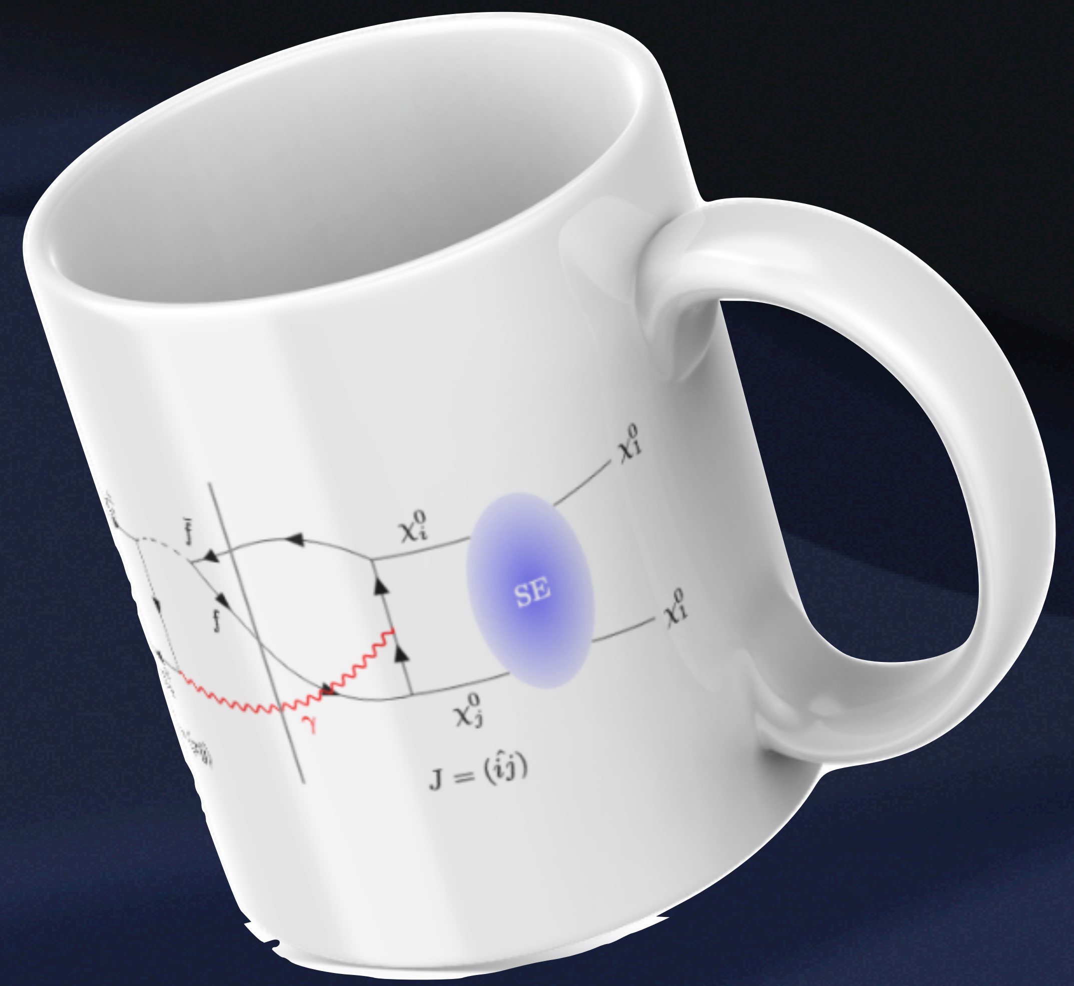
TBA

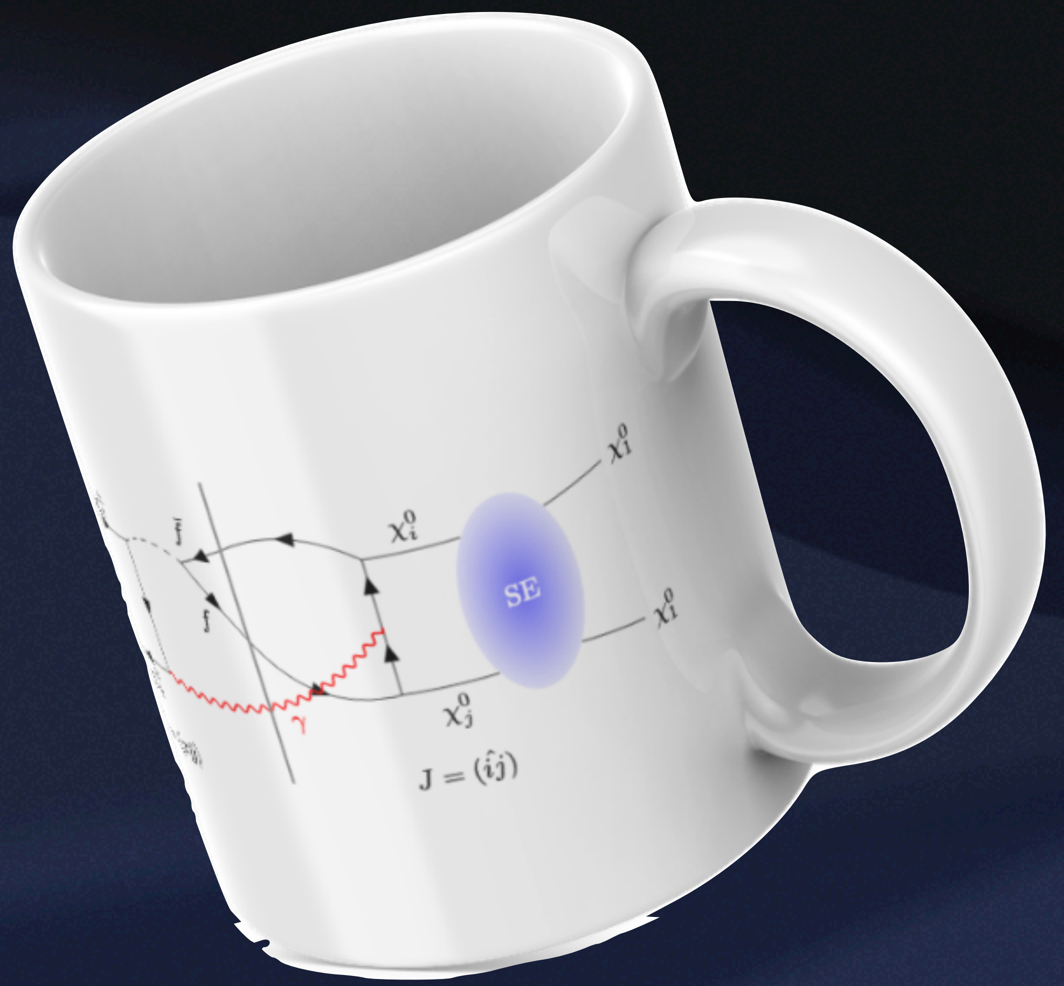
The Dark Matter Landscape
MITP 2024



Martin Vollmann — Uni Tuebingen — 13.9.2024

The Basics of Annihilation*

The Dark Matter Landscape
MITP 2024

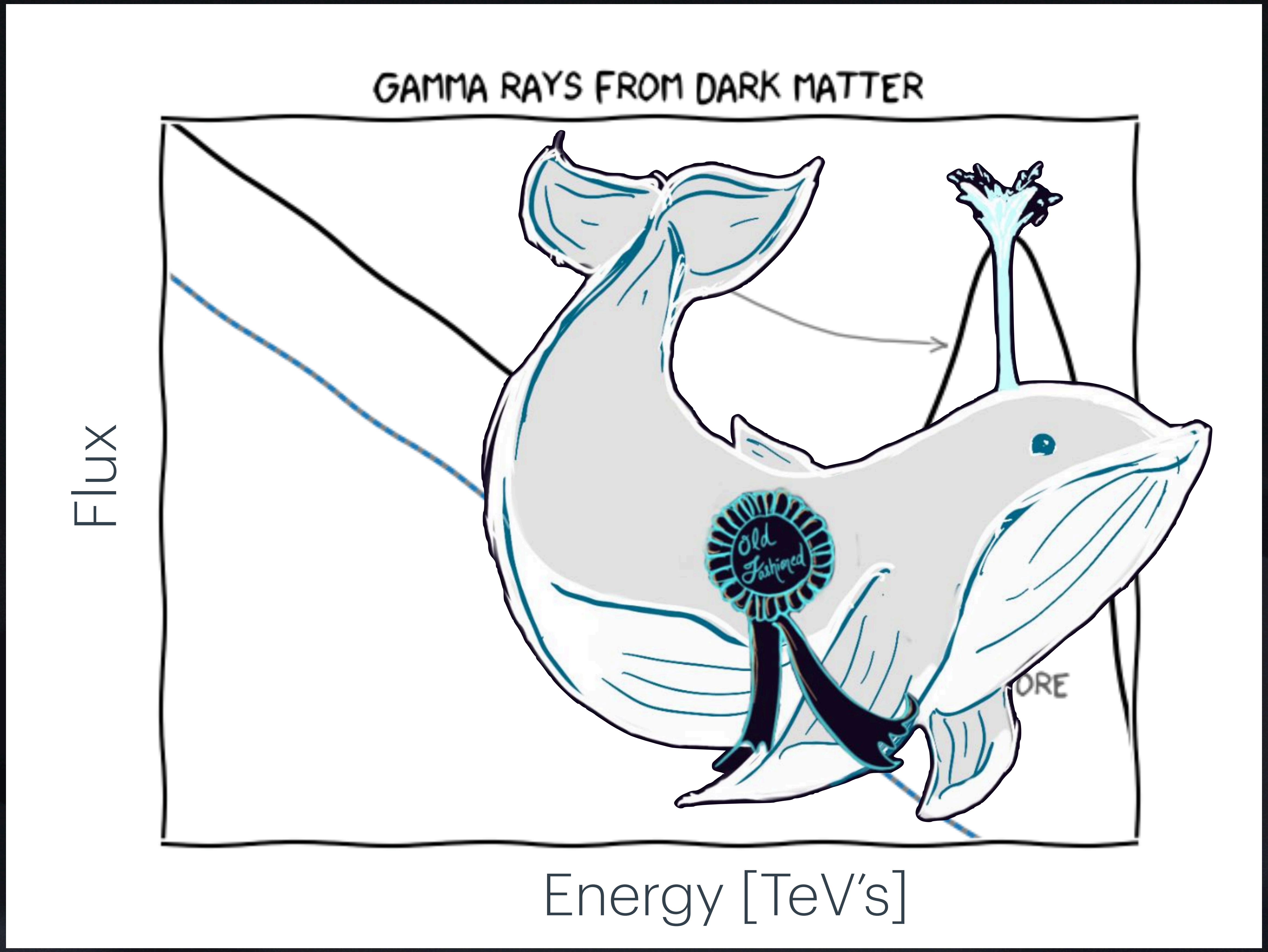


Martin Vollmann — Uni Tuebingen — 13.9.2024

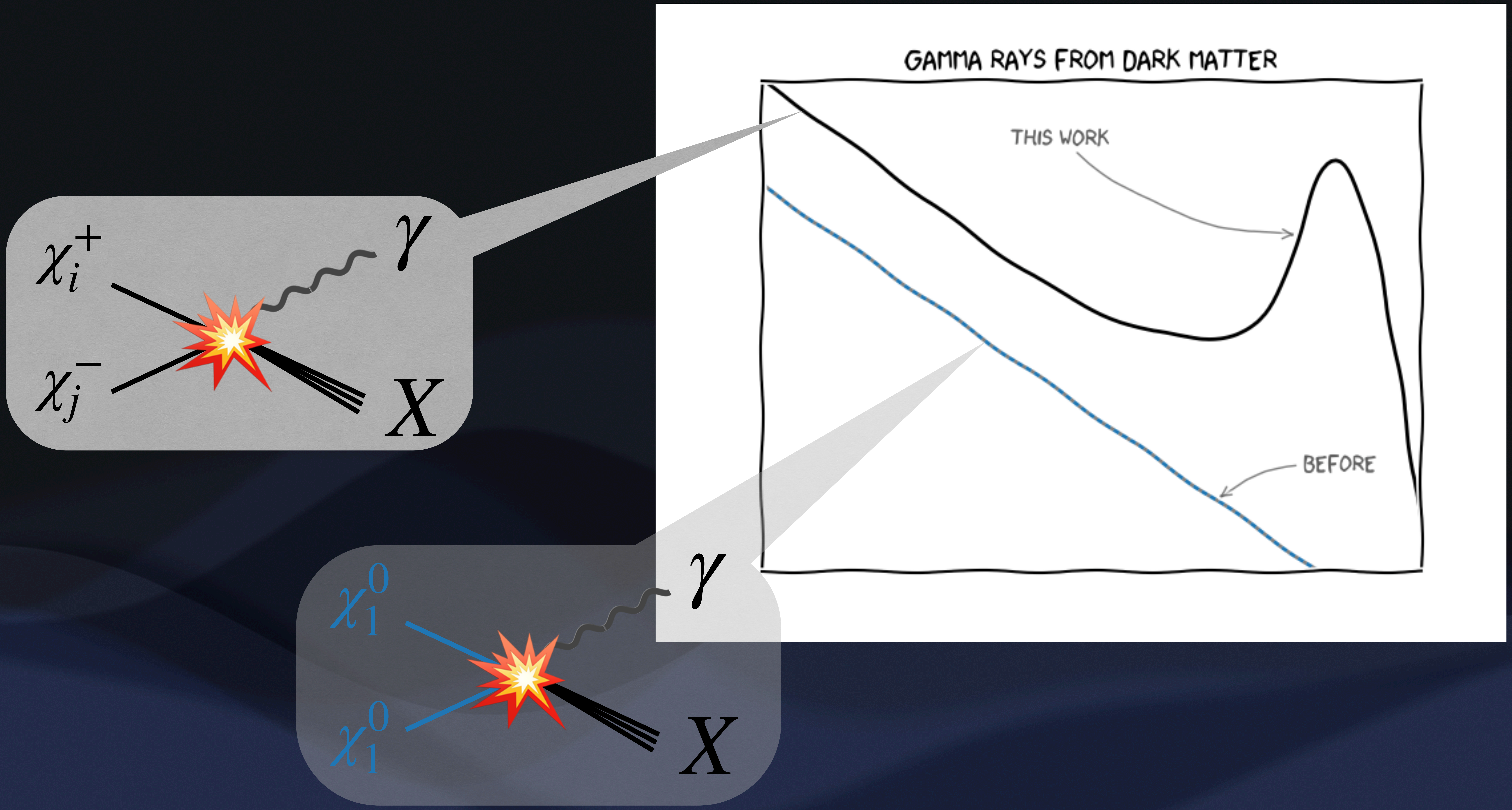
Credit: S. Sevillano/M. Fujiwara

Intro

Very rough and (deliberately) misleading picture



Credit: W. Linda Xu


GAMMA RAYS FROM DARK MATTER
THIS WORK
BEFORE
χ_i^+
χ_j^-
γ
X
χ_1^0
χ_1^0
γ
X

arXiv:2310.11067

Sommerfeld effect for continuum gamma-ray spectra from Dark Matter annihilation

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October 18, 2023

2410.XXXXX

Resummed photon spectrum from MOTOKINO
~~interacting spin 1 dark matter~~ annihilation

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Outline

Motivation

Indirect detection

Sommerfeld factor

Endpoint resummations

Plots

Conclusions

Motivation

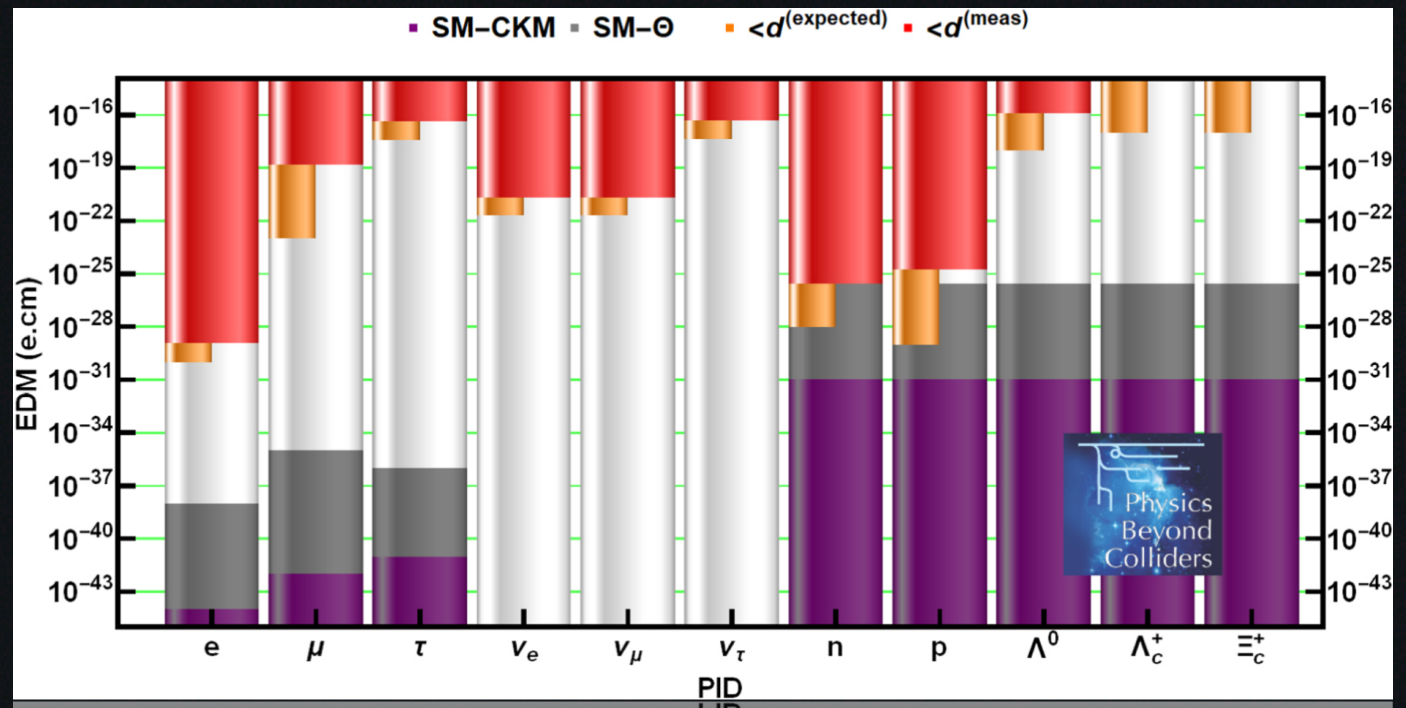
WIMP: the devil that you know

Did you know that...

- There is experimental evidence for **Dark Matter**
- There is experimental evidence for **electroweak interactions**
- Although there is no experimental evidence for the **freeze-out mechanism**
    - still the simplest!

High-scale SUSY

- Unification of gauge couplings improved
- No SUSY CP problem (EDMs)
- Pure wino/higgsino -> very predictive scenarios
  - Maybe detectable with next-generation γ-ray telescopes (e.g. Rodd, Safdi, Xu 2405.13104)
- ~~Naturalness~~



But really... Why?

And why you should still care!

- WIMPs are **not** dead yet!
- The miracle is still a miracle
- If you want to rule them out better be sure that you didn't overlook anything

NEED ACCURATE THEORETICAL PREDICTIONS

- The physics is fun and the "spare parts" are useful as long as there are electroweak interactions in nature

Outline

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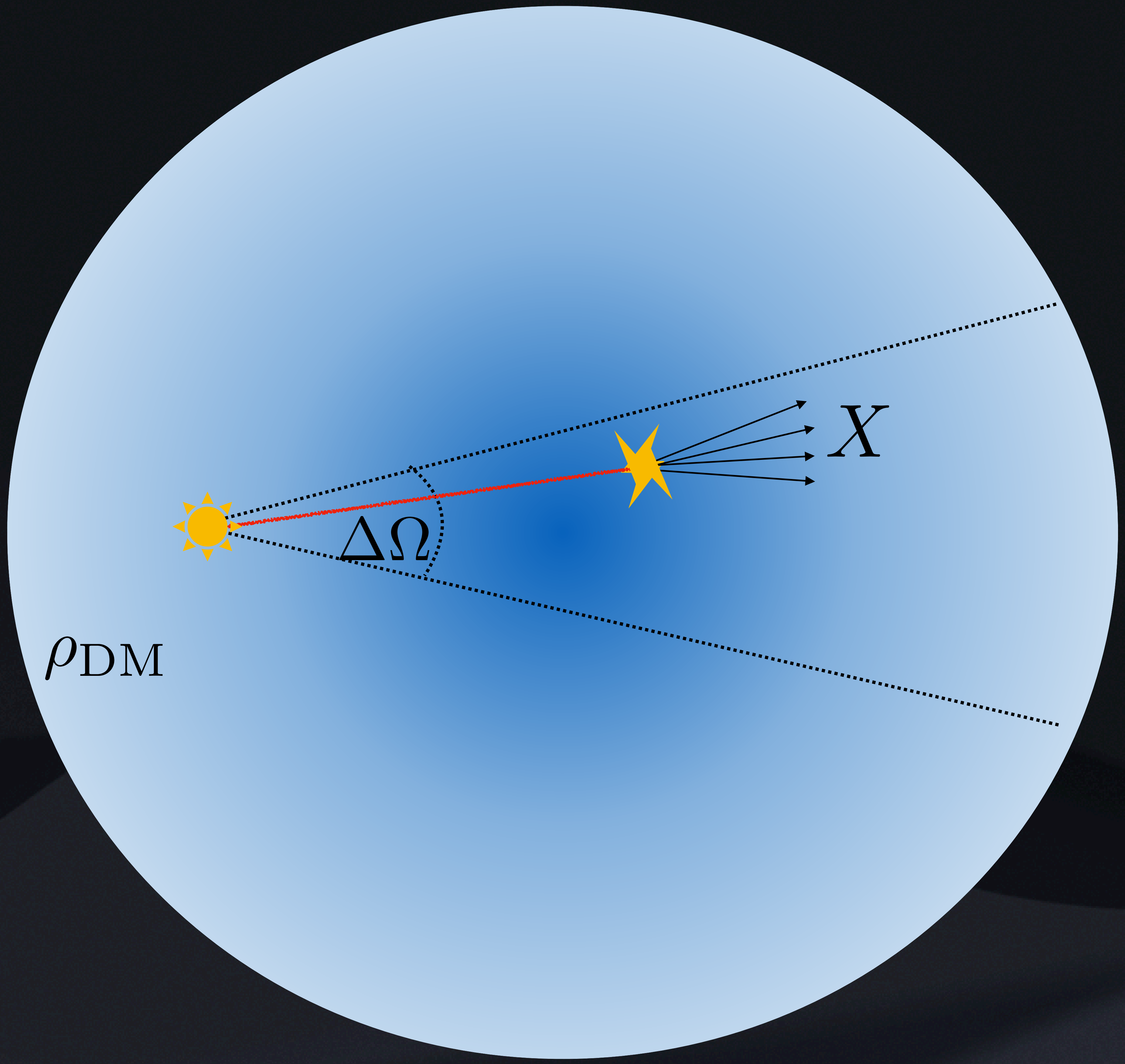
- Sommerfeld factor
- Endpoint resummations
- Plots
- Conclusions

Indirect detection

Gamma-ray flux formula

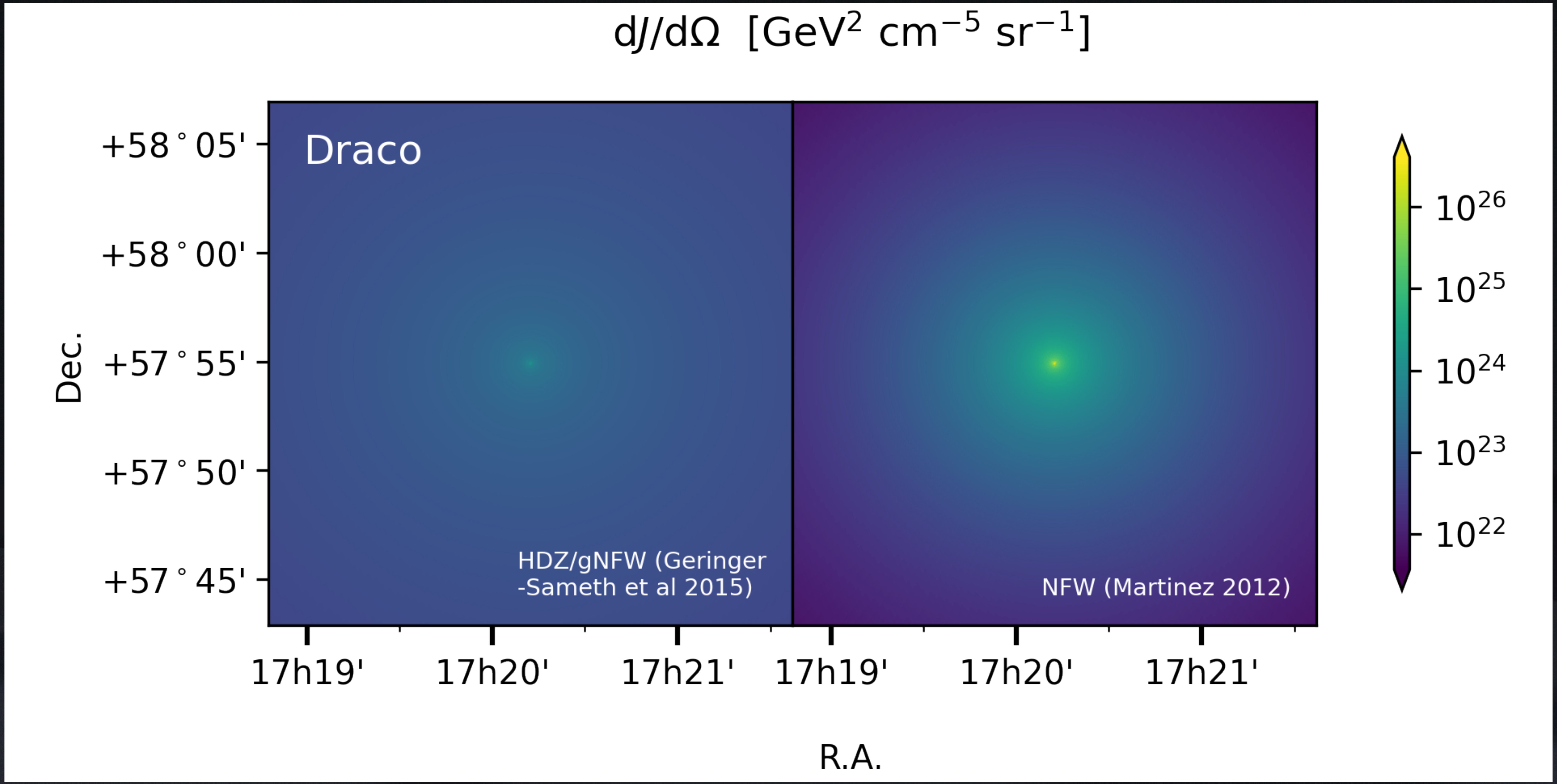
$$\Phi_\gamma = \frac{1}{8\pi m_\chi^2} \times J \times \frac{\mathrm{d}\,\sigma v}{\mathrm{d}E_\gamma}$$

$$J = \int \mathrm{d}\Omega \int_{l.o.s.} \mathrm{d}s\, \rho_{\mathrm{DM}}^2$$



Example (Ad break)

