Thermal relics beyond minimal dark sectors

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The Dark Matter Production Mechanism Program

What is dark matter?

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Starting point:

$$\rho_{\mathrm{DM},0} \simeq 1.26 \cdot 10^{-6}\,\mathrm{GeV\,cm^{-3}}$$

→ *Where did it come from?*

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$\longrightarrow$ *Where did it come from?*

Thermal relic particle dark matter

- stable neutral particles are automatically dark matter candidates
- thermal bath of the early Universe accounts for production

$\longrightarrow$ *relate production to signatures*

Thermal history of the visible sector

- All we know about early Universe is from *relic particles*
- *Relic abundances* calculable from GR + known particle and atomic physics
  - $T_\gamma \sim$ MeV: neutrinos decouple $\rightarrow \rho_\nu$
  - $T_\gamma \sim$ MeV: neutrons decouple $\rightarrow {}^4\text{He/H}$
  - $T_\gamma \sim 0.1\,\text{MeV}$: nuclear reactions decouple $\rightarrow$ D/H, ^{3}He/H, ^{7}Li/H
  - $T_\gamma \sim$ eV: atoms form, photons decouple $\rightarrow$ CMB
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- $t \geq 1\,$s, Universe is dominated by SM radiation bath of temperature T
- can *extrapolate* cosmology to earlier times
  - assuming SM particle physics
- introducing (meta-)stable particles that interact with the SM, we can relate their properties to their relic abundance

maybe dark matter is a thermal relic, too?

This talk

1. thermal relics
    - textbook basics
    - WIMP successes
    - simple model failures
2. details in the dark: multiple DM candidates
3. details in the dark: self-interactions

Boltzmann Equation

std. treatment [GondoloGelmini'91]

$$E\frac{\partial f_\chi}{\partial t} - H|\vec{p}|^2\frac{\partial f_\chi}{\partial E} = -\frac{1}{2g_\chi}\int d\Pi_b\, d\Pi_i\, d\Pi_j\, (2\pi)^4\, \delta^4\left(p_\chi + p_b - p_i - p_j\right)$$
$$\times\, |\mathcal{M}|^2_{\chi+b\leftrightarrow i+j}\left[f_\chi f_b(1\pm f_i)(1\pm f_j) - f_i f_j(1\pm f_\chi)(1\pm f_b)\right] + \cdots$$

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- assume SM bath dominates Universe

$$H^2 = \frac{8\pi G}{3}\rho_R \quad \text{with} \quad \rho_R = \frac{\pi^2}{30}g_{\text{eff}}(T)T^4, \qquad f_{\text{SM}}(\vec{p}) = \frac{1}{e^{(E-\mu)/T}\pm 1}$$

- assume *kinetic equilibrium*, MB, $f_\chi(E) \longrightarrow e^{\mu/T}e^{-E/T}$

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle_{\chi+b\to i+j}\left(n_\chi n_b - n_\chi^{\text{eq}}n_b^{\text{eq}}\frac{n_i n_j}{n_i^{\text{eq}}n_j^{\text{eq}}}\right) + \cdots,$$

$$\langle\sigma v\rangle = \frac{1}{n_\chi^{\text{eq}}n_b^{\text{eq}}}\int d^3p_\chi\, d^3p_b\,\sigma v_{\text{Møl}}e^{-(E_\chi+E_b)/T}$$

for absence of kin.eq., see eg. [1706.07433]

WIMP freeze-out: the standard paradigm

- The WIMP paradigm:
  - DM stabilised by a dark parity
  - freeze-out of $2 \to 2$ interactions determines the relic density

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle_{\chi\chi\to\mathrm{SM}}\left(n_\chi^2 - n_\chi^{\mathrm{eq}2}\right)$$

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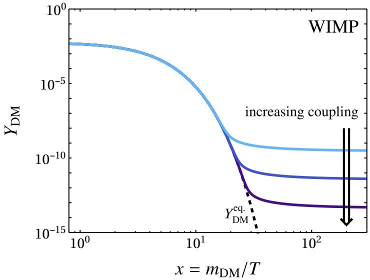
- introduce evolution parameter $x = m/T$ and *abundance* $Y \equiv n/s$

$$\frac{dY_\chi}{dx} = -\frac{s\langle\sigma v\rangle_{\chi\chi\to\mathrm{SM}}}{xH}\left(Y_\chi^2 - Y_\chi^{\mathrm{eq}2}\right)$$

$$Y_{\mathrm{DM}}^{\mathrm{observed}} = 4.35\cdot 10^{-10}\left(\frac{m_{\mathrm{DM}}}{\mathrm{GeV}}\right)^{-1}$$

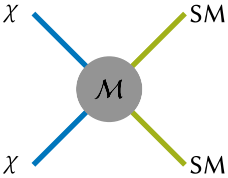


- quick estimate: $n_\chi(x_{\mathrm{fo}})\langle\sigma v\rangle(x_{\mathrm{fo}}) \simeq H(x_{\mathrm{fo}})$, $\quad Y_\chi|_{\mathrm{today}} \simeq Y_\chi^{\mathrm{eq}}(x_{\mathrm{fo}})$

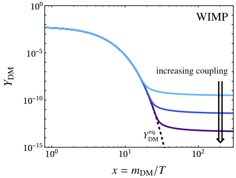
$$\langle\sigma v\rangle_{\chi\chi\to\mathrm{SM}} \simeq (2\sim 3)\times 10^{-26}\,\mathrm{cm}^3/\,\mathrm{s}$$

WIMP freeze-out: the search

The WIMP paradigm is very predictive and has inspired a large experimental program.



