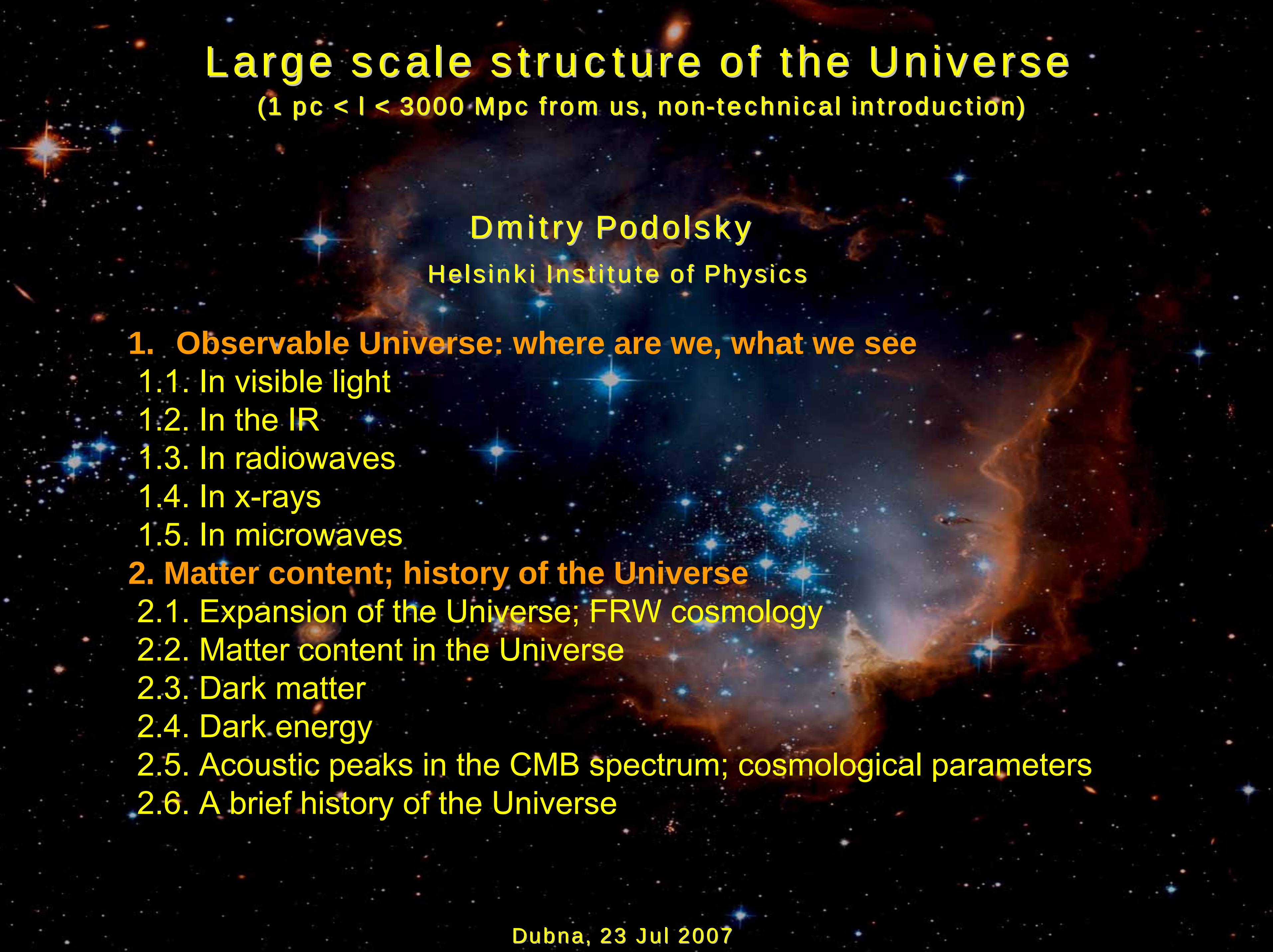


Large scale structure of the Universe

(1 pc < l < 3000 Mpc from us, non-technical introduction)

Dmitry Podolsky

Helsinki Institute of Physics

1. **Observable Universe: where are we, what we see**
   - 1.1. In visible light
   - 1.2. In the IR
   - 1.3. In radiowaves
   - 1.4. In x-rays
   - 1.5. In microwaves
2. **Matter content; history of the Universe**
   - 2.1. Expansion of the Universe; FRW cosmology
   - 2.2. Matter content in the Universe
   - 2.3. Dark matter
   - 2.4. Dark energy
   - 2.5. Acoustic peaks in the CMB spectrum; cosmological parameters
   - 2.6. A brief history of the Universe

Dubna, 23 Jul 2007

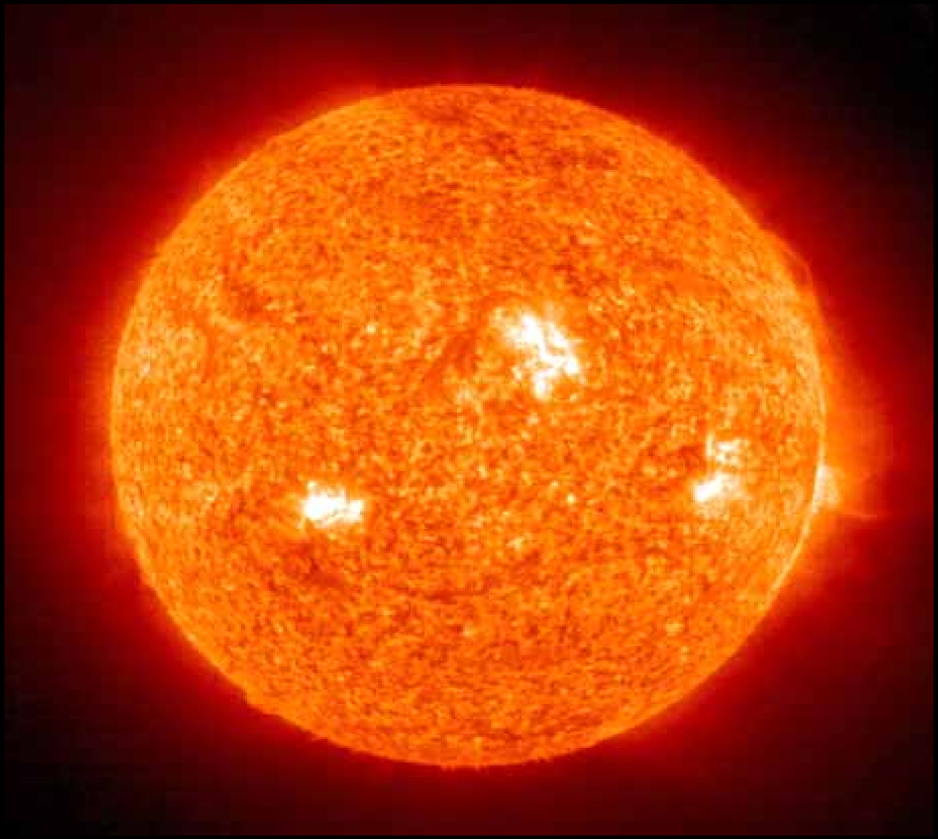
1. OBSERVABLE UNIVERSE

Small Magellanic Cloud (200000 ly away from us)
and the star cluster NGC 602 (5 million years old, in our galaxy).
1 light year is the distance passed by a ray of light during 1 year, about 10^{13} km

HST

In visible light

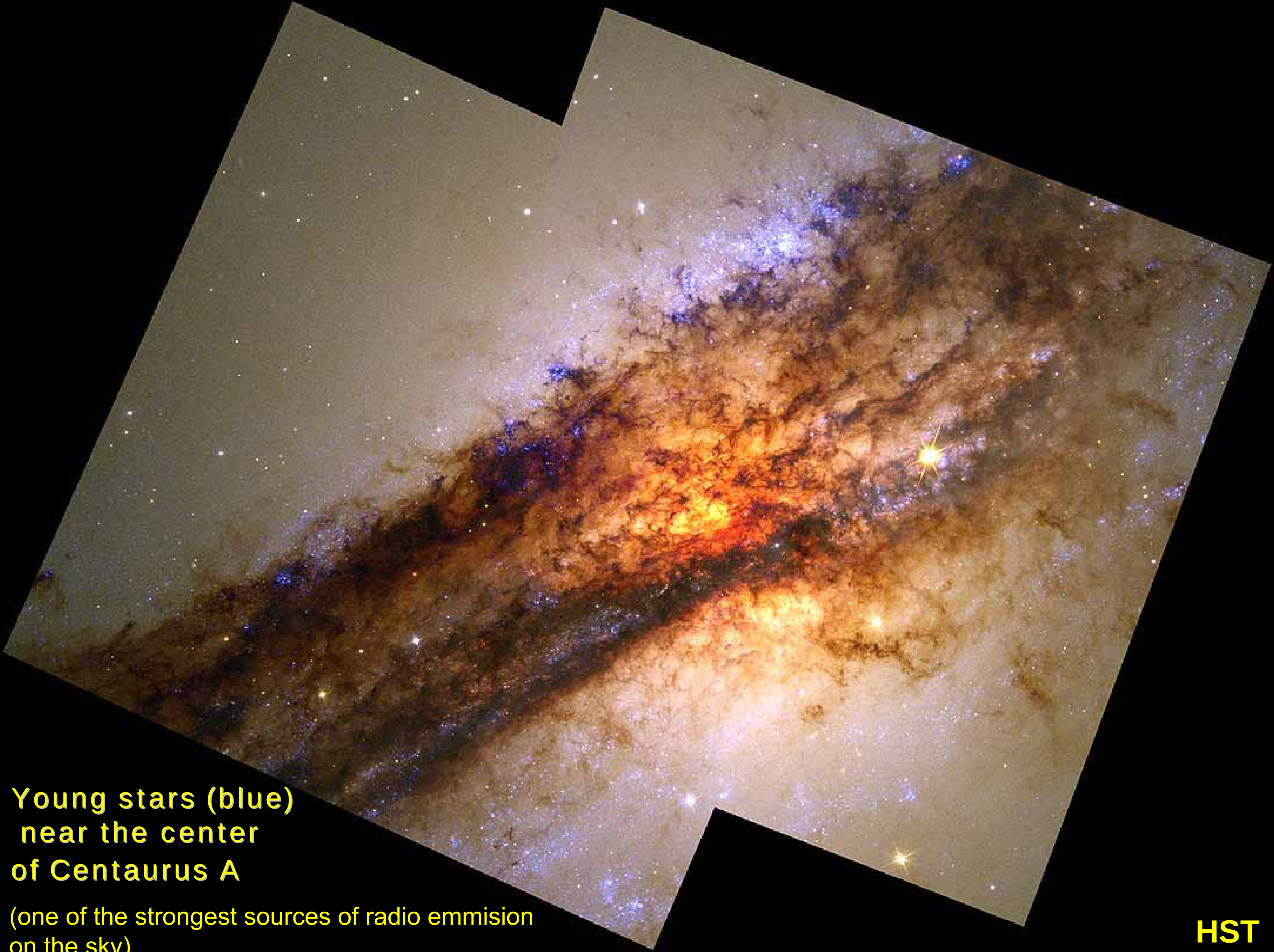
1. Stars. Main source of visible light in the Universe is nuclear fusion within stars (mainly, H → He).
   Our Sun is a typical yellow dwarf star with the mass about 2×10^{30} kg.



It is 100 times more massive then all planets of Solar system combined.

There are stars in our galaxy with mass about 100 times larger than the mass of the Sun.

As you know, closest stars are a few ly away from us (Proxima Centaurus – 3.261 ly = 1 parsec away)



Young stars (blue)
near the center
of Centaurus A

(one of the strongest sources of radio emmision on the sky)

HST

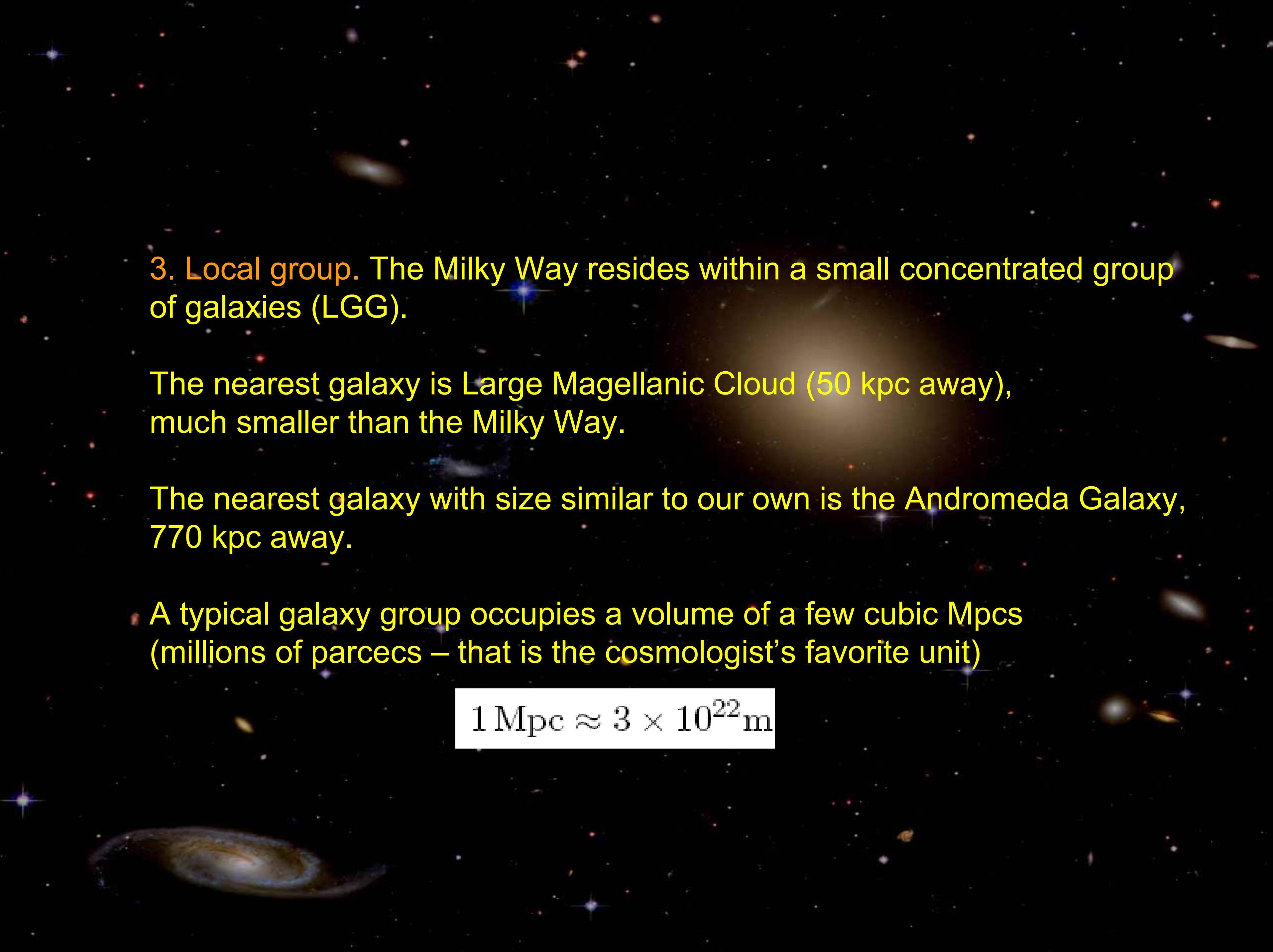
2. Galaxies. The solar system is way off-centre in the Milky Way.

Its disk radius is about
12500 parsecs;
thickness is about
300 parsecs

Disc is rotating
differentially;
the period at our
radius is about
200 million years.

