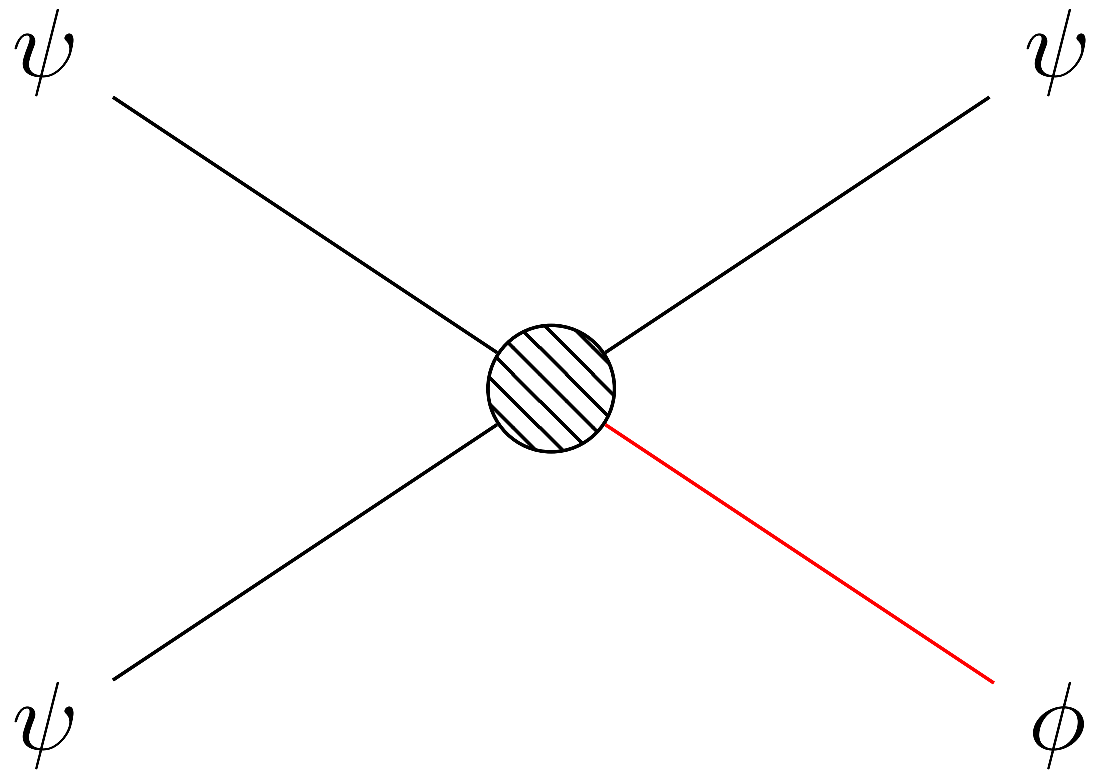


General Perspective on Boosted Dark Matter from Semi-annihilation

Seongsik Kim
With Jong-Chul Park,
Chungnam National University
Work in progress (2608.XXXXX)
The 5th workshop on Symmetry and Structure of the Universe

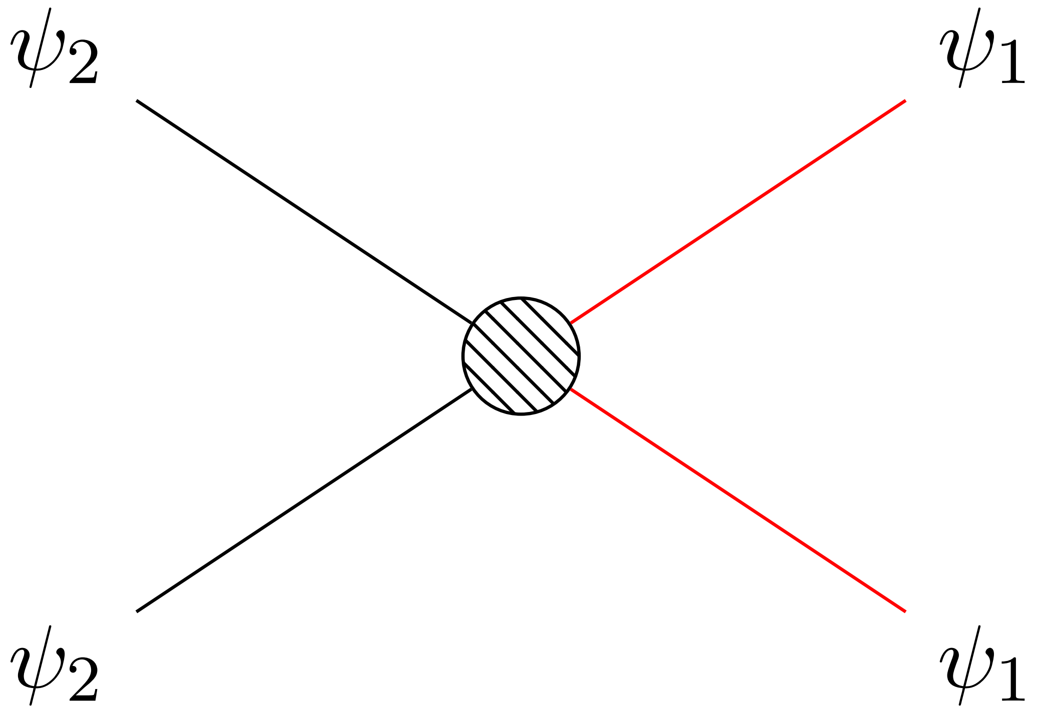
Boosted Dark Matter

Note: Throughout this talk, we denote DM as ψ

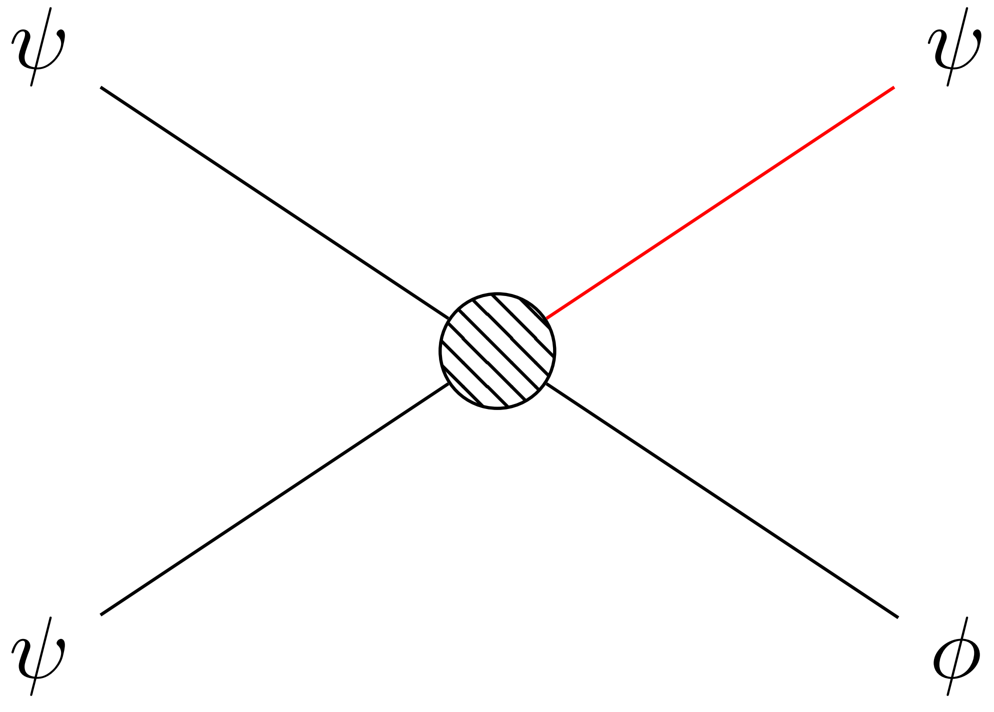
Dark Matter particle with sufficient kinetic energy

Particle Model

Multi-component DM

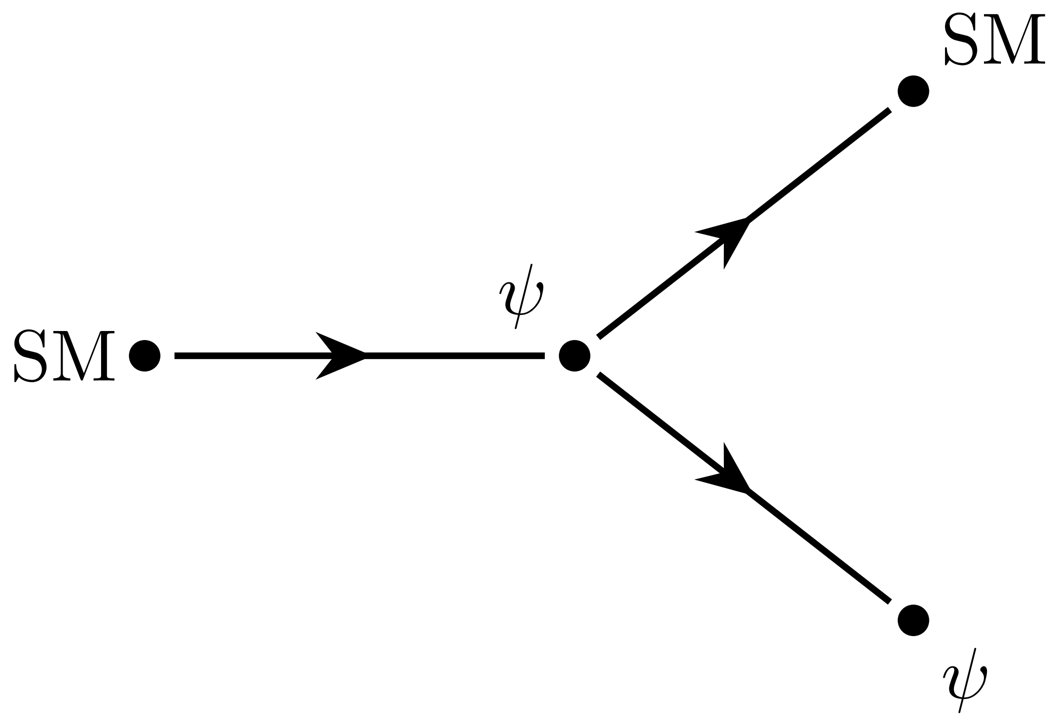


Semi-annihilation



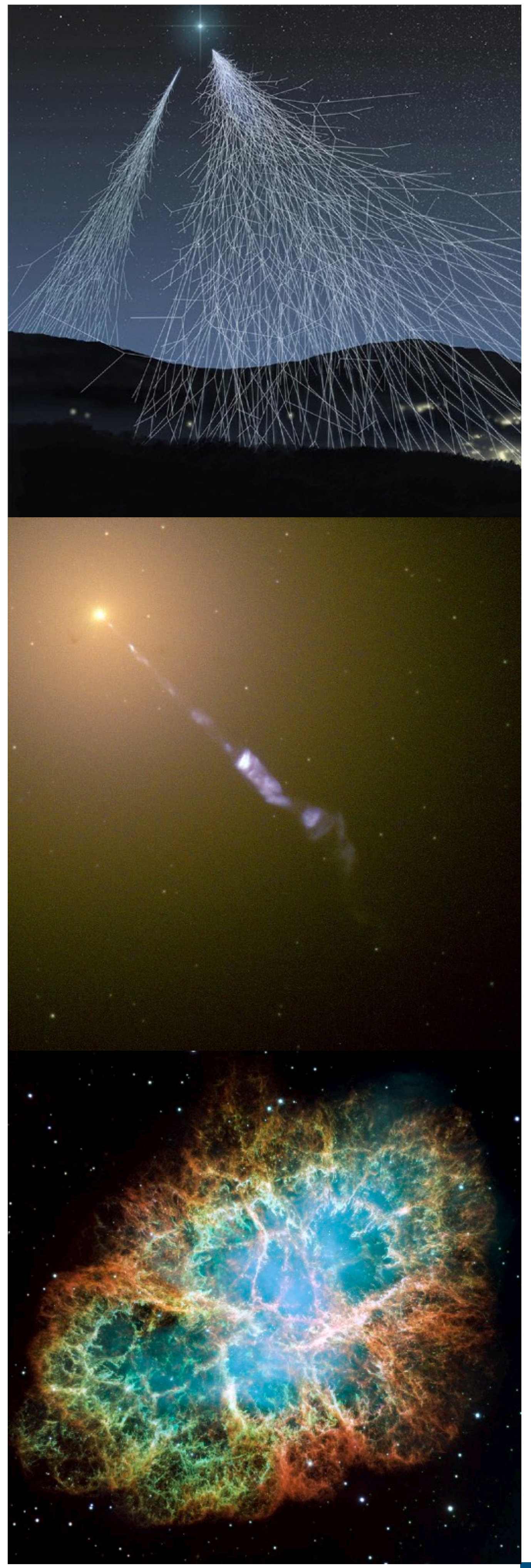
Astrophysical Source

Collision by High-Energy Particle



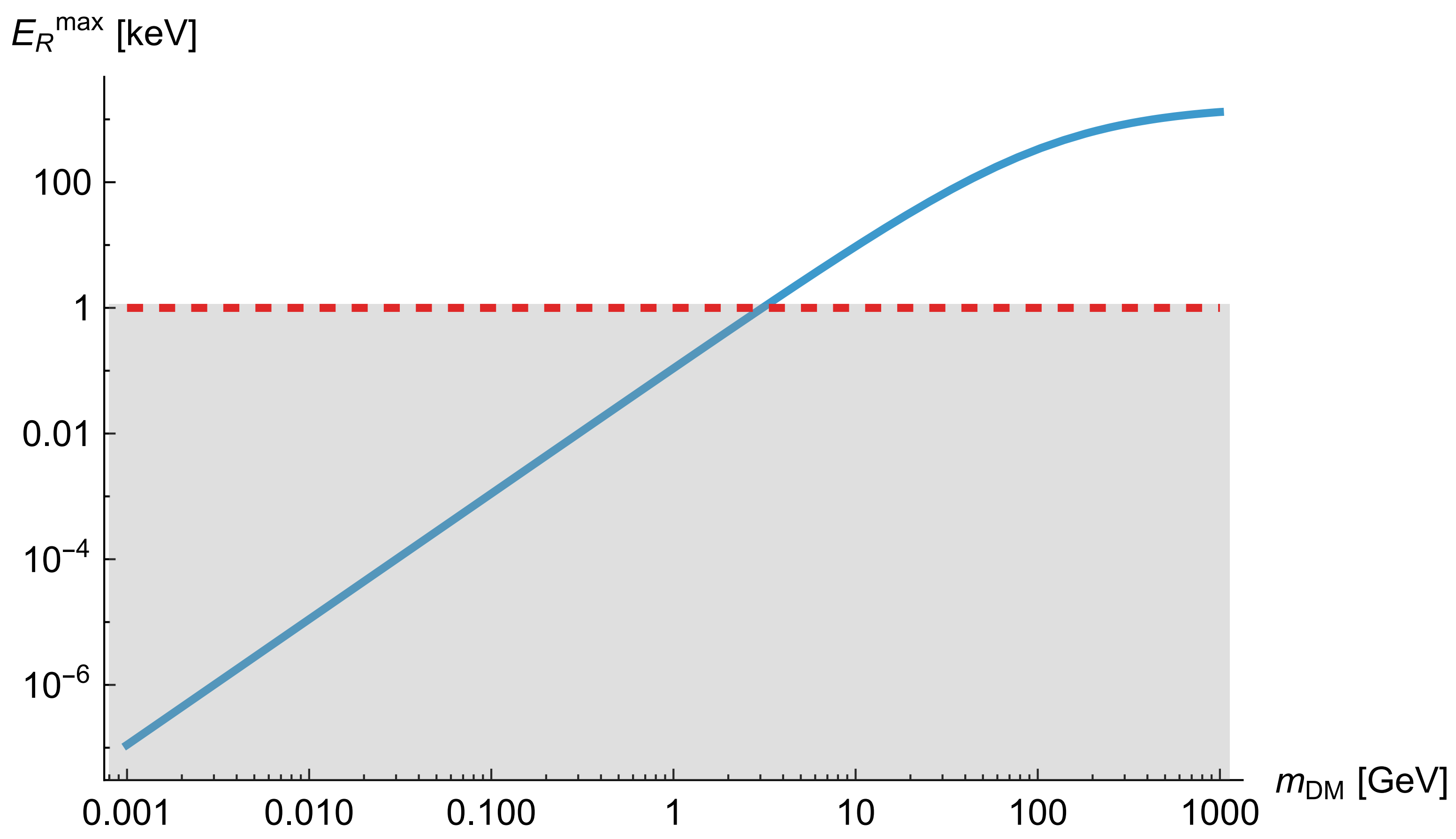
Cosmic-Ray $e, p, \nu, \ldots$

(Blazar Jet, Stars, Supernovae, PBHs, etc)



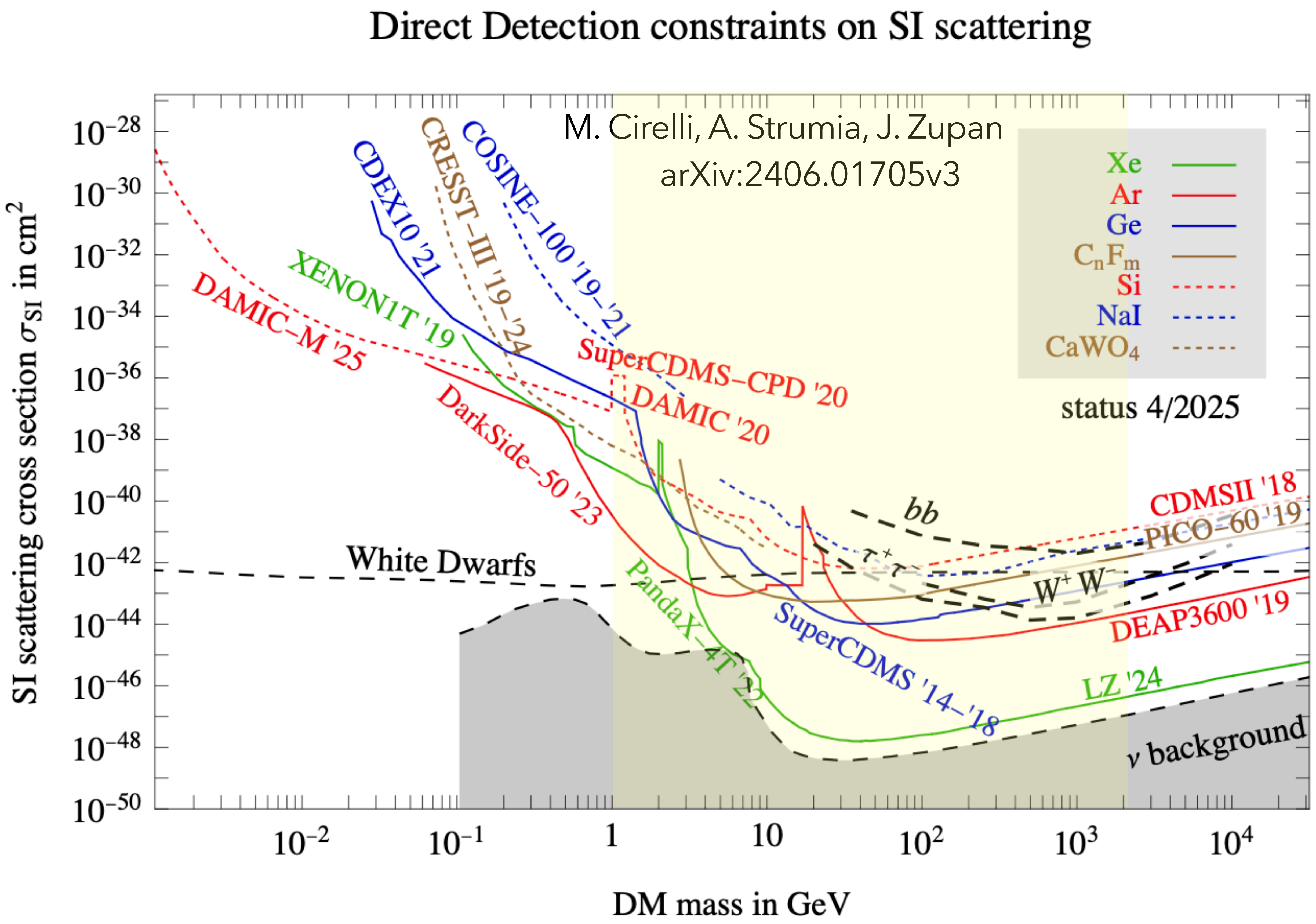
Kinematics

$$E_R^{\max} = \frac{2 m_T m_{\rm DM}^2}{(m_T + m_{\rm DM})^2}\, v_{\max}^2$$



For virialized DM, only sufficiently heavy DM deposits recoil energy above the detector threshold.

