Lecture #1
Introduction to the Hot Big Bang Theory

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Standard Model + GR : Major Problems

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

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

- Describes all experiments dealing with
  - electroweak and strong interactions (anomalies! $g-2$, B-physics, ...)
- Does not describe

(PHENO)

- Neutrino oscillations
- Dark matter (Ω_{DM})
- Baryon asymmetry (Ω_B)
- Why the Universe is flat and homogeneous?
- Where did the matter perturbations come from?

(THEORY)

- Dark energy (Ω_Λ)
- Strong CP-problem
- Gauge hierarchy
- Quantum gravity
- Quantization of electric charge
- Why 3 generations?
- Why $Y_e \ll Y_\mu \ll .. \ll Y_t$

Problems in astrophysics. . . (?)

- Origin of extragalactic magnetic fields
- First stars and reionization of the Universe
- Mechanism of SuperNovae explosion
- Sources of Ultra-high energy cosmic rays (EeV-scale)
- Extremely low IR extragalactic background
- Too old White Dwarfs
- Origin of Fast Radio Bursts
- Origin of ICECUBE neutrinos (PeV-scale)
- Origin of Superheavy Black holes in the galactic centers
- . . .
- Helioseismology vs spectroscopy
- Origin of the internal heat at the Earth

New Physics and New Cosmology may be either responsible for or testable there

Experimental data in Particle Physics

- We know the initial states of particles before interaction,
  use photons, electrons, positrons, protons, neutrons, ions, neutrinos...
- Then they collide and we measure the particles in the final state
- Thus we learn about interaction
- Each experiment may be repeated:
  – with the same facility
  – building a copy in the same or other place
  – constructing similar devise
  ...
  And results must be the same
  ...on average within QM need many collisions

  theory predicts distributions

Experimental data in Cosmology and Astrophysics

- Each experiment may be unique (unrepeatable):
  – observe only one Universe
  – (so far) registered only one SN explosion
  – might observe only one magnetic monopole (?)
  – can study only one star
  – (so far) can study only one planet
  ...
- we register photons, neutrinos, gravitational waves, electrons, positrons, protons, nuclei,
  but only photons, neutrinos and gravitational waves can point at the source
- Can not directly check the model of sources
- Can not directly check the media in between

Outline

"Natural" units in particle physics

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

measured in GeV: energy E, mass M, temperature T

$m_p = 0.938$ GeV, $1\ \text{K} = 8.6 \times 10^{-14}$ GeV

measured in GeV^{-1}: time t, length L

$1\ \text{s} = 1.5 \times 10^{24}\ \text{GeV}^{-1}$, $1\ \text{cm} = 5.1 \times 10^{13}\ \text{GeV}^{-1}$

Gravity (General Relativity): $V(r) = -G\frac{m_1 m_2}{r}$ $\quad [G] = M^{-2}$

$M_{\text{Pl}} = 1.2 \times 10^{19}\ \text{GeV} = 22\ \mu\text{g}$ $\quad G \equiv \frac{1}{M_{\text{Pl}}^2}$

"Natural" units in cosmology

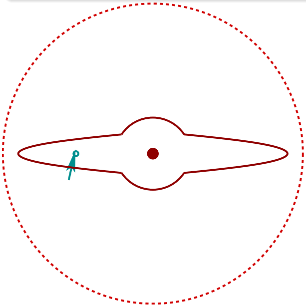
$1\ \mathrm{Mpc} = 3.1 \times 10^{24}\ \mathrm{cm}$

$1\ \mathrm{AU} = 1.5 \times 10^{13}\ \mathrm{cm}$ — mean Earth-to-Sun distance

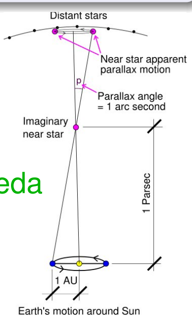
$1\ \mathrm{ly} = 0.95 \times 10^{18}\ \mathrm{cm}$ — distance light travels in one year

$1\ \mathrm{yr} = 3.16 \times 10^{7}\ \mathrm{s}$

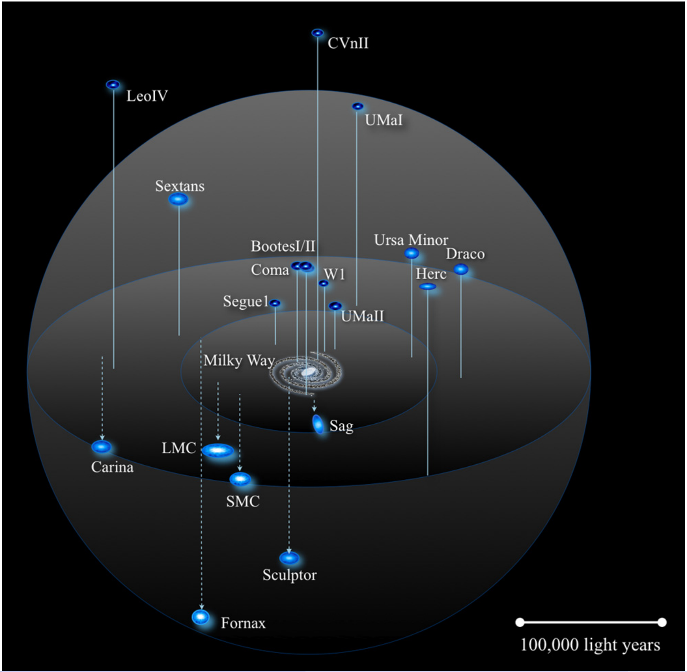
$1\ \mathrm{pc} = 3.3\ \mathrm{ly} = 3.1 \times 10^{18}\ \mathrm{cm}$ — distance to object which has a parallax angle of one arcsec



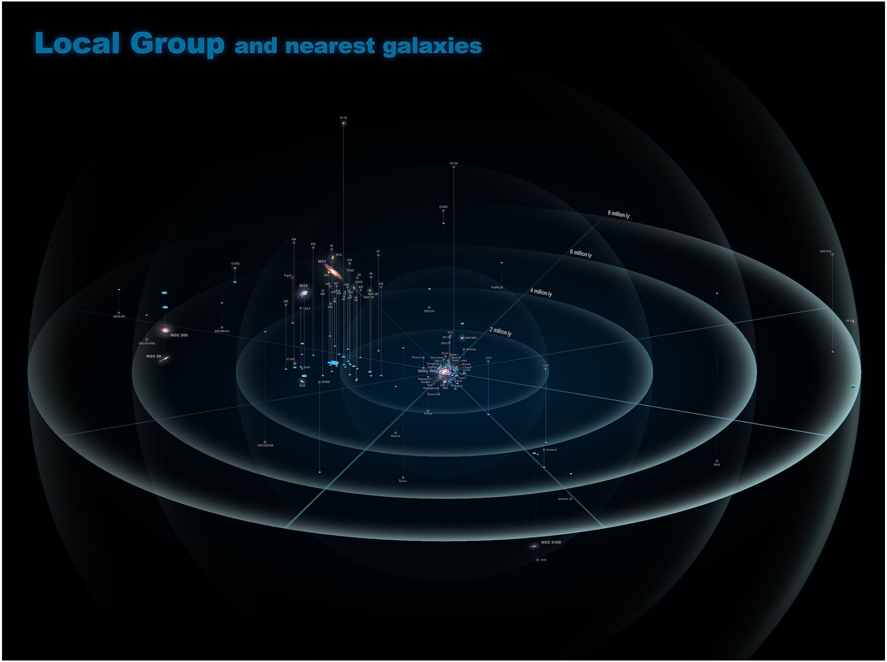
100 AU — Solar system size
1.3 pc — nearest-to-Sun stars
1 kpc — size of dwarf galaxies
50 kpc — distance to dwarfs
0.8 Mpc — distance to Andromeda
1-3 Mpc — size of clusters
15 Mpc — distance to Virgo



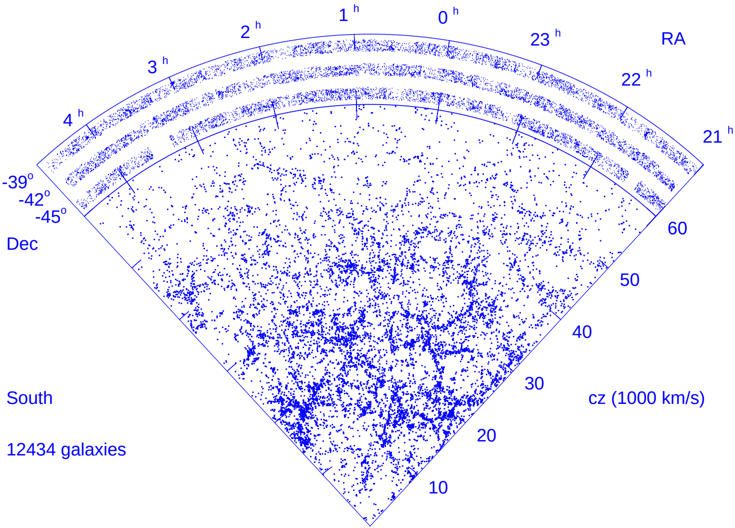
Outline



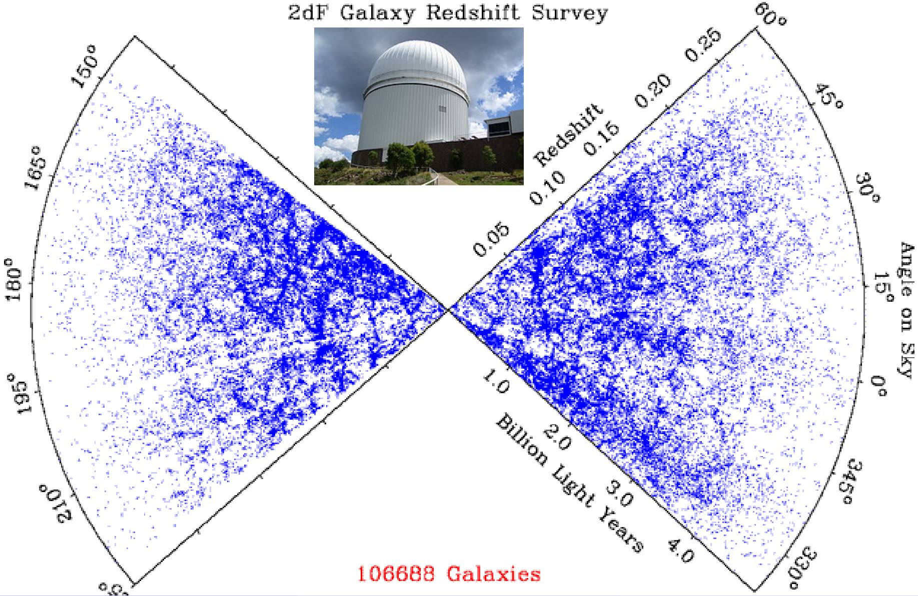
The Universe is very inhomogeneous at small spatial scales and we cannot predict 'our neighborhood' from the first principles and we possibly have (?) problems with structure and abundance of dwarf galaxies

