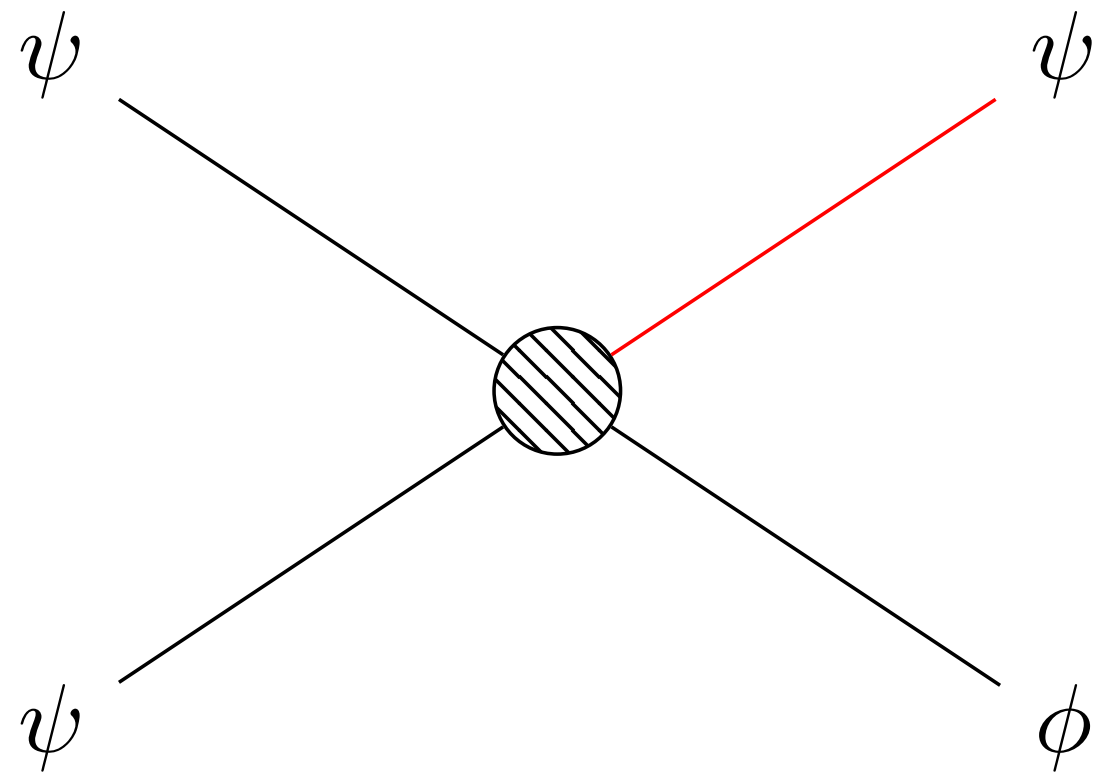




General Perspective on Boosted Dark Matter from Semi-annihilation

Seongsik Kim

With Jong-Chul Park,

Chungnam National University

Work in progress (2608.XXXXX)

12th Workshop on Flavor Symmetries and Consequences in Accelerators and Cosmology

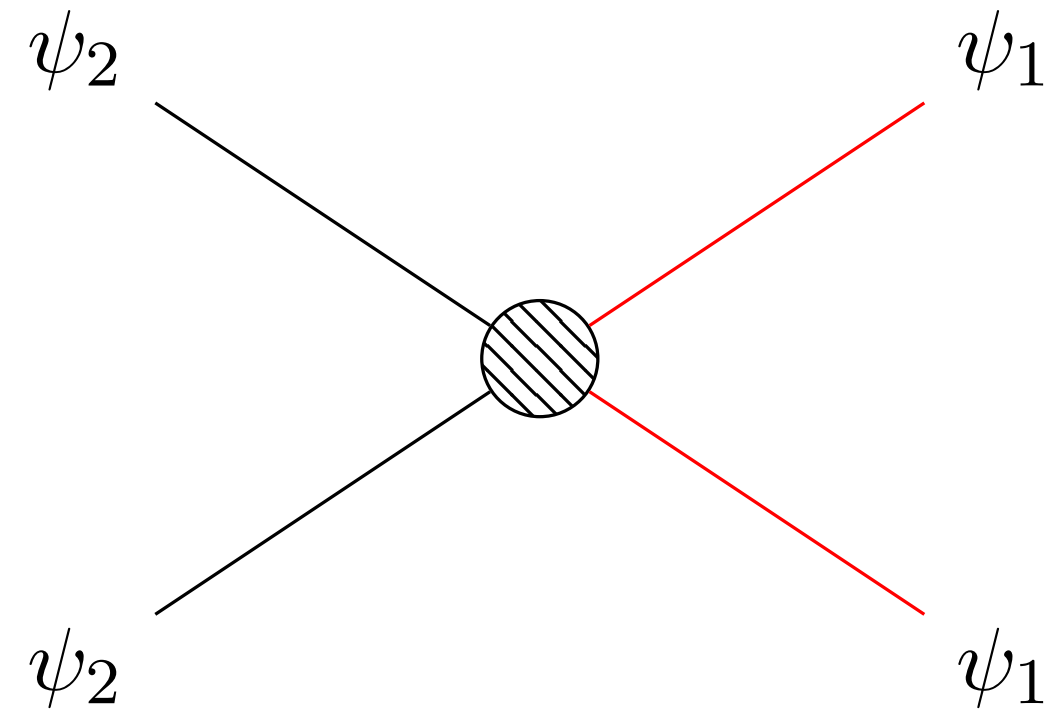
Boosted Dark Matter

Note: Throughout this talk, we denote DM as ψ

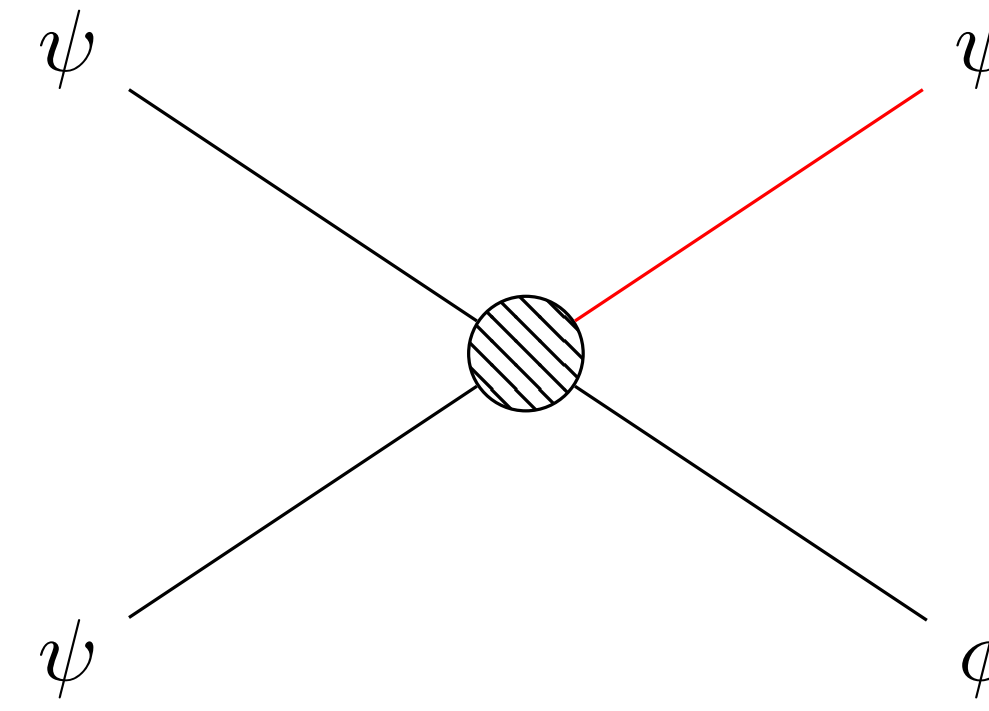
Dark Matter particle with sufficient kinetic energy

Particle Model

Multi-component DM

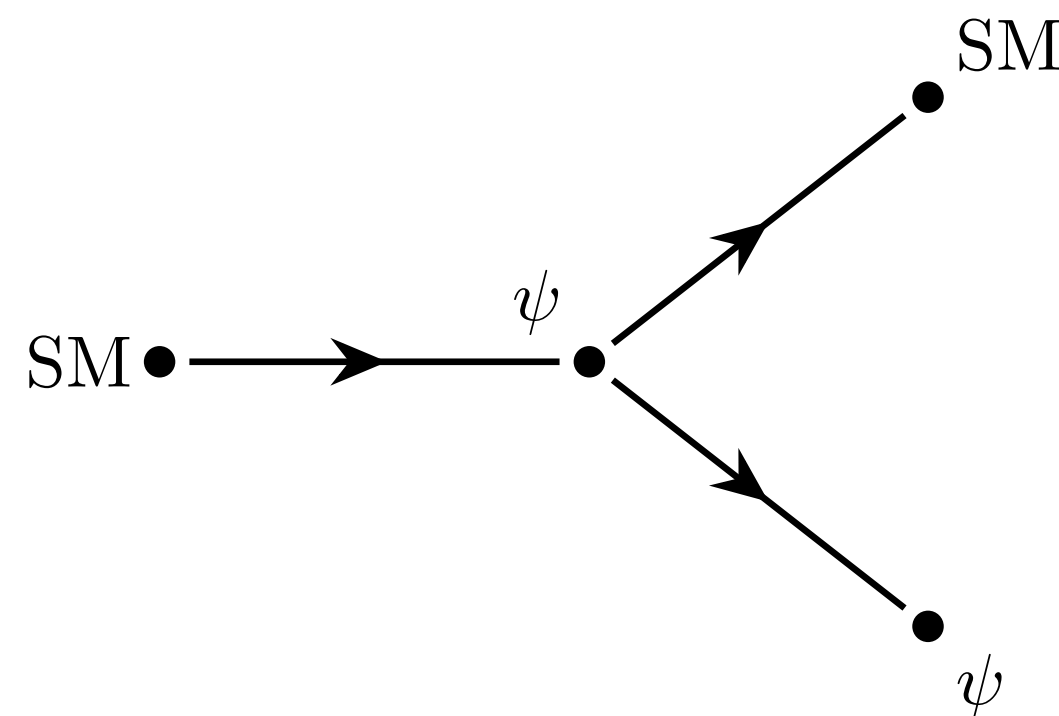


Semi-annihilation

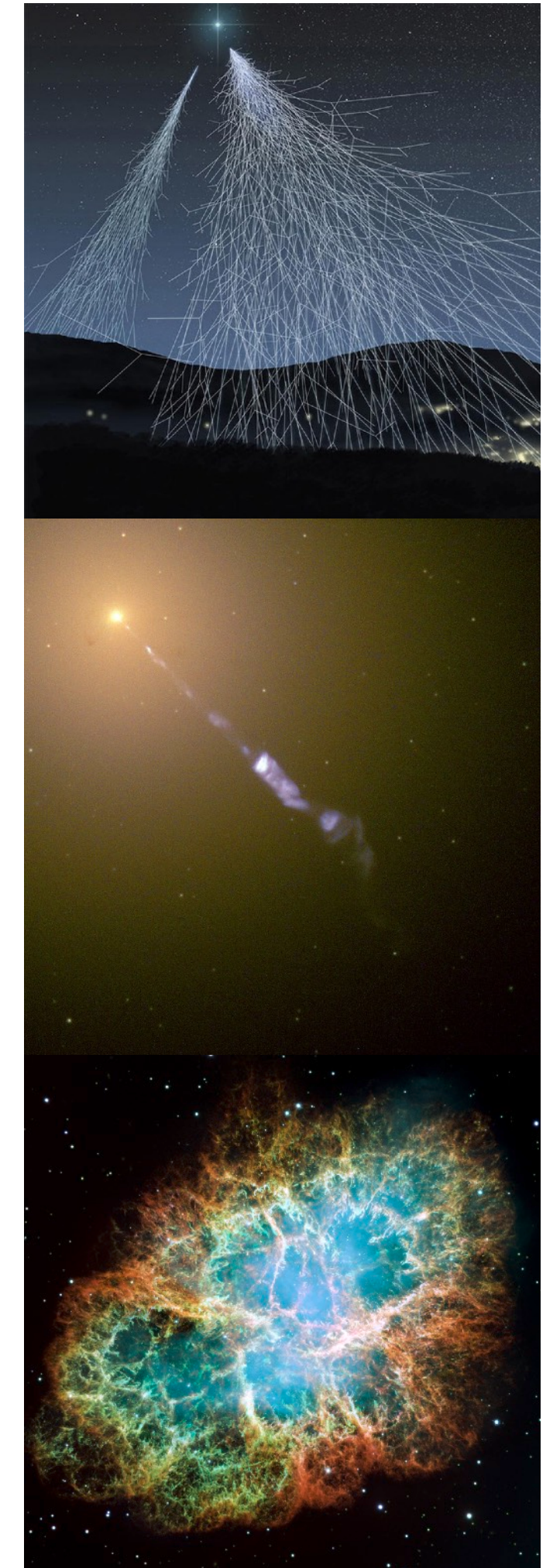


Scattering by High-Energy Particle

Astrophysical Source

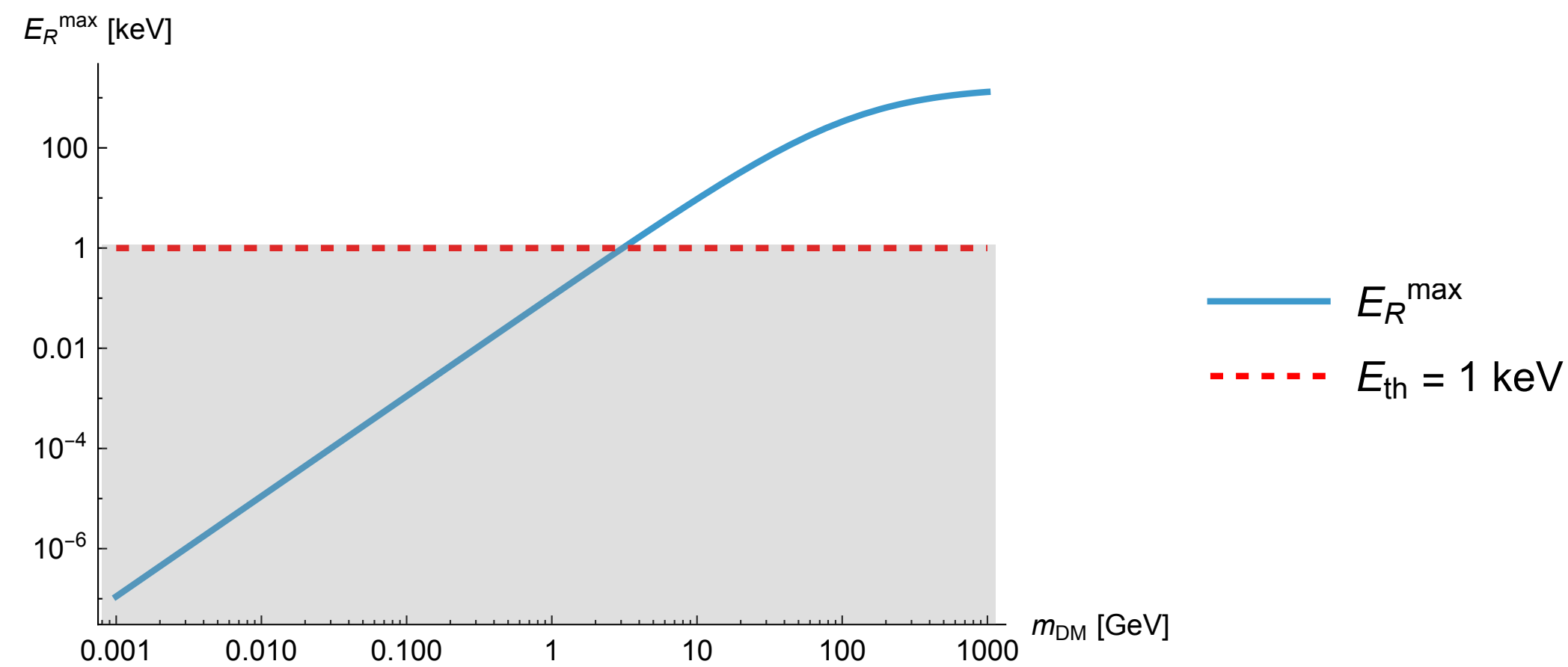


Cosmic-Ray e , p , ν , ...
(Blazar Jet, Stars,
Supernovae, PBHs,
etc)



