A short walk through cosmology

C. Spiering, summer lecture, Zeuthen 2009

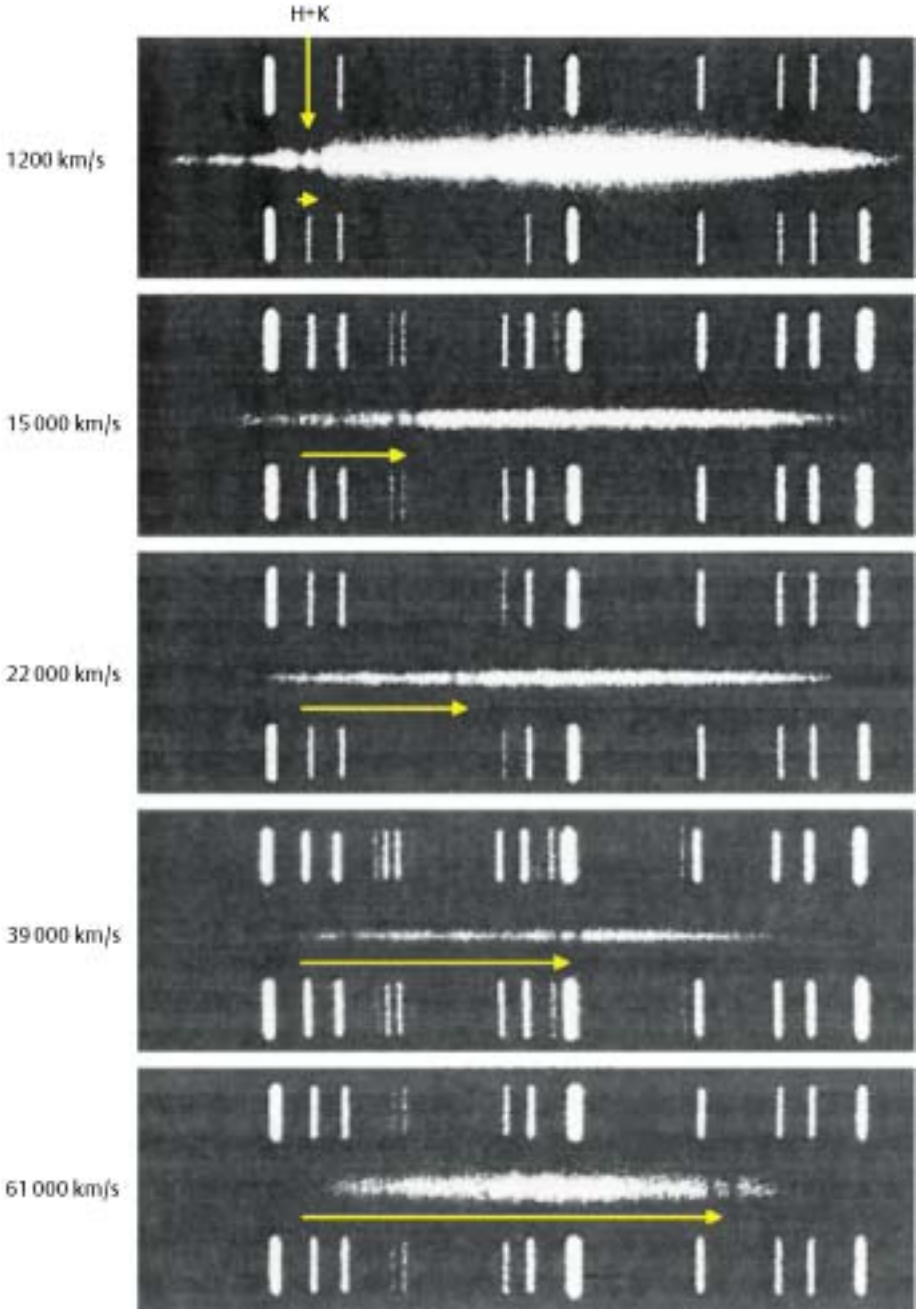
Content

1. Astronomical observations
2. Dark Matter
3. The Cosmic Drama

1. Astronomical Observations

- Redshift and the expanding Universe
- Cosmological constant and accelerated expansion
- He/H ratio
- 3K radiation (CMBR)
- Temperature fluctuations of CMBR
- Large Scale Structures
- Dark Matter

Redshift



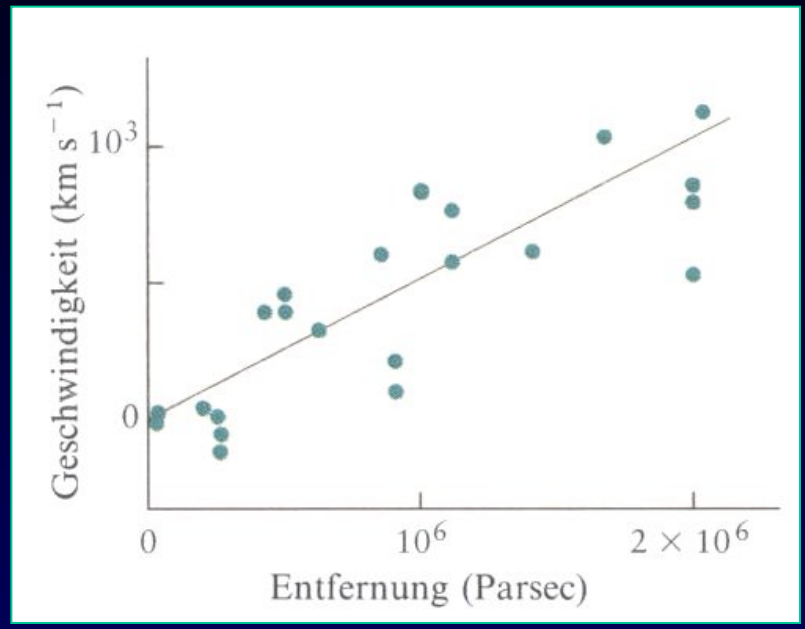
First seen for
„distant nebulae“
by Slipher 1910-1920

- no reliable distance scale yet
- faint nebulae not yet identified as Galaxies

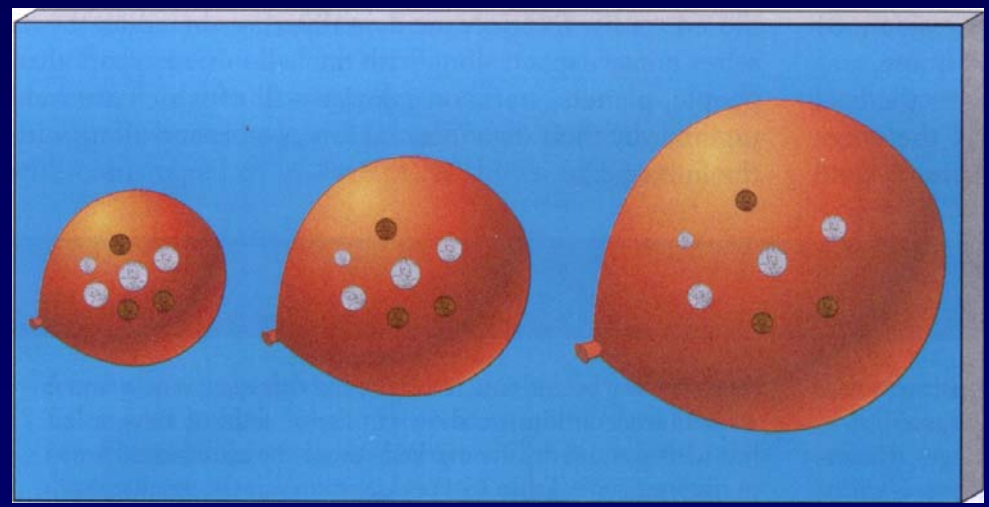
Redshift vs. distance

Edwin Hubble
1929

$$v = H \cdot d$$



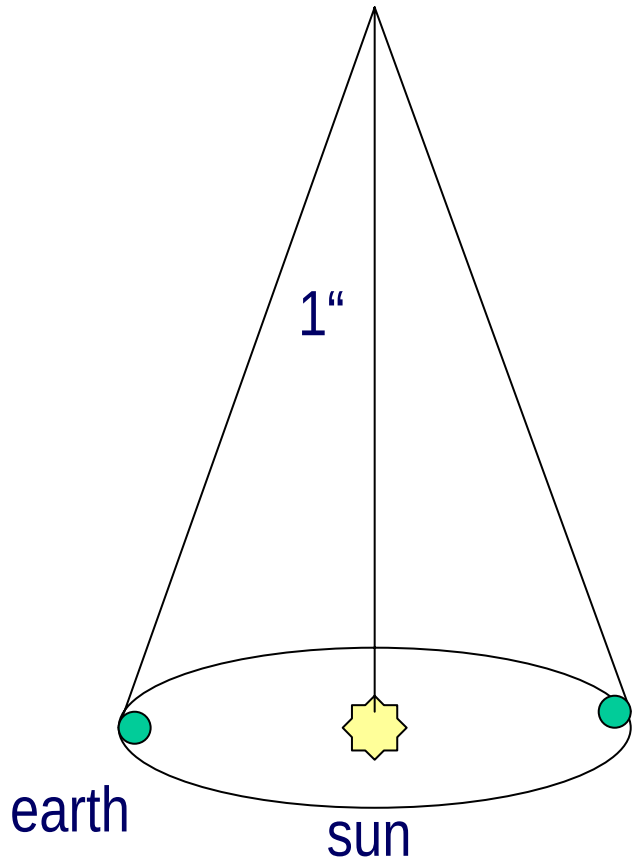
The Universe expands



Distances

1 light year = $3 \cdot 10^8$ m /s $\times$ $3.15 \cdot 10^7$ s = $9.46 \cdot 10^{15}$ m

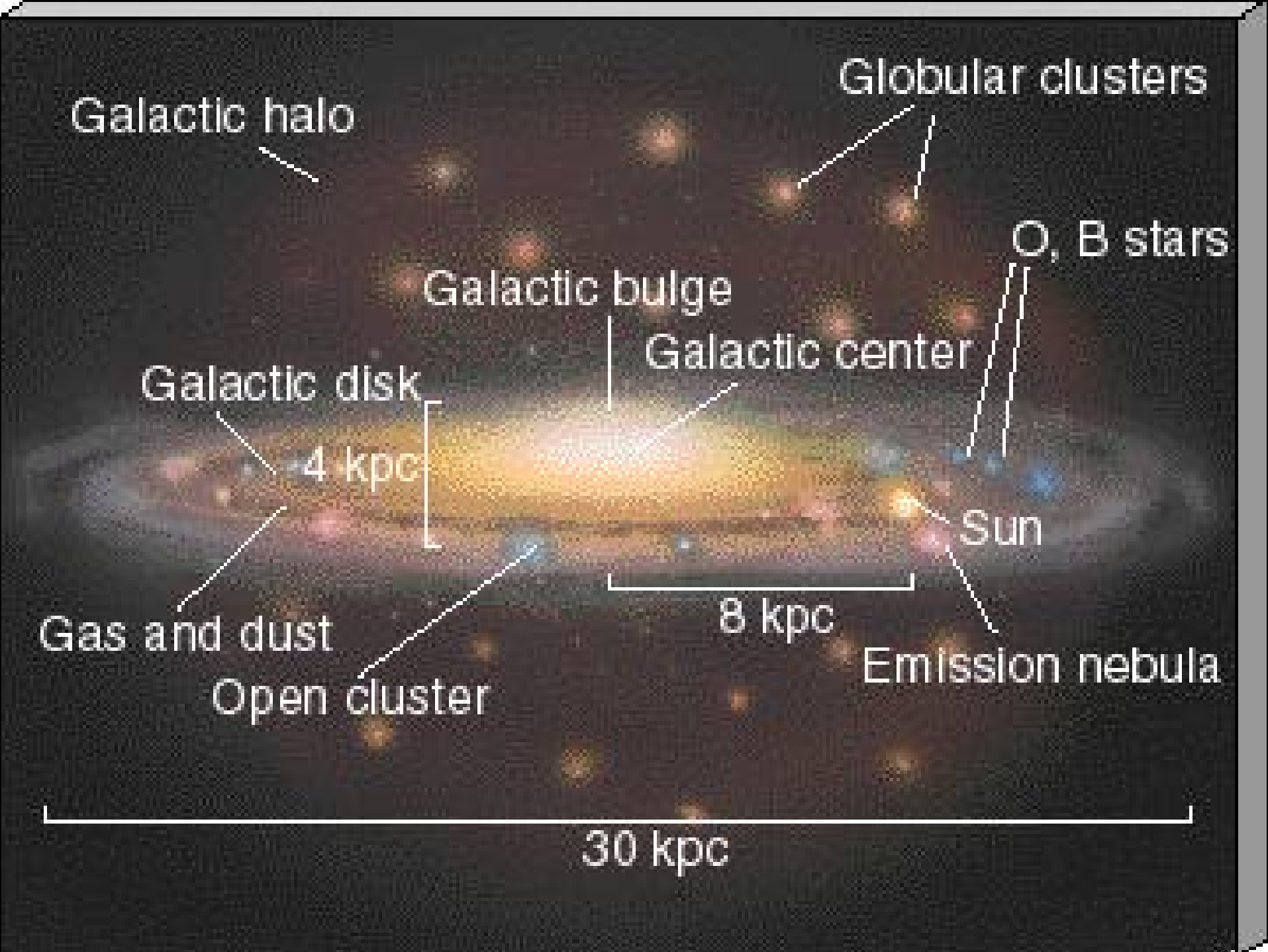
Galactic Center	~ 25 kLy
Large Magellanic Cloud	~ 150 kLy
Andromeda	~ 2 MLy



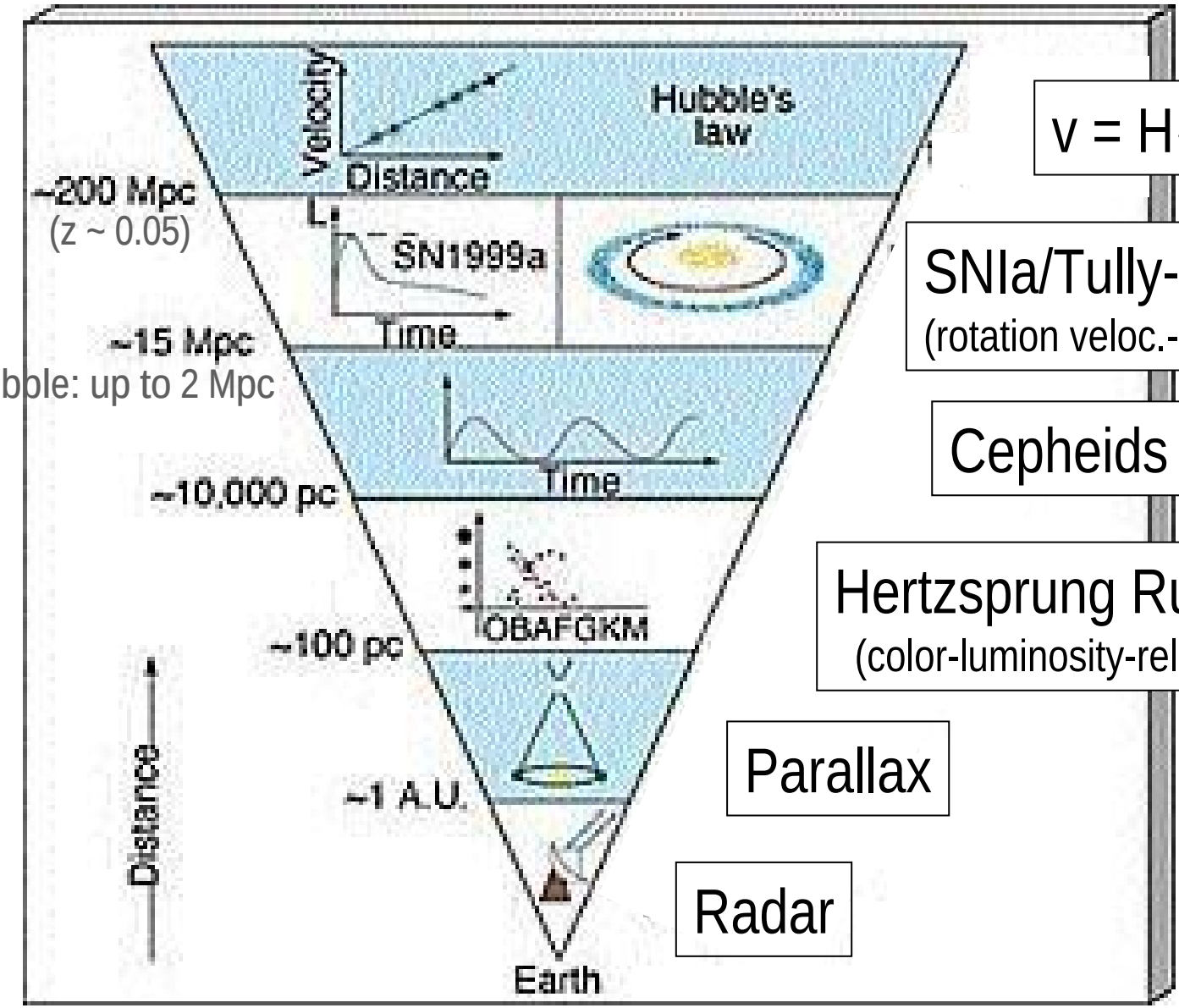
1 parsec (pc) =

$3.09 \cdot 10^{16}$ m = 3.26 Ly

Galactic Center	~ 8 kpc
Andromeda	~ 0.7 Mpc
Typical Quasar	~ 1000 Mpc


Galactic halo
Globular clusters
O, B stars
Galactic bulge
Galactic center
Galactic disk
4 kpc
Sun
8 kpc
Gas and dust
Open cluster
Emission nebula
30 kpc

The distance ladder



$v = H \cdot d$

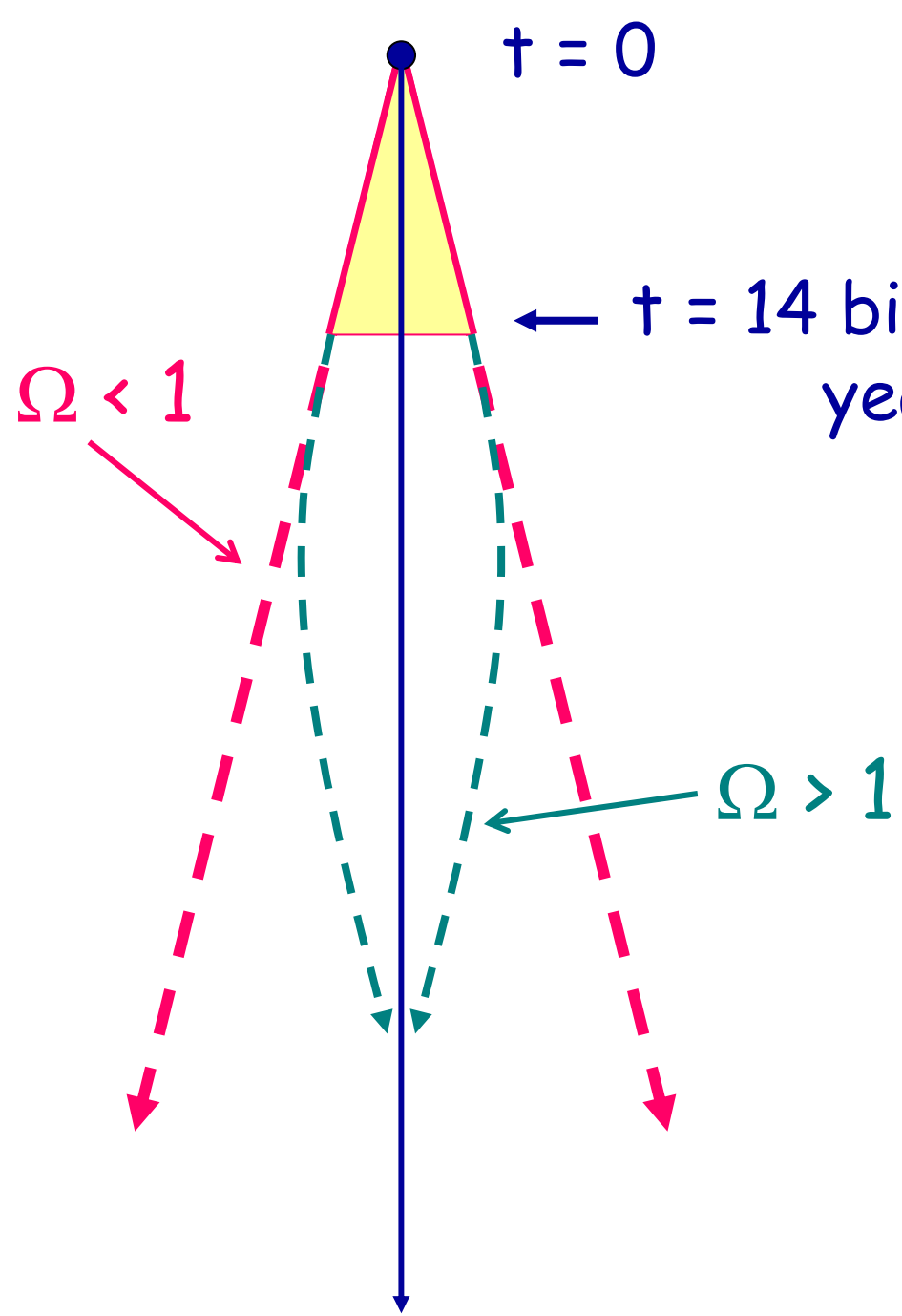
SNIa/Tully-Fisher
(rotation veloc.-mass relation)