$\langle \sigma v \rangle_{T\sim m/20}$ determines relic abundance



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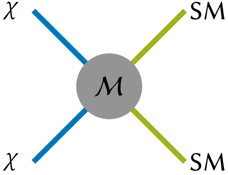

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 $\langle\sigma v\rangle_{v\sim v_{\rm gal}}$ dark matter indirect detection

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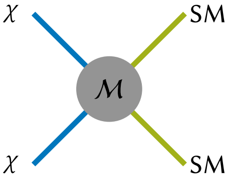

- $\langle \sigma v \rangle_{T\sim m/20}$ determines relic abundance
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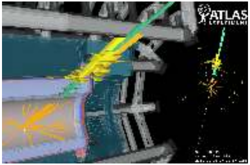
- $\sigma_{pp\to\chi\chi+X}$ collider signatures



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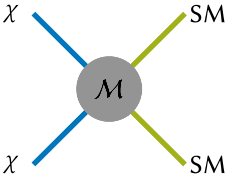

- $\langle \sigma v \rangle_{T \sim m/20}$ determines relic abundance
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- $\sigma_{pp \to \chi\chi + X}$ collider signatures
- $\sigma_{\chi n}$ dark matter direct detection

Freeze-out: variations on a theme

there may be multiple particles odd under the stabilising symmetry
$\Rightarrow$ *dark sector*

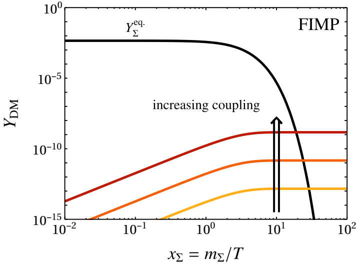
- *co-annihilation*: other particles in the dark sector may aid DM depletion [Griest,Seckel'91]
  - *chemical equilibrium* within the dark sector $\to$ effective WIMP

$$n_i = n_{\rm dark}\left(\frac{n_i^{\rm eq}}{n_{\rm dark}^{\rm eq}}\right) \quad \Rightarrow \quad \frac{dn_{\rm dark}}{dt} + 3Hn_{\rm dark} = -\langle\sigma v\rangle_{\rm eff}\left(n_{\rm dark}^2 - n_{\rm dark}^{\rm eq2}\right)$$

- different processes can deplete the dark sector, *e.g.*
  - $2 \to 2$ may be “forbidden” [1505.07107,2012.11766] $\Rightarrow 3 \to 2$ [1702.07716]
  - “secluded” dark matter, annihilation into unstable dark sector particles [0711.4866]
  - dark matter number changing interactions $\phi\phi\phi \to \phi\phi$, $\chi\chi\chi\chi \to \chi\chi$
  - ...
- same motivation, different signatures possible

Freeze-in: FIMPs

example: from heavy particle decay



$$\frac{dn_\chi}{dt} + 3Hn_\chi = \langle \Gamma_{\Sigma\to\chi X} \rangle \left(n_\Sigma - n_\Sigma^{\rm eq} \frac{n_\chi}{n_\chi^{\rm eq}} \right) - \langle \sigma v \rangle_{\chi\chi\to {\rm SM}} \left(n_\chi^2 - n_\chi^{\rm eq2} \right)$$

- for FIMP from heavy partilce Σ decay

$$c\tau_\Sigma \simeq 1.6\,{\rm m} \times g_\Sigma \left(\frac{m_\Sigma}{100\,{\rm GeV}} \right)^{-2} \left(\frac{m_\chi}{10\,{\rm keV}} \right) \left(\frac{\Omega_\chi}{\Omega_{\rm DM}} \right)^{-1}$$

- lack of thermalisation → cosmological history relevant!

Let's look at an example!

Singlet scalar dark matter

The simplest model, arguably

- add one dof. to the SM, real scalar singlet ϕ, stabilised by a $\mathbb{Z}_2$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2 - \frac{1}{4!}\lambda_\phi\phi^4 - \frac{1}{2}\lambda_{\phi h}\left(H^\dagger H\right)\phi\phi$$

- production in SM thermal bath

$$\begin{aligned}\frac{dn_\phi}{dt} + 3Hn_\phi = &- \langle\sigma v\rangle_{\phi\phi\to{\rm SM}}\left(n_\phi^2 - n_\phi^{\rm eq2}\right) && \leftarrow \text{WIMP}\\ &- \langle\sigma v\rangle_{\phi\phi\phi\phi\to\phi\phi}\left(n_\phi^4 - n_\phi^2 n_\phi^{\rm eq2}\right) && \leftarrow \text{SIMP}\\ &+ \langle\Gamma_{h\to\phi\phi}\rangle\left(n_h - n_h^{\rm eq} n_\phi^2/n_\phi^{\rm eq2}\right) && \leftarrow \text{FIMP}\end{aligned}$$

- different mechanisms can determine the relic abundance
    - standard WIMP
    - self-interactions $\longrightarrow$ SIMP [eg. 1906.07659]
    - freeze-in [eg. 1908.05491]

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- different mechanisms can determine the relic abundance
  - standard WIMP ✔
  - self-interactions → SIMP [eg. 1906.07659] ?
  - freeze-in [eg. 1908.05491] ✖ $\lambda_{\phi h} \lesssim 10^{-10}$; *no signatures!*
- *signatures?*

I like minimal models – why?