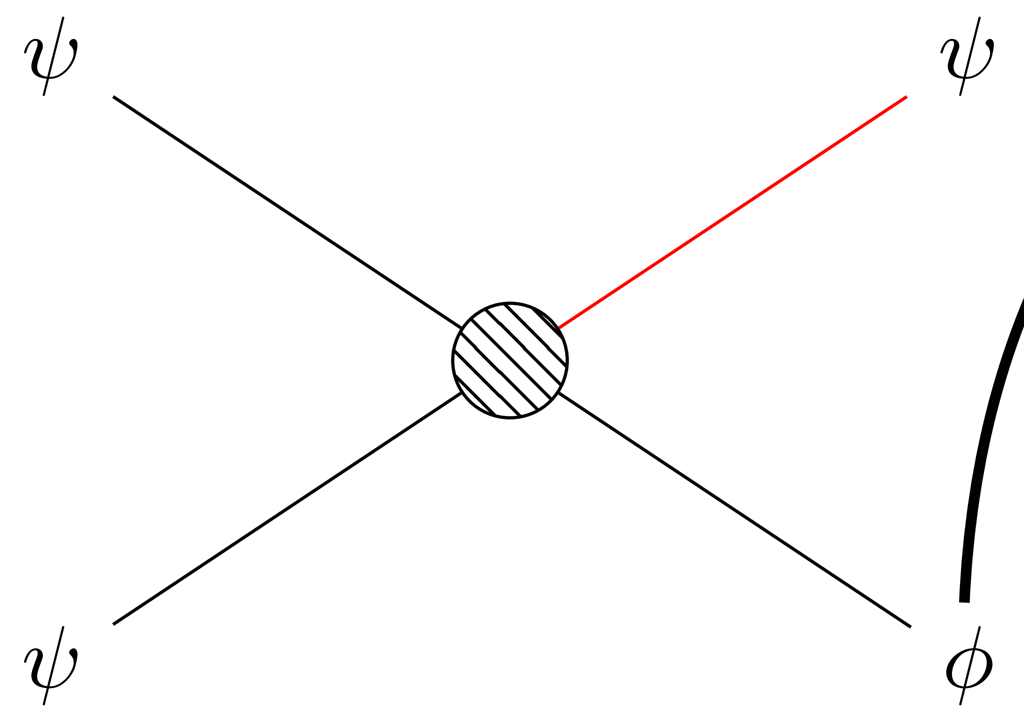
Note: $v_{\max} \approx 776\ \mathrm{km/s}$, $m_T = m(^{131}\mathrm{Xe}) \approx 122\ \mathrm{GeV}$ are used in the graph



Detector Threshold list

	XENONnT	LUX-ZEPLIN	PandaX-4T
NR	3.3 keV	5.4 keV	1.1 keV
ER	0.5 keV	0.9 keV	~1 keV

Boosted Dark Matter from Semi-annihilation



ϕ can be SM species!

- Single Component DM is enough for semi-annihilation
- Less uncertainty in the BDM flux
- Monochromatic kinetic energy distribution

F. D'Eramo, J. Thaler 1003.5912 / M. Aoki, T. Toma 1405.5870
G. Arcadi, F. S. Queiroz, C. Siqueira 1706.02336 / A. Kamada, H. J. Kim, H. Kim, T. Sekiguchi 1707.09238
F. S. Queiroz, C. Siqueira 1901.10494 / R. Primulando, J. Julio, P. Uttayarat 2006.13161
P. Ko, Y. Tang 2006.15822 / S. Chigusa, M. Endo, K. Kohri 2007.01663
A. Ghosh, D. Ghosh, S. Mukhopadhyay 2103.03650 / T. Toma 2109.05911
T. Miyagi, T. Toma 2201.05412 / P. Bandyopadhyay, D. Choudhury, D. Sachdeva 2206.05811
M. Frigerio, N. Grimbaum-Yamamoto, T. Hambye 2212.11918 / J. Guo, J. Zhao 2306.14091
M. Aoki, T. Toma 2309.00395 / B. Kamenetskaia, M. Fujiwara, A. Ibarra, T. Toma 2501.12117
J. Davighi, S. Moldovsky, H. Murayama, C. Scherb, N. Selimovic 2506.05468 / M. Fujiwara, T. Toma 2606.02751
And much more!

Because of its simplicity, BDM from semi-annihilation and its phenomenological applications have been widely studied

Boosted Dark Matter from Semi-annihilation

What's the matter?

Almost every studies on semi-ann BDM model simply 'assumes' an additional semi-ann process and analyze the BDM flux/detection rate

This may be misleading:
because the BDM flux and detection rate are highly correlated with other phenomenological quantities so they must be analyzed simultaneously

Only a few work address this point

F. D'Eramo, J. Thaler 1003.5912 / M. Aoki, T. Toma 1405.5870
G. Arcadi, F. S. Queiroz, C. Siqueira 1706.02336 / A. Kamada, H. J. Kim, H. Kim, T. Sekiguchi 1707.09238
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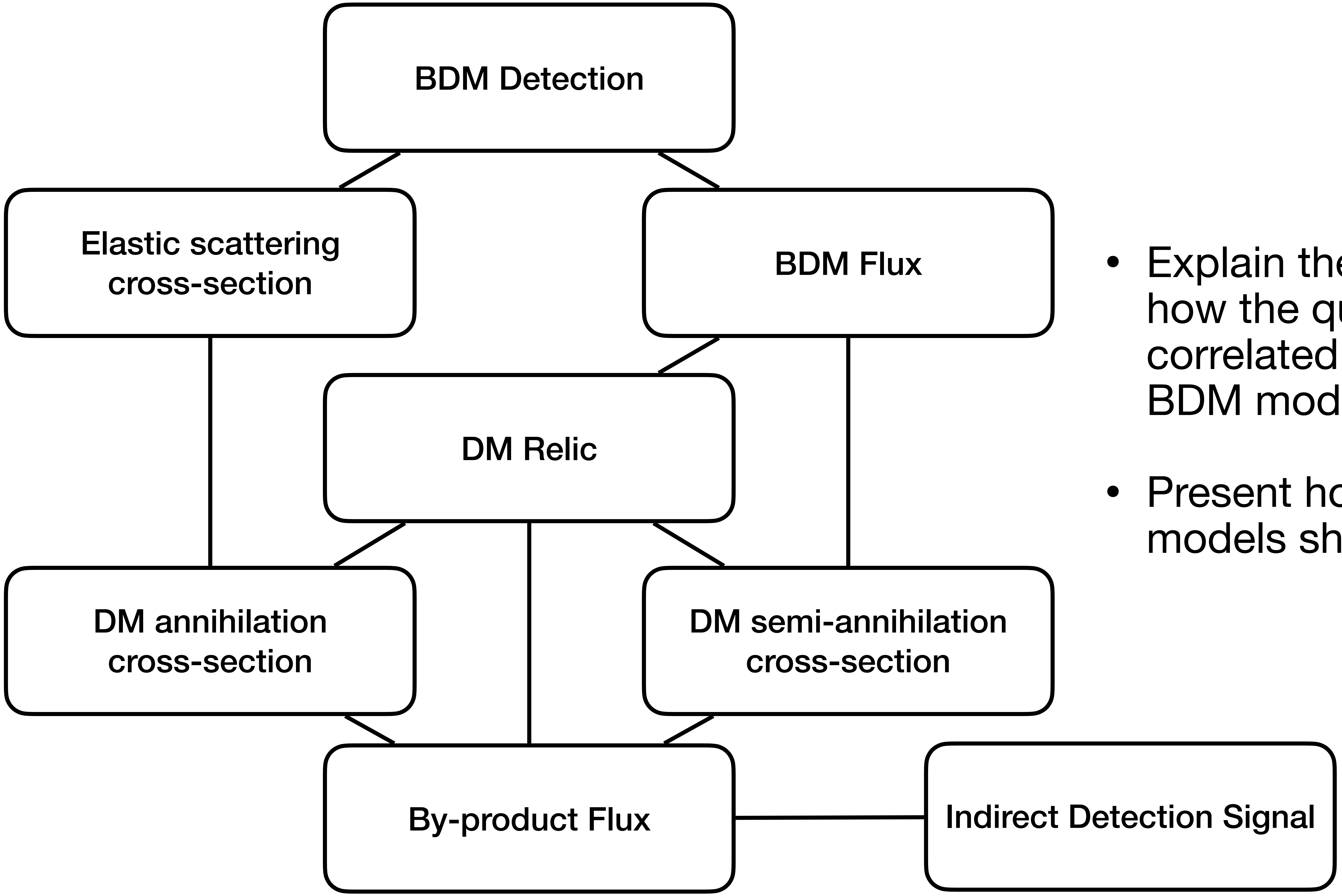
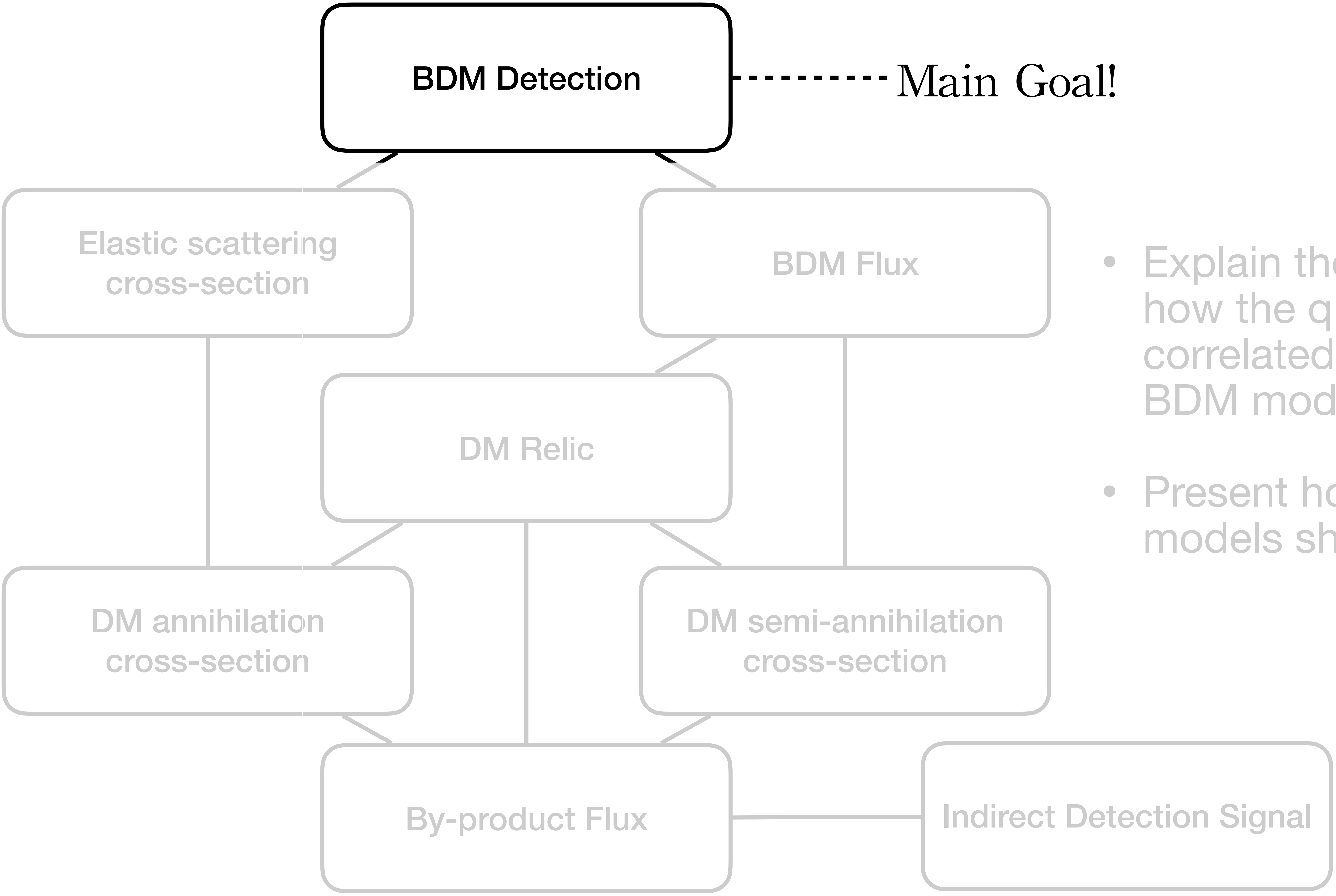
And much more!

The Goal of This Work



- Explain the link: how the quantities are correlated in semi-annihilating BDM models
- Present how semi-annihilating models should be analyzed.

The Goal of This Work



- Explain the link: how the quantities are correlated in semi-annihilating BDM models
- Present how semi-annihilating models should be analyzed.

The BDM Detectability

The Primary Object on Any BDM Model

Differential Flux $\frac{d\Phi}{dE_K}$

$$\frac{d\Phi}{dE_K} = \frac{1}{2}\frac{1}{4\pi}\langle\sigma v\rangle_{\rm sa}\frac{dN}{dE_K}\int d\Omega \int_{\rm l.o.s} ds \left(\frac{\rho_\psi^{\rm MW}}{m_\psi}\right)^2$$

$$= \frac{\langle\sigma v\rangle_{\rm sa}}{8\pi m_\psi^2}\frac{dN}{dE_K}J$$

For semi-ann DM with $\psi\psi \to \psi\phi$

$$\frac{dN}{dE_K} = \delta\left(E_K - \frac{5m_\psi^2 - m_\phi^2}{4m_\psi}\right)$$

Differential Rate per target mass

$$\frac{1}{m_T}\frac{dR}{dE_R} = \frac{1}{m_T}\int_{E_{\rm th}}^{E_{\rm max}} dE_K \frac{d\sigma_{\rm el}}{dE_R}\frac{d\Phi}{dE_K}$$

BDM Detection

Elastic scattering

BDM Flux

$$\frac{1}{m_T}\frac{dR}{dE_R} \approx \frac{3.2\times 10^{-3}}{m_T}\left(\frac{100\,{\rm MeV}}{m_\psi}\right)^2\left(\frac{\langle\sigma v\rangle_{\rm sa}}{10^{-26}\,{\rm cm^3 s^{-1}}}\right)\left.\frac{d\sigma_{\rm el}}{dE_R}\right|_{E_K=E_f} {\rm cm^2\ s^{-1}}$$

Event rate depends on

- DM mass
- Semi-ann cross-section
- Elastic scattering cross-section

The BDM Detectability

The Primary Object on Any BDM Model

Differential Flux $\frac{d\Phi}{dE_K}$

$$\frac{d\Phi}{dE_K} = \frac{1}{2}\frac{1}{4\pi}\langle\sigma v\rangle_{\rm sa}\frac{dN}{dE_K}\int d\Omega \int_{\rm l.o.s} ds \left(\frac{\rho_\psi^{\rm MW}}{m_\psi}\right)^2$$

