ICHEP 2018, Friday, 6th July

Low-Temperature Enhanced Semi-Annihilation and AMS-02

Andrew Spray & Yi Cai

JHEP 1601 (2016) 087
JHEP 1606 (2016) 156
JHEP 1702 (2017) 120
1807.00832

Motivation

- Bounds on thermal DM starting to get quite strong

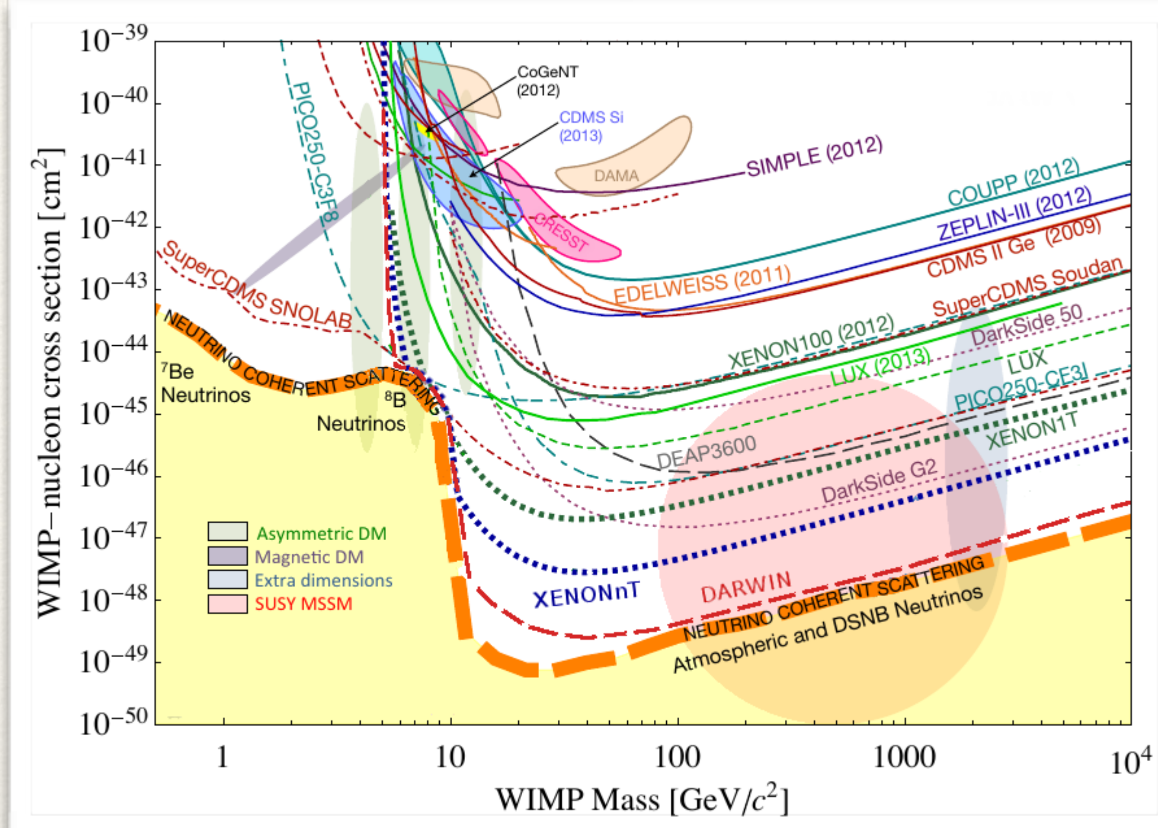
LPT-Orsay-17-09, CPHT-RR009.032017, SCIPP 17/03

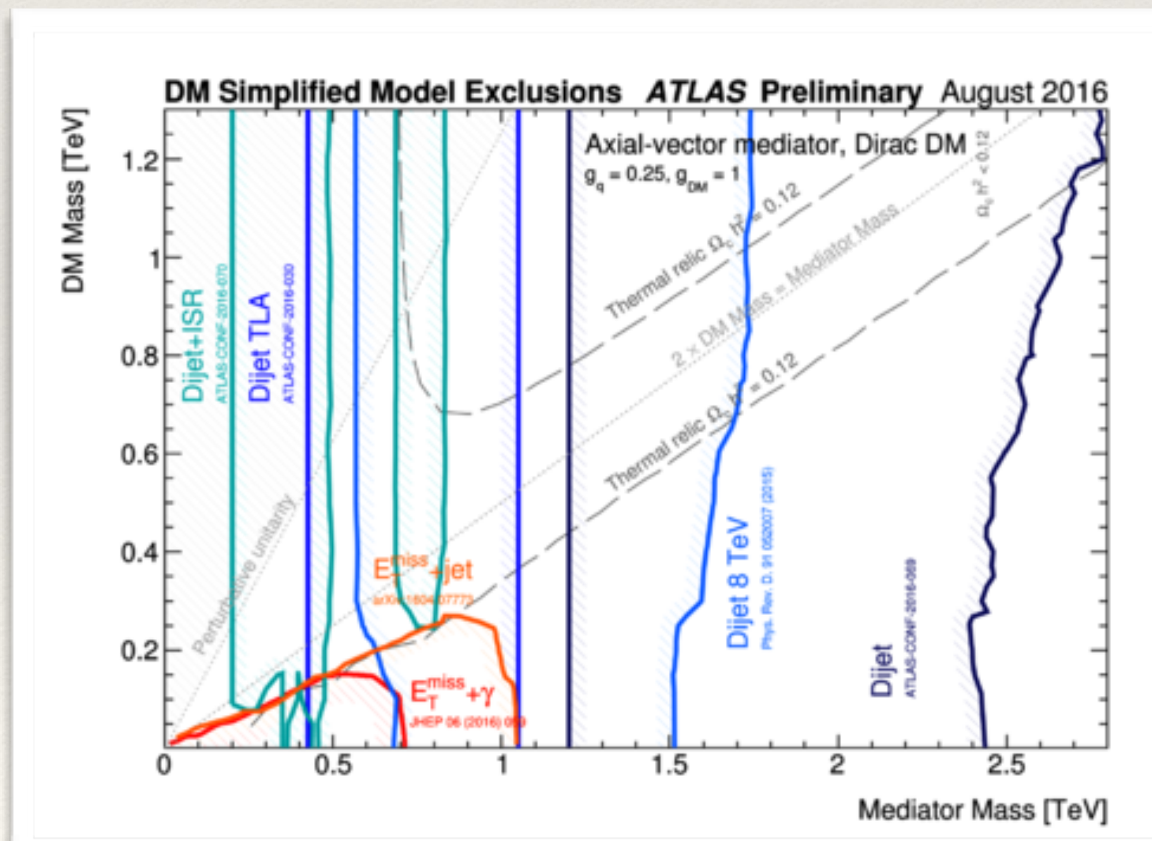
The Waning of the WIMP?

A Review of Models, Searches, and Constraints

Giorgio Arcadi[a,*] Maíra Dutra[b,†] Pradipta Ghosh[b,c,‡] Manfred Lindner [a,§] Yann Mambrini[b,¶] Mathias Pierre[b,**] Stefano Profumo[d,e,††] and Farinaldo S. Queiroz[a‡‡]

- Successful test of this idea!
- But we should be diligent in checking for loopholes
- What are our assumptions? What if we relax them?





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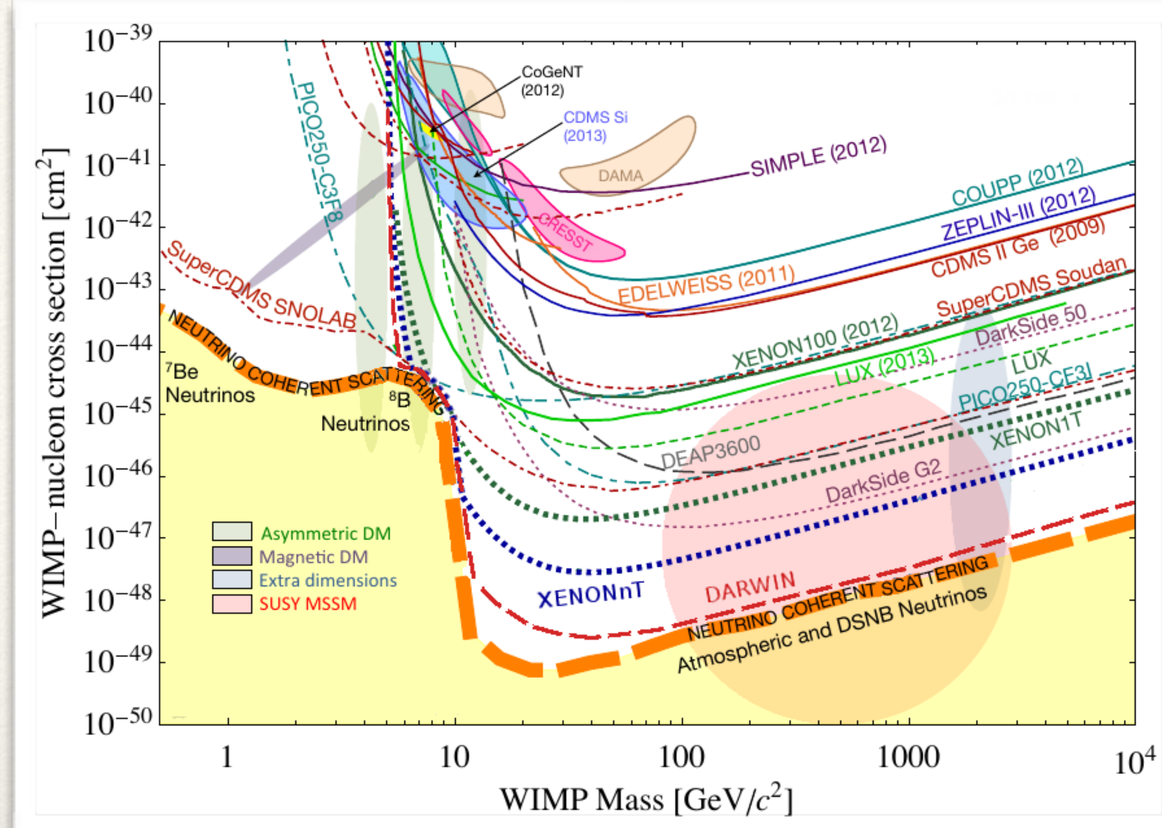

