Introduction to Cosmology: Lecture #2 Big Bang Nucleosynthesis, Dark Matter production, Baryogenesis

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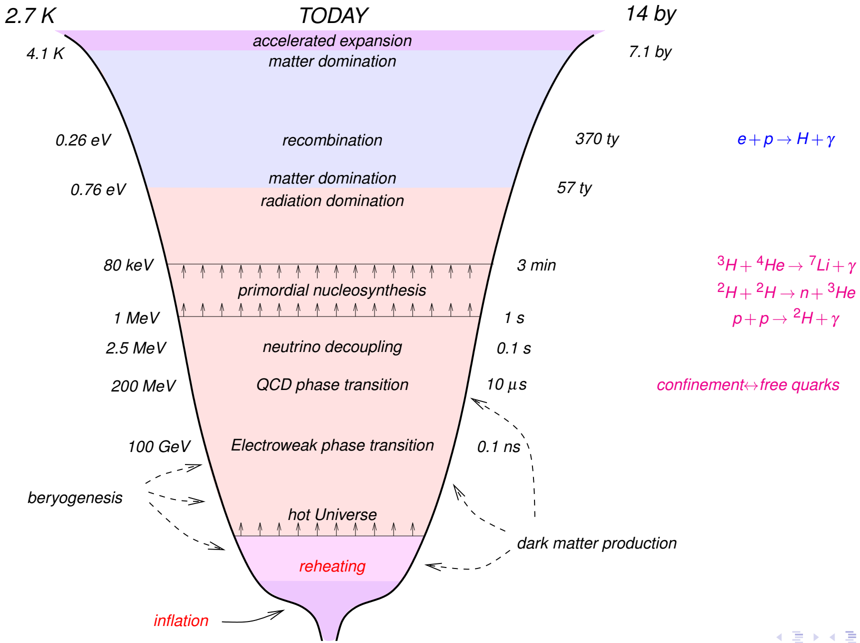

2.7 K
TODAY
14 by
accelerated expansion
4.1 K
matter domination
7.1 by
0.26 eV
recombination
370 ty
$e + p \to H + \gamma$
matter domination
0.76 eV
57 ty
radiation domination
80 keV
3 min
$^3H + ^4He \to ^7Li + \gamma$
primordial nucleosynthesis
$^2H + ^2H \to n + ^3He$
1 MeV
1 s
$p + p \to ^2H + \gamma$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

Outline

1. Big Bang Nucleosynthesis
   - Neutrino freeze-out
   - Neutron decoupling
   - Thermodynamical approach
   - Kinetic approach
   - Deuterium production
   - Observed abundances
2. Dark Matter
   - WIMPs
   - Sterile neutrinos
   - Axion
3. Baryogenesis
4. Summary

Outline

Neutrino freeze-out

$T > m_e$ $\qquad$ $e^+e^- \leftrightarrow \nu\bar{\nu},\ e\nu \leftrightarrow e\nu$

$$\sigma_\nu \sim G_F^2 E^2$$

neutrino interaction rate

$$\tau_\nu = \frac{1}{\langle \sigma_\nu n v \rangle} \sim \frac{1}{G_F^2 T^5}$$

$$\tau_\nu(T) \sim H^{-1}(T) = \frac{M_{Pl}^*}{T^2}$$

$$T_{\nu,f} \sim \left(\frac{1}{G_F^2 M_{Pl}^*} \right)^{1/3} \sim 2 \div 3\ \text{MeV}$$

