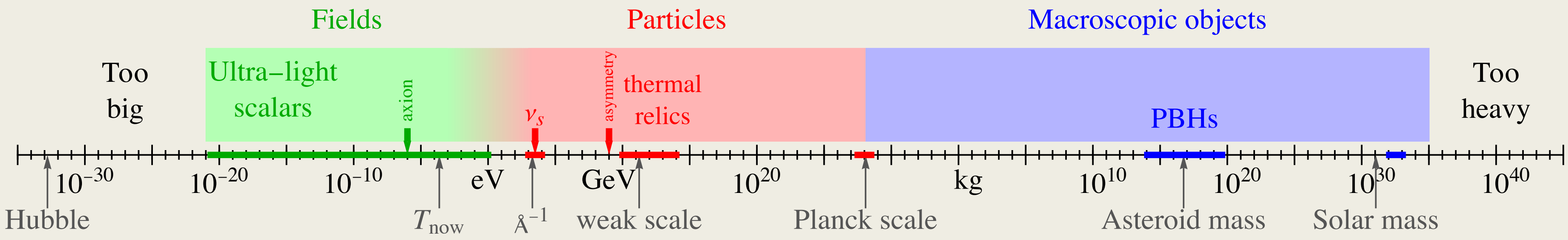
DARK MATTER

Yasaman Farzan
IPM, Tehran

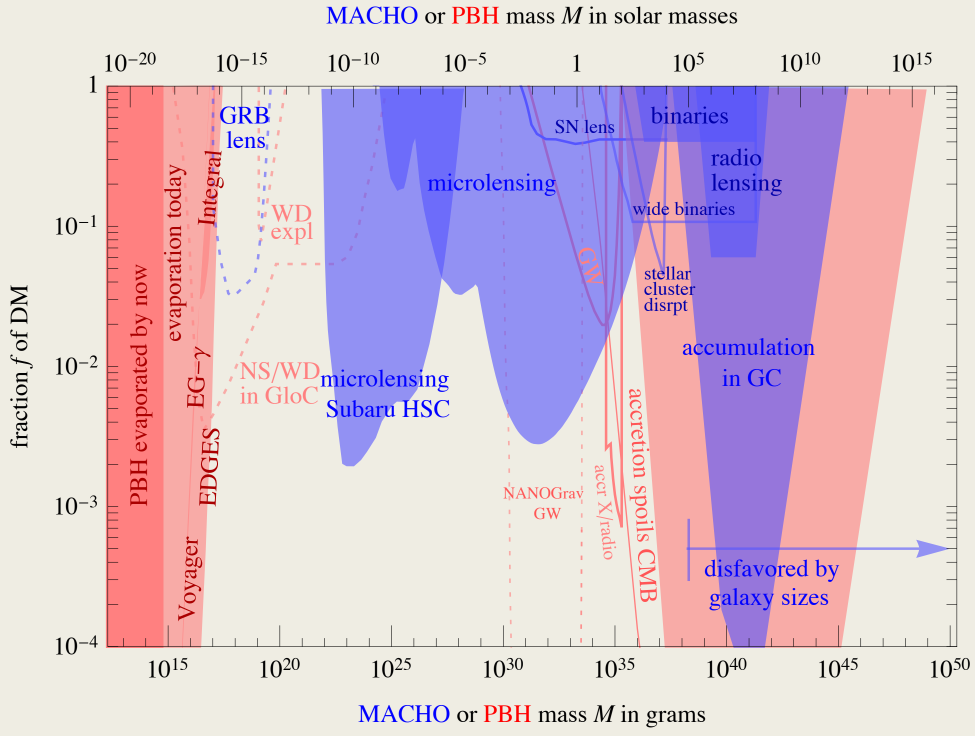
DM mass range



$$10^{-21}\,\mathrm{eV} < M < 10^{37}\,\mathrm{kg}.$$

Massive Astrophysical Compact Halo Objects

- MACHO



Particle Dark Matter

1. DM must be *cold* or at least *not too hot*.
2. The *electric charge* q of a DM particle must be *null or very small*.
3. Bounds from direct detection experiments,
4. The *cross section among two DM particles*
5. The DM particle must be *stable*,

Fermionic dark matter

Fermionic DM is subject to the Pauli exclusion principle,

The de Broglie wave-length is $\lambda = 2\pi/Mv$.

$$\rho \lesssim M/\lambda^3,$$

$$M > 0.1\,\mathrm{keV} \qquad \text{(fermionic DM).}$$

Can SM neutrinos play the role of DM?

- No

- They would be hot which is in conflict with structure formation.

Warm dark matter

$$M \gtrsim 1.9\,\mathrm{keV} \left\langle \frac{p}{T} \right\rangle_{\mathrm{prod}} \left(\frac{106.75}{g_{\mathrm{SM}}(T_{\mathrm{prod}})} \right)^{1/3} .$$

Self-Interacting Dark Matter

Cusped cored problem

$$\frac{\sigma}{M} \sim (0.1 - 1)\frac{\mathrm{cm}^2}{\mathrm{g}},$$

Dark Matter as waves of light and ultra-light fields

- Axion
- Fuzzy dark matter
- ....