- laziness.
- Occam's razor?

I like minimal models – why?

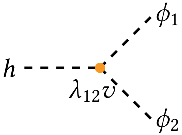
- laziness.
- Occam's razor?
  - dark matter identification is not a beauty pageant $\rightarrow$ not really...
- simple = generic?
  - simple model $\rightarrow$ expect to find common signatures
  - what do we do if we find *no* signatures?
    $\rightarrow$ take more detail into account!

Multi-flavour singlet scalars

Add *two* real scalars $\phi_{1,2}$ to the SM, stabilised by a $\mathbb{Z}_2$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu\phi_i\partial^\mu\phi_i - \frac{1}{2}m_{ij}\phi_i\phi_j - \frac{1}{4!}\lambda'_{ijkl}\phi_i\phi_j\phi_k\phi_l - \frac{1}{2}\lambda'_{ij}\left(H^\dagger H\right)\phi_i\phi_j,$$

FIMP production is governed by the decay



$$\Rightarrow \qquad \lambda_{12\,\rm DM} \simeq 1.2\cdot 10^{-11}\left(\frac{m_1+m_2}{\rm GeV}\right)^{-1/2}\sqrt{\frac{\Omega_{\lambda_{12}}}{\Omega_{\rm DM}}}$$

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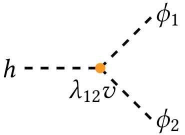

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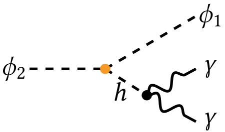
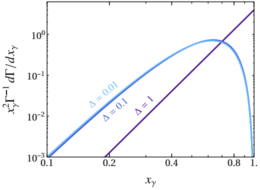
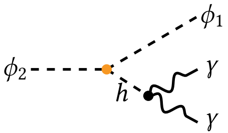
λ_{12} induces dark matter decay into γ-rays [Ghosh et.al. 1909.13292]

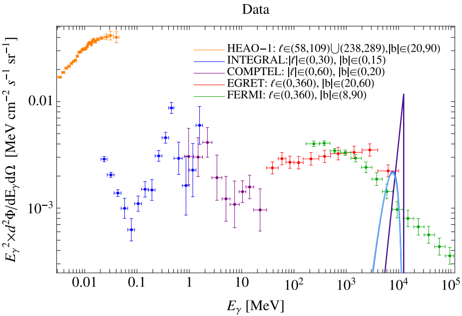


$\Rightarrow$

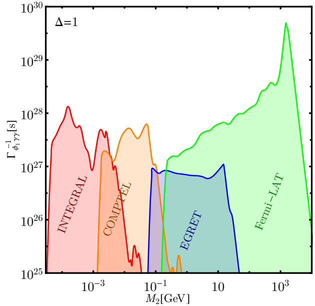


Gamma ray spectral features





adapted from Essig et.al. [1309.4091]

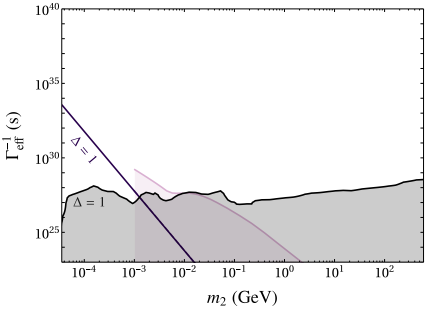


Ghosh et.al. [1909.13292]

Probing multiflavour FIMP dark matter

1912.09458 w. Alejandro Ibarra

⇒ can relate production mechanism to signature!



- Lines show expected signal strength for $\Omega_{\lambda_{12}} = \Omega_{\rm DM}$
- small mass splitting $\Delta \equiv 1 - m_1^2/m_2^2$ suppresses signal
- $\delta m_{ij}^2 \sim \lambda'_{ij} v^2/2 \sim$ MeV

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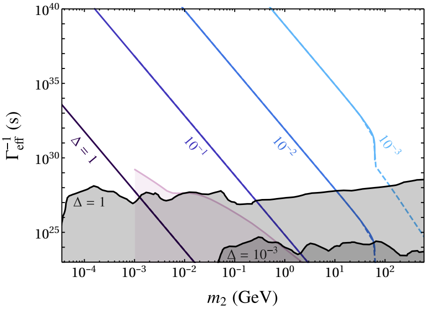

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Generally: What about DM-“flavour”?

- SM fermions come in 3 generations, 1st generation dominates cosmology and astrophysics
- DM fermions?

however...

