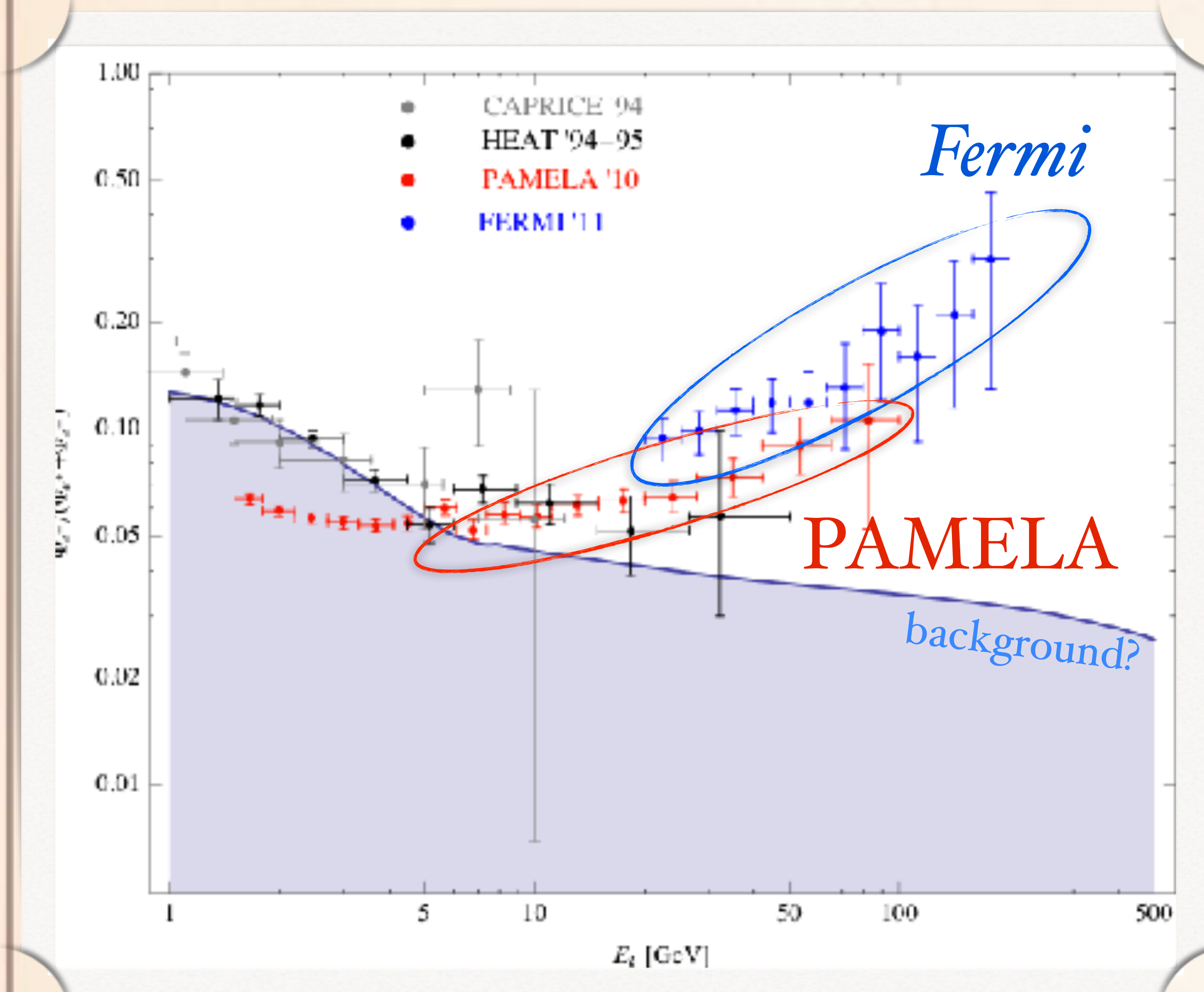
# SOMMERFELD EFFECT
## FROM THE MSSM PERSPECTIVE
### RELIC DENSITY AND INDIRECT DETECTION

Andrzej Hryczuk

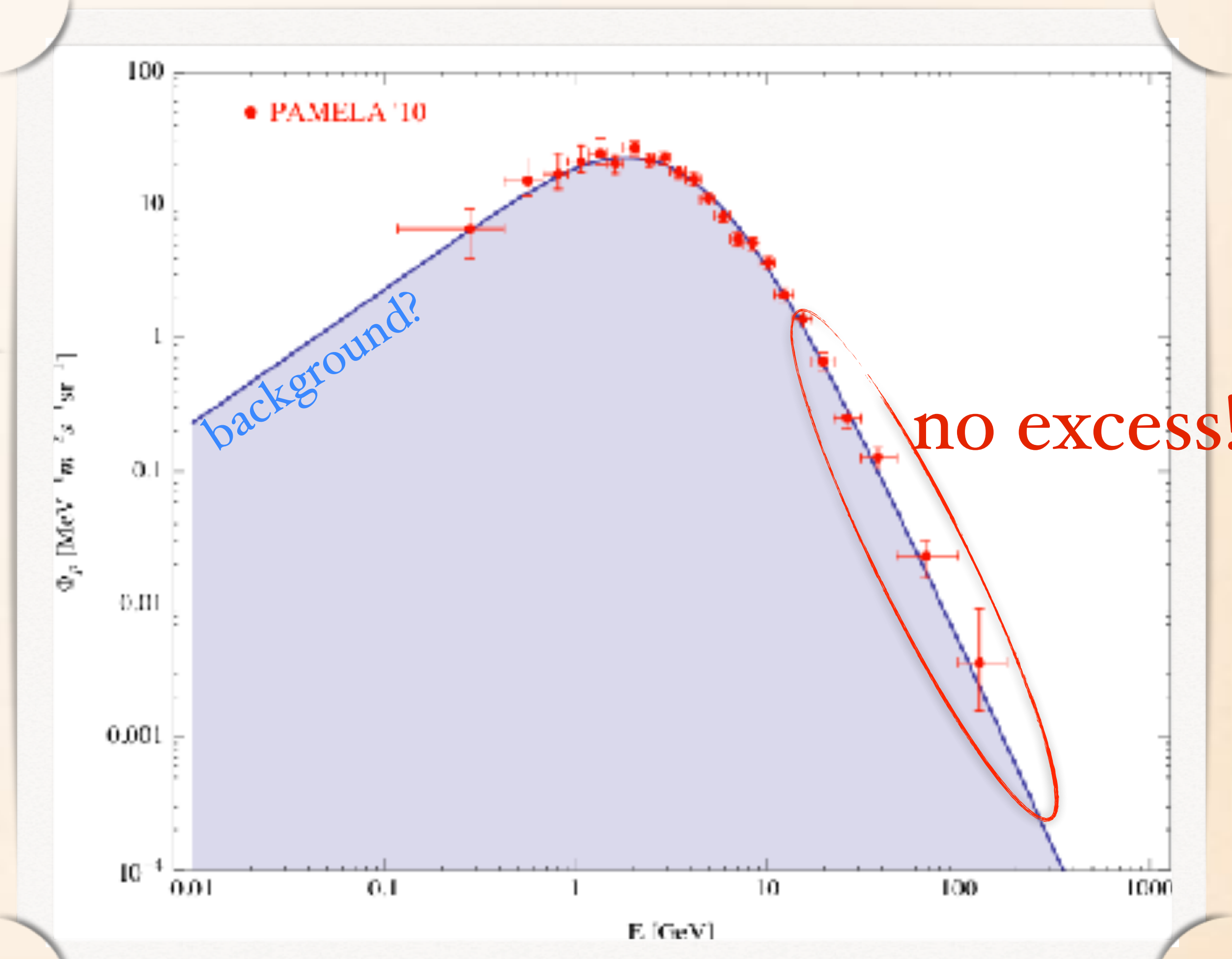
- Electroweak loop corrections — AH, R. Iengo; 1111.2916
- Sommerfeld effect — AH, R. Iengo, P. Ullio; 1010.2172
  AH; 1102.4295
- Implications for indirect detection

AH, R. Iengo, I. Cholis, M. Tavakoli, P. Ullio; 1103.????

# CR LEPTON PUZZLE

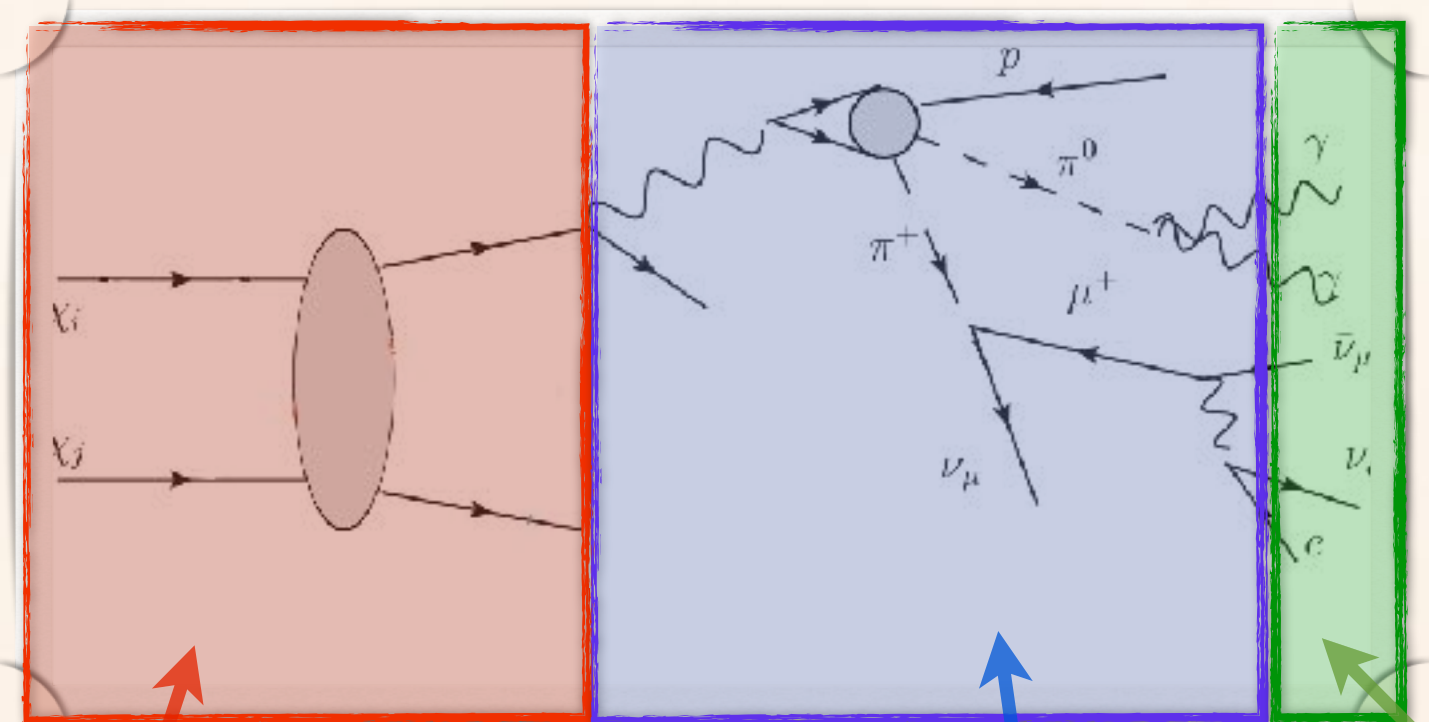



Unexpected rise in positron fraction spectrum observed for $E \gtrsim 10$ GeV




... but no accompanying excess in antiproton flux!

# Dark Matter annihilation

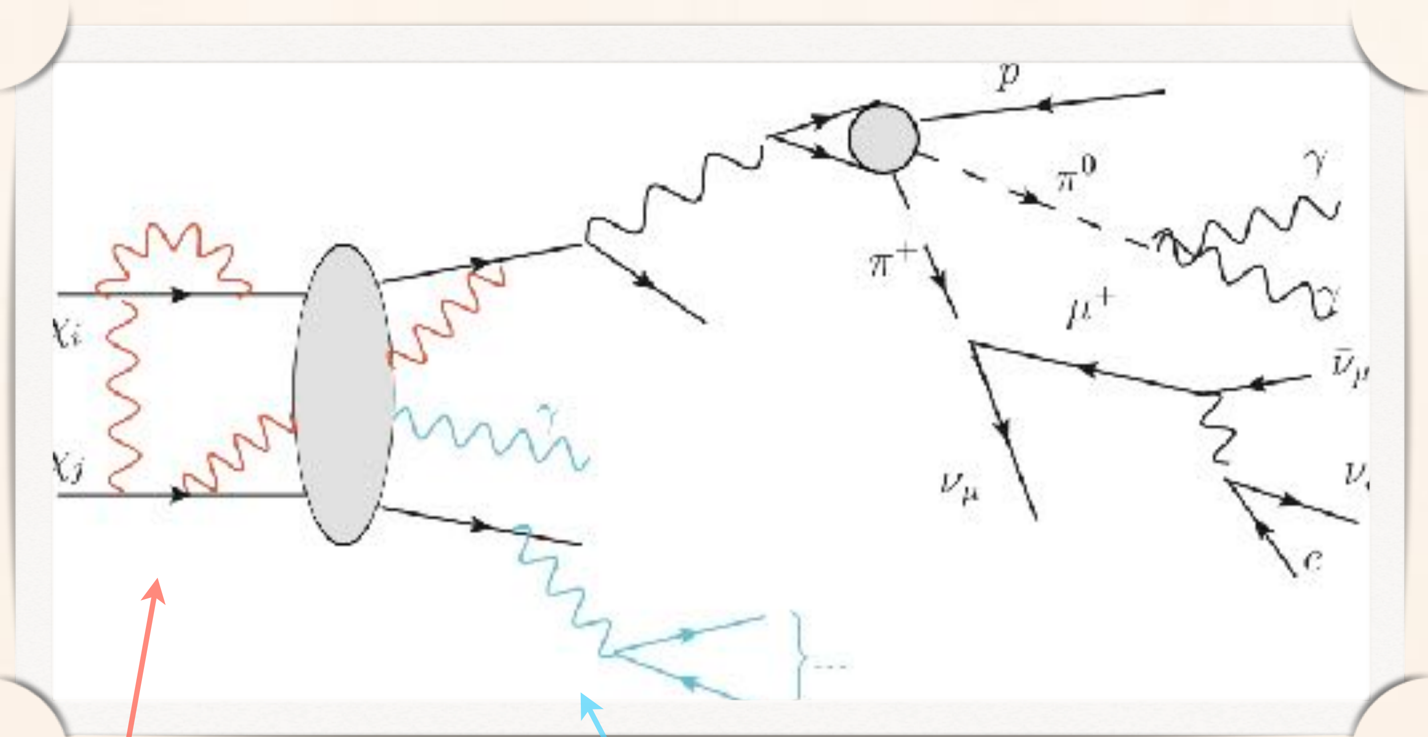



primary annihilation process

shower development: splitting, hadronization, fragmentation/decay (e.g. PYTHIA)

indirect detection

# DARK MATTER ANNIHILATION
## WITH EW CORRECTIONS




loop corrections

internal bremsstrahlung

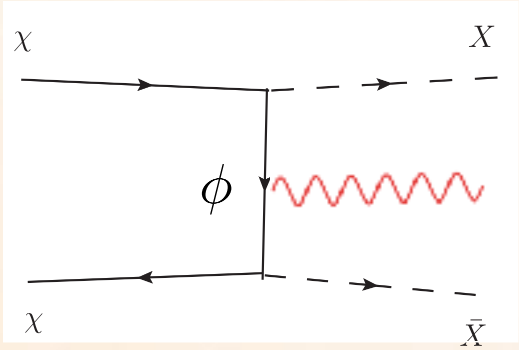
# When the effect is large?
## 1. virtual Internal Bremsstrahlung

i) Gauge boson emission evades a symmetry constraint

→ e.g. helicity suppression lifting

Bergstrom, Phys. Lett. B225 (1989) 372

ii) t - channel annihilation into bosons




$$D_t = \frac{1}{m_\chi^2 - m_\phi^2 + m_X^2 + 2m_\chi E_X}$$

if $\approx 0$ enhancement for small $E_X$

Bringmann *et al.*,JHEP 0801 (2008) 049

model dependent!

# When the effect is large?

## 2. final state radiation

iii) TeV-scale DM

→ enhancement by large (Sudakov) logarithms

$$\alpha_2 \log \frac{m^2}{m_W^2} \qquad \qquad \alpha_2 \left( \log \frac{m^2}{m_W^2} \right)^2$$

$$m = 1 \text{ TeV}, \ \alpha_2 \approx \frac{1}{30} \quad \Rightarrow \quad \approx 0.17 \qquad \qquad \approx 0.86$$

$m \gg m_W$ resambles IR divergence of QED or QCD

→ Bloch-Nordsieck violation

Ciafaloni *et al.*, Nucl. Phys. B589 (2000) 359

Bloch-Nordsieck: QED in the **inclusive** cross-section IR logs cancel

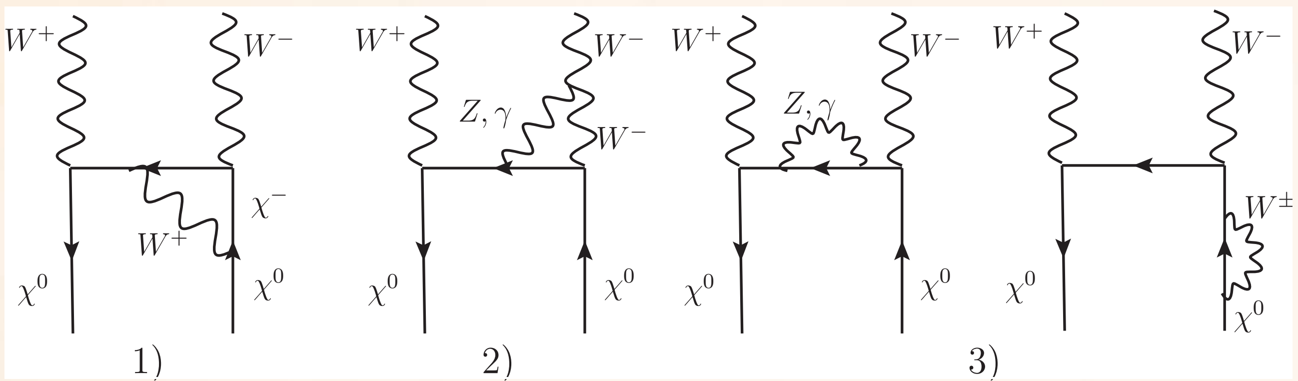
Kinoshita-Lee-Nauenberg: generalized to SM, but only when summed over initial non-abelian charge

model independent!