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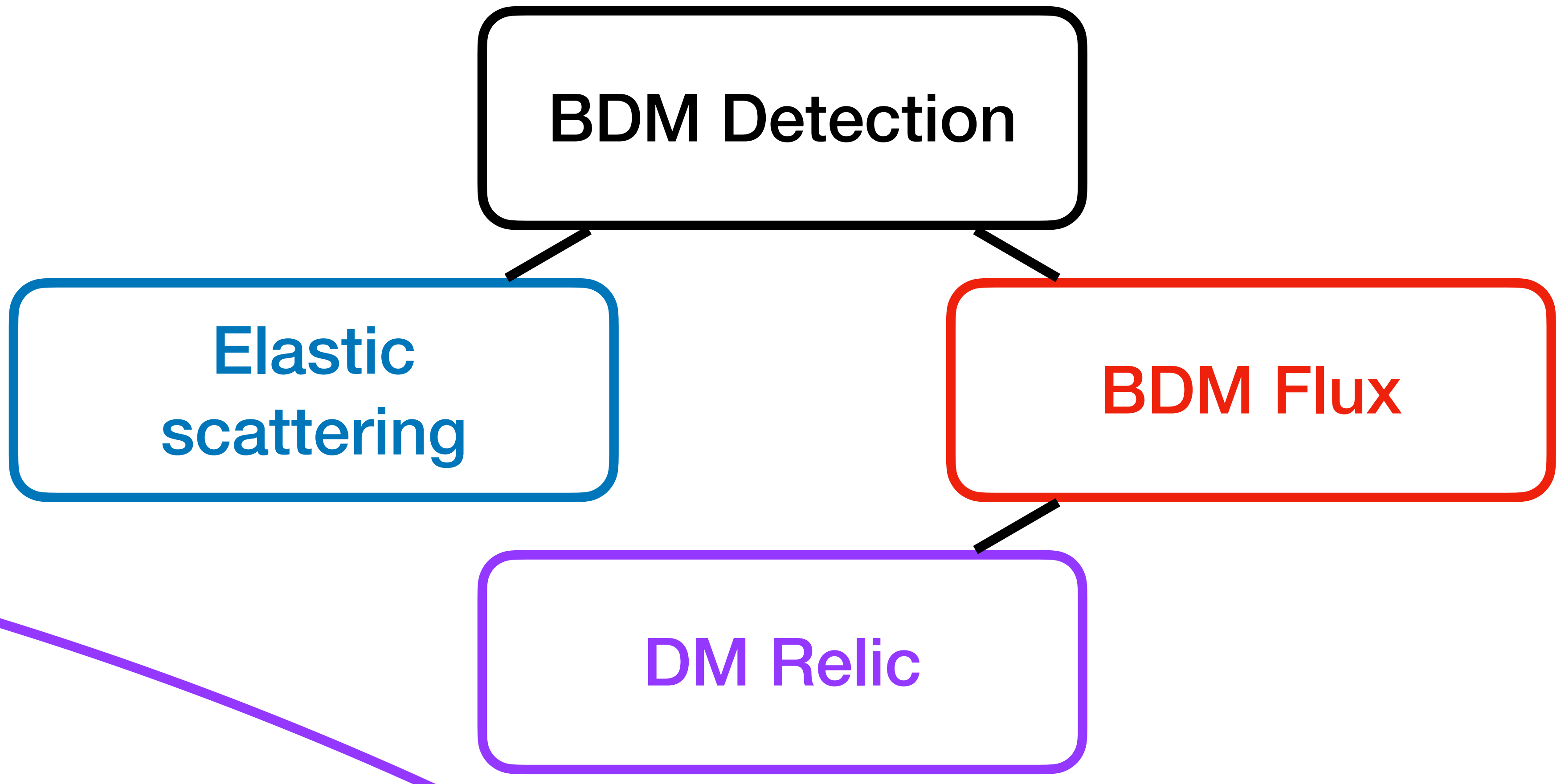


Hidden Factor: Relic Density!

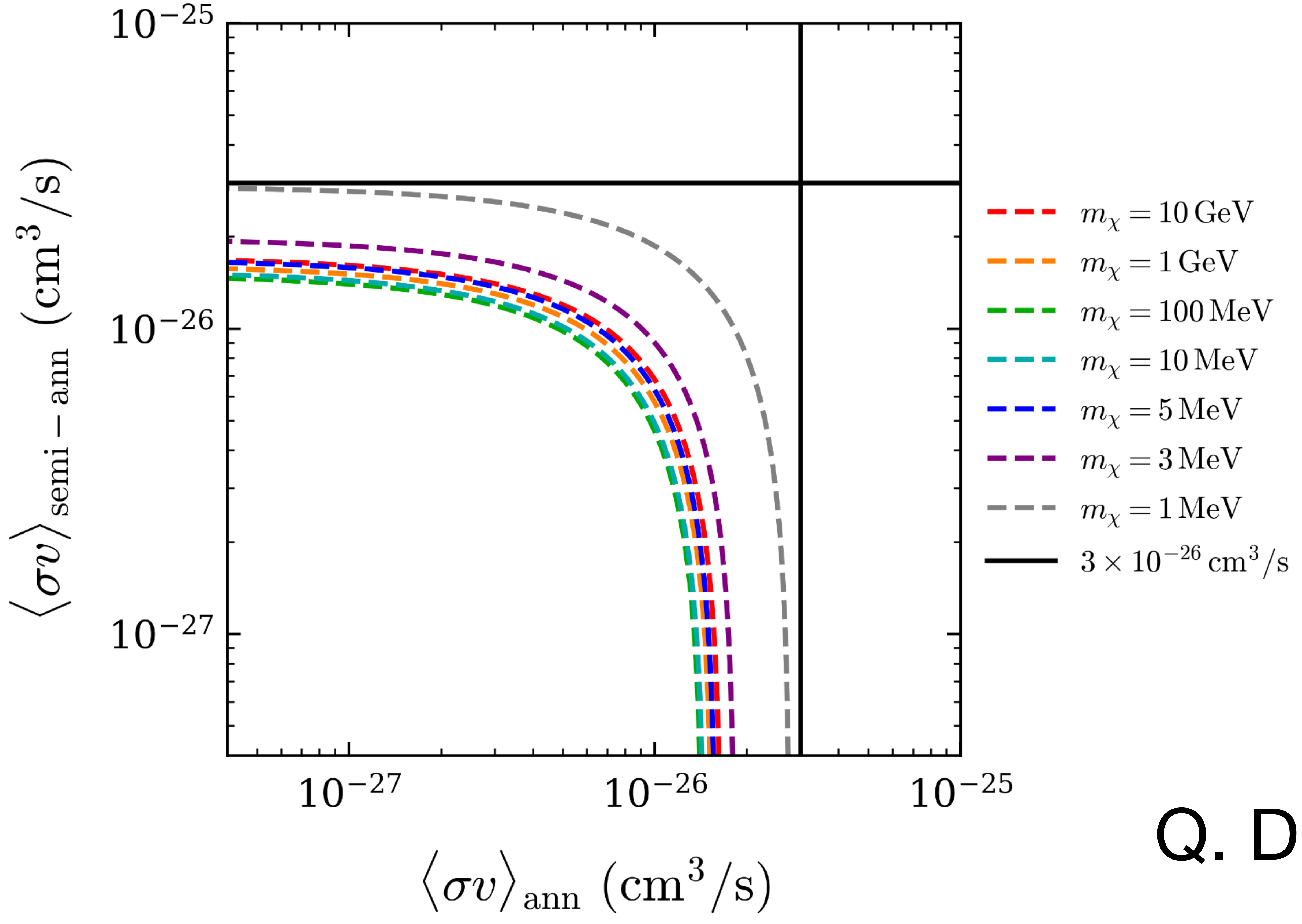
DM mass distribution $\rho_\psi^{\rm MW}$ is grounded on the current relic density: $\Omega h^2 \approx 0.12$

Relic Density of BDM

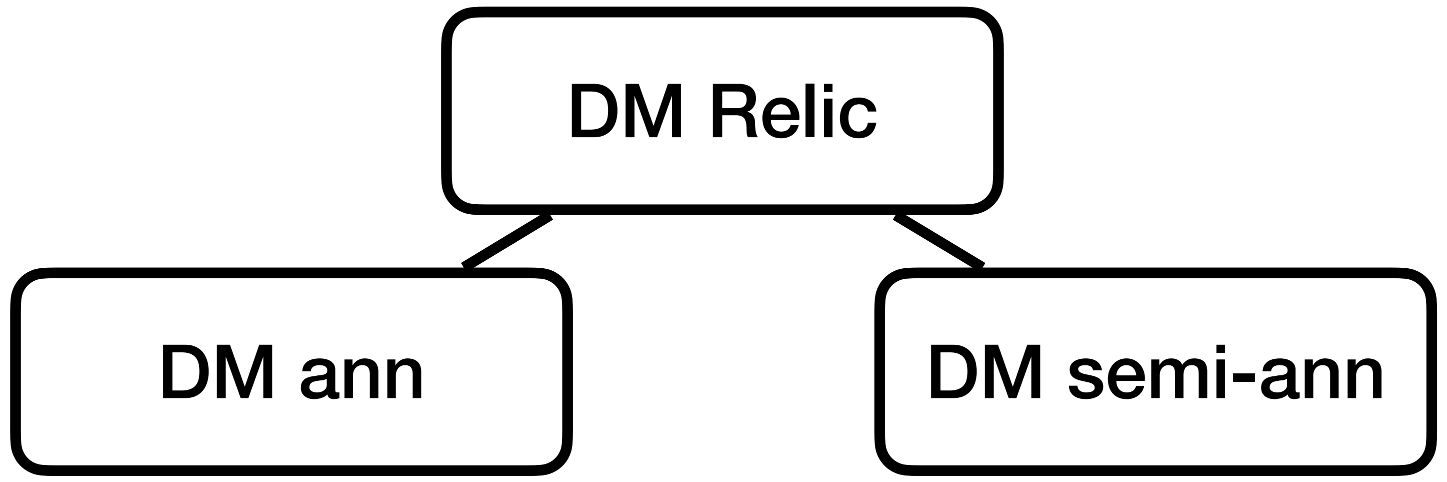
Boltzmann Equation for semi-annihilating DM

$$\frac{dY}{dx} = -\sqrt{\frac{8\pi^2}{45}} M_{\rm pl} \frac{g_{*s}(T)}{\sqrt{g_*(T)}} \left(1 + \frac{T}{3 g_{*s}(T)}\right) \frac{m_\psi}{x^2} \left(\langle \sigma v \rangle_{\rm ann} (Y^2 - Y_{\rm eq}^2) + \langle \sigma v \rangle_{\rm sa} Y (Y - Y_{\rm eq}) \right)$$

$$\langle \sigma v \rangle_{\rm ann} = \frac{1}{2}(\langle \sigma v \rangle_{\psi\psi \to {\rm ann}} + \langle \sigma v \rangle_{\psi\bar{\psi} \to {\rm ann}}) \,, \; \langle \sigma v \rangle_{\rm sa} = \frac{1}{4}(\langle \sigma v \rangle_{\psi\psi \to \psi\phi} + 2\langle \sigma v \rangle_{\psi\bar{\psi} \to \psi\phi})$$



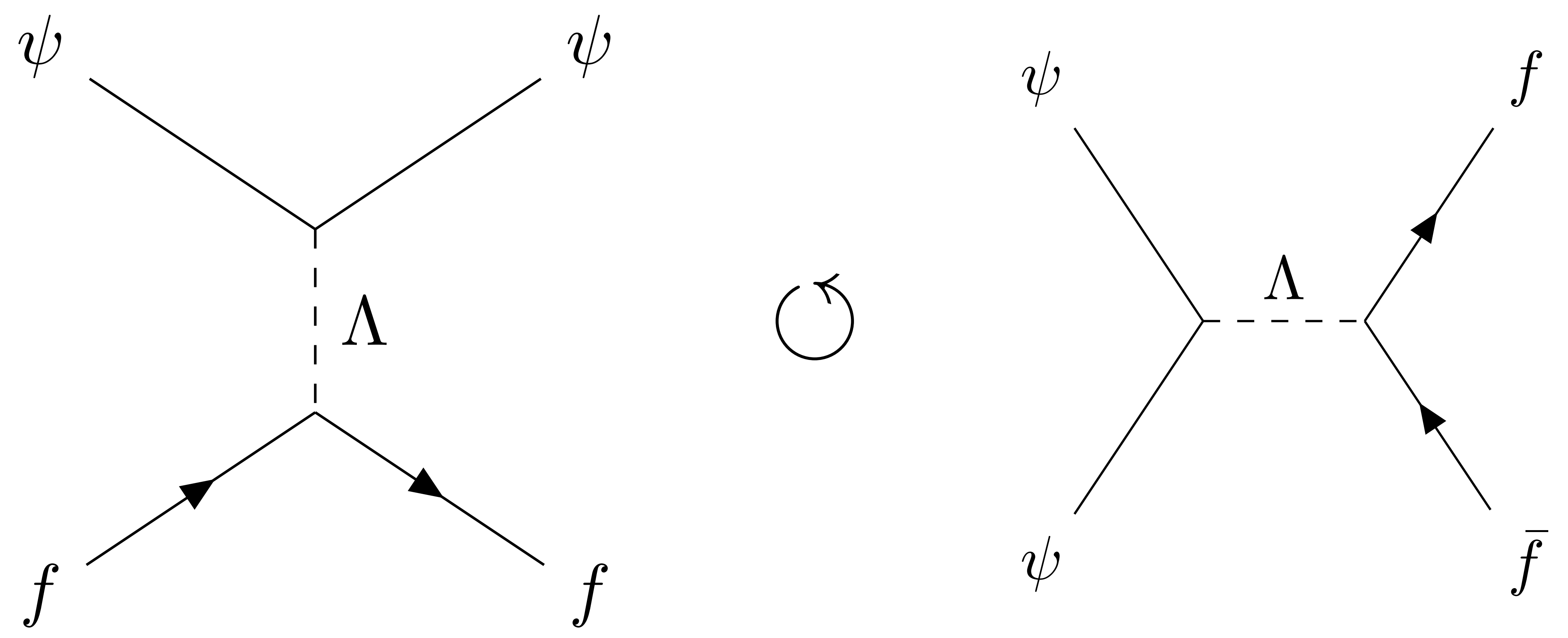
Reproducing the observed relic density requires a suitable combination of the annihilation and semi-annihilation cross-sections.



Q. Do we even need another annihilation?

The Annihilation of semi-annihilating DM model

BDM Model aiming at direct detection naturally implies an annihilation channel



Detection

Annihilation

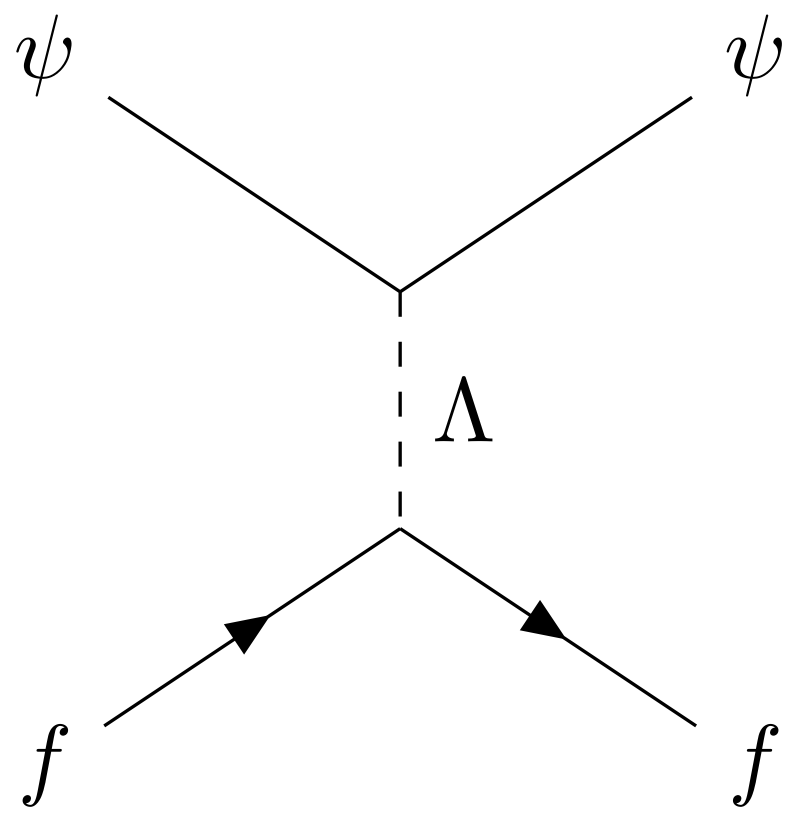
Possible Exception: electrophobic & lighter than pion

The Annihilation of semi-annihilating DM model

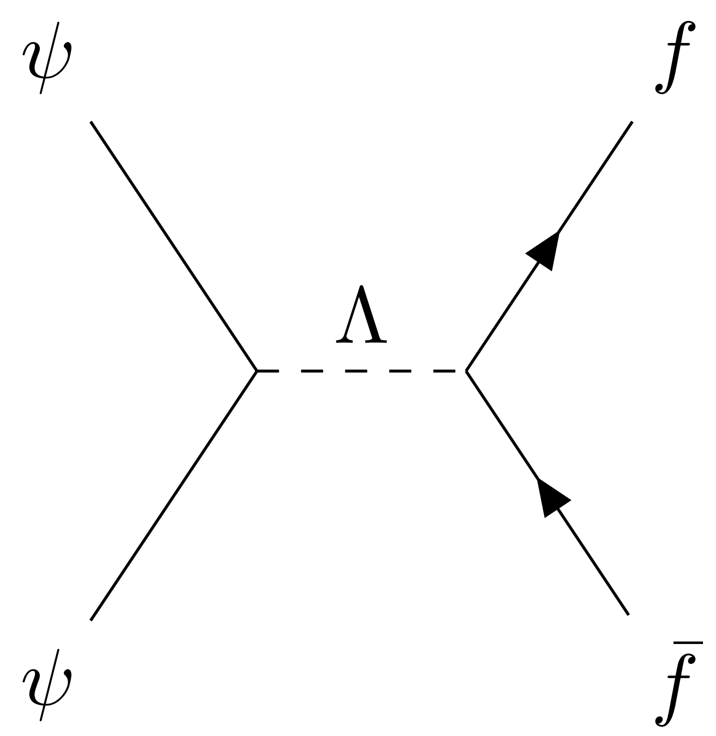
Sufficient annihilation is also required for enhancing the visibility of BDM

Differential Rate per target mass

$$\frac{1}{m_T}\frac{dR}{dE_R} = \frac{1}{m_T}\int_{E_{\rm th}}^{E_{\rm max}} dE_K \frac{d\sigma_{\rm el}}{dE_R}\frac{d\Phi}{dE_K}$$



Detection



Annihilation

Annihilation and $\sigma_{\rm el}$ share the same underlying amplitude!

