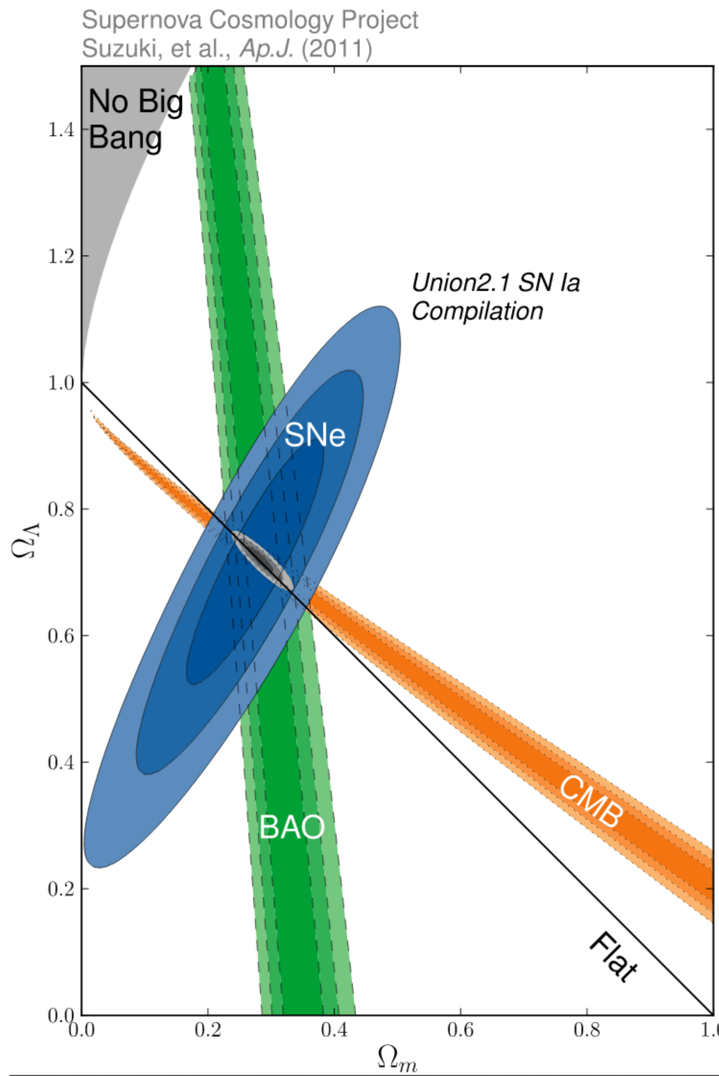
Understanding Where the Benchmark Cosmology Comes From

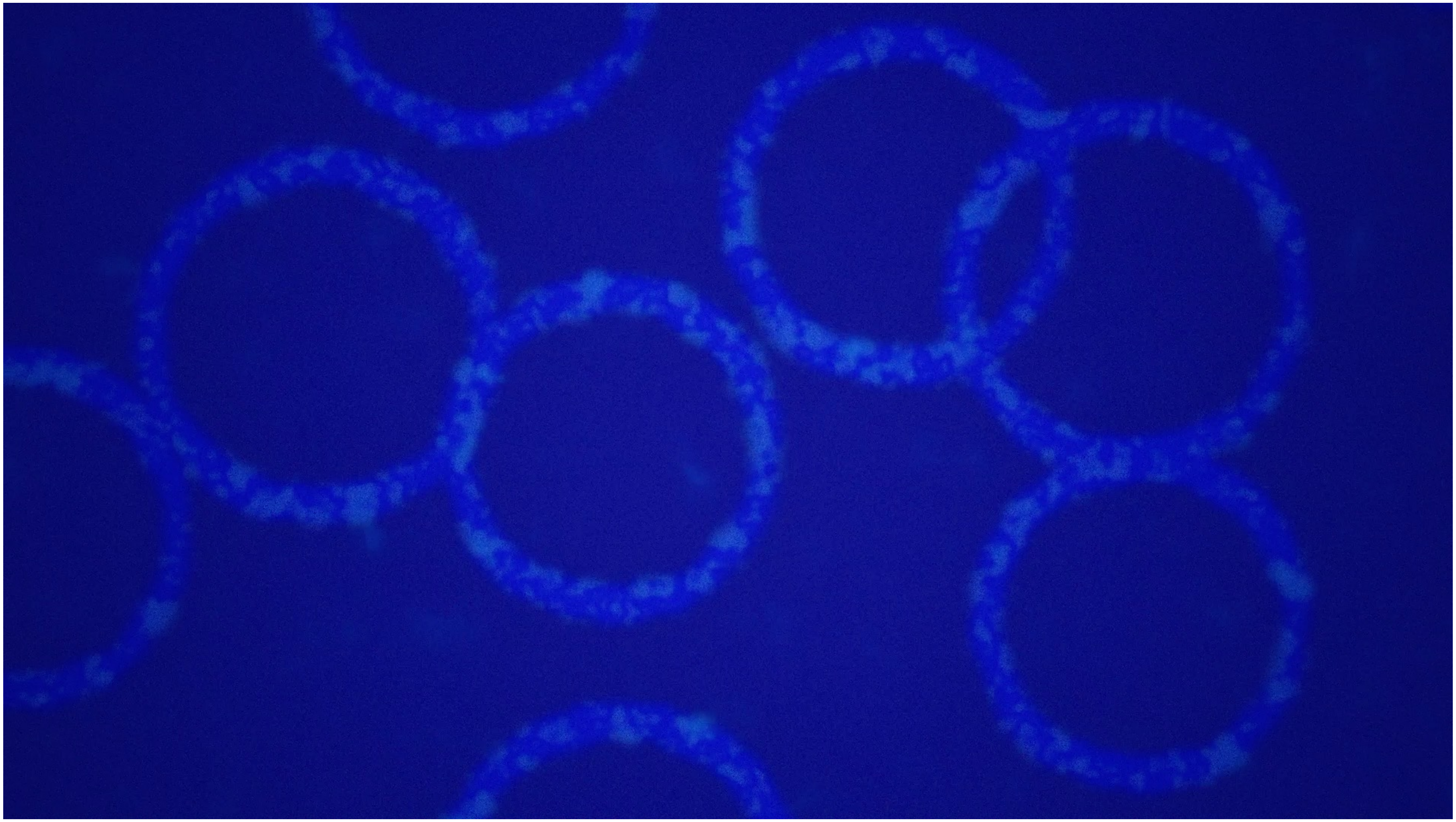
Curvature is FLAT

$$\Omega_{m0} = 0.308 \pm 0.012 \qquad \Omega_{\Lambda 0} = 0.692 \pm 0.012$$

$$\Omega_{\mathrm{rad}0} = 8.24 \times 10^{-5} \qquad H_o = 67.81 \pm 0.92$$

Lab 13: Under assumption that curvature is flat and the above cosmology, we expect there to be a sound horizon of the scale of ~150 Mpc and angular scale of ~1 degree.

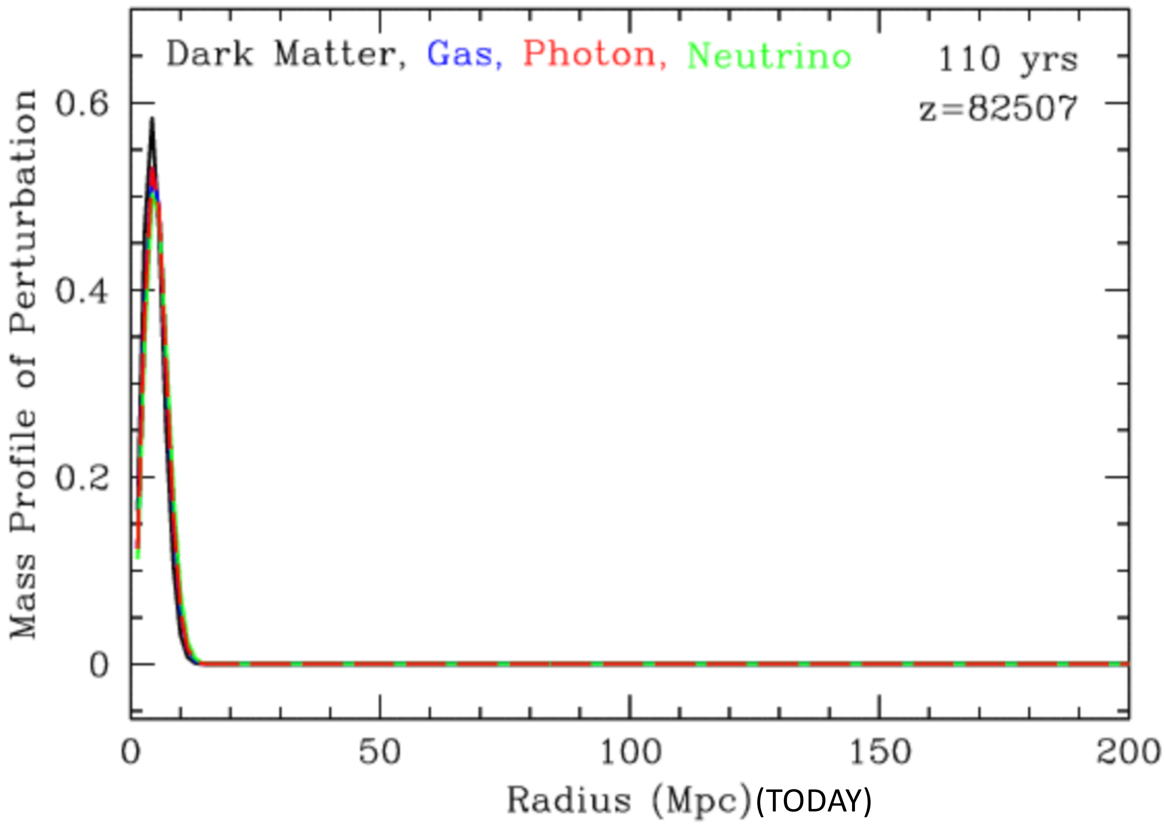




Scott Weissinger

Baryon Acoustic Oscillations

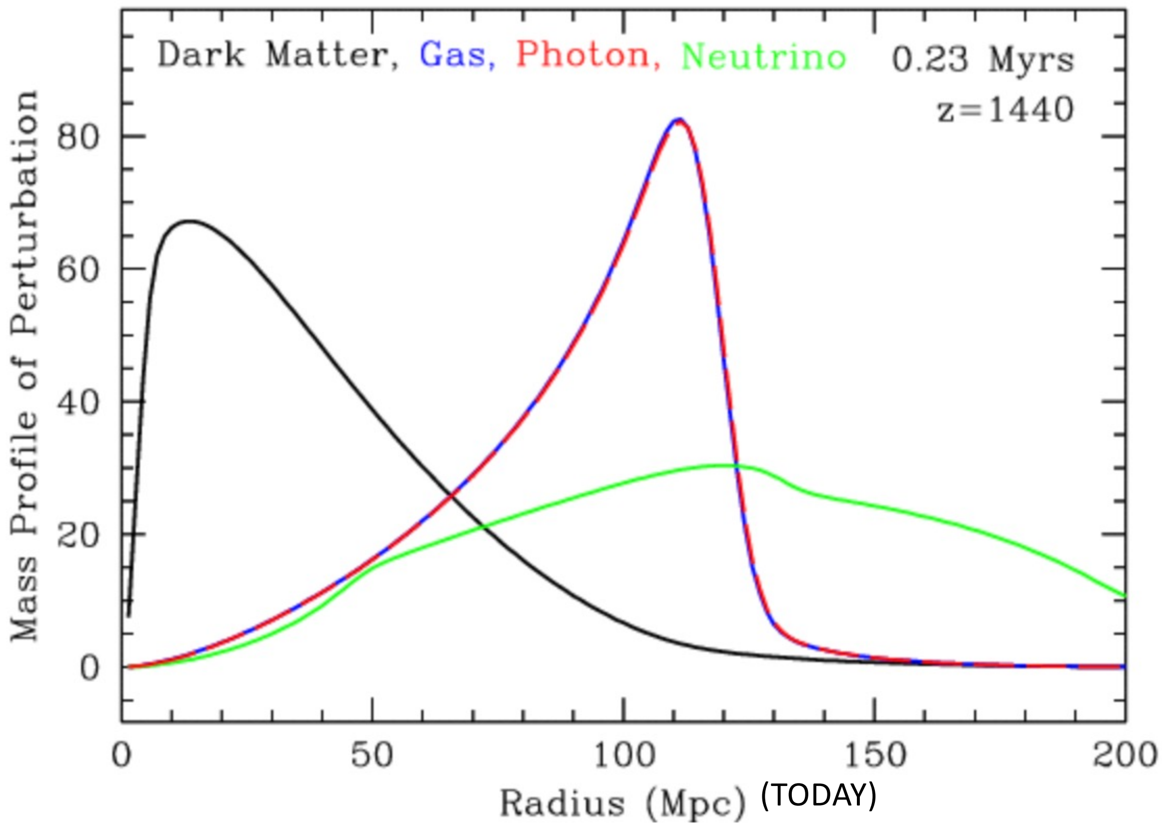
First Detected in Eisenstein+2005
Using SDSS data



- Consider a point-like initial, adiabatic perturbation
- All species impacted ~similarly

