ESHEP 2018, Maratea (Italy)

Cosmology and Dark Matter
Lecture 1

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WHY SHOULD A PARTICLE PHYSICIST
CARE ABOUT COSMOLOGY?

- cosmology provides insight on particle physics at **energy scales** impossible to probe on Earth

- cosmology provides alternative/competitive **constraints** on particle physics properties (neutrinos, dark matter ...)

- cosmology provides **motivations/completions** of models for physics beyond the Standard Model (inflation, baryogenesis, dark matter...)

> Outline

- **LECTURE 1:**

The Universe around us. Dynamics. Energy Budget.

The Standard Model of Cosmology:
the 3 pillars (Expansion, Nucleosynthesis, CMB).

- **LECTURE 2:**

Dark Energy.
Dark Matter as a thermal relic. Searches for WIMPs.

- **LECTURE 3:**

Shortcomings of Big Bang cosmology. Inflation. Baryogenesis

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Natural Units

$$[\text{Energy}] = [\text{Mass}] = [\text{Temperature}] = [\text{Length}]^{-1} = [\text{Time}]^{-1}$$

$$\hbar = c = k_B = 1$$

from which it follows that:

$$1 = \hbar \cdot c \simeq 197.33 \text{ MeV} \cdot \text{ fm} = 1.9733 \times 10^{-14}\text{GeV} \cdot \text{cm}$$

$$\begin{aligned} 1\text{GeV}^{-1} &= 1.9733 \times 10^{-14}\text{cm} = 1.9733 \times 10^{-14}\frac{\text{cm}}{c} \\ &= 6.5822 \times 10^{-25}\text{s} \end{aligned}$$

the fundamental mass scale of gravitational interactions $\quad M_P = 1.22 \times 10^{19} \text{ GeV}$

astronomical distances $\quad 1 \text{ pc} = 3.08 \times 10^{18} \text{ cm}$

> The 3 Pillars of Standard Cosmology

From observations of the Universe around us:

- The Universe is **expanding**

- The abundances of light element are in agreement with **Big Bang Nucleosynthesis**

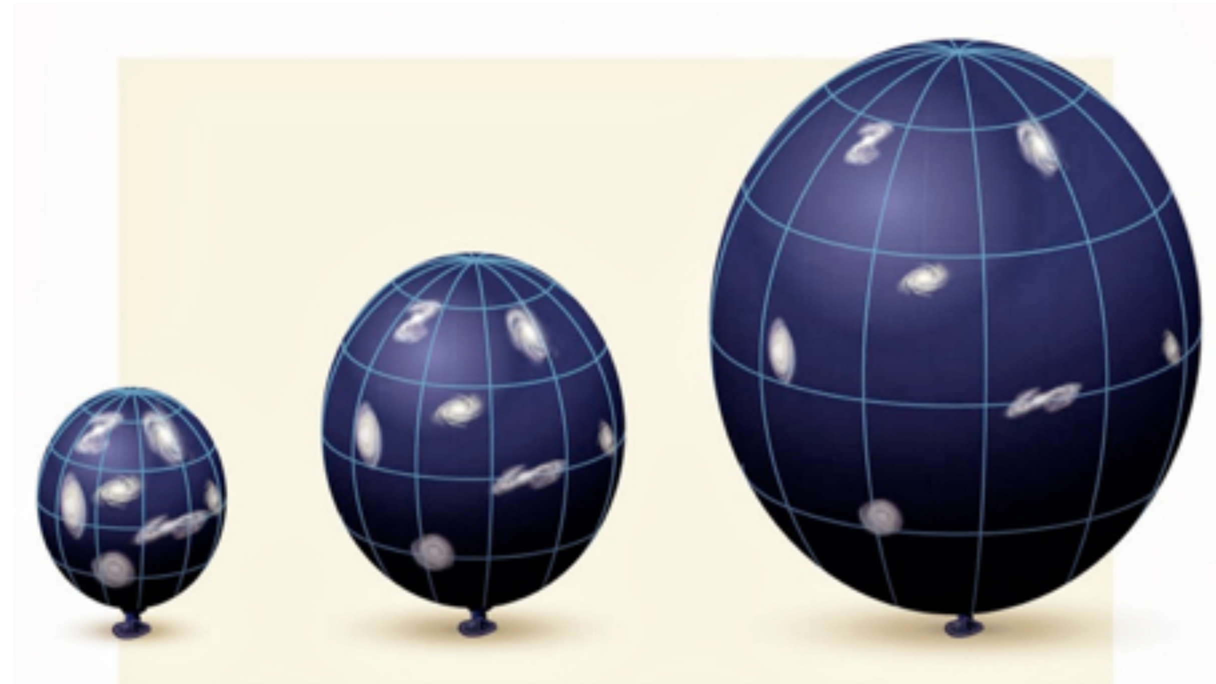
- The Universe is filled by blackbody radiation (**Cosmic Microwave Background**)

> Expansion

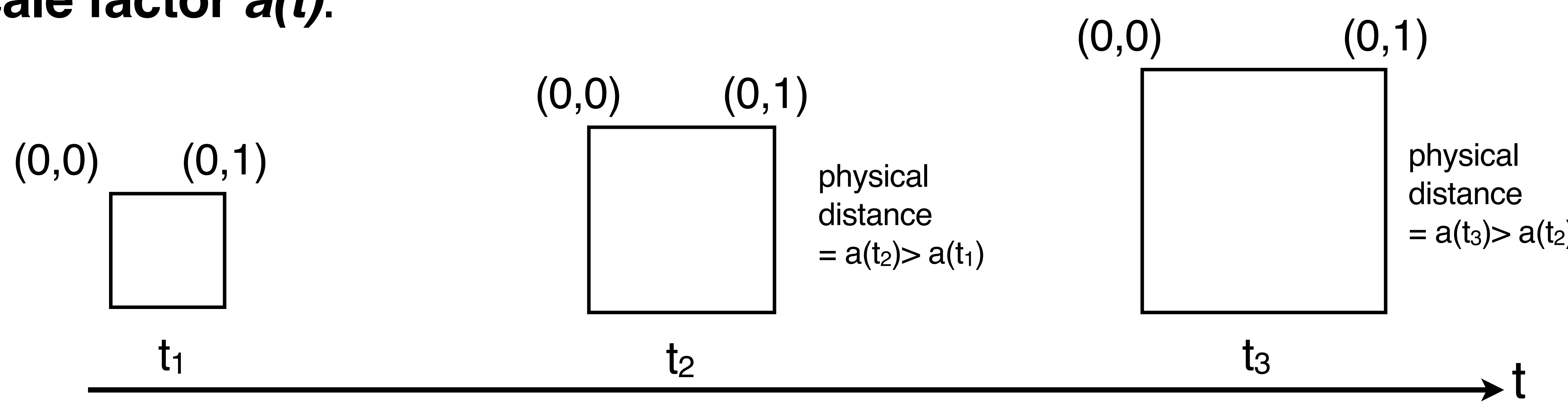
in the past, the relative physical distance between any two points was smaller