Draco dwarf galaxy with diffSph [2401.05255]



https://github.com/mertio1/diffsph

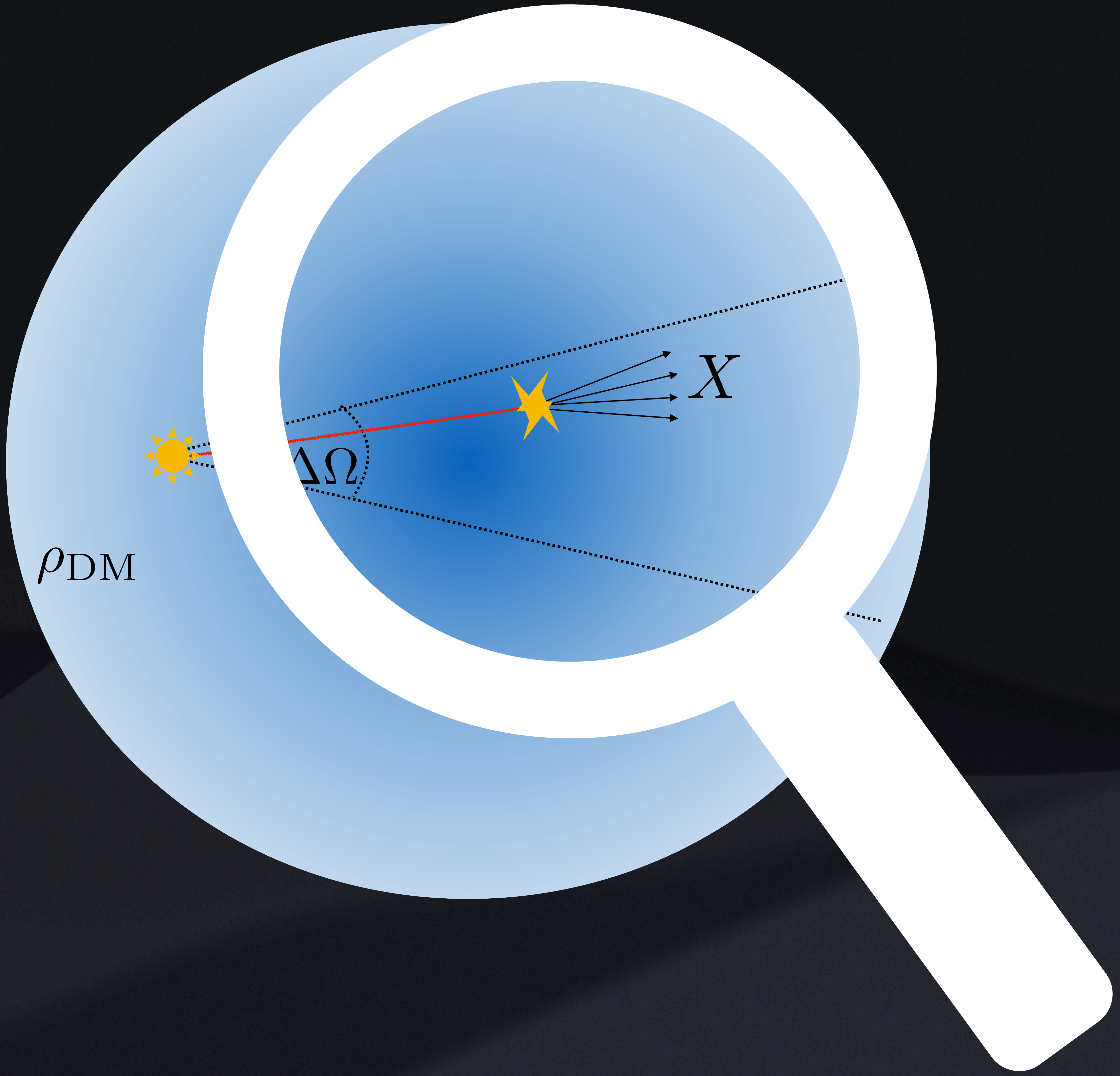
diffSph
(2401.05255)

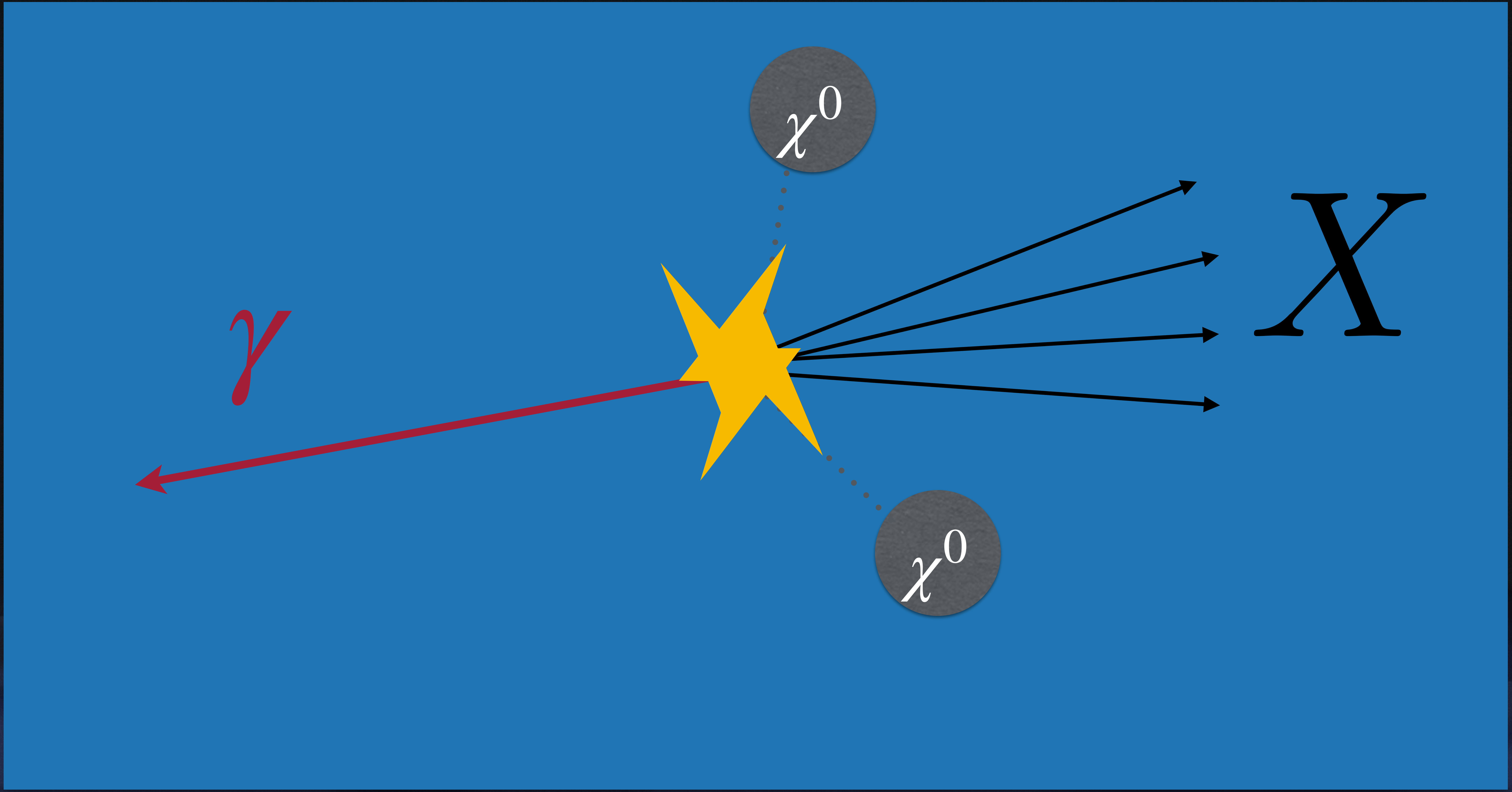
Lovorka

Finn

Gamma-ray flux formula

$$\Phi_\gamma = \frac{1}{8\pi m_\chi^2} \times J \times \frac{\mathrm{d}\,\sigma v}{\mathrm{d}E_\gamma}$$

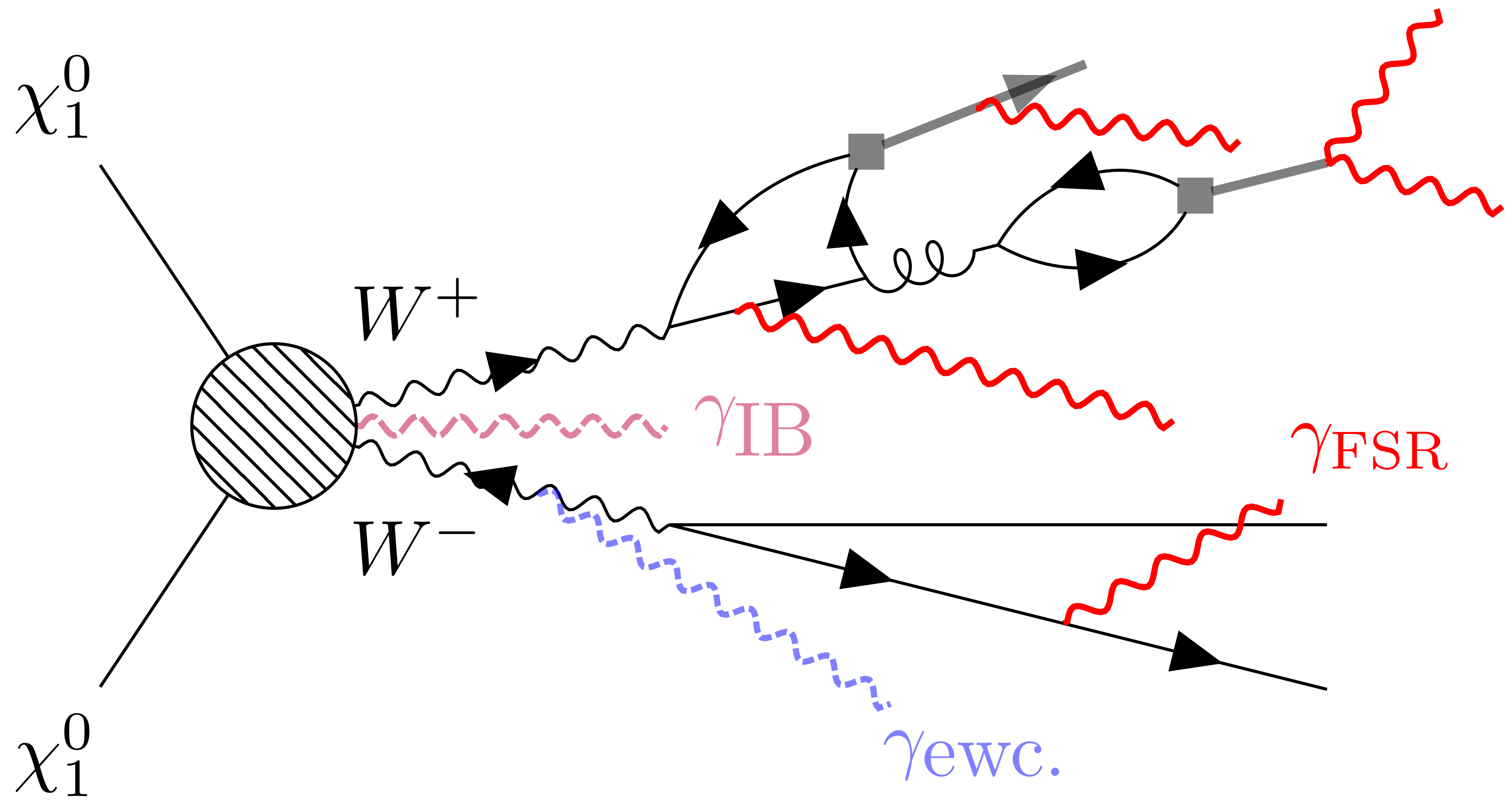




χ^0
X
γ
χ^0

The problem:

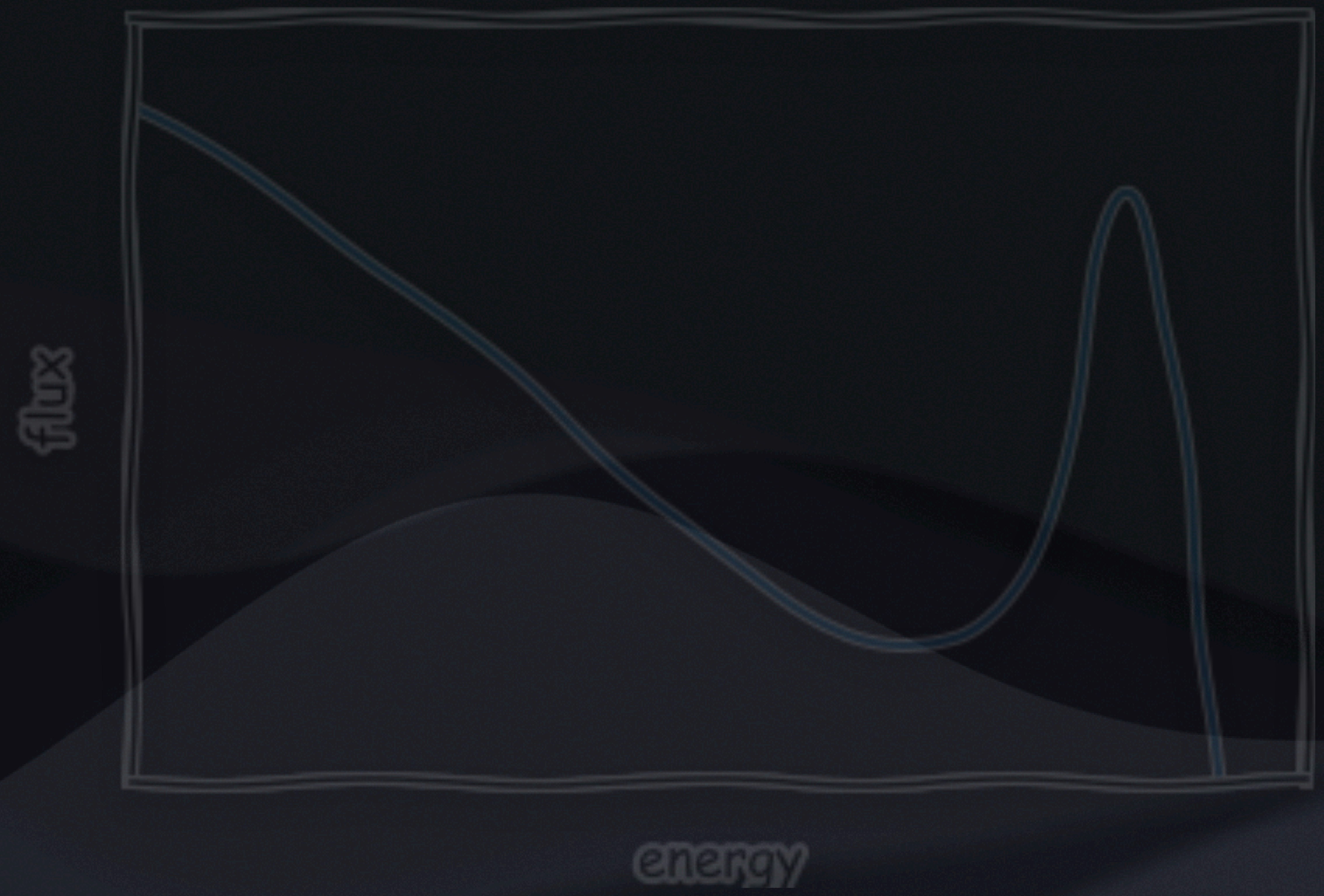
Obtain the annihilation spetrum



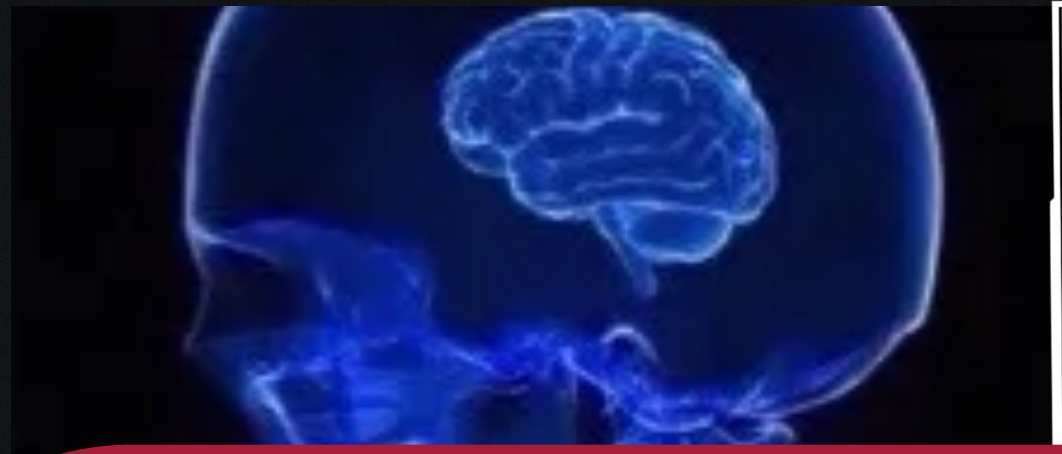
$$\frac{\mathrm{d}\sigma v}{\mathrm{d}E_\gamma}$$

TBA

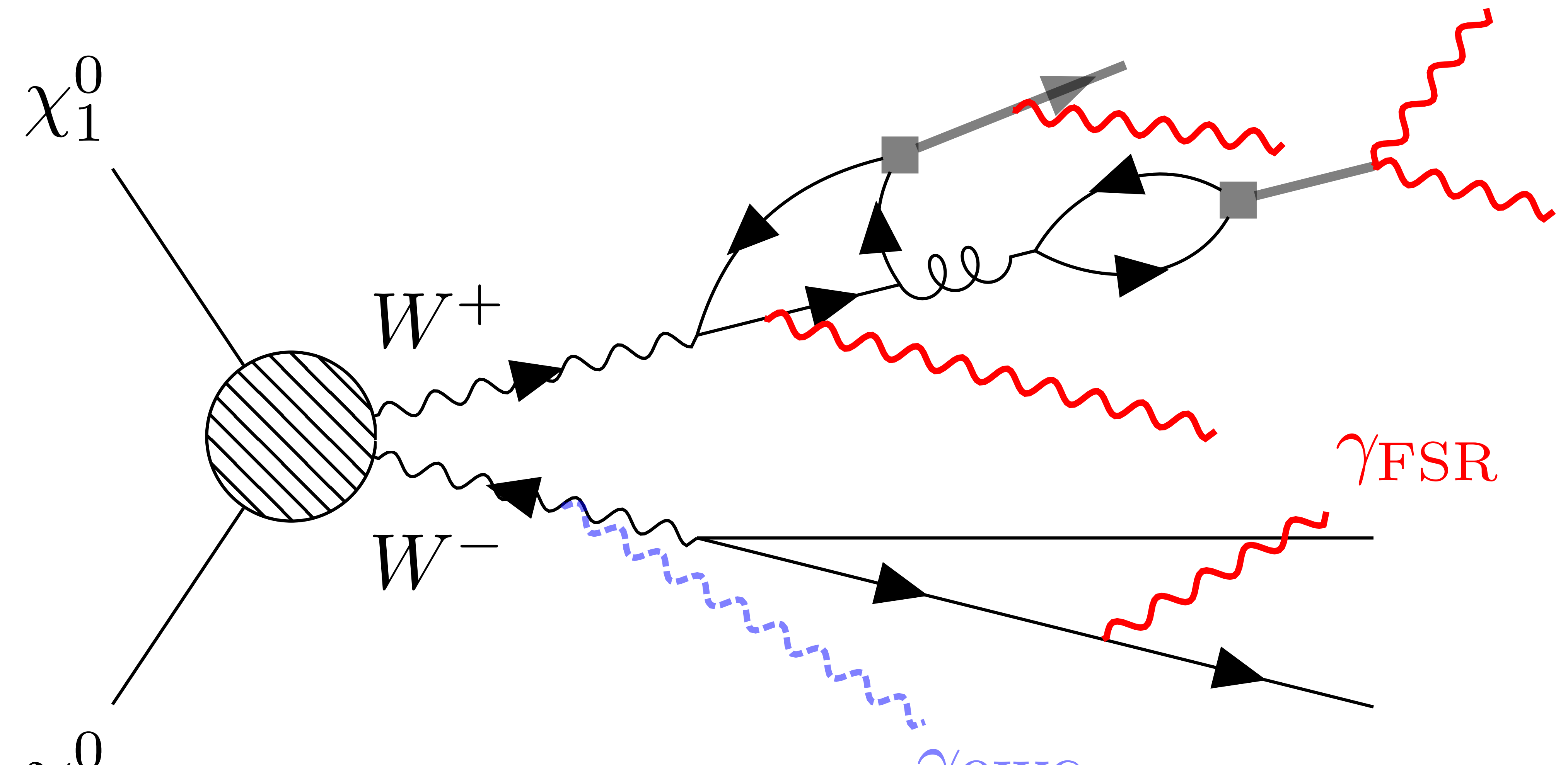
The Basics of Annihilation



2000-2010s



Fixed-order 2 → 2 (tree)
+ Parton Shower



Ciafaloni et al 1009.0224

Helicity suppression

If $m_{DM} \gg m_b, m_\tau$ (and $v \ll c$):

$$\langle \sigma v \rangle_{b\bar{b}} \propto \frac{m_b^2}{m_{DM}^2} \to 0$$

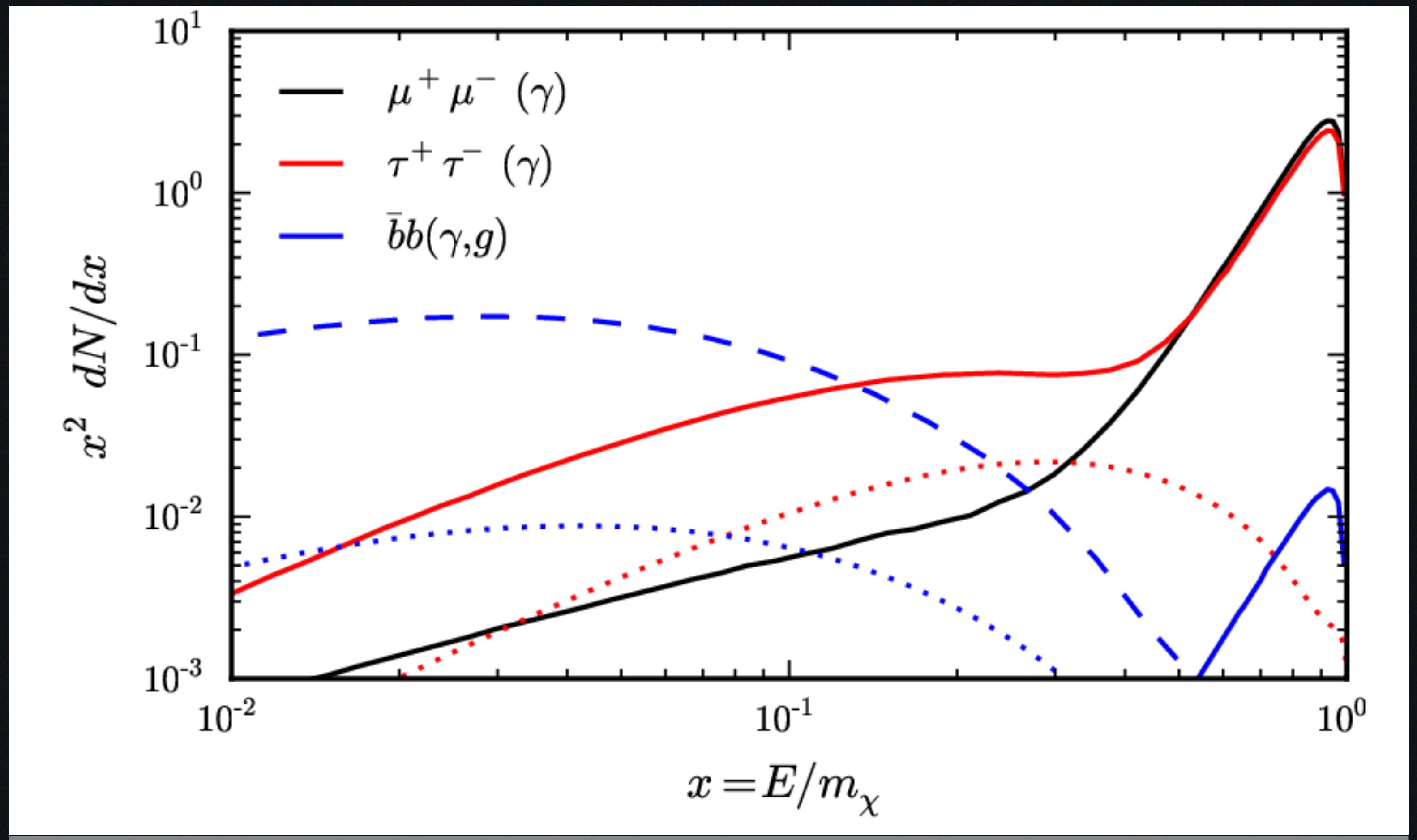
$$\frac{\mathrm{d}\,\sigma v}{\mathrm{d}\,E_\gamma} = (\sigma v)_{\bar{b}b} \frac{\mathrm{d}\,N^{\mathrm{MC}}_{\bar{b}b}}{\mathrm{d}\,E_\gamma} + (\sigma v)_{\tau^+\tau^-} \frac{\mathrm{d}\,N^{\mathrm{MC}}_{\tau^+\tau^-}}{\mathrm{d}\,E_\gamma} + \ldots$$