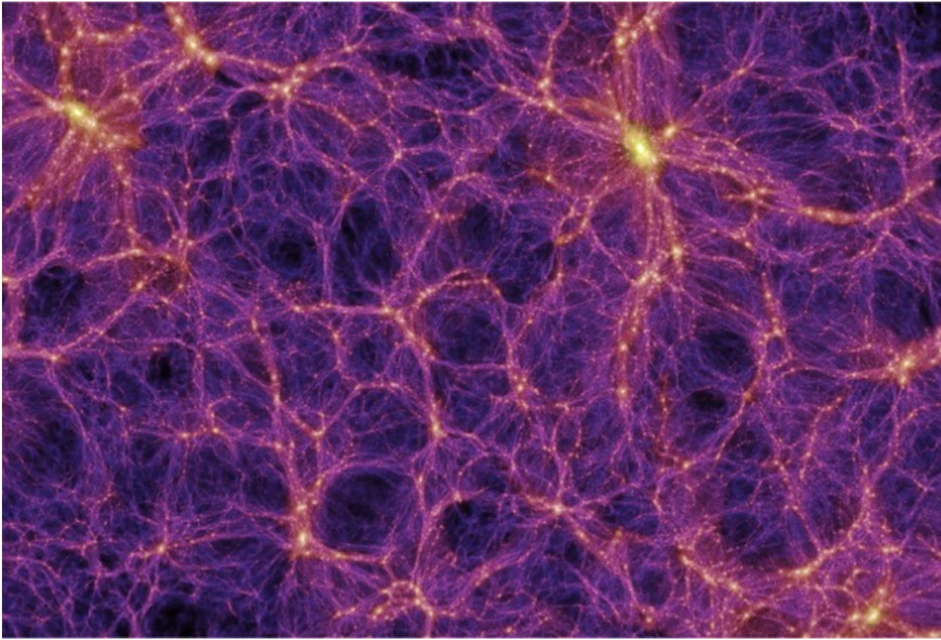

Local Group and nearest galaxies
8 million ly
6 million ly
4 million ly
2 million ly
M31
M33
NGC 300
NGC 55
Milky Way
NGC 3109

Large scales: we can predict galaxy mass spectrum



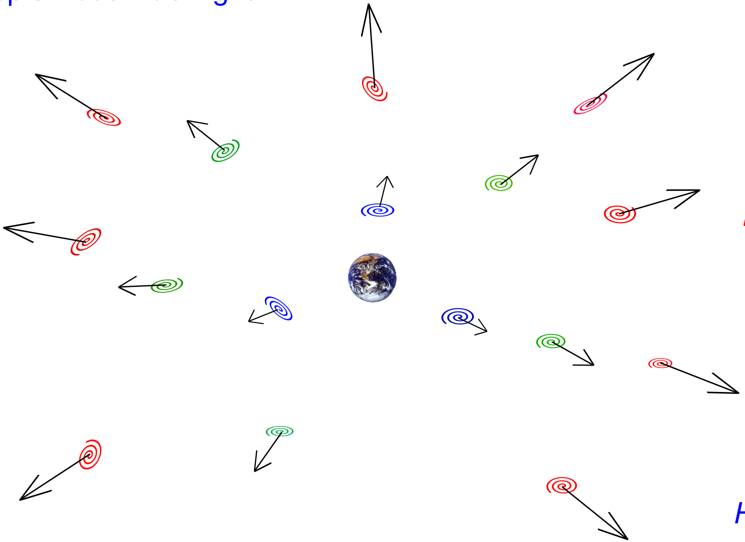
Very large scales: homogeneity and isotropy





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

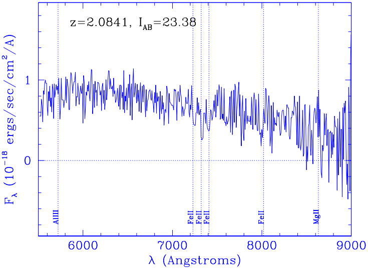
Hubble Law

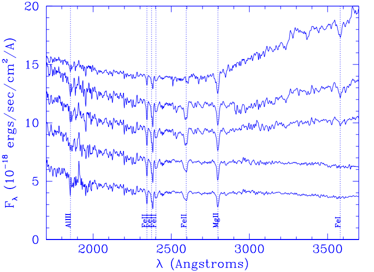
$H(t_0)\, r = v_r$

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

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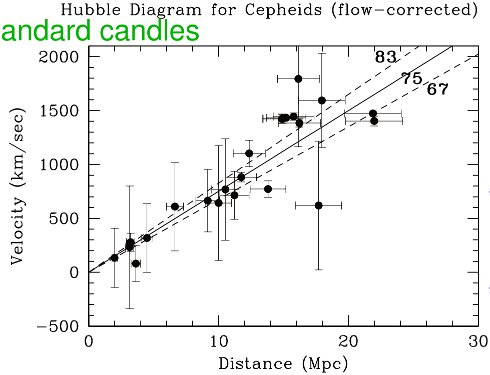
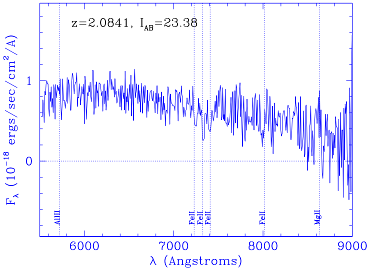
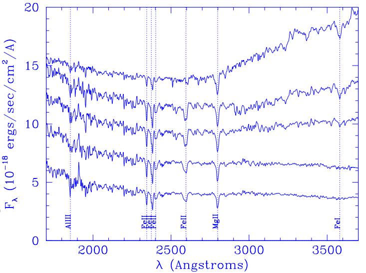
standard candles







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 $R_{curv} > 10 \times l_{H_0}$

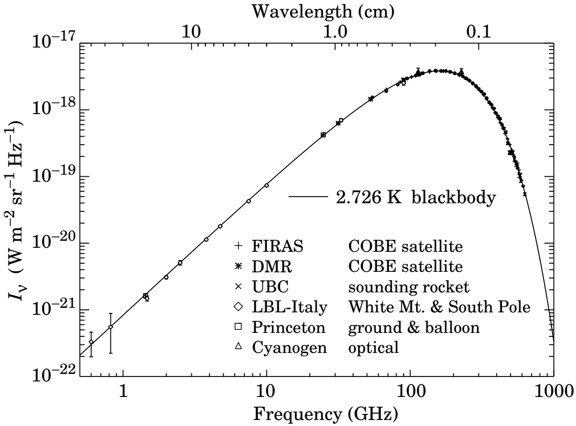
order-of-magnitude estimate: $GM_U/l_U \sim G\rho_0 l_{H_0}^3/l_{H_0} \sim 1$

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



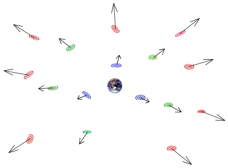
$T_0 = 2.726$ K

the spectrum (shape and normalization!) is thermal

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

Conclusions from observations

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



Conclusions

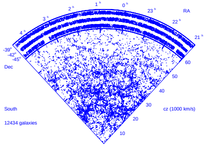
- interval between events gets modified

$$ds^2 = c^2\,dt^2 - a^2(t)\,d\mathbf{x}^2$$

in GR expansion is described by the Friedmann equation

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

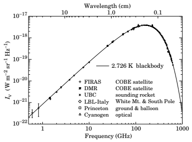
$$\rho^{\text{energy}}_{\text{density}} = \rho_{\text{radiation}} + \rho_{\text{matter}} + \dots$$



- 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 back to $T \sim 1\,\text{MeV} \sim 10^{10}\,\text{K}$



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

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

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

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

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

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

Gas of free particles in the expanding Universe

homogeneous gas $$dN = f(\mathbf{p}, t) d^3\mathbf{X} d^3\mathbf{p}$$

in comoving coordinates:

$$d^3\mathbf{x} = \text{const}\,, \quad d^3\mathbf{k} = \text{const}\,, \quad f(k) = \text{const}$$

$$f(k) d^3\mathbf{x} d^3\mathbf{k} = \text{const}$$

comoving volume equals physical volume

$$d^3\mathbf{x} d^3\mathbf{k} = d^3(a\mathbf{x}) d^3\left(\frac{\mathbf{k}}{a}\right) = d^3\mathbf{X} d^3\mathbf{p}$$

$$f(\mathbf{p}, t) = f(\mathbf{k}) = f[a(t) \cdot \mathbf{p}]\,.$$

$$t = t_i \;:\quad f_i(\mathbf{p}) \;\longrightarrow\; f(\mathbf{p}, t) = f_i\left(\frac{a(t)}{a(t_i)}\mathbf{p}\right)$$

