TRISEP 2013

COSMOLOGY & DARK MATTER

Part II

Viktor Zacek, Université de Montréal

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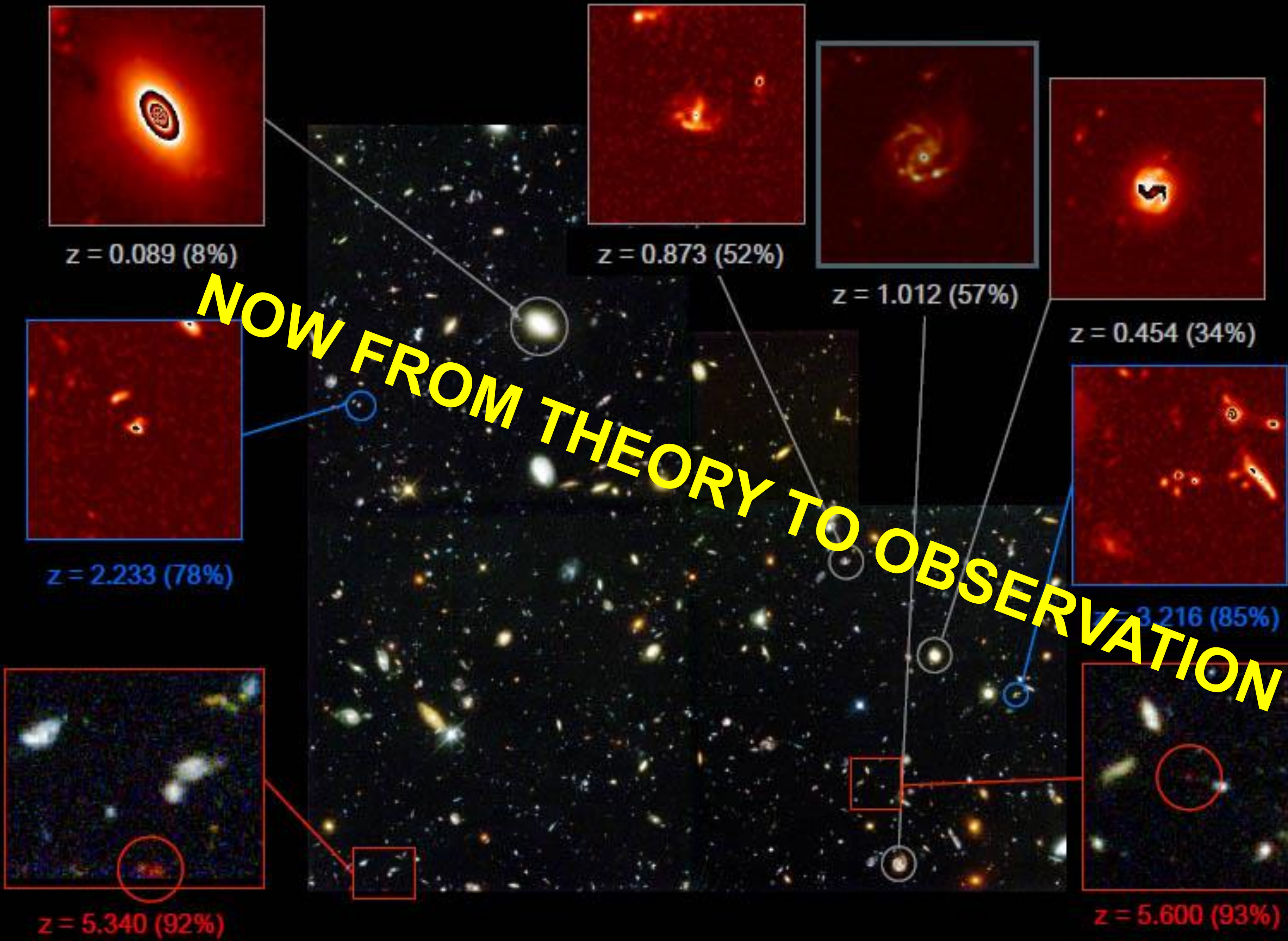
Lecture II

- Observations
- Redshift and scale factor
- Distance measurements
- SN1a and the accelerating Universe
- The Cosmic Microwave Background
- Present knowledge of the content of the Universe
- Evidence for dark matter

NOW FROM THEORY TO OBSERVATION



Hubble space telescope

REDSHIFT & SCALE FACTOR

- Scale factor *a*(*t*) is related to the redshift !
- Measurements involve redshifts and radiant fluxes of distant objects

Wavelength of a receding object is stretched out…

Sretching factor: $z = \frac{\lambda_o - \lambda_e}{\lambda_e} = \frac{\lambda_o}{\lambda_e} - 1$

$$1 + z = \frac{\lambda_o}{\lambda_e} = \frac{a(t_0)}{a(t_e)}$$

→

time of observation

$$\frac{a(t_0)}{a(t_e)} = 1 + z$$

time of emission

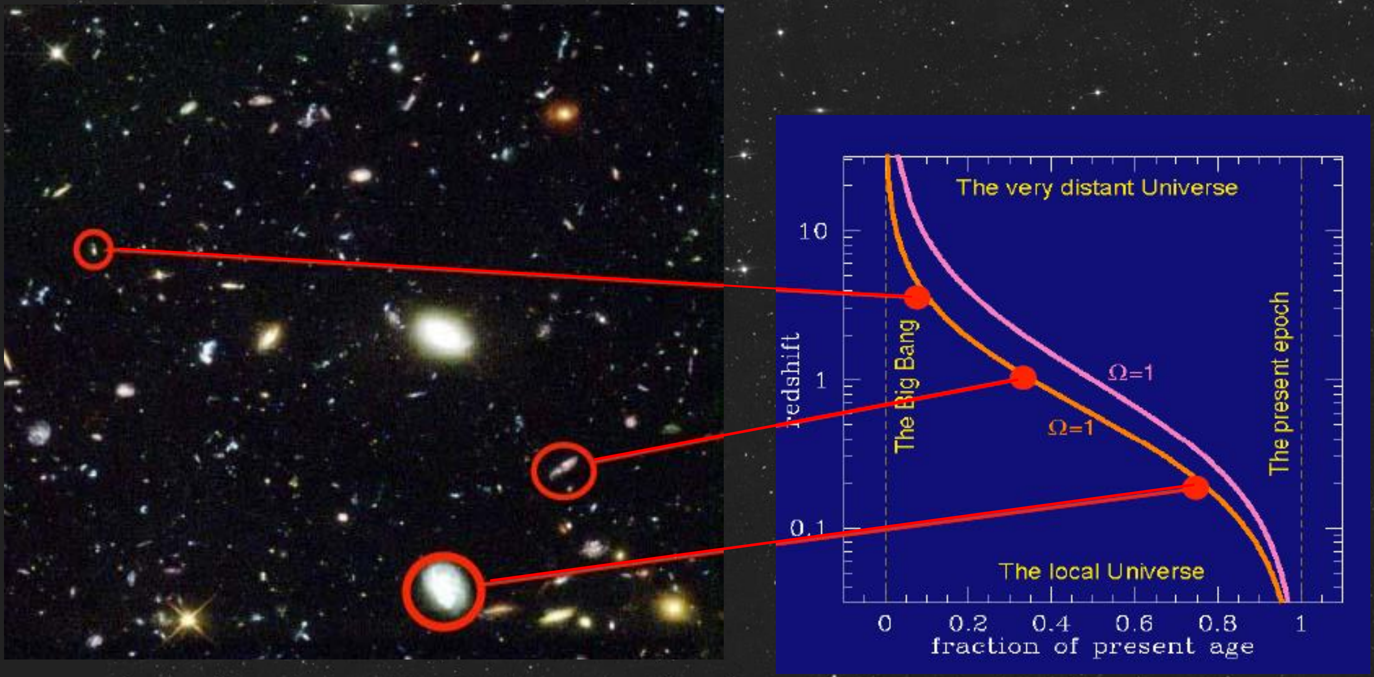
$$1 + z = \left(1 + \frac{v}{c}\right)\gamma \quad \rightarrow \quad z \approx \frac{v}{c} \quad (v \ll c)$$

γ = Lorentz factor

U. at redshift z → U. of size 1/(1+z) with respect to today

REDSHIFT & SCALE FACTOR

$$\frac{a(t_0)}{a(t_e)} = \frac{1}{1+z}$$



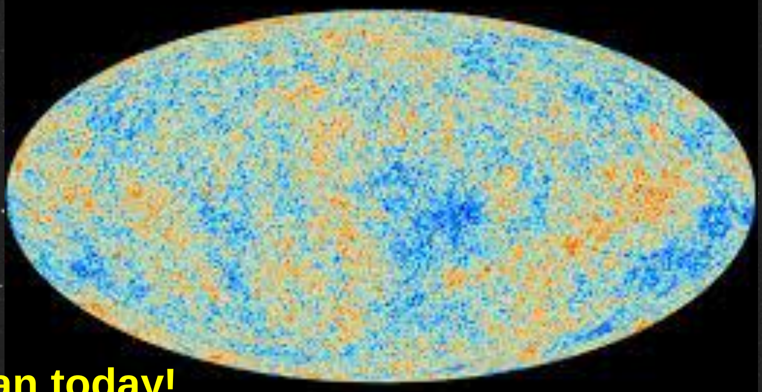
50 objects with z > 8

Protogalaxies, GRB, quasars

Record: z = 11.9 !

CMB: Cosmic Microwave Background radiation

z = 1089!



