Title: Codecaying Dark Matter

Date: Jul 15, 2016 01:00 PM

URL: http://pirsa.org/16070062

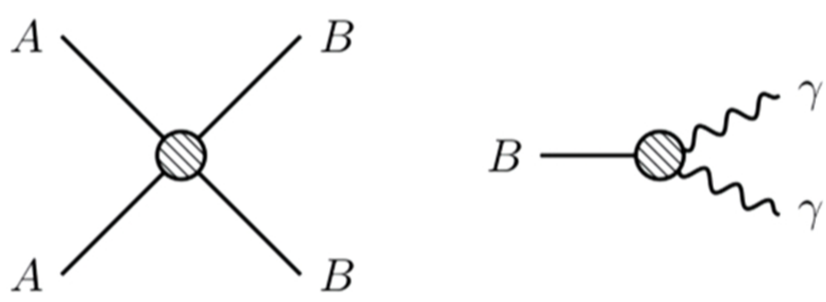
Abstract: <p>In this talk I will propose a new mechanism for thermal dark matter freezeout, termed Co-Decaying Dark Matter. Multi-component dark sectors with degenerate particles and out-of-equilibrium decays can co-decay to obtain the observed relic density. The dark matter density is exponentially depleted through the decay of nearly degenerate particles, rather than from Boltzmann suppression. The relic abundance is set by the dark matter annihilation cross-section, which is predicted to be boosted, and the decay rate of the dark sector particles. Finally, I'll present a simple model that realizes co-decaying dark matter. </p>

Co-Decaying Dark Matter

Freezeout mechanism for decoupled DM with decay to SM

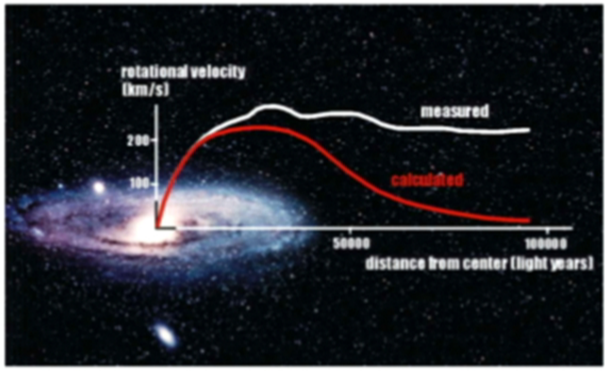
arXiv: 1607.03110

Jeff Dror, Eric Kuflik , and Wee Hao Ng



Outline

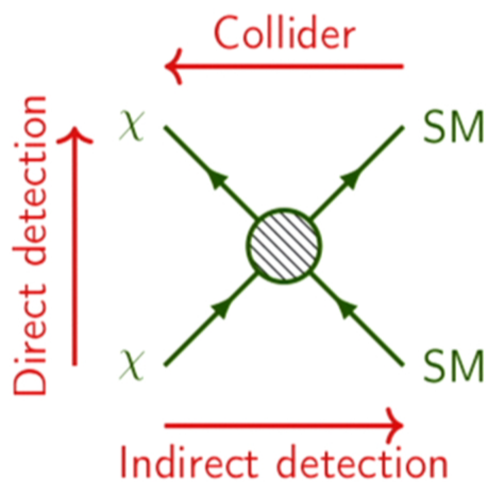
1. Experimental overview → Direct detection / Indirect detection / Collider searches
2. Co-decay basics
3. Compute relic density
4. Boltzmann equations
5. Parameter space
6. Effects of a mass splitting
7. Explicit model



- http://cdn.phys.org/newman/gfx/news/hires/2011/coulddarkmat.jpg

Finding dark matter through all avenues

- To detect a WIMP:



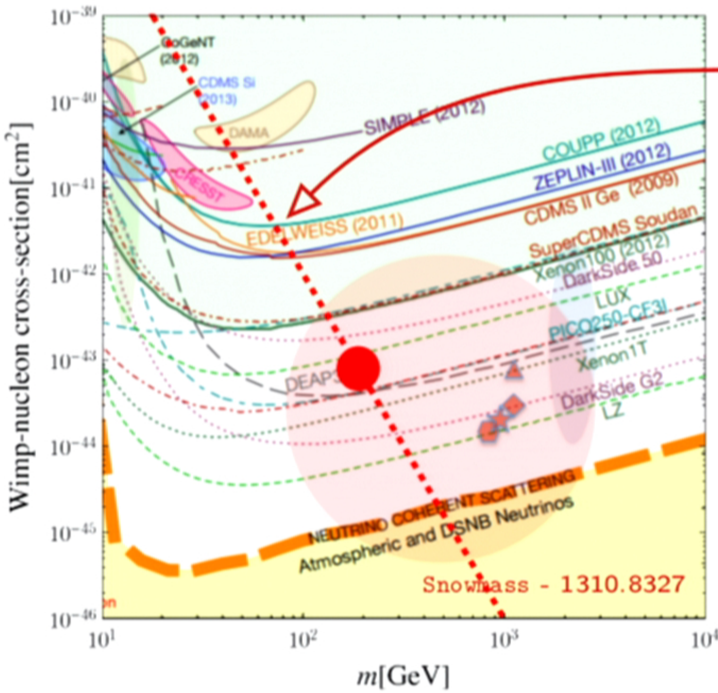
① Direct detection: Tightest constraints

