Basics of Cosmology

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Standard Model: Success and Problems

Gauge fields (interactions): γ, $W^{\pm}$, Z, g

Three generations of matter: $L = \binom{\nu_L}{e_L}$, e_R; $Q = \binom{u_L}{d_L}$, d_R, u_R

- Describes
  - all experiments dealing with electroweak and strong interactions
- Does not describe (PHENO) (THEORY)
  - Neutrino oscillations
  - Dark matter (Ω_{DM})
  - Baryon asymmetry (Ω_B)
  - Inflationary stage
  - Dark energy (Ω_Λ)
  - Strong CP-problem
  - Gauge hierarchy
  - Quantum gravity

Cosmology asks for new physics and limits neutrino mass

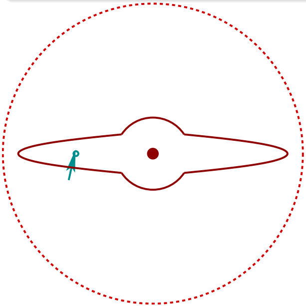
severely constrains many BSM relaxation..?

Outline

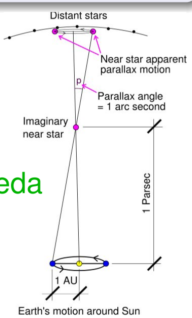
“Natural” units in cosmology

$$1\ \text{Mpc} = 3.1 \times 10^{24}\ \text{cm}$$

$1\ \text{AU} = 1.5 \times 10^{13}\ \text{cm}$	mean Earth-to-Sun distance
$1\ \text{ly} = 0.95 \times 10^{18}\ \text{cm}$	distance light travels in one year
	$1\ \text{yr} = 3.16 \times 10^{7}\ \text{s}$
$1\ \text{pc} = 3.3\ \text{ly} = 3.1 \times 10^{18}\ \text{cm}$	distance to object which has a parallax angle of one arcsec



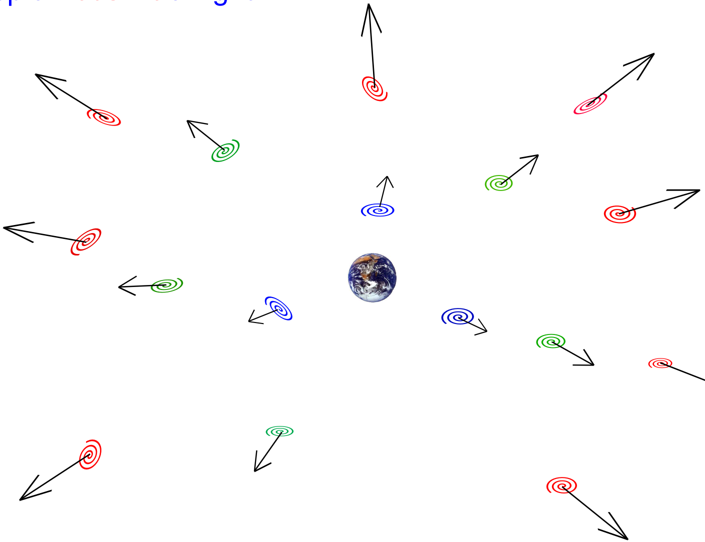
100 AU — Solar system size
1.3 pc — nearest-to-Sun stars
1 kpc — size of dwarf galaxies
50 kpc — distance to dwarves
0.8 Mpc — distance to Andromeda
1-3 Mpc — size of clusters
15 Mpc — distance to Virgo



Outline

Universe is expanding

Doppler redshift of light



$L \propto a(t)$

$n \propto a^{-3}(t)$

$H(t) = \frac{\dot{a}(t)}{a(t)}$

Hubble parameter

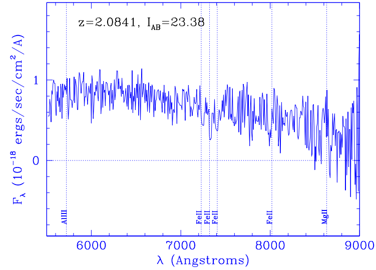
Hubble Law

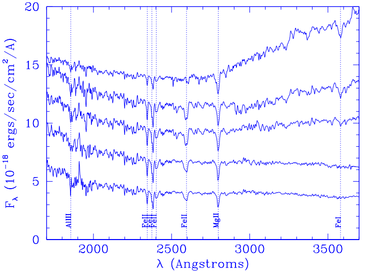
$H(t_0)\, r = v_r$

Expansion: redshift z $\qquad \lambda_{\text{abs.}}/\lambda_{\text{em.}} \equiv 1 + z$

$z \ll 1$ Hubble law : $z = H_0 r$

$$H_0 = h \cdot 100 \, \frac{\text{km}}{\text{s} \cdot \text{Mpc}} \,, \qquad h \approx 0.68$$