distant galaxies are observed with red-shifted spectra

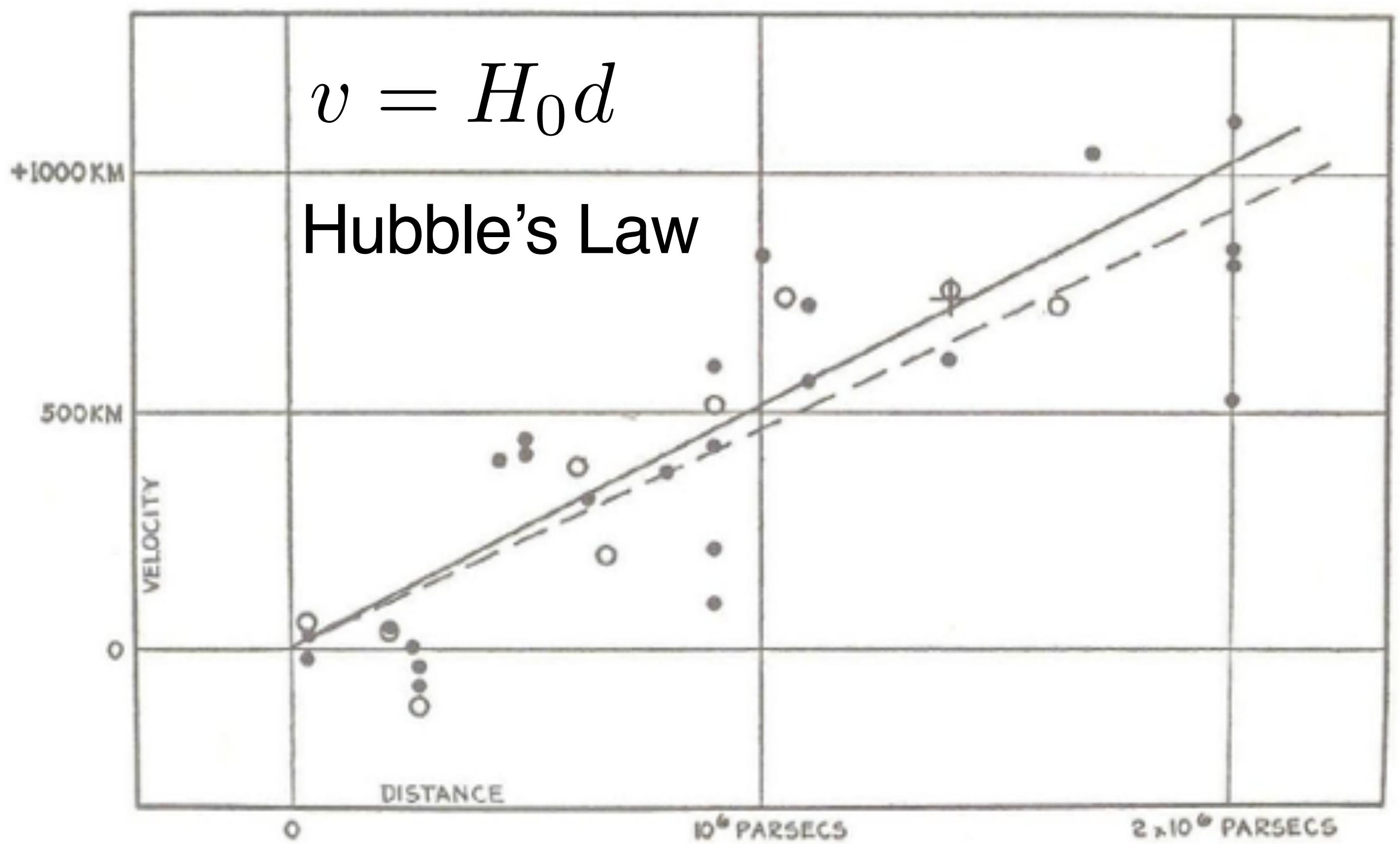
→ Universe is expanding

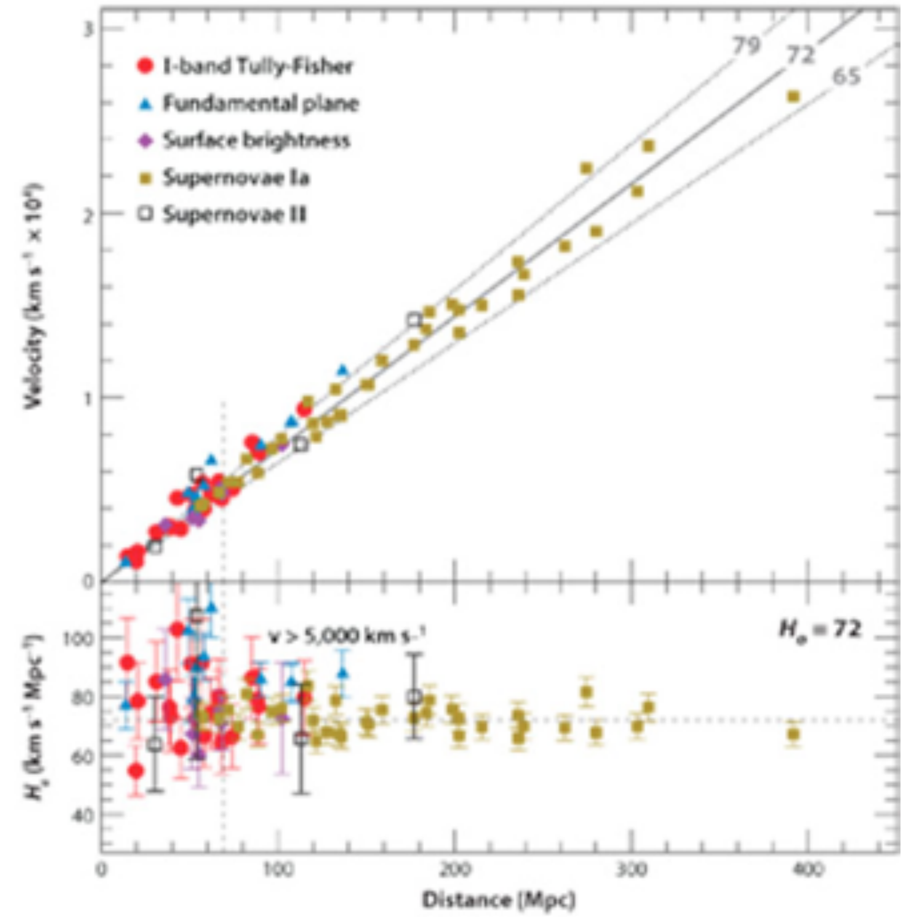


in an expanding universe the physical distances between 2 points get larger. they are proportional to a factor measuring the expansion of the universe: the **scale factor *a(t)***.



> Kinematics





for a photon of given wavelength: $$v = \frac{\lambda_{\text{observation}} - \lambda_{\text{emission}}}{\lambda_{\text{emission}}} \equiv z$$

Hubble's Law $z = H_0 d$ (for z<<1)

$$1 + z \equiv \frac{\lambda_{\text{observation}}}{\lambda_{\text{emission}}} = \frac{a(t_0)}{a(t_e)}$$

redshift measures how much the Universe has expanded since the emission.

> Kinematics

$$1+z \equiv \frac{\lambda_{\text{observation}}}{\lambda_{\text{emission}}} = \frac{a(t_0)}{a(t_e)}$$

Taylor-expand around today t_0: $$\frac{a(t)}{a(t_0)} = \overbrace{1 + H_0(t-t_0)}^{\text{Hubble law}} - \frac{1}{2} q_0 H_0^2 (t-t_0)^2 + \cdots$$

$$H_0 \equiv \left.\frac{\dot a}{a}\right|_{t_0}$$ local expansion rate today ("Hubble constant")

$$q_0 \equiv -\left.\frac{\ddot a}{aH_0^2}\right|_{t_0} = -\left.\frac{\ddot a a}{\dot a^2}\right|_{t_0}$$ deceleration parameter (deviation from Hubble law)

Measurements:

$$1/H_0 \simeq 1.4 \times 10^{10}\,\text{yrs} \simeq 4.3\,\text{Gpc} \simeq 1.3 \times 10^{26}\,\text{m}$$

"Hubble time"
"Hubble length"

$$h \equiv \frac{H_0}{100\,\text{km s}^{-1}\,\text{Mpc}^{-1}} \simeq 0.67$$

> The Universe Around Us

HOMOGENEITY: the distribution of matter in the Universe looks homegenous (= ~constant density) on large scales (> 100 Mpc)

(i.e.: 2-point function of galaxies and galaxy clusters << 1/H0)

ISOTROPY: if the expansion of the universe were not isotropic, we would observe large temperature anisotropies in the CMB (more later...).

Rotation invariance is around any point of the Universe, so it is isotropic.

Cosmological Principle: the Universe is **homogeneous** and **isotropic** (no observer is special, no preferred directions)

> FRW

Build a metric for a **homogeneous** and **isotropic** Universe

Friedmann-Robertson-Walker

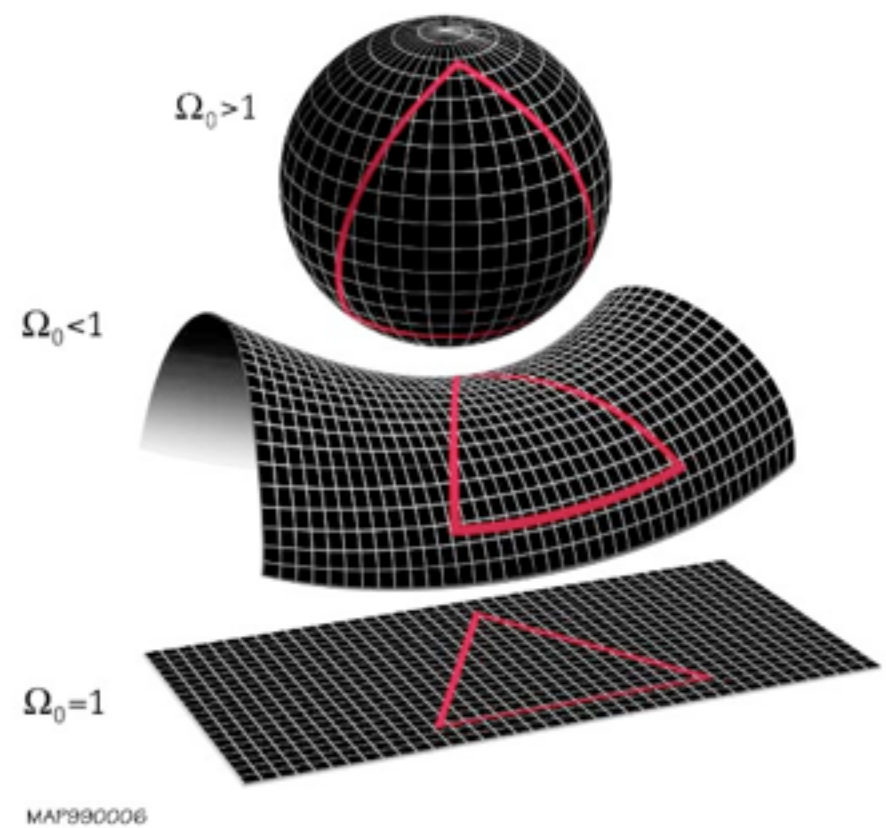
$$ds^2 = dt^2 - a(t)^2 \left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2) \right]$$

$$k = \begin{cases} +1 \\ 0 \\ -1 \end{cases}$$

positive spatial curvature

zero spatial curvature

negative spatial curvature



scalar curvature of spatial slices

$$|{}^3\mathcal{R}| = \frac{6|k|}{a^2} \equiv \frac{6}{R^2_{\rm curv}}$$

Rcurv is a sort of curvature radius of the Universe

> Dynamics

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G_N T_{\mu\nu} + \Lambda g_{\mu\nu}$$ **Einstein's Equations**

Energy-momentum tensor for a perfect fluid: $$T_{\mu\nu} = (\rho + p) u_\mu u_\nu - p g_{\mu\nu}$$

p : pressure
ρ : energy density

in the *comoving frame* (moving with the fluid)

$$u^0 = 1, \vec{u} = 0 \qquad T_{\mu\nu} = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & -p & 0 & 0 \\ 0 & 0 & -p & 0 \\ 0 & 0 & 0 & -p \end{pmatrix}$$

0-component of Energy-Momentum conservation ($\nabla_\mu T^{\mu\nu} = 0$) in expanding Universe

$$\nabla_\mu T^{\mu 0} = 0 \Longrightarrow \dot{\rho} + 3\frac{\dot{a}}{a}(\rho + p) = 0$$

same equation

$dU + pdV = TdS$ 1st law of thermodyn.
entropy cons. d*S=0*

$$d(a^3\rho) + pd(a^3) = 0$$

> Fluids

$$p = w\rho \qquad (\dot{w} = 0)$$

$$\dot{\rho} + 3(1+w)\frac{\dot{a}}{a}\rho = 0 \;\Rightarrow\; \frac{\dot{\rho}}{\rho} = -3(1+w)\frac{\dot{a}}{a} \;\Rightarrow\; \rho \propto a^{-3(1+w)}$$

radiation	$w = 1/3 \implies \rho \propto a^{-4}$		(radiation domination - RD)
dust	$w = 0 \implies \rho \propto a^{-3}$		(matter domination - MD)
vacuum energy	$w = -1 \implies \rho \propto \mathrm{const}$		(vacuum energy domination)

- rest-mass energy must be constant
- volume ~ a^3

$\Rightarrow$ energy density of matter ~ a^{-3}

for radiation, energy density has a further 1/a due to redshift so ~ a^{-4}

> Friedmann Equation

- (00) component of the Einstein Eq. for FRW:

$$H^2 = \frac{8\pi G_N}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3}$$ **Friedmann Equation**

