Observing the Origin of the Universe: A Century of Progress in Cosmology

Edward L. (Ned) Wright

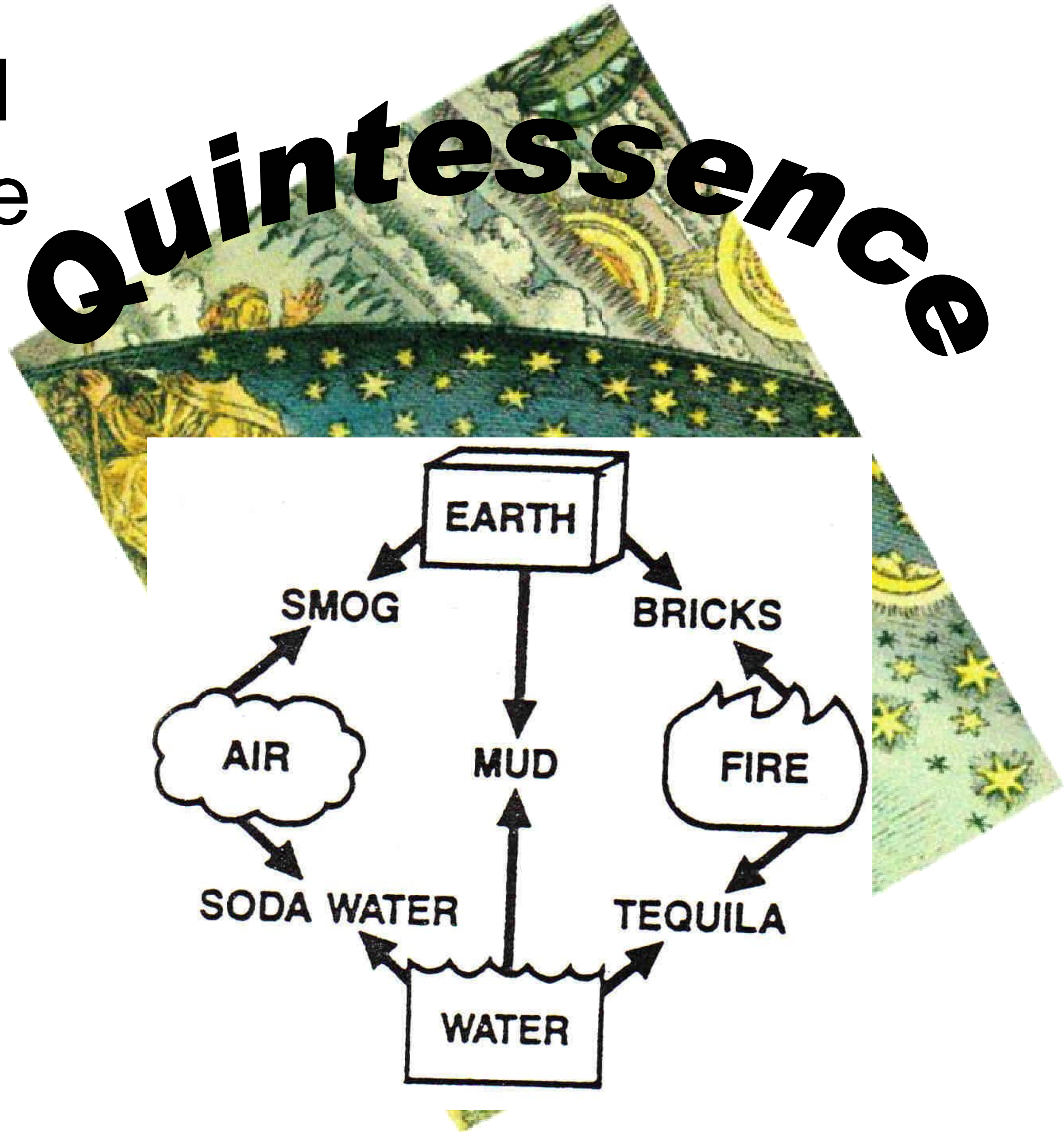
UCLA

28 October 2008

Cosmology is an Observational Science

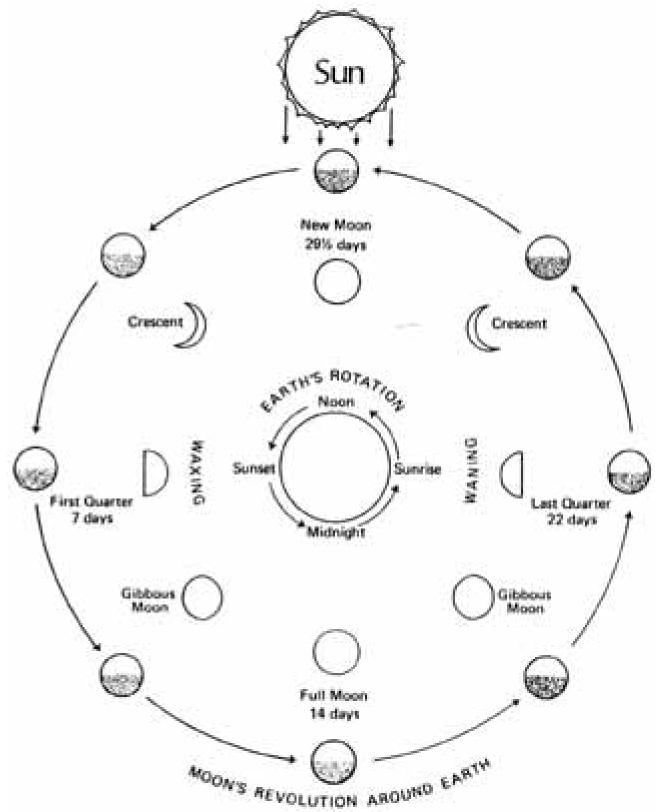
- We can’t do experiments on the Universe.
- We can’t change the initial conditions and see what happens.
- But we can observe what is the Universe is like.
- And we can study what past, present and future conditions of the Universe are compatible with our observations and the same laws of physics that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

No special laws for the heavens

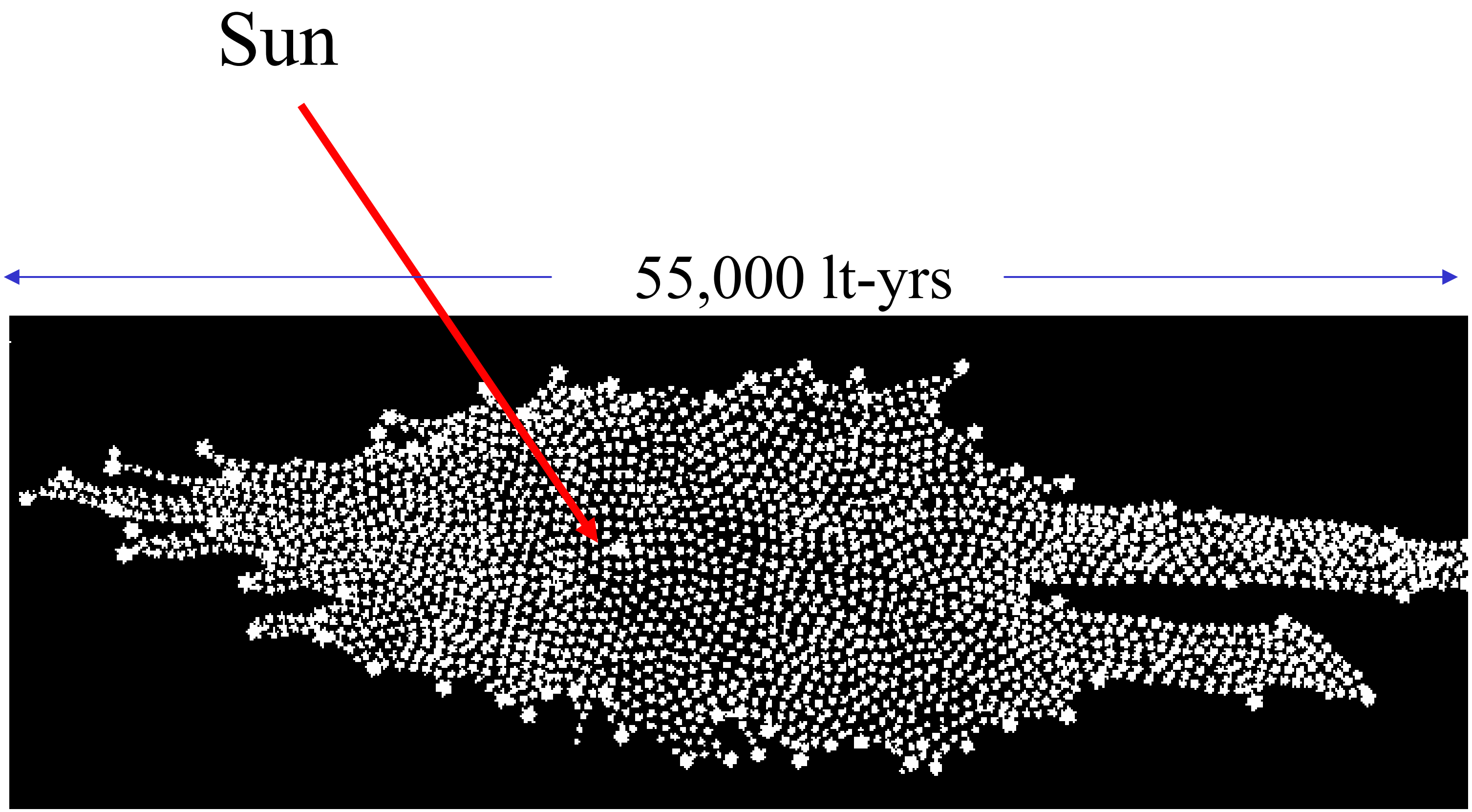


Newton’s Apple & the Moon

- 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.



In 1908, Kapteyn thought the Milky Way was the Universe



- Herschel’s map of star counts

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	3×10^5 km/sec
Now	$>10^{23}$ km	13.7 Gyr	3×10^5 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

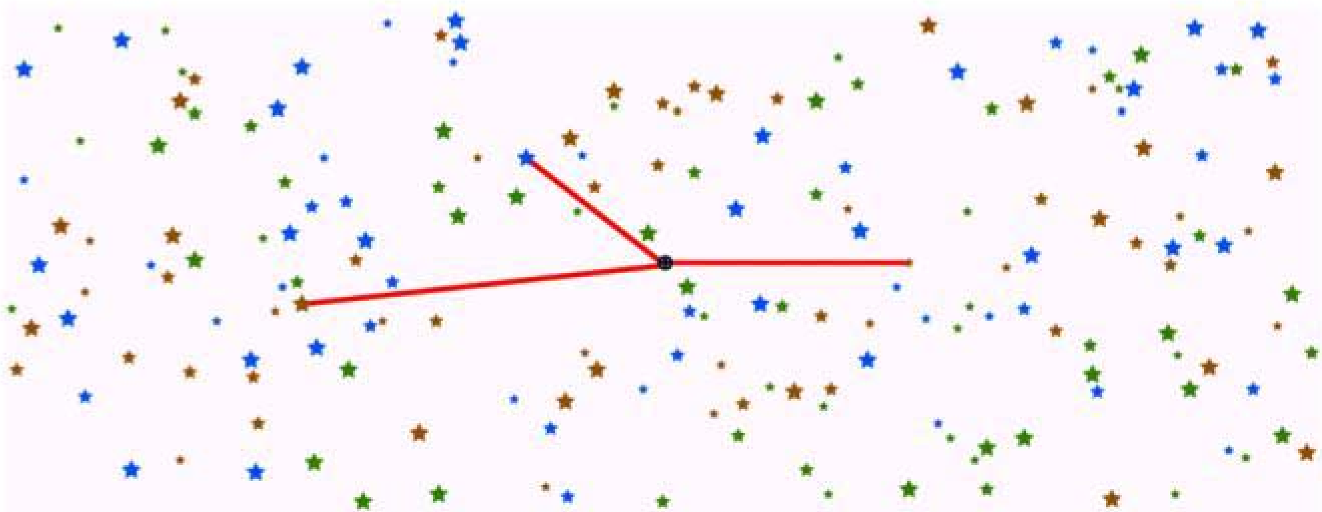
Two and a half Facts

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.

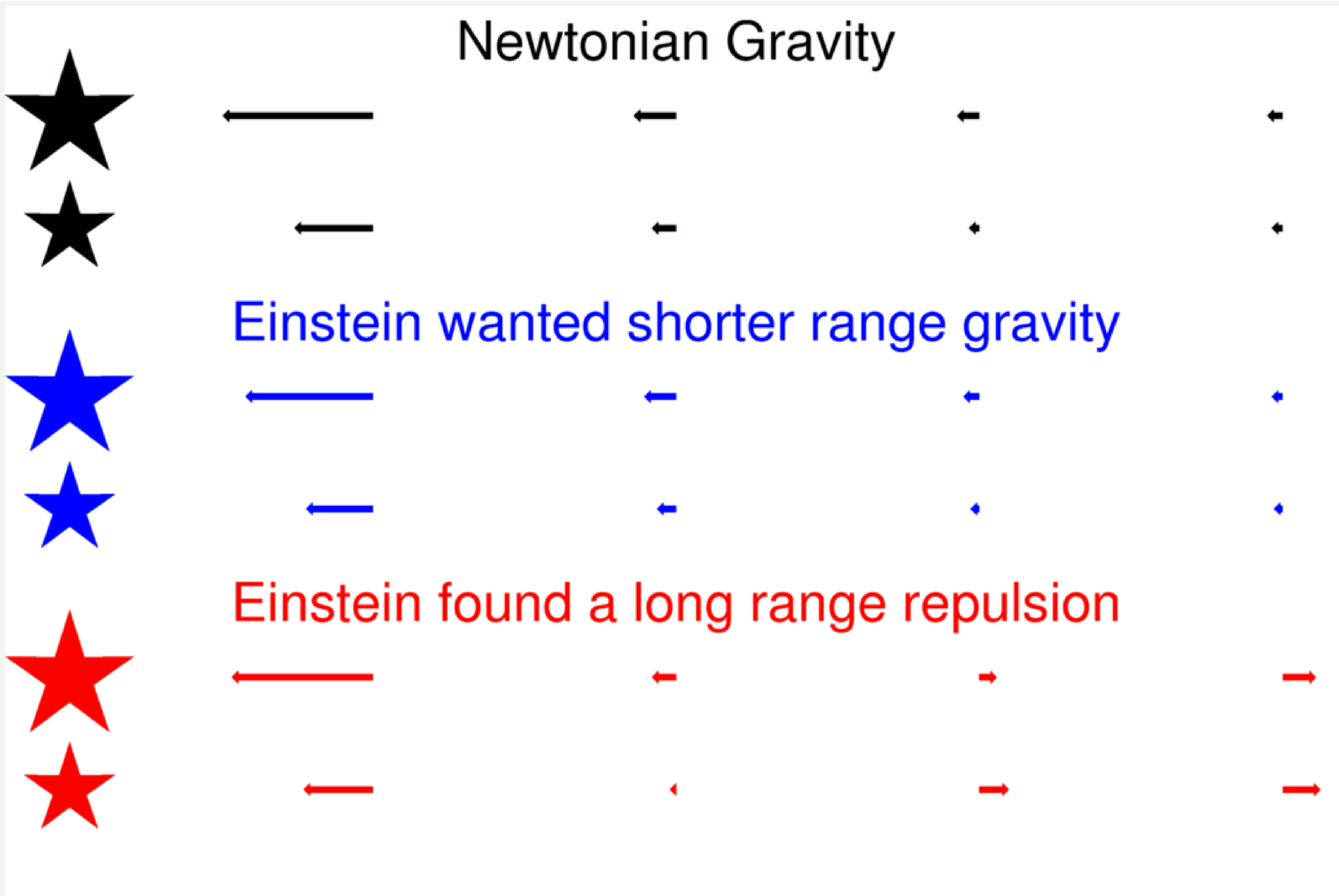


In a homogeneous, unchanging Universe every line of sight will end on a star. The whole sky should be a bright as the surface of the Sun. This is Olbers' Paradox.

General Relativity & Cosmology

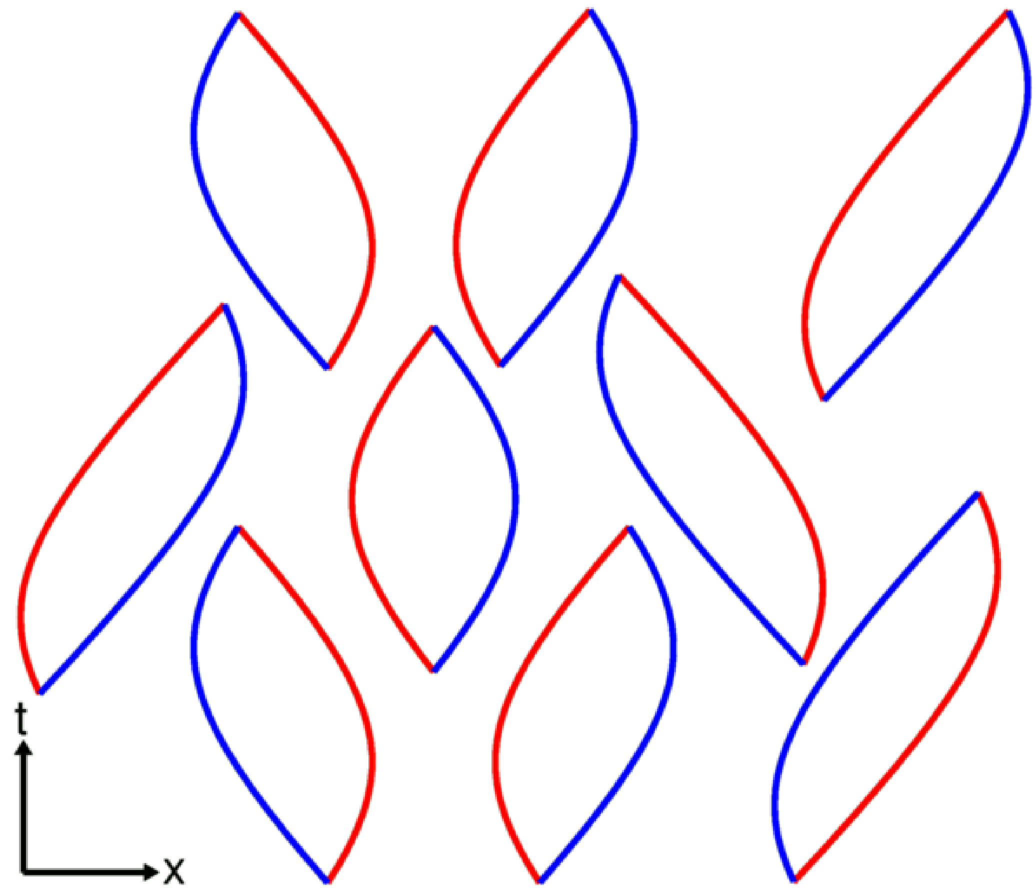
- General relativity allows a consistent calculation of the effects of gravity in a uniform distribution of galaxies that fills the entire Universe.
- But Einstein thought the Universe was static, and a static uniform distribution of galaxies that filled the entire Universe would be unstable to collapsing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

Effect of Λ term was unexpected

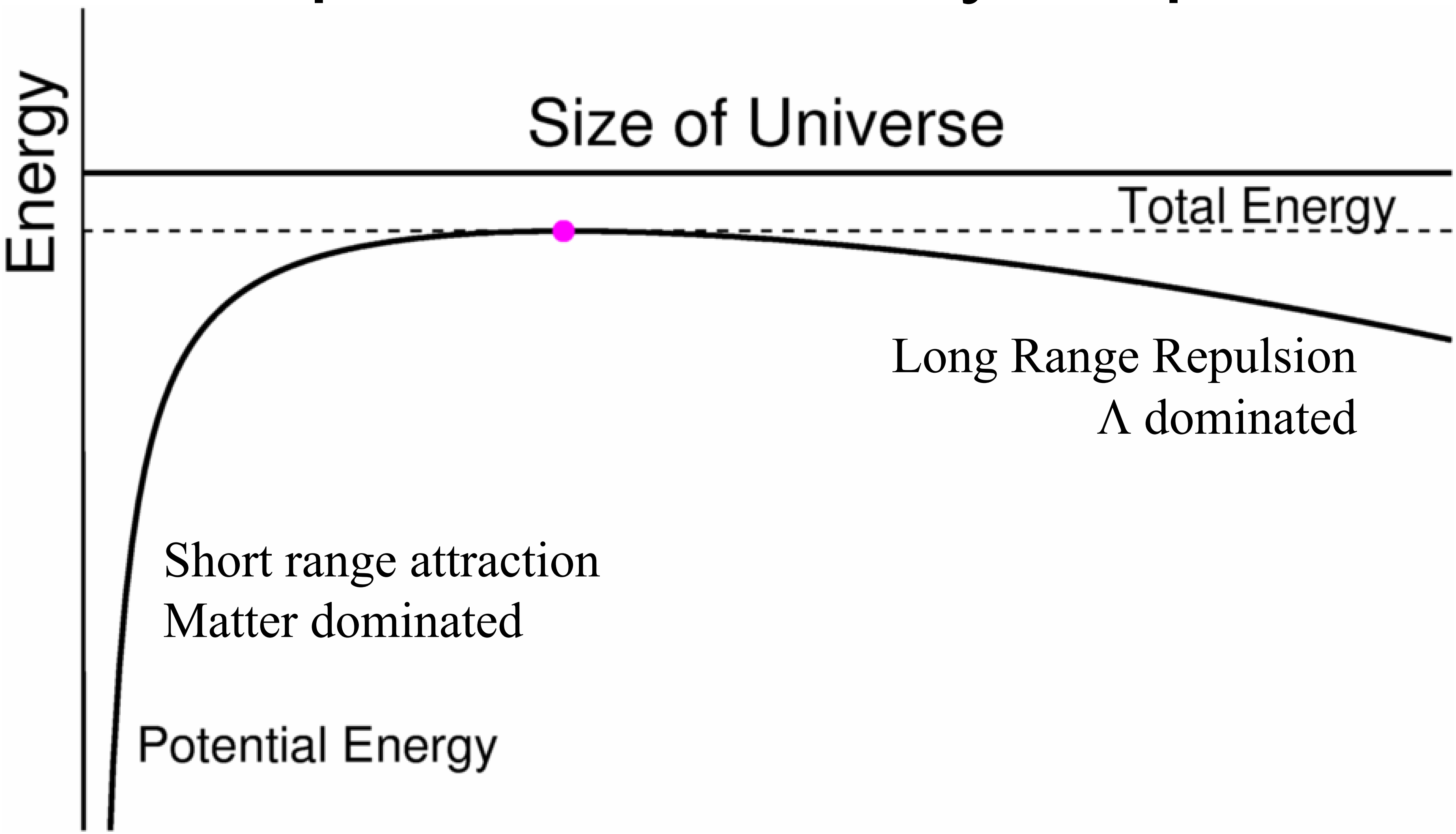


Source of Cosmological Constant

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



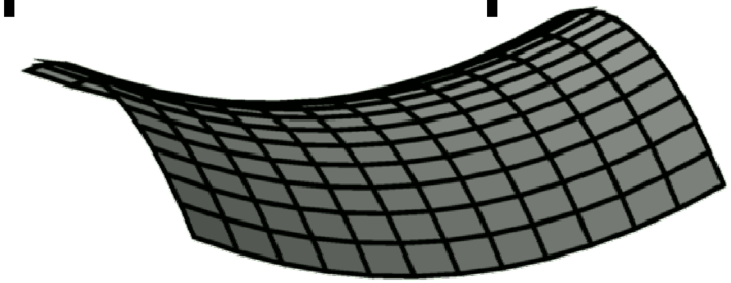
Represent Force by Slope

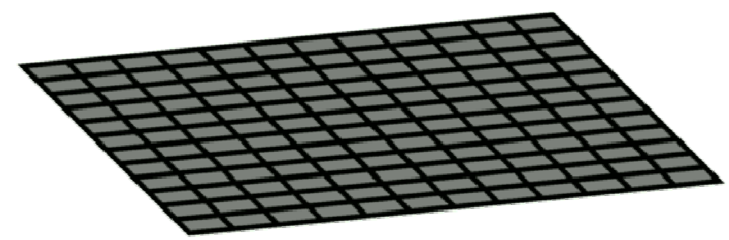


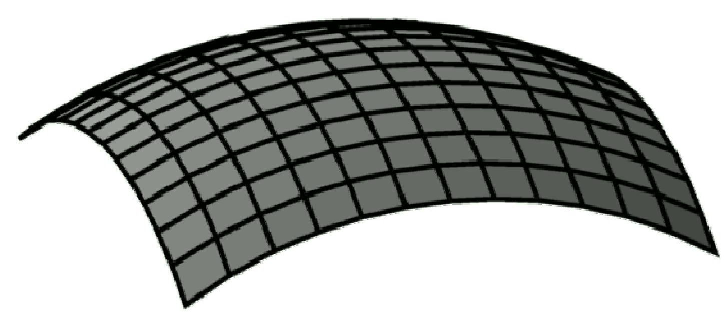
- This is quite a good analogy for cosmological models.

