Cosmology:
Lecture #3
Dark Matter models. Inflation.
Inhomogeneities in the expanding Universe

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Outline

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Dark Matter Properties $p = 0$

(If) particles:

1. stable on cosmological time-scale
2. nonrelativistic long before RD/MD-transition (either Cold or Warm, $v_{RD/MD} \lesssim 10^{-3}$)
3. (almost) collisionless
4. (almost) electrically neutral

If were in thermal equilibrium: $M_X \gtrsim 1$ keV

If not: for bosons

$\lambda = 2\pi/(M_X v_X)$, in a galaxy $v_X \sim 0.5 \cdot 10^{-3} \longrightarrow M_X \gtrsim 3 \cdot 10^{-22}$ eV

for fermions

Pauli blocking: $M_X \gtrsim 750$ eV

$$f(\mathbf{p},\mathbf{x}) = \frac{\rho_X(\mathbf{x})}{M_X} \cdot \frac{1}{\left(\sqrt{2\pi} M_X v_X\right)^3} \cdot e^{-\frac{\mathbf{p}^2}{2M_X^2 v_X^2}}\Bigg|_{\mathbf{p}=0} \leq \frac{g_X}{(2\pi)^3}$$

Dark Matter Candidates

- WIMPs (neutralino, . . .)
- sterile neutrinos
- gravitino
- axion
- Heavy relics
- (Topological) defects
- Massive Astrophysical Compact Halo Objects
- Primordial black hole remnants

Weakly Interacting Massive Particles

Assumptions:

1. no $X - \bar{X}$ asymmetry $\qquad n_X = n_{\bar{X}}$
2. @ $T < M_X$ in thermal equilibrium with plasma

$$n_X = n_{\bar{X}} = g_X \left(\frac{M_X T}{2\pi}\right)^{3/2} e^{-M_X/T}$$

$$X\bar{X} \longrightarrow \text{light particles}$$

freeze-out temperature T_f $\qquad M_{Pl}^* = M_{Pl}/1.66\sqrt{g_*}$

$$\frac{1}{n_X}\frac{1}{\langle\sigma_{ann} v\rangle} = H^{-1}(T_f) \longrightarrow T_f = \frac{M_X}{\log\left(\frac{g_X M_X M_{Pl}^* \sigma_0}{(2\pi)^{3/2}}\right)}\,.$$

Bethe formula: $\qquad$ annihilation in s-wave: $\sigma_{ann} = \frac{\sigma_0}{v}$

Weakly Interacting Massive Particles (WIMPs)

density after freeze-out: $n_X(T_f) = \frac{T_f^2}{M_{Pl}^* \sigma_0}$

present density: $n_X(T_0) = \left(\frac{a(T_f)}{a(T_0)}\right)^3 n_X(T_f) = \left(\frac{s_0}{s(T_f)}\right) n_X(T_f) \propto \frac{1}{T_f} \propto \frac{1}{M_X}$

$X + \bar{X}$ contribution to critical density:

$$\Omega_X = 2\frac{M_X n_X(T_0)}{\rho_c} = 7.6 \frac{s_0 \log\left(\frac{g_X M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}}\right)}{\rho_c \sigma_0 M_{Pl} \sqrt{g_*(T_f)}}$$

$$= 0.1 \cdot \left(\frac{(10\ \text{TeV})^{-2}}{\sigma_0}\right) \frac{0.3}{\sqrt{g_*(T_f)}} \log\left(\frac{g_X M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}}\right) \cdot \frac{1}{2h^2}$$

natural dark matter: $\sigma_0 \sim 0.01 \times \sigma_{weak}$

naturaly “light” $\sigma_0 \lesssim \frac{4\pi}{M_X^2} \longrightarrow M_X \lesssim 100\ \text{TeV}$

WIMPs are mostly welcome

- Do not need new physical scale (and interaction?)
- Can search for WIMPs in collision experiments (LHC):

$$X + \bar{X} \leftrightarrow \text{SM} + \text{SM'} + \ldots$$

- Can search for WIMPs in cosmic rays: products of WIMPs annihilation (in Galactic center, dwarf galaxies, Sun)

$$X + \bar{X} \to p\bar{p}\,,\;\; e^+e^-\,,\;\; \nu, \gamma, \ldots$$

- Direct searches for Galactic Dark Matter ($v \sim 10^{-3}$)

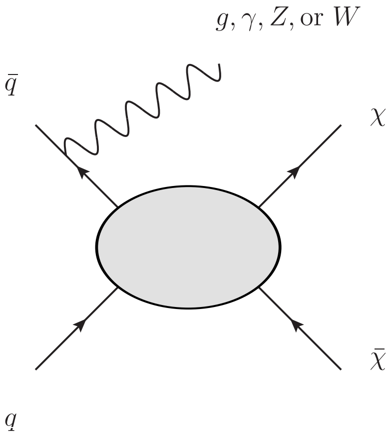
$$X + \text{nuclei} \to X + \text{nuclei} + \Delta E$$

Direct searches for DM particles

LHC helps!