Star clusters of NGC 1313; the typical number of stars in a galaxy is quite large; the Milky Way contains about 100 billion (thous. million) stars

HST



3. Local group. The Milky Way resides within a small concentrated group of galaxies (LGG).

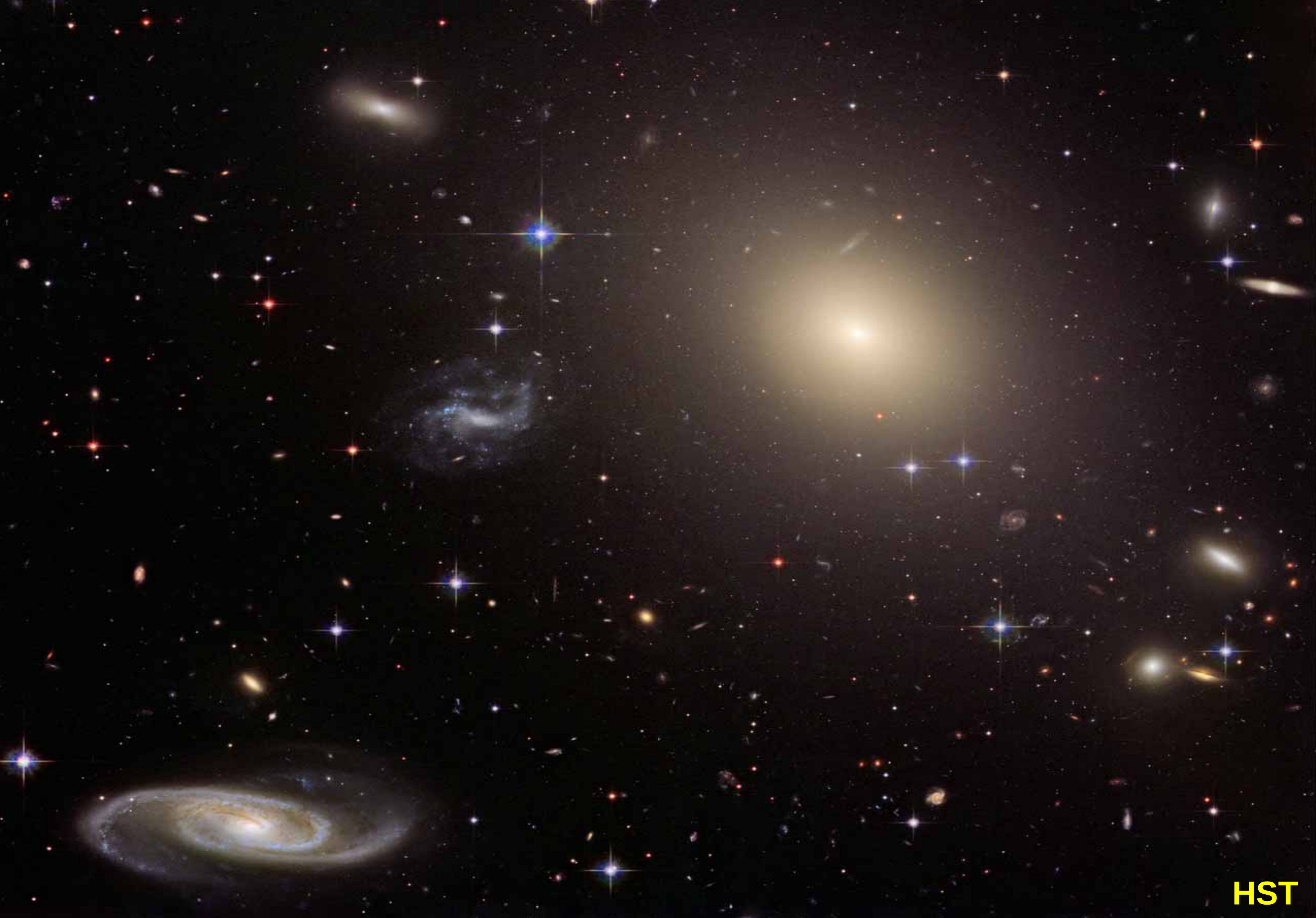
The nearest galaxy is Large Magellanic Cloud (50 kpc away), much smaller than the Milky Way.

The nearest galaxy with size similar to our own is the Andromeda Galaxy, 770 kpc away.

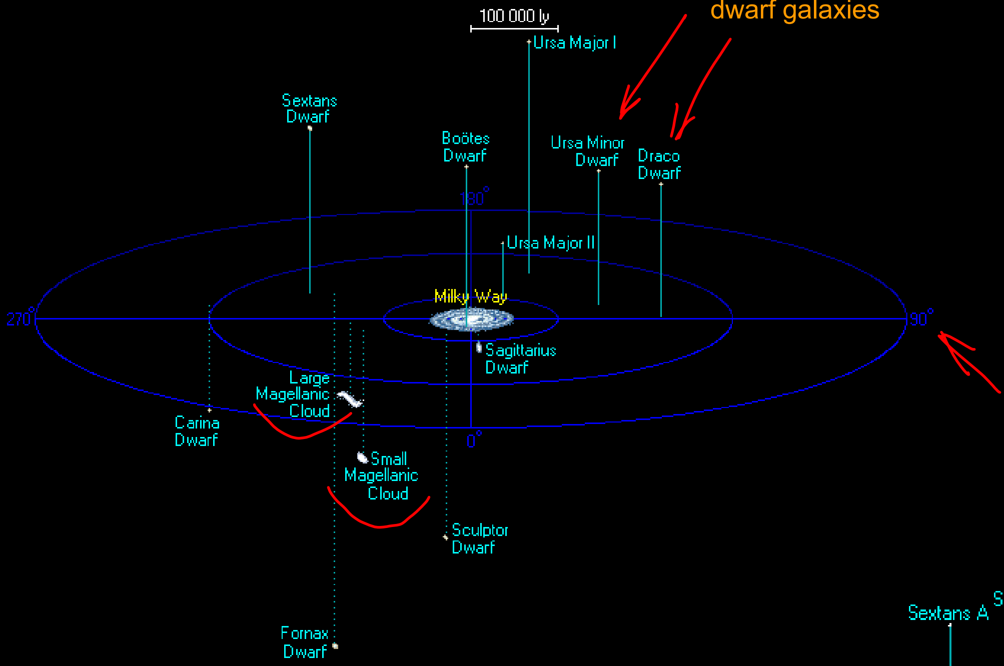
A typical galaxy group occupies a volume of a few cubic Mpcs (millions of parcecs – that is the cosmologist’s favorite unit)

$$1\,\mathrm{Mpc} \approx 3 \times 10^{22}\mathrm{m}$$

Cluster of galaxies ABEL S0740 – 450 million ly away from us



HST

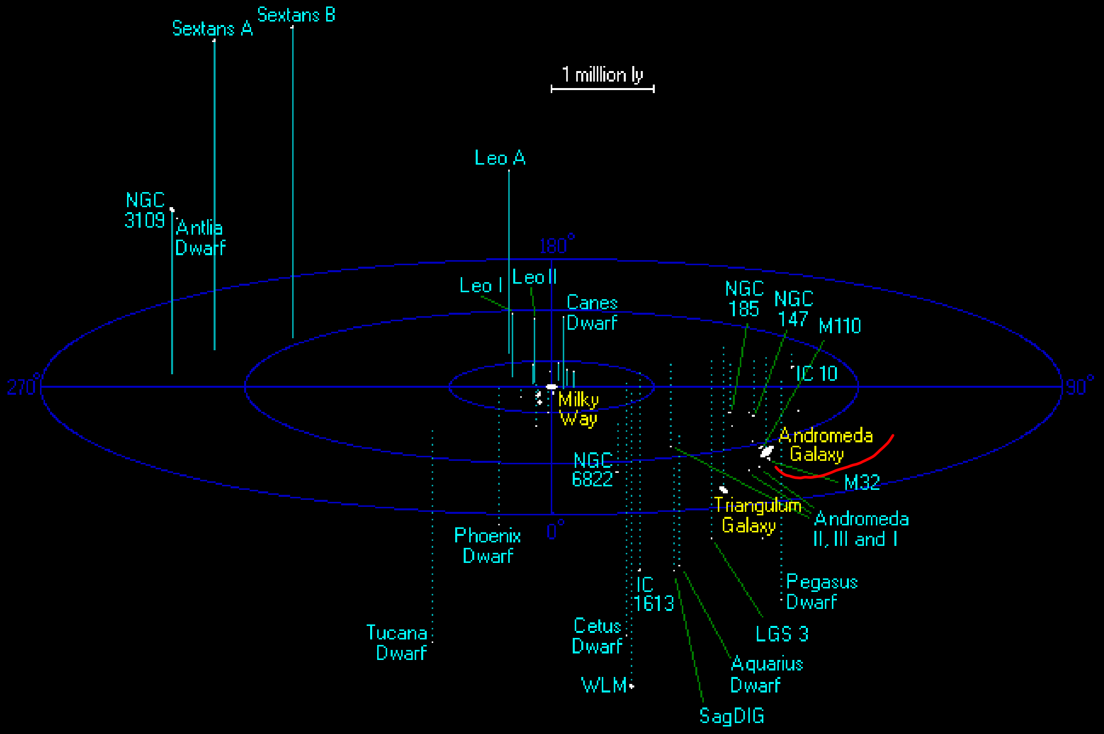


dwarf galaxies

the plane of Milky Way

← Nearest neighbors and satellites

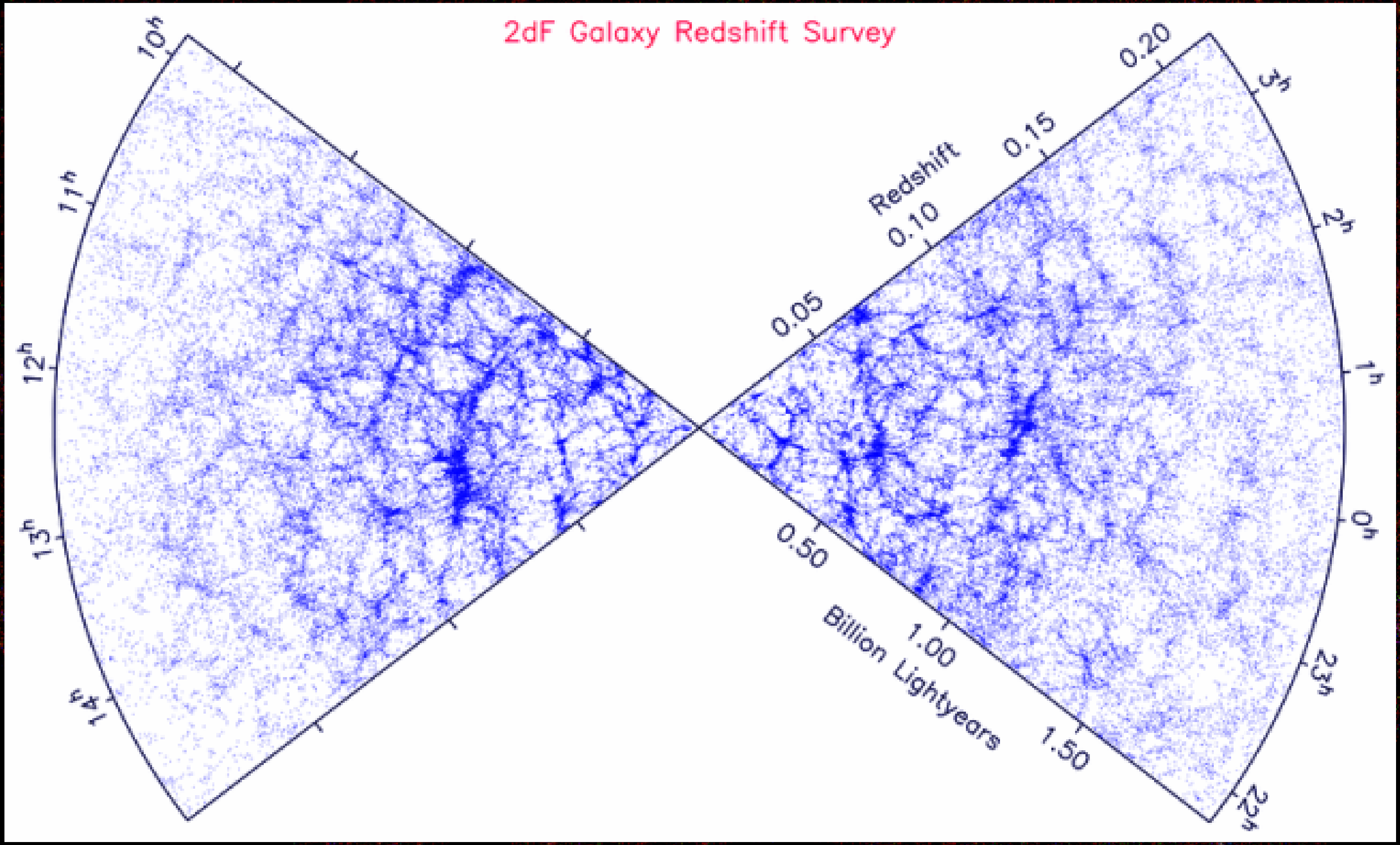
Nearest large galaxies (LG) →



r powell

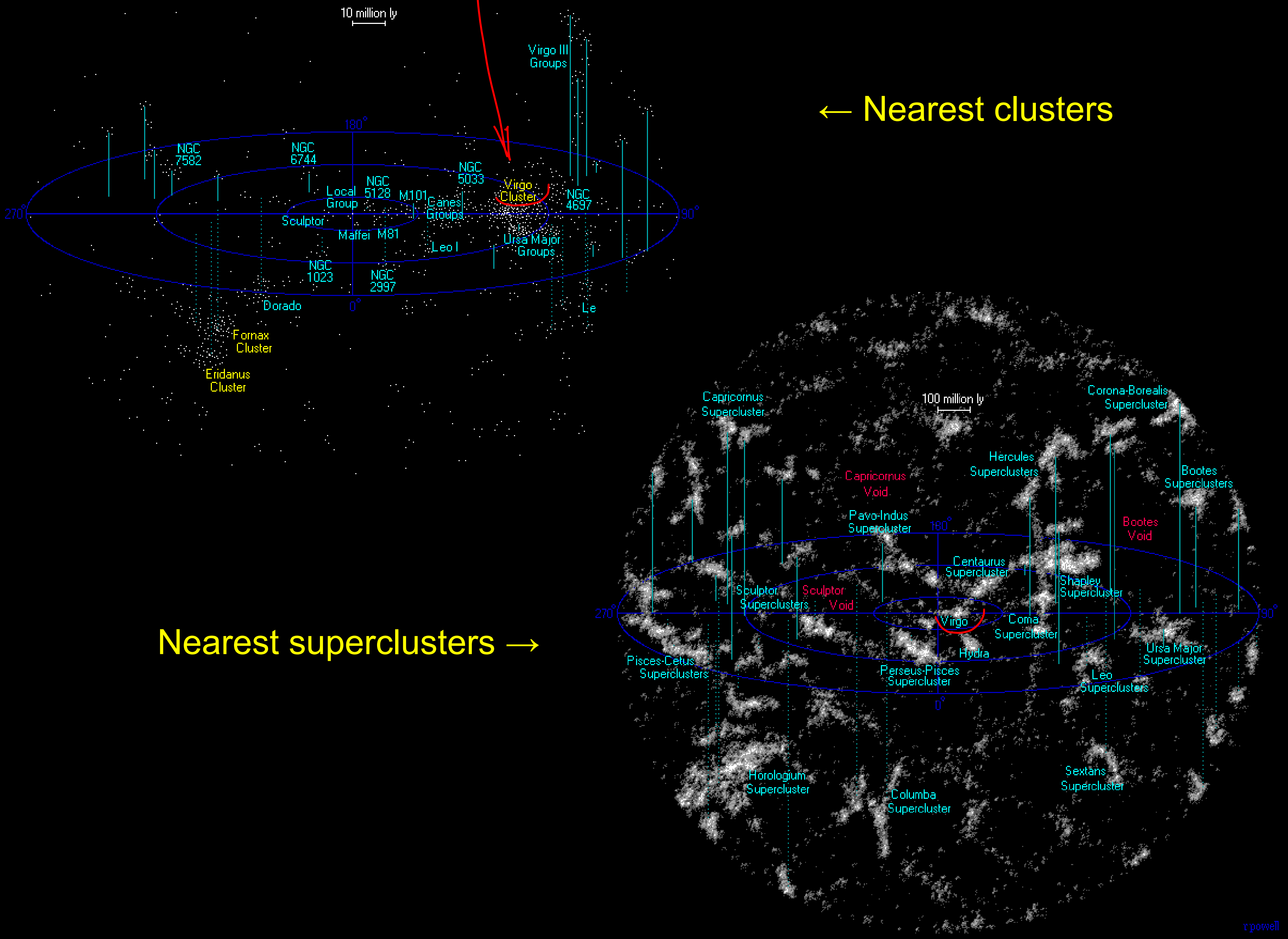
3. Clusters of galaxies, superclusters, voids. At scales larger than 100 Mpc one sees a lot of structures – in some places galaxies are grouped into clusters (some of them contain about 10000 galaxies).