② Indirect detection: Probes DM freezeout cross-section

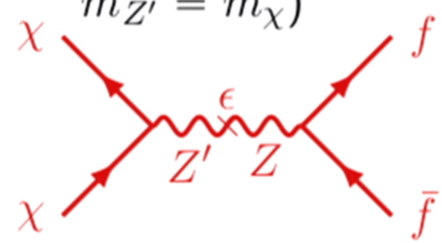
③ Collider: Constrains motivation for WIMPs

Direct detection

- Powerful limits at $\mathcal{O}(\text{TeV})$
- Naive WIMP models are getting ruled out



- e.g., Z' ($\epsilon = 0.01$, $m_{Z'} = m_\chi$)

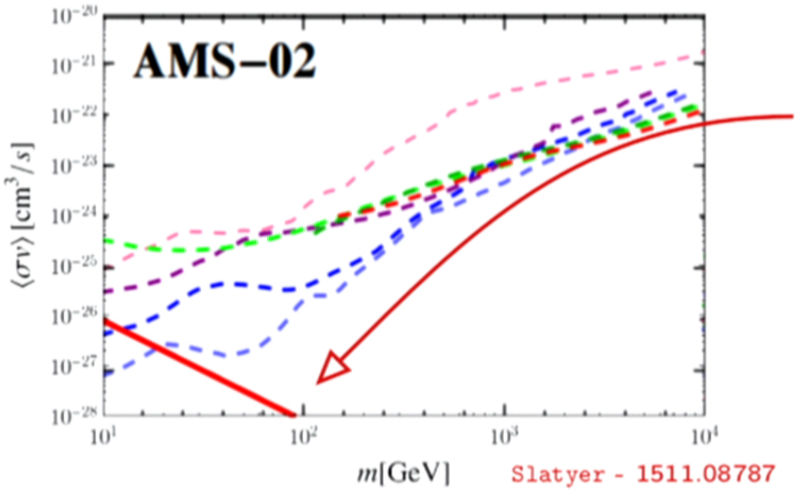


- Dashed line: direct detection
- Dot: $\Omega = 0.11$

Cline et al - 1405.7691

Indirect detection

- Constraining if
  - Low mass
  - Velocity independent
- Sample limits recast from AMS-02 telescope data:

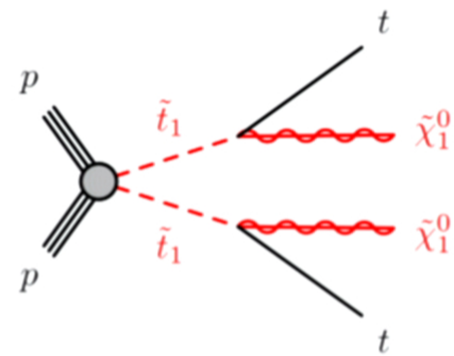


- e.g., Z'
- $\Omega = 0.11$ out of plot

Collider searches

- mono-X: $m_\chi \gtrsim 300$ GeV ATLAS - 1604.07773
  - light DM
  - spin-dependent
- Searches for additional particles: $m_{\tilde{t}} \gtrsim 800$ GeV
  ATLAS - 1606.03903