Total Energy implies Shape

- Total Energy > 0
  - Sum of angles < 180^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







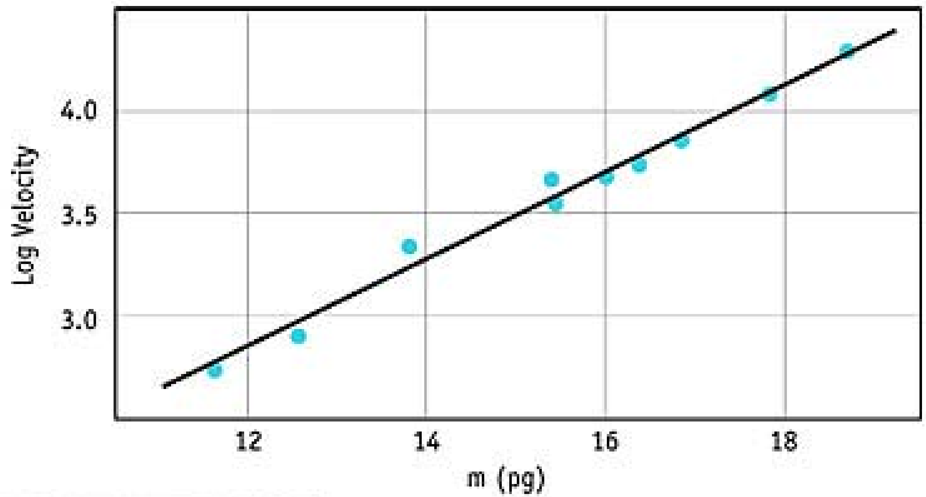
Other models based on GR

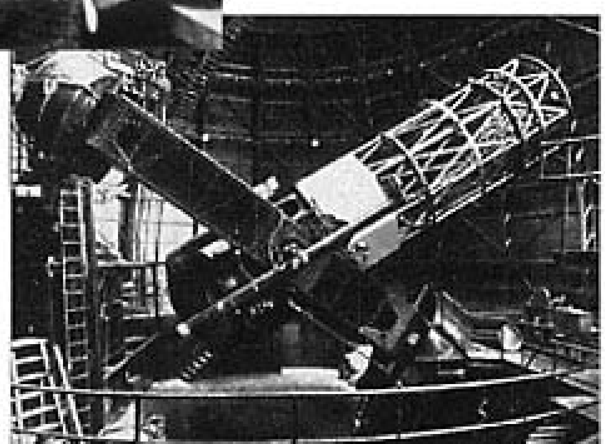
- Einstein had a very special combination of matter, Λ and total energy to give a static Universe. But this model is only metastable. If perturbed, it would either collapse or expand forever.
- de Sitter considered a model with no matter, only Λ. This model had an exponentially accelerating expansion.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

New Data: Hubble 1929

Discovery of Expanding Universe

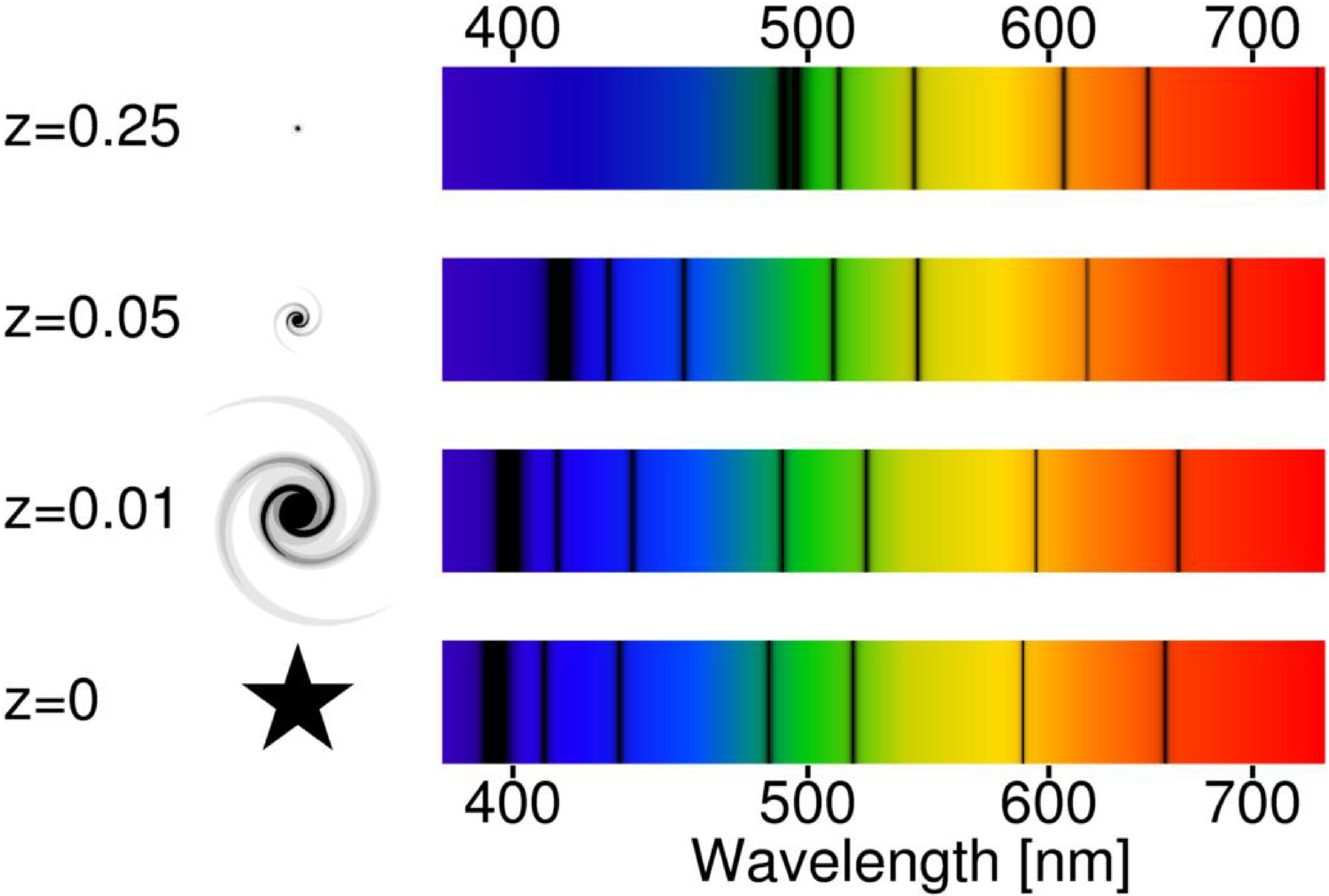
Edwin Hubble





Mt. Wilson
100 Inch
Telescope

Measuring brightness & velocity



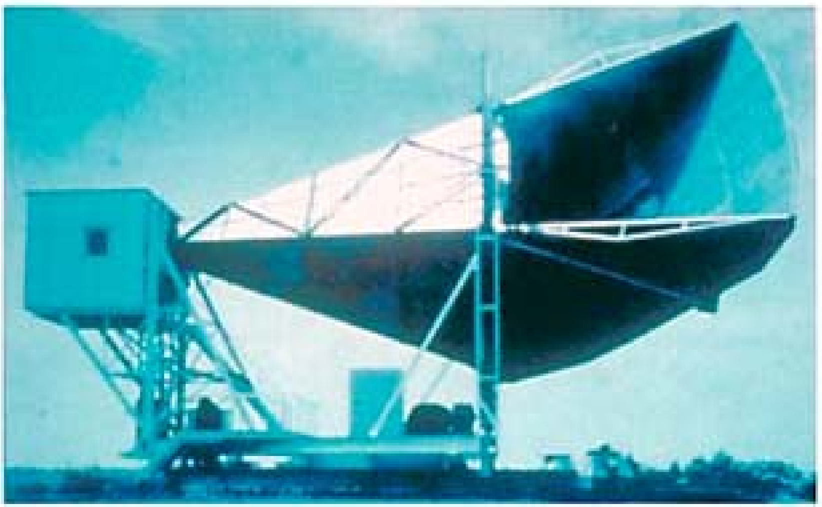
Hubble Law: $v = HD$

- Hubble found a recession velocity proportional to the distance.
  - Einstein static fails, de Sitter & Friedmann pass

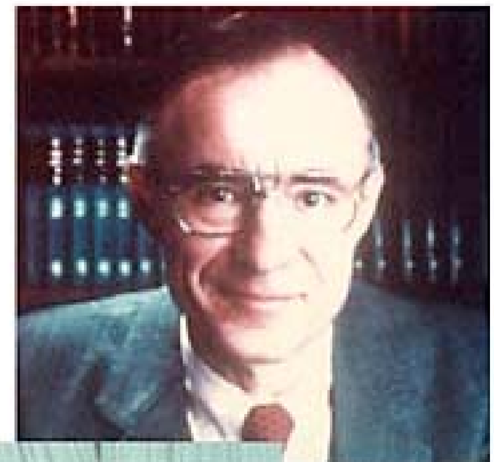
Models vs Olbers' Paradox

- 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.

Discovery of the Cosmic Microwave Background



Microwave Receiver

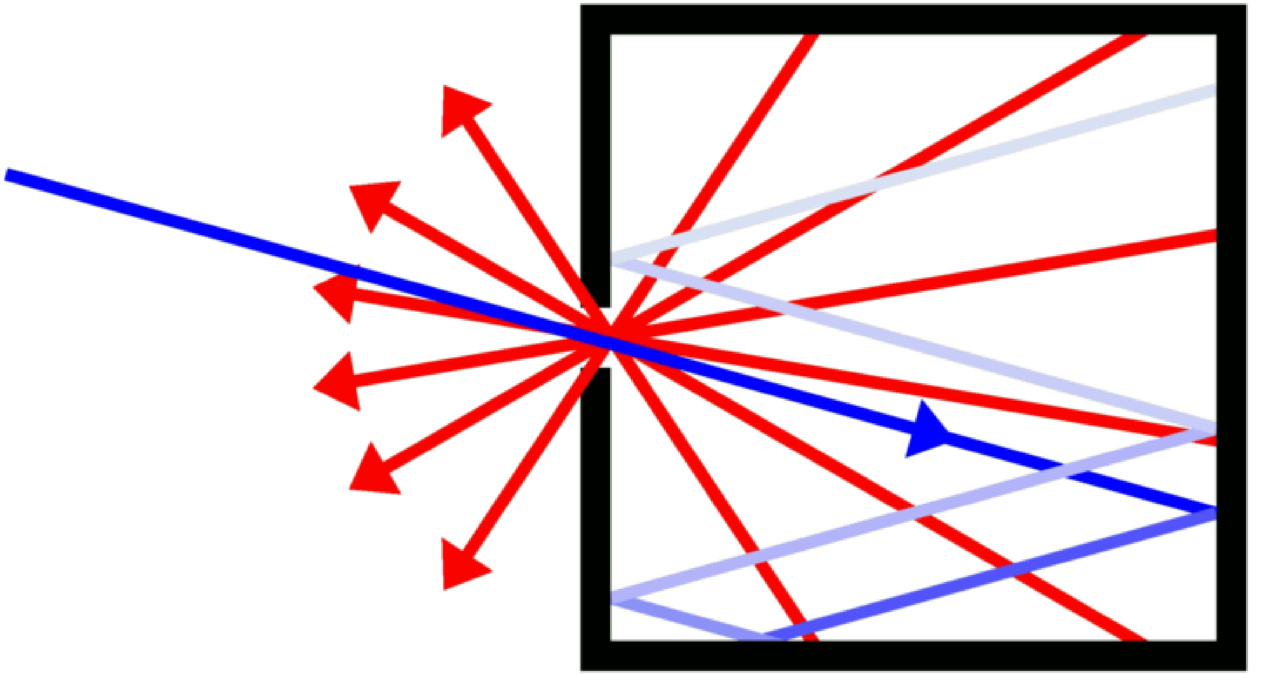


Arno Penzias

Robert Wilson

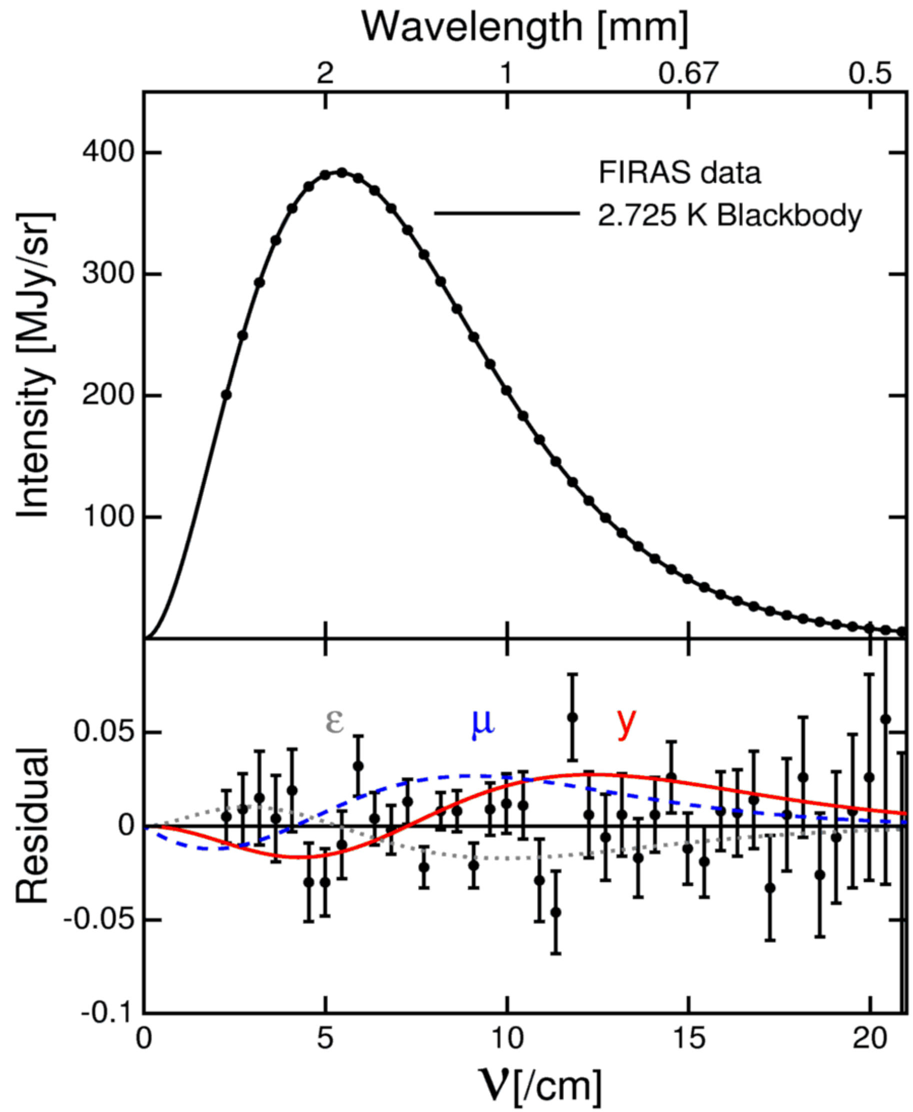
CMB Spectrum is a Blackbody

- 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.



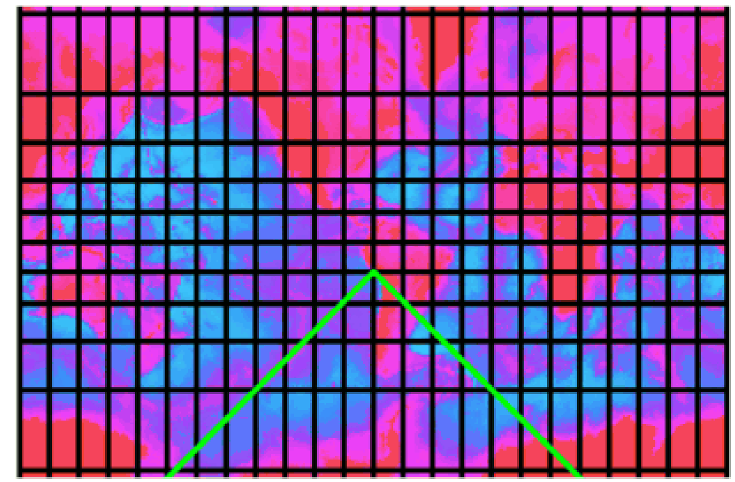
Spectrum is Very Black

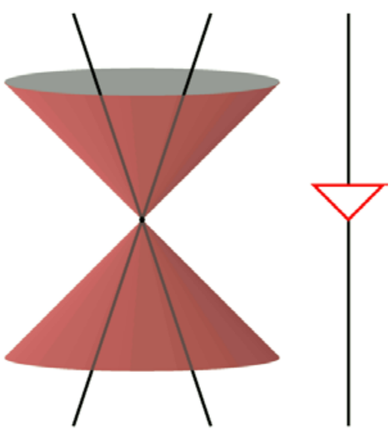
- Residuals in lower panel are what FIRAS measured: Sky-Blackbody
- RMS residual 50 parts per million
- Energy from hot electrons into CMB < 60 parts per million

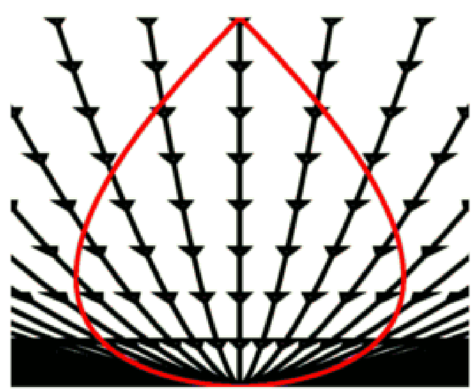


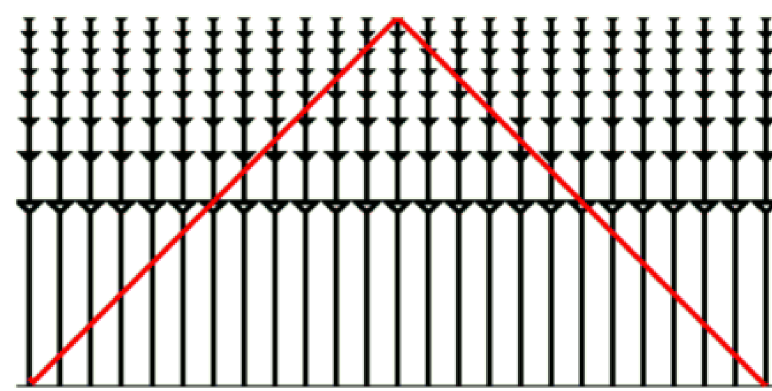
“Normal” vs Conformal ST Diagram

- 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.



