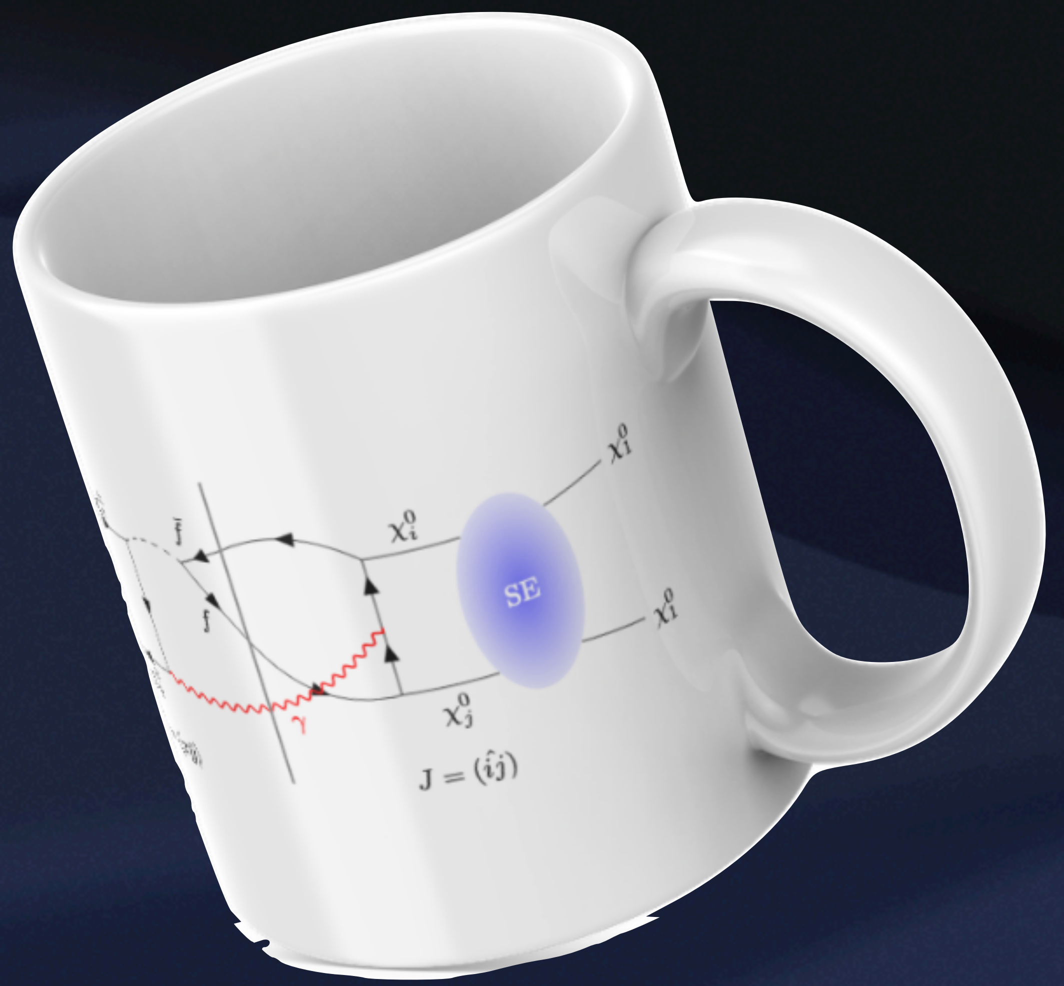
Gamma rays from Neutralino annihilation in the 2020s

SUSY 2024



Martin Vollmann — Uni Tuebingen — 14.6.2024

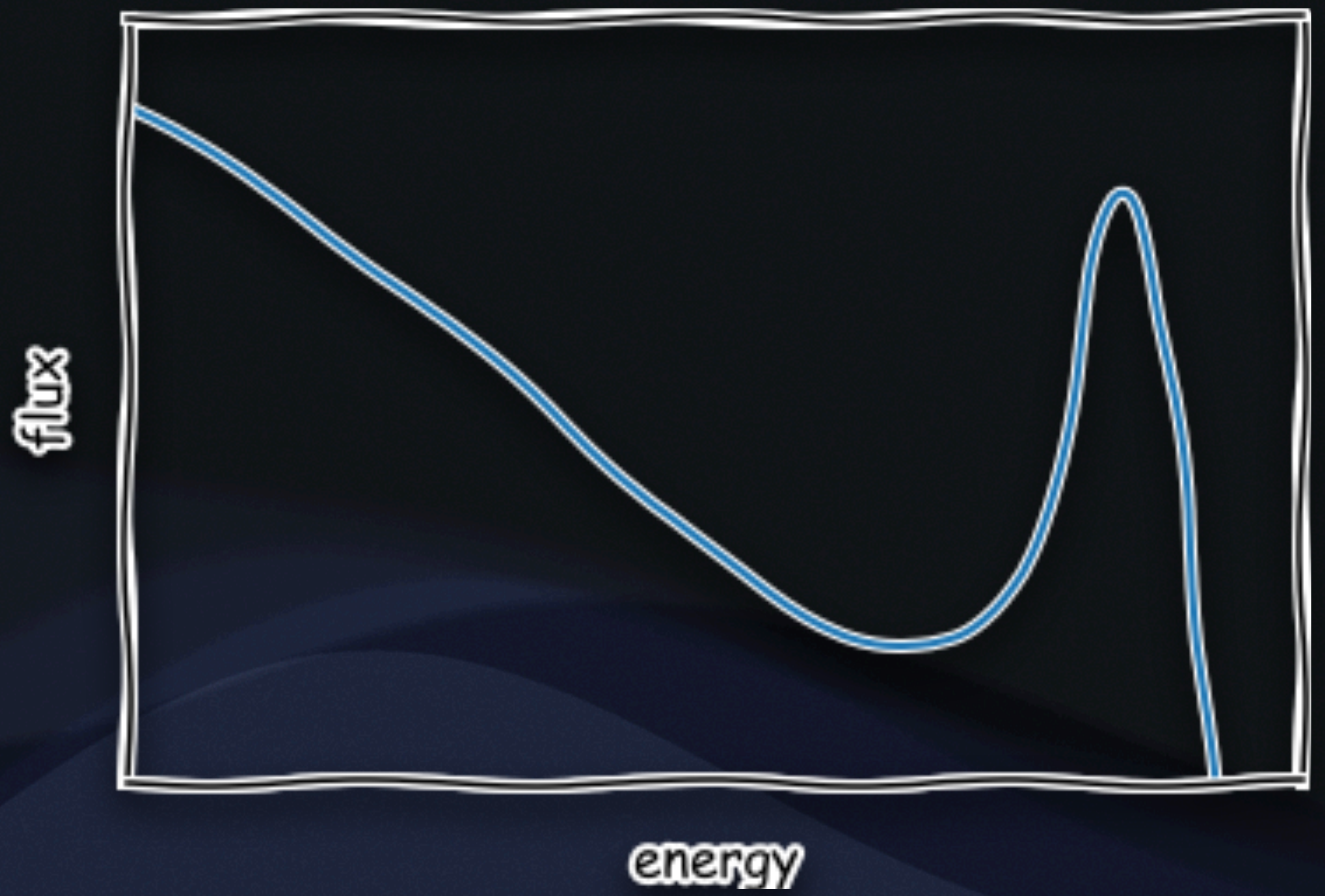
If Dark Matter is WIMPs (e.g. MSSM neutralinos)

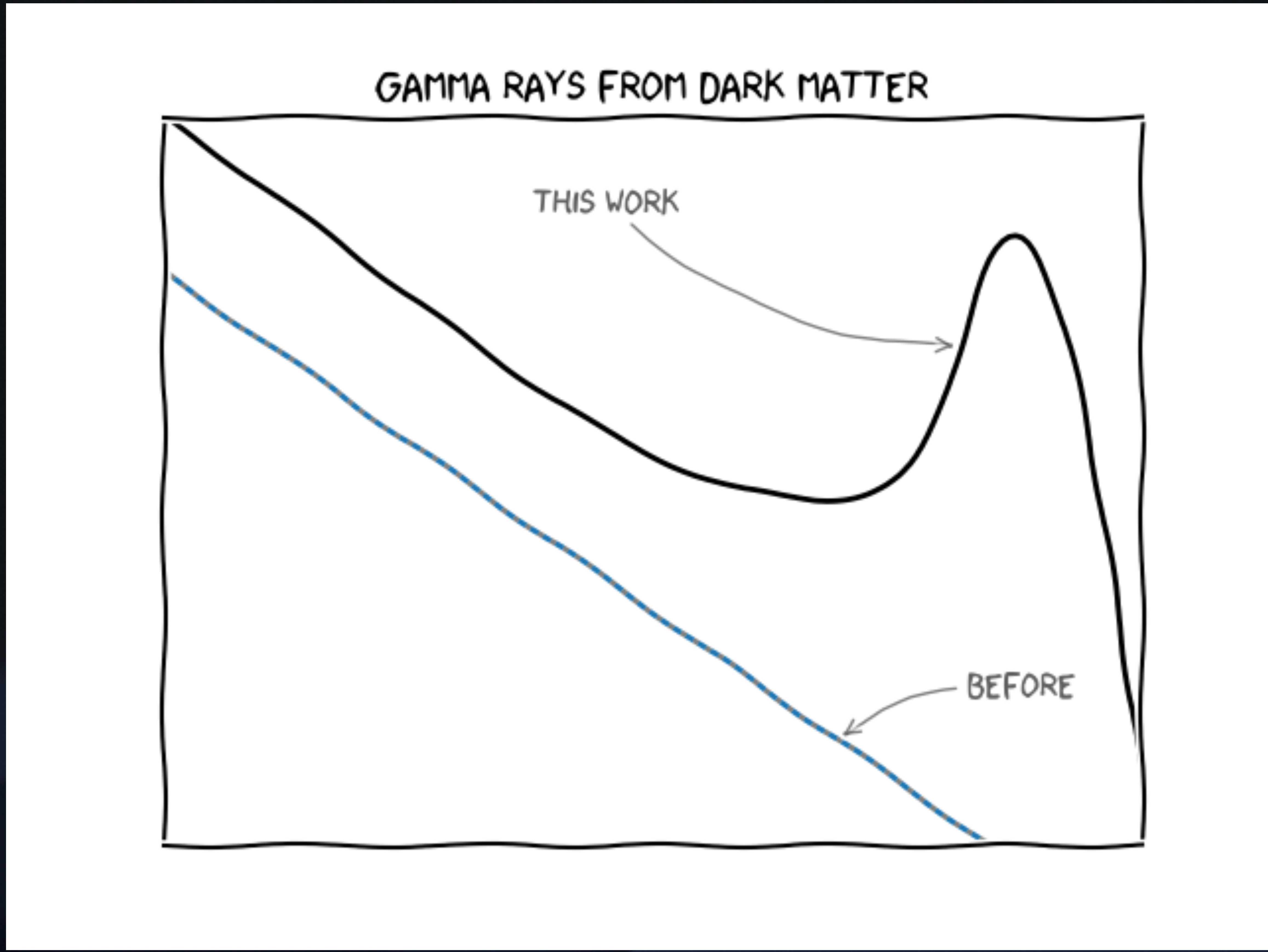
➡ Signal in the gamma-ray sky (from Dark Matter Annihilation)

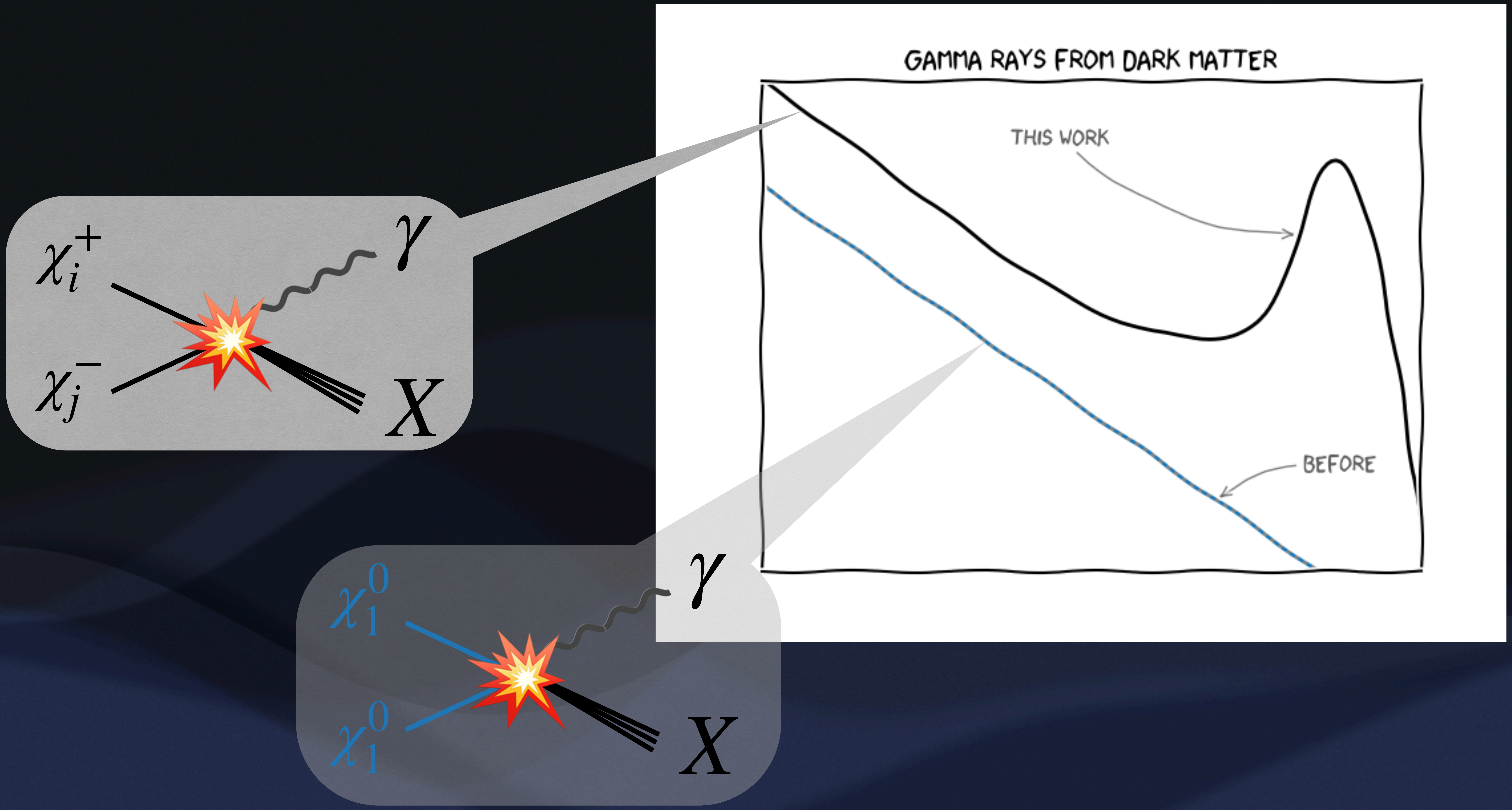
Theoretical prediction is complicated (Sommerfeld effect, radiative effects, ...)

This talk:

Most accurate calculation to date




GAMMA RAYS FROM DARK MATTER
THIS WORK
BEFORE


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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Outline

Motivation

Indirect detection

Sommerfeld effect

Continuum gamma rays for MSSM neutralinos

Numerics

Conclusions

Motivation

Why SUSY Dark Matter?

DARK MATTER

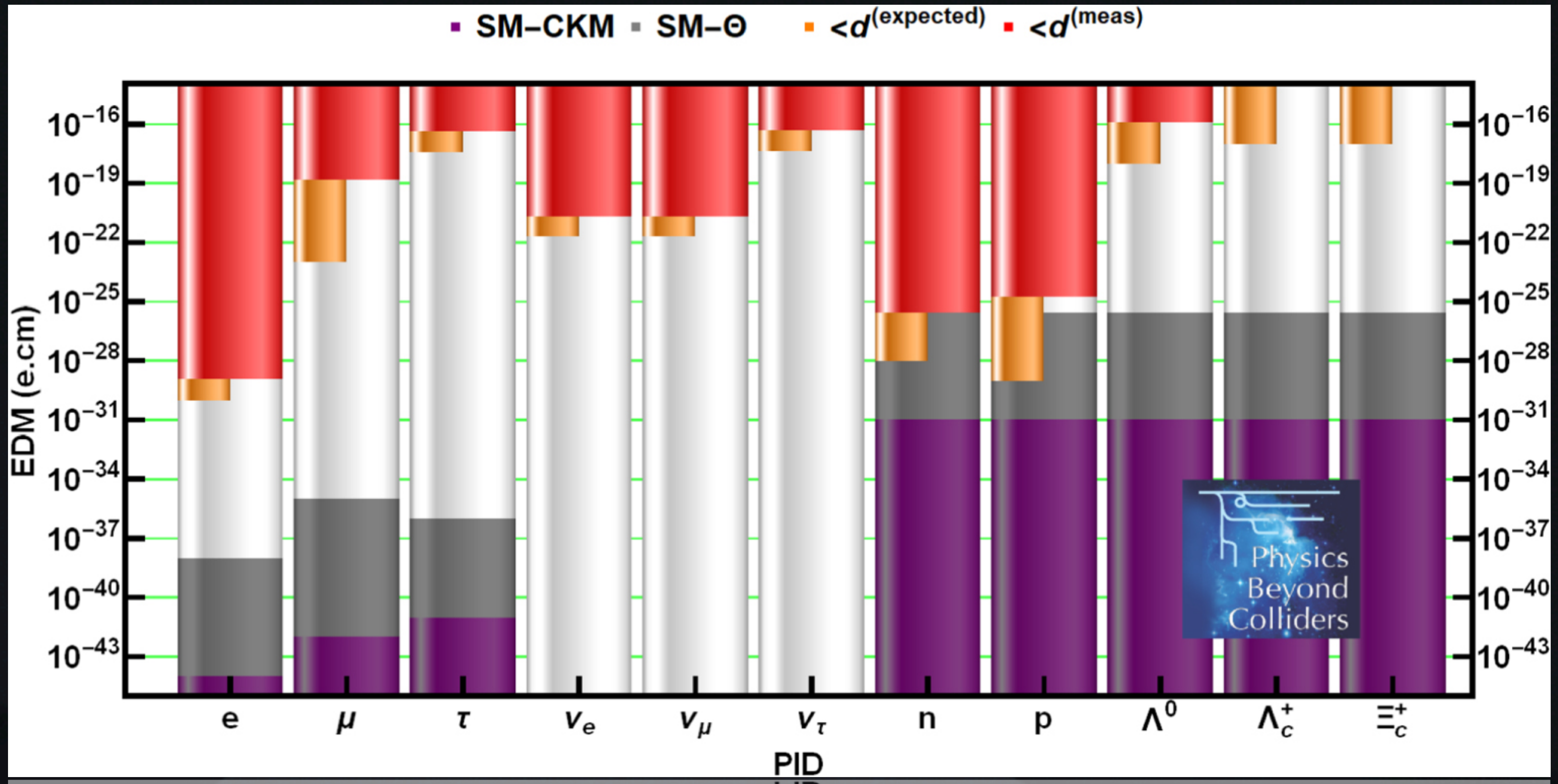
ELECTROWEAK interactions

SUPERSYMMETRY

Split (high-scale) SUSY

- 125GeV Higgs favoured
- Unification of gauge couplings
- CP SUSY problems (EDMs)
- TeV-scale WIMP —> Cherenkov telescopes!

- ~~Naturalness~~



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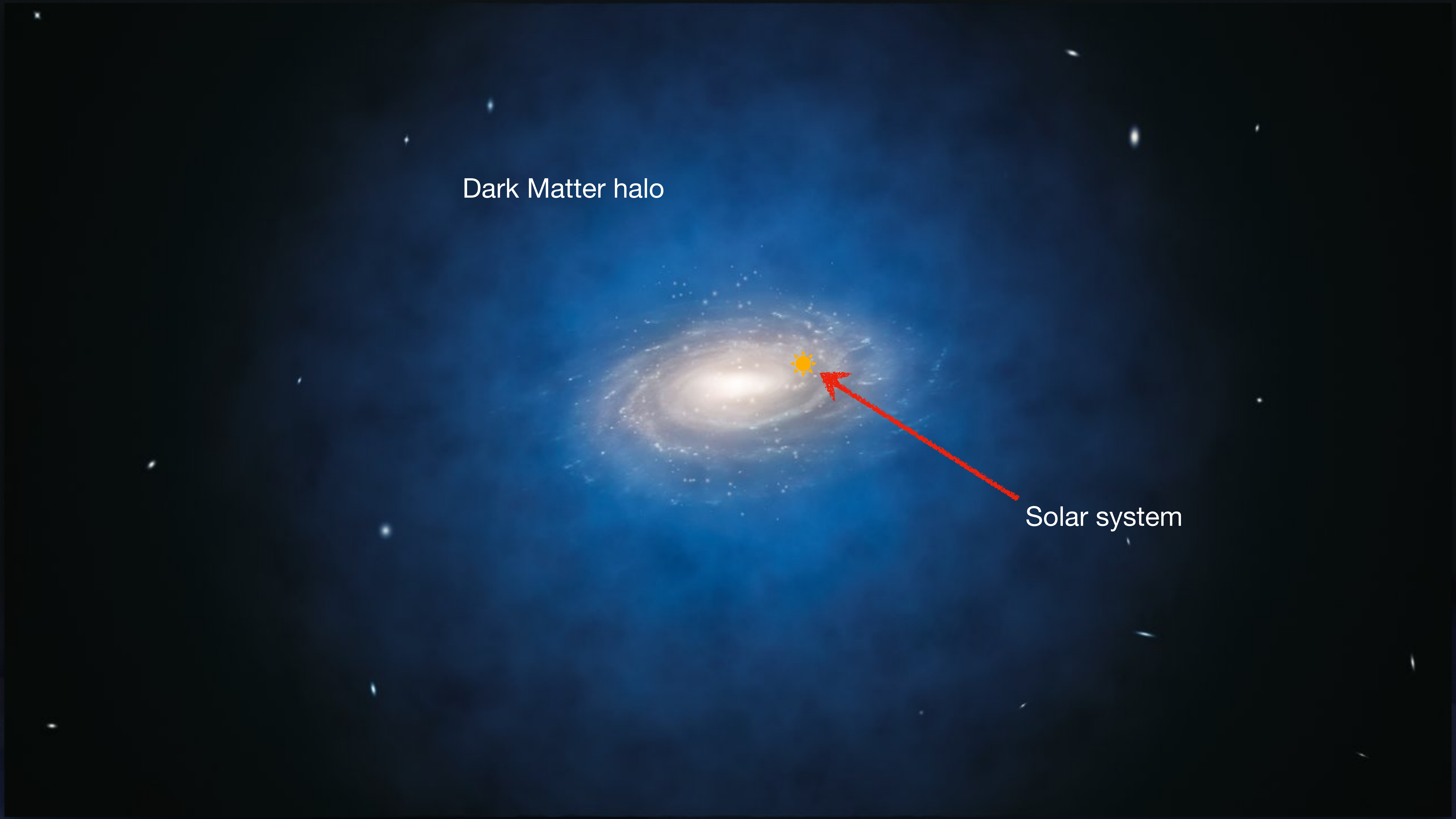
Indirect detection