U. by factor 1000 smaller than today!

LUMINOSITY DISTANCE

- Cosmological distances are measured with Standard Candles
- Standard Candles are sources of known size or luminosity (rad.power)
- E.g. Cepheid stars (< 10 Mpc), SN1a. (50 – 800 Mpc)
- Luminosity distance connects observed energy flux to luminosity of SC

Nearby object:

$$F = \frac{L}{4\pi d^2}$$

F: energy flux

L: luminosity

d: distance

Far away in an expanding U:

- All photons redshifted by (1+z)
- Time btw. photons increased by (1+z)

$$F = \frac{L}{4\pi {d_{eff}}^2} \frac{1}{(1+z)^2} = \frac{L}{4\pi {d_L}^2}$$

d_{eff} : co-moving distance

$$d_L = \frac{c}{H_0}\left[z + \frac{1}{2}(1 - q_0)z^2 + \cdots\right]$$

d

$$q_0 = \frac{\Omega_{m,0}}{2} - \Omega_\Lambda$$

Luminosity distance → a measure of cosmological parameters!

SUPERNOAVAE TYPE 1A

Motivation: **If we could find Standard Candles with 10% precision at z ~ 0.5 we could distinguish betw. models dominated by Ω_m or Ω_Λ**

- SN1a can be observed up to z ~ 1 (800 Mpc)
- $L_{SN} \sim L_G$!
- SN1a are binary star system with a white dwarf
- Accretion up to mass limit of 1.38 $\mathbf{M_\odot}$
- Merger starts run-away fusion from C up to Fe
- Peak Lumi correlated w. decay time: 10% precison in L_{SN}

Thanks to SN1a for all the oxygen we breath !!!

A technical detail (of ancient greek origin) **:**

Weber-Fechner: $$m_1 - m_2 = -2.5 log\left(\frac{L1}{L2}\right)$$ $m_{1,2}$: apparent "brightness" at $L_{1,2}$

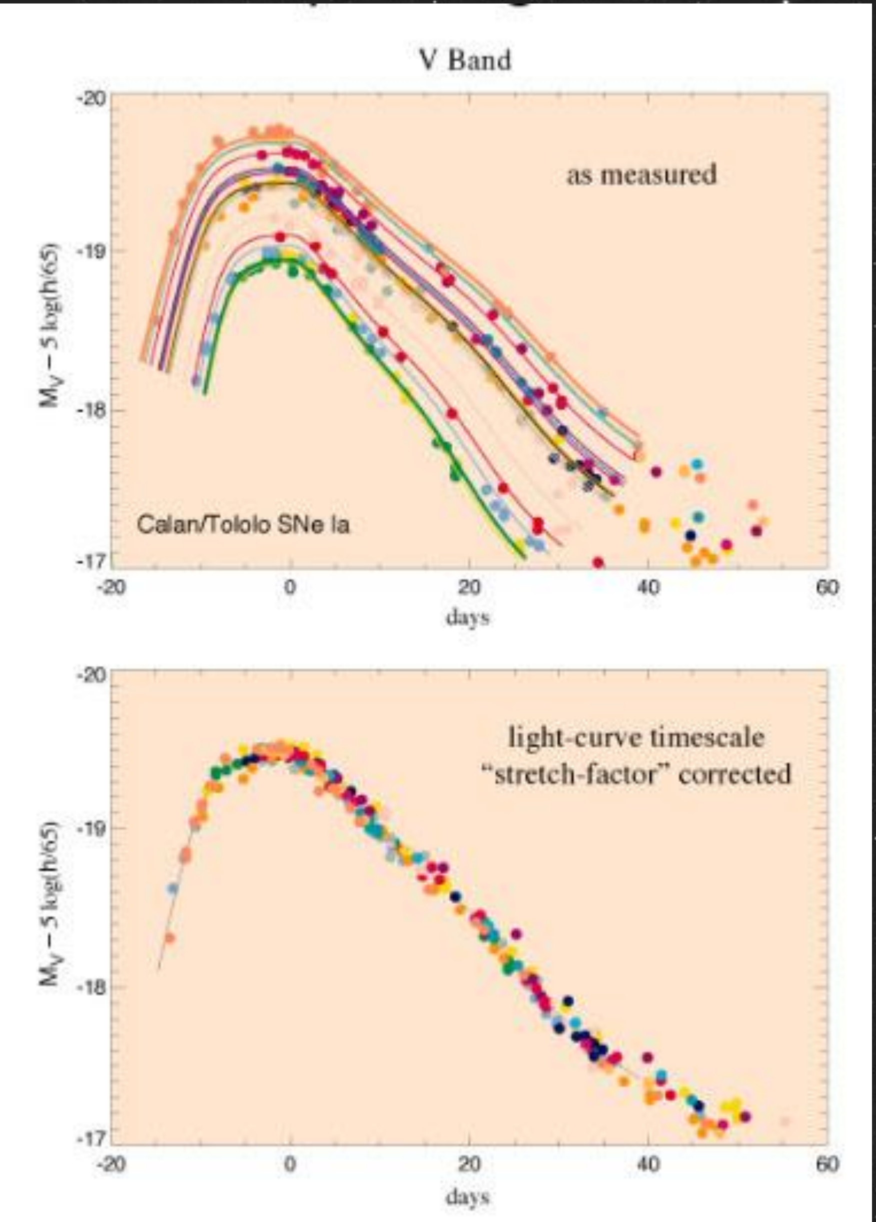
Cosmology: $$m - M = 5 log(d_L) + 5$$ …with Stand. Candle at 1 Mpc

app. abs. magnitude

App. Magnitude of sun : - 26.7

….the fainter the object the larger m-M

SUPERNOAVAE TYPE 1A

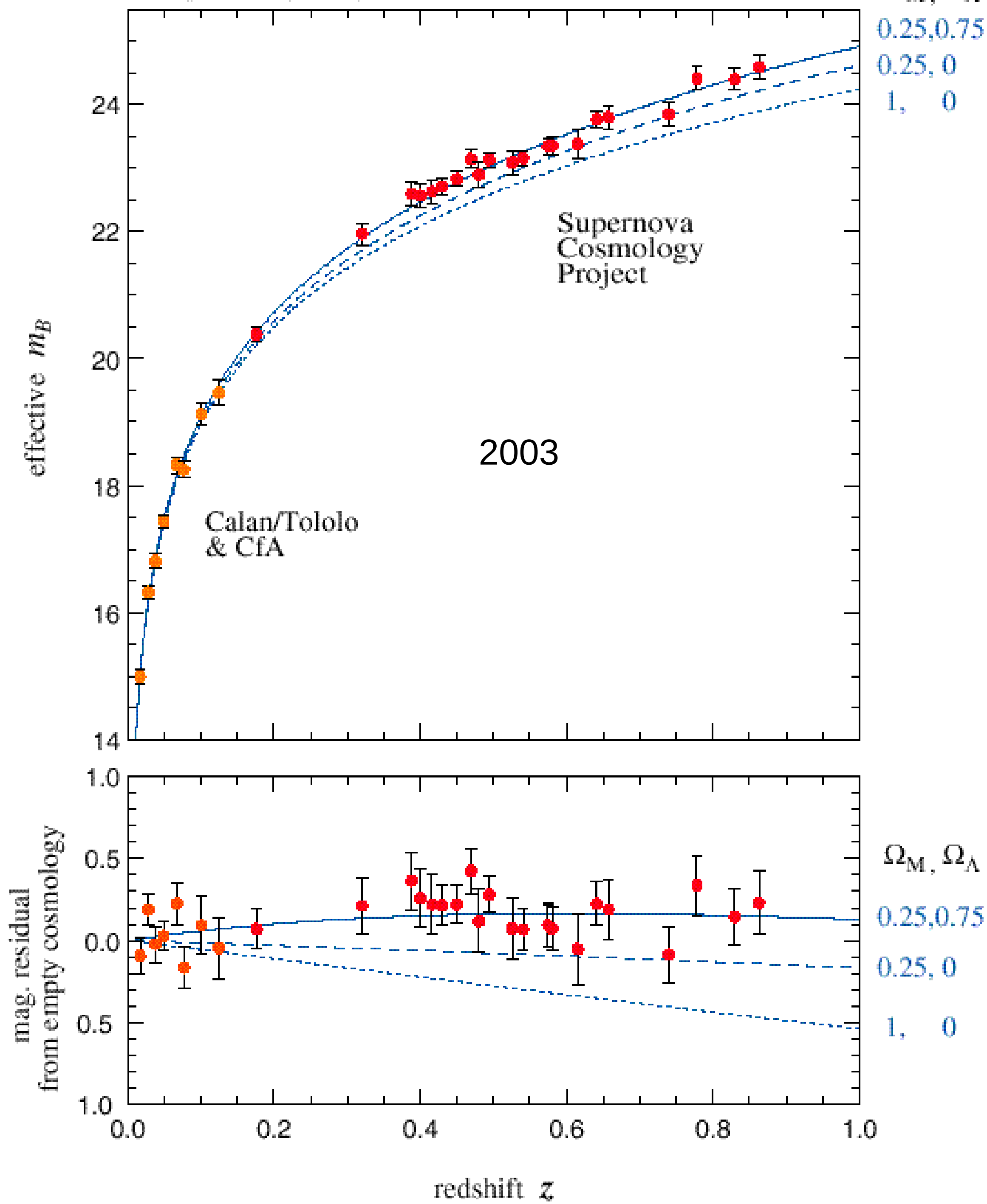


- Near SN at known distances
- Abs. magnitude related to decay time

Correct M by "stretching factor"