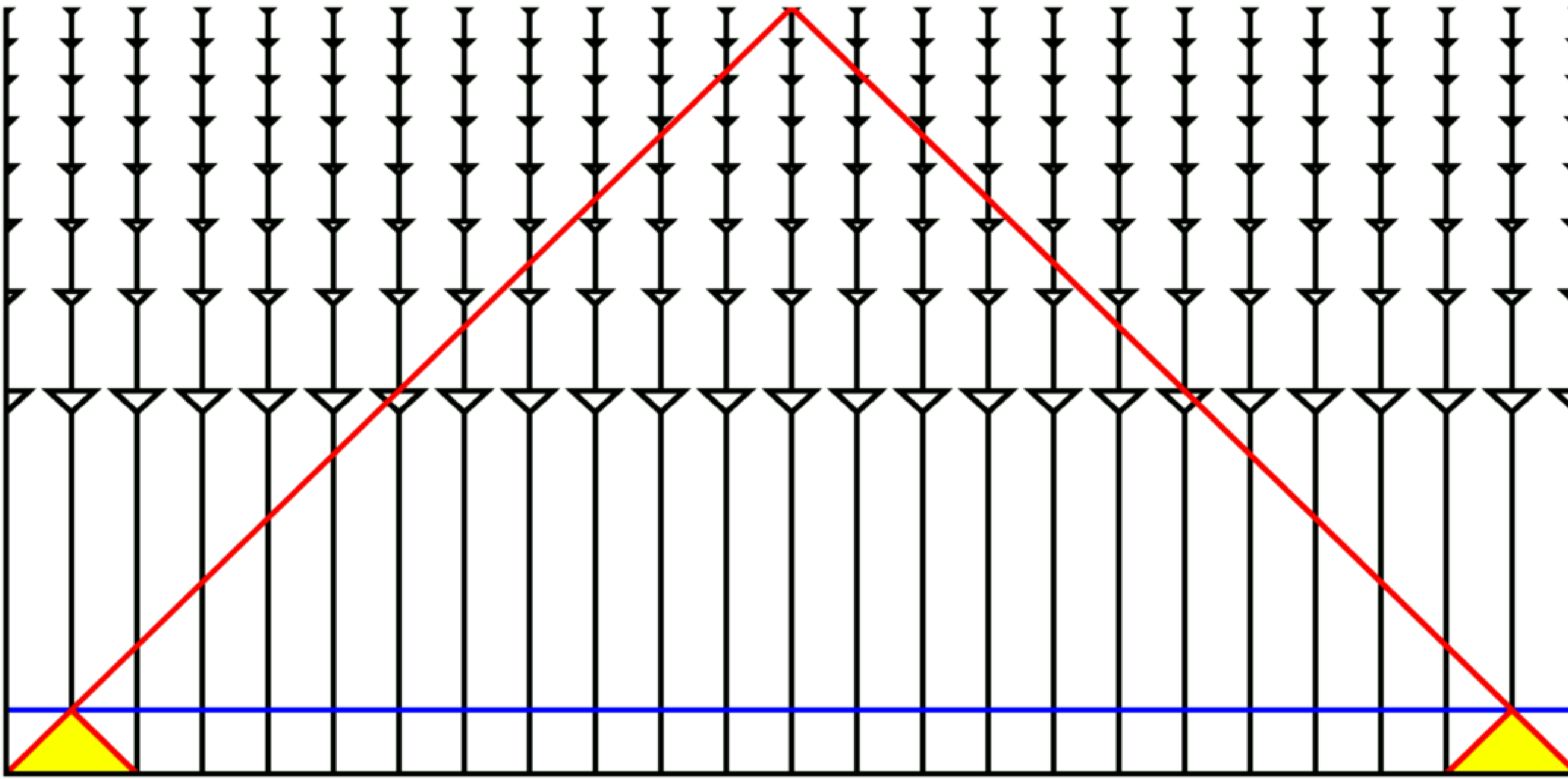




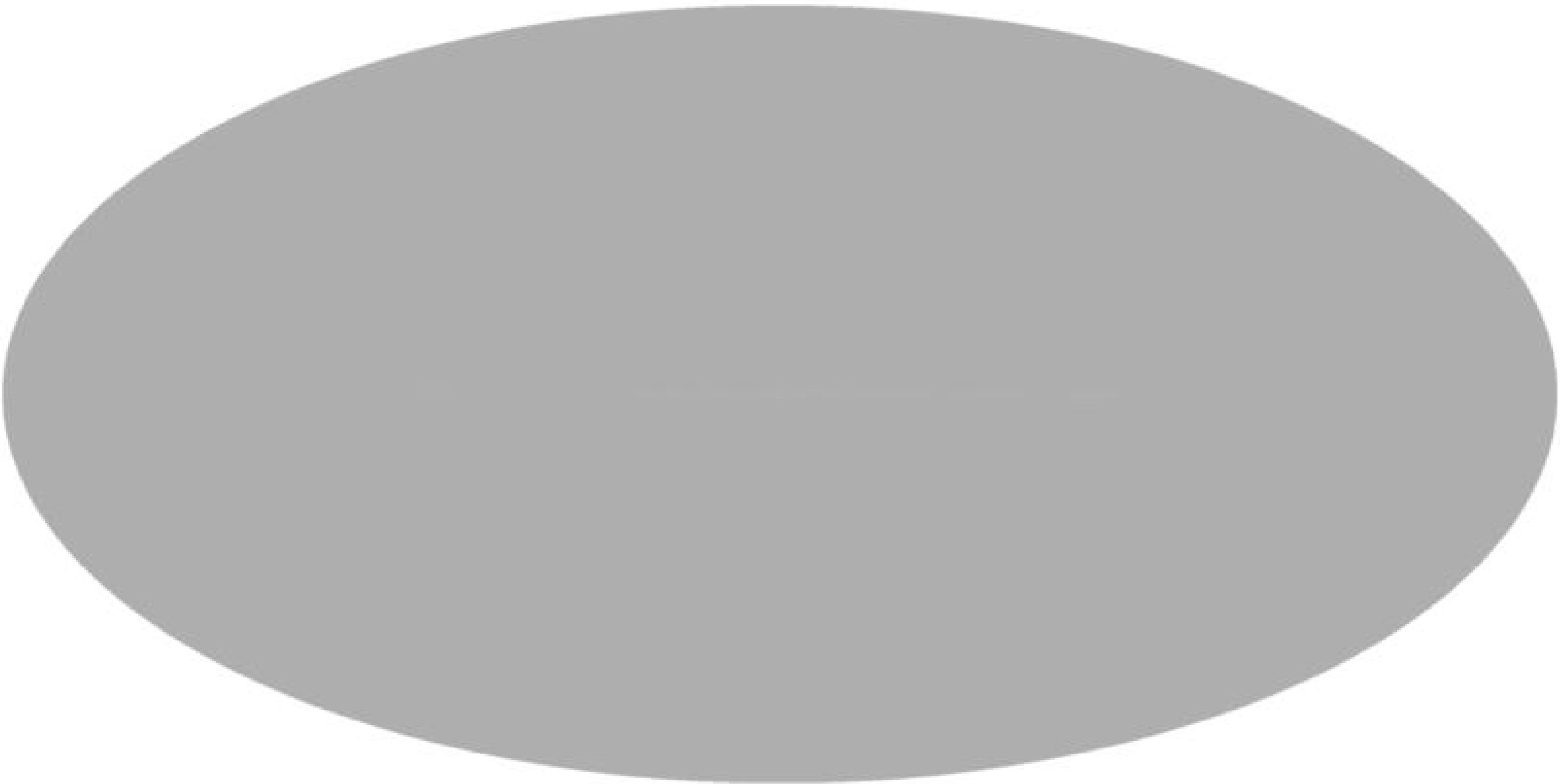


Horizon Problem

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?

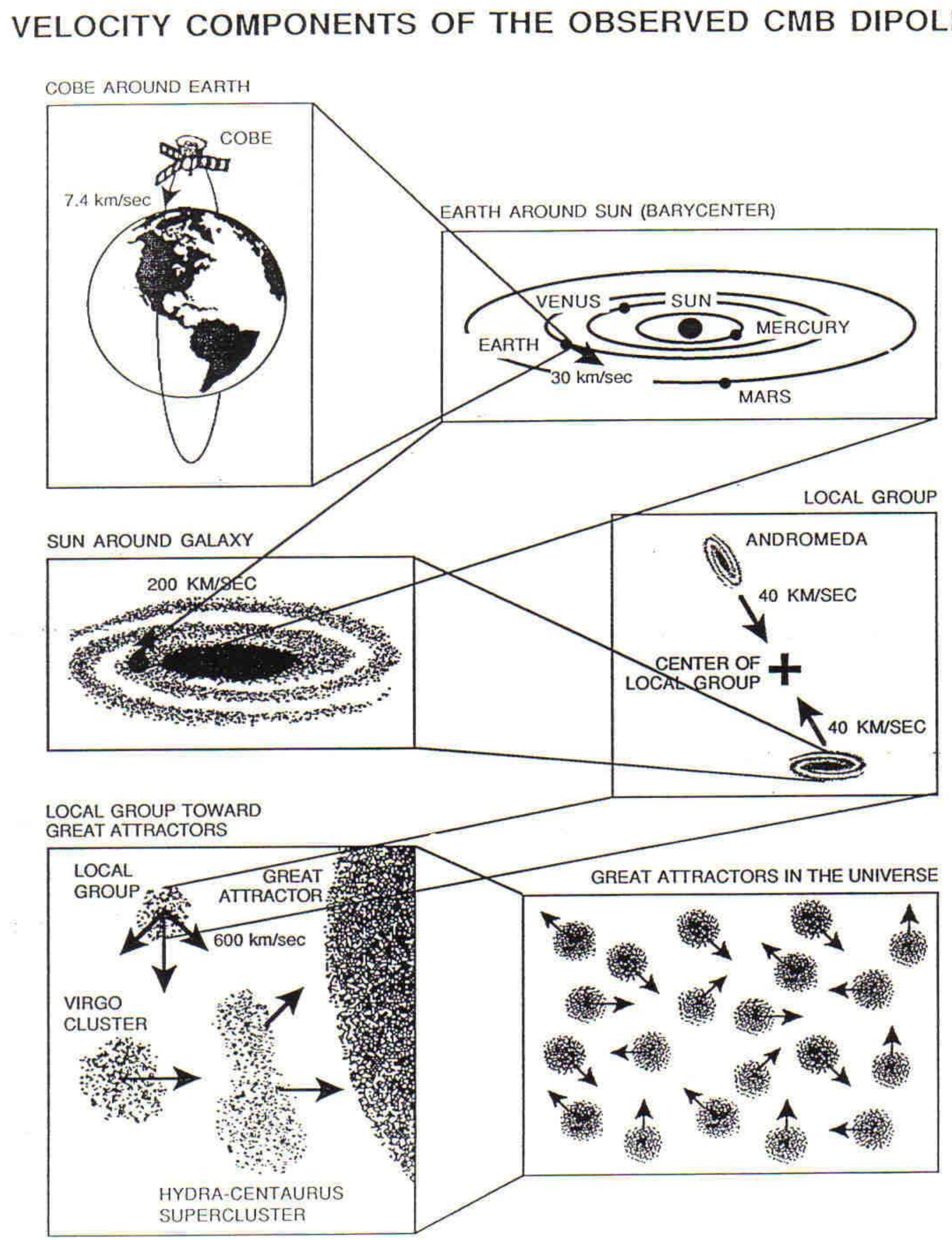


True Contrast CMB Sky



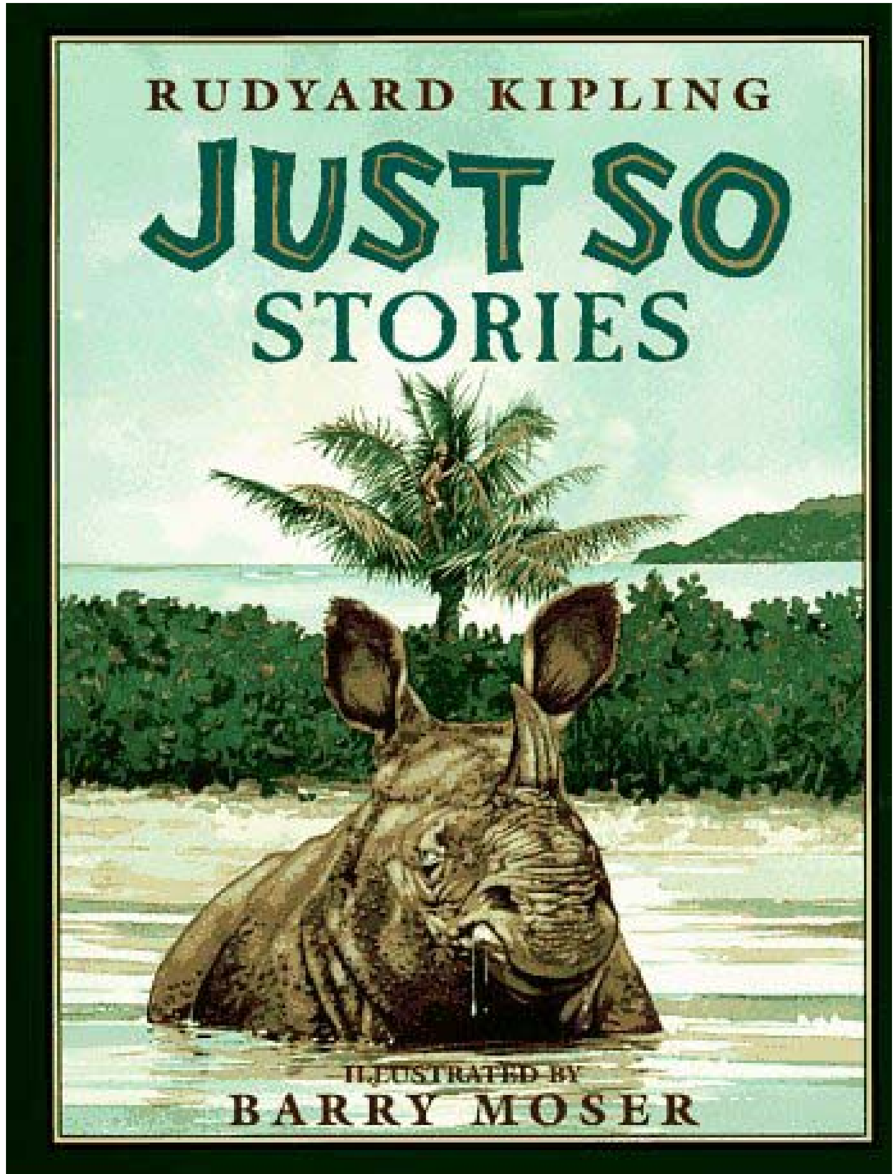
23, 41 & 94 GHz as RGB, 0-4 K scale

Enhanced Contrast:

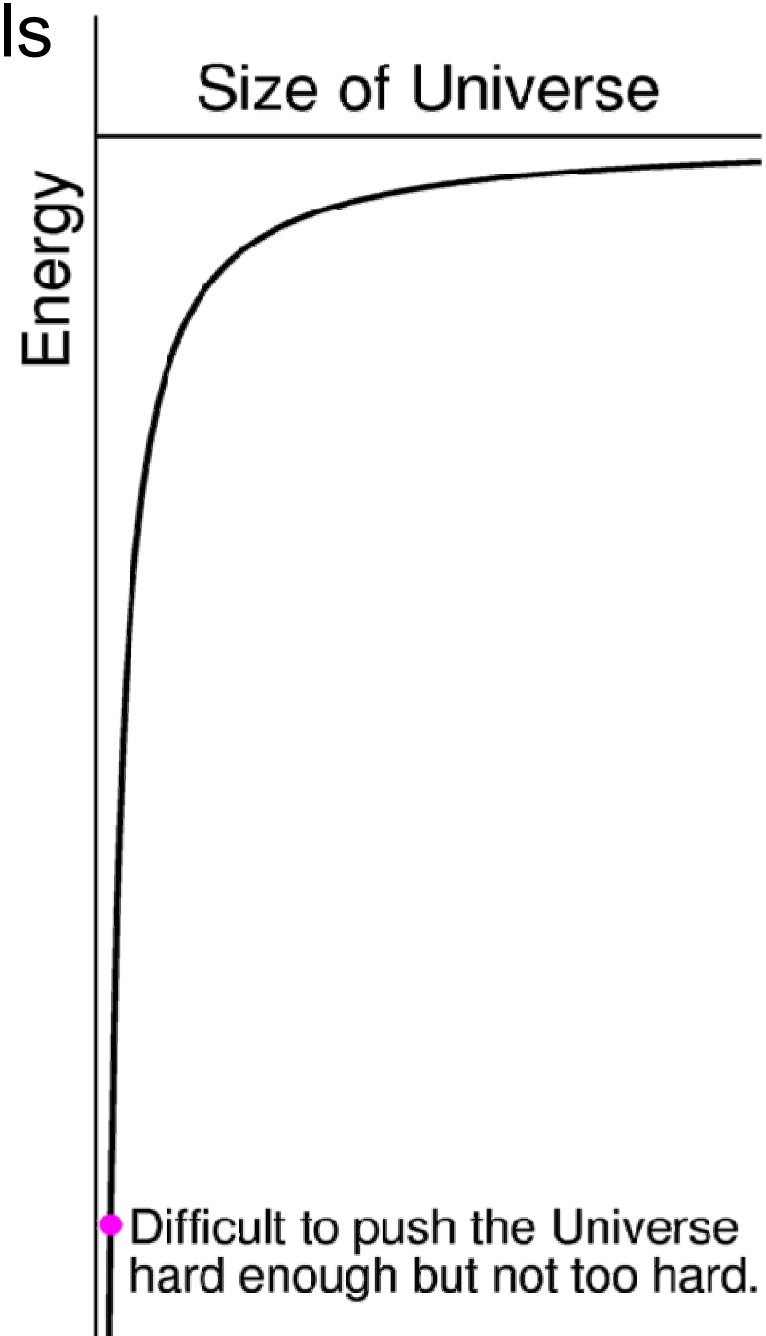


- Conklin 1969 - 2σ
- Henry 1971 - 3σ
- Corey & Wilkinson 1976 - 4σ
- Smoot *et al.* 1977 - 6σ

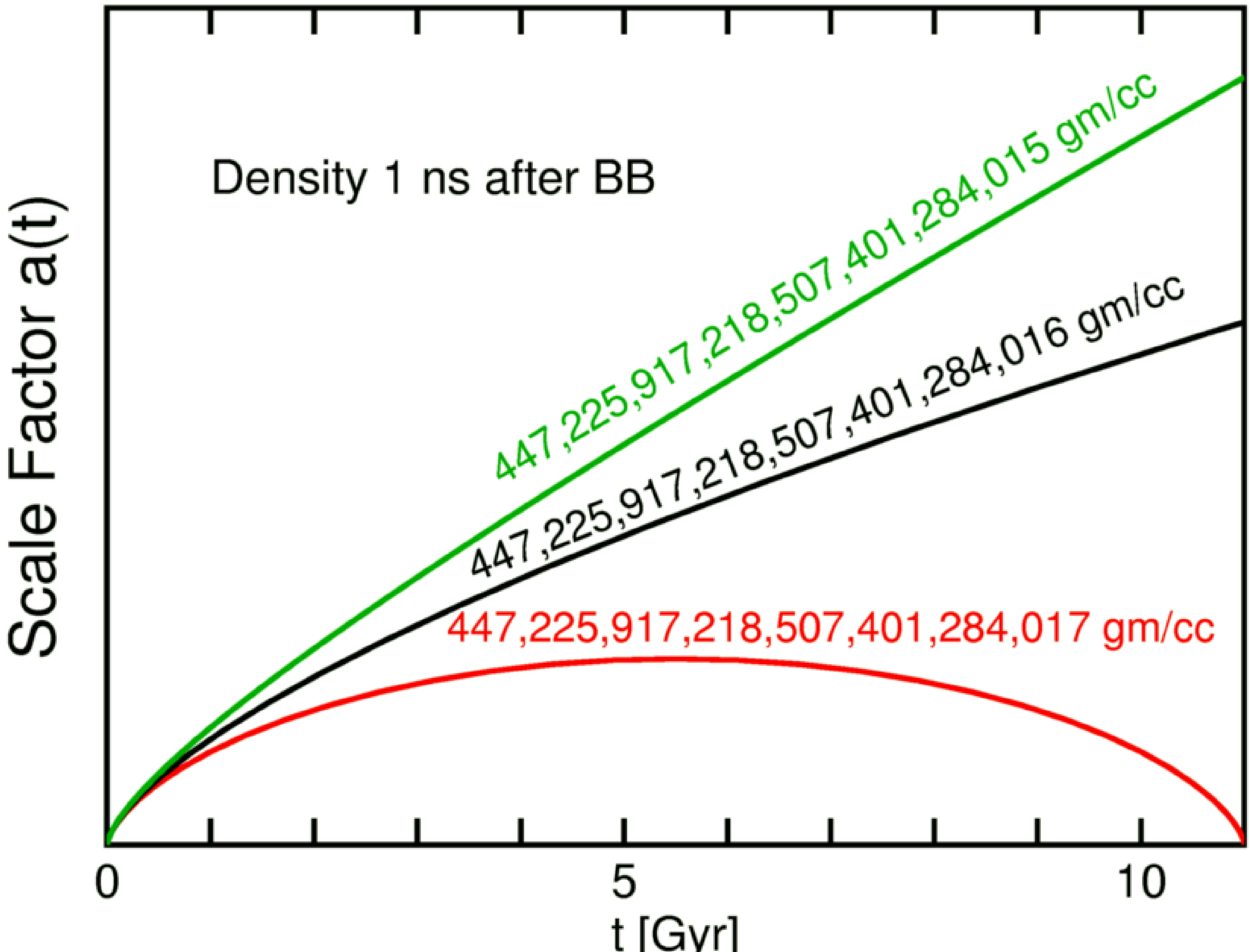
Just So?


RUDYARD KIPLING
JUST SO
STORIES
ILLUSTRATED BY
BARRY MOSER

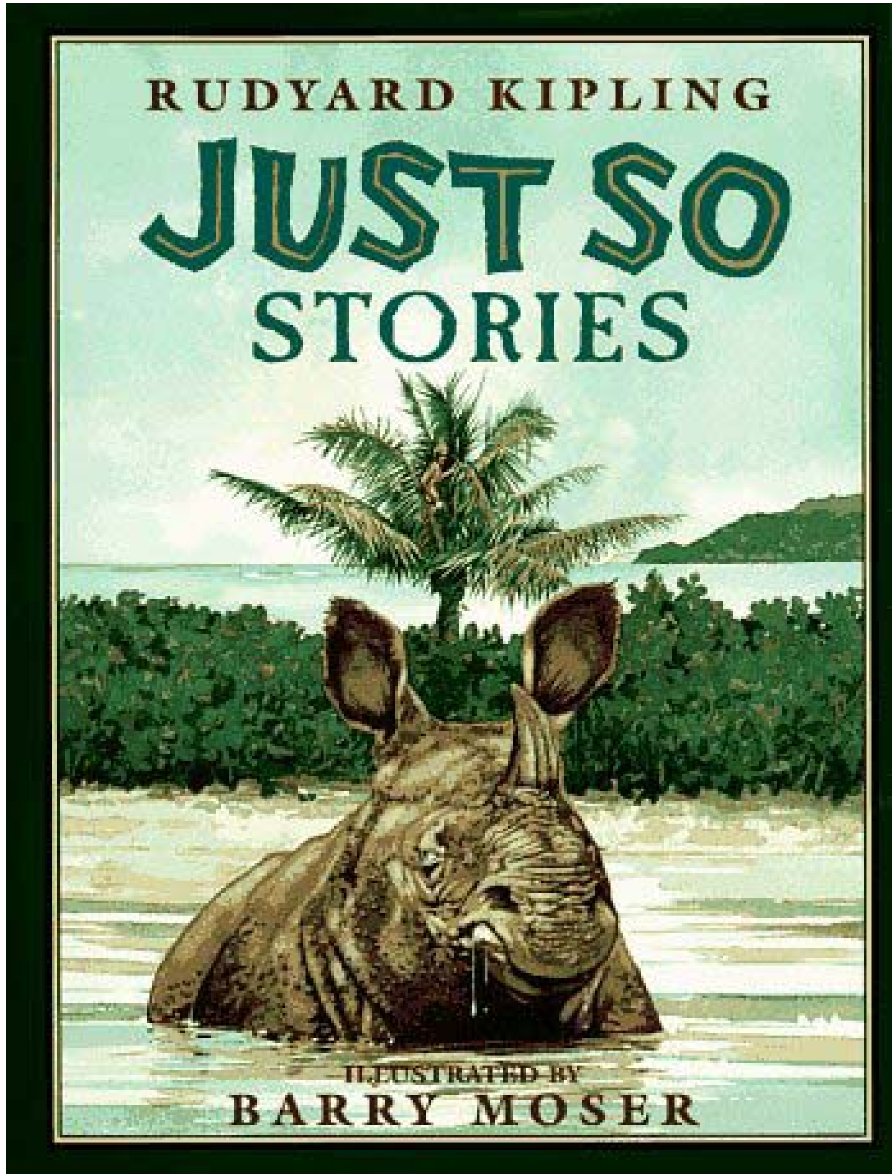
Problems with Friedmann Models



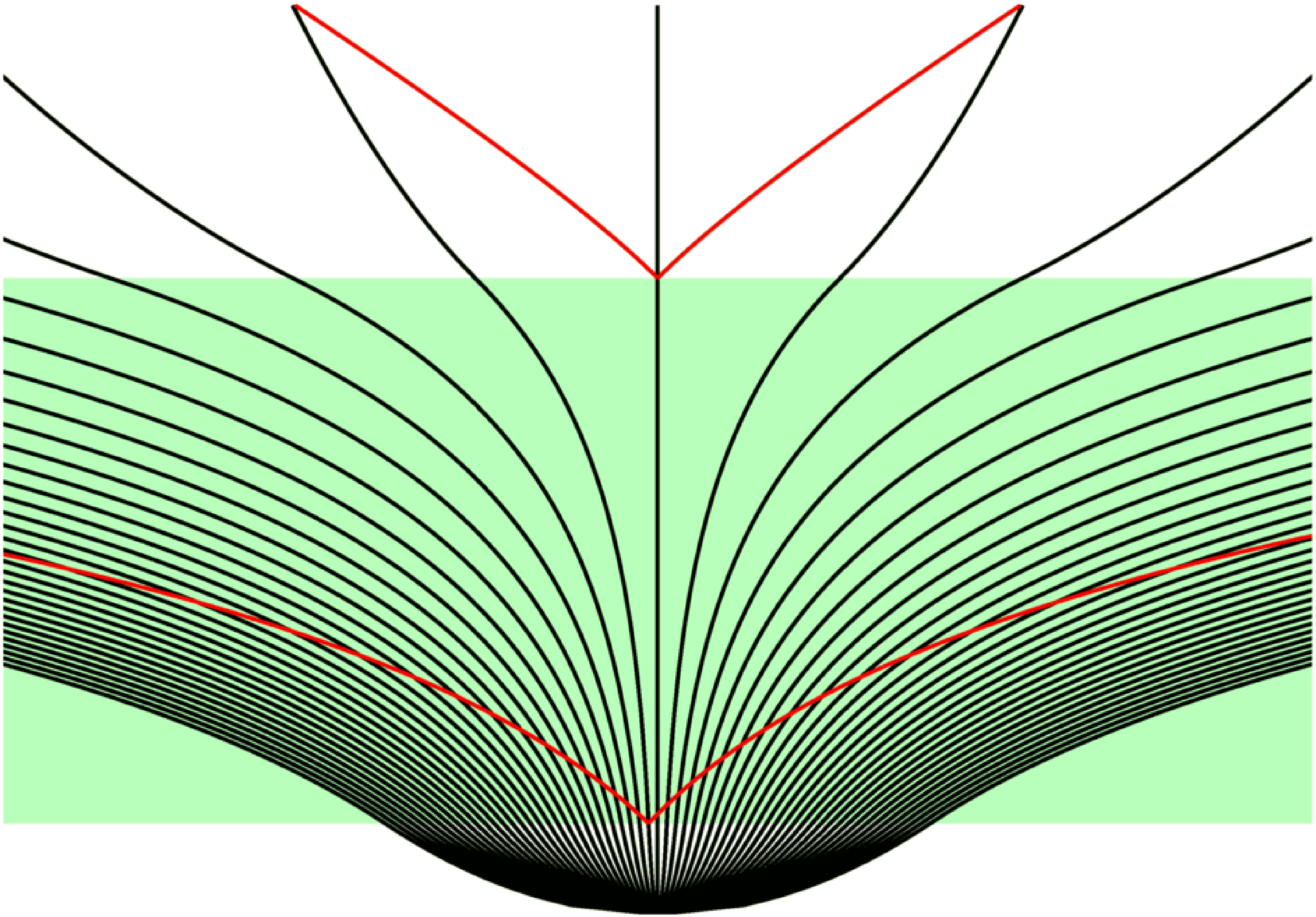
Flatness-Oldness Problem: density must be fine-tuned



Just So?