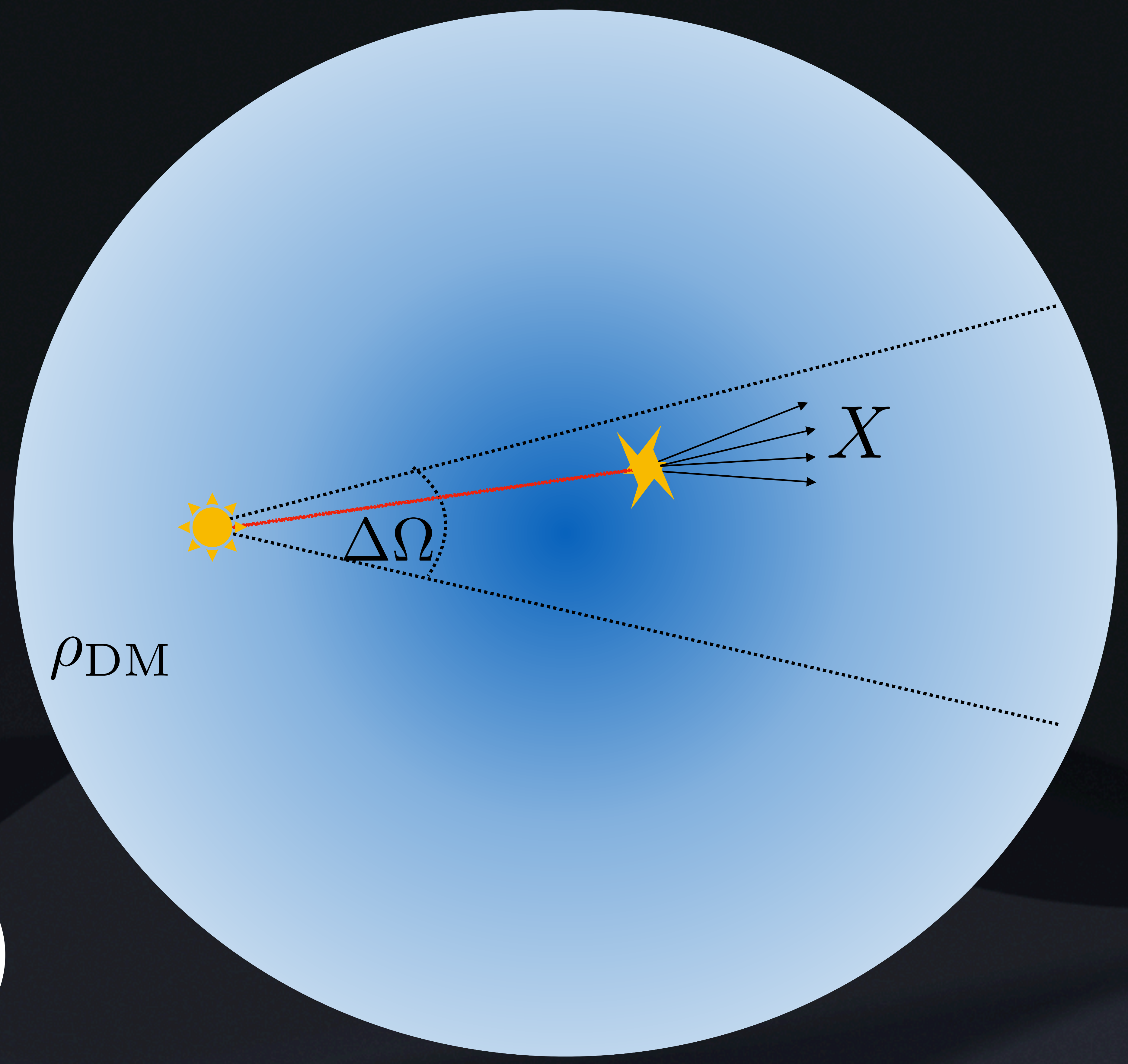


Credit: ESO/L. Calçada

Gamma-ray flux formula

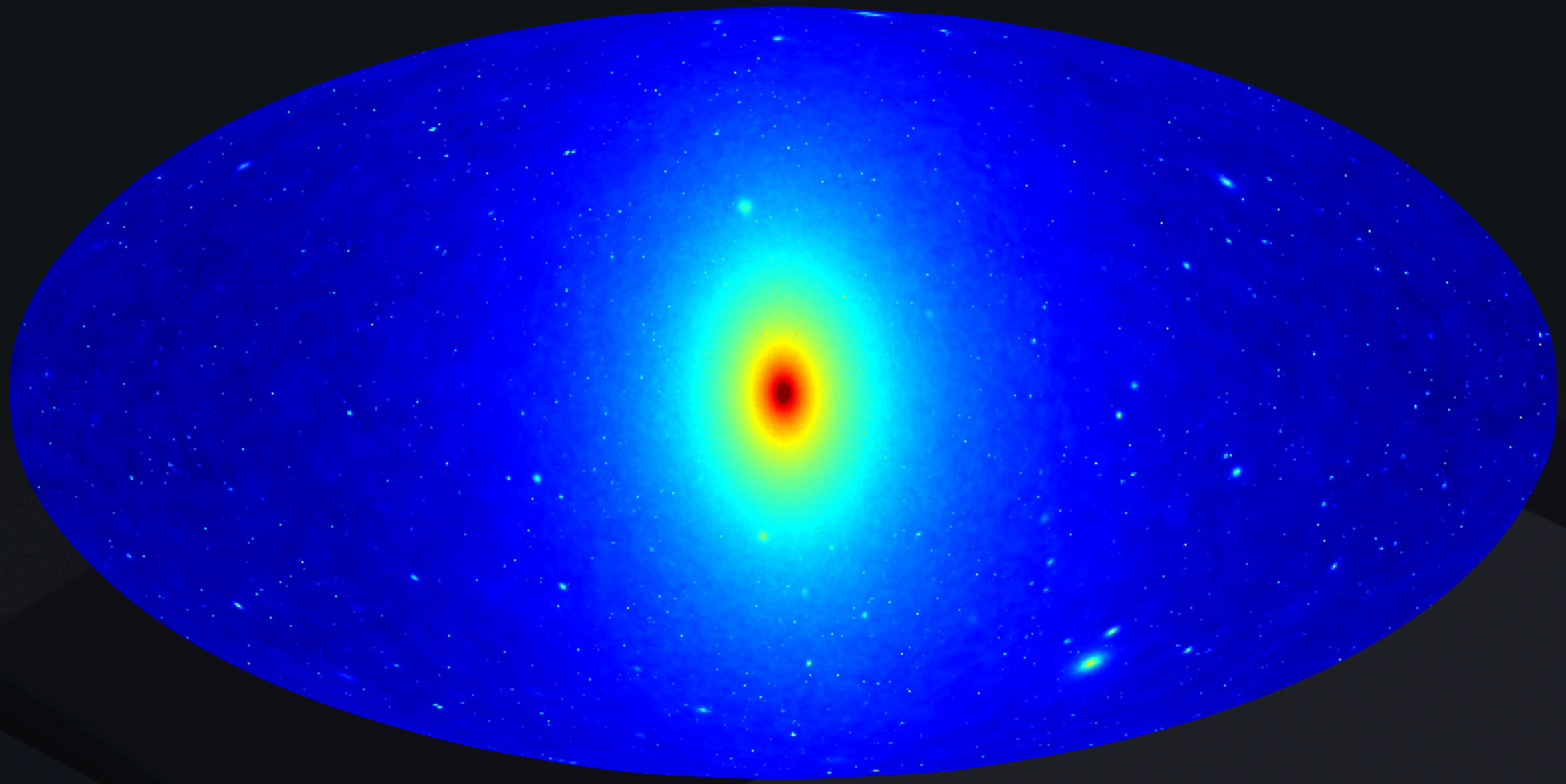
$$\Phi_\gamma = \frac{1}{8\pi m_\chi^2} \times J \times \frac{\mathrm{d}\,\sigma v}{\mathrm{d}E_\gamma}$$

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



Example

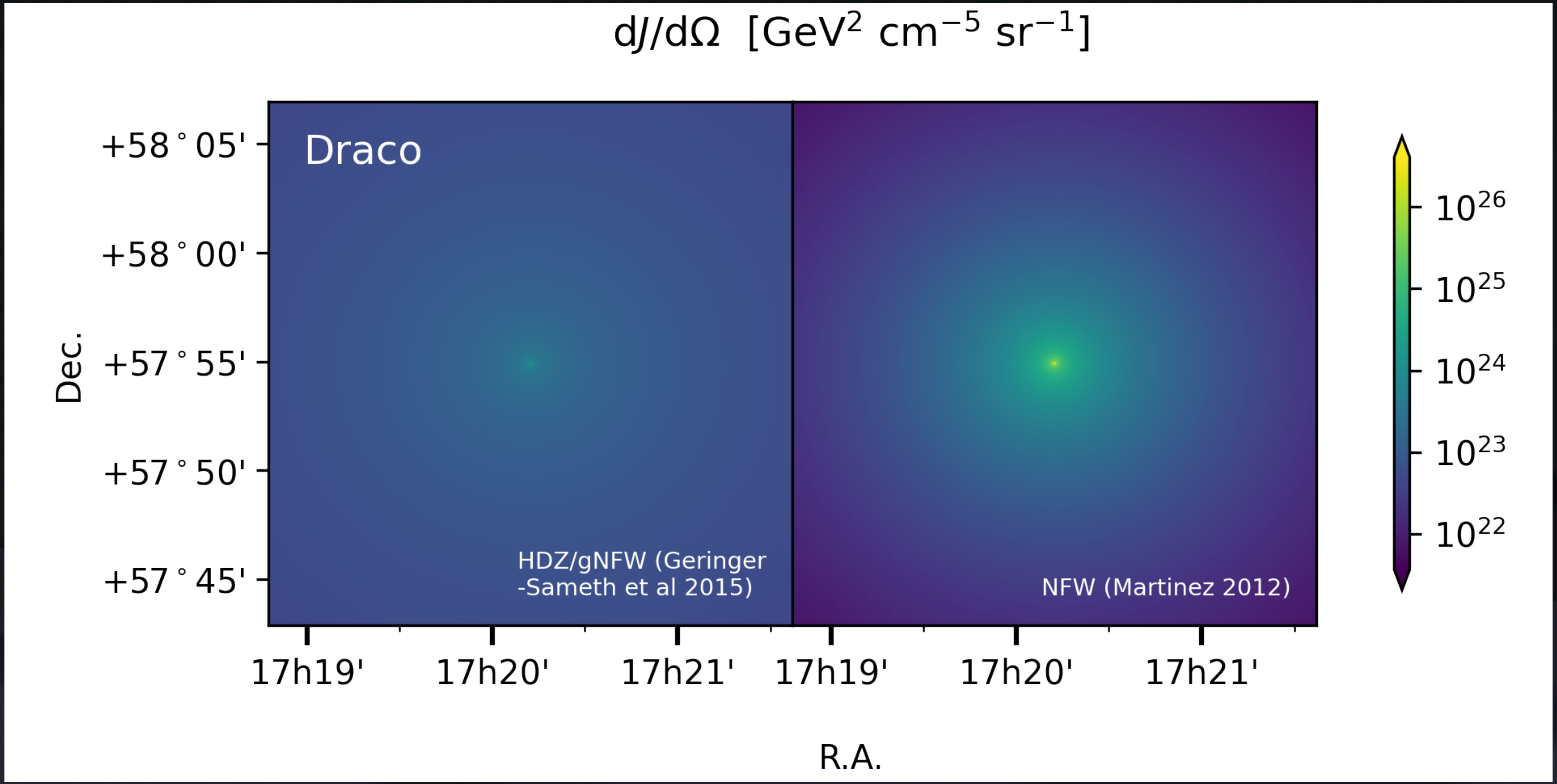
Milky Way-like galaxy from Aquarius (Aq-A-1) N-body simulation



https://wwwmpa.mpa-garching.mpg.de/aquarius/

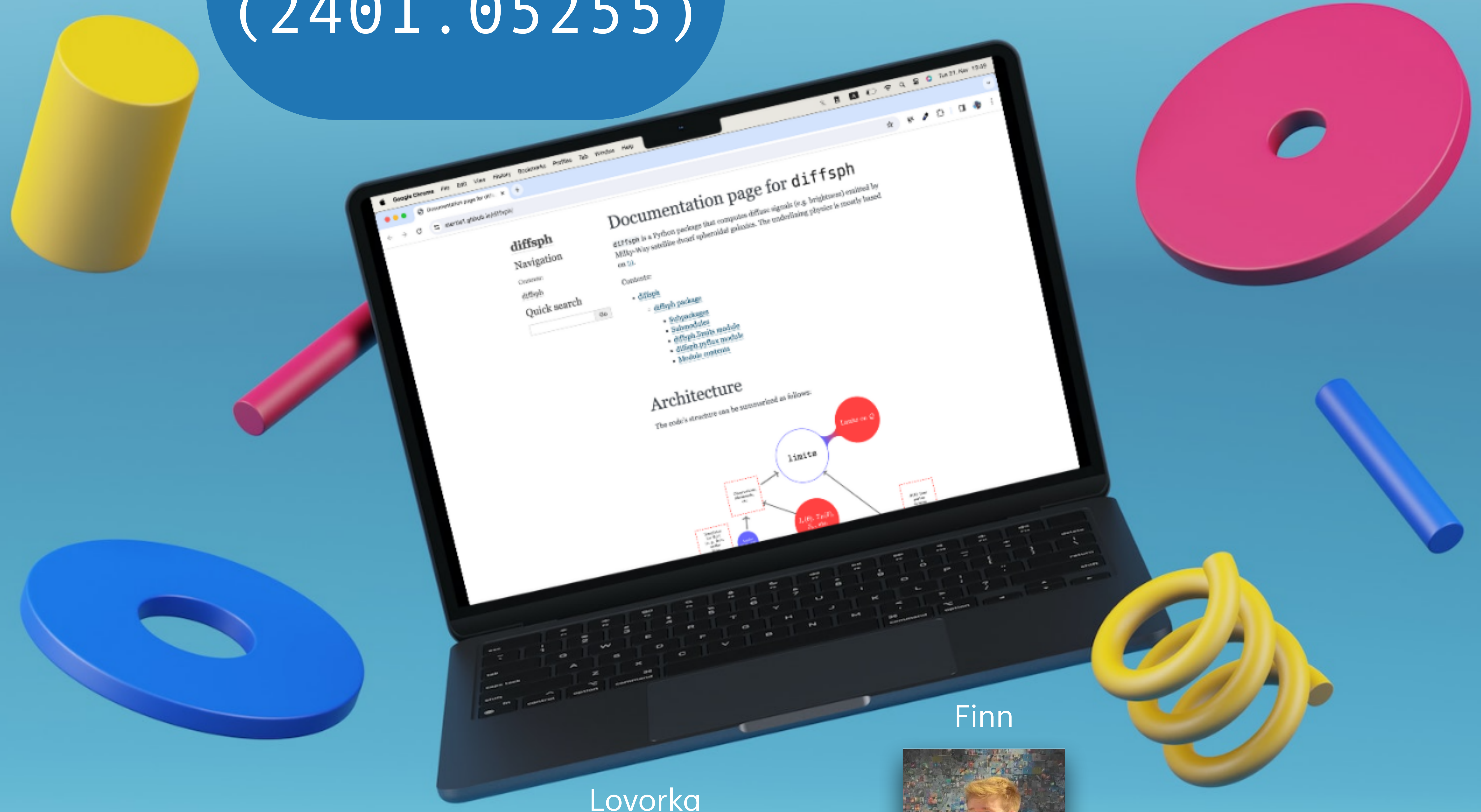
Example (Ad break)

Draco dwarf galaxy with diffSph [2401.05255]



https://github.com/mertio1/diffsph

diffSph
(2401.05255)

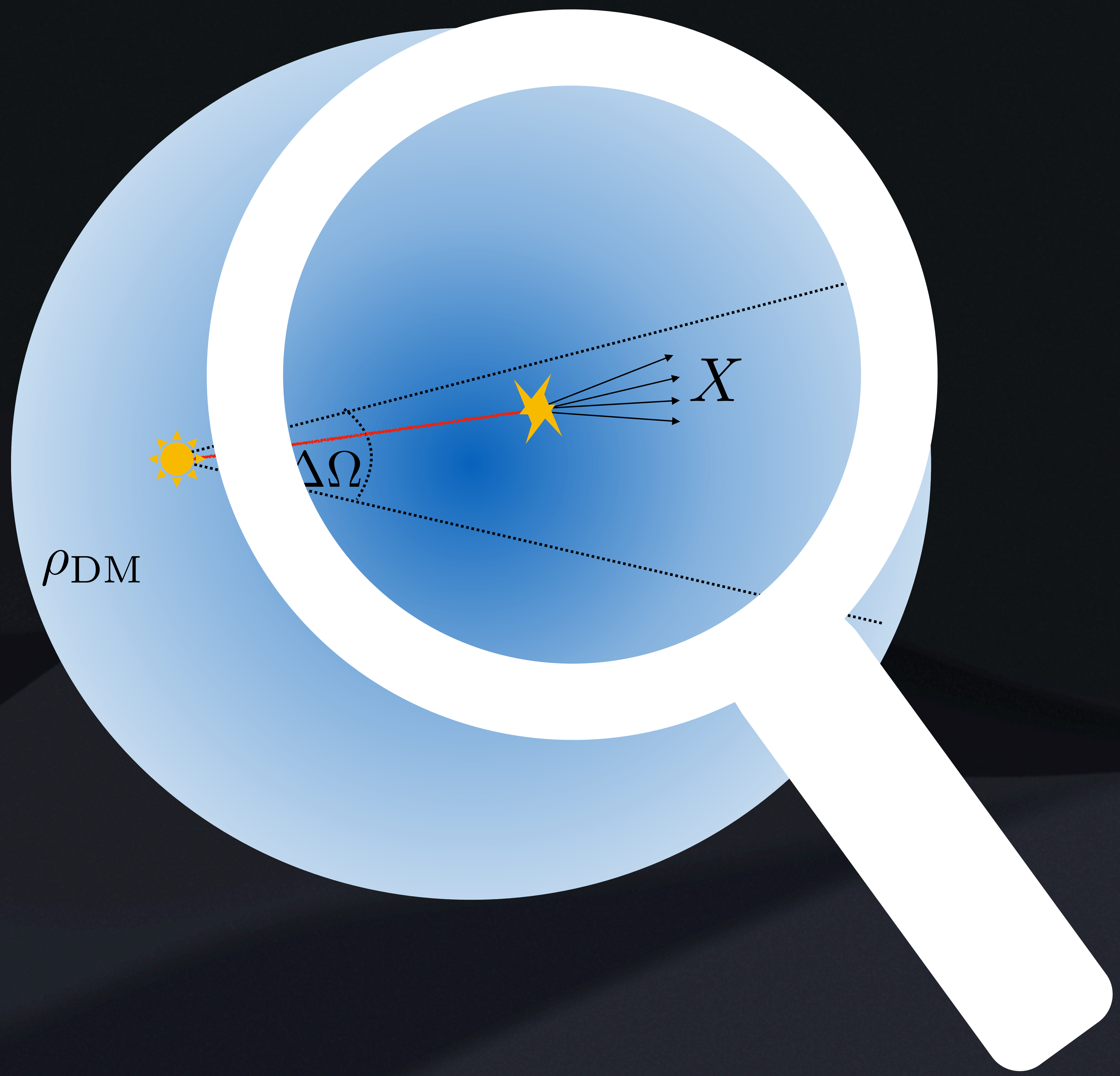


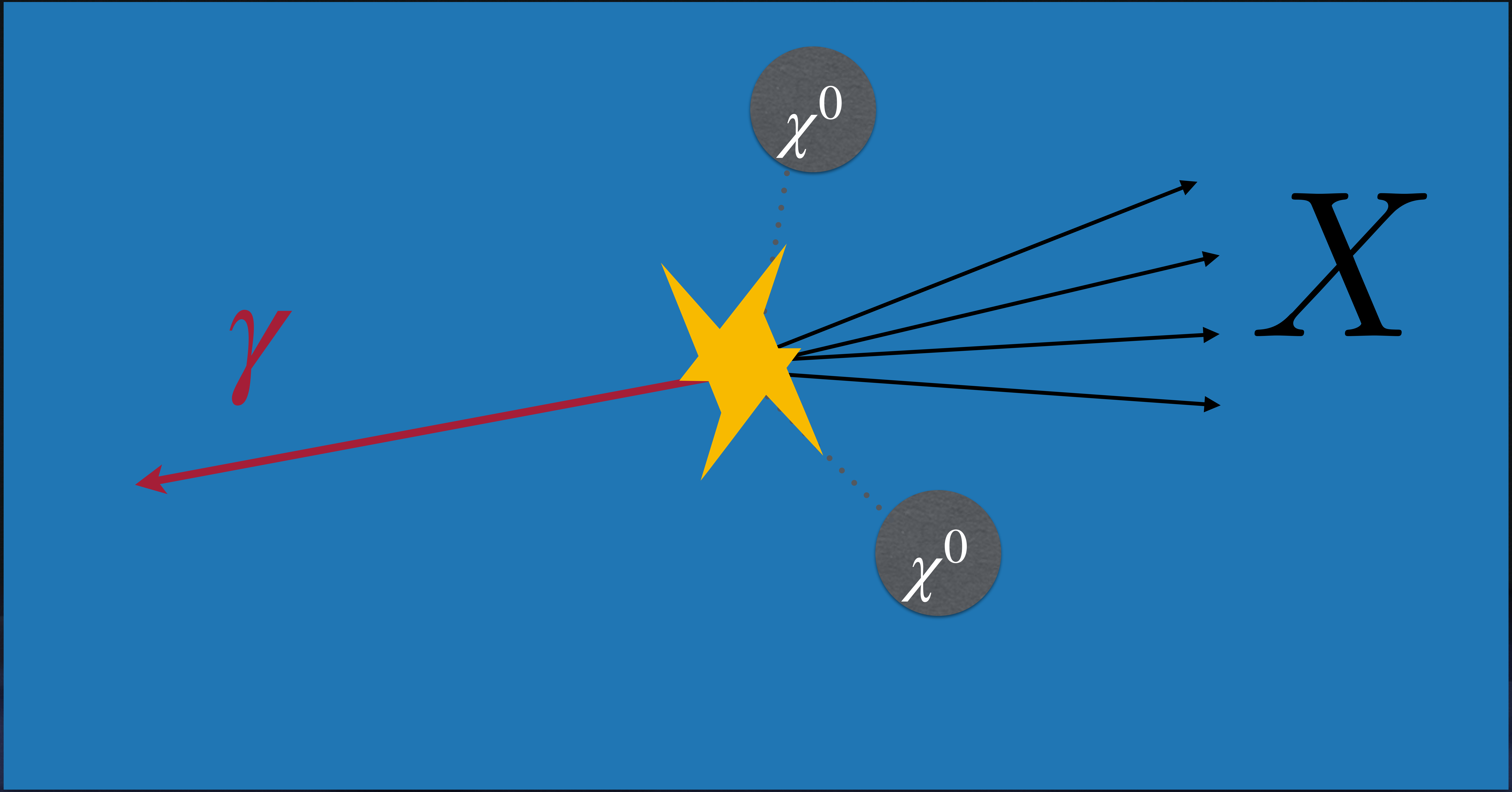
Lovorka

Finn

Gamma-ray flux formula

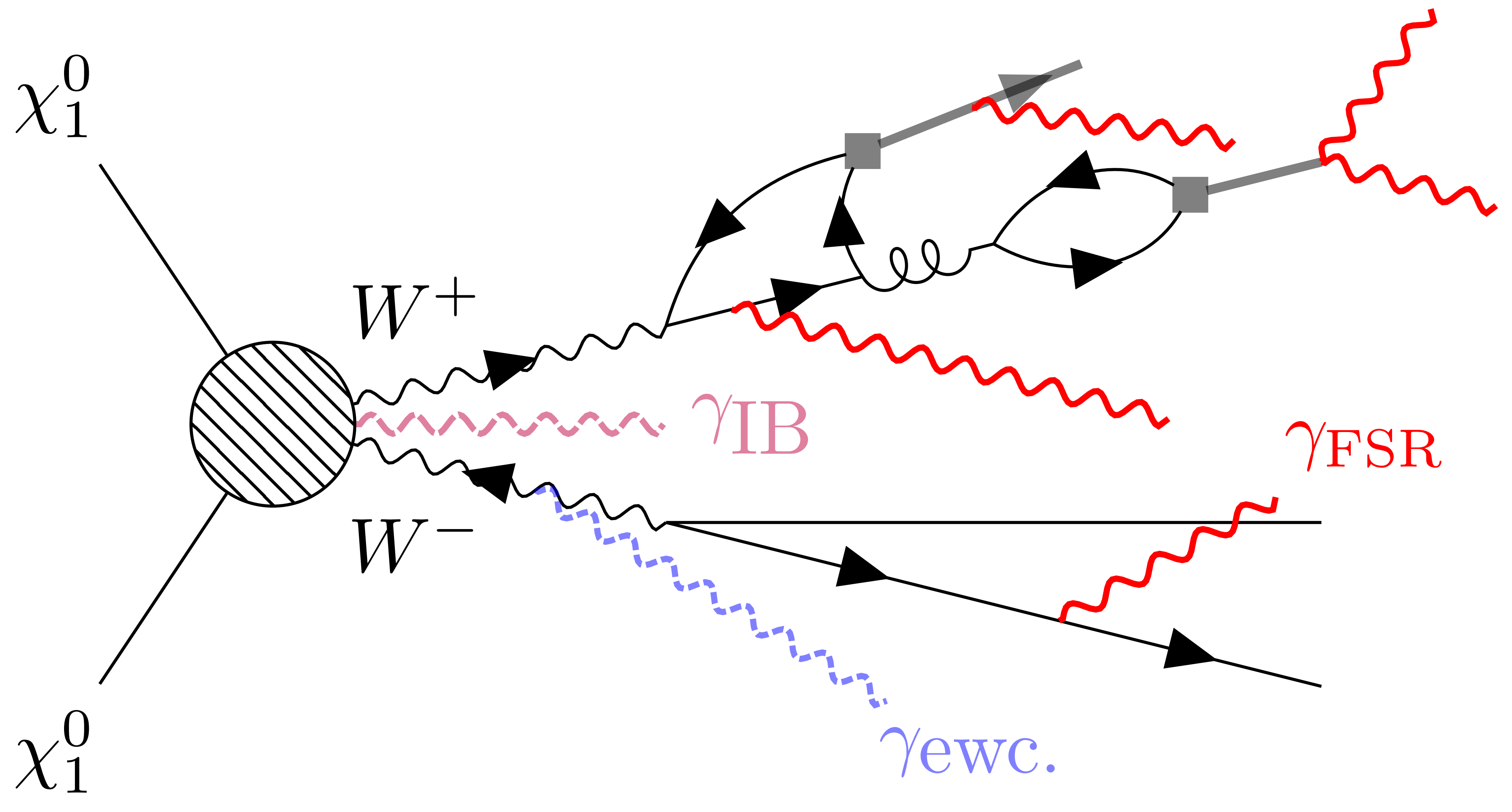
$$\Phi_\gamma = \frac{1}{8\pi m_\chi^2} \times J \times \frac{\mathrm{d}\,\sigma v}{\mathrm{d}E_\gamma}$$




χ^0
X
γ
χ^0

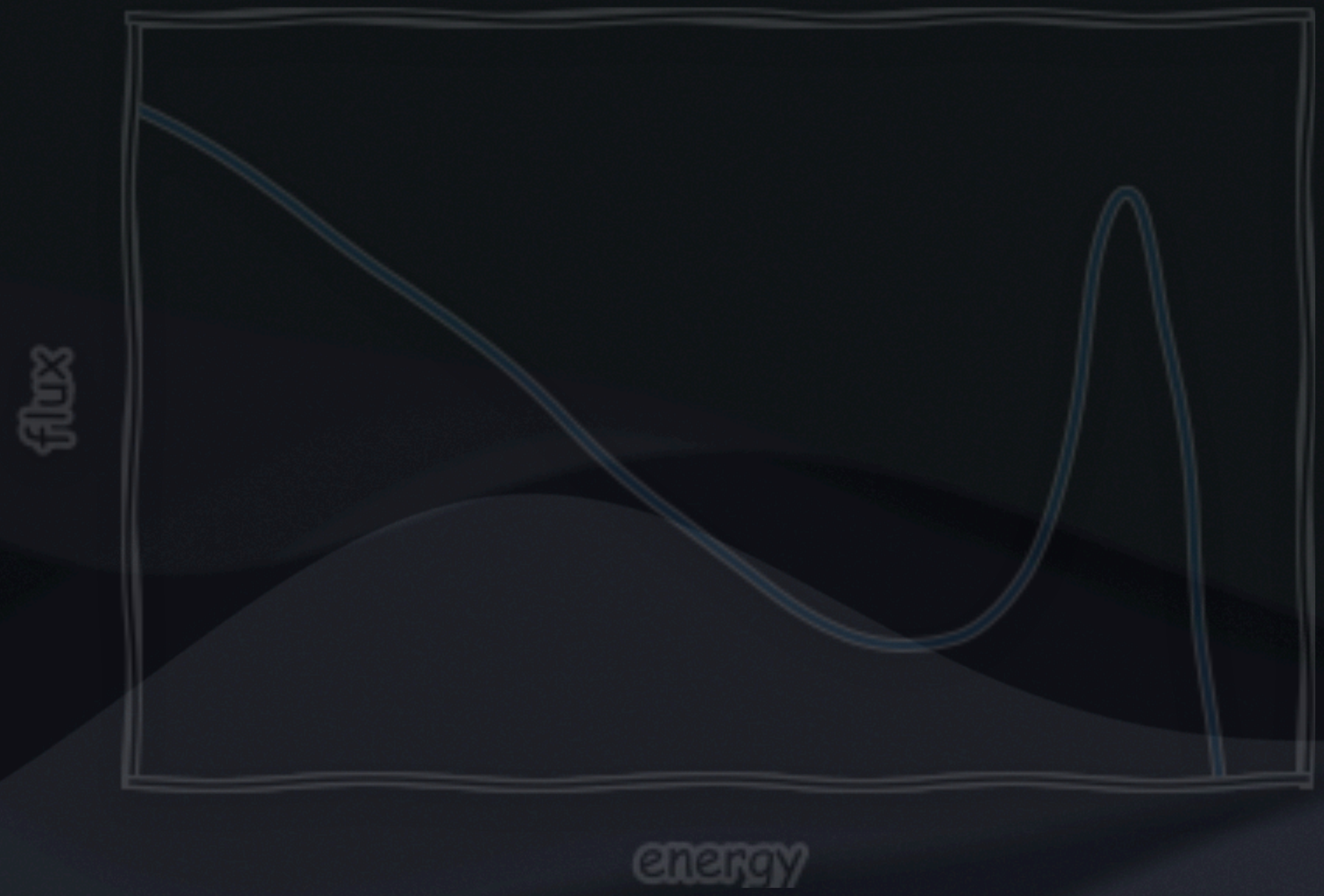
The problem:

Obtain the annihilation spetrum

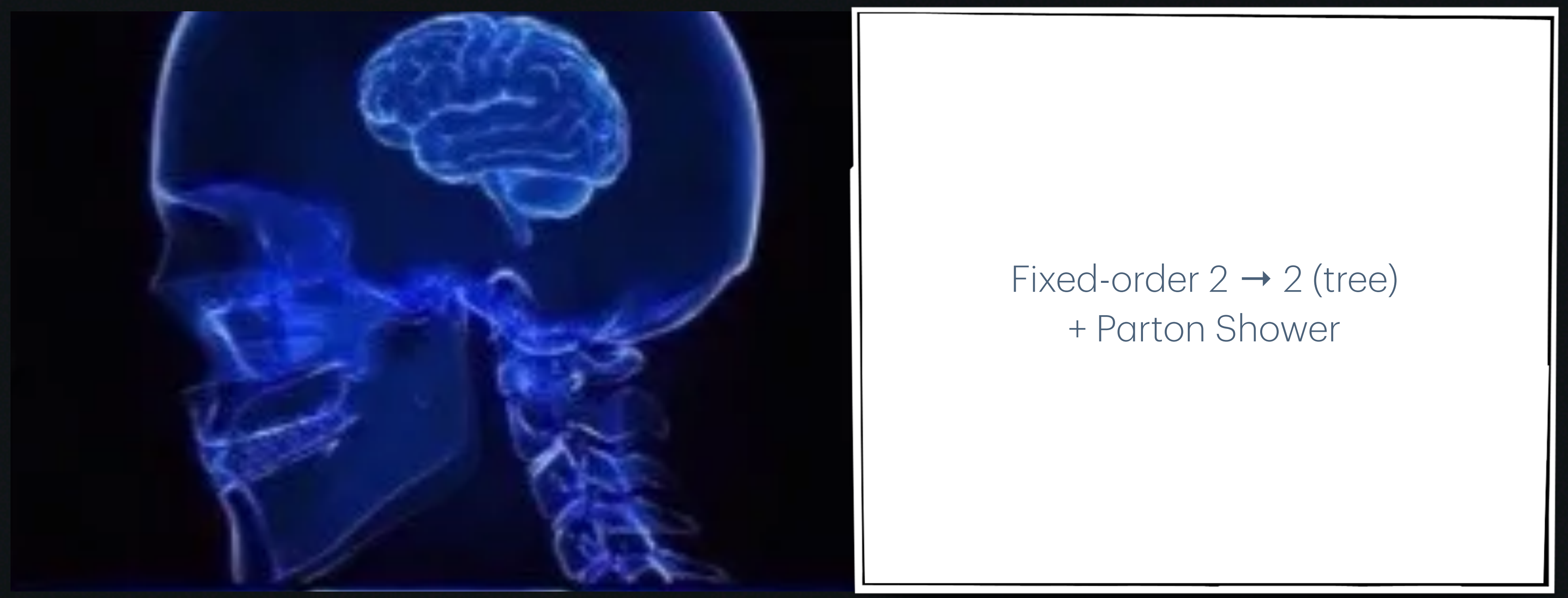


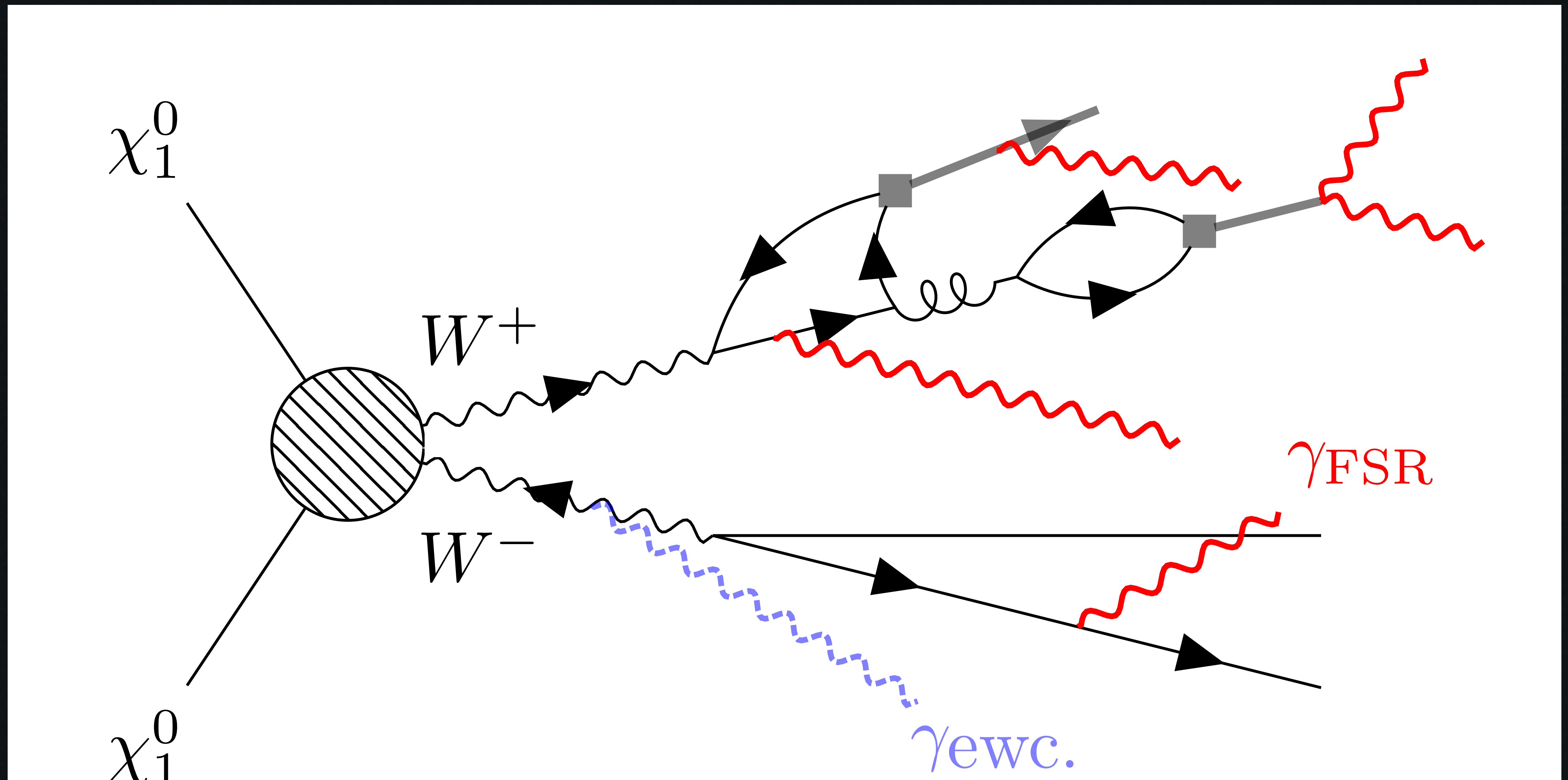
$$\frac{\mathrm{d}\sigma v}{\mathrm{d}E_\gamma}$$

Possible approaches



2000-2010s

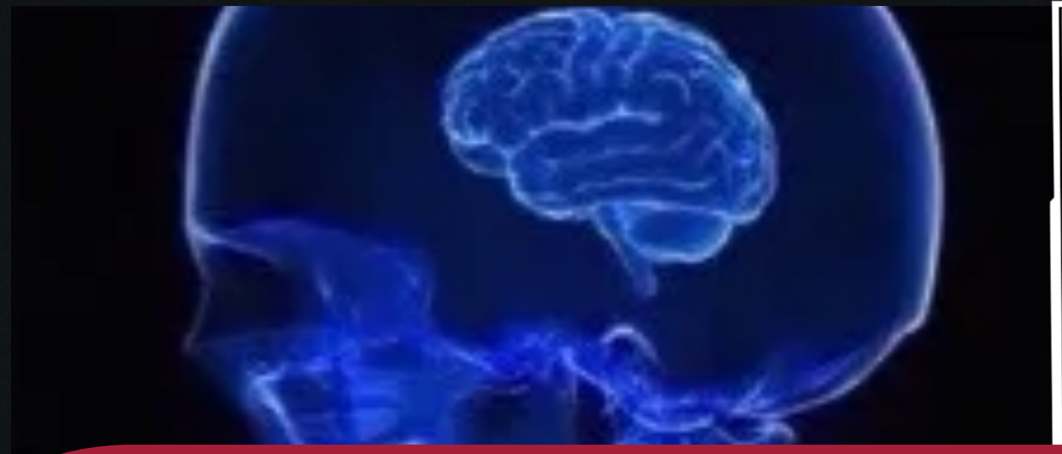




Ciafaloni et al 1009.0224

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

2000-2010s

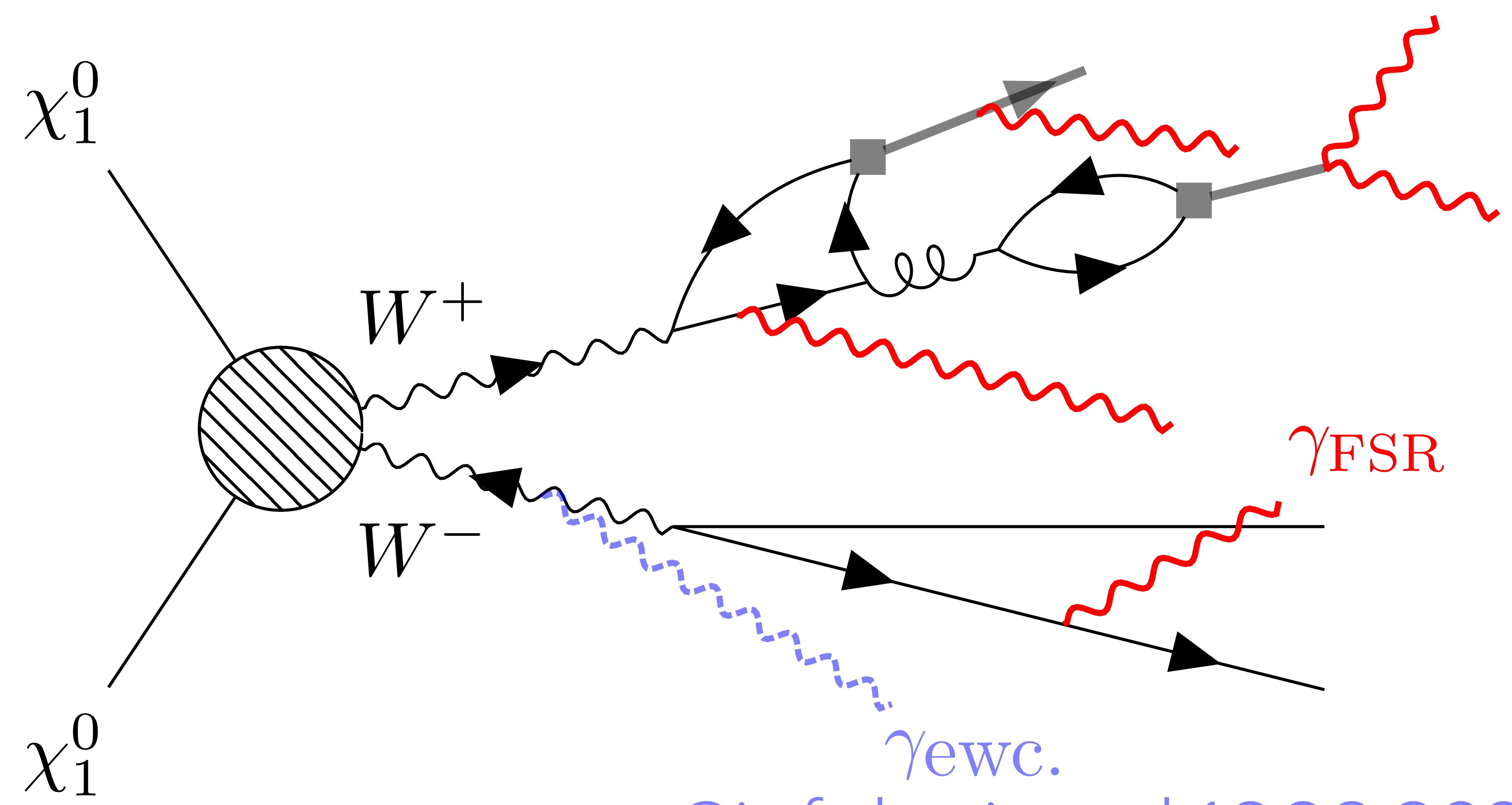


Fixed-order 2 → 2 (tree)
+ Parton Shower

Helicity suppression

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

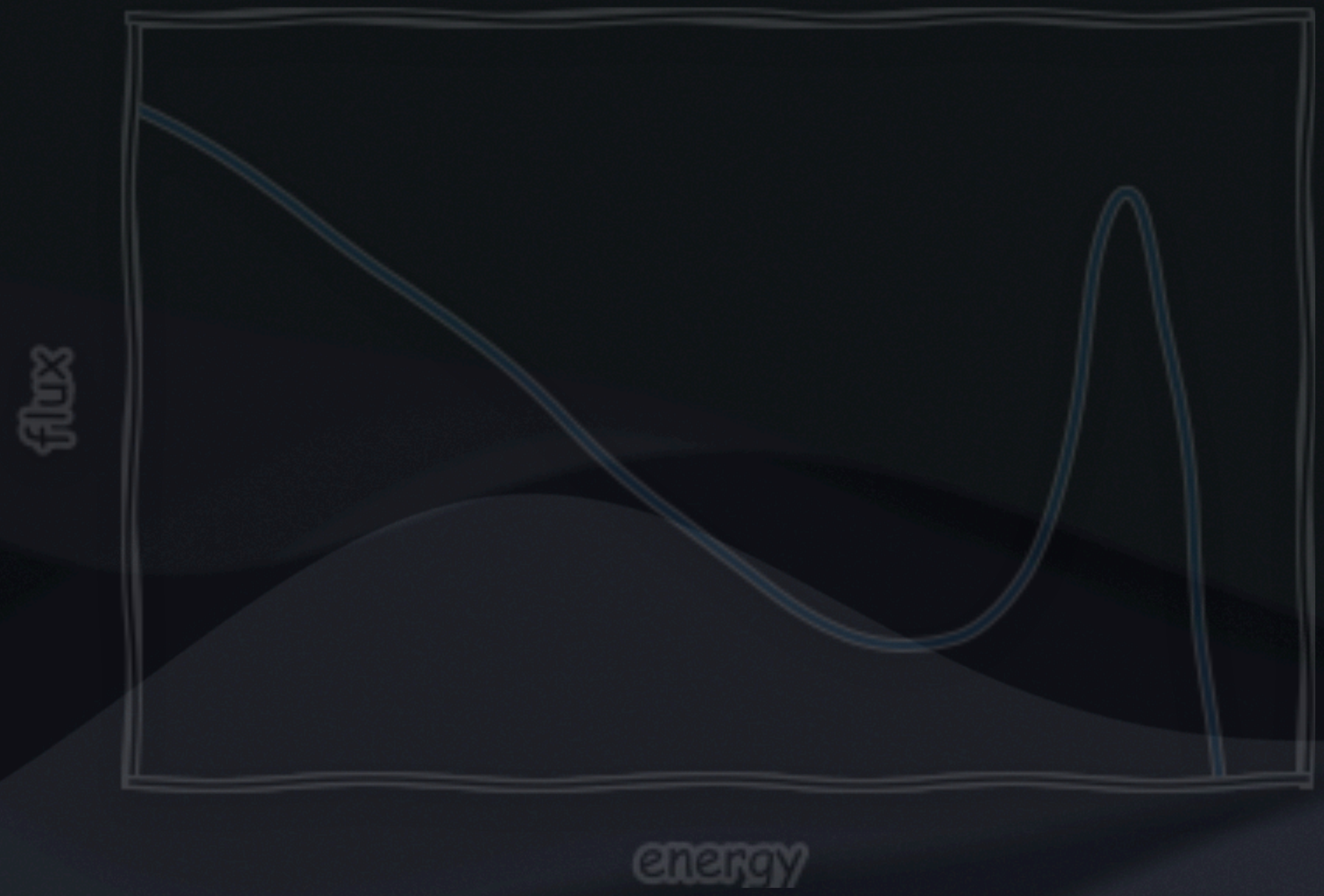
$$\langle \sigma v \rangle_{b\bar{b}} \propto \frac{m_b^2}{m_{DM}^2} \to 0$$



Ciafaloni et al 1009.0224

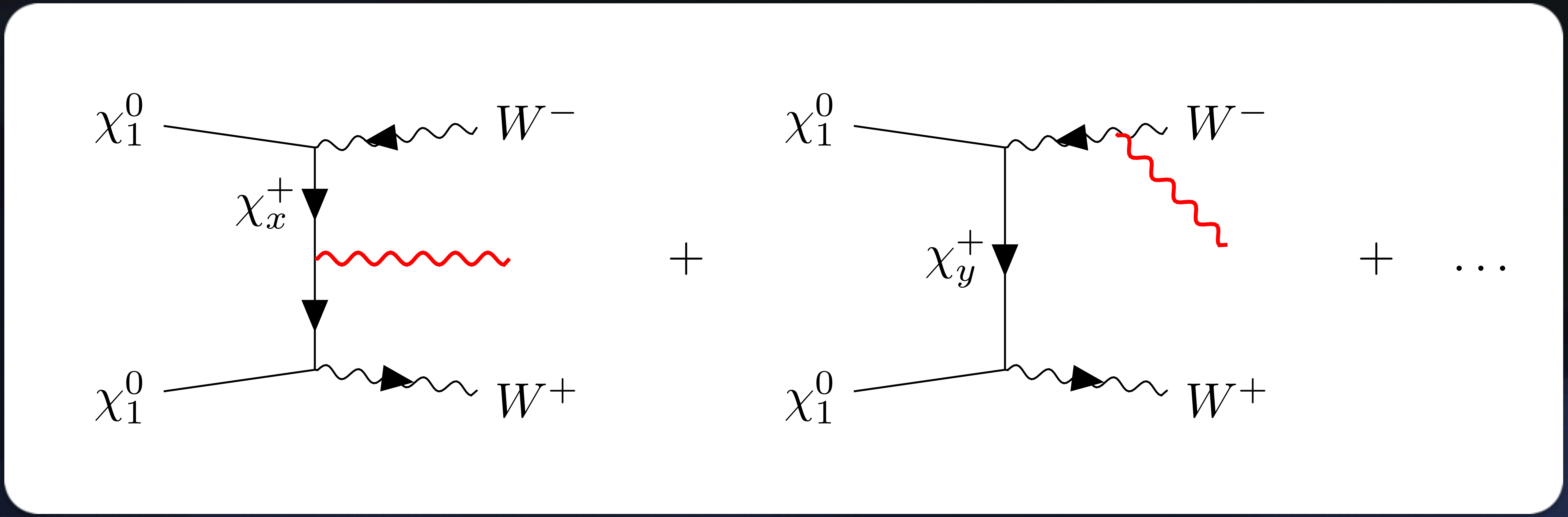
$$\frac{\mathrm{d}\,\sigma v}{\mathrm{d}\,E_\gamma} = \cancel{(\sigma v)}_{\bar{b}b} \frac{\mathrm{d}\,N^{\rm MC}_{\bar{b}b}}{\mathrm{d}\,E_\gamma} + \cancel{(\sigma v)}_{\tau^+\tau^-} \frac{\mathrm{d}\,N^{\rm MC}_{\tau^+\tau^-}}{\mathrm{d}\,E_\gamma} + \ldots$$

Possible approaches



2000-2010s

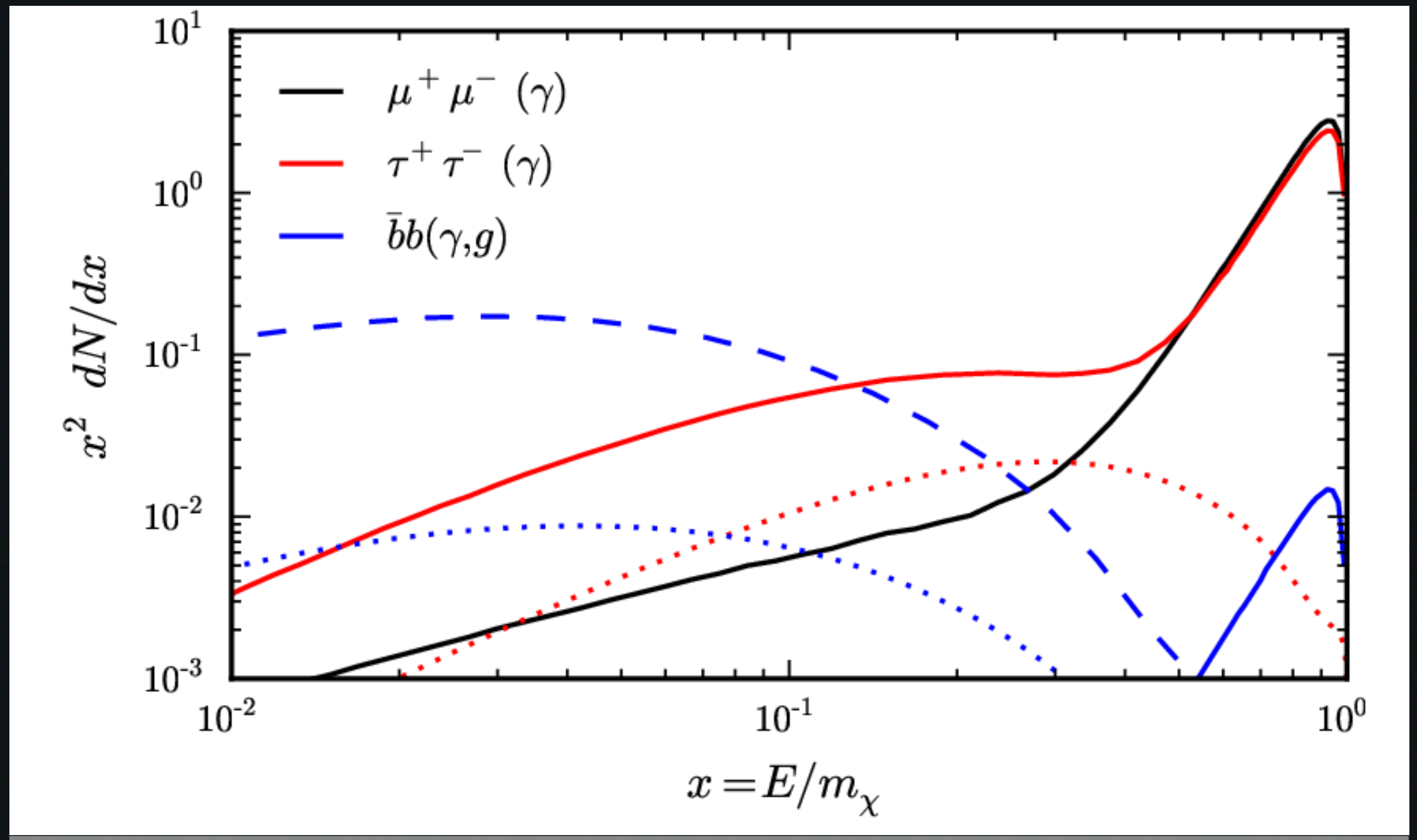
Fixed-order 2 → 3 (tree)
+ Parton Shower



Bringmann et al 0710.3169

2000-2010s

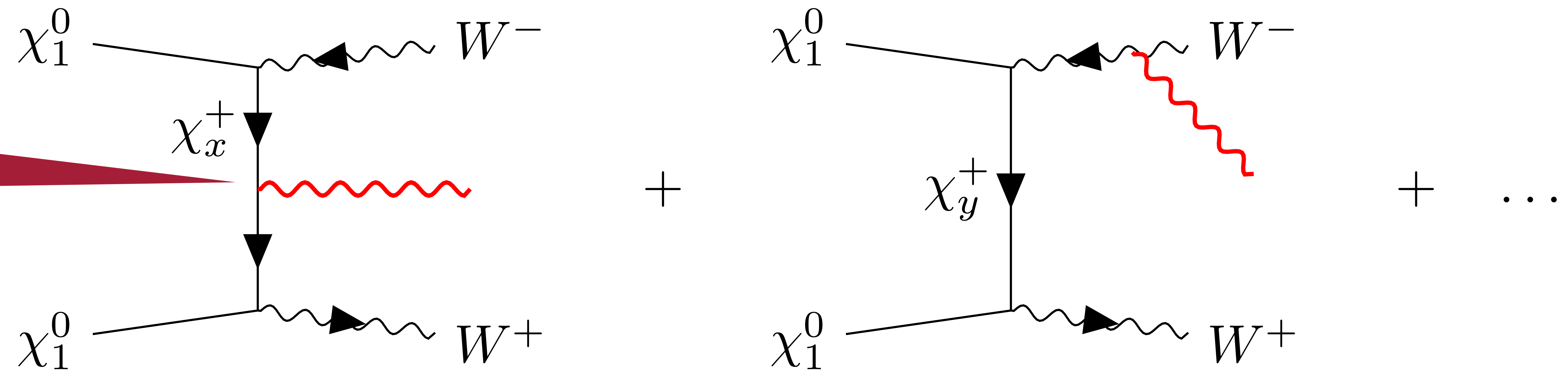
Fixed-order 2 → 3 (tree)
+ Parton Shower