Kinematics

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

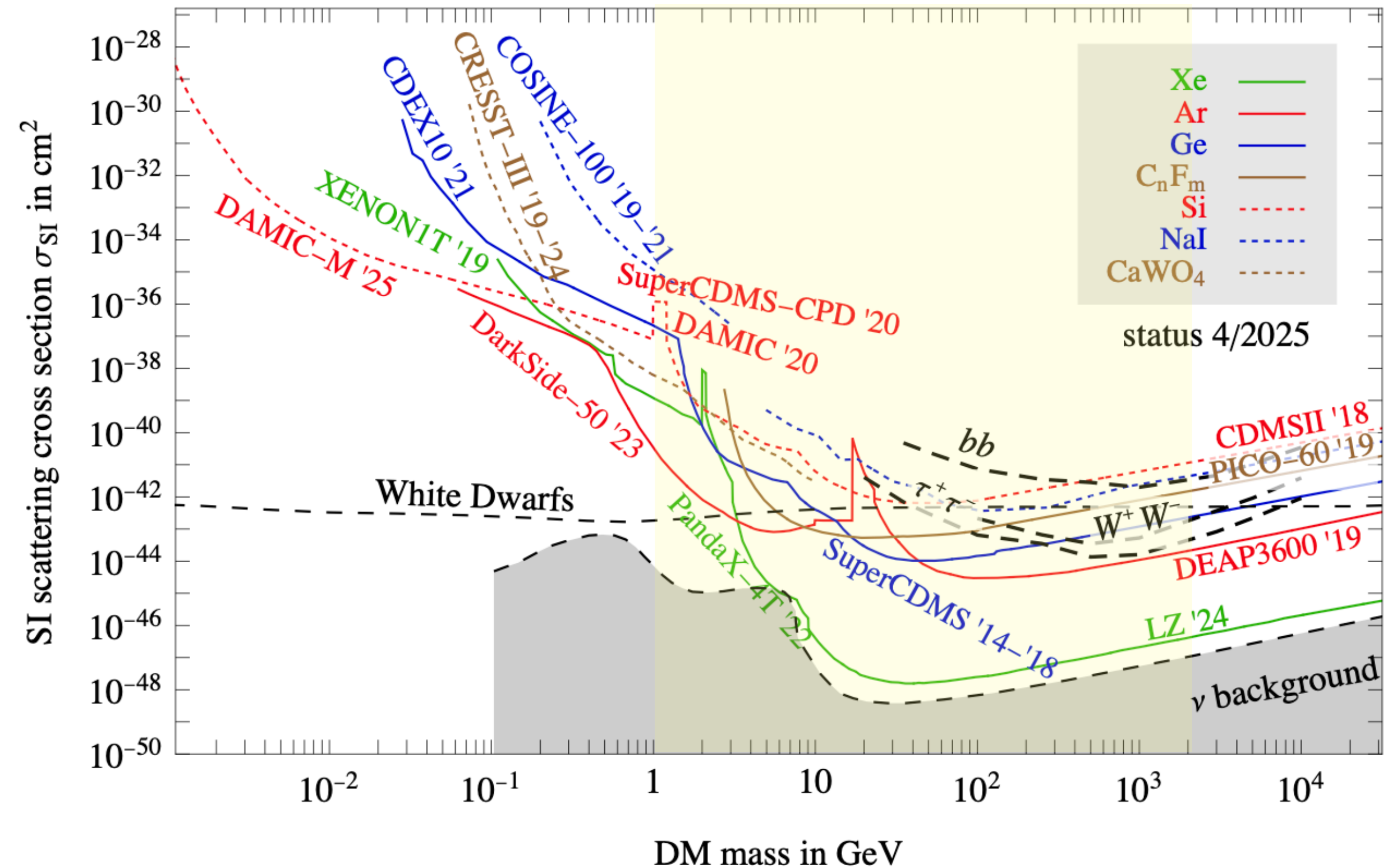


For virialized DM, only sufficiently heavy DM deposits recoil energy above the detector threshold.

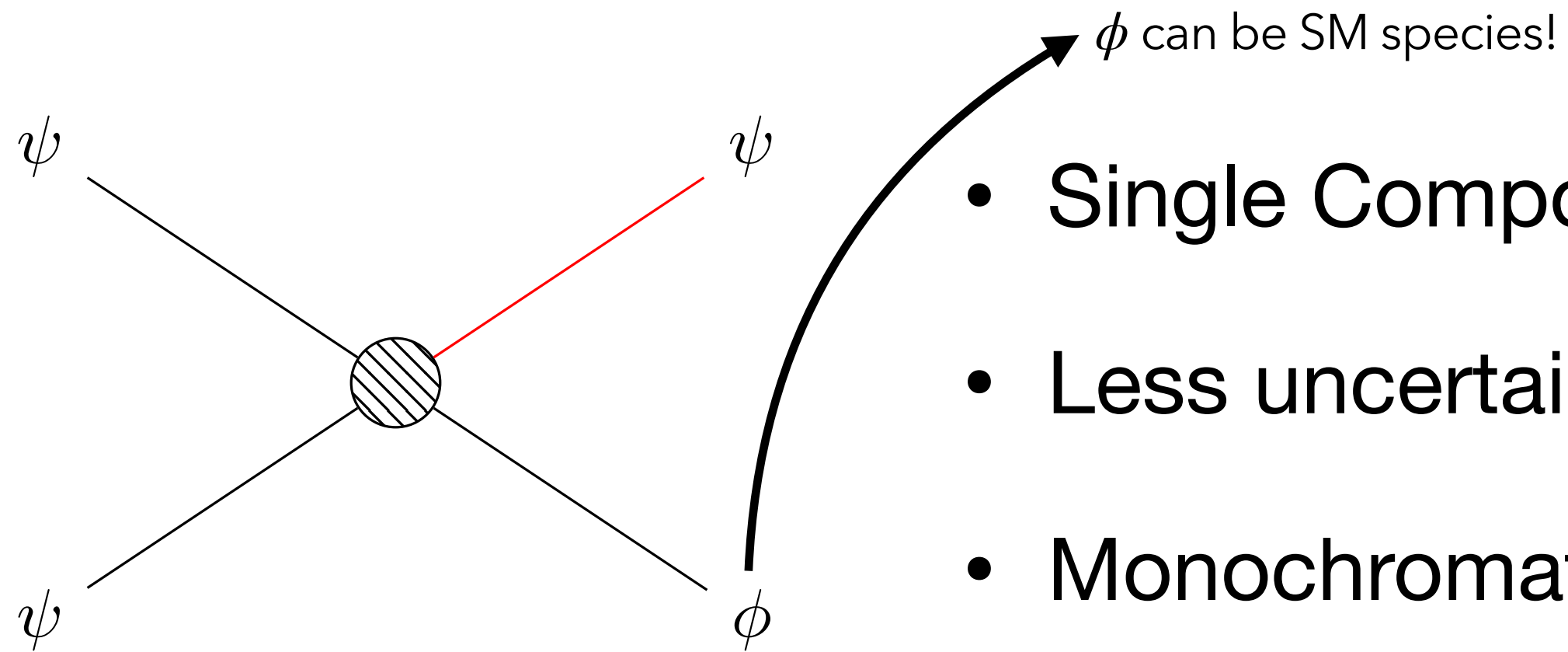
Note: $v_{\max} \approx 776 \text{ km/s}$, $m_T = m(^{131}\text{Xe}) \approx 122 \text{ GeV}$ are used in the graph

M. Cirelli, A. Strumia, J. Zupan
arXiv:2406.01705v3

Direct Detection constraints on SI scattering



Boosted Dark Matter from Semi-annihilation



- 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

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 and J. Zhao 2306.14091

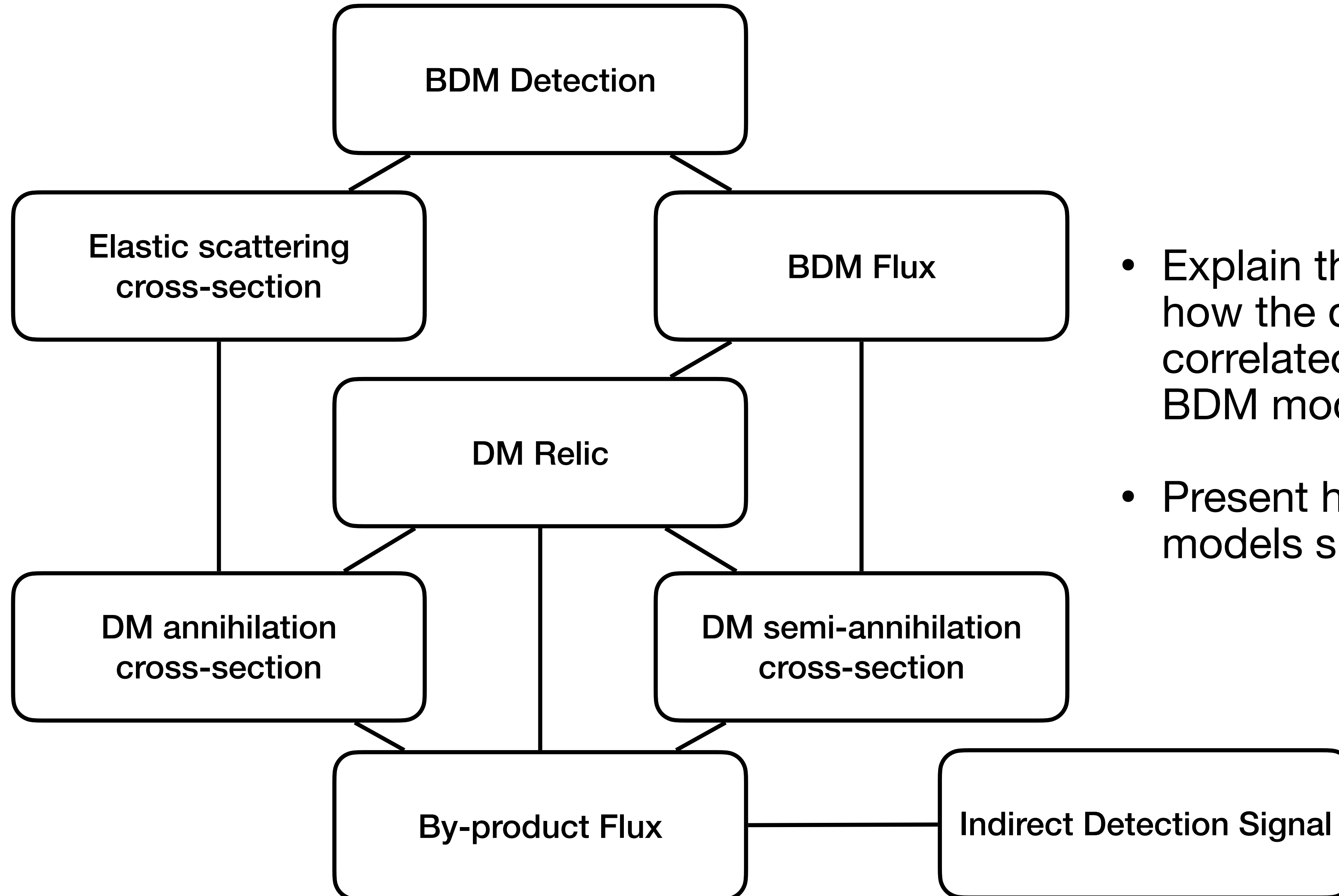
M. Aoki, T. Toma 2309.00395 / B. B. Kamenetskaia, M. Fujiwara, A. Ibarra, T. Toma 2501.12117

J. Davighi, S. Moldovsky, H. Murayama, C. Scherb, N. Selimovic 2506.05468 / M. Fujiwara, T. Toma 2606.02751

And much more!

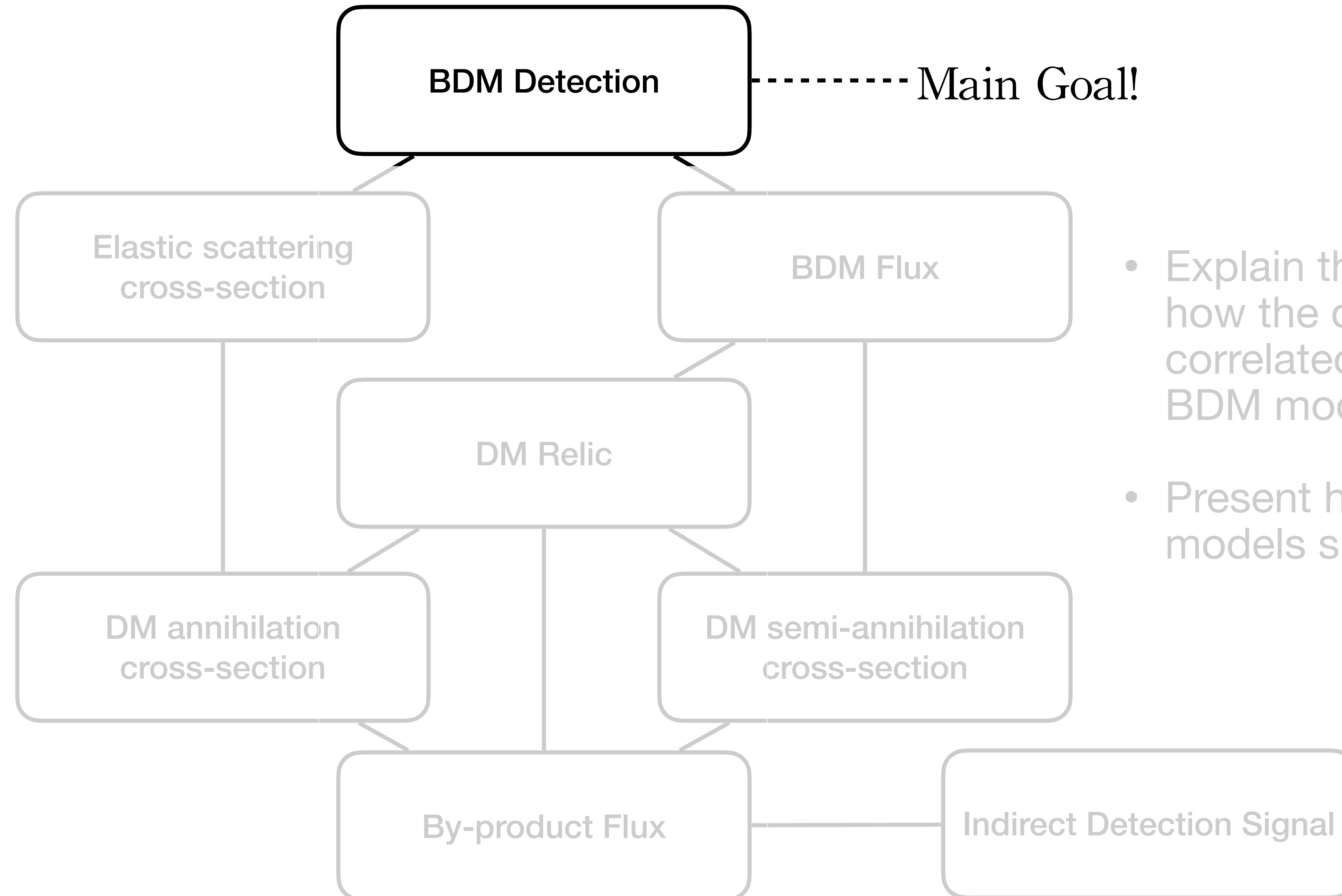
Only a few work address this point

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

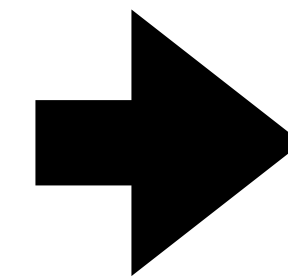
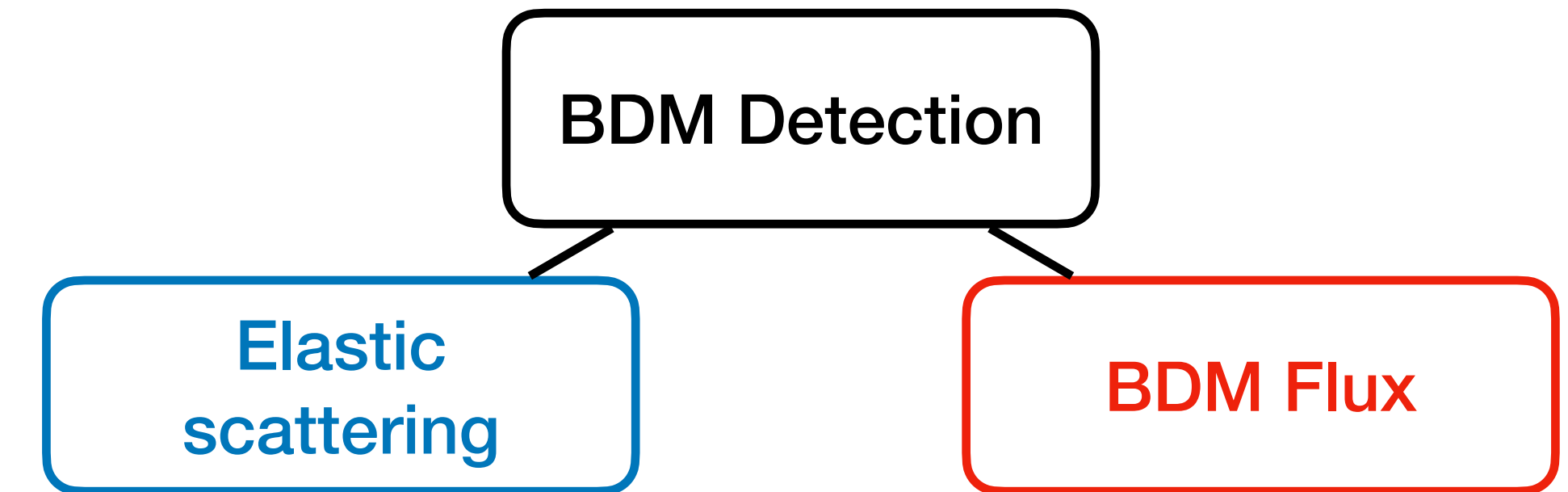
$$\begin{aligned}\frac{d\Phi}{dE_K} &= \frac{1}{2} \frac{1}{4\pi} \langle \sigma v \rangle_{\text{sa}} \frac{dN}{dE_K} \int d\Omega \int_{\text{l.o.s}} ds \left(\frac{\rho_{\psi}^{\text{MW}}}{m_{\psi}} \right)^2 \\ &= \frac{\langle \sigma v \rangle_{\text{sa}}}{8\pi m_{\psi}^2} \frac{dN}{dE_K} J\end{aligned}$$