- “Flavour physics” relies on complex, chiral nature of SM
- Flavour violation limits put strong constraints on non-trivial flavoured interactions of DM [eg. Kopp+’1401.6457]

$\Rightarrow$ *as fist step: look at 2 DM candidates w. same gauge QNs*

Fermionic multi-flavour Dark Matter

DM fermion $\psi_{1,2}$, odd under $\mathbb{Z}_2$ $\longrightarrow$ need mediator Σ to couple to SM

$$\mathcal{L} \supset \left(\mathcal{D}_\mu \Sigma\right)^\dagger \left(\mathcal{D}^\mu \Sigma\right) - m_\Sigma \Sigma^\dagger \Sigma - \lambda_{H\Sigma} |H|^2 |\Sigma|^2$$
$$+ \left(\frac{1}{2} \overline{\psi_i} i \partial\!\!\!/ \psi_i - \frac{1}{2} m_i \overline{\psi_i^c} \psi_i - g_i \bar{f}_{R,L} \psi_i \Sigma + \text{h.c.} \right)$$

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- choose *leptophilic* scenario

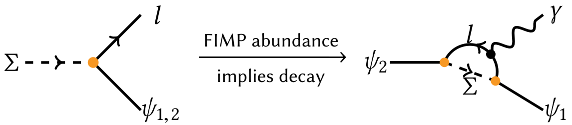
$$\mathcal{L} \supset -g_i \bar{l}_R \psi_i \Sigma$$

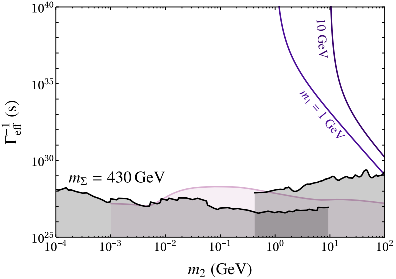
- single component scenario popular model: $m_\Sigma,\ m_1,\ g_1$
- multi-flavour scenario:

$$m_\Sigma,\ m_2,\ m_1,\ g_2,\ g_1$$

$\longrightarrow$ *qualitatively different signatures?*

Decaying fermion FIMP DM





- Decay signal suppressed by two small couplings
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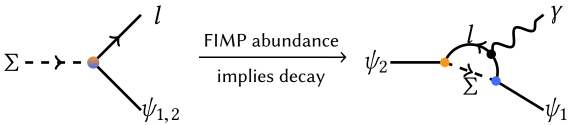
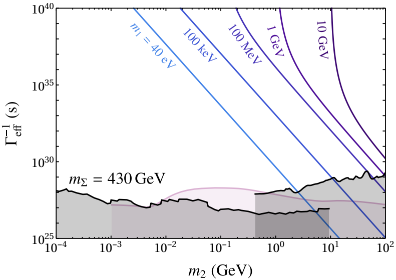




- Decay signal suppressed by two small couplings
- γ-ray line limits from [FermiLAT'1506.00013] and [Essig+'1309.4091], CMB limits from [Slatyer+'1610.06933]
- large coupling possible for small m_1 $\Rightarrow$ *how small?*

Lower limits to the DM mass

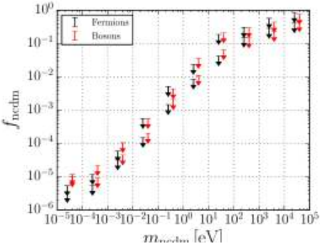
- general: DM free-streaming erases primordial inhomogeneities

$$\lambda_{\text{FS}} = \int_{t_i}^{t_{\text{EQ}}} \frac{\langle v\rangle(t')}{R(t')}\, dt'$$

- limits on DM mass [Irsic+,1702.01764]

$$m_{\text{WDM}} > 5.3\,\text{keV} \xrightarrow[\text{[Kamada+'1907.04558]}]{\text{recast to}} m_{\text{FIMP}} > 15.6\,\text{keV}\cdot\left(\frac{106.75}{g_{s,\text{eff}}(T_{\text{prod}})}\right)^{1/3}$$

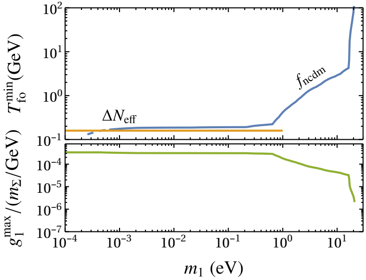
  - WDM actually rather cool: $\Omega_{\text{DM}}^{\text{obs}} \equiv (T_{\text{WDM}}/T_\nu)^3\,(m_{\text{WDM}}/94\,\text{eV})$
- subdominant non-cold component [eg. Diamanti+'1701.03128]

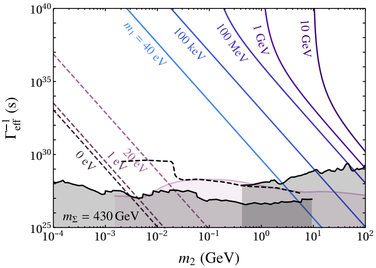


[1701.03128]

Mixed FIMP - HDM

- for very light m_1: g_1 allowed to thermalise ψ_1
- abundance set by $T_{\mathrm{fo},1}$
- coupling g_1 constrained by f_{ncdm}





- signals possible in proposed MeV-range γ-ray instruments [eg. eASTROGAM, 1711.01265]

