Non-Abelian Discrete Dark Matter

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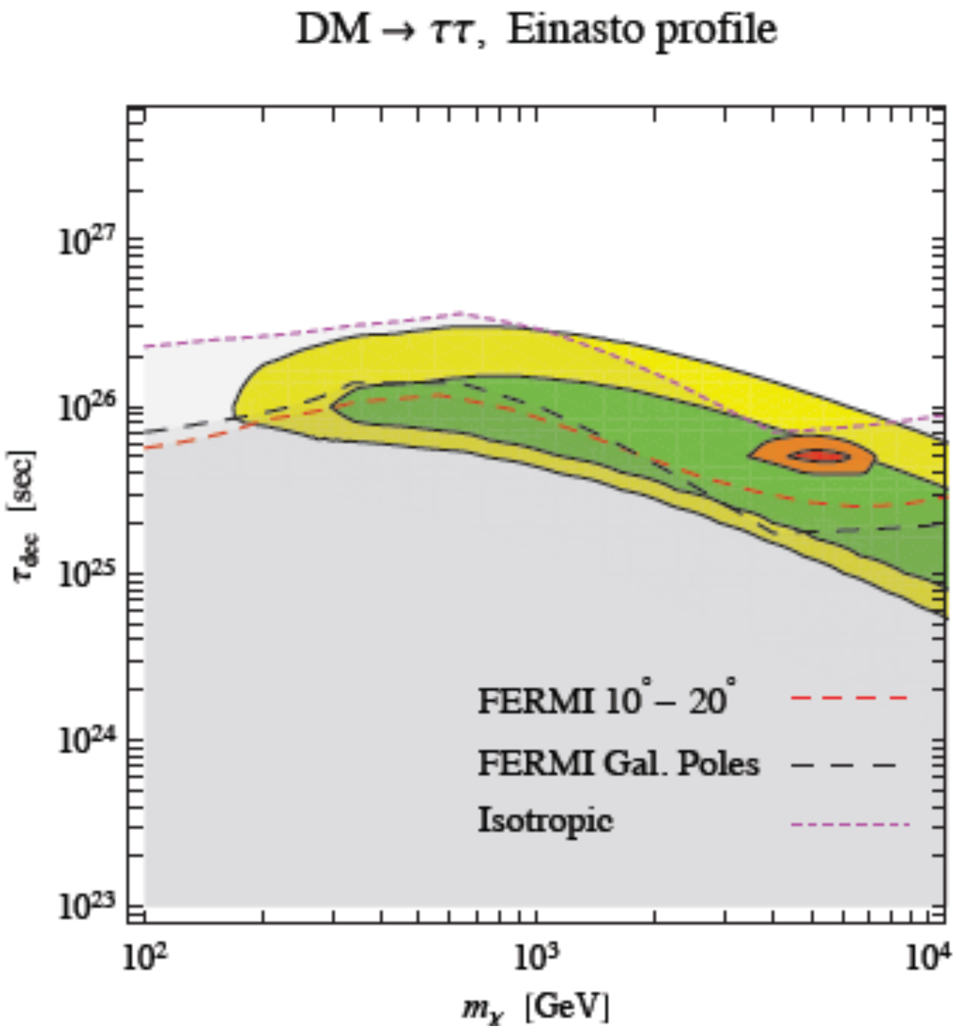
PONT Avignon

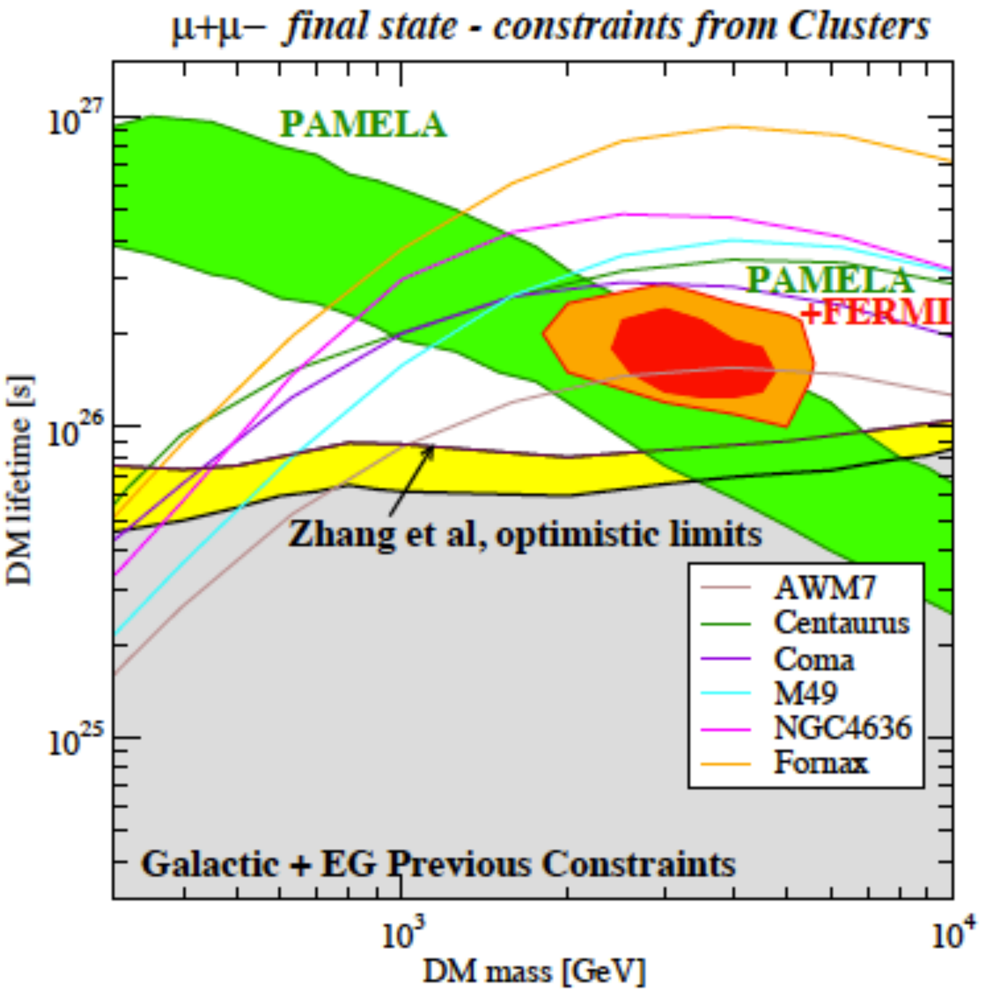
a (relatively) robust fact on dark matter

- DM stable on cosmological time-scales: $\tau_{DM} \gtrsim H_0^{-1} = \mathcal{O}(10^{17}\,\mathrm{s})$

  - if decays accompanied by Standard Model radiation: $\tau_{DM} \gtrsim \mathcal{O}(10^{26}\,\mathrm{s})$



[Cirelli, Panci, Di Serpico, 2009]



[Dugger, Jeltema, Profumo, 2010]

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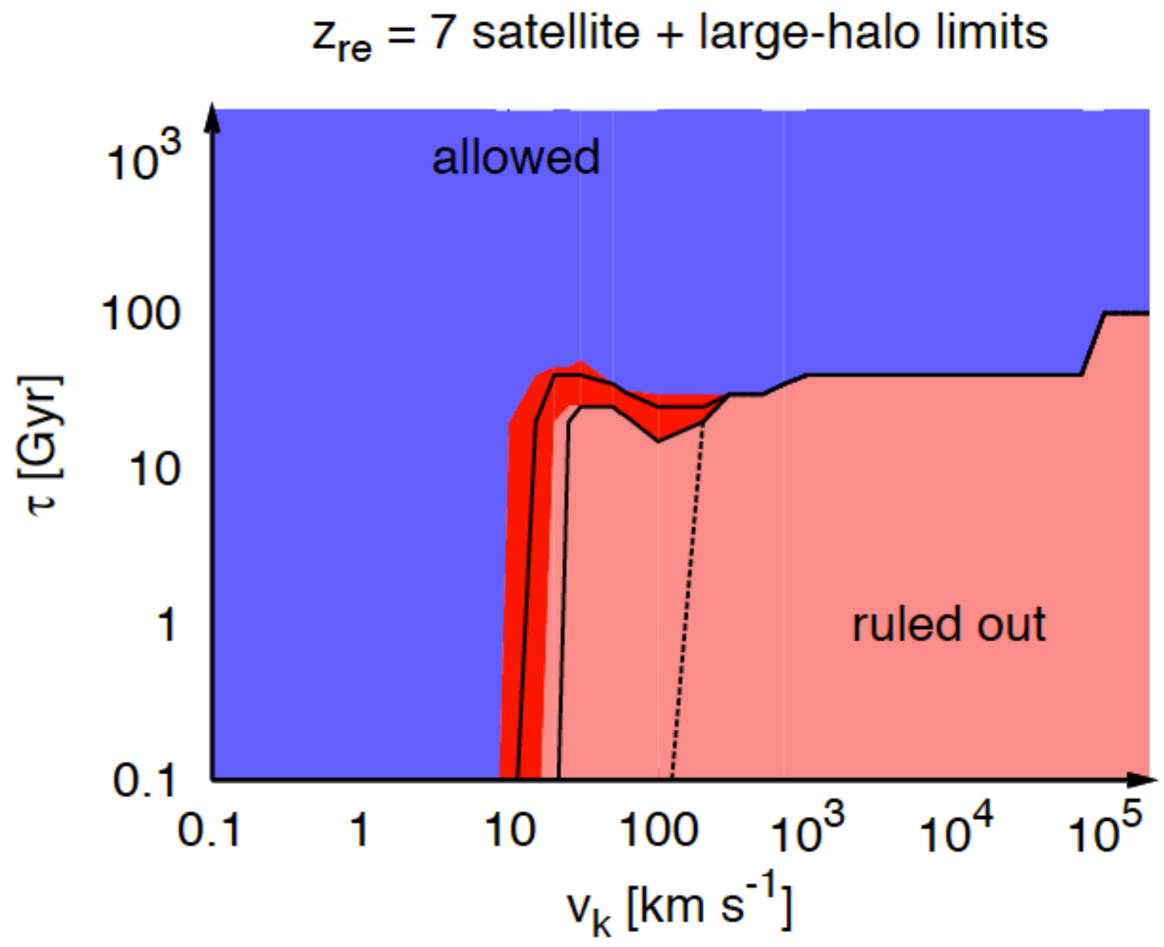
  - "dark decays" disrupt halos and influence on the number of Milky Way satellite galaxies

$$m_2 = m_1(1-\epsilon)$$

$$v_k \sim \epsilon$$



[Peter, Benson, 2010]

Dark Matter stabilization

...whatever can decay, will - unless protected by symmetry...

canonical way to stabilize a species against decay to SM:

=> introduce parity between SM and Dark states

R-parity, KK-parity, T-parity, ...