Neutron decoupling $\quad p+e\longleftrightarrow n+\nu_e$

typical energy scales

$$T\gtrsim\Delta m=1.3\text{ MeV},\qquad T\gtrsim m_e=0.5\text{ MeV}$$

neutron interaction rate

$$\tau_{n\leftrightarrow p}=\frac{1}{\Gamma_{n\leftrightarrow p}}=\frac{1}{C_n G_F^2 T^5}$$

neutron decoupling $\quad \Gamma_{n\leftrightarrow p}(T)\sim H(T)=T^2/M_{Pl}^*$

$$T_n=\frac{1}{\left(C_n M_{Pl}^* G_F^2\right)^{1/3}}\approx 1.4\text{ MeV}$$

$g_*=2+\frac{7}{8}\cdot 4+\frac{7}{8}\cdot 2\cdot N_\nu$ $\qquad t=\frac{1}{2H(T_n)}=\frac{M_{Pl}^*}{2T_n^2}=1.2\text{ s}$ $\qquad T_n\approx 0.8\text{ MeV}$

Neutron density after decoupling

$$n_n = g_n \left(\frac{m_n T}{2\pi}\right)^{3/2} e^{\frac{\mu_n - m_n}{T}} \qquad \mu_n + \mu_\nu = \mu_p + \mu_e$$

$$\frac{n_n}{n_p} = e^{-\frac{m_n - m_p}{T}} e^{\frac{\mu_n - \mu_p}{T}}$$

for relativistic e^+ and e^- Why ?

$$n_{e^-} - n_{e^+} \sim \mu_e T^2 \longrightarrow \frac{\mu_e}{T} \sim \frac{n_{e^-} - n_{e^+}}{T^3} = \frac{n_p}{T^3} \sim \eta_B \sim 10^{-9}$$

✍ find coefficient ⇑

$$\frac{n_n}{n_p} = e^{-\frac{m_n - m_p}{T_n}} \equiv e^{-\frac{\Delta m}{T_n}} \approx \frac{1}{5} e^{-\frac{\mu_\nu}{T_n}}$$

$p + n \longrightarrow \mathrm{D} + \gamma$ Saha equation

$$n_n = 2\left(\frac{m_p T}{2\pi}\right)^{3/2} \mathrm{e}^{\frac{\mu_n - m_n}{T}}\,, \qquad n_p = 2\left(\frac{m_p T}{2\pi}\right)^{3/2} \mathrm{e}^{\frac{\mu_p - m_p}{T}}\,,$$

Chemical equilibrium for nuclei: $\mu_A = \mu_p \cdot Z + \mu_n \cdot (A - Z)$

✍ prove that: $$n_A = n_p^Z n_n^{A-Z} 2^{-A} g_A A^{3/2} \left(\frac{2\pi}{m_p T}\right)^{\frac{3}{2}(A-1)} \mathrm{e}^{\frac{\Delta_A}{T}}$$

$$X_A = \frac{A n_A}{n_\mathrm{B}} \qquad n_\mathrm{B} = \eta_\mathrm{B} \cdot n_\gamma = 0.24 \eta_\mathrm{B} T^3$$

$$X_A = X_p^Z X_n^{A-Z} 2^{-A} g_A A^{5/2} \eta_\mathrm{B}^{A-1} \left(\frac{2.5 T}{m_p}\right)^{\frac{3}{2}(A-1)} \mathrm{e}^{\frac{\Delta A}{T}}$$

Temperature of BBN T_{NS}: $X_{\mathrm{D}} \sim 1$

$$X_A = X_p^Z X_n^{A-Z} 2^{-A} g_A A^{5/2} \eta_{\mathrm{B}}^{A-1} \left(\frac{2.5T}{m_p}\right)^{\frac{3}{2}(A-1)} \mathrm{e}^{\frac{\Delta A}{T}}$$

$\Delta_{\mathrm{D}} = 2.23$ MeV

$$X_{\mathrm{D}}(T_{NS}) \sim \eta_{\mathrm{B}} \left(\frac{2.5T_{NS}}{m_p}\right)^{3/2} \mathrm{e}^{\frac{\Delta_{\mathrm{D}}}{T_{NS}}} \sim 1 \longrightarrow T_{NS} \approx 65 \text{ keV}$$

$$t_{NS} = \frac{1}{2H(T_{NS})} = \frac{M_{Pl}^*}{2T_{NS}^2} = 265 \text{ s} \approx 4.5 \text{ minutes}$$