General 2-flavour leptophilic DM thermal relics

solve Boltzmann eqn. to obtain relic abundance ($i = \psi_1, \psi_2, \Sigma$)

$$\frac{dn_i}{dt} + 3Hn_i = -\sum_j \langle\sigma v\rangle^{\text{ann}}_{ij\to AB}\left(n_i n_j - n_i^{\text{eq}} n_j^{\text{eq}}\right)$$
$$- \sum_j \langle\sigma v\rangle^{\text{sca}}_{iA\to jB}\left(n_i n_A^{\text{eq}} - n_j n_B^{\text{eq}} \frac{n_i^{\text{eq}}}{n_j^{\text{eq}}}\right)$$
$$- \sum_j \tilde{\Gamma}_{i\to j}\left(n_i - n_j \frac{n_i^{\text{eq}}}{n_j^{\text{eq}}}\right),$$

fast conversions can ensure chemical equilibrium $n_i = n_{\text{dark}} \frac{n_i^{\text{eq}}(T)}{n_{\text{dark}}^{\text{eq}}(T)}$,

$$\frac{dn_{\text{dark}}}{dt} + 3Hn_i = -\langle\sigma v\rangle^{\text{ann}}_{\text{eff}}\left(n_{\text{dark}}^2 - n_{\text{dark}}^{\text{eq}\,2}\right)$$

[Griest,Seckel'91], ...

Numerical solution to the Boltzmann Eqn

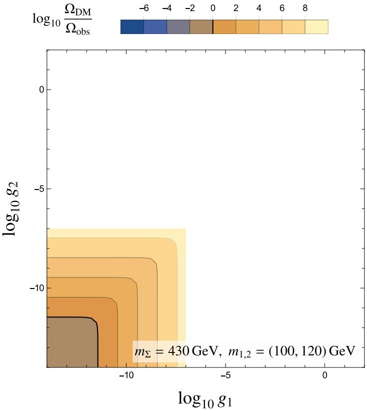
- no chemical equilibrium → no MICROMEGAs etc.
- cast BE into numerics-friendly form

$$\frac{d\ln Y_i}{dx} = -\sum_j \left[\frac{\langle\sigma v\rangle^{\text{ann}}_{ij\to AB} s Y_i \frac{Y_j^{\text{eq}}}{Y_i^{\text{eq}}}}{x\tilde{H}} \right] \left(\frac{Y_j}{Y_i}\frac{Y_i^{\text{eq}}}{Y_j^{\text{eq}}} - \frac{Y_i^{\text{eq}\,2}}{Y_i^2} \right)$$
$$- \sum_j \left[\frac{\langle\sigma v\rangle^{\text{sca}}_{iA\to jB} s Y_A^{\text{eq}}}{x\tilde{H}} + \frac{\tilde{\Gamma}_{i\to j}}{x\tilde{H}} \right] \left(1 - \frac{Y_j}{Y_i}\frac{Y_i^{\text{eq}}}{Y_j^{\text{eq}}} \right) .$$

- if $\Gamma_{\text{aa}\leftrightarrow\text{bb}} \gg H$: stiff equation!
- physics to the resuce: consider summed equation, imposing equilibrium relations

The full range of couplings

- Numerically solve Boltzmann system for particles $i = \Sigma, \psi_2, \psi_1$ in complete coupling parameter space



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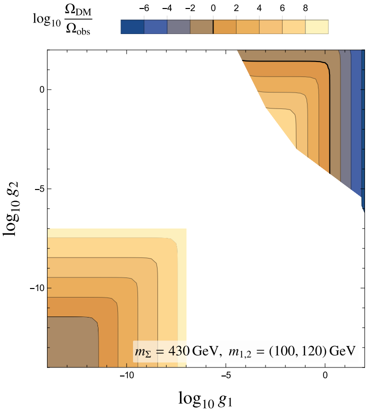

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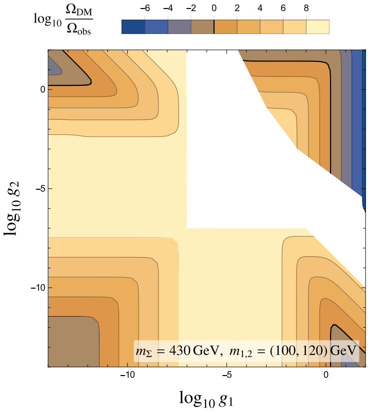

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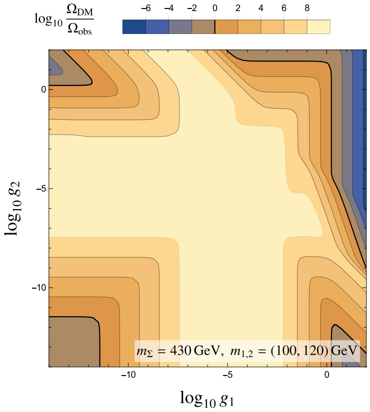

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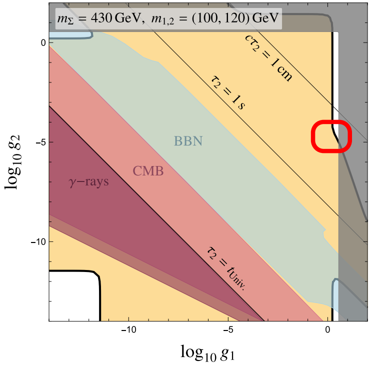
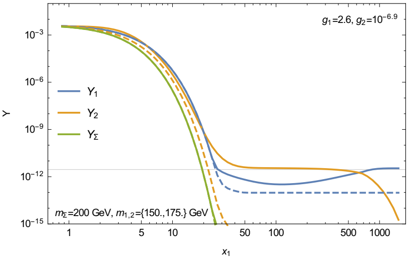
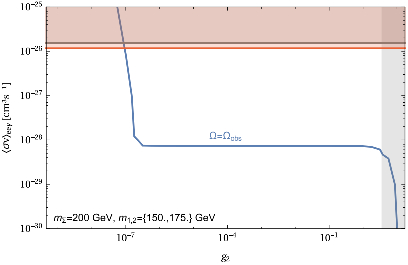