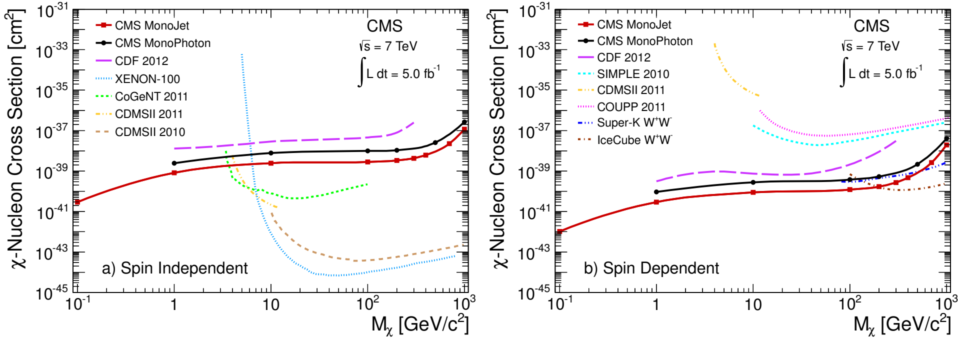
provided some (reasonably) weak interactions between quarks and invisible (dark) particles

Illustration with searches for WIMP-signal



N.Zhou et al (2013)

CMS results of (in)direct searches @ 7 TeV

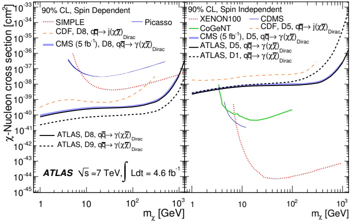


for WIMPs 1206.5663

Logic: no light superpartners, $M_{SUSY} > 500\,\mathrm{GeV}$

$D1\ (scalar):\ \frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q \qquad D8\ (axial):\ \frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$

$D5\ (vector):\ \frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q \qquad D9\ (tensor):\ \frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$



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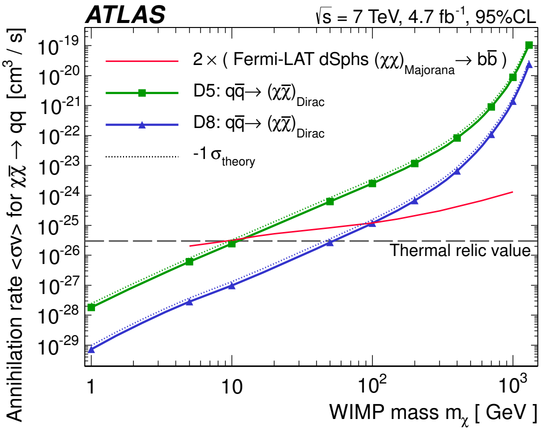
ATLAS results of (in)direct searches @ 7 TeV



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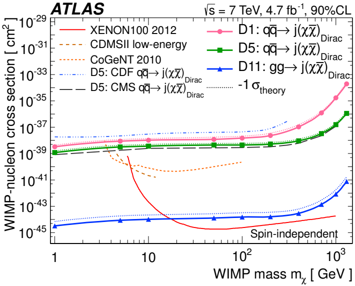
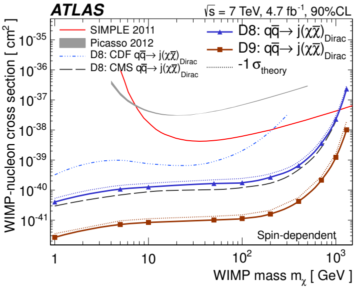
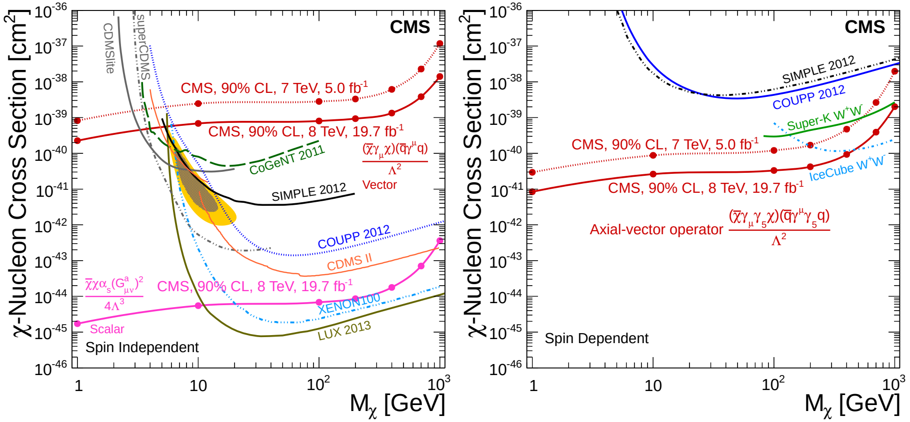




CMS results of searches at @ 8 TeV

V. Khachatryan et al (2014)



Decoupling of relativistic specia (DM?)

Thermal equilibrium is forbidden:

$T_d \gg M_X$, and then $n_X/s = \text{const}$

$$\Omega_{3/2} = \frac{m_X \cdot n_{X,0}}{\rho_c} = \frac{m_X \cdot s_0}{\rho_c}\frac{n_{X,0}}{s_0} = 0.2\frac{M_X}{100\text{ eV}}\left(\frac{g_X}{2}\right)\cdot\left(\frac{100}{g_*(T_d)}\right)\cdot\frac{1}{2h^2}$$

- If fermions: limit from Pauli-blocking
- Generally: too hot at Equality:
  from structure formation we need at $T_{Eq} \sim 1$ eV, $v_{DM} \lesssim 10^{-3}$

Other Dark Matter candidates are not in equilibrium!

- WIMPs (neutralino, ...) $\Longleftarrow$ thermal ! $\Longrightarrow$ Singlet scalar field:

$$\mathscr{L} = \mathscr{L}_{SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{m_0^2}{2}S^2 - \lambda S^2 H^\dagger H + ...$$

Invisible decay $H \to SS$ if kinematically allowed, missing energy

direct searches for dark matter

- sterile neutrinos $\Longleftarrow$ Price: sensitive to mass and couplings! not seesaw neutrino!
- axion $\Longleftarrow$ Price: sensitive to mass and (=couplings) and history!
- gravitino $\Longleftarrow$ Price: sensitive to mass, couplings and reheating temperature !!! yet it is natural LSP if $\Lambda_{SUSY} \lesssim 10^{10}$ GeV
- Heavy relics $\Longleftarrow$ Price: sensitive to mass and untestable
- Asymmetric WIMPS, $n_X \neq n_{\bar{X}}$ $\Longleftarrow$ No cosmic ray signals, but trapped in stars
  Why asymmetric? But other matter, baryons, is asymmetric...
- Why non-thermal DM? $\Longleftarrow$ But major processes we know (recombination and nucleosymthesis) were out-of-equilibrium...

