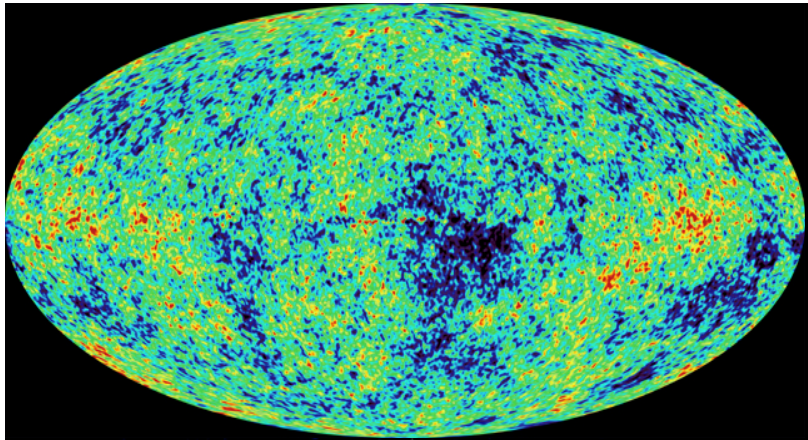

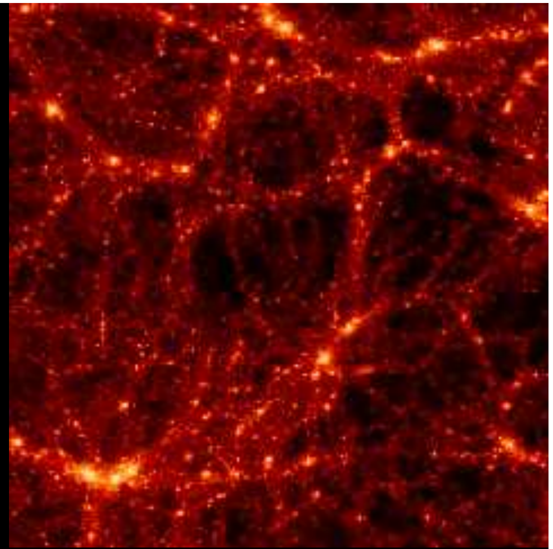

A taste of cosmology

Licia Verde

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icrea Institució Catalana de Recerca i Estudis Avançats

ICCUB Institut de Ciències del Cosmos

IEEC

erc

OUTLINE

- The standard cosmological model
- The successes of cosmology over the past 10 years
- Cosmic Microwave Background
- Large-scale structure
- Inflation and outlook for the future

Lectures and additional material will appear at
http://icc.ub.edu/~liciaverde/CLASHEP.html

Cosmology

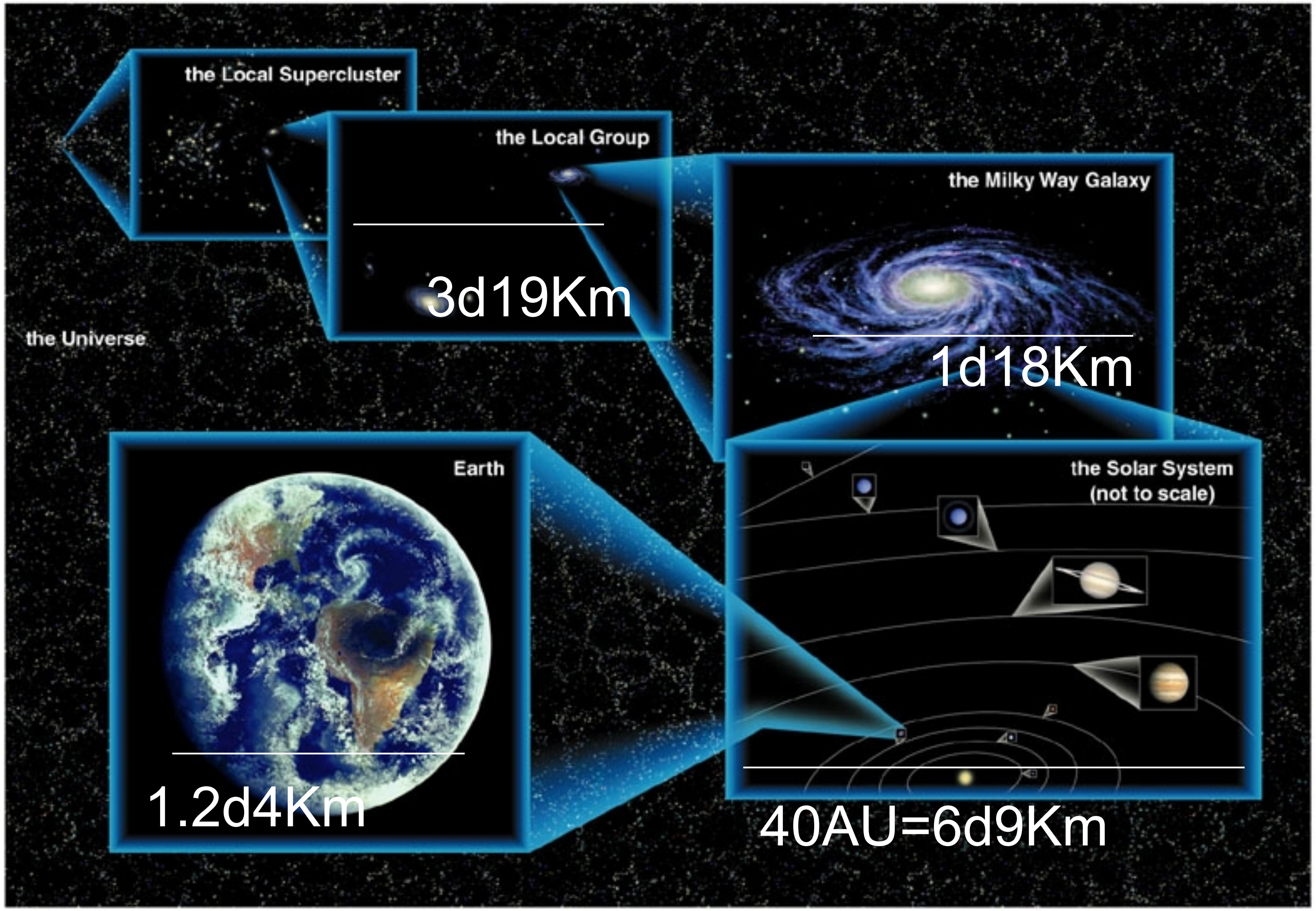
Cosmos= Universe, Order, beauty
-logy= study

Greek!

Study of the Universe as a whole
Aim at getting an understanding of:
-its origin
-its structure and composition
(where do galaxies, stars, planets, people come from?)
-its evolution
-its fate

In general for cosmologists galaxies are points….

Scales involved!



New units of measure

For distance, we use pc, Kpc & Mpc

$$1 \text{ pc} = 3.086 \times 10^{16} \text{m}$$

$$1 \text{ Mpc} = 3.086 \times 10^{22} \text{m}$$

For comparison, mean Earth-Sun distance (Astronomical Unit):

$$1 \text{ AU} = 1.496 \times 10^{11} \text{m}$$

$$1 \text{ pc} = 2.1 \times 10^{5} \text{AU}$$

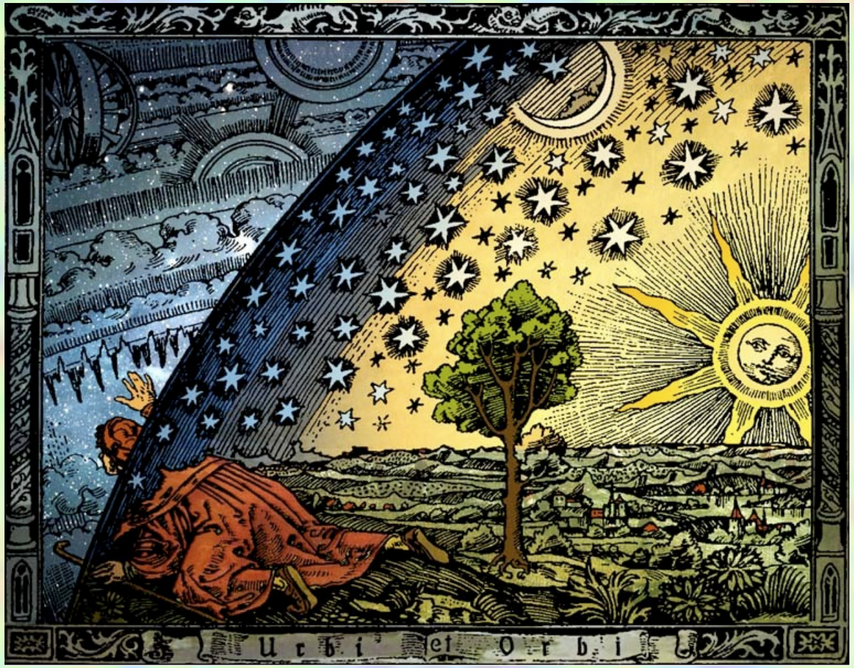
- Cosmologists often express masses
- in units of the solar mass:

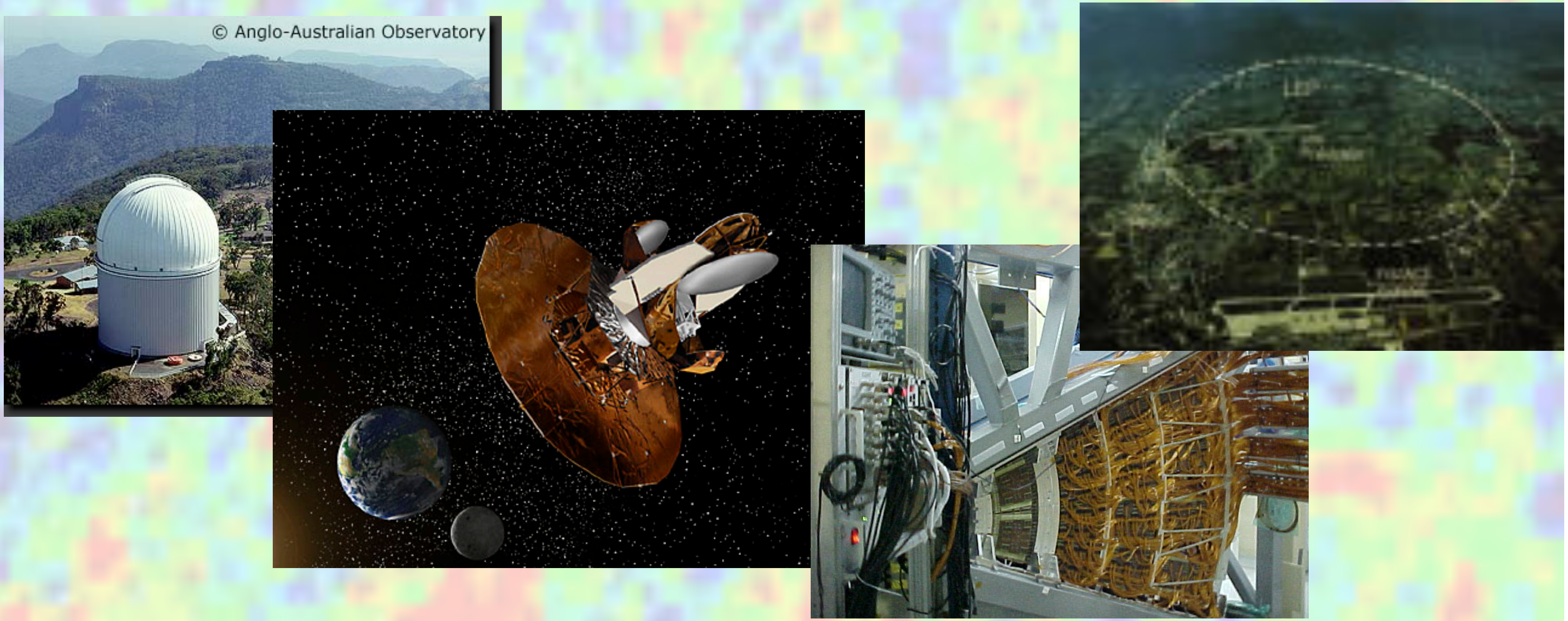
$$1 \text{ M}_{\odot} = 1.99 \times 10^{30} \text{kg}$$

MOTIVATION

- Cosmology over the past 15 years has made the transition to *precision cosmology*
- Cosmology has moved from a *data-starved science* to a *data-driven science*
- Cosmology has now a *standard model.* The *standard cosmological model* only needs few parameters to describe origin composition and evolution of the Universe
- Big difference between modeling and understanding

Motivation: Why should you care about observational cosmology?





Deep connections
between cosmology and fundamental physics

Testing fundamental physics by looking up at the sky is not new

The interplay between astrophysics and fundamental physics has already produced spectacular findings (e.g. the solar neutrino problem)

Cosmology has entered the precision era very recently

Cosmological data can be used to test fundamental physics

4 Areas

- Dark matter
- Neutrinos
- **Inflation**
- **Dark energy**

Fundamental assumptions

Physics as we know it can describe the Universe

On the largest scales the driving force is gravity
(forget about “gastrophysics”)

General Relativity rules!
(for many applications you can be Newtonian)

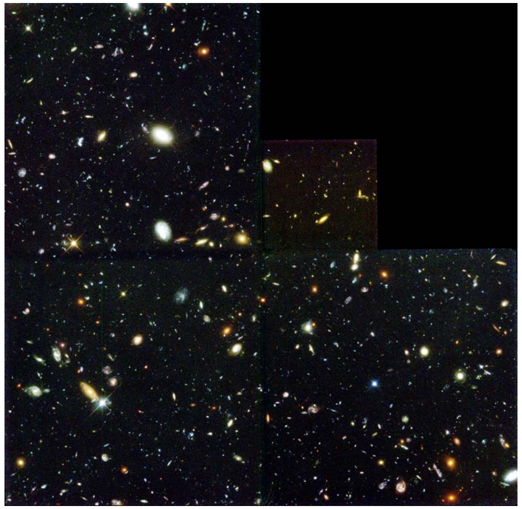
Homogeneity and isotropy

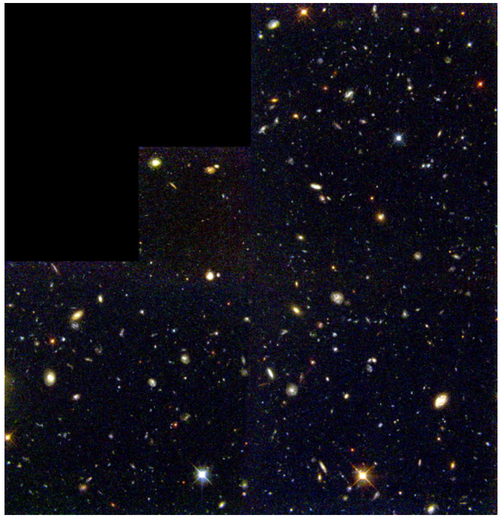
FLRW metric

Thee possible global geometries only

Some assumptions

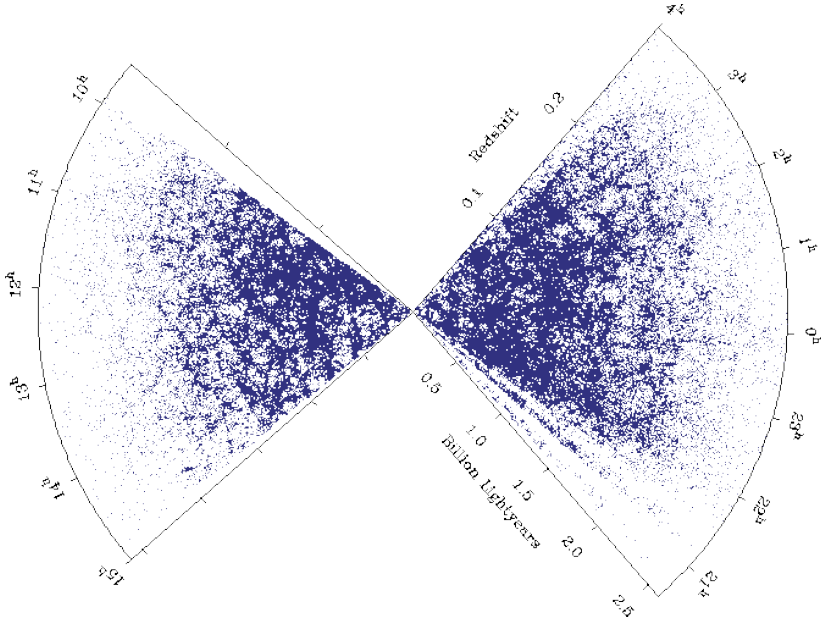
The Universe is homogeneous and isotropic on large scales





This is supported by observations

HDF north and south



2dF GRS

Large volumes of the sky in different directions, 100's of Mpc in size, look about the same.

The standard cosmological model: parameters

Different type of parameters

The smooth Universe {
- Parameters that govern the global geometry of space-time
- Parameters that govern the expansion rate

GR geometry, fate of Universe, content (but not much details)

Inhomogeneous Universe { Parameters that characterize inhomogeneities

Statistically speaking: clustering, galaxies etc…

Parameterizing our ignorance { Derived parameters

Beyond the minimal model: “extra” parameters

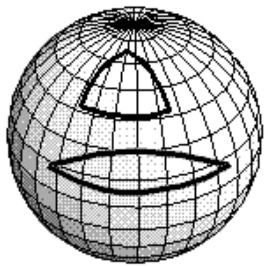
test: which is which?

The smooth Universe: content

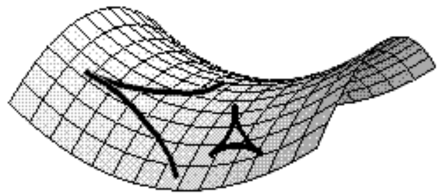
$$\Omega = \frac{\rho}{\rho_{crit}}$$

Gives the global geometry/curvature

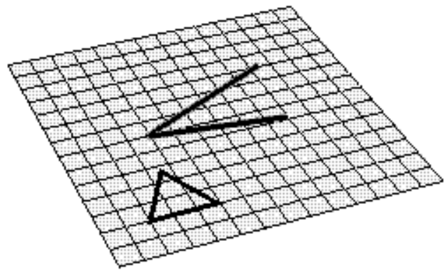
$$\Omega = \Omega_m + ???$$



Universe with *positive* curvature. Diverging line converge at great distances. Triangle angles add to more than 180°.

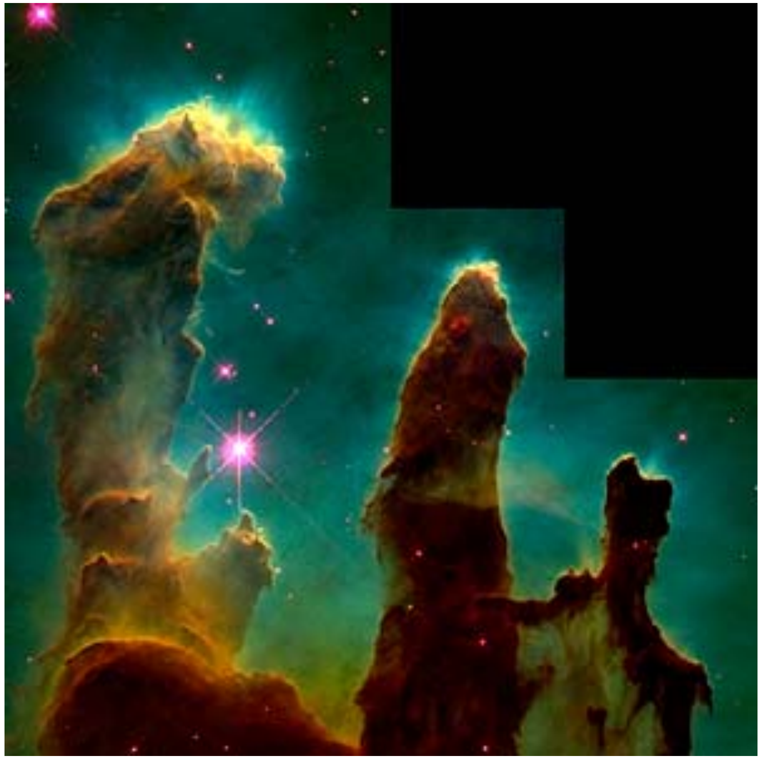


Universe with *negative* curvature. Lines diverge at ever increasing angles. Triangle angles add to less than 180°.



Universe with no curvature. Lines diverge at constant angle. Triangle angles add to 180°.