Relic photons exhibit thermal spectrum

$$f_i(\mathbf{p}) = f_{\text{Pl}}\left(\frac{|\mathbf{p}|}{T_i}\right) = \frac{1}{(2\pi)^3}\frac{1}{e^{|\mathbf{p}|/T_i}-1}$$

$$f(\mathbf{p},t) = f\left(\frac{a(t)|\mathbf{p}|}{a_i T_i}\right) = f\left(\frac{|\mathbf{p}|}{T_{eff}(t)}\right)$$

$$T_{eff}(t) = \frac{a_i}{a(t)}T_i$$

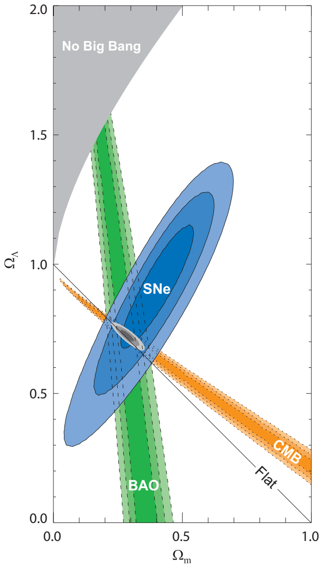
decoupling at $T \gg m$: neutrinos, hot(warm) dark matter

decoupling at $T \ll m$: $f(\mathbf{p}) = \frac{1}{(2\pi)^3}\exp\left(-\frac{m-\mu_i}{T_i}\right)\exp\left(-\frac{a^2(t)\mathbf{p}^2}{2ma_i^2 T_i}\right)$

$$f(\mathbf{p},t) = \frac{1}{(2\pi)^3}\exp\left(-\frac{m-\mu_{eff}}{T_{eff}}\right)\exp\left(-\frac{\mathbf{p}^2}{2mT_{eff}}\right)$$

$$T_{eff}(t) = \left(\frac{a_i}{a(t)}\right)^2 T_i\,, \qquad \frac{m-\mu_{eff}(t)}{T_{eff}} = \frac{m-\mu_i}{T_i}$$

Cosmological data suggest . . . DM, DE, flatness, etc



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

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

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

$$\rho_\Lambda = \text{const}, \quad 1/a^2(t) \propto \rho_{\text{curvature}} = 0$$

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

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

Outline

Einstein equations for homogeneous Universe

$T_{\mu\nu}$: 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 fluid with $\rho(t)$ and $p(t)$

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

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

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

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

$(00):\quad \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3}G\rho$ both expansion and contraction $t \to -t$

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

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

the equation of state

$$p = p(\rho)$$

many-component fluid, 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

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

usefull: for any decouled component $n_X/s = \text{const}$

Examples of realistic cosmological solutions

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

dust: $p = 0$ singular at $t = t_s$

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

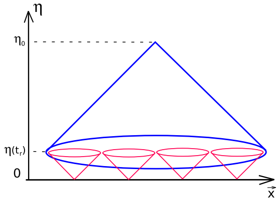
$$t_s = 0\,, \quad H(t) = \frac{\dot{a}}{a}(t) = \frac{2}{3t}\,, \quad \rho = \frac{3}{8\pi G} H^2 = \frac{1}{6\pi G}\frac{1}{t^2}$$

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 — horizon problem

$$l_H(t) = 3t = \frac{2}{H(t)}\,.$$

Examples of realistic cosmological solutions

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

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

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

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

If 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 realistic cosmological solutions

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

$$S_\Lambda = -\Lambda \int \sqrt{-g} d^4 x \, .$$

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

de Sitter space: space-time of constant curvature

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

$\ddot{a} > 0$, 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 $H_{dS} = 0.8 \times H_0$

Outline

Friedmann equation for the present Universe

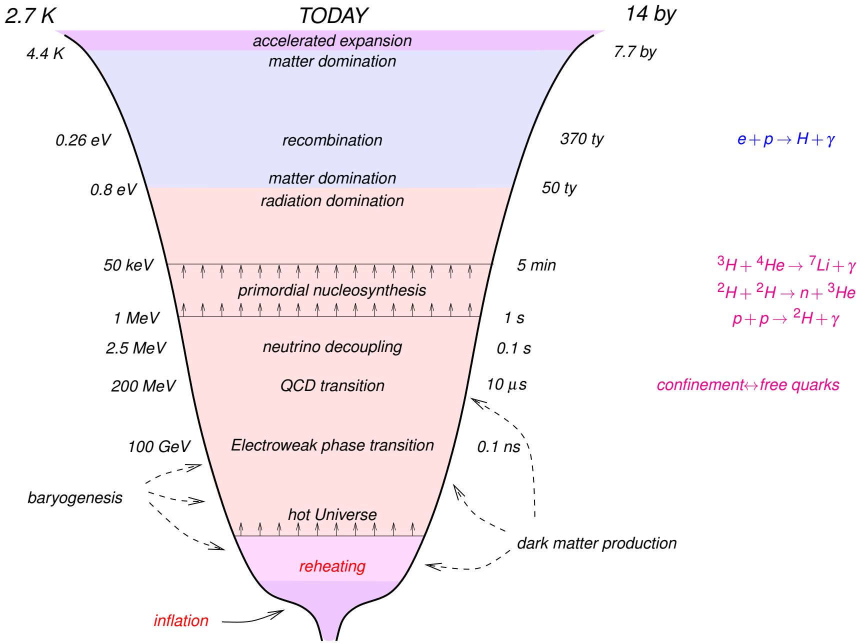
$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G\left(\rho_{\mathrm{M}} + \rho_{rad} + \rho_{\Lambda}\right)$$

$$\rho_c \equiv \frac{3}{8\pi G} H_0^2$$

$$\rho_c = \rho_{\mathrm{M},0} + \rho_{rad,0} + \rho_{\Lambda,0} = \rho_c = 0.5 \cdot 10^{-5} \frac{\mathrm{GeV}}{\mathrm{cm}^3} \,,$$

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

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


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
radiation domination
50 ty
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

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: $\frac{d}{dt}\left(n\,a^3\right) = a^3 \int \dots$

production:

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

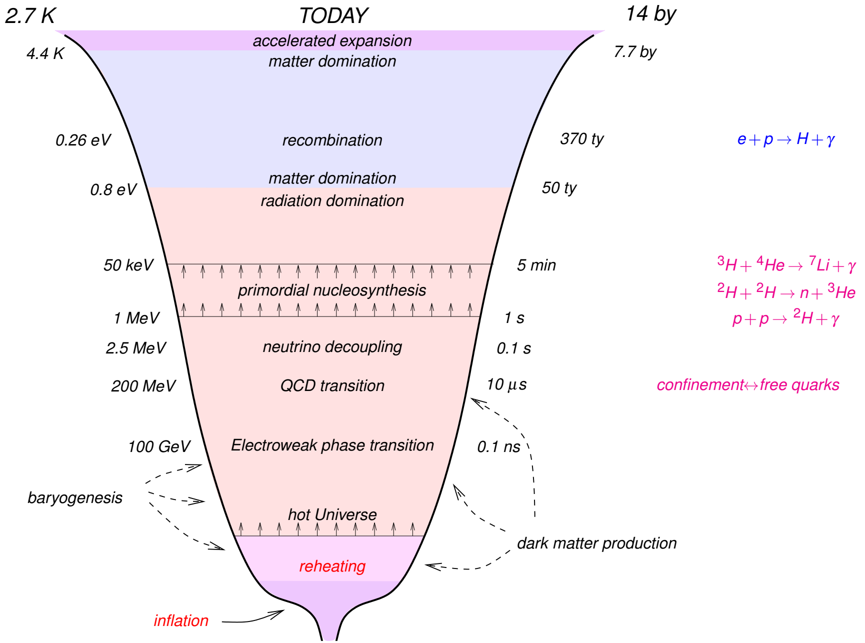
destruction:

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

Fast processes, $\Gamma \gtrsim H$, are in equilibrium, $\sum(\ ) = 0$

and thermalize particles

no history-dependence


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$\leftrightarrow$free quarks
100 GeV
Electroweak phase transition
0.1 ns
baryogenesis
hot Universe
dark matter production
reheating
inflation

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

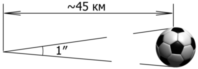
$\Delta s^2 = c^2\,\Delta t^2 - a^2\,(t)\,\Delta\vec{x}^2 \;\rightarrow\; ds^2 = g_{\mu\nu}\,dx^\mu\,dx^\nu$ Light propagation changes. . .

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

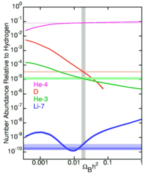
"standard candles"

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

In the expanding Universe all these laws get modified

Present knowledge about the past: back to 2-3 MeV

past stages		observables
deceleration/acceleration	$\ddot{a} = 0$	SN Ia, CMB, clusters
reionization	$\gamma + H \to p + e$	CMB, quasars, stars
recombination	$p + e \to \gamma + H^*$	CMB, BAO
RD/MD equality	$\rho_{\text{matter}} = \rho_{\text{radiation}}$	CMB, BAO
nucleosynthesis	$p + n \to D + \gamma,\ etc$	cold gas clouds
neutrino decoupling	$\nu_e + n \to p + e$	cold gas clouds



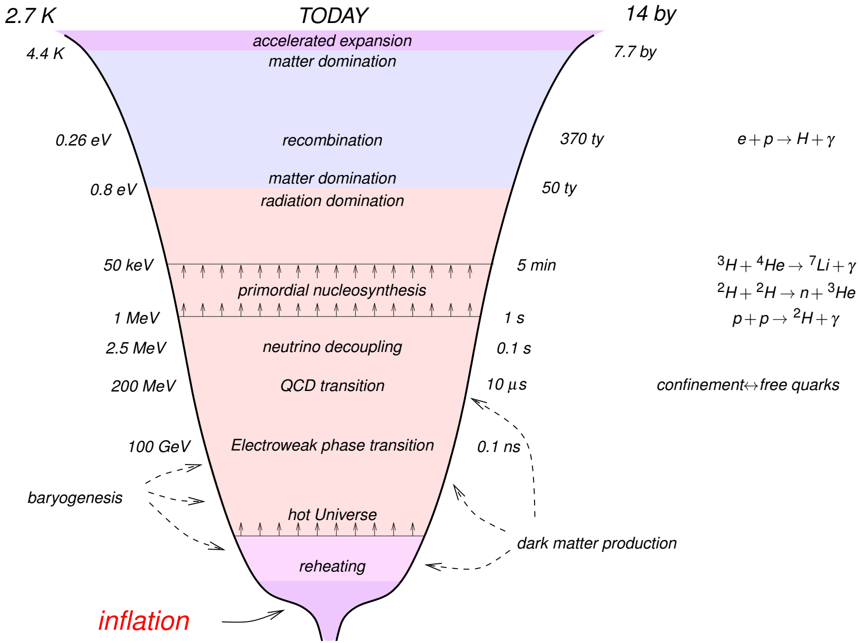
$$H^2 \propto \rho_\gamma + \rho_\nu$$

New Physics in Cosmology: any energy scales. . .