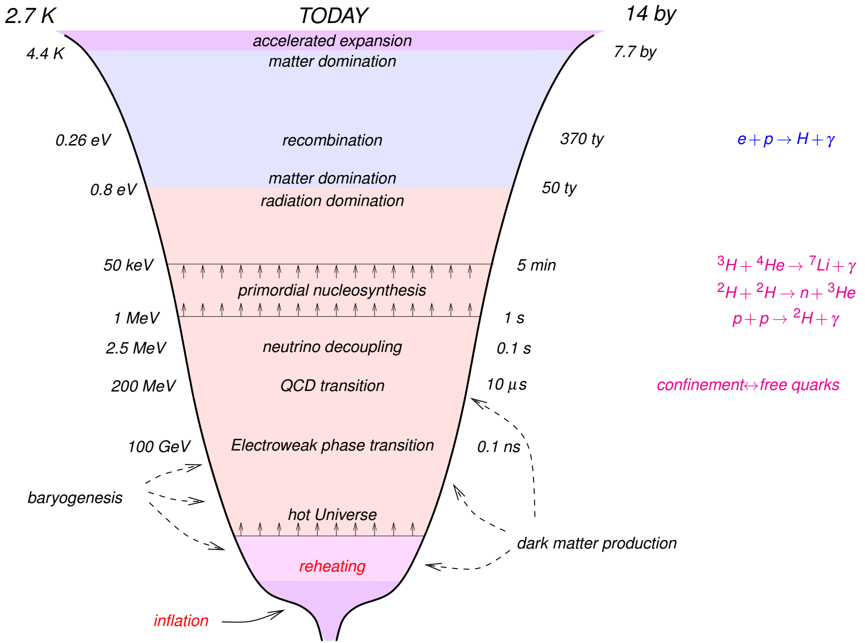
Outline

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 $\delta T/T \sim \delta\rho/\rho \sim 10^{-4}$, scale-invariant
- Dark Energy $0 \neq \Lambda \ll M_{Pl}^4\ M_W^4\ \Lambda_{QCD}^4$ etc ?
- Coincidence problems:

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

- ΛCDM tensions: lack of dwarfs? cusps? (recall: reionization @ $z = 10$)


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

Initial singularity problem (Bang!)

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G\rho\,, \qquad p = w\rho\,,\ \ w > -\frac{1}{3} \qquad (?)$$

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

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

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

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

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

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

Entropy problem

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

for equation of state

$$p = p(\rho)$$

of the primordial plasma we obtain

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

entropy is conserved in a comoving volume

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

For the visible part of the Universe: $S \sim s_{\gamma,0} \cdot l_H^3 \sim 10^{88}$

At the “Bang” for the Planck-size volume: $S_{BB} \sim s_{\gamma,0} \cdot l_{Pl}^3 \sim 100$

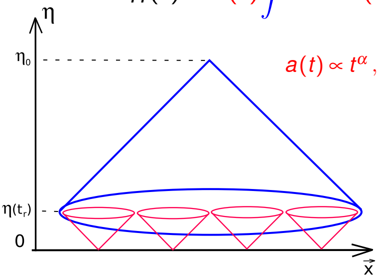
Horizon problem $l_H(t)$

a distance covered by photon emitted at $t = 0$

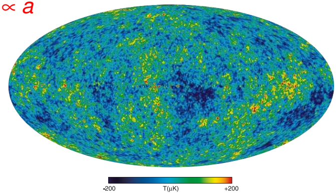
size of the causally connected part, that is the visible part of the Universe ("inside horison")

$$ds^2 = dt^2 - a^2(t)\,dx^2 = a^2(\eta)\left(d\eta^2 - dx^2\right) \qquad ds^2 = 0$$

$$l_H(t) = a(t)\int dx = a(t)\int d\eta = a(t)\int_0^t \frac{c\,dt'}{a(t')} \propto t \quad \propto 1/H(t)$$



$a(t) \propto t^\alpha\,,\ 0 < \alpha < 1\,,\ L_{phys} \propto a$



$$l_{H_0}/l_{H,r}(t_0) \sim l_{H_0}/l_{H,r}(t_r)\,a(t_r)/a_0 \sim H_r/H_0\,a(t_r)/a_0 \sim \sqrt{1+z_r} \simeq 30$$

Flatness problem

- Take non-flat 3-dim manifold (general case)
- Curvature contribution to the total energy density behaves as $\rho_{curv}(t) \propto 1/a^2(t)$
- Then at present:

$$0.01 > \Omega_{curv} = \frac{\rho_{curv}(t_0)}{\rho_c} \sim 10^{-4} \times \frac{\rho_{curv}(t_0)}{\rho_{rad}(t_0)} = 10^{-4} \times \frac{a^2(t_0)}{a^2(t_*)} \frac{\rho_{curv}(t_*)}{\rho_{rad}(t_*)}$$

$$\sim 10^{-4} \times \frac{T_*^2}{T_0^2} \frac{\rho_{curv}(T_*)}{\rho_{tot}(T_*)}$$