Hubble parameter $H \equiv \dot{a}/a$ is <u>not</u> a constant

- (ii) component of the Einstein Eq. $\frac{\ddot{a}}{a} = -\frac{4\pi G_N}{3}(\rho + 3p) + \frac{\Lambda}{3}$

does not give anything new wrt Friedmann equation + energy-mom conservation

$$\boxed{\begin{aligned} H^2 &= \frac{8\pi G_N}{3}\rho_{\rm tot} - \frac{k}{a^2} \\ \dot{\rho} + 3H(\rho + p) &= 0 \end{aligned}}$$

$$\rho_\Lambda \equiv \frac{\Lambda}{8\pi G_N}$$

$$\rho_{\rm tot} \equiv \rho + \rho_\Lambda$$

this system of eqns encodes the evolution of the Universe and its constituents

> Cosmological Dynamics

what is the evolution of the scale factor?

$$\boxed{\begin{aligned} H^2 &= \frac{8\pi G_N}{3}\rho_{\rm tot} - \frac{k}{a^2} \\ \dot\rho + 3H(\rho+p) &= 0 \end{aligned}}$$

critical density $\rho_c \equiv \dfrac{3H^2}{8\pi G_N}$

today
$$\begin{aligned} \rho_c &\simeq 1.88\times 10^{-29} h^2 \,\mathrm{g\ cm^{-3}} \\ &\simeq 1.05\times 10^{-5} h^2\, \mathrm{GeV cm^{-3}}. \end{aligned}$$

$$\Omega_i \equiv \frac{\rho_i}{\rho_c} \qquad \Omega_k \equiv -\frac{k}{a^2H^2} \qquad \Omega_\Lambda \equiv \frac{\rho_\Lambda}{\rho_c} = \frac{\Lambda}{3H^2}$$

$$\Omega_m + \Omega_r + \Omega_\Lambda + \Omega_k = 1$$

$$\left\{\begin{aligned} &\left(\frac{\dot a}{a}\right)^2 = H_0^2\left(\frac{a}{a_0}\right)^{-3(1+w)} \\ &y \equiv a/a_0 \end{aligned}\right.$$

(exercise) $\longrightarrow$ $\dot y = H_0 y^{-\frac{3(1+w)}{2}+1}$ $\longrightarrow$ $y^{\frac12+\frac32 w}dy = H_0 dt$

$\longrightarrow$

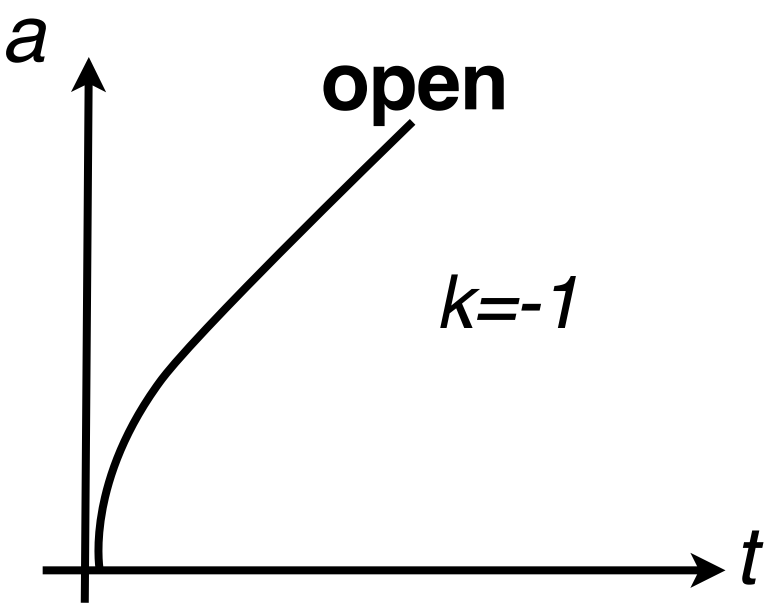
$a(t) \propto t^{\frac{2}{3(1+w)}}$ $\quad (w\neq -1)$ $\longrightarrow$

$a(t) \propto e^{H_0 t}$ $\quad (w=-1)$
vacuum energy

dust (*w=0*): $a(t)\propto t^{2/3}$

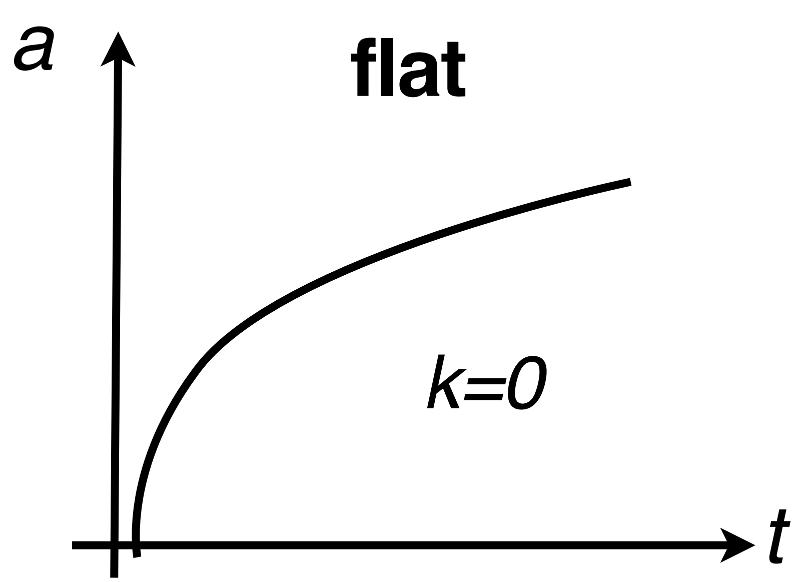
radiation (*w=1/3*): $a(t)\propto t^{1/2}$

> Cosmological Dynamics

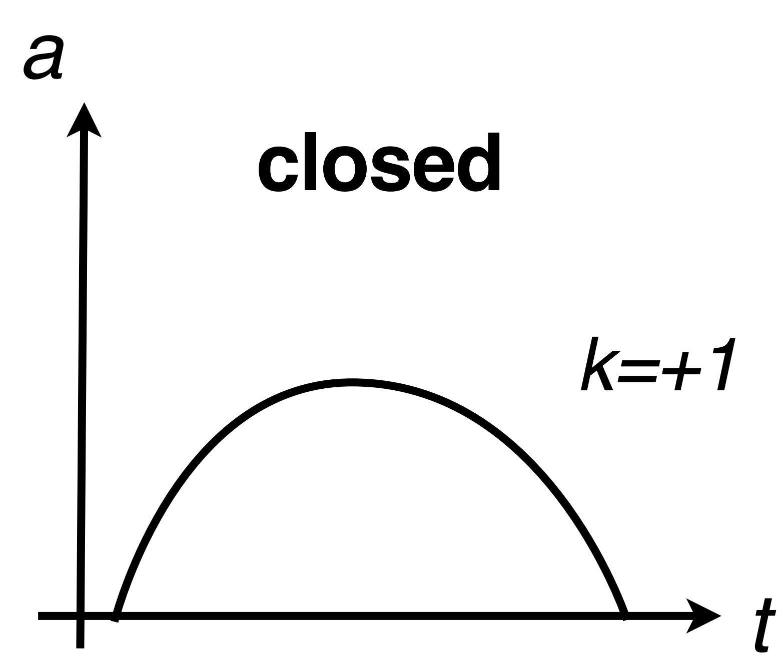


$$H^2 = \frac{8\pi G_N}{3}\rho_{\rm tot} - \frac{k}{a^2}$$

$$\dot{\rho} + 3H(\rho + p) = 0$$



$$R_{\rm curv} = \frac{1}{H\sqrt{|\Omega_k|}}$$



$\rho_{\rm tot} = \rho_c$ <--> k=0 <--> **FLAT** universe

> Energy Budget

Picture of the Universe today (from PLANCK 2015)

$$h = 0.6774 \pm 0.0046$$

$$\Omega_m h^2 = 0.14170 \pm 0.00097 \left\{ \begin{array}{l} \Omega_b h^2 = 0.02230 \pm 0.00014 \\ \Omega_{\rm CDM} h^2 = 0.1188 \pm 0.0010 \end{array} \right.$$

$$\Omega_k = 0.0008^{+0.0040}_{-0.0039} \qquad \Omega_\Lambda = 0.6911 \pm 0.0062$$

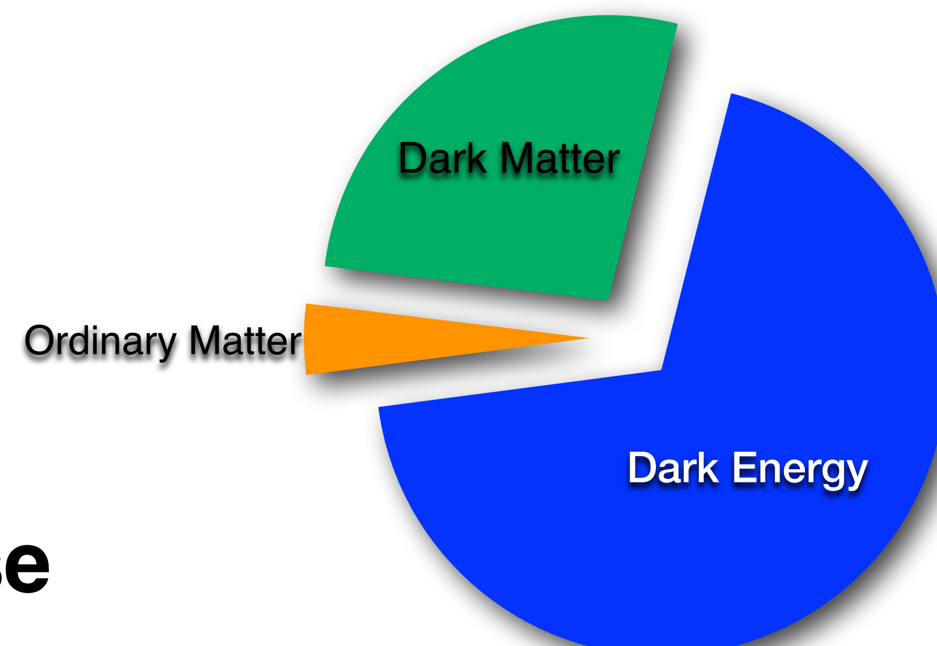
$\text{curvature} \simeq 0\%$ → FLAT universe

$$\text{matter} \simeq 31\% \left\{ \begin{array}{l} \text{baryonic matter} \simeq 4\% \\ \text{dark matter} \simeq 27\% \end{array} \right.$$

what we know

$\text{vacuum energy} \simeq 69\%$ →

what we
don't know



Energy budget of the Universe

> Age of the Universe

almost irrelevant contribution from very early (uncertain) times:
we can compute the age of the universe from when it started RD or MD eras

$$\frac{da}{dt} = Ha \qquad\qquad H^2 = H_0^2\left[\Omega_r^0\left(\frac{a_0}{a}\right)^4 + \Omega_m^0\left(\frac{a_0}{a}\right)^3 + \Omega_k^0\left(\frac{a_0}{a}\right)^2 + \Omega_\Lambda^0\right]$$

$$\longrightarrow \quad dt = \frac{da}{aH_0}\frac{1}{\left[\Omega_r^0\left(\frac{a_0}{a}\right)^4 + \Omega_m^0\left(\frac{a_0}{a}\right)^3 + \Omega_k^0\left(\frac{a_0}{a}\right)^2 + \Omega_\Lambda^0\right]^{1/2}}$$