Fuzzy dark matter

$$\lambda_{dB} \sim \text{Galaxy core}$$

Suarez, Robles and Matos, Astrophys Space Sci Proc 38 (2014) 107;
Rindler-Daller and Shapiro, Mod Phys Lett A 29; Chavanis, PRD 84 (2011) 43531;
Marsh, Phys Rep 643 (2016);
Hui, Ostriker, Tremaine and Witten, PRD 95 (2017) 043541

Lower bound on scalar

- Lyman alpha
- Rotation curves
- Superradiance M87*
- Precision cosmology
- …

$$m_{DM} \gtrsim 10^{-21}\ \mathrm{eV}$$

Classical limit

$$\lambda_{dB} \sim n_{DM}^{-1/3} = \left(\frac{m_{DM}}{\rho_{DM}}\right)^{1/3}$$

Real scalar:

$$\phi = A\cos(m_{DM}t)$$

$$T^{00} = \rho_{DM}$$

$$A^2 = \frac{2\rho_{DM}}{m_{DM}^2}$$

Complex scalar:

$$\phi = A\cos(m_{DM}t) + iB\sin(m_{DM}t + c)$$

$$A^2 + B^2 = \frac{\rho_{DM}}{m_{DM}^2}$$

Two main classes of DM models

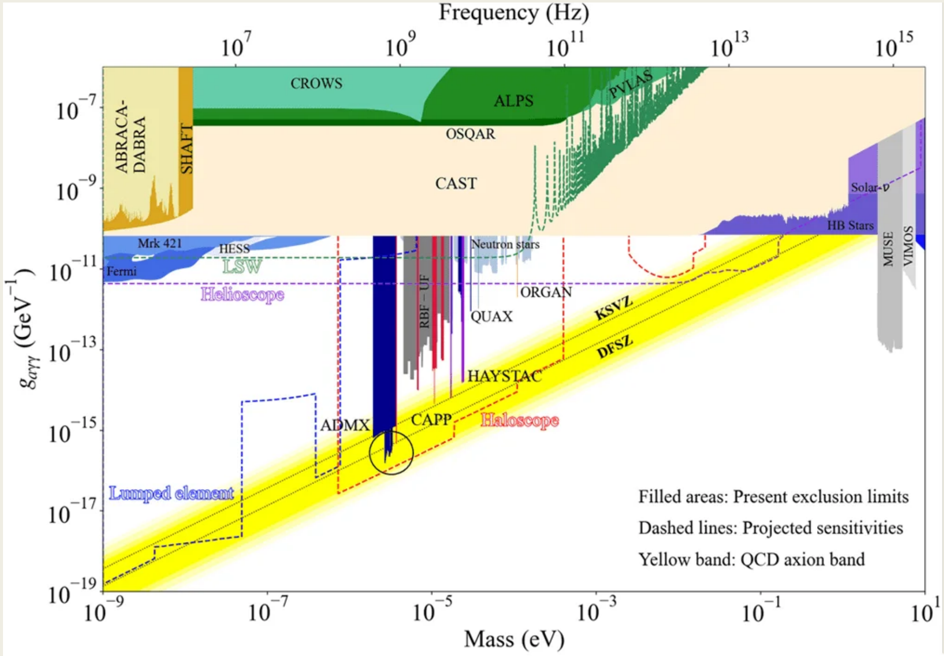
- WIMP=Weekly Interacting Massive Particle

Like neutralino, KK modes in LED,…

- Axion (or ALP=Axion-Like Particle)

Axion

- https://www.azoquantum.com/News.aspx?newsID=9446



$$g_{a\gamma\gamma} a[\epsilon_{\mu\nu\alpha\beta} F^{\mu\nu} F^{\alpha\beta}]$$

Production

- Freeze-in
- Freeze-out
- Decay of heavier particle

- Freeze-out scenario

Boltzmann equation

$$\frac{dn}{dt} = -3Hn + \langle \sigma v \rangle (n^2 - n_{eq}^2)$$

$$n_{eq} = g_X \left(\frac{m_X T}{2\pi} \right)^{3/2} e^{-m_X/T}$$

Average time before annihilation

$$\tau = \frac{1}{n_X} \frac{1}{\langle \sigma_{\rm ann} v \rangle},$$

Annihilation ends when

$$\frac{1}{n_X} \frac{1}{\langle \sigma_{\rm ann} v \rangle} = H^{-1}(T_f),$$

where T_f is the freeze-out temperature in question.