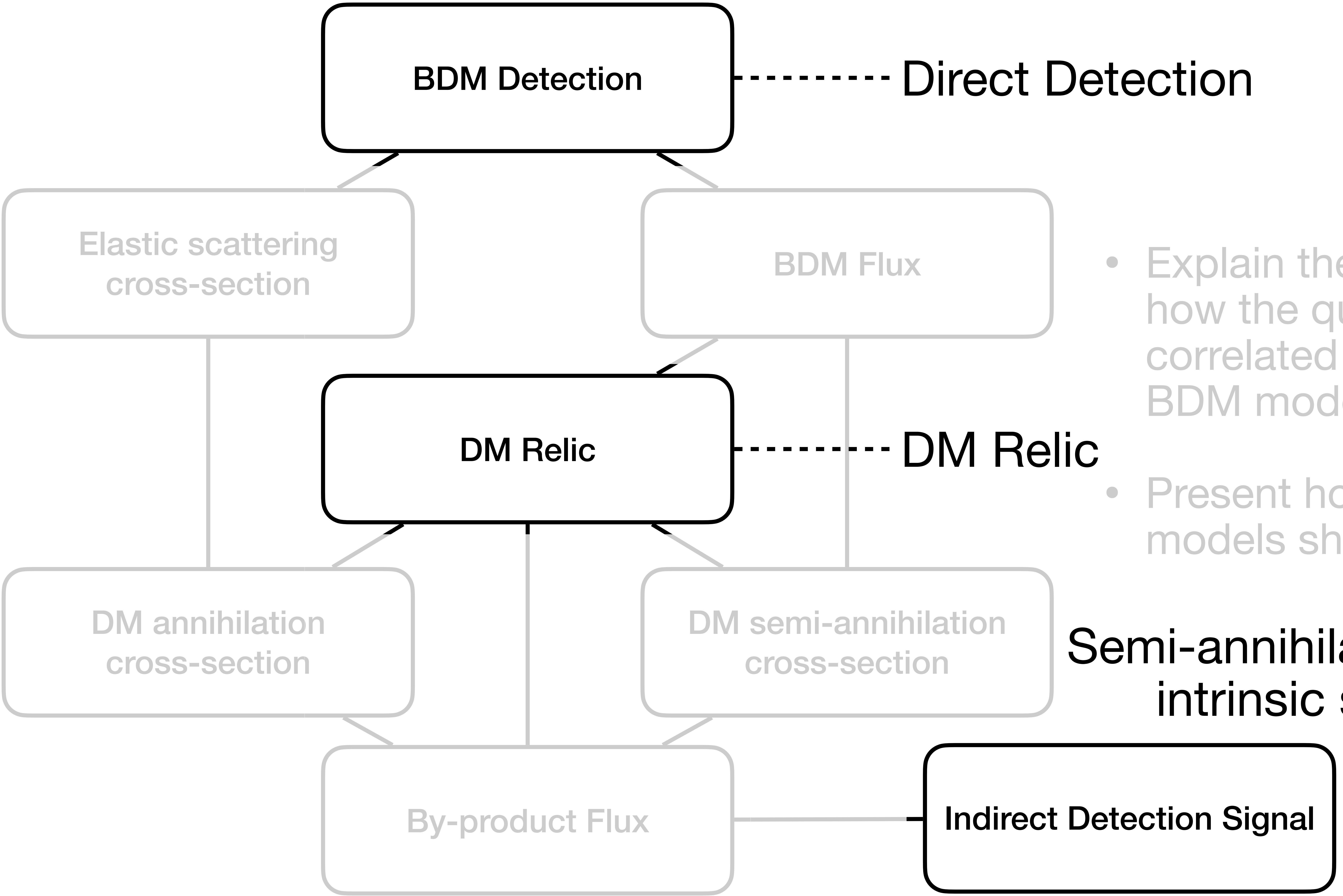
Elastic scattering cross-section

DM annihilation cross-section

Naive relation

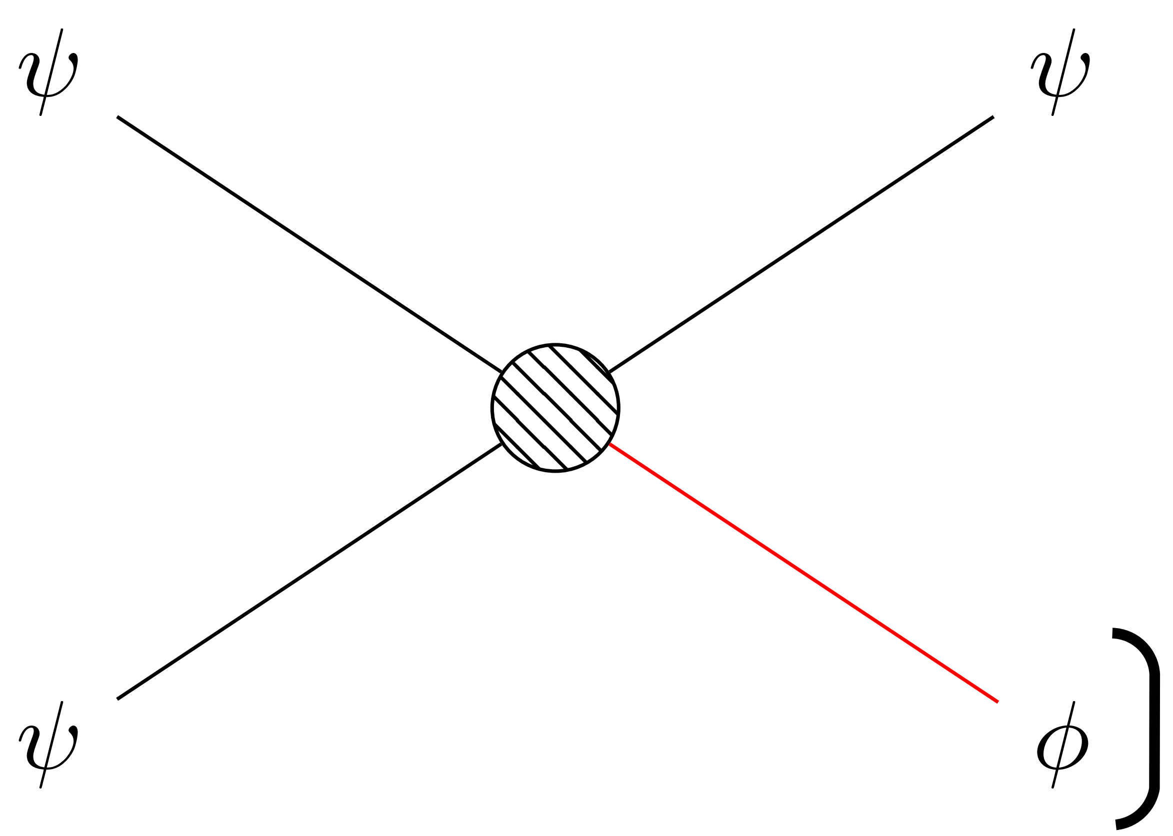
$$\frac{dR}{dE_R} \propto \mathcal{B}_{\psi\to f}\langle\sigma v\rangle_{\rm sa}(\sigma v)_{\rm ann}$$

The Goal of This Work

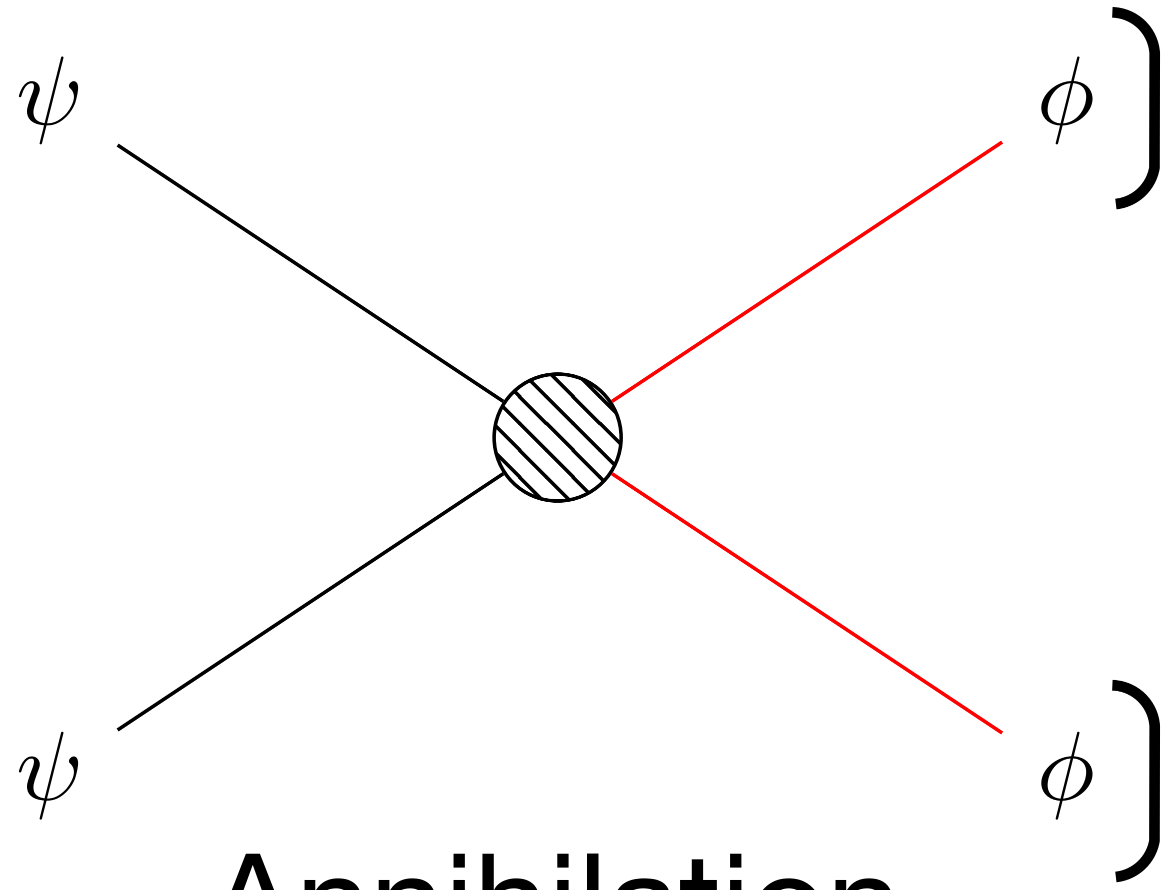


- Explain the link: how the quantities are correlated in semi-annihilating BDM models
- Present how semi-annihilating models should be analyzed.

The Boosted By-product

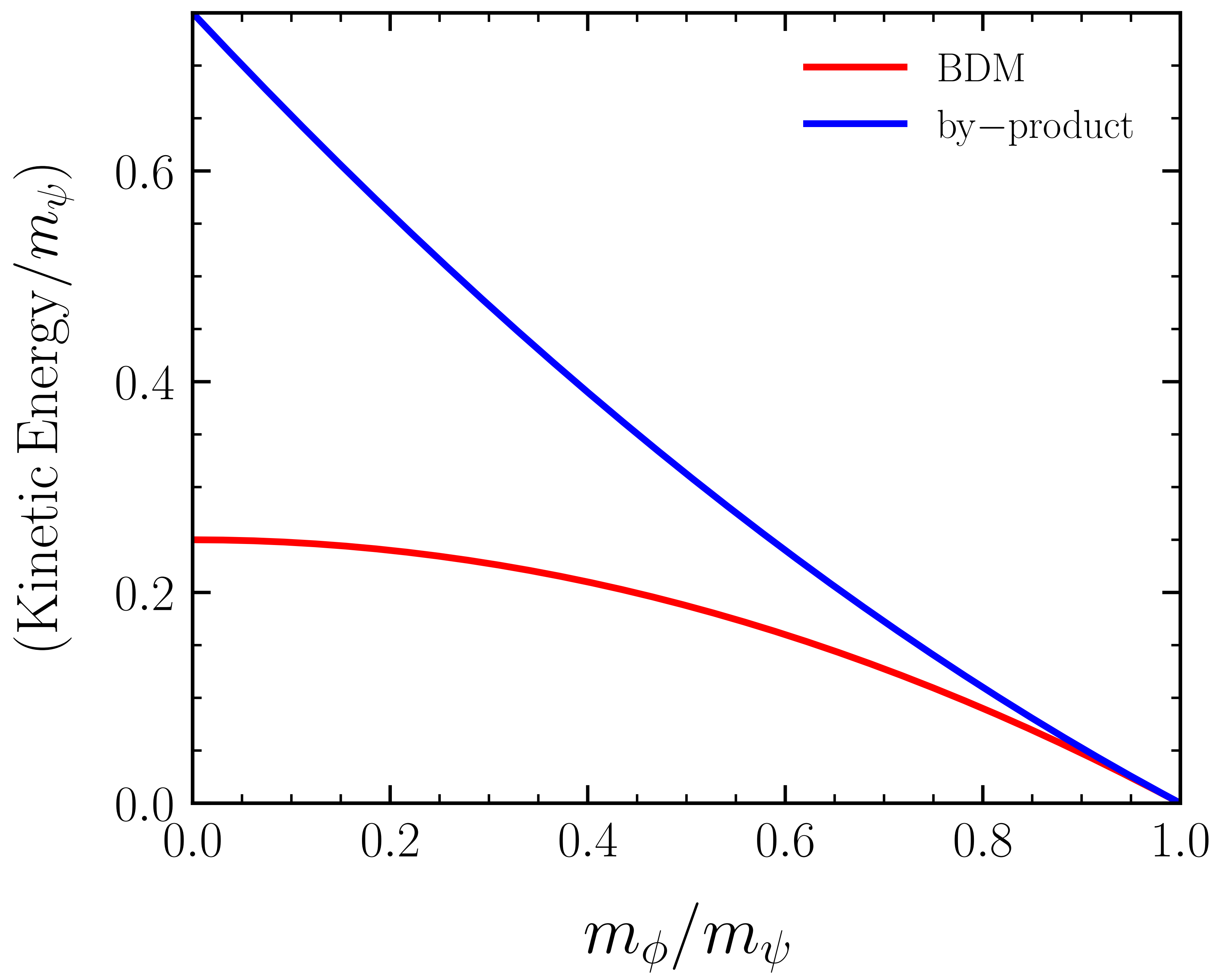


Semi-annihilation



By-products!

Annihilation



Always have greater kinetic energy than BDM

+ Additional flux from annihilation

➡ <u>No reason for ignoring them</u>

The Boosted By-product

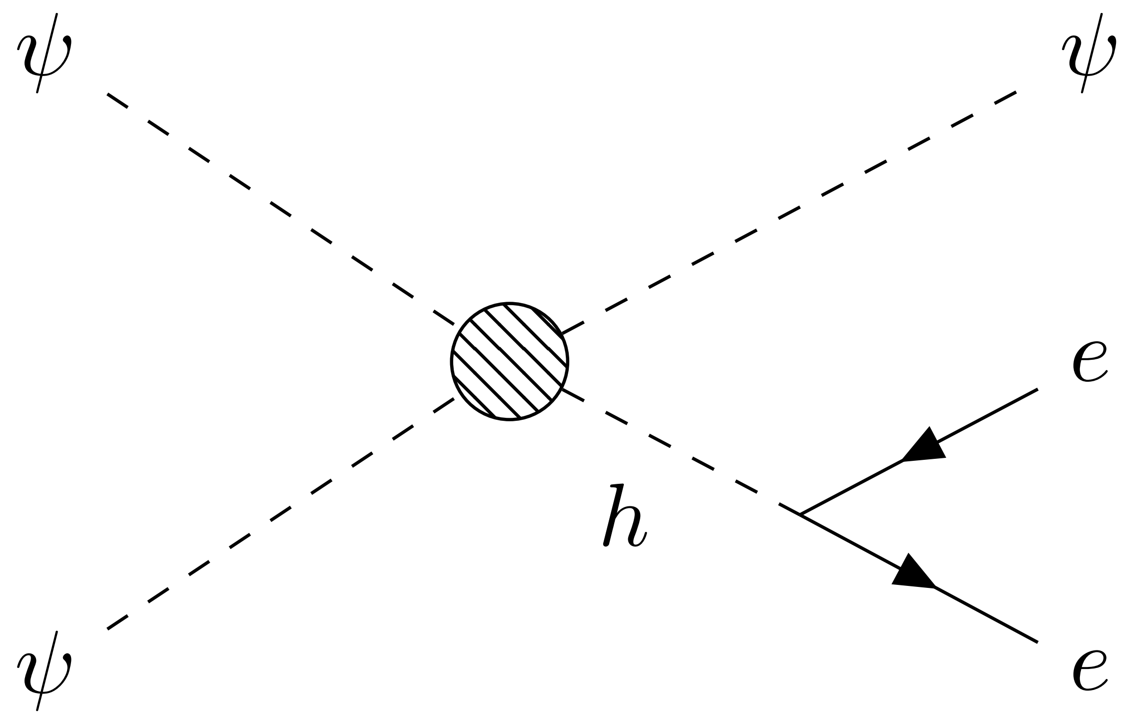
Which kinds of by-product are possible?

