Introduction to Cosmology lecture 2

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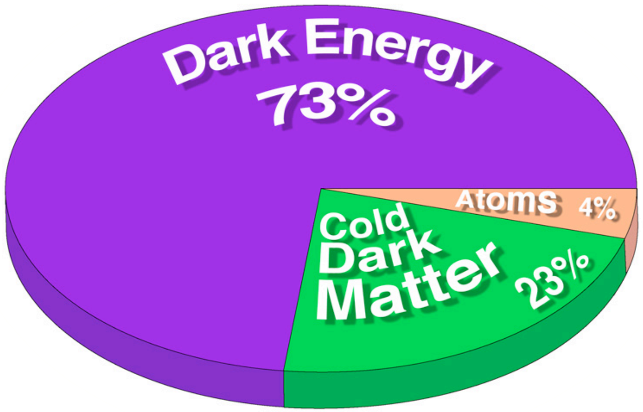
Composition of the Universe



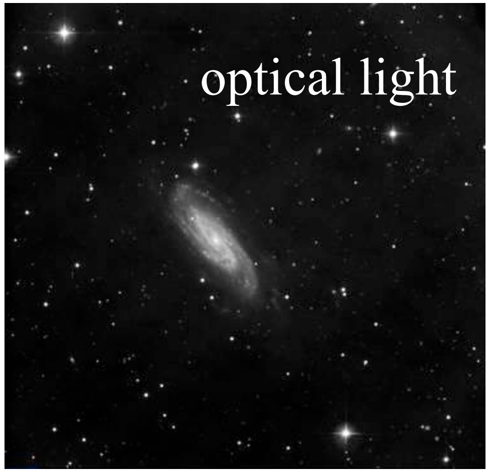
Radiation…

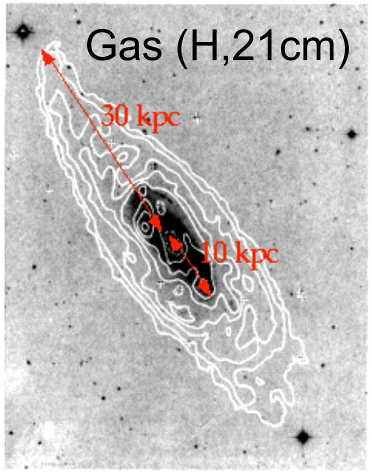
There is more than meets the eye

In the solar system sun + planets

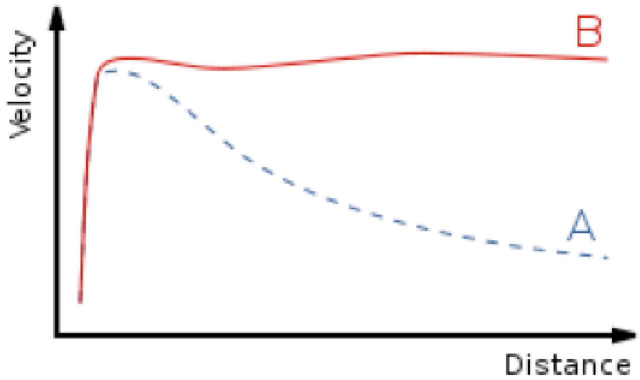
Mass-to-light ratio

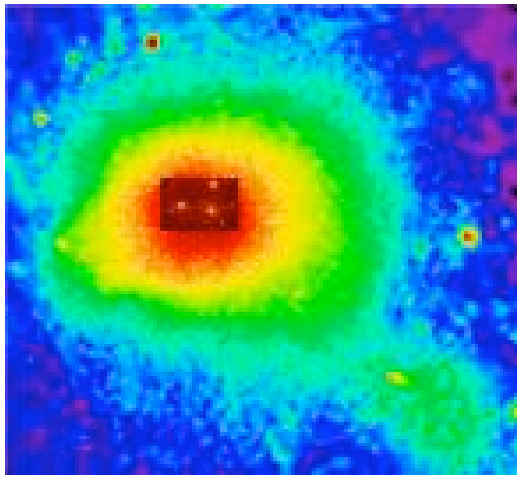
Let's consider galaxies





rotating





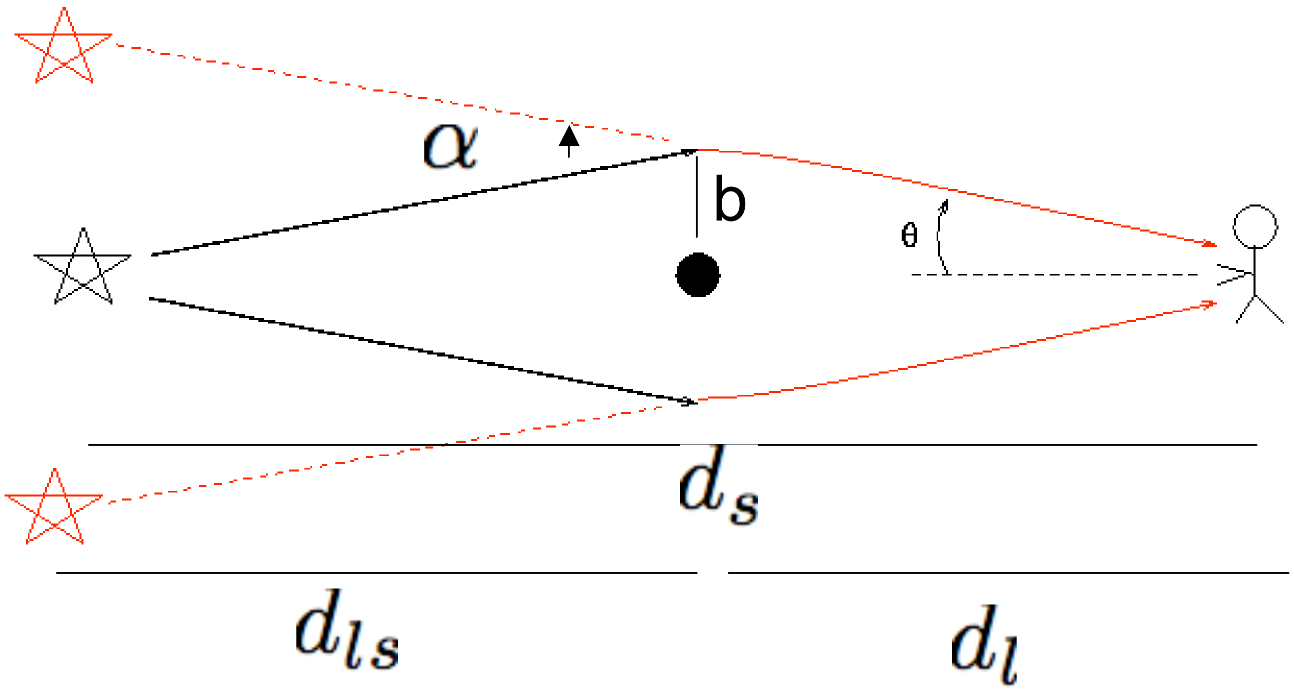
And clusters: Xrays

$$K.E. \sim \frac{3}{2}kT = \frac{3}{2}m_H\sigma_v^2$$

$$T \sim 6 \times 10^7 K; \lambda \sim \frac{c}{\nu} = \frac{ch}{KT}$$

Gravitational lensing

Gravitational lensing

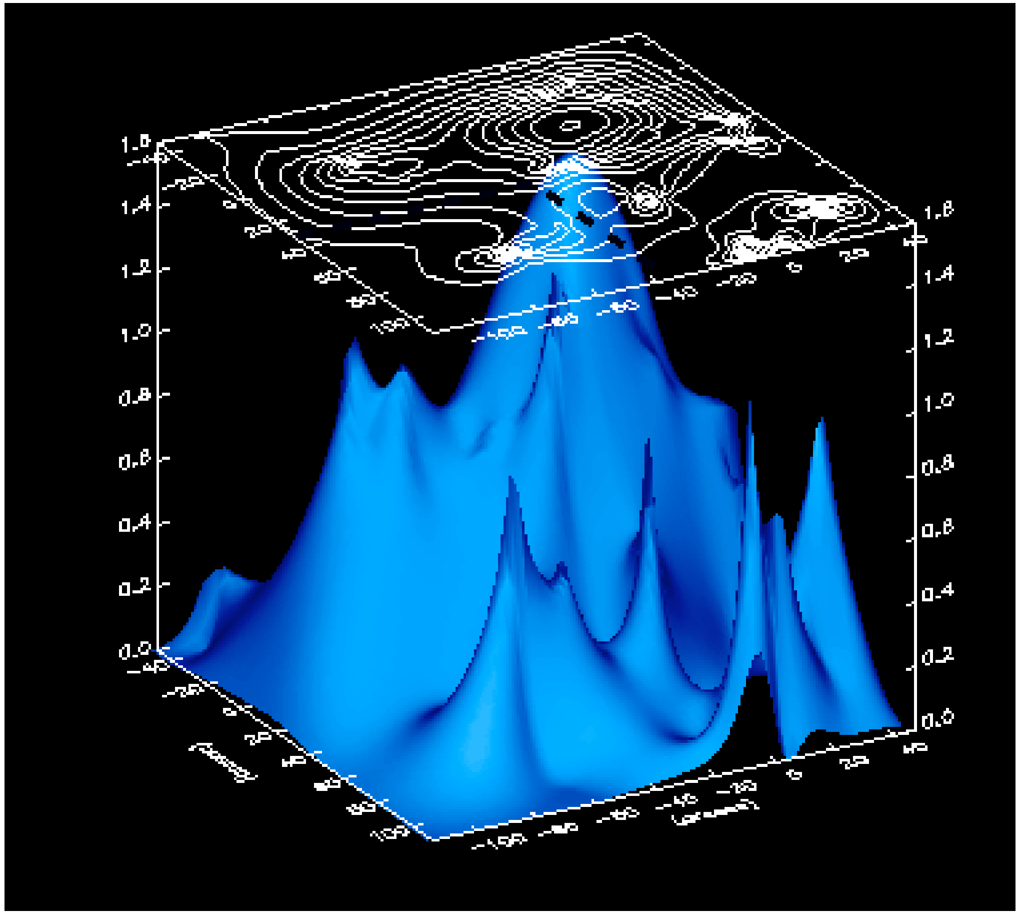


$$\alpha = \frac{4GM}{bc^2}$$

$$\begin{aligned} d_s\theta &= d_{ls}\alpha \\ b &= \theta d_l \\ \theta^2 &= \frac{4GM}{d_l c^2}\frac{d_{ls}}{d_s} \end{aligned}$$

HA!

Reconstructed dark matter distribution of cluster Abell 2218

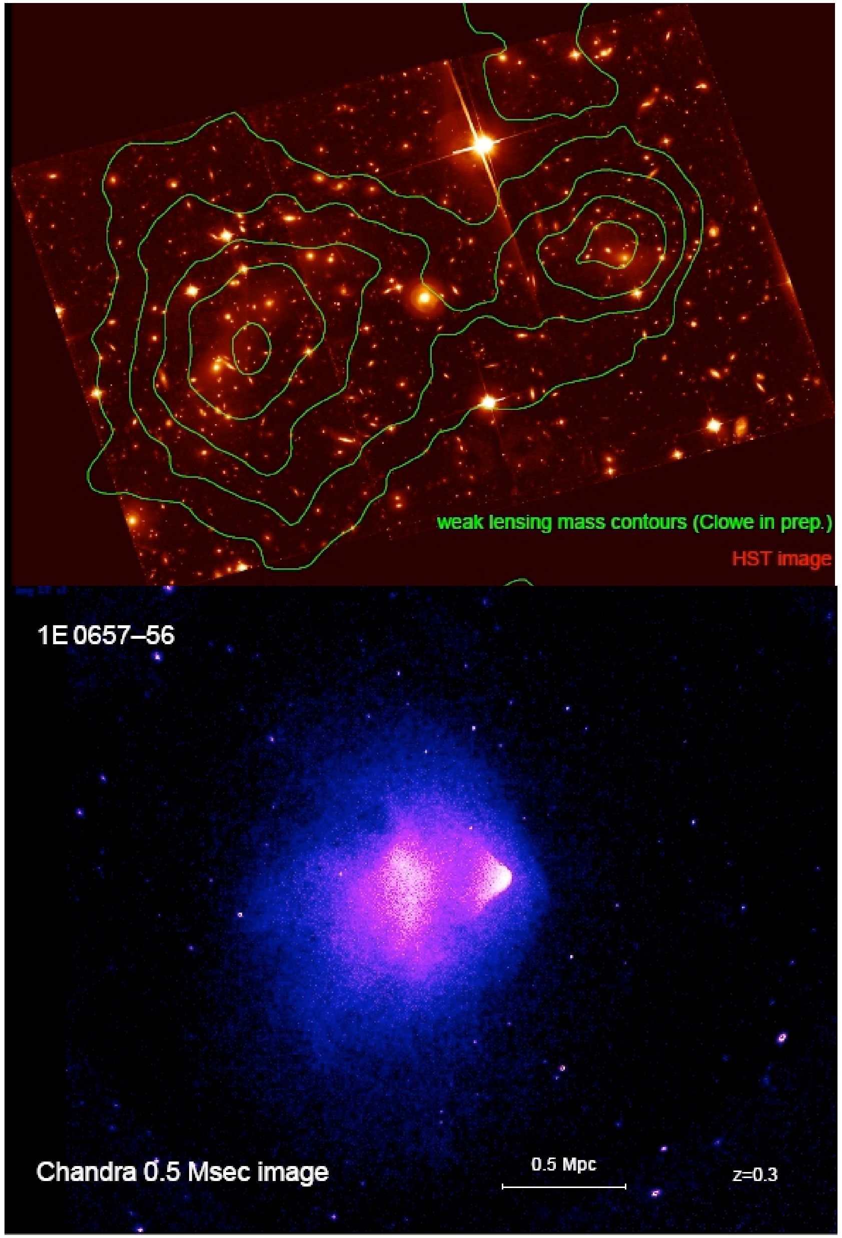


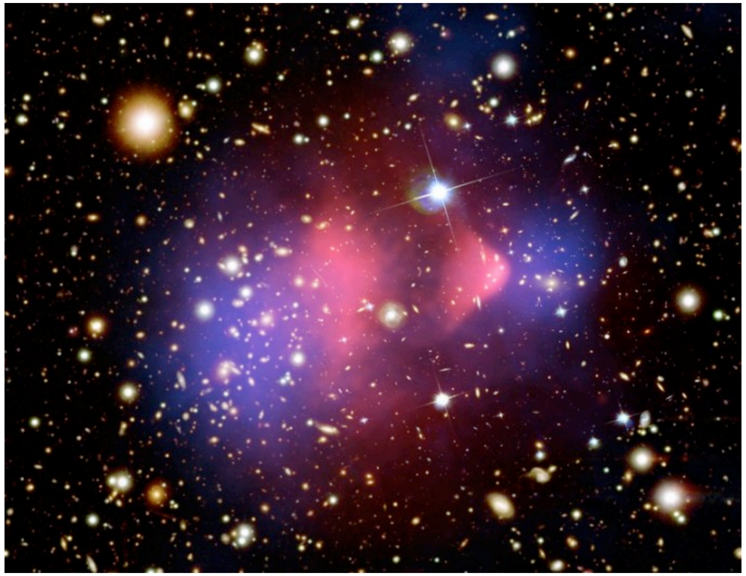
Abell 2218

New evidence

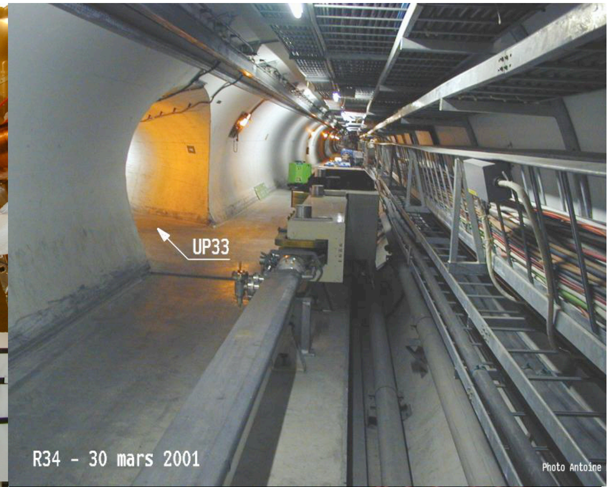
REAL DATA!