$X\bar{X}$-annihilation often occurs in s-wave.

$$\sigma_{\text{ann}} = \frac{\sigma_0}{v}$$

$$\frac{1}{g_X \sigma_0} \left(\frac{2\pi}{M_X T_f} \right)^{3/2} \mathrm{e}^{\frac{M_X}{T_f}} = H^{-1}(T_f) \equiv \frac{M^*_{Pl}}{T_f^2},$$

Freeze-out temperature

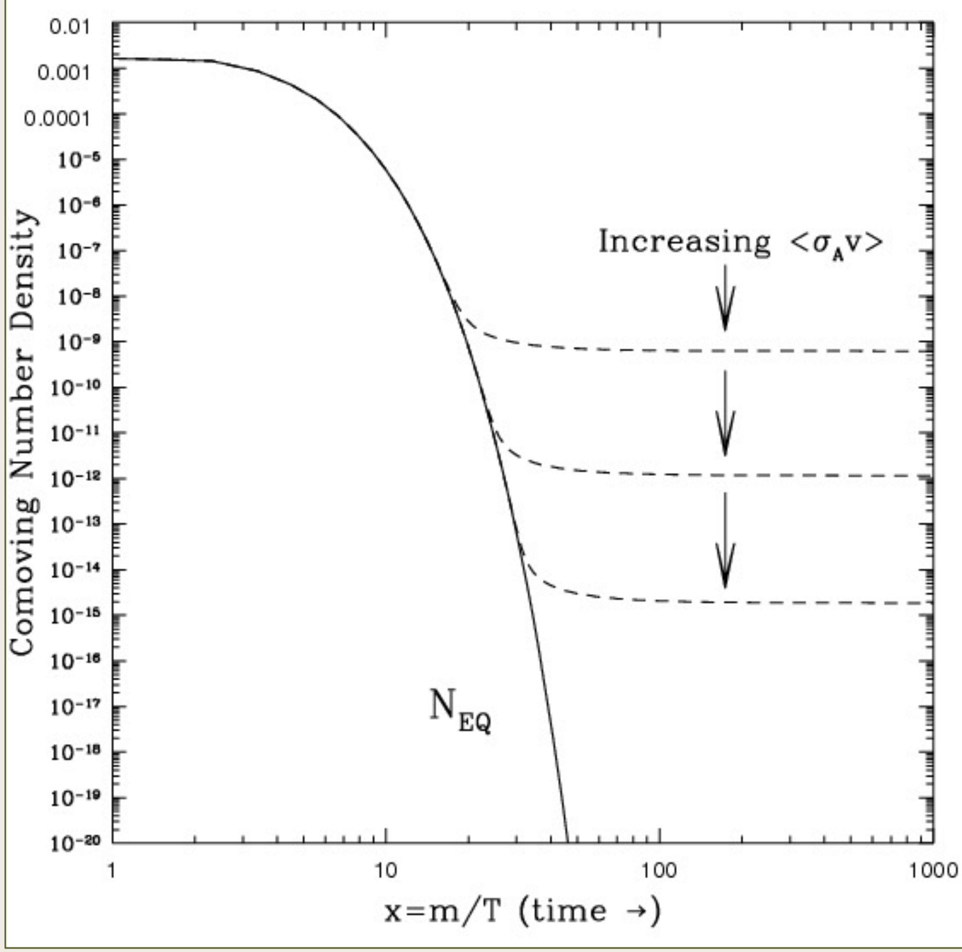
$$T_f = \frac{M_X}{\log\left(\frac{g_X M_X M^*_{Pl}\sigma_0}{(2\pi)^{3/2}}\right)}.$$

$$\frac{1}{n_X}\frac{1}{\langle\sigma_{\rm ann}v\rangle} = H^{-1}(T_f), \quad \Rightarrow \quad n_X(t_f) = \frac{T_f^2}{M^*_{Pl}\sigma_0}.$$

$$n_X(t_0) = \left(\frac{a(t_f)}{a(t_0)}\right)^3 n_X(t_f).$$

$$n_X(t_0) = \left(\frac{s_0}{s(t_f)}\right) n_X(t_f),$$

$$M_{Pl}^* = \frac{M_{Pl}}{1.66 g_*^{1/2}}, \quad s(t_f) = g_*(t_f) \cdot \frac{2\pi^2}{45} T_f^3.$$



$$\Omega_X = 2\frac{M_X n_X(t_0)}{\rho_c} = 7.6\frac{s_0 \log\left(\frac{g_X M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}}\right)}{\rho_c \sigma_0 M_{Pl}\sqrt{g_*(t_f)}}.$$

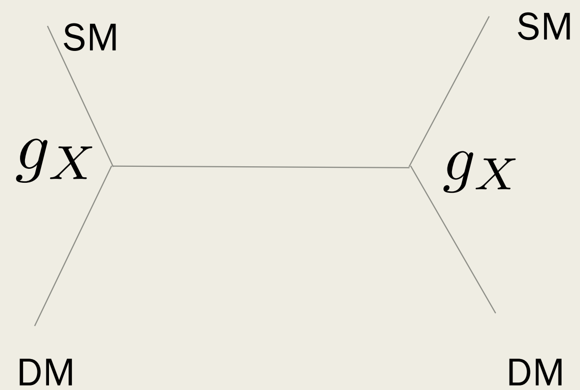
$$\log\frac{g_X M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}} \sim \log\frac{g_X M_{Pl}^*}{(2\pi)^{3/2} M_X} \sim 30.$$