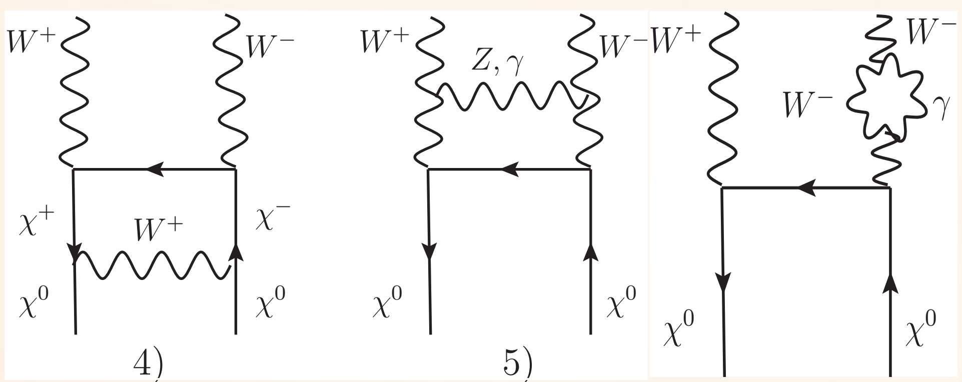
Ciafaloni *et al.*, JCAP 1103 (2011) 09

PPPC 4DM ID: Cirelli *et al.*, JCAP 1103(2011) 051

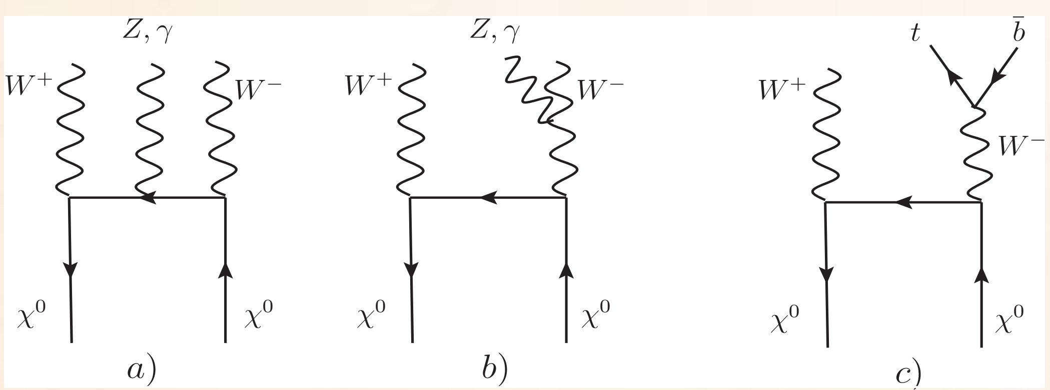
# ONE-LOOP COMPUTATION
## FOR A WINO DM MODEL




