Cosmology and particle physics
Lecture #4
dark matter, baryogenesis, neutrinos, . . .

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Outline

Dark Matter: non-thermal production

1. in the primordial plasma of SM particles (via scatterings (freeze-in), via oscillations):
   gravitino
   sterile neutrino of 1-50 keV
2. at phase transitions:
   axion of $10^{-4} - 10^{-7}$ eV
   Q-balls
   strangelets (?)
3. during reheating (after inflation?): black holes
   any guy coupled (only) to inflaton
   - perturbatively: inflaton decays
     production by external (inflaton) field
   - non-perturbatively: Bose-enhancement of
     coherent production by external field
4. while the Universe expands:
   gravity produces any particles at $H \sim M_X$

A simple example of scalar DM

most general renormalizable coupled to SM:

Z_2-invariant Higgs (Φ) portal

$$\Delta\mathscr{L} = \frac{1}{2}g^{\mu\nu}\partial_\mu X\partial_\nu X - \frac{1}{2}M^2X^2 + g^2X^2\Phi^\dagger\Phi - \frac{\lambda}{4}X^4$$

Options:

- freeze-out: sufficiently large g^2

$$v\sigma_{hh\to XX}\times n_h \gtrsim H \;\to\; \Omega_X \propto \frac{1}{\sigma_0}, \;\text{with}\; \frac{g^4}{(4\pi...)^2M^2} = \sigma_0 \equiv \sigma v$$

- freeze-in: intermediate g^2

$$\dot{n}_X + 3Hn_X = \sigma_{hh\to XX}n_h^2 \;\to\; \frac{n_X}{s} = \#\int dT\,\frac{n_h^2}{sHT}\times\frac{g^4}{T^2} \sim g^4\frac{M_{Pl}}{M} \;\to$$

$\Omega_X \propto g^4 \;\to\; g^2 \approx 10^{-11}$ still natural...

Freeze in via gravitational scatterings..?

any particles A in plasma

$$\sigma_{AA\to XX} \propto \frac{T^2}{M_{Pl}^4} \;\to\; \Omega_X \propto M_X \frac{T_i^3}{M_{Pl}^3} \ldots$$

assuming $m \ll T_i$

called “unnatural” being dependent on the initial conditions

Free massive scalar field $g^2 = 0$

$$\mathscr{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - \frac{1}{2} m_\phi^2 \phi^2$$

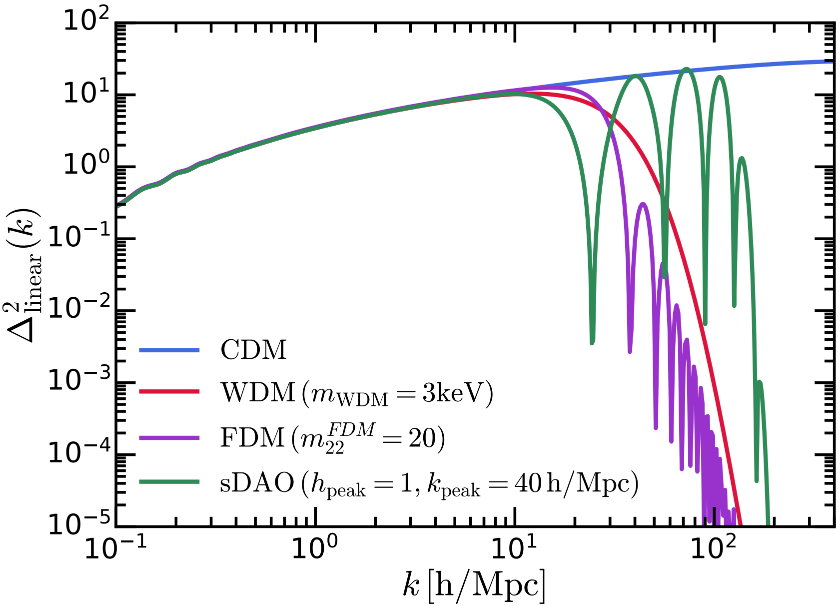
Homogeneous scalar field in the expanding Universe

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

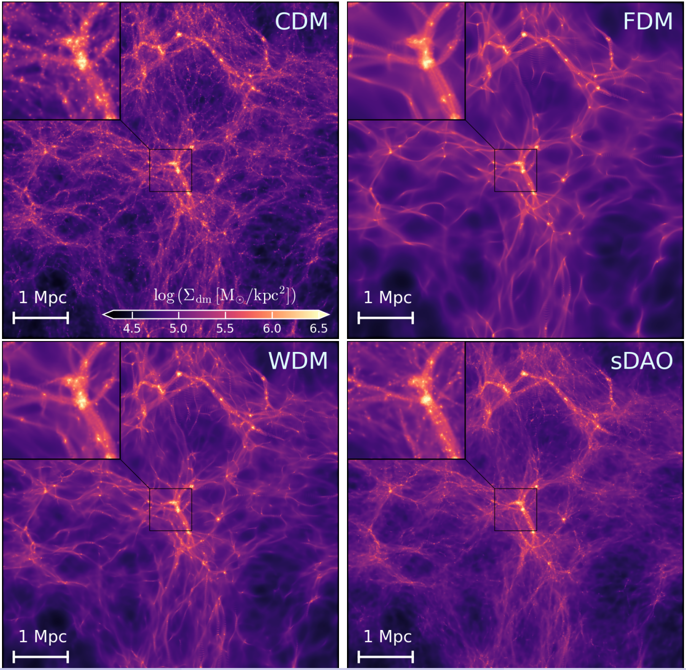
Two-stage evolution:

$$m_\phi < H(t) \quad \Longrightarrow \quad \phi = \phi_i = \text{const}$$
$$m_\phi > H(t) \quad \Longrightarrow \quad p = \langle E_k \rangle - \langle E_p \rangle = 0\,, \quad \rho \sim m_\phi^2 \phi^2 \propto 1/a^3$$

- dust-like substance in the late Universe, $\Omega \propto m_\phi^{1/2} \phi_i^2$
  at scales $l > 2\pi/m_\phi$ depends on initial conditions
  perturbations are suppressed at $l > M_{Pl}^{1/2}/(m_\phi^{1/2} \rho^{1/4})$ fuzzy DM



10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$\Delta^2_{\rm linear}(k)$
CDM
WDM ($m_{\rm WDM} = 3$keV)
FDM ($m_{22}^{FDM} = 20$)
sDAO ($h_{\rm peak} = 1$, $k_{\rm peak} = 40$ h/Mpc)
10^{-1}
10^0
10^1
10^2
k [h/Mpc]


CDM
FDM
WDM
sDAO
1 Mpc
1 Mpc
1 Mpc
1 Mpc
$\log(\Sigma_{dm}\,[M_\odot/kpc^2])$
4.5
5.0
5.5
6.0
6.5