$$\sigma_0 \sim 1\ pb \sim 10^{-36} cm^2$$

$$1\ pb \sim 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{sec}$$

WIPM

- Weekly Interacting Massive Particles

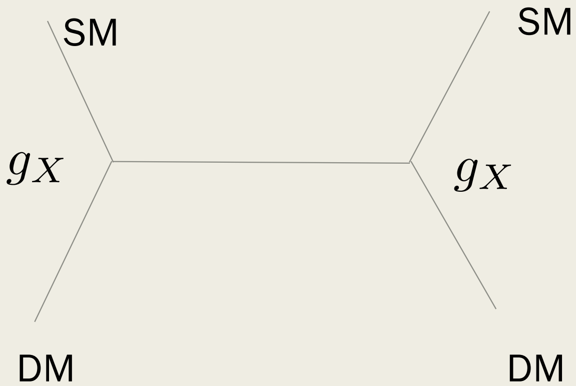


m_{NEW}

$$\sigma_0 \sim \frac{g_X^4}{4\pi m_{NEW}^2}$$

WIMP

- Weekly Interacting Massive Particles

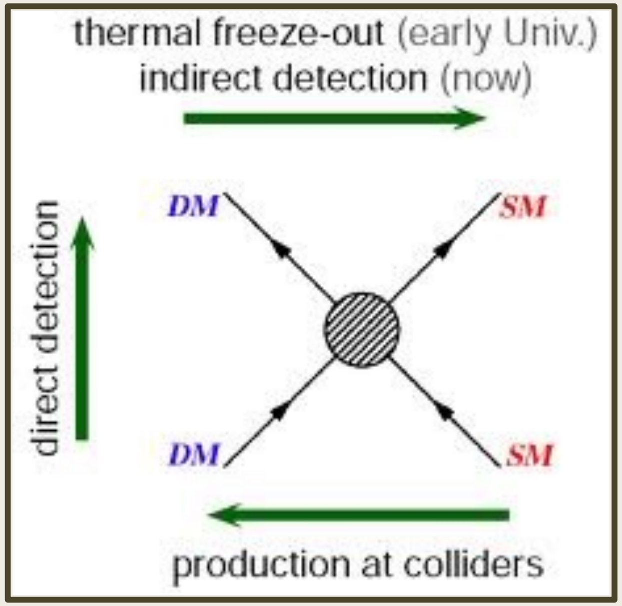


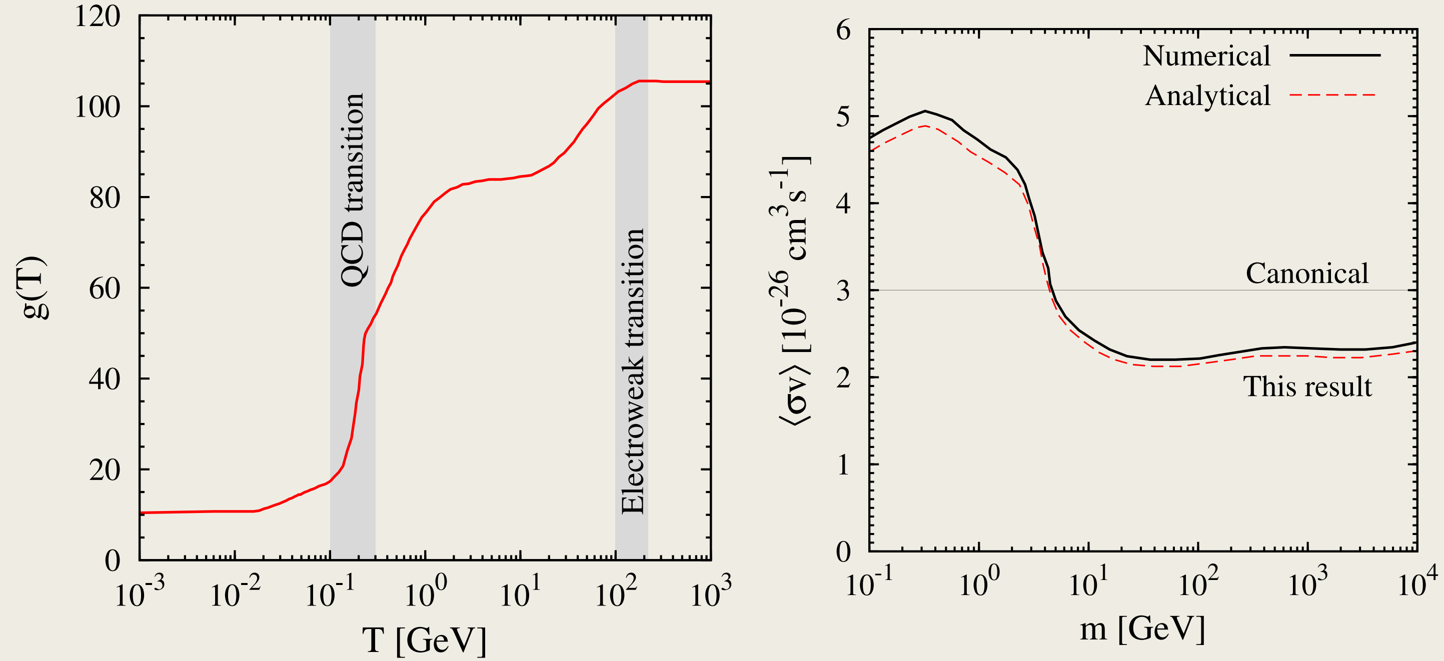
$$\sigma_0 \sim \frac{g_X^4}{4\pi m_{NEW}^2}$$