Content: Baryons: stars



HST image of stars being born, but it has no direct use for Cosmology; exploding stars (supernovae) are very useful (you'll see later on)

By the way, we are star-dust

galaxies

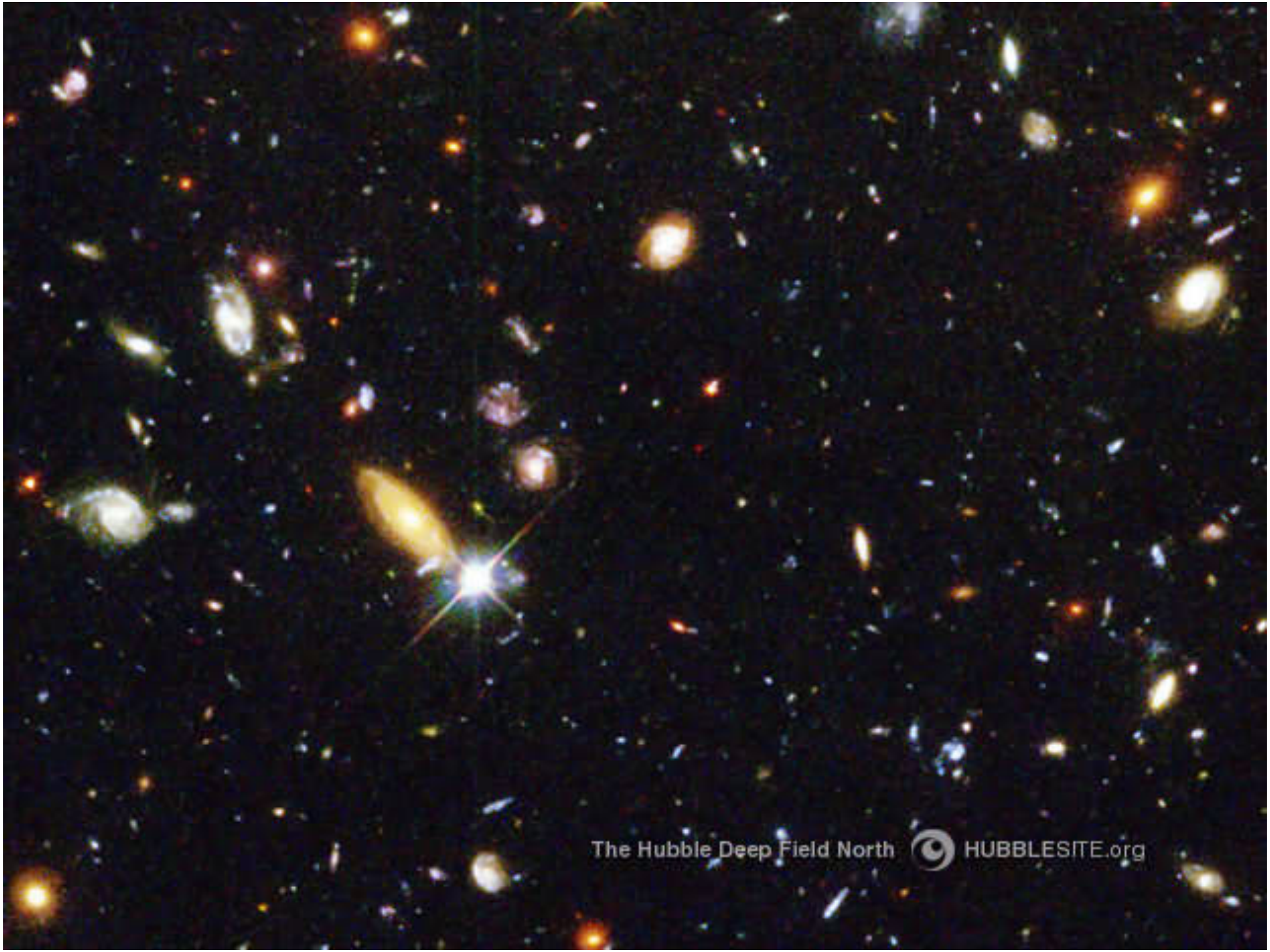
Collections of ~10^{11}~ 10^{12} Stars

galaxies

galaxies

groups

Hubble deep field

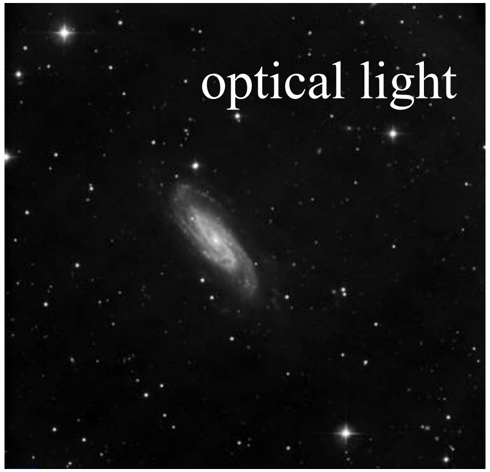


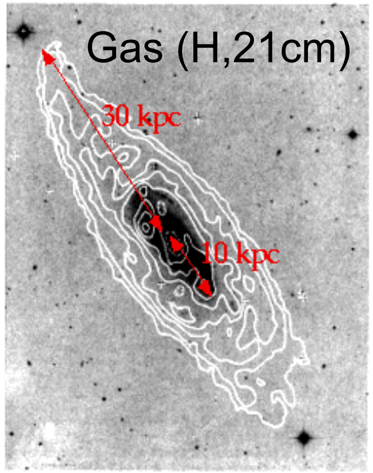
There is more than meets the eye

In the solar system sun + planets

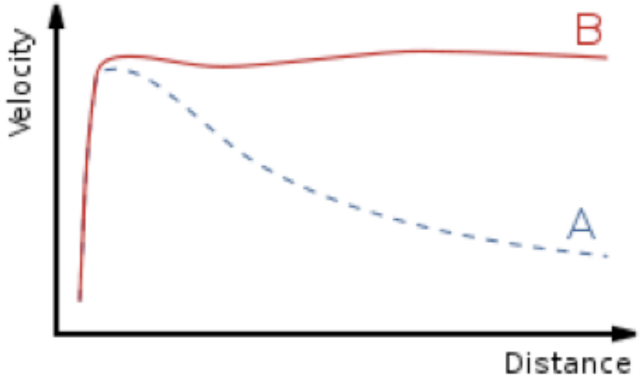
Mass-to-light ratio

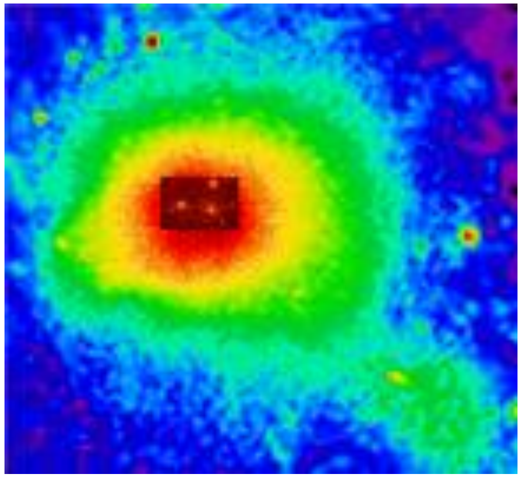
Let's consider galaxies





rotating





And clusters: Xrays

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

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

Content: Dark matter

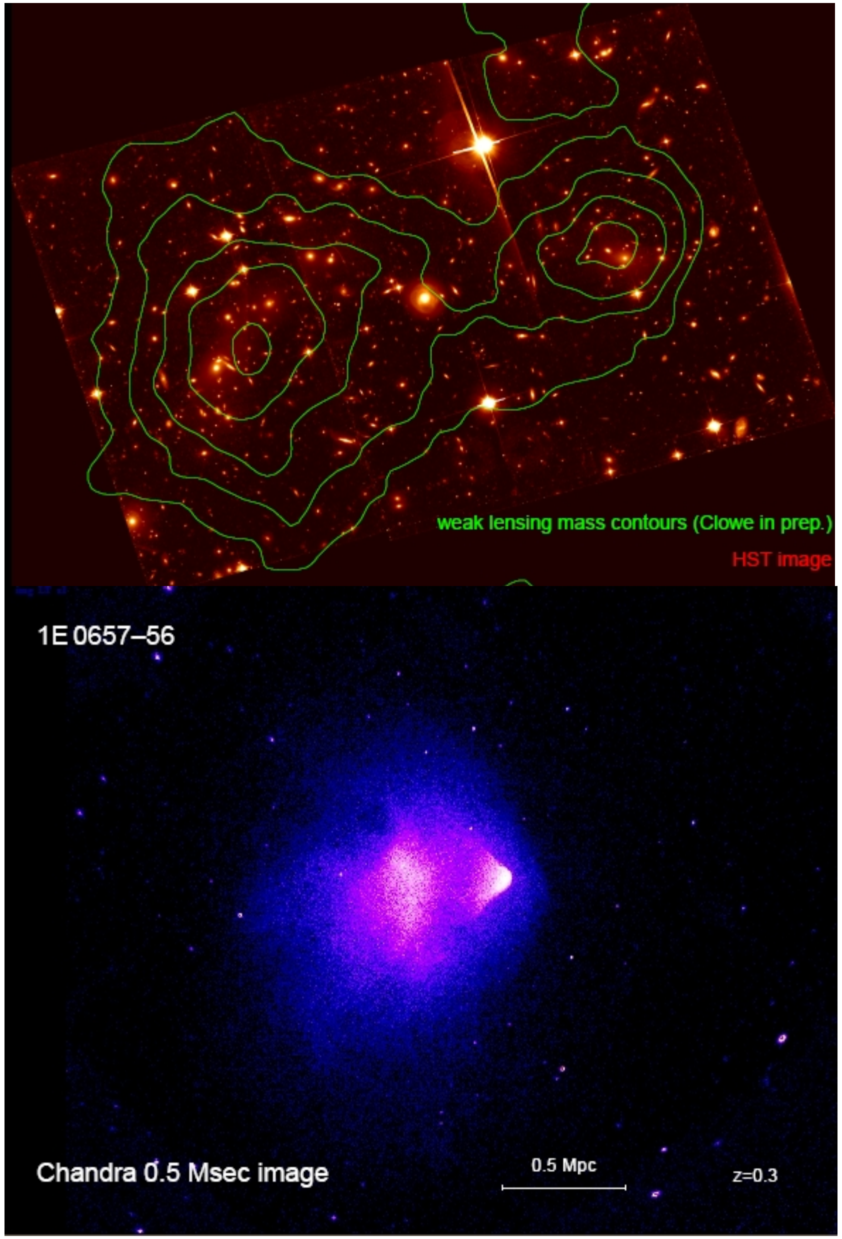
Dark matter

Gravitational lensing

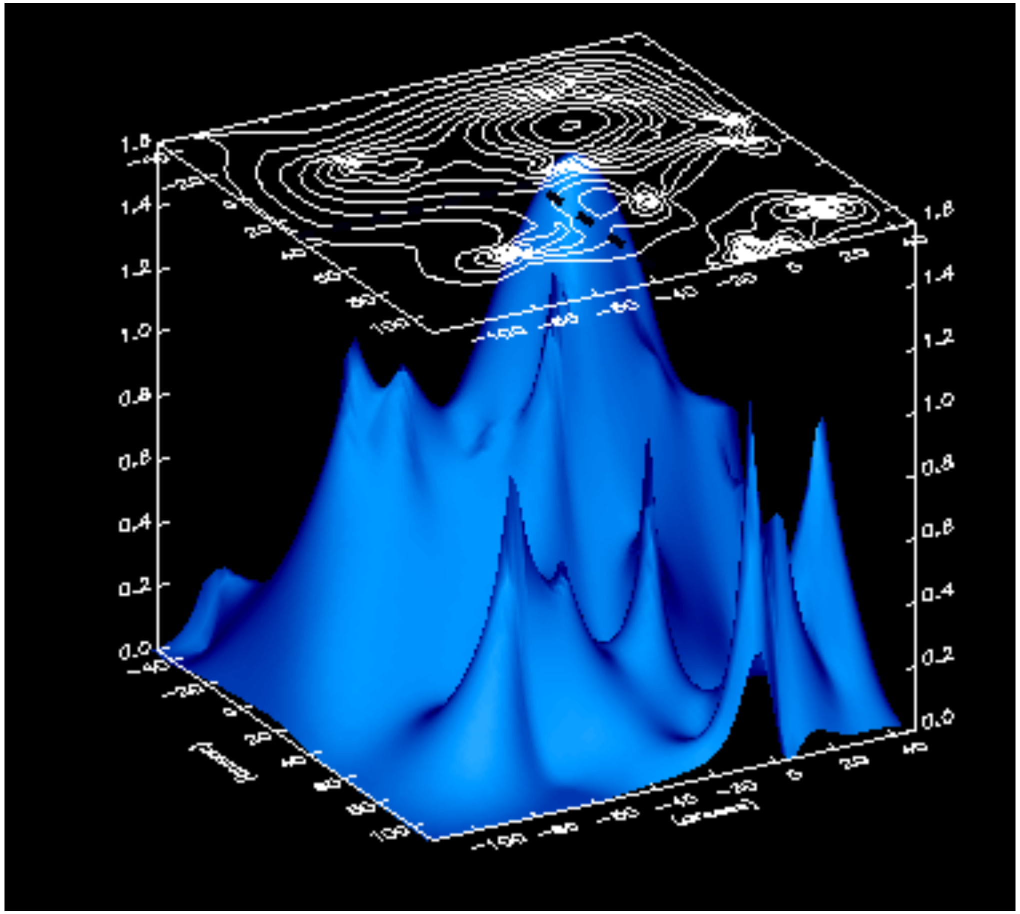
New evidence

REAL DATA!

Bullet cluster

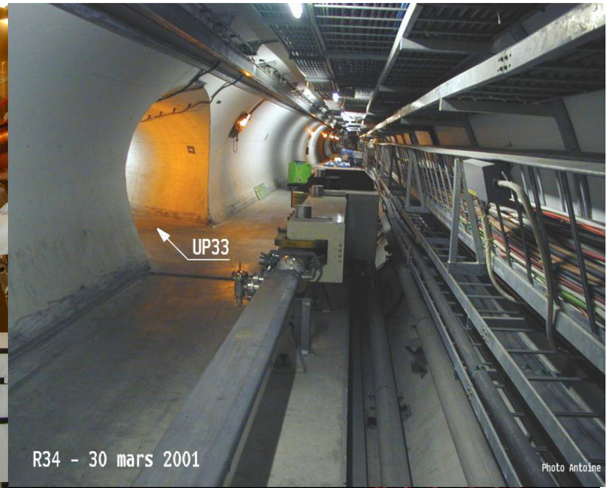


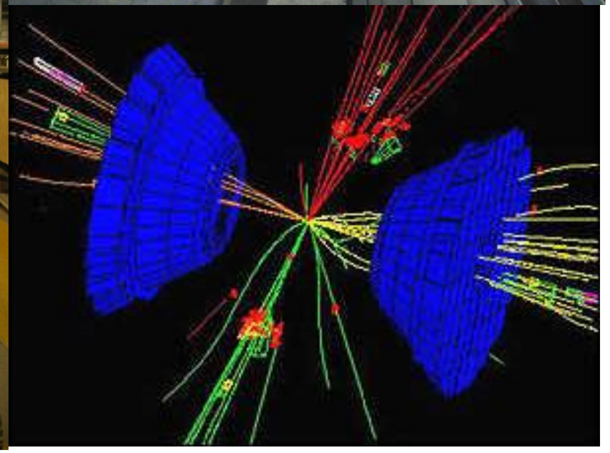
Reconstructed dark matter distribution of cluster Abell 2218

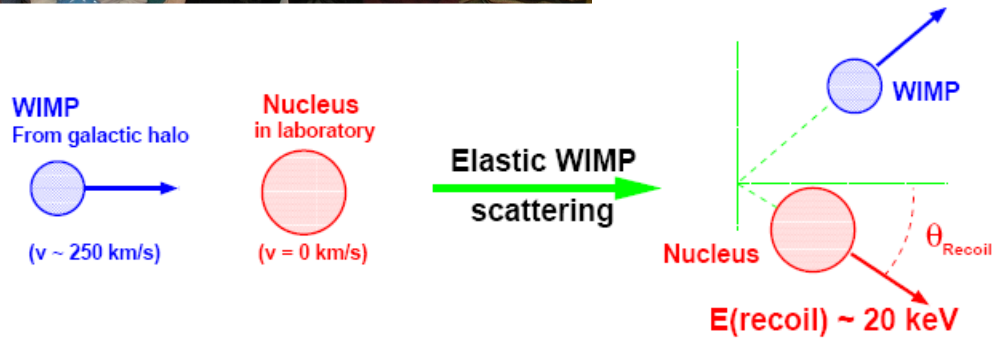


Abell 2218

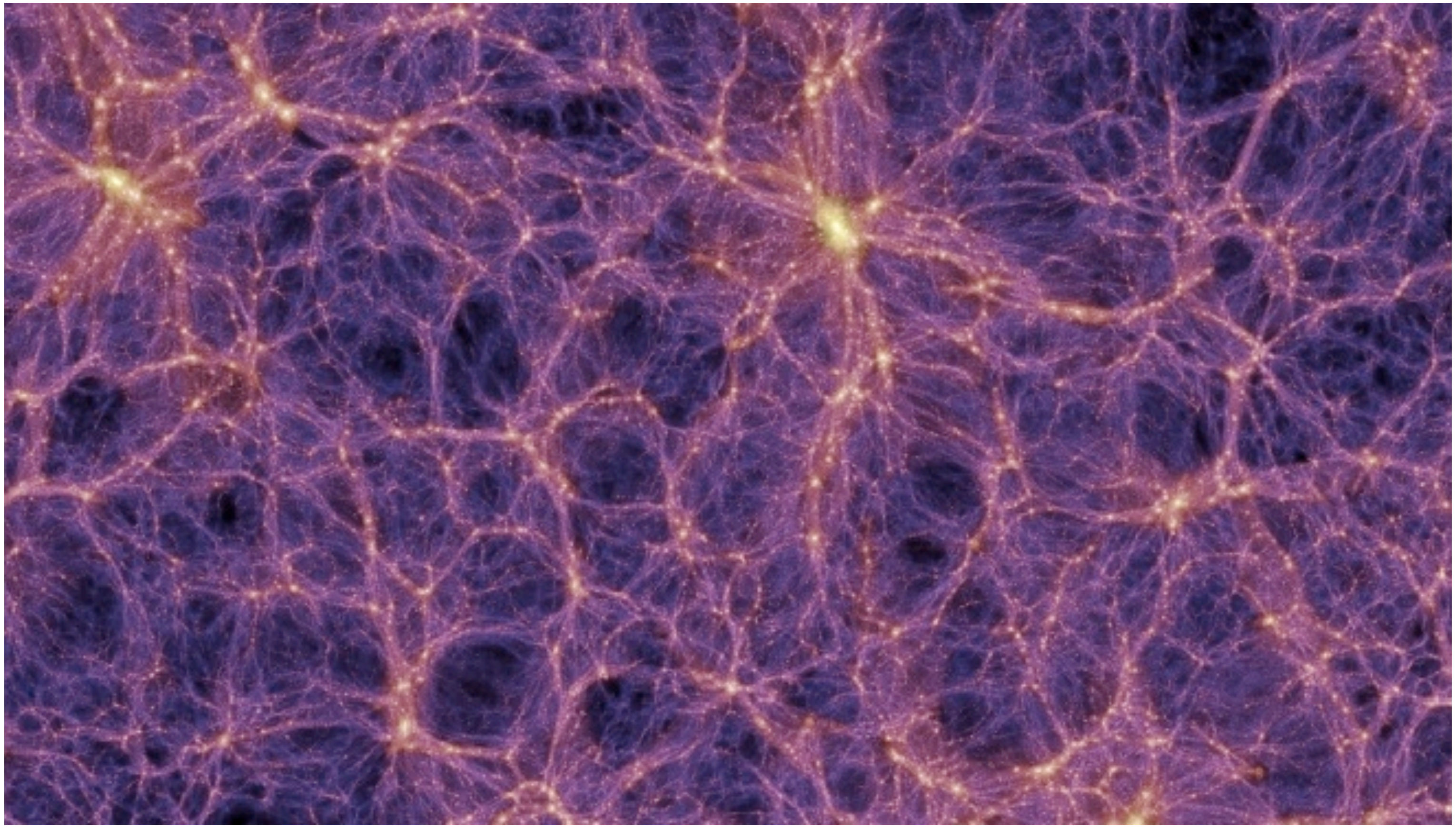
DIY dark matter





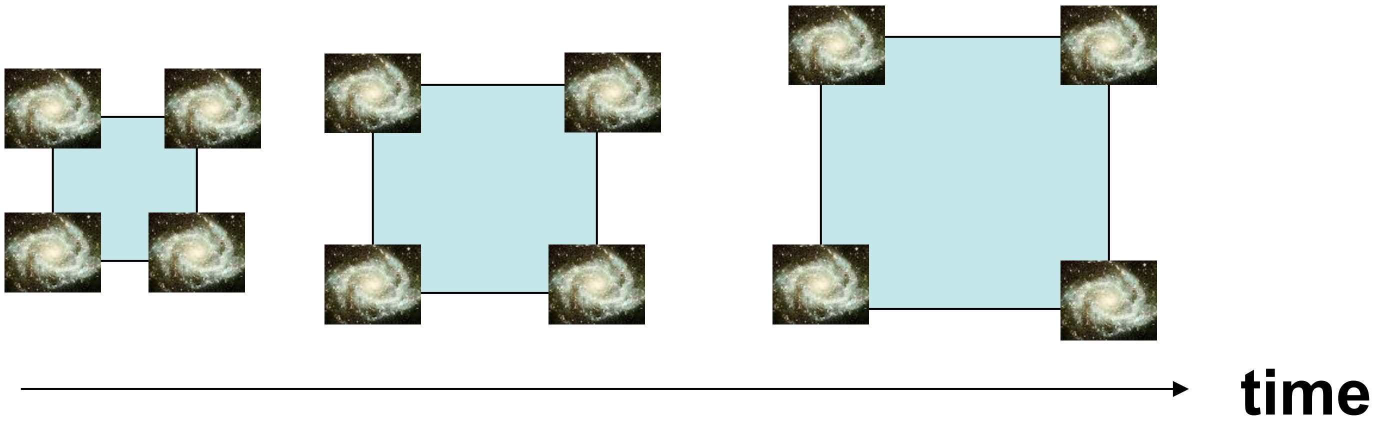


Computer simulation of dark matter distribution



Expanding Universe

The scale factor a



$r(t)=r(t_0)\ a(t)$ **Comoving coordinates!**

$v_{12}=dr_{12}/dt=\dot{a}\ r_{12}(t_0)=\dot{a}/a\ r_{12}(t)$ Looks like Hubble law