Where is

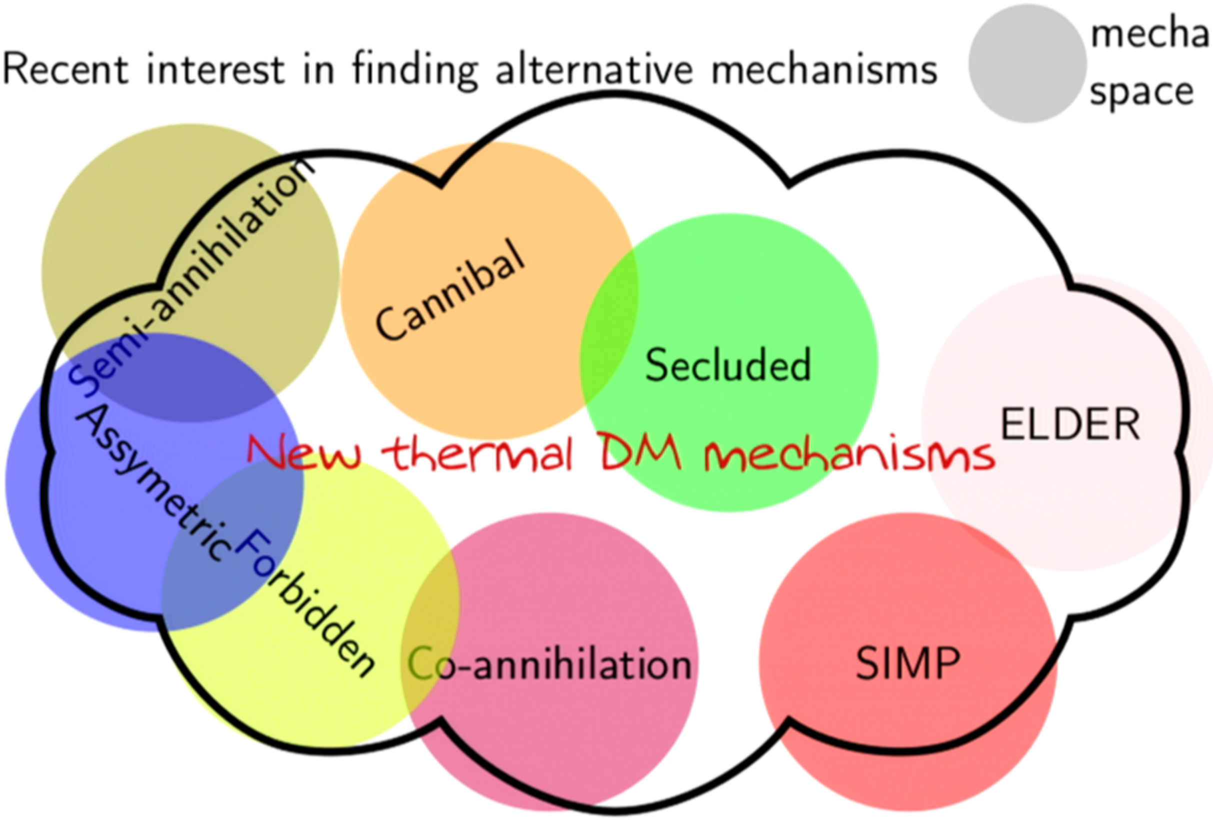


?

- Only SM at LHC $\Rightarrow$ less faith in WIMPs

WIMP alternatives

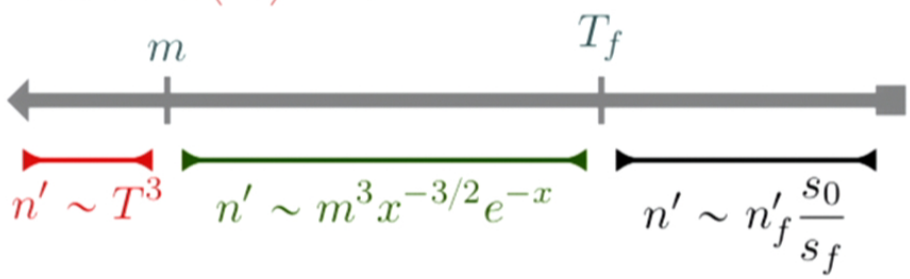
- Recent interest in finding alternative mechanisms



Setting the stage: WIMP freezeout

$$x \equiv \frac{m}{T}, H_T \equiv H(T), \ldots$$

- Classic thermal dark matter:
  1. Chemical equilibrium with the SM
  2. $T \lesssim m$ DM becomes non-relativistic
  3. $n \neq \bar{n}$ when $\bar{n}\langle\sigma v\rangle \sim H$

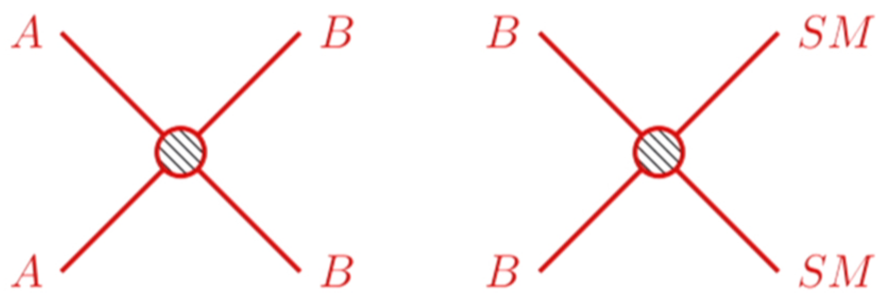


$$\Omega = \frac{\rho_0}{\rho_c} = \frac{m n'_f}{\rho_c} \frac{s_0}{s_f} \simeq \frac{x_f}{\langle\sigma v\rangle_f} \left(\frac{s_0}{\rho_c} \frac{m H_m}{s_m} \right)$$

- Many variations driven by Boltzmann suppression

Expanding dark sector content

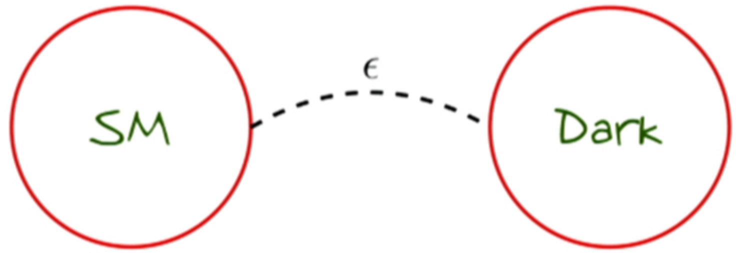
- DM part of larger sector?
- Usually assume only lightest dark particle sets relic density
- Famous counter-example: co-annihilation
- Degeneracies → particles freezeout simultaneously
- e.g.,



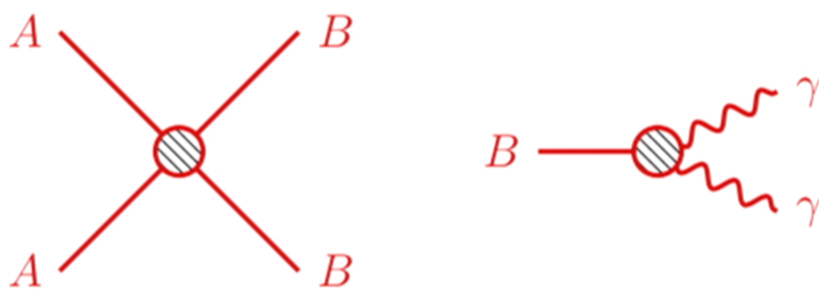
- Details change, but qualitatively similar to WIMP