Z_2

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worthwhile exploring other symmetries

new states

new interactions

new phenomenology

Abelian vs. non-Abelian finite groups

#group elements	Abelian	non-Abelian
2	Z_2	-
3	Z_3	-
4	$Z_4, Z_2 \otimes Z_2$	-
5	Z_5	-
6	Z_6	D_3
7	Z_7	-
8	$Z_8, Z_4 \otimes Z_2, Z_2^{\otimes 3}$	D_4, Q_8
...	...	...

↑

general case Z_N: [Batell, 2009]

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=> construct the minimal model respecting this symmetry

non-Abelian discrete symmetries for DM in the literature*

- additional Higgs doublet in a $\underline{5}$ representation of a non-Abelian discrete group (DM + improved gauge coupling unification) [Lisanti, Wacker, 2007]

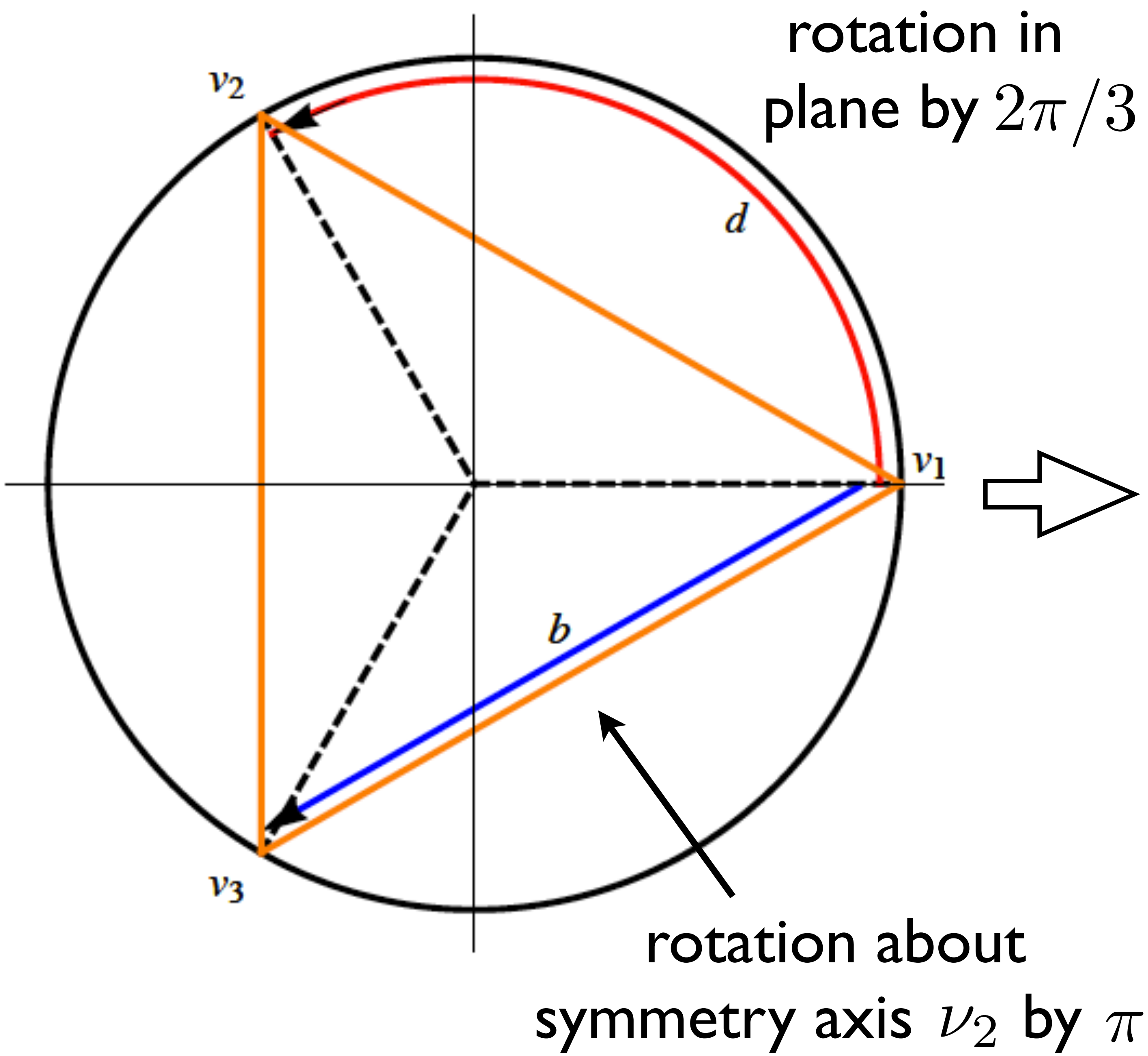
- non-Abelian discrete symmetries may lead to distinct decay patterns in *decaying* DM scenarios [Haba et al, 2010; Kajiyama, Okada, 2010]

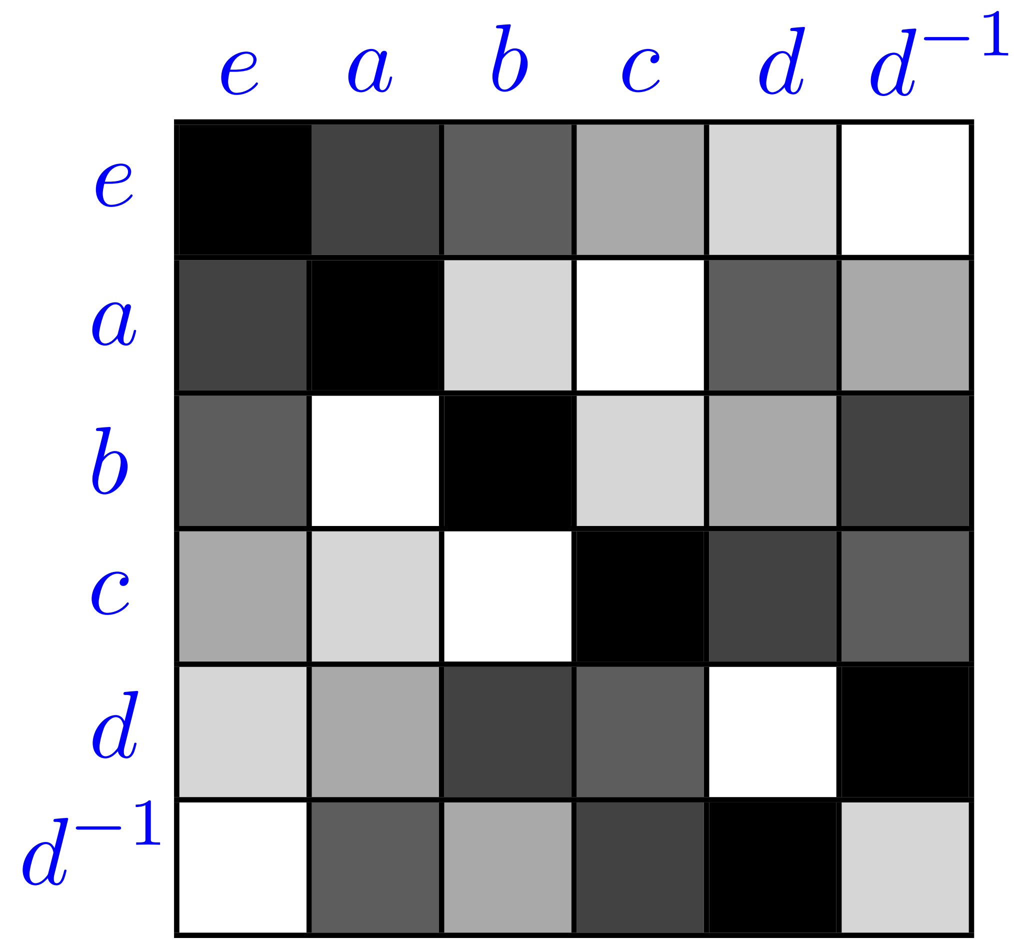
- *Abelian* discrete symmetries descending from higher non-Abelian ones can also stabilize DM e.g. [Walker, 2009]

* incomplete list

Dihedral group D_3 :

- symmetries of equilateral triangle in 3D





$D_3 \cong S_3$

Dihedral group D_3 :

- **Generators** acting on the edges of the triangle:

  - cyclic rotations Z_3: $A^3 = 1$
  - reflections Z_2: $B^2 = 1$

$$\left. \begin{array}{l} A^3 = 1 \\ B^2 = 1 \end{array} \right\} \quad ABA = B$$