$$g_X \sim e \quad \text{and} \quad \sigma_0 \sim 1 \text{ pb}$$

$$m_{NEW} \sim 100 \text{ GeV} - 1000 \text{ GeV}$$

The reason to be excited





Steigman, Dasgupta, Beacom,
PRD 86 (2012) 023506

Freeze-In

$$A + B \to \mathrm{DM} + \mathrm{DM} \quad A, B \in \mathrm{SM}$$

$$\rho_{DM} = n_{DM} m_{DM} = 2 m_{DM} \int_0^{t_{NEW}} n_A(T) n_N(T) \sigma(T) dt$$

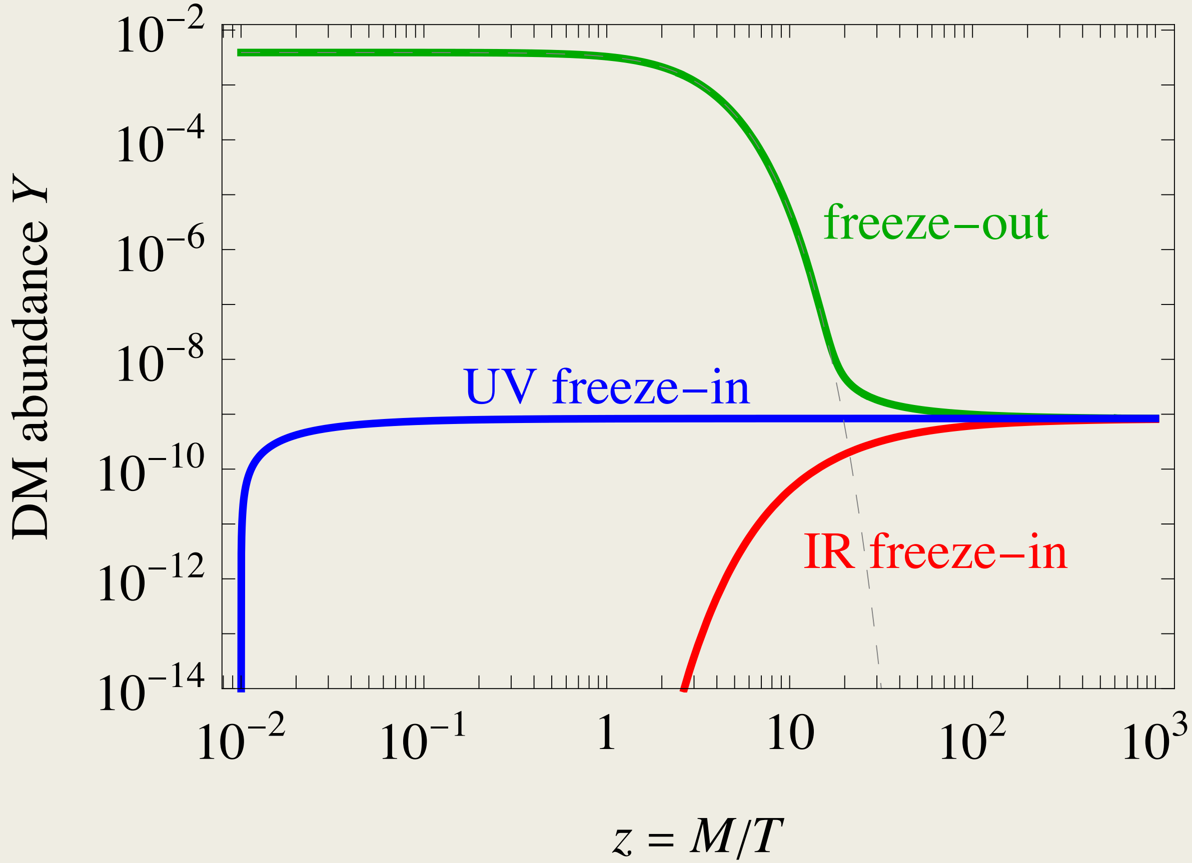
UV vs IR Freeze-In

IR freeze-in. $small\ renormalizable\ interactions\ g$

$$\dot{n}_{DM} \propto g^4 T^4$$

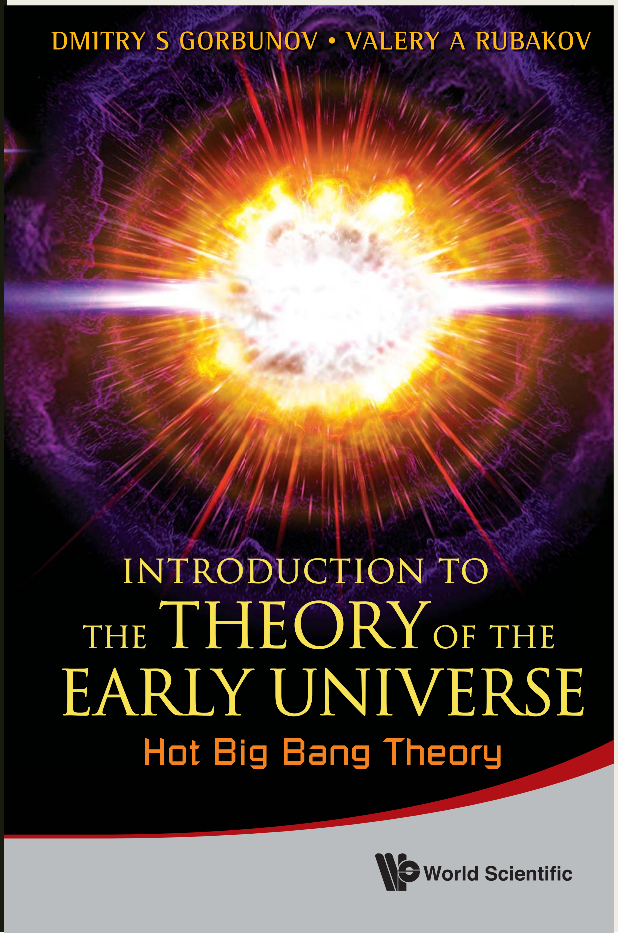