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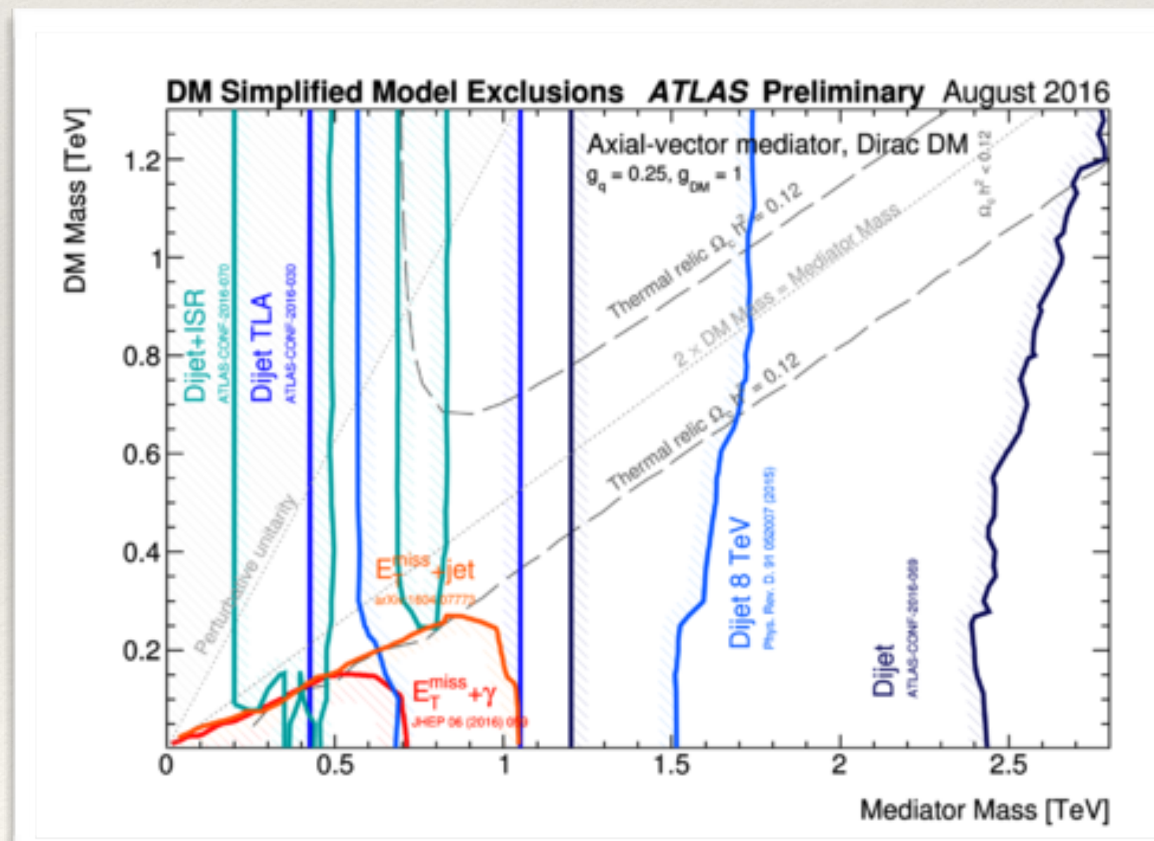
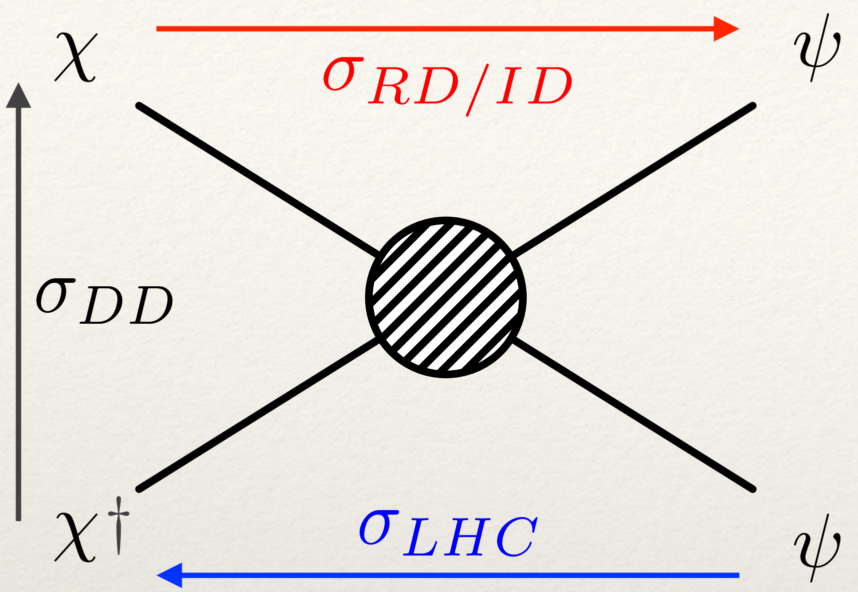
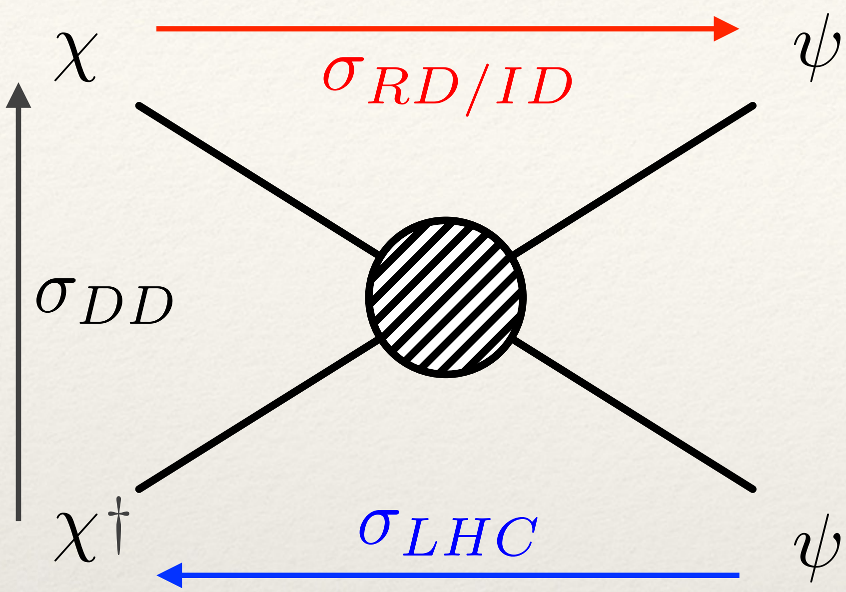
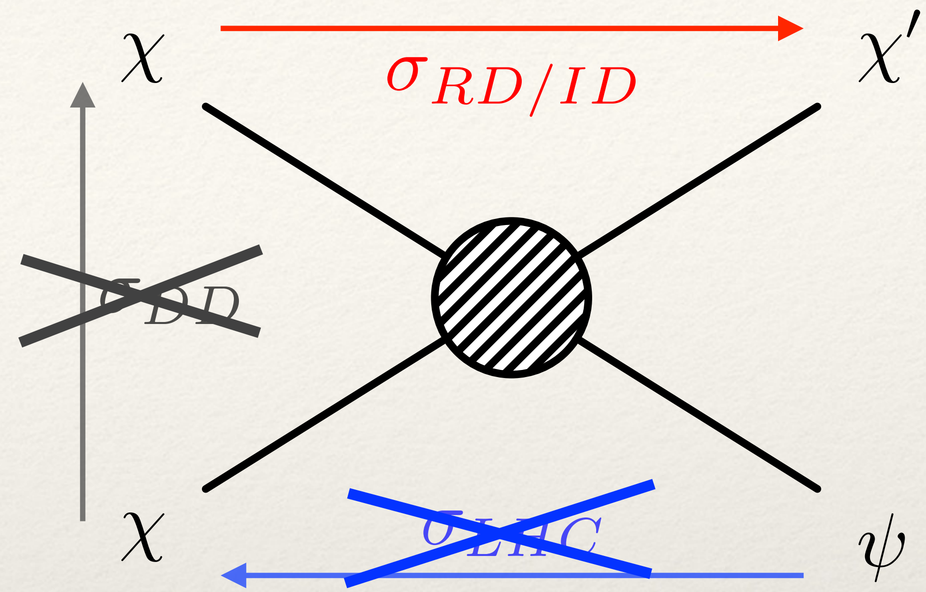
- But we should be diligent in checking for loopholes
- What are our assumptions? What if we relax them?
- Very basic assumption: DM stabilised by Z_2 symmetry





- Implies this familiar diagram
- Detection rates related to relic density calculation
- Leads to these strong bounds





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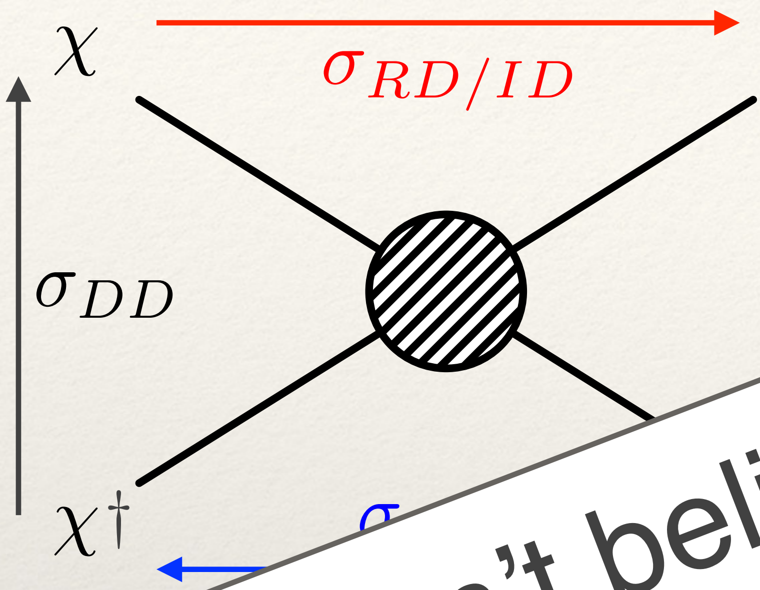
- Not Generic! (D'Eramo & Thaler, 2010)
- Non-Z_2 syms ➼ Semi-Annihilation:
  - Non-decay processes
  - Odd number of external dark states
- Irrelevant for colliders & DD



You won't believe this 1 weird trick for avoiding dark matter constraints!