- **Representations**

  - (trivial) Singlet $\underline{\mathbf{1}}_{\mathbf{1}}$: $A = B = 1$
  - non-trivial Singlet $\underline{\mathbf{1}}_{\mathbf{2}}$: $A = 1,\ B = -1$
  - doublet $\underline{\mathbf{2}}$:

$$A = \begin{pmatrix} e^{2\pi i/3} & 0 \\ 0 & e^{-2\pi i/3} \end{pmatrix}, \quad B = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}.$$

Minimal model - field content and Lagrangian

- singlet (real scalar) $\eta \sim \underline{\mathbf{1_2}}$
- complex scalar doublet $X = \begin{pmatrix} \chi \\ \chi^* \end{pmatrix} \sim \underline{\mathbf{2}}$
- most general scalar potential invariant under D_3:

$$\begin{aligned} V_{DM} &= \frac{1}{2}m_2^2\eta^2 + m_3^2\chi^*\chi + \frac{\mu_1}{3!}(\chi^3 + {\chi^*}^3) \\ &+ \frac{\lambda_2}{4}\eta^4 + \lambda_3(\chi^*\chi)^2 + \alpha_3\eta^2(\chi^*\chi) \\ &+ \frac{i\alpha_4}{3!}\eta(\chi^3 - {\chi^*}^3) \end{aligned}$$

$$V_{DM\leftrightarrow SM} = \alpha_1\eta^2(H^\dagger H) + 2\alpha_2(\chi^*\chi)(H^\dagger H)$$ (Higgs portal)

$$V = V_{DM} + V_{DM\leftrightarrow SM} + V_H$$

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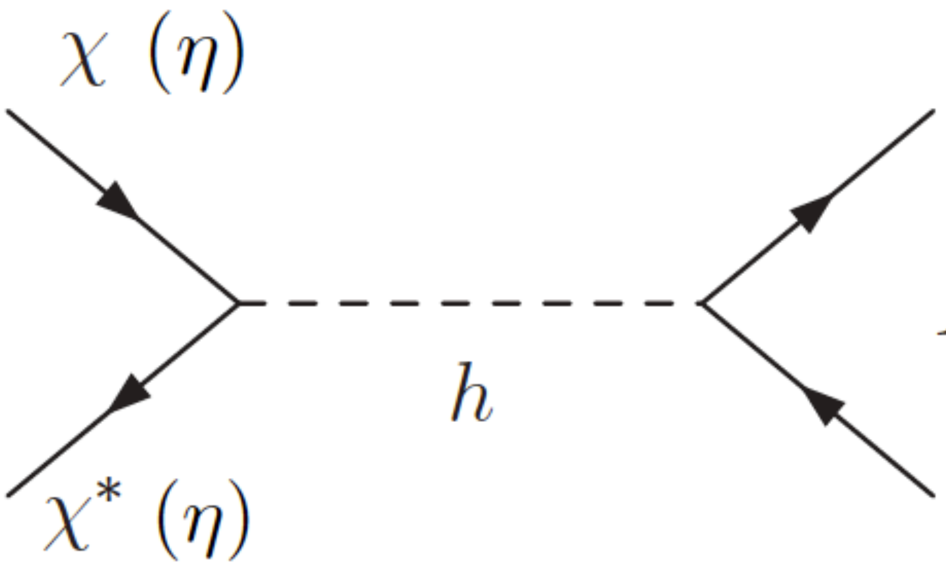
Generic feature of higher stabilization symmetries:

multi-component dark matter

- this talk: on the example of D_3 look at
  - Cosmology
  - direct detection signals

The Higgs portal to the relic abundance

- familiar process: Annihilation to SM through Higgs

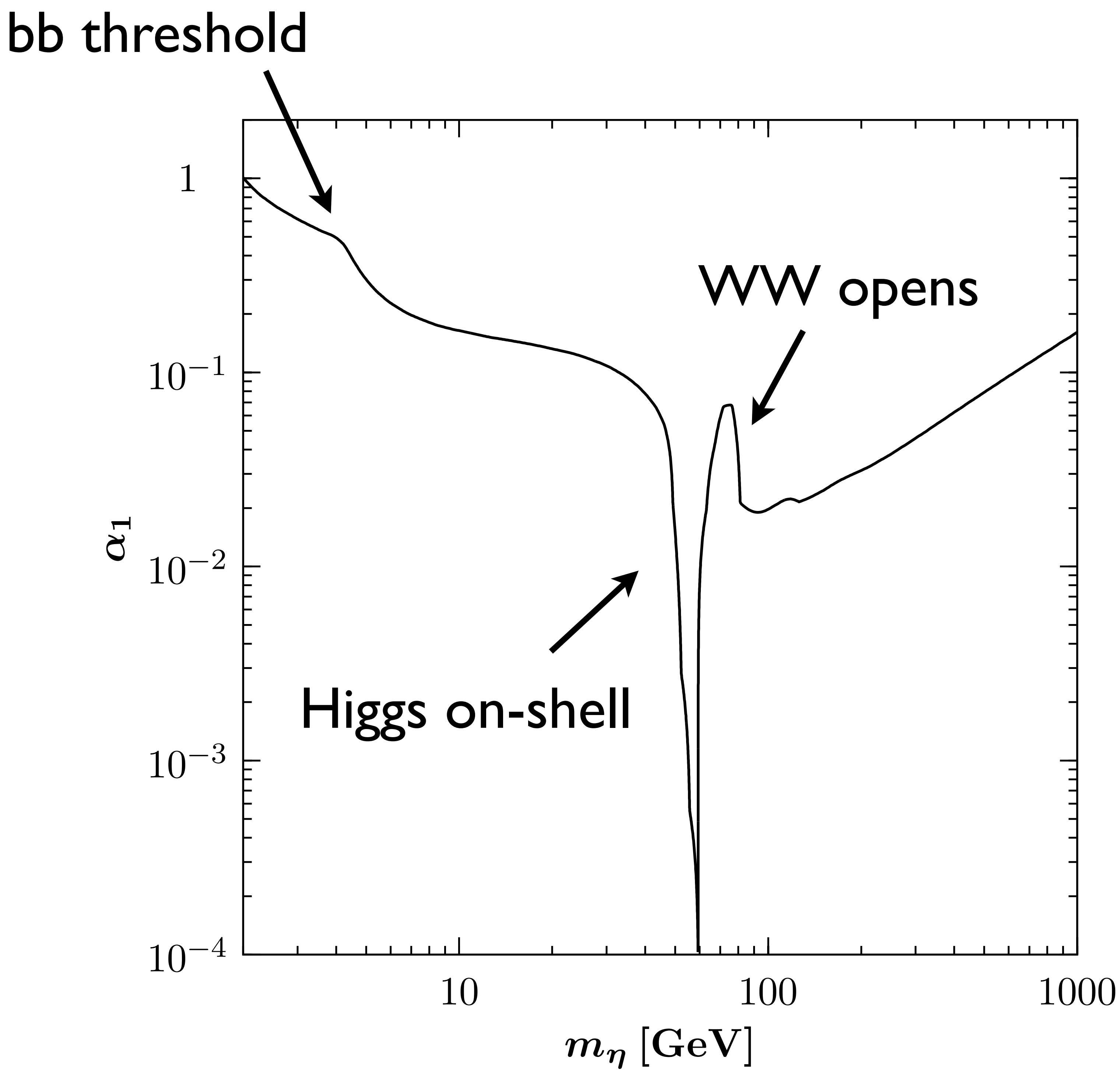


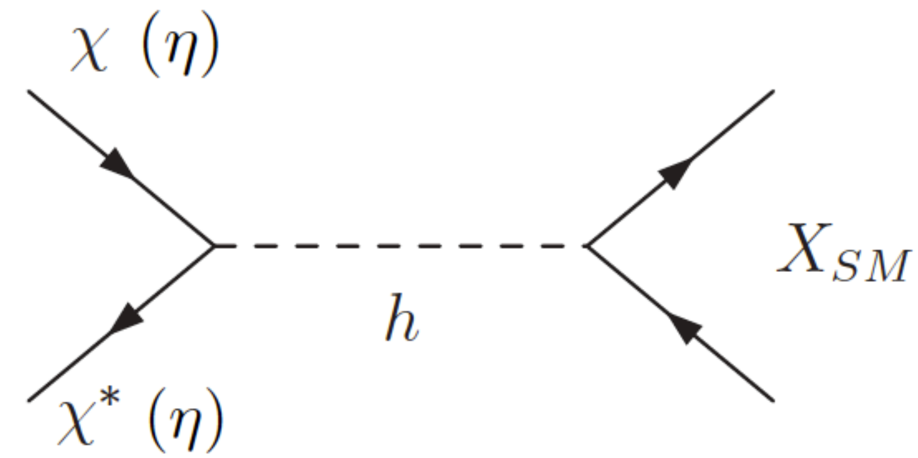
$$X_{SM} = t\bar{t}, hh, ZZ, WW, b\bar{b} \ldots$$

$$\langle \sigma v \rangle_{ii \to X_{SM}} \simeq \frac{4\alpha_i^2 v^2}{(4m_i^2 - m_h^2)^2 + m_h^2 \Gamma_h^2} \times \frac{\Gamma_{h^* \to X_{SM}}(m_{h^*} = 2m_i)}{m_i},$$

e.g. [Burgess, Pospelov, ter Veldhuis, 2000]

