Sterile neutrinos as SIMP dark matter

Johannes Herms

Technical University of Munich

SUSY 17, Mumbai

12.12.2017

in collaboration with Alejandro Ibarra and Takashi Toma

Particle Dark Matter

Dark Matter

- what is it?
- where did it come from?

Classification by production mechanism

- has it been in equilibrium with visibles?
  - yes: freeze-out like
  - no: freeze-in like
  - neither: asymmetric DM, primordial axion condensate, dilution by entropy production, ...
- particle physics setting the relic abundance?
  - complete BSM model
  - higgs, hidden photon, neutrino portals
  - dark sector internals

Sterile Neutrinos

- Majorana fermion, singlet under SM
- neutrino portal: [Dodelson, Widrow'94], [Shi, Fuller'99]
- extended dark sector: production through scalar decays [Merle et.al.'14]
- this talk: **relic abundance set by sterile neutrino self-interactions**

SIMP Dark Matter

- "strongly interacting massive particle" $=$ relic abundance set by freeze out of number changing interactions $N \to N'$ [Hochberg et.al.'14] [Carlson et.al.'92]
- requires self-thermalised dark sector before fo.
  - dark matter chemical potential $\mu = 0$, dark sector temperature T'
  - may or may not be in kinetic eq. with the visible sector, $T' \neq T$ possible
- two options for a self-thermalised dark sector
  - DM not lightest dark particle
    - freeze out of annihilations to the lighter, unstable (else $\Delta N_{\rm eff}$) dark particle, parameter space very constrained [eg.1704.02149]
  - DM is lightest dark particle
    - freeze out of number changing interactions $\to$ SIMP DM

What if a sterile neutrino is the lightest particle in a self-thermalised dark sector?

Fermionic SIMP

- Majorana singlet χ, or "sterile neutrino"
- dark matter Lagrangian, including operators up to dimension 6:

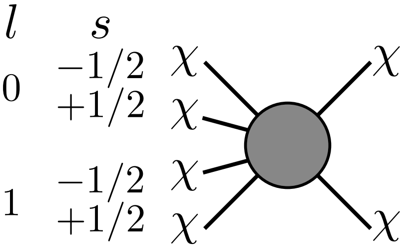
$$\mathcal{L}_{\rm DM} = \frac{1}{2}\overline{\chi^c} i\partial\!\!\!/ \chi - \frac{1}{2} m_\chi \overline{\chi^c}\chi - y_\chi \bar{L}\widetilde{H}\chi - \frac{1}{4!\Lambda^2}(\overline{\chi^c}\chi)(\overline{\chi^c}\chi) + \text{h.c.}\ ,$$

- $y_\chi \lesssim 10^{-16} \left(\frac{\rm MeV}{m_\chi}\right)^{3/2}$ from decay $\chi \to \nu\gamma$ to γ-ray background
- dim-6 operator induces dark matter two-to-two scatterings

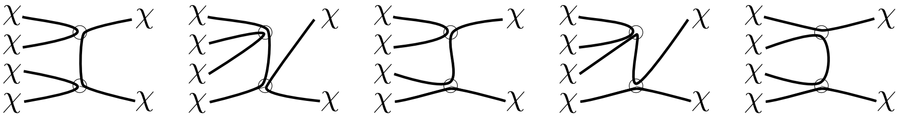
$$\sigma_{2\to2} = \frac{1}{72\pi}\frac{m_\chi^2}{\Lambda^4}$$

- cluster collision bound: $\sigma_{2\to2}/m_{\rm DM} \lesssim 1\ {\rm cm}^2/{\rm g}$ [e.g. 1503.07675]
- may address small scale structure hints if $\gtrsim 0.1\ {\rm cm}^2/{\rm g}$ [e.g. 1508.03339]

- $2 \to \mathrm{SM}$ annihilation rate required to be small by gamma ray bound
- $3 \to 2$ annihilation impossible by Lorentz structure
- $4 \to 2$ annihilation d-wave velocity suppressed for Majorana fermions



- including fermion lines: 5 topologies



- including external state permutations, > 100 diagrams, solved by FeynCalc, nonrelativistic limit, expand in velocities
- by diagram:
  - first: $\bar{v}(p_4)u(p_3)\bar{v}(p_2)u(p_1) \sim v^2 \to |\mathcal{M}|^2 \sim v^4$
  - last: $\mathcal{O}(v^0)$
  - total: $|\mathcal{M}|^2 \sim (v_i v_j)(v_k v_l) \sim T'^2/m^2 \sim x'^{-2}$

$$\langle \sigma v^3 \rangle = \frac{1201}{20480\sqrt{3}\pi\Lambda^8} \frac{1}{x'^2}$$