Tweaking co-annihilation

- What if annihilations to SM are small?
- Weak connection between dark sector to SM



- Can dominantly induce decay in dark sector to SM
- Thermal history dependent on size of Γ



Fast decay: $\Gamma \gg H_m$

- Inverse decays are fast
- Keep dark sector in chemical equilibrium when non-relativistic

- A remains in equilibrium until freezeout,

$$n \propto x^{-3/2} e^{-x}$$

- Qualitatively similar to co-annihilation

Slow decay: $\Gamma \ll H_m$

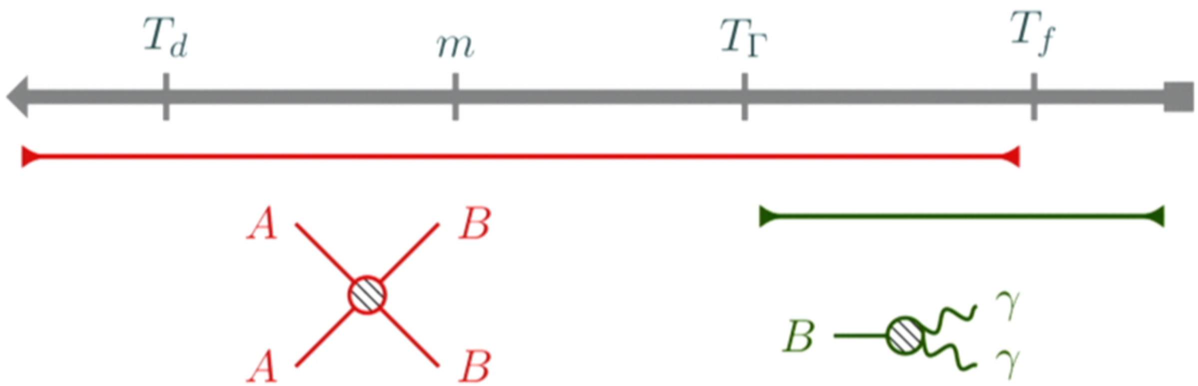
- Inverse decays are too slow
- Decoupled from SM
  - Nothing happens at $T \sim m$!
- At $e^{-\Gamma t} \sim 1$ decay begins to deplete dark sector
- Depletion of dark sector with novel rate,

$$n \propto e^{-\Gamma t} \sim e^{-\frac{\Gamma}{H_m} x^2}$$

- "Co-decaying Dark Matter"

Qualitative overview

- Order of events:
  1. Dark sector is decoupled from SM at early times
  2. At $T \sim m$ nothing happens
  3. At $e^{-\Gamma t} \sim 1$ Bs begins decaying
  4. As track Bs until $AA \to BB$ freezes out setting A relic density
  5. B decays indefinitely



- $\Omega(m, \langle\sigma v\rangle, \Gamma)$

Relic density

- Relic density equation same as WIMP:

$$\Omega \simeq \frac{x_f}{\langle \sigma v \rangle_f} \left(\frac{s_0}{\rho_c} \frac{m H_m}{s_m} \right)$$

- s-wave: $\langle \sigma v \rangle \simeq \sigma / \sqrt{x'}$ ⟵ $x' \equiv m/T'$ $(T' \neq T!)$

$$\Omega \simeq \frac{x_f \sqrt{x'_f}}{\sigma} \left(\frac{s_0}{\rho_c} \frac{m H_m}{s_m} \right)$$

- To compute relic density need x_f and x'_f
- Goal: track dark sector from $x_d \to x_f$

Step 1: Find T_f

- Start by finding T_f:

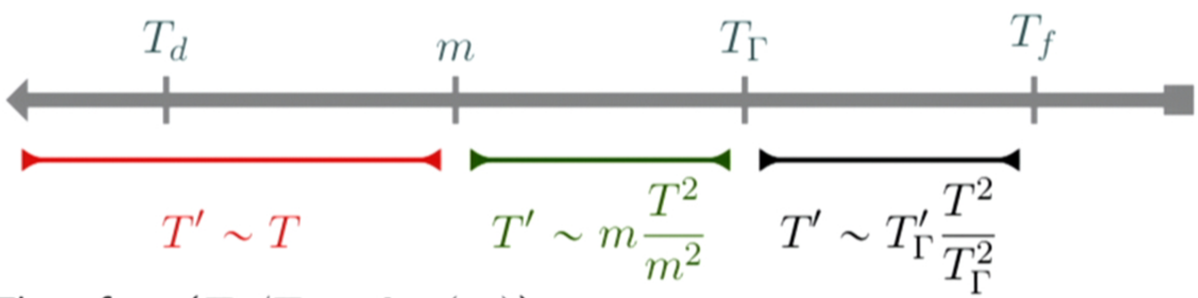
$$n'_f = \overbrace{n'_\Gamma}^{\sim s_\Gamma} \underbrace{\frac{a_\Gamma^3}{a_f^3}}_{\sim x_\Gamma^3/x_f^3} \overbrace{e^{-\Gamma(t_f - t_\Gamma)}}^{\sim e^{-\frac{\Gamma}{H_m} x_f^2}}$$