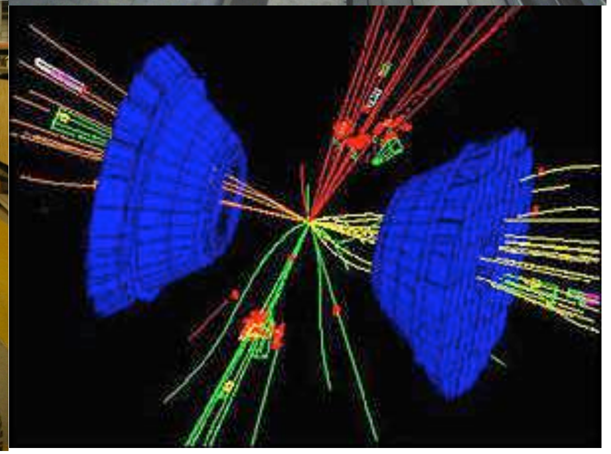
Bullet cluster

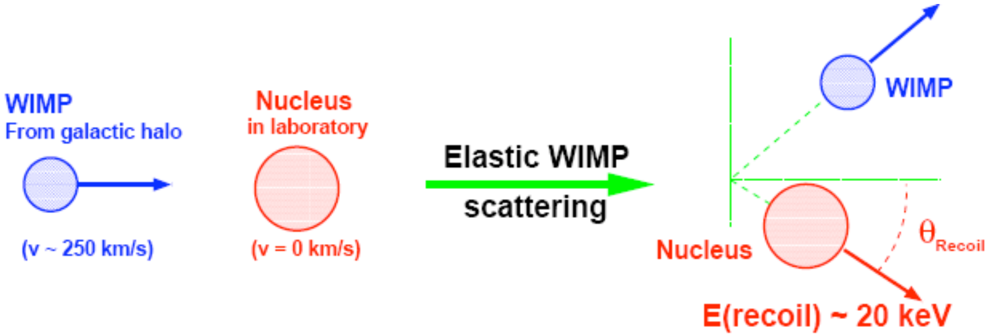




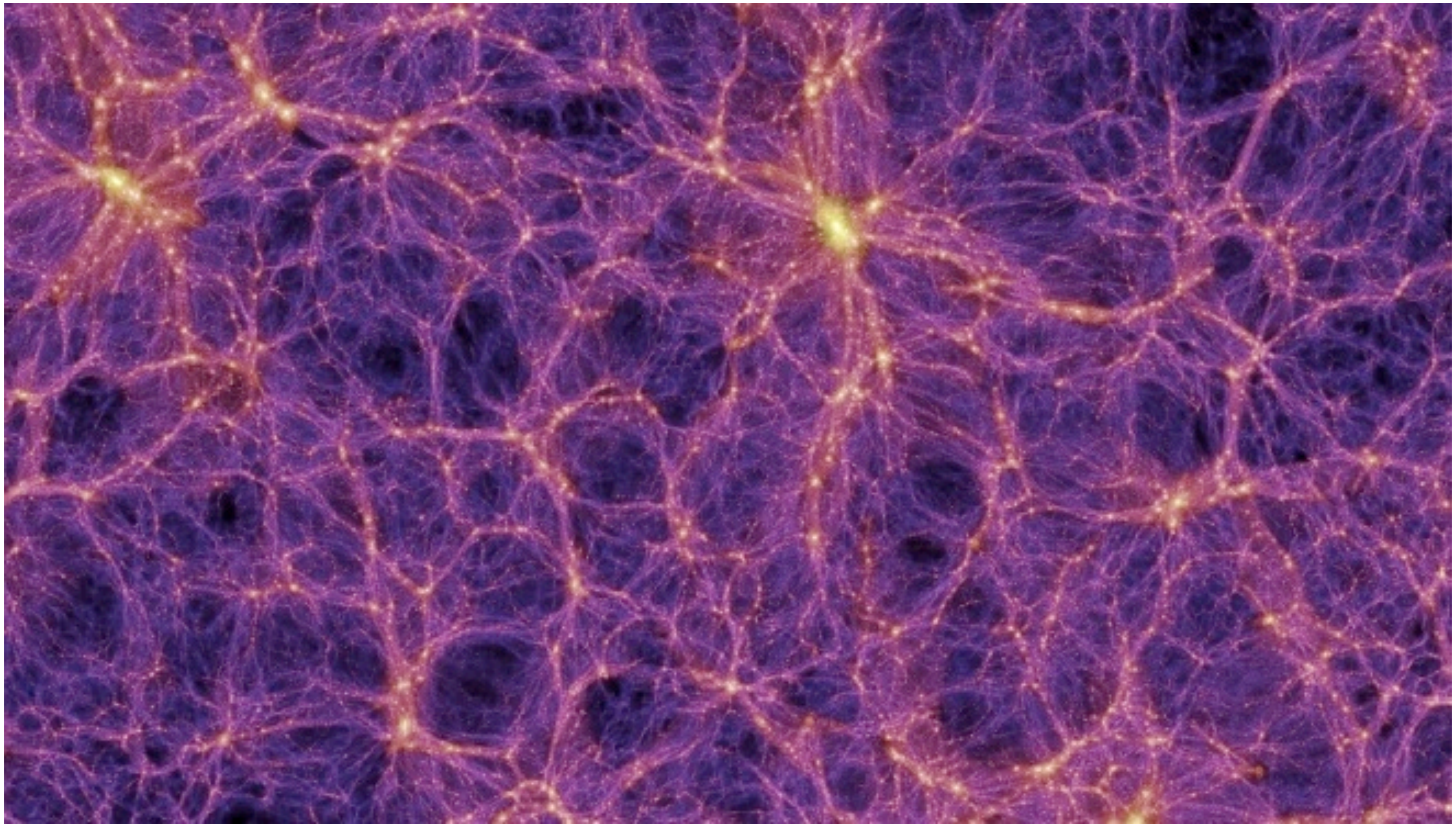
DIY dark matter

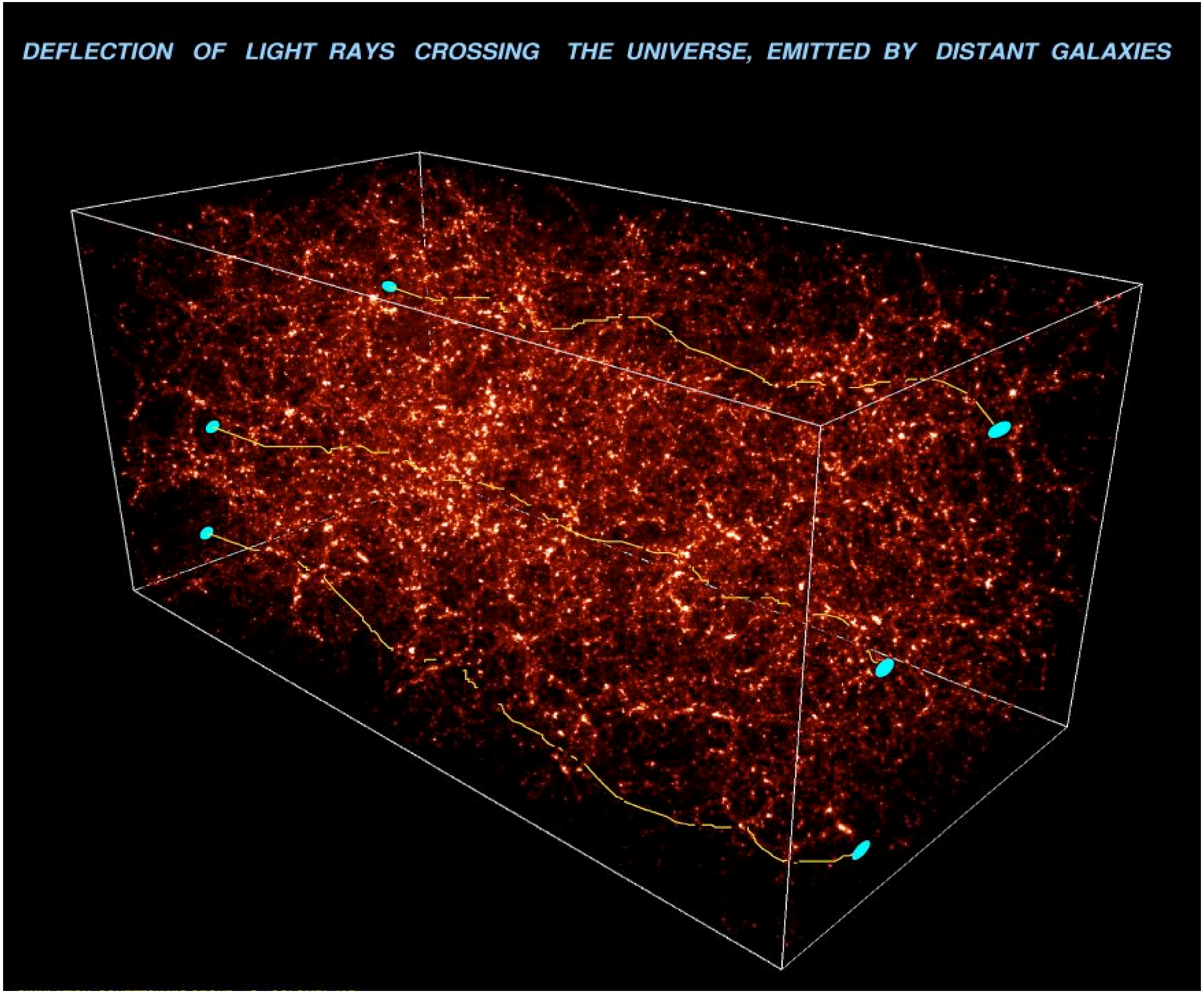




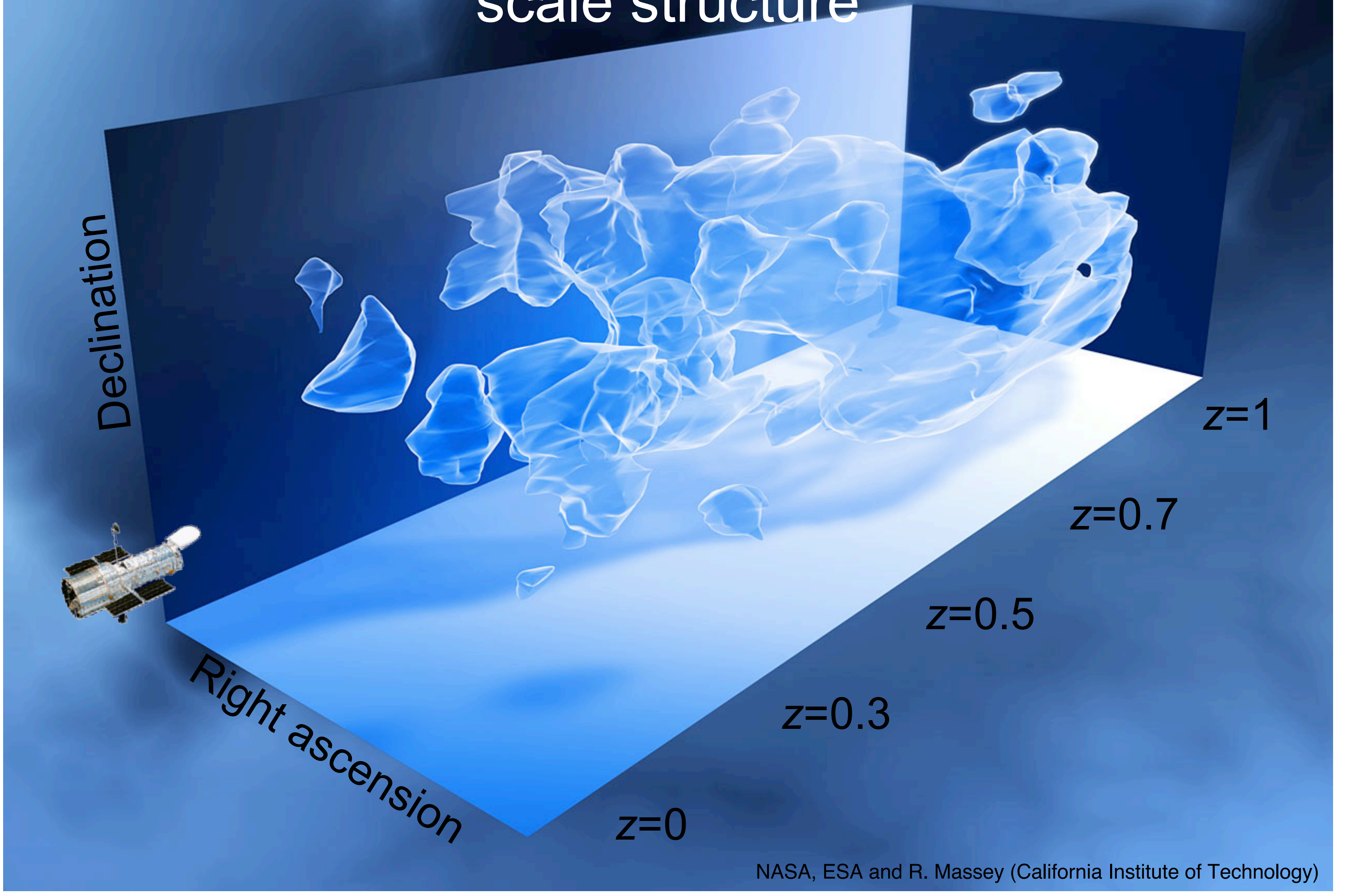


Computer simulation of dark matter distribution




DEFLECTION OF LIGHT RAYS CROSSING THE UNIVERSE, EMITTED BY DISTANT GALAXIES

Weak lensing reconstruction of dark matter large-scale structure



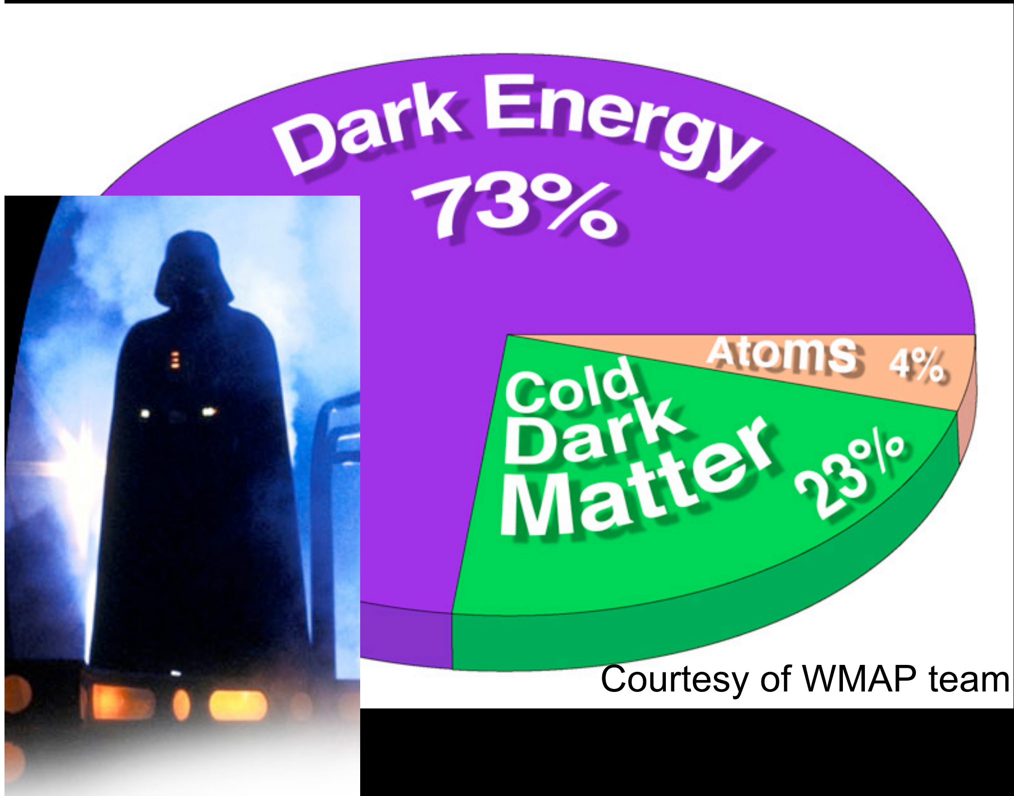
NASA, ESA and R. Massey (California Institute of Technology)

Key concepts today

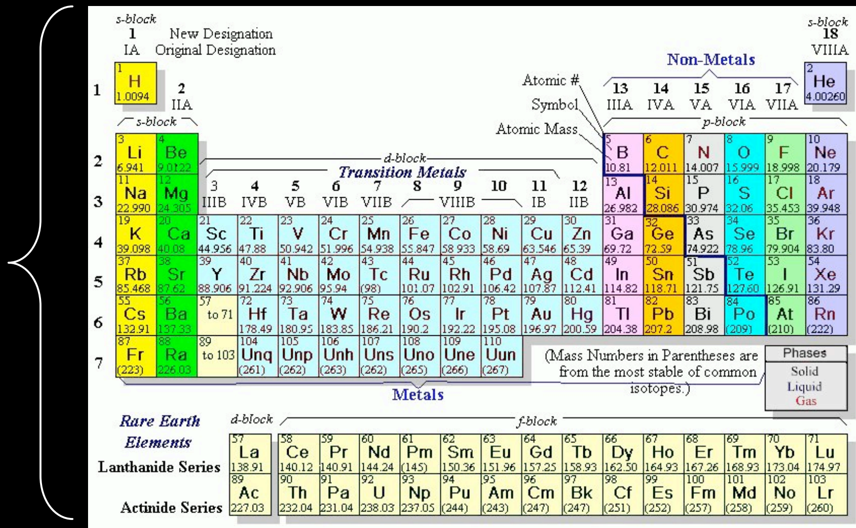
The expansion of the Universe
Hubble's Law
Redshift
Geometry
FRW metric
Universe composition and background evolution

Take a good look at: http://arxiv.org/pdf/astro-ph/9905116v4
Play with icosmo

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



Courtesy of WMAP team



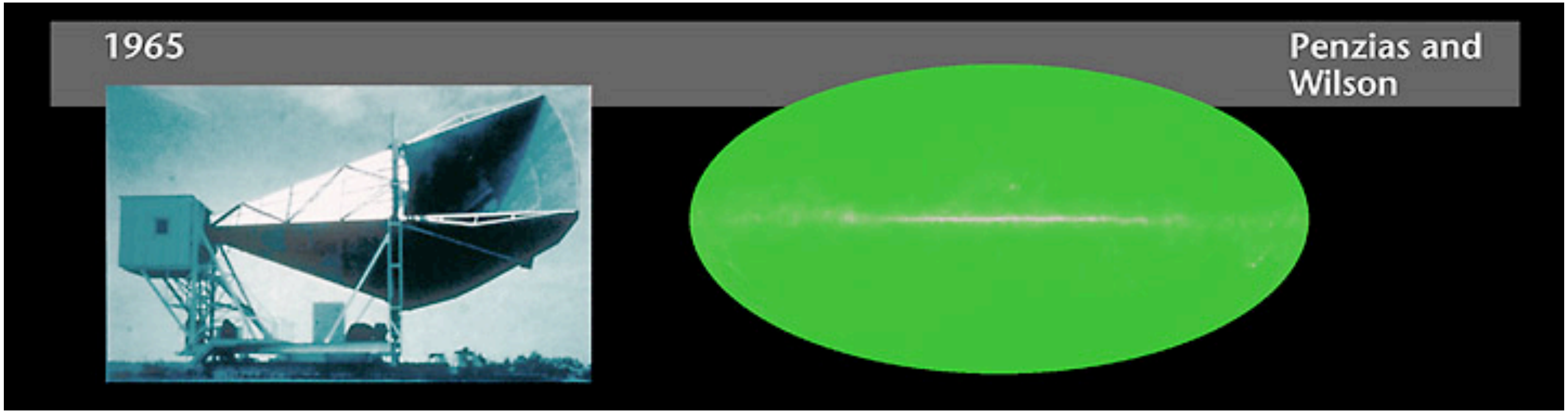
+radiation….

(yeah yeah… +neutrinos)

We do not know what 96% of the Universe is !

Radiation dominated the Universe at early time!

Radiation.....



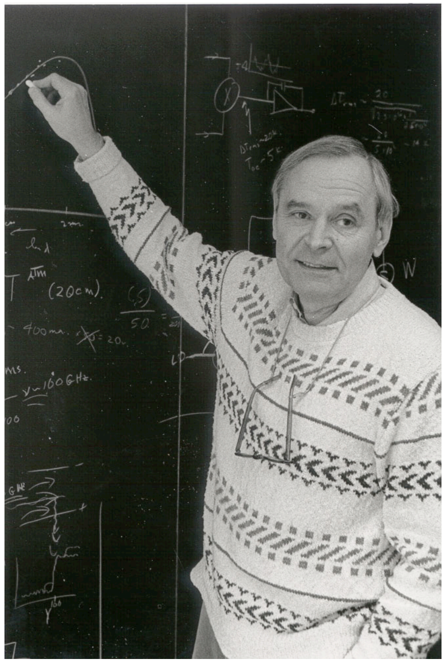
Two engineers for Bell Labs accidentally discovered the CMB radiation, as a **uniform** glow across the sky in the radio part of the spectrum, in 1965. It is the blackbody emission of hot, dense gas (T~3000 K, λ_{max}~1000 nm) red-shifted by a factor of 1000, to a peak wavelength of 1 mm and T~3K.

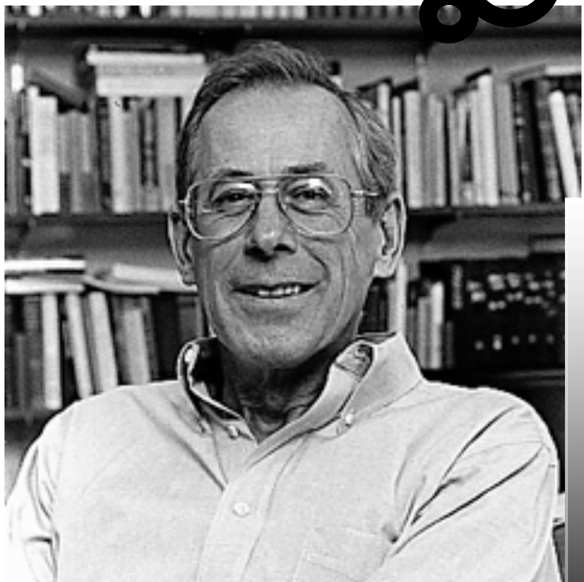
Nobel prize 1978

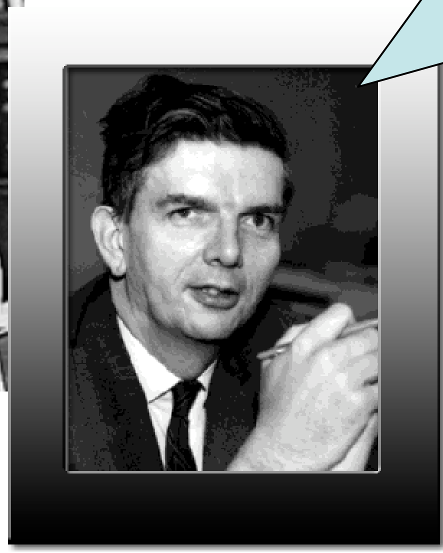
Some history

1965

Penzias & Wilson







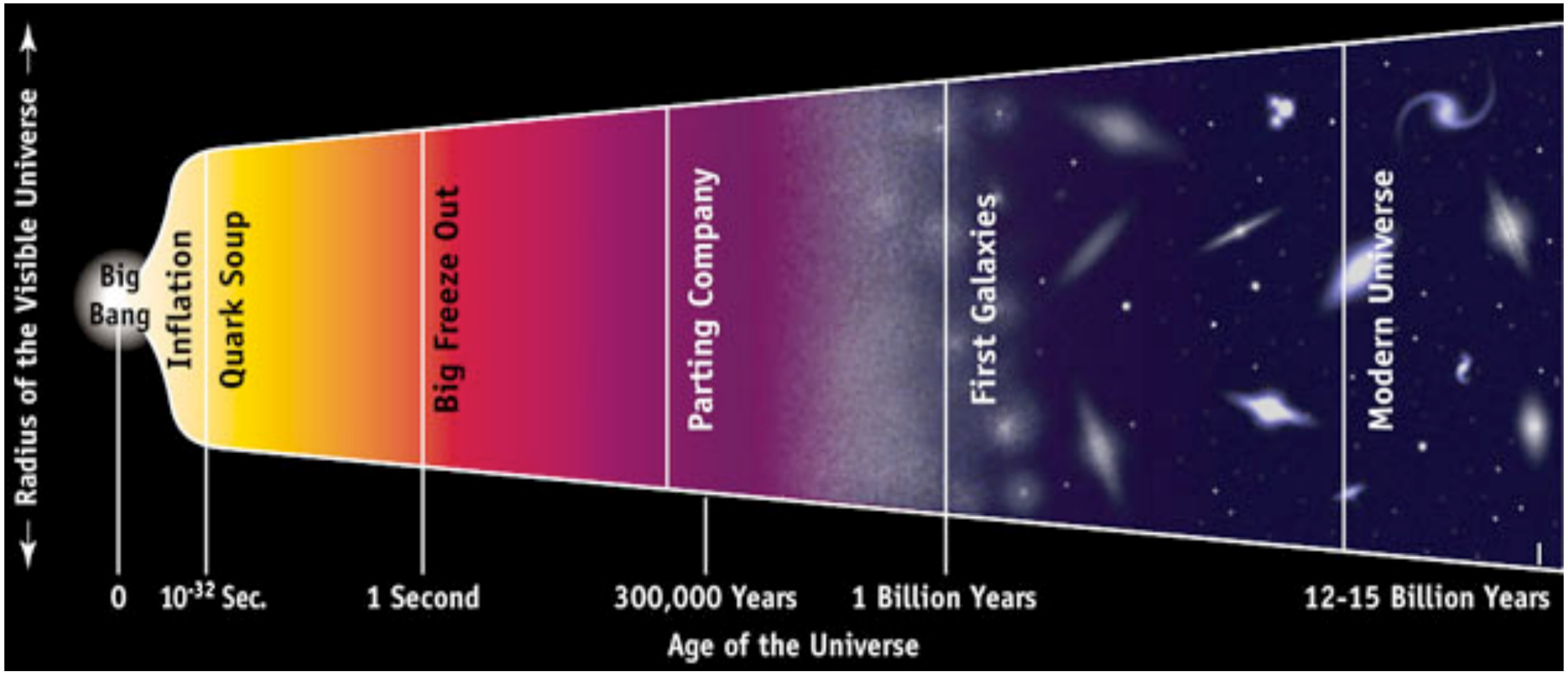
Well boys, we have been scooped

With Roll

The universe cools as it expands; the stretching of light results in a reduction of temperature (think Wien's Law).

If the universe is large, cool, and expanding today, it must have been smaller, warmer, and expanding in the past.

This leads to the cosmic microwave background.

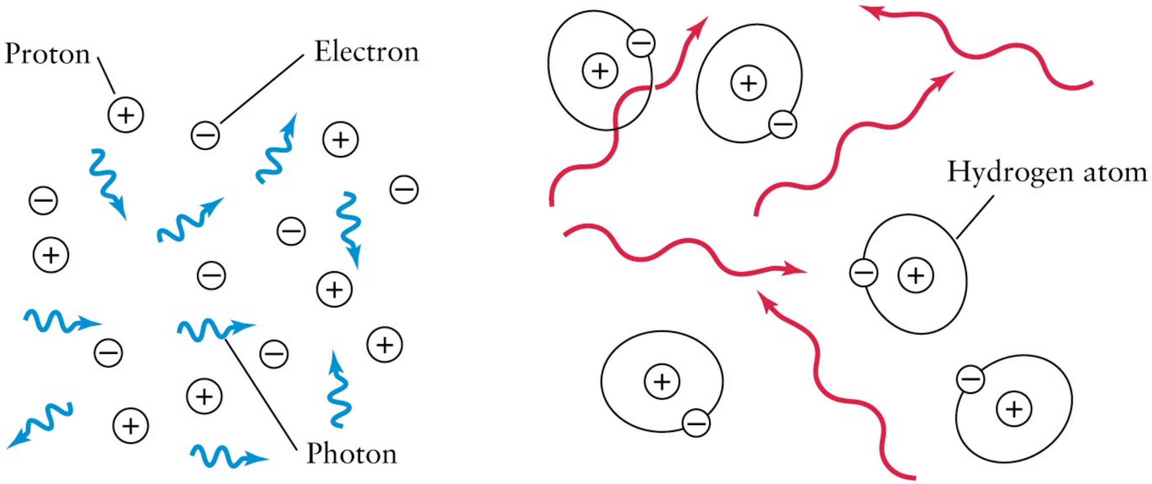


The cosmic microwave background (CMB) radiation

Regular hydrogen gas lets light pass through more or less unimpeded. This is the case today, where the hydrogen gas is either cold and atomic, or very thin, hot, and ionized.

But in the early universe, when it was much warmer, the gas would have been ionized, and the universe opaque to light—as if you were in a dense fog.