The Higgs portal to the relic abundance

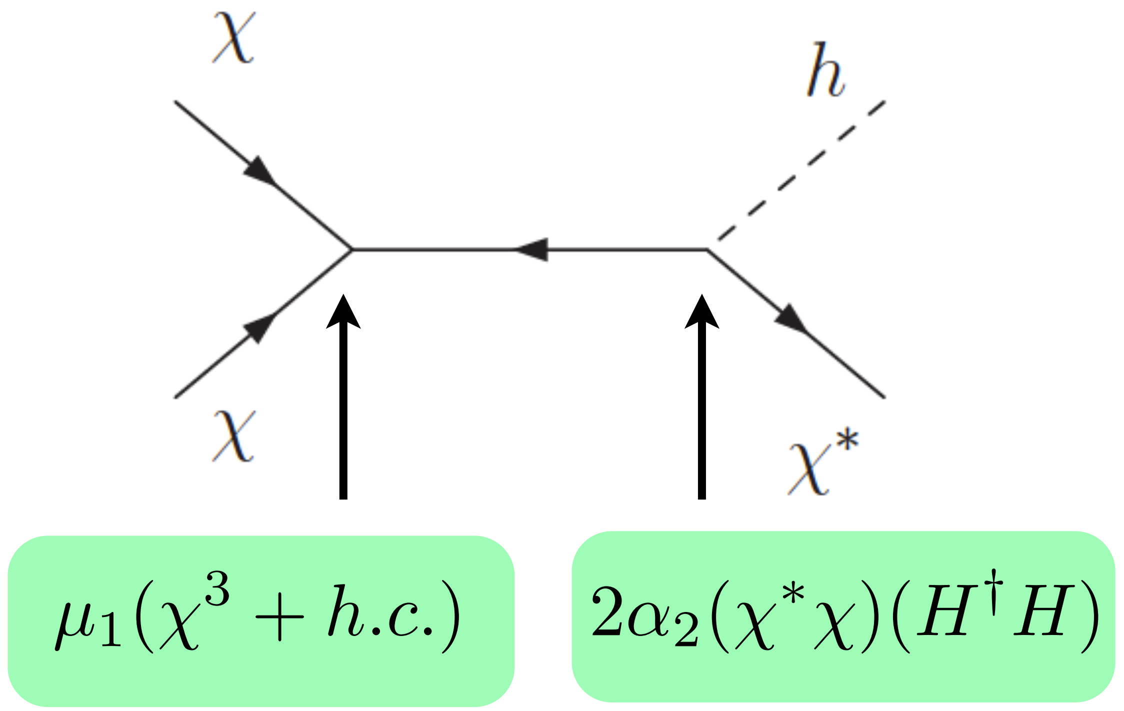


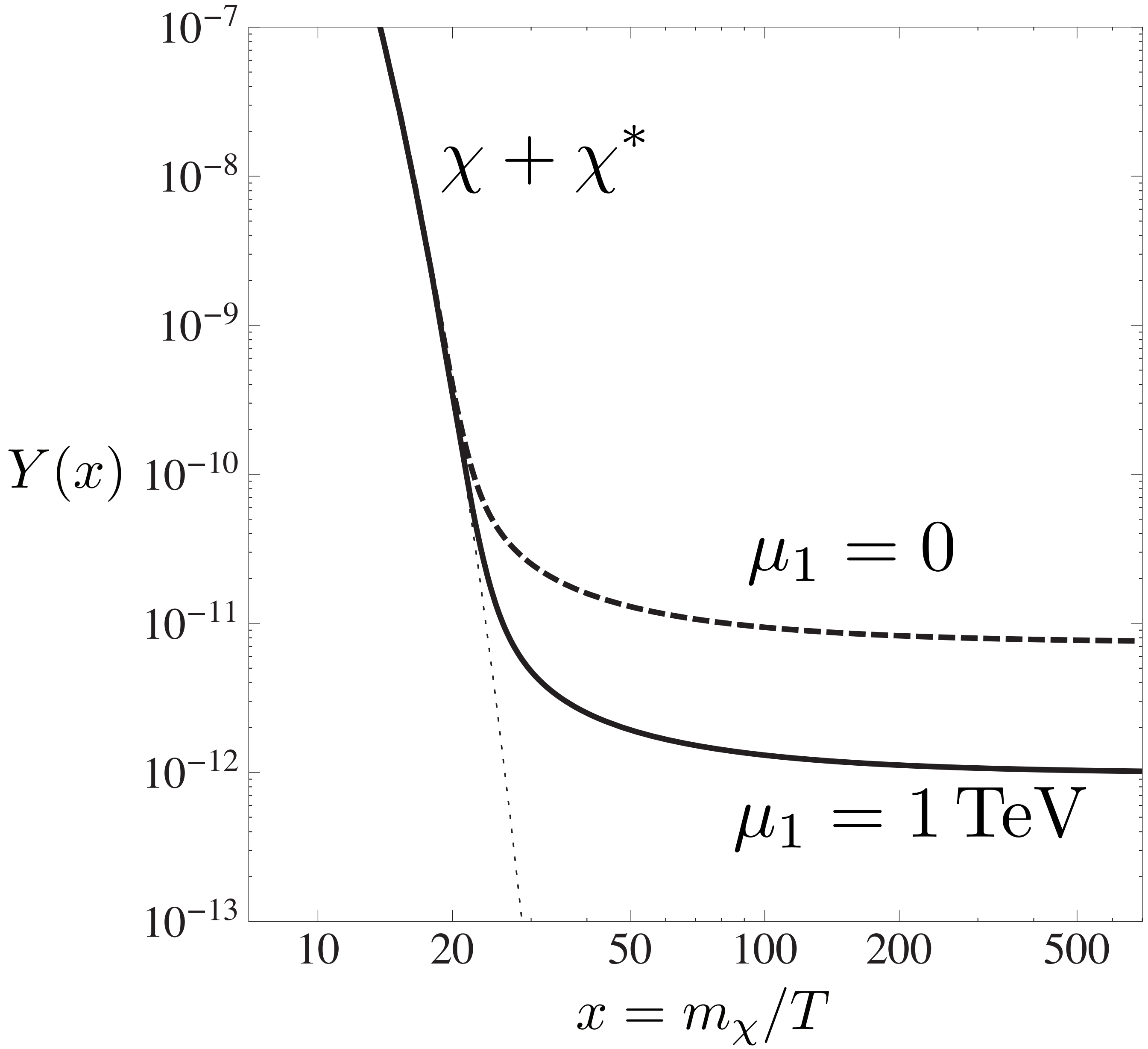


$$m_h = 120\,\mathrm{GeV}$$

=> Higgs portal couplings have to be sizable

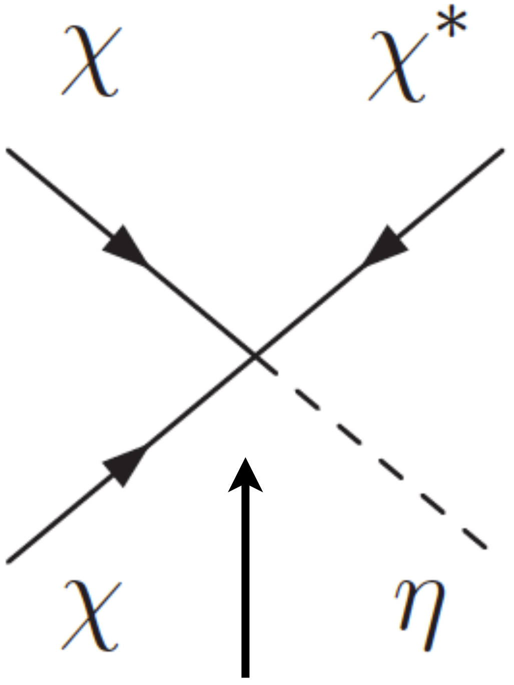
Semi-annihilation



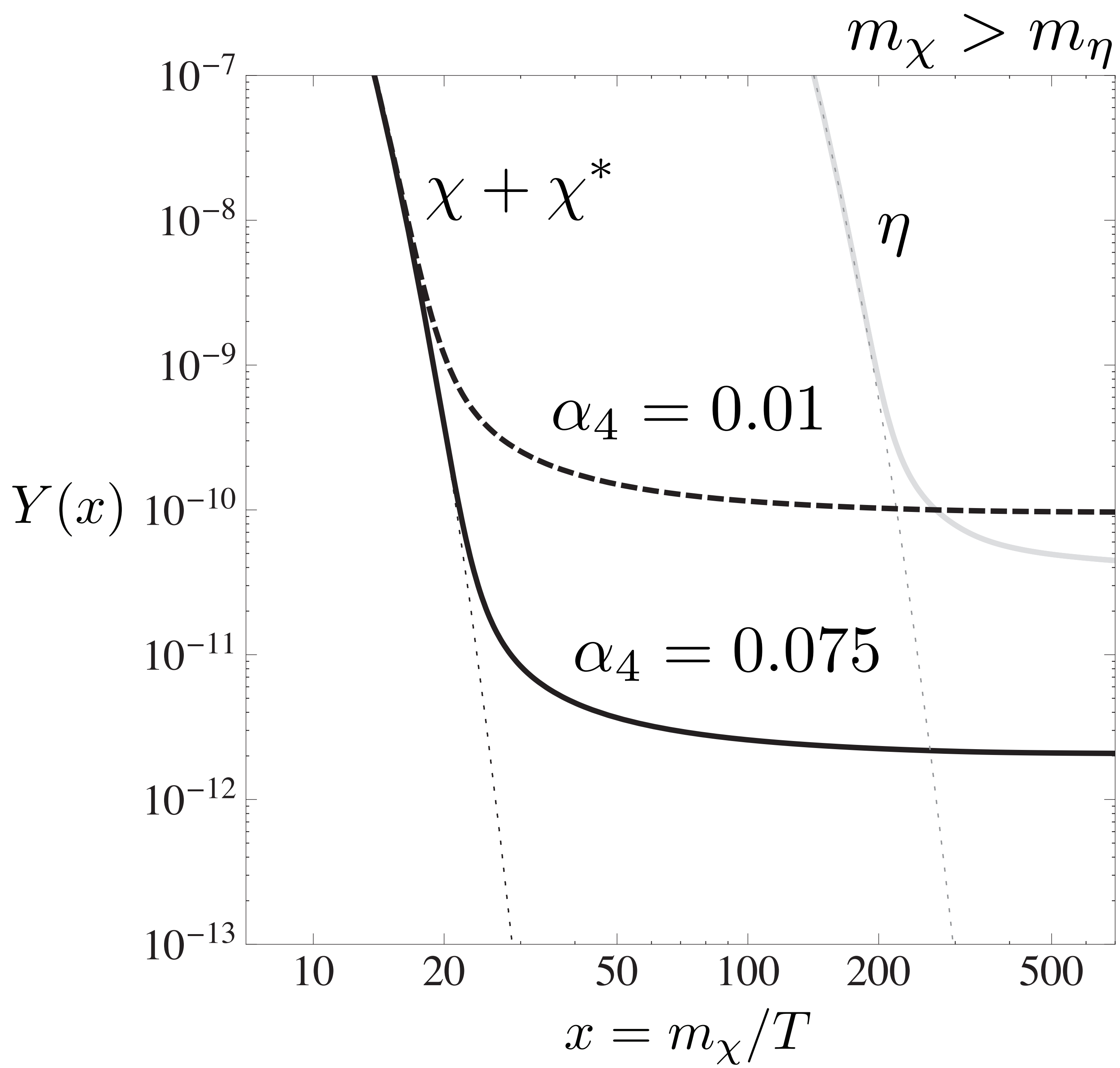


see also [Hambye, 2009; D'Eramo, Thaler 2010]