Internal bremsstrahlung

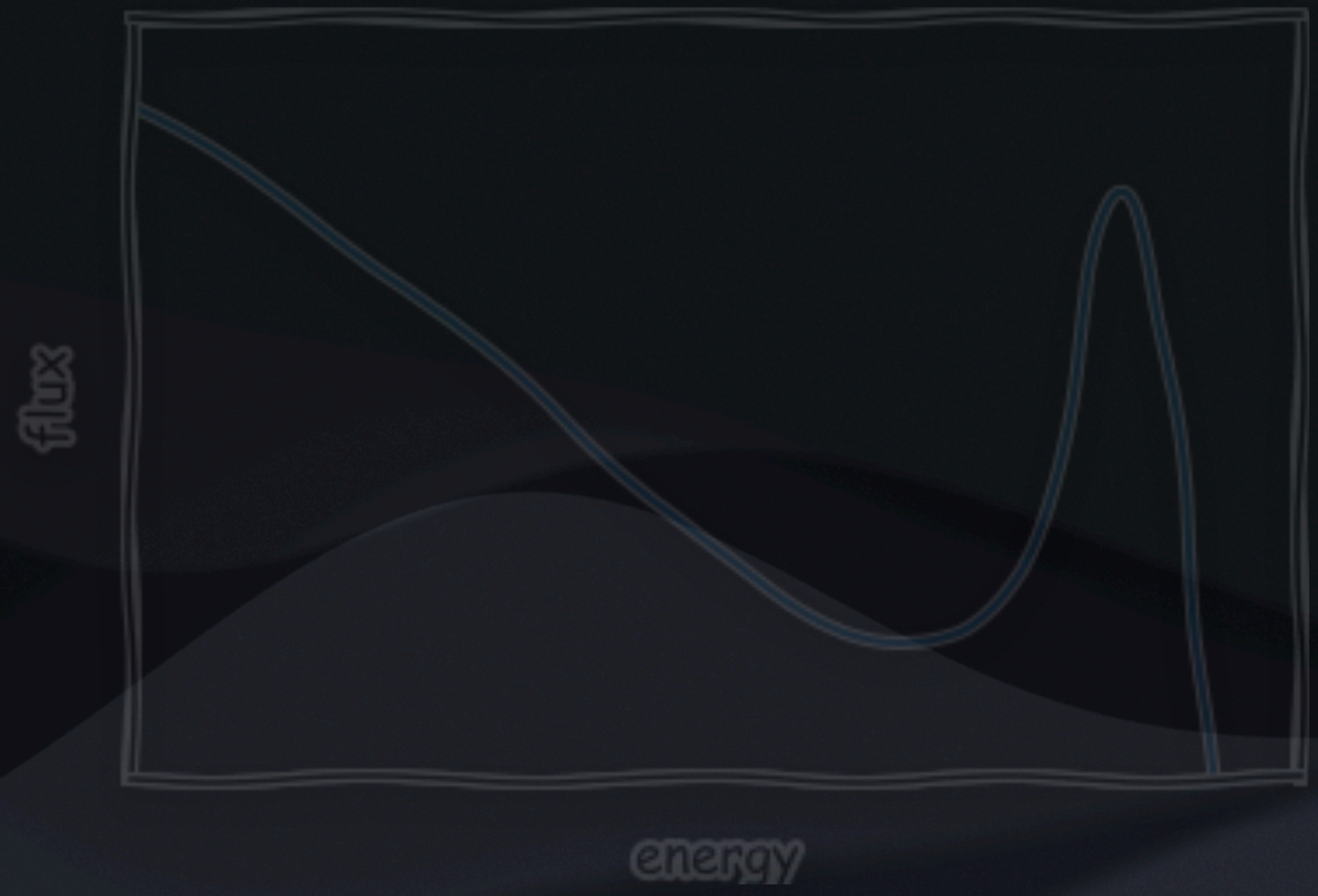
Lift helicity suppression

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

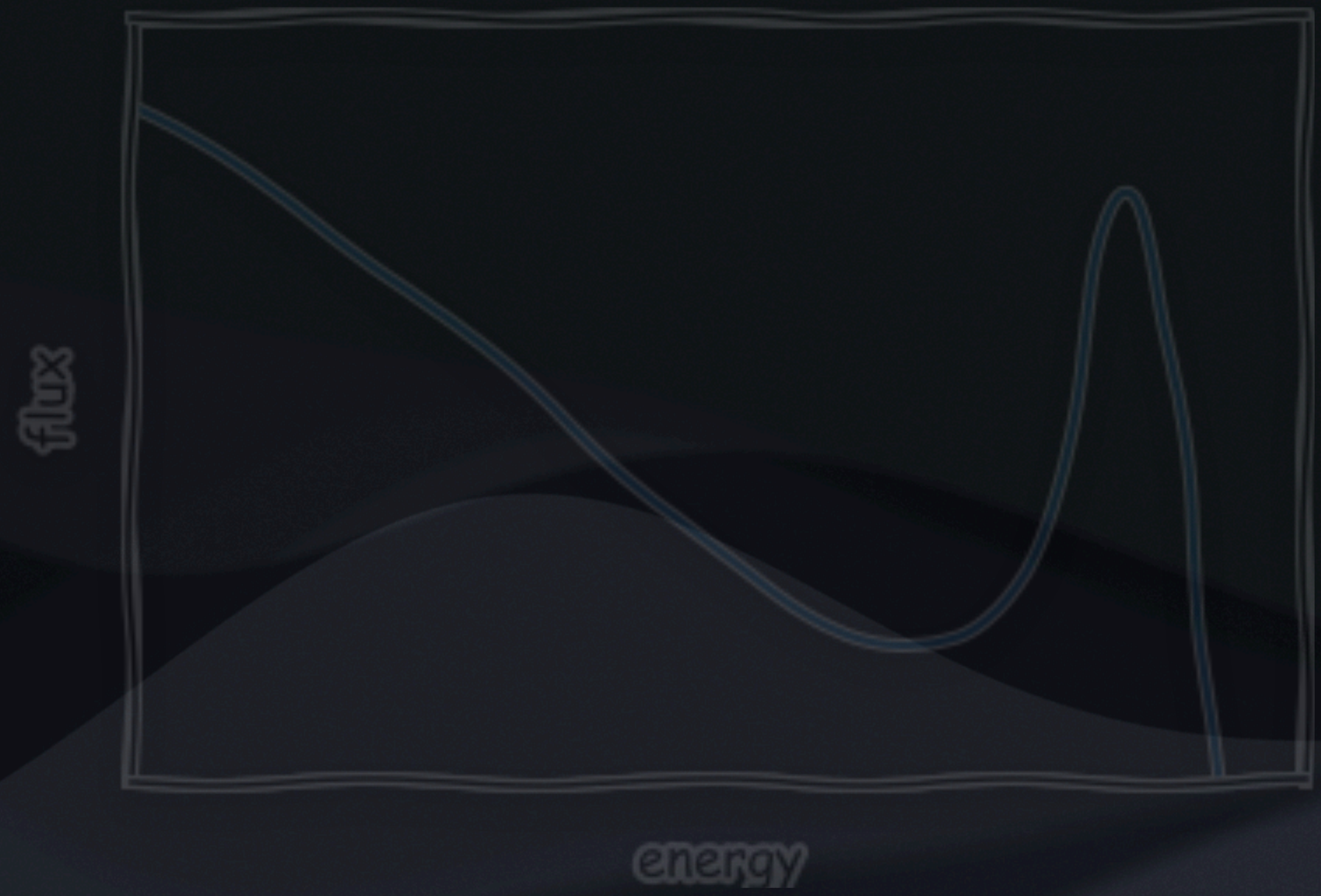


Bringmann et al 0710.3169

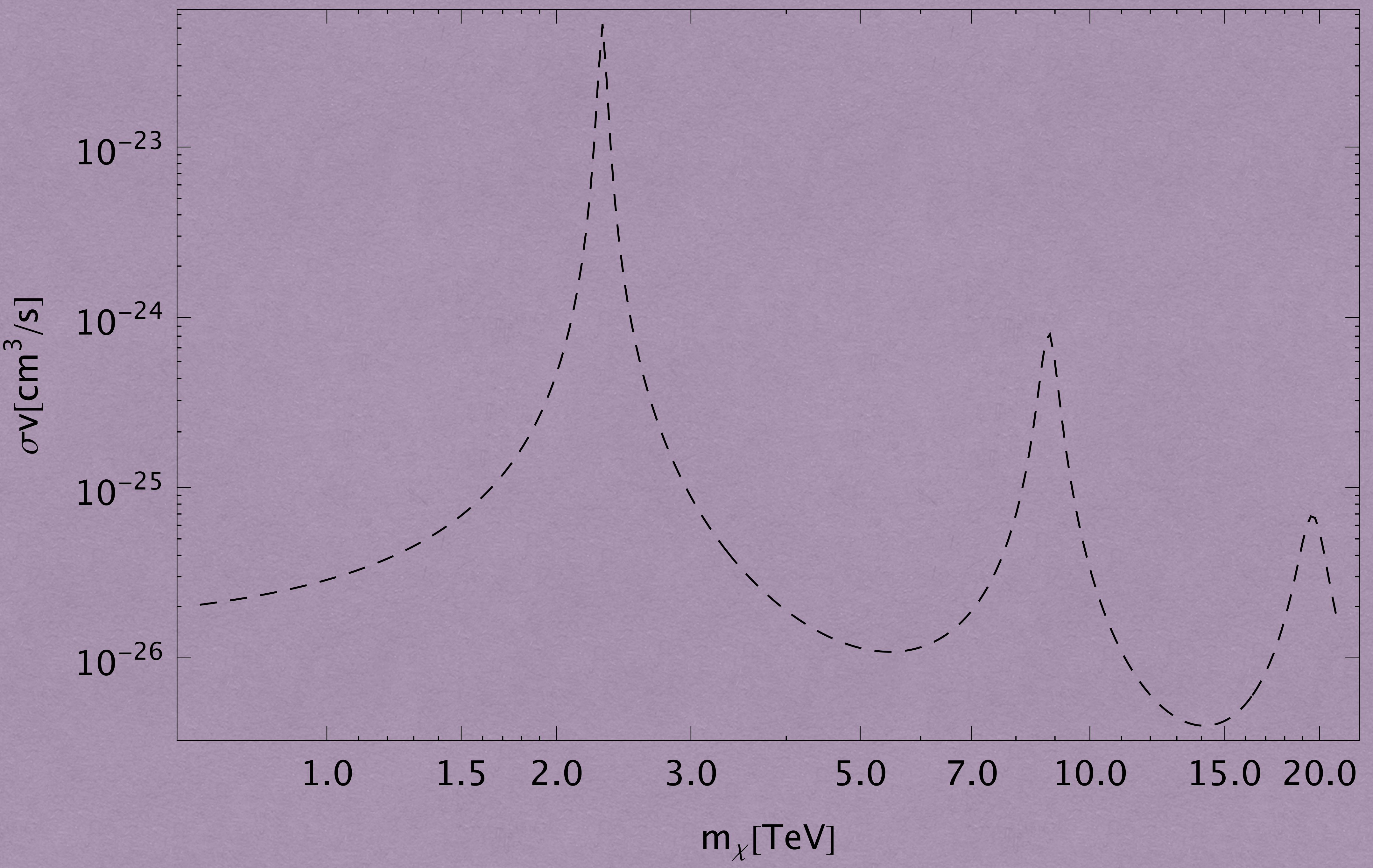
Possible approaches



Possible approaches



Possible approaches



2020s (before 2310.11067 came out)

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

- Incomplete (missing shower for e.g. $\chi^0\chi^0 \rightarrow H^{\pm}W^{\mp}$)
- 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

Goal: Account for
Internal bremsstrahlung +
Sommerfeld effect in the MSSM

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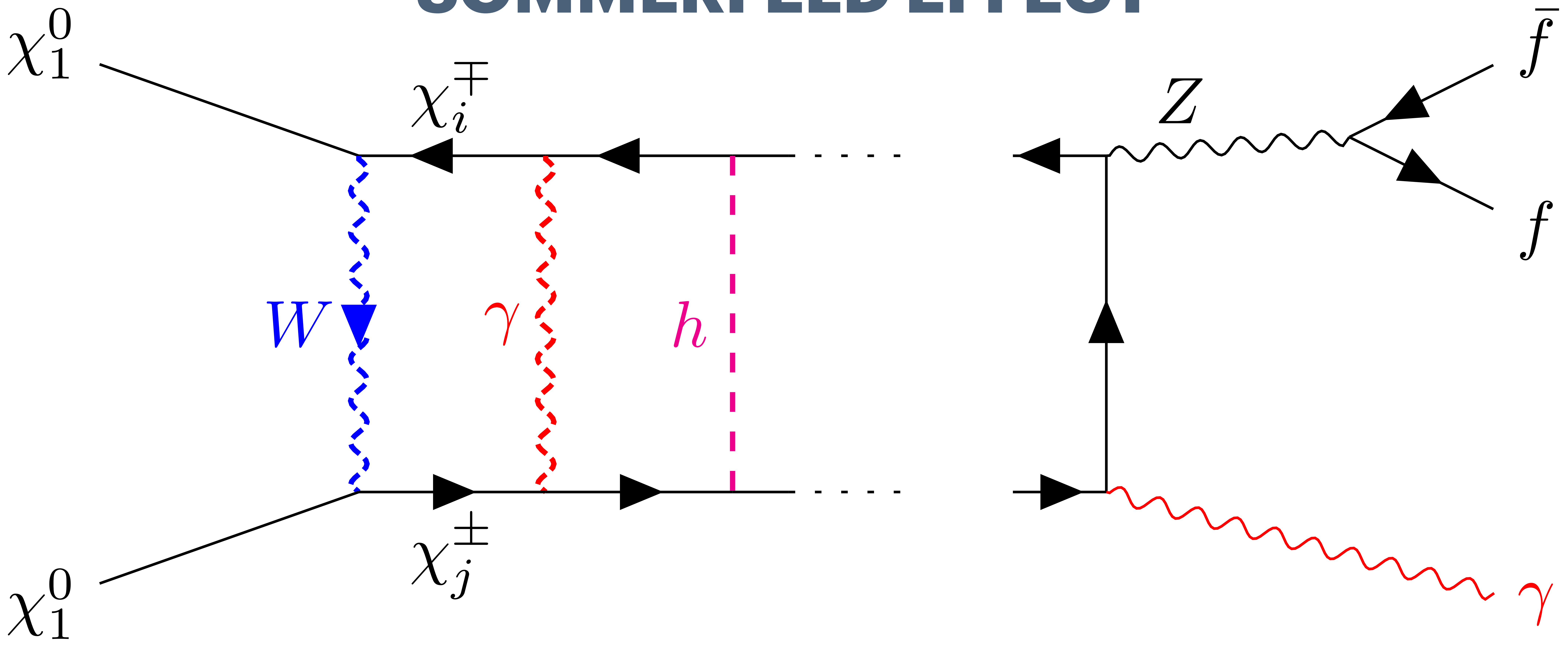
SOMMERFELD EFFECT



Resummation

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

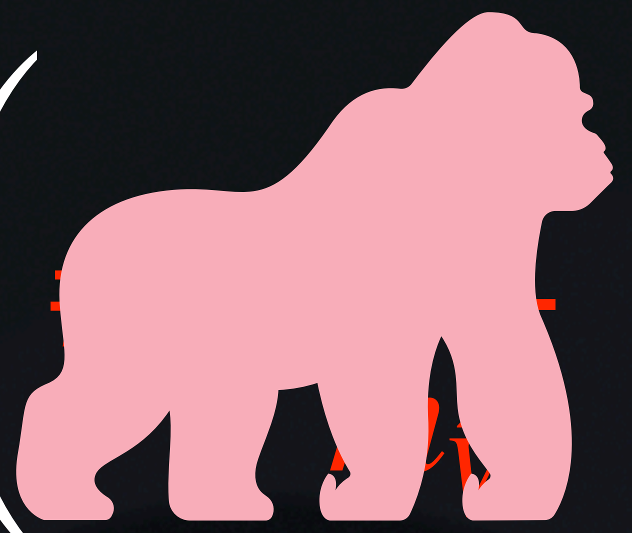
$$\frac{\mathrm{d}\,\sigma v}{\mathrm{d}\,E_\gamma} \sim \#\,\alpha_{ew}^3 + \alpha_{ew}^4\left(\# \times \frac{m_\chi^2}{m_W^2} + \ldots\right) + \alpha_{ew}^5\left(\# \times \frac{m_\chi^4}{m_W^4} + \ldots\right) + \ldots$$

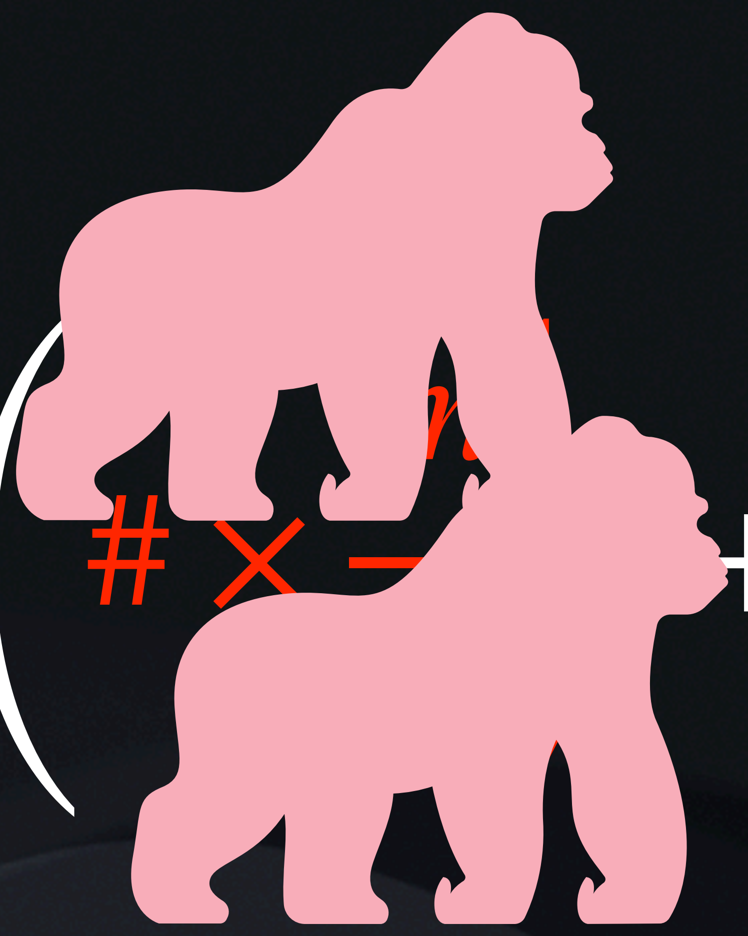
Tree (LO) 1-loop (NLO) 2-loop (NNLO)

Resummation

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

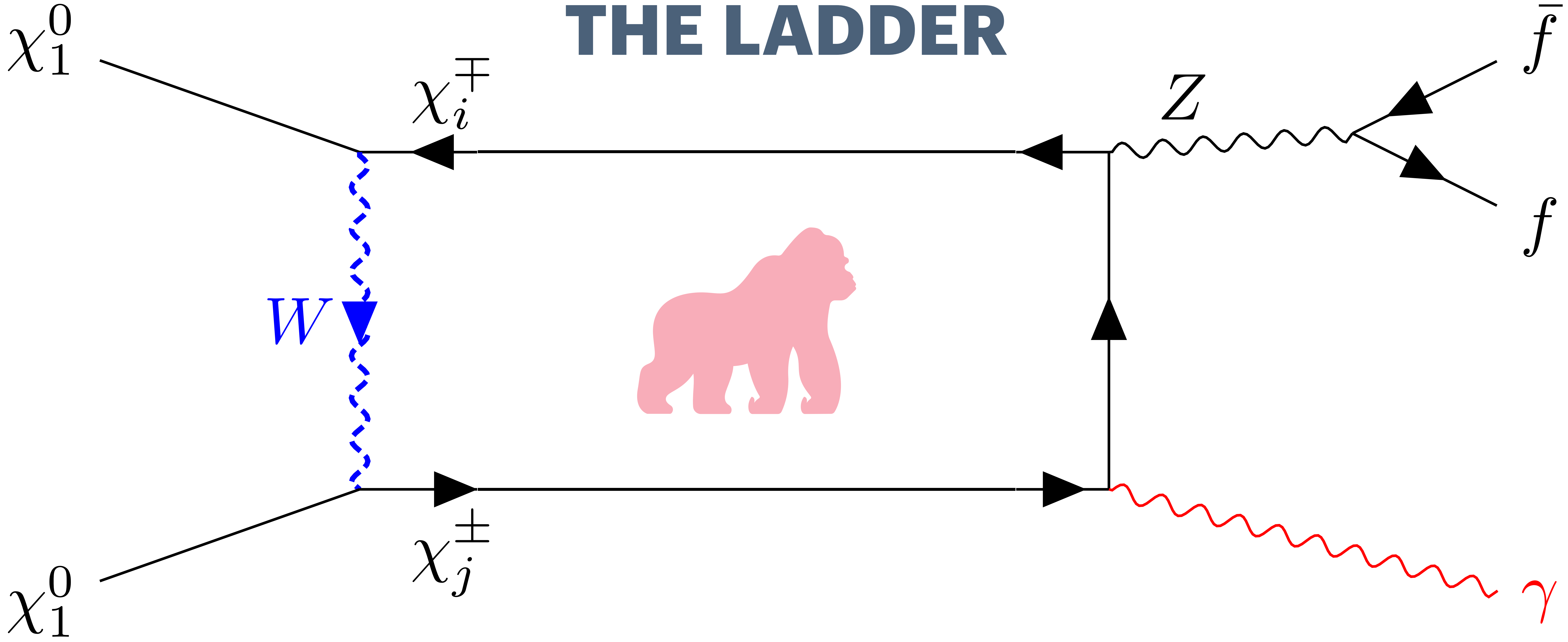
$$\frac{\mathrm{d}\,\sigma v}{\mathrm{d}\,E_\gamma} \sim \#\,\alpha_{ew}^3 + \alpha_{ew}^4 \left(\quad + \ldots \right) + \alpha_{ew}^5 \left(\# \times - \quad + \ldots \right) + \ldots$$



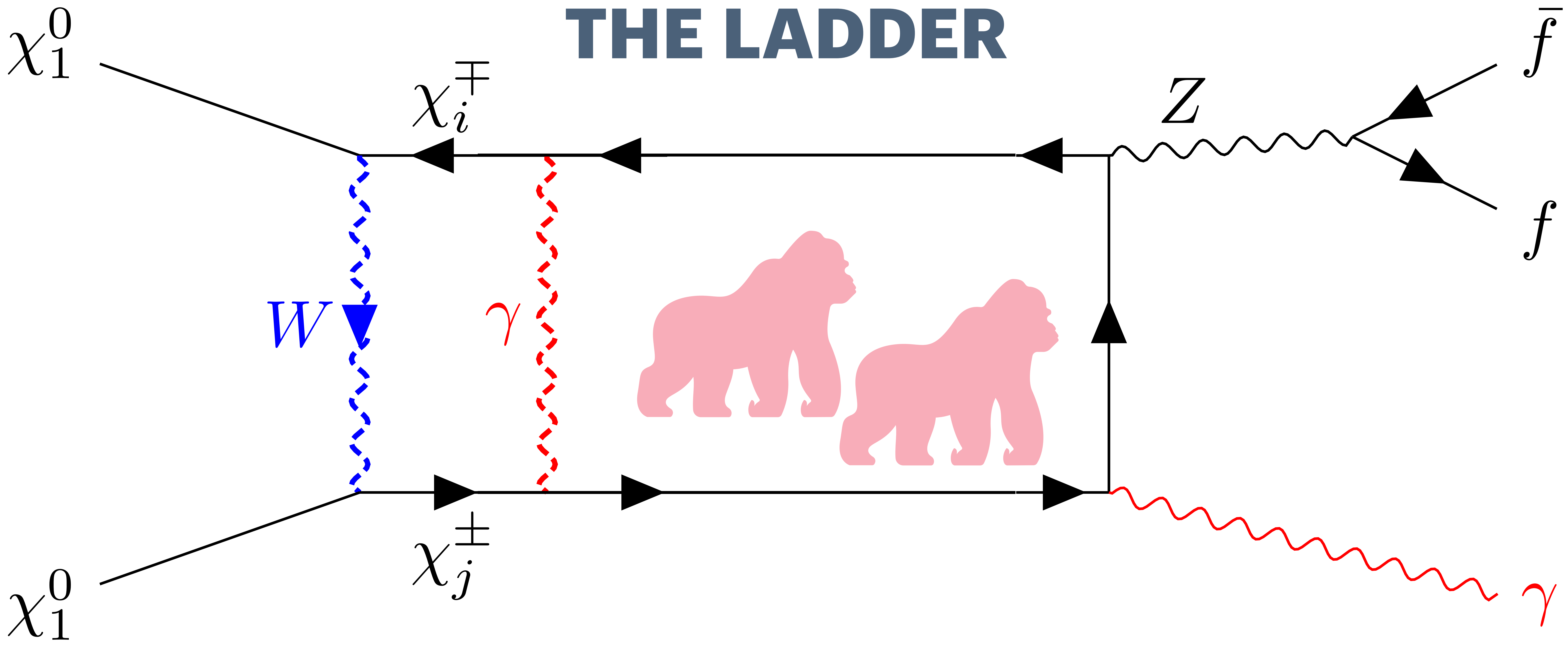


Tree (LO) 1-loop (NLO) 2-loop (NNLO)

