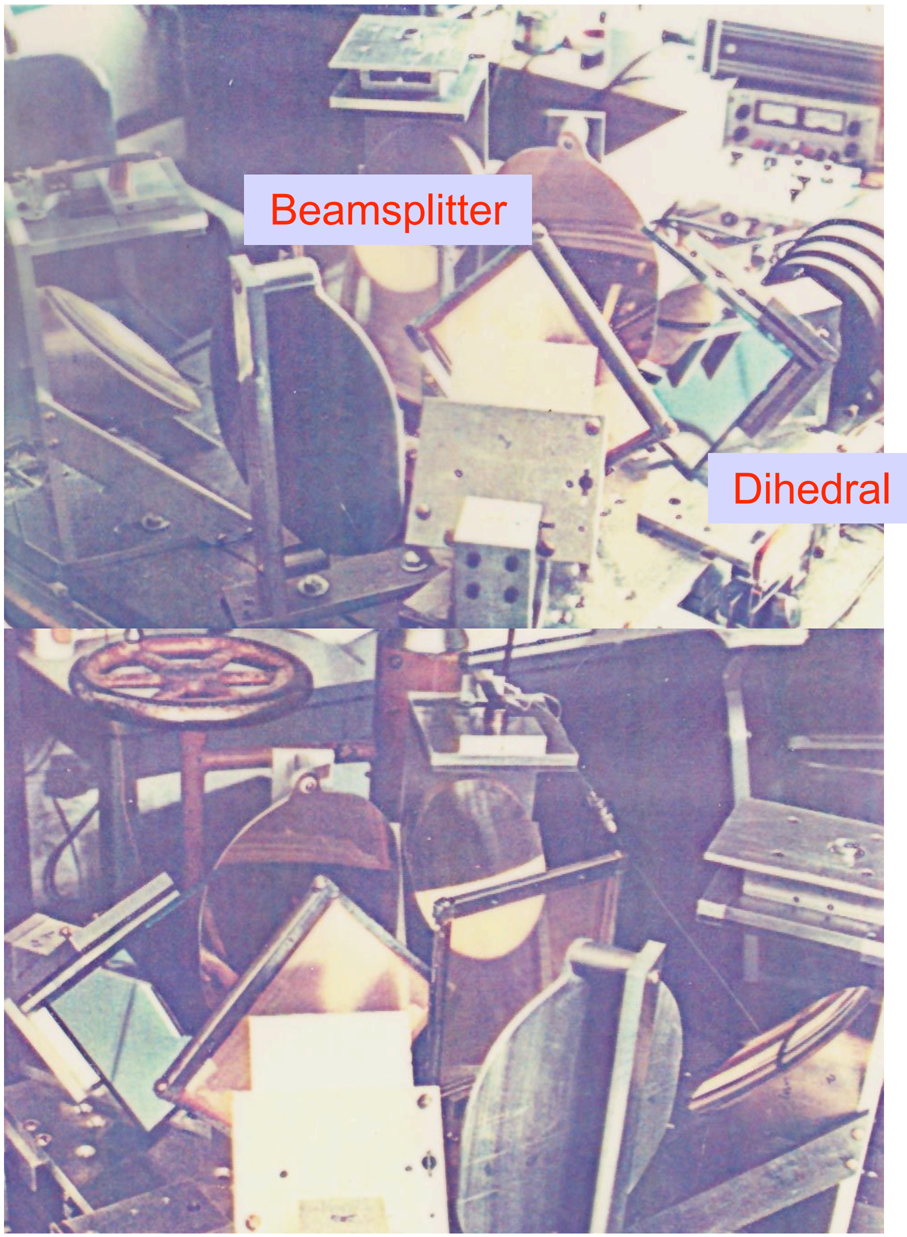
MAP
990045

CMB Spectrum is a Blackbody

- A blackbody is an opaque, non-reflective, isothermal body.
- The best laboratory blackbodies use cavities with small entrances so light is almost trapped inside, giving very small reflections.



Personal History: my FIRAS breadboard at MIT



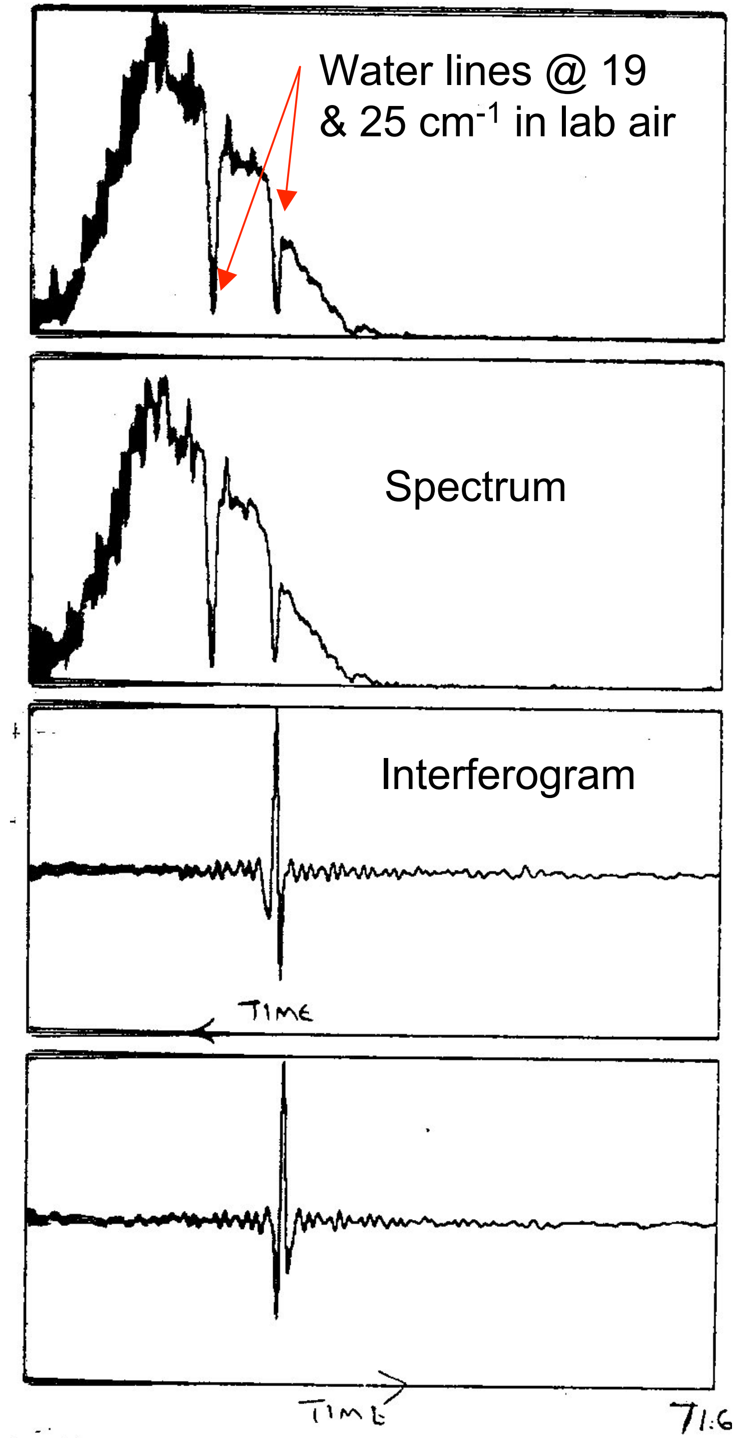
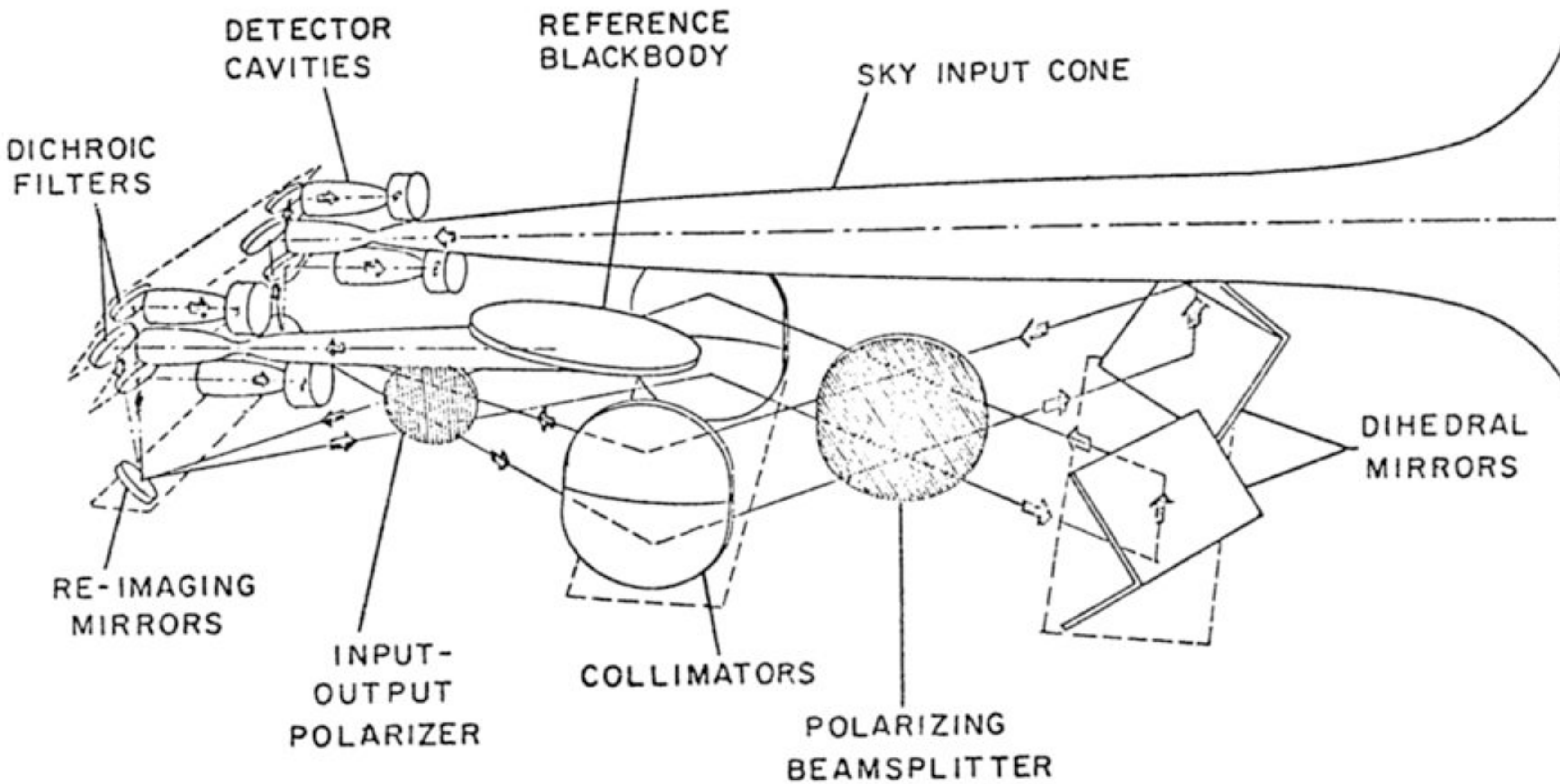
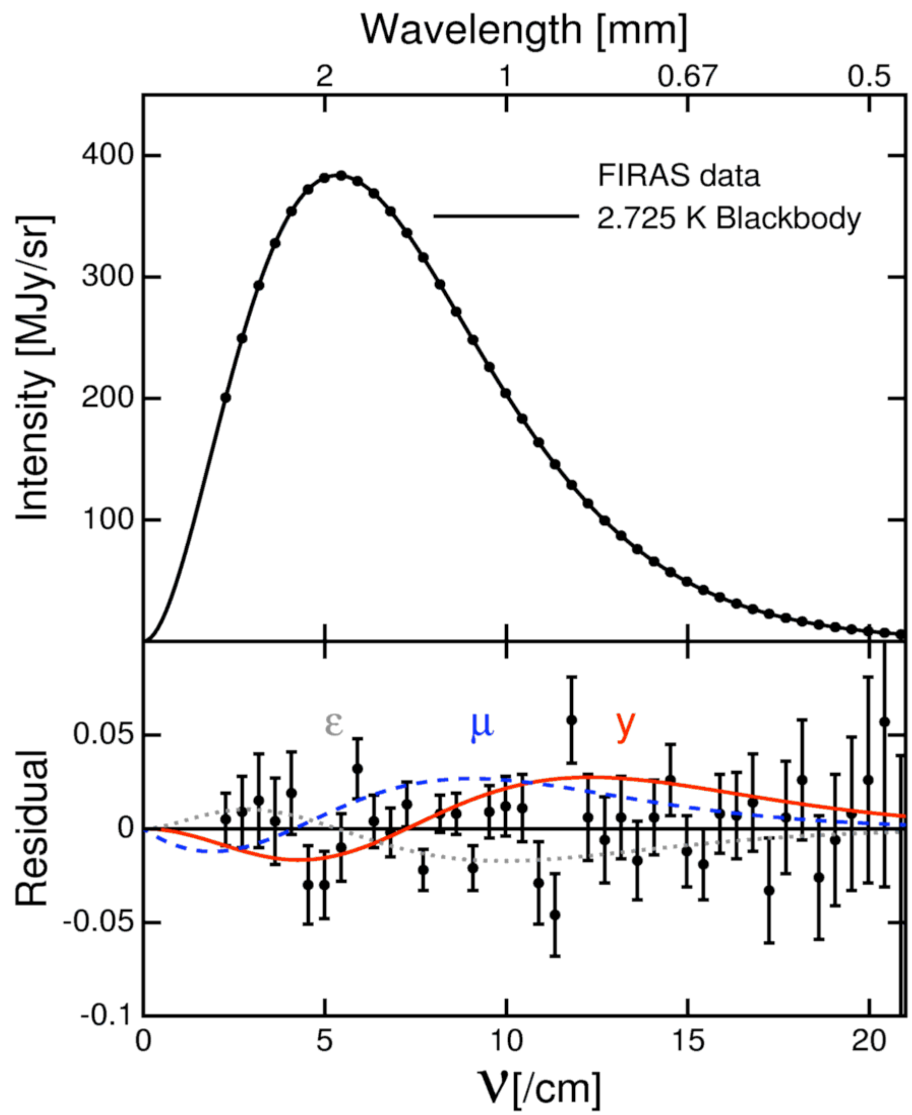


Diagram of FIRAS



Spectrum is Very Black

- Residuals in lower panel are what FIRAS measured: Sky-Blackbody
- RMS residual 50 parts per million
- Energy from hot electrons into CMB < 60 parts per million



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.

CN non-discovery of the CMB

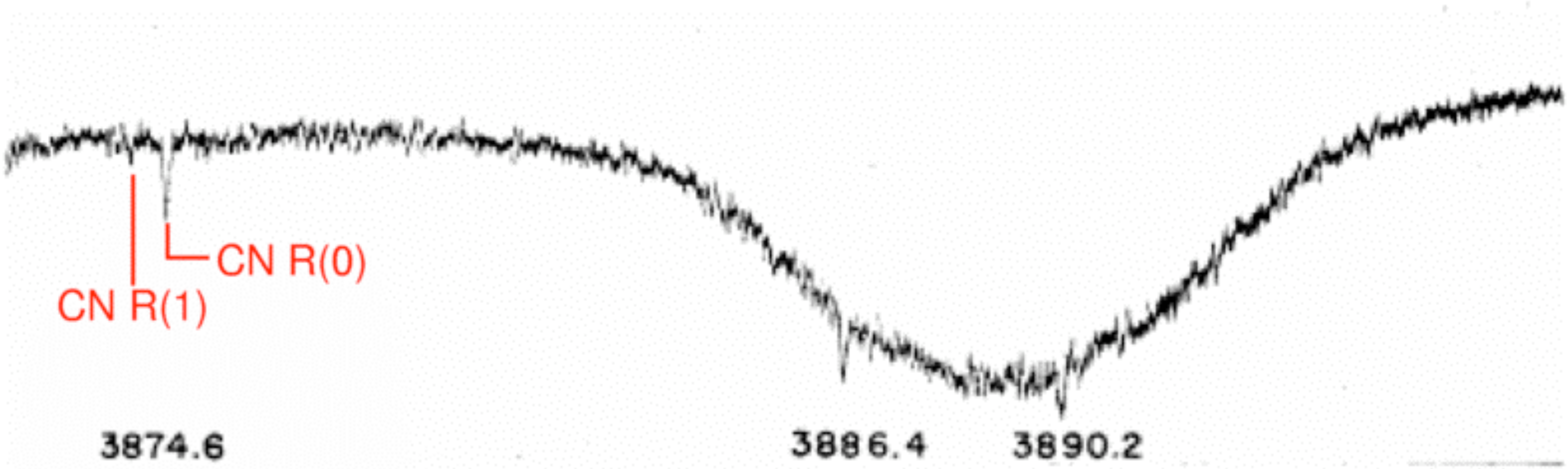


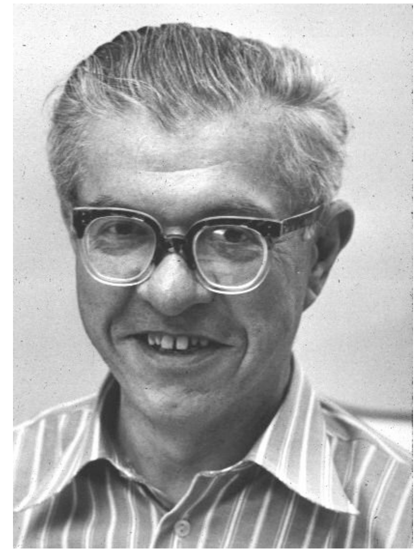
Plate 3 of Adams (1941, ApJ, 93, 11-23) reporting McKellar's work

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

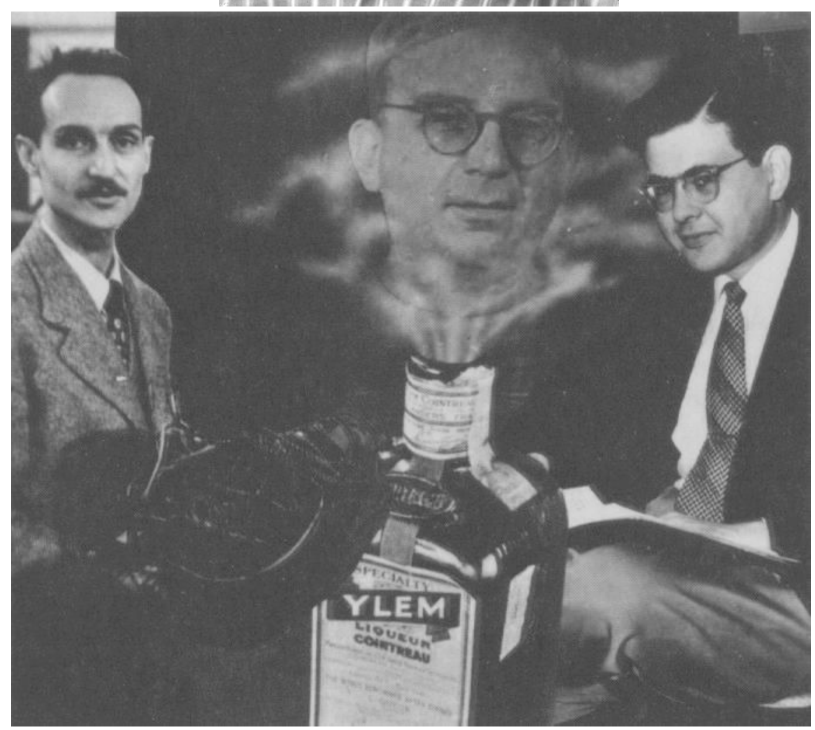
"From the intensity ratio of the lines with K=0 and K=1 a rotational temperature of 2.3^o K follows, which has of course only a **very restricted meaning**."