Helium density (chemical equilibrium)

$$X_A = X_p^Z X_n^{A-Z} 2^{-A} g_A A^{5/2} \eta_B^{A-1} \left(\frac{2.5T}{m_p}\right)^{\frac{3}{2}(A-1)} \mathrm{e}^{\frac{\Delta A}{T}}$$

$X_{^4\mathrm{He}}$ @ $T = T_{NS}$? $\Delta_{^4\mathrm{He}} = 28.3$ MeV

$$X_{^4\mathrm{He}} = X_p^2 X_n^2 \cdot 8\eta_B^3 \left(\frac{2.5T}{m_p}\right)^{9/2} \mathrm{e}^{\frac{\Delta_{^4\mathrm{He}}}{T}} \longrightarrow 10^{128}$$

Let $X_{^4\mathrm{He}} \sim 1$ $(2p, 2n)$, $n_n < n_p$ $X_p \sim 1$

$$X_n = X_{^4\mathrm{He}}^{1/2} \eta_B^{-3/2} \left(\frac{2.5T}{m_p}\right)^{-9/4} \mathrm{e}^{-\frac{\Delta_{^4\mathrm{He}}}{2T}}$$

Light element densities (chemical equilibrium)

$$X_A = \left[\eta_B \cdot \left(\frac{2.5T}{m_p}\right)^{3/2}\right]^{\frac{3}{2}Z-\frac{1}{2}A-1} e^{\frac{\Delta_A - \Delta_{^4He}(A-Z)/2}{T}} \simeq 10^{7.4(A+2-3Z)}\, e^{(A-Z)\frac{\Delta_A/(A-Z)-\Delta_{^4He}/2}{T}}$$

Z	Nucleus	Δ_A	Δ_A/A	$\Delta_A/(A-Z)$	X_A
1	$^2H \equiv D$	2.23	1.11	2.23	10^{-79}
	$^3H \equiv T$	8.48	2.83	4.24	10^{-118}
2	^3He	7.72	2.57	7.72	10^{-51}
	$^4He \equiv \alpha$	28.30	7.75	14.15	1
3	^6Li	31.99	5.33	10.66	10^{-78}
	^7Li	39.24	5.61	9.81	10^{-116}
4	^7Be	37.60	5.37	12.53	10^{-55}
5	^8B	37.73	4.71	12.58	10^{-69}
6	^{12}C	92.2	7.68	15.37	10^{19}

Helium abundance (NO chemical equilibrium)

Neutrons remain mostly in helium

$$n_{^4\mathrm{He}}(T_{NS}) = \frac{1}{2} n_n(T_{NS}) \; ,$$

neutron-to-proton ratio $\tau_n \approx 886$ s

$$\frac{n_n(T_{NS})}{n_p(T_{NS})} \approx \frac{1}{5} \cdot \mathrm{e}^{-\frac{t_{NS}}{\tau_n}} \cdot \mathrm{e}^{-\frac{\mu_\nu}{T_n}} \approx \frac{1}{7} \; ,$$

$$Y_p \equiv X_{^4\mathrm{He}} = \frac{m_{^4\mathrm{He}} \cdot n_{^4\mathrm{He}}(T_{NS})}{m_p\left(n_p(T_{NS}) + n_n(T_{NS})\right)} = \frac{2}{\frac{n_p(T_{NS})}{n_n(T_{NS})} + 1} \approx 25\% \; .$$

from observations of relic helium abundance:

$$\Delta N_{\nu,eff} \leq 1 \; , \qquad \left|\frac{\mu_\nu}{T_n}\right| \lesssim 0.01$$

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

$$H(T_{NS} = 70 \text{ keV}) = 4 \cdot 10^{-3} \text{ s}^{-1}$$

to obtain nonequilibrium concentrations

Neutron burning $p + n \longrightarrow \mathrm{D} + \gamma$

@ $T = T_{NS} = 65$ keV

$$(\sigma v)_{p(n,\gamma)D} \approx 6 \cdot 10^{-20}\ \frac{\mathrm{cm}^3}{\mathrm{s}}\ .$$

for the rate of neutron disappearance (it meets proton!)