Courtesy: Daniel Eisenstein

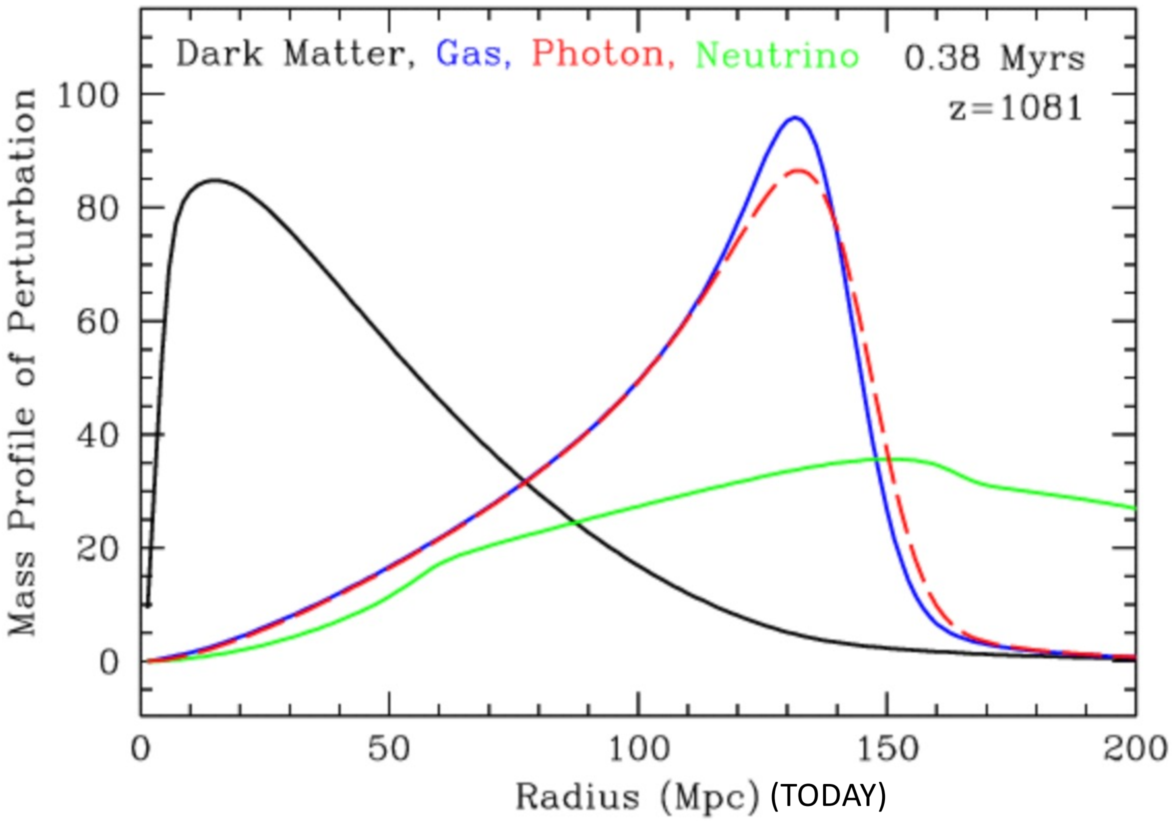
Baryon Acoustic Oscillations



- Neutrinos stream away
- Cold DM has no intrinsic motion – it sits still
- The perturbation is overdense so it pull mos DM -- causes the DM overdensity to grow in width
- Baryon-Photon fluid with enormous pressure relative to its density
- The pressure tries to equalize itself with the surroundings → expanding spherical sound wave
- Perturbation in baryon-photon fluid is carried outwards

Courtesy: Daniel Eisenstein

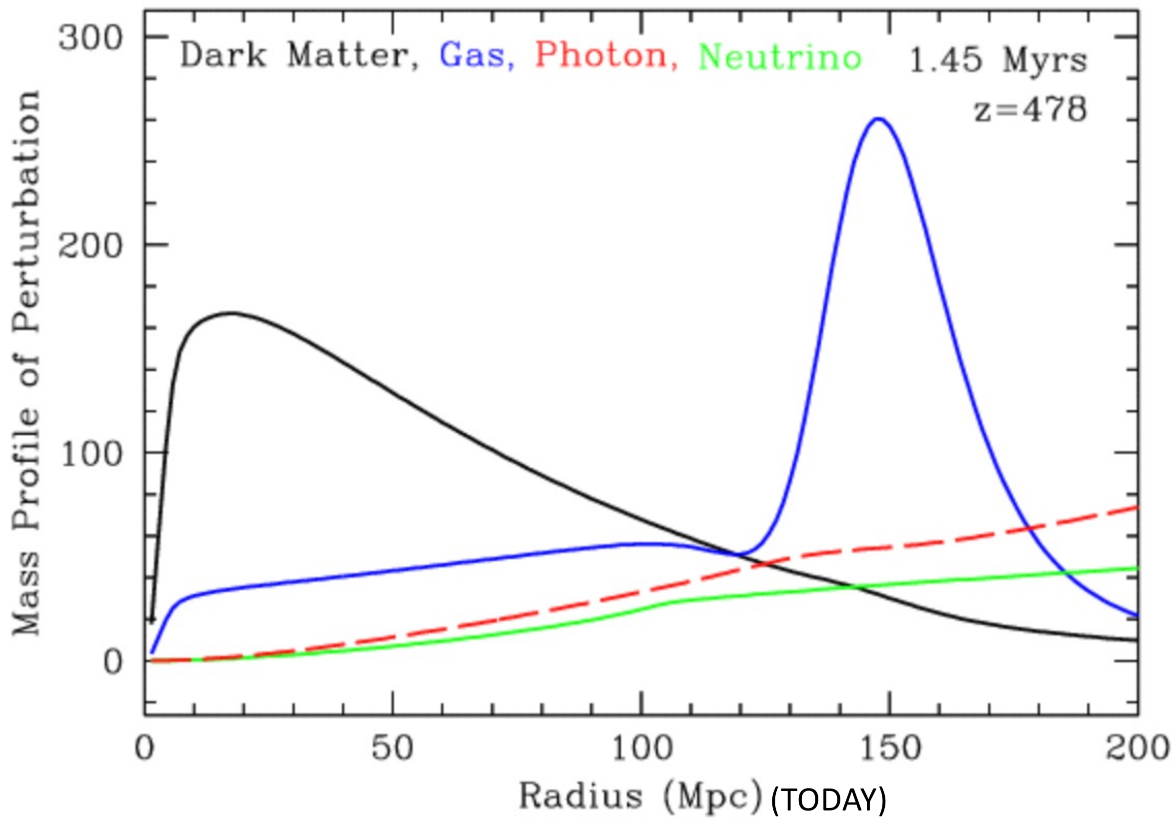
Baryon Acoustic Oscillations



- Recombination ~ 380K years after the Big Bang – atoms. Photons and baryons decouple.
- The sound speed begins to drop because of the reduced coupling between the photons and
- Hence, the pressure wave slows down

Courtesy: Daniel Eisenstein

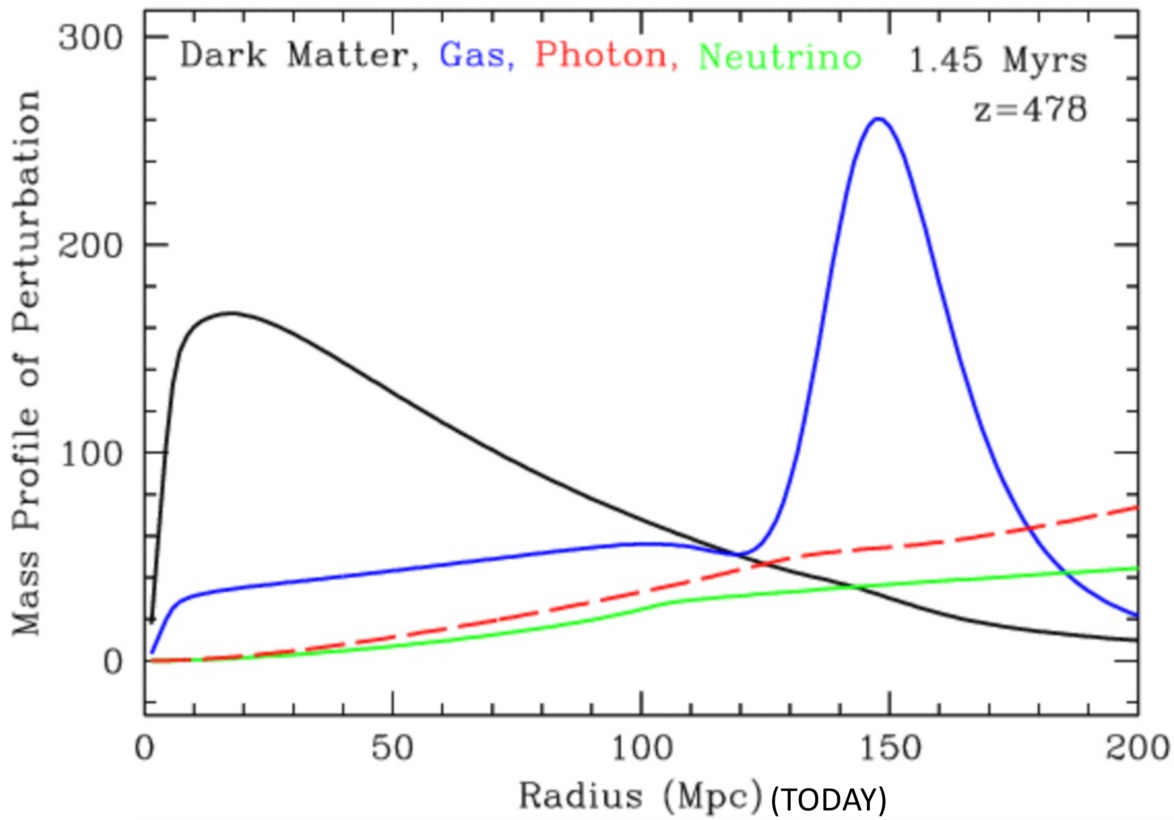
Baryon Acoustic Oscillations



- The photons travel (mostly) unimpeded until the present-day, where we can record them as the microwave background
- the sound speed in the gas has dropped to much less than the speed of light, so the pressure wave stalls.

Courtesy: Daniel Eisenstein

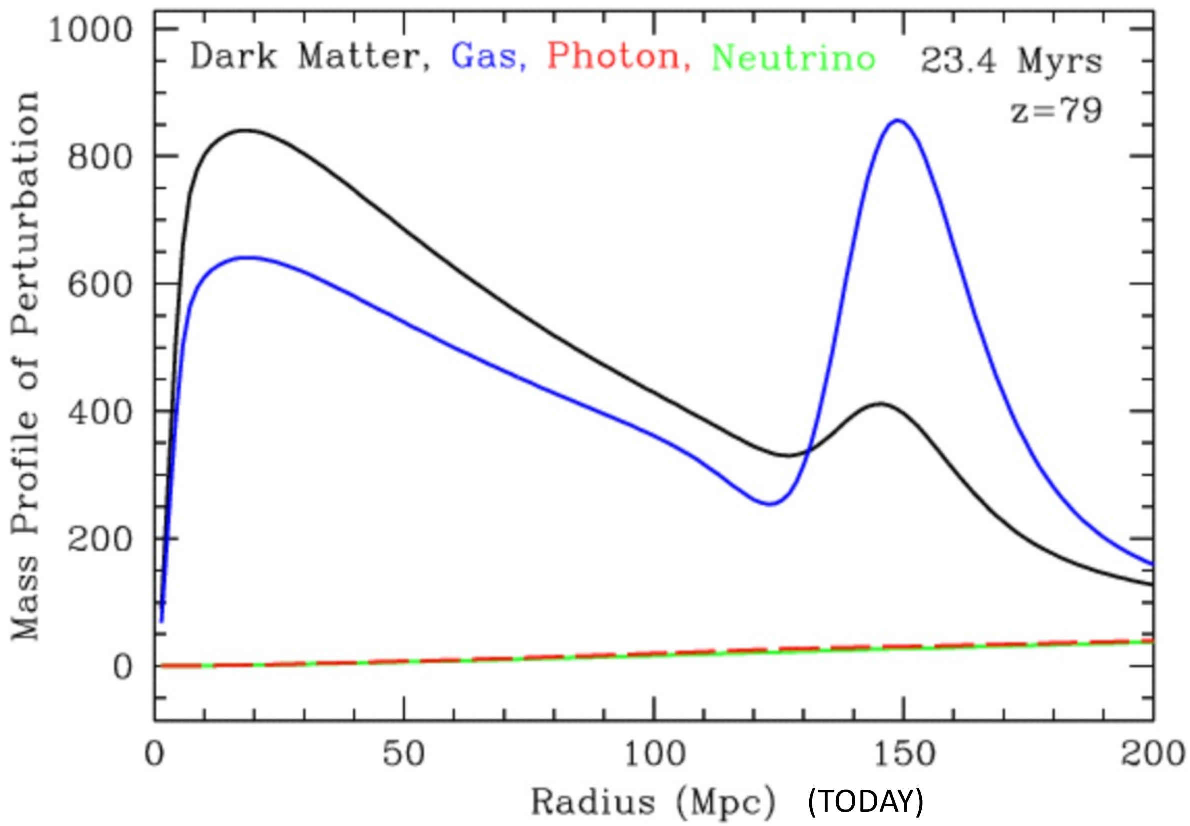
Baryon Acoustic Oscillations



- We are left with a dark matter perturbation around the original center and a gas perturbation in a shell about 150 Mpc (500 million light-years) in radius.
- **150 Mpc is the sound horizon**