- …ated to r… …y calculation
- Leads to these strong bounds

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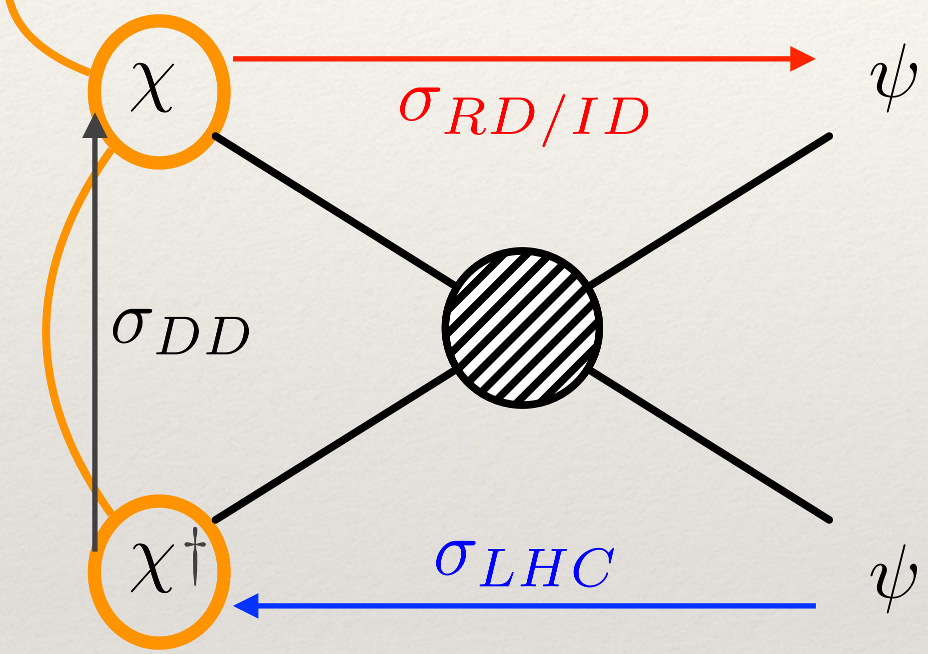
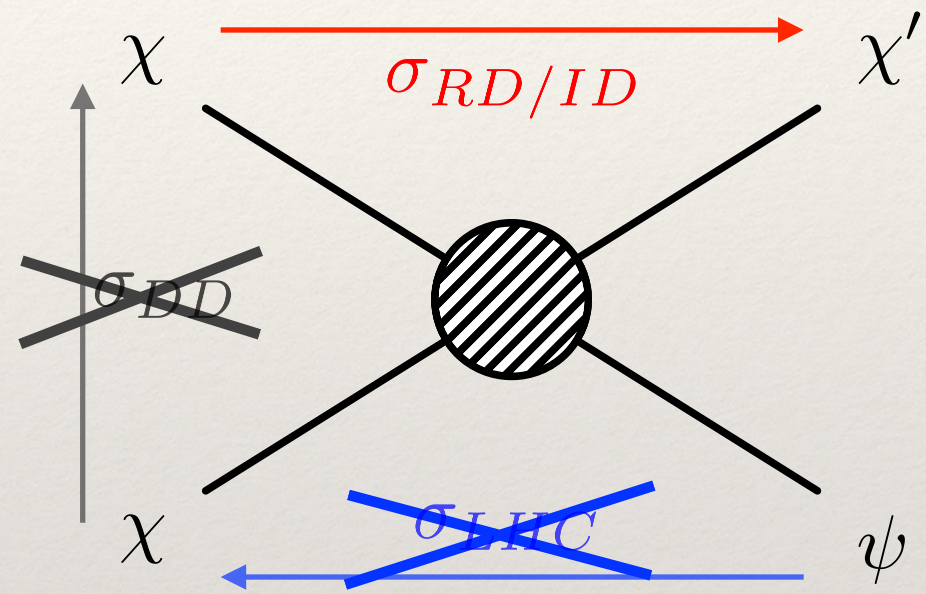
  - No symmetry can forbid this diagram



  - Semi-annihilation leads to cosmic ray signals



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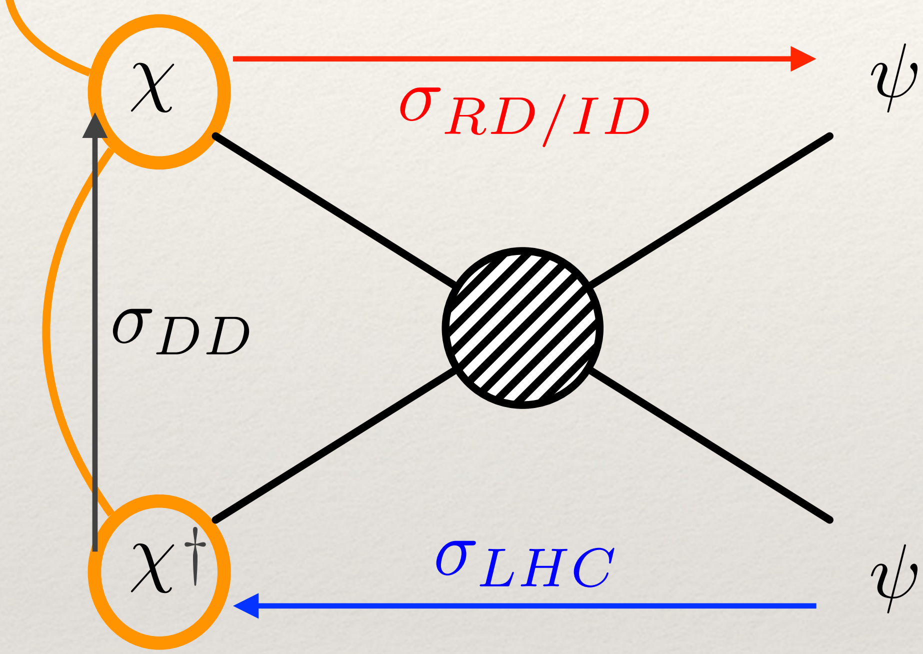

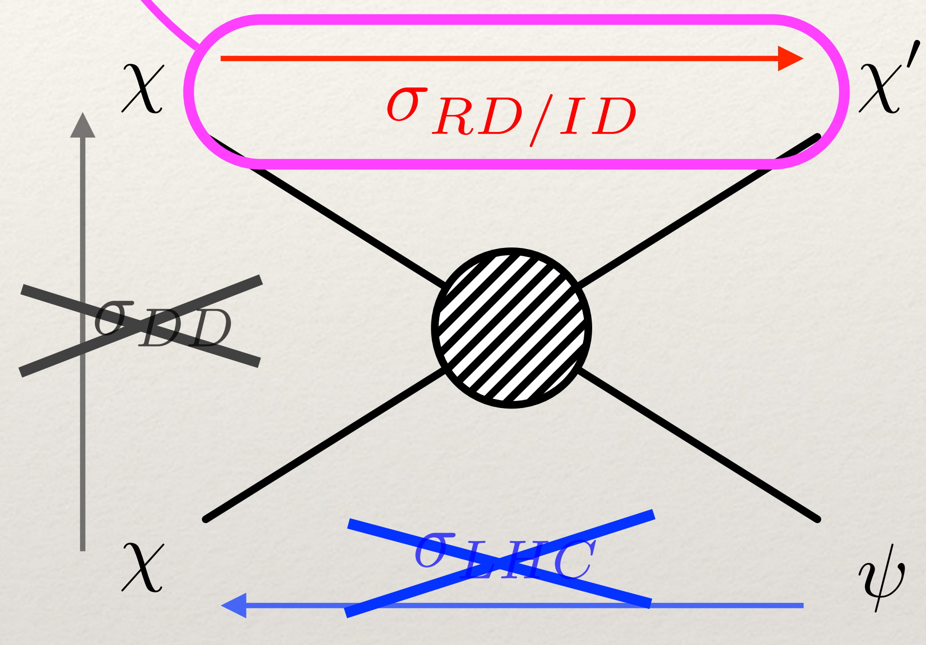

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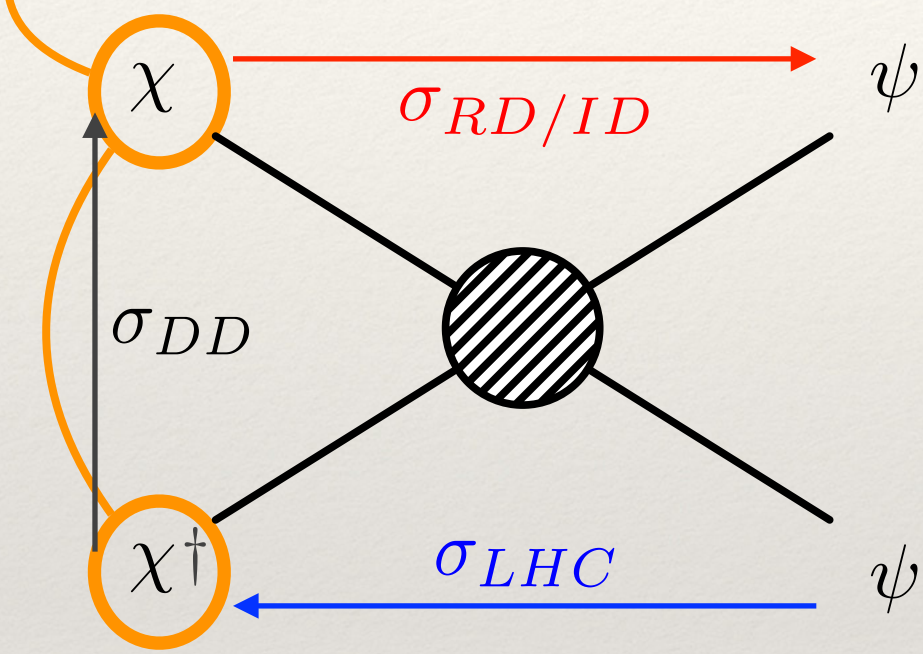

