Taking an Inventory of the Baryon + Dark Matter Content of the Universe

+

What can we learn from cosmic microwave background?

Layout of the Course

Feb 3: Introduction / Overview / General Concepts
Feb 5: Age of Universe / Distance Ladder / Hubble Constant
Feb 10: Distance Ladder / Hubble Constant Distant Measures
Feb 12: SNe science / Baryonic Content / Dark Matter Content of Universe
Feb 17: Dark Matter + Cosmic Microwave Background
Feb 19: Cosmic Microwave Background
Feb 26: Large Scale Structure / Baryon Acoustic Oscillations
Mar 5: Dark Energy / Clusters
Mar 12: Cosmic Shear / Dark Energy Missions
Mar 19: No Class
Mar 26: Review for Final Exam

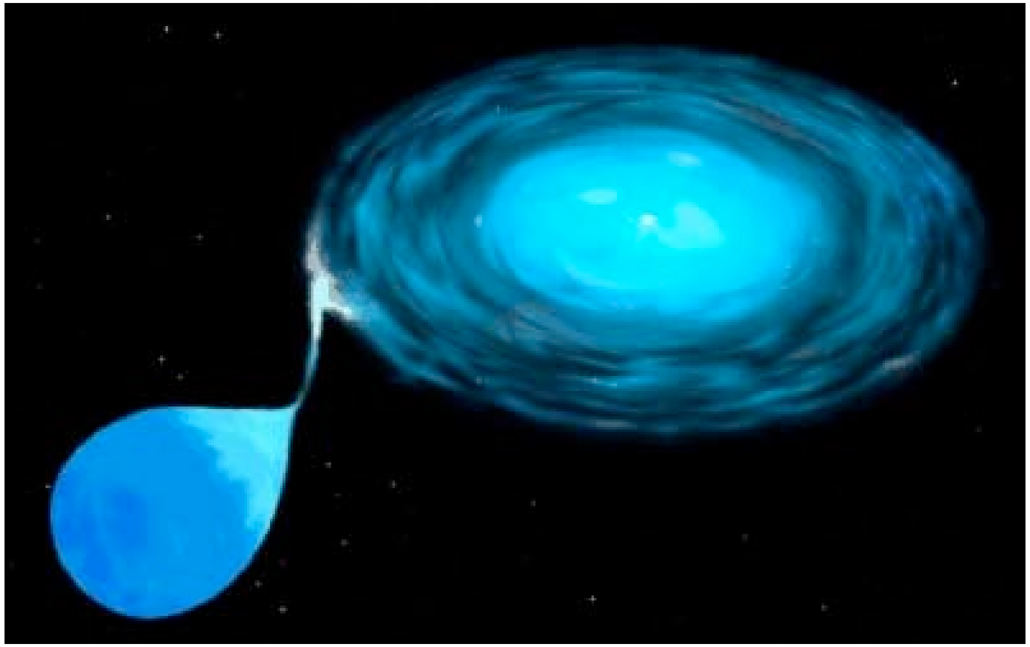
Apr 11: Final Exam

This Week

Review Material from Last Week

Supernovae Ia

Accretion of matter from a nearby companion onto a white dwarf

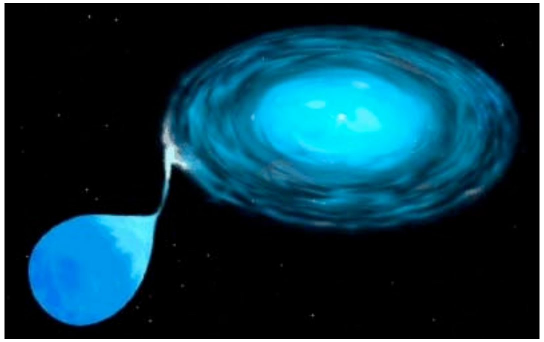


-- Likely occurs when a white dwarf is pushed over the Chandrashekhar limit of >1.4 M_{solar} by accretion from a nearby companion

Exceeding the Fermi pressure, inverse beta decay occurs:

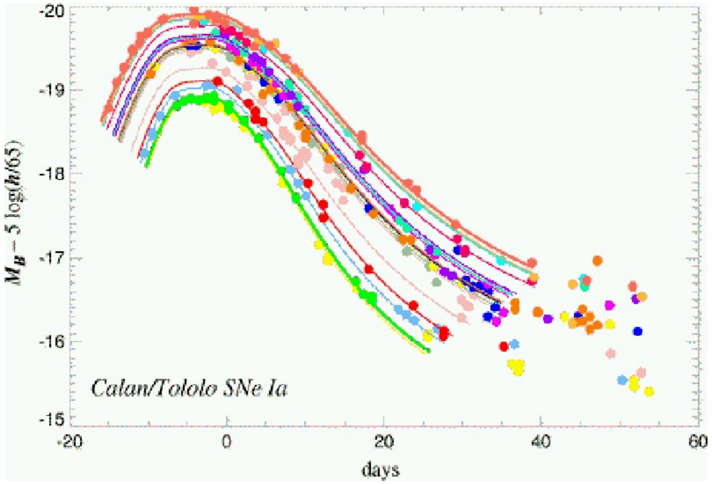
$$p + e^{-} \rightarrow n + \nu_e + \gamma$$

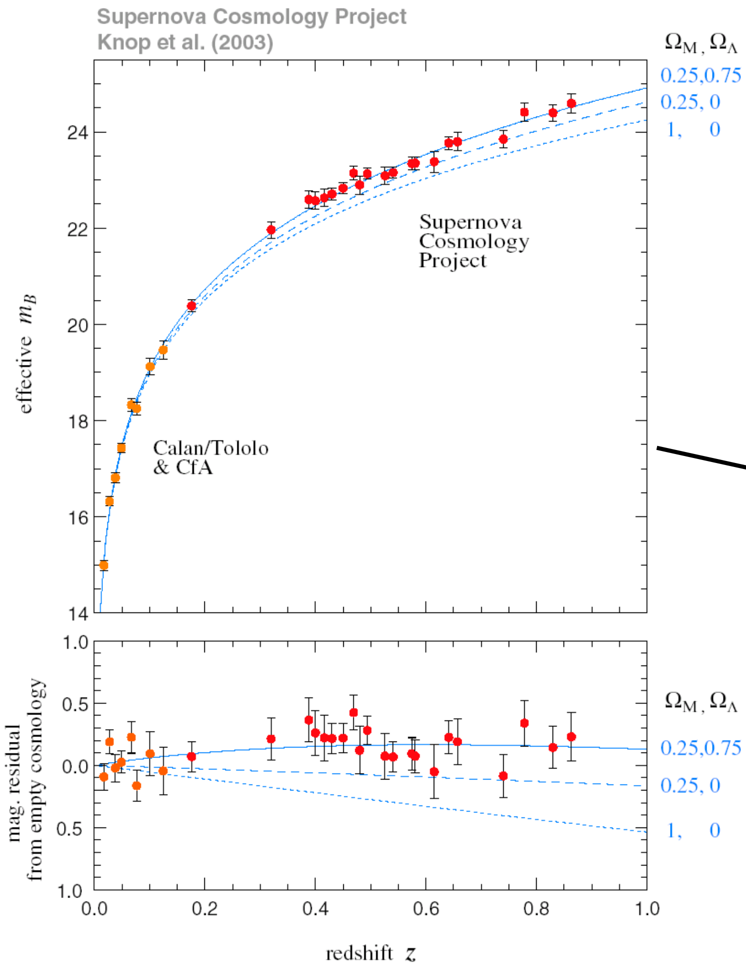
Insight into Topology of Universe from SNIa

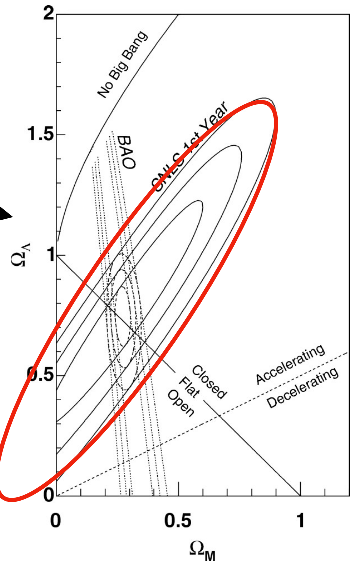


Accretion of matter from a nearby companion onto a white dwarf

The luminosity of Supernovae Ia varies somewhat depending upon the decay time for the light curve







Cosmological parameter constraints derived from the same data.

Error contours clearly prefer Ω_Λ values greater than 0

What is the Baryonic mass density of the universe?

(summary)

$$\Omega_{stars} = 0.002$$

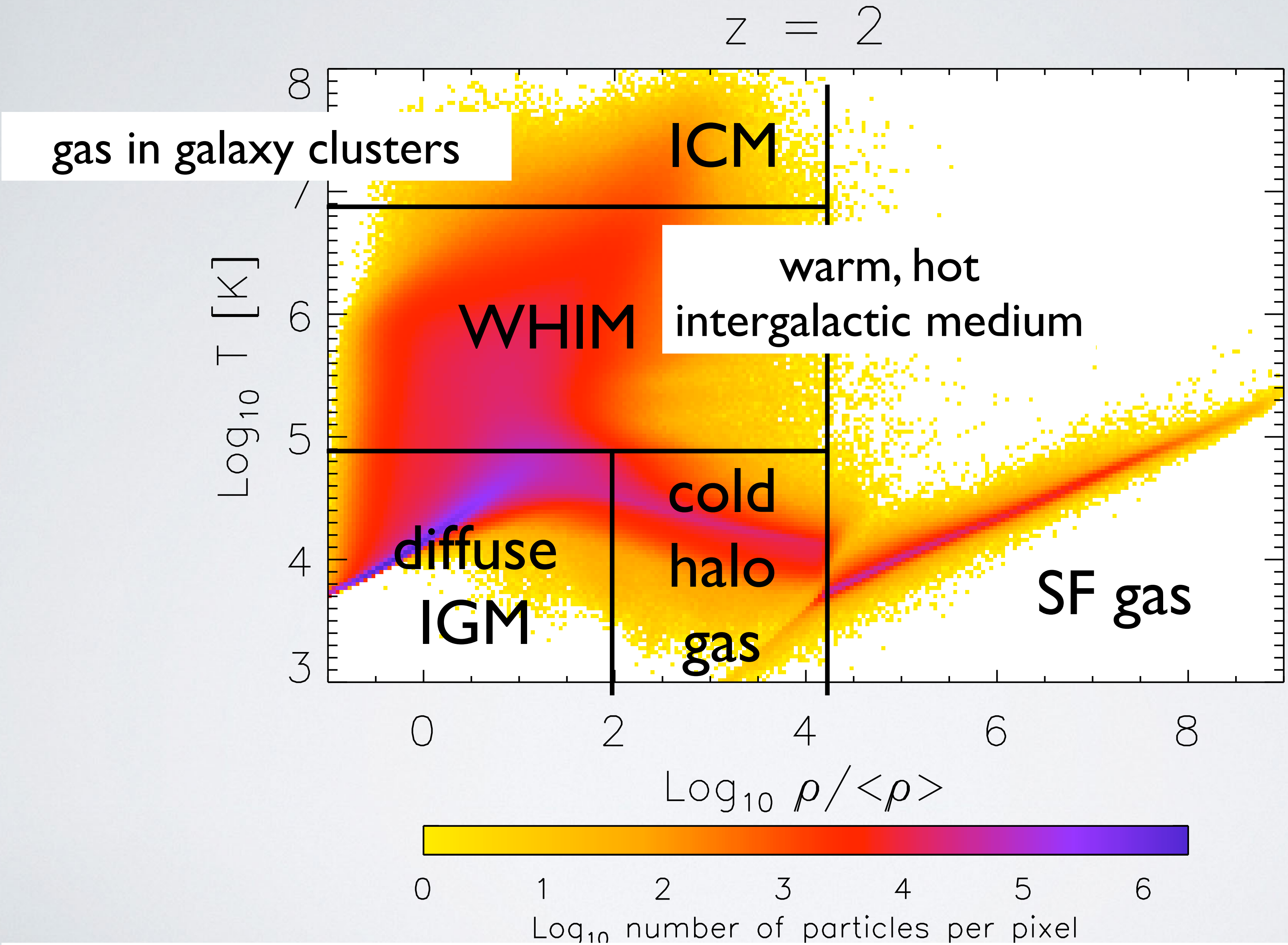
$$\Omega_{cold\ gas,\ HI} = 0.0003$$

$$\Omega_{cold\ gas,\ molecular\ hydrogen} = 0.0003$$

$$\Omega_{ionized\ hydrogen} = 0.02$$ (But with large ±0.02 uncertainties)

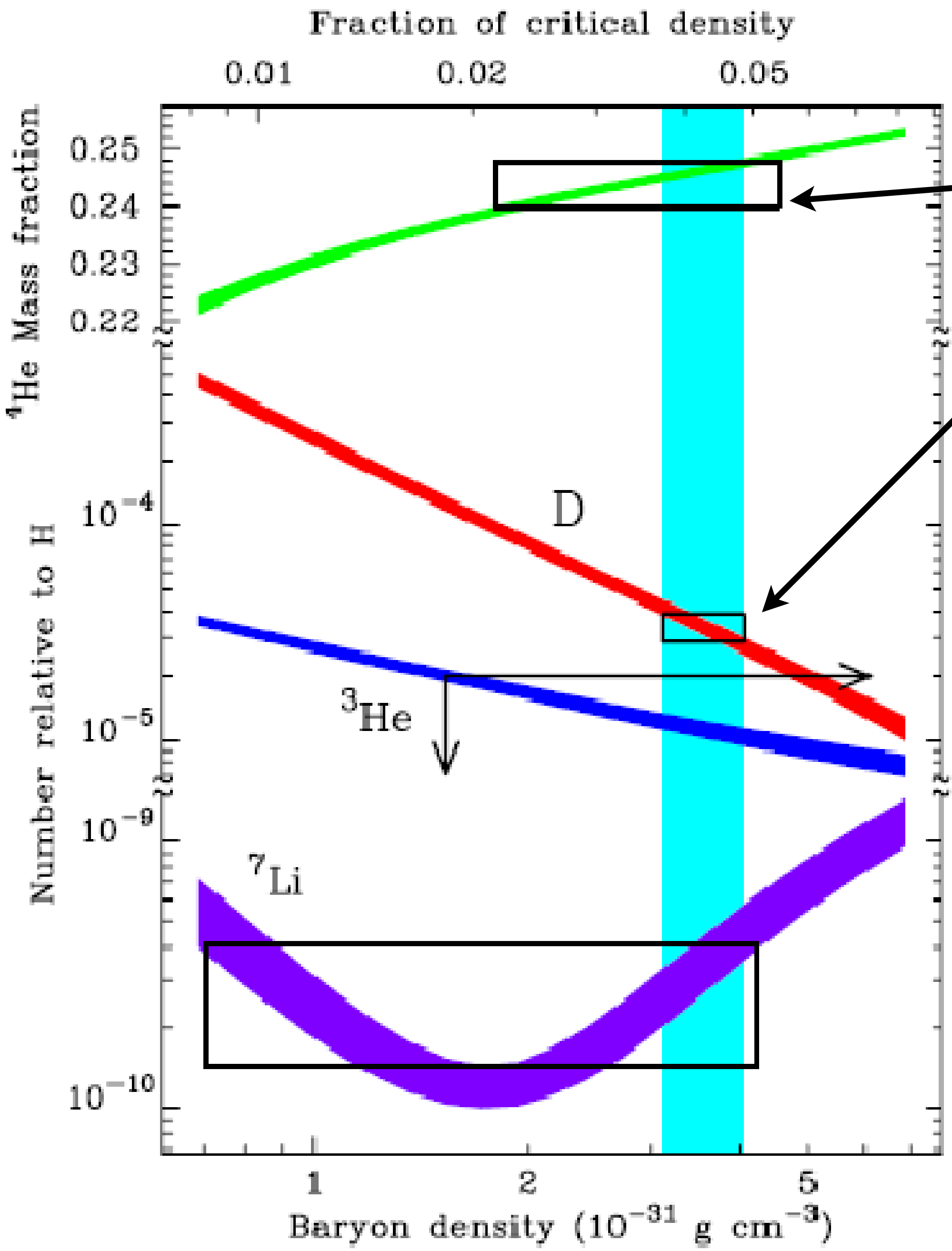
$$\Omega_{total} = 0.0226$$ (But with large ±0.02 uncertainties)

Multi-phase Diagram from Cosmological Hydrodynamical Simulation Showing where the Baryons Are Predicted to be:



van der Voort et al. 2011 (was a student of Joop Schaye here)

What is bottom line putting together constraints?



Boxes show constraints on abundances relative to hydrogen

Best Fit Baryon Density

$$\Omega_B h^2 = 0.019 \pm 0.0024$$

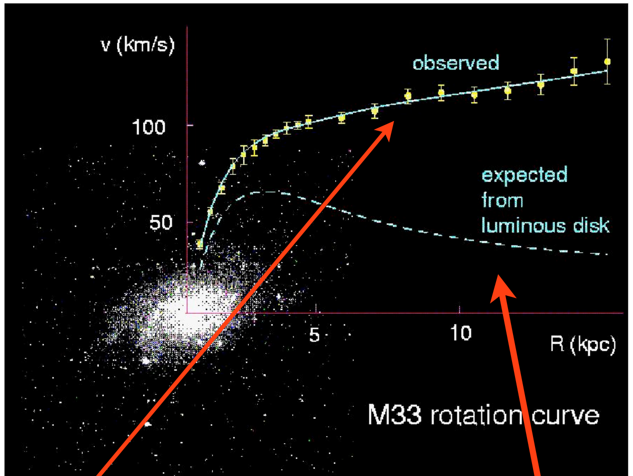
$$\Omega_B = 0.037 \pm 0.009$$

Most useful constraint is from deuterium abundances given steep dependence on $\Omega_b h^2$

Evidence for Dark Matter

Rotational Curves in Spiral Galaxies

$$M(\leq r) = \frac{v_{\text{rot}}^2 r}{G}$$

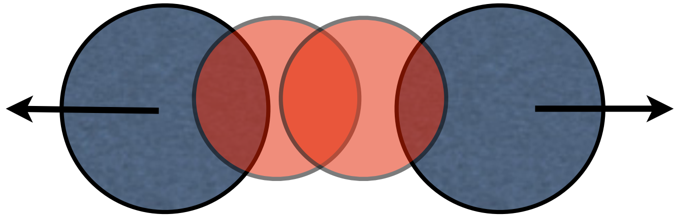


Inferred Mass Increases as Radius Increases

But light is largely only at small radii in galaxies

Collisions Between Galaxy Clusters

this presents us with a situation where the light (from baryons) and mass (from dark matter) are in different places



-- ionized gas from the colliding clusters "run into each other" forming a shock

-- dark matter from the colliding clusters pass right through each other

New Material for this Week

What is the mass density in dark matter in the universe?

Context

As we measure the mass in dark matter, we'll see how the measured M/L (mass to light) ratio for the universe increases to larger scales (indicating the greater importance of dark matter at such scales!)

Sun: M/L = 1 (by definition)

Universe: $M/L = 1400\Omega_M h^2$

$\sim 200 (\Omega_M/0.3)(h/0.7)^2$

Let’s start by estimating the apparent amount of dark matter in galaxies

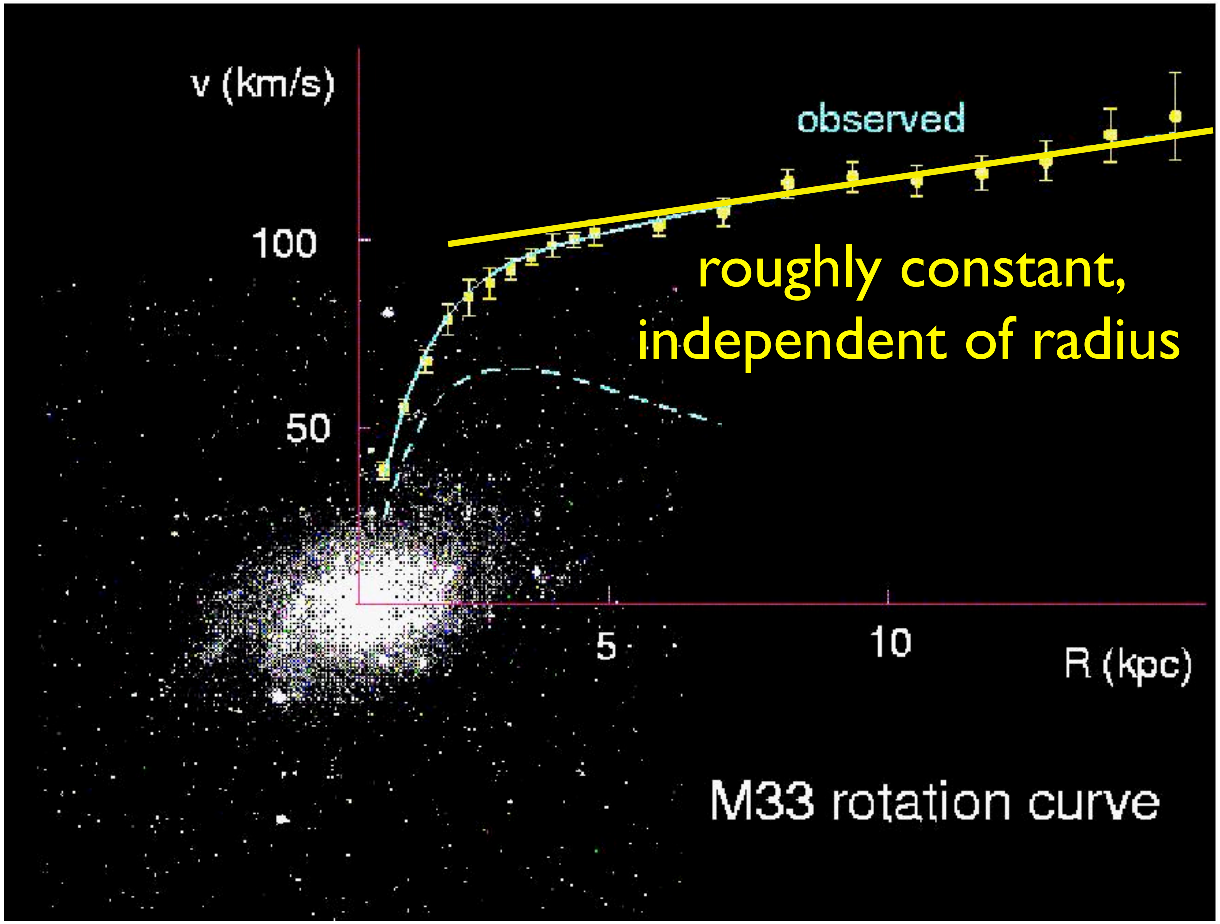
Dark matter in galaxies

-- Rotation velocities of spiral galaxies increase rapidly from their centers to their outer radii

-- Rotation velocities tend to asymptote towards some constant value

$$M(\leq r) = \frac{v_{\text{rot}}^2 r}{G}$$

$$\Rightarrow \quad M(\leq r) \propto r$$



Dark matter in galaxies

-- What is the total gravitational mass inferred in galaxies from this type of analysis and how does it compare with the light?

i.e. what is the apparent mass to light ratio in galaxies?

$(M/L)_{galaxy} \sim 10\text{-}20\ M_{solar}/L_{solar}$

i.e. how does it compare to typical stellar populations?

$(M/L)_{stars} \sim 1\text{-}3\ M_{solar}/L_{solar}$

Total Mass ~ 10 x [mass in stars]

$\Omega_{Galaxy\text{-}Matter} \sim 10 \times \Omega_{stars} \sim 10 \times (0.002)$

$\Omega_{DM} >\sim \Omega_{galaxy,Matter} \sim 0.02$

Now let's move to a bigger system:

a cluster of galaxies

How can we infer this amount of mass in dark matter?

We need to be able to determine the mass of a galaxy cluster (and see what is missing)

Weighing Galaxy Clusters (from the motions of galaxies in a cluster)

Virial Theorem:

For systems that have collapsed gravitationally and relaxed, we expect:

Kinetic Energy = −1/2(Potential Energy)

Implication for galaxy clusters: if galaxies move around inside galaxy clusters at a very fast speed, then the mass of a cluster must be very high

Weighing Galaxy Clusters (from the motions of galaxies in a cluster)

By doing spectroscopy of many galaxies inside a cluster, we can measure Doppler shifts and hence the scatter in the average velocity along line of sight.

However, there is no reason that the direction we observe a cluster is special, so the random motions in the two other directions is likely similar

$$\left\langle v^2 \right\rangle = \left\langle v_x^2 \right\rangle + \left\langle v_y^2 \right\rangle + \left\langle v_z^2 \right\rangle = 3 \left\langle v_\parallel^2 \right\rangle$$

This implies the following kinetic energy:

$$E_{\rm kin} = \frac{1}{2} \sum_i m_i \mathbf{v}_i^2 = \frac{3}{2} M \left\langle v_\parallel^2 \right\rangle$$

Weighing Galaxy Clusters (from the motions of galaxies in a cluster)

Now, for the potential energy:

$$E_{\rm pot} = \frac{GM^2}{R_{\rm cl}}$$

Relating the potential energy to the kinetic energy, we can solve for the mass:

$$M = \frac{3}{G}\left\langle v_{\parallel}^2 \right\rangle R_{\rm cl}$$

For typical velocity dispersions v ~ 1000 km s^{-1} and cluster radii ~1 Mpc, we derive M ~ 10^{15} M_{solar}

Weighing Galaxy Clusters (from the motions of galaxies in a cluster)

For typical velocity dispersions v ~ 1000 km s^{-1} and cluster radii ~1 Mpc, we derive M ~ 10^{15} M_{solar}

The total amount of stellar mass in galaxies themselves in clusters is typically ~10^{13} M_{solar}

Therefore, the total baryonic mass in galaxies is much less than that inferred to exist from the velocities of the galaxies

i.e. what is the apparent mass to light ratio in clusters?

$(M/L)_{cluster}$ ~ 100-200 M_{solar}/L_{solar}

vs. 10-20 M_{solar}/L_{solar} for galaxies (dark matter even more important)

Context

Measured M/L ratios indicate the increasing importance of dark matter on largest scales!

Sun: $M/L = 1$

$(M/L)_{galaxy} \sim 10\text{-}20\ M_{solar}/L_{solar}$

$(M/L)_{cluster} \sim 100\text{-}200\ M_{solar}/L_{solar}$

Weighing Galaxy Clusters (from the motions of galaxies in a cluster)

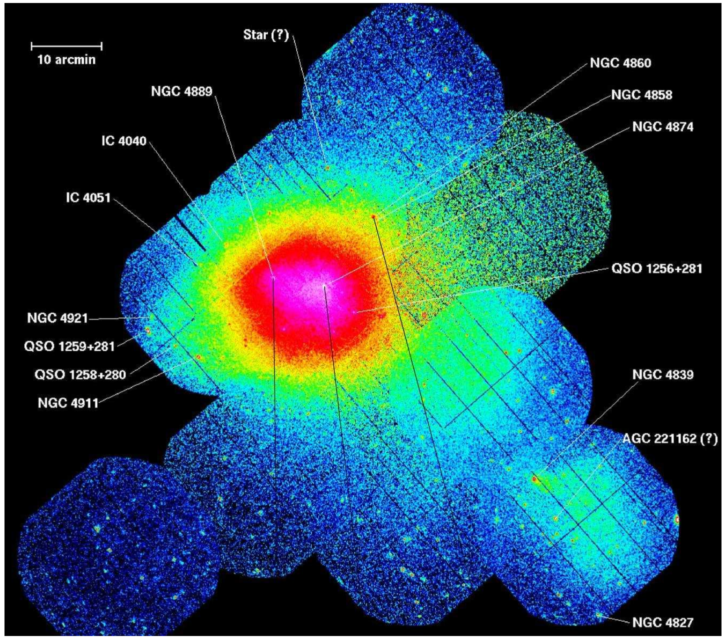
The observation that the velocities of individual galaxies in clusters suggested a total mass much greater than that seen in galaxies was originally suggested by Fritz Zwicky in 1933 (based on observations of Coma cluster)!

Fritz Zwicky (1898 - 1974)

What are other ways to measure the mass in galaxy clusters?

Weighing Galaxy Clusters (from the ionized gas in clusters)

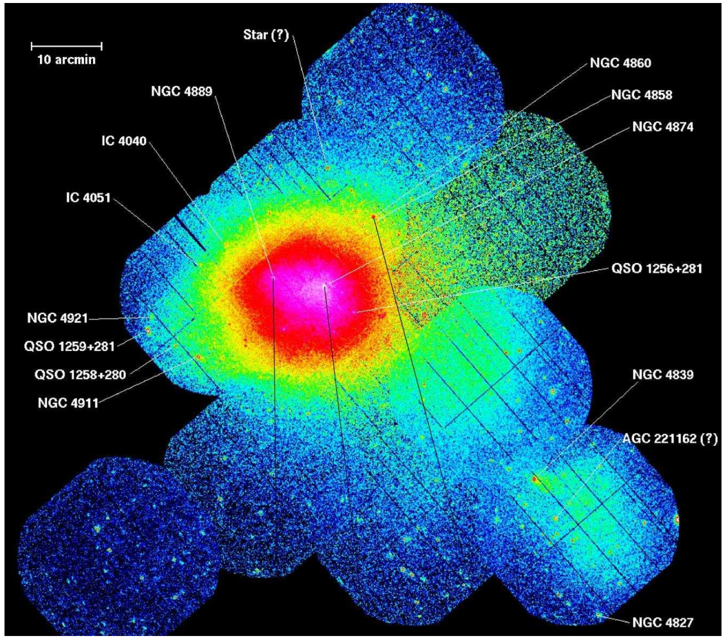
It is also possible to make use of the very significant x-ray emission from ionized gas in galaxies to estimate the total mass in a galaxy cluster



XMM-Newton x-ray image of Coma cluster

Weighing Galaxy Clusters (from the ionized gas in clusters)

The x-ray light comes from bremstrahlung radiation, i.e., energetic ions colliding with each other and emitting radiation



XMM-Newton x-ray image of Coma cluster

Weighing Galaxy Clusters (from the ionized gas in clusters)

The basic idea is that:
since the ionized gas in a cluster is pressure supported and we can determine the density and temperature of gas in a cluster

From hydrostatic equilibrium:

$$\frac{1}{\rho}\frac{\mathrm{d}p}{\mathrm{d}r} = -\frac{GM(r)}{r^2},$$

Able to model this from observations

p = pressure
r = radius
ρ = density

We can infer this!

Weighing Galaxy Clusters (from the ionized gas in clusters)

If we put in the ideal gas law p = nKT where n = ρ / m_p, then we find

$$\frac{kT}{m_{\rm p}\rho}\frac{{\rm d}\rho}{{\rm d}r} = -\frac{GM(r)}{r^2}$$

Solving for the mass, we find

$$M(r) = -\frac{rkT}{Gm_{\rm p}}\frac{{\rm d}\ln\rho}{{\rm d}\ln r}\ ;$$

Weighing Galaxy Clusters (from the ionized gas in clusters)

The following simple axisymmetric model is found to fit the density profile of clusters well (assuming an x-ray emissivity that scales as the density squared)

$$n(x) = \frac{n_0}{(1 + x^2)^{3\beta/2}} \,, \qquad x \equiv \frac{r}{r_\mathrm{c}} \,,$$

where r_c is the core radius and n_0 is a density normalization factor (the above profile is King model -- which relieve problem of diverging mass for the isothermal sphere)

$$\frac{\mathrm{d}\ln\rho}{\mathrm{d}\ln r} = \frac{\mathrm{d}\ln n}{\mathrm{d}\ln r} = -3\beta\frac{r^2}{1 + r^2} \,,$$

$$M(r) = -\frac{rkT}{Gm_\mathrm{p}}\frac{\mathrm{d}\ln\rho}{\mathrm{d}\ln r} \quad \Rightarrow \quad M(r) = \frac{3\beta rkT}{Gm_\mathrm{p}}\frac{r^2}{1 + r^2}$$

Weighing Galaxy Clusters (from the ionized gas in clusters)

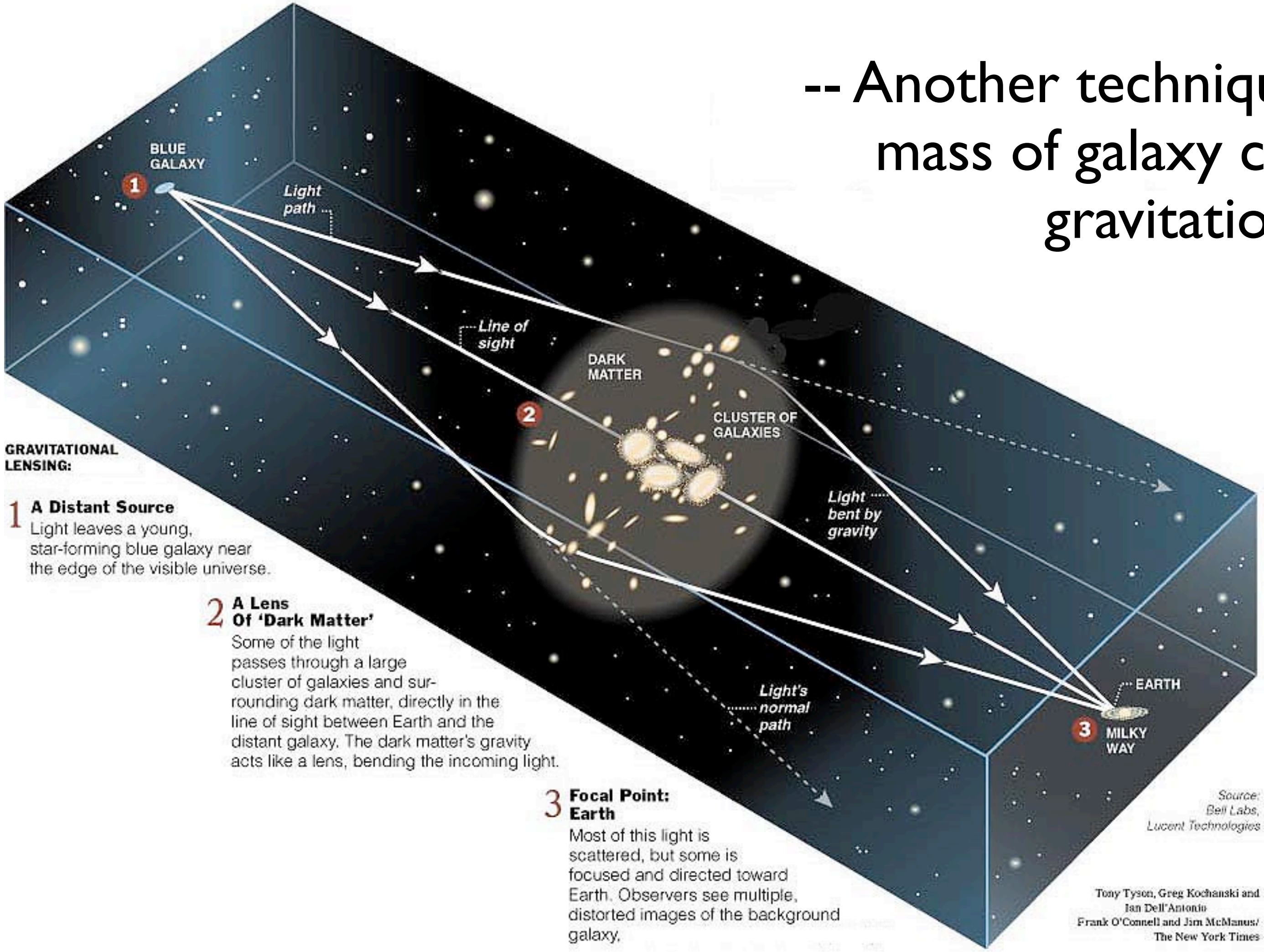
$$M(r) = \frac{3\beta rkT}{Gm_{\rm p}} \frac{r^2}{1 + r^2}$$

Plugging in typical numbers for clusters R ~ 2.5 Mpc, β ~ 2/3, and kT ~ 10 keV

$M_{cluster} \sim 1 \times 10^{15}\ M_{solar}$

Weighing Galaxy Clusters (from gravitational lensing)

-- Another technique for estimating the mass of galaxy clusters is through gravitational lensing

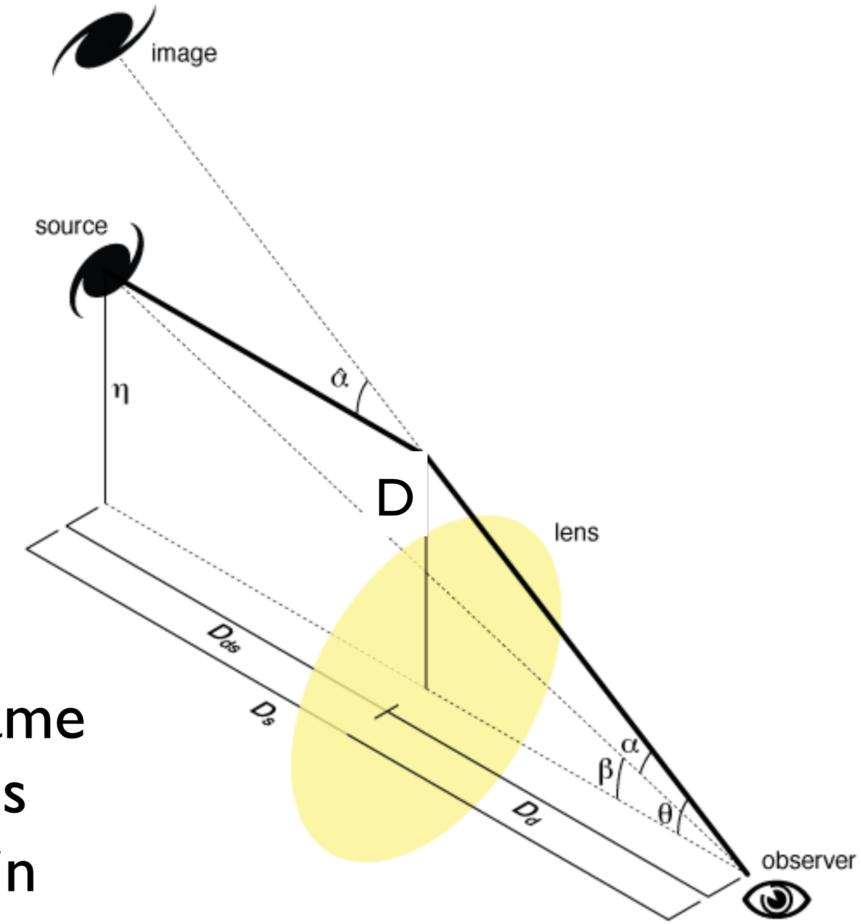


credit: LSST website

Weighing Galaxy Clusters (from gravitational lensing)

-- Gravitational lensing from a galaxy cluster causes light from some background source to deflect by some angle α

$$\tilde{\alpha} = \frac{4GM}{\mathrm{D}c^2} = \frac{2}{c^2} \cdot \frac{2GM}{\mathrm{D}}$$



-- By finding multiple images of the same source, one can determine the mass enclosed (Θ_E is the so-called Einstein radius)

$$\theta_E^2 = \frac{4GM}{c^2} \frac{1}{D}$$

where $D = D_d D_{ds}/D_S$

We presented three approaches to measuring the mass of clusters:

Virialized motions of galaxies,
x-ray profiles, and
gravitational lensing analyses

Similar mass estimates for clusters are obtained using each of these techniques.

note that each of these techniques make use of gravity to estimate the cluster mass

Caveat: All methods being used to estimate mass in clusters make assumptions about axisymmetry, isotropy, and therefore suffer from possible systematics...