- most of parameter space ruled out by overabundance
- complex interplay of reactions in WIMP-WIMP region

2nd component effects on WIMP signatures

- even if ψ_2 not around today, can modify expectations for WIMP signals





- commonplace: reduction of signals due to *coannihilation*
- here: can have *enhancement of $\langle\sigma v\rangle$* over canonical WIMP value
  - surprises possible also for instruments that don't reach canonical benchmark

Falsifying WIMP Dark Matter?

- direct/indirect/collider WIMP identification inconclusive so far
- WIMP CDM scenario has other predictions
  - cuspy halos following Navarro-Frenk-White profile [NFW'97]
  - subhalos form down to $M_{\rm halo} \ll M_\odot$ [eg. Bringmann'09]

- small scale issues of ΛCDM
  - cored halos, diverse halos [eg. 1504.01437]
  - missing satellites, missing small-but-"too-big-to-fail" galaxies [eg. 1111.2048]

- dark matter *self-interactions*? [review eg. 1705.02358] [1904.10539]
  - thermalised cores
  - host halo effects amplified
  - gravothermal collapse possible

Self interacting dark matter

Singlet fermions for concreteness, “sterile neutrino”

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

- self-scattering

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

- constraints

$$\sigma_{2\to 2}/m_{\rm DM} \lesssim 1\,\text{cm}^2/\text{g}$$

[0704.0261]

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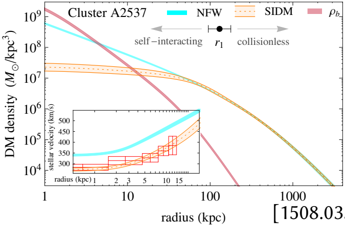
- self-scattering

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

- constraints and possible evidence?

$$0.1\,\text{cm}^2/\text{g} \lesssim \sigma_{2\to 2}/m_{\rm DM} \lesssim 1\,\text{cm}^2/\text{g}$$



[1508.03339]

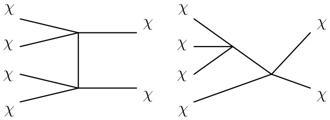
[0704.0261]

Majorana SIMPs

connecting self-interactions to DM production

- number-changing interactions can deplete n_χ

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v^3\rangle_{4\to2}\left(n_\chi^4 - n_\chi^2 n_\chi^{\text{eq}\,2}\right)$$



$\longrightarrow$ Strongly Interacting Massive Particle (SIMP) DM

Majorana SIMPs

connecting self-interactions to DM production

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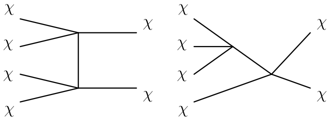
$$\frac{dn_\chi}{dt} + 3H(T)n_\chi = -\langle\sigma v^3\rangle_{4\to2}\left(n_\chi^4 - n_\chi^2 n_\chi^{\mathrm{eq}\,2}(T')\right)$$



→ Strongly Interacting Massive Particle (SIMP) DM

- what about T' ?

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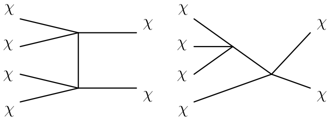

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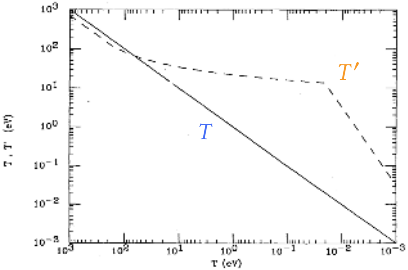
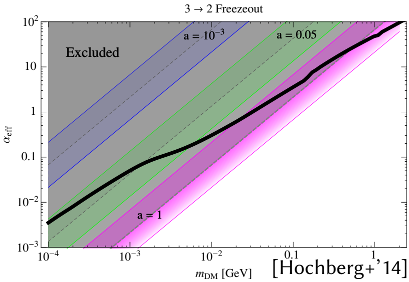


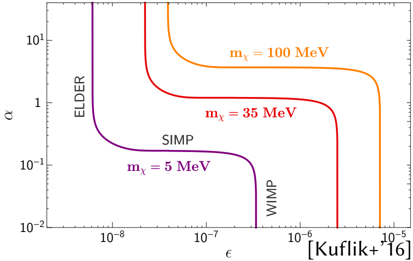
[Carlson+'92]

Solutions to the SIMP heat problem

- couple DM to SM kinetically, $T' \equiv T$ [Hochberg+'14]
  - dump entropy to SM $\longrightarrow$ need sizable couplings!