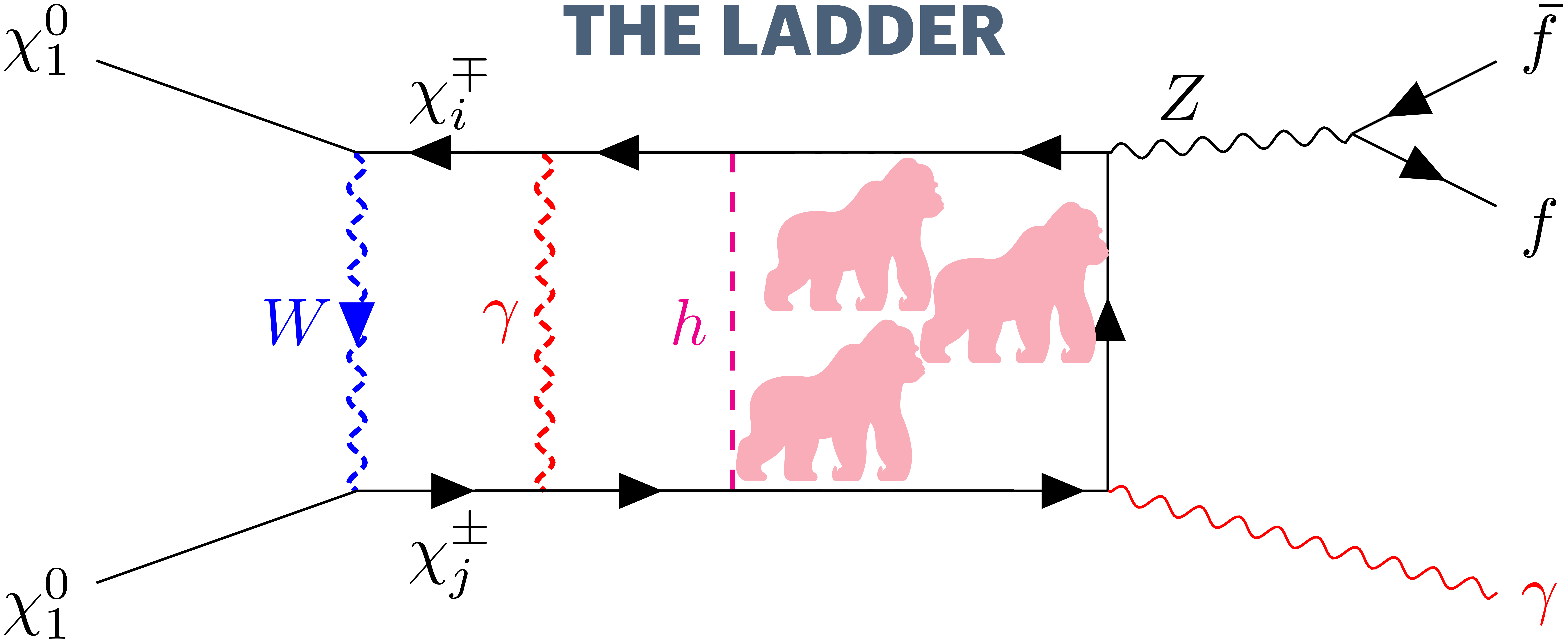
THE LADDER

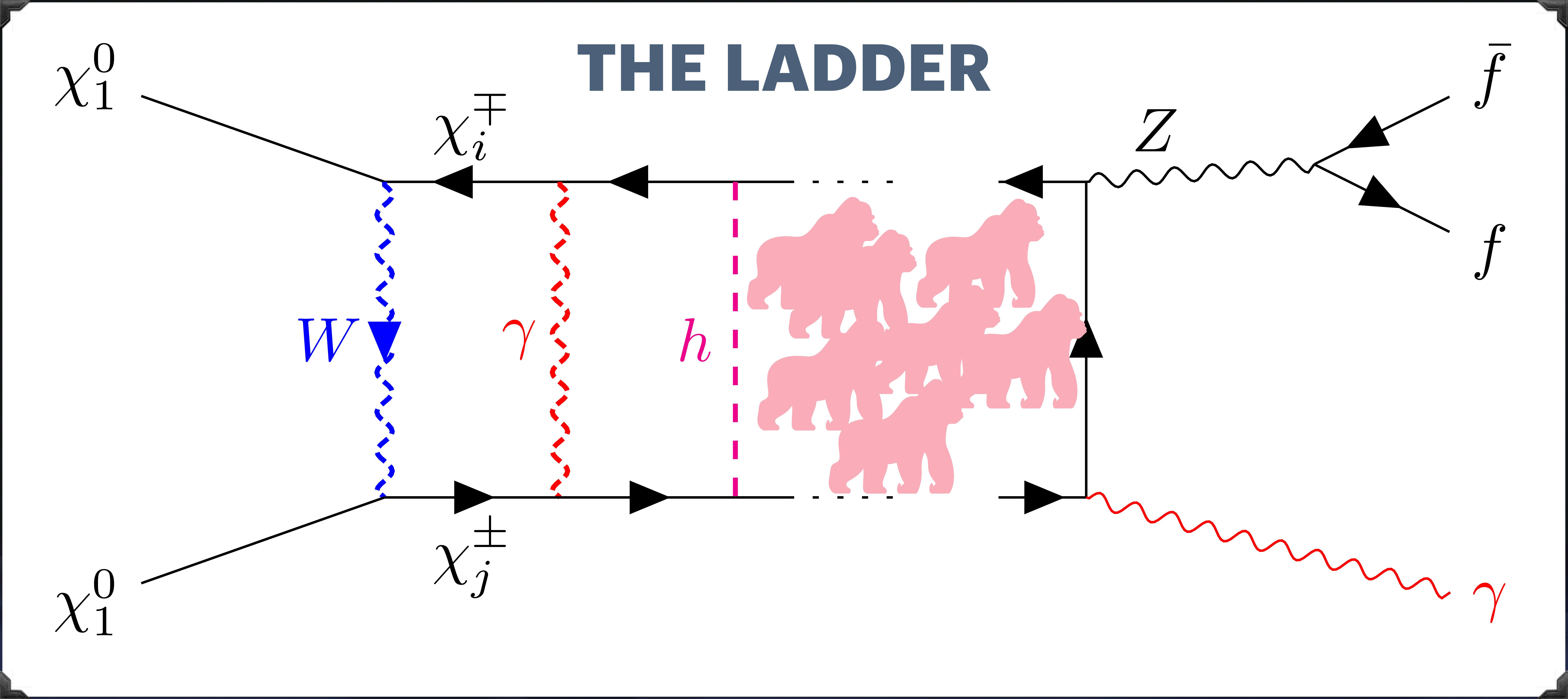


THE LADDER



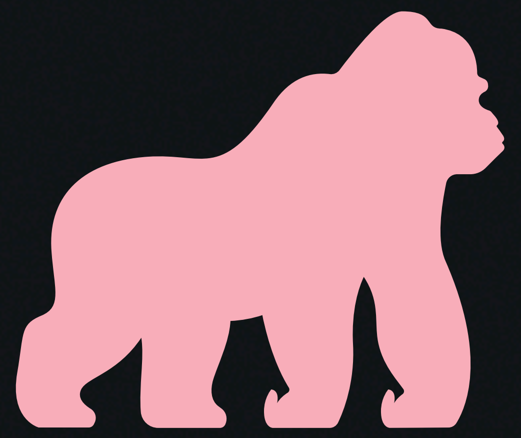
THE LADDER

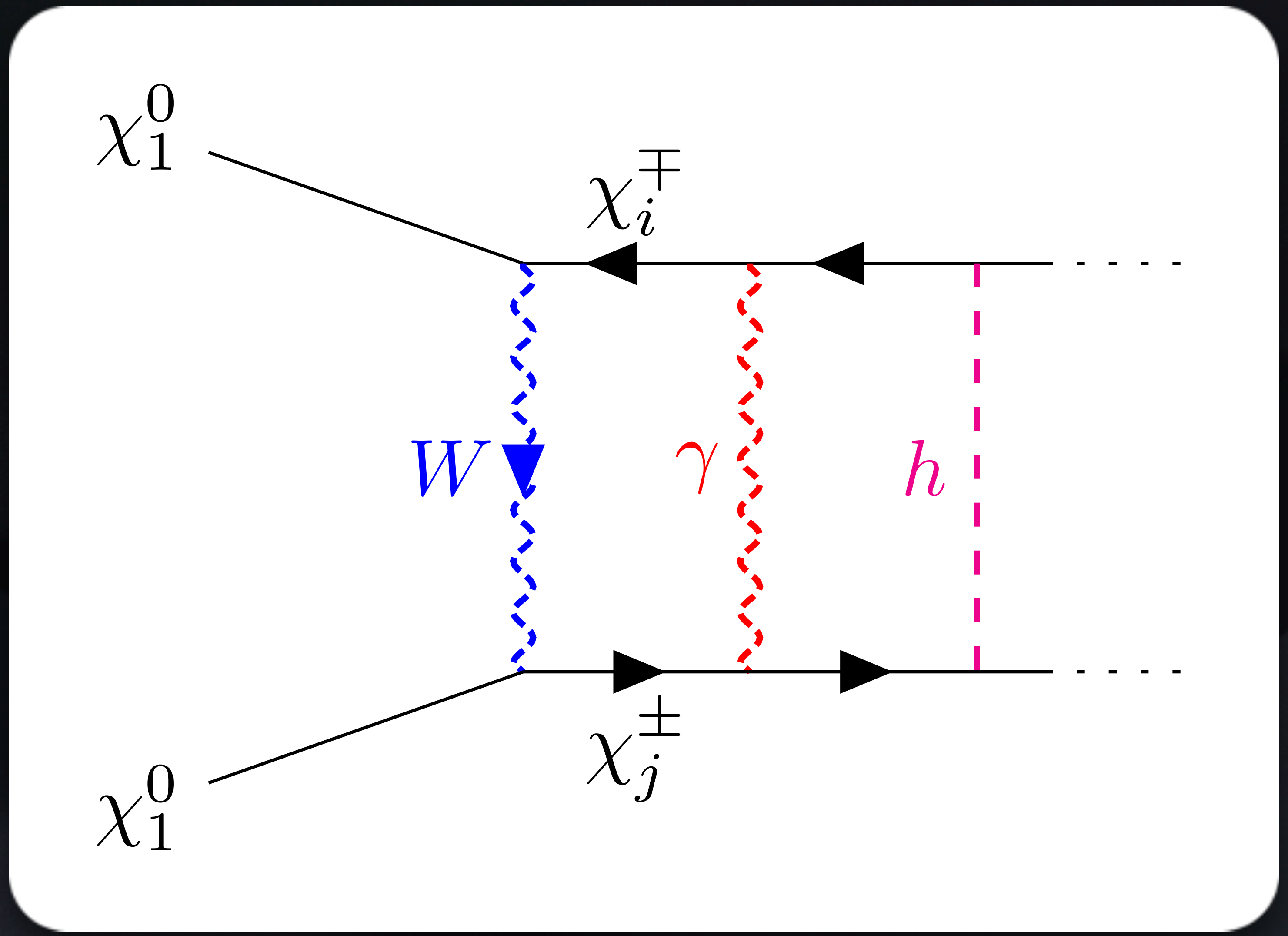


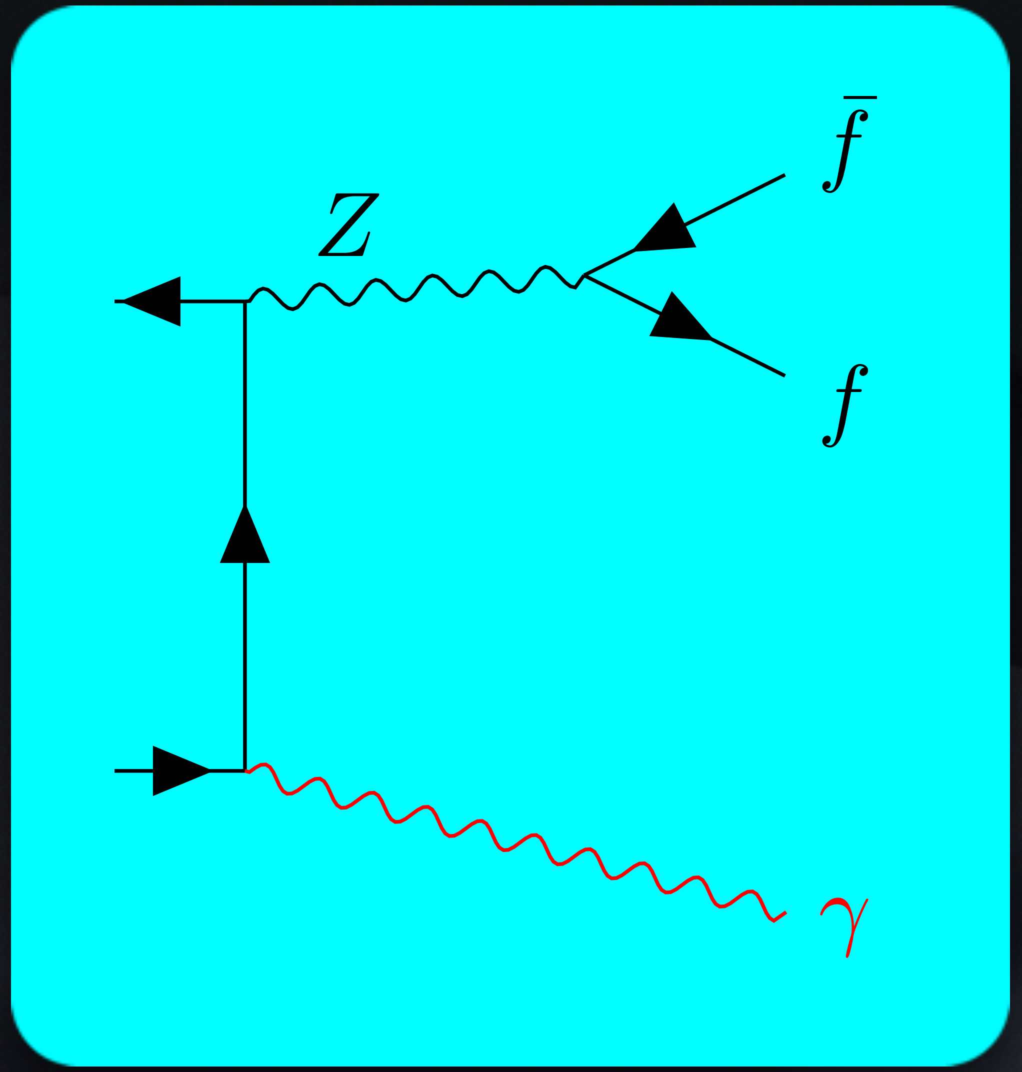

THE LADDER
χ_1^0
$\chi_i^\mp$
Z
$\bar{f}$
W
γ
h
f
χ_1^0
$\chi_j^\pm$
γ

Resummation

Goal: factor out the "gorillas"

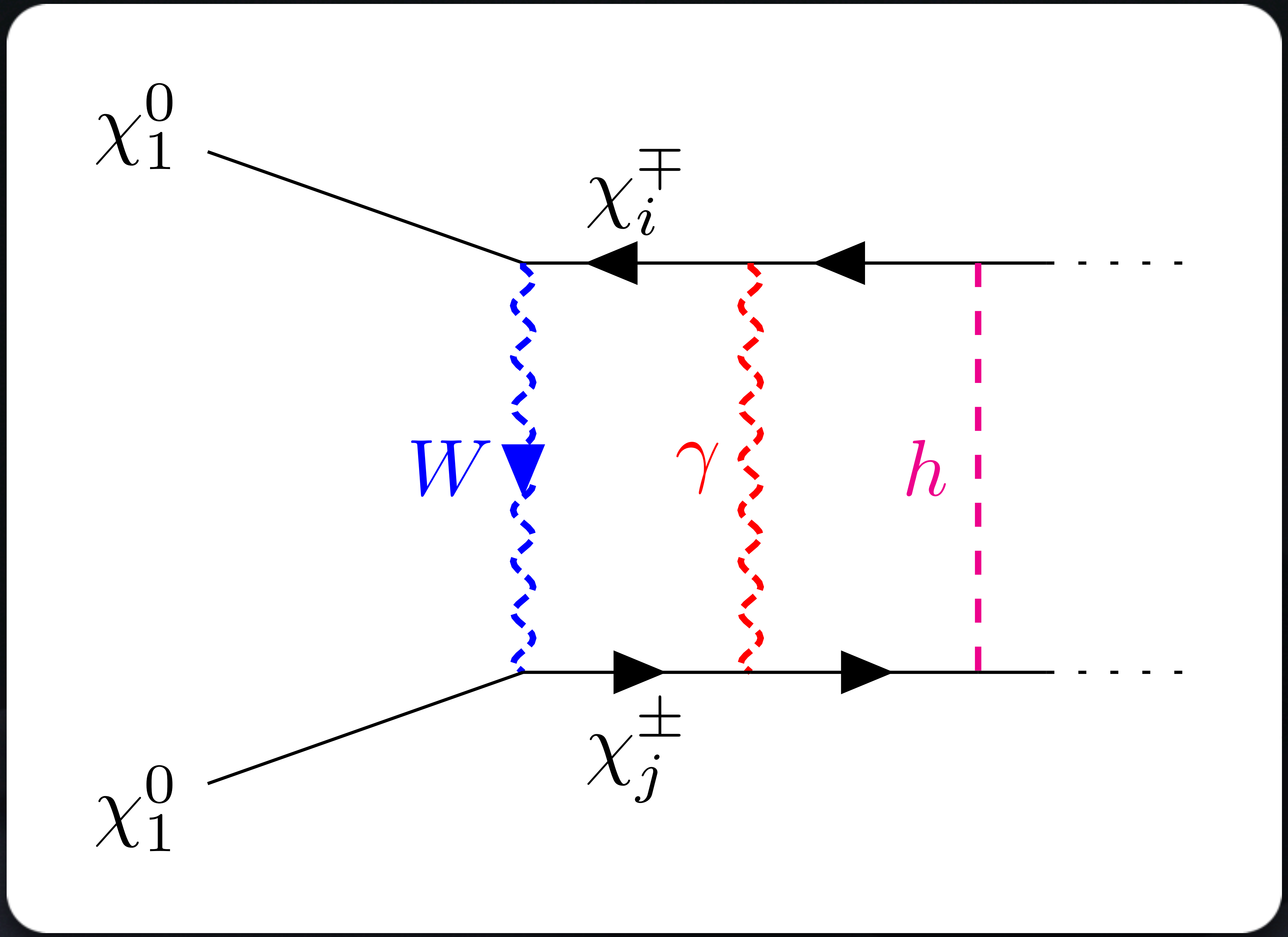
$$\frac{\mathrm{d}\,\sigma v}{\mathrm{d}\,E_\gamma} = f\left(\alpha_{ew} \times$$

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





Sommerfeld factor

Reframe the question: QFT ☞ Quantum Mechanics



Sommerfeld factor

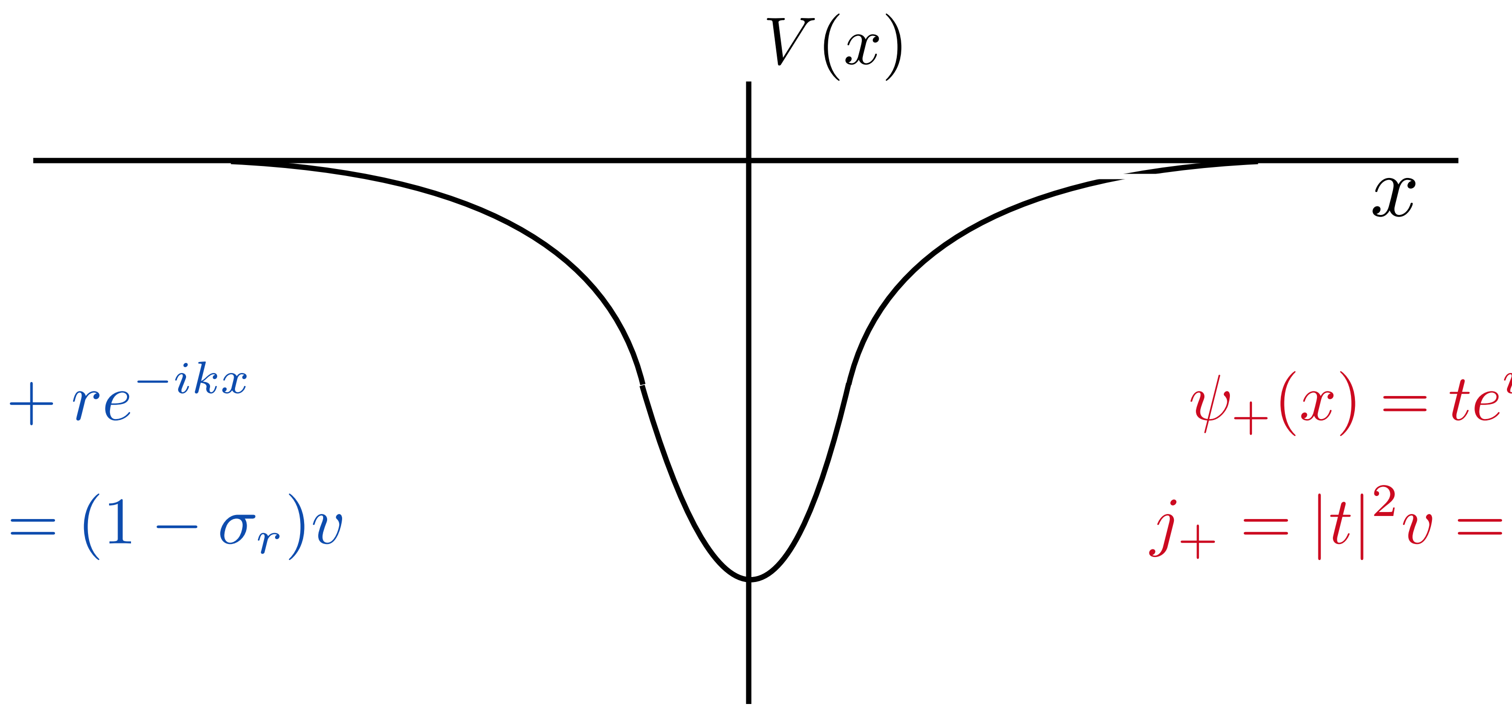
How to compute it? Illustrative example

$$\left(-\frac{1}{m_\chi}\frac{\mathrm{d}^2}{\mathrm{d}x^2} + V(x) \qquad\qquad\qquad \right)\psi(x) = E\psi(x)$$

$$j(x) = \frac{i}{m_\chi}\left[\psi(x)\psi'^*(x) - \psi^*(x)\psi'(x)\right] \text{ = const.}$$

$$\psi_-(x) = e^{ikx} + re^{-ikx}$$

$$j_- = (1-|r|^2)v = (1-\sigma_r)v$$



$$\psi_+(x) = te^{ikx}$$

$$j_+ = |t|^2 v = \sigma_t v$$

Unitarity: $\quad j_- = j_+ \quad \rightarrow \quad \sigma_r + \sigma_t = 1 \quad$ (only scattering)

Sommerfeld factor

How to compute it? Illustrative example

$$\left(-\frac{1}{m_\chi}\frac{\mathrm{d}^2}{\mathrm{d}x^2}+V(x)+\frac{i}{2}\sigma_a^{(0)}v\delta(x)\right)\psi(x)=E\psi(x)$$

Unitarity-violating term $\rightarrow\ j_+=j_-+|\psi(0)|^2\sigma_a v$

$$\sigma_r+\sigma_t+\boldsymbol{\sigma_a}=1$$

$$\boxed{\sigma_a=|\boldsymbol{\psi(0)}|^{\mathbf{2}}\sigma_a^{(0)}}$$

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

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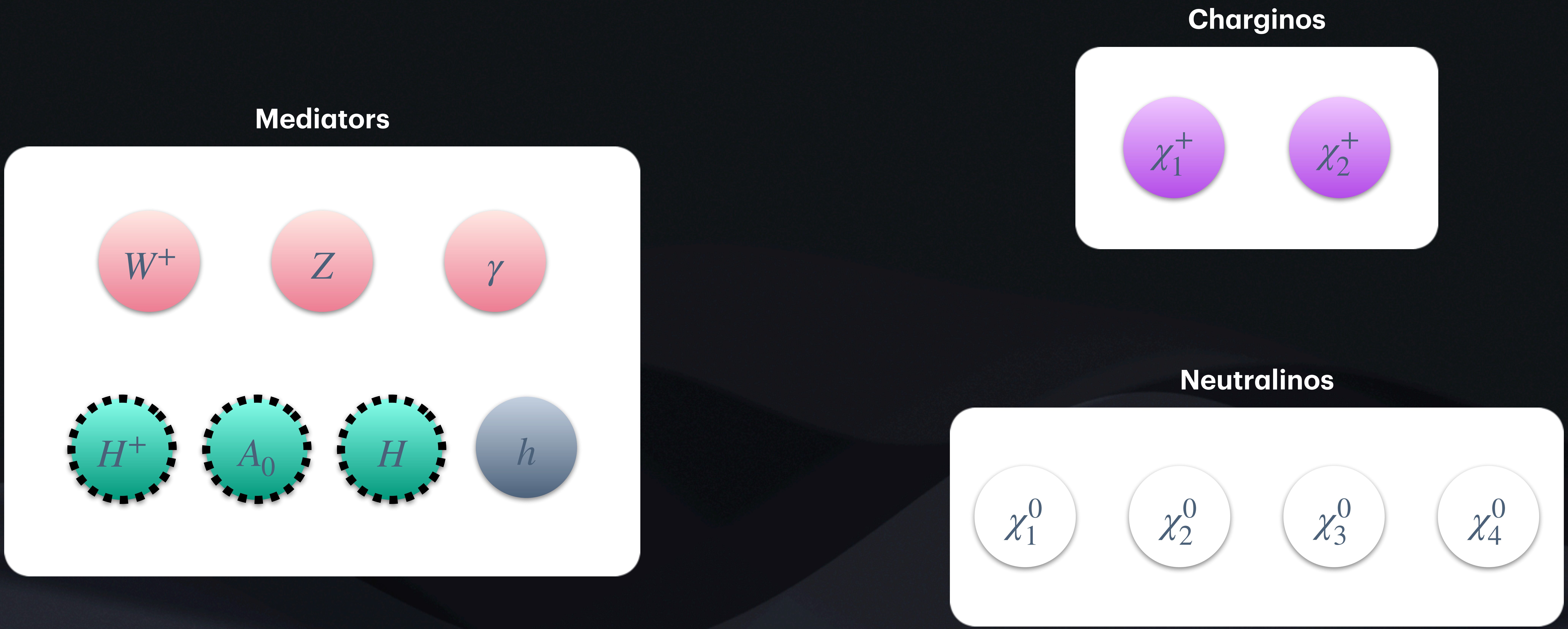
The MSSM in a nutshell