Cosmology constrains the time-scale, rather than energy-scale

$$\Gamma \sim H \propto T^2/M_{\rm Pl}$$

- Dark matter (if particles) — be produced by $T \gg 1\,\text{eV}$
- Dark energy — be present by $T \gg 5\,\text{K}$
- Baryon asymmetry — be generated by $T \gg 1\,\text{MeV}$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0.1 s
200 MeV
QCD transition
10 μs
confinement↔free quarks
100 GeV
Electroweak phase transition
0.1 ns
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hot Universe
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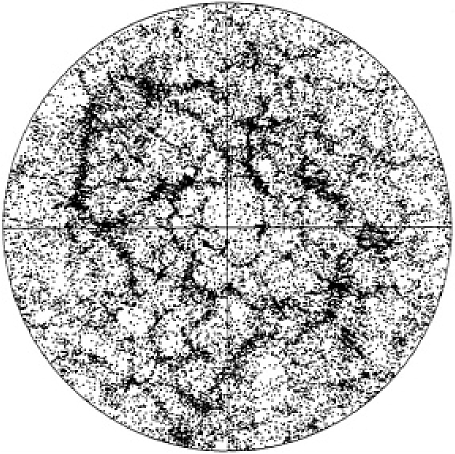
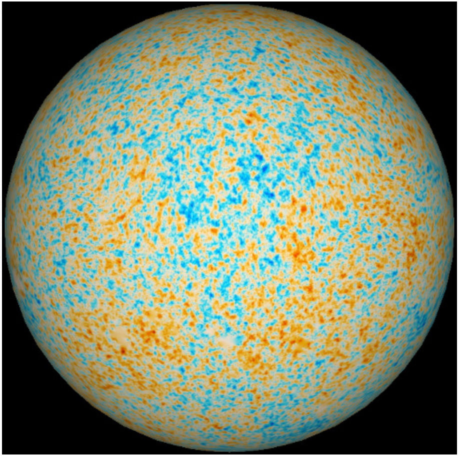
Inhomogeneous Universe





Large Scale Structure

CMB anisotropy

These inhomogeneities (matter perturbations)

originate from the initial matter density (scalar) perturbations

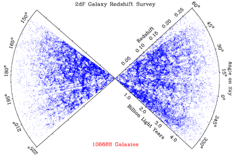
$\delta\rho/\rho \sim \delta T/T \sim 10^{-4}$, which are

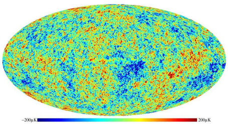
adiabatic $\quad \delta\left(\frac{n_B}{s}\right) = \delta\left(\frac{n_{DM}}{s}\right) = \delta\left(\frac{n_L}{s}\right)$

Gaussian $\quad \langle \frac{\delta\rho}{\rho}(\mathbf{k}) \frac{\delta\rho}{\rho}(\mathbf{k}') \rangle \propto \left(\frac{\delta\rho}{\rho}(\mathbf{k})\right)^2 \times \delta(\mathbf{k}+\mathbf{k}')$

flat spectrum $\quad \langle \left(\frac{\delta\rho}{\rho}(\mathbf{x})\right)^2 \rangle = \int_0^\infty \frac{\mathbf{dk}}{\mathbf{k}} \mathscr{P}_S(\mathbf{k}) \qquad \mathscr{P}_S(\mathbf{k}) \approx \text{const}$

LSS and CMB $\quad \mathscr{P}_S \equiv A_S \times \left(\frac{k}{k_*}\right)^{n_s-1} \qquad A_S \approx 2.5 \times 10^{-9}, \quad n_S \approx 0.97$





Standard cosmological model $ds^2 = dt^2 - a^2(t)dx^2$

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = H_0^2 \left[\Omega_\Lambda + (\Omega_{DM} + \Omega_B + \Omega_{\nu,m\neq 0})\left(\frac{a_0}{a}\right)^3 + (\Omega_\gamma + \Omega_{\nu,m=0})\left(\frac{a_0}{a}\right)^4\right]$$

- $T_\gamma = 2.735\,\text{K}, \quad \Longrightarrow \quad \Omega_\gamma \sim 10^{-5}$
- $N_\nu \approx 3, \quad \sum m_\nu < 0.2\,\text{eV} \quad \Longrightarrow \quad \Omega_{\nu,\neq 0}, \Omega_{\nu,0} \sim 10^{-5}$?
- $\Omega_B = 4.5\% \quad \Longrightarrow \quad \eta_B \equiv n_B/n_\gamma = 6 \times 10^{-10}$
- $\Omega_{DM} = 27.5\%$
- $l_{s,rec} \sim l_{H,rec}/\sqrt{3} \to \quad H_0 = 67\,\text{km/s/Mpc} \quad \Longrightarrow \quad \rho_0 = 5\,\text{GeV}/\text{m}^3$
- $\Omega_\Lambda = 68\% \quad \Longrightarrow$ flat space
- adiabatic, gaussian matter perturbations

$$\langle\left(\frac{\delta\rho}{\rho}\right)^2\rangle \sim A_S \int \frac{dk}{k}\left(\frac{k}{k_*}\right)^{n_S-1}$$

  with $A_S = 3 \times 10^{-9}$ and $n_S = 0.97$
- no tensor perturbations, $r \equiv A_T/A_S < 0.05$
- reionization at $z \equiv a_0/a = 8$

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

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

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

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

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

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

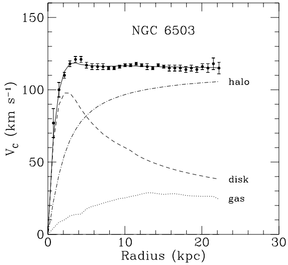
$$\rho_\Lambda = \text{const}$$

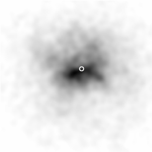
Why do we think it is most probably new particle physics
(new gravity if any is not enough) ?

DM at various spatial scales, BAU requires baryon number violation

Universe content from astrophysics

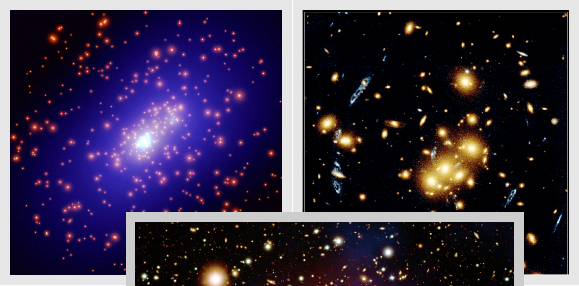
Rotational curves





X-rays from centers of galaxy clusters

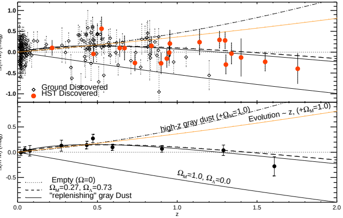
Gravitational lensing



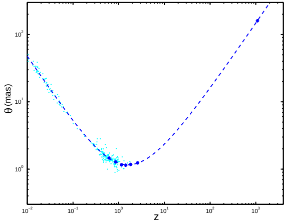
“Bullet” cluster

Universe content from cosmology

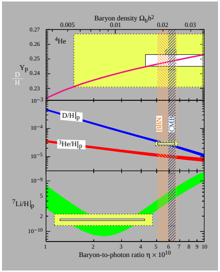
Standard candles

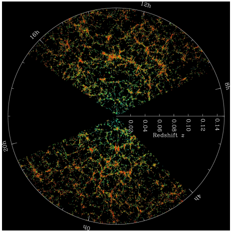


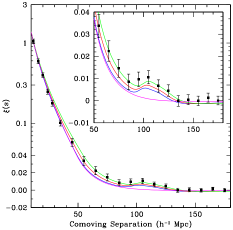
Angular distance

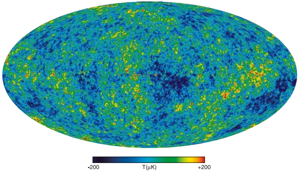


Nucleosynthesis









Large Scale Structures | Baryon acoustic oscillations | CMB anisotropy

Outline

World-wide accepted problems. . .

Origins of...?

- Dark Matter
- Matter-antimatter asymmetry
- Dark Energy
- matter perturbations
- entropy
- flatness
- homogeneity
- extragalactic magnetic field
- superheavy black holes in the galaxy centers
- . . .

Coincidences

- $\Omega_{DM} \sim \Omega_B$
- $\Omega_M \sim \Omega_{DE}$
- $(\delta\rho/\rho)^2 \simeq n_B/n_\gamma$
- $T_d^n \sim (m_n - m_p)$
-

Discrepancies in cosmological parameters

- Hubble parameter measurements

  Hubble from local measurements and cosmic ladder vs CMB

  astrophysics vs cosmology

- Cluster counts

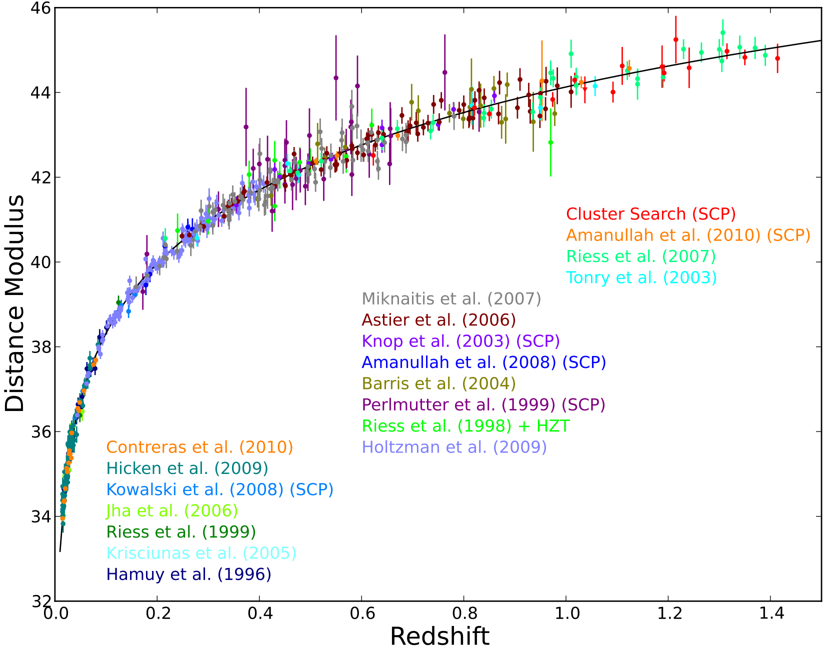
  matter clustering σ_8 from cluster number counts vs CM & BAO