Bosonic DM - Bosonic, EM neutral (possibly off-shell) by-product

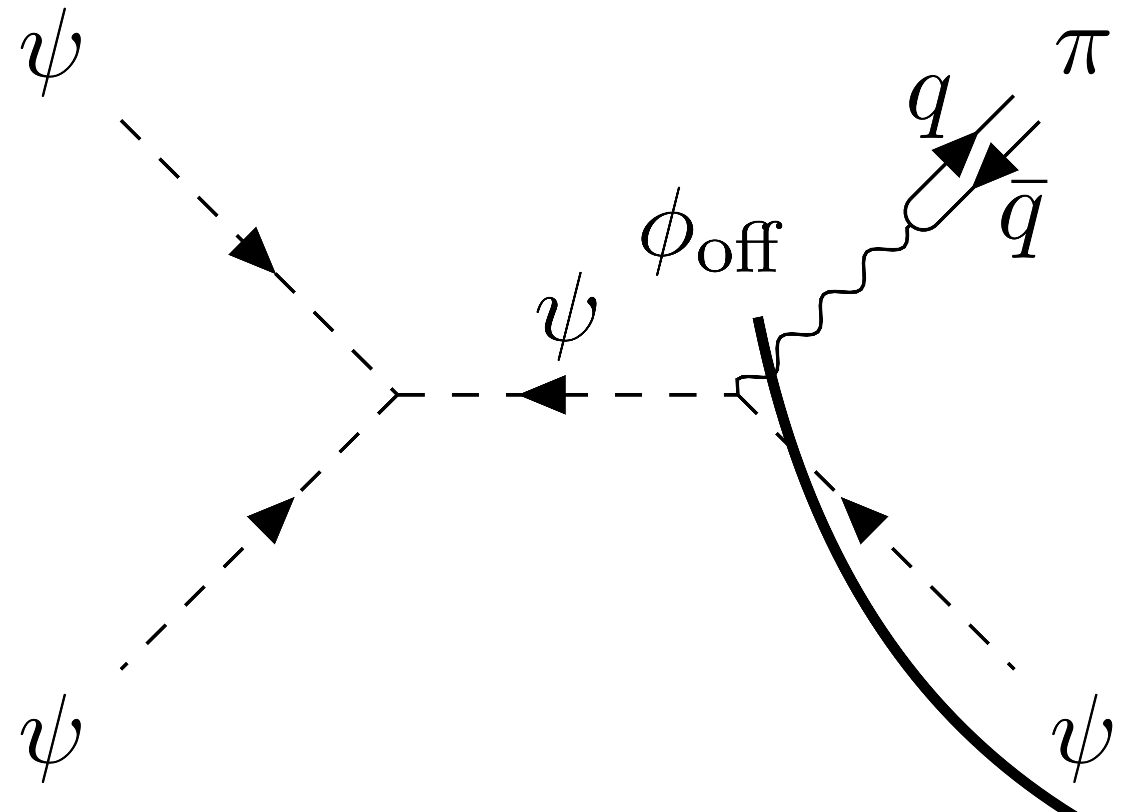
- BSM Option: Additional Dark sector Species - (Multi-component DM model)
- SM option 1: off-shell h, Z. (γ, g seems not plausible.)
  $\rightarrow$ In this option, semi-ann of sub-GeV DM should be $2 \rightarrow 3$ process!
  Monochromatic BDM Energy spectrum $\frac{dN}{dE_K} = \delta\left(E_K - \frac{5m_\psi^2 - m_\phi^2}{4m_\psi}\right)$ is no more valid!
- SM option 2: EM neutral mesons (π^0 etc)
  $\rightarrow$ DM mass must be greater than m_{π^0}

The Boosted By-product

Bosonic semi-ann BDM to SM induce energetic secondary photon!



Secondary photon from
boosted charged particle in galactic media

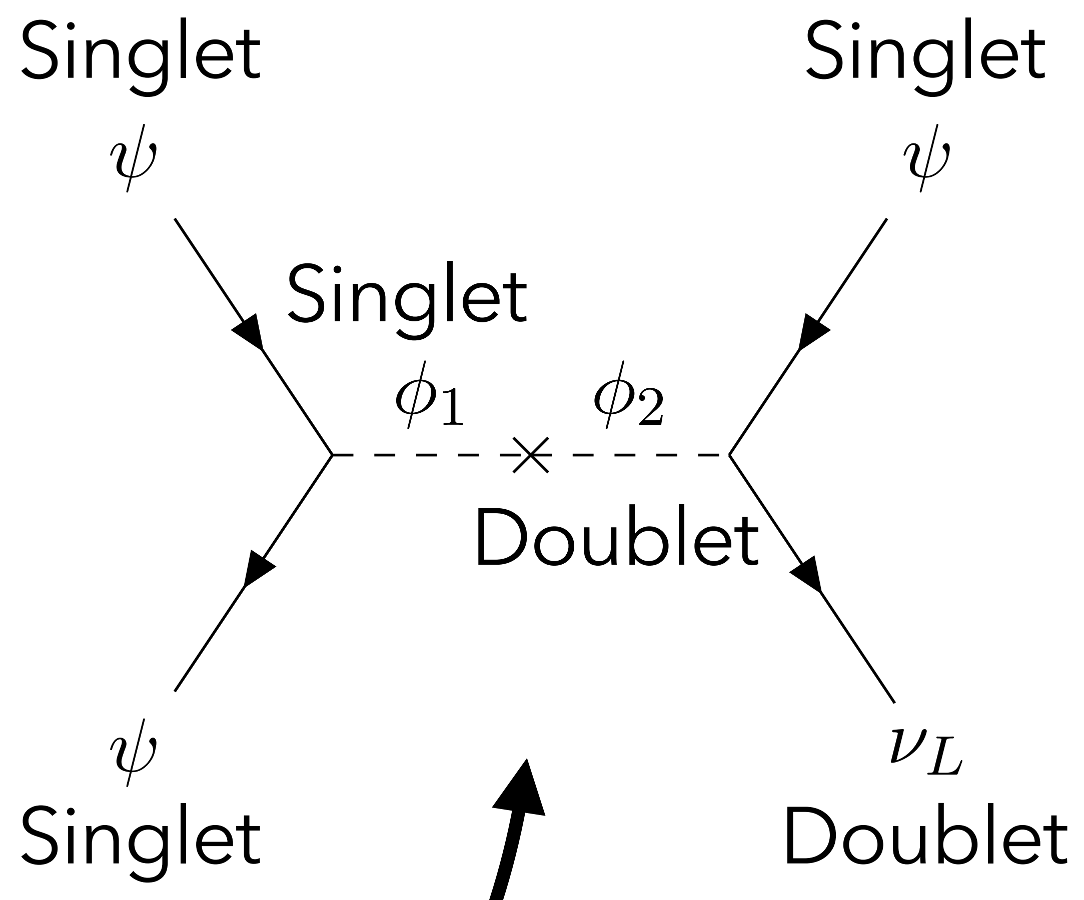


Secondary photon from neutral pion decay

This mediator is also responsible to Direct Detection!

The Boosted By-product

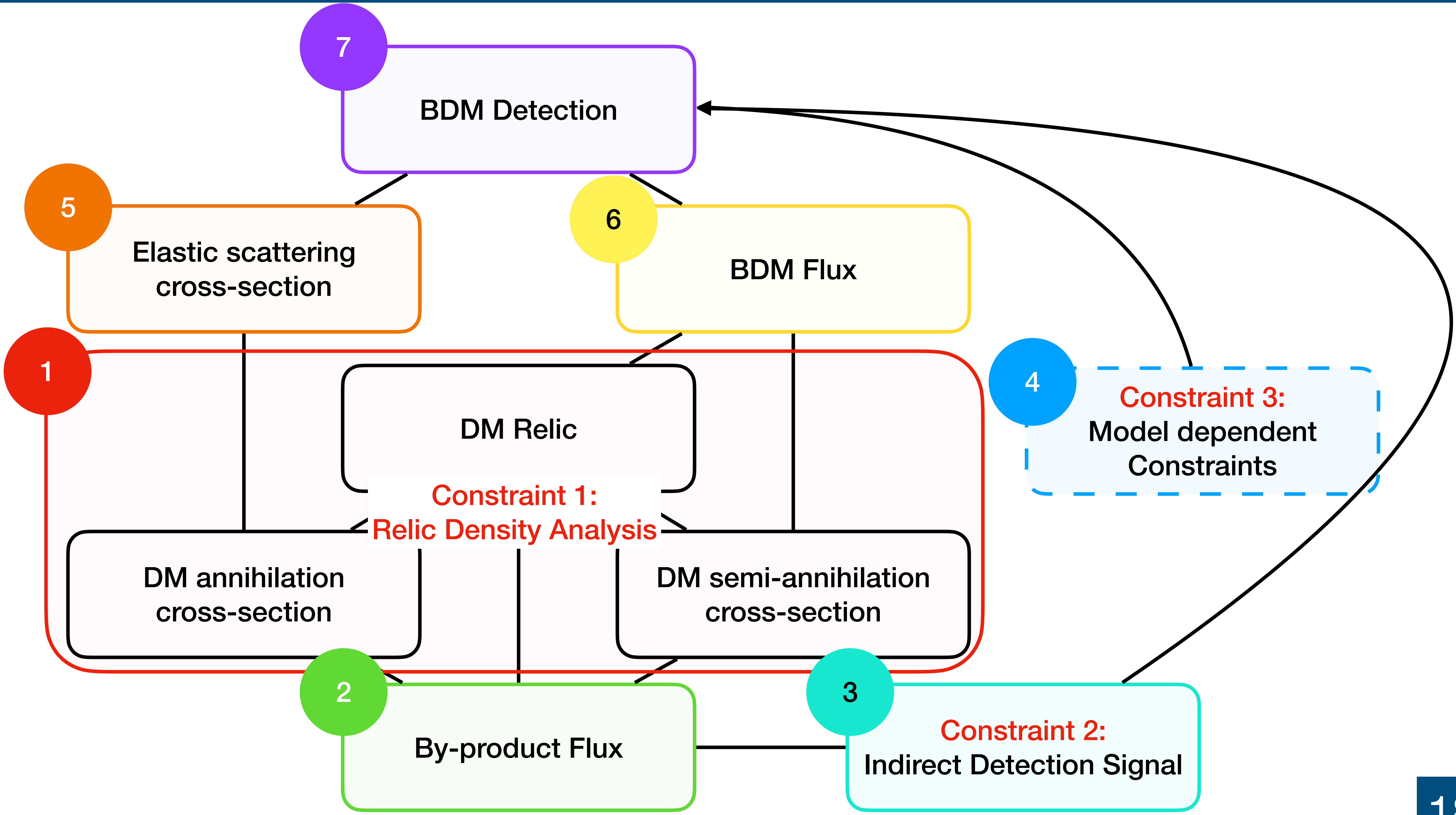
Which kinds of by-product are possible?



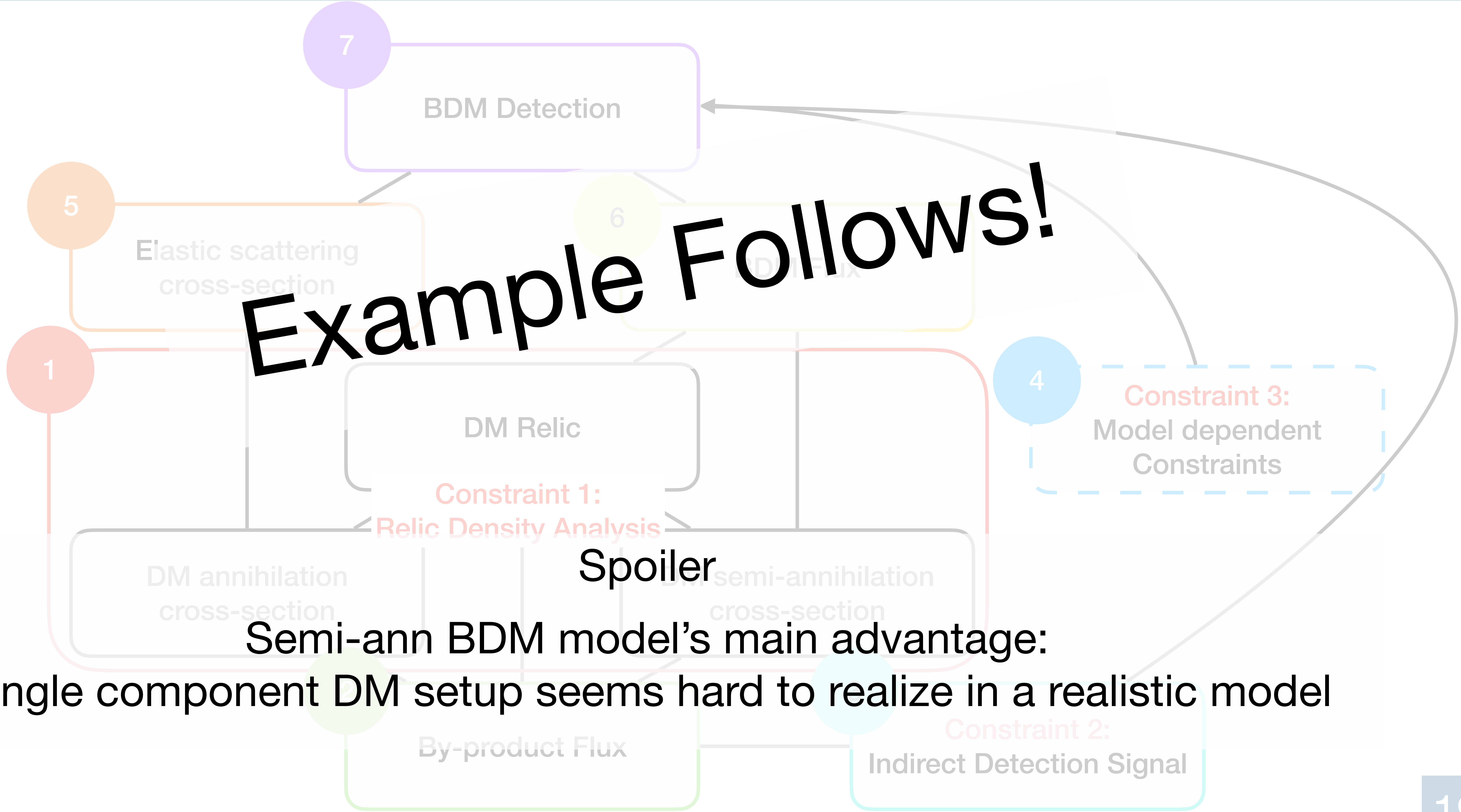
Fermionic DM - Fermionic EM neutral by-product

- Additional Dark Species - (Multi-component DM model)
- SM option: exclusively neutrino
  To respect $\mathrm{SU(2)_L}$ symmetry, three options
  - Option 1: DM charged under $\mathrm{SU(2)_L}$ (highly restricted)
  - Option 2: mediator coupled to DM & neutrino charged under $\mathrm{SU(2)_L}$
    At least two mediators, each $\mathrm{SU(2)_L}$ singlet and doublet, and their mixing required
    = No simple single mediator analysis! (unless hierarchy b/w mediators is provided)
  - Option 3 : DM interact with (light) right-handed neutrino.

Summary of Flow



Summary of Flow



Example Follows!

Spoiler

Semi-ann BDM model’s main advantage:
Single component DM setup seems hard to realize in a realistic model

Example Model

0

Build the Model

Simplified version of M. Aoki and T. Toma's Model (arXiv:1405.5870)

$$\mathcal{L}_N = \bar{\psi}(i\gamma^\mu \partial_\mu - m_\psi)\psi + |D_\mu \eta|^2 + |\partial\chi|^2 + \left(y_i^\nu \eta \bar{\psi} P_L L_i + \frac{y_\psi}{2} \chi \bar{\psi}^c \psi + \text{h.c.} \right) - V(H, \eta, \chi)$$

$$V(H,\eta,\chi) = \mu_H^2 |H|^2 + \mu_\eta^2 |\eta|^2 + \mu_\chi^2 |\chi|^2 + \frac{\lambda_1}{4}|H|^4 + \frac{\lambda_2}{4}|\eta|^4 + \frac{\lambda_\chi}{4}|\chi|^4$$
$$+ \lambda_3 |H|^2 |\eta|^2 + \lambda_4 (H^\dagger \eta)(\eta^\dagger H) + \lambda_{H\chi} |H|^2 |\chi|^2 + \lambda_{\eta\chi} |\eta|^2 |\chi|^2 + \left(\mu'_\chi (H^\dagger \eta)\chi^\dagger + \frac{\mu''_\chi}{3!} \chi^3 + \text{h.c.} \right)$$

- Single Component DM model: The advantage only allowed for semi-ann
- Fermionic DM: Simple $2 \to 2$ kinematics!
- Less constrained by-product: neutrino flux is hard to see!

Example Model

0

Build the Model

Simplified version of M. Aoki and T. Toma's Model (arXiv:1405.5870)

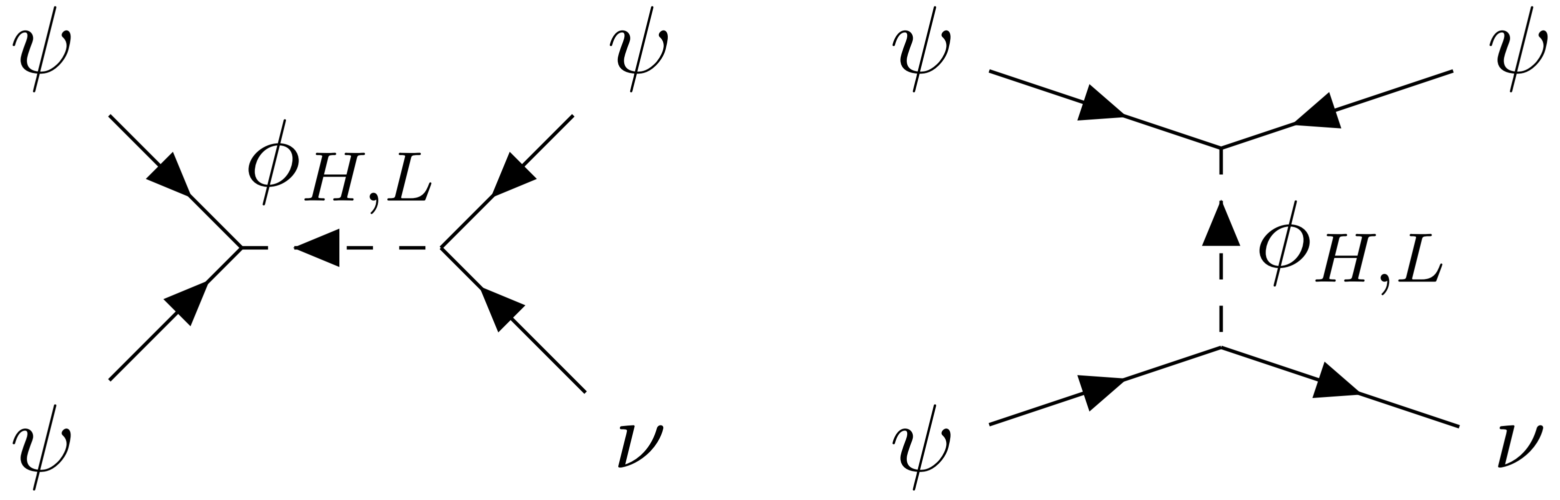
$$\mathcal{L}_N = \bar{\psi}(i\gamma^\mu \partial_\mu - m_\psi)\psi + |D_\mu \eta|^2 + |\partial \chi|^2 + \left(y_i^\nu \eta \bar{\psi} P_L L_i + \frac{y_\psi}{2} \chi \bar{\psi}^c \psi + \text{h.c.} \right) - V(H, \eta, \chi)$$

$$\begin{aligned} V(H,\eta,\chi) = {} & \mu_H^2 |H|^2 + \mu_\eta^2 |\eta|^2 + \mu_\chi^2 |\chi|^2 + \frac{\lambda_1}{4}|H|^4 + \frac{\lambda_2}{4}|\eta|^4 + \frac{\lambda_\chi}{4}|\chi|^4 \\ & + \lambda_3 |H|^2|\eta|^2 + \lambda_4 (H^\dagger \eta)(\eta^\dagger H) + \lambda_{H\chi}|H|^2|\chi|^2 + \lambda_{\eta\chi}|\eta|^2|\chi|^2 + \left(\mu'_\chi (H^\dagger \eta)\chi^\dagger + \frac{\mu''_\chi}{3!}\chi^3 + \text{h.c.} \right) \end{aligned}$$