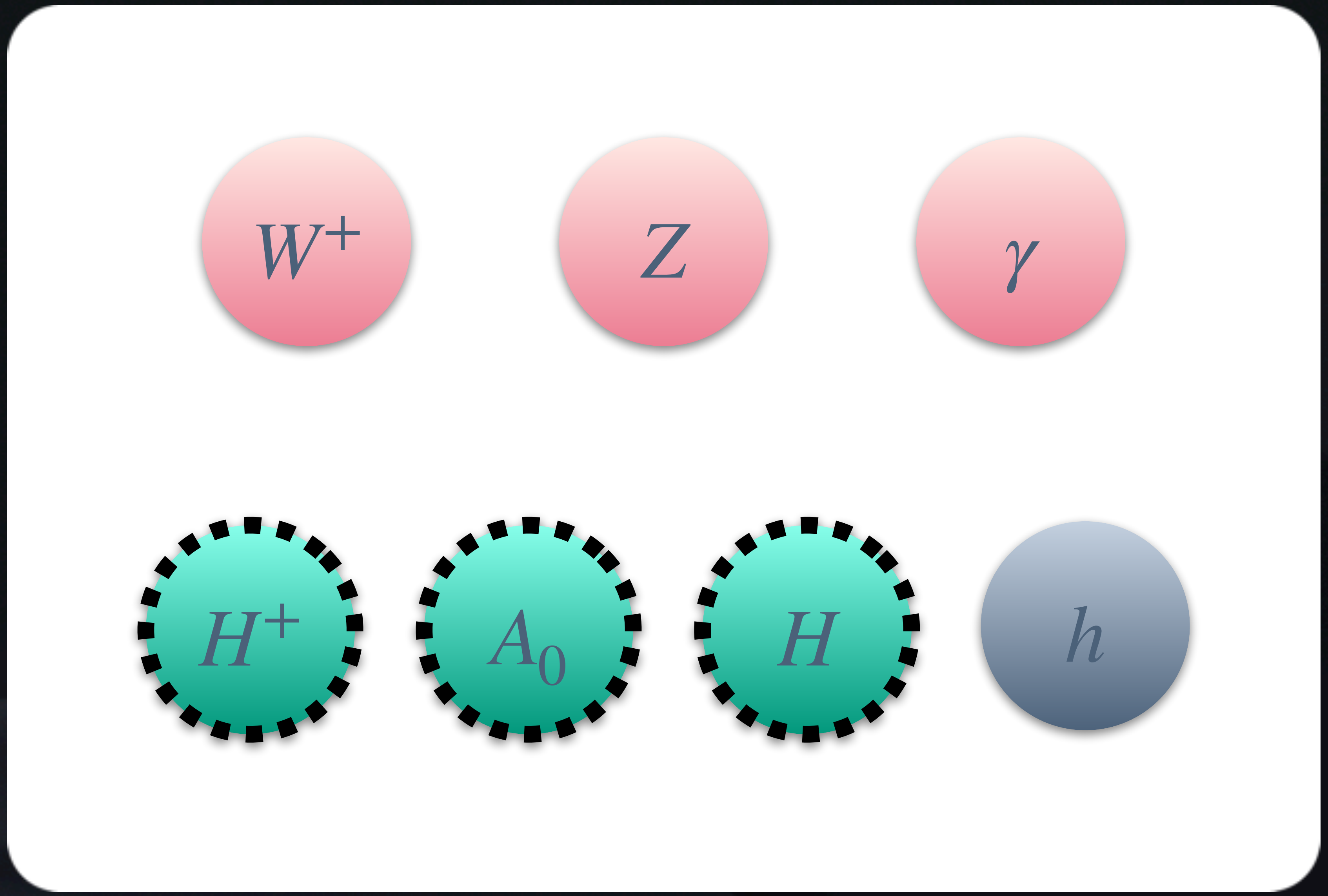
Neutralino/chargino sector



Sommerfeld effect in the MSSM

Dark Matter NR potential

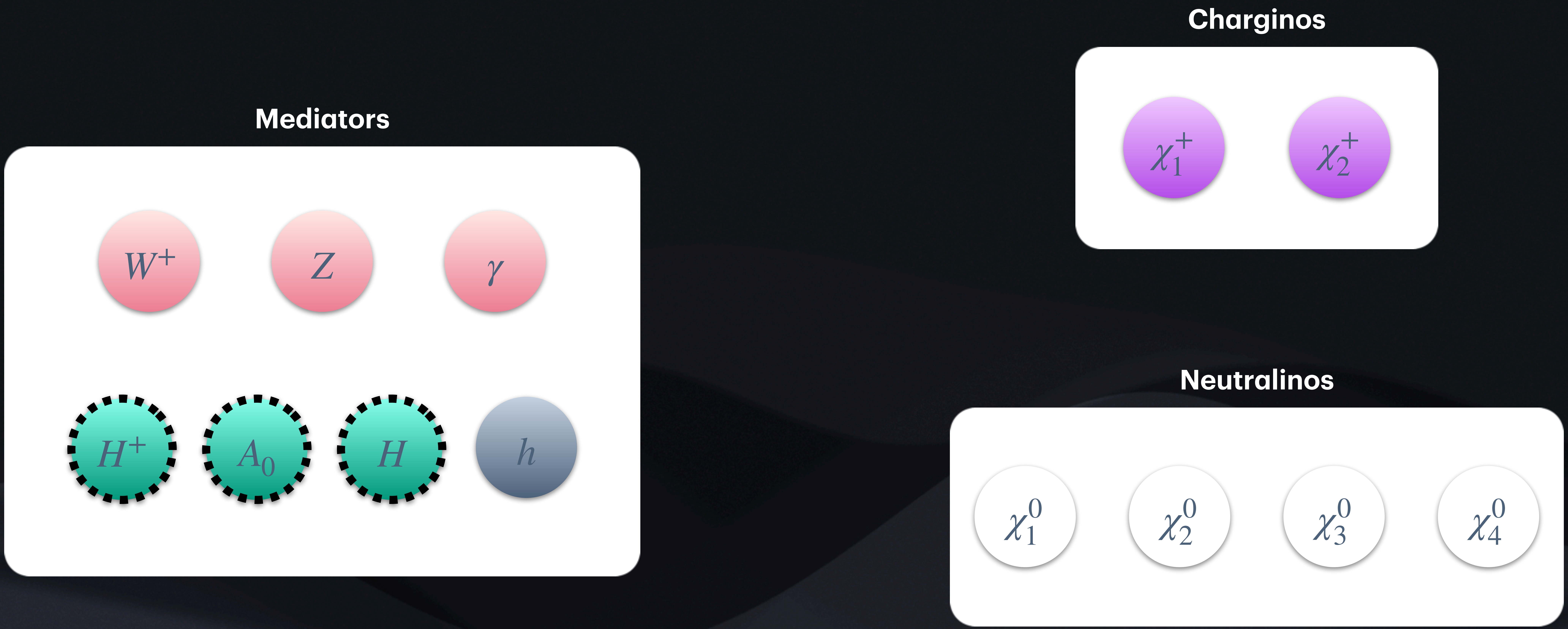
Mediators



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

Sommerfeld effect in the MSSM

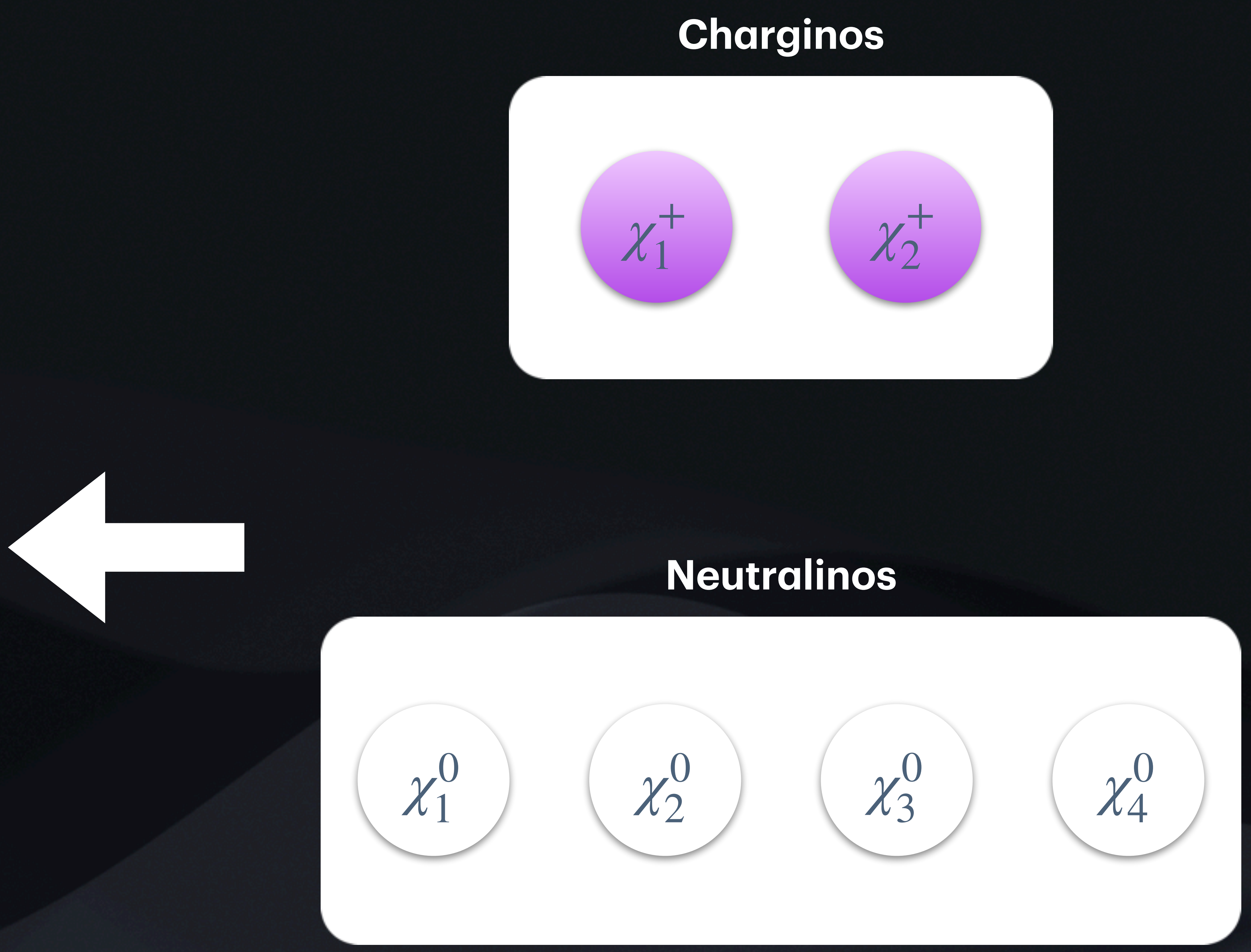
Dark Matter NR potential



Sommerfeld effect in the MSSM

Dark Matter NR potential

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



Sommerfeld effect in the MSSM

Dark Matter NR potential

$$
V(r) = \begin{pmatrix}
v_{(1\hat{1})(1\hat{1})} & v_{(1\hat{1})(1\hat{2})} & v_{(1\hat{1})(1\hat{3})} & v_{(1\hat{1})(1\hat{4})} & v_{(1\hat{1})(2\hat{2})} & v_{(1\hat{1})(2\hat{3})} & v_{(1\hat{1})(2\hat{4})} & v_{(1\hat{1})(3\hat{3})} & v_{(1\hat{1})(3\hat{4})} & v_{(1\hat{1})(4\hat{4})} & v_{(1\hat{1})\langle 1\bar{1}\rangle} & v_{(1\hat{1})\langle 1\bar{2}\rangle} & v_{(1\hat{1})\langle 2\bar{1}\rangle} & v_{(1\hat{1})\langle 2\bar{2}\rangle} \\
v_{(1\hat{2})(1\hat{1})} & v_{(1\hat{2})(1\hat{2})} & v_{(1\hat{2})(1\hat{3})} & v_{(1\hat{2})(1\hat{4})} & v_{(1\hat{2})(2\hat{2})} & v_{(1\hat{2})(2\hat{3})} & v_{(1\hat{2})(2\hat{4})} & v_{(1\hat{2})(3\hat{3})} & v_{(1\hat{2})(3\hat{4})} & v_{(1\hat{2})(4\hat{4})} & v_{(1\hat{2})\langle 1\bar{1}\rangle} & v_{(1\hat{2})\langle 1\bar{2}\rangle} & v_{(1\hat{2})\langle 2\bar{1}\rangle} & v_{(1\hat{2})\langle 2\bar{2}\rangle} \\
v_{(1\hat{3})(1\hat{1})} & v_{(1\hat{3})(1\hat{2})} & v_{(1\hat{3})(1\hat{3})} & v_{(1\hat{3})(1\hat{4})} & v_{(1\hat{2})(2\hat{2})} & v_{(1\hat{3})(2\hat{3})} & v_{(1\hat{3})(2\hat{4})} & v_{(1\hat{3})(3\hat{3})} & v_{(1\hat{3})(3\hat{4})} & v_{(1\hat{3})(4\hat{4})} & v_{(1\hat{3})\langle 1\bar{1}\rangle} & v_{(1\hat{3})\langle 1\bar{2}\rangle} & v_{(1\hat{3})\langle 2\bar{1}\rangle} & v_{(1\hat{3})\langle 2\bar{2}\rangle} \\
v_{(1\hat{4})(1\hat{1})} & v_{(1\hat{4})(1\hat{2})} & v_{(1\hat{4})(1\hat{3})} & v_{(1\hat{4})(1\hat{4})} & v_{(1\hat{2})(2\hat{2})} & v_{(1\hat{4})(2\hat{3})} & v_{(1\hat{4})(2\hat{4})} & v_{(1\hat{4})(3\hat{3})} & v_{(1\hat{4})(3\hat{4})} & v_{(1\hat{4})(4\hat{4})} & v_{(1\hat{4})\langle 1\bar{1}\rangle} & v_{(1\hat{4})\langle 1\bar{2}\rangle} & v_{(1\hat{4})\langle 2\bar{1}\rangle} & v_{(1\hat{4})\langle 2\bar{2}\rangle} \\
v_{(2\hat{2})(1\hat{1})} & v_{(2\hat{2})(1\hat{2})} & v_{(2\hat{2})(1\hat{3})} & v_{(2\hat{2})(1\hat{4})} & v_{(2\hat{2})(2\hat{2})} & v_{(2\hat{2})(2\hat{3})} & v_{(2\hat{2})(2\hat{4})} & v_{(2\hat{2})(3\hat{3})} & v_{(2\hat{2})(3\hat{4})} & v_{(2\hat{2})(4\hat{4})} & v_{(2\hat{2})\langle 1\bar{1}\rangle} & v_{(2\hat{2})\langle 1\bar{2}\rangle} & v_{(2\hat{2})\langle 2\bar{1}\rangle} & v_{(2\hat{2})\langle 2\bar{2}\rangle} \\
v_{(2\hat{3})(1\hat{1})} & v_{(2\hat{3})(1\hat{2})} & v_{(2\hat{3})(1\hat{3})} & v_{(2\hat{3})(1\hat{4})} & v_{(2\hat{3})(2\hat{2})} & v_{(2\hat{3})(2\hat{3})} & v_{(2\hat{3})(2\hat{4})} & v_{(2\hat{3})(3\hat{3})} & v_{(2\hat{3})(3\hat{4})} & v_{(2\hat{3})(4\hat{4})} & v_{(2\hat{3})\langle 1\bar{1}\rangle} & v_{(2\hat{3})\langle 1\bar{2}\rangle} & v_{(2\hat{3})\langle 2\bar{1}\rangle} & v_{(2\hat{3})\langle 2\bar{2}\rangle} \\
v_{(2\hat{4})(1\hat{1})} & v_{(2\hat{4})(1\hat{2})} & v_{(2\hat{4})(1\hat{3})} & v_{(2\hat{4})(1\hat{4})} & v_{(2\hat{4})(2\hat{2})} & v_{(2\hat{4})(2\hat{3})} & v_{(2\hat{4})(2\hat{4})} & v_{(2\hat{4})(3\hat{3})} & v_{(2\hat{4})(3\hat{4})} & v_{(2\hat{4})(4\hat{4})} & v_{(2\hat{4})\langle 1\bar{1}\rangle} & v_{(2\hat{4})\langle 1\bar{2}\rangle} & v_{(2\hat{4})\langle 2\bar{1}\rangle} & v_{(2\hat{4})\langle 2\bar{2}\rangle} \\
v_{(3\hat{3})(1\hat{1})} & v_{(3\hat{3})(1\hat{2})} & v_{(3\hat{3})(1\hat{3})} & v_{(3\hat{3})(1\hat{4})} & v_{(3\hat{3})(2\hat{2})} & v_{(3\hat{3})(2\hat{3})} & v_{(3\hat{3})(2\hat{4})} & v_{(3\hat{3})(3\hat{3})} & v_{(3\hat{3})(3\hat{4})} & v_{(3\hat{3})(4\hat{4})} & v_{(3\hat{3})\langle 1\bar{1}\rangle} & v_{(3\hat{3})\langle 1\bar{2}\rangle} & v_{(3\hat{3})\langle 2\bar{1}\rangle} & v_{(3\hat{3})\langle 2\bar{2}\rangle} \\
v_{(3\hat{4})(1\hat{1})} & v_{(3\hat{4})(1\hat{2})} & v_{(3\hat{4})(1\hat{3})} & v_{(3\hat{4})(1\hat{4})} & v_{(3\hat{4})(2\hat{2})} & v_{(3\hat{4})(2\hat{3})} & v_{(3\hat{4})(2\hat{4})} & v_{(3\hat{4})(3\hat{3})} & v_{(3\hat{4})(3\hat{4})} & v_{(3\hat{4})(4\hat{4})} & v_{(3\hat{4})\langle 1\bar{1}\rangle} & v_{(3\hat{4})\langle 1\bar{2}\rangle} & v_{(3\hat{4})\langle 2\bar{1}\rangle} & v_{(3\hat{4})\langle 2\bar{2}\rangle} \\
v_{(4\hat{4})(1\hat{1})} & v_{(4\hat{4})(1\hat{2})} & v_{(4\hat{4})(1\hat{3})} & v_{(4\hat{4})(1\hat{4})} & v_{(4\hat{4})(2\hat{2})} & v_{(4\hat{4})(2\hat{3})} & v_{(4\hat{4})(2\hat{4})} & v_{(4\hat{4})(3\hat{3})} & v_{(4\hat{4})(3\hat{4})} & v_{(4\hat{4})(4\hat{4})} & v_{(4\hat{4})\langle 1\bar{1}\rangle} & v_{(4\hat{4})\langle 1\bar{2}\rangle} & v_{(4\hat{4})\langle 2\bar{1}\rangle} & v_{(4\hat{4})\langle 2\bar{2}\rangle} \\
v_{\langle 1\bar{1}\rangle(1\hat{1})} & v_{\langle 1\bar{1}\rangle(1\hat{2})} & v_{\langle 1\bar{1}\rangle(1\hat{3})} & v_{\langle 1\bar{1}\rangle(1\hat{4})} & v_{\langle 1\bar{1}\rangle(2\hat{2})} & v_{\langle 1\bar{1}\rangle(2\hat{3})} & v_{\langle 1\bar{1}\rangle(2\hat{4})} & v_{\langle 1\bar{1}\rangle(3\hat{3})} & v_{\langle 1\bar{1}\rangle(3\hat{4})} & v_{\langle 1\bar{1}\rangle(4\hat{4})} & v_{\langle 1\bar{1}\rangle\langle 1\bar{1}\rangle} & v_{\langle 1\bar{1}\rangle\langle 1\bar{2}\rangle} & v_{\langle 1\bar{1}\rangle\langle 2\bar{1}\rangle} & v_{\langle 1\bar{1}\rangle\langle 2\bar{2}\rangle} \\
v_{\langle 1\bar{2}\rangle(1\hat{1})} & v_{\langle 1\bar{2}\rangle(1\hat{2})} & v_{\langle 1\bar{2}\rangle(1\hat{3})} & v_{\langle 1\bar{2}\rangle(1\hat{4})} & v_{\langle 1\bar{2}\rangle(2\hat{2})} & v_{\langle 1\bar{2}\rangle(2\hat{3})} & v_{\langle 1\bar{2}\rangle(2\hat{4})} & v_{\langle 1\bar{2}\rangle(3\hat{3})} & v_{\langle 1\bar{2}\rangle(3\hat{4})} & v_{\langle 1\bar{2}\rangle(4\hat{4})} & v_{\langle 1\bar{2}\rangle\langle 1\bar{1}\rangle} & v_{\langle 1\bar{2}\rangle\langle 1\bar{2}\rangle} & v_{\langle 1\bar{2}\rangle\langle 2\bar{1}\rangle} & v_{\langle 1\bar{2}\rangle\langle 2\bar{2}\rangle} \\
v_{\langle 2\bar{1}\rangle(1\hat{1})} & v_{\langle 2\bar{1}\rangle(1\hat{2})} & v_{\langle 2\bar{1}\rangle(1\hat{3})} & v_{\langle 2\bar{1}\rangle(1\hat{4})} & v_{\langle 2\bar{1}\rangle(2\hat{2})} & v_{\langle 2\bar{1}\rangle(2\hat{3})} & v_{\langle 2\bar{1}\rangle(2\hat{4})} & v_{\langle 2\bar{1}\rangle(3\hat{3})} & v_{\langle 2\bar{1}\rangle(3\hat{4})} & v_{\langle 2\bar{1}\rangle(4\hat{4})} & v_{\langle 2\bar{1}\rangle\langle 1\bar{1}\rangle} & v_{\langle 2\bar{1}\rangle\langle 1\bar{2}\rangle} & v_{\langle 2\bar{1}\rangle\langle 2\bar{1}\rangle} & v_{\langle 2\bar{1}\rangle\langle 2\bar{2}\rangle} \\
v_{\langle 2\bar{2}\rangle(1\hat{1})} & v_{\langle 2\bar{2}\rangle(1\hat{2})} & v_{\langle 2\bar{2}\rangle(1\hat{3})} & v_{\langle 2\bar{2}\rangle(1\hat{4})} & v_{\langle 2\bar{2}\rangle(2\hat{2})} & v_{\langle 2\bar{2}\rangle(2\hat{3})} & v_{\langle 2\bar{2}\rangle(2\hat{4})} & v_{\langle 2\bar{2}\rangle(3\hat{3})} & v_{\langle 2\bar{2}\rangle(3\hat{4})} & v_{\langle 2\bar{2}\rangle(4\hat{4})} & v_{\langle 2\bar{2}\rangle\langle 1\bar{1}\rangle} & v_{\langle 2\bar{2}\rangle\langle 1\bar{2}\rangle} & v_{\langle 2\bar{2}\rangle\langle 2\bar{1}\rangle} & v_{\langle 2\bar{2}\rangle\langle 2\bar{2}\rangle}
\end{pmatrix}
$$

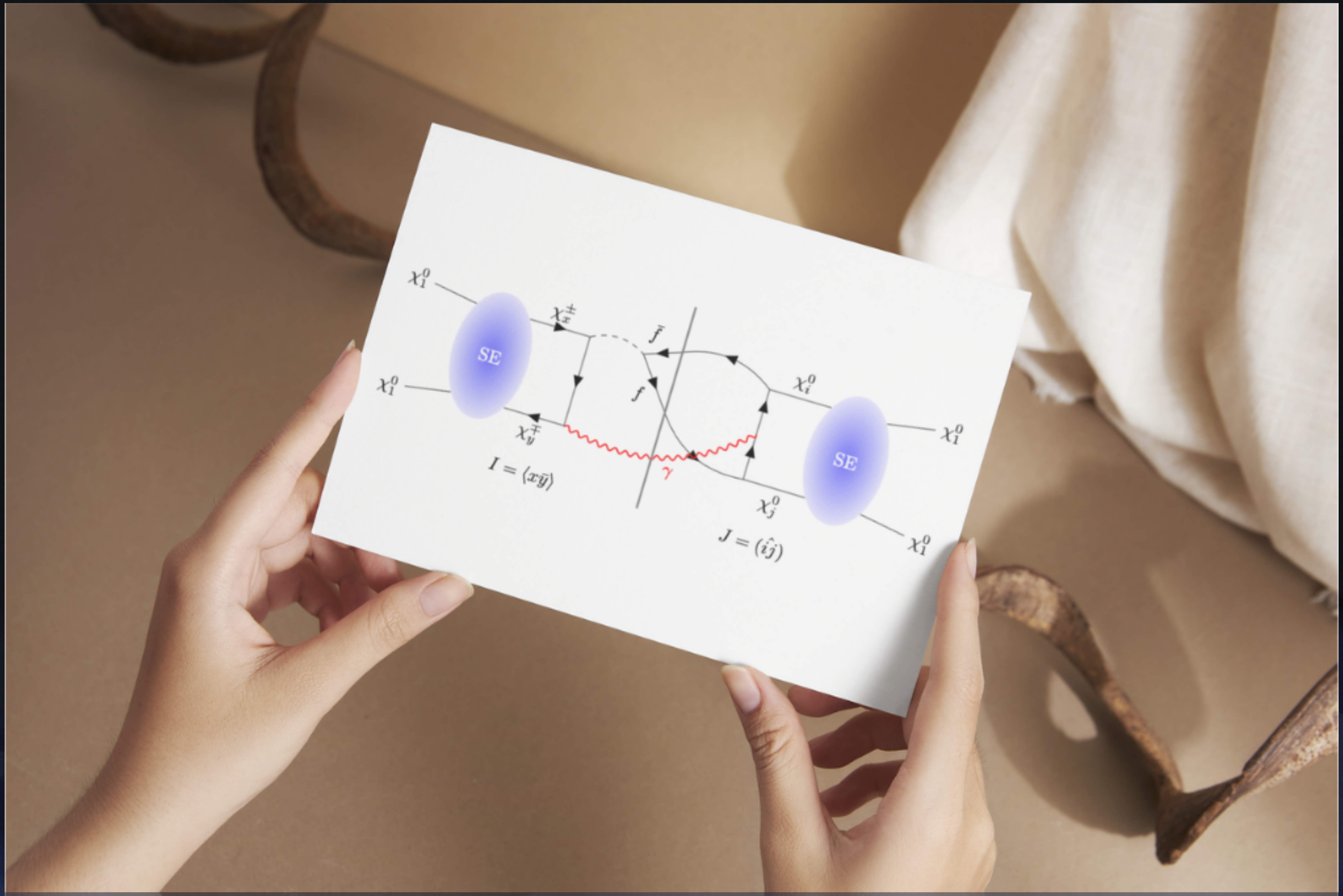
Sommerfeld effect in the MSSM

14×14 matrix

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

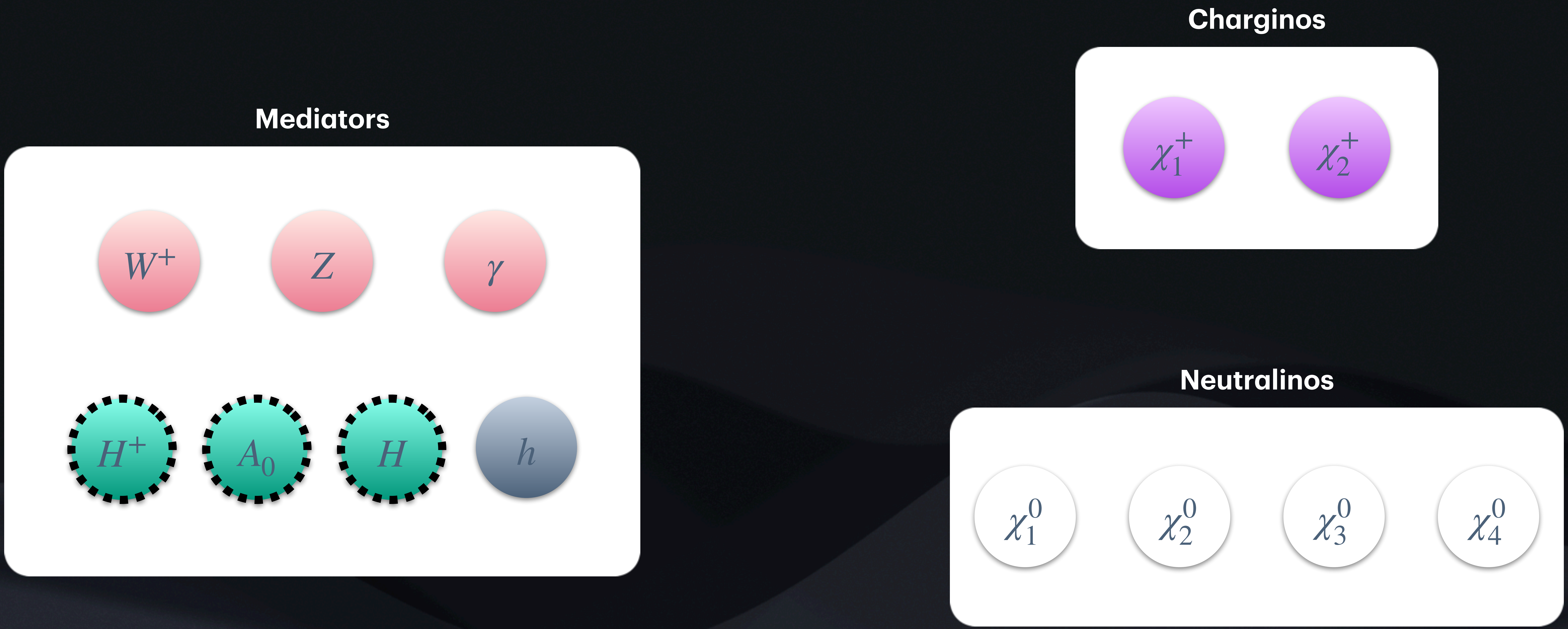
105 independent terms

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

Neutralinos

χ_1^0 χ_2^0

Charginos

χ_1^+

Mediators

W^+ Z γ

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

Further properties:

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

Outline

Motivation

Indirect detection

Sommerfeld effect

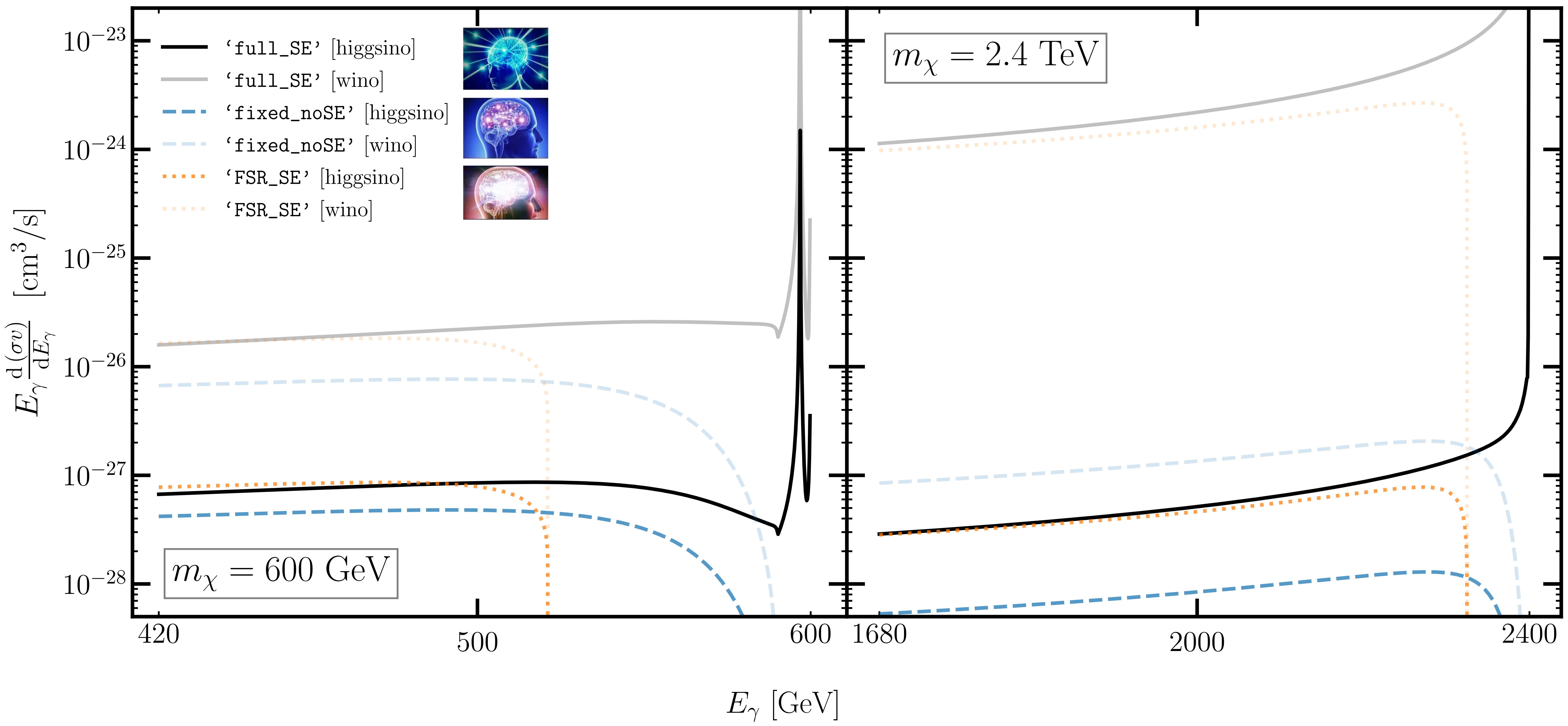
Continuum gamma rays for MSSM neutralinos

Numerics

Conclusions

Numerics

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]

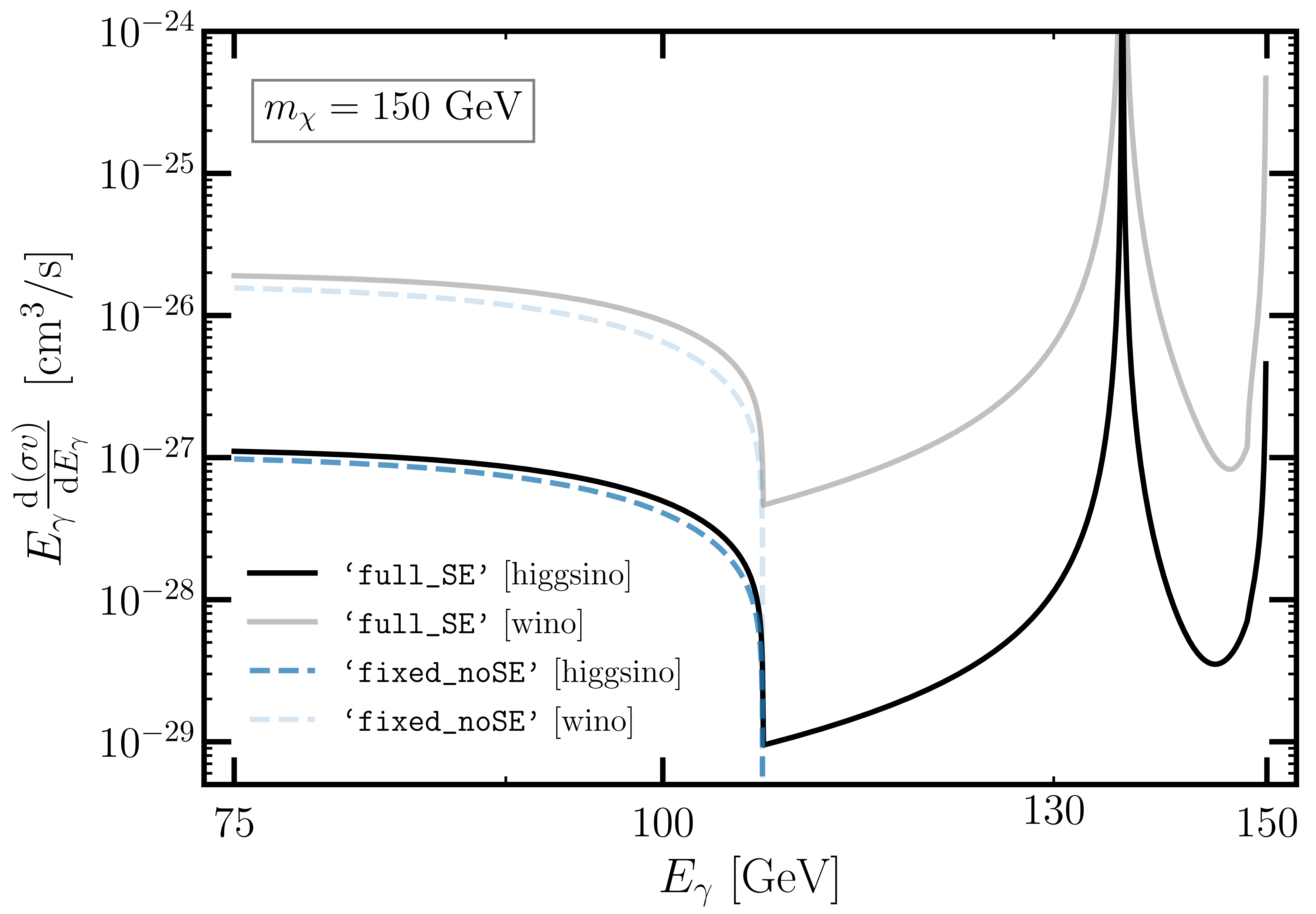
‘fixed_noSE’ [wino]

‘FSR_SE’ [higgsino]

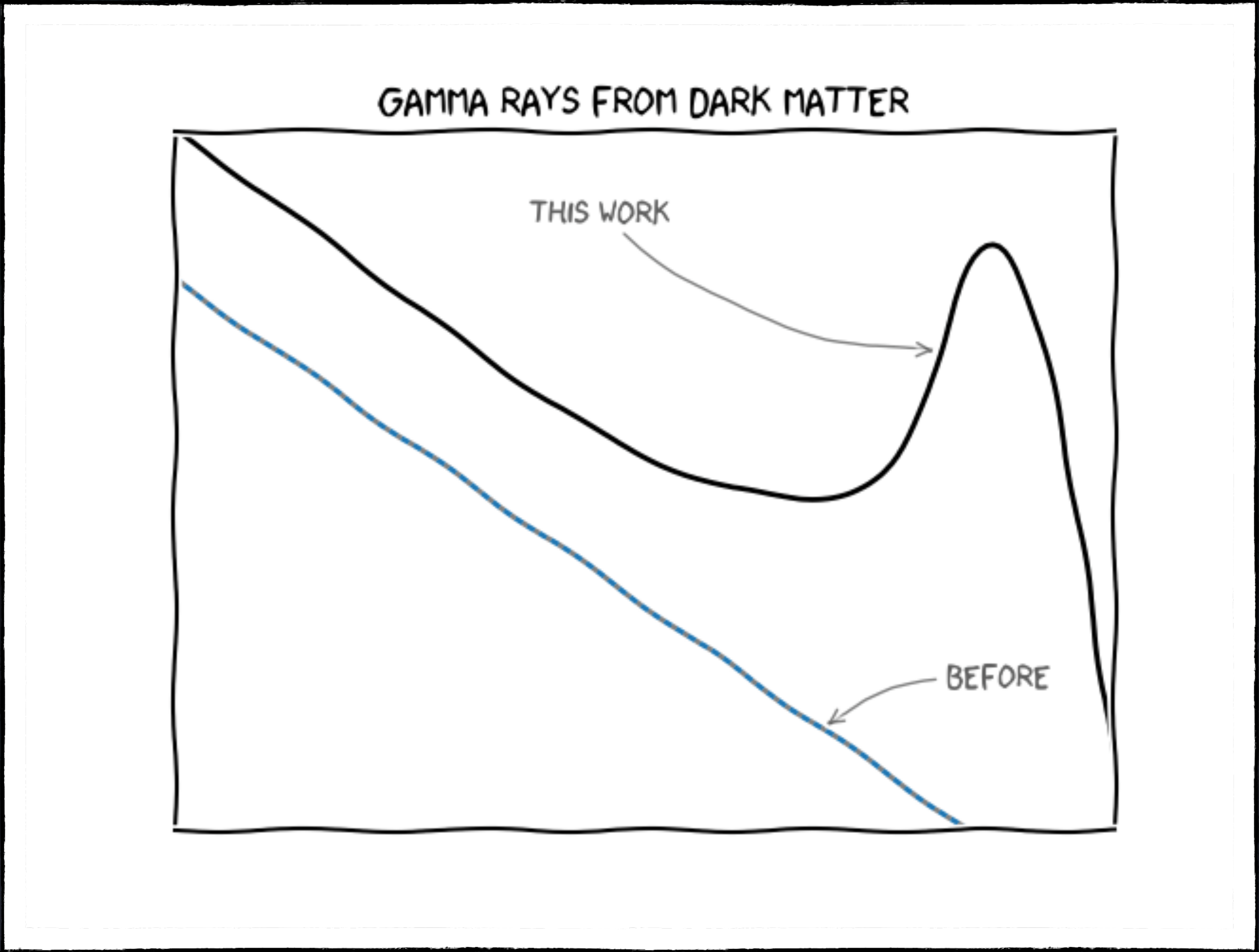
‘FSR_SE’ [wino]

Lighter winos/higgsinos

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

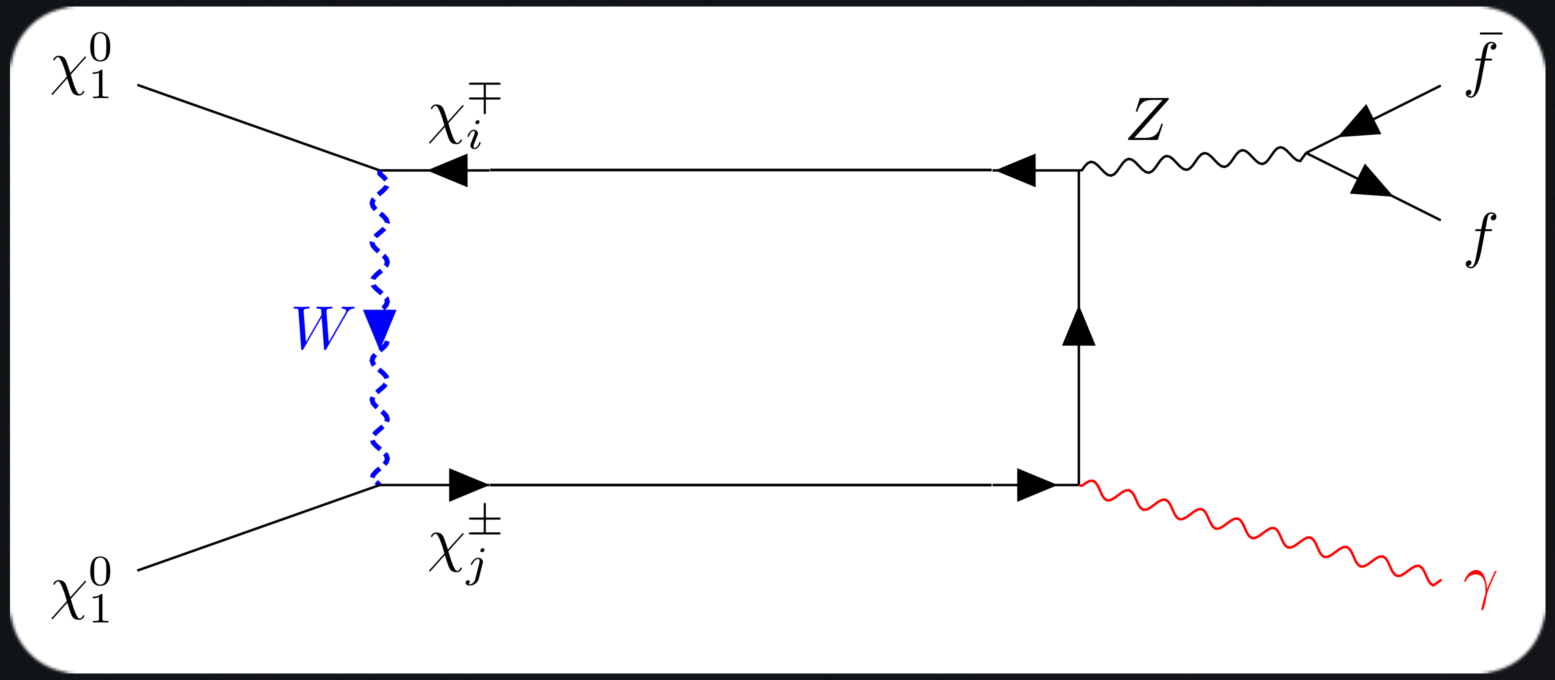


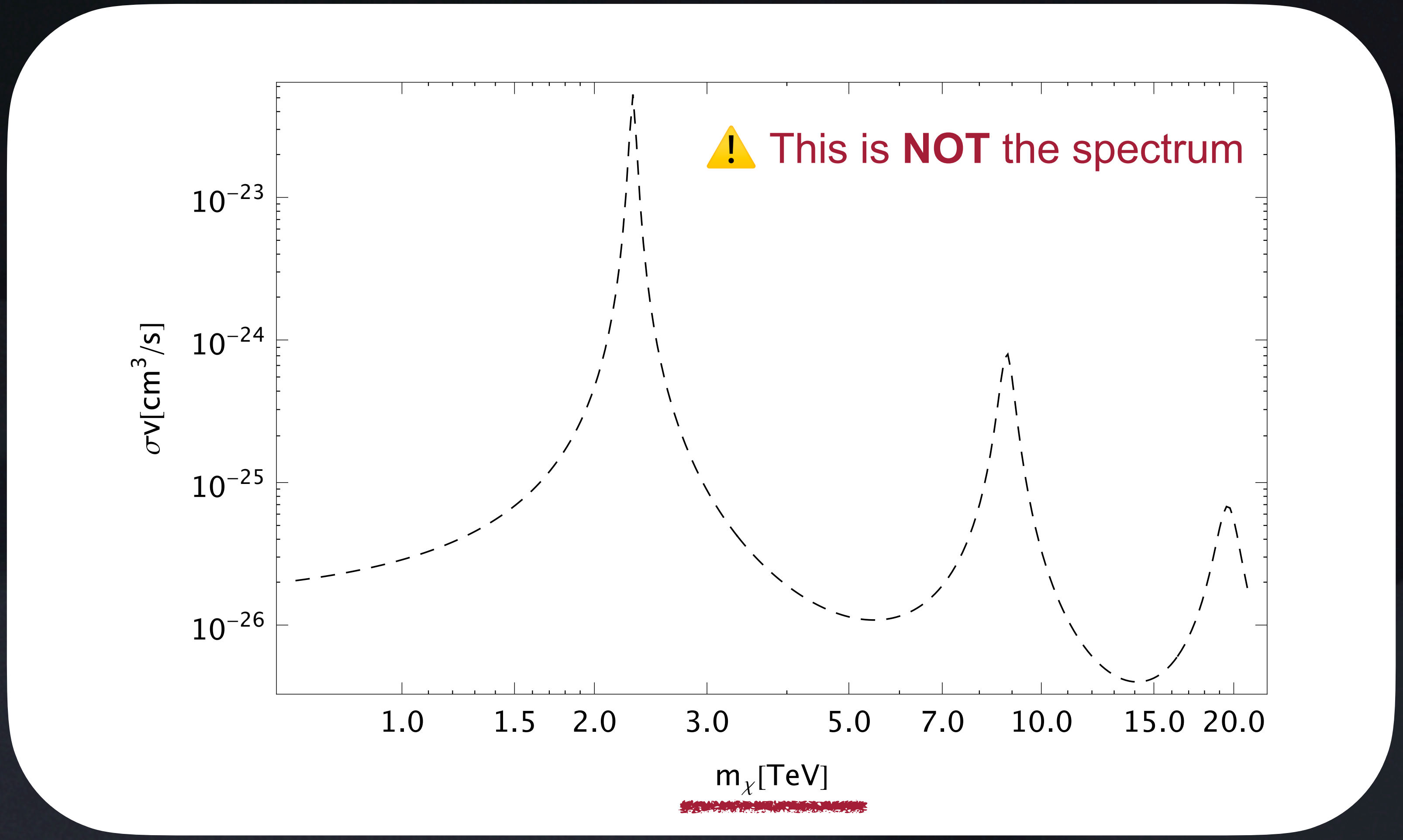
What's going on ?

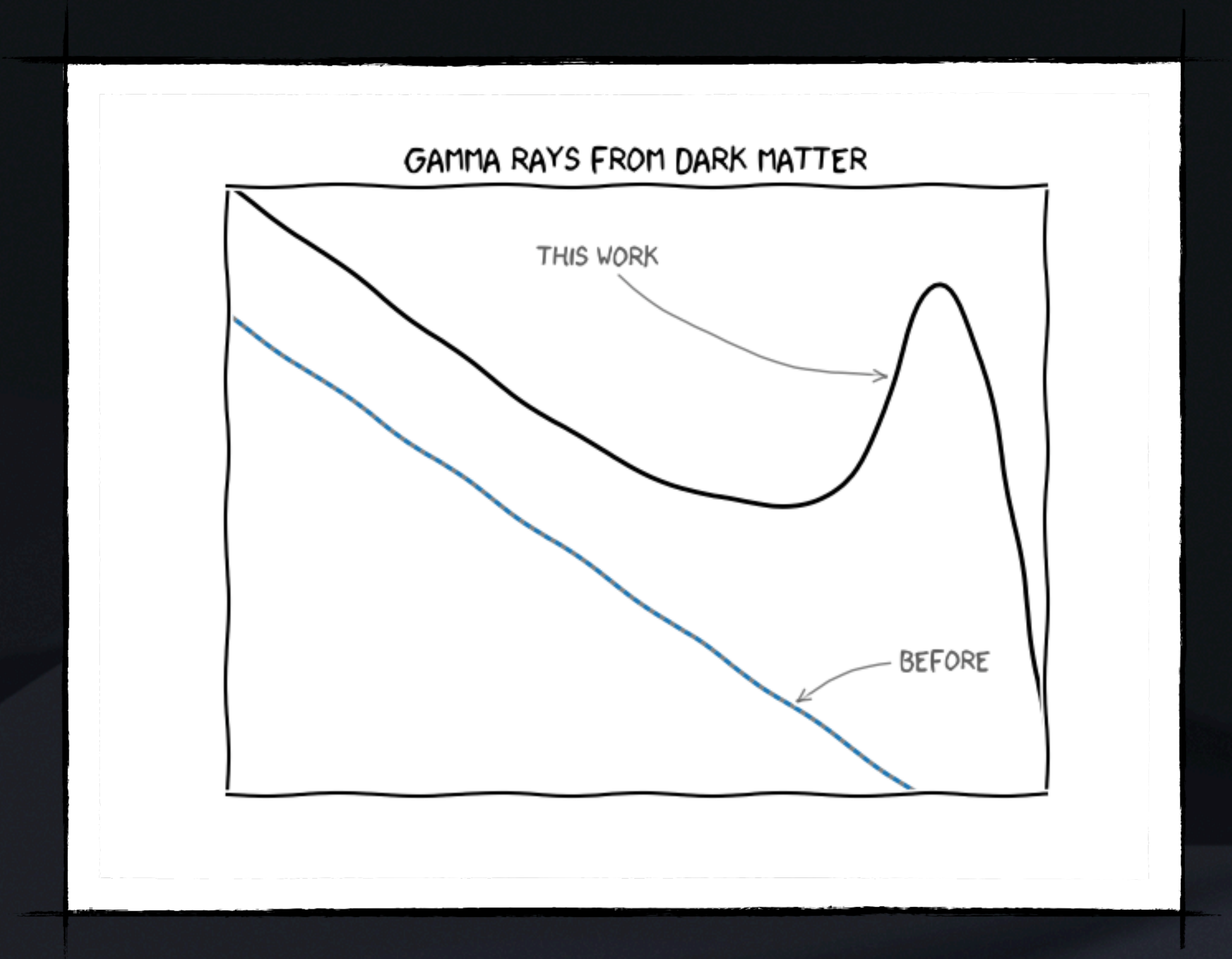


What's going on ?