- For hypothetical Planck epoch $T_* \sim M_{Pl} \sim 10^{19}$ GeV one gets

$$0.01 > \Omega_{curv} \sim 10^{60} \times \frac{\rho_{curv}(M_{Pl})}{\rho_{tot}(M_{Pl})}$$

Heavy relics problem (monopole problem)

- Let's introduce new stable particle X of mass M_X
- Imagine: at moment t_X they appear in the early Universe with small velocities (e.g. nonrelativistic) and small density $n_X(t_X) \ll n_{rad}(t_X)$
- Since $n_X \propto a^{-3} \propto n_{rad}$ then $n_X(t)/n_{rad}(t) \simeq \text{const}$

$$\frac{\rho_X(t)}{\rho_{rad}(t)} \sim \frac{M_X}{T(t)} \cdot \frac{n_X(t_X)}{n_{rad}(t_X)} \propto a(t)$$

- Radiation dominates at least while $1\,\text{eV} \lesssim T \lesssim 3\,\text{MeV}$
- Therefore even for $M_X = 10\,\text{TeV}$ we must require $n_X(t_X)/n_{rad}(t_X) \ll 10^{-12}$!!!
- In some SM extenstions it is difficult to avoid heavy relics production: gravitational production, $M_X \sim H$, phase transitions. . .

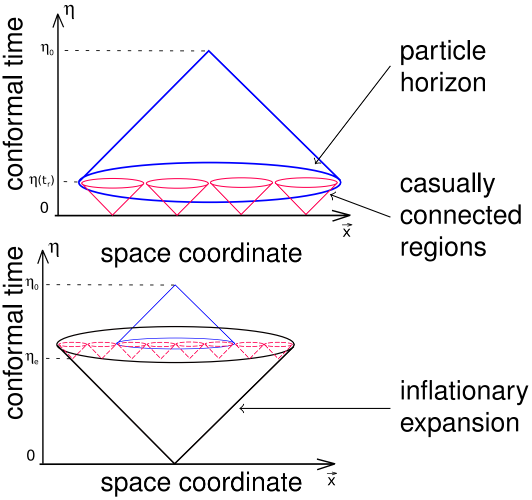
Example: monopoles, produced "one per horizon volume", $n_X(t_X) = 1/l_H^3(t_X) = H^3(t_X)$; Then for its present contribution:

$$\Omega_X = \frac{\rho_X}{\rho_c} \sim 10^{17} \times \frac{M_X}{10^{16}\,\text{GeV}} \left(\frac{T_X}{10^{16}\,\text{GeV}}\right)^3 \sqrt{\frac{g_*}{100}}$$

Outline

Inflationary solution of Hot Big Bang problems

- no initial singularity in dS space
- all scales grow exponentially, including the radius of the 3-sphere
  the Universe becomes exponentially flat
- any two particles are at exponentially large distances
  no heavy relics
  no traces of previous epochs!
- no particles in post-inflationary Universe
  to solve entropy problem we need post-inflationary reheating



Inflation: general remarks

- Simplest variant

$$H^2 = \frac{8\pi}{3M_{Pl}^2}\rho_\Lambda = \text{const}\,, \Rightarrow\ a(t) \propto e^{Ht}$$

is not suitable: inflation must not last for ever!

- Universe has to reheat after! T_{reh}

$$\rho_e \gtrsim (3\,\text{MeV})^4\,, \text{ and better } \rho_e \gtrsim (100\,\text{GeV})^4\,,$$

- How long? Horizon problem:
present size of the horizon at the end of inflation

$$l_{H,e}(t_0) = a_0 \int_{t_{Pl}}^{t_e} \frac{dt}{a(t)} = a_0 \int_{t_{Pl}}^{t_e} \frac{da}{a^2}\frac{1}{H} \sim \frac{a_0}{a(t_{Pl})}\cdot\frac{1}{H(t_{Pl})}$$

Solution to the horizon problem:

$$1 \lesssim \frac{l_{H,e}(t_0)}{l_{H,0}} \sim \frac{a_0}{a(t_{Pl})}\frac{H_0}{H(t_{Pl})} = \frac{a_0}{a(t_{reh})}\frac{a_{reh}}{a(t_e)}\frac{a(t_e)}{a(t_{Pl})}\cdot\frac{H_0}{H(t_{Pl})}$$

Introducing the number of e-foldings

$$N_e^{tot} = \log\frac{a(t_e)}{a(t_{Pl})}\,, \quad N_e^{tot} = \int_{t_{Pl}}^{t_e} dt\, H(t) \sim H_e \cdot \Delta t_{infl}$$

For relativistic particles $\rho \propto T^4 \propto 1/a^4 \ \Rightarrow\ a_0/a(t_{reh}) \sim T_{reh}/T_0$

Inflation: general remarks

- How long? Solution to the horizon problem:

$$1 \lesssim \frac{l_{H,e}(t_0)}{l_{H,0}} \Rightarrow N_e^{tot} \gtrsim \log \frac{T_0}{H_0} + \log \frac{a(t_e)}{a_{reh}} + \log \frac{H(t_{Pl})}{T_{reh}} \simeq 50 - 60$$

  Inflation lasts not less than (accepting $H^2 \sim \rho / M_{Pl}^2$)

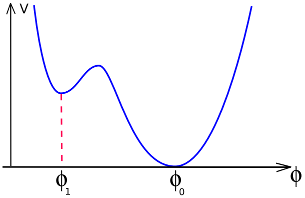
$$\Delta t_{infl} \sim N_e^{tot} / H_e \sim 10^{-11}\,\text{c} \cdot \left(\frac{1\ \text{TeV}}{T_{reh}} \right)^2$$

  we must reheat the Universe then!