Clusters are grouped into superclusters, joined by filaments and walls of galaxies.
Voids in this foam-like structure are as large as 50 Mpc across.
Superclusters of galaxies are the largest gravtationally-collapsed objects in nature.



The APM Galaxy Survey
Maddox et al

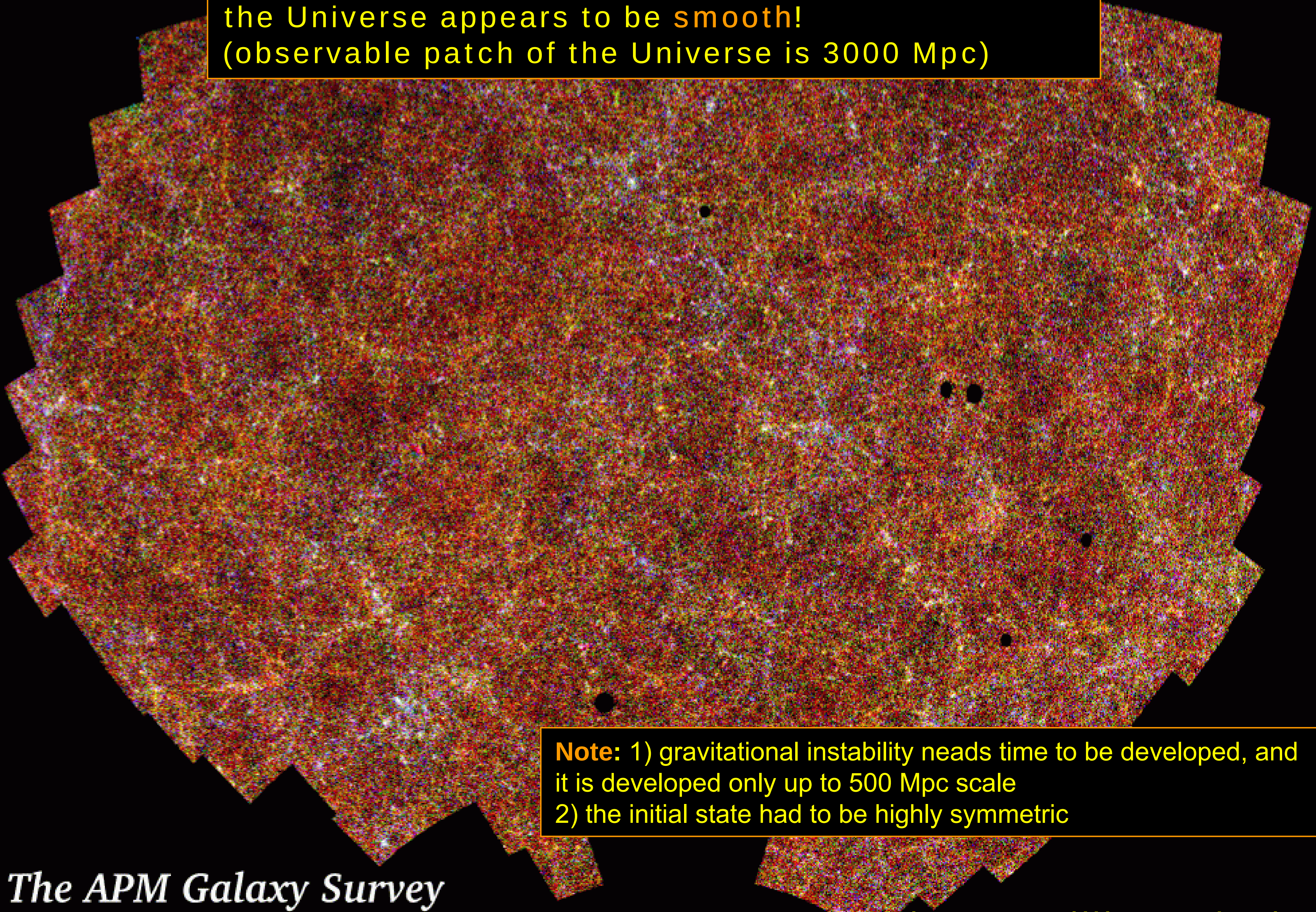
The Local Group is attracted to this cluster and rapidly moving towards it



← Nearest clusters

Nearest superclusters →

At larger scales (much more than hundreds of Mpcs)
the Universe appears to be smooth!
(observable patch of the Universe is 3000 Mpc)

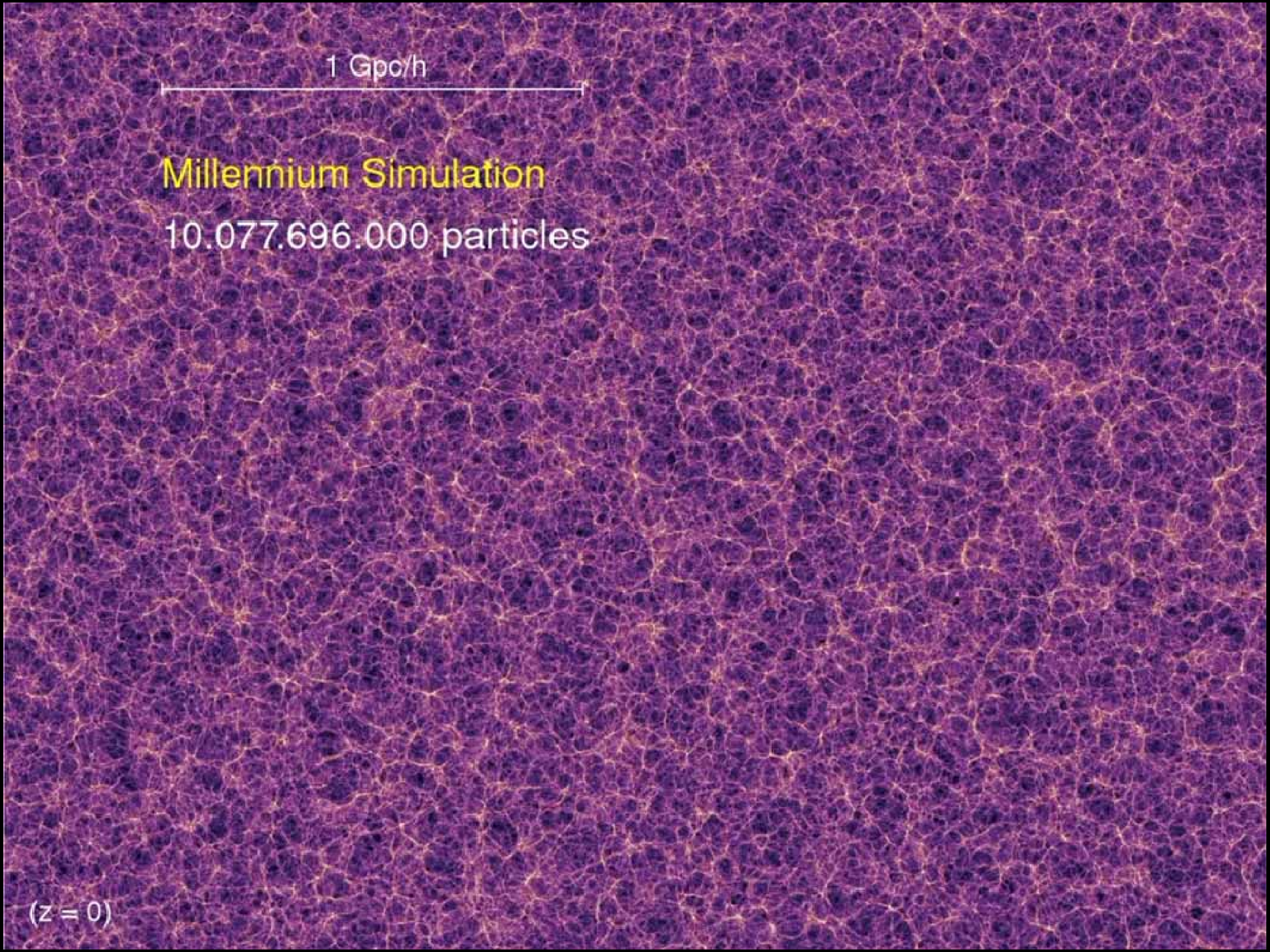


The APM Galaxy Survey
Maddox et al

Note: 1) gravitational instability neads time to be developed, and
it is developed only up to 500 Mpc scale
2) the initial state had to be highly symmetric

- about 2 million galaxies

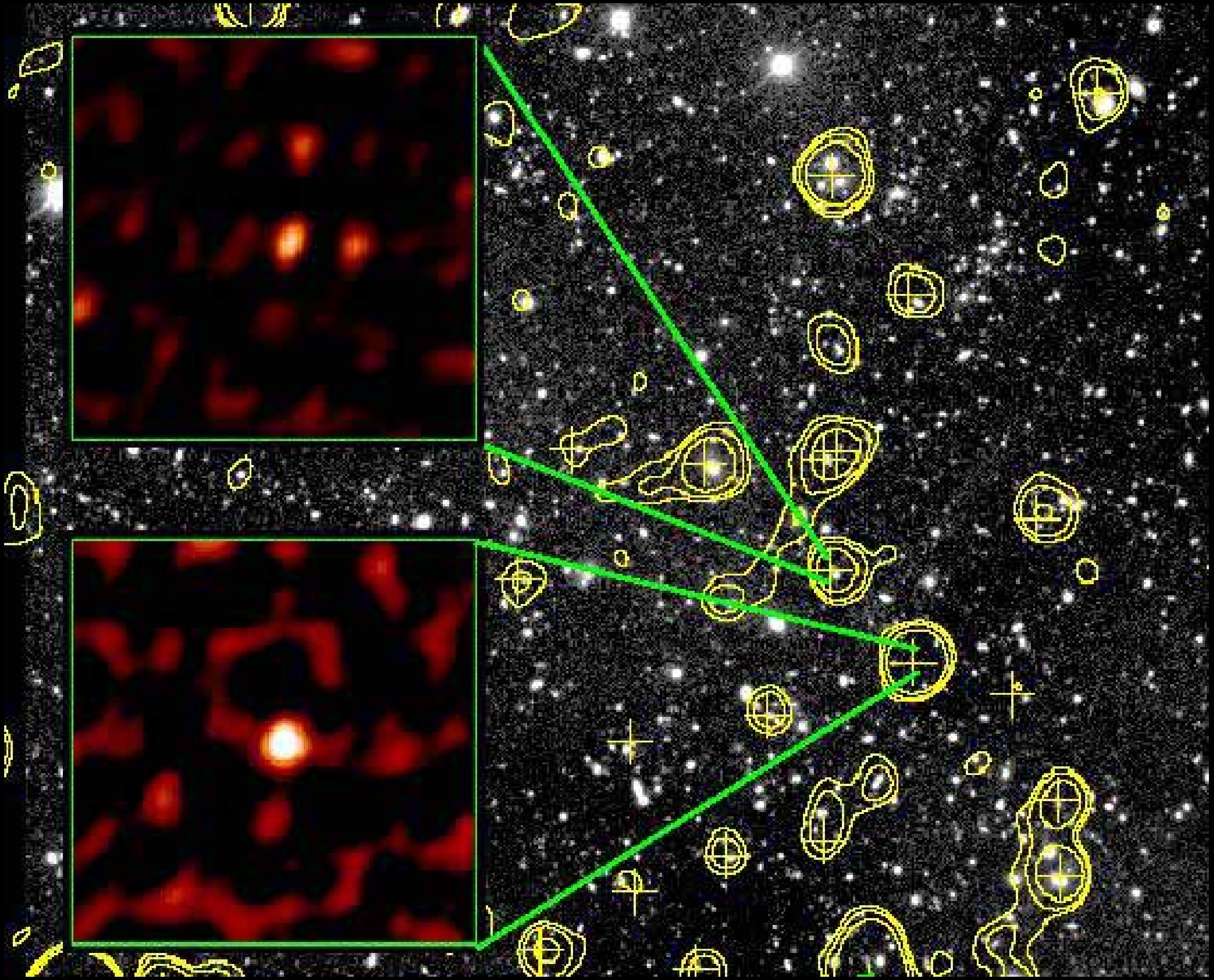
All scales together:



From V. Springel, S. White et al., astro-ph/0504097

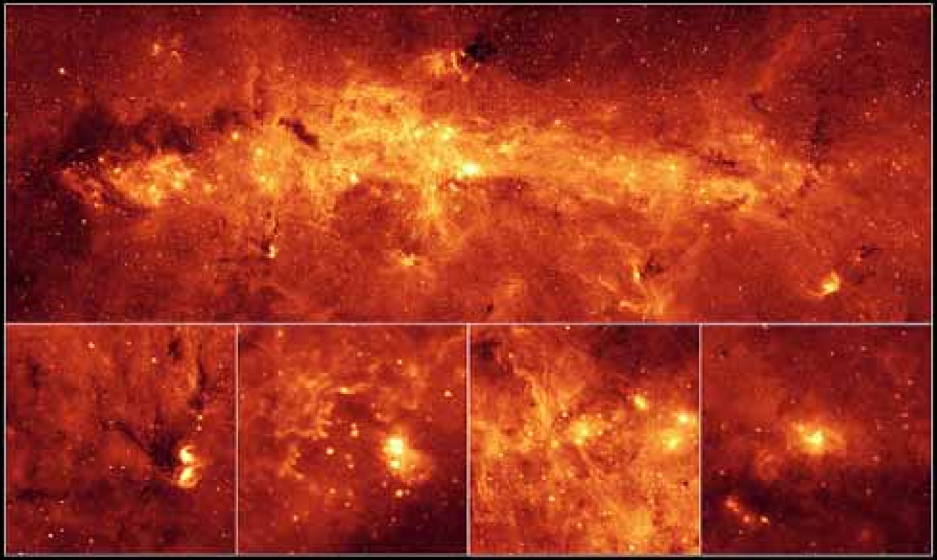
In radiowaves

One sees essentially the same structure. Powerful way for gaining high resolution maps of very distant galaxies and very energetic sources (quasars); mapping hydrogen (21 cm)



In the infrared

The same structure. Spotting young galaxies in which star formation is at early age. Particularly good for looking through the dust in our own galaxy – IR is absorbed and scattered much less strongly than the visible radiation.