$$\Gamma_{p(n,\gamma)D} = n_p \cdot (\sigma v)_{p(n,\gamma)D} = \eta_B \cdot 2\frac{\zeta(3)}{\pi^2} T^3 \cdot (\sigma v)_{p(n,\gamma)D} = 0.31\ \mathrm{s}^{-1}$$

for $\eta_B = 6.15 \cdot 10^{-10}$ and $T = T_{NS}$

So, neutrons disappear very rapidly

$$\Gamma_{p(n,\gamma)D} \gg H(T_{NS}) = 4 \cdot 10^{-3}\ \mathrm{s}^{-1}$$

Deuterium burning $D(D,n)^3He$, $D(D,p)T$

Coloumb barier: tunneling $T_9 \equiv T/(10^9\ \text{K}) = T/(86\ \text{keV})$

$$\langle \sigma v \rangle_{DD} = 3 \cdot 10^{-15} \frac{\text{cm}^3}{\text{s}} \cdot T_9^{-2/3} \cdot e^{-4.26 \cdot T_9^{-1/3}} \ .$$

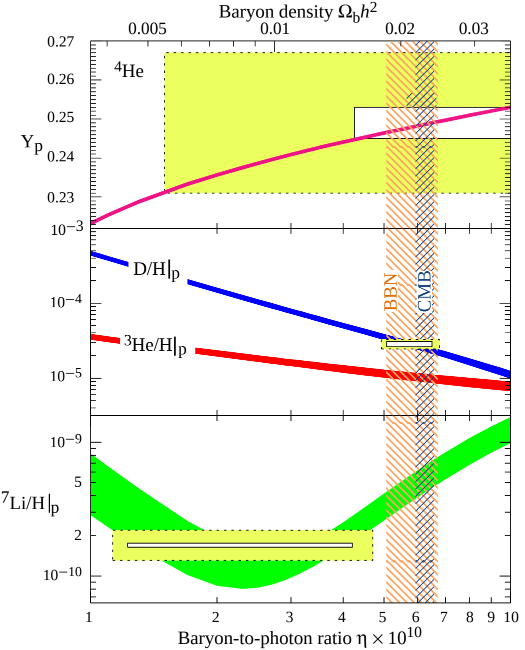
deuterium stops burning when $T = T_{NS} (T_9 = 0.75)$

$$\Gamma_{DD} = n_D(T) \cdot \langle \sigma v \rangle_{DD}(T) \sim H(T) \ .$$

Then relic deuterium abundance is estimated as

$$\frac{n_D}{n_p} = \frac{1}{0.75 \eta_B} \cdot \frac{n_D}{n_\gamma(T_{NS})} = 0.3 \cdot 10^{-4}$$

for $\eta_B = 6.15 \cdot 10^{-10}$

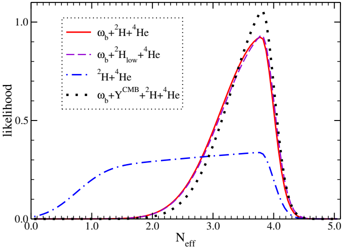


Lack of Lithium. . .

$$Y_p = 0.2581 \pm 0.025\,,$$

$$D/H\big|_p = (2.87 \pm 0.21) \times 10^{-5}$$

1103.1261



similar results from other recent studies including structure formation

1001.4440, 1001.5218, 1202.2889

$N_\nu < 4.2$ @ 95%CL

$N_\nu < 4.3$ with shorter neutron's life...

