Novel gamma-ray features from dark matter cascade processes involving scalar and fermions as intermediate states

Sergio Lopez-Gehler

TU München - T30d

08/09/2015 **TAUP 2015** Torino - Italy

Based on works done in collaboration with:

A.Ibarra, M.Pato, E. Molinaro

OUTLINE

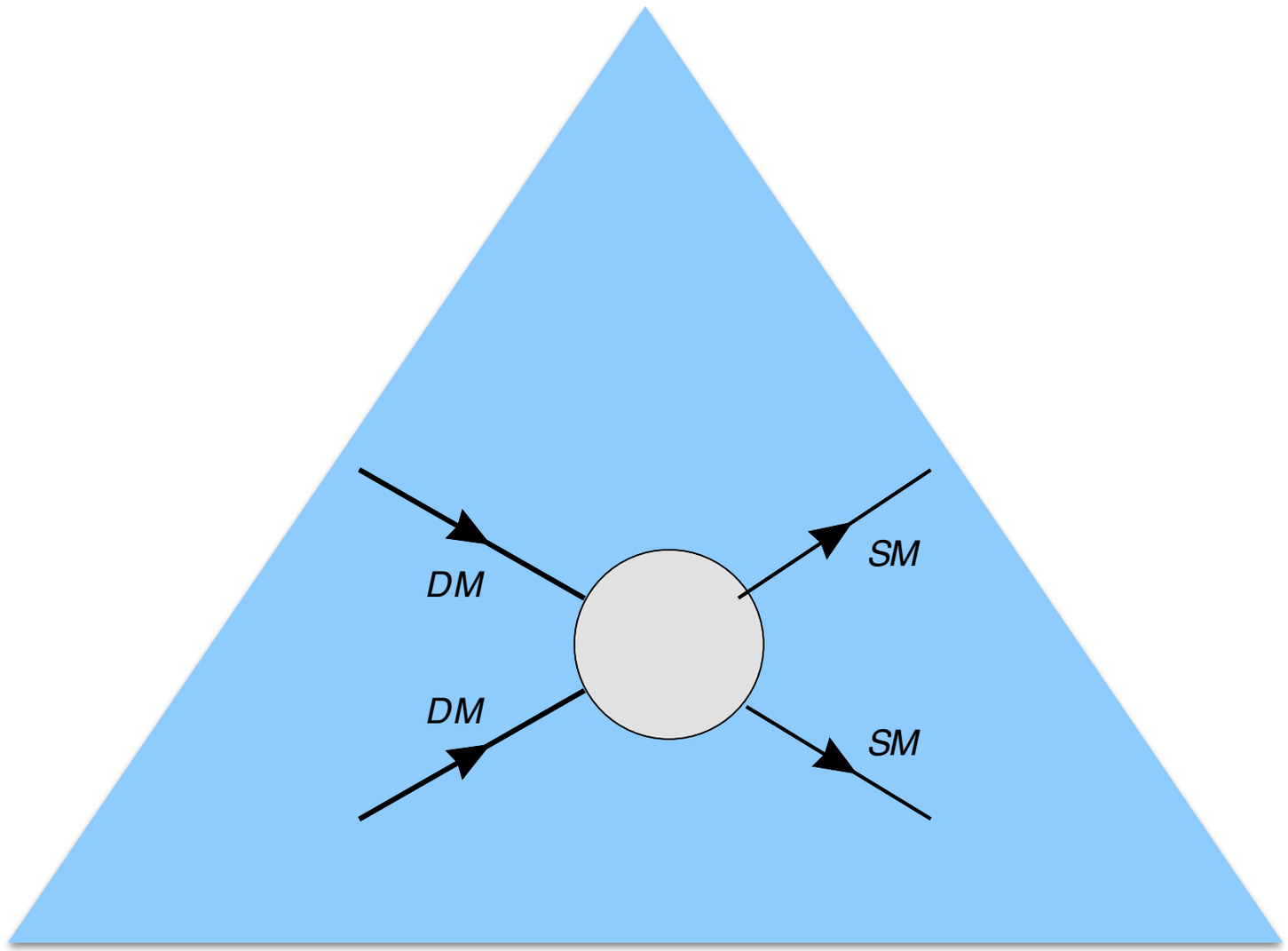
1. Gamma rays from cascade processes
2. Models and physical realisations
3. Comparing with experimental data
4. Conclusions

Dark matter indirect detection

Gamma-rays from cascade processes

Direct Detection

DM + nucleus →DM + nucleus



Indirect Detection

DM + DM → $e^{\pm}$,γ , $p^{\pm}$

Collider Searches

p + p → DM + X

Direct Detection

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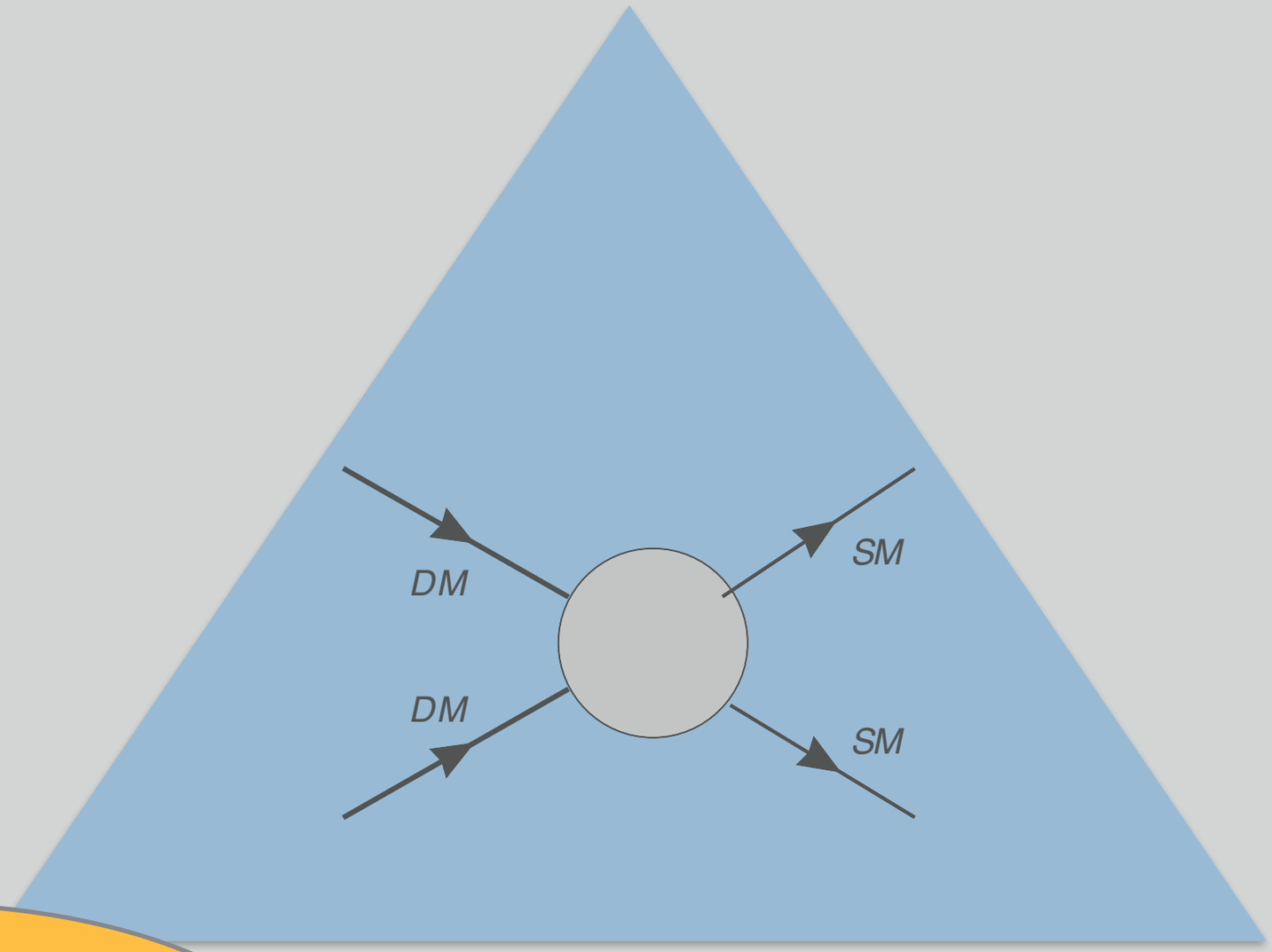

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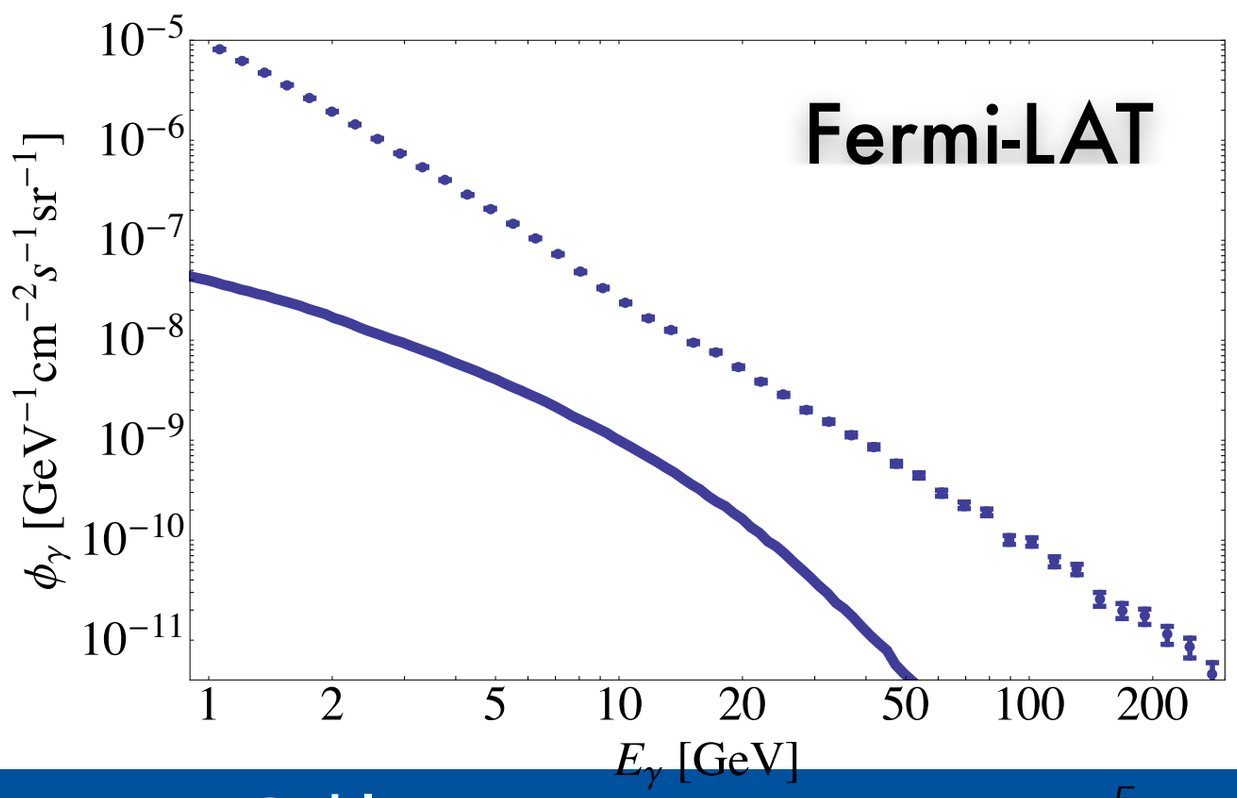
- An observation in this channel would be subject to many tests before we claim a discovery



$$m_\chi = 150\,\mathrm{GeV}$$
$$\langle \sigma v \rangle = 3 \times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$$
$$\chi\chi \to b\bar{b}$$

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- Instead of struggling with the background consider a case where the spectrum of DM origin differs from the power-law background

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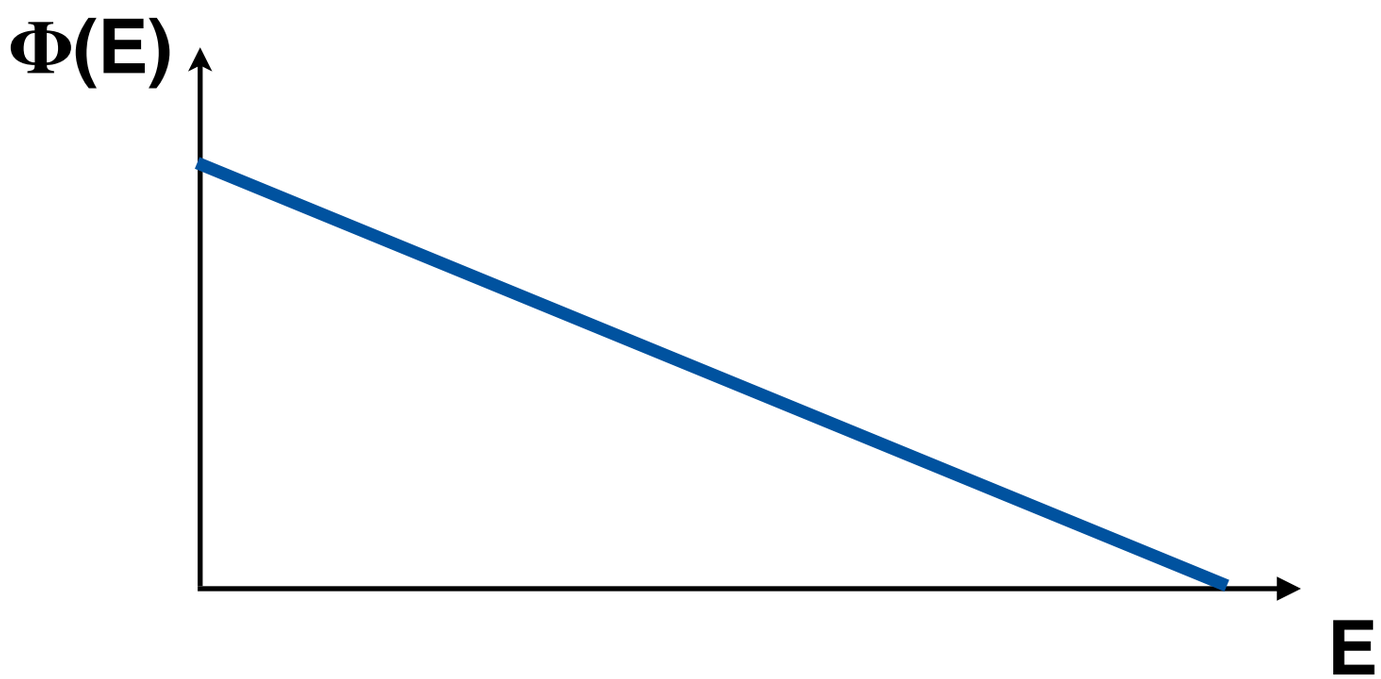

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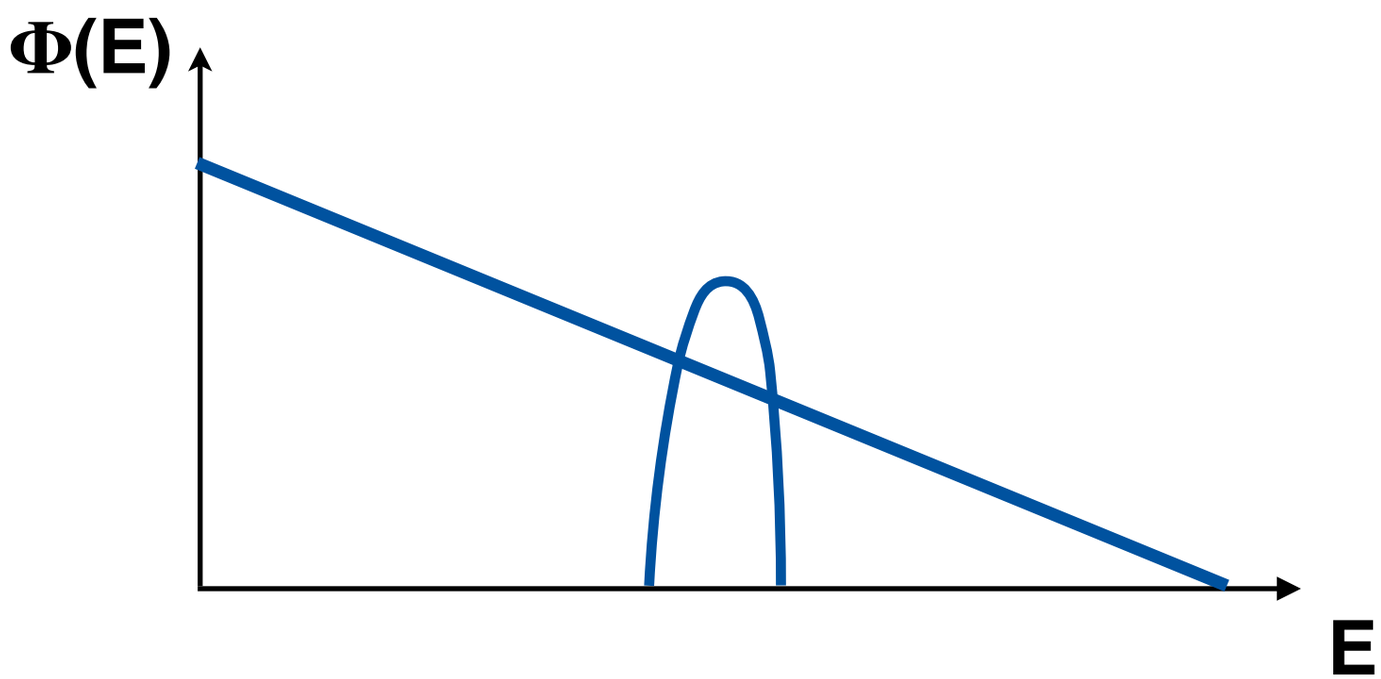

Indirect Detection with Gamma rays

Gamma-rays spectral features

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  1. Gamma-ray lines

Indirect Detection with Gamma rays

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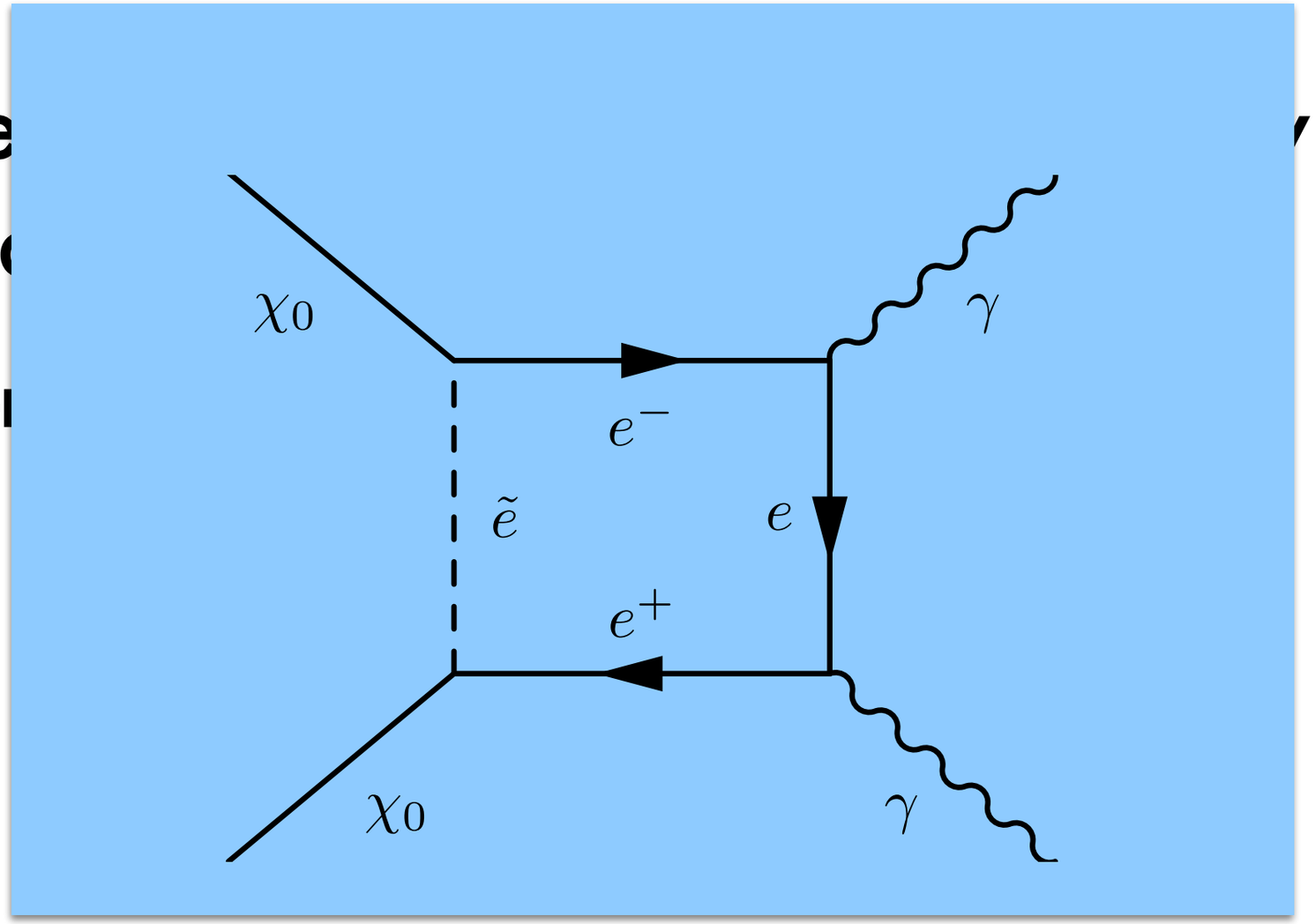