Age of the Universe estimate: $t \sim 13$ Gyrs

MD universe

$$\Omega_r^0 = \Omega_k^0 = \Omega_\Lambda^0 = 0\,,\Omega_m^0 = 1 \xrightarrow{\text{exercise}} t_0 = \frac{2}{3}\frac{1}{H_0} \simeq 9\times 10^9 \text{ yrs}$$

too young!

$$\Omega_r^0 = 0, \Omega_k^0 = 0, \Omega_m^0 = 1 - \Omega_\Lambda^0 = 0.3 \xrightarrow{\text{exercise}} t = \frac{2}{3H_0\sqrt{\Omega_\Lambda^0}}\sinh^{-1}\sqrt{\frac{\Omega_\Lambda^0}{1-\Omega_\Lambda^0}\left(\frac{a}{a_0}\right)^3}$$

$$\longrightarrow \quad t_0 = \frac{2}{3H_0\sqrt{\Omega_\Lambda^0}}\sinh^{-1}\sqrt{\frac{\Omega_\Lambda^0}{1-\Omega_\Lambda^0}} \simeq 0.96\frac{1}{H_0} \longrightarrow t_0 \simeq 1.3\times 10^{10}\text{yrs}$$

OK! Λ makes the universe older

> Distance-Redshift Relation

Friedmann: $$H^2 = H_0^2\left[\Omega_r^0\left(\frac{a_0}{a}\right)^4 + \Omega_m^0\left(\frac{a_0}{a}\right)^3 + \Omega_k^0\left(\frac{a_0}{a}\right)^2 + \Omega_\Lambda^0\right]$$

$$a_0/a = 1+z$$

$$\longrightarrow \quad H^2 = H_0^2\left[\Omega_r^0(1+z)^4 + \Omega_m^0(1+z)^3 + \Omega_k^0(1+z)^2 + \Omega_\Lambda^0\right]$$

light $$ds = 0 \longrightarrow \begin{array}{l} dr = dt/a \\ \dfrac{da}{dt} = Ha \end{array} \longrightarrow \quad dr = \frac{da}{a^2 H}$$

$$\longrightarrow \quad r(a) = \frac{1}{H_0}\int_a^{a_0} \frac{da'}{a'^2\left[\Omega_r^0\left(\frac{a_0}{a}\right)^4 + \Omega_m^0\left(\frac{a_0}{a}\right)^3 + \Omega_k^0\left(\frac{a_0}{a}\right)^2 + \Omega_\Lambda^0\right]^{1/2}}$$

redshift-distance relation $$r(z) = \frac{1}{H_0}\int_0^z \frac{dz'}{\left[\Omega_r^0(1+z')^4 + \Omega_m^0(1+z')^3 + \Omega_k^0(1+z')^2 + \Omega_\Lambda^0\right]^{1/2}}$$

Luminosity distance: $$\text{Flux} = \frac{\text{Luminosity}}{4\pi\, r(z)^2(1+z)^2} \equiv \frac{\text{Luminosity}}{4\pi d_L^2} \longrightarrow \boxed{d_L = (1+z)r(z)}$$

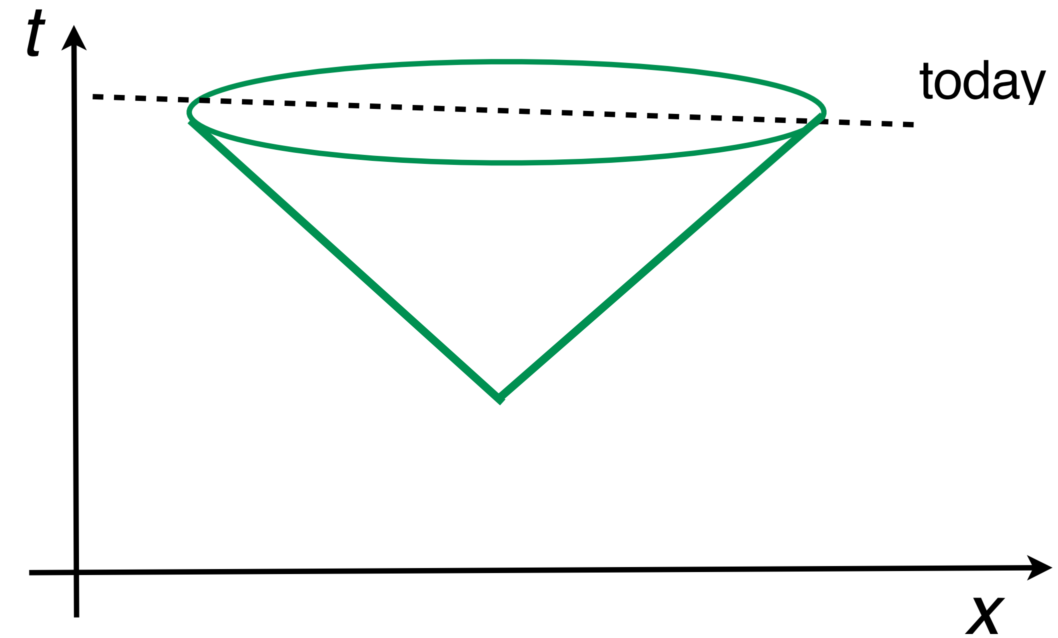
redshift of energy+dilated time

depends on Universe content

> Particle Horizon

$$d_H(t) = a(t)\int_0^t \frac{dt'}{a(t')}$$

the boundary between the visible universe and the part of the universe from which light signals have not reached us



measure the portion of the Universe in causal contact

$$d_H(t) = \frac{a(t)}{H_0}\int_0^{a(t)} \frac{da'}{a'^2\left[\Omega_r^0\left(\frac{a_0}{a}\right)^4 + \Omega_m^0\left(\frac{a_0}{a}\right)^3 + \Omega_k^0\left(\frac{a_0}{a}\right)^2 + \Omega_\Lambda^0\right]^{1/2}}$$

dust	radiation	vacuum energy
$d_H(t) = 3t = \frac{2}{H(t)} \propto a^{3/2}$	$d_H(t) = 2t = \frac{1}{H(t)} \propto a^2$	$d_H(t) = \infty$ (no horizon!)

> Equilibrium Thermodynamics

equilibrium number density and energy density

d.o.f.

$$n = \frac{g}{(2\pi)^3}\int f(\vec{p})d^3p$$

distrib. function

$$\rho = \frac{g}{(2\pi)^3}\int E(\vec{p})f(\vec{p})d^3p$$

$$f(\vec{p}) = \left[e^{E/T} \pm 1\right]^{-1}$$ FD BE

in extreme cases, these integrals can be solved analytically (**do it!**)

- for NON-RELATIVISTIC species (T << m) $\quad n = g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T} \qquad \rho = n\cdot m$

- for ULTRA-RELATIVISTIC species (T >> m)

$$n_{\rm BE} = \frac{\zeta(3)}{\pi^2} g T^3 \qquad \rho_{\rm BE} = \frac{\pi^2}{30} g T^4$$

$$n_{\rm FD} = (3/4) n_{\rm BE} \qquad \rho_{\rm FD} = (7/8)\rho_{\rm BE}$$

total number of massless d.o.f. at temperature T (species "*i*" has thermal distr. of temperature T_i)

$$g_* = \sum_{i\in{\rm bosons}} g_i\left(\frac{T_i}{T}\right)^4 + \frac{7}{8}\sum_{j\in{\rm fermions}} g_j\left(\frac{T_j}{T}\right)^4$$

Hubble rate in RD era:

$$H^2 = \frac{8\pi G_N}{3}\rho_{rel} = \frac{8\pi G_N}{3}\frac{\pi^3}{30} g_* T^4 \quad\Rightarrow\quad \boxed{H \simeq 1.66\sqrt{g_*}\frac{T^2}{M_P}}$$

> Temperature-Expansion Relation

$dU + pdV = TdS$ 1st law of thermodynamics

entropy density
$$s(T) \equiv \frac{S(V,T)}{V} = \frac{\rho(T)+p(t)}{T} = \frac{4}{3}\frac{\rho(T)}{T}$$

radiation domination w=1/3

$$\rho(T) \propto T^4 \longrightarrow s \propto T^3$$

conservation of entropy in comoving volume in thermal equilibrium:

$$S(V,T) = s(T)V = \text{const.} \Longrightarrow T^3 a^3 = \text{const.}$$

$$\Longrightarrow \boxed{T \propto 1/a}$$

> Exercises

Observation of a high-redshift object: $z=10$

- how long ago was the light we observe today emitted from there?
- what is the present distance of that object?
- what was the distance of the object when the light was emitted?