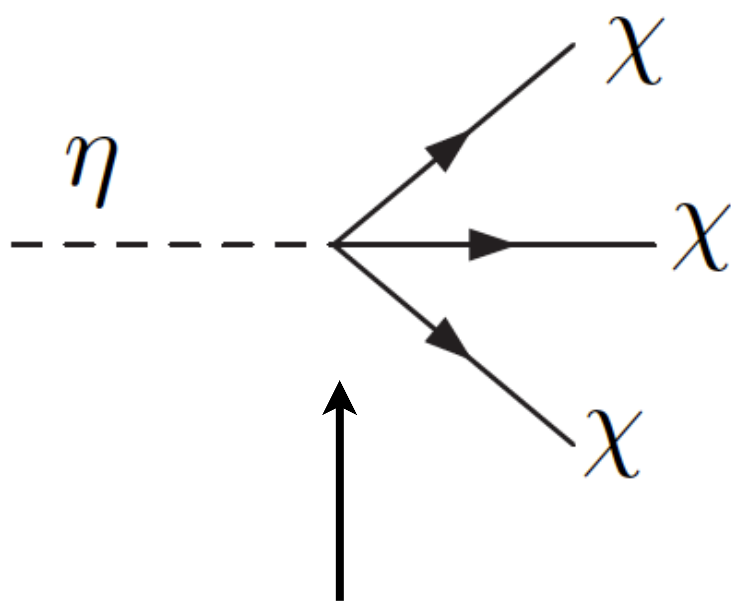
Dark Matter conversion



$$i\alpha_4\eta(\chi^3 - \chi^{*3})$$



Late Decays $\tau_\eta > t_{\mathrm{f},\eta}$



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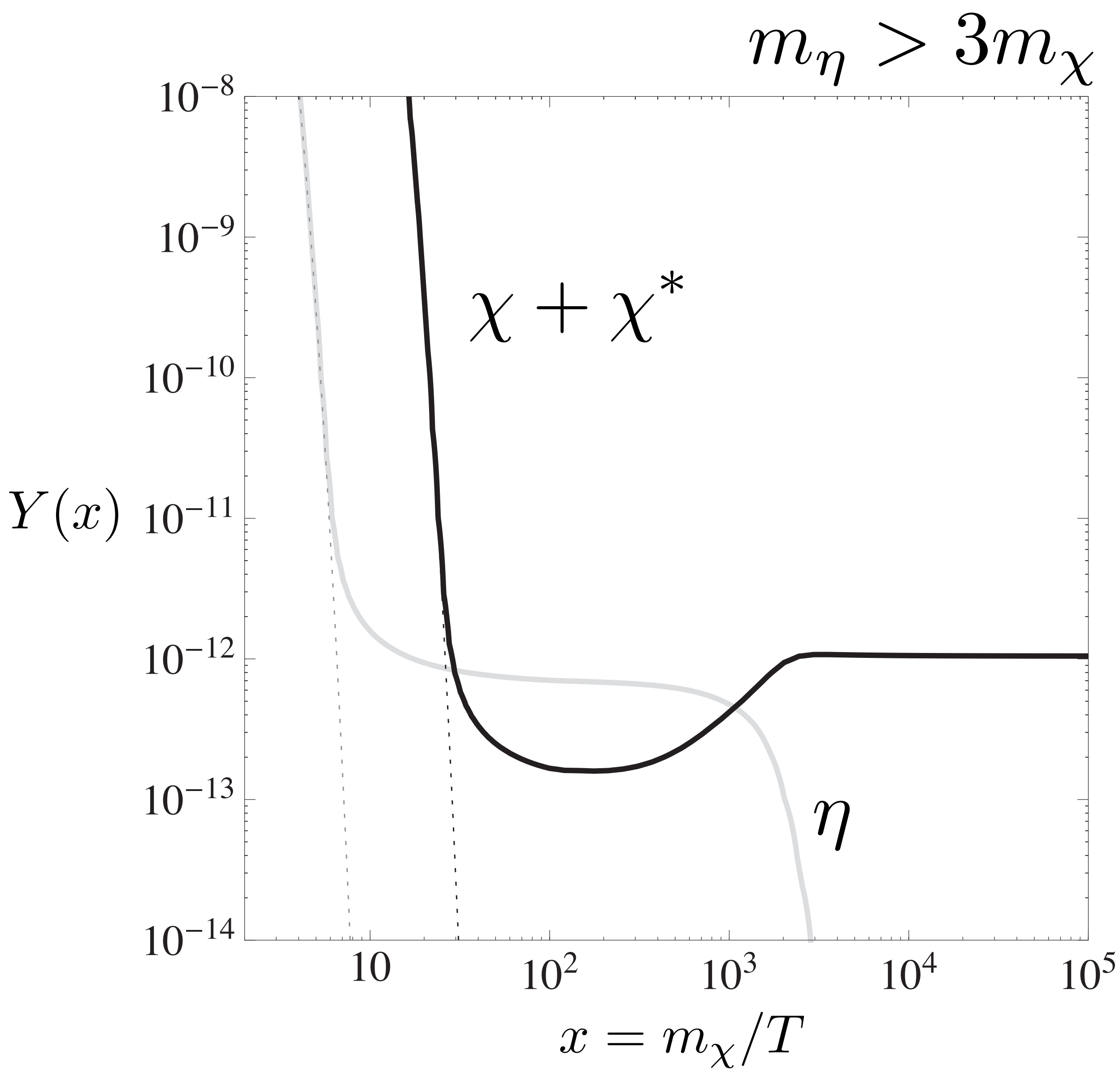
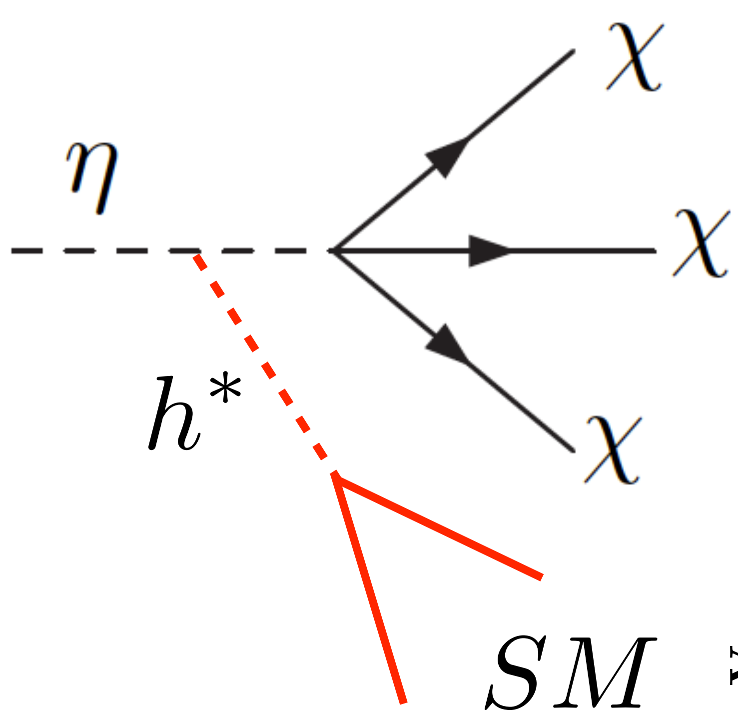
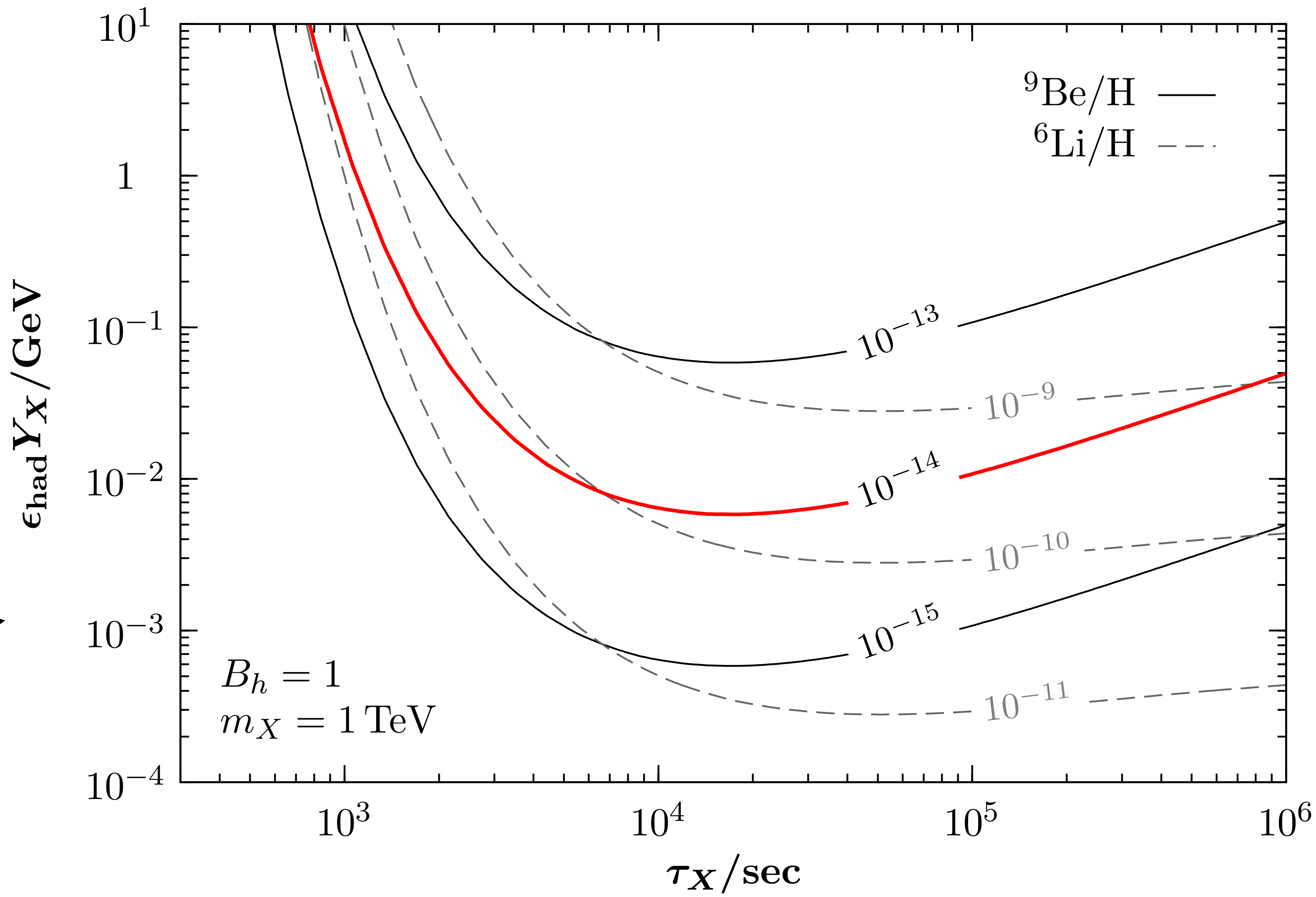