Indirect Detection with Gamma rays

Gamma-rays spectral features

- Spectral features present a very clean way to pinpoint dark matter → Smoking gun
  1. Gamma-ray lines
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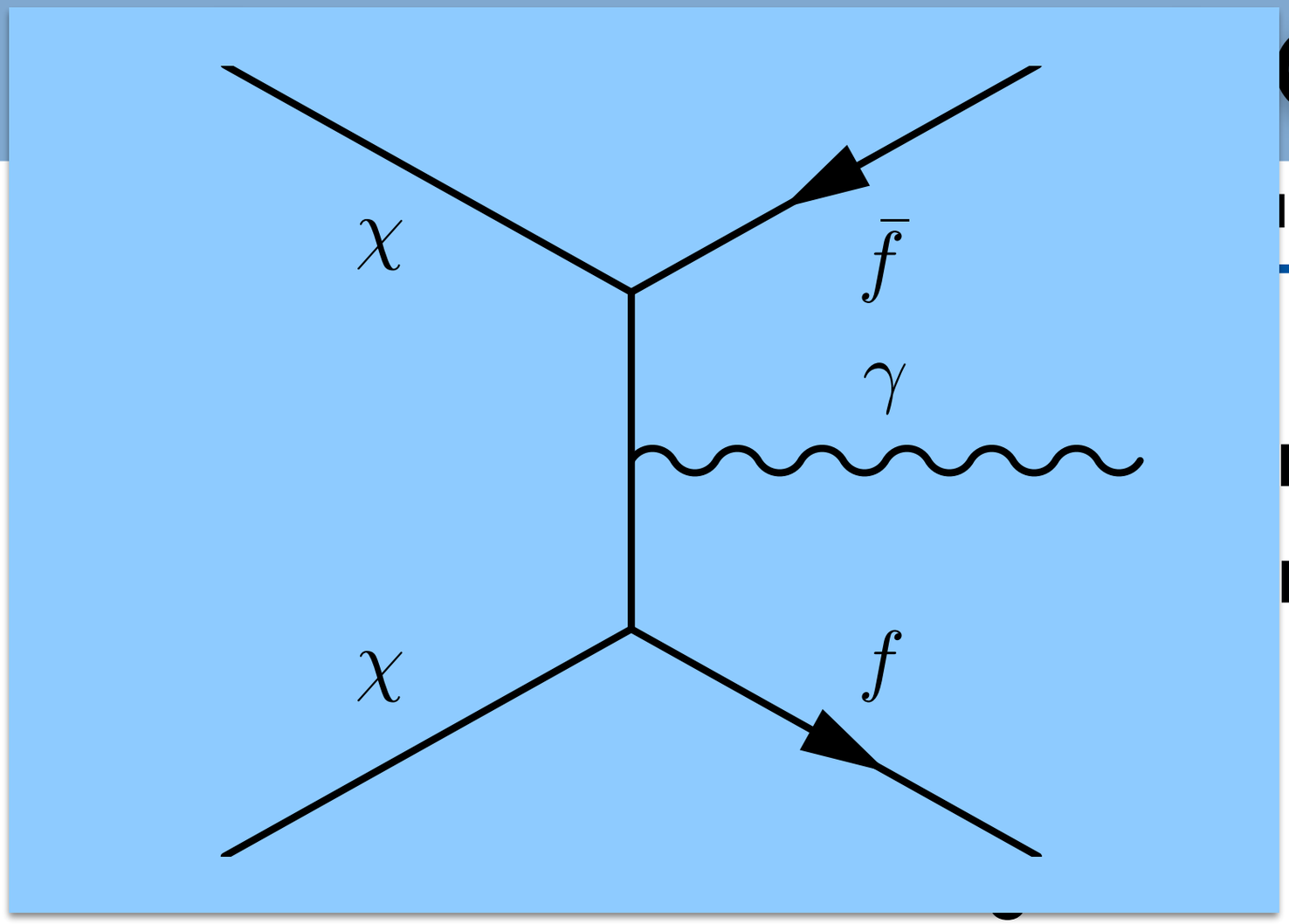
Gamma rays



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Indirect Detection with Gamma rays

Gamma rays spectral features

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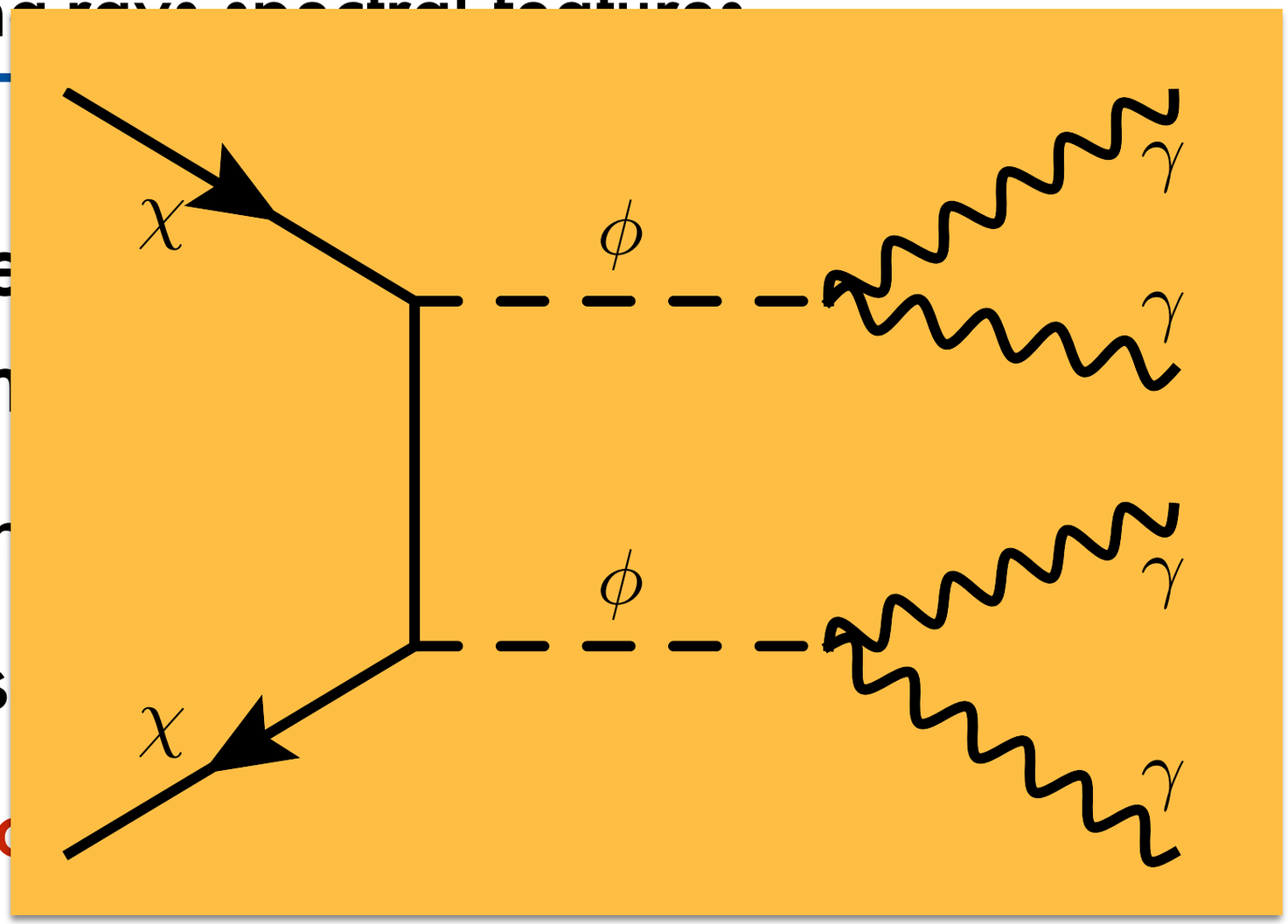

One-step cascades and "boxed" spectra

- Consider the process:

$$\chi\chi \to \phi\phi \implies \phi \to \gamma X$$

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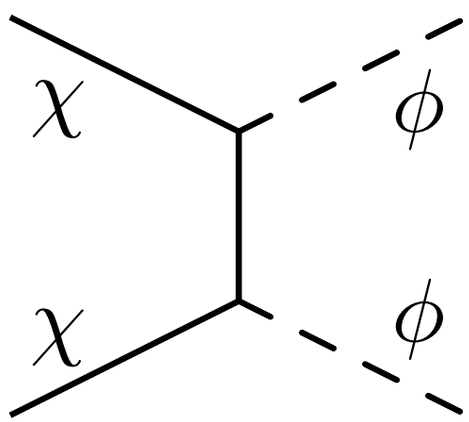

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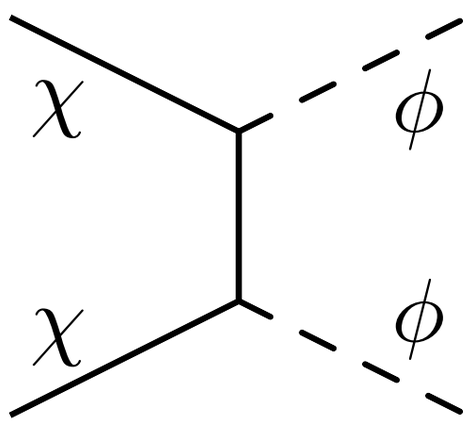

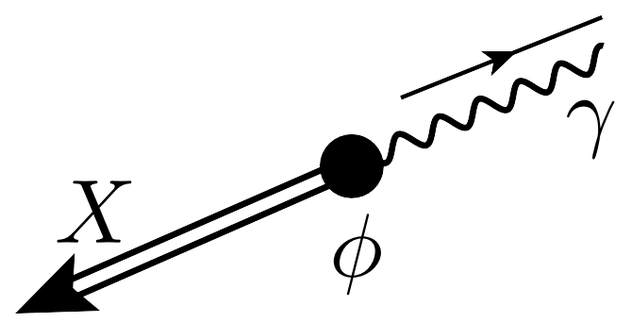

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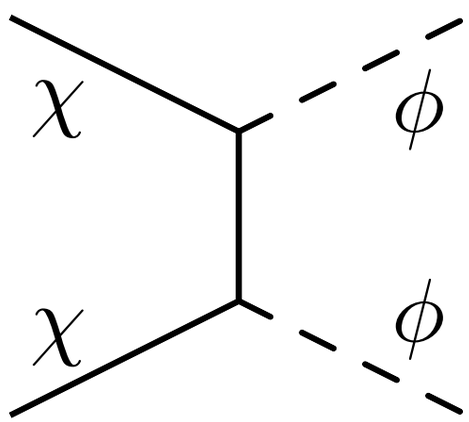

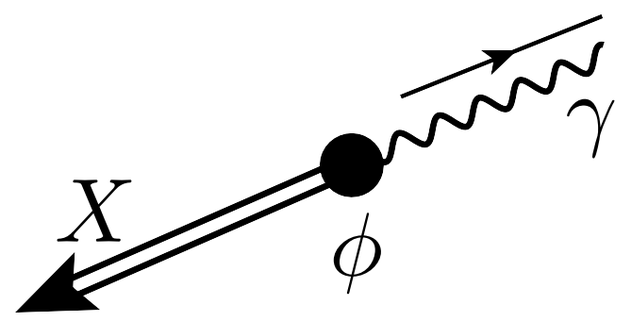

- Energy of the photons on the r.f. of ϕ

$$E_\gamma^{\mathrm{RF}} = \frac{1}{2}\delta_{\phi X} m_\chi \qquad \text{and} \qquad \delta_{\phi X} = 1 - \frac{m_X^2}{m_\phi^2}$$

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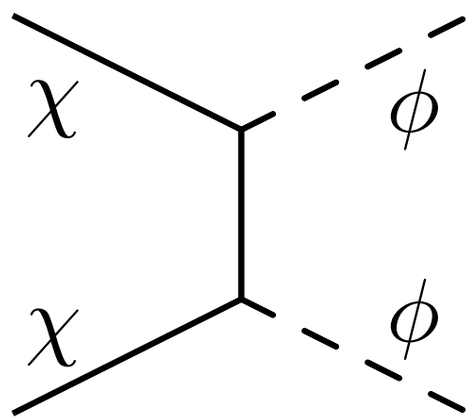

$$E_\gamma^{\rm lab} = \frac{1}{2}\delta_{\phi X} m_\chi \left(1 + \beta\cos\theta\right)$$

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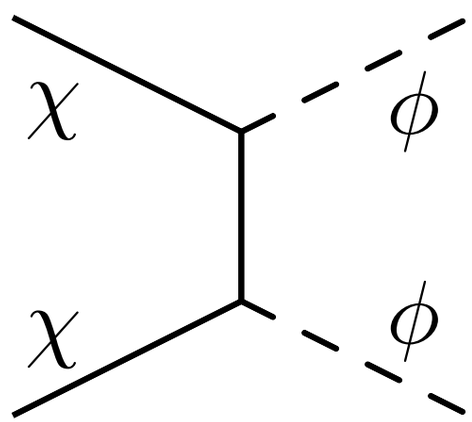

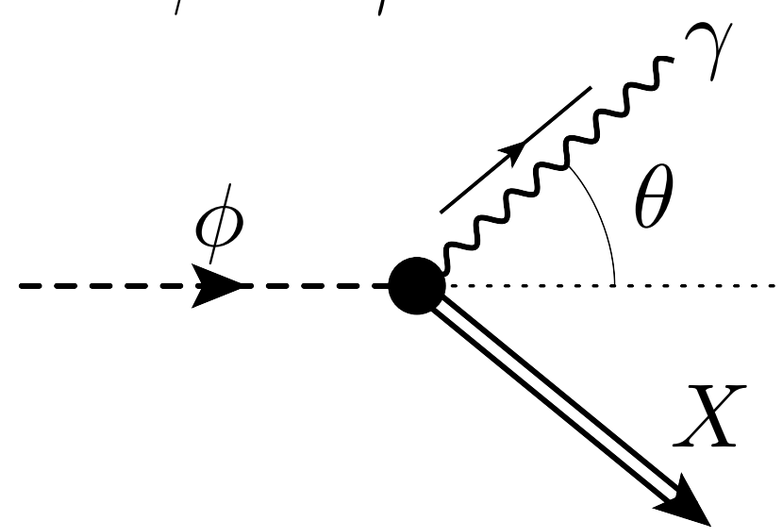

- In the lab frame:

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Scalars or fermions

- The intermediate be either a *scalar* or a *fermion*

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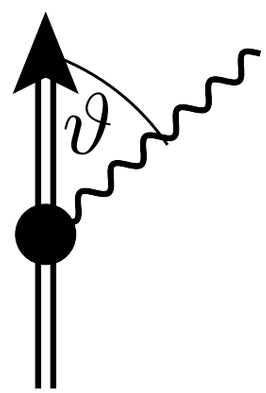
  Dirac Fermions



- Angular distribution of the radiated photons

$$\frac{\mathrm{d}N^{\mathrm{RF}}}{\mathrm{d}\cos\vartheta} = \frac{1}{2}\left(1 - \alpha\cos\vartheta\right)$$

- Decay modes: $\psi \to \nu\gamma$

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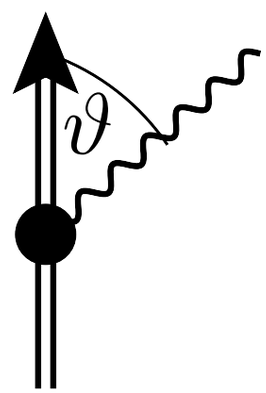
Dirac Fermions



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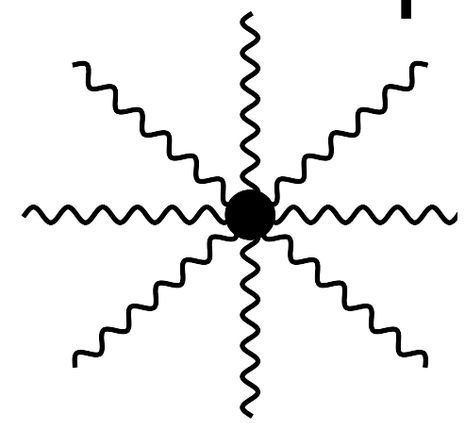
Scalars and Majorana F.



- Isotropic radiation of photons in the rest frame of the scalar

$$\alpha = 0$$

- Decay modes: $\phi \to \gamma\gamma$ or $\phi \to \gamma Z$

One-step cascades with scalars

- Consider the process:

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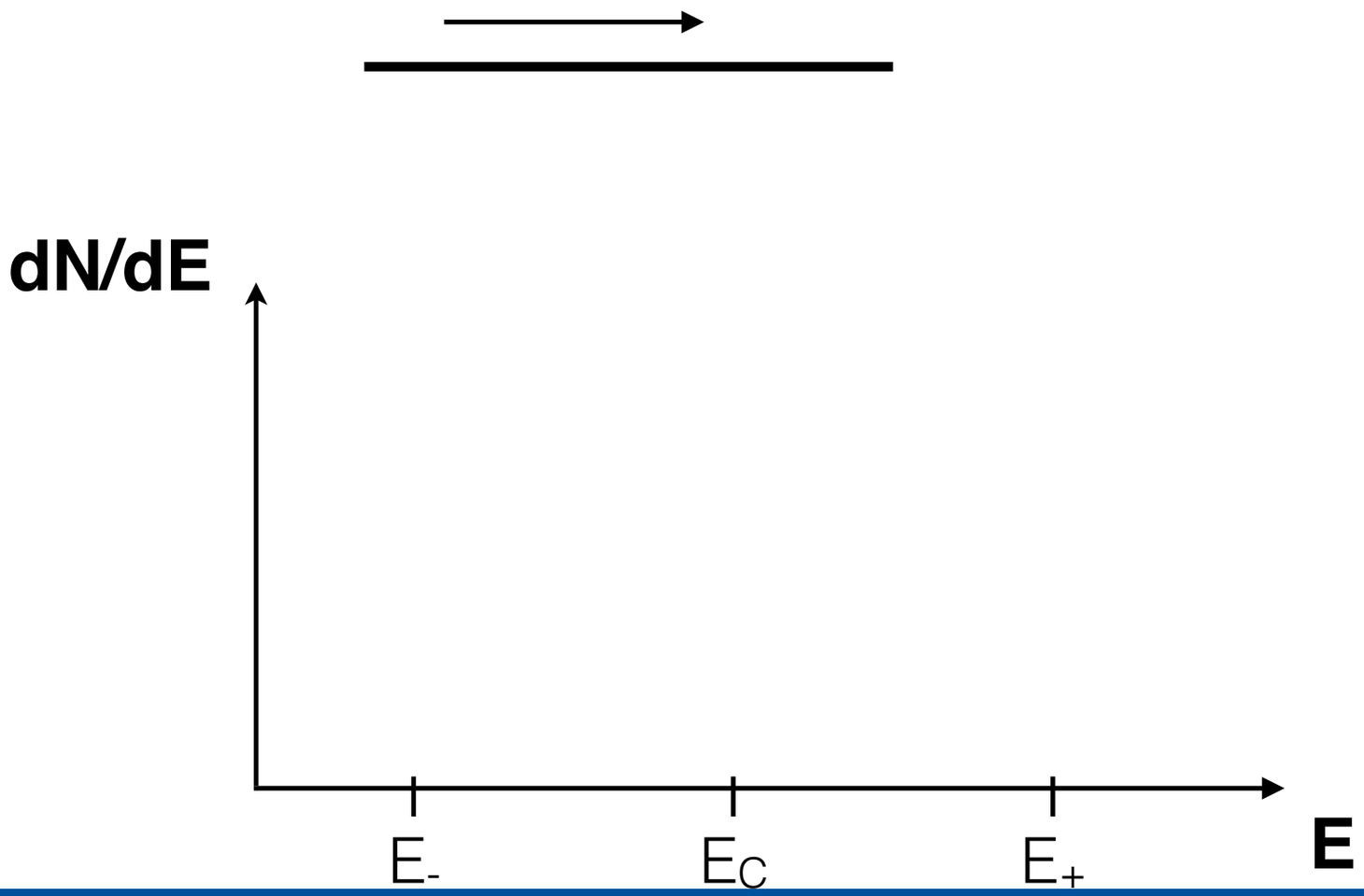