If we take clusters as representative, what is the matter density of the universe?

Stellar System: M/L = 1-2 $M_\odot/L_\odot$

↓ 100x

Clusters: M/L = ~100-200 $M_\odot/L_\odot$

Stars: $\Omega_{star} = 0.002$

↓ 100x

Clusters: $\Omega_{matter} \sim 0.2$

Can we use these results to estimate the dark matter content of universe?

Yes -- but to do so we will take advantage of

1) information we have on the baryonic content of the universe

2) clusters are large enough collapsed regions of the universe to contain representative proportions of baryons, dark matter, etc.

Therefore, if we can establish the baryonic mass in addition to the total gravitational mass for a cluster, we can estimate Ω_M directly

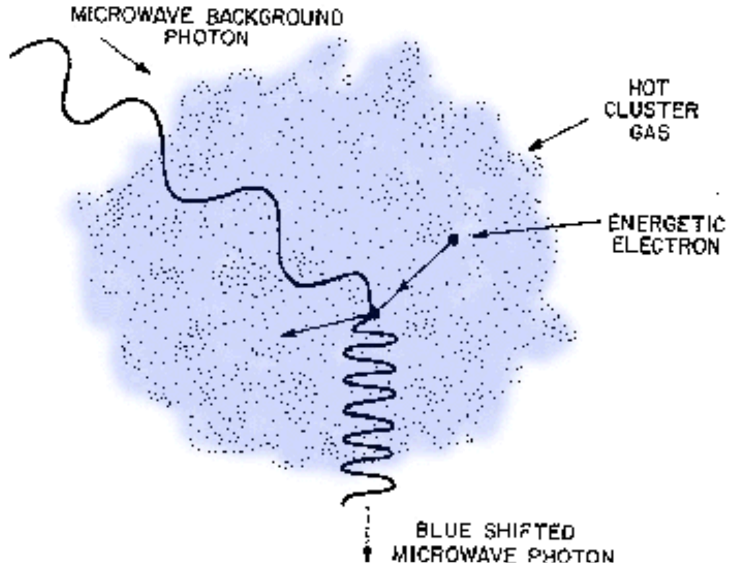
How can we estimate the total baryonic mass in galaxy clusters?

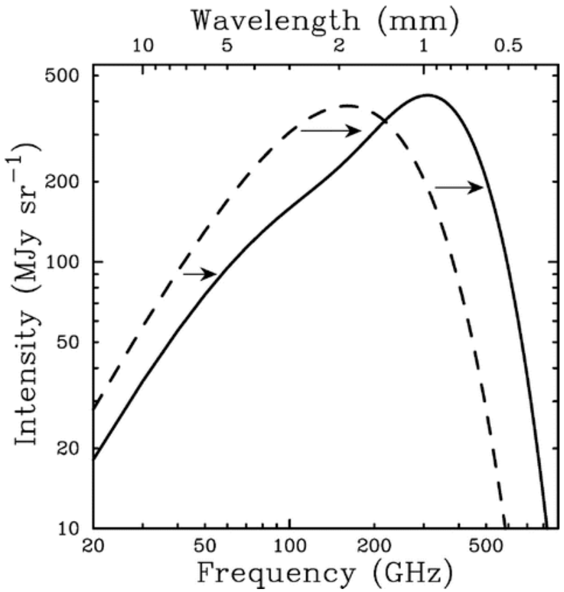
Baryons in Galaxy Clusters (from the SZ effect)

-- When light from the microwave background radiation passes by hot ionized gas in a galaxy cluster, light can gain energy by scattering off of the hot electrons in ionized gas.

-- This process causes light from the microwave backround to look hotter over regions of the sky that intersect galaxy clusters. The process is known as the Sunyaev-Zeldovich (SZ) effect.

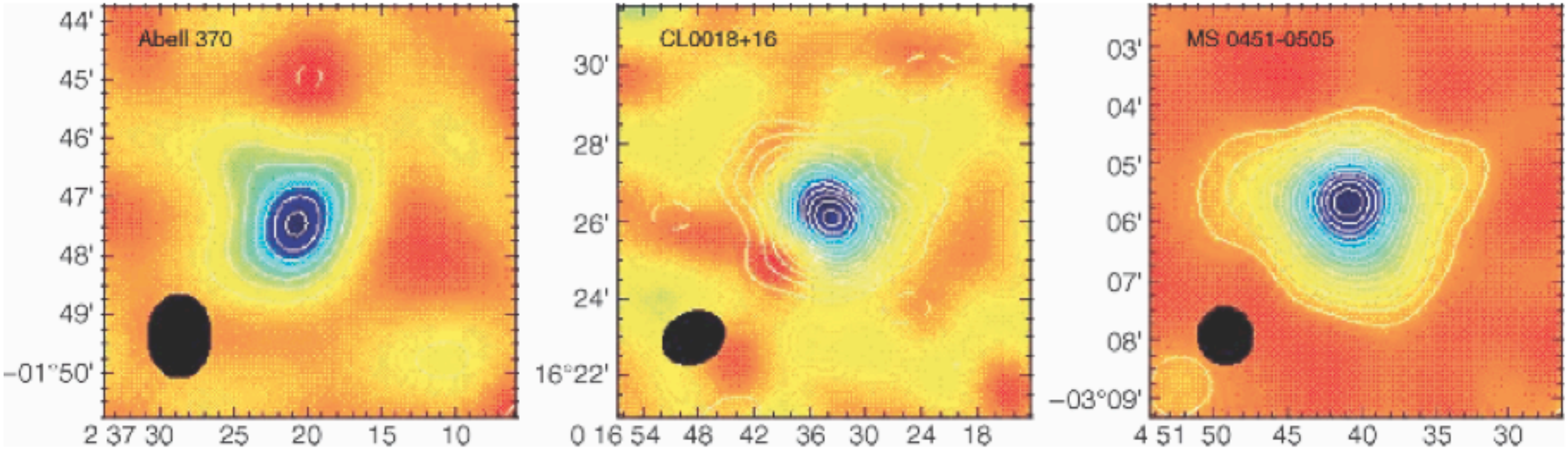
-- Since the magnitude of the effect depends on the total number of hot electrons in a galaxy cluster, it provides a direct probe of its total baryon content.





Sunyaev Zeldovich Effect

Images of the cosmic microwave background radiation seen through galaxy clusters



SZ maps of three clusters at $0.37 < z < 0.55$. Since SZ is proportional to electron density, mass fraction of baryons can be measured if one knows the total mass of the cluster.

So, assuming that galaxy clusters contain representative proportions of baryons and dark matter and using our previous measurements of the total cluster masses, we can directly estimate Ω_M

$$\Omega_M / \Omega_b = (M_{cluster,total\text{-}mass} / M_{cluster,baryons})$$

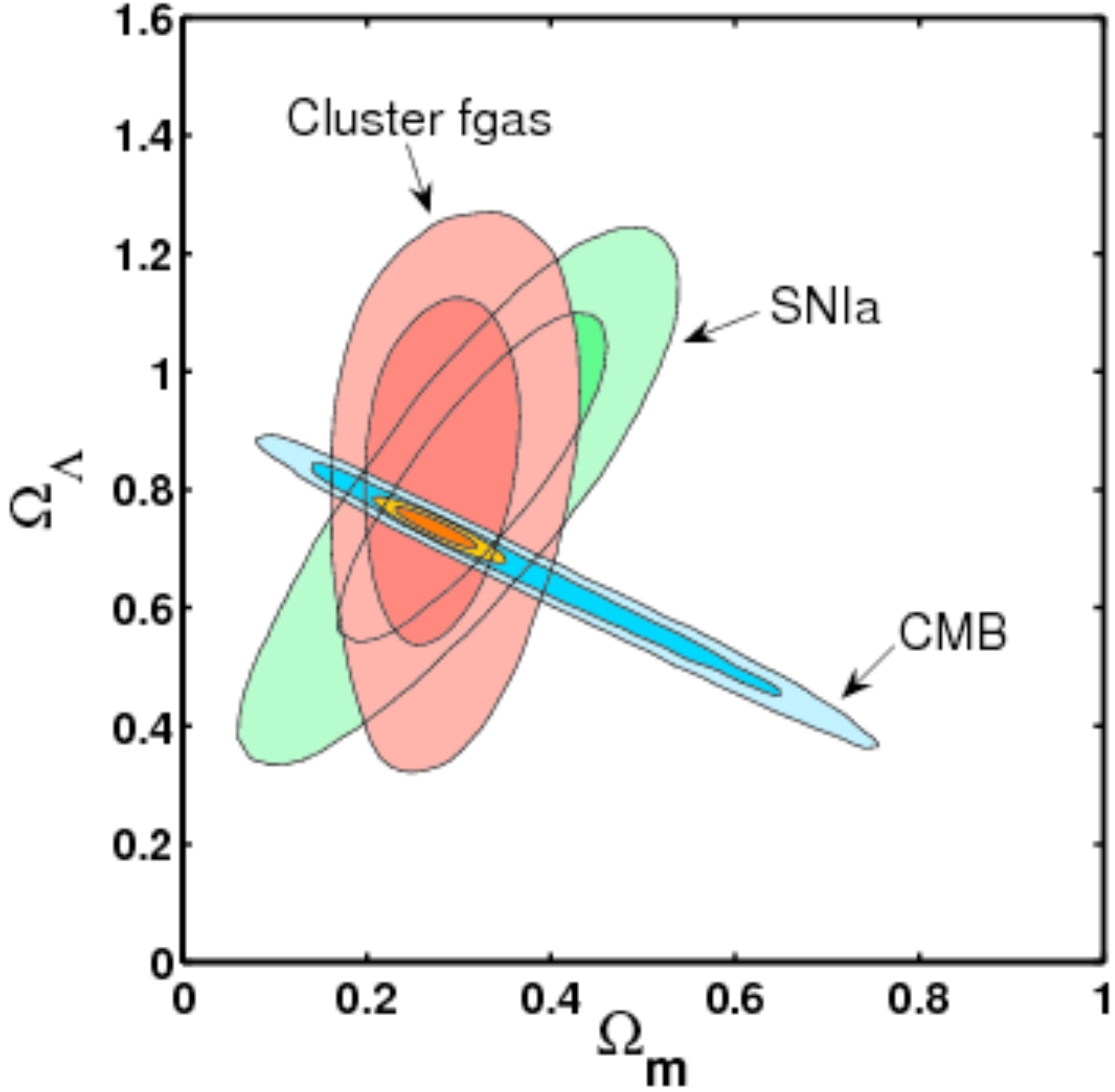
$$\Omega_M = \Omega_b \, (M_{cluster,total\text{-}mass} / M_{cluster,baryons})$$

$$\Omega_M = (0.04)\,(M_{cluster,total\text{-}mass} / M_{cluster,baryons})$$

$$\Omega_M = (0.04)\,(\sim 7) = \sim 0.28$$

Using this reasoning, here are the typical constraints one can set on Ω_m

Mantz, Allen et al.



Dark matter inferences from velocity flows

One can also use the peculiar velocities (bulk flows) of galaxies in the nearby universe to estimate the amount of dark matter in the universe

This is because the peculiar velocities are set by the matter within the universe -- which causes galaxies to fall towards each other.

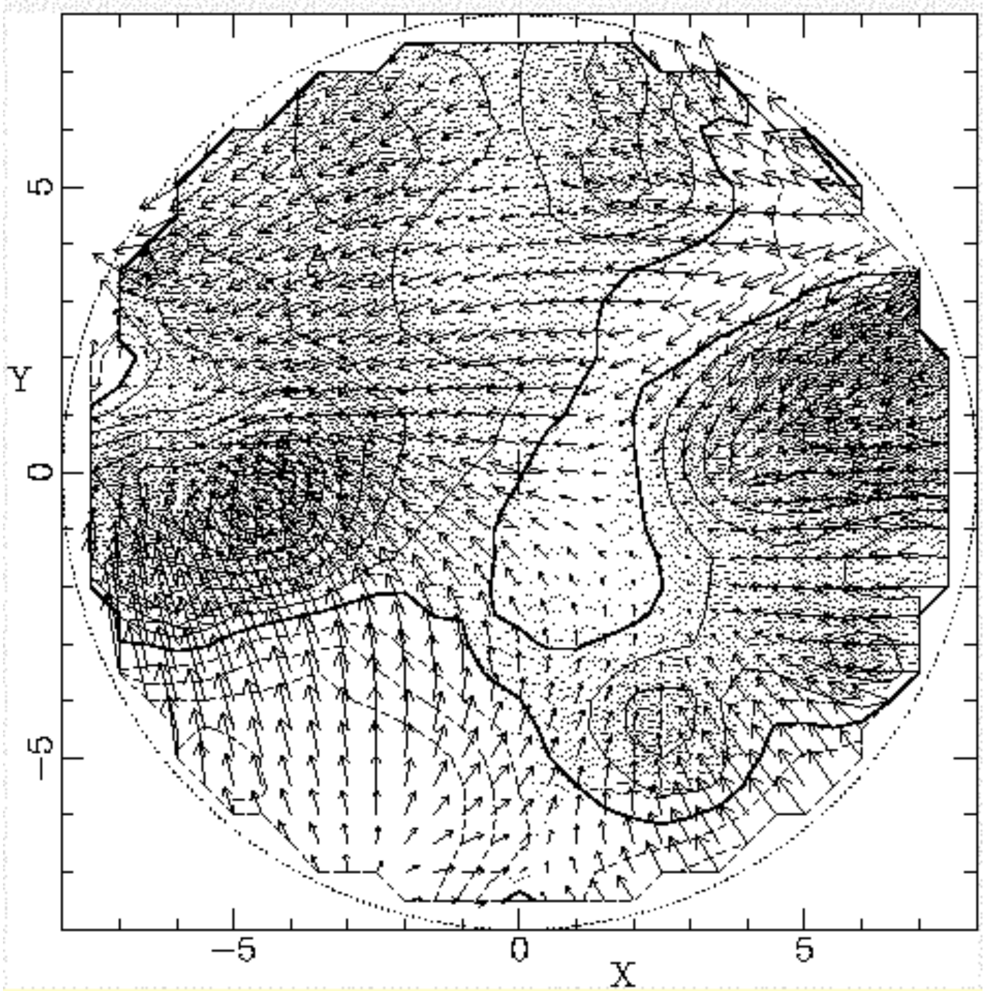
An approximate equation to describe this is the following:

$$\nabla \cdot v = -\Omega_M^{0.6}\, \delta_M$$

convergence points for fluid flow

gravitational mass

Velocity flow model in the nearby universe

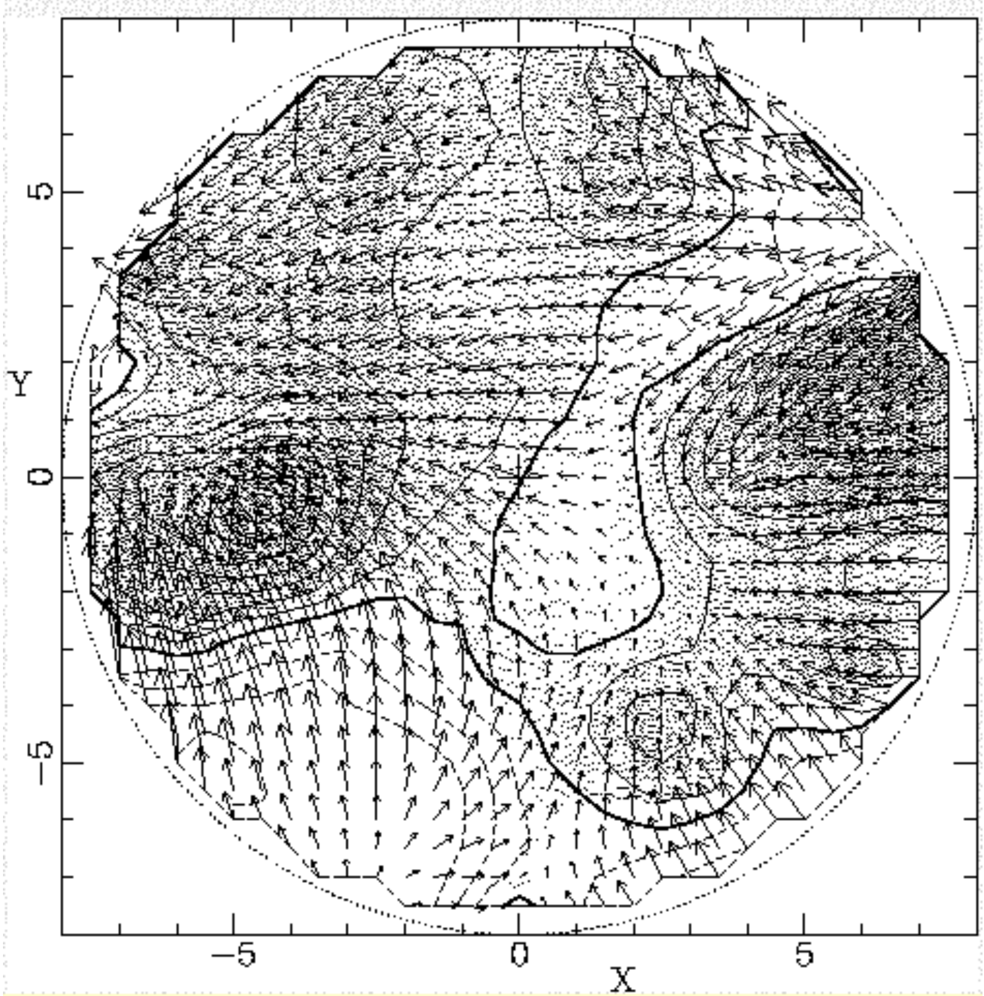


Dark matter inferences from velocity flows

From peculiar velocity bulk flow studies, people have concluded that

$\Omega_M \sim 0.3$

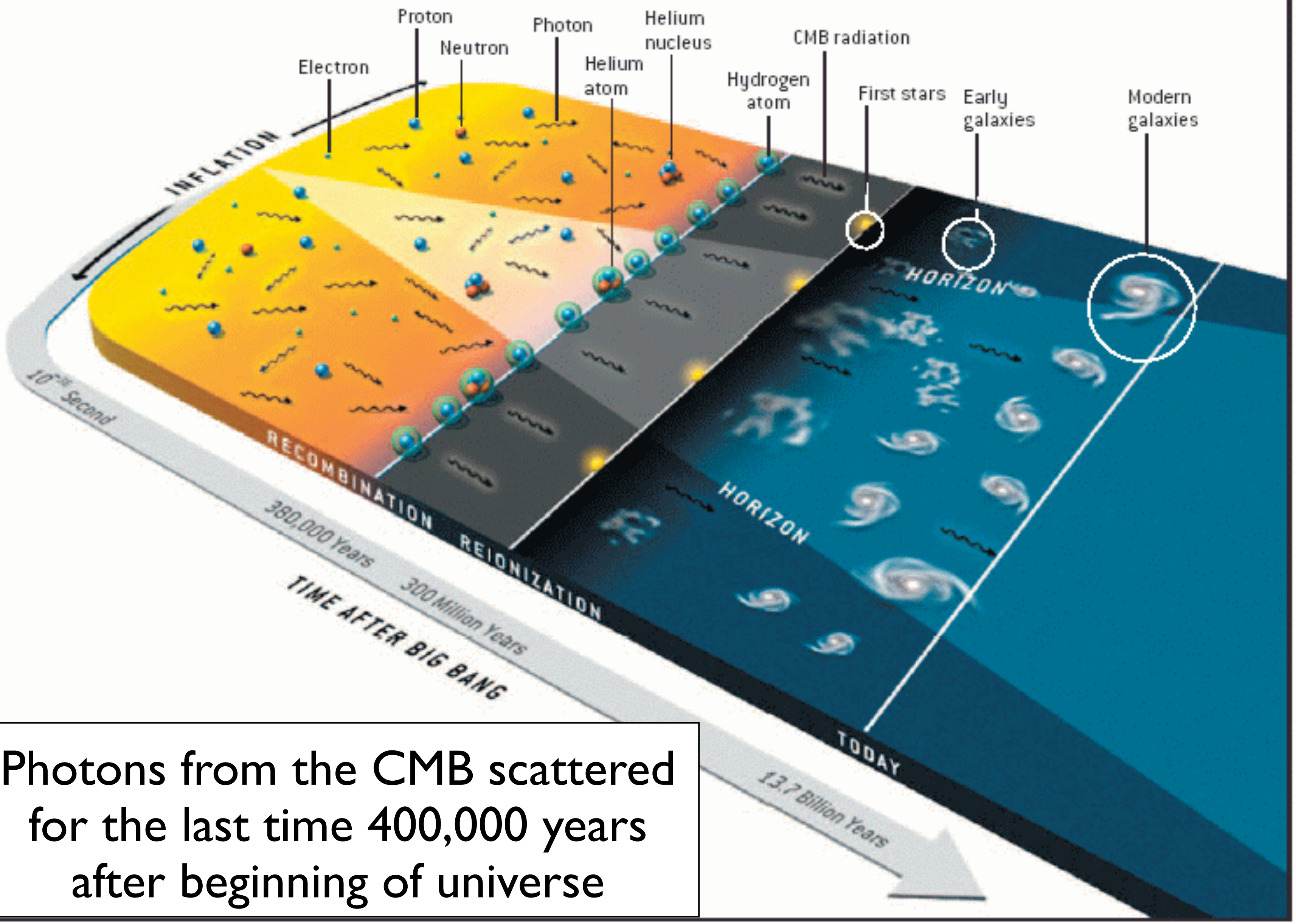
Velocity flow model in the nearby universe



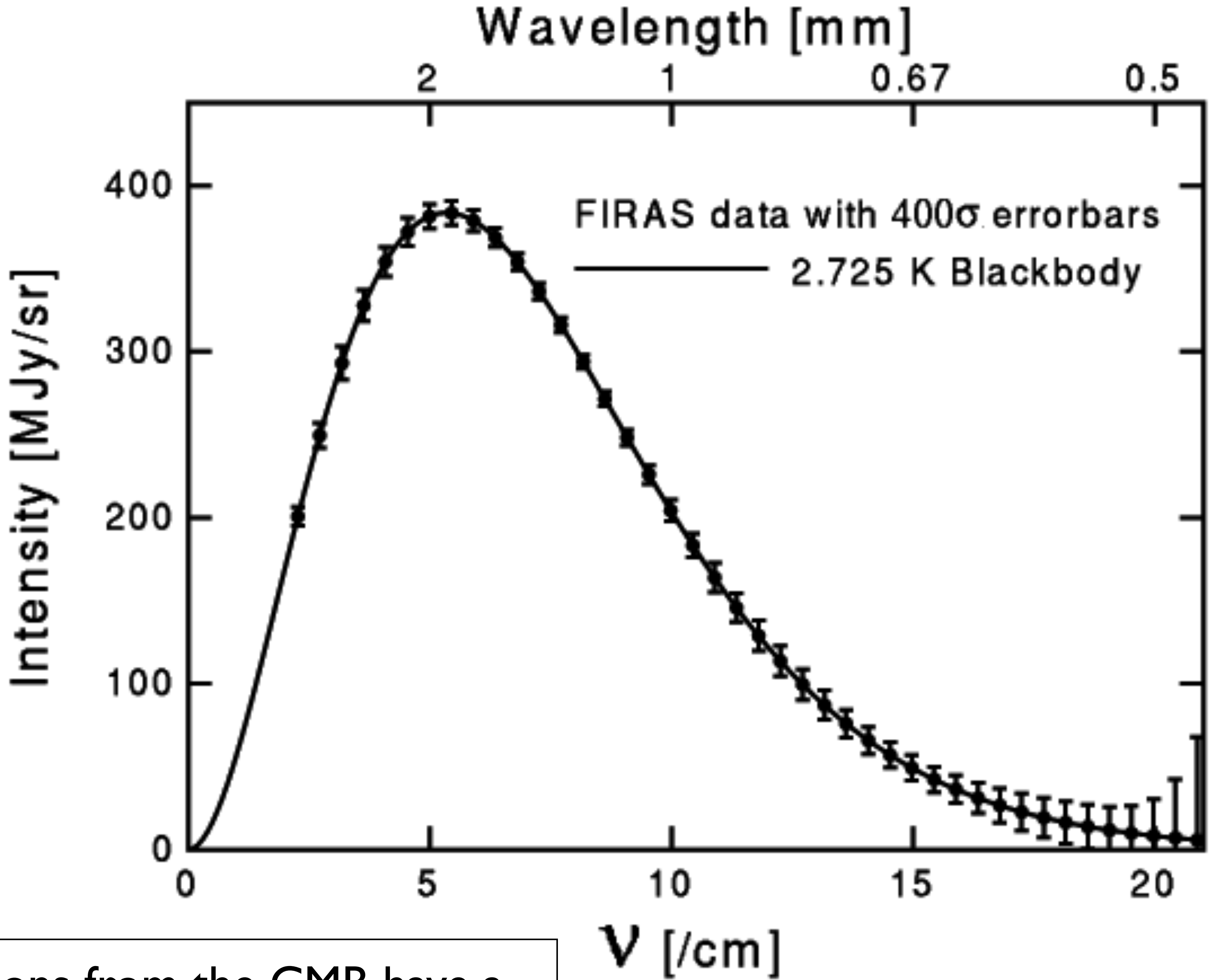
What is the cosmic microwave background?

TIMELINE OF THE UNIVERSE

AS INFLATION EXPANDED the universe, the plasma of photons and charged particles grew far beyond the horizon (the edge of the region that a hypothetical viewer after inflation would see as the universe expands). During the recombination period about 380,000 years later, the first atoms formed and the cosmic microwave background (CMB) radiation was emitted. After another 300 million years, radiation from the first stars reionized most of the hydrogen and helium.

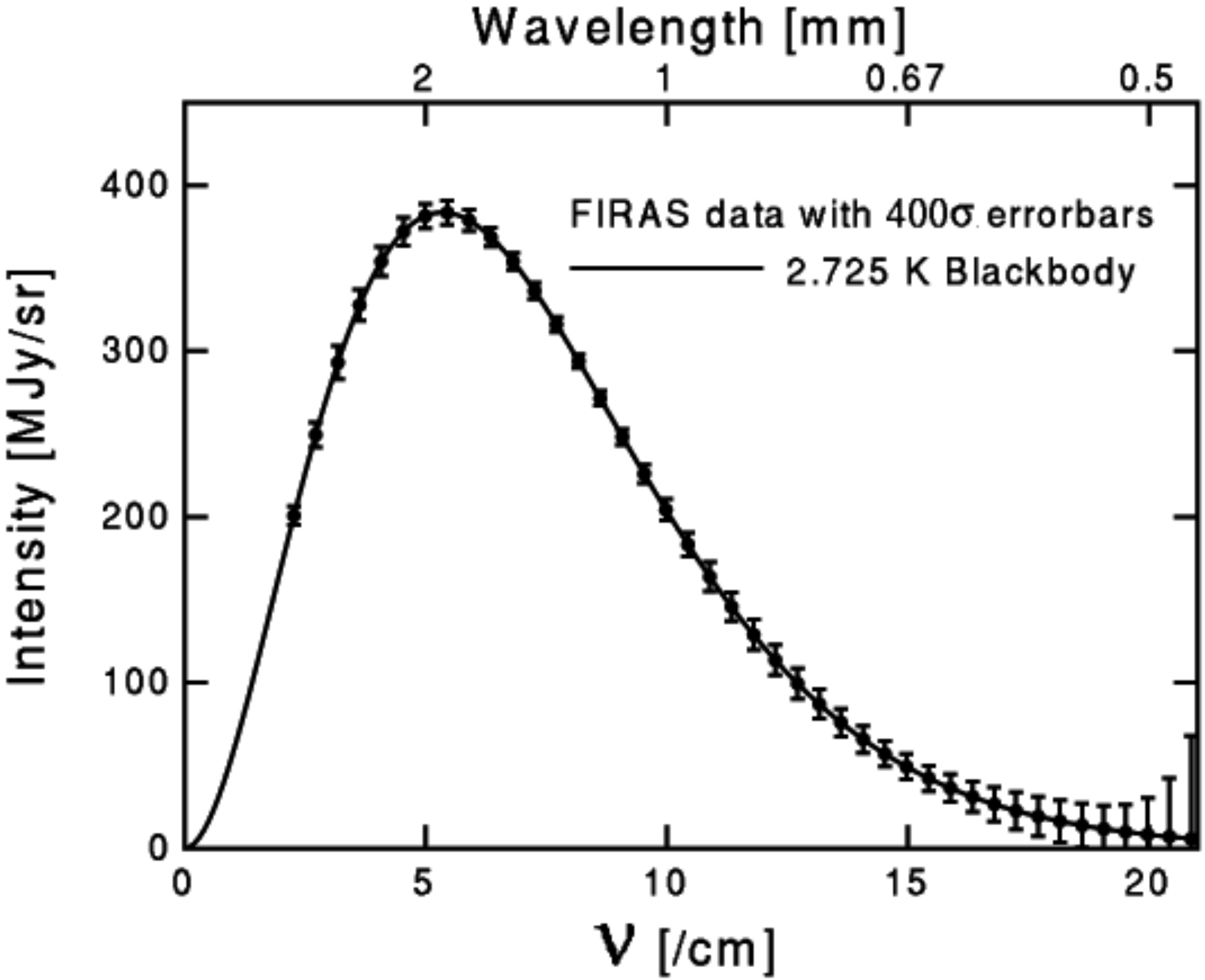


Photons from the CMB scattered for the last time 400,000 years after beginning of universe



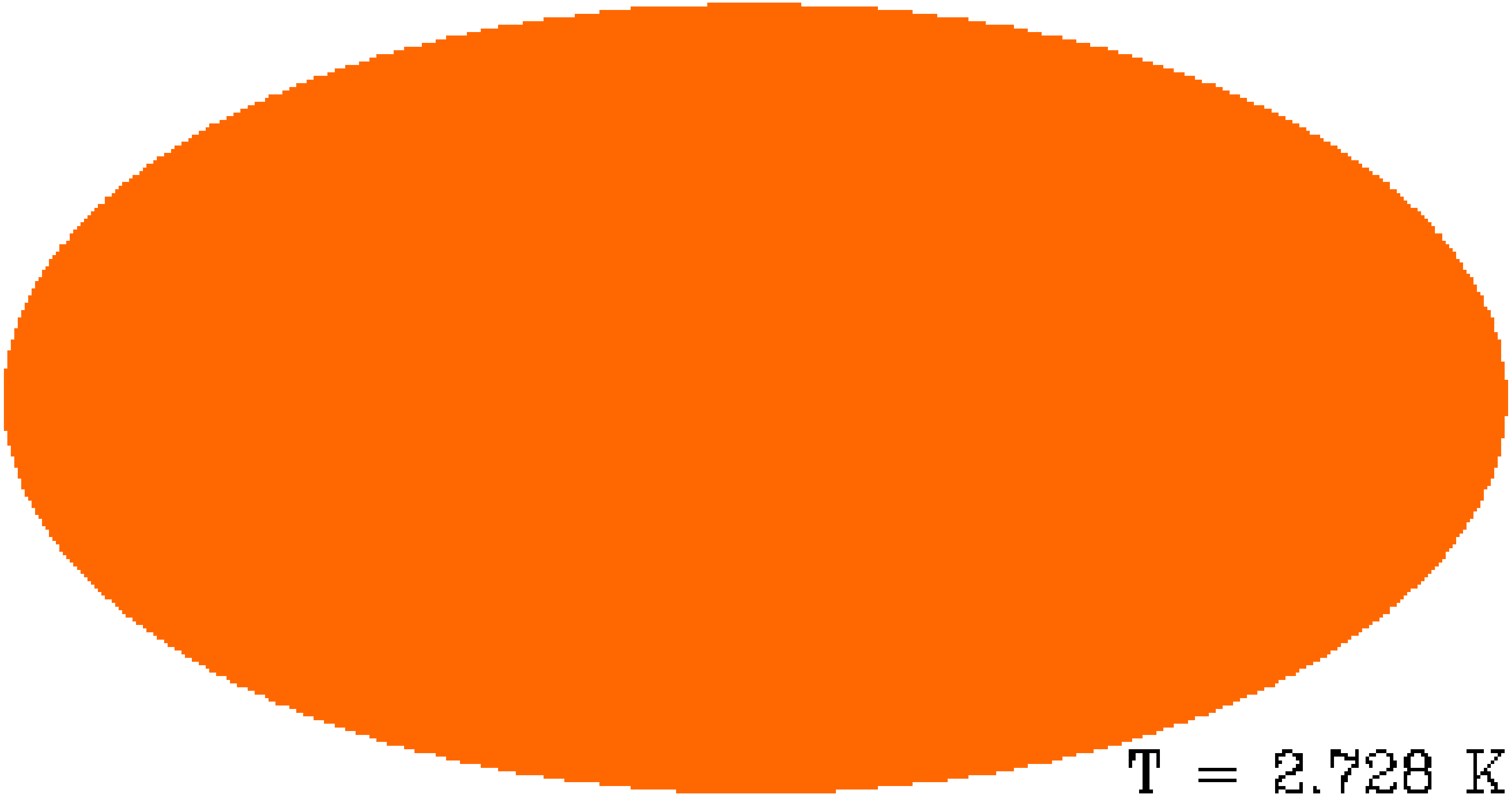
Photons from the CMB have a spectral energy distribution which is almost a perfect black body.

