Observations of Dark Matter from the Solar Neighborhood to the Universe

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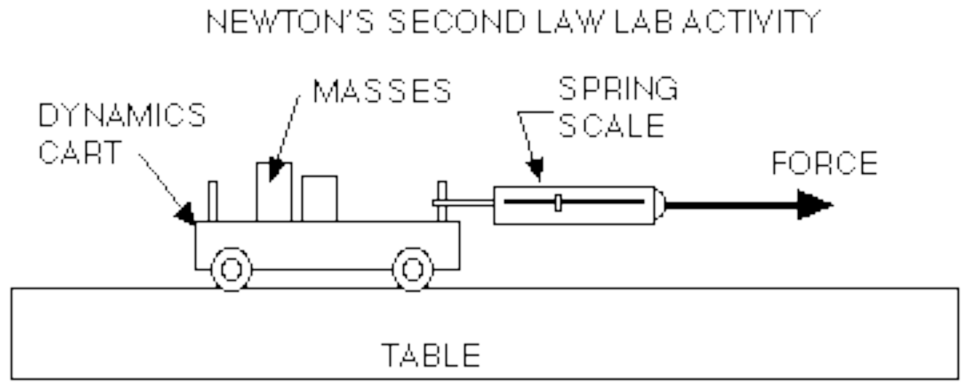
UCLA

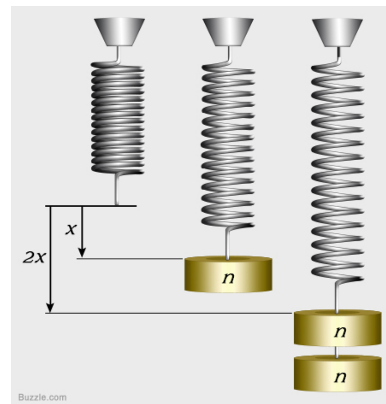
13 October 2015

Three Kinds of Mass

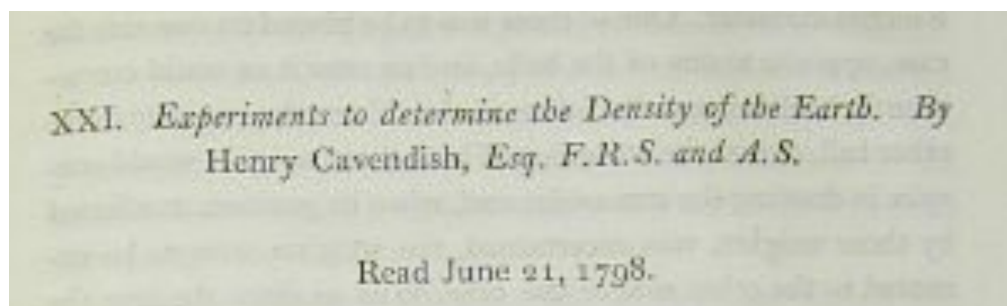
- Inertial mass
  - $m_i = F_{spring}/a$



- Passive gravitational mass
  - $m_p = F_{grav}/g$



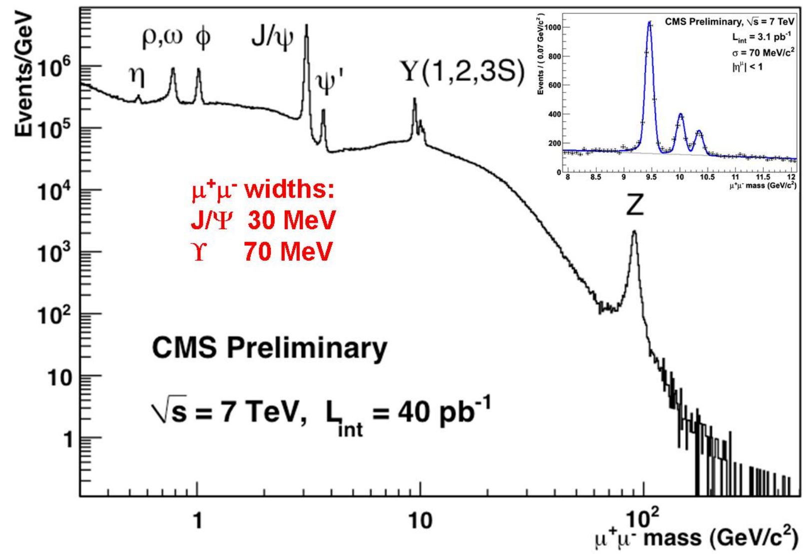
- Active gravitational mass
  - $m_a = v_{circ}^2 R/G$


XXI. *Experiments to determine the Density of the Earth.* By Henry Cavendish, *Esq. F.R.S. and A.S.*

Read June 21, 1798.

How can we measure mass?

- $E = mc^2$ in particle collision experiments
- For small particles we apply an electromagnetic force and measure the acceleration.
- For kg sized objects we null the force of gravity with an electromagnetic force and calibrate using a standard kilogram.
- But in astronomy we can only measure the gravitational acceleration produced by the object.

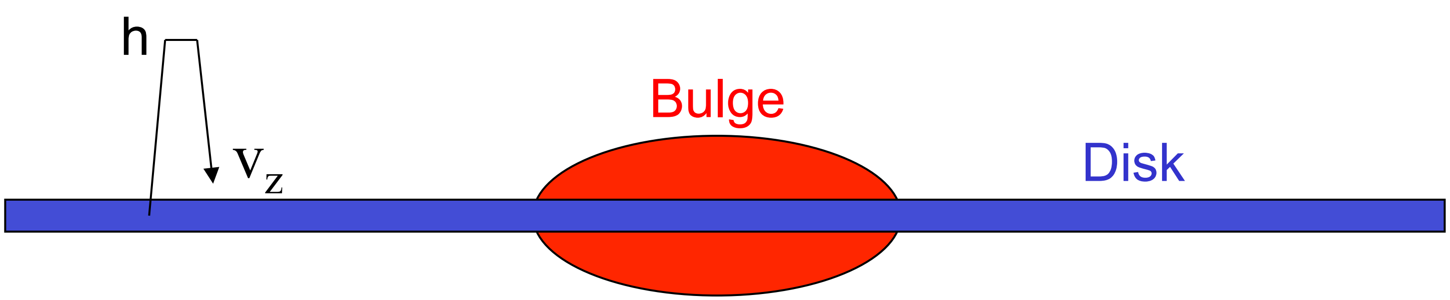


Objects with mass known only gravitationally

- The Moon
- The Earth
- The Sun
- Jupiter
- Stars
- Galaxies
- Dark Matter

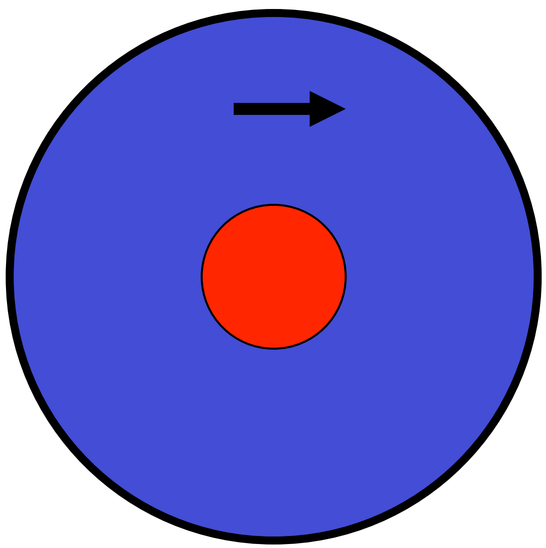
Dark Matter in the Universe

- Counting stars in the Solar neighborhood gives a luminosity of 15 $L_\odot$ per square parsec and a mass density of 50 $M_\odot$ per square parsec. This is luminous matter.
- Typical vertical velocity v_z and scale height h of stars give $g = v_z^2/2h$ implying a mass density of 75 $M_\odot$ per square parsec [Oort 1932].



Dark Halo is needed

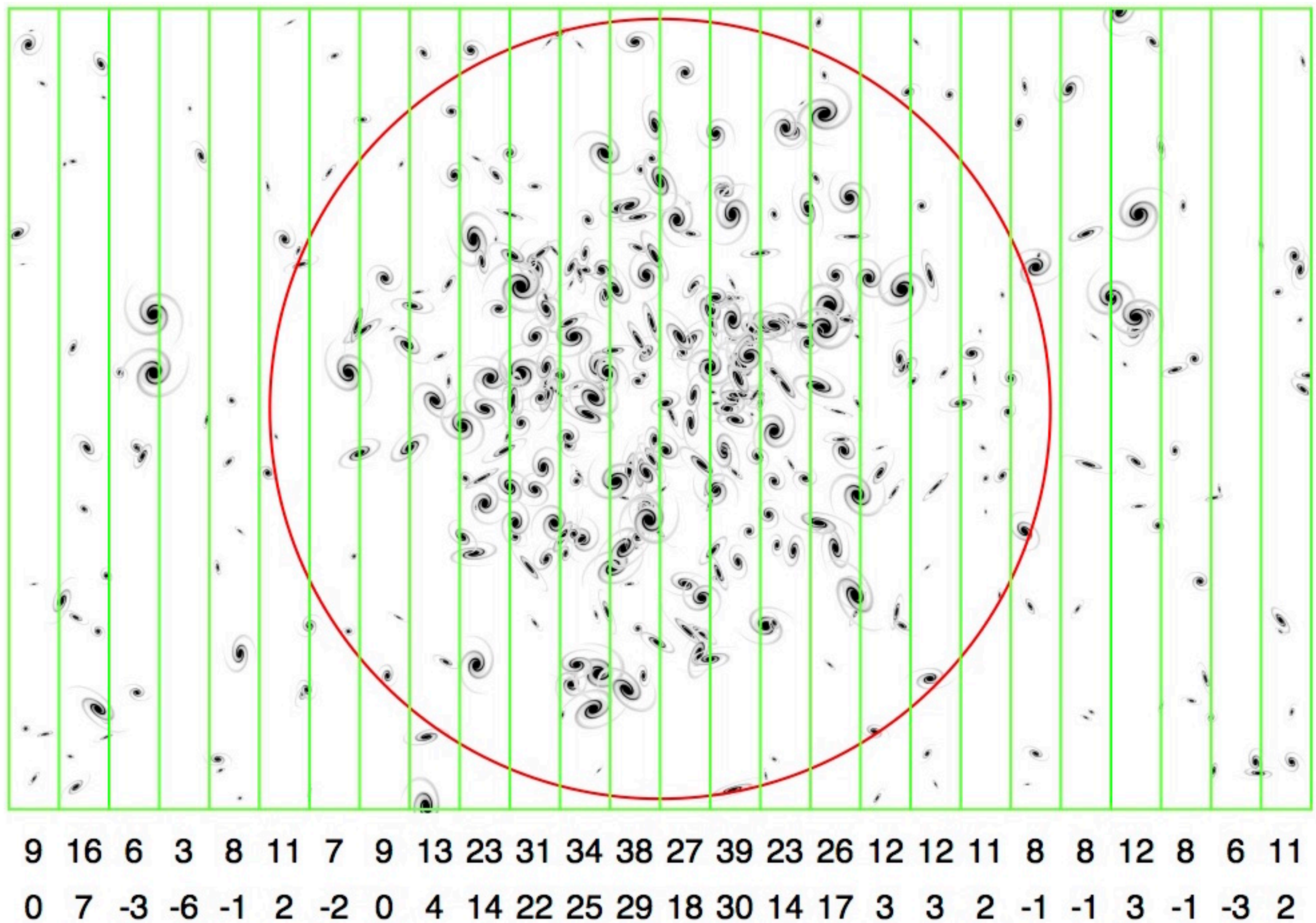
- A disk mass density of 210 $M_\odot$ per square parsec is needed to explain the rotational velocity v_t at radius R.
- Thus a spherical halo with mass density of 0.008 $M_\odot$ per cubic parsec scaling like $1/R^2$ is needed.



Darker still in Clusters of Galaxies

- Zwicky (1933) used the radial velocity dispersion in the Coma cluster to conclude that the M/L ratio was >100× larger than M/L for the luminous matter near the Sun.

Virial Theorem



- KE = -0.5 PE or $\frac{1}{2}M(3\sigma^2) = \frac{1}{2}GM^2/R_e$
- Note R_e is pretty large (red circle above)

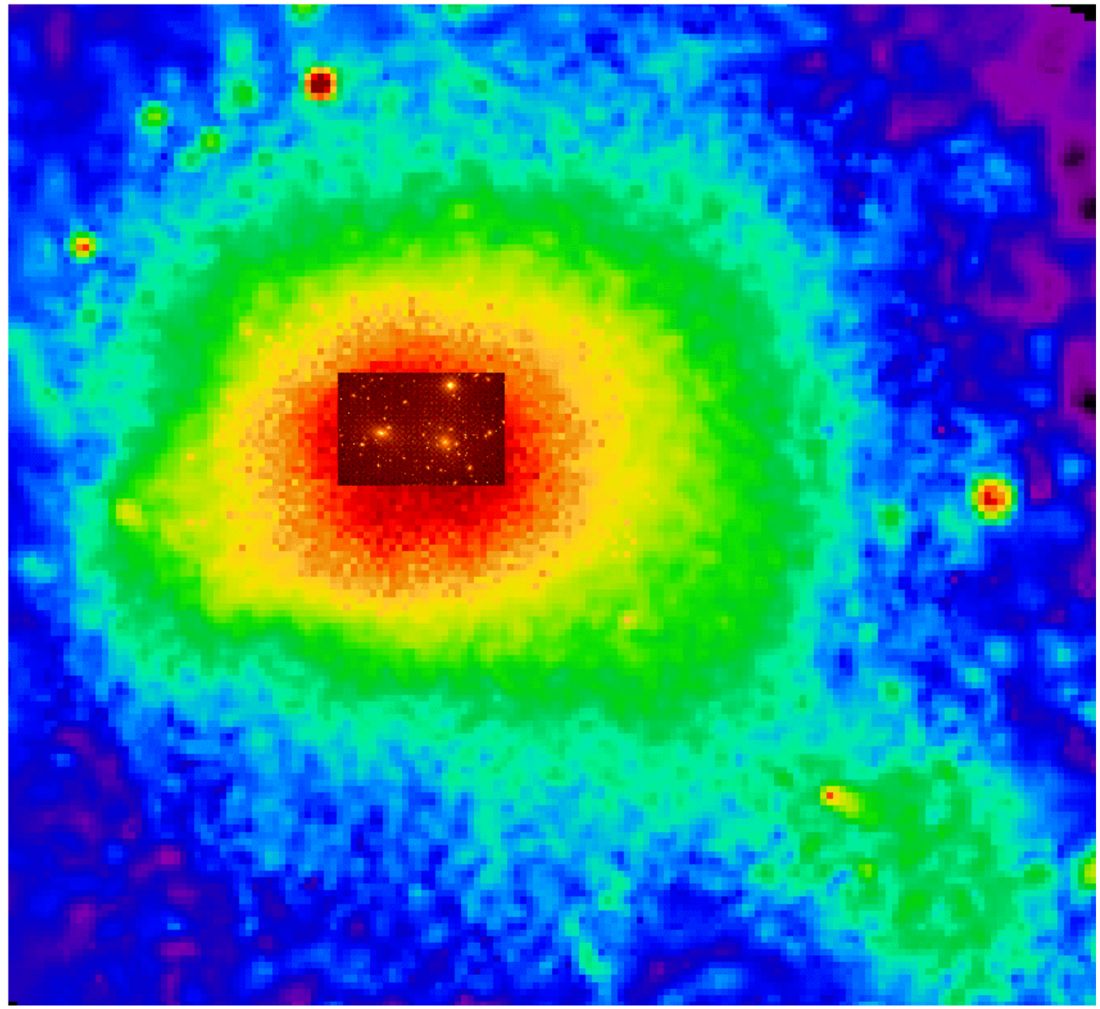
Hot gas in clusters of galaxies

- X-ray telescopes have seen emission from gas in clusters of galaxies with temperatures of 50 to 100 million Kelvin.
- With the X-ray data, one can compute how much matter is in this hot, ionized gas, and it is much more than the mass of the stars and galaxies in the cluster.
- The gradient in the density of the hot gas and the temperature can be used to compute the gravitational acceleration "g" in the cluster, and one needs about 5 times more mass in dark matter than in hot gas to produce the "g".

The Coma Cluster = Abell 1656

- 484 galaxies in 5.3^o diameter, v_{rad} = 6925 km/sec

The Coma cluster of galaxies



- X-ray emitting hot gas is quite extended

Dark Matter has high M/L

- In the solar neighborhood 50 $M_\odot$ per square parsec of stars gives 15 $L_\odot$ per square parsec so M/L is 3.3 for stars.
- Dark matter has to have M/L > 1000
- A very low mass star with M = 0.1 $M_\odot$ and L = 0.0001 $L_\odot$ would be just barely OK with M/L = 1000.
- Jupiter with $L = 10^{-9}\ L_\odot$ and $M = 10^{-3}\ M_\odot$ gives $M/L = 10^6$ which is certainly OK.

Dark Matter is Transparent

- Interstellar medium: 0.05 kg/m^2 is opaque.
- Air: atmosphere has 10,000 kg/m^2 and is transparent.
- Universe: need 1 kg/m^2 of dark matter to be transparent.

Examples:

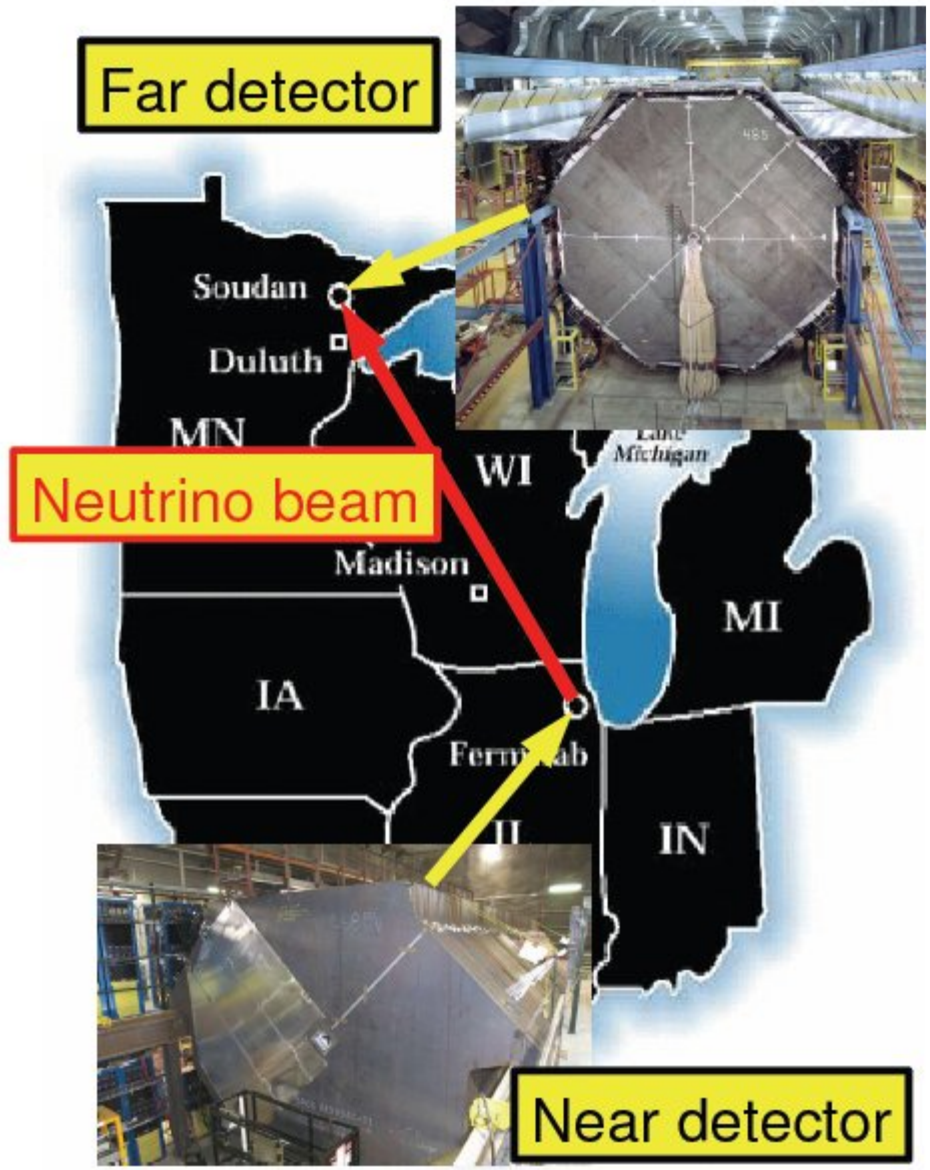
- Iron 5.5 kg (12 pound) cannonballs:
  - M/L is close to infinity
  - Radius is 5.7 cm, cross-section is $\pi R^2 = 0.0103$ m^2, so 0.002 m^2/kg. Clearly transparent enough.
- Planets (Jupiter):
  - $L = 10^{-9} L_\odot$, $M = 10^{-3} M_\odot$ so $M/L = 10^6$ which is dark enough.
  - $R = 7\times10^7$ m, $M = 2\times10^{27}$ kg, so cross-section per unit mass is $\pi R^2/M = (3.14\times49\times10^{14}/2\times10^{27})$ or 8×10^{-12} m^2/kg which is clearly transparent enough.