TBA

The Basics of Annihilation

2000-2010s

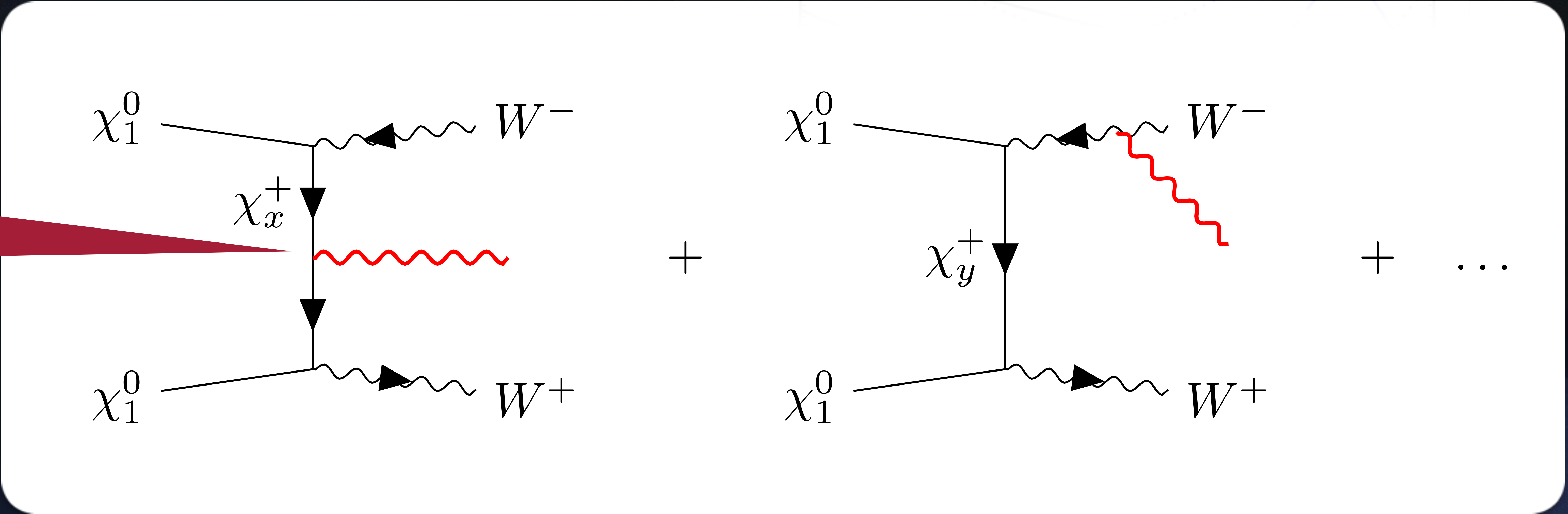
Fixed-order 2 → 3 (tree)
+ Parton Shower



Internal bremsstrahlung

Lift helicity suppression

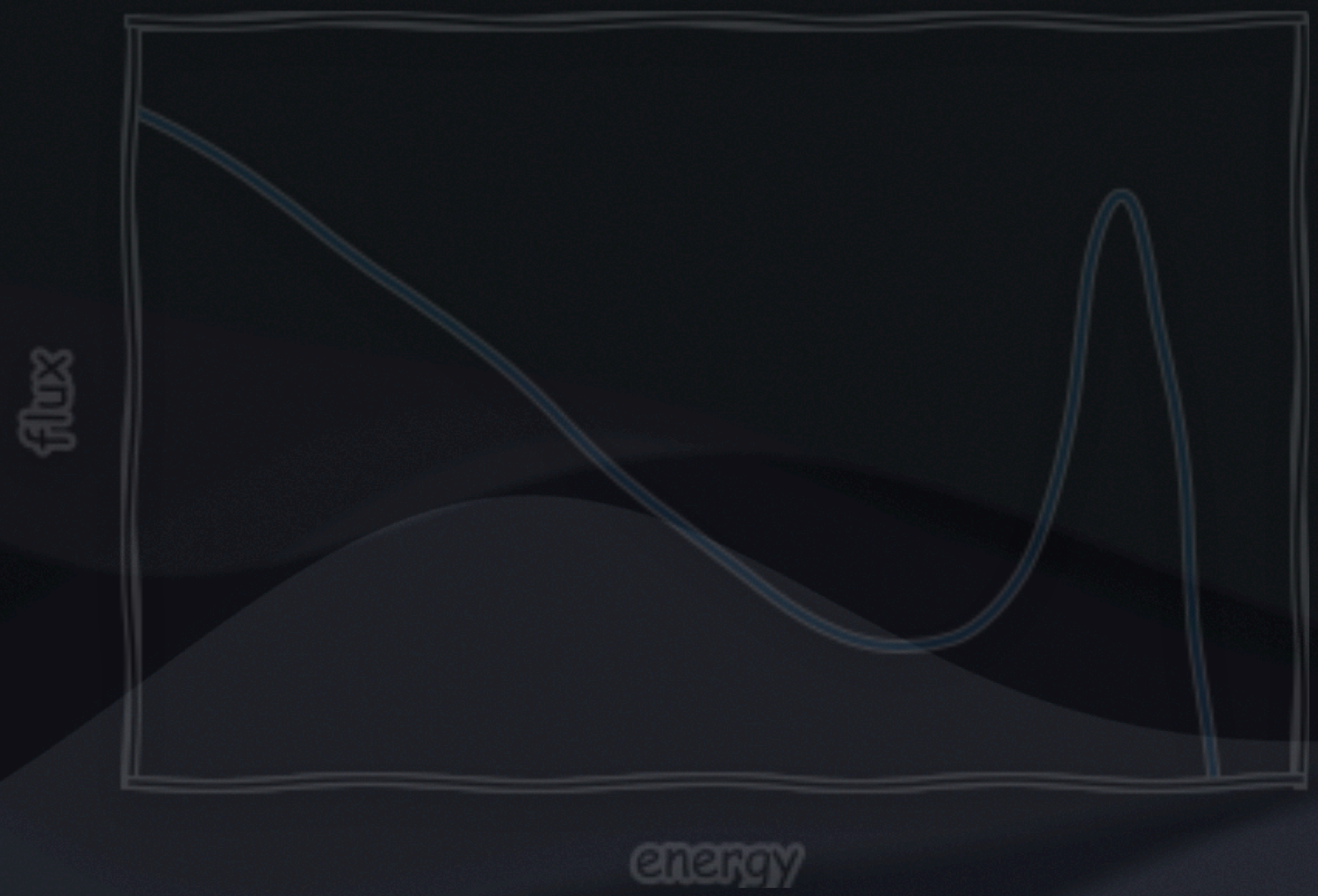
- 2→2 process $\langle\sigma v\rangle_{b\bar{b}} \propto \frac{m_b^2}{m_{DM}^2} \to 0$
- 2→3 process $\langle\sigma v\rangle_{b\bar{b}\gamma} \neq 0$



Bringmann et al 0710.3169

TBA

The Basics of Annihilation

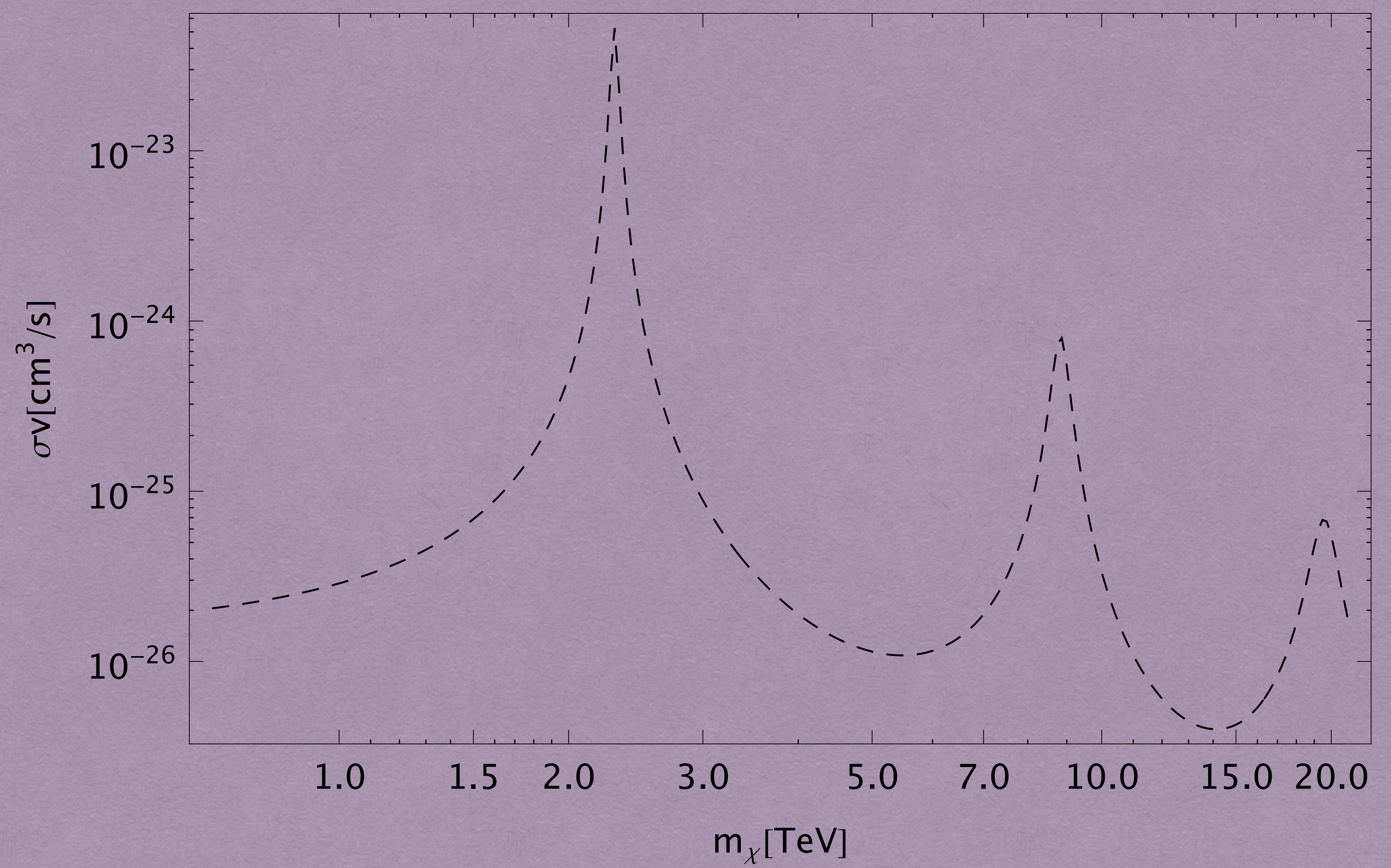


TBA

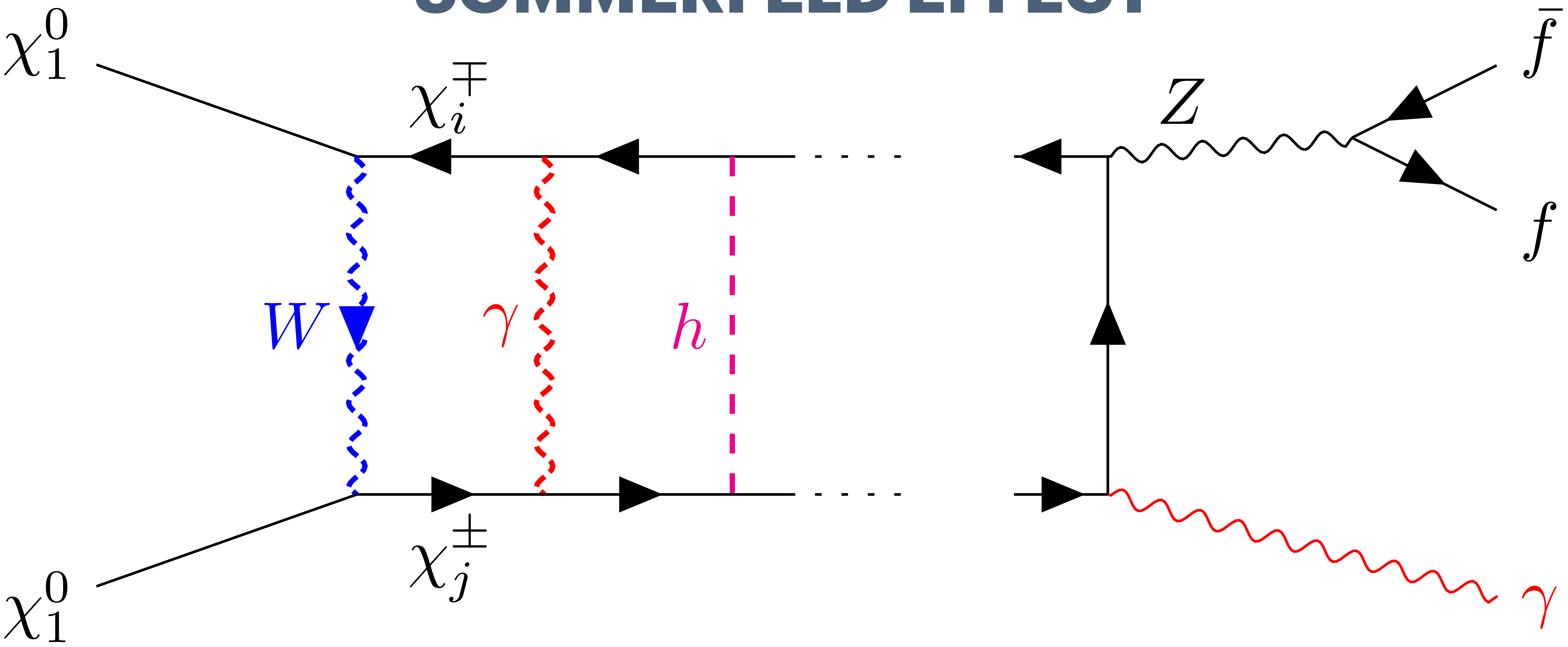
The Basics of Annihilation

Hisano, Matsumoto, Nojiri hep-ph/0307216

Arkani-Hamed, Slatyer, Weiner 0810.0713



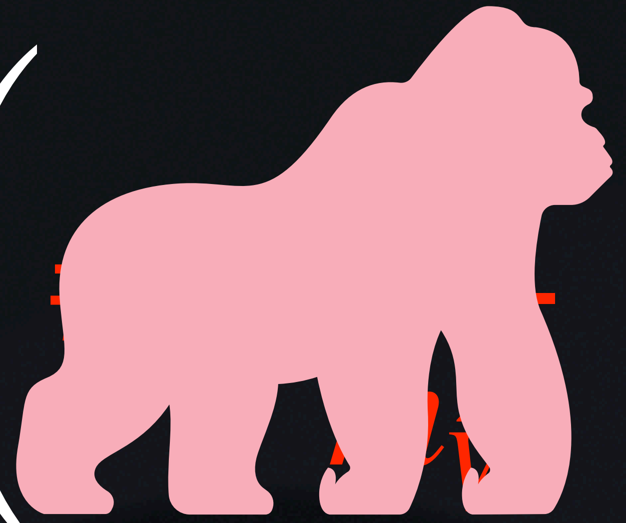
SOMMERFELD EFFECT

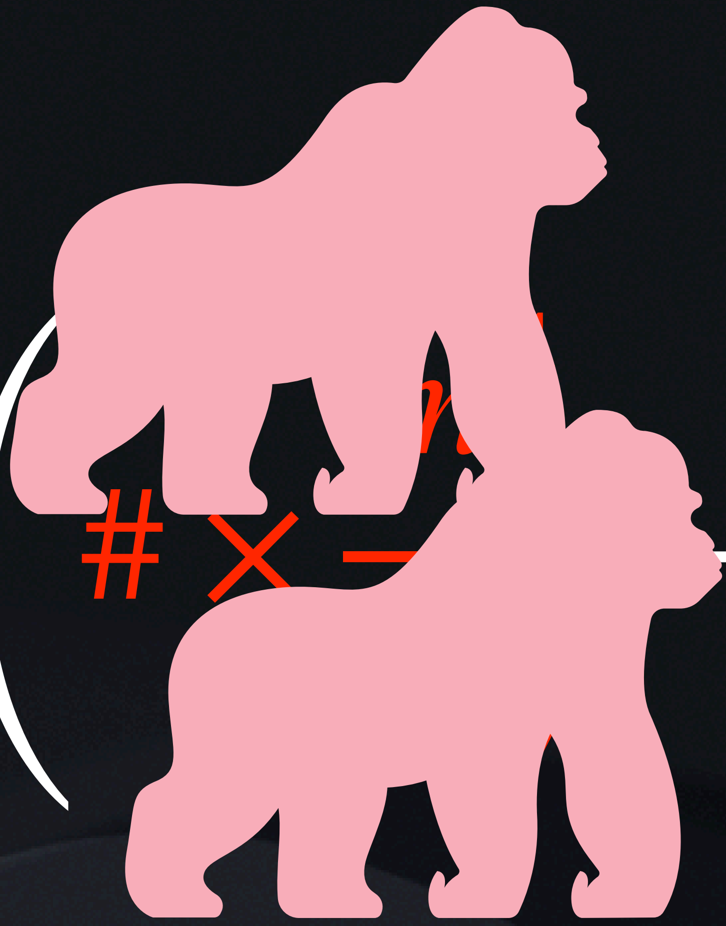


Resummation

Breakdown of perturbative expansion when $m_\chi \gg m_W$

$$\frac{\mathrm{d}\,\sigma v}{\mathrm{d}\,E_\gamma} \sim \#\,\alpha_{ew}^3 + \alpha_{ew}^4 \left(\quad + \ldots \right) + \alpha_{ew}^5 \left(\# \times \quad + \ldots \right) + \ldots$$

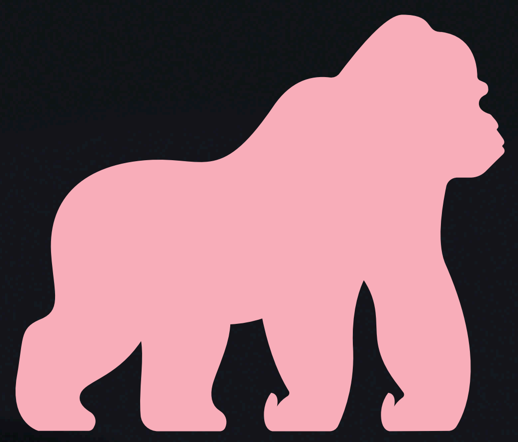




Tree (LO) 1-loop (NLO) 2-loop (NNLO)

Resummation

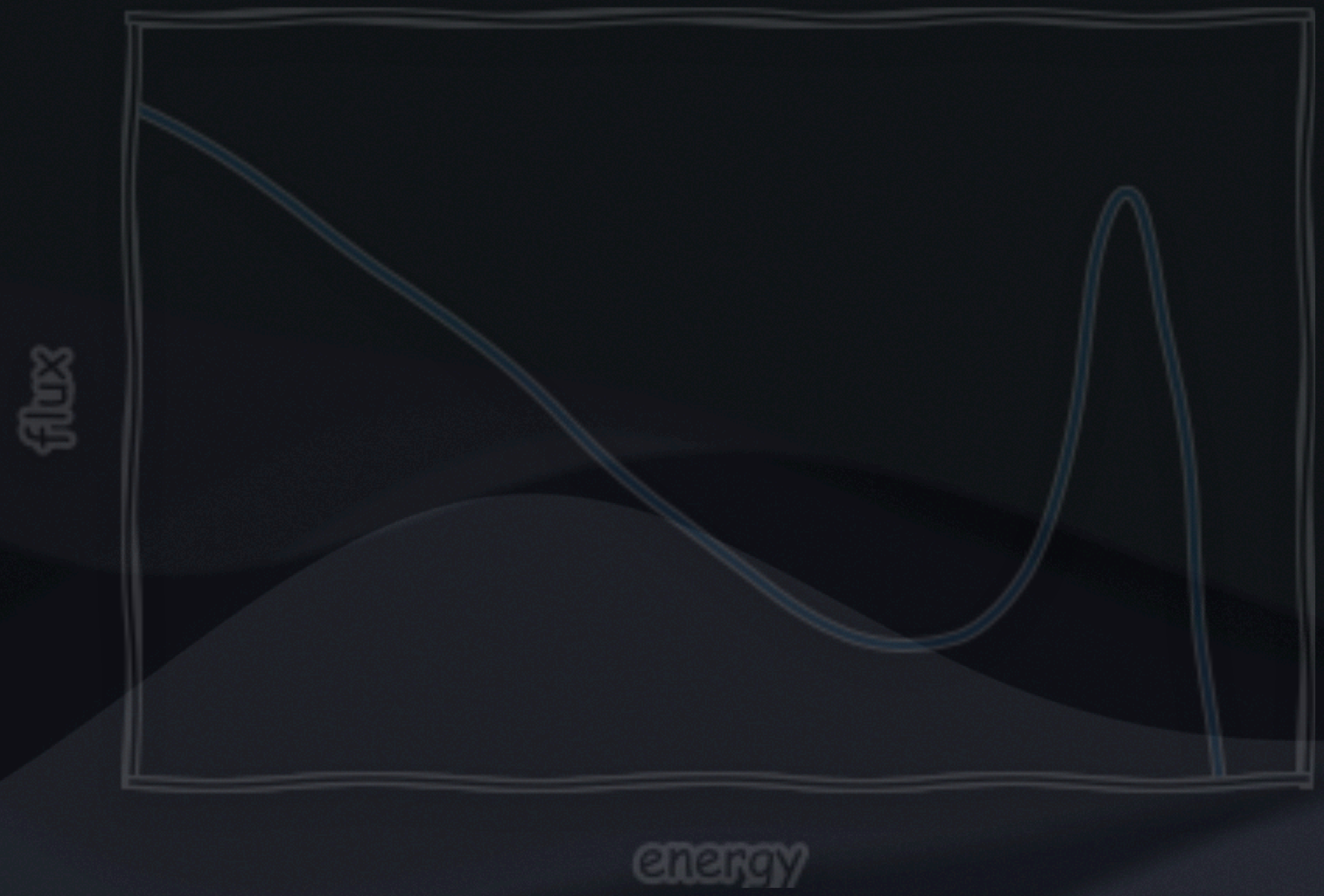
<u>Goal</u>: factor out the "gorillas"

$$\frac{\mathrm{d}\,\sigma v}{\mathrm{d}\,E_\gamma} = f\left(\alpha_{ew} \times$$  $$\right) \times \left(\#\,\alpha_{ew}^3 + \mathcal{O}(\alpha_{ew}^4)\right)$$

"safe" to use perturbation theory

TBA

The Basics of Annihilation



2020s (before our paper came out)

Fixed-order 2 → 2
+ Parton Shower +
Sommerfeld factor

- Incomplete (missing shower for e.g. $\chi^0\chi^0 \to H^\pm W^\mp$)
- Helicity-suppressed cross sections still suppressed
- ...