- $n'_f \langle \sigma v \rangle_f = H_f \Rightarrow$

$$x_f \simeq \frac{1}{\sqrt{\Gamma/H_m}} \log^{1/2}(\ldots)$$

Step 2: Find T'_f

- We now move onto T'_f
- For $T \gtrsim m$, DM is relativistic
- Non-relativistic DM redshifts

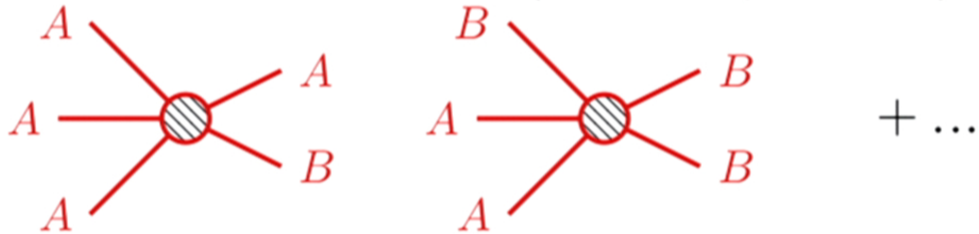


- Therefore $(T_f/T_\Gamma = \log(...))$:

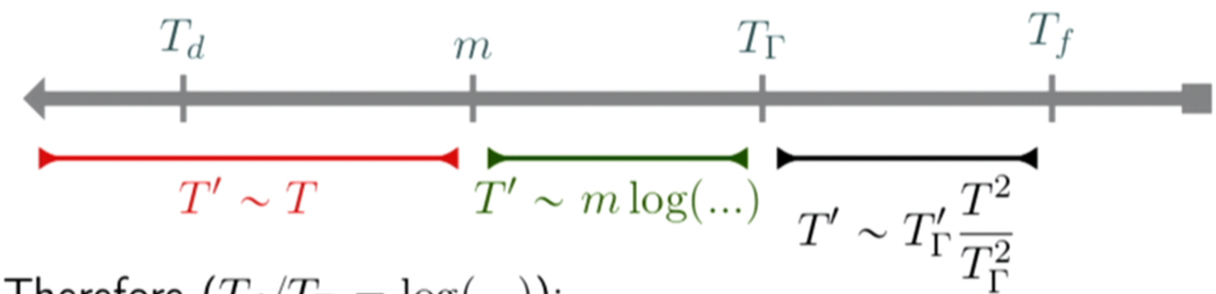
$$x'_f \simeq x_f^2 \log(...)$$

Step 2: Find dark temperature (with cann)

- What if we have cannibalization ($4 \to 2$ and/or $3 \to 2$)?



- Number changing processes stop dark sector from cooling



- Therefore ($T_f / T_\Gamma = \log(\ldots)$):

$$x'_f \simeq \log(\ldots) \log(\ldots)$$

Relic density

- We conclude:
  - Without cannibalization: ${x_f}' \sim x_f^2$, $x_f \sim \dfrac{1}{\sqrt{\Gamma/H_m}}$
  - With cannibalization: $x'_f \sim \log(...)$, $x_f \sim \dfrac{1}{\sqrt{\Gamma/H_m}}$
- Careful analysis gives (recall $\Omega \propto x_f \sqrt{x'_f}/\sigma$):

$$\frac{\Omega_A}{\Omega_{\rm DM}} \simeq \left(\frac{10^{-36}}{\sigma/\mathrm{cm}^2}\right) \times \begin{cases} \left(\dfrac{m}{\mathrm{GeV}}\right)\left(\dfrac{10^{-18}}{\Gamma_B/m}\right) & \text{(w/o canb)} \\ \left(\dfrac{m}{\mathrm{GeV}}\right)^{\frac{1}{2}}\left(\dfrac{10^{-17}}{\Gamma_B/m}\right)^{\frac{1}{2}} & \text{(w canb)} \end{cases}$$

- For WIMP: $\Omega = \Omega_{DM}$ for $\sigma \simeq 10^{-36}$ cm^2

Boltzmann equations

- Solving Boltzmann equations is straightforward
- Equations I expect you to forget:

$$\frac{dn_A}{dt} + 3Hn_A = -\langle \sigma v \rangle (n_A^2 - n_B^2)$$
$$\frac{dn_{A+B}}{dt} + 3Hn_{A+B} = -\left(\langle \Gamma_B \rangle_{T'} n_B - \langle \Gamma_B \rangle_T n_T^{\text{eq}} \right)$$
$$\frac{d\rho_{A+B}}{dt} + 3H(\rho_{A+B} + P_{A+B}) = -m\Gamma_B \left(n_B - n_T^{\text{eq}} \right)$$

- $\langle \Gamma_B \rangle_T \equiv m\Gamma_B \left\langle E_B^{-1} \right\rangle_T$
- Large $x_\Gamma \Rightarrow$ DM dominate the universe
- To solve equations need to convert $\frac{d}{dt} \to \frac{d}{dT}$