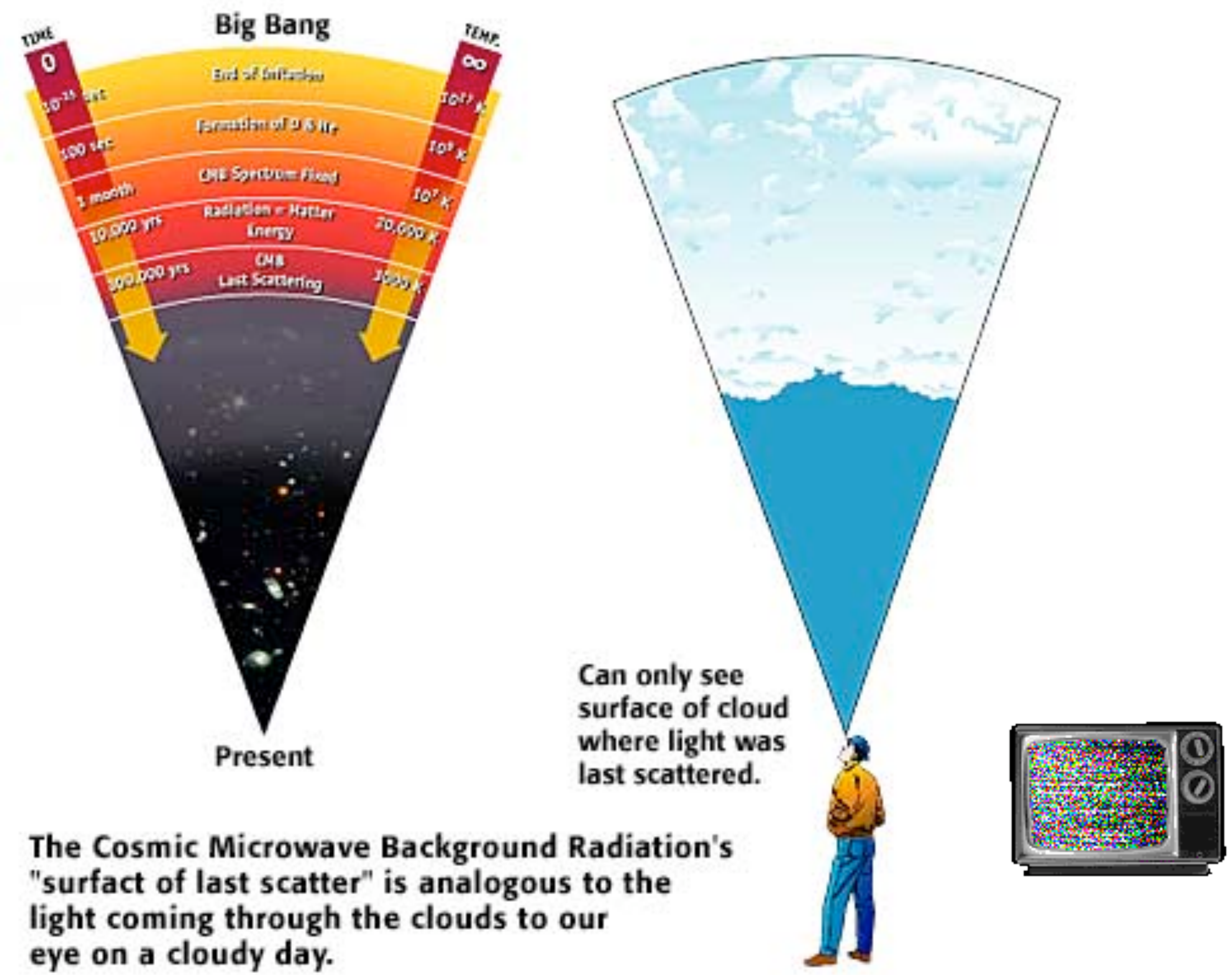
As the universe cooled, the electrons and protons "recombined" into normal hydrogen, and the universe suddenly became transparent.



a Before recombination

b After recombination

The last scattering surface: a snapshot of the early universe

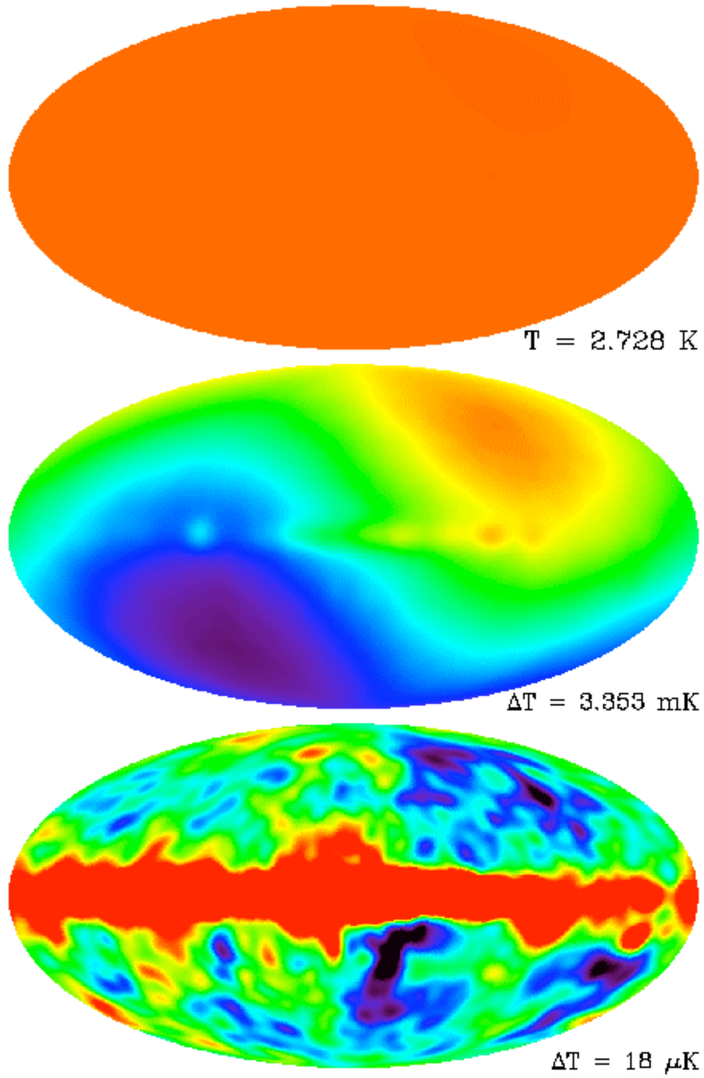


THREE IMPORTANT RESULTS (see Bersanelli Lectures)

•Penzias & Wilson saw only a uniform glow…

•Later, Doppler shift from Milky Way's motion seen; the Galaxy is moving towards Hydra/Centaurus at 620 km/s…

•Only in 1992 was any nonuniformity in the CMB observed—and then only about 10^{-5} K worth.



Another Nobel prize (2006)

Clustering and gravitational instability

If the Universe is homogeneous and isotropic on large scales $\bar{\rho} = \langle \rho \rangle = \frac{1}{V} \int_V \rho \, d^3 r$

Dark matter

$$\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}}; \quad \text{where} \;\; \rho(r,t),\; \bar{\rho}(t)$$

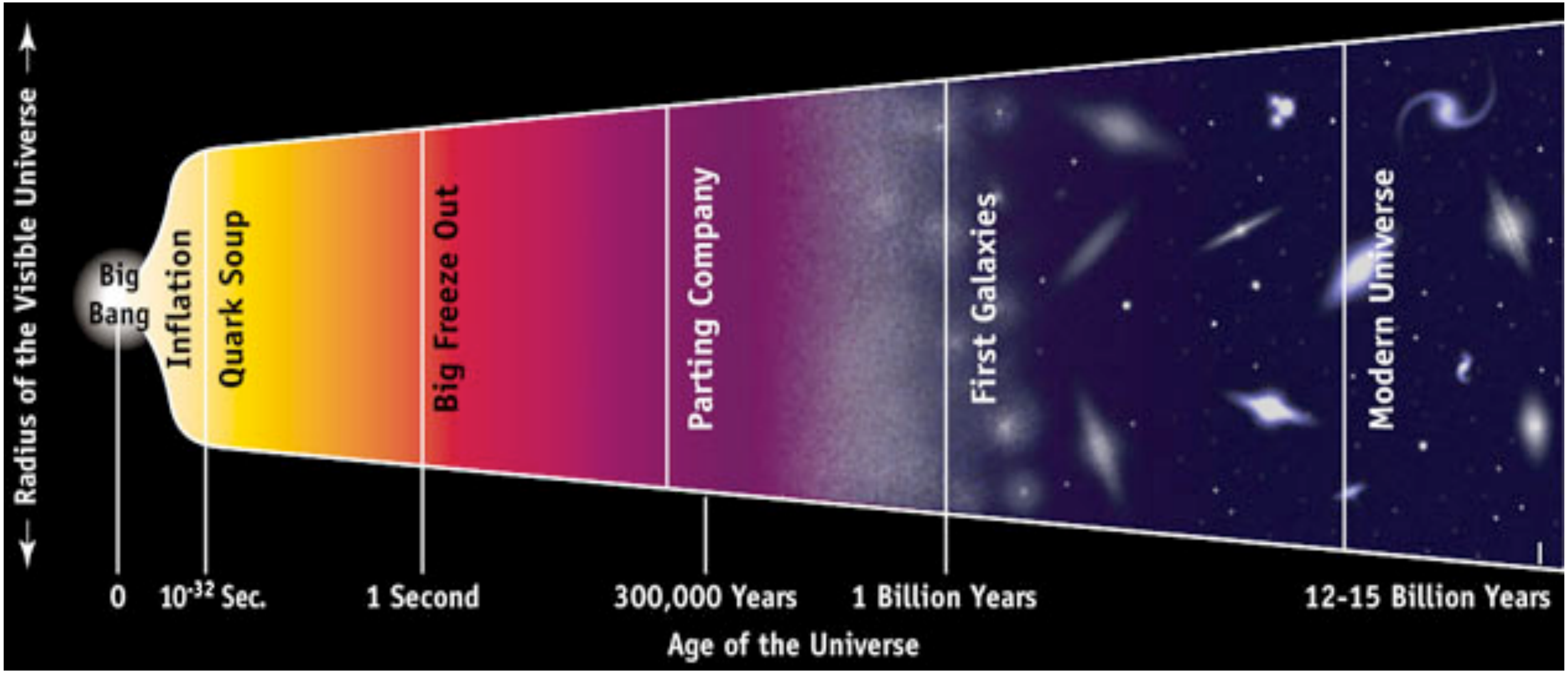
$$\begin{aligned} \rho_0 &= 0.3\rho_{c,0} = 3 \times 10^{-27} kg/m^3 \\ \delta_{you} &= 2 \times 10^{30} \end{aligned}$$

How did we get there from an almost uniform distribution?

Recall Penzias and Wilson!!!!

This has puzzled cosmologists for decades and (with hindsight)
Is one of the crucial evidences for DARK MATTER
(and dark energy)

Structure formation

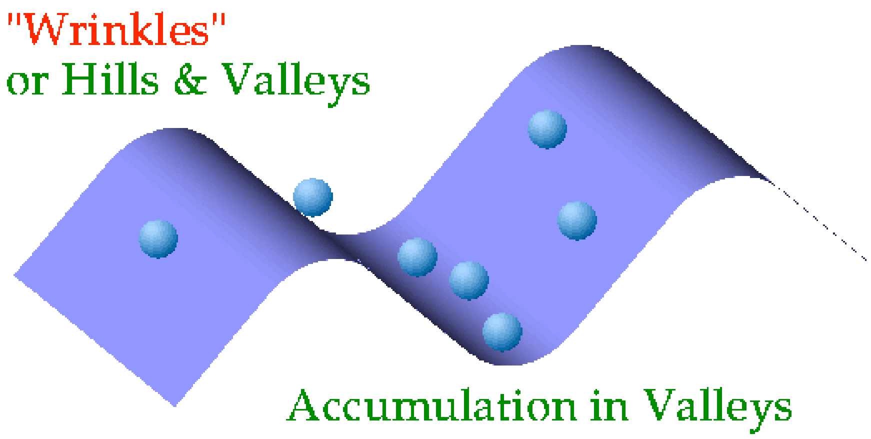


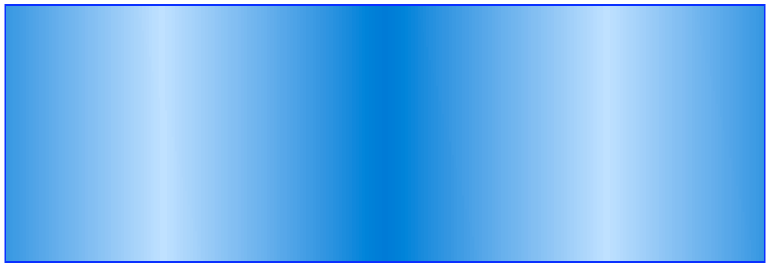
BUT FIRST…

Too difficult…

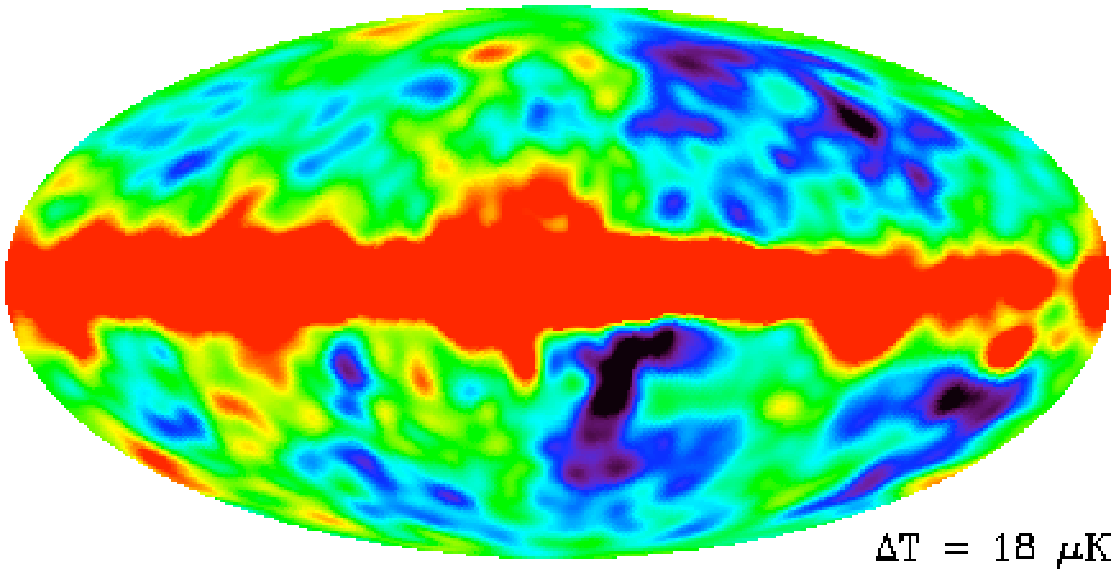
Where do the perturbations come from?

How is that we see the perturbations?





"Top View"

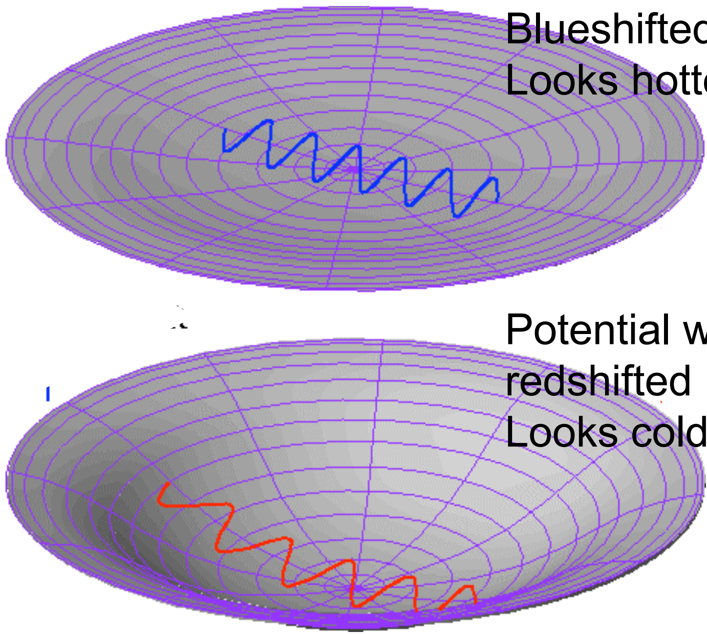


We see them like temperature

On scales larger than a degree, fluctuations were outside the Hubble horizon at decoupling

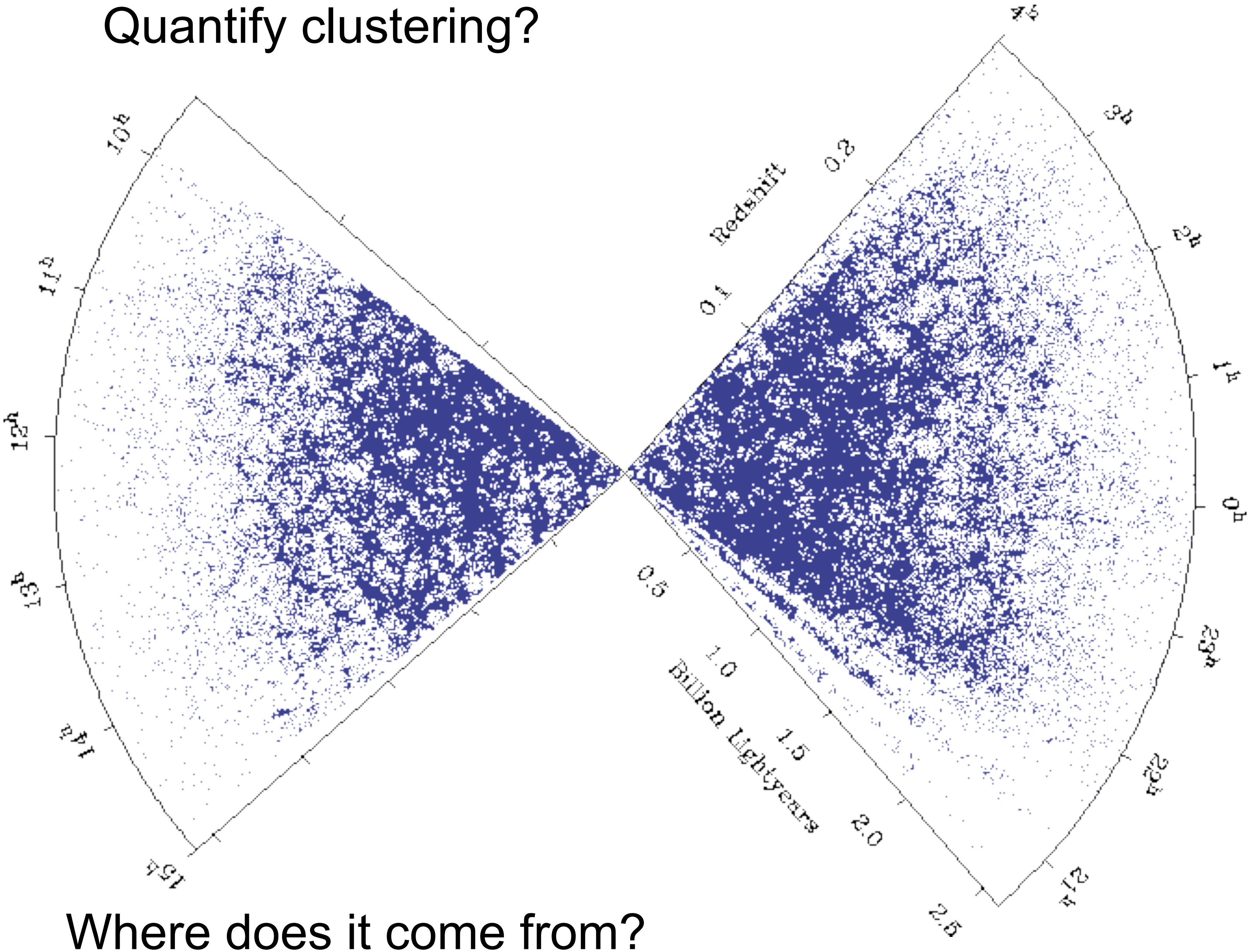
Photons need to climb out of potential wells before they can travel to us (redshift or blueshift) $h\nu/c^2\delta\phi$

$$\frac{\delta T}{T} = \frac{1}{3}\frac{\delta\phi}{c^2} \longleftarrow \text{Given by } \delta\rho$$



Back to this later

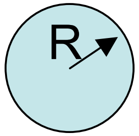
Is there information in the clustering?
Quantify clustering?



Where does it come from?

THE GROWTH OF PERTURBATIONS

Take $\rho = \bar{\rho}(1+\delta)$ Assume a static background for now



$$\Delta M_{inside} = \frac{4\pi}{3} R^3 \bar{\rho}\delta \qquad \ddot{R}(t) = -\frac{G\Delta M}{R^2} = -\frac{4\pi}{3} G R \bar{\rho}\delta(t)$$

$$\frac{\ddot{R}}{R} = -\frac{4\pi}{3} G\bar{\rho}\delta(t)$$

Use extra info:
Mass conservation

$$M = \frac{4\pi}{3}\bar{\rho}(1+\delta)R^3 = const$$

$$(1+\delta)R^3 = const$$

$$R = R_0(1+\delta)^{-1/3} \sim R_0(1-\frac{1}{3}\delta)$$

$$\delta \ll 1$$

$$\ddot{R} = -\frac{1}{3}R_0\ddot{\delta} \sim -\frac{1}{3}R\ddot{\delta}$$

$$\ddot{\delta} = 4\pi G\bar{\rho}\delta \Rightarrow \delta = A_1 e^{t/t_{Dyn}} + A_2 e^{-t/t_{Dyn}}$$

$$t_{Dyn} = \frac{1}{(4\pi G\bar{\rho})^{1/2}}$$

Dynamical time depends on $<\rho>$ not on R

For air? (1kg/m^3) 9hr… tornados????

PRESSURE & sound speed

$$P = w\rho c^2;\ c_s \equiv \left(\frac{dP}{d\rho}\right)^{1/2} = \sqrt{w}c$$

$$t_{press} \sim \frac{R}{c_s}$$

Cs for air 300km/s

Jeans Length

$$t_{dyn} = t_{press}$$

$$\boxed{\frac{1}{\sqrt{\bar{\rho}G}} \sim \frac{\lambda_J}{c_s}}$$

Overdense regions larger than Jeans length can collapse, smaller than that… oscillations (sound).

Jeans length for air .. 10^5 km… sound waves are stable

$$\lambda_J = 2\pi c_s t_{dyn}$$

$$\lambda_J = 2\pi c_s t_{dyn};\ t_{dyn} = \sqrt{\frac{1}{4\pi G\bar{\rho}}} \propto H^{-1}$$

For the Universe: $\lambda_J = 2\pi 1.22 \dfrac{c_s}{H(t)}$

Radiation dominated era: $c_s = c/\sqrt{3} \sim 0.6c;\ \lambda_j \sim 3\dfrac{c}{H}$

Inside horizon perturbations are stable! Sound! Implications for CMB?

Baryons(Matter):

$$c_s = \left(\frac{kT}{mc^2}\right)^{1/2} c = 1.5 \times 10^{-5} c$$

Decreases by factor 3×10^5

M_j decreases by $2 \times 10^{14} = 10^5 M_\odot$

Size of a GC, small galaxy!

Expansion cannot be neglected

$$\rho(t) = \bar{\rho}(t)[1+\delta(t)]$$

$$\bar{\rho} \rightarrow a^{-3}$$

$$\ddot{R} = -\frac{GM}{R^2} = -\frac{G}{R^2}\frac{4\pi}{3}\rho R^3 \ldots\ldots$$

$$R(t) \sim \rho(t)^{-1/3}(1-\frac{1}{3}\delta) \sim a(t)(1-\frac{1}{3}\delta)$$

$$\dot{R} = \dot{a}(1-\frac{1}{3}\delta) - \frac{a}{3}\dot{\delta}$$

$$\ddot{R} = \ddot{a}(1-\frac{1}{3}\delta) - 2\frac{\dot{a}}{3}\dot{\delta} - \frac{a}{3}\ddot{\delta}$$

$$= \ddot{a} - \ddot{a}\frac{\delta}{3} - \frac{2}{3}\dot{a}\dot{\delta} - \frac{a}{3}\ddot{\delta}$$

$$\frac{\ddot{R}}{R} = \frac{\ddot{a}(1-\frac{1}{3}\delta) - \frac{2}{3}\dot{\delta}\dot{a} - \frac{a}{3}\ddot{\delta}}{a}(1+\frac{1}{3}\delta)$$

$$\simeq \frac{\ddot{a}}{a} - \frac{1}{3}\ddot{\delta} - \frac{2}{3}\frac{\dot{a}}{a}\dot{\delta} = -\frac{4}{3}\pi\bar{\rho}(1+\delta)$$

$$\frac{\dot{a}}{a} \rightarrow H$$

if $\delta = 0$ $\quad \frac{\ddot{a}}{a} = -\frac{4\pi G\bar{\rho}}{3}$

Ok, we knew that
But we can use it

$$\boxed{\ddot{\delta} + 2H\dot{\delta} - \frac{3}{2}\Omega_m H^2\delta = 0}$$

Study solutions!