Same abs. magnitude M after correction

Far SN: get redshift from host galaxy



SN Type Ia Redshifts

$$d_L = \frac{c}{H_0}\left[z + \frac{1}{2}(1 - q_0)z^2 + \cdots\right]$$

$$q_0 = \frac{\Omega_{m,0}}{2} - \Omega_\Lambda$$

SN Cosmology Project

High z SN Search

> 12 SN

at z =0.5

~ 50% fainter than for Ω_m =1, Ω_Λ =0

Best fit:

Ω_m = 0.25, Ω_Λ = 0.75

PHYSICS NOBEL PRIZE 2011

S.Perlmutter

B. Schmidt

A.Riess

“for the discovery of the accelerating expansion of the Universe through observations of distant supernovae”

“dark energy [...] is an enigma, perhaps the greatest in physics today”

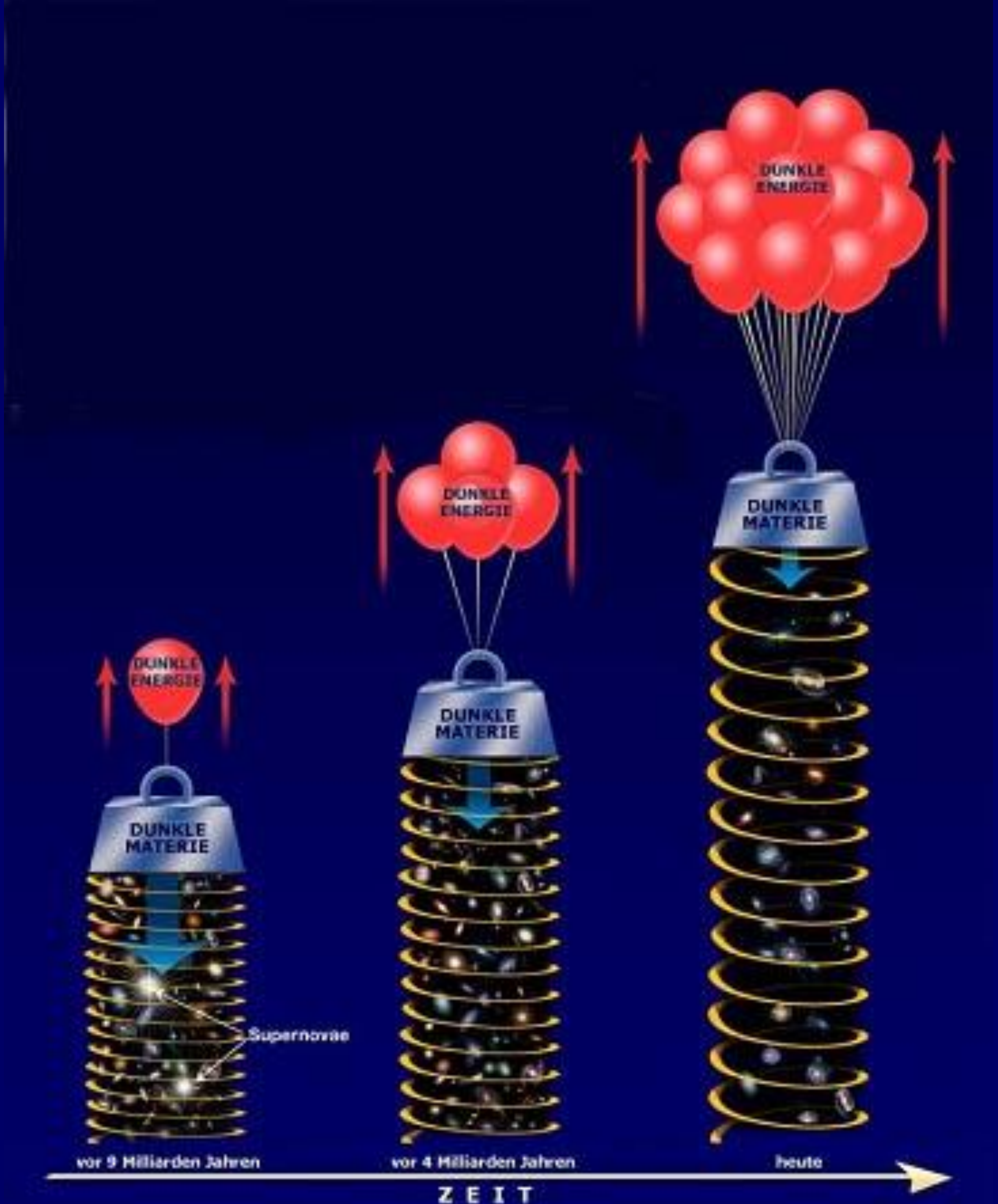
- Ridiculous small value: $\Lambda \sim 1.3 \times 10^{-52}\ m^2$
- $\Lambda = 0$ more natural
- ..or ridiculously much larger ?
- important at beginning of U. and in future

QFT prediction : $\rho_{vac} \sim 10^{92}\ gcm^{-3}$

From Λ observed: $\rho_{vac} \sim 10^{-31}\ gcm^{-3}$

Factor 10^{123} off !

Cosmological constant problem



Dark energy

Dark Matter

9 By ago

4 By ago

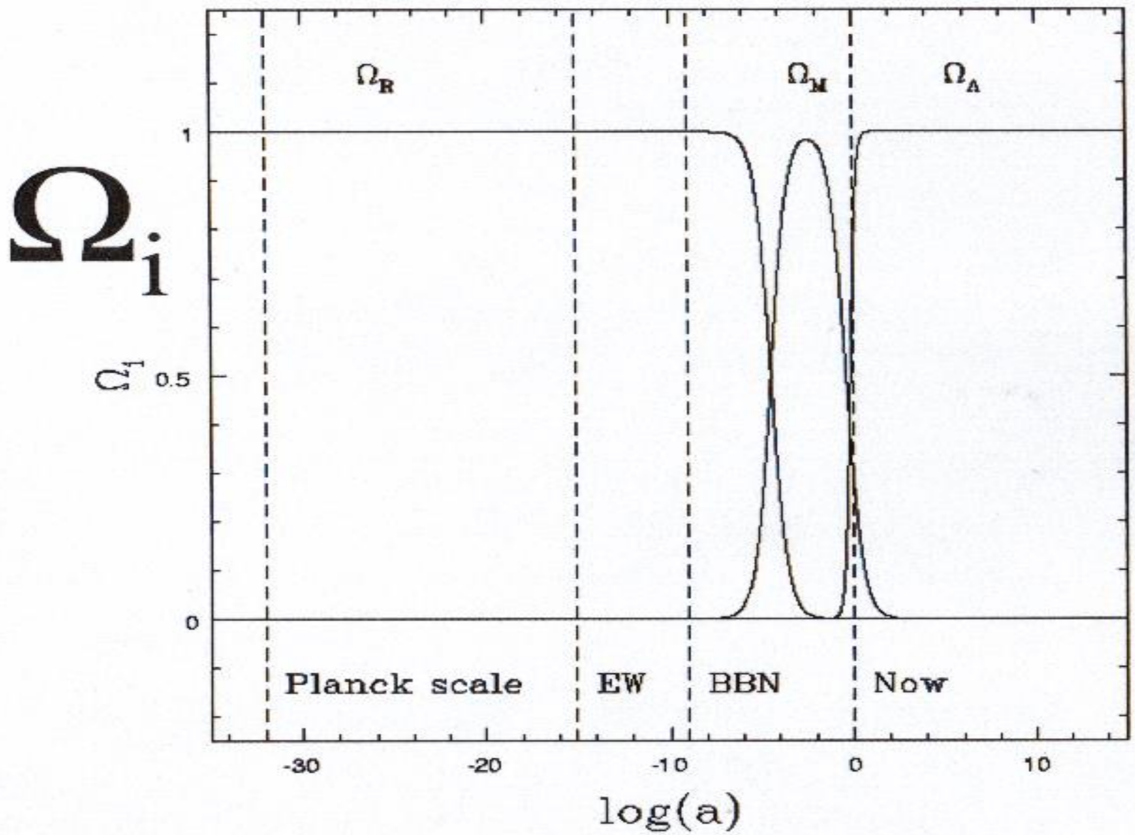
Today

Time

A COSMIC COINCIDENCE ?

$$\Omega_{tot} = \Omega_m + \Omega_r + \Omega_\Lambda = 1$$

$\Omega_\Lambda \sim \Omega_m$ just now??