Dust in the Center of the Milky Way Galaxy
NASA / JPL-Caltech / S. Stolovy (Spitzer Science Center/Caltech)

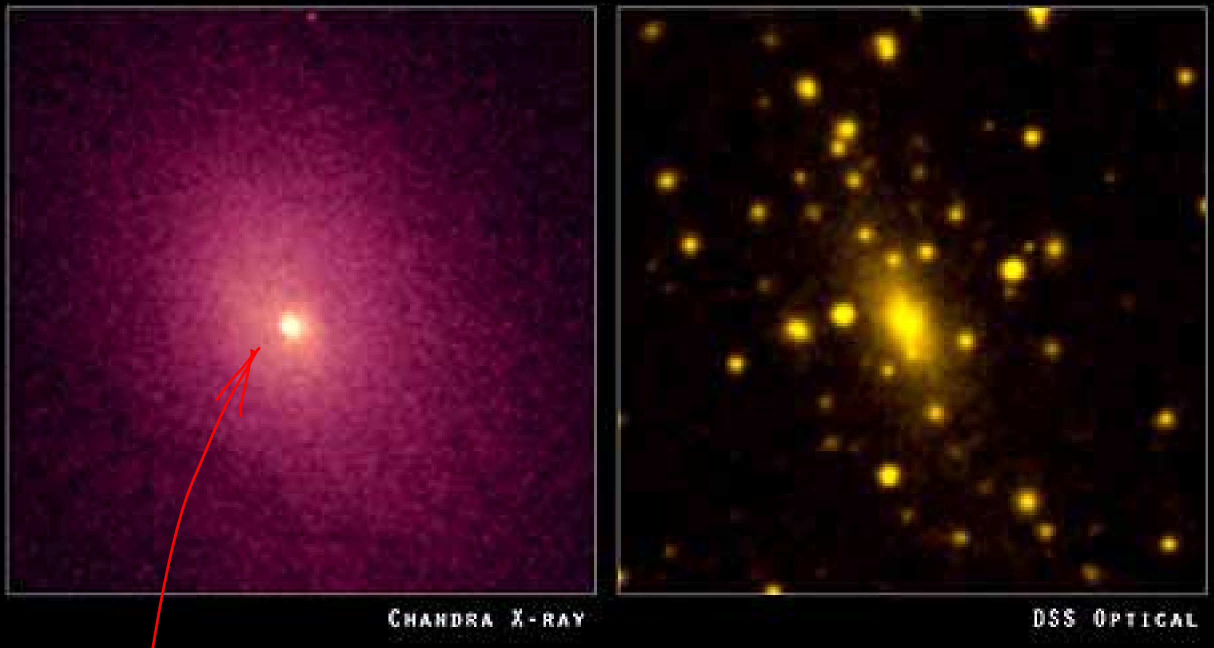
Spitzer Space Telescope • IRAC
ssc2006-02b

IR

Visible light

In X-rays

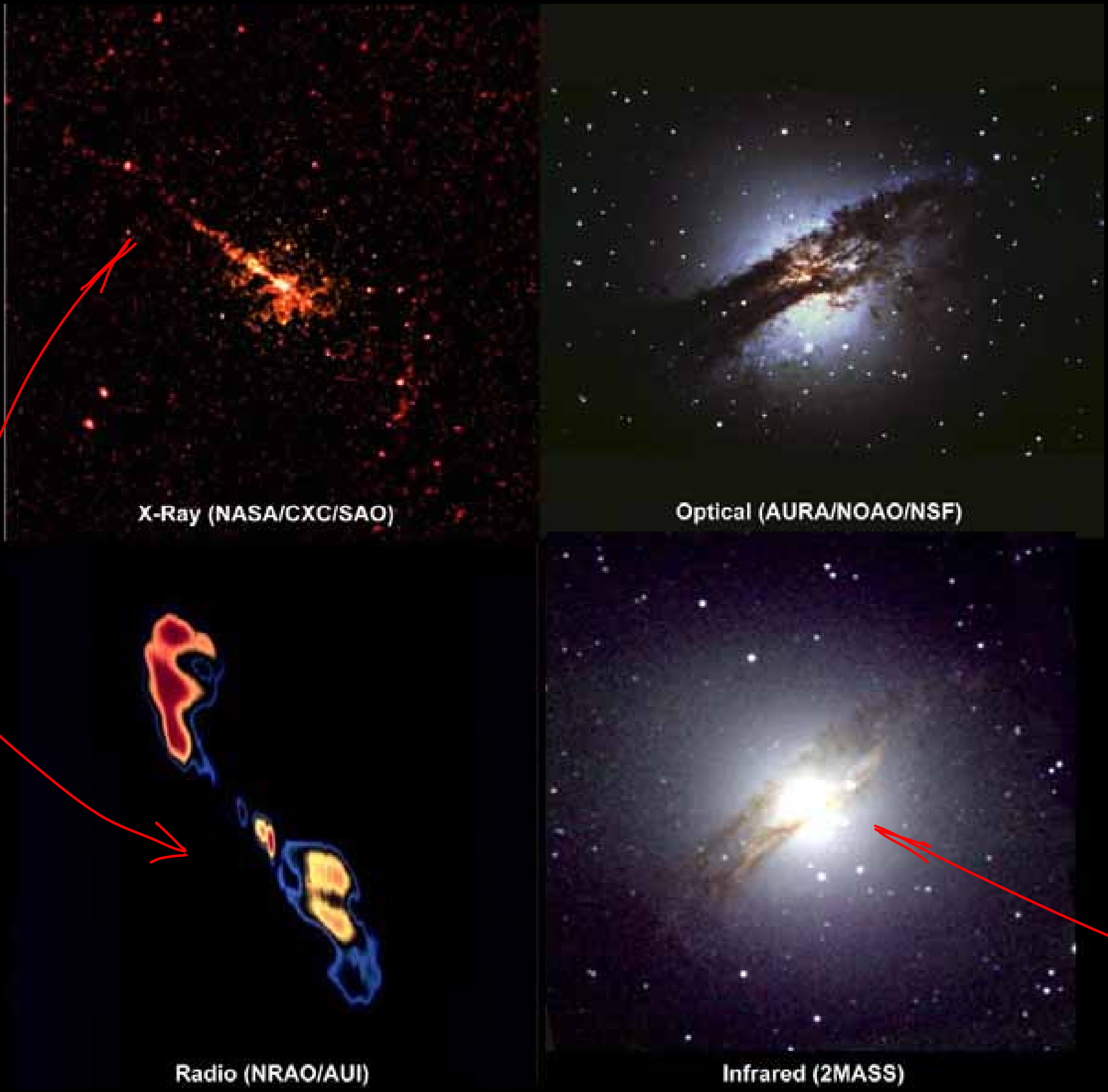
The same structure. A nice probe of clusters of galaxies; gas in between galaxies emits X-rays with temperature of tens of millions K (gas which did not have time to collapse)



Galaxy cluster Abell 2029

accretion of gas towards the most massive galaxy within the cluster; during accretion the gas emits a lot

Our "multiband eyes": example of "combined" vision



X-Ray (NASA/CXC/SAO)

Optical (AURA/NOAO/NSF)

Radio (NRAO/AUI)

Infrared (2MASS)

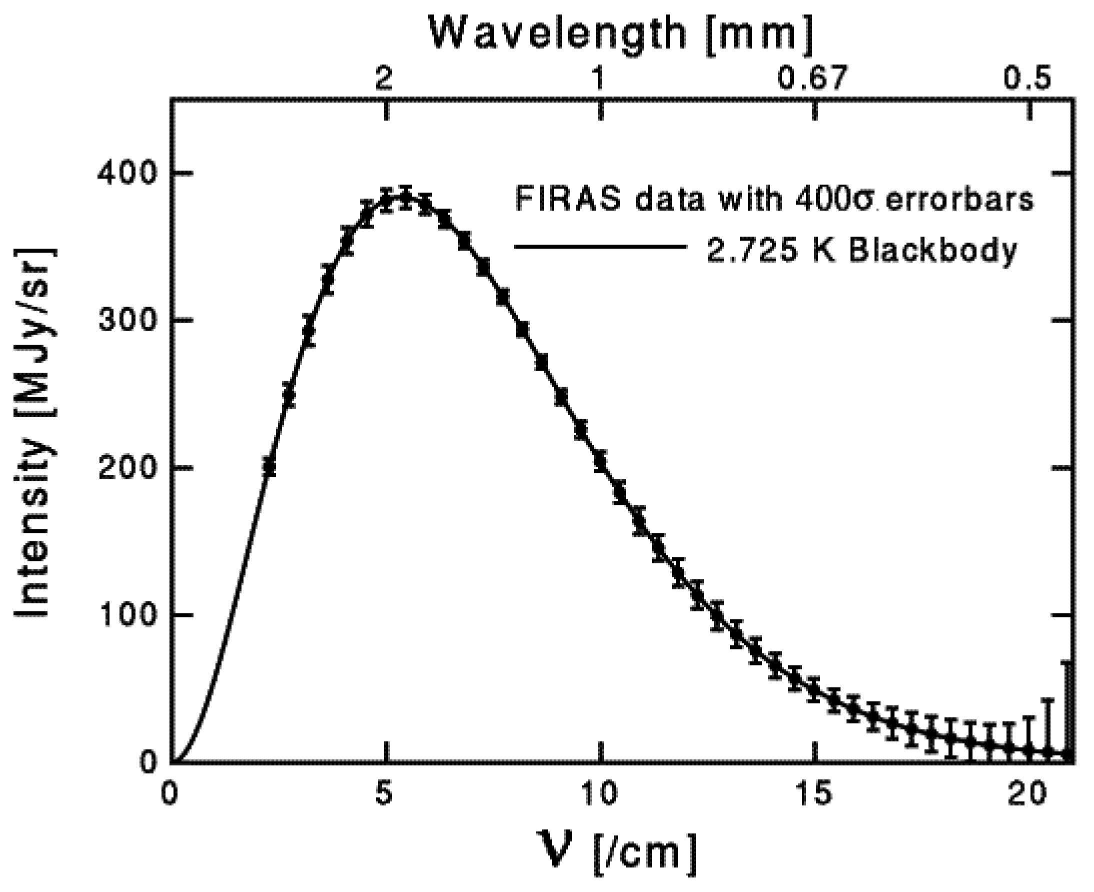
Hot gas:
you don't see these
jets in optics

looking through
dust: bright center

Centaurus A: very bright radio galaxy

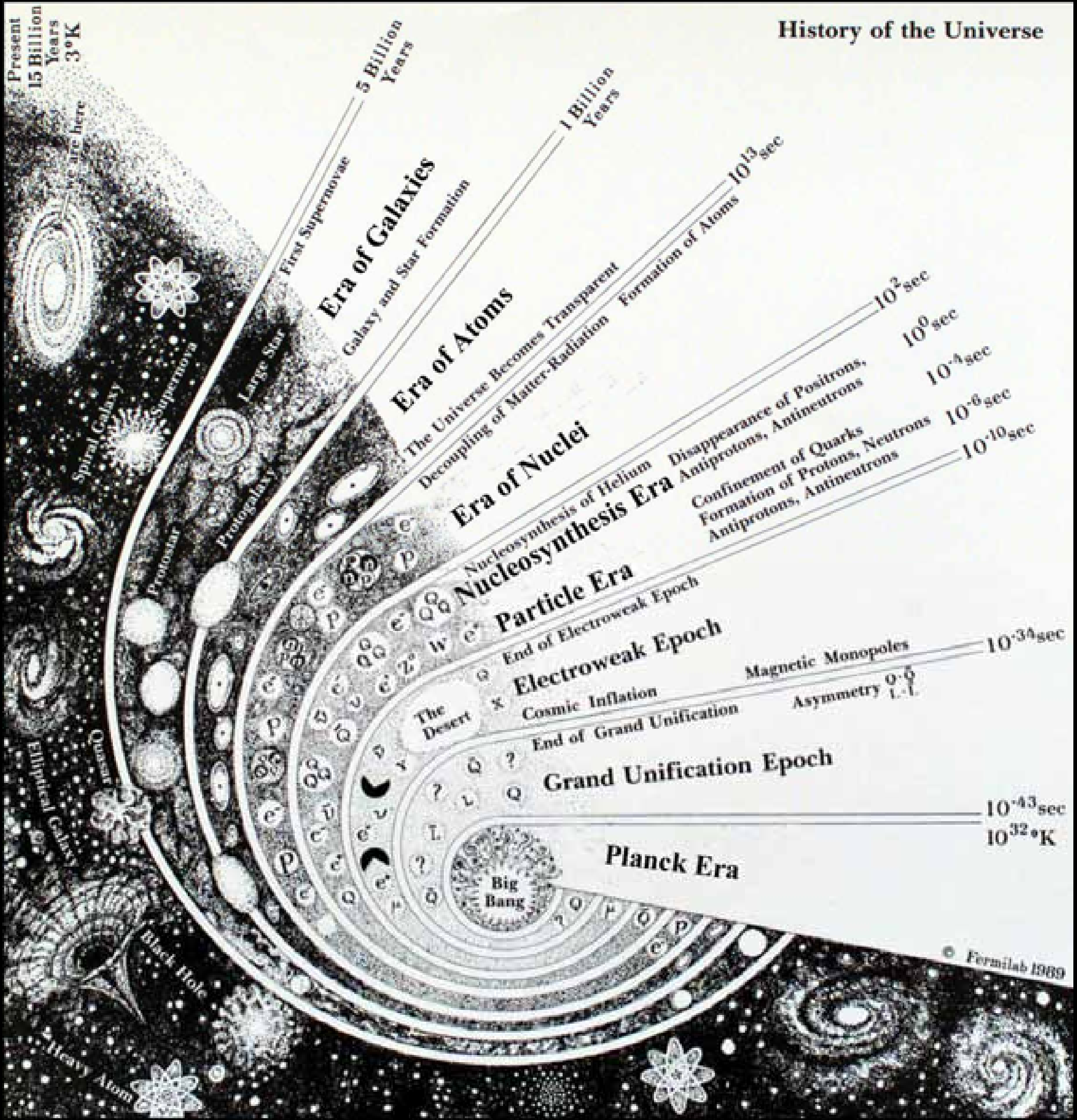
In microwaves

The Earth is bathed in microwave radiation, with black-body spectrum and the temperature $T = 2.725 \pm 0.001\ K$

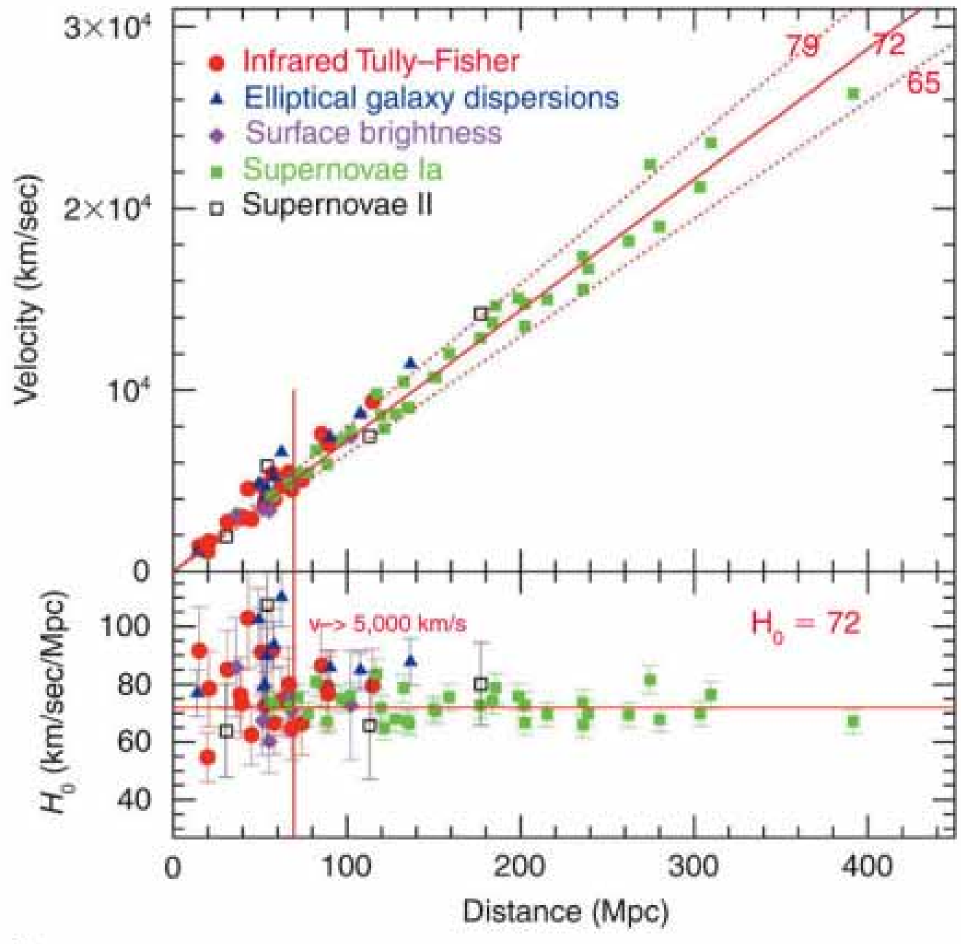


Most precisely measured black body spectrum in nature

2. MATTER CONTENT; HISTORY
(who are the main players)



The Universe is expanding



B

(Wendy L. Freedman, Observatories of the Carnegie Institution of Washington, and NASA)

$$H_0 = 72 \pm 8 \ \mathrm{km} \cdot \mathrm{s}^{-1} \cdot \mathrm{Mpc}^{-1}$$

Hubble law: $\vec{v} = H\vec{r}$

1) Galaxies have in their spectrum well determined emission and absorbtion lines; velocity of a distant object is determined by its redshift

$$z = \frac{\lambda_{\text{obs}} - \lambda_{\text{em}}}{\lambda_{\text{em}}} = \sqrt{\frac{1 + v/c}{1 - v/c}} - 1 \approx \frac{v}{c}$$

2) Distances within our galaxy can be measured by parallax (for example, Proxima Centaurus 1 pc away has a parallax 1 arcsec). Galaxies at the distance of few Mpcs have unmeasurable parallax < 1 milliarcsec.