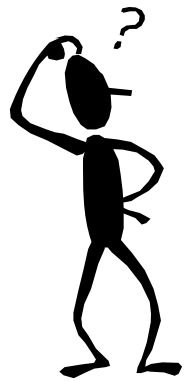
Cepheids

Hertzsprung Russell
(color-luminosity-relation)

Parallax

Radar

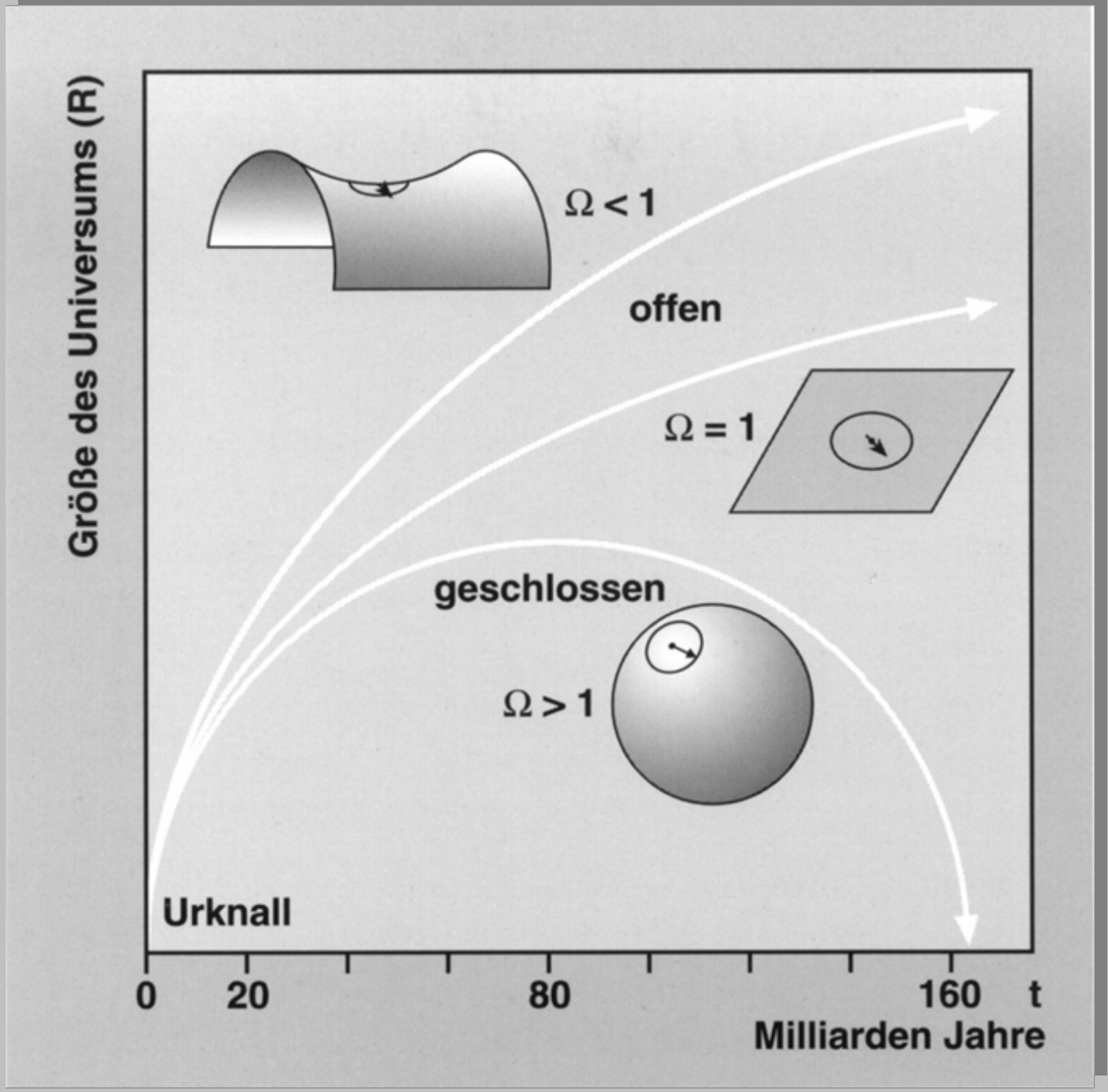




„critical density“

$\approx 10^{-29}$ g/cm^3

$$\Omega = \frac{\text{actual density}}{\text{critical density}}$$


Größe des Universums (R)
Ω < 1
offen
Ω = 1
geschlossen
Ω > 1
Urknall
0
20
80
160
t
Milliarden Jahre

The Friedmann Equations (1)

gravitational constant curvature parameter

$$H^2 - (8\pi G\rho/3) = k/a^2$$

1st Friedmann Equation

$$\frac{\ddot{a}}{a} = -\frac{4}{3}\pi G(\rho + 3p)$$

2nd Friedmann Equation

radiation pressure

Density of matter and radiation

Distance between 2 points: $d = R \cdot a(t)$

scale factor

$H_0 \sim 72$ km/s per Mpc (today)

The Friedmann Equations (2)

Today: a ≡ 1 ⇒ $H_0^2 - (8\pi G\rho/3) = k$

k > 0: *H* always well defined, Universe expands forever
k < 0: *H* becomes imaginary, Universe stops to expand

For *k = 0* $\rho_{crit} = 3H_0^2/8\pi G$

Estimate of the critical density ρ_c

$$H_0 = \frac{1}{5 \cdot 10^{17} s}$$

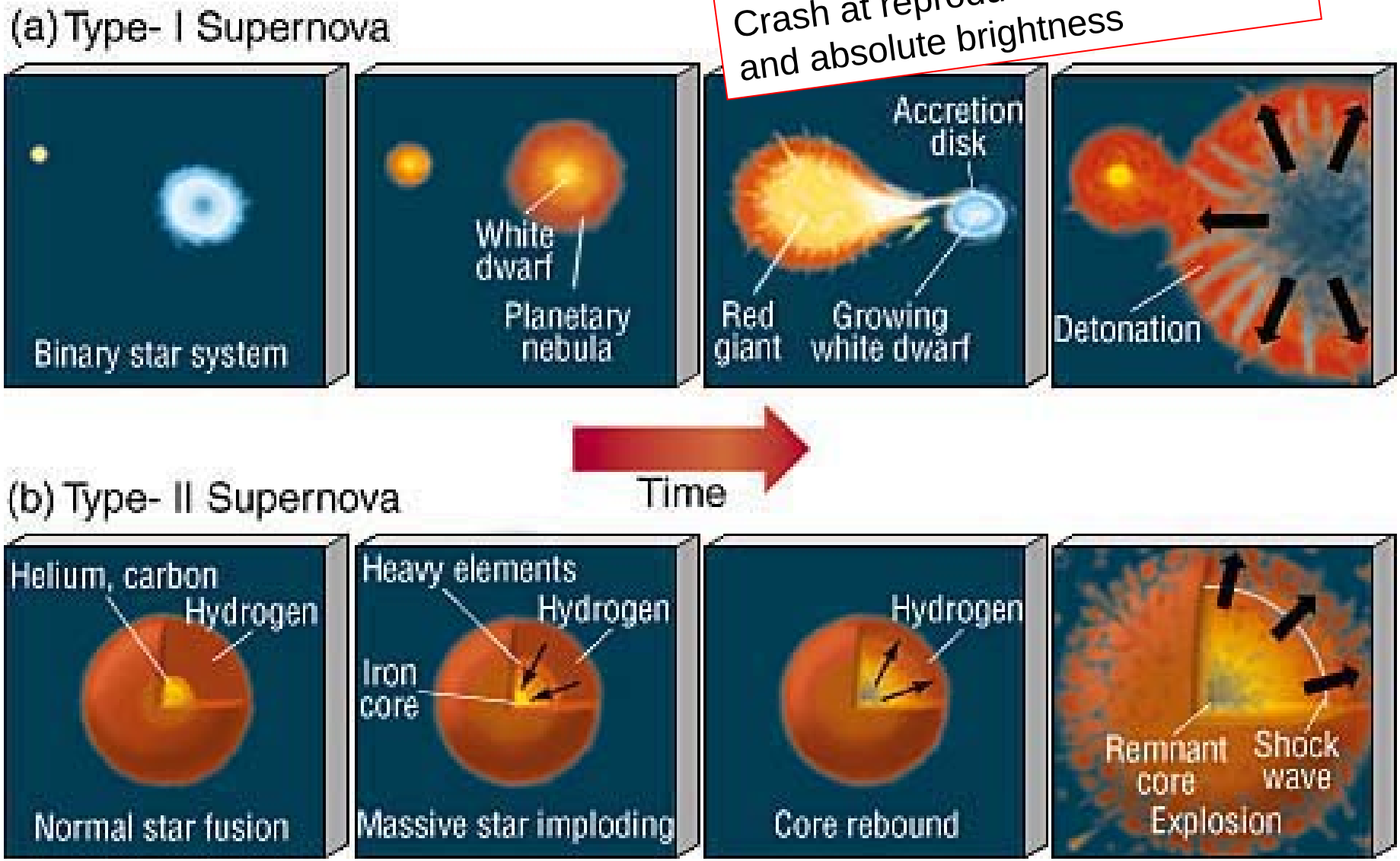
$$\rho_c = \frac{3H_0^{\,2}}{8\pi G} = \frac{3 \cdot (5 \cdot 10^{17} s)^{-2}}{8 \cdot 3.14 \cdot (6.67 \cdot 10^{-11} m^3 kg^{-1} s^{-2})}$$

$$= 7 \cdot 10^{-27} kg/m^3 \approx 10^{-29} g/cm^3 \approx 4\, GeV/m^3$$

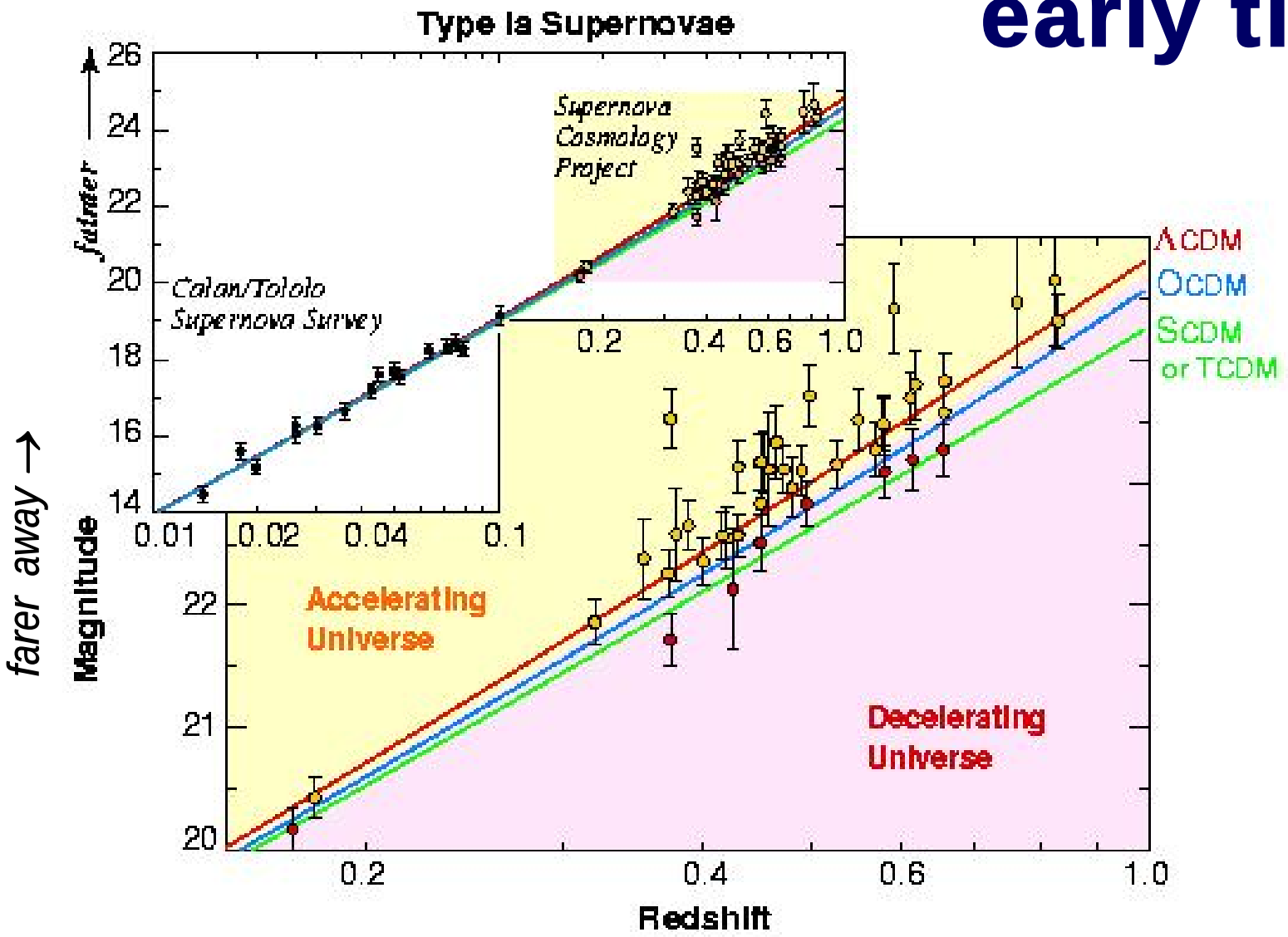
1 GeV/c² = 1.78·10^{-27} g

Supernovae

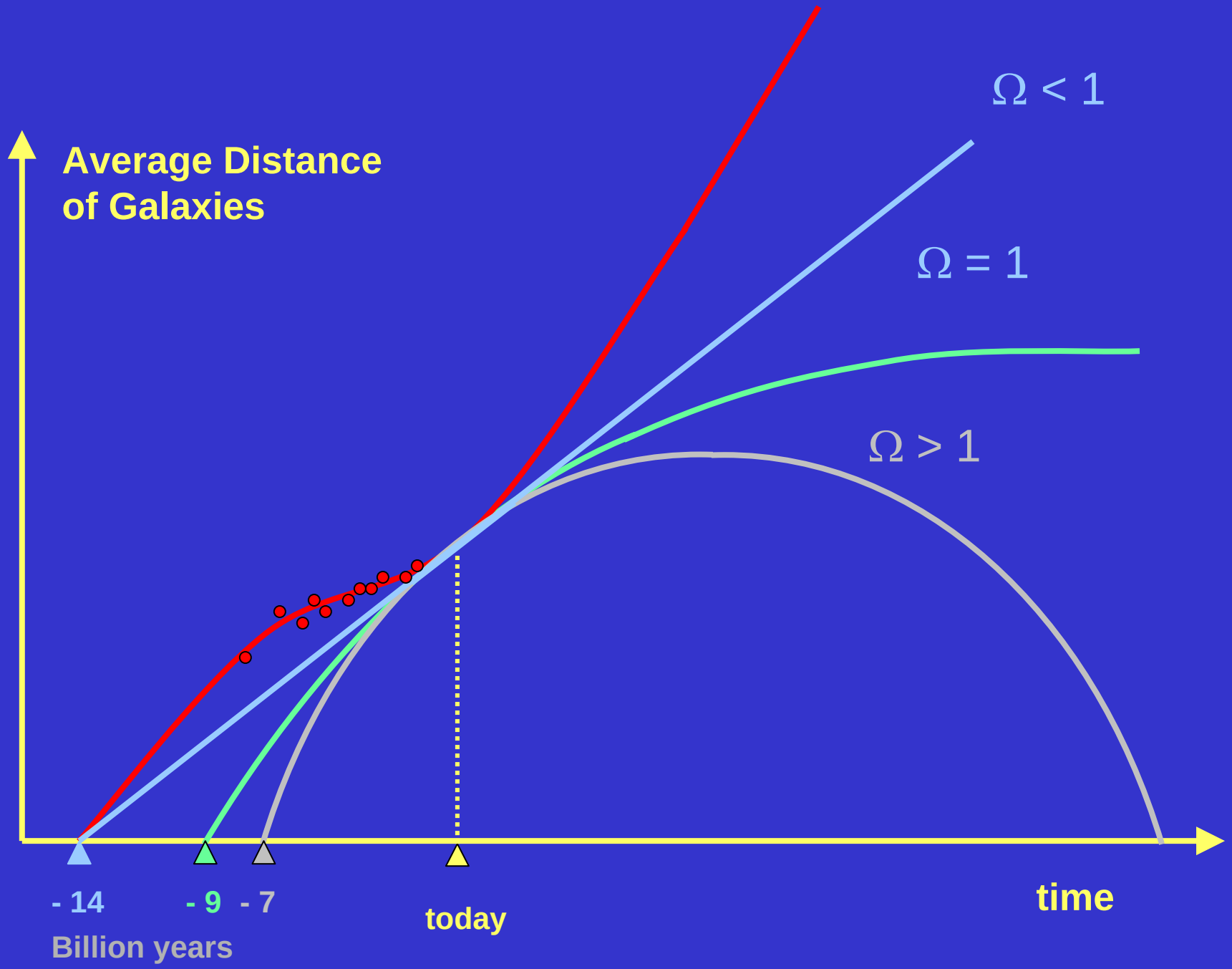
Crash at reproducable dwarf mass and absolute brightness



SN-Ia: expansion was *slower* in early times



SN-Ia as “Standard-Candles”


Ω < 1
Ω = 1
Ω > 1
Average Distance
of Galaxies
- 14
- 9
- 7
today
time
Billion years

A non-zero cosmological constant Λ ?

(Einstein‘s „grösste Eselei“ – to get a static Universe ....)

$$H^2 - (8\pi G\rho/3) = k/a^2 + \frac{\Lambda}{3}$$

$$\frac{\ddot{a}}{a} = -\frac{4}{3}\pi G(\rho + 3p) + \frac{\Lambda}{3}$$

What is Dark Energy ?

- Vacuum energy ? ($w_{vac} = p_{vac}/\rho_{vac} = -1$)
- Non-relativistic matter ? ($w = 0$)
- Relativistic particles ? ($w = 1/3$)
- Other models ($-1 < w < +1$)
- Experimentally: $w \sim (-1)$

1. Astronomical Observations

- Redshift and the expanding Universe
- Cosmological constant and accelerated expansion
- He/H ratio
- 3K radiation (CMBR)
- Temperature fluctuations of CMBR
- Large Scale Structures
- Dark Matter

He/H – ratio

See details in part III !