Courtesy: Daniel Eisenstein

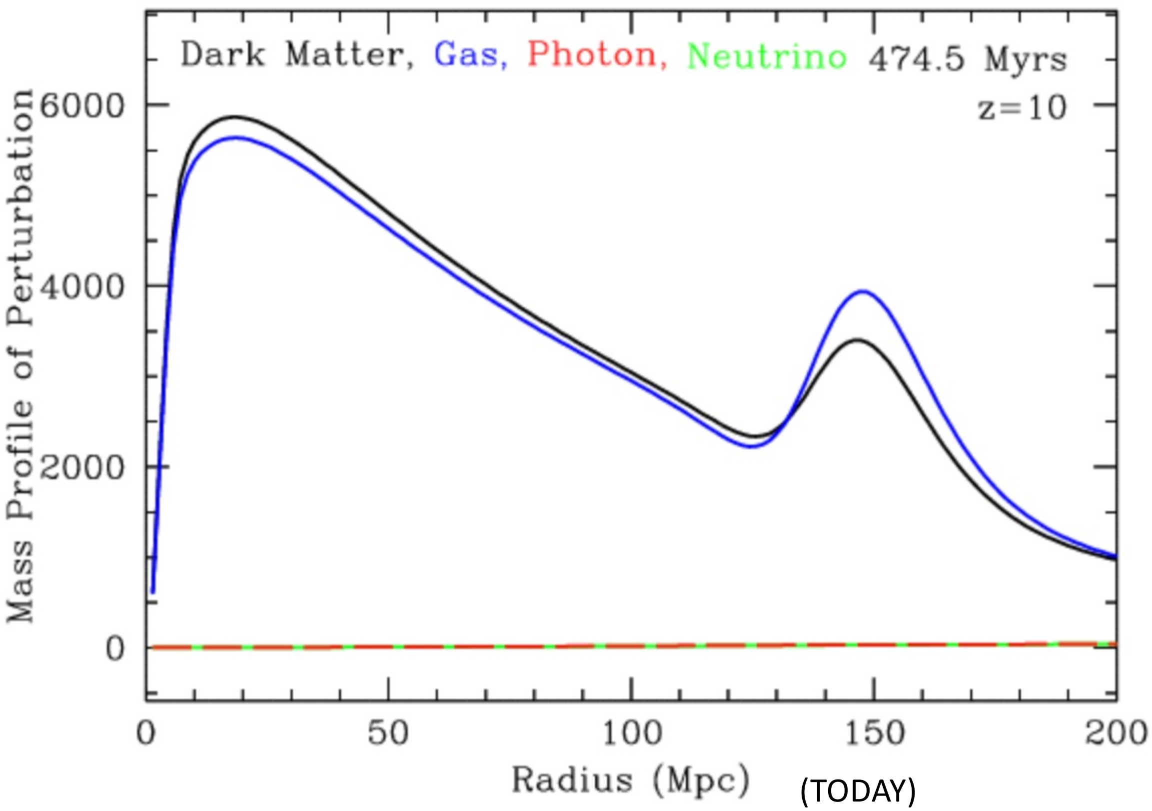
Baryon Acoustic Oscillations



- As time goes on these two species gravitationally attract each other.
- both perturbations are growing quickly in response to the combined gravitational forces of both the dark matter and the gas

Courtesy: Daniel Eisenstein

Baryon Acoustic Oscillations

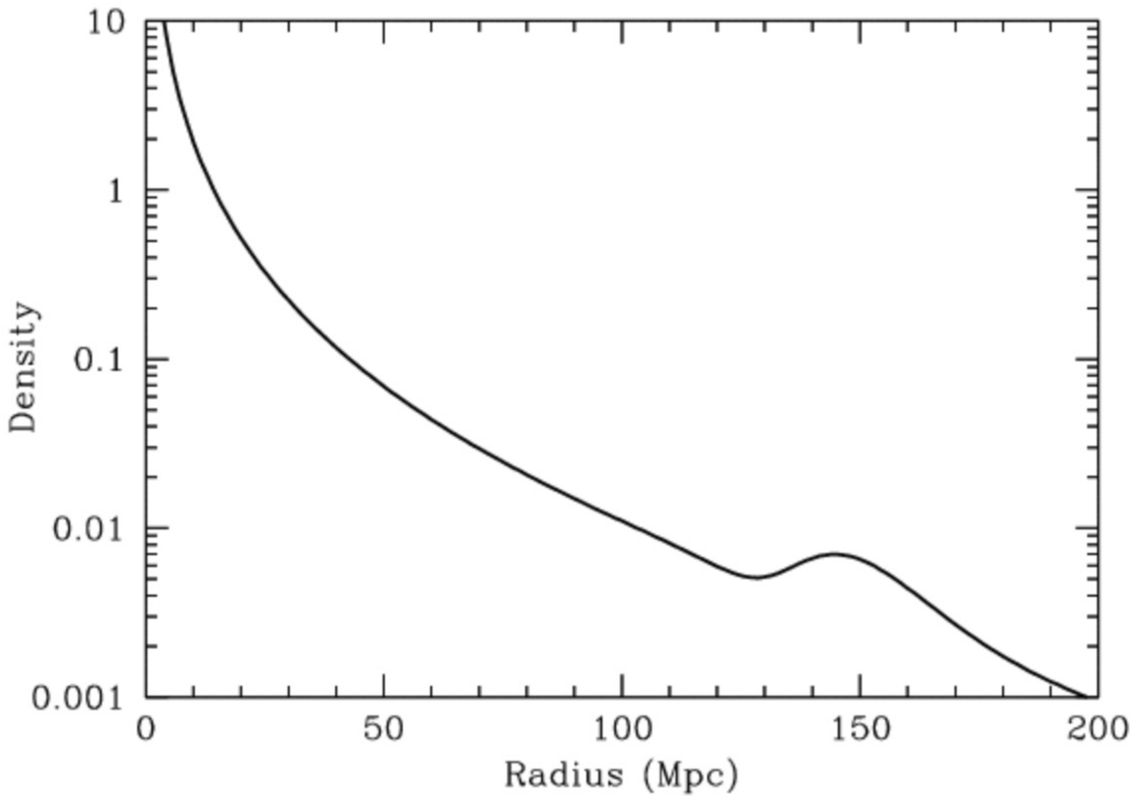


(TODAY)

- Eventually, the two look quite similar.
- The spherical shell of the gas perturbation has imprinted itself in the dark matter.
- This is known as the acoustic peak

Courtesy: Daniel Eisenstein

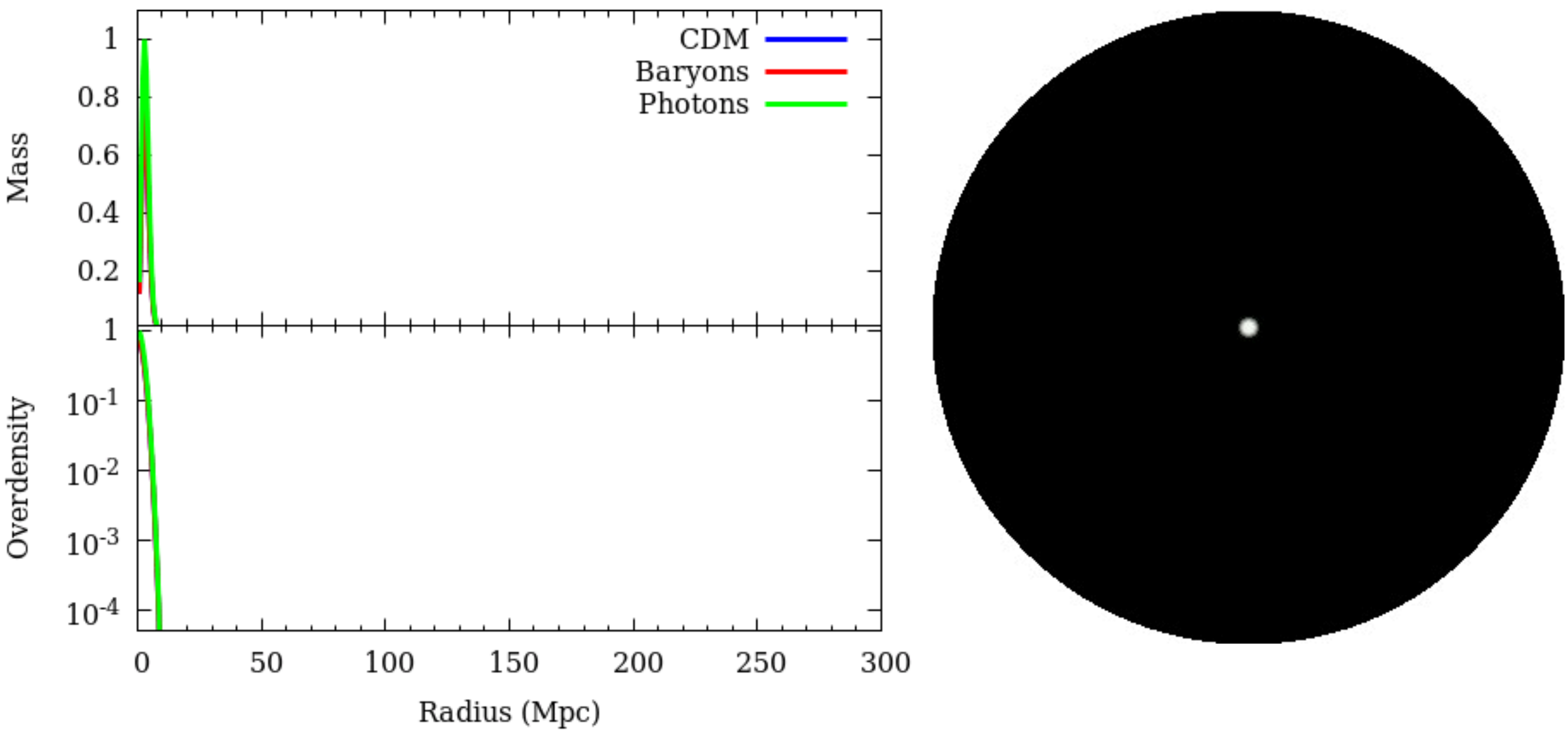
Baryon Acoustic Oscillations



(TODAY)

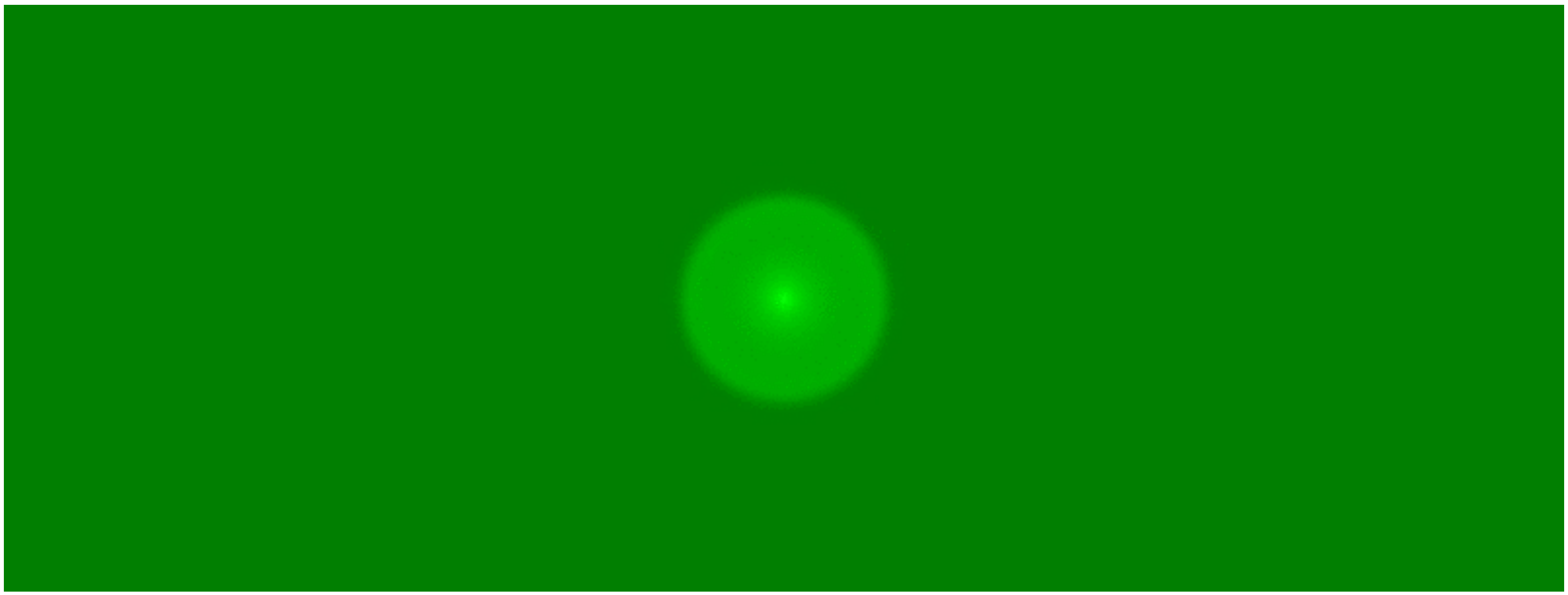
- We have been plotting the mass profile (density times radius squared). The density profile is much steeper, so that the peak at 150 Mpc is much less than 1% of the density near the center.
- At late times, galaxies form in the regions that are overdense in gas and dark matter.
- there should be a small excess of galaxies 150 Mpc away from other galaxies, as opposed to 120 or 180 Mpc