Using the "standard candle" for them:

a) brightess-distance relation (the brightest galaxies within a cluster)

b) cepheid variable stars: period-luminocity relation

c) type 1a supernovae, etc.

All methods should give the same answer!

FRW Universe
(but you surely know all this already :-)

Space is homogeneous and isotropic:

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right)\right]$$

The dynamics of spacetime is governed by the Einstein equations:

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu}$$

At large scales and times only hydrodynamic modes survive: $T_{\mu\nu} = (\rho + p)U_\mu U_\nu + pg_{\mu\nu}$

After substituting the EM tensor and metric into the Einstein equations one gets

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\sum_i \rho_i - \frac{k}{a^2} \qquad \frac{\ddot{a}}{a} + \frac{1}{2}\left(\frac{\dot{a}}{a}\right)^2 = -4\pi G\sum_i p_i - \frac{k}{2a^2}$$

For a particular equation of state $p = w\rho$ one has

$$a(t) = a_0\left(\frac{t}{t_0}\right)^{2/3(1+w)} \qquad \rho(a) \propto \frac{1}{a(t)^{3(1+w)}}$$

Please remember those:
I'll use them during the next lecture

The matter content of the Universe

Units:"critical density" $\rho_c = 3H^2M_P^2/8\pi$

(presently is about 10^{-26} kg/m^3)

The density in these units is $\Omega = \rho/\rho_c$

(total density today is almost precisely 1)

1) Baryons, leptons, atoms:

a) counting stars $\Omega_{\rm stars} \sim 0.005$

b) nucleosynthesis (observable abundance of elements is compatible with) $0.03 \le \Omega_B \le 0.046$

(at all we have about 1 baryon per 10^9 photons; almost no antibaryons; chemical composition – 75% H, 25% He, trace amount of heavier elements; more in D. Gorbunov's lectures)

2) Radiation (photons - CMB, neutrinos): this gives $\Omega_{\rm rad} \approx 5 \cdot 10^{-5}$

3) Dark matter (does not radiate but clusters; it is cold, with negligible pressure)

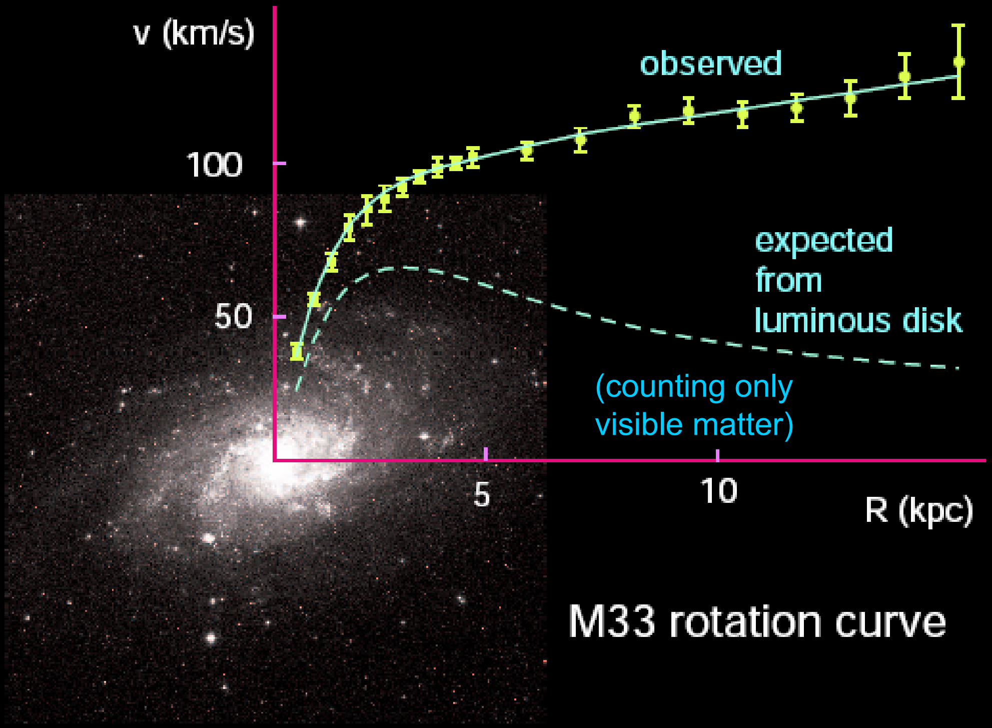
4) Dark energy (does not cluster due to the gravitational interaction)

Dark matter 1

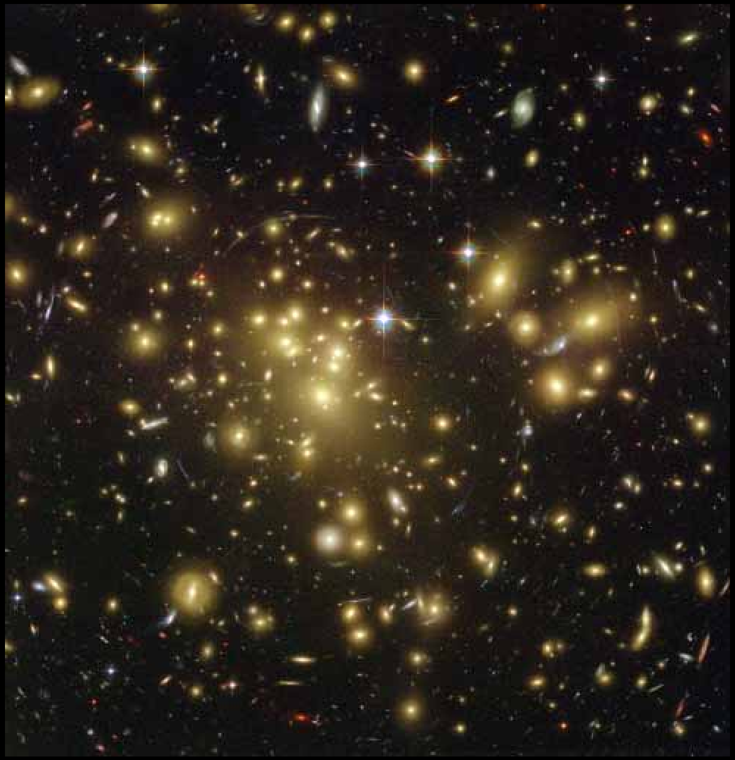
There are several strong evidences that not all matter in the Universe is made of SM particles

1) galaxy rotation curves

2) gravitational lensing



M33 rotation curve



(powerful way to detect clusters of dark matter)

In more details – V. Rubakov's lectures

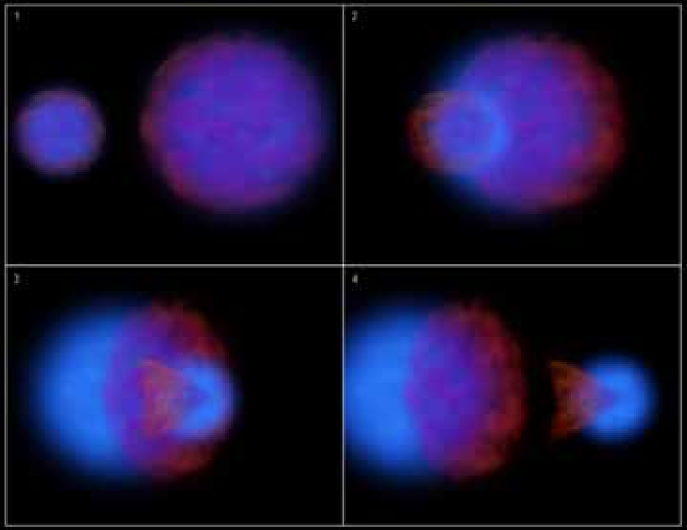
Dark matter 2

”Bullet” galaxy cluster 1E 0757-56

Optical lensing map

X-ray + optical

Combined X-ray and lensing maps



History of the bullet cluster

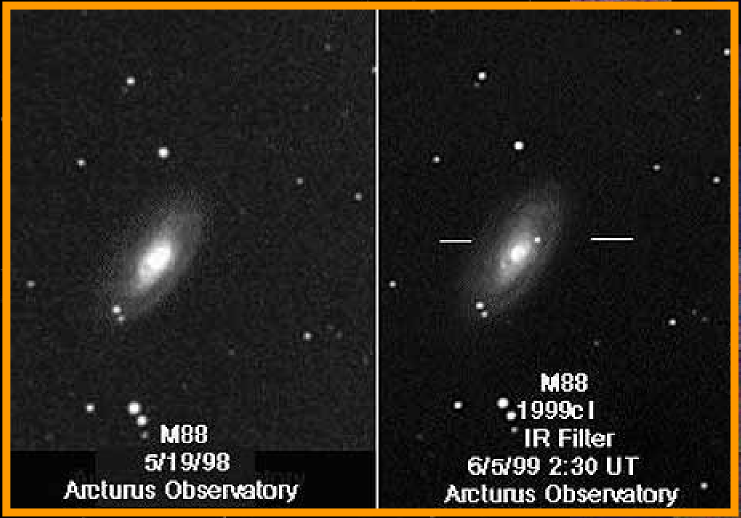
Dark energy 1

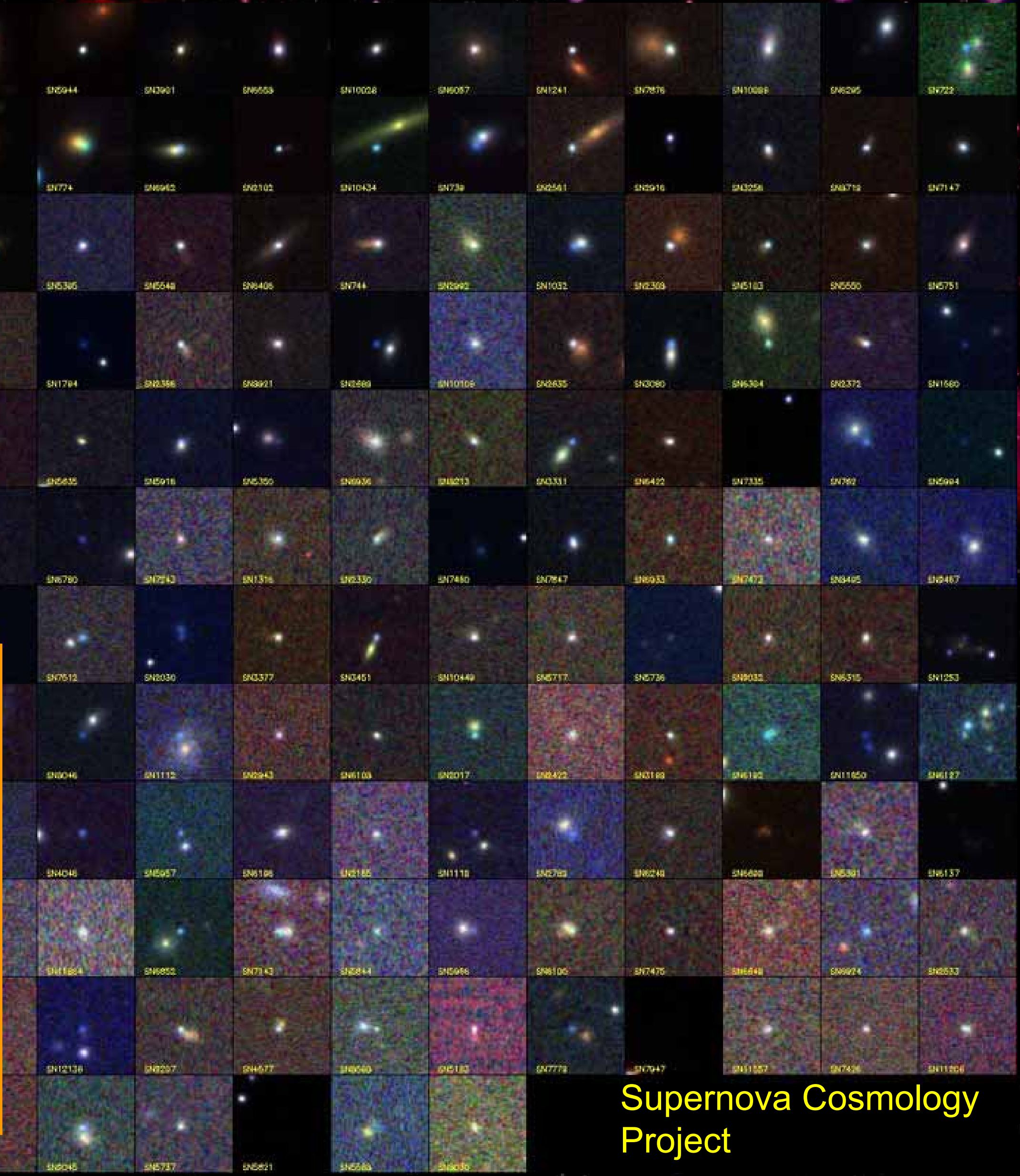
Searching for type Ia supernovae:

1. bright (comparable to galaxy brightness), z>1
2. standard candles

   (small star in pair blows up at the same mass threshold)
3. looking for more data at intermed. redshifts

   (dark energy started to dominate only recently – cosmological coincidence problem)