75%	***H***
23%	***He***
2%	***all the rest***

produced in stars

Big Bang Model:

He/H ≈ 1/3

The Cosmic Microwave Background Radiation (CMBR)

Isotropic radio noise
at 7.5 cm

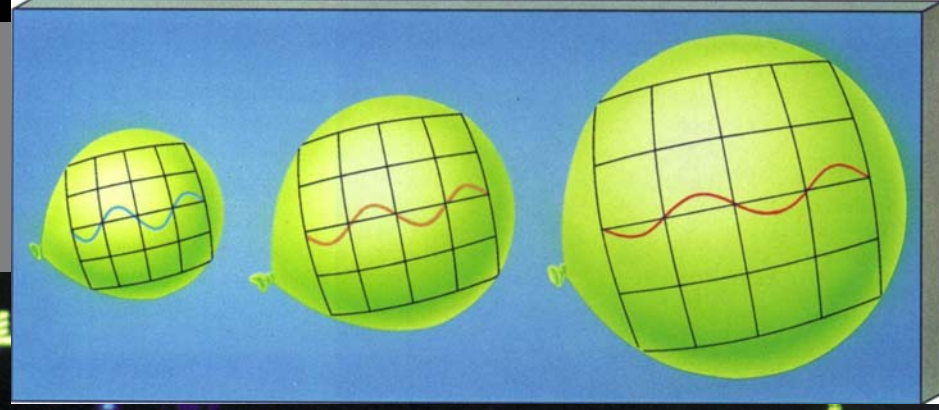
Intensity
$\rightarrow$ photon gas at ~ 2.7 K

$\gamma/p = 10^9:1$

Penzias and Wilson, 1965

COBE-Satellite (1989):

$T = 2.735 \pm 0.006$ K



CMBR wavelength spectrum

$1/\lambda$ (cm^{-1})

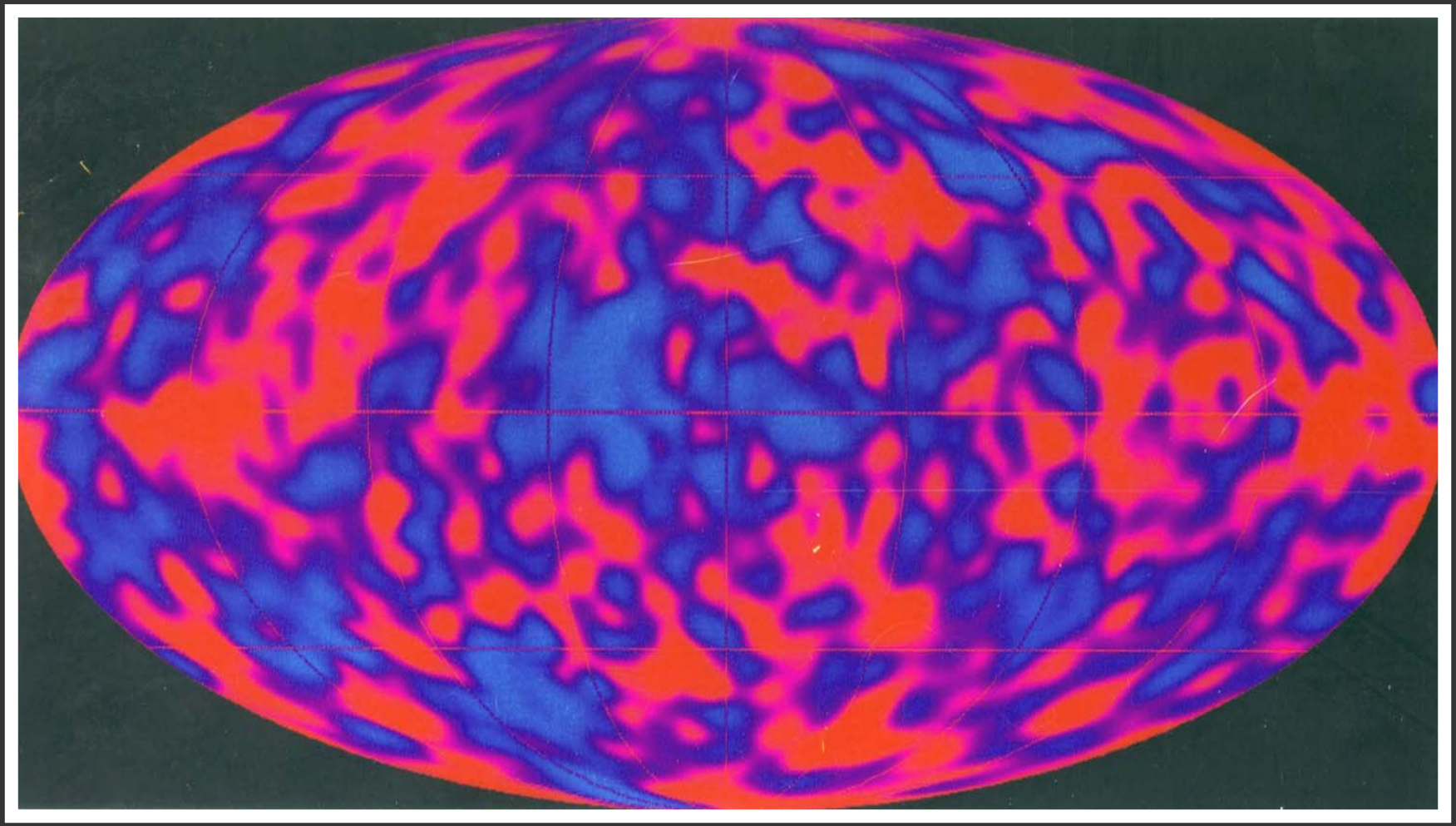
Fluctuations in CMBR

10 mK accuracy → isotropy

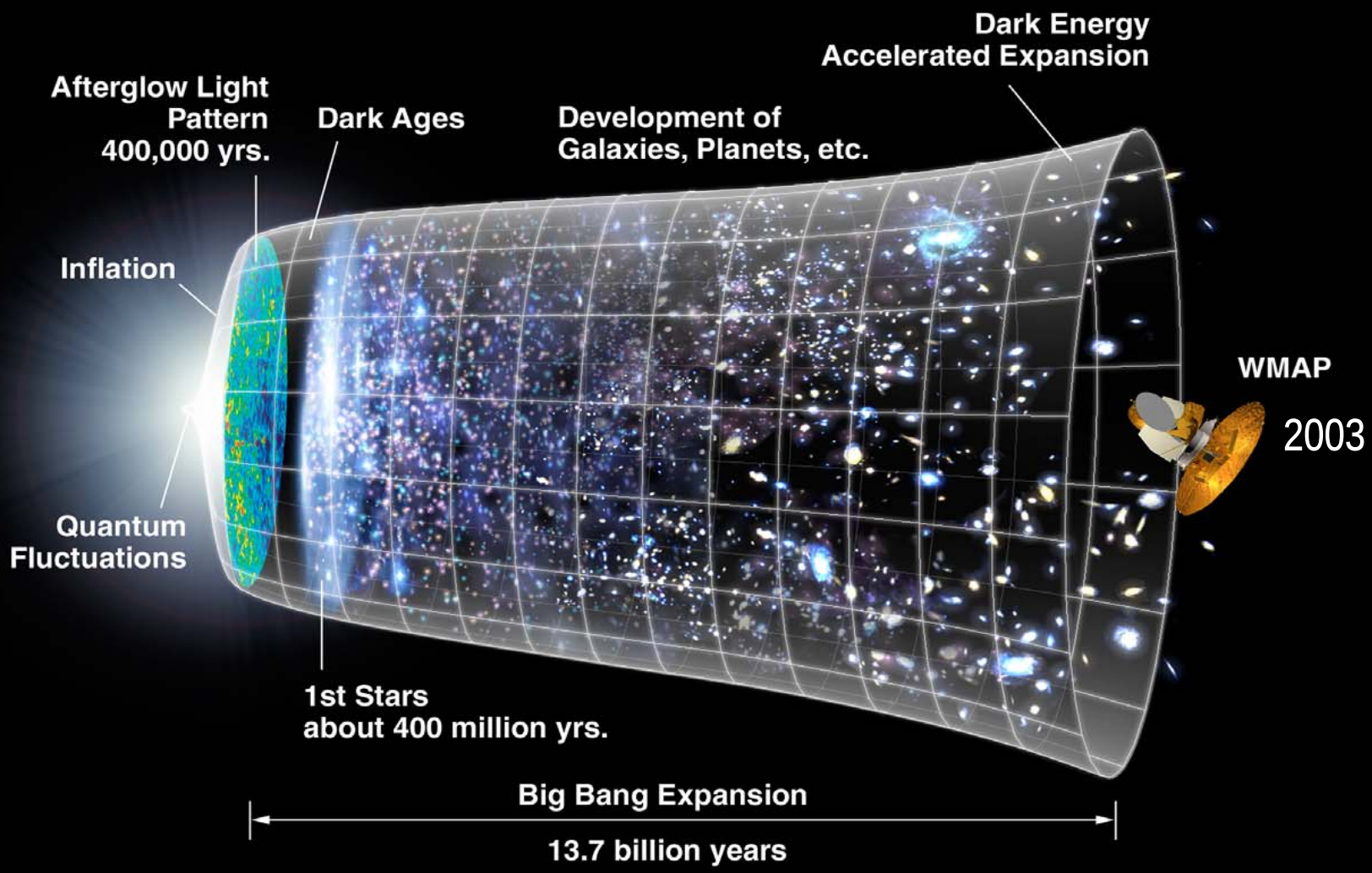
1 mK accuracy → dipole structure
(Earth moves with 400 km/s)

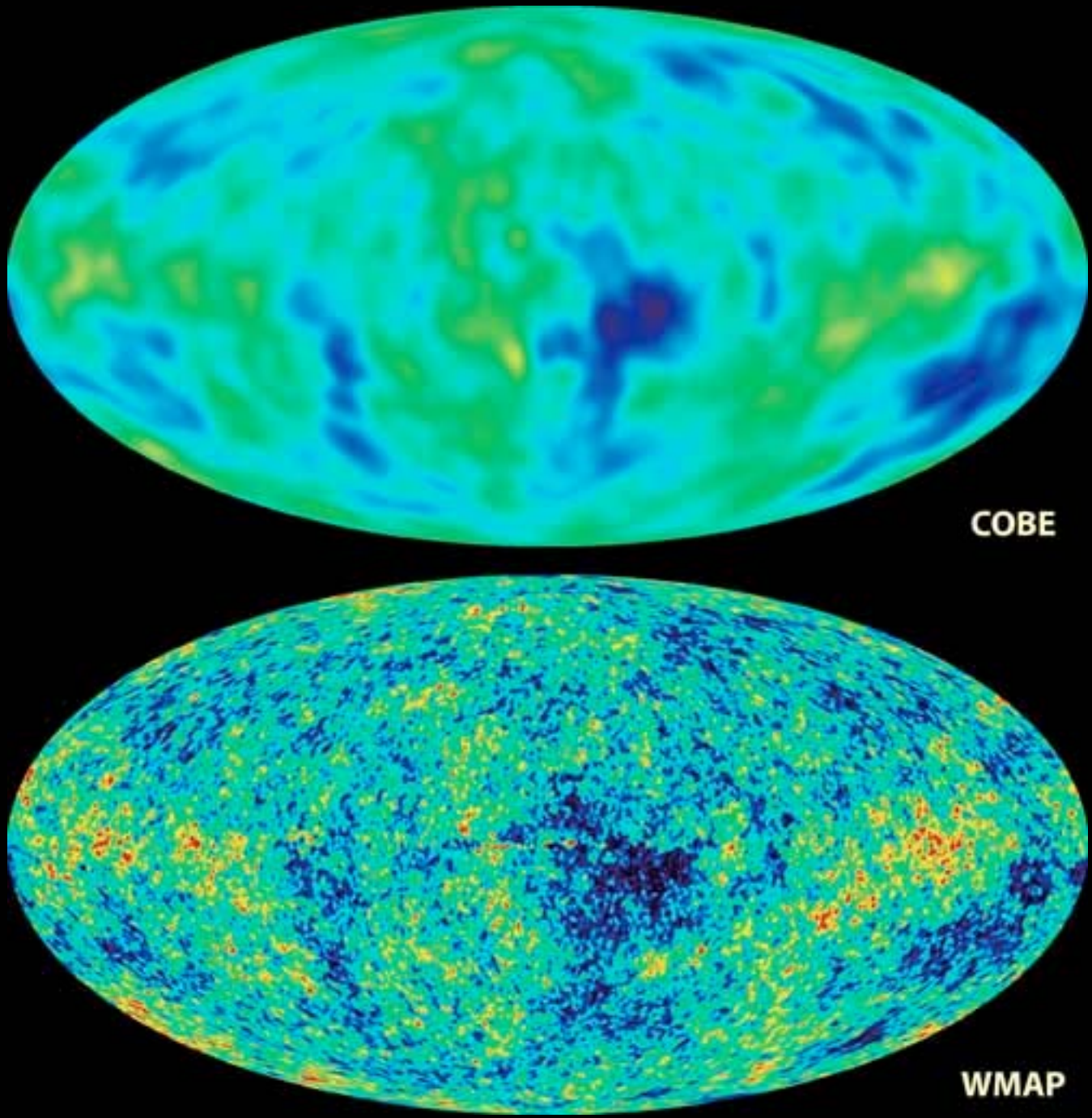
0.1 mK accuracy → galactic plane

COBE 1992

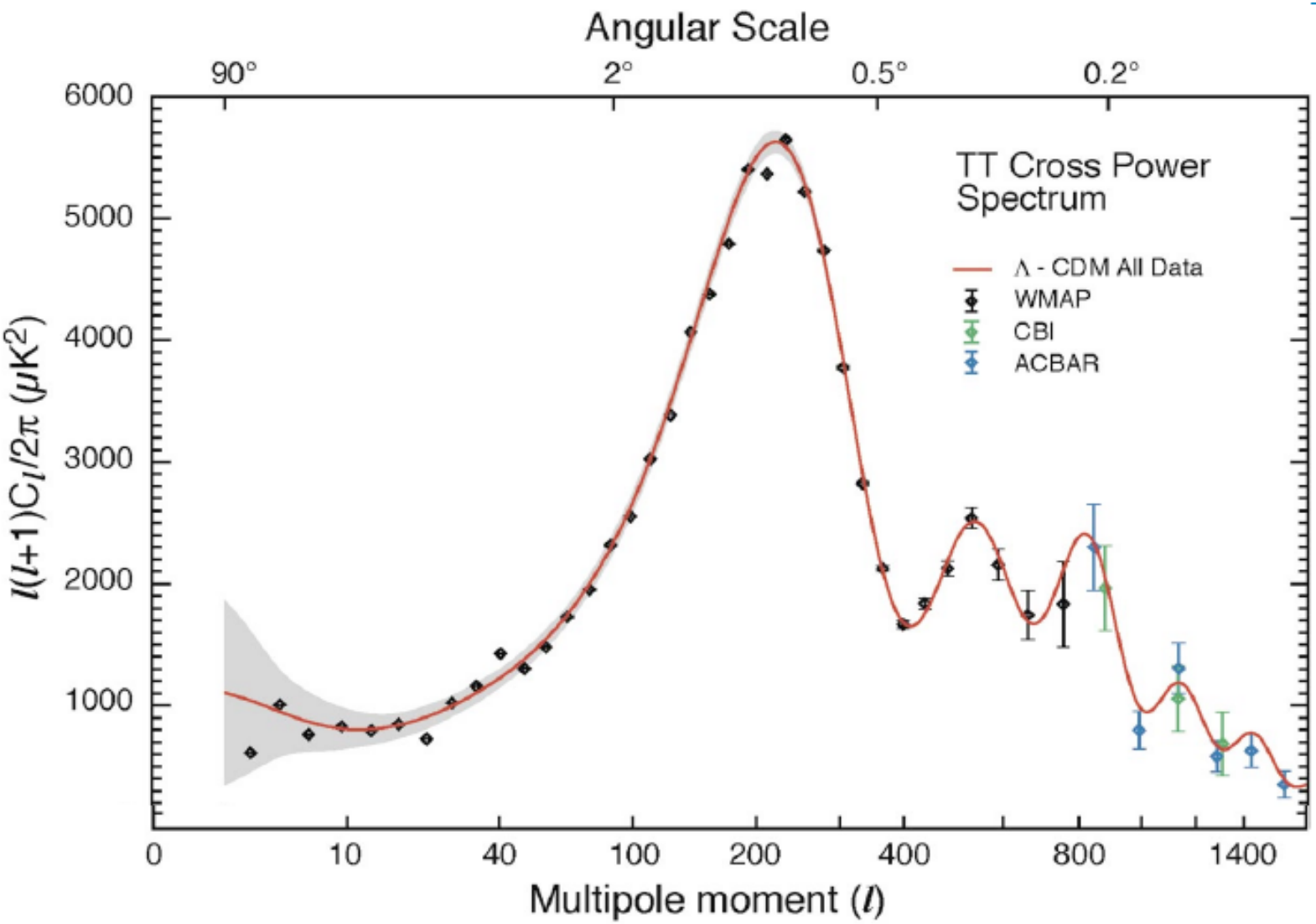


Fluctuations of up to 60 μK,
born at $t \approx 10^{-35}$ seconds. (Resolution ~ 7°)


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
2003
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years