Neutrinos

- Neutrinos certainly don't interact much.
- We have measured the mass differences between neutrino types. It looks like the three types have masses of 0.001, 0.009 and 0.05 eV which are too small to make the dark matter out of neutrinos.

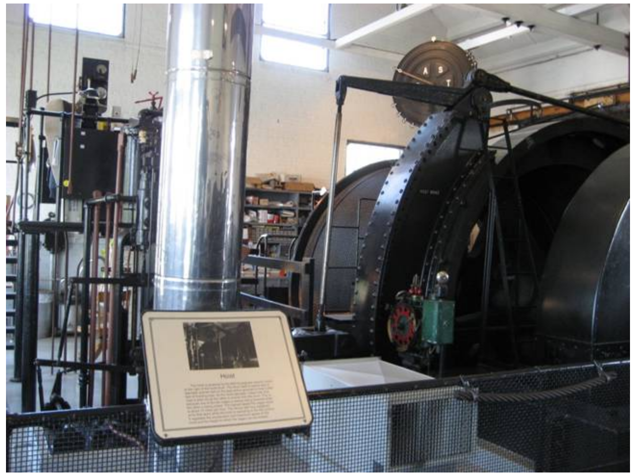
MINOS

- MINOS is an experiment to measure the neutrino mass differences. It sends a neutrino beam from Illinois all the way under Wisconsin to a detector in an old iron mine in Minnesota.



Touring the MINOS far detector

- Detector alone weighs 12 million pounds.
- It and the whole laboratory all went down in a tiny mine elevator that barely holds 10 people.



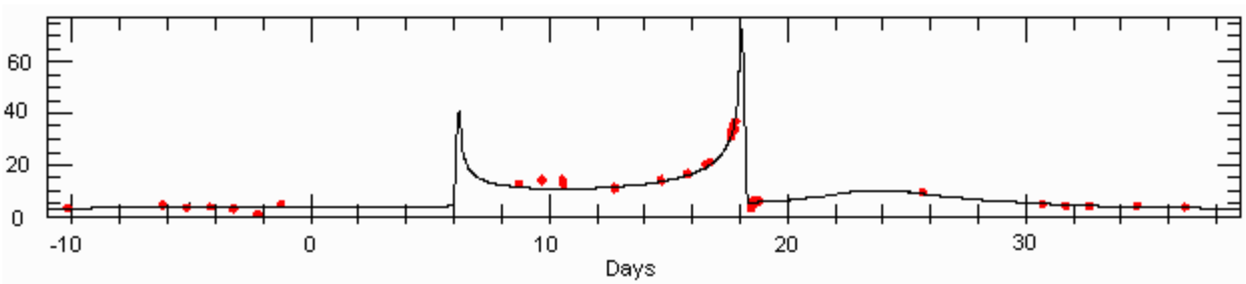
MACHOs vs WIMPs vs Axions

- Massive Compact Halo Objects
  - Stars with $M < 0.08\ M_{\odot}$
  - White dwarfs
  - Neutron Stars
  - Free floating planets
  - Black holes
- Weakly Interacting Massive Particles
  - Only the weak nuclear force, like a neutrino
  - Mass near 100× the proton mass
- Axions – very light – proposed by UCLA Vice Chancellor Roberto Peccei

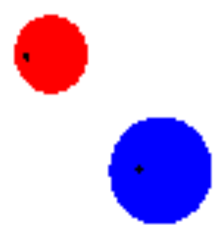
MACHOs can be seen by lensing

- A MACHO moves across the line of sight to a star in the Large Magellanic Cloud (LMC) and gravitationally lenses it, making it temporarily brighter.
- Too few events are seen toward the LMC so MACHOs are not the dark matter in the Milky Way.

Example of Lensing



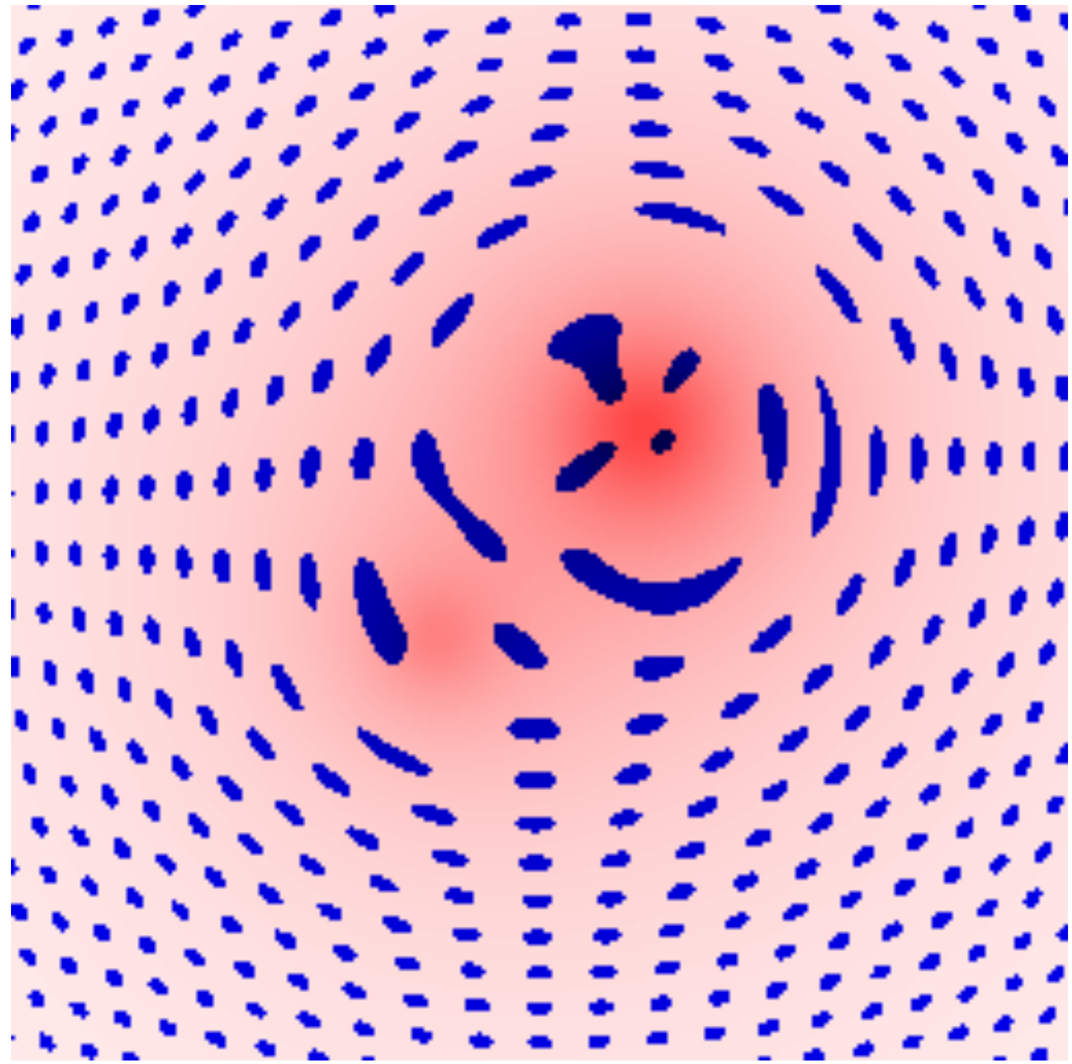
A star lensed by a binary lens.

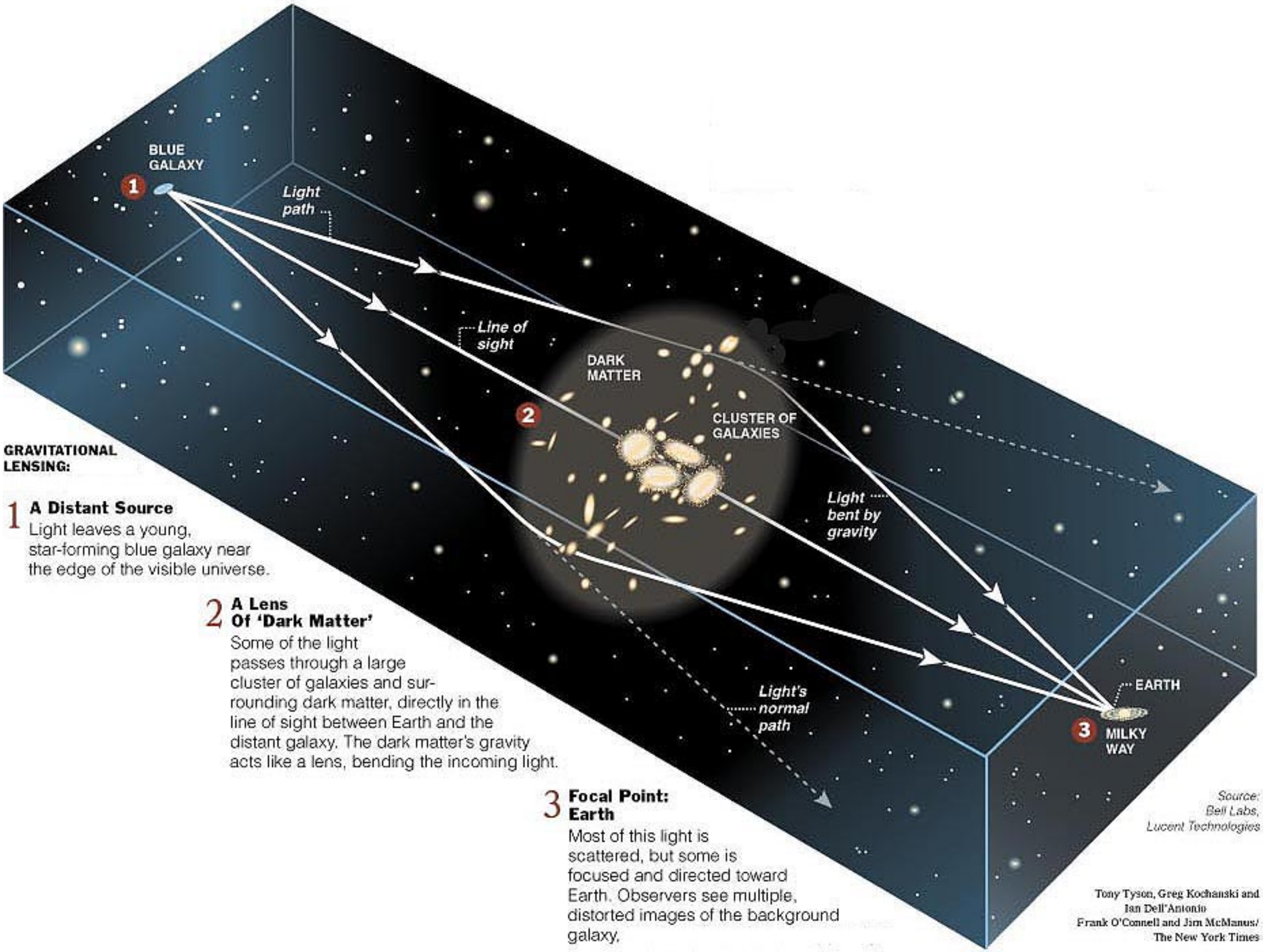


- Animation of a binary star lensed by a binary lens

Cluster Lensing

- Gravitational lensing by clusters of galaxies produces giant arcs and a pattern of distorted background galaxy shapes.
- This is a good way to measure the dark matter in clusters of galaxies.
- The animation at right shows the distortion, with background galaxies in blue, but unlike the stellar mass lens case, we cannot actually see the pattern change in a human lifetime.





GRAVITATIONAL LENSING:

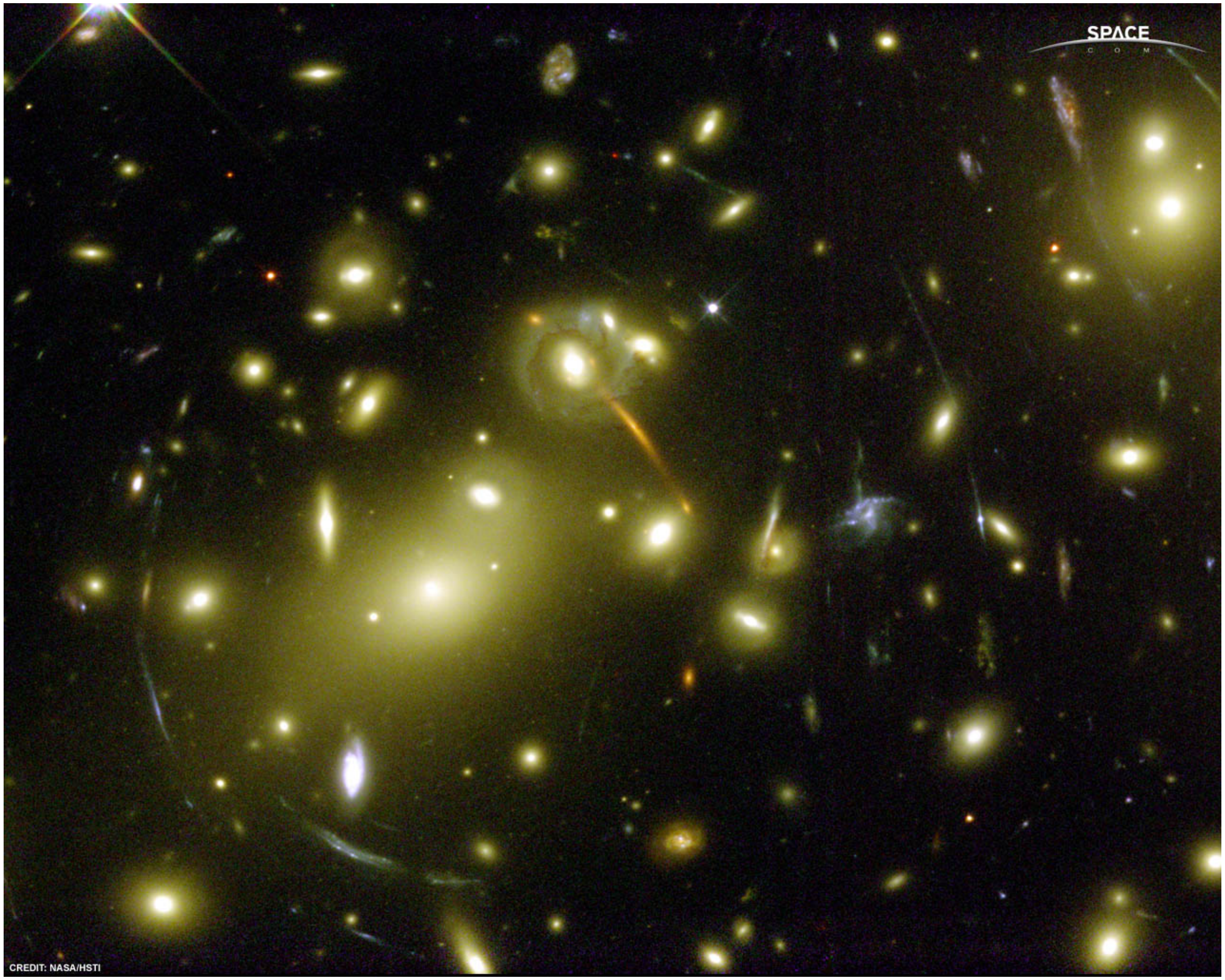
1 A Distant Source
Light leaves a young, star-forming blue galaxy near the edge of the visible universe.

2 A Lens Of 'Dark Matter'
Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter's gravity acts like a lens, bending the incoming light.

3 Focal Point: Earth
Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.

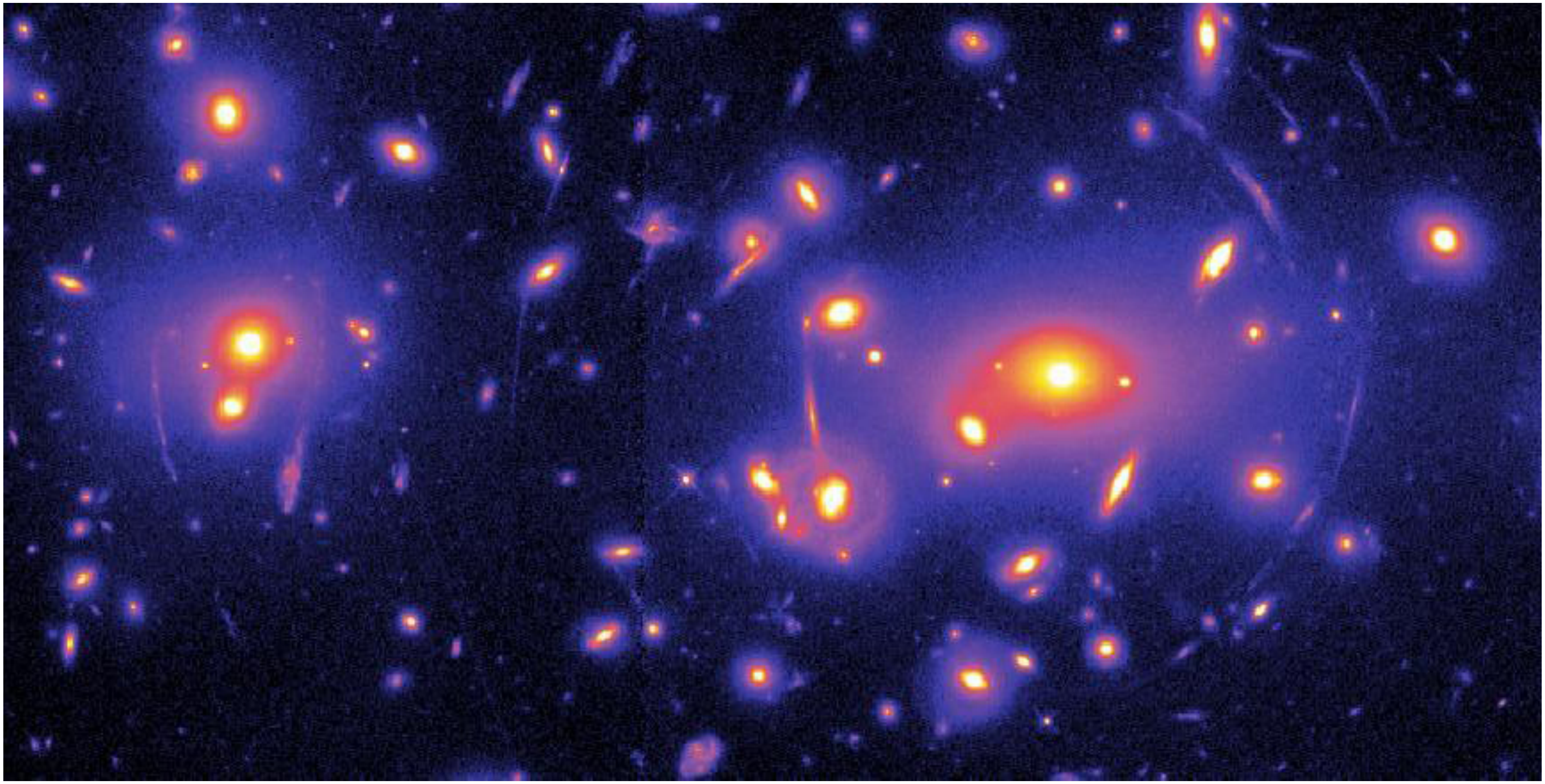
Tony Tyson, Greg Kochanski and Ian Dell'Antonio
Frank O'Connell and Jim McManus/The New York Times

Abell 2218



- Example of giant arcs

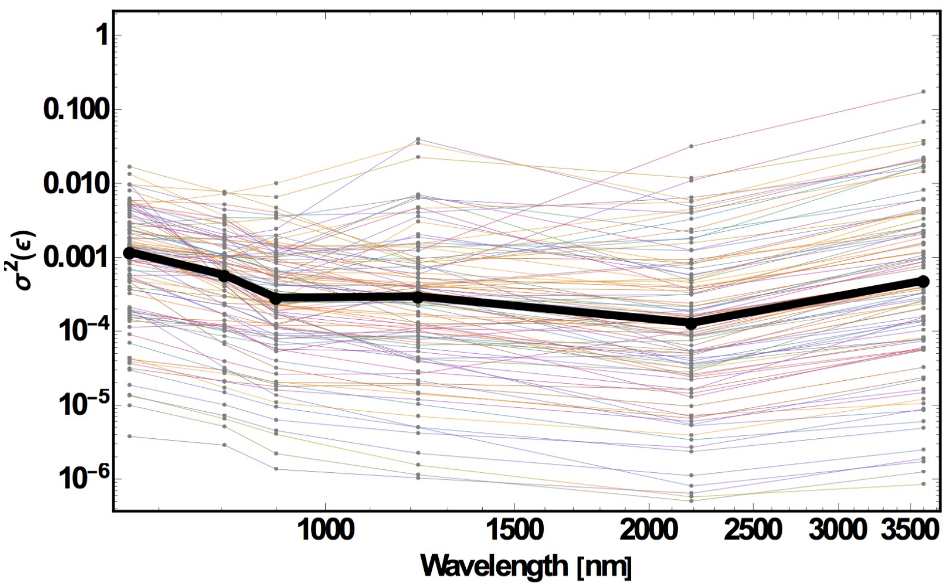
Mapping out dark matter



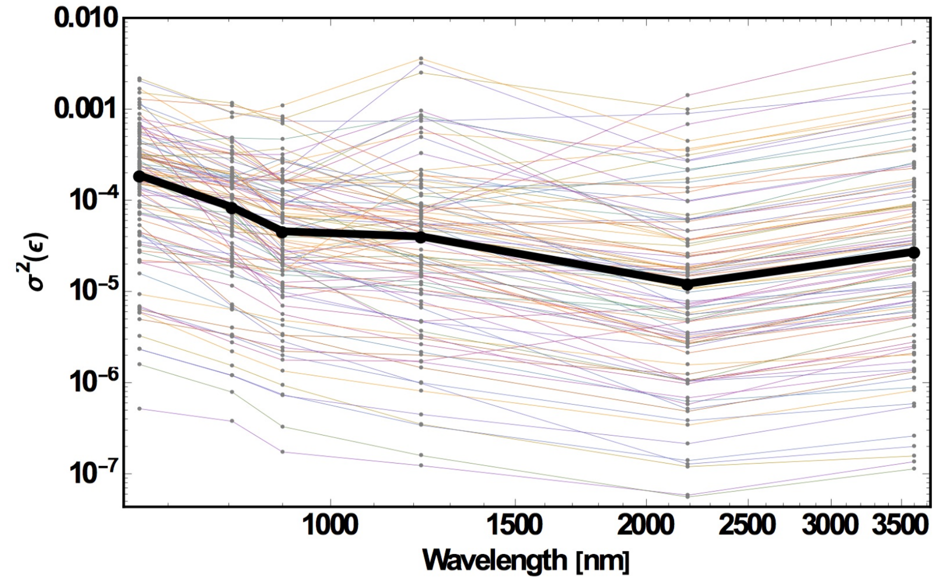
- Blue shows the dark matter from lensing
- Red/Yellow shows the galaxies.