- In realistic models $N_e^{tot} \ggg 100$!!!
  Inflatinary stage may be short, but expansion is enormous!

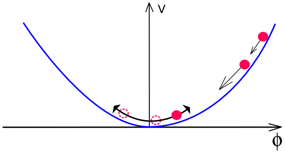
Inflatinary stage: simplest models

"Old inflation" by Guth



does not work in fact!
starts from a hot stage
and ends up in a false vacuum
reheating due to percollations
However: for sufficiently long inflationary stage requires
$\Gamma < H^4_{infl}$
hence the bubbles never collide!

"Chaotic inflation"



needs superplanckian field values!

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

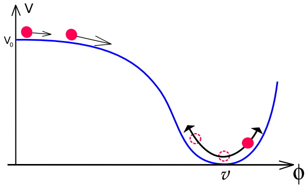
$$p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

$$\varepsilon = \frac{M_{Pl}^2}{16\pi}\left(\frac{V'}{V}\right)^2, \; \eta = \frac{M_{Pl}^2}{8\pi}\frac{V''}{V},$$

$V(\phi) \propto \phi^n \Rightarrow \varepsilon, \eta \sim M_{Pl}^2/\phi^2 \ll 1$ $\leftarrow$ slow-roll conditions

"New inflation"



Initial condition is very specific!

$$H^2 = \frac{8\pi}{3M_P^2}V(\phi), \quad a(t) \propto e^{Ht}$$

and we require

$$V(\phi) < M_{Pl}^4$$

Unexpected bonus: generation of perturbations

- Quantum fluctuations of wavelength λ of a free massless field φ have an amplitude of $\delta\varphi_\lambda \simeq 1/\lambda$
- In the expanding Universe: $\lambda \propto a$

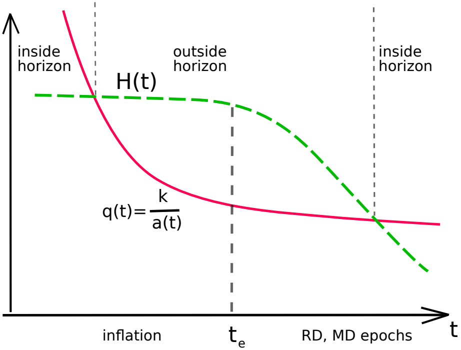
  inflation: $l_H \sim 1/H = \text{const}$, so modes "exit horizon"
  Ordinary stage: $l_H \sim 1/H \propto t$, $l_H/\lambda \nearrow$, modes "enter horizon"

Evolution at inflation

- inside horizon: $\lambda < l_H$
  $\lambda \propto a \Rightarrow$ $\delta\varphi_\lambda \propto 1/\lambda \propto 1/a$

- outside horison: $\lambda > l_H$
  $\lambda \propto a \Rightarrow$ $\delta\varphi_\lambda = \text{const} = H_{infl}$!!!

- got "classical" fluctuations:
  $$\delta\varphi_\lambda = \delta\varphi_\lambda^{quantum} \times e^{N_e}$$



Power spectrum of perturbations

In the Minkowski space-time:

- fluctuations of a free quantum field φ are gaussian its power spectrum is defined as

$$\int_0^\infty \frac{dq}{q}\,\mathcal{P}_\varphi(q) \equiv \langle \varphi^2(x) \rangle = \int_0^\infty \frac{dq}{q}\,\frac{q^2}{(2\pi)^2}$$

  We define amplitude as $\delta\varphi(q) \equiv \sqrt{\mathcal{P}_\varphi} = q/(2\pi)$

- In the expanding Universe momenta $q = k/a$ gets redshifted
- Cast the solution in terms $\phi(\mathbf{x},t) = \phi_c(t) + \varphi(\mathbf{x},t)\,, \quad \varphi(\mathbf{x},t) \propto e^{\pm i\mathbf{kx}}\,\varphi(\mathbf{k},t)$
  φ solves the equation

$$\ddot{\varphi} + 3H\dot{\varphi} + \frac{k^2}{a^2}\,\varphi + V''(\phi_c)\varphi = 0$$

- $q = k/a \gg H \;\Rightarrow$ as in Minkowski space-time
- $q = k/a \ll H \;\Rightarrow$ for inflaton $\varphi = \text{const}$
- Matching at t_k: $q(t_k) = k/a(t_k) = H(t_k) \equiv H_k$ gives

$$\delta\varphi(q) = \frac{H_k}{2\pi} \;\Rightarrow\; \mathcal{P}_\varphi(q) = \frac{H_k^2}{(2\pi)^2}$$

amplification $H_k/q = e^{N_e(k)}$!!!

$H_k \approx \text{const} = H_{infl}$ hence (almost) flat spectrum

Transfer to matter perturbations: simple models

Illustration: Local delay(advance) δt in evolution due to impact of $\delta\phi$ of all modes with $\lambda > H$:

$$\delta\phi = \dot{\phi}_c \delta t\,, \quad \delta\rho \sim \dot{\rho}\,\delta t$$

at the end of inflation $\dot{\rho} \sim -H\rho$, then

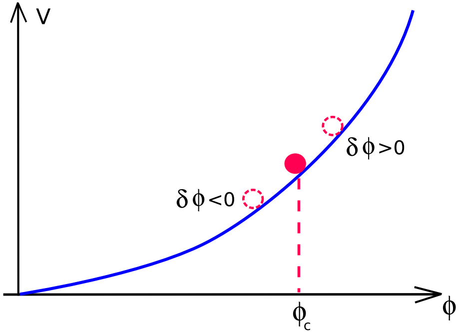
$$\frac{\delta\rho}{\rho} \sim \frac{H}{\dot{\phi}_c}\delta\phi$$

Hence, $\delta\rho/\rho$ is also gaussian.