  or X-ray telescopes & Planck vs Planck

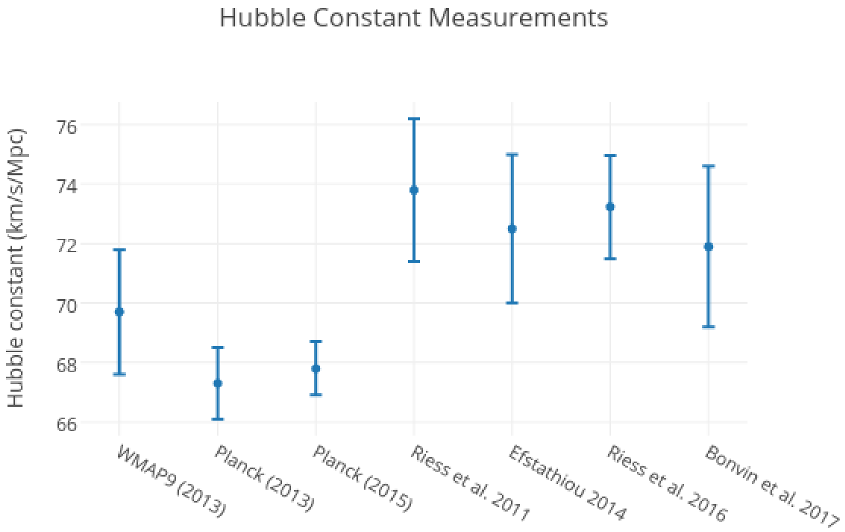
- Cosmic shear

  galaxies vs CMB spots as sources for gravitational lensing

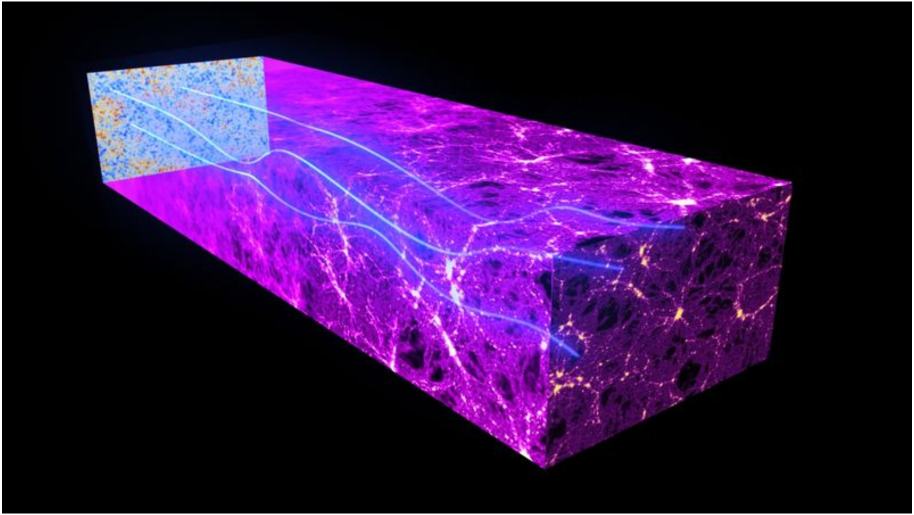
  or CFHTLens vs Planck

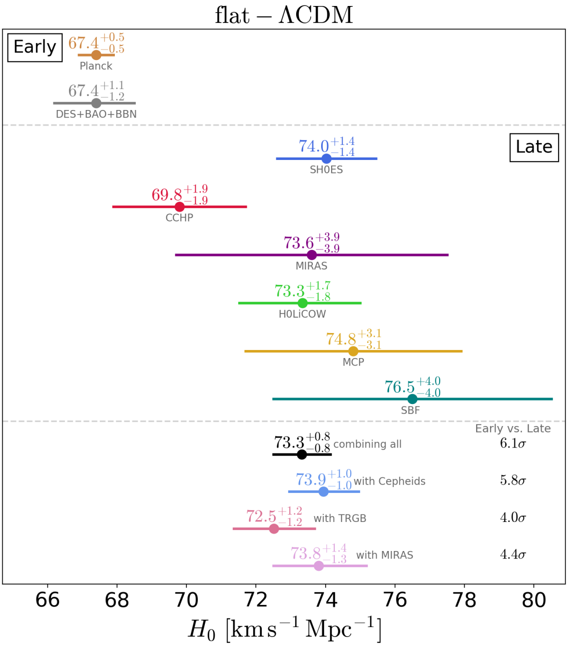


46
44
42
40
38
36
34
32
Distance Modulus
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Redshift
Cluster Search (SCP)
Amanullah et al. (2010) (SCP)
Riess et al. (2007)
Tonry et al. (2003)
Miknaitis et al. (2007)
Astier et al. (2006)
Knop et al. (2003) (SCP)
Amanullah et al. (2008) (SCP)
Barris et al. (2004)
Perlmutter et al. (1999) (SCP)
Riess et al. (1998) + HZT
Holtzman et al. (2009)
Contreras et al. (2010)
Hicken et al. (2009)
Kowalski et al. (2008) (SCP)
Jha et al. (2006)
Riess et al. (1999)
Krisciunas et al. (2005)
Hamuy et al. (1996)


Hubble Constant Measurements
Hubble constant (km/s/Mpc)
76
74
72
70
68
66
WMAP9 (2013)
Planck (2013)
Planck (2015)
Riess et al. 2011
Efstathiou 2014
Riess et al. 2016
Bonvin et al. 2017

Inhomogeneities from CMB & LSS: propagation in expanding Universe

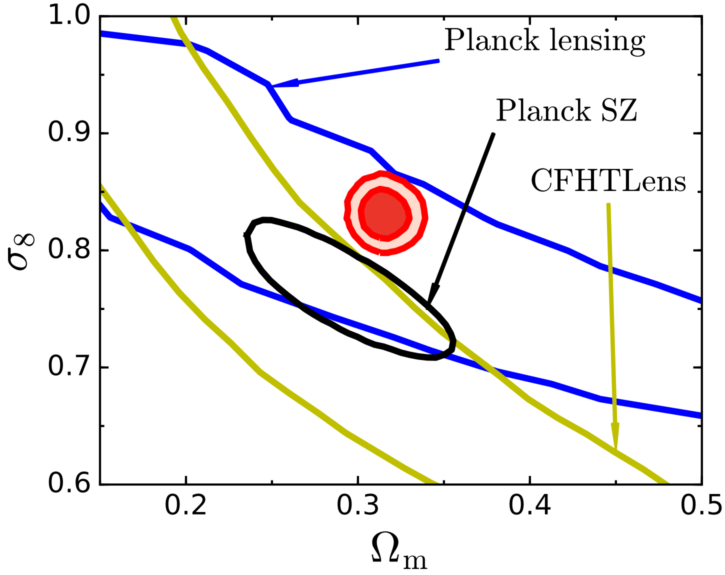



flat − ΛCDM
Early
$67.4^{+0.5}_{-0.5}$
Planck
$67.4^{+1.1}_{-1.2}$
DES+BAO+BBN
Late
$74.0^{+1.4}_{-1.4}$
SH0ES
$69.8^{+1.9}_{-1.9}$
CCHP
$73.6^{+3.9}_{-3.9}$
MIRAS
$73.3^{+1.7}_{-1.8}$
H0LiCOW
$74.8^{+3.1}_{-3.1}$
MCP
$76.5^{+4.0}_{-4.0}$
SBF
Early vs. Late
$73.3^{+0.8}_{-0.8}$ combining all
6.1σ
$73.9^{+1.0}_{-1.0}$ with Cepheids
5.8σ
$72.5^{+1.2}_{-1.2}$ with TRGB
4.0σ
$73.8^{+1.4}_{-1.3}$ with MIRAS
4.4σ
66
68
70
72
74
76
78
80
$H_0\ [\mathrm{km\,s^{-1}\,Mpc^{-1}}]$