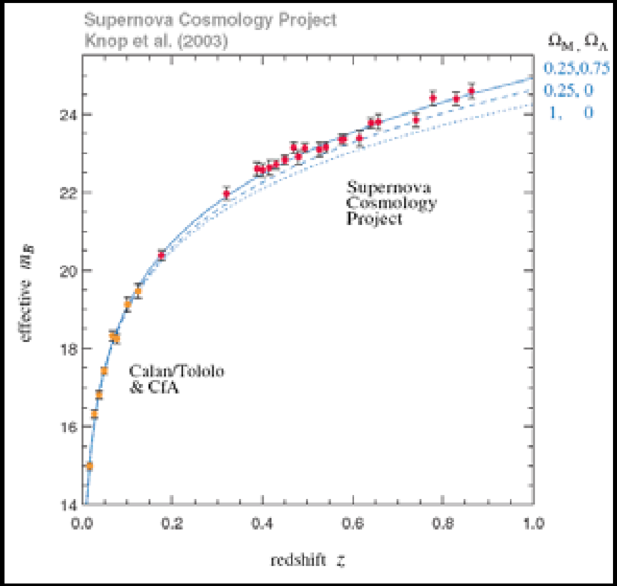
Supernova Cosmology Project

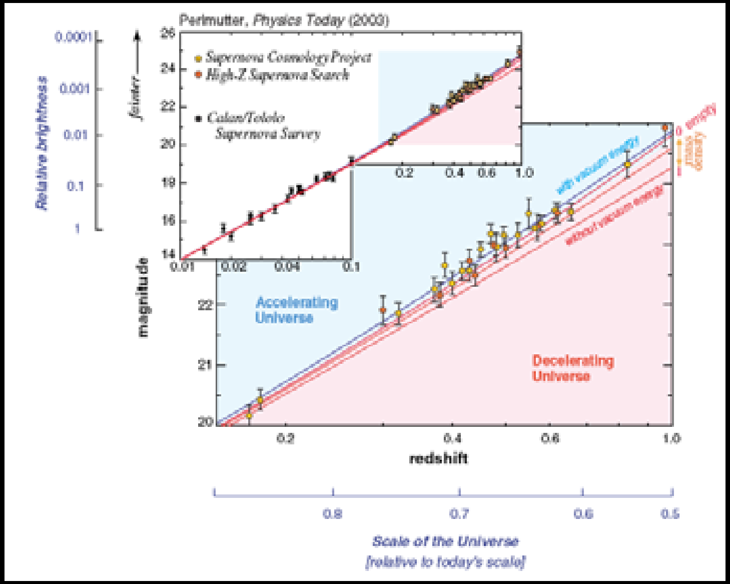
In more details – A. Starobinsky's lectures

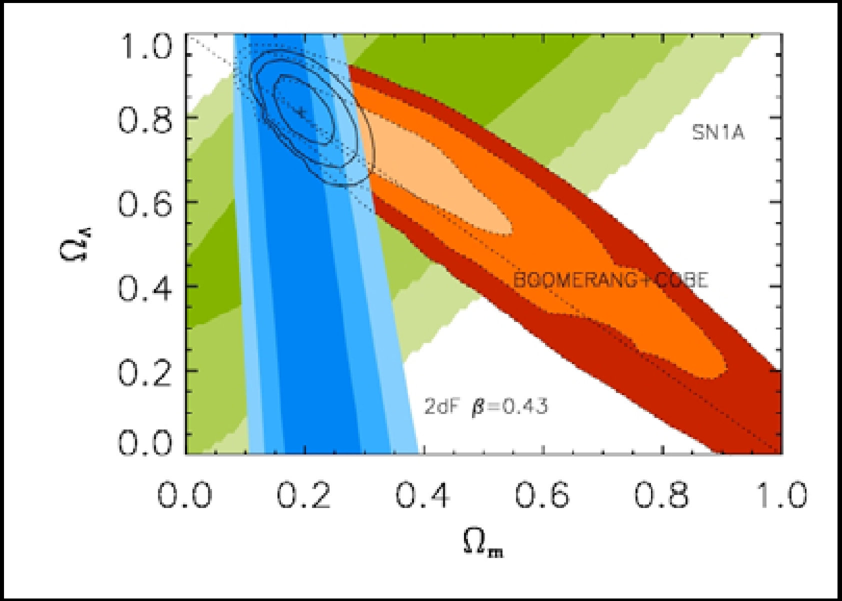
Supernova remnant (blue) near Small Magellanic Cloud

HST

Dark energy 2



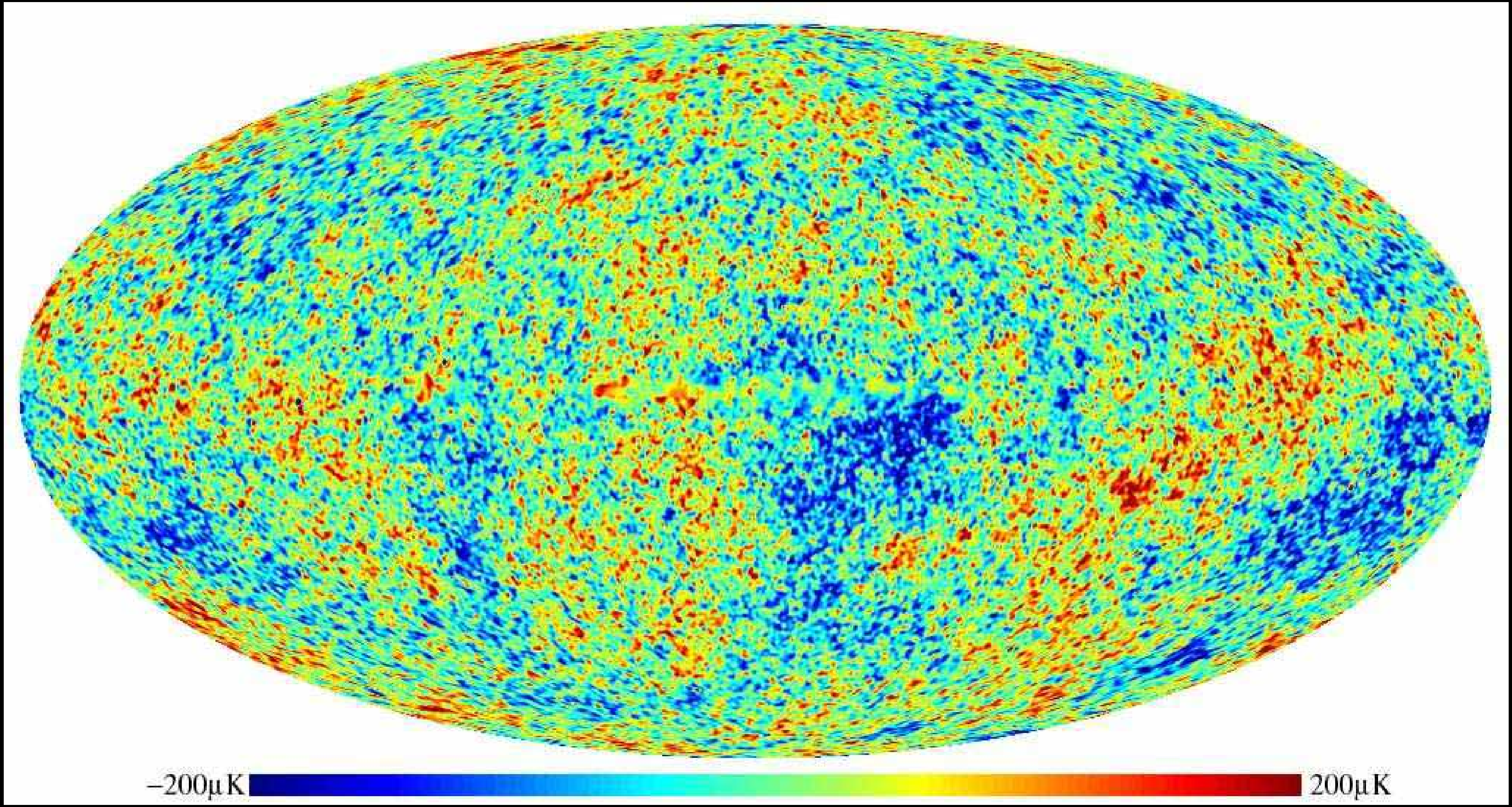




Combined supernovae, COBE (CMB) and 2dF (lensing) data (L. Verde 2005)

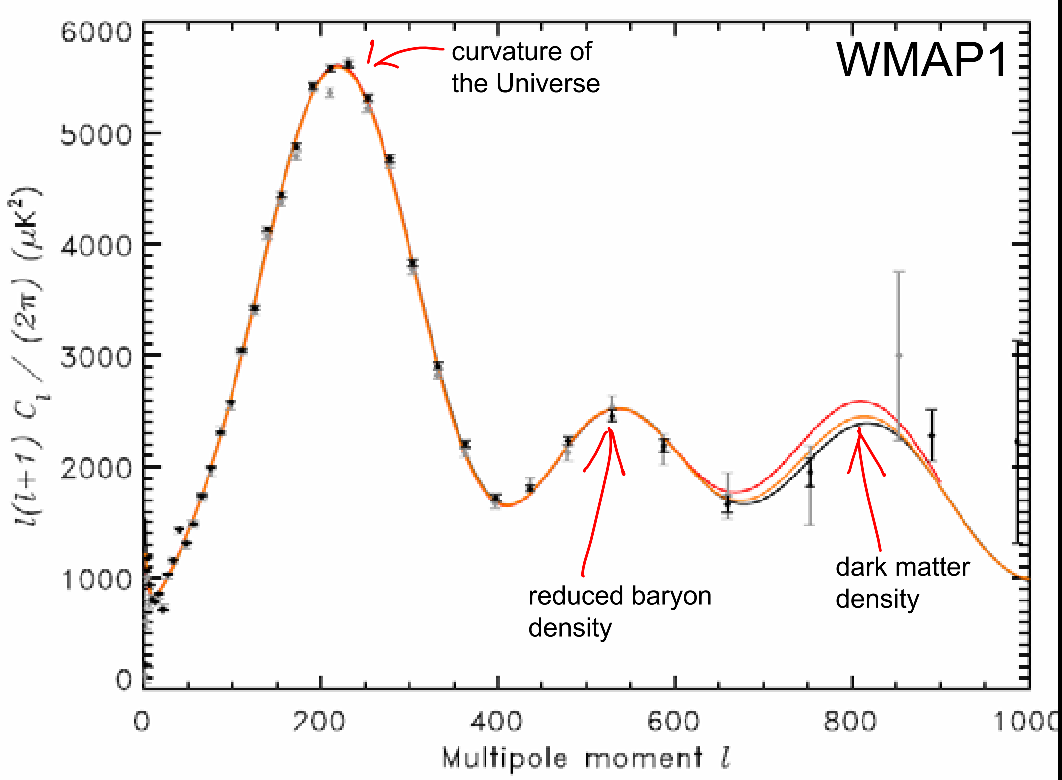
The high precision cosmology – measuring CMB anisotropies

Temperature coming from different parts of the sky is extremely uniform – tiny variations at the level of one part in a hundred thousand!



WMAP: angular map of CMB

Anisotropy of CMB



curvature of the Universe

reduced baryon density

dark matter density

Small anisotropy of the CMB temperature

$$\frac{\Delta T}{T} = \sum_{l,m} a_{lm} Y_{lm}(\theta, \phi)$$

Multipoles are defined as $C_l = \langle |a_{lm}|^2 \rangle$

This light came from the epoch 400000 years after the BB (recombination and photon decoupling, primordial plasma became neutral)

The structure of anisotropy is determined mainly by two effects:

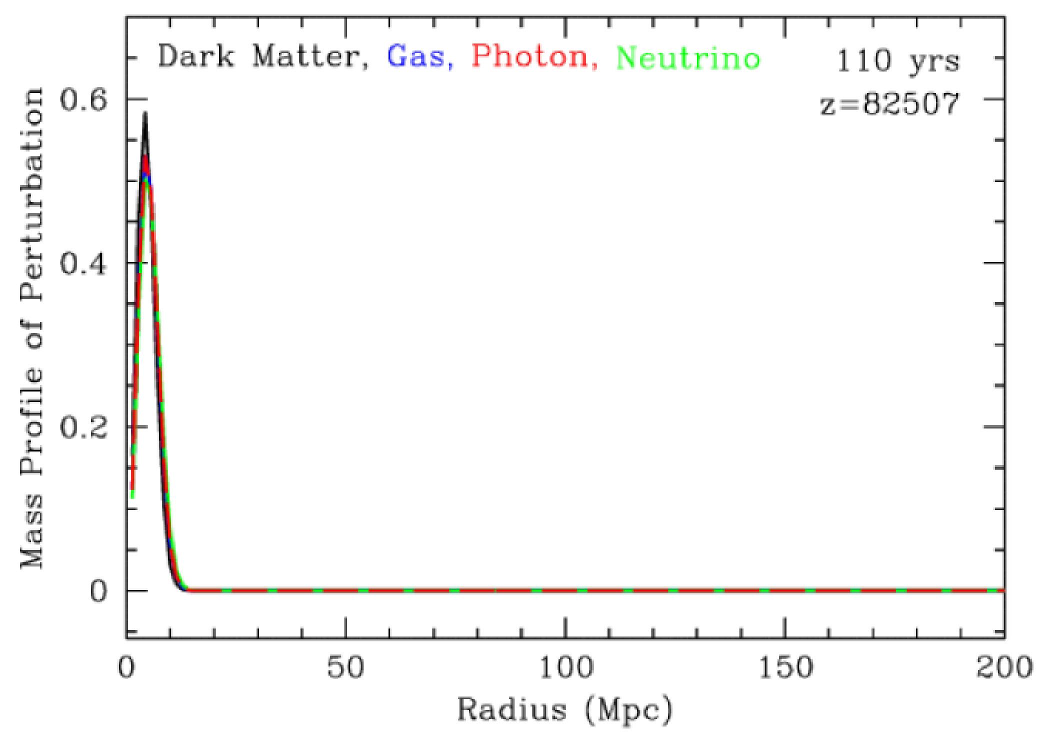
1) acoustic oscillations
2) diffusion (Silk) damping

Acoustic oscillations: competition in the photon-baryon plasma – pressure of relativistic liquid tends to erase anisotropies, gravitational attraction tends to increase instab. Through the Sachs-Wolfe effect this leads to famous oscillations:

$$\left(\frac{\delta T}{T} + \Phi \right) = \mathrm{const}$$

What is acoustic peak 1
(in the correlation function of matter)

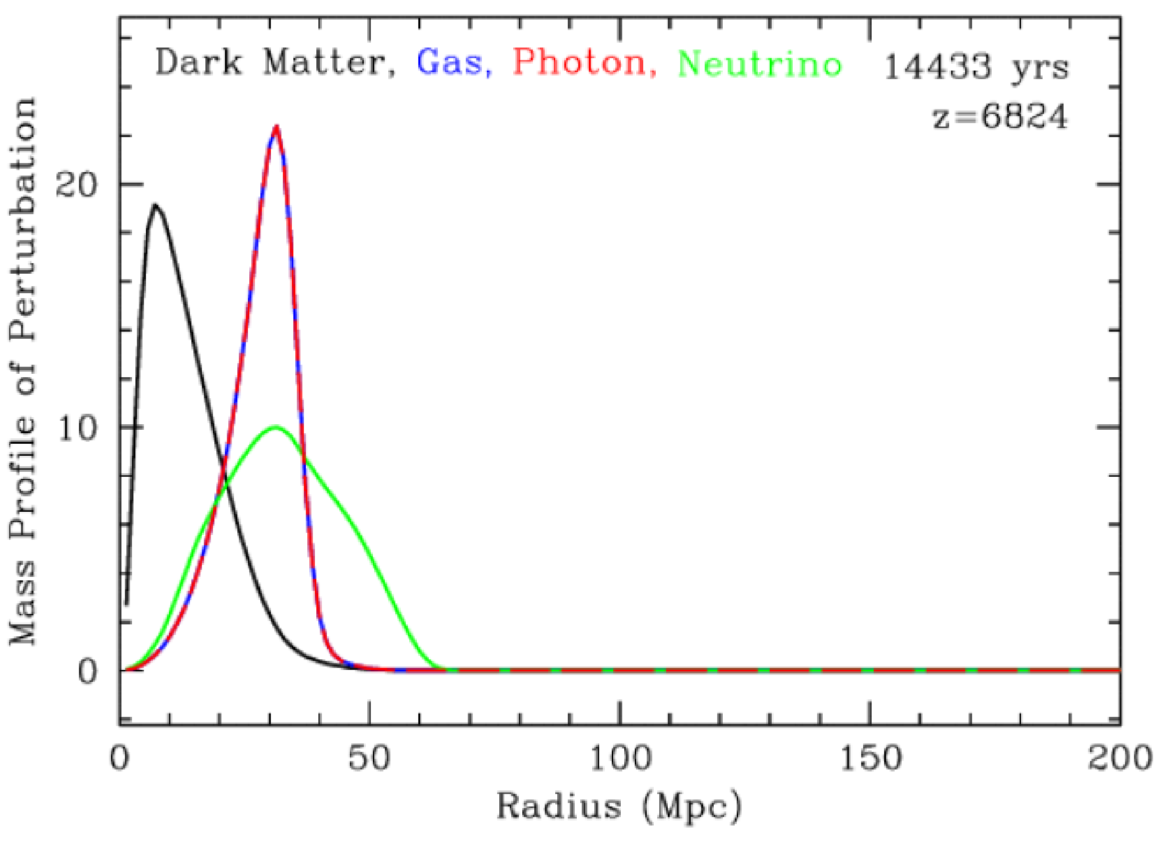
As an example of the interplay between pressure and gravity, let us discuss the behaviour of perturbation in the primordial plasma.