Expansion: redshift z $\lambda_{\text{abs.}}/\lambda_{\text{em.}} \equiv 1+z$

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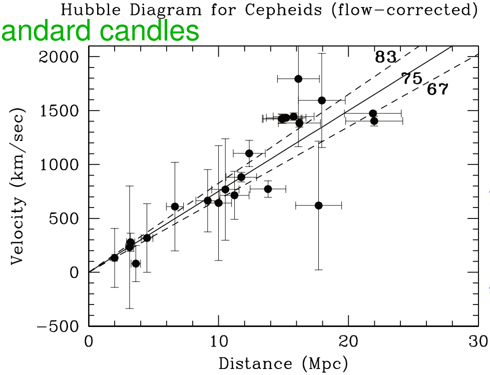
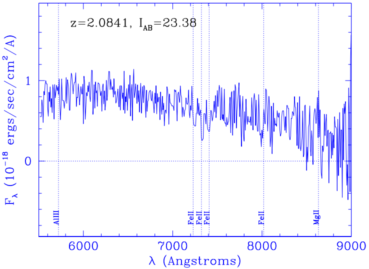
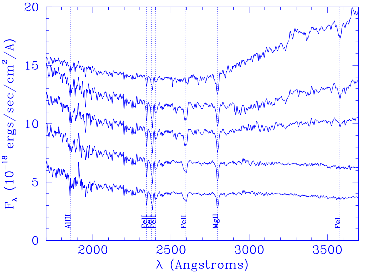
standard candles



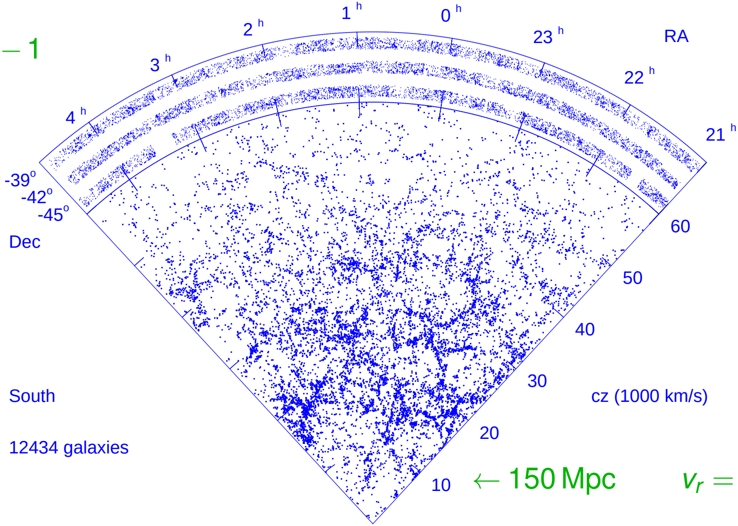




Universe is homogeneous and isotropic

redshift

$$z \equiv \frac{\lambda_{\text{detector}}}{\lambda_{\text{source}}} - 1$$



$\leftarrow$ 150 Mpc

$$v_r = c\,z$$

The Universe: age & geometry & energy density

$$[H_0] = L^{-1} = t^{-1}$$

time scale: $t_{H_0} = H_0^{-1} \approx 14 \times 10^9$ yr — age of our Universe

spatial scale: $l_{H_0} = H_0^{-1} \approx 4.3 \times 10^3$ Mpc — size of the visible Universe

t_{H_0} is in agreement with various observations

homogeneity and isotropy in 3d:

flat, spherical or hyperbolic

Observations: "very" flat $R_{curv} > 10 \times l_{H_0}$

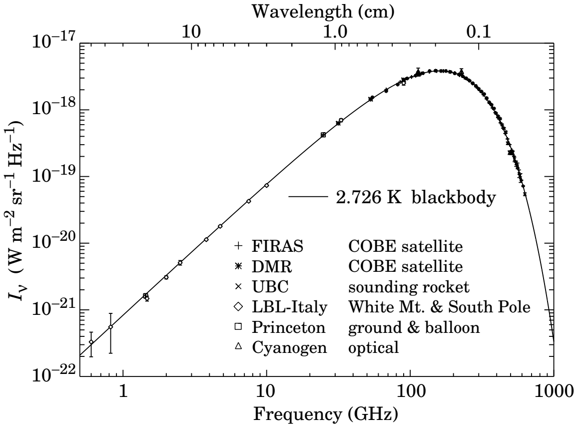
order-of-magnitude estimate: $GM_U/l_U \sim G\rho_0 l_{H_0}^3/l_{H_0} \sim 1$

flat Universe

$$\rho_c = \frac{3}{8\pi} H_0^2 M_{Pl}^2 \approx 0.53 \times 10^{-5} \frac{\text{GeV}}{\text{cm}^3}$$

$\longrightarrow$ 5 protons in each 1 m^3

Universe is occupied by “thermal” photons



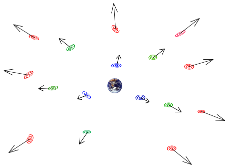
$T_0 = 2.726$ K

the spectrum (shape and normalization!) is thermal

$n_\gamma = 411$ cm^{-3}

Conclusions from observations

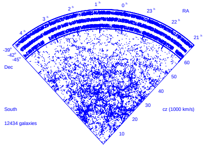
The Universe is homogeneous, isotropic, flat,
hot, and expanding...