There went Herzberg's [second] Nobel Prize.

Fred Hoyle missed the Nobel Prize

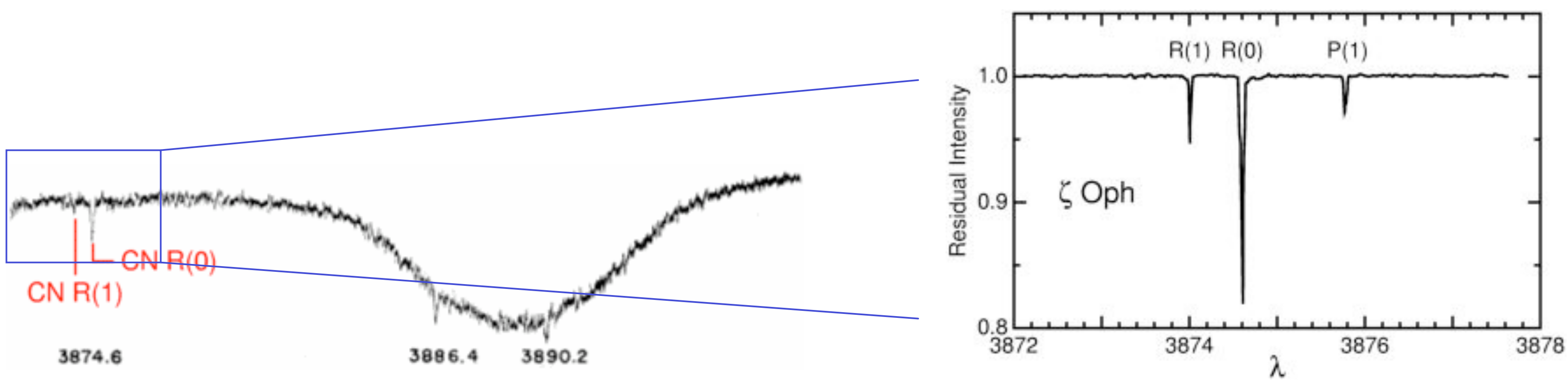


- Hoyle (1950), reviewing a book by Gamow & Critchfield: "[the Big Bang model] would lead to a temperature of the radiation at present maintained throughout the whole of space much greater than McKellar's determination for some regions within the Galaxy."
- This book implied T_o = 11 K. Gamow in 1956 *Scientific American* implied 6 K. Alpher & Herman explicitly gave 5 K or 1 K in 1949 *Phys Rev*.
- Nobody followed this up!



CN followup after Penzias & Wilson

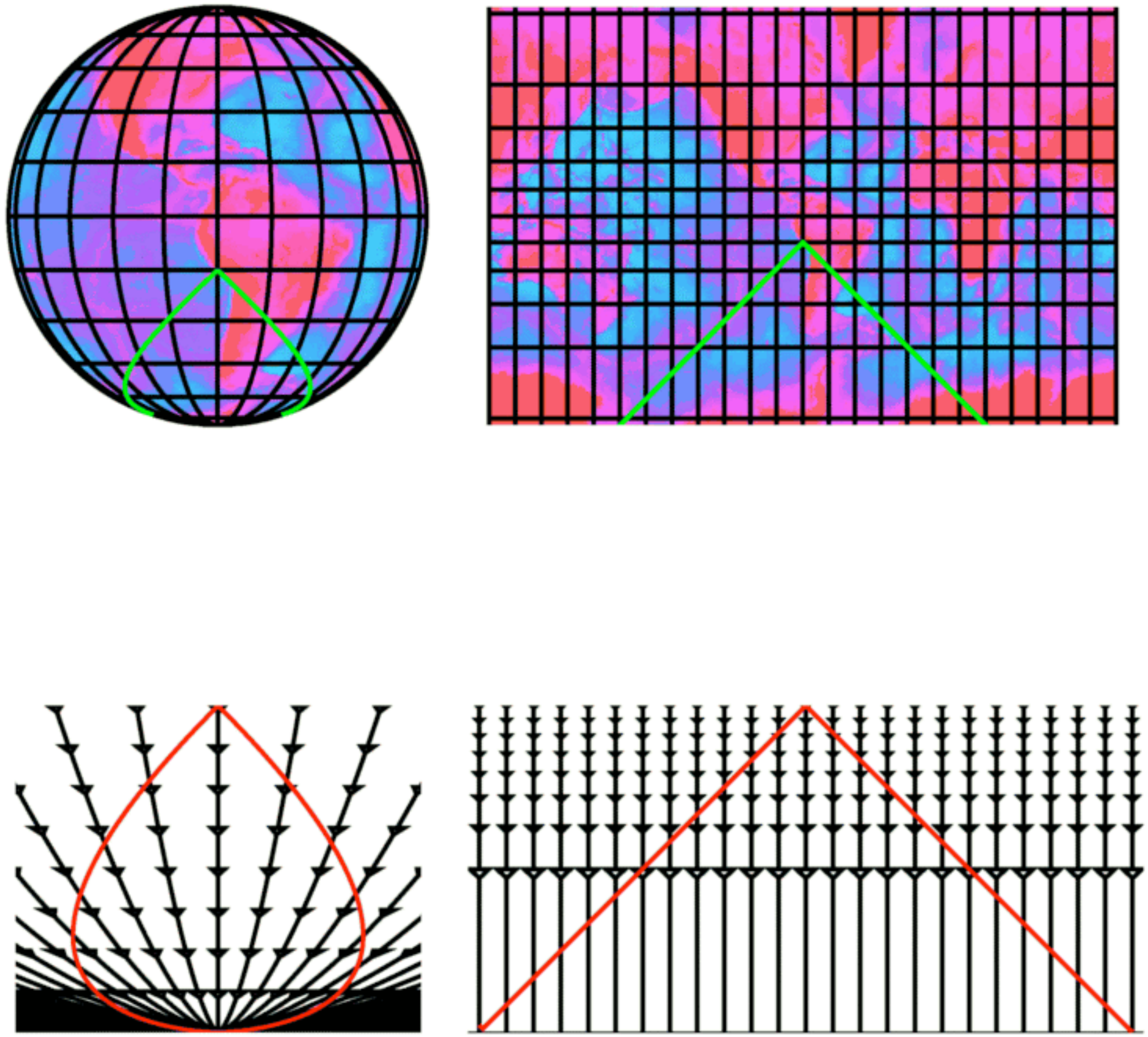
- Reworking and reobserving the CN lines gave 2.78±0.10 K at 2.64 mm. (Thaddeus, 1972, ARAA, 10, 305-334)
- By 1993, 2.73±0.03 K (Roth, Meyer & Hawkins 1993)



(UCLA PhD's)

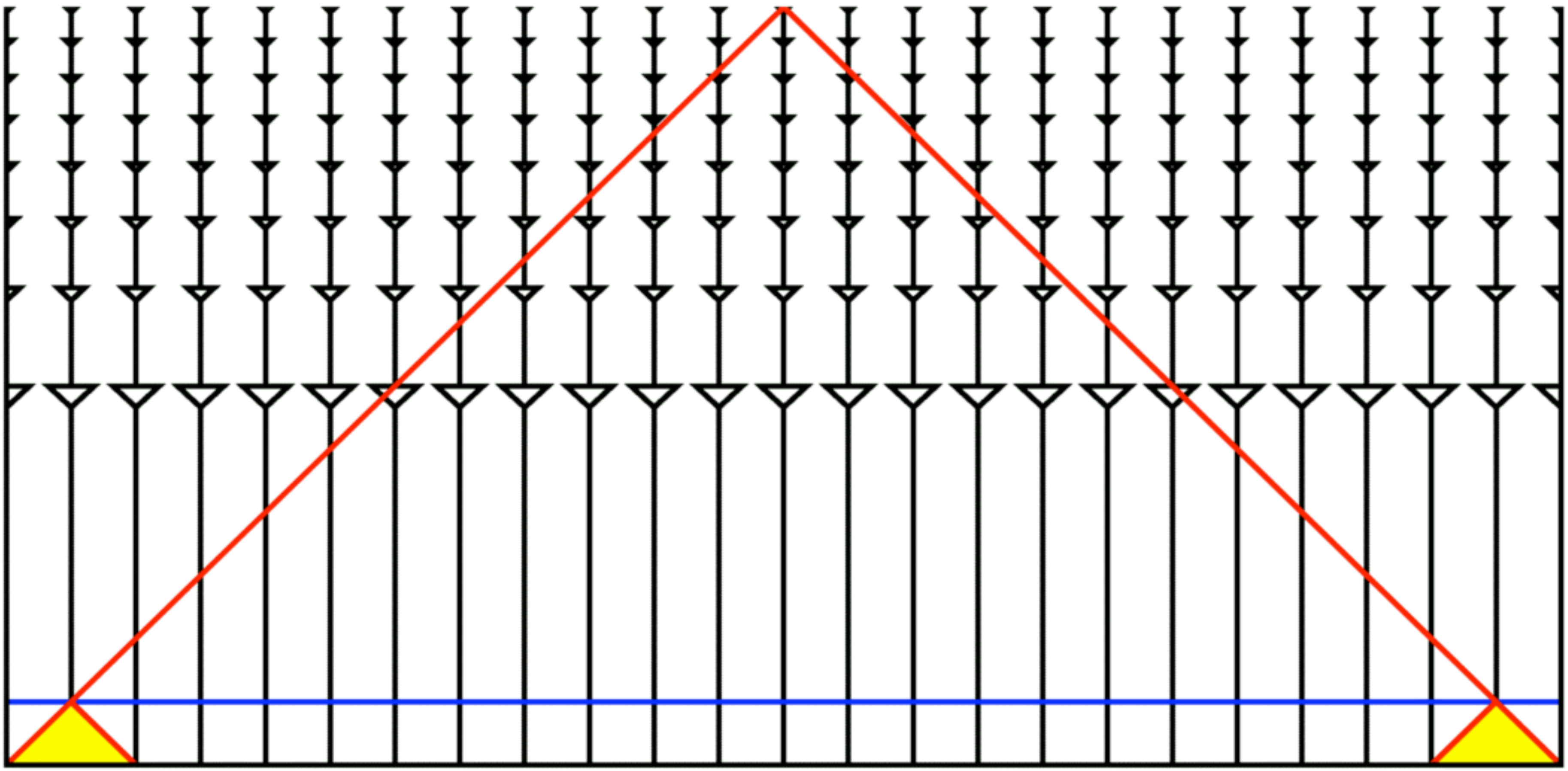
“Normal” vs Conformal ST Diagram

- 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.

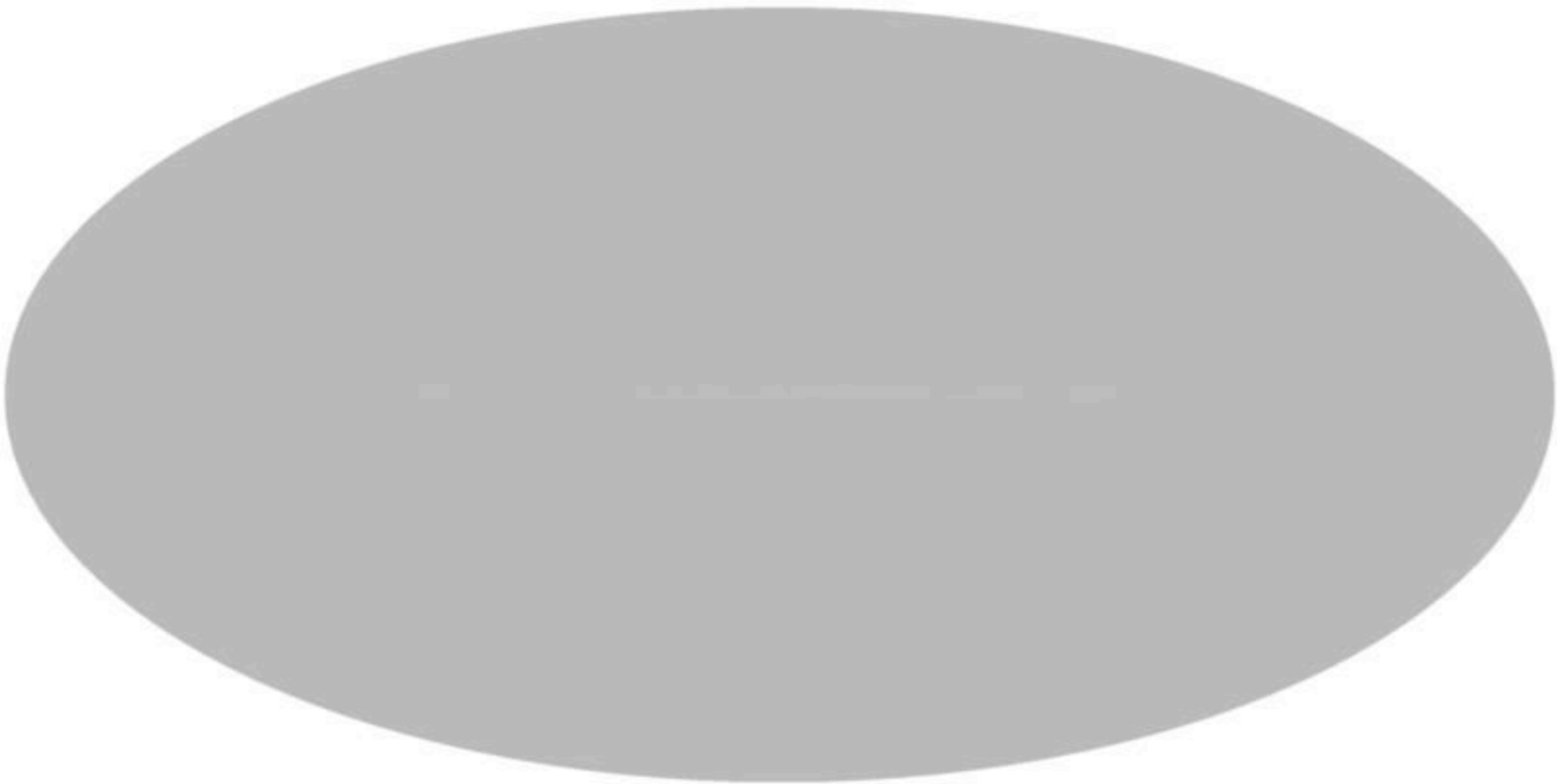


Horizon Problem

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?