Non-conservation of entropy

- Convert between $t \leftrightarrow T$:

$$\frac{d}{dt} = \frac{da}{dt}\frac{d}{da} = aH\frac{dT}{da}\frac{d}{dT}$$

- Usual case: use conservation of entropy:

$$\frac{d(sa^3)}{da} = 0 \implies \frac{dT}{da} = -\frac{T}{a} \quad \text{(up to } \frac{\partial g_{\star,S}}{\partial T} \neq 0\text{)}$$

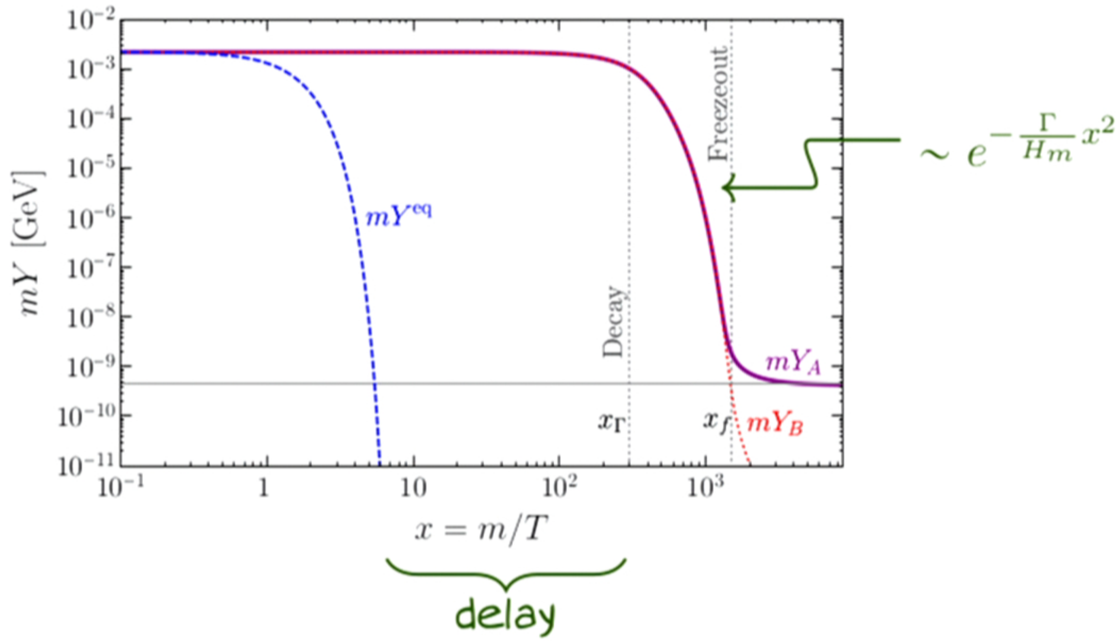
- Here entropy is not conserved:

$$\frac{d(sa^3)}{da} = \frac{1}{T}\frac{dQ}{da} = -\frac{1}{T}\frac{d(\rho' a^3)}{da} = \frac{m\Gamma_B}{HT}(n_B - n_T^{eq})a^3$$

- Small effect in practice

Money plot

- Solving the Boltzmann equations for no cannibalization:
- $Y_i \equiv n_i/s$



Where can co-decay take place?

- Co-decay is constrained on several fronts
- Constrains (m, Γ, σ) plane
- Can use relic density constraint to map onto (m, Γ).
- Focus on case without cannibalization for simplicity
- Use

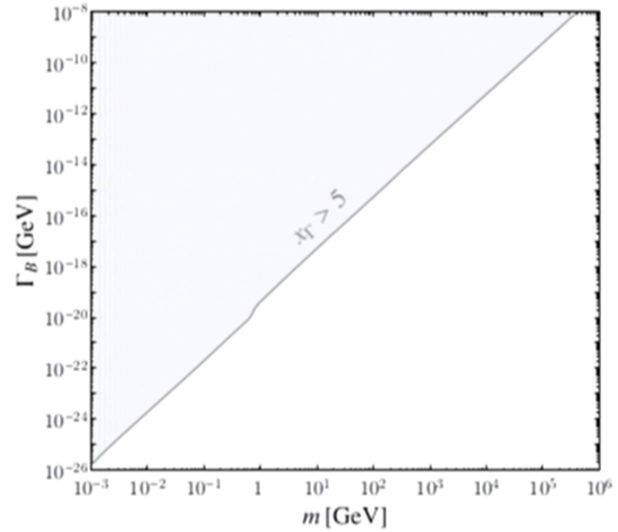
$$\frac{\Omega_A}{\Omega_{DM}} = \left(\frac{10^{-36}}{\sigma/\ \text{cm}^2}\right)\left(\frac{m}{\text{GeV}}\right)\left(\frac{10^{-18}}{\Gamma_B/m}\right)$$

- Constraint gives,

$$\sigma \propto \frac{m^2}{\Gamma}$$

Get out of equilibrium!