On Using a Space Telescope to Detect Weak Lensing Shear

Tung & Wright, PASP submitted



1.2 meter telescope



2.4 meter telescope

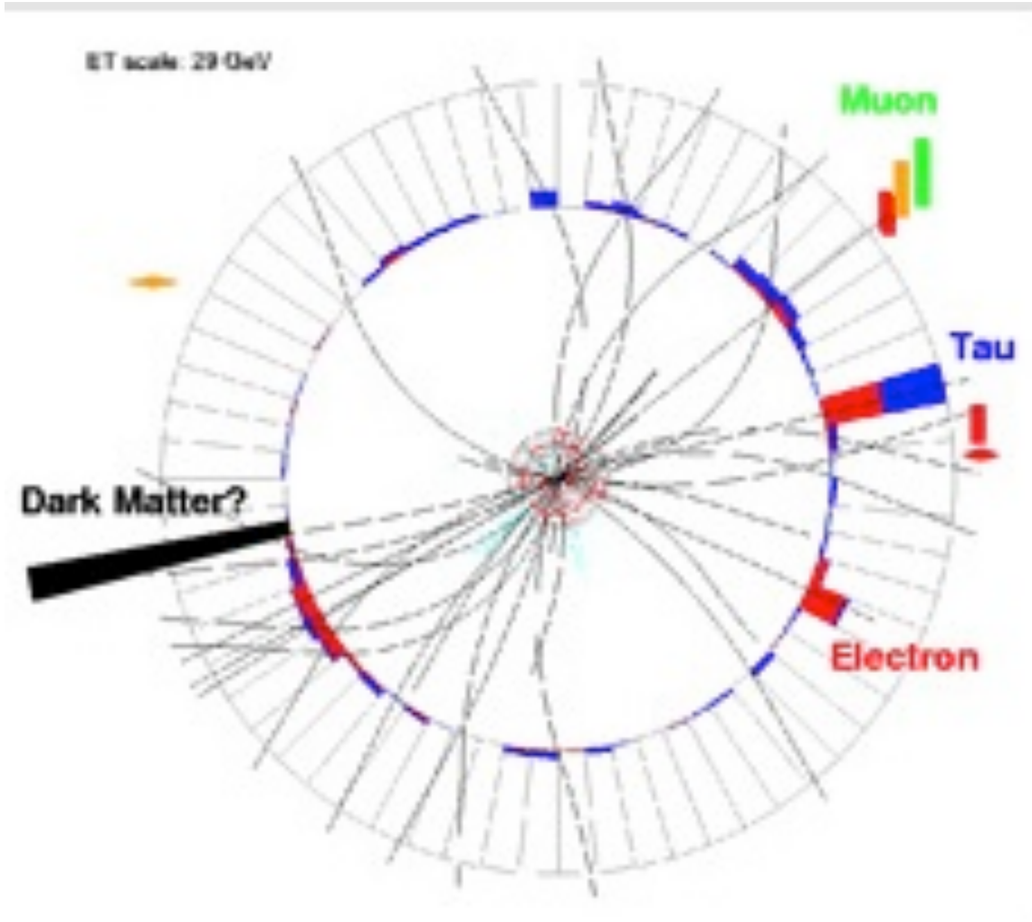
Best λ for measuring shear is 2.2 μm in space. About 10x better than the R band.

K band even more strongly favored. Much better than 1.2 m

WIMPs

- The highest priority in particle physics is to see supersymmetric partner particles. The LHC has not yet seen any such particles.
- It might see some charged massive particles (CHAMPs).
- Neutral versions, which can not be seen directly, could be the dark matter.

An asymmetric event

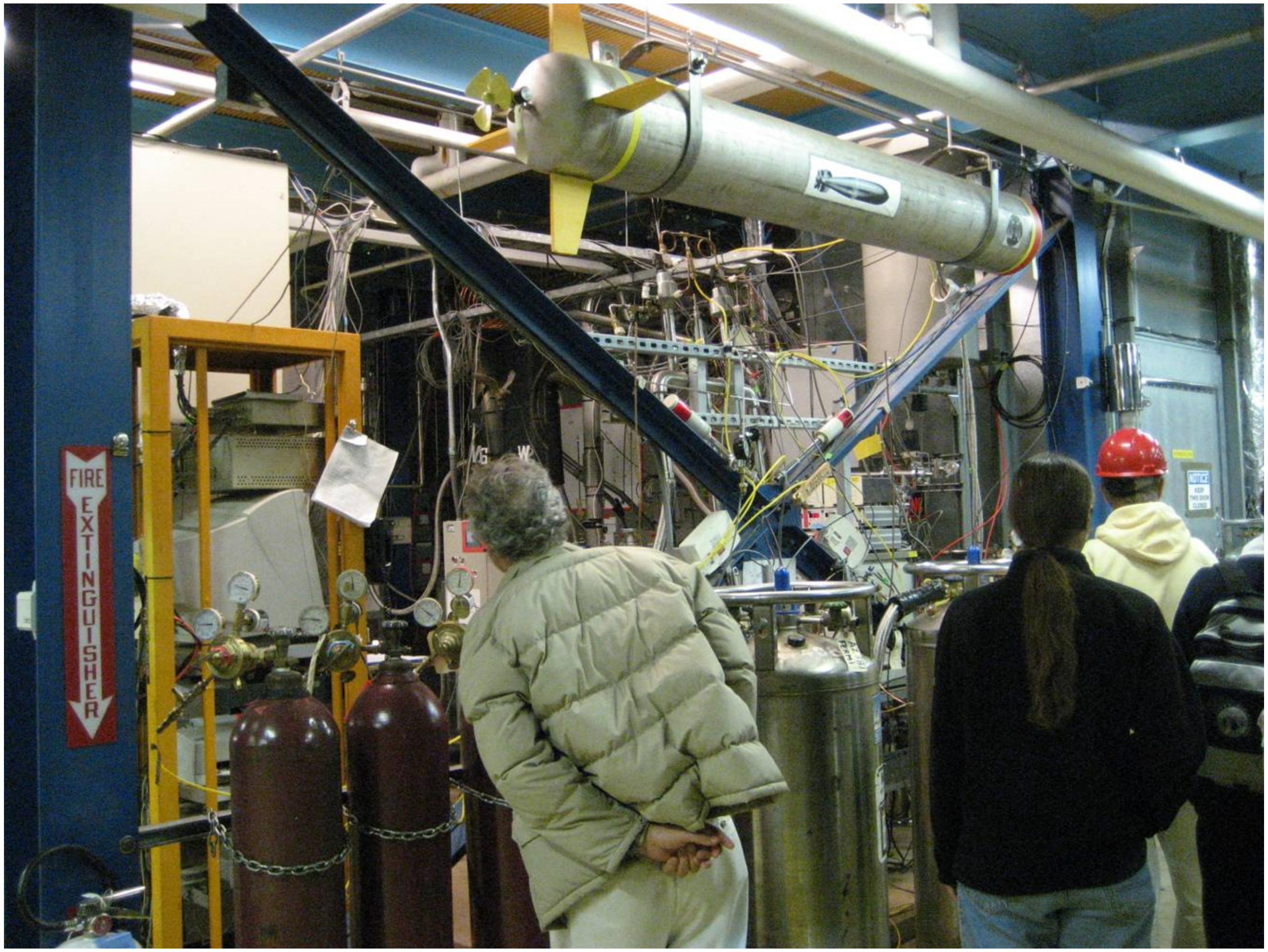


- The black bar is the missing transverse energy. The original colliding protons were traveling into and out of the page.

WIMP detection

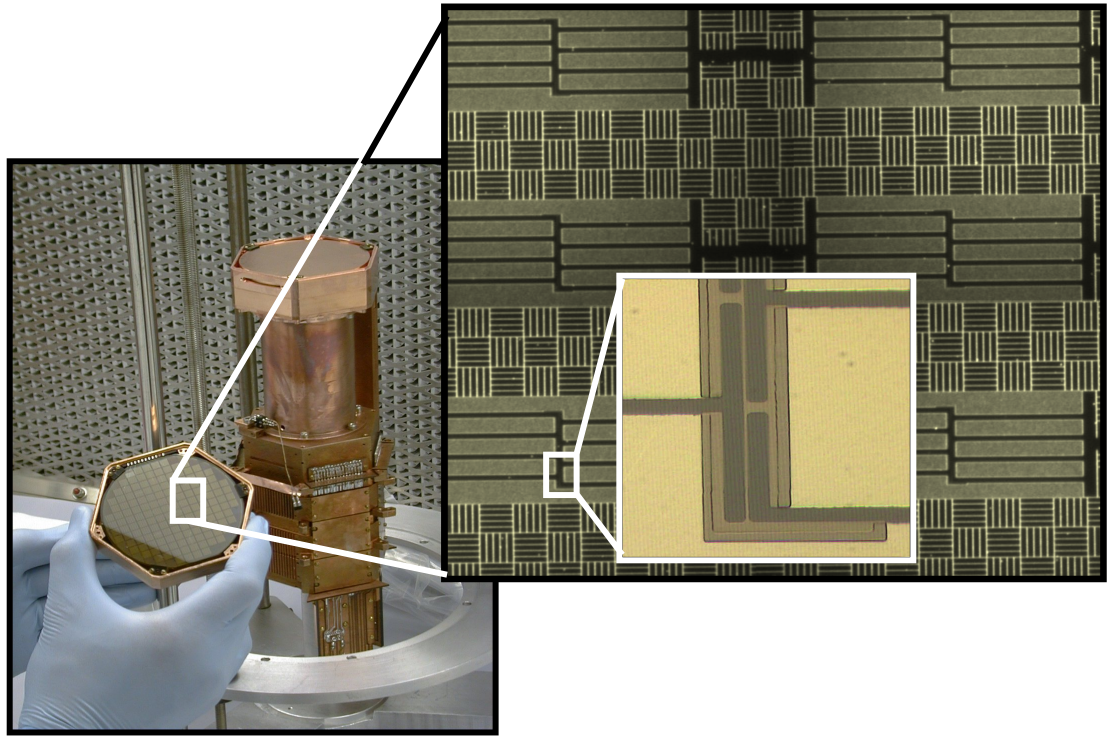
- WIMPs can also be detected in deep mine shafts, away from most cosmic rays.
- Occasionally a WIMP will bump into the nucleus of an atom in a detector, and cause a detectable flash of light, ionization, and heat.
- Another experiment in the Soudan mine underground laboratory is looking for cosmic dark matter.

Cryogenic Dark Matter Search



- CDMS looks for ionization and heat pulses.

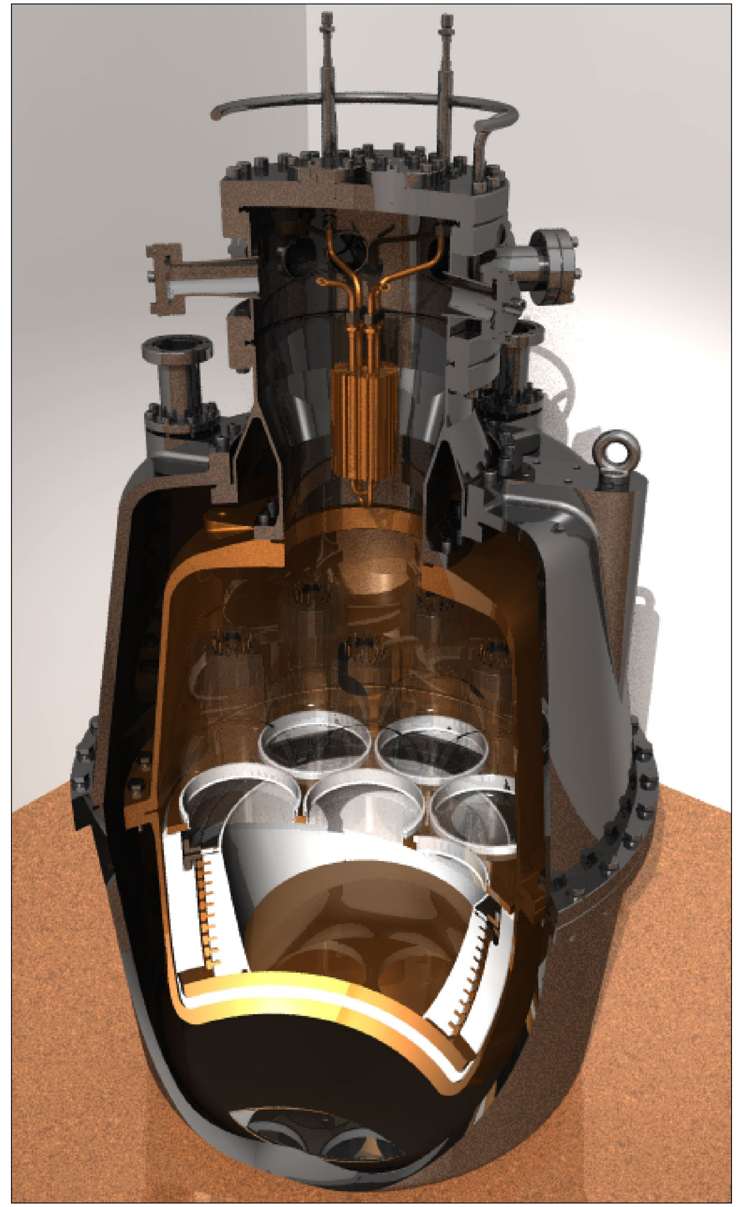
CDMS



- The silicon or germanium crystals seen on the right are inside a dewar (fancy thermos bottle), cooled to 0.02 K above absolute zero. The dewar is inside the shielded box at left.

UCLA is also in this field

- UCLA's experiment is Zeplin, which uses liquid xenon as a detector. It is down in a mine in the UK.
- The cutaway diagram at right shows Zeplin II.
- The current state of the art is XENON-100 with 100 kg of liquid xenon. And Xenon1T is nearly done.
- So far no detections.



Axion Searches

- An axion can convert to a photon in the presence of a magnetic field.
- But the magnet has to be tuned to the correct value that depends on the axion mass, which we don’t know.
- So at Lawrence Livermore National Laboratory people are sweeping the magnetic fields and searching for photons.
- So far, no detections.

Other possibilities

- Primordial black holes:
  - Black holes smaller than a solar mass can only be made in the Big Bang.
  - But Hawking showed that small black holes, such as trillion kg black hole, will radiate Hawking radiation which will be gamma rays.
  - We don’t see much gamma radiation so primordial black holes are not the dark matter.
- Planck mass remnants of evaporated primordial black holes:
  - ***IF*** Hawking radiation stops at the Planck mass, there could be enough 20 microgram remnants to be the dark matter.

More possibilities

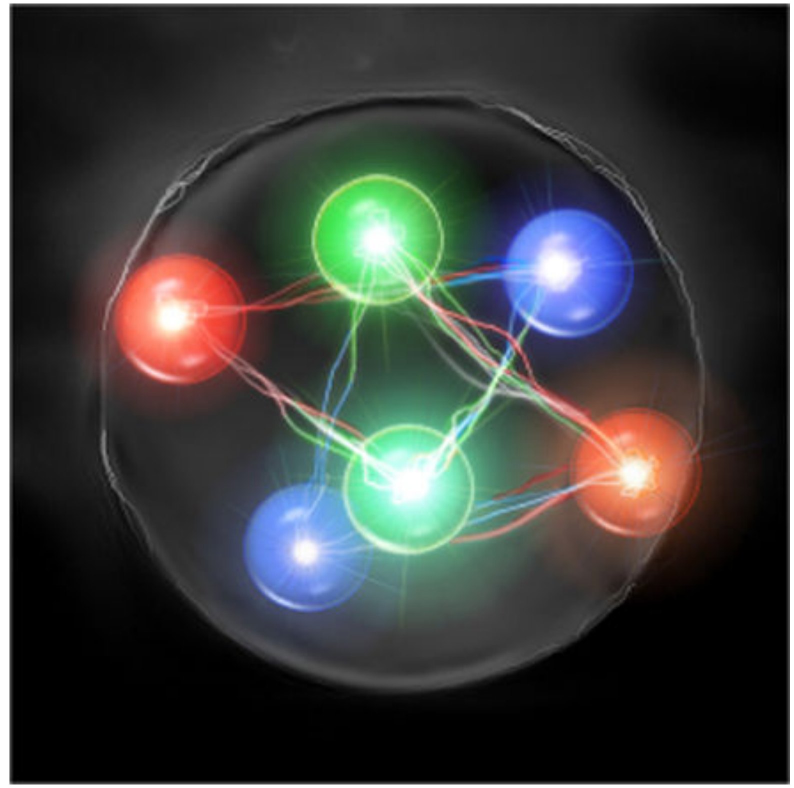
- Quark nuggets:
  - A neutron is 1 up quark and 2 down quarks. It is almost stable.
  - A neutron star is 12×10^{56} up quarks and 24×10^{56} down quarks, and it is stable: this is a neutron star.
  - Hypothetically there could be quark stars which would have 12×10^{56} up quarks, 12×10^{56} down quarks and 12×10^{56} strange quarks.
- If there is an $N \ll 10^{57}$ such that N up quarks, N down quarks and N strange quarks is stable, then this is a quark nugget.

OK for BBNS?

- Yes if formed during first second.
- Free baryons in the 1-180 second range would affect the light element abundances.

Could N=2 Work?

- The H dibaryon
- If the mass is too high it decays at least weakly in 10^{-10} seconds
- If the mass is too low then nuclei are too unstable



- Lattice QCD calculations (Shanahan, Thomas & Young arxiv:1106.2851) suggest that the H is unbound by 13 Mev with respect to ΛΛ so the decay is a strong interaction, or that H is between NΞ and ΛΛ (Inoue arxiv:1212.4230).

Search for quark nuggets

- If a big quark nugget hit the Earth, it would plow right through and exit on the other side.
- As it passed though at about 300 km/sec, it would create an *"epilinear"* earthquake. (instead of an epicenter).
- Searches for epilinear earthquakes have found a few candidates but nothing conclusive.