Most perfect blackbody spectrum seen anywhere!



The reason the universe produces such a perfect blackbody spectrum is the significant interaction rate between photons and ionized matter in the early universe

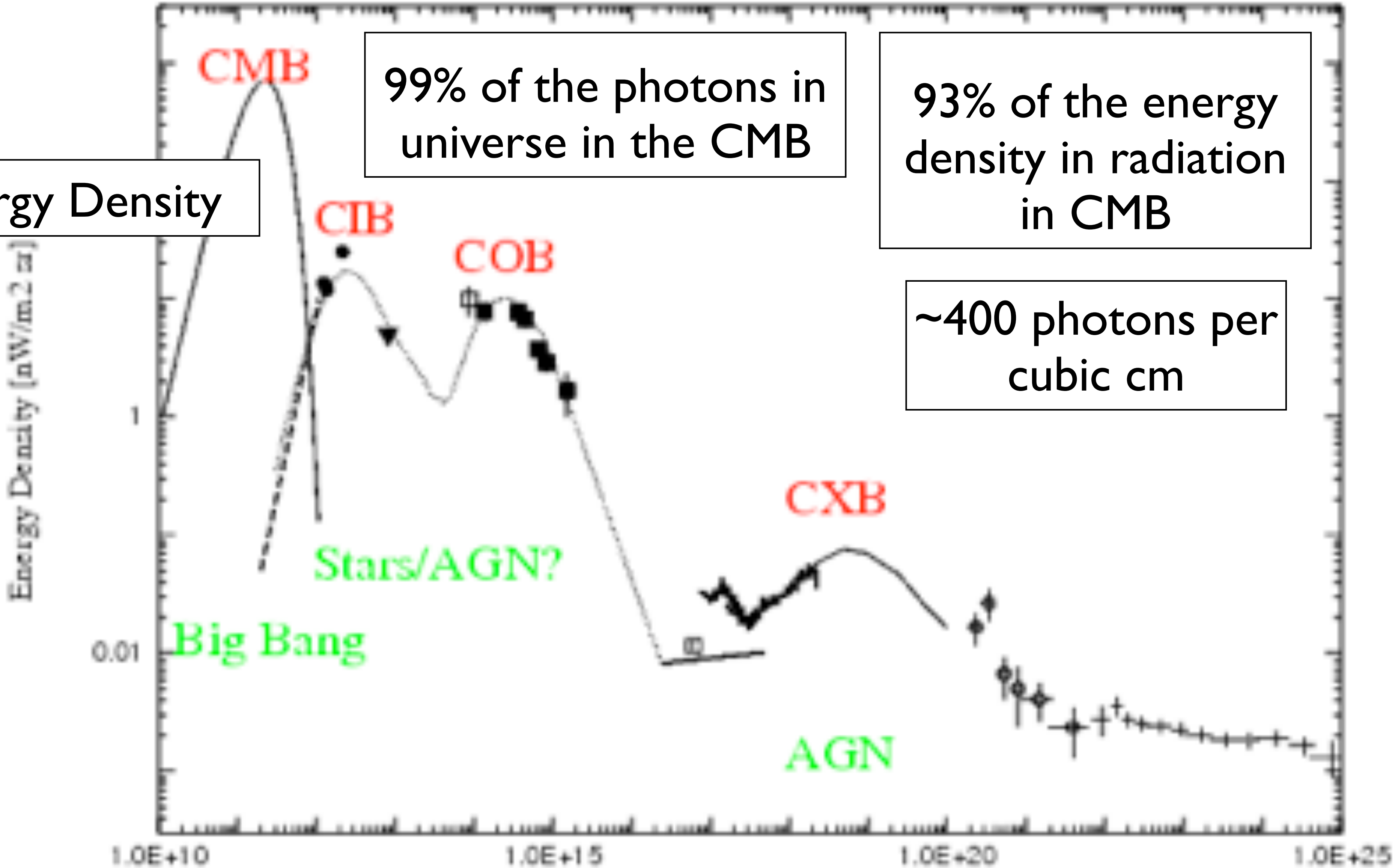
Cosmic Microwave Background is Isotropic



The cosmic microwave background radiation has essentially the same spectrum / temperature in every direction!

Isotropic to one part in 10^5

Cosmic Microwave Background dominates the total energy density in radiation!



Energy Density

Frequency [Hz]

99% of the photons in universe in the CMB

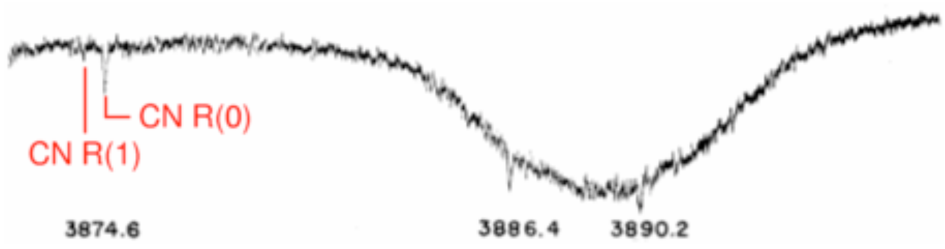
93% of the energy density in radiation in CMB

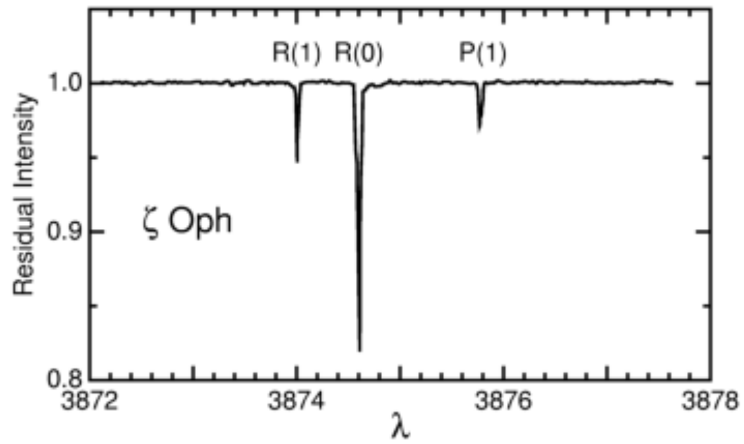
~400 photons per cubic cm

Credit: Hasinger

How was the cosmic microwave background discovered?

Discovery of the CMB





-- The first indication that the universe was emersed in a sea of photons with temperature ~2-3 K was actually in ~1940

-- McKellar identified CN absorption in interstellar space and by comparing the strength of two rotation lines estimated a temperature of ~2 K for interstellar space

-- Little was thought of the finding at the time

Discovery of the CMB

-- The existence of the cosmic microwave background radiation with temperature of 5 K was predicted to be found in the hot big bang model in 1949 by Alpher & Herman following α-β-γ paper on big-bang nucleosynthesis

-- Doroshkevich & Novikov (1964) predict this radiation will have a blackbody spectrum, and argue it could be detected

-- Not aware of the Alpher & Herman paper, Robert Dicke and collaborators also predicted the existence of isotropic radiation from the Big Bang and was preparing to look for it.

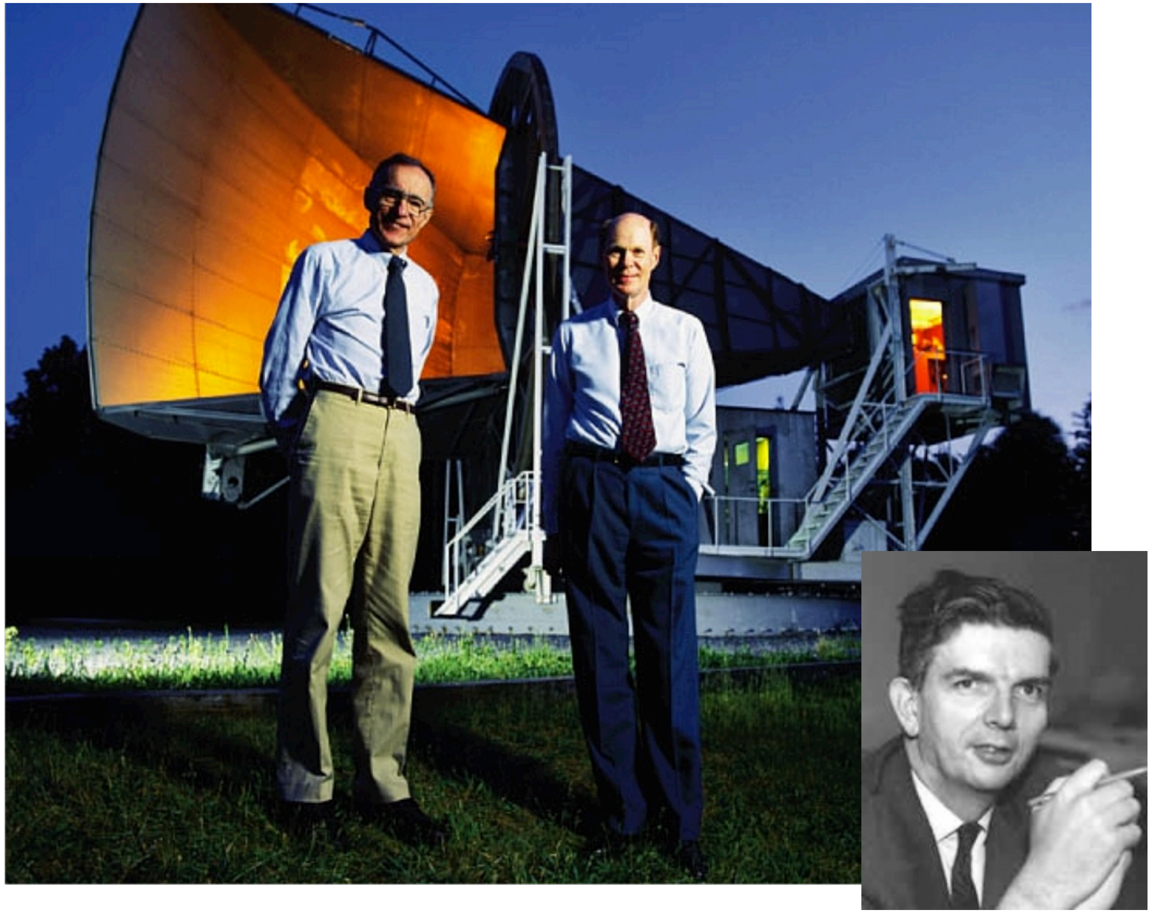
Discovery of the CMB

-- Penzias & Wilson were looking to study emission from the galaxy at λ=7.3 cm

-- Found a direction independent "noise" with temperature ~3 K that they could not eliminate -- despite drastic measures

-- Not being able to solve the problem, they spoke with colleagues

-- An explanation for the noise was provided by Robert Dicke and collaborators. Their theory paper appeared together with the paper by Penzias & Wilson in 1965.



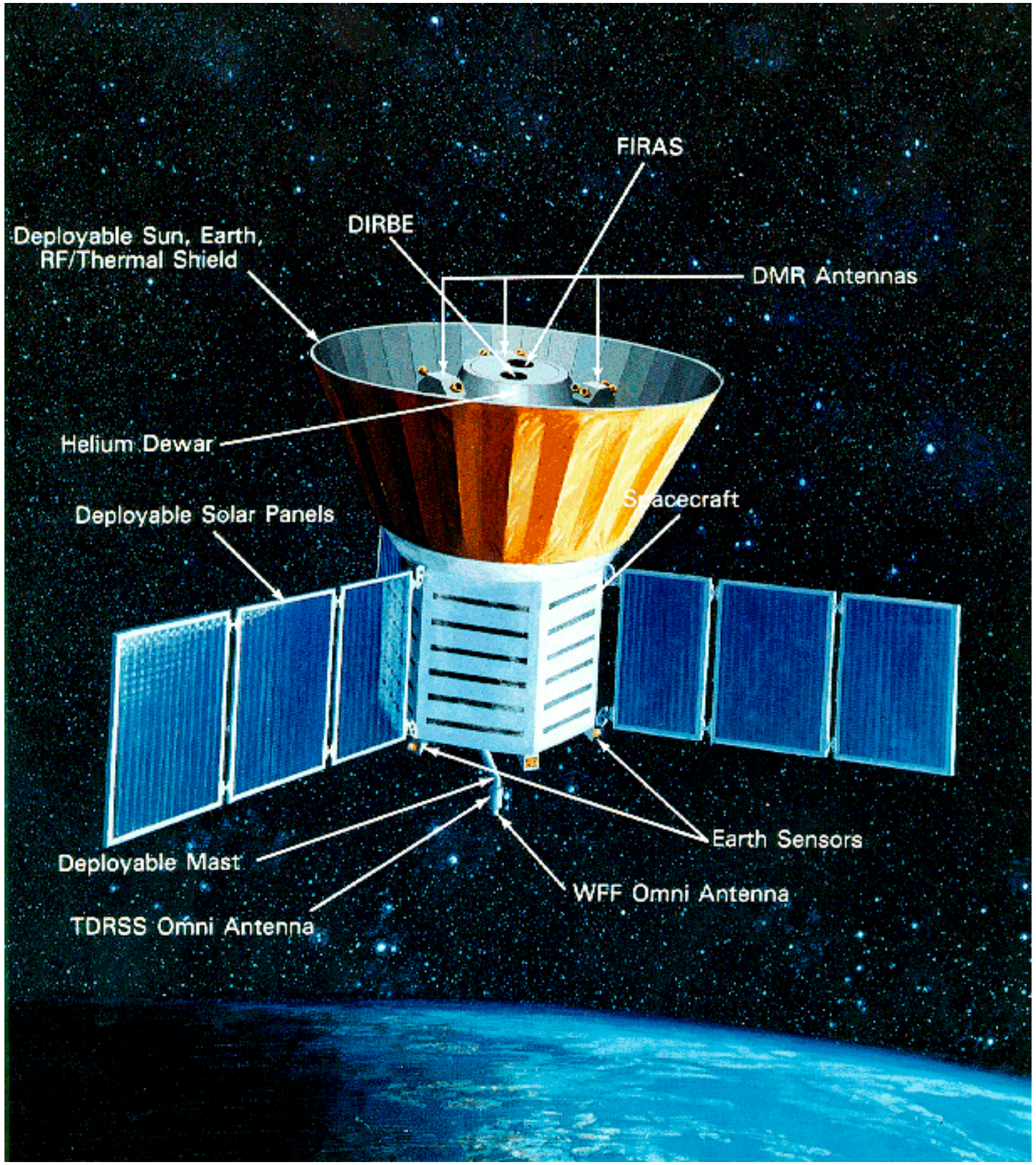
-- In 1978, Penzias & Wilson were awarded the Nobel Prize for their discovery

Discovery of the CMB

People continued to obtain measurements on the cosmic microwave background for years after the original Penzias & Wilson experiment, but no one was successful in identifying any anisotropy in the cosmic microwave background (except for a dipole).

People realized that to measure the temperatures of the cosmic microwave background accurately and to map the sky, they would need to go to space (where the thermal stability was much superior to experiments on the ground).

COBE



First experiment to convincingly measure anisotropies in the cosmic microwave background

Launched in 1989 and continued observations to 2003

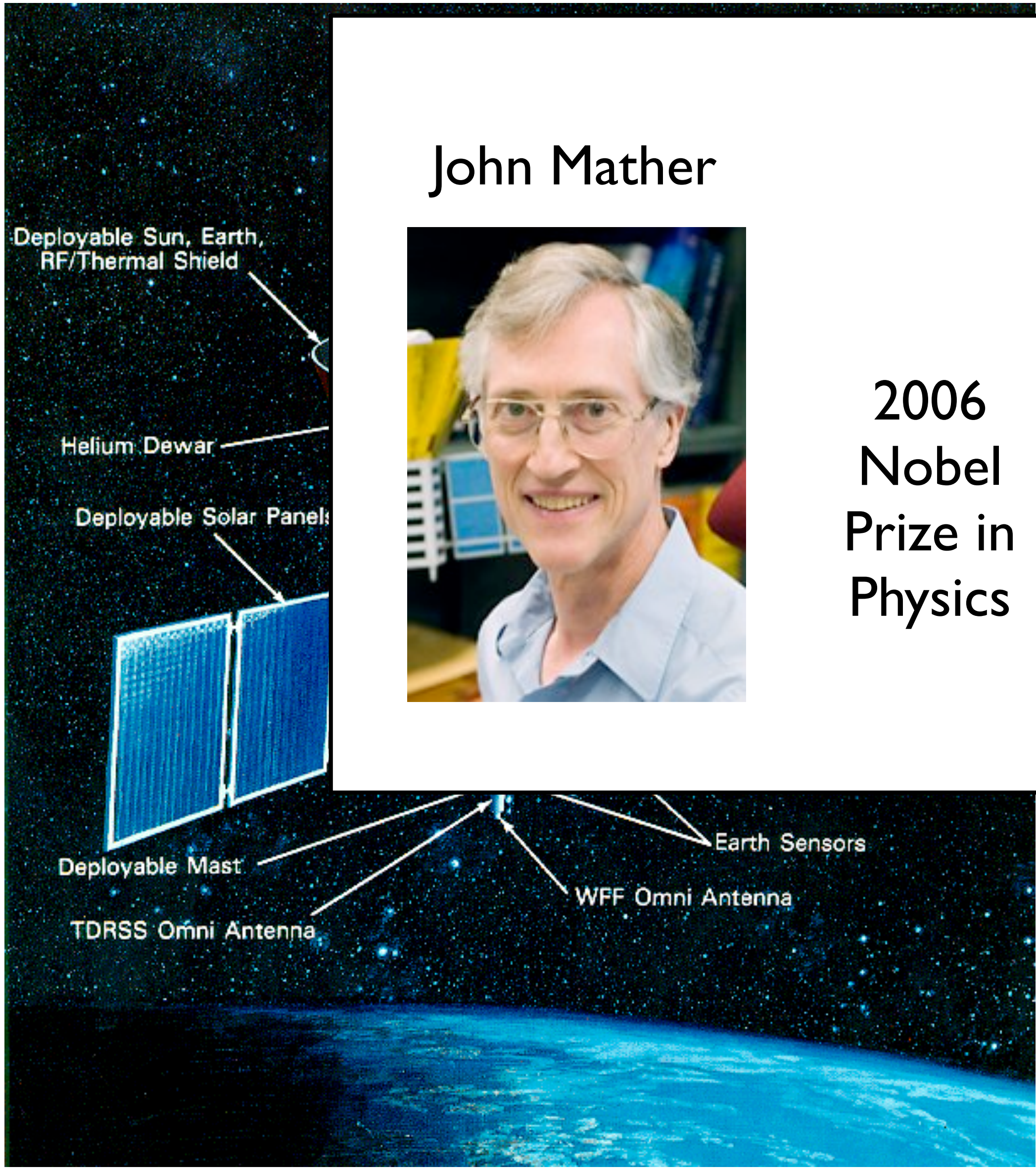
Featured three instruments:

DIRBE: Measure absolute sky brightness from 1 to 240 μm to determine brightness of infrared sky

FIRAS: Measure the spectral energy distribution for the CMB, compute the temperature, and compare with a blackbody

DMR: Measured anisotropies in the cosmic microwave background for the first time.

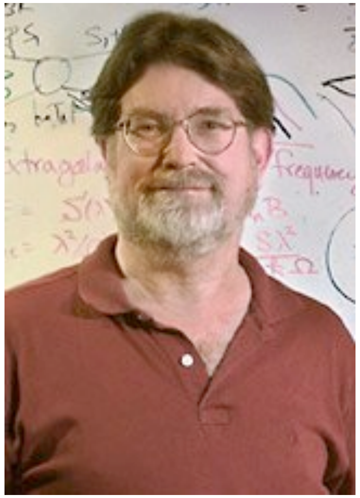
COBE



John Mather

2006 Nobel Prize in Physics

George Smoot



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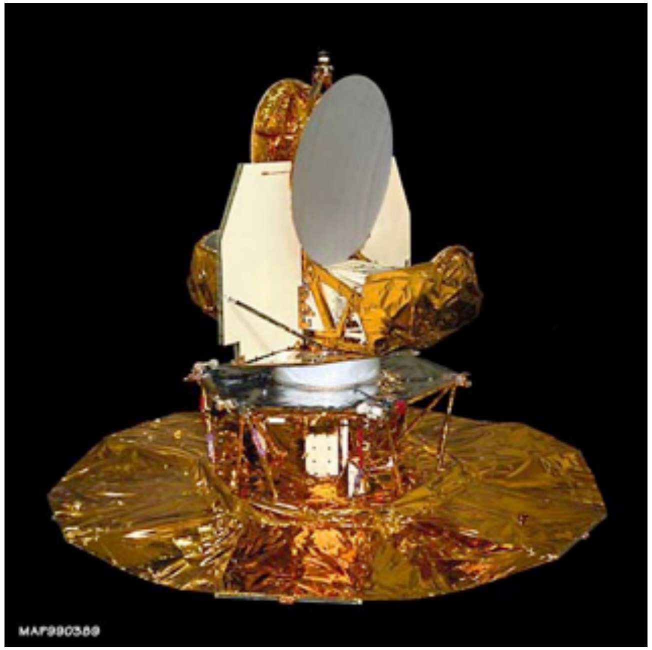
DMR: Measured anisotropies in the cosmic microwave background for the first time.

WMAP launched June 2001

Credit: NASA



Note the same dual receivers as COBE. This design, added with the very stable conditions at the L2, minimizes the "1/f noise" in amplifiers and receivers.

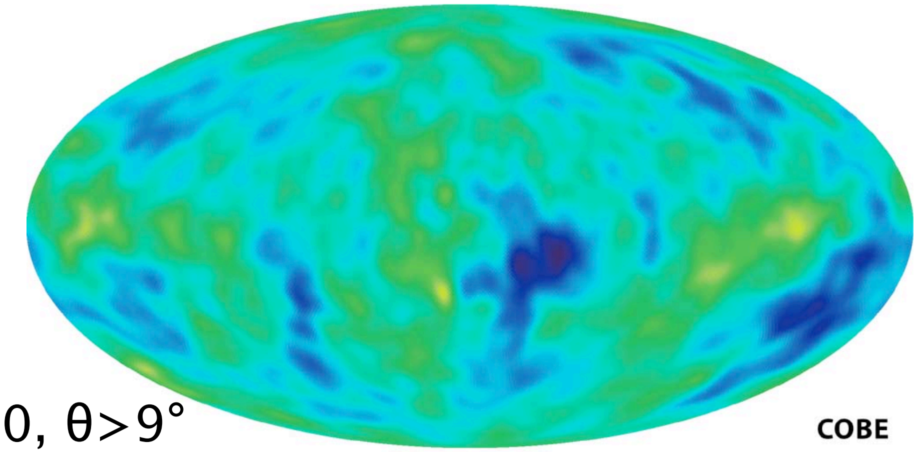
Thus after 7 years, the data can still be added and noise lowered (of course, the improvement will be marginal).

Credit: Porciano

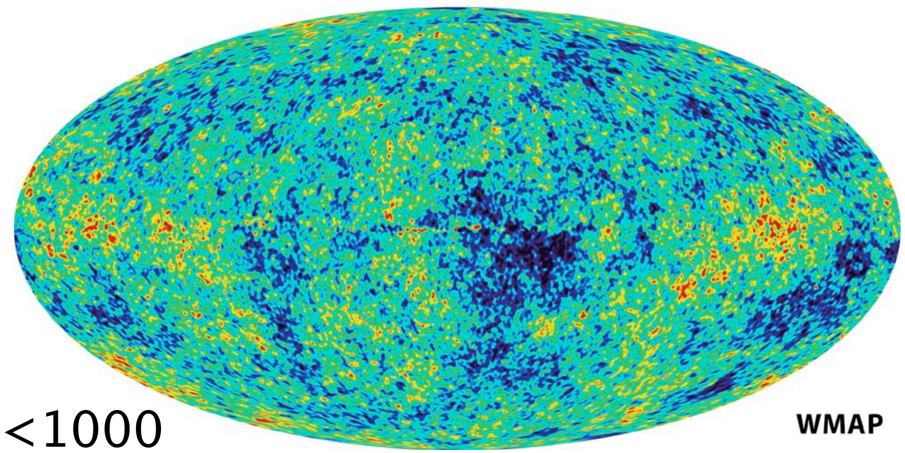
Credit: Porciano

2001-2009: WMAP

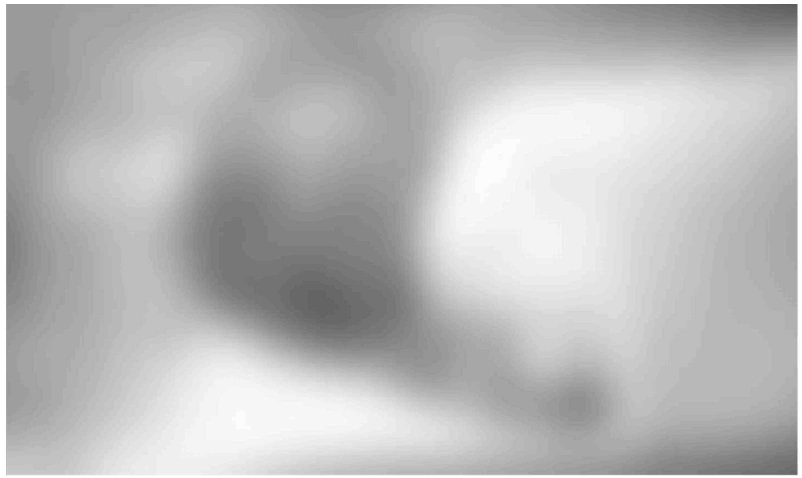
Resolution more than 20 times better with WMAP



$l<20,\ \theta>9°$

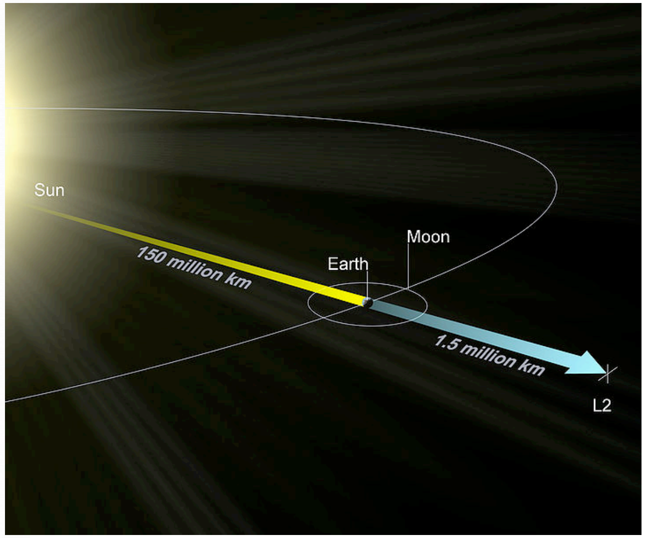


$2<l<1000$
$0.02°<\theta<90°$



Credit: ??

PLANCK launch May 2009



Destination L2: the second Lagrangian point

(getting crowded there!)

Credit: ESA

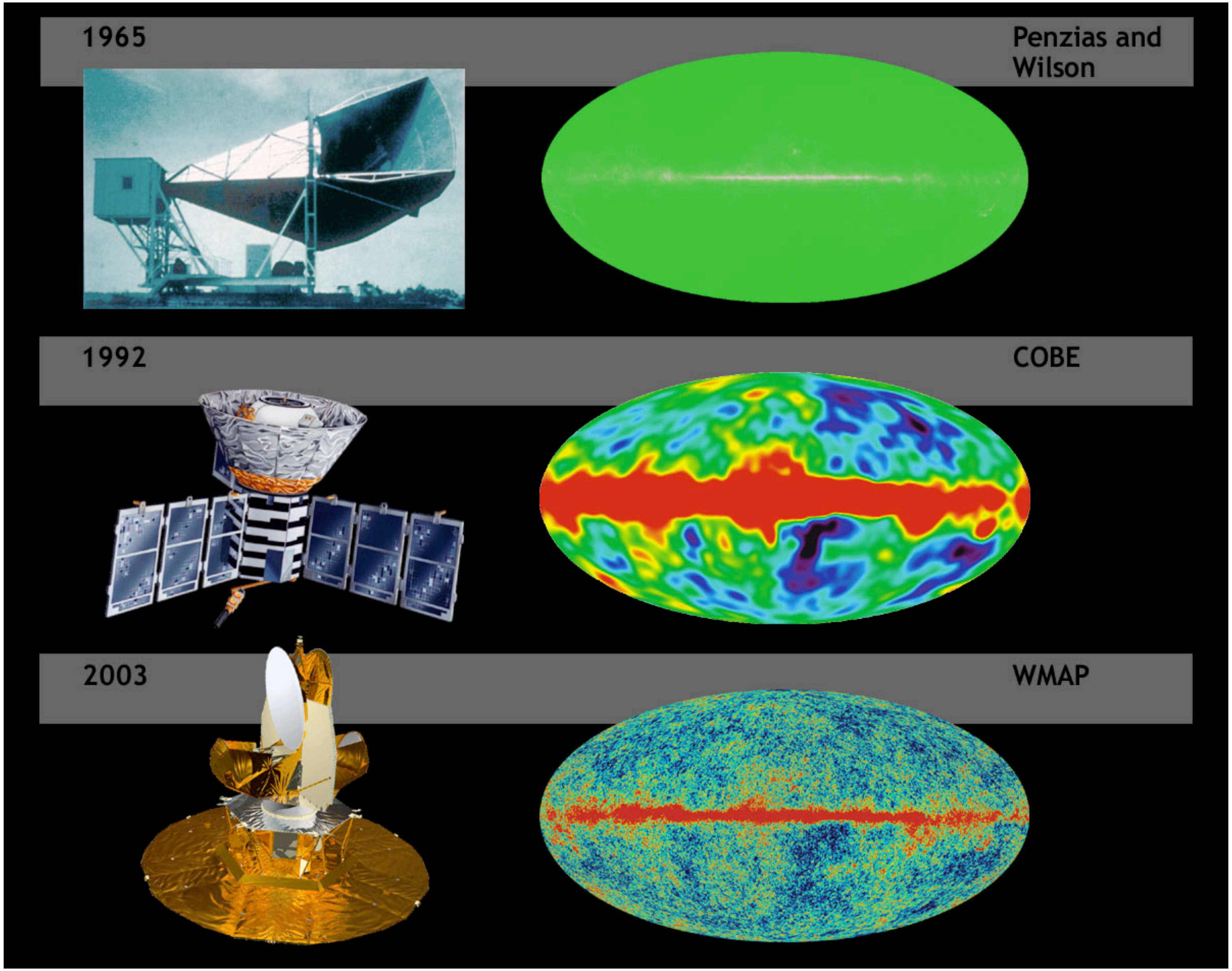
Credit: Porciano

2010-2014: The Planck satellite

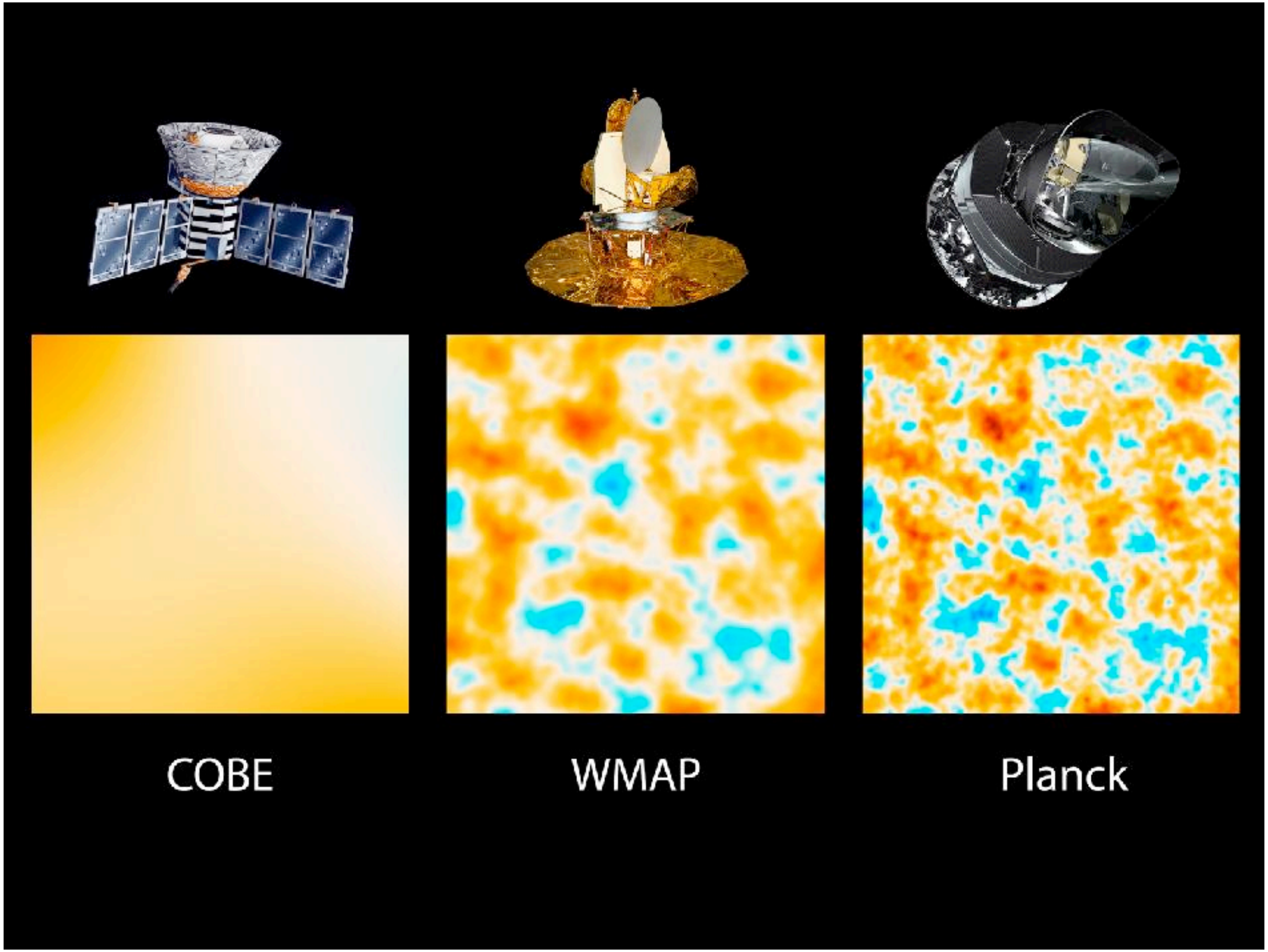
Credit: ESA

Credit: Porciano

Look at significant difference in detail



Look at the Resolution Differences:



Key Advances in Study of the CMB

- 1965 : CMB Discovery (Penzias & Wilson)
- 1977 : CMB Dipole Observed (Smoot et al)
- 1989 : CMB anisotropies observed (COBE)
- 2001 : Fundamental acoustic peak observed (Boomerang, Maxima)
- 2002 : Secondary acoustic peaks observed (Maxima,Boomerang DASI)
- 2002 : CMB Polarization (E-modes) observed (DASI)
- 2001 : Acoustic Peaks mapped (WMAP)
- 2005 ? : Discovery of B-modes ? (Polar Bear)
- 2007? : Characterize E-modes, Discovery of B-modes ? (Planck)
- 2015? : Discovery of B-modes ? (CMBPOL Einstein Probe Satellite)

Credit: Pearson

What happened during the recombination epoch and how did it result in the cosmic microwave background?