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

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

Differential Rate per target mass

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



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

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

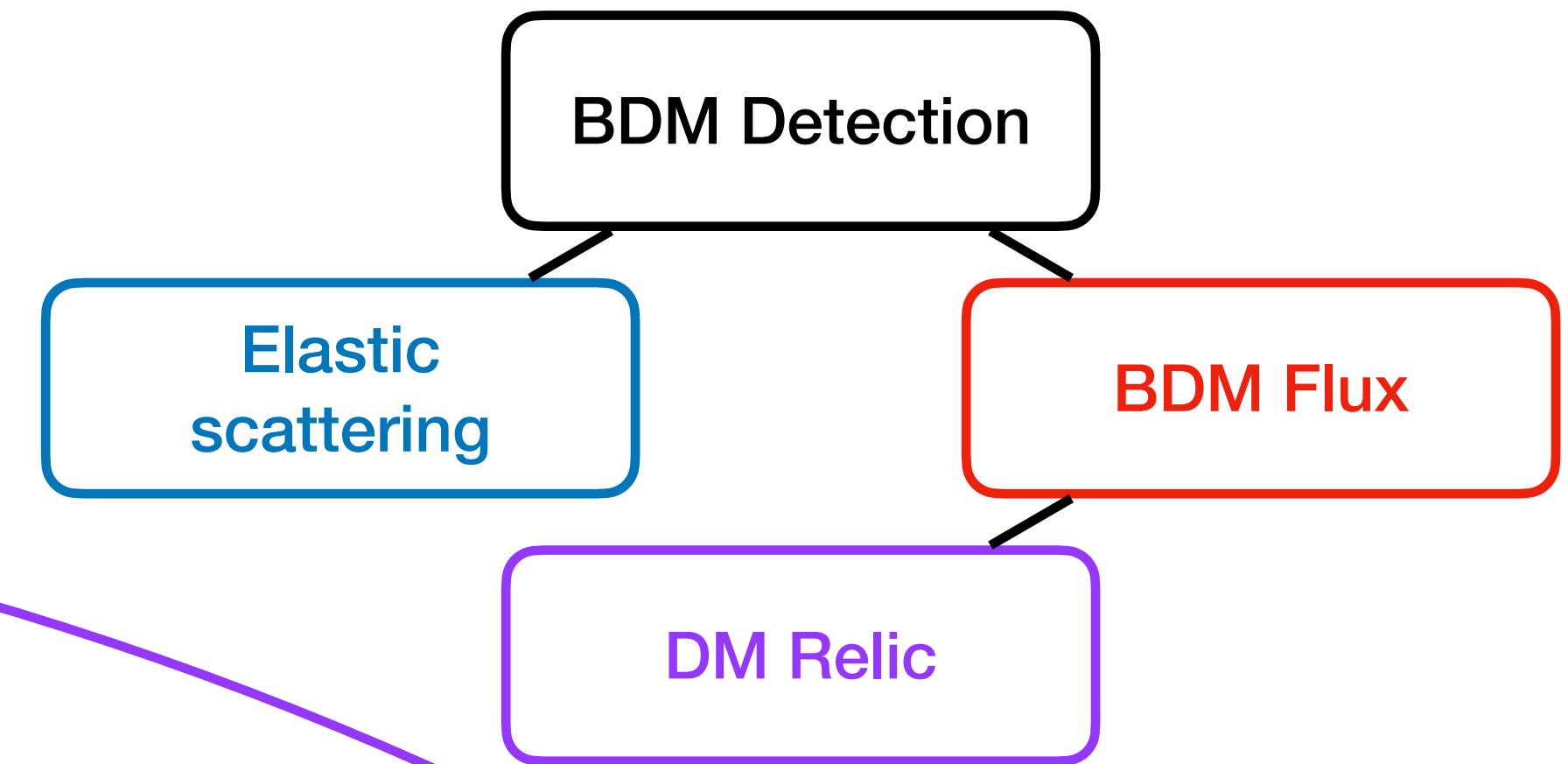
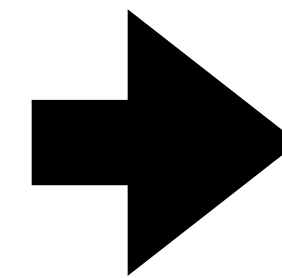
$$\begin{aligned}\frac{d\Phi}{dE_K} &= \frac{1}{2} \frac{1}{4\pi} \langle \sigma v \rangle_{\text{sa}} \frac{dN}{dE_K} \int d\Omega \int_{\text{l.o.s}} ds \left(\frac{\rho_{\psi}^{\text{MW}}}{m_{\psi}} \right)^2 \\ &= \frac{\langle \sigma v \rangle_{\text{sa}}}{8\pi m_{\psi}^2} \frac{dN}{dE_K} J\end{aligned}$$

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

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

Differential Rate per target mass

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



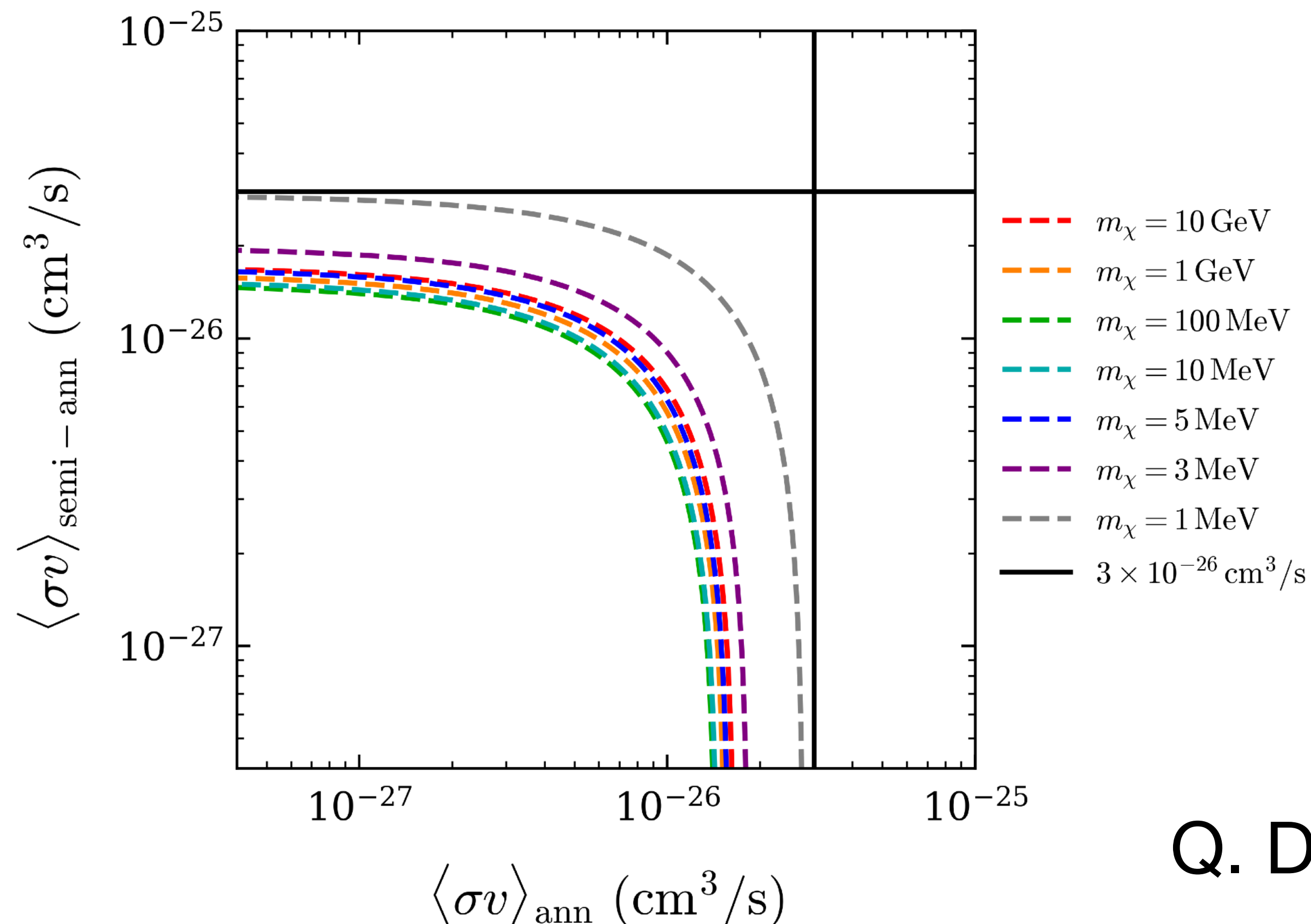
Hidden Factor: Relic Density!

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

Relic Density of BDM

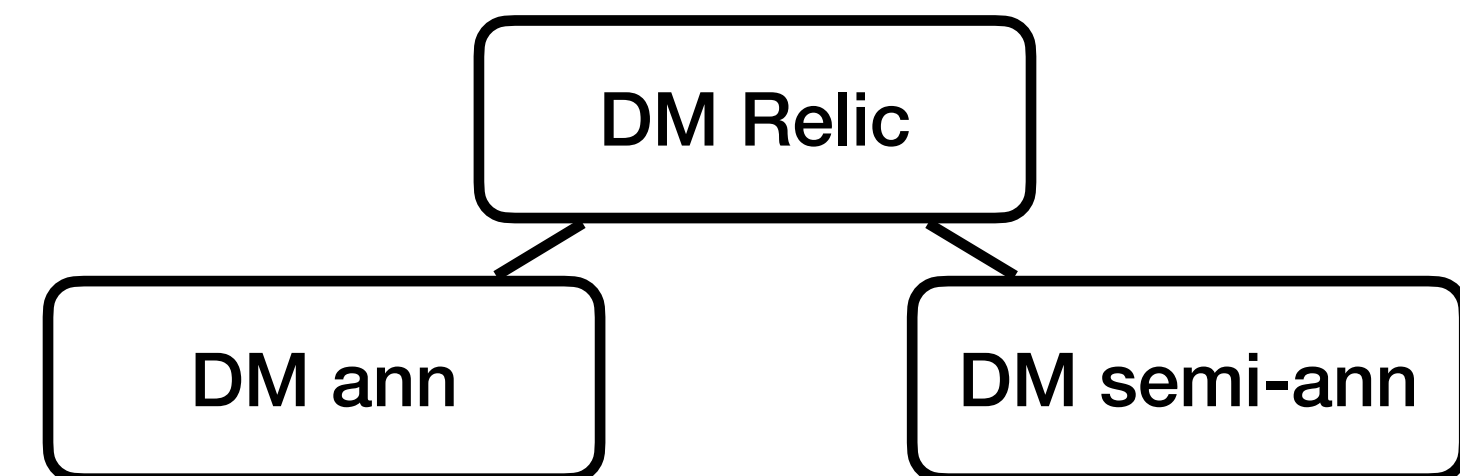
Boltzmann Equation for semi-annihilating DM

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



$$\langle\sigma v\rangle_{\text{ann}} = \frac{1}{2}(\langle\sigma v\rangle_{\psi\psi\rightarrow\text{ann}} + \langle\sigma v\rangle_{\psi\bar{\psi}\rightarrow\text{ann}}), \quad \langle\sigma v\rangle_{\text{sa}} = \frac{1}{4}(\langle\sigma v\rangle_{\psi\psi\rightarrow\psi\phi} + 2\langle\sigma v\rangle_{\psi\bar{\psi}\rightarrow\psi\phi})$$

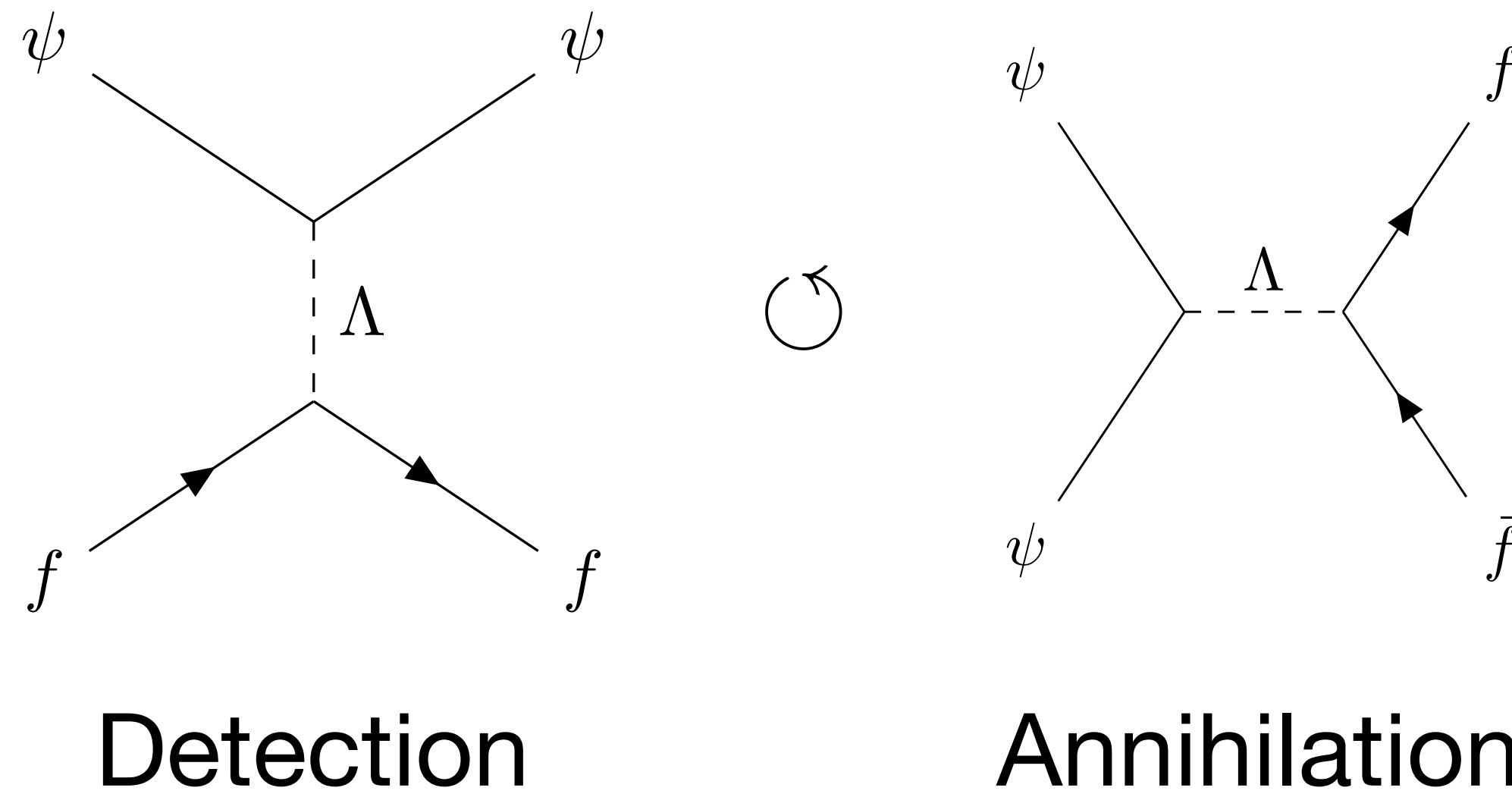
Reproducing the observed relic density requires a suitable combination of the annihilation and semi-annihilation cross-sections.