SUMMARY:

- expanding $1/H_0 \simeq 1.4 \times 10^{10}\,\mathrm{yrs} \simeq 4.3\,\mathrm{Gpc} \simeq 1.3 \times 10^{26}\,\mathrm{m}$

- homogeneous

- isotropic

- flat

$$\begin{aligned} \rho_c &\simeq 1.88 \times 10^{-29} h^2\,\mathrm{g\ \ cm}^{-3} \\ &\simeq 1.05 \times 10^{-5} h^2\,\mathrm{GeV cm}^{-3}. \end{aligned}$$

Energy budget

$$\text{curvature} \simeq 0\%$$

$$\text{matter} \simeq 31\% \left\{ \begin{array}{l} \text{baryonic matter} \simeq 4\% \\ \text{dark matter} \simeq 27\% \end{array} \right.$$

$$\text{vacuum energy} \simeq 69\%$$

KEEP
CALM
AND
TAKE A DEEP
BREATH

> Big Bang Nucleosynthesis

in hot Universe, no atoms/nuclei because of high energy photons around

as Universe cools down below binding energies of nuclei,
light elements begin to form

T ~ MeV

- all elements heavier than ^{7}Li are produced in stars or astrophysical processes

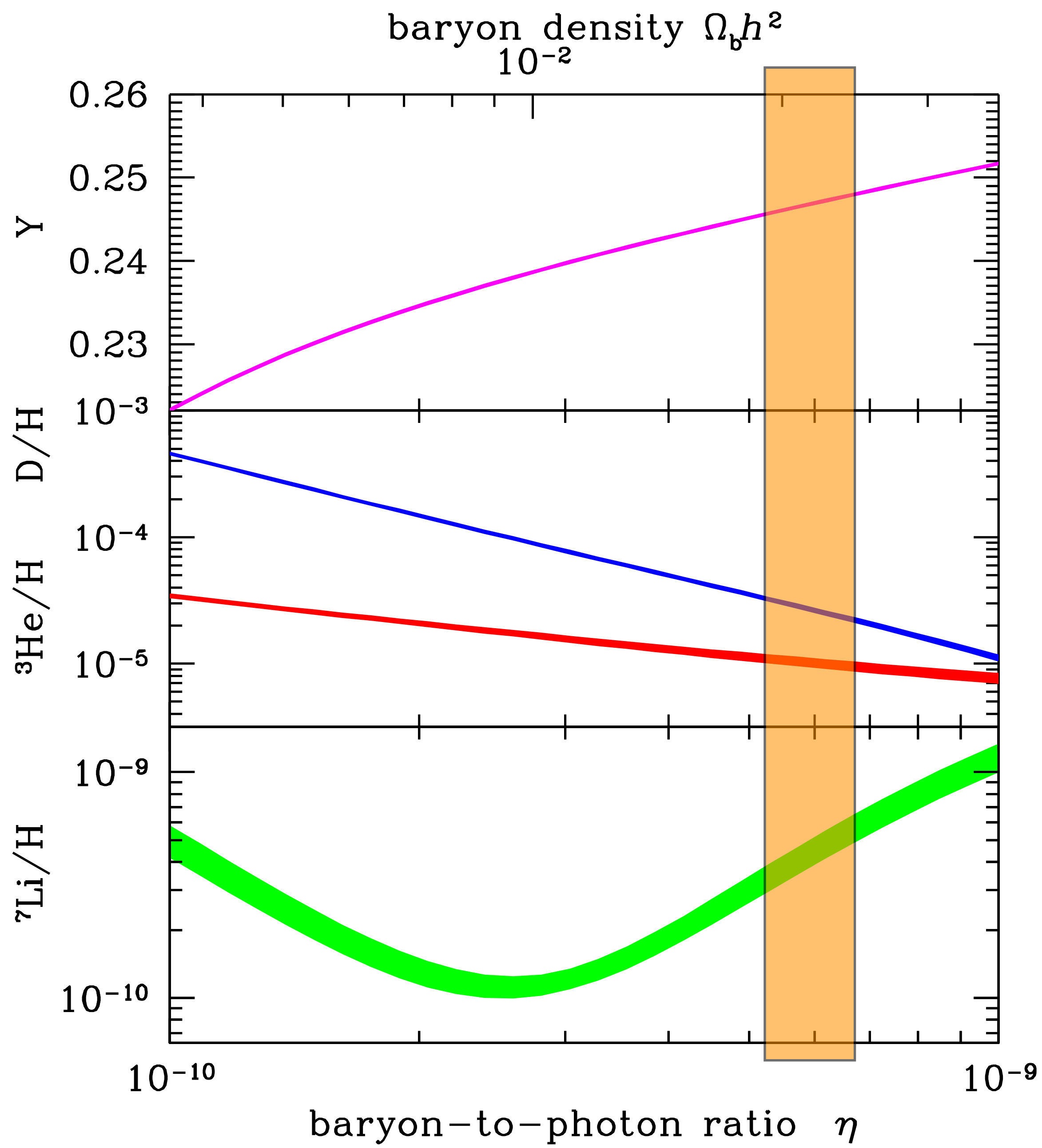
- ligther elements (^{2}H, ^{3}He, ^{4}He, ^{7}Li) have a **cosmological** origin.

- predictions depending on the baryon densities at T~MeV

> Big Bang Nucleosynthesis

predictions for abundances (spanning **9 orders of magnitude**) well fitted by a **single** parameter:

baryon-to-photon ratio $\eta = n_b/n_\gamma \sim 10^{-10}$



[arXiv:1505.01076]

Great Success of Standard Cosmology!

scaling a^{-3} and n_γ are known, so measure light element abundances

→ measure η

→ measure Ω_b today

BBN provides a compelling argument for non-baryonic DM

> Big Bang Nucleosynthesis

experimental measurements of primordial ^{4}He fraction in metal-poor stars ad gas clouds:

$$Y(^4\mathrm{He}) \equiv \frac{4n_{\mathrm{He}}}{n_n + n_p} \simeq 0.25$$

Need to compute neutron-to-proton ratio n_n/n_p and Helium-4 abundance n_{He}.

- at very early times (t<< 1 s, T>>1 MeV), the reactions

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

are in equilibrium so $n_n = n_p$.

- at T~ 1 MeV << m_n, m_p, mass difference starts to be important

$$n_i = g_i \left(\frac{m_i T}{2\pi}\right)^{3/2} e^{-m_i/T}$$
$$g_n = g_p = 2$$

$$\longrightarrow \quad \frac{n_n}{n_p} = e^{-(m_n - m_p)/T} = e^{-(1.29\ \mathrm{MeV})/T}$$

- equilibrium is broken by expansion. Scattering rate < expansion rate, so neutrons are not created or distroyed by scatterings. Neutron abundance gets ``frozen in".

$$\Gamma(\nu_e + n \leftrightarrow p + e^-) \sim 2.1 \left(\frac{T}{1\ \mathrm{MeV}}\right)^5 \mathrm{s}^{-1} < H \simeq 6\, T^2/M_P \longrightarrow \quad T \lesssim 0.8\ \mathrm{MeV}$$

At T=0.8 MeV $n_n/n_p \simeq e^{-1.29/0.8} \simeq 0.2$. After that, some *n* decay, and at the end of BBN (T~ 0.01 MeV) there are slightly fewer neutrons **$n_n/n_p \sim 0.14$**.

> Big Bang Nucleosynthesis

Now we need to find n_{He}.

Helium nuclei are produced by **deuterium** ***²H*** by the chains

$$\begin{aligned} {}^2H + {}^2H &\leftrightarrow {}^3He + n \\ {}^3He + {}^2H &\leftrightarrow {}^4He + p \end{aligned}$$

or

$$\begin{aligned} {}^2H + {}^2H &\leftrightarrow {}^3H + p \\ {}^3H + {}^2H &\leftrightarrow {}^4He + n \end{aligned}$$

Deuterium is produced by $p + n \leftrightarrow {}^2H + \gamma$ which is fast for T>0.1 MeV.
Photo-dissociation prevents deuterium formation.

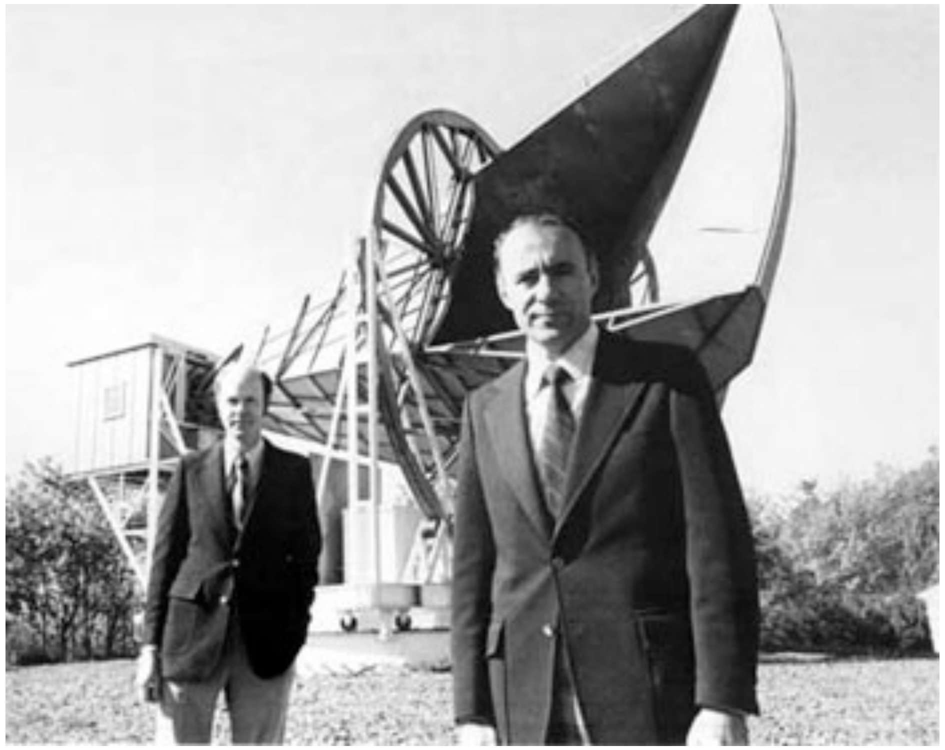
For T<0.1 MeV, deuterium is produced and feeds reactions for He production.

Most neutrons are consumed to make Helium-4 nuclei, so $n_{He} \sim n_n/2$.

$$n_n/n_p \simeq 0.14 \longrightarrow Y({}^4\mathrm{He}) = \frac{4(n_n/2)}{n_n + n_p} = \frac{2n_n/n_p}{1 + n_n/n_p} \simeq 0.25!$$

Impressive success of BBN is the earliest and most stringent test of standard cosmology!