Courtesy: Daniel Eisenstein



Courtesy Dr. Adam Hincks: https://adh-sj.info/bao_cmb.php

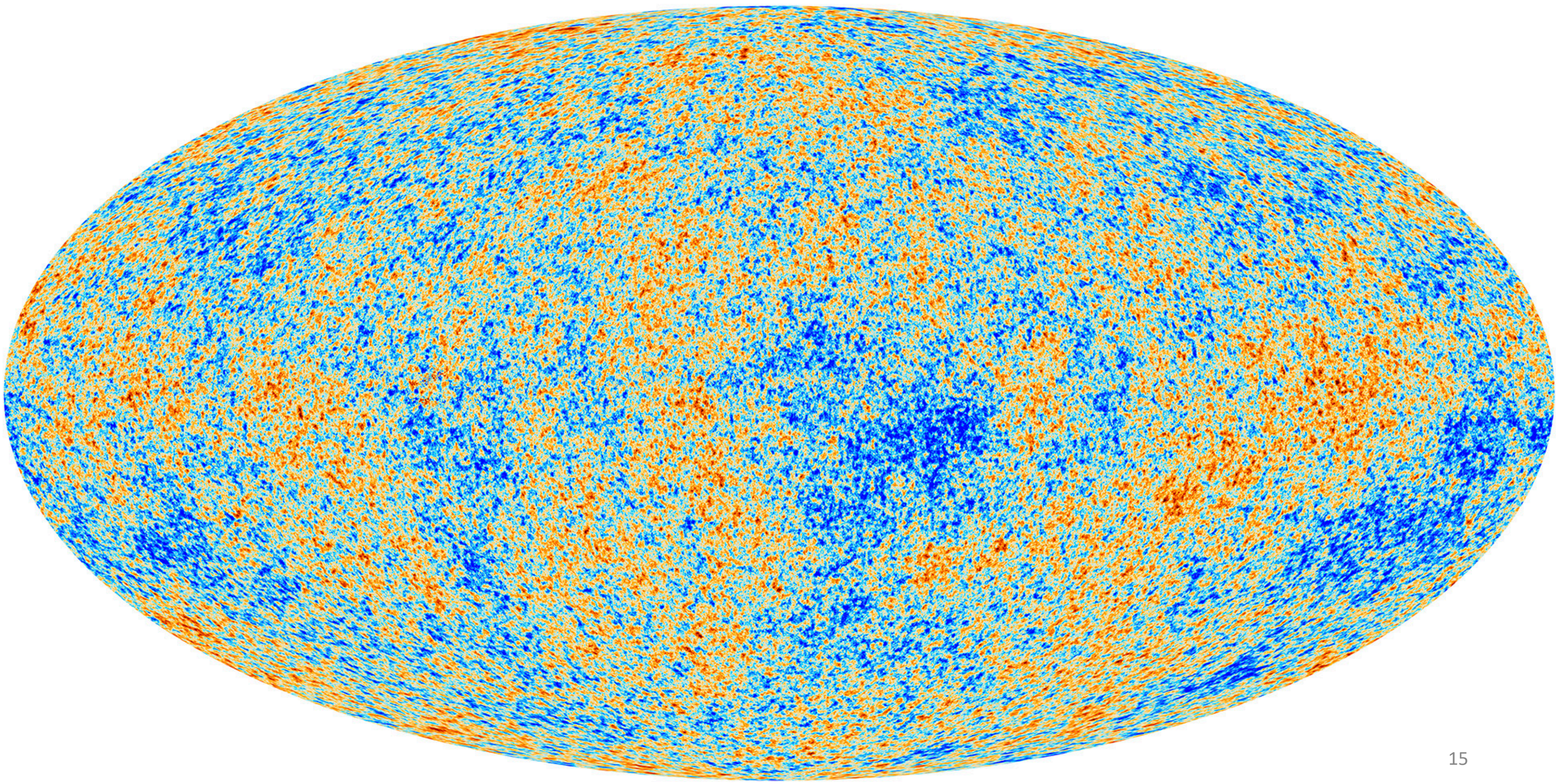
The CMB is then the superposition of many shells (here maximally 470,000)



cartoon of a roughly 10×3 deg^2 area showing how the CMB is composed of the superposition of lots of BAO shells.
As the number of shells becomes appreciable, no single shell can be distinguished, but the resulting patterns do have a size that is roughly the size of the 150 Mpc shells.

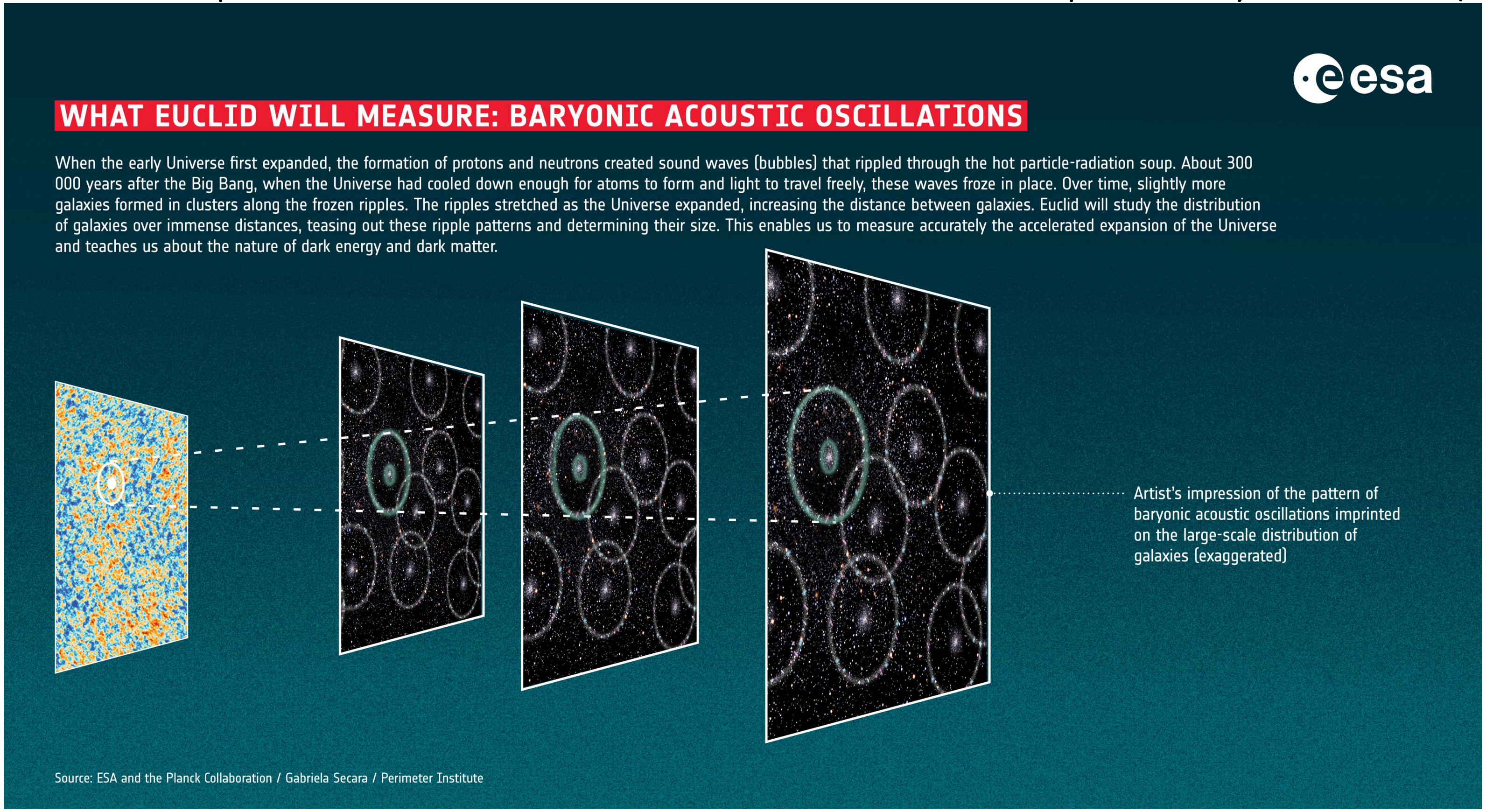
Courtesy Dr. Adam Hincks: https://adh-sj.info/bao_cmb.php

PLANCK 2015



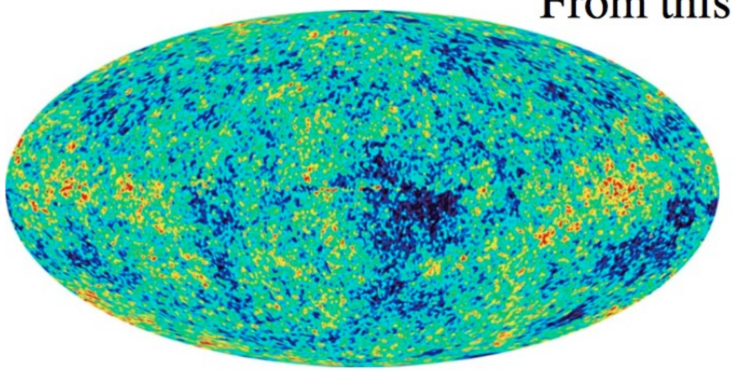
BAO: Baryon Acoustic Oscillations

"Standard Ruler" = maximum distance the acoustic waves could travel in the primordial plasma before recombination ~ 150 Mpc today = 150*R(t)

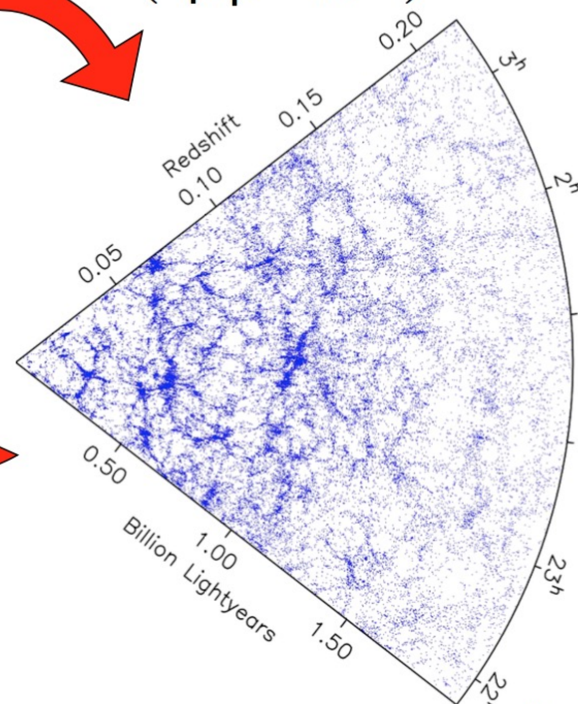


Structure Formation and Evolution

From this $(\Delta\rho/\rho \sim 10^{-6})$

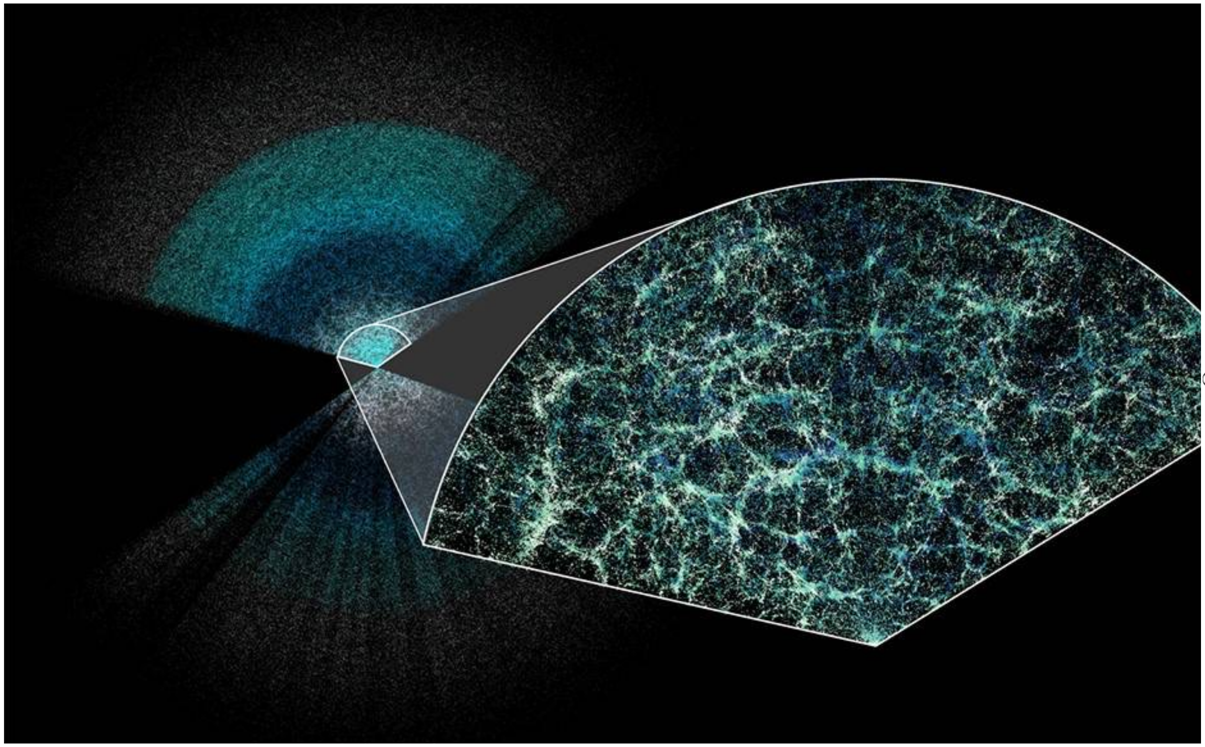


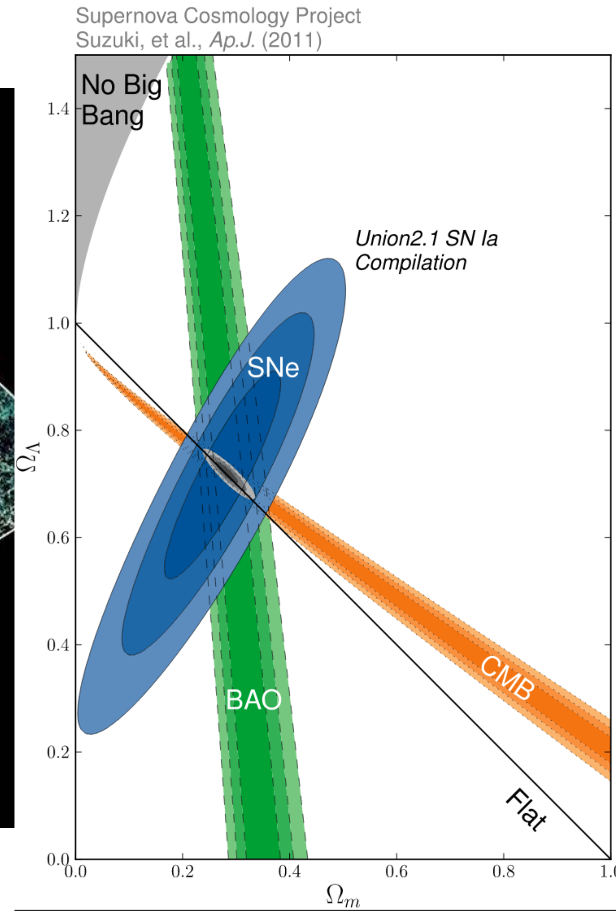
to this
$(\Delta\rho/\rho \sim 10^{+2})$