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



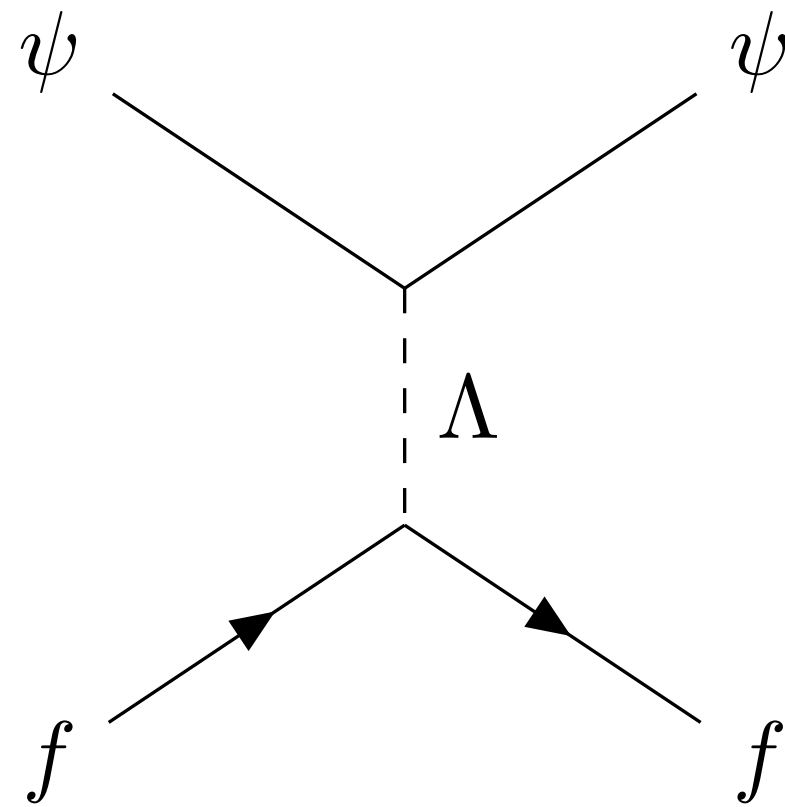
Possible Exception: electrophobic & lighter than pion

The Annihilation of semi-annihilating DM model

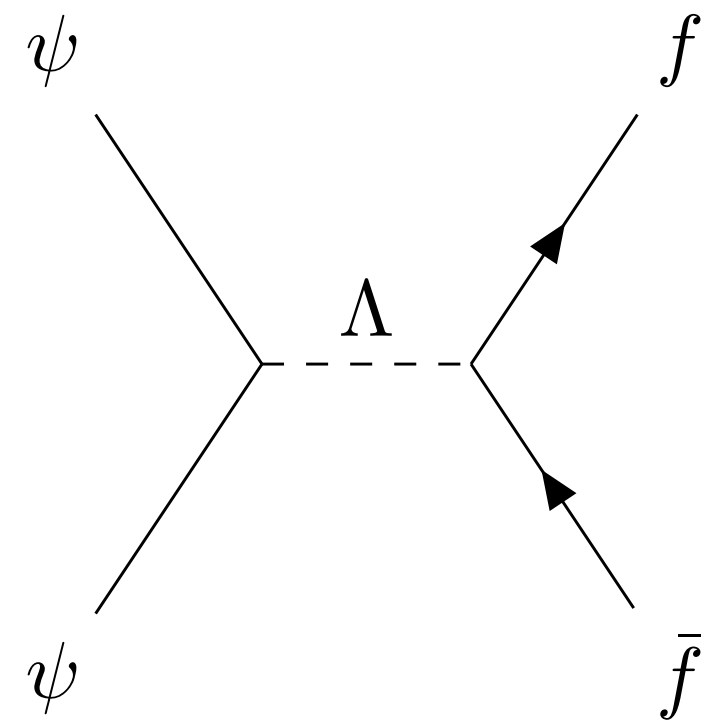
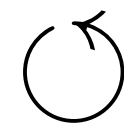
Sufficient annihilation is also required for enhancing the visibility of BDM

Differential Rate per target mass

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



Detection



Annihilation

Annihilation and σ_{el} share the same underlying amplitude!

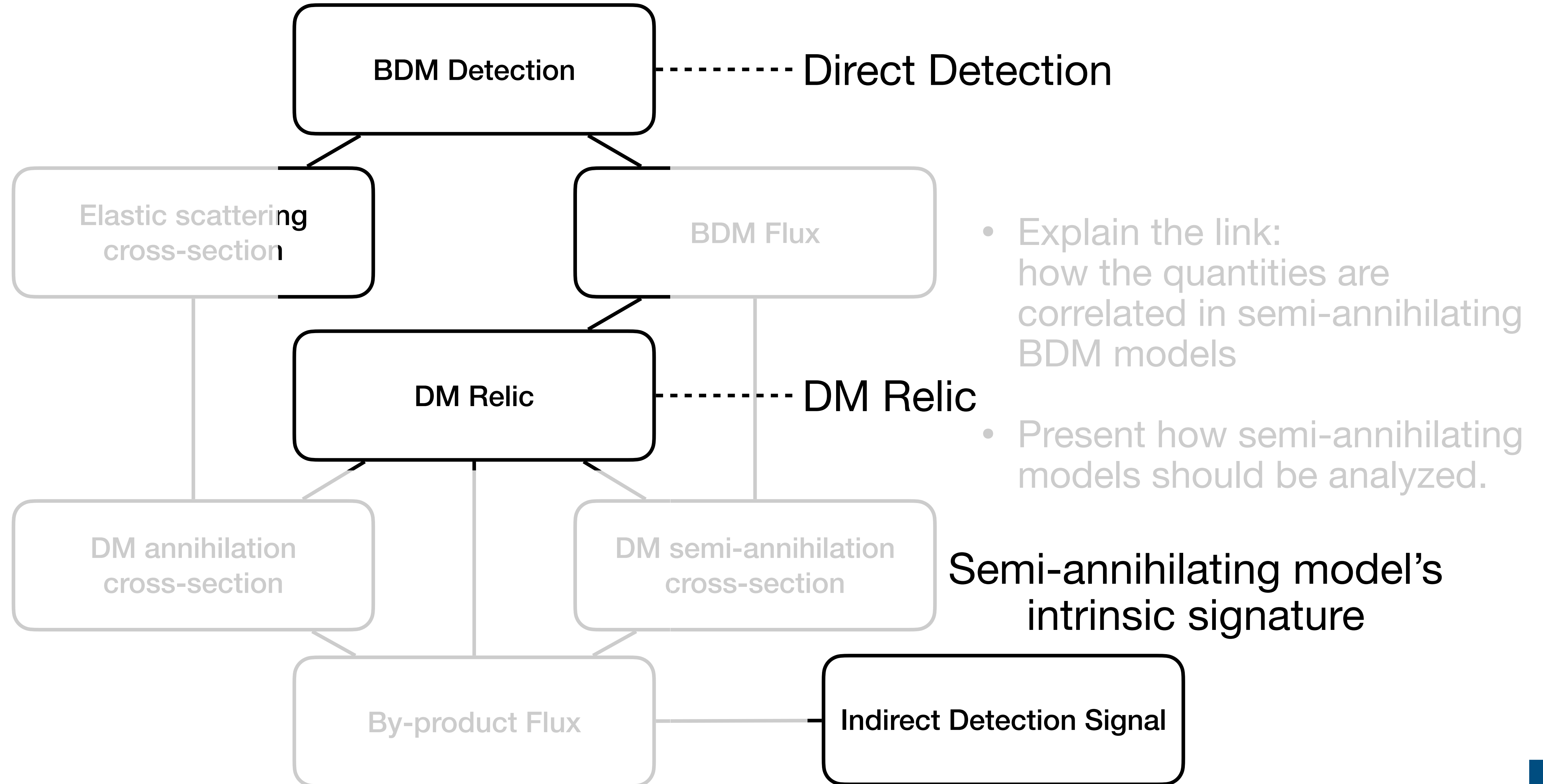
Elastic scattering
cross-section

DM annihilation
cross-section

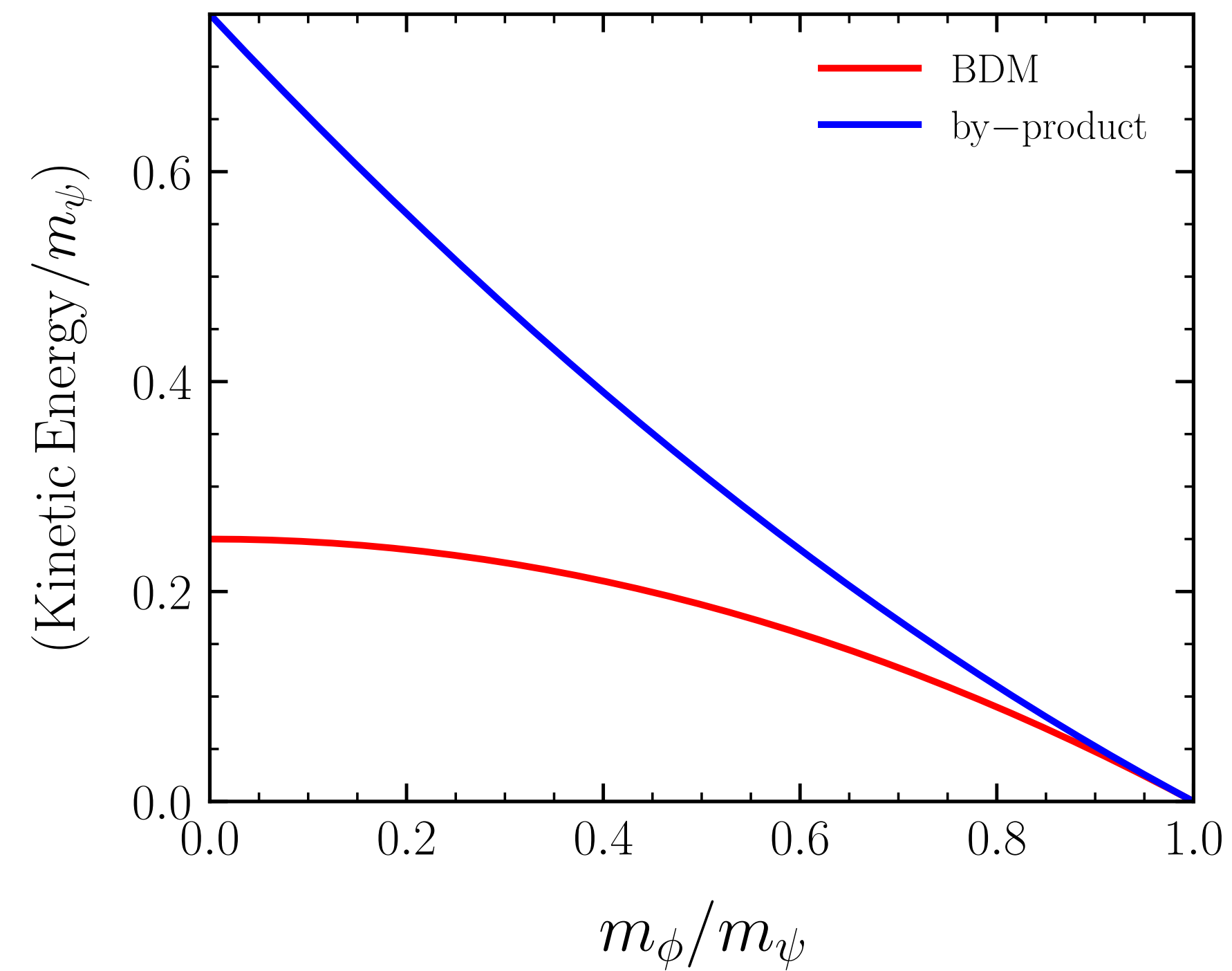
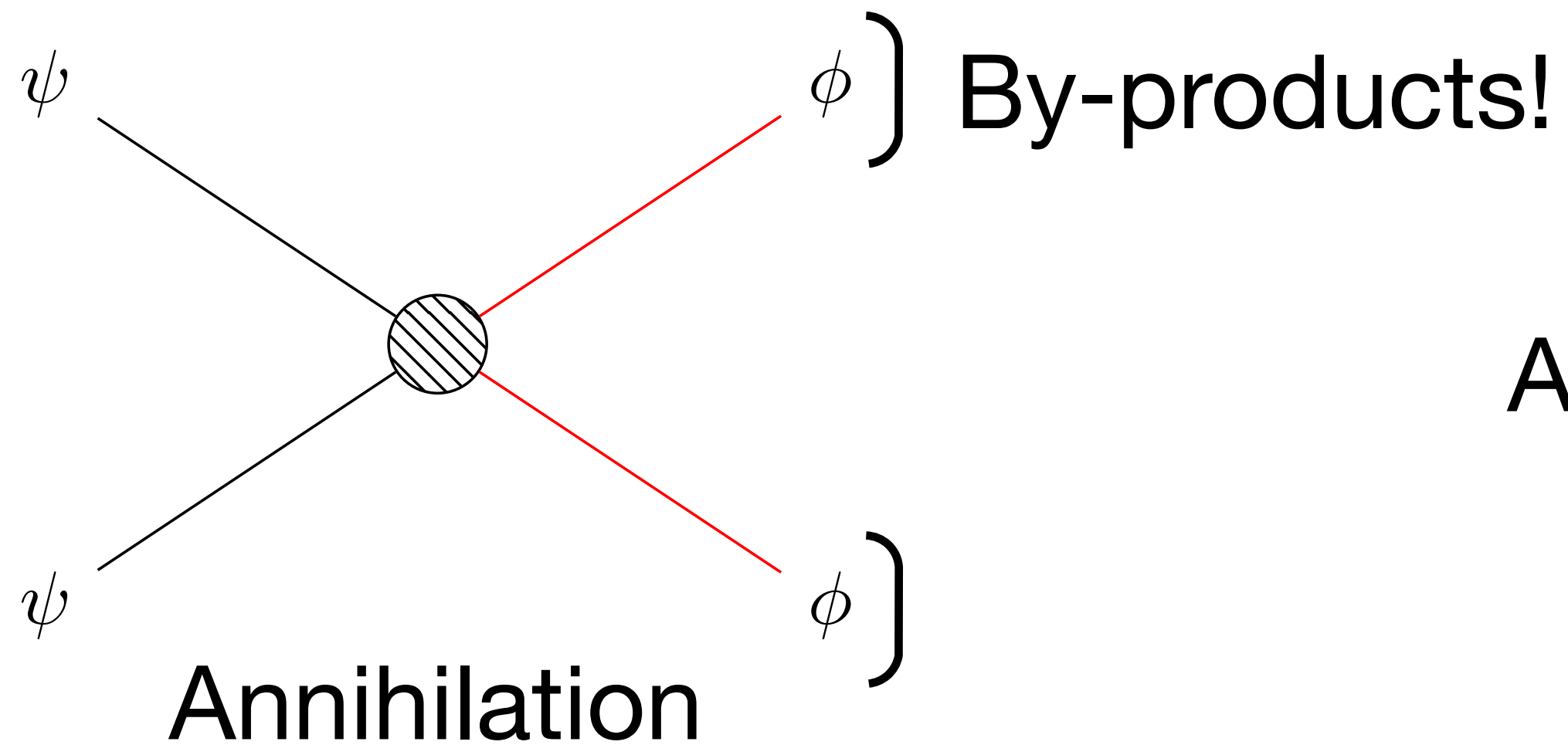
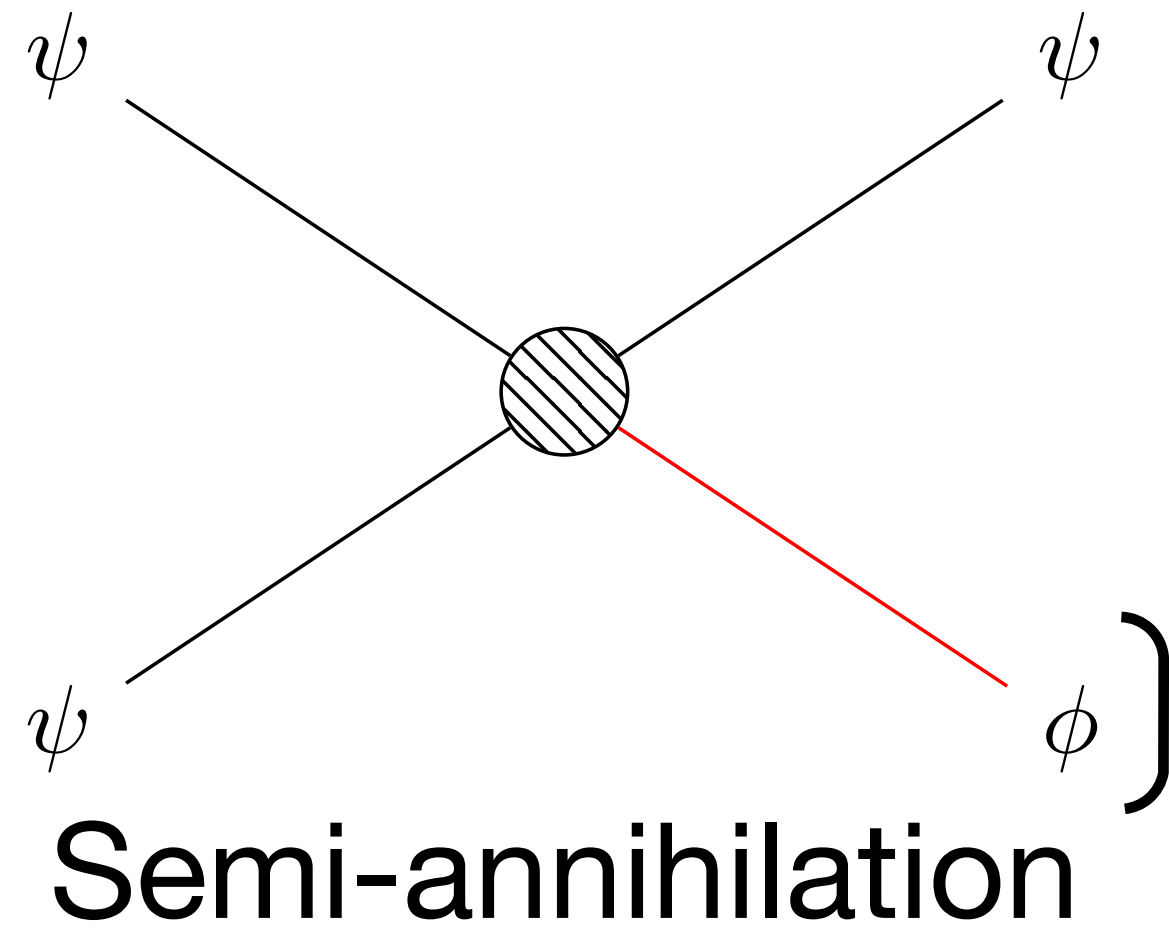
Naive relation