Outline

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 $\qquad M_{Pl}^* = M_{Pl}/1.66\sqrt{g_*}$

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

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

Weakly Interacting Massive Particles

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:

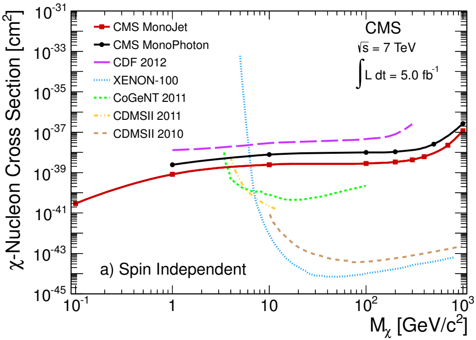
$$\Omega_X = 2\frac{M_X n_X(T_0)}{\rho_c} = 7.6 \frac{s_0 \ln\left(\frac{g_X M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}}\right)}{\rho_c \sigma_0 M_{Pl} \sqrt{g_*(T_f)}}$$

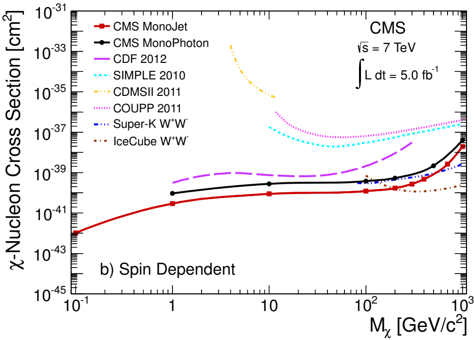
$$= 0.1 \cdot \left(\frac{(10\ \text{TeV})^{-2}}{\sigma_0}\right) \frac{0.3}{\sqrt{g_*(T_f)}} \ln\left(\frac{g_X M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}}\right) \cdot \frac{1}{2h^2}$$

natural dark matter: $\sigma_0 \sim 0.01 \times \sigma_W$

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

Recent results of (in)direct searches

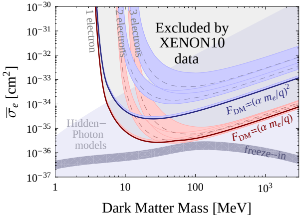




for WIMPs 1206.5663

there are analyses for lower mass ranges and other type of interactions:

e.g. 1206.2644



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, $v_{DM} \lesssim 10^{-3}$

NB: for $M_X = 100$ eV at Equality ($T_{Eq} \sim 1$ eV) X-particle velocities are ?

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NB: for $M_X = 100$ eV at Equality ($T_{Eq} \sim 1$ eV) X-particle velocities are ! $v \simeq 10^{-2}$

Other Dark Matter candidates are not in equilibrium!

- WIMPs (neutralino, . . .) $\Longleftarrow$ thermal !
- sterile neutrinos $\Longleftarrow$ Price: sensitive to mass and couplings!
- axion $\Longleftarrow$ Price: sensitive to mass and (=couplings)!
- gravitino $\Longleftarrow$ Price: sensitive to mass, couplings and reheating temperature !!!
- Heavy relics
- (Topological) defects
- Massive Astrophysical Compact Halo Objects
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DM keV sterile neutrino

Sterile neutrino of keV scale mass provides the Warm Dark Matter

Relevant parameters: mass $M_N \sim$1-10 keV and active-sterile neutrino mixing angle $\theta \ll 1$

Bounds on mass

- Phase space density (refined Pauli-blocking): $M_N \gtrsim 0.3$ keV
- Lyman-α forest: $M_N \gtrsim 10$ keV