2304.06742

DM from oscillating scalar

$0 \neq g^2 < 10^{-11}$

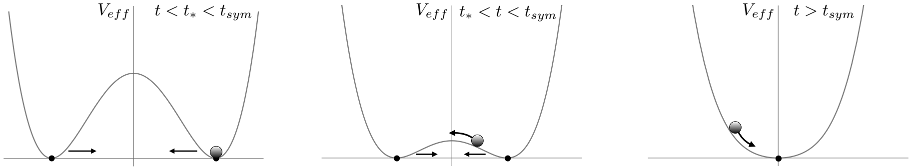
Z_2-invariant Higgs (Φ) portal

$$\Delta\mathscr{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu X \partial_\nu X - \frac{1}{2} M^2 X^2 + g^2 X^2 \Phi^\dagger \Phi - \frac{\lambda}{4} X^4$$

Higgs particles in plasma change the potential:

$$g^2 X^2 \Phi^\dagger \Phi \;\to\; g^2 X^2 T^2/3$$

Z_2 symmerty is broken after reheating by the plasma contribution



Temperature decrease restores Z_2

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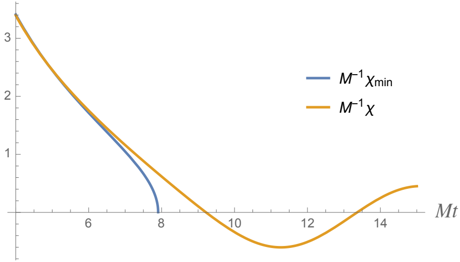
$$\Delta\mathscr{L} = \frac{1}{2} g^{\mu\nu}\partial_\mu X \partial_\nu X - \frac{1}{2} M^2 X^2 + g^2 X^2 T^2/3 - \frac{\lambda}{4} X^4$$

X starts from the false vacuum



at $g^2 T_*^2 \simeq M^2$ sign changes
and X starts to oscillate
gravitational misalignment

$$\rho_{DM}(t_*) = \frac{M^2 \cdot S_*^2}{2} \simeq \frac{\left(M^5 H_*\right)^{2/3}}{4\lambda}$$

And the correct amount of DM by classical oscillating field

$$p = \langle E_{kin}\rangle - \langle E_p\rangle = 0$$

$$g^2 \simeq 10^{-12} \times \left(\frac{\lambda}{10^{-6}}\right)^{6/5} \times \left(\frac{10^6\,\text{GeV}}{M}\right)^2$$

Dark Matter with general setup: white area

$$\beta \equiv \lambda/g^4 < 1$$

$$V = \frac{1}{2}M^2X^2 + \frac{\lambda}{4}X^4 - \frac{g^2T^2}{12}X^2$$

The inverse phase transition may be accompanied by the production of GW

strong enough to be

detected by the present or

next genertation

experiments

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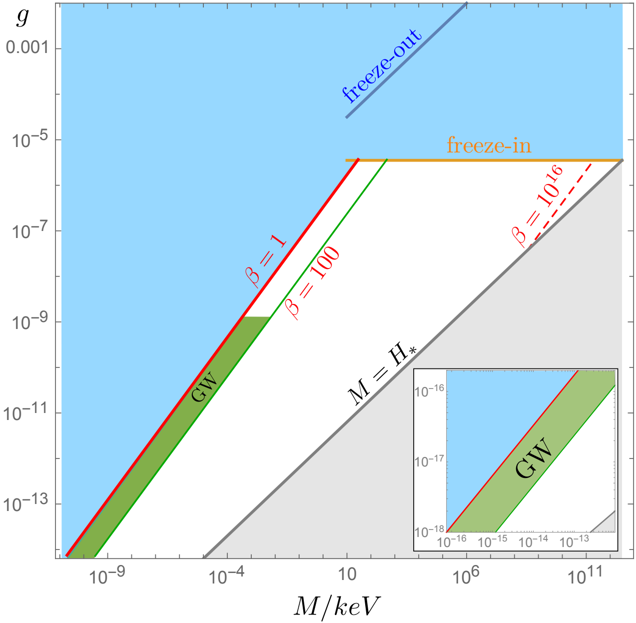

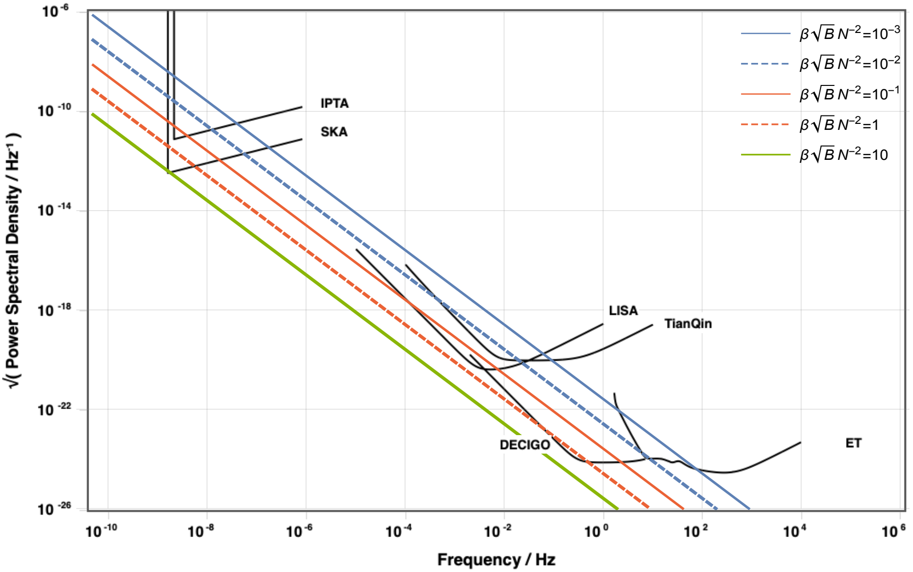

strain: $\Omega_{GW}H_0^2 \equiv 2\pi^2 f^3 S/3$

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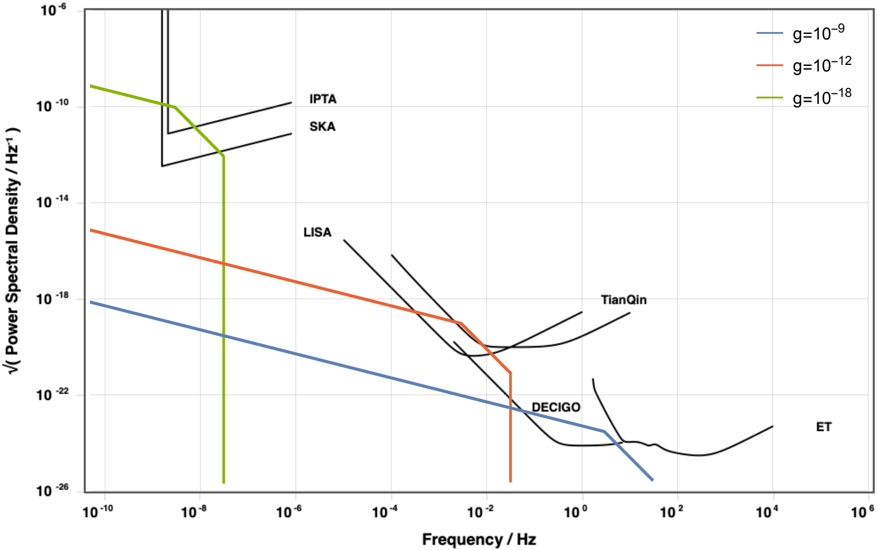