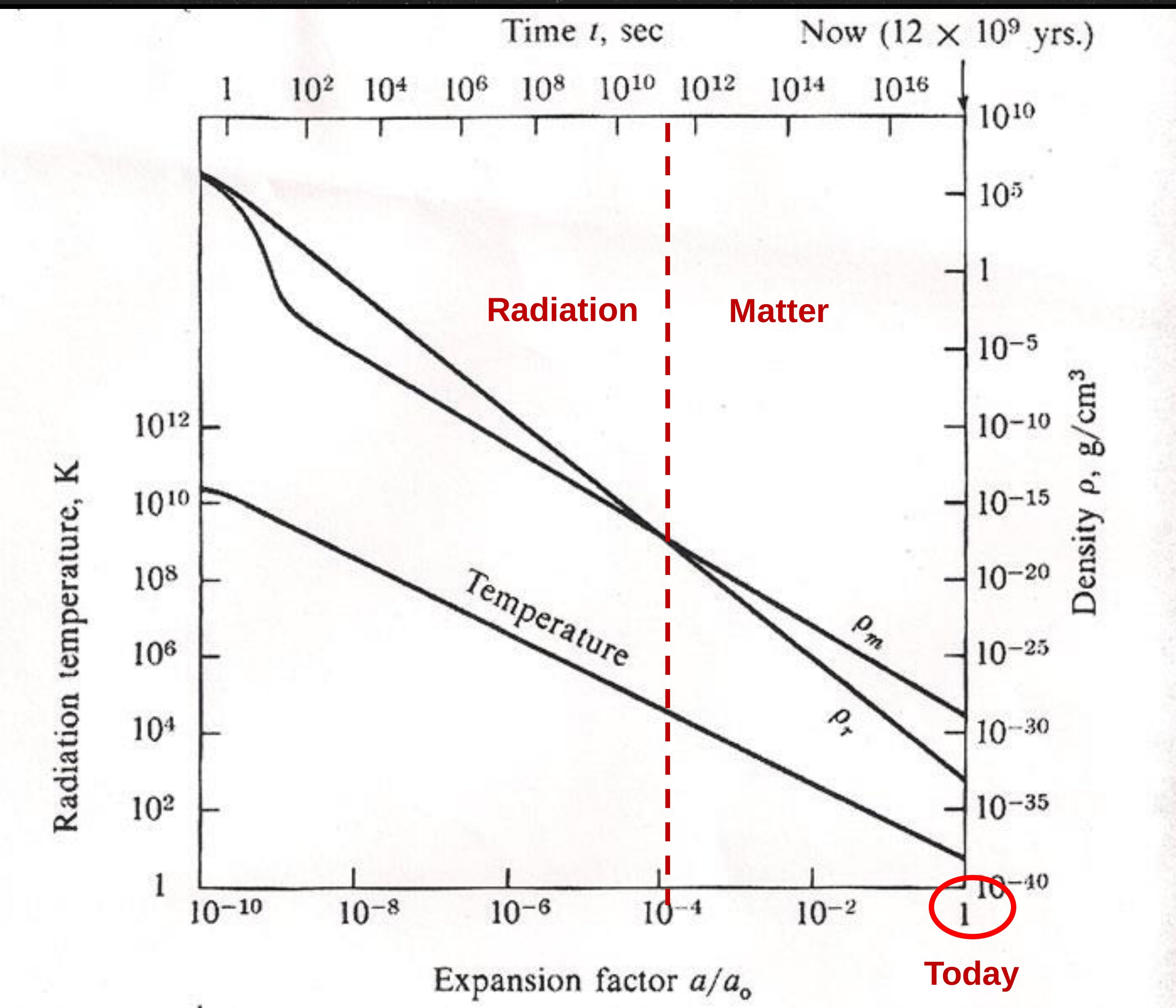
S. Weinberg:

- $\Lambda \sim 10^{120}$ x smaller than predicted by particle physics!
- $\Lambda \sim 10$ x larger than todays value $\rightarrow$ catastrophic inflation!
- Other regions, other U. in a Multiverse with different Ω_I and fundamental constants?
- Anthropic principle?

Do we live in a special time?

THE THERMAL HISTORY OF THE UNIVERSE

Density of black body radiation (Stefan-Boltzmann) : $\rho_r \propto T^4$



$$\rho_r(t) = \rho_r(t_0)\left(\frac{a(t_0)}{a(t)}\right)^4$$

$a(t_0)=1$

$$\rho_r(t) = \frac{\rho_r(t_0)}{a(t)^4} \propto t^{-2}$$

$$T(t) = \frac{T(t_0)}{a(t)} \propto t^{-1/2}$$

Hot history of the Universe!

THERMODYNAMICS OF THE UNIVERSE

….is a simple* description possible? Yes, if …

adiabaticity

- there is thermodynamic equilibrium $\rightarrow$ very frequent collisions
- evolution of U $\rightarrow$ sequence of equilibrium states $T(t)$, $p(t)$, $\rho(t)$, $S(t)$
- Local energy conservation in co-moving volume S = const.
- Interaction rate of constituents $\Gamma = n \cdot \sigma \cdot v$ (n # - density)

⬇

Thermal equilibrium when $\Gamma >> H$ (int. rate larger than expansion)

* S. Weinberg: (in therm. equilibrium) "the U. is simpler and easier to describe than it ever will be"

THERMODYNAMICS OF THE UNIVERSE

Thermal equilibrium when $\Gamma \gg H$ (rate larger than expansion)

…typically $\Gamma(t)$ decreases faster than $H(t)$

➡ particles will leave equilibrium… are "frozen out"

➡ "frozen out" particles are the dominant matter content of U now

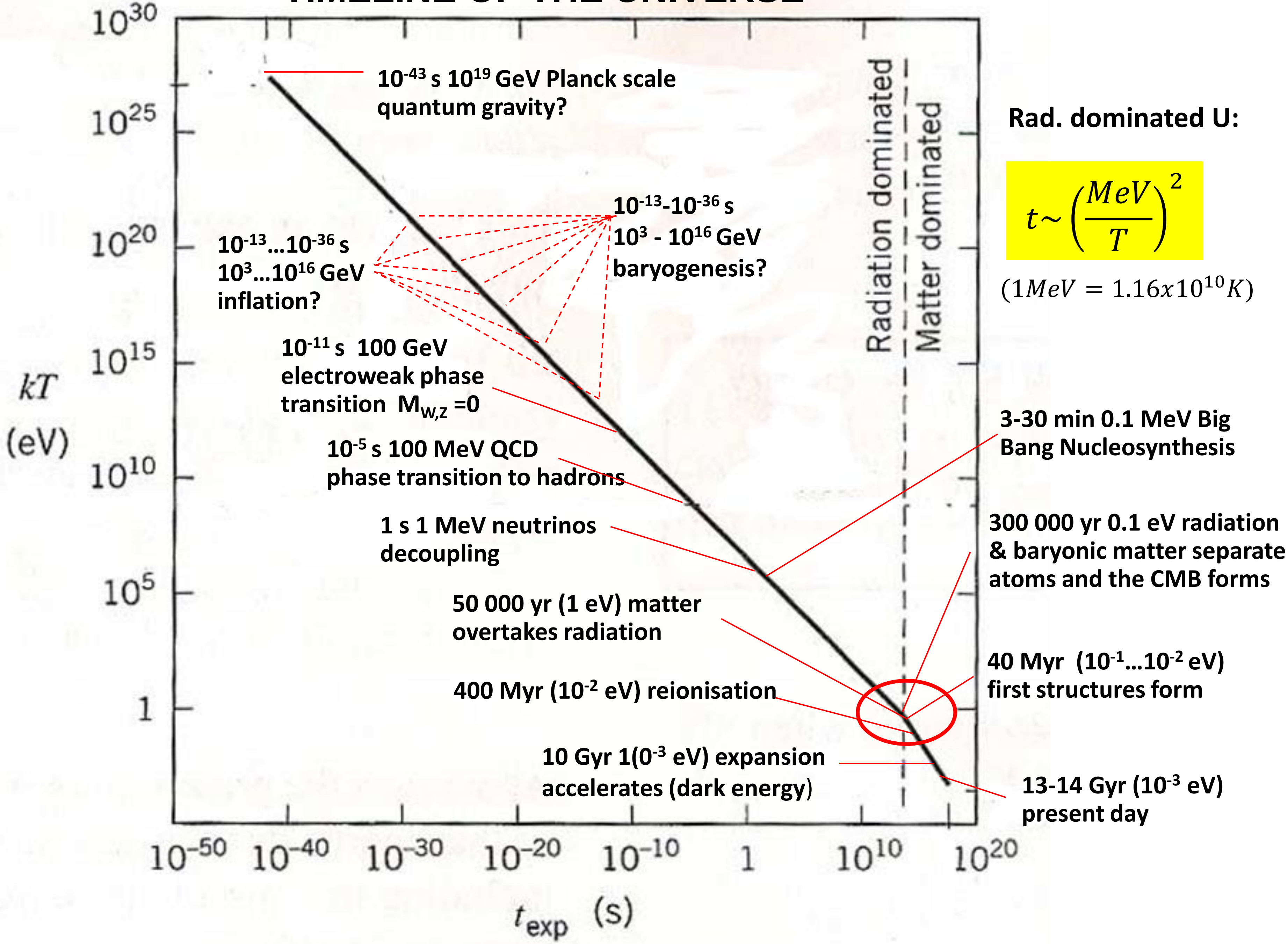
….and then we have phase transitions!