Evolution of perturbations

$$\ddot{\delta} + 2H\dot{\delta} - \frac{3}{2}\Omega_m H^2 \delta = 0$$

Radn dominated era

$$if\ \Omega_m \ll 1\ H = \frac{1}{2t}\ \delta \text{ grows logaritmically}$$

Λ dominated era

$$if\ \Omega_\Lambda \gg \Omega_m \ll 1\ \ H = H_\Lambda \longrightarrow \delta = C_1 + C_2 \exp[-2H_\Lambda t]$$

Only when matter dominates perturbations grow

$$\delta(t) \sim D_1 t^{2/3} + D_2 t^{-1}$$

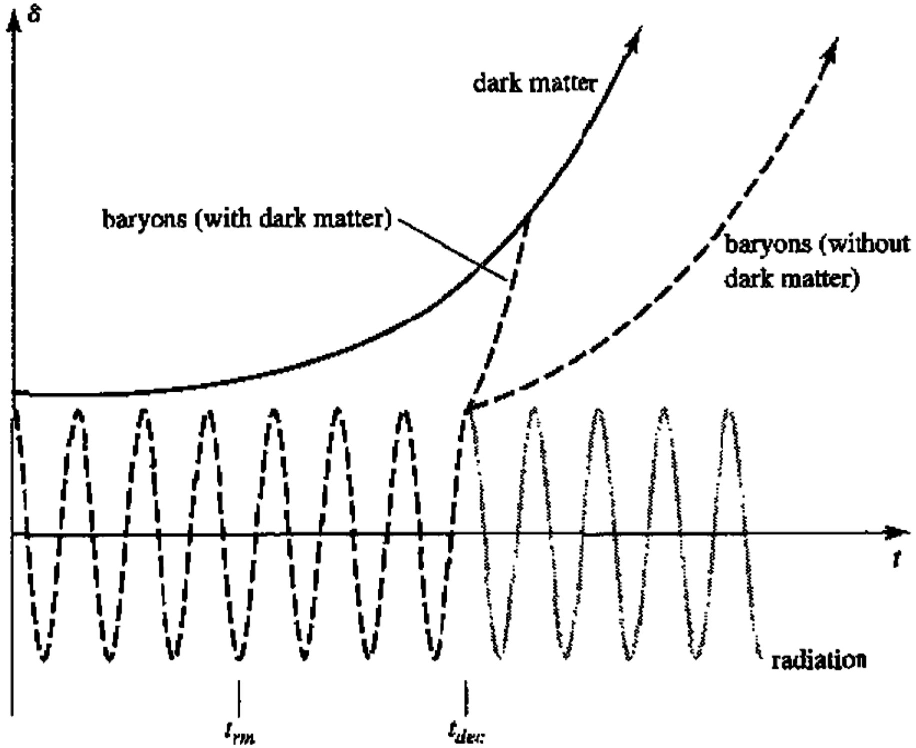
Decaying, neglect

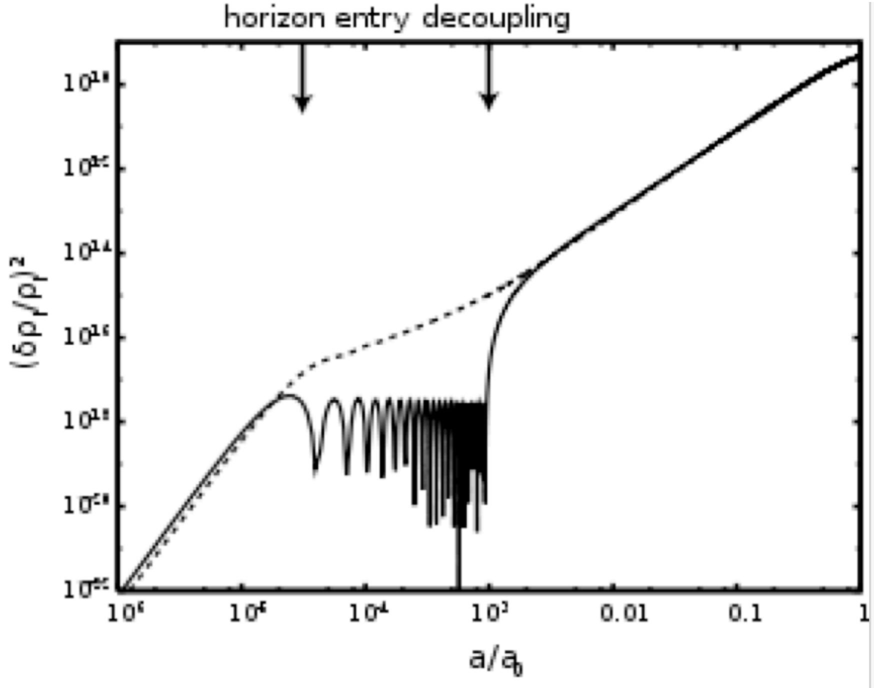
$$\delta(t) \propto t^{2/3} \propto a(t) \propto \frac{1}{1+z}$$

AH!

$$\text{caveat } \delta < 1$$

Schematic of perturbation growth





Can we verify all this?

The power spectrum $$(2\pi)^3 P(\vec{k},t)\delta^D(\vec{k}+\vec{k}') = \langle\hat{\delta}(\vec{k},t)\hat{\delta}(\vec{k}',t)\rangle,$$

Correlation function $$\xi(\vec{r}) = \langle\delta(\vec{x})\delta(\vec{x}+\vec{r})\rangle$$

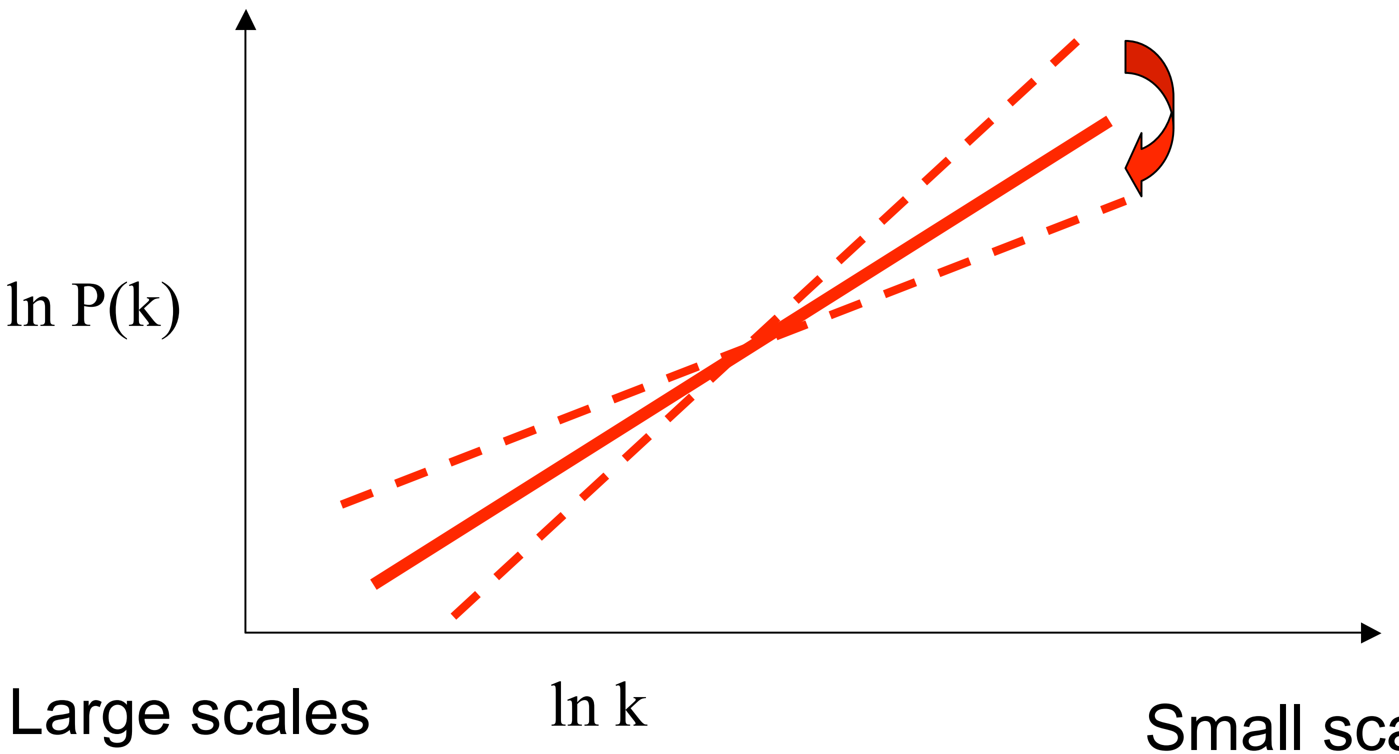
Statistics!

Assume that SOME MECHANISM set out primordial perturbations

Primordial power spectrum$= A\, k^{n}$

Amplitude of the power law

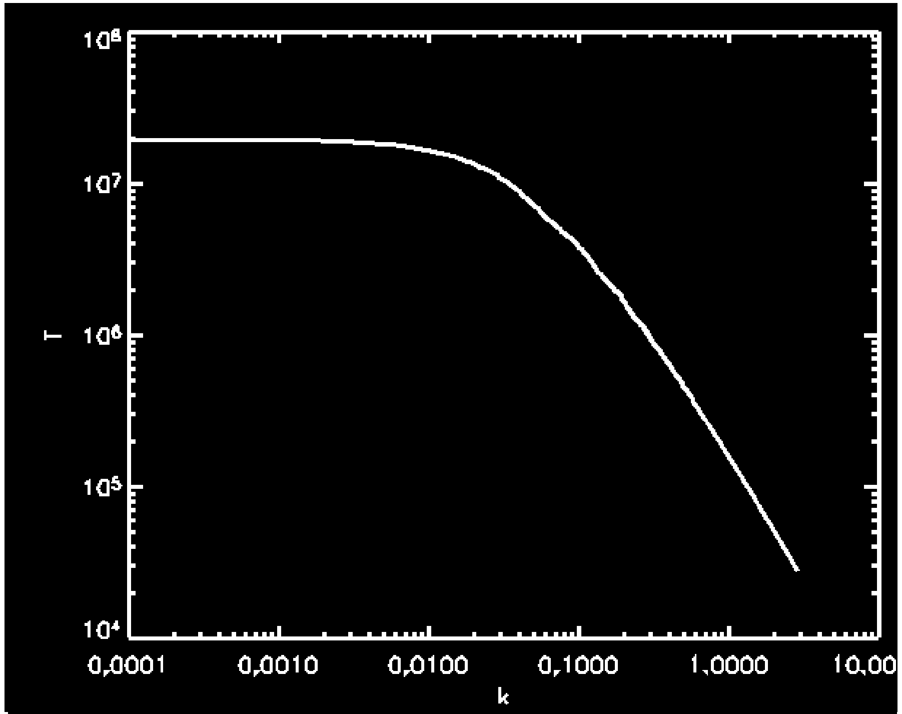
slope



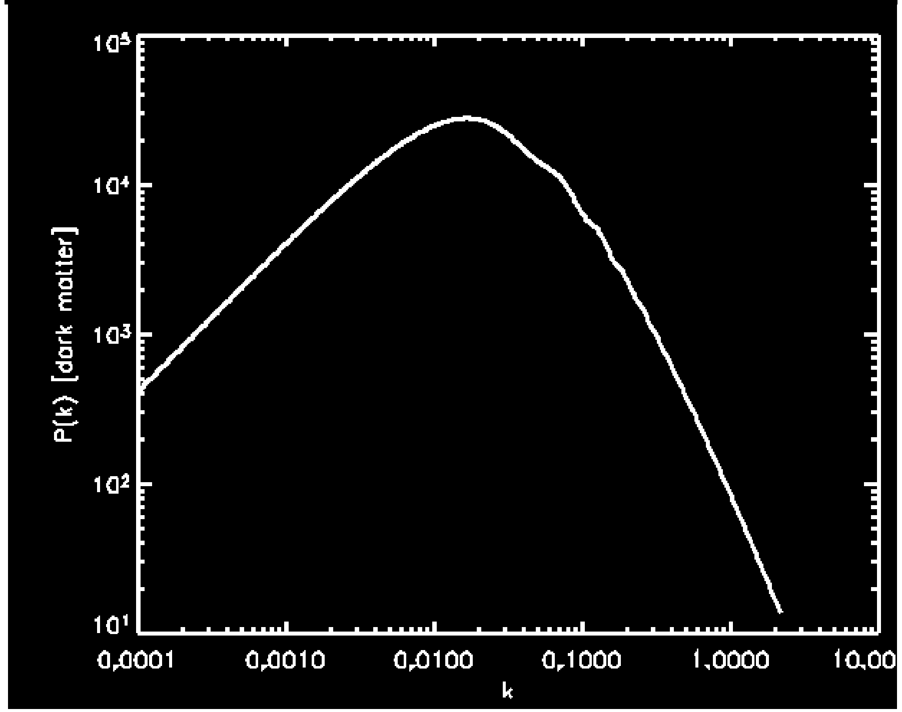
Transfer function

$$P(k)_{final} = P(k)_{primordial} T^2(k)$$

Matter domination



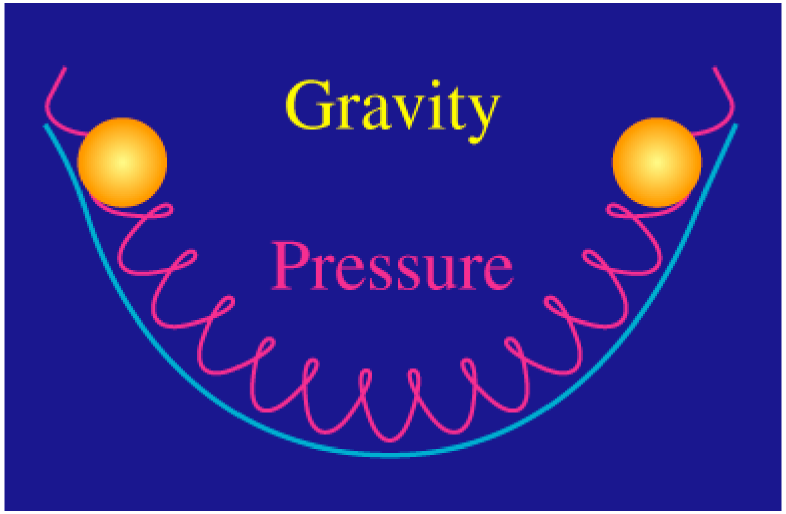
A power law becomes ……



BACK TO THE CMB

We see matter perturbations like temperature…

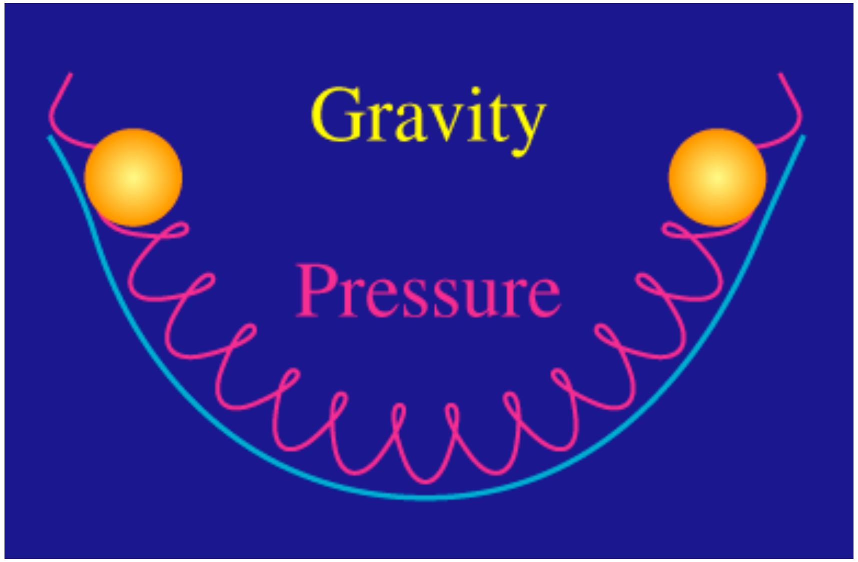
On smaller scales things get more complicated:
baryon and photons were coupled,
and photons oscillate (sound waves)

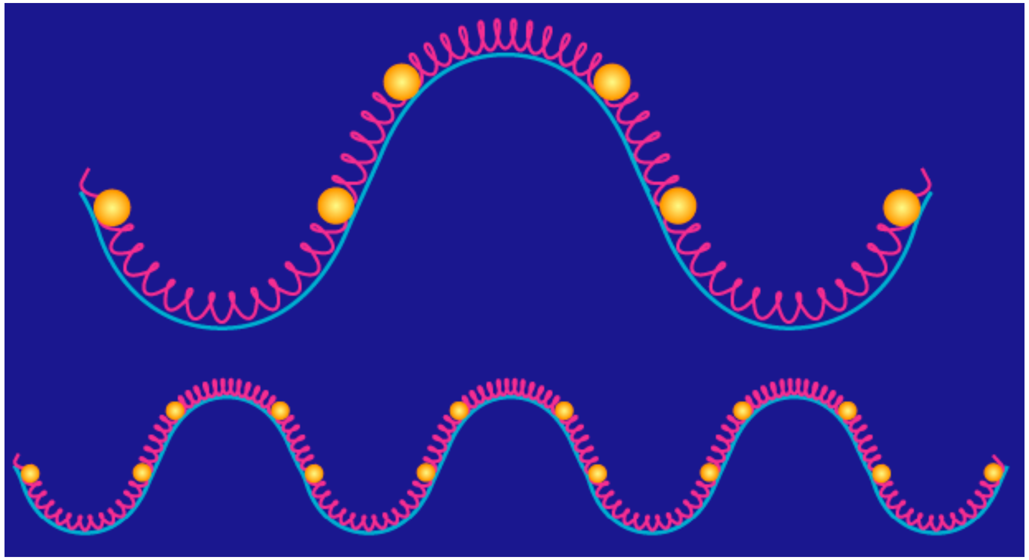


Horizon size at LSS --> Fundamental mode (over tones)

Until the universe is cool enough that H recombines and photons can travel freely to us, giving us a snapshot of the early Universe

There is time between when a perturbation enters the horizon (and starts oscillate)
And decoupling, when oscillations freeze…. And get imprinted in the CMB.





Longer wavelength modes oscillate slower

The frequency of the oscillation is equal to the wavenumber times the speed of sound: $\omega = kc_s$

The largest scales (sound horizon) can only go through a compression,
Smaller scales can go through a compression and a rarefaction
Etc…

Animations courtesy of W. Hu

Cosmology from the CMB?

HOW? ***WHY?***

"Seeing sound" (W. Hu)

Last scattering surface : snapshot of the photon-baryon fluid

On large scales : primordial ripples

What put them there?

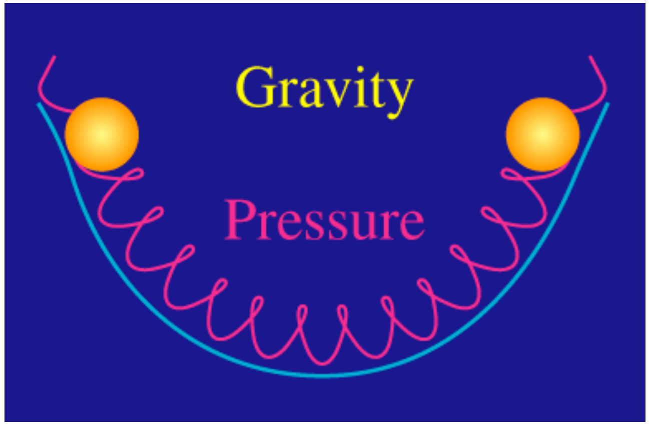
On smaller scales:

Photons radiation pressure

Gravity compression

Sound waves

Stop oscillating at recombination



Horizon size at LSS --> Fundamental mode (over tones)

What's going on

Matter overdensities compress cosmic fluids through gravity

Photons (tightly coupled to the baryons) counteract this

Acoustic oscillations set in

Sound speed is high (photon/baryon high) $c_s = c/3^{1/2}$

Sound horizon $c_s t$ defines a maximum size

Phase correlation:structures of a given size start oscillating together

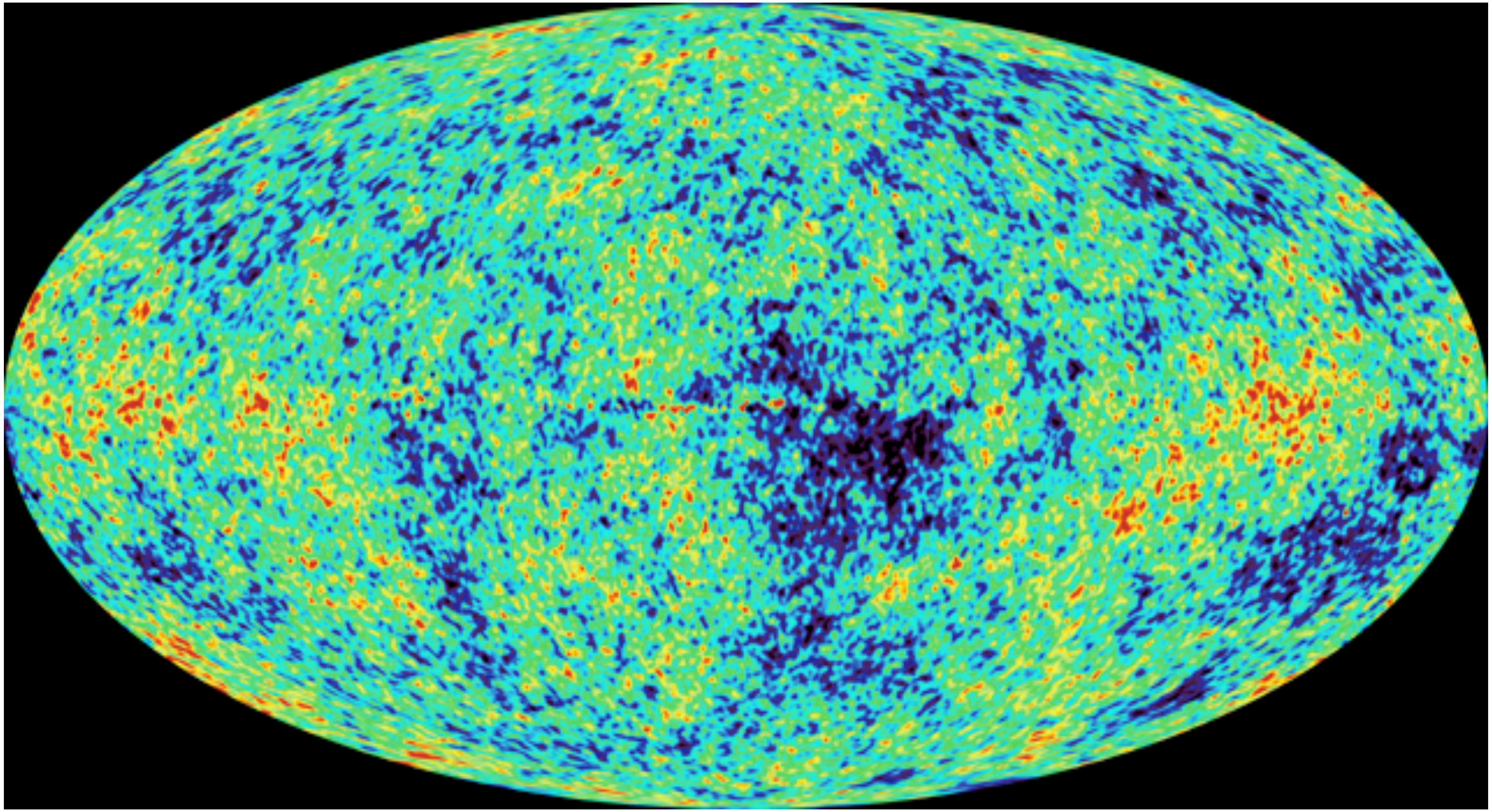
Damping: photons free streaming, finite thickness of LSS

Work of Peebles & Yu, Sunyaev & Zeldovich '70

Can we see this in the sky?