[Hochberg+'14]



[Kuflik+'16]

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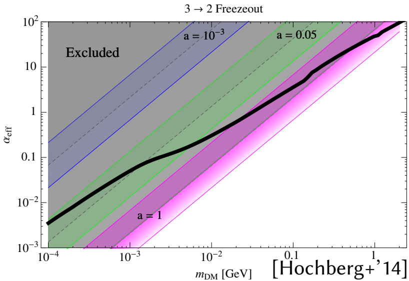
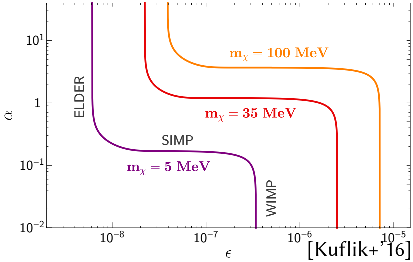


[Hochberg+'14]



[Kuflik+'16]

- start out colder, $T'(0) < T(0)$ [e.g. Bernal,Chu'15]
  - both $3 \longrightarrow 2$, $4 \longrightarrow 2$ possible
  - less predictive, depends on initial condition

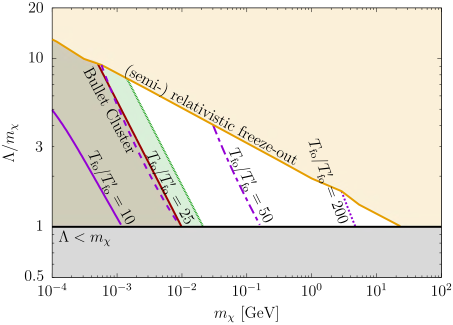
Self-interacting Majorana singlets

1802.02973 w. Takashi Toma, Alejandro Ibarra

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v^3 \rangle_{4\to 2} \left(n_\chi^4 - n_\chi^2 n_\chi^{\mathrm{eq}\,2} \right)$$

- instantaneous freeze-out approx

$$H(T_{\mathrm{fo}}) = \langle \sigma v^3 \rangle (T'_{\mathrm{fo}})\, n_\chi^3 (T'_{\mathrm{fo}})$$



Populating the dark sector in a UV-complete model

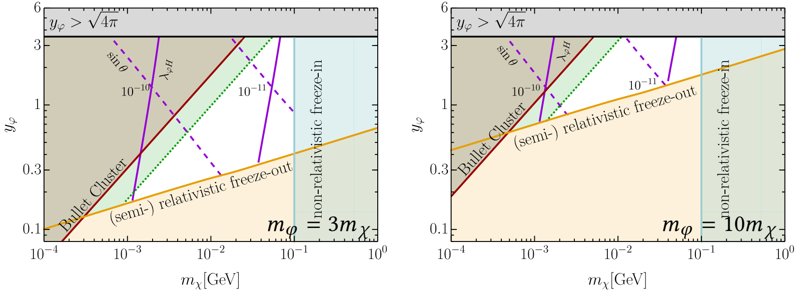
add a real scalar!

$$\mathcal{L}_{\varphi,\text{int}} = -\frac{y_\varphi}{2}\varphi\overline{\chi^c}\chi \qquad - \mu_{\varphi H}\,\varphi|H|^2 - \frac{1}{2}\lambda_{\varphi H}\,\varphi^2|H|^2$$

- Higgs portal as possible source of dark entropy

$$\frac{d(\rho'/\rho)}{dT} = -\frac{1}{HT\rho}\Gamma_{h\to\text{dark}}m_h n_h(T)$$

- relate ρ'/ρ to entropy ratio $S/S' = s/s' \equiv \zeta \in\sim [10^5, 10^{10}]$



- recently: methods to extend to relativistic regions [1906.07659]

Conclusions

- Thermal relic scenario attractive and plausible
  - implications for particle physics
  - implications for astrophysical DM properties
- production modelling to find range of expectable signatures
- multi-flavour dark matter
  - predicts signals in otherwise untestable FIMP regime
  - can amplify/reduce WIMP signals
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Conclusions

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Future directions

- *self-thermalisation* of decoupled dark sectors?
- *tests of decoupled dark sectors?*
- can we get any mileage out of dark sector entropy?
- where else do we need to model harder to arrive at signatures?

Backup

Gamma ray signals from dark matter

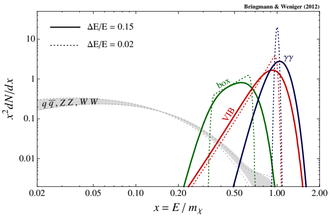
- Gamma ray flux measured by telescopes

$$\frac{d\Phi}{dE_\gamma}(E_\gamma,\psi) = \frac{1}{4\pi}\int_{\text{l.o.s.}} ds\, Q\left(E_\gamma, \vec{r}(s,\psi)\right)$$

- source terms

$$Q_{\text{dec}}(E,\vec{r}) = \Gamma_{\text{dec}}\left(\frac{\rho_{\text{DM}}(\vec{r})}{m_{\text{DM}}}\right)\frac{dN_\gamma}{dE}$$

$$Q_{\text{ann}}(E,\vec{r}) = \langle\sigma v\rangle_{\text{ann}}\left(\frac{\rho_{\text{DM}}(\vec{r})}{m_{\text{DM}}}\right)^2\frac{dN_\gamma}{dE}$$



[1208.5481]

  - extragalactic contribution

$$\frac{d\Phi^{\text{dec}}_{\text{extragalactic}}}{dE_\gamma}(E_\gamma) = \frac{1}{4\pi}\frac{\Omega_{\text{DM}}\rho_c}{m_{\text{DM}}}\int_0^\infty dz\,\frac{1}{H(z)}\frac{d\Gamma}{dE_\gamma}\left(E_\gamma(1+z)\right)e^{-\tau(E_\gamma,z)}$$