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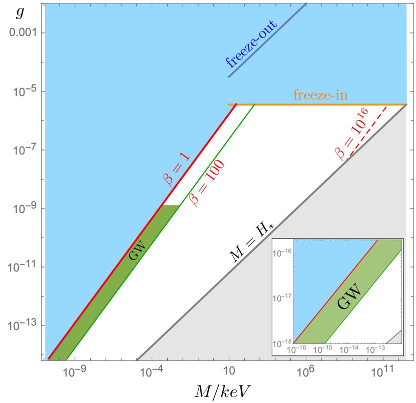

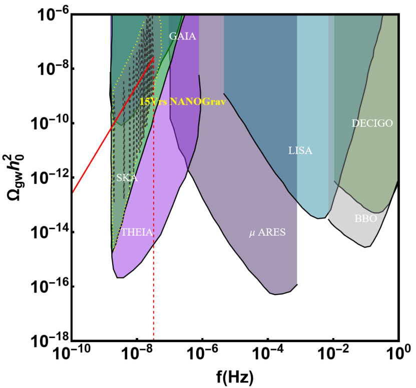

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$$\beta \equiv \lambda/g^4$$

$$V = \frac{1}{2}M^2X^2 + \frac{\lambda}{4}X^4 - \frac{g^2T^2}{12}X^2$$

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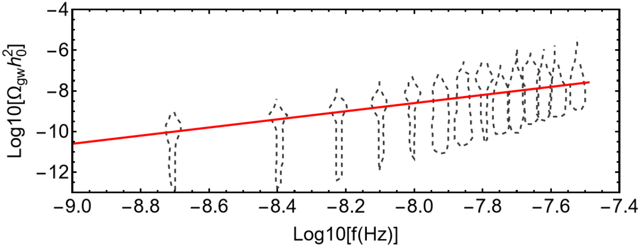


Three Portals to the hidden World

Renormalizable interaction including SM field and new (hypothetical) fields singlets with respect to the SM gauge group

Attractive feature: couplings are insensitive to energy in c.m.f., hence low energy experiments (intensity frontier) are favorable

- Scalar portal: SM Higgs doublet H and hidden scalar S

  the simplest dark matter

$$\mathscr{L}_{\text{scalar portal}} = -\beta\, H^\dagger H S^\dagger S$$

- Spinor portal: SM lepton doublet L, Higgs congugate field $\tilde{H} = \varepsilon H^*$ and hidden fermion N

  sterile neutrino !!

$$\mathscr{L}_{\text{spinor portal}} = -y \bar{L} \tilde{H} N$$

- Vector portal: SM gauge field of $U(1)_Y$ and gauge hidden field of abelian group $U(1)'$

$$\mathscr{L}_{\text{vector portal}} = -\frac{\varepsilon}{2} B_{\mu\nu}^{U(1)_Y} B_{\mu\nu}^{U(1)'}$$

Massive vectors (paraphotons)

NA64

Vector portal to a secluded sector:

one more $U(1)'$ gauge group [spontaneously broken] in secluded sector

e.g. with Dark matter Ψ

0711.4866

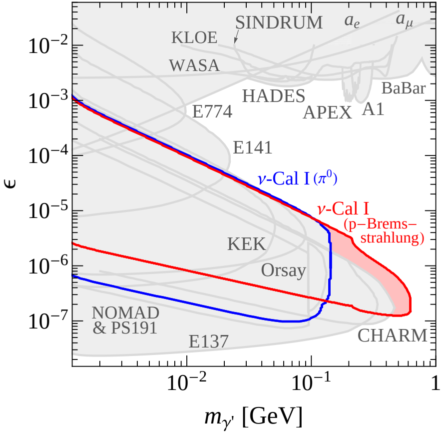
$$\mathscr{L}_{\text{DM+mediator}} = \bar{\Psi}\left(i\gamma^\mu\partial_\mu - e'\gamma^\mu A'_\mu - m_\Psi\right)\Psi - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \frac{m_{\gamma'}^2}{2}A'_\mu A'^\mu + \varepsilon A'_\mu \partial_\nu B^{\mu\nu}$$

when $m_\Psi > m_{\gamma'} \sim 1\,\text{GeV}$

- limit from BBN:

$$\tau_V < 1\,\text{s}, \quad \Longrightarrow \varepsilon^2\left(\frac{m_{\gamma'}}{1\,\text{GeV}}\right) \gtrsim 10^{-21}$$

- light for $(g-2)$
- light for Pamela, Fermi, etc



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Production by virtual photon $\sigma \propto \varepsilon^2$

Decay through virtual photon, $\Gamma \propto \varepsilon^2$

$V \to e^+e^-$, $\mu^+\mu^-$, etc

Searches for visible decays

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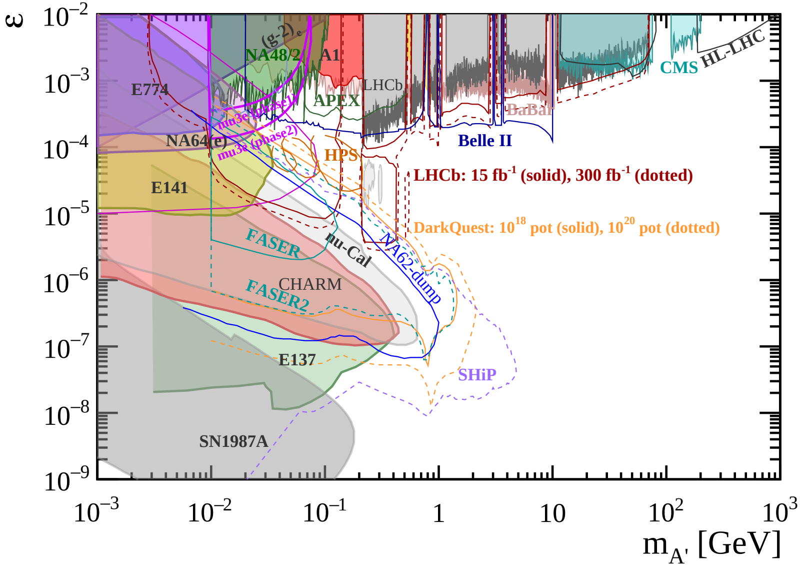