- Need $x_\Gamma \simeq \dfrac{1}{\sqrt{\Gamma/H_m}} \gtrsim 1$ to co-decay
- DM must not rethermalize with SM
- Safer condition, $x_\Gamma \gtrsim 5$



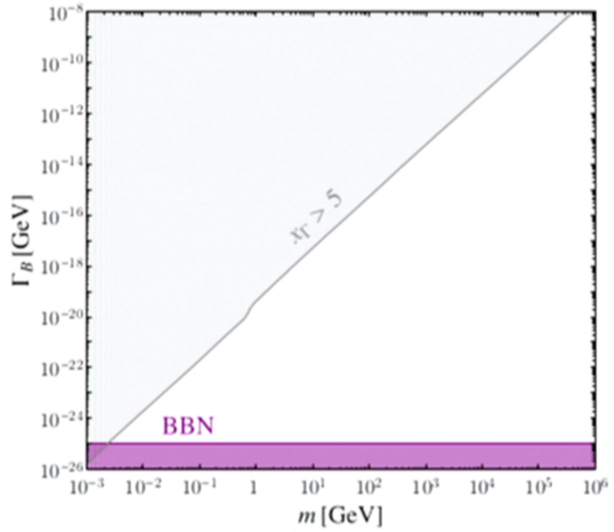
BBN

- Energy injections to the SM after BBN constrained by $N_{\rm eff}$,

Di Valentino et al - 1601.07557

$$2.5 \lesssim N_{eff} \lesssim 3.5$$

- Rough bound: $\Gamma \gtrsim H_{m_e}$

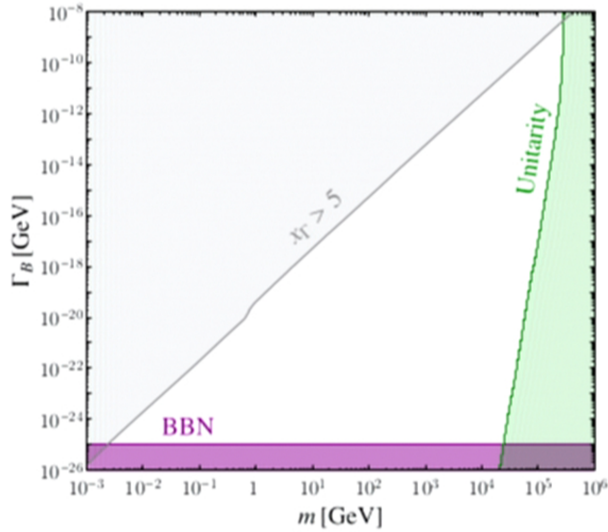


Unitarity

- Unitarity during freezeout constrains σ

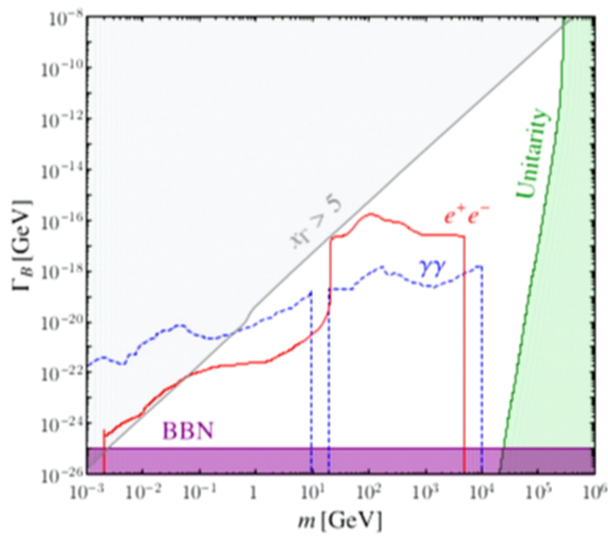
Griest and Kamionkowski - PRL 64 615 (1990)

$$\langle \sigma v \rangle_f \leqslant \frac{4\pi \left\langle v^{-1} \right\rangle_f}{m^2} \implies \sigma \lesssim \frac{\pi\sqrt{2}}{m^2} x'_f \qquad \begin{array}{l} \sigma \propto m^2/\Gamma \\ x'_f \propto 1/\Gamma \end{array}$$