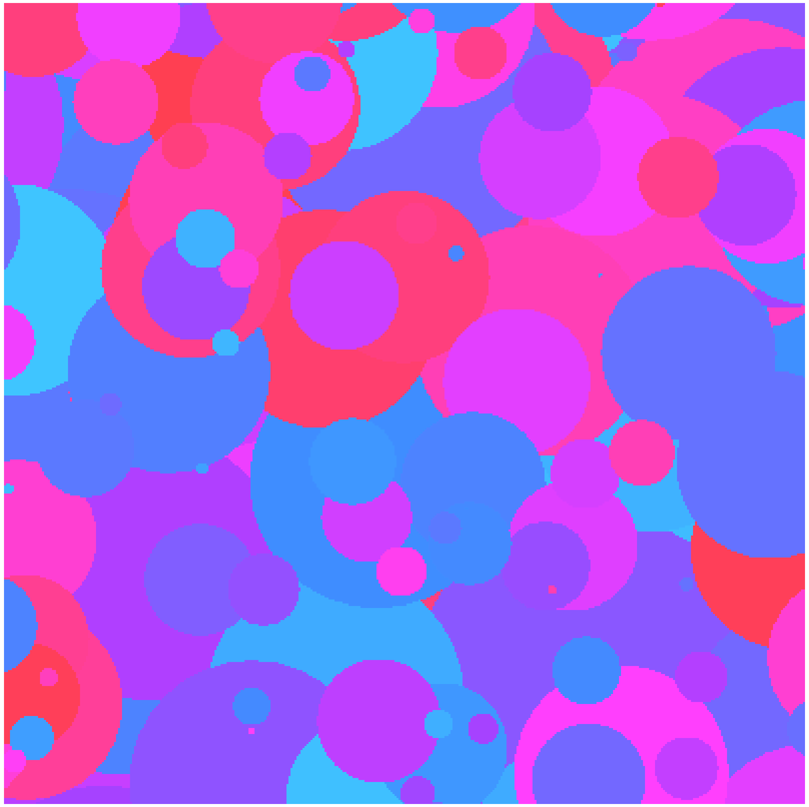

RUDYARD KIPLING
JUST SO
STORIES
ILLUSTRATED BY
BARRY MOSER

Inflation: Large Λ during an early phase

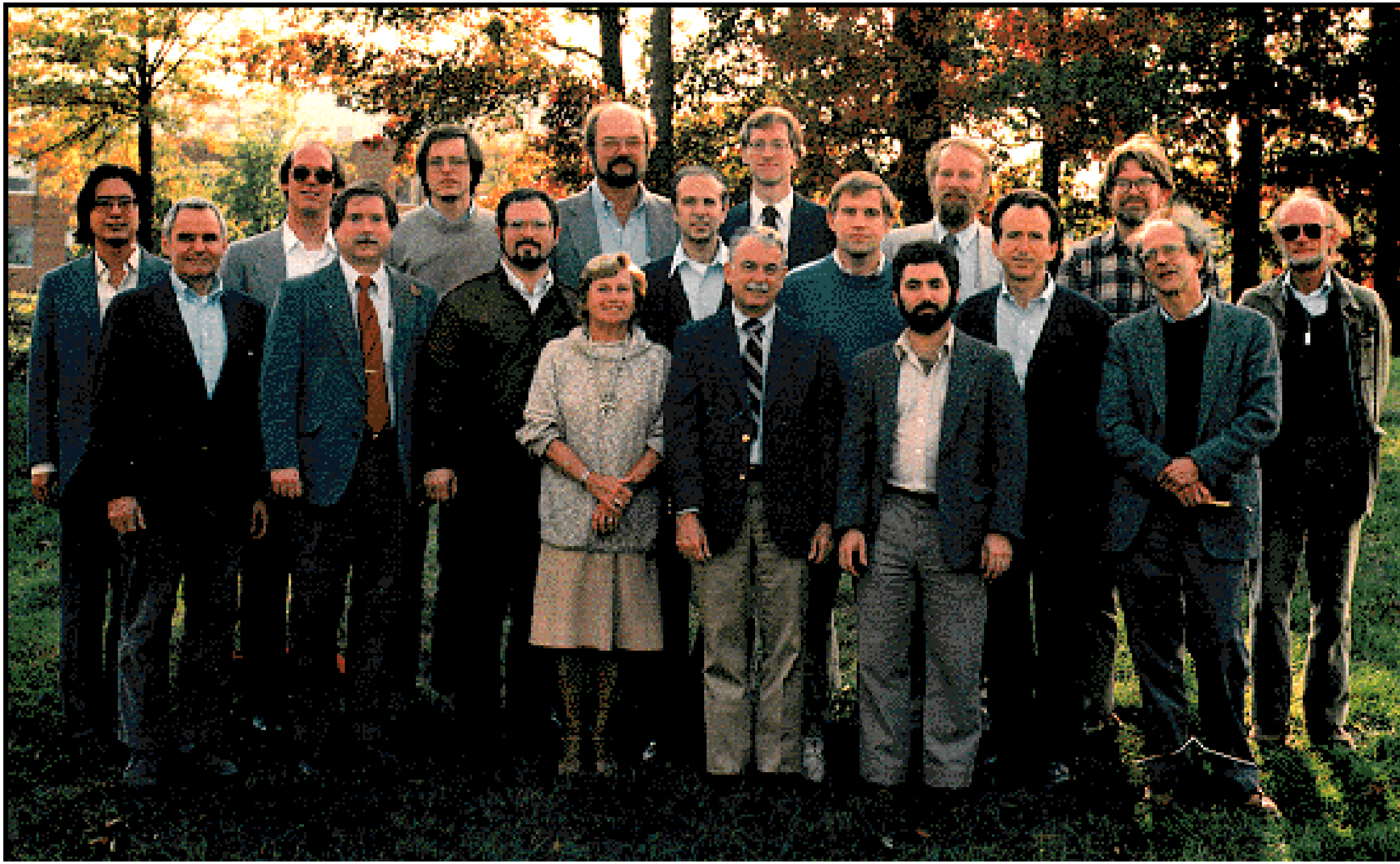


Animated View of Inflation

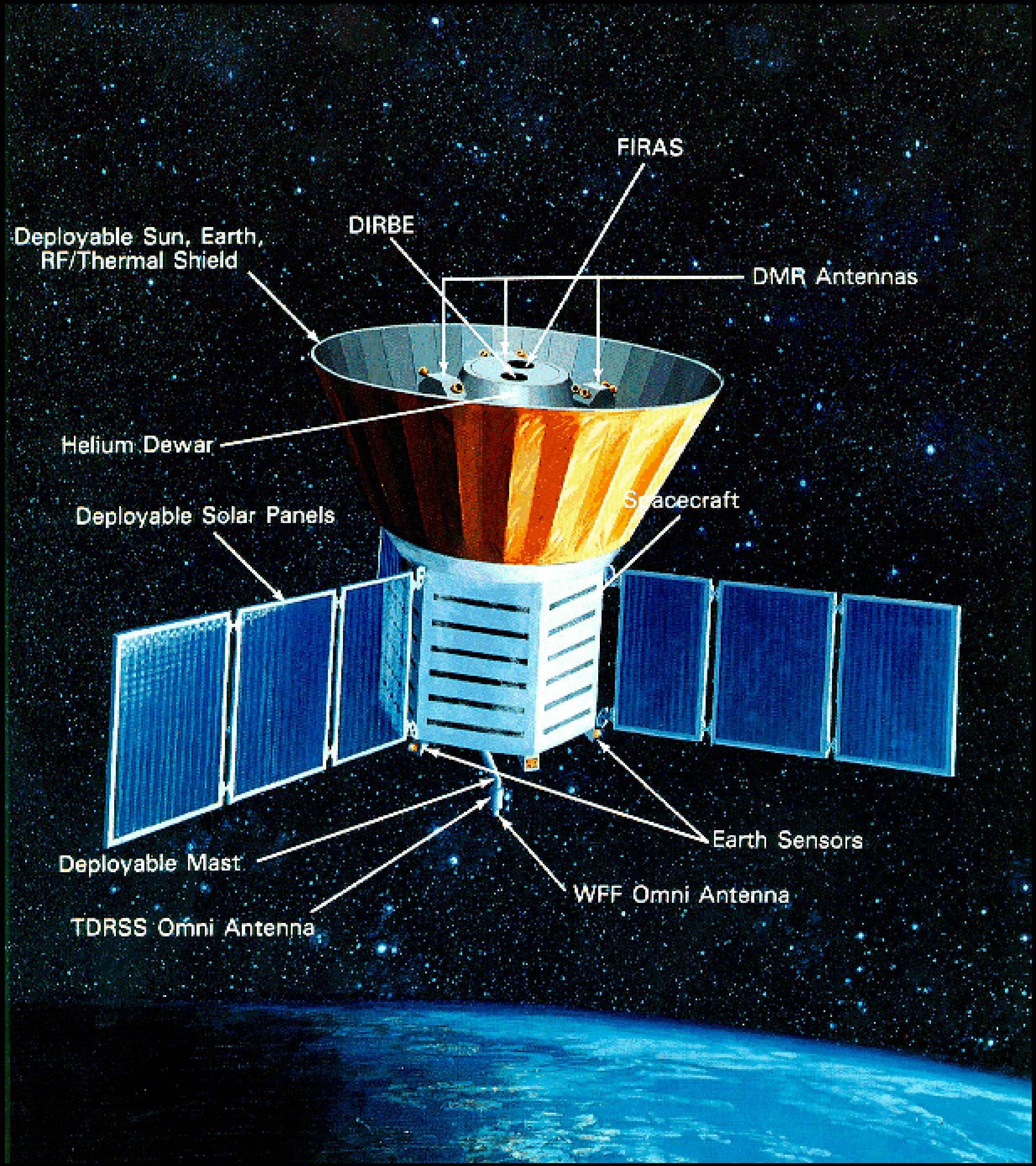
- Quantum fluctuations occur uniformly throughout space-time.
- Future light cones of fluctuations grow making big circles but new fluctuations continuously replenish the small circles.
- Result is Equal Power on All Scales (EPAS).



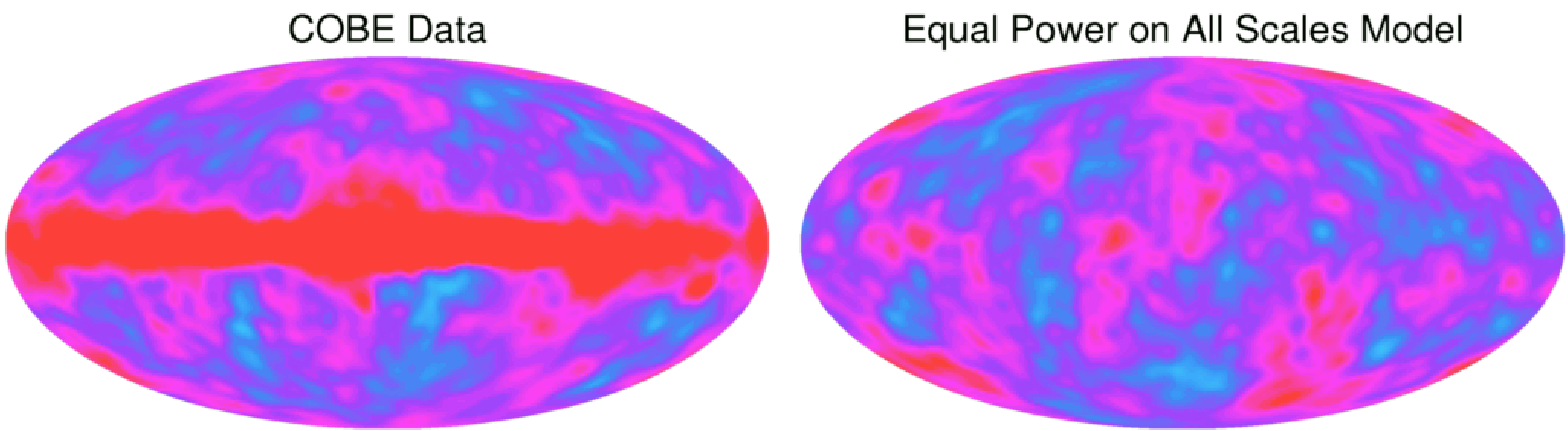
COBE Science Working Group



COBE


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



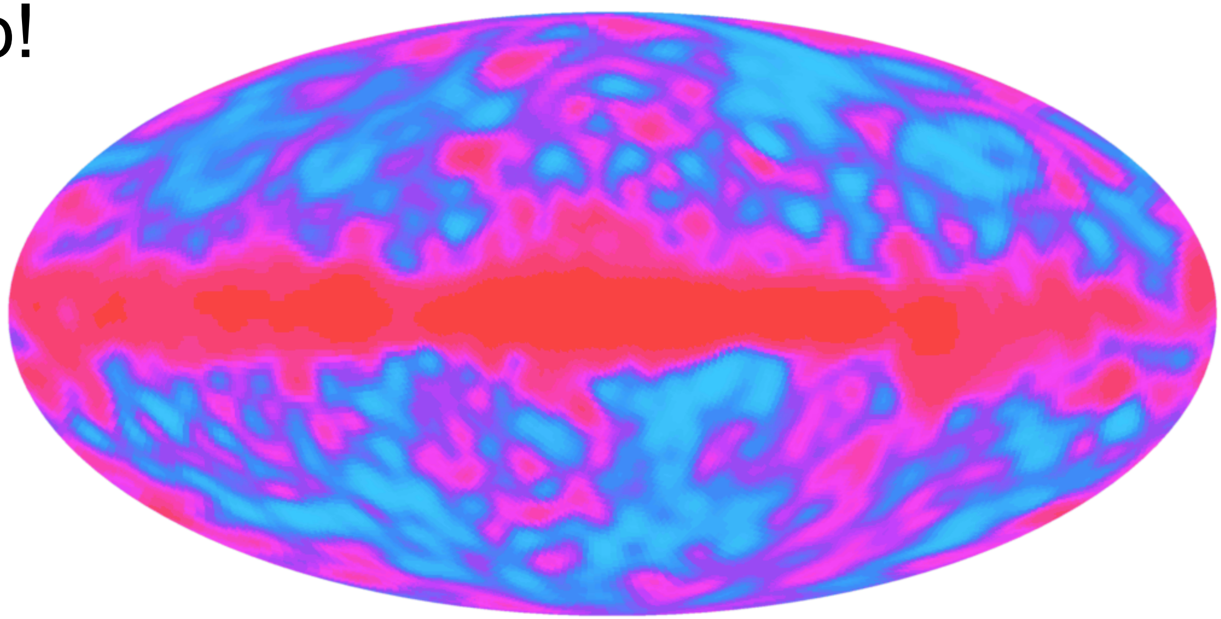
"Chi-by-eye" suggests that the "Equal Power on All Scales" prediction of inflation is correct.

CMB Anisotropy

THE TIMES

25 April 1992

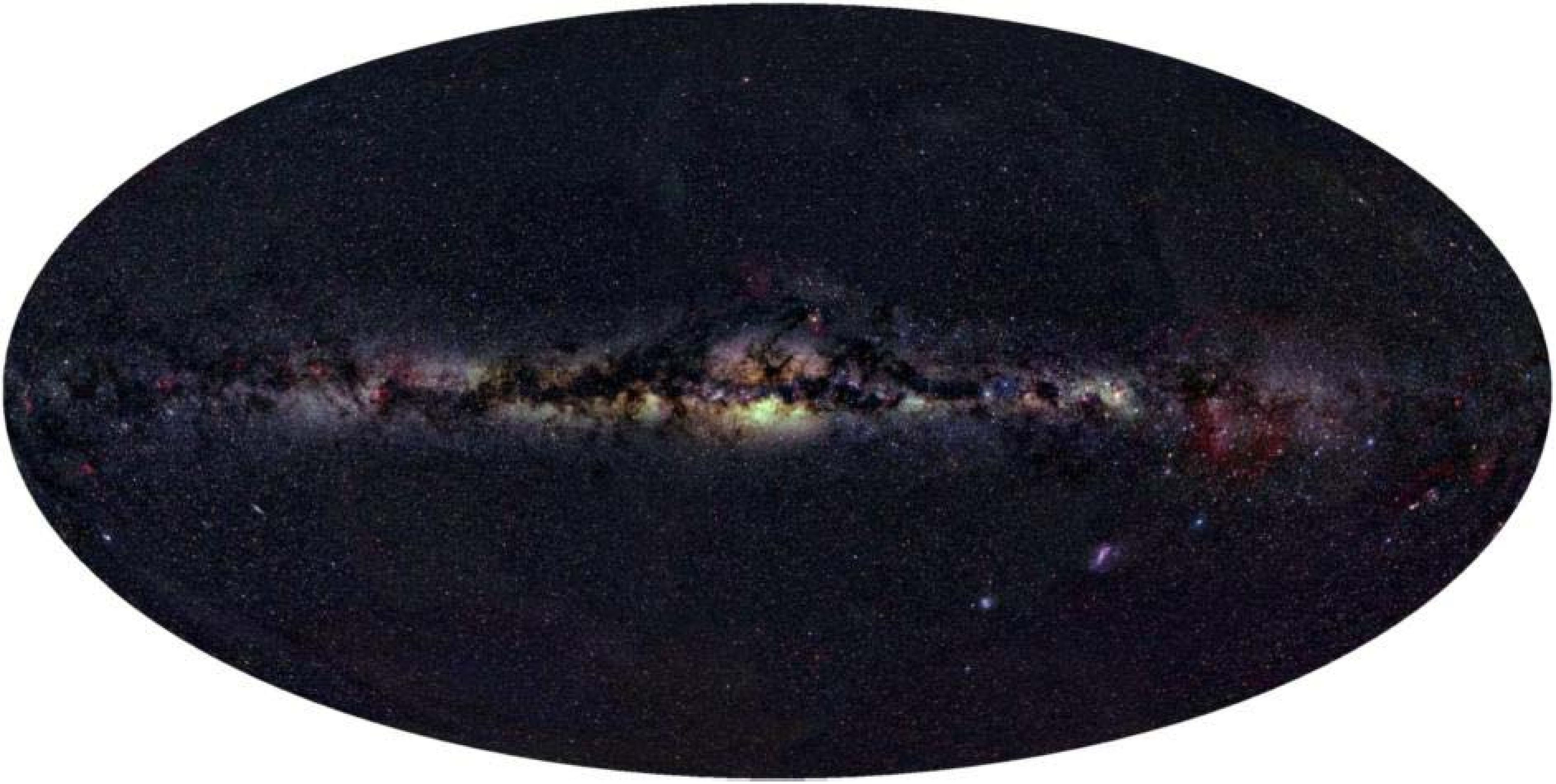
Prof. Stephen Hawking of Cambridge University, not usually noted for overstatement, said: “It is the discovery of the century, if not of all time.” – What a blurb!



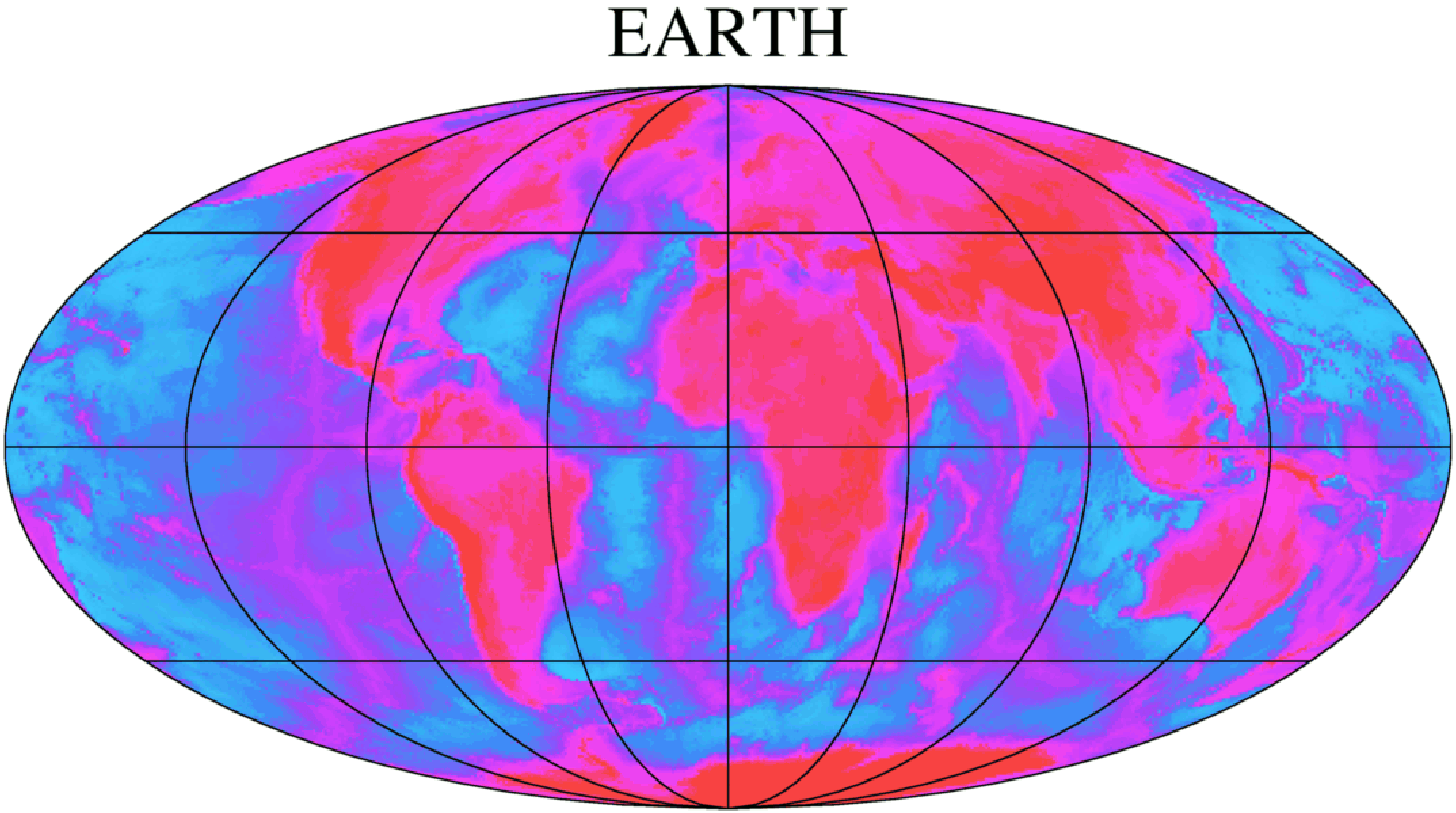
Mather & Smoot win the 2006 Physics Nobel prize

"You may have already won the Nobel Prize...."