UV divergent



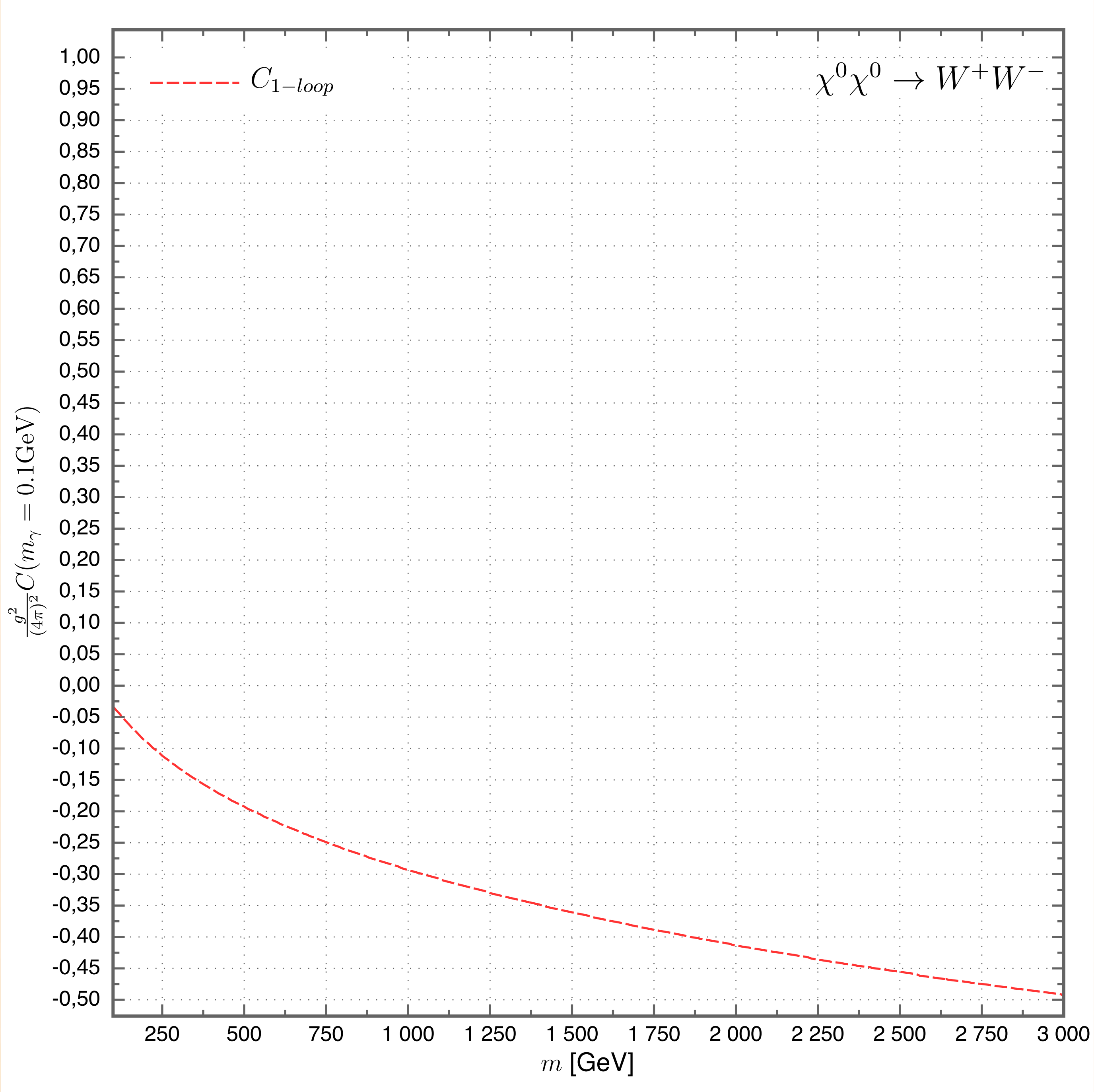

UV finite




radiative

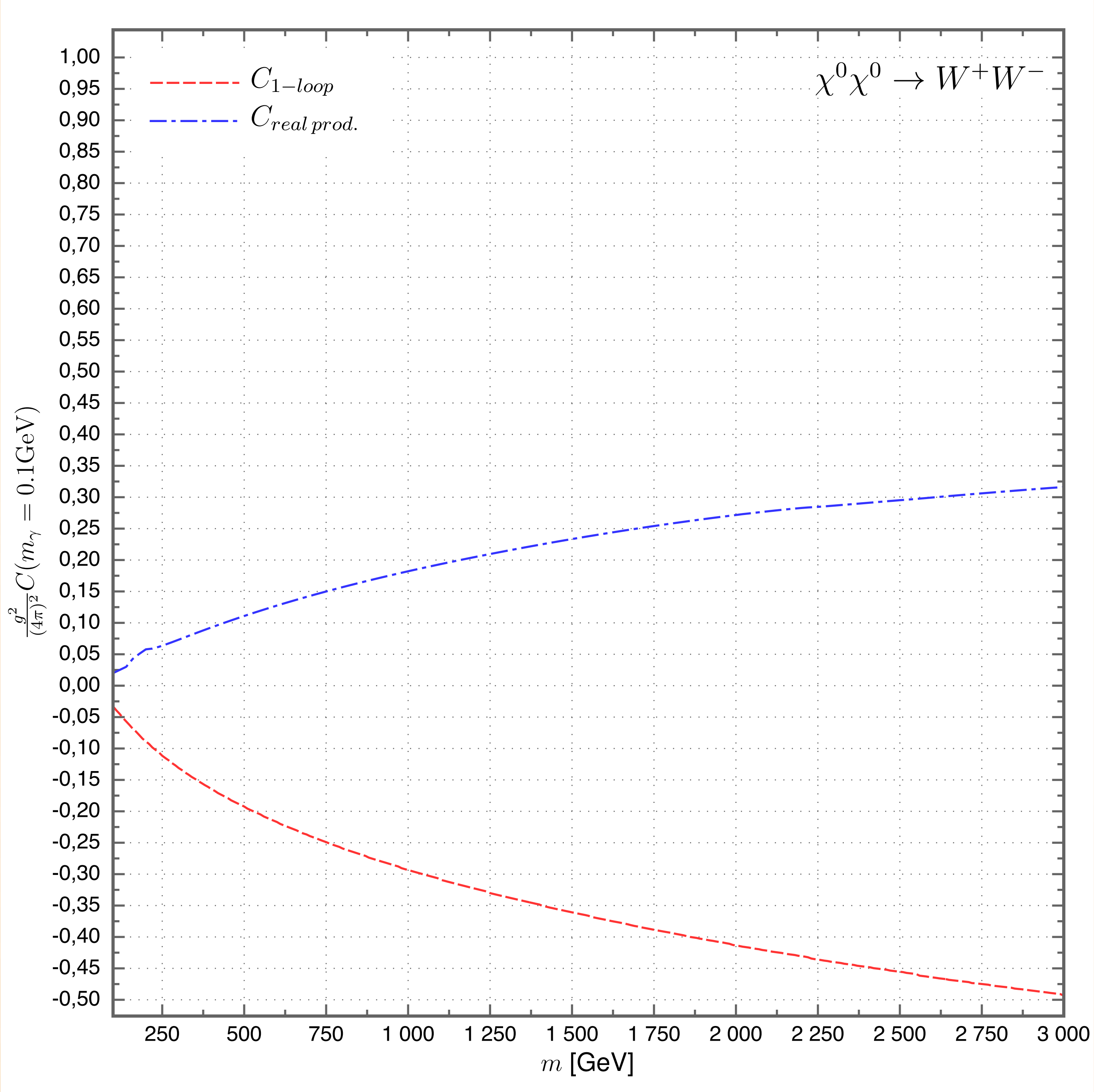
# Results

$$\chi^0\chi^0 \to W^+W^-$$




loop corrections

# RESULTS
## $\chi^0\chi^0 \to W^+W^-$

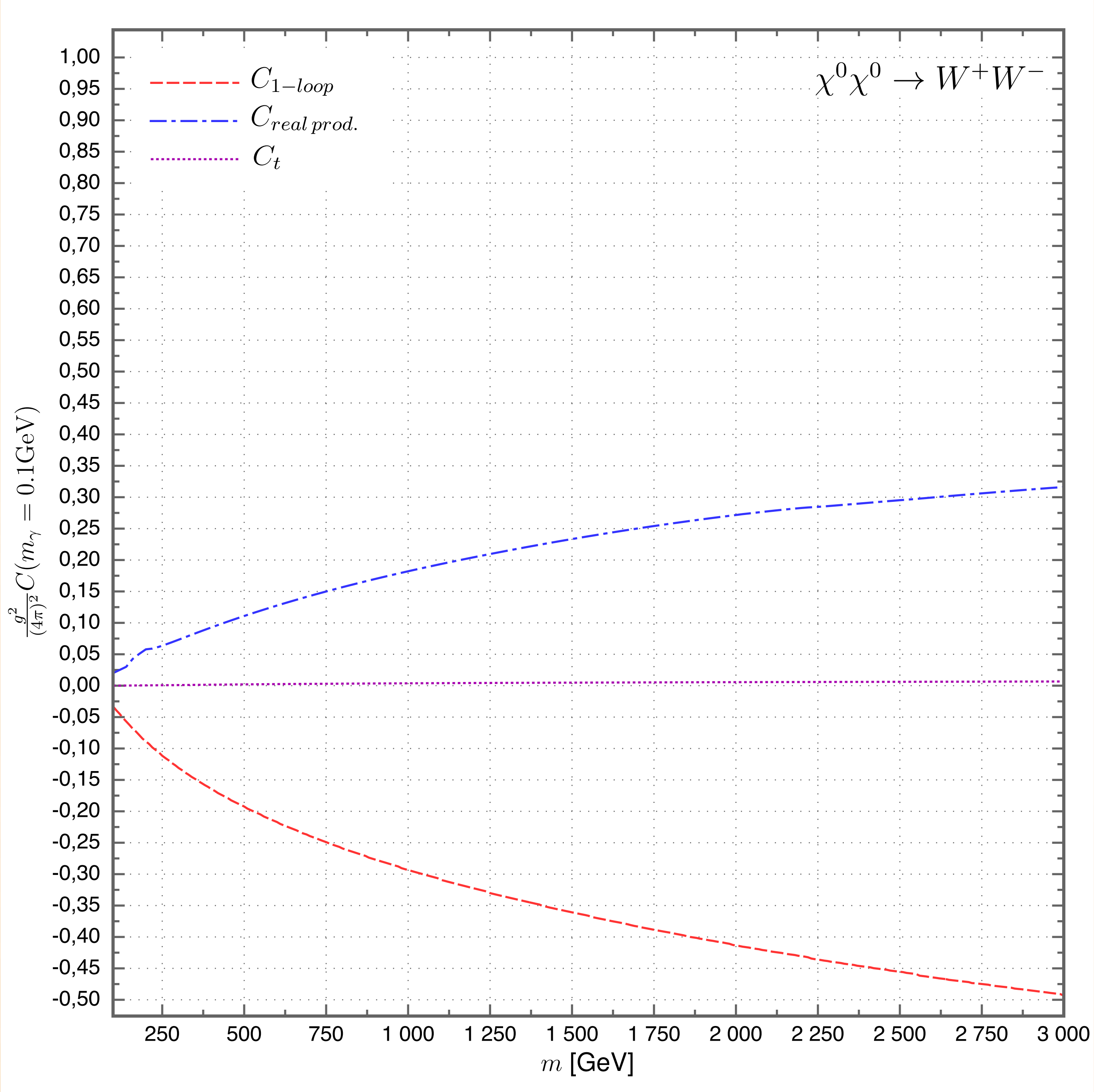



loop corrections

radiative corrections

# Results

## $\chi^0\chi^0 \to W^+W^-$



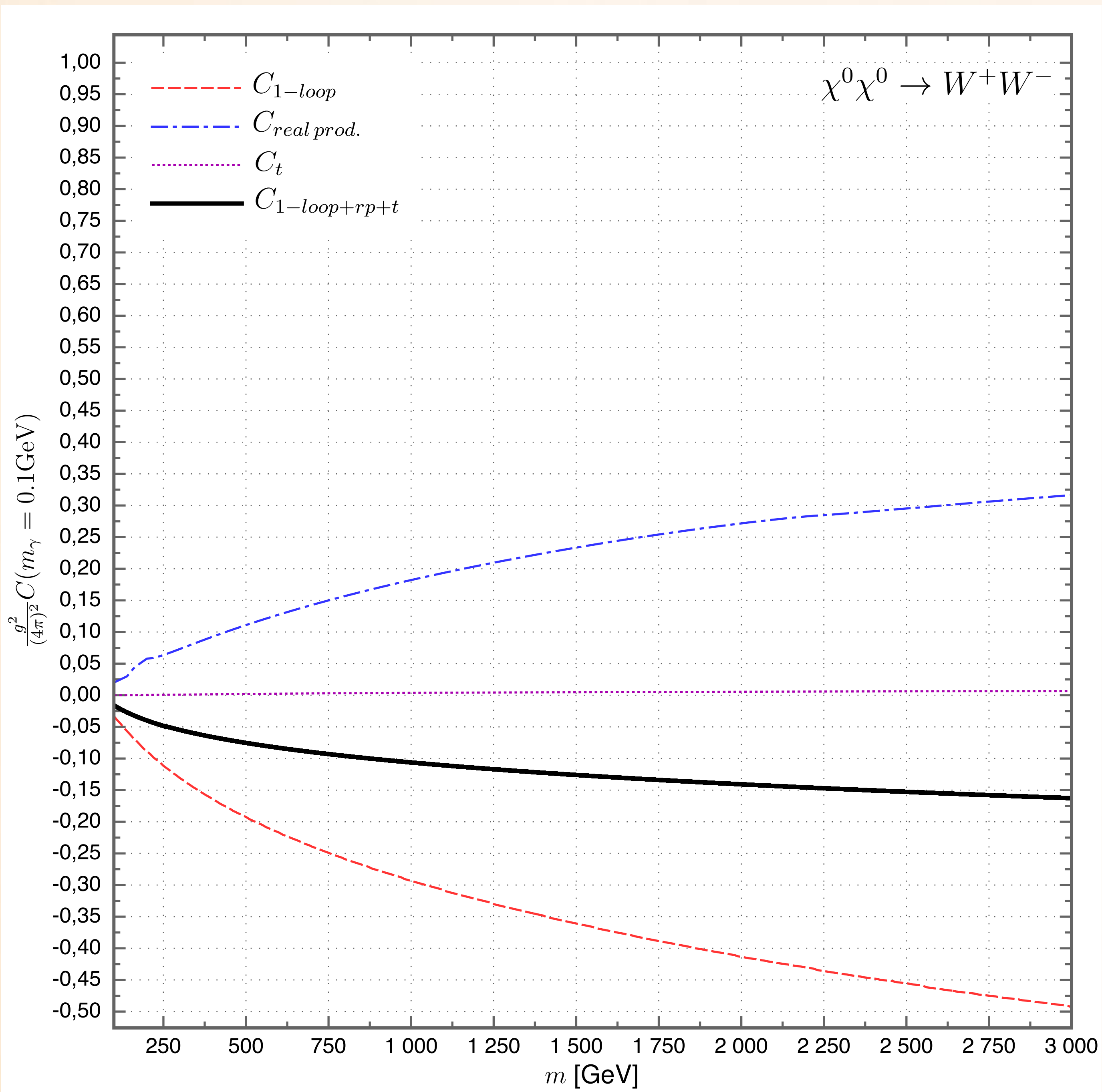

loop corrections

radiative corrections

t quark production

# RESULTS

$$\chi^0\chi^0 \to W^+W^-$$




loop corrections

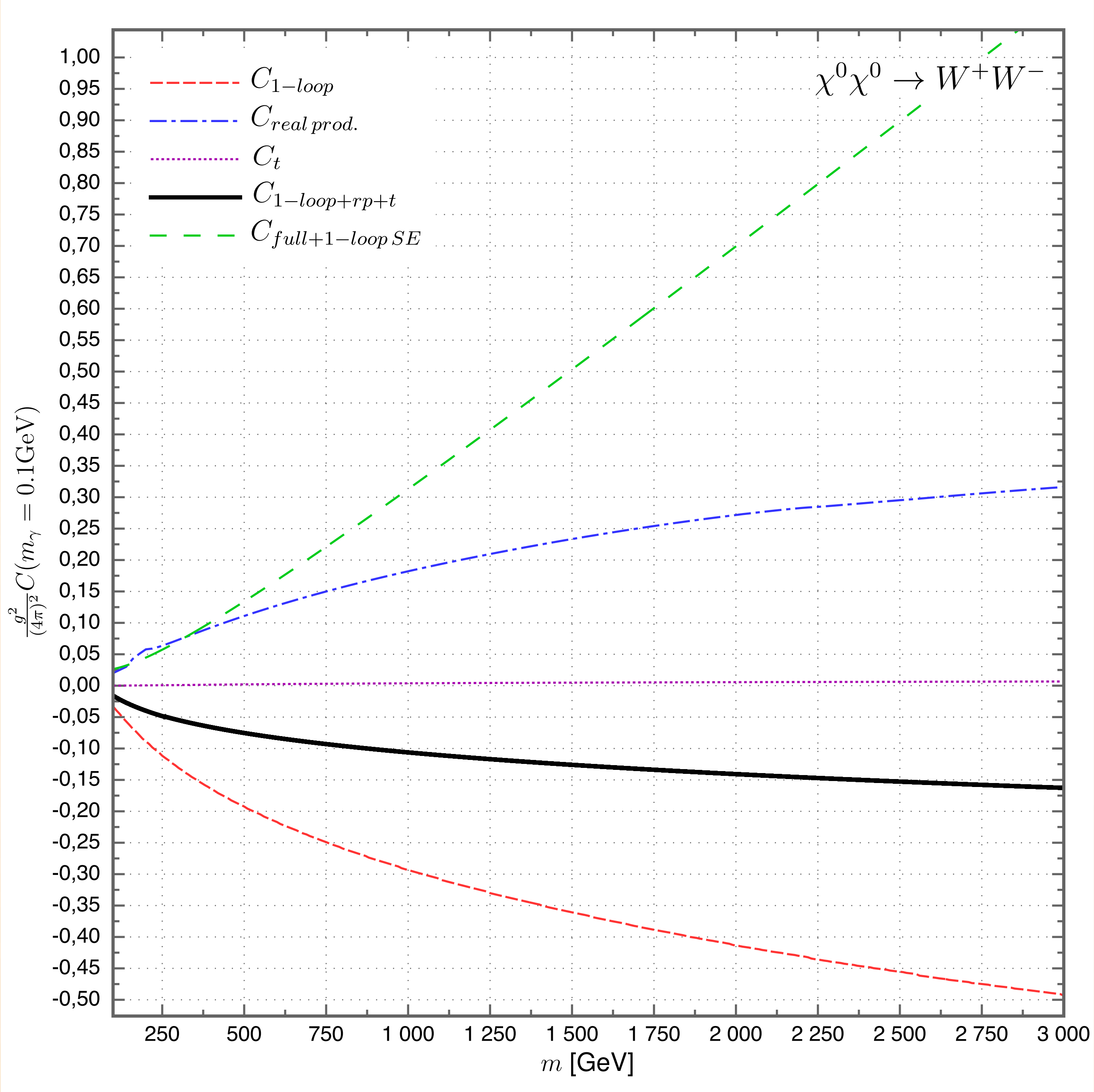
radiative corrections

t quark production

total

# RESULTS

$$\chi^0\chi^0 \to W^+W^-$$




loop corrections excluding term $\mathcal{O}\left(\frac{m_\chi}{m_W}\right)$

radiative corrections

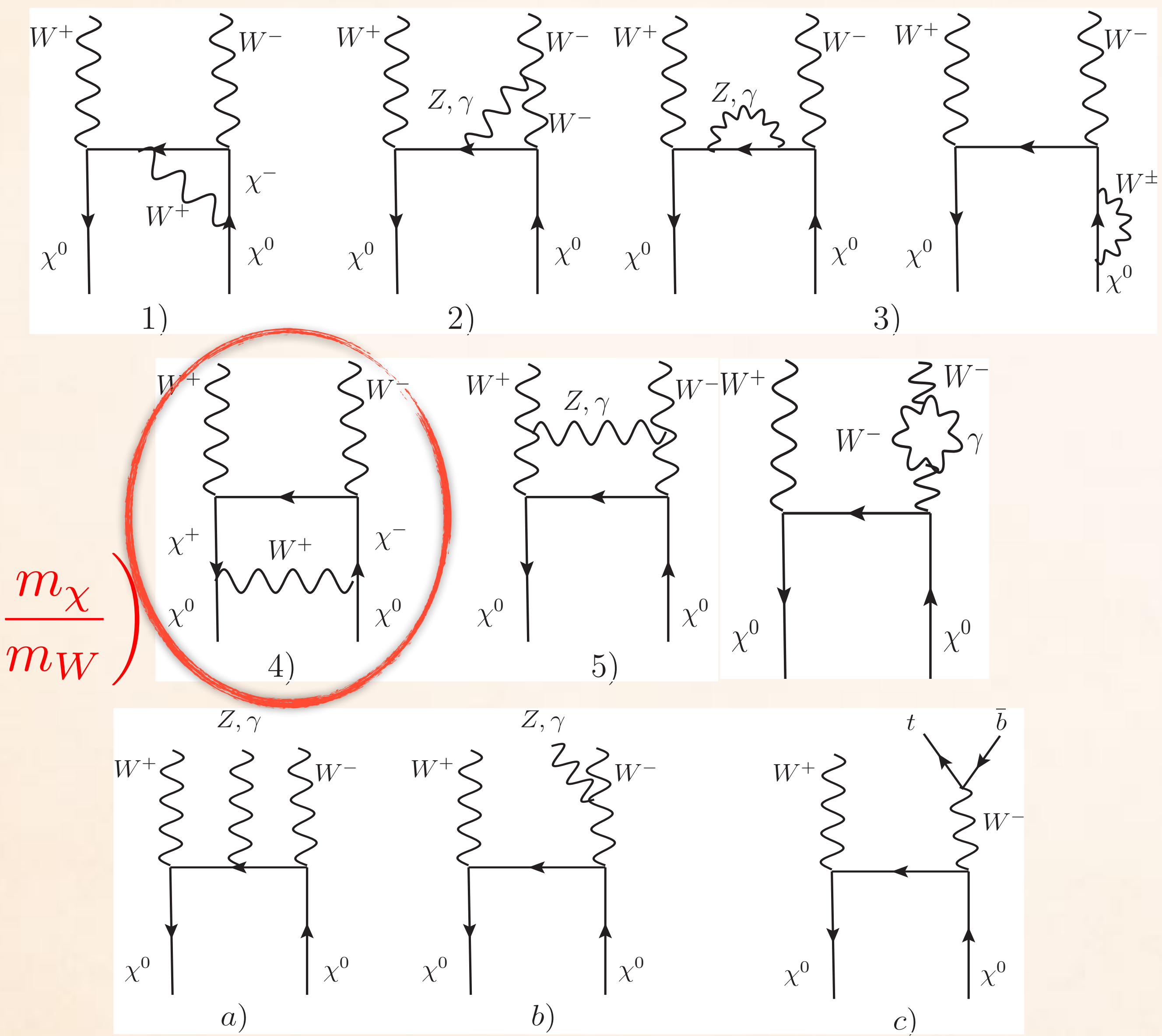
t quark production

total

full one-loop result with $\mathcal{O}\left(\frac{m_\chi}{m_W}\right)$

# ONE-LOOP COMPUTATION

## FOR A WINO DM MODEL




$\mathcal{O}\left(\frac{m_\chi}{m_W}\right)$

← UV divergent

← UV finite

← radiative

# The Sommerfeld effect

# The Sommerfeld effect

re-summation

one-loop $\propto \alpha \frac{m_\chi}{m_\phi}$

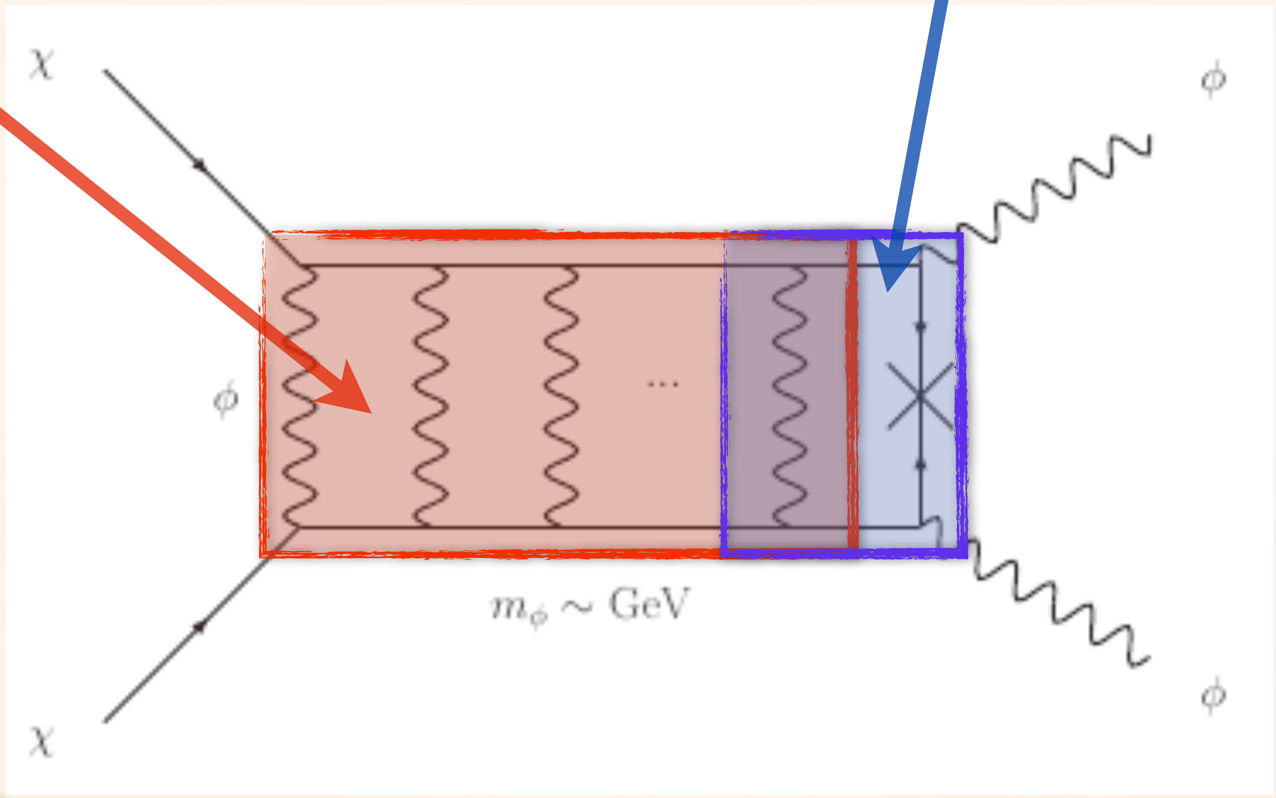
$$\frac{1}{m_\phi} \gtrsim \frac{1}{\alpha m_\chi}$$

force range    Bohr radius

$$m_\chi v^2 \lesssim \alpha^2 m_\chi$$

kinetic energy    Bohr energy

$$\sigma_{\rm SE} = S(v)\,\sigma_0$$



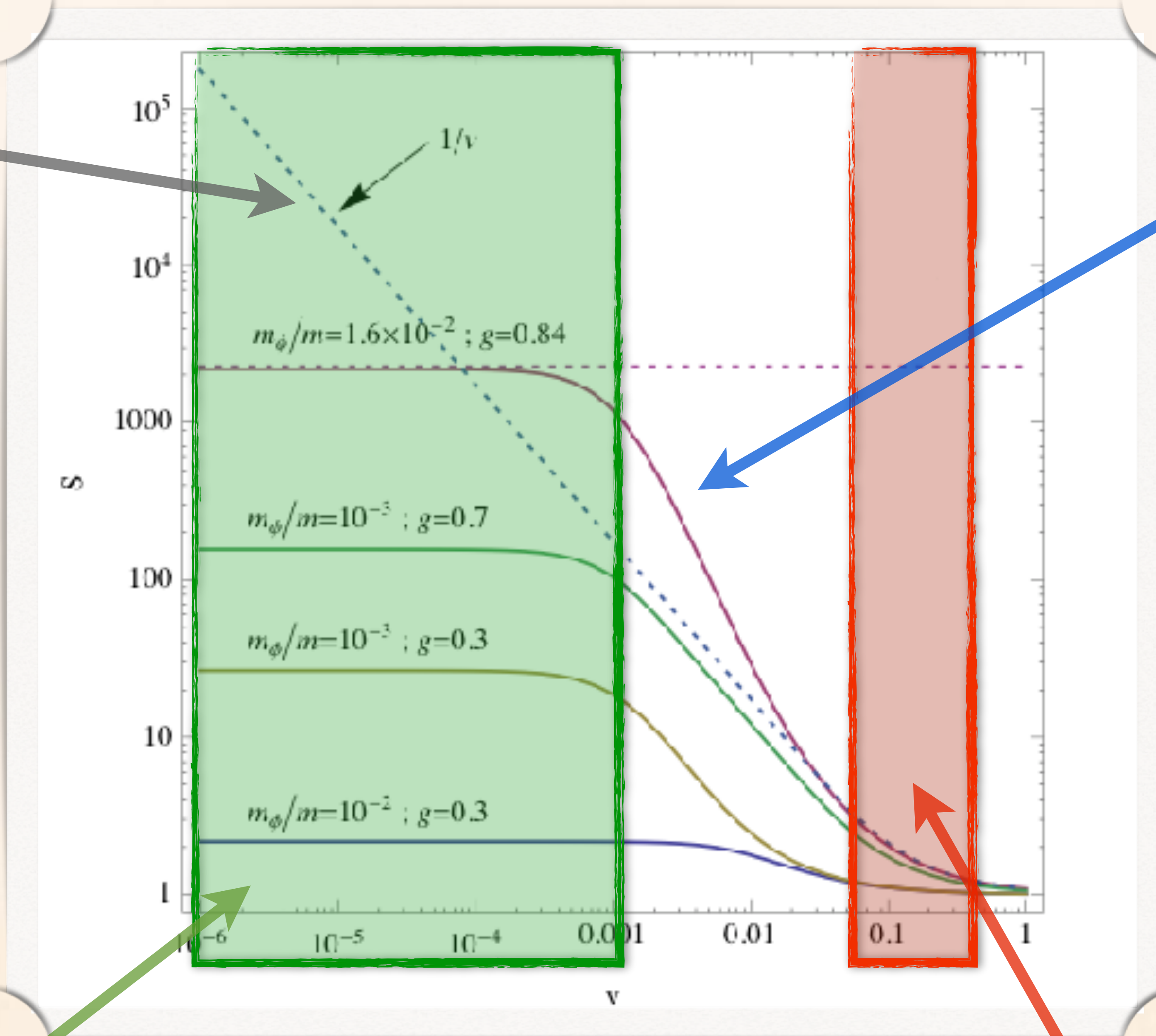

Arkani-Hamed *et al.*, Phys.Rev. D79 (2009) 015014

→ in a special case of Coulomb force: $S(v) = \frac{\pi\alpha/v}{1-e^{-\pi\alpha/v}} \approx \pi\frac{\alpha}{v}$

# THE SOMMERFELD EFFECT

## WITH A DARK FORCE

Coulomb




resonance

$$\frac{1}{m_\phi} \approx \frac{1}{\alpha m_\chi}$$

present day: indirect detection

freeze-out: relic density

# The Sommerfeld effect
## in the MSSM

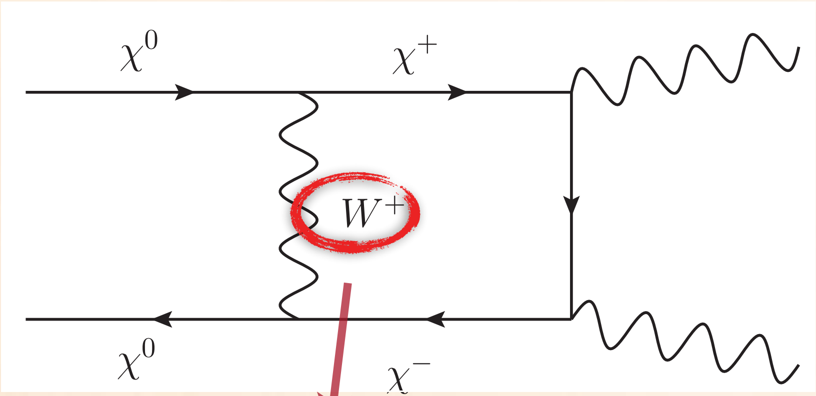
neutralino — YES!

gravitino — NO

sneutrino — NO

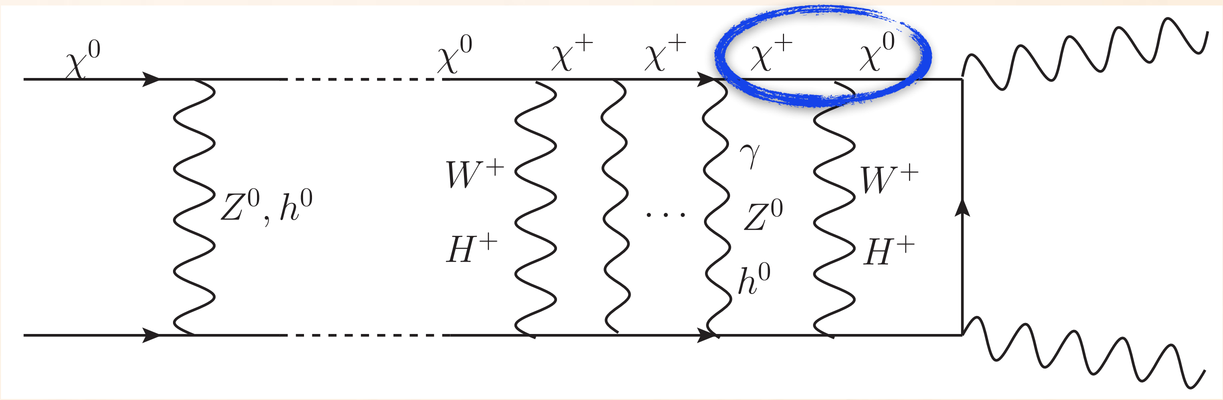
force carriers:

~~$\gamma$~~, $W^{\pm}$, $Z^0$, $h_1^0$, $h_2^0$, $H^{\pm}$



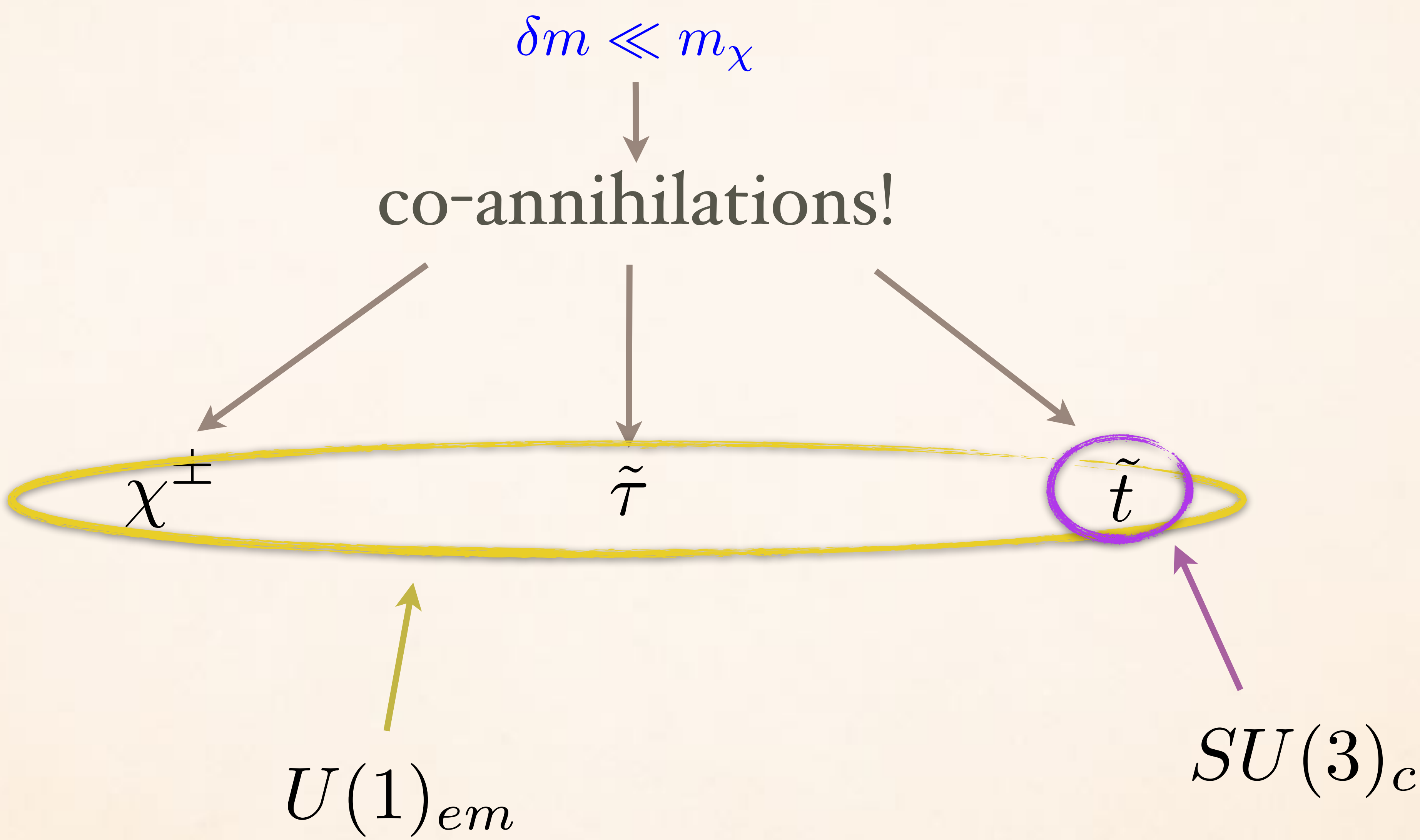

$m_\chi \gg m_W$

$\delta m \ll m_\chi$




Hisano *et al.*, Phys.Rev. D67 (2003) 075014

# THE SOMMERFELD EFFECT
## IN THE MSSM




Sommerfeld effect for co-annihilating channels!

# RELIC DENSITY

Boltzmann equation for the comoving number density;

$$\frac{dY}{dx} = \sqrt{\frac{g_* \pi m_\chi^2}{45G}} \frac{\langle \sigma_{\rm eff} \mathrm{v} \rangle}{x^2} \left(Y^2 - Y_{\rm eq}^2\right)$$

effective thermal averaged annihilation cross-section:

$$\langle \sigma_{\rm eff} \mathrm{v} \rangle = \sum_{ij} \langle \sigma_{ij} \mathrm{v}_{ij} \rangle \frac{n_i^{\rm eq} n_j^{\rm eq}}{n_{\rm eq}^2}$$

with: $\sigma_{ij} = \sum_X \sigma(\chi_i \chi_j \to X)$

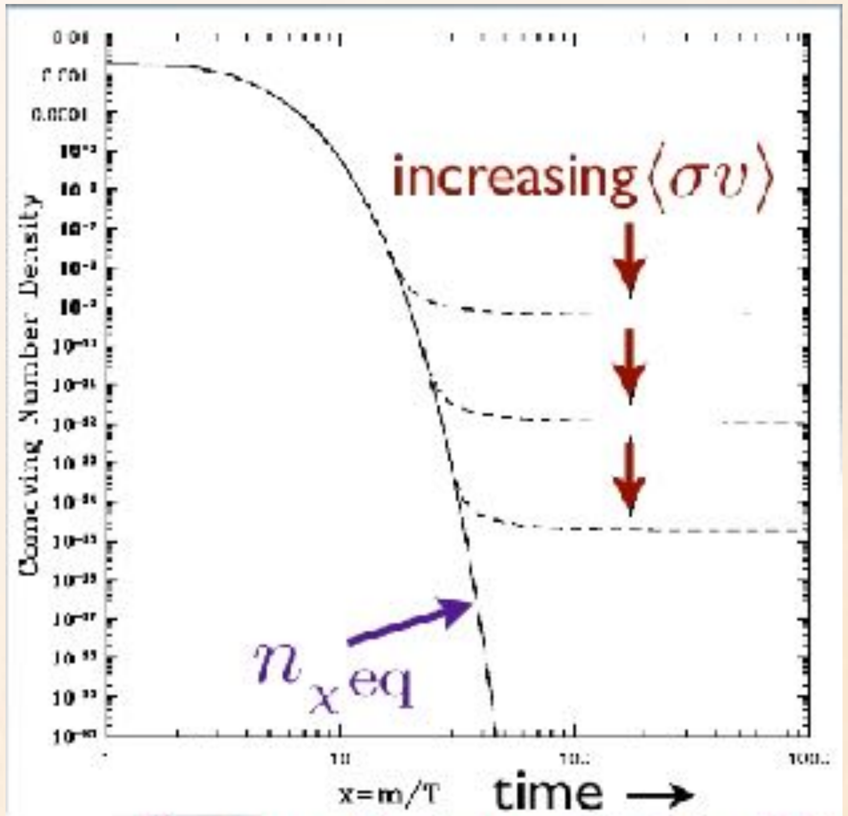



Fig.: Jungman, Kamionkowski & Griest, PR'96

# RELIC DENSITY
## WITH THE SE

Boltzmann equation for the comoving number density;

$$\frac{dY}{dx} = \sqrt{\frac{g_* \pi m_\chi^2}{45G}} \frac{\langle \sigma_{\text{eff}} \mathrm{v} \rangle}{x^2} \left(Y^2 - Y_{\text{eq}}^2\right)$$

effective thermal averaged annihilation cross-section:

$$\langle \sigma_{\text{eff}} \mathrm{v} \rangle = \sum_{ij} \langle \sigma_{ij} \mathrm{v}_{ij} \rangle \frac{n_i^{\text{eq}} n_j^{\text{eq}}}{n_{\text{eq}}^2}$$

with: $\sigma_{ij} = \sum_X \sigma(\chi_i \chi_j \to X)$

$$\langle \sigma_{\text{eff}} \mathrm{v} \rangle = \sum_{ij} S_{ij}(T, \mathrm{v}) \langle \sigma_{ij} \mathrm{v}_{ij} \rangle \frac{n_i^{\text{eq}} n_j^{\text{eq}}}{n_{\text{eq}}^2}$$