One candidate epilinear event

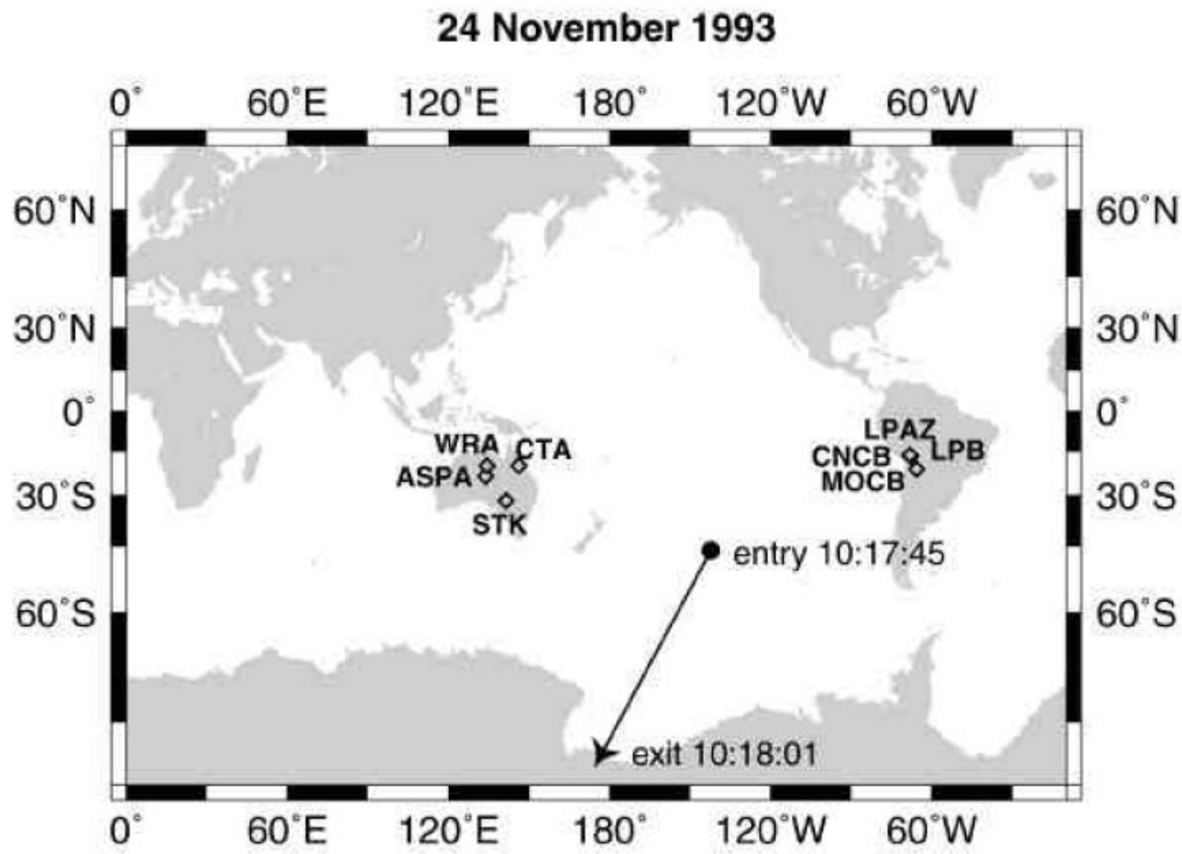
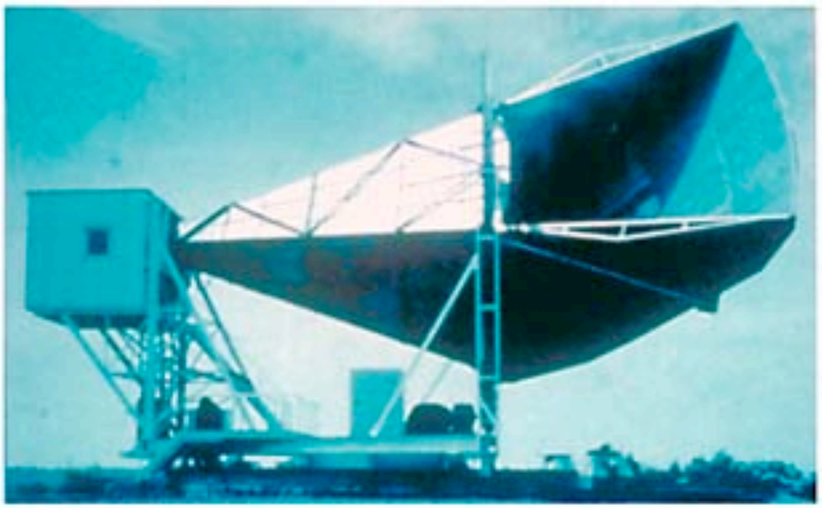


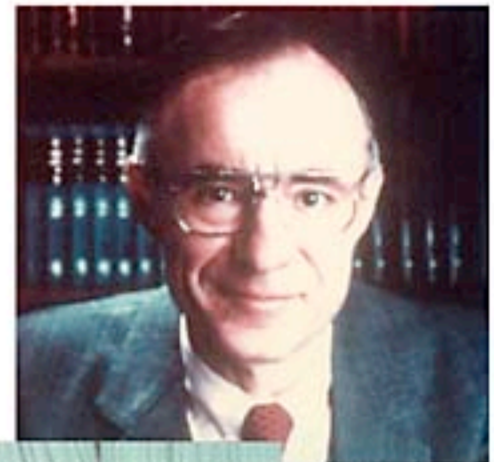
Figure 4. Surface trace for November 1993 linear event.

- From http://www.geology.smu.edu/~dpa-www/sqm/sqm_bssa.pdf
- But one of the stations had a clock error in November 1993

Discovery of the Cosmic Microwave Background



Microwave Receiver

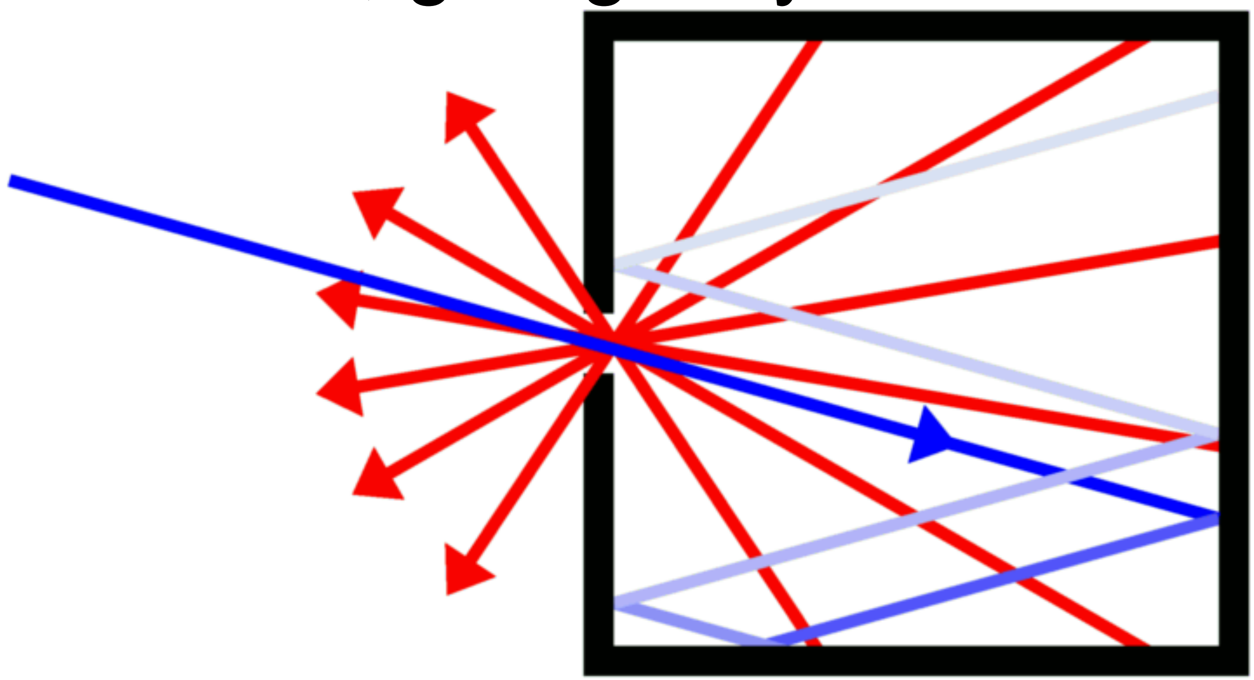


Arno Penzias

Robert Wilson

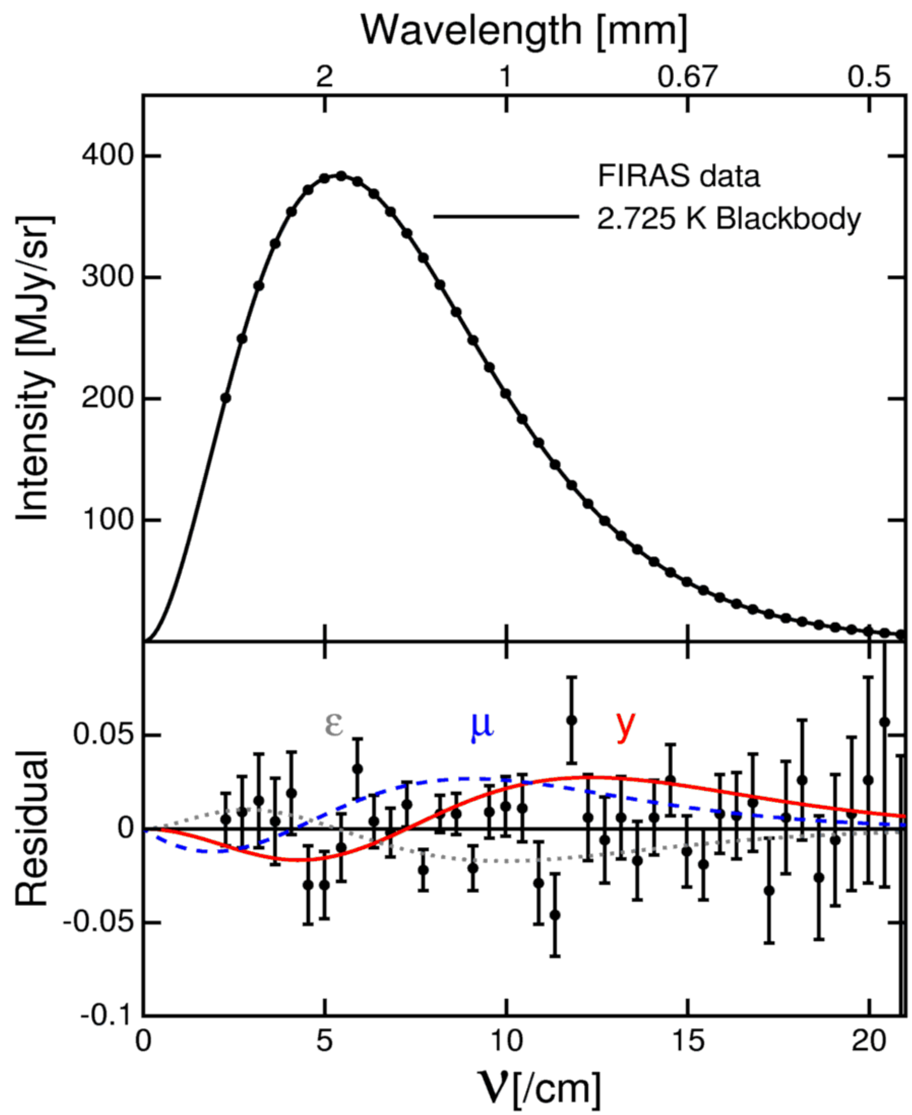
CMB Spectrum is a Blackbody

- 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.

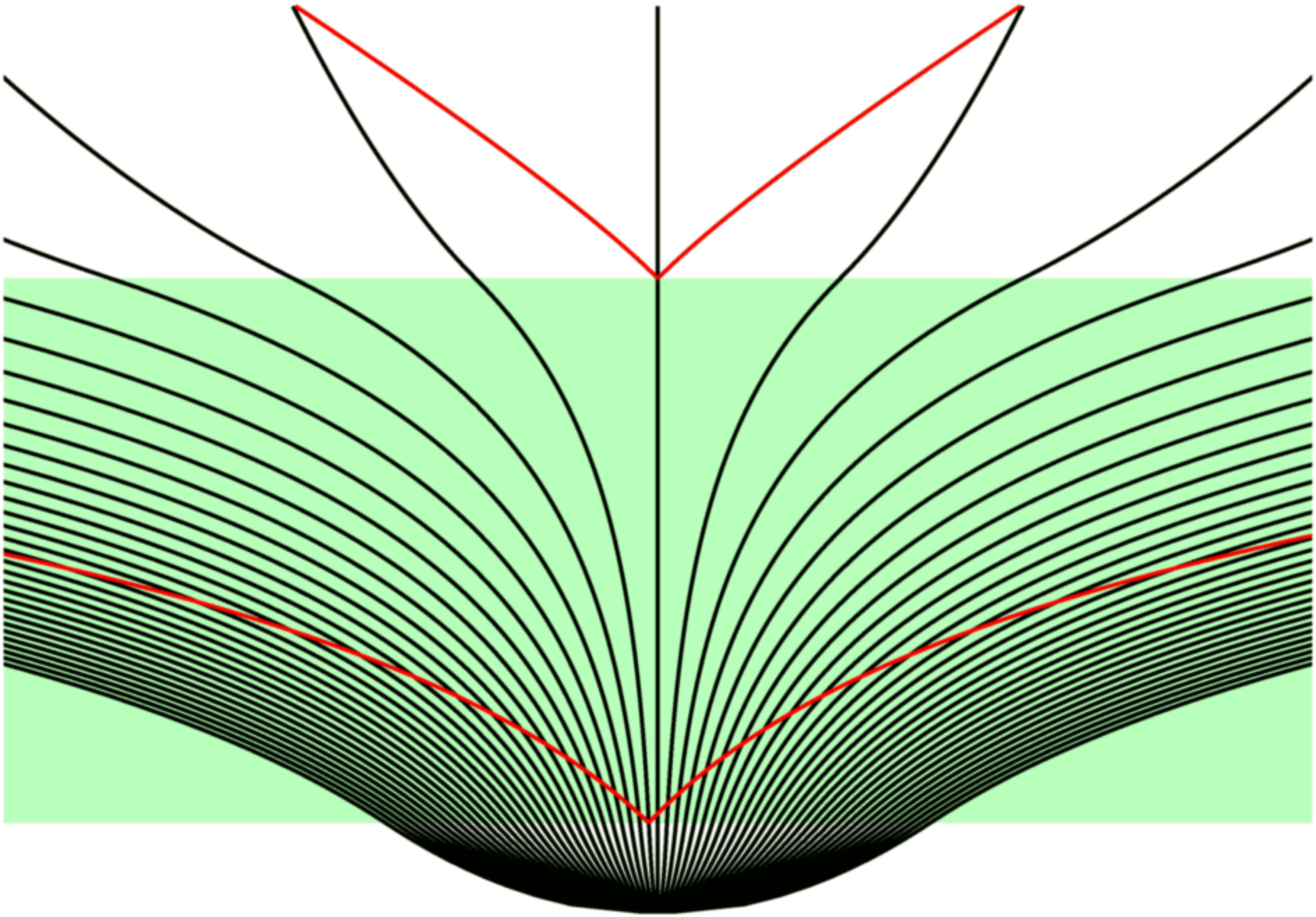


Spectrum is Very Black

- 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

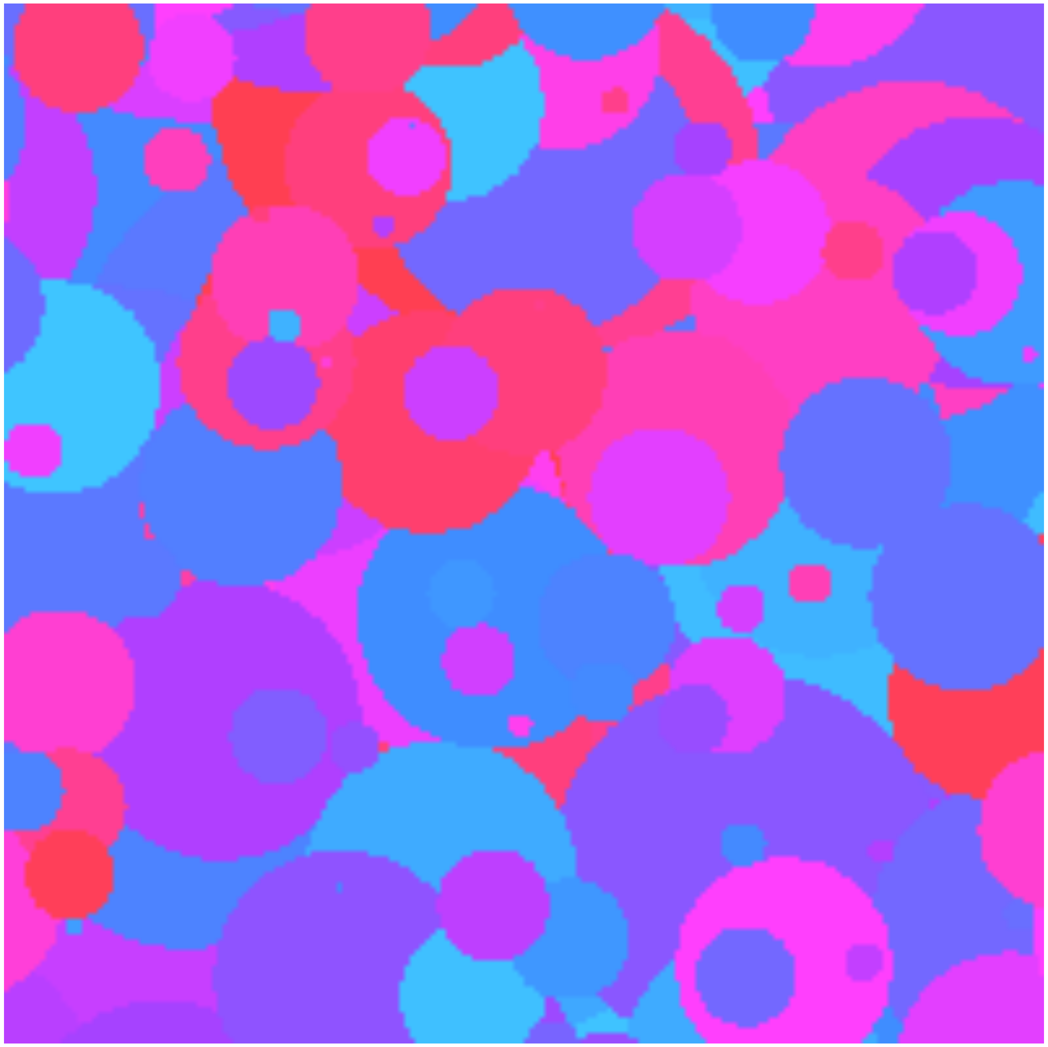


Inflation: Large Λ during an early phase



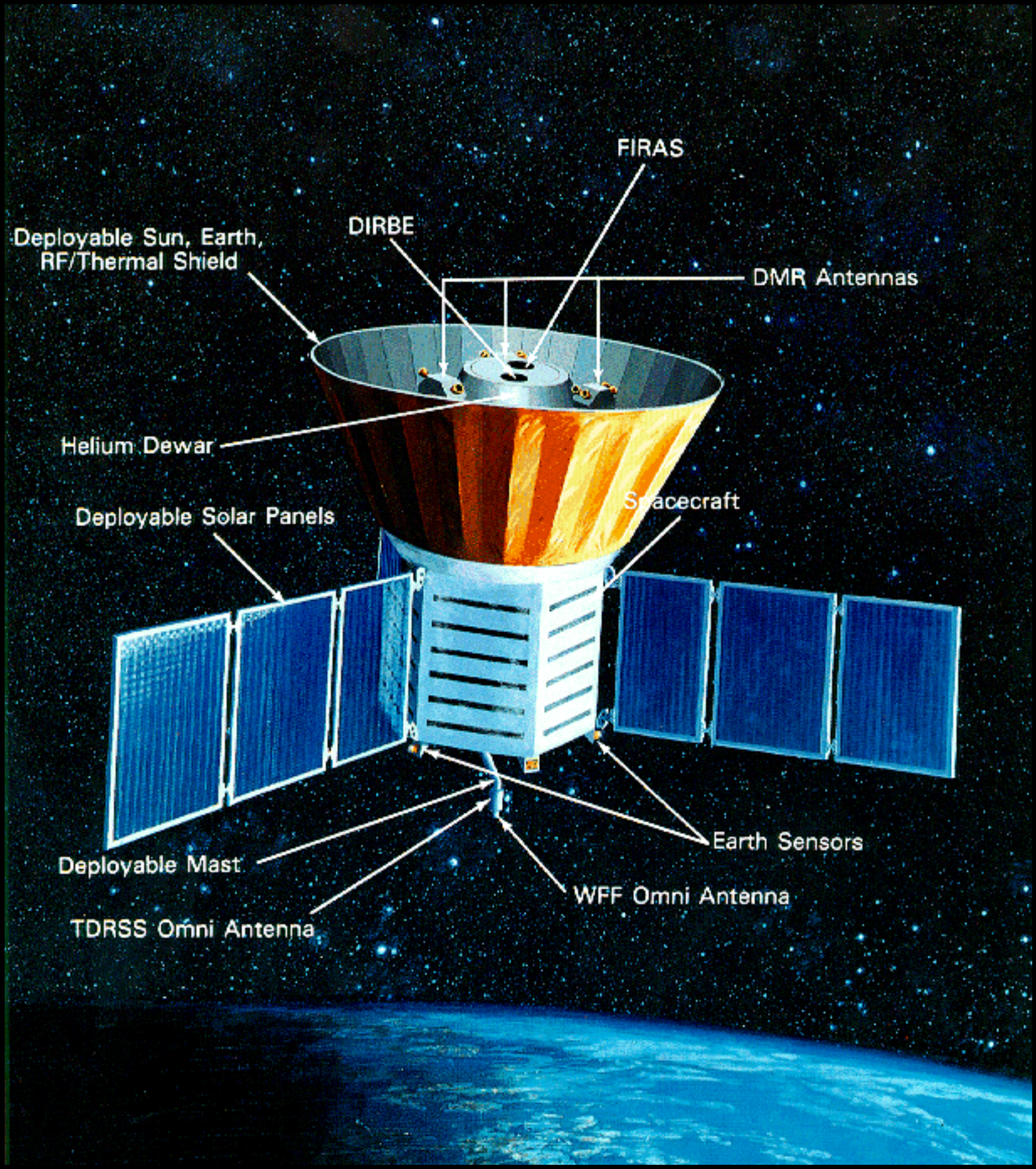
Animated View of Inflation

- 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).