	Role	$\mathrm{SU(2)_{EW}}$	VEV
ψ	DM	Singlet	-
χ	Additional Scalar	Singlet	0
η	Additional Scalar	Doublet: $\eta = (\eta^+ \ \eta^0)^T$	0

Higgs SSB

$$\begin{pmatrix} \eta^0 \\ \chi \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} \phi_H \\ \phi_L \end{pmatrix}$$



Semi-annihilation process

Example Model

0

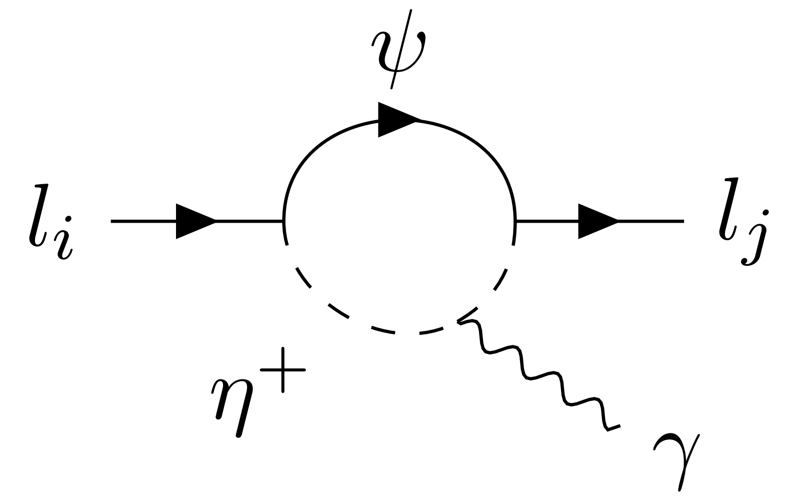
Build the Model

Simplified version of M. Aoki and T. Toma's Model (arXiv:1405.5870)

$$\mathcal{L}_N = \bar{\psi}(i\gamma^\mu \partial_\mu - m_\psi)\psi + |D_\mu \eta|^2 + |\partial\chi|^2 + \left(y_i^\nu \eta \bar{\psi} P_L L_i + \frac{y_\psi}{2} \chi \bar{\psi}^c \psi + \text{h.c.} \right) - V(H, \eta, \chi)$$

$$\begin{aligned} V(H,\eta,\chi) &= \mu_H^2 |H|^2 + \mu_\eta^2 |\eta|^2 + \mu_\chi^2 |\chi|^2 + \frac{\lambda_1}{4}|H|^4 + \frac{\lambda_2}{4}|\eta|^4 + \frac{\lambda_\chi}{4}|\chi|^4 \\ &+ \lambda_3 |H|^2 |\eta|^2 + \lambda_4 (H^\dagger \eta)(\eta^\dagger H) + \lambda_{H\chi}|H|^2|\chi|^2 + \lambda_{\eta\chi}|\eta|^2|\chi|^2 + \left(\mu'_\chi (H^\dagger \eta)\chi^\dagger + \frac{\mu''_\chi}{3!}\chi^3 + \text{h.c.} \right) \end{aligned}$$

DM couples only to the electron (among leptons) - for simplicity and to evade LFV constraints



Example of LFV

Total seven parameters for DM relic:
m_ψ (DM mass), $m_{\phi_{L,H}}$ (semi-ann mediator masses), m_η^+, α (Mixing angle), y_ν, y_ψ

Relic Density Parameter Scan

First Constraint on parameters

1

Constraint 1:
Relic Density Analysis

Parametric Estimate

$$\langle\sigma v\rangle_{\text{ann}} + \langle\sigma v\rangle_{\text{sa}} \approx \frac{y_\nu^4}{64\pi}\frac{m_\psi^2}{m_{\phi_H}^4}\left[\frac{(s_\alpha^2 m_{\phi_H}^2 + c_\alpha^2 m_{\phi_L}^2)^2}{m_{\phi_L}^4} + \frac{m_{\phi_H}^4}{m_{\eta^+}^4} + \frac{729}{64}\frac{y_\psi^2}{y_\nu^2}\frac{s_\alpha^2 c_\alpha^2 (m_{\phi_H}^2 - m_{\phi_L}^2)^2}{m_{\phi_L}^4}\right] \approx 2 \times \frac{1.07\times 10^9\ \text{GeV}^{-1}}{\sqrt{g_*}M_{\text{pl}}}\frac{x_f}{\Omega_\psi h^2}$$

(For $m_e \ll m_\psi \ll m_{\phi_{L,H}}, m_{\eta^+}$ limit)

We take this relation as a guide for setting the scan ranges.
A Monte-Carlo scan then maps out
which regions of the parameter space remain viable.

m_ψ	$m_{\phi_{L,H}}$	λ_4	y_ν, y_ψ	s_α
$[0.01, 10]$ GeV	$[m_\psi, 1\ \text{TeV}]$	$[-3.5, 3.5]$	$[0.5, 3.5]$	$[10^{-3}, 0.5]$

$$m_{\eta^+}^2 = m_{\phi_H}^2\cos^2\alpha + m_{\phi_L}^2\sin^2\alpha - \tfrac{1}{2}\lambda_4 v^2$$

BDM Detectability

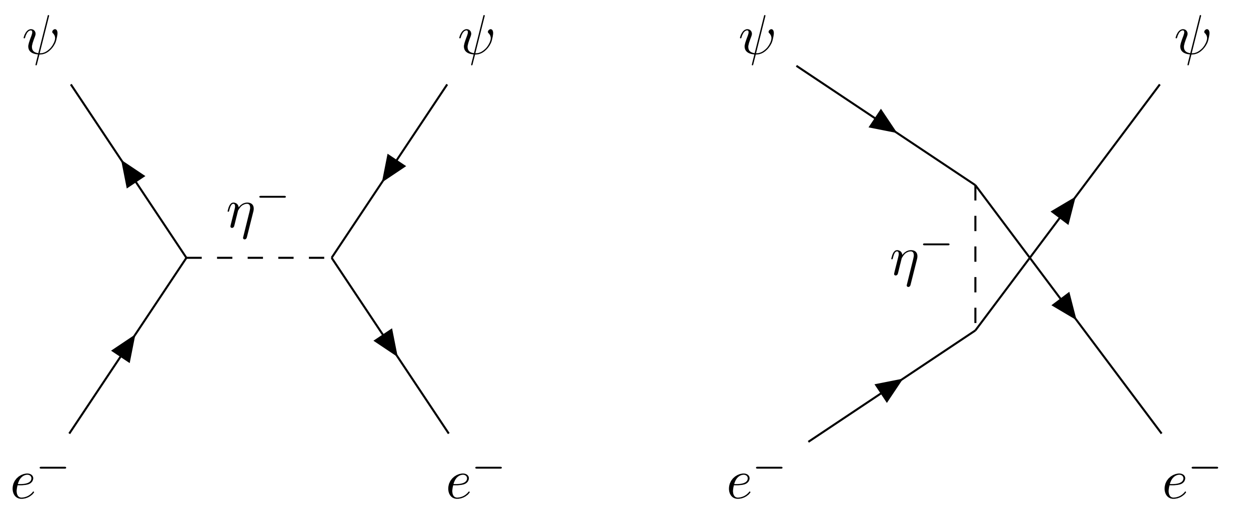
Two kinds of the targets: electron and nucleus

$$\frac{1}{m_T}\frac{dR}{dE_R} \approx \frac{3.2\times 10^{-3}}{m_T}\left(\frac{100\,\mathrm{MeV}}{m_\psi}\right)^2\left(\frac{\langle\sigma v\rangle_{\mathrm{sa}}}{10^{-26}\,\mathrm{cm^3 s^{-1}}}\right)\underline{\left.\frac{d\sigma_{\mathrm{el}}}{dE_R}\right|_{E_K=E_f}}\ \mathrm{cm^2\ s^{-1}}$$

5 Elastic scattering cross-section

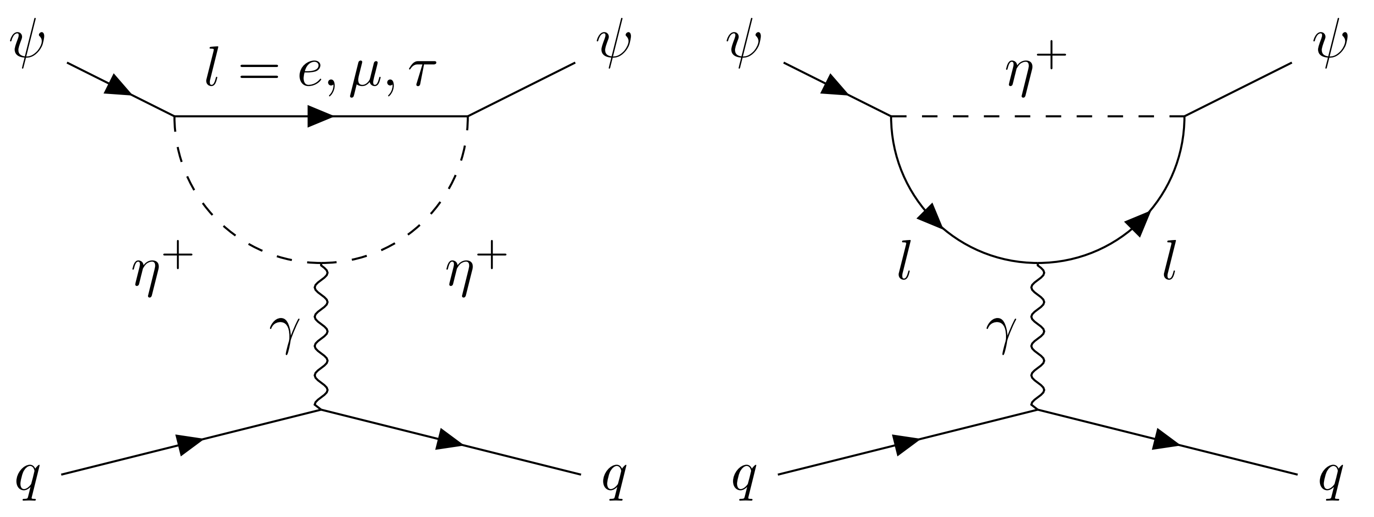
6 BDM Flux

Electron Target



$$\left.\frac{d\sigma_{\mathrm{el}}}{dE_R}\right|_{E\ =5m_\psi/4} = \frac{25 m_e y_\nu^4}{576\pi(m_{\eta^+}^2 - m_\psi^2)^2}\left(\left(1+\frac{4E_R}{5m_\psi}\right)^2+1\right)$$
$$= \frac{25 m_e}{9 m_\psi^2}\frac{(m_{\eta^0}^2 + m_\psi^2)^2}{(m_{\eta^+}^2 - m_\psi^2)^2}\left(\left(1+\frac{4E_R}{5m_\psi}\right)^2+1\right)\langle\sigma v\rangle_{\mathrm{ann},e\bar{e}}$$

Nuclear Target



(One-loop suppressed but still comparable to electron target)

Dipole Form Factor is used

$$\frac{d\sigma}{dE_R} = \frac{\sigma^{\mathrm{coh}}}{E_{R,\mathrm{max}}}F^2(q^2) + \frac{\sigma^{\mathrm{inc}}}{E_{R,\mathrm{max}}}(1-F^2(q^2)) \qquad F(q^2) = \left(1+\frac{q^2}{\Lambda^2}\right)^{-2}$$

$$\sigma^{\mathrm{coh}} = Z^2\left(\frac{m_T}{m_p}\frac{m_\psi + m_p}{m_\psi + m_T}\right)^2\sigma_{\psi p},\quad \sigma^{\mathrm{inc}} = Z\sigma_{\psi p}$$

$$E_{R,\mathrm{max}} = \frac{T_\psi^2 + 2m_\psi T_\psi}{T_\psi + (m_\psi + m_T)^2/2m_T} \to \frac{9}{4}\frac{m_\psi^2 m_T}{m_\psi m_T + 2(m_\psi + m_T)^2}$$

See 1405.5870 for $\sigma_{\psi p}$

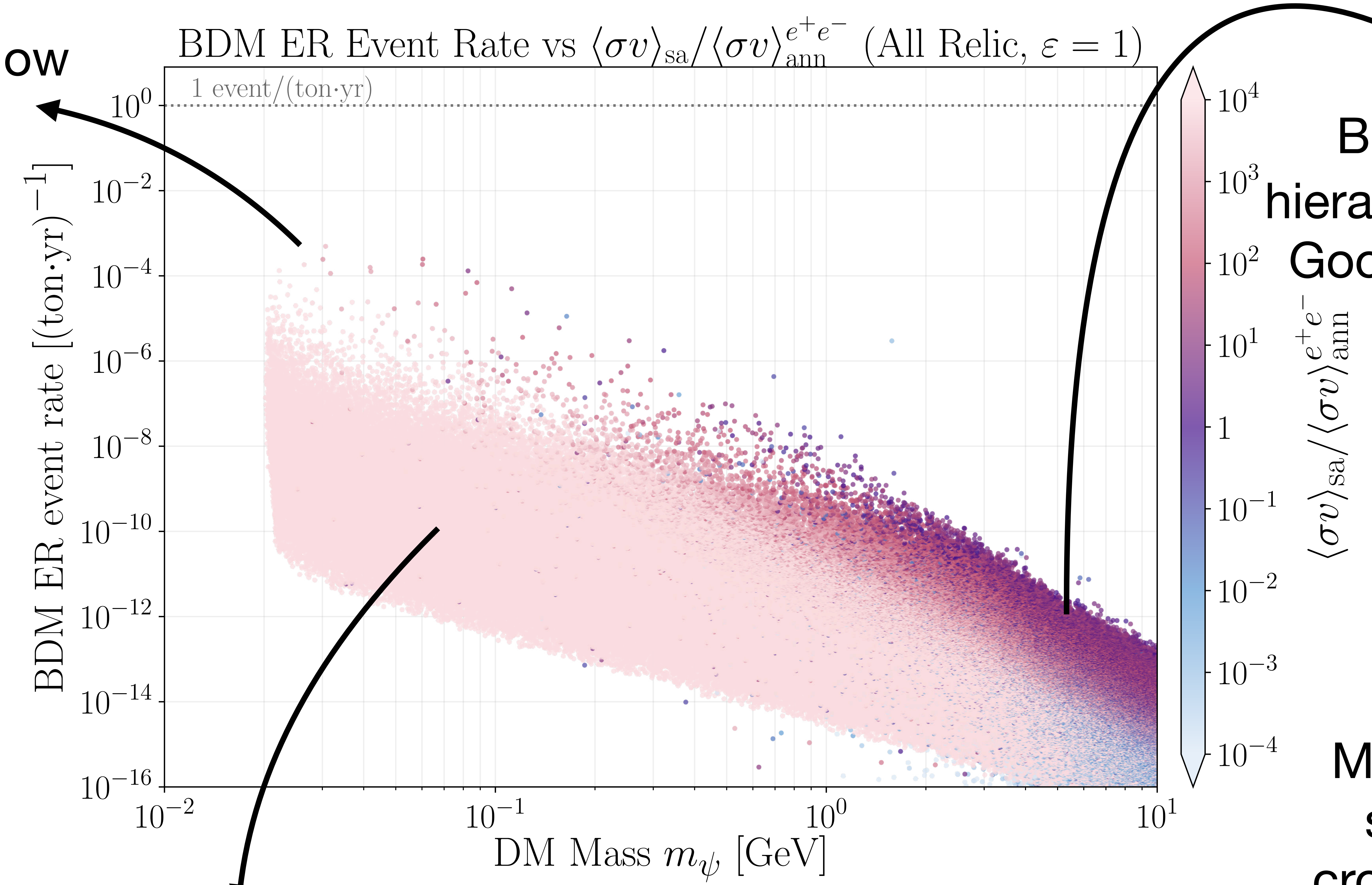
BDM Detectability: Few Remarks

7

BDM Detection

<u>Before</u> considering *other bounds*

BDM detectability is too low even before excluding experimental bounds



High mass region:
Both $\langle\sigma v\rangle_{\rm sa} \sim \langle\sigma v\rangle_{\rm ann}$ and hierarchical regimes are available:
Good parameter regime for test

$$\frac{dR}{dE_R} \propto \mathcal{B}_{\psi\to f}\langle\sigma v\rangle_{\rm sa}(\sigma v)_{\rm ann}$$

Maximum detectability when semi-ann and annihilation cross-section are comparable!