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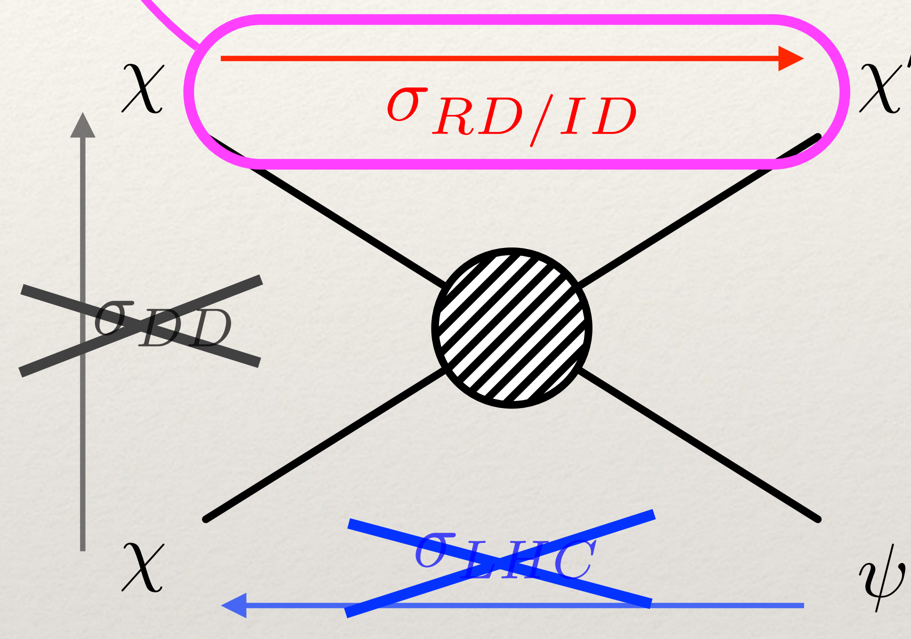
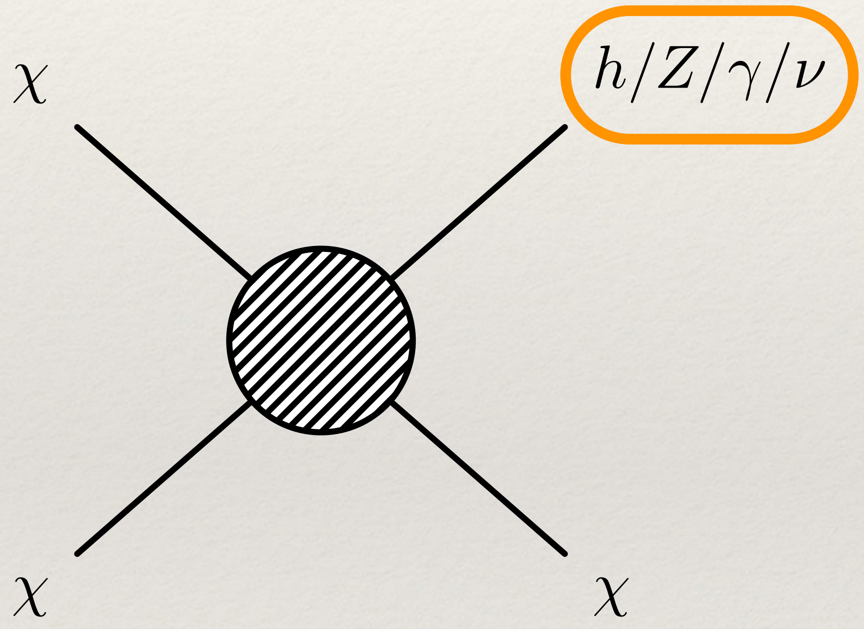


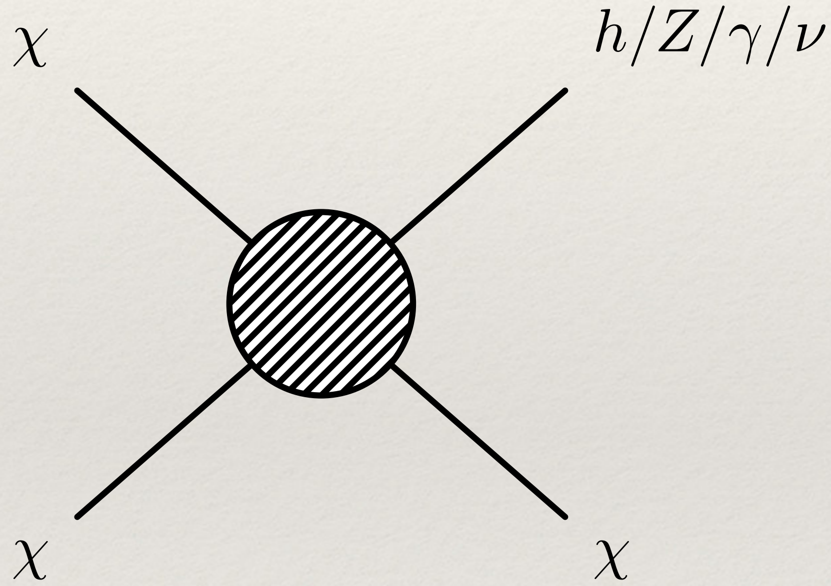
- Important to understand model space, phenomenology and thus constraints
- Initial effort in EFT language, JHEP 1702 (2017) 120

- $2 \to 2$ SA phenomenologically limited

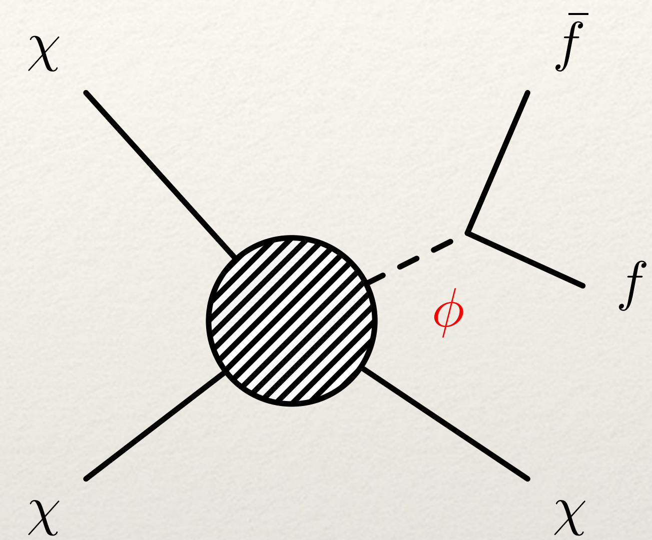


- $2 \to 2$ SA phenomenologically limited
- $2 \to 3+$ SA phase space suppressed…

… unless it is really $2 \to 2$



Usual



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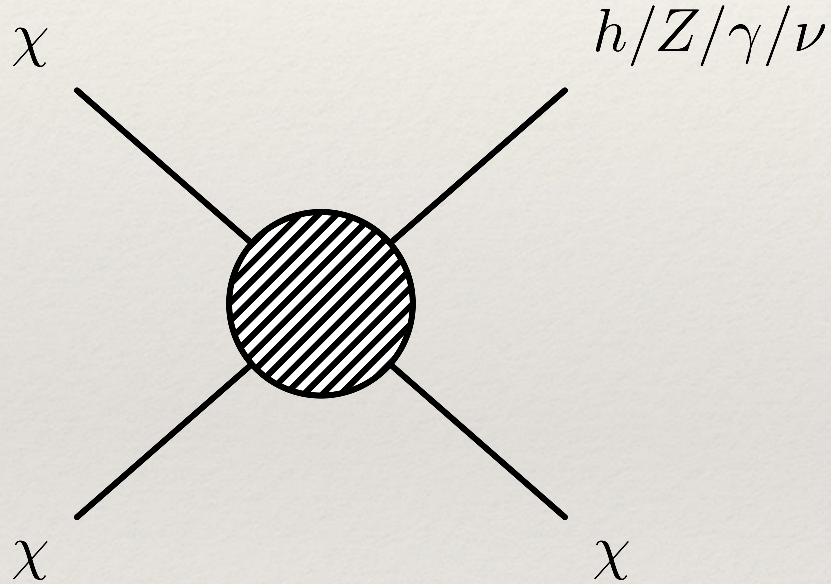

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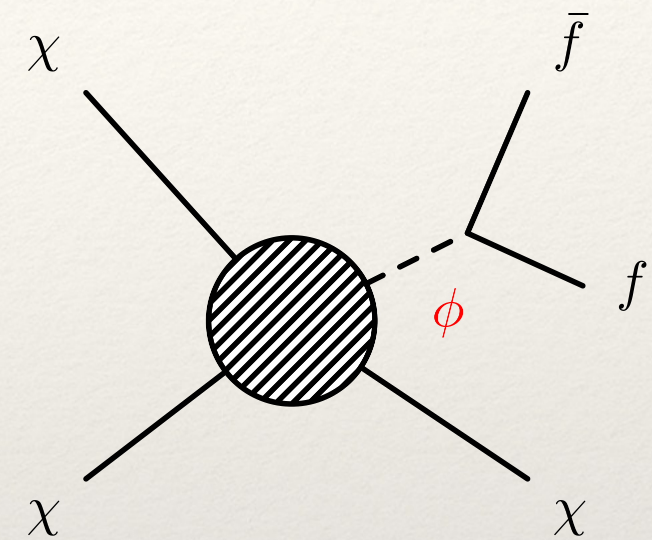
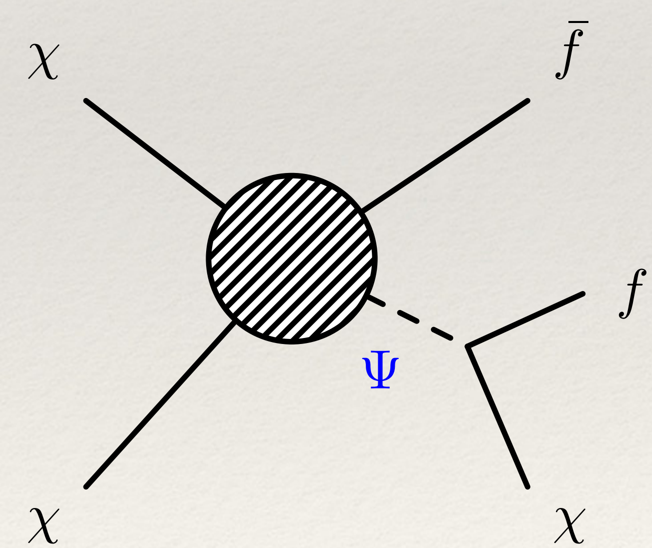
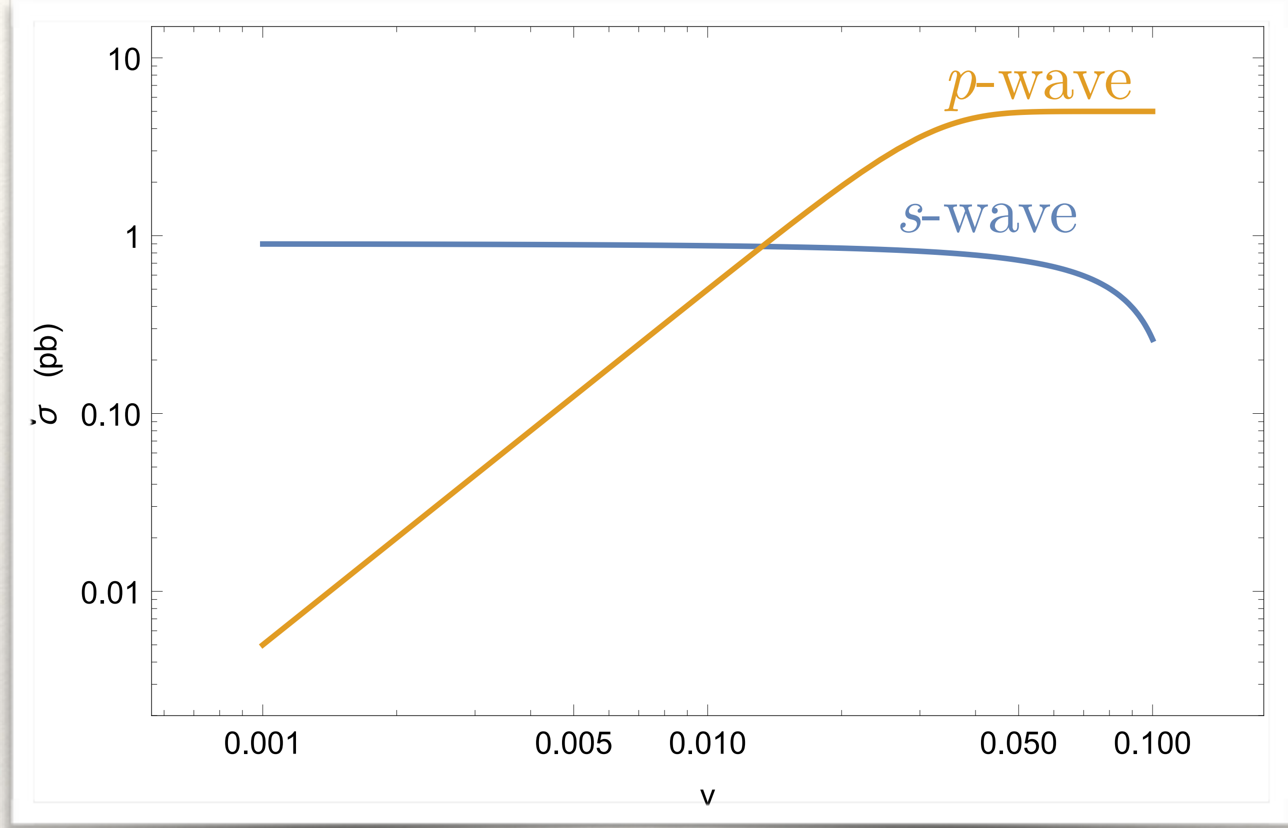