1907.10625

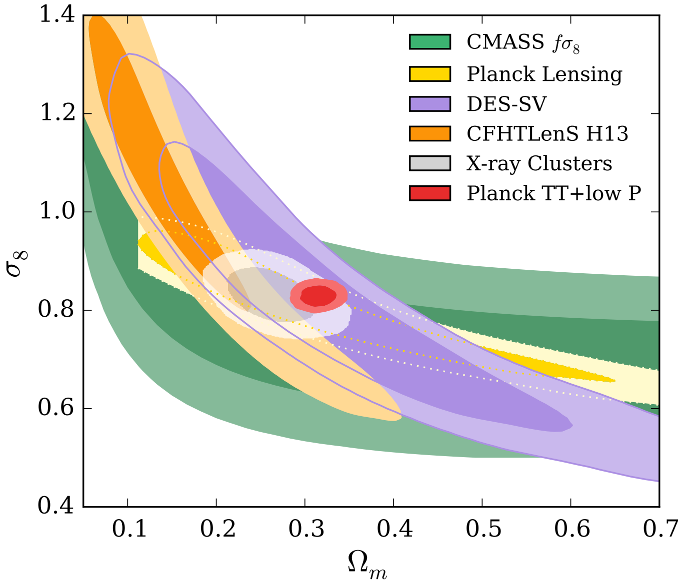
Lensing vs clusters

1801.07348



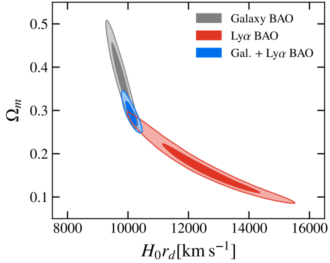
Cosmic shear and clusters

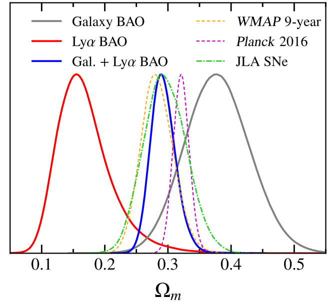
1507.05552

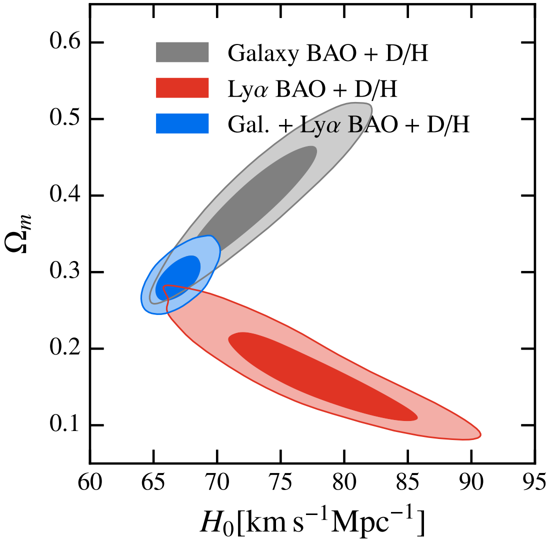


Impact of BAO: Galaxies vs Ly-α

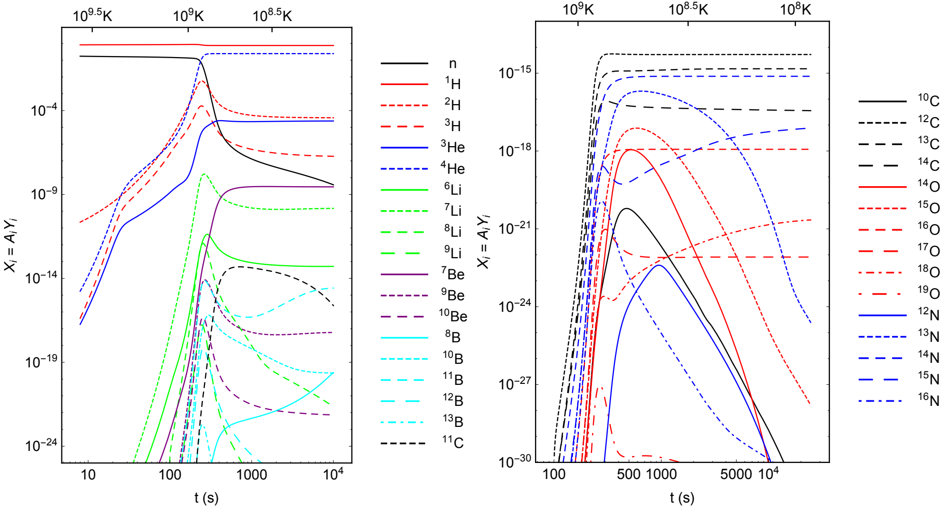
1707.06547







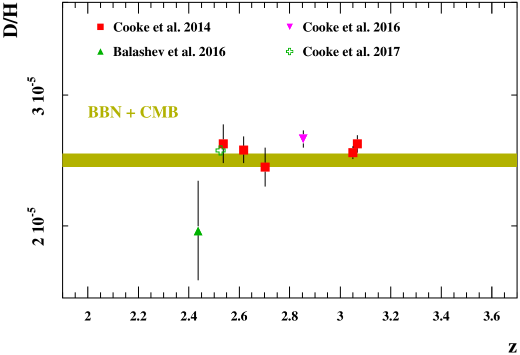
Discrepancy in Nucleosynthesis: Lithium (for decades)

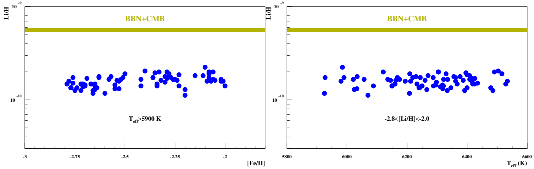


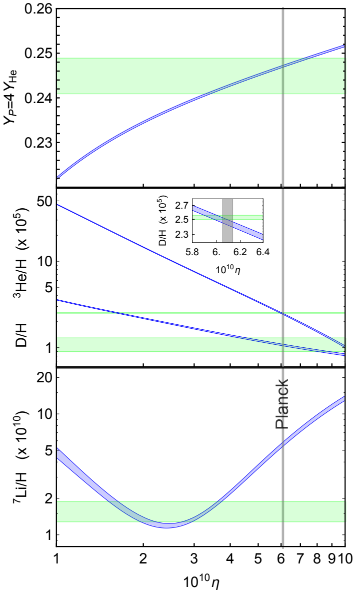
1801.08023

Nucleosynthesis

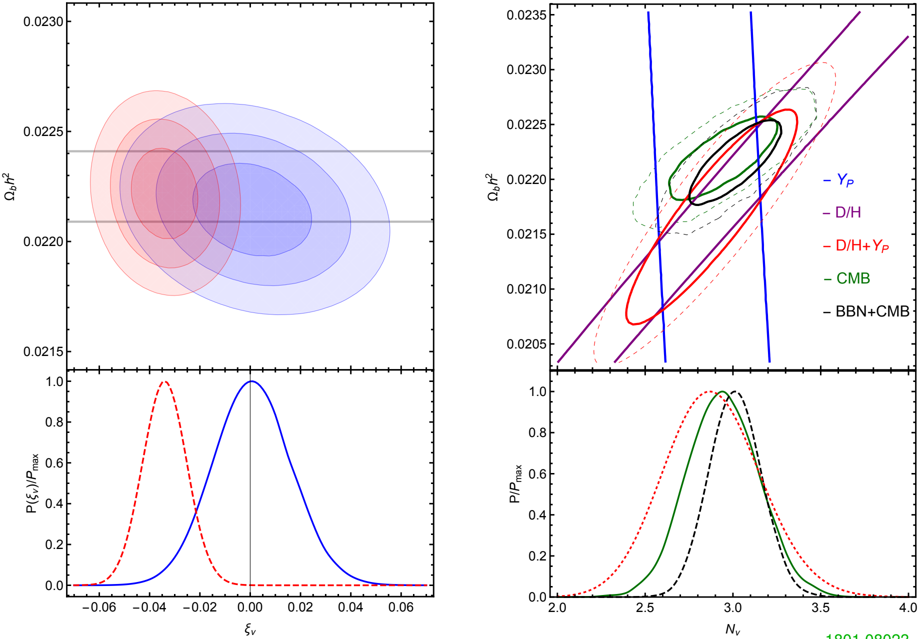
$$\eta = n_B/n_\gamma$$







1801.08023


0.0230
0.0225
0.0220
0.0215
$\Omega_b h^2$
1.0
0.8
0.6
0.4
0.2
0.0
$P(\xi_\nu)/P_{max}$
−0.06
−0.04
−0.02
0.00
0.02
0.04
0.06
ξ_ν
0.0235
0.0230
0.0225
0.0220
0.0215
0.0210
0.0205
– Y_P
– D/H
– D/H+Y_P
– CMB
– BBN+CMB
P/P_{max}
2.0
2.5
3.0
3.5
4.0
N_ν

1801.08023

Anomalies with matter structures at small scales

- Core-cusp problem

  Dark Matter density profiles in the centers of simulated halos are cusped
  while in observed dwarf galaxies are cored

- Lack of dwarf galaxies

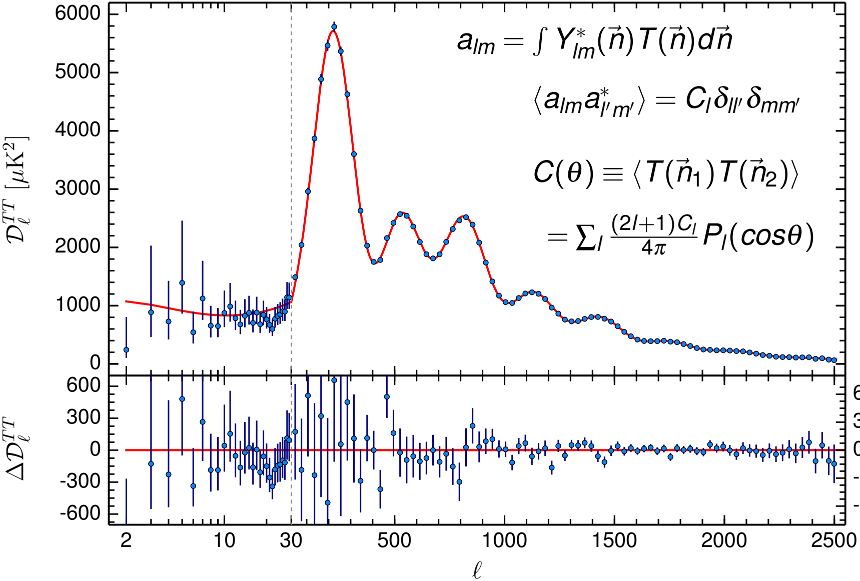
  Matter perturbations of almost flat spectrum produce flat halo mass spectrum
  low abundance of small galaxies

- Too-big-To-fail problem

  There must be galaxies heavy enough to keep baryons inside
  Milky Way hosts only two such galaxies

CMB anisotropy spectrum by Planck

1502.01582



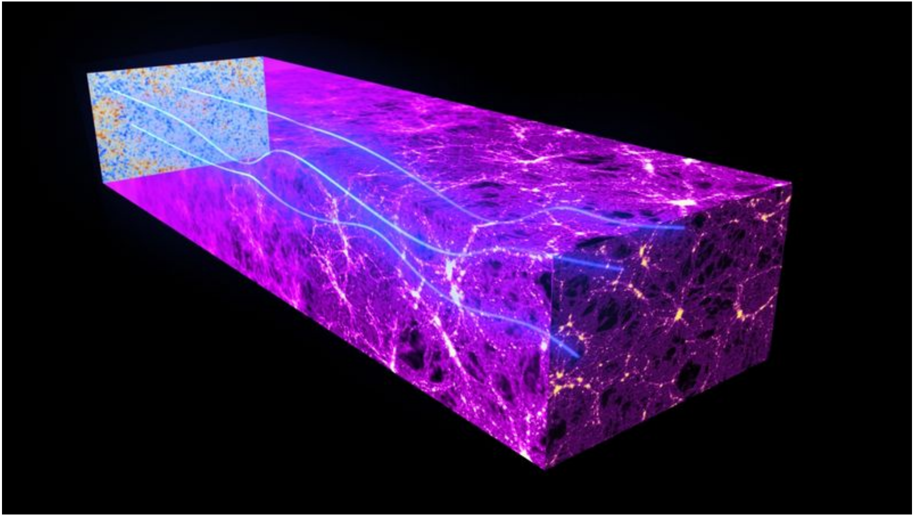
$$a_{lm} = \int Y^*_{lm}(\vec{n})T(\vec{n})d\vec{n}$$