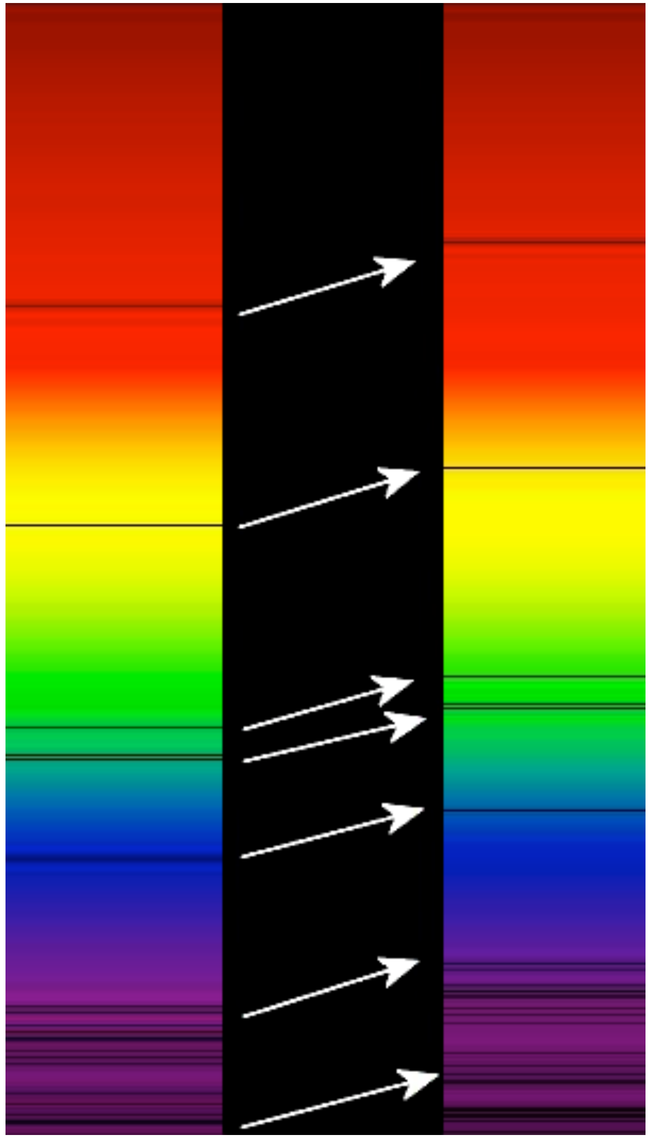
$$H=\frac{\dot{a}}{a}$$

Important!

Distances are difficult: velocities are “easy” Thank you Edwin Hubble

REDSHIFT

$$z = \frac{\lambda_{\rm obsv} - \lambda_{\rm emit}}{\lambda_{\rm emit}}$$ or $$1 + z = \frac{\lambda_{\rm obsv}}{\lambda_{\rm emit}}$$



In relativity:

$$1 + z = \gamma\left(1 + \frac{v_{||}}{c}\right)$$

$$z \approx \frac{v_{||}}{c}$$ For small velocity

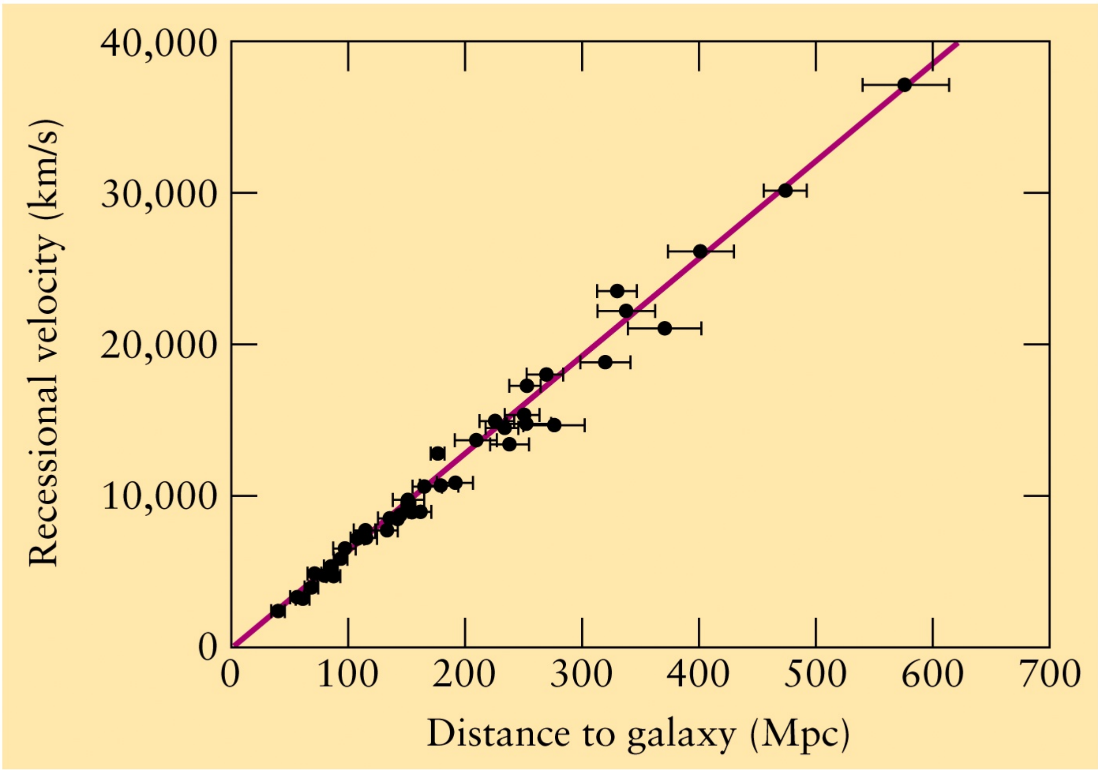
or $$1 + z = \frac{1 + v\cos(\theta)/c}{\sqrt{1 - v^2/c^2}}$$

Hubble's Law

$$cz = v = H_0 d$$

Ho=74.2 +- 3.8   km/s/Mpc

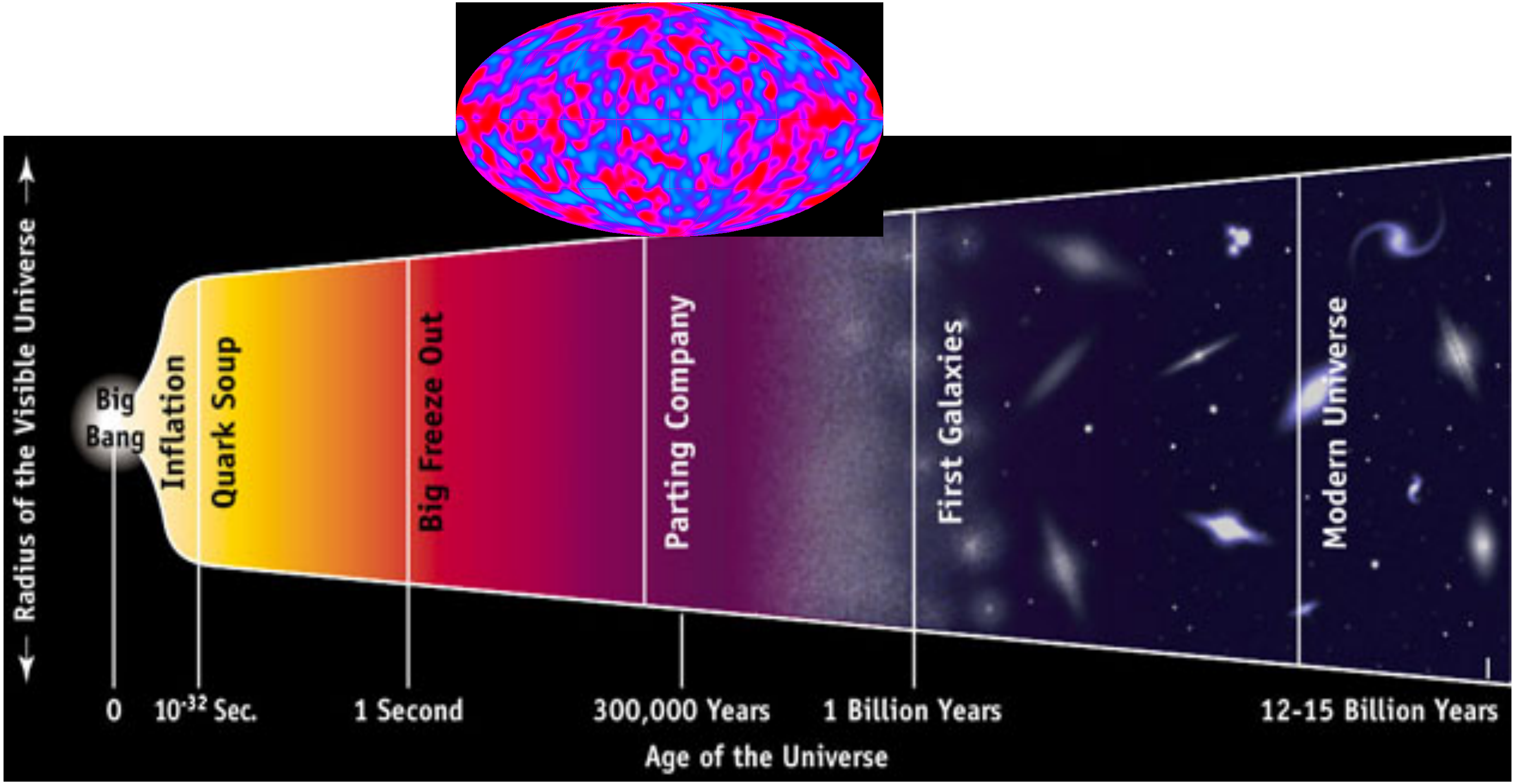
Hubble 1929
(PNAS vol 15)



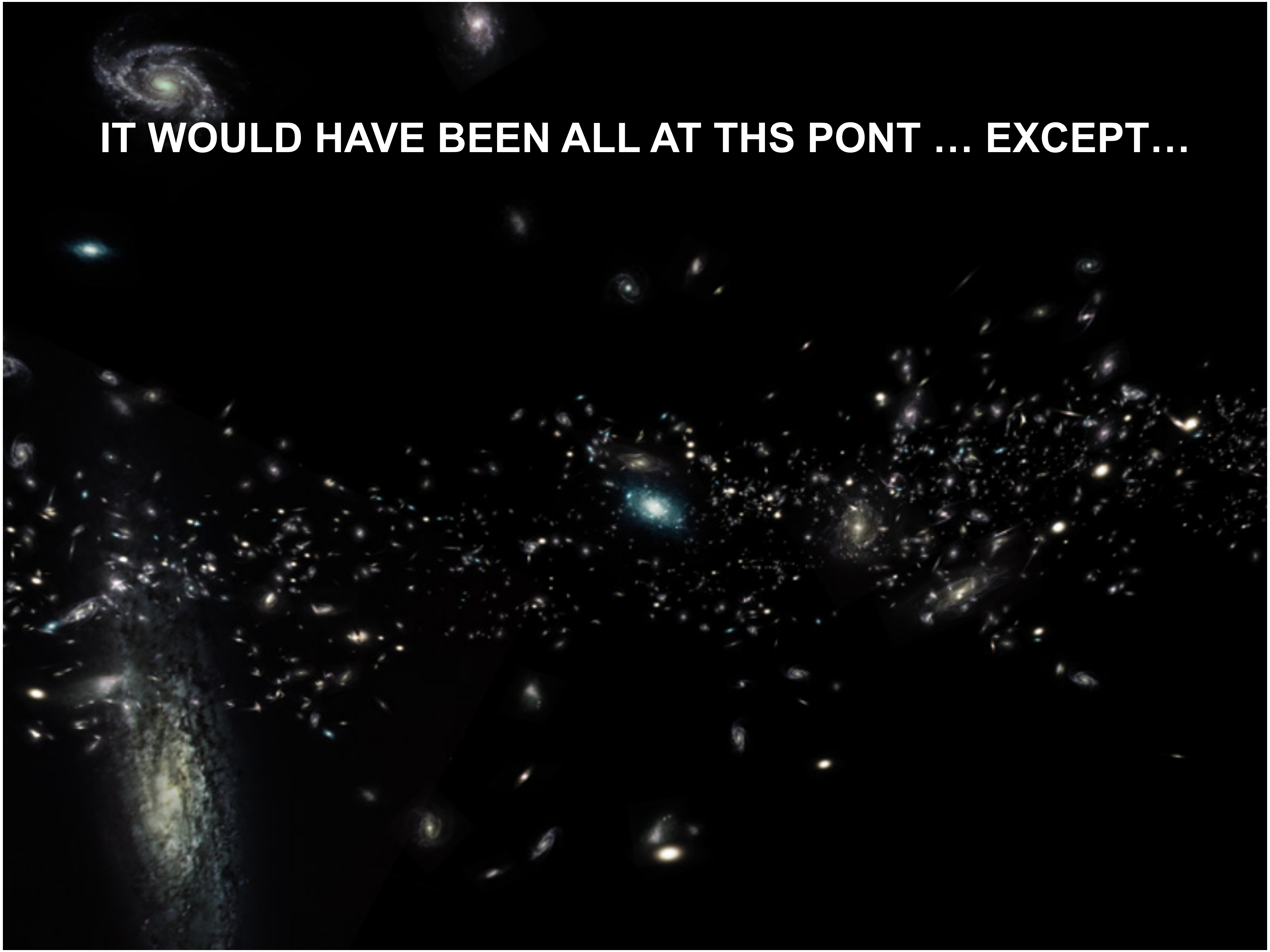
The universe is expanding!

The universe had a beginning!

The extremely successful BIG BANG theory!

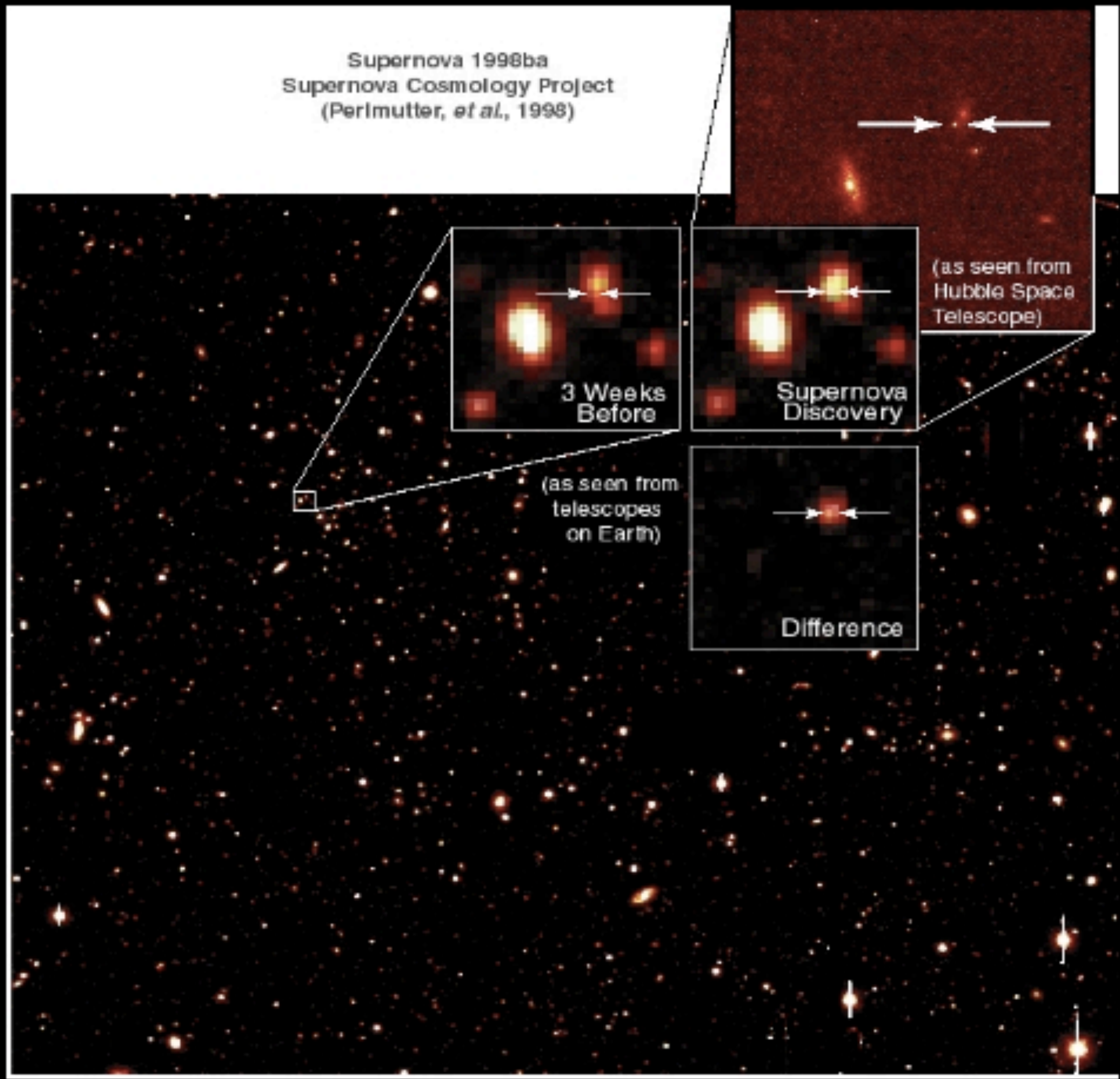


IT WOULD HAVE BEEN ALL AT THS PONT … EXCEPT…



Standard candles

Strategy: stare at one patch of the sky for a long time, waiting for a star to blow up.



1998!

Humm the expansion seems to accelerate…

Einstein's Greatest Blunder

1909: Einstein's general theory of relativity
predicts the expansion of the universe!

