Multi-flavour thermal relic dark matter

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[2103.10392] together with Alejandro Ibarra (TUM)

Dark matter production – name of the game

- we know precisely [PlanckColl.'18]

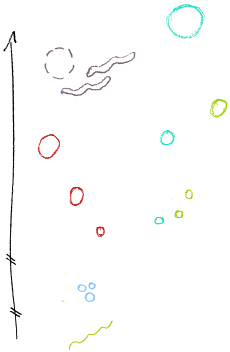
$$\Omega_{\mathrm{DM}} h^2 = 0.120 \pm 0.001$$

- + lots of constraints on DM doing anything interesting
- Hypothesis: *maybe it's particles!*

$\Rightarrow$ study production to predict signatures

If fitting only one number, better keep the model simple.
However: *Make sure not to miss the relevant phenomenology.*

The Standard Model is complicated



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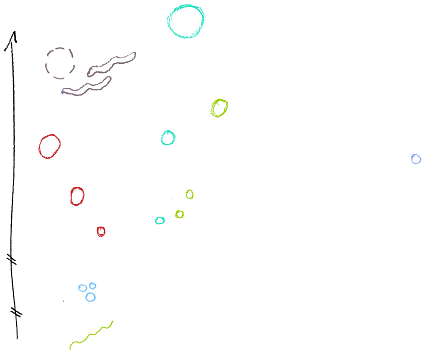

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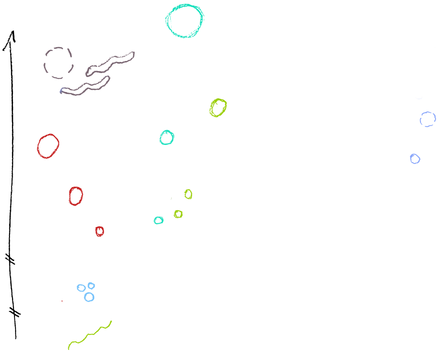

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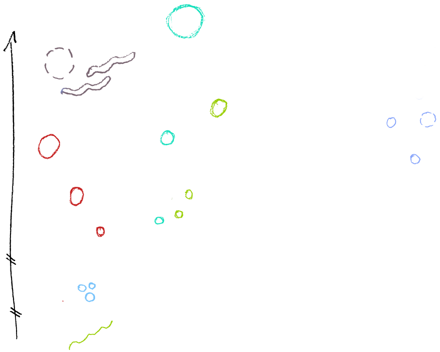

- "DM flavour" ≡ multiple DM candidates with same gauge quantum numbers, stabilised by same symmetry
- this talk: effect of DM flavour on production + signatures

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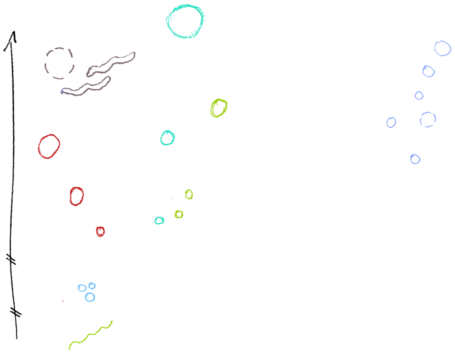

- "DM flavour" ≡ multiple DM candidates with same gauge quantum numbers, stabilised by same symmetry
- this talk: effect of DM flavour on production + signatures

A toy model for DM flavour

- SM flavour is complicated
  - BSM: permit *some* complication to search for distinct signatures
- single $\mathbb{Z}_2$ to stabilize dark sector ($\neq$ most 'multicomponent DM')
- 2 flavours of DM fermions (Majorana)

$$\psi_1, \psi_2$$

- need mediator to couple to SM

$$\Sigma$$

$$\mathcal{L} \supset -y_i \bar{f}_{R,L} \psi_i \Sigma$$

- choose: leptophilic scenario, coupling to e_R only

$$\mathcal{L} \supset -y_i \bar{e}_R \psi_i \Sigma$$

$\rightarrow$ *greatest freedom to explore production*

Thermal relics – deplete or create

see also J.Ruderman's talk yesterday

- *task:*

$$Y_{\rm DM}^{\rm today} \equiv \frac{n_{\rm DM}}{s_0} = \frac{\Omega_{\rm DM}\rho_c}{m_{\rm DM}s_0} = 4.35 \cdot 10^{-10} \left(\frac{m_{\rm DM}}{\rm GeV}\right)^{-1}$$