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

The Goal of This Work



The Boosted By-product

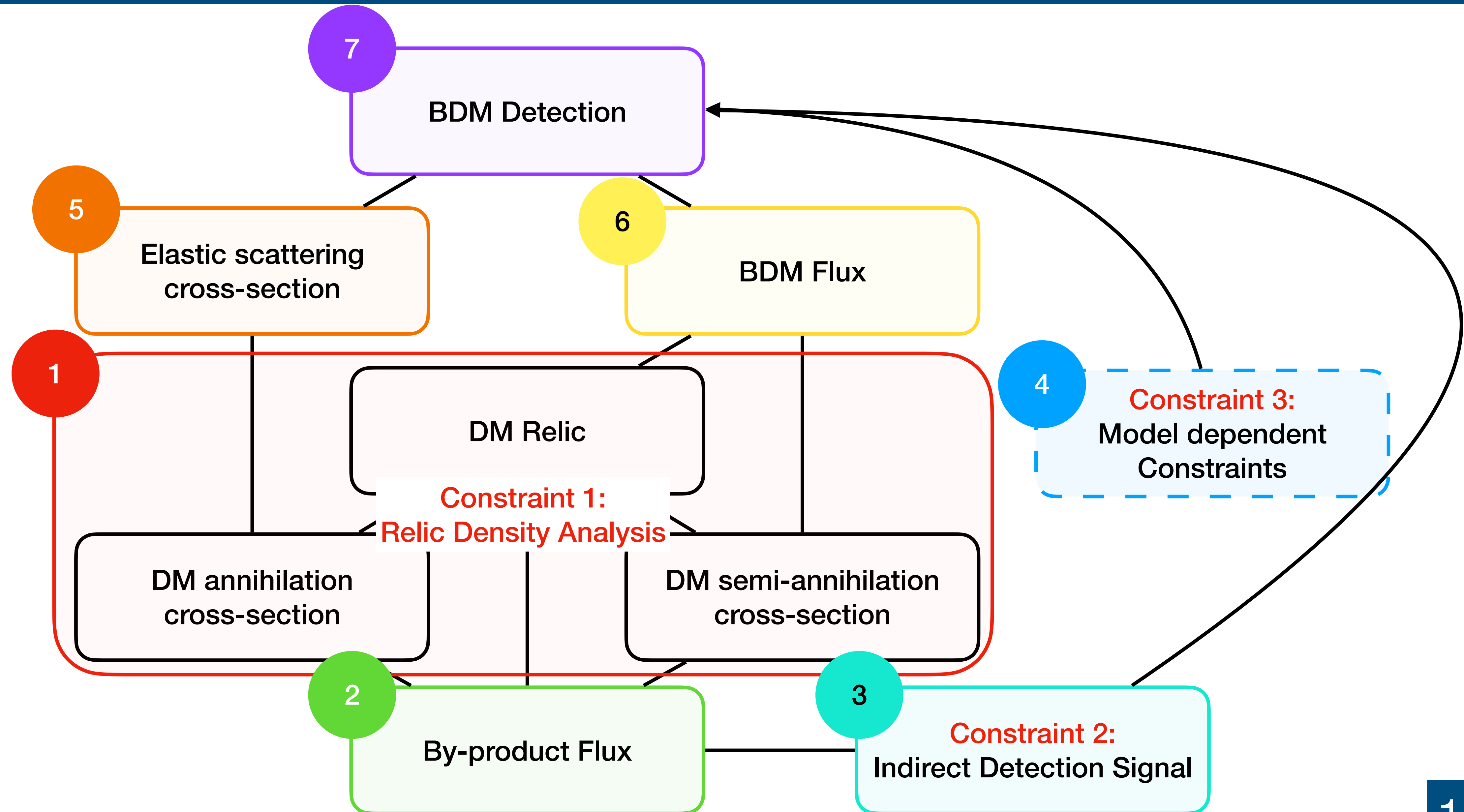


Always have greater kinetic energy than BDM

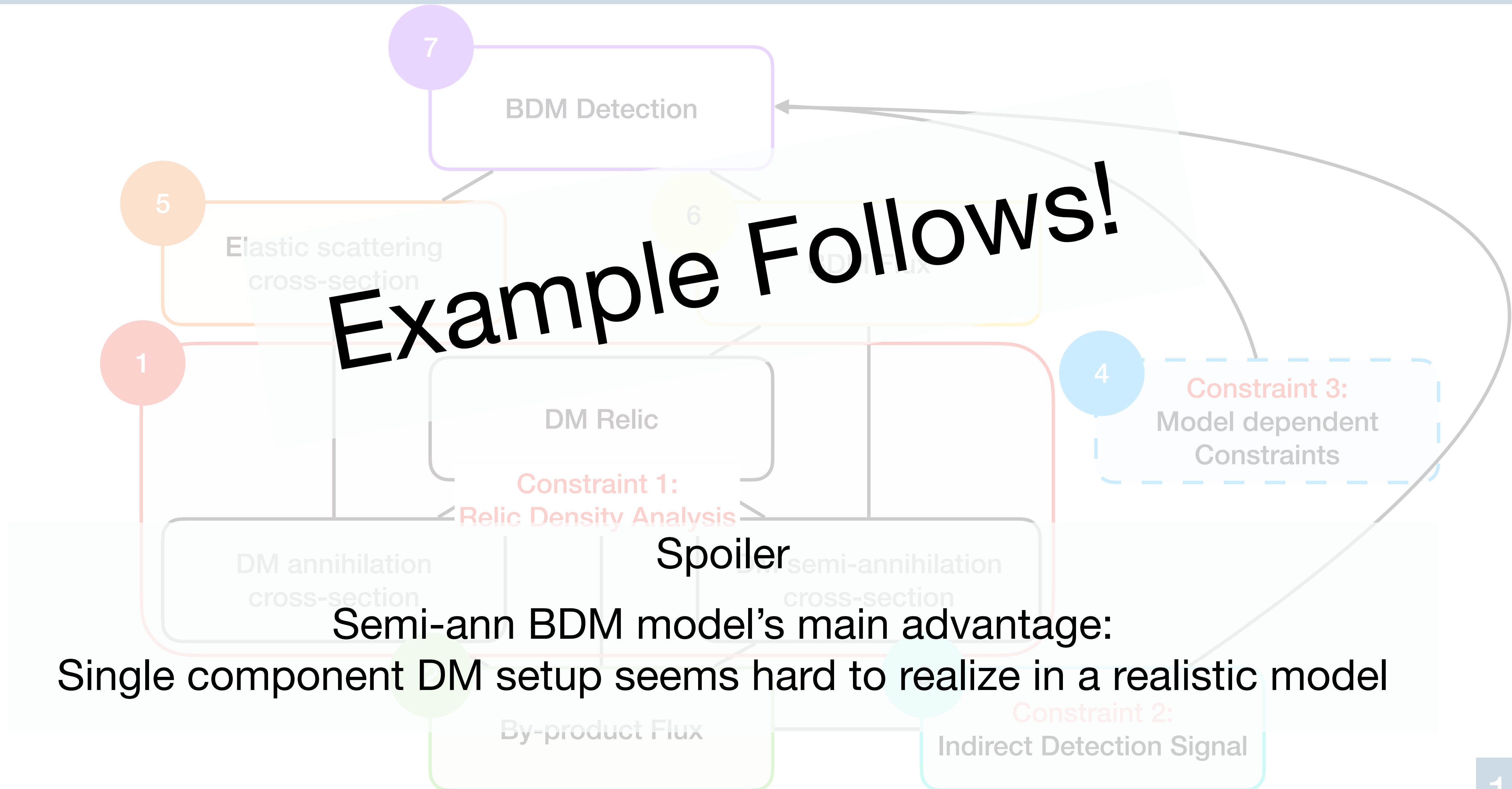
+ Additional flux from annihilation

➔ No reason for ignoring them

Summary of Flow



Summary of Flow



Example Model

0

Build the Model

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

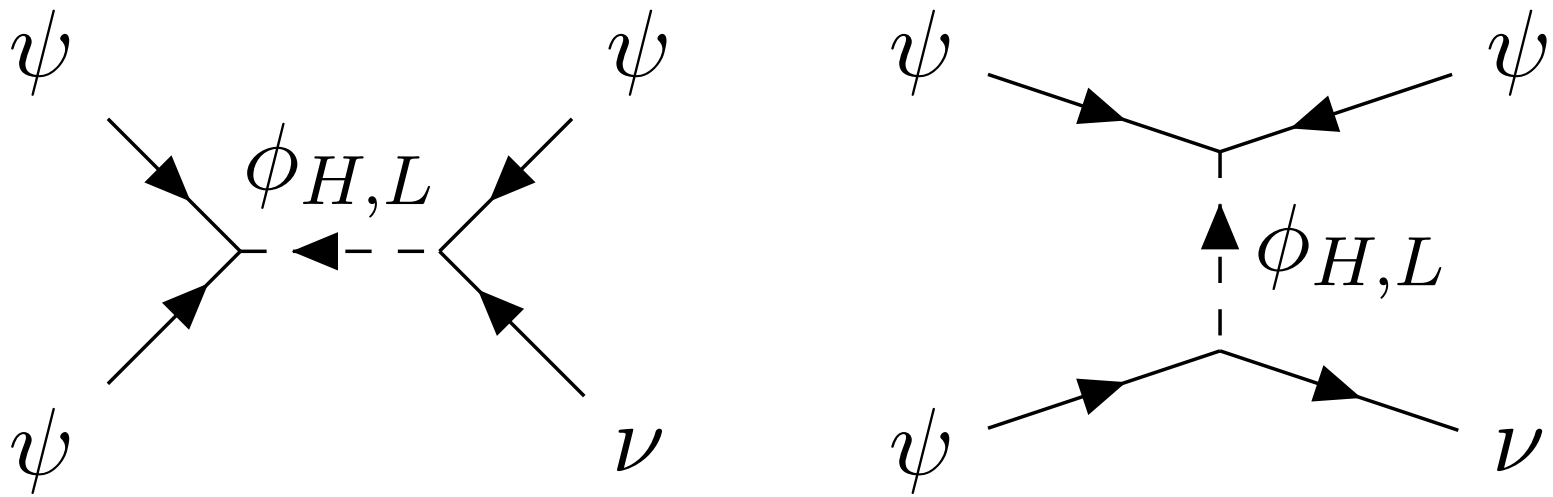
$$\mathcal{L}_N = \bar{\psi}(i\gamma^\mu \partial_\mu - m_\psi)\psi + |D_\mu \eta|^2 + |\partial \chi|^2 + \left(y_i^\nu \eta \bar{\psi} P_L L_i + \frac{y_\psi}{2} \chi \bar{\psi}^c \psi + \text{h.c.}\right) - V(H, \eta, \chi)$$

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

	Role	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

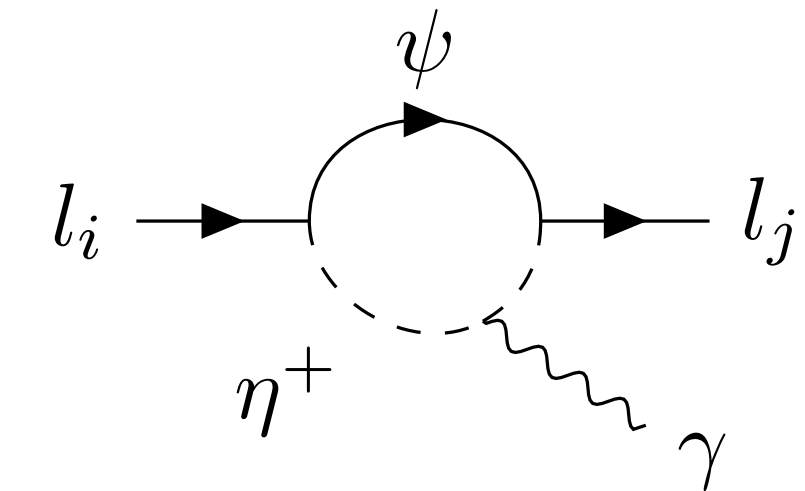
Build the Model

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

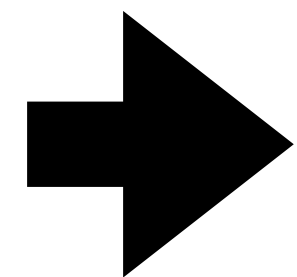
$$\mathcal{L}_N = \bar{\psi}(i\gamma^\mu \partial_\mu - m_\psi)\psi + |D_\mu \eta|^2 + |\partial \chi|^2 + \left(y_i^\nu \eta \bar{\psi} P_L L_i + \frac{y_\psi}{2} \chi \bar{\psi}^c \psi + \text{h.c.} \right) - V(H, \eta, \chi)$$

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

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
$[0.01, 10] \text{ GeV}$	$[m_\psi, 1 \text{ TeV}]$	$[-3.5, 3.5]$	$[0.5, 3.5]$	$[10^{-3}, 0.5]$

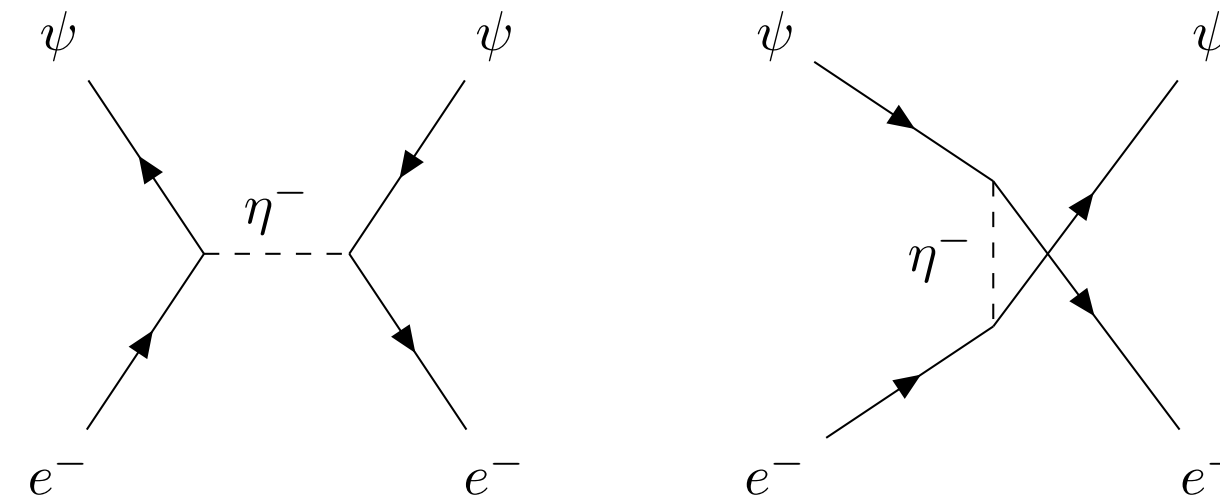
$$m_{\eta^+}^2 = m_{\phi_H}^2 \cos^2 \alpha + m_{\phi_L}^2 \sin^2 \alpha - \frac{1}{2} \lambda_4 v^2$$

BDM Detectability

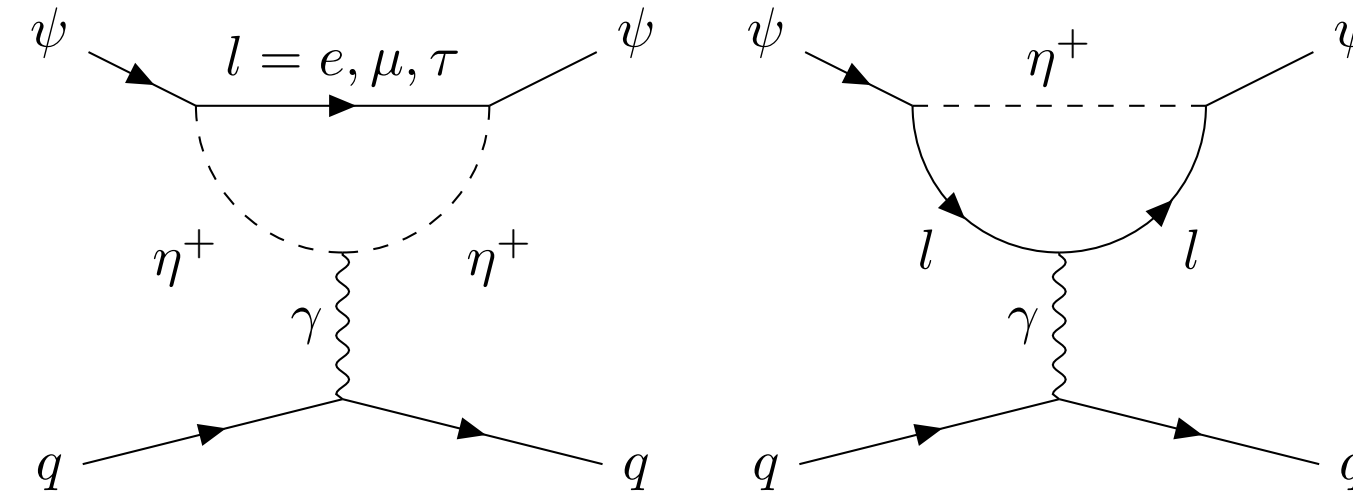
Two kinds of the targets: electron and nucleus