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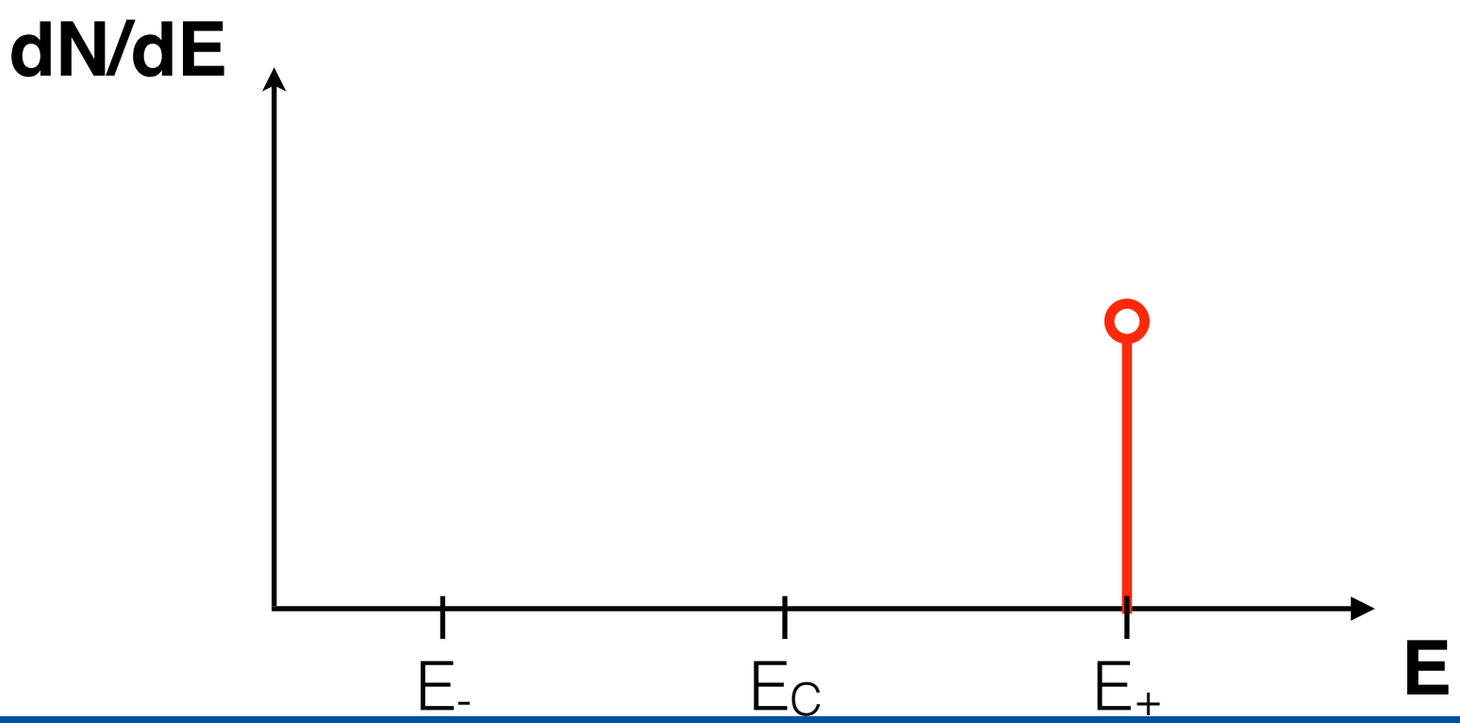

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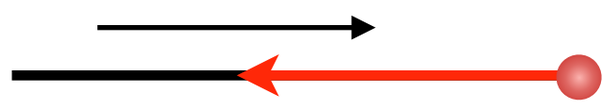

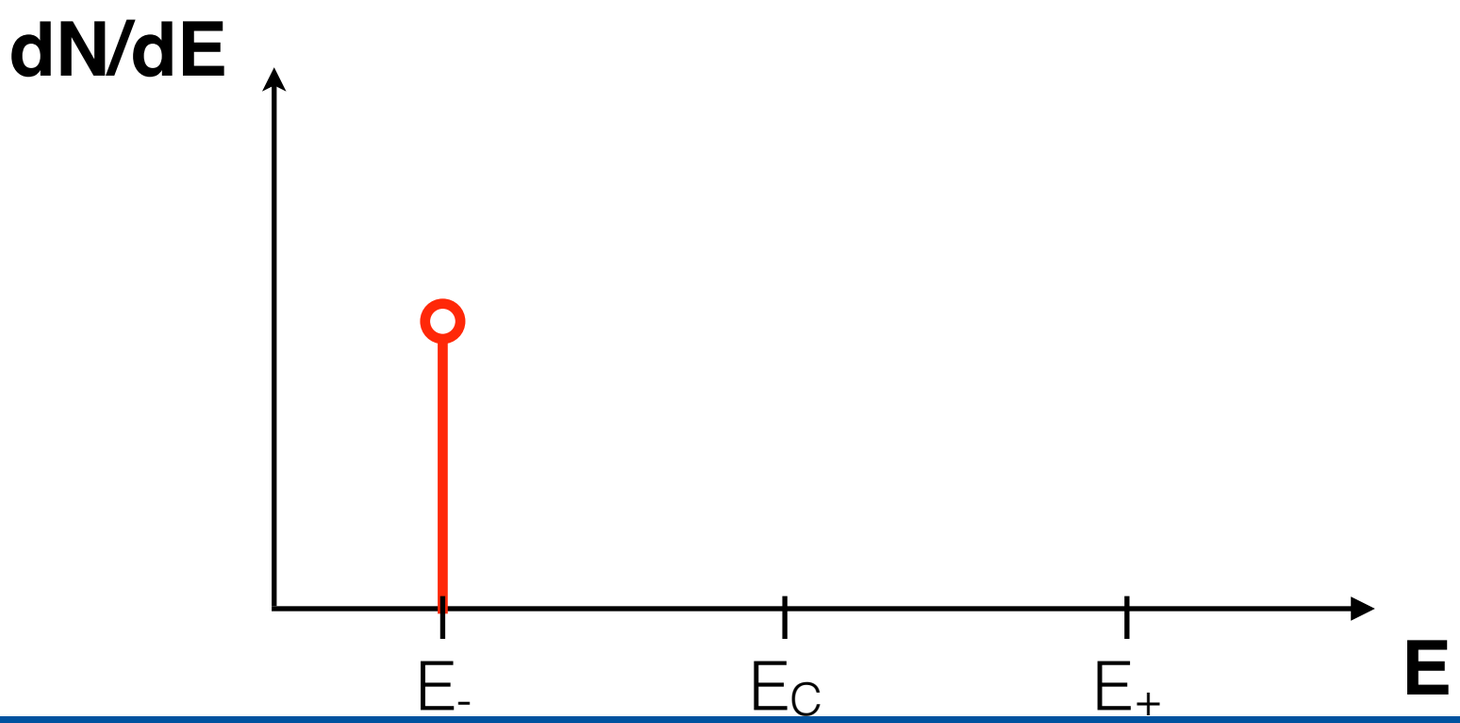

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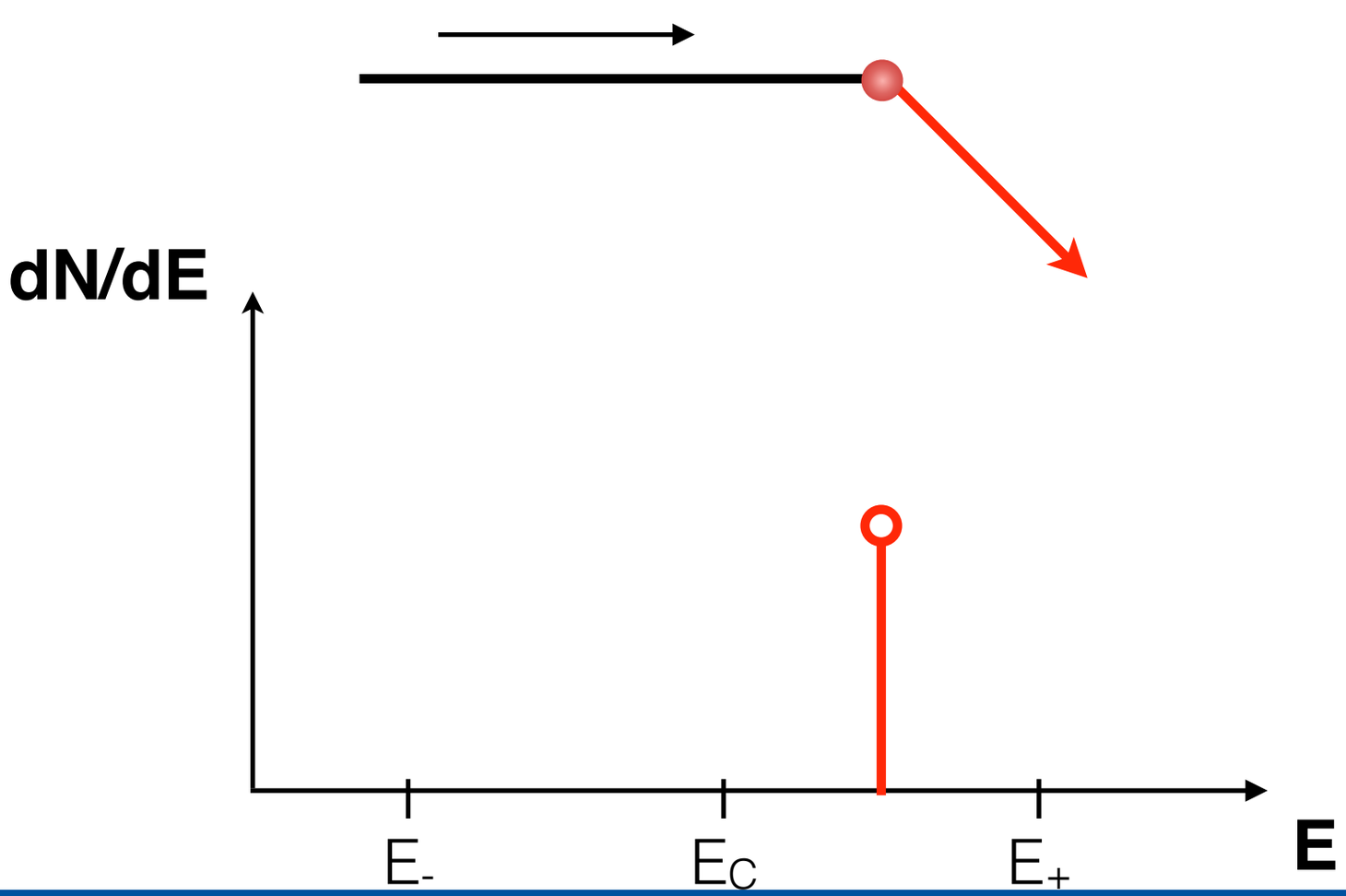

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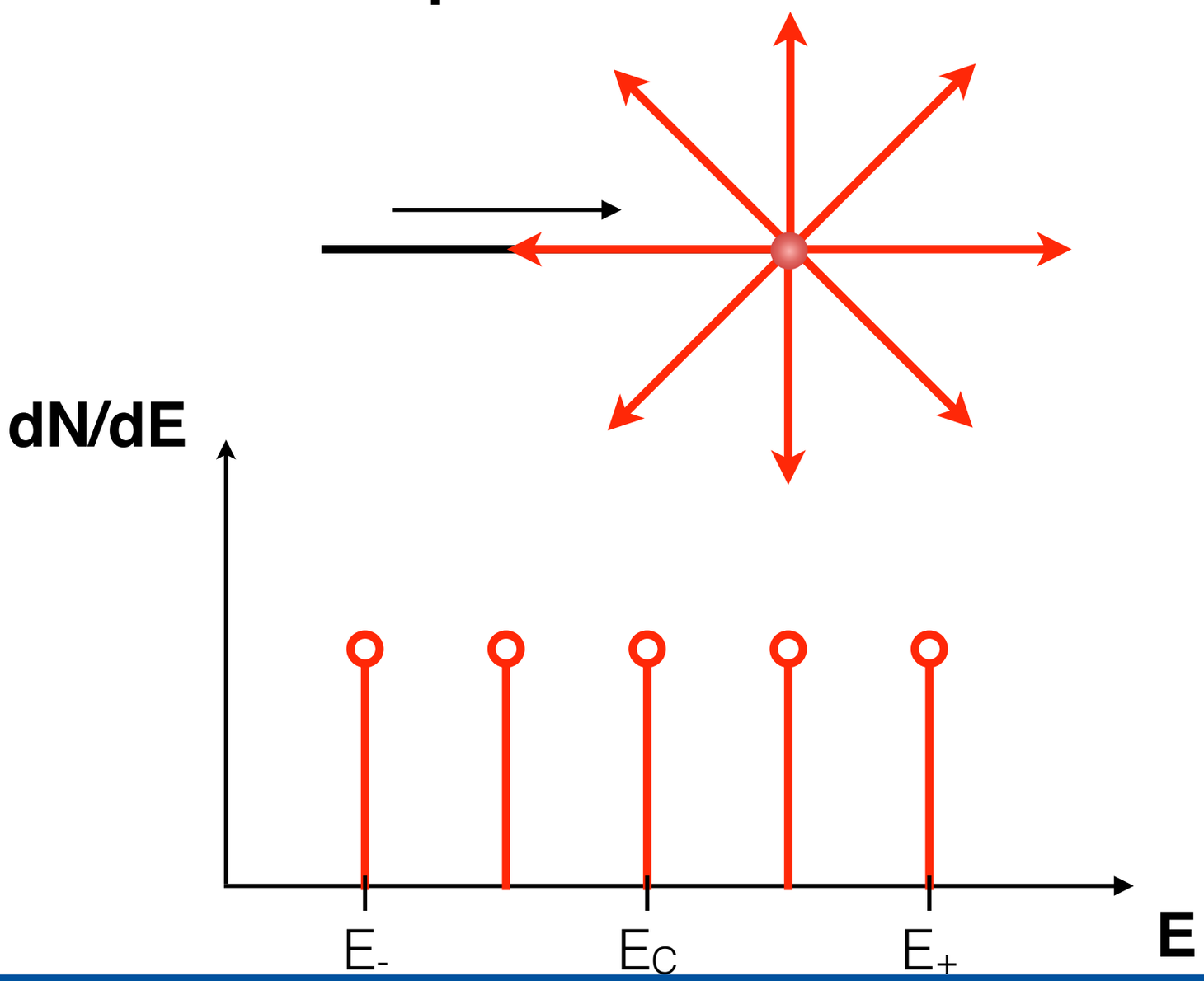

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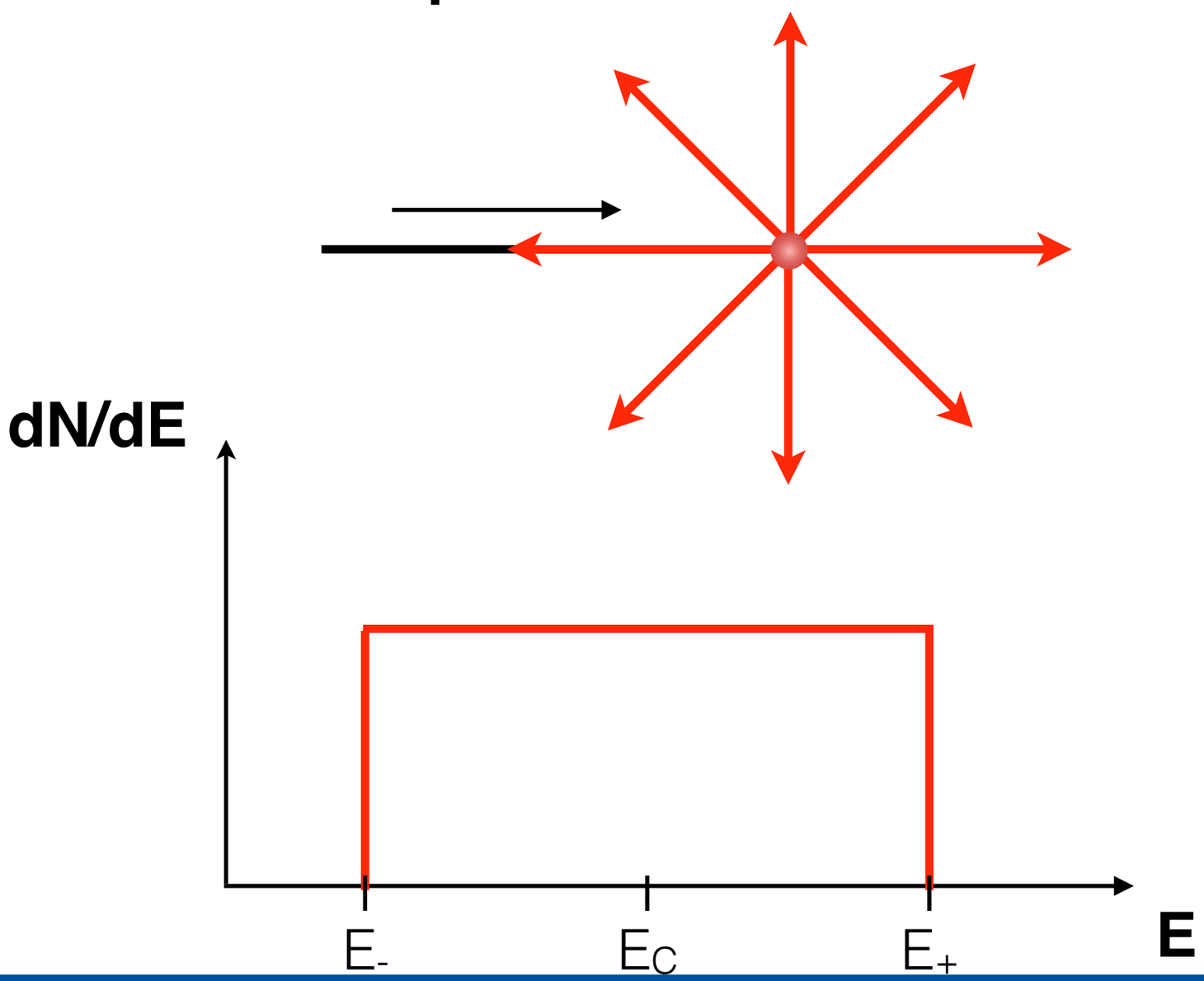

One-step cascades with fermions

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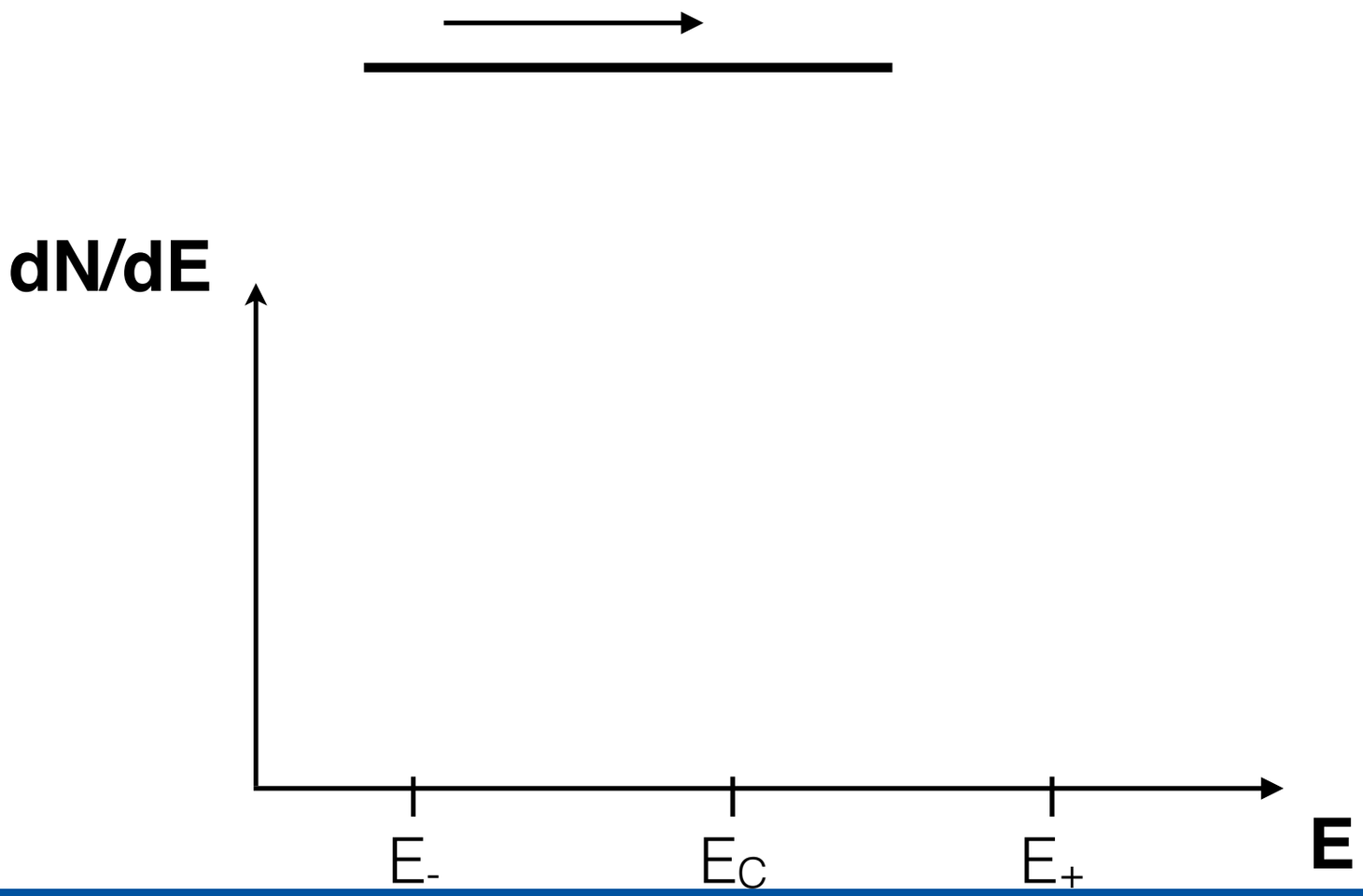