Seeing sound!

Cosmic symphony



Courtesy of WMAP

Power spectrum, again

$$\langle T \rangle = \frac{1}{4\pi} \int T(\theta, \phi) \sin\theta d\theta d\phi = 2.726K$$

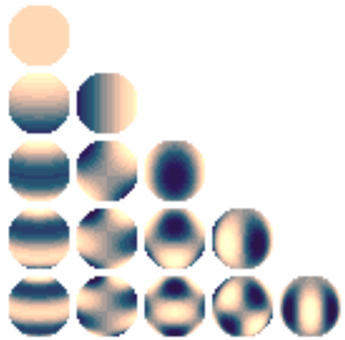
Challenge!

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

rms 1 in 10^5

Even bigger challenge!

Expand in spherical harmonics



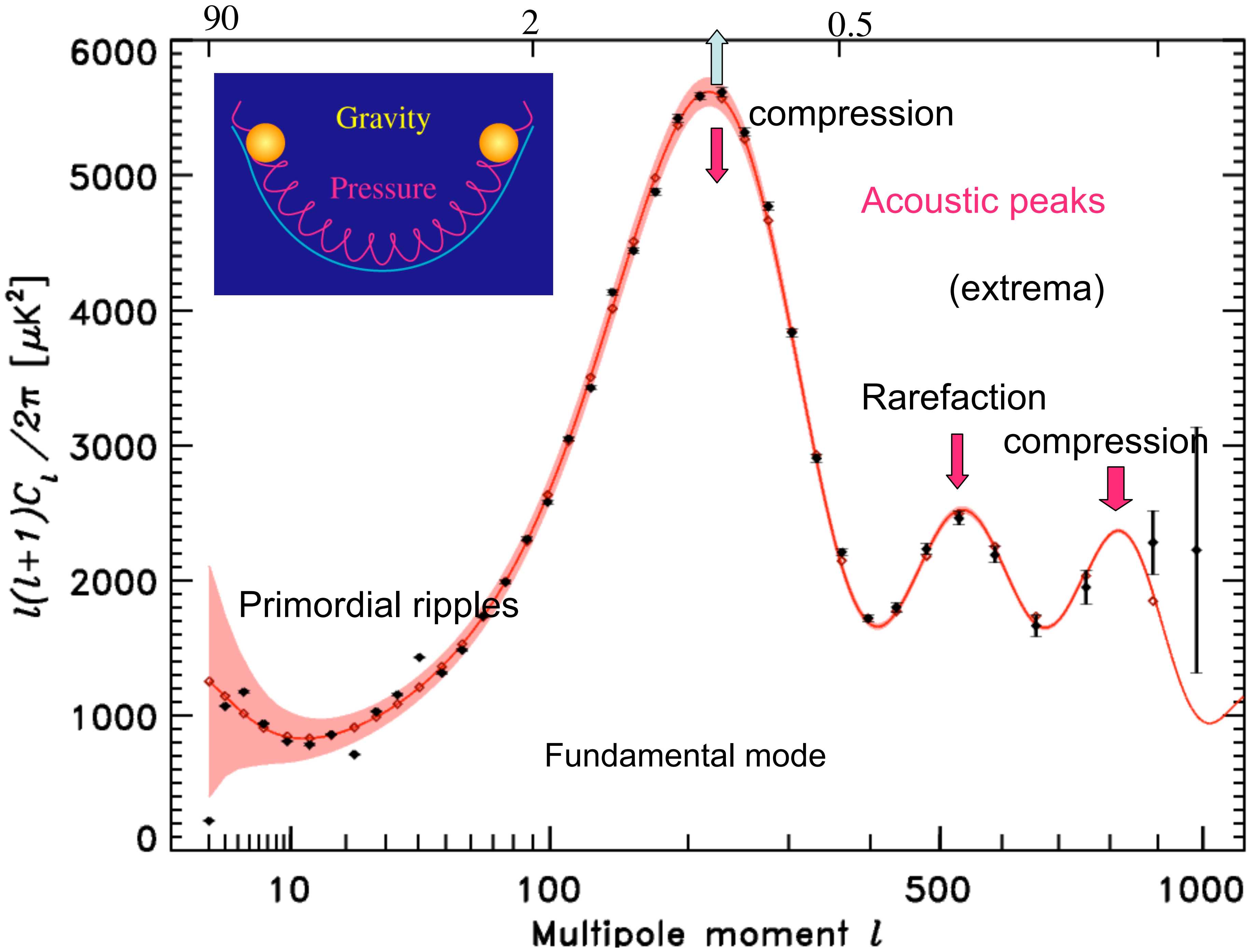
$$\frac{\Delta T}{\langle T \rangle} = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_l^m(\theta, \phi)$$

$$C(\theta) = \langle \frac{\Delta T}{T}(n) \frac{\Delta T}{T}(n') \rangle = \frac{1}{4\pi} \sum_l (2l+1) C_l P_l(\cos\theta)$$

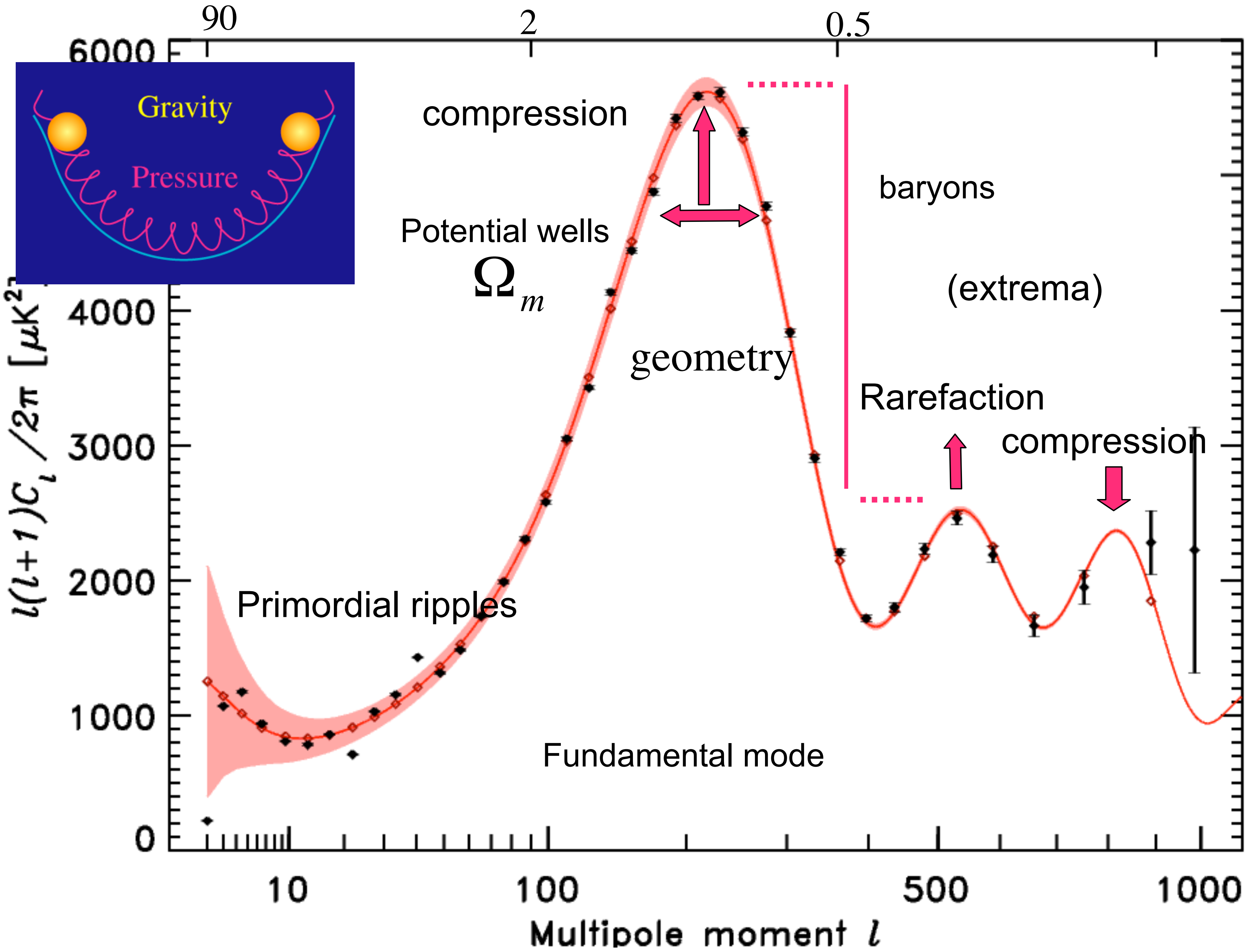
Legendre polynomials

$$C_l = \frac{1}{2l+1} \sum_l |a_{lm}|^2$$

Angular power spectrum

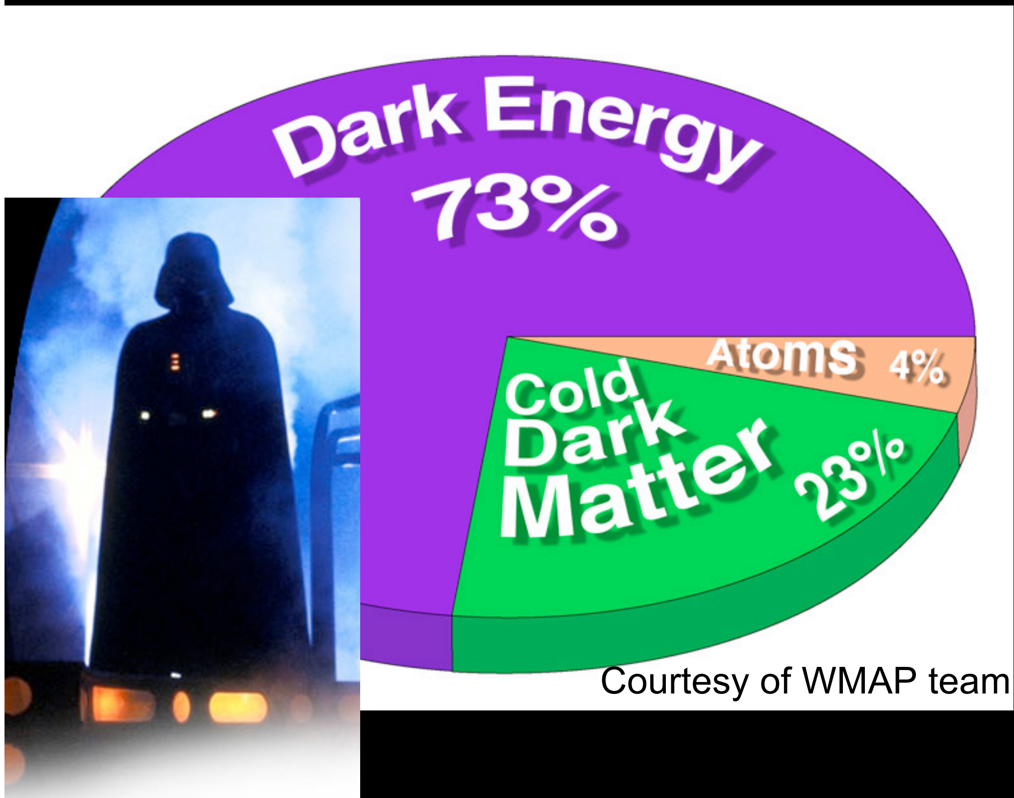


90
2
0.5
6000
5000
4000
3000
2000
1000
0
Gravity
Pressure
compression
Acoustic peaks
(extrema)
Rarefaction
compression
Primordial ripples
Fundamental mode
$l(l+1)C_l/2\pi\ [\mu K^2]$
10
100
500
1000
Multipole moment l

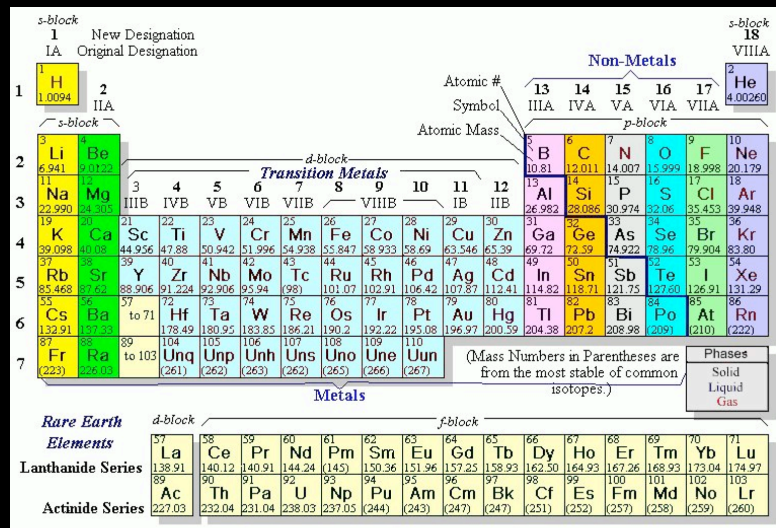


90
2
0.5
6000
5000
4000
3000
2000
1000
0
Gravity
Pressure
compression
Potential wells
Ω_m
geometry
baryons
(extrema)
Rarefaction
compression
Primordial ripples
Fundamental mode
$l(l+1)C_l/2\pi$ [μK^2]
10
100
500
1000
Multipole moment l

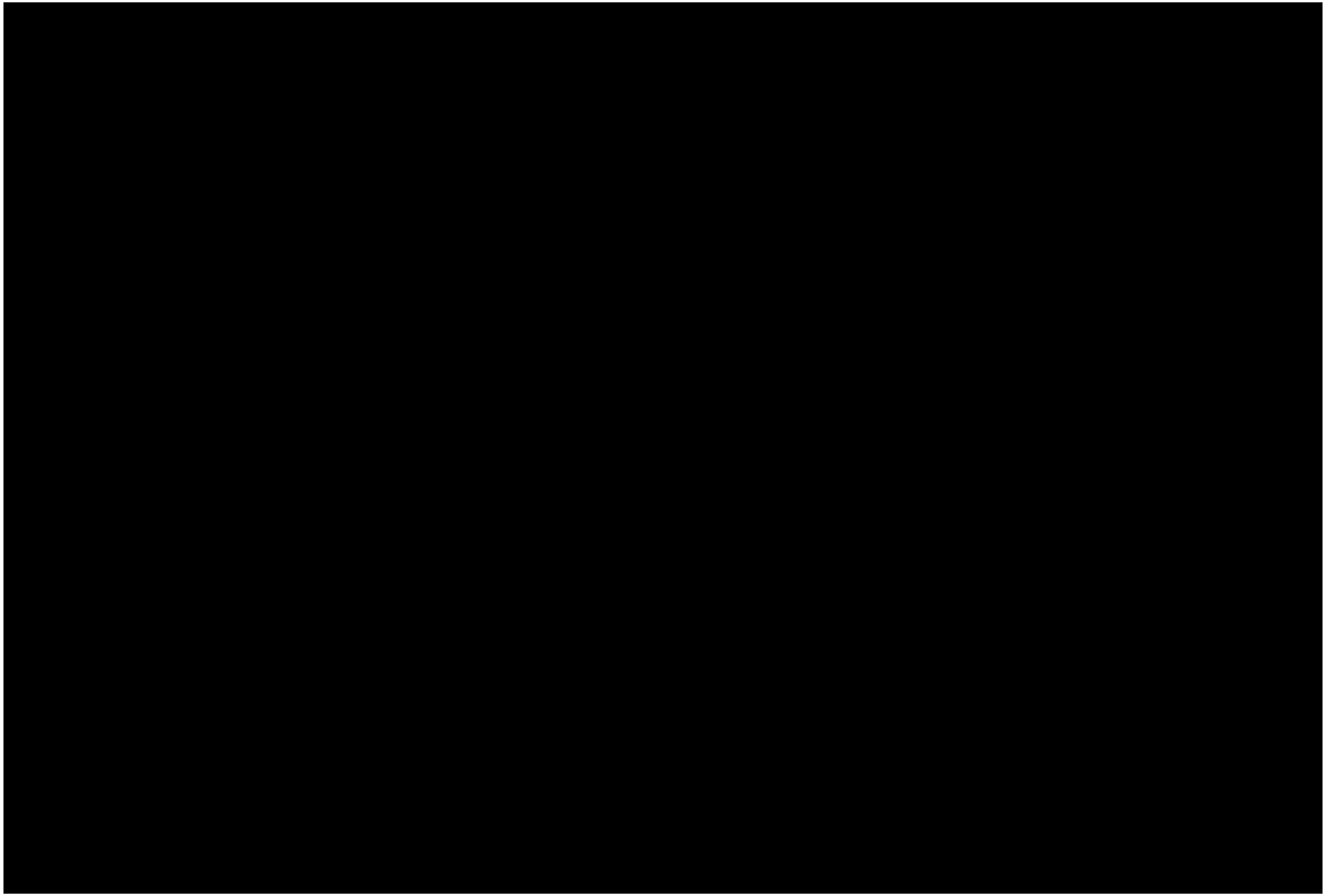
We (and all of chemistry) are a small minority in the Universe.



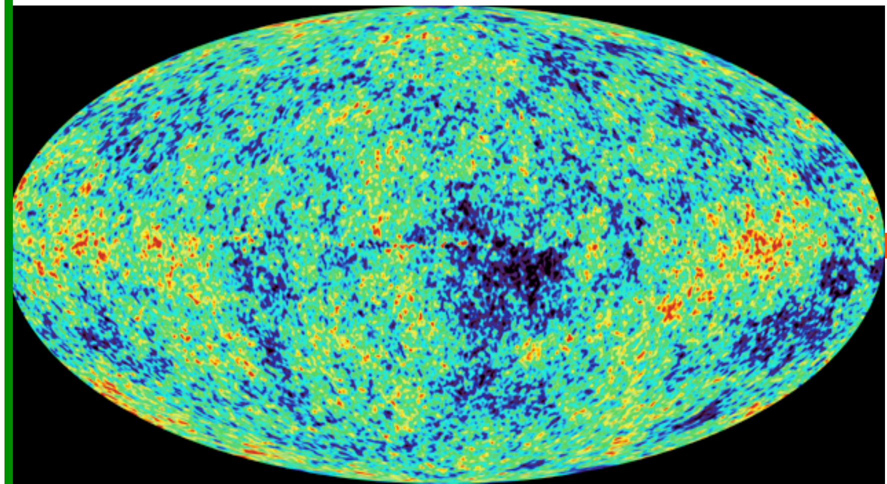
Courtesy of WMAP team

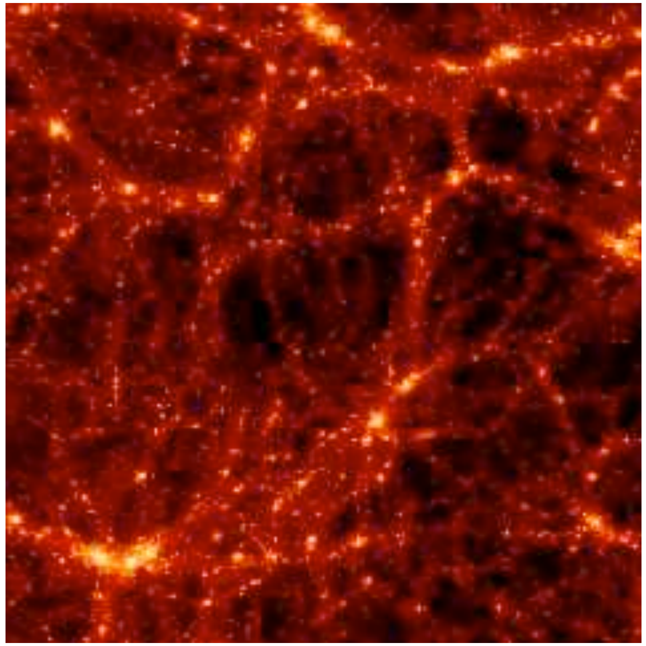


We do not know what 96% of the Universe is !