Recombination Epoch (z~1100)

Ionized Plasma → Neutral Gas

Ionized Plasma

(z > 1100)

< 380,000 years

Temperature
> 3600 K

Hydrogen ionized

Photons Thomson-scattering off of the ionized hydrogen

Neutral Gas

(z < 1100)

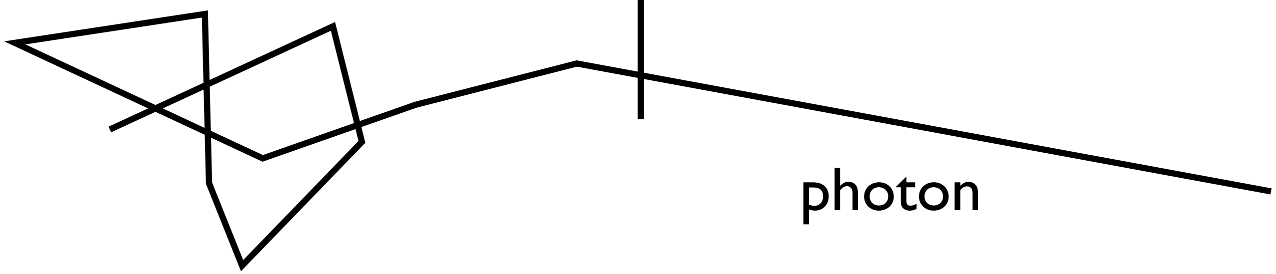
> 380,000 years

Temperature
< 3600 K

Hydrogen neutral

Almost no free electrons

Photons unbound from plasma



Recombination Epoch (z~1100)

Ionized Plasma ⟶ Neutral Gas

In more detail, transition occurs in three stages:

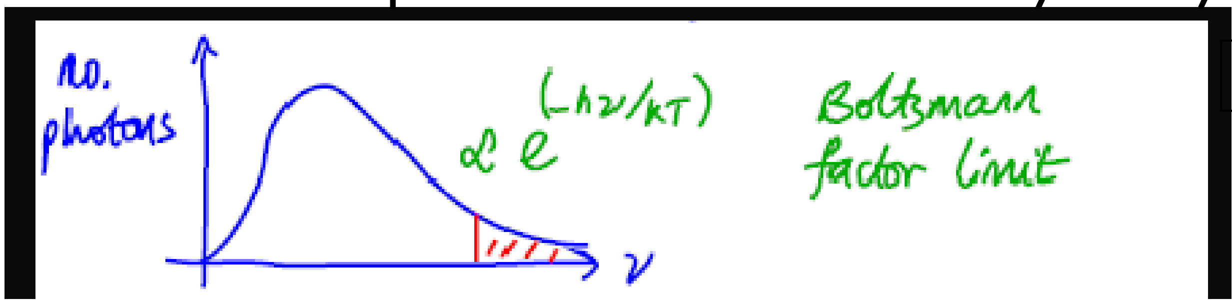
1. Recombination (starting at z~1500)

   -- Temperature drops sufficiently that protons can recombine with electrons

2. Decoupling (starting at z~1200)

   -- Stage where photons are no longer closely tied to baryons

   -- Occurs at a slightly later stage than the initial recombination, because the # of photons exceeds # of baryons by 10^9



Credit: Abdalla

-- With so many more photons, the temperature of the background radiation can fall well below what would normally be necessary to ionize hydrogen. It is because of the high energy tail of distribution.

Recombination Epoch (z~1100)

Ionized Plasma ⟶ Neutral Gas

In more detail, transition occurs in three stages:

1. Recombination (starting at z~1500)

   -- Temperature drops sufficiently that protons can recombine with electrons

2. Decoupling (starting at z~1200)

   -- Stage where photons are no longer closely tied to baryons

   -- Occurs at a slightly later stage than the initial recombination, because the # of photons exceeds # of baryons by 10^9

3. Last Scattering (mostly occurs after z~1080)

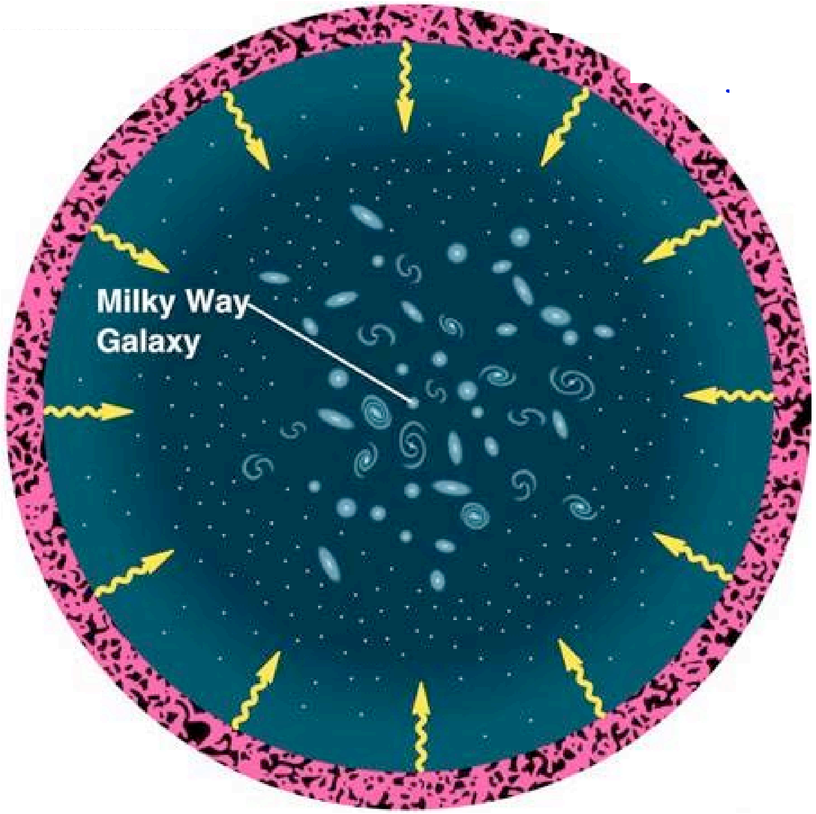
   -- Last time a cosmic microwave photon scatters off of matter

Origin of Microwave Background

-- The last time cosmic microwave photons interacted with matter was at the last scattering surface

-- Cosmic Microwave Photons we observe are a relic of the Big Bang

-- We cannot observe the universe directly at any earlier time than the last scattering surface (~400,000 years after the Big Bang)

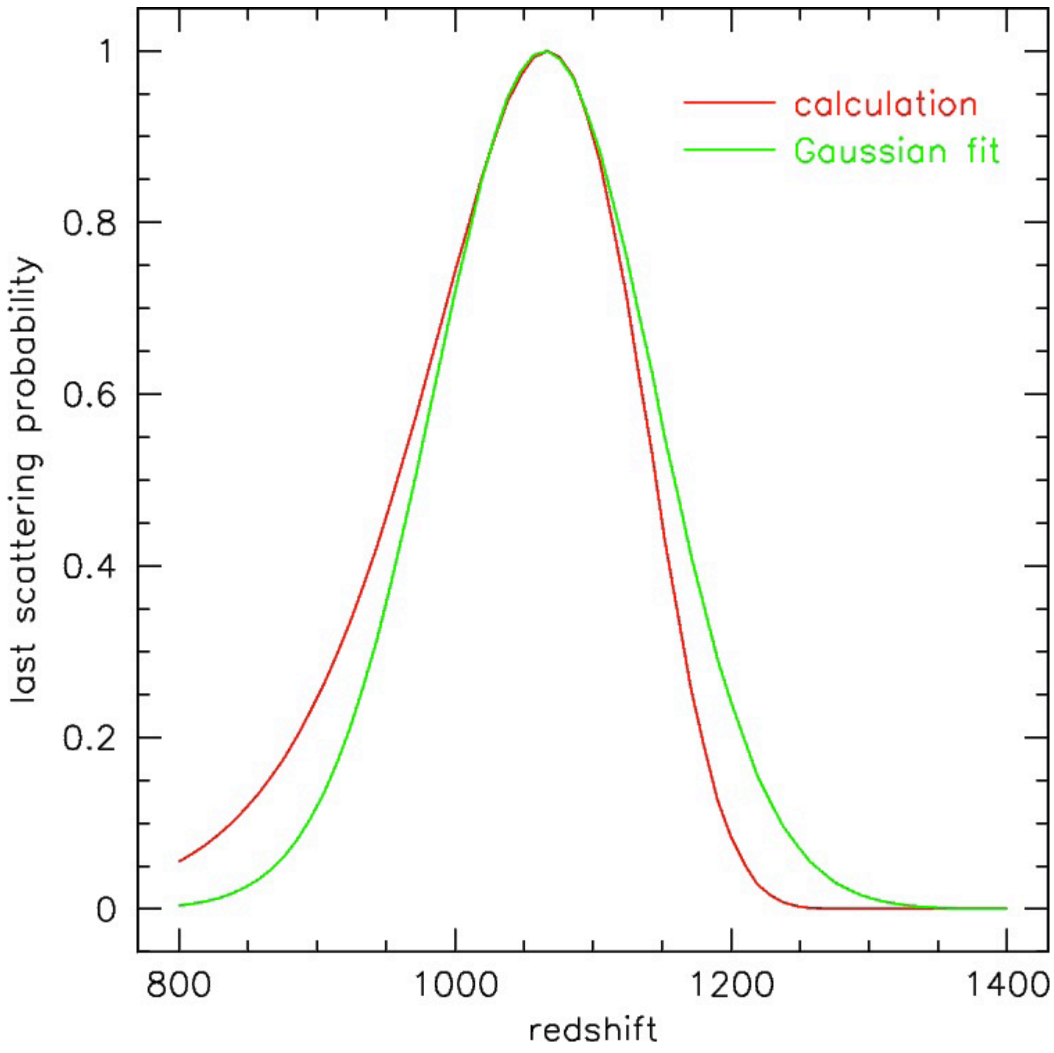


Credit: Pearson

How extended is the surface of last scattering?

-- Distribution describes the probability that a photon from the cosmic microwave background was last scattered at a given redshift.

-- Can roughly be described by a normal distribution with mean z = 1080 and standard deviation dz = 80



Thermalization of the CMB:

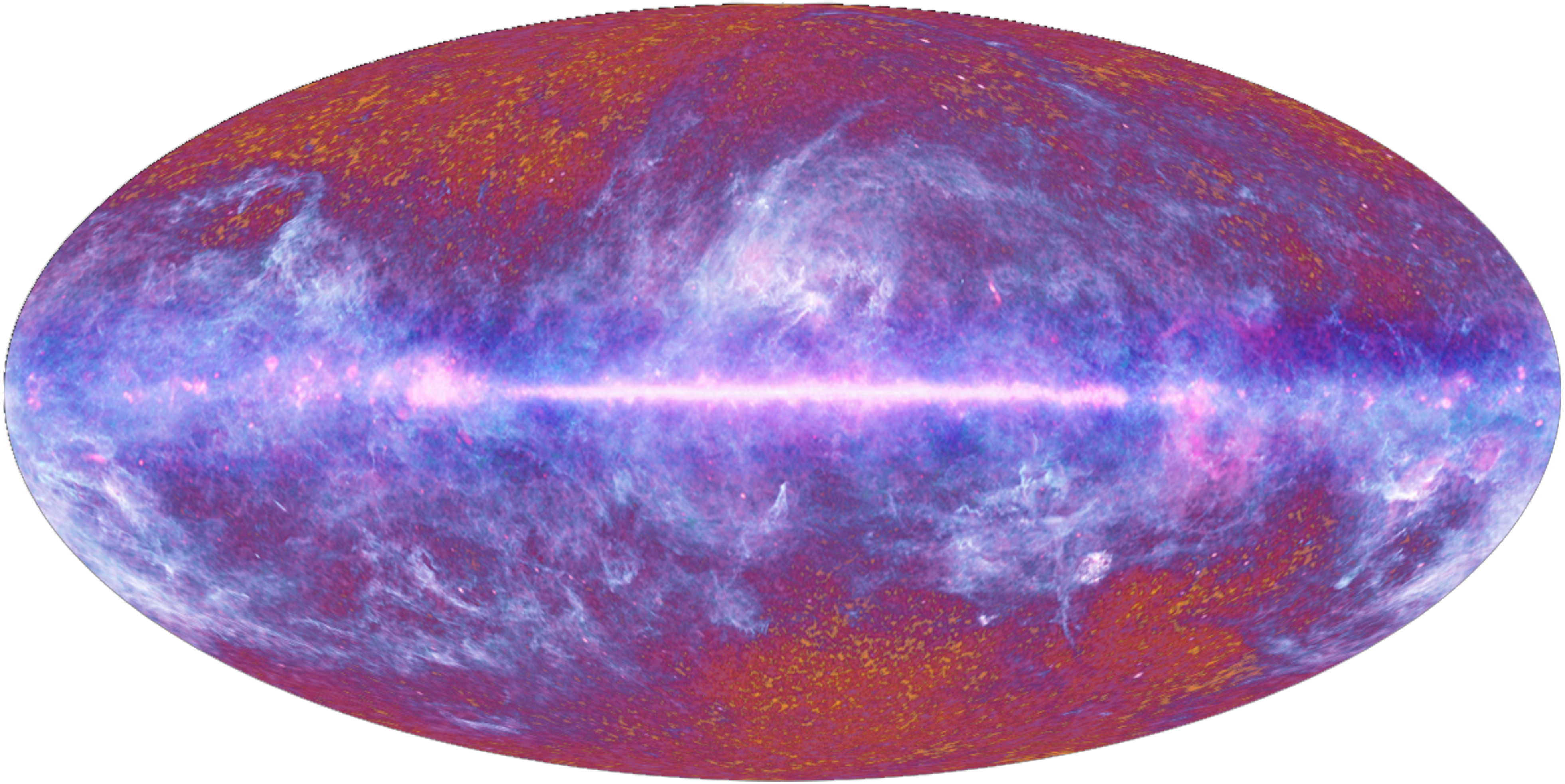
-- To have such a perfect blackbody shape, the rate of thermal and photon-scattering processes must be much faster than the rate of expansion of the universe. This happens at the redshifts $z > 2 \times 10^6$ (2 months after big bang)

-- This thermalization effectively removes any thermal and energy signatures from epochs before this point.

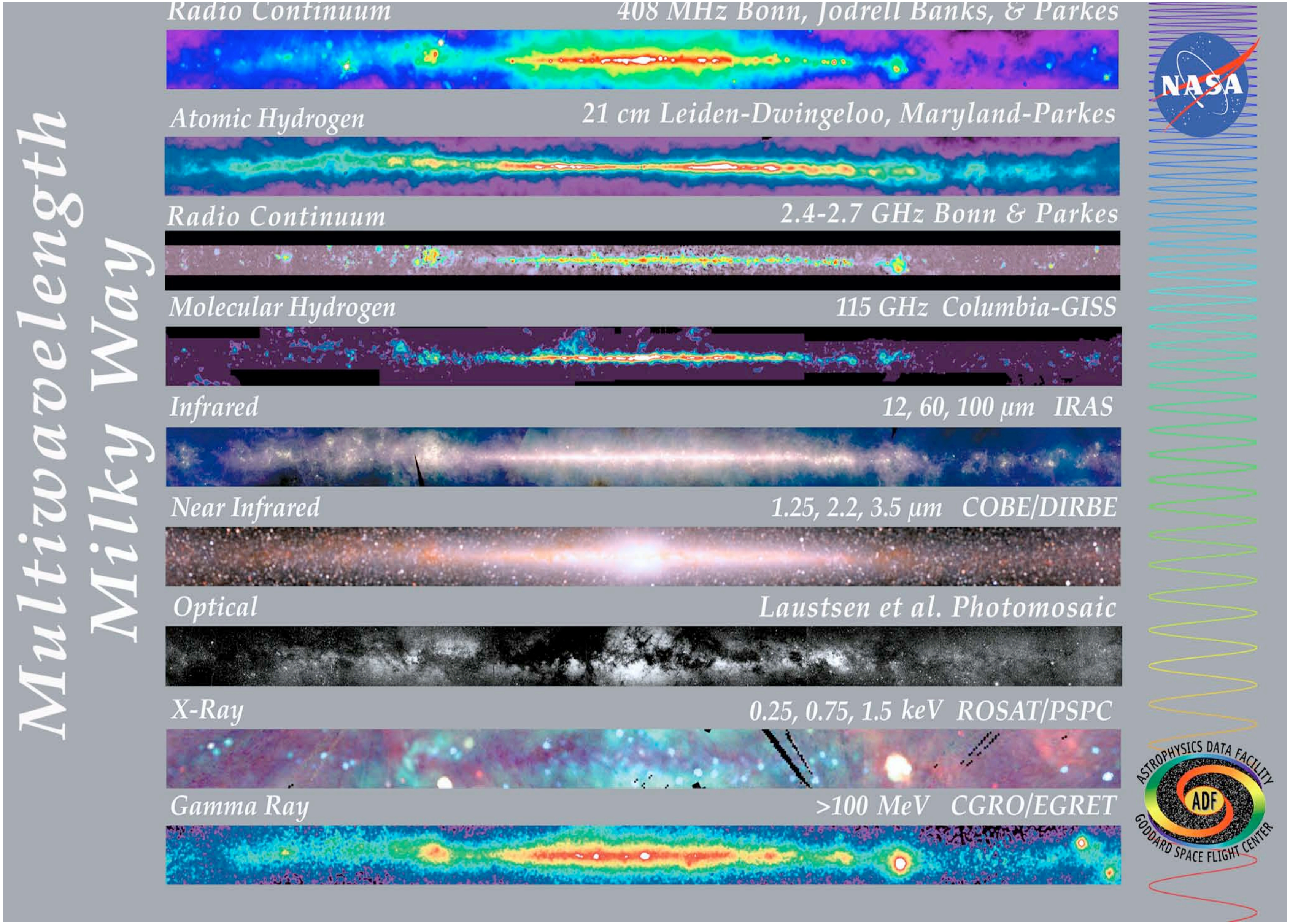
-- Since the universe expands adiabatically, once a blackbody spectrum is set up, it is maintained.

What fundamentally do we observe?

View of the sky as seen by Planck



Challenge of looking through the Milky Way

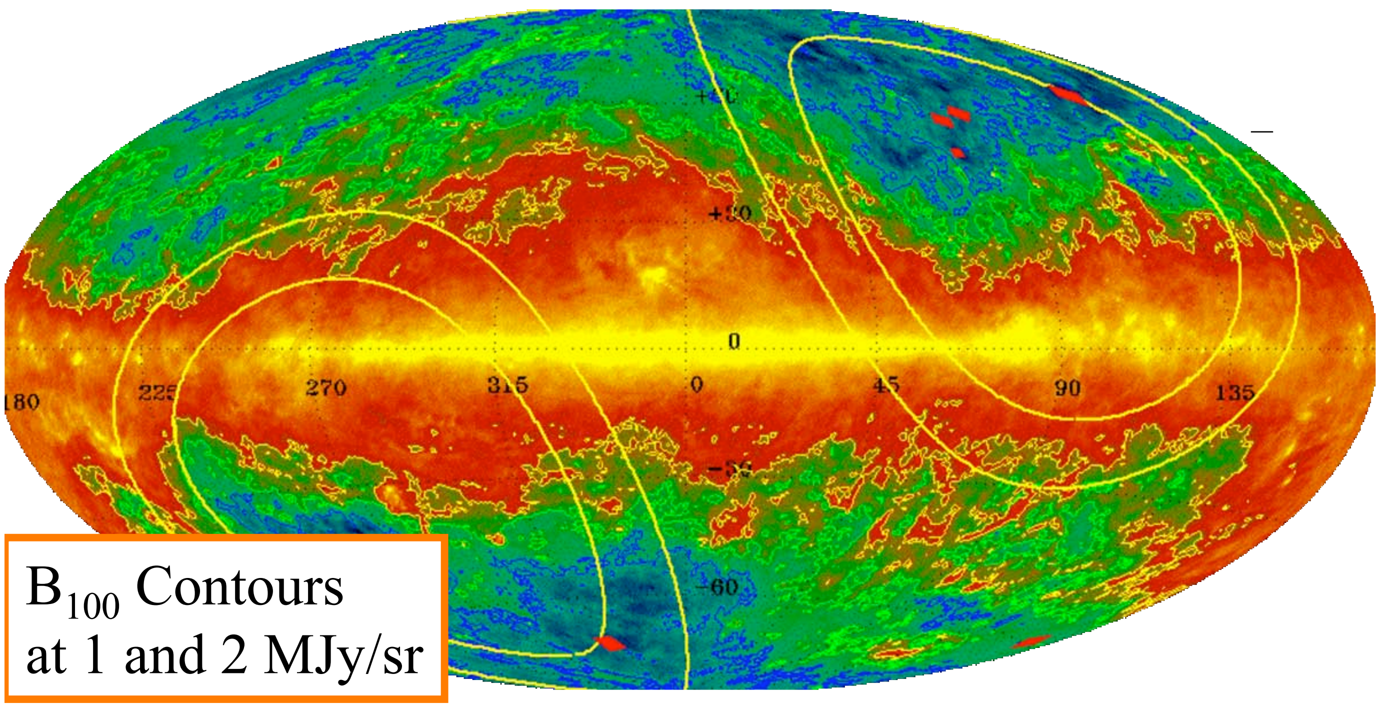


Substantial Foreground Light

One Example is Infrared Cirrus:

-- Interstellar dust in our galaxy is heated by the interstellar radiation field.

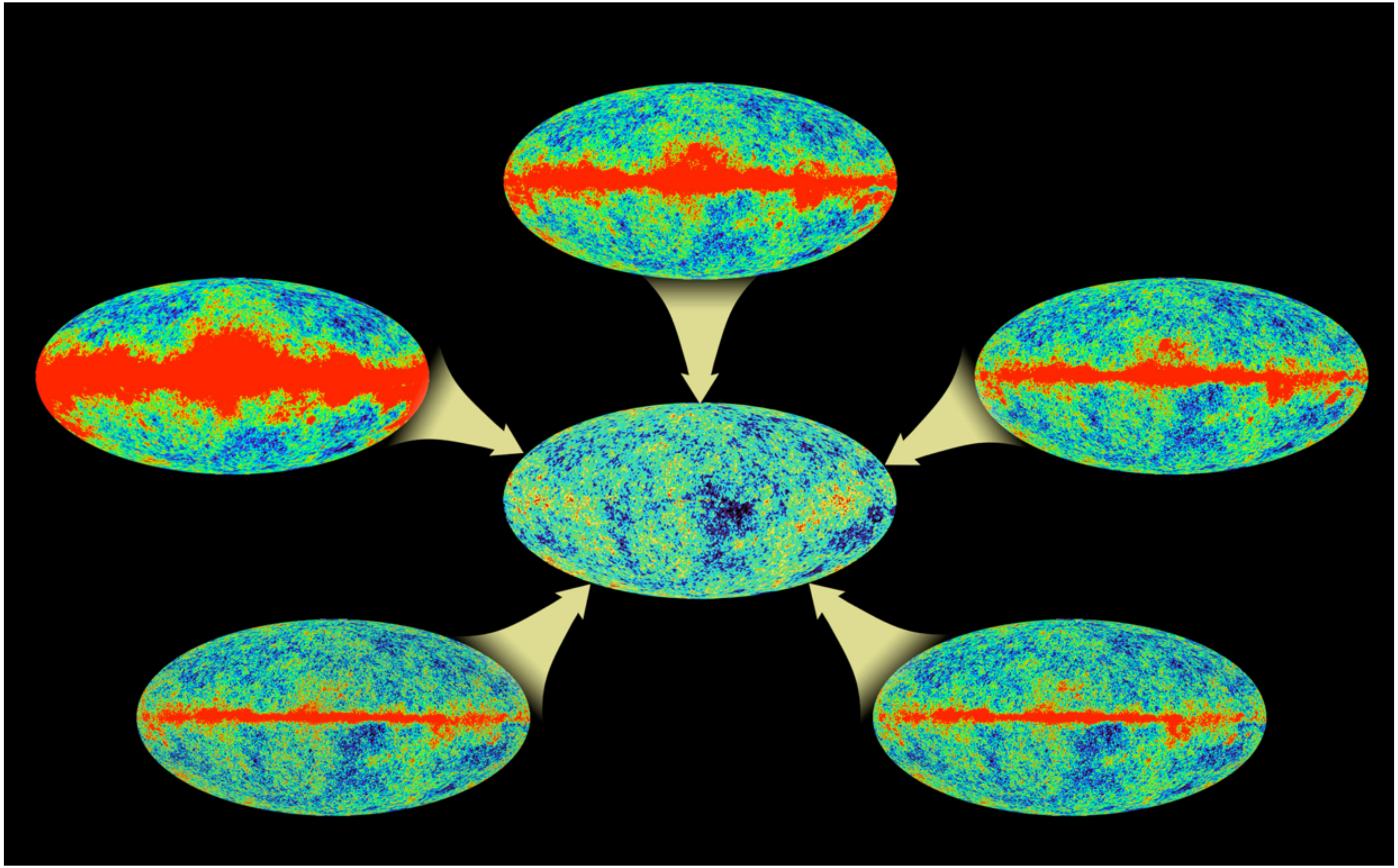
-- Emission depends on galaxy latitute and is significant longward of 60 μm



Other Examples are Synchrotron (from supernovae remnants) and Free-free Emission (from ionized regions around hot stars)

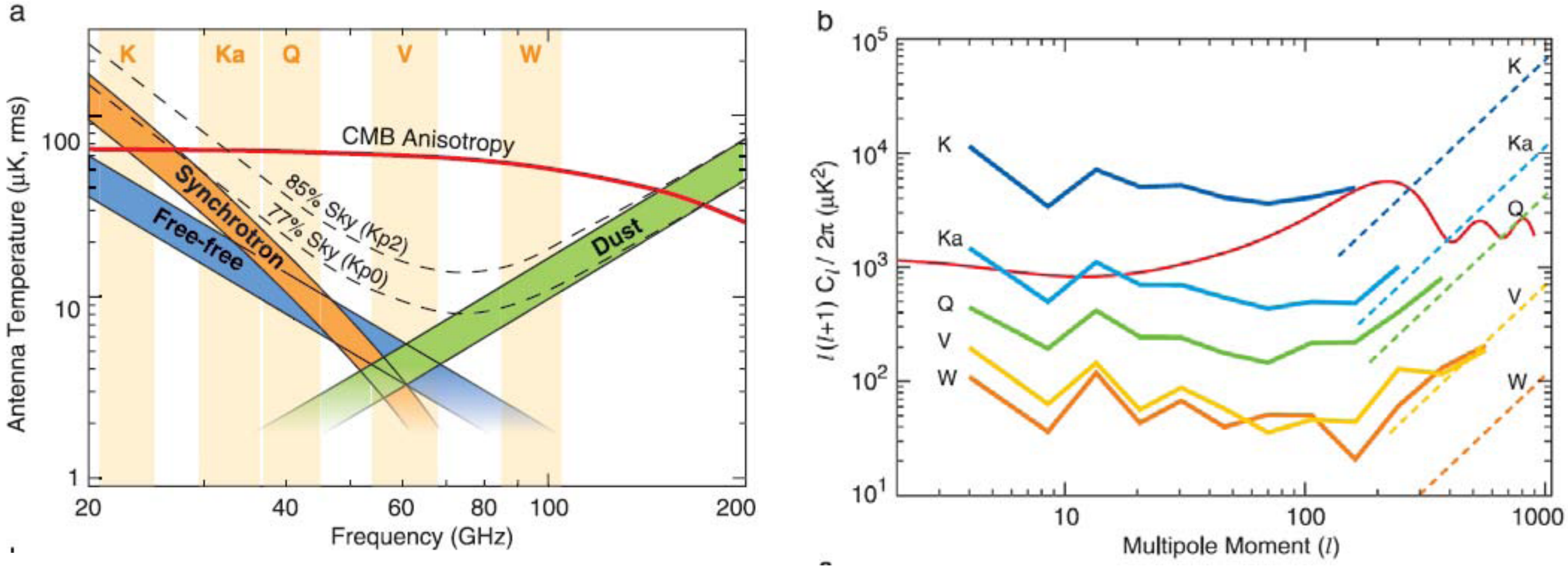
How can we distinguish microwave background light from foreground emission?