Cold = rarefaction of photon-baryon fluid
Hot = Compression of photon-baryon fluid

to this
$(\Delta\rho/\rho \sim 10^{+6})$



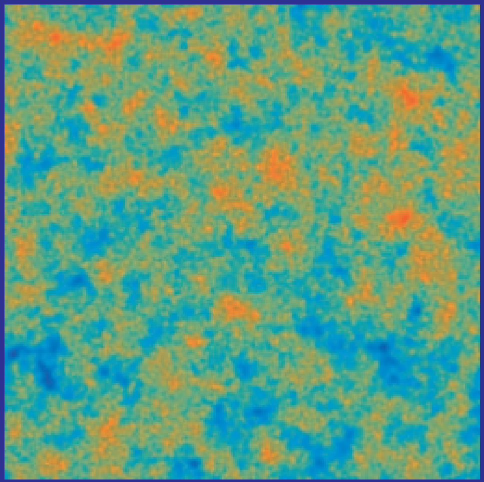


Looking back in time: a slice in time of the universe showing bubbles of galaxies that are a result of baryon acoustic oscillations. (Courtesy: Claire Lamman/DESI collaboration/custom colormap package by cmastro)

- 1 part in 100000 variations in temperature
- Spot sizes ranging from a fraction of a degree to 180 degrees

So these variations in temperature in the CMB provide a snapshot of the distribution of dark matter at this epoch.

64°



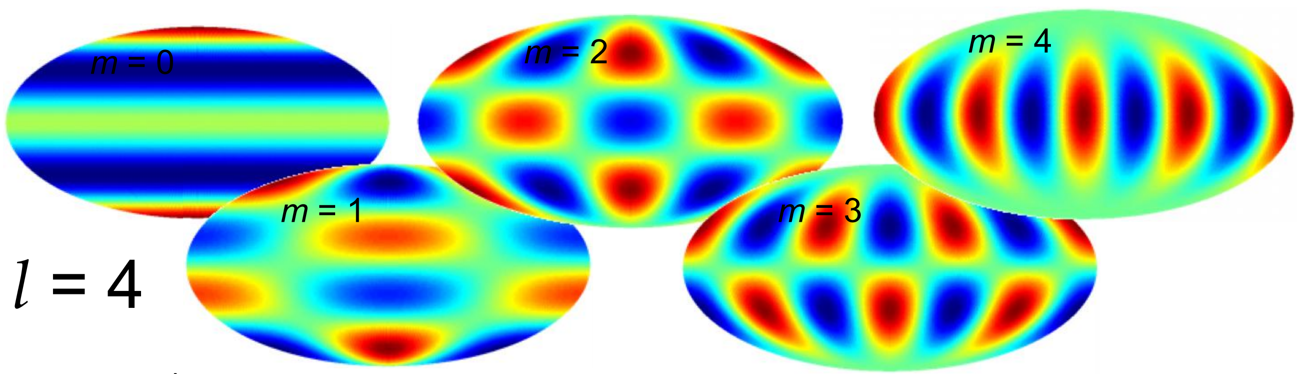
- Selecting only spots of a given range of sizes gives a power spectrum or frequency spectrum of the variations much like a graphic equalizer for sound.

Spherical harmonics

- The spherical harmonics are wave functions on the sphere
  - Completely analogous to the complex exponential in flat space

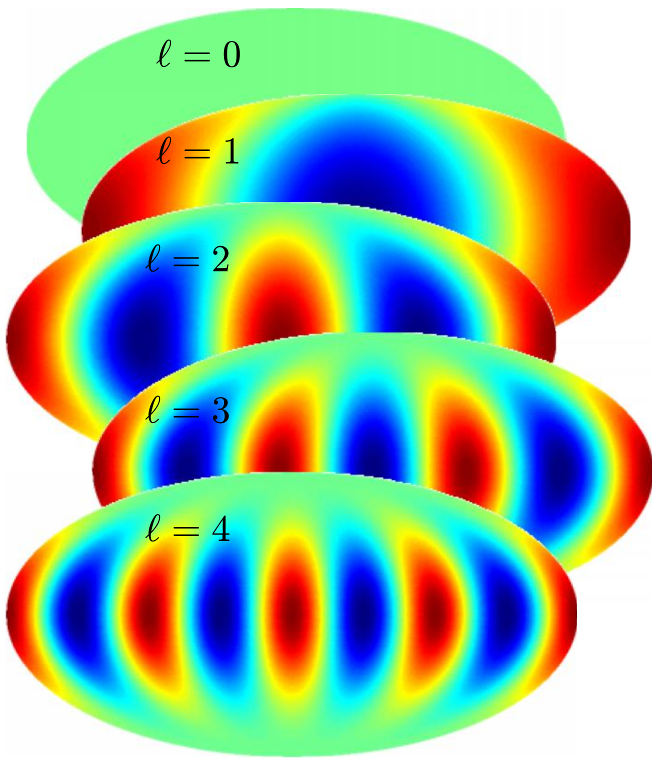
$$e^{ikx} \leftrightarrow Y_{\ell m}(\theta, \phi)$$

- Instead of wave number k, these are described by l and *m*
  - l determines "the wave length" of the mode
    - l is the number of waves along a meridian
  - *m* determines the "shape" of the mode
    - m is the number of modes along equator



Courtesy Hans Eriksen

Relationship between l and scale

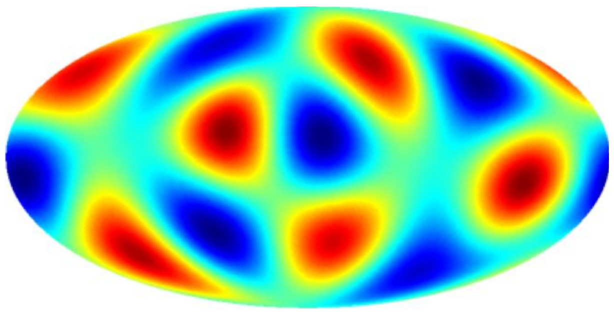


- If l increases by one, the number of waves between 0 to 2π increases by one
- The wave length is therefore

$$\lambda = \frac{2\pi}{\ell}$$

- This only holds along equator
- For a general mode (summed over m) we say more generally that the typical "size "of a spot is

$$\lambda \sim \frac{180^\circ}{\ell}$$



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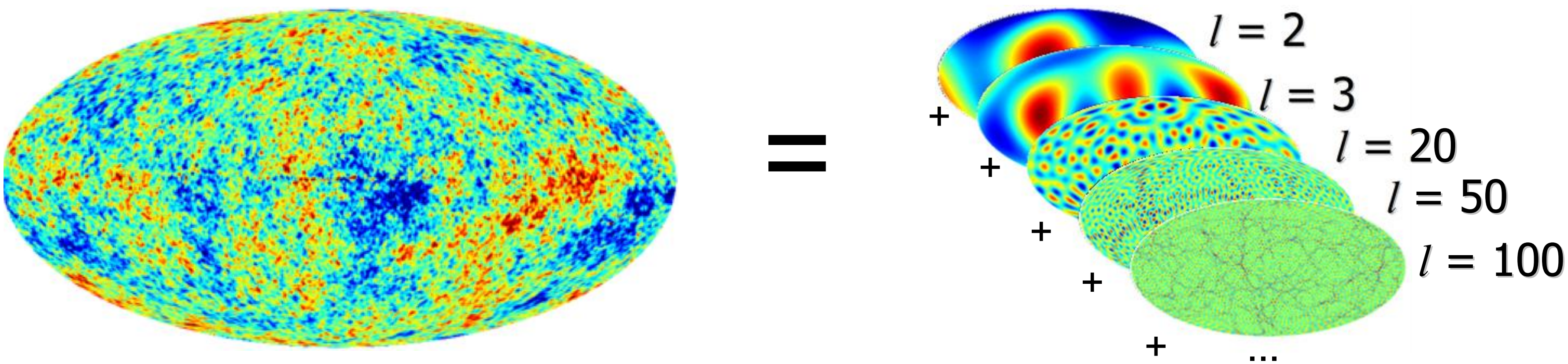
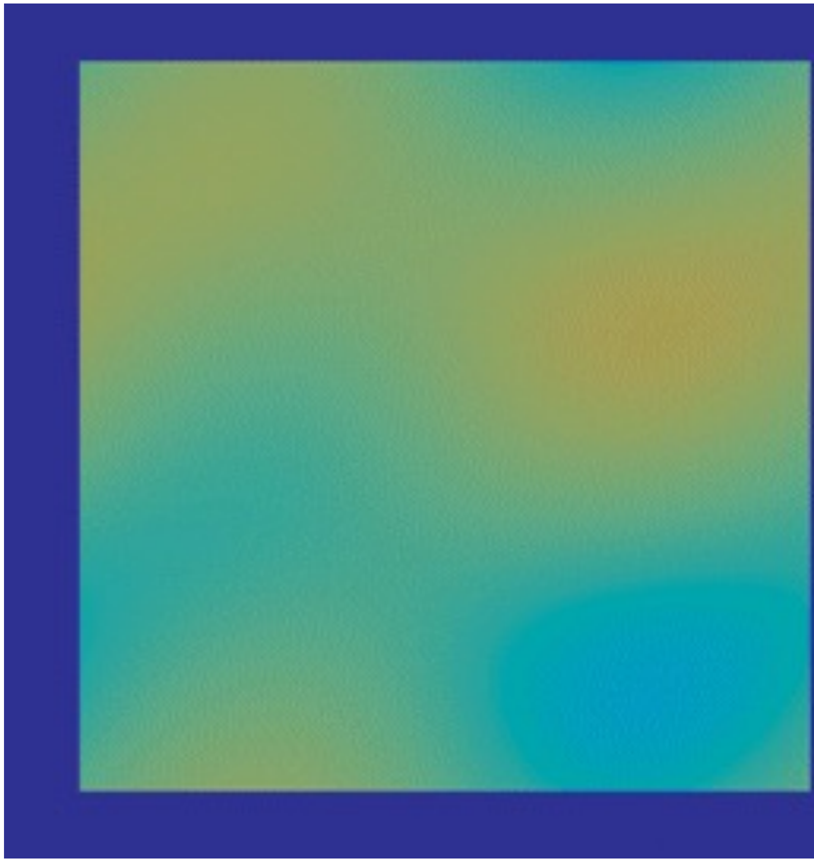
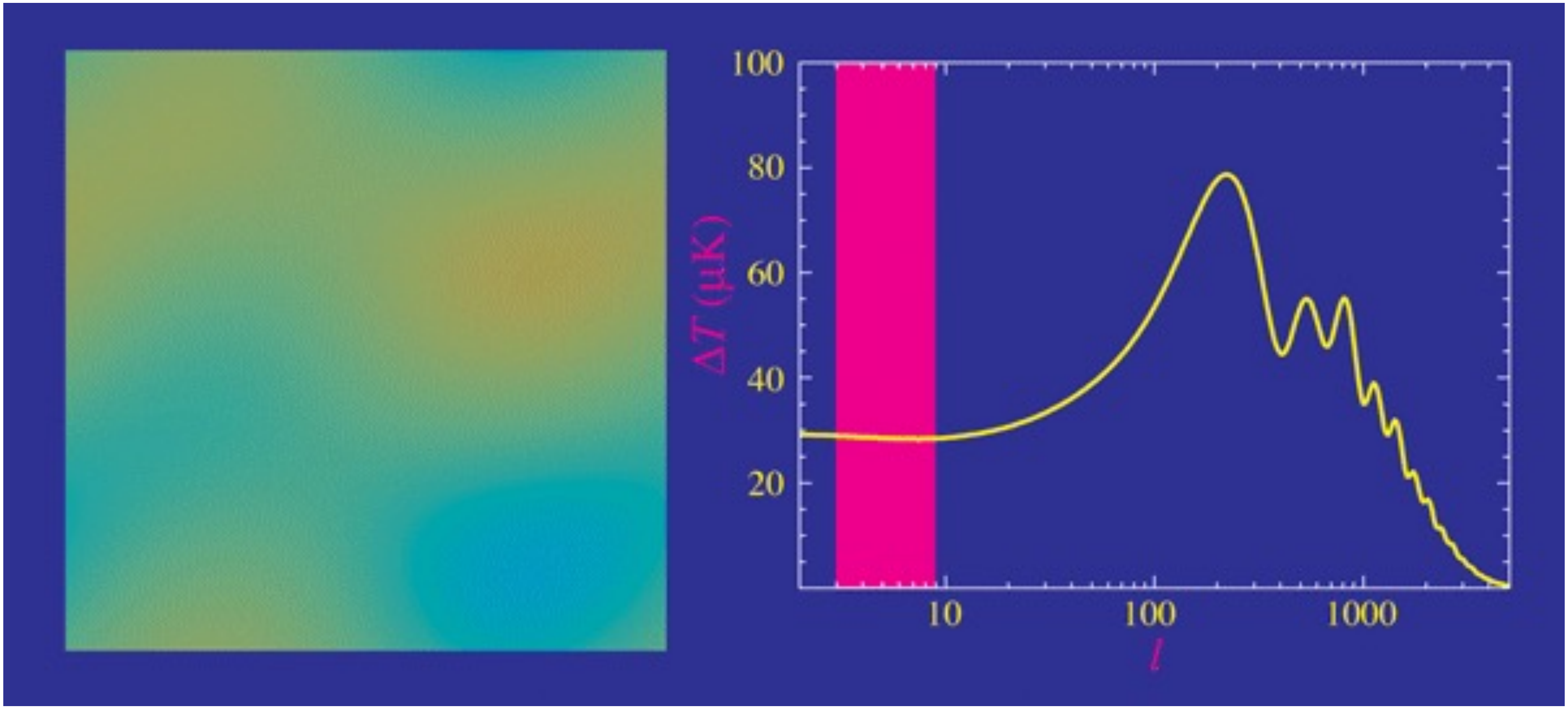