Conclusions

- interval between events gets modified

$$\Delta s^2 = \Delta t^2 - a^2(t)\,\Delta \mathbf{x}^2$$

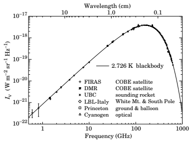


in GR expansion is described by the Friedmann equation

$$\left(\frac{\dot a}{a}\right)^2 = H^2(t) = \frac{8\pi}{3}\,G\rho_{\text{density}}^{\text{energy}}$$

$$\rho_{\text{density}}^{\text{energy}} = \rho_{\text{radiation}} + \rho_{\text{matter}} + \dots$$

- in the past the matter density was higher, our Universe was “hotter” filled with electromagnetic plasma



$$\rho_{\text{matter}} \propto 1/a^3(t)\,,\quad \rho_{\text{radiation}} \propto 1/a^4(t)\,,\quad \rho_{\text{curvature}} \propto 1/a^2(t)$$

certainly known up to $T \sim 1\,\text{MeV} \sim 10^{10}\,\text{K}$

Determination of $a(t)$ reveals the composition of the present Universe

$\Delta s^2 = c^2\,\Delta t^2 - a^2(t)\,\Delta\vec{x}^2 \;\rightarrow\; ds^2 = g_{\mu\nu}dx^\mu dx^\nu$

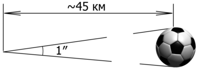
Light propagation changes...

How do we check it?

by measuring distance L to an object!

- Measuring angular size θ of an object of known size d – single-type galaxies

$$\theta = \frac{d}{L}$$



- Measuring angular size $\theta(t)$ corresponding to physical size $d(t)$ with known evolution
  – BAO in galaxy distribution
  – lensing of CMB anisotropy

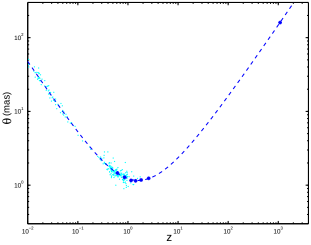
$$\theta(t) = \frac{d(t)}{L}$$

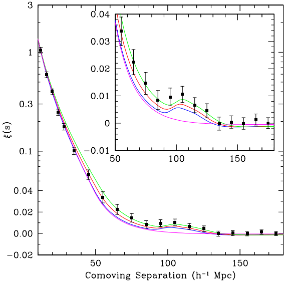
- Measuring brightness J of an object of known luminosity F – "standard candles"

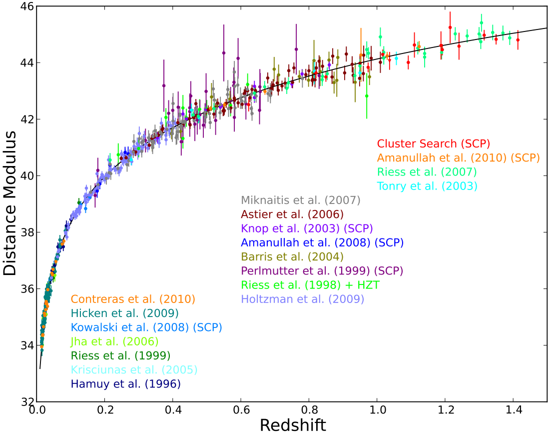
$$J = \frac{F}{4\pi L^2}$$

In the expanding Universe all these laws get modified

Results of distance measurements

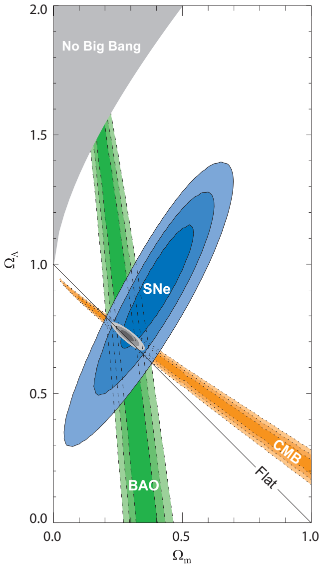






$$\xi_z(s) = \langle n_z(\vec{x}) n_z(\vec{x}+\vec{s})\rangle_{\vec{x}}$$

Astrophysical and cosmological data are in agreement



$$\left(\frac{\dot a}{a}\right)^2 = H^2(t) = \frac{8\pi}{3} G \rho^{\text{energy}}_{\text{density}}$$

$$\rho^{\text{energy}}_{\text{density}} = \rho_{\text{radiation}} + \rho^{\text{ordinary}}_{\text{matter}} + \rho^{\text{dark}}_{\text{matter}} + \rho_\Lambda$$

$$\rho_{\text{radiation}} \propto 1/a^4(t) \propto T^4(t)\,, \quad \rho_{\text{matter}} \propto 1/a^3(t)$$

$$\rho_\Lambda = \text{const}$$

$$\frac{3H_0^2}{8\pi G} = \rho^{\text{energy}}_{\text{density}}(t_0) \equiv \rho_c \approx 0.53 \times 10^{-5}\,\frac{\text{GeV}}{\text{cm}^3}$$

radiation: $\Omega_\gamma \equiv \frac{\rho_\gamma}{\rho_c} = 0.5 \times 10^{-4}$