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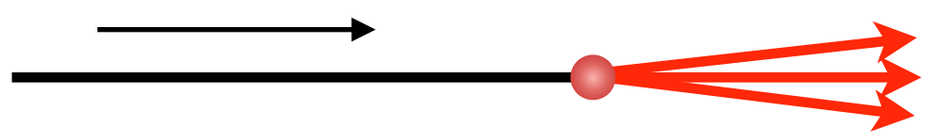

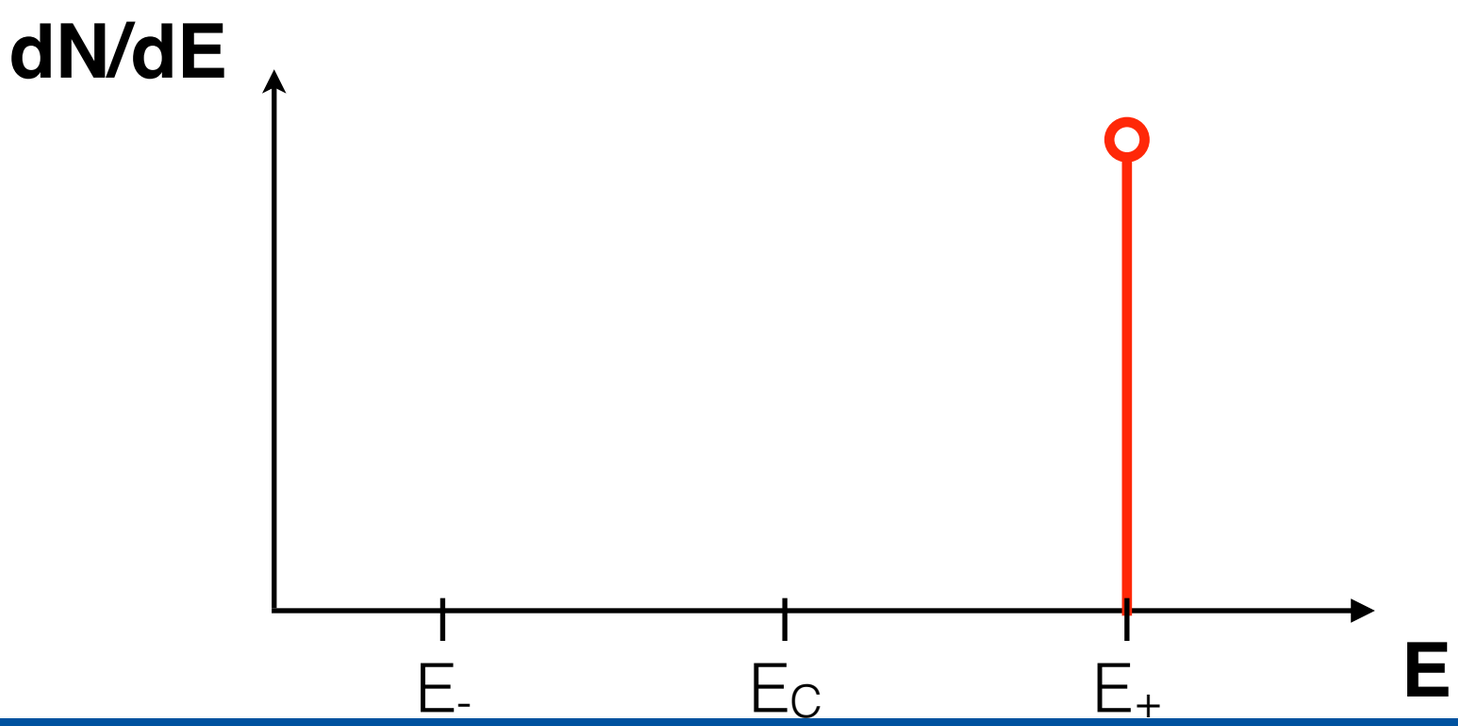

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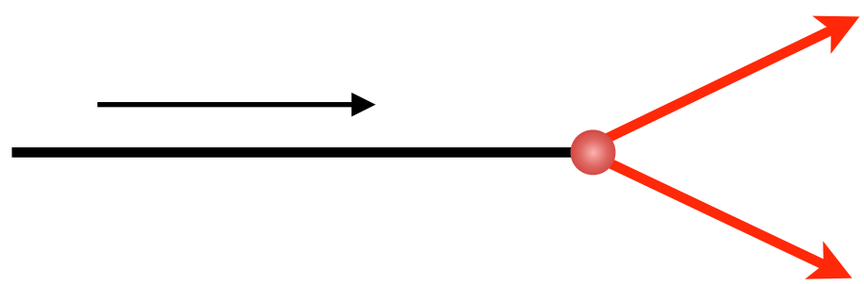

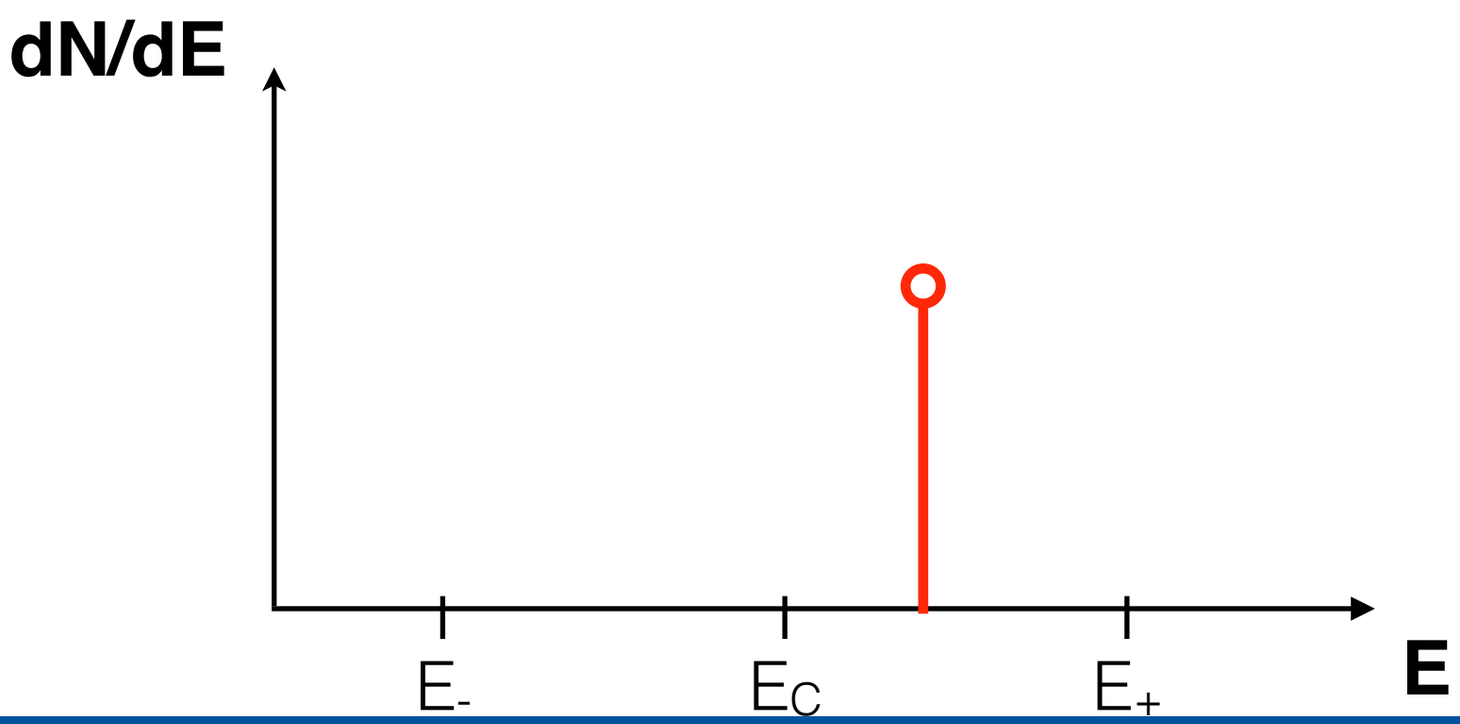

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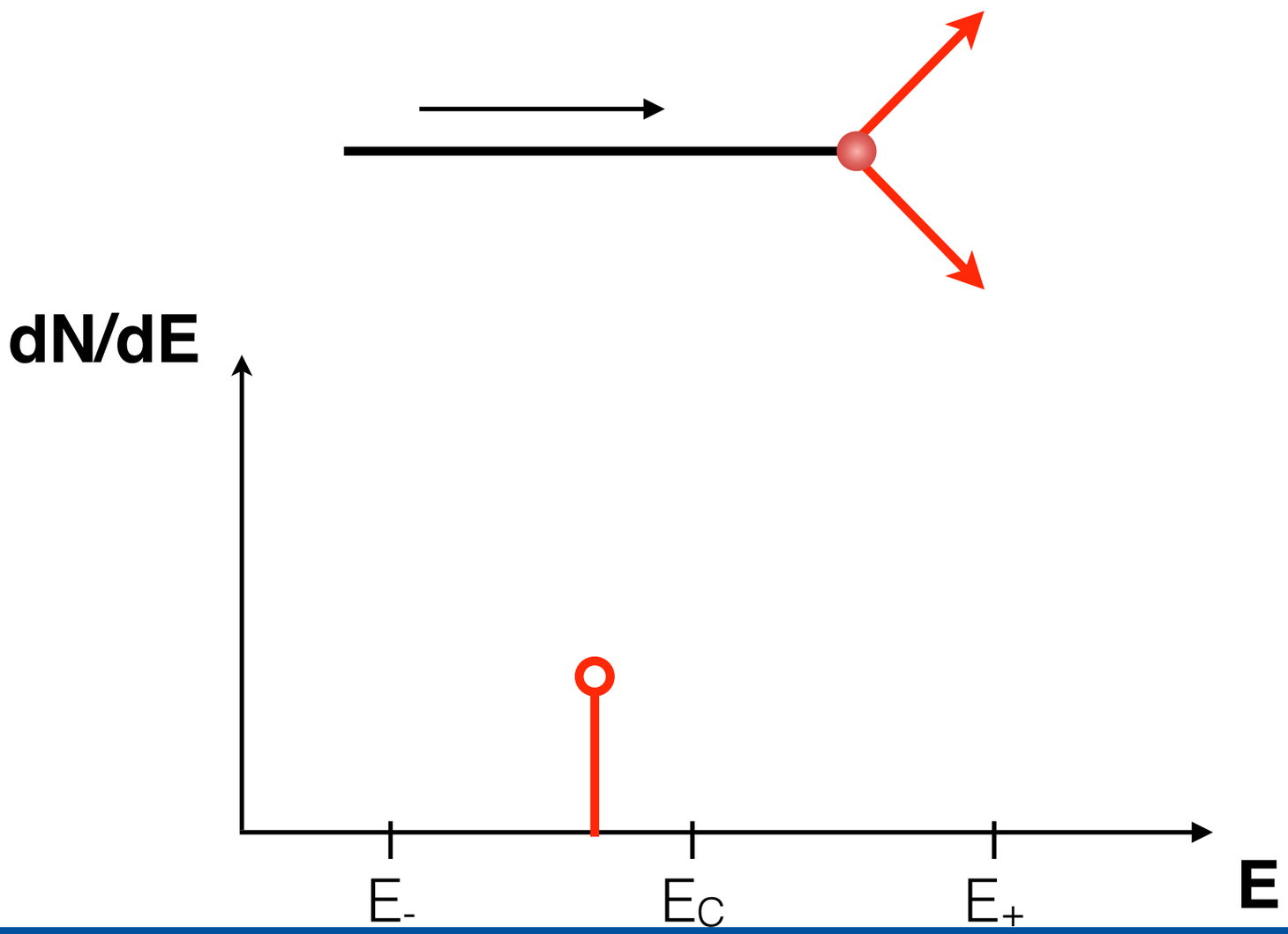

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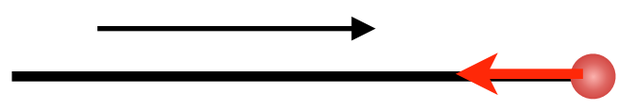

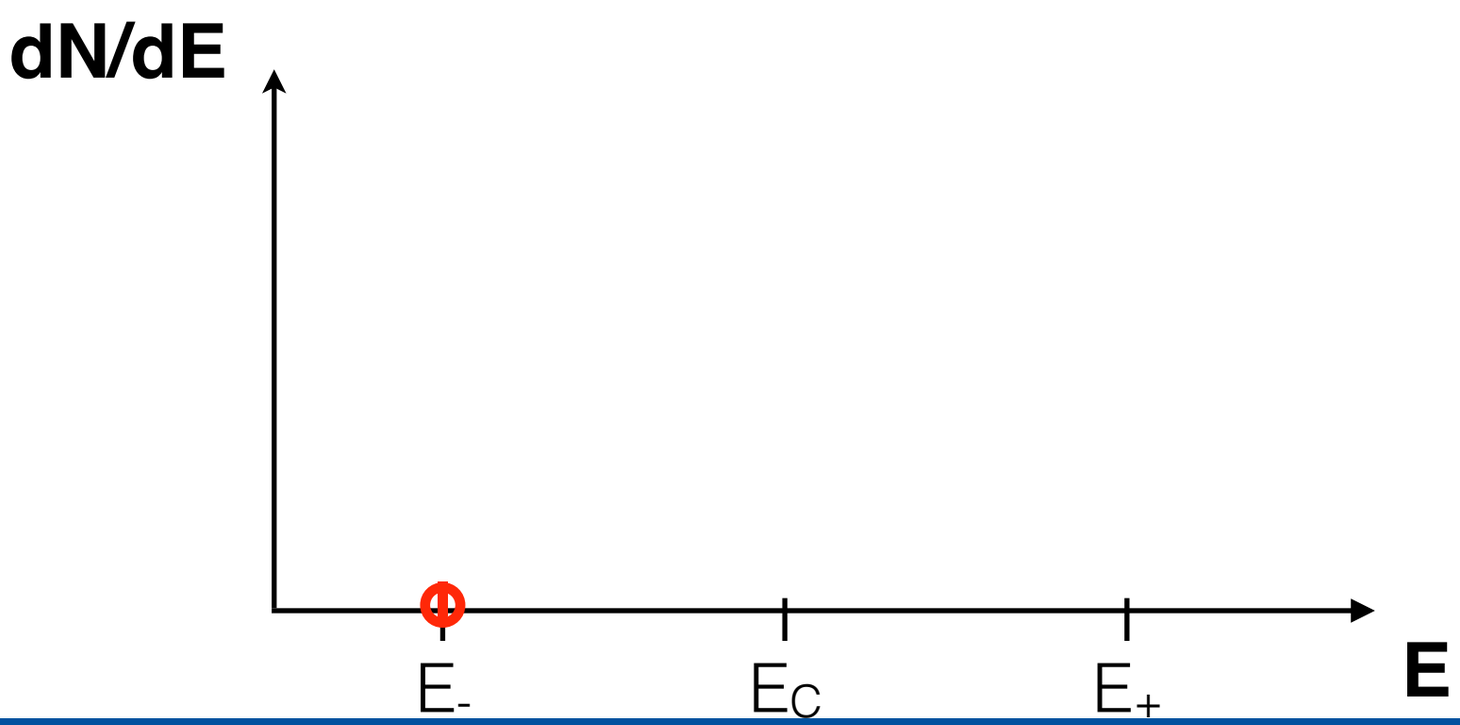

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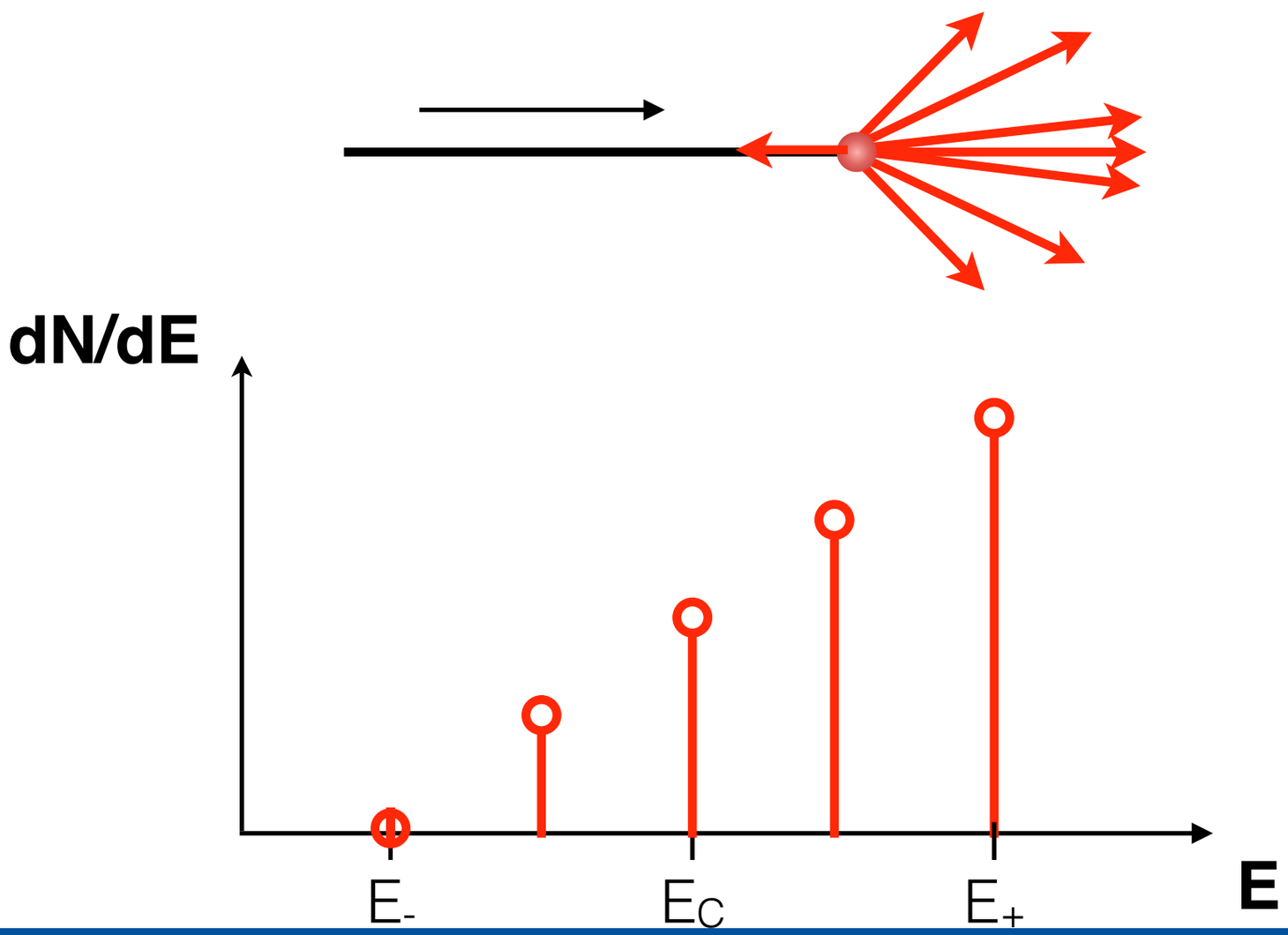