Bound on mass M_N and mixing angle θ

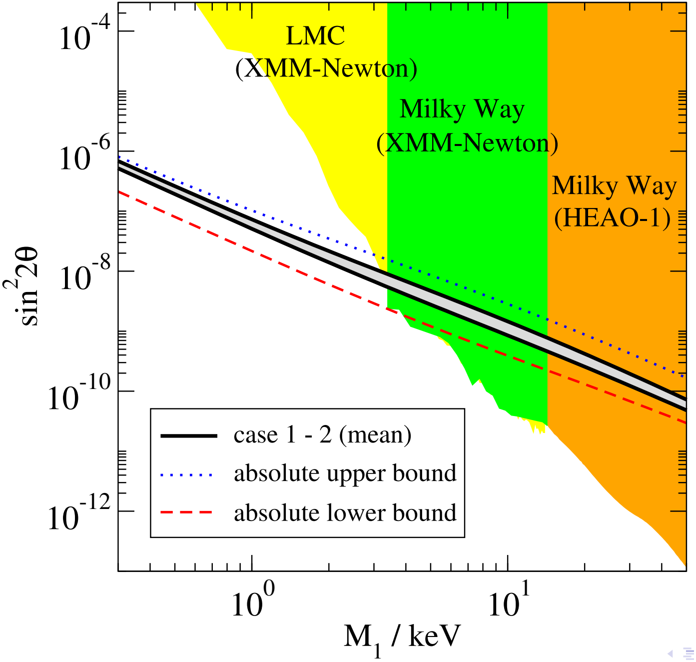
- X-ray observation: $N \to \nu + \gamma$, a peak at $\omega_\gamma = M_N/2$ of intensity $\propto \theta^2$

Production mechanism

- Dodelson-Widrow (thermal) scenario: $\nu_a \to N$ due to mixing,

$$\rho_N \propto \theta^2$$

- Primordial abundance: physics at higher energies
  - Lepton asymmetries
  - Production from inflaton decay
  - etc.


LMC
(XMM-Newton)
Milky Way
(XMM-Newton)
Milky Way
(HEAO-1)
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
$\sin^2 2\theta$
case 1 - 2 (mean)
absolute upper bound
absolute lower bound
10^0
10^1
M_1 / keV

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- Dodelson-Widrow (thermal) scenario: $\nu_a \to N$ due to mixing,

$$\rho_N \propto \theta^2$$

  is ruled out
- Primordial abundance: physics at higher energies
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Free scalar field as Cold Dark Matter (axion)

Homogeneous scalar field

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$

at $m \ll H$ no evolution: $\phi = \text{const}$, at $m \gg H$ it oscillates, so

$$\rho = \frac{1}{2}\left(\frac{d\phi}{dt}\right)^2 + \frac{m^2}{2}\phi^2 = \langle E_k \rangle + \langle E_p \rangle = 2\langle E_p \rangle\,, \quad p = \frac{1}{2}\left(\frac{d\phi}{dt}\right)^2 - \frac{m^2}{2}\phi^2 = \langle E_k \rangle - \langle E_p \rangle = 0\,,$$

behaves as nonrelativistic (dark) matter (dust-like component) !!

nonperturbative CP-violation in QCD

$$L_\theta = \frac{\alpha_s}{8\pi}\left(\theta_0 + \text{Arg}\left(\text{Det}\hat{M}_q\right)\right) G^a_{\mu\nu}\tilde{G}^{\mu\nu\,a} \equiv \frac{\alpha_s}{8\pi}\cdot\theta\cdot G^a_{\mu\nu}\tilde{G}^{\mu\nu\,a}\,.$$

$$\theta \to \bar{\theta}(x) = \theta + C_g\frac{a(x)}{f_{PQ}}\,.$$

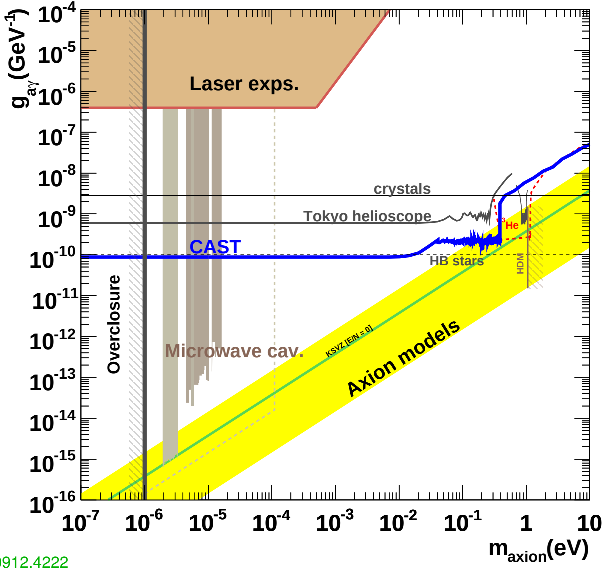
$$\mathscr{L} = \frac{f_{PQ}^2}{2}\cdot\left(\frac{d\bar{\theta}}{dt}\right)^2 - \frac{m_a^2(T)}{2}f_{PQ}^2\bar{\theta}^2\,,$$