Baryons (H, He): $\Omega_B \equiv \frac{\rho_B}{\rho_c} = 0.05$

Neutrino: $\Omega_\nu \equiv \frac{\sum \rho_{\nu_i}}{\rho_c} < 0.01$

Dark matter: $\Omega_{DM} \equiv \frac{\rho_{DM}}{\rho_c} = 0.27$

Dark energy: $\Omega_\Lambda \equiv \frac{\rho_\Lambda}{\rho_c} = 0.68$

Dark Matter Properties

– dust-like pressureless component, $p = 0$
– clumping substance, gets confined in structures

If particles (or compact macroscopic objects):

1. stable on cosmological time-scale
2. electrically neutral
3. decoupled from visible matter
4. nonrelativistic long before RD/MD-transition, $v_{RD/MD} \lesssim 10^{-3}$
   free streaming prevents formation of small-scale structures

Key observable: matter perturbations

- CMB is isotropic, but “up to corrections, of course...”
    1. Earth movement with respect to CMB
    $$\frac{\Delta T_{\text{dipole}}}{T} \sim 10^{-3}$$
    2. More complex anisotropy!
    $$\frac{\Delta T}{T} \sim 10^{-4} - 10^{-5}$$
- There were matter inhomogenities $\Delta\rho/\rho \sim \Delta T/T$ at the stage of recombination ($e + p \to \gamma + H^*$)
- Jeans instability in the system of gravitating particles at rest $\Longrightarrow$ $\Delta\rho/\rho \nearrow$ $\Longrightarrow$ galaxies (CDM halos)
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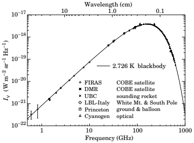
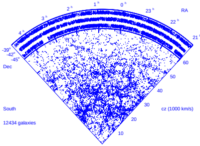
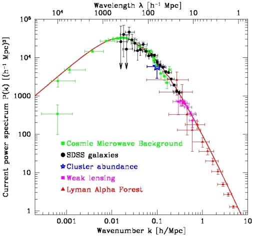
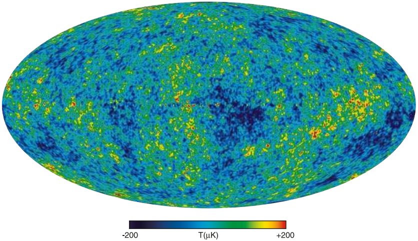
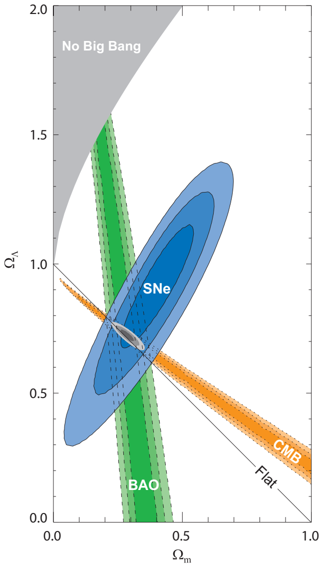








Dark Energy: nonclumping substence



- estimates of Matter contribution confined in galaxies and clusters
  $\rho_c - \rho_M \neq 0$ but the Universe is flat, so $\rho_{curv} \simeq 0$
- corrections to the Hubble law : red shift – brightness curves for standard candles (SN Ia)
- The age of the Universe
- CMB anisotropy, large scale structures (galaxy clusters formation), etc

$$\rho_\Lambda = 0.68\rho_c$$

$$\rho_\Lambda \sim 10^{-5}\ \text{GeV/cm}^3 \sim \left(10^{-11.5}\ \text{GeV}\right)^4$$

Dark Energy: all evidences are from cosmology

Working hypothesis is cosmological constant $\Lambda \approx \left(2.5 \times 10^{-3}\,\text{eV}\right)^4$:
$p = w(t)\rho$, $w = \text{const} = -1$, $\rho = \Lambda$

$$S_\Lambda = -\Lambda \int d^4x \sqrt{-\det g_{\mu\nu}}$$

both parts contribute

$$S_{\text{grav}} = -\frac{1}{16\pi G} \int d^4x \sqrt{-\det g_{\mu\nu}}\, R\,,$$
$$S_{\text{matter}} = \int d^4x \sqrt{-\det g_{\mu\nu}} \left(\frac{1}{2} g^{\lambda\rho} \partial_\lambda \phi \partial_\rho \phi - V(\phi)\right)$$

natural values

$$\Lambda_{\text{grav}} \sim 1/G^2 \sim \left(10^{19}\,\text{GeV}\right)^4\,, \quad \Lambda_{\text{matter}} \sim V(\phi_{vac}) \sim (100\,\text{GeV})^4, (100\,\text{MeV})^4, \dots$$

Why Λ is small? Why $\Lambda \sim \rho$? Why $\rho_B \sim \rho_{DM} \sim \rho_\Lambda$ today?