UV freeze-in. $small\ non\text{-}renormalizable\ interactions$ $\frac{1}{\mathcal{M}^n}$

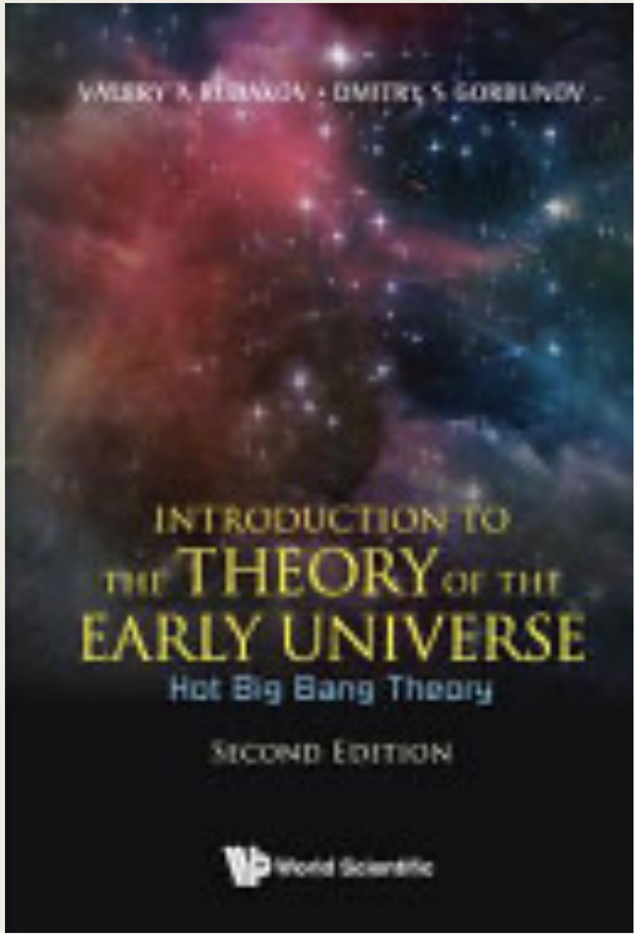
$$\dot{n}_{DM} \propto \frac{T^{4+2n}}{\mathcal{M}^{2n}}$$


DM abundance Y
freeze–out
UV freeze–in
IR freeze–in
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
$z = M/T$

$$Y = n/s$$

Standard cosmology in a nutshell





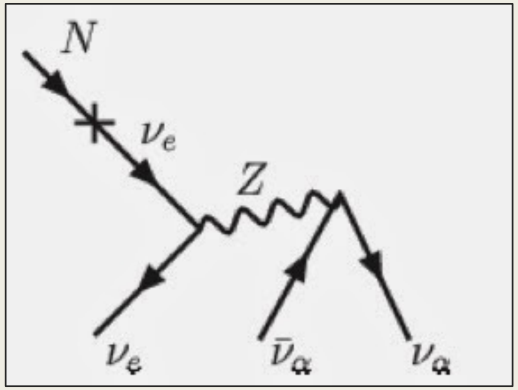
Sterile neutrinos

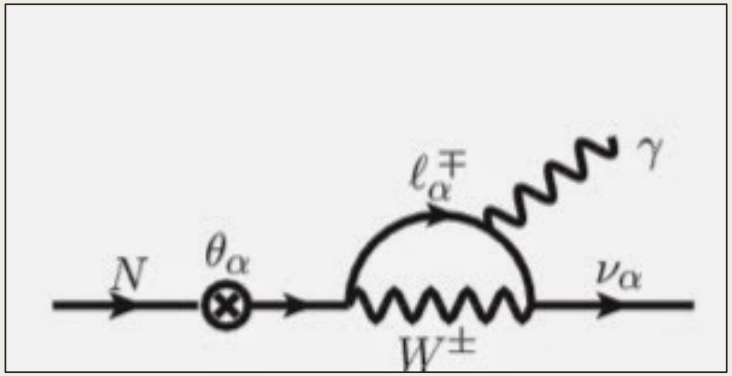
$$|\nu_\alpha\rangle = \cos\theta_\alpha|\nu_1\rangle + \sin\theta_\alpha|\nu_2\rangle, \quad |\nu_s\rangle = -\sin\theta_\alpha|\nu_1\rangle + \cos\theta_\alpha|\nu_2\rangle,$$