Boltzmann equation:

$$\frac{dY_\chi}{dx} \simeq -\frac{s^3}{Hx}\langle\sigma v^3\rangle \left(Y_\chi^4 - Y_\chi^2 Y_{\chi,\mathrm{eq}}{}^2\right)$$

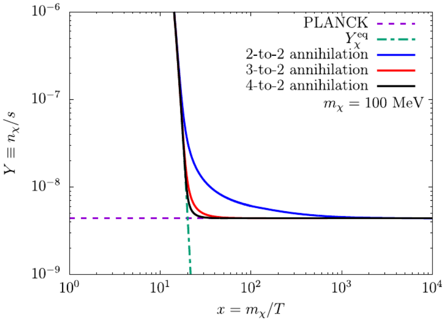
- interactions freeze at T'_f determined by

$$H(T_f) = \langle\sigma v^3\rangle n^3_{\chi,\mathrm{eq}}(T'_f)$$

- freeze-out abundance given by

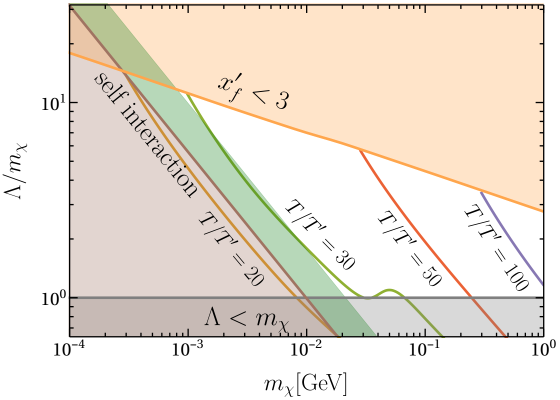
$$Y_\infty \simeq Y_{\mathrm{eq}}(T'_f, T_f)$$

- WIMP: $\Gamma_{2\to2} = \langle\sigma v\rangle n_\chi \sim T^3$, Majorana SIMP: $\Gamma_{4\to2} = \langle\sigma v^3\rangle n_\chi^3 \sim T'^2 T^9$



Correct relic abundance $\{m_\chi,\ \Lambda,\ T_f/T'_f = x'_f/x_f\}$

- $x'_{\rm fo} = 7.2 + \log\left[\left(\frac{m}{\rm MeV}\right)\left(\frac{x_{\rm fo}/x'_{\rm fo}}{10}\right)^3\left(\frac{x'_{\rm fo}}{7.2}\right)^{3/2}\left(\frac{10}{h_{\rm eff}(x_{\rm fo})}\right)\right]$
- $\Lambda \approx 0.045\,{\rm GeV}\left(\frac{m_\chi}{\rm GeV}\right)^{1/2}\left(\frac{x'_{\rm fo}}{x_{\rm fo}}\right)^{7/8}\left(\frac{x'_{\rm fo}}{10}\right)^{-9/8}\left(\frac{g_{\rm eff}(x_{\rm fo})}{10}\right)^{-1/16}\left(\frac{h_{\rm eff}(x_{\rm fo})}{10}\right)^{3/8}$



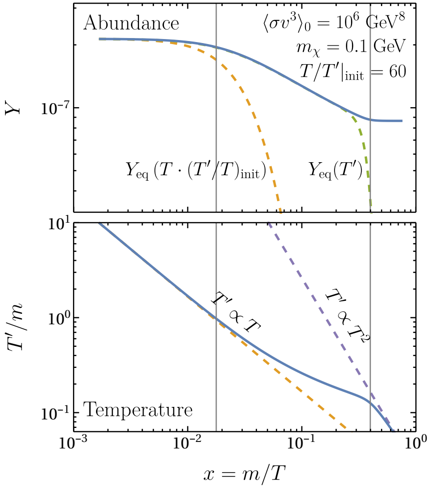
Boltzmann Equations

The dark sector evolution is described by the Boltzmann equations for number and energy density (assuming Boltzmann statistics and kinetic equilibrium):

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v^3 \rangle \left(n_\chi^4 - n_\chi^2 n_\chi^{\mathrm{eq}\,2} \right) + \Gamma_{\text{particle injection from visible sector}},$$

$$\frac{d\rho_\chi}{dt} + CH\rho_\chi = \Gamma_{\text{energy injection from visible sector}}$$

- $C(T') \in [3, 4]$, depending on dark sector redshifting as matter or radiation
- expansion $H(T)$ governed by SM temperature T (assuming $g_s^{\mathrm{SM}} \gg g_s^{\mathrm{DM}}$)
- $\Rightarrow$ system of equations, coupled by $T'(n, \rho)$



[Carlson et.al.'92]

- Temperature ratio T/T' not constant
- initially, T' scales as radiation $T, T' \propto R^{-1}$
- $4 \to 2$ heat the dark sector, decreasing T/T'
- after freeze out, T' scales as a nonrelativistic decoupled species $T' \propto R^{-2} \propto T^{-2}$
- better way to characterise the dark sector?