Fortunately all of these telescopes observe at multiple wavelengths



Fortunately all of these telescopes observe at multiple wavelengths

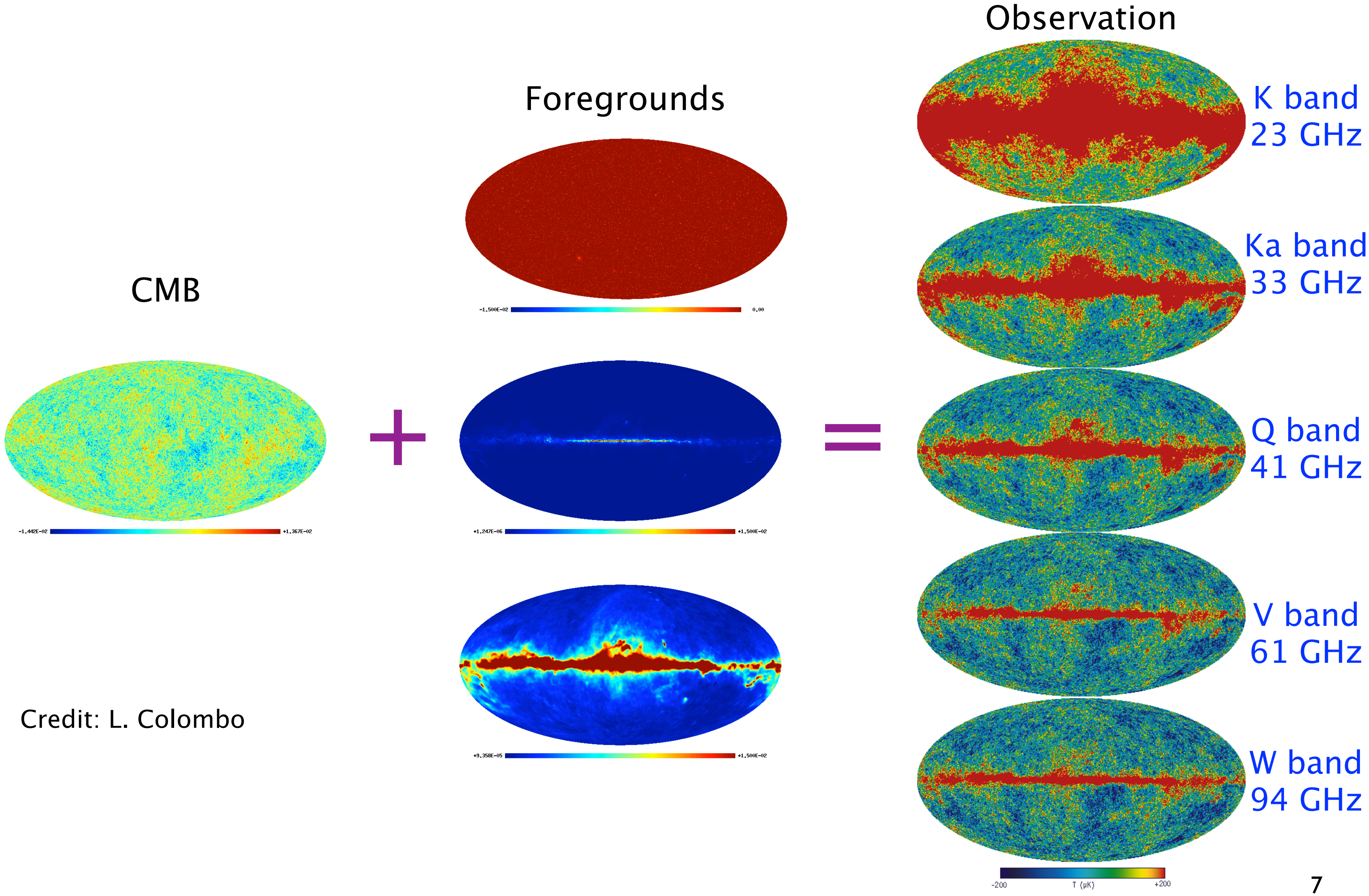
-- This foreground emission has a very different looking spectrum than the cosmic microwave background (each has unique multiwavelength signature)



CMB vs. foreground anisotropies (Bennett et al. 2003, WMAP 1st year)

-- 5 Wavelength channels for telescopes like WMAP chosen at wavelengths where CMB is particularly prominent (9 channels for Planck)

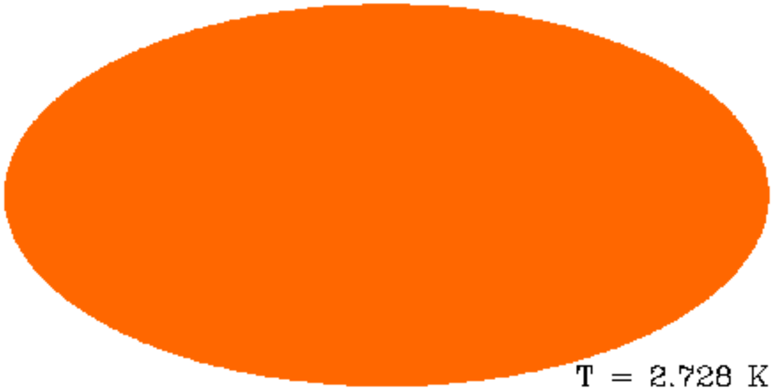
Using unique multiwavelength signatures of the CMB and the foregrounds, find the right linear combination to match the multi-wavelength observations



Credit: L. Colombo

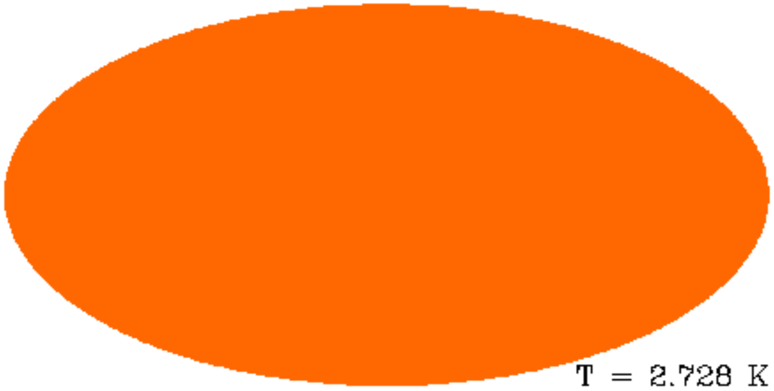
Now that we've explained the observational procedure, let's look at the cosmic microwave radiation a little closer

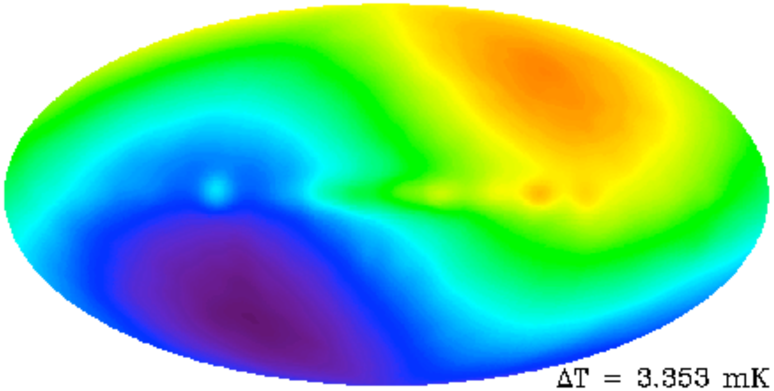
Examining the CMB at different contrast levels:



To first approximation, the cosmic microwave background is isotropic

Examining the CMB at different contrast levels:

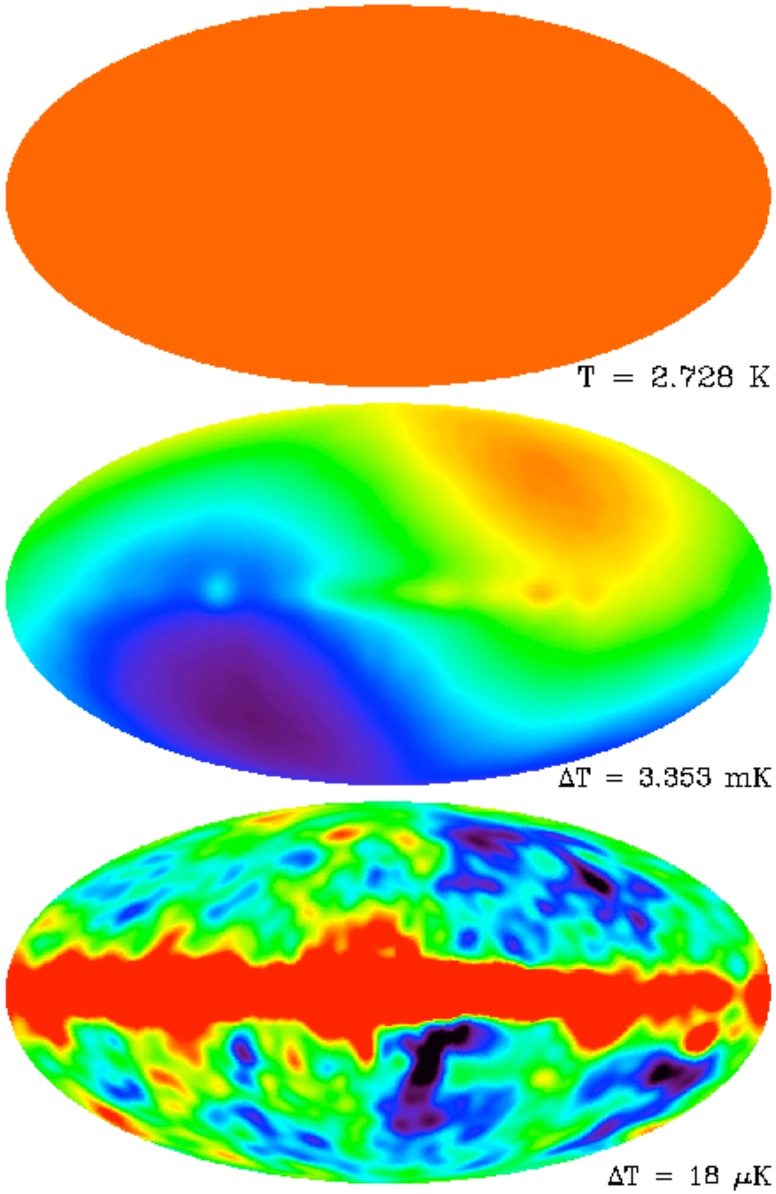




To first approximation, the cosmic microwave background is isotropic

At the ~10^{-3} level, one finds a dipole -- that arises from the motion of the earth relative to the CMB frame

Examining the CMB at different contrast levels:

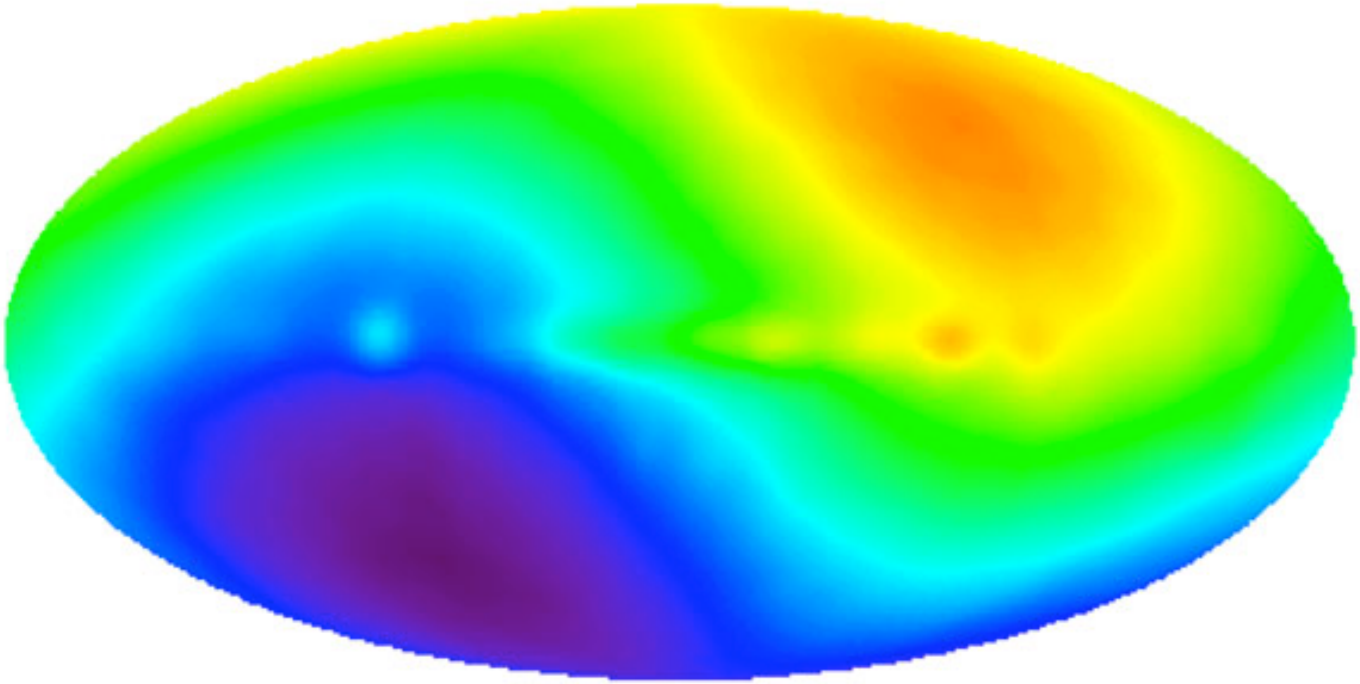


To first approximation, the cosmic microwave background is isotropic

At the ~10^{-3} level, one finds a dipole -- that arises from the motion of the earth relative to the CMB frame

At the ~10^{-5} level (and subtracting the dipole), one observes anisotropies in the CMB.

Dipole in the Cosmic Microwave Background



-- magnitude of the dipole is 390 ± 30 km/s

-- if we correct for

satellite-earth ~ 8 km s^{-1}

earth-sun ~ 30 km s^{-1}

sun-galaxy ~ 220 km s^{-1}

galaxy-local group~ 220 km s^{-1}

we find our local group moving towards Hydra at 630±20 km s^{-1}

How do we analyze the cosmic microwave background?

How to represent or model anisotropies in the CMB?

-- Since the observed temperature of the CMB as a function of position on sky only differs by a small amount from the mean, represent the anisotropies as a temperature difference

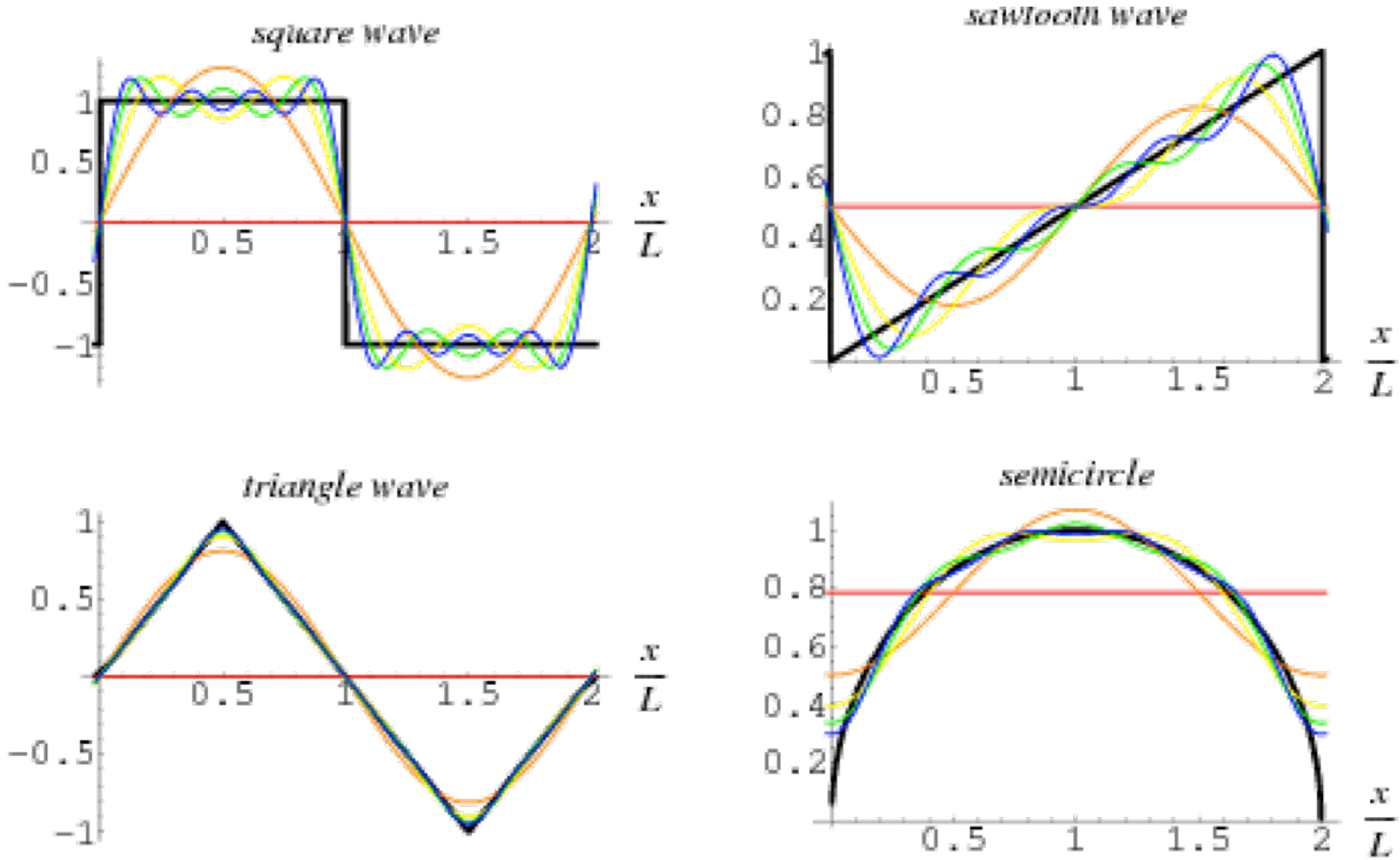
$$\frac{\Delta T}{T}(\theta, \phi) = \frac{T(\theta, \phi) - \bar{T}}{\bar{T}}$$

-- Represent this temperature difference as a function of position using an equivalent Fourier series in spherical coordinates -- which are spherical harmonics

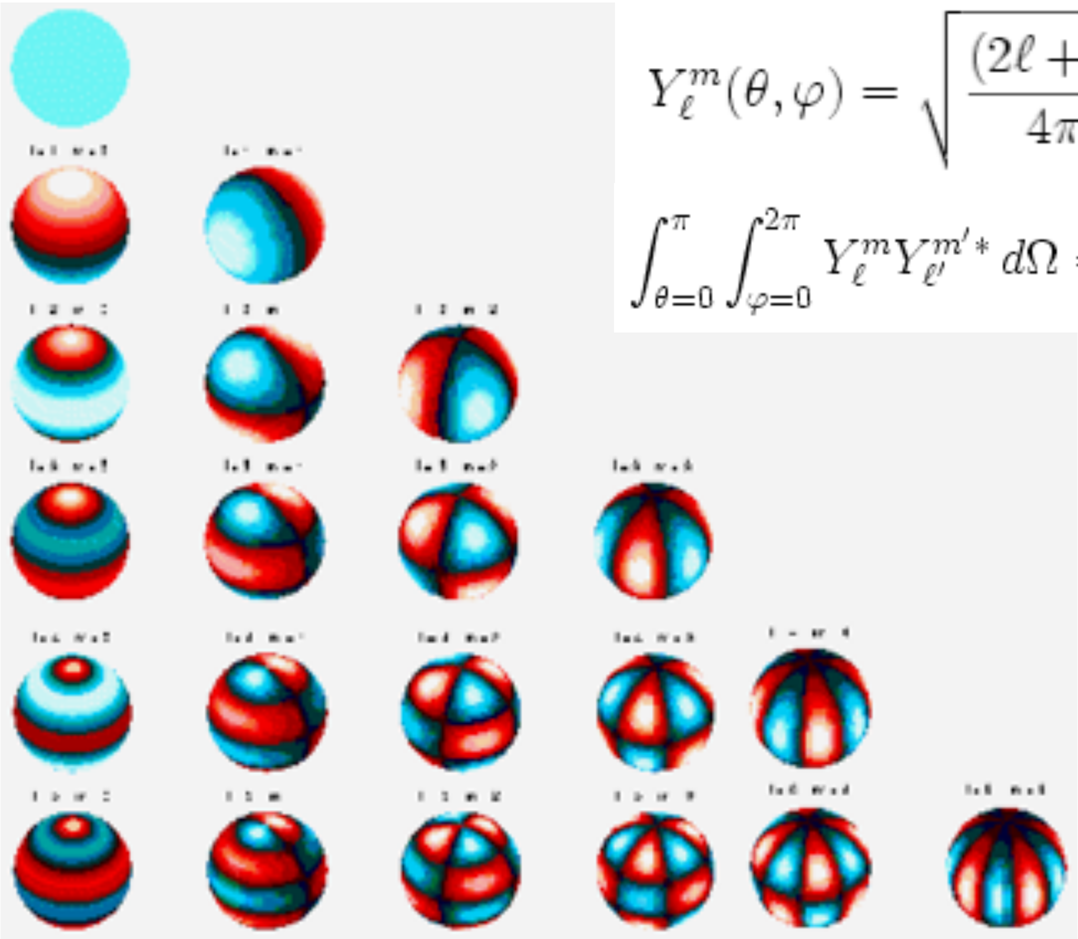
$$\frac{\Delta T}{T}(\theta, \phi) = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_m^{\ell}(\theta, \phi)$$

Similar concept to Fourier Series

-- Most of you are probably familiar with the fact that one can use a fourier series to represent an arbitrary one-dimensional function



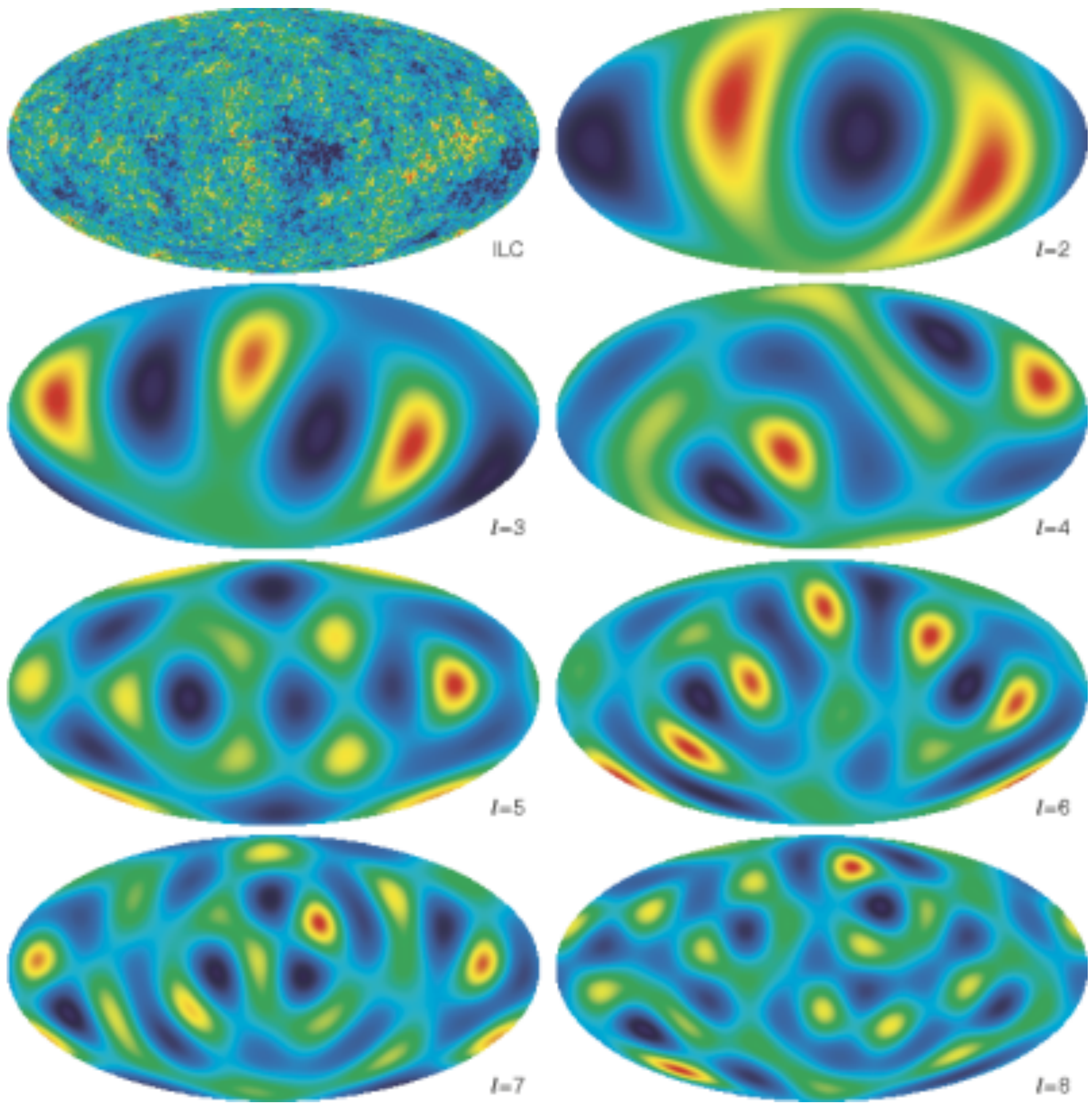
Spherical harmonics (used to represent the anisotropies in the CMB)



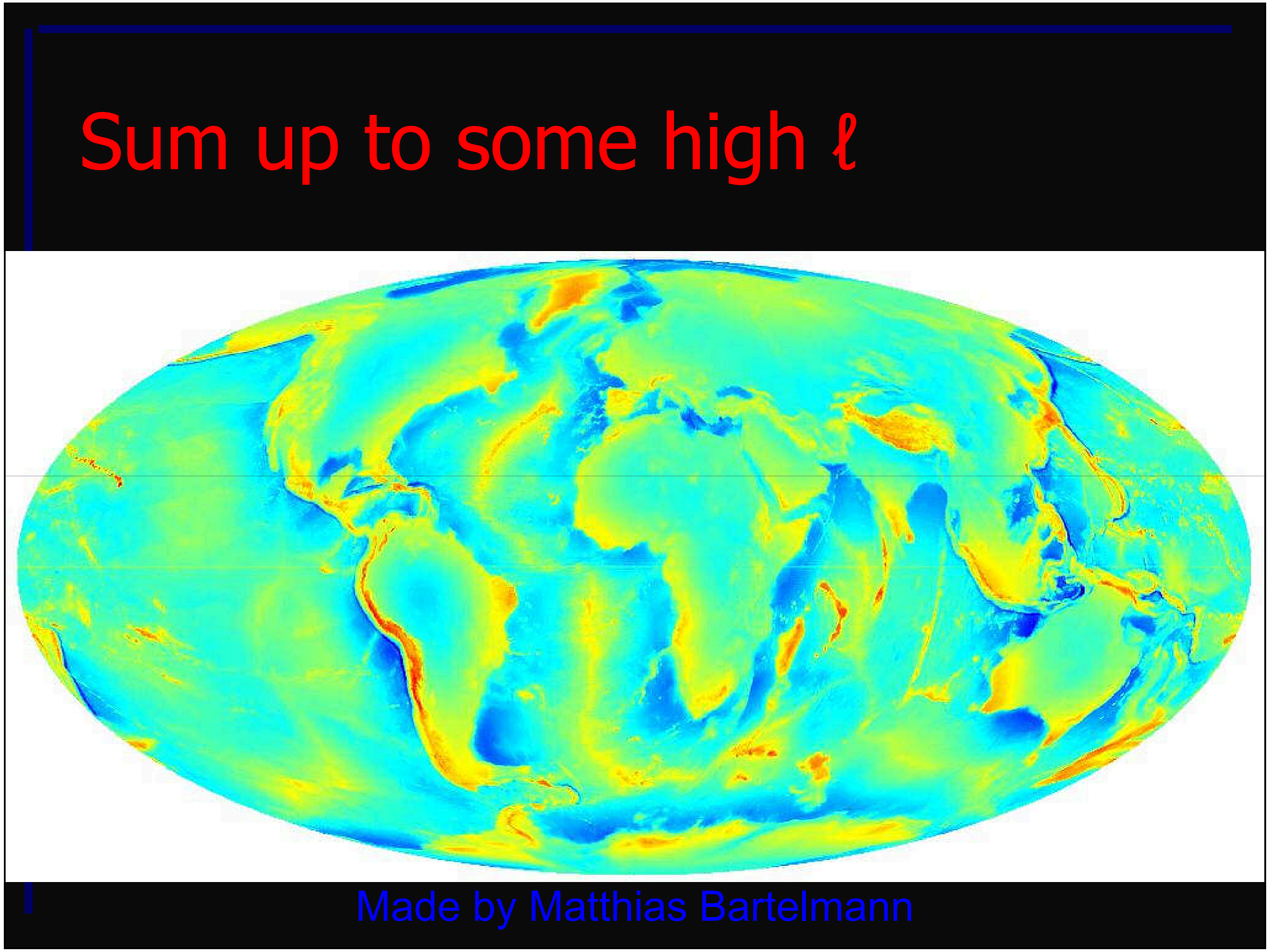
$$Y_\ell^m(\theta,\varphi) = \sqrt{\frac{(2\ell+1)}{4\pi}\frac{(\ell-m)!}{(\ell+m)!}} \cdot e^{im\varphi} \cdot P_\ell^m(\cos\theta)$$

$$\int_{\theta=0}^{\pi}\int_{\varphi=0}^{2\pi} Y_\ell^m Y_{\ell'}^{m'*}\, d\Omega = \delta_{\ell\ell'}\delta_{mm'} \qquad d\Omega = \sin\theta\, d\varphi\, d\theta$$

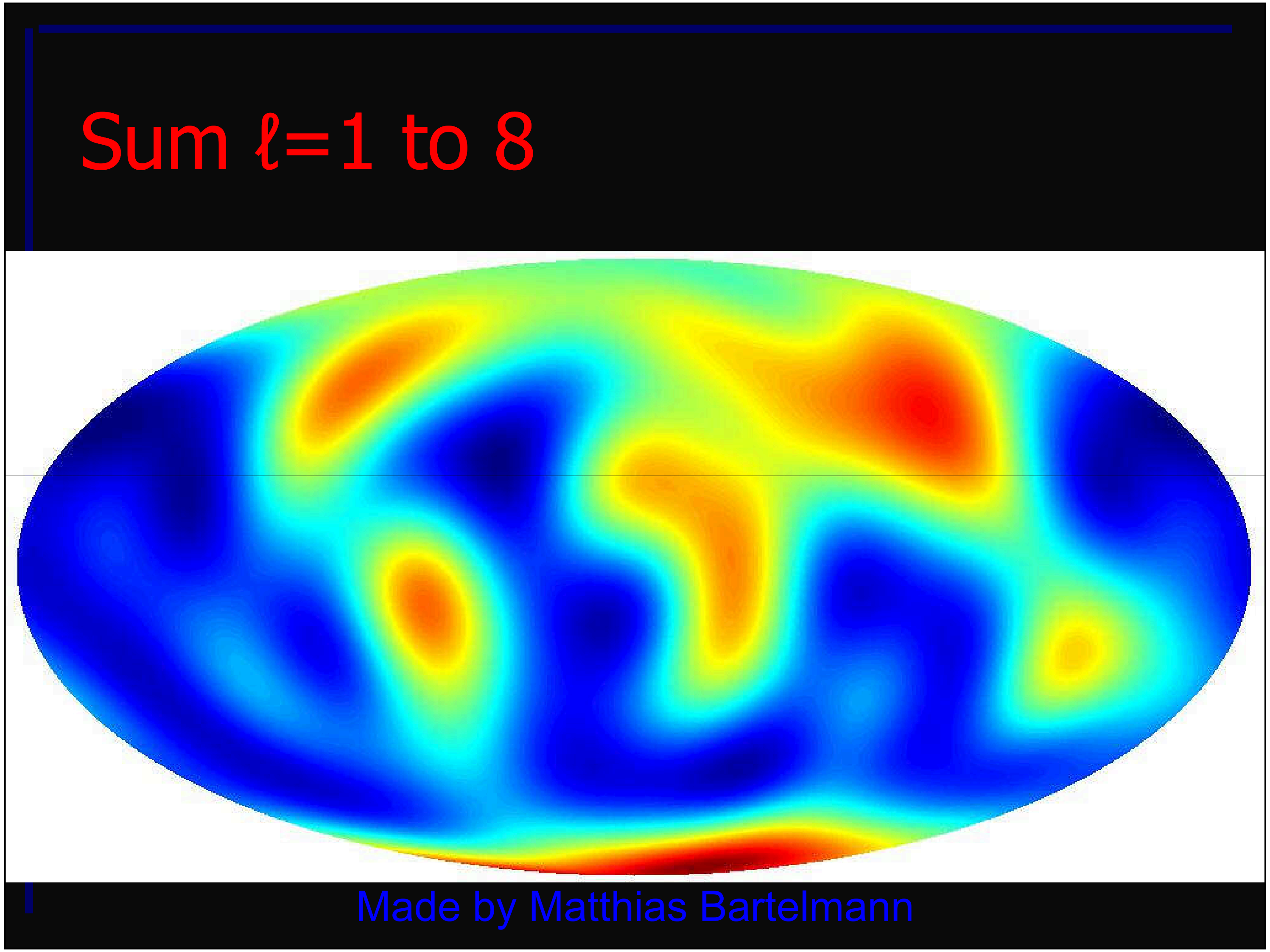
Closer look at all the multipoles



One can represent any spherical surface using an expansion in Legendre polynomials

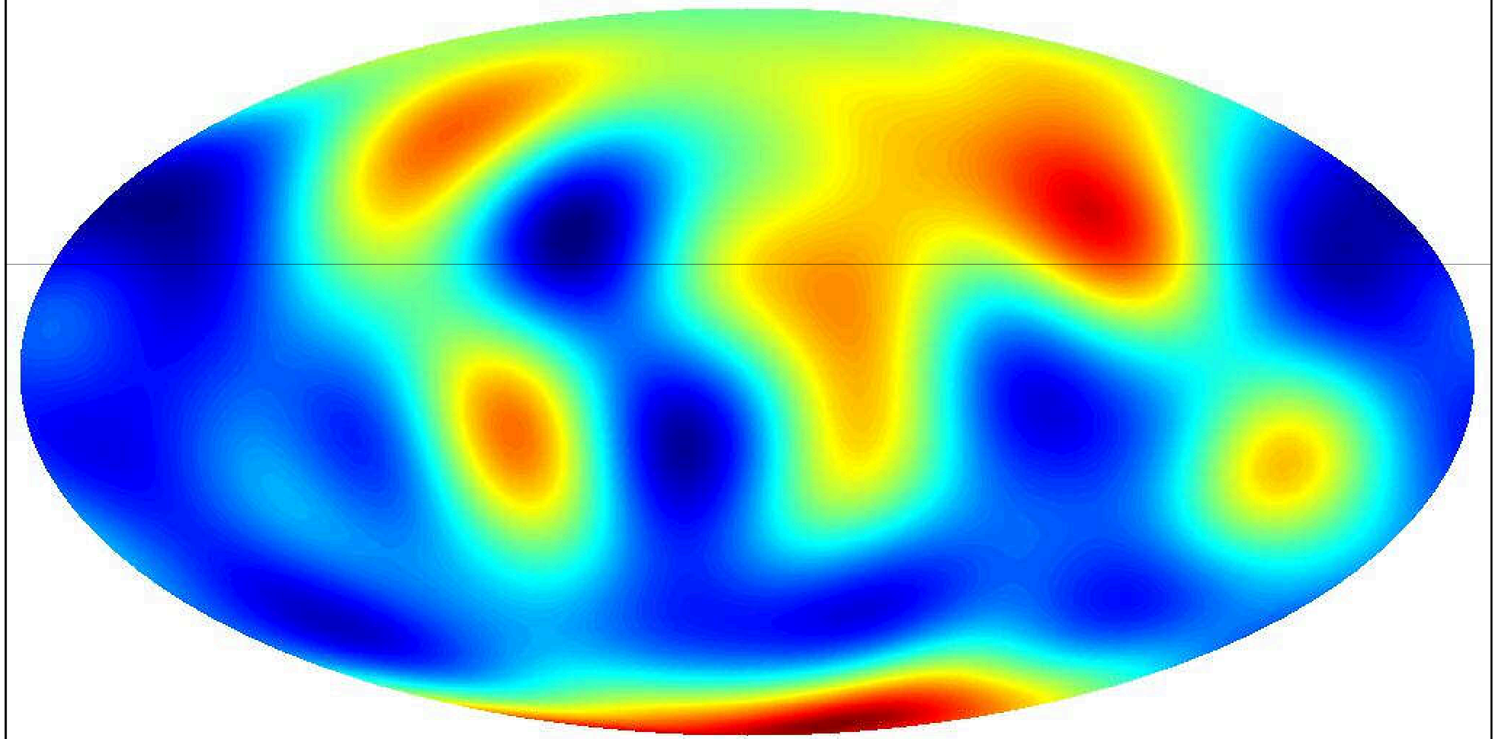


Credit: Bartelmann



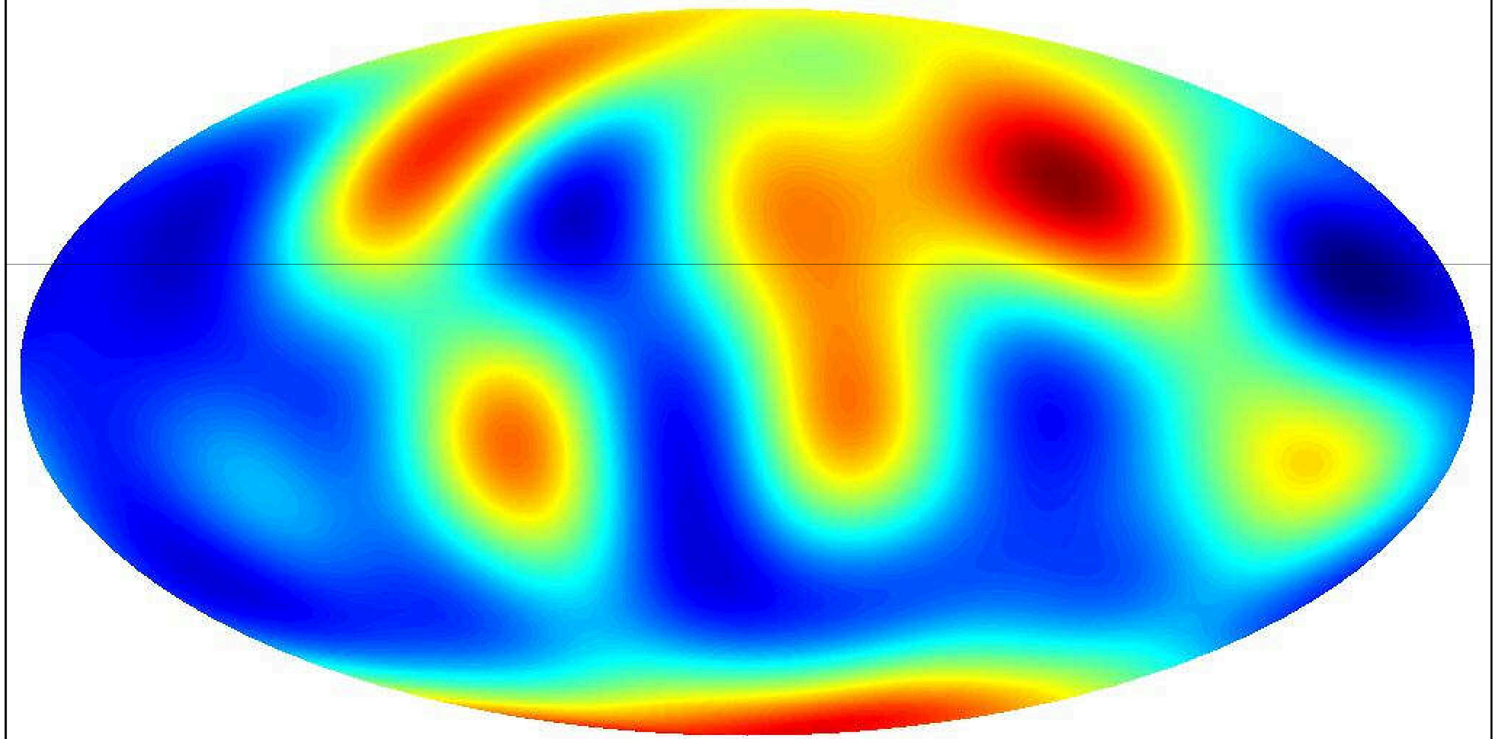
Credit: Bartelmann

Sum ℓ=1 to 7



Made by Matthias Bartelmann

Sum ℓ=1 to 6



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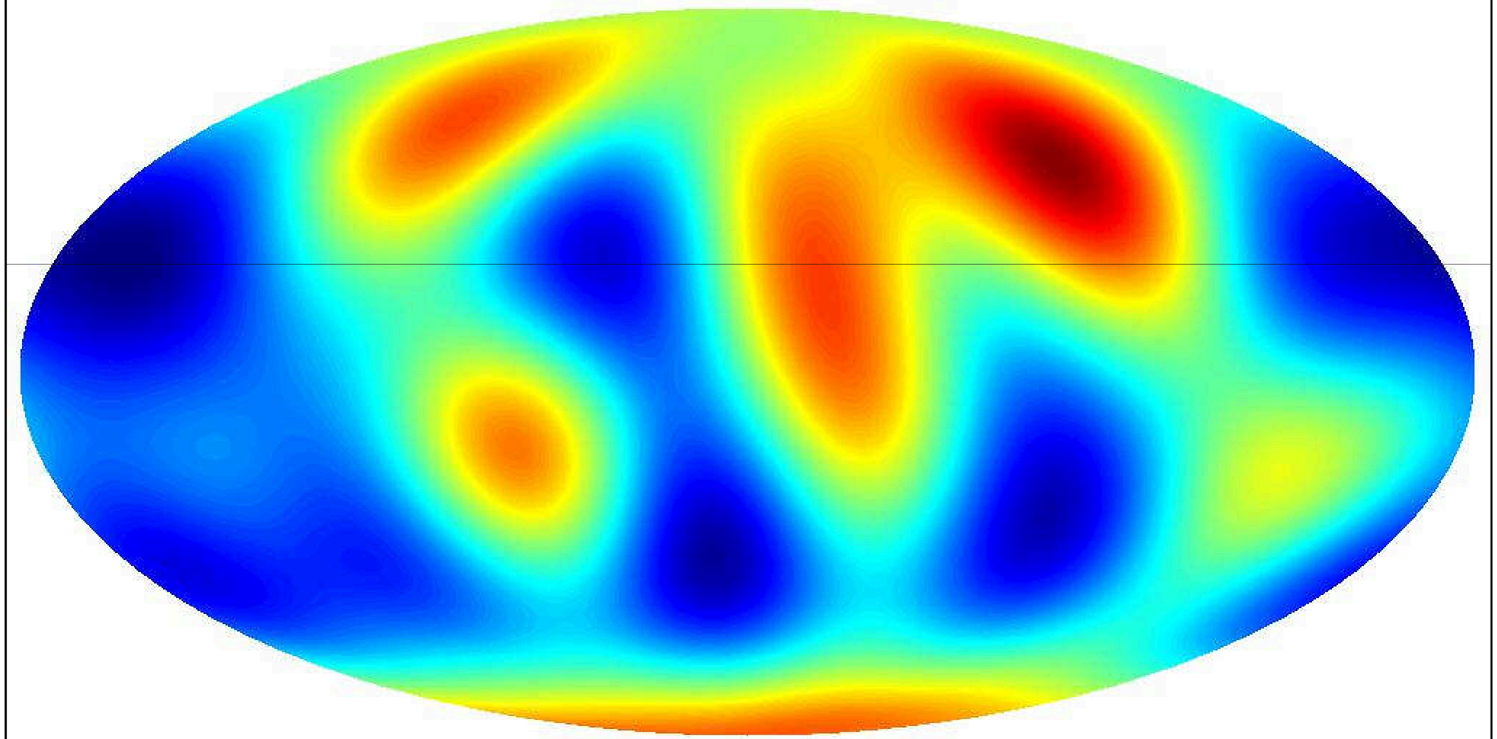
Sum ℓ=1 to 5