Searches for invisible mode

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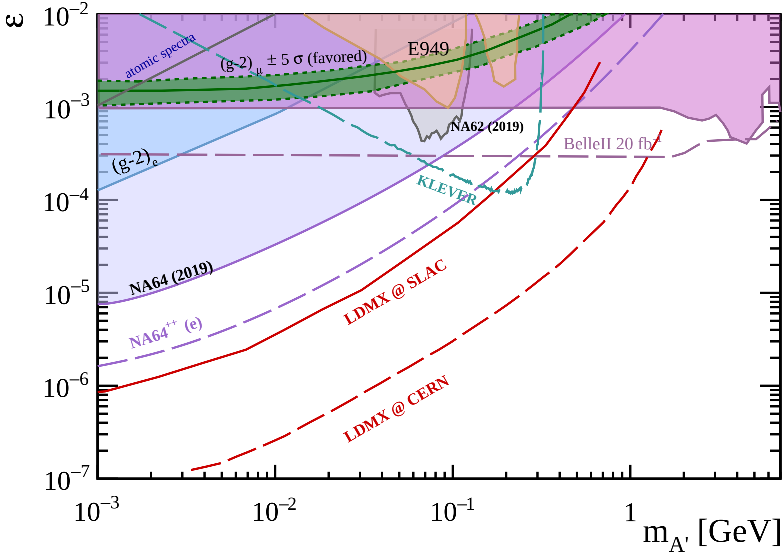

Searches for dark matter

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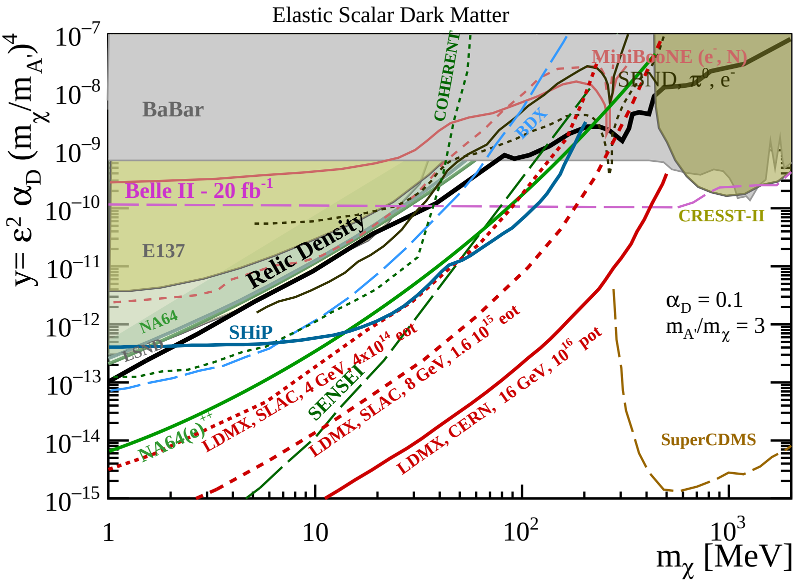

Searches for dark matter

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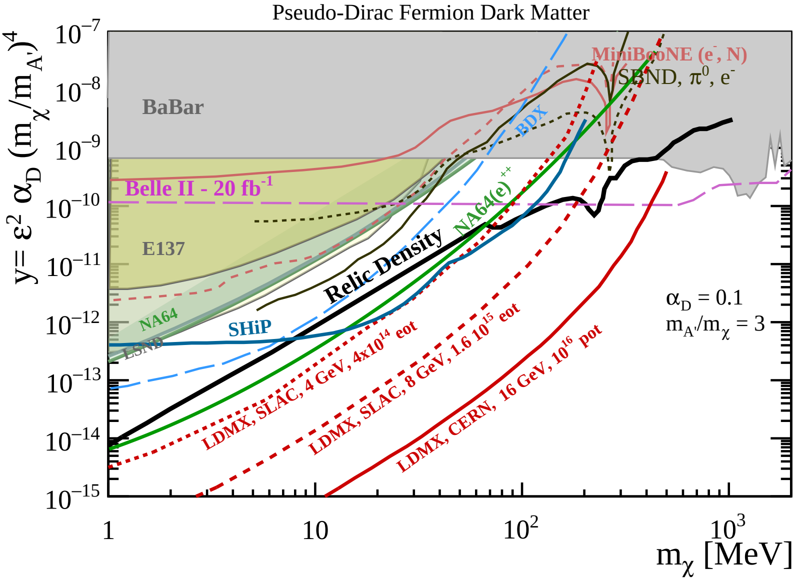


Strong *CP*-problem and axion

$$L_\theta = \frac{\alpha_s}{8\pi}\left(\theta_0 + \text{Arg}\left(\text{Det}\hat{M}_q\right)\right) G^a_{\mu\nu}\tilde{G}^{\mu\nu\, a} \equiv \frac{\alpha_s}{8\pi}\theta\, G^a_{\mu\nu}\tilde{G}^{\mu\nu\, a} \equiv \partial_\mu K^\mu$$ *P*- *CP*-violation

tree-level and $U(1)_A$-anomaly contributions, $\bar{q}_L \hat{M}_q q_R + h.c$ strong *CP*-problem

Theory and Nature: neutron EDM $\theta < 10^{-9}$ nonantropic parameter!

Transformation (PQ-symmetry)