New



- Call these new states Dark Partners

- EFT approach assumes cross section simple function of velocity
- Exceptions (enhanced at low v) are well-known:
    - Sommerfeld, bound states, Breit-Wigner resonance
- Bigger signals today ➼ phenomenologically interesting
- Thermal history becomes sensitive to DM temperature



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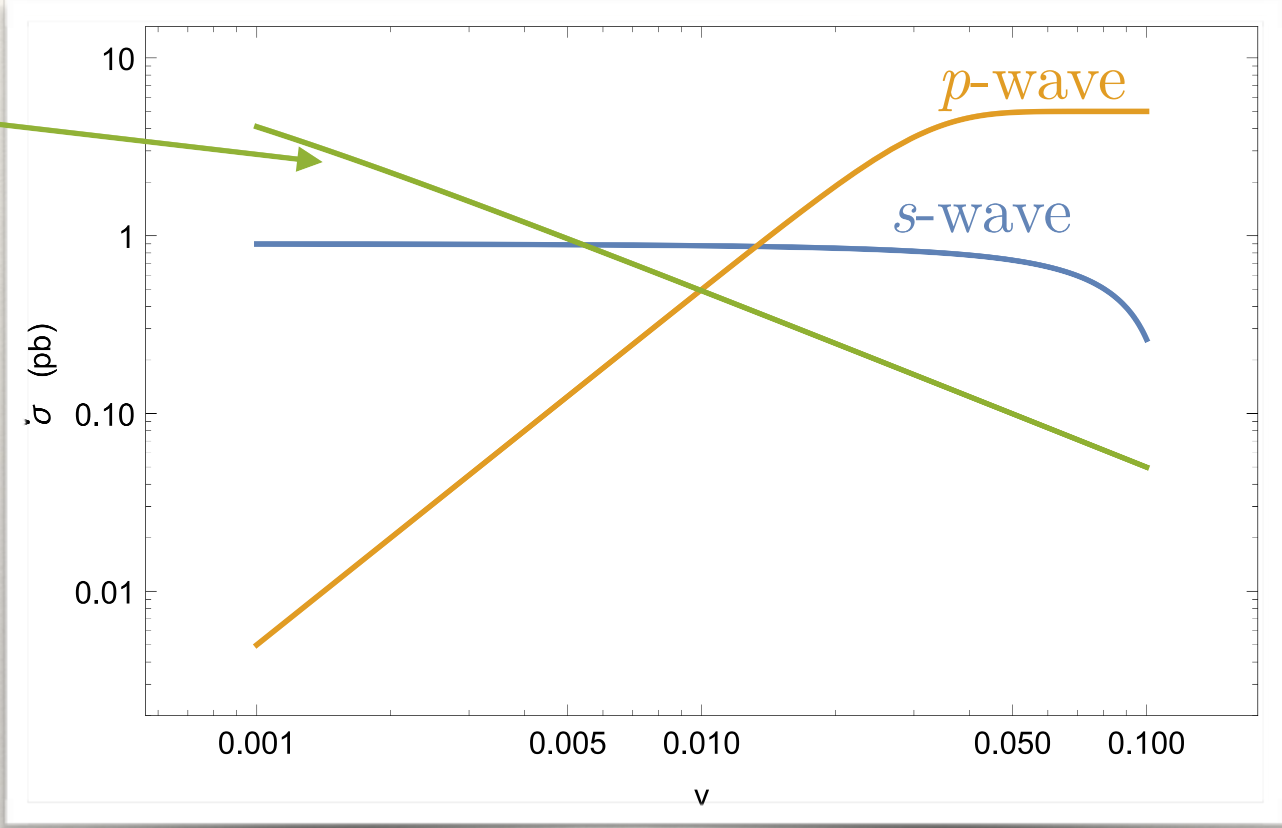


Dark Matter Temperature and Semi-annihilation

- Definition of DM temperature T_χ: (Binder et al, `1706.07433`)

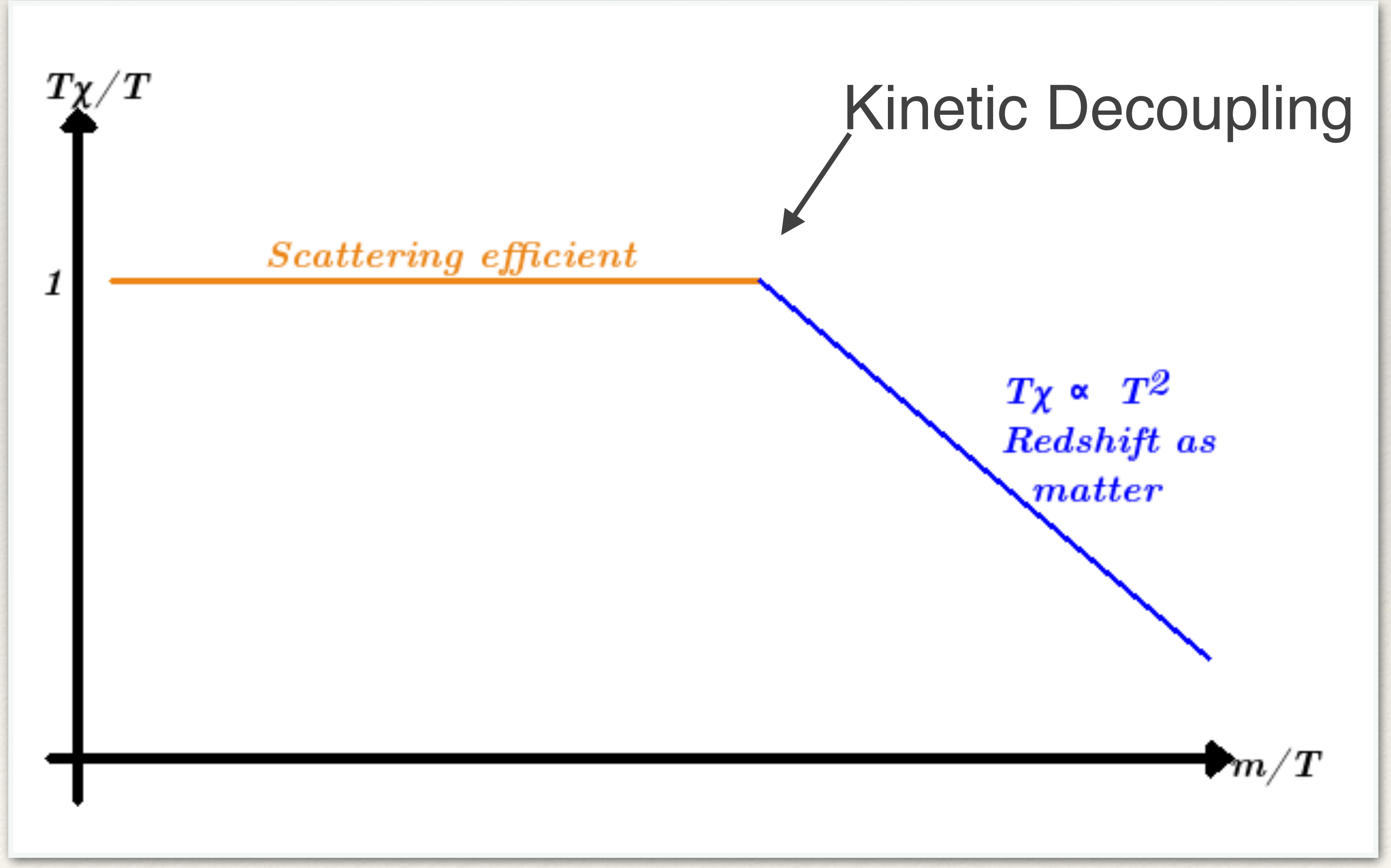
Maxwellian

$$f(E) = e^{-E/T_\chi}$$

Any

$$T_\chi = \frac{g_\chi}{n_\chi} \int \frac{d^3 p_\chi}{(2\pi)^3} \frac{\vec{p}_\chi^{\,2}}{3E_\chi} f(p_\chi)$$

- Usual behaviour:



- Details require solving an extra Boltzmann equation

- T_χ B.E. depends on modified cross section average (except scattering, which is more complicated)

$$\langle \sigma v \rangle_2 = \frac{g_\chi^2}{n_\chi^3} \int \frac{d^3 p_1}{(2\pi)^3} \frac{d^3 p_2}{(2\pi)^3} \frac{p_\chi^2}{3 T_\chi E_\chi} f_1(p_1)\, f_2(p_2)\, \sigma v$$

- Average of p^2/E for external DM particle
- Effect of SA first discussed in Kamada *et al* `[1707.09238]`:
  - Must include forward and backward contributions
  - Self-heating: fraction q_χ of mass converted to DM kinetic energy

$$\frac{dT_\chi}{dT} \sim \frac{1}{n_\chi} \frac{dt}{dT} \frac{dE_\chi}{dt} \sim \frac{1}{n_\chi} \frac{1}{HT} q_\chi\, m_\chi\, n_\chi^2 \langle \sigma v(SA) \rangle$$

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$\frac{s}{HT}$: Constant (rad. dom.)

