Dark Energy

- a mystery?

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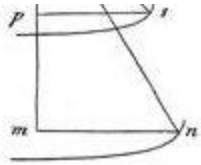
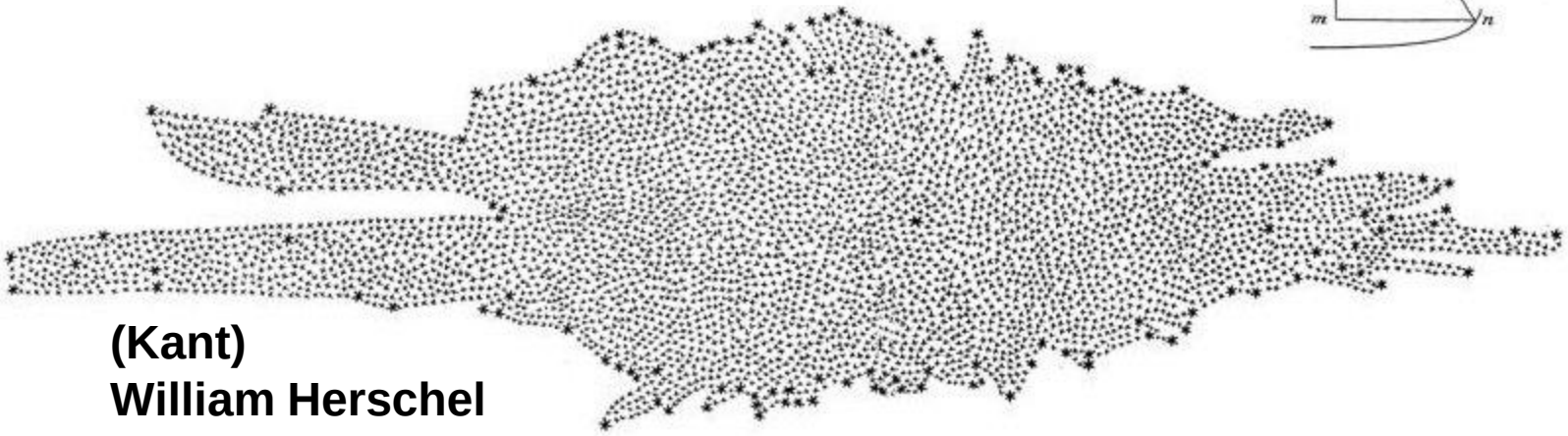
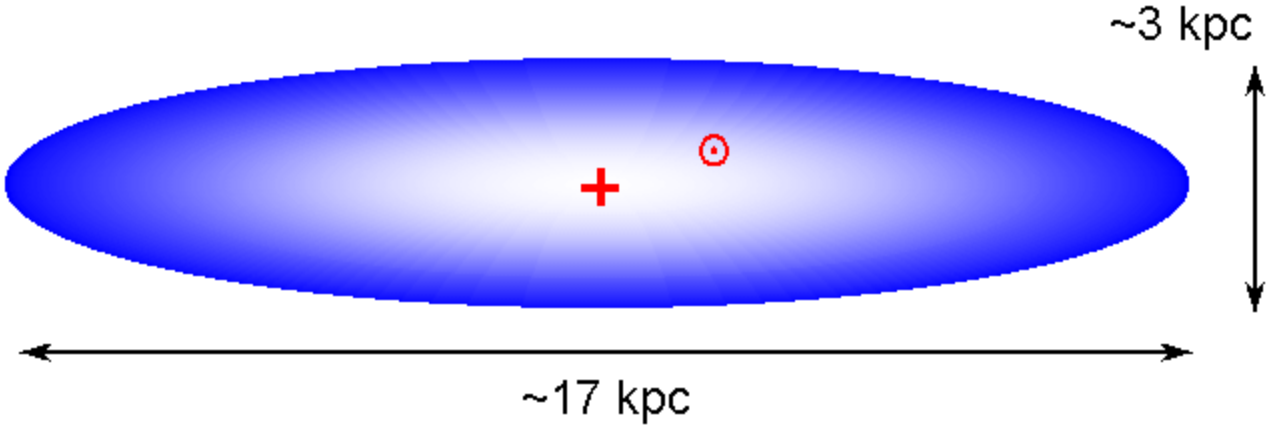
From the island universe …





(Kant)
William Herschel

… to Kapteyn's universe (1922)



kpc = kiloparsec = 1000 pc

1917: Einstein applied general relativity to the universe as a whole

Universe = Milky Way should be collapsing

add an extra term to the theory

cosmological constant

vacuum energy

pushes space apart

Edwin Hubble

- 1925: there are galaxies outside the Milky Way …

- 1929: … and their redshift increases as a linear function of the distanced

space expands

Einstein: ”the greatest blunder of my life”

Big Bang á la Einstein

- did not take place in any single place: time and space were created at the Big Bang
- space is not expanding into some empty volume
- velocity of light is 300 000 km/s: by looking far away one looks into the past

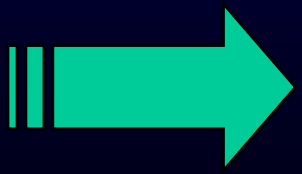
How to see the Big Bang?