Multipole moments

Courtesy Hans Eriksen



Wayne Hu's Cosmology Tutorial
http://background.uchicago.edu/~whu/metaanim.html



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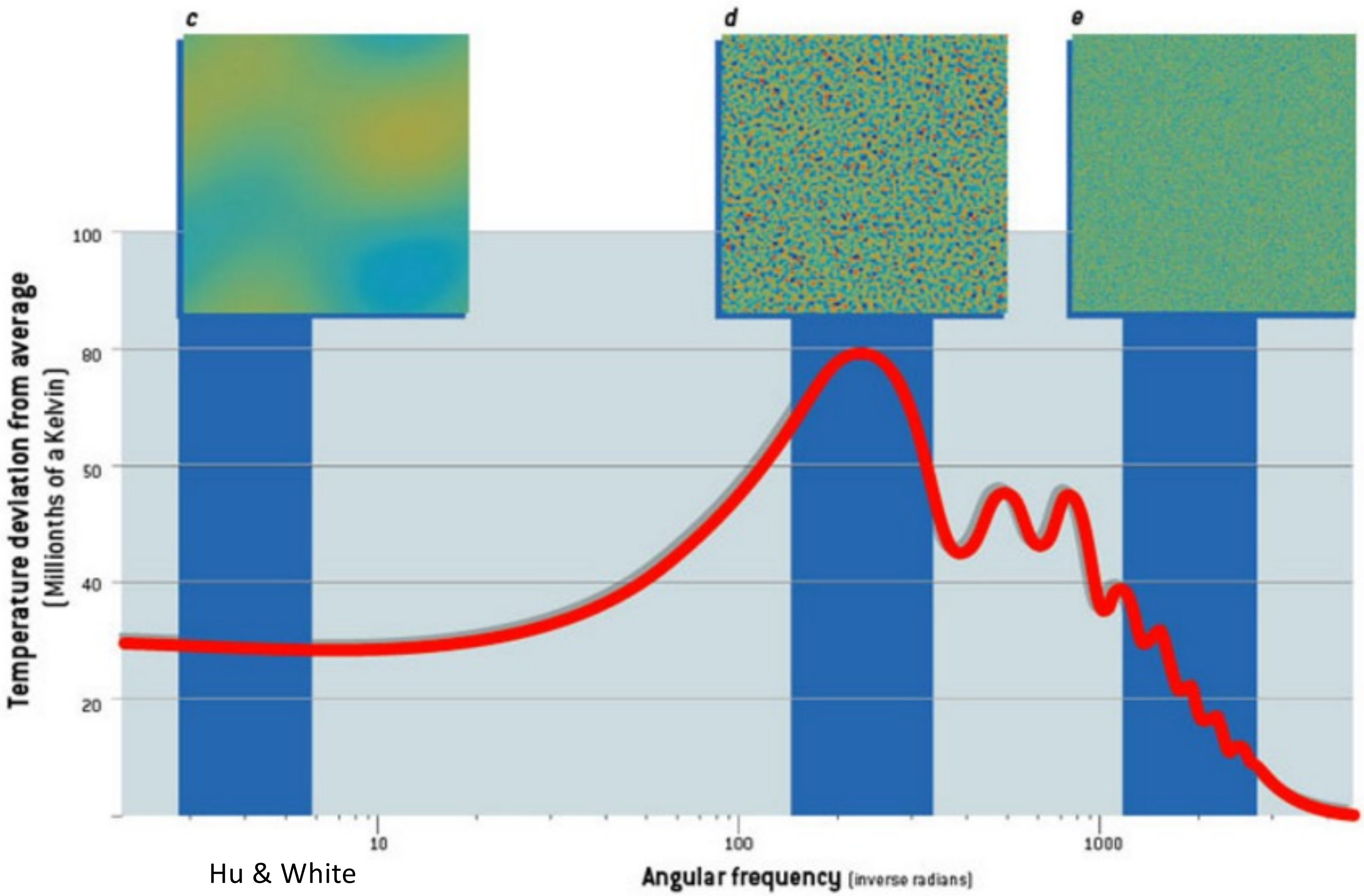
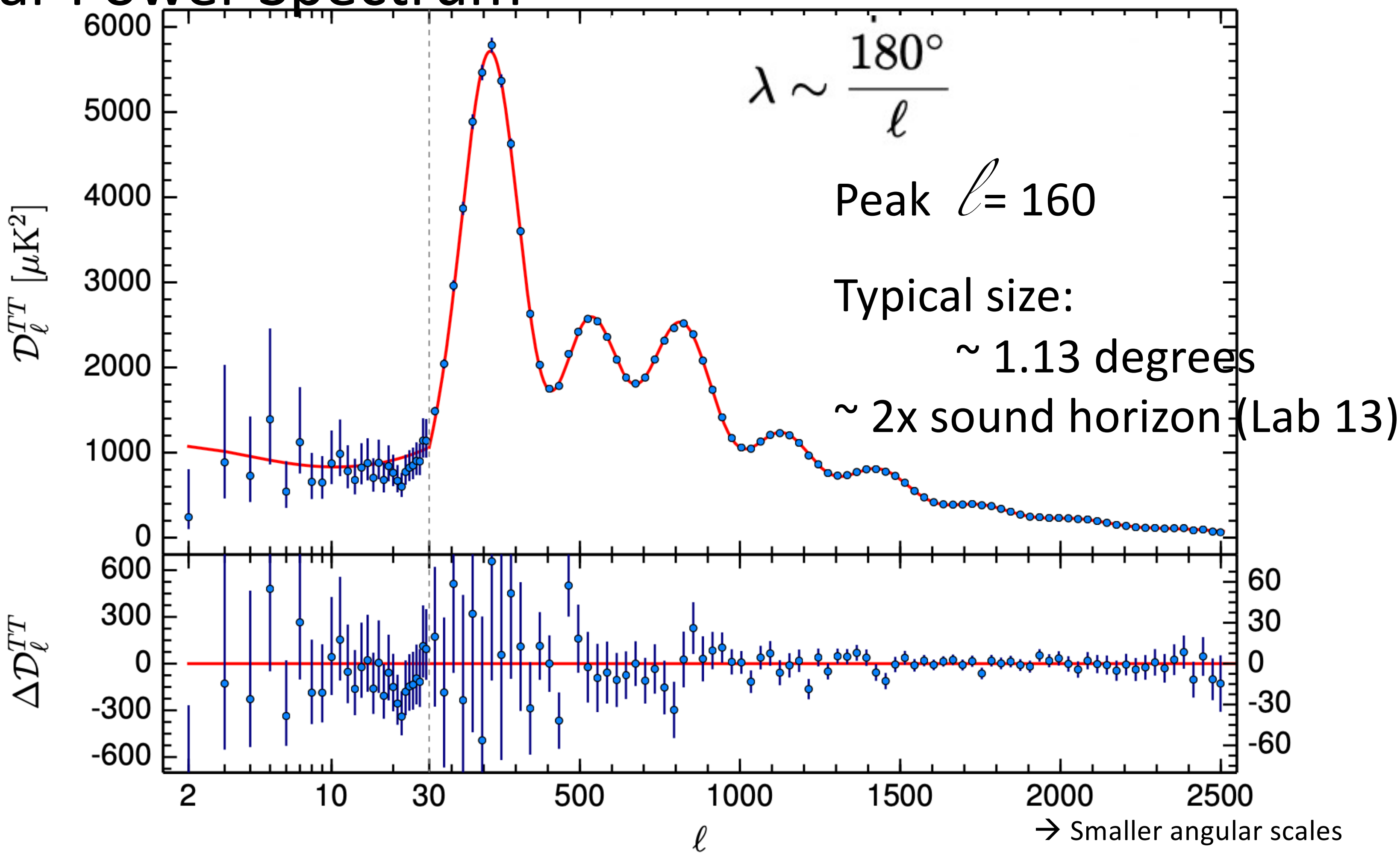
Angular Power Spectrum


c
d
e
100
80
50
40
20
Temperature deviation from average
(Millionths of a Kelvin)
10
100
1000
Angular frequency (inverse radians)

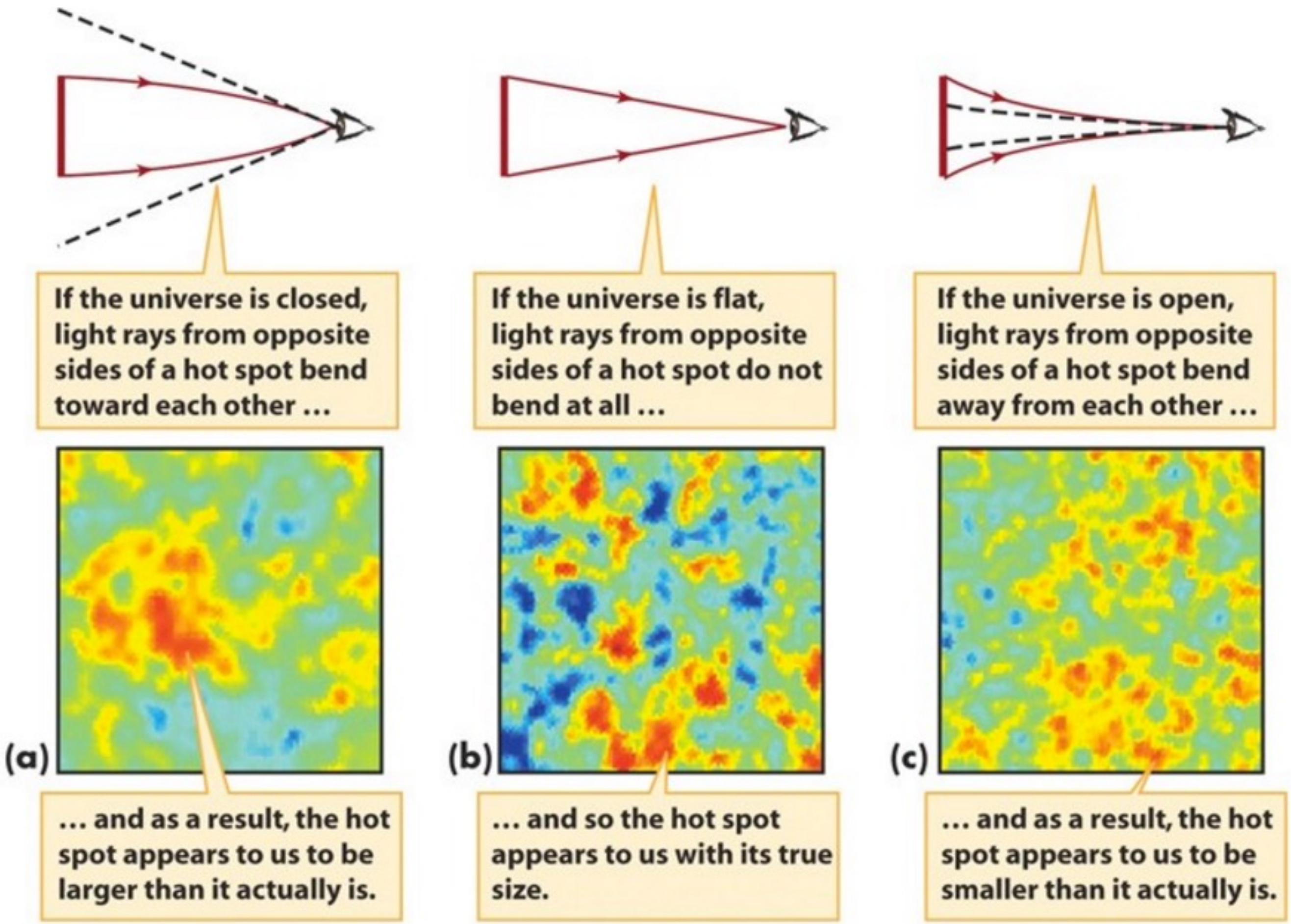
Hu & White

Angular Power Spectrum



Planck 2015

→ Smaller angular scales



Curvature changes the angular size of the peaks – changes the angular diameter distance