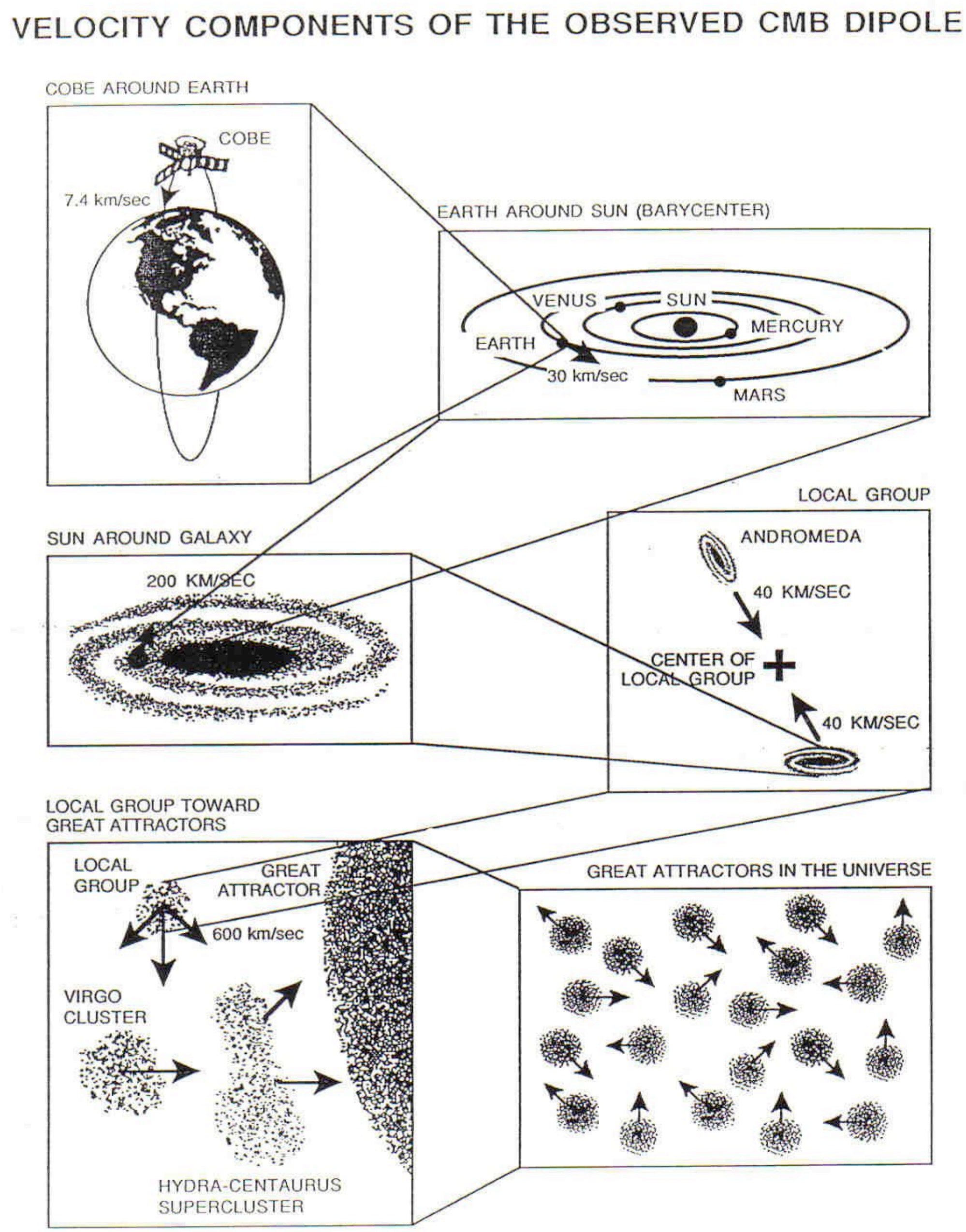
True Contrast CMB Sky



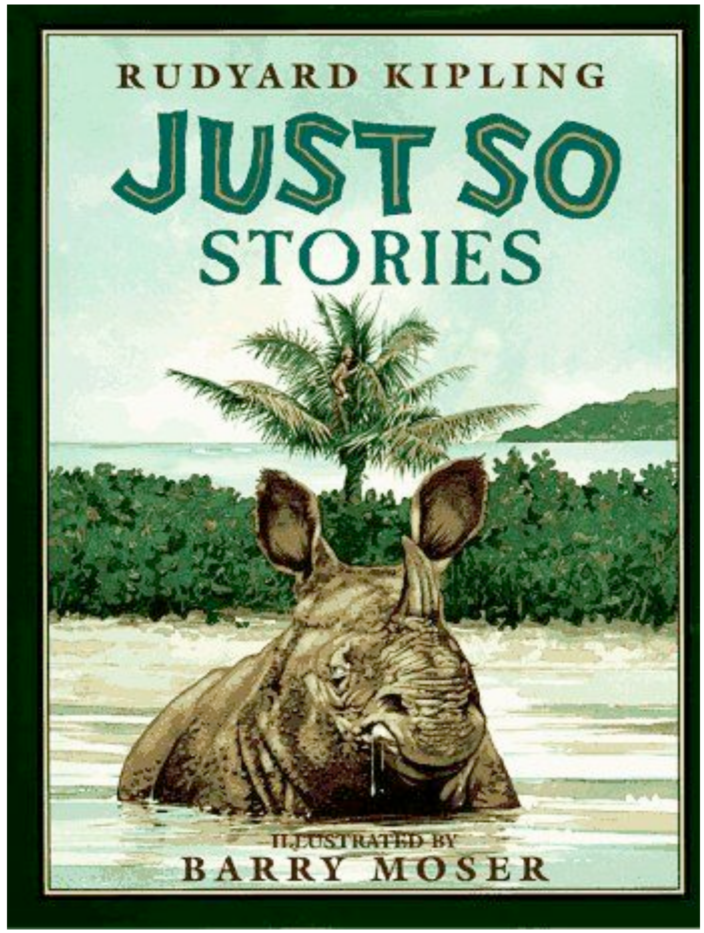
23, 41 & 94 GHz as RGB, 0-4 K scale

Enhanced Contrast:

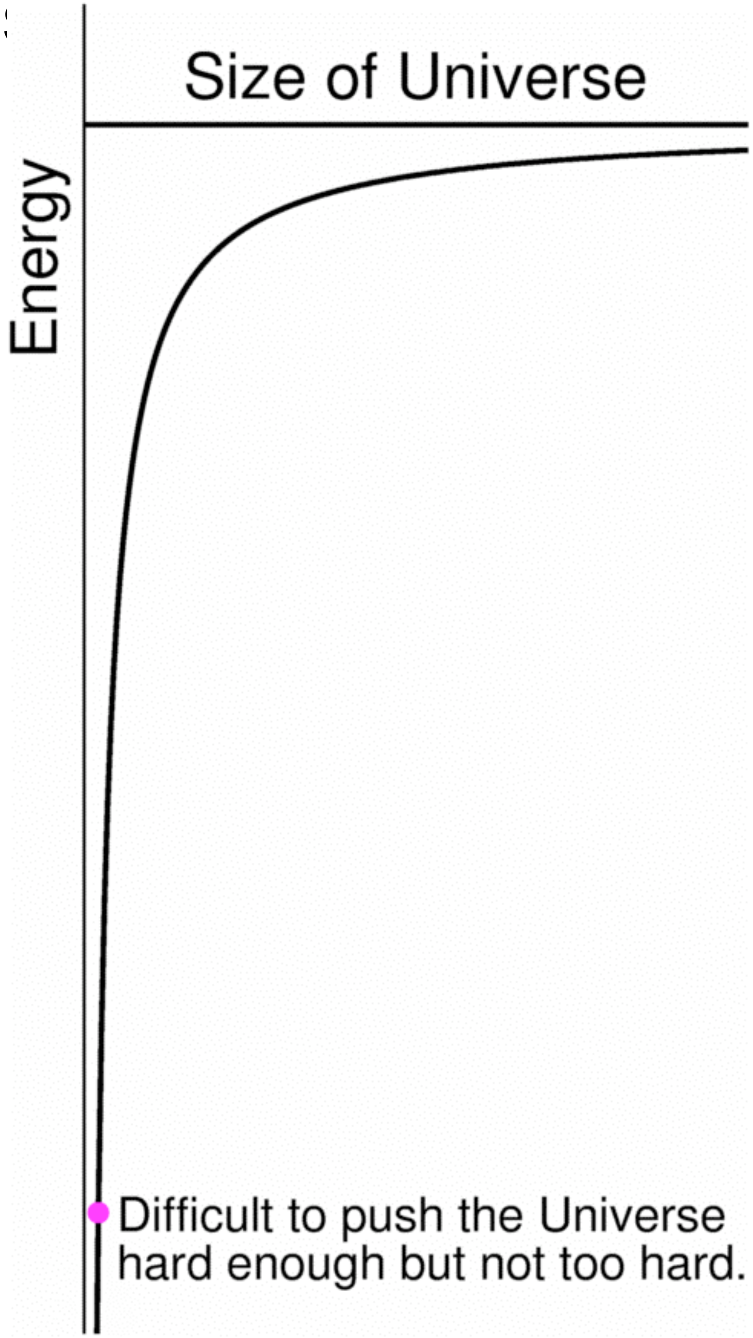
- Conklin 1969 - 2σ
- Henry 1971 - 3σ
- Corey & Wilkinson 1976 - 4σ
- Smoot *et al.* 1977 - 6σ



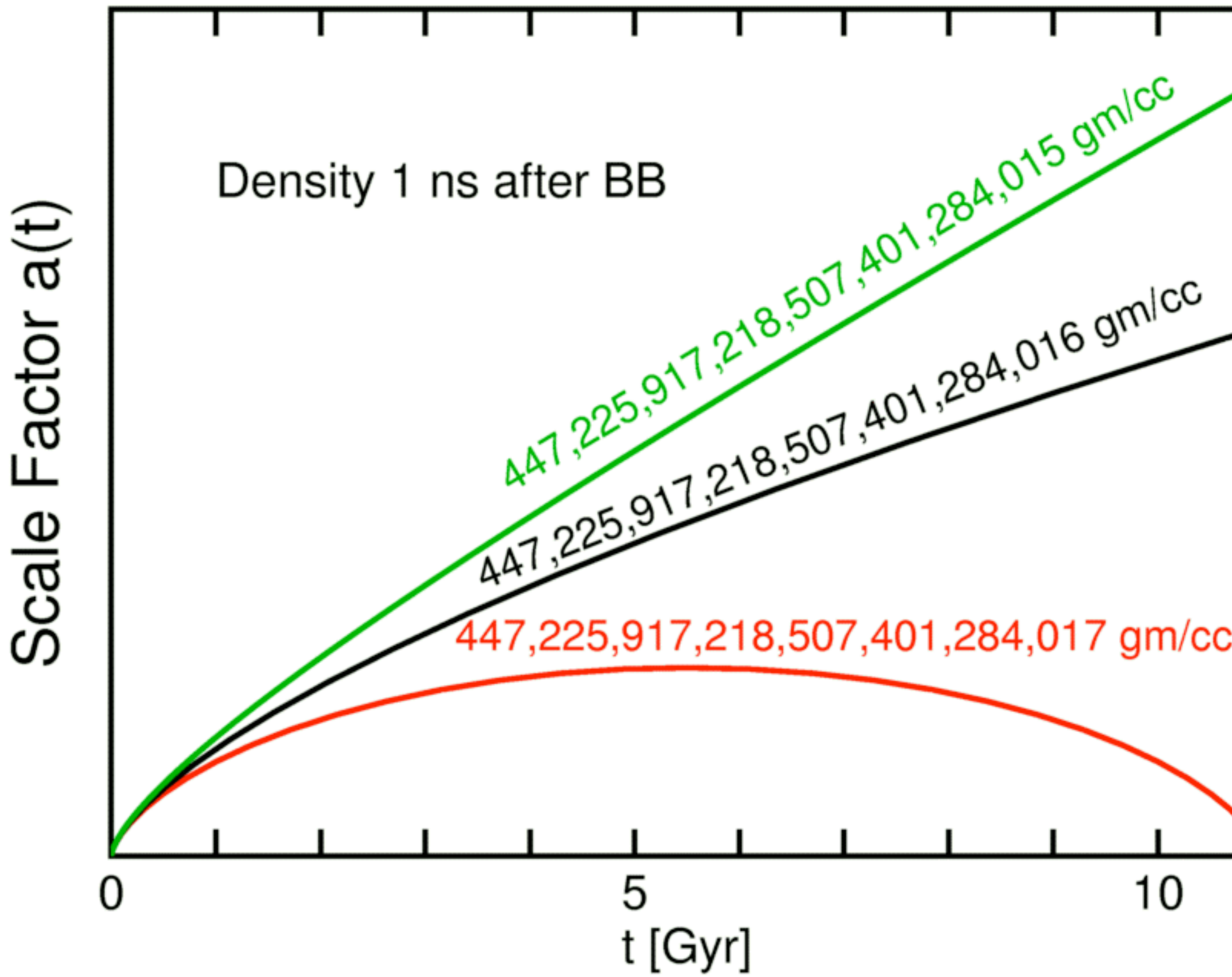
Just So?


RUDYARD KIPLING
JUST SO
STORIES
ILLUSTRATED BY
BARRY MOSER

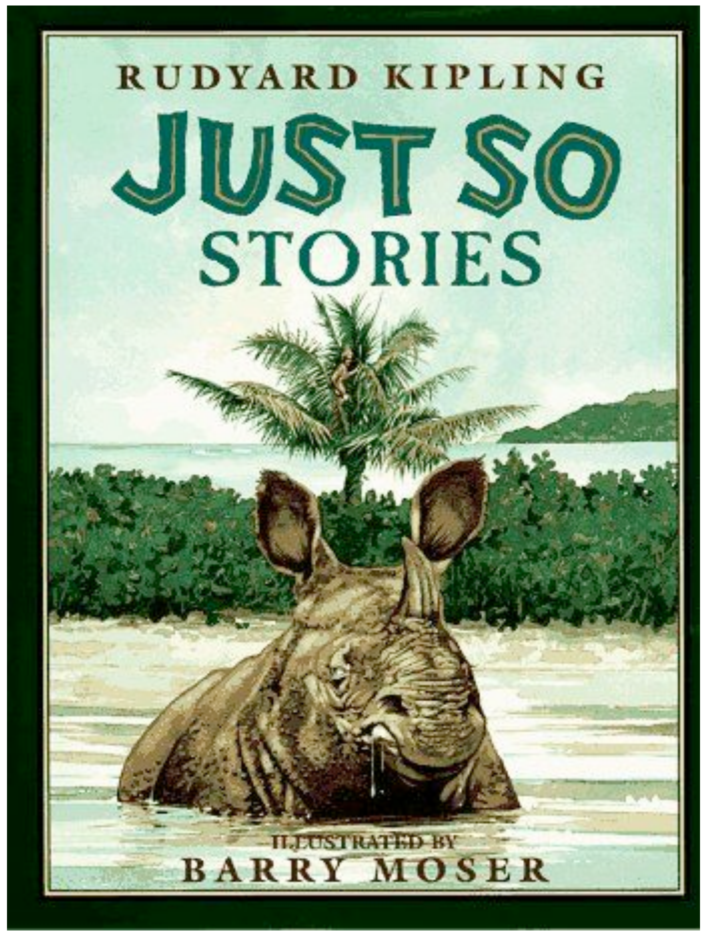
Problems with Friedmann Models



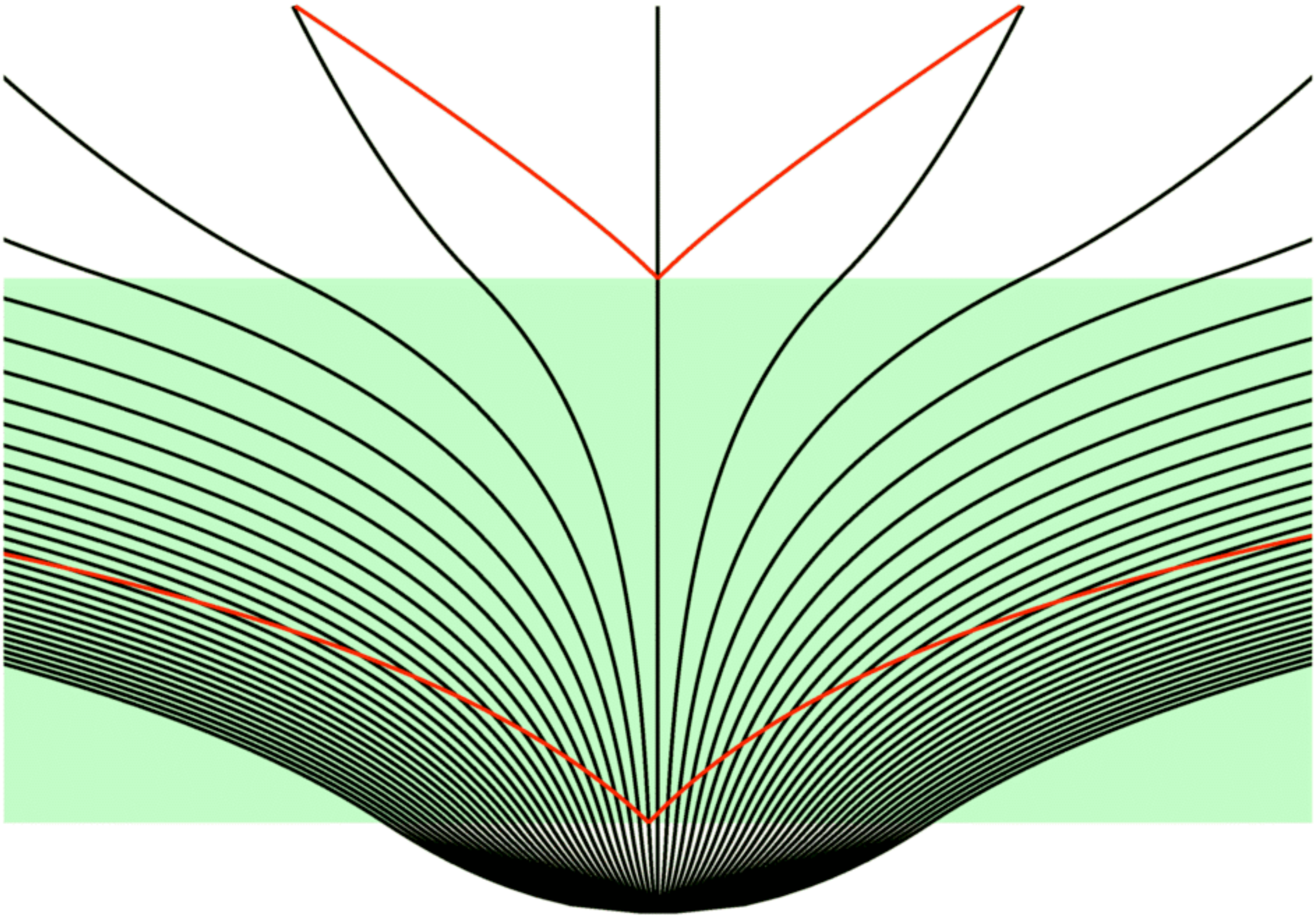
Flatness-Oldness Problem: density must be fine-tuned



Just So?