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

Electron Target



Nuclear Target



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

5

Elastic scattering
cross-section

6

BDM Flux

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

$$\frac{d\sigma}{dE_R} = \frac{\sigma^{\text{coh}}}{E_{R,\text{max}}} F^2(q^2) + \frac{\sigma^{\text{inc}}}{E_{R,\text{max}}} (1 - F^2(q^2)) \quad \text{Dipole Form Factor is used} \quad F(q^2) = \left(1 + \frac{q^2}{\Lambda^2} \right)^{-2}$$

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

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

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

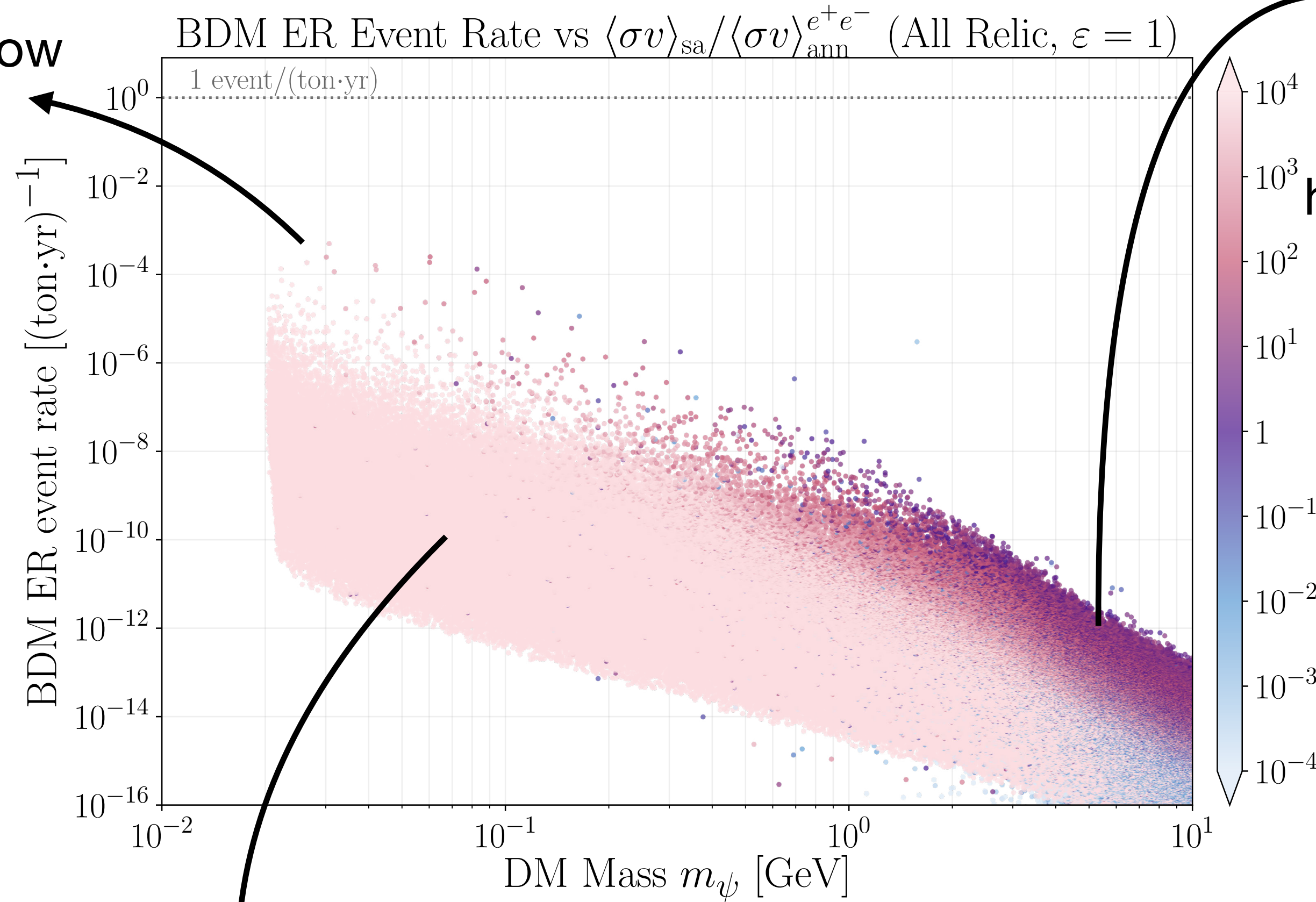
BDM Detectability: Few Remarks

7

Before considering *other bounds*

BDM Detection

BDM detectability is too low
even before excluding
experimental bounds



High mass region:

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

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

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

Low mass region:

No parameter space for $\langle\sigma v\rangle_{\text{sa}} \sim \langle\sigma v\rangle_{\text{ann}}$

DM semi-ann dominates its relic for low mass region

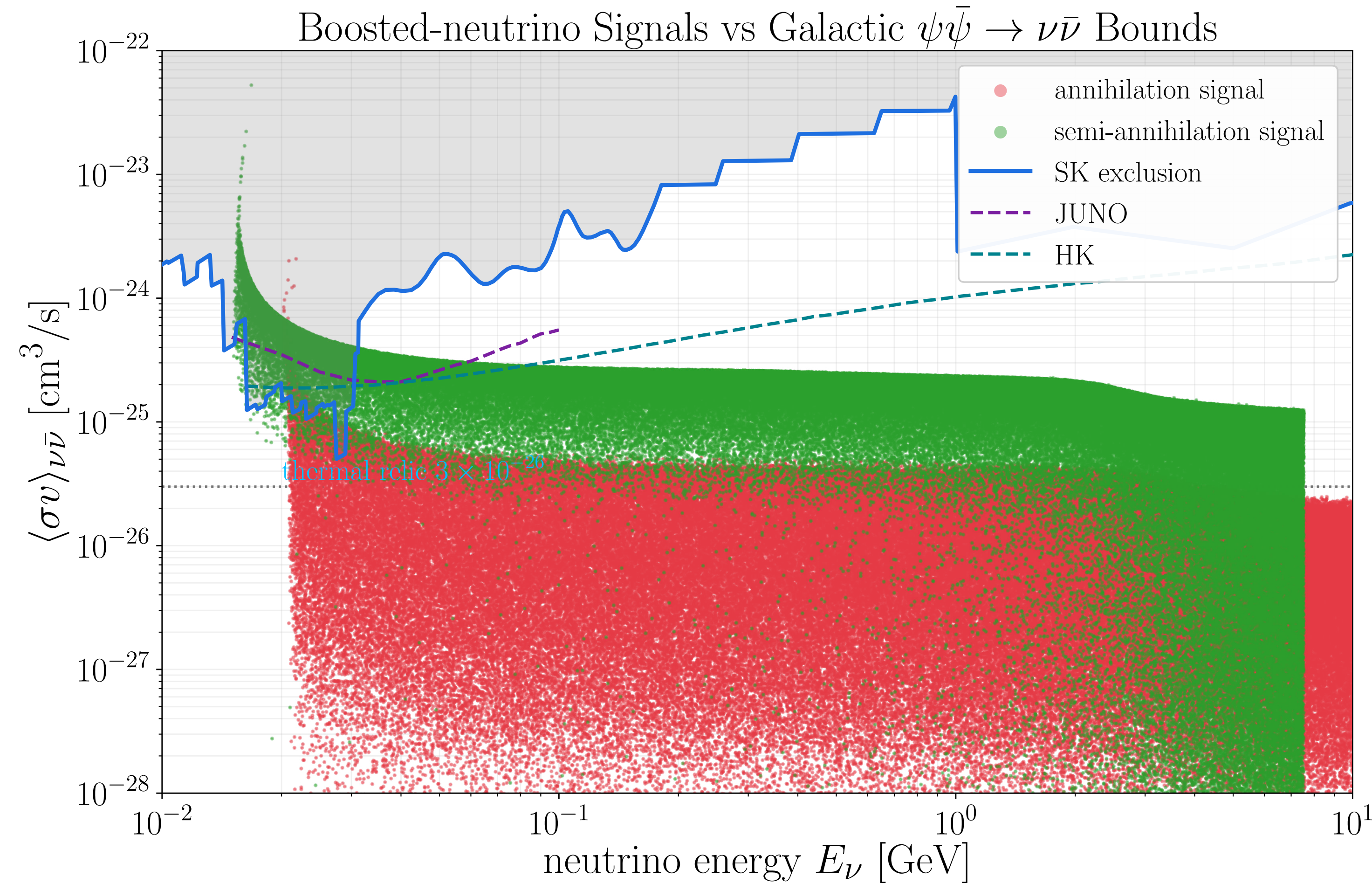
Boosted By-product

Boosted Neutrino!

2

3

Constraint 2:
Indirect Detection Signal



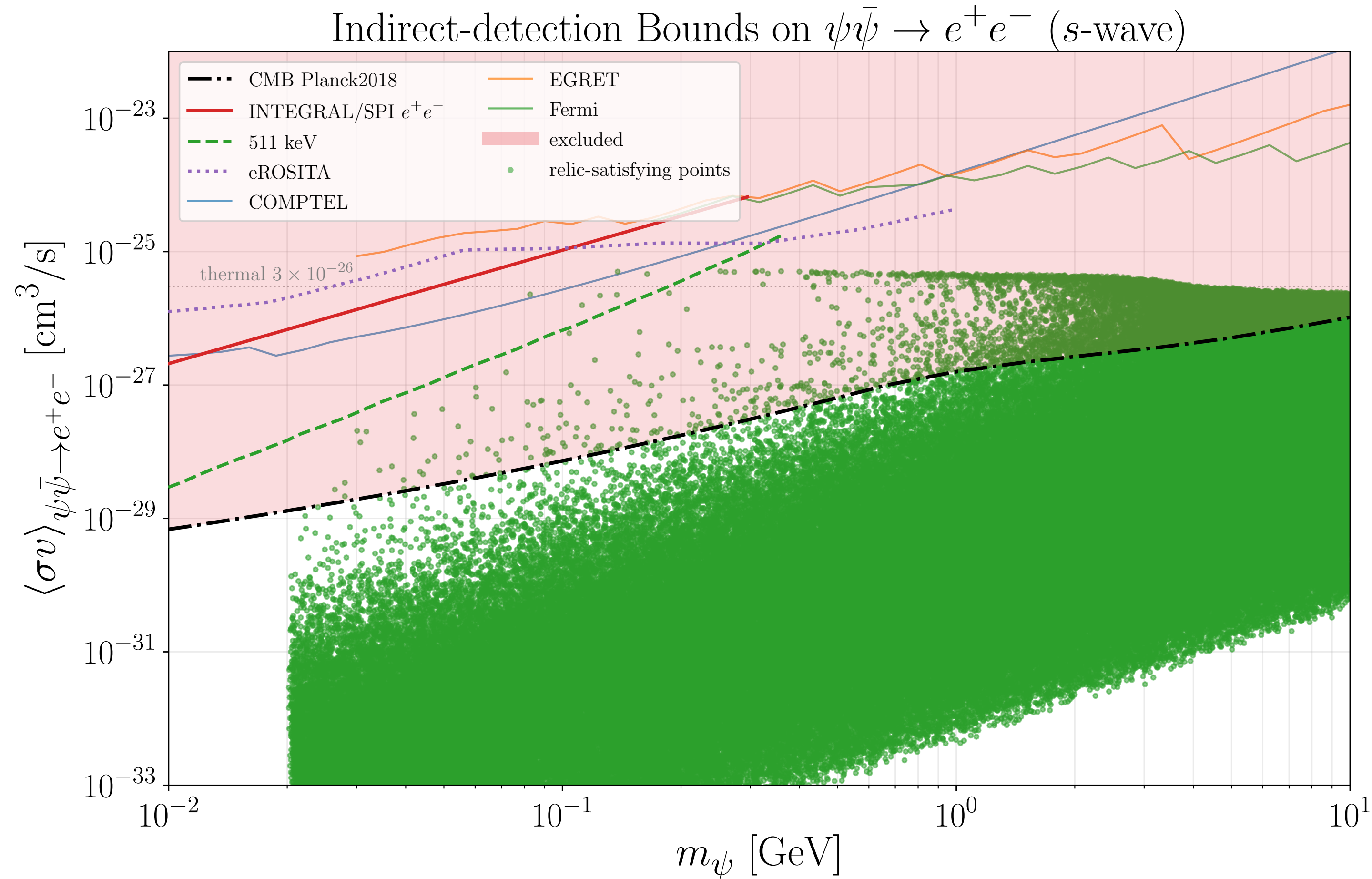
Significant neutrino flux from semi-annihilation

Model Specific Bounds

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

4

Constraint 3:
Model dependent
Constraints



Strong bounds from CMB anisotropy

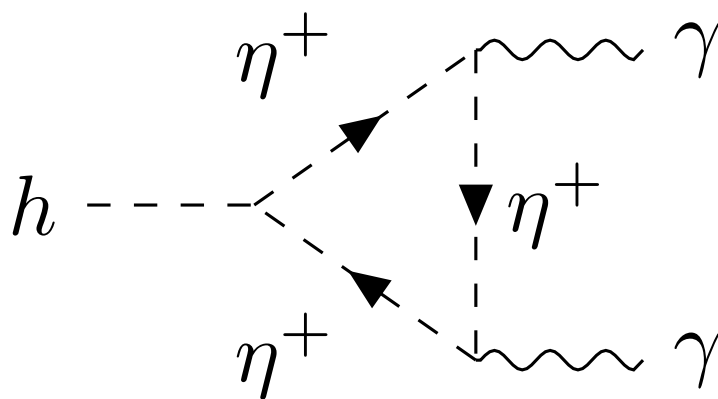
Model Specific Bounds

Bound from Collider

4

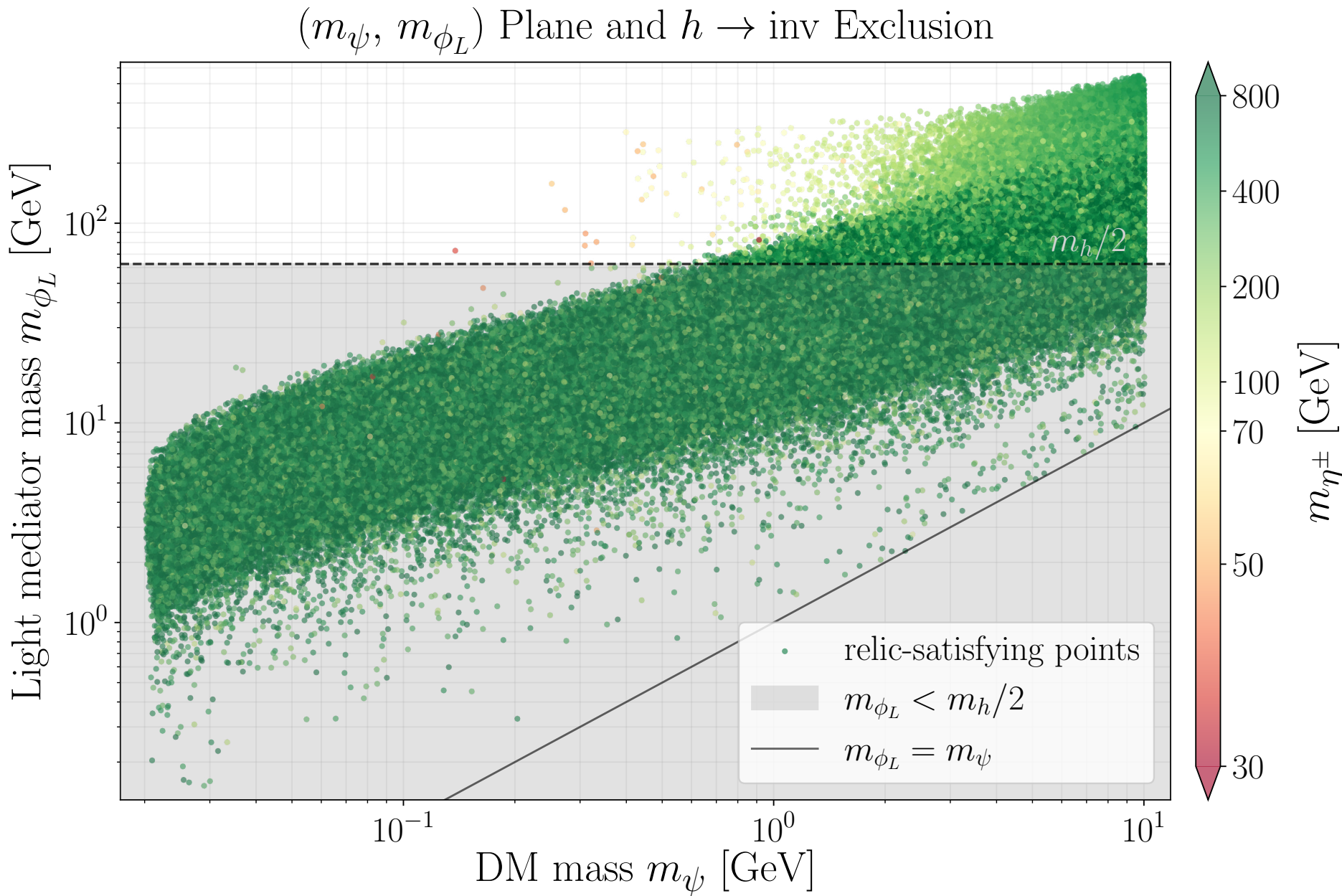
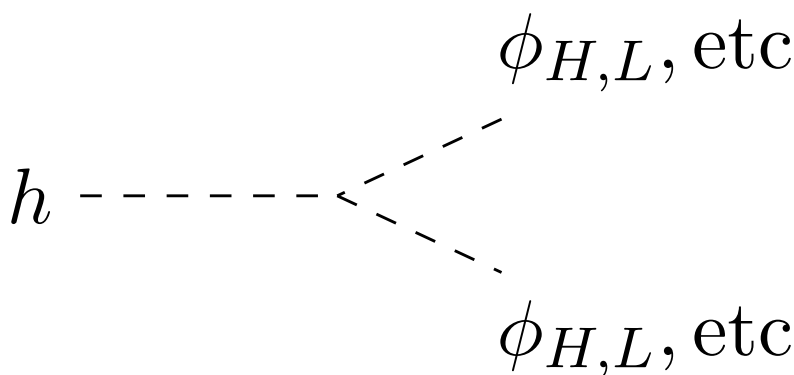
Constraint 3:
Model dependent
Constraints