COBE
WMAP

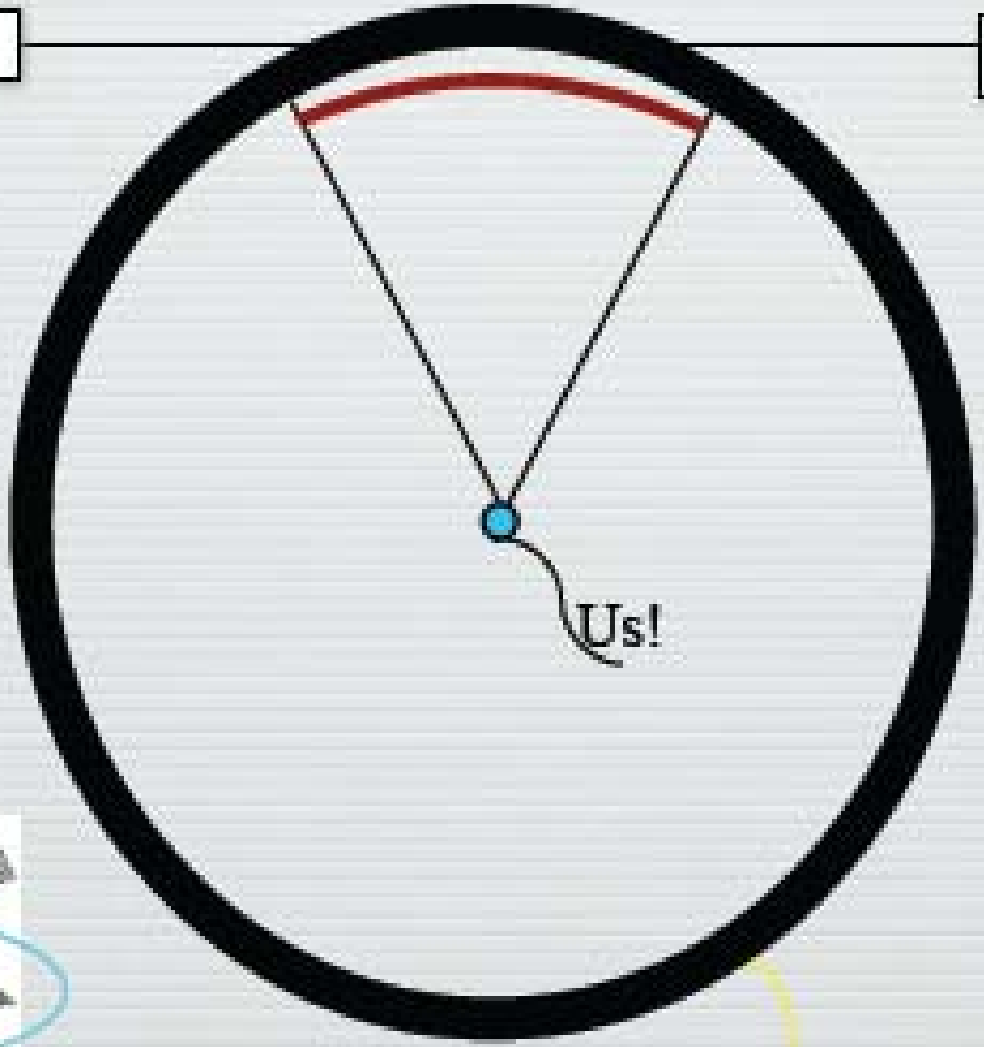
Angular Power Spectrum

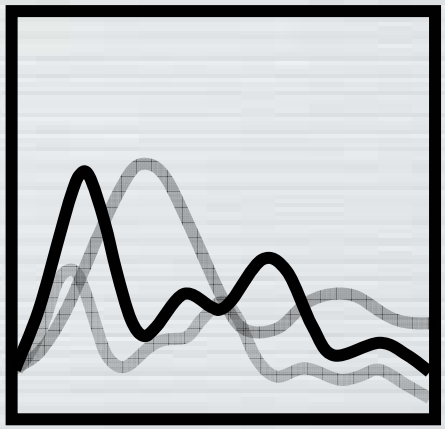


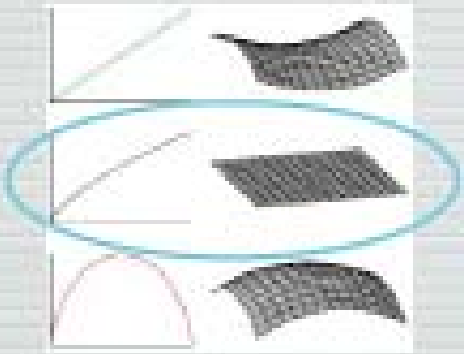
Measuring Curvature with the CMB

Flat

Ω=1





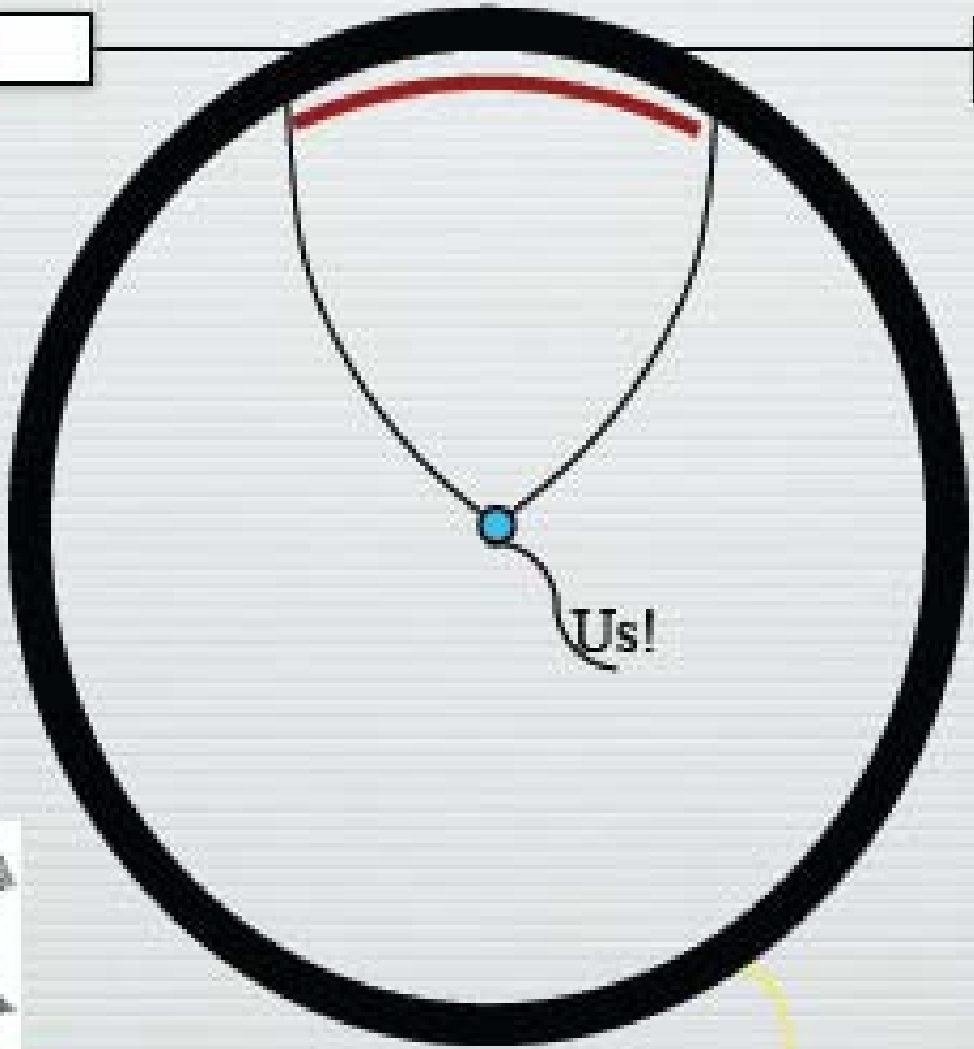


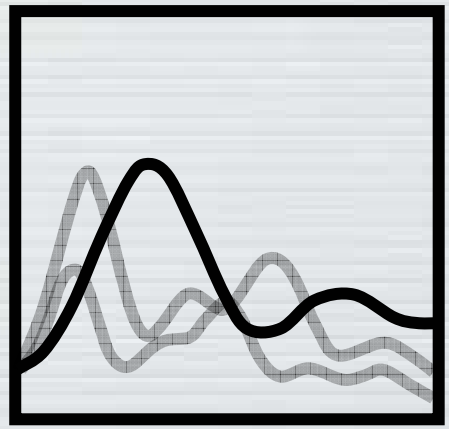
Last Scattering Surface

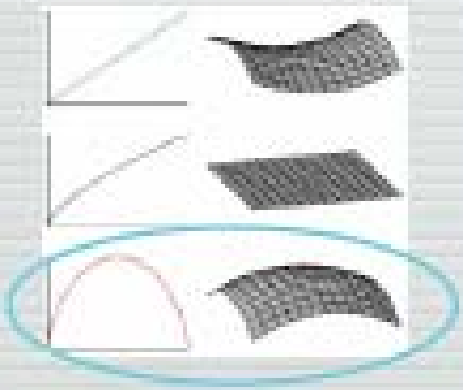
Measuring Curvature with the CMB

Closed

$\Omega > 1$

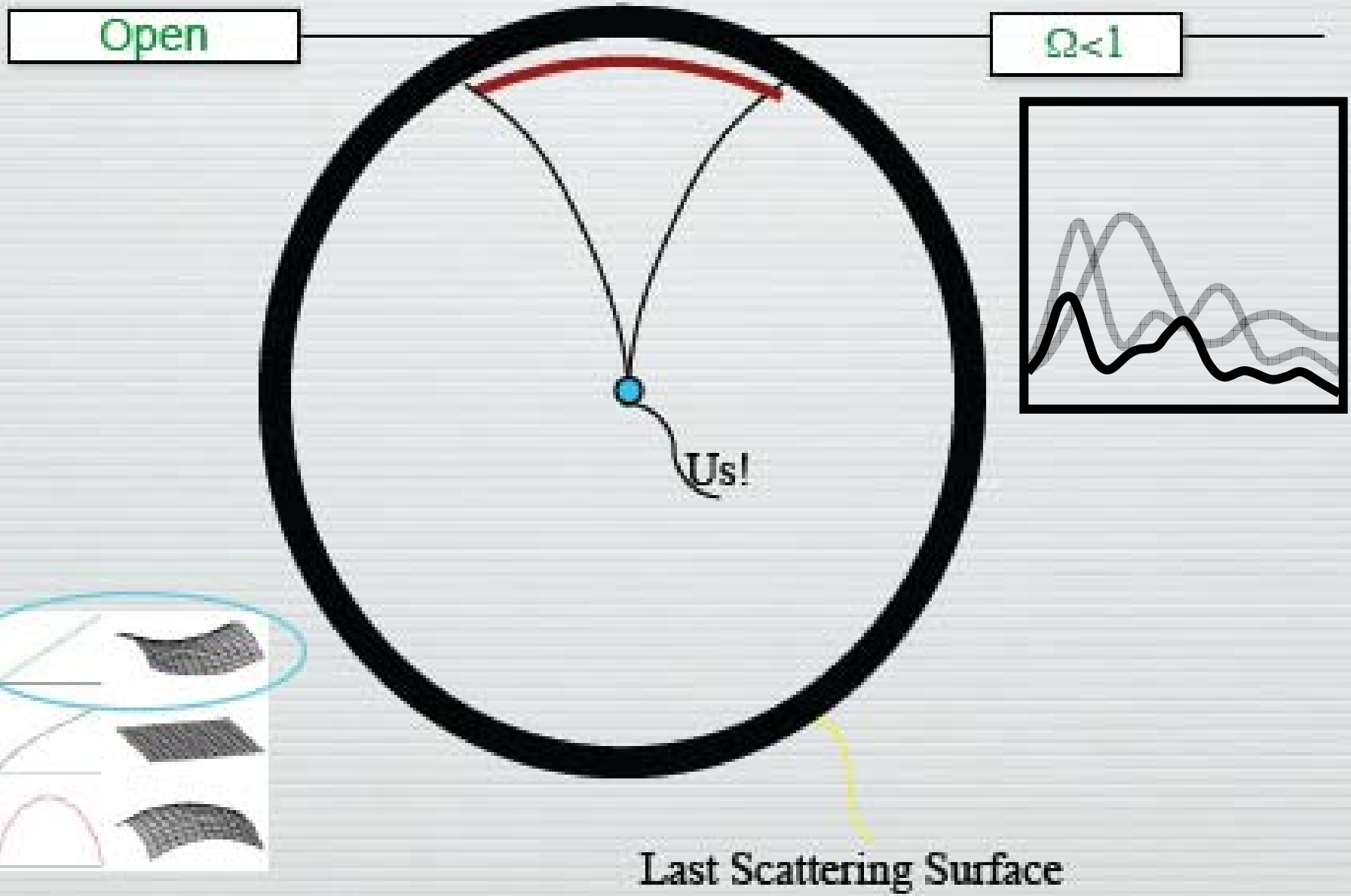




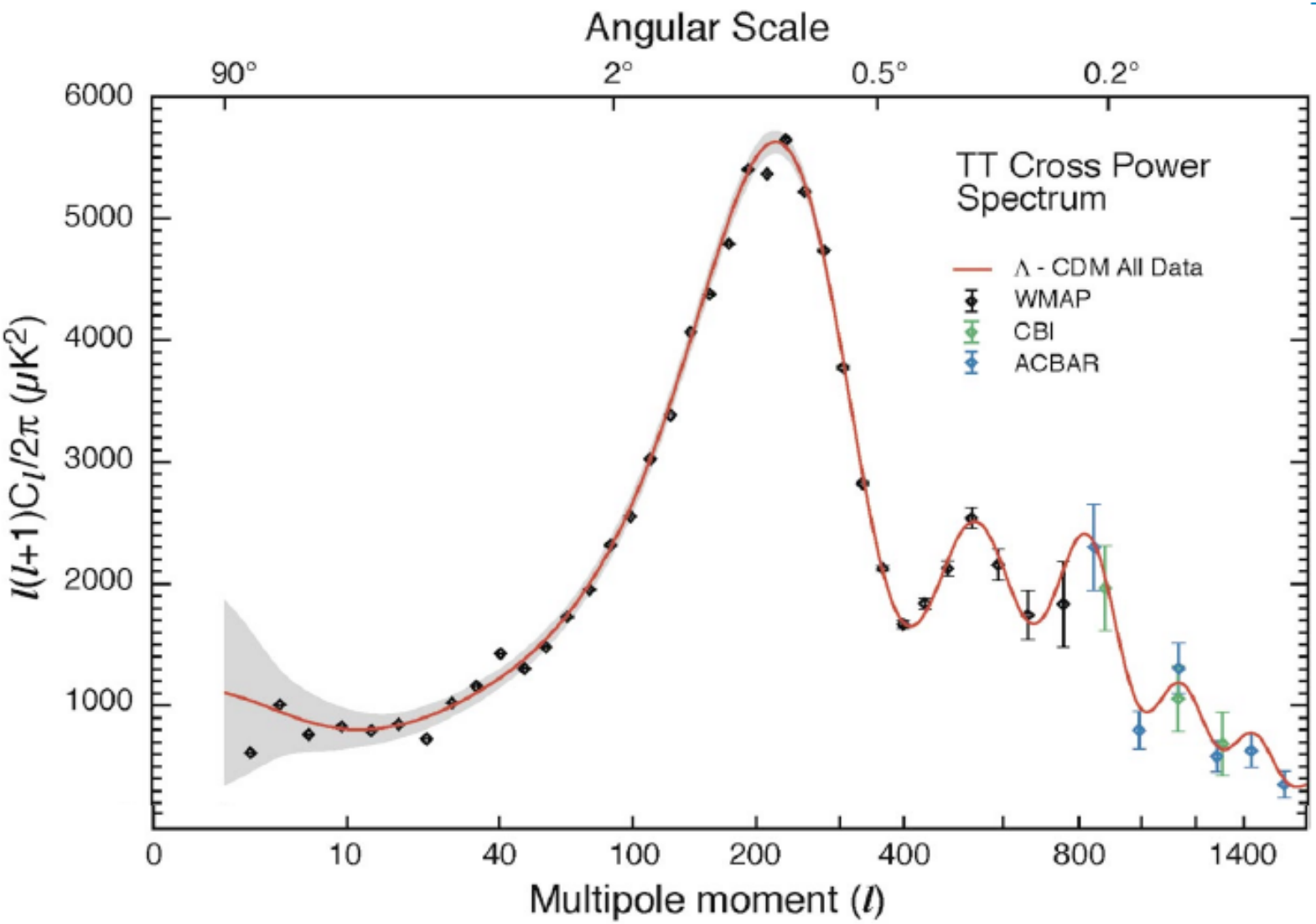


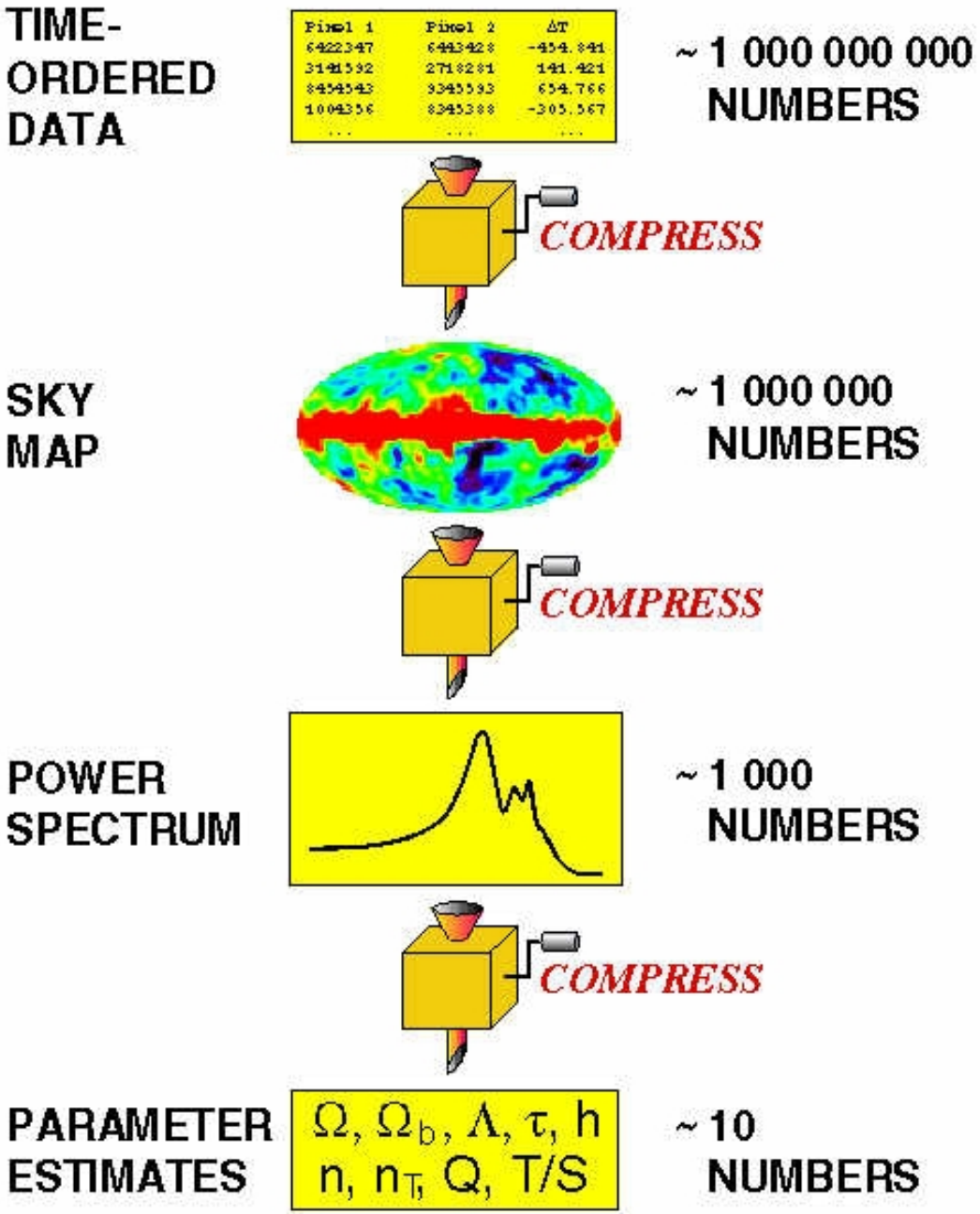
Last Scattering Surface

Measuring Curvature with the CMB



Angular Power Spectrum





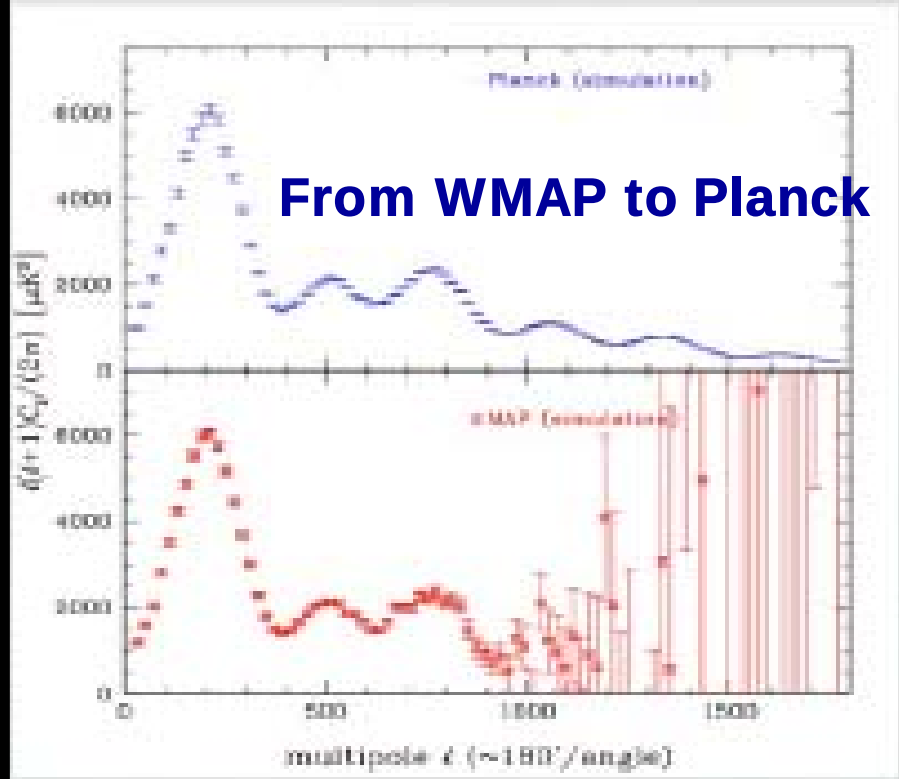
Huge amount of information from power spectrum

e.g.
position of 1st peak defines Ω,

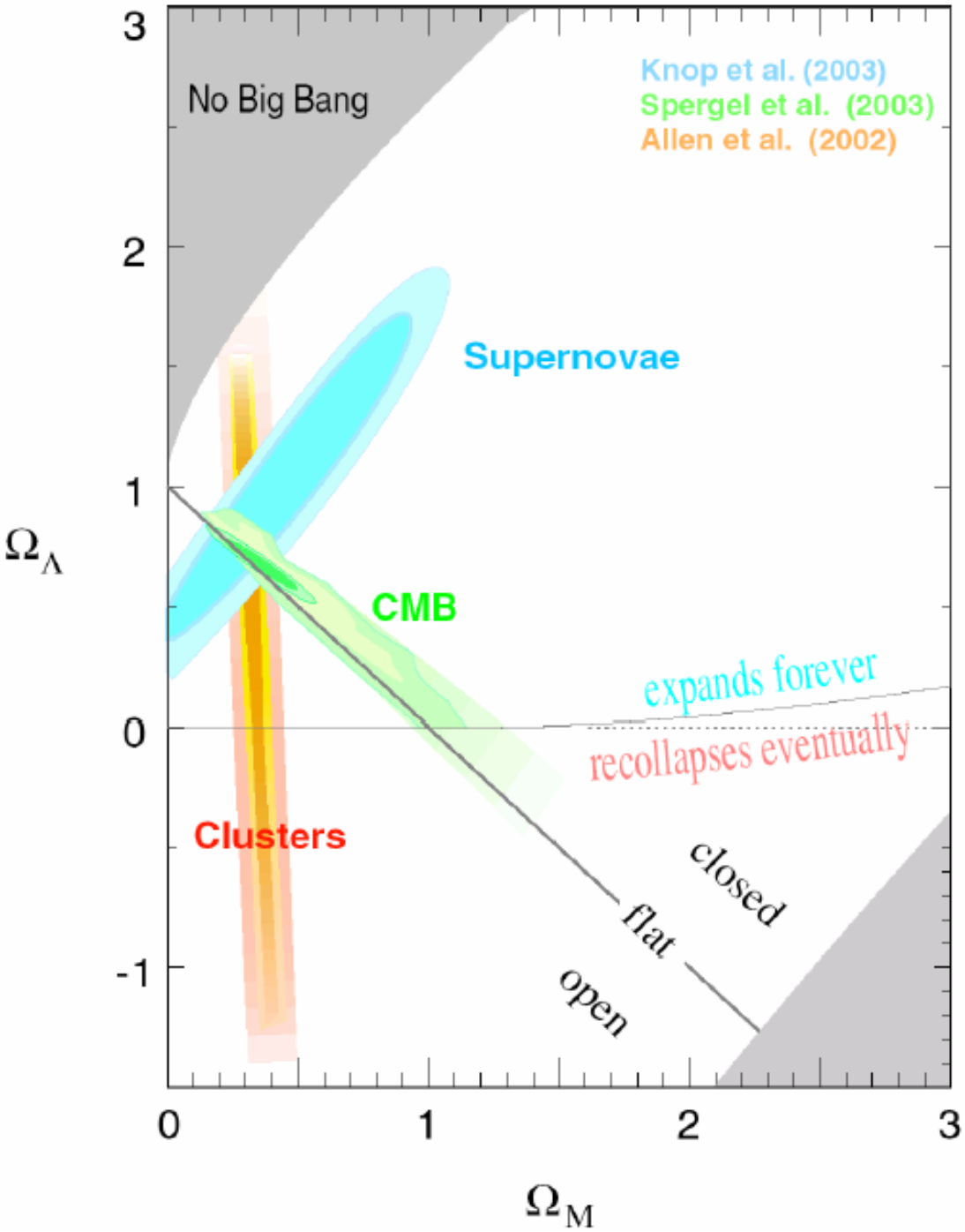
Hight relation of 2nd to 1st peak defines baryon density Ω_B