$1 \text{ eV} \approx 10^4 \text{ K}$

➡ Phase transitions happen

- when T (eV/c^2) < mass of particles
- when T (eV/c^2) < binding energy (latent heat)

TIMELINE OF THE UNIVERSE



Rad. dominated U:

$$t \sim \left(\frac{MeV}{T}\right)^2$$

$(1MeV = 1.16x10^{10}K)$

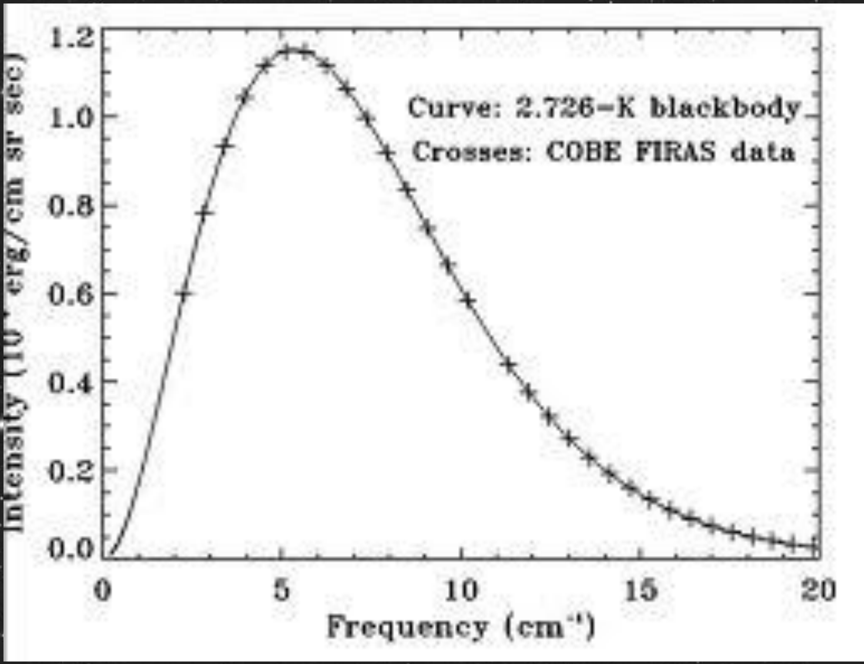
THE 2.7K COSMIC MICROWAVE RADIATION (CMB)

1965 accidental discovery by A. Penzias & R.Wilson (1978 NP)

Perfect and isotropic black body spectrum of 2.725±0.001 K

$$\epsilon(f)df = \frac{8\pi h}{c^3}\frac{f^3 df}{exp(hf/k_B T - 1)}$$

Energy density



Preservation of bb-spectrum if *f* &*T* scale with (1+z);

Explains low temperature today → matter & radiation @ 2K are not in equilibrium!

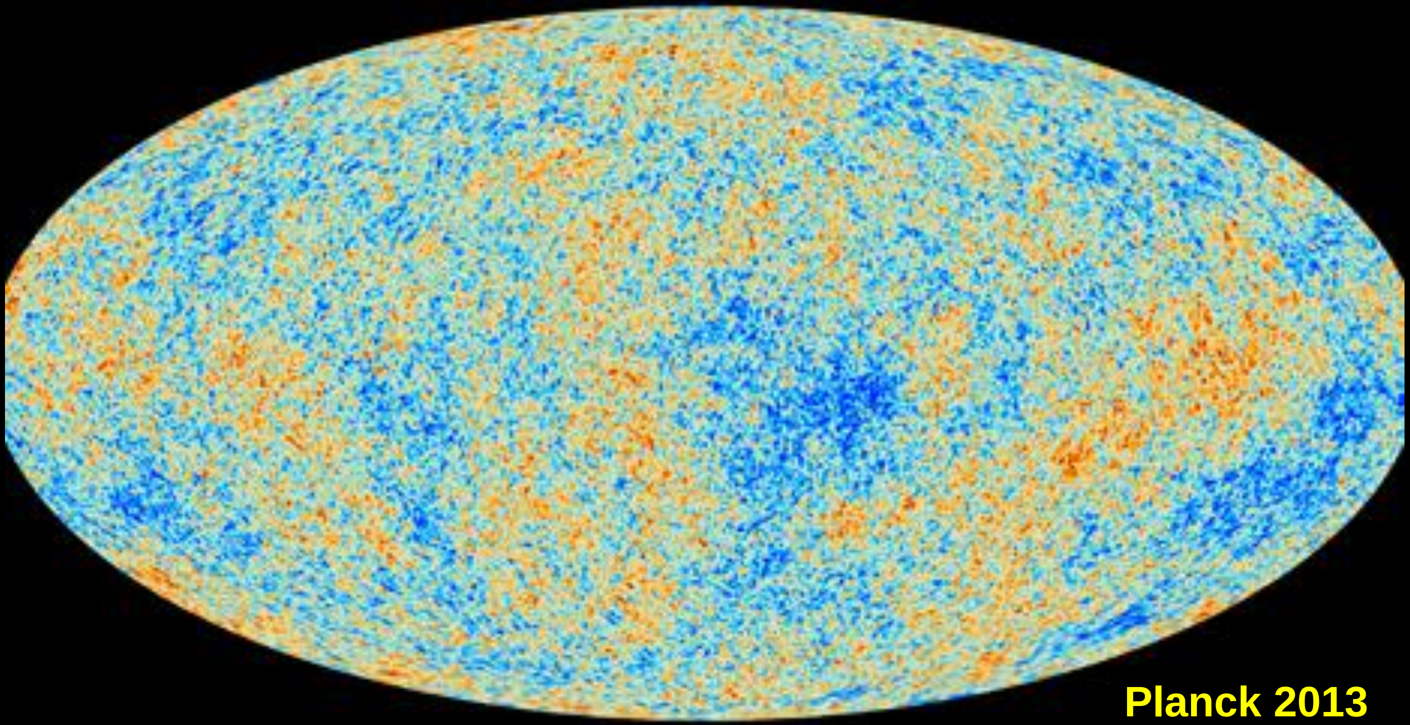
Earlier U. very much hotter → thermal equilibrium of matter & radiation

CMB is a “relic radiation” which you could see as noise at home on a CTR TV!!!