$$m_a(T) \simeq 0\,, T > \Lambda_{QCD} \quad \text{and} \quad m_a(T) \simeq m_a \simeq m_\pi f_\pi / f_{PQ}$$

✍ Check this $\Longrightarrow$

$$\Omega_a \simeq 0.2\cdot\bar{\theta}_i^2\cdot\left(\frac{4\cdot 10^{-6}\ \text{eV}}{m_a}\right)\cdot\frac{1}{2h^2}$$

Axion: extensive searches

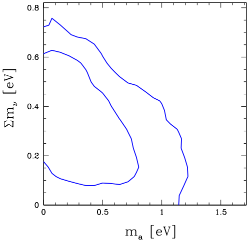


0912.4222

Solar axions:
$\gamma + e^- \to a + e^-$

2005-2007: ^{4}He,
$m_a < 0.4$ eV
2008-2009: ^{3}He,
$m_a < 1.2$ eV

Early Universe: $\pi\pi \leftrightarrow \pi a$
become Hot Dark Matter



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Outline

Baryogenesis

Sakharov conditions of successful baryogenesis

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

At $100\,\text{GeV} \lesssim T \lesssim 10^{12}$ 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 ... due to sterile neutrinos

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

Outline

Phenomenological problems of the Standard Model

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
  - Neutrino oscillations
  - Dark matter (Ω_{DM})
  - Baryon asymmetry

- BBN, CMB, structure formation:

  $\sum m_\alpha$, mass hierarchy (Planck, CMBPole, BOSS)

  …light sterile neutrinos?
- Many models, but new ideas are welcome !

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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
  - Neutrino oscillations
  - Dark matter (Ω_{DM})
  - Baryon asymmetry
  - BBN, CMB, structure formation:

    $\sum m_\alpha$, mass hierarchy

    (Planck, CMBPole, BOSS)

    ...light sterile neutrinos?
  - Many models, but new ideas are welcome !

Backup slides

Production of ^{3}He & ^{3}H

$$\langle \sigma v \rangle_{^3\mathrm{He}(D,p)^4\mathrm{He}} = 10^{-15} \frac{\mathrm{cm}^3}{\mathrm{s}} \cdot T_9^{-1/2} e^{-1.8 T_9^{-1}}$$

@ $T = t_{NS}$ this rate exceeds the deuterium-burning rate

^{3}He stops burning when @ some $T = T_{^3\mathrm{He}} < T_{NS}$

$$\langle \sigma v \rangle_{^3\mathrm{He}(D,p)^4\mathrm{He}} \cdot n_D \sim H \,, \quad T = T_{^3\mathrm{He}} \simeq 0.6\, T_{NS}$$

^{3}He is produced via $\mathrm{D} + \mathrm{D} \to {}^3\mathrm{He} + n$ and for the Hubble time

$$n_{^3\mathrm{He}} \sim \langle \sigma v \rangle_{D(D,n)^3\mathrm{He}} \cdot n_D^2 \cdot \frac{1}{H} \,, \quad T = T_{^3\mathrm{He}} \,.$$

$$\frac{n_{^3\mathrm{He}}}{n_D} \simeq \frac{\langle \sigma v \rangle_{D(D,n)^3\mathrm{He}}}{\langle \sigma v \rangle_{^3\mathrm{He}(D,p)^4\mathrm{He}}} \longrightarrow \frac{n_{^3\mathrm{He}}}{n_p} \simeq 0.9 \cdot 10^{-5}$$