Charginos are electrically charged / Sommerfeld resonances

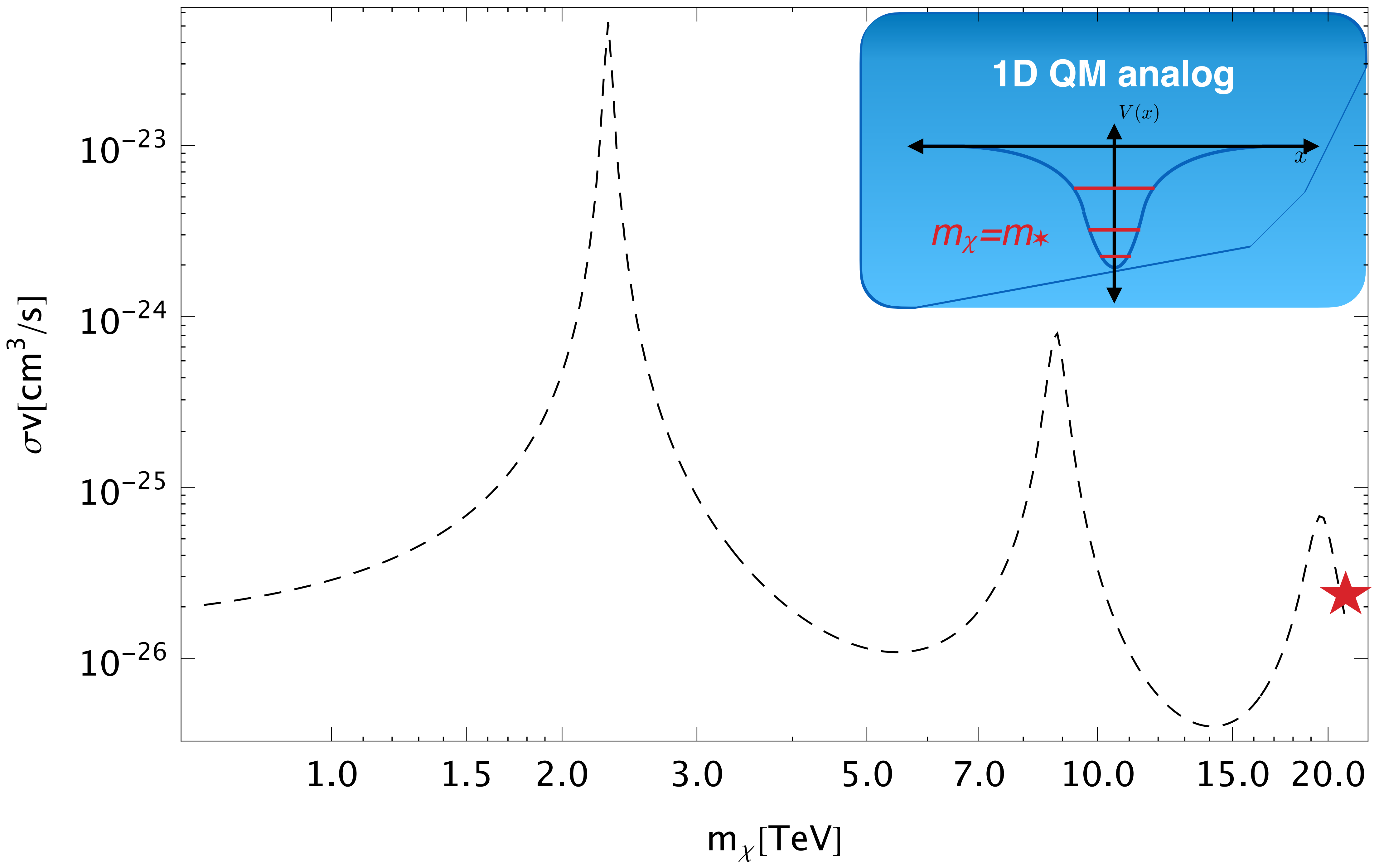






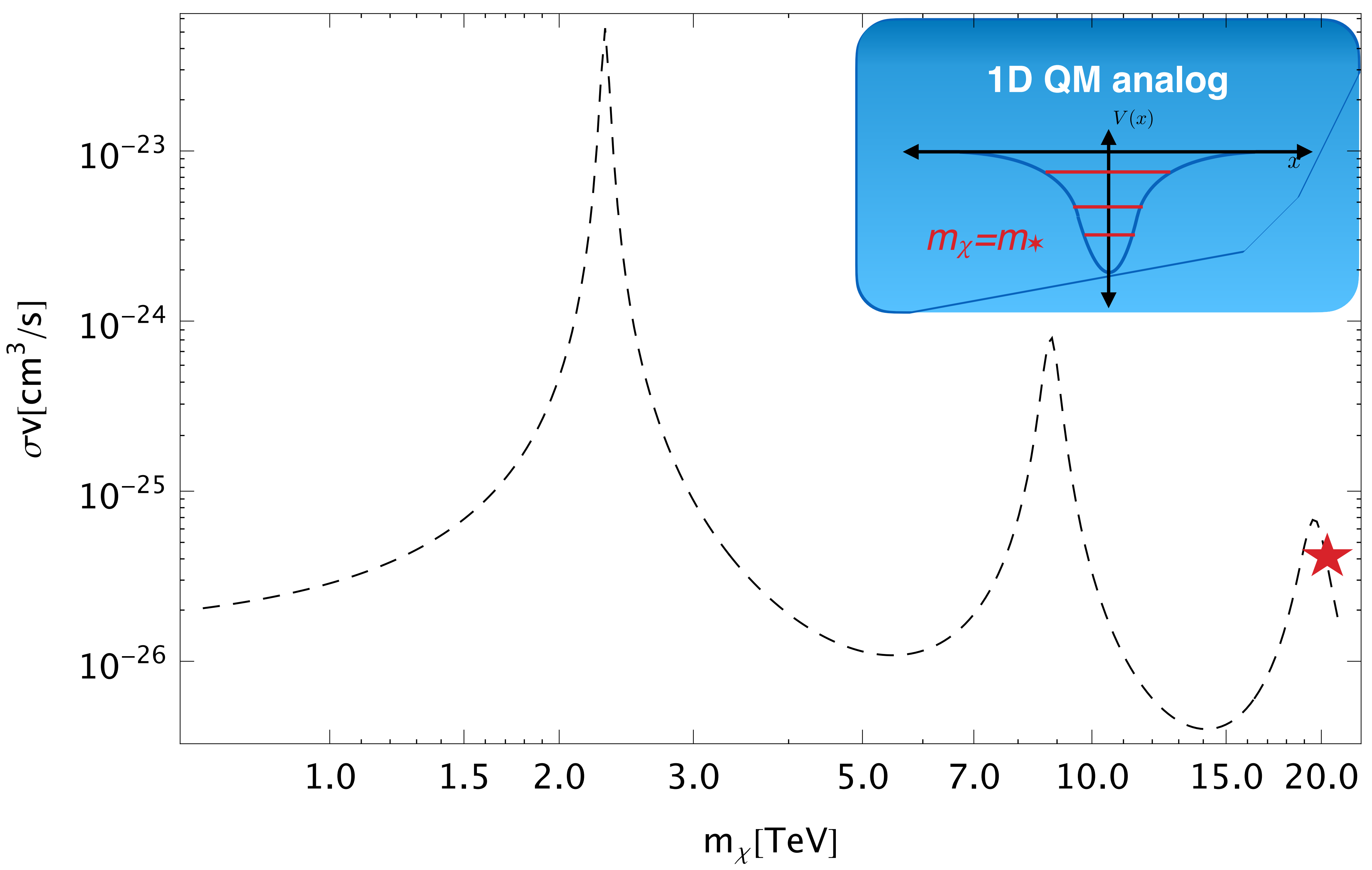
What's going on ?

Sommerfeld resonances



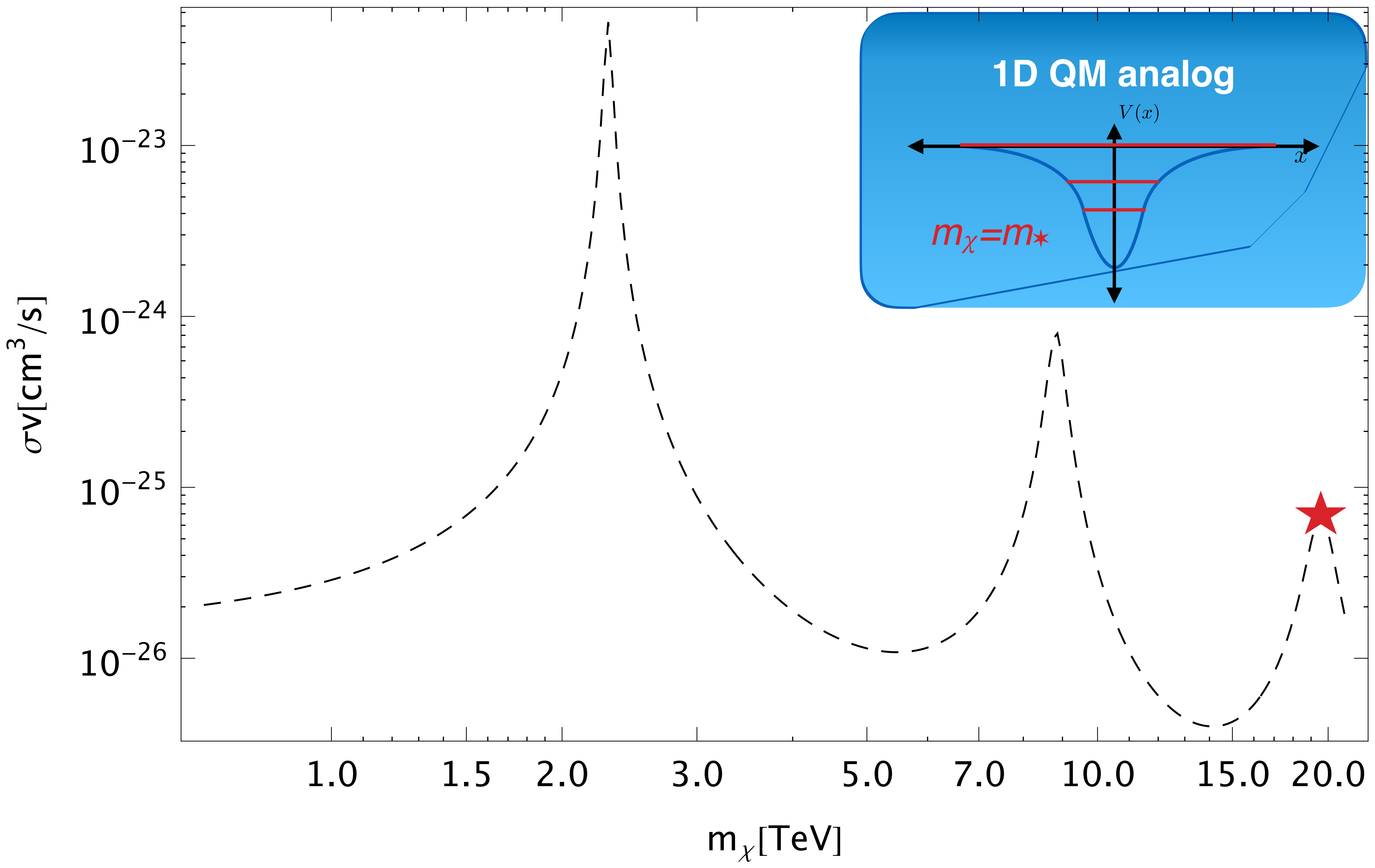
What's going on ?

Sommerfeld resonances

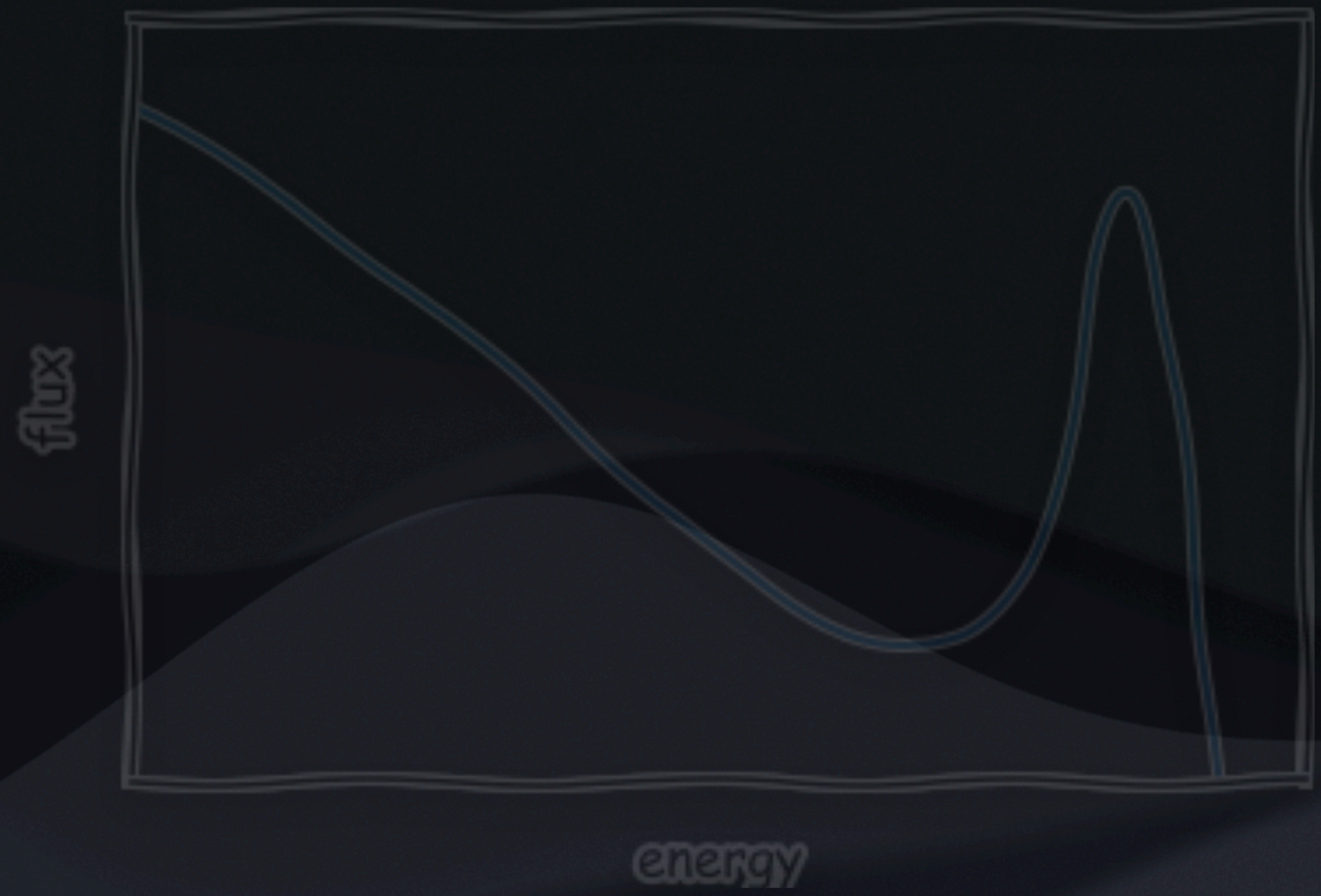


What's going on ?

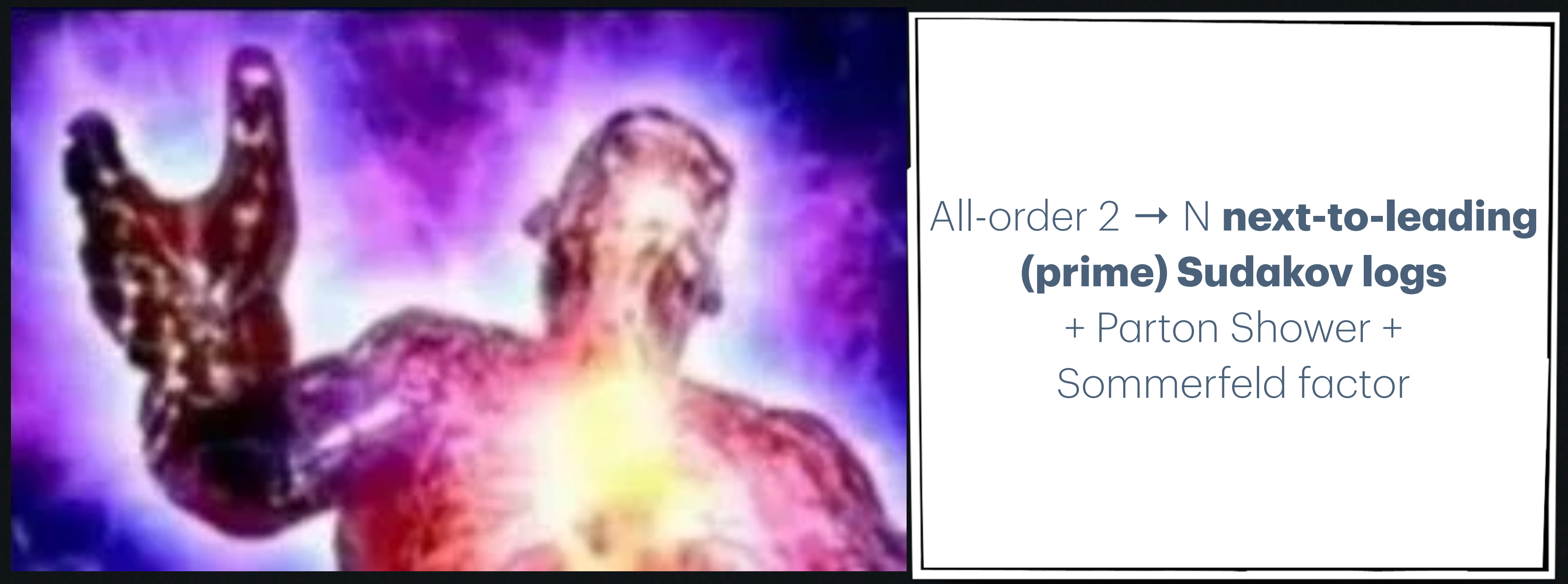
Sommerfeld resonances



Possible approaches



Possible approaches



Possible approaches

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

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

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

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

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

Electroweak resummation of neutralino dark-matter annihilation into high-energy photons

M. Beneke[a], S. Lederer[a], and C. Peset[b]

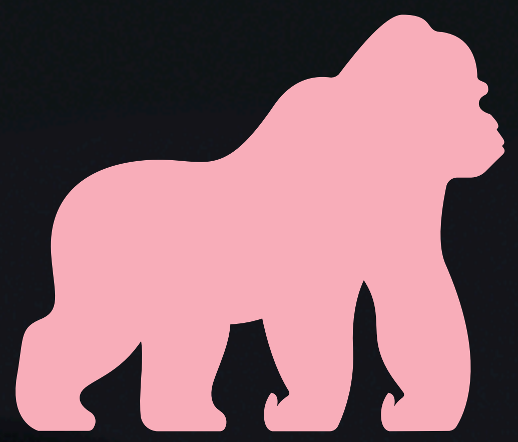
[a] *Physik Department T31, James-Franck-Straße 1, Technische Universität München, D–85748 Garching, Germany*

[b] *Dpto. de Física Teórica & IPARCOS, Universidad Complutense de Madrid, E–28040 Madrid, Spain*

Resummation

Goal: factor out the "gorillas"

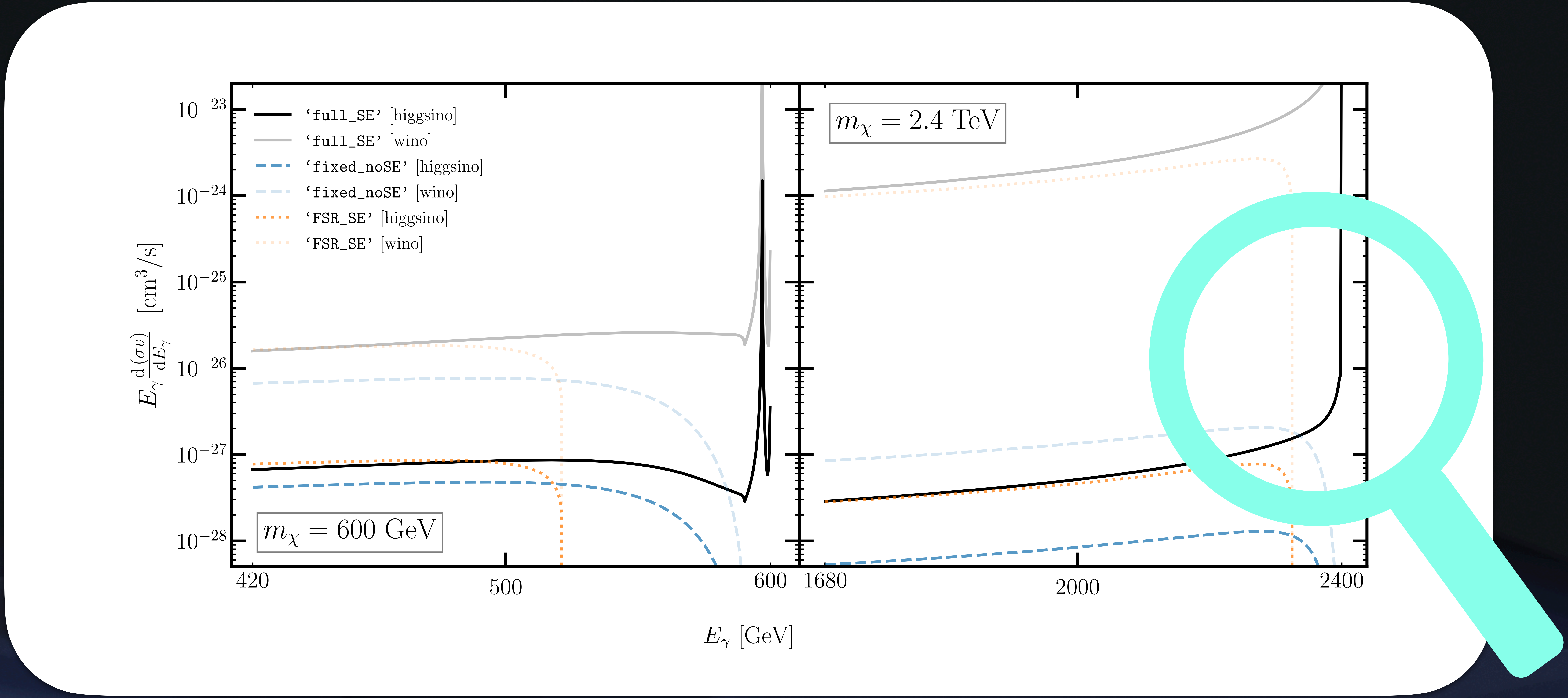
$$\frac{\mathrm{d}\,\sigma v}{\mathrm{d}\,E_\gamma} = f\Big(\alpha_{ew} \times$$



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

"safe" to use perturbation theory

?

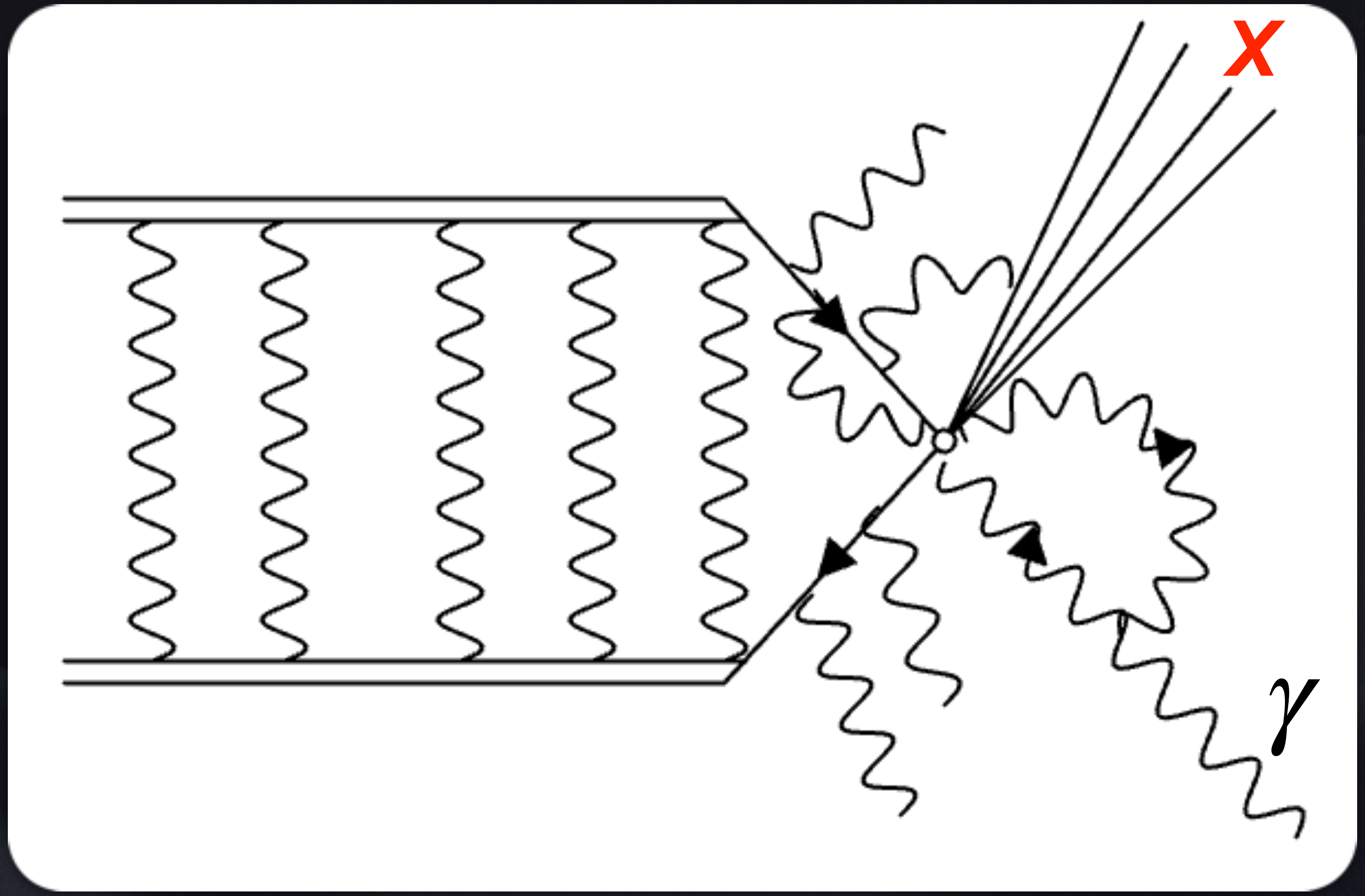

'full_SE' [higgsino]
'full_SE' [wino]
'fixed_noSE' [higgsino]
'fixed_noSE' [wino]
'FSR_SE' [higgsino]
'FSR_SE' [wino]
$m_\chi = 600$ GeV
$m_\chi = 2.4$ TeV
$E_\gamma \frac{\mathrm{d}(\sigma v)}{\mathrm{d}E_\gamma}$ [cm^3/s]
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
420
500
600
1680
2000
2400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

Sudakov double-log resummation

Soft-collinear effective field theory approach

$$\left[\frac{\mathrm{d}(\tilde{\sigma v})}{\mathrm{d}E_\gamma}\right]_{IJ} = \frac{1}{(\sqrt{2})^{n_{id}}}\frac{1}{4}\frac{2}{\pi m_\chi}\sum_{i,j} C_i(\mu)C_j^*(\mu) \times Z_\gamma^{33}(\mu,\nu) \times \int \mathrm{d}\omega J^{\mathrm{SU(2)}}(4m_\chi(m_\chi - E_\gamma - \omega/2),\mu)\tilde{W}_{IJ}^{ij}(\omega,\mu,\nu)$$

Endpoint → $m_X^2 \ll 4m_\chi^2$



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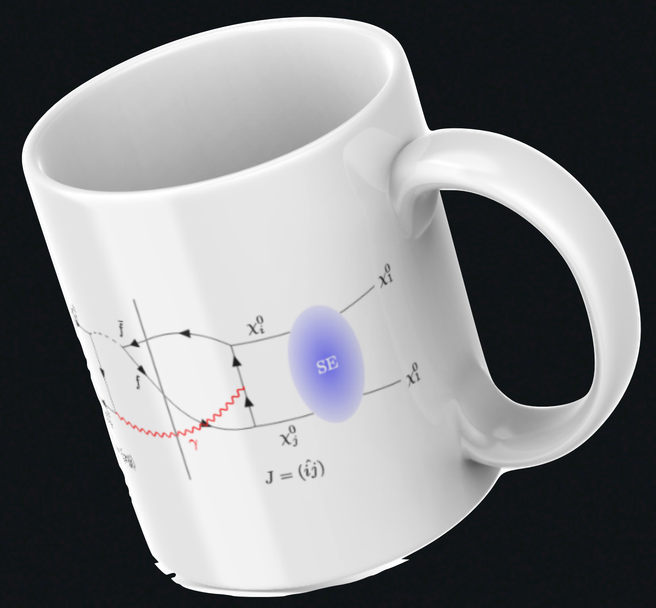

- Cherenkov telescopes are excelent instruments to search for TeV-scale SUSY
- Beautiful and complex phenomenology for indirect detection: Sommerfeld effect, internal bremsstrahlung, resonances, spectral lines, radiative electroweak effects, ...
- Incorporated all these effects (consistently) for the first time!
    - Most complete theoretical prediction for the continuum gamma-ray spectrum from MSSM neutralinos
        - See **2310.11067**
- Effects can lead to qualitative differences with respect to previous calculations
    - Thorough explorations in the remaining 2020s are thus **crucial**