Planck

launch May 2009



From WMAP to Planck



"Omega-ology"

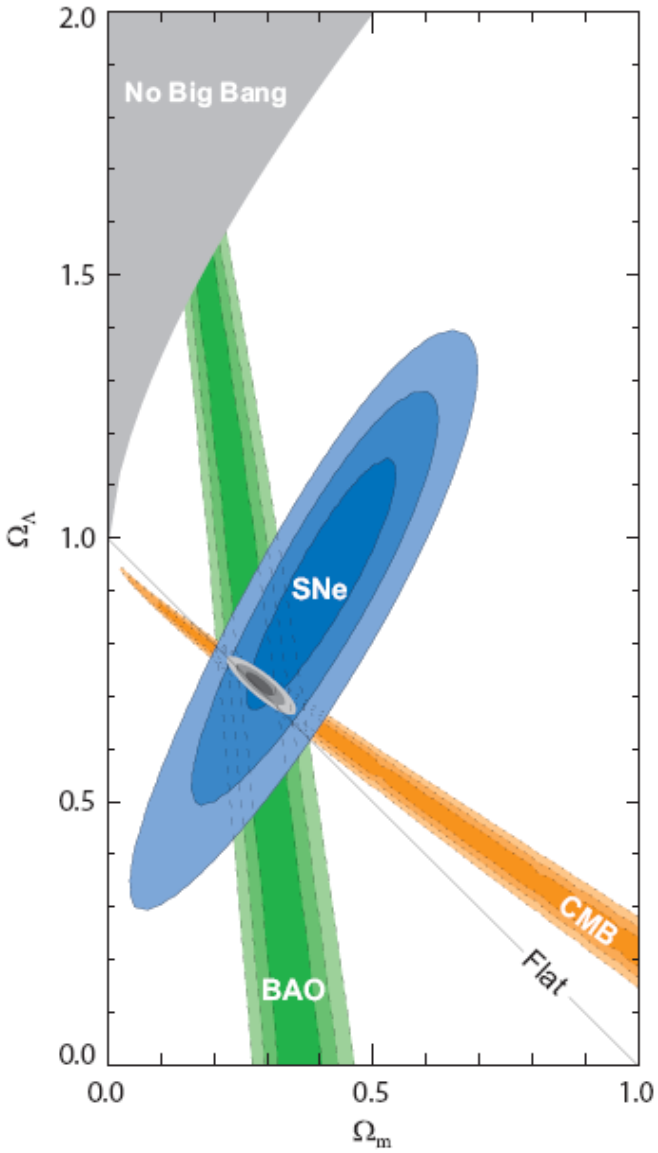
SN-al: $\Omega_\Lambda - \Omega_M \sim 0.4$

CMBR: $\Omega_M + \Omega_\Lambda \sim 1$

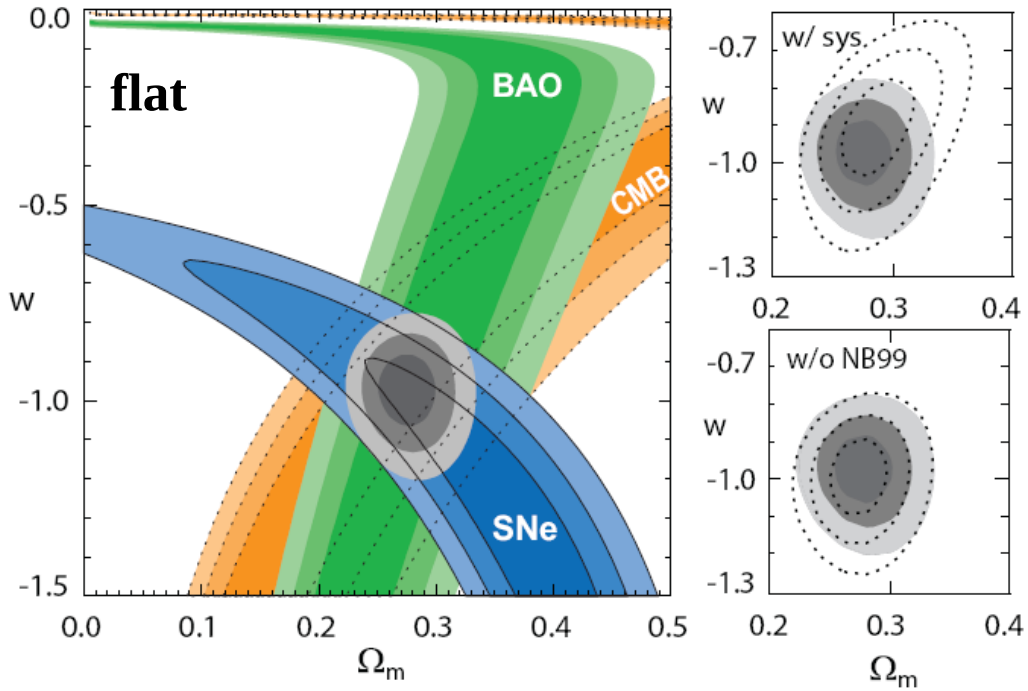
Galaxies: $\Omega_M \sim 0.3$

Large Scale Structure: $\Omega_M \sim 0.3$

$\Omega_M \sim 0.3$ $\Omega_\Lambda \sim 0.7$



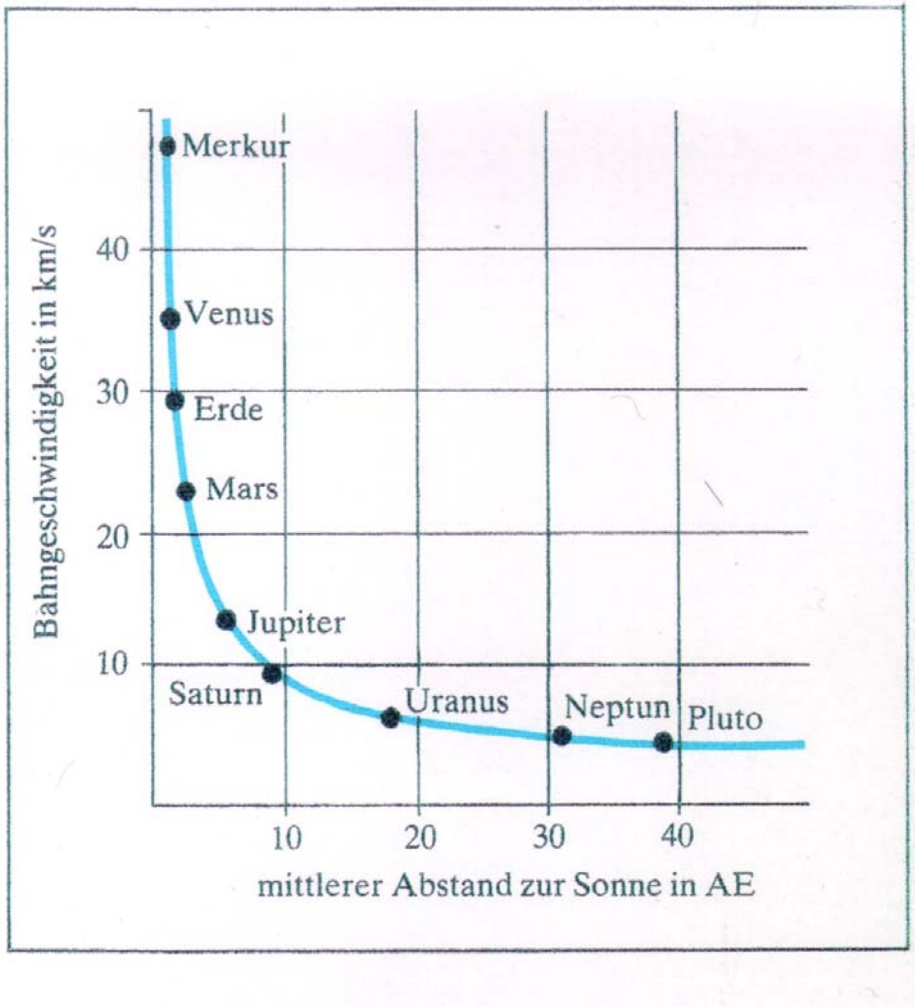
- Kowalski et al., 2008
- Combining all available data in one analysis

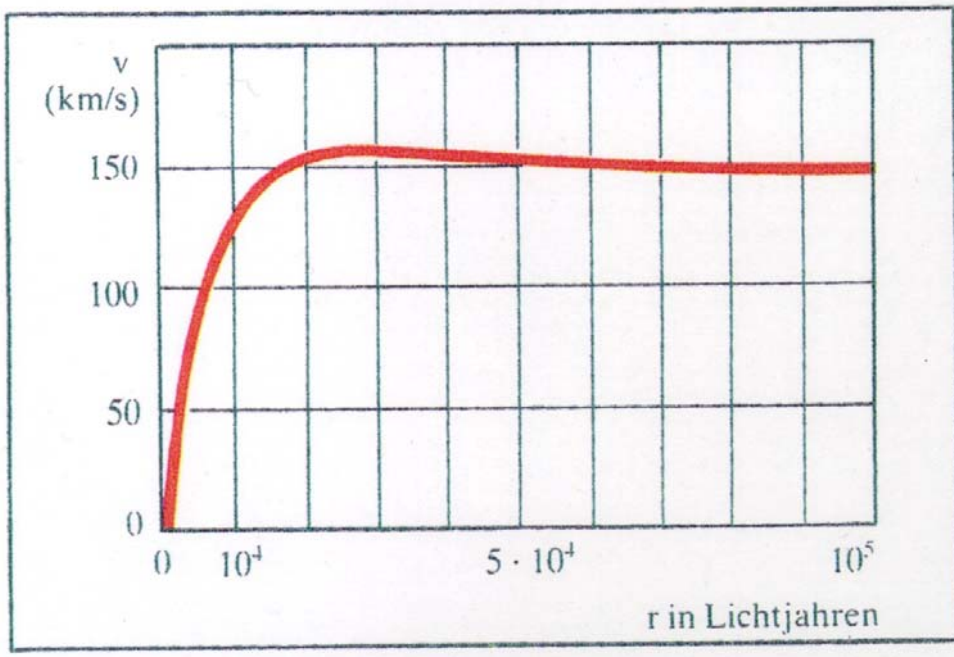


2. Dark Matter

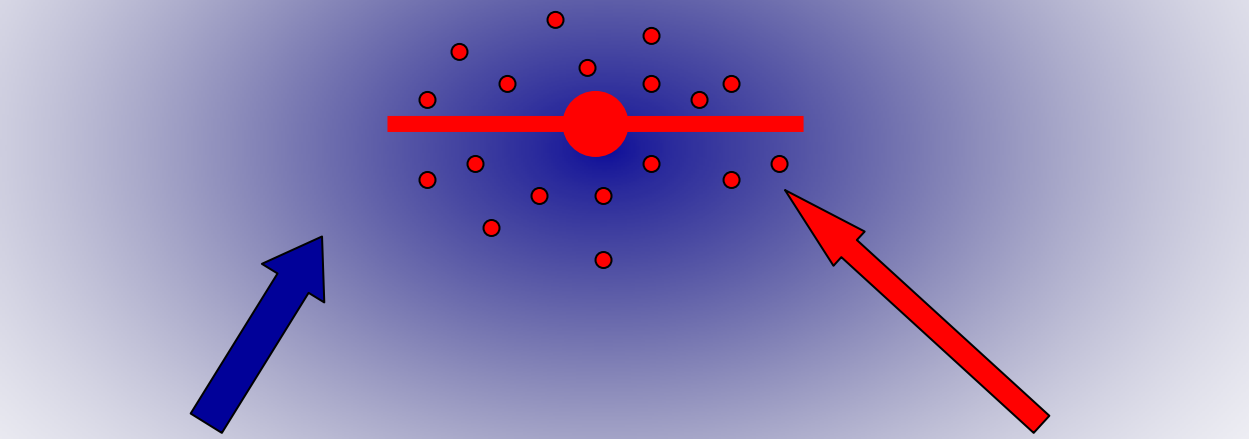
- Dark matter evidences
- Dark matter and structure formation
- Dark matter searches

Rotation Curves of Galaxies





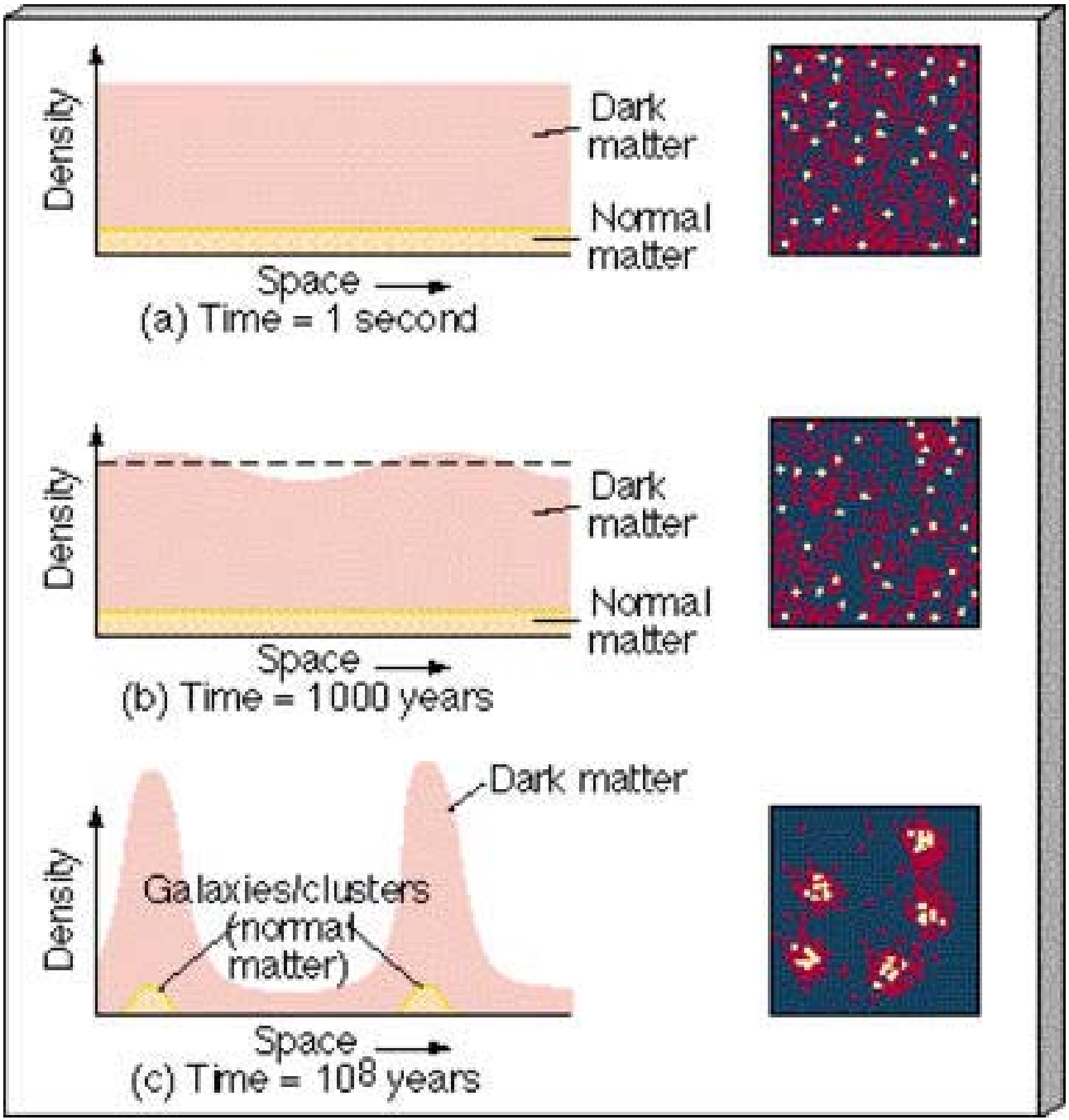
Dark Matter around our Galaxy



Invisible Halo

Visible Galaxy

10 : 1

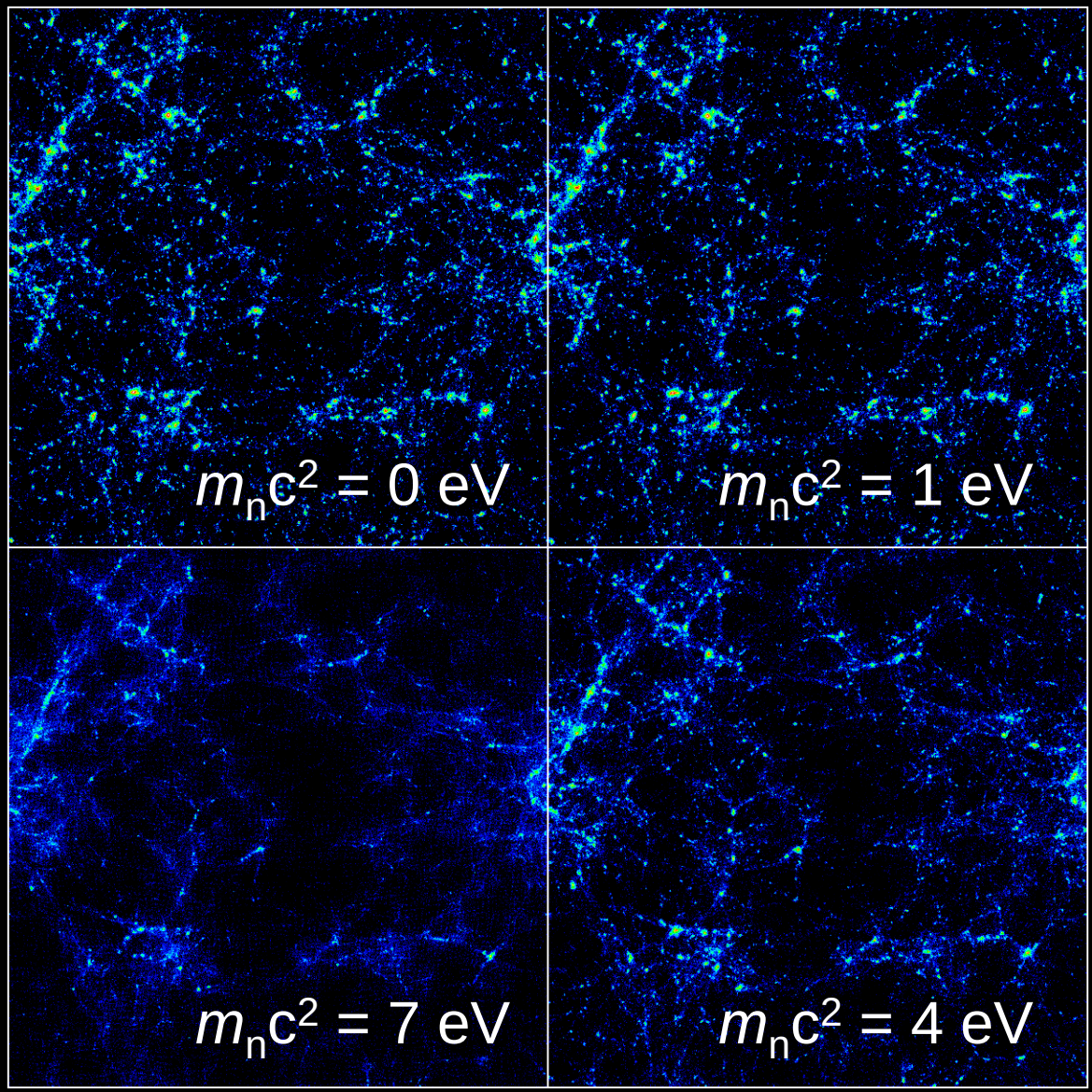


Dark-Matter-clusters as seeds for Galaxy formation

Large Scale Structure (Galaxy clusters and Superclusters) gives information on Ω(DM) and on nature of DM („hot“ or „cold“)