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

Courtesy of W.Kinney

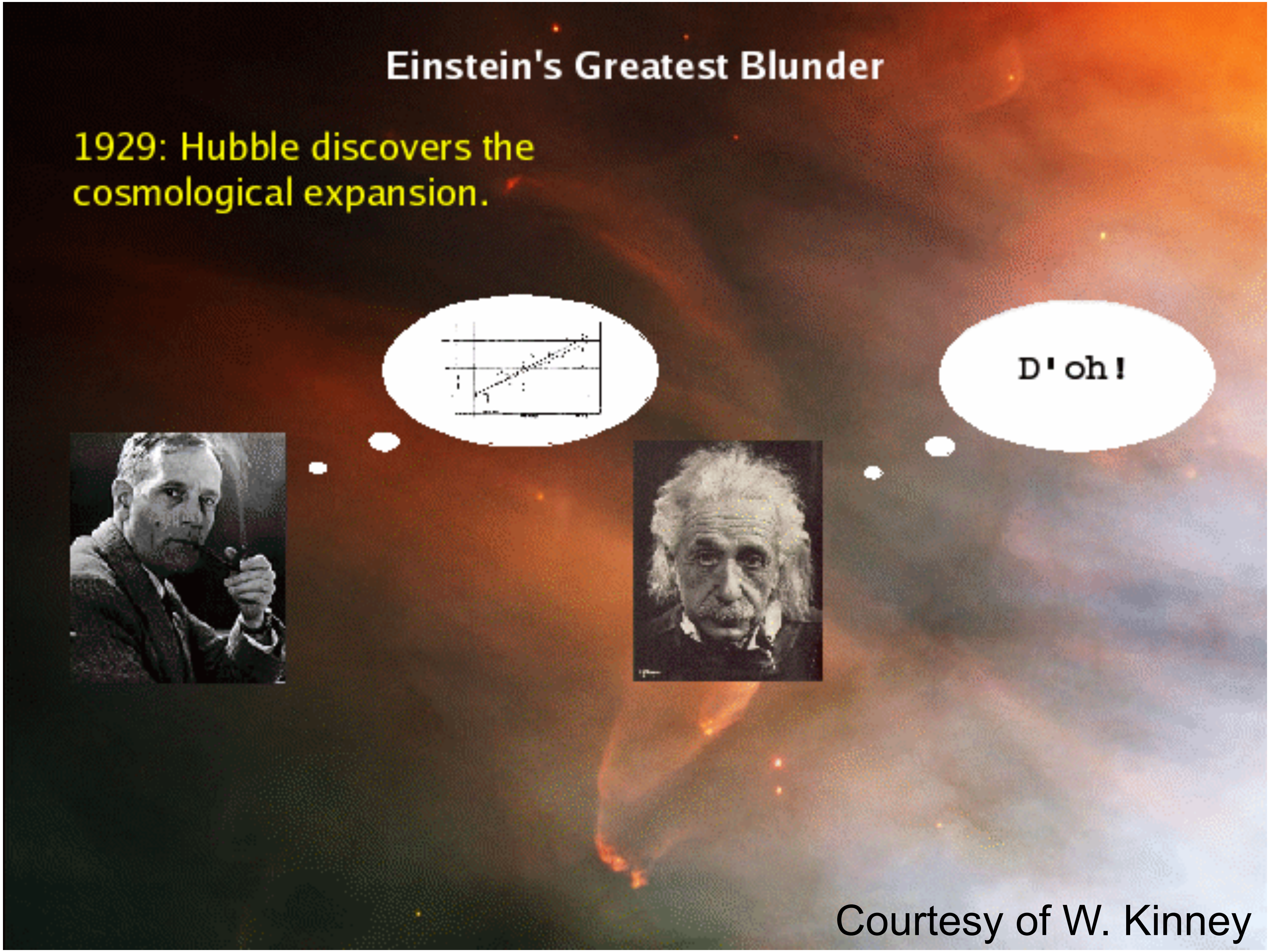
Einstein's Greatest Blunder

1909: Einstein's general theory of relativity
predicts the expansion of the universe!

$$G_{\mu\nu} = 8\pi T_{\mu\nu} + \Lambda\delta_{\mu\nu}$$

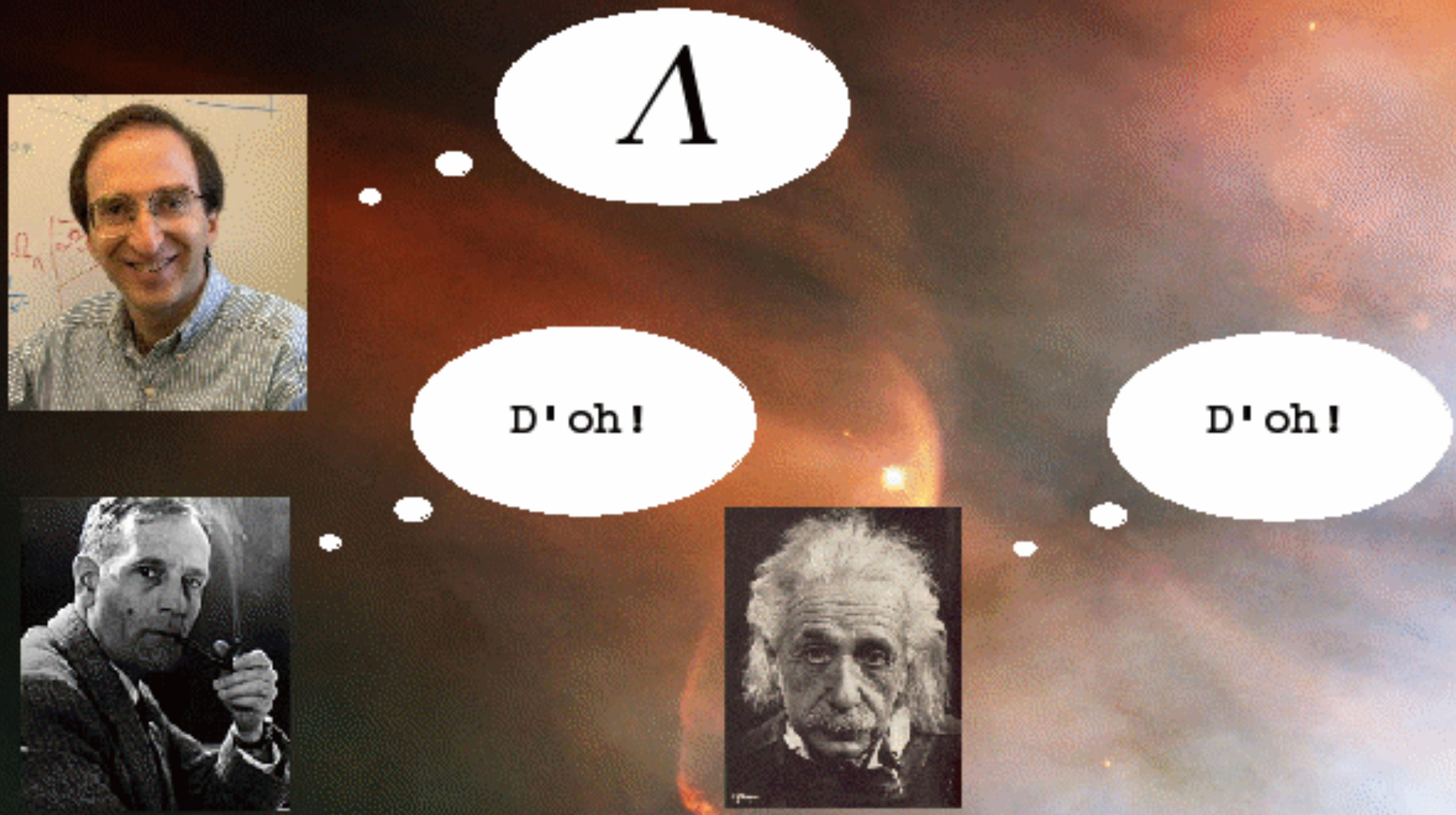
Einstein introduced a fudge factor to make the universe static: the *cosmological constant*,
Λ = the energy of empty space.

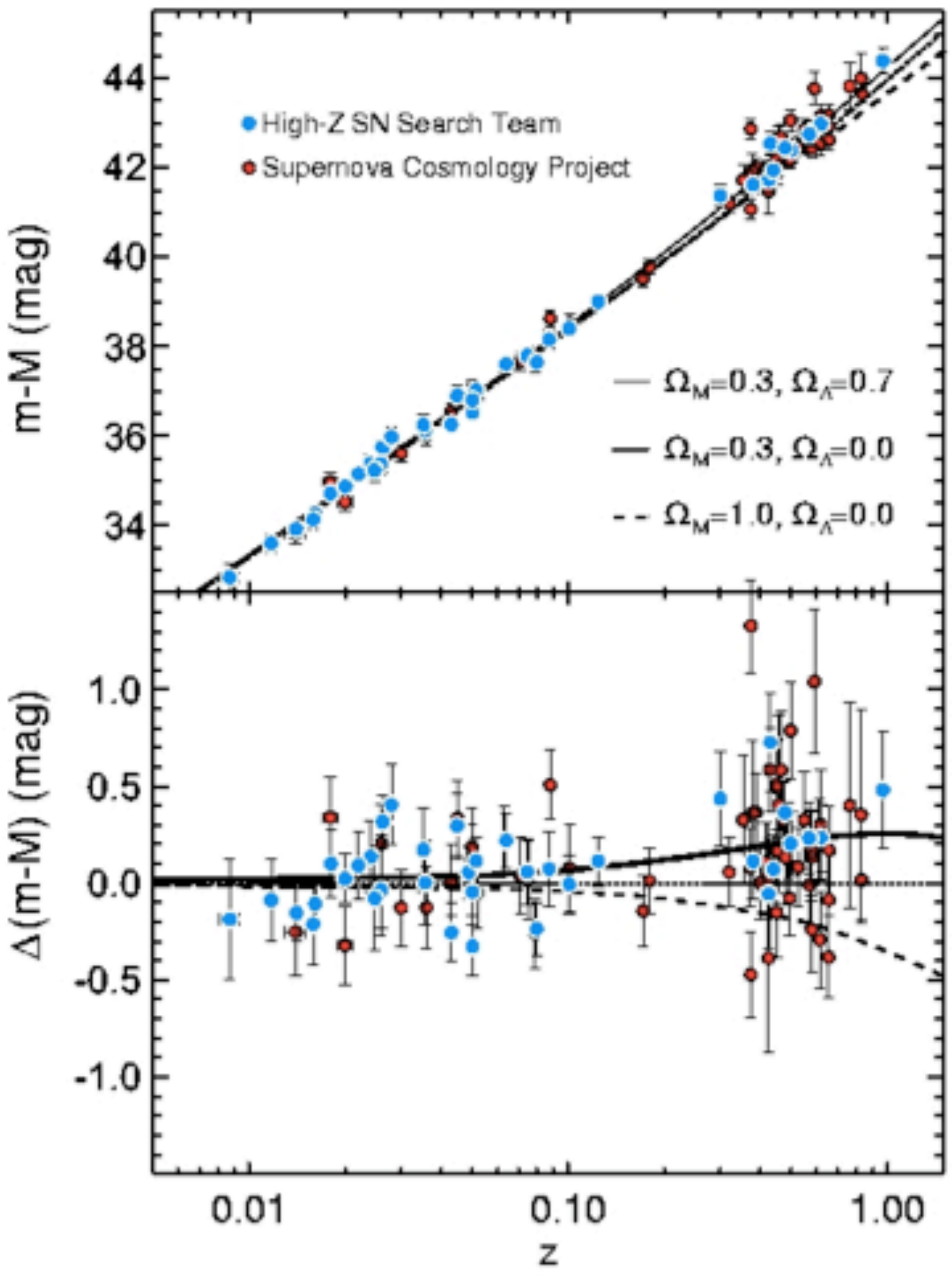
Courtesy of W.Kinney


Einstein's Greatest Blunder
1929: Hubble discovers the cosmological expansion.
D'oh!
Courtesy of W. Kinney

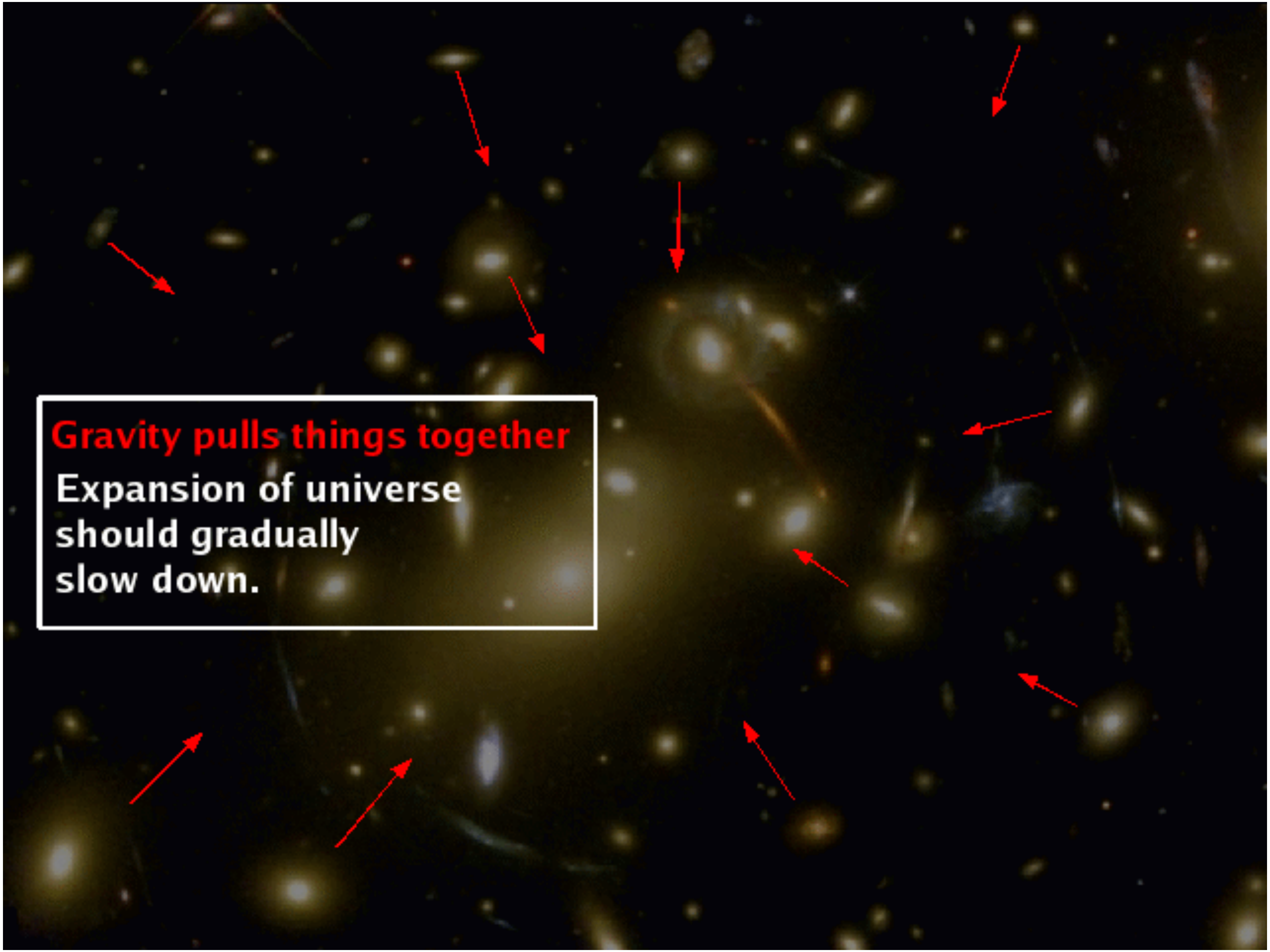
Einstein's Greatest Blunder

1998: Accelerating expansion





- This program gives most accurate value for Hubble's constant
  - H=74.2 km/s/Mpc, error<4%
- Find acceleration, not deceleration!
  - Very subtle, but really is there in the data!
  - Profound result!



Gravity pulls things together
Expansion of universe
should gradually
slow down.


Something is pushing the galaxies apart
DARK ENERGY

Friedmann equations

NOT independent!

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho(t) - \frac{kc^2}{R_0^2 a^2}$$

$$\dot{\epsilon} + 3\frac{\dot{a}}{a}(\epsilon + P) = 0$$

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

$$\rho(t)c^2 = \epsilon(t)$$

If you want to solve for

$$a(t), \epsilon(t), P(t)$$

need more info…

$$P = P(\epsilon)$$

$$P = w\epsilon$$

Interesting cases:

Non-relativistic matter	$w \simeq 0$
R adiation	$w = 1/3$
Accelerating fluid	$w < -1/3$
Cosmological constant	$w = -1$

This is weird……
but looks like we are stuck with it

Parameters: the smooth Universe

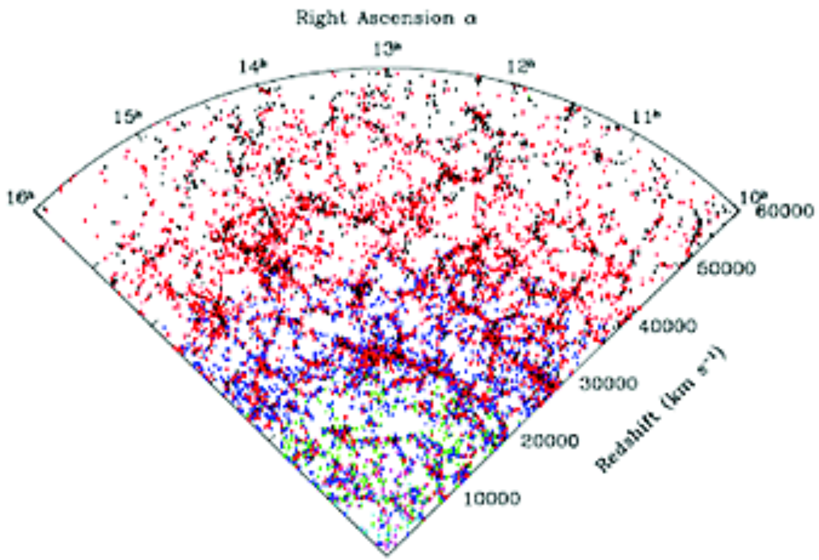
$$\Omega = \Omega_c + \Omega_b + \Omega_\Lambda \qquad \Omega_m = \Omega_c + \Omega_b$$

+radiation

During the Universe expansion different components scale
Differently (eq. of state parameter)

Next: the perturbations

Parameters describing structure



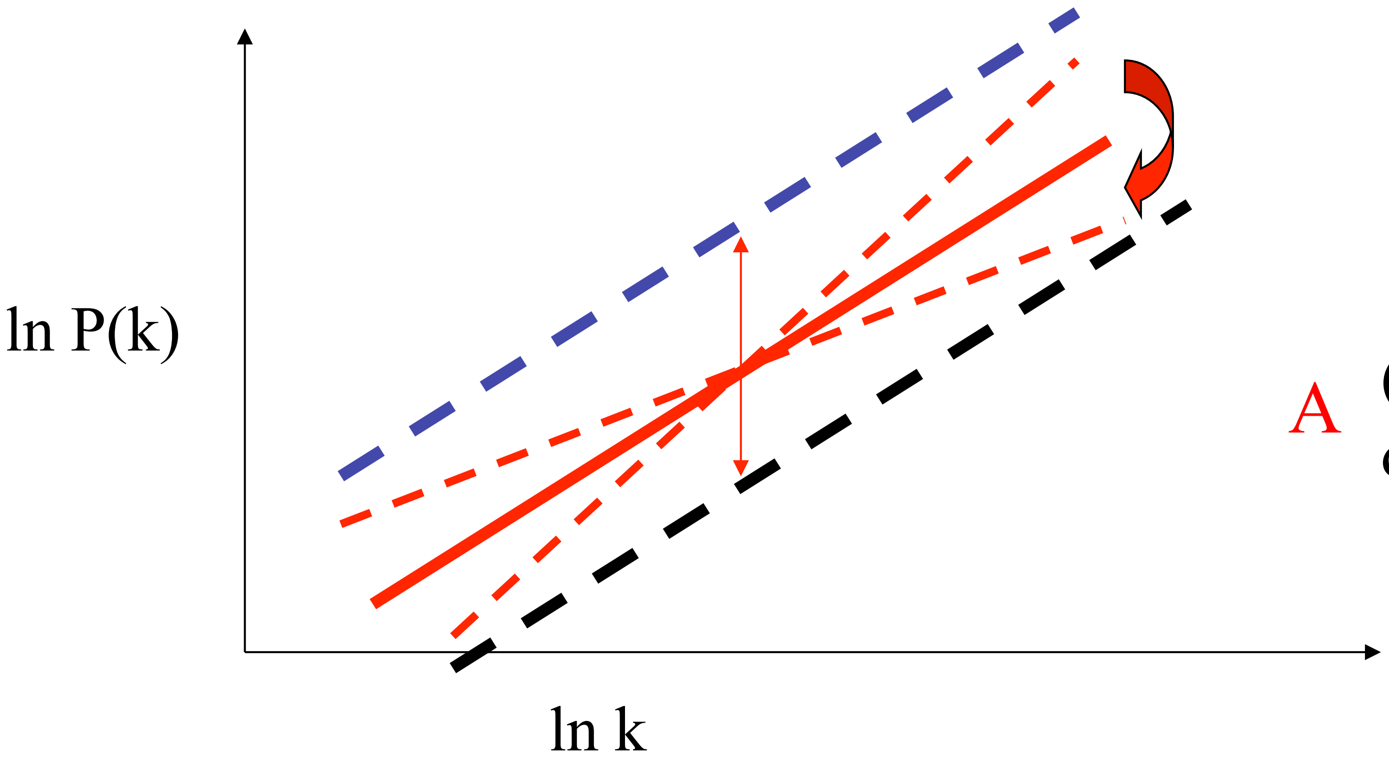
These fluctuations grew under gravity

THE POWER SPECTRUM

Primordial power spectrum= $A\ k^n$

slope

Amplitude of the power law



A (convention dependent)

The standard cosmological model (LCDM)

Only 6 parameters, fits observations of the Universe from z=1100 to today.