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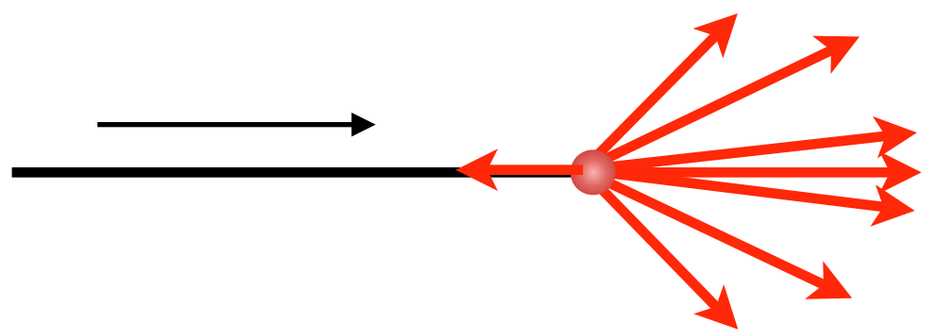

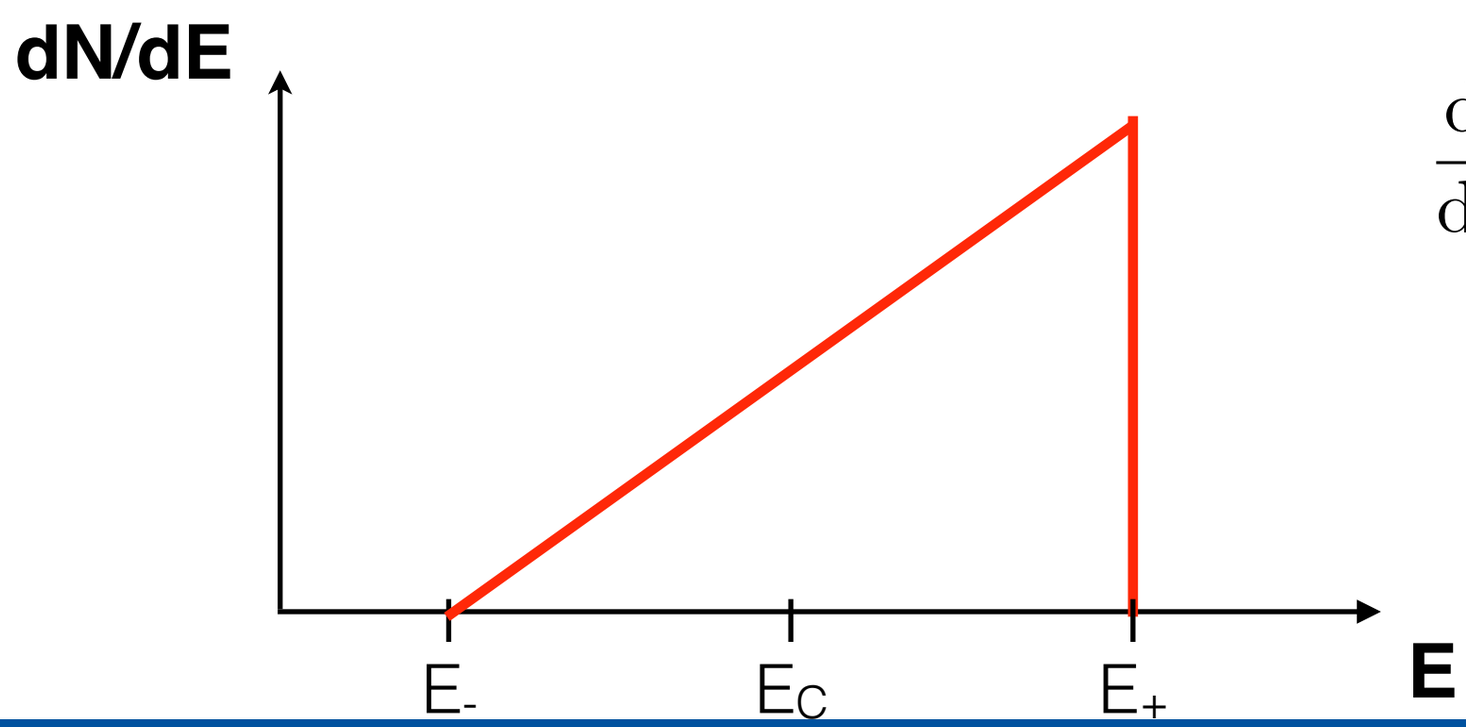

$$\frac{\mathrm{d}N^{\mathrm{RF}}}{\mathrm{d}\cos\vartheta} = \frac{1}{2}\left(1 - \alpha\cos\vartheta\right)$$

$$\alpha > 0$$

One-step cascades with fermion

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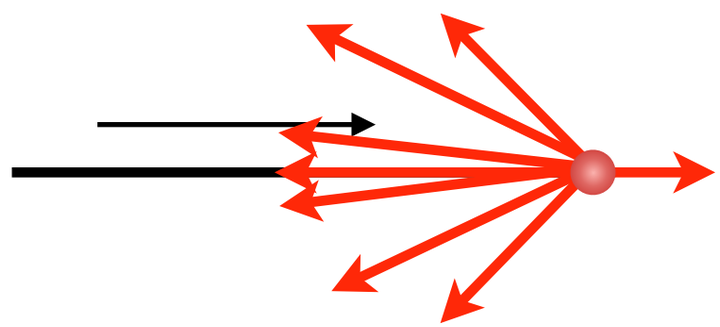
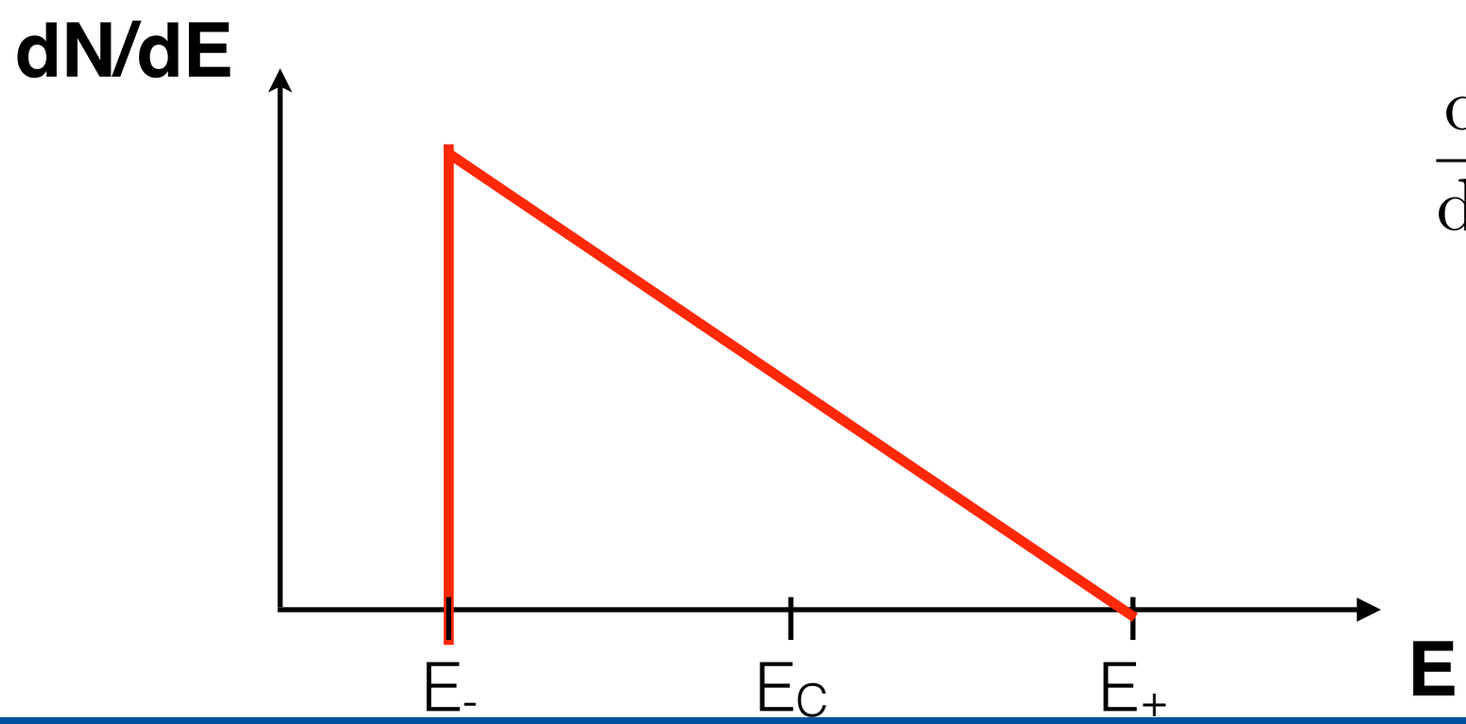




$$\frac{\mathrm{d}N^{\mathrm{RF}}}{\mathrm{d}\cos\vartheta} = \frac{1}{2}\left(1 - \alpha\cos\vartheta\right)$$

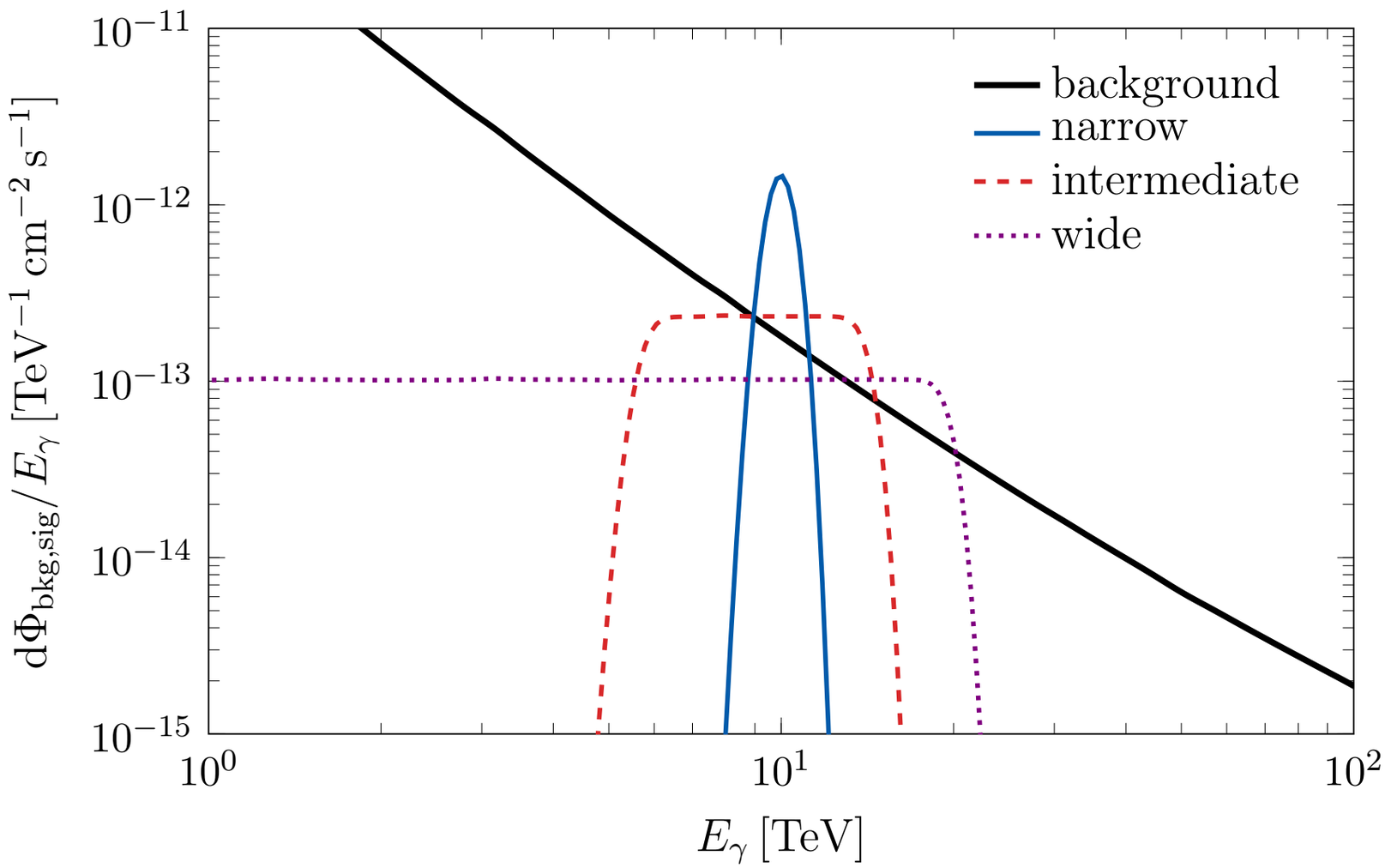
$$\alpha < 0$$

Measured flux - boxes

- Expected flux at earth:

$$\phi_\gamma(E_\gamma) = \frac{\mathrm{d}^4 N_\gamma}{\mathrm{d}E_\gamma \mathrm{d}S \mathrm{d}\Omega \mathrm{d}t} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}\frac{\mathrm{d}N_\gamma^{\mathrm{res}}}{\mathrm{d}E_\gamma}\frac{1}{\Delta\Omega}\int_{\Delta\Omega}\mathrm{d}\Omega\, J_{ann}$$

$$\delta_{\chi\phi} = 1 - \frac{m_\phi^2}{m_\chi^2}$$



narrow

$$\delta_{\chi\phi} = 0.002$$

intermediate

$$\delta_{\chi\phi} = 0.2$$

wide

$$\delta_{\chi\phi} = 0.99$$

Measured flux - triangles

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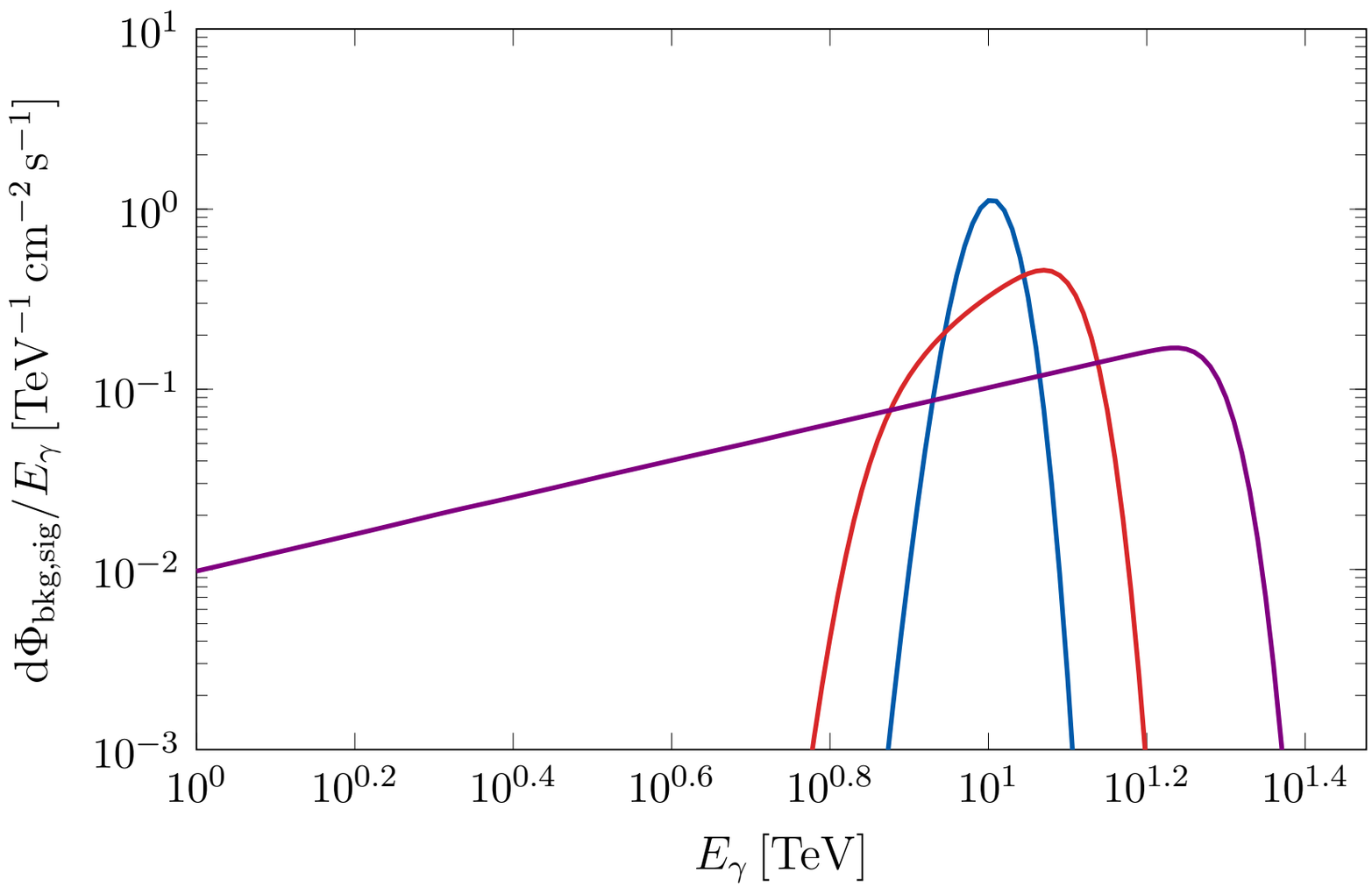

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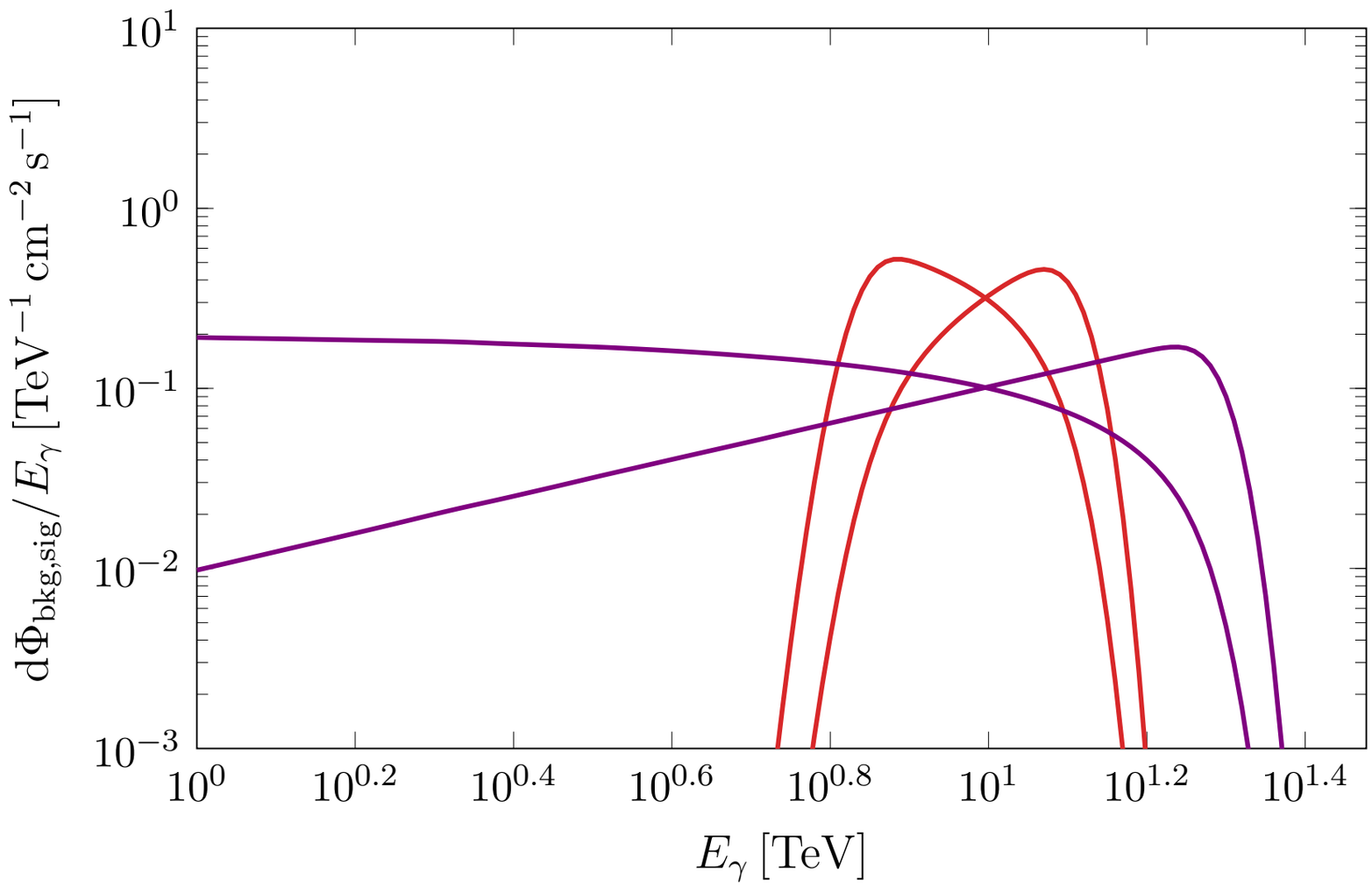