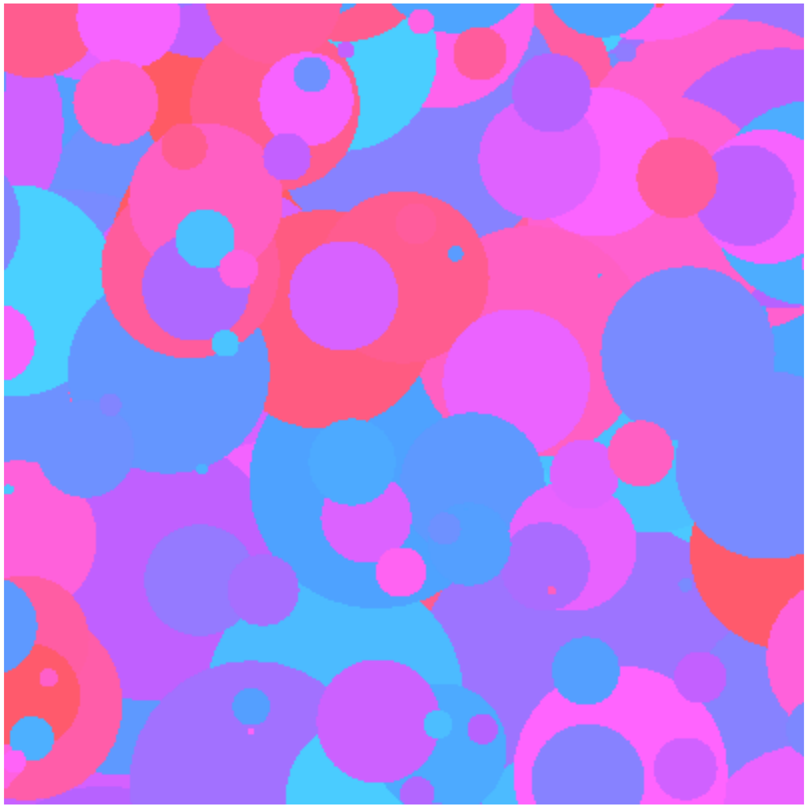

RUDYARD KIPLING
JUST SO
STORIES
ILLUSTRATED BY
BARRY MOSER

Inflation: Large Λ during an early phase

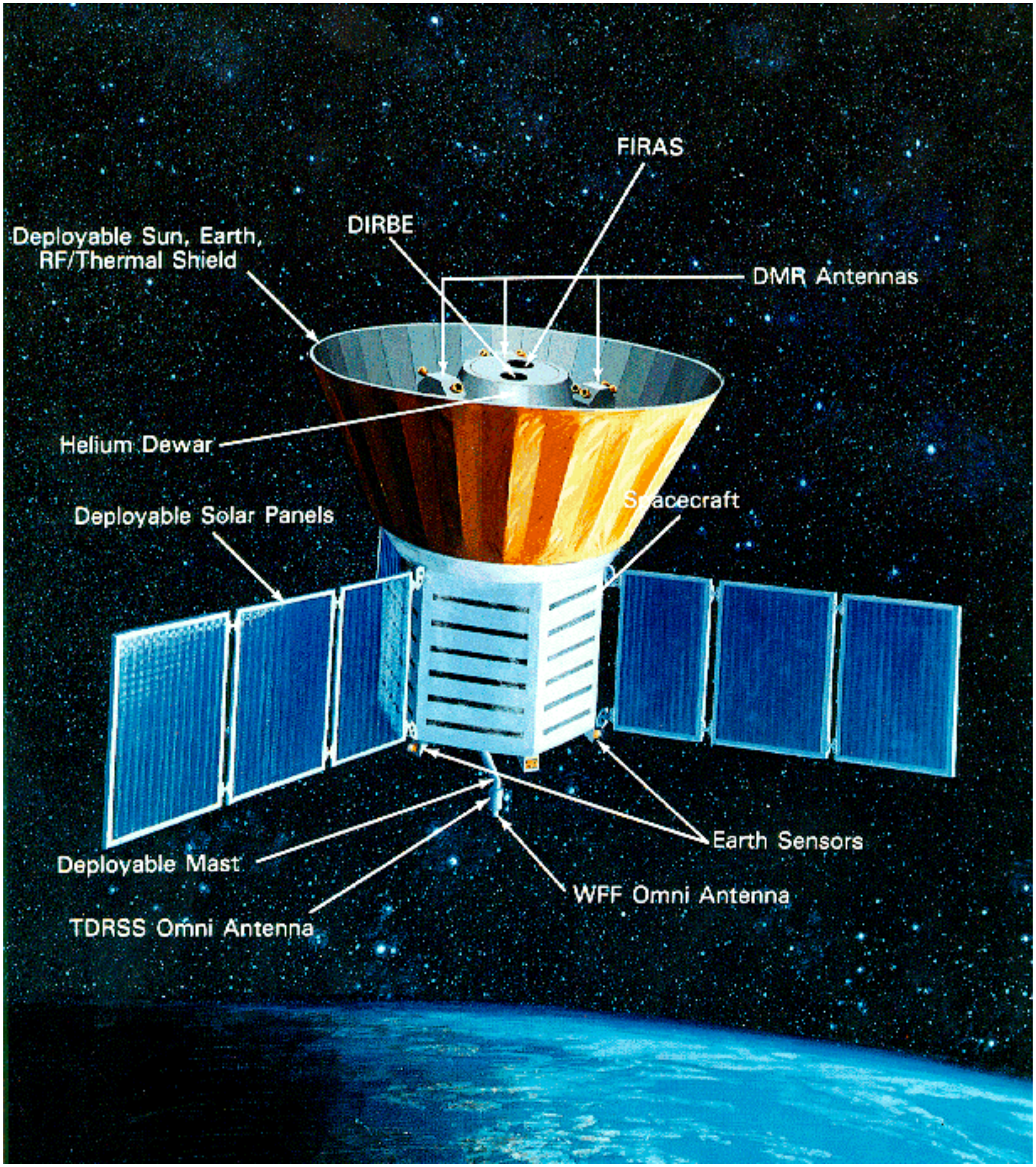


Animated View of Inflation

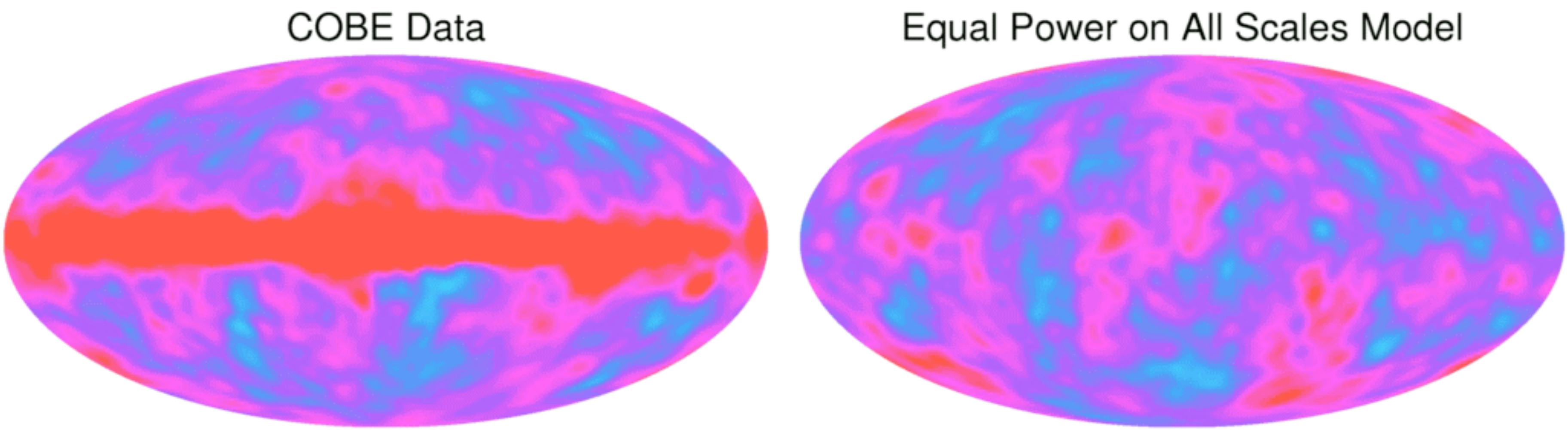
- Quantum fluctuations occur uniformly throughout space-time.
- Future light cones of fluctuations grow making big circles but new fluctuations continuously replenish the small circles.
- Result is Equal Power on All Scales (EPAS).



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



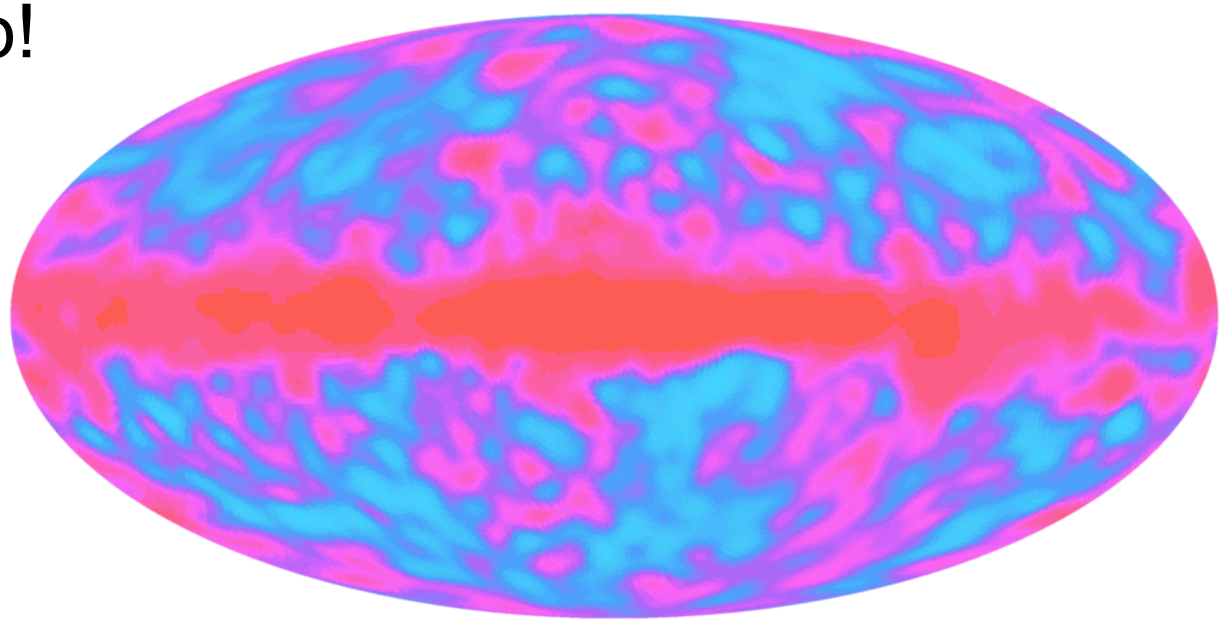
"Chi-by-eye" suggests that the "Equal Power on All Scales" prediction of inflation is correct.

CMB Anisotropy

THE TIMES

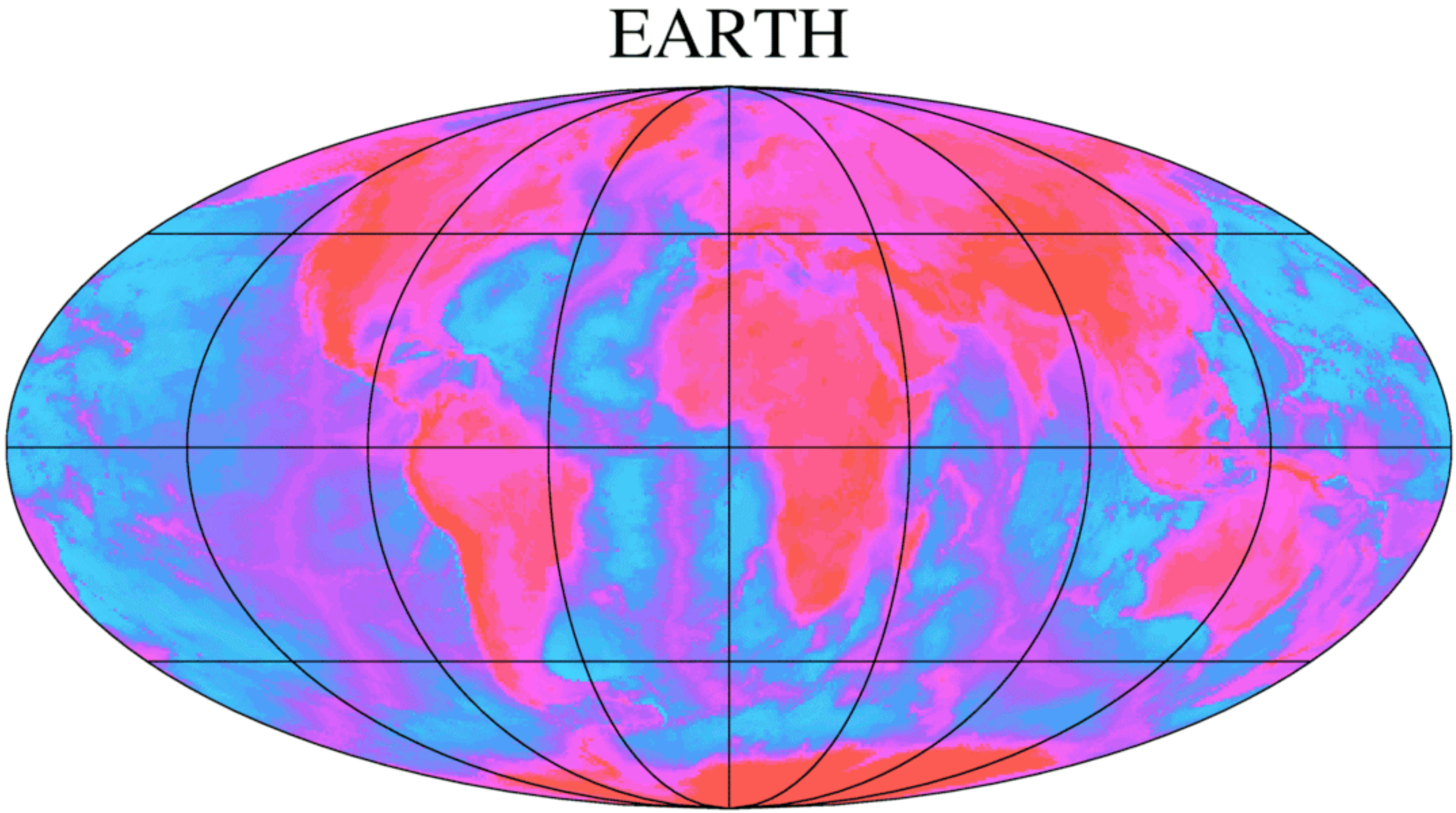
25 April 1992

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



The oval is an all-sky map in galactic coordinates:

An equal area projection:



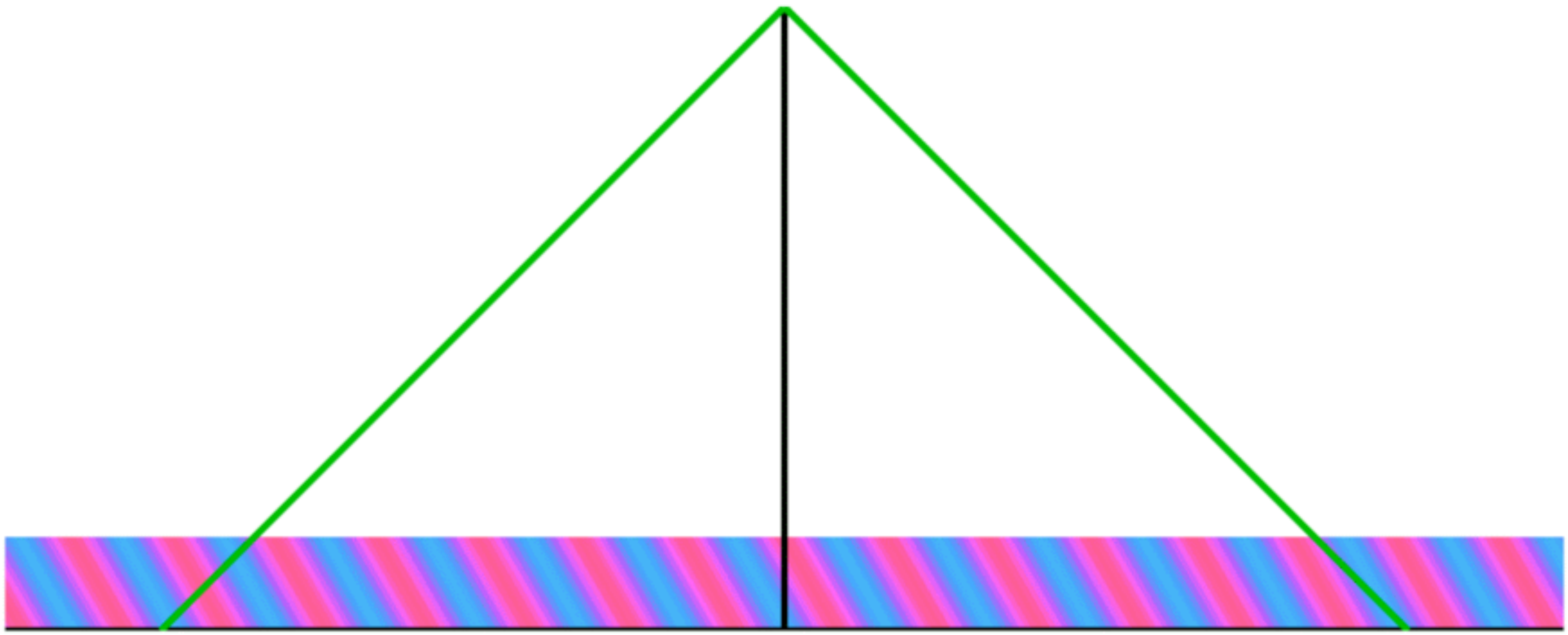
Color Means Temperature

- Red areas are 30 μK hotter than average and the blue areas are 30 μK colder than average.
- As on the Earth map, color also maps into gravitational potential, with red=high and blue=low.
- So this is a topographic map of the Universe, with an astronomical height range of 1 billion km!