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

$$t_\alpha^{vac} = \frac{2E_\nu}{\Delta m^2}, \quad \Delta m^2 = m_s^2 - m_1^2 \simeq m_s^2.$$

Mixing makes unstable





Matter effects

$$H = U \cdot \mathrm{diag}\left(\frac{m_1^2}{2E_\nu}, \frac{m_2^2}{2E_\nu}\right) \cdot U^\dagger + V_{int},$$

where the mixing matrix U and matrix V_{int} describing matter effects are

$$U = \begin{pmatrix} \cos\theta_\alpha & \sin\theta_\alpha \\ -\sin\theta_\alpha & \cos\theta_\alpha \end{pmatrix}, \quad V_{int} = \begin{pmatrix} V_{\alpha\alpha} & 0 \\ 0 & 0 \end{pmatrix}.$$

- Shi-Fuller (requires lepton asymmetry)

$$V_{int} \propto G_F$$

- Dodelson- Widrow (in absence of lepton asymmetry)

$$V_{int} \propto G_F^2$$

the momentum dependence of the W-boson propagator.

$$V_{\tau\tau} = \frac{14\pi}{45\alpha}\sin^2\theta_W\cos^2\theta_W \cdot G_F^2 T^4 \cdot E_\nu \approx 25 \cdot G_F^2 T^4 \cdot E_\nu,$$

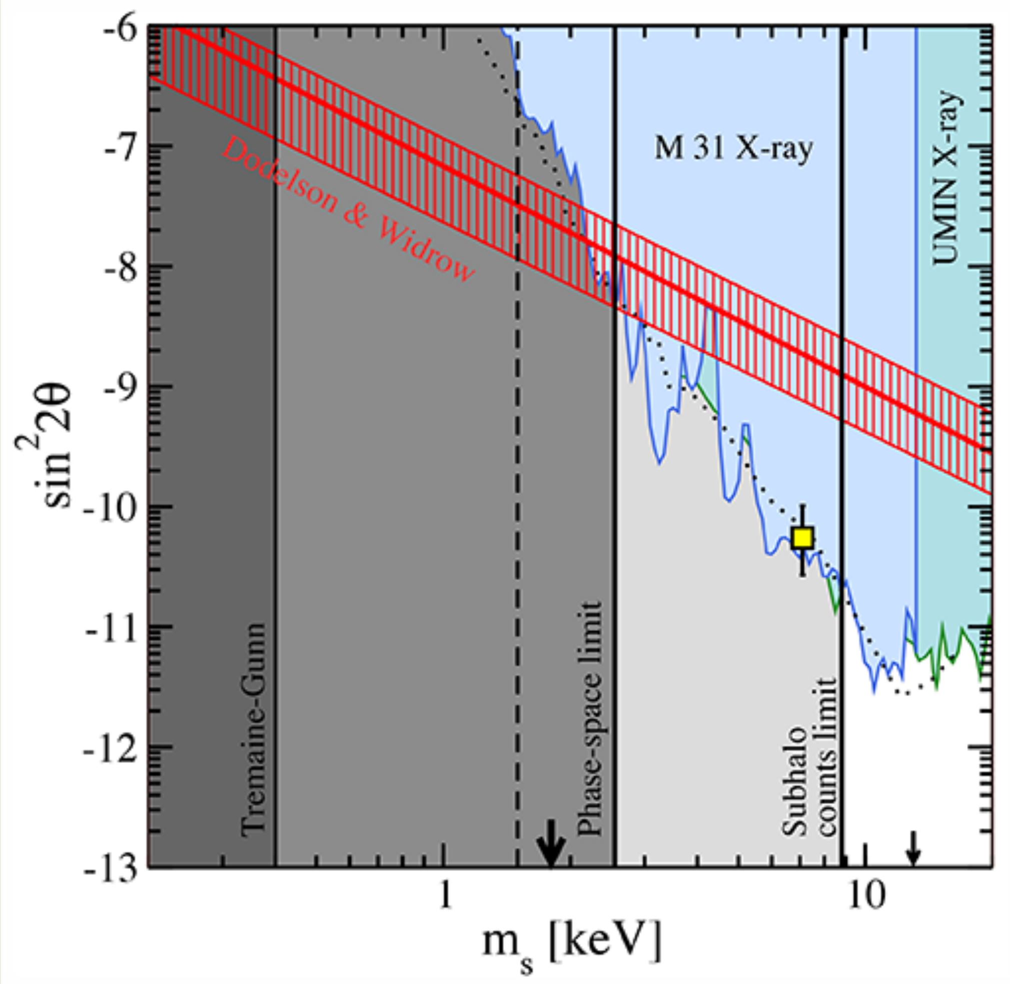
$$
\begin{aligned}
P(\nu_\alpha \to \nu_s) &= \sin^2 2\theta_\alpha^{\mathrm{mat}} \cdot \sin^2\left(\frac{t}{2t_\alpha^{\mathrm{mat}}}\right), \\
t_\alpha^{\mathrm{mat}} &= \frac{t_\alpha^{vac}}{\sqrt{\sin^2 2\theta_\alpha + (\cos 2\theta_\alpha - V_{\alpha\alpha} \cdot t_\alpha^{vac})^2}}, \\
\sin 2\theta_\alpha^{\mathrm{mat}} &= \frac{t_\alpha^{\mathrm{mat}}}{t_\alpha^{vac}} \cdot \sin 2\theta_\alpha,
\end{aligned}
$$