→ U. Is expanding! First proof of hot BB-theory …a revolution in cosmology

THE ANISOTROPY OF THE COSMIC MW BACKGROUND

Image of early Universe imprinted on temp. anisotropy of CMB

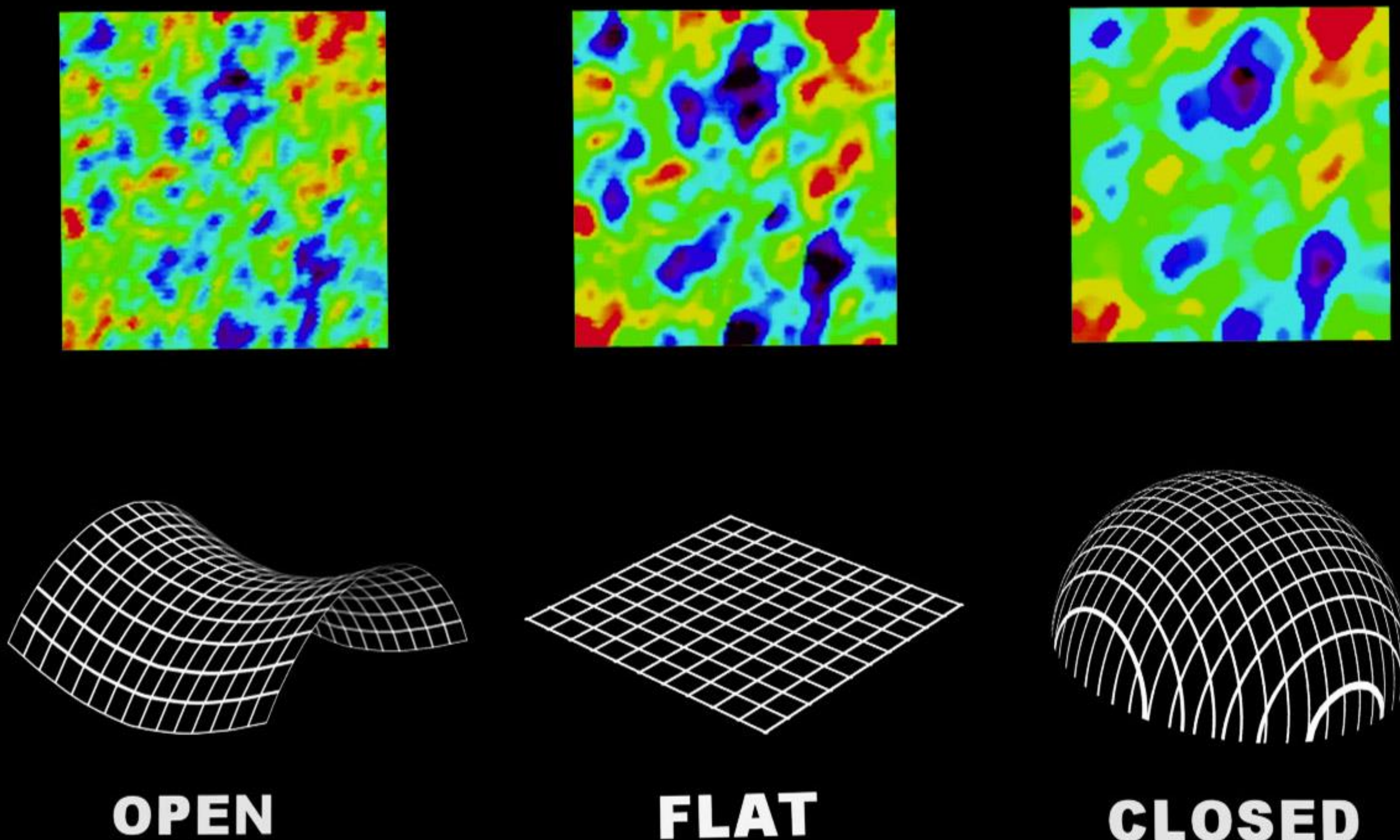


$\Delta T/T \approx 10^{-5}$

Planck 2013

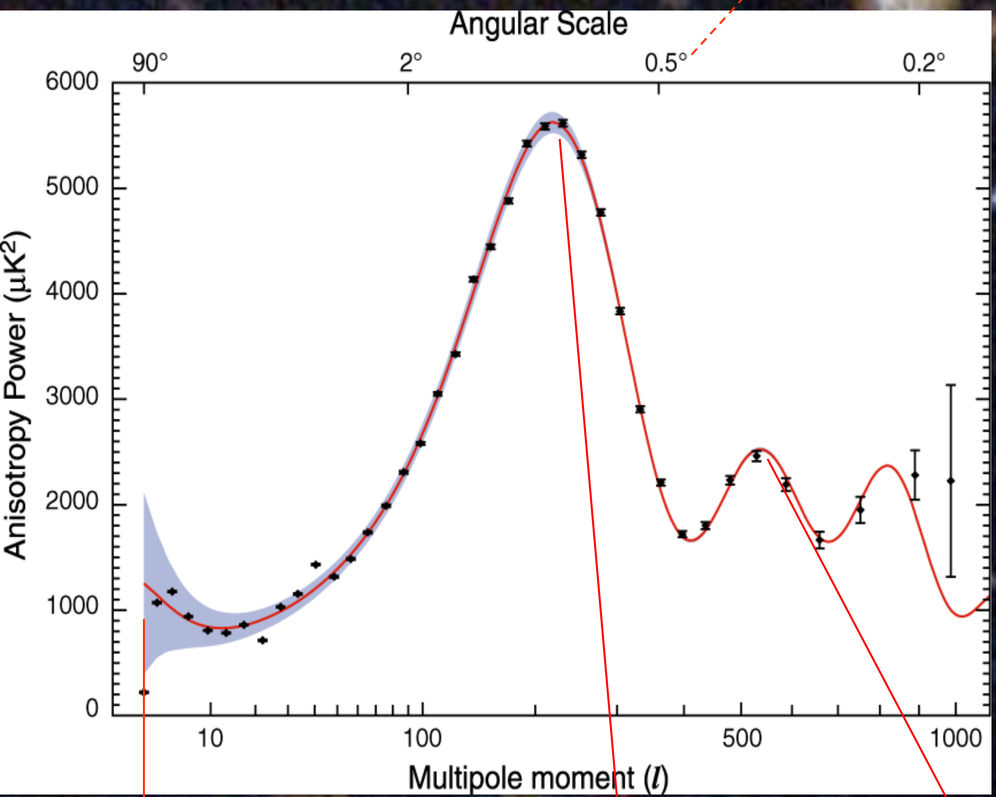
- **300 ky after BB photons decouple from matter   T ≈ 6000 K**
- **before decoupling: plasma oscill./ of photon-baryon “liquid” → sound waves**
- **CMB: snap shot of sound waves when rad. decoupled**
- **Today light red shifted by 1/1000 → 2.7 K**
- **Smallness of $\Delta T/T$ → visible Universe once causally connected → Inflation!**
- **Image of quantum fluctuation at 10^{19} GeV**

GEOMETRY OF THE UNIVERSE



Expansion in spherical harmonics of CMB temp. field

Angular diameter of the moon



Multipole development ⇔ angular scale

- ***l*** **number of cycles in the sky**
- $\theta = \pi / l$
- $l_{peak} = 200 / \sqrt{\Omega_{tot}}$
- $l_{peak} = 197 \pm 6$ **(0.9°)**

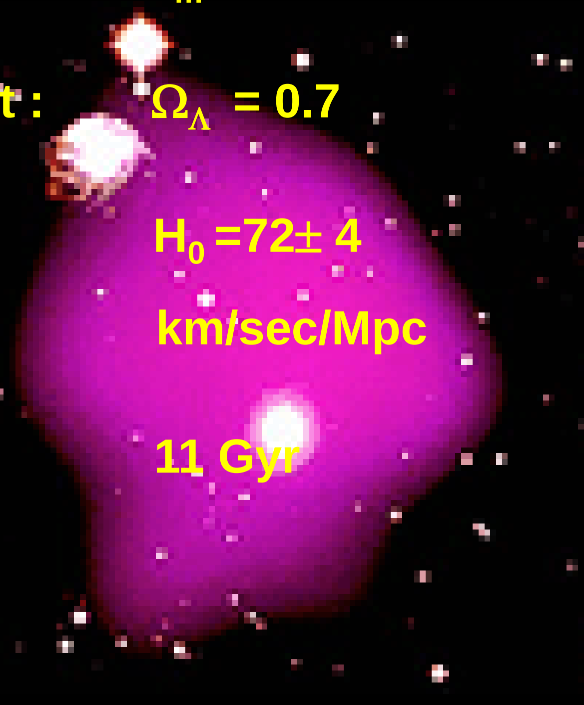
Curvature of Universe: Ω_{tot}

"Cosmic variance"

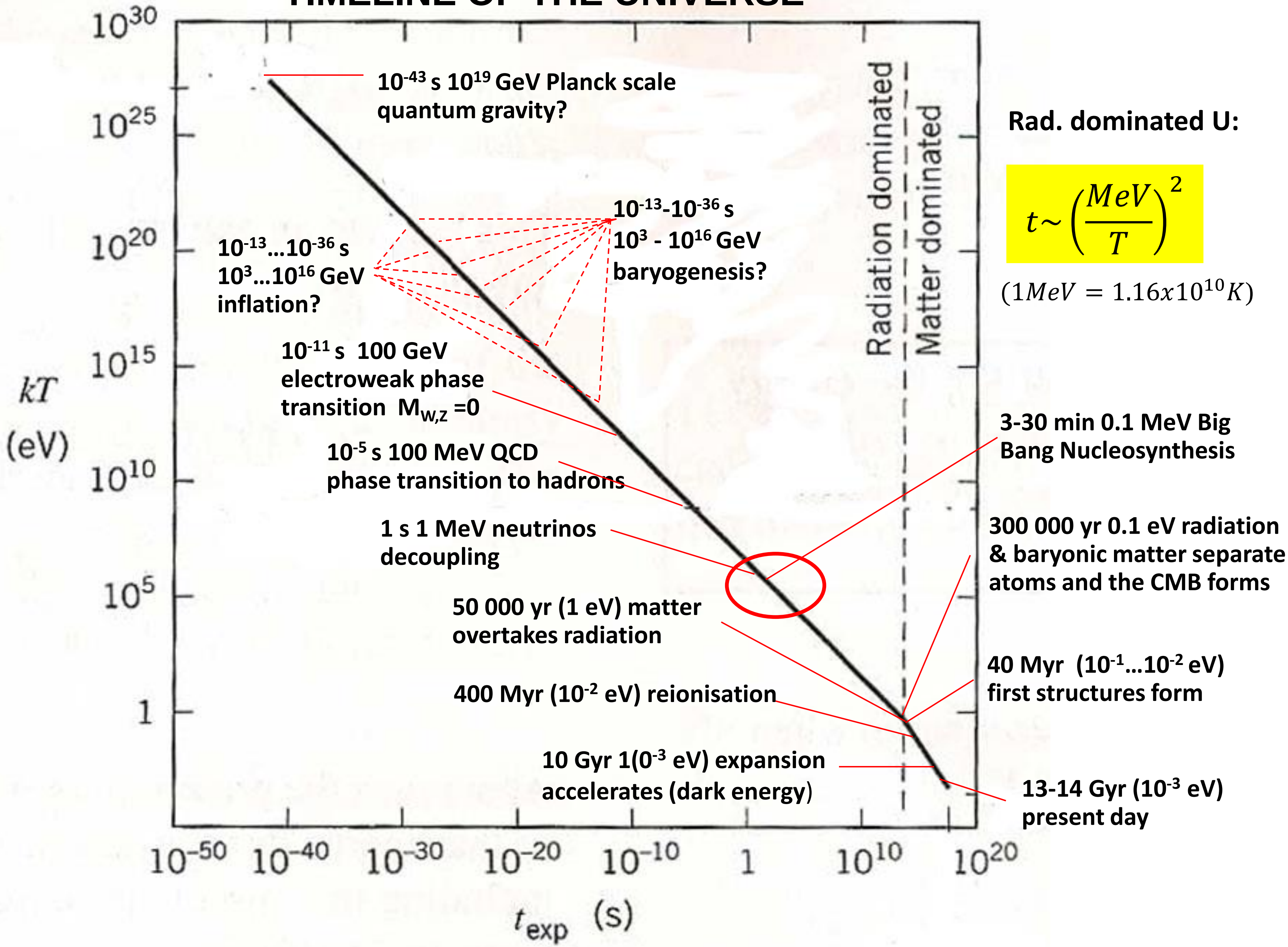
(only one Universe)

Baryon density small: Ω_b

PLANCK RESULTS:	Other :	
$\Omega_{tot} = 0.989 \pm 0.02$	Inflation :	$\Omega_{tot} = 1$
$\Omega_b = 0.049 \pm 0.007$	BBN:	$\Omega_b = 0.039$
$\Omega_{dm} = 0.262 \pm 0.007$	clusters of galaxies, grav. lensing	
	hot x-ray gas :	$\Omega_m = 0.3$
$\Omega_\Lambda = 0.69 \pm 0.02$	SN1a –redshift :	$\Omega_\Lambda = 0.7$
$H_0 = 67.3 \pm 1.2$ km/sec/Mpc	HST:	$H_0 = 72 \pm 4$ km/sec/Mpc
$T_0 = 13.81 \pm 0.058$ Gyr	HST:	11 Gyr



TIMELINE OF THE UNIVERSE



Rad. dominated U:

$$t \sim \left(\frac{MeV}{T}\right)^2$$

$$(1MeV = 1.16x10^{10}K)$$

BIG BANG NUCLEOSYNTHESIS

- Corner stone of BB cosmology → rel. abundance of ^2D, ^4He, ^3He, ^7Li
- n, p in thermal equil. e.g. : $n + \nu_e \leftrightarrow p + e^-$ until $T < 0.8$ MeV (1 sec)
- Later expansion rate > interaction rate $\Gamma_{np} < H$

1 sec

$$\frac{N_n}{N_p} \propto exp\left(-\frac{m_n - m_p}{k_B T}\right) \propto exp\left(-\frac{1.3MeV}{0.8MeV}\right) = \frac{1}{5}$$