Fixed-order 2 → 3
+ Parton Shower +
Sommerfeld factor

- Only extrapolations from our endpoint factorization formulas available and for pure wino/higgsino

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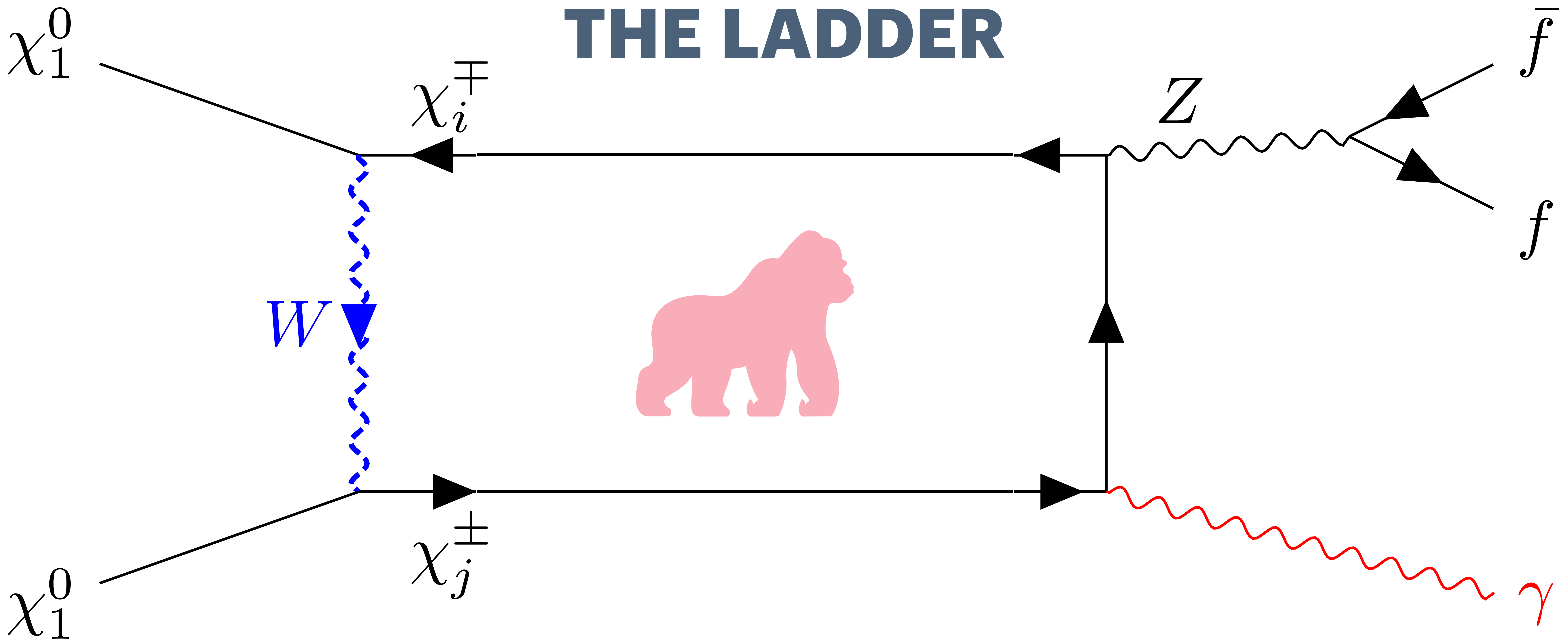
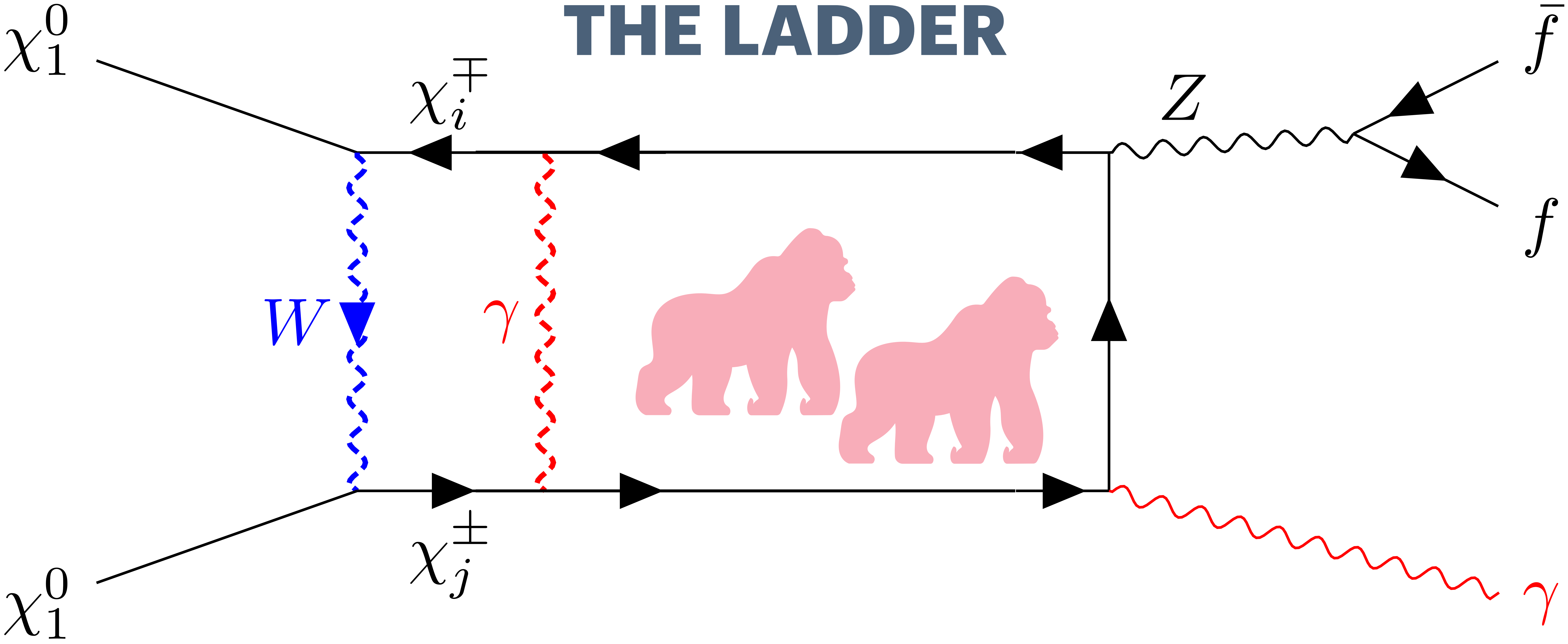
Sommerfeld factor

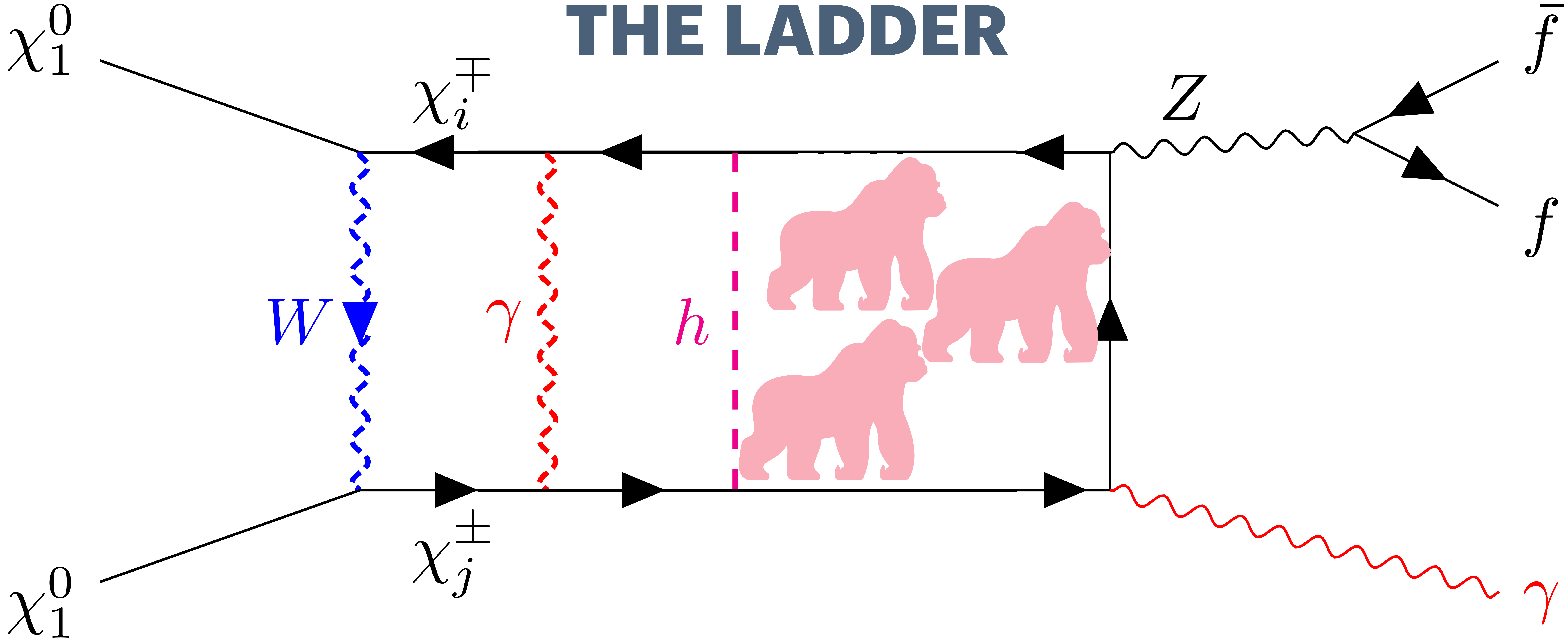
THE LADDER



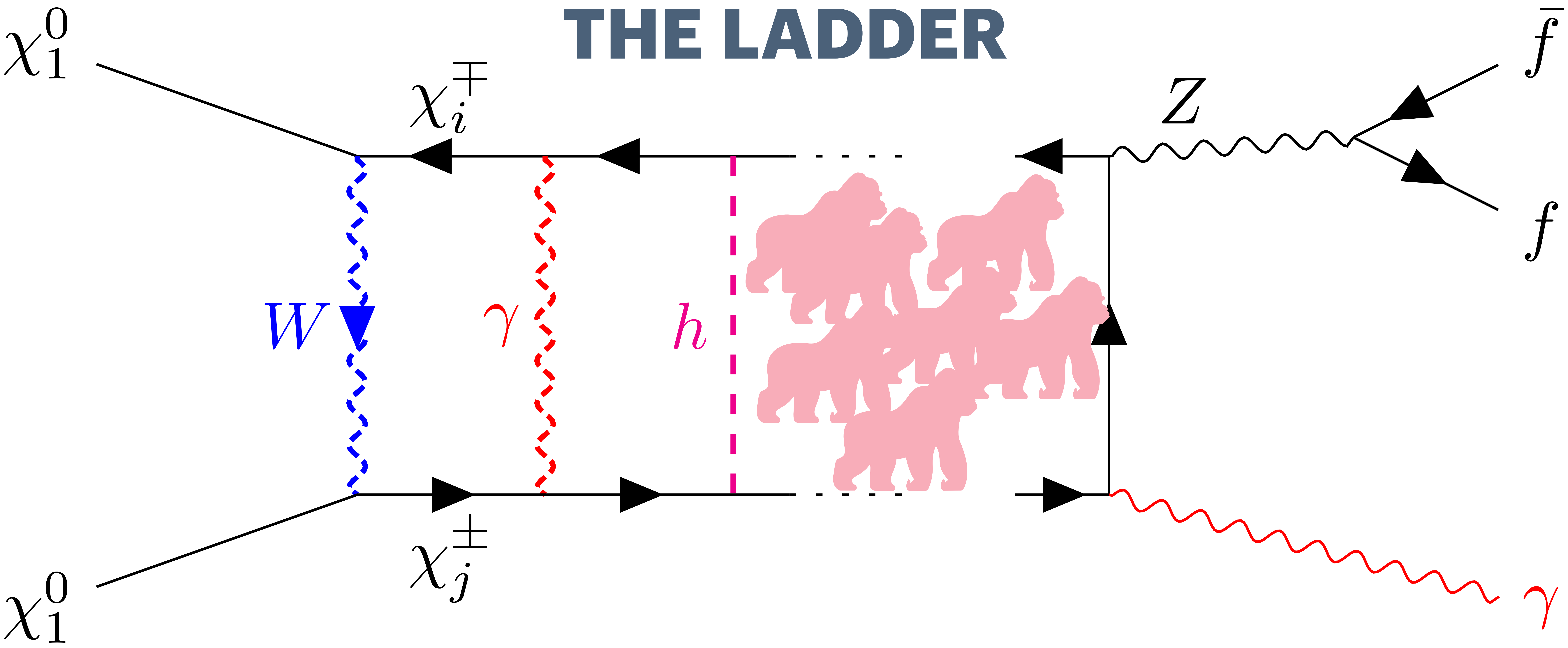
THE LADDER



THE LADDER

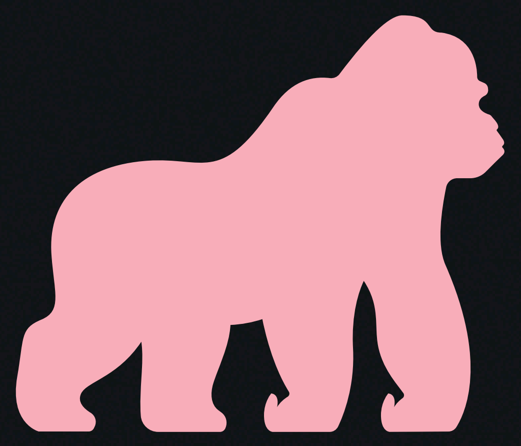


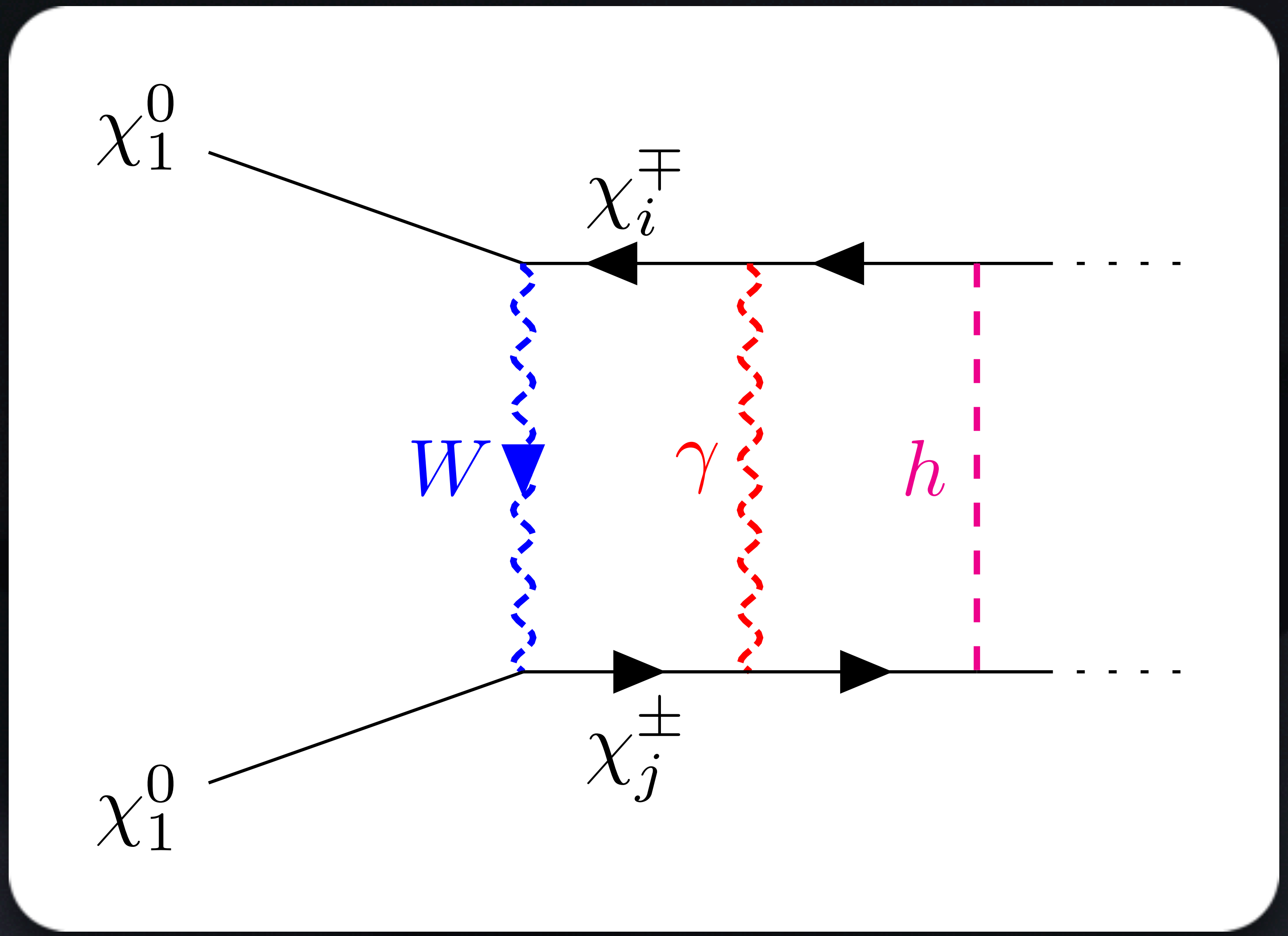
THE LADDER

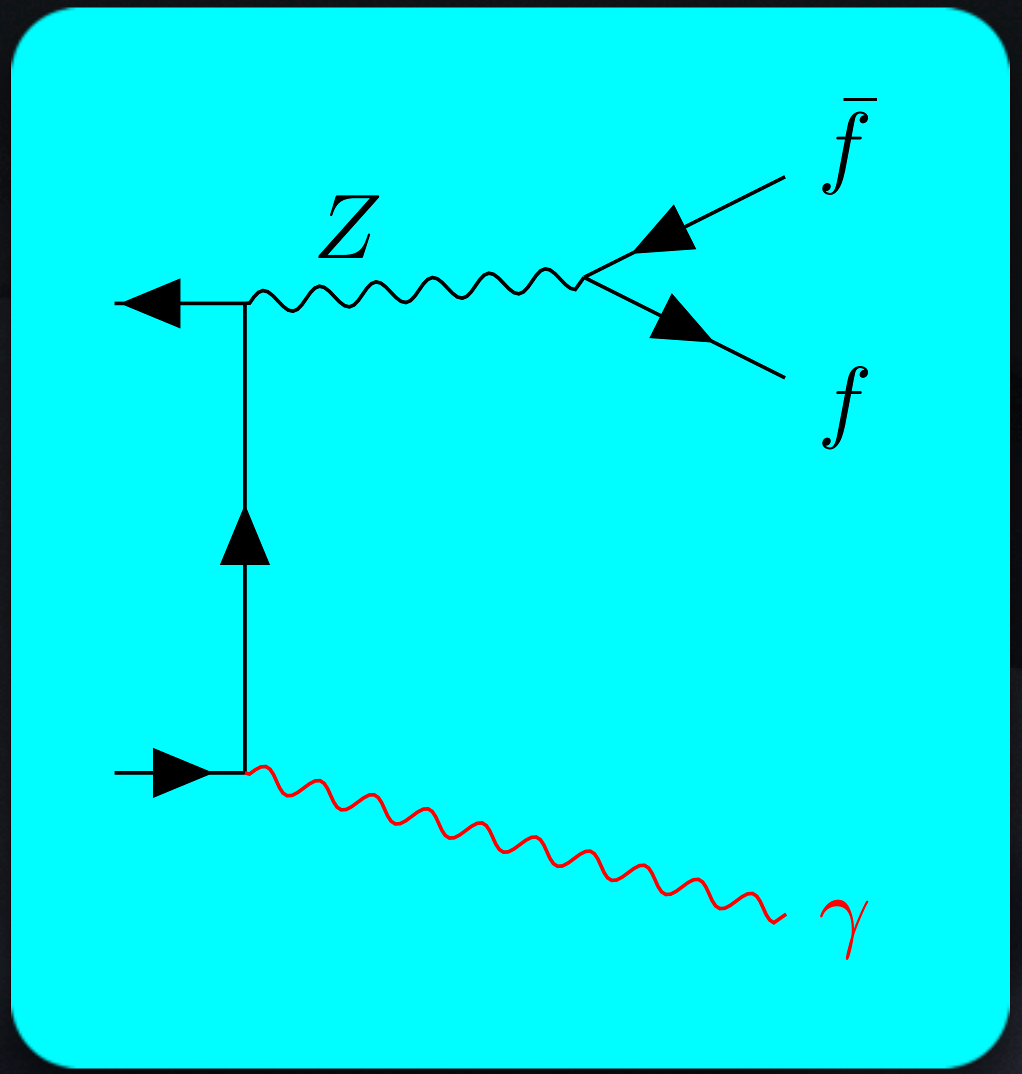


Resummation

Goal: factor out the "gorillas"

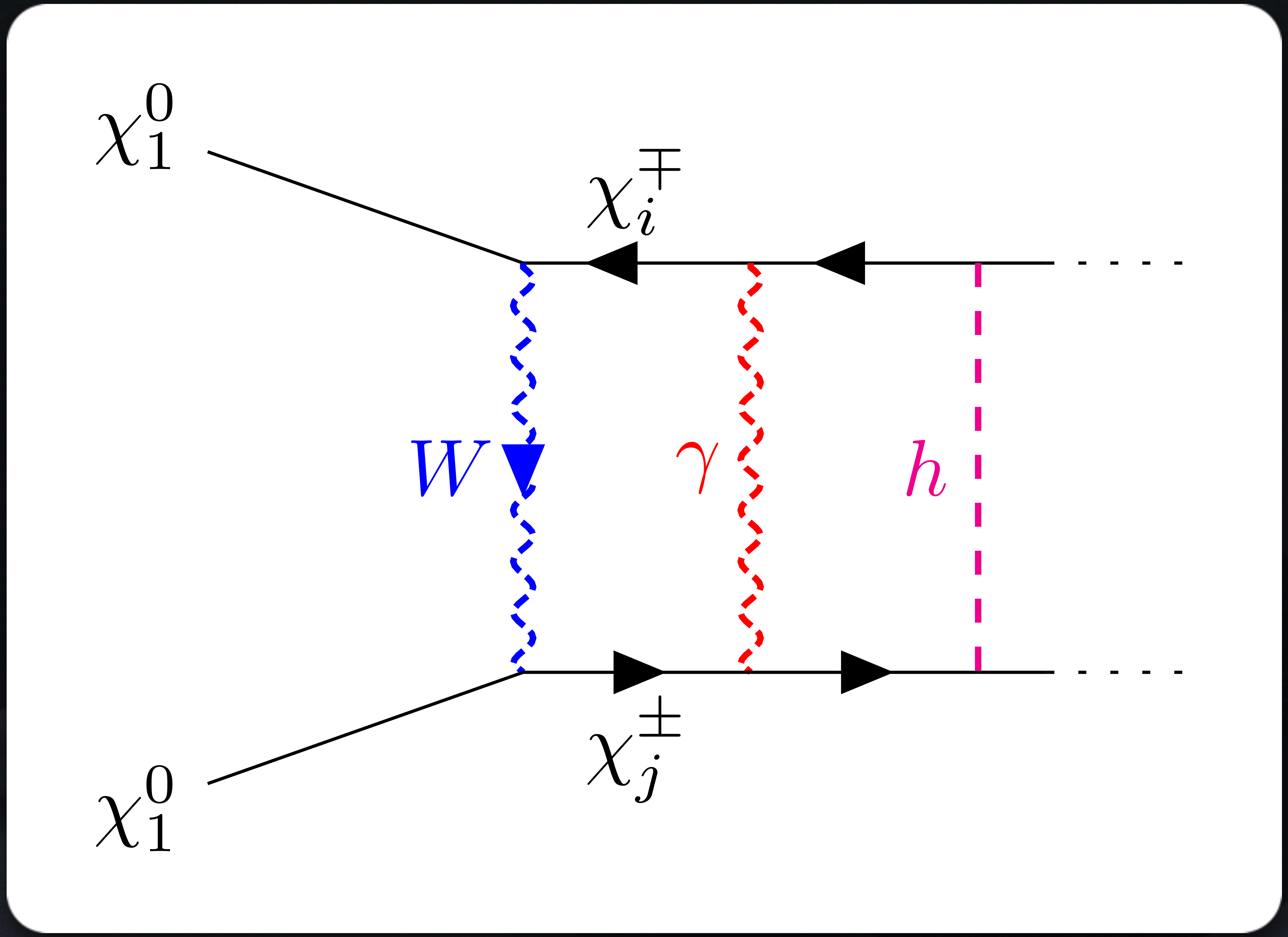
$$\frac{\mathrm{d}\,\sigma v}{\mathrm{d}\,E_\gamma} = f\left(\alpha_{ew} \times \right.$$  $$\left. \right) \times \left(\#\,\alpha_{ew}^3 + \mathcal{O}(\alpha_{ew}^4)\right)$$





Sommerfeld factor

Reframe the question: QFT ☞ Quantum Mechanics



Sommerfeld factor

Putting all things together

Quantum mechanics
(*ladder*)

$$\frac{\mathrm{d}\,\sigma v}{\mathrm{d}\,E_\gamma} = 2\sum_{I,J} S_{IJ}\left[\frac{\mathrm{d}\,(\tilde{\sigma v})}{\mathrm{d}\,E_\gamma}\right]_{IJ}$$