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



An equal area projection:



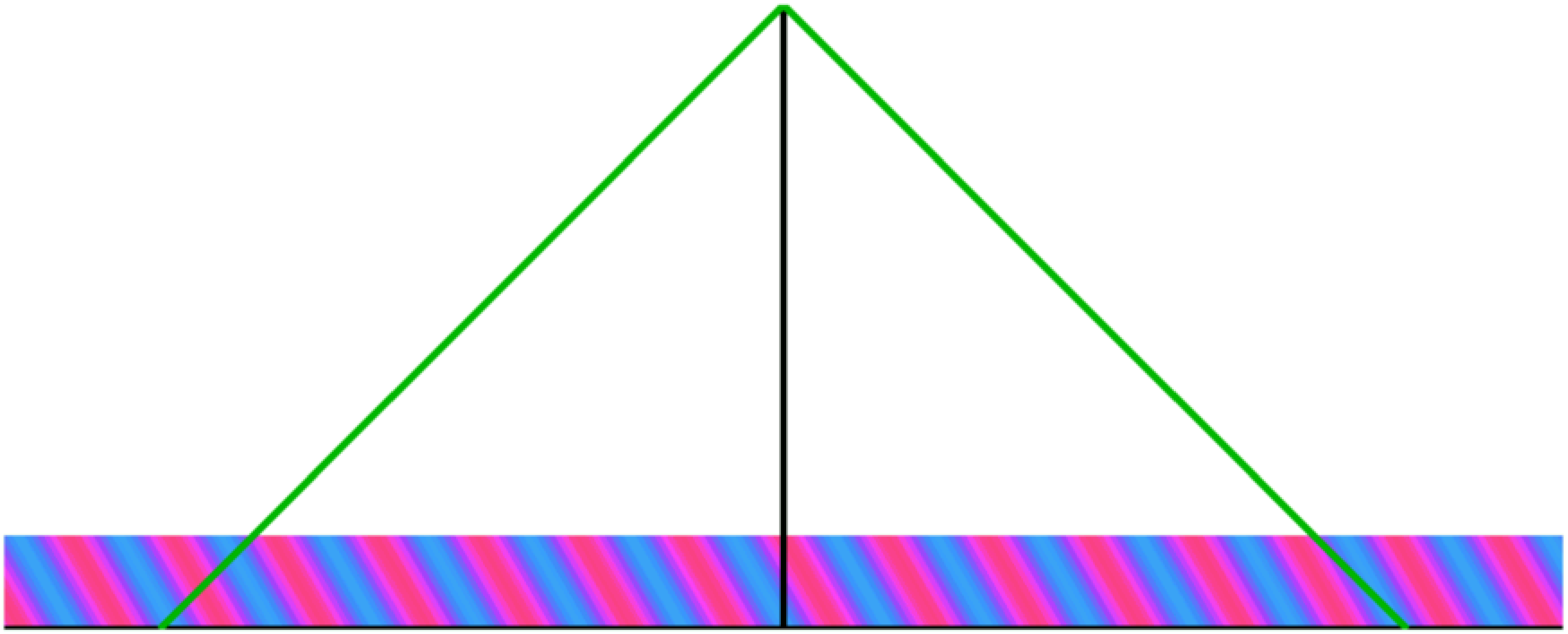
Color Means Temperature

- 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!

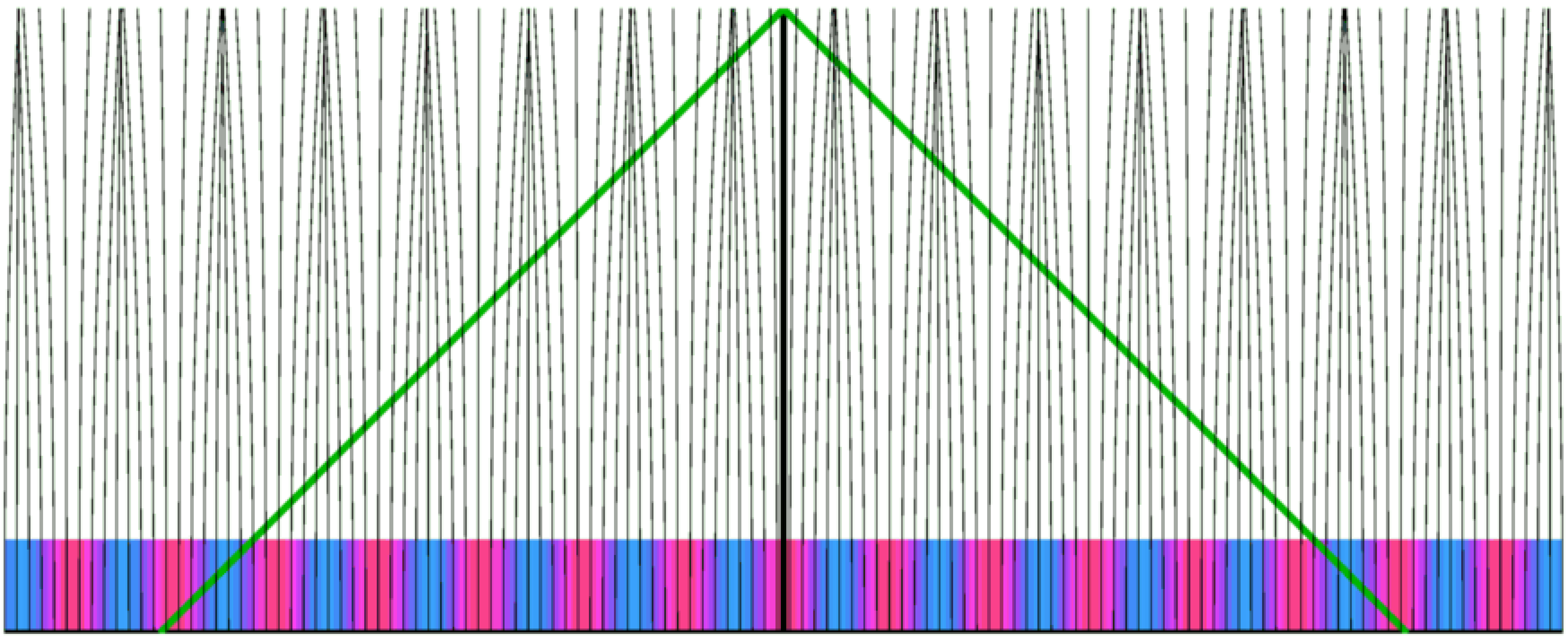
Two Fluids in the Early Universe

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

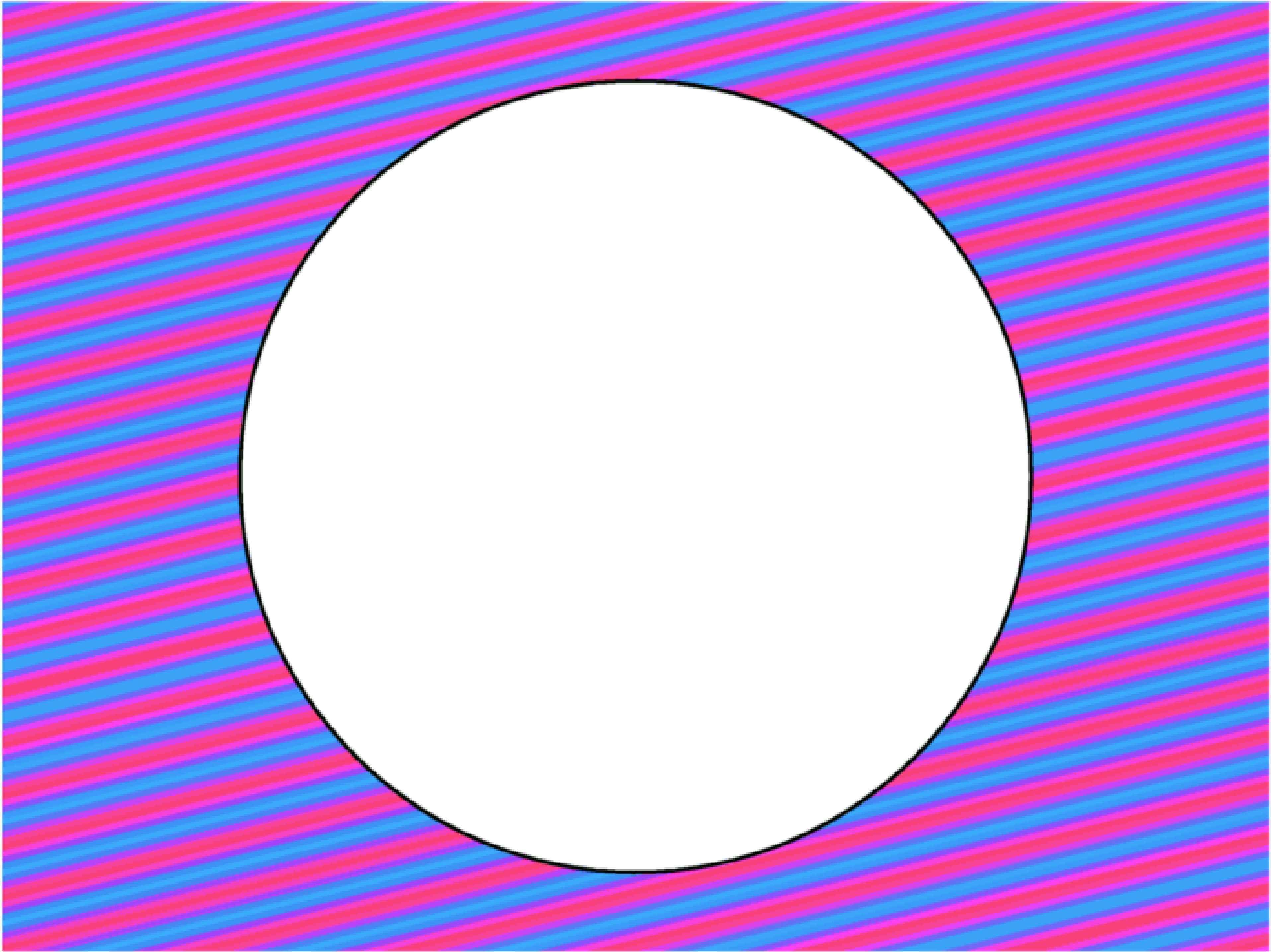


Stay at home Dark Matter

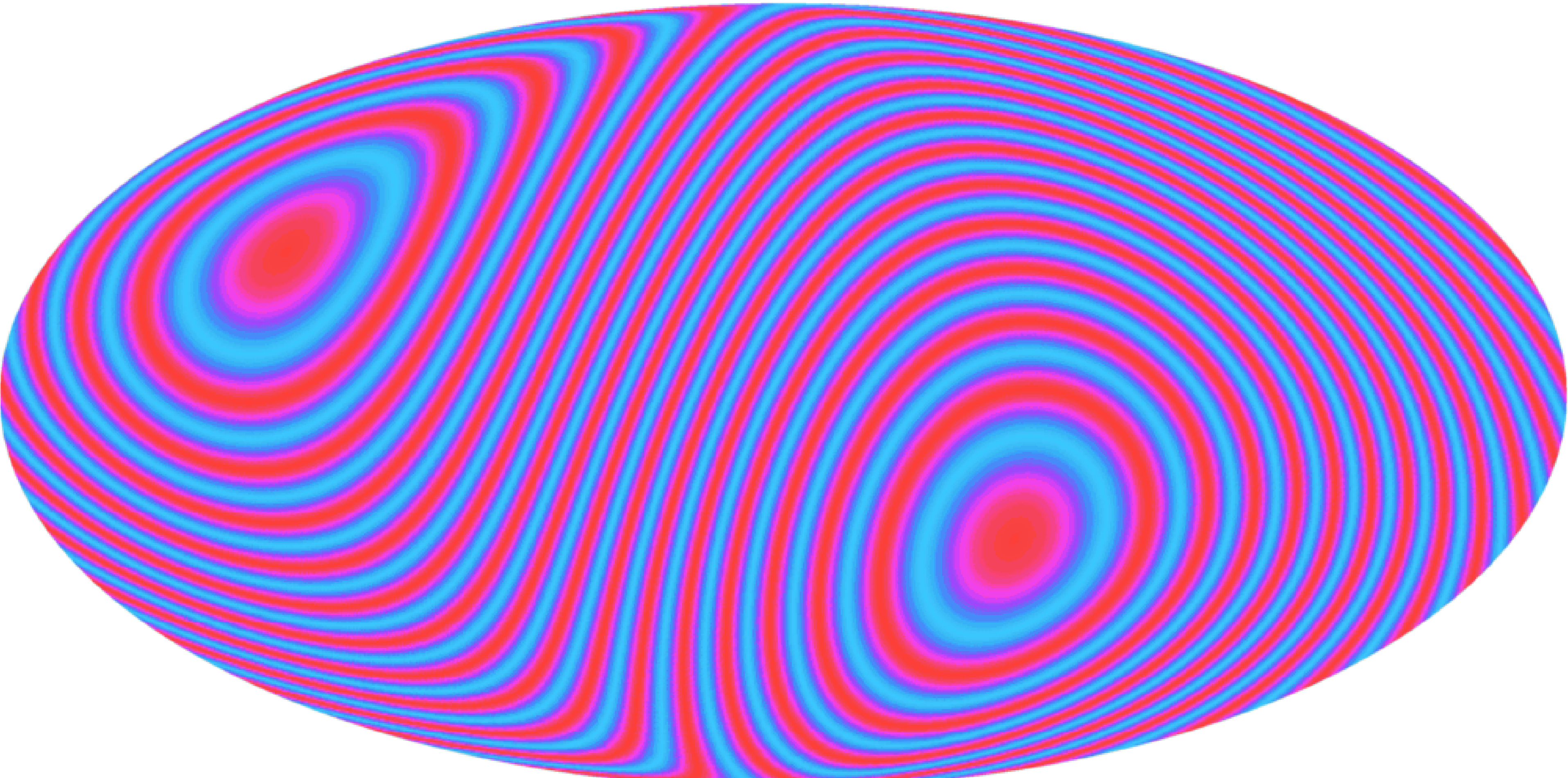


Interference at last scattering

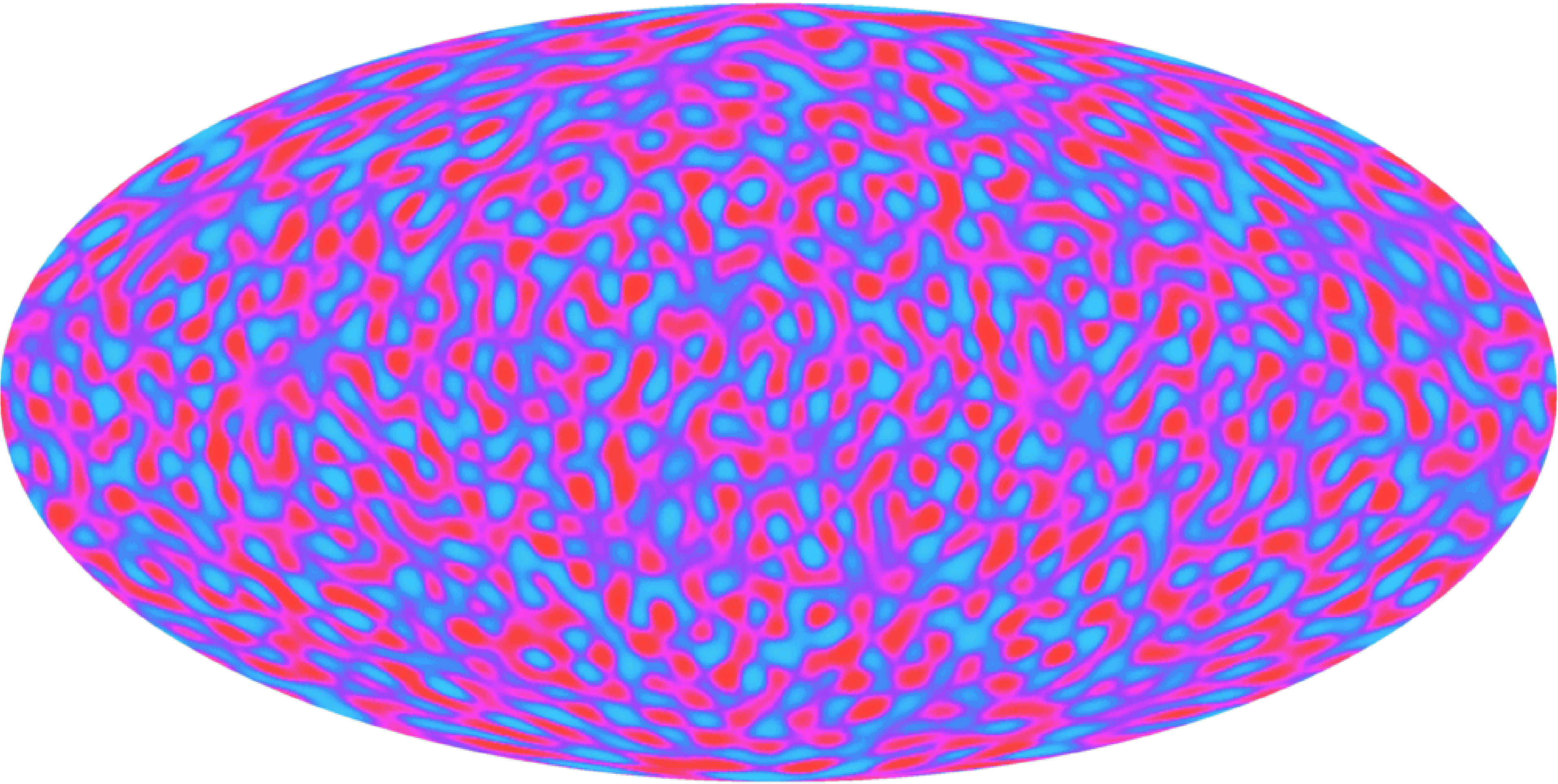
- For the wavelength illustrated [1/2 period between the Big Bang and recombination], the denser = hotter effect and potential well = cooler effect have gotten in phase.
- For larger wavelengths they are still out of phase at recombination.