$$\langle a_{lm}a^*_{l'm'}\rangle = C_l\delta_{ll'}\delta_{mm'}$$

$$C(\theta) \equiv \langle T(\vec{n}_1)T(\vec{n}_2)\rangle$$

$$= \sum_l \frac{(2l+1)C_l}{4\pi} P_l(cos\theta)$$

Initial or Induced: propagation in expanding Universe



CMB anomalies

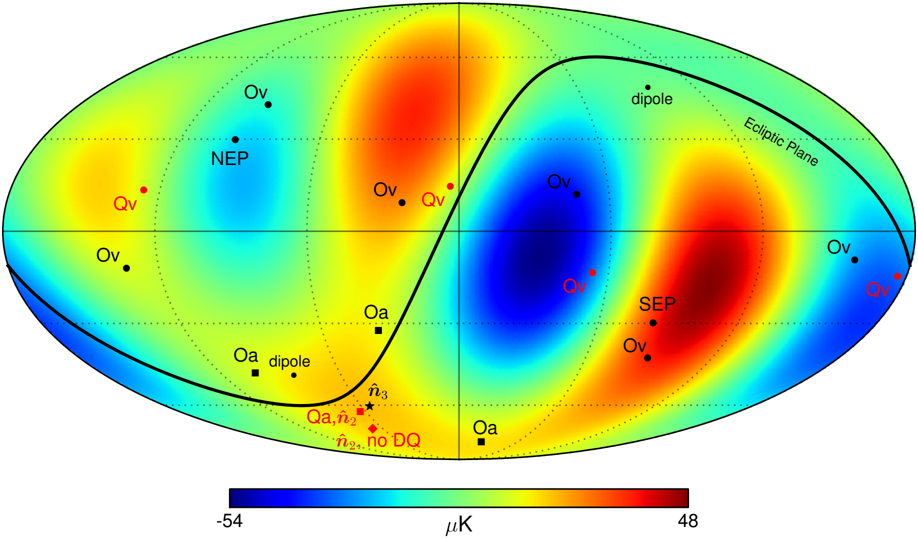
- quadrupole-octopole alignment, $p < 0.5\%$
- $l = 1, 2, 3$ alignment, $p < 0.2\%$
- odd parity preference $l_{max} = 28$, $p < 0.3\%$; $l_{max} < 50$, $p < 2\%$ (lee)
- dipolar modulation for $l = 2 - 67$, $p < 1\%$
- cold spot, $p < 1\%$
- low variance ($N_{side} = 16$), $p < 0.5\%$
- 2-correlation $\chi^2(\theta > 60^\circ)$, $p < 3.2\%$
- 2-correlation $S_{1/2}$, $p < 0.3\%$; (larger masks) $p < 0.1\%$
- hemispherical variance asymmetry, $p < 0.1\%$

$$S_{1/2} \equiv \int_{-1}^{1/2} C^2(\theta) d(\cos\theta)$$

topology? primordial spectrum with broken scale invariance or isotropy? ISW from local LSS? ... Foregrounds?