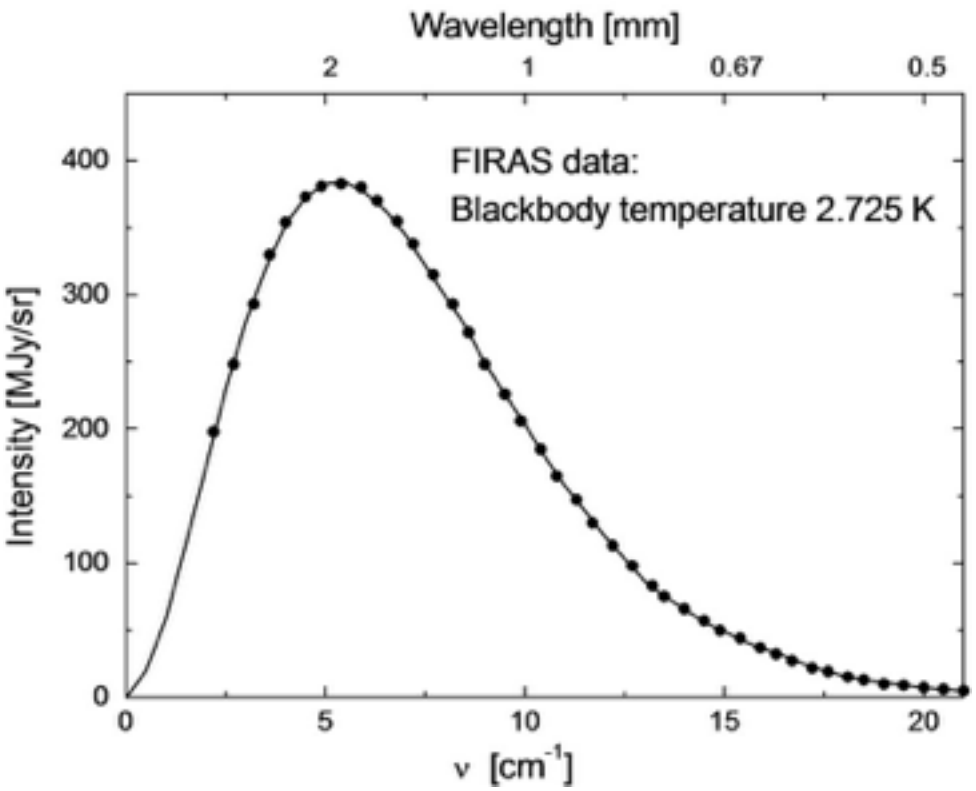
> Cosmic Microwave Background



1965: Arno Penzias and Robert Wilson published a paper where they admitted to have *failed* to eliminate a background *noise* coming from all directions (corresponding to a residual **T=3.5±1.0 K**).

1975: Penzias & Wilson shared Nobel prize in physics.

>> WHAT WAS THAT NOISE? <<



Very early Universe ($T>m_e$): EM radiation kept in thermal equilibrium by pair-productions and Compton scatterings

$$\gamma + \gamma \leftrightarrow e^+ + e^-$$
$$e^- + \gamma \leftrightarrow e^- + \gamma$$

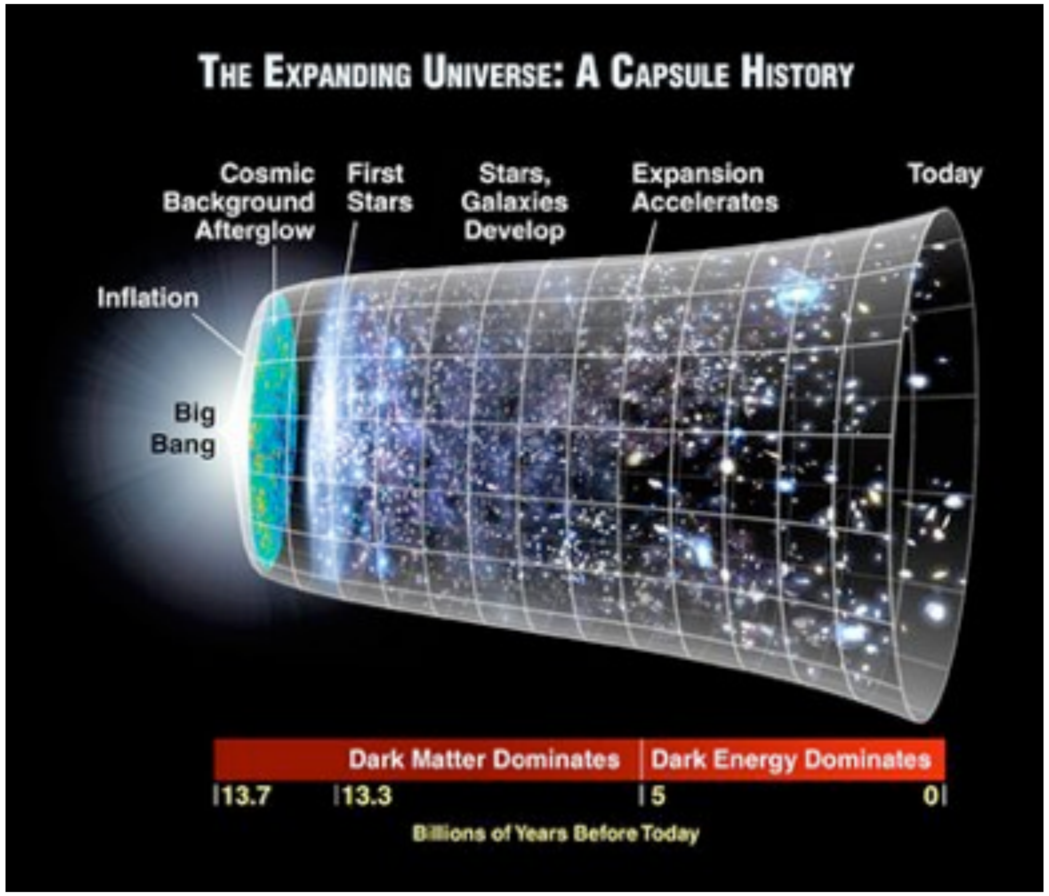
photons were continuously created/absorbed or annihilated/emitted

→ **The Universe was an almost perfect BLACK-BODY**

> Cosmic Microwave Background

electrons linked to protons by H production $p + e^- \leftrightarrow H + \gamma$

when this went out of equilibrium (LAST SCATTERING), photons “decoupled” from matter



then photons propagated <u>un-scattered</u> until today

CMB photons ***last scattered*** off electrons at $z \sim z_{dec}$ and then travelled freely.

They cooled down with expansion to $T_0 = 2.7\ \mathrm{K} = 2.3 \times 10^{-4}\,\mathrm{eV}$

The CMB is a residual EM radiation from the Big Bang.

Snapshot of the Universe when it was a baby (only 300,000 yrs old)

The most powerful probe of the early Universe

> Cosmic Microwave Background

photon energy distribution (Planck)

photons polarizations

$$n(\omega,T)d\omega = \frac{1}{c^3}\frac{1}{e^{\hbar\omega/(k_BT)}-1}\frac{2d^3\omega}{(2\pi)^3} = \frac{1}{\pi^2c^3}\frac{\omega^2 d\omega}{e^{\hbar\omega/(k_BT)}-1}$$

differential energy spectrum (black-body)

$$u(\omega,T)d\omega = (\hbar\omega)n(\omega,T)d\omega = \frac{\hbar}{\pi^2c^3}\frac{\omega^3 d\omega}{e^{\hbar\omega/(k_BT)}-1}$$

Total energy density

$$\rho_\gamma = \int_0^\infty u(\omega,T)d\omega = \frac{\hbar}{\pi^2c^3}\left(\frac{k_BT}{\hbar}\right)^4 \underbrace{\int_0^\infty \frac{\xi^3 d\xi}{e^\xi - 1}}_{\pi^4/15}$$

$$\rho_\gamma = \frac{\pi^2 k_B^4}{15\hbar^3c^3}T^4 \equiv \sigma T^4$$ (Stefan-Boltzmann relation)

$$\sigma = 4.72\times 10^{-3}\ \mathrm{eV\ cm^{-3}\ K^{-4}}$$

With T=2.73 K:

$$\rho_\gamma \simeq 0.26\ \mathrm{eV\ cm^{-3}} \longrightarrow \boxed{\Omega_r^0 h^2 = \frac{\rho_\gamma}{\rho_c/h^2} \simeq 4\times 10^{-5}}$$

Present radiation energy density is **negligible**!

> Cosmic Microwave Background

let's compute the time when CMB formed (the time of decoupling z_{dec})

$$p + e^- \leftrightarrow H + \gamma \quad \begin{cases} \mu_p + \mu_e = \mu_H & \text{chemical equilibrium} \\ n_p = n_e & \text{charge neutrality} \\ n_p + n_H = n_B = \eta_B n_\gamma & \text{tot. number of baryons} \end{cases} \quad (\, n_\gamma \simeq (1/4) T^3 \,)$$

free electron fraction (ionization fraction): $$X_e \equiv \frac{n_e}{n_p + n_H} = \frac{n_e}{n_e + n_H}$$

$$m_i \gg T \qquad n_i = g_i \left(\frac{m_i T}{2\pi} \right)^{3/2} e^{(\mu_i - m_i)/T} \qquad g_p = g_e = 2, g_H = 4$$

$$\frac{X_e^2}{1 - X_e} = \frac{n_e + n_H}{n_H} \frac{n_e n_p}{(n_e + n_H)^2} = \frac{1}{\eta_B n_\gamma} \left(\frac{m_e T}{2\pi} \right)^{3/2} e^{\mu_p + \mu_e - \mu_H} e^{-B/T} = \cdots$$

$$= \frac{1}{4\eta_B} \left(\frac{m_e}{T} \right)^{3/2} e^{-B/T} \qquad (B \equiv m_p + m_e - m_H \simeq 13.6 \text{ eV})$$

$$B \lesssim T \Longrightarrow \frac{X_e^2}{1 - X_e} \simeq 10^9 (m_e/T)^{3/2} \simeq 10^{15} \Longrightarrow X_e \simeq 1$$ (all Hydrogen ionized)

$$B > T \Longrightarrow X_e \ll 1 \Longrightarrow X_e \simeq \left[\frac{1}{4\eta_B} \left(\frac{m_e}{T} \right)^{3/2} e^{-B/T} \right]^{1/2}$$

> Cosmic Microwave Background

Decoupling occurs when rate for photon-electron scattering < expansion rate

$$\Gamma \simeq H \qquad \Gamma \simeq n_e \sigma_T$$

$$n_e \sigma_T \simeq H$$

Thomson scattering cross section

$$\sigma_T = \frac{8\pi}{3}\left(\frac{e^2}{m_e c^2}\right)^2 \simeq 6.65 \times 10^{-25}\ \mathrm{cm}^2$$

assume matter-dominated universe $\quad H \simeq H_0 a^{-3/2} = H_0 (T/T_0)^{3/2}$

compare

$$n_e = X_e n_B$$

$$n_B = \frac{\Omega_b^0 \rho_c}{m_p a^3} = \frac{\Omega_b^0 \rho_c}{m_p}\left(\frac{T}{T_0}\right)^3 \simeq 2.2 \times 10^{-7}\ \mathrm{cm}^{-3}\left(\frac{T}{T_0}\right)^3$$

$$\longrightarrow \quad n_e \sigma_T \simeq X_e\, 1.5 \times 10^{-31}\ \mathrm{cm}^{-1}\left(\frac{T}{T_0}\right)^3$$

$$\longrightarrow \quad (T/T_0)^{3/2} \simeq \frac{1}{2 \times 10^{-3} X_e} \xrightarrow{\text{solve implicit eq.}} T \simeq 1000\, T_0 \simeq 0.2\ \mathrm{eV}$$

$$\longrightarrow 1 + z_{\mathrm{dec}} = T/T_0 \simeq 1000 \longrightarrow t_{\mathrm{dec}} = (2/3) H_0^{-1} (1 + z_{\mathrm{dec}})^{-3/2} \simeq 300,000\ \mathrm{yrs}$$

photons stop scattering off electrons at z~z_{dec} but electrons keep scatter off photons until much later. WHY? there are many more photons than baryons!