$$\tau_\eta \simeq 10^{-8}\,\mathrm{s} \times \left(\frac{10^{-7}}{\alpha_4}\right)^2 \left(\frac{100\,\mathrm{GeV}}{m_\eta}\right) \qquad (m_\eta \gg 3m_\chi)$$

Late Decays $\tau_\eta > t_{f,\eta}$



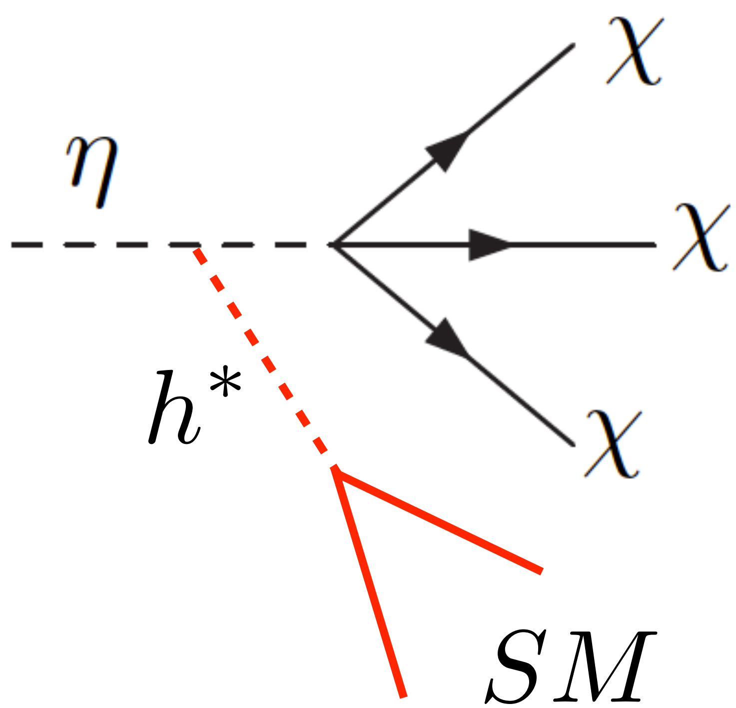
- Scenario cosmologically constrained
- Potential energy injection during BBN



- BBN can probe few MeV/baryon visible energy!

for recent work see e.g. [Pospelov, JP, 2010]

Late Decays $\tau_\eta > t_{\mathrm{f},\eta}$

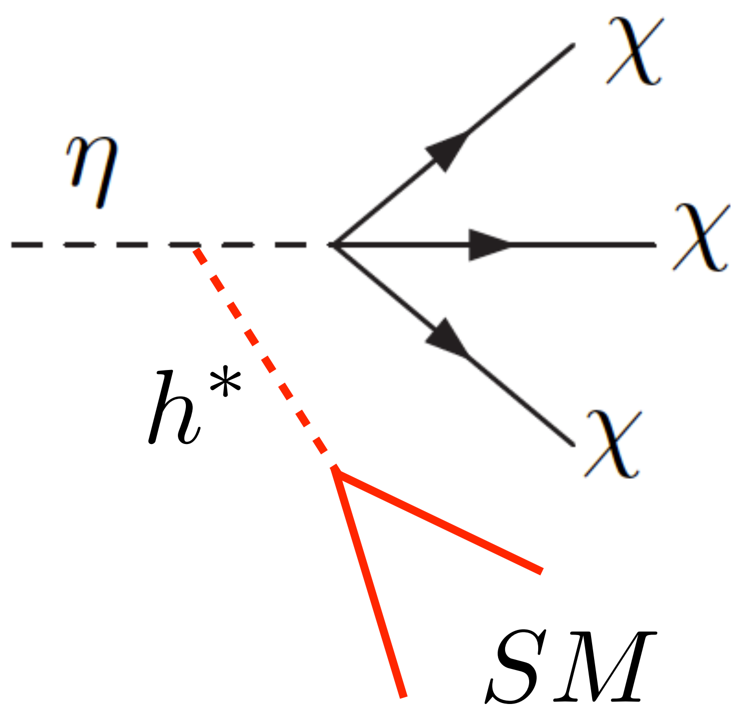


- simple solution:

$$\tau_\eta < 1\,\mathrm{s} \qquad \text{for} \qquad |\alpha_4| \gtrsim 10^{-11}\sqrt{100\,\mathrm{GeV}/m_\eta}$$

- also avoids potential free streaming constraints

Late Decays $\tau_\eta > t_{\mathrm{f},\eta}$



$m_\eta > 3m_\chi$: χ stable

$m_\eta < 3m_\chi$: $\chi + \eta$ stable

- simple solution:

$$\tau_\eta < 1\,\mathrm{s} \quad \text{for} \quad |\alpha_4| \gtrsim 10^{-11}\sqrt{100\,\mathrm{GeV}/m_\eta}$$

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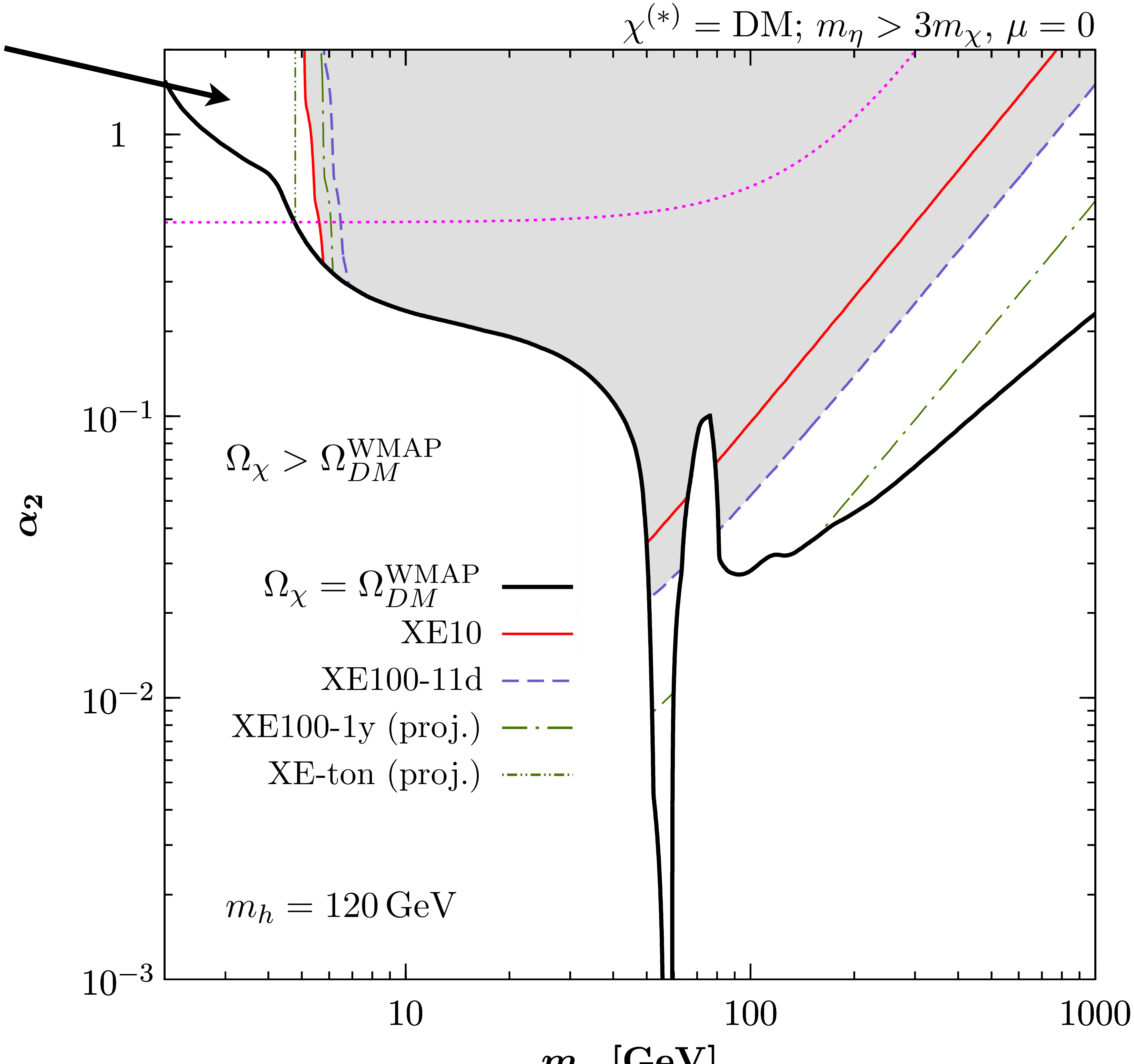
$\chi + \chi^* = DM$