$$T_* \sim \left(\frac{m_s}{5G_F}\right)^{1/3} \simeq 200\,\mathrm{MeV} \cdot \left(\frac{m_s}{1\,\mathrm{keV}}\right)^{1/3}.$$

$$\frac{n_{\nu_s}(T_*)}{n_{\nu_\alpha}(T_*)} \sim \frac{\sin^2 2\theta_\alpha}{H(T_*) \cdot \tau_\nu(T_*)} \sim T_*^3 M_{Pl}^* G_F^2 \cdot \sin^2 2\theta_\alpha$$
$$\sim 10^{-2} \cdot \left(\frac{m_s}{1\,\mathrm{keV}}\right) \cdot \left(\frac{\sin 2\theta_\alpha}{10^{-4}}\right)^2.$$

$$\Omega_{\nu_s} \simeq 0.2 \cdot \left(\frac{\sin 2\theta_\alpha}{10^{-4}}\right)^2 \cdot \left(\frac{m_\nu}{1\,\mathrm{keV}}\right)^2.$$

http://resonaances.blogspot.com/2014/02/signal-of-neutrino-dark-matter.html



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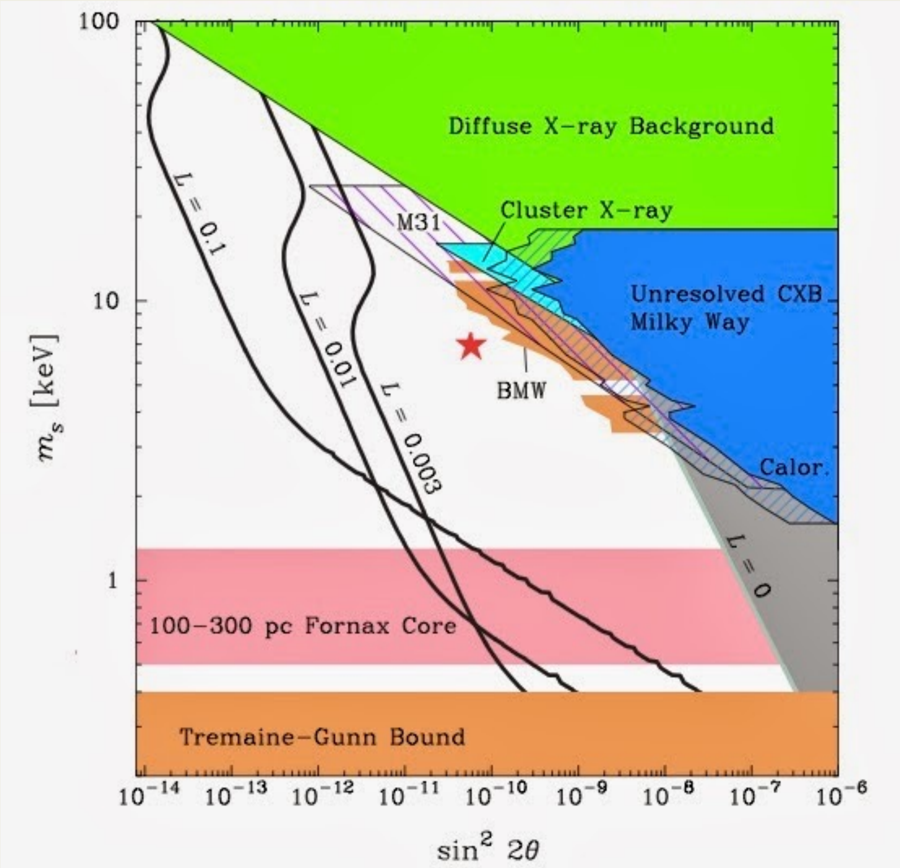

Exotic production mechanisms

Hawking radiation

Inflation decay to DM $m_\phi \gtrsim 2M,$

Quantum fluctuations during inflation: heavy fields

Quantum fluctuations during inflation: light scalar

Asymmetric DM