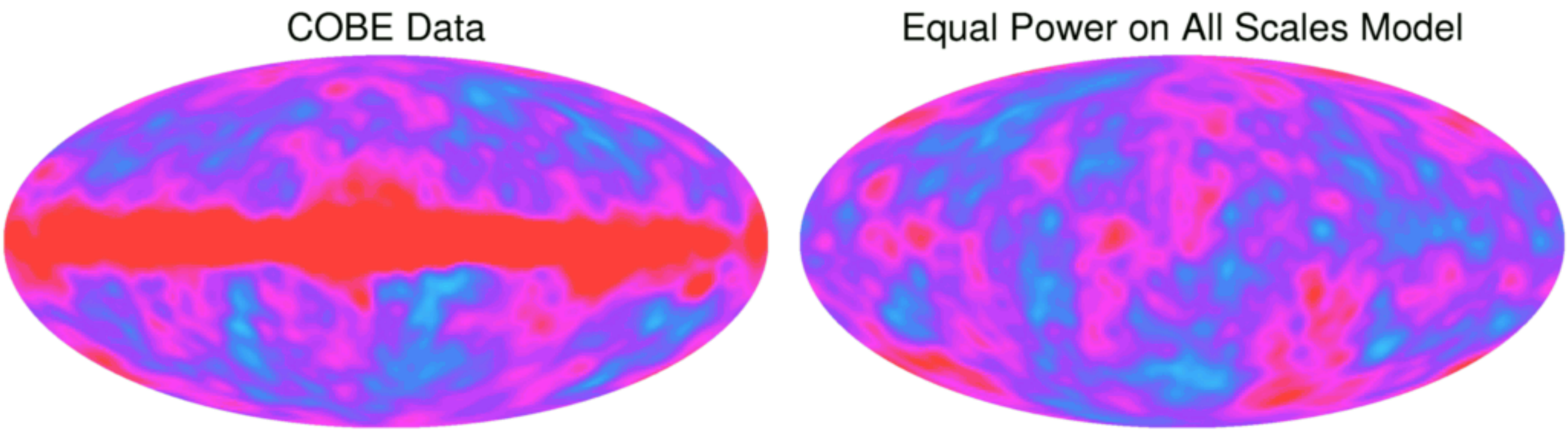
COBE Science Working Group

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



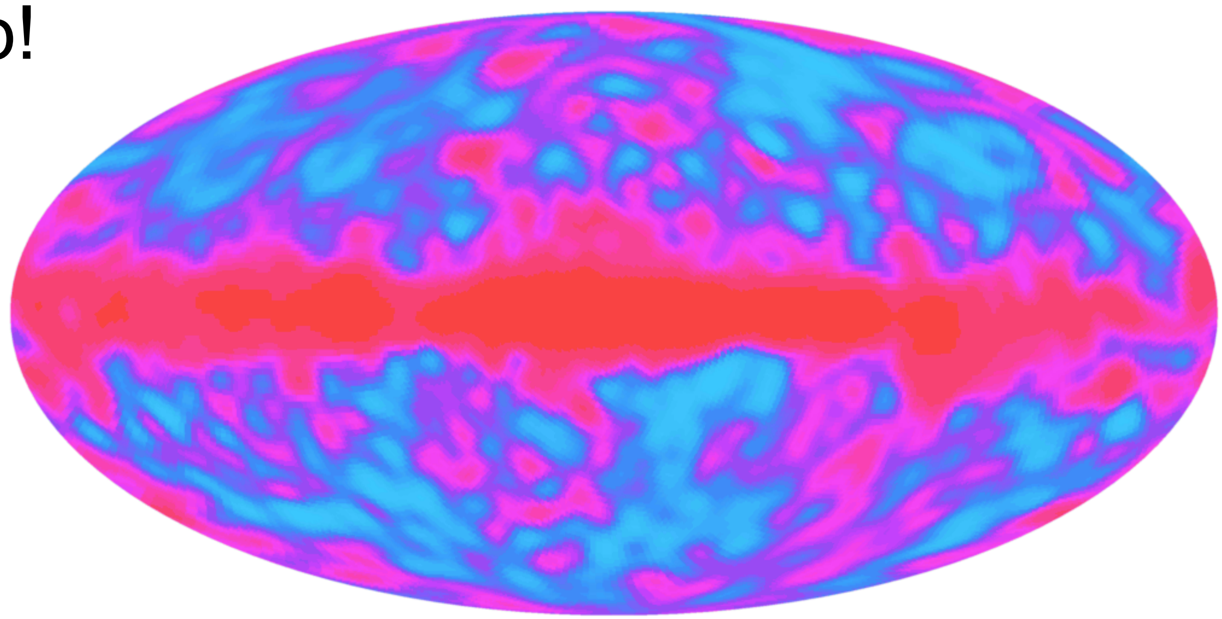
“Chi-by-eye” suggests that the “Equal Power on All Scales” prediction of inflation is correct.

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!

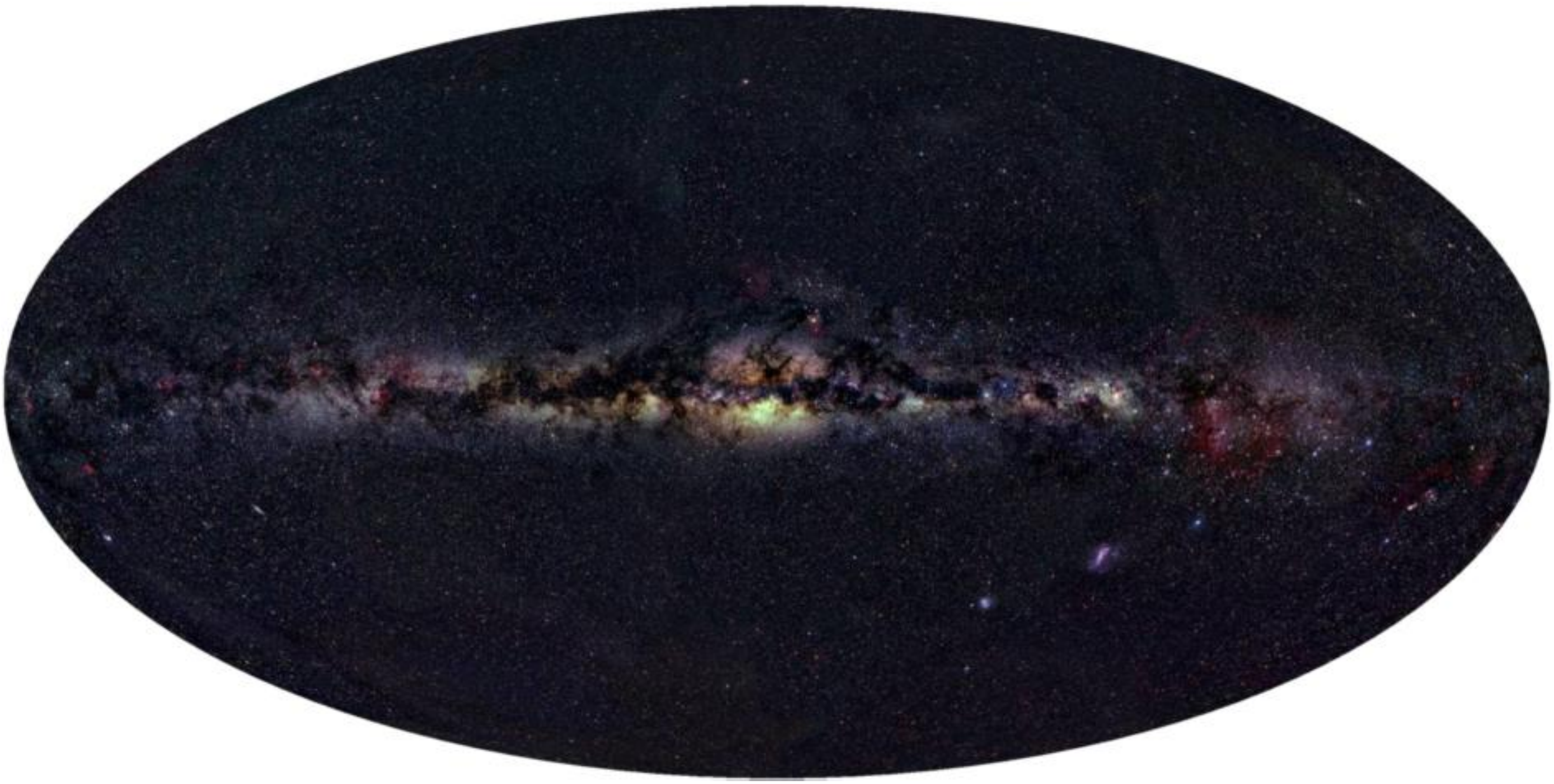


Mather & Smoot win the 2006 Physics Nobel prize

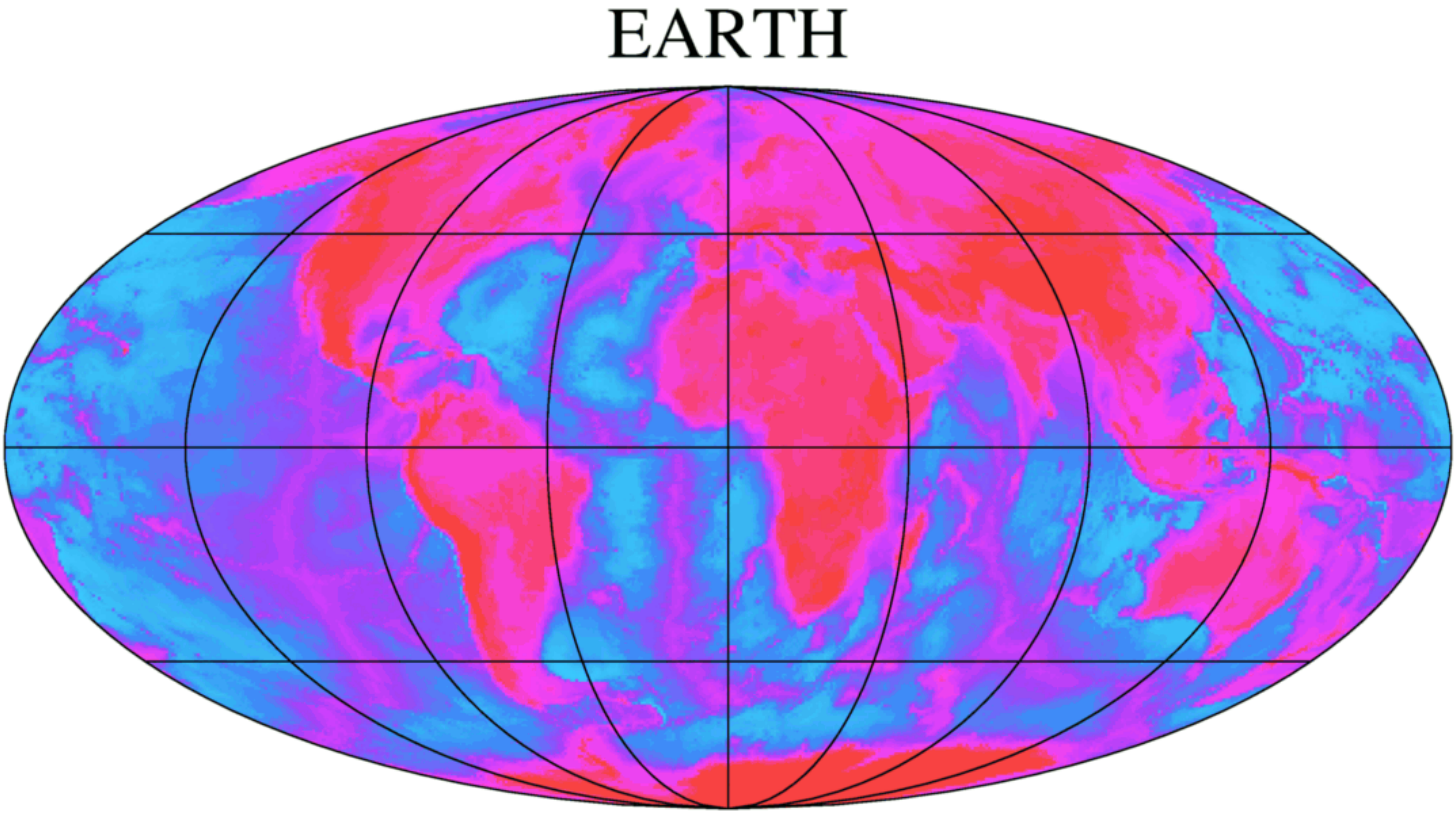
"You may have already won the Nobel Prize...."

492 American Scientist, Volume 86

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



An equal area projection:



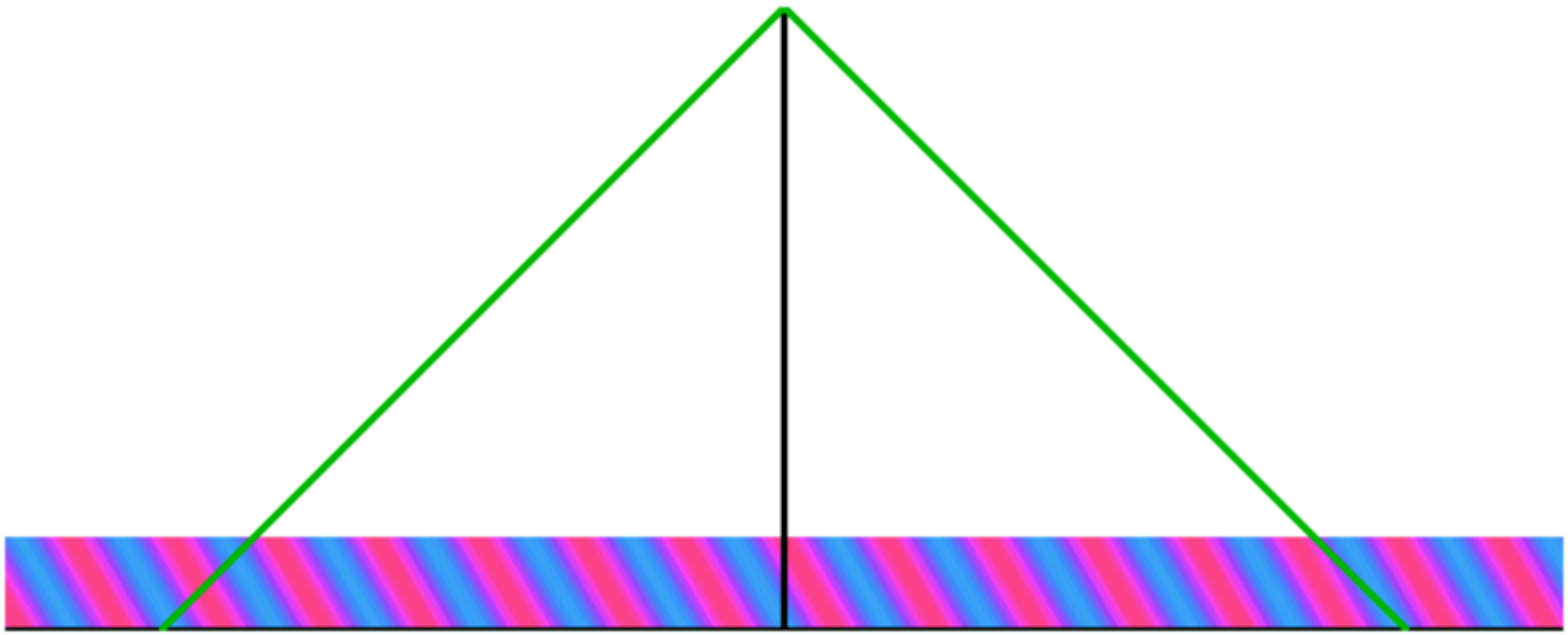
Color Means Temperature

- 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!