$$h \rightarrow \gamma\gamma$$

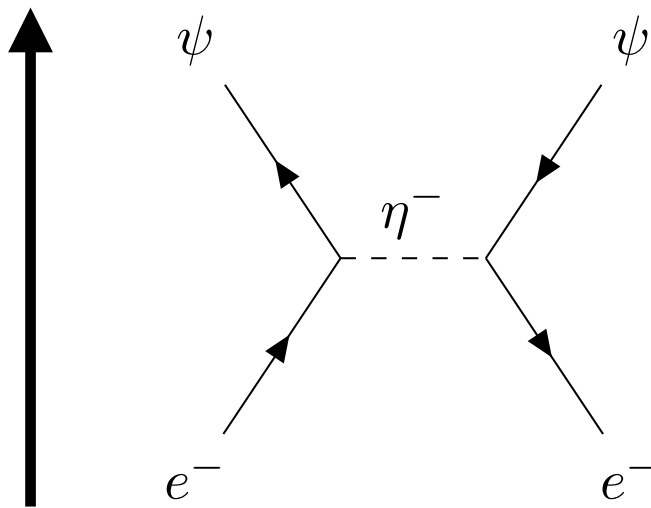


$$|\lambda_3| \lesssim \mathcal{O}(1) (m_{\eta^\pm}/100 \text{ GeV})^2$$

$$h \rightarrow \text{inv}$$



Charged LEP



Limit from $e^+e^- \rightarrow \eta^+\eta^-$:
 $m_{\eta^+} \gtrsim 70 \text{ GeV}$

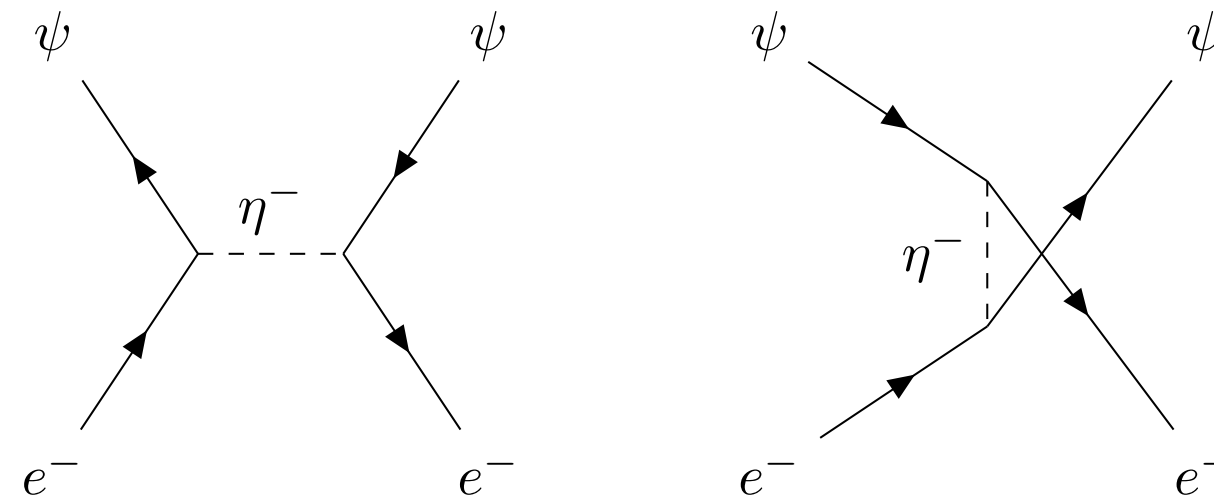
Note: Gray region is approximate bound.
Some points within the gray region survive due to their low branching ratios.

BDM Detectability

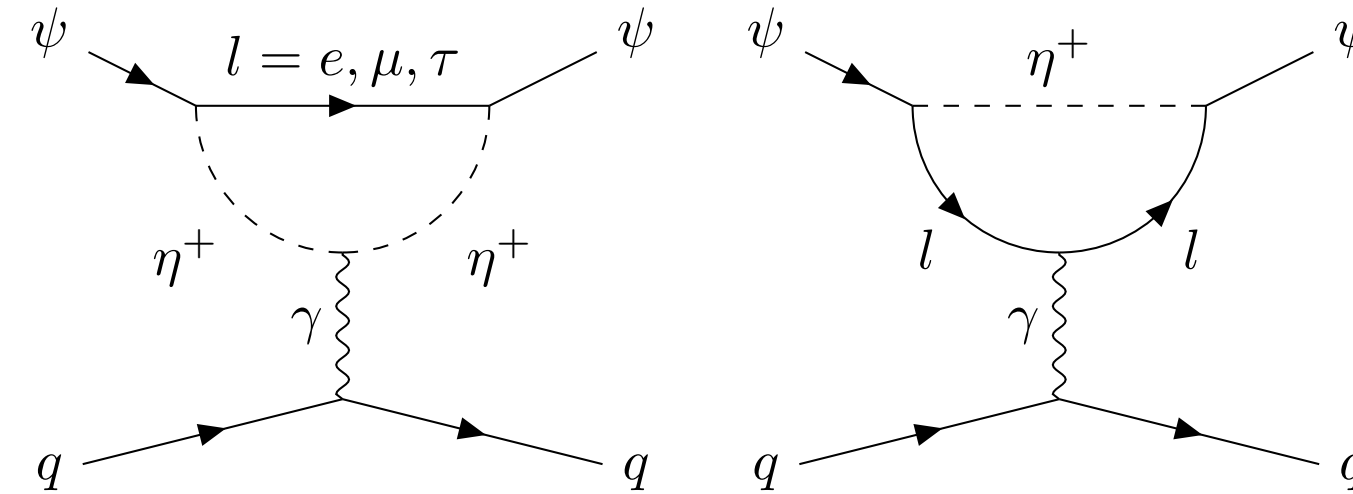
Two kinds of the targets: electron and nucleus

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

Electron Target



Nuclear Target



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

5

Elastic scattering
cross-section

6

BDM Flux

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

$$\frac{d\sigma}{dE_R} = \frac{\sigma^{\text{coh}}}{E_{R,\text{max}}} F^2(q^2) + \frac{\sigma^{\text{inc}}}{E_{R,\text{max}}} (1 - F^2(q^2)) \quad \text{Dipole Form Factor is used} \quad F(q^2) = \left(1 + \frac{q^2}{\Lambda^2} \right)^{-2}$$