- *thermal relic* ≡ particle population calculable from connection to thermal bath

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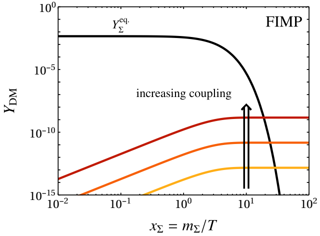
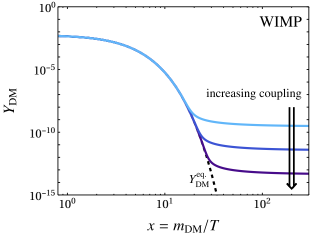
- *thermal relic* ≡ particle population calculable from connection to thermal bath
- two scenarios: dark matter abundance determined by ...

- production → *freeze-in*



- depletion → *freeze-out*



→ *consider full range of couplings* y_1, y_2

Thermal relics – when life is simple

- Thermal relic abundance determined by interaction w. SM bath
- DM stability forces pair-annihilation as lowest order process

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

Thermal relics – when life is simple

- Thermal relic abundance determined by interaction w. SM bath
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- multicomponent dark sector?

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

Thermal relics – when life is simple

- Thermal relic abundance determined by interaction w. SM bath
- DM stability forces pair-annihilation as lowest order process
- multicomponent dark sector?
- fast conversions can ensure chemical equilibrium $n_i = n_{\mathrm{dark}} \frac{n_i^{\mathrm{eq}}(T)}{n_{\mathrm{dark}}^{\mathrm{eq}}(T)}$,

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

[Griest,Seckel'91]

→ *simplest case: additional dark sector states only enter* $\langle\sigma v\rangle_{\mathrm{eff}}^{\mathrm{ann}}$

Numerical solution to the Boltzmann Eqn

- no chemical equilibrium → no MICROMEGAs etc.

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

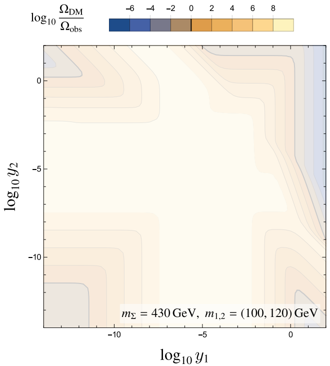
Numerical solution to the Boltzmann Eqn

- no chemical equilibrium → no MICROMEGAs etc.
- cast BE into numerics-friendly form, $Y_i \equiv n_i/s$, $x = m_1/T$:

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

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

Thermal dark matter production regimes



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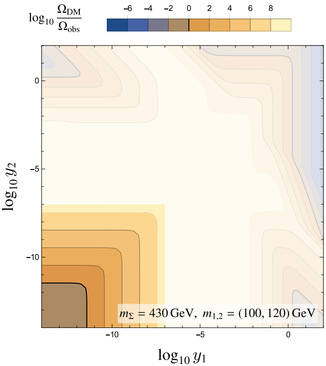
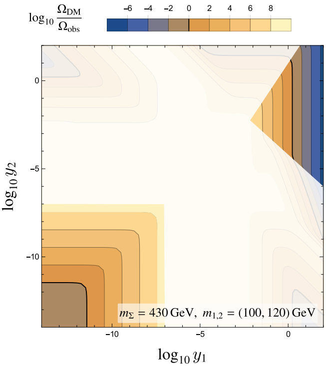