MOON is about 1 second in the past

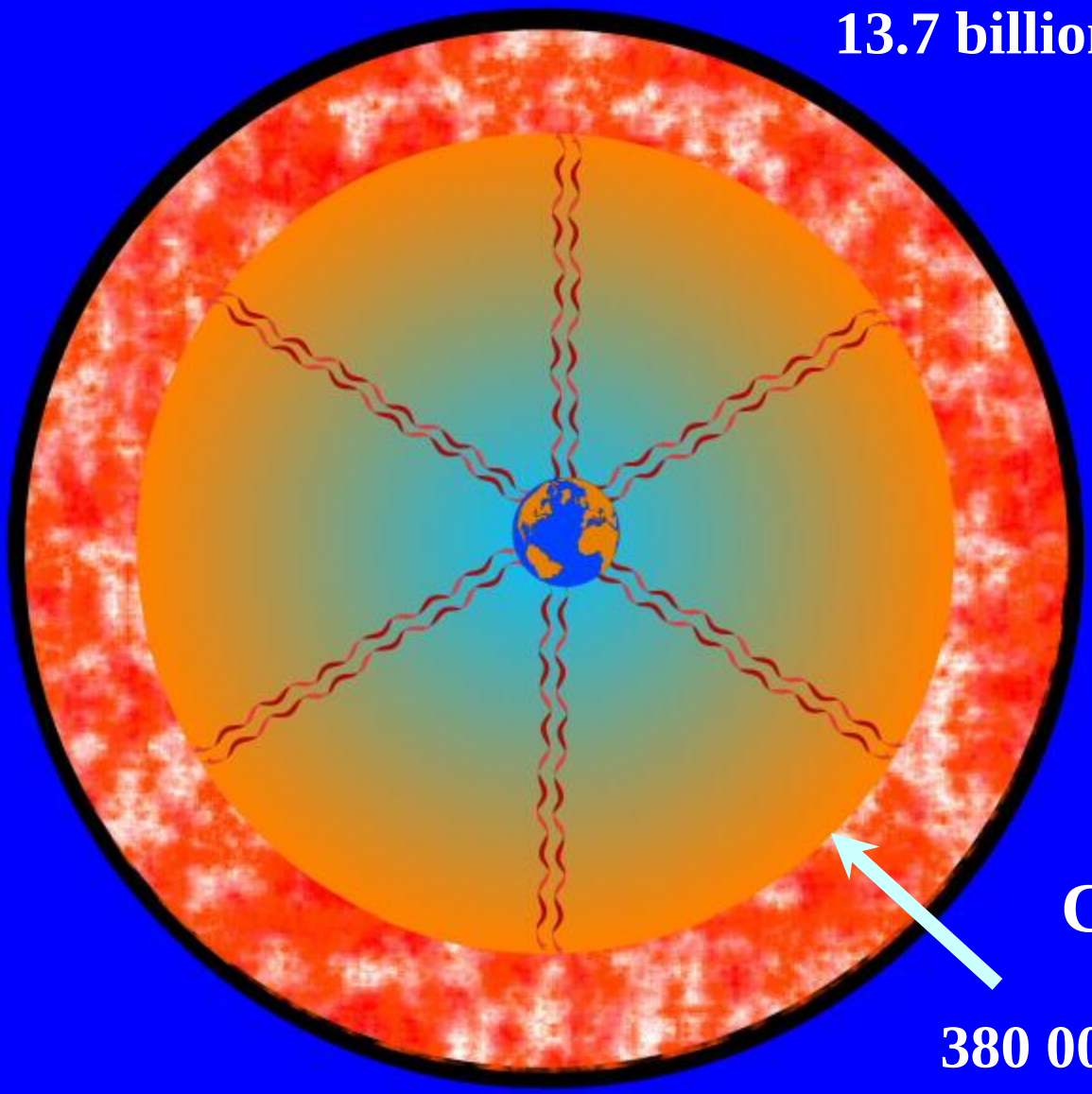
SUN is about 8 minutes in the past

ANDROMEDA GALAXY is 2 million years in the past

BIG BANG is 13.7 billion years in the past

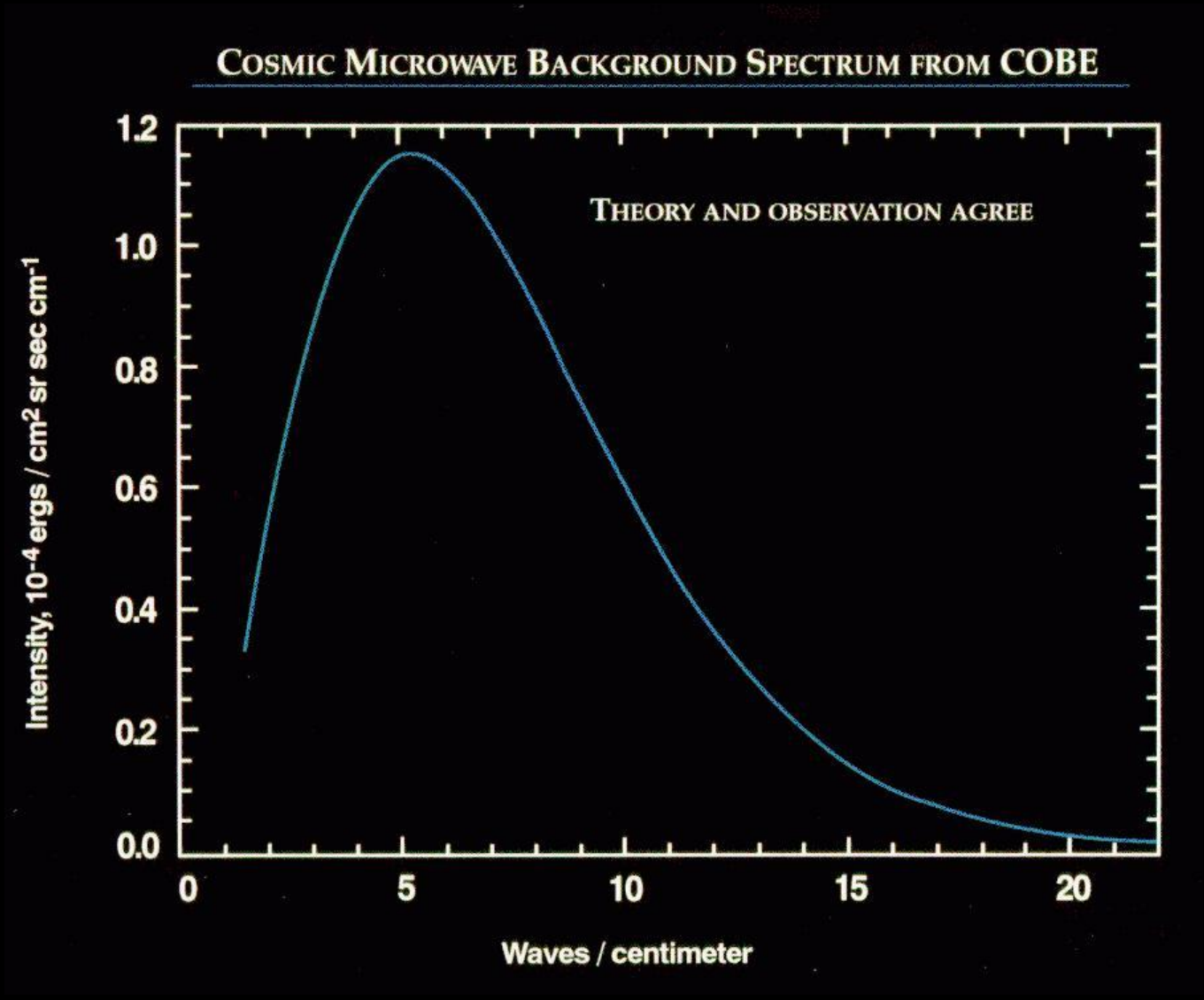


just look far enough

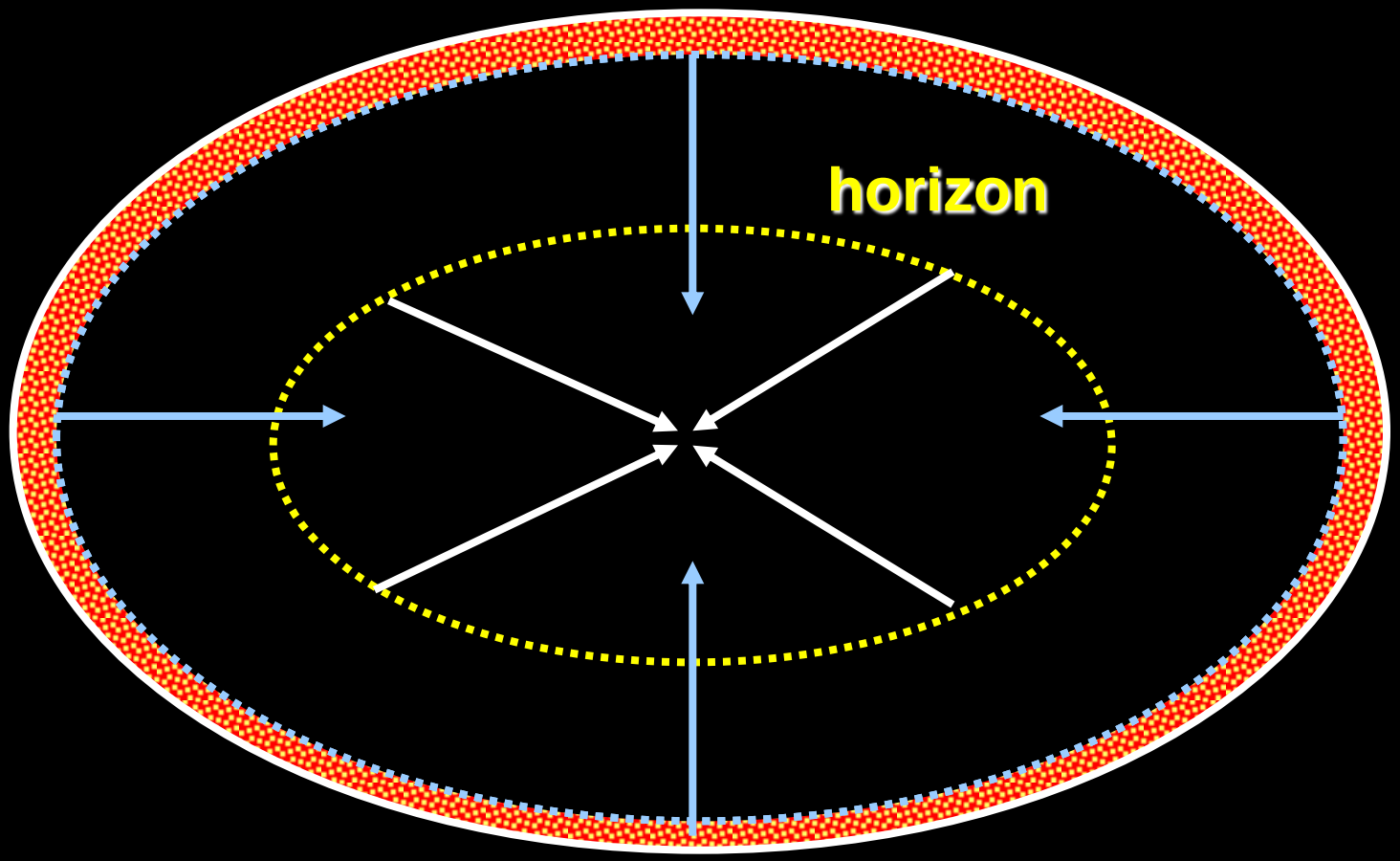

13.7 billion years
CMB
380 000 years from
the Big Bang

hot initial state → thermal radiation

Penzias, Wilson 1965

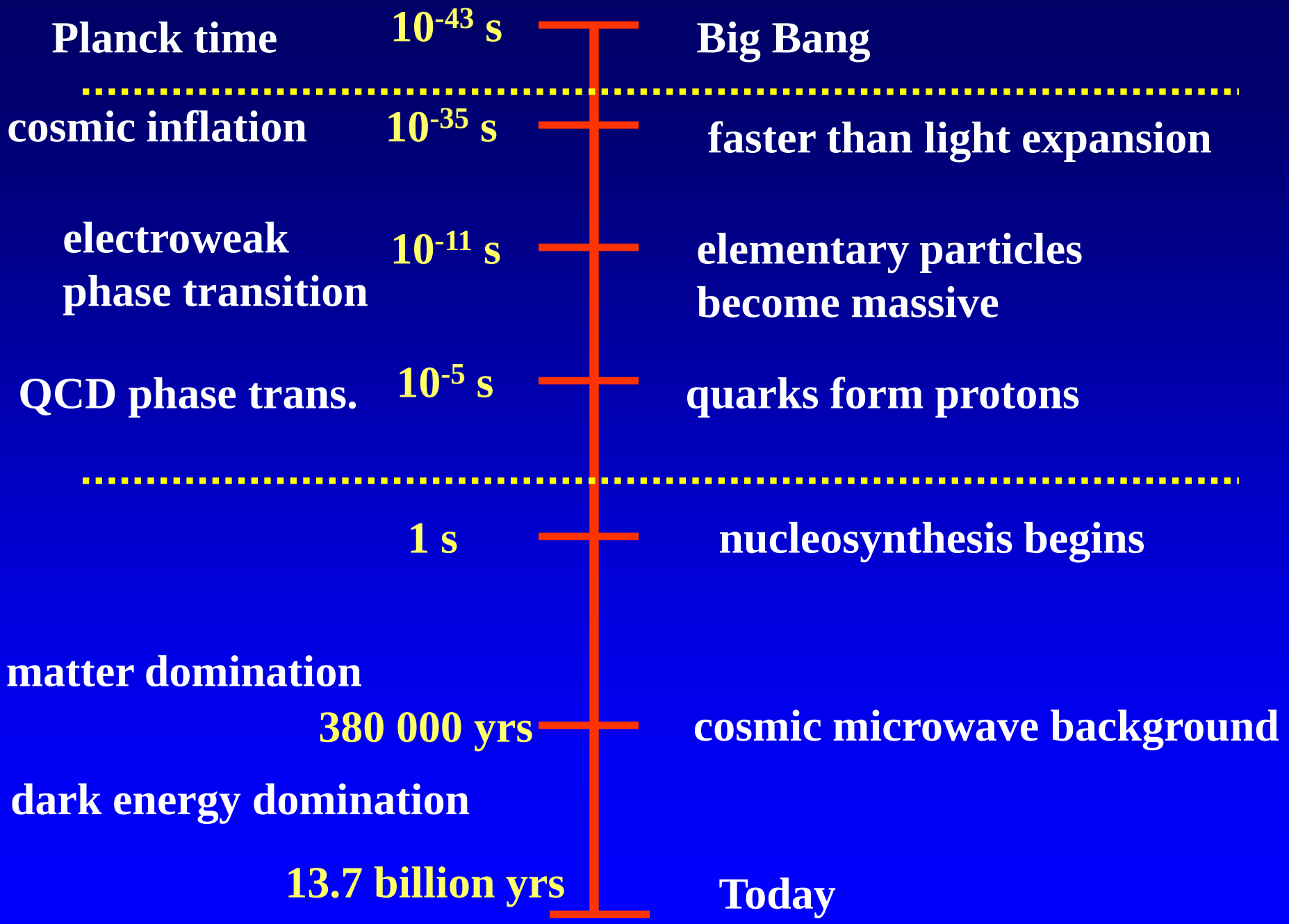


light that has not yet reached us



the universe may well be infinite, but we only see the part from which light has reached us