Dark Sector Entropy

- disconnected ($T \neq T'$) sectors: Comoving entropies of visible sector S, and dark sector S' stay constant
- $\Rightarrow$ ratio ζ stays constant:

$$\zeta = \frac{s}{s'} \qquad = \left(\frac{T}{T'}\right)^3 \frac{g^s_{\mathrm{SM}}(T)}{g^s_{\mathrm{dark}}(T')}.$$

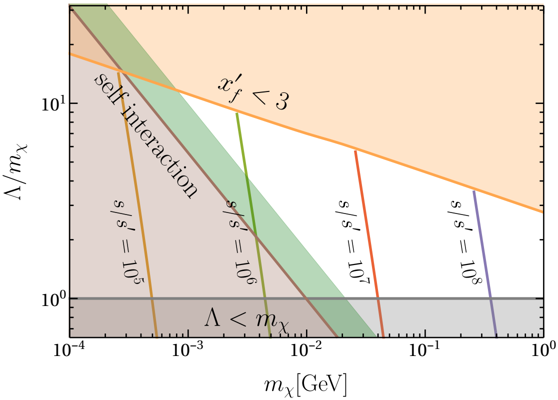
- Instantaneous freeze-out approx. of number changing interactions in a decoupled dark sector

$$Y^{\mathrm{eq}}_\chi = \frac{n^{\mathrm{eq}}_\chi(T')}{s(T)} \qquad = \frac{45}{4\pi^4} \frac{g_\chi}{g^s_{\mathrm{SM}}(T)} \left(\frac{T'}{T}\right)^3 x'^2 K_2(x').$$

- substitute $g^s_{\mathrm{dark,Maxwell}}(x') = \frac{45}{4\pi^4} g_\chi \left(x'^3 K_1(x') + 4x'^2 K_2(x')\right)$
- instantaneous freeze-out result as function of the entropy ratio

$$Y^\infty_\chi \simeq Y^{\mathrm{eq}}_\chi(x'_f, \zeta) = \frac{1}{\zeta} \frac{K_2(x'_f)}{x' K_1(x'_f) + 4K_2(x'_f)}$$

Correct relic abundance – $\{m_\chi,\, \Lambda,\, s/s'\}$

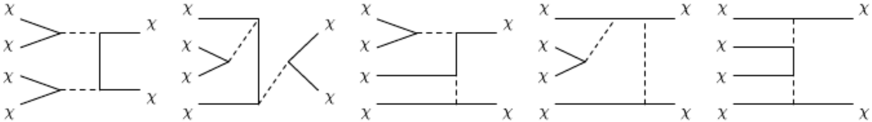


Toy model – sterile neutrino plus real scalar

- add real scalar singlet φ, $m_\varphi > m_\chi$

$$\mathcal{L}_{\rm int} \supset -\frac{y_\varphi}{2}\varphi\overline{\chi^c}\chi - y_\chi \bar{L}\widetilde{H}\chi - \frac{\lambda_{\varphi H}}{2}\varphi^2|H|^2 - \mu\varphi|H|^2 + \text{ h.c.}$$

- φ mediates $\chi\chi \to \chi\chi$ self interaction and $\chi\chi\chi\chi \leftrightarrow \chi\chi$ number-changing interaction



$$\langle\sigma v^3\rangle = \frac{27\sqrt{3}y^8\sum_{n=0}^{8}a_n\xi^n}{81920\pi m_\chi^8(16-\xi)^2(4-\xi)^4(2+\xi)^6 x'^2}$$

where $\xi = m_\varphi^2/m_\chi^2$ and the coefficients $\{a_i\} = \{2467430400, -1648072704, 491804416, -25463616, 4824144, -1528916, 473664, -35259, 1201\}$, and off resonances at resonances at $m_\varphi \sim 2, 4\ m_\chi$

Toy model dark sector evolution

- dark sector can be populated by freeze-in via higgs decays through $\lambda_{\varphi H}$ or scalar mixing $\sin\theta$

$$\Gamma(h \to ss\,,\, h \to \chi\chi) = \frac{\lambda_{h\varphi}^2 v^2}{8\pi m_h} + \frac{m_h}{16\pi} y^2 \left(\sin\theta\right)^2$$

- energy yield from

$$\frac{d\left(\rho'/\rho\right)}{dT} = -\frac{1}{HT\rho}\Gamma_h m_h n_h(T)$$

- temperature ratio, assuming all particles stay relativistic between start of freeze-in and dark matter chemical equilibration