$q_\chi\, m_\chi$: Constant

Y_χ: Constant (relic dens.)

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$T_\chi \propto T$ in far IR

- Situation with dark partners more complex
- Dark partner number density?

Inverse decay

$$Y_\Psi \approx Y_\chi \frac{Y_\Psi^{eq}}{Y_\chi^{eq}} + \frac{s\langle \sigma v(SA)\rangle}{2\Gamma_\Psi} Y_\chi^2$$

SA production
Dominates at late time

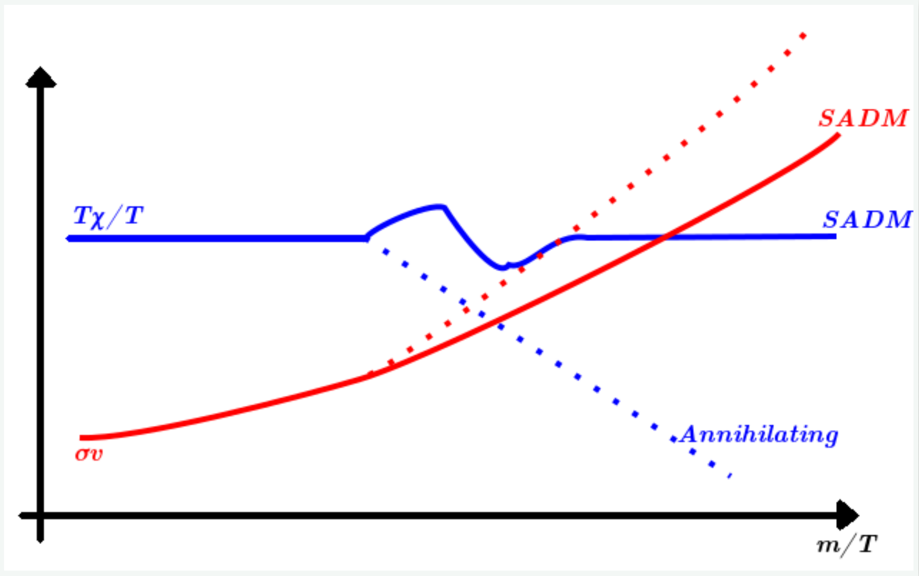
- Does dark partner scatter before decaying?
  Do we need to track dark partner temperature?

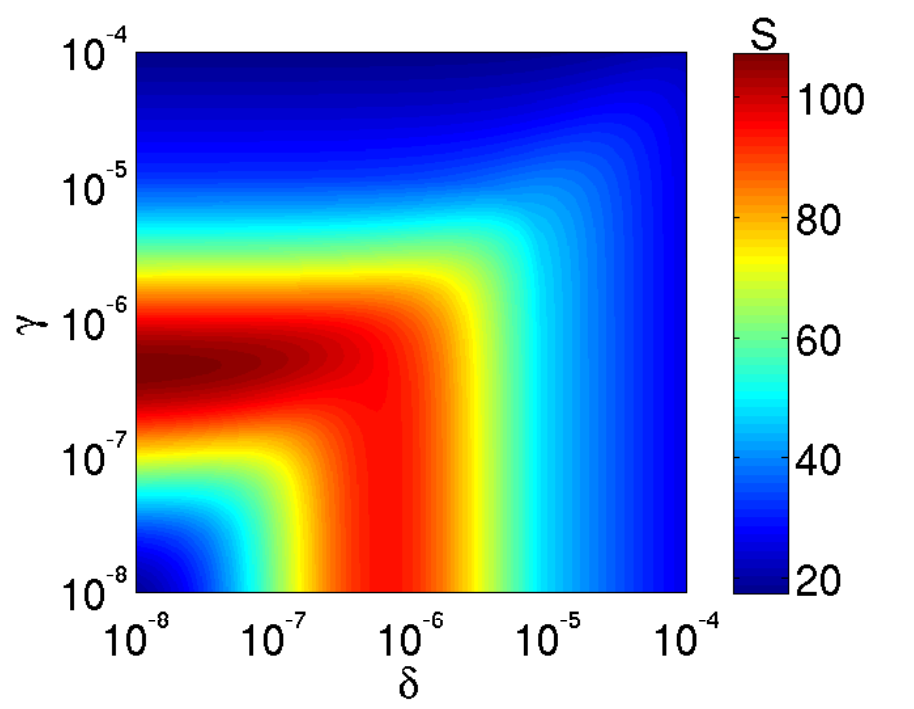
$$\frac{dy_\chi}{dx} \supset \frac{1}{xHZ}\left\langle \frac{p_\chi^2}{3E_\chi T_\chi}\right\rangle \Gamma_\Psi \left(\frac{Y_\Psi}{Y_\chi} - \frac{Y_\Psi^{eq}}{Y_\chi^{eq}} \mathcal{D}_\mathcal{T}(T, T_\chi)\right)$$

- General conclusion is unchanged

$T_\chi \propto T$ in far IR

- SADM vs annihilating DM with low-temperature enhancements:
  - Warmer at late times
  - Smaller rates after kinetic decoupling
  - Relic density for larger couplings
  - Larger possible signals today
- Annihilating DM max signal ~100 times thermal cross section
- What about SADM?

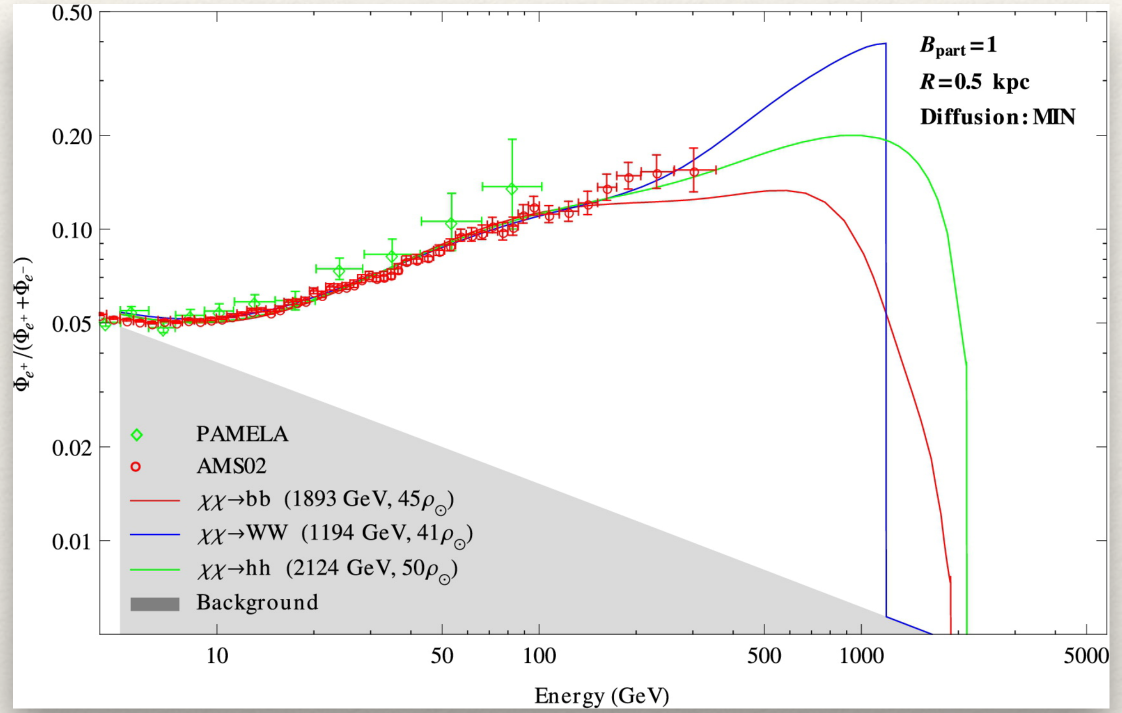




Bi, Yin & Yuan, 1106.6027

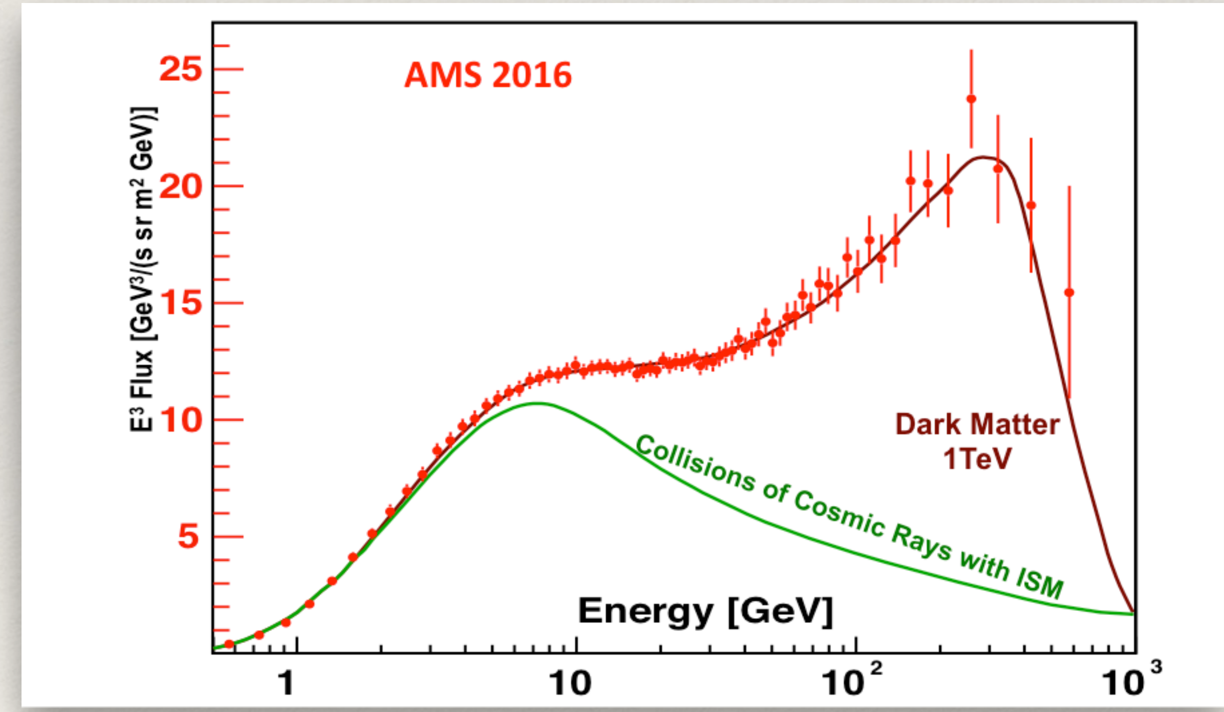
Case Study: AMS-02

- Positron anomaly
  - Old excess in e^+ at E > 10 GeV
  - AMS-02 most recent, best precision
  - Could be astrophysics, esp. pulsars (HAWC observations of Geminga)