Spatially flat, made of baryonic matter, cold dark matter, cosmological constant, radiation-unimportant today-, present-day expansion rate

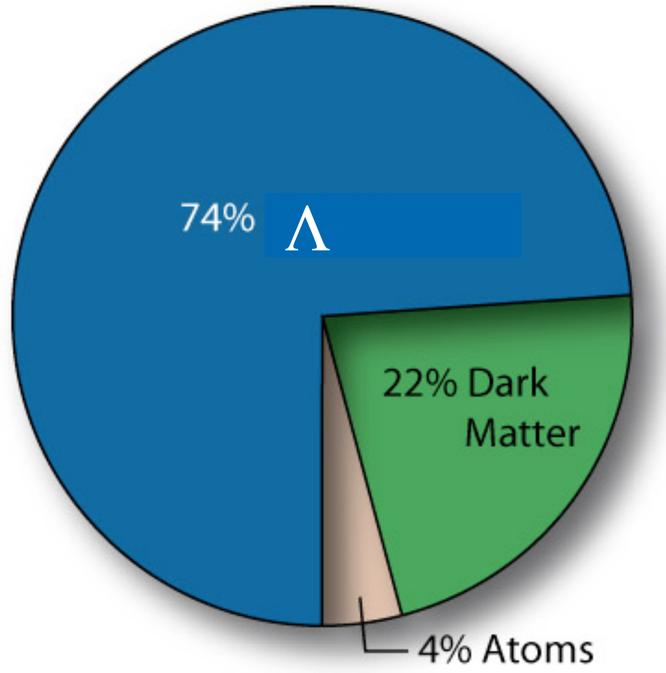
inflationary scenario generated perturbations: amplitude and slope of the power spectrum of primordial perturbations

Optical depth (reionization)

Extremely successful model

The standard cosmological model

ΛCDM model



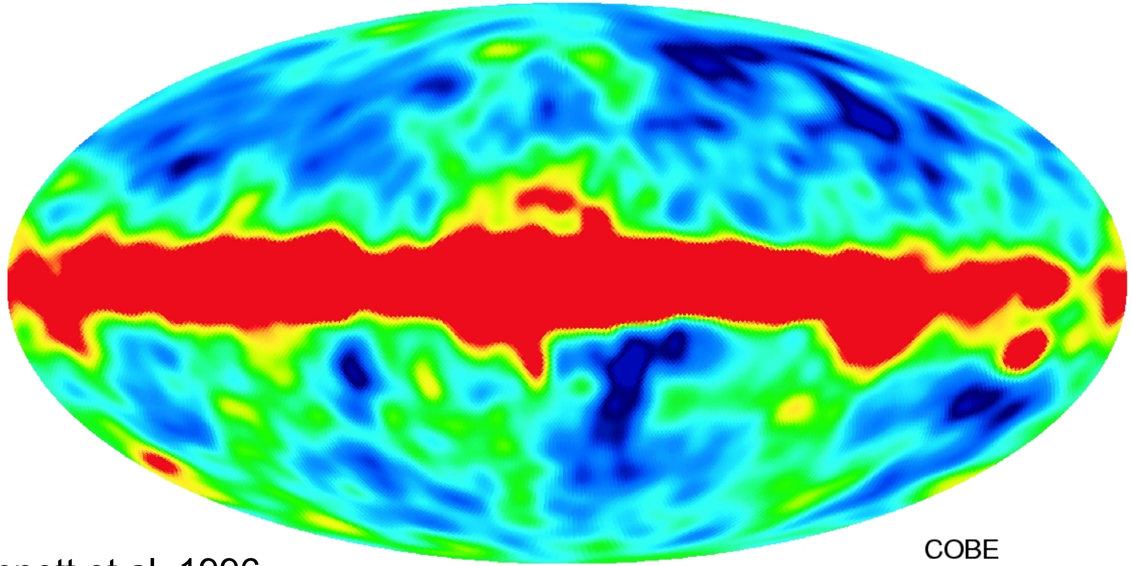
Spatially flat Universe

Power-law, primordial power spectrum

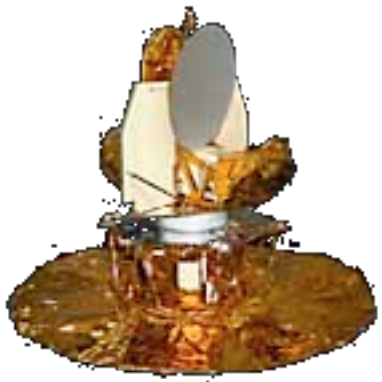
Only 6 parameters

Parameter	WMAP Only	WMAP +CBI+VSA	WMAP+ACBAR +BOOMERanG	WMAP + 2dFGRS	WMAP+ SDSS	WMAP+ SNLS	WMAP + SN Gold
$100\Omega_b h^2$	$2.233^{+0.072}_{-0.091}$	$2.212^{+0.066}_{-0.084}$	$2.231^{+0.070}_{-0.088}$	$2.223^{+0.066}_{-0.083}$	$2.233^{+0.062}_{-0.086}$	$2.233^{+0.069}_{-0.088}$	$2.227^{+0.065}_{-0.082}$
$\Omega_m h^2$	$0.1268^{+0.0072}_{-0.0095}$	$0.1233^{+0.0070}_{-0.0086}$	$0.1259^{+0.0077}_{-0.0095}$	$0.1262^{+0.0045}_{-0.0062}$	$0.1329^{+0.0056}_{-0.0075}$	$0.1295^{+0.0056}_{-0.0072}$	$0.1349^{+0.0056}_{-0.0071}$
h	$0.734^{+0.028}_{-0.038}$	$0.743^{+0.027}_{-0.037}$	$0.739^{+0.028}_{-0.038}$	$0.732^{+0.018}_{-0.025}$	$0.709^{+0.024}_{-0.032}$	$0.723^{+0.021}_{-0.030}$	$0.701^{+0.020}_{-0.026}$
A	$0.801^{+0.043}_{-0.054}$	$0.796^{+0.042}_{-0.052}$	$0.798^{+0.046}_{-0.054}$	$0.799^{+0.042}_{-0.051}$	$0.813^{+0.042}_{-0.052}$	$0.808^{+0.044}_{-0.051}$	$0.827^{+0.045}_{-0.053}$
τ	$0.088^{+0.028}_{-0.034}$	$0.088^{+0.027}_{-0.033}$	$0.088^{+0.030}_{-0.033}$	$0.083^{+0.027}_{-0.031}$	$0.079^{+0.029}_{-0.032}$	$0.085^{+0.028}_{-0.032}$	$0.079^{+0.028}_{-0.034}$
n_s	$0.951^{+0.015}_{-0.019}$	$0.947^{+0.014}_{-0.017}$	$0.951^{+0.015}_{-0.020}$	$0.948^{+0.014}_{-0.018}$	$0.948^{+0.015}_{-0.018}$	$0.950^{+0.015}_{-0.019}$	$0.946^{+0.015}_{-0.019}$
σ_8	$0.744^{+0.050}_{-0.060}$	$0.722^{+0.043}_{-0.053}$	$0.739^{+0.047}_{-0.059}$	$0.737^{+0.033}_{-0.045}$	$0.772^{+0.036}_{-0.048}$	$0.758^{+0.038}_{-0.052}$	$0.784^{+0.035}_{-0.049}$
Ω_m	$0.238^{+0.030}_{-0.041}$	$0.226^{+0.026}_{-0.036}$	$0.233^{+0.029}_{-0.041}$	$0.236^{+0.016}_{-0.024}$	$0.266^{+0.026}_{-0.036}$	$0.249^{+0.024}_{-0.031}$	$0.276^{+0.023}_{-0.031}$

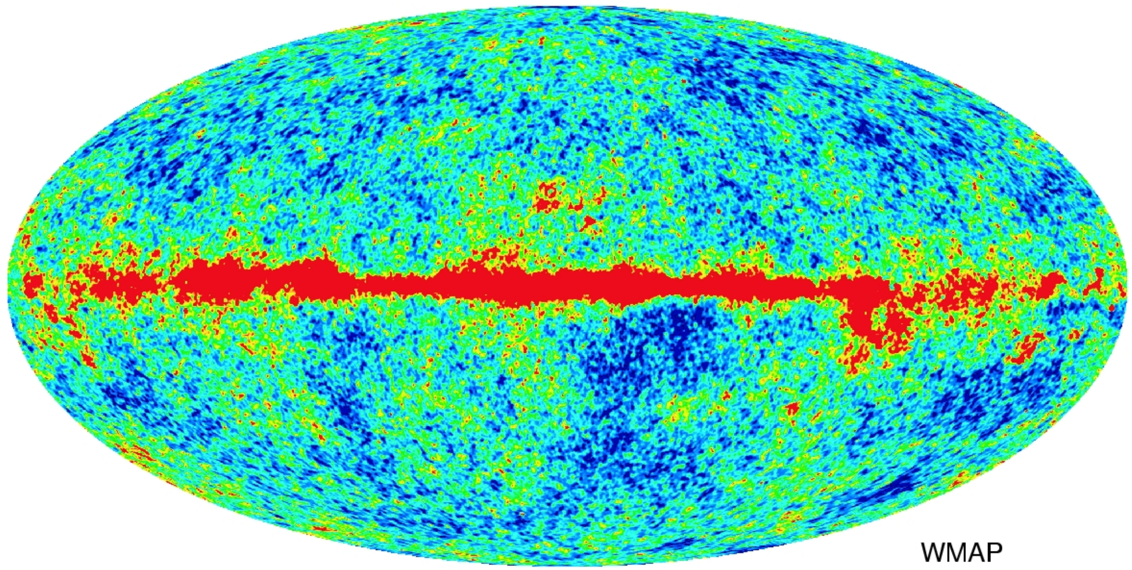
COBE 1992



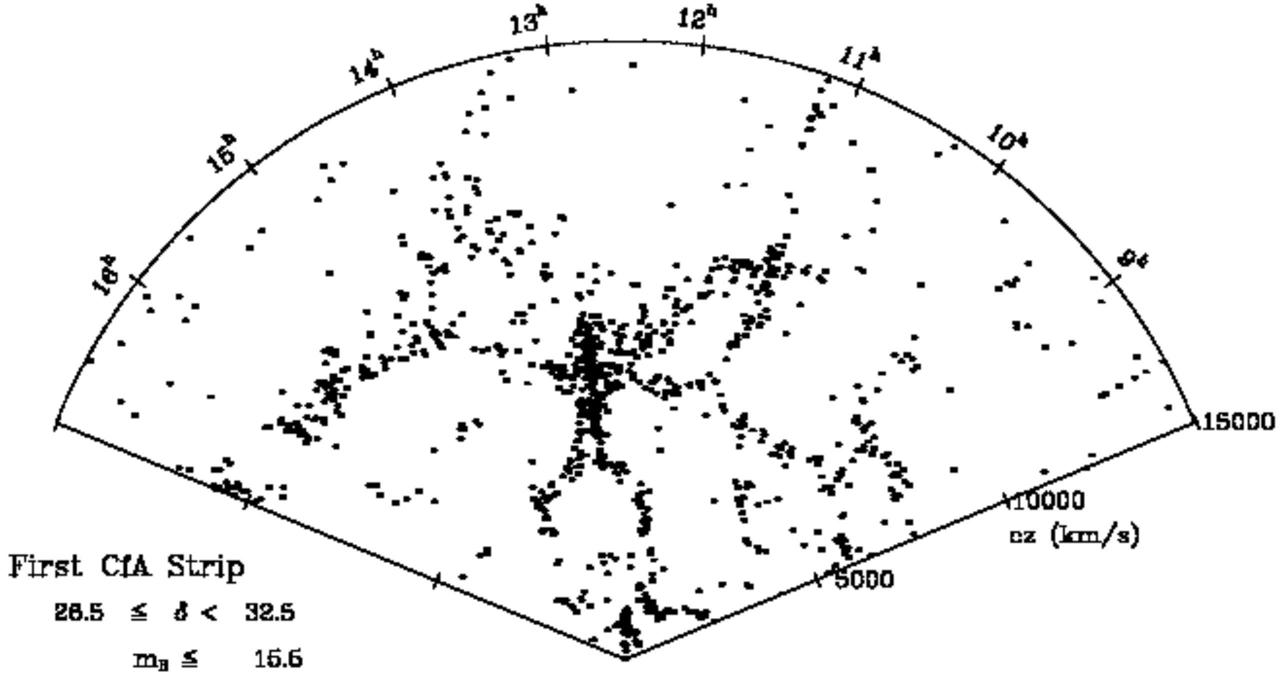
Bennett et al. 1996



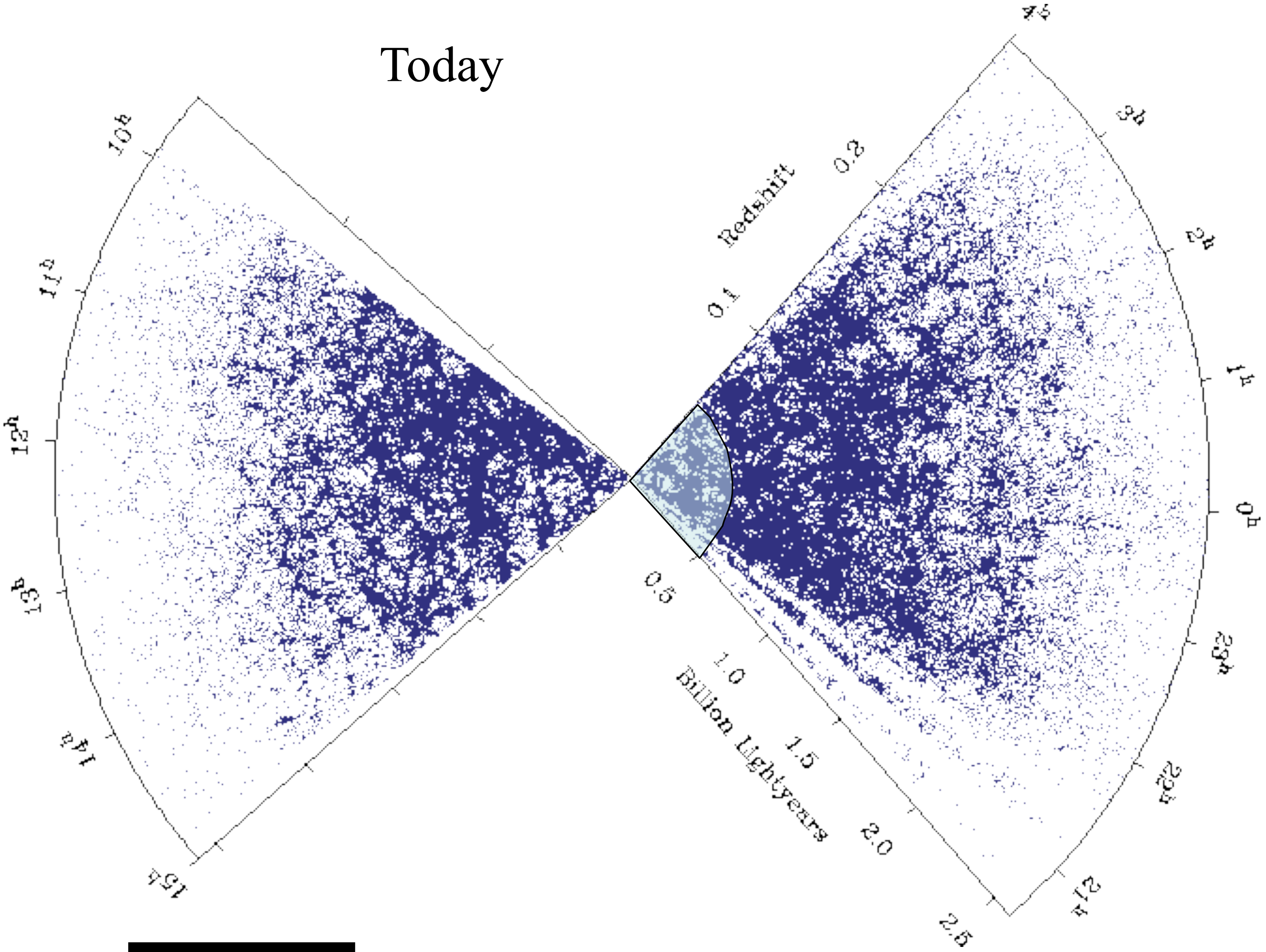
WMAP 2003



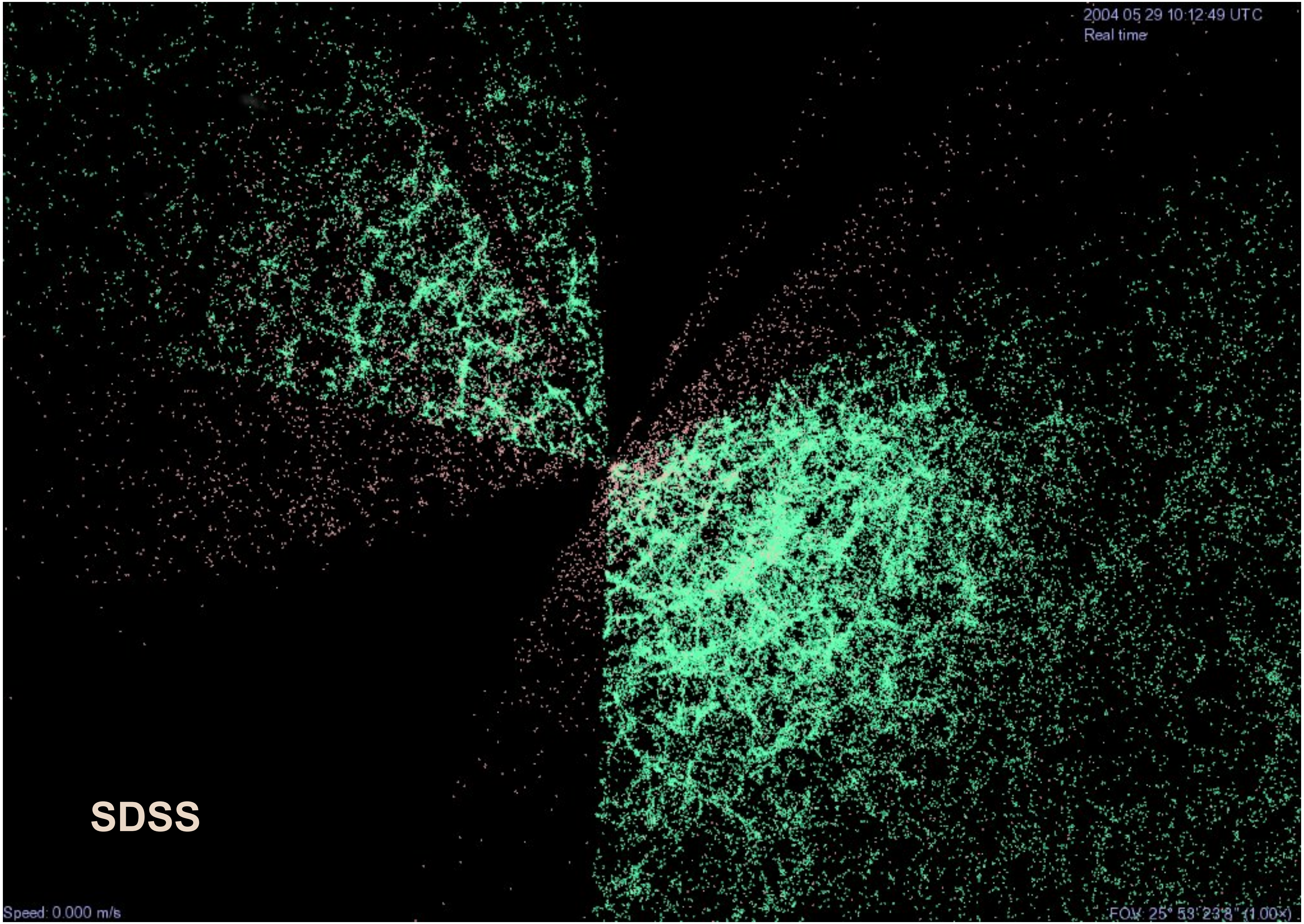
Bennett et al 2003


13ʰ
12ʰ
14ʰ
11ʰ
15ʰ
10ʰ
16ʰ
9ʰ
15000
10000
cz (km/s)
5000
First CfA Strip
26.5 ≤ δ < 32.5
m_B ≤ 15.5