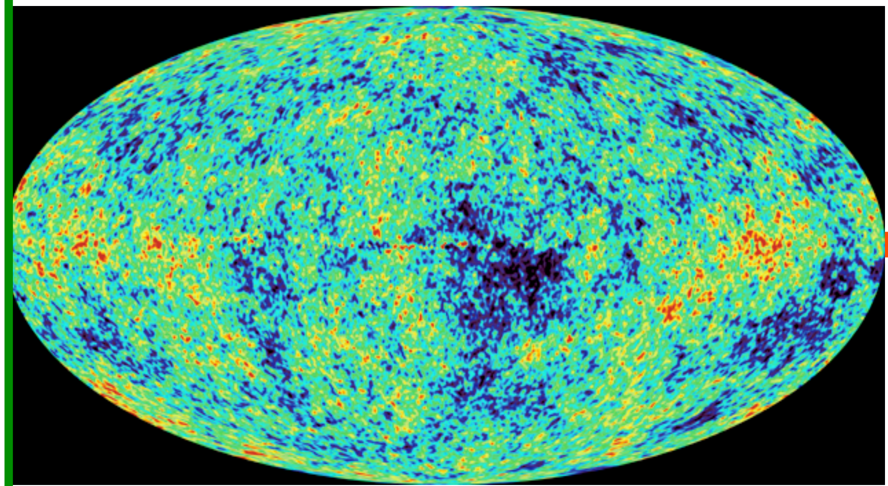


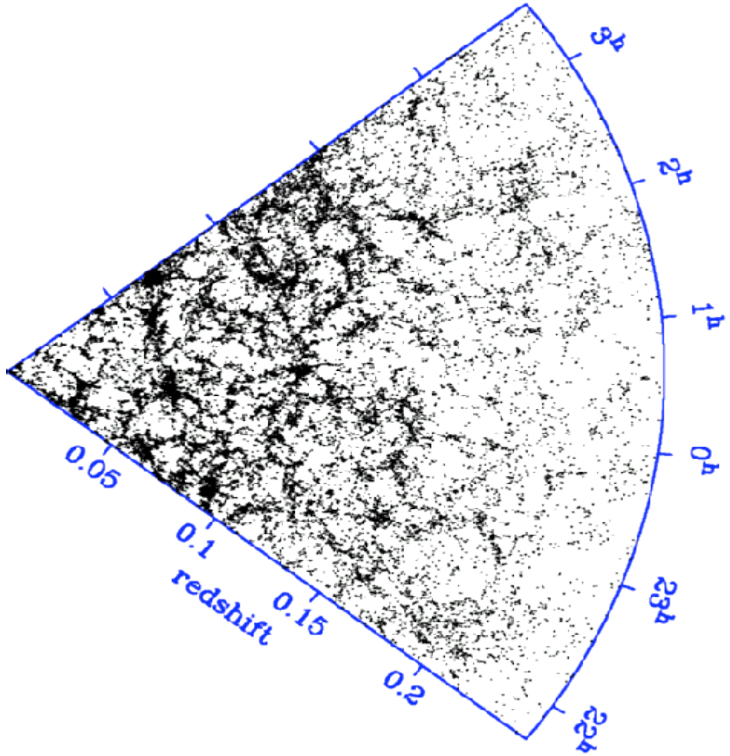
Courtesy of WMAP





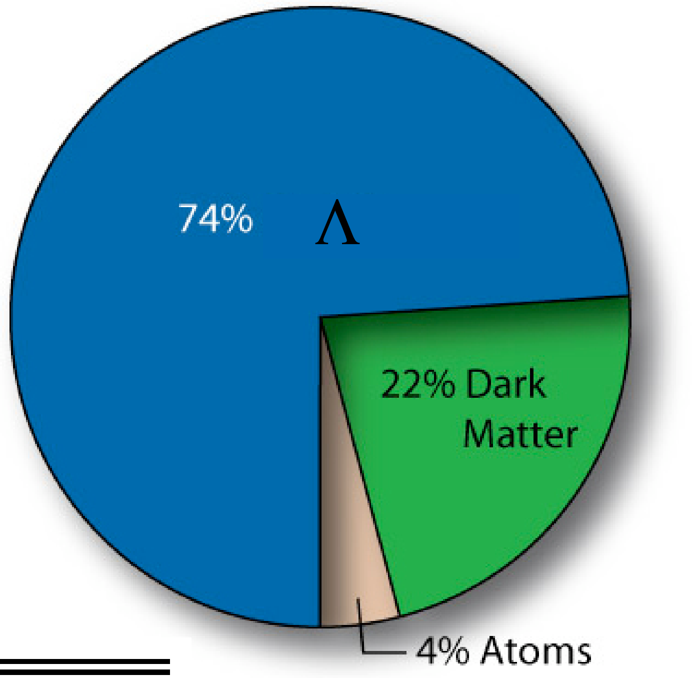
VIRGO




3^h
2^h
1^h
0^h
23^h
22^h
0.05
0.1
0.15
0.2
redshift

?

The standard cosmological model
ΛCDM model



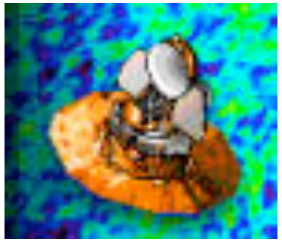
Spatially flat Universe

Power-law, primordial power spectrum

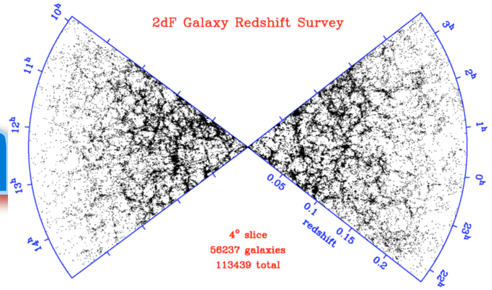
Only 6 parameters: WMAP5yr analysis

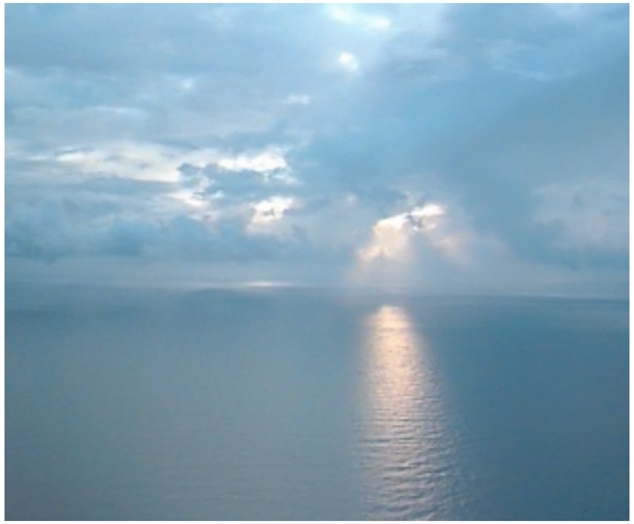
Class	Parameter	*WMAP* 5-year Mean[b]	*WMAP*+BAO+SN Mean
Primary	$100\Omega_b h^2$	2.273 ± 0.062	2.265 ± 0.059
	$\Omega_c h^2$	0.1099 ± 0.0062	0.1143 ± 0.0034
	Ω_Λ	0.742 ± 0.030	0.721 ± 0.015
	n_s	$0.963^{+0.014}_{-0.015}$	$0.960^{+0.014}_{-0.013}$
	τ	0.087 ± 0.017	0.084 ± 0.016
	$\Delta^2_{\mathcal{R}}(k_0{}^e)$	$(2.41 \pm 0.11) \times 10^{-9}$	$(2.457^{+0.092}_{-0.093}) \times 10^{-9}$
Derived	σ_8	0.796 ± 0.036	0.817 ± 0.026
	H_0	$71.9^{+2.6}_{-2.7}$ km/s/Mpc	70.1 ± 1.3 km/s/Mpc
	Ω_b	0.0441 ± 0.0030	0.0462 ± 0.0015
	Ω_c	0.214 ± 0.027	0.233 ± 0.013
	$\Omega_m h^2$	0.1326 ± 0.0063	0.1369 ± 0.0037
	$z_{\rm reion}{}^f$	11.0 ± 1.4	10.8 ± 1.4
	$t_0{}^g$	13.69 ± 0.13 Gyr	13.73 ± 0.12 Gyr

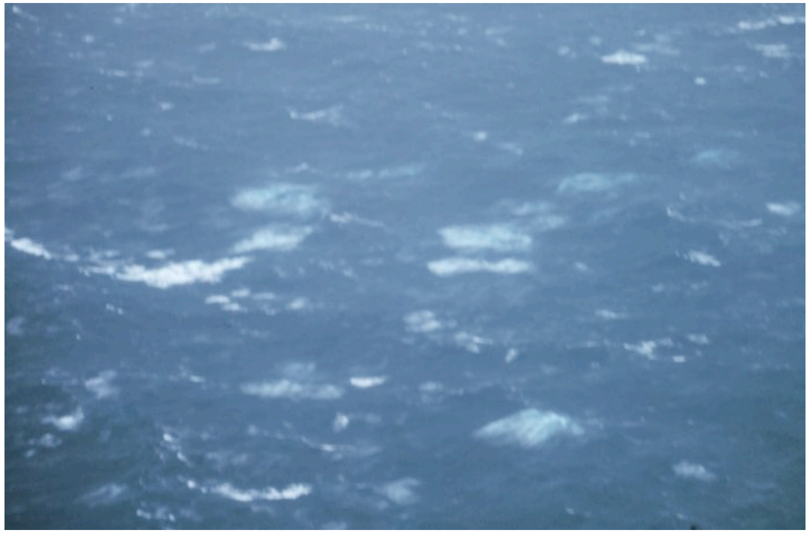
Survived!



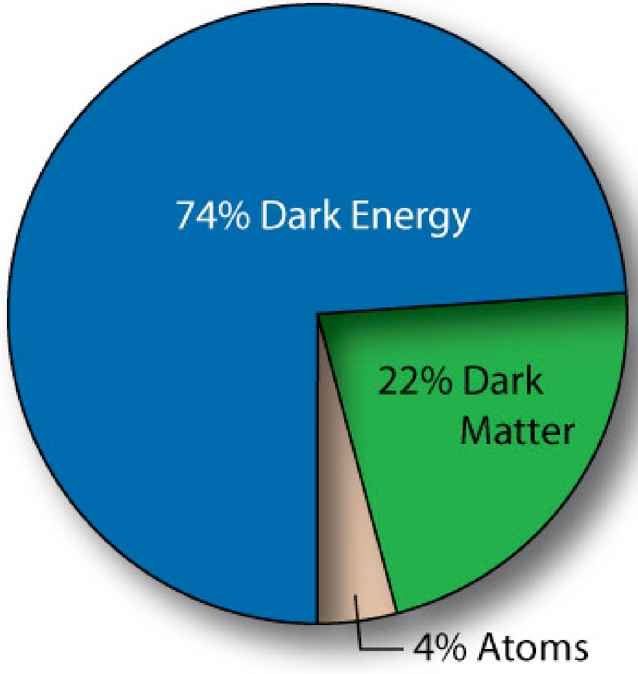
Structure formation







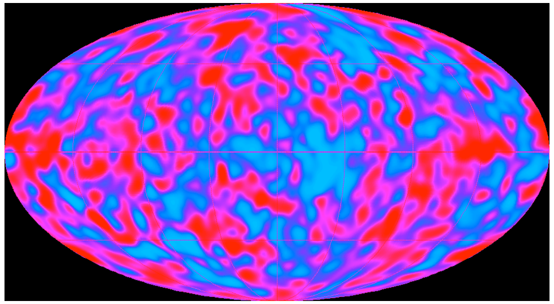
The standard cosmological model



96% of the Universe is missing!!!

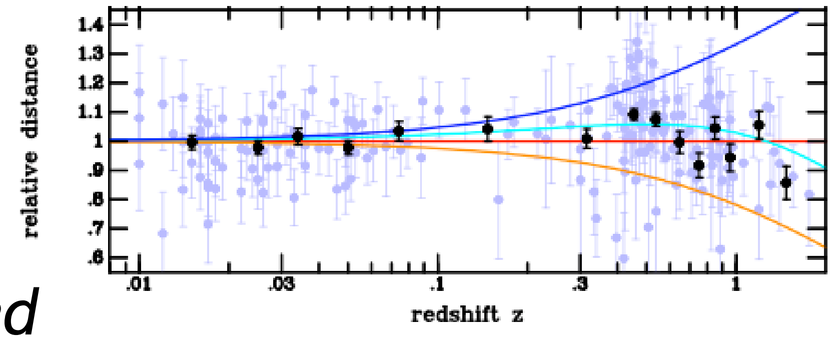
Major questions :

Questions that can be addressed exclusively by looking up at the sky



1)What created the primordial perturbations?

2) What makes the Universe accelerate?



These questions may not be unrelated

Successes of the Big Bang model

GR+cosmological principle

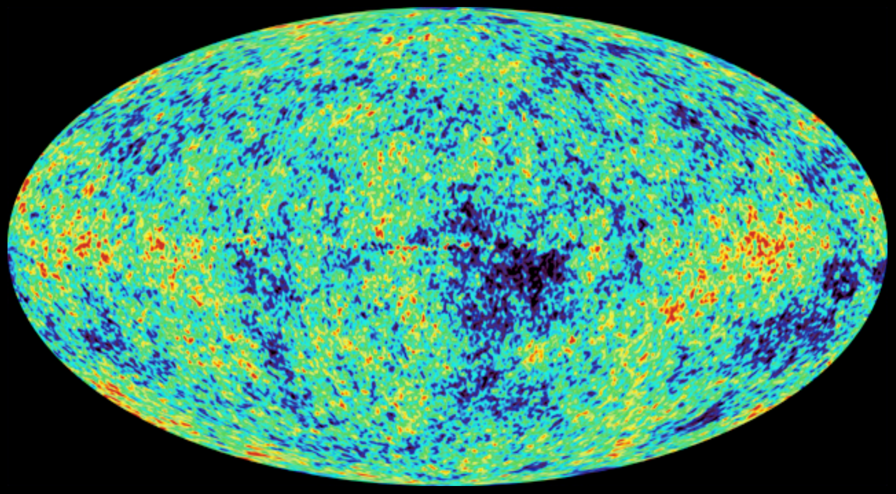
$\Downarrow$

Hubble’s law
CMB
Abundance of light elements

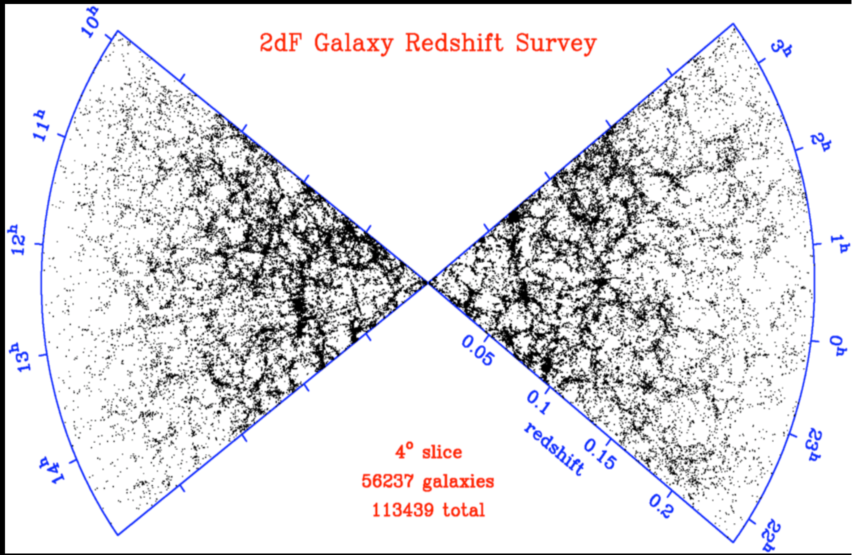
.. And problems

Flatness problem
Horizon problem
Monopole problem

Origin of perturbations

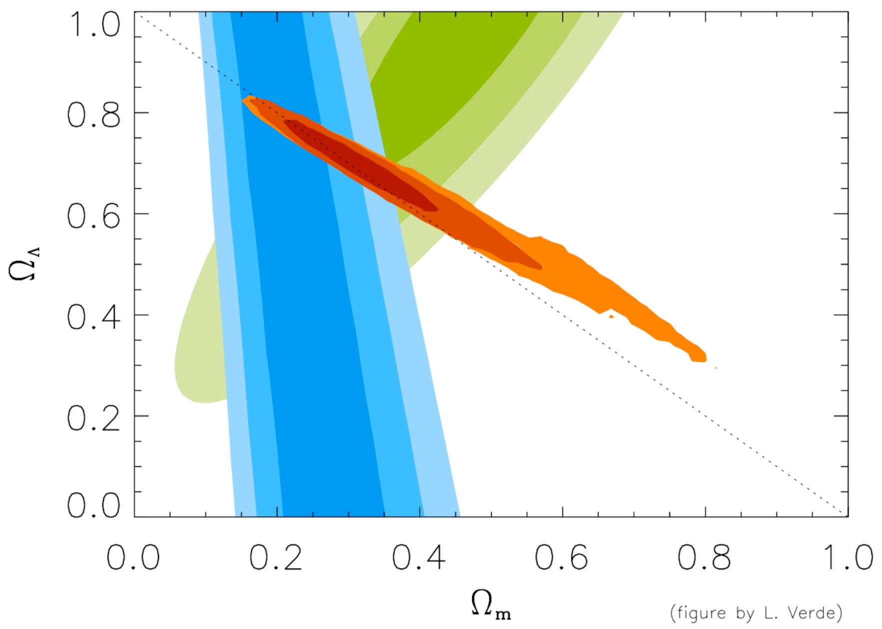


Horizon problem



Structure Problem

Flatness problem



The flatness problem

$$1-\Omega = -\frac{c^2 k}{R_0^2 a^2 H^2}$$

Remember Friedmann equations?

today $\quad |1-\Omega_0| < 0.01$

$$1-\Omega_0 = -\frac{kc^2}{R_0^2 H_0^2} \quad 1-\Omega = -\frac{kc^2}{R_0^2 a(t)^2 H(t)^2} = \boxed{1-\Omega(t) = \frac{H_o^2(1-\Omega_0)}{H^2(t)a^2(t)}}$$

For most of the life of the universe: matter+radiation only

$$\frac{H^2}{H_0^2} = \frac{\Omega_{r,0}}{a^4} + \frac{\Omega_{m,0}}{a^3} \longrightarrow \boxed{1-\Omega(t) = \frac{(1-\Omega_0)a^2}{\Omega_{r,0}+\Omega_{m,0}a}}$$

Matter domination $\quad a \sim t^{2/3} \quad 1-\Omega(t) = \frac{1-\Omega_0}{\Omega_{m,0}}\left(\frac{t}{t_0}\right)^{2/3}$

Universe was flatter in the past!

Exercise: $@t_{eq}? \quad z_{m,r\,eq} \sim 3000?$

Radiation dominated $\quad 1-\Omega(t) \sim a^2 \sim t \qquad 1-\Omega(t) = (1-\Omega(t_{eq}))\frac{t}{t_{eq}}$

Exercise: $@t = 1s?$

Very quickly you find that early on $|1-\Omega|<10^{-60}$

It is like balancing a pencil on its tip, coming back years later and still fining it balancing on its tip

The Horizon problem

Different type of Horizons in Cosmology

Since light travels at a final speed & Universe is expanding

PARTICLE HORIZON: Maximum comoving distance light can have propagated in ti to tf

$$d_p(t) = \int_{t_i}^{t_f} \frac{dt}{a(t)}$$

Accounts for all the past expansion history

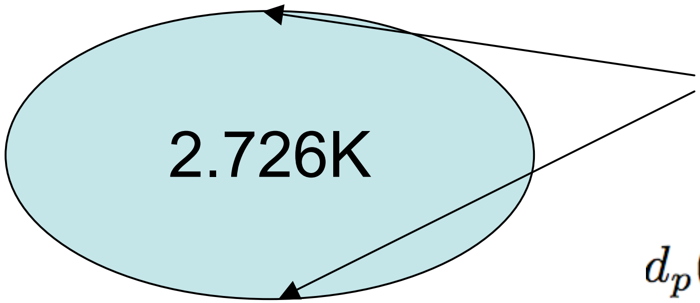
Given the same dt, dp can be very different if a(t) is weird!

HUBBLE HORIZON: c/H or c/t0.
For normal expansion histories dp ~ c/H
For weird ones BEWARE!

$$\frac{c}{H}$$

The Horizon problem

The universe is homogeneous and isotropic on large scales



Consider 2 antipodal points they are separated by $2d_H$~30000 Mpc

$$d_p(t_0) = c\int_{t_{cmb}}^{t_0} \frac{dt}{a(t)} \sim d_H(t_0);\;\; t_{cmb} << t_0$$

What was the Hubble radius (horizon) back then?

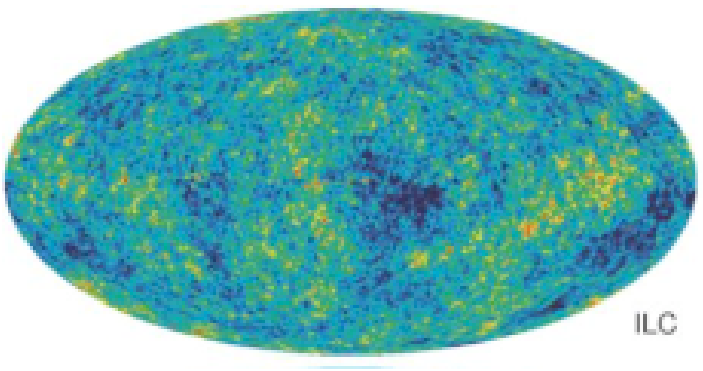
$$H(z)^2 \sim H_0^2 \Omega_{m,0}(1+z)^3 \longrightarrow \frac{c}{H_{z=1000}} \simeq 0.2Mpc$$

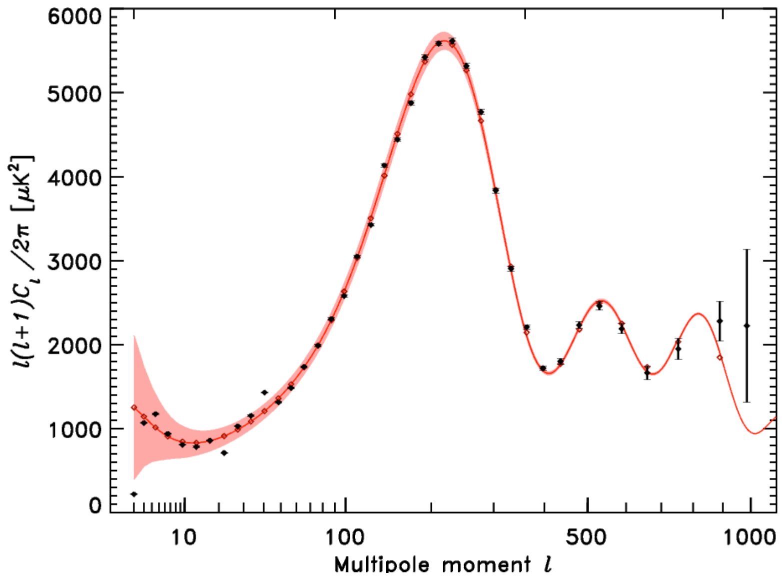
Only points at ~0.2 Mpc could have “talked”

Small aside

$$\theta_H(z_{CMB}) = \frac{d_H}{d_A} = \frac{d_H}{d_p/(1+z)} \sim 1^\circ$$

c_s ~c





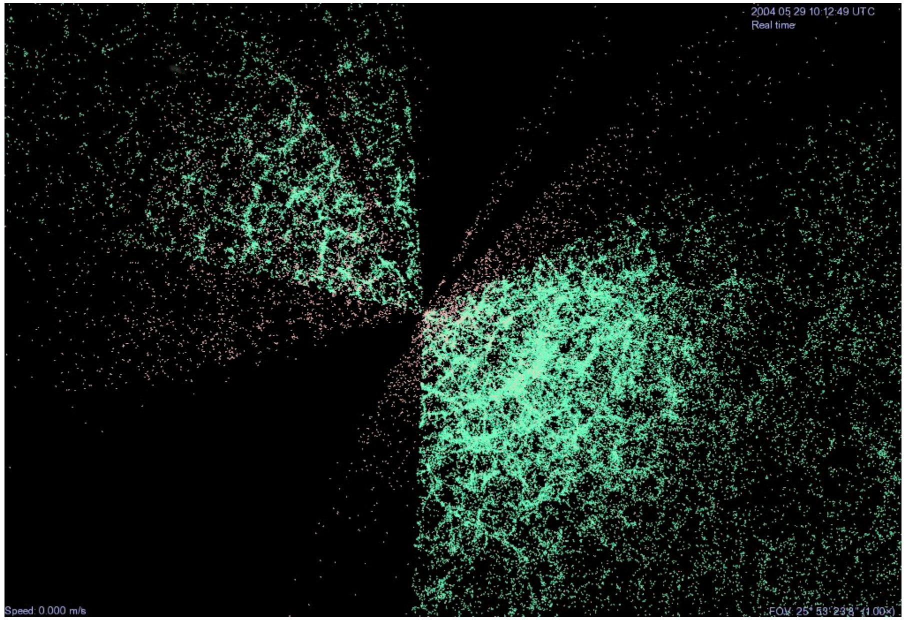
Compare with the size of the CMB spots!