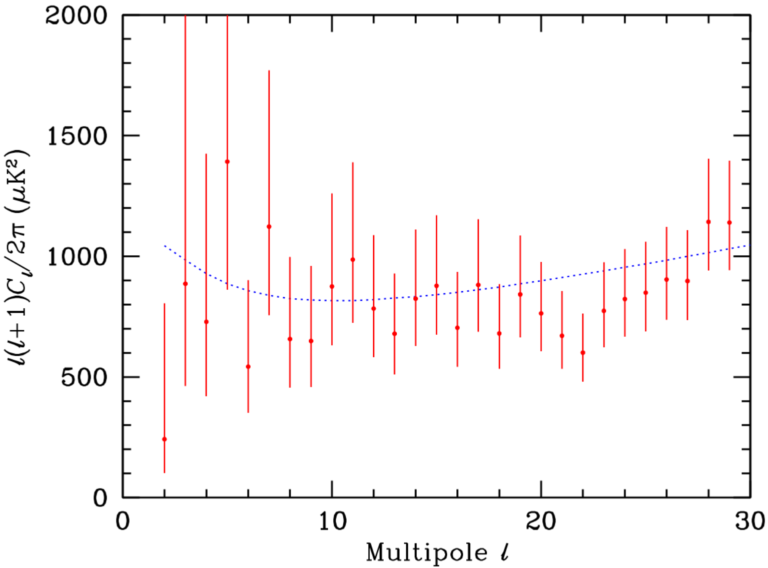
CMB anisotropy: alignment

1502.01582



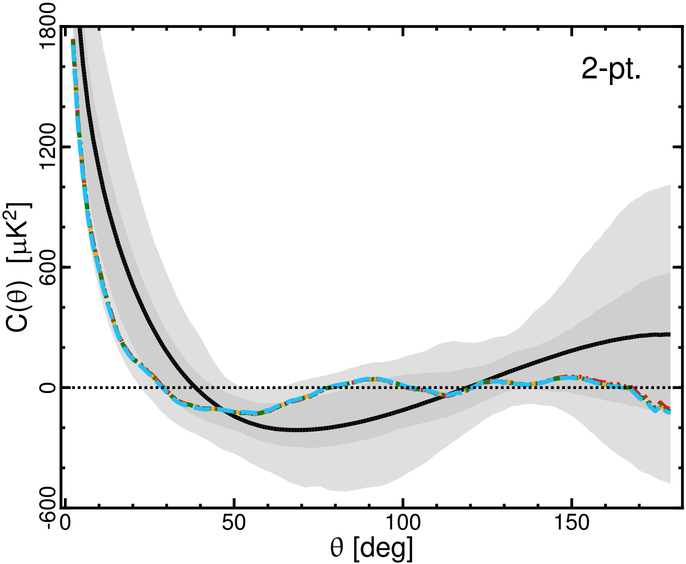
CMB anisotropy at large angles

1603.09703



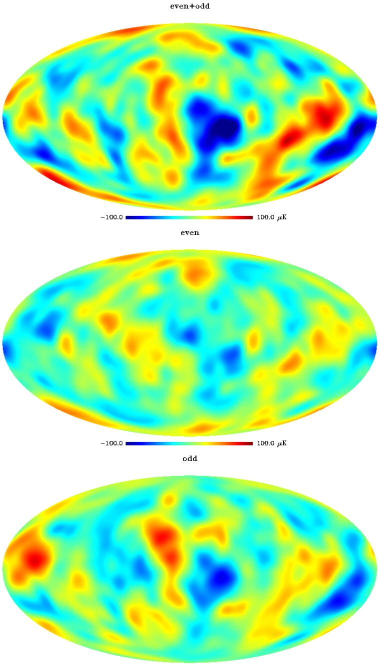
Low variance and correlation

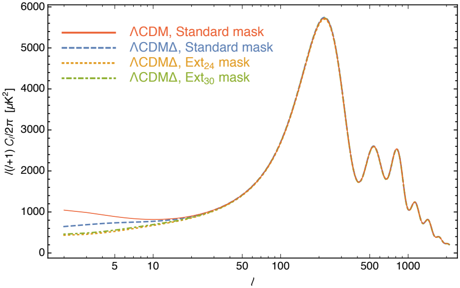
1506.07135

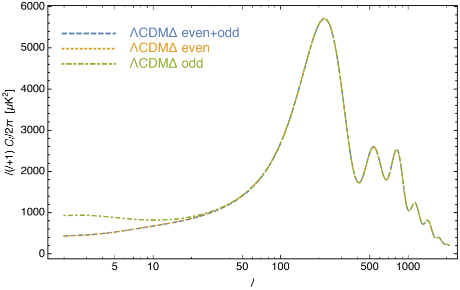


$C_l = \frac{1}{2l+1}\sum_{m=-1}^{m=1}|a_{lm}|^2$

$\mathrm{Var}[C_l] = \frac{2}{2l+1}C_l^2$





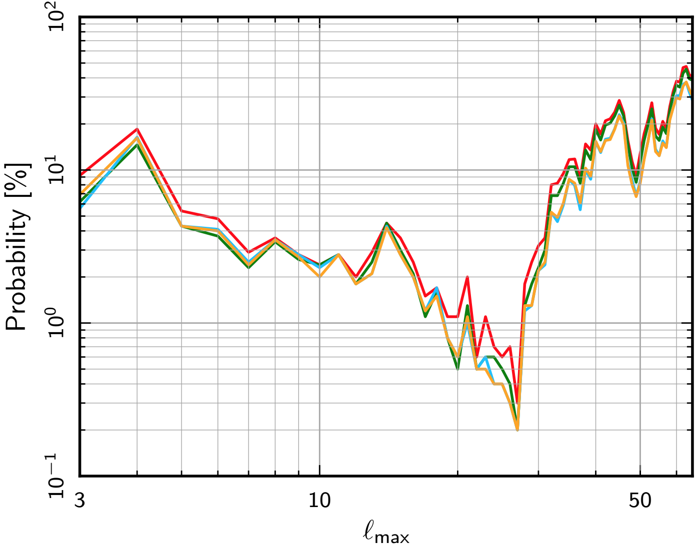


$$P(k) = k^3/(k^2 + \Delta^2)^{2-n_s/2}$$

1712.03288

Odd parity

1506.07135

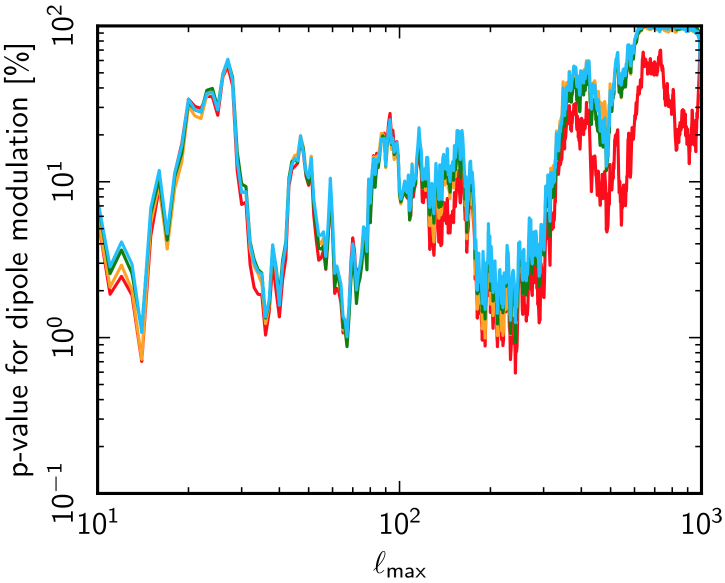


$$2\left(\frac{\delta T}{T}(\vec{n})\right)_{\pm} \equiv$$

$$\frac{\delta T}{T}(\vec{n}) \pm \frac{\delta T}{T}(-\vec{n})$$

Dipolar modulation

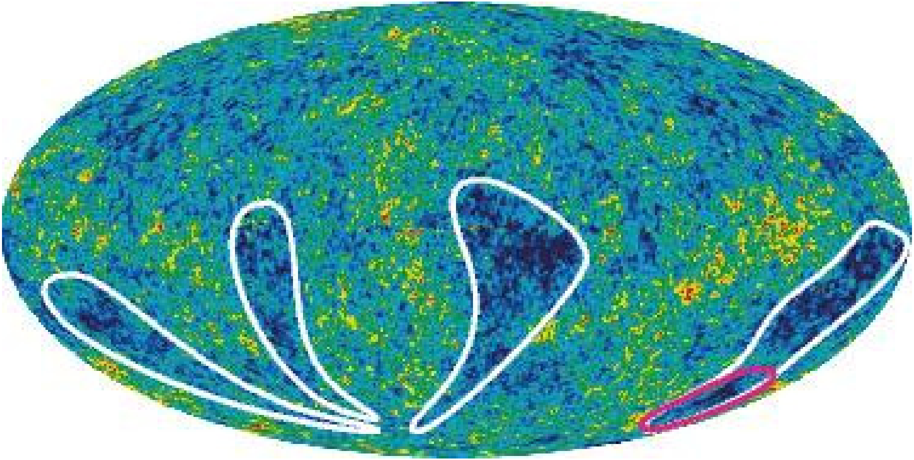
1506.07135



$T(\vec{n}) \to (1 + \vec{w}\vec{n})\,T(\vec{n})$

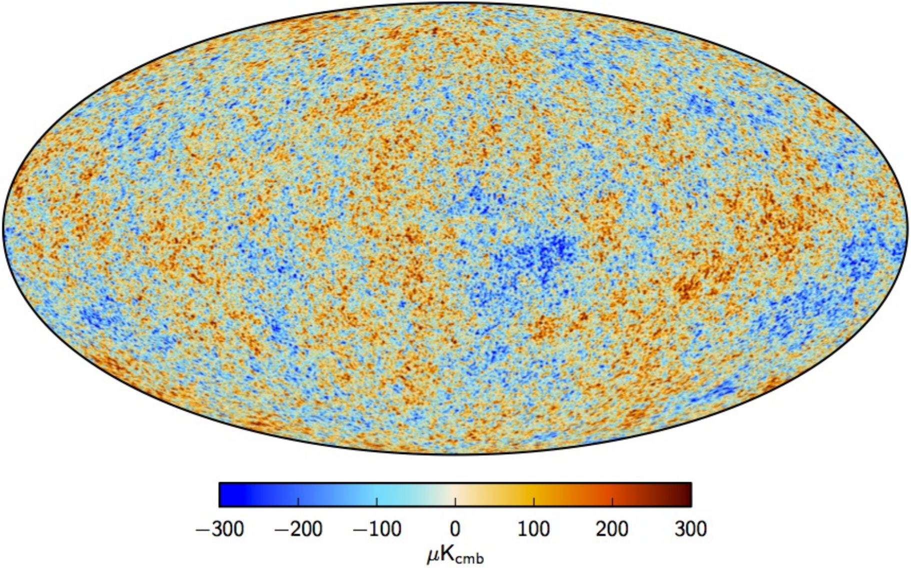
Cold spot (WMAP)

1001.4758



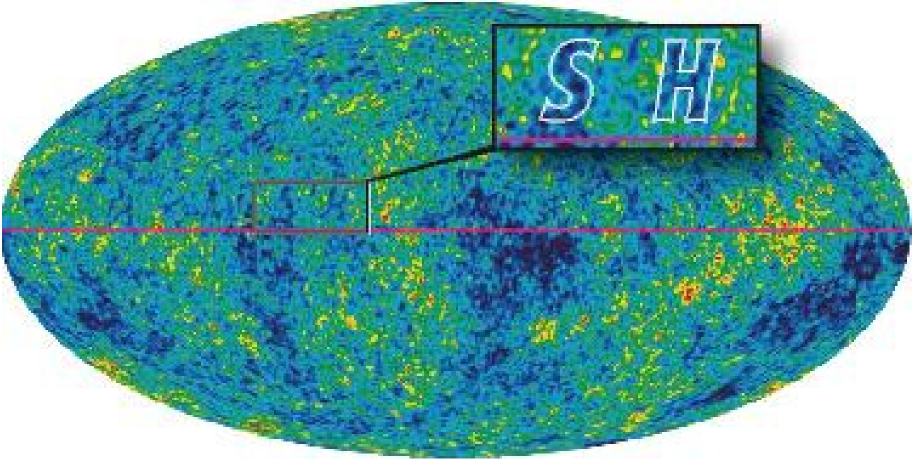
Cold spot (Planck)

1502.01582



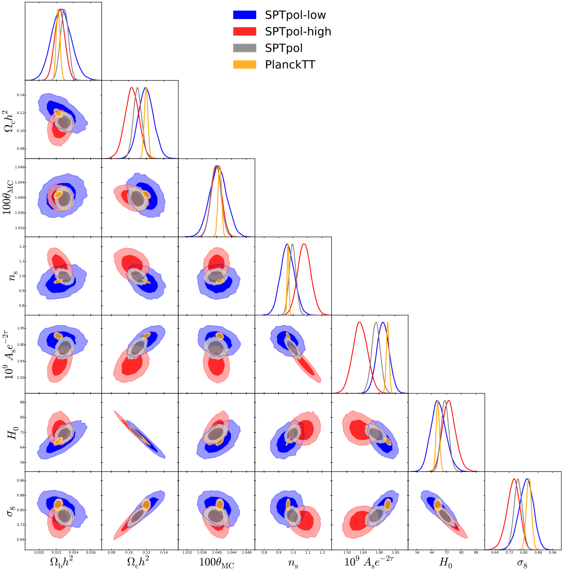
Letters in the sky

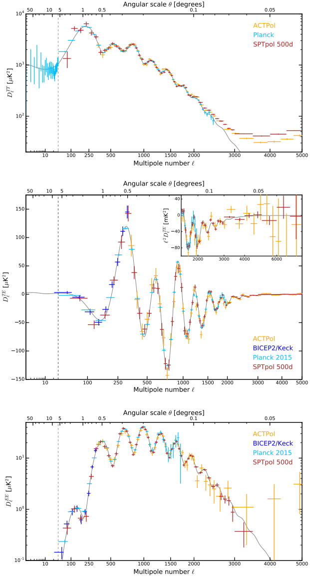
1001.4758



SPTPole with critical $l = 1000$

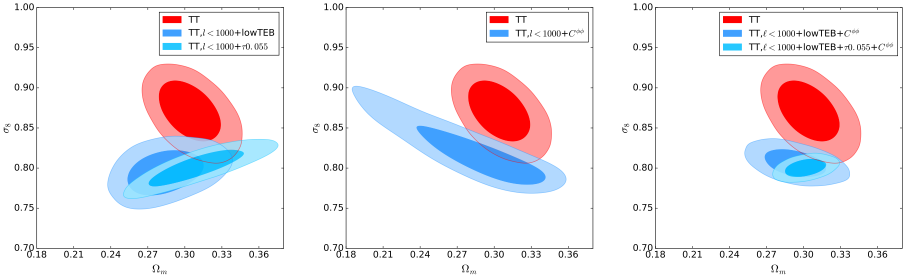
1707.09353





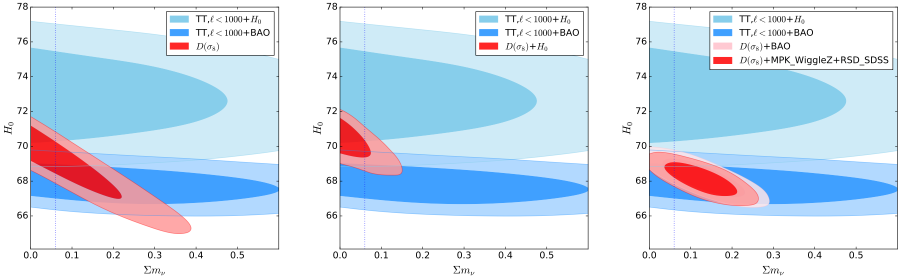
Neglecting Planck results with $l > 1000$

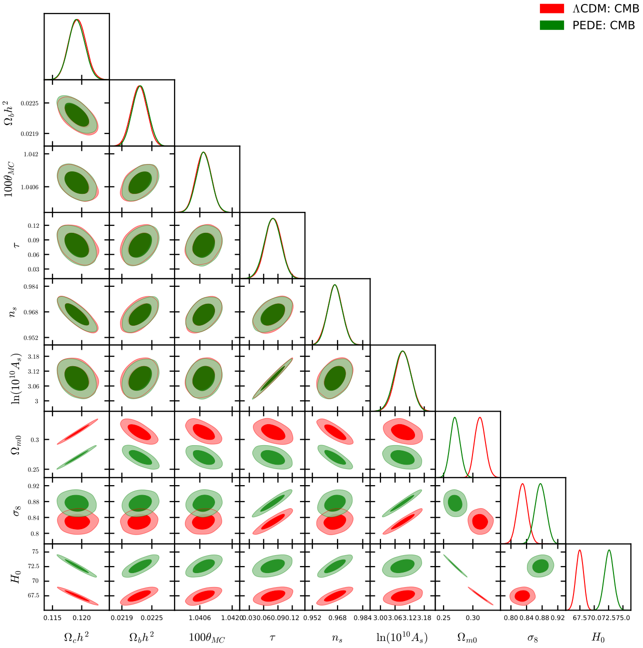
R. Burenin, 1806.03261



Neutrino mass?? (but not Hubble)

R. Burenin, 1806.03261





DE evolution?

(ad hoc) 1907.12551

but not σ_8

Conclusions

We well may be at the edge of new fundamental discovery in cosmology

- Dark Energy
- Dark Matter
- Dark Radiation

almost guaranteed: $\sum m_\nu$, details of first star formation