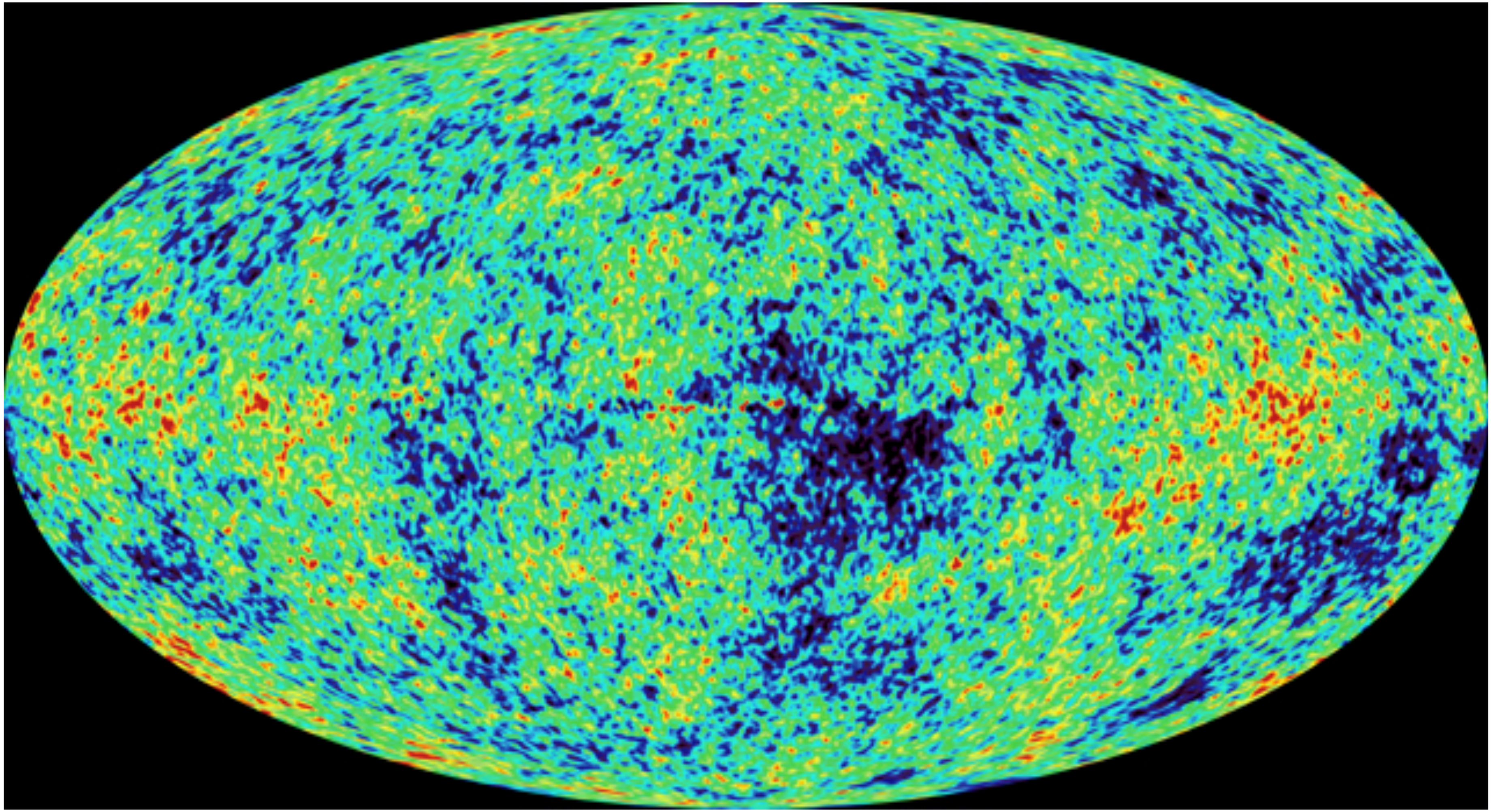
Today



2dFGRS


2004 05 29 10:12:49 UTC
Real time
SDSS
Speed: 0.000 m/s
FOV: 25° 53' 23.8" (1.00×)

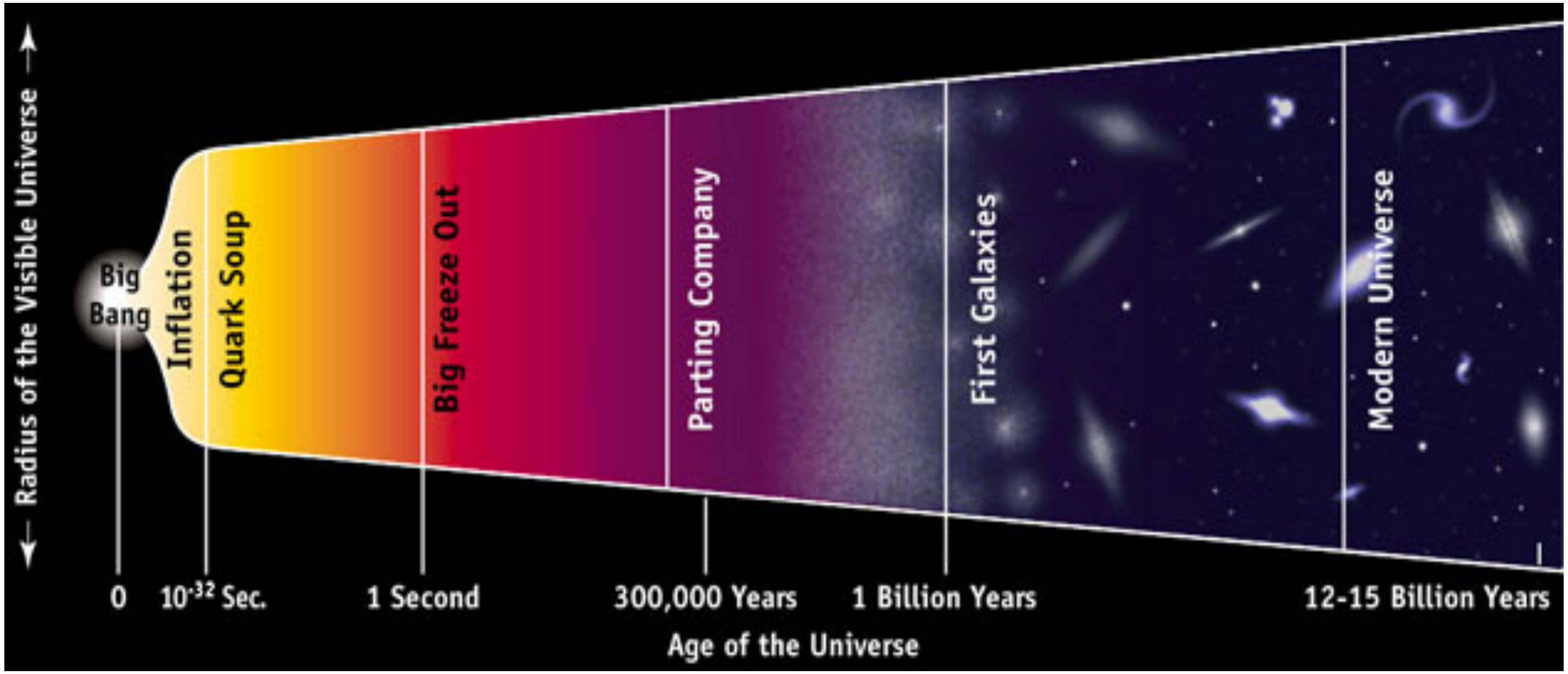
The Cosmic Microwave background



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.

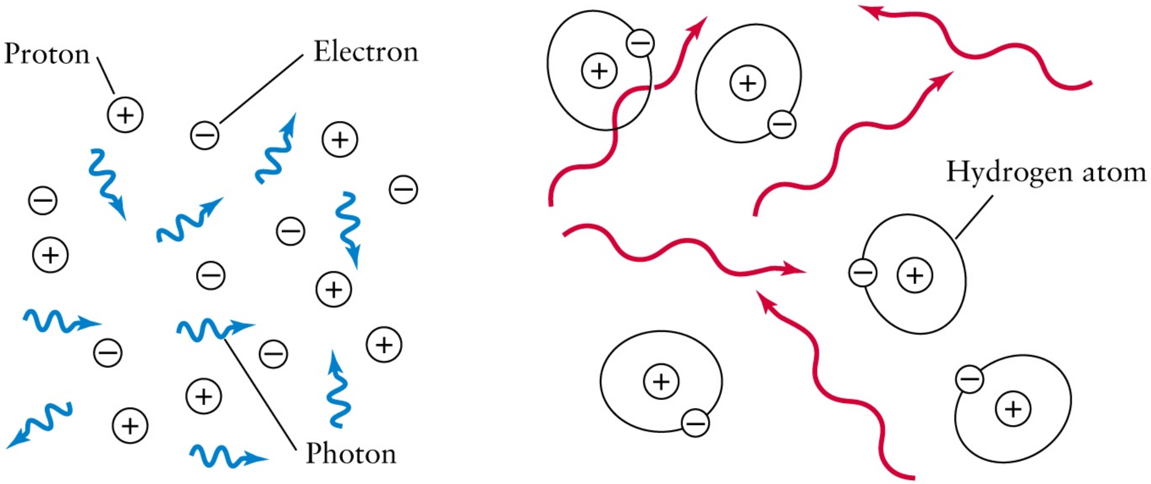


The cosmic microwave background (CMB) radiation

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.

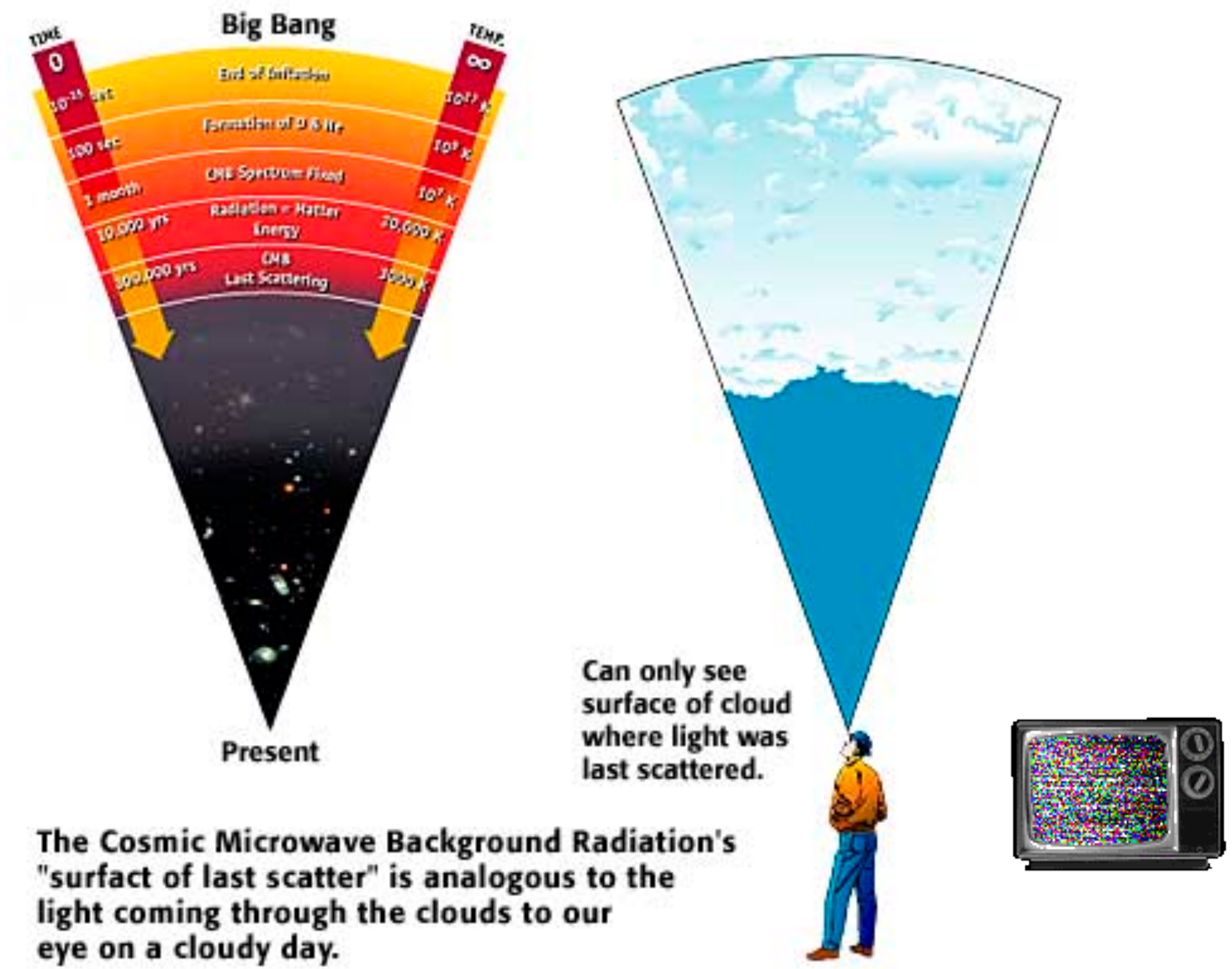
But in the early universe, when it was much warmer, the gas would have been ionized, and the universe opaque to light—as if you were in a dense fog.

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



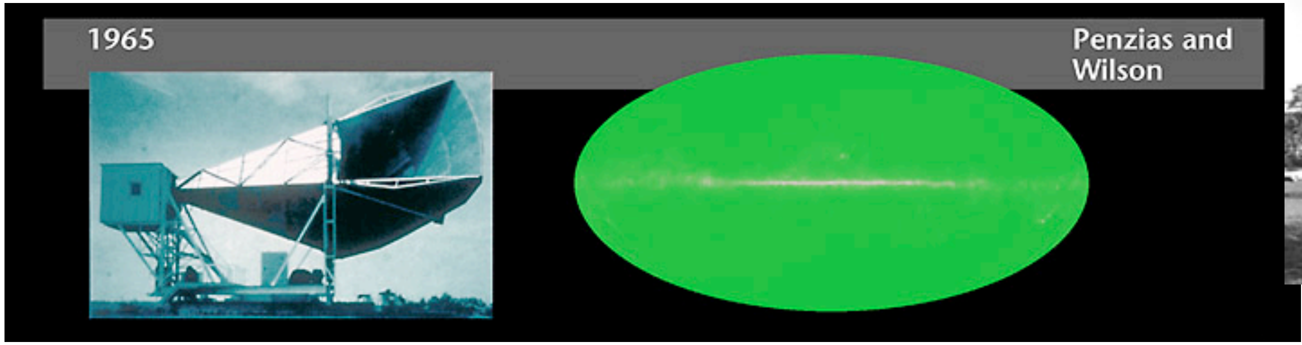
a Before recombination b After recombination

The last scattering surface: a snapshot of the early universe



Some history

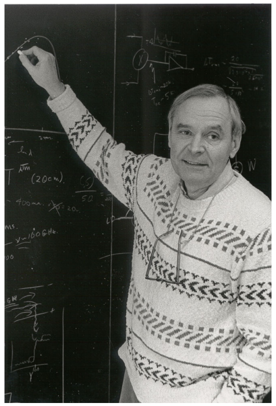
Discovery

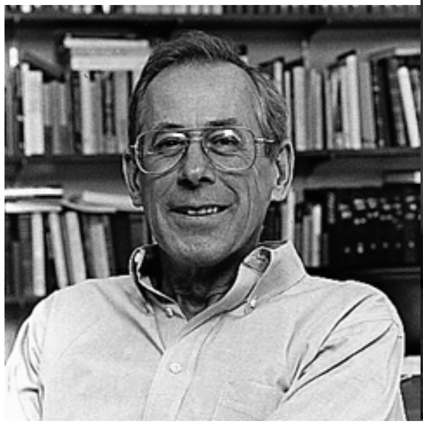


1978 Nobel

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.

"The primordial fireball"



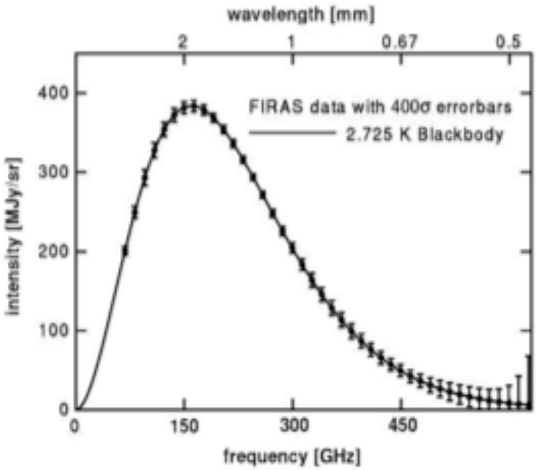


Support to the hot big bang theory

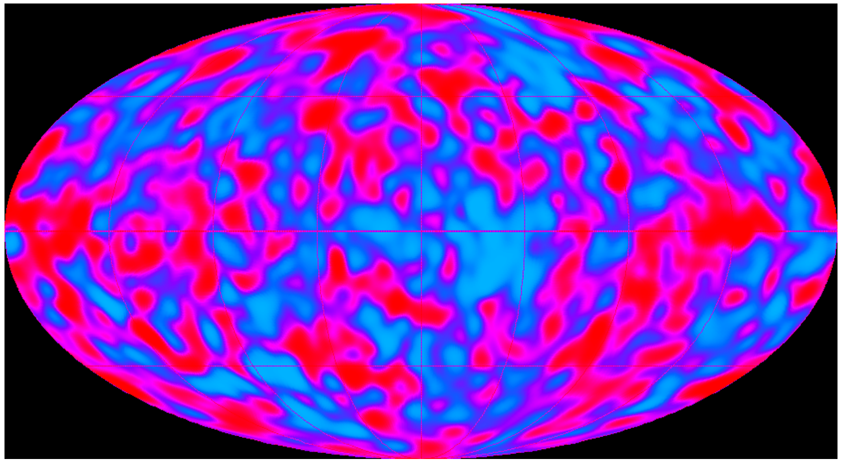
"Well boys, we have been scooped"

Some history

COBE (1992): Nobel prize in Physics in 2006



Mather: for measuring the CMB to be a Blackbody



Smoot: for measuring the tiny temperature variations

Density fluctuations: seeds of cosmological structures

"These measurements... marked the inception of cosmology as a precise science"

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!!!!

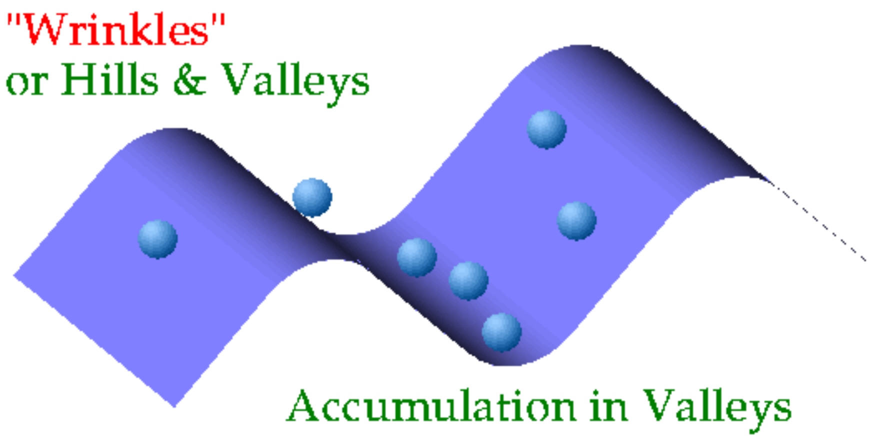
This has puzzled cosmologists for decades and (with hindsight)
Is one of the crucial evidences for DARK MATTER
(and dark energy)

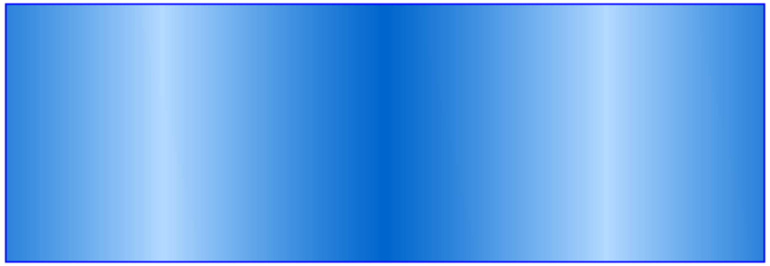
But first…

Too difficult…

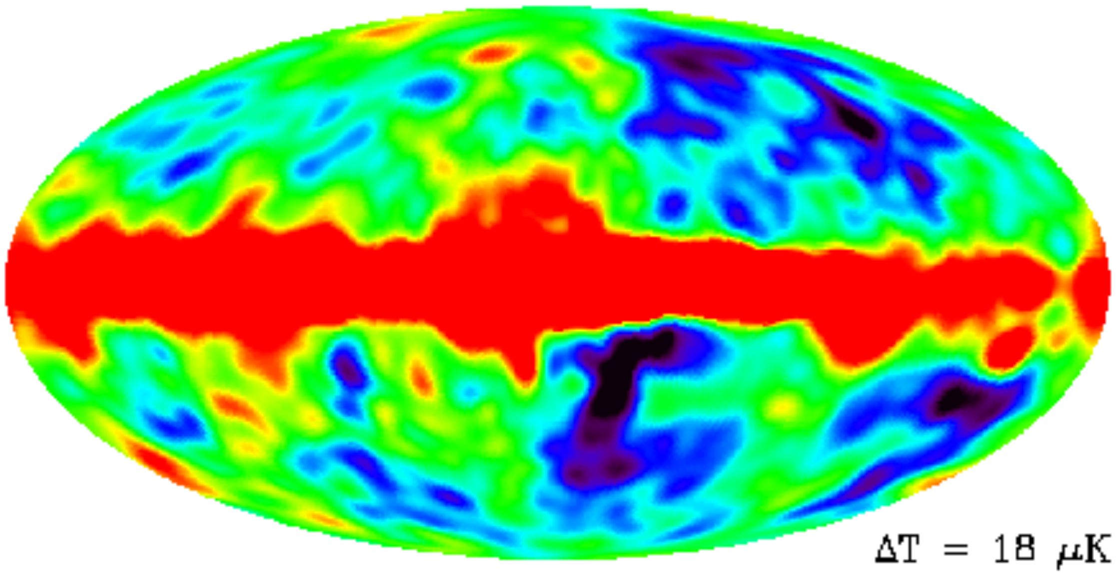
Where do the perturbations come from?