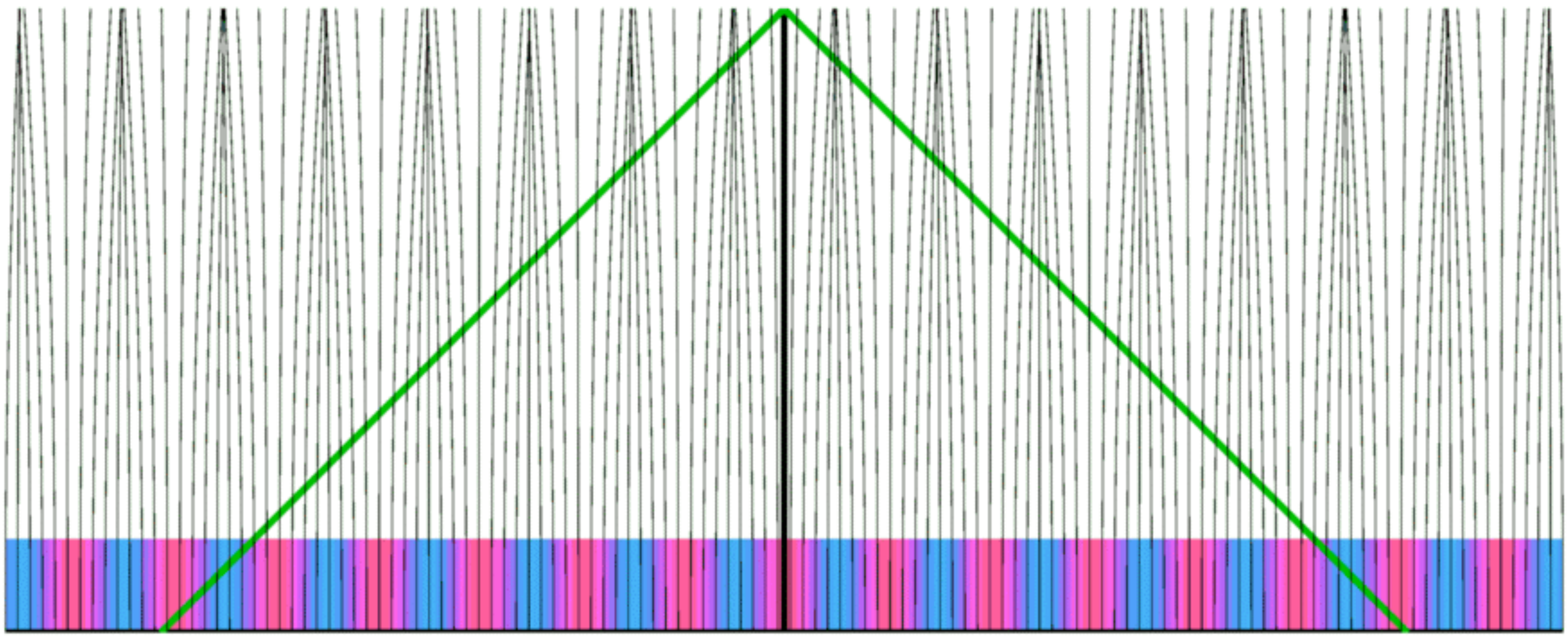
Two Fluids in the Early Universe

- 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: $c_s = c/\sqrt{3}$

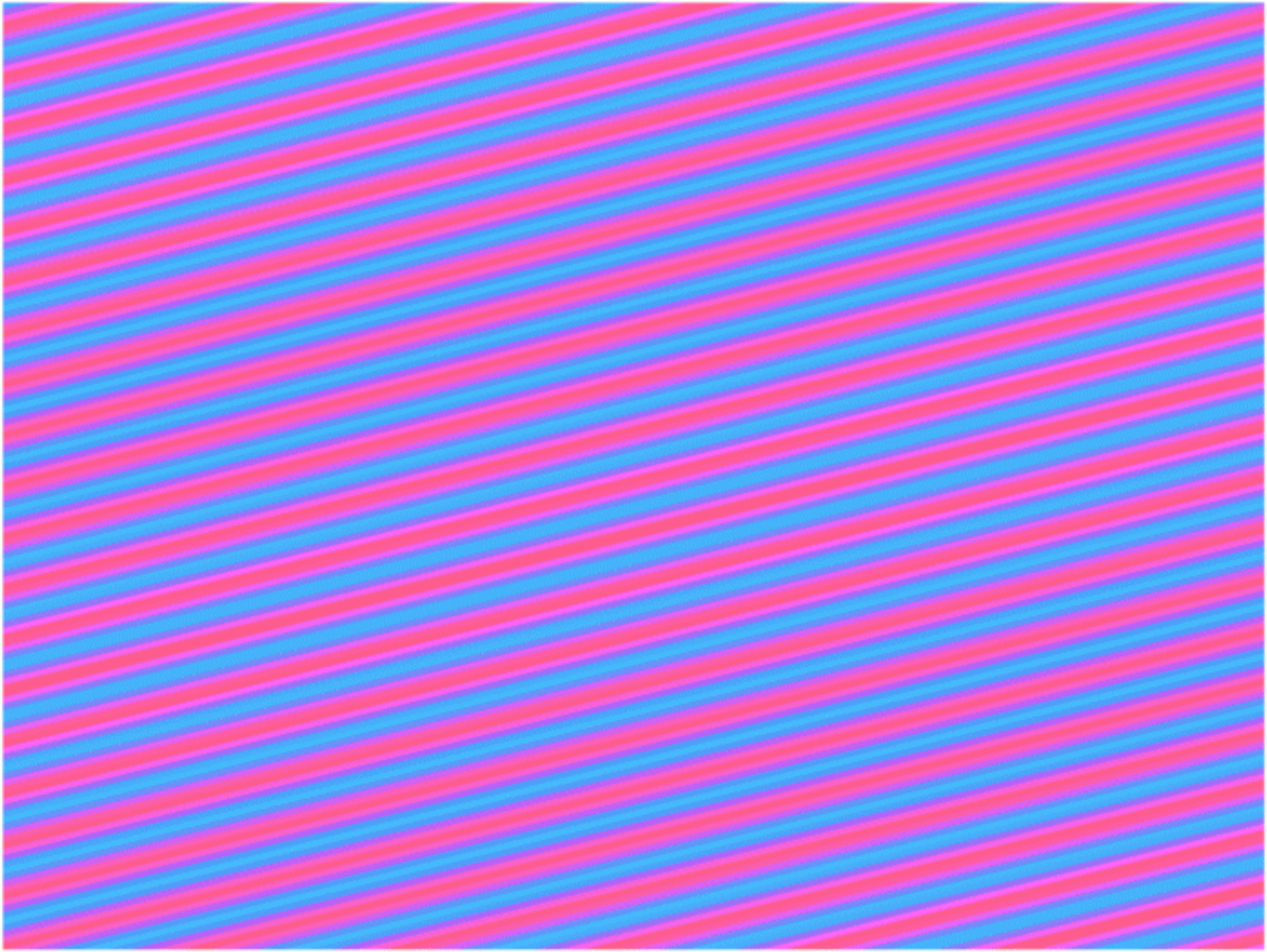


Stay at home Dark Matter

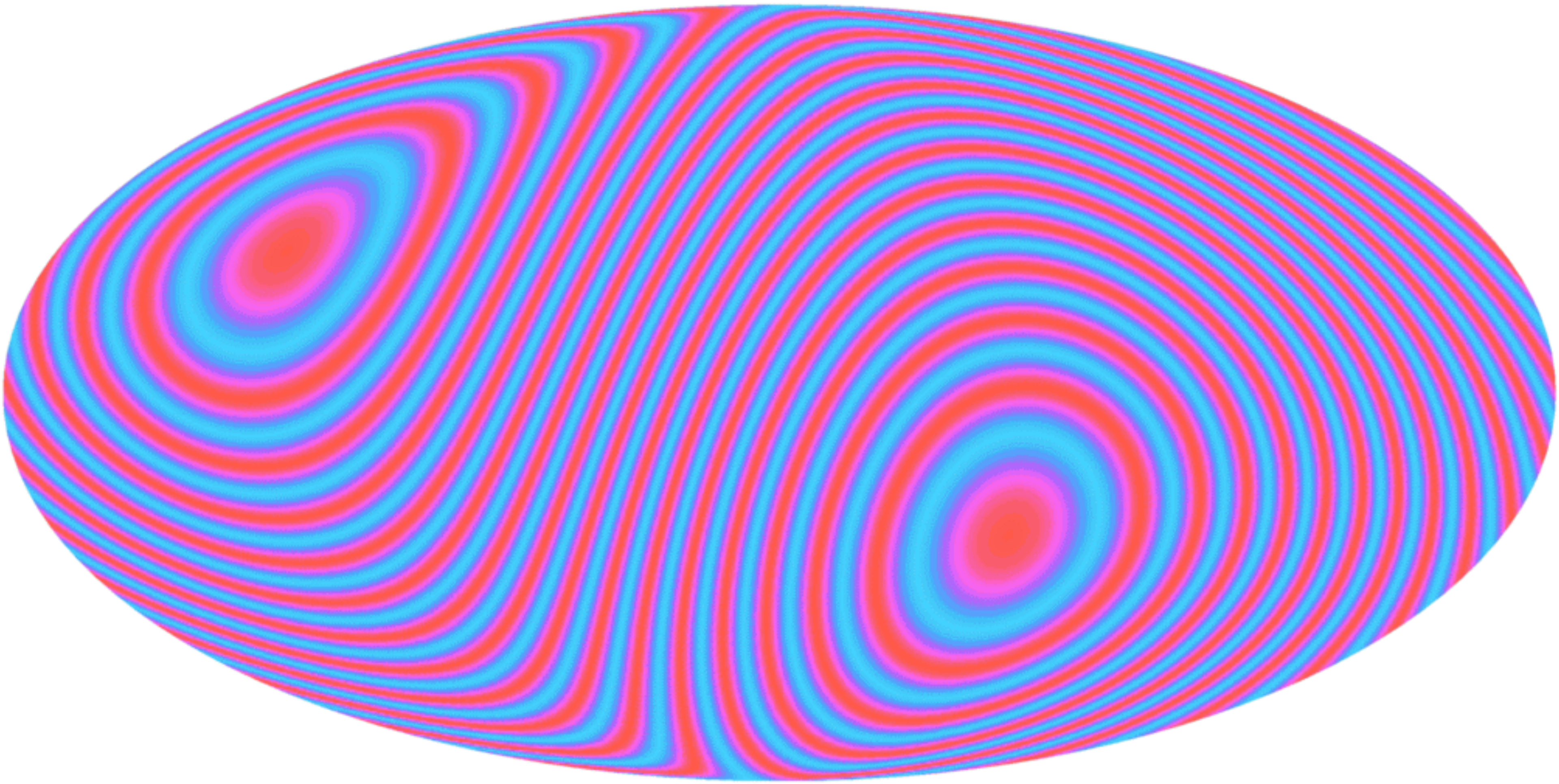


Interference at last scattering

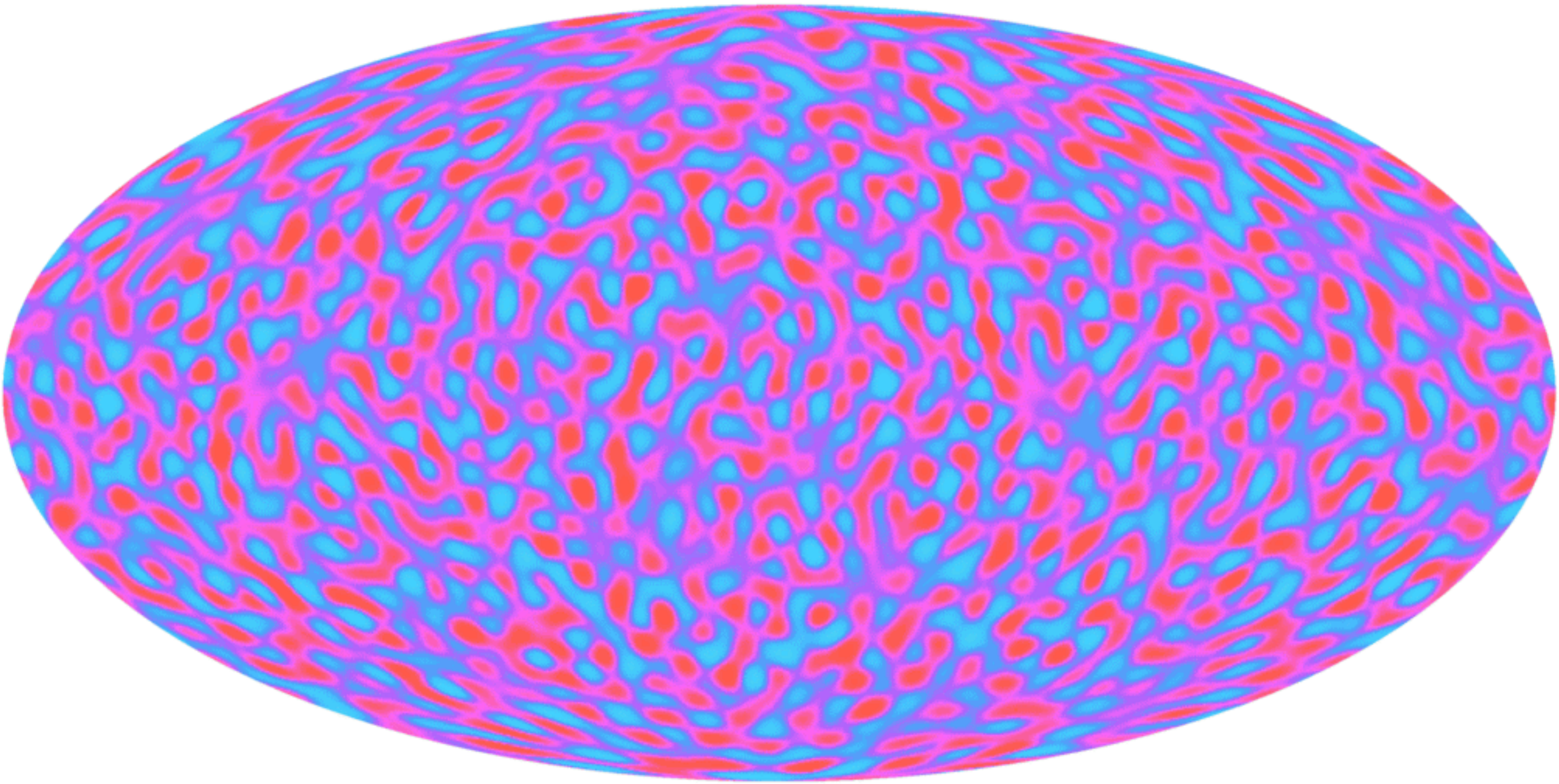
- For the wavelength illustrated [1/2 period between the Big Bang and recombination], the denser = hotter effect and potential well = cooler effect have gotten in phase.
- For larger wavelengths they are still out of phase at recombination.