Curvature

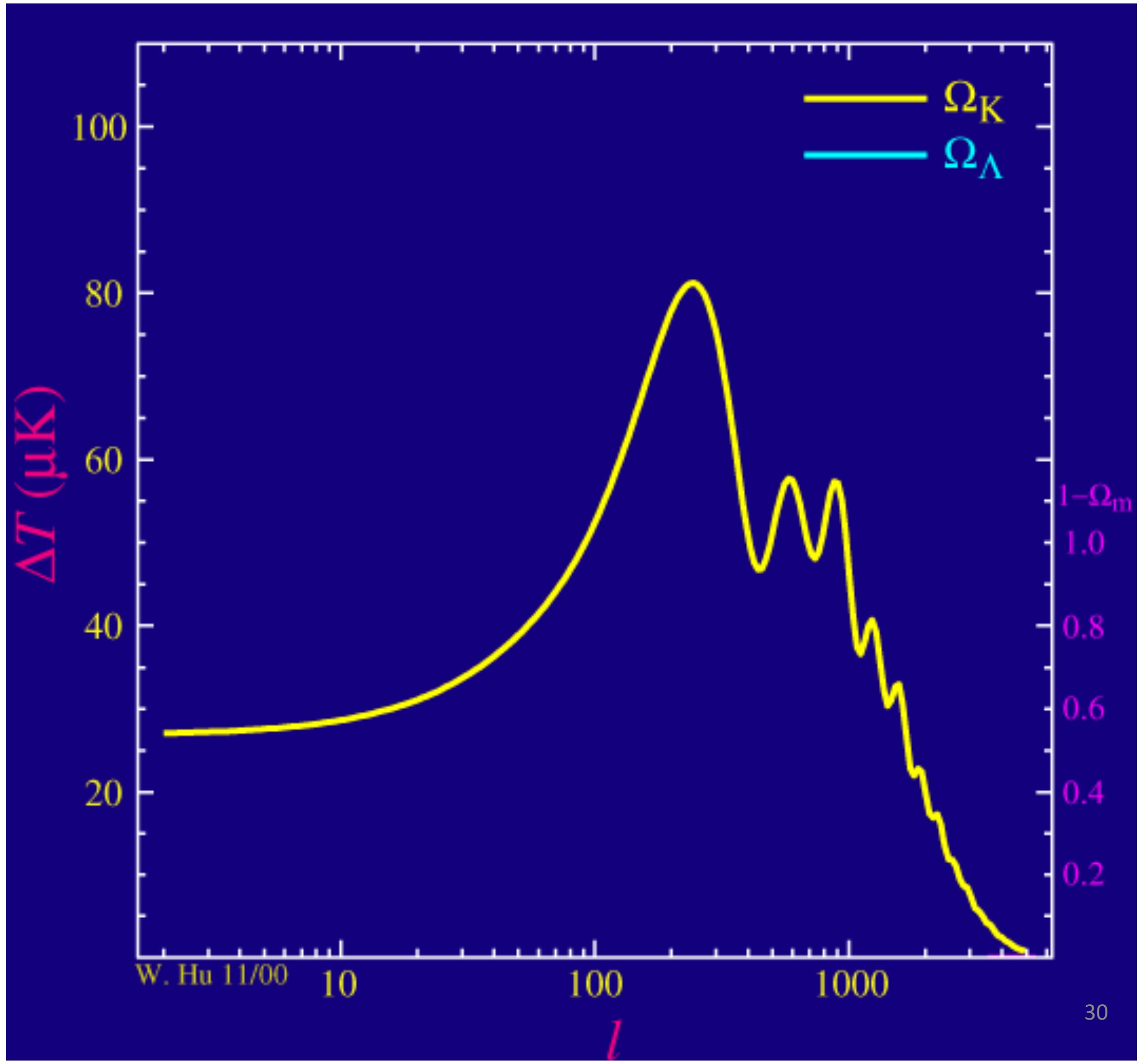
Location of the first peak tells us that

Curvature is flat

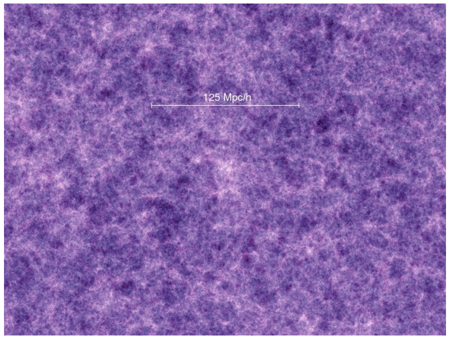
$1 - \Omega_0 = \Omega_k$ = 0

(a flat universe is also expected from inflation)

Wayne Hu's Cosmology Tutorial



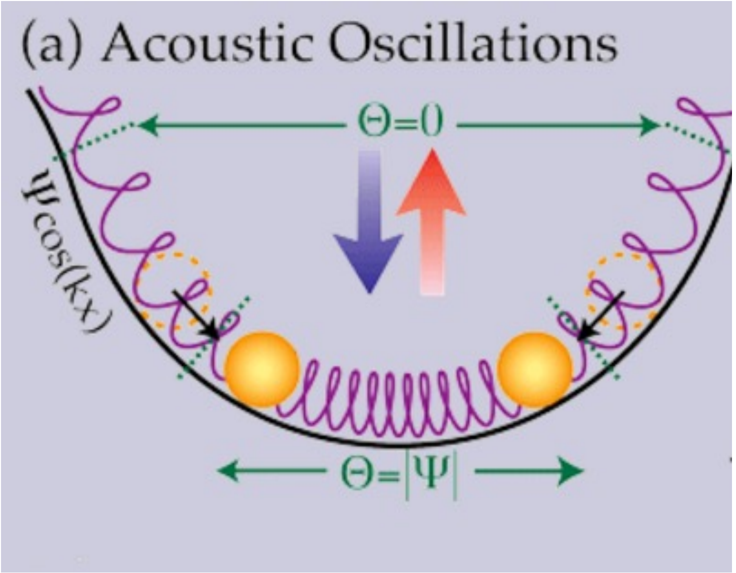
Acoustic Oscillations



Baryon-photon fluid falls into overdensities established by dark matter, heating up.
This increases radiation pressure, causing fluid to expand (rarefaction wave).
The fluid then cools and gravity wins again.
The fluid falls back into an overdensity and heat up.

Called “acoustic oscillations”. The typical scale of these oscillations is the sound horizon distance.

At recombination, these oscillations “freeze” - if caught in a compressed state, it will give rise to a hot spot. else, cold spot.



Baryons = balls
Photons = Springs
Potential (black) = Dark Matter

3rd acoustic peak

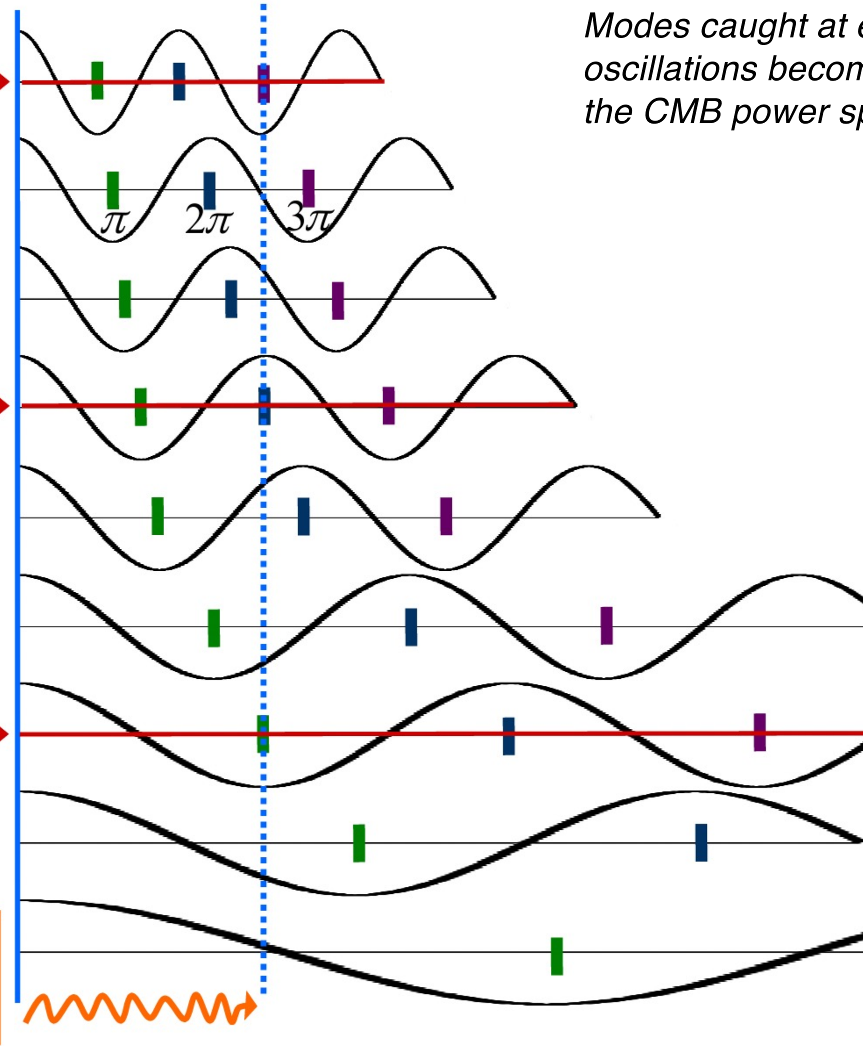
compressed then rarefied, then compressed before recombination

2nd acoustic peak

compressed then rarefied before recombination

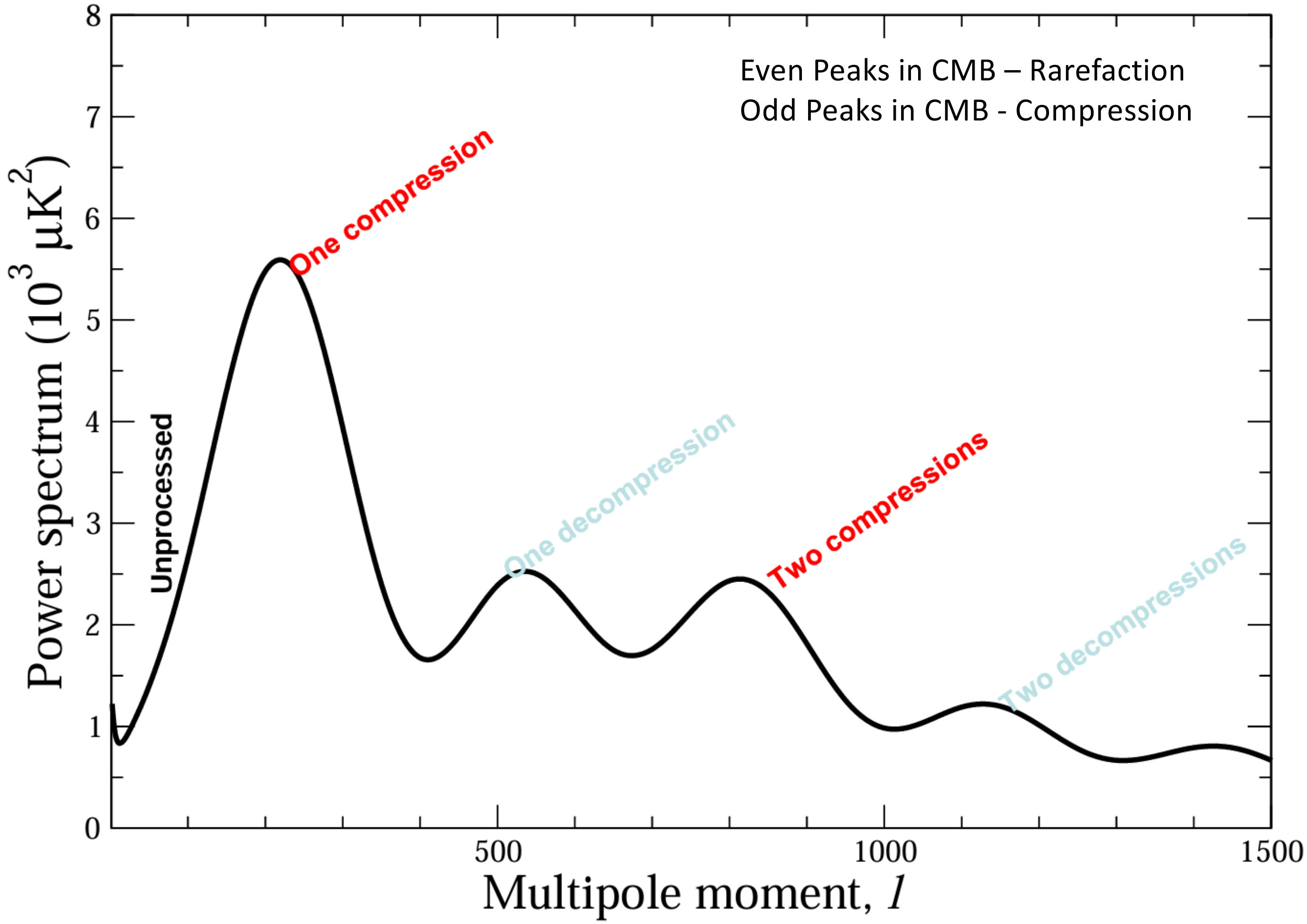
1st acoustic peak

compressed once inside potential wells before recombination



baryon-photon fluid propagated this far since Big Bang

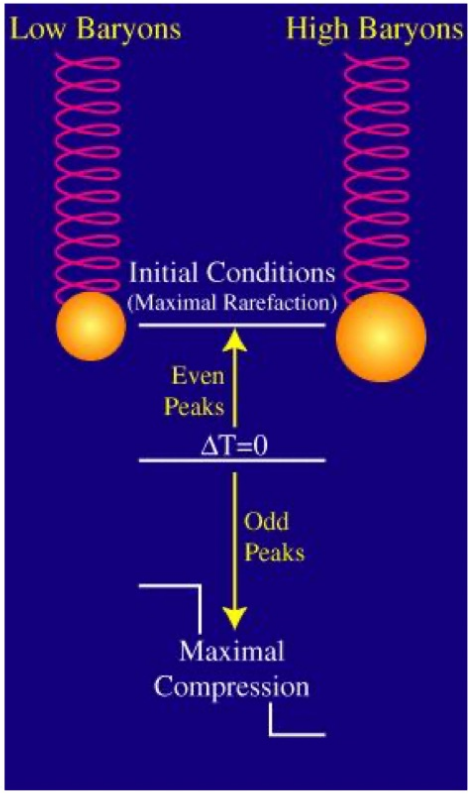
Modes caught at extrema of their oscillations become the peaks in the CMB power spectrum,



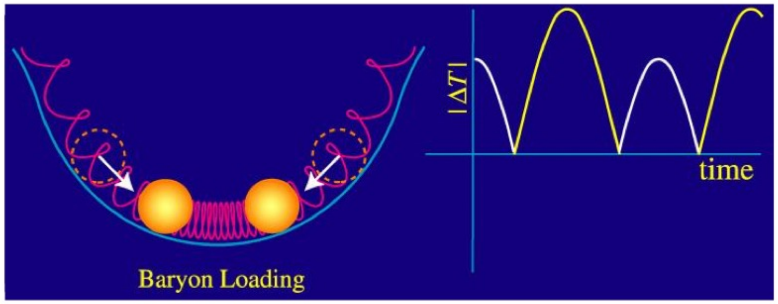
Even Peaks in CMB – Rarefaction
Odd Peaks in CMB - Compression
One compression
Unprocessed
One decompression
Two compressions
Two decompressions
Power spectrum ($10^3\ \mu K^2$)
Multipole moment, l
0
1
2
3
4
5
6
7
8
500
1000
1500

Constraining Baryon Density

More baryons increases the load



Increased load, adds to the potential at compression.
Compressions become stronger than Decompressions.