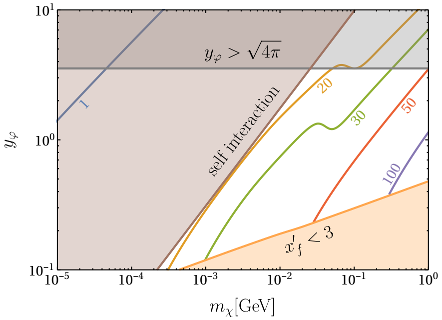
$$T'_{\text{fi}} = T_{\text{fi}} \left(\frac{g_{\text{SM}}(T_{\text{fi}})}{g_{\text{dark}}(T'_{\text{fi}})} \cdot \left.\frac{\rho'}{\rho}\right|_{\text{fi}} \right)^{1/4}$$

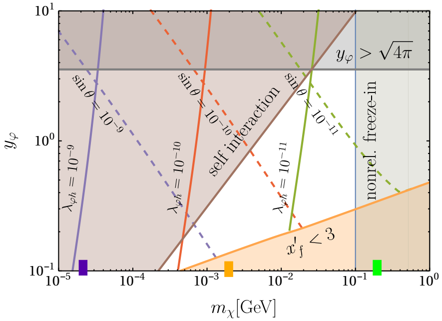
- entropy ratio ζ calculated at end of freeze in then stays constant

[Carlson et.al.'92] [Bernal,Chu'2016]

Results – Toy model

- Temperature ratio T_f/T_f'
- Freeze-in production $\lambda_{\varphi H}, \sin\theta$





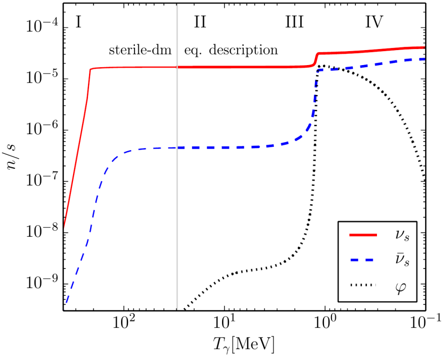
- plots for $m_\varphi = 3m_\chi$
- abundance enhanced by $2 \to 4$ scatterings in viable parameter space
- limited region of parameter space from self-interaction constraints and non-rel. freeze-out condition

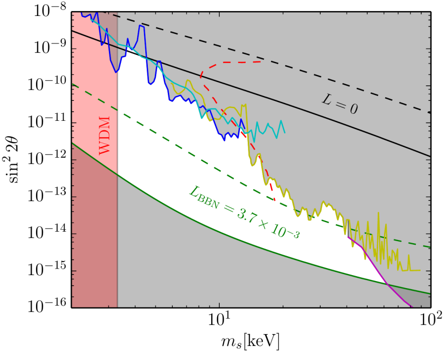
Summary – SIMP Sterile Neutrino DM

- New mechanism to set sterile neutrino relic abundance
  - dark sector thermalises itself through $2 \to 4$ reactions
  - freeze out of number changing interaction within dark sector sets relic abundance
  - relevant number changing interaction $4 \to 2$ d-wave velocity suppressed
- ν_s self-interaction
  - small scale structure hints may (if corroborated) indicate non-minimal dark sector physics
  - interesting ν_s self interaction indicates SIMP mechanism for production
- decoupled dark sector evolution: s/s'
- $100\,\mathrm{keV} - \mathrm{few\,GeV}$ decaying dark matter $\to \gamma$-rays!

- $m_\chi \lesssim 100\,\mathrm{keV}$ sterile neutrinos cannot thermalise through $4 \to 2$ without violating self interaction bounds
- coupling them to a thermalising scalar field circumvents this constraint

[Hansen,Vogl'2017]





Coupled Boltzmann Equation

- The energy density of an isolated sector shifts as

$$C(T) = \frac{1}{\rho}(3\rho + 3\mathcal{P}) = 3\left(1 + \frac{1}{x}\frac{K_2(x)}{K_1(x) + 3K_2(x)/x}\right),$$

- Coupling of Boltzmann equations for ρ, n

The equations for n_χ and ρ_χ are linked via the dark sector temperature, which can be obtained from the average energy per particle

$$\frac{\rho}{n} = m\left(\frac{K_1(x')}{K_2(x')} + \frac{3}{x'}\right).$$

This relation can be numerically inverted to give $x'(\rho/nm)$.

- Entropy ratio result in the toy model

$$\zeta = \frac{s}{s'} \simeq 1.6 \cdot 10^5 \left(\frac{\lambda_{h\varphi}}{10^{-10}}\right)^{-3/2} + 7.4 \cdot 10^5 \left(\frac{y_\varphi^2 \sin^2\theta}{10^{-10}}\right)^{-3/2},$$

Toy model, full evolution

- [N. Bernal, X. Chu'1510.08527]: scalar SIMP via $4 \to 2$ annihilations:
- DM abundance $Y = n/s$
- Temperature T'