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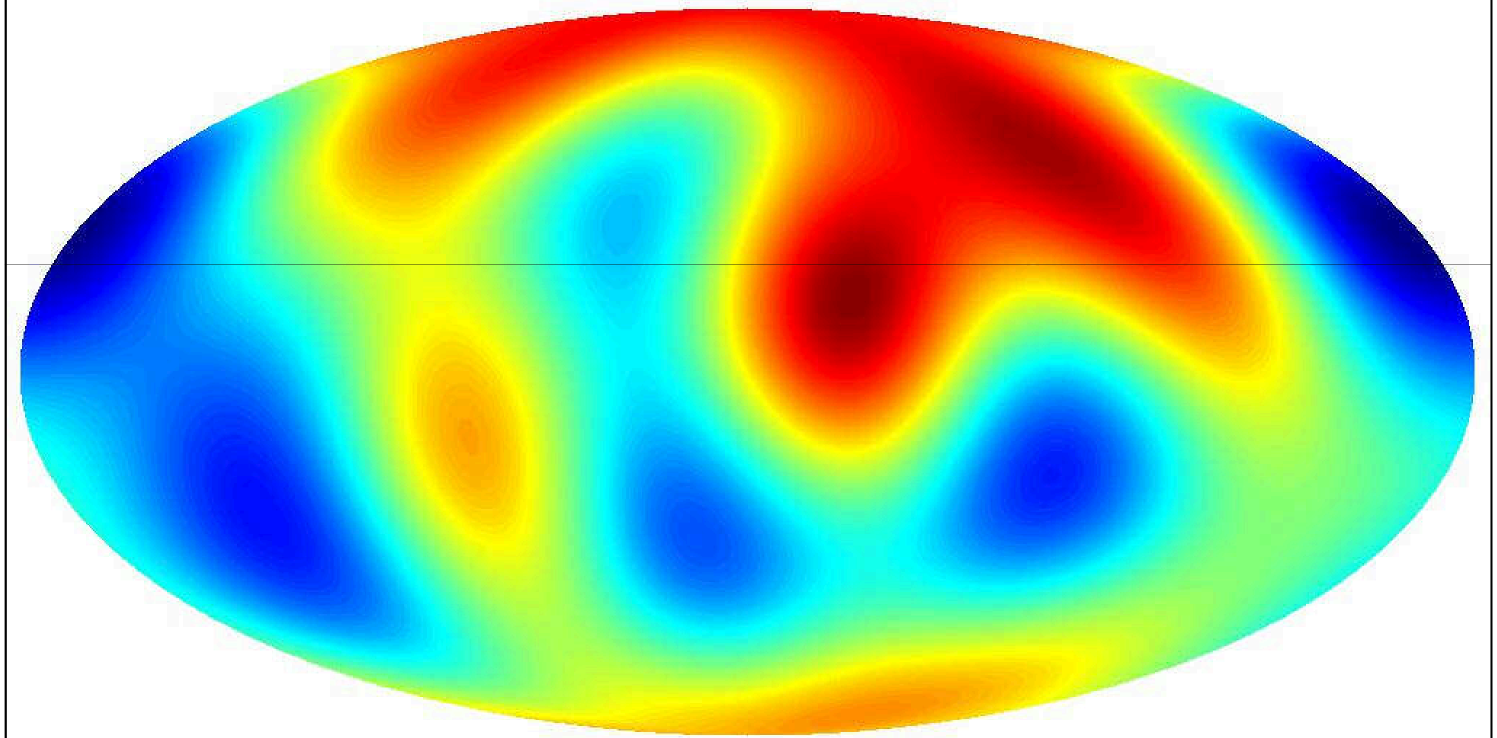
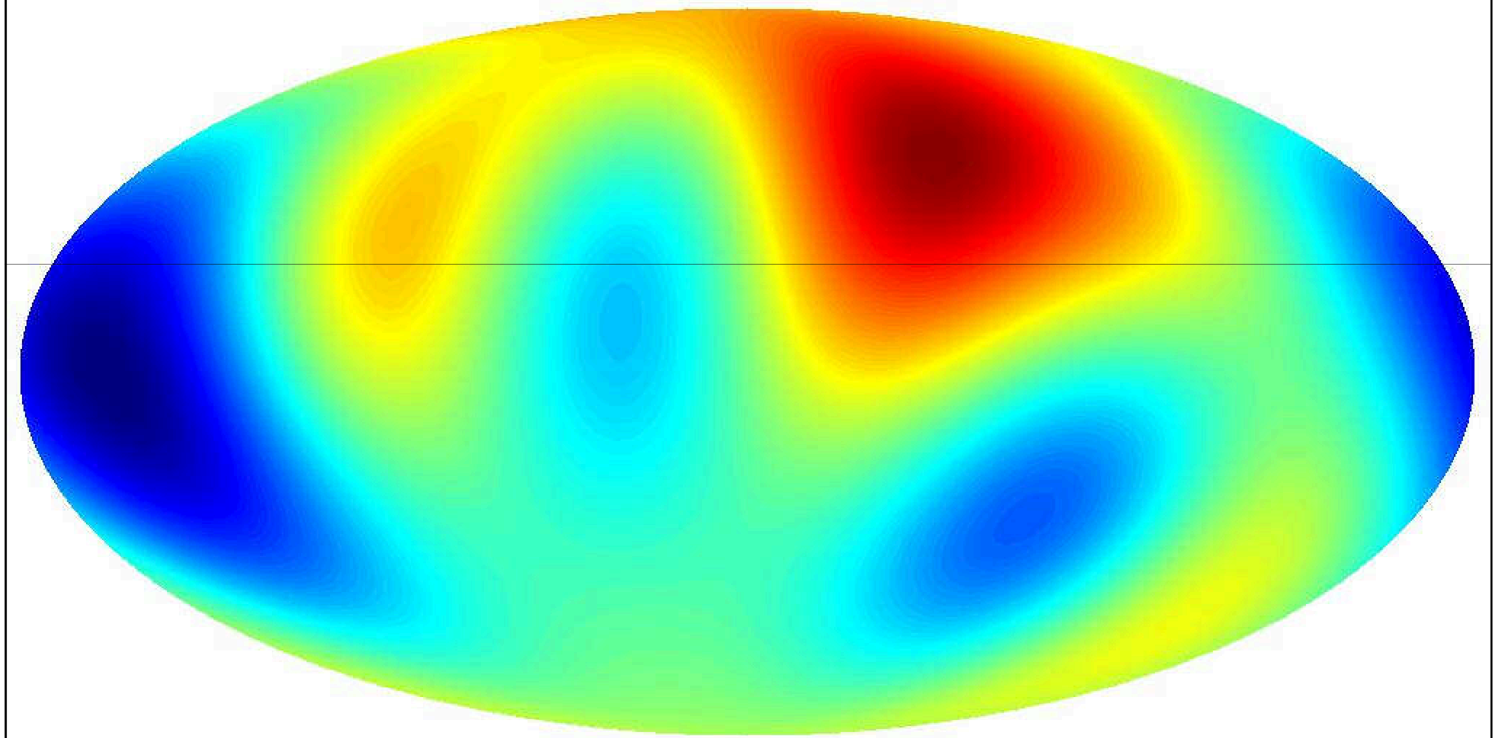
Sum ℓ=1 to 4



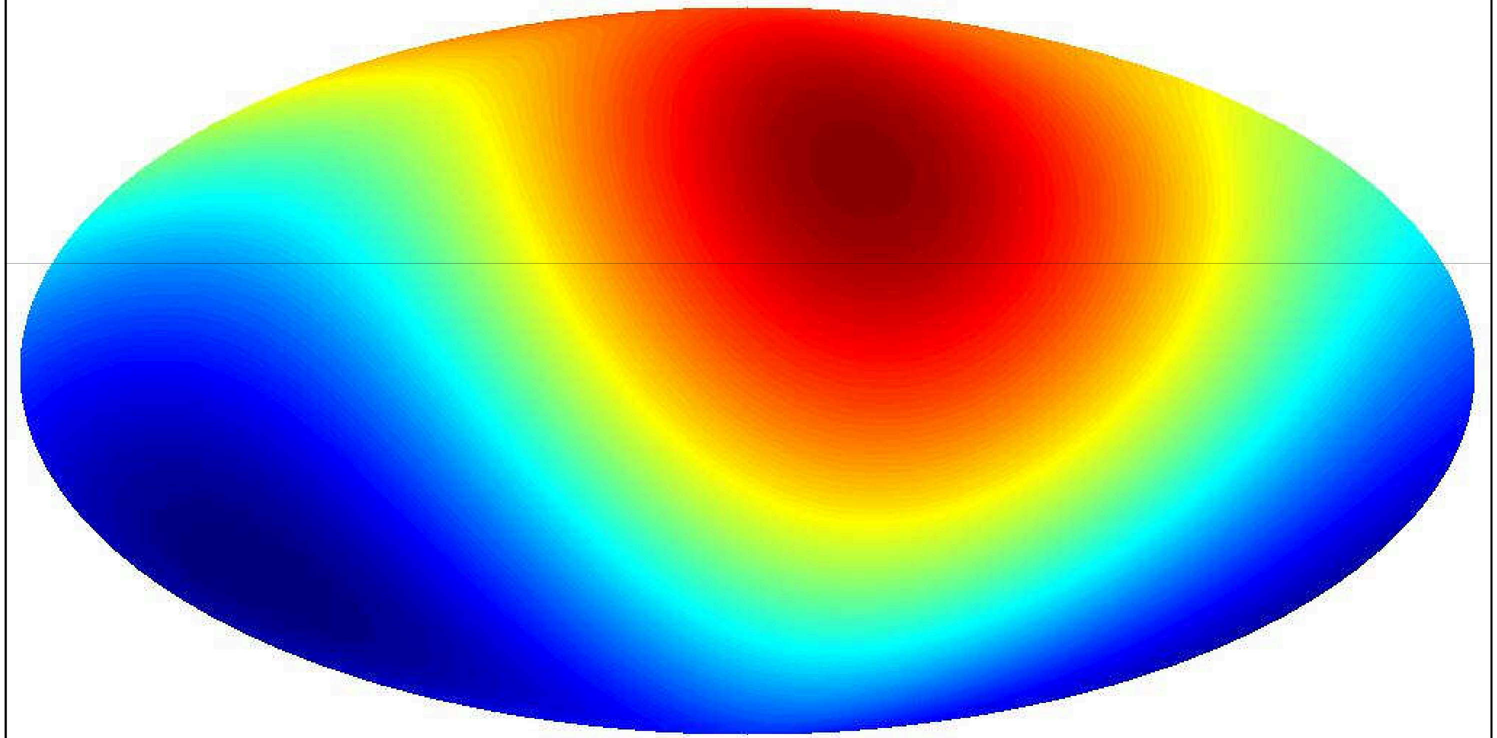
Made by Matthias Bartelmann

ℓ=1 plus ℓ=2 plus ℓ=3



Made by Matthias Bartelmann

Spherical harmonics:
The spherical equivalent of sine waves
ℓ=1



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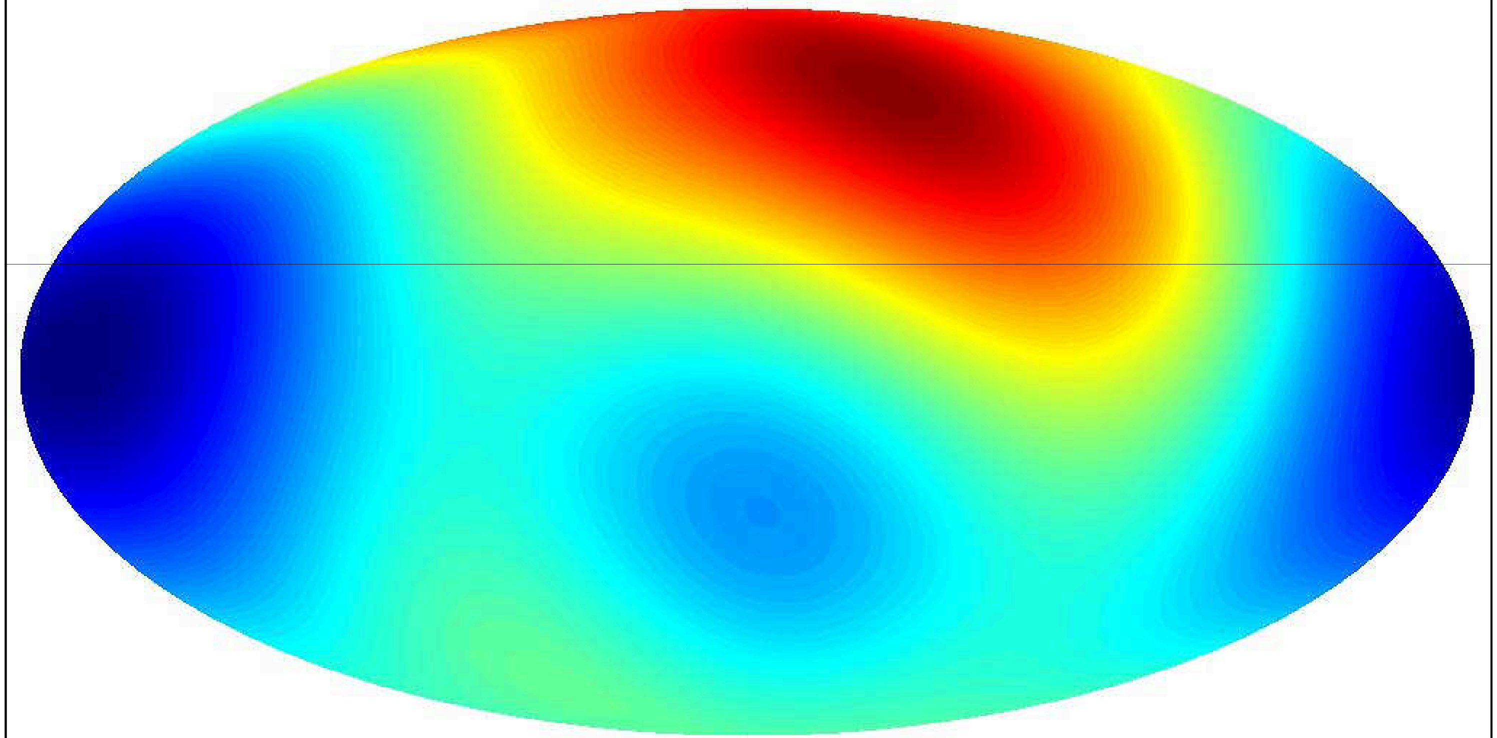
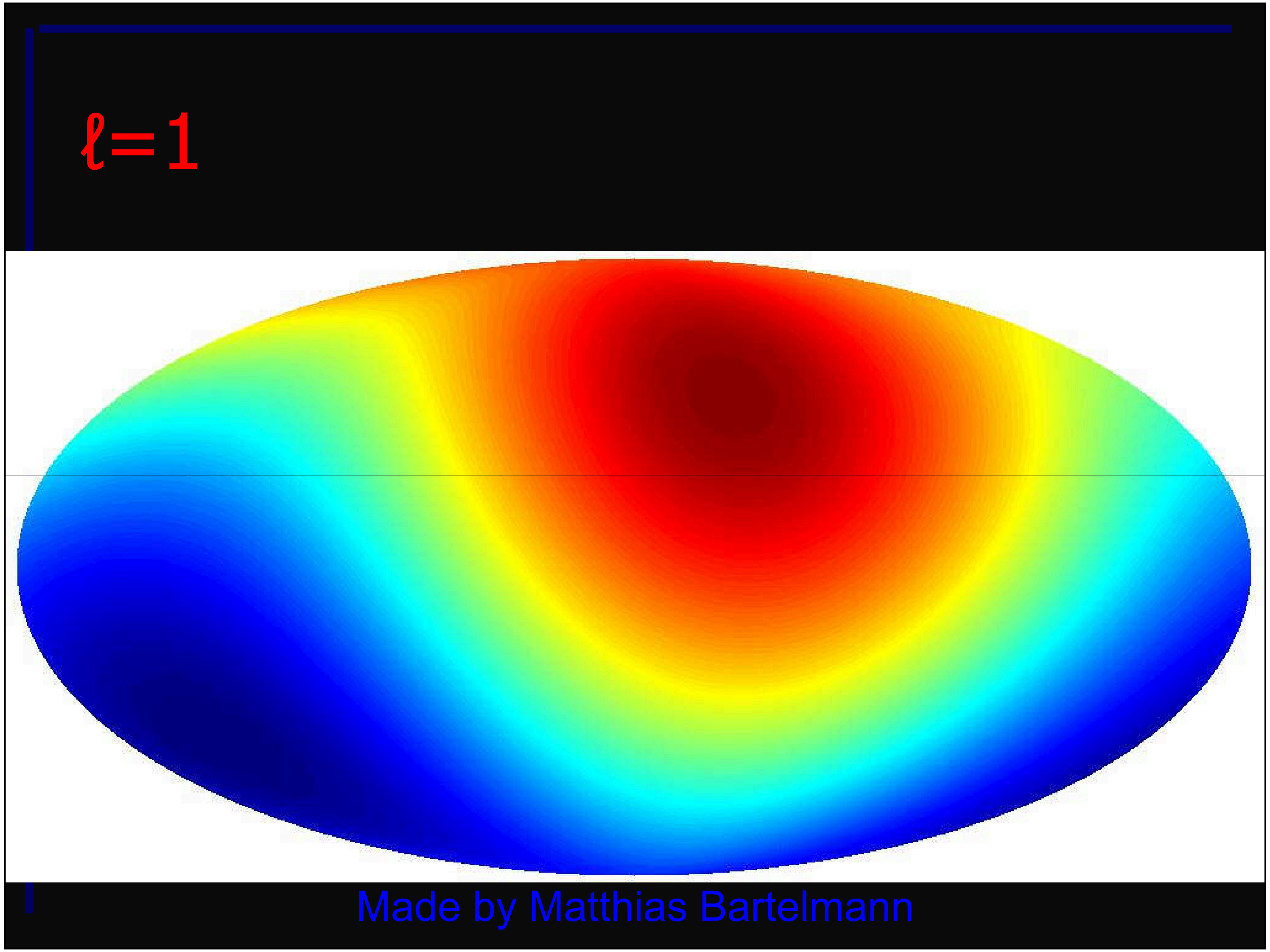
ℓ=1 plus ℓ=2

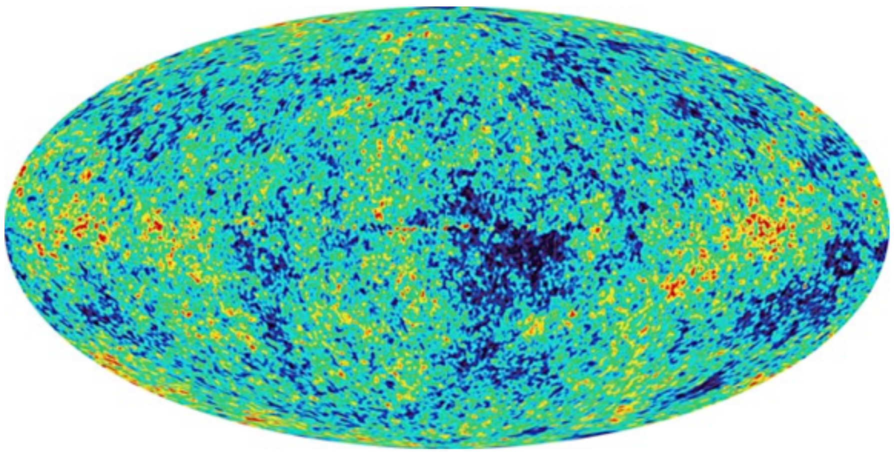


Made by Matthias Bartelmann

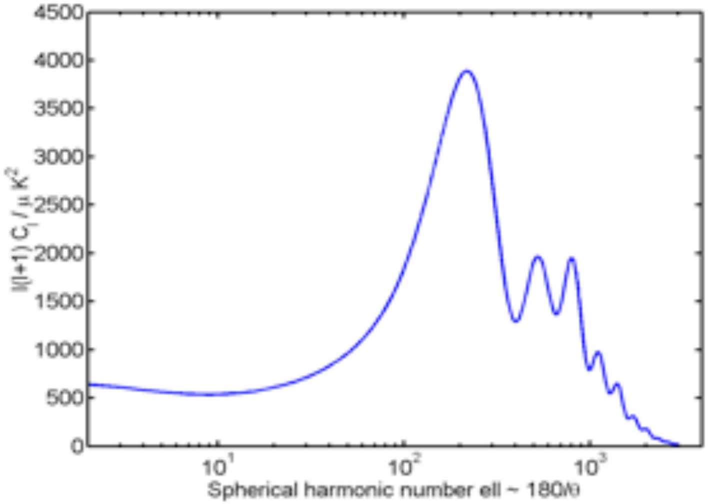

ℓ=1
Made by Matthias Bartelmann

Power Spectrum for CMB

-- Use the spherical harmonic expansion to construct a power spectrum to describe anisotropies of the CMB on the sky



Power Spectrum



l = 180 / θ

Expansion:

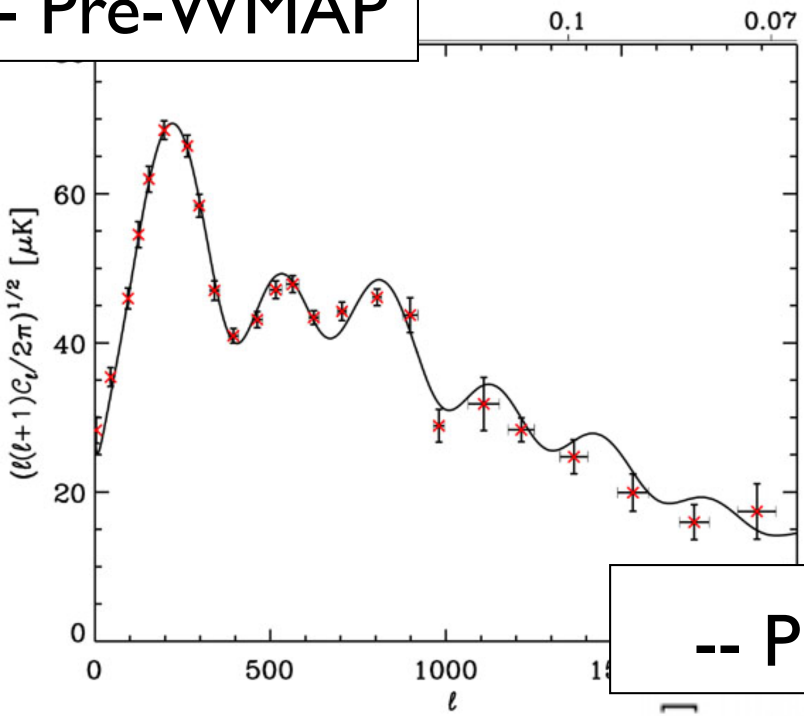
$$\frac{\Delta T}{T}(\theta, \phi) = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_m^{\ell}(\theta, \phi)$$

After deriving the a_{lm} coefficients from the data, determine the statistical average

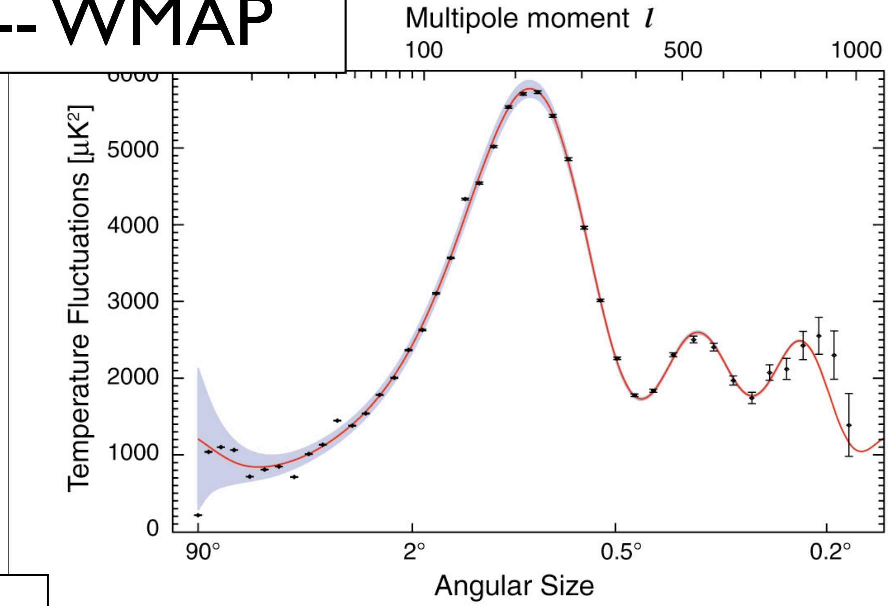
$$c_\ell = \langle |a_{\ell m}| \rangle^2$$

How do the new Planck results compare to earlier results!

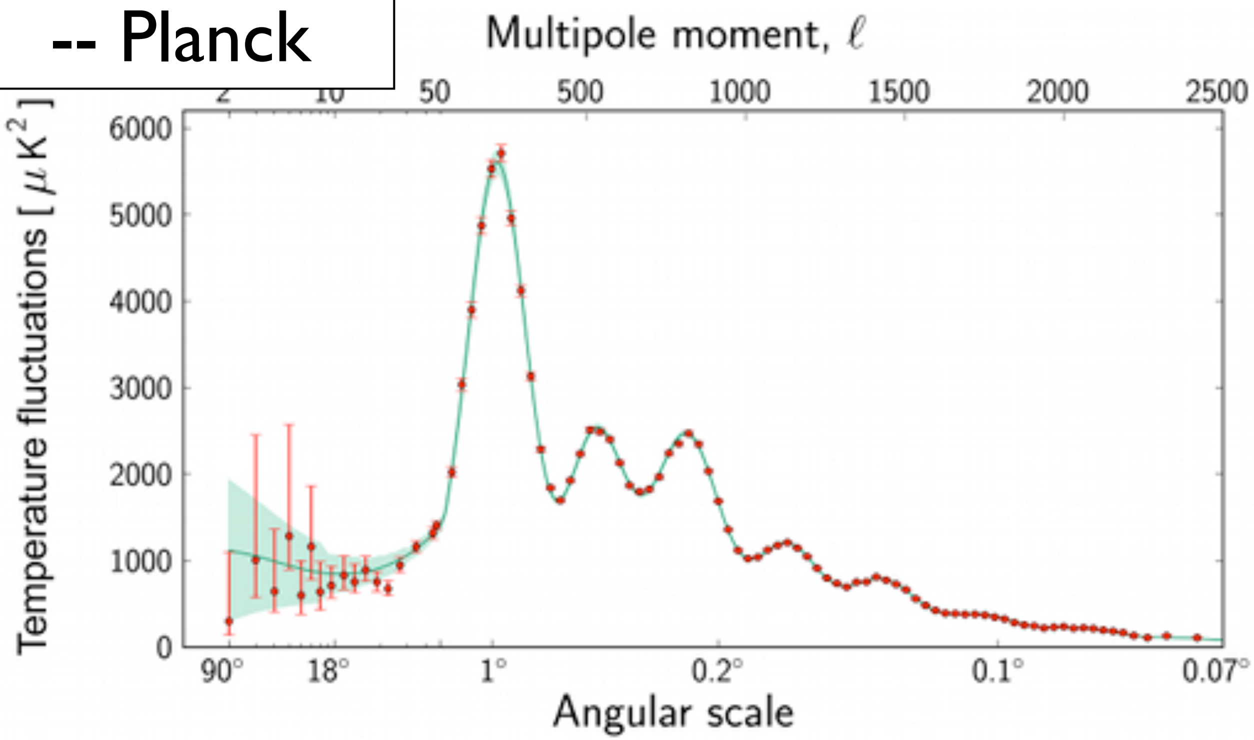
-- Pre-WMAP



-- WMAP



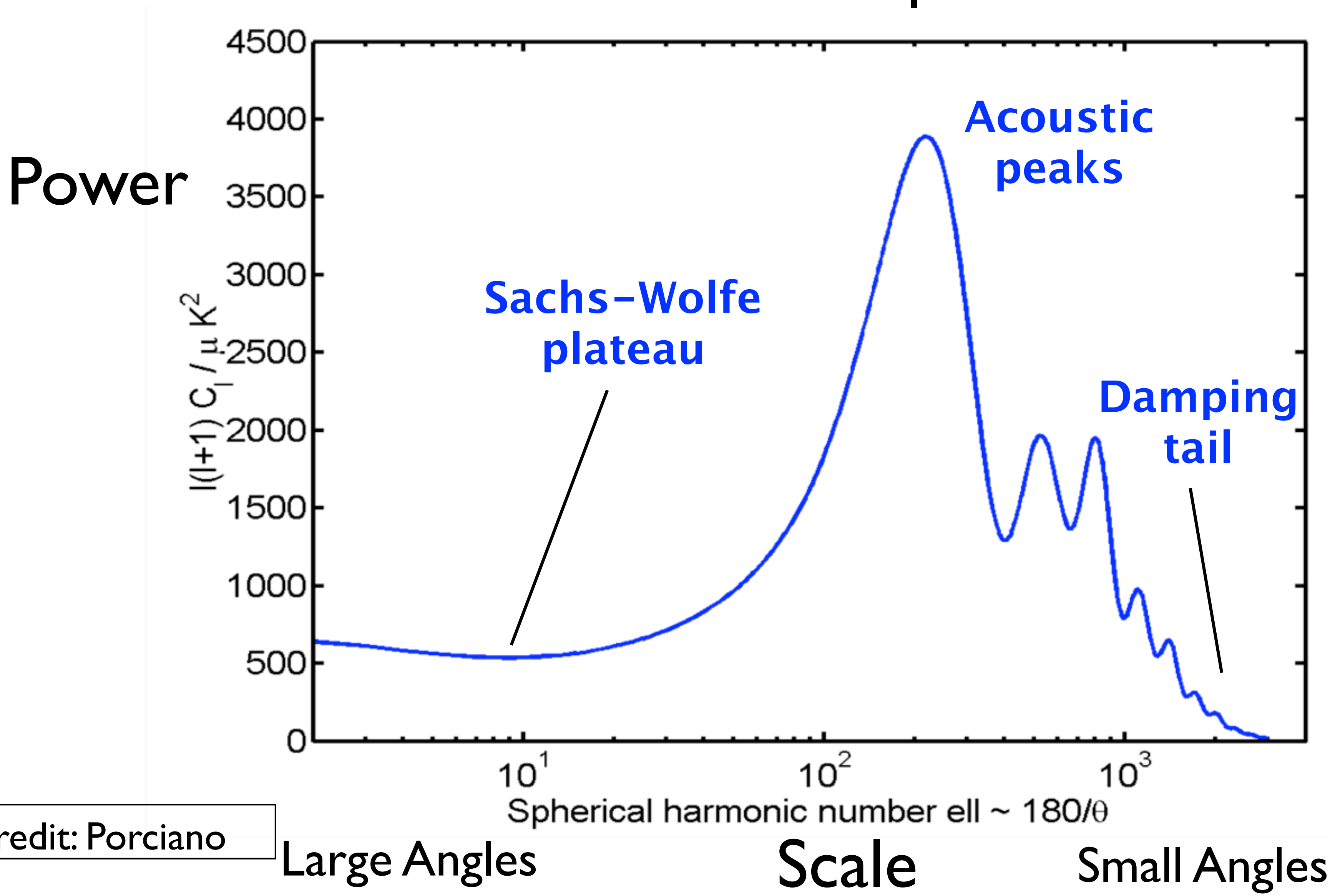
-- Planck



What can we learn from CMB power spectrum?