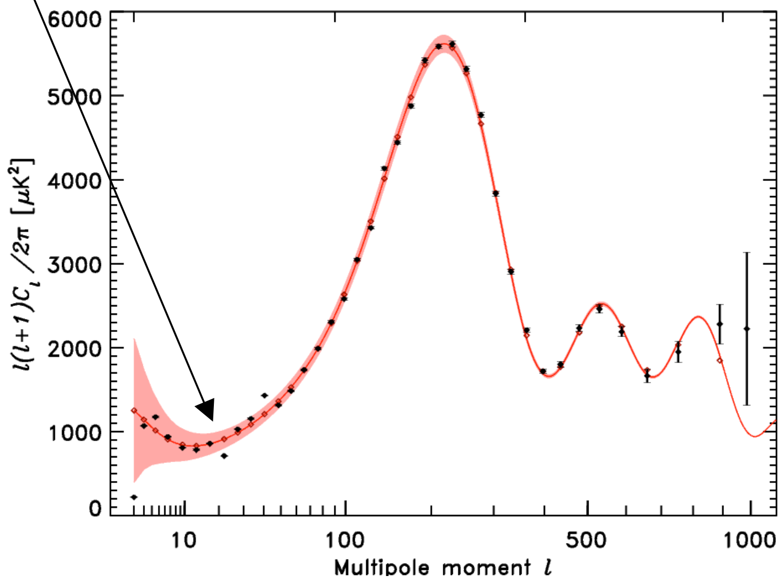
The last scattering surface can be divided in 40000 patches of degree size I.e. 40000 “horizons”….

How could they all be at 2.726K?

Imagine 40000 students taking an exam, and all returning THE SAME exam down to the commas…

And where the heck these perturbations come from?



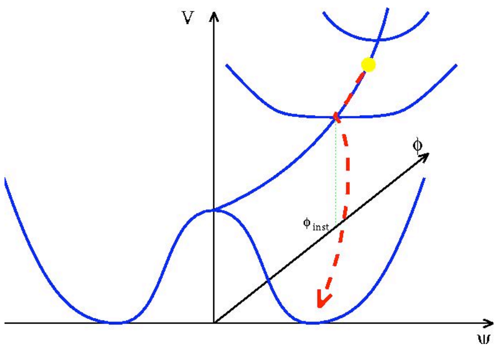


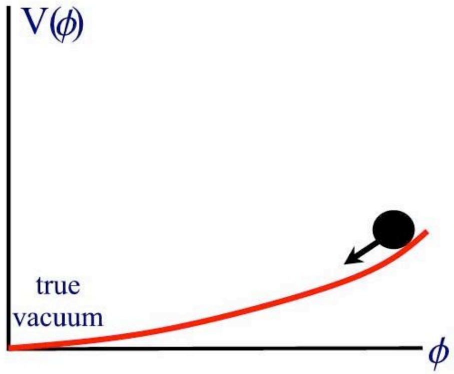
INFLATION to the rescue

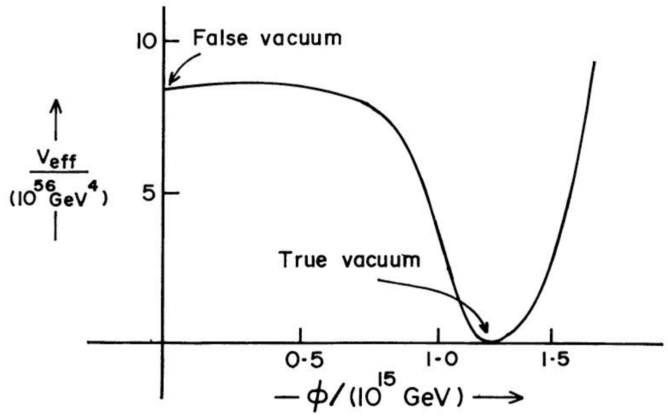
Started in the 1980 with A. Guth, active research area.
Still a “paradigm” not a proven fact…

Postulate a period of accelerated expansion
at the very beginning!
Something like a cosmological constant

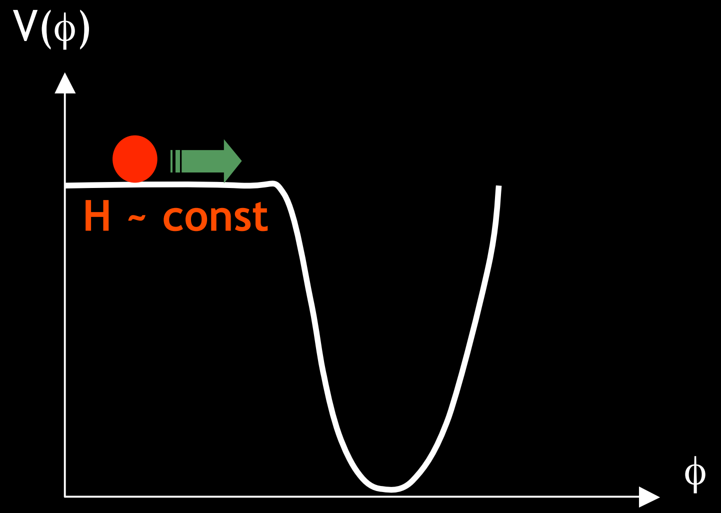
Different scenarios, particle-physics motivated (?)







Inflation



Solves cosmological problems (Horizon, flatness).

Cosmological perturbations arise from quantum fluctuations, evolve classically.

Guth (1981), Linde (1982), Albrecht & Steinhardt (1982), Sato (1981), Mukhanov & Chibisov (1981), Hawking (1982), Guth & Pi (1982), Starobinsky (1982), J. Bardeen, P.J. Steinhardt, M. Turner (1983), Mukhanov et al. 1992), Parker (1969), Birrell and Davies (1982)

Made the Universe undergo accelerated expansion

Why is the Universe so BIG?

Inflation to the rescue: an accelerated expansion

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\epsilon + 3P) \qquad \text{take } P = -\epsilon \text{ for simplicity}$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{\Lambda}{3} \longrightarrow a \propto e^{H_\Lambda t}$$

t_i Inflation begins

t_f Inflation ends

$$a(t) = \begin{cases} a_i \left(\frac{t}{t_i}\right)^{1/2} & t < t_i \\ a_i e^{H_i(t-t_i)} & t_i < t < t_f \\ a_i e^{H_i(t_f-t_i)} \left(\frac{t}{t_f}\right)^{1/2} & t > t_f \end{cases}$$

$$\frac{a(t_f)}{a(t_i)} = e^N \quad N = H_i(t_f - t_i) \quad \text{number of e} - \text{foldings}$$

Example: $t_i = T_{GUT} = 10^{-36} s \quad H_i \sim t_{GUT}^{-1} \sim 10^{36} s^{-1}$ $\quad N \sim 100$

Even if inflation lasts for $\Delta t \sim 10^{-34} s$

$$\frac{a(t_f)}{a(t_i)} \simeq 10^{43}$$

NOT BAD!

Any weirdness like monopole

Would be diluted away!

Inflation solves the Flatness problem

Something like a Λ

$$H = const\,; \quad a \sim \exp(H_I t)$$

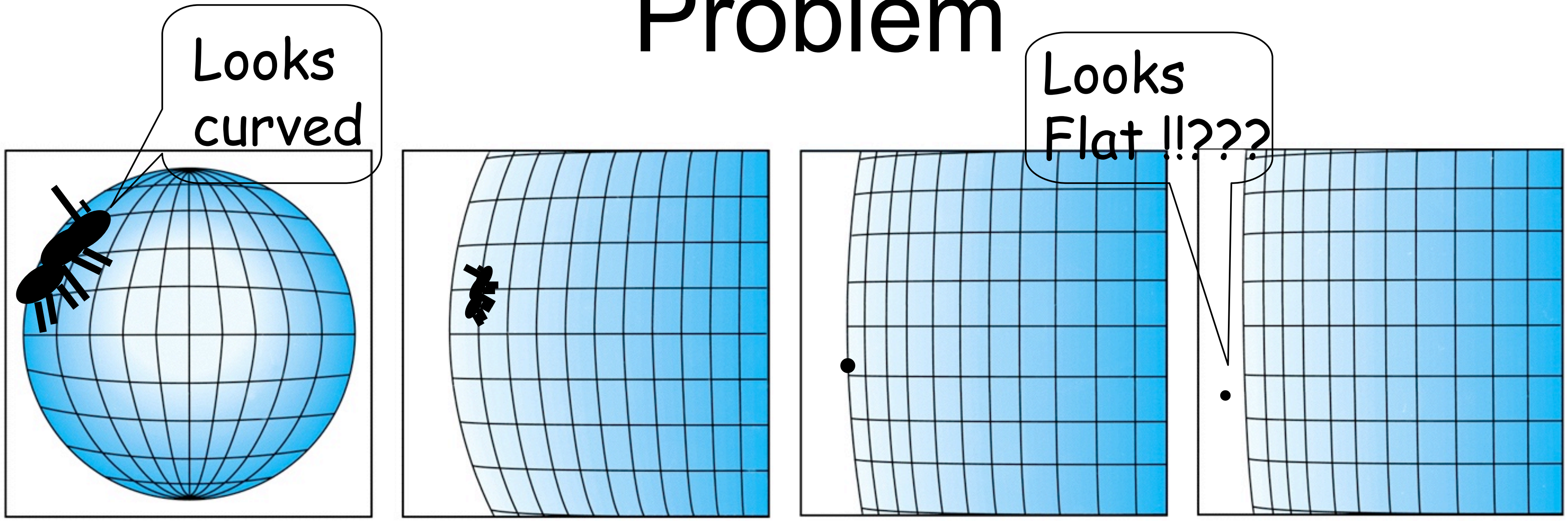
$$1 - \Omega(t) = \frac{c^2}{R_0^2 a^2 H^2}$$

$$\frac{a(t_f)}{a(t_i)} = e^N \quad N = H_i(t_f - t_i) \quad \text{number of e-foldings}$$

$$|1 - \Omega(t_f)| = \exp(-2N)|1 - \Omega(t_i)|$$

For N~100 NOT BAD!

Inflation Solves the Flatness Problem



What made the Universe so flat?

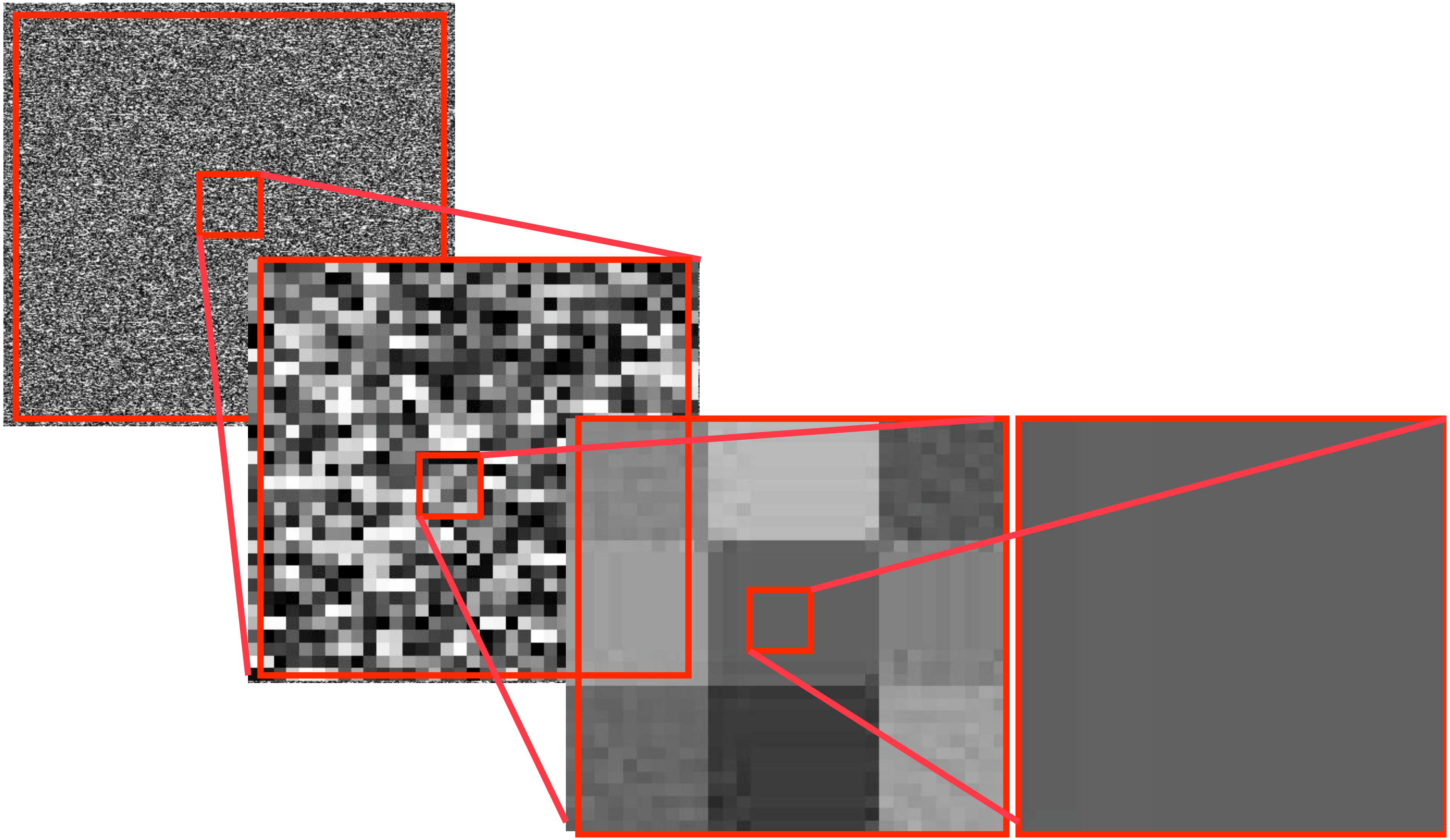
What made the Universe so big?

What made the universe so uniform?

What seeded the galaxies?

Why is the Universe so uniform?

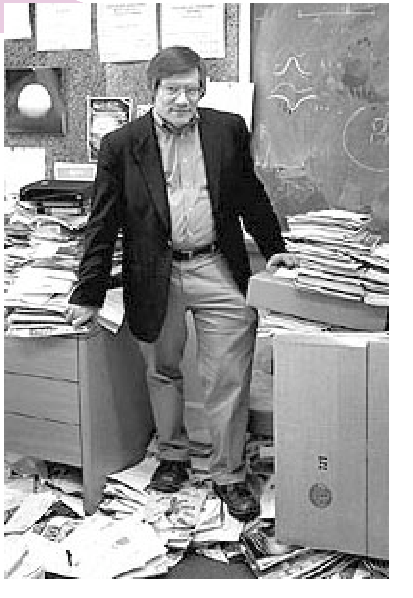
Inflation solves that

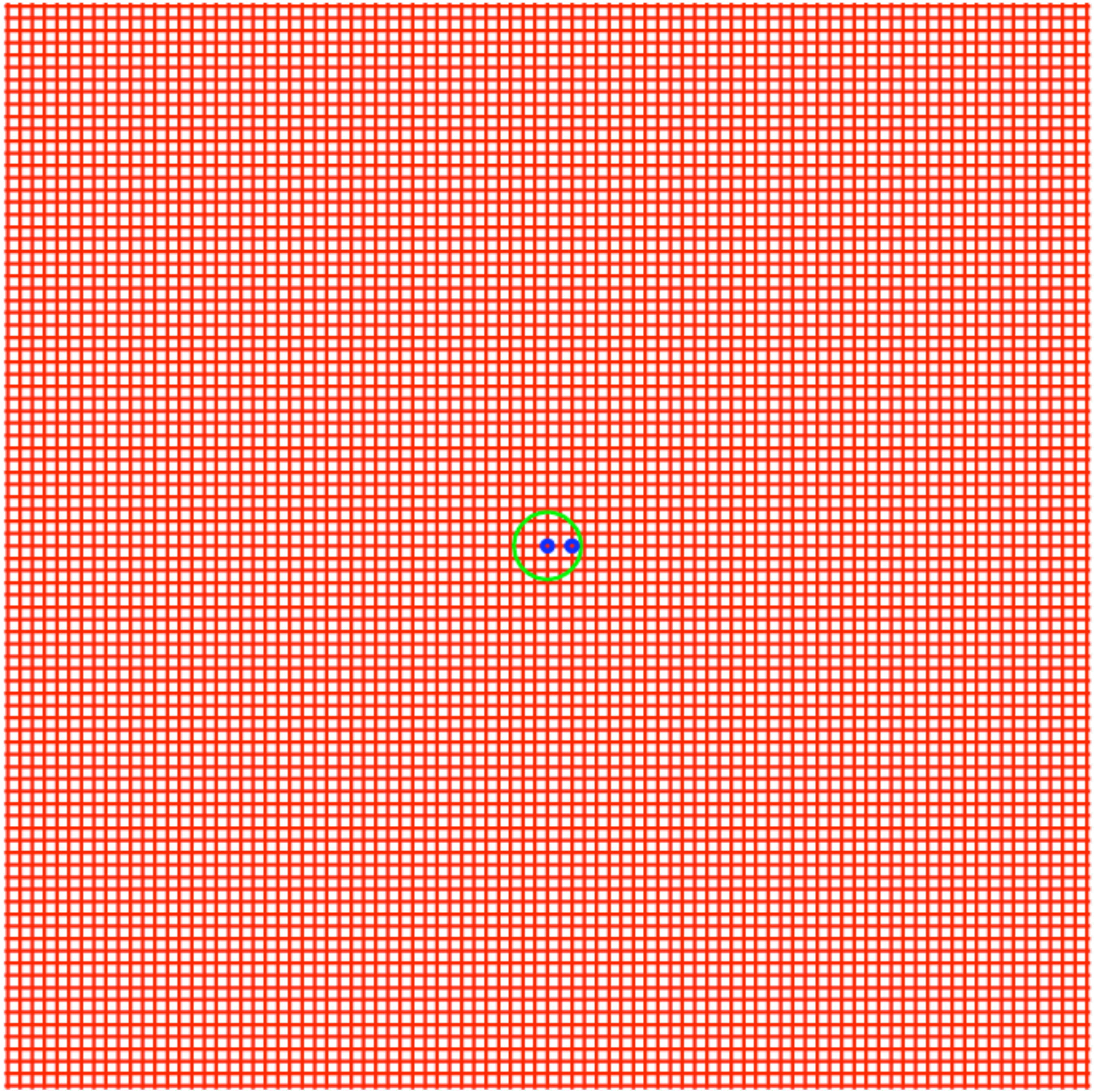


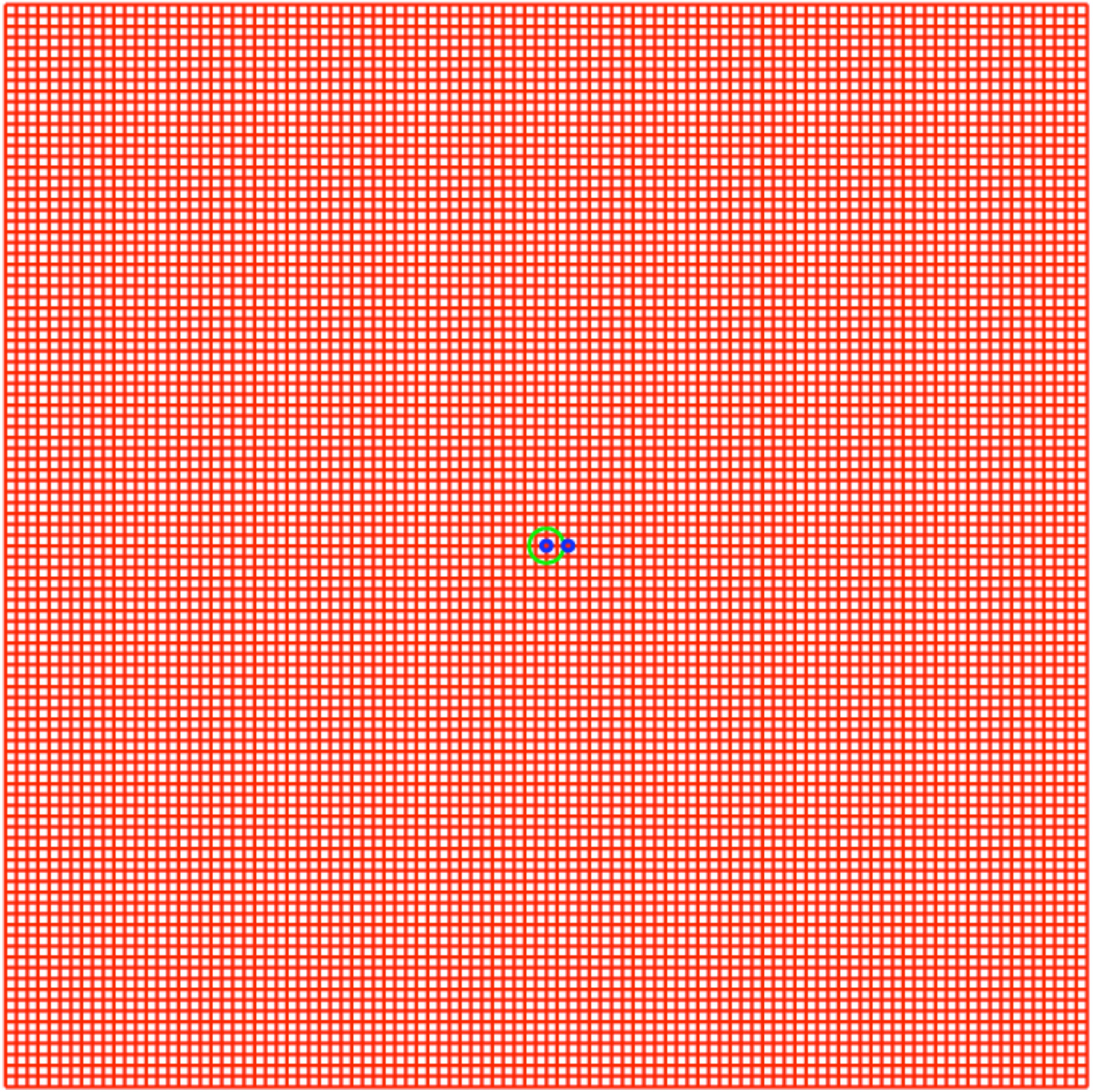
Inflation solves the Horizon problem

In an accelerated expansion the particle horizon and the Hubble horizon can be VERY DIFFERENT

Given the same dt, dp can be very different if a(t) is weird!