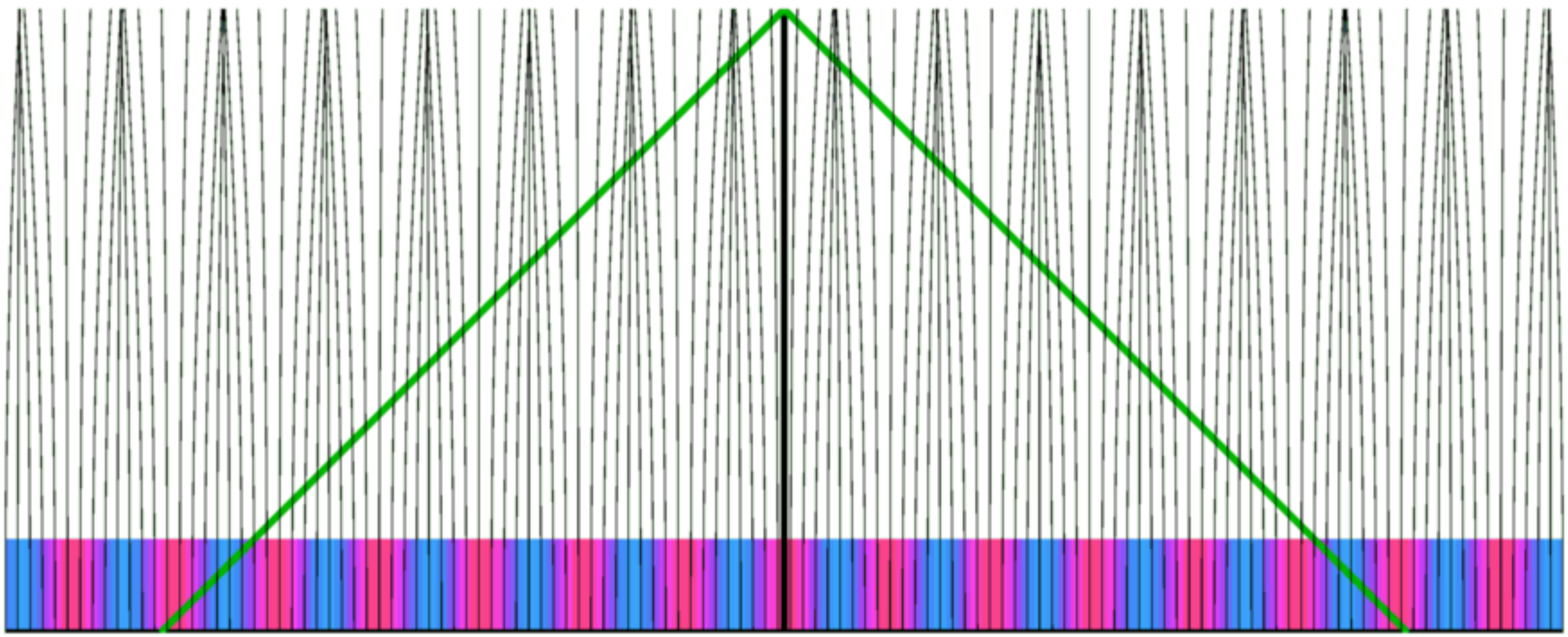
Two Fluids in the Early Universe

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

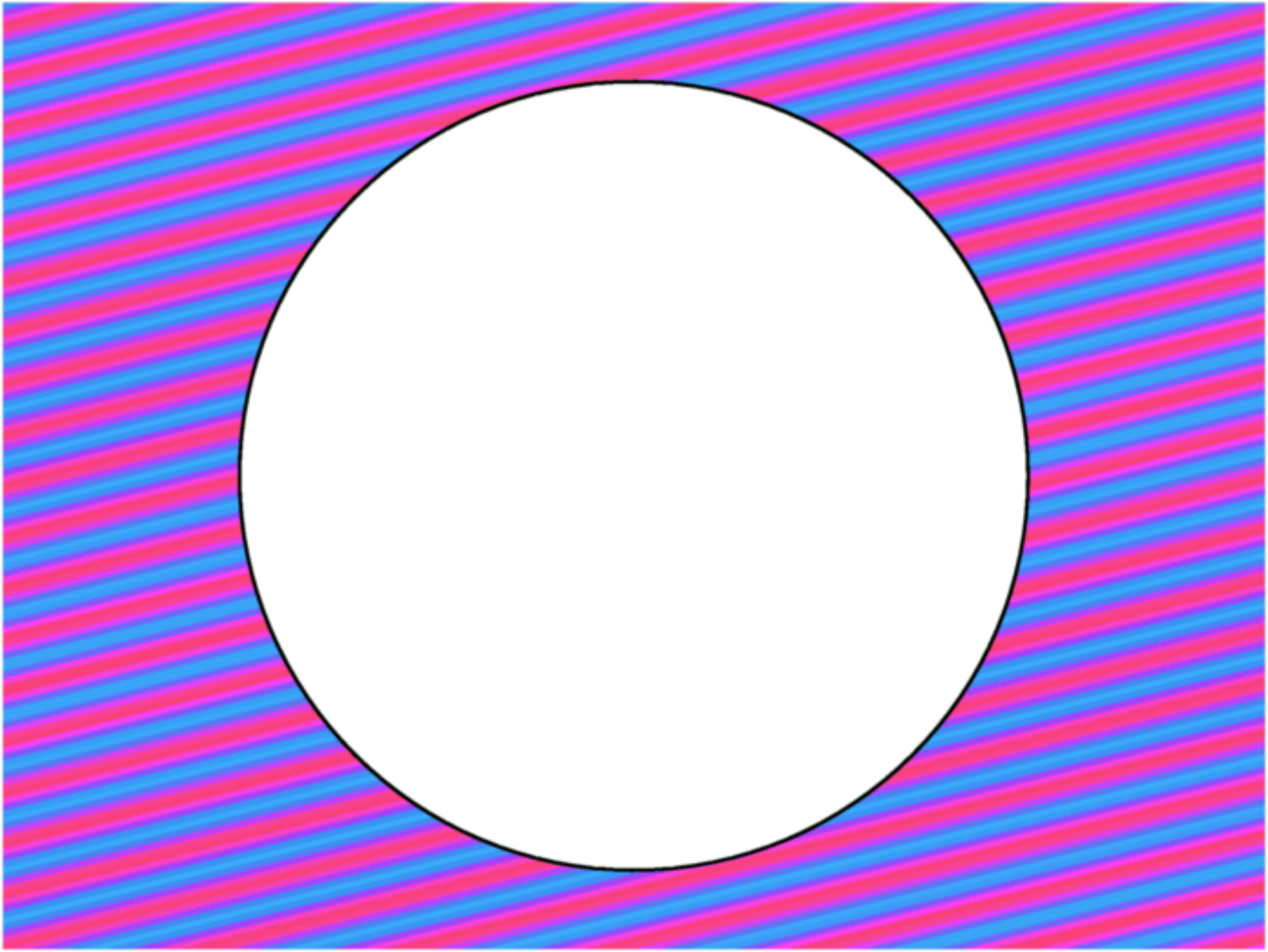


Stay at home Dark Matter

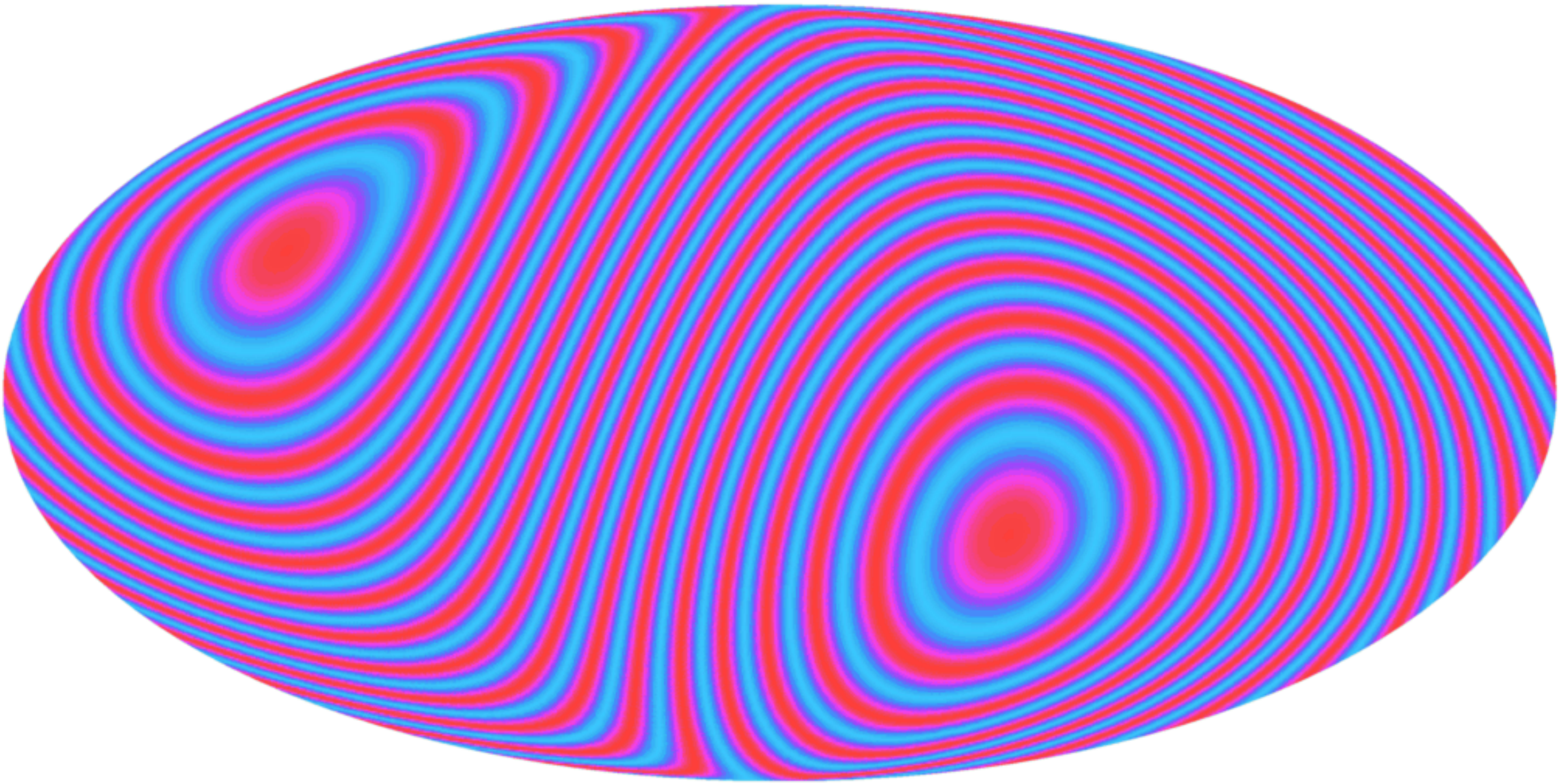


Interference at last scattering

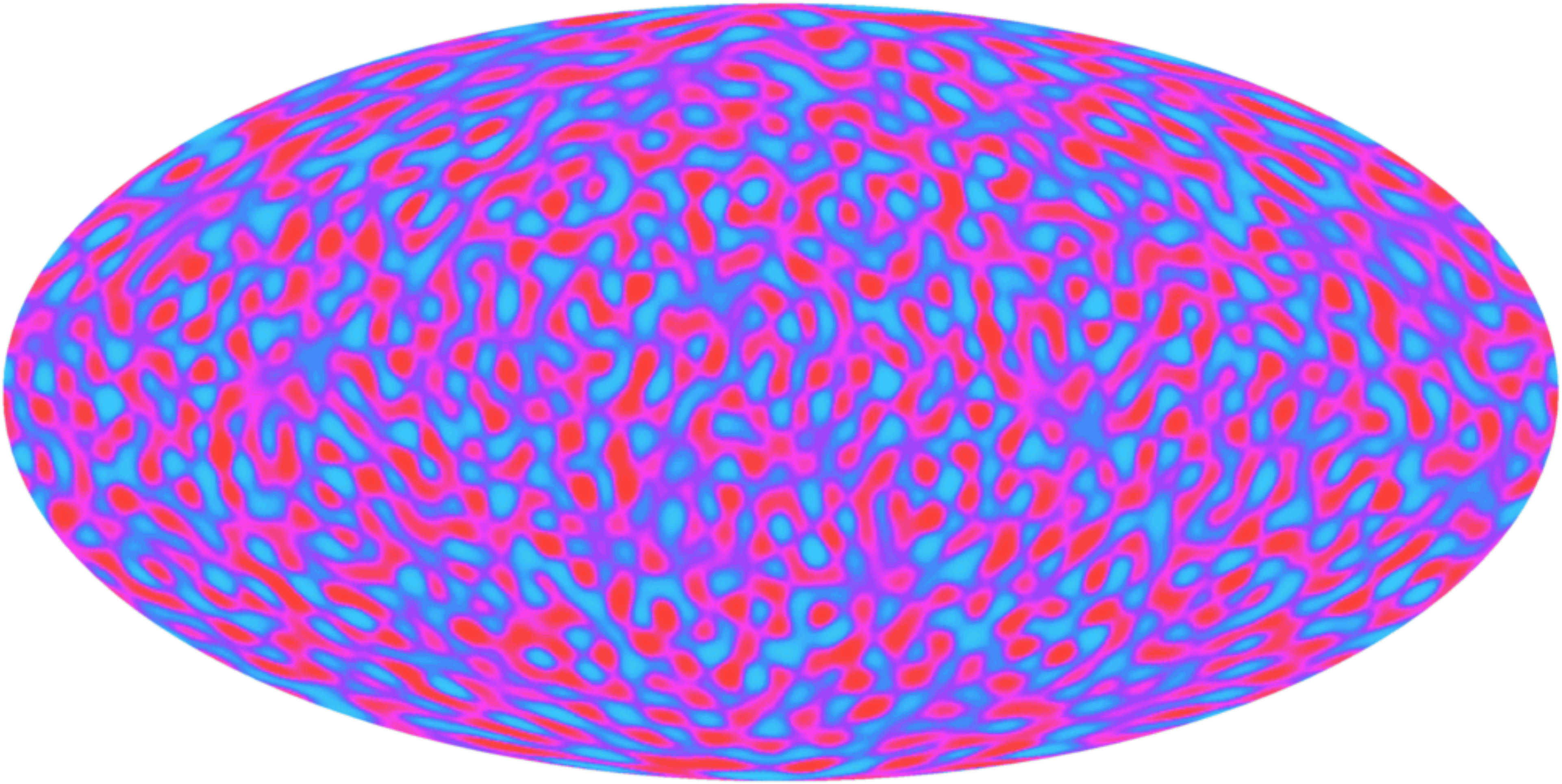
- For the wavelength illustrated [1/2 period between the Big Bang and recombination], the denser = hotter effect and potential well = cooler effect have gotten in phase.
- For larger wavelengths they are still out of phase at recombination.



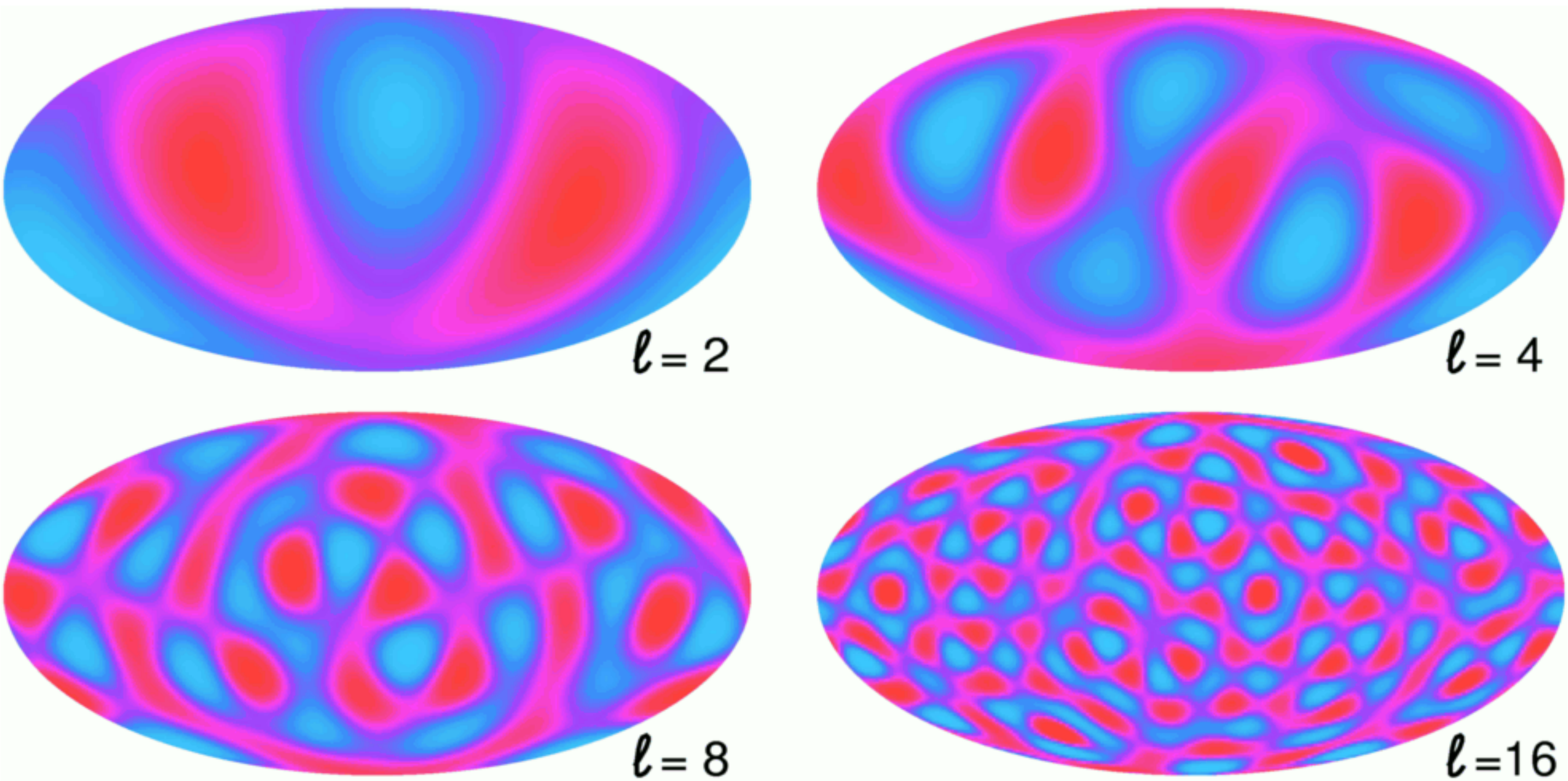
k*Rls = 50 plane wave



99 k*Rls=50 plane waves

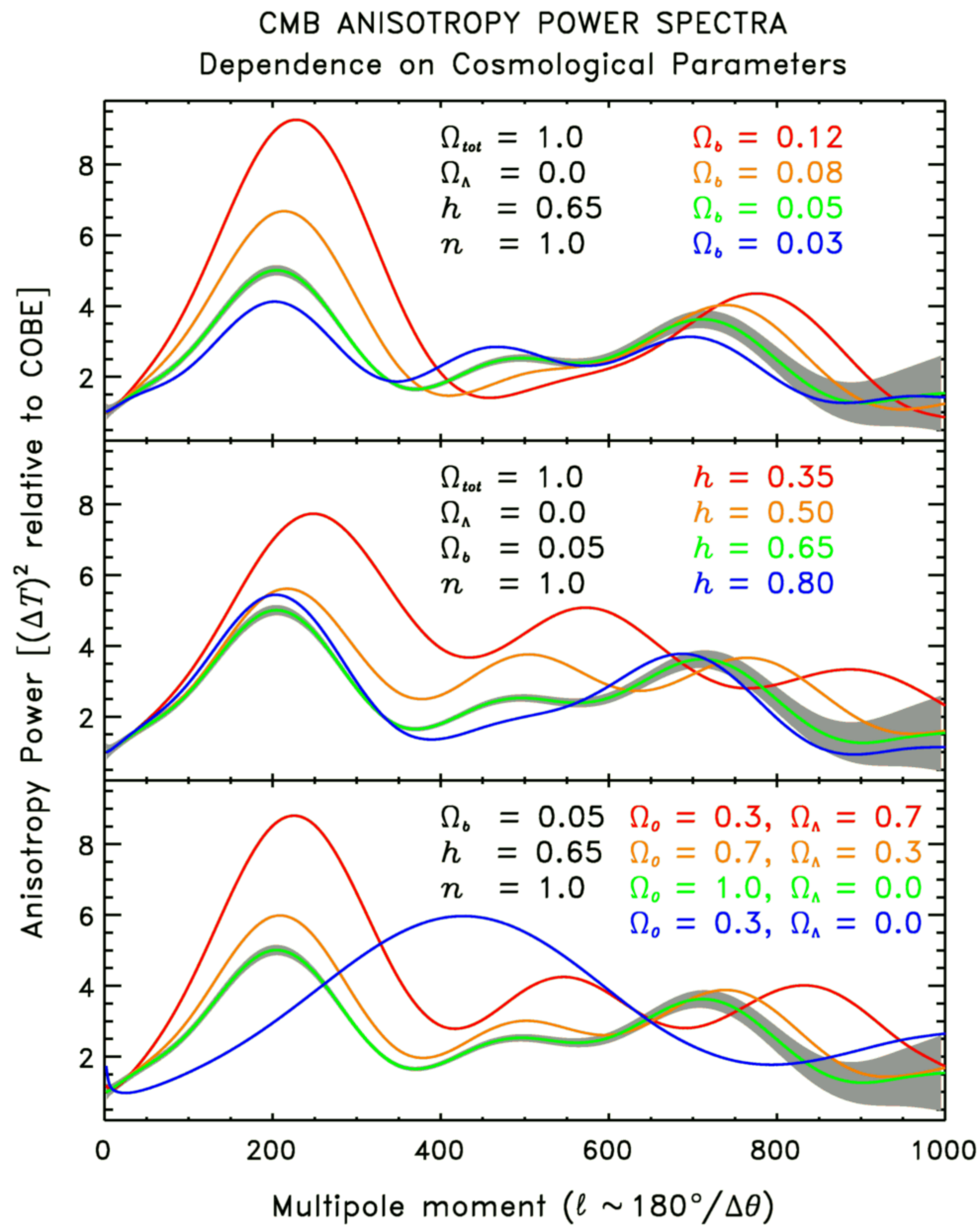


Spherical Harmonic Decomposition



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.