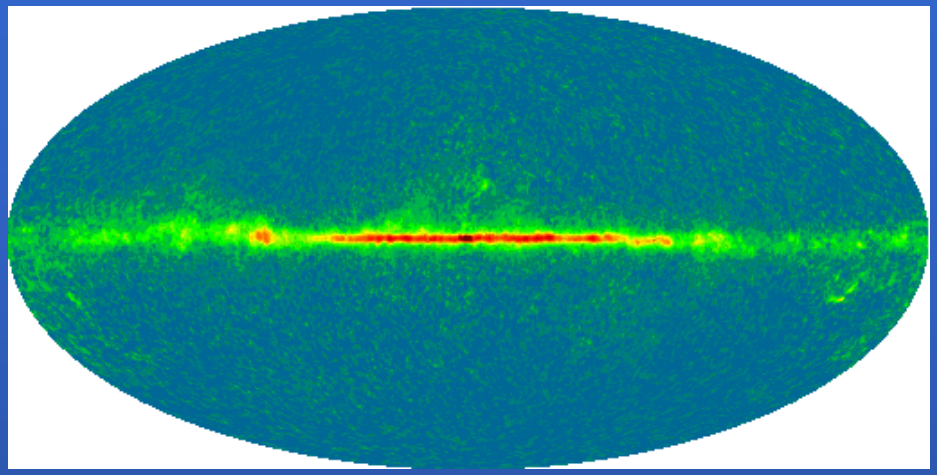

BIG BANG
galaksi
3K
H
D
He


Planck time
10^{-43} s
Big Bang
cosmic inflation
10^{-35} s
faster than light expansion
electroweak
phase transition
10^{-11} s
elementary particles
become massive
QCD phase trans.
10^{-5} s
quarks form protons
1 s
nucleosynthesis begins
matter domination
380 000 yrs
cosmic microwave background
dark energy domination
13.7 billion yrs
Today

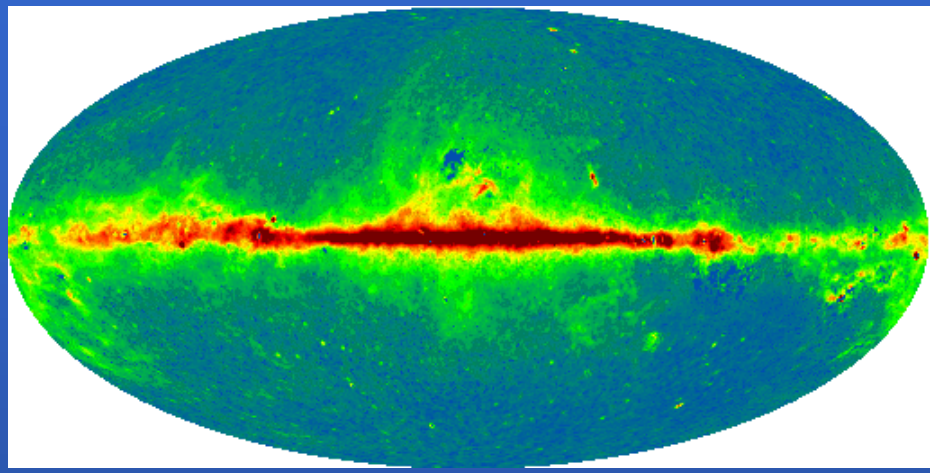
Satellites measuring the CMB

- COBE (Cosmic Background Explorer) 1992
- WMAP (Wilkinson microwave anisotropy probe) 2003
- Planck launch Fall 2008