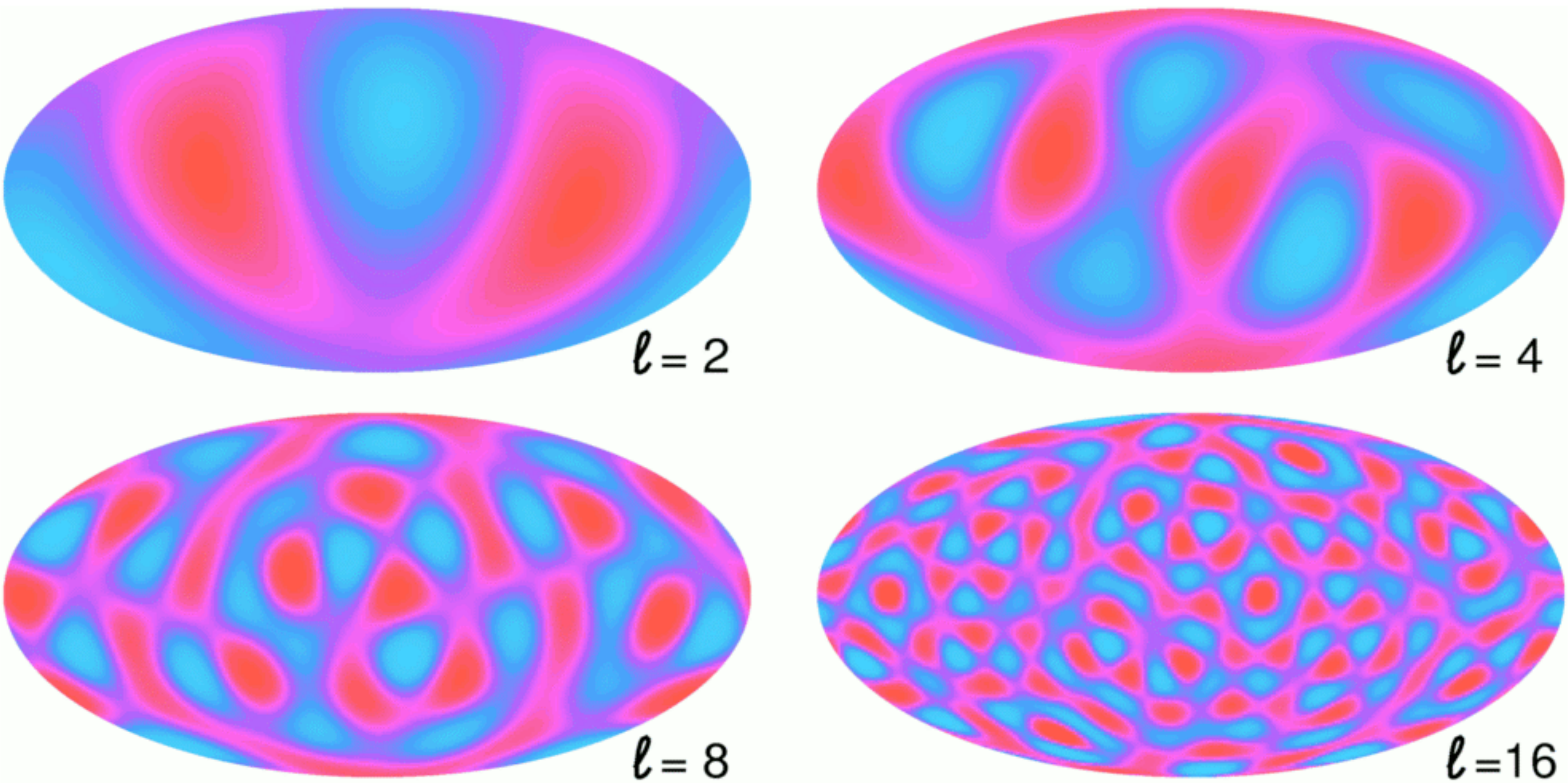
k*Rls = 50 plane wave



99 k*Rls=50 plane waves

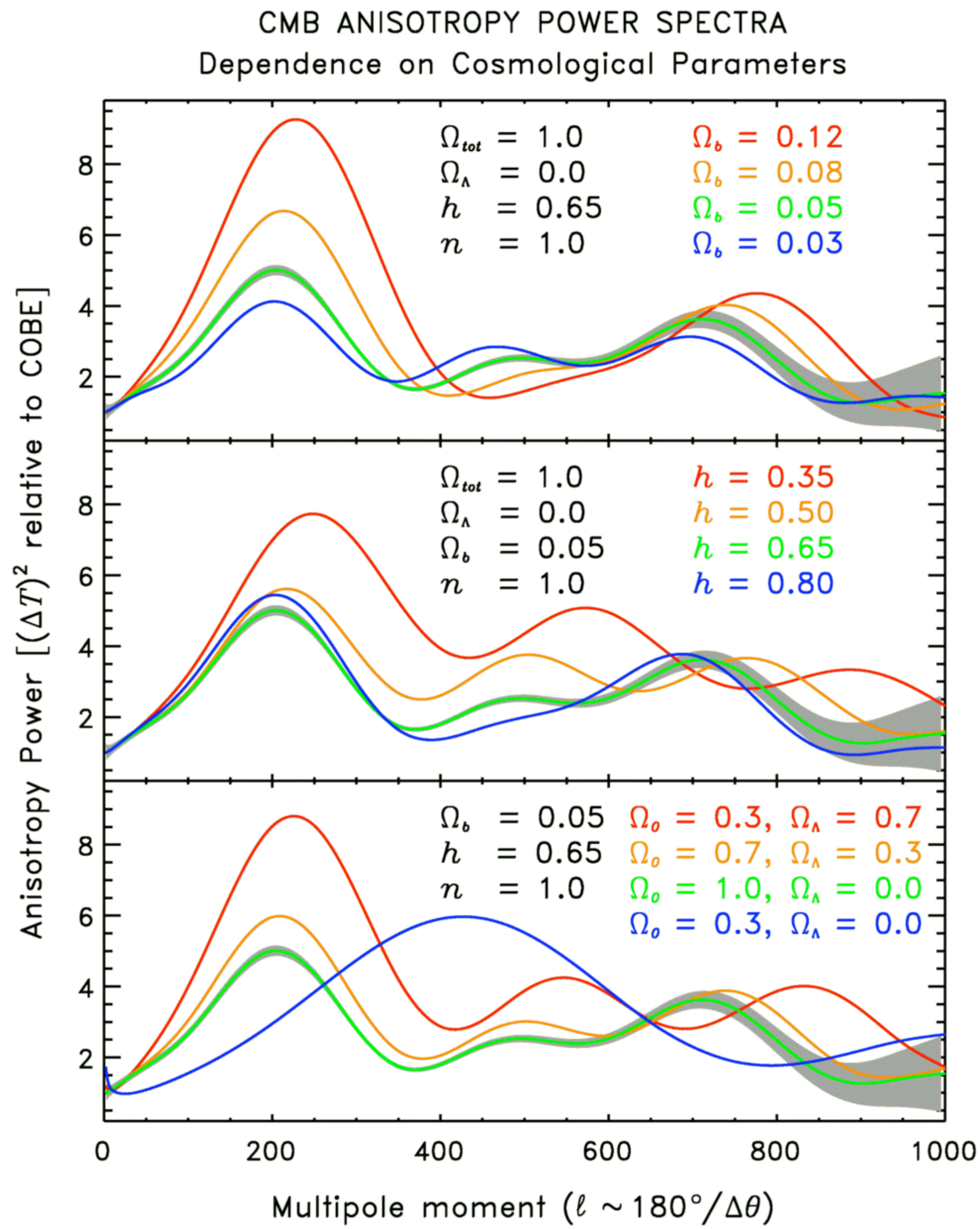


Spherical Harmonic Decomposition



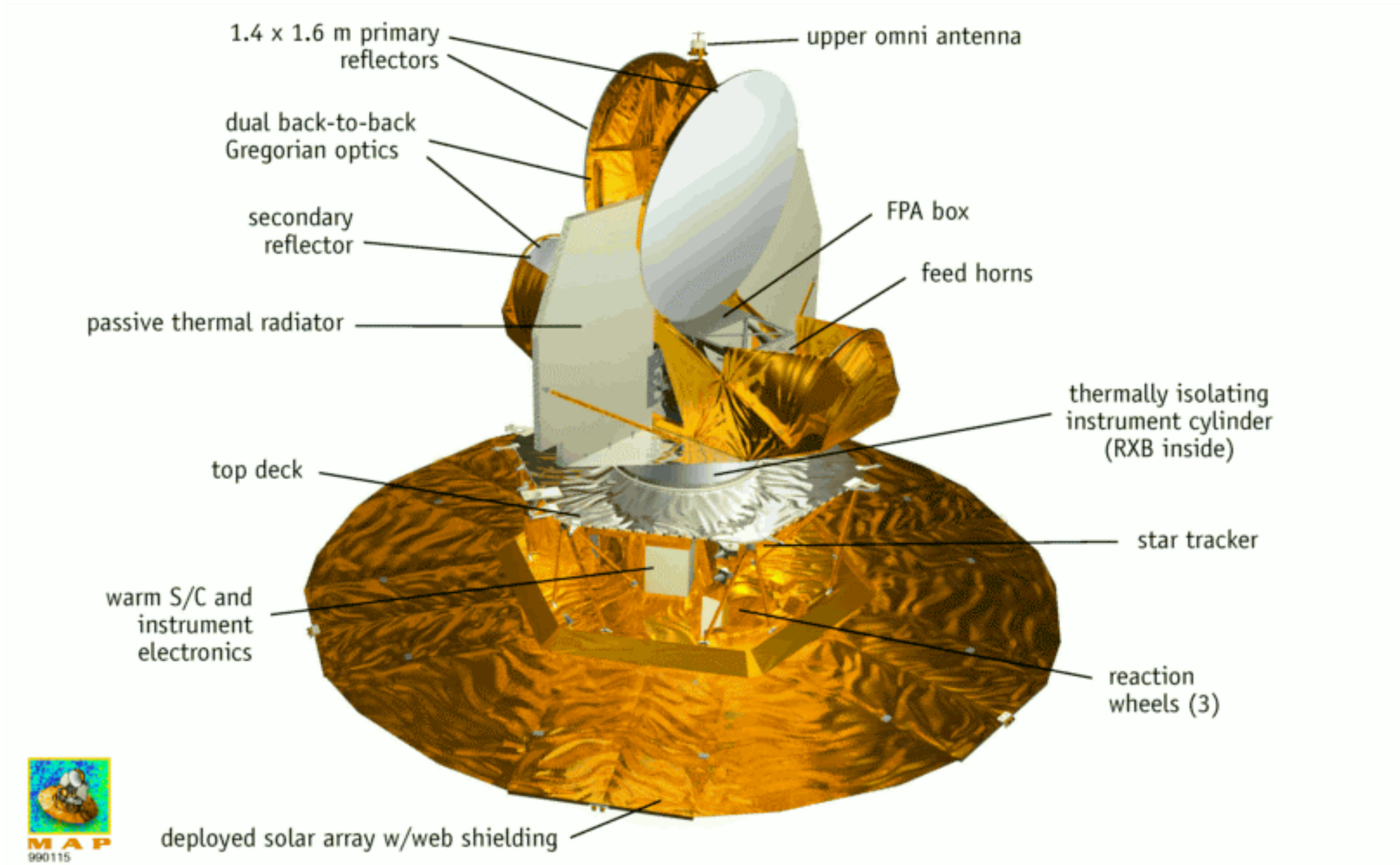
Many parameters to measure

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

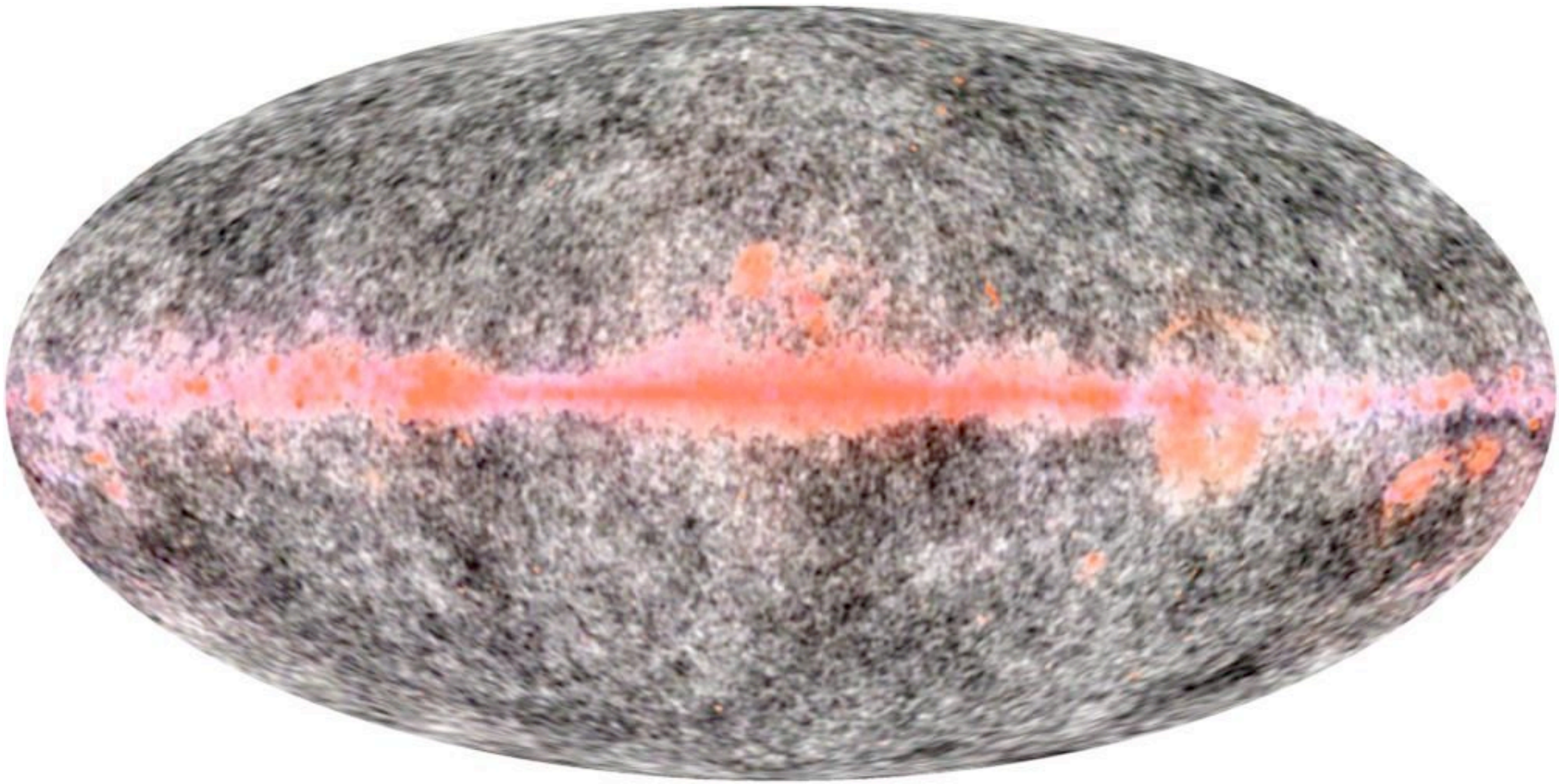


WMAP Science Working Group

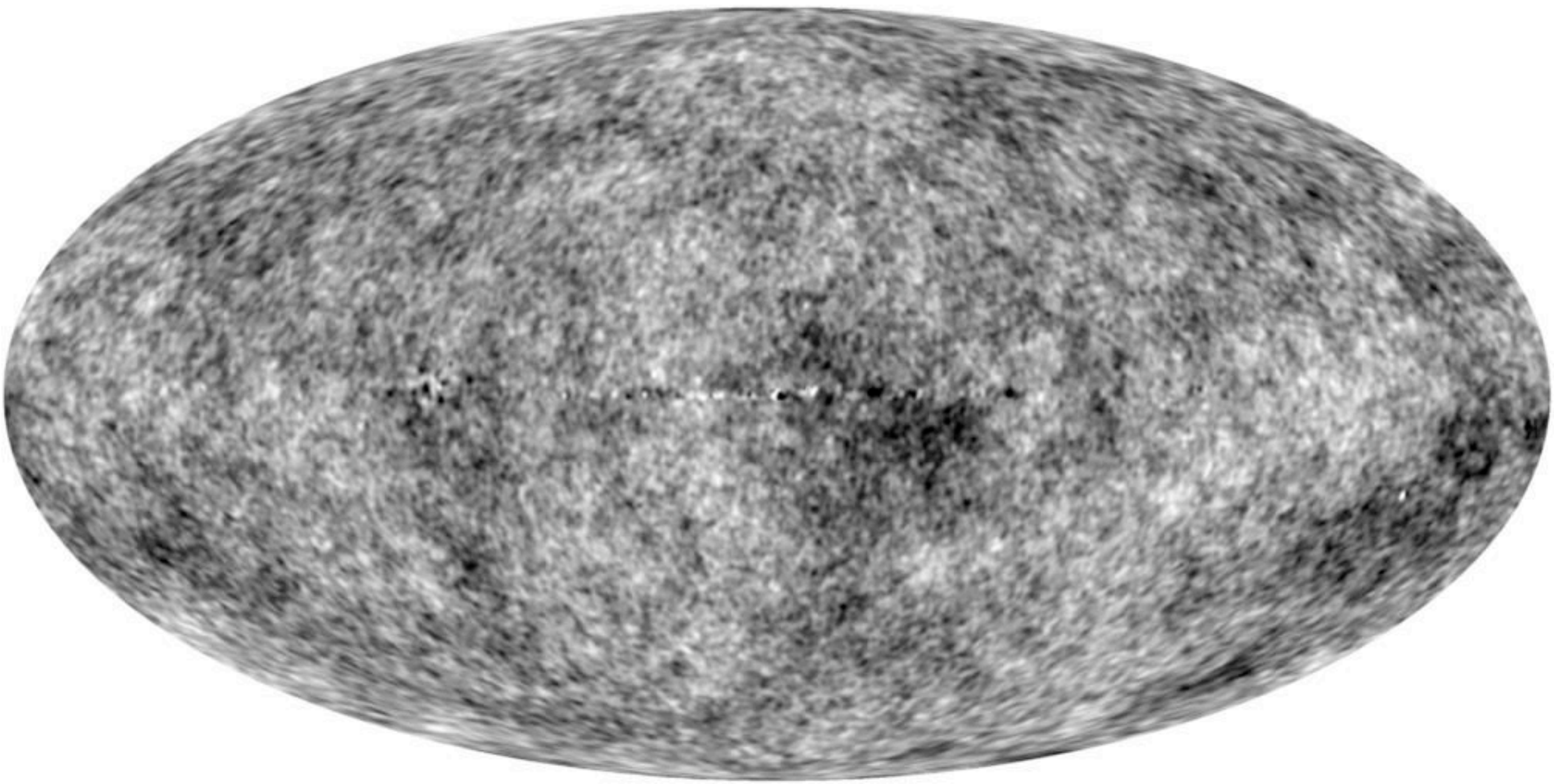
A New Cosmology Satellite



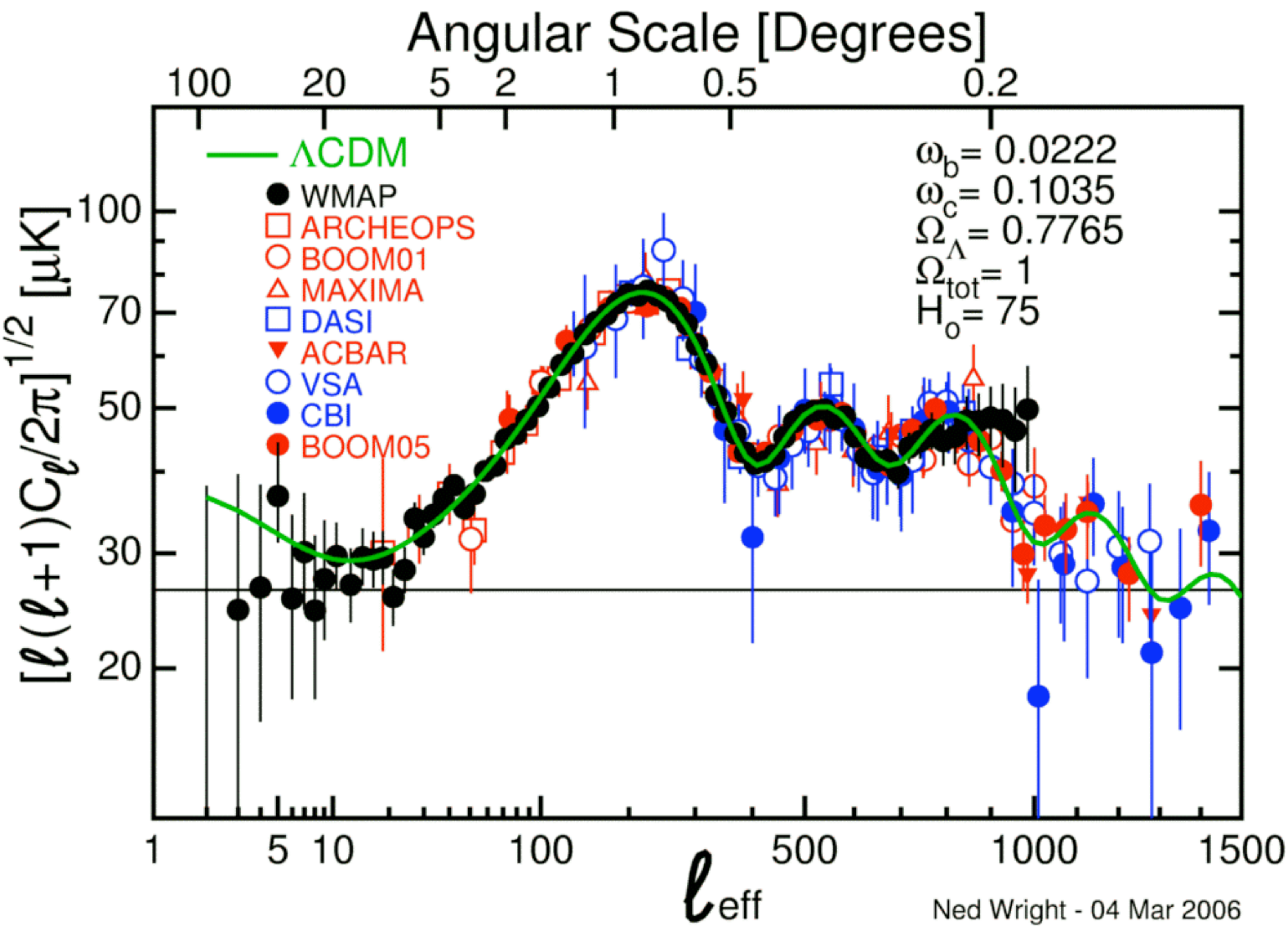
WMAP 41, 61 & 94 GHz Map