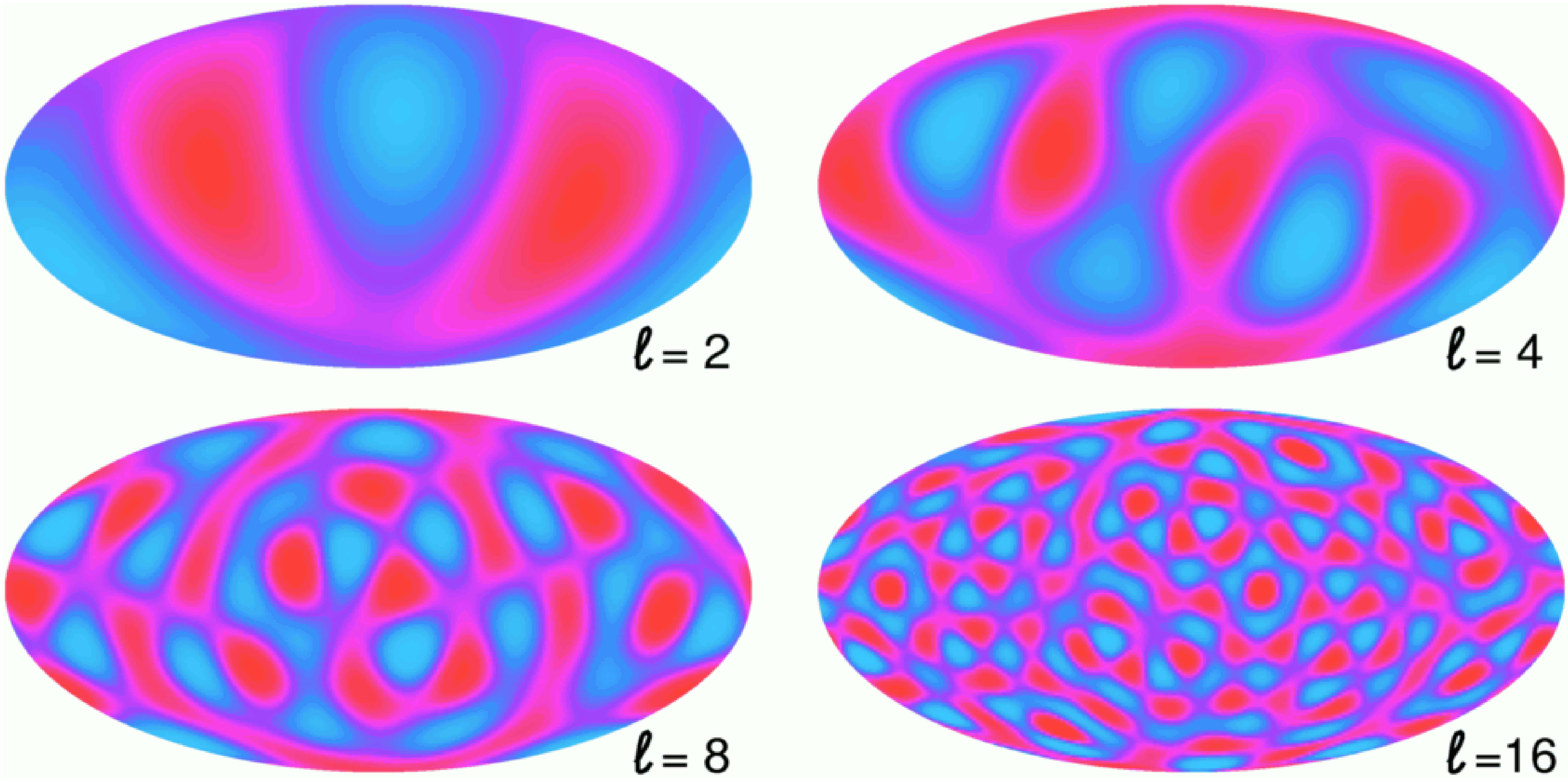
k*Rls = 50 plane wave



99 k*Rls=50 plane waves

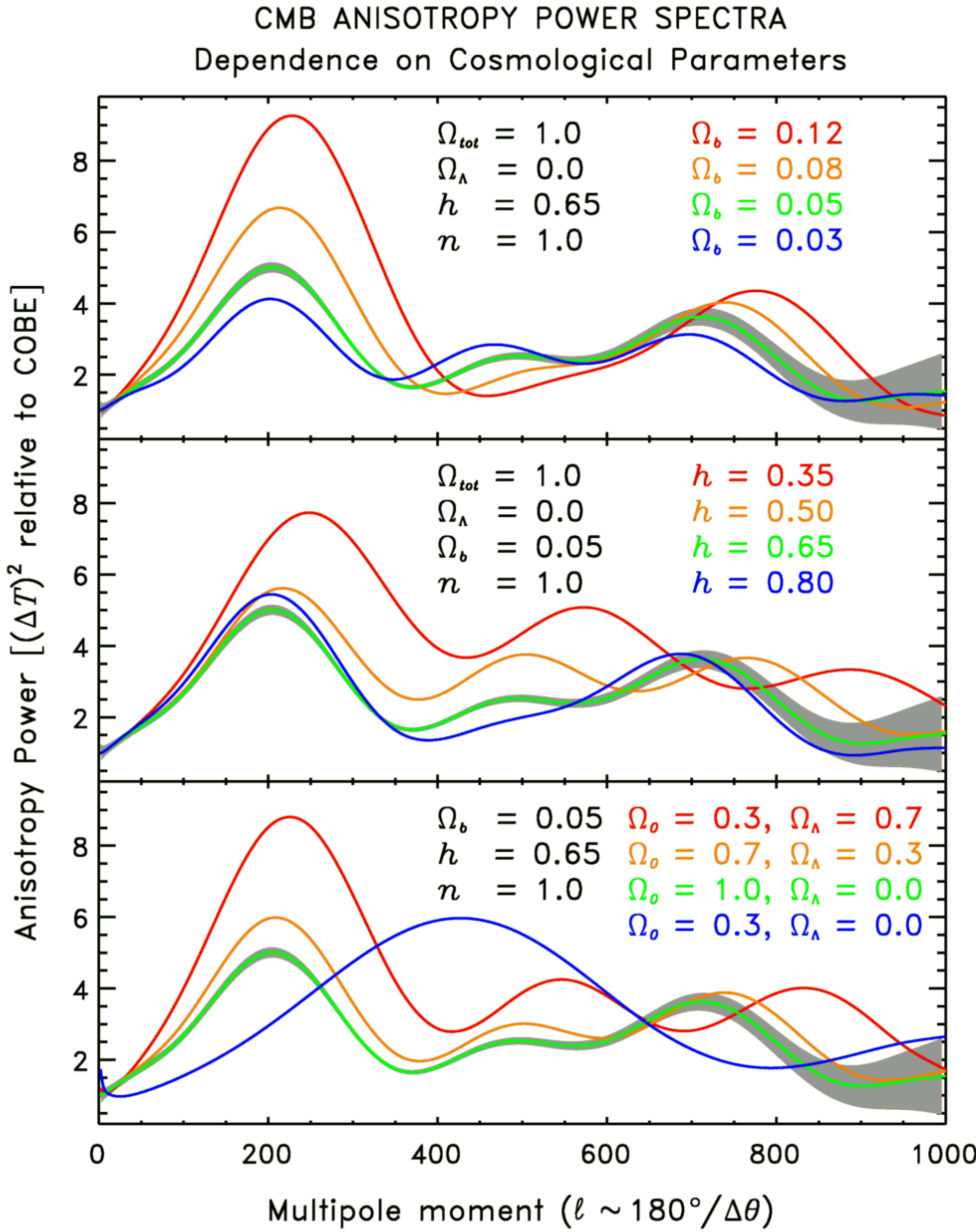


Spherical Harmonic Decomposition



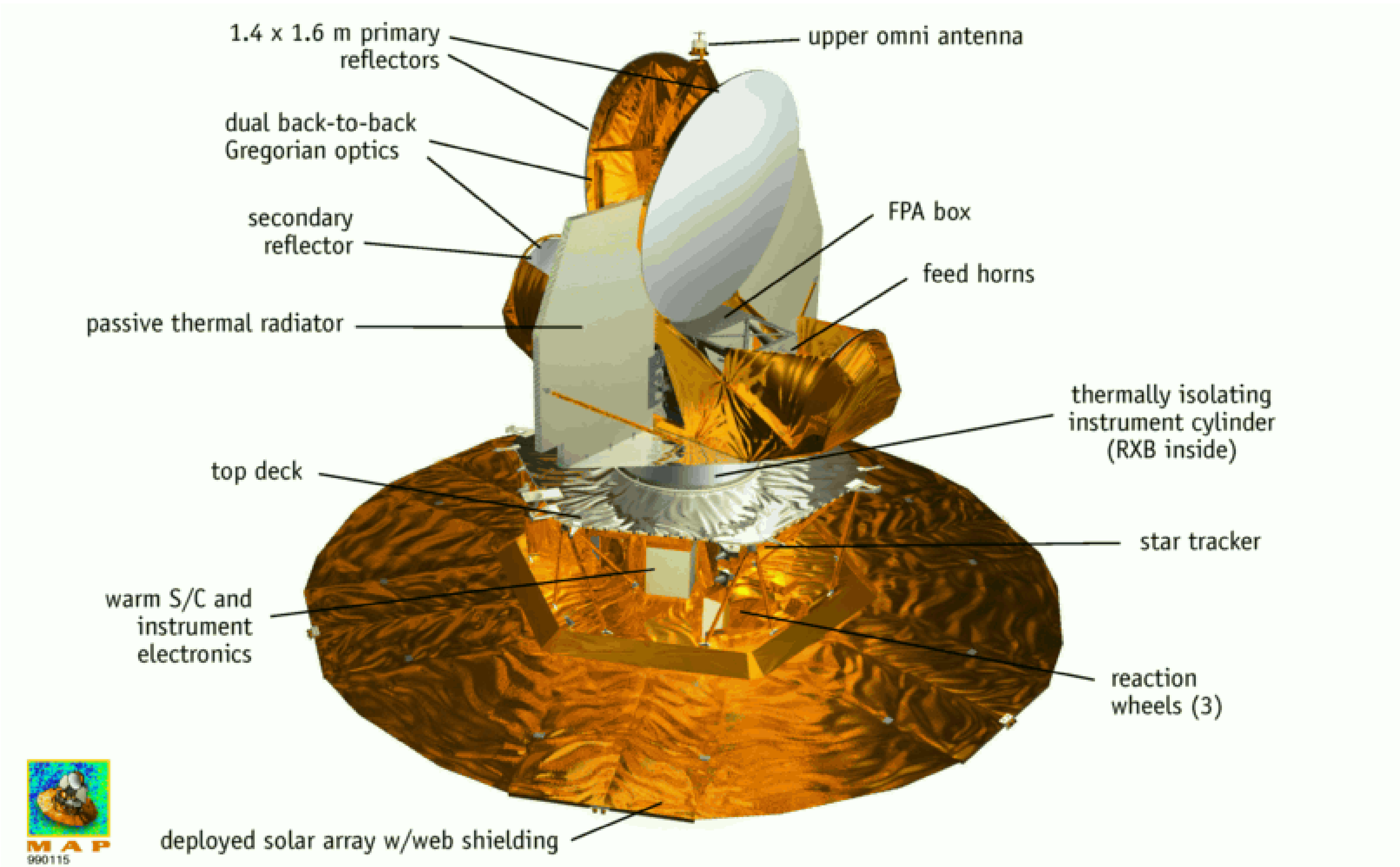
Many parameters to measure

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

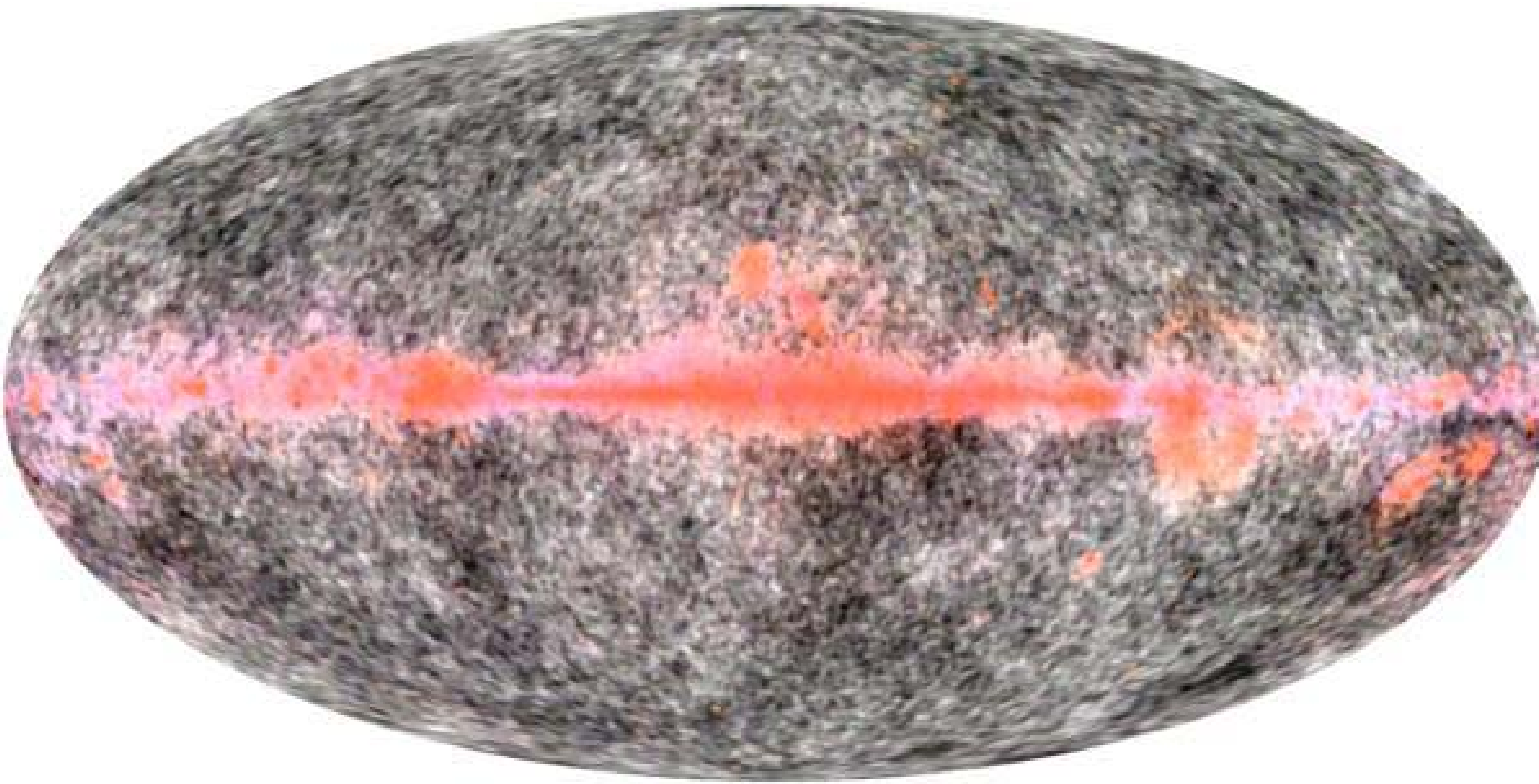


WMAP Science Working Group

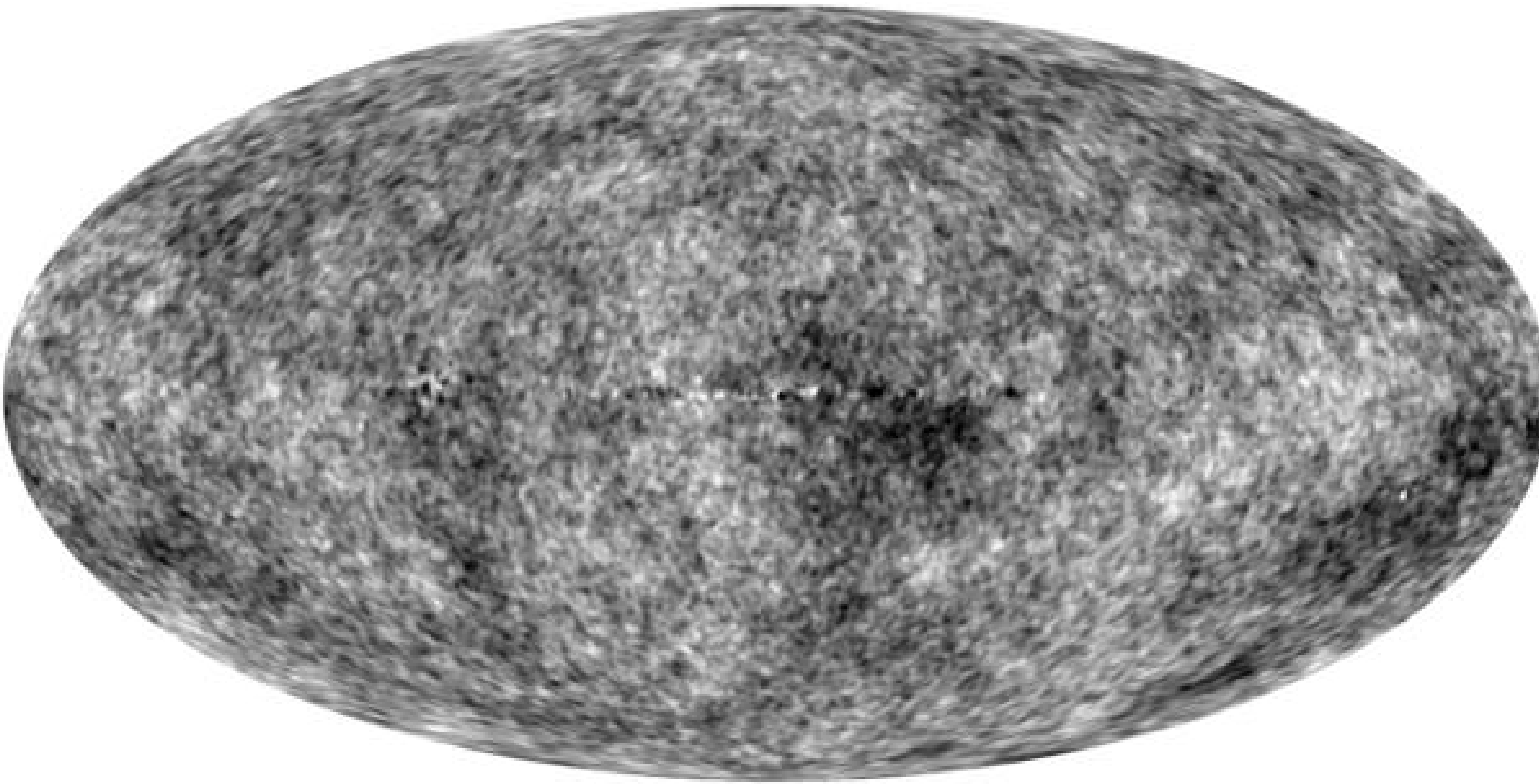
A New Cosmology Satellite



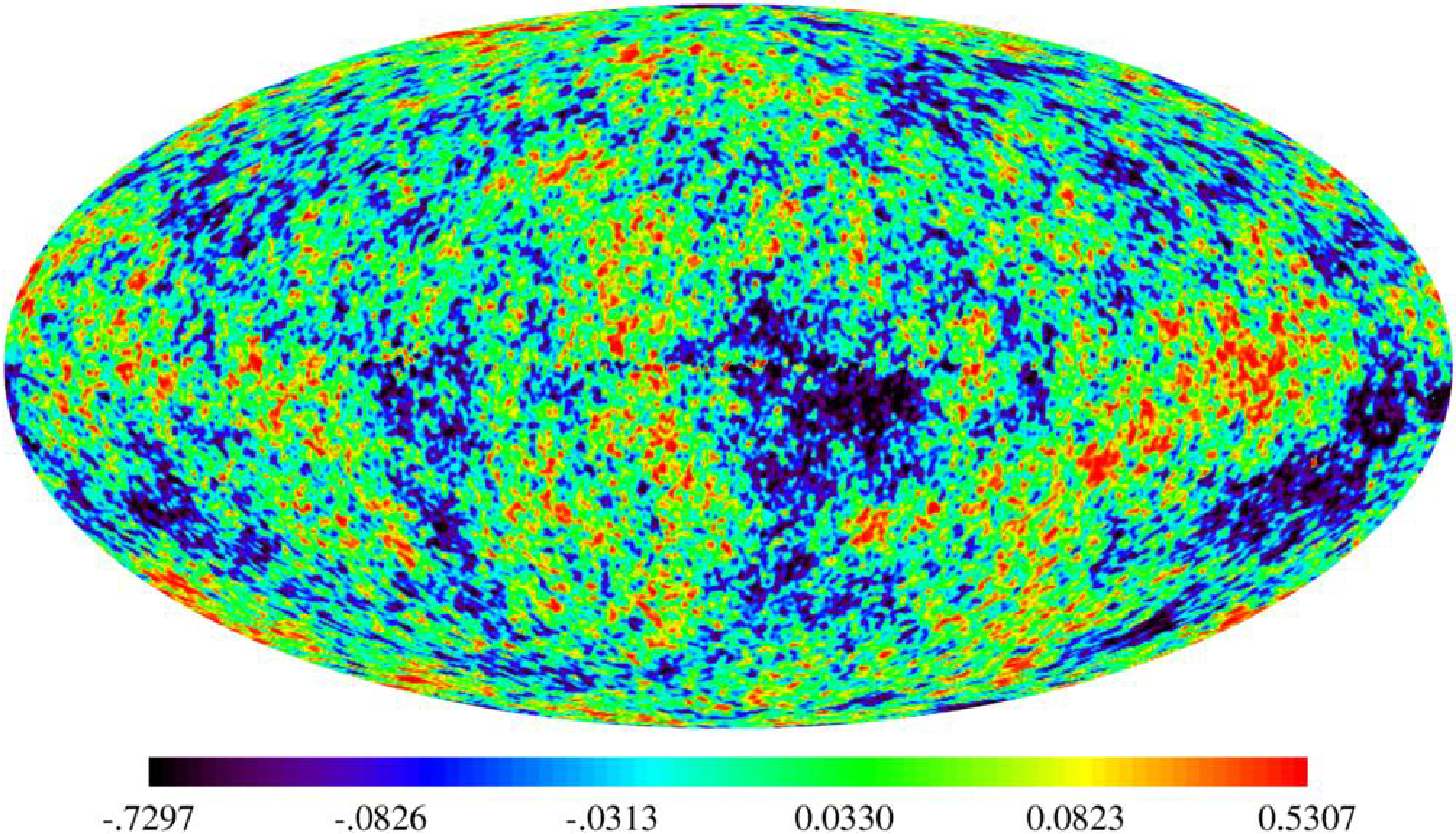
WMAP 7, 5 & 3 mm data as RGB



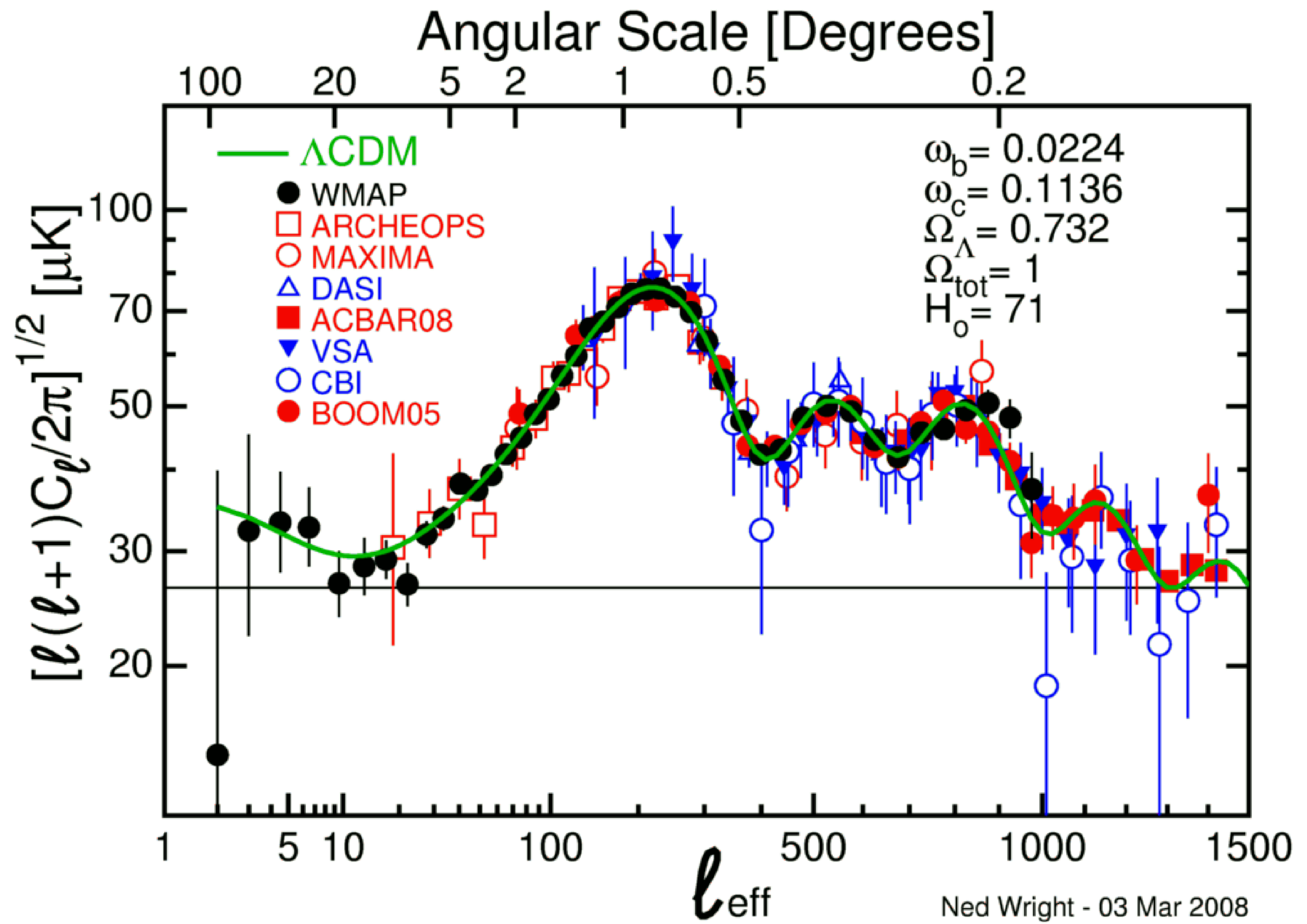
Combine maps to subtract galaxy



WMAP 5 year Data Released March 5



- Contrast enhanced by 12,500 times



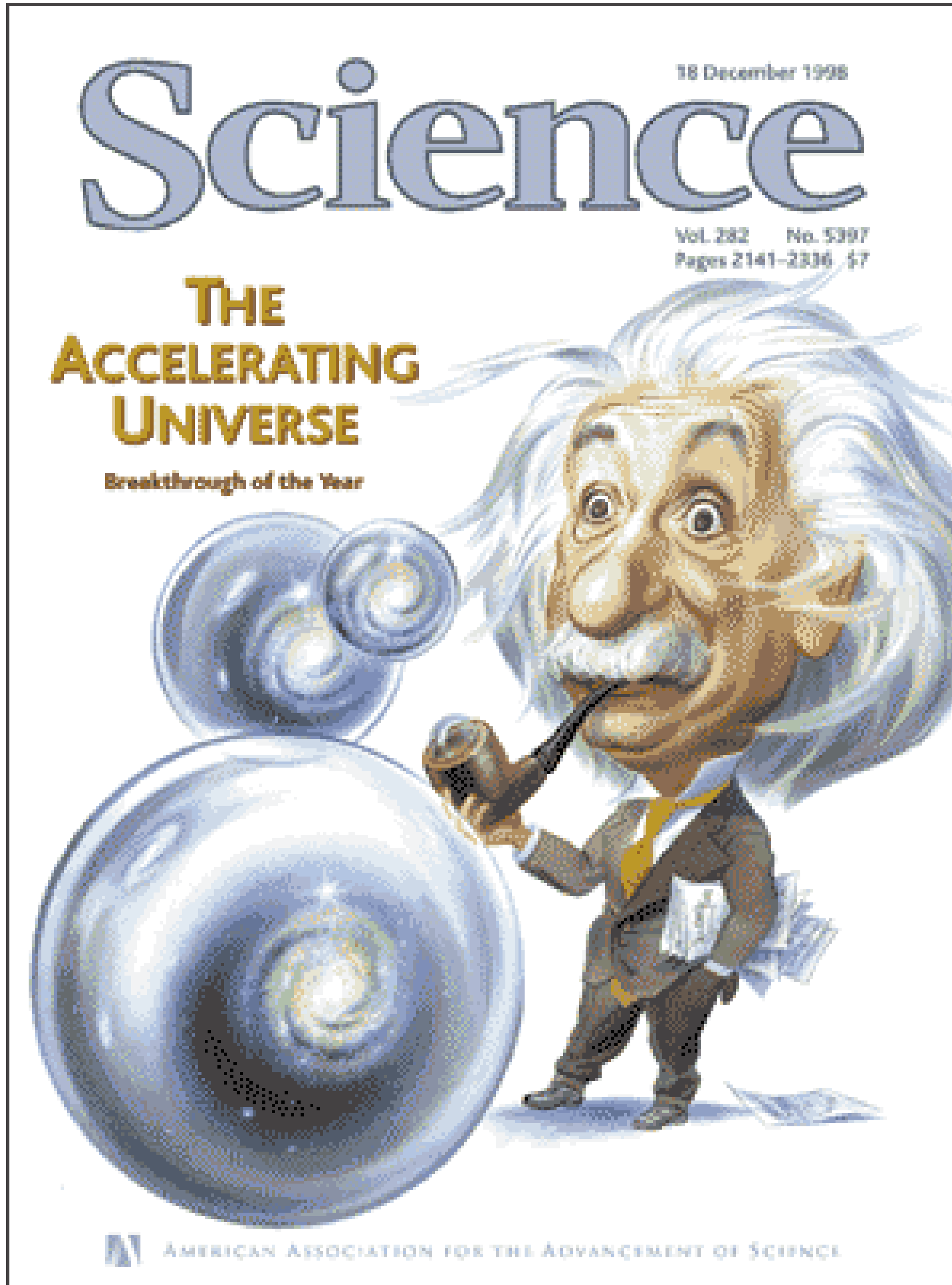
Angular Scale [Degrees]
100
20
5
2
1
0.5
0.2
ΛCDM
WMAP
ARCHEOPS
MAXIMA
DASI
ACBAR08
VSA
CBI
BOOM05
$\omega_b = 0.0224$
$\omega_c = 0.1136$
$\Omega_\Lambda = 0.732$
$\Omega_{tot} = 1$
$H_o = 71$
$[\ell(\ell+1)C_\ell/2\pi]^{1/2}$ [μK]
100
70
50
30
20
1
5
10
100
500
1000
1500
ℓ_{eff}
Ned Wright - 03 Mar 2008