$$q^k_L \to e^{ie^{(PQ)}_k \beta/2} q^k_L$$

$$q^k_R \to e^{-ie^{(PQ)}_k \beta/2} q^k_R,$$

with $\sum_k e^{(PQ)}_k \neq 0$

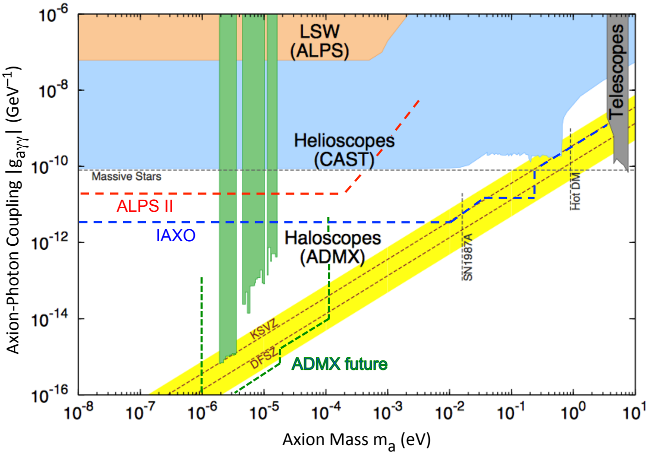
cancels θ with β

$$\theta \to \theta + a(x)/f_a$$

$$m_{axion} \simeq f_\pi m_\pi / f_a$$

Dark Matter region

$$\mathscr{L} \sim g_{a\gamma\gamma} \times a(x) F_{\mu\nu} F^{\mu\nu}$$



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

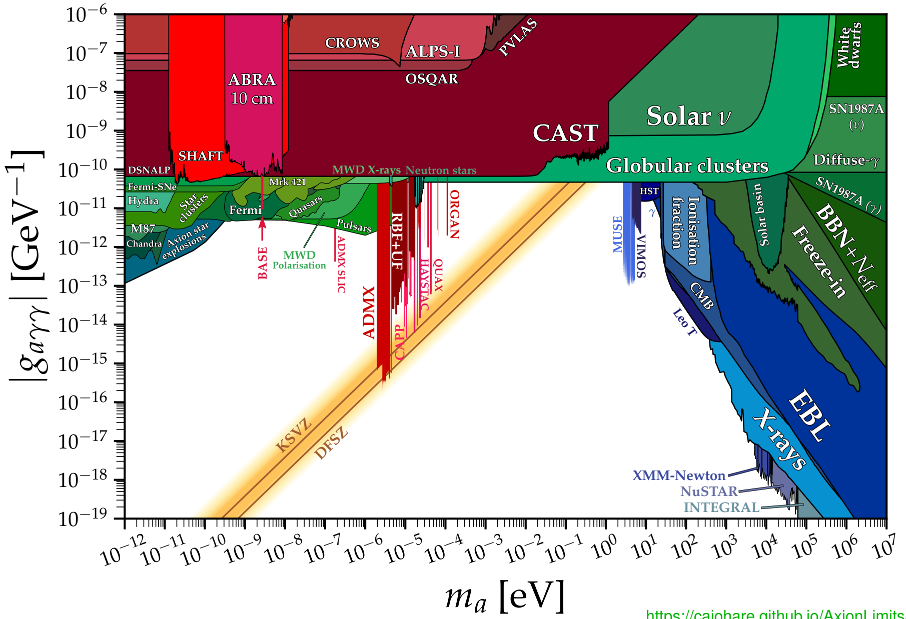
$$L_\theta = \frac{\alpha_s}{8\pi}\left(\theta_0 + \text{Arg}\left(\text{Det}\hat{M}_q\right)\right) G^a_{\mu\nu}\tilde{G}^{\mu\nu\,a} \equiv \frac{\alpha_s}{8\pi}\cdot\theta\cdot G^a_{\mu\nu}\tilde{G}^{\mu\nu\,a} \,.$$

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

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

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

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



https://cajohare.github.io/AxionLimits/

Very light scalars: more options

- mass implies huge phase space density !!
  e.g. galaxy: $\rho_{DM} = m_\phi \times n_\phi$, and $p \sim m_\phi \times v \sim 10^{-3} \times m_\phi$
  typical phase space density is

$$f \sim \frac{\rho_{DM}}{m_\phi} \left(\frac{1}{m_\phi v} \right)^3 \to \infty$$

- even tiny interaction makes condensation !!
  – gravity: all particles in $L \sim 1/(m_\phi v)$ interact coherently

$$F_{drag} \propto m_\phi^2 \times G_N$$

  – selfinteraction: . . . e.g. axion instability: attraction force

$$V = m_a^2 f_a^2 \left(1 - cos\left(\frac{\phi}{f_a} \right) \right) \to \frac{1}{2} m_a^2 \phi^2 - \frac{1}{4!} \frac{m_a^2}{f_a^2} \phi^4$$

Light sterile neutrinos in cosmology

Impact on processes

- Big Bang Nucleosynthesis: increase of expansion rate

$$H^2 = \frac{8\pi}{3} G\rho\,, \quad \rho = \frac{\pi^2}{30}\left(2\times T_\gamma^4 + 2\times(3+\Delta N_\nu)\times T_\nu^4\right)$$

  with $\Delta N_\nu > 0$ higher H neutrons freeze out earlier giving more Helium

- expansion rate at Equality, $\rho_{rad} = \rho_{mat}$, and at CMB epoch
  change of CMB anisotropy $-0.34 < \Delta N_\nu < 0.33$ (95% CL)

- become non-relativistic, but have high velocity
  free streaming leads to washing out of low-scale perturbations
  change galaxy spectrum limits on ΔN_ν & neutrino masses

Primordial Nucleosynthesis: solving kinetic equations

Neutrons freeze out ($p + e \leftrightarrow n + \nu_e$) at $T_n \approx 0.8\,\mathrm{MeV}$, and then

$$p + n \leftrightarrow D + \gamma$$

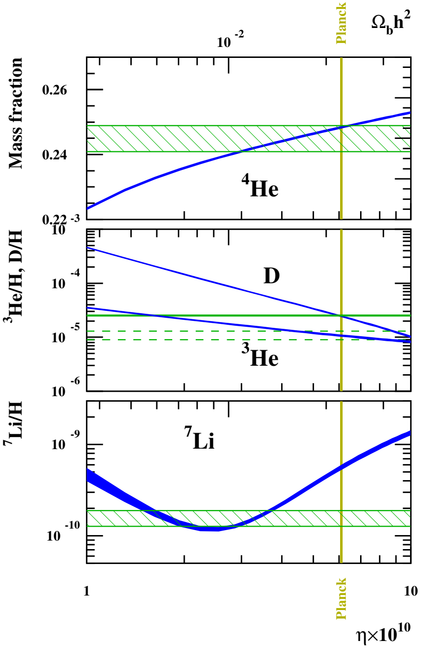
D survive γ-hitting later, at $T < T_{NS} \approx 65\,\mathrm{keV}$

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

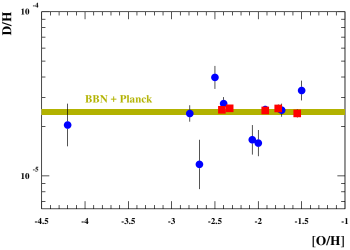
neutron-to-proton ratio $\qquad \tau_n \approx 880$ s

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

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

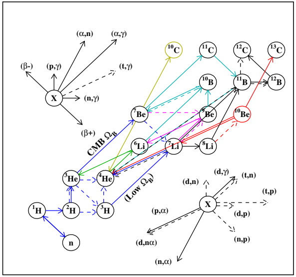


1707.01004 Measurement of $\eta_B = n_B/n_\gamma$ at $T \sim 1$ MeV



Lack of Lithium. . .

Exotics needed?