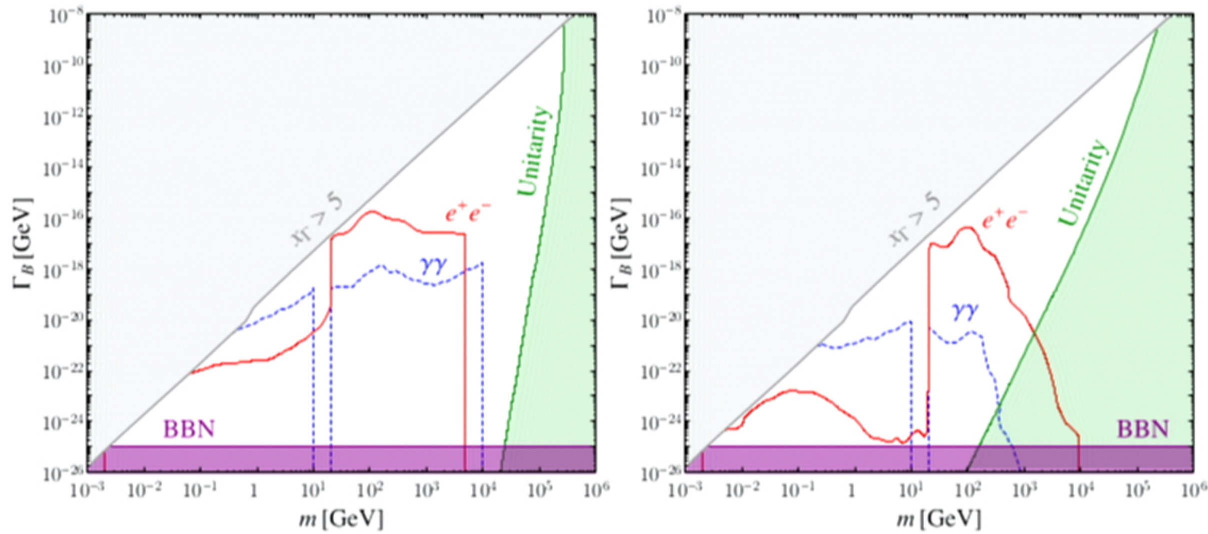
Indirect detection

- Indirect detection are powerful constraints on the parameter space
- Recast limits for e^+e^- or $\gamma\gamma$ Essig et al - 1309.4091 Slatyer et al - 1511.08787
- Gap in $\gamma\gamma$ limits due thresholds in recasts



Summary of parameter space

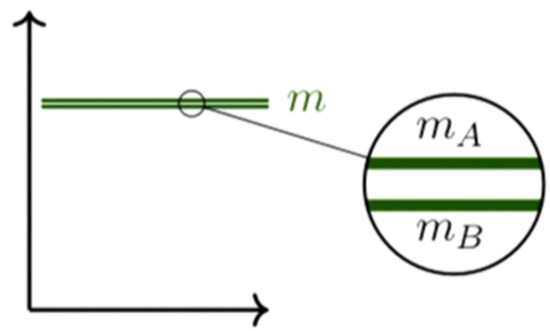
- Summary of both constraints:



- Indirect detection is a powerful probe in either case, but model dependent
- Lots of open parameter space

When is m_A really equal to m_B?

- Assumed $m_A = m_B$
- Natural if there is some symmetry protecting it
  - Often broken by loop corrections ($\sim$ %)
- What if there is a small splitting?



- RECALL: annihilations occur at $T' \ll m$!

$m_A > m_B$

- $AA \to BB$ allowed at $T = 0$
- Small splitting:

$$\langle \sigma v \rangle_{m_A > m_B} \simeq \frac{\sqrt{\pi x'}}{2} \langle \sigma v \rangle_{m_A = m_B}$$

- Large splitting freezeout is a two step process:

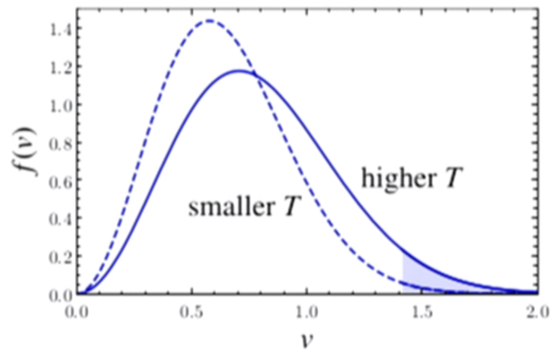
- Entropy dump dilutes A relic abundance

Pappadopulo, Ruderman, and Trevisan - 1602.04219
Ruderman et al - 1607.03108

$m_A < m_B$

- $AA \to BB$ forbidden $T = 0$
- Annihilations proceed off tail of exponential distribution,

Griest and Seckel - PRD 43 3191 (1991)
D'Angnolo and Ruderman - 1505.07107



$$\langle \sigma v \rangle_{AA\to BB} \propto e^{-2\Delta x'}, \quad \Delta \equiv \frac{m_A - m_B}{m_A}$$

- Novel form of forbidden DM
- Future study JAD, Kuflik, and Ng - to appear

Model

- So far focused on generic sector with As and Bs
- Can we build a complete model?
- Dark $SU(2)$ gauge symmetry,

$$W_D^{\pm} \equiv \frac{1}{\sqrt{2}}(W_1 \mp iW_2)$$
$$Z_D \equiv W_3$$

- Dark Higgs doublet, Φ_D

$$\mathcal{L} \supset D^{\mu}\Phi_D^{\dagger}D_{\mu}\Phi_D - \frac{1}{4}F_D^{a,\mu\nu}F_{D,\mu\nu}^{a} - \lambda_D\left(\Phi_D^{\dagger}\Phi_D - \frac{v_D^2}{2}\right)^2$$

- $\langle\Phi_D\rangle \neq 0$ giving masses to W_D, Z_D

Custodial symmetry

- Theory has an accidental (global) custodial symmetry
  - $W_i \to (e^{i\sigma_a \alpha_a/2})_{ij} W_j$
  - No explicit breaking of symmetry (unlike SM custodial)
- To decay one of the particles, need to violate symmetry
- Symmetry is broken by dim-6 operator,

$$\frac{1}{\Lambda^2}(\Phi^\dagger D_\mu \Phi)(\Phi_D^\dagger D^\mu \Phi_D)$$

- Opens decay channel for Z_D but not $W_D^\pm$:

$$Z_D \to Z^{(*)} \to \text{SM}$$

- Z_D is the "B particle"
- $W_D^\pm$ is the "A particle"

Conclusion

- Null results on all frontiers should reduce faith in WIMPs
- Time to explore alternative freeze-out mechanisms
- Co-decay can deplete a dark sector while avoiding constraints
- $\langle \sigma v \rangle$ and Γ set relic density
- To do:
  - Model space still largely unexplored
  - Study forbidden regime