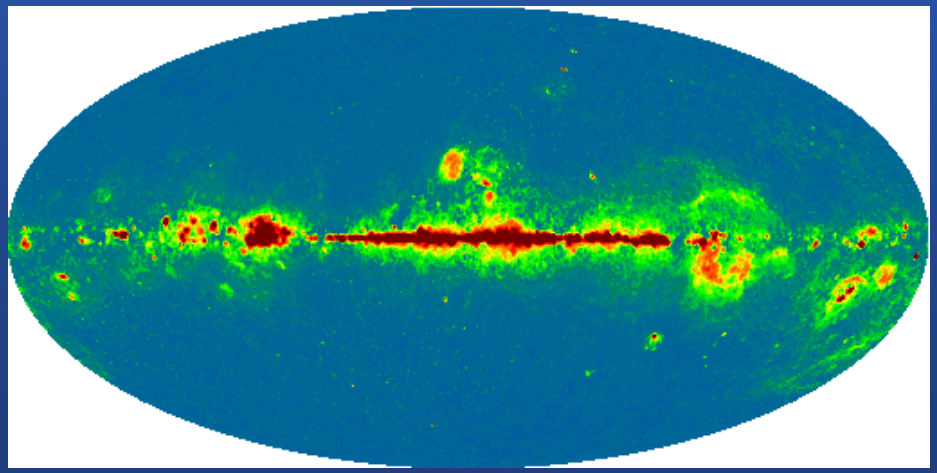
derived maps



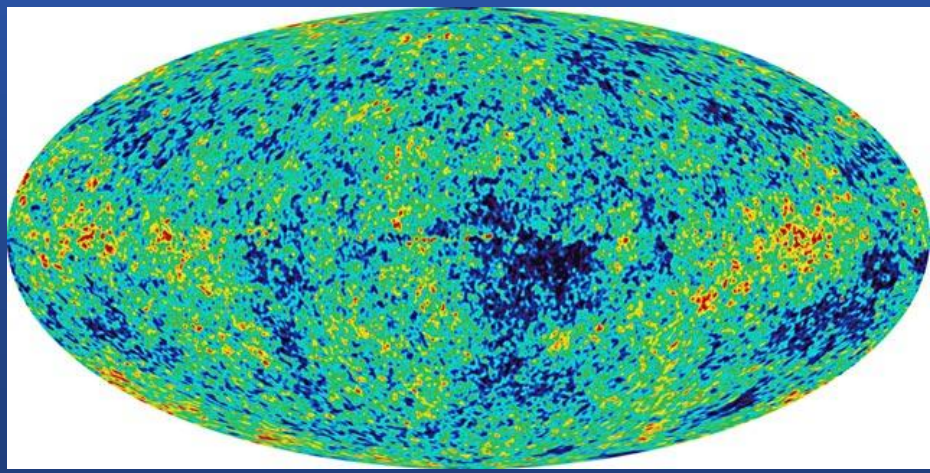
Dust map



Synchrotron map



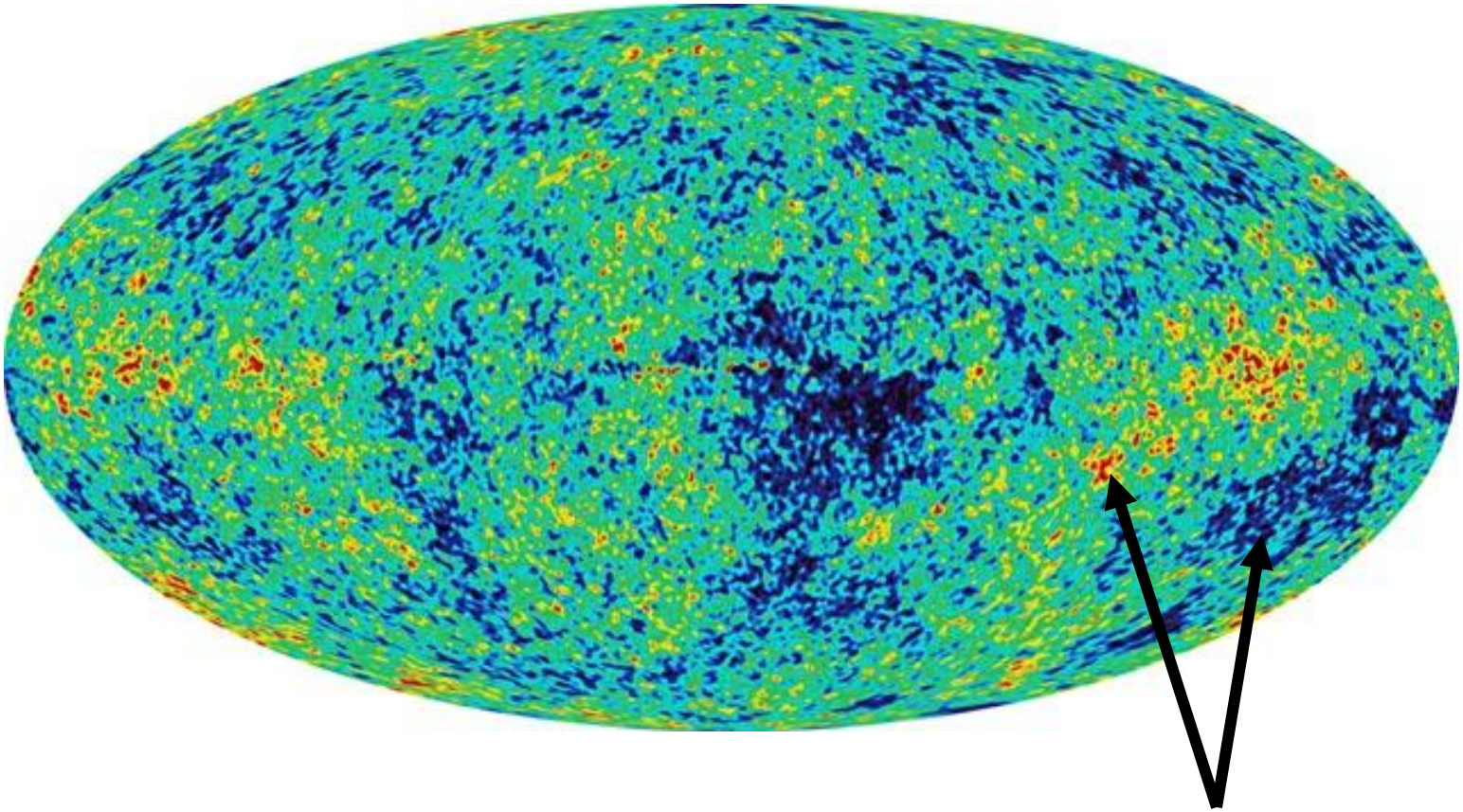
Free-free map



CMB map

WMAP PRIMORDIAL SKY MAP

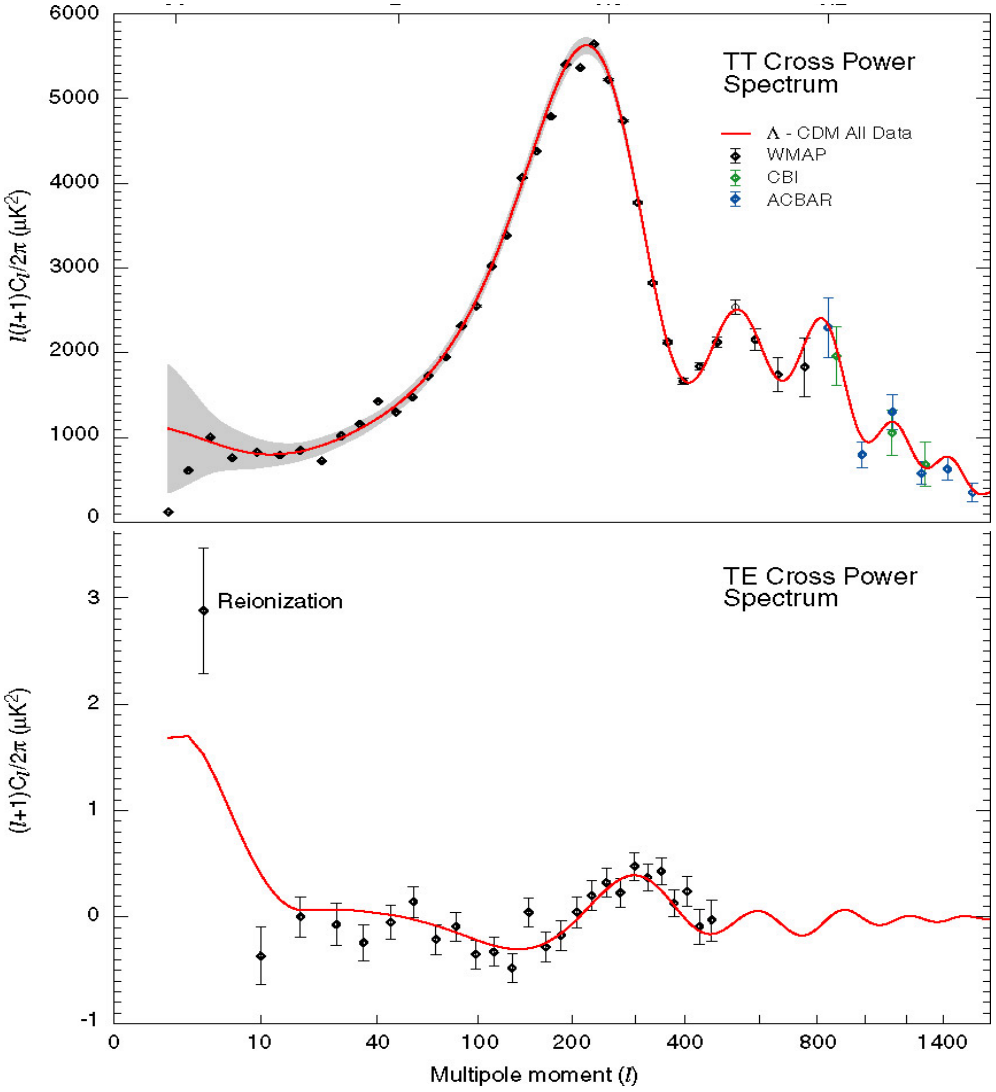
Average temperature 2.725 K



hot ja cold spots

differences of the order of 1/100 000 K

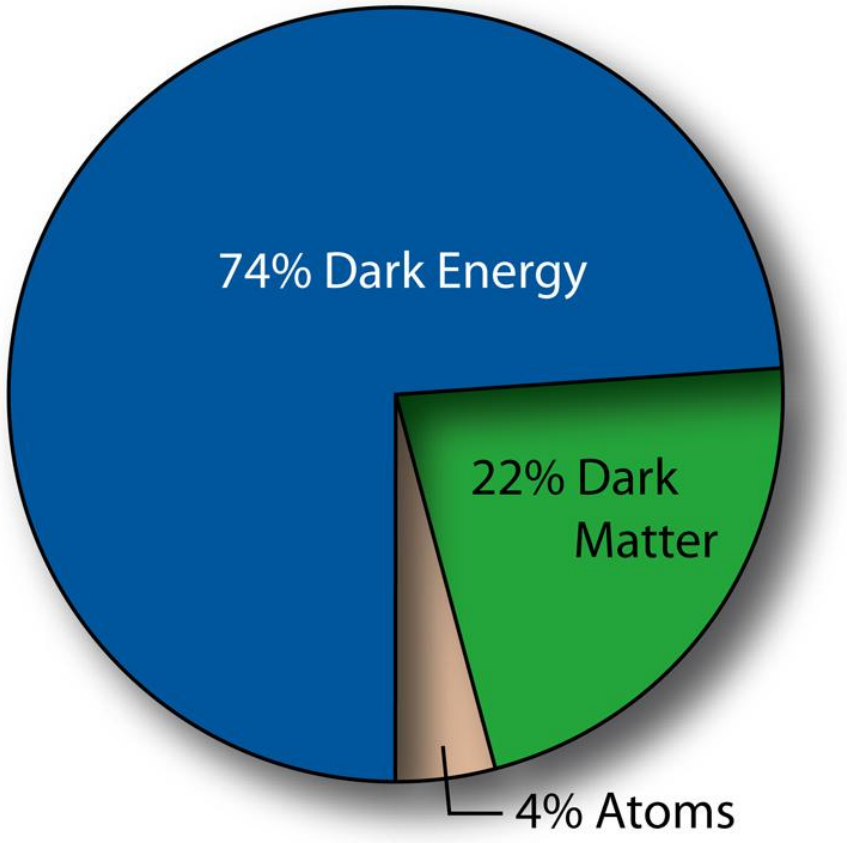
Power spectrum



ENERGIES IN THE UNIVERSE

- *ordinary matter 4.4%*
- *dark matter 23%*
- *dark energy 73%*

first indication in 1998



DARK ENERGY

"transparent energy"