$$\frac{\mathrm{d}N^{\mathrm{RF}}}{\mathrm{d}\cos\vartheta} = \frac{1}{2}\left(1 - \alpha \cos\vartheta\right)$$

forward

$$\alpha > 0$$

backward

$$\alpha < 0$$

Measured flux - triangles

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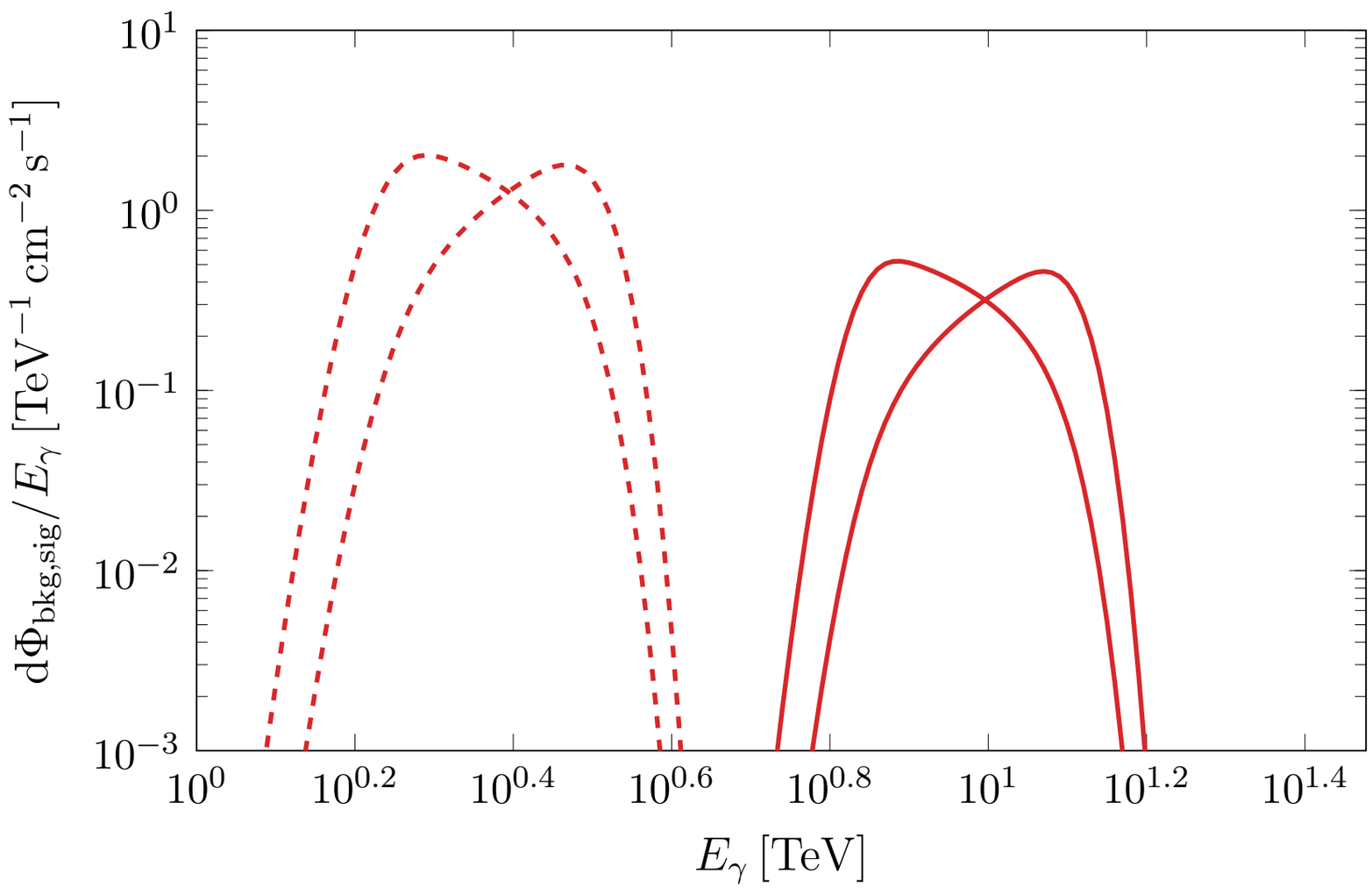
$$\delta_{\psi\nu} = 1 - \frac{m_\nu^2}{m_\psi^2}$$



high energies

$$\delta_{\psi\nu} = 1$$

low energies

$$\delta_{\psi\nu} = 0.25$$

Models and physical realisations

What do we need?

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- An intermediate state –fermion or scalar– which couples to DM
- A decay channel of the i.s. into photons (with sizeable BR)

Models for boxes

- Models involving the U(1) SSB and PQ mechanism

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3. Branching ratio $a \to \gamma\gamma$ of 20-100% depending on the choice of the anomaly factors involved

Ibarra, Lee, SLG, Park, Pato (arXiv:0810.5397)

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(Motivated by the galactic positron excess)

1. A TeV DM Dirac fermion χ with dominant annihilation mode $\chi\chi\to as$ (s-wave)
2. BR into photons of $\approx 10^{-3}$; simultaneously boost factor of $\approx 10^{3}$
3. Only wide boxes

Y. Nomura, J. Thaler (arXiv:0810.5397)

Models for triangles

- If the intermediate states are Majorana, boxes are produced → intermediate states have to be Dirac

- Intermediate states are Dirac → U(1) charge, this means dm has also to be Dirac

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu S\,\partial^\mu S + i\,\overline{\chi}\,\partial\!\!\!/\,\chi + i\,\overline{N}_D\,\partial\!\!\!/\,N_D - \frac{1}{2}\mu_S^2\,S^2 - M_\chi\,\overline{\chi}\,\chi - M_N\,\overline{N}_D\,N_D$$
$$- \left(\lambda_\alpha\,\overline{L}_\alpha\,N_D\,H + f\,\overline{N}_D\,P_{L,R}\,\chi\,S + \text{h.c.}\right) - V(H,\,S)\,,$$

Preliminary

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Field	L_α	$e_{R\alpha}$	N_D	χ	S
$U(1)_X$	1	1	1	1	0
Z_2	1	1	1	-1	-1

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$$\chi\chi \to N_{D,R}N_{D,R} \to \gamma\gamma + \nu\nu$$

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- First clear indirect detection signal for ADM models

Comparing with experimental data

Upper limits on the cross section

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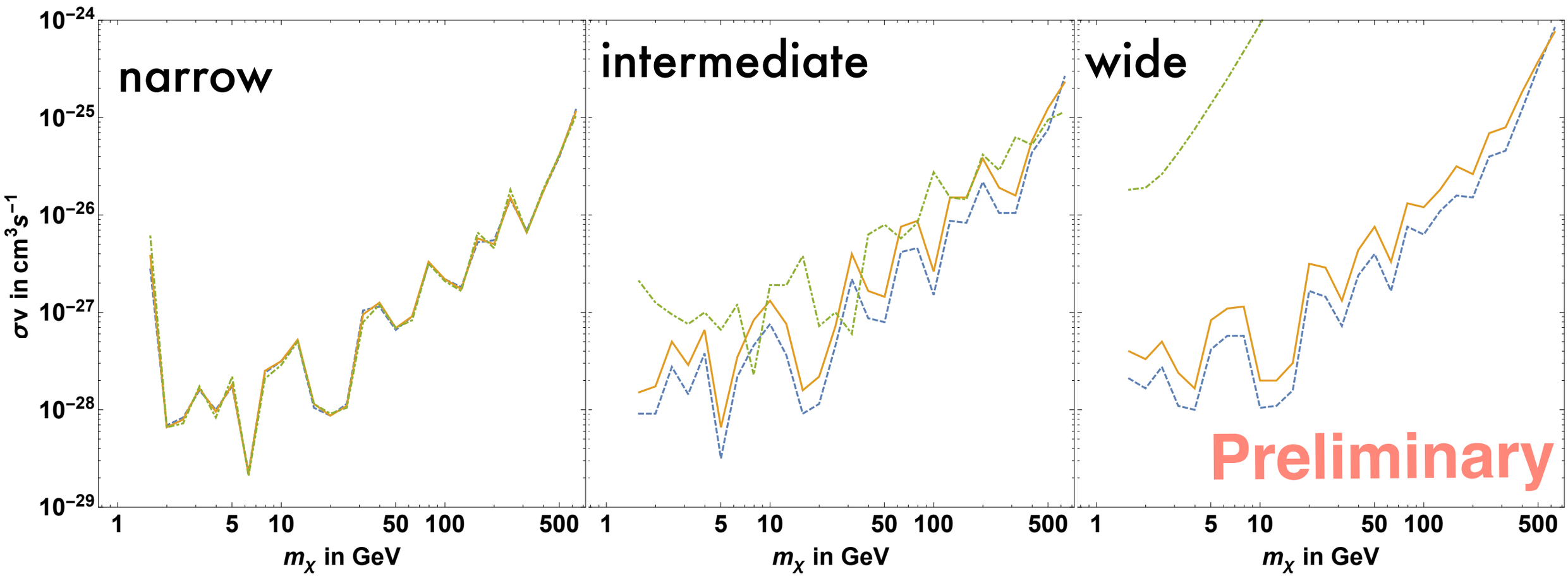
- We perform a sliding-window profile likelihood analysis all the sets of mock data
- We use three different sets of data: H.E.S.S., Fermi and CTA (prospects)

Upper limits on the cross section

Using Fermi-LAT data from arXiv:1101.2610

- Varying the box/triangle width → $\delta_{\chi\phi}$ or $\delta_{\chi\psi}$

  $\epsilon = 2 \quad \delta_{\psi\nu} = 1$

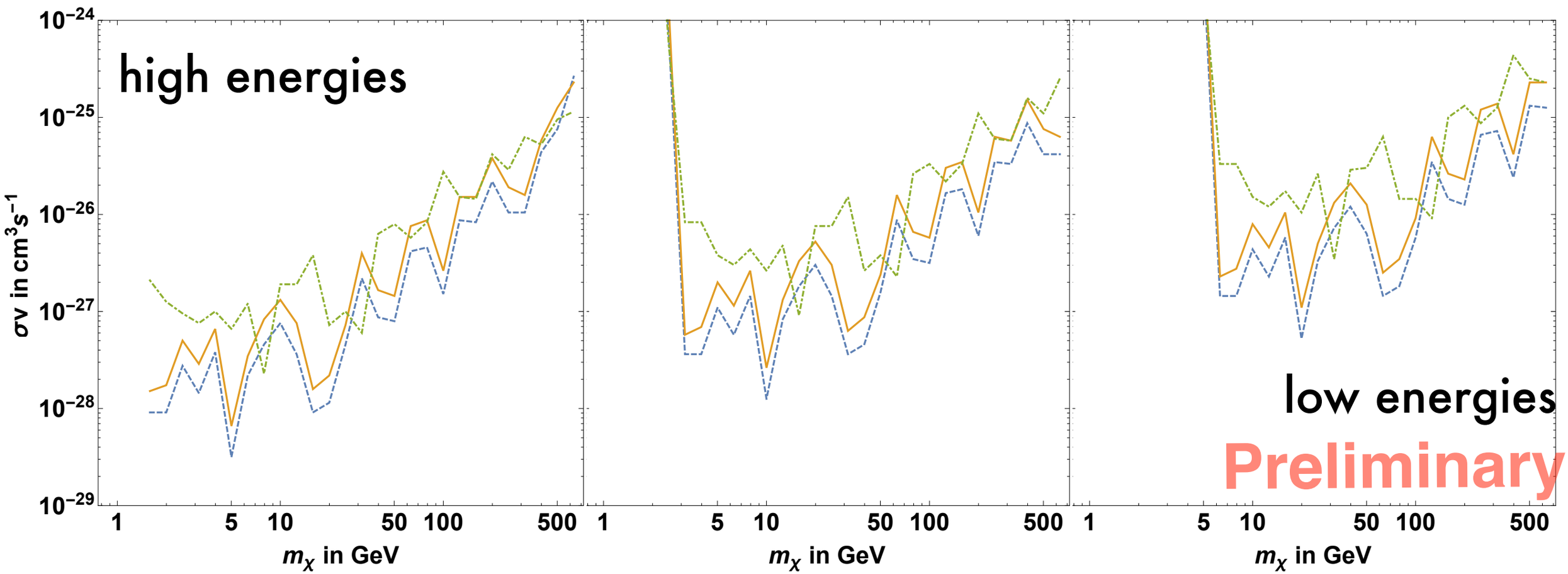


Upper limits on the cross section

Using Fermi-LAT data from arXiv:1101.2610

- Varying the centre of the triangle → $\delta_{\psi\nu}$

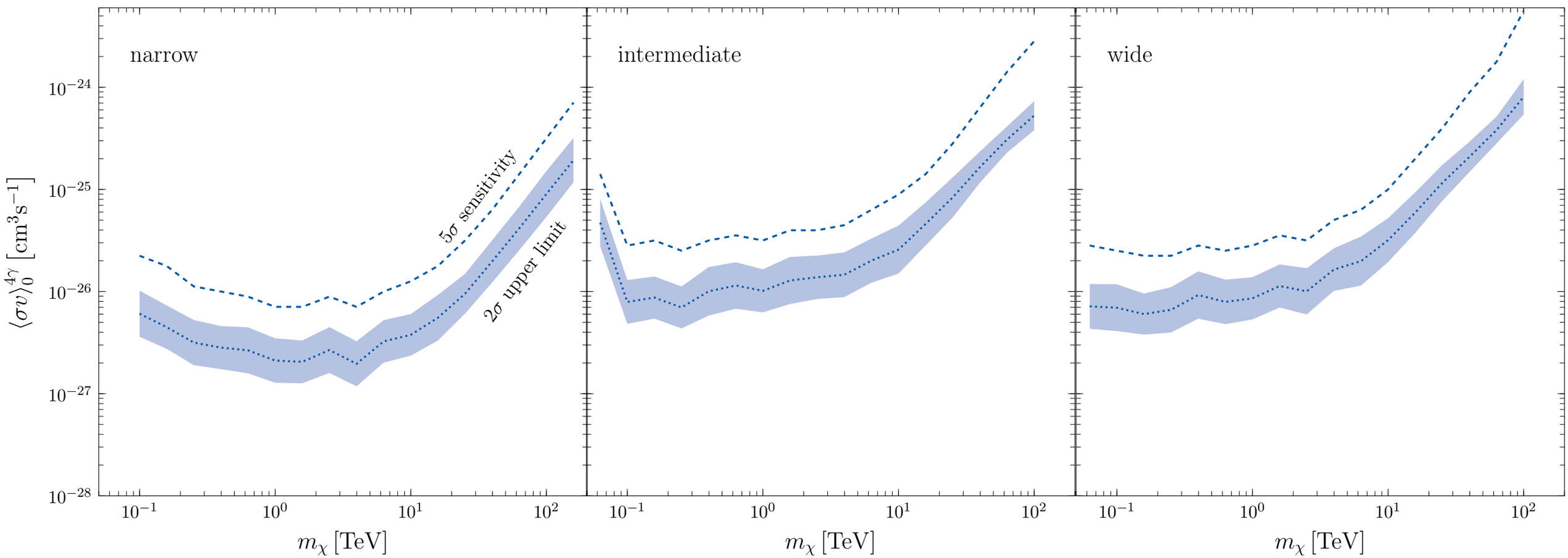
  $\epsilon = 2 \quad \delta_{\chi\psi} = 0.1$



Prospects on CTA

Ibarra, Lamperstorfer, SLG, Pato, Bertone arXiv:1503.06797 [astro-ph.HE]

- 2σ upper limits and 5σ sensitivity to gamma-ray boxes for the upcoming CTA experiment



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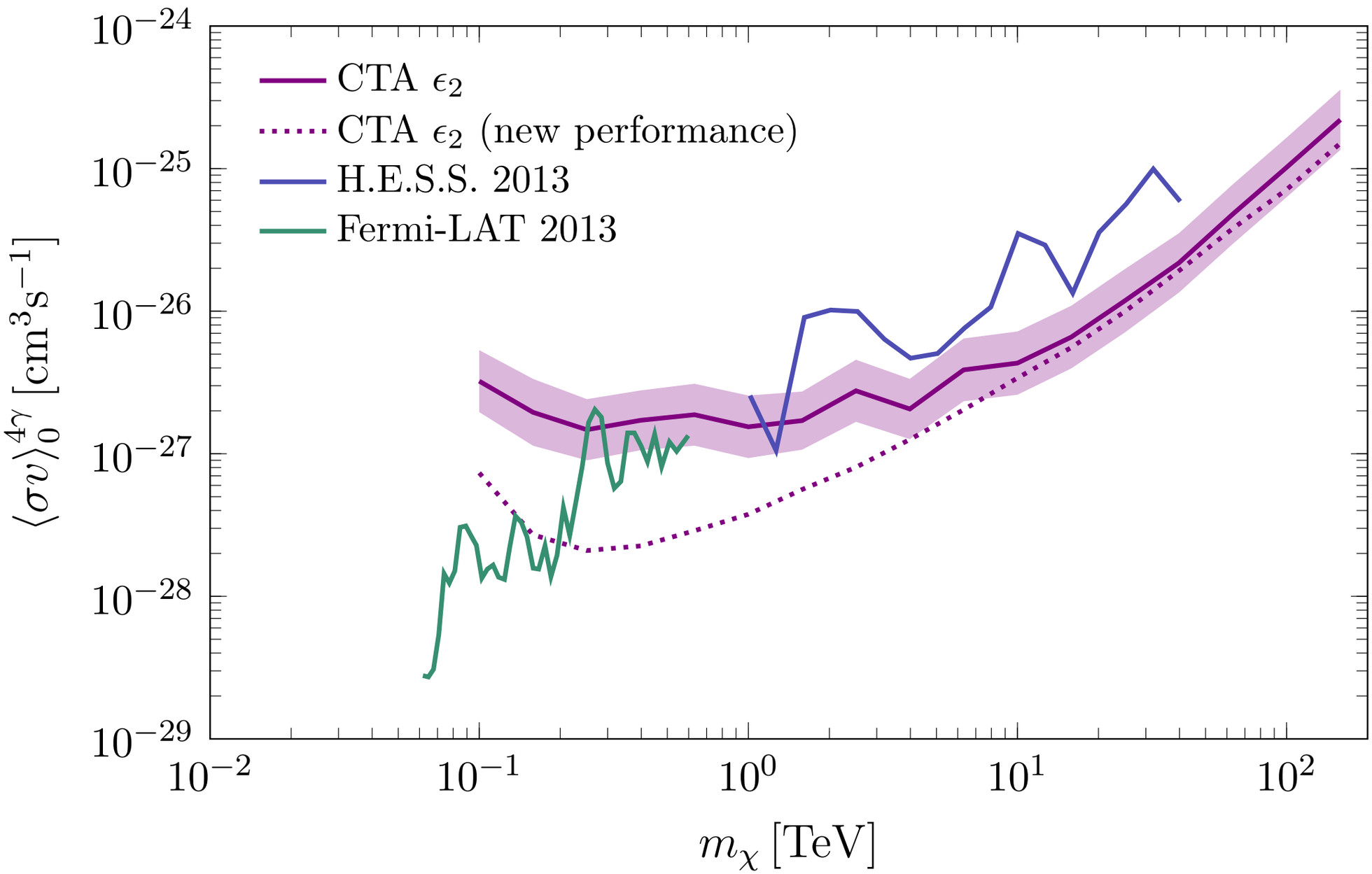

Conclusions

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- Spectral features in the gamma-ray sky would be an unequivocal signal of dark matter

  → If not observed it constrains strongly such scenarios

- Gamma-ray boxes are a third kind of spectral features that show naturally in some scenarios circumventing issues such as fine tuning

- There are feasible models that have such a behaviour and through this analysis we may set powerful limits on such scenarios

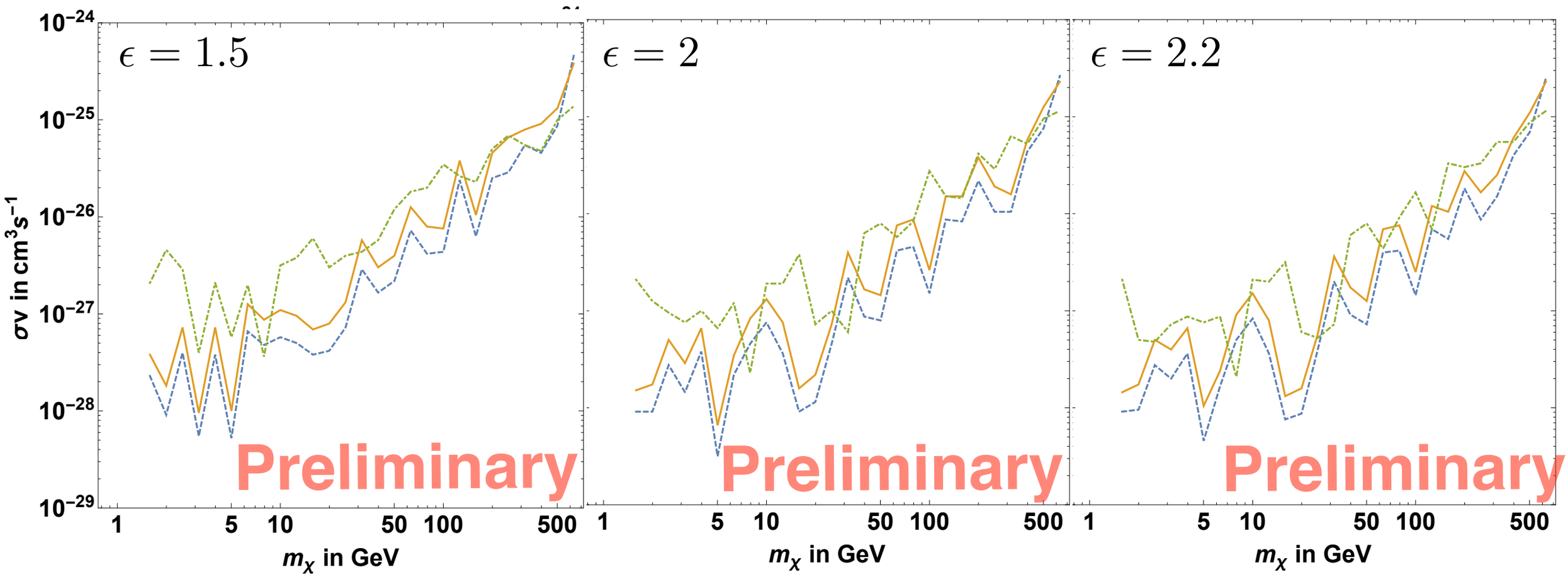
- Gamma-ray triangles are the only known DMID signal known for a ADM scenario

Thank you for your attention!!