Power spectrum of scalar perturbations

$$\mathscr{P}_{\mathscr{R}}(k) = \left(\frac{H^2}{2\pi\,\dot{\phi}_c}\right)^2\,,$$

everything is calculated at $t = t_k : H = k/a$



Analogously for the tensor perturbations: each of the two polarizations of the gravity waves solves the free scalar field equation!

$$\mathscr{P}_T(k) = \frac{16}{\pi}\frac{H_k^2}{M_{Pl}^2}$$

To the leading order no k-dependence: both spectra are “flat” (scale-invariant)!

Inflaton parameters and spectral parameters

- Observation of CMB anisotropy gives $\delta T/T$

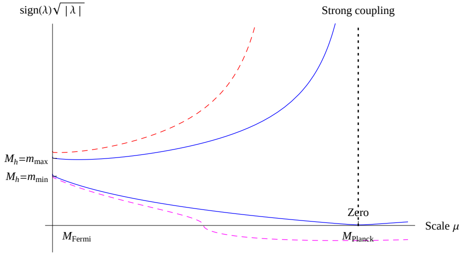
$$\frac{\delta T}{T} \sim \frac{\delta\rho}{\rho} \quad \Rightarrow \Delta_{\mathscr{R}} \equiv \sqrt{\mathscr{P}_{\mathscr{R}}} = 5\times 10^{-5}$$

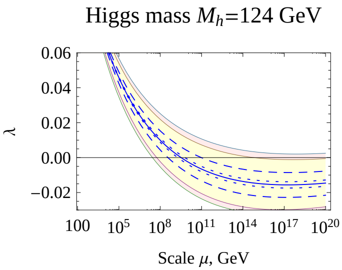
- These are so-called adiabatic perturbations!
  Other possibles (isocurvature) modes (e.g. $\delta T = 0$, but $\delta n_B/n_B \neq 0$) are not found.
- $\Delta_{\mathscr{R}} = 5\times 10^{-5} \Rightarrow$ fixes model paramaters, e.g.:

$$V(\phi) = \frac{\beta}{4}\phi^4 \to \lambda \sim 10^{-13}$$

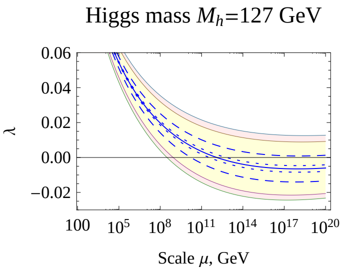
  With such a tiny coupling perturbations are obviously gaussian
  So far confirmed by observations
- That's why Higgs boson in the SM does not help!
  However, it can be exploited as inflaton if non-minimally coupled to gravity $\xi RH^\dagger H$

Critical point: where EW-vacuum becomes unstable





F.Bezrukov, M.Shaposhnikov (2009)
F.Bezrukov, D.G. (2011)
F.Bezrukov, M.Kalmykov, B.Kniehl, M.Shaposhnikov (2012)



G. Degrassi et al (2012)

$$m_h^{cr} > \left[129.0 + \frac{m_t - 172.9\,\mathrm{GeV}}{1.1\,\mathrm{GeV}} \times 2.2 - \frac{\alpha_s(M_Z) - 0.1181}{0.0007} \times 0.56\right] \mathrm{GeV}$$

theoretical uncertainties 1-2 GeV

present measurements at CMS and ATLAS (?):

$$m_h \simeq 125.8 \pm 0.9\ \mathrm{GeV}$$

Important for inflation, when usually $h \sim H$

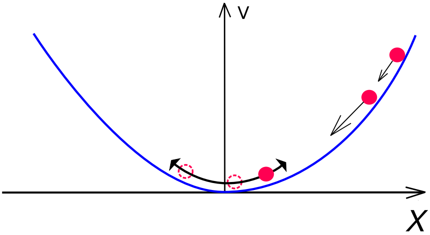
Inflation & Reheating: simple realization with Higgs

$$\ddot{X}+3H\dot{X}+V'(X)=0$$

$X_e > M_{Pl}$

generation of scale-invariant scalar (and tensor) perturbations from exponentially stretched quantum fluctuations of X

$\delta\rho/\rho \sim 10^{-5}$ requires
$V=\beta X^4$: $\beta \sim 10^{-13}$



Chaotic inflation, A.Linde (1983)

reheating ? renormalizable?

the only choice: $\alpha H^\dagger H X^2$
"Higgs portal"

larger α larger T_{reh}

quantum corrections $\propto \alpha^2 \lesssim \beta$

No scale, no problem

Inflaton parameters and spectral parameters

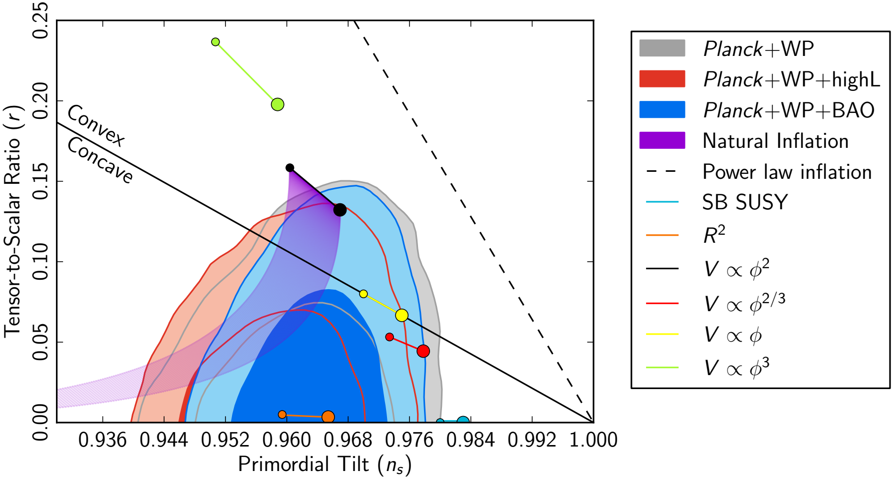
- In fact, spectra are a bit tilted, as H_{infl} slightly evolves

$$\mathcal{P}_{\mathcal{R}}(k) = A_{\mathcal{R}} \left(\frac{k}{k_*}\right)^{n_s-1} , \qquad \mathcal{P}_T(k) = A_T \left(\frac{k}{k_*}\right)^{n_T} .$$