(Maxwell-Boltzmann)

$$\left.\begin{array}{l} p + n \rightarrow {}^2D + \gamma \\ {}^2D + p \rightarrow {}^3He + \gamma \\ {}^3He + {}^2D \rightarrow {}^4He + p \\ {}^2D + {}^2D \rightarrow {}^3T + p \\ {}^3T + {}^4He \rightarrow {}^7Li + \gamma \end{array}\right\}$$

- But 10^9 γ/p and important high energy tail in γ- distribution
- Nuclei broken apart again by photo-fission until $T = 0.06$ MeV (314 sec)
- …in the meantime neutrons decay with $\tau = 824$ sec

314 sec

$$\frac{N_n}{N_p}(314s) = \frac{1}{5} exp\left(-\frac{314s}{884s}\right) = \frac{1}{7{,}3}$$

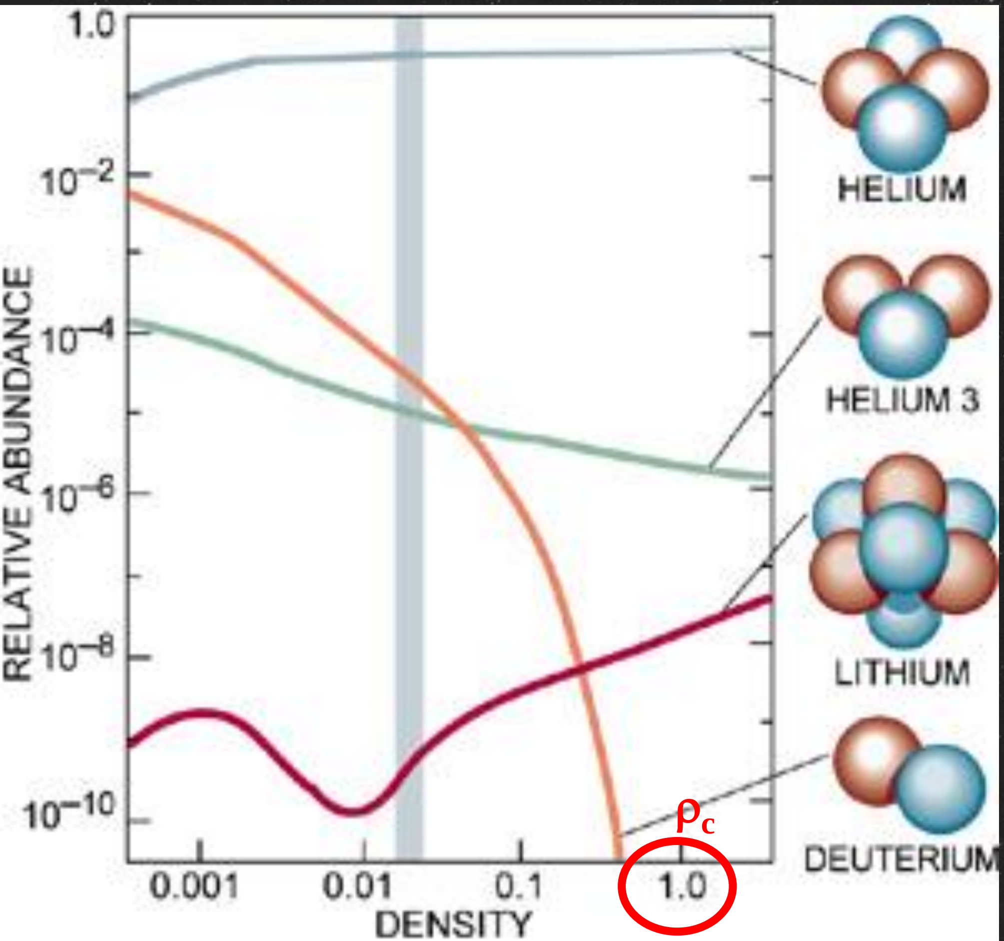
- Since all neutrons end up in ^{4}He:

$$Y_{He} = \frac{4 \cdot N_n/2}{N_n + N_p} = 0.24$$

rel. abundance

Ω_B FROM BIG BANG NUCLEOSYNTHESIS

- ^4He ^2D, ^3He, ^7Li (0.24, ~10^{-4}, 10^{-5}, 10^{-10})
- no nuclei with A =5, 8 end of BBN
- heavier nuclei in stars @ t > 10 My



BBN abundances depend on:

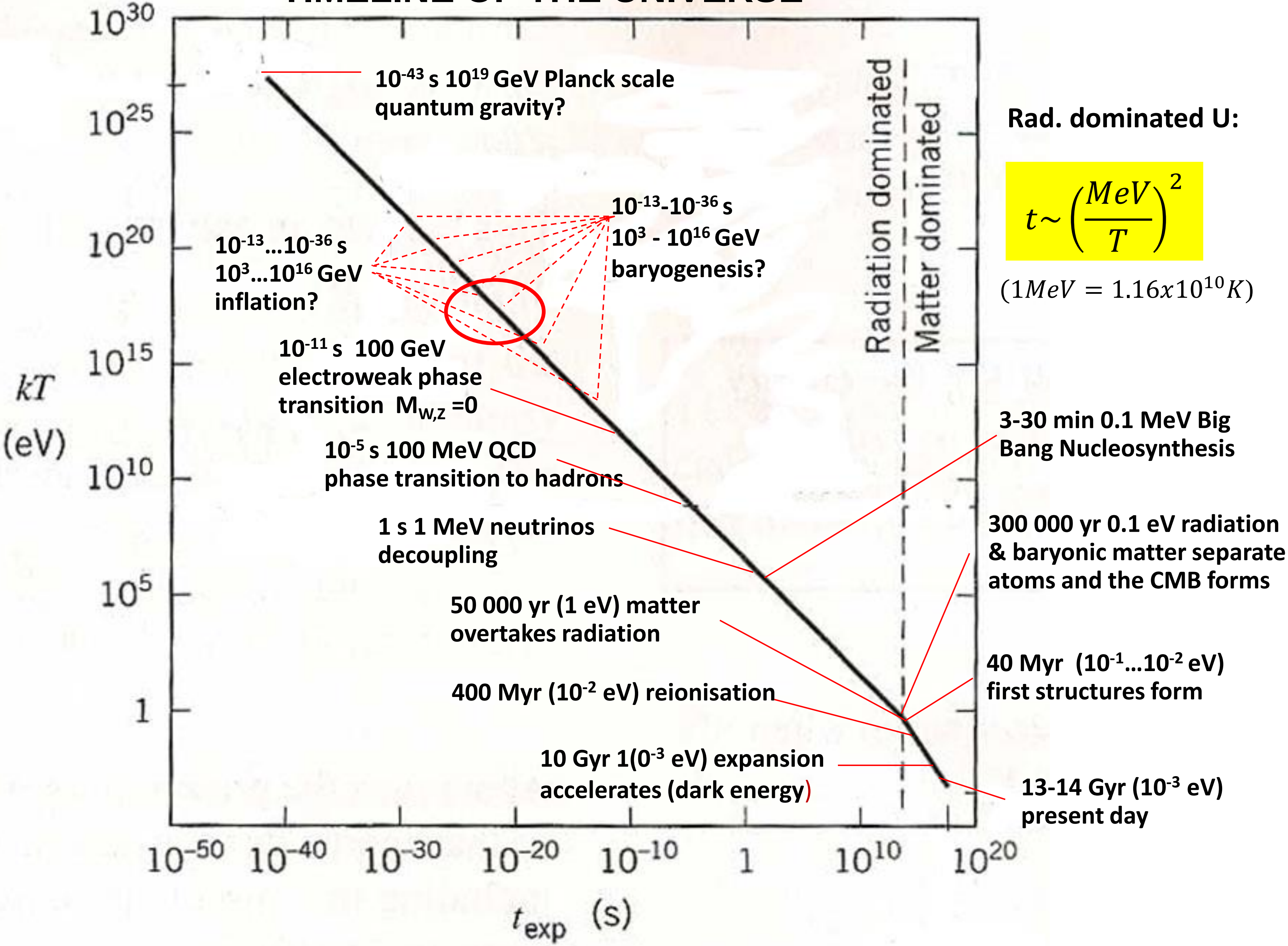
- # of neutrino flavors → exp.rate
- ρ_b or Ω_b
- *T and* ρ_γ …

Light el. abund. consistent over O(9) with:

$\Omega_b = 0.04 \pm 0.007$

Non-baryonic dark matter! !

TIMELINE OF THE UNIVERSE



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THE MATTER - ANTIMATTER ASYMMETRY

Suppose:

- U. started with equal abundance $e^+, e^-, q, \bar{q} \ldots \rightarrow$ C & CP symmetry.
- $q, \bar{q} \rightarrow p\, \bar{p},$ in perfect sym. equal amount
- at some point U too cold for $p\bar{p} \Leftrightarrow 2E_\gamma$ ($E_\gamma < m_p$ ...due to expansion)

$$p + \bar{p} \rightarrow \gamma + \gamma \qquad p\ \bar{p} \text{ depleted}$$

Later..

$$e^+ + e^- \rightarrow \gamma + \gamma \qquad e^+e^- \text{ depleted}$$

Only γ's remain!

...unless at some moment excess of protons!

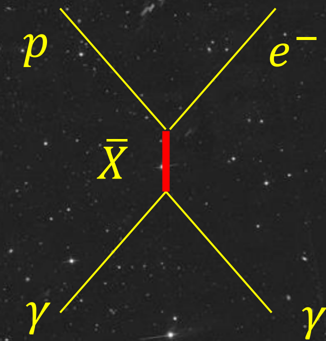
Another unsolved question: where did the entropy at the beginning come from?