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2(t) = \frac{8\pi}{3} G \rho_{\text{density}}^{\text{energy}}$$

$$\rho_{\text{density}}^{\text{energy}} = \rho_{\text{radiation}} + \rho_{\text{matter}}^{\text{ordinary}} + \rho_{\text{matter}}^{\text{dark}} + \rho_{\Lambda}$$

$$\rho_{\text{radiation}} \propto 1/a^4(t) \propto T^4(t)\,, \quad \rho_{\text{matter}} \propto 1/a^3(t)$$

$$\rho_{\Lambda} = \text{const}$$

Why do we think it is most probably new particle physics
(new gravity if any is not enough) ?

DM at various spatial scales, BAU requires baryon number violation

Friedmann equation for the present Universe

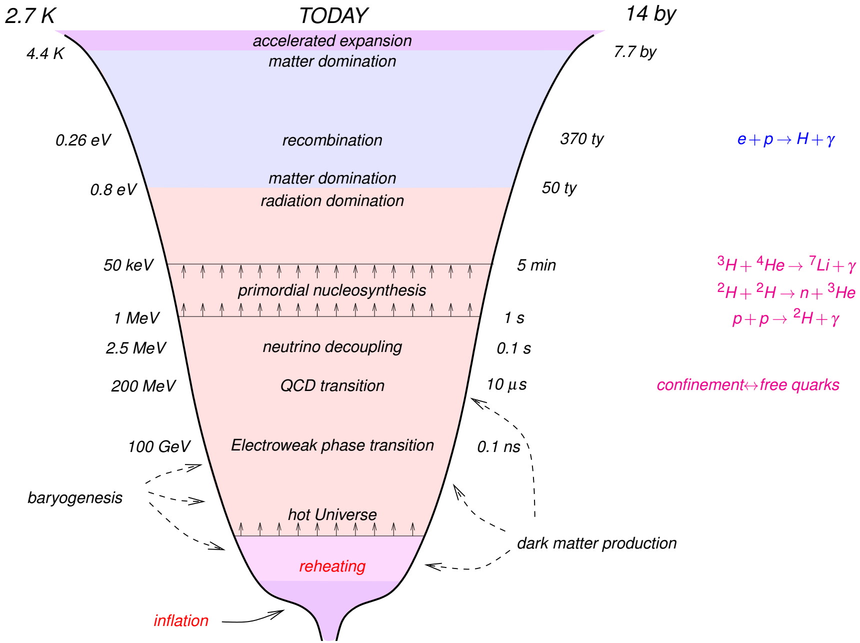
$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G \left(\rho_{\mathrm{M}} + \rho_{rad} + \rho_{\Lambda} + \rho_{\mathrm{curv}}\right)$$

$$\frac{8\pi}{3} G\rho_{\mathrm{curv}} = -\frac{\varkappa}{a^2}\,, \quad \rho_c \equiv \frac{3}{8\pi G} H_0^2$$

$$\rho_c = \rho_{\mathrm{M},0} + \rho_{rad,0} + \rho_{\Lambda,0} = \rho_c = 0.53 \cdot 10^{-5} \frac{\mathrm{GeV}}{\mathrm{cm}^3}\,,$$

$$\Omega_X \equiv \frac{\rho_{X,0}}{\rho_c}$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G\rho_c \left[\Omega_{\mathrm{M}} \left(\frac{a_0}{a}\right)^3 + \Omega_{rad} \left(\frac{a_0}{a}\right)^4 + \Omega_{\Lambda}\right]$$


2.7 K
TODAY
14 by
accelerated expansion
4.4 K
matter domination
7.7 by
0.26 eV
recombination
370 ty
$e+p \to H+\gamma$
matter domination
0.8 eV
50 ty
radiation domination
50 keV
5 min
$^3H+{}^4He \to {}^7Li+\gamma$
primordial nucleosynthesis
$^2H+{}^2H \to n+{}^3He$
1 MeV
1 s
$p+p \to {}^2H+\gamma$
2.5 MeV
neutrino decoupling
0.1 s
200 MeV
QCD transition
10 μs
confinement↔free quarks
100 GeV
Electroweak phase transition
0.1 ns
baryogenesis
hot Universe
dark matter production
reheating
inflation