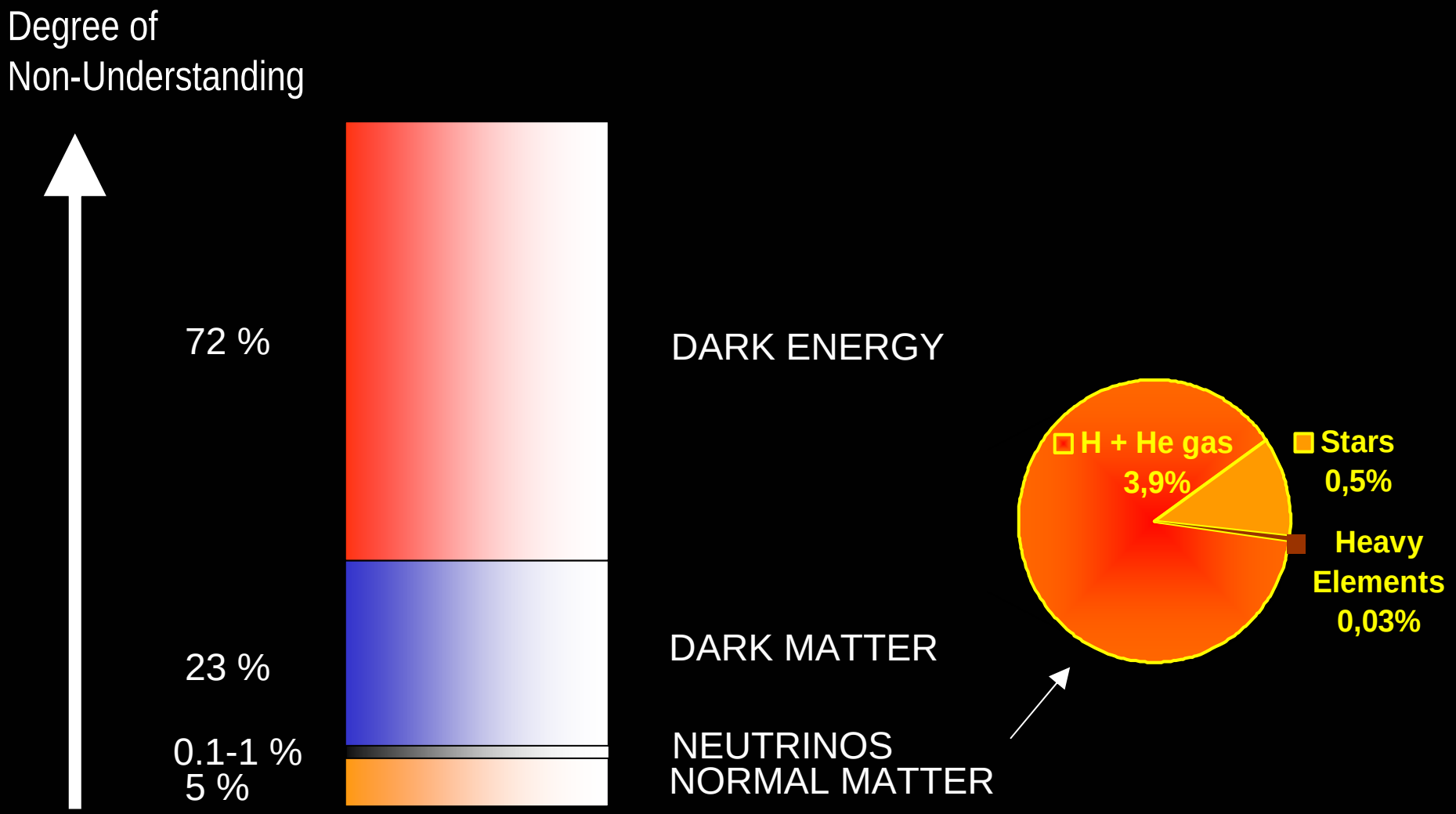
→ Most DM must be ***cold*** (non-relativistic when it decoupled)

Cosmological Structure Formation and the Mass of the Neutrino



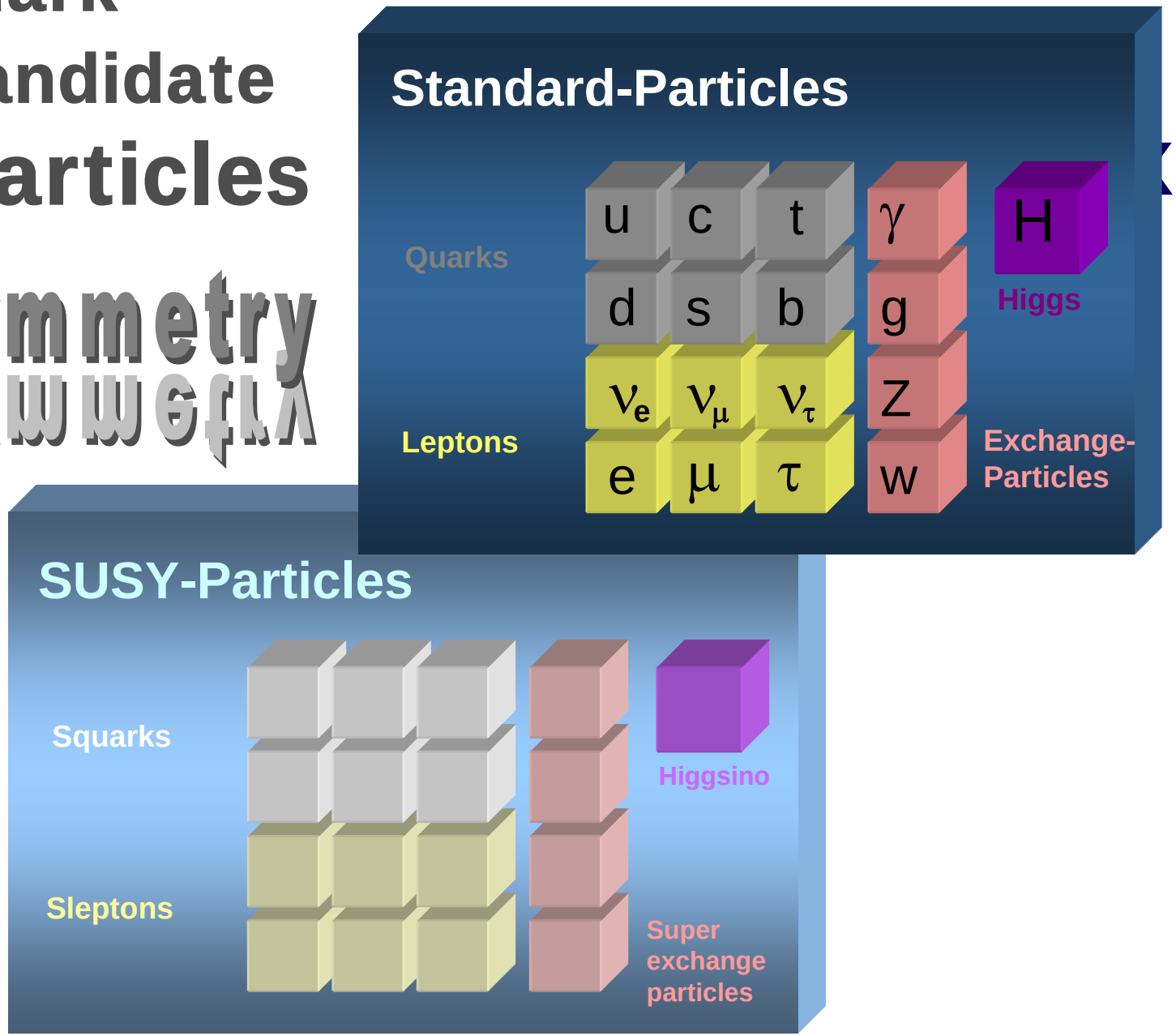
$m_\nu < 1$ eV

The Cosmic Inventory



The top dark matter candidate SUSY particles

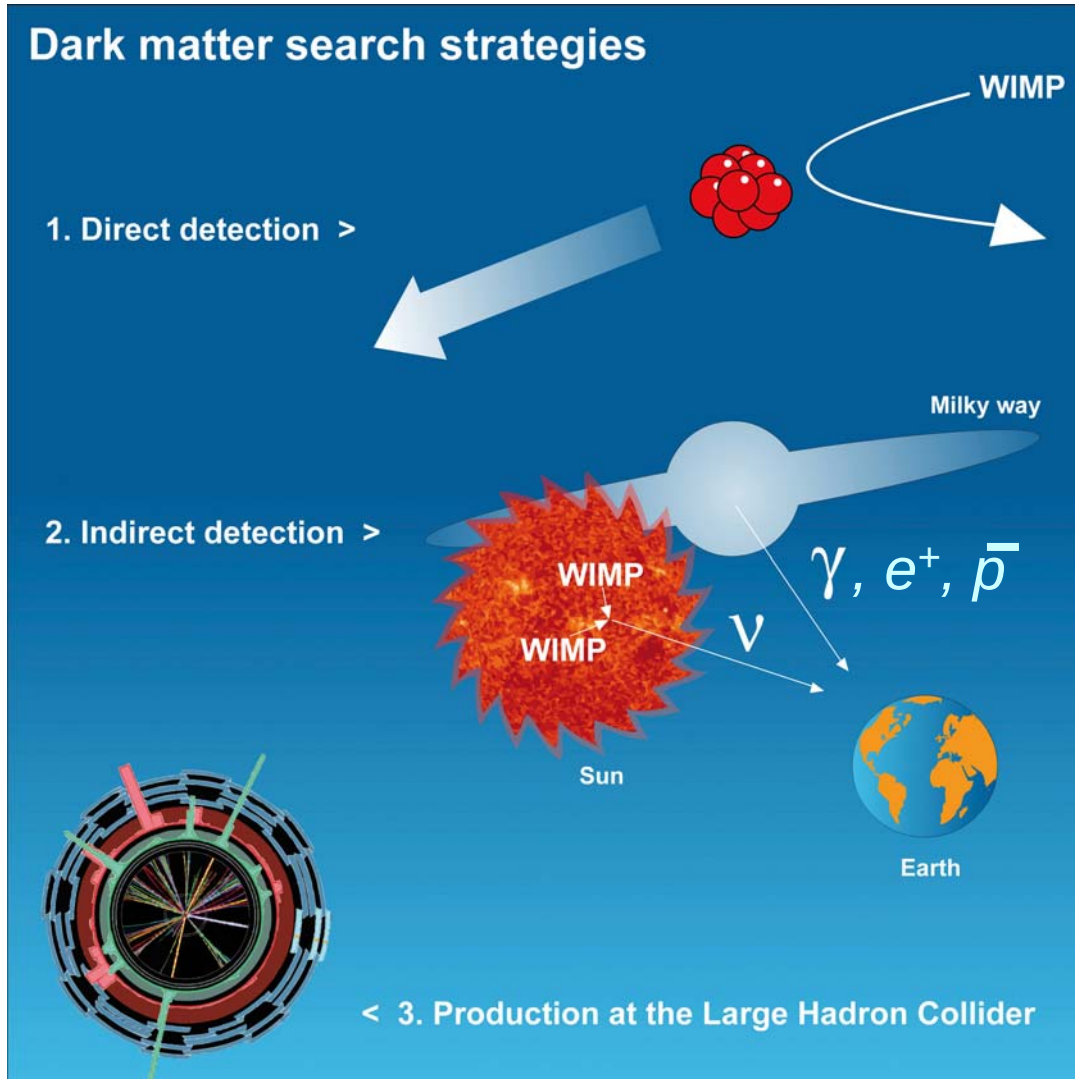
Supersymmetry



WIMP Searches

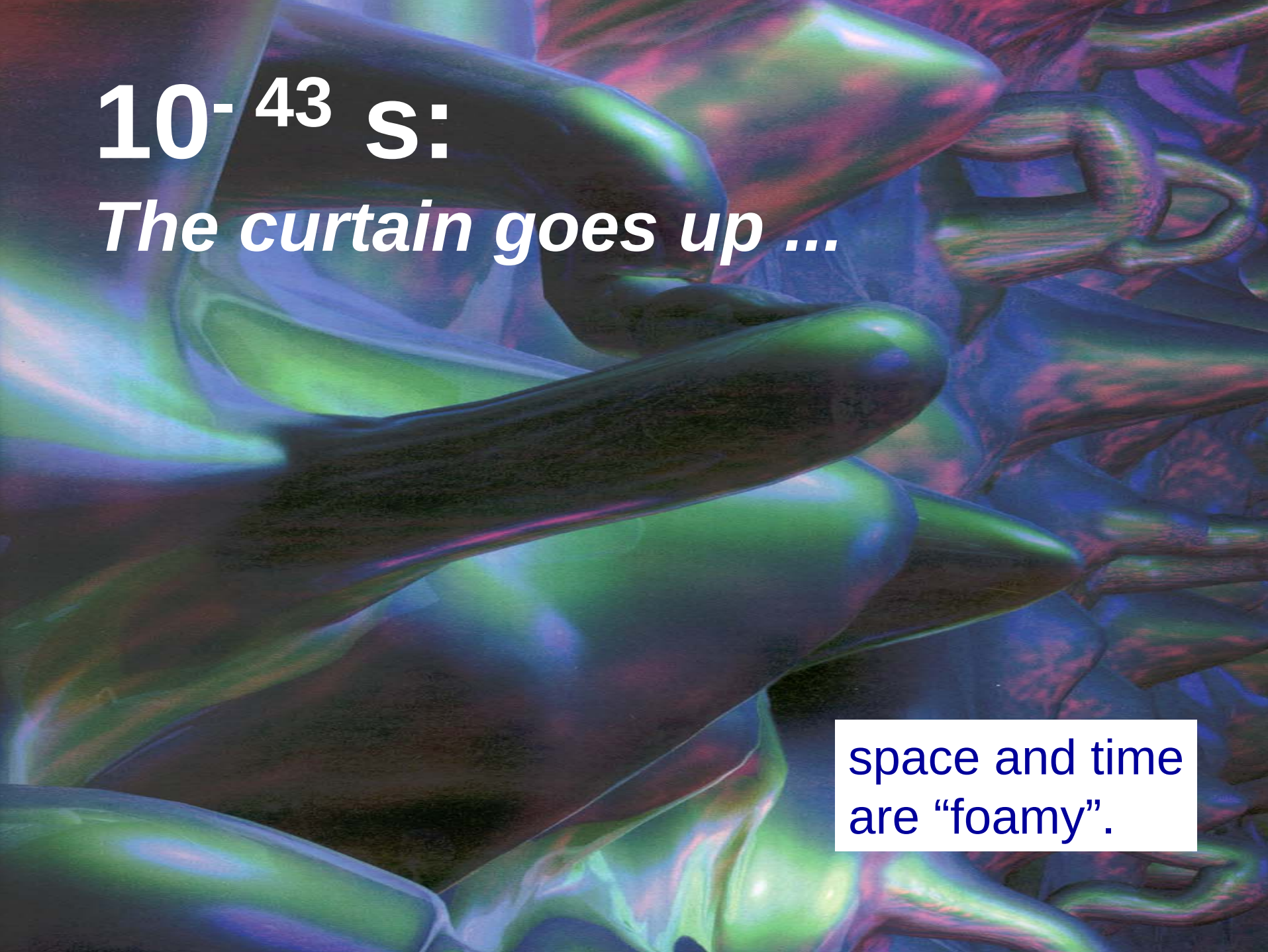
DM candidates:

- WIMPs
  Weakly Interacting Massive Particles
  - Neutralinos
  - Kaluza-Klein particles
  - ...
- Axinos
- Super-WIMPs
- Axions
- Axion-like light bosons
- Sterile neutrinos
- Q-balls
- WIMPzillas
- Elementary BHs
- ...



3.

The cosmic drama

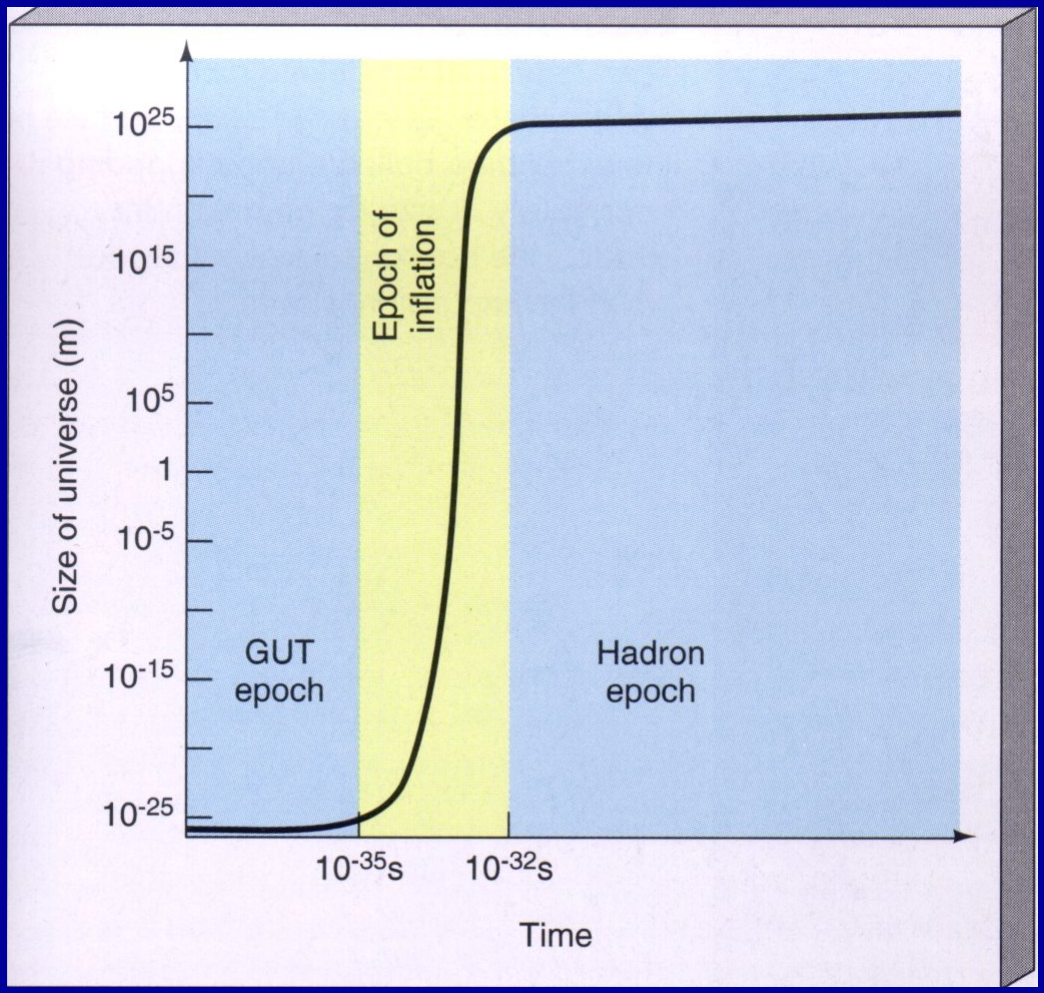


10^{-43} s:

The curtain goes up ...

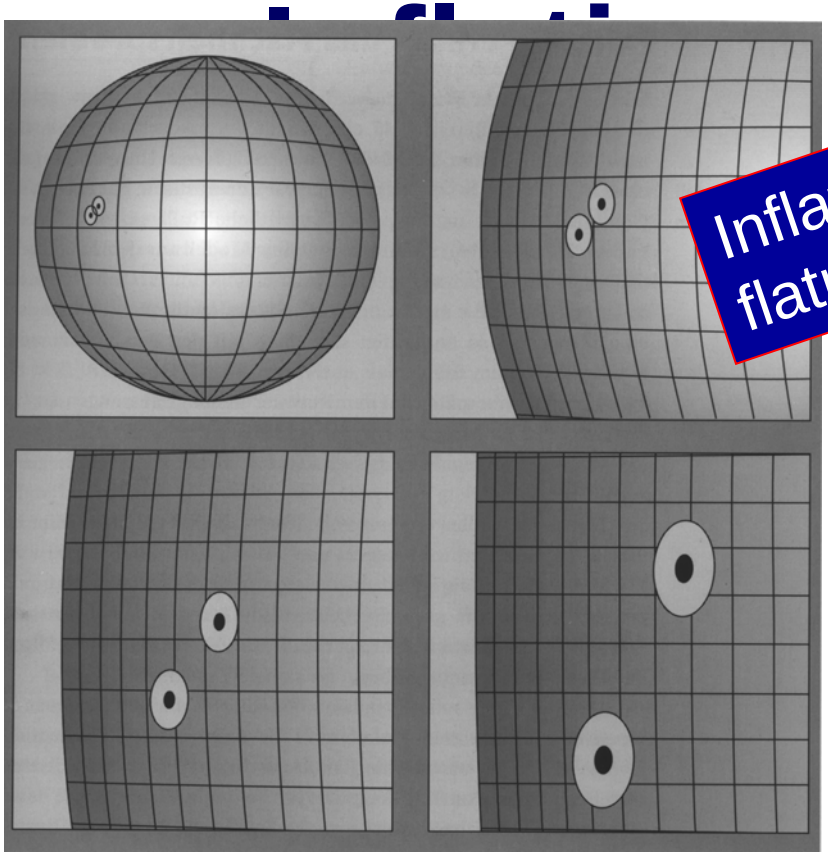
space and time are “foamy”.