- Measure $\Delta_{\mathcal{R}}$ at present scales $q \simeq 0.002/\text{Mpc}$, it fixes the number of e-foldings left N_e
- For tensor perturbations one introduces:

$$r \equiv \frac{\mathcal{P}_T}{\mathcal{P}_{\mathcal{R}}} = \frac{1}{\pi} \frac{M_{Pl}^2 V'^2}{V} = 16\,\varepsilon \;\to\; \frac{16}{N_e} \text{ for } \beta\phi^4$$

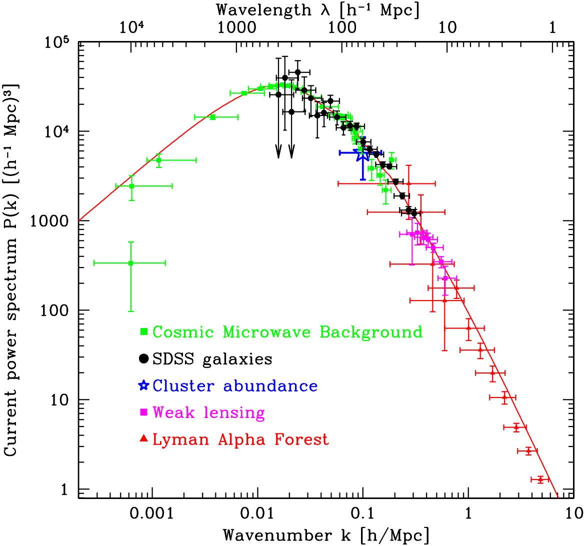
Recent analysis (Planck) of cosmlogical data



1303.5062

$N_e = 50 - 60$

Actually we observe rather narrow range



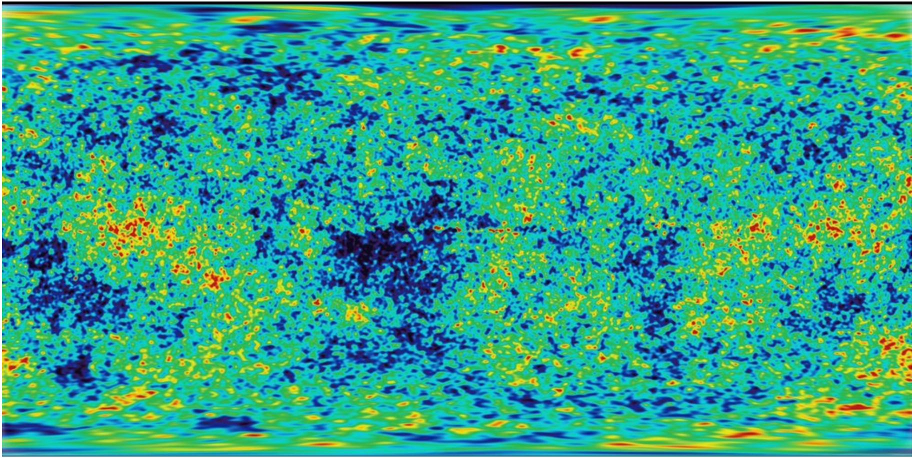
Observable range:

$$\frac{k_{max}}{k_{min}} \sim 10^5$$

$$\Delta N_e \simeq 10$$

Small scales cannot describe:
for a long time in nonlinear regime

CMB map



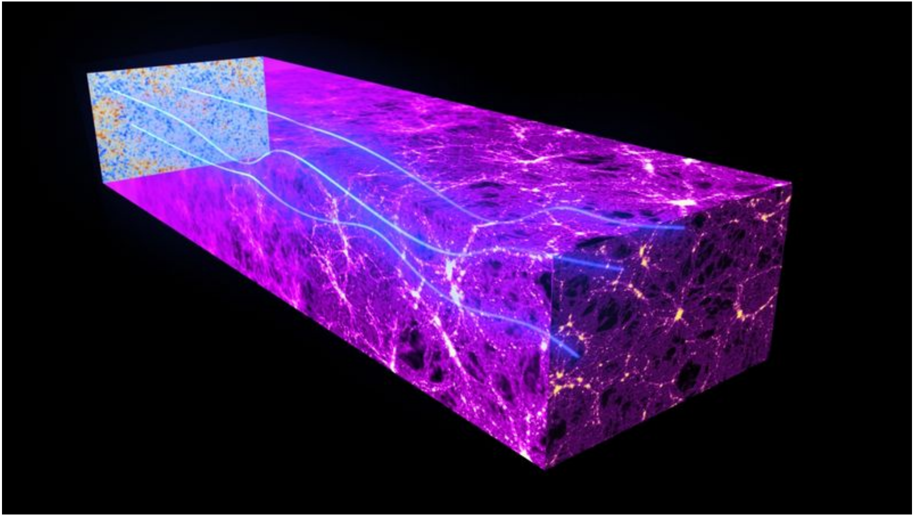
Mode evolution

- Amplitude remains constant, while superhorizon, e.g. $k/a < H$
- Subhorizon Inhomogeneities of DM start to grow at MD-stage, $\delta\rho_{CDM}/\rho_{CDM} \propto a$ from $T \approx 0.8\,\text{eV}$
  Smaller objects (first stars, dwarf galaxies) are first to form
- Subhorizon Inhomogeneities of baryons join those of DM only after recombination, $\delta\rho_{CDM}/\rho_{CDM} \propto a$ from $T_{rec} \approx 0.25\,\text{eV}$
- at recombination $\delta\rho_B/\rho_B \sim \delta T/T \sim 10^{-4}$ and would grow only by a factor $T_{rec}/T_0 \sim 10^3$ without DM
- Subhorizon Inhomogeneities of photons $\delta\rho_\gamma/\rho_\gamma$ oscillate with constant amplitude at RD and with decreasing amplitude at MD, thus we can measure $T_{RD/MD}/T_{rec}$
- Phase of oscillations decoupled after recombination depends on the wave-length, recombination time and sound speed

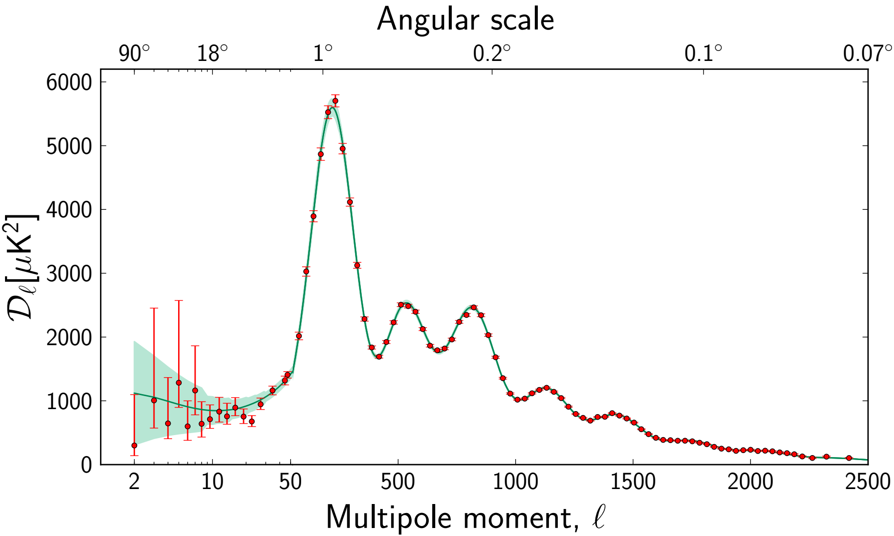
$$\delta\rho_\gamma/\rho_\gamma \propto \cos\left(k\int_0^{t_r} \frac{v_s\,dt}{a(t)}\right) = cos(kl_{sound})$$

- $$\delta T(\theta,\varphi) = \sum a_{lm} Y_{lm}(\theta,\varphi)\,, \qquad \langle a^*_{lm} a_{lm}\rangle = C_l \equiv 2\pi\mathscr{D}_l/(l(l+1))$$

On top of that: propagation in expanding Universe



CMB measurements (Planck) $H_0, \Omega_{DM}, \Omega_B, \Omega_\Lambda, \Delta_{\mathscr{R}}, n_s$



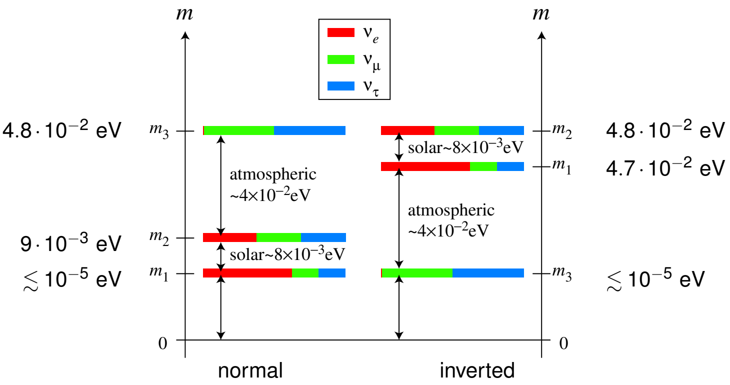
Outline

CMB, LSS and Neutrinos

Evolution of perturbations depends both on $N_{\nu,eff}$ and $\sum m_\nu$
- active neutrinos contribute to radiation at early stage, and to DM today
- active neutrinos fall into galaxy clusters, but not into dwarfs (too hot)
- ...

Cosmology is sensitive to active neutrino mass scale, and to additional light neutrinos (e.g. to explain anomalies in some neutrino oscillation experiments)

Planck promised to probe inverted hierarchy scenario



New physics from the (still unknown) Higgs sector

- EW baryogenesis:
  not enough CP, not I order phase transition
  could be 2 Higgs doublets!
- Dark Matter candidate: stable due to Z_2-symmetry
  Natural CDM from primordial plasma
  Singlet scalar field: (e.g. Burgess, Pospelov, ter Veldhuis, 2001)

$$\mathscr{L} = \mathscr{L}_{SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{m_0^2}{2} S^2 - \lambda S^2 H^\dagger H + \ldots$$

  may be responsible for reheating
- One of the SM portals to hidden sectors (SM-gauge singlets: no FCNC!)

$$\beta B^{\mu\nu}_{U(1)_Y} B^{\mu\nu}_{U(1)_{Y'}} \qquad \alpha H^\dagger H \cdot X^\dagger X$$

- Cosmology asks for precision measurement of m_t, m_h and α_s :
  Higgs must evolve to EW vacuum
  (and may even drive inflation, if $\lambda(M_{Pl}) > 0$)