How is that we see the perturbations?





"Top View"

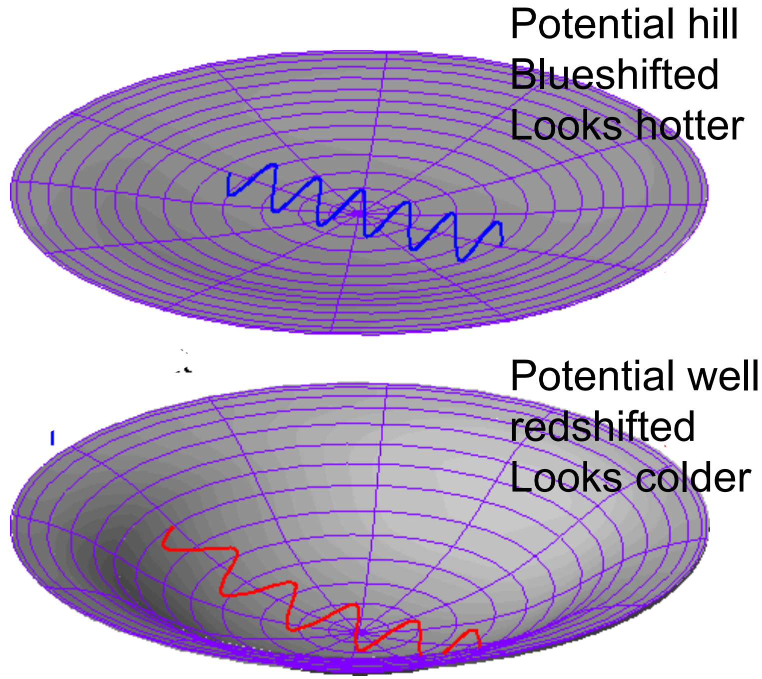


We see them like temperature

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) $h\nu/c^2\delta\phi$

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



CMB THEORY

HOW? ***WHY?***

"Seeing sound" (W. Hu)

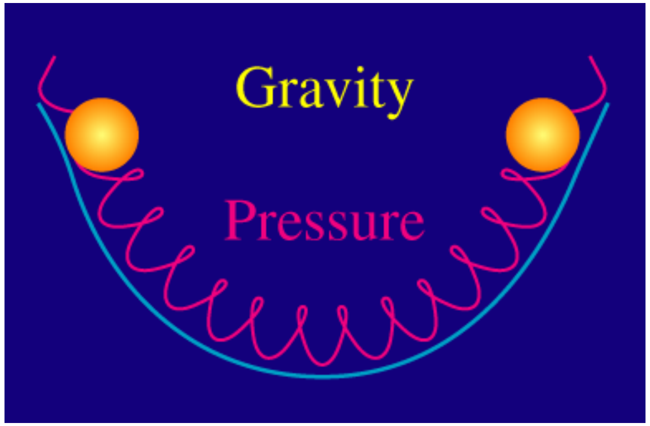
Last scattering surface : snapshot of the photon-baryon fluid

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)

Perturbations: Some history

SMALL-SCALE FLUCTUATIONS OF RELIC RADIATION*

R. A. SUNYAEV and YA. B. ZELDOVICH
Institute of Applied Mathematics, Academy of Sciences of the U.S.S.R., Moscow, U.S.S.R.

(Received 11 September, 1969)

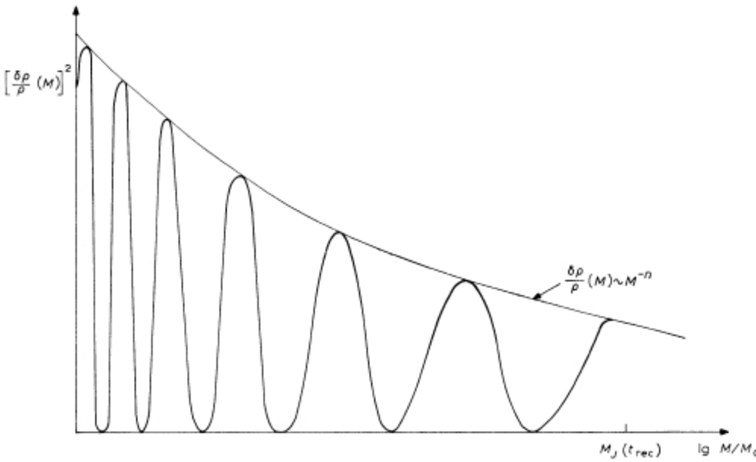


Fig. 1b. The dependence of the square of the amplitude of density perturbations of matter on scale. The fine line designates the usually assumed dependence $(\delta\varrho/\varrho)_M \sim M^{-n}$. It is apparent that fluctuations of relic radiation should depend on scale in a similar manner.

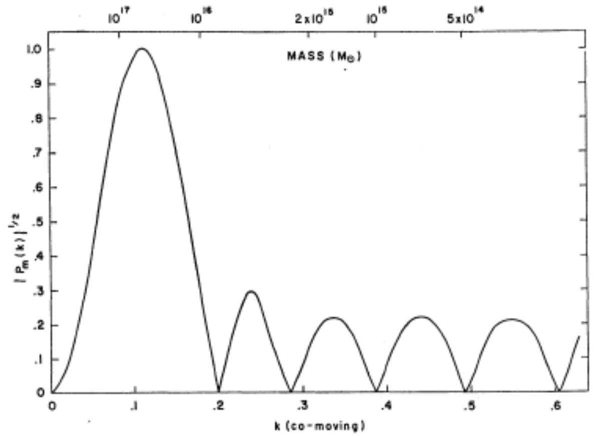
* Translated from the Russian by D. F. Smith.

Astrophysics and Space Science 7 (1970) 3–19.

THE ASTROPHYSICAL JOURNAL, 162:815–836, December 1970

PRIMEVAL ADIABATIC PERTURBATION IN AN EXPANDING UNIVERSE*

P. J. E. PEEBLES†
Joseph Henry Laboratories, Princeton University
AND
J. T. YU‡
Goddard Institute for Space Studies, NASA, New York
Received 1970 January 5; revised 1970 April 1



Compress the CMB map to study cosmology

Express sky as: $$\delta T(\theta,\varphi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\varphi)$$

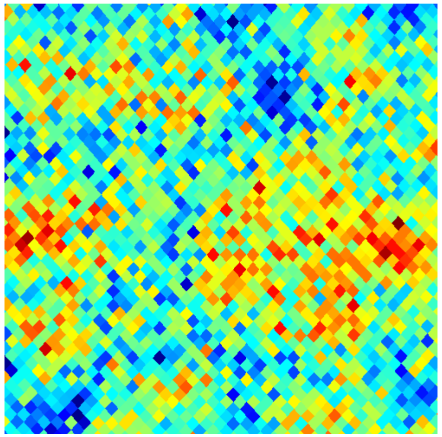
If the anisotropy is a Gaussian random field

(real and imaginary parts of each a_{lm} independent normal deviates, not correlated.)

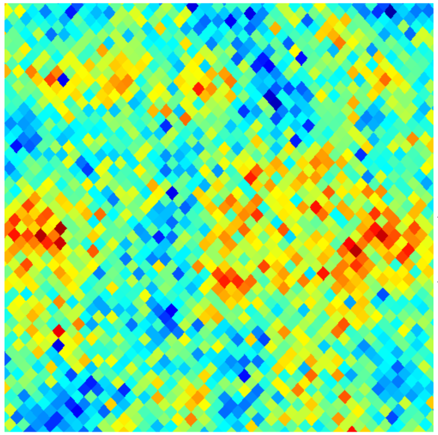
all the statistical information is contained in the angular power spectrum

0.06% of map

5 deg



X



1 deg

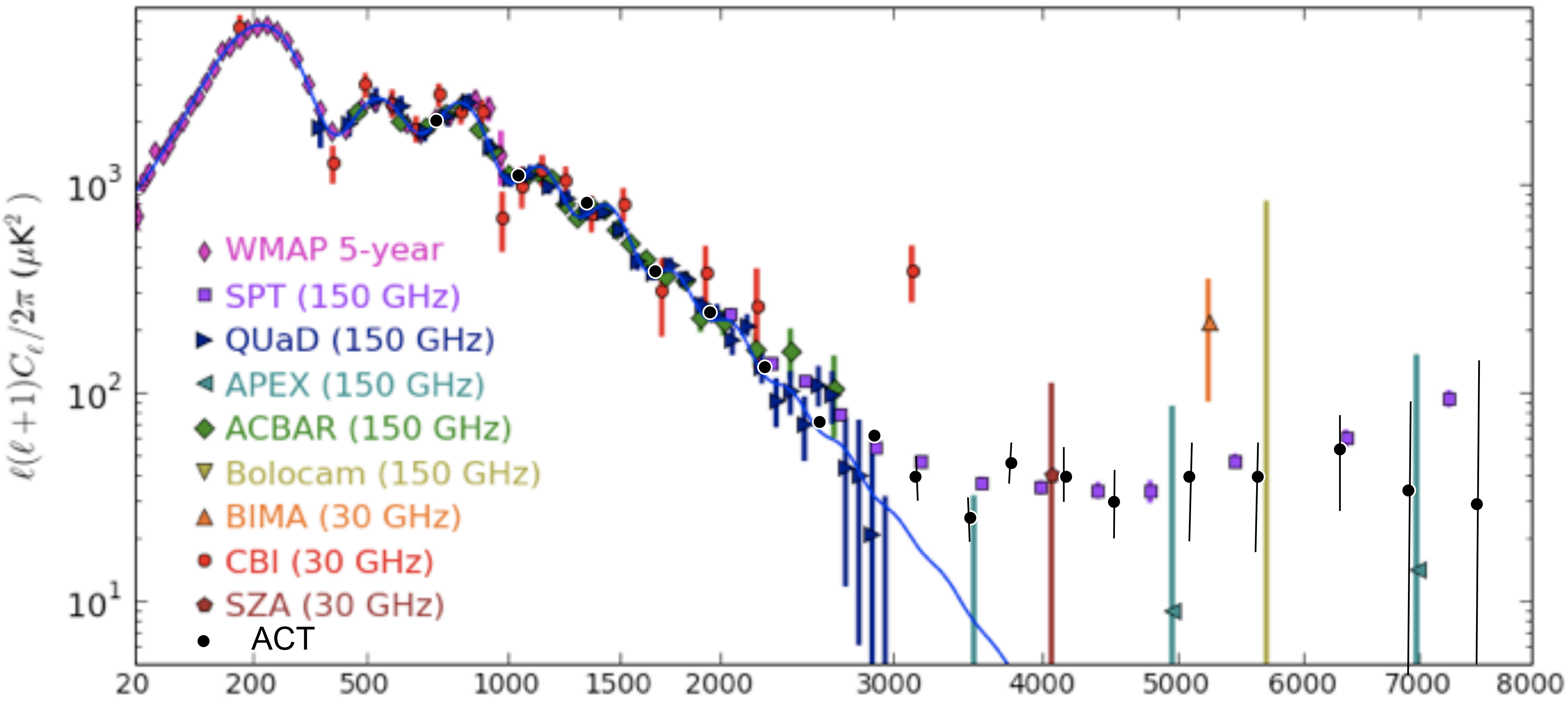
$$C_l = \frac{1}{2l+1}\sum_m |a_{lm}|^2$$

Raw 94 GHz
near NEP

+/- 32 uK

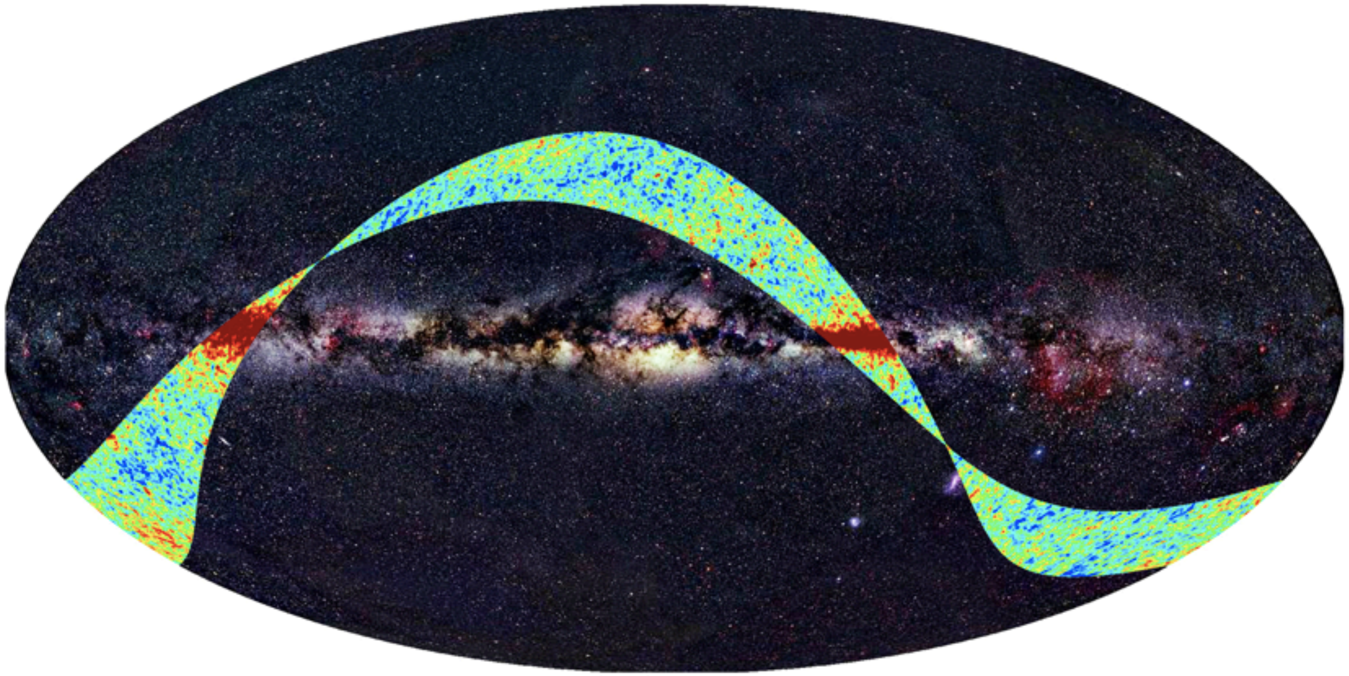
Raw 61 GHz
near NEP

State of the art: temperature



The future is here

Planck satellite successfully launched in May!



“PR” image

How's that?

The Universe back then was made of a very hot and dense "gas", so it was emitting radiation

This is the radiation we see when we look at the CMB

Uniform , but with tiny (contrast x 100000) density (and temperature) ripples

Ripples in a gas? SOUND WAVES!

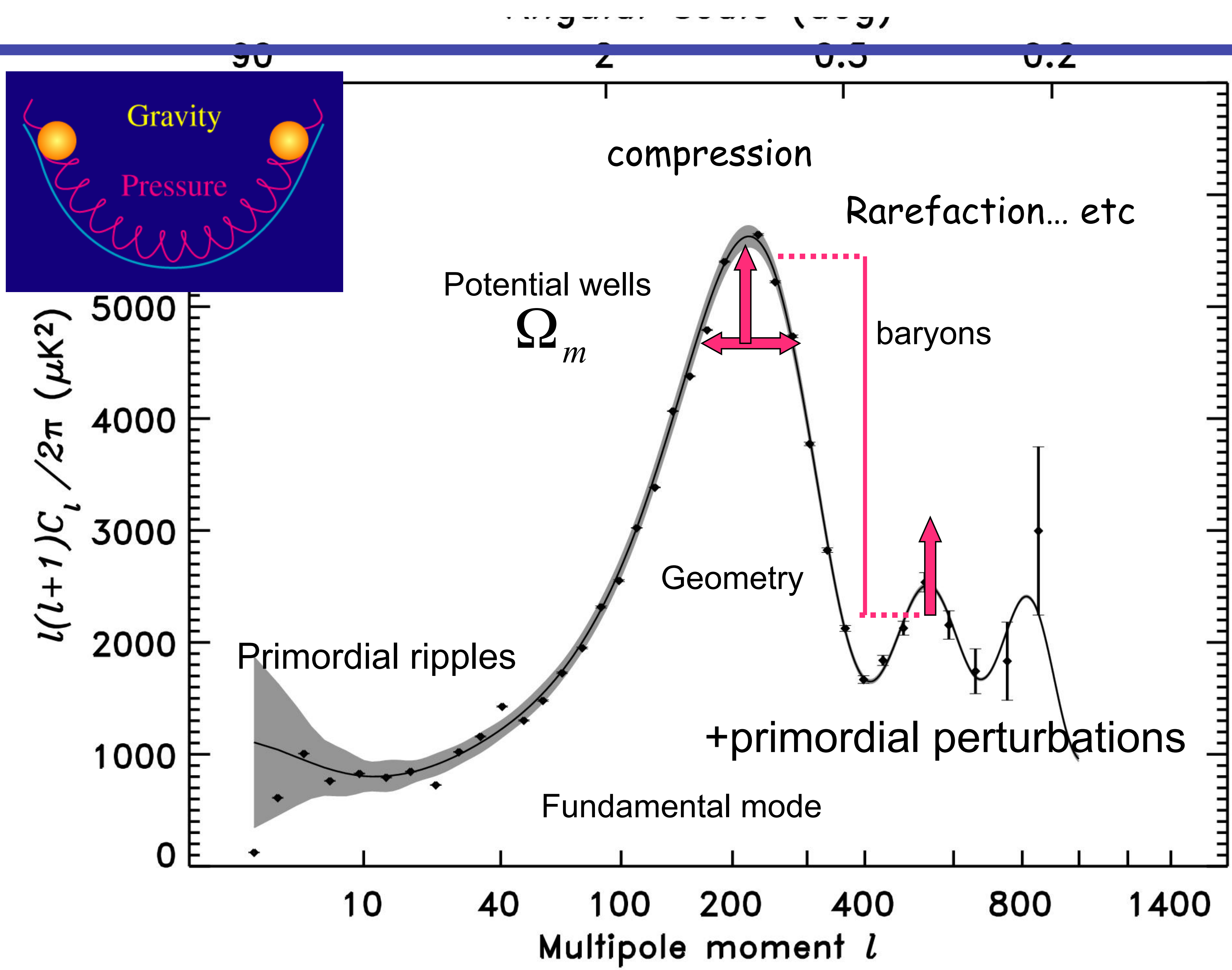
Truly a cosmic symphony… We are seeing sound!