The cosmic inflation

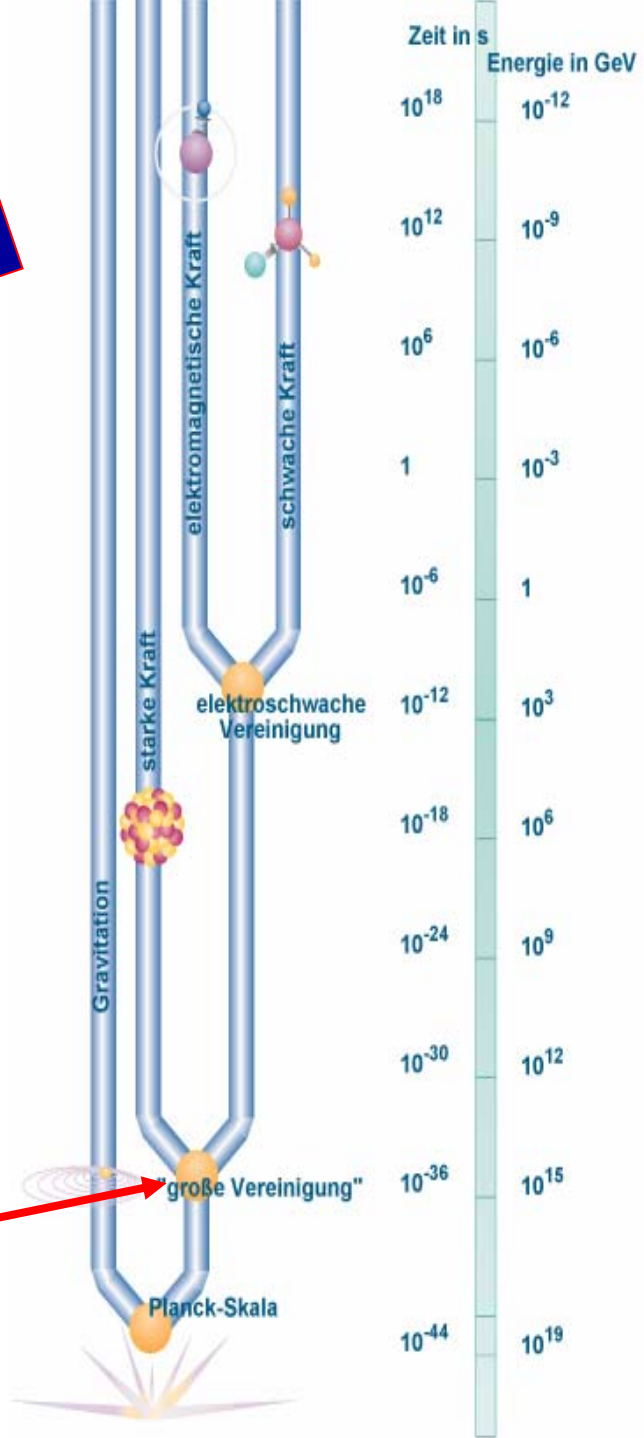


$t = 10^{-35} - 10^{-32}$ s

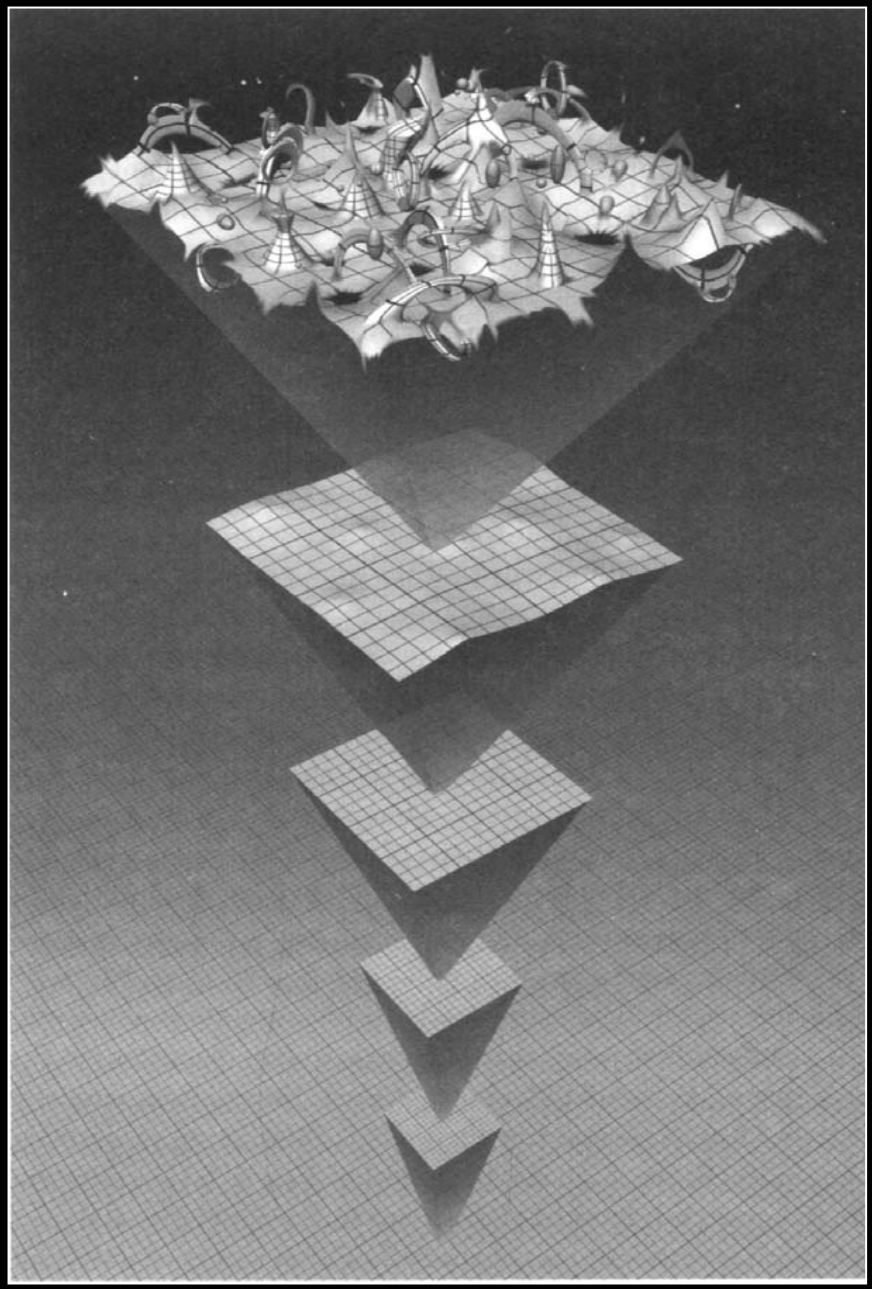
Blow up by factor 10^{50} in 10^{-32} seconds

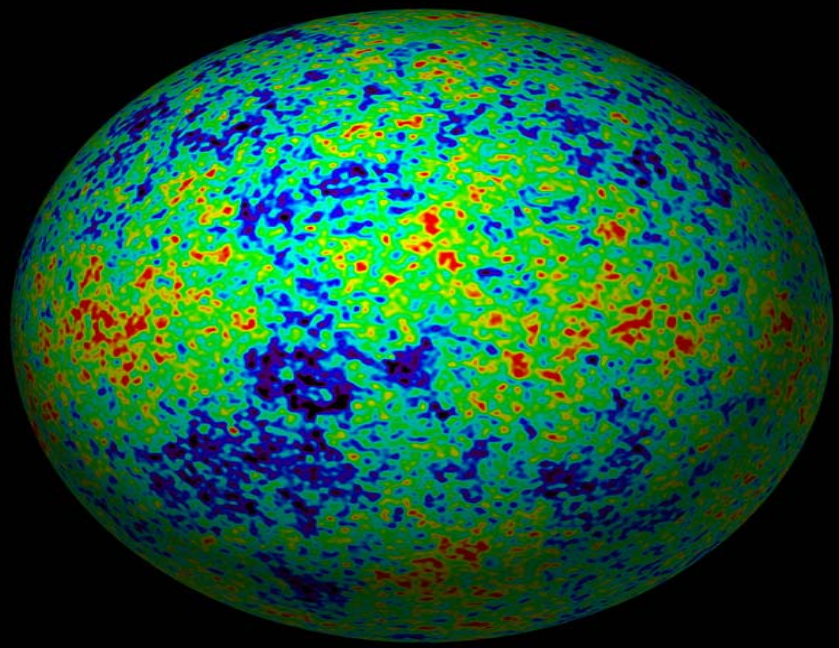


Inflation solves flatness problem.



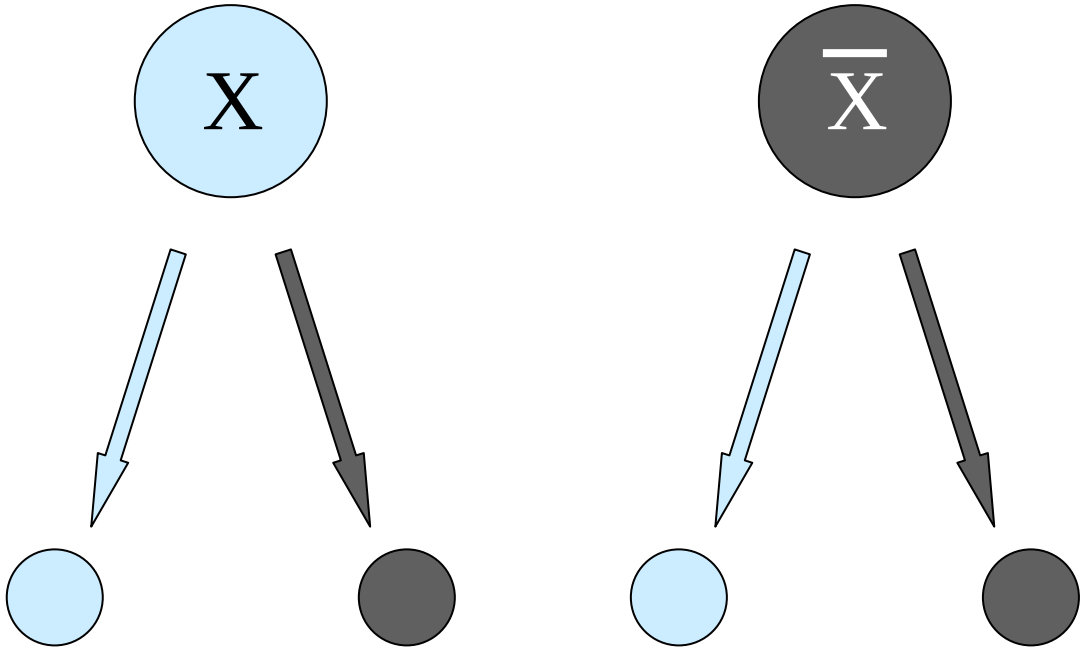
Delayed transition from phase of symmetry between strong and electro-weak force to phase with broken symmetry.





Inflation blows
up quantum
fluctuations
to cosmic scales.

A feeble excess of matter over antimatter



1.000000001 : 1 1.000000001 : 1

Andrej Sacharov

We are made from the 1 the nineth positon.

time
(seconds)

10^{-10}

q e^- ν

$\bar{q}$ e^+ $\bar{\nu}$

γ

Electro-weak symmetry breaks down

quark-antiquark-annihilation

10^{-6}

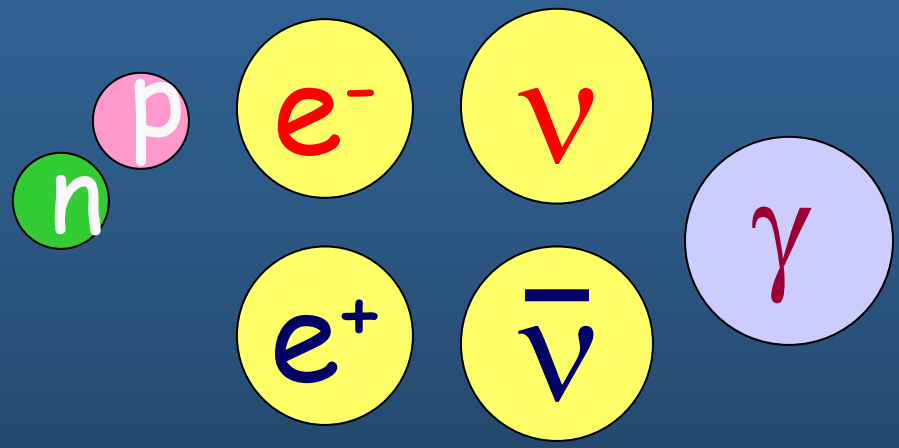
q e^- ν

e^+ $\bar{\nu}$

γ

time
(seconds)

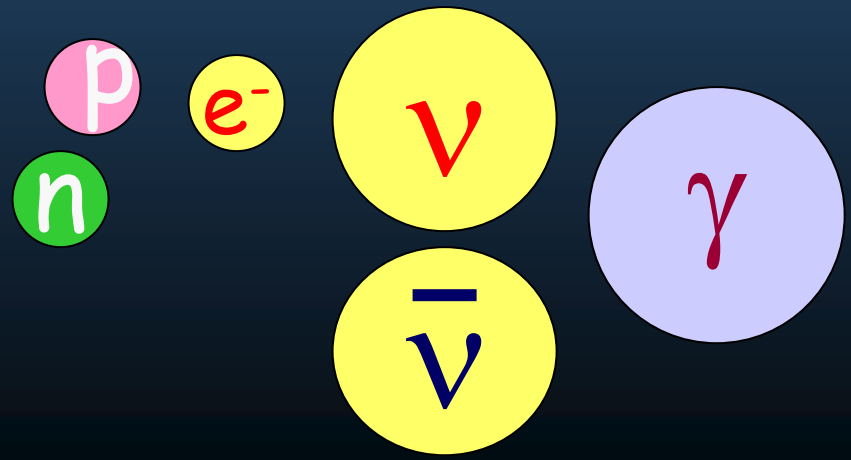
synthesis of proton and neutron



10^{-4}

10^{-2}

electron-positron-annihilation



E ~ 20 MeV

T ~ 10^{11} K, t ~ 10^{-2} s

mass(neutron) – mass(proton) = 1.3 MeV

$$e^- + p \leftrightarrow \nu_e + n$$

$$e^+ + n \leftrightarrow \bar{\nu}_e + p$$

E ~ 2 MeV

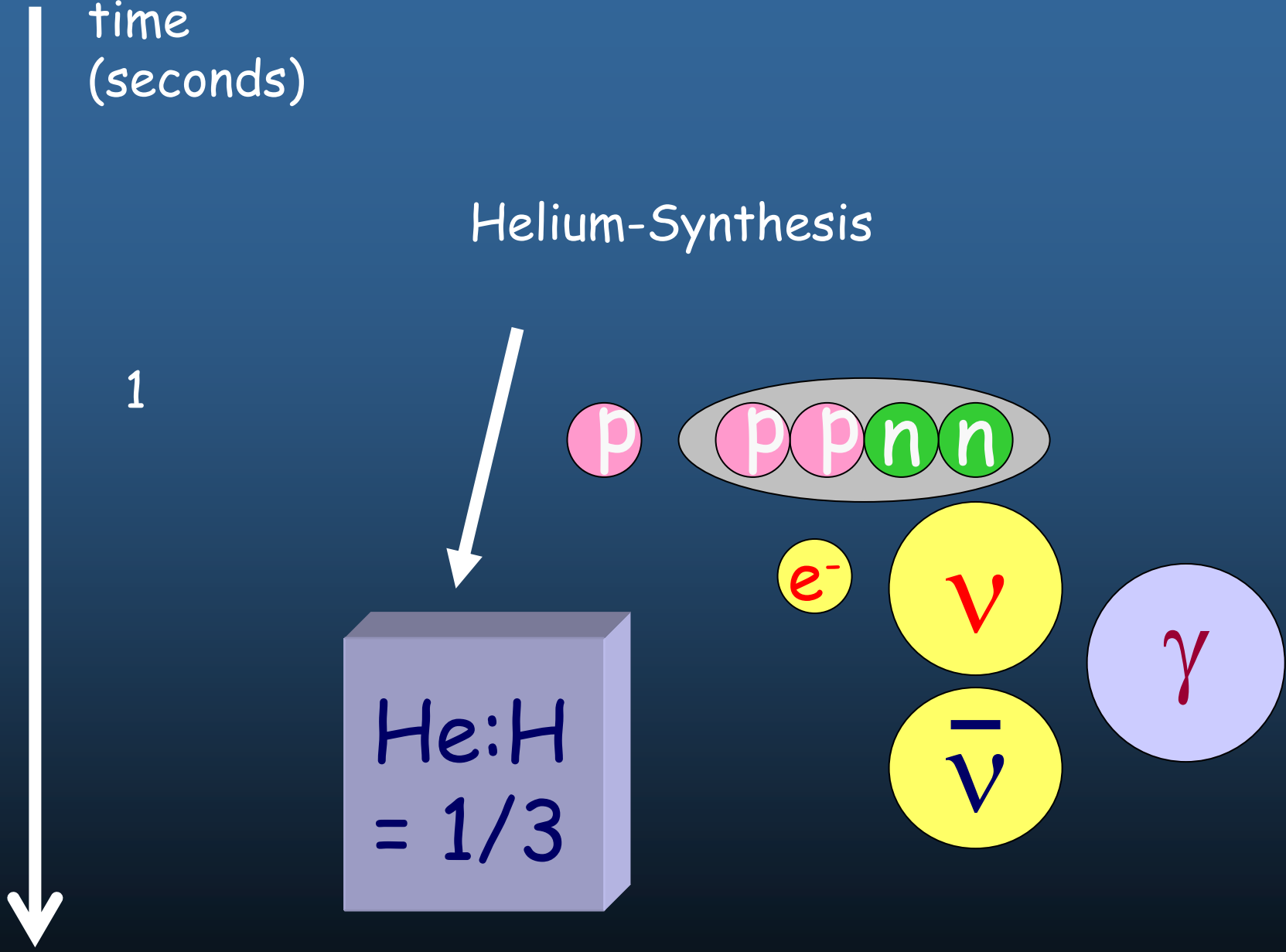
T ~ 10^{10} K, t ~ 1 s

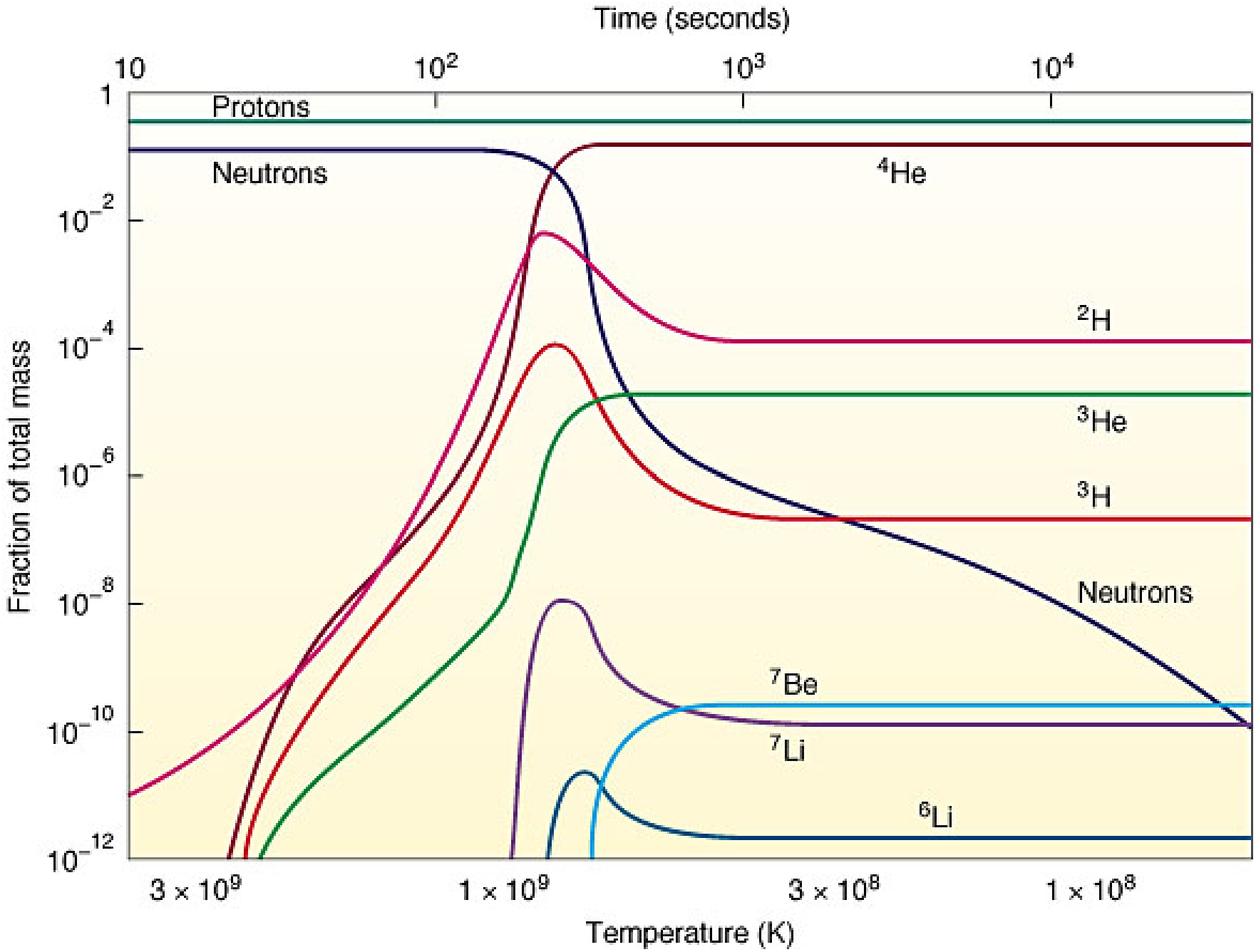
$$e^- + p \rightarrow \nu_e + n \qquad (1)$$