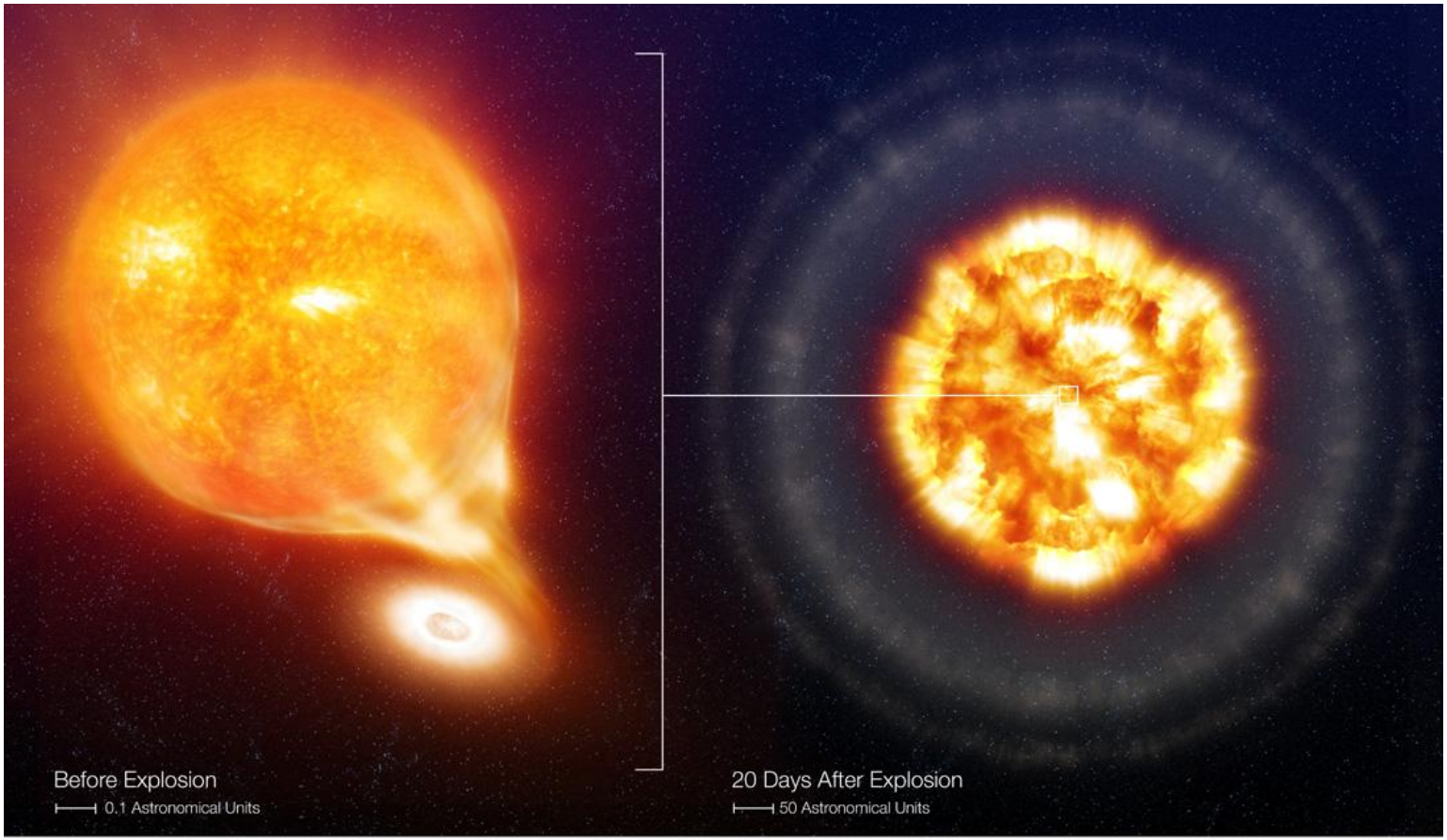
continuous energy field

vacuum energy = cosmological constant

"dark energy" more general: cosmological constant may vary in time

cannot be seen, but affects the expansion rate

Type Ia supernova



SN 2006X, before and after the Type Ia Supernova Explosion
(Artist Impression)

ESO Press Photo 31b/07 (12 July 2007)

Chandrasekhar limit → standard candle

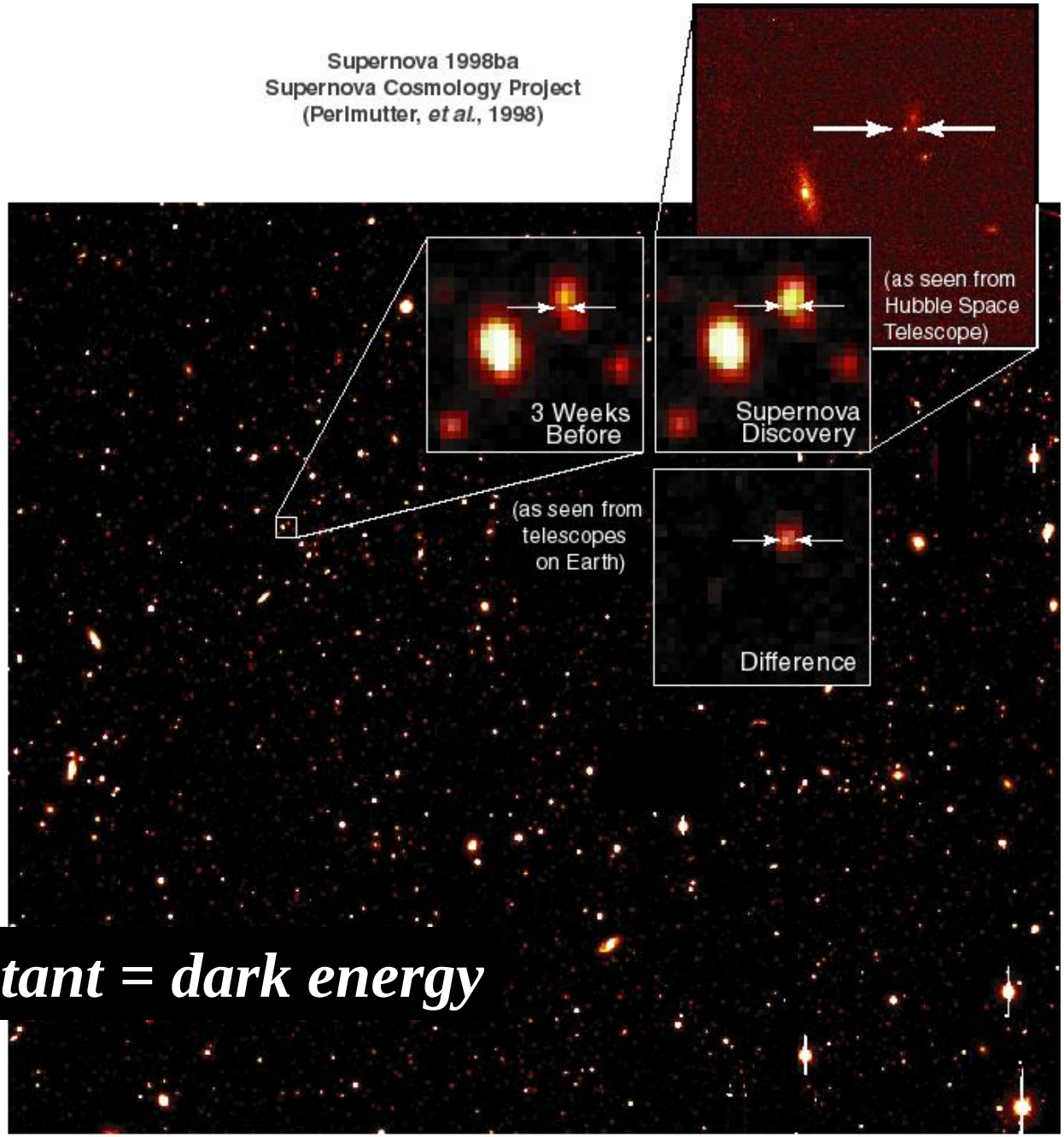
distant supernovas fainter than expected

must be further away than what seems

space must have expanded faster

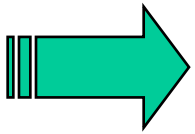
accelerating expansion

cosmological constant = dark energy



Einstein equations

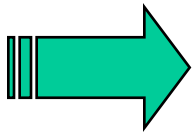
$$H^2 = \frac{8\pi G}{3}\rho$$



expansion rate depends on the mass and energy content of the universe

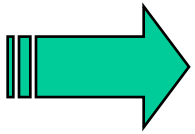
homogeneous Friedmann-Robertson-Walker universe