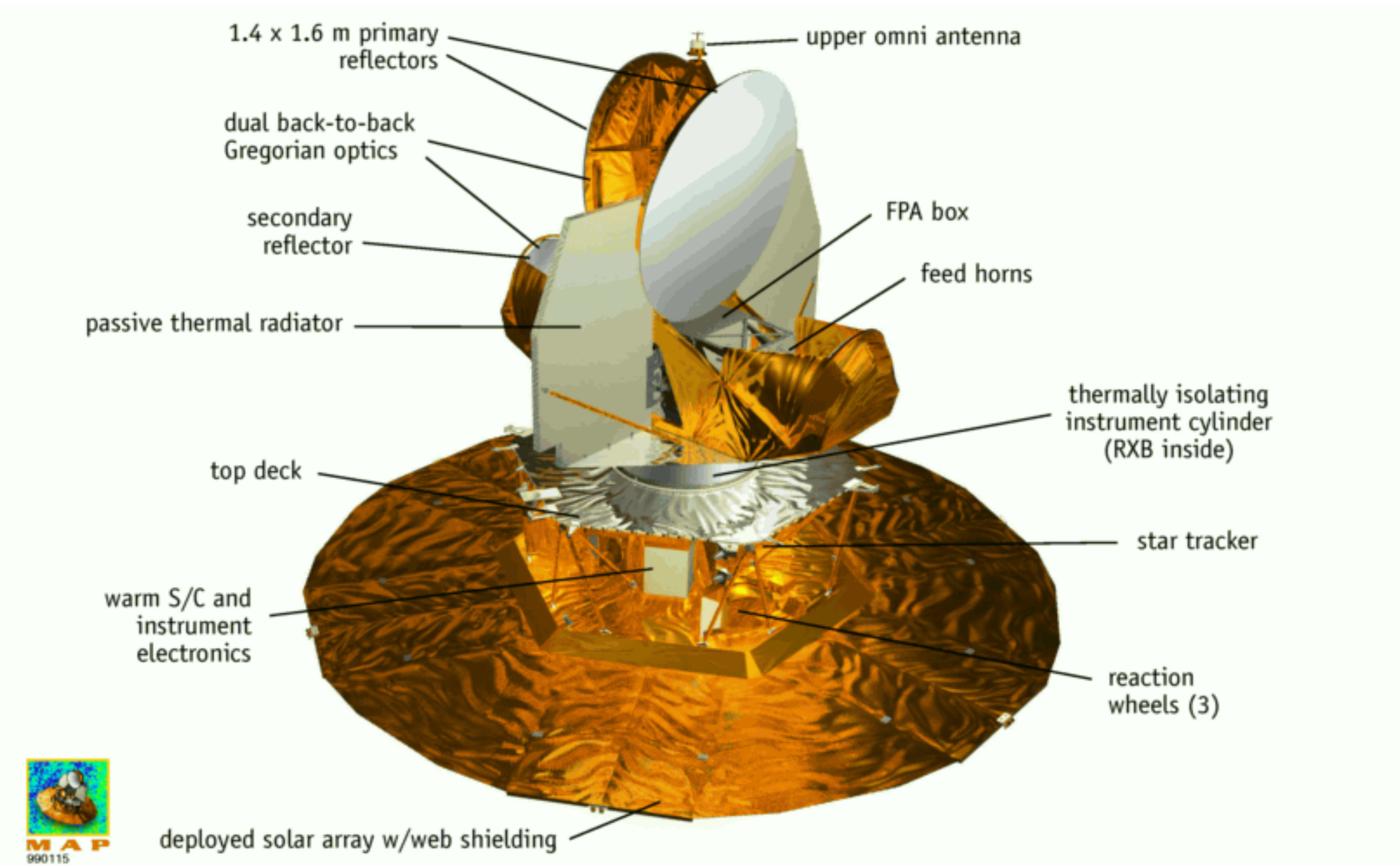
COBE View was Blurry

Sometimes higher resolution...

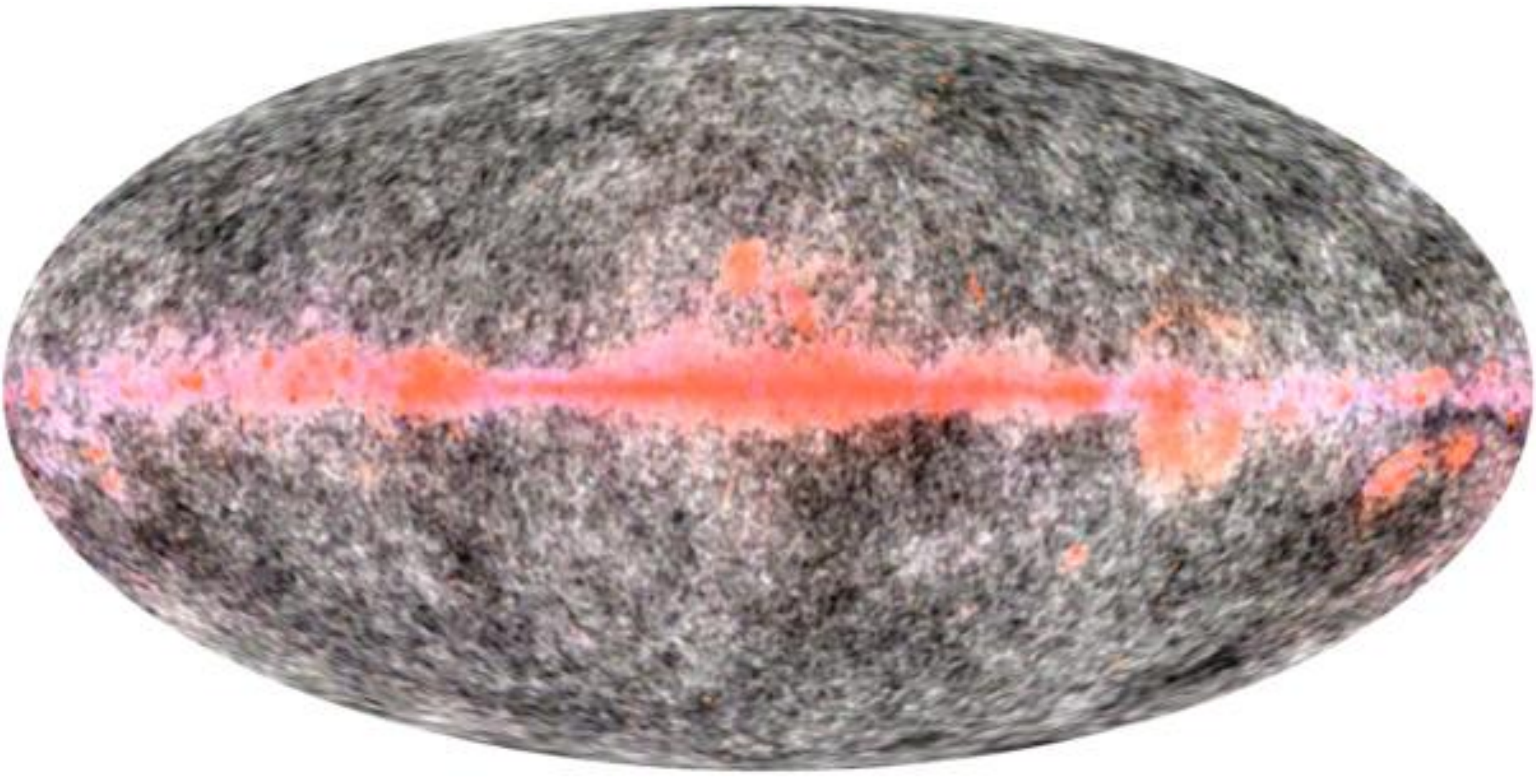
reveals the secret of the Universe

WMAP Science Working Group

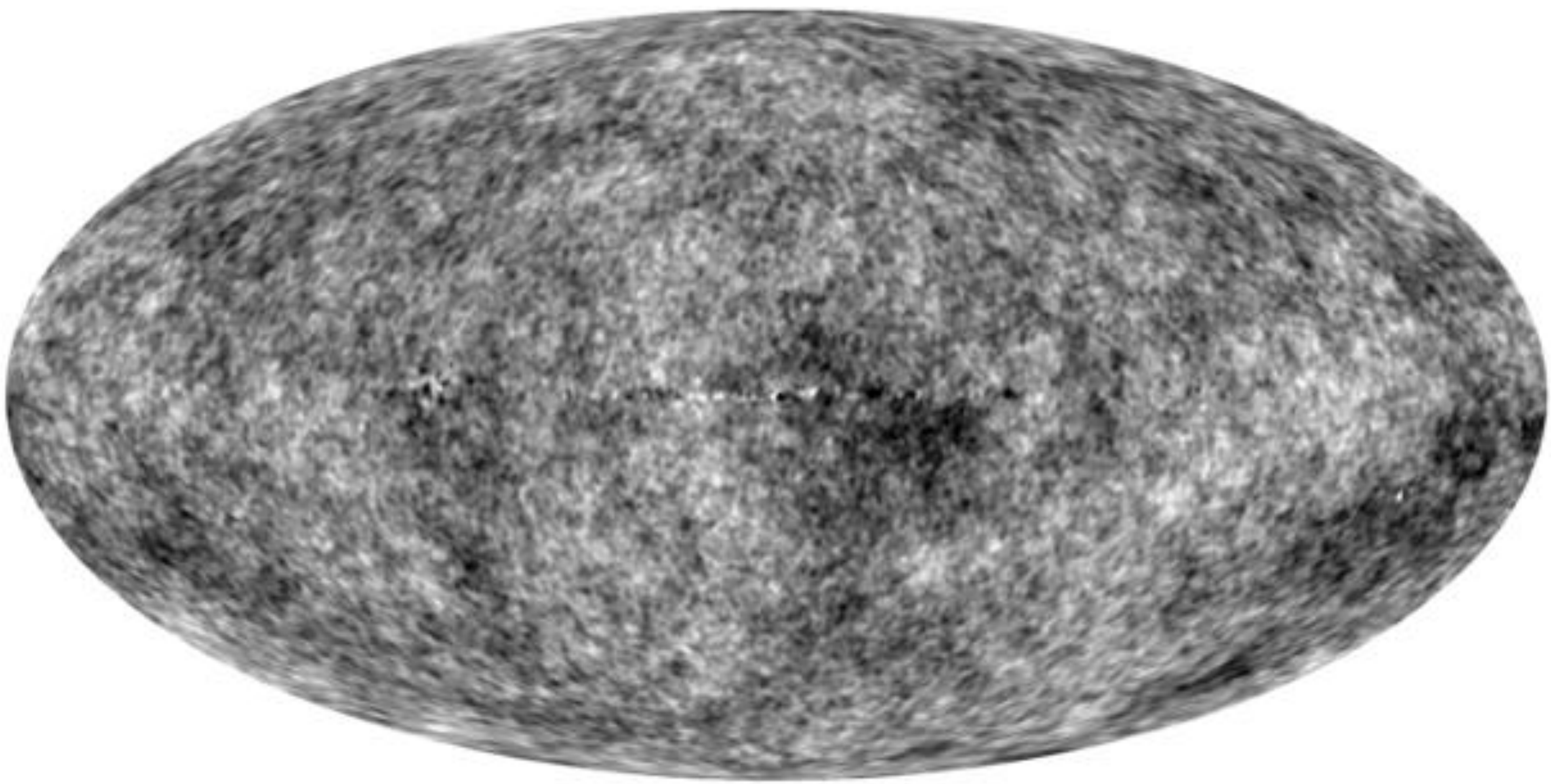
A New Cosmology Satellite



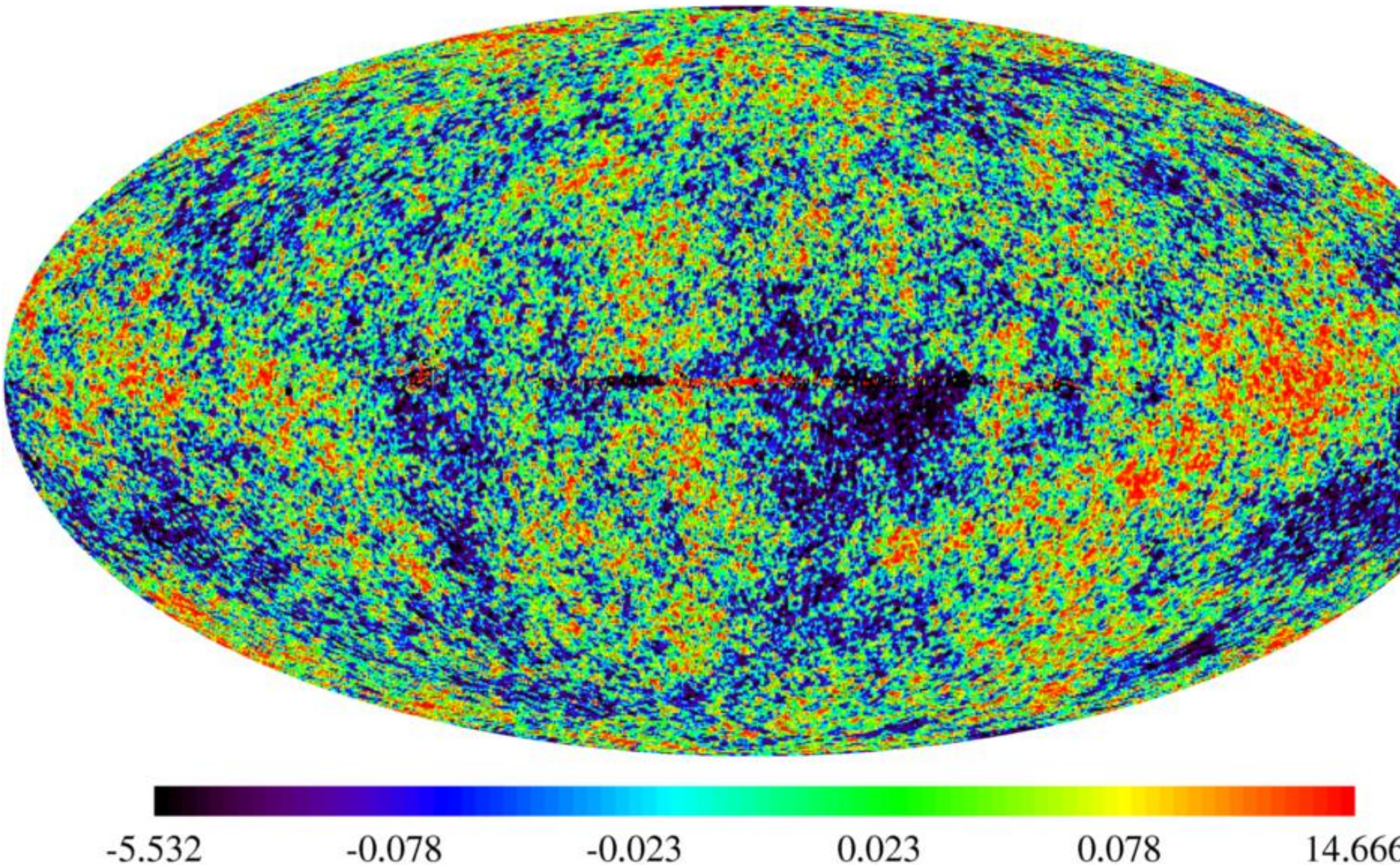
WMAP 7, 5 & 3 mm data as RGB



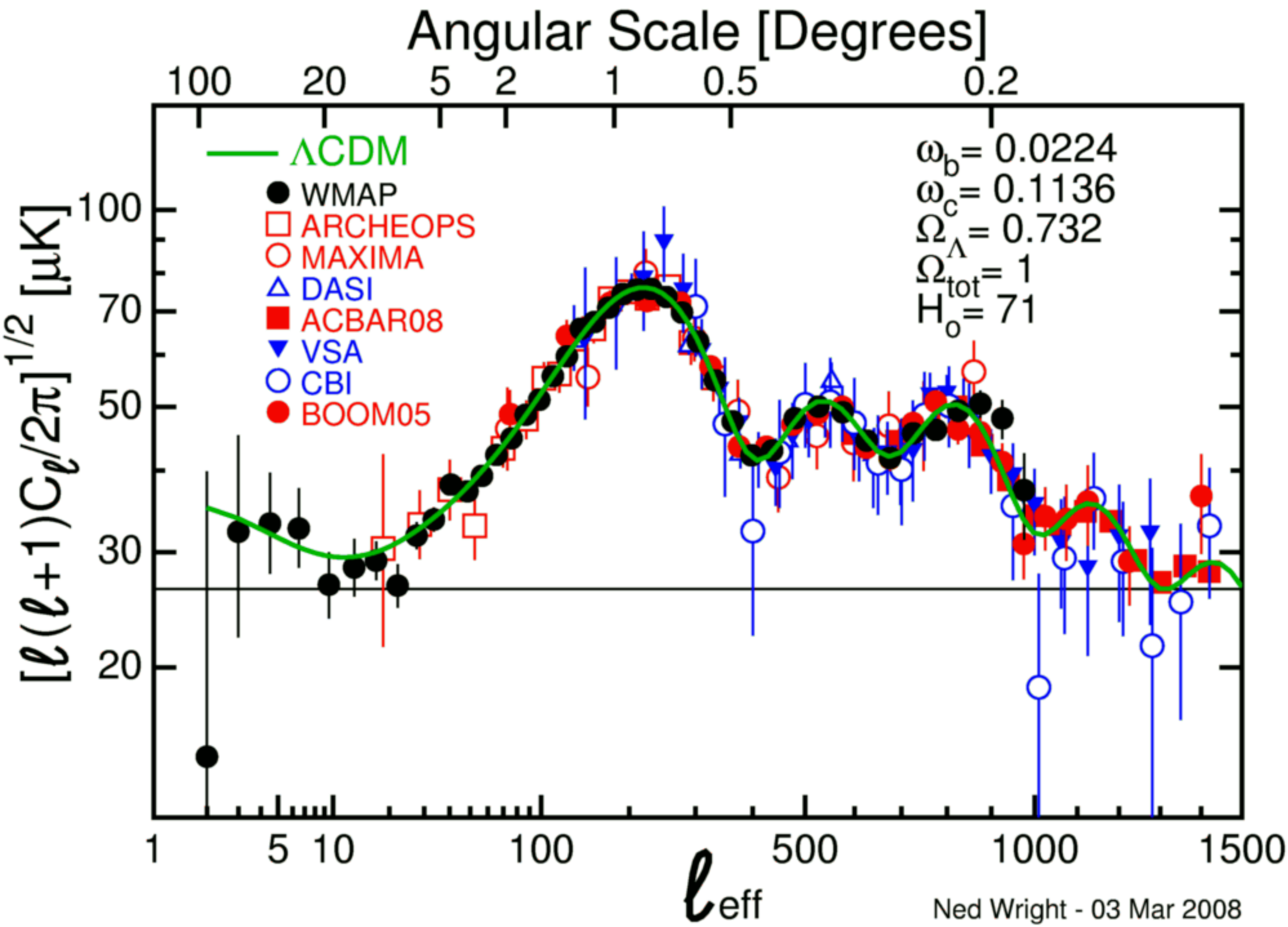
Combine maps to subtract galaxy



9 Years of WMAP Data



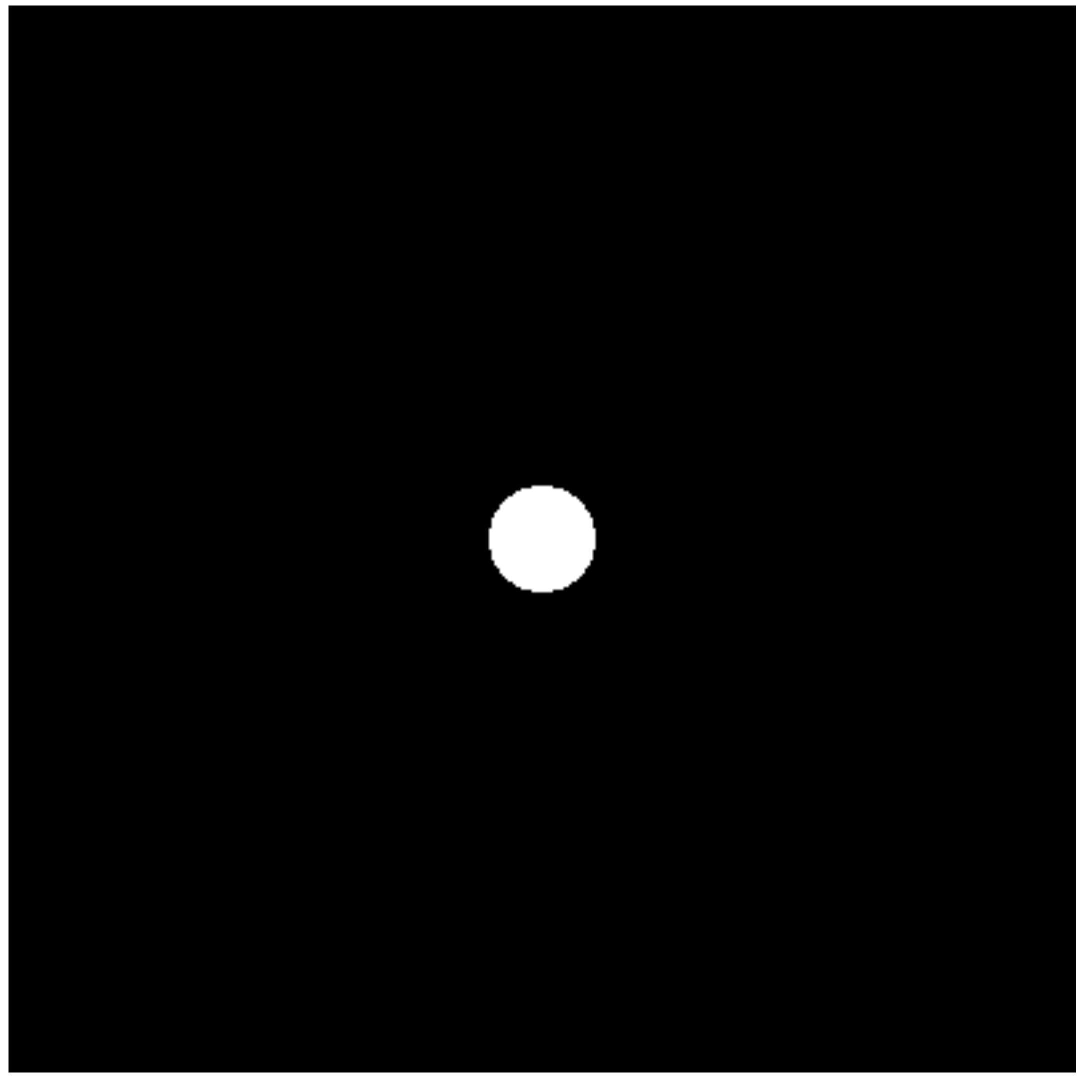
- Contrast enhanced by 19,000 times


Angular Scale [Degrees]
100
20
5
2
1
0.5
0.2
ΛCDM
WMAP
ARCHEOPS
MAXIMA
DASI
ACBAR08
VSA
CBI
BOOM05
ω_b= 0.0224
ω_c= 0.1136
Ω_Λ= 0.732
Ω_{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