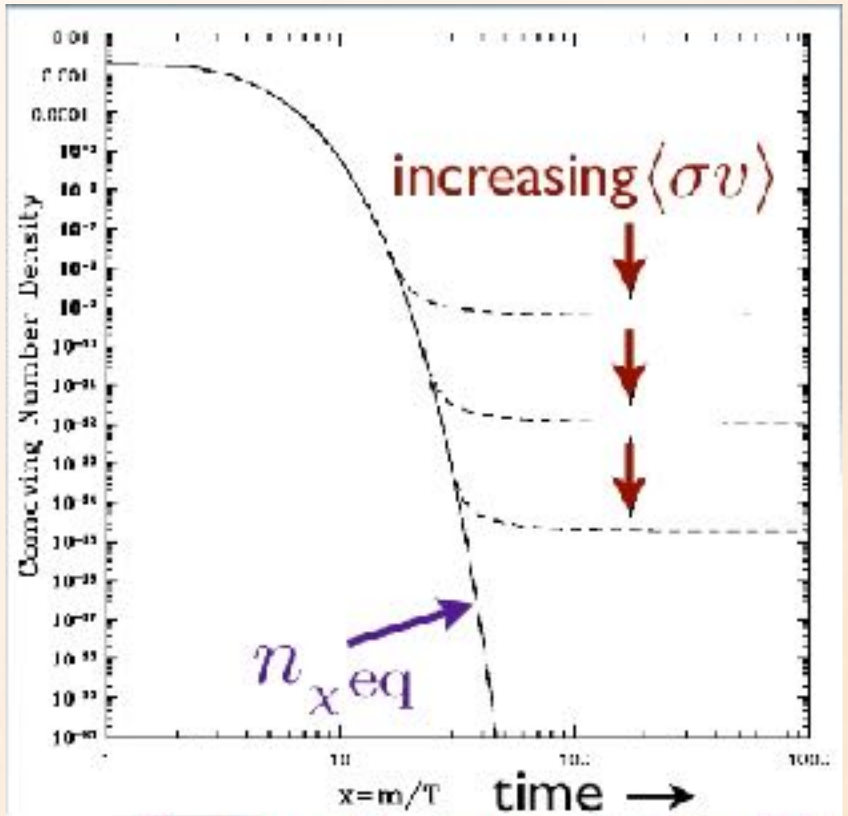
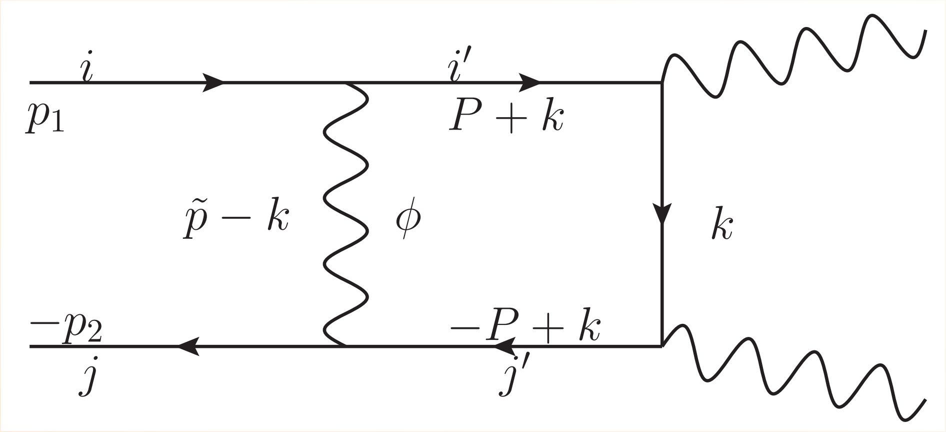



Fig.: Jungman, Kamionkowski & Griest, PR'96

# SOMMERFELD FACTORS
## THE METHOD

Idea: treat every possible interaction separately




compute potentials and obtain set of Schrodinger eqns.:

R. Iengo, JHEP 0905 (2009) 024

$$\frac{d^2\varphi_{ij}(x)}{dx^2} + \frac{m^r_{ij}}{m^r_{ab}}\left[\left(1-\frac{2\delta m_{ij}}{\mathcal{E}}\right)\varphi_{ij}(x) + \frac{1}{\mathcal{E}}\sum_{i'j'} V^{\phi}_{ij,i'j'}(x)\varphi_{i'j'}(x)\right] = 0$$

with:

$$V^{\phi}_{ij,i'j'}(x) = p\frac{c_{ij,i'j'}(\phi)}{4\pi}\frac{e^{-\frac{m_\phi}{p}x}}{x}$$

notation:

$\mathcal{E} = \vec{p}^2/2m_r^{ab} \qquad x = p\,r$

$\delta m_{ij} = m_{i'} + m_{j'} - (m_i + m_j)$

# SOMMERFELD FACTORS

## COEFFICIENTS: FERMIONS

| | Spin singlet | | |
|---|---|---|---|
| $\phi$ : | scalar $(\Gamma = \mathbb{1})$ | vector $(\Gamma = \gamma_0)$ | axial $(\Gamma = \gamma_i\gamma_5)$ |
| $c_{+-,+-}$ | $g^2$ | $g^2$ | $-3g^2$ |
| $c_{++,++}$ | $g^2$ | $-g^2$ | $-3g^2$ |
| $c_{ii,+-}$ | $\sqrt{2}\lvert g_{i+}\rvert^2$ | $\sqrt{2}\lvert g_{i+}\rvert^2$ | $-3\sqrt{2}\lvert g_{i+}\rvert^2$ |
| $c_{ij,+-}$ | $2\mathrm{Re}\,(g_{i+}g^*_{j+})$ | $2\mathrm{Re}\,(g_{i+}g^*_{j+})$ | $-6\mathrm{Re}\,(g_{i+}g^*_{j+})$ |
| $c_{ii,jj}$ | $2\lvert g_{ij}\rvert^2 + g_{ij}^2 + g_{ij}^{*2}$ | $2\lvert g_{ij}\rvert^2 - g_{ij}^2 - g_{ij}^{*2}$ | $-3(2\lvert g_{ij}\rvert^2 + g_{ij}^2 + g_{ij}^{*2})$ |
| $c_{ij,ij}$ | $2\lvert g_{ij}\rvert^2 + g_{ij}^2 + g_{ij}^{*2} + 4g_{ii}g_{jj}$ | $-2\lvert g_{ij}\rvert^2 + g_{ij}^2 + g_{ij}^{*2}$ | $-3(2\lvert g_{ij}\rvert^2 + g_{ij}^2 + g_{ij}^{*2}) - 12g_{ii}g_{jj}$ |
| $c_{+i,+i}$ | $\lvert g_{i+}\rvert^2 + 2g_{ii}g$ | $-\lvert g_{i+}\rvert^2$ | $-3\lvert g_{i+}\rvert^2 - 6g_{ii}g$ |
| $c_{+i,+j}$ | $g_{i+}g^*_{j+} + 2g\mathrm{Re}\,(g_{ij})$ | $-g_{i+}g^*_{j+} - 2gi\mathrm{Im}\,(g_{ij})$ | $-3g_{i+}g^*_{j+} - 6g\mathrm{Re}\,(g_{ij})$ |
| $c_{ii,ii}$ | $4g_{ii}^2$ | 0 | $-12g_{ii}^2$ |
| $c_{ij,ii}$ | $4\sqrt{2}g_{ii}\mathrm{Re}\,(g_{ij})$ | 0 | $-12\sqrt{2}g_{ii}\mathrm{Re}\,(g_{ij})$ |
| | Spin triplet | | |
| $c_{+-,+-}$ | $g^2$ | $g^2$ | $g^2$ |
| $c_{++,++}$ | $g^2$ | $-g^2$ | $g^2$ |
| $c_{ii,+-}$ | 0 | 0 | 0 |
| $c_{ij,+-}$ | $2i\mathrm{Im}\,(g^*_{i+}g_{j+})$ | $2i\mathrm{Im}\,(g^*_{i+}g_{j+})$ | $2i\mathrm{Im}\,(g^*_{i+}g_{j+})$ |
| $c_{ii,jj}$ | 0 | 0 | 0 |
| $c_{ij,ij}$ | $-(2\lvert g_{ij}\rvert^2 + g_{ij}^2 + g_{ij}^{*2}) + 4g_{ii}g_{jj}$ | $2\lvert g_{ij}\rvert^2 - g_{ij}^2 - g_{ij}^{*2}$ | $-(2\lvert g_{ij}\rvert^2 + g_{ij}^2 + g_{ij}^{*2}) + 4g_{ii}g_{jj}$ |
| $c_{+i,+i}$ | $-\lvert g_{i+}\rvert^2 + 2gg_{ii}$ | $\lvert g_{i+}\rvert^2$ | $-\lvert g_{i+}\rvert^2 + 2gg_{ii}$ |
| $c_{+i,+j}$ | $-g_{i+}g^*_{j+} + 2g\mathrm{Re}\,(g_{ij})$ | $g_{i+}g^*_{j+} - 2gi\mathrm{Im}\,(g_{ij})$ | $-g_{i+}g^*_{j+} + 2g\mathrm{Re}\,(g_{ij})$ |
| $c_{ii,ii}$ | 0 | 0 | 0 |
| $c_{ij,ii}$ | 0 | 0 | 0 |

Couplings: $g^\Gamma_{ij}\bar\chi_j\Gamma\chi_i\phi$ $(+h.c.$ iff $i \neq j)$, $g^\Gamma_{i+}\bar\psi\Gamma\chi_i\phi$ $+ h.c.$, $g^\Gamma\bar\psi\Gamma\psi\phi$, where $\Gamma = \mathbb{1}, \gamma_0, \gamma_i\gamma_5$

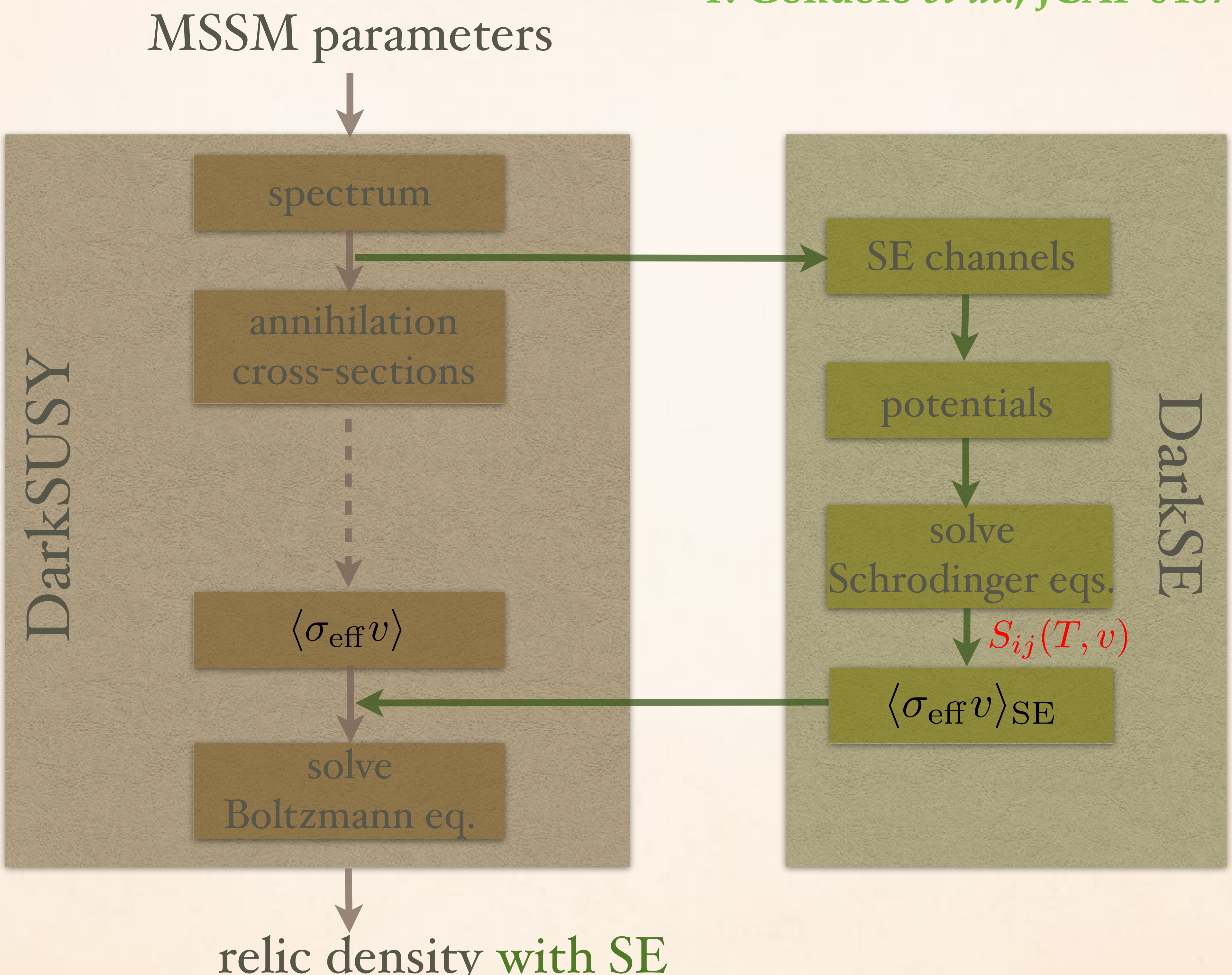
repulsive

attractive

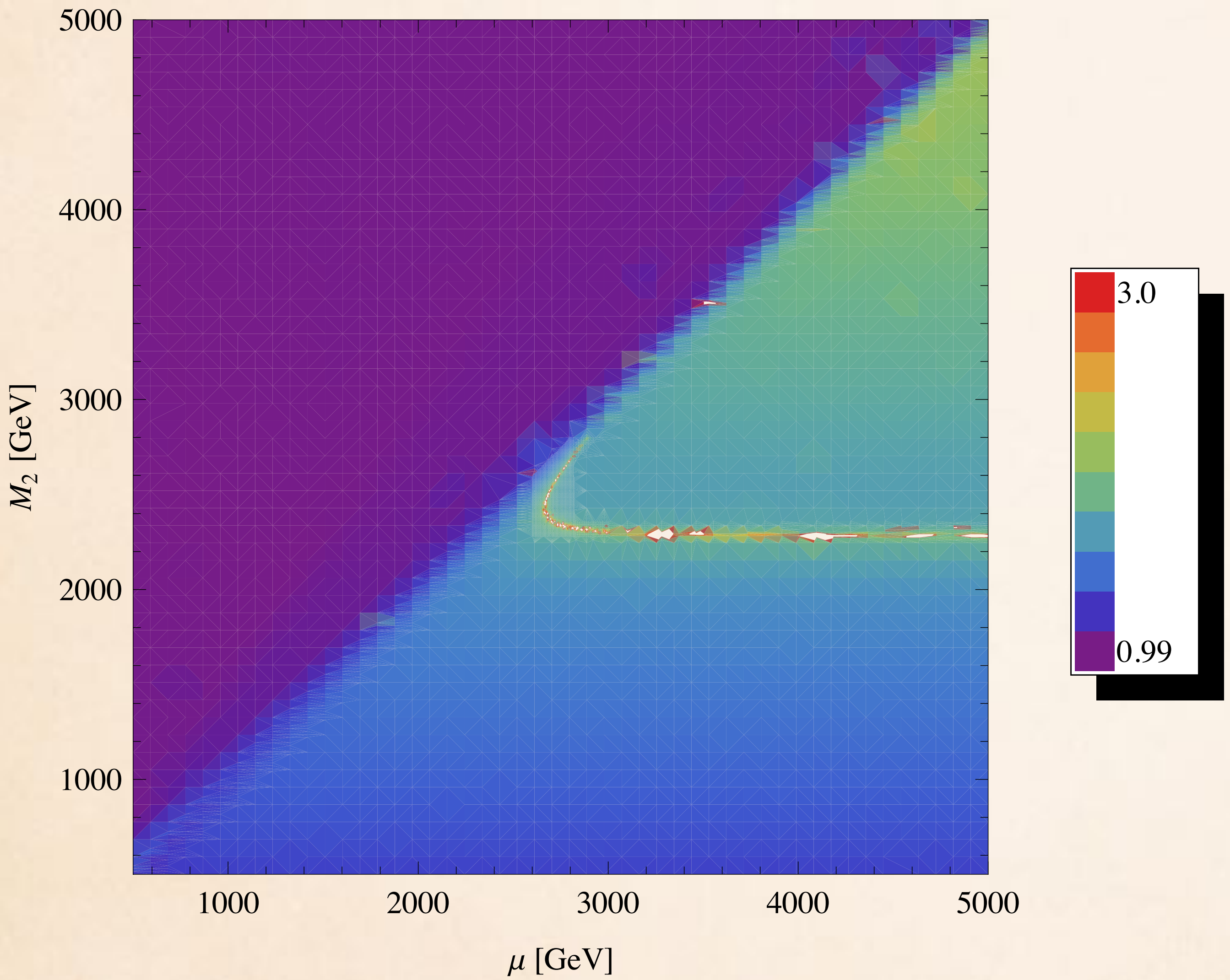
# DarkSE

## numerical package for DarkSUSY

P. Gondolo *et al.*, JCAP 0407 (2004) 008



# RESULTS
## WINO-HIGGSINO

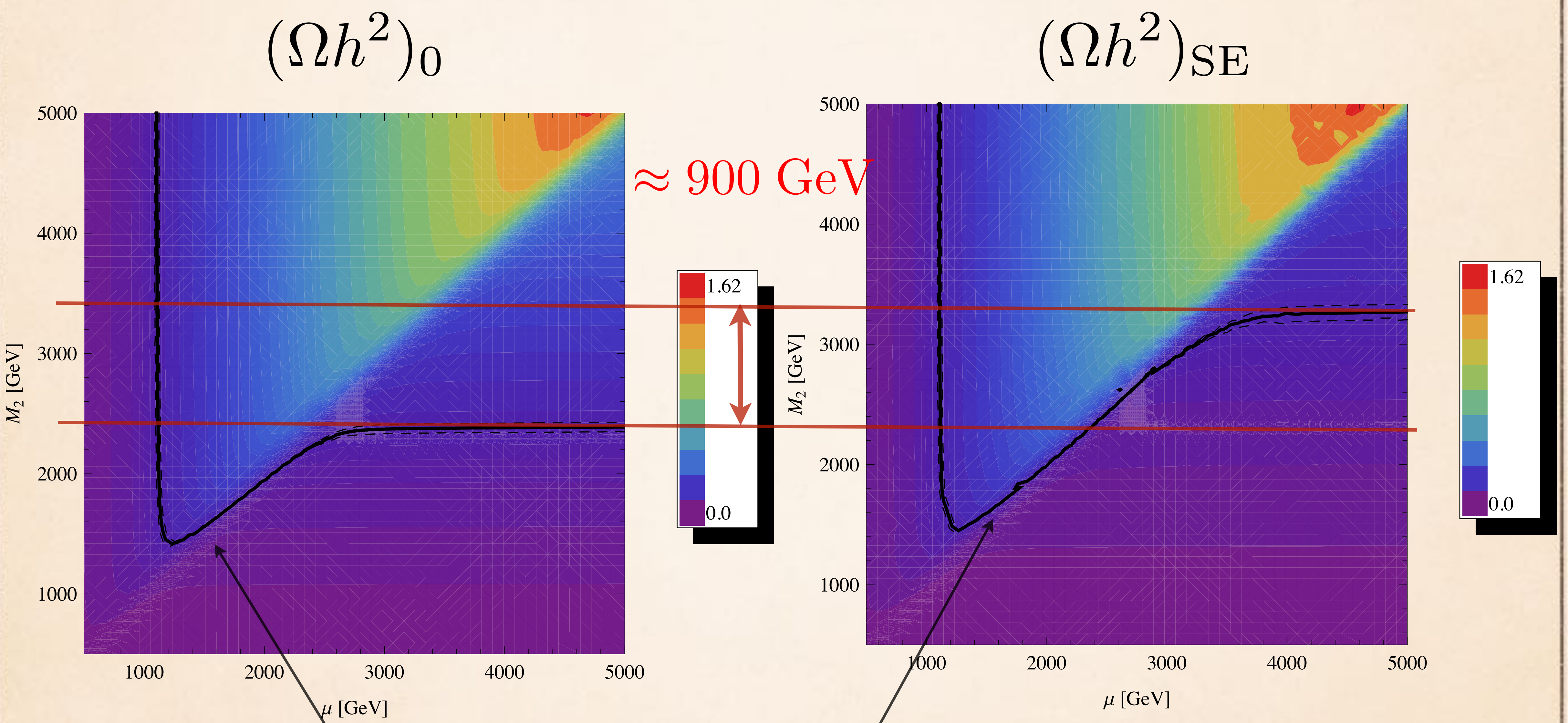



Ratio of relic densities without and with SE:

$$\frac{(\Omega h^2)_0}{(\Omega h^2)_{\mathrm{SE}}}$$

# Results

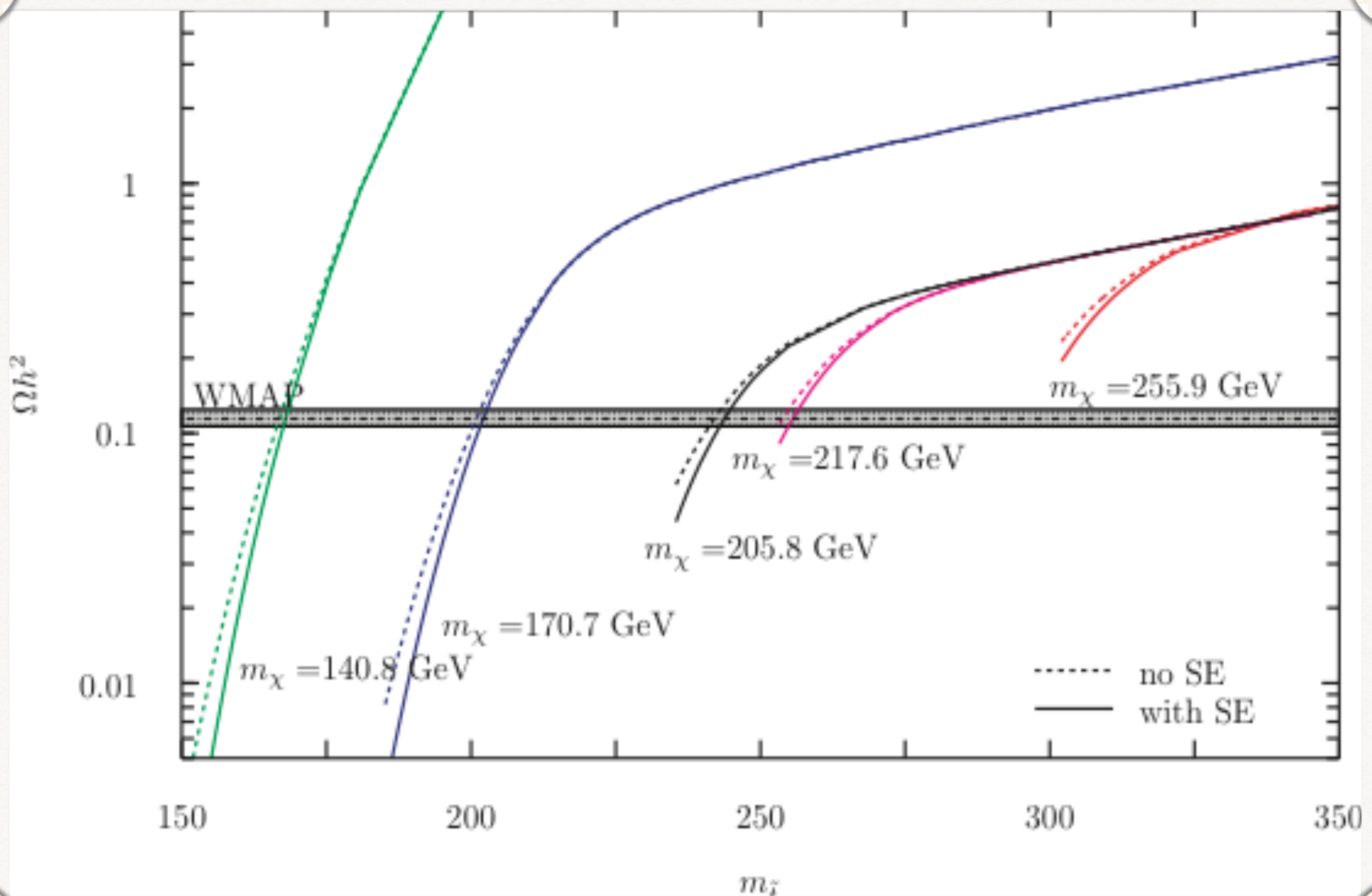
## WINO-HIGGSINO




$$\text{WMAP: } \Omega h^2 = 0.1123 \pm 0.0035$$

# RESULTS

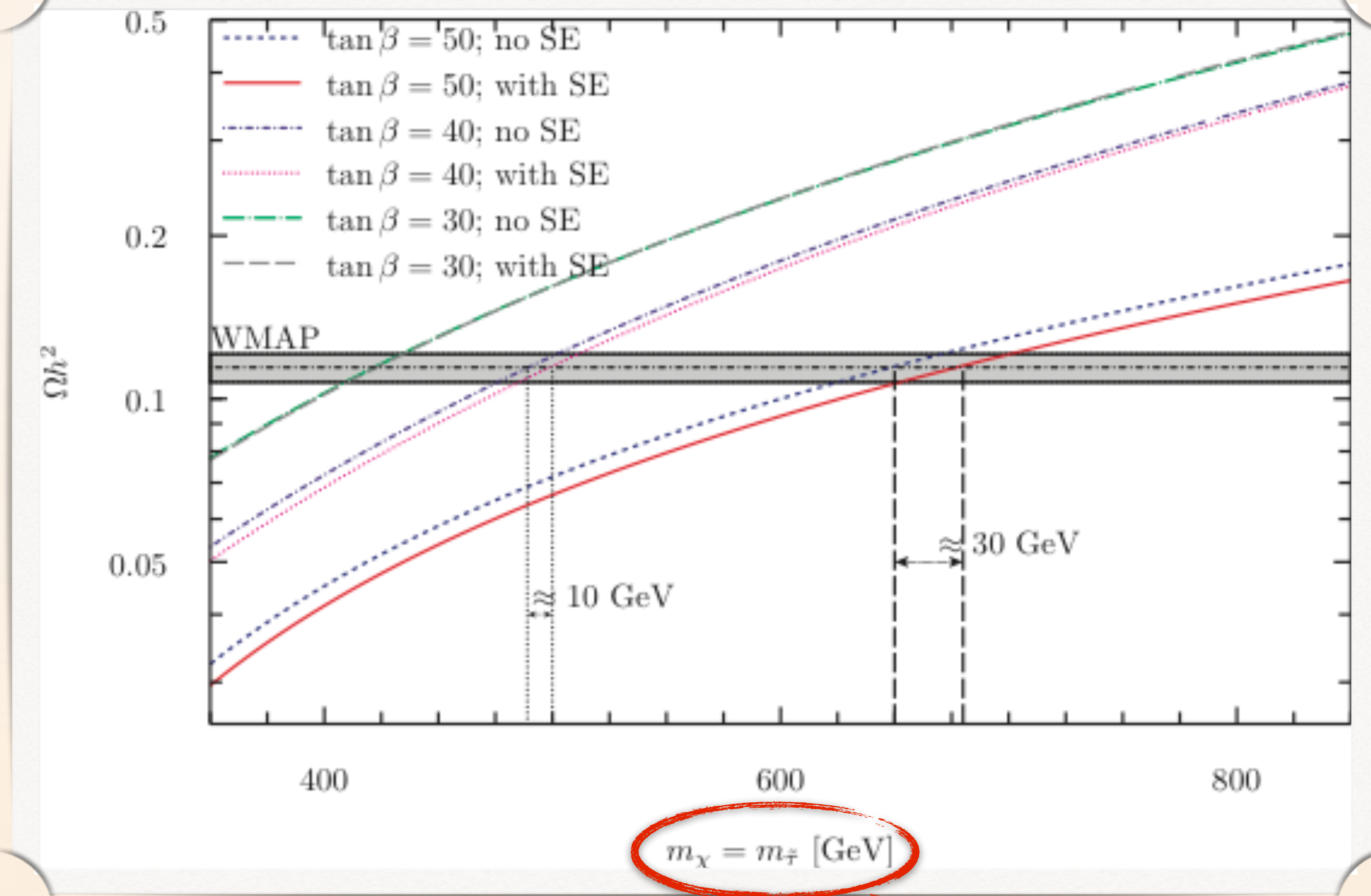
## $\tilde{t}$ CO-ANNIHILATION




Even factor of few suppression of the relic density

see also **Freitas, Phys.Lett. B652 (2007) 280**

# RESULTS
## $\tilde{\tau}$ CO-ANNIHILATION




Nevertheless, visible shift of the maximal mass allowed

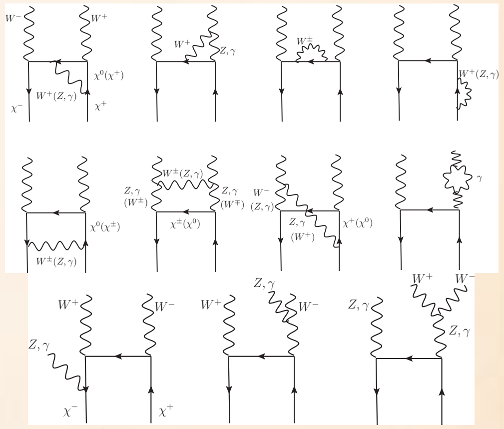
# INDIRECT DETECTION SIGNALS
## FOR A WINO DM MODEL

# WINO DM

- viable, well-motivated SUSY DM candidate
- simple but rich phenomenology
- thermal Wino: mass at TeV scale
- t-channel annihilation to $W^+W^-$

} large EW corrections

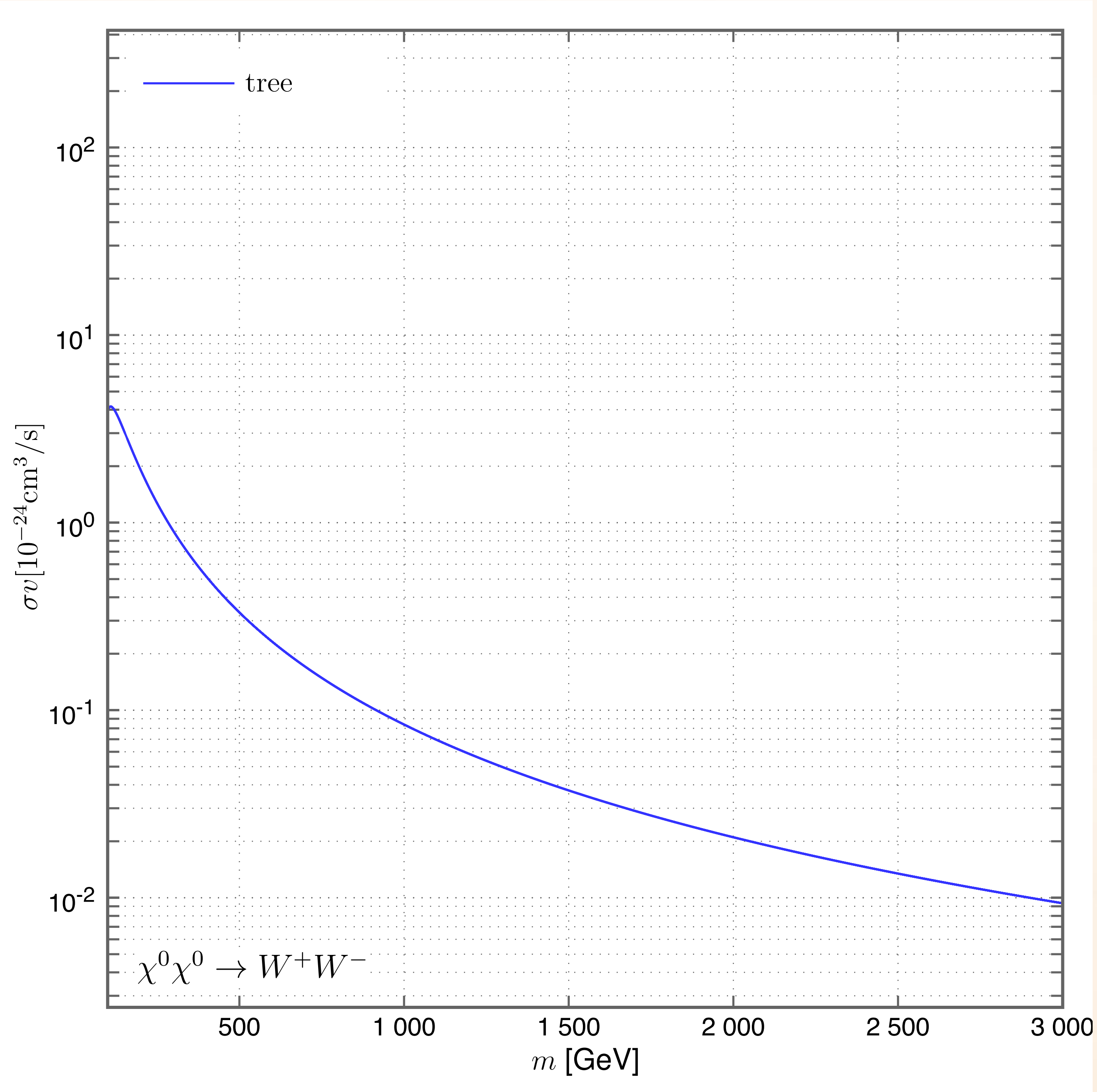
- degenerate with chargino } Sommerfeld effect
- possibly testable only in ID



$$s_0 \equiv \partial_x \varphi^0(x)|_{x=0}, \qquad s_\pm \equiv \partial_x \varphi^\pm(x)|_{x=0}$$

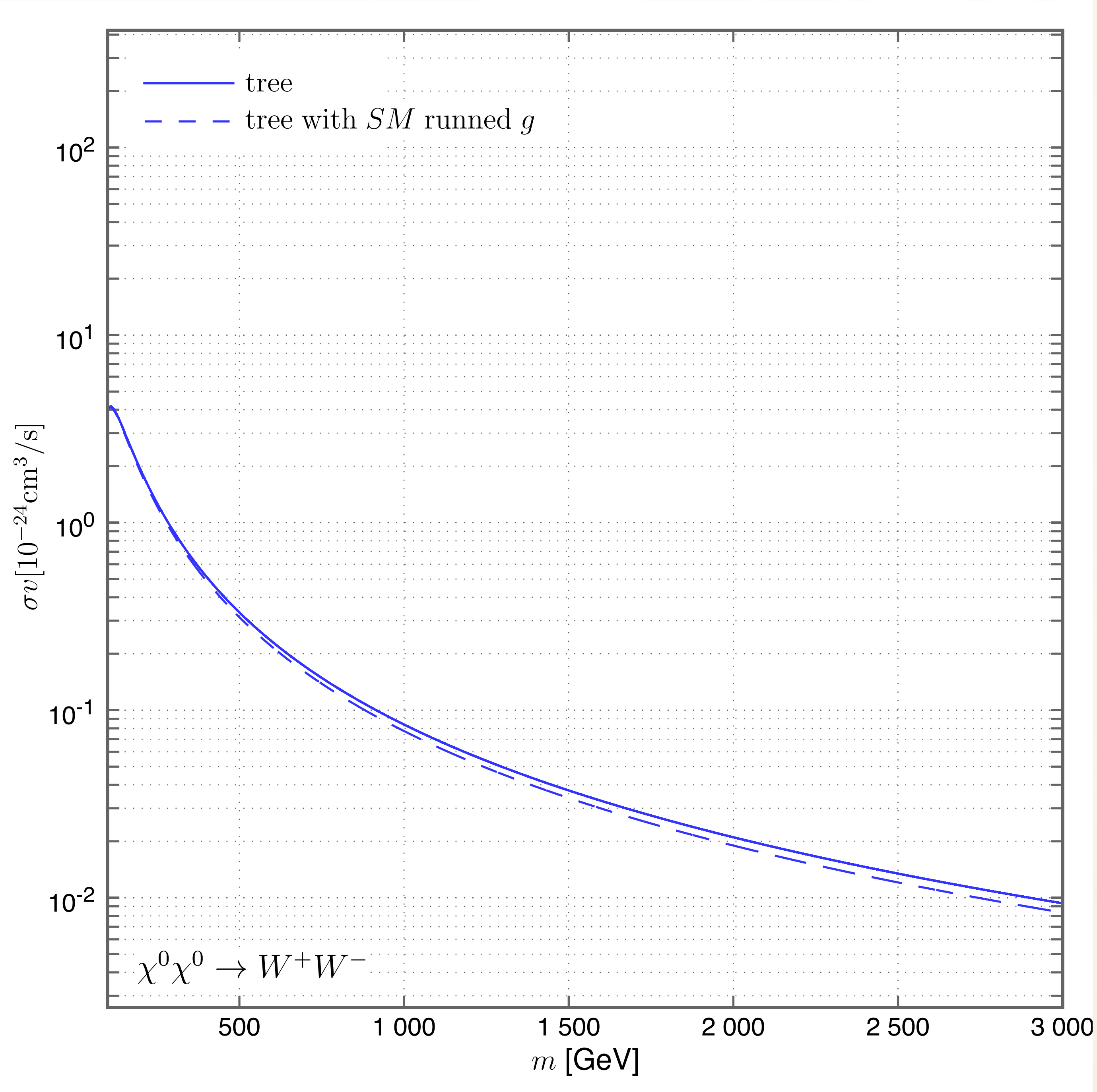
$$A_{\chi^0\chi^0 \to \mathrm{SM}} = s_0 A^0_{\chi^0\chi^0 \to \mathrm{SM}} + s_\pm A^0_{\chi^+\chi^- \to \mathrm{SM}}$$