BBN: extra-radiation and lepton asymmetry

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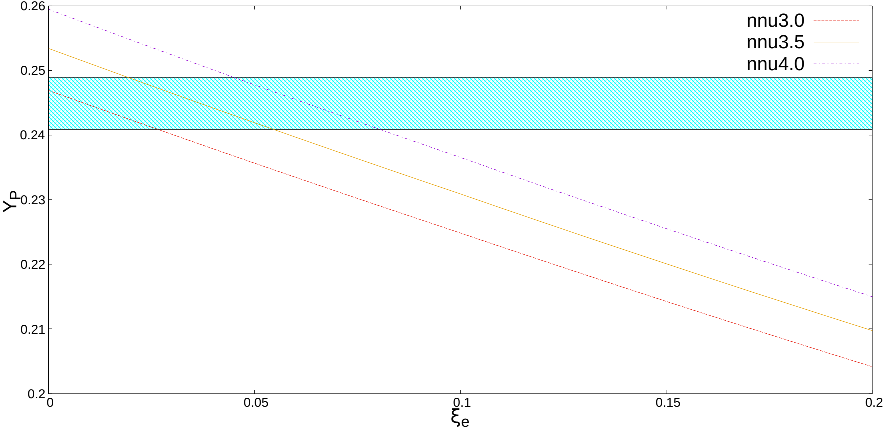


Sterile neutrinos: NEW ingredients

One of the optional physics beyond the SM:

sterile: new fermions uncharged under the SM gauge group
neutrino: explain observed oscillations by mixing with SM (active) neutrinos

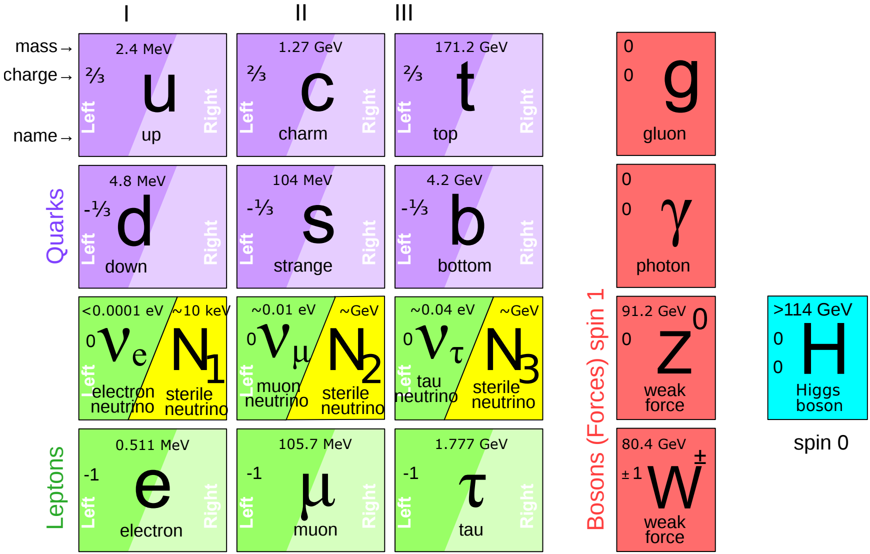
Attractive features:

- possible to achieve within renormalizable theory
- only $N = 2$ Majorana neutrinos needed
- baryon asymmetry via leptogenesis
- dark matter (with $N \geq 3$ at least)
- light(?) sterile neutrinos might be responsible for neutrino anomalies. . . ?

Disappointing feature:

Major part of parameter space is UNTESTABLE

Three Generations
of Matter (Fermions) spin ½



Seesaw mechanism: $M_N \gg 1$ eV

With $m_{active} \lesssim 1$ eV we work in the seesaw (type I) regime:

$$\mathscr{L}_N = \overline{N} i \partial\!\!\!/ N - f \overline{L}_e^c \tilde{H} N - \frac{M_N}{2} \overline{N}^c N + \text{h.c.}$$

Higgs gains $\langle H \rangle = v/\sqrt{2}$ and then

$$\mathscr{V}_N = \frac{1}{2} \left(\overline{\nu}_e \,, \overline{N}^c \right) \begin{pmatrix} 0 & v \frac{f}{\sqrt{2}} \\ v \frac{f}{\sqrt{2}} & M_N \end{pmatrix} \begin{pmatrix} \nu_e \\ N \end{pmatrix} + \text{h.c.}$$

For a hierarchy $M_N \gg M^D = v \frac{f}{\sqrt{2}}$ we have

flavor state $\nu_e = U \nu_1 + \theta\, N$ with $U \approx 1$ and

active-sterile mixing: $$\theta = \frac{M^D}{M_N} = \frac{v f}{2 M_N} \ll 1$$

and mass eigenvalues

$$\approx M_N \quad \text{and} \quad - m_{active} = \theta^2 M_N \lll M_N$$

Violation of L, C and CP symmetries

$$\mathscr{L}_N = \overline{N} i \partial\!\!\!/ N - f \overline{L}_e^c \tilde{H} N - \frac{M_N}{2} \overline{N}^c N + \text{h.c.}$$

- $f = 0 \quad \longrightarrow \quad$ free fermion, no need to call 'sterile'
- $M_N = 0 \quad \longrightarrow \quad$ N and ν form pure Dirac neutrino,
  the most boring case, worth than we have with the Higgs boson
  one may refuse to call it 'new physics'
- $f \neq 0, \quad M_N \neq 0 \quad \longrightarrow \quad$ introduces new massive parameter,
  violates lepton symmetry L
  (and C- and CP-symmetry with several N's)

Sterile neutrino: a vast region of mass

Within the seesaw paradigm, as far as

$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

Any set

(mass scale M_N, Yukawa coupling f)

is viable

And with special tunning or symmetry larger (but not smaller) mixing
3 sterile neutrinos is viable

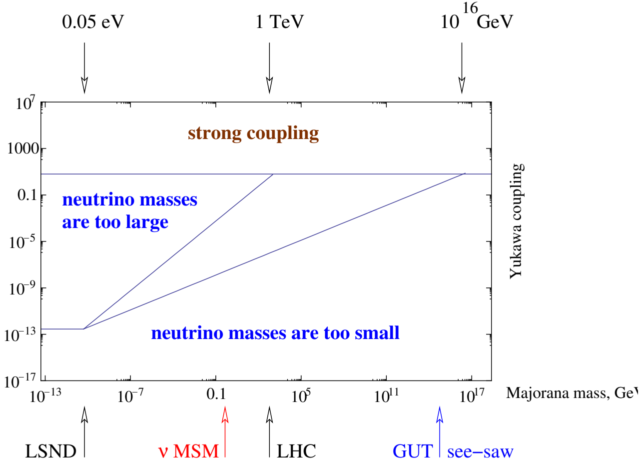
$$\hat{m}_a \sim \hat{f}^T \frac{1}{\hat{M}_N} \hat{f} v^2$$

Sterile neutrino mass scale: $\hat{M}_\nu = -v^2 \hat{f}^T \hat{M}_N^{-1} \hat{f}$

NB: With fine tuning in $\hat{M}_N$ and $\hat{f}$ we can get a hierarchy in sterile neutrino masses, and 1 keV and even 1 eV sterile neutrinos

$L_e - L_\mu - L_\tau$ or discrete symmetries
Froggatt-Nielsen mechanism

Extended seesaw



Seesaw diagram

Sterile neutrino lagrangian

Most general renormalizable with 2(3...) right-handed neutrinos N_I

$$\mathcal{L}_N = \overline{N}_I i\partial\!\!\!/ N_I - f_{\alpha I}\overline{L}_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2}\overline{N}_I^c N_I + \text{h.c.}$$

Parameters to be determined from experiments

9(7): active neutrino sector

- 2 Δm_{ij}^2: oscillation experiments
- 3 θ_{ij}: oscillation experiments
- 1 CP-phase: oscillation experiments
- 2(1) Majorana phases: $0\nu ee$, $0\nu\mu\mu$
- 1(0) m_ν: $^3\text{H} \to {}^3\text{He} + e + \bar{\nu}_e$, cosmology, ...