”dust” (= galaxies), radiation

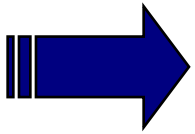


decelarating expansion (gravity attractive) $H \propto 1/t$

cosmological constant



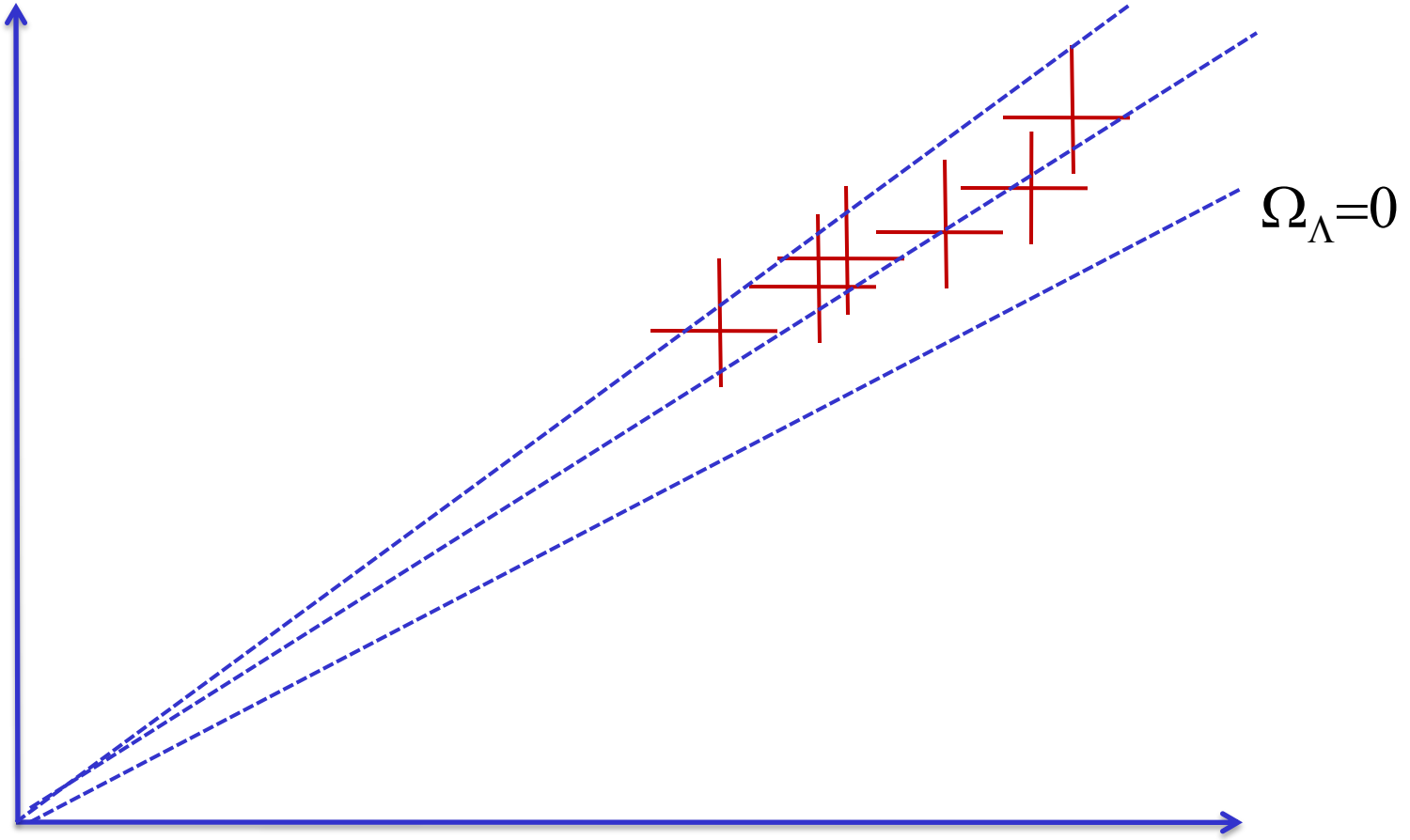
accelerating expansion $H \propto const$