First and third peaks become stronger than the second and fourth, depending on the load

(Remember dark matter won't do this – can't compress it!)

Courtesy Hans Eriksen

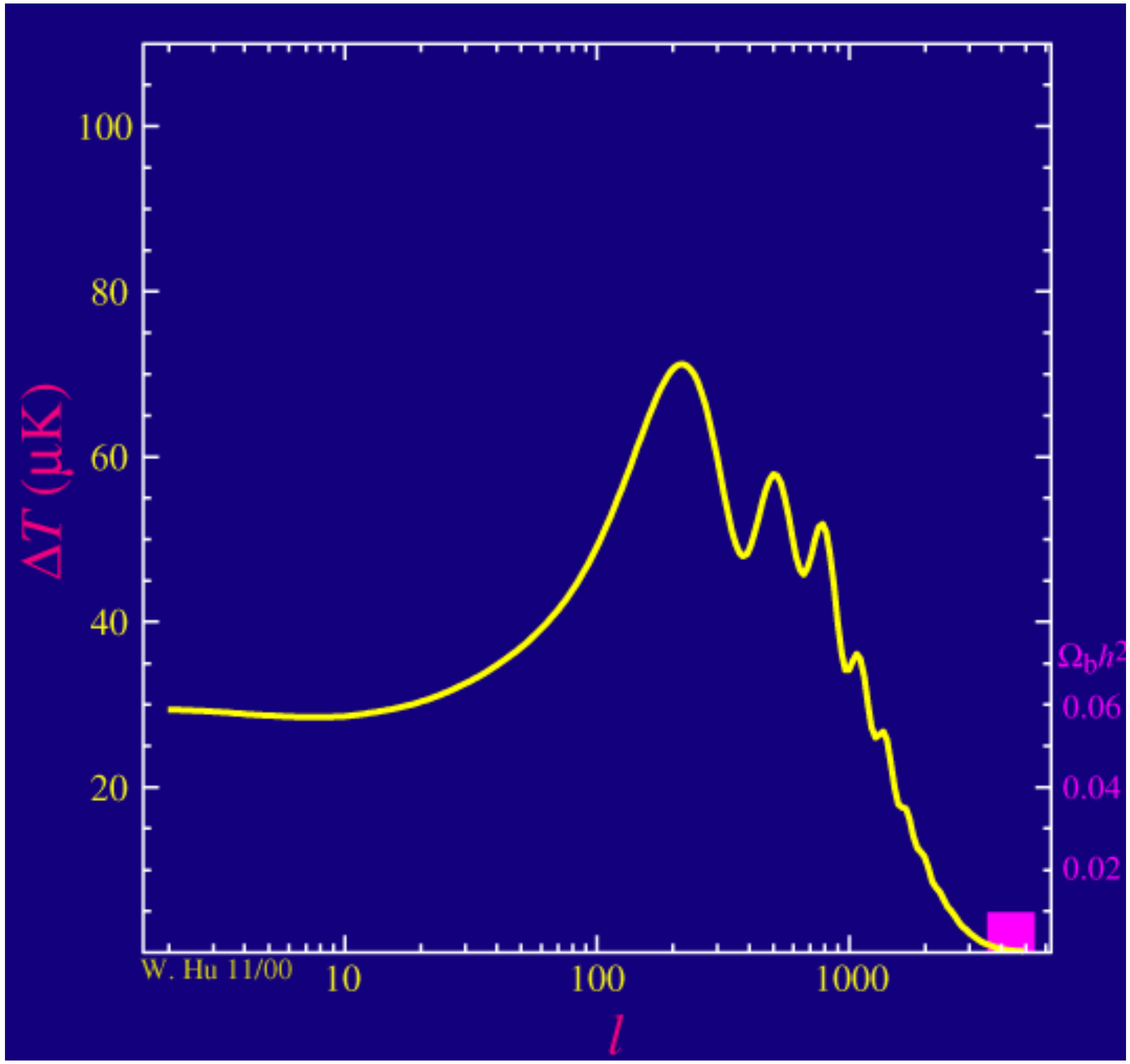
Baryon Density

$\Omega_b h^2$ $\rho_b / \rho_{\text{crit}}$

$$0.02226 \pm 0.00023$$

The ratio of the observed even and odd peaks constrains the amount of normal matter in the universe.

The fact that the third peak is not much lower than the 2nd is good evidence that the baryon fraction must be low (i.e. that dark matter exists).



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Total Matter Density

Impacts the amplitude of the first peak

$\Omega_m h^2$ 0.09591 ± 0.00045

Ω_m 0.308 ± 0.012

Therefore:

1) Cosmic Baryon Fraction

$\frac{\Omega_b h^2}{\Omega_m h^2}$ = 0.157 → ~16%

2) Dark Energy

Ω_Λ 0.692 ± 0.012

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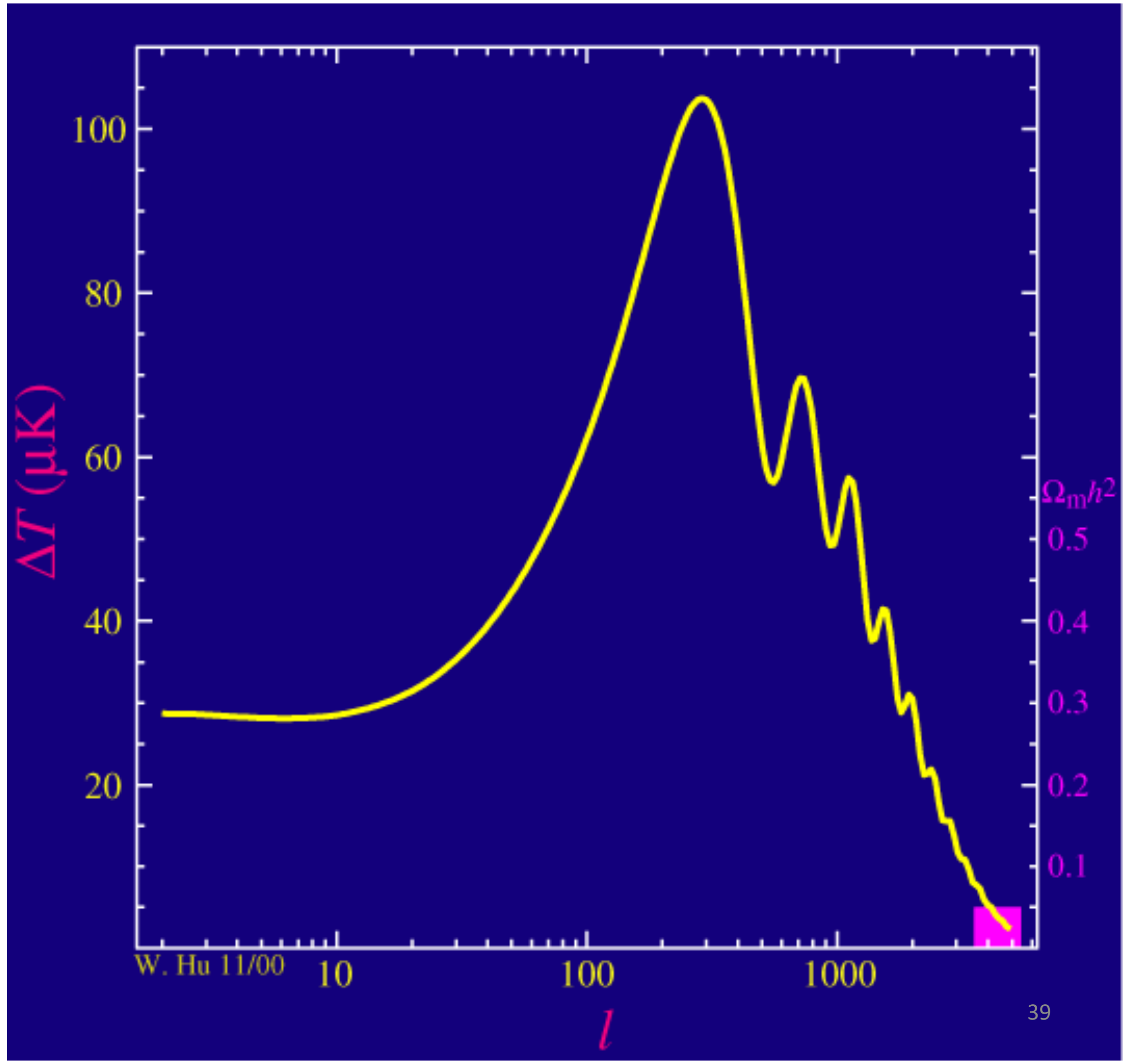

Benchmark Cosmology

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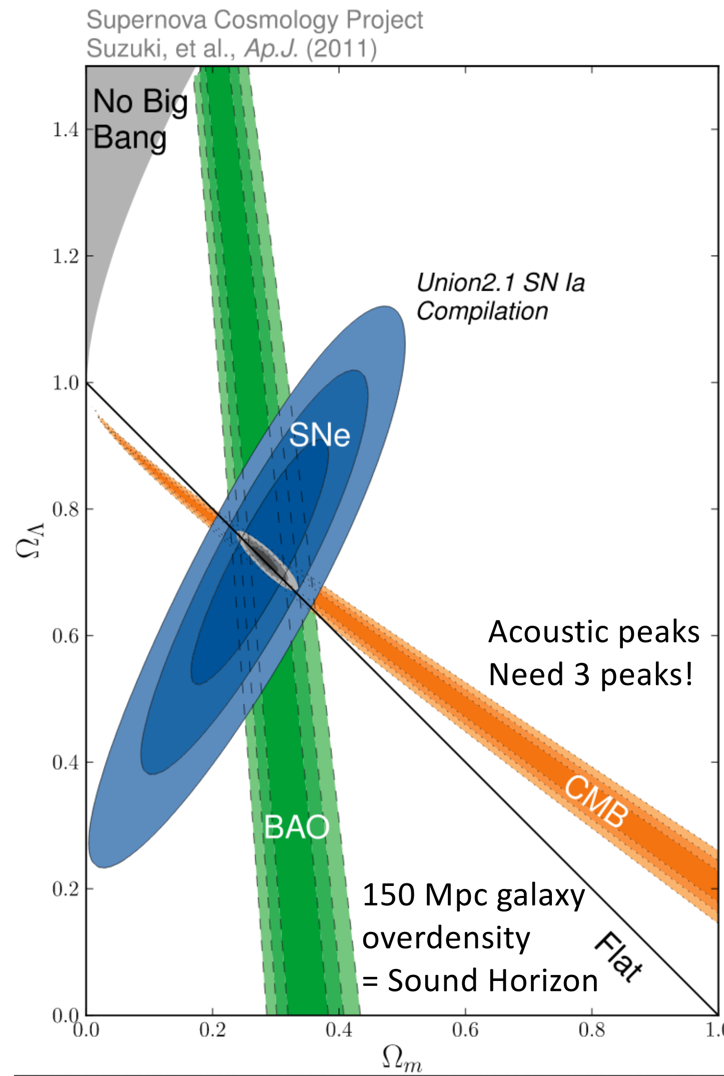
Energy density of the universe is currently 30% matter (16% of which is baryons) and 70% Dark Energy

Lab 14

$$\Omega_{m0} = 0.308 \pm 0.012 \qquad \Omega_{\Lambda 0} = 0.692 \pm 0.012$$

$$\Omega_{\mathrm{rad0}} = 8.24 \times 10^{-5} \qquad H_o = 67.81 \pm 0.92$$



Joint likelihood contours (68%, 95%, and 99.7% confidence limits) for a recent compilation of SN Ia data, together with the WMAP measure of the temperature anisotropies of the CMB, and the large-scale distribution of galaxies in the nearby Universe (BAO).