- Particle DM explanations:
  - Dominantly produce leptons (no antiproton excess)
  - Direct e^+ typically a poor fit
  - Need large cross sections

$$\sigma \sim 10^3\,\mathrm{pb}$$

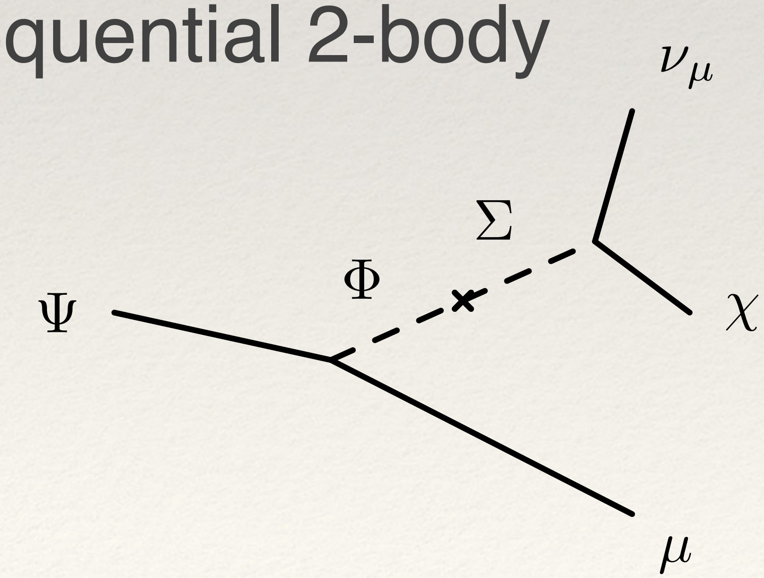


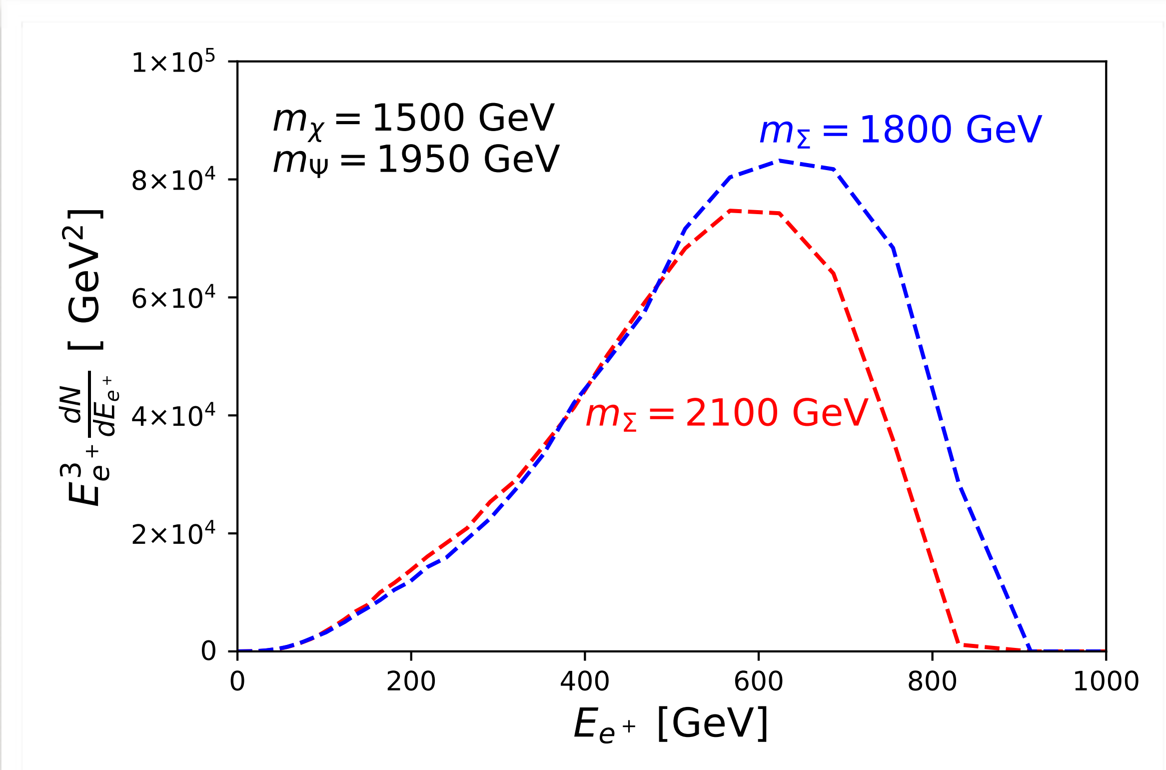
- Simplified model

$$\mathcal{L} \supset y_\chi \, \Phi \, \bar{\chi}^c \gamma^5 \chi + y_\Psi \, \Phi \, \bar{\Psi} \mu_R + y_\Sigma \, \Sigma \, \bar{\chi} L_\mu + h.c.$$

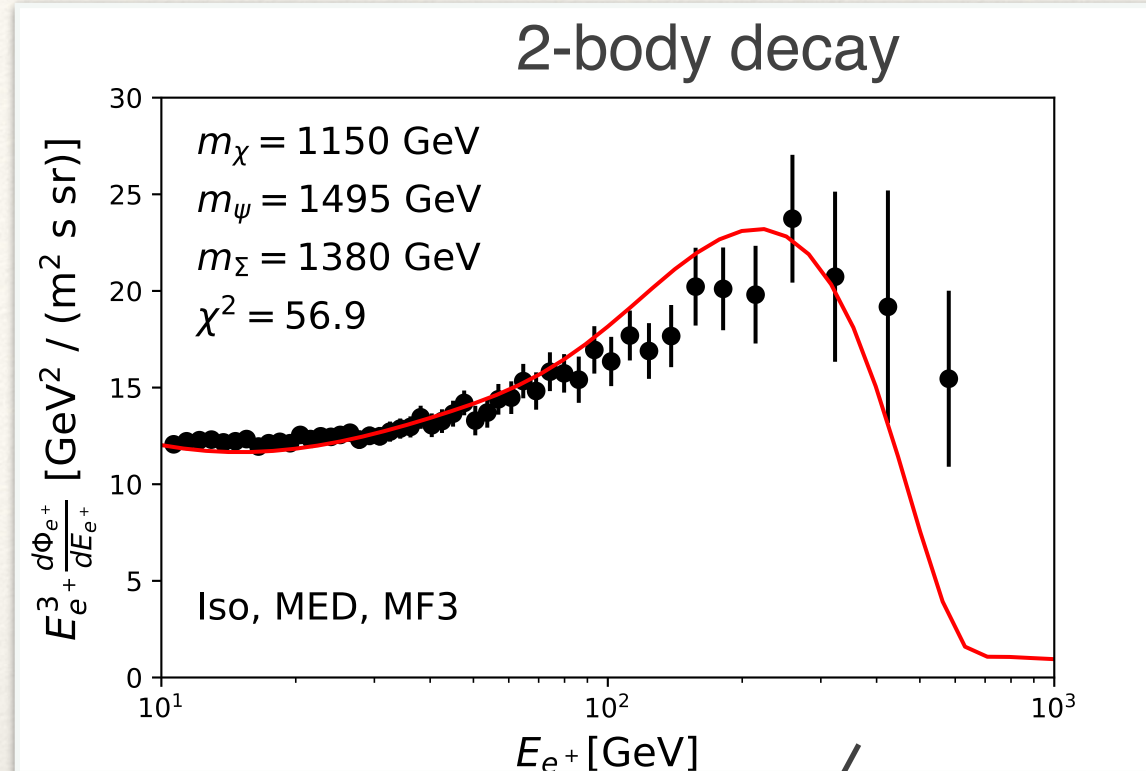
DM Semi-annihilation — Resonance decay — Scattering