Upper limits on the cross section

- Varying the window width → ϵ

$\delta_{\chi\phi}(\delta_{\chi\phi}) = 0.001 \quad \delta\psi\nu = 1$



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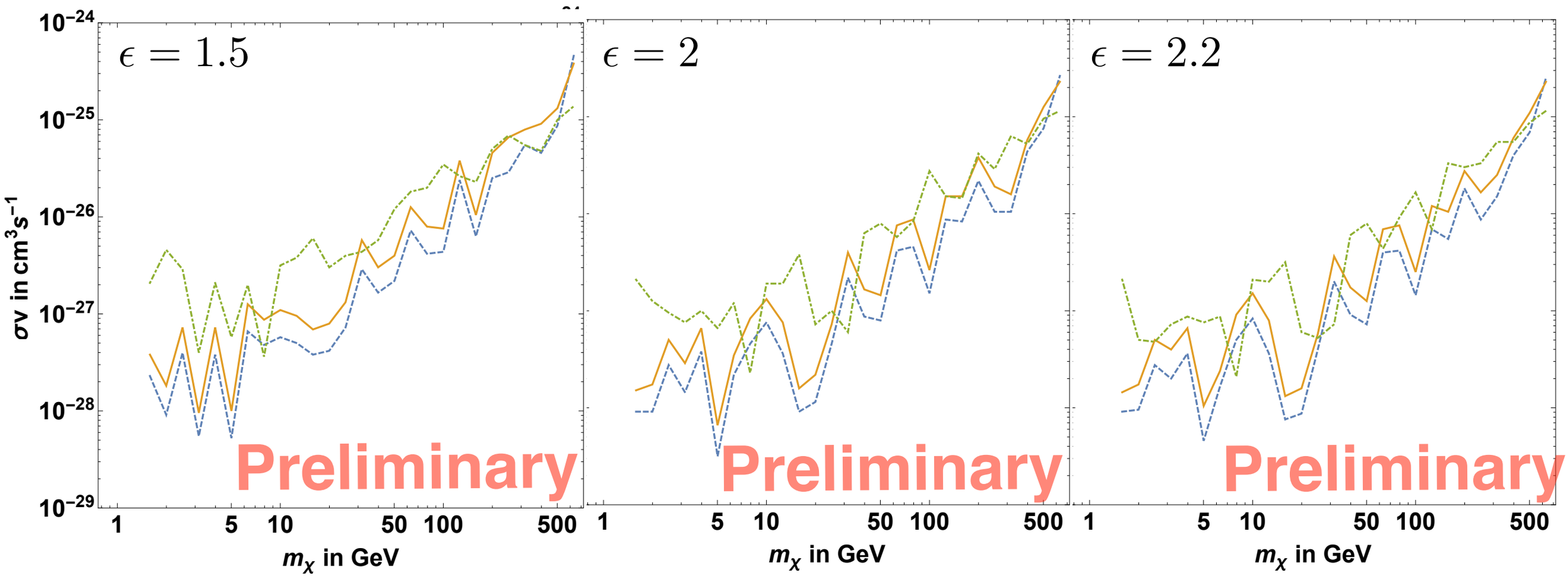
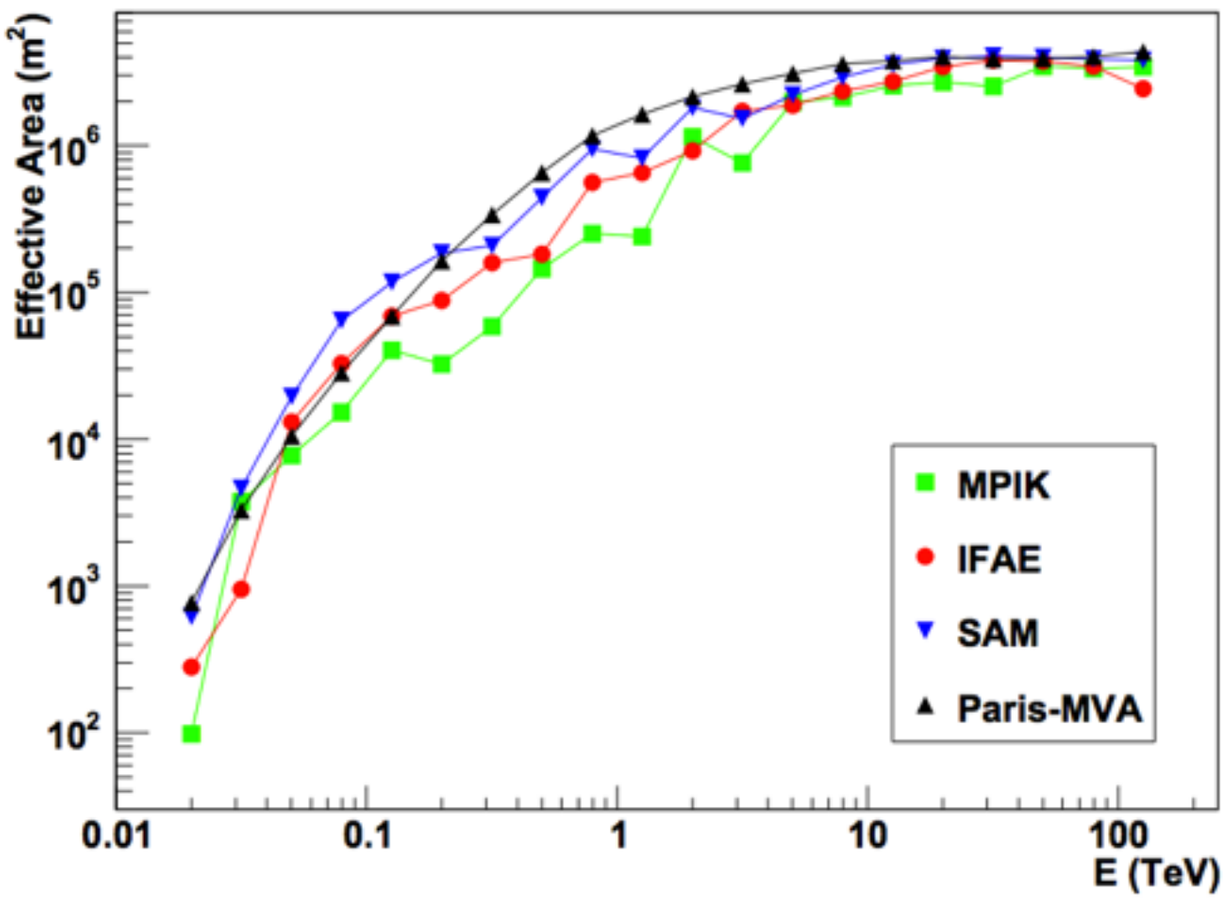
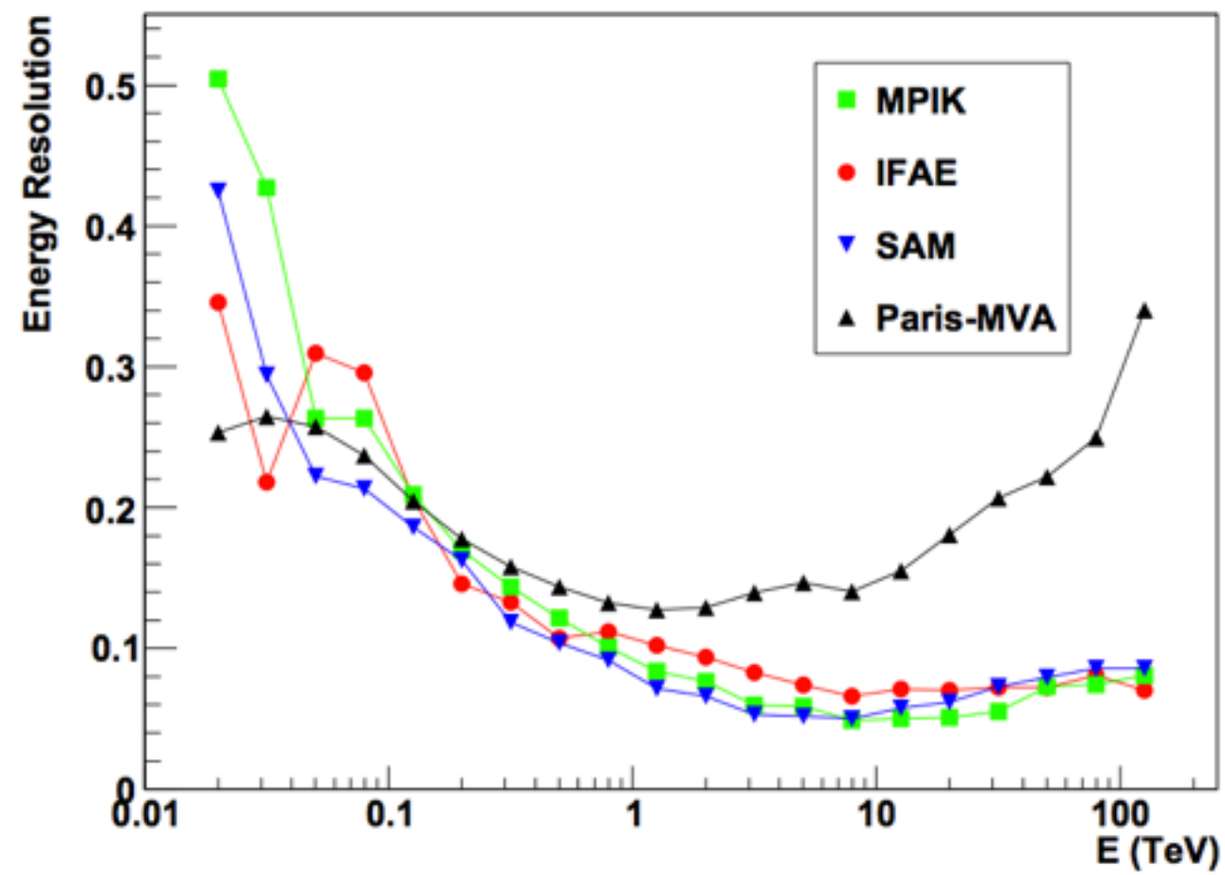


Performance of CTA





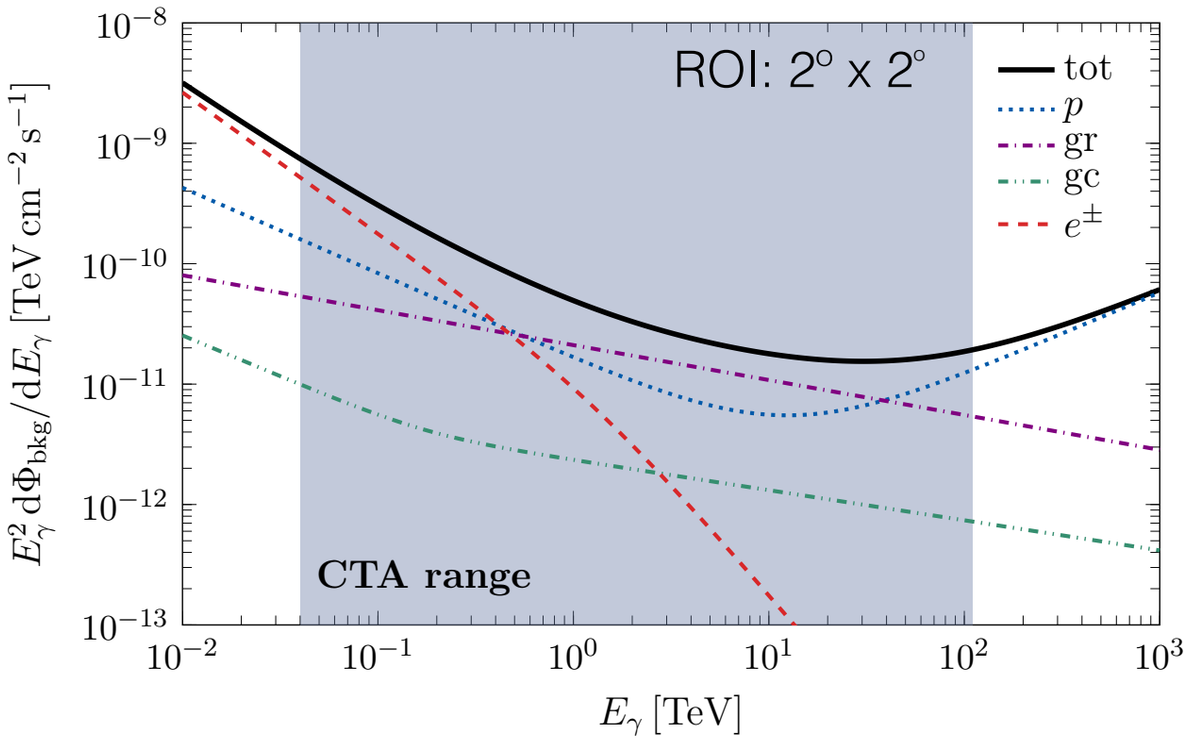
Prospects on CTA for boxes

Ibarra, Lamperstorfer, SLG, Pato, Bertone arXiv:1503.06797 [astro-ph.HE]

- We deliver prospects on the upper limits and sensitivity for the forthcoming CTA experiment

arXiv:1210.3503 [astro-ph.IM]

- Using information delivered by the CTA consortium we simulate 300 sets of mock data using a well motivated background:
    - Protons
    - gamma rays
    - gc point source
    - electrons/positrons



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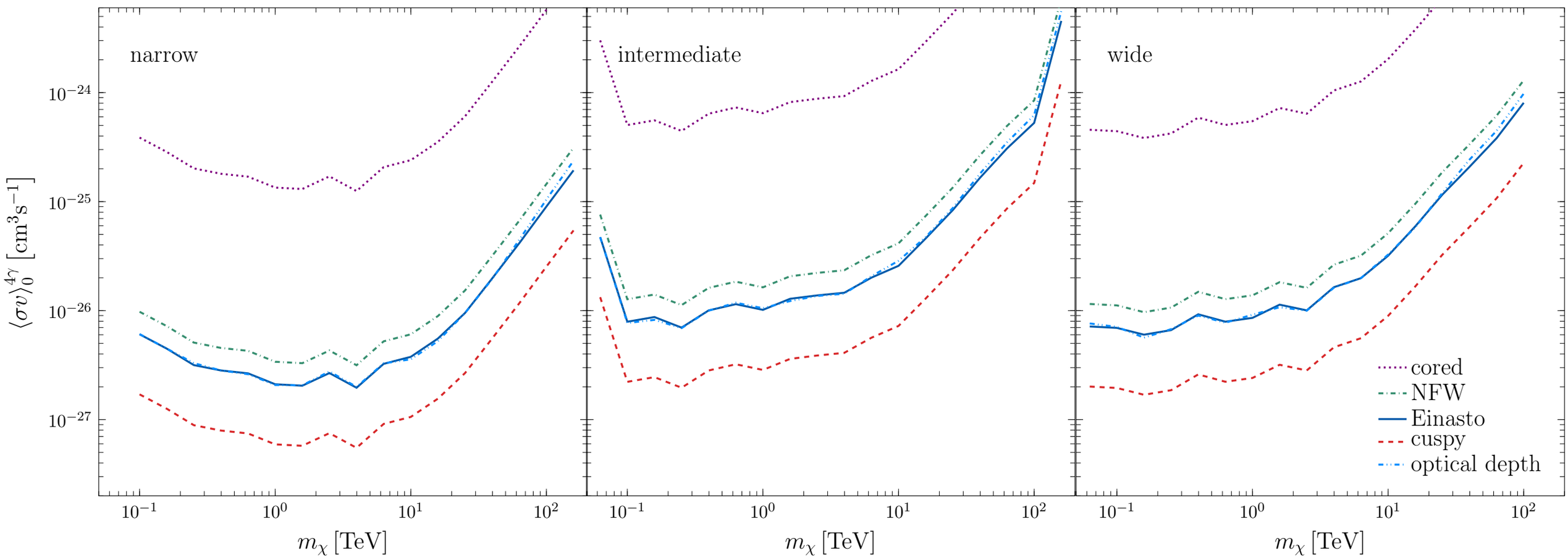

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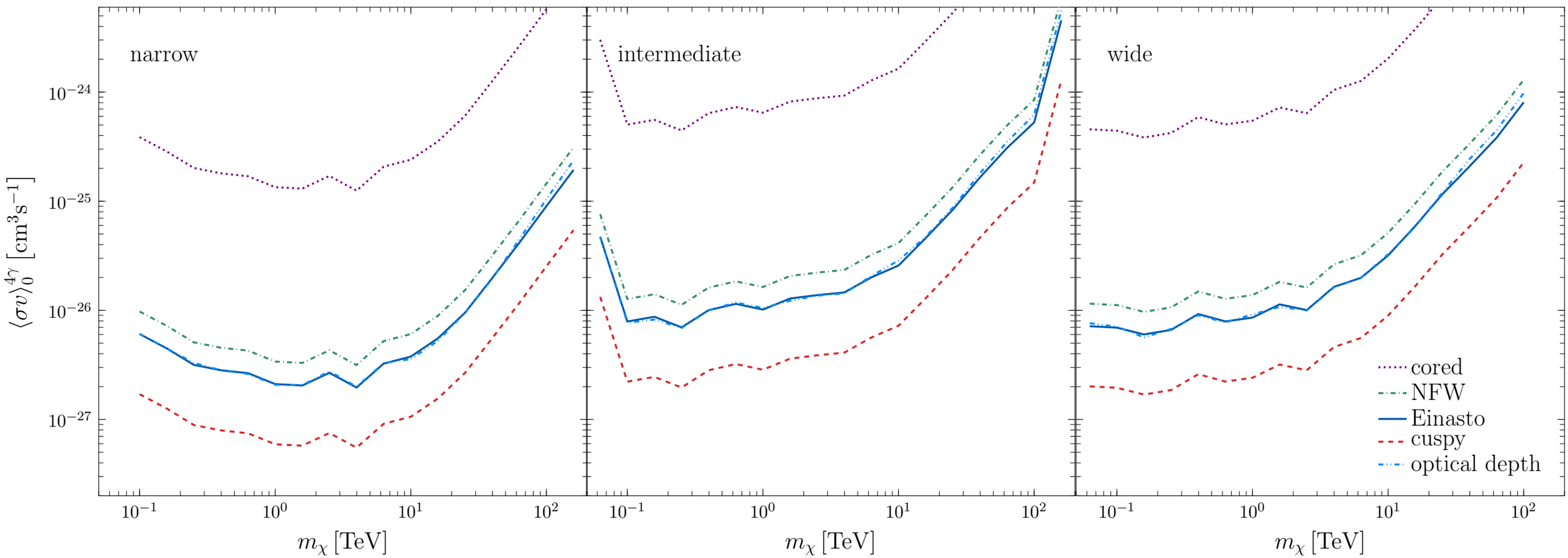