replenish by late η decays

smaller abundances

$\Omega_\chi \propto 1/\alpha_1^2$



multi-component DM $m_\eta < 3m_\chi$

$$\Omega_\eta + \Omega_\chi = \Omega_{DM}$$

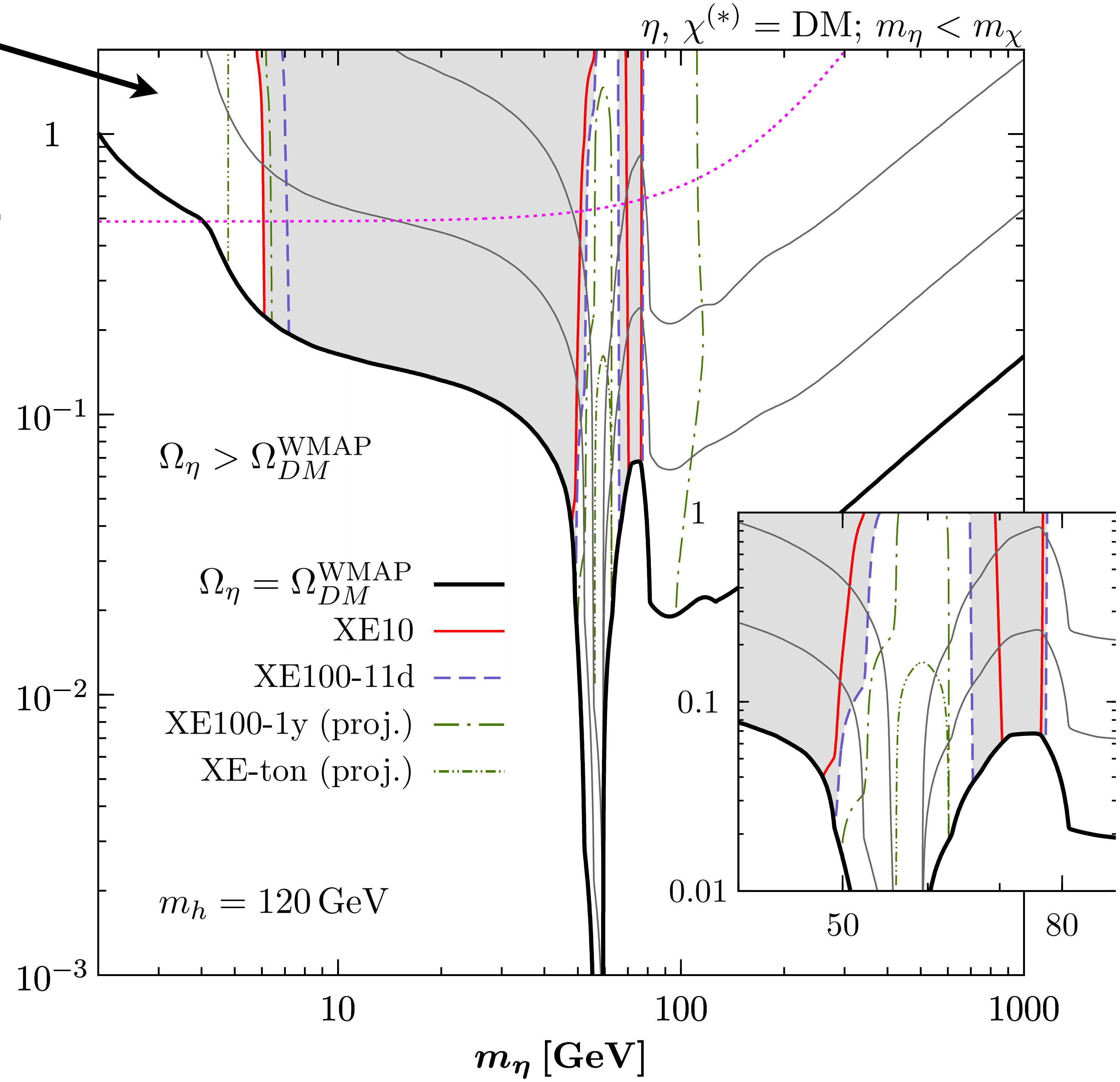
- Strong direct detection constraints independent of fractional η abundance

$$dR_\eta/dE_R \propto \rho_\eta \sigma_n^\eta$$

$$\rho_\eta \propto \alpha_1^{-2}$$

$$\sigma_n^\eta \propto \alpha_1^2$$

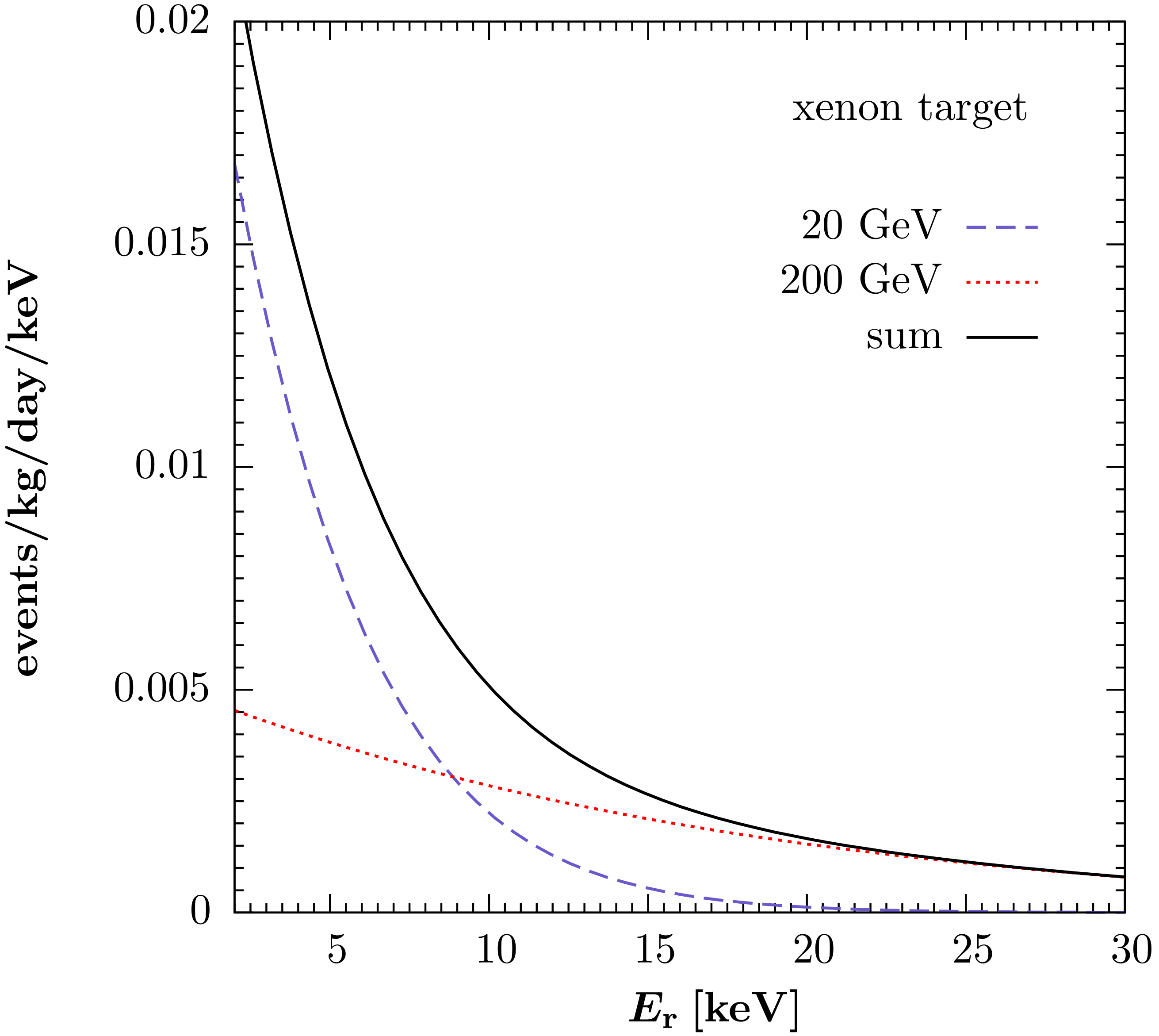
Constraints on η



Two-component DM in direct detection

- Given a solid direct detection signal, how well may we discriminate a single component from a dual one?