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

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

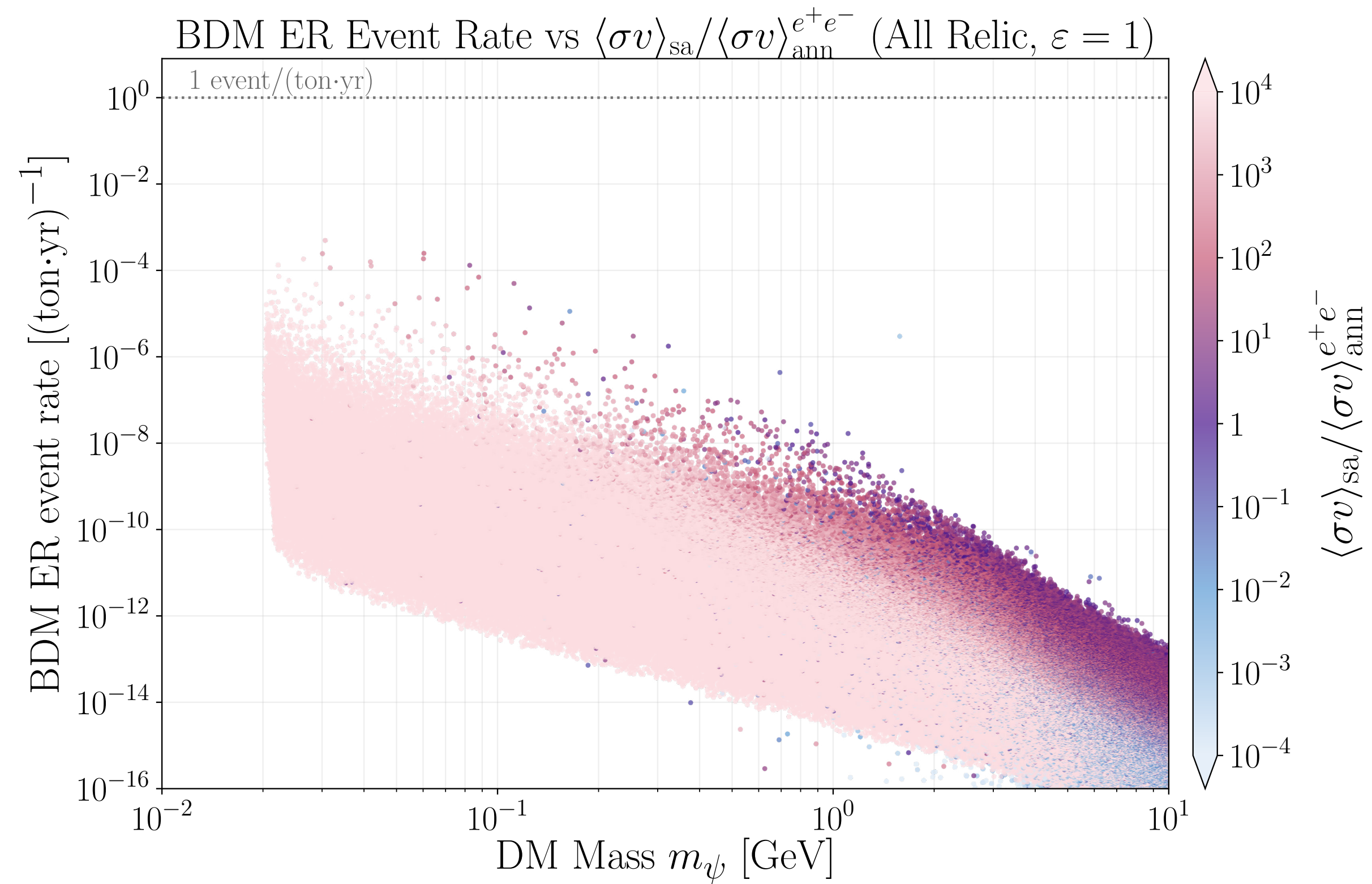
See 1405.5870 for $\sigma_{\psi p}$

BDM Detectability

7

BDM Detection

How phenomenological bounds carve BDM detectability



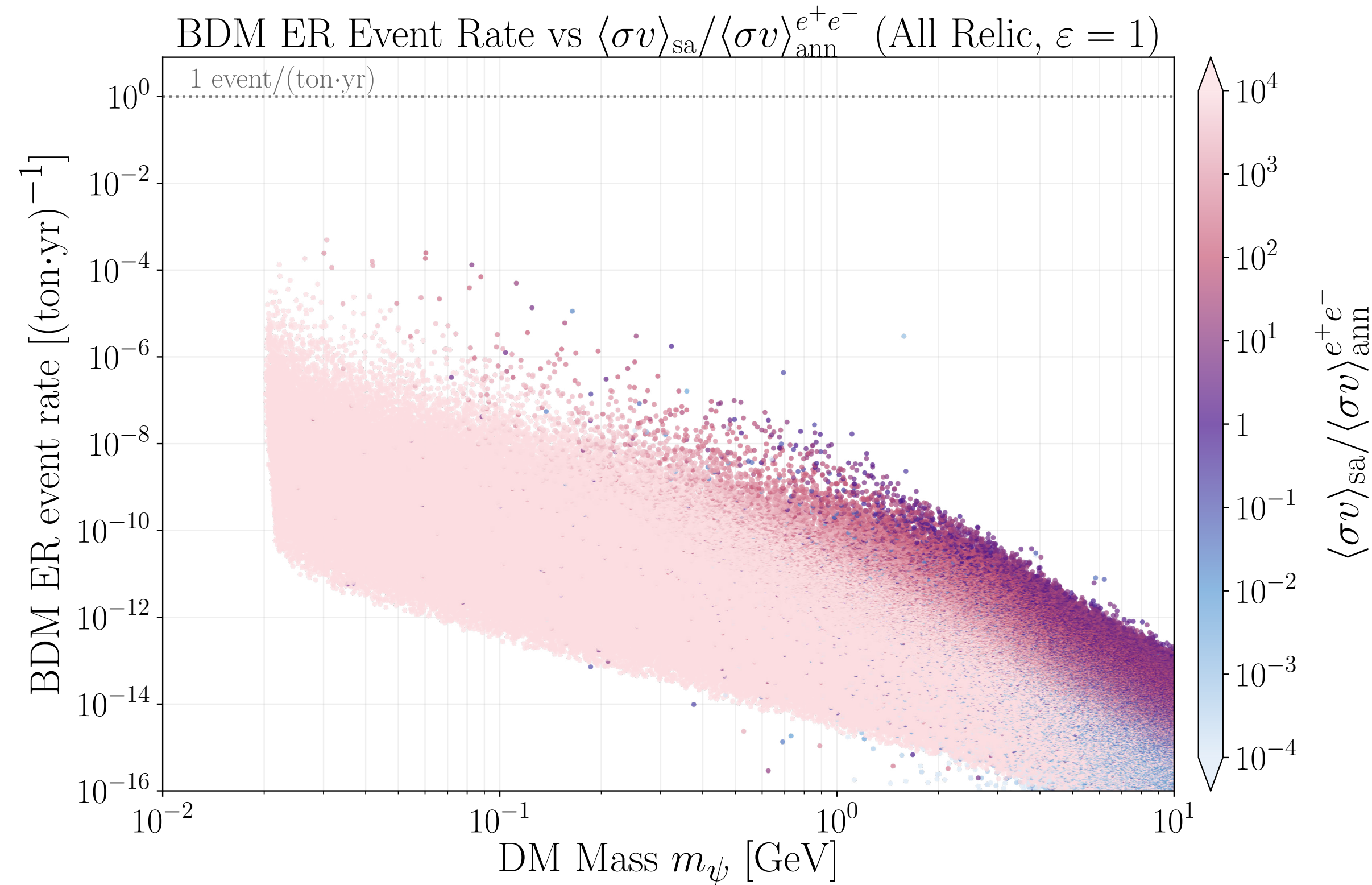
Before excluding experimental bounds

BDM Detectability

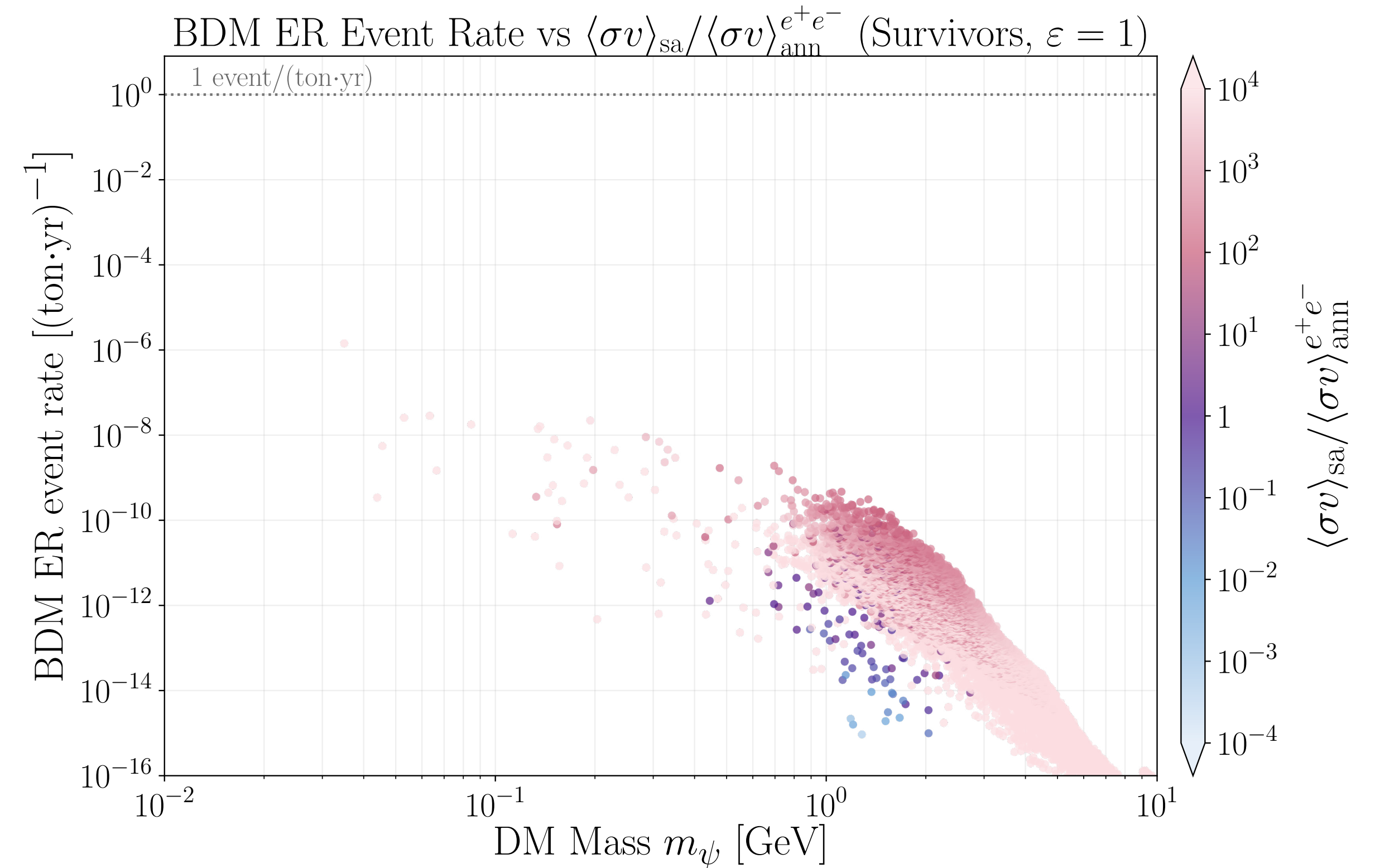
7

How phenomenological bounds carve BDM detectability

BDM Detection



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 $\psi\psi \rightarrow \psi^c\nu$
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

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

Lighter DM at the sub-GeV scale is
hard to detect with conventional
techniques!

The Boosted By-product

Which kinds of by-product are possible?

Bosonic DM - Bosonic EM neutral by-product (which could be off-shell)

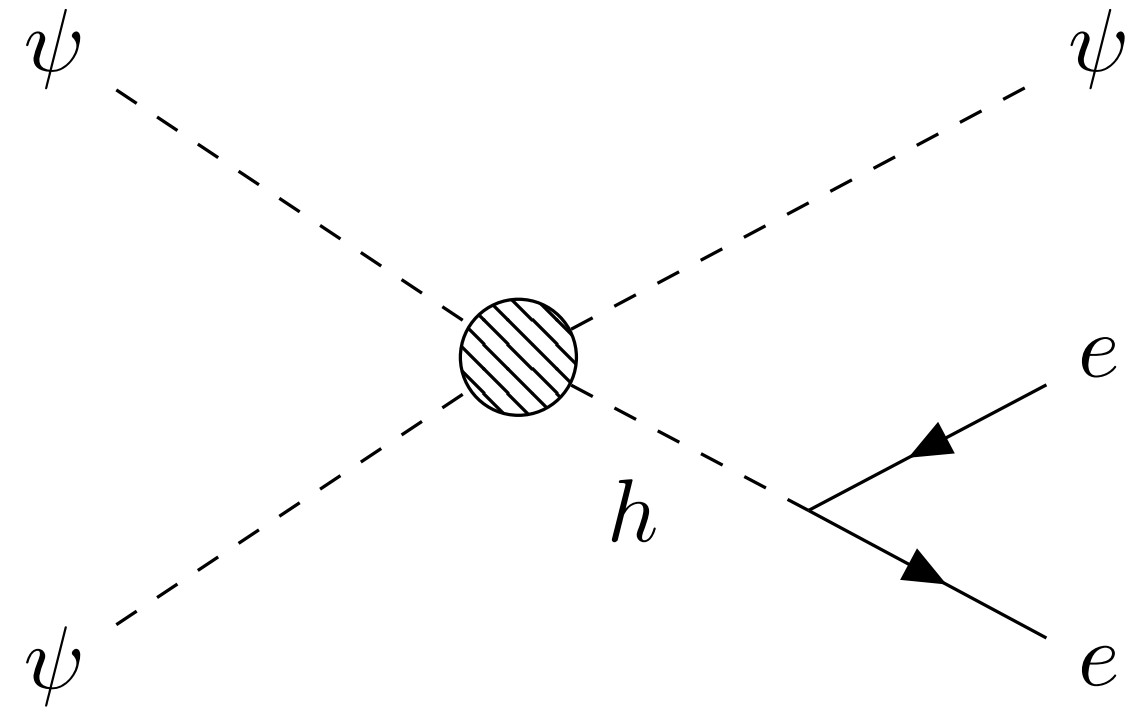
- Additional Dark Species - (Multi-component DM model)
- SM option 1: off-shell h, Z . (γ, g seems not plausible.)
→ In this option, semi-ann of sub-GeV DM should be $2 \rightarrow 3$ process!

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!

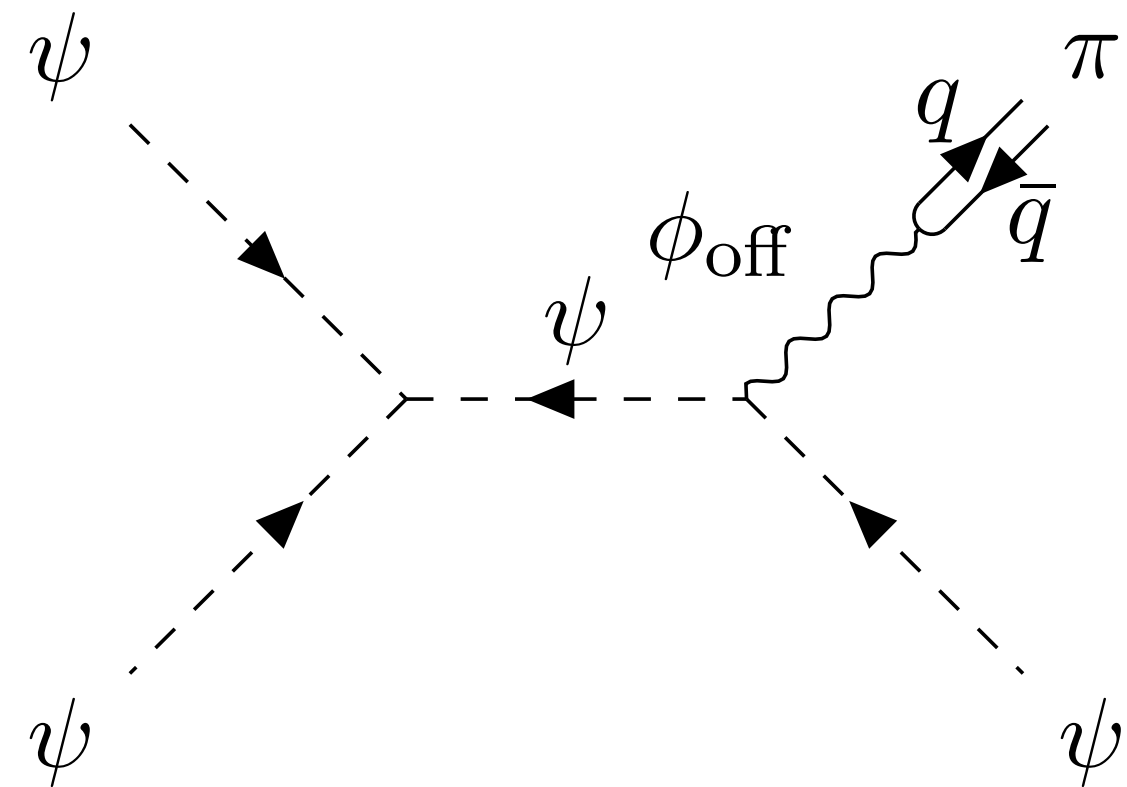
- SM option 2: EM neutral mesons (π^0 etc)
→ DM mass must be greater than m_{π^0}

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

The Boosted By-product

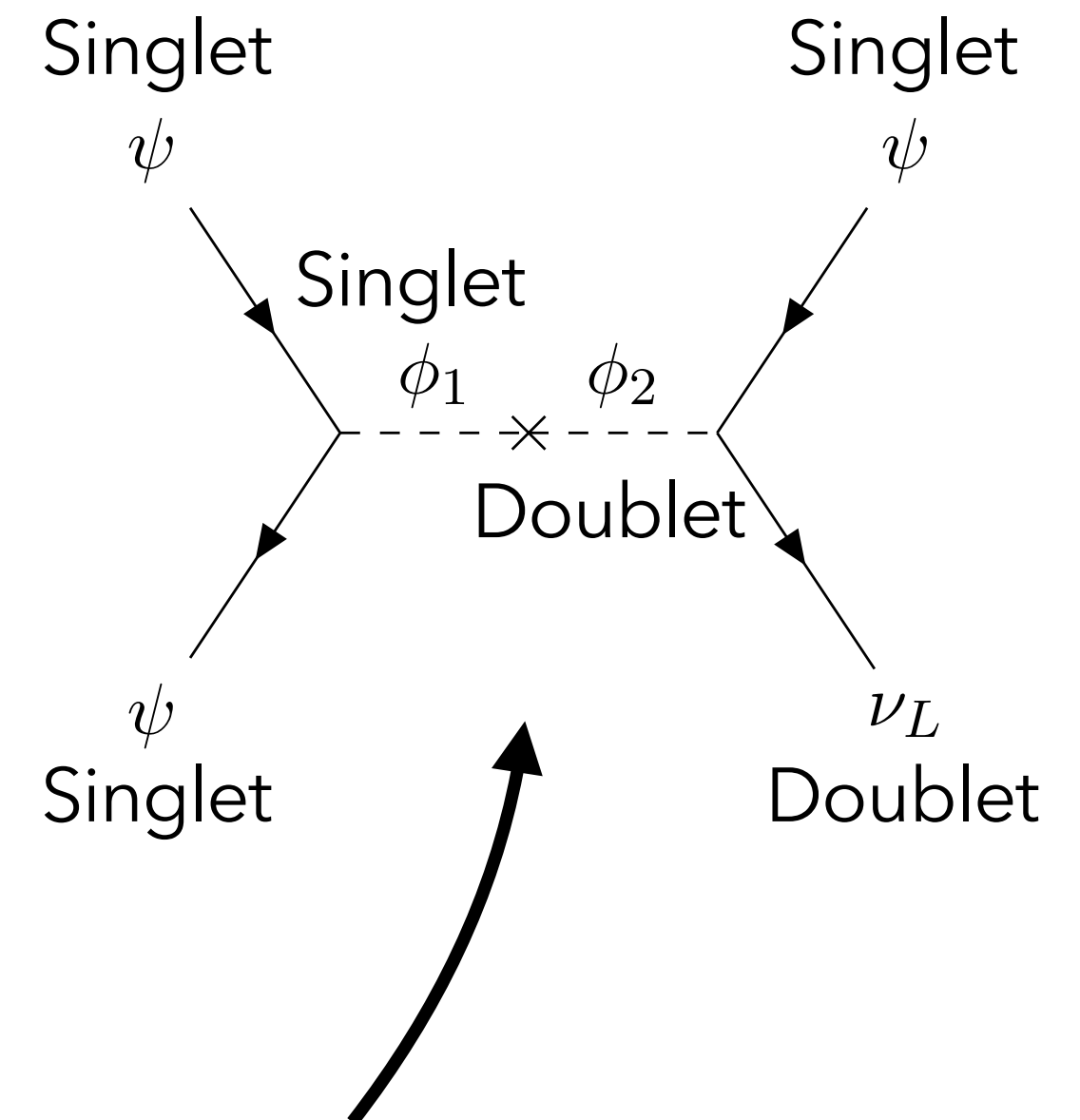
Which kinds of by-product are possible?

Fermionic DM - Fermionic EM neutral by-product

- Additional Dark Species - (Multi-component DM model)
- SM option: exclusively neutrino

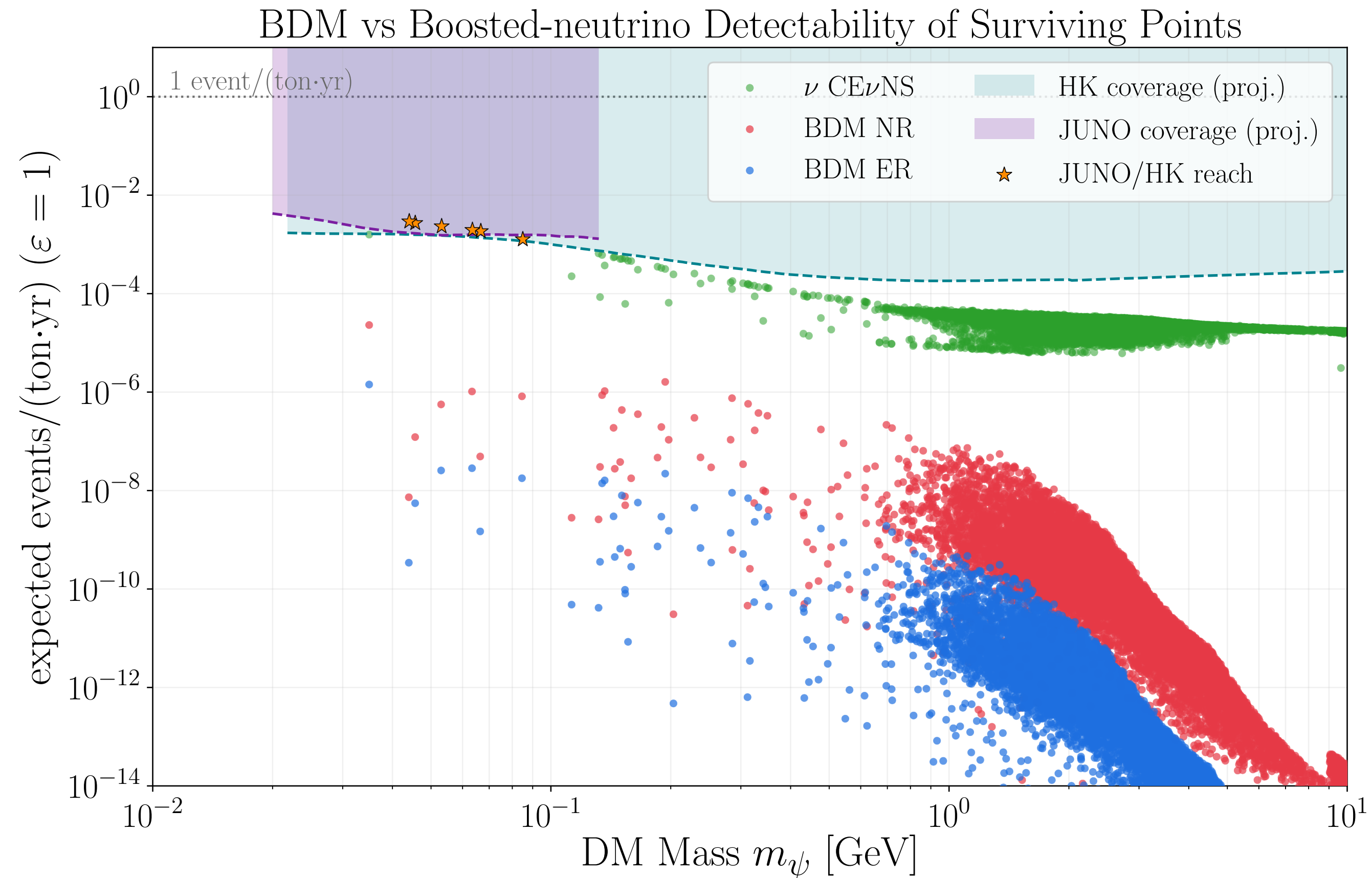
To respect $SU(2)_L$ symmetry, three options

- Option 1: DM charged under $SU(2)_L$ (Seems not good)
- Option 2: mediator coupled to DM & neutrino charged under $SU(2)_L$ (at least two mediators, each $SU(2)_L$ singlet and doublet required)
- Option 3 : DM interact with right-handed neutrino.



Comparison

Boosted DM vs Boosted Neutrino



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