Low mass region:
No parameter space for $\langle\sigma v\rangle_{\rm sa} \sim \langle\sigma v\rangle_{\rm ann}$

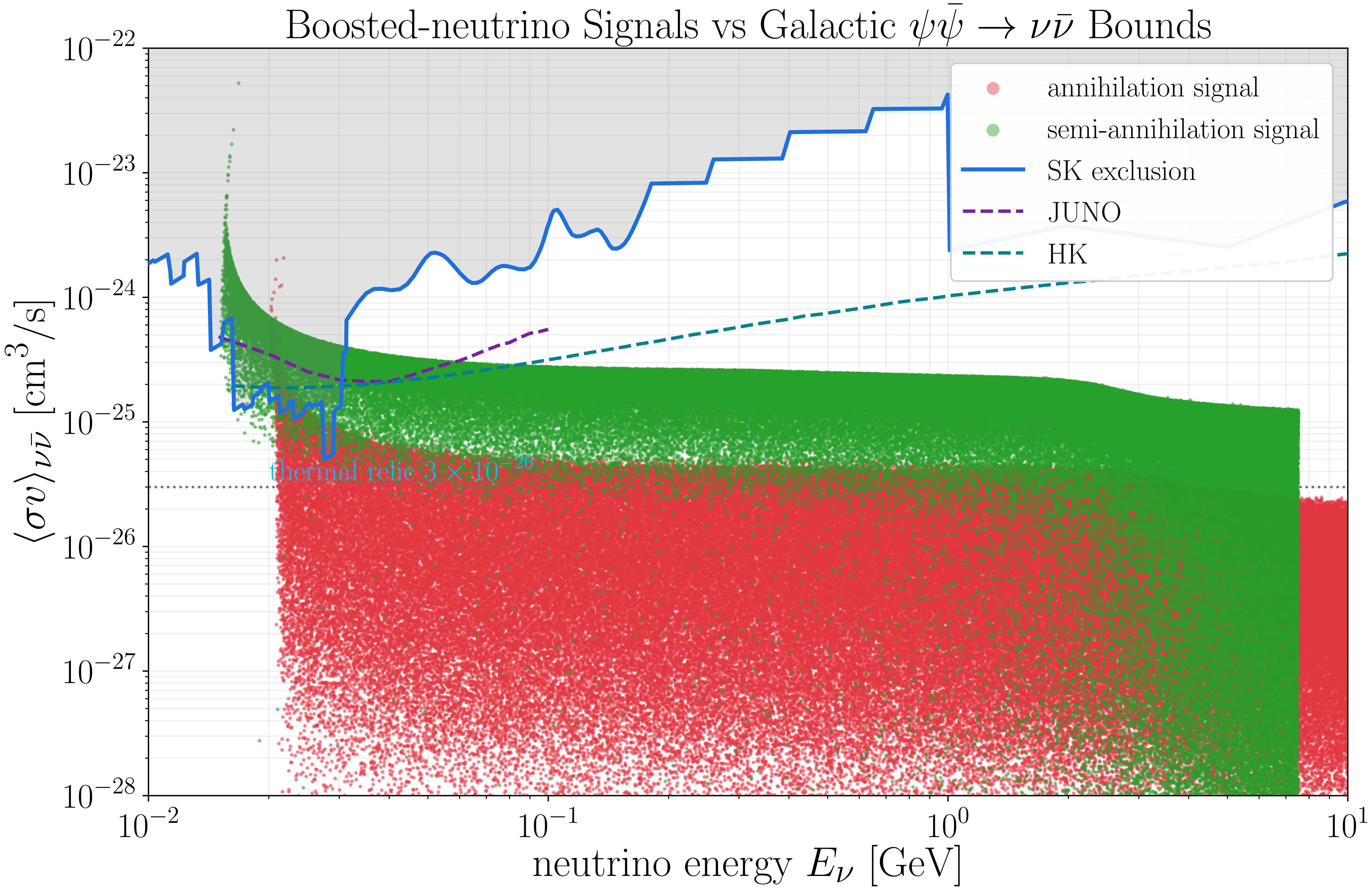
DM semi-ann dominates its relic for low mass region

Boosted By-product

Boosted Neutrino!

2 3

Constraint 2:
Indirect Detection Signal



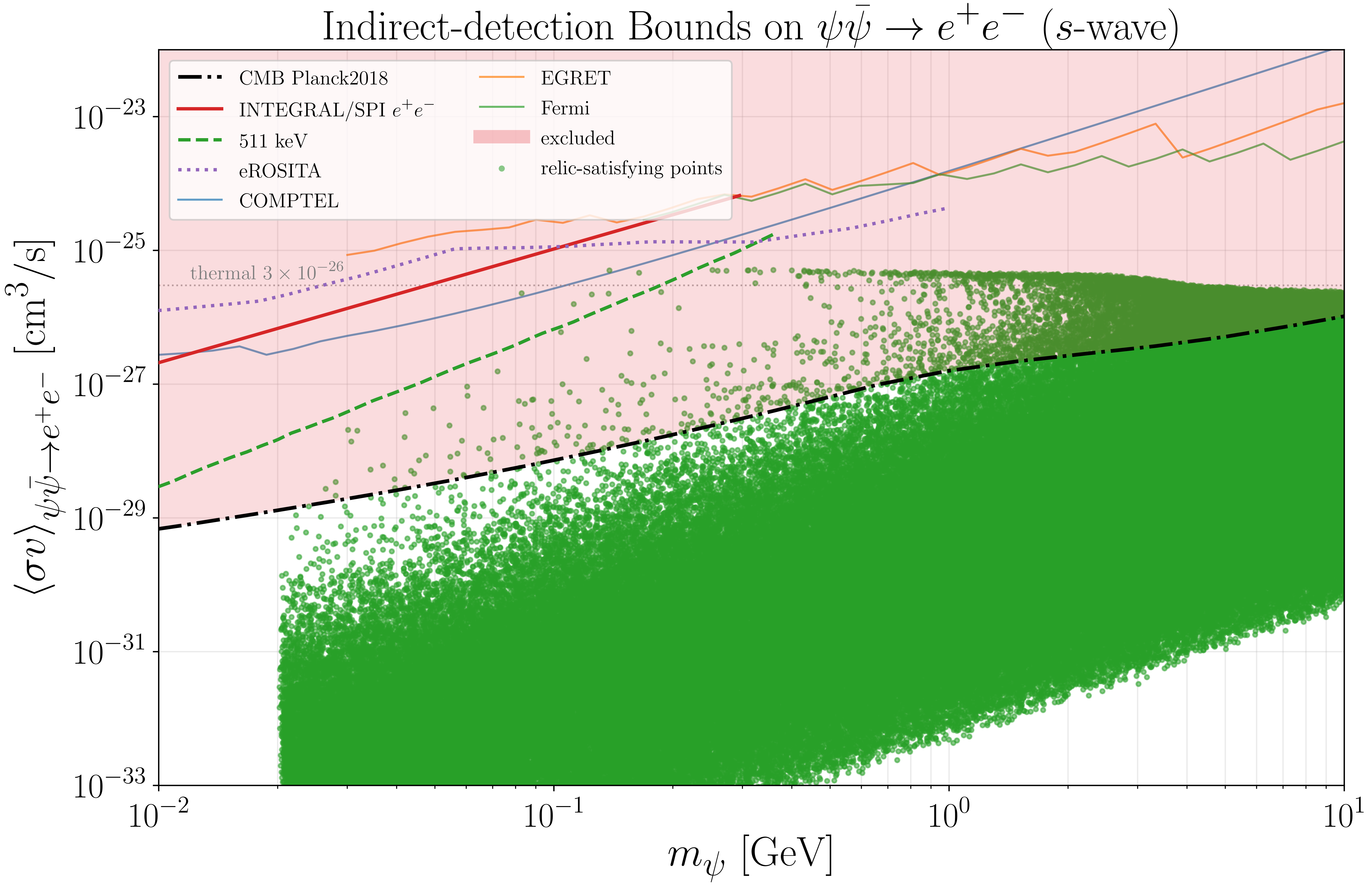
Significant neutrino flux from semi-annihilation

Model Specific Bounds

Bound from $\psi\bar{\psi} \to e^+e^-$

4

Constraint 3:
Model dependent Constraints



Strong bounds from CMB anisotropy

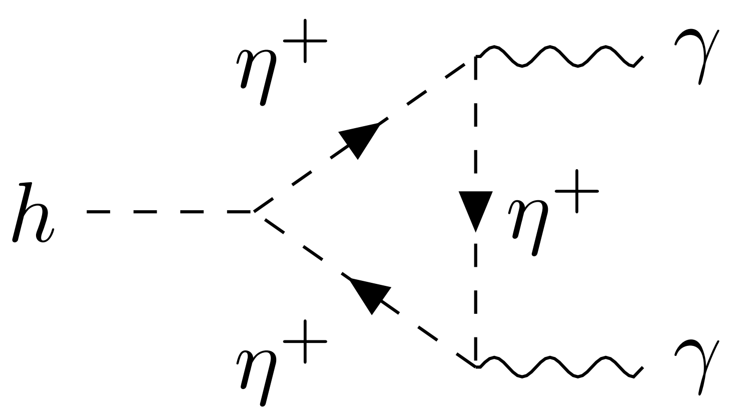
Model Specific Bounds

Bound from Collider

4

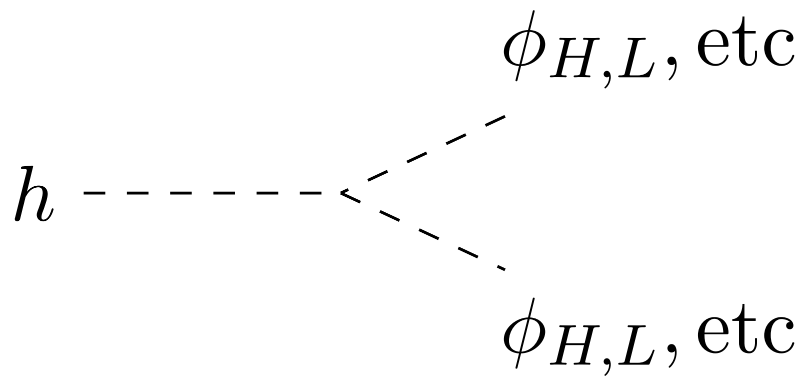
Constraint 3:
Model dependent Constraints

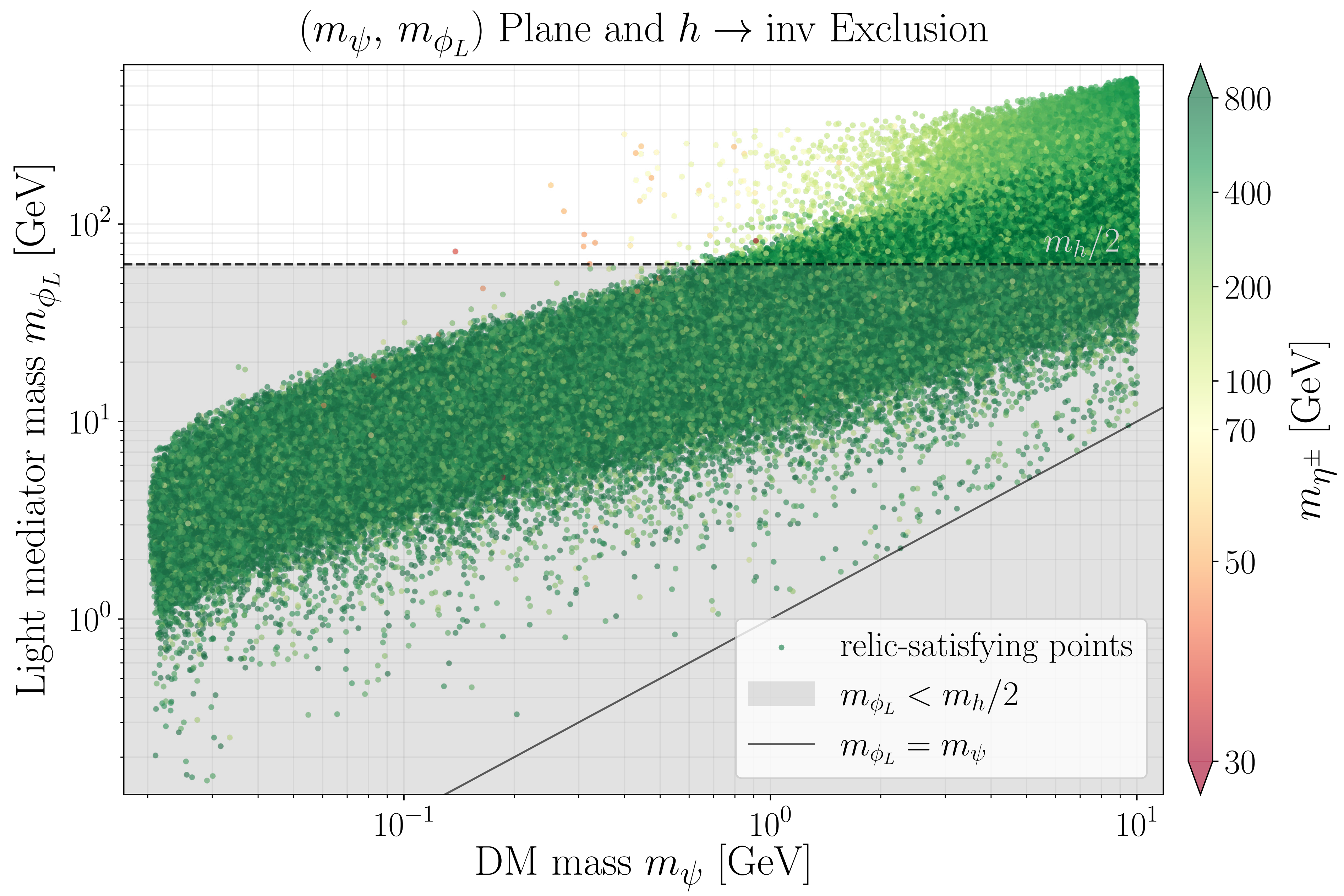
$$h \to \gamma\gamma$$



$$|\lambda_3| \lesssim \mathcal{O}(1)\,(m_{\eta^\pm}/100\text{ GeV})^2$$

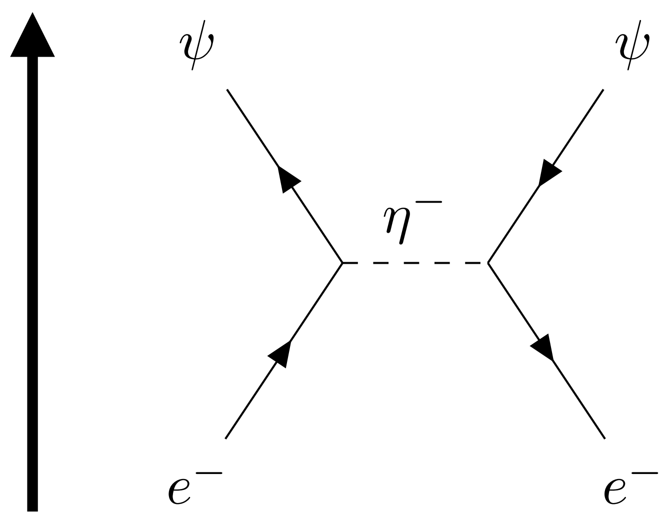
$$h \to \text{inv}$$





Note: Gray region is approximate bound.
Some points within the gray region survive due to their low branching ratios.

Charged LEP



Limit from $e^+e^- \to \eta^+\eta^-$:

$$m_{\eta^+} \gtrsim 70\text{ GeV}$$

BDM Detectability

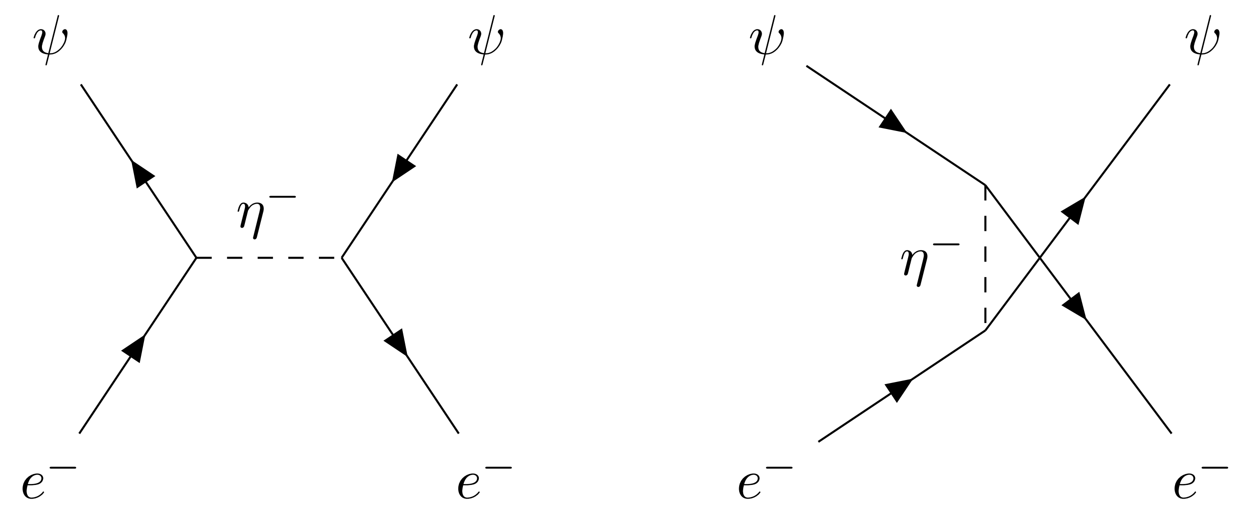
5 Elastic scattering cross-section

6 BDM Flux

Two kinds of the targets: electron and nucleus

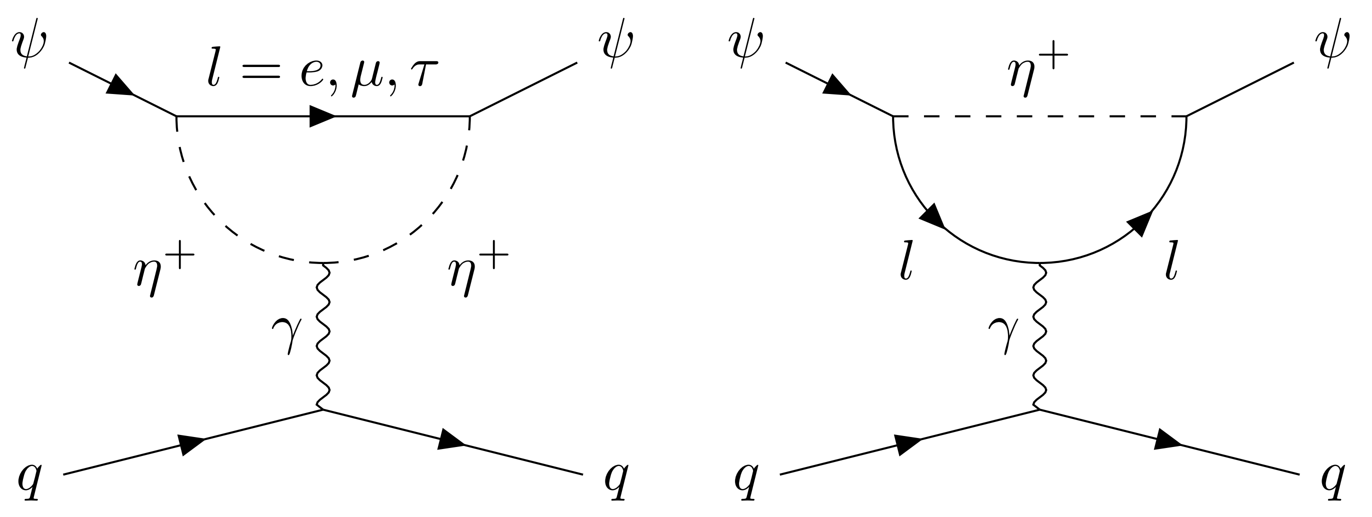
$$\frac{1}{m_T}\frac{dR}{dE_R} \approx \frac{3.2\times 10^{-3}}{m_T}\left(\frac{100\,\mathrm{MeV}}{m_\psi}\right)^2\left(\frac{\langle\sigma v\rangle_{\mathrm{sa}}}{10^{-26}\,\mathrm{cm^3 s^{-1}}}\right)\underline{\left.\frac{d\sigma_{\mathrm{el}}}{dE_R}\right|_{E_K=E_f}}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$$