  => have to use spectral shape information



this is how it looks like to a theorist

Two-component DM in direct detection

Monte Carlo study

- Simulate a ton-scale Xenon detector

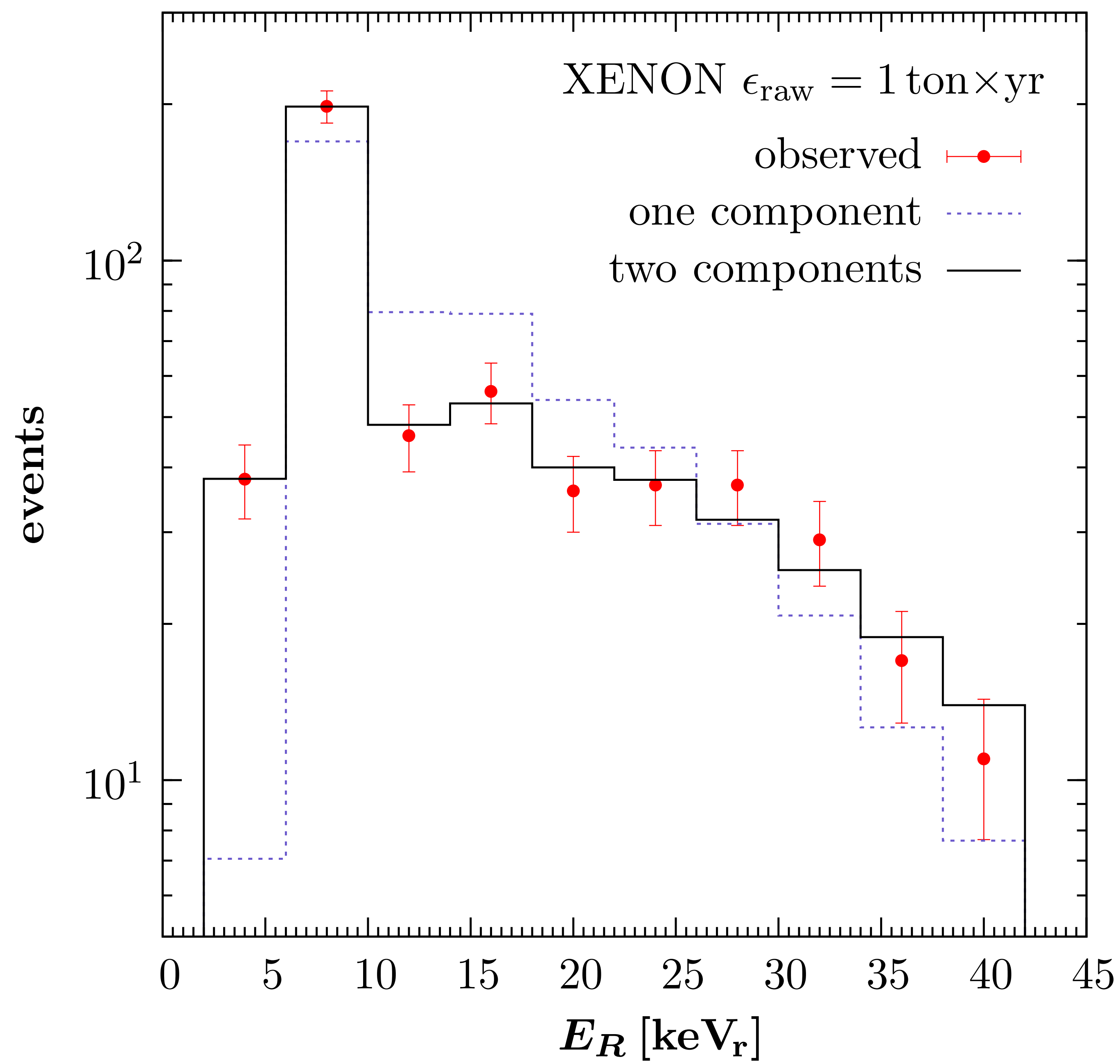
  => employ [Sorensen, 2010] study on detection efficiency and detector resolution for Xenon10 detector

- benchmark point:

$$m_\eta = 5\,\mathrm{GeV} \qquad m_\chi = 200\,\mathrm{GeV}$$

$$\alpha_1 = 0.45 \qquad \alpha_2 = 0.065$$

$$\rho_\eta = \rho_{DM}/2 \qquad \alpha_4 = 0.3$$



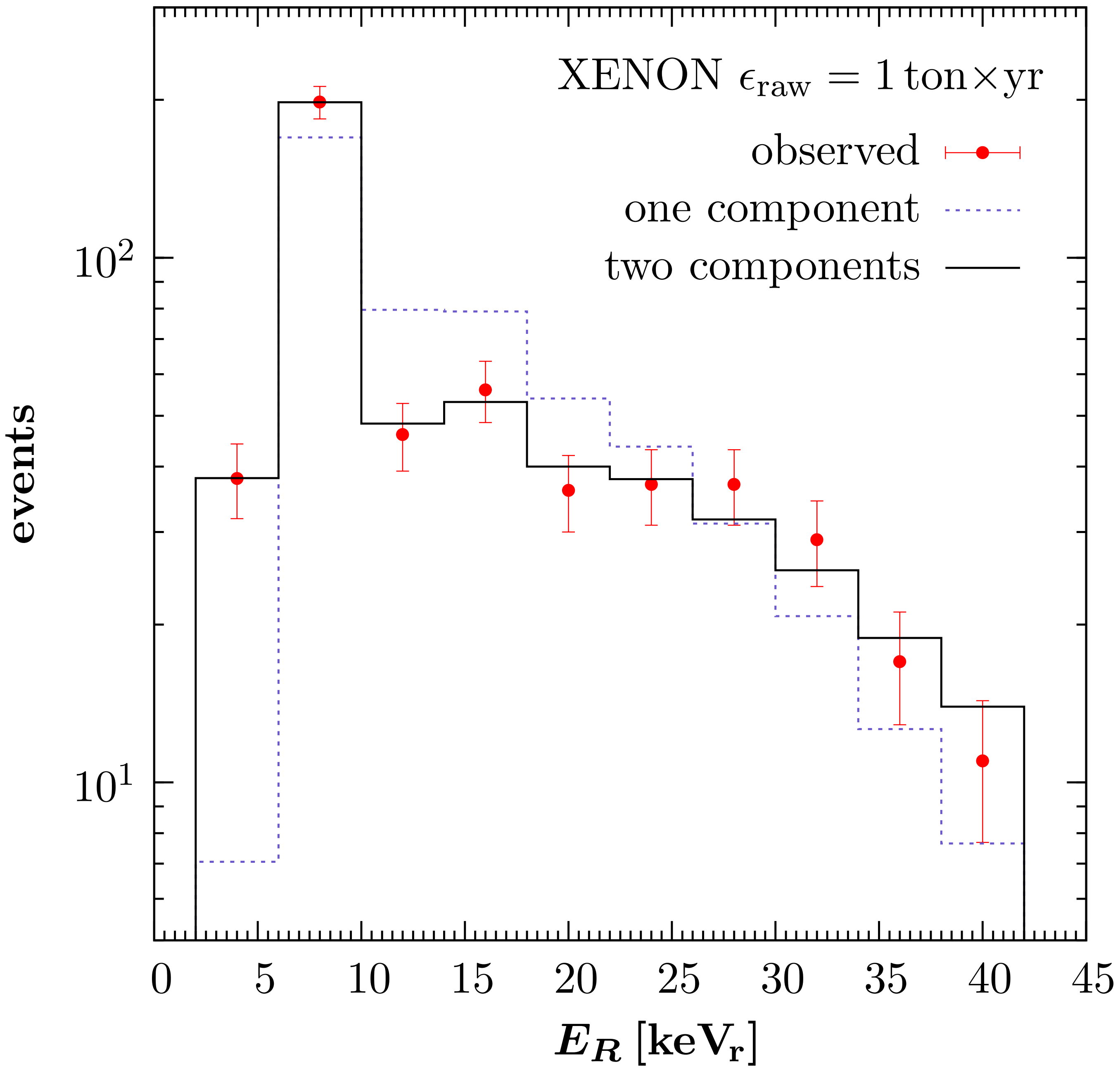
Two-component DM in direct detection

testing the single-WIMP hypothesis

- fit data and test goodness-of-fit using Poisson log-likelihood

$$\chi^2_\lambda = 2 \sum_{\text{bins } i} \left[N_i^{\text{th}} - N_i^{\text{obs}} + N_i^{\text{obs}} \ln\left(\frac{N_i^{\text{obs}}}{N_i^{\text{th}}}\right)\right]$$

=> reject single-component DM with well above 99% confidence



Two-component DM in direct detection

extracting the model parameters

- NOT possible to completely recover the model

$$\frac{dR_i}{dE_R} \propto \frac{\rho_i \sigma_n^{(i)}}{m_i} \exp\left[-\left(1+\frac{m_N}{m_i}\right)^2 \frac{E_R}{2 m_N v_0^2}\right]$$

high degree of degeneracy between ρ_i and $\sigma_n^{(i)}$.

loss of spectral shape information on m_i for $m_i \gg m_N$.

- => CASE for **complementarity of different targets**

Conclusions

- considered minimal Dark Matter model stabilized by the smallest non-Abelian discrete group D_3

  - two stable states possible

  - non-standard cosmology:

    => semi-annihilation, DM conversion, late decays

- Multi-component DM scenario may already be accessible with moderate exposure at ton-scale direct detection experiments