# CROSS-SECTION




tree level result $\sim 1/m^2$

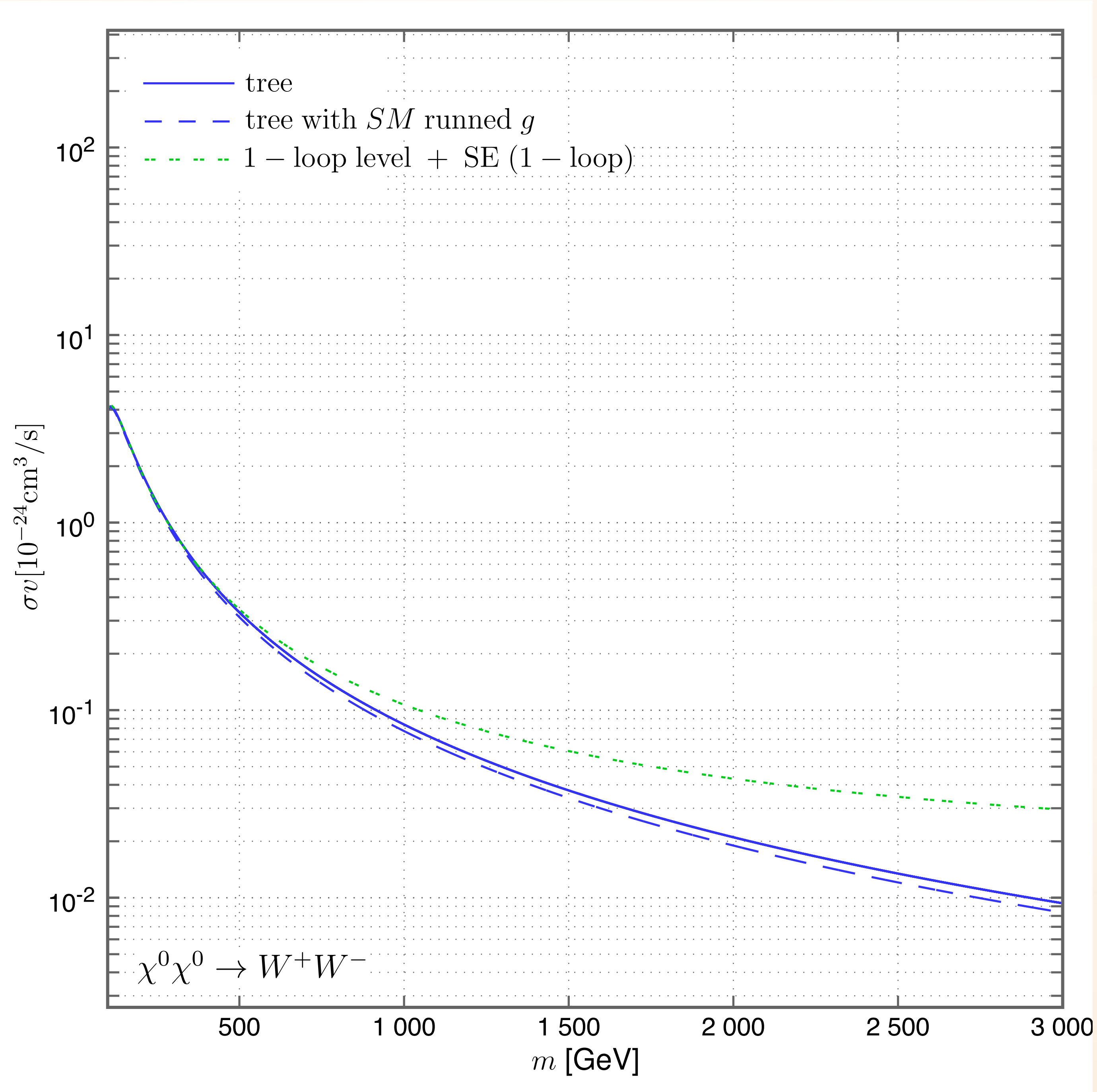
# Cross-section




tree level result $\sim 1/m^2$

with g at scale $m$
with SM running

# CROSS-SECTION

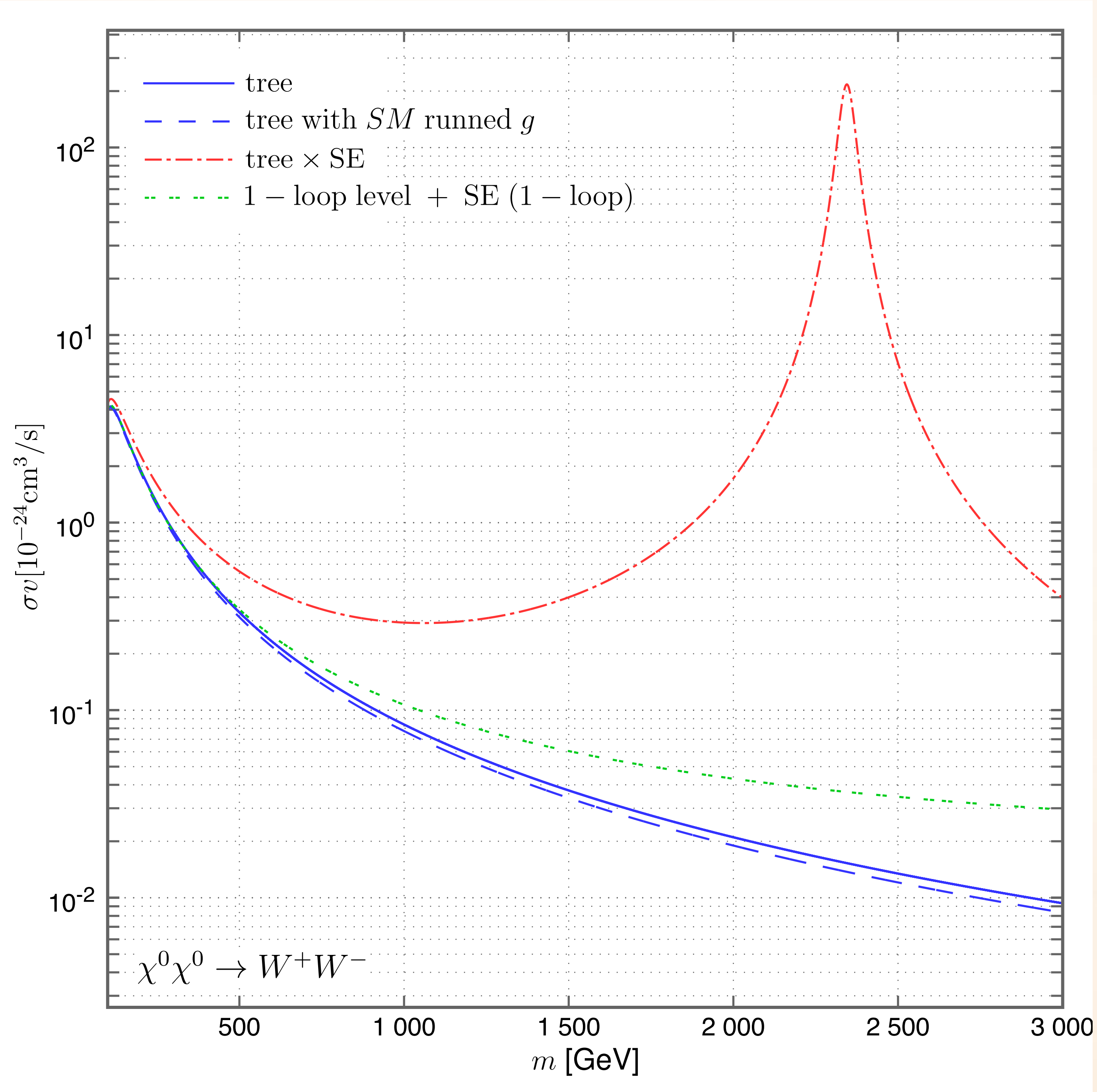



tree level result $\sim 1/m^2$

with g at scale $m$
with SM running

full one-loop result

# CROSS-SECTION



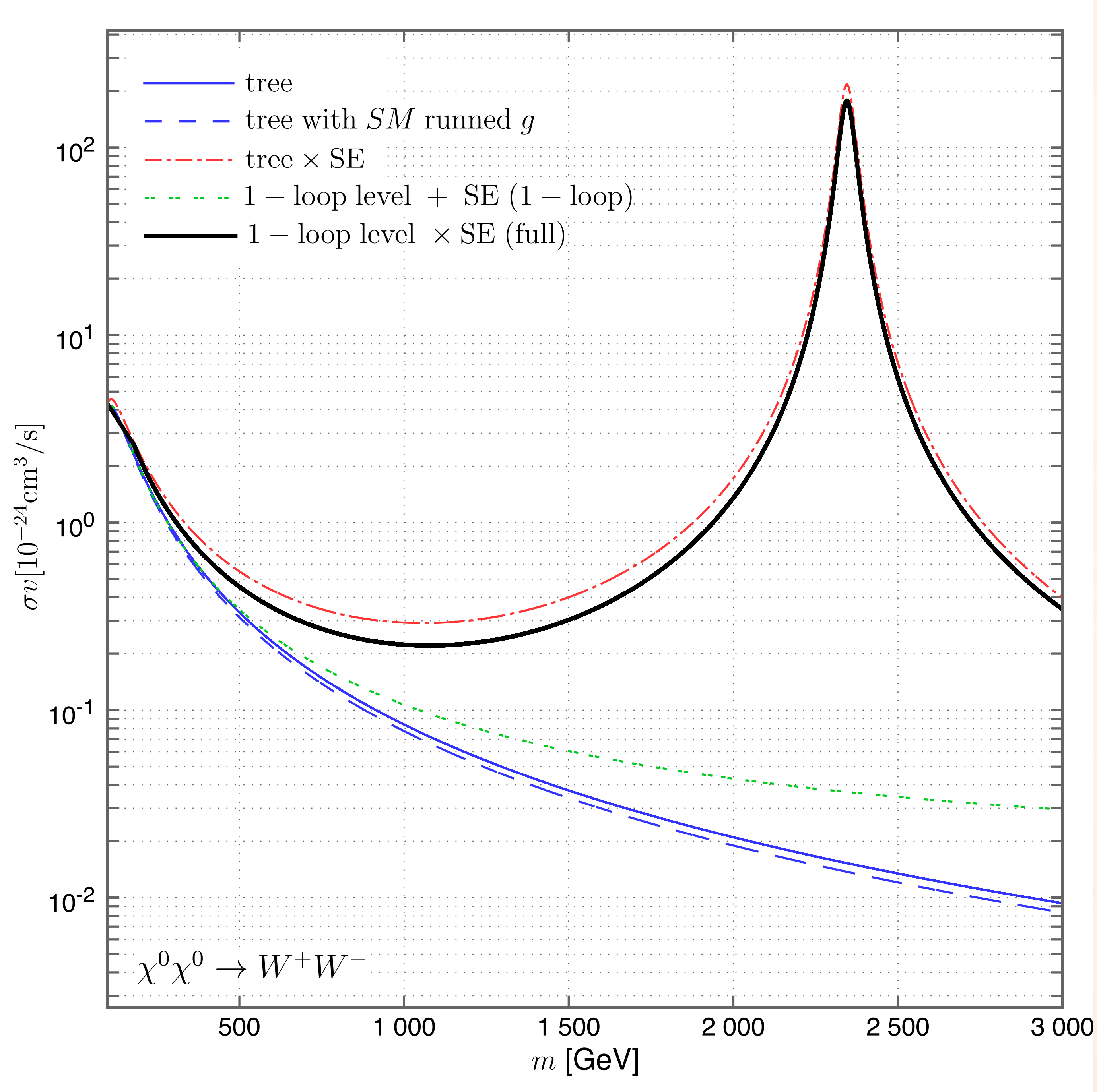

tree level result $\sim 1/m^2$

with g at scale $m$
with SM running

full one-loop result

tree level + Sommerfeld

# CROSS-SECTION




tree level result $\sim 1/m^2$

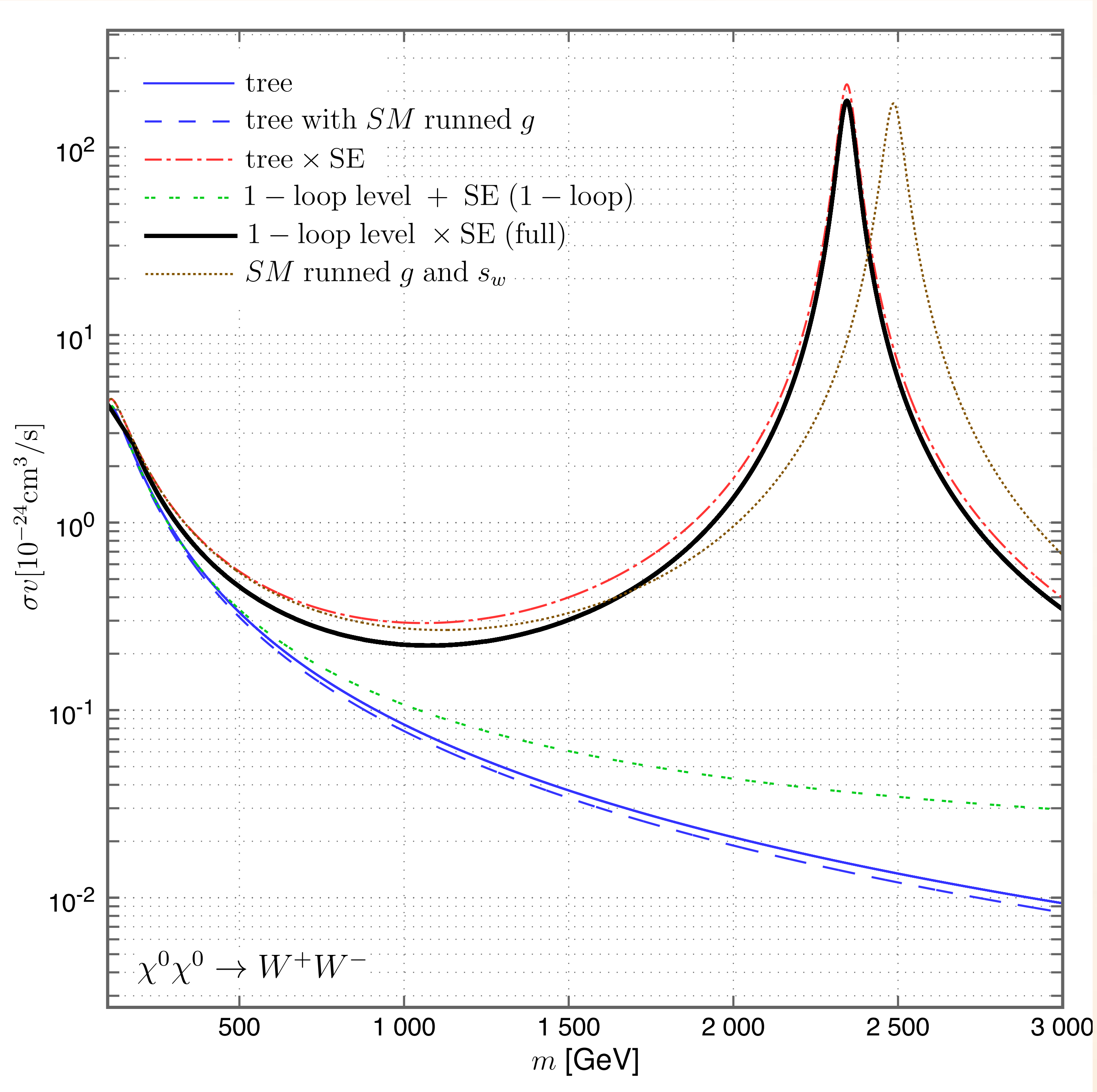
with g at scale $m$
with SM running

full one-loop result

tree level + Sommerfeld

one-loop + Sommerfeld

# CROSS-SECTION




tree level result $\sim 1/m^2$

with g at scale $m$
with SM running

full one-loop result

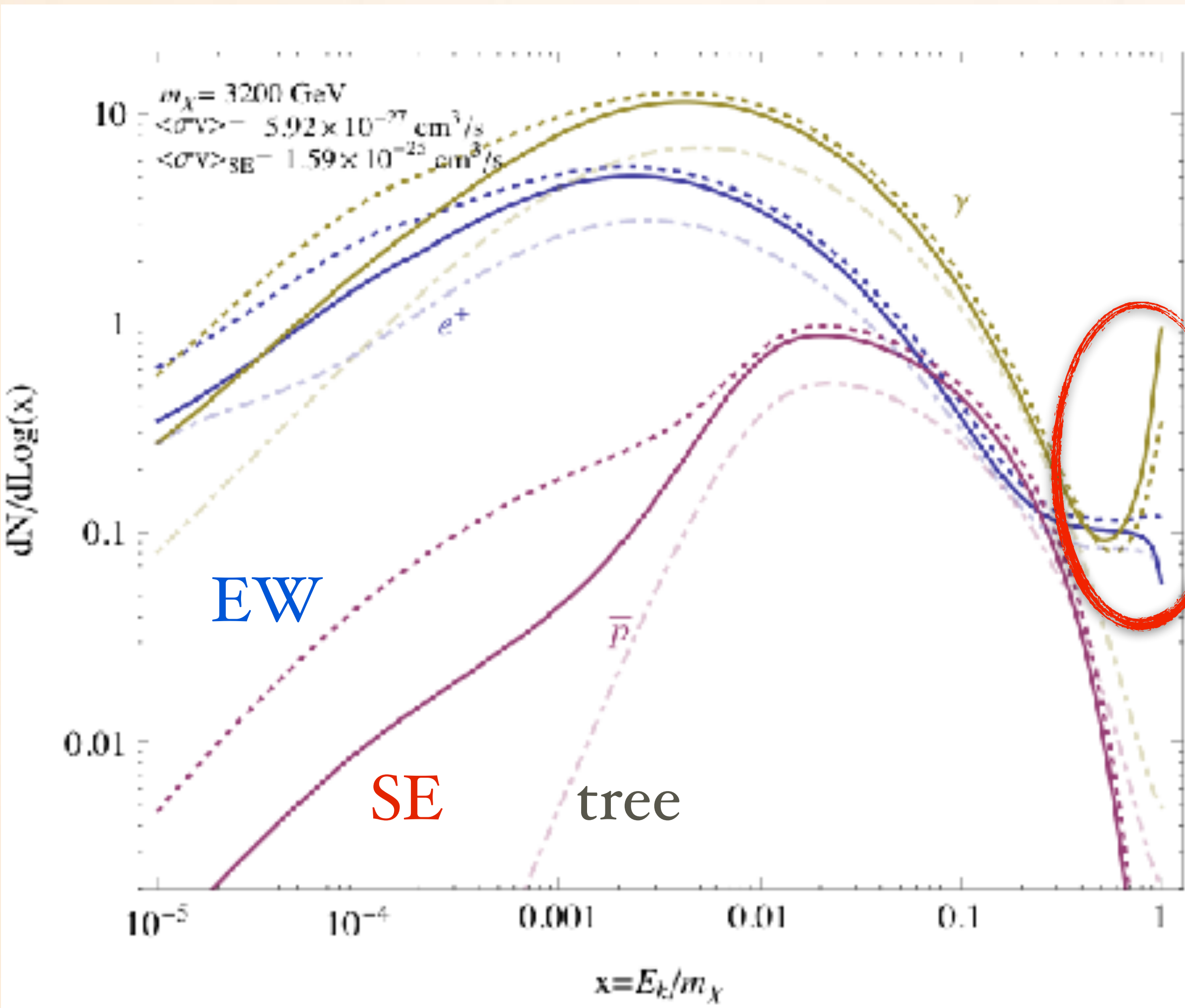
tree level + Sommerfeld

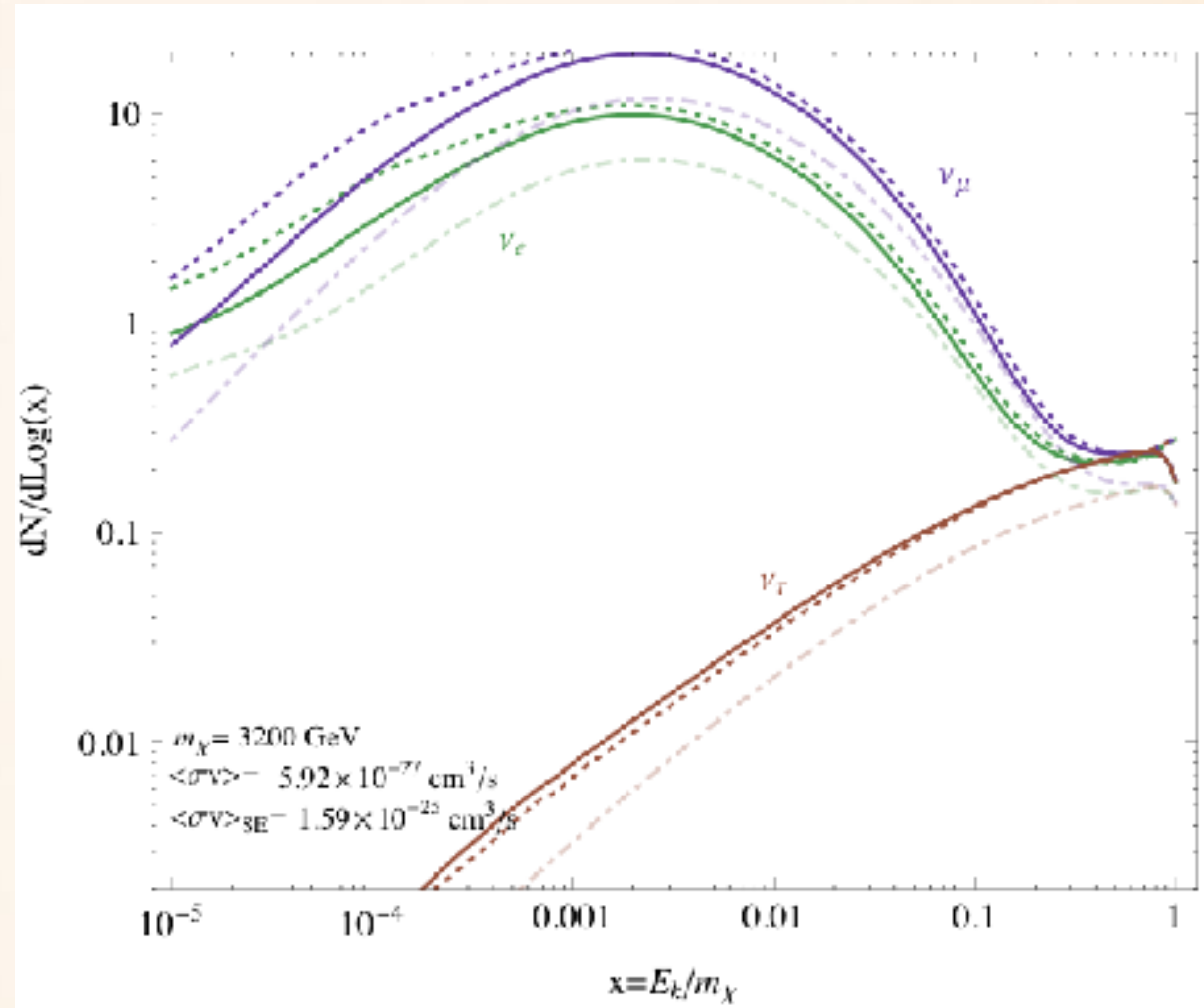
one-loop + Sommerfeld

if for the Sommerfeld
g at scale $m$ is used

# ANNIHILATION SPECTRA

## AT PRODUCTION




Number of final particles per annihilation: $$\frac{dN}{dx} = \frac{1}{\sigma}\frac{d\sigma}{dx}$$

the same cross-section

# Cosmic-ray propagation

spatial diffusion

convection

cont. E loss

reacceleration

$$\frac{\partial N^i}{\partial t} - \vec{\nabla} \cdot \left( D_{xx} \vec{\nabla} - \vec{v_c} \right) N^i + \frac{\partial}{\partial p} \left( \dot{p} - \frac{p}{3} \vec{\nabla} \cdot \vec{v_c} \right) N^i - \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{N^i}{p^2} =$$

$$Q^i(p, r, z) + \sum_{j>i} c\beta n_{\rm gas}(r,z) \sigma_{ij} N^j - c\beta n_{\rm gas} \sigma_{\rm in}(E_k) N^i - \sum_{j<i} \frac{N^i}{\tau^{i\to j}} + \sum_{j>i} \frac{N^j}{\tau^{j \to i}}$$