quite similar $\frac{n_T}{n_p} \simeq 2 \cdot 10^{-7}$

Lithium in $\mathrm{T}(\alpha,\gamma)^7\mathrm{Li}$ & $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$

$$\langle \sigma v \rangle_{T(\alpha,\gamma)^7\mathrm{Li}} \sim 10^{-18} \frac{\mathrm{cm}^3}{\mathrm{s}} \cdot T_9^{-2/3} e^{-8.0 T_9^{-1/3}} .$$

tritium burning rate is smaller than H

$$\langle \sigma v \rangle_{T(\alpha,\gamma)^7\mathrm{Li}} \cdot n_\alpha \simeq 1.5 \cdot 10^{-4}\ \mathrm{s}^{-1} , \quad T_9 = 0.75$$

$$\langle \sigma v \rangle_{^7\mathrm{Li(p,}\alpha)^4\mathrm{He}} \sim 10^{-15} \frac{\mathrm{cm}^3}{\mathrm{s}} \cdot T_9^{-2/3} e^{-8.5 T_9^{-1/3}} .$$

lithium burning rate exceeds H

$$\langle \sigma v \rangle_{^7\mathrm{Li(p,}\alpha)^4\mathrm{He}} \cdot n_p \simeq 0.7\ \mathrm{s}^{-1} , \quad T_9 = 0.75 , \quad \eta_B = 6.15 \cdot 10^{-10}$$

$$\frac{n_{^7\mathrm{Li}}}{n_T} \simeq \frac{\langle \sigma v \rangle_{T(\alpha,\gamma)^7\mathrm{Li}}}{\langle \sigma v \rangle_{^7\mathrm{Li(p,}\alpha)^4\mathrm{He}}} \cdot \frac{n_\alpha}{n_p} \sim 2 \cdot 10^{-5}$$

Gravitino production: strong fine-tuning

$$\mathscr{L} = \frac{1}{F}\partial^\mu\psi\cdot J_\mu^{SUSY}\,, \quad \tilde{G}_\mu \to \tilde{G}_\mu + i\sqrt{4\pi}\frac{M_{Pl}}{F}\partial_\mu\psi$$

$$m_{3/2} = \sqrt{\frac{8\pi}{3}\frac{F}{M_{Pl}}}$$

$$1\text{ TeV} \lesssim \sqrt{F} \lesssim M_{Pl}\,, \quad 2\cdot 10^{-4}\text{ eV} \lesssim m_{3/2} \lesssim M_{Pl}\,.$$

LSP in low scale SUSY breaking models

$$2\cdot 10^{-4}\text{ eV} \lesssim m_{3/2} \lesssim 100\text{ GeV} \longrightarrow \sqrt{F} \lesssim 10^{10}\text{ GeV}$$

Thermal equilibrium is forbidden:

$$\Omega_{3/2} = \frac{m_{3/2}\cdot n_{3/2}}{\rho_c} = 0.2\frac{m_{3/2}}{200\text{ eV}}\left(\frac{g_{3/2}}{2}\right)\cdot\left(\frac{210}{g_*(T_f)}\right)\cdot\frac{1}{2h^2}$$

$$\tilde{X}_i \to \tilde{G} + X_i\,, \quad X_i + X_j \to X_k + \tilde{G}$$

Gravitino non-thermal production

$$\frac{dn_{3/2}}{dt} + 3Hn_{3/2} = \sum_i \Gamma_{\tilde{X}_i} \cdot \gamma_i^{-1} \cdot n_{\tilde{X}_i} + \langle \sigma_{tot} \rangle \cdot n_\gamma^2 \,,$$

$$\Omega_{3/2} \sim \left(\frac{200}{m_{3/2}} \right) \cdot \left(\frac{T_{max}}{10} \right) \cdot \left(\frac{M_S}{1} \right)^2 \cdot \left(\frac{15}{\sqrt{g_*(T_{max})}} \right) \cdot \frac{1}{2h^2}$$