Outline

FLRW metric $g_{\mu\nu}$

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu = dt^2 - a^2(t) dl^2 = dt^2 - a^2(t)\gamma_{ij} dx^i dx^j \ ,$$

$$H(t) = \frac{\dot{a}(t)}{a(t)}$$

Special frame: different parts look similar
Also this is comoving frame: world lines of particles at rest are geodesics,

$$\frac{du^\mu}{ds} + \Gamma^\mu_{\nu\lambda} u^\nu u^\lambda = 0$$

$$\gamma_{ij} \approx \delta_{ij}$$

Photons in the expanding Universe

$$S = -\frac{1}{4}\int d^4x \sqrt{-g} g^{\mu\nu} g^{\lambda\rho} F_{\mu\lambda} F_{\nu\rho}$$

$dt = a d\eta$ conformally flat metric

$$ds^2 = dt^2 - a^2(t)\delta_{ij} dx^i dx^j \longrightarrow ds^2 = a^2(\eta)[d\eta^2 - \delta_{ij} dx^i dx^j]$$

$$S = -\frac{1}{4}\int d^4x \, \eta^{\mu\nu} \eta^{\lambda\rho} F_{\mu\lambda} F_{\nu\rho} \,, \qquad A_\mu^{(\alpha)} = e_\mu^{(\alpha)} e^{ik\eta - i\mathbf{kx}} \,, \quad k = |\mathbf{k}|$$

$$\Delta x = 2\pi/k \,, \quad \Delta\eta = 2\pi/k$$

$$\lambda(t) = a(t)\Delta x = 2\pi \frac{a(t)}{k} \,, \quad T = a(t)\Delta\eta = 2\pi \frac{a(t)}{k}$$

Redshift and the Hubble law $\lambda_0 = \lambda_i \frac{a_0}{a(t_i)} \equiv \lambda_i(1 + z(t_i))$

$$\mathbf{p}(t) = \frac{\mathbf{k}}{a(t)}\,, \quad \omega(t) = \frac{k}{a(t)}$$

for not very distant objects $1\,\text{pc} \approx 3\,\text{ly}$

$$a(t_i) = a_0 - \dot{a}(t_0)(t_0 - t_i) \quad \longrightarrow \quad a(t_i) = a_0[1 - H_0(t_0 - t_i)]$$

$$z(t_i) = H_0(t_0 - t_i) = H_0 r\,, \qquad z \ll 1$$

$$H_0 = h \cdot 100\,\frac{\text{km}}{\text{s} \cdot \text{Mpc}}\,, \qquad h \approx 0.68$$

similar reddening for other relativistic particles (small H, $\dot{H}$, etc.)

$\mathbf{p} = \frac{\mathbf{k}}{a(t)}$ is true for massive particles as well

Einstein equations

$T_{\mu\nu}$: macroscopic description $\frac{1}{2}\int d^4x\sqrt{-g}T_{\mu\nu}\delta g^{\mu\nu}$

$T_{\mu\nu} = (p+\rho)u_\mu u_\nu - g_{\mu\nu}p$ ideal liquid with $\rho(t)$ and $p(t)$

in the comoving frame $u^0 = 1$, $\mathbf{u} = 0$ (almost) always works

$$T_\mu^\nu = diag(\rho,\, -p)$$

$$ds^2 = dt^2 - a^2(t)\gamma_{ij}dx^i dx^j\,, \qquad \text{flat:}\quad \gamma_{ij} = \delta_{ij}$$

$$S_{EH} = -\frac{1}{16\pi G}\int d^4x\sqrt{-g}R \;:\quad R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G T_{\mu\nu}$$

$$(00):\quad \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3}G\rho - \frac{\varkappa}{a^2}$$

Expansion: an Adiabatic Process

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

the equation of state

$$p = p(\rho)$$

many-component liquid, in case of thermal equilibrium

other equations

$$-3d(\ln a) = \frac{d\rho}{p+\rho} = d(\ln s)$$

entropy of cosmic primordial plasma is conserved in a comoving frame

$$sa^3 = \text{const}$$

Examples of cosmological solutions

$$\varkappa = 0 \qquad \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G\rho$$

dust: $p = 0$ — singular at $t = t_s$

$$\rho = \frac{\text{const}}{a^3}\,, \quad a(t) = const \cdot (t - t_s)^{2/3}\,, \quad \rho(t) = \frac{\text{const}}{(t - t_s)^2}$$

$$t_s = 0\,, \quad H(t) = \frac{\dot{a}}{a}(t) = \frac{2}{3t}\,, \quad \rho = \frac{3}{8\pi G} H^2 = \frac{1}{6\pi G}\frac{1}{t^2}$$

the Universe is too young

$$t_0 = \frac{2}{3H_0} = 0.9 \times 10^{10}\ \text{yr} \quad (h = 0.7)$$

Cosmological (particle) horizon $l_H(t)$

distance covered by photons emitted at $t = 0$

the size of causally-connected region — the size of the visible part of the Universe

in conformal coordinates: $ds^2 = 0 \longrightarrow |d\mathbf{x}| = d\eta$
coordinate size of the horizon equals $\eta(t) = \int d\eta$