Electron Target



$$\left.\frac{d\sigma_{\mathrm{el}}}{dE_R}\right|_{E\ \ =5m_\psi/4} = \frac{25 m_e y_\nu^4}{576\pi(m_{\eta^+}^2 - m_\psi^2)^2}\left(\left(1+\frac{4E_R}{5m_\psi}\right)^2+1\right)$$
$$= \frac{25 m_e}{9 m_\psi^2}\frac{(m_{\eta^0}^2+m_\psi^2)^2}{(m_{\eta^+}^2-m_\psi^2)^2}\left(\left(1+\frac{4E_R}{5m_\psi}\right)^2+1\right)\langle\sigma v\rangle_{\mathrm{ann},e\bar{e}}$$

Nuclear Target



(One-loop suppressed but still comparable to electron target)

Dipole Form Factor is used

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$$\sigma^{\mathrm{coh}} = Z^2\left(\frac{m_T}{m_p}\frac{m_\psi+m_p}{m_\psi+m_T}\right)^2\sigma_{\psi p}, \quad \sigma^{\mathrm{inc}} = Z\sigma_{\psi p}$$

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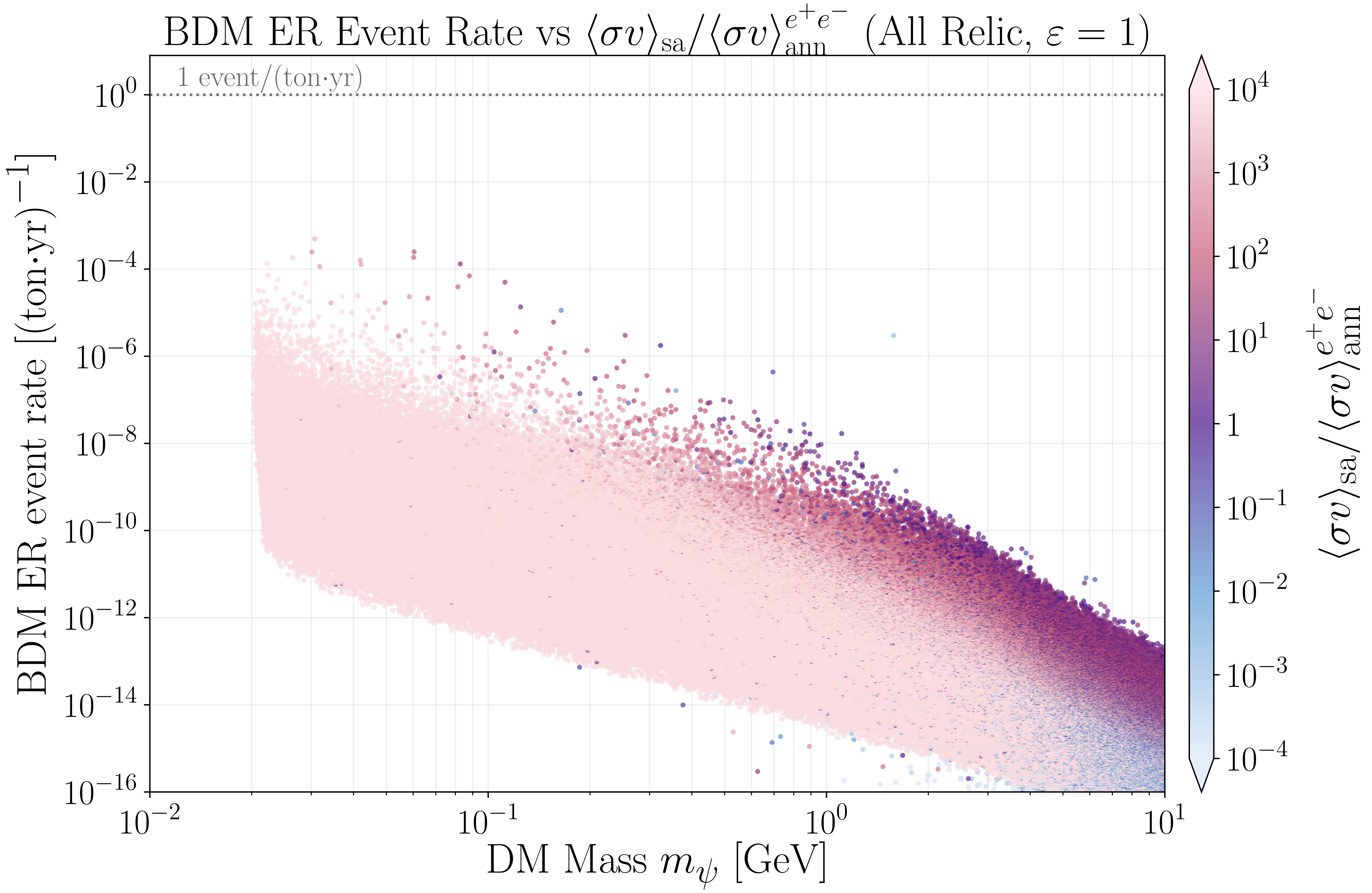
See 1405.5870 for $\sigma_{\psi p}$

BDM Detectability

How phenomenological bounds carve BDM detectability

7

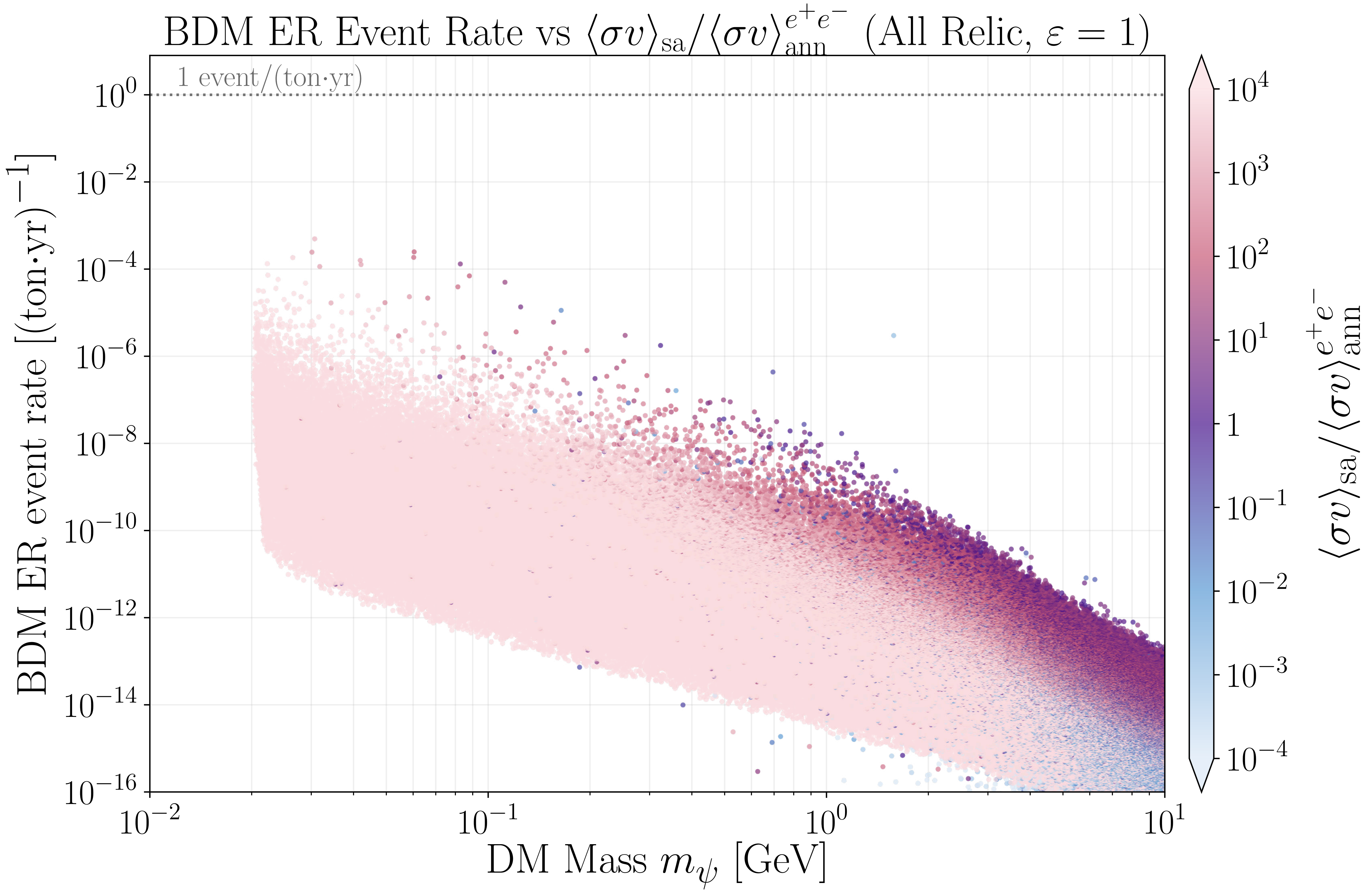
BDM Detection



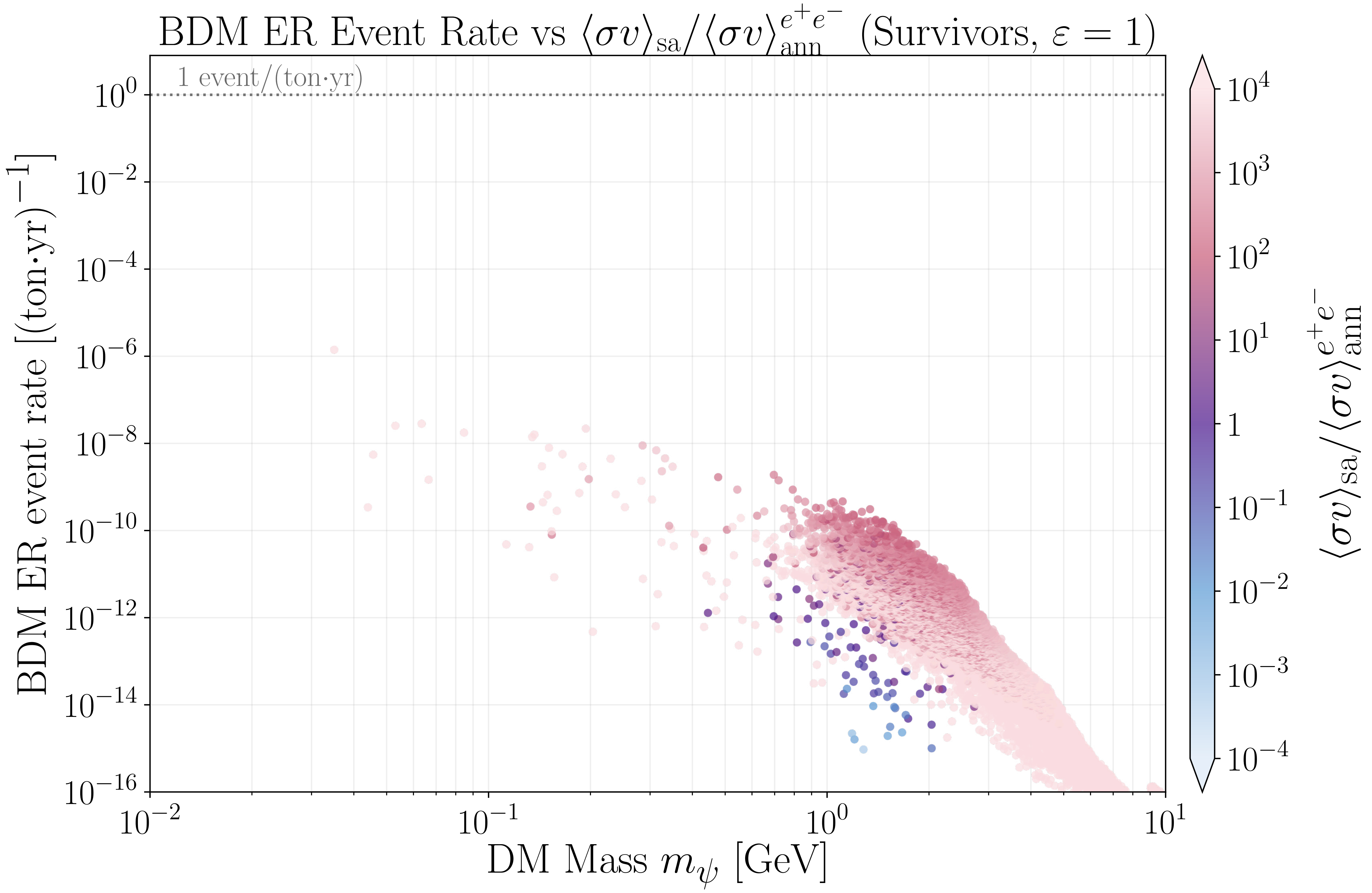
<u>Before</u> excluding experimental bounds

BDM Detectability

How phenomenological bounds carve BDM detectability



Before excluding experimental bounds



After excluding experimental bounds

Few survivors with lower detectability!

Conclusion

- Boosting Dark matter via semi-annihilation is well motivated due to its simplicity.
  But the general methodology for analyzing Semi-ann BDM model has not been developed.

- We argue careful analysis is needed for the semi-ann BDM model.
  In particular, their annihilation and by-product detectability are important.

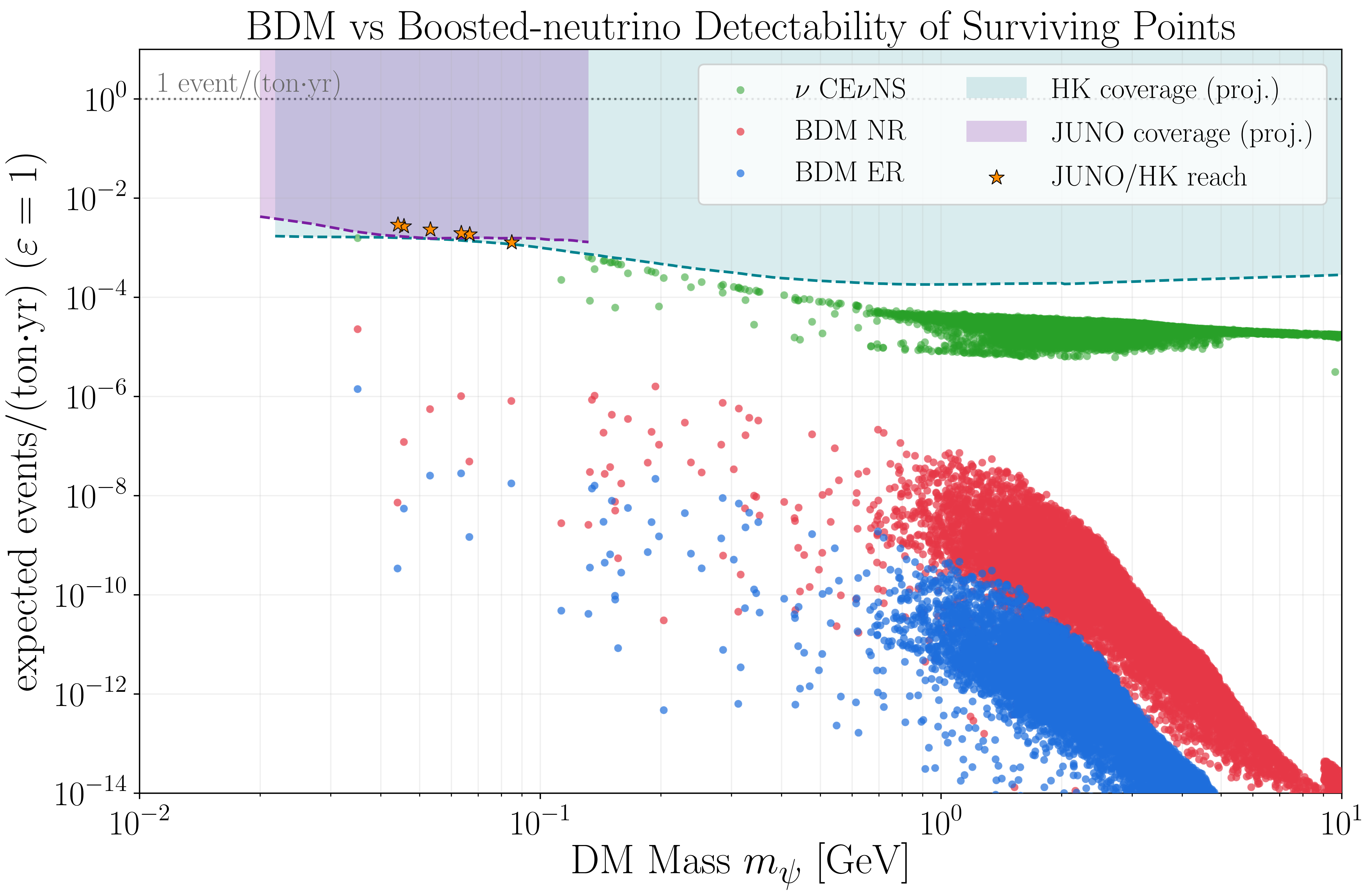
- We apply our methodology to a simple model with $\psi\psi \to \psi^c \nu$
  There, the neutrino signal outpaces the BDM signal, suggesting that a realistic semi-annihilating BDM model is not easy to construct.

Thank You For Your Attention!

Backup

Comparison

Boosted DM vs Boosted Neutrino



In this example model, BDM is produced but by-product is far more visible!