What does the CMB power spectrum look like?

Here is such a spectrum:



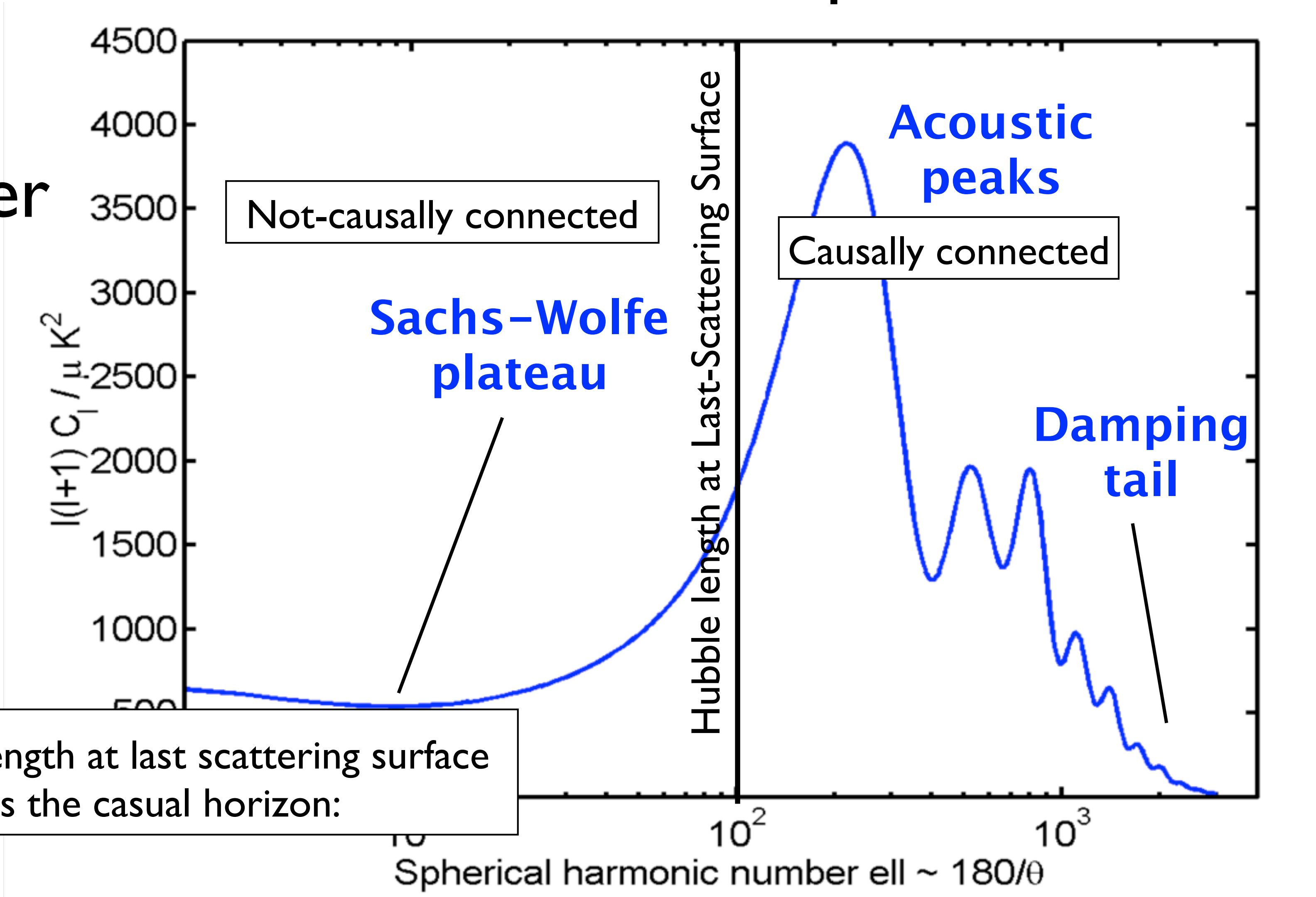
Credit: Porciano

First question: how large can the angle become before the regions become causally disconnected?

What does the CMB power spectrum look like?

Here is such a spectrum:

Power



Hubble length at last scattering surface
is the casual horizon:

Large Angles   Scale   Small Angles

Sachs-Wolfe Plateau

How do we explain the power spectrum of the anisotropies that are not causally connected, i.e., beyond the horizon?

These fluctuations are thought to be quantum fluctuations that are blown up in an initial inflationary phase of the universe

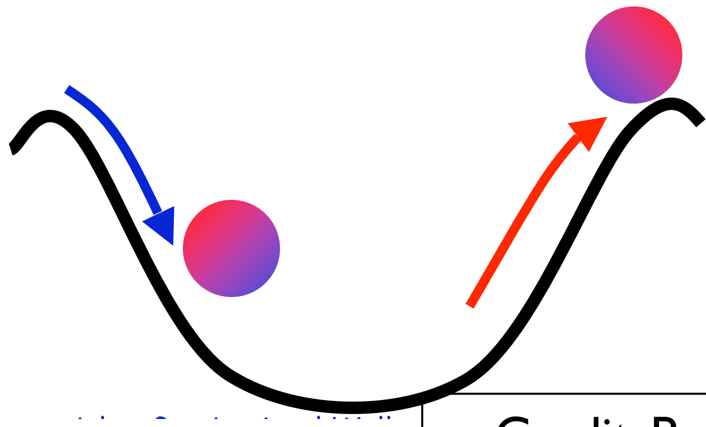
But how do these fluctuations translate into temperature fluctuations?

Sachs-Wolfe Effect (1967)

$\Delta\nu/\nu \sim \Delta T/T \sim \Phi/c^2$

Additional effect of time dilation while potential evolves (full GR):

$$\frac{\Delta T}{T} \sim \frac{1}{3}\frac{\Delta\Phi}{c^2}$$



Credit: Pearson

Photons climbs out of potential minimum, loses energy ↔ lower temperature

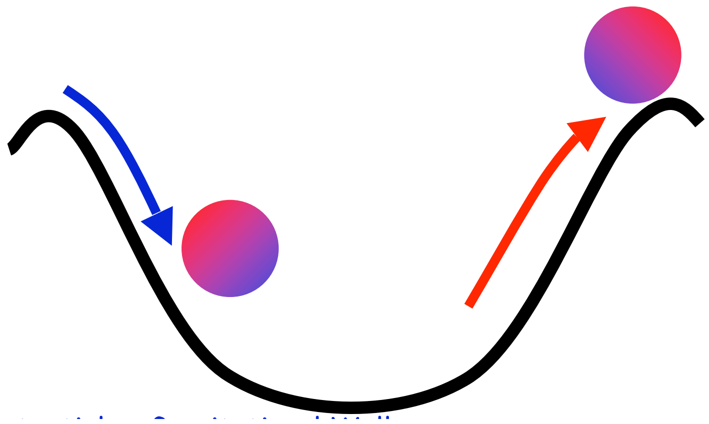
Photons falls out of potential maximum, gains energy ↔ higher temperature

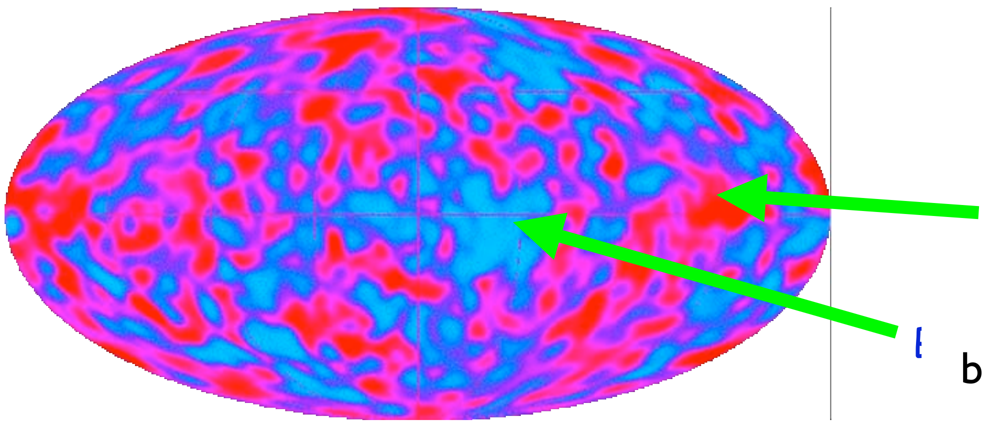
Sachs-Wolfe Effect (1967)

$\Delta\nu/\nu \sim \Delta T/T \sim \Phi/c^2$

Additional effect of time dilation while potential evolves (full GR):

$$\frac{\Delta T}{T} \sim \frac{1}{3}\frac{\Delta\Phi}{c^2}$$





red regions -- lower temperature (potential maxima)

blue regions -- higher temperature (potential minima)

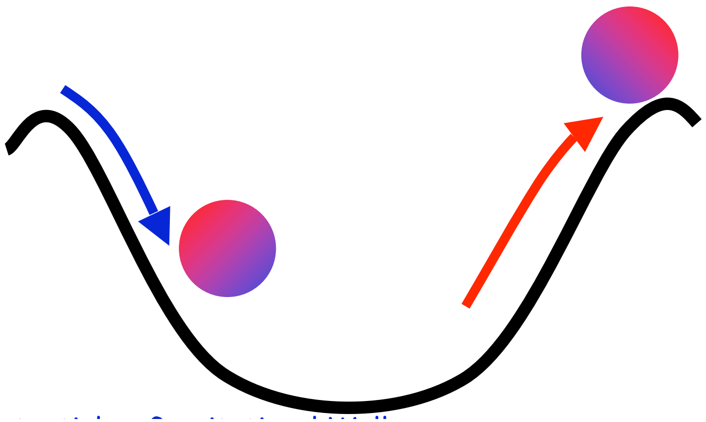
Credit: Pearson

Sachs-Wolfe Effect (1967)

$\Delta\nu/\nu \sim \Delta T/T \sim \Phi/c^2$

Additional effect of time dilation while potential evolves (full GR):

$$\frac{\Delta T}{T} \sim \frac{1}{3}\frac{\Delta\Phi}{c^2}$$



But what distribution of potential minima and maxima do we expect?

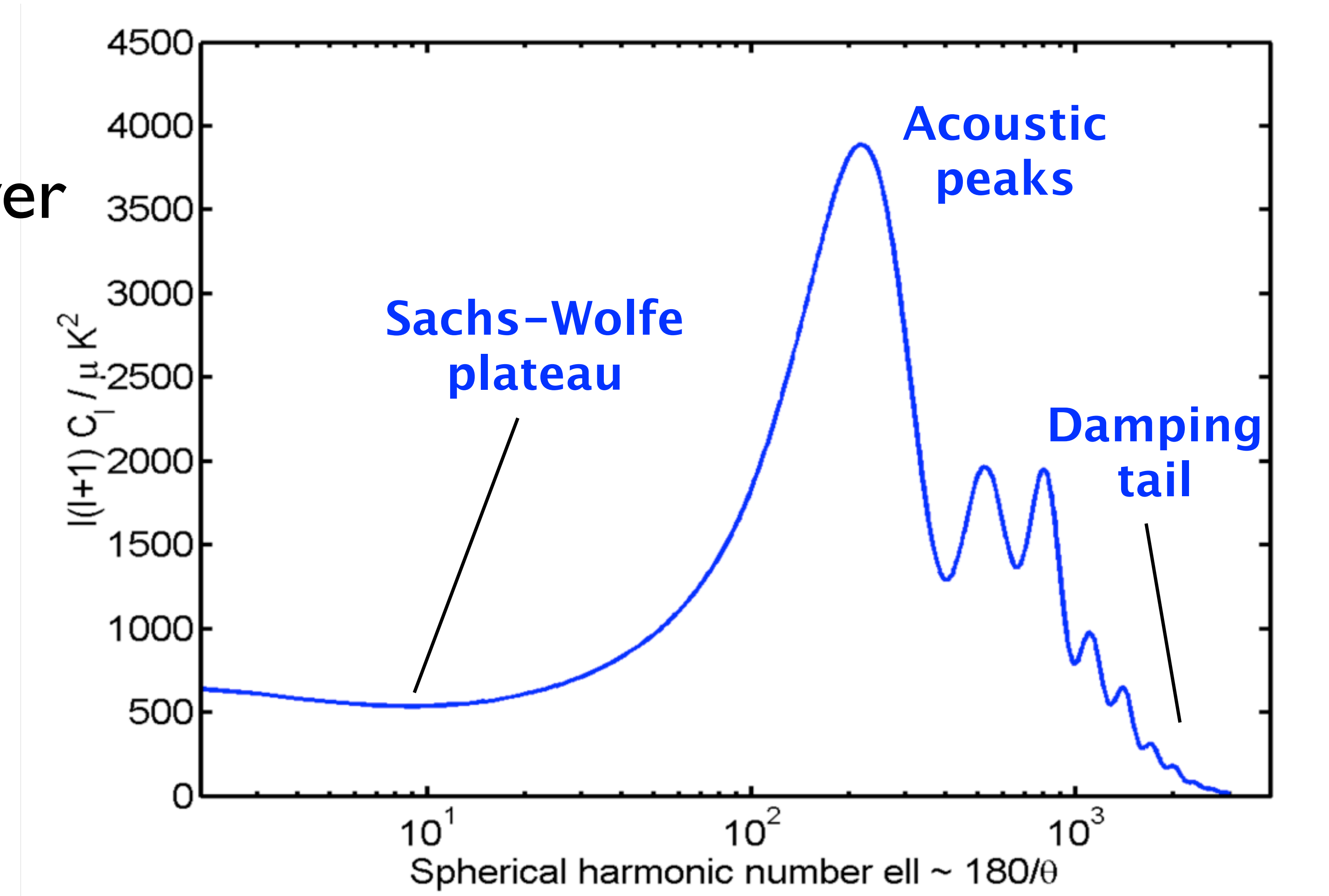
This comes from inflation

For a Harrison-Zeldovich power spectrum $P(k) \propto k$ (expected from inflation), the CMB power spectrum is expected to be flat, i.e., $C_l \propto 1/l(l+1)$

Second Topic: Now let's discuss the acoustic peaks in the CMB power spectrum

What about the Acoustic Peaks?

Power



Large Angles Scale Small Angles

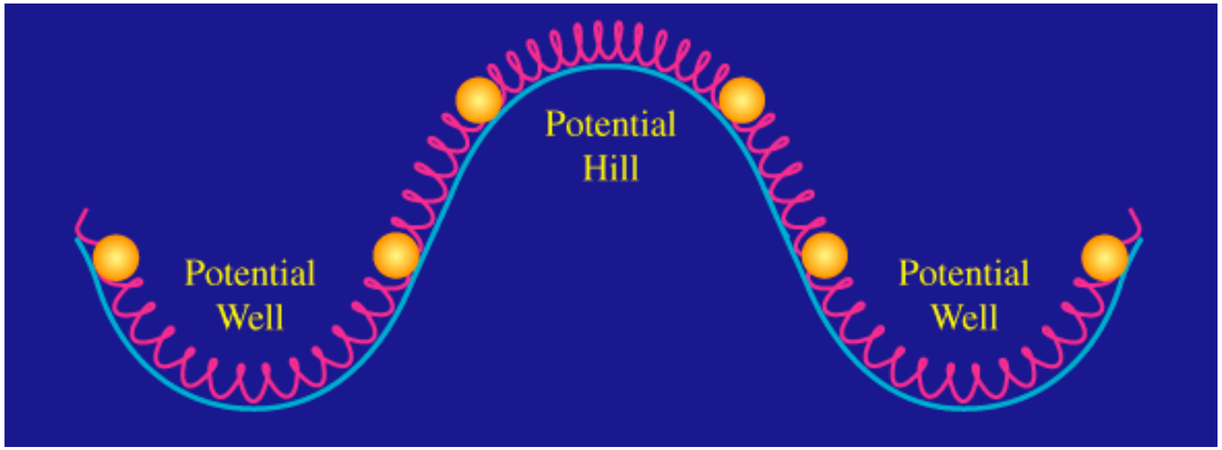
Acoustic Oscillations:

-- Universe filled with slight dark matter overdensities on all scales

-- Baryons will fall onto these overdensities due to the force of gravity heating the fluid up

-- Large number of baryons falling onto overdensity causes an increase in pressure due to baryon-photon coupling -- which resists gravitational forces and causes it to expand (cooling the fluid down)

-- An oscillation is set up and continues until decoupling



-- credit: Wayne Hu

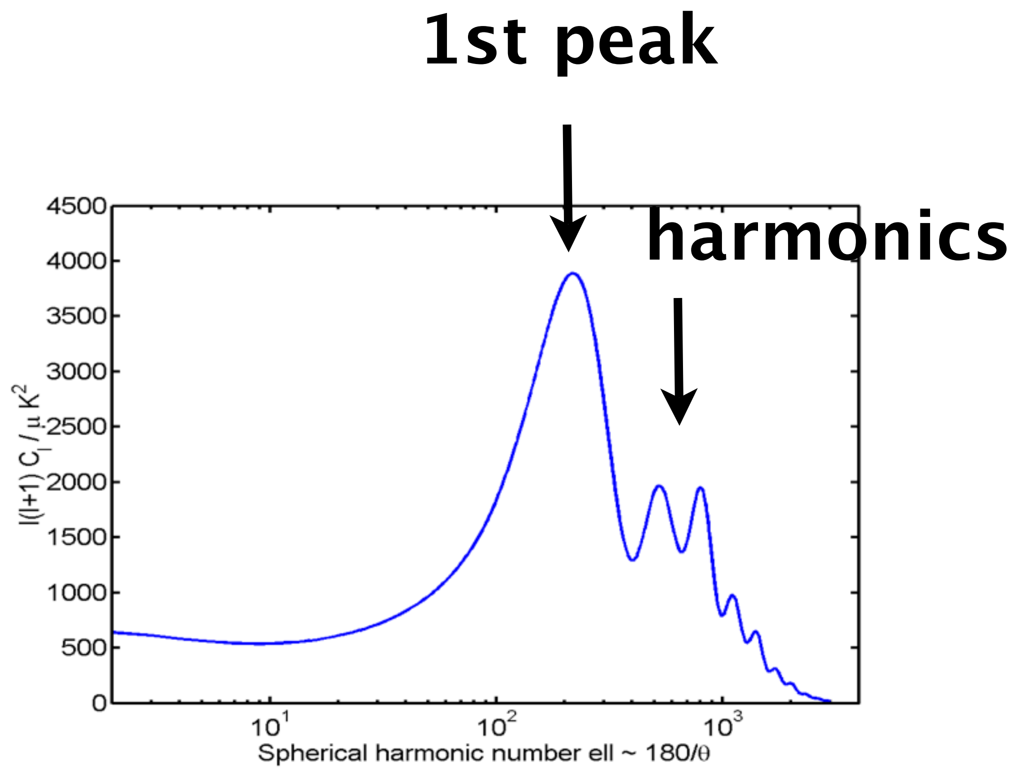
Acoustic Oscillations:

-- First peak is a compression mode

-- Second peak is a rarefaction mode

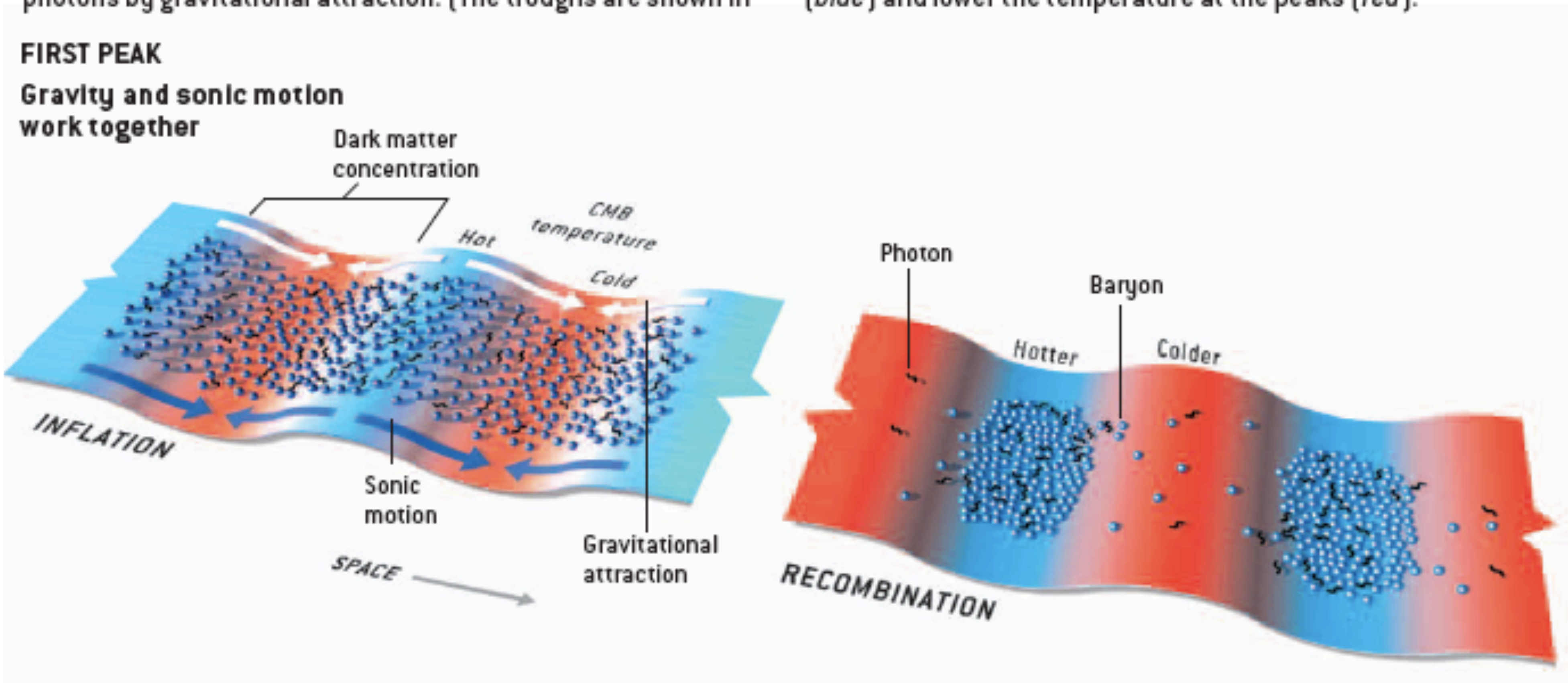
-- Third peak is a compression mode

(Similar to harmonics on a musical instrument/string/pipe!)



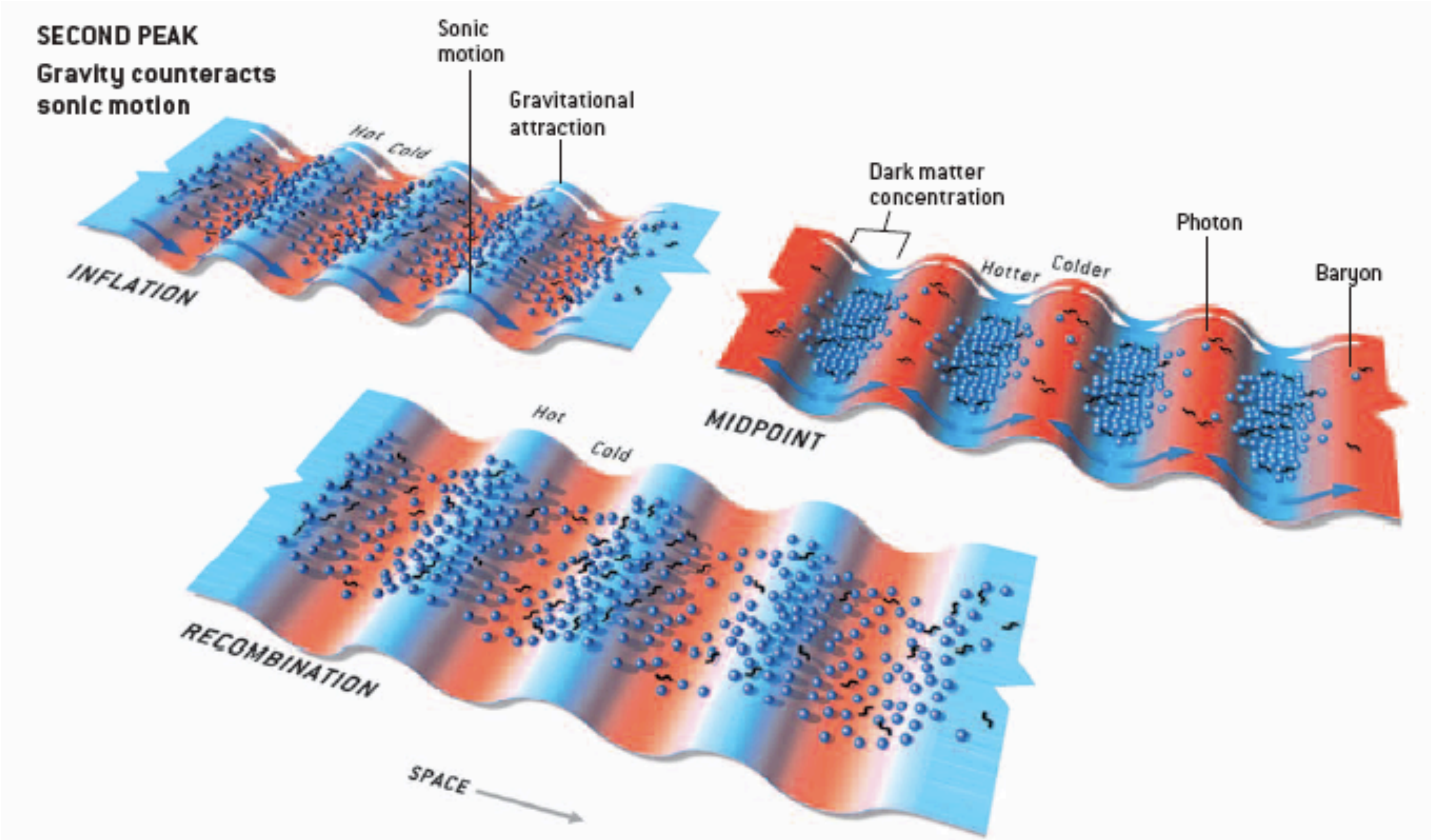
First Peak: Illustration

INFLUENCE OF DARK MATTER modulates the acoustic signals in the CMB. After inflation, denser regions of dark matter that have the same scale as the fundamental wave (*represented as troughs in this potential-energy diagram*) pull in baryons and photons by gravitational attraction. (The troughs are shown in red because gravity also reduces the temperature of any escaping photons.) By the time of recombination, about 380,000 years later, gravity and sonic motion have worked together to raise the radiation temperature in the troughs (*blue*) and lower the temperature at the peaks (*red*).



[Image Credit: Hu & White 2004]

Second Peak: Illustration



[Image Credit: Hu & White 2004]

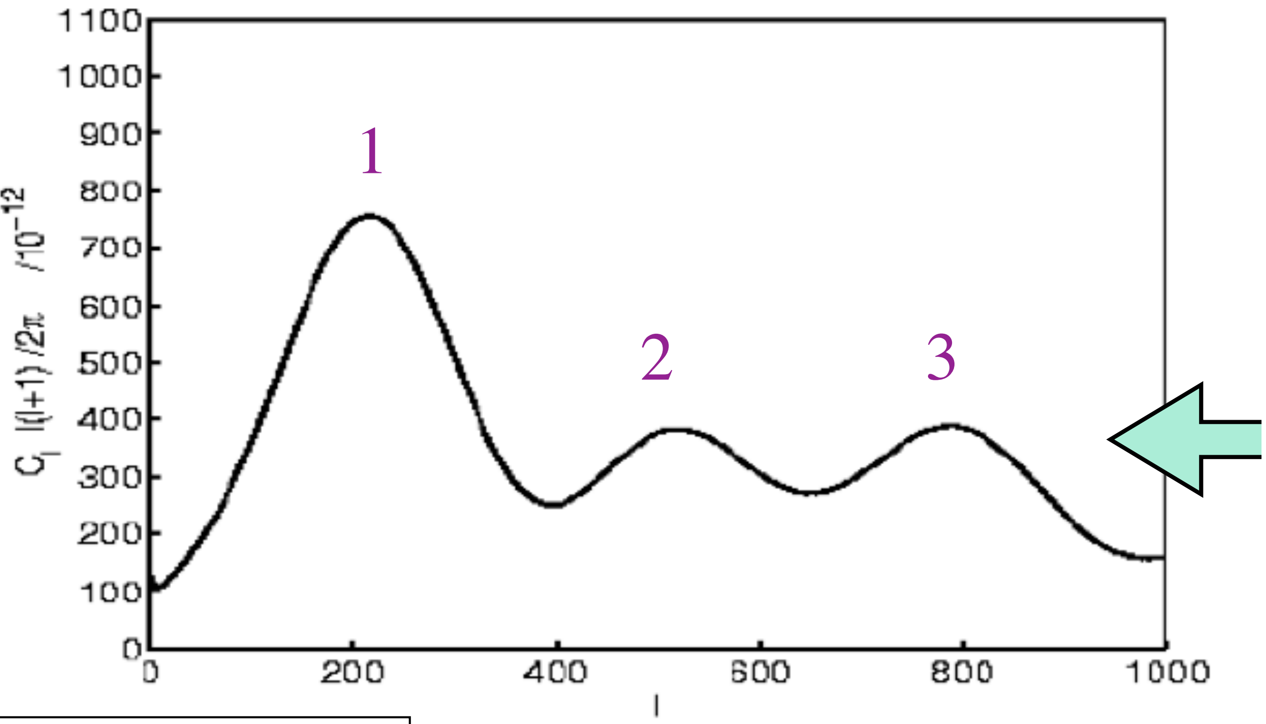
Acoustic Oscillations:

-- First peak is a compression mode

-- Second peak is a rarefaction mode

-- Third peak is a compression mode

(Similar to harmonics on a musical instrument/string/pipe!)



Peaks are spaced approximately equally in spherical harmonic number l

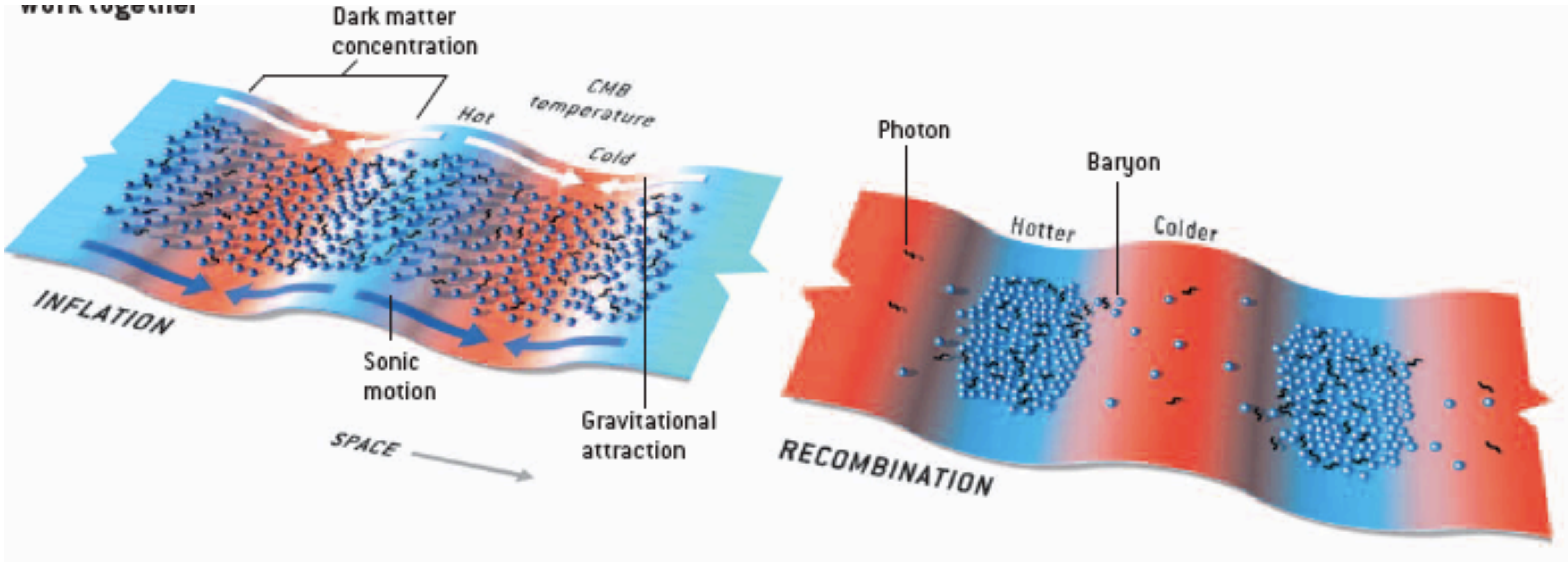
Credit: Porciani

What can we learn from the properties of these acoustic peaks?

Let's examine acoustic peak #1

(What can we learn from the angular scale at which is observed?)
(they give us standard rods to measure geometry of universe)

-- For this peak, baryonic matter would be falling onto this pattern of overdensities for the first time



[Image Credit: Hu & White 2004]

Let's examine acoustic peak #1

(What can we learn from the angular scale at which is observed?)
(they give us standard rods to measure geometry of universe)

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-- Length scale spanned by peak is comoving length transversed by a sound wave to the point of last scattering:

$$L_S(t_R) = R(t_R) \int_0^{t_R} \frac{c_S \, dt}{R(t)}$$

where sound speed

$$c_S \approx \frac{c}{\sqrt{3}}$$

$$\approx 110 \left(\frac{0.7}{h}\right)\left(\frac{0.3}{\Omega_M}\right)^{1/2} \text{kpc}$$

-- This length scale acts as a standard rod

Let's examine acoustic peak #1

(What can we learn from the angular scale at which is observed?)