> CMB Anisotropies

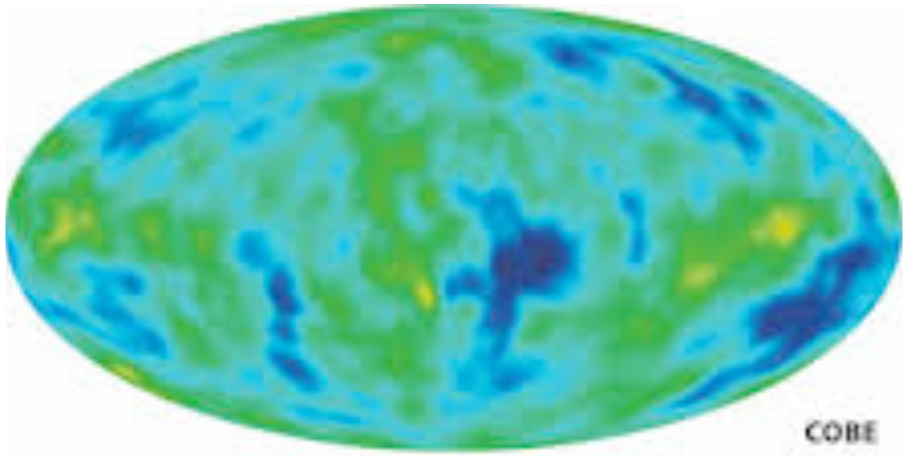
CMB Radiation is not perfectly isotropic

temperature anisotropies

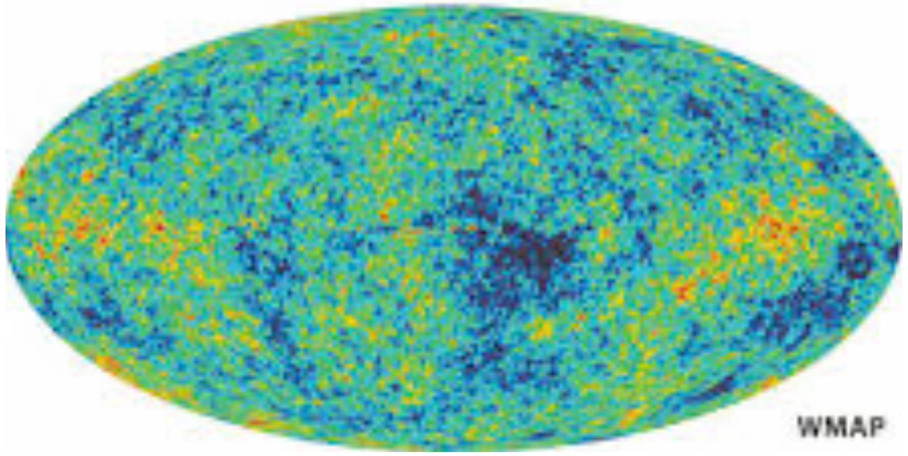
$$\frac{\Delta T}{T} \simeq 10^{-5}$$

A lot of information from temperature maps.

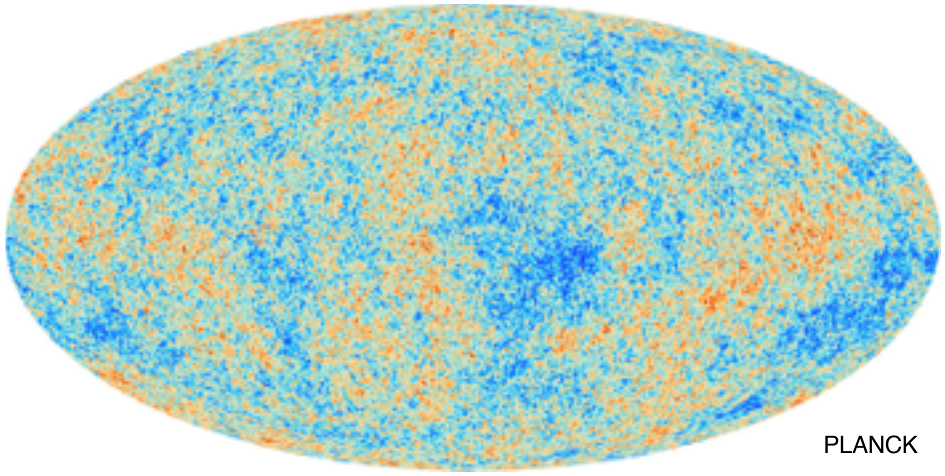
Two-point correlation functions crucially depend on cosmological parameters (H_0, Ω_{tot}, Ω_B etc).



COBE



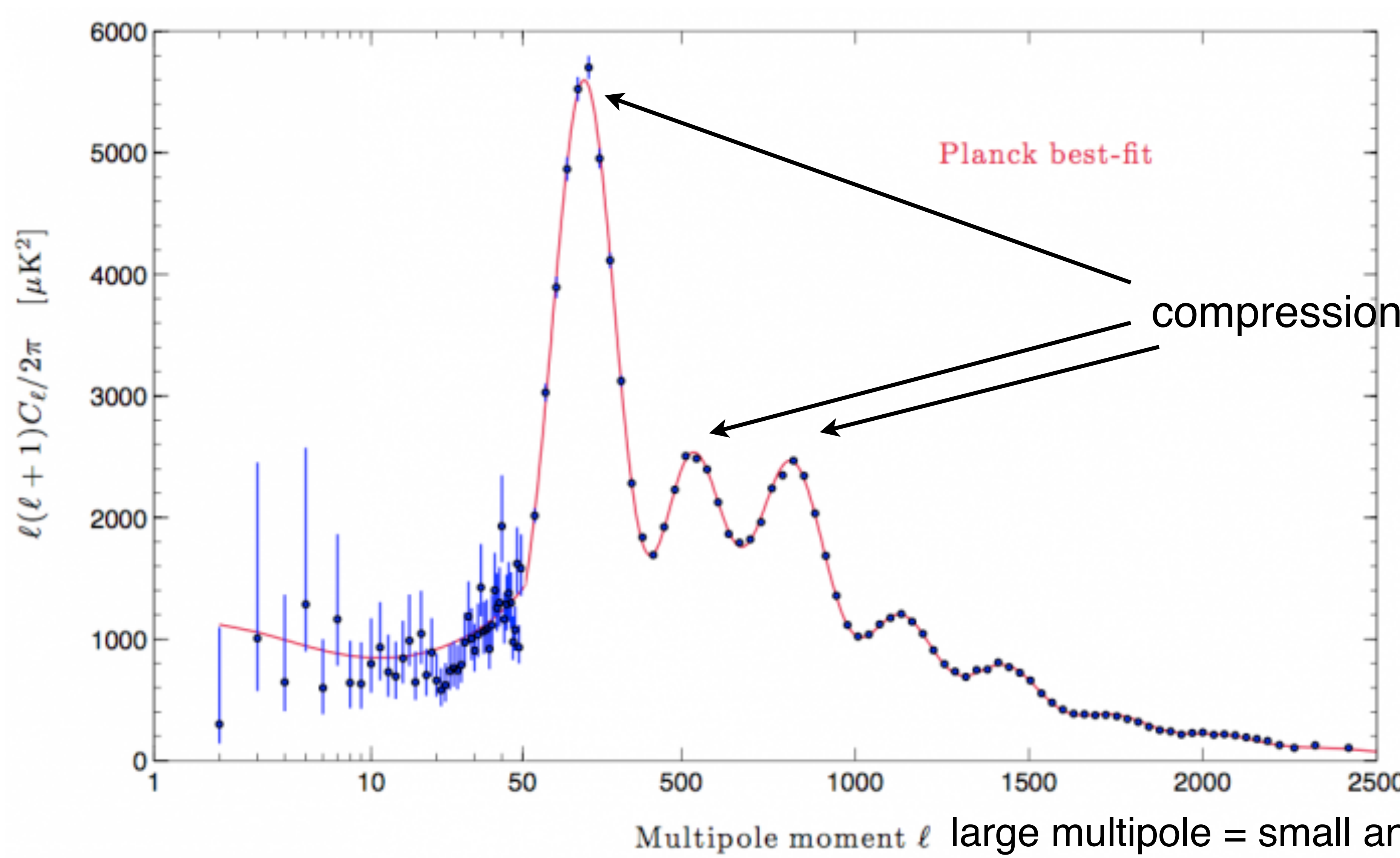
WMAP



PLANCK

> CMB Anisotropies

snapshot of the oscillating photon field at z~1100



(acoustic) peaks:
compression/rarefaction of the baryon fluid

competing forces:
- gravity (attractive)
- photon pressure (repulsive)

large multipole = small angular scale

fit with cosmological model provides
energy content of the Universe

$\Omega_{tot} \sim 1.0,\ \Omega_{matter} \sim 0.3,\ \Omega_{radiation} \sim 0.0 \longrightarrow \Omega_\Lambda \sim 0.7$

"ΛCDM MODEL"

Great triumph of cosmology!