BARYO -/ LEPTO - GENESIS

U expands adiabatically → net # of particles constant → S constant

Today: $10^{9-10}\gamma/p$ $10^{9}p/\bar{p}$

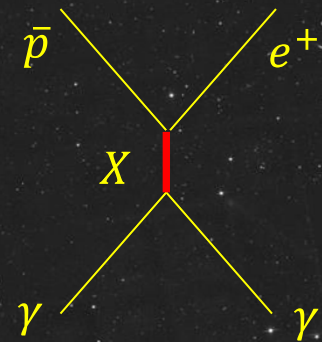
➡ 10^{90} particles (γ,….) in Universe → ~10^{80} p



Violates *B*, *L*

3 conditions to create baryon asymmetry *

- Violation of B # conservation $|N_p - N_{\bar{p}}| \neq 0$
- Violation of CP symmetry CP $|p> \rightarrow |\bar{p}>$
- Deviation of strict thermal equilibrium

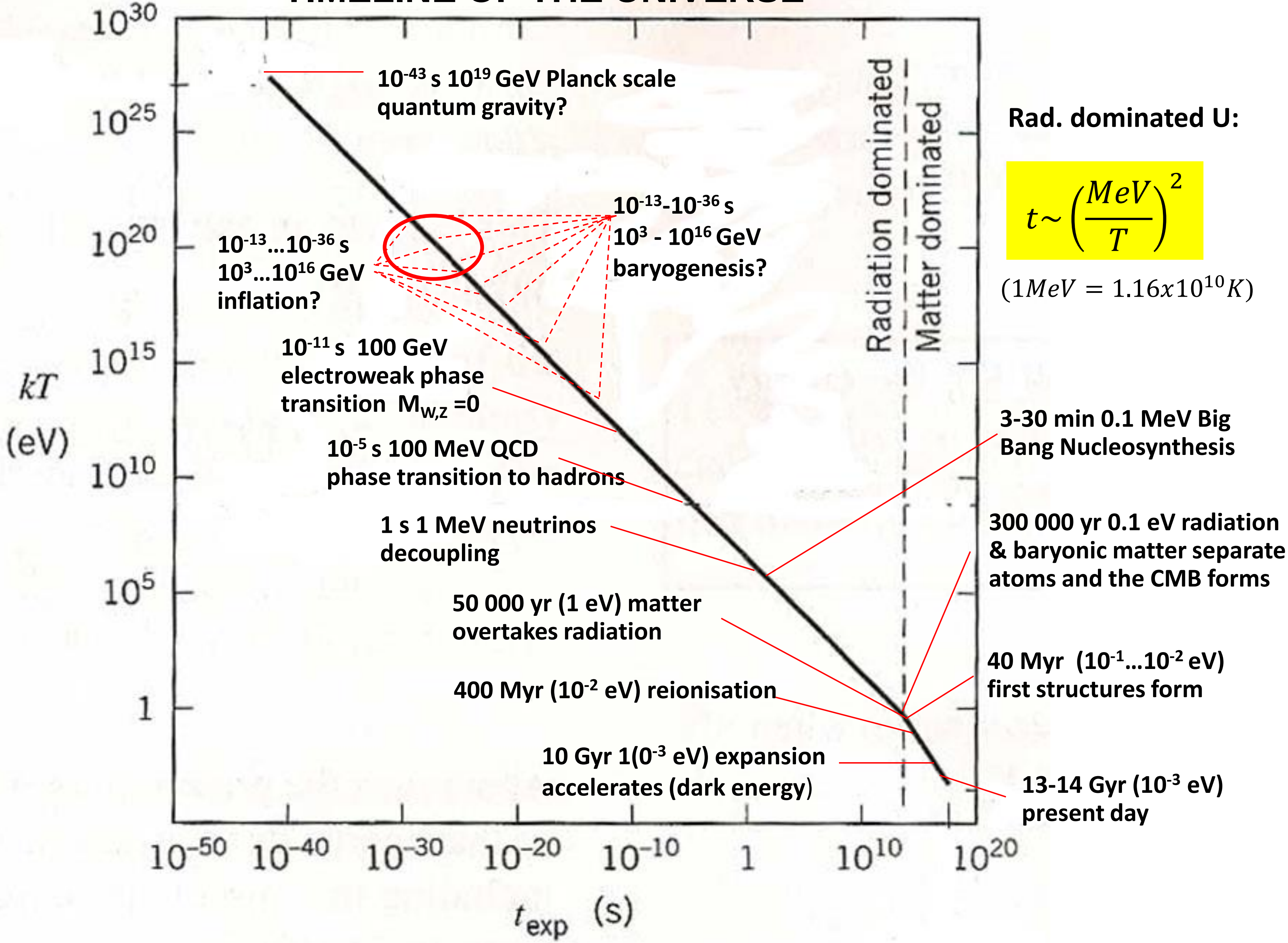


One possibility: new interaction → with lepto-quarks X

…proton should be unstable…$T_{1/2}$ >10^{34} y

*A. Sacharov (1967), S. Dimopoulos, L, Susskind (1980)

TIMELINE OF THE UNIVERSE



Rad. dominated U:

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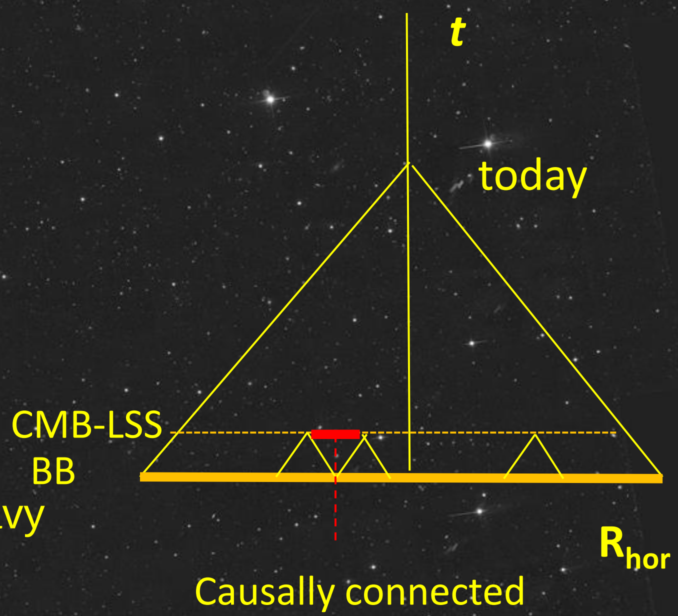
PROBLEMS WITH BIG BANG THEORY

1) Flatness problem

any deviation from Ω_{tot} = 1 grows $|\Omega_{tot} - 1| \propto t^{1/2}, t^{2/3}$

$t_{BBN} \sim 1 \ \text{sec} \quad \rightarrow \quad |\Omega_{tot} - 1| < 10^{-18}$

$t_{ew} \sim 10^{-12} \ \text{sec} \quad \rightarrow \quad |\Omega_{tot} - 1| < 10^{-30}$



2) Horizon problem

how to explain the isotropy of the CMB

3) Relic particle problem

GUT theories predict large abundance of heavy particles , e.g. magnetic monopoles

M_{mm} = O (10^{16} GeV) → non- rel. during rad. era

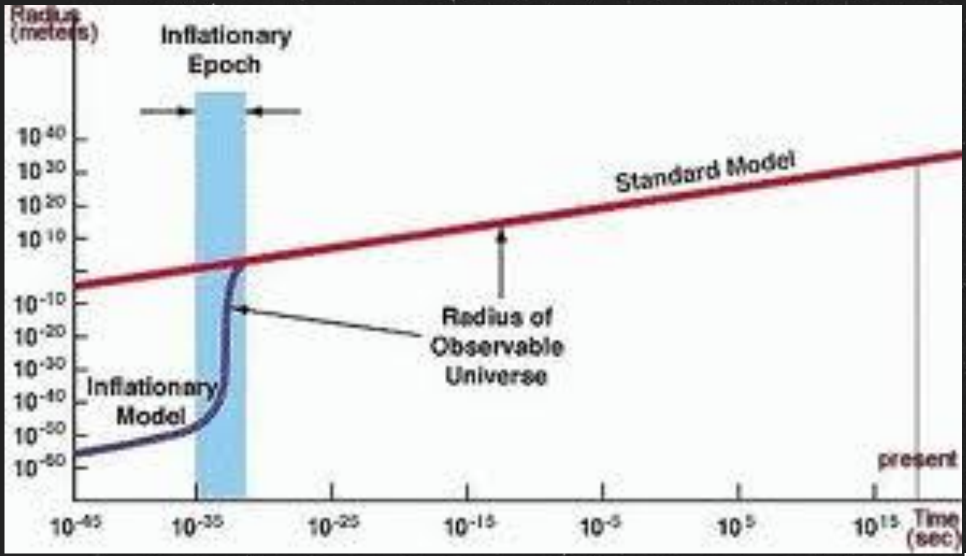
…would have dominated radiation era

4) Large scale structure problem

how to explain the observed large scale structure in the galaxy distributions?

INFLATION

A. Guth 1981: Inflationary expansion of U. at GUT scale



- Scalar field creates a "cosm. constant"
- exponential growth of space
- ~ 60 e-foldings w/in 10^{-34} sec
- Like super-cooled liquid
- Phase transition (lat. Heat) creates particles

- All curvature smoothed out
- Relic particles diluted
- Quantum fluctuations $\rightarrow$ seeds of later large scale structure