Accelerating Universe: 1998

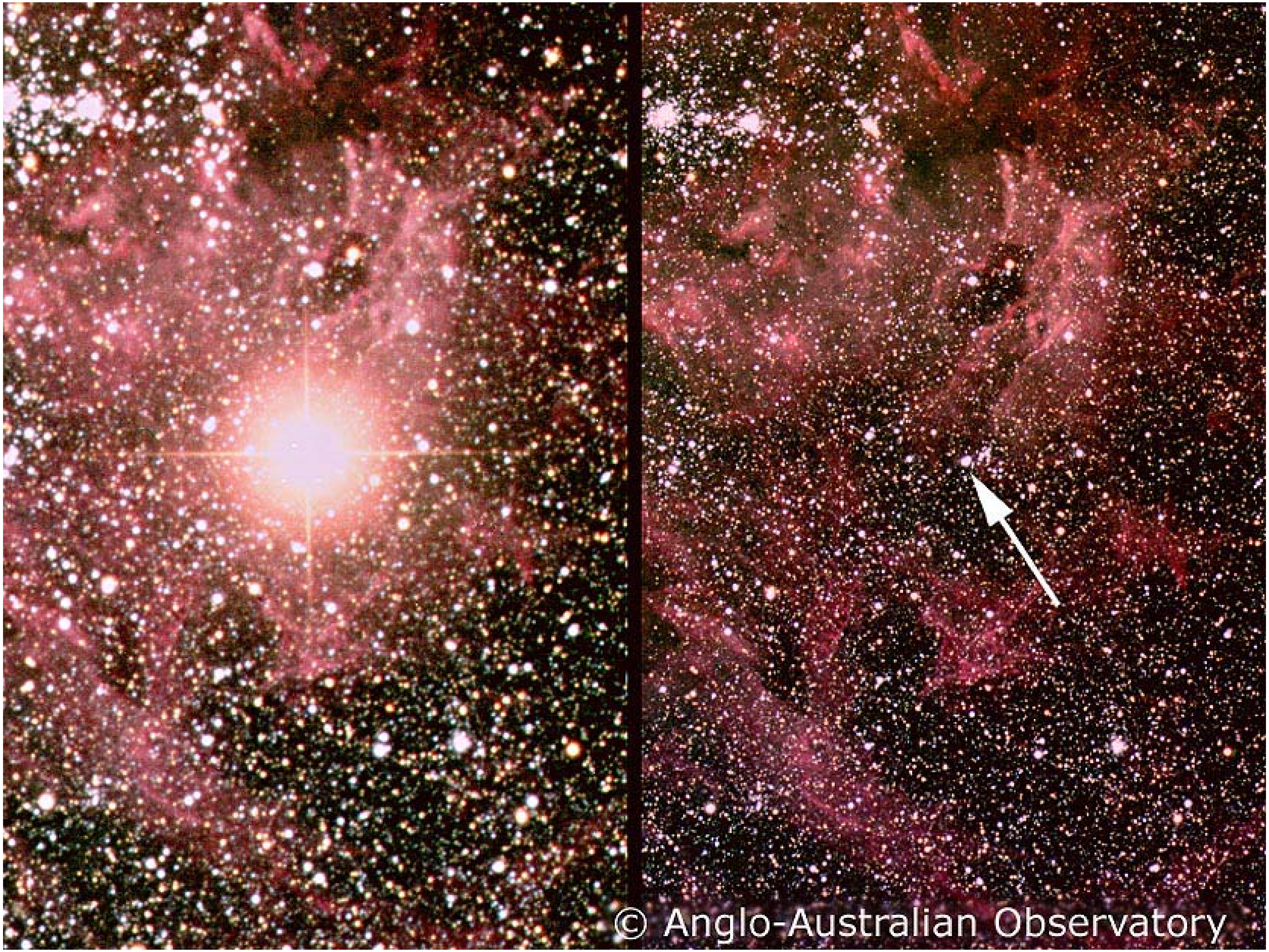
Distant (high z) supernovae fainter than expected.

This was the AAAS discovery of the year in 1998.

Λ causes acceleration!

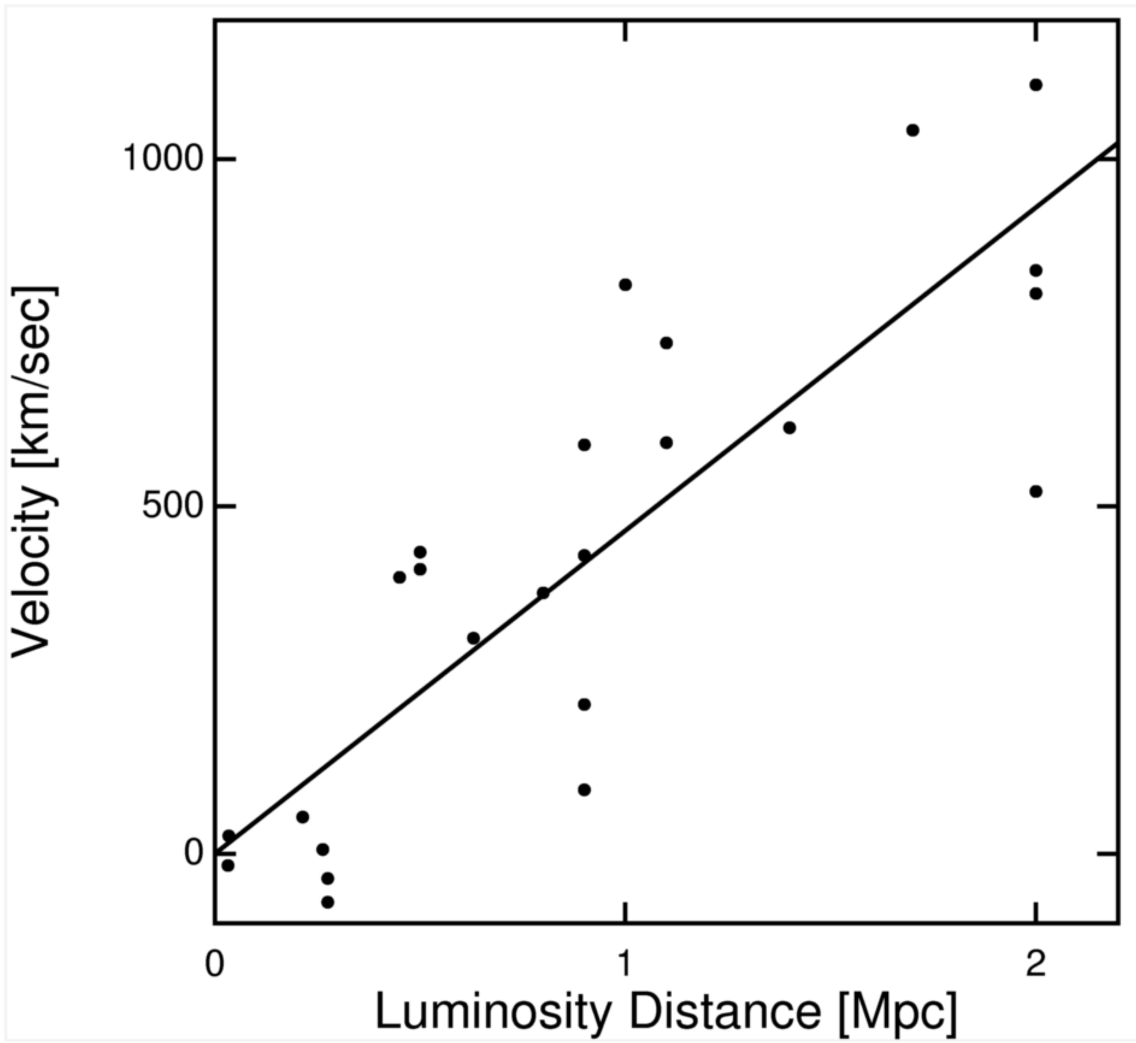


What is a supernova?

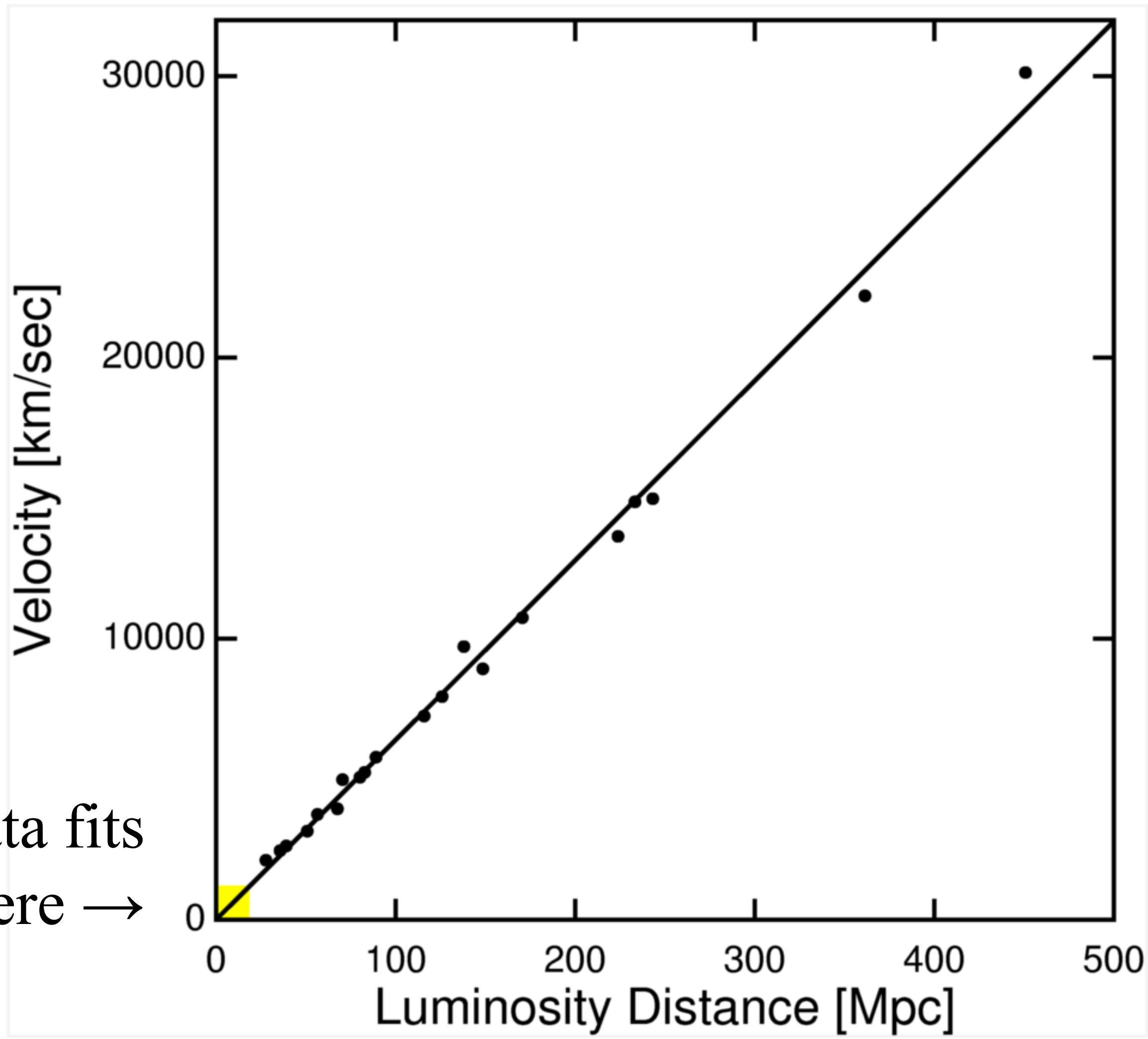


We recently learned how to read the "wattage" label on supernovae:

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

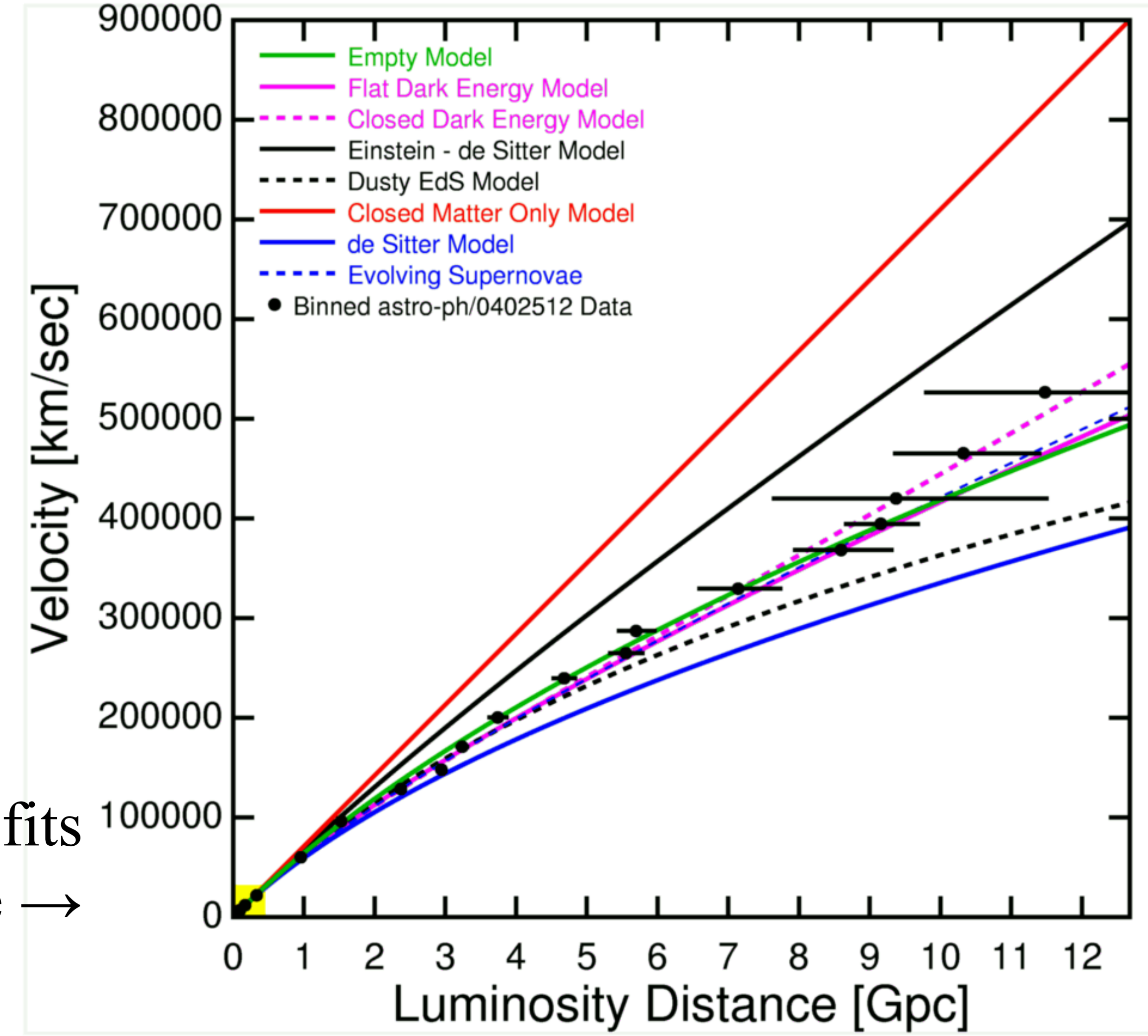


As a result, data on velocity vs distance is now much better! 1995



1929 data fits
in here →

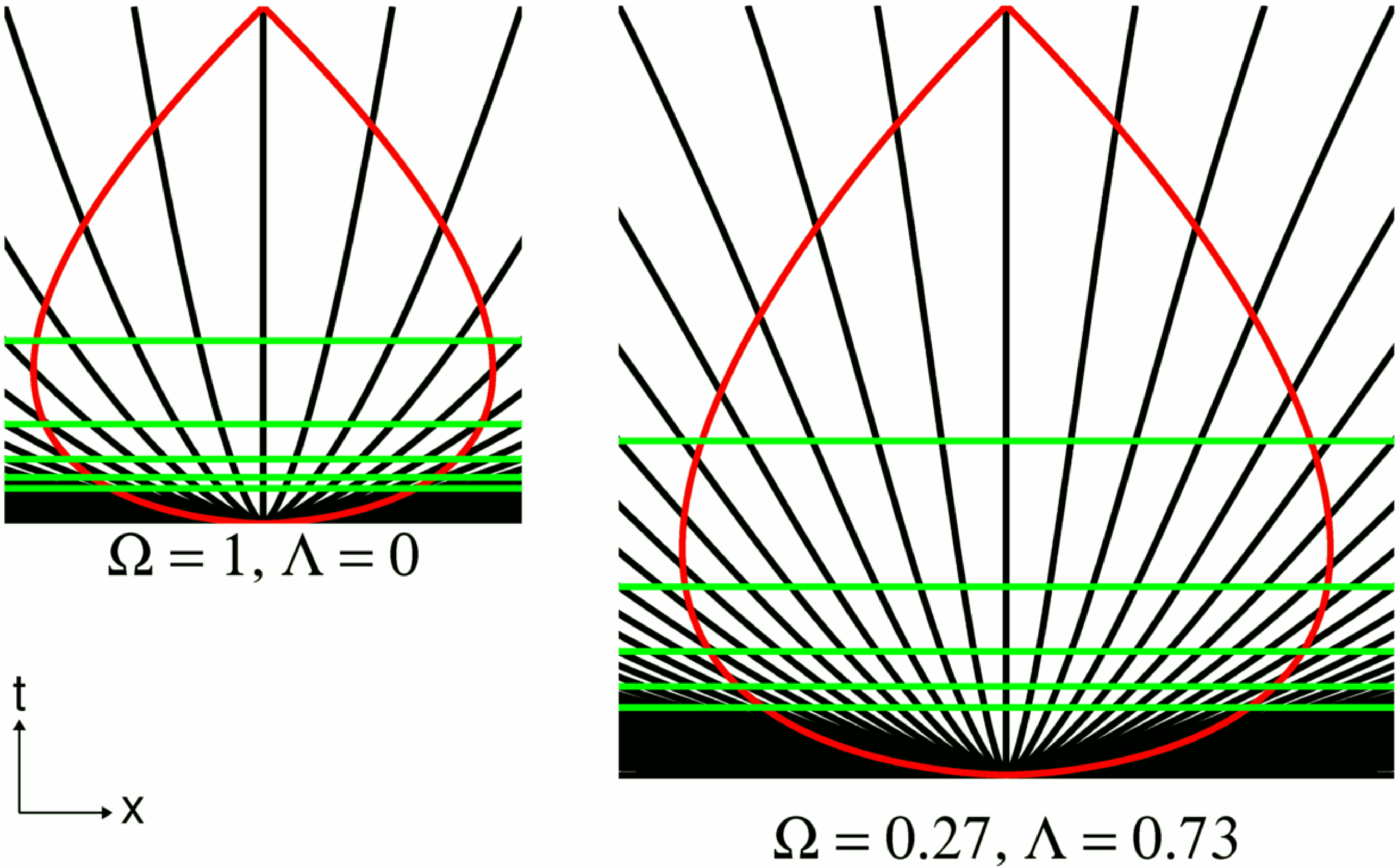
As a result, data on velocity vs distance is now much better! 2004



1995 data fits in here →

$v = cz$

Acceleration causes Faintness

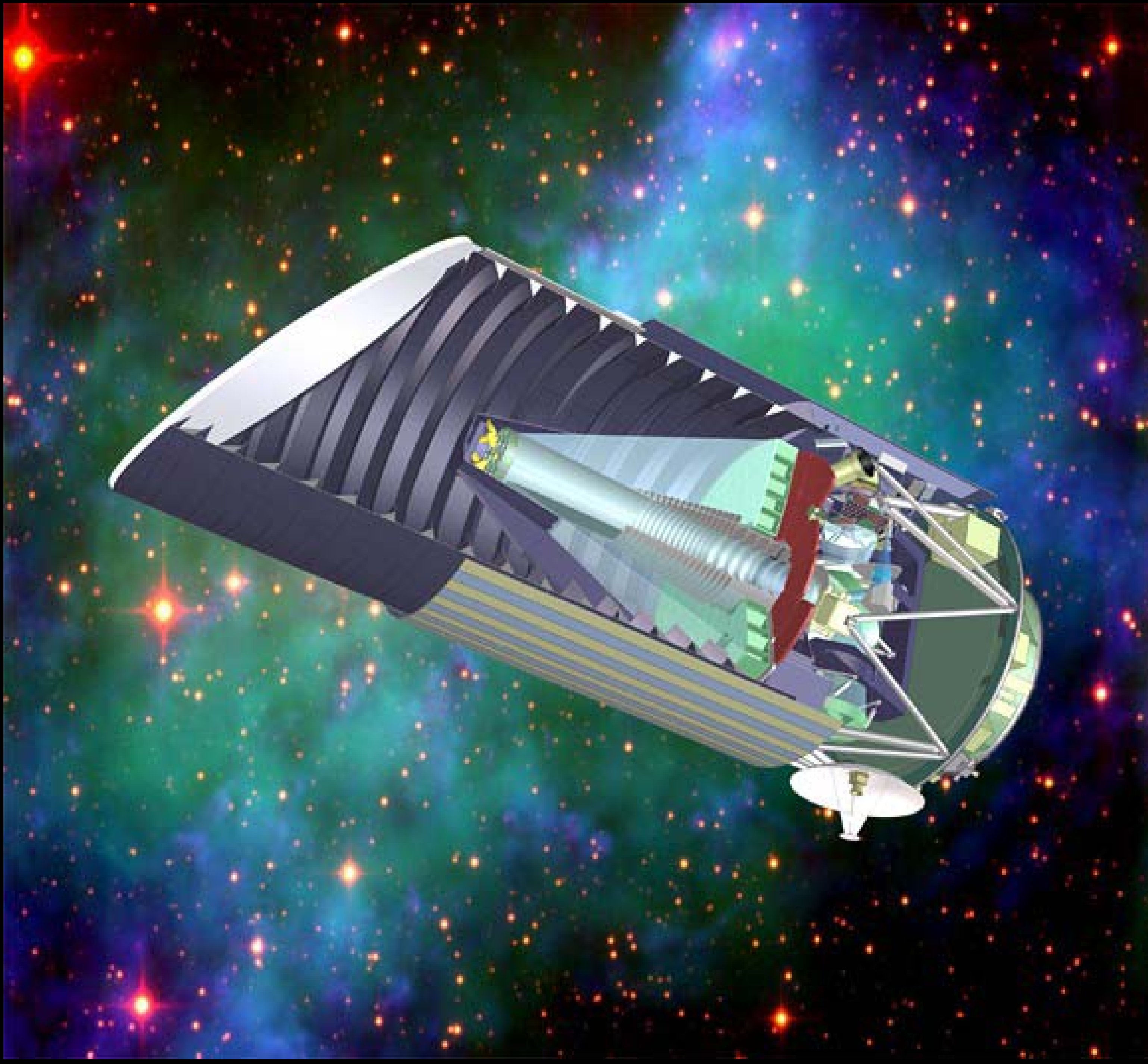


Is Λ really a *CONSTANT*?