source

spallation

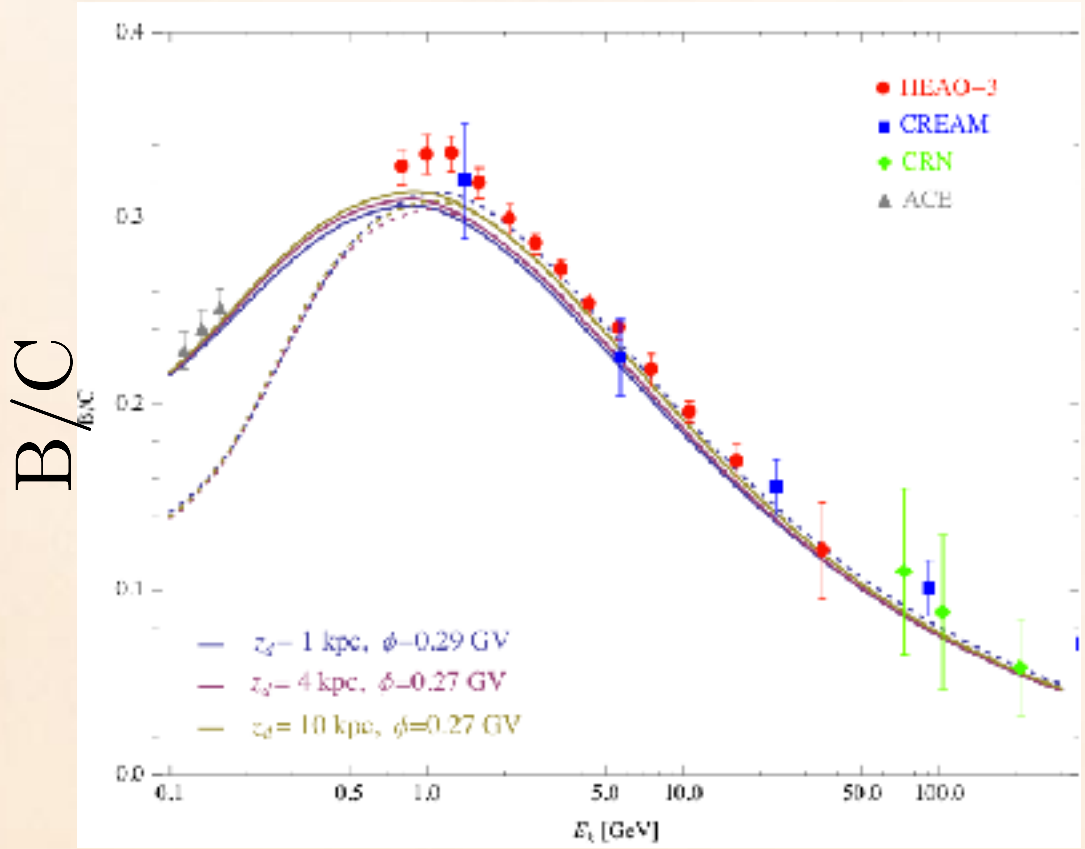
decays

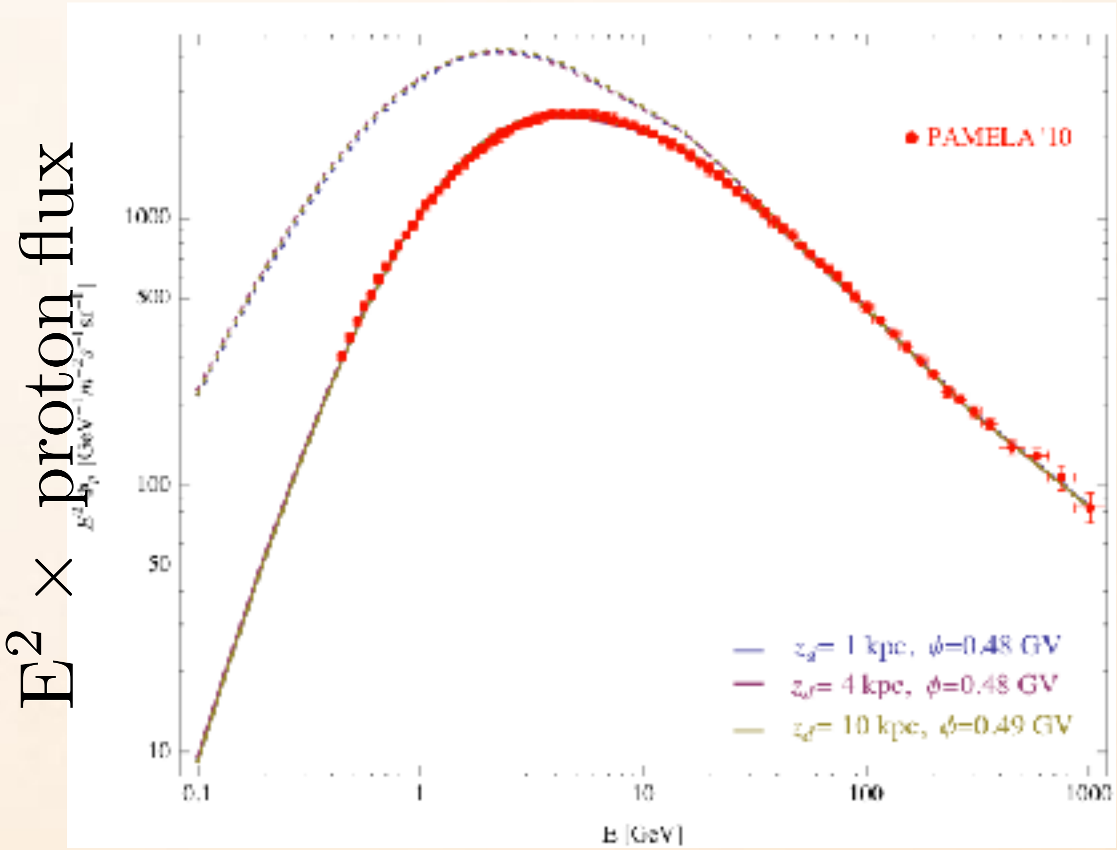
and solved it with DRAGON

C. Evoli *et al.*, JCAP 0810 (2008) 018

# PROPAGATION MODELS

| Benchmark | | | Fitted | | | Fitted | | Goodness | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $z_d$ [kpc] | $\delta$ | $r_d$ [kpc] | $D_0 \times 10^{28}$ [cm$^2$s$^{-1}$] | $v_A$ [km s$^{-1}$] | $\eta$ | $\gamma_1^p/\gamma_2^p$ | $R_{0,1}^p$ GV | $\chi^2_{B/C}$ | $\chi^2_p$ | $\chi^2_{\bar{p}}$ | $\chi^2_e$ $E_k > 5$ GeV | $\chi^2_{\rm tot}$ |
| 0.5 | 0.5 | 20 | 0.191 | 11.0 | -0.60 | 2.11/2.36/2.18 | 16.9 | 0.69 | 0.67 | 0.37 | 0.68 | 0.65 |
| 1 | 0.5 | 20 | 0.53 | 16.3 | -0.521 | 2.04/2.34/2.18 | 16.0 | 0.96 | 0.46 | 0.38 | 0.69 | 0.58 |
| 1.4 | 0.5 | 20 | 0.738 | 15.5 | -0.499 | 2.11/2.36/2.18 | 16.1 | 0.51 | 0.62 | 0.36 | 0.71 | 0.60 |
| 1.7 | 0.5 | 20 | 0.932 | 16.2 | -0.476 | 2.11/2.35/2.18 | 14.6 | 0.47 | 0.65 | 0.35 | 0.72 | 0.60 |
| 2 | 0.5 | 20 | 1.13 | 16.7 | -0.458 | 2.11/2.35/2.18 | 14.6 | 0.48 | 0.59 | 0.35 | 0.72 | 0.58 |
| 3 | 0.5 | 20 | 1.75 | 18.5 | -0.40 | 2.05/2.35/2.18 | 16.0 | 0.34 | 0.39 | 0.35 | 0.75 | 0.46 |
| 4 | 0.5 | 20 | 2.45 | 19.5 | -0.363 | 2.05/2.35/2.18 | 16.0 | 0.79 | 0.33 | 0.36 | 0.75 | 0.49 |
| 6 | 0.5 | 20 | 3.17 | 19.2 | -0.40 | 2.05/2.35/2.18 | 16.0 | 0.38 | 0.44 | 0.35 | 0.77 | 0.49 |
| 8 | 0.5 | 20 | 3.83 | 19.2 | -0.370 | 2.05/2.35/2.18 | 15.2 | 0.39 | 0.53 | 0.35 | 0.77 | 0.54 |
| 10 | 0.5 | 20 | 4.36 | 19.1 | -0.373 | 2.05/2.35/2.18 | 15.2 | 0.38 | 0.47 | 0.35 | 0.77 | 0.51 |
| 15 | 0.5 | 20 | 4.86 | 17.5 | -0.448 | 2.11/2.36/2.18 | 14.8 | 0.46 | 0.89 | 0.34 | 0.77 | 0.74 |
| 20 | 0.5 | 20 | 5.19 | 17.1 | -0.448 | 2.10/2.36/2.18 | 14.2 | 0.45 | 0.95 | 0.34 | 0.77 | 0.77 |



# PROPAGATION MODELS

| Benchmark | | | Fitted | | | Fitted | | Goodness | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $z_d$ [kpc] | $\delta$ | $r_d$ [kpc] | $D_0 \times 10^{28}$ [$\mathrm{cm^2 s^{-1}}$] | $v_A$ [$\mathrm{km\ s^{-1}}$] | $\eta$ | $\gamma_1^p/\gamma_2^p$ | $R_{0,1}^p$ GV | $\chi^2_{B/C}$ | $\chi^2_p$ | $\chi^2_{\bar{p}}$ | $\chi^2_e$ $E_k > 5$ GeV | $\chi^2_{\mathrm{tot}}$ |
| 0.5 | 0.5 | 20 | 0.191 | 11.0 | -0.60 | 2.11/2.36/2.18 | 16.9 | 0.69 | 0.67 | 0.37 | 0.68 | 0.65 |
| 1 | 0.5 | 20 | 0.53 | 16.3 | -0.521 | 2.04/2.34/2.18 | 16.0 | 0.96 | 0.46 | 0.38 | 0.69 | 0.58 |
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| 1.7 | 0.5 | 20 | 0.932 | 16.2 | -0.476 | 2.11/2.35/2.18 | 14.6 | 0.47 | 0.65 | 0.35 | 0.72 | 0.60 |
| 2 | 0.5 | 20 | 1.13 | 16.7 | -0.458 | 2.11/2.35/2.18 | 14.6 | 0.48 | 0.59 | 0.35 | 0.72 | 0.58 |
| 3 | 0.5 | 20 | 1.75 | 18.5 | -0.40 | 2.05/2.35/2.18 | 16.0 | 0.34 | 0.39 | 0.35 | 0.75 | 0.46 |
| 4 | 0.5 | 20 | 2.45 | 19.5 | -0.363 | 2.05/2.35/2.18 | 16.0 | 0.79 | 0.33 | 0.36 | 0.75 | 0.49 |
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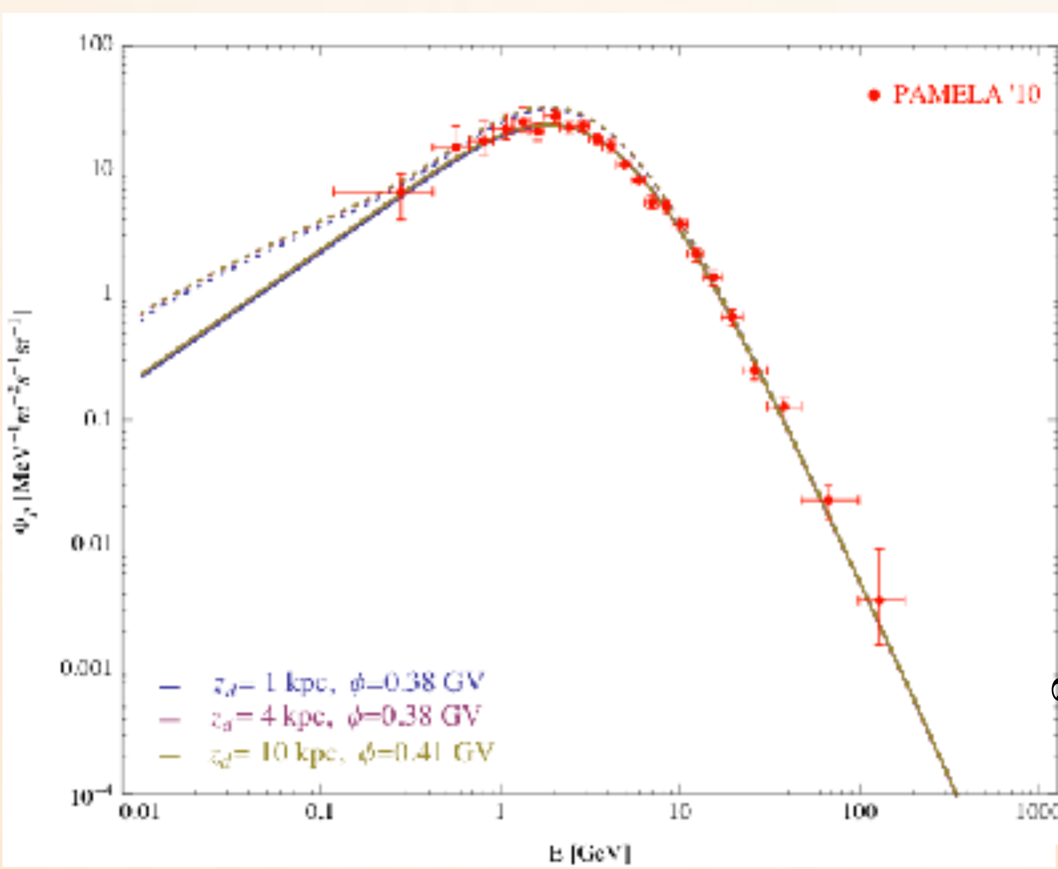
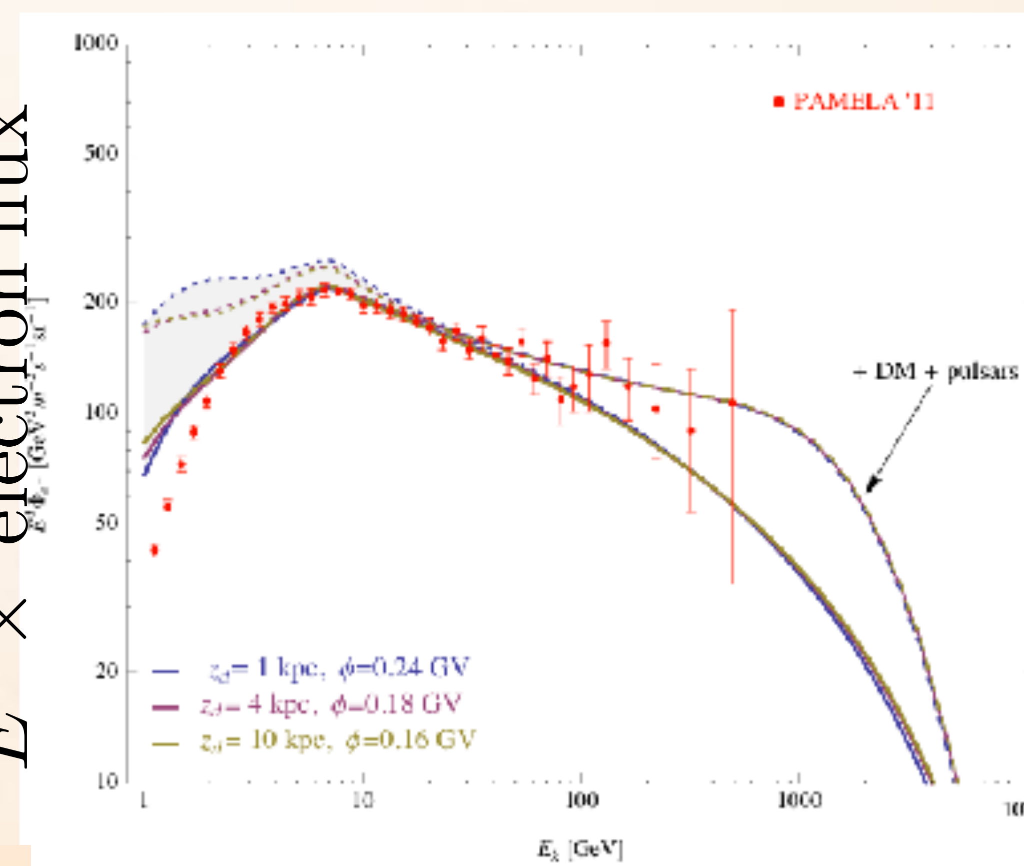
| 20 | 0.5 | 20 | 5.19 | 17.1 | -0.448 | 2.10/2.36/2.18 | 14.2 | 0.45 | 0.95 | 0.34 | 0.77 | 0.77 |

$\bar{p}$ flux




$E^3 \times$ electron flux



# PROPAGATION MODELS

| Benchmark | | | Fitted | | | Fitted | | Goodness | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $z_d$ [kpc] | $\delta$ | $r_d$ [kpc] | $D_0 \times 10^{28}$ [$\mathrm{cm^2 s^{-1}}$] | $v_A$ [$\mathrm{km\ s^{-1}}$] | $\eta$ | $\gamma_1^p/\gamma_2^p$ | $R_{0,1}^p$ GV | $\chi^2_{B/C}$ | $\chi^2_p$ | $\chi^2_{\bar{p}}$ | $\chi^2_e$ $E_k > 5$ GeV | $\chi^2_{\mathrm{tot}}$ |
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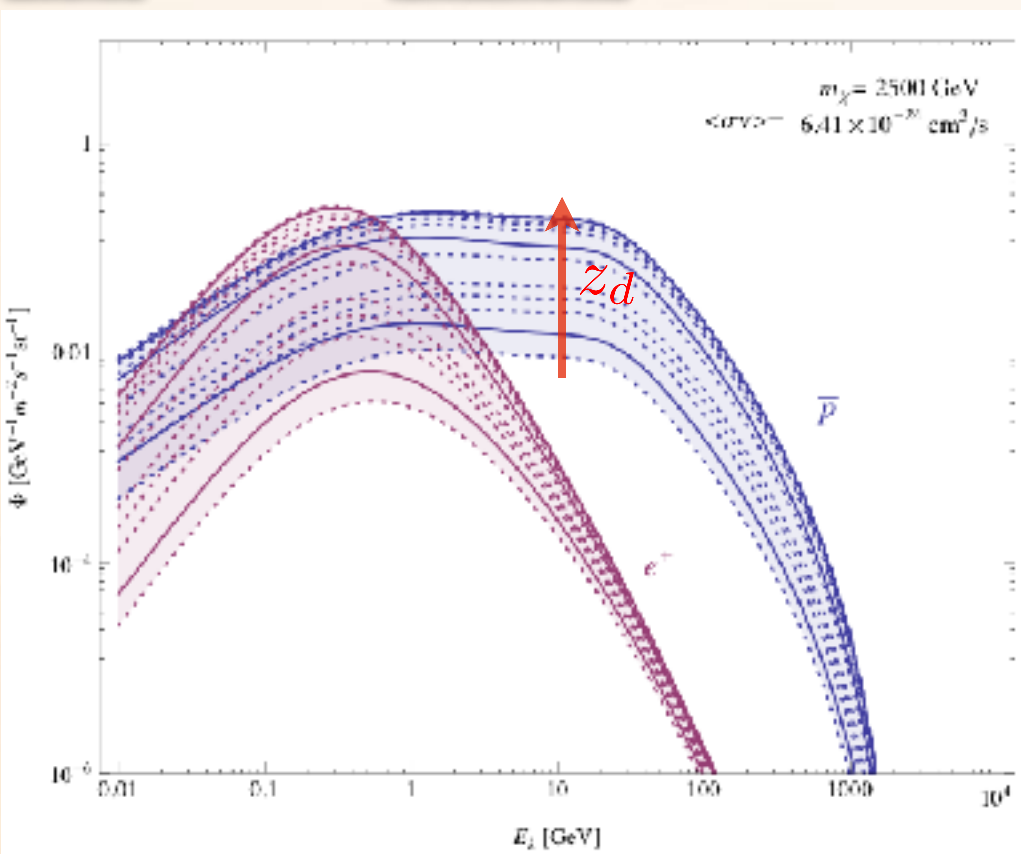
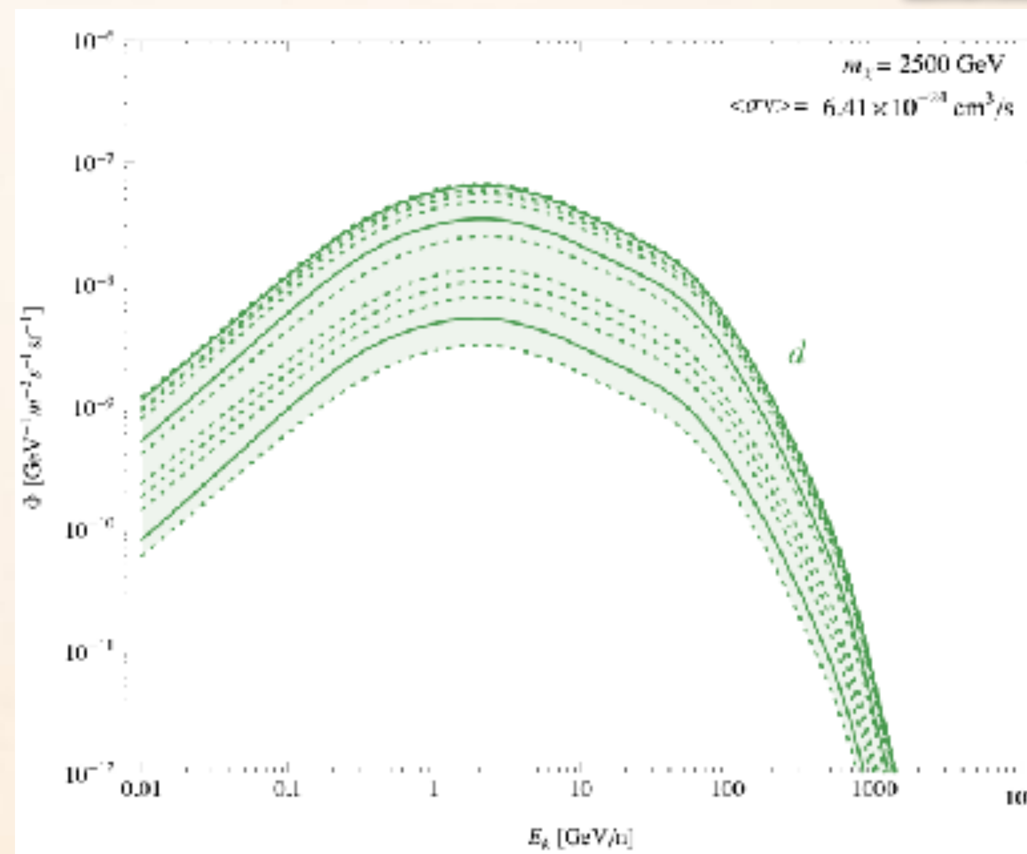
| 1.4 | 0.5 | 20 | 0.738 | 15.5 | -0.499 | 2.11/2.36/2.18 | 16.1 | 0.51 | 0.62 | 0.36 | 0.71 | 0.60 |
| 1.7 | 0.5 | 20 | 0.932 | 16.2 | -0.476 | 2.11/2.35/2.18 | 14.6 | 0.47 | 0.65 | 0.35 | 0.72 | 0.60 |
| 2 | 0.5 | 20 | 1.13 | 16.7 | -0.458 | 2.11/2.35/2.18 | 14.6 | 0.48 | 0.59 | 0.35 | 0.72 | 0.58 |
| 3 | 0.5 | 20 | 1.75 | 18.5 | -0.40 | 2.05/2.35/2.18 | 16.0 | 0.34 | 0.39 | 0.35 | 0.75 | 0.46 |
| 4 | 0.5 | 20 | 2.45 | 19.5 | -0.363 | 2.05/2.35/2.18 | 16.0 | 0.79 | 0.33 | 0.36 | 0.75 | 0.49 |
| 6 | 0.5 | 20 | 3.17 | 19.2 | -0.40 | 2.05/2.35/2.18 | 16.0 | 0.38 | 0.44 | 0.35 | 0.77 | 0.49 |
| 8 | 0.5 | 20 | 3.83 | 19.2 | -0.370 | 2.05/2.35/2.18 | 15.2 | 0.39 | 0.53 | 0.35 | 0.77 | 0.54 |
| 10 | 0.5 | 20 | 4.36 | 19.1 | -0.373 | 2.05/2.35/2.18 | 15.2 | 0.38 | 0.47 | 0.35 | 0.77 | 0.51 |
| 15 | 0.5 | 20 | 4.86 | 17.5 | -0.448 | 2.11/2.36/2.18 | 14.8 | 0.46 | 0.89 | 0.34 | 0.77 | 0.74 |
| 20 | 0.5 | 20 | 5.19 | 17.1 | -0.448 | 2.10/2.36/2.18 | 14.2 | 0.45 | 0.95 | 0.34 | 0.77 | 0.77 |