As an added bonus:

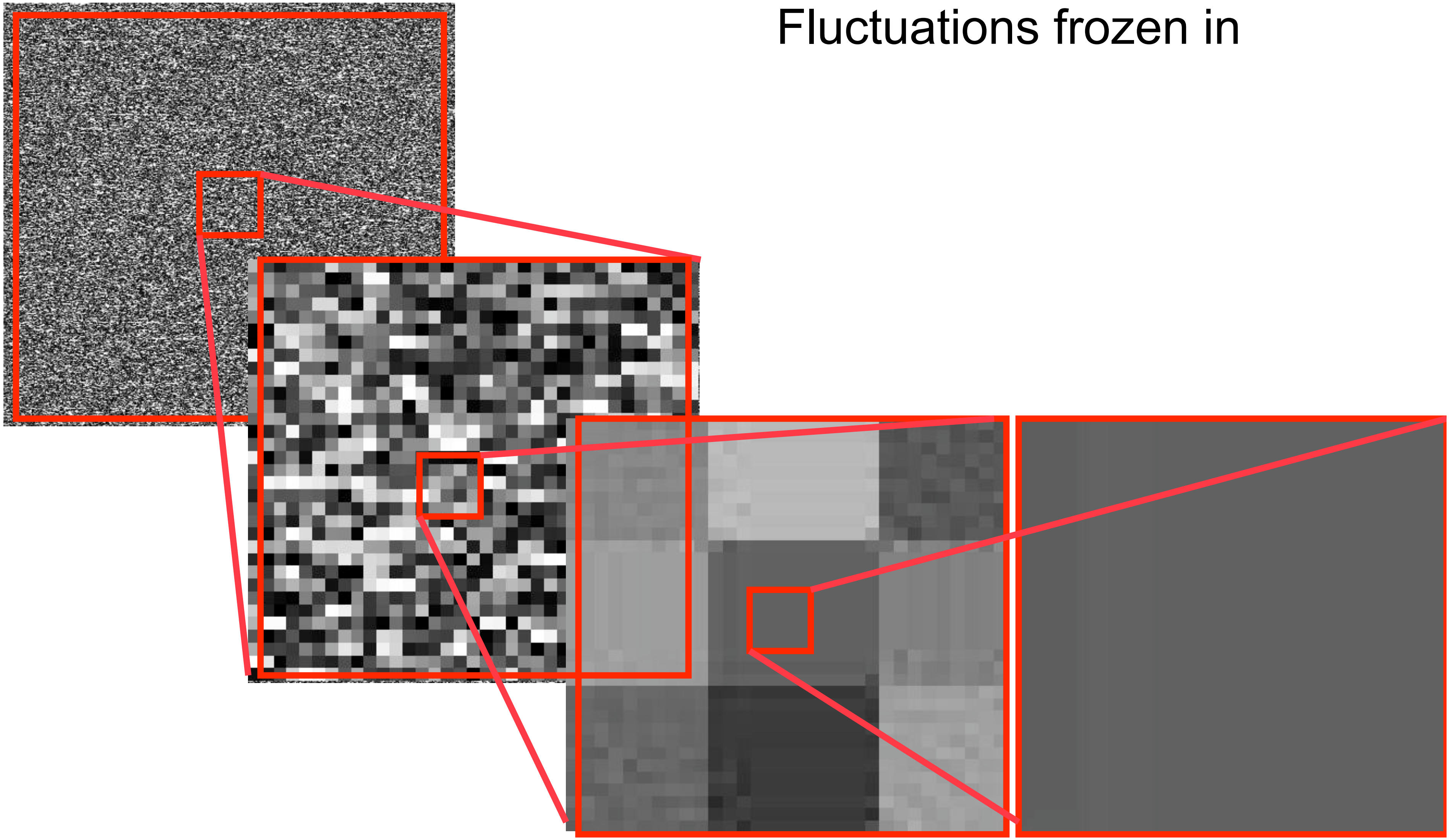
Inflation generates Gaussian perturbations:
quantum fluctuations stretched to become classical
by the expansion. The mechanism is similar to Hawkings
radiation. (The event horizon being the complementary
concept to the particle horizon…)

Turns out that the power spectrum of these perturbations will be
a power law: different model of inflation predict slightly different
power laws, but all close to “scale invariant”..

Perturbations outside the Horizon?

Inflation solves that

Fluctuations frozen in



CAN THIS BE TESTED?

flatness 

Power law primordial power spectrum 

Can even hope to distinguish specific models

Super horizon fluctuations (polarization) 

gaussianity 

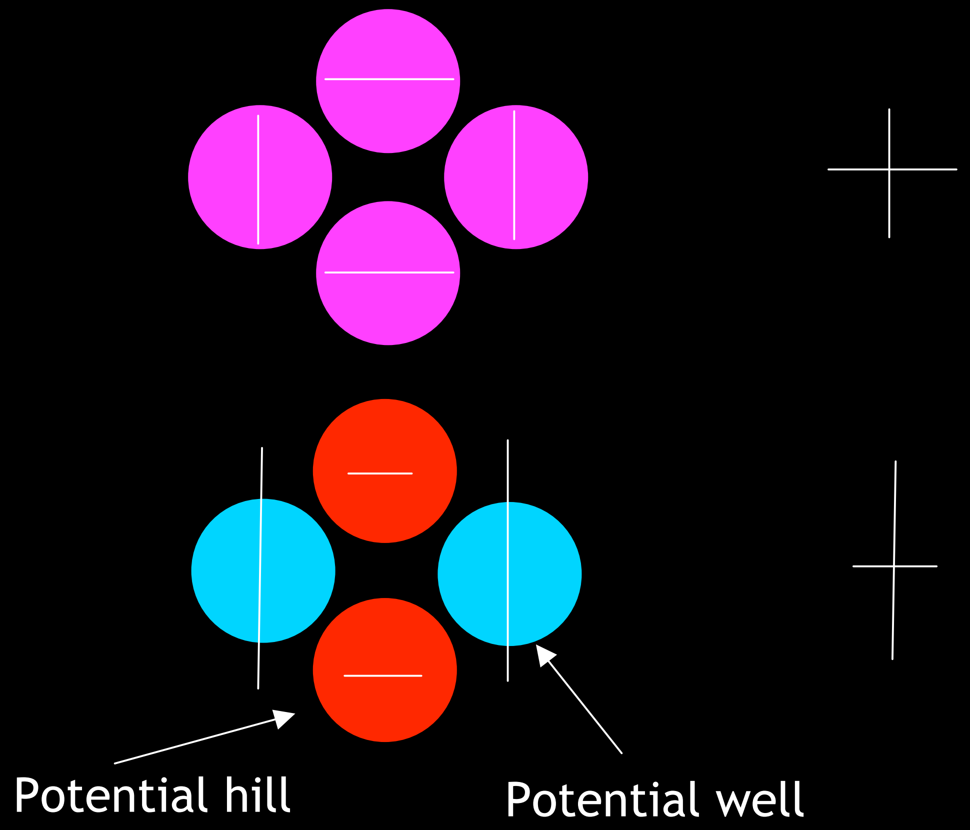
Can even hope to distinguish specific models

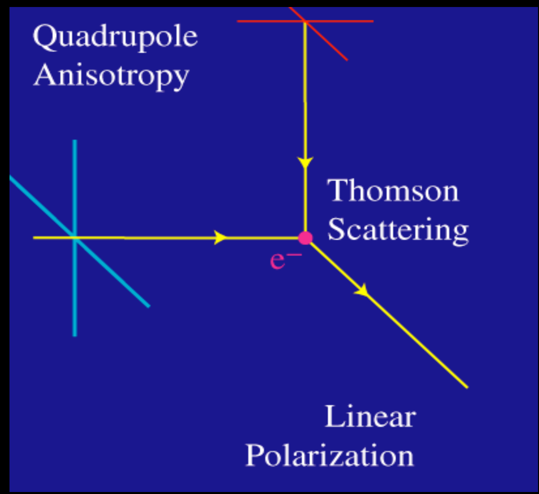
Stochastic background of gravity waves

(polarization)

Generation of CMB polarization

- Temperature quadrupole at the surface of last scatter generates polarization.





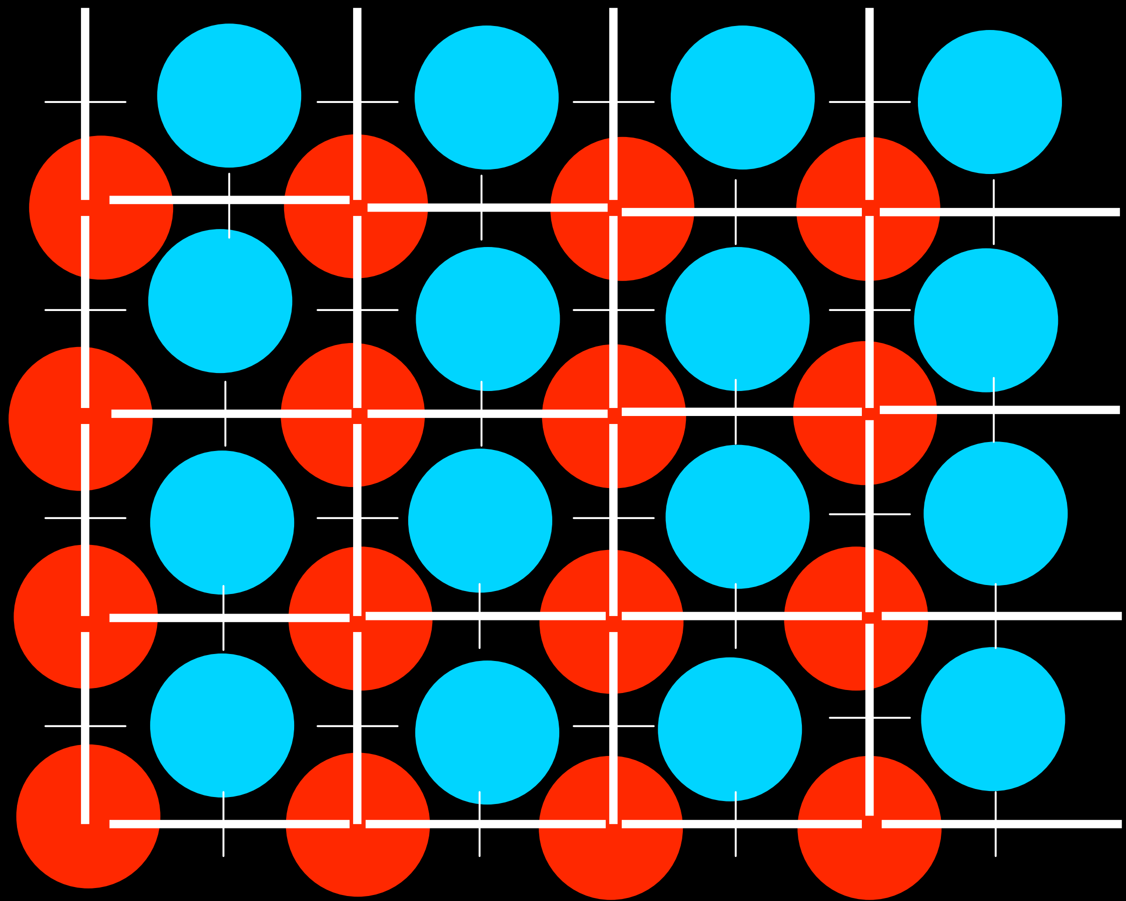
From Wayne Hu

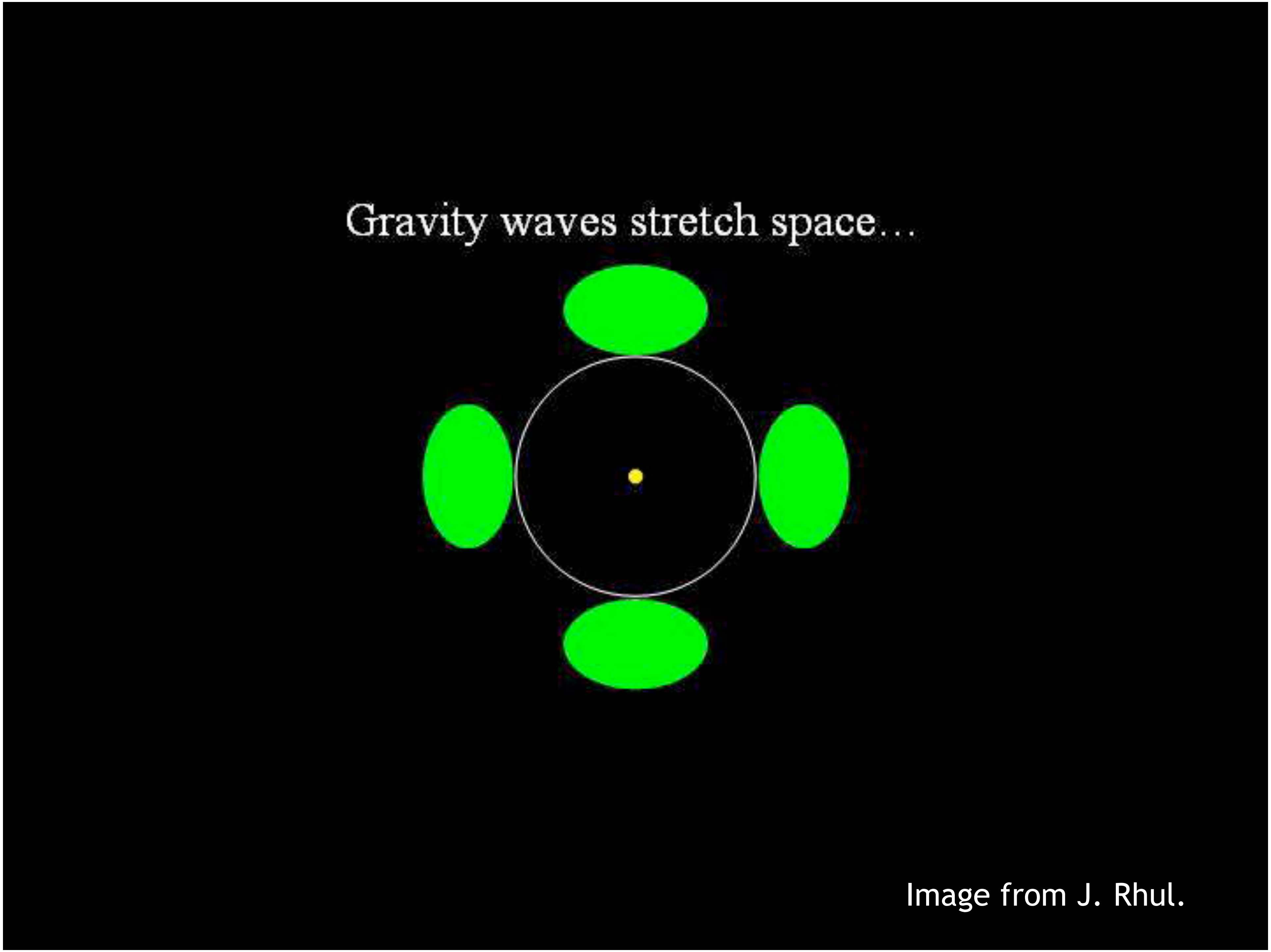
YES, there is also reionization

Rees 68, Coulson et al '94
….. Hu& White 97(pedagogical)

Polarization for density perturbation

- Radial (tangential) pattern around hot (cold) spots.




Gravity waves stretch space…
Image from J. Rhul.

… and create variations

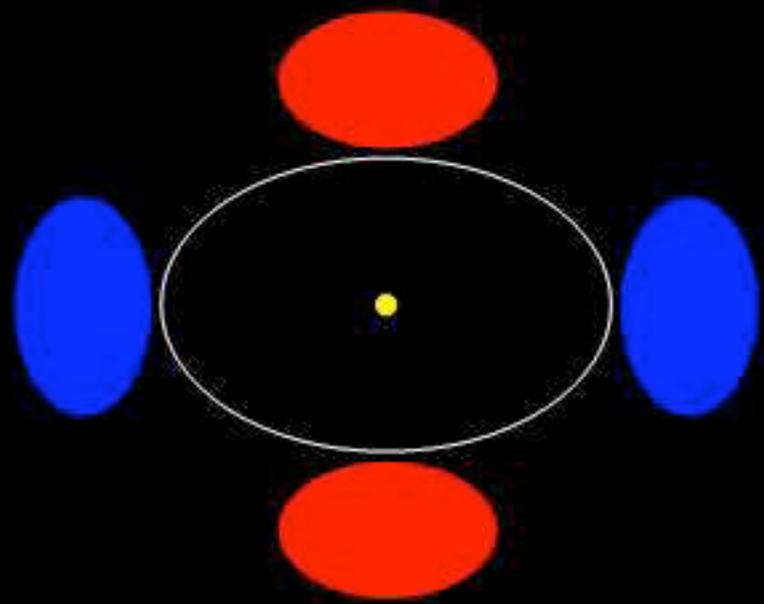
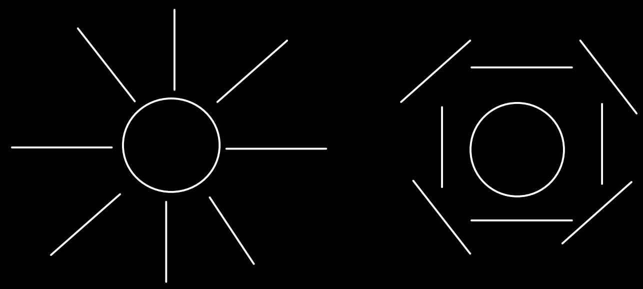
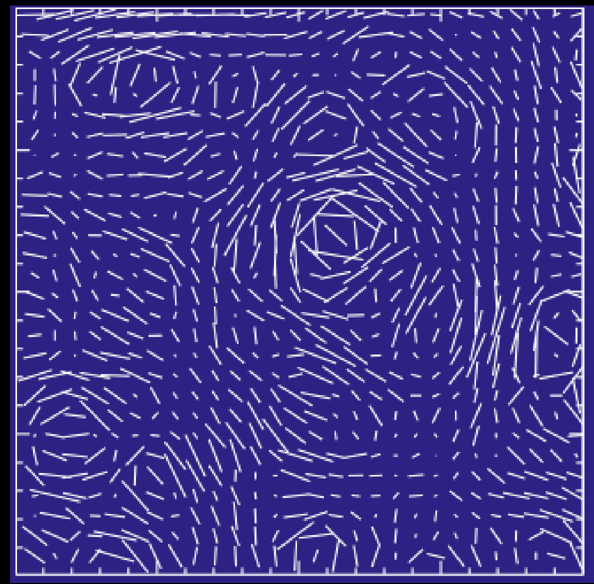


Image from J. Rhul.

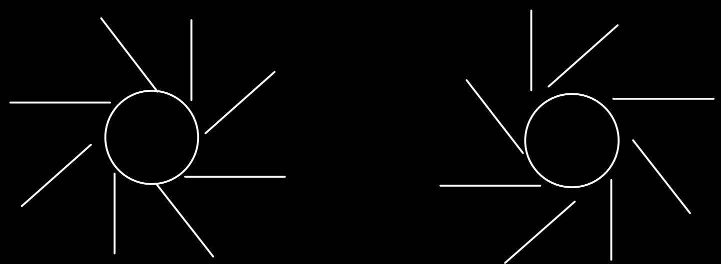
E and B modes polarization

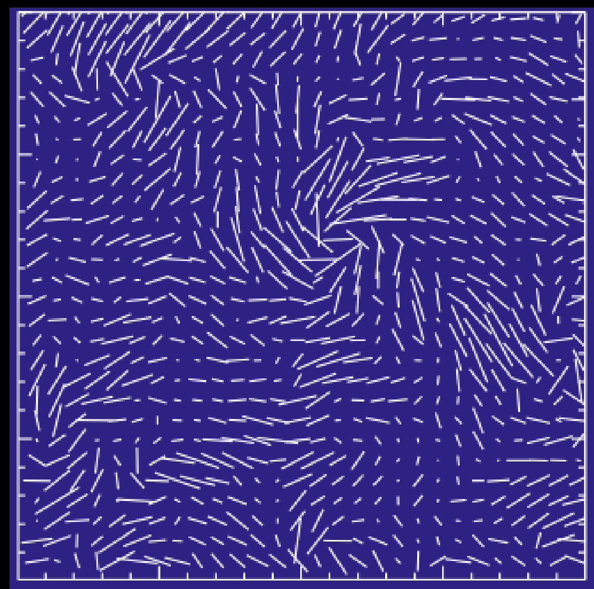
E polarization
from scalar, vector and tensor modes





B polarization only from (vector)
 tensor modes





Kamionkowski, Kosowsky, Stebbings 1997, Zaldarriga & Seljak 1997

Seeing (indirectly) z>>1100

Hot issue!

Information about the shape of the inflaton potential is enclosed in the shape and amplitude of the primordial power spectrum of the perturbations.

Information about the energy scale of inflation (the height of the potential) can be obtained by the addition of B modes polarization amplitude.

In general the observational constraints of Nefold>50 requires the potential to be flat (not every scalar field can be the inflaton). But **detailed measurements of the shape of the power spectrum can rule in or out different potentials**.

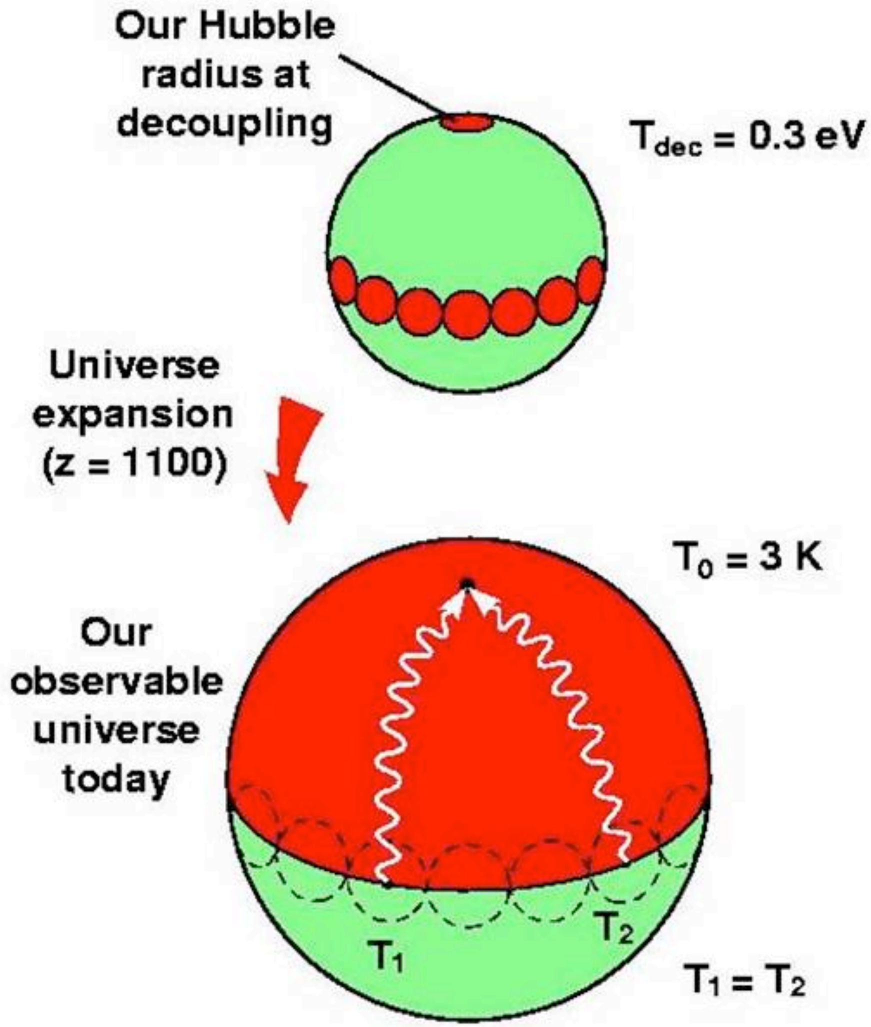
Summary and key concepts today

There is a lot of dark matter out there; we believe it is “cold”. Cosmologists also have faith that soon there will be direct detection and that DM can be identified with a particle within a particle physics model

(Most) cosmologists believe that the early Universe underwent Inflation. So far inflation is a paradigme.
Huge observational effort.

Coming next: is the Universe today undergoing inflation?

http://icc.ub.edu/~liciaverde/TAElectures.html


Our Hubble
radius at
decoupling
T_{dec} = 0.3 eV
Universe
expansion
(z = 1100)
T_0 = 3 K
Our
observable
universe
today
T_1
T_2
$T_1 = T_2$