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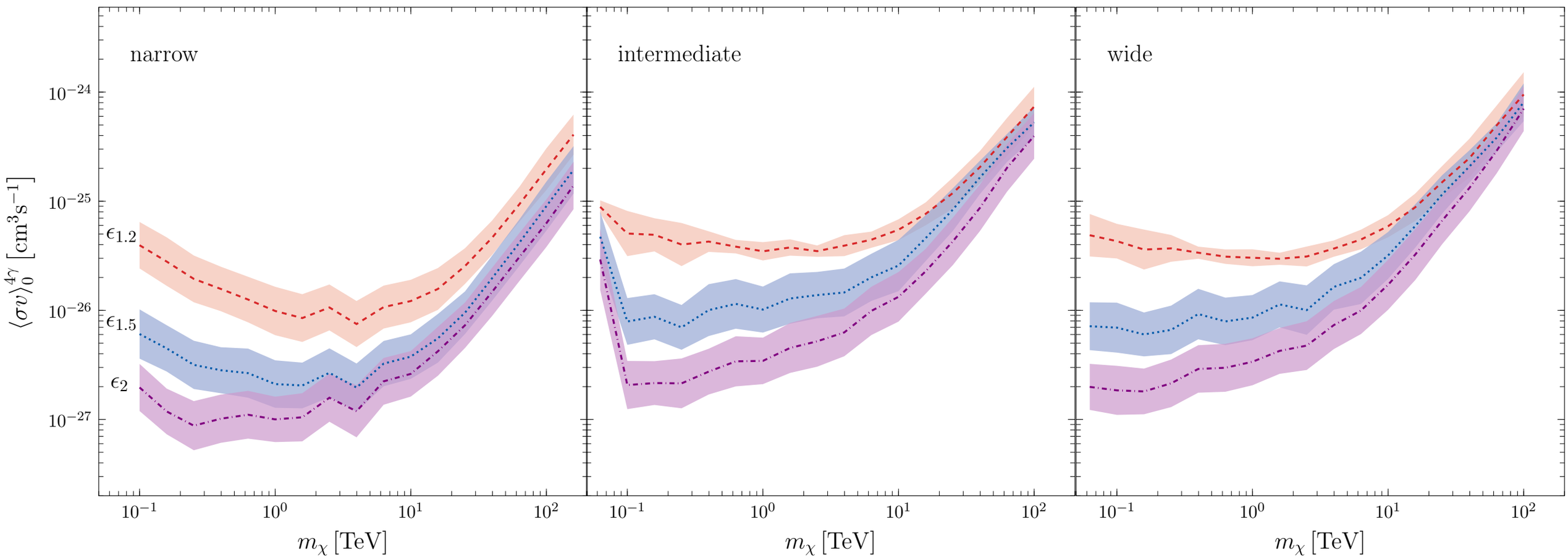

Concrete model A

Ibarra, Lee, SLG, Park, Pato (arXiv:0810.5397)

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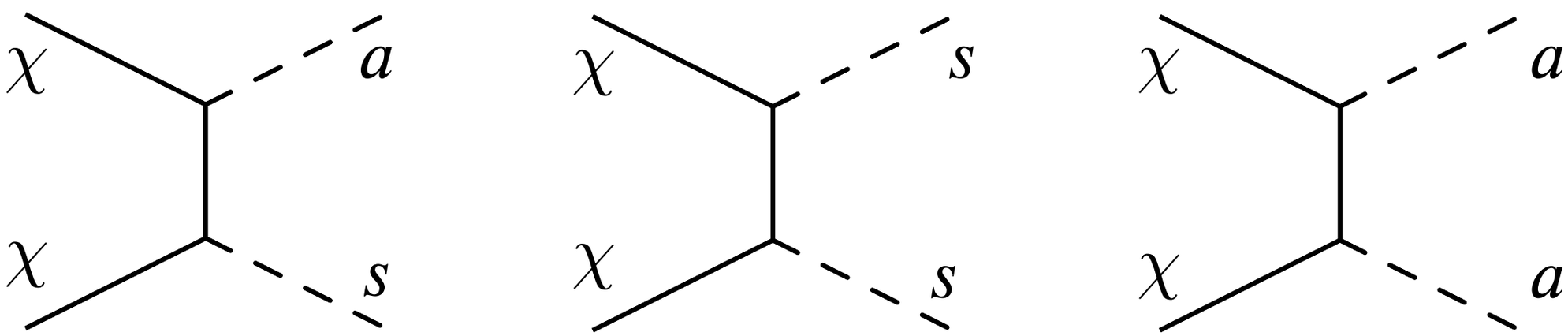

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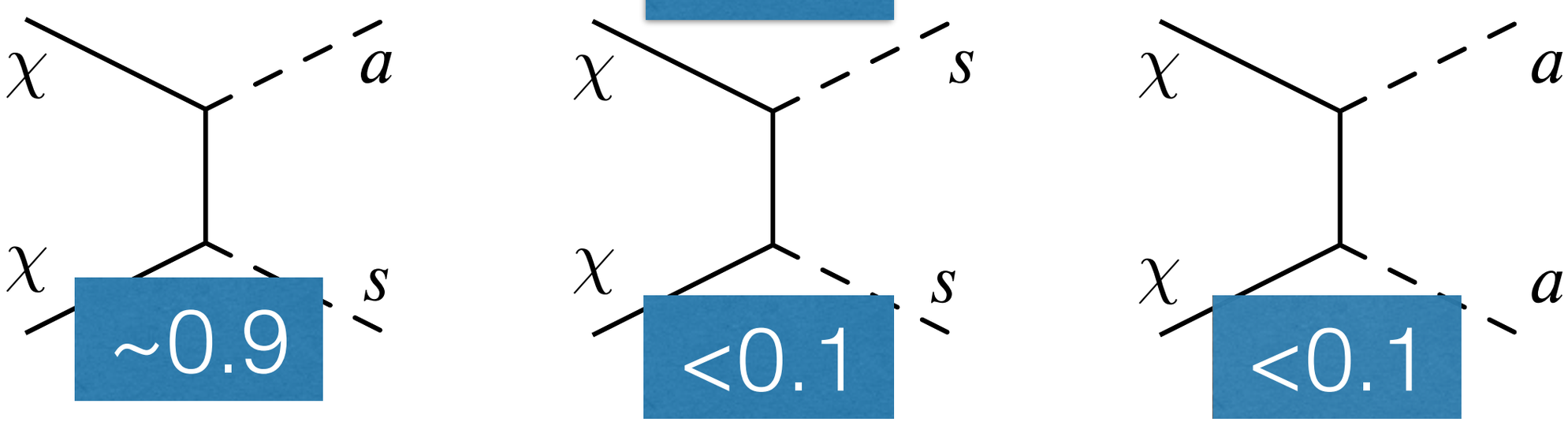

Narrow box

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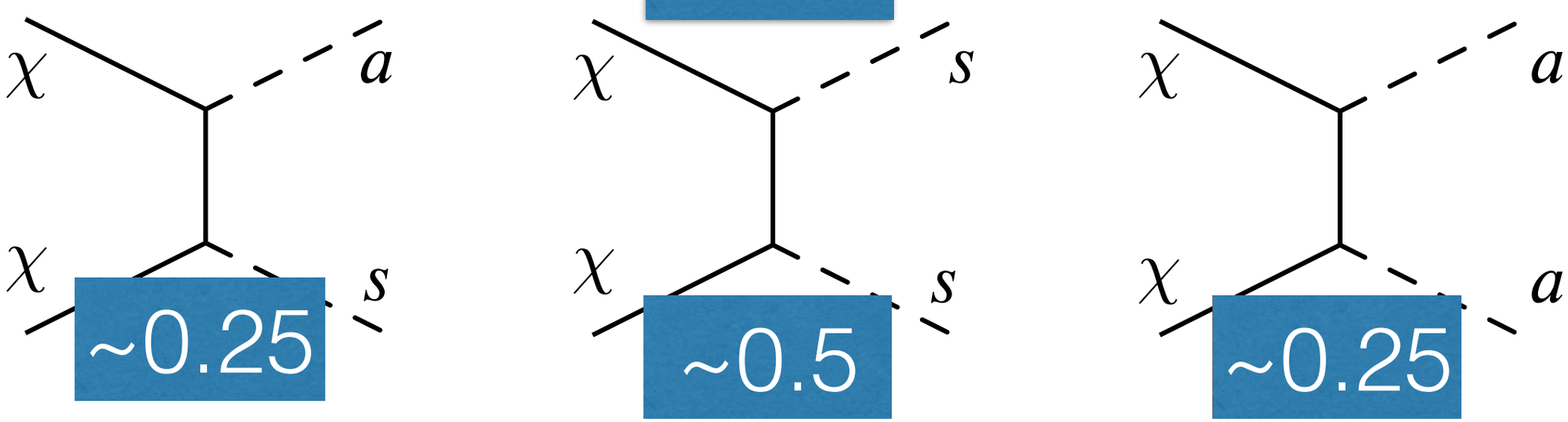

Wide box

Concrete model B

Y. Nomura, J. Thaler (arXiv:0810.5397)

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(Motivated by the galactic positron excess)

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2. BR into photons of $\sim 10^{-3}$

3. The scalar $\boldsymbol{s}$ is responsible for a boost factor of $\sim 10^{3}$

Concrete model B

Y. Nomura, J. Thaler (arXiv:0810.5397)

- Such a theory arises naturally where m_χ is generated by the SSB of a global $U(1)_X$ symmetry ($X \to PQ$) $\boldsymbol{a}$ *is the axion-like particle related to this symmetry*

- *Physical parameters:*

$$m_\chi = 1\,\mathrm{TeV}$$
$$360\,\mathrm{MeV} \lesssim m_a \lesssim 800\,\mathrm{MeV}$$

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Wide box

Models A and B

A: $$\langle\sigma v\rangle_0^{4\gamma} = \langle\sigma v\rangle_0 \left(\mathrm{BR}(\chi\bar{\chi}\to aa) + \frac{\mathrm{BR}(\chi\bar{\chi}\to as)}{2}\right)\mathrm{BR}(a\to\gamma\gamma)\,,$$

B: $$\langle\sigma v\rangle_0^{4\gamma} = B_S\,\langle\sigma v\rangle_0 \frac{\mathrm{BR}(\chi\bar{\chi}\to as)}{2}\mathrm{BR}(a\to\gamma\gamma)\,.$$

	m_a/m_χ	$\mathrm{BR}(\chi\bar{\chi}\to as)$	$\mathrm{BR}(\chi\bar{\chi}\to aa)$	$\mathrm{BR}(\chi\bar{\chi}\to ss)$	$\langle\sigma v\rangle_0/\langle\sigma v\rangle_{\mathrm{th}}$	References
A1 (narrow)	0.999	0.99	2×10^{-3}	4×10^{-3}	0.13	[39, 56, 57]
A2 (intermediate)	0.9	0.64	0.12	0.24	0.76	[39, 56, 57]
A3 (wide)	0.1	0.25	0.25	0.50	0.96	[39, 56, 57]
B (wide)	0.1	1	0	0	1	[58–60]

Limits on the models

Ibarra, Lamperstorfer, SLG, Pato, Bertone arXiv:1503.06797 [astro-ph.HE]

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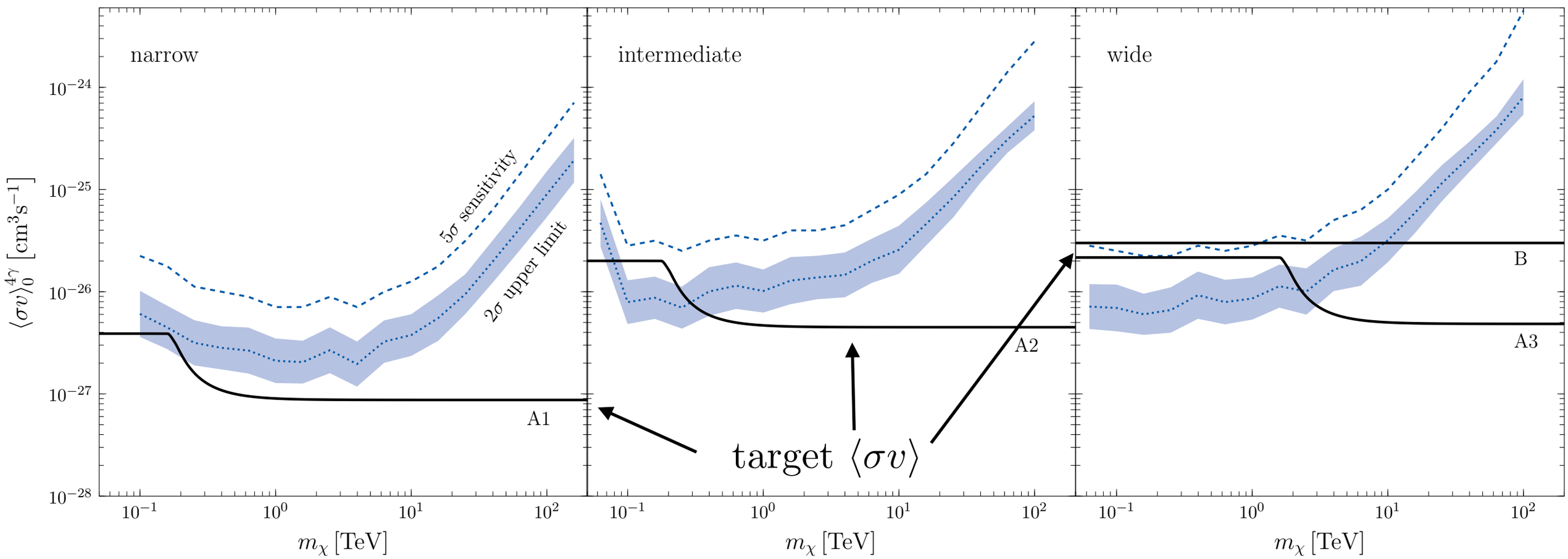
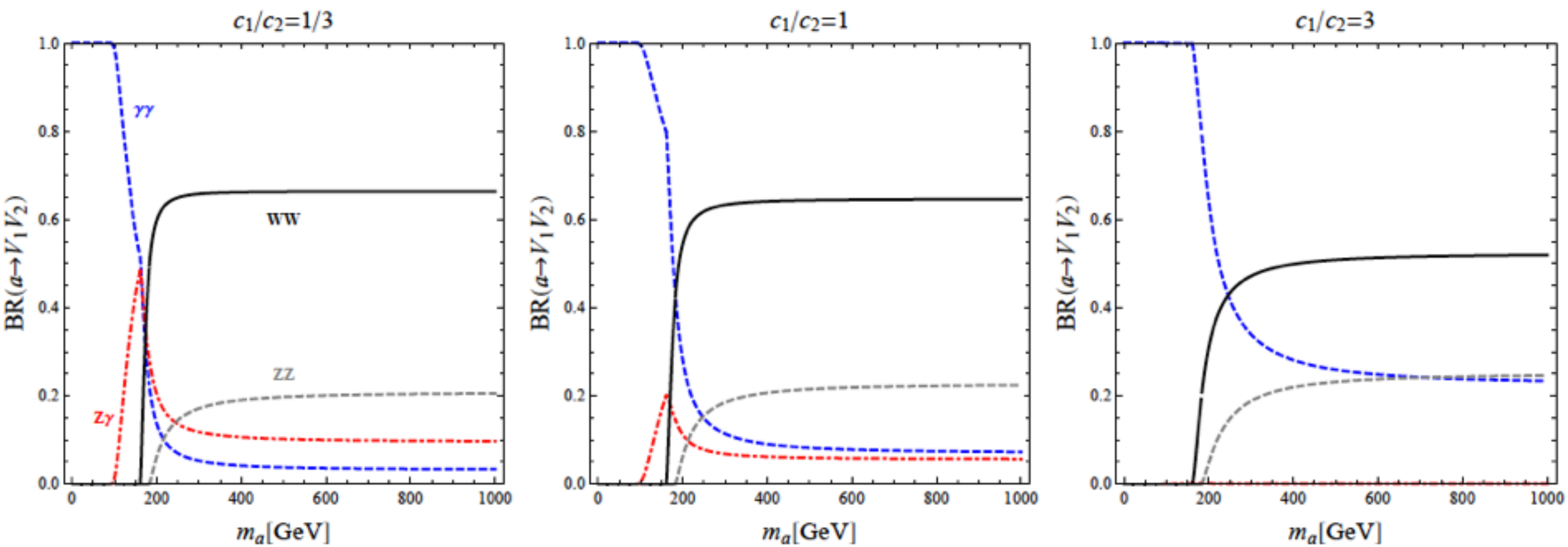


Concrete model

Ibarra, Lee, SLG, Park, Pato (arXiv:0810.5397)

- Branching ratio of a into two photons



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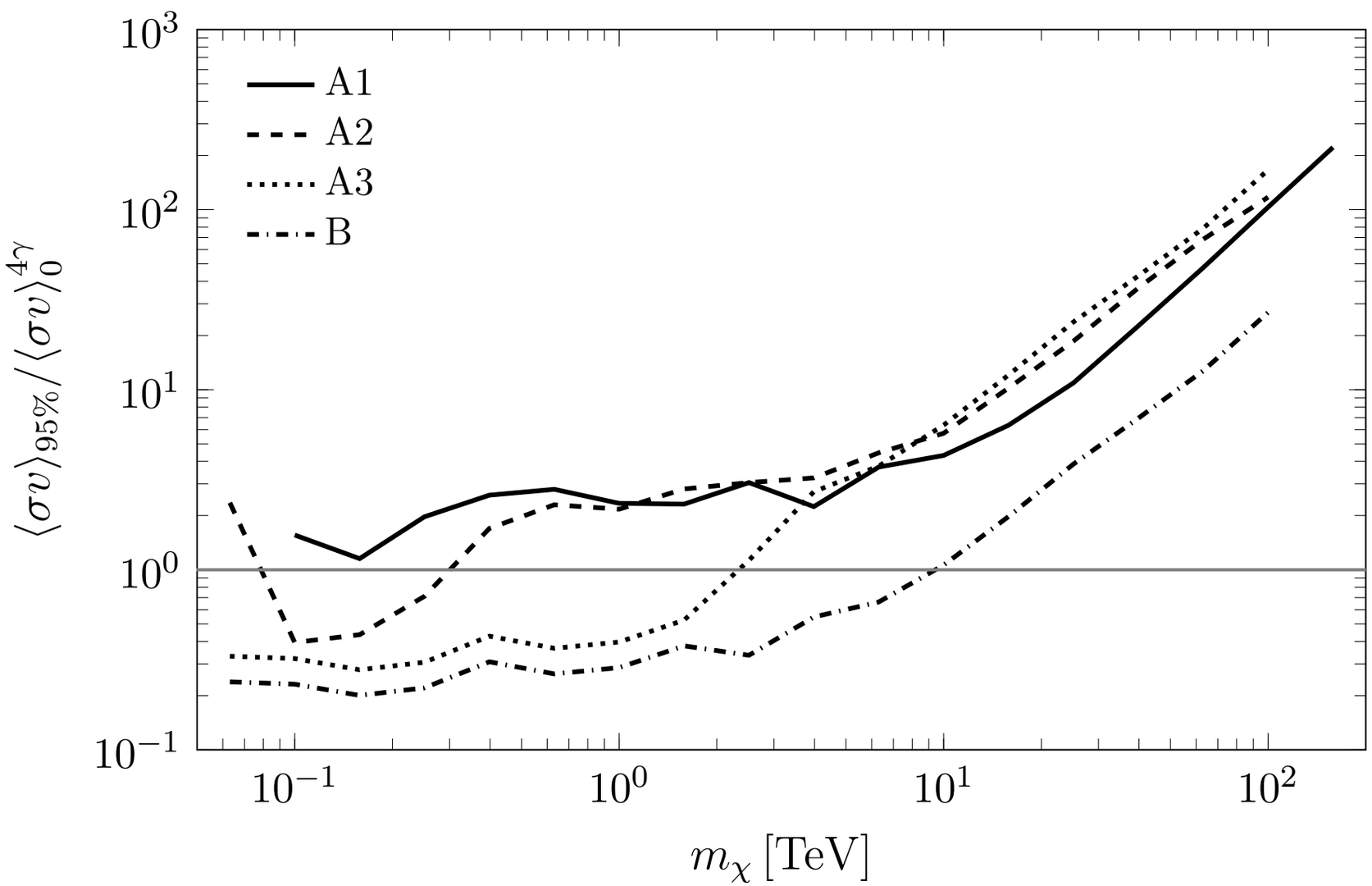

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