WMAP “No galaxy” ILC Map



An Excellent Fit to all Data

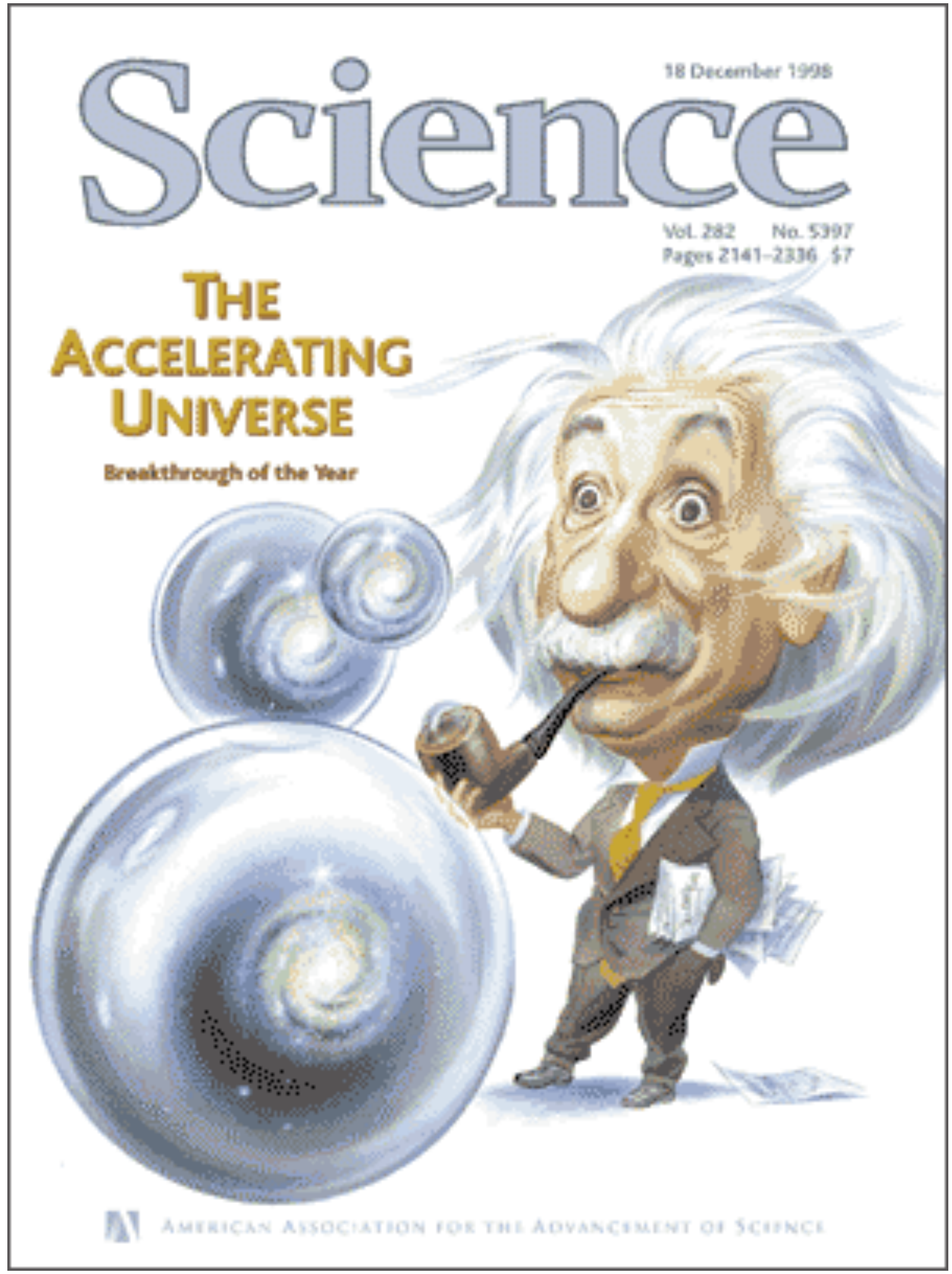


Accelerating Universe: 1998

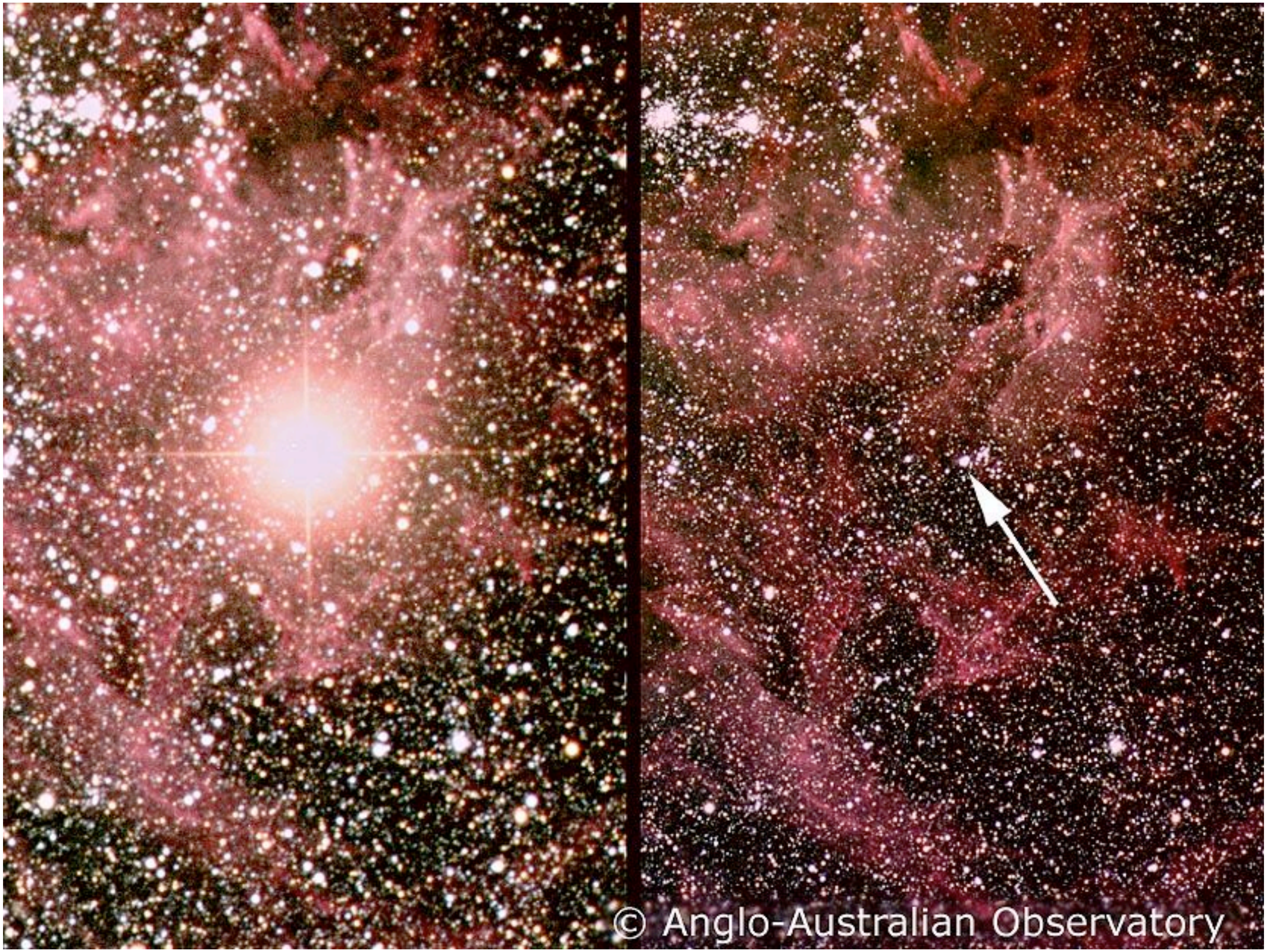
Distant (high z) supernovae fainter than expected.

This was the AAAS discovery of the year in 1998.

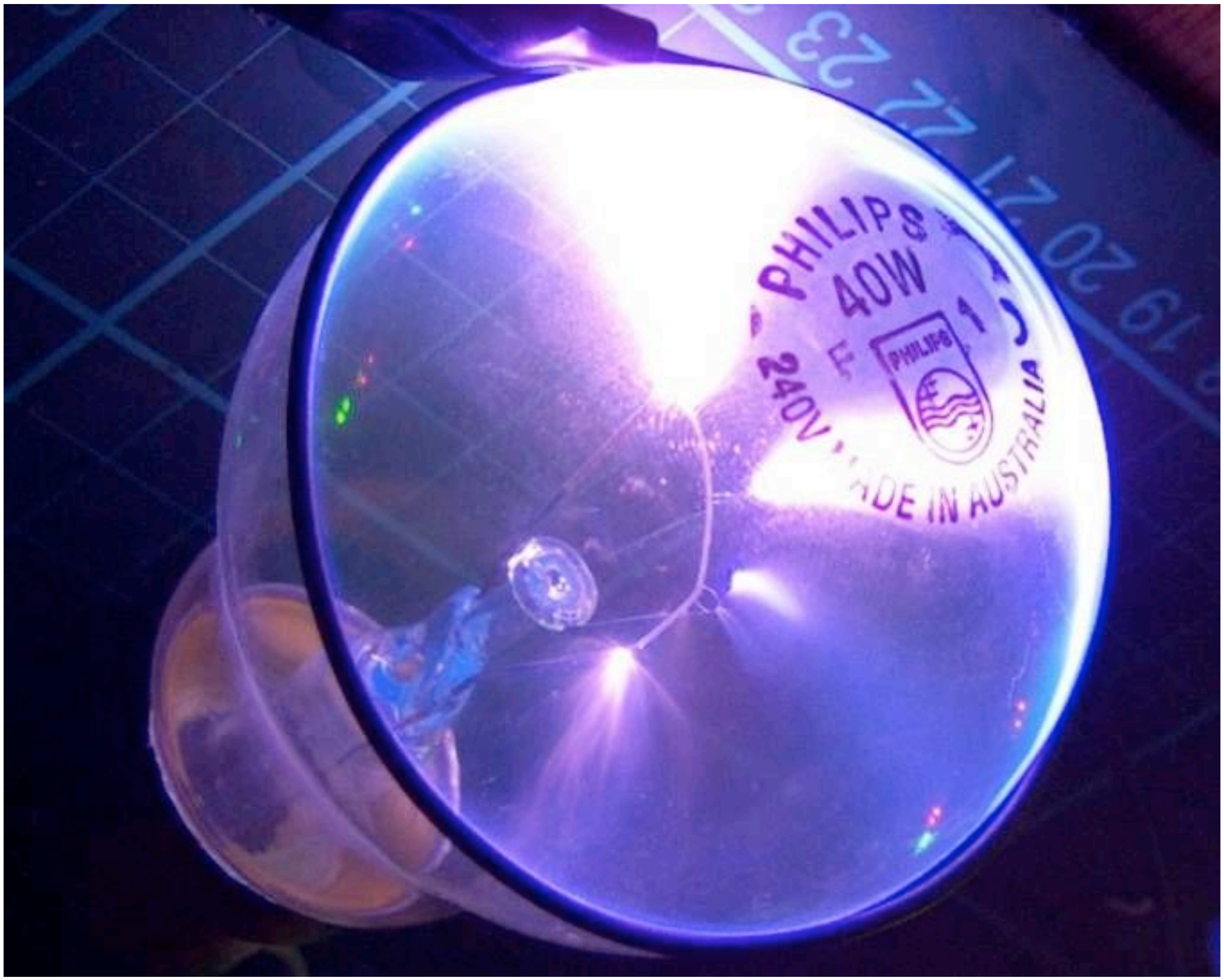
Λ causes acceleration!



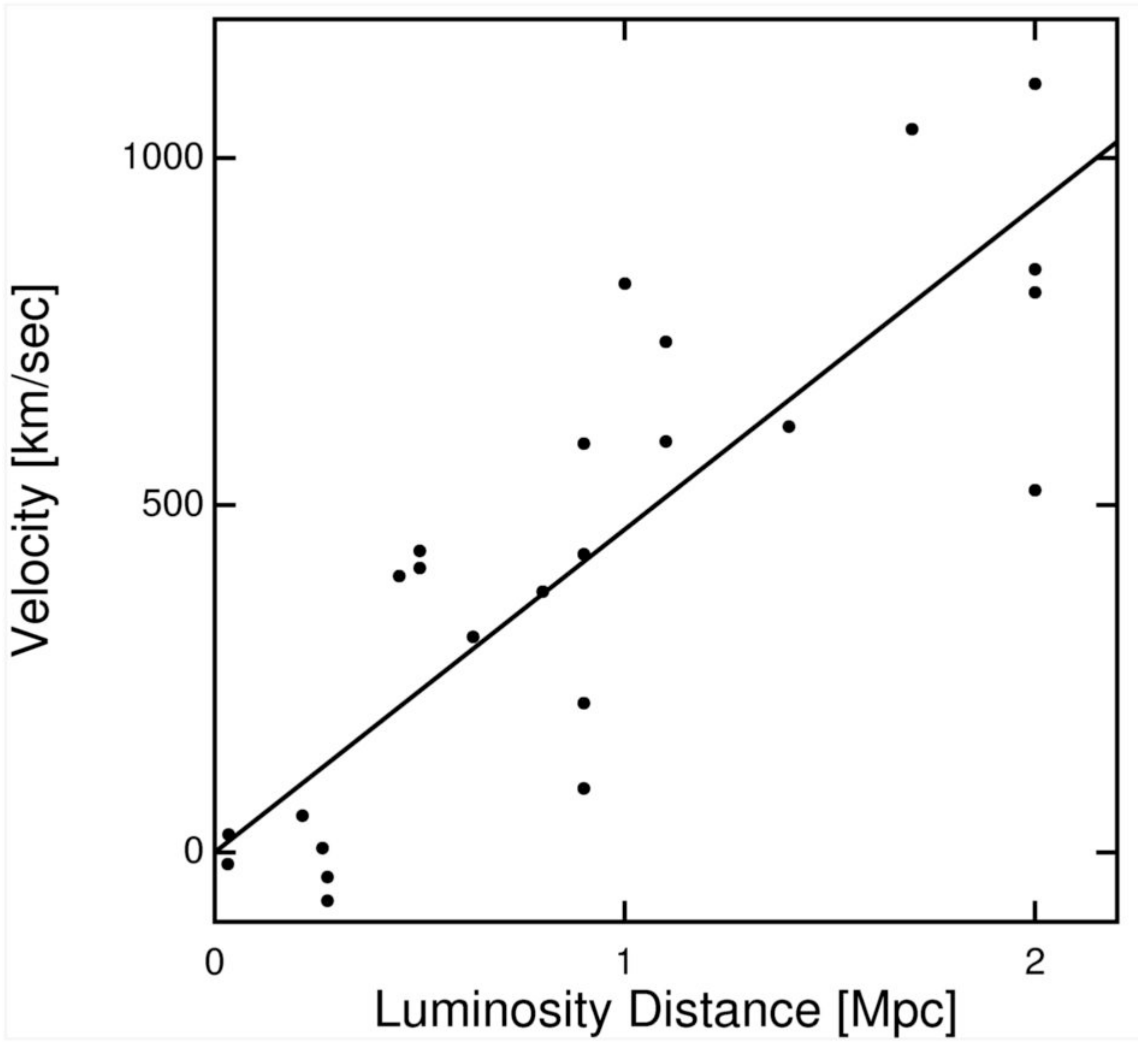
What is a supernova?



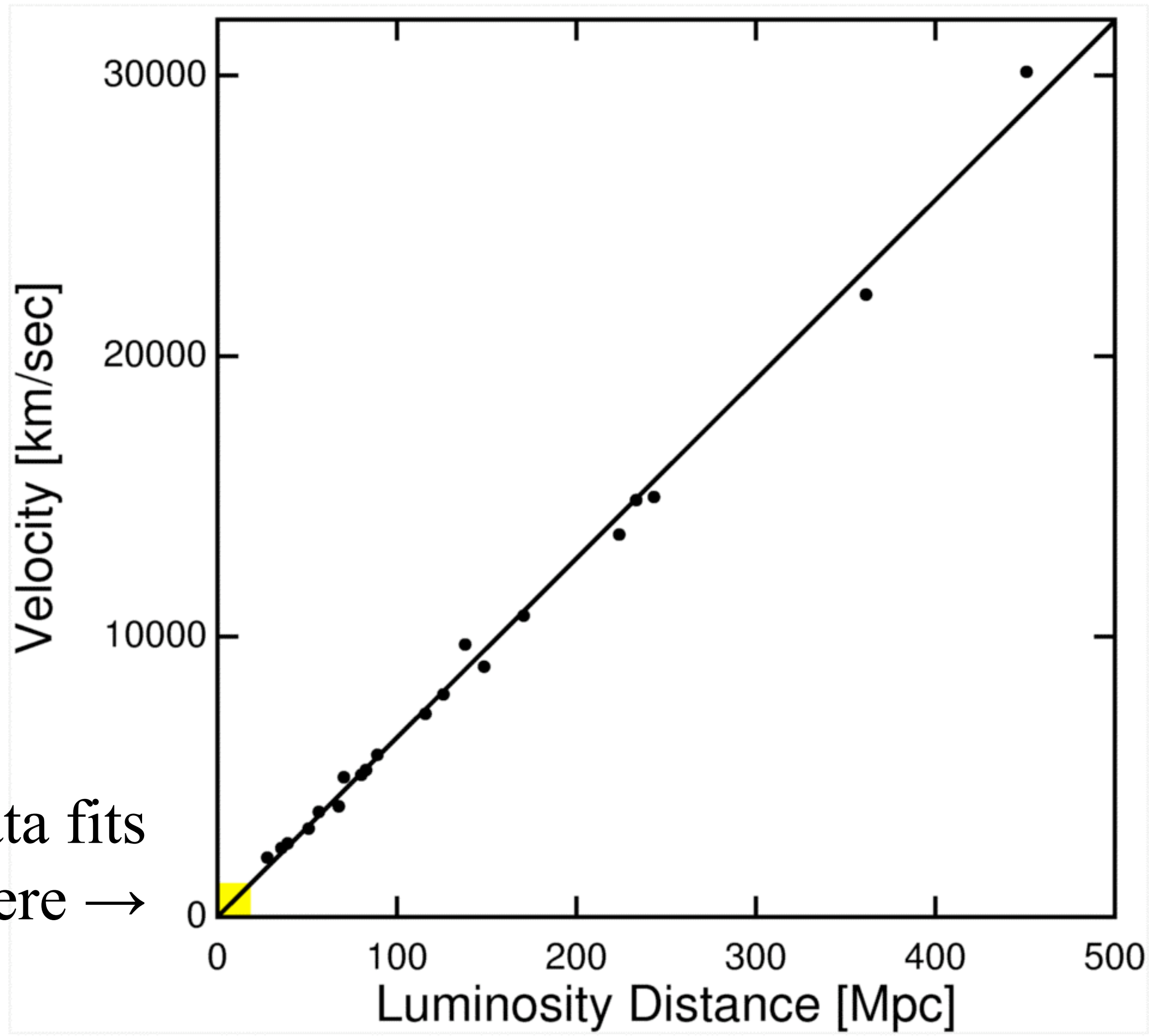
We recently learned how to read the "wattage" label on supernovae:



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

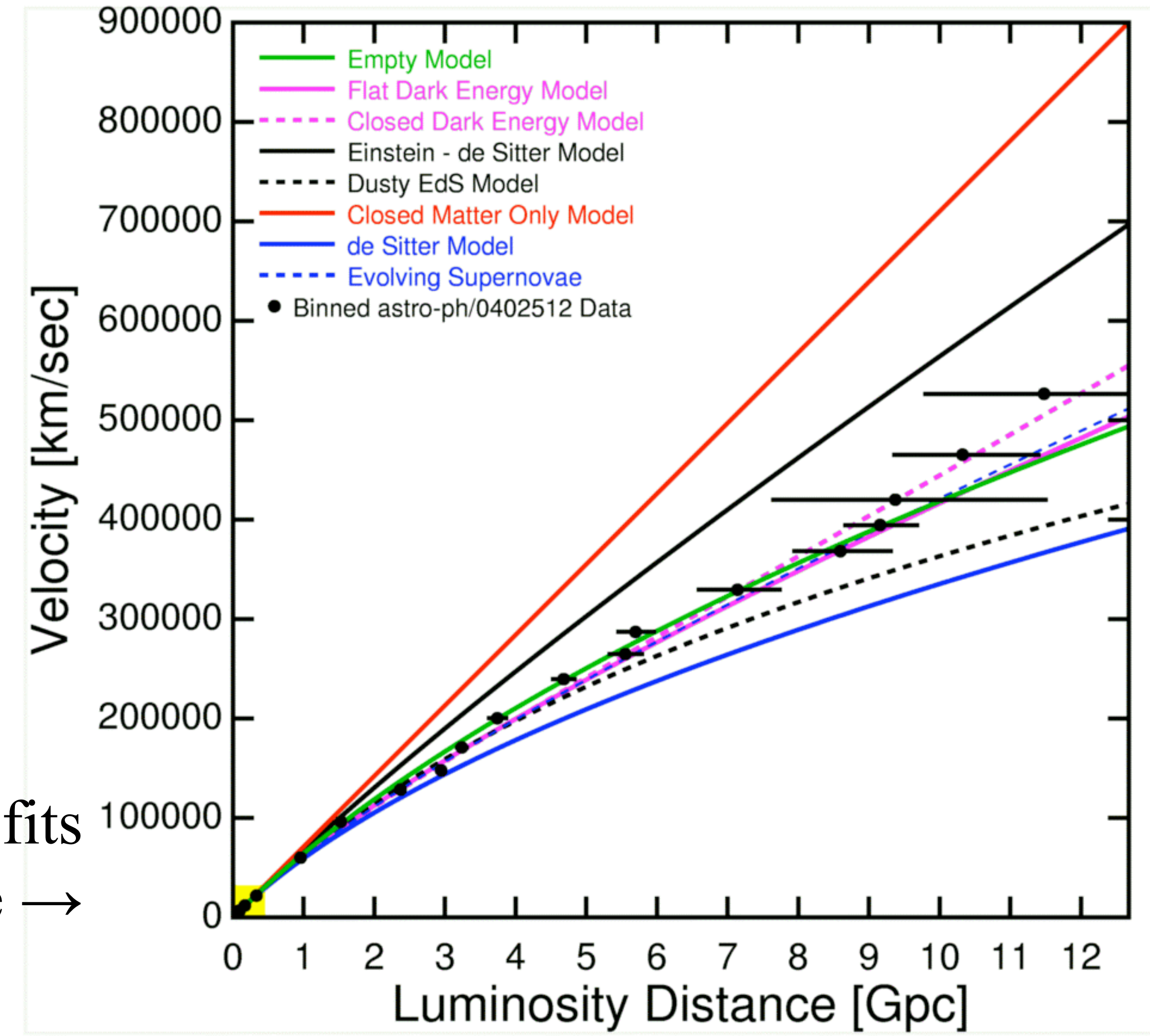


As a result, data on velocity vs distance is now much better! 1995



1929 data fits in here →

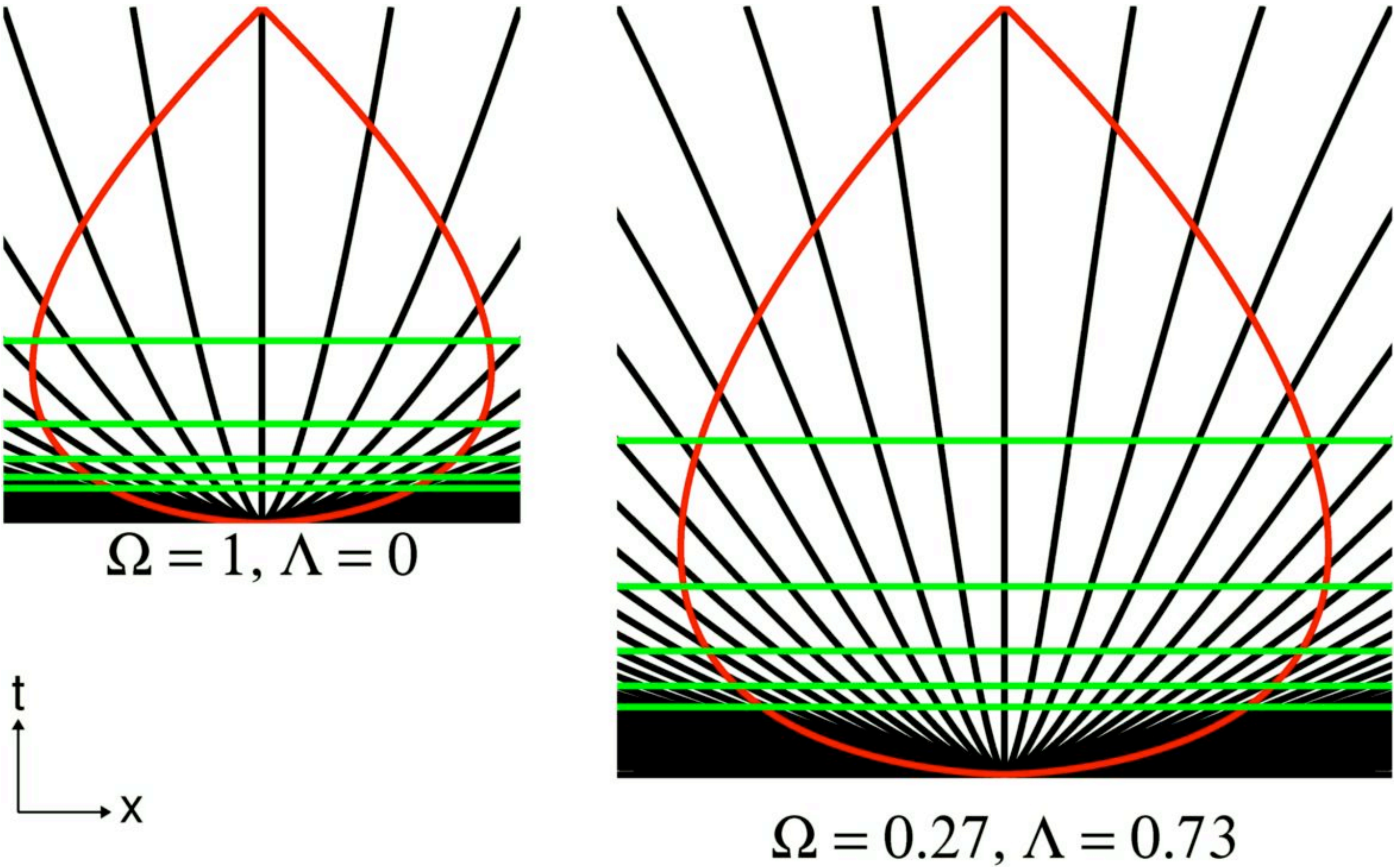
As a result, data on velocity vs distance is now much better! 2004



1995 data fits in here →

v = cz

Acceleration causes Faintness

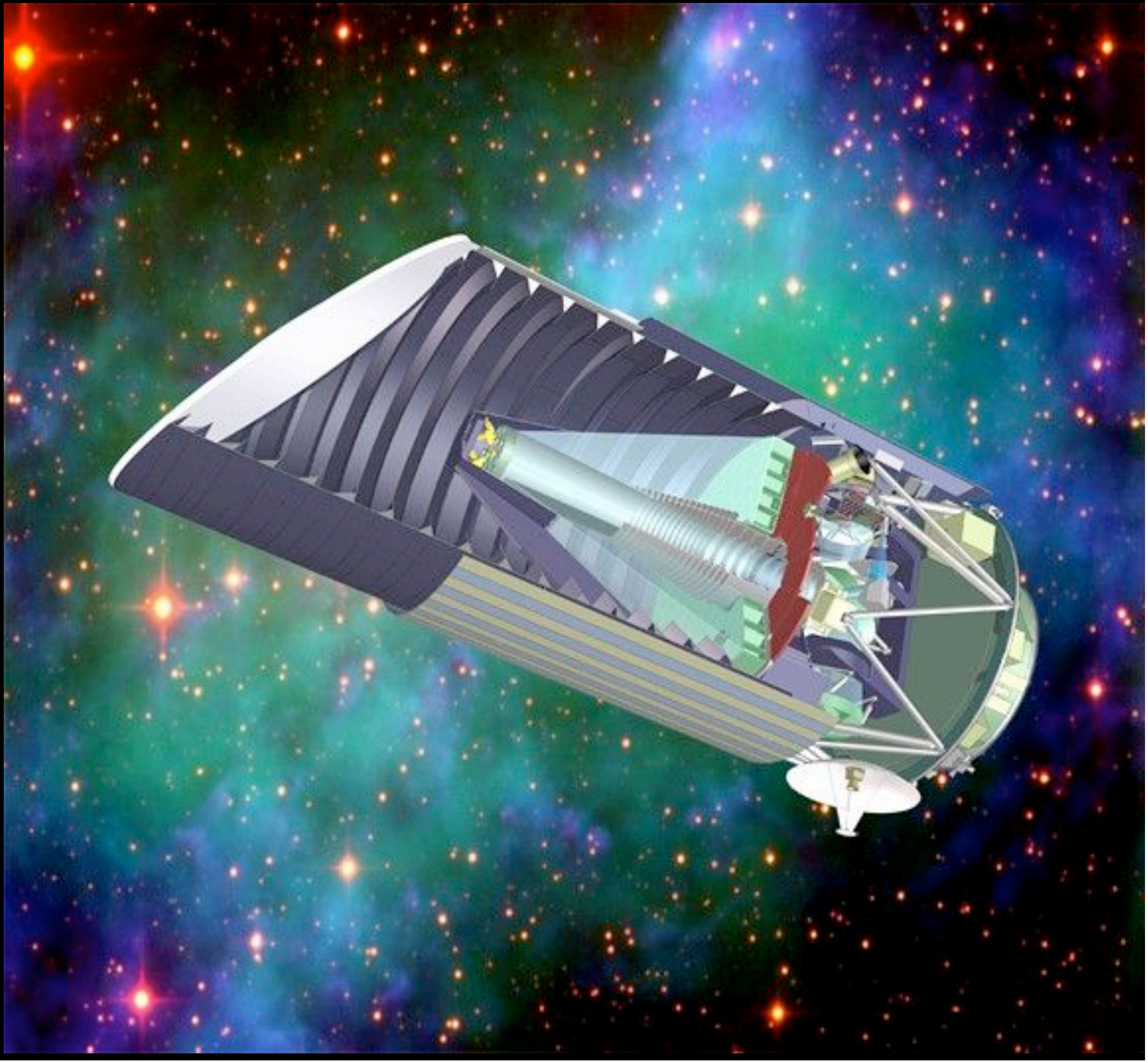


Is Λ really a *CONSTANT*?

- 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 $$$

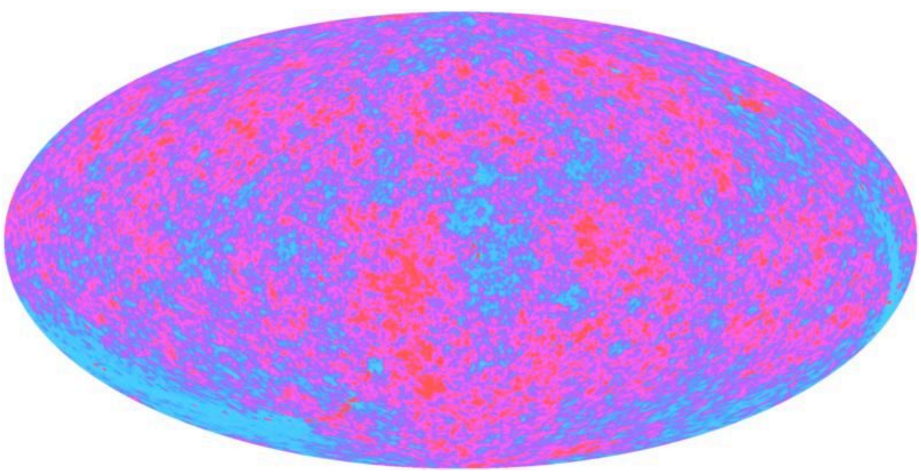


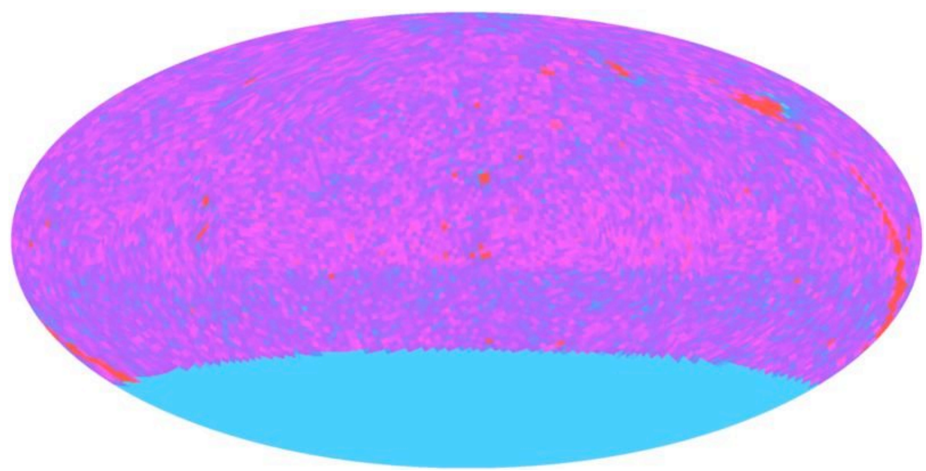
Same Laws of Physics?

- 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.

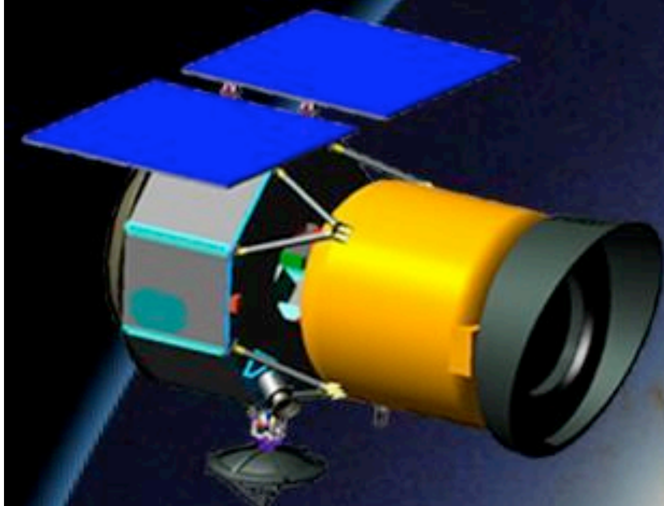
Λ Confirmed by CMB & IR maps

- This 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 at 98% confidence with the NRAO VLA Sky Survey
  - Ashfordi 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 24 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.

“Nothing” really funny

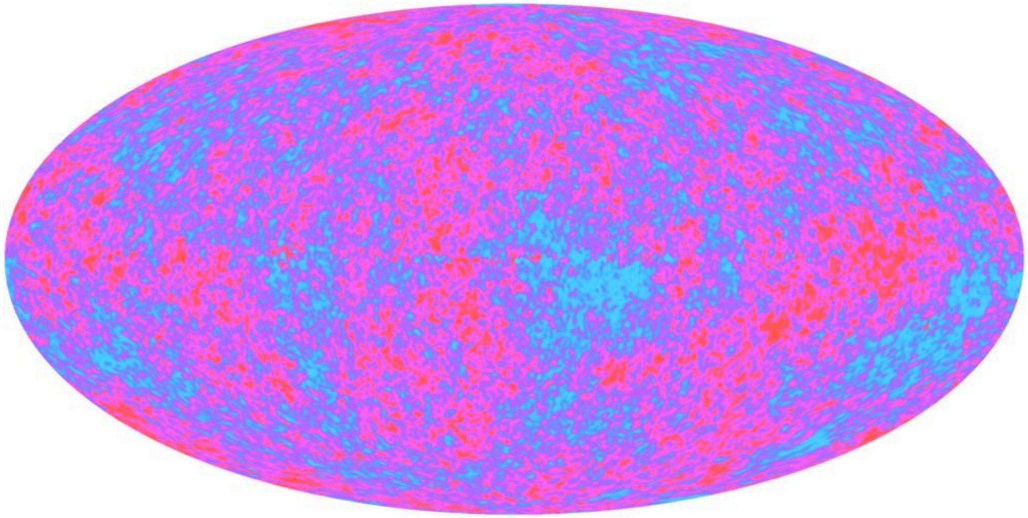
- A Sydney Harris cartoon:
  - “Where the hell did it all come from?”
- But now we ask:
  - “Where the hell did Λ come from?”

Λ: Blunder or Triumph?

- Einstein invented General Relativity, the best current theory for gravity.
- GR allows a place for Λ, and predicts its gravitational effects.
- Einstein inserted Λ to explain a “fact” about the Universe that was not true. The model he developed was unstable and violated Olber’s Paradox.
- But Λ lives on in the Universe now, during inflation in the very early Universe, and in high energy particle physics.

Have we seen the beginning?

- We have seen back to inflation, which erases the initial conditions and removes the "just so" stories.
- The CMB map shows the "mountains" formed during the first picosecond.
- The Universe became transparent 400,000 years after the Big Bang but the mountains already existed.



For More Information

- http://www.astro.ucla.edu/~wright/cosmolog.htm
  - Many good books are listed on the Bibliography page of the above Web site
  - http://www.astro.ucla.edu/~wright/cosmo_constant.html
  - http://www.astro.ucla.edu/~wright/sne_cosmology.html
- http://map.gsfc.nasa.gov
  - The home page of the WMAP mission to measure the Cosmic Microwave Background sky