These tiny fluctuations, quantitatively, give rise galaxies

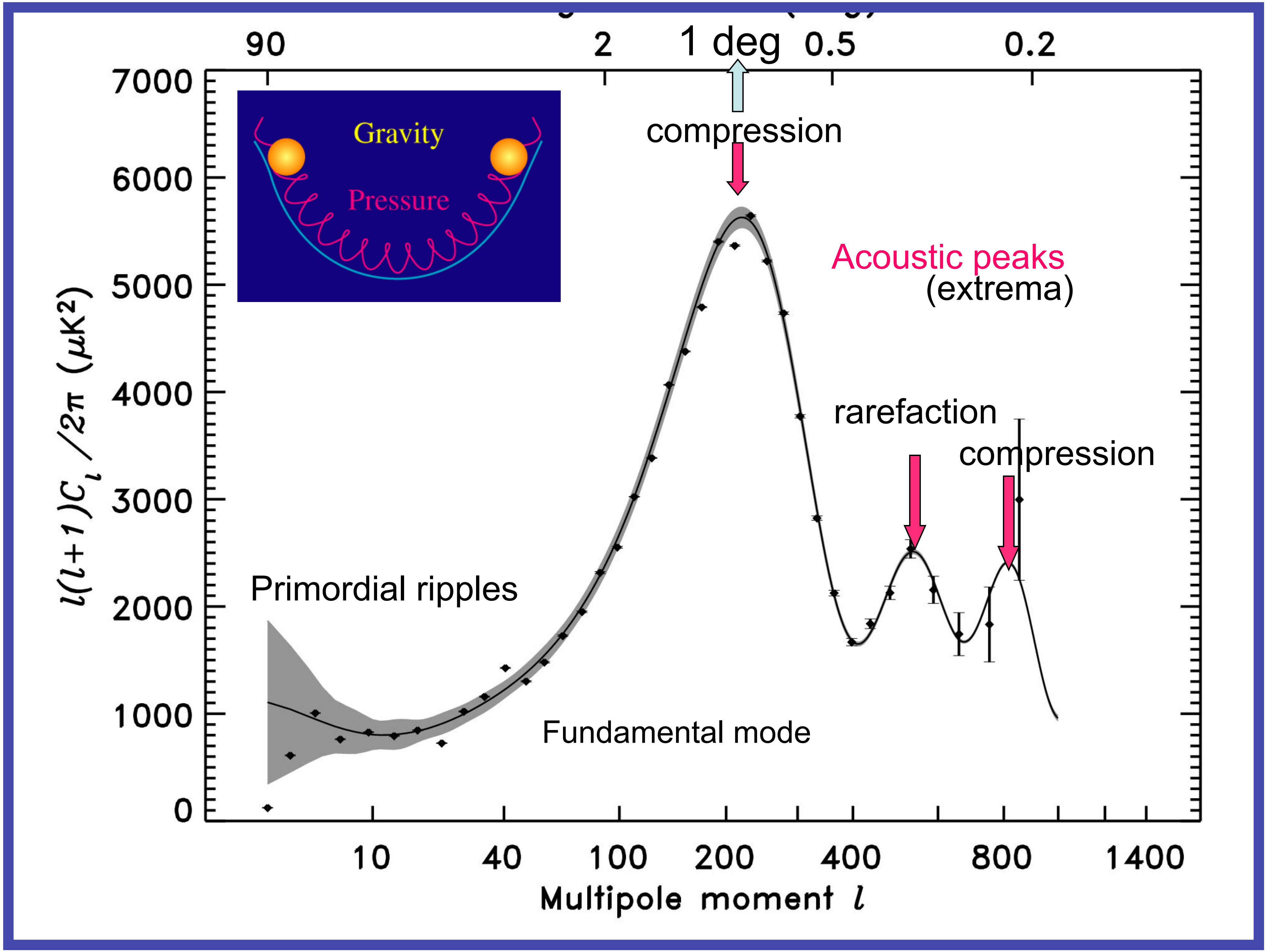
We try to listen to the sound and figure out how the instrument is made

Fundamental scale→ Fundamental mode and overtones

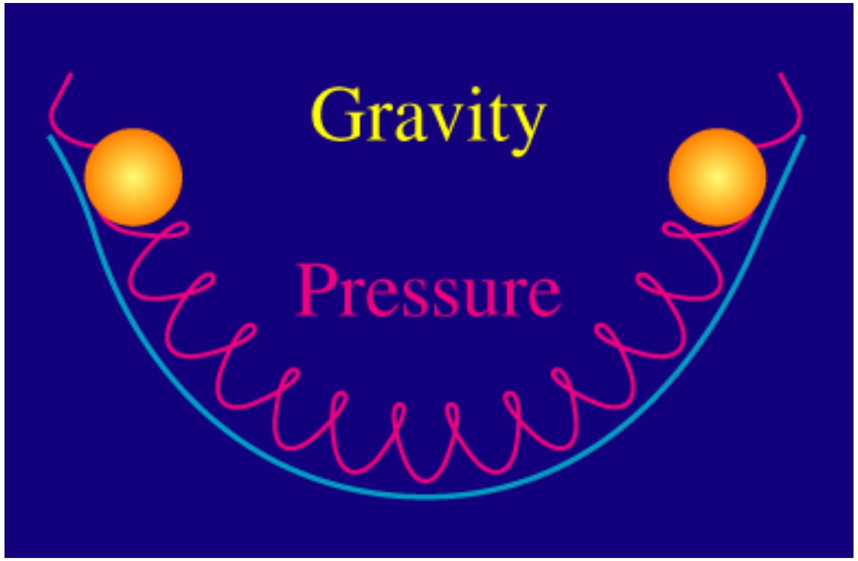
like blowing on a pipe….

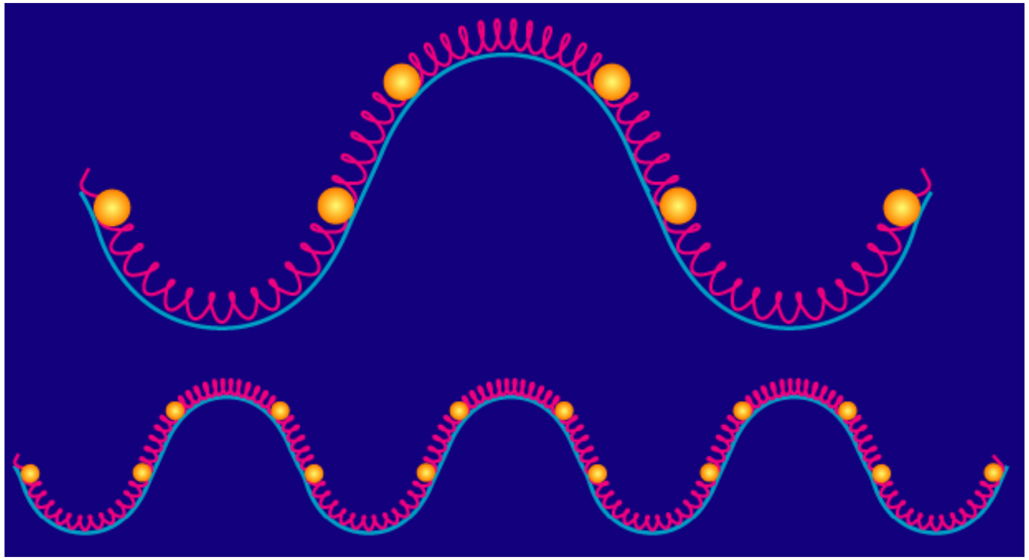


Jungman, Kamionkowski, Kosowsky, Spergel, 1996


90
2
1 deg
0.5
0.2
compression
Gravity
Pressure
Acoustic peaks
(extrema)
rarefaction
compression
Primordial ripples
Fundamental mode
7000
6000
5000
4000
3000
2000
1000
0
10
40
100
200
400
800
1400
Multipole moment l
l(l+1)C_l /2π (μK²)

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



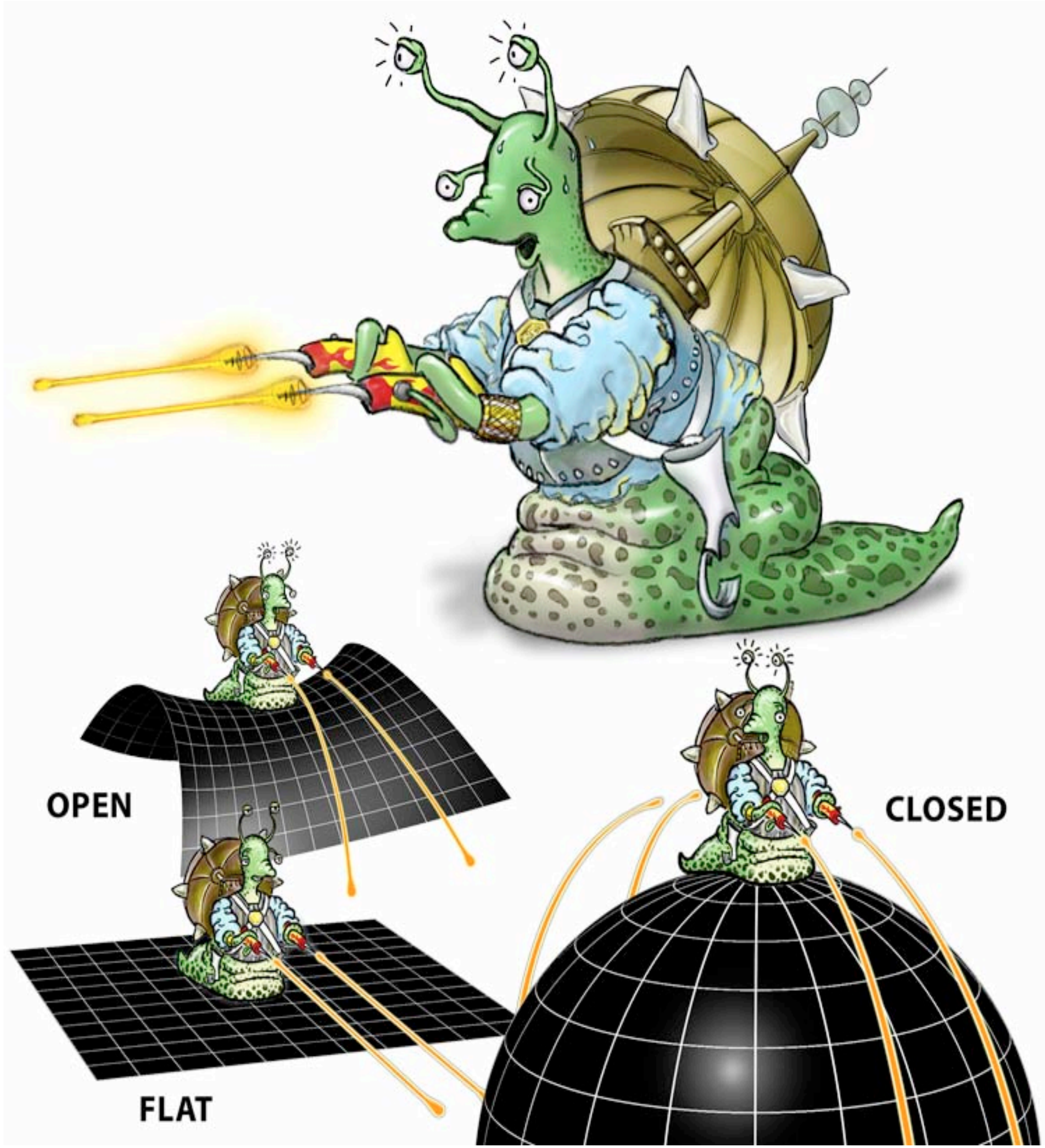


Longer wavelength modes oscillate slower

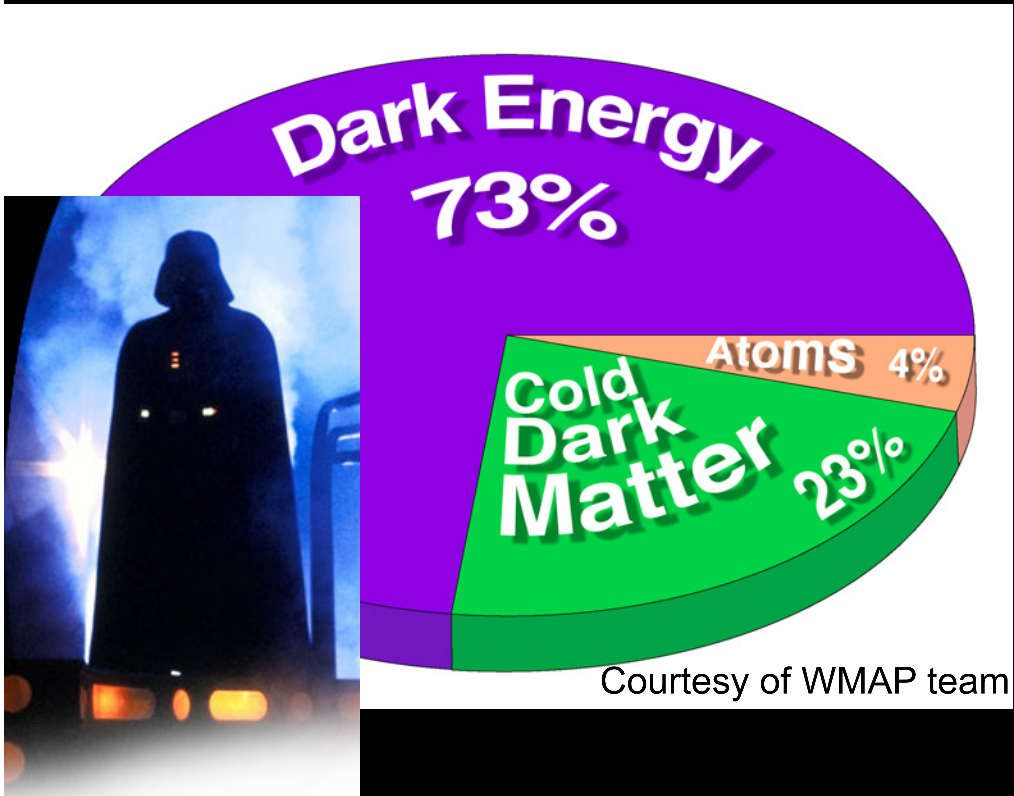
The frequency of the oscillation is equal to the wavenumber times the speed of sound: $\omega = kc_s$

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

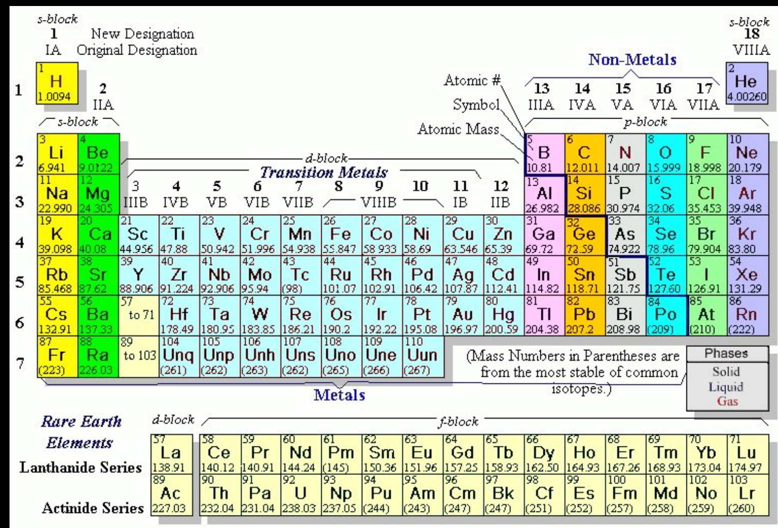
Animations courtesy of W. Hu


OPEN
CLOSED
FLAT

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



Courtesy of WMAP team



	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 H 1.0094																	2 He 4.00260
2	3 Li 6.941	4 Be 9.0122											5 B 10.81	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.179
3	11 Na 22.990	12 Mg 24.305											13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.06	17 Cl 35.453	18 Ar 39.948
4	19 K 39.098	20 Ca 40.08	21 Sc 44.956	22 Ti 47.88	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.847	27 Co 58.933	28 Ni 58.69	29 Cu 63.546	30 Zn 65.39	31 Ga 69.72	32 Ge 72.59	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.80
5	37 Rb 85.468	38 Sr 87.62	39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.75	52 Te 127.60	53 I 126.91	54 Xe 131.29
6	55 Cs 132.91	56 Ba 137.33	57 to 71	72 Hf 178.49	73 Ta 180.95	74 W 183.85	75 Re 186.21	76 Os 190.2	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra 226.03	89 to 103	104 Unq (261)	105 Unp (262)	106 Unh (263)	107 Uns (262)	108 Uno (265)	109 Une (266)	110 Uun (267)								

	d-block	f-block													
Lanthanide Series	57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
Actinide Series	89 Ac 227.03	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np 237.05	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (260)

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

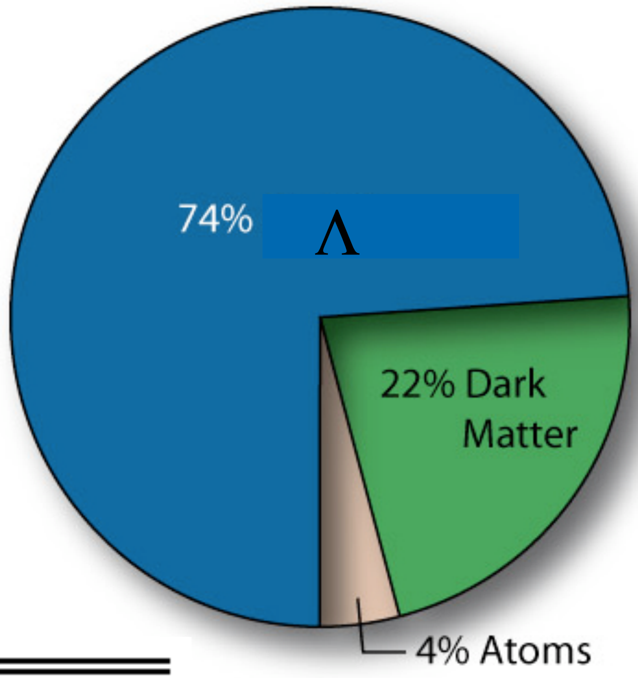
The standard cosmological model

ΛCDM model

Spatially flat Universe

Power-law, primordial power spectrum

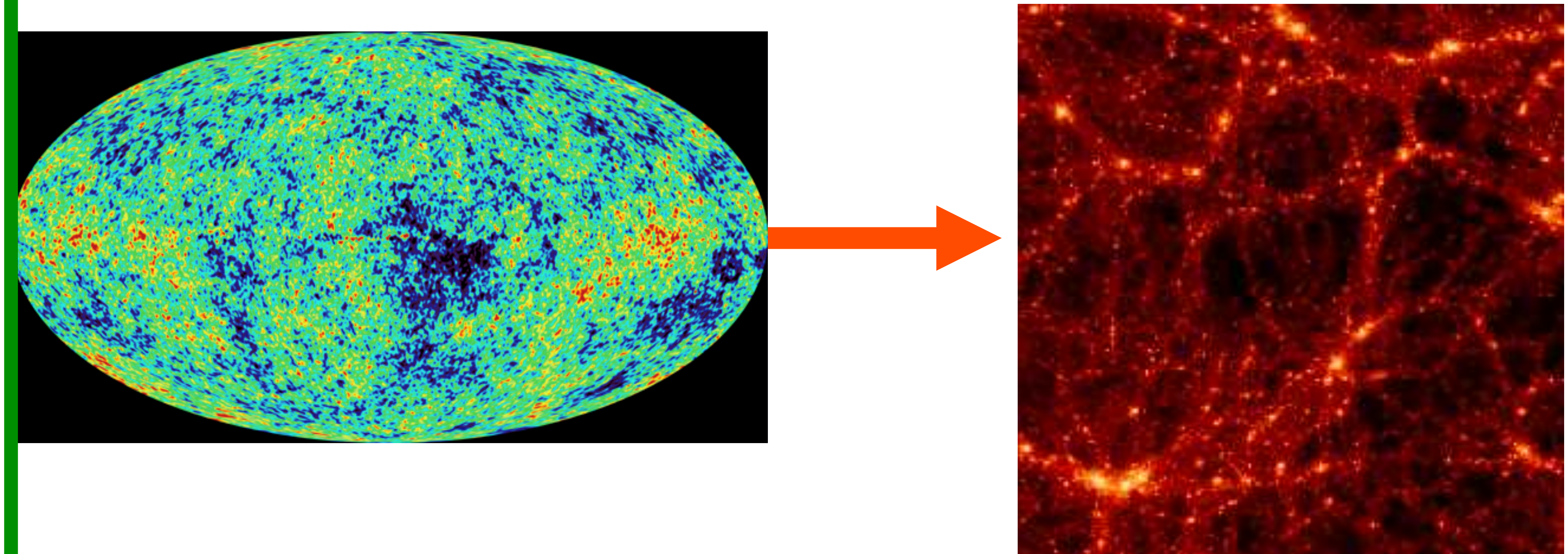
Only 6 parameters: WMAP5yr analysis



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!

Next…



VIRGO