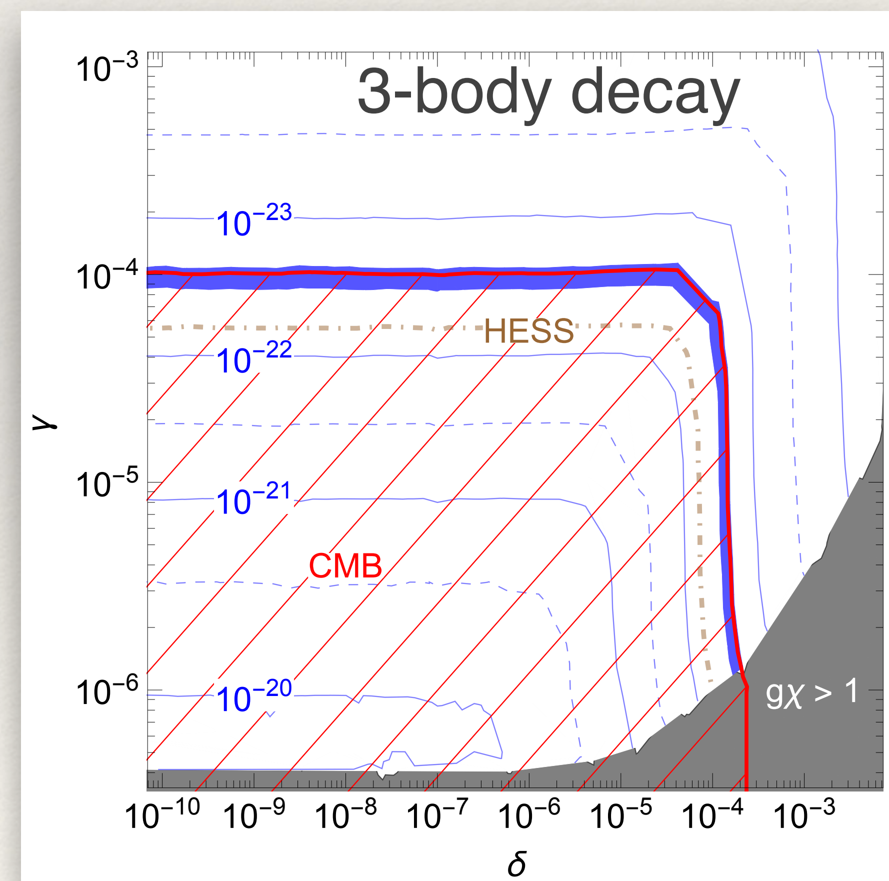
- Coupling structure could derive from $U(1)_{L\mu - L\tau}$
- Two dark partner decay modes:
  - Direct 3-body
  - Sequential 2-body

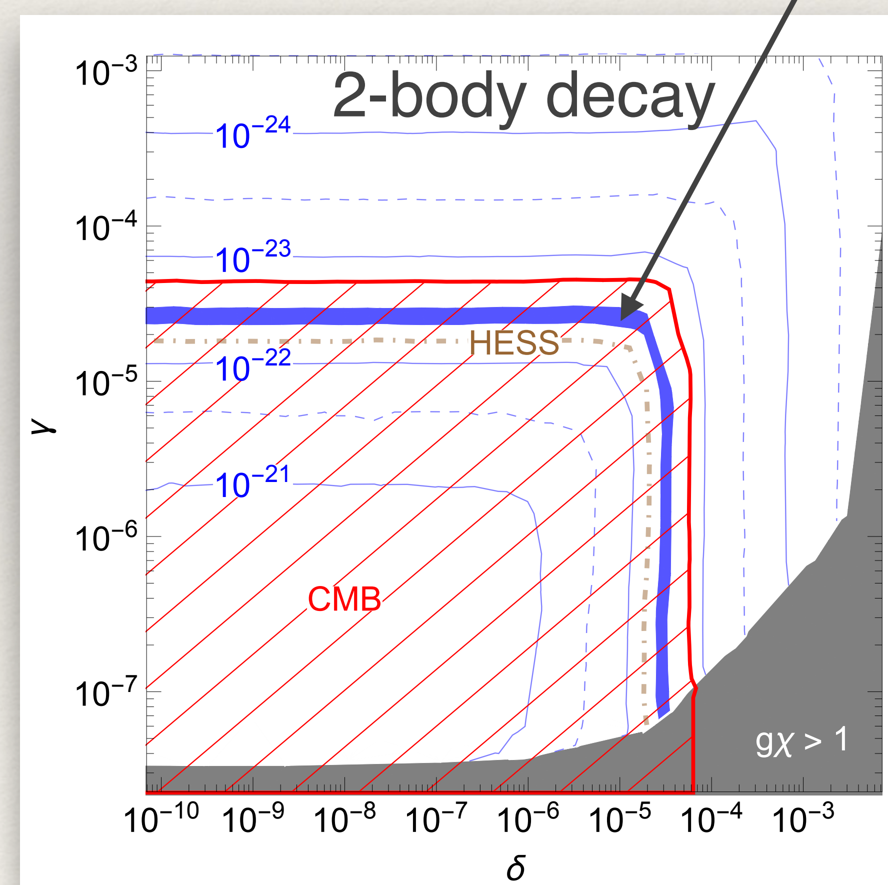




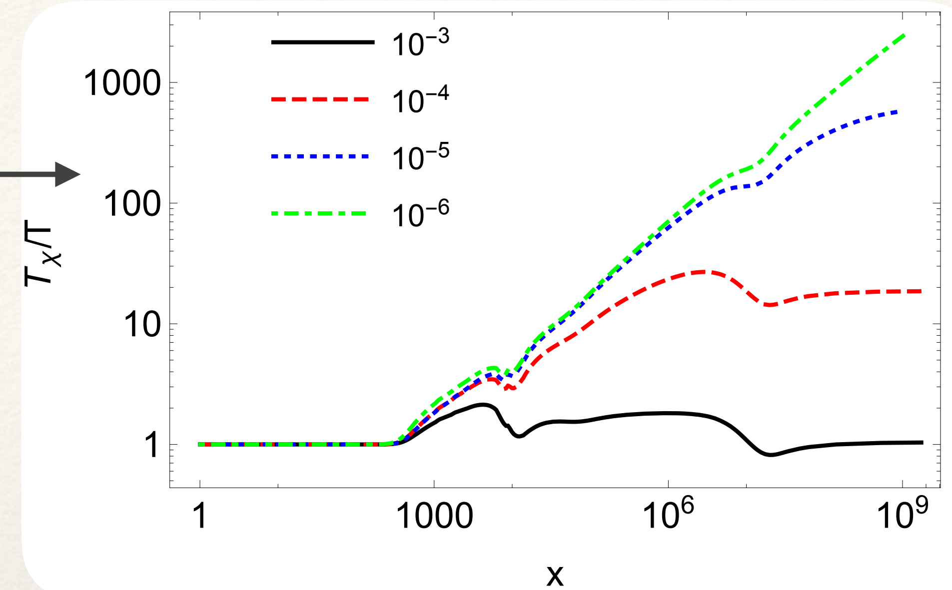
- Can fit excess well, though constrained by CMB
- Very large signals possible
  - 10^5 enhancement consistent with relic density
  - Smaller enhancement requires less tuning of parameters

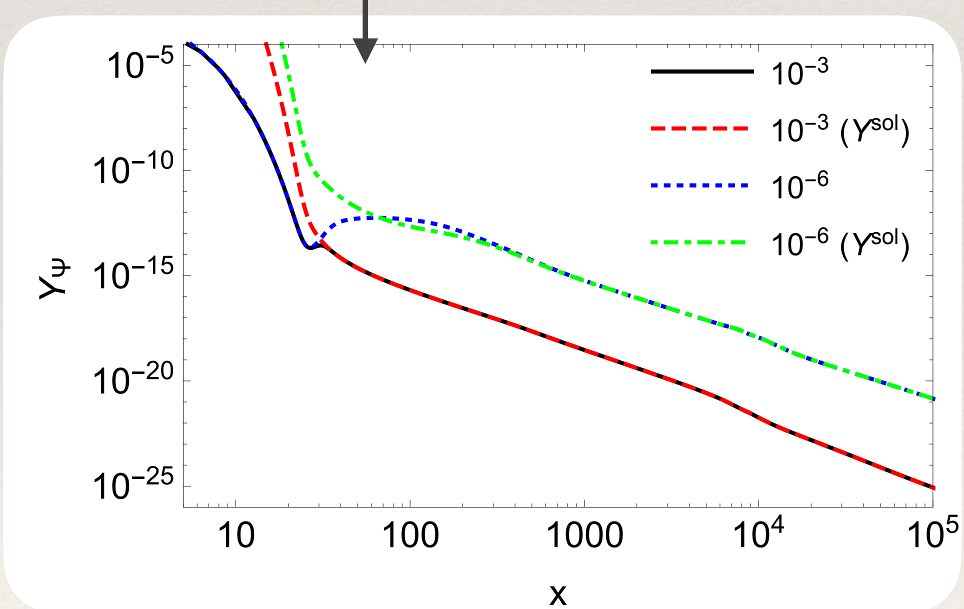


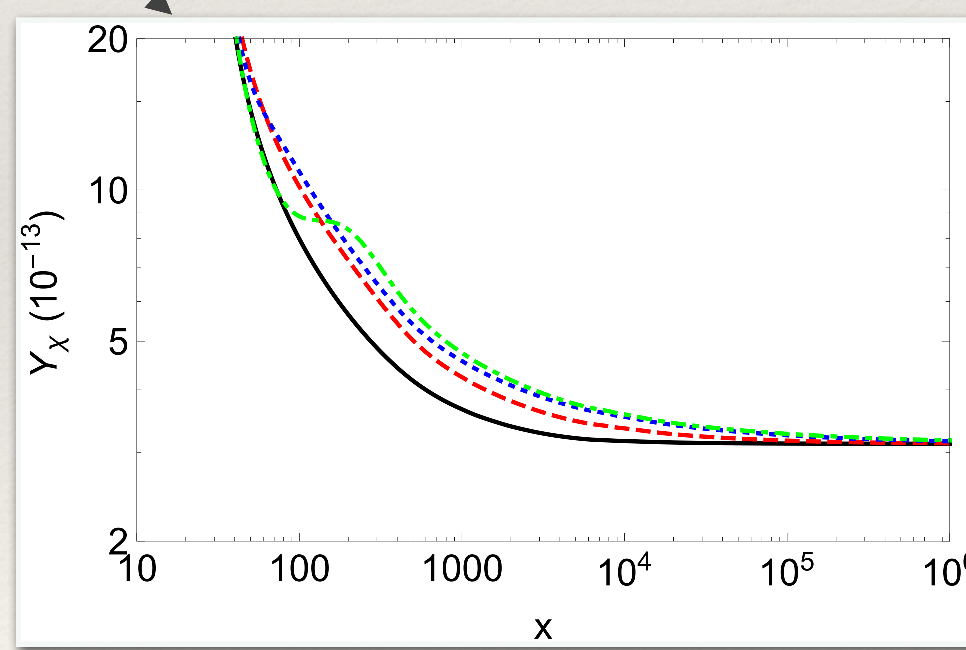




- T_χ is (eventually) proportional to T
- DM much hotter than SM
- SA effective till $x \sim 10^6$
- Dark partner tracks approximate solution quickly







Conclusions

- Semi-annihilation is a generic feature of dark matter stabilised by any symmetry other than a $\mathbf{Z}_2$
- It eases the bounds from colliders and direct detection
- Cosmic ray observations are relevant, motivating models where SA today is enhanced
- All SADM models redshift like radiation, $T_\chi \sim T$, in far IR
- Warmer DM allows signal enhanced by up to 10^5, much greater than possible for annihilating DM
- We have used this to explain AMS-02 positron excess

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