- both FIMP

Thermal dark matter production regimes



- both FIMP
- standard $\langle\sigma v\rangle_{11}$ WIMP

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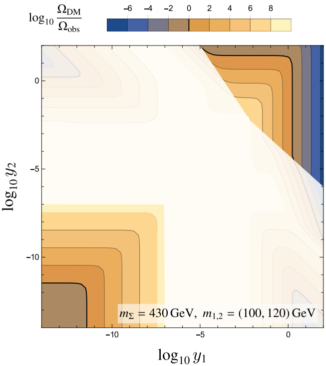
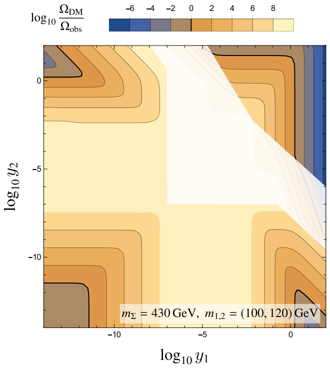


- both FIMP
- standard $\langle \sigma v \rangle_{11}$ WIMP
- $\langle \sigma v \rangle_{22}$ coannihilation

Thermal dark matter production regimes



- both FIMP
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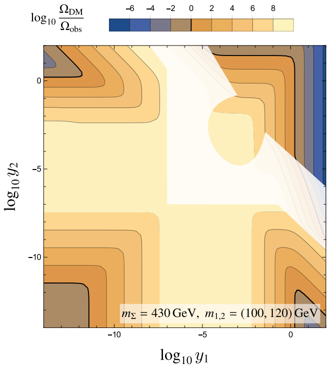
- WIMP – FIMP

Thermal dark matter production regimes



- both FIMP
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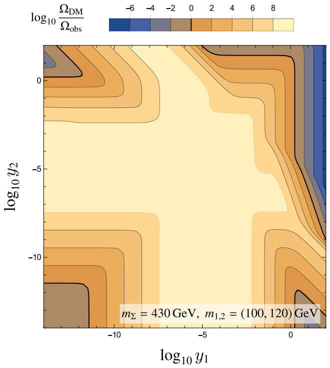
Thermal dark matter production regimes



- both FIMP
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- WIMP – FIMP
- $\langle\sigma v\rangle_{\Sigma\Sigma}$ coannihilation
- $\psi_1 \leftrightarrow \psi_2 \leftrightarrow \Sigma$ conversion freeze-out [Garny+'17] [Junius+'19]

  $\rightarrow$ no chem.eq.

Signatures

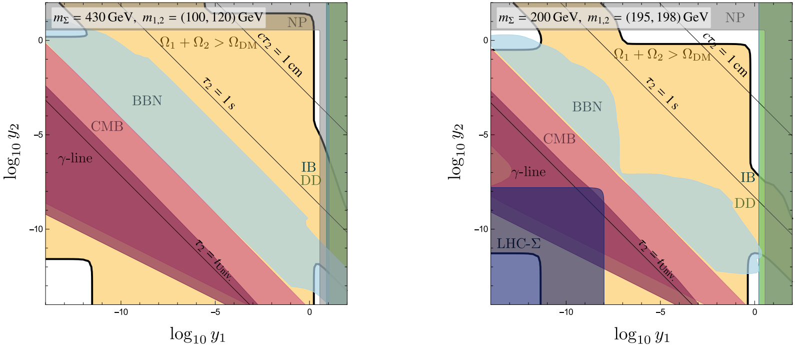
The point of studying dark matter production

$\Rightarrow$ *does the 2-flavour setup open up new ways to identify dark matter?*

- general particle physics
  - precision tests: flavour and EWPT
  - Σ at colliders (eg. [Belanger+'18], see also A. Jueid, Parallel 4B)
    - anomalous charged tracks up to $m_\Sigma \sim 430\,\mathrm{GeV}$ [ATLAS'19]
    - displaced decays
    - prompt leptons + $\not{E}_T$
    - in principle, lots of specific info on specific model
- dark matter specific
  - standard WIMP searches
    - direct detection
    - indirect detection
  - dark matter decay
  - non-cold dark matter