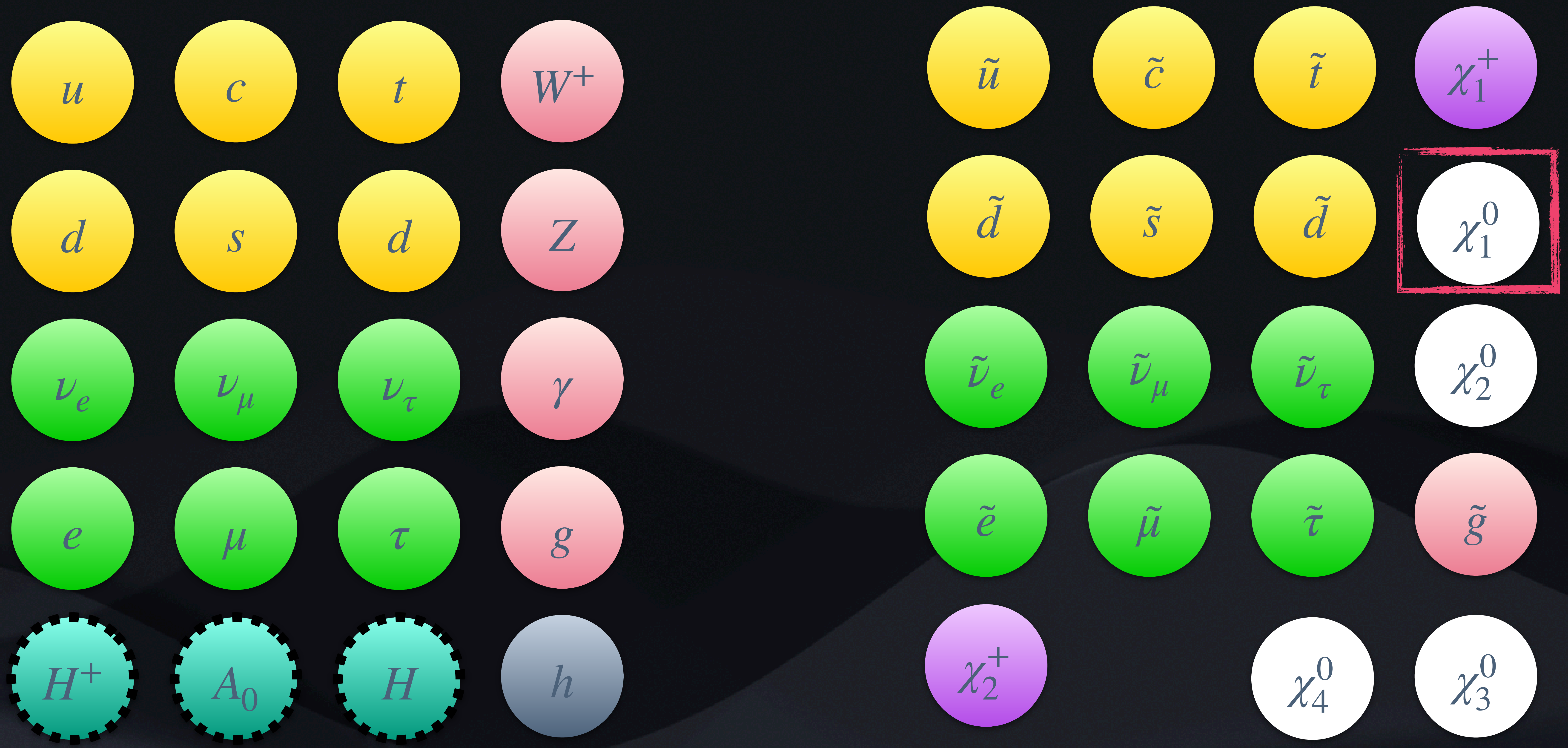
Particle pairs

QFT perturbation theory

Go to the blackboard I

The MSSM in a nutshell

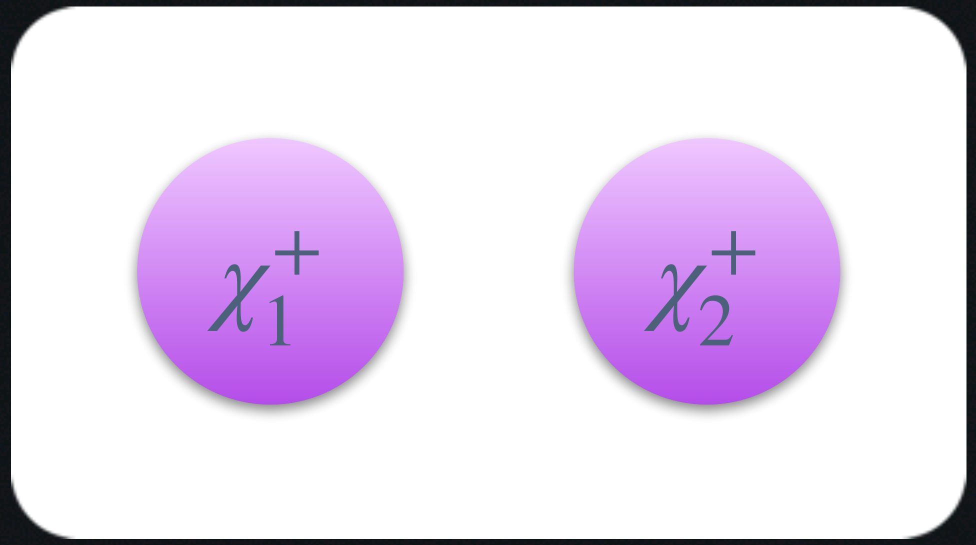
Particles and more particles



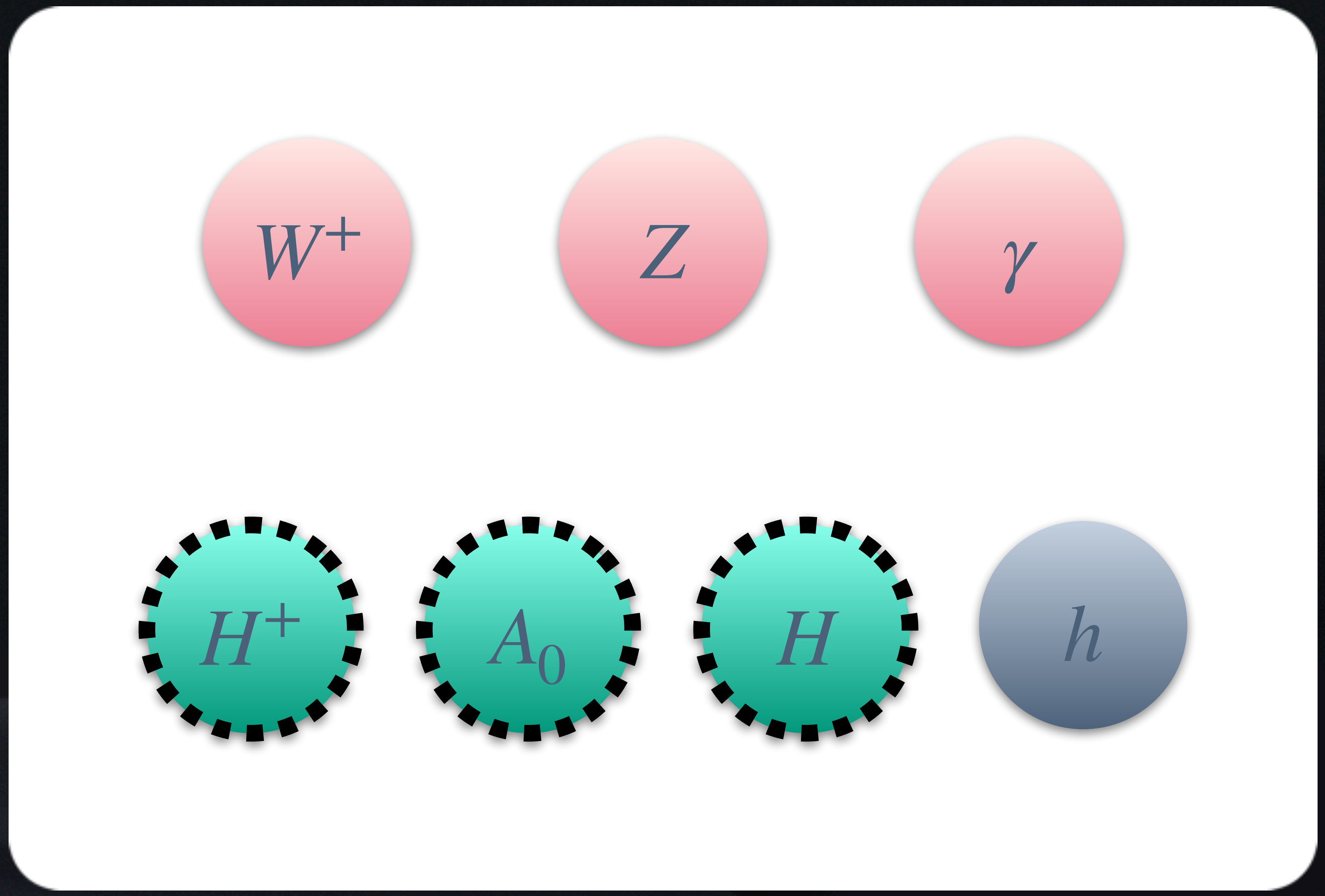
The MSSM in a nutshell

Neutralino/chargino sector

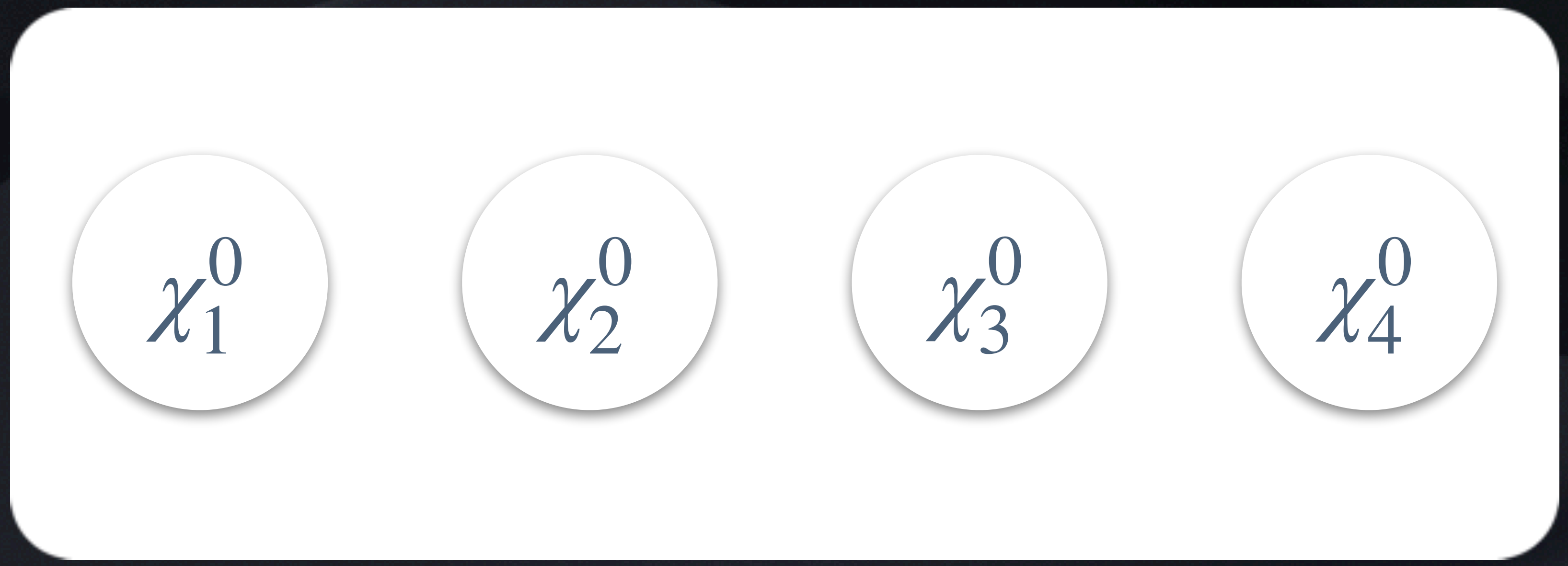
Charginos



Mediators



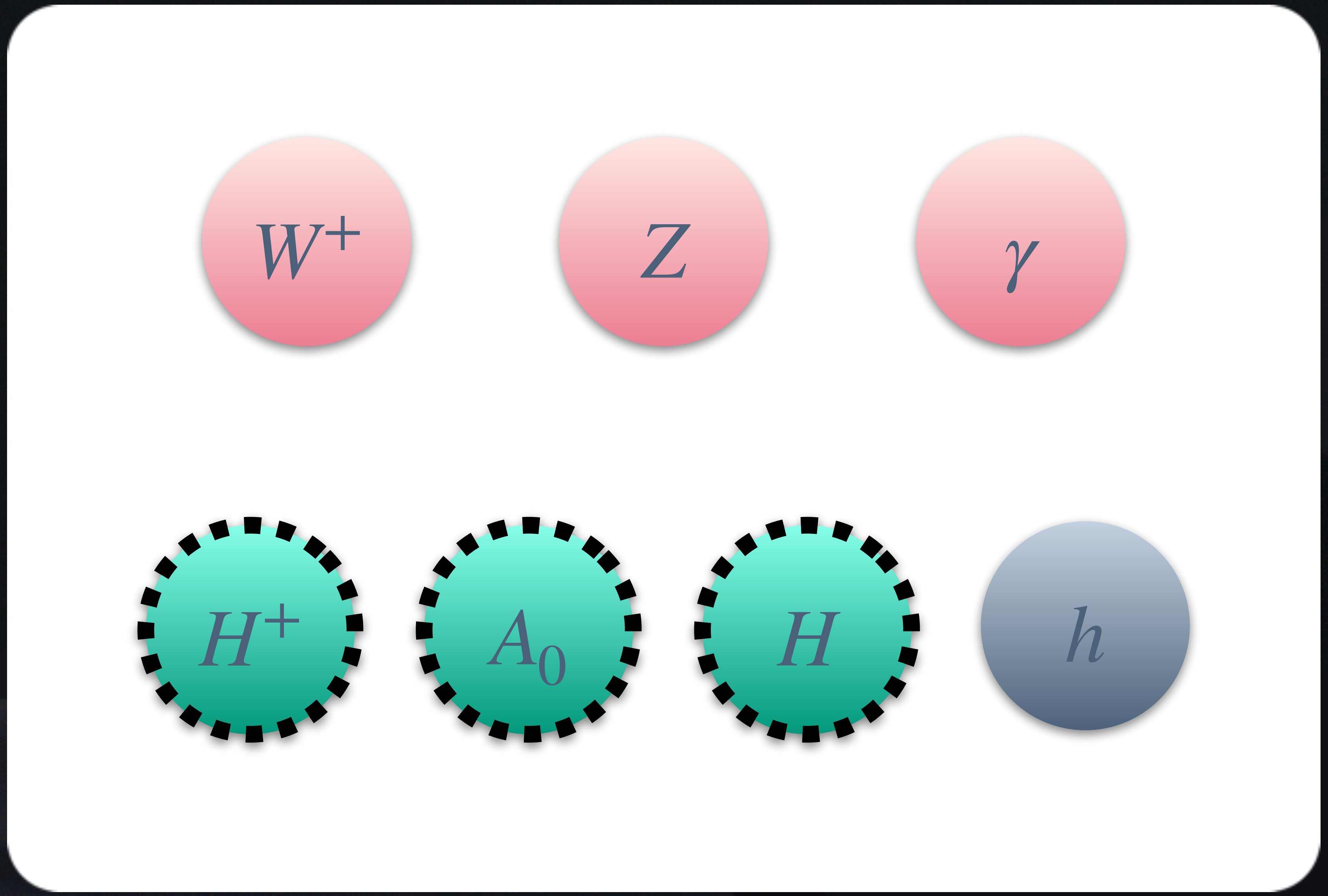
Neutralinos



Sommerfeld effect in the MSSM

Dark Matter NR potential

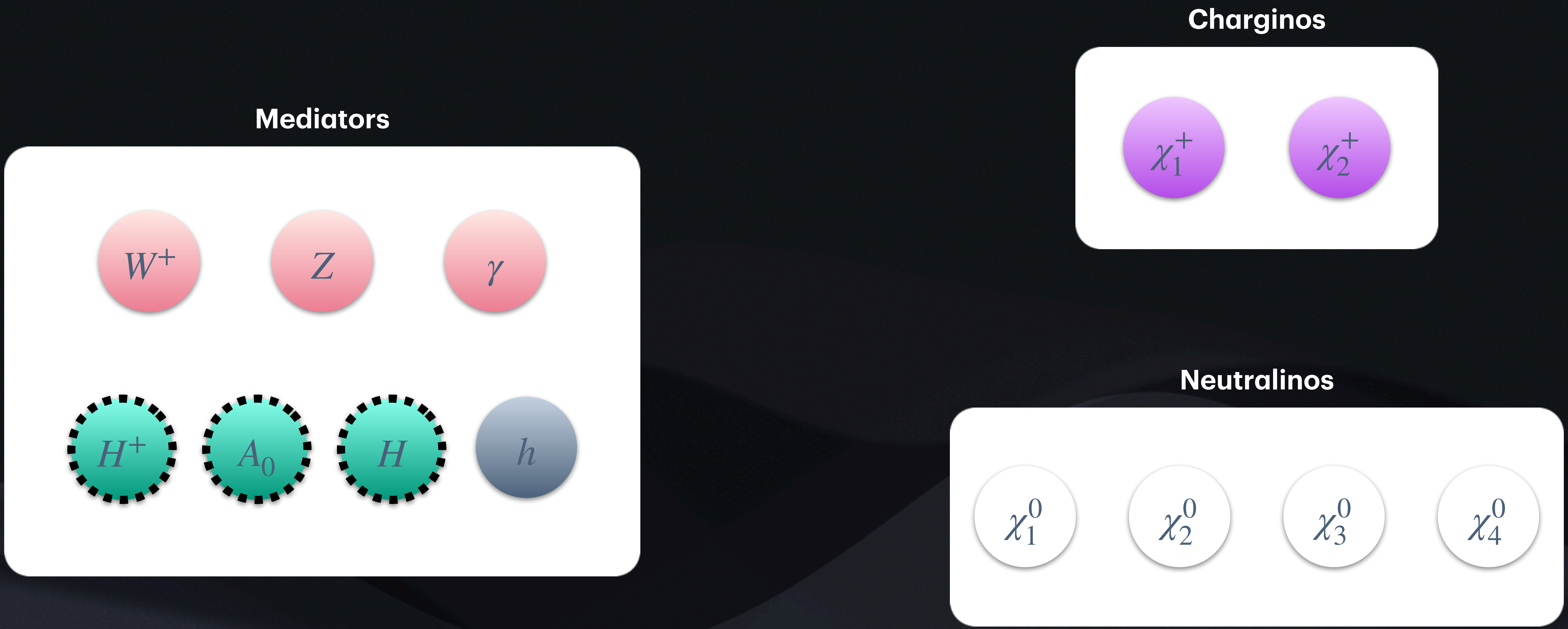
Mediators



$$V(r) \sim \frac{\alpha}{r} + \frac{\alpha_{ew} e^{-m_W r}}{r} + \frac{\alpha_{ew} e^{-m_Z r}}{r} + \dots$$

Sommerfeld effect in the MSSM

Dark Matter NR potential



Sommerfeld effect in the MSSM

Dark Matter NR potential

$$V(r) \to V_{IJ}(r)$$

Charginos

χ_1^+ χ_2^+

Neutralinos

χ_1^0 χ_2^0 χ_3^0 χ_4^0

Sommerfeld effect in the MSSM

Dark Matter NR potential

$$V(r) = \begin{pmatrix}
v_{(\hat{11})(\hat{11})} & v_{(\hat{11})(\hat{12})} & v_{(\hat{11})(\hat{13})} & v_{(\hat{11})(\hat{14})} & v_{(\hat{11})(\hat{22})} & v_{(\hat{11})(\hat{23})} & v_{(\hat{11})(\hat{24})} & v_{(\hat{11})(\hat{33})} & v_{(\hat{11})(\hat{34})} & v_{(\hat{11})(\hat{44})} & v_{(\hat{11})\langle\bar{11}\rangle} & v_{(\hat{11})\langle\bar{12}\rangle} & v_{(\hat{11})\langle\bar{21}\rangle} & v_{(\hat{11})\langle\bar{22}\rangle} \\
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v_{(\hat{44})(\hat{11})} & v_{(\hat{44})(\hat{12})} & v_{(\hat{44})(\hat{13})} & v_{(\hat{44})(\hat{14})} & v_{(\hat{44})(\hat{22})} & v_{(\hat{44})(\hat{23})} & v_{(\hat{44})(\hat{24})} & v_{(\hat{44})(\hat{33})} & v_{(\hat{44})(\hat{34})} & v_{(\hat{44})(\hat{44})} & v_{(\hat{44})\langle\bar{11}\rangle} & v_{(\hat{44})\langle\bar{12}\rangle} & v_{(\hat{44})\langle\bar{21}\rangle} & v_{(\hat{44})\langle\bar{22}\rangle} \\
v_{\langle\bar{11}\rangle(\hat{11})} & v_{\langle\bar{11}\rangle(\hat{12})} & v_{\langle\bar{11}\rangle(\hat{13})} & v_{\langle\bar{11}\rangle(\hat{14})} & v_{\langle\bar{11}\rangle(\hat{22})} & v_{\langle\bar{11}\rangle(\hat{23})} & v_{\langle\bar{11}\rangle(\hat{24})} & v_{\langle\bar{11}\rangle(\hat{33})} & v_{\langle\bar{11}\rangle(\hat{34})} & v_{\langle\bar{11}\rangle(\hat{44})} & v_{\langle\bar{11}\rangle\langle\bar{11}\rangle} & v_{\langle\bar{11}\rangle\langle\bar{12}\rangle} & v_{\langle\bar{11}\rangle\langle\bar{21}\rangle} & v_{\langle\bar{11}\rangle\langle\bar{22}\rangle} \\
v_{\langle\bar{12}\rangle(\hat{11})} & v_{\langle\bar{12}\rangle(\hat{12})} & v_{\langle\bar{12}\rangle(\hat{13})} & v_{\langle\bar{12}\rangle(\hat{14})} & v_{\langle\bar{12}\rangle(\hat{22})} & v_{\langle\bar{12}\rangle(\hat{23})} & v_{\langle\bar{12}\rangle(\hat{24})} & v_{\langle\bar{12}\rangle(\hat{33})} & v_{\langle\bar{12}\rangle(\hat{34})} & v_{\langle\bar{12}\rangle(\hat{44})} & v_{\langle\bar{12}\rangle\langle\bar{11}\rangle} & v_{\langle\bar{12}\rangle\langle\bar{12}\rangle} & v_{\langle\bar{12}\rangle\langle\bar{21}\rangle} & v_{\langle\bar{12}\rangle\langle\bar{22}\rangle} \\
v_{\langle\bar{21}\rangle(\hat{11})} & v_{\langle\bar{21}\rangle(\hat{12})} & v_{\langle\bar{21}\rangle(\hat{13})} & v_{\langle\bar{21}\rangle(\hat{14})} & v_{\langle\bar{21}\rangle(\hat{22})} & v_{\langle\bar{21}\rangle(\hat{23})} & v_{\langle\bar{21}\rangle(\hat{24})} & v_{\langle\bar{21}\rangle(\hat{33})} & v_{\langle\bar{21}\rangle(\hat{34})} & v_{\langle\bar{21}\rangle(\hat{44})} & v_{\langle\bar{21}\rangle\langle\bar{11}\rangle} & v_{\langle\bar{21}\rangle\langle\bar{12}\rangle} & v_{\langle\bar{21}\rangle\langle\bar{21}\rangle} & v_{\langle\bar{21}\rangle\langle\bar{22}\rangle} \\
v_{\langle\bar{22}\rangle(\hat{11})} & v_{\langle\bar{22}\rangle(\hat{12})} & v_{\langle\bar{22}\rangle(\hat{13})} & v_{\langle\bar{22}\rangle(\hat{14})} & v_{\langle\bar{22}\rangle(\hat{22})} & v_{\langle\bar{22}\rangle(\hat{23})} & v_{\langle\bar{22}\rangle(\hat{24})} & v_{\langle\bar{22}\rangle(\hat{33})} & v_{\langle\bar{22}\rangle(\hat{34})} & v_{\langle\bar{22}\rangle(\hat{44})} & v_{\langle\bar{22}\rangle\langle\bar{11}\rangle} & v_{\langle\bar{22}\rangle\langle\bar{12}\rangle} & v_{\langle\bar{22}\rangle\langle\bar{21}\rangle} & v_{\langle\bar{22}\rangle\langle\bar{22}\rangle}
\end{pmatrix}$$

Sommerfeld effect in the MSSM

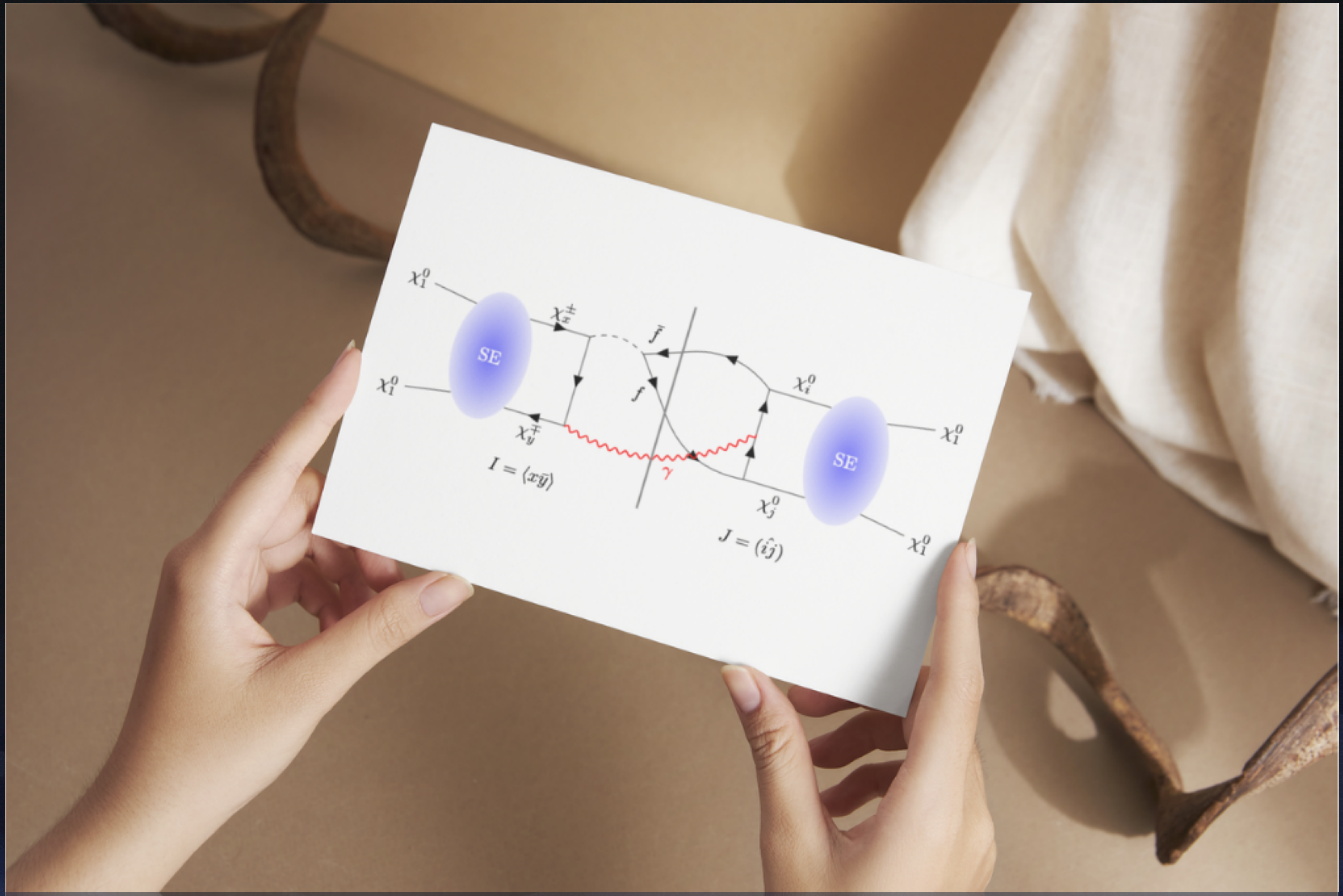
14×14 matrix

$$\frac{\mathrm{d}\,\sigma v}{\mathrm{d}\,E_\gamma} = 2\sum_{I,J} S_{IJ}\left[\frac{\mathrm{d}\,(\tilde{\sigma v})}{\mathrm{d}\,E_\gamma}\right]_{IJ}$$