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

dust

$$l_H(t) = 3t = \frac{2}{H(t)}\,, \quad l_{H,0} = 2.6 \times 10^{28}\text{cm} \quad (h = 0.7)$$

Examples of cosmological solutions

radiation: $p = \frac{1}{3}\rho$ singular at $t = t_s$

$$\rho = \frac{\text{const}}{a^4}\,, \quad a(t) = const\cdot(t - t_s)^{1/2}\,, \quad \rho(t) = \frac{\text{const}}{(t-t_s)^2}$$

$$t_s = 0\,, \quad H(t) = \frac{\dot{a}}{a}(t) = \frac{1}{2t}\,, \quad \rho = \frac{3}{8\pi G}H^2 = \frac{3}{32\pi G}\frac{1}{t^2}$$

$$l_H(t) = a(t)\int_0^t \frac{dt'}{a(t')} = 2t = \frac{1}{H(t)}\,.$$

In case of thermal equilibrium $T = \text{const}/a$

$$\rho_b = \frac{\pi^2}{30}g_b T^4\,, \quad \rho_f = \frac{7}{8}\frac{\pi^2}{30}g_f T^4$$

$$\rho = \frac{\pi^2}{30}g_* T^4\,, \quad g_* = \sum_b g_b + \frac{7}{8}\sum_f g_f = g_*(T)$$

Examples of cosmological solutions

vacuum: $T_{\mu\nu} = \rho_{vac}\eta_{\mu\nu}$ $p = -\rho$

$$S_G = -\frac{1}{16\pi G}\int R\sqrt{-g}d^4x\ , \quad S_\Lambda = -\Lambda\int\sqrt{-g}d^4x\ .$$

$$a = \text{const}\cdot e^{H_{\text{dS}}t}\ , \quad H_{\text{dS}} = \sqrt{\frac{8\pi}{3}G\rho_{vac}}$$

de Sitter space: space-time of constant curvature

$$ds^2 = dt^2 - e^{2H_{dS}t}d\mathbf{x}^2$$

$\ddot{a} > 0$, no initial singularity

$ds^2 = dt^2 - e^{2H_{dS}t} d\mathbf{x}^2$

no cosmological horizon: $l_H(t) = e^{H_{dS}t} \int_{-\infty}^{t} dt' e^{-H_{dS}t'} = \infty$

de Sitter (events) horizon ($\mathbf{x} = 0$, t):

from which distance $l(t)$ one can detect light emitted at t?

in conformal coordinates: $ds^2 = 0 \longrightarrow |d\mathbf{x}| = d\eta$

coordinate size: $\eta(t \to \infty) - \eta(t) = \int_t^{\infty} \frac{dt'}{a(t')}$

physical size: $l_{dS} = a(t) \int_t^{\infty} \frac{dt'}{a(t')} = \frac{1}{H_{dS}}$

observer will never be informed what happens at distances larger than $l_{dS} = H_{dS}^{-1}$

Our future? with $H_{dS} = 0.8 \times H_0$

Microscopic processes in the expanding Universe

A competition between scattering, decays, etc and expansion

for general processes one should solve kinetic equations

$$\frac{dn_{X_i}}{dt} + 3Hn_{X_i} = \sum(production - destruction)$$

Boltzmann equation in a comoving volume: $\frac{d}{dt}\left(n\,a^3\right) = a^3 \int \ldots$

production:

$$\sigma(A+B \to X+C)n_A n_B, \quad \Gamma(D \to E+X)n_D \cdot M_D/E_D, \quad \text{etc}$$

desrtuction:

$$\sigma(A+X \to C+B)n_A n_X, \quad \Gamma(X \to F+G)n_X \cdot M_X/E_X, \quad \text{etc}$$