$$e^+ + n \rightarrow \bar{\nu}_e + p \qquad (2)$$

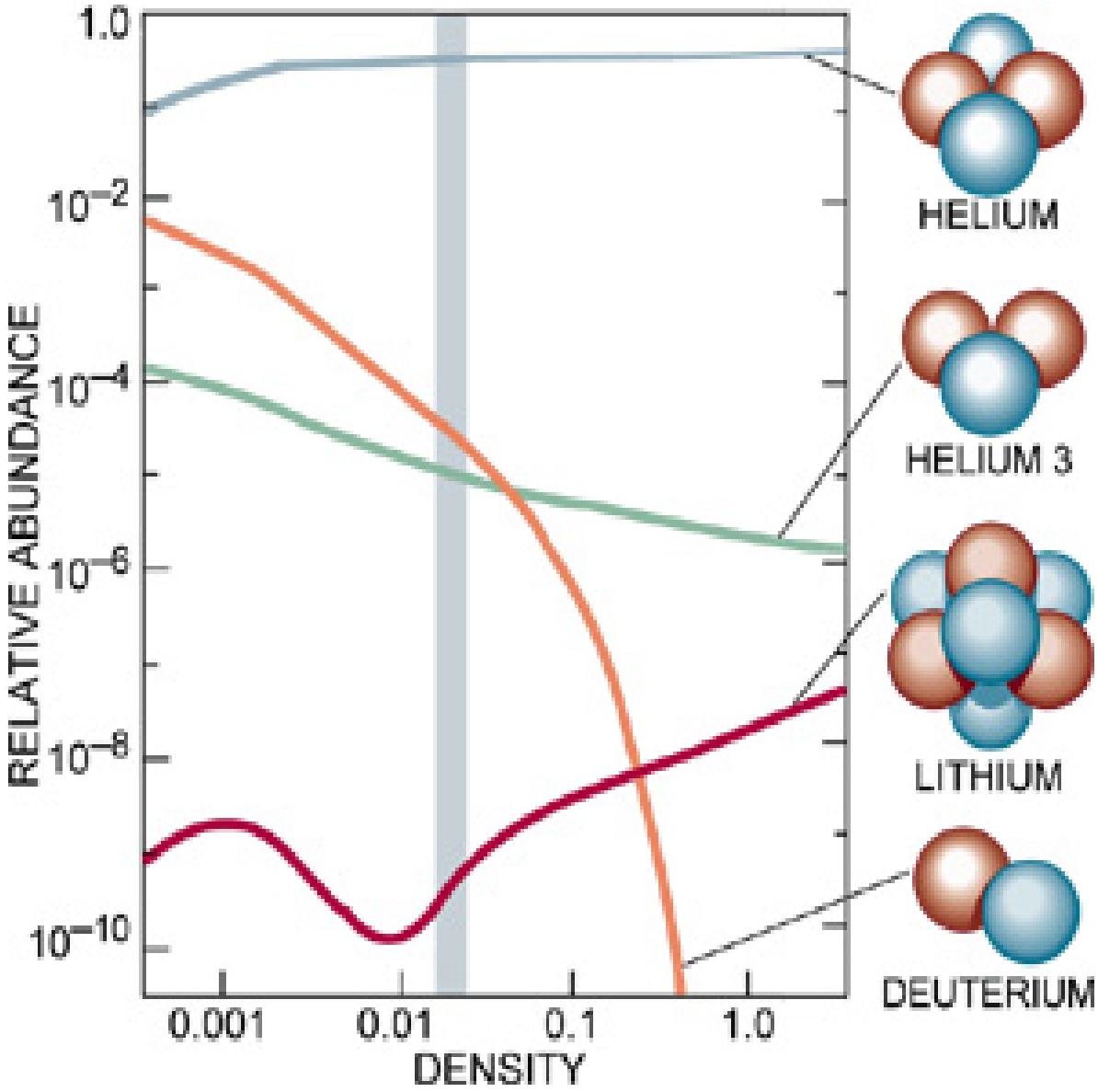
neutrinos freeze out
→ today at 1.9 K

Reaction (2) more frequent than reaction (1)
→ less and less neutrons

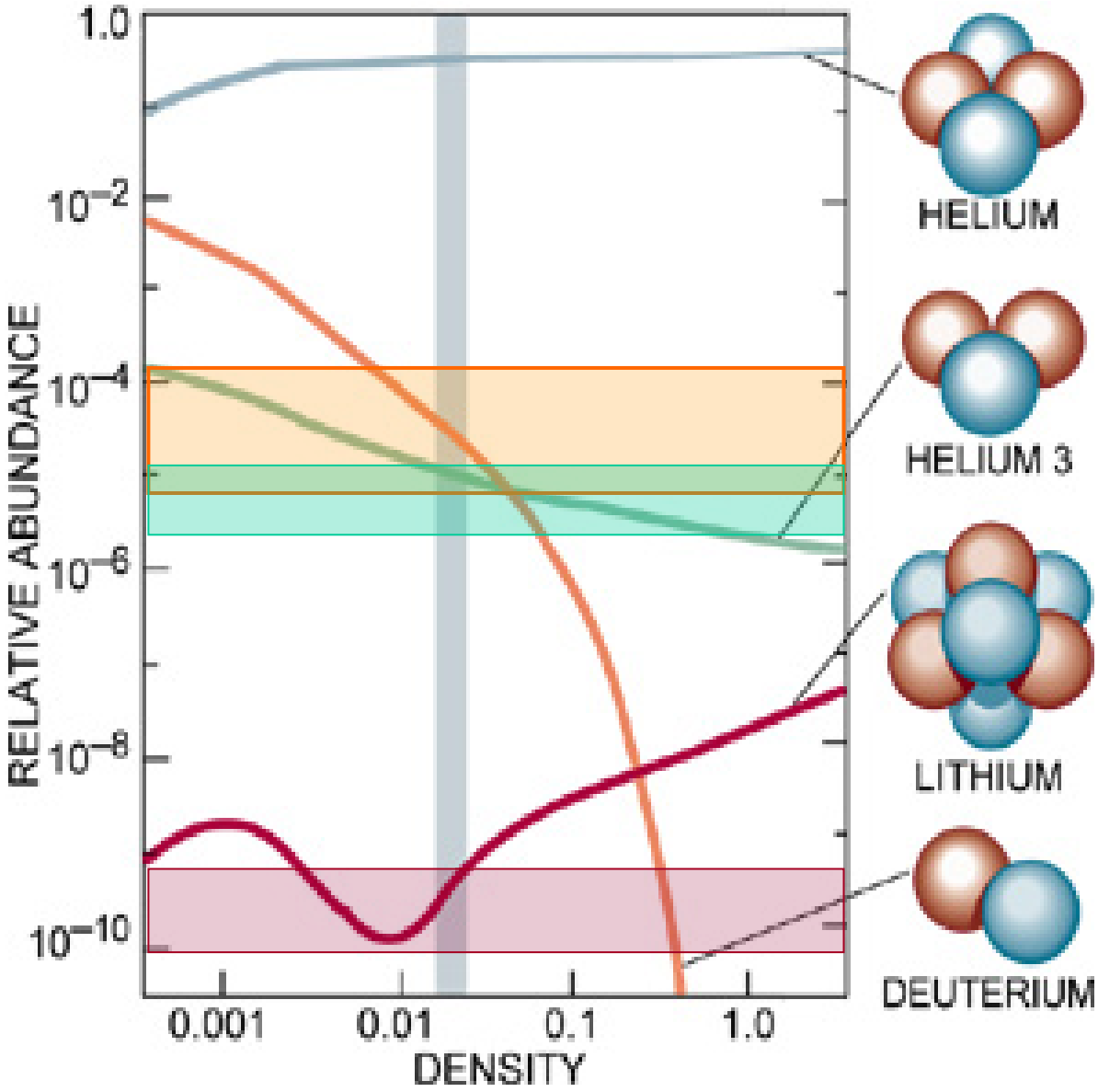

time
(seconds)
Helium-Synthesis
1
p
p p n n
e^-
ν
$\bar{\nu}$
γ
He:H
= 1/3


Time (seconds)
10
10^2
10^3
10^4
1
Protons
Neutrons
^{4}He
^{2}H
^{3}He
^{3}H
Neutrons
^{7}Be
^{7}Li
^{6}Li
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
Fraction of total mass
3×10^9
1×10^9
3×10^8
1×10^8
Temperature (K)

Element abundance vs. density of nuclear matter



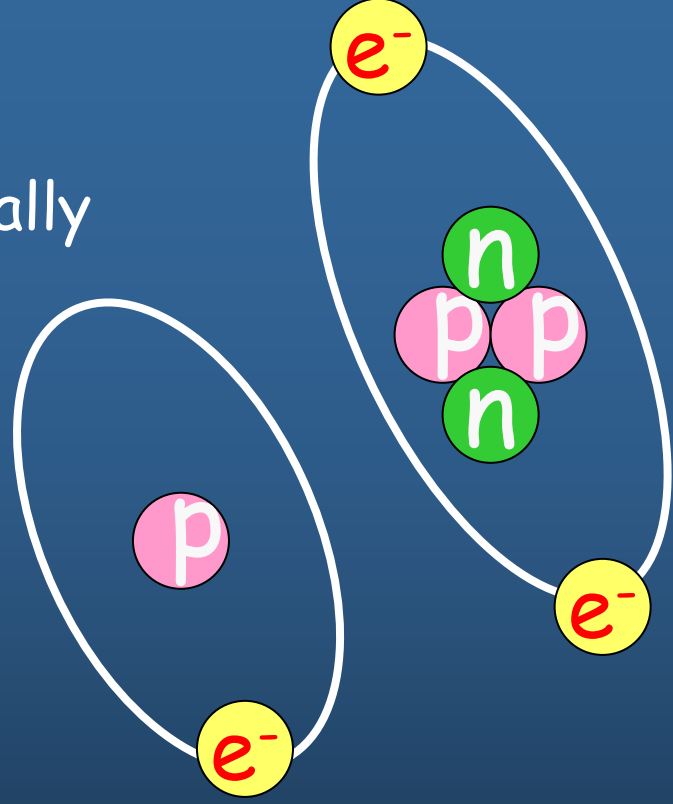
Element abundance vs. density of nuclear matter

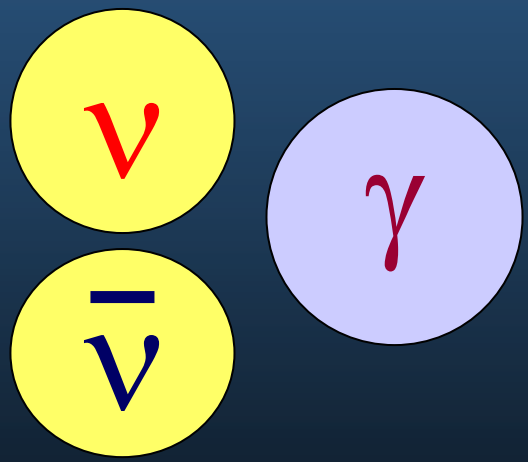


300 000
years

electrically
neutral
atoms

T = 4000°K

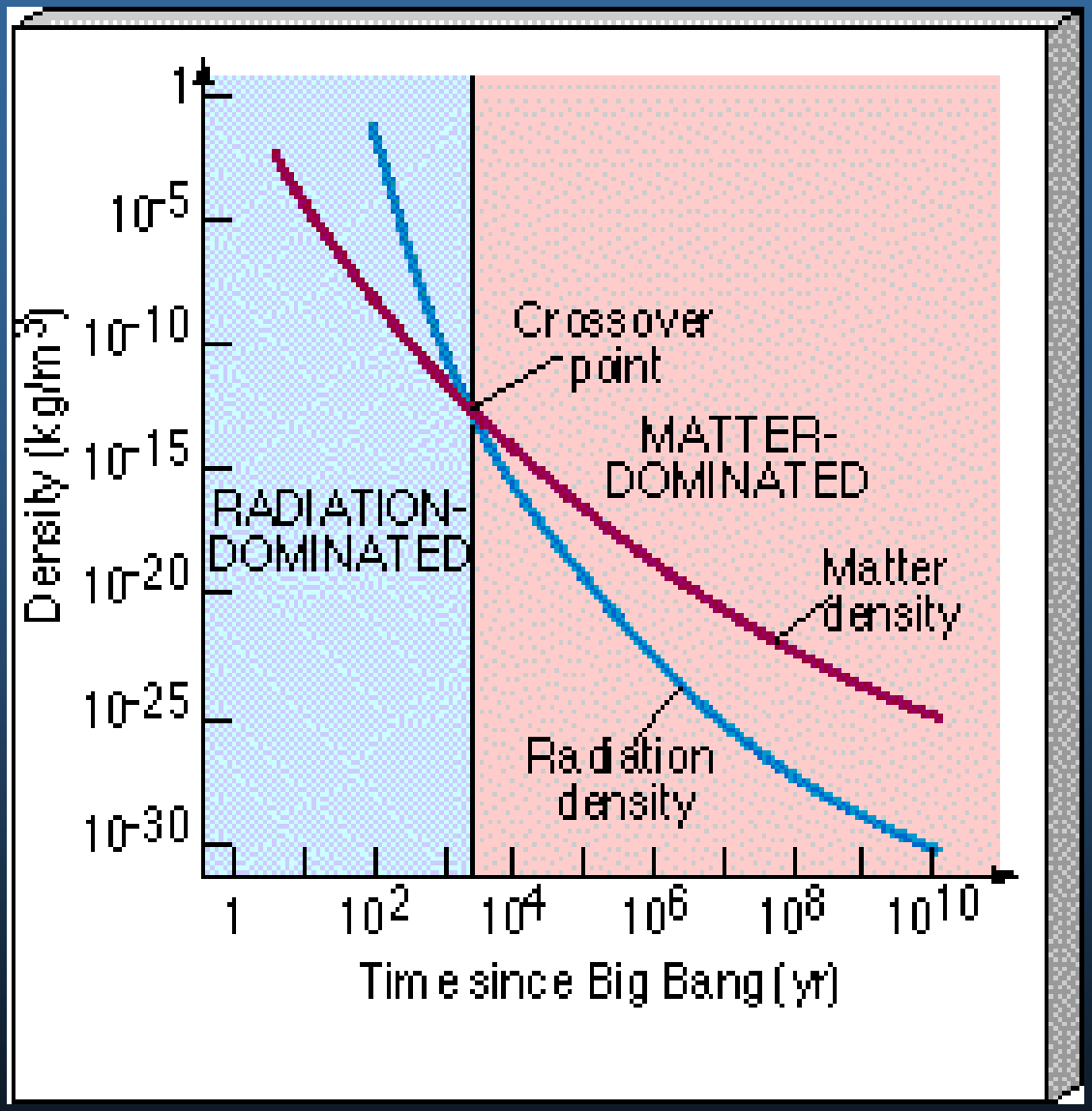




15 billion years

T = 2.735 °K

3000 years



15 billion years

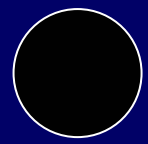
300 000 years electrically neutral atoms:
Universe becomes transparent

Galaxies
First stars synthesis of heavy elements

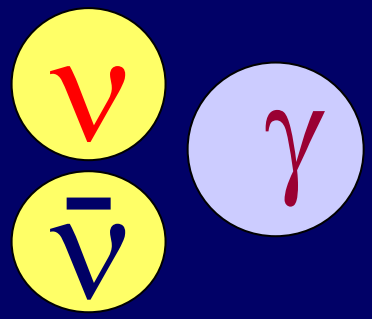
Birth of sun
15 bill. mankind
Dead of sun

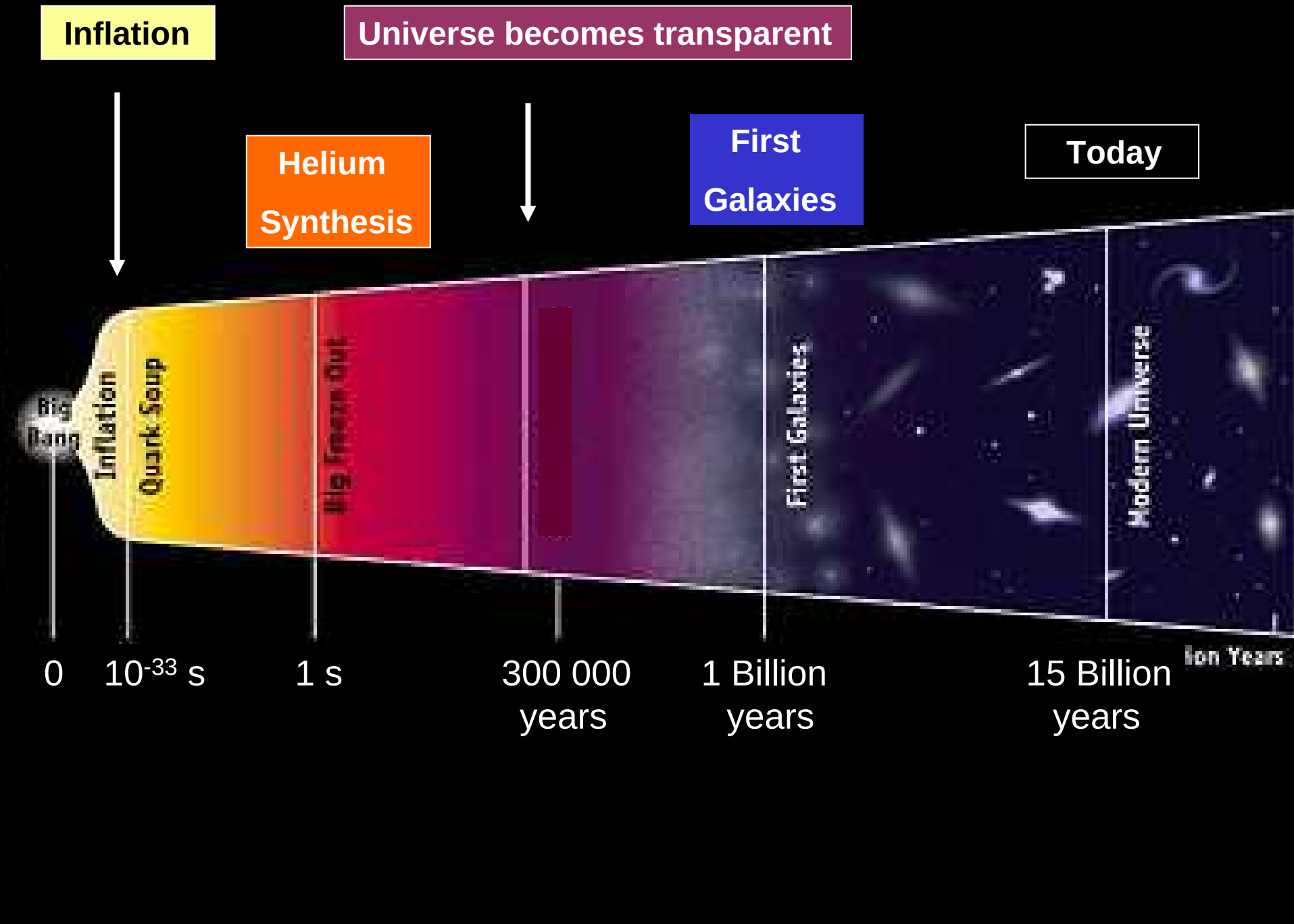
Dead of last stars

Black holes



10^{33} Proton decay ?




Inflation
Universe becomes transparent
Helium Synthesis
First Galaxies
Today
Big Bang
Inflation
Quark Soup
Big Freeze Out
First Galaxies
Modern Universe
0
10-33 s
1 s
300 000 years
1 Billion years
15 Billion years
Billion Years

"HE HAD THE PRESENCE OF MIND THOSE DAYS TO TAKE A SNAP OF THE BIG BANG. HE STILL THINKS THAT IT'S RATHER IMPRESSIVE"