105 independent terms

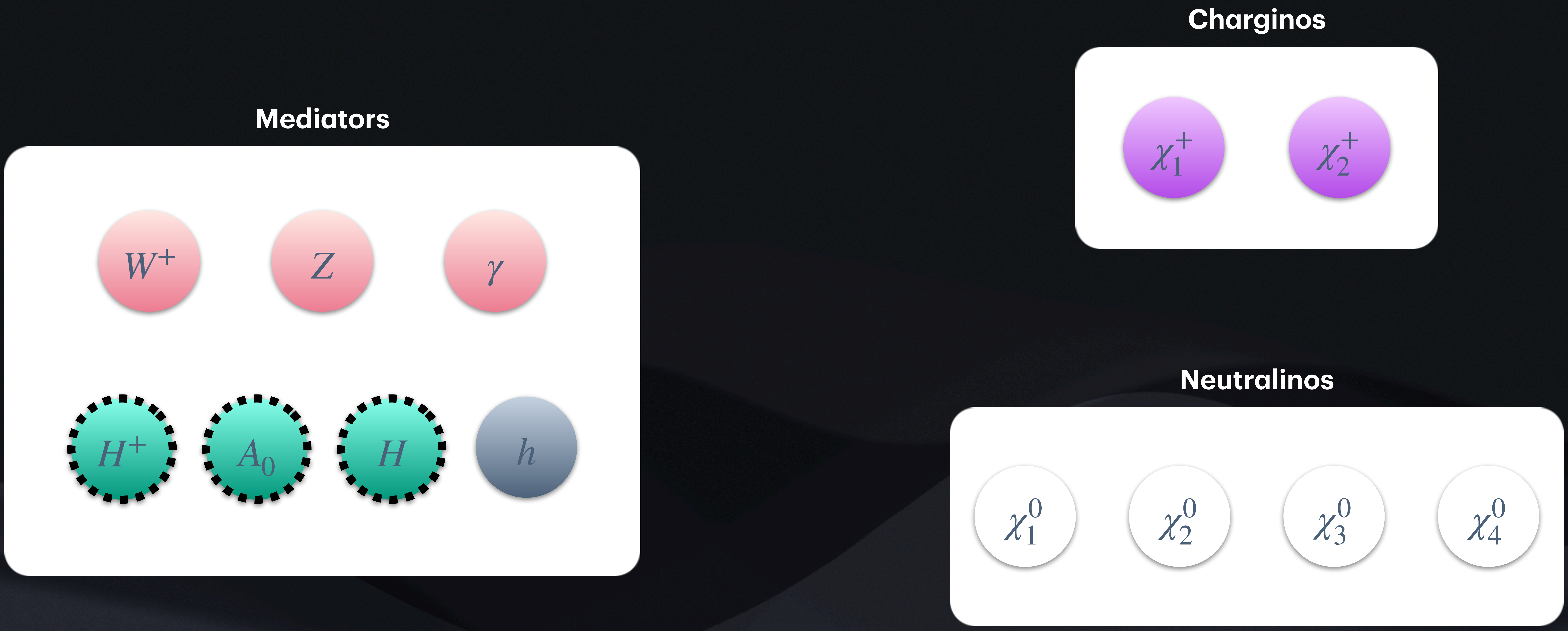
Jäger Vollmann 2023

arXiv: 2310.11067



The MSSM in a nutshell

Neutralino/chargino sector



Pure wino

Neutralinos

χ_1^0

Charginos

χ_1^+

Mediators

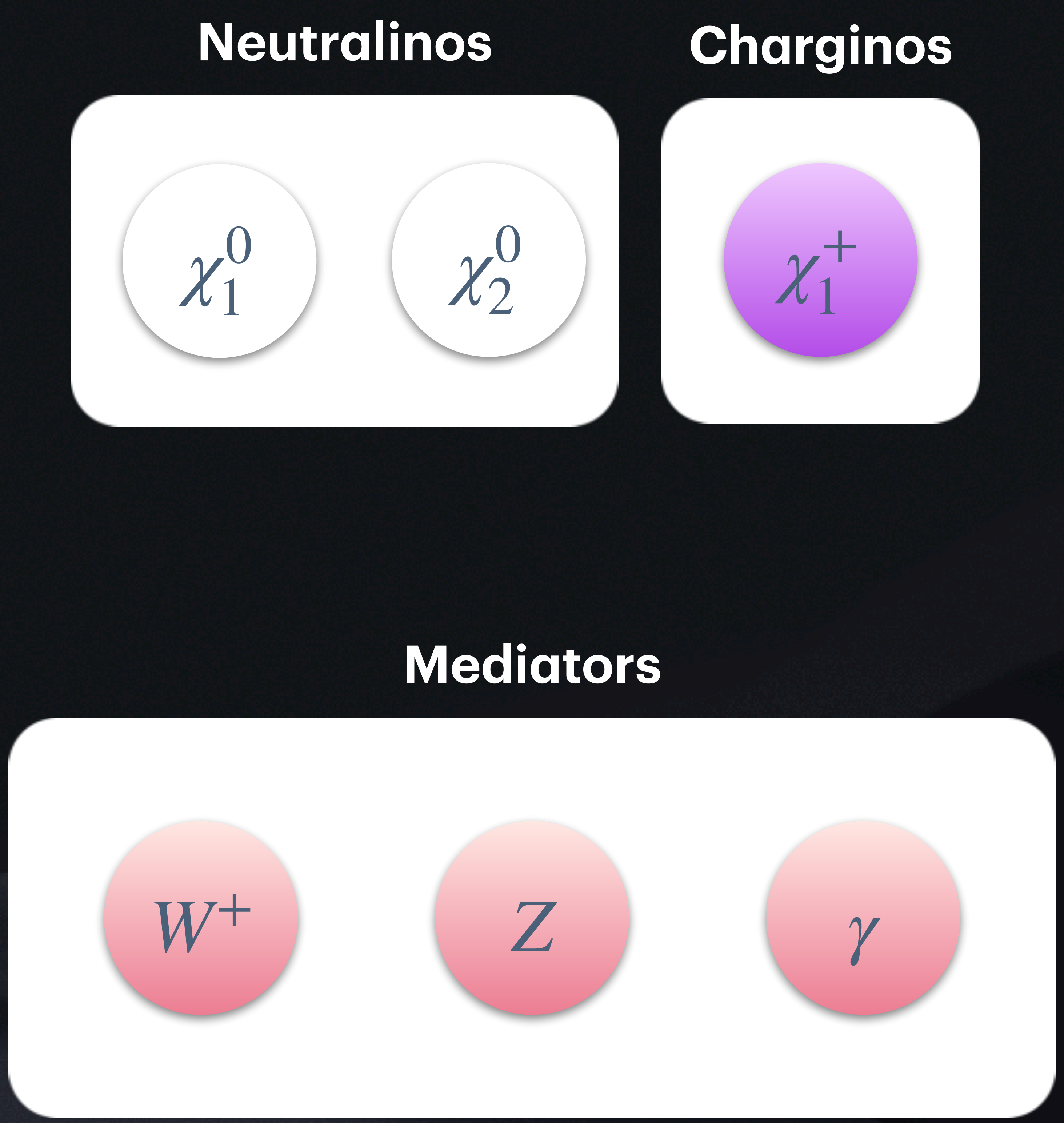
W^+ Z γ

$$V(r) = \begin{pmatrix} 0 & -\sqrt{2}\alpha_2 \frac{e^{-m_W r}}{r} \\ -\sqrt{2}\alpha_2 \frac{e^{-m_W r}}{r} & -\frac{\alpha}{r} - \alpha_2 c_W^2 \frac{e^{-m_Z r}}{r} \end{pmatrix}$$

Further properties:

- $m_{\chi_1^0}^{\text{wimp}} \simeq 3\,\text{TeV}$
- $\dfrac{m_{\chi_1^+} - m_{\chi_1^0}}{m_{\chi_1^0}} \simeq 5.5 \times 10^{-5}$
- No couplings to quarks or gluons

Pure higgsino (see Linda's & Graham's slides)

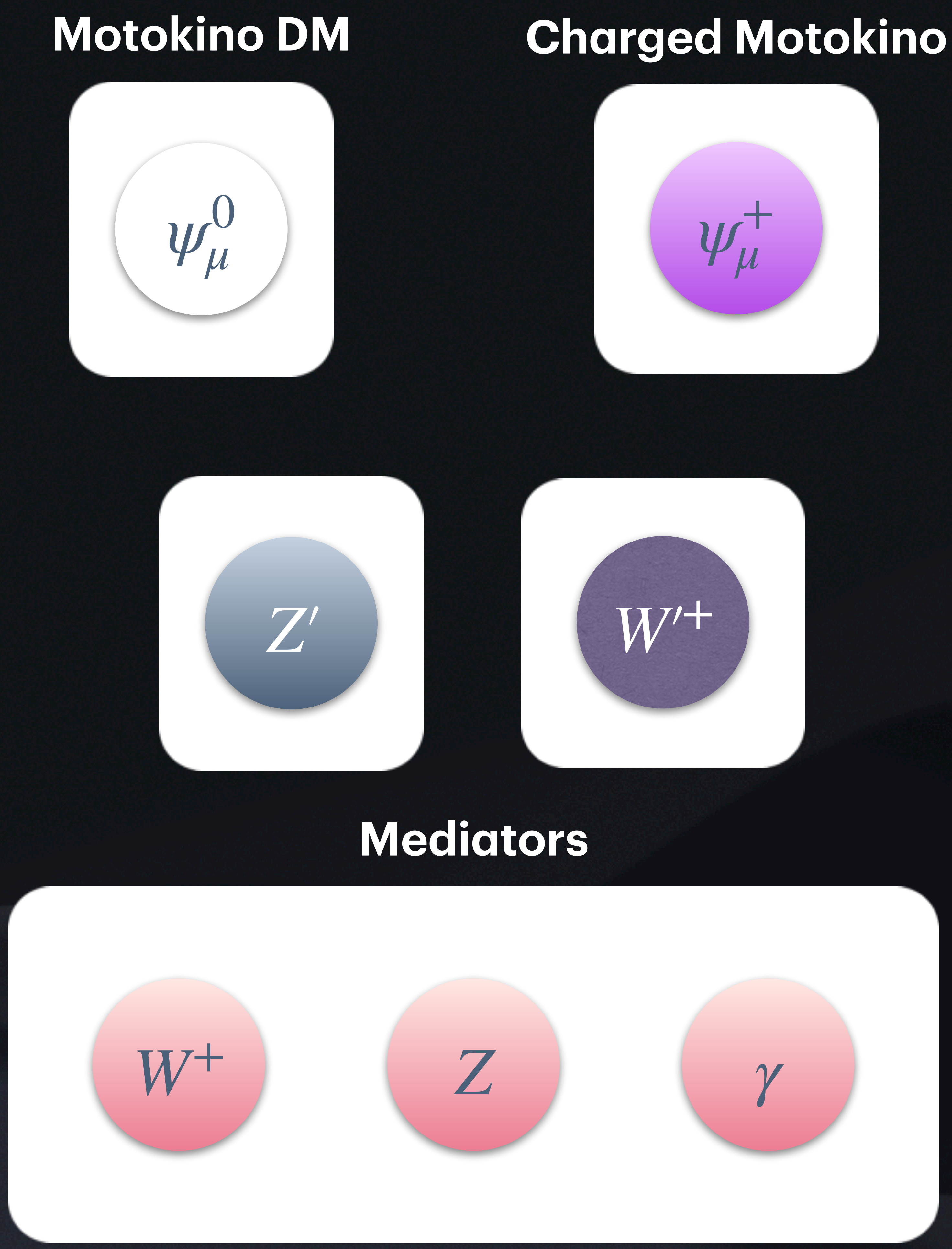


$$V(r) = \begin{pmatrix} 0 & -\frac{\alpha_2}{4c_W^2}\frac{e^{-m_Z r}}{r} & -\frac{\alpha_2}{2\sqrt{2}}\frac{e^{-m_W r}}{r} \\ -\frac{\alpha_2}{4c_W^2}\frac{e^{-m_Z r}}{r} & 0 & -\frac{\alpha_2}{2\sqrt{2}}\frac{e^{-m_W r}}{r} \\ -\frac{\alpha_2}{2\sqrt{2}}\frac{e^{-m_W r}}{r} & -\frac{\alpha_2}{2\sqrt{2}}\frac{e^{-m_W r}}{r} & -\frac{\alpha}{r} - \frac{\alpha_2(s_W^2 - c_W^2)^2)}{4c_W^2}\frac{e^{-m_Z r}}{r} \end{pmatrix}$$

Further properties:

- $m_{\chi_1^0}^{\mathrm{wimp}} \simeq 1\,\mathrm{TeV}$
- $\dfrac{m_{\chi_1^+} - m_{\chi_1^0}}{m_{\chi_1^0}} \simeq 3.5 \times 10^{-4}$
- No couplings to quarks or gluons
  - Small admixture with wino/bino required in order to avoid direct-detection constraints

Motokino



$$V^{\text{even}\,S}(r) = \begin{pmatrix} 0 & -\sqrt{2}\alpha_2 \frac{e^{-m_W r}}{r} \\ -\sqrt{2}\alpha_2 \frac{e^{-m_W r}}{r} & -\frac{\alpha}{r} - \alpha_2 c_W^2 \frac{e^{-m_Z r}}{r} \end{pmatrix}$$

Further properties:

- $m_{\psi^0}^{\text{wimp}}$ depend on th. parameters
- No couplings to quarks or gluons
- Identical potential as for wino DM

Outline

Motivation

Indirect detection

Sommerfeld factor

Endpoint resummations

Plots

Conclusions

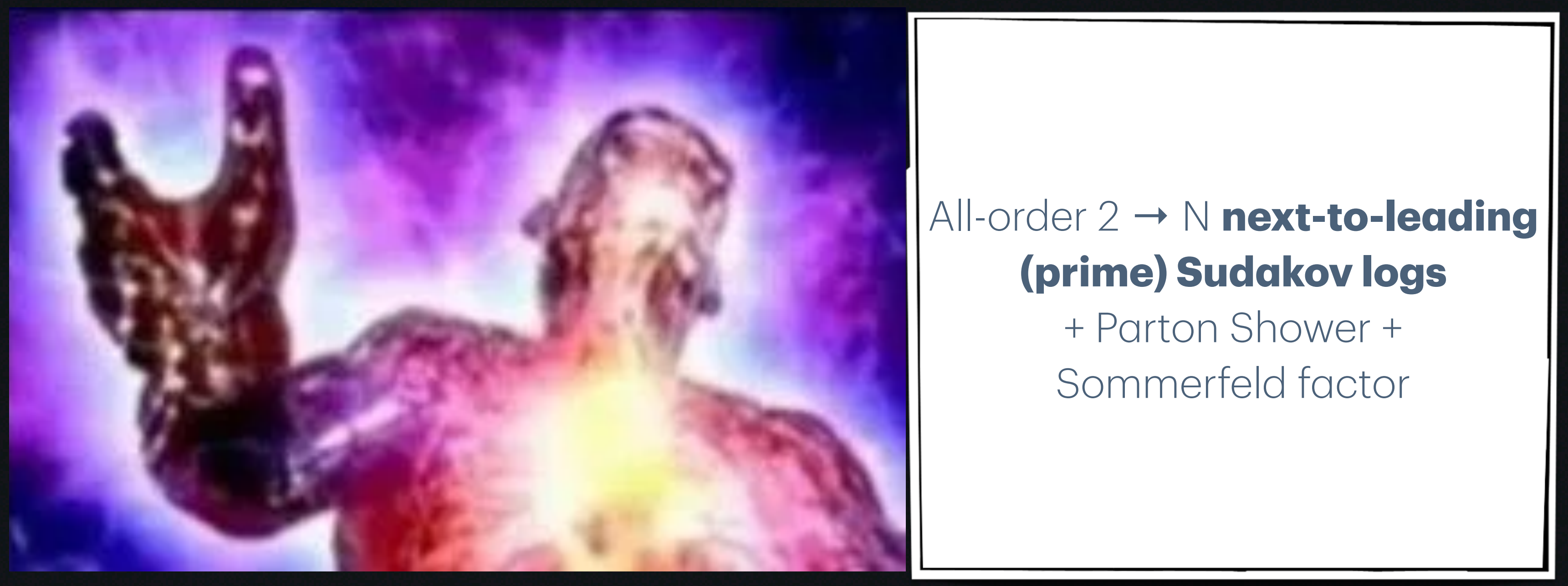
Endpoint resummations

TBA

The Basics of Annihilation

TBA

The Basics of Annihilation

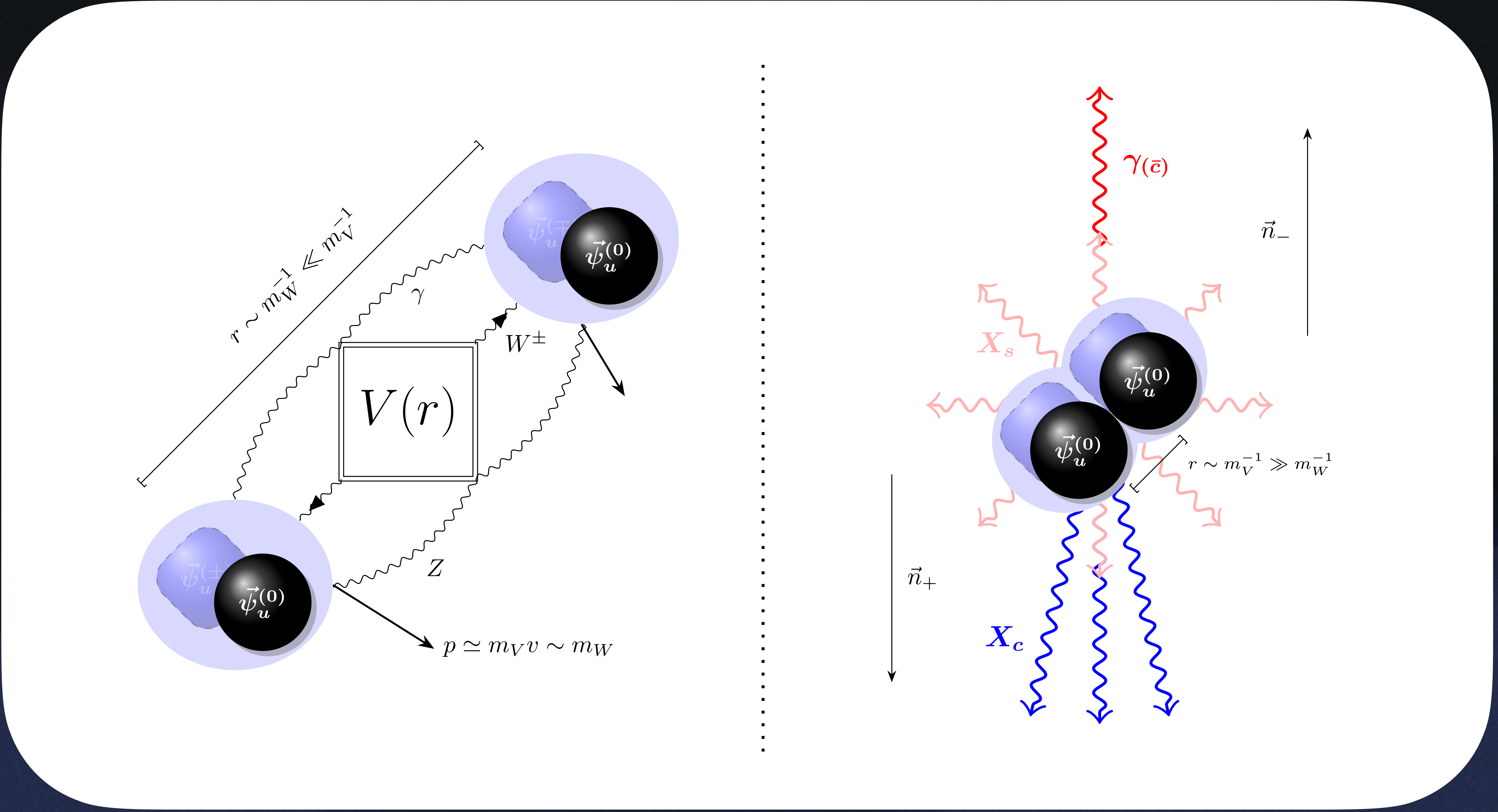


All-order 2 → N **next-to-leading (prime) Sudakov logs** + Parton Shower + Sommerfeld factor

Baumgart, Cohen et al — 1712.07656

Beneke, Broggio, Hasner, MV, Urban — 1903.08702

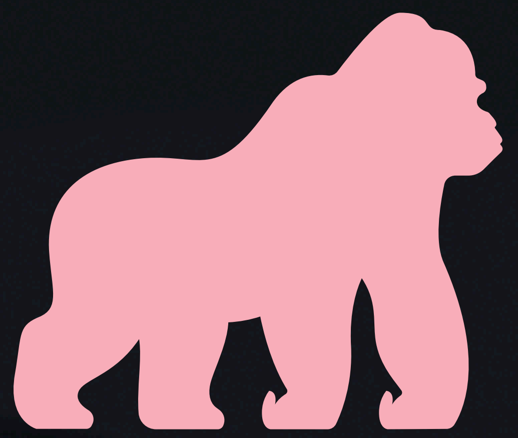
Fujiwara, Vollmann — 2411.XXXX



Resummation

Goal: factor out the "gorillas"

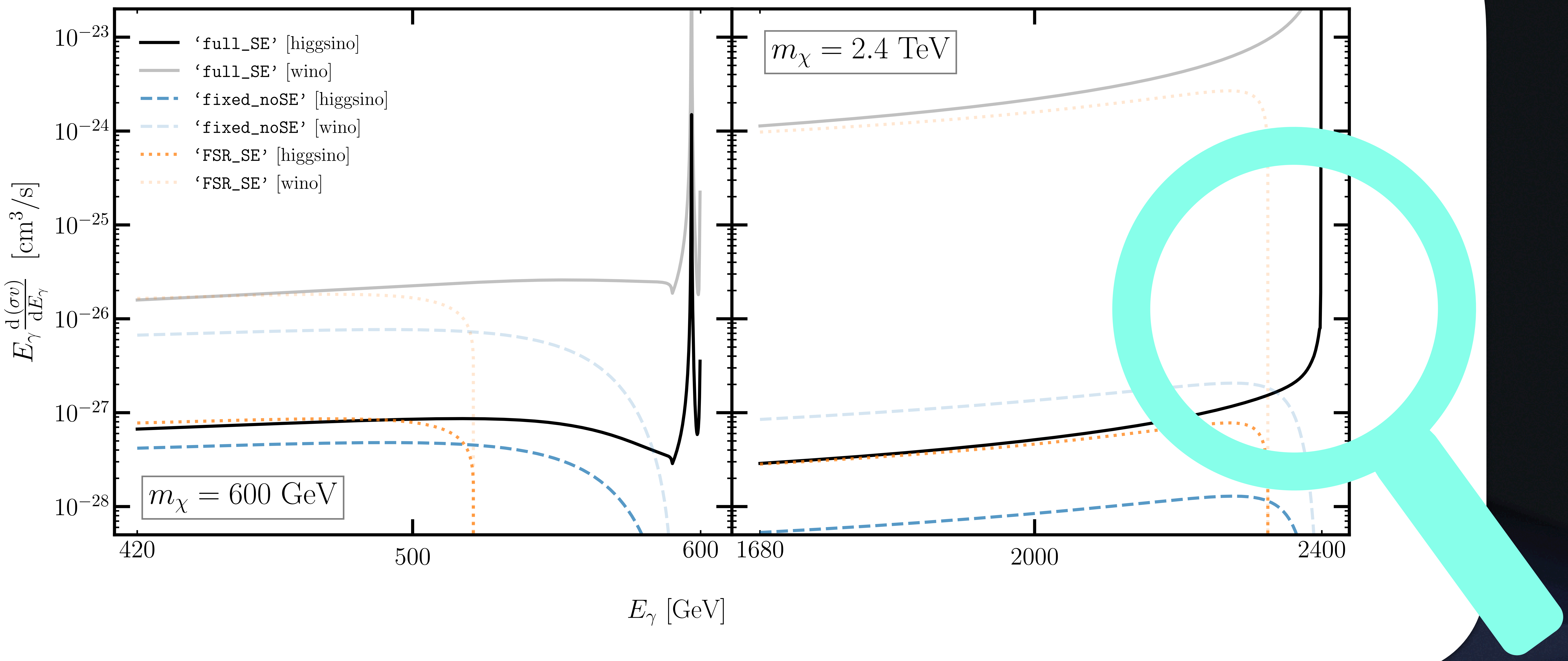
$$\frac{\mathrm{d}\,\sigma v}{\mathrm{d}\,E_\gamma} = f\Big(\alpha_{ew} \times$$



$$\Big) \times \Big(\#\,\alpha_{ew}^3 + \mathcal{O}(\alpha_{ew}^4)\Big)$$

"safe" to use perturbation theory

?