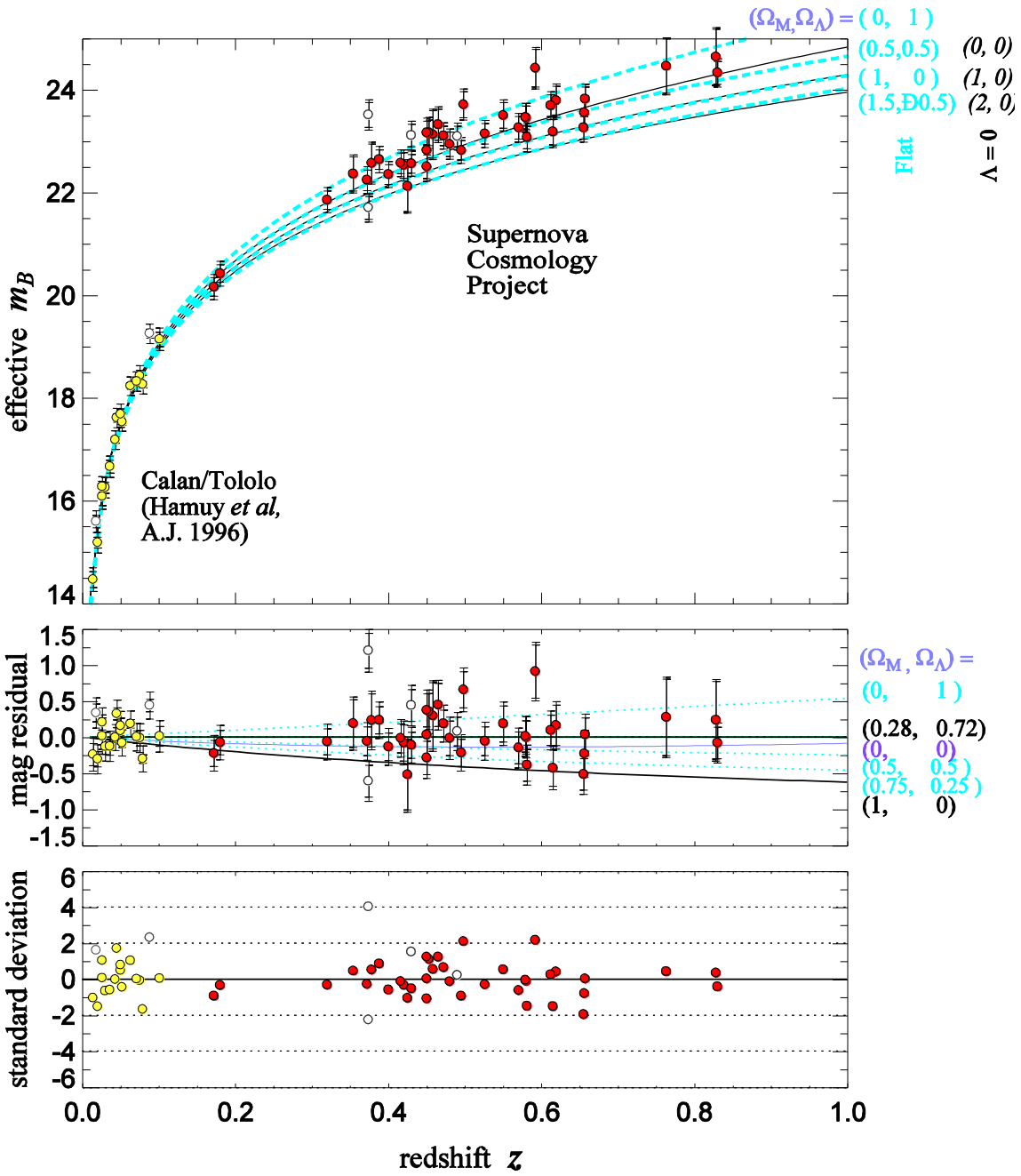
$a \propto e^{Ht}$

SN luminosity d

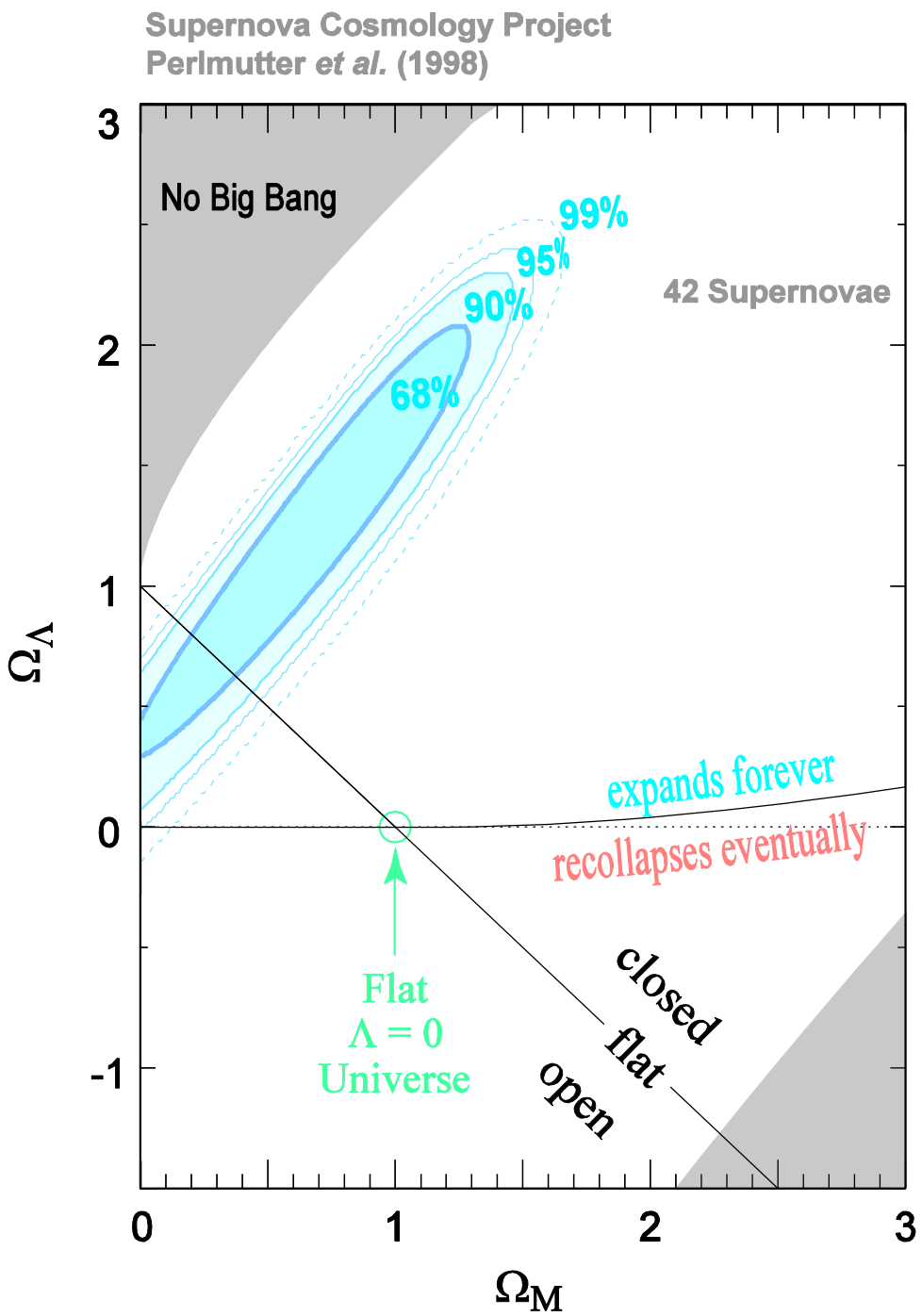
$$d=[z+f(\Omega_\Lambda,\Omega_m)z^2]/H_0$$



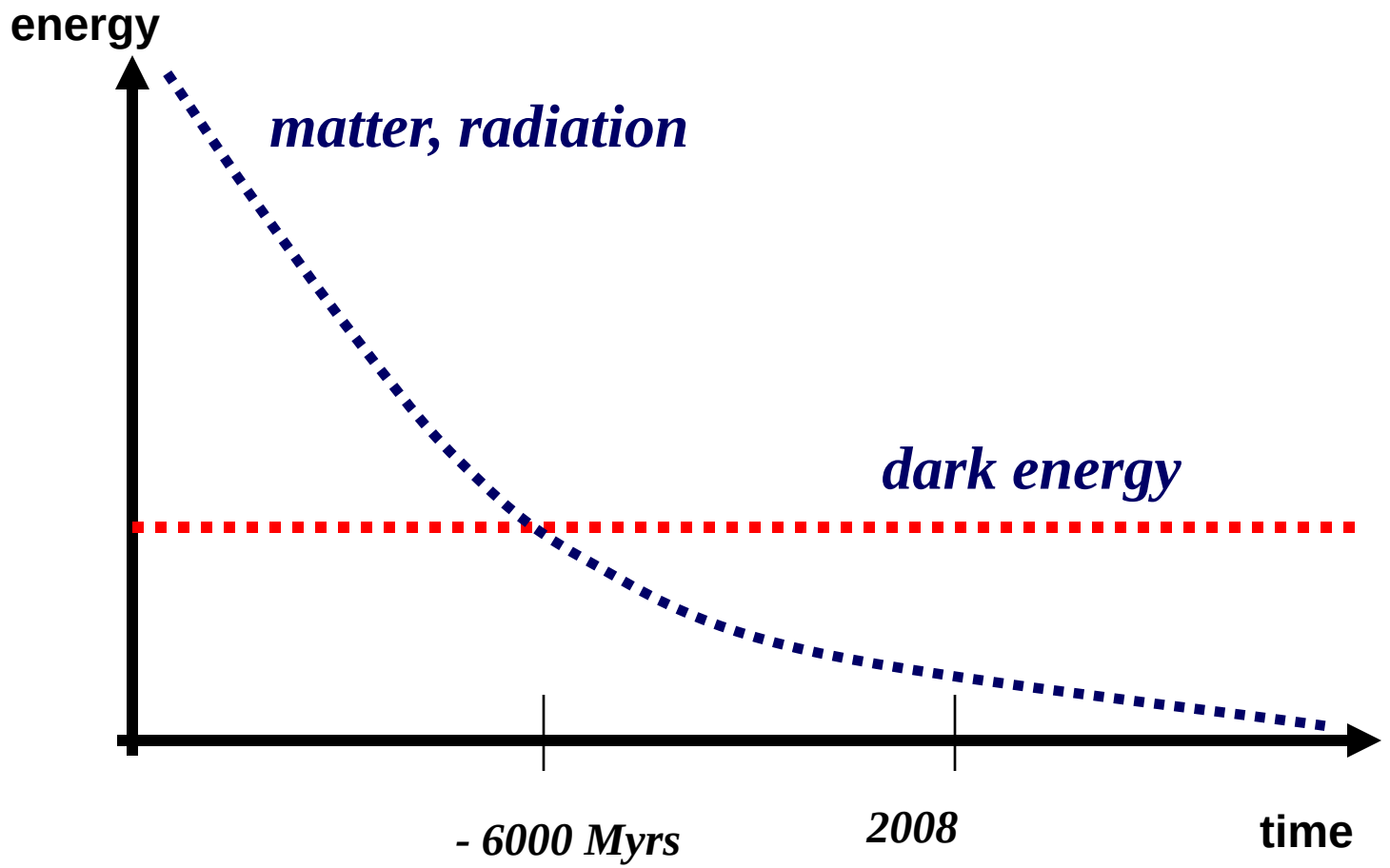
Ω = energy/critical energy



Perlmutter, *et al.* (1998)


Supernova Cosmology Project
Perlmutter et al. (1998)
No Big Bang
99%
95%
90%
68%
42 Supernovae
expands forever
recollapses eventually
Flat
Λ = 0
Universe
closed
flat
open
Ω_Λ
Ω_M
3
2
1
0
-1
0
1
2
3

expansion started to accelerate about 6 billion years ago

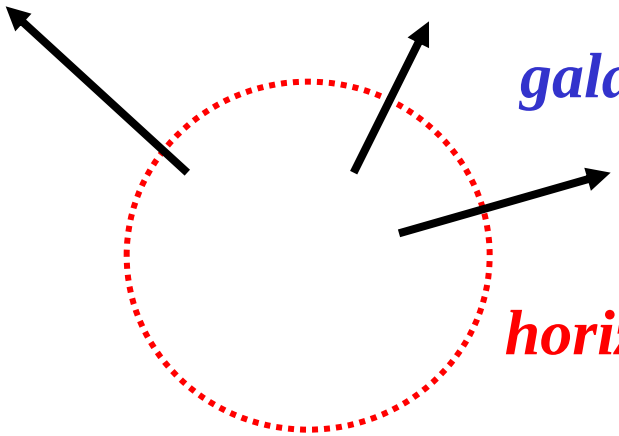


in the future dark energy will determine the expansion of the universe

accelerating (exponential) expansion

expansion rate will exceed the speed of light!

OK



galaxies disappear

horizon

dark energy = theoretical problem

- why $E_{DE} \sim 10^{-120}$?

- why now?

greatest challenge of modern cosmology

Is it absolutely certaint that dark energy exists?

expansion cannot be seen – we only see light

inhomogeneities → mirage?

Should general relativity be modified?

not the most general theory of gravitation

two model classes: ugly and very ugly

$$R \to R + R^2 + \ldots$$

$$R \to R, \phi$$

Dark Energy

- a mystery?

Yes, sort of – at least for the time being