Constraints

bird's eye view

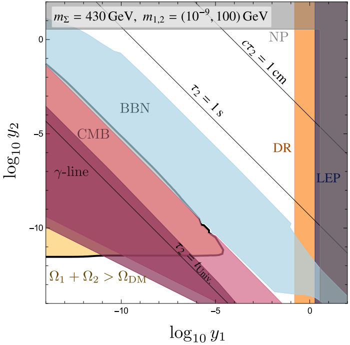


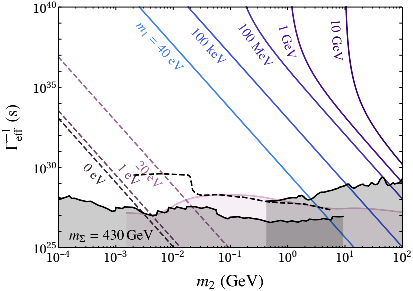
- overabundance → good job of carving up parameter space
- dark matter decay constrains mixed WIMP-FIMP scenarios
- freeze-out: heavy ψ_2 'decouples' from DM pheno

Dark matter decay

... maybe there is hope for freeze-in

- DM decay can probe multiflavour freeze-in [Herms,Ibarra'19]

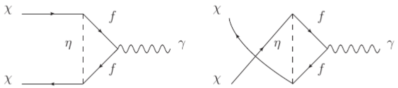




- ψ_1 DM subcomponent can be really light (limits eg. [Diamanti+'17])
- ψ_1 may thermalise, allowing for large y_1 → large signal possible at MeV → eASTROGAM/AMEGO?

WIMP searches

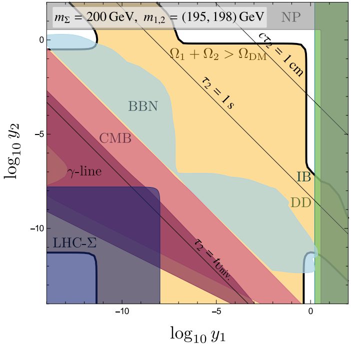
- WIMP $\Rightarrow$ large couplings $\Rightarrow$ DM $= \psi_1$, signals $\propto y_1$
- Direct detection
  - leptophilic model evades most constraints
  - however: Anapole moment induces DM-nucleus scattering (eg. [Kang+'18]+[Xenon'18])

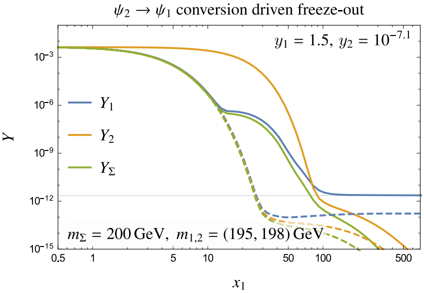


[Kopp+'14]

- Indirect detection
  - $\psi_1\psi_1 \to l^+l^-$ p-wave suppressed
  - $\psi_1\psi_1 \to l^+l^-\gamma$ distinct γ-ray spectral feature (eg. [Bringmann+'12])

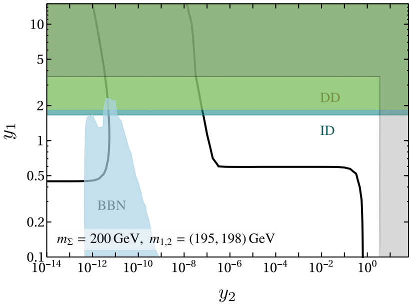
$\psi_2 \to \psi_1$ modifies relic abundance





- conversion $\psi_2 \to \psi_1$ affects y_1 necessary to obtain correct abundance
- interplay between conversion freeze-out, decay and annihilation

WIMP Signal boosts



- large y_2 → coannihilation, WIMP signals reduced
- small/intermediate y_2 → WIMP signals *boosted*
  - important for interpretation of possible signals (cf. [Fairbain,Zupan'08] in context of Pamela positrons)

Conclusion

- *DM flavour* possible detail of dark sector
  - *here:* study leptophilic DM with t-channel mediator
- second flavour modifies *relic abundance*
  - feeble coupling: $\sim$ additive yields
  - large couplings: standard coannihilation
  - intermediate couplings: non-trivial interplay $\leftarrow$ *no chemical eq.!*
- second dark matter flavour modifies *signals* we can expect
  - $\psi_2 \to \psi_1 \gamma$ can probe freeze-in production
  - signal strength in standard WIMP searches can be boosted

Thank you for your attention! *Questions and comments welcome: herms@mpi-hd.mpg.de*