'full_SE' [higgsino]
'full_SE' [wino]
'fixed_noSE' [higgsino]
'fixed_noSE' [wino]
'FSR_SE' [higgsino]
'FSR_SE' [wino]
$m_\chi = 600$ GeV
$m_\chi = 2.4$ TeV
$E_\gamma \frac{d(\sigma v)}{dE_\gamma}$ [cm^3/s]
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
420
500
600
1680
2000
2400
E_γ [GeV]

Sudakov double-log resummation

Soft-collinear effective field theory approach

$$\left[\frac{\mathrm{d}(\tilde{\sigma v})^S}{\mathrm{d}E_\gamma}\right]_{IJ} = \frac{1}{(\sqrt{2})^{n_{id}}}\,\frac{1}{9}\,\frac{2}{\pi m_V}\sum_{\mathcal{J},\mathscr{J}=0,2}\;\sum_{i,j}\kappa^S_{ij}\,H^{S;i,j}_{\mathcal{J},\mathscr{J}}\,Z^{33}_\gamma \times \int d\omega\, J\left(4m_V(m_V - E - \omega/2)\right) W_{\mathcal{J},\mathscr{J};IJ}(\omega)$$

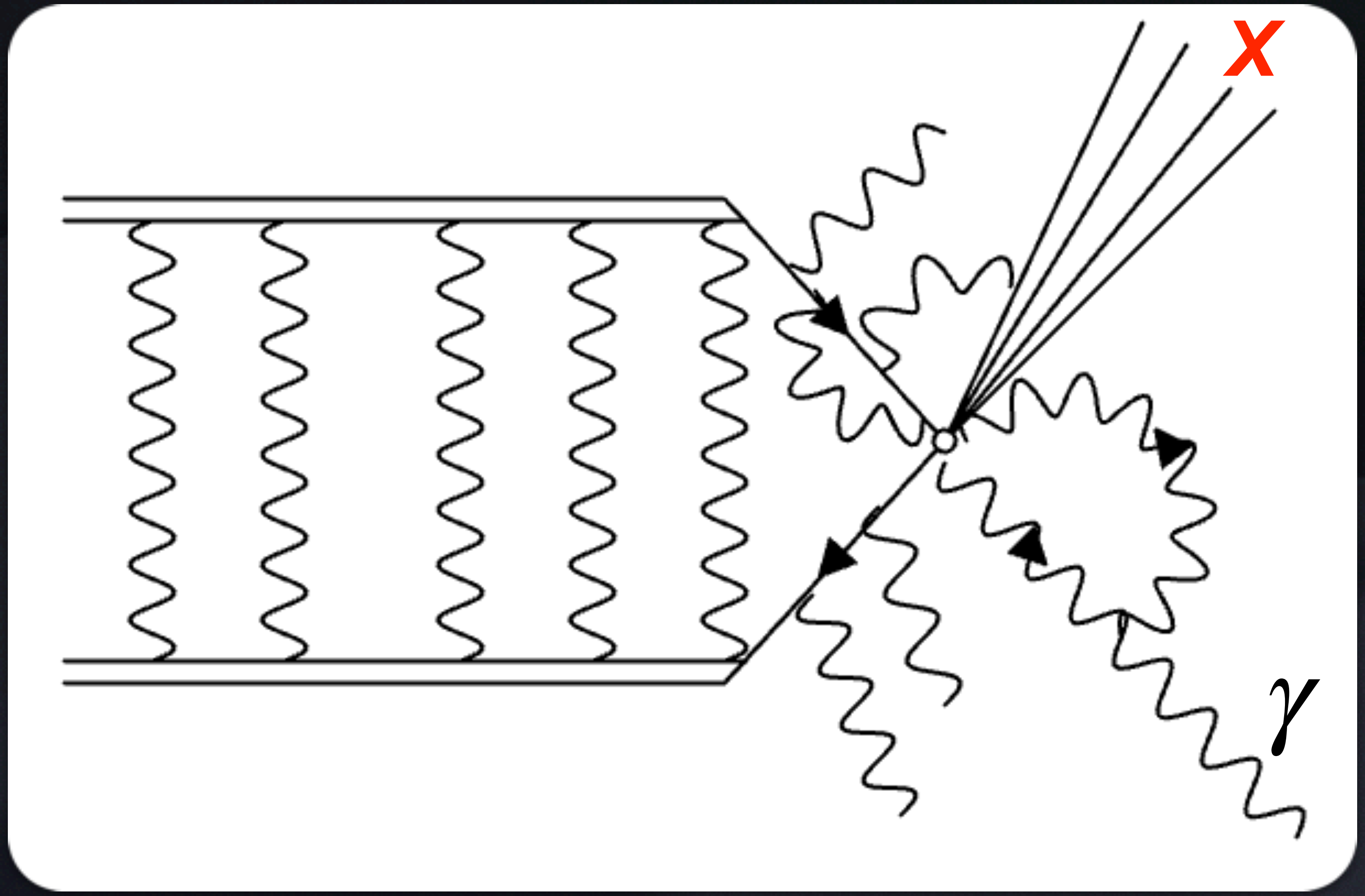
<u>Six</u> Motokino-annihilation operators

$$\mathcal{O}^{(0)}_{\mathcal{J}} = \tilde{\Upsilon}^{A}_{u\alpha}\eta^{\alpha\beta}_{u}\tilde{\Upsilon}^{B}_{u\beta}T^{ABCD}_{\mathcal{J}}\tilde{\mathcal{A}}^{C}_{\perp c,\mu}(sn_+)\eta^{\mu\nu}_{\perp}\tilde{\mathcal{A}}^{D}_{\perp\bar{c},\nu}(tn_-)\,,$$

$$\mathcal{O}^{(2)_1}_{\mathcal{J}} = \tilde{\Upsilon}^{A}_{u\alpha}\tilde{\Upsilon}^{B}_{u\beta}T^{ABCD}_{\mathcal{J}}(\eta^{\alpha\mu}_{\perp}\eta^{\beta\nu}_{\perp} + \eta^{\alpha\nu}_{\perp}\eta^{\beta\mu}_{\perp})\tilde{\mathcal{A}}^{C}_{\perp c,\mu}(sn_+)\tilde{\mathcal{A}}^{D}_{\perp\bar{c},\nu}(tn_-) - \frac{2}{3}\mathcal{O}^{(0)}_{\mathcal{J}}$$

$$\mathcal{O}^{(2)_2}_{\mathcal{J}} = \tilde{\Upsilon}^{A}_{u\alpha}(n_+ - n_-)^{\alpha}\tilde{\Upsilon}^{B}_{u\beta}(n_+ - n_-)^{\beta}T^{ABCD}_{\mathcal{J}}\tilde{\mathcal{A}}^{C}_{\perp c,\mu}(sn_+)\eta^{\mu\nu}_{\perp}\tilde{\mathcal{A}}^{D}_{\perp\bar{c},\nu}(tn_-) + \frac{4}{3}\mathcal{O}^{(0)}_{\mathcal{J}}\,;$$

Endpoint → $m_X^2 \ll 4m_\chi^2$



Go to the blackboard II

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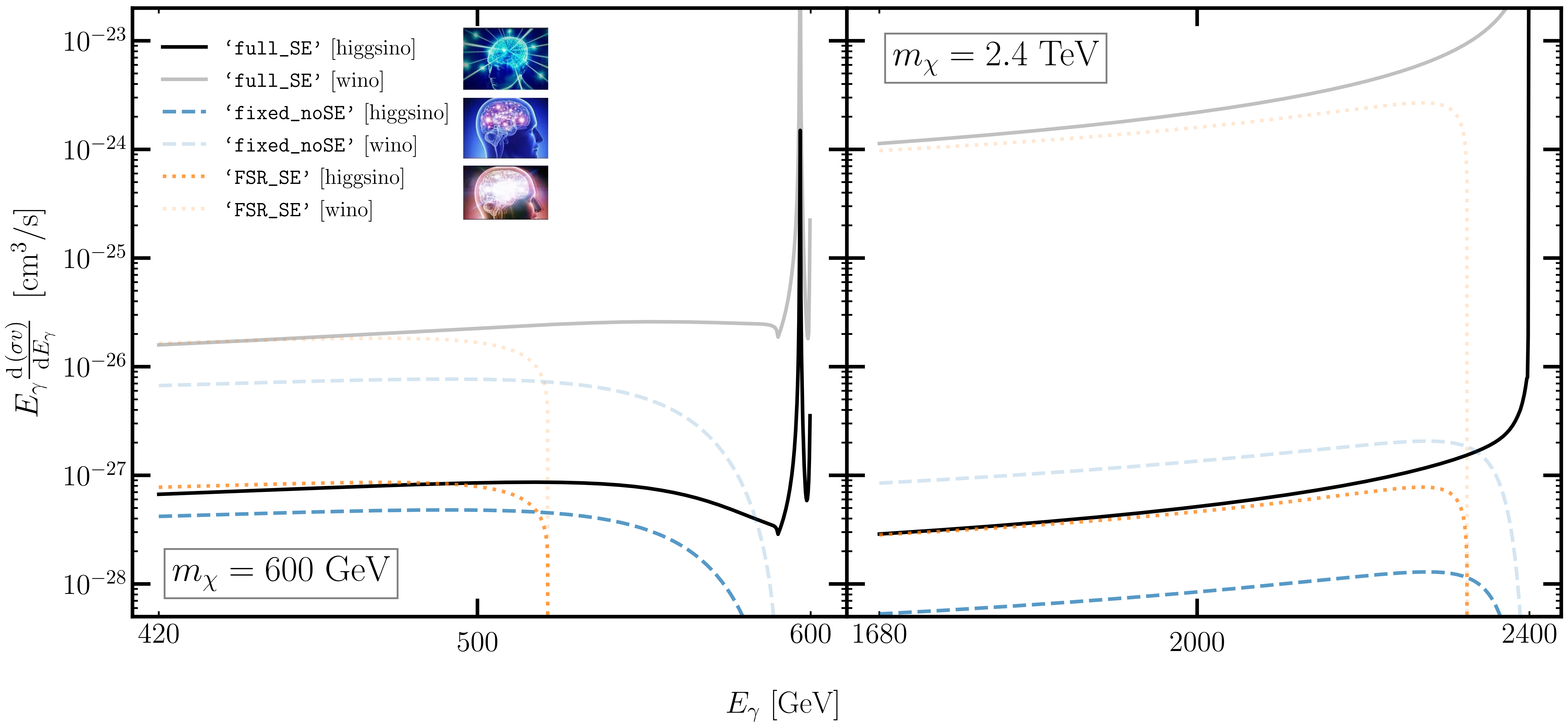
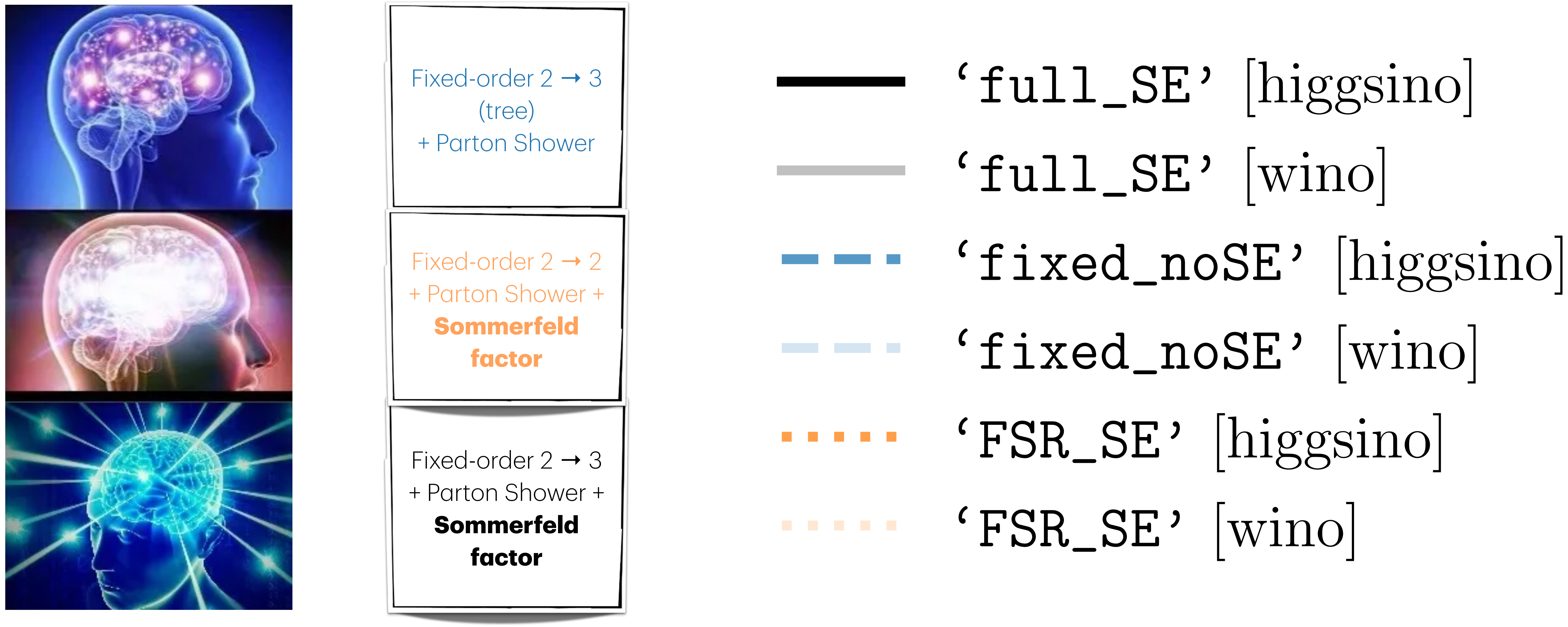
Without further due...



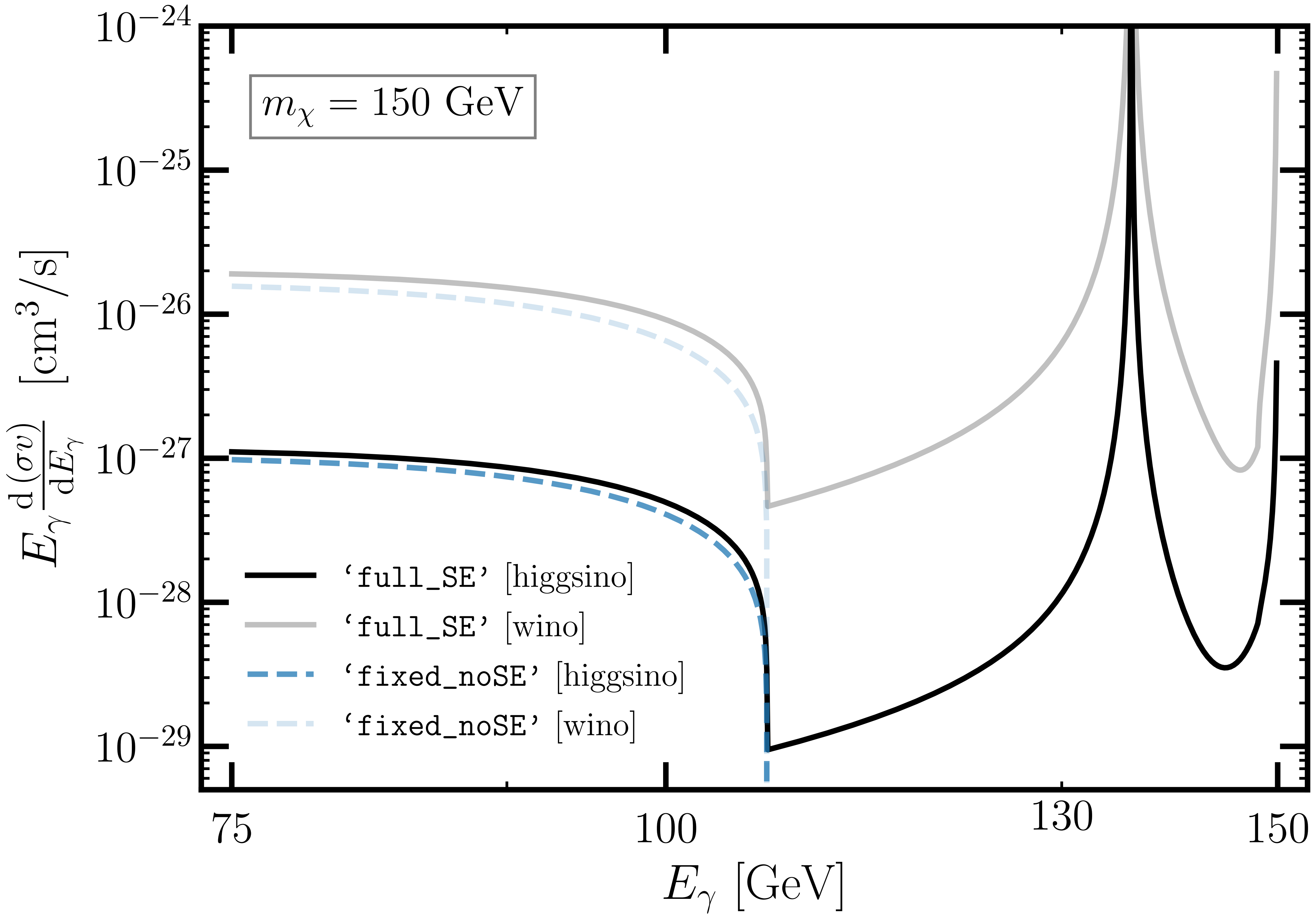
Meme legend



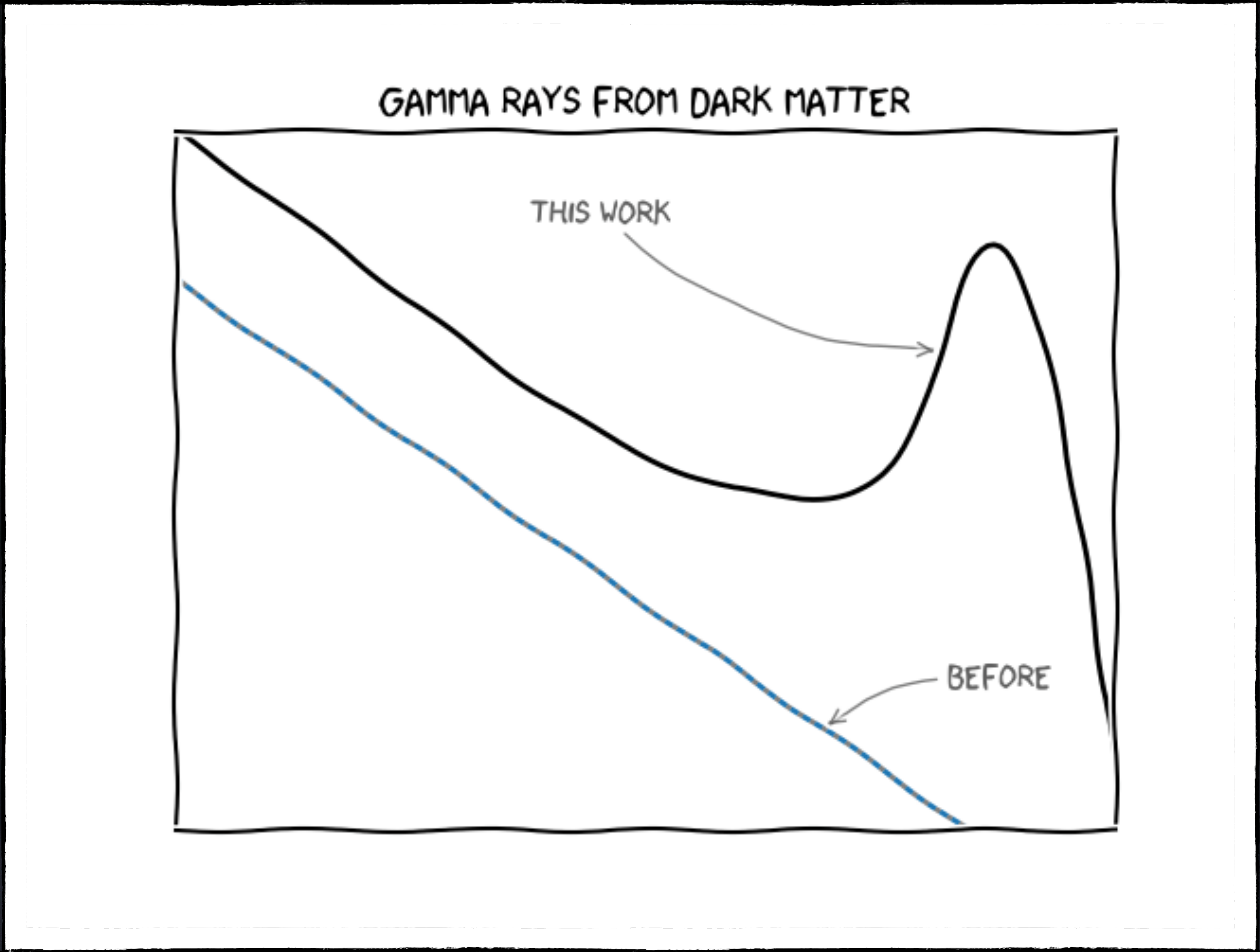
Fixed-order 2 → 3 (tree) + Parton Shower
Fixed-order 2 → 2 + Parton Shower + **Sommerfeld factor**
Fixed-order 2 → 3 + Parton Shower + **Sommerfeld factor**
'full_SE' [higgsino]
'full_SE' [wino]
'fixed_noSE' [higgsino]
'fixed_noSE' [wino]
'FSR_SE' [higgsino]
'FSR_SE' [wino]

Lighter winos/higgsinos

Kinematic $W^+W^-\gamma$ threshold "lifted" by the Sommerfeld effect

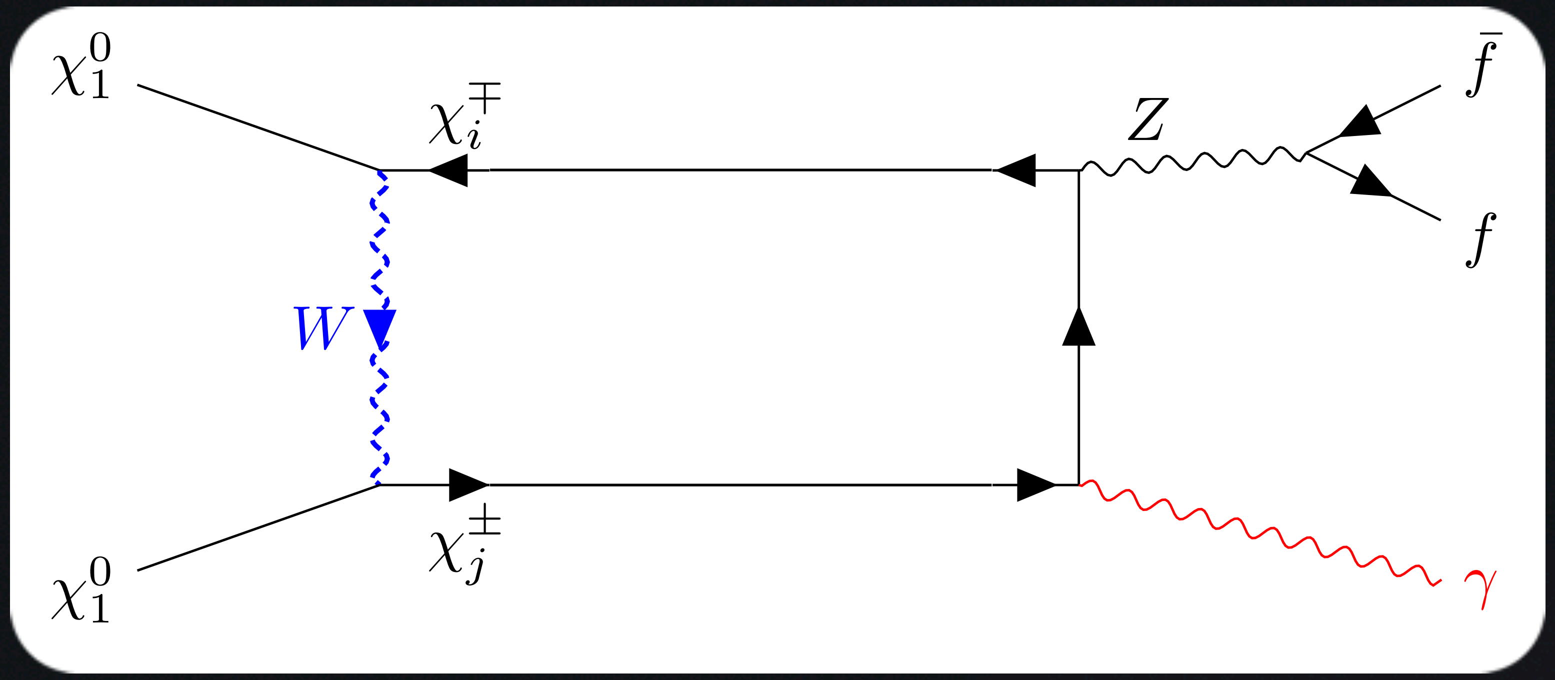


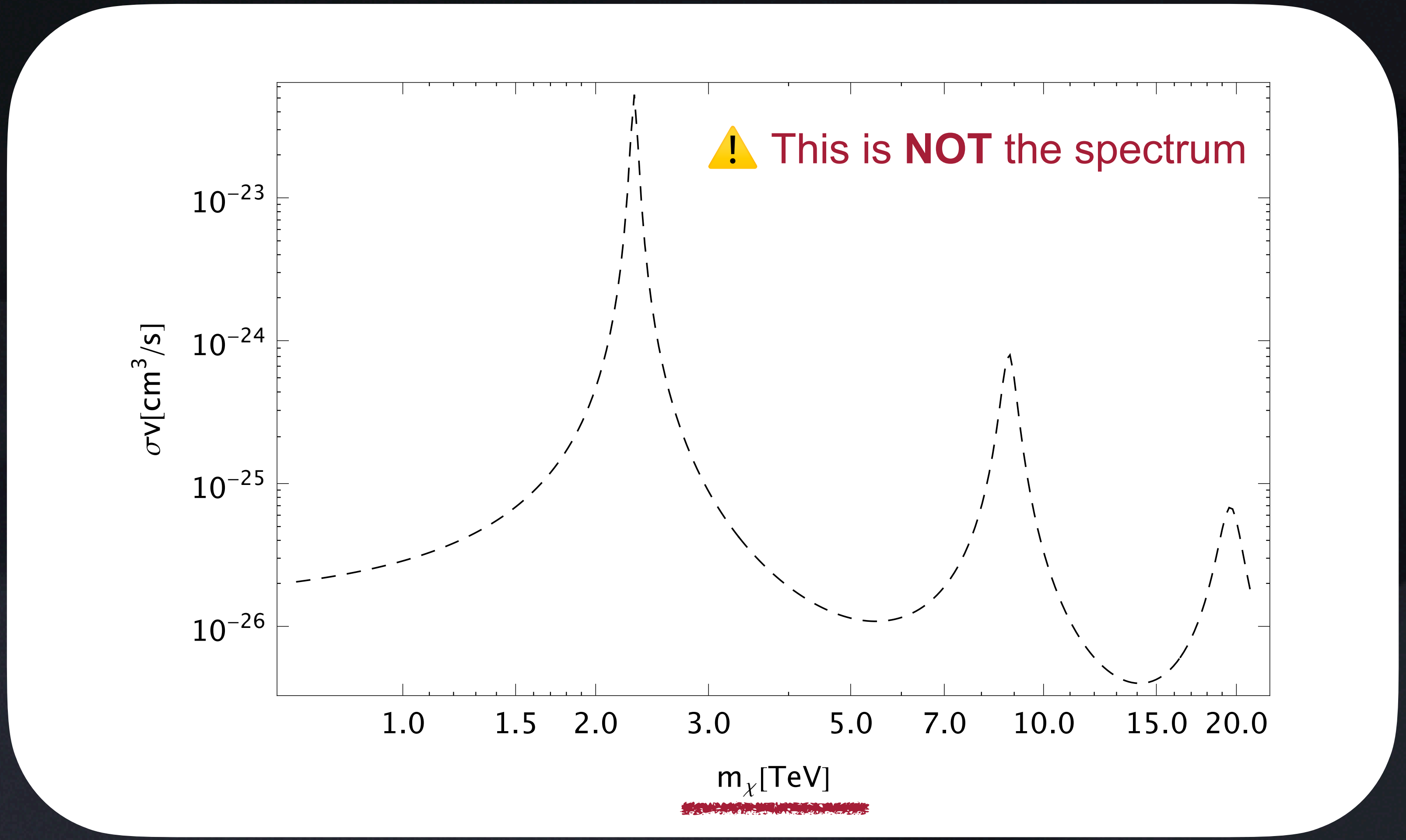
What's going on ?