- 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.

JDEM
in 10
years?

NASA
needs
$$$

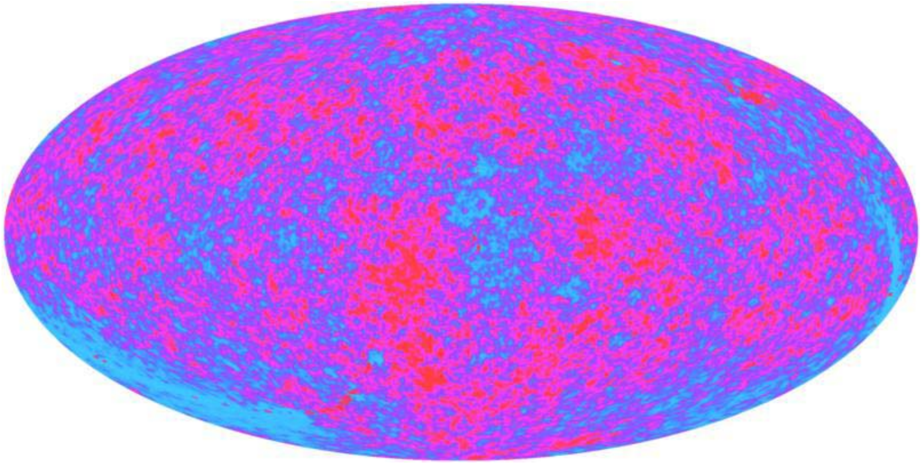


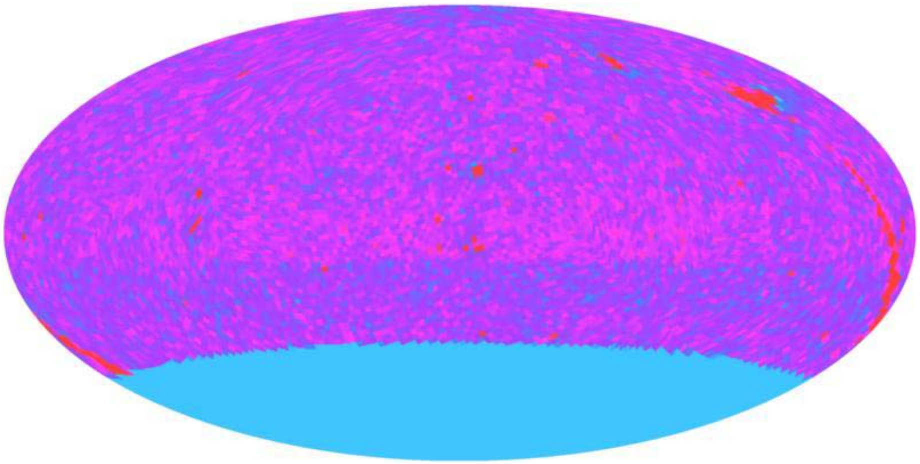
Same Laws of Physics?

- 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.

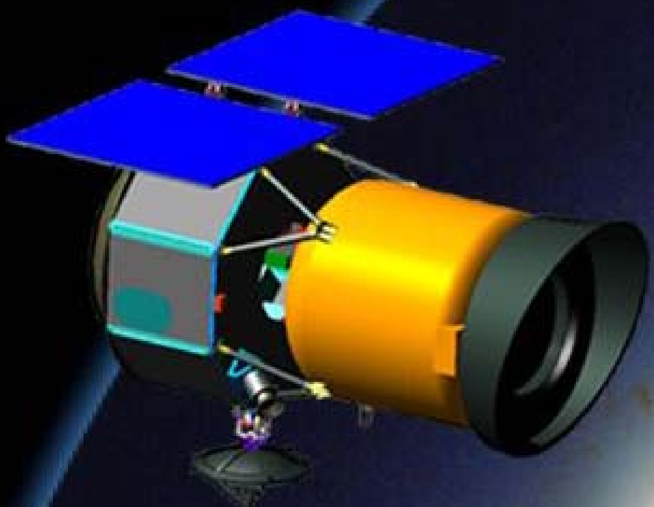
Λ Confirmed by CMB & IR maps

- 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 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.

Something really funny

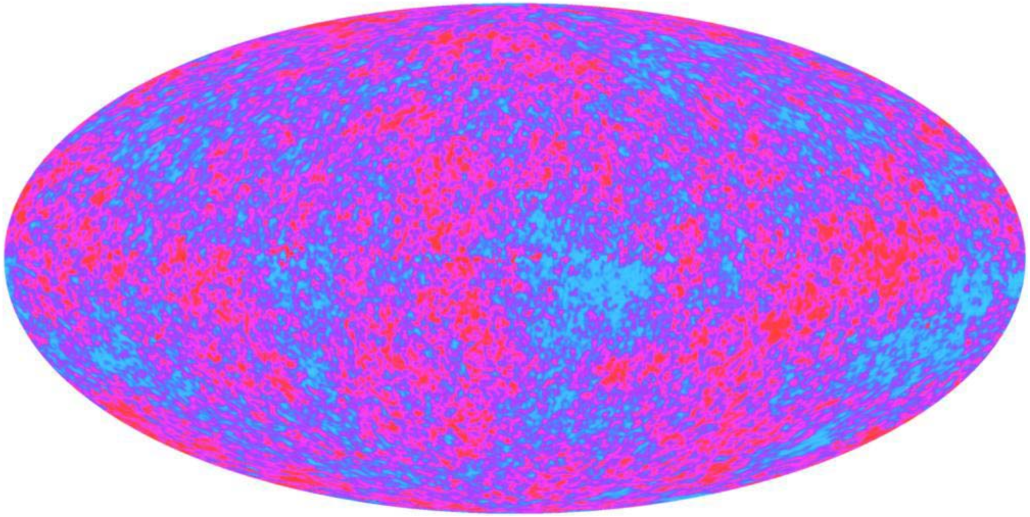
- Cosmology Marches On - a Sydney Harris cartoon
  - The caveman looks up at the dark night sky and wonders “Where the hell did it all come from?”
  - The modern astronomer sits in his office, ignoring his big telescope, and wonders “Where the hell did it all come from?”

“Nothing” really funny

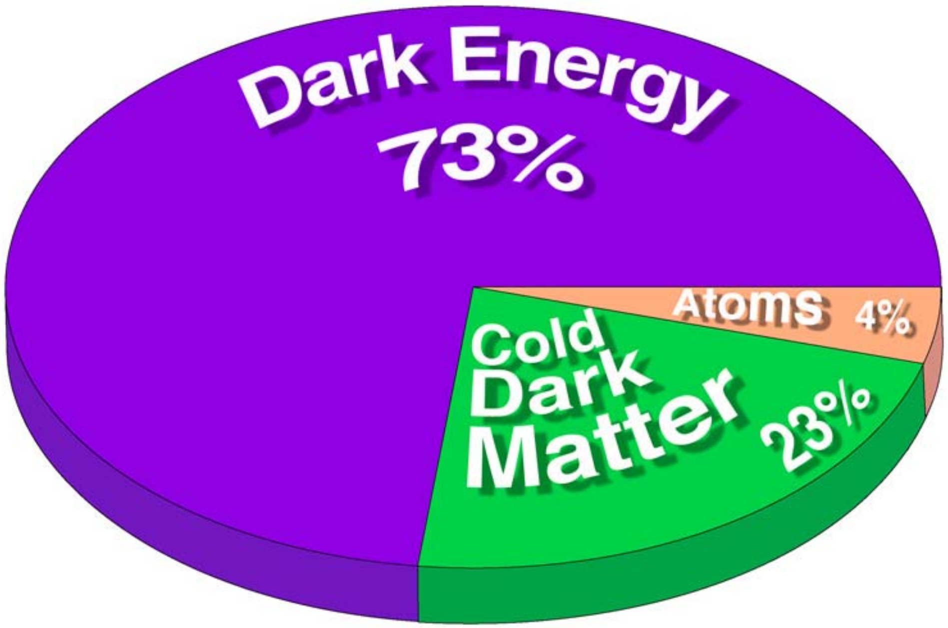
- Cosmology Marches On - a Sydney Harris cartoon
  - The caveman looks up at the dark night sky and wonders “Where the hell did it all come from?”
  - The modern astronomer sits in his office, ignoring his big telescope, and wonders “Where the hell did Λ come from?”
- And Λ is a funny “nothing” - the energy density of the vacuum.

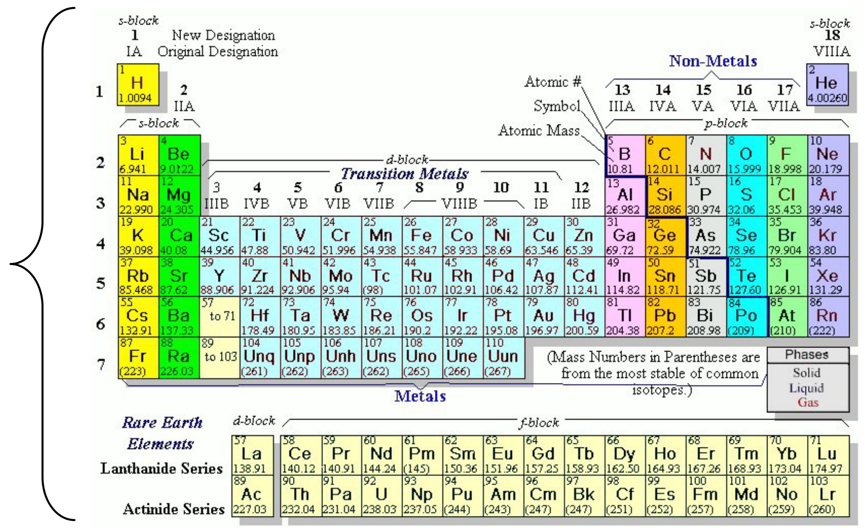
Have we seen the beginning?

- 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.



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



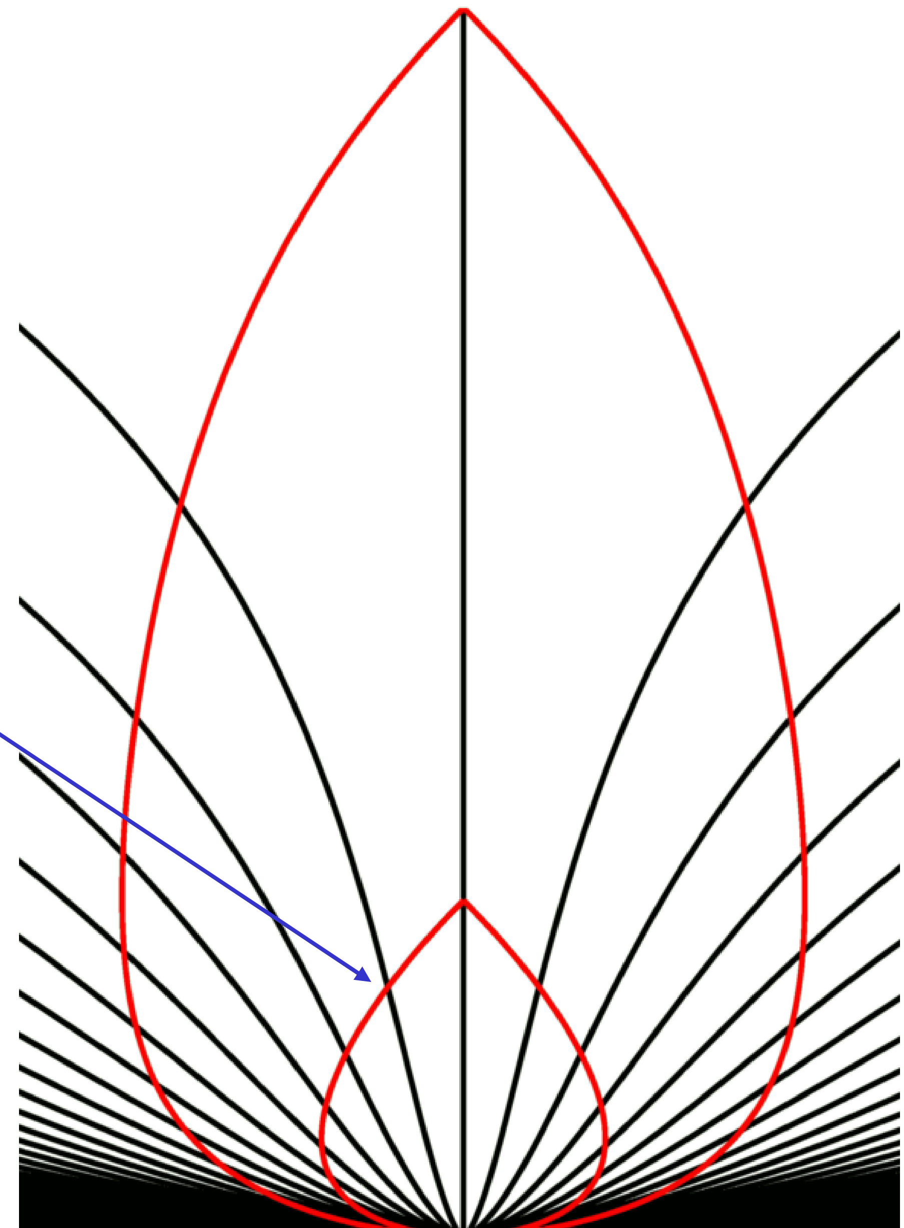


Future of the Universe

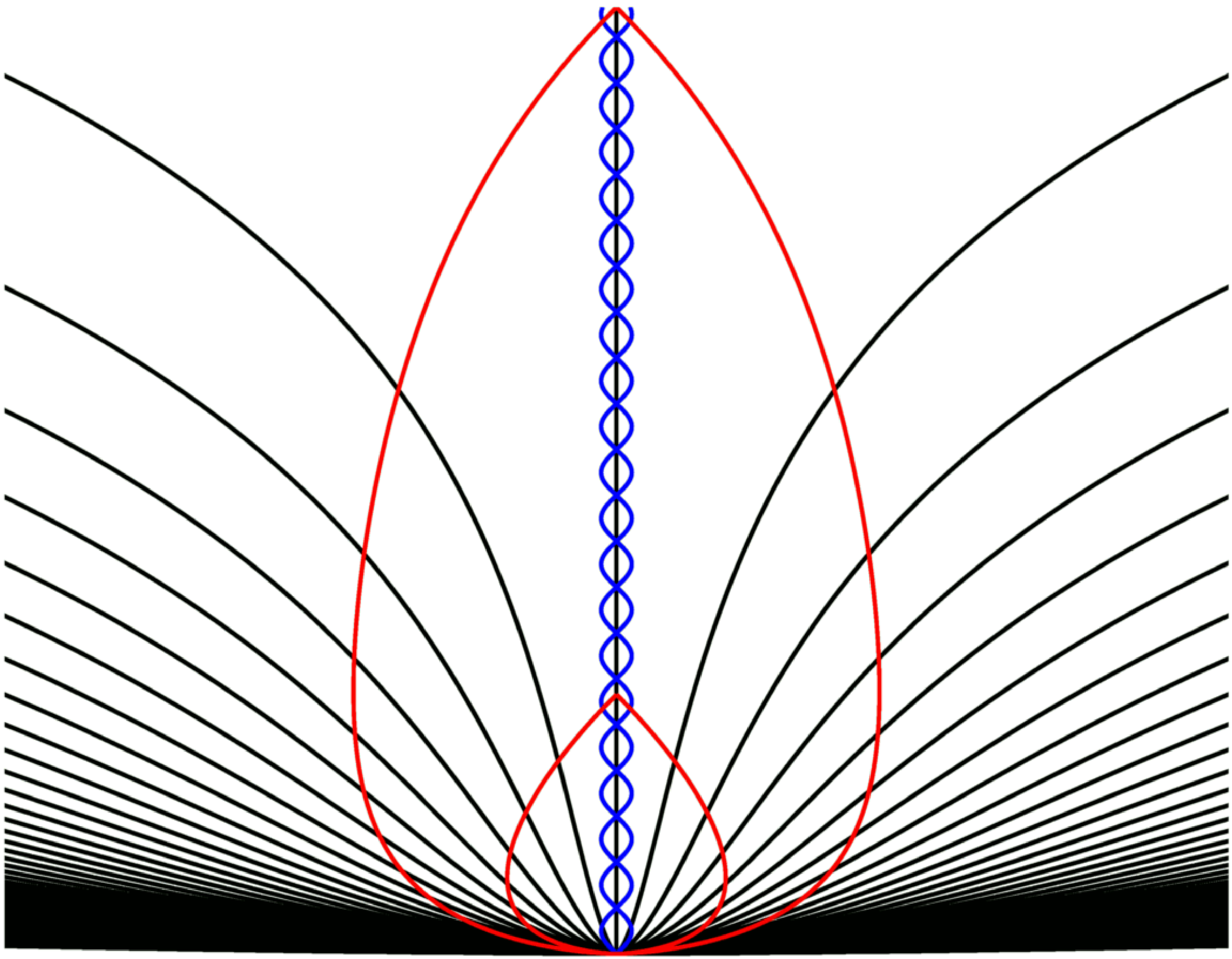
- Krauss & Scherrer, *Scientific American*, March 2008
- Accelerating expansion continues.
- After 100 billion years, Universe is 500 times bigger, so:
  – T_{CMB} is only 5 mK, and the CMB can't be seen.
  – The local group has combined with the Virgo supercluster to make one giant galaxy.
  – All the other galaxies are so far away and highly redshifted that they probably would not be seen.
- So we are back the Kapteyn universe! Only our own galaxy can be seen.

When Universe is 10× Bigger

- 36 Gyr from now
- Lower lightcone is now, upper lightcone starts at 36 Gyr from now.
- First galaxy shown is 3.4 billion lightyears away now, but will be 34 billion lightyears away 36 Gyr from now.
- It will be 625 times fainter and hard to see.

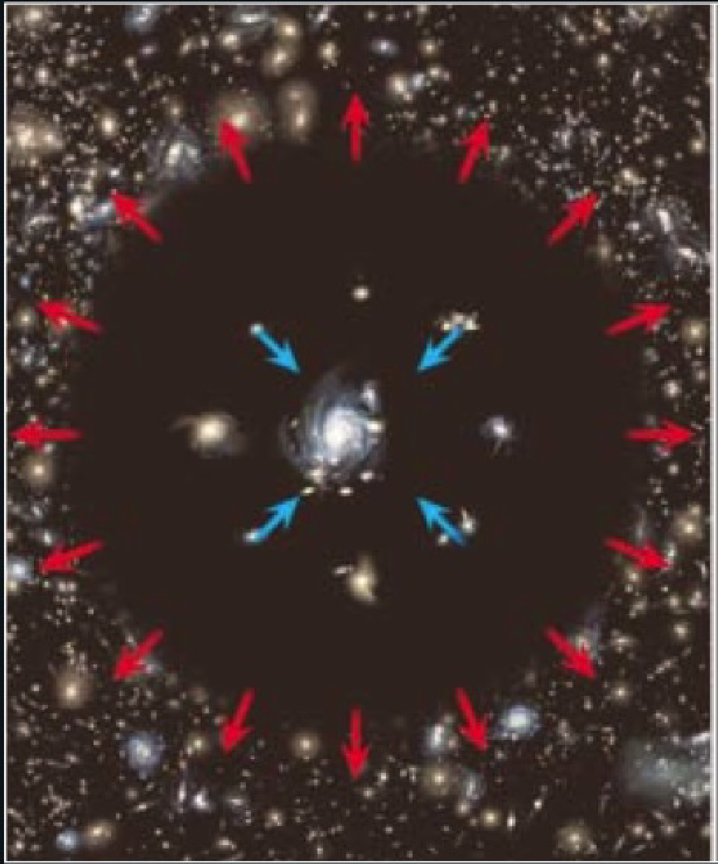


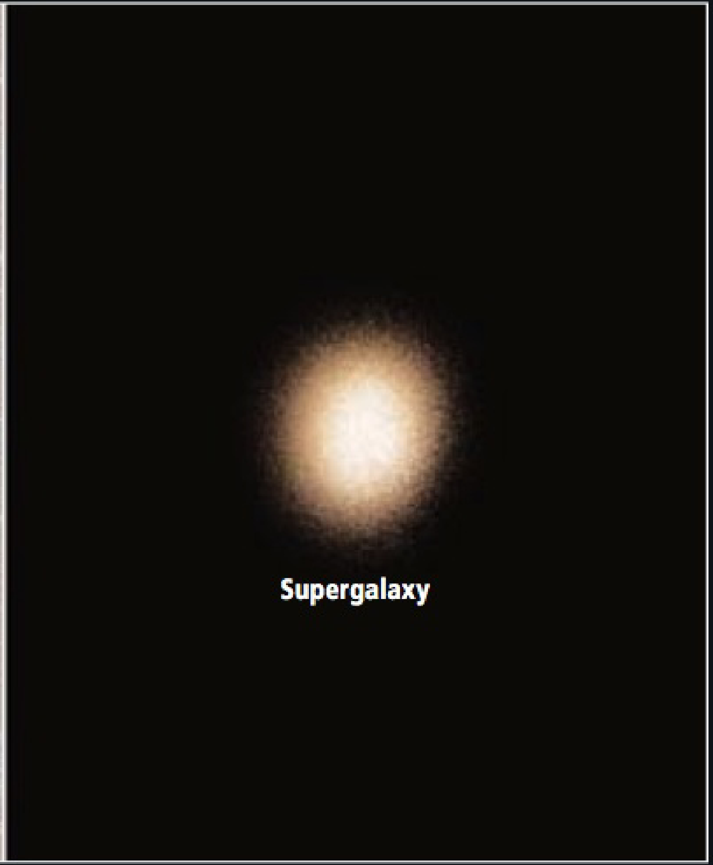
But Bound Clusters do NOT Expand



THE APOCALYPSE OF KNOWLEDGE

The accelerating cosmic expansion is beginning to undermine the three observational pillars of the big bang theory: the motion of galaxies away from one another, the cosmic microwave background radiation, and the relative quantities of light chemical elements such as hydrogen and helium.





TODAY all three pillars are prominent. We see distant galaxies recede from us (*red arrows*) as nearby ones pull tighter (*blue*); background radiation suffuses space; and cosmic gas largely retains the chemical mix produced early in the big bang.

BILLIONS OF YEARS LATER nearby galaxies have merged and distant ones have receded from view. The background radiation is undetectably dilute. Multiple generations of stars have contaminated the original chemical mix.

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