Suppose you have a perturbation in a multi-component plasma like this one. How does it develop in time?

D. Eisenstein, U of Arizona

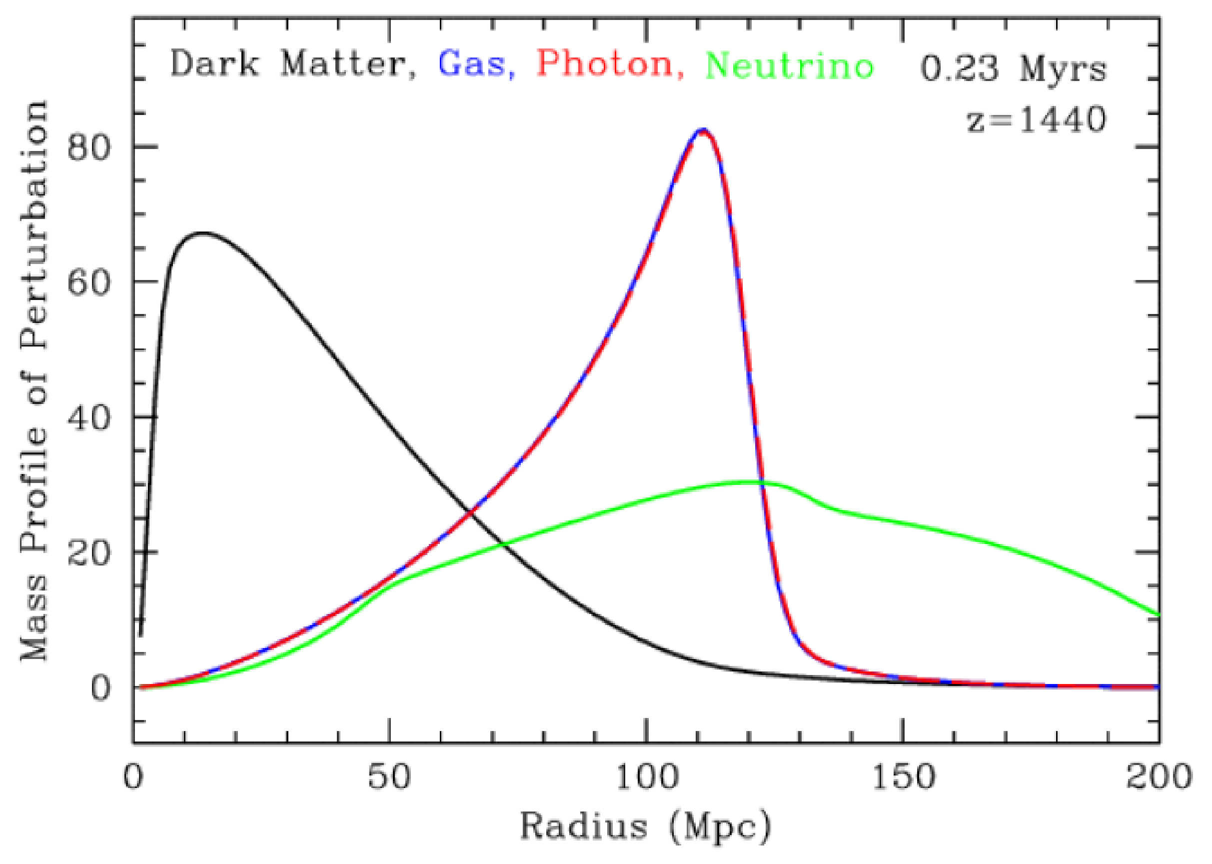
What is acoustic peak 2



Free streaming of neutrino; dark matter feels only gravitation, so clusters; gas of photons and charged particles (baryons) is very hot, i.e., relativistic, having very large pressure)

D. Eisenstein, U of Arizona

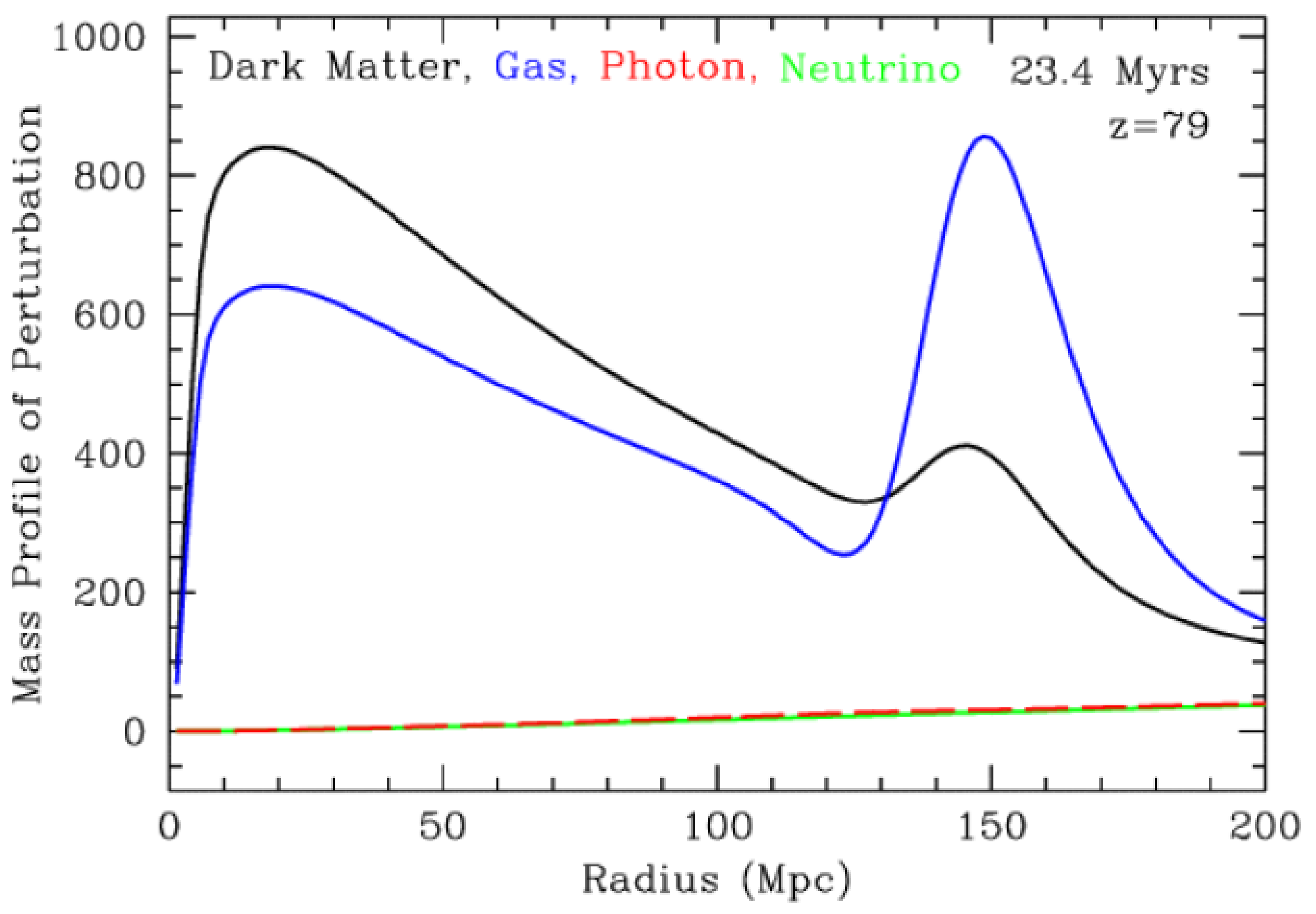
What is acoustic peak 3



Free streaming of neutrino; dark matter feels only gravitation; temperature in the relativistic gas drops below the energy of ionization, so atoms become neutral and photons start to stream freely similar to neutrino

D. Eisenstein, U of Arizona

What is acoustic peak 4



Free streaming of neutrino and photons; dark matter is attracted to the gas; the bump in the spectrum of the gravitational perturbations.

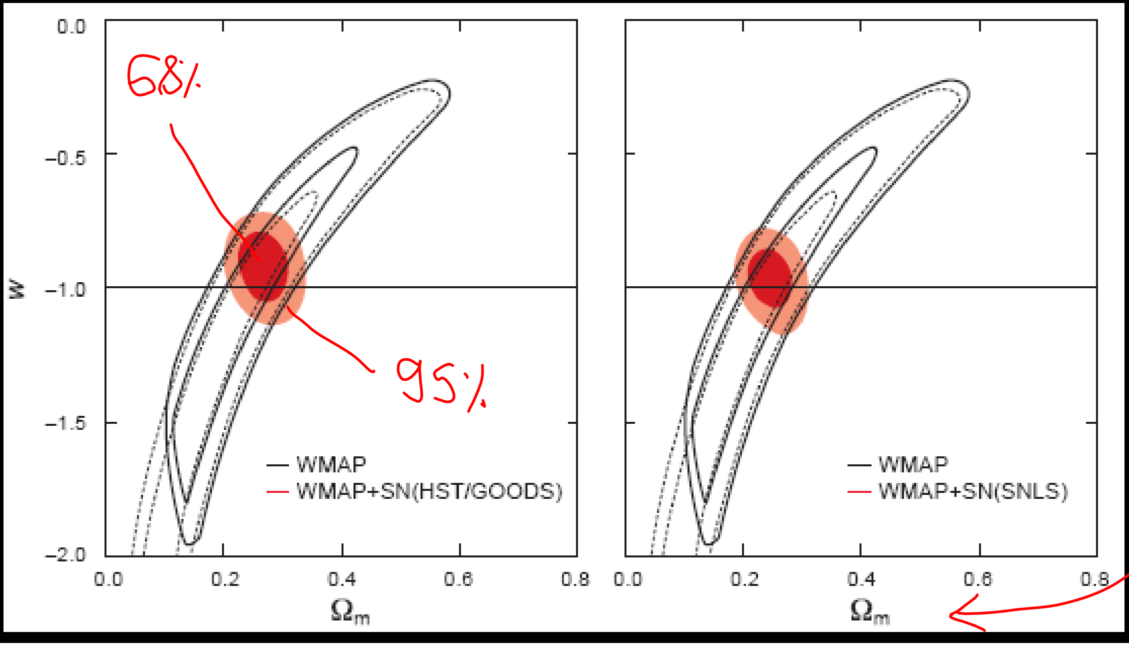
In the case of CMB we have similar picture: interplay between gravitation and the gas pressure leading to the acoustic oscillations in CMB power spectrum.

D. Eisenstein, U of Arizona

More on cosmological parameters 1

(what exactly CMB tells us about the Universe?)

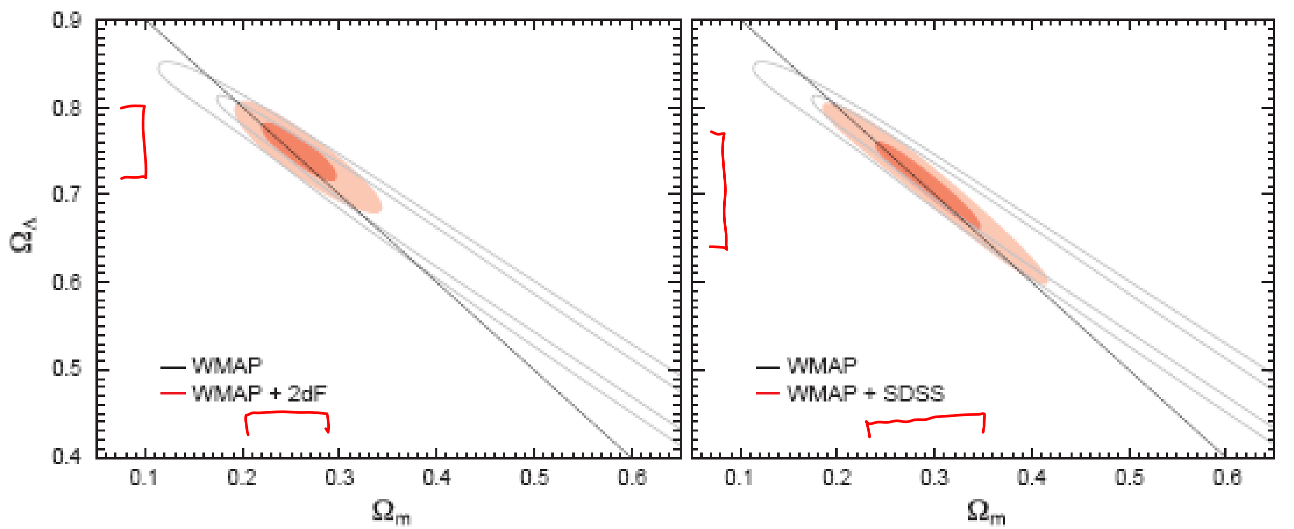
Equation of state of the dark energy: cosmological constant