11: $N = 2$ sterile neutrinos (works if $m_\nu = 0$!!!)

- 2: Majorana masses M_{N_I}
- 9: New Yukawa couplings $f_{\alpha I}$ which form
  - 2: Dirac masses $M^D = f\langle H\rangle$
  - 3+1: mixing angles
  - 2+1: CP-violating phases

4 new parameters in total

18: $N = 3$ sterile neutrinos:

- 3: Majorana masses M_{N_I}
- 15: New Yukawa couplings $f_{\alpha I}$ which form
  - 3: Dirac masses $M^D = f\langle H\rangle$
  - 3+3: mixing angles
  - 3+3: CP-violating phases

9 new parameters in total

Profit: can suggest why neutrinos are so light, $m_\nu \sim 0.1 - 0.01\,\text{eV}$

Sterile neutrino: well-motivated keV-mass Dark Matter

- massive fermions giving mass to active neutrino through mixing (seesaw)

$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

- unstable, $N \to \nu\nu\nu$ is always open by mixing
  but exceeding the age of the Universe if

(applicable for $M_N < M_W$)

$$\tau_{N\to 3\nu} \sim 1/\left(G_F^2 M_N^5 \theta_{\alpha N}^2\right) \quad \Longrightarrow \quad \theta^2 < 1.5\times 10^{-7}\left(\frac{50\,\text{keV}}{M_N}\right)^5$$

- with seesaw relation $m_a \sim \theta^2 M_N$

$$\tau_{N\to 3\nu} \sim 1/\left(G_F^2 M_N^4 m_\nu\right) \sim 10^{11}\,\text{yr}\,(10\,\text{keV}/M_N)^4$$

Sterile neutrino: indirect searches

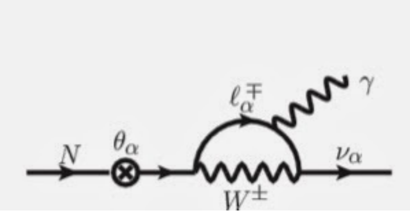
$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

- unstable, but exceeding the age of the Universe if

$$\frac{\theta^2}{3 \times 10^{-3}} < \left(\frac{10\,\text{keV}}{M_N}\right)^5$$

- DM sterile neutrinos can be searched at X-ray telescopes because of two-body radiative decay

give limits in absence of the feature



a narrow line $(\delta E_\gamma / E_\gamma \sim v \sim 10^{-3})$
at photon frequency $E_\gamma = M_N/2$

$$\frac{\theta^2}{10^{-11}} \lesssim \left(\frac{10\text{ keV}}{M_N}\right)^4$$

. . . present searches: NuSTAR

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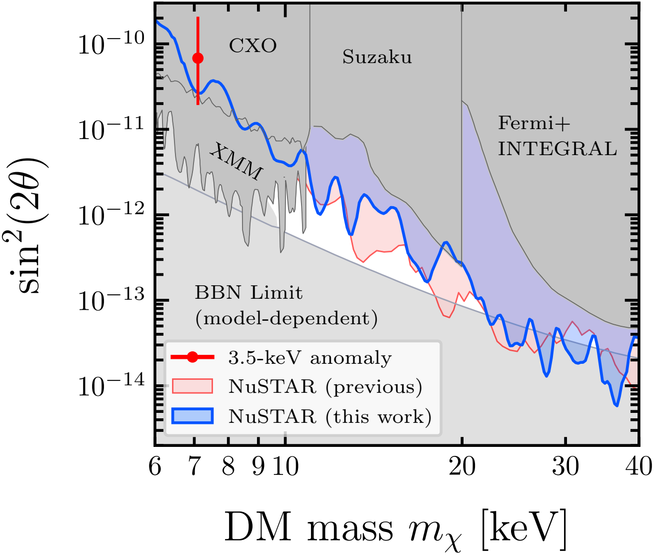
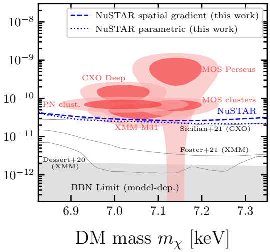


- upper limits on mixing: from *X*-ray searches
- lower limits on mass: from structure formation

  and BBN predictions



Production in oscillations

$$\frac{\partial}{\partial t} f_s(t,\mathbf{p}) - H\mathbf{p}\frac{\partial}{\partial \mathbf{p}} f_s(t,\mathbf{p}) = \Gamma_\alpha \, P(\nu_\alpha \to \nu_s)\, f_\alpha(t,\mathbf{p}) \,.$$

$\Gamma_\alpha \propto G_F^2 T^4 E$ is the weak interaction rate in plasma

$$P(\nu_\alpha \to \nu_s) = \sin^2 2\theta_\alpha^{\mathrm{mat}} \cdot \sin^2\left(\frac{t}{2t_\alpha^{\mathrm{mat}}}\right),$$

$$t_\alpha^{\mathrm{mat}} = \frac{t_\alpha^{vac}}{\sqrt{\sin^2 2\theta_\alpha + (\cos 2\theta_\alpha - V_{\alpha\alpha}\cdot t_\alpha^{vac})^2}},$$

$$\sin 2\theta_\alpha^{\mathrm{mat}} = \frac{t_\alpha^{\mathrm{mat}}}{t_\alpha^{vac}} \cdot \sin 2\theta_\alpha \,, \quad t_\alpha^{vac} = \frac{2E}{M_N^2}$$

sign of the effective plasma potential matters: as compared to vacuum

$V_{\alpha\alpha} < 0 \implies$ mixing gets suppressed

$V_{\alpha\alpha} > 0 \implies$ amplification via resonance

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 $X'Y' \ldots B \to XY \ldots$