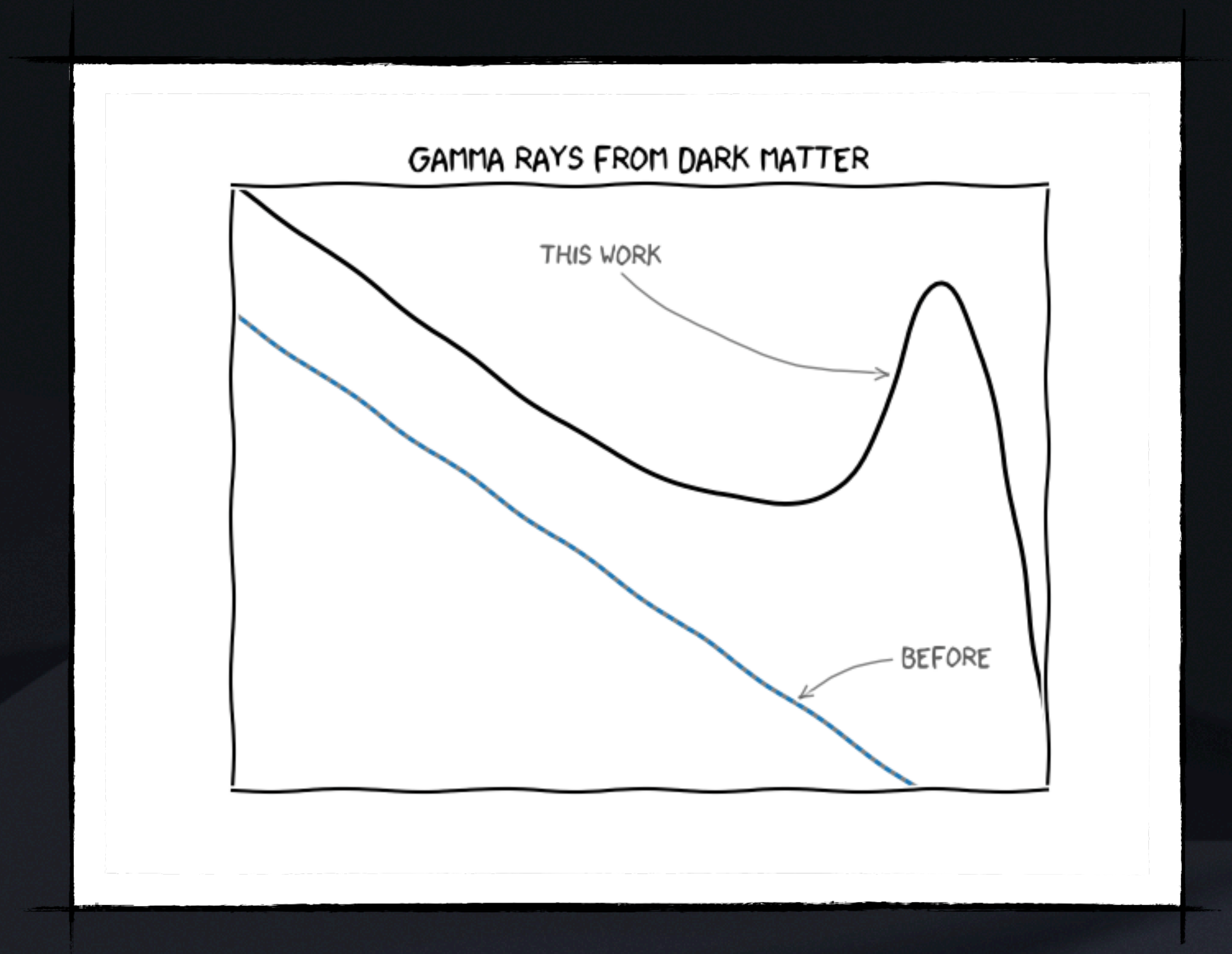


What's going on ?

Charginos are electrically charged / Sommerfeld resonances

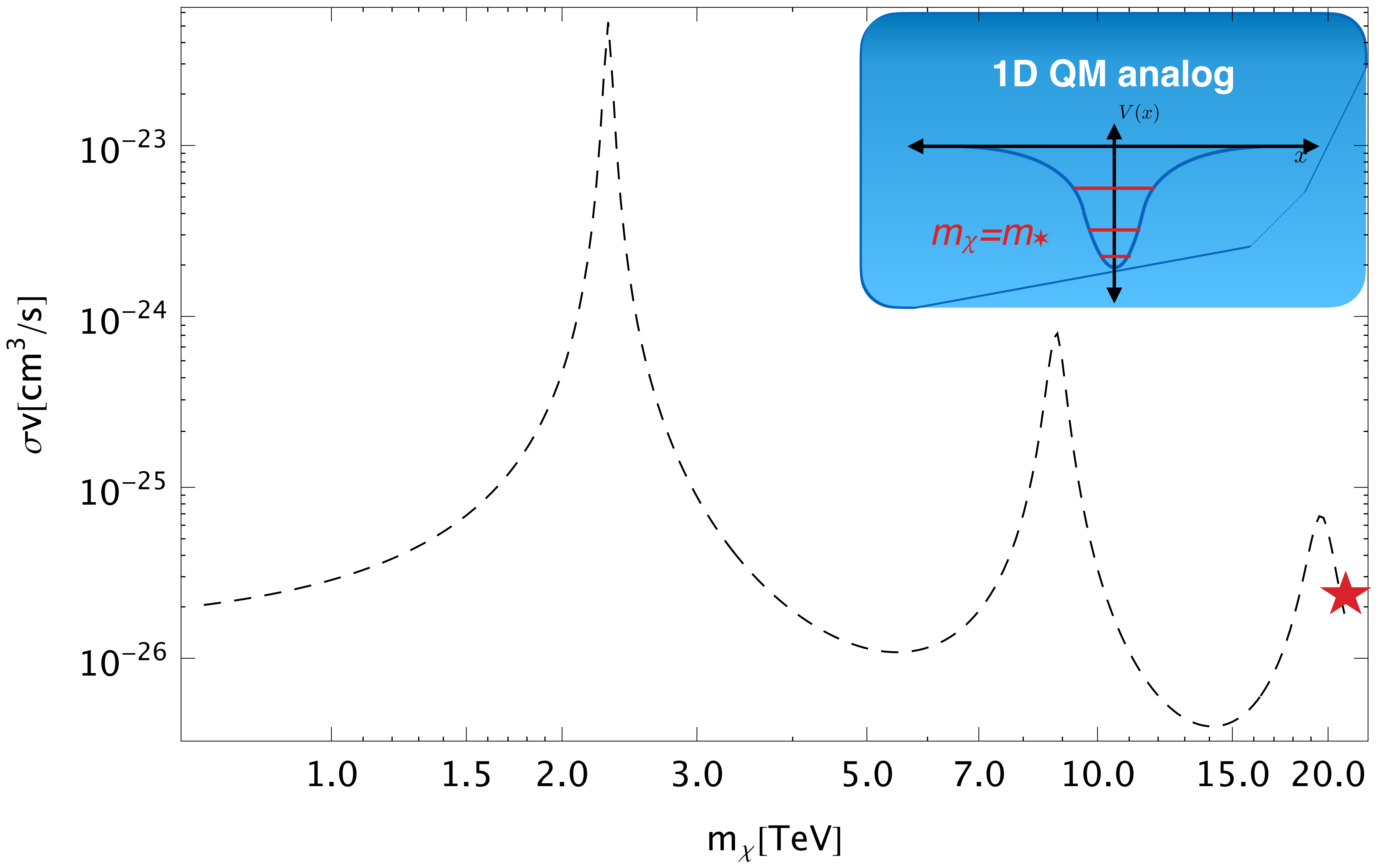






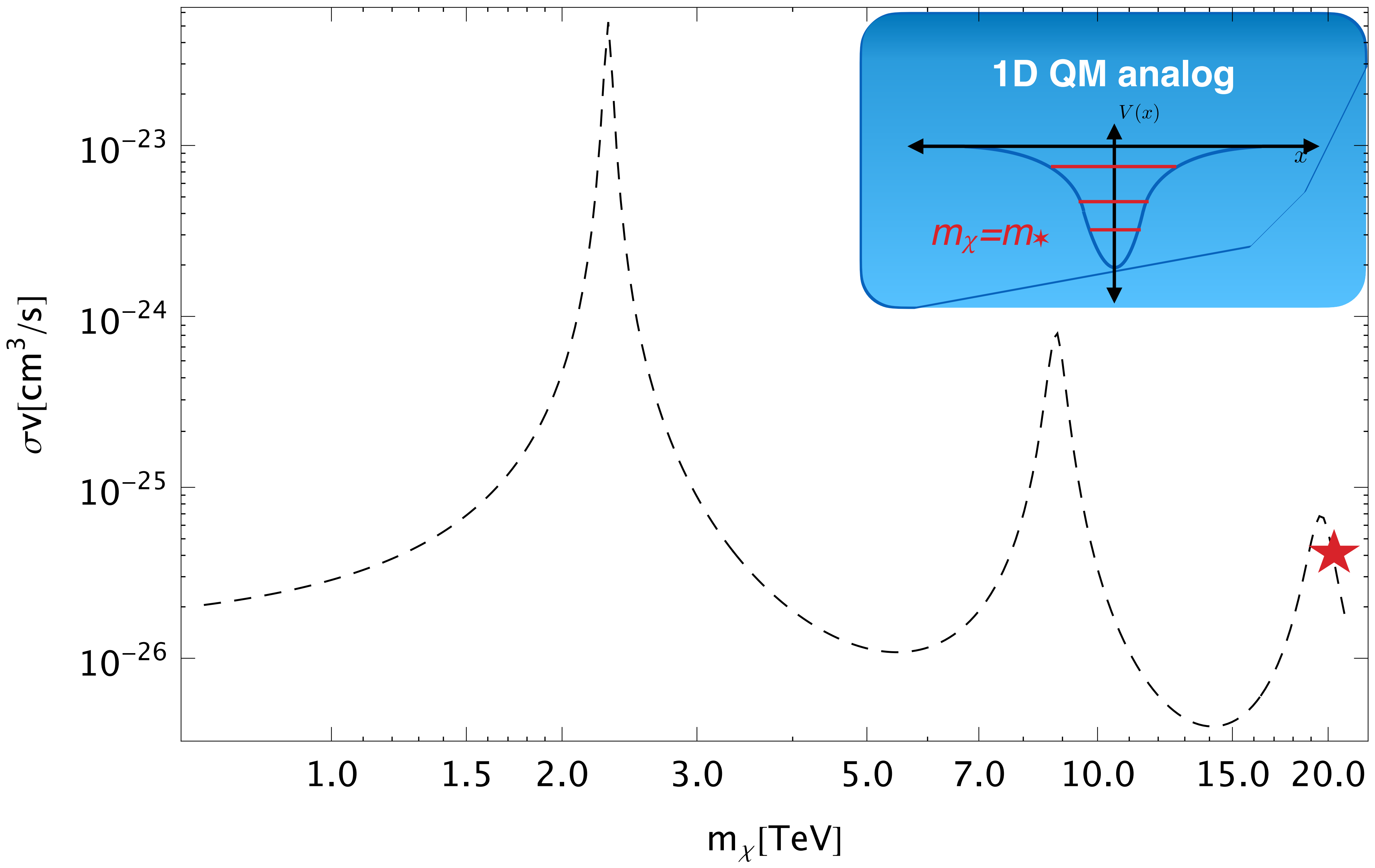
What's going on ?

Sommerfeld resonances



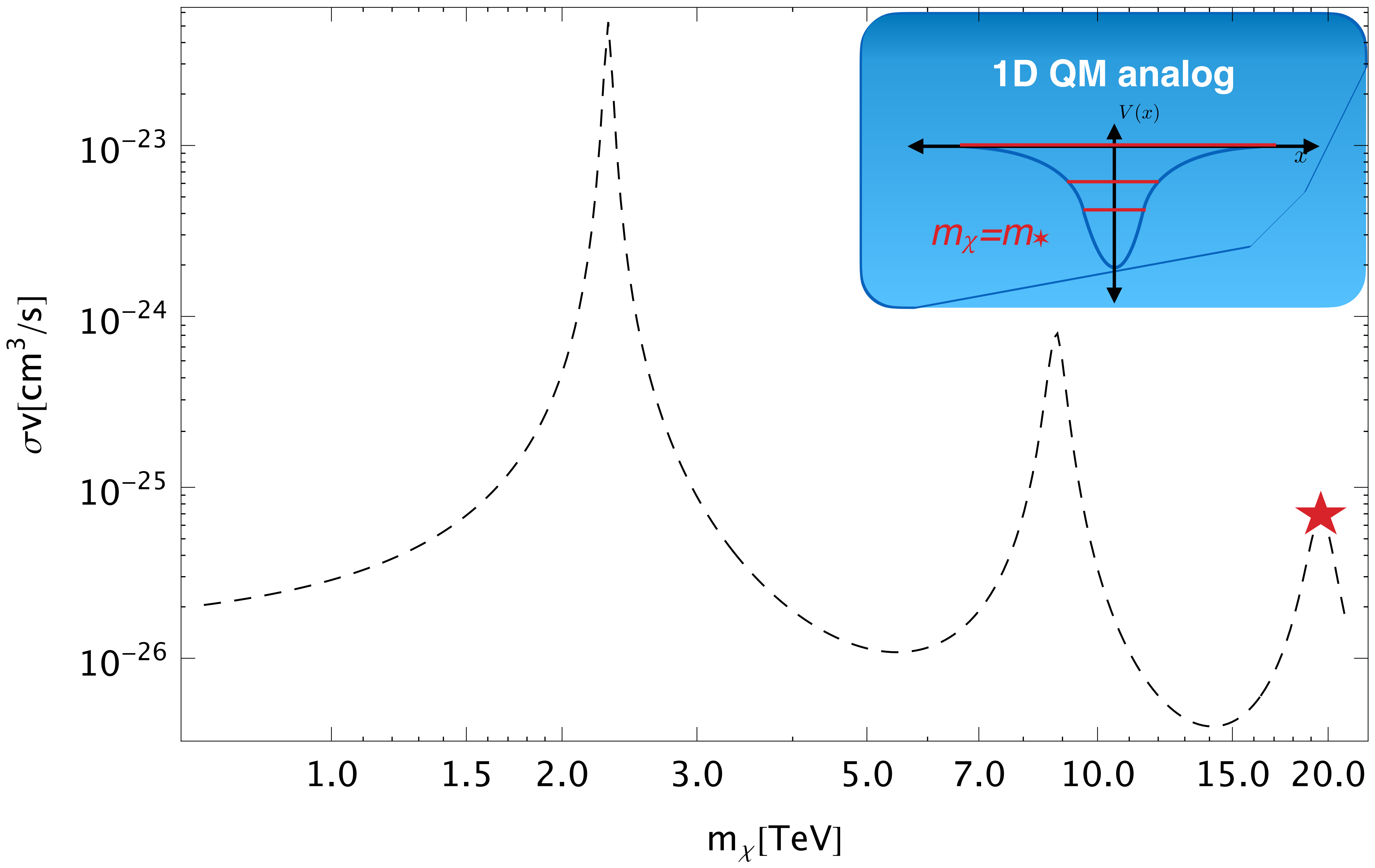
What's going on ?

Sommerfeld resonances



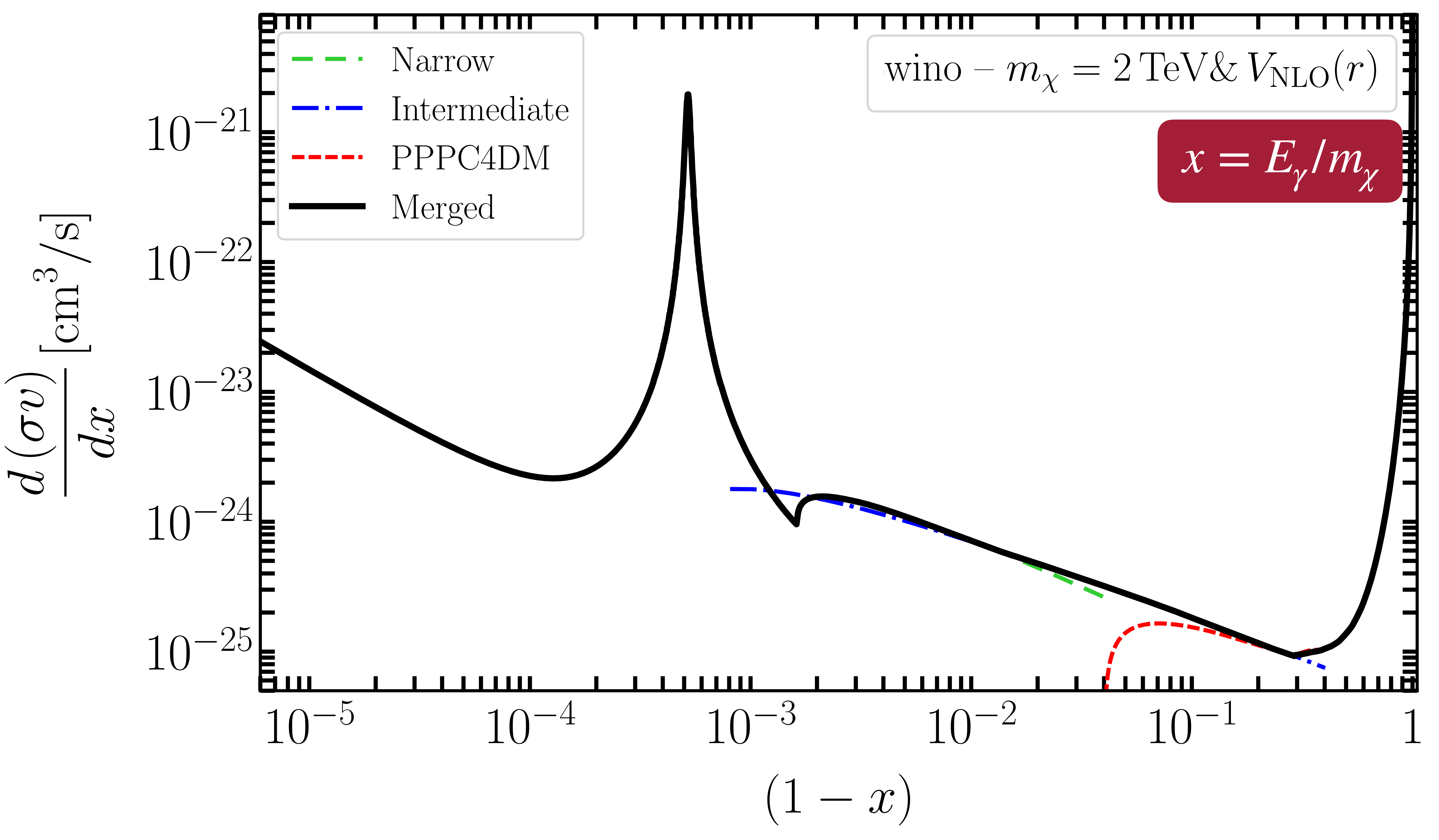
What's going on ?

Sommerfeld resonances

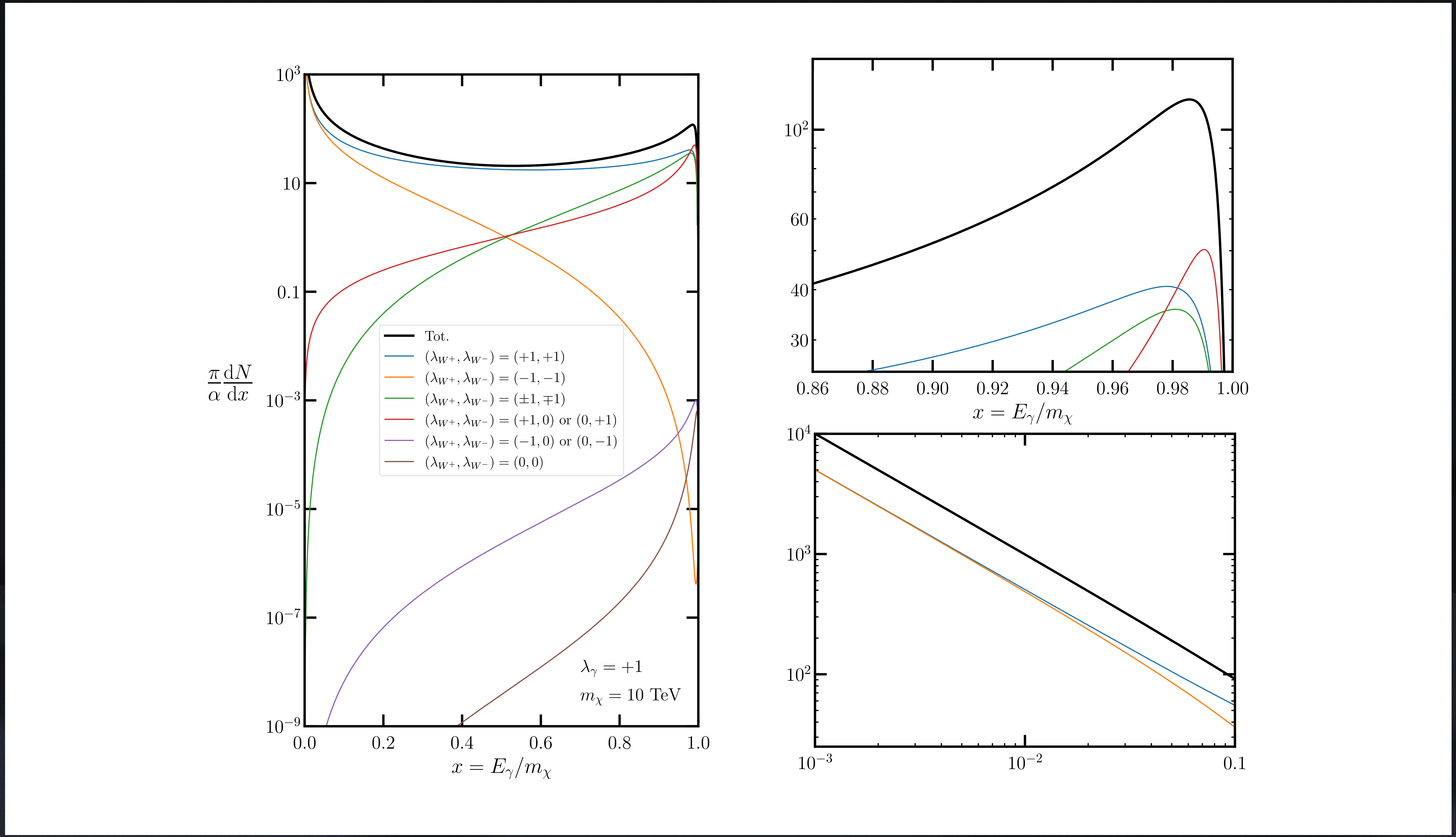


DMγSpec

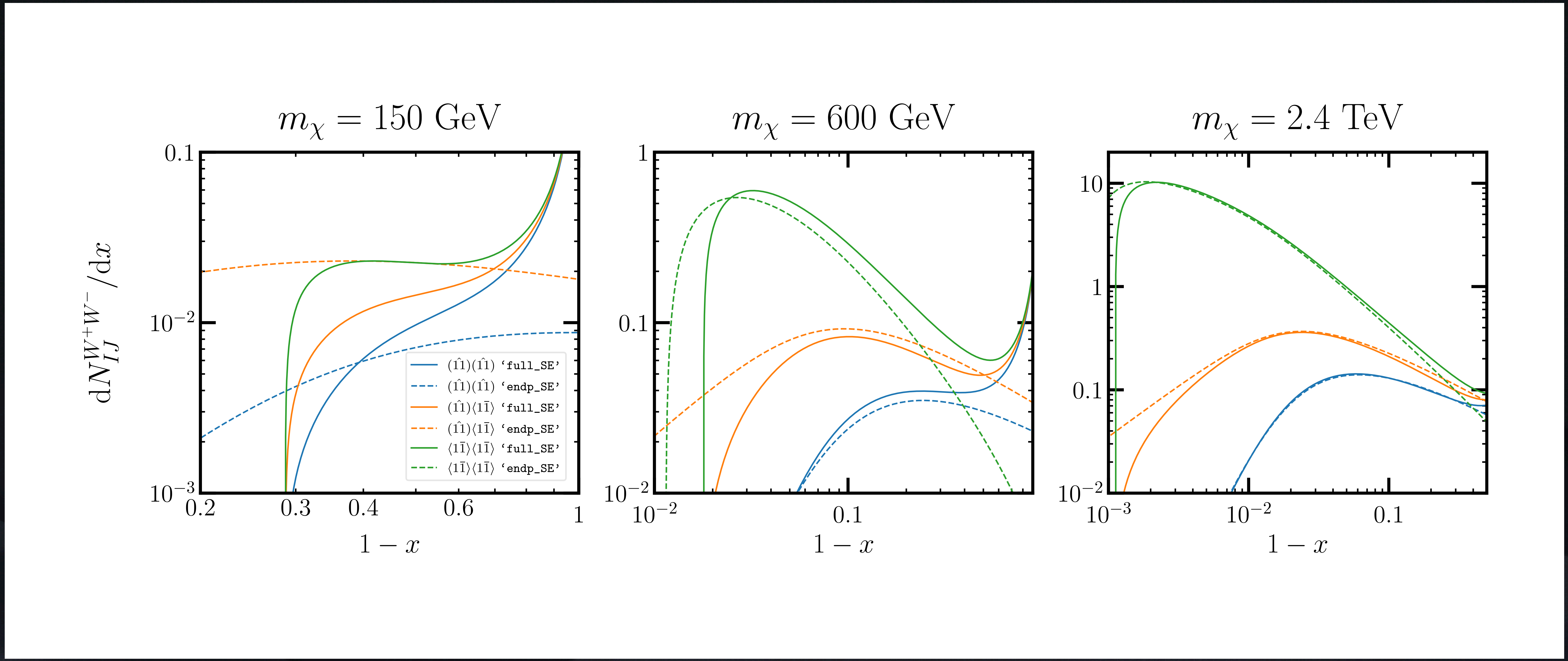
https://dmyspec.hepforge.org/



More results to brag about



More results to brag about



Outline

- Motivation
- Indirect detection
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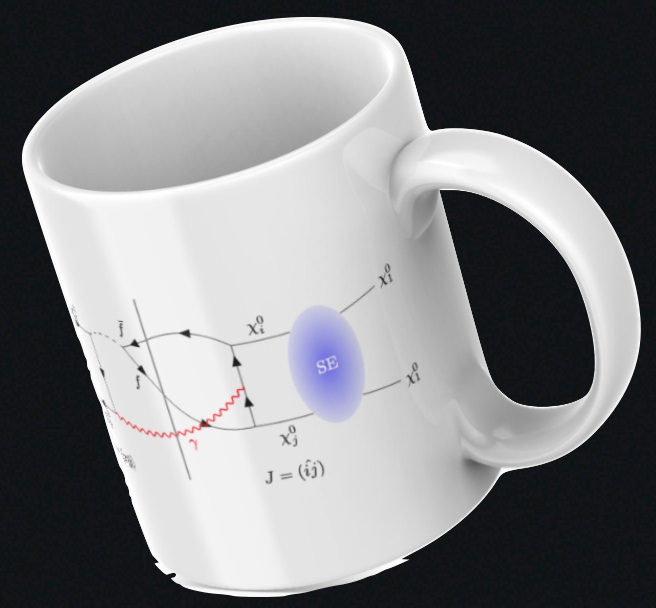
Conclusions



- TeV-scale WIMP Dark Matter is still “a thing” in 2024
- Cherenkov telescopes are excelent instruments to search for DM
- Beautiful and complex phenomenology for indirect detection
  - Sommerfeld effect, internal bremsstrahlung, resonances, spectral lines, radiative electroweak effects, ...
- Armed with sophisticated EFT tools tackled these obstacles
  - ready for implementation in future observations
- Further explorations in the remaining 2020s **crucial**


MITP 2024
THE DM LANDSCAPE