68%

95%

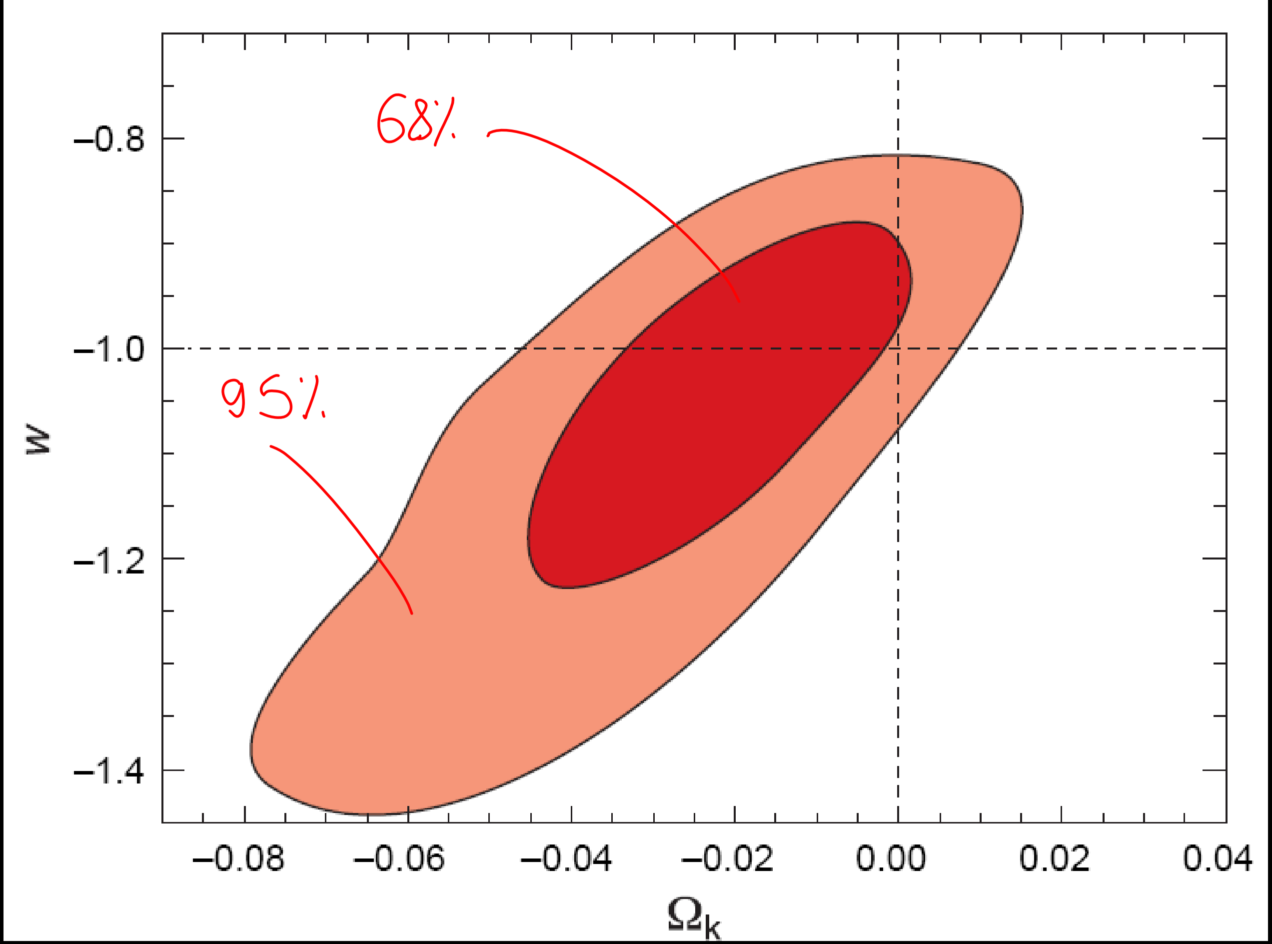
Matter: almost all is dark matter, and it is non-relativistic (i.e., cold)



$\Omega_m + \Omega_\Lambda = 1!$

From WMAP3

More on cosmological parameters 2



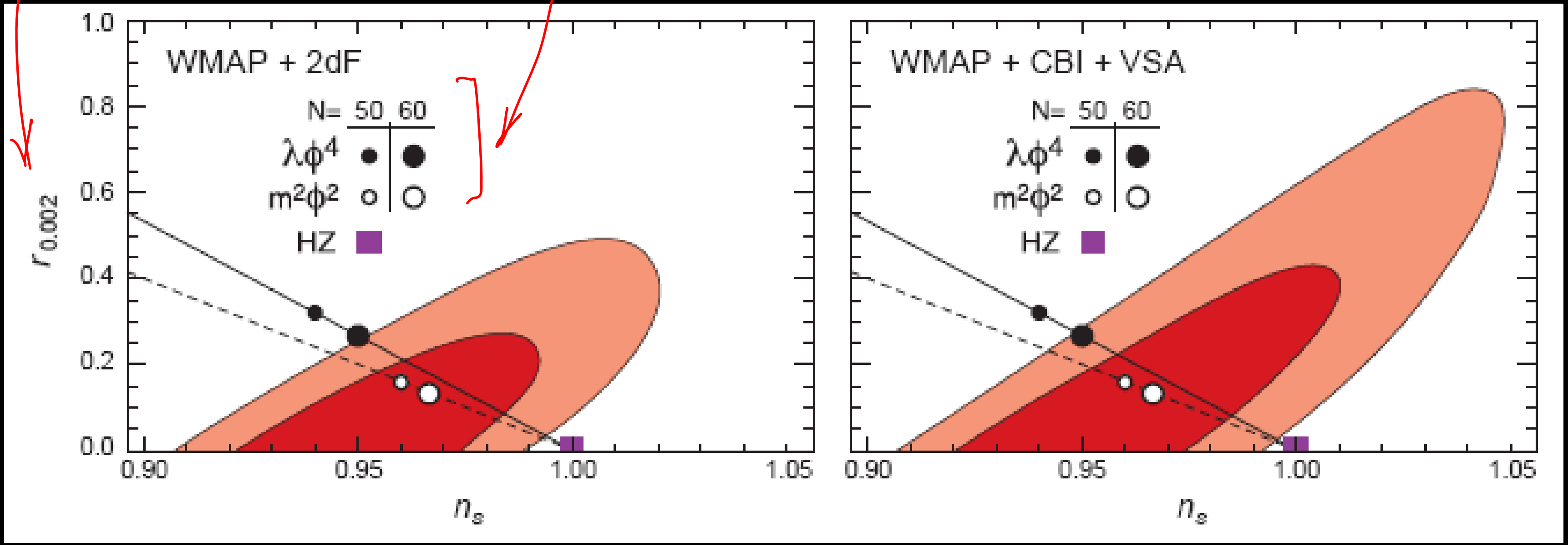
this is spatial curvature (from data of LSS formation should be essentially zero, but looks like a bit negative, doesn't it? Still, zero is acceptable answer)

From WMAP3

More on cosmological parameters 3

tensor-to-scalar ratio

discuss it at the next lecture

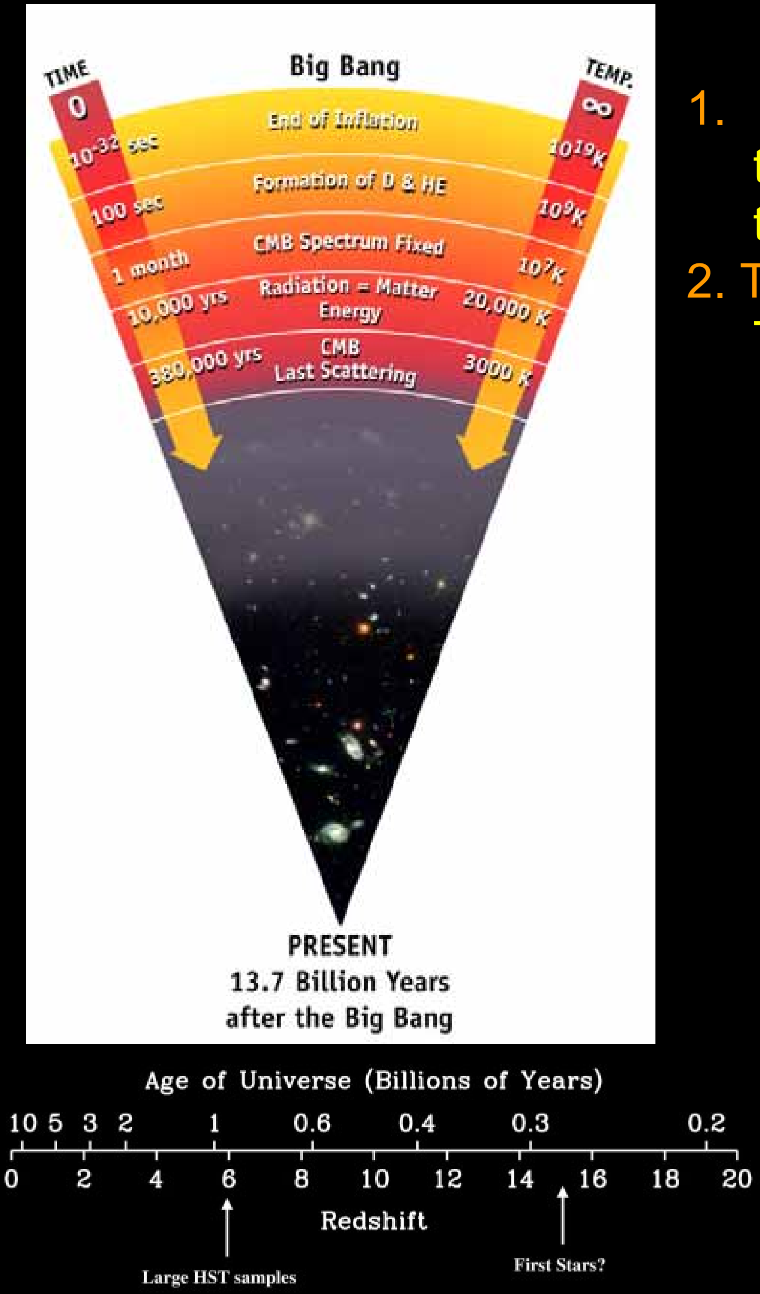


The spectral index is defined according to $P_s(k) \sim k^{n_s - 1}$

The spectrum of scalar primordial gravitational perturbations is very close to the flat one (HZ)

From WMAP3

A brief history of the Universe 1



Main ideas

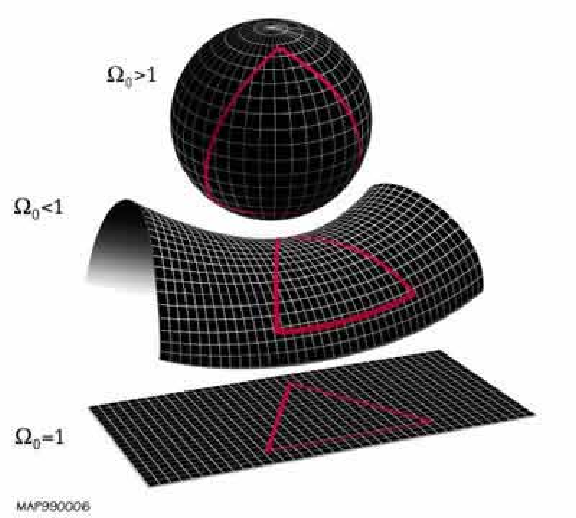
1. Kinetics in expanding Universe: inverse mean free time of each process should be compared to the Hubble parameter; if $1/\tau << H$, then decoupling
2. Temperature drops while the Universe expands: $T \infty 1/a(t)$

Stages

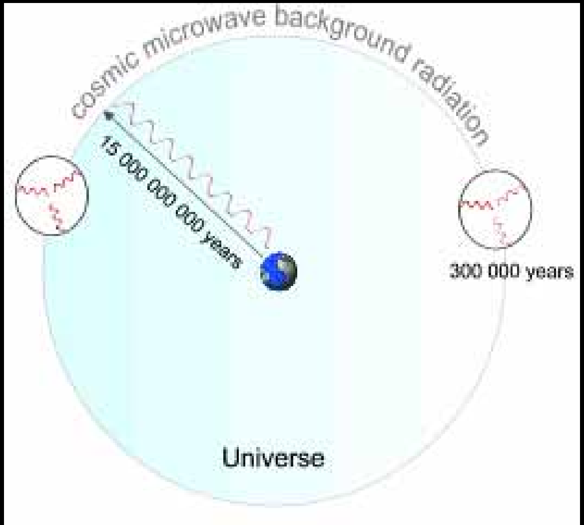
1. Large scale structure formation, stars (z<5, 8 – 10 bill. yrs old)
2. T ∞ 3000 K (z ∞ 1000, 380000 yrs old) ”Last scattering surface” – electrons and photons decouple; atoms
3. T ∞ 20000 K (z∞10000, 10000 yrs old) Energy densities of matter and radiation become comparable; radiation dominates for earlier stages
4. $T \infty 10^9$ K ($z \infty 10^{10}$, 100 sec old) Big Bang nucleosynthesis – cretation of H, D, He3, He4 nuclei (more in D. Gorbunov’s lectures)

A brief history of the Universe 2
What was earlier (what happens at larger distances)?

1. Flatness (or euclidicity) problem:
   the three-dimensional space is extremely flat as seen from observations

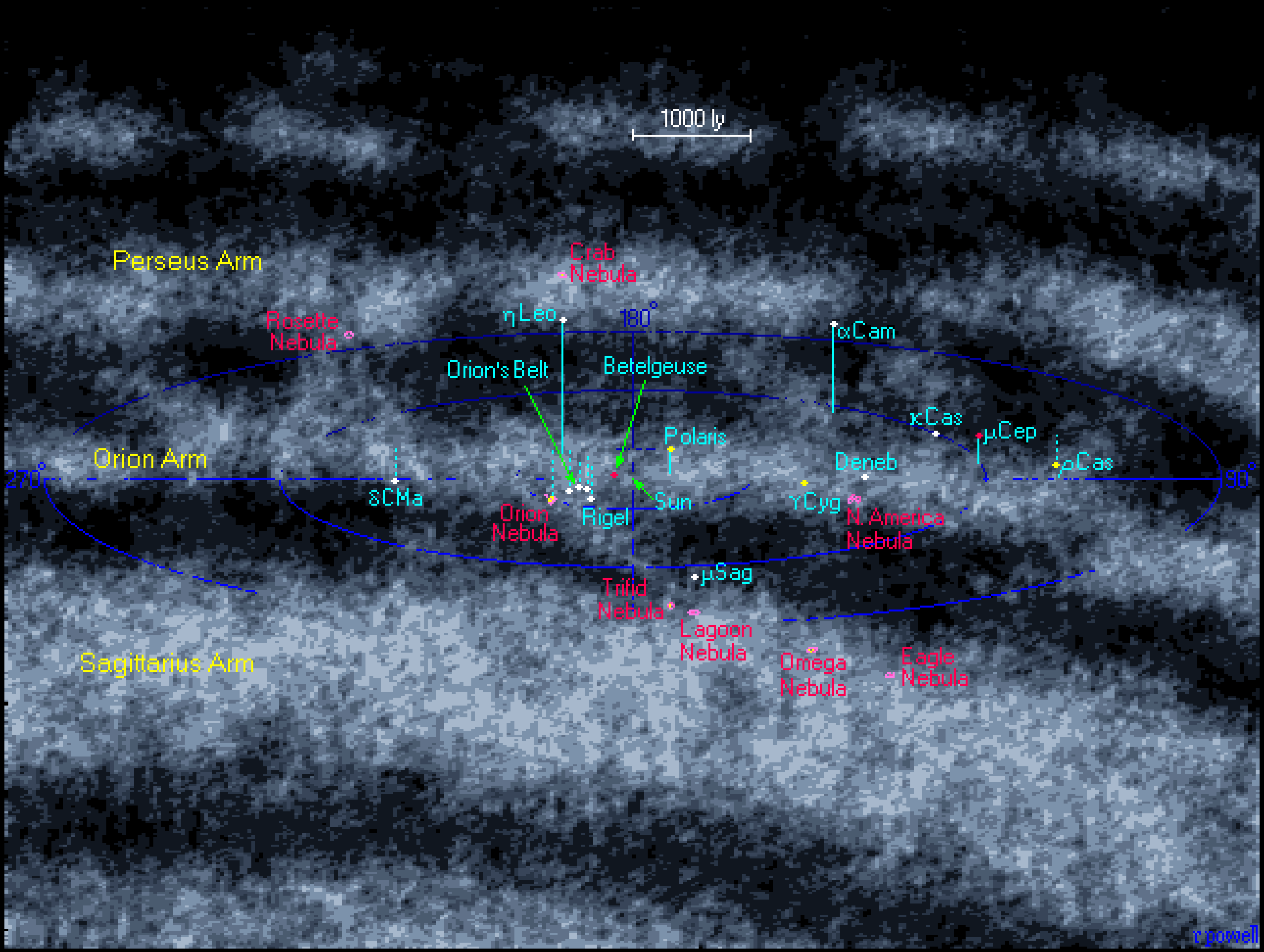


2. Horizon problem: the Universe is extremely isotropic. No matter what distant corners of the Universe you look at, the sizes and distributions of objects are the same.
   If one approximates the Friemann evolution to Planckian scales, the size of casually connected patch (L ∞ 0.0001 cm) is much larger the the Planckian volume (contains about 10^{89} patches which are not connected casually with each other)



3. Why the spectrum of primordial inhomogeneities is so flat?

The ultimate answer for these questions is inflation (the next lecture)



Nearest stars and nebulae