Fast direct and inverse processes, $\Gamma \gtrsim H$, are in equilibrium,

$\sum(\ ) = 0$ and thermalize particles

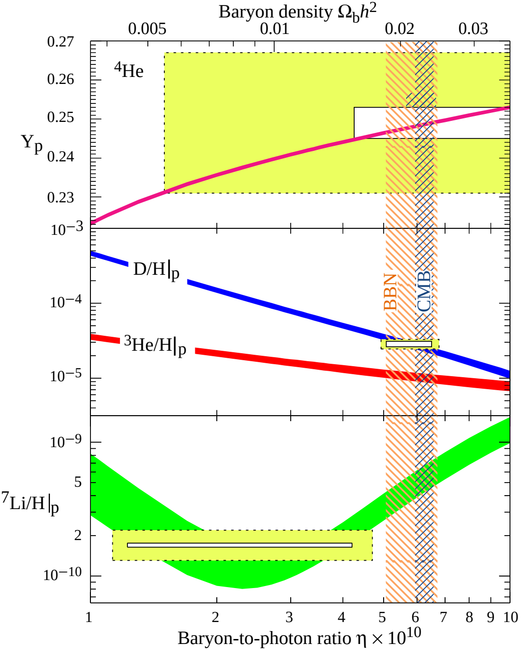
BBN: Main nuclear reactions

1. $p(n,\gamma)$D — deuterium production, BBN starts.
2. D$(p,\gamma)^3$He, D(D,n)^{3}He, D(D,p)T, ^{3}He(n,p)T — intermediate stage.
3. T(D,n)^{4}He, ^{3}He(D,p)^{4}He — production of ^{4}He.
4. T$(\alpha,\gamma)^7$Li, ^{3}He$(\alpha,\gamma)^7$Be, ^{7}Be$(n,p)^7$Li — production of the heaviest baryonic relics.
5. ^{7}Li$(p,\alpha)^4$He — ^{7}Li burning.

One has to compare reaction rates to the expansion rate

$$H(T_{NS} = 80 \text{ keV}) = 4 \times 10^{-3} \text{ s}^{-1}$$

to obtain nonequilibrium concentrations



Primordial Element Abundance Observations:

- Lack of Lithium. . . Exotics needed?
- Measurement of $\eta_B = n_B/n_\gamma$ at $T \sim 1$ MeV consistent with present and recombination values
  – no "decaying relics"
- measurement of the Universe expansion rate
  $H^2 \sim \rho_{relativistic}$
  in particular:
  – neutrino number $N_\nu \approx 3$
  – no "dark radiation"

Baryon asymmetry must be produced before BBN !!

Baryogenesis

Sakharov conditions of successful baryogenesis

- B-violation $(\Delta B \neq 0)\ XY \dots \to X'Y' \dots B$
- C- & CP-violation $(\Delta C \neq 0,\ \Delta CP \neq 0)\ \bar{X}\bar{Y} \dots \to \bar{X}'\bar{Y}' \dots \bar{B}$
- processes above are out of equilibrium $X'Y' \dots B \to XY \dots$

At 100 GeV$\lesssim T \lesssim 10^{12}$ GeV nonperturbative processes (EW-sphalerons) violate B, L_α, so that only three charges are conserved out of four, e.g.

$$B - L\,, \quad L_e - L_\mu\,, \quad L_e - L_\tau$$

and $B = \alpha \times (B - L)$, $L = (\alpha - 1) \times (B - L)$

Leptogenesis: Baryogenesis from lepton asymmetry of the Universe ...

Why $\Omega_B \sim \Omega_{DM}$? antropic principle?

Outline

Big Bang within GR and SM: facts and numbers

- Universe is homogeneous, isotropic, flat and expanding
- present Universe age is 14 by, visible size is 4.5 Gpc
- present Universe density is like 5 protons/m^3
- Baryons (5%), Dark Matter (27%), Dark Energy (68%)
- Universe was hot at least from $T \simeq 1$ MeV
- Expansion is an adiabatic process
- Homogeneous 3-d Universe has no “center”
- Big Bang was global rather than local phenomenon

Cosmology asks for New Physics

Big Bang within GR and SM: problems

- Dark Matter
- Baryogenesis
- Horizon, Enthropy, Flatness, ... problems
  $l_{H_0}/l_{\mathrm{H},r}(t_0) \sim \sqrt{1+z_r} \simeq 30$
- Singularity at the beginning
- Heavy relics
- Initial fluctuations $\qquad \delta T/T \sim \delta\rho/\rho \sim 10^{-4}$, scale-invariant
- Dark Energy $\qquad 0 \neq \Lambda \ll M_{Pl}^4\,,\; M_W^4\,,\; \Lambda_{QCD}^4\,,$ etc ?
- Coincidence problems:

$$\Omega_B \sim \Omega_{DM} \sim \Omega_\Lambda\;,$$
$$\eta_B = n_B/n_\gamma \sim (\delta T/T)^2\;,$$
$$T_d^n \sim (m_n - m_p)\;,$$
$$\ldots$$

- ΛCDM tensions: lack of dwarfs? cusps? ...

Simple tasks to be solved ✍

1. Refine the estimate of the age of our Universe

$$t_0 = \frac{1}{H_0} = 14 \times 10^9 \,\text{years}$$

2. When (z_{acc}, t_{acc}, T_γ – ?) did deceleration-acceleration transition happen?
3. When (z_{EQ}, t_{EQ}, T_γ – ?) did matter-radiation transition (Equality) happen?

   Hint: neutrino contribution to radiation energy density is 70% of photon contribution
4. Find the time of Electroweak phase transition, $T \sim 100\,\text{GeV}$

   The early Universe to be tested at LHC . . .

   Hint: all SM particles contribute to energy density as about 50 photon species