Numerical solution of the Boltzmann equation

- Boltzmann system for particles $i = \Sigma, \psi_2, \psi_1$

$$\frac{dn_i}{dt} + 3Hn_i = -\sum_j \langle\sigma v\rangle^{\text{ann}}_{ij\to AB}\left(n_i n_j - n_i^{\text{eq}} n_j^{\text{eq}}\right)$$

$$- \sum_j \langle\sigma v\rangle^{\text{sca}}_{iA\to jB}\left(n_i n_A^{\text{eq}} - n_j n_B^{\text{eq}} \frac{n_i^{\text{eq}}}{n_j^{\text{eq}}}\right)$$

$$- \sum_j \tilde{\Gamma}_{i\to j}\left(n_i - n_j \frac{n_i^{\text{eq}}}{n_j^{\text{eq}}}\right)$$

$$\frac{d\ln Y_i}{dx} = -\sum_j \left[\frac{\langle\sigma v\rangle^{\text{ann}}_{ij\to AB} s Y_i \frac{Y_j^{\text{eq}}}{Y_i^{\text{eq}}}}{x\tilde{H}}\right]\left(\frac{Y_j}{Y_i}\frac{Y_i^{\text{eq}}}{Y_j^{\text{eq}}} - \frac{Y_i^{\text{eq}\,2}}{Y_i^2}\right)$$

$$- \sum_j \left[\frac{\langle\sigma v\rangle^{\text{sca}}_{iA\to jB} s Y_A^{\text{eq}}}{x\tilde{H}} + \frac{\tilde{\Gamma}_{i\to j}}{x\tilde{H}}\right]\left(1 - \frac{Y_j}{Y_i}\frac{Y_i^{\text{eq}}}{Y_j^{\text{eq}}}\right).$$

- fast rates give stiff equation → use summed equations if chemical equilibrium

Evolution of a decoupled dark sector

- Boltzmann equations

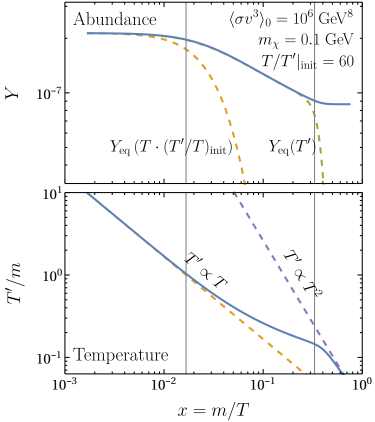
$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v^3\rangle \left(n_\chi^4 - n_\chi^2 n_\chi^{\mathrm{eq}\,2}\right),$$
$$\frac{d\rho_\chi}{dt} + CH\rho_\chi = 0$$

with

$$C(x) = \frac{1}{\rho}(3\rho + 3\mathcal{P})$$

- T' from

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



Populating the dark sector

- energy transfer from SM through Higgs decay

$$\frac{d\rho'}{dt} + CH\rho' = \frac{g_i}{(2\pi)^3} \int f_h(p) E_h(p) \Gamma_h\left(E_h(p)\right) d^3p = \Gamma_{h\to\text{dark}} m_h n_h(T)$$

$$\frac{d\left(\rho'/\rho\right)}{dT} = -\frac{1}{HT\rho} \Gamma_{h\to\text{dark}} m_h n_h(T)$$

- relate ρ'/ρ to entropy ratio $S/S' = s/s' \equiv \zeta$

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

$$\zeta \equiv \frac{s}{s'} = \left(\frac{T}{T'}\right)^3 \left.\frac{h_{\text{eff}}(T)}{h'_{\text{eff}}(T')}\right|_{T=10\,\text{GeV}}$$

SIMP Boltzmann equation

- General Boltzmann eqn. can be recast as

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v^3 \rangle_{4\to 2} \left(n_\chi^4 - n_\chi^2 n_\chi^{\mathrm{eq}\,2} \right)$$

where in the non-rel.-limit

$$\langle \sigma v^3 \rangle_{4\to 2} \simeq \frac{\int d^3v_1\, d^3v_2\, d^3v_3\, d^3v_4 \left(\sigma v^3 \right) \delta^3(\vec{v}_1 + \vec{v}_2 + \vec{v}_3 + \vec{v}_4) e^{-\frac{m_\chi}{2T'}(v_1^2+v_2^2+v_3^2+v_4^2)}}{\int d^3v_1\, d^3v_2\, d^3v_3\, d^3v_4\, \delta^3(\vec{v}_1 + \vec{v}_2 + \vec{v}_3 + \vec{v}_4) e^{-\frac{m_\chi}{2T'}(v_1^2+v_2^2+v_3^2+v_4^2)}}$$

with all particle physics contained in

$$\left(\sigma v^3 \right) = \frac{\sqrt{3}}{6144\pi m_\chi^4} \int \frac{d\Omega}{4\pi} \overline{|\mathcal{M}|^2}$$

- result

$$\frac{1201}{245760\sqrt{3}\pi\Lambda^8} \frac{T'^2}{m_\chi^2}$$

- more versatile treatment, including relativistic effects [1906.07659]

$$\Gamma_{4\to 2} = \Gamma_{2\to 4} e^{2\mu/T}$$