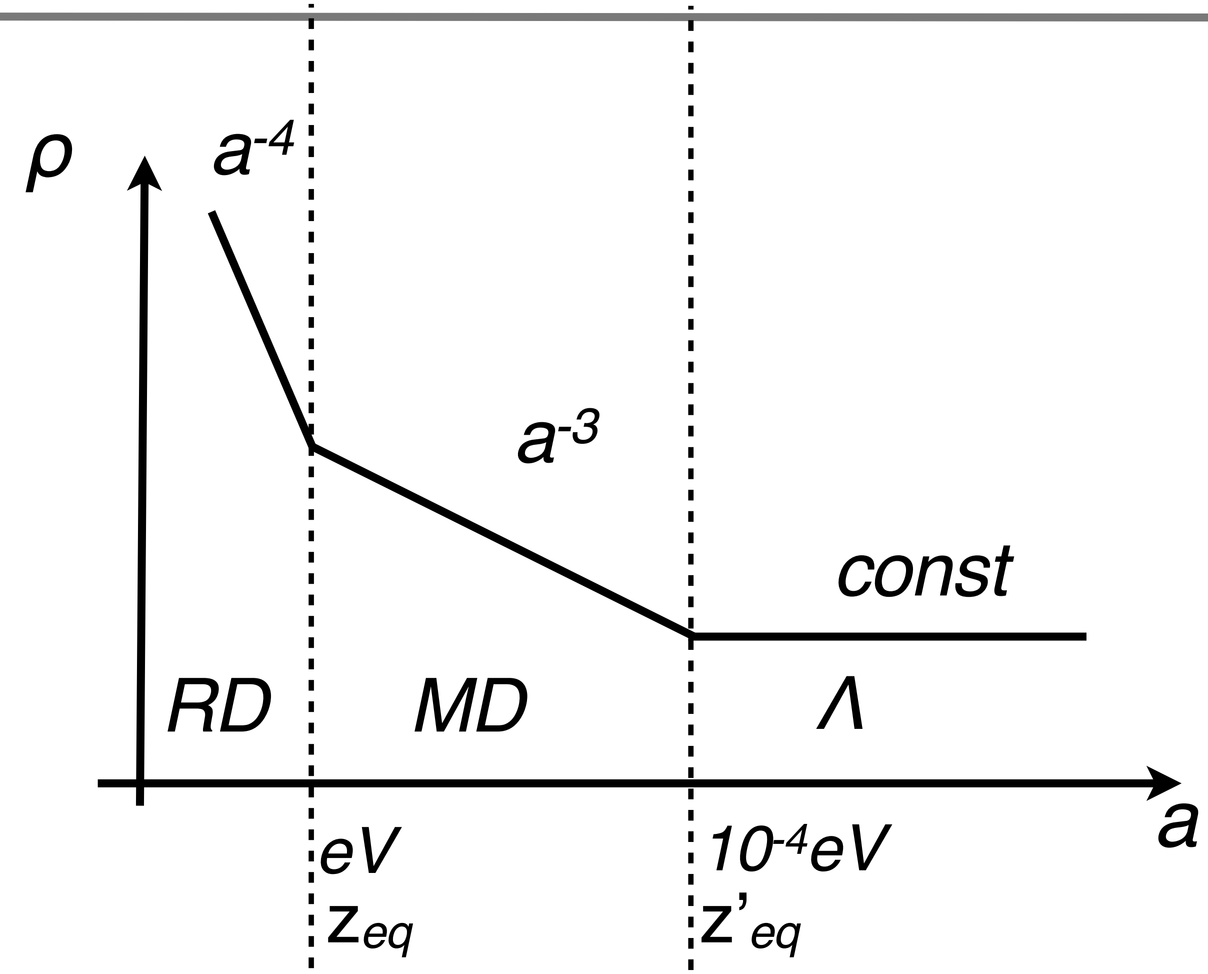
> Phases of the Universe

$$\rho_r = \rho_c \Omega_r^0 / a^4$$

$$\rho_m = \rho_c \Omega_m^0 / a^3$$

$$\Omega_r^0 \equiv \rho_{\rm CMB}/\rho_c \simeq 8.5 \times 10^{-5}$$

$$a = (1+z)^{-1}$$



Matter-radiation equality $\rho_r = \rho_m \Longrightarrow z_{\rm eq} \simeq 3300$

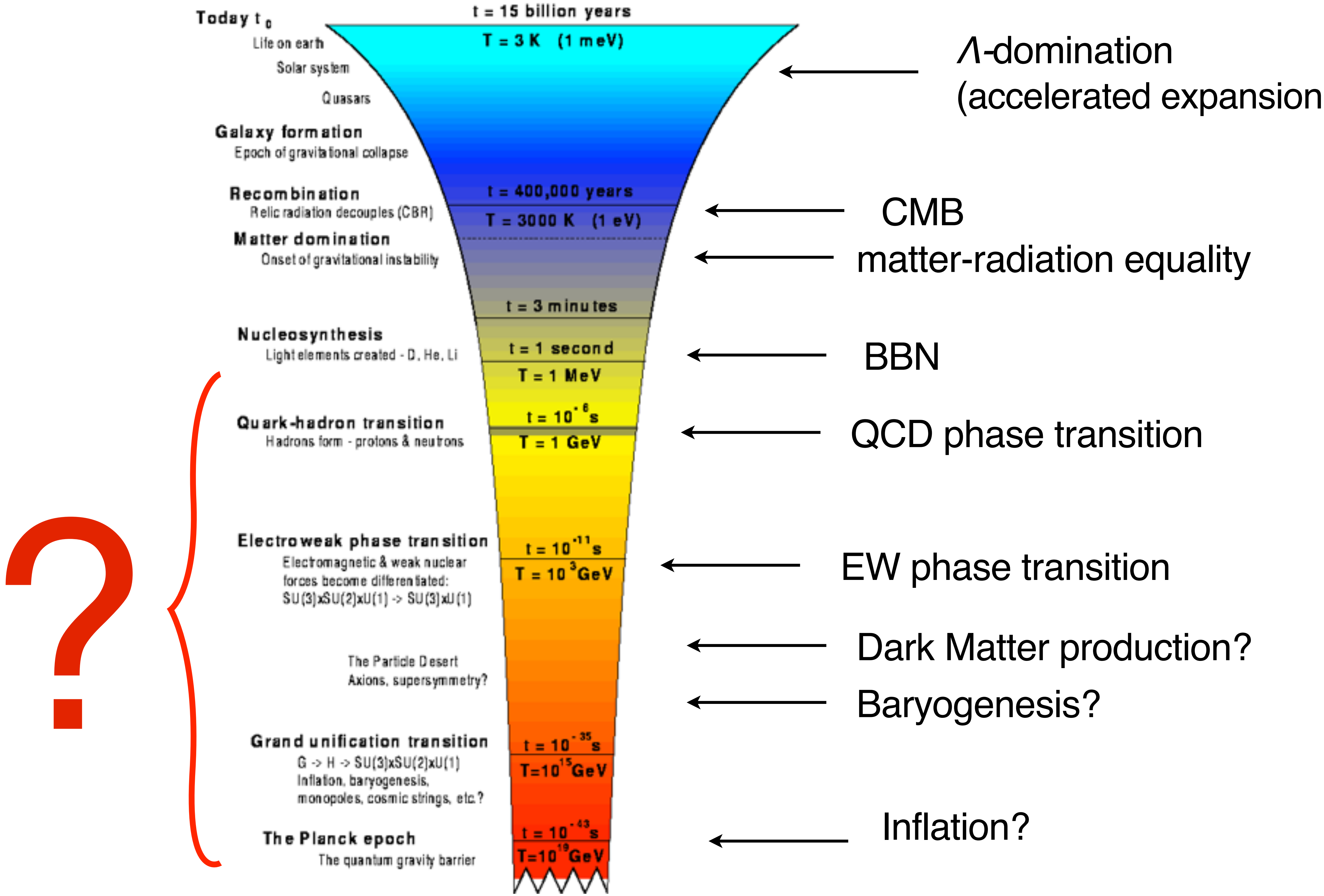
Matter-Λ equality $\rho_m = \rho_\Lambda \Longrightarrow z'_{\rm eq} \simeq 0.3$

Exercise: *compute z_{eq}, z_{eq}'*

Λ-domination started very recently:

$z'_{\rm eq} \simeq 0.3 \Longrightarrow T_\Lambda = (1+z'_{\rm eq}) T_0 \simeq 3.5$ K Coincidence (or "WHY NOW") problem!

> Thermal History of the Universe



> Beyond the SM of Cosmology?

Open problems of the Standard Model of Cosmology

- what is Dark Energy?
- why cosmological constant so small?
- what is Dark Matter?
- what happened in the first 3 minutes (before BBN)?
- why matter and not antimatter?

?

> Summary of Lecture 1

- our Universe is <u>homogeneous</u>, <u>isotropic</u> and it is <u>expanding</u>.

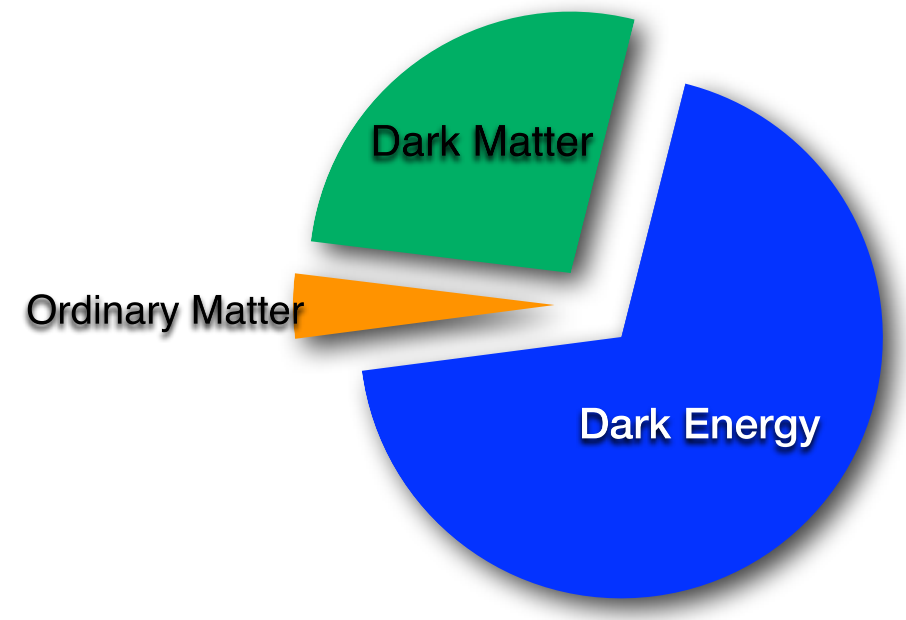
- Energy budget

ΛCDM

$$\text{baryonic matter} \simeq 4\%$$

$$\text{dark matter} \simeq 27\%$$

$$\text{vacuum energy} \simeq 69\%$$



- **Big Bang Nucleosynthesis** is the earliest epoch we have tested (successfully)

- **CMB** temperature and anisotropies provide great deal of info about the Universe today

- Still the picture is not complete... many open problems on the table!