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

Example: EW Ist order Phase Transition

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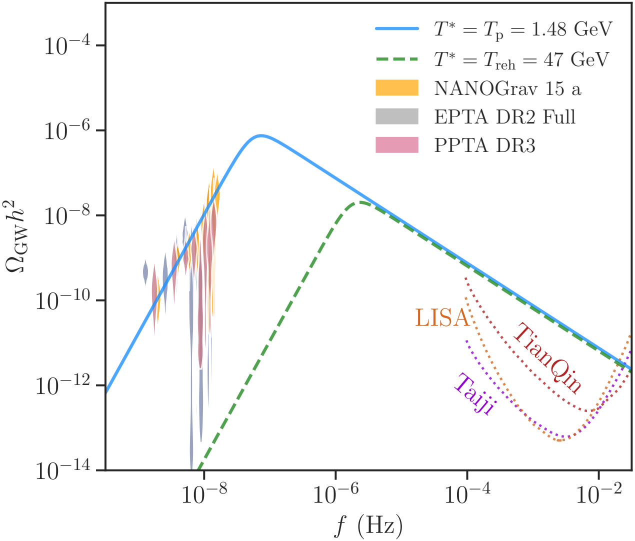

Electroweak sphalerons: $B-L$

$$\partial^\mu j_\mu{}^{B} = 3\,\frac{g^2}{16\pi^2}\,V^{a\;\mu\nu}\,\tilde{V}^a{}_{\mu\nu}\;,$$

$$\partial^\mu j_\mu{}^{Ln} = \frac{g^2}{16\pi^2}\,V^{a\;\mu\nu}\,\tilde{V}^a{}_{\mu\nu}\;,\quad n=1,2,3\;,$$

$V^a{}_{\mu\nu} = \partial_\mu V^a_\nu - \partial_\nu V^a_\mu + g\varepsilon^{abc} V^b_\mu V^c_\nu$ refer to $SU(2)_{\text{W}}$, $\tilde{V}^a{}_{\mu\nu} = \frac{1}{2}\varepsilon_{\mu\nu\lambda\rho} V^{a\;\lambda\rho}$
Anomaly: only left fermions couple to fields V^a_μ.
For nontrivial gauge fields in vacuum or plasma

$$\Delta B = B(t_f) - B(t_i) = \int_{t_i}^{t_f} dt \int d^3\mathbf{x}\,\partial^\mu j^{B}_\mu = 3\int_{t_i}^{t_f} d^4x\,\frac{g^2}{16\pi^2}\,V^{a\;\mu\nu}\,\tilde{V}^a{}_{\mu\nu}\;,$$

Strong fields are needed: $V^a{}_{\mu\nu} \propto \frac{1}{g}$, (integral is natural number!). Energies of such configurations $\propto \frac{1}{g^2}$.

$$\Delta B = 3\,\Delta L_e = 3\,\Delta L_\mu = 3\,\Delta L_\tau$$

At temperatures 100 GeV $\lesssim T \lesssim 10^{12}$ GeV only 3 linear combinations survive, e.g.

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

where

$$L \equiv L_e + L_\mu + L_\tau$$

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 $100\,\text{GeV} \lesssim T \lesssim 10^{12}$ 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?

Lepton asymmetry from sterile neutrino decays

Most general renormalizable lagrangian with Majorana neutrinos N_I, $I, \alpha = 1, 2, 3$.

$$\mathscr{L}_{SM} + \overline{N}_I i \partial\!\!\!/ N_I - y_{I\alpha} \bar{L}_\alpha \widetilde{H} N_I - \frac{M_I}{2} \overline{N}_I^c N_I + \text{h.c.}$$

where $\widetilde{H}_i = \varepsilon_{ij} H_j^*$, $i, j = 1, 2$; complex Yukawas, Majorana mass: $\Delta L \neq 0$ lepton number violating processes ($N = N^c$!):

$$N_I \to h l_\alpha \;, \quad N_I \to h \bar{l}_\alpha \;,$$
$$h l_\alpha \to h \bar{l}_\beta$$

- neutrino oscillations are explained
- BAU via leptogenesis (decays for $M_I > 10^9$ GeV or oscillations for light neutrinos, even $M_I \gtrsim 100\,\text{MeV}$
- dark matter with $M_I \sim$ 1-100 keV

Degeneracy for Leptogenesis

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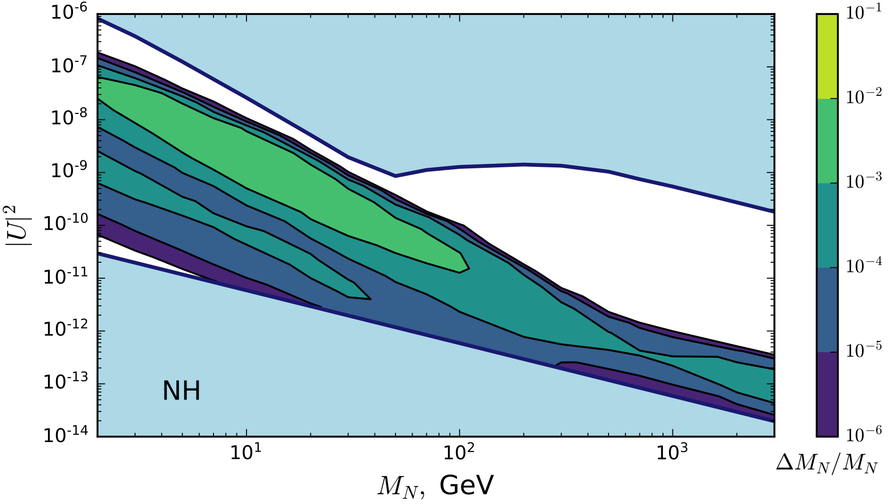
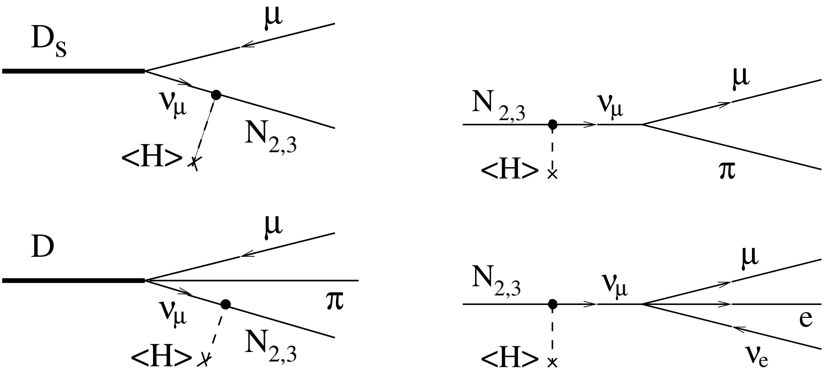


Sterile neutrinos: production and decays



Interaction via neutral and charged weak hadronic currents

mixing with ν_τ ... $\tau^\pm \to N + H^\pm$

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