-- For this peak, baryonic matter would be falling onto these overdensities for the first time

-- Key Question: What is the angle of the peak on the sky?

$$\theta = \frac{L_S(z)}{D_A(z)}$$

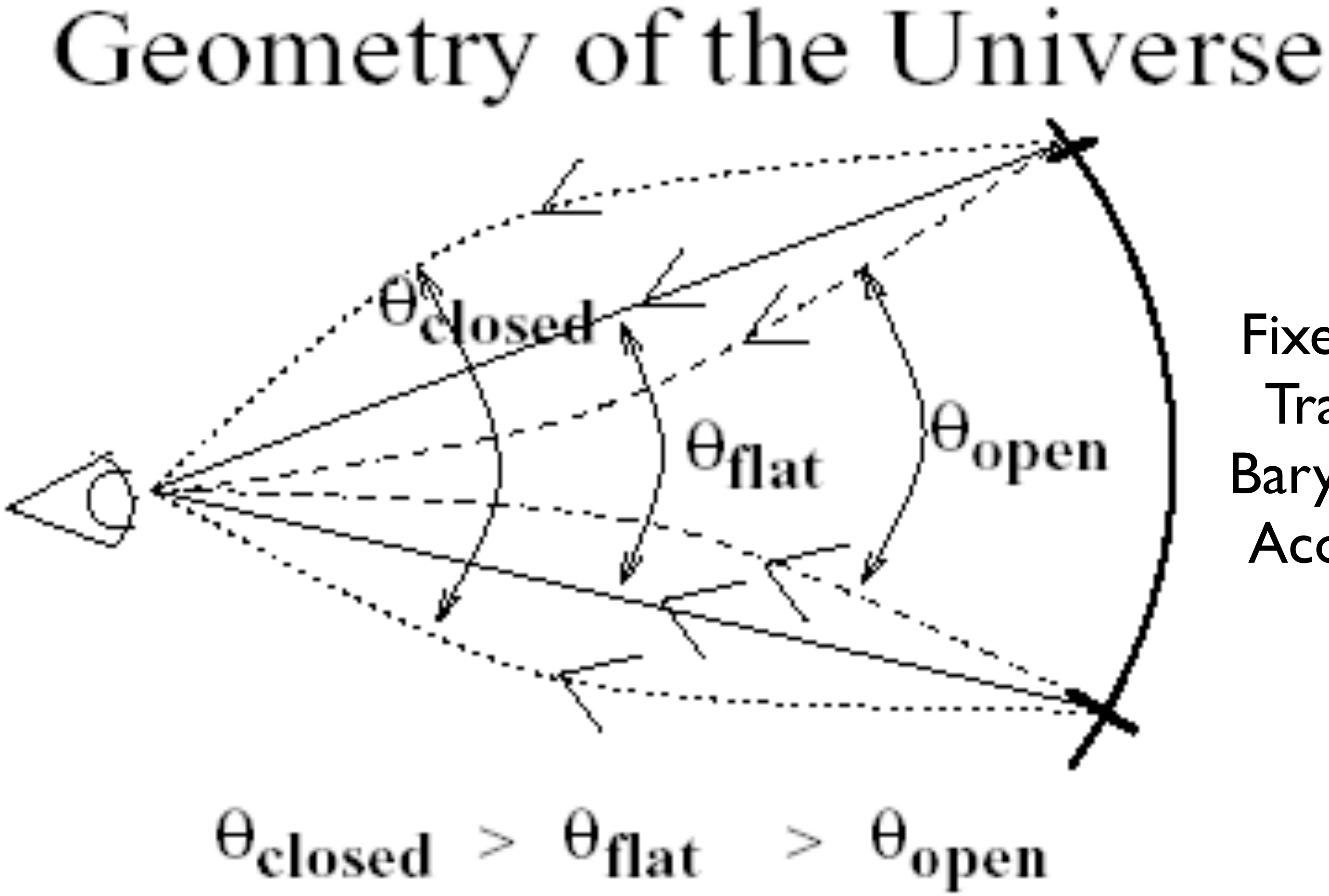
length scale traversed by matter

angular diameter distance

-- Can compute $L_S(z)$ and can measure θ

-- Can solve for D_A (z) and use to constrain geometry of universe

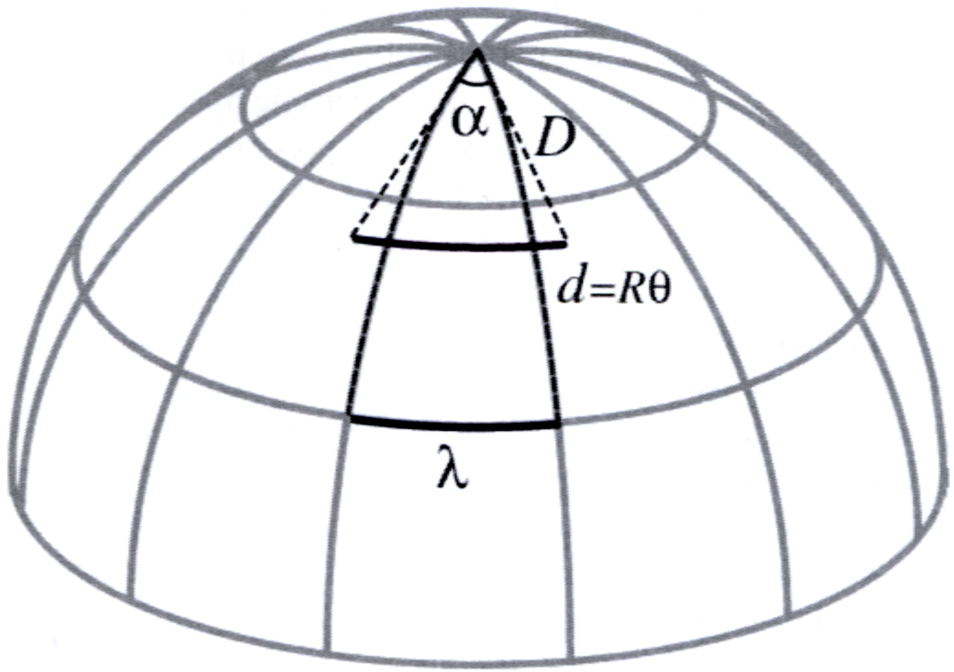
How does the angular diameter distance depend on the cosmological parameters?



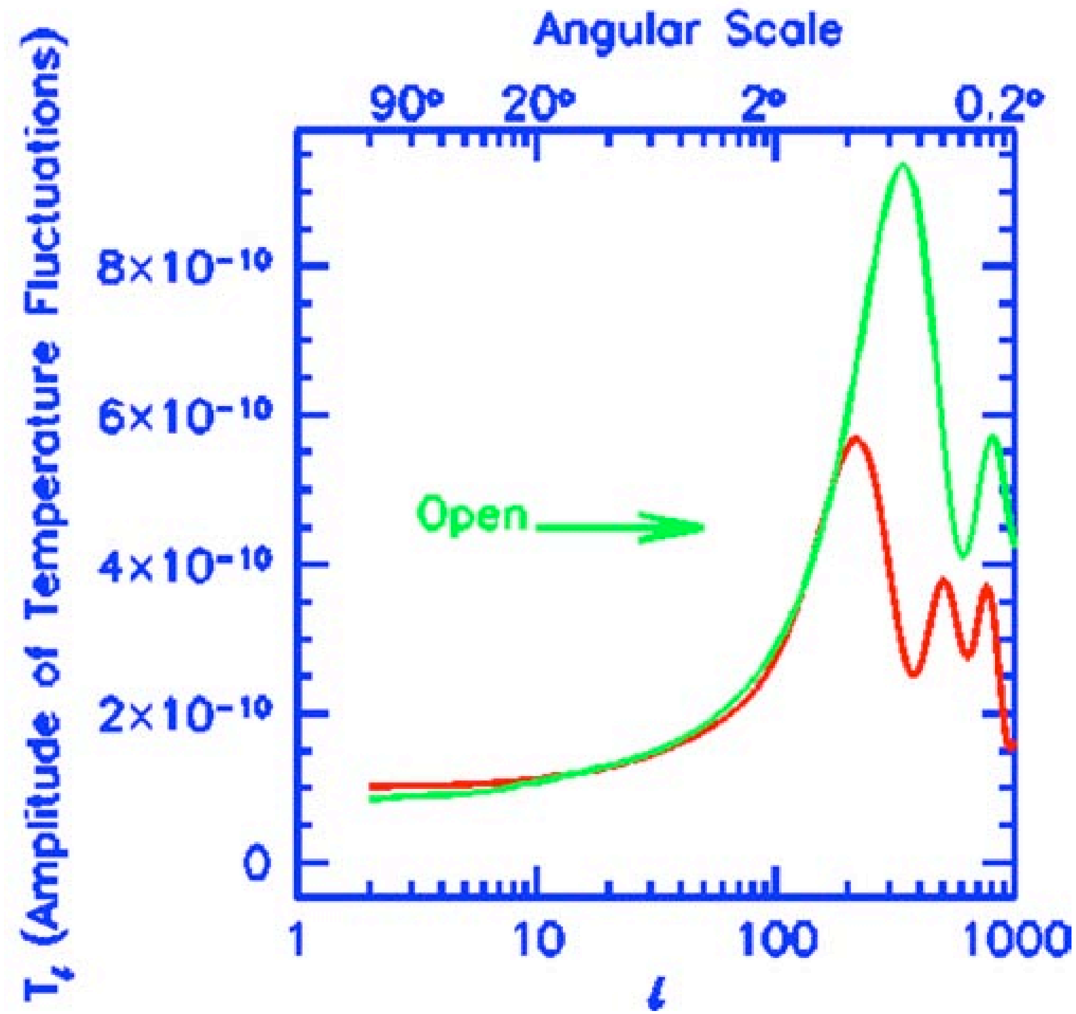
Fixed Distance Traversed by Baryons in First Acoustic Peak

How does the angular diameter distance depend on the cosmological parameters?

For example, in closed universe, objects subtend larger angle than they would in flat spacetime.

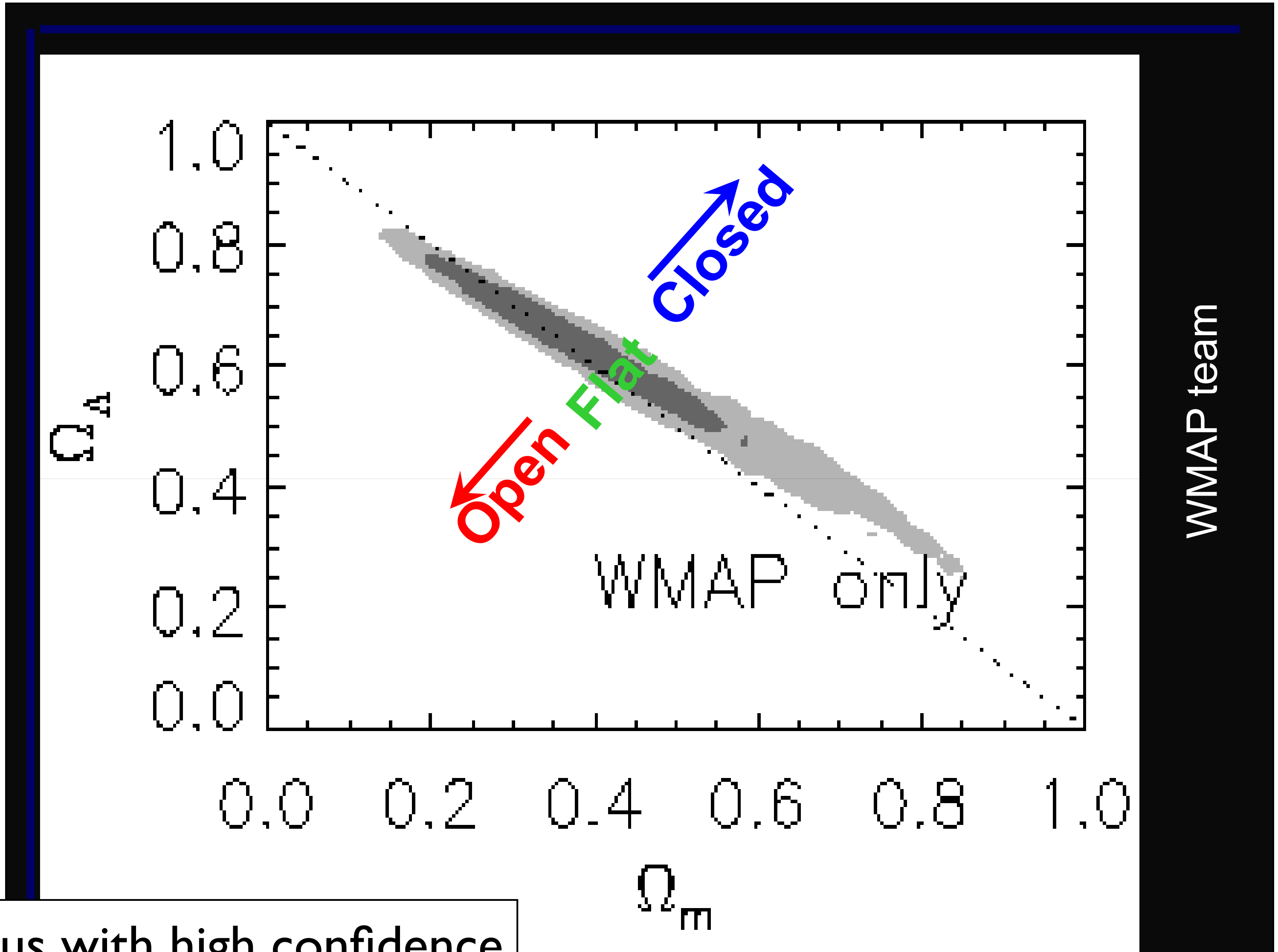


How does the angular diameter distance depend on the cosmological parameters?



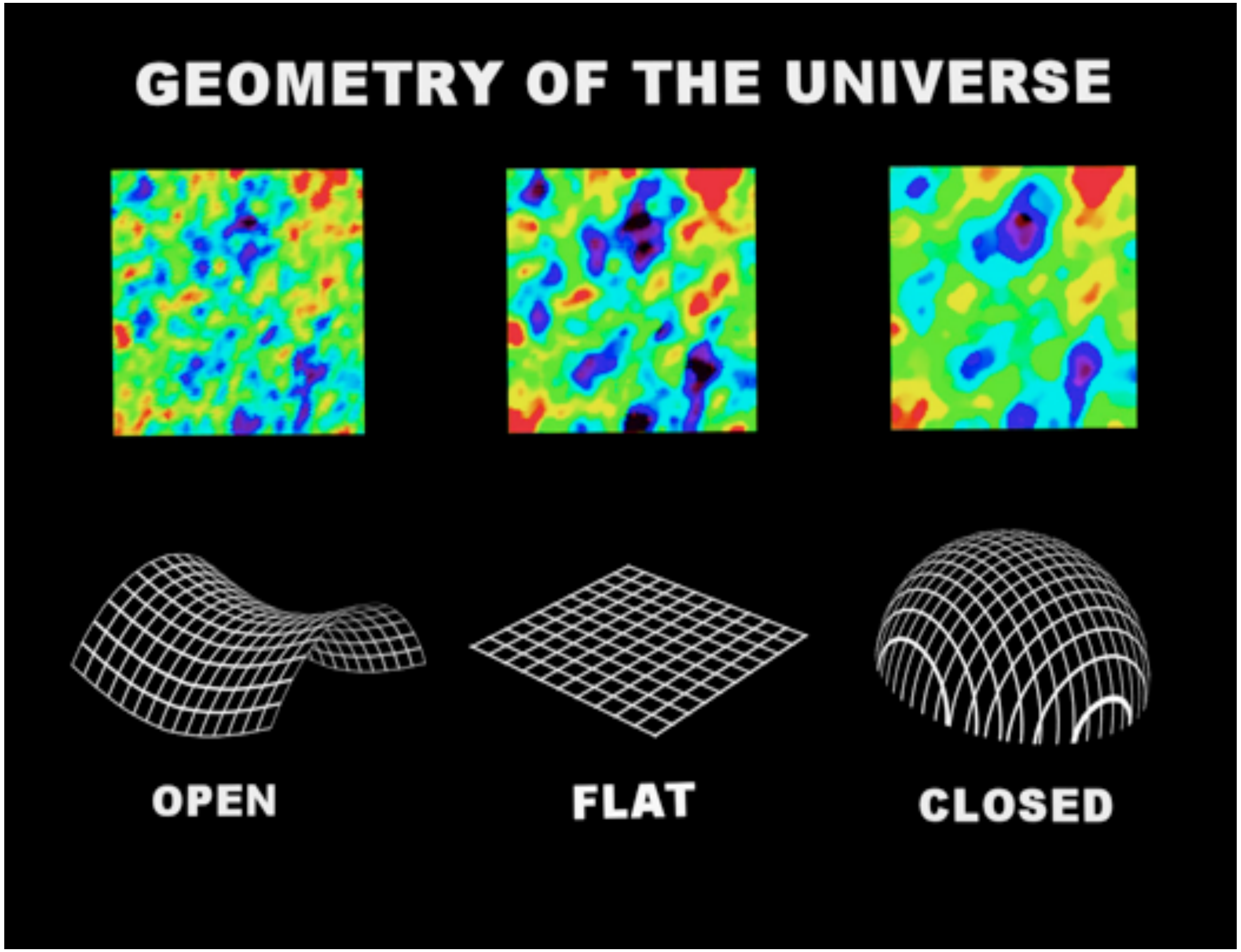
Here is how the peak would shift in an open universe (green) and a flat universe (red)

What does the position of the first acoustic peak teach about Ω_M and Ω_Λ?



It shows us with high confidence that universe is likely flat

How might we expect the CMB anisotropies to look like on the sky for different geometries?



What can we learn from the other peaks?

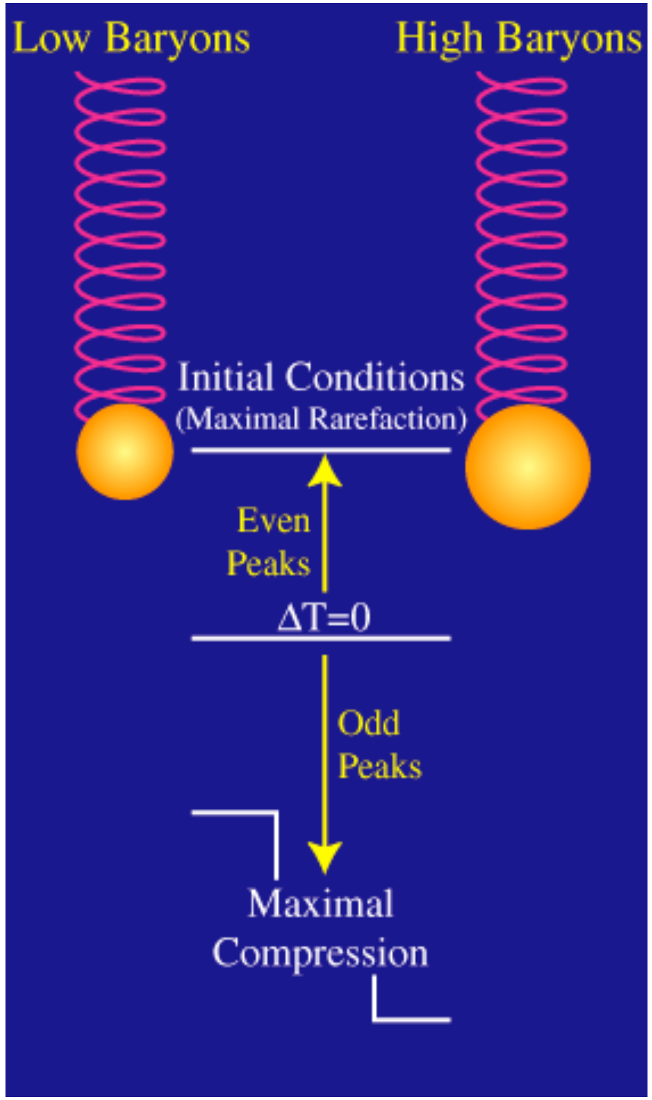
What can we learn from the other peaks?

Learn about baryon content

-- The presence of more baryons increases the amplitude of the oscillations

-- As a result, the fluid is compressed more before photon pressure can resist the compression

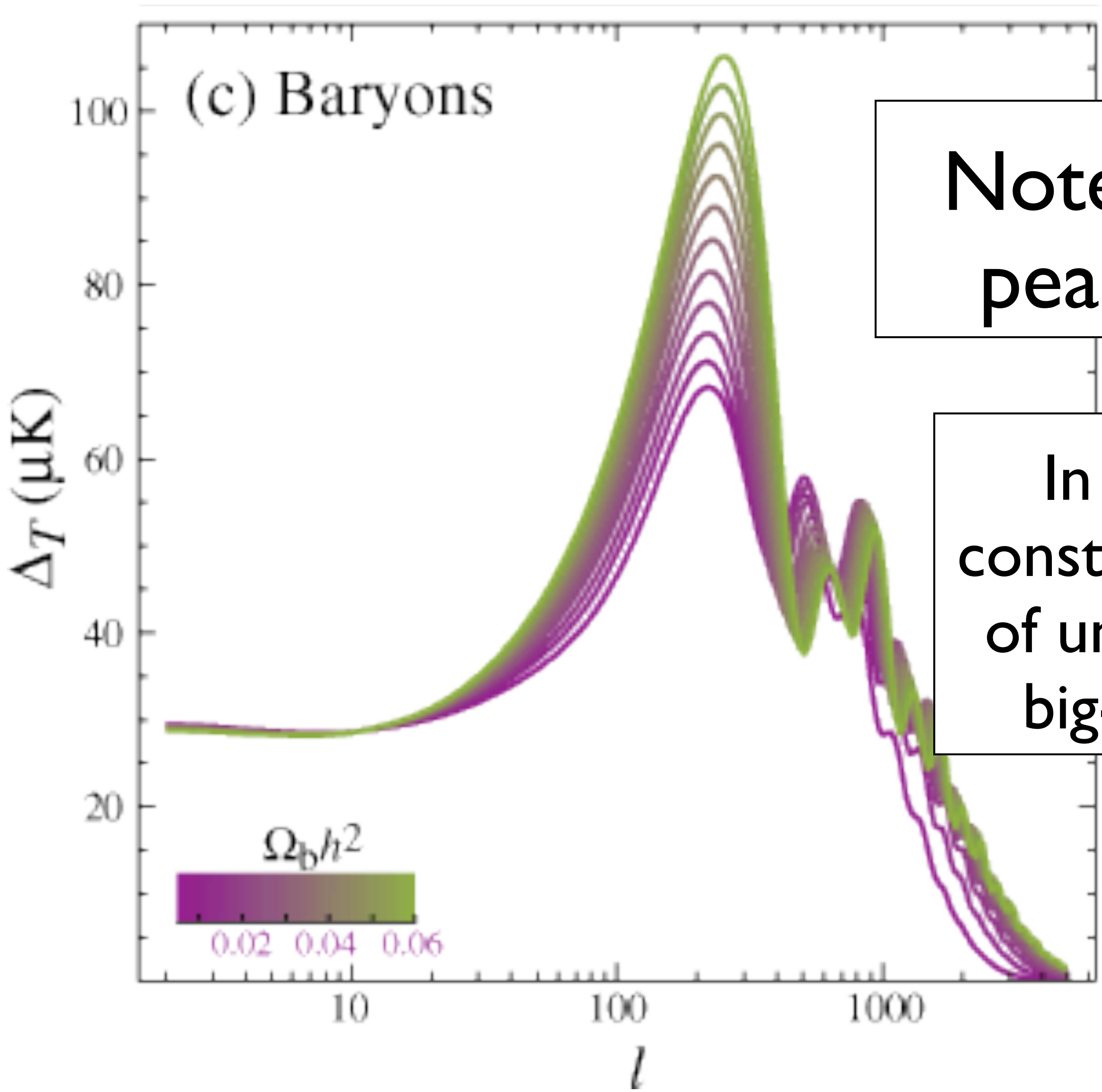
-- This results in an asymmetry between the even and odd peaks



Credit: Wayne Hu

What can we learn from the other peaks?

Learn about baryon content

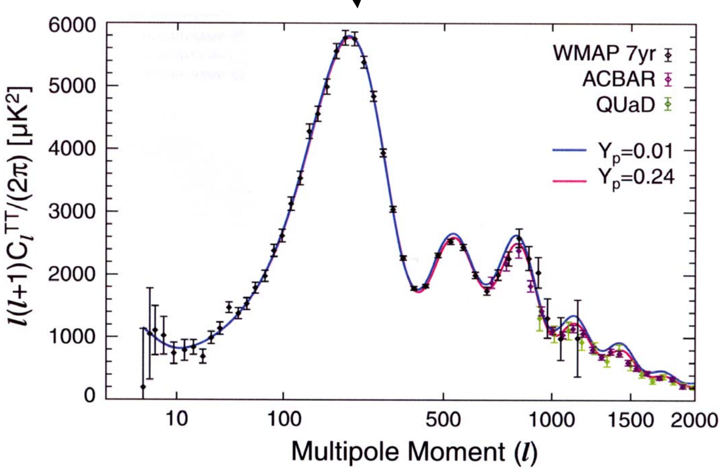


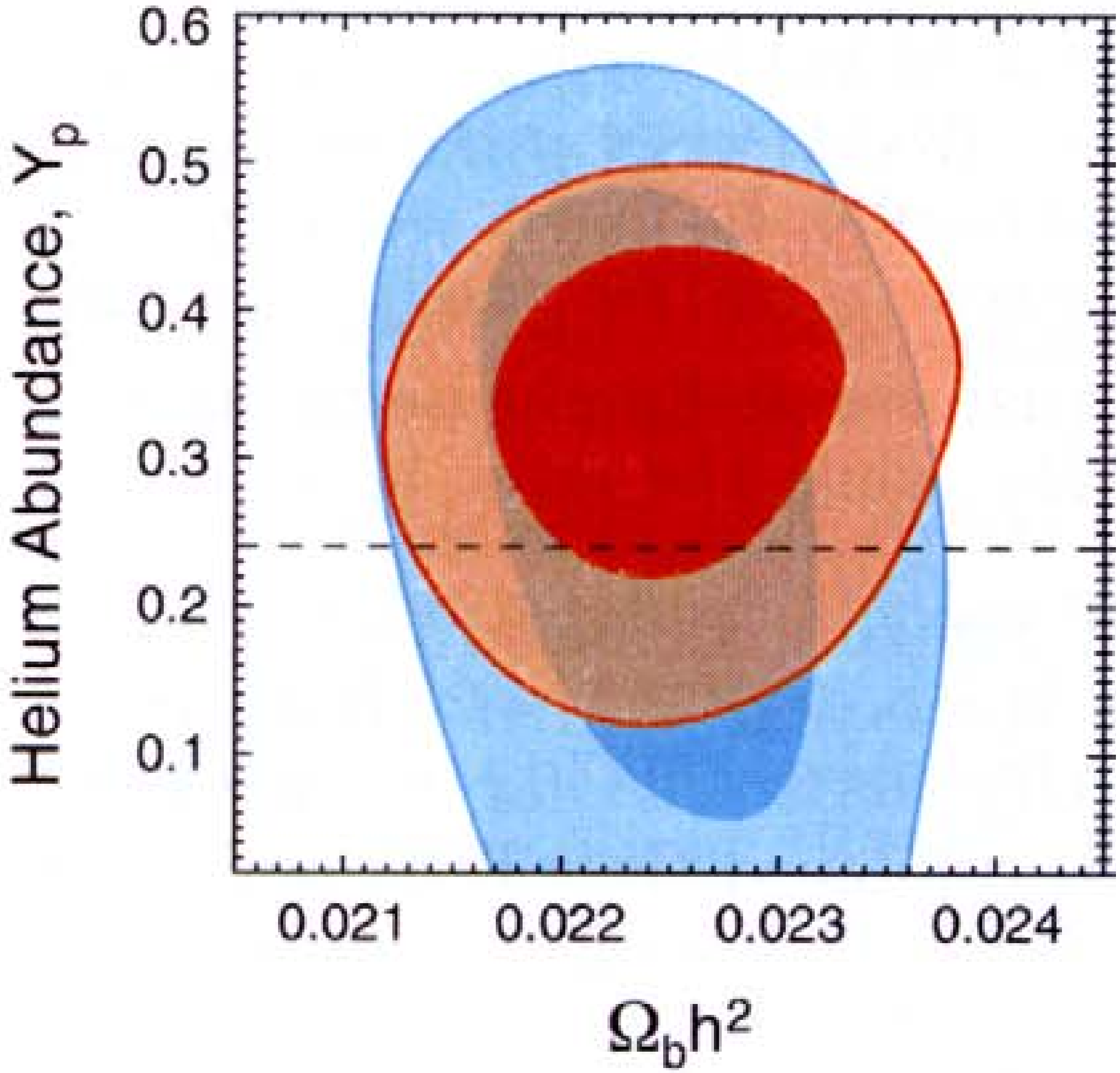
Note how 1st and 3rd peaks are enhanced!

In fact, this provides best constraint on baryonic content of universe (even better than big-bang nucleosysnthesis)

What type of constraints can we set on Ω_{baryon}?

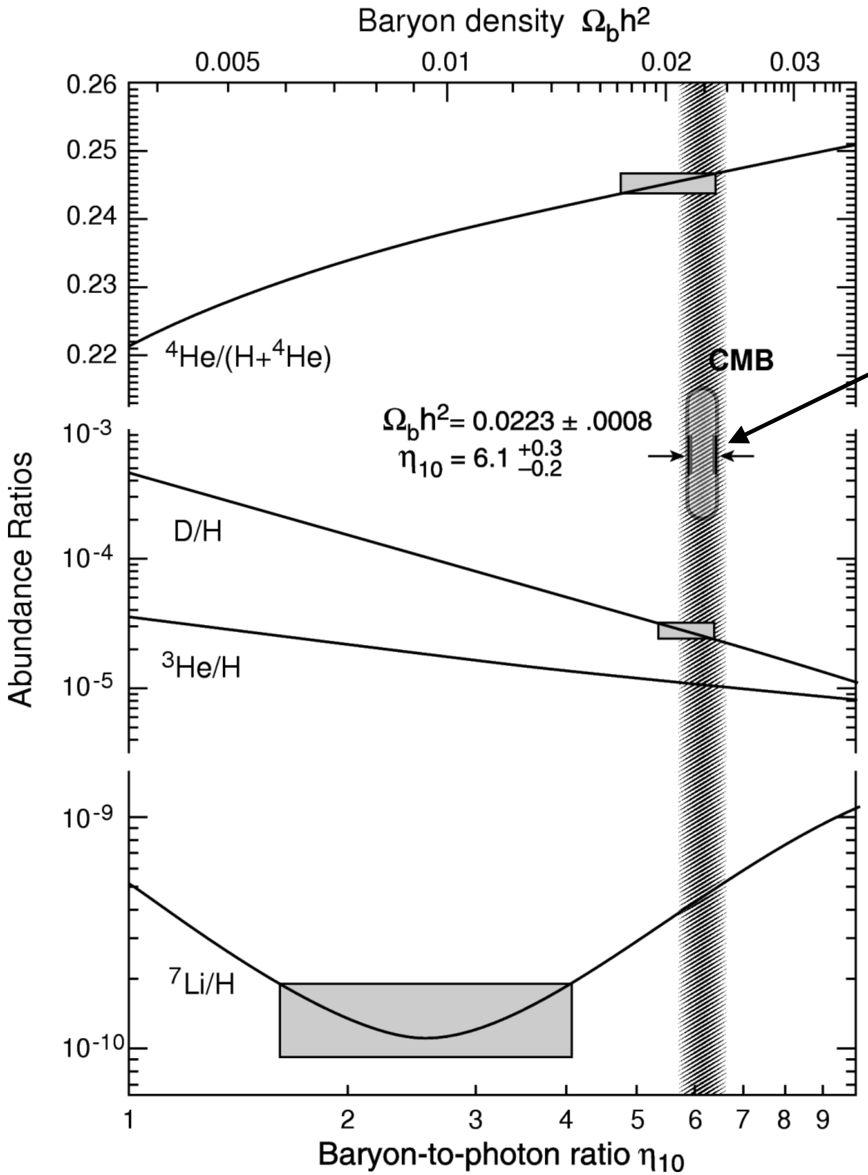
Amazingly, one can even weakly constrain the abundance of primordial helium (to better than 1% using the latest data)





Source: WMAP team

How do constraints on Ω_{baryon} from the CMB compare with Big Bang Nucleosynthesis?

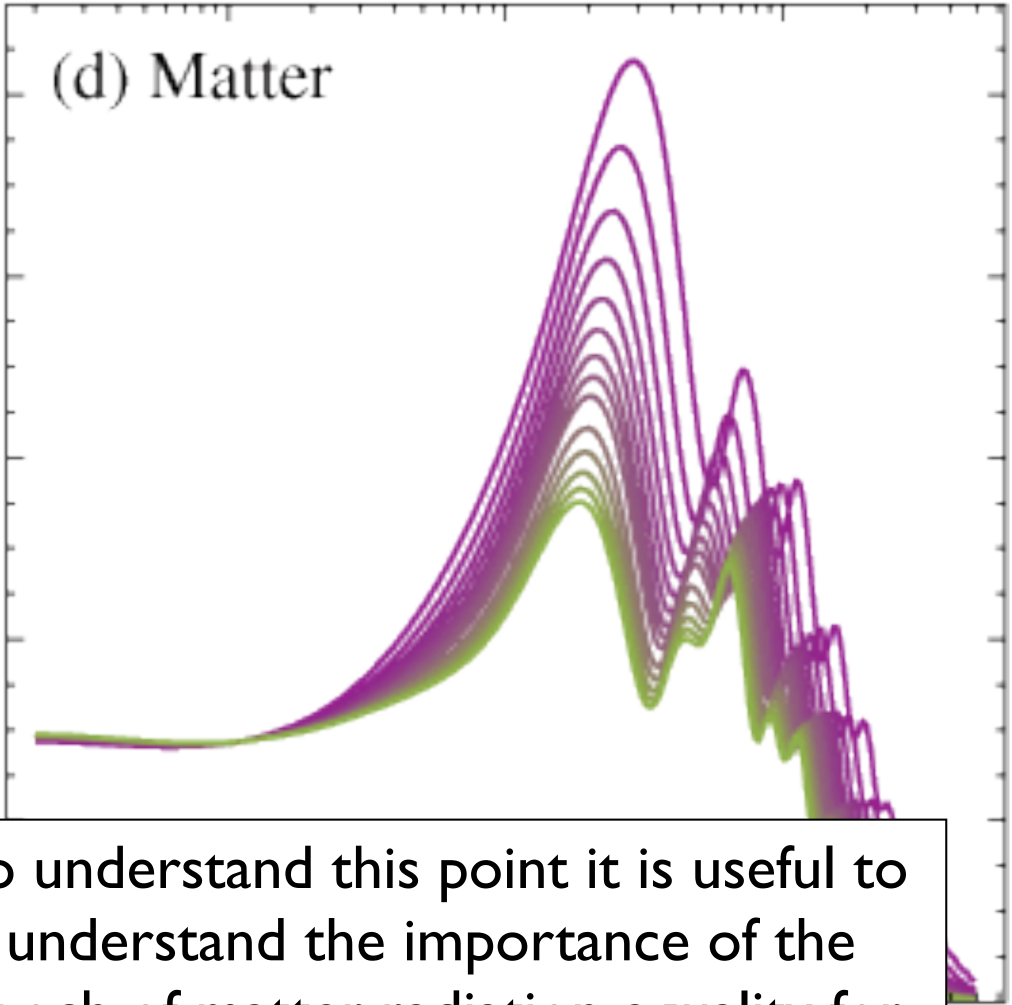


Constraints on Ω_{baryon} from CMB (derivable now to 0.4% accuracy) in perfect agreement with Big Bang Nucleosynthesis

Observations of He^3 and Li^7 not well enough understood to set competitive constraints on Ω_{baryon}

What can we learn from the other peaks?

Learn about dark matter content



To understand this point it is useful to understand the importance of the epoch of matter-radiation equality for the growth of fluctuations in the universe

Note how 3rd peak is enhanced when dark matter density higher!

To ensure this peak is prominent, necessary to have a relatively high dark matter content earlier in universe. Otherwise, the universe will have a longer radiation dominated phase -- inhibiting the growth of fluctuations