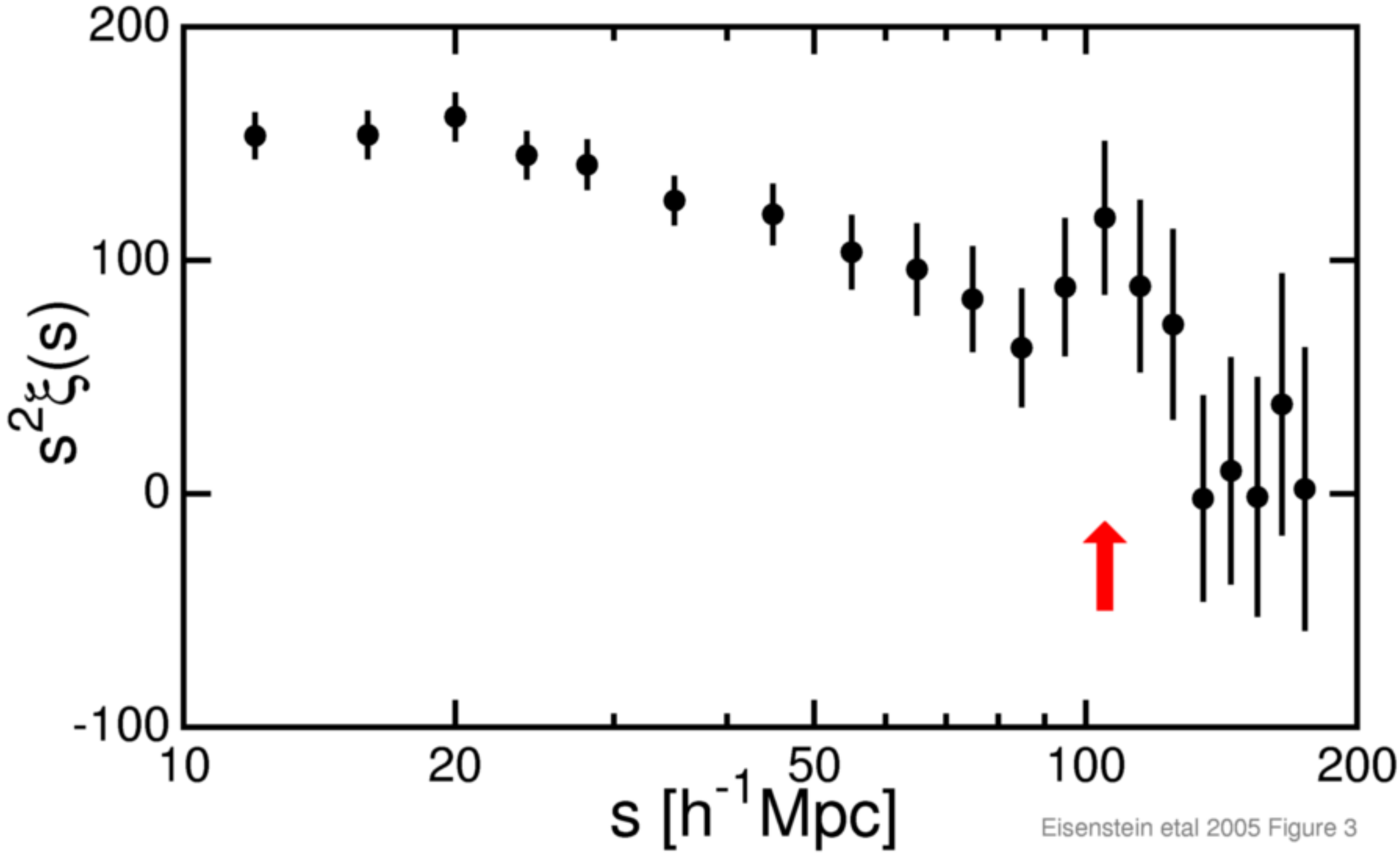
Spreading Sphere of Sound

The baryon-photon fluid spreads out in an expanding spherical shell surrounding the cold dark matter which does not move. After recombination, the Universe becomes transparent and the photons exit the shell, leaving a spherical density enhancement which should show up as a sharp feature in the 3D two-point correlation function at a radius equal to the distance sound could travel before recombination.

This is the same scale involved in the acoustic peaks of the CMB angular power spectrum.

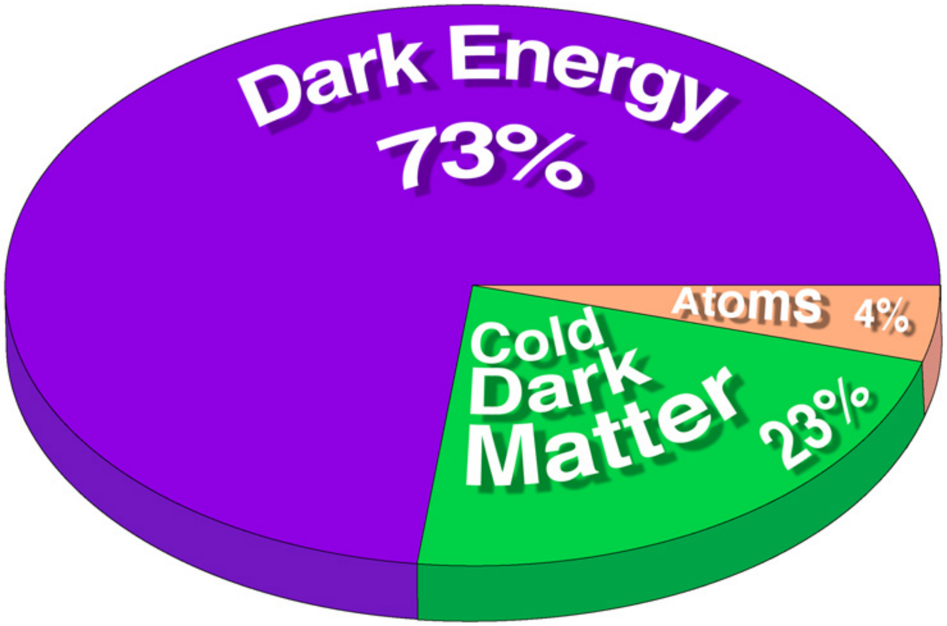


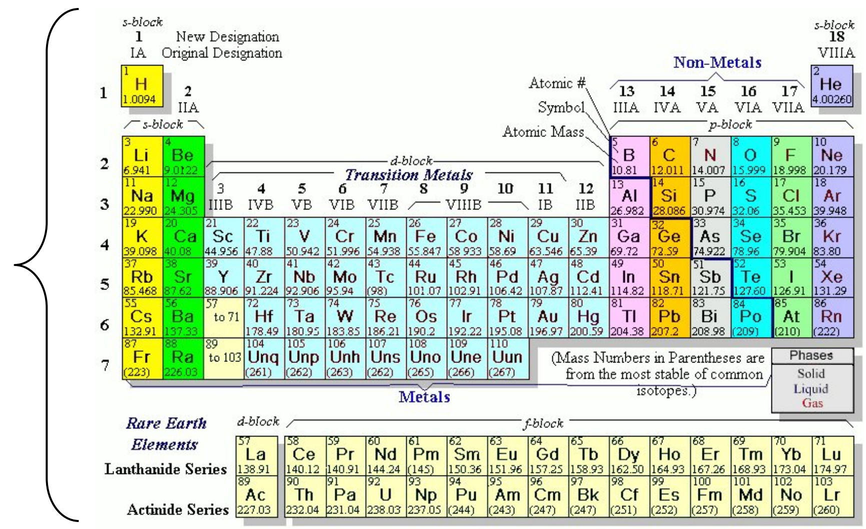
Baryonic Oscillations in SDSS LRGs



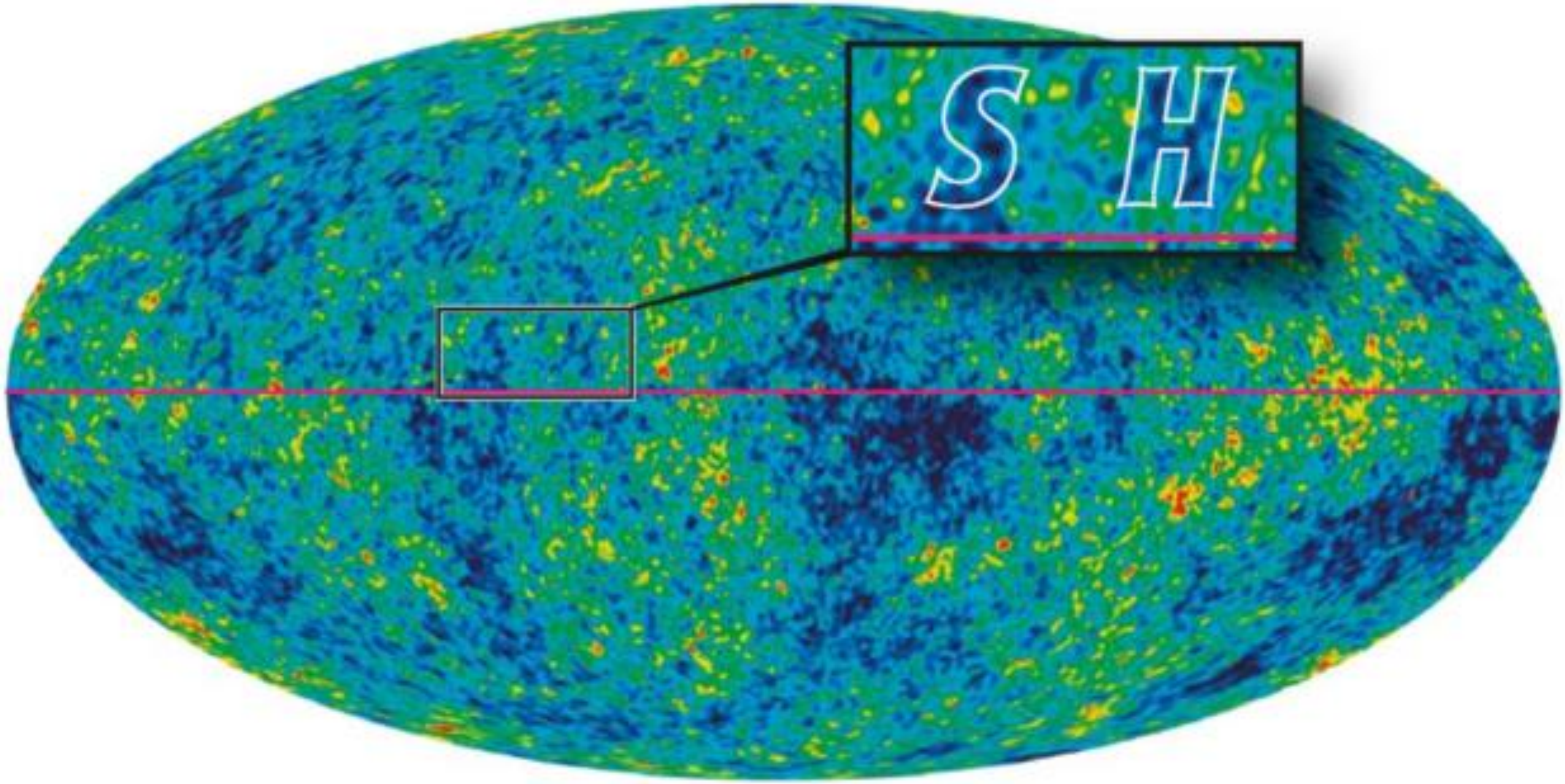
Eisenstein etal 2005 Figure 3

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



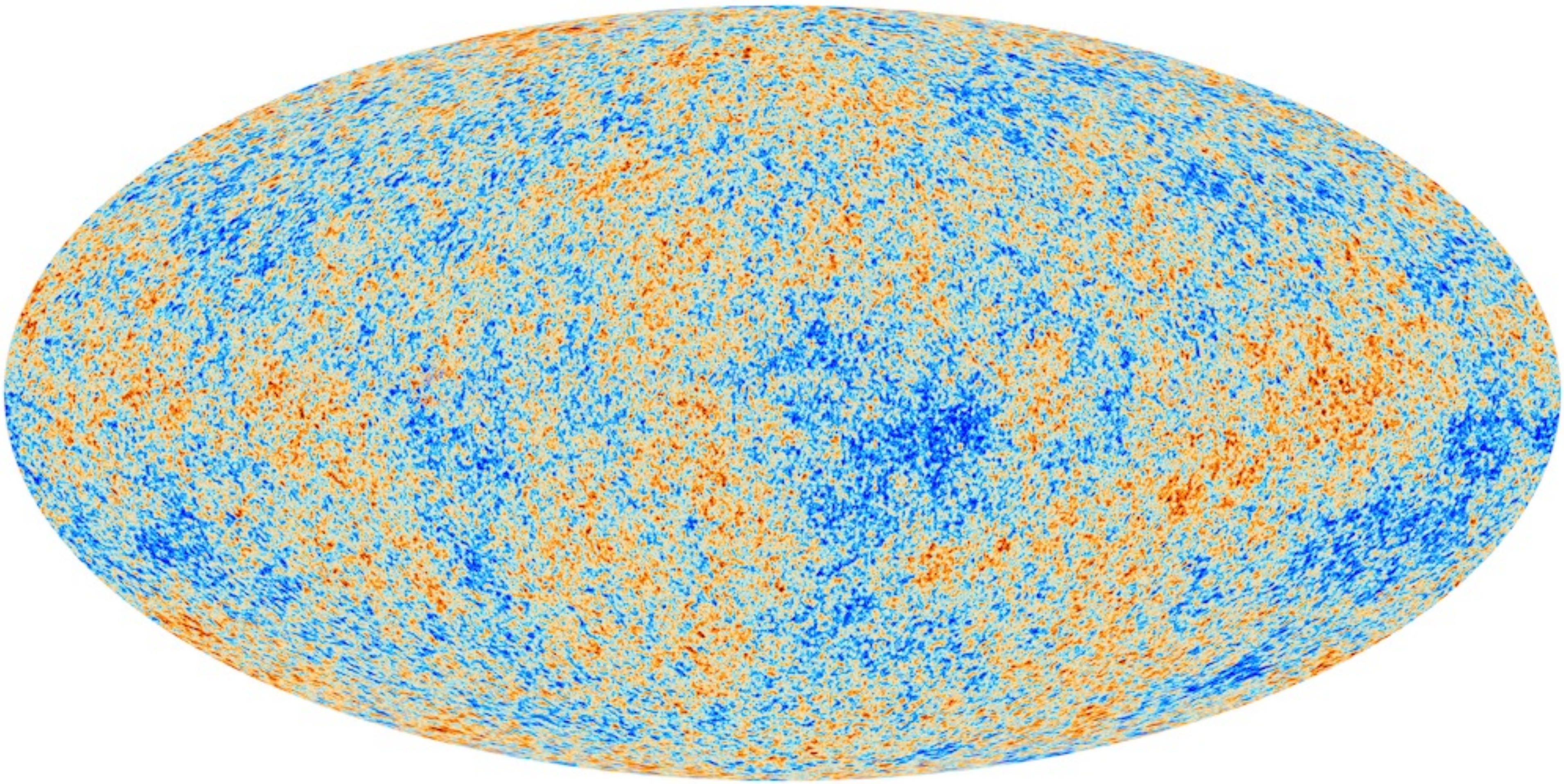


CONCLUSION



- The real discovery of the century: Stephen Hawking's initials on the CMB sky.

SH not so obvious in Planck map



6 parameter ΛCDM is still a good fit

Planck Core Science Team

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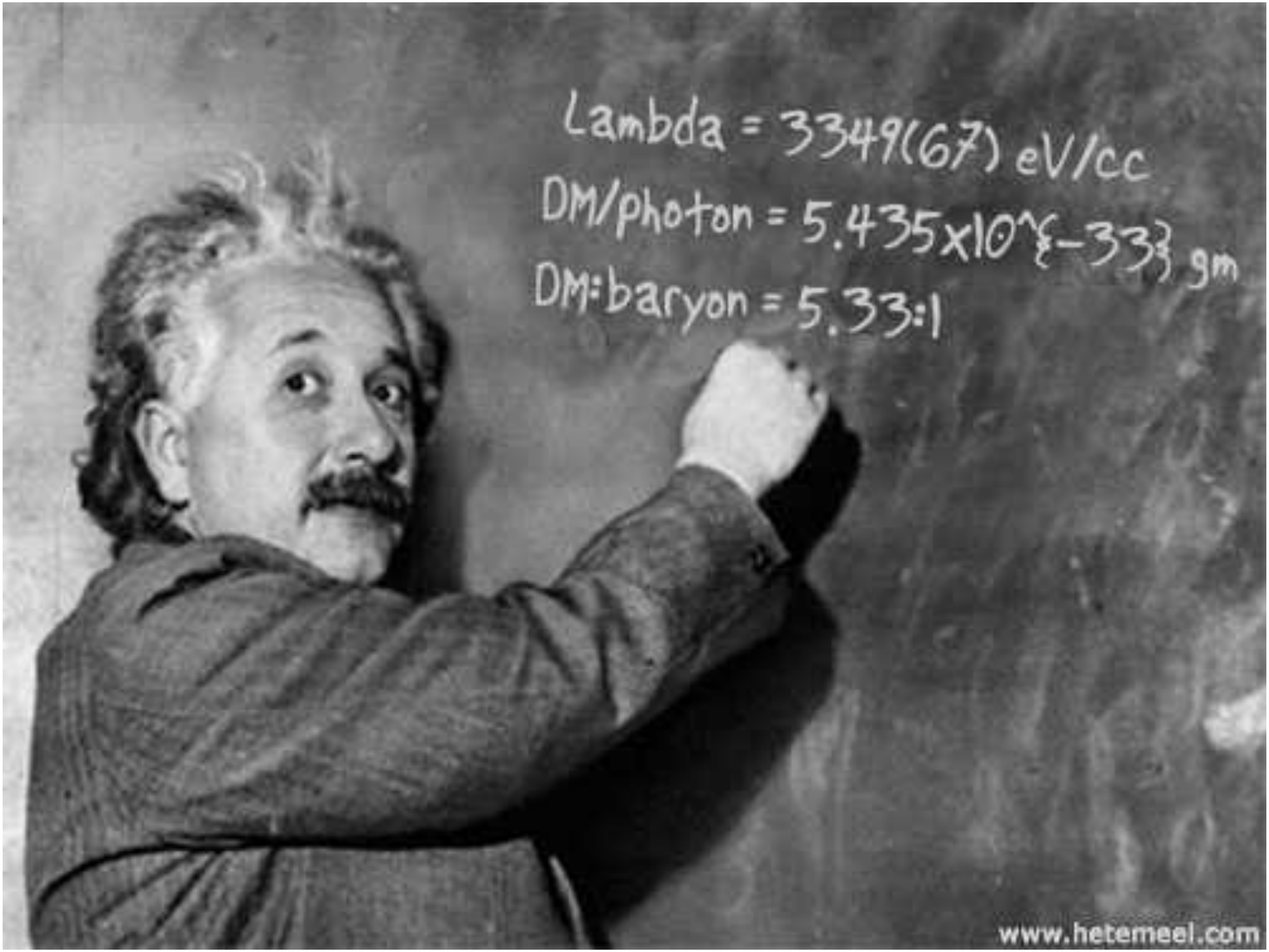
Lambda = 3349(67) eV/cc
DM/photon = 5.435x10^{-33} gm
DM:baryon = 5.33:1
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