$z_d$ ↓

DM originated fluxes



# SEARCH CHANNELS

antimatter

$\bar{p}$ $e^+$ $\bar{d}$

gamma-rays

diffuse

galactic GC

favors thick diff. zones!

extragalactic

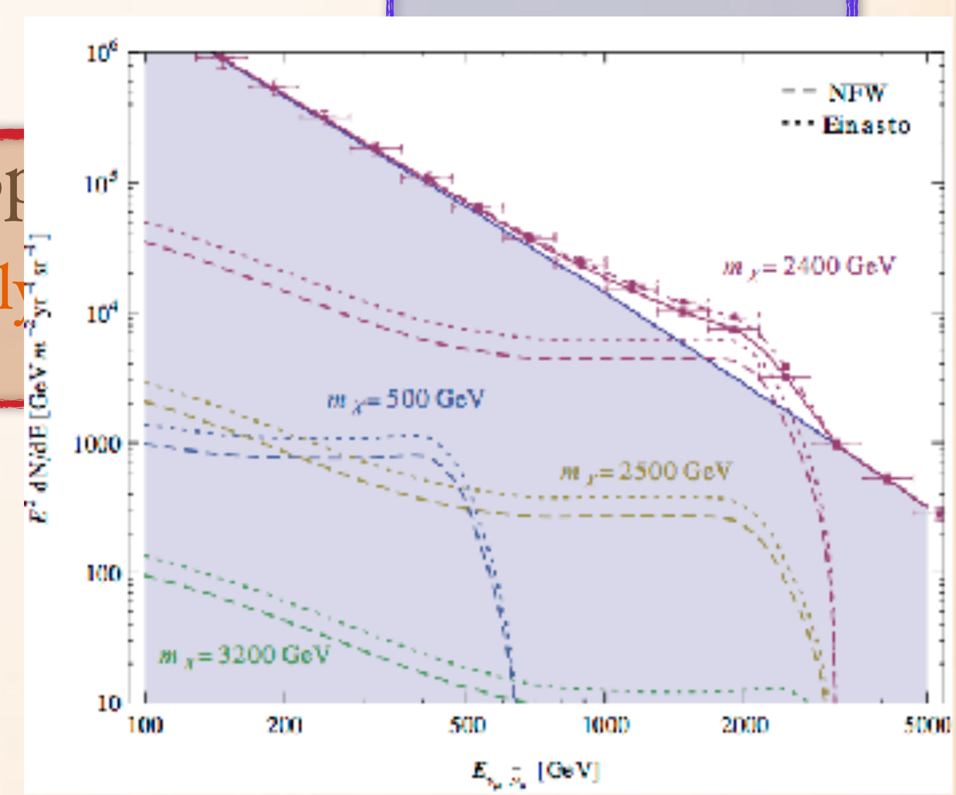
lines

dSp

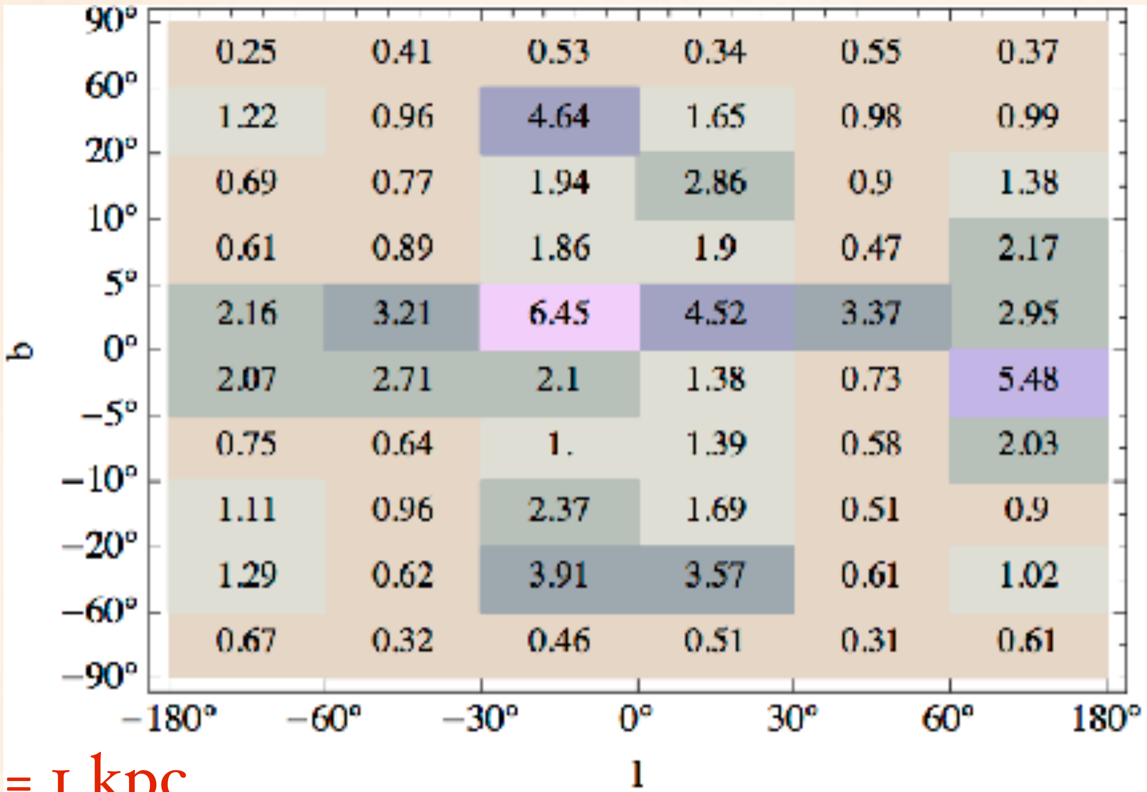
mainly

neutrinos

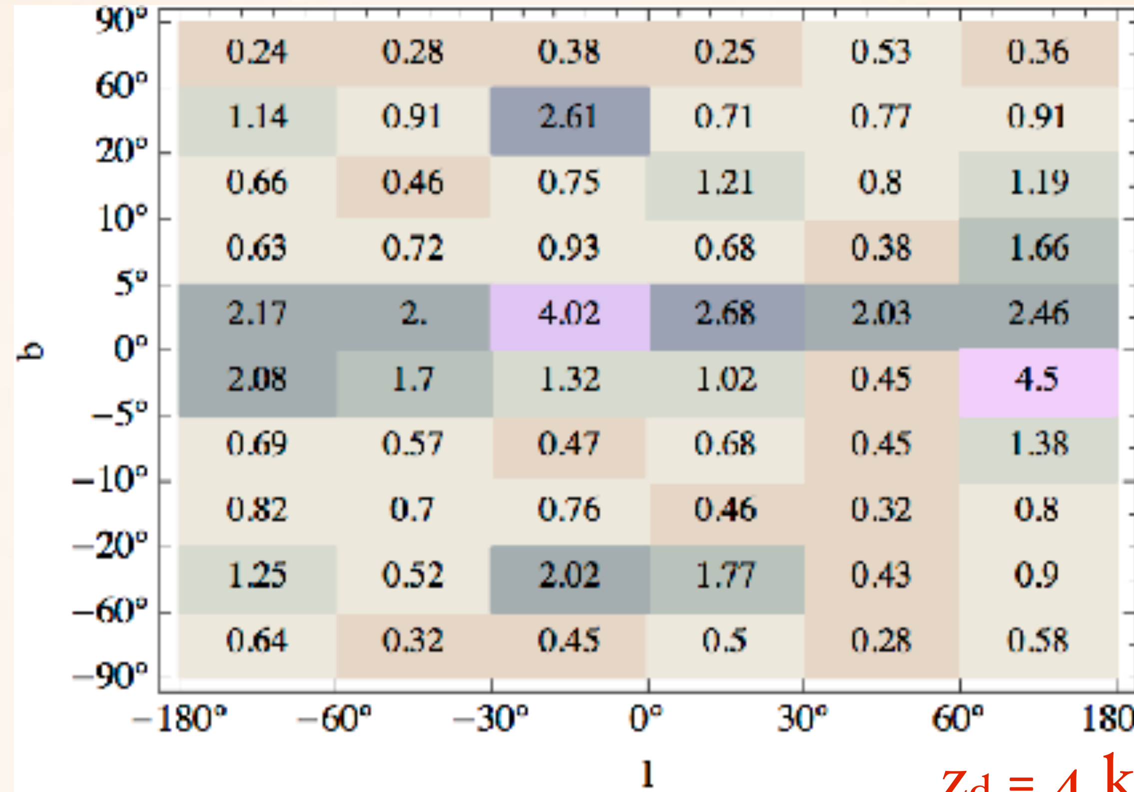
only resonance



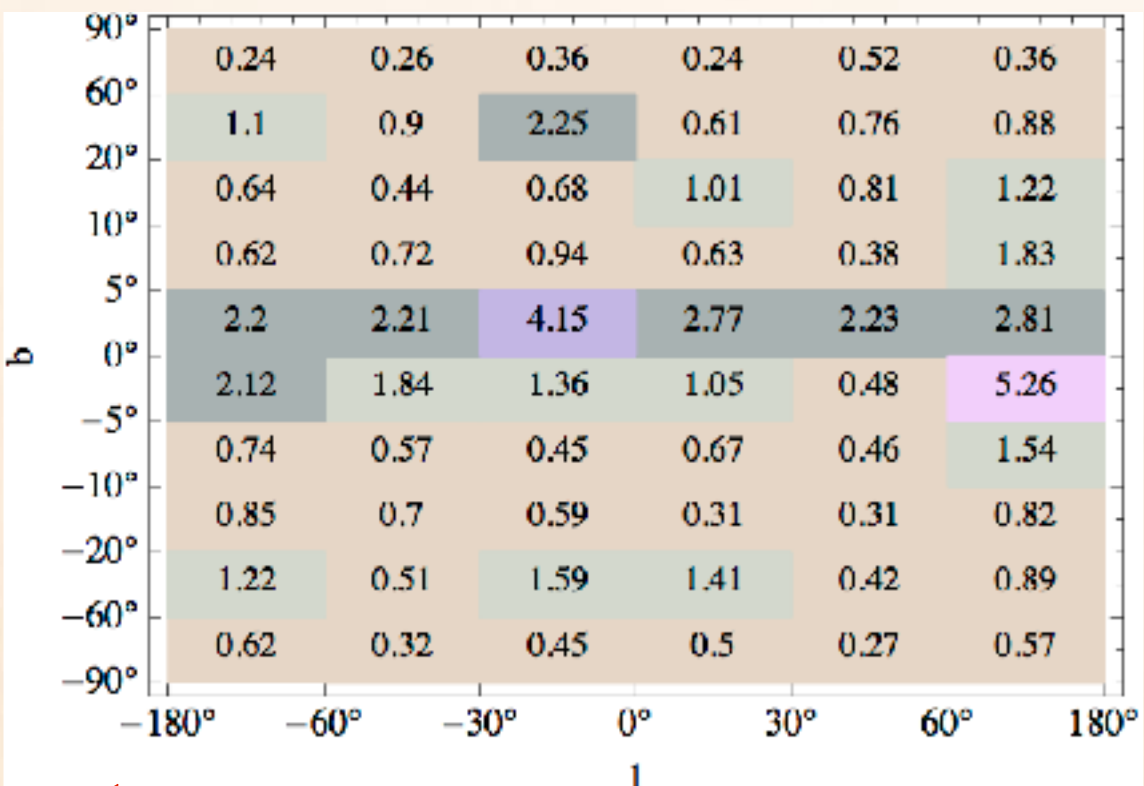
# Gamma ray Sky-maps




$z_d$ = 1 kpc



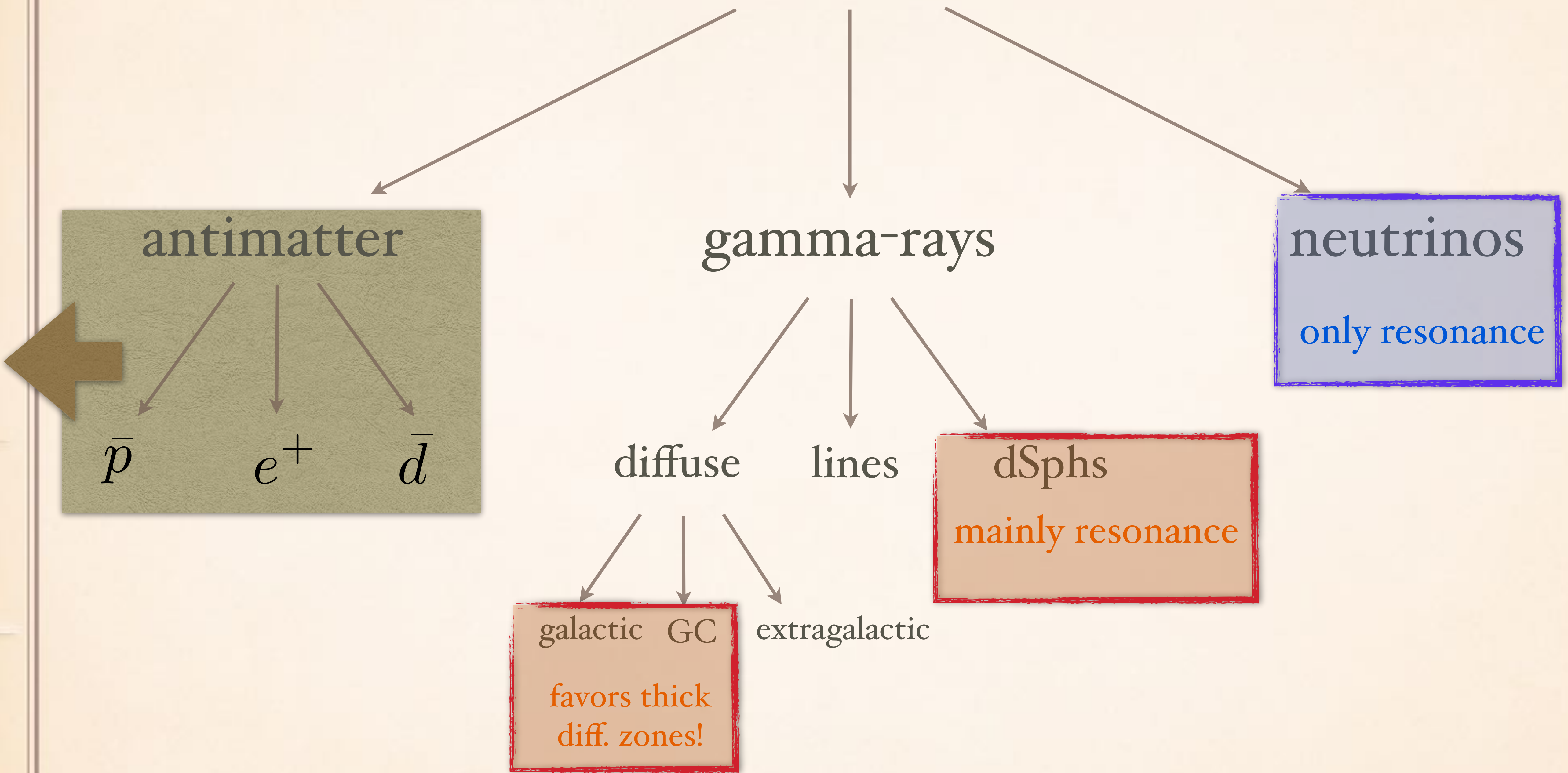

$z_d$ = 4 kpc



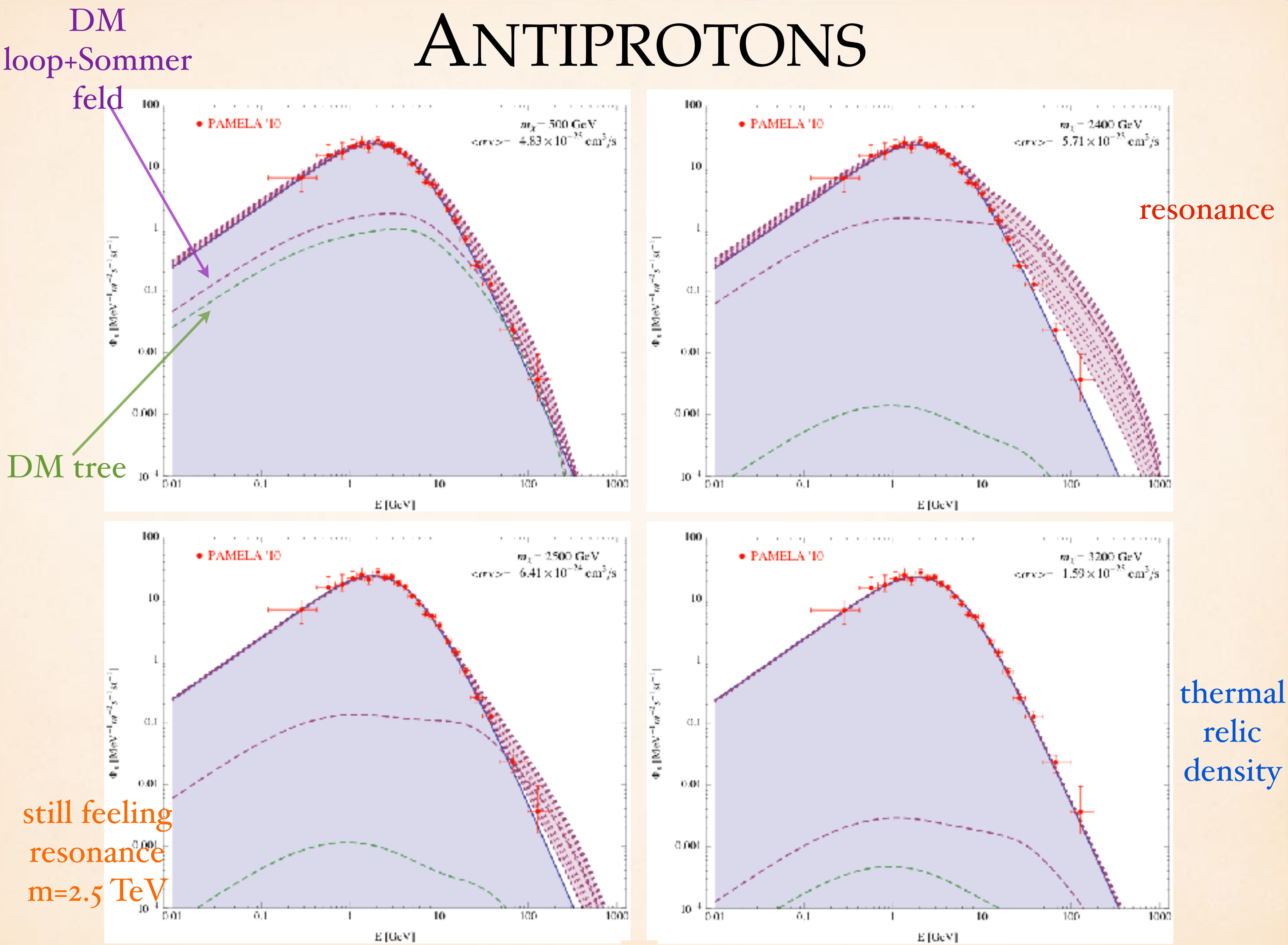

$z_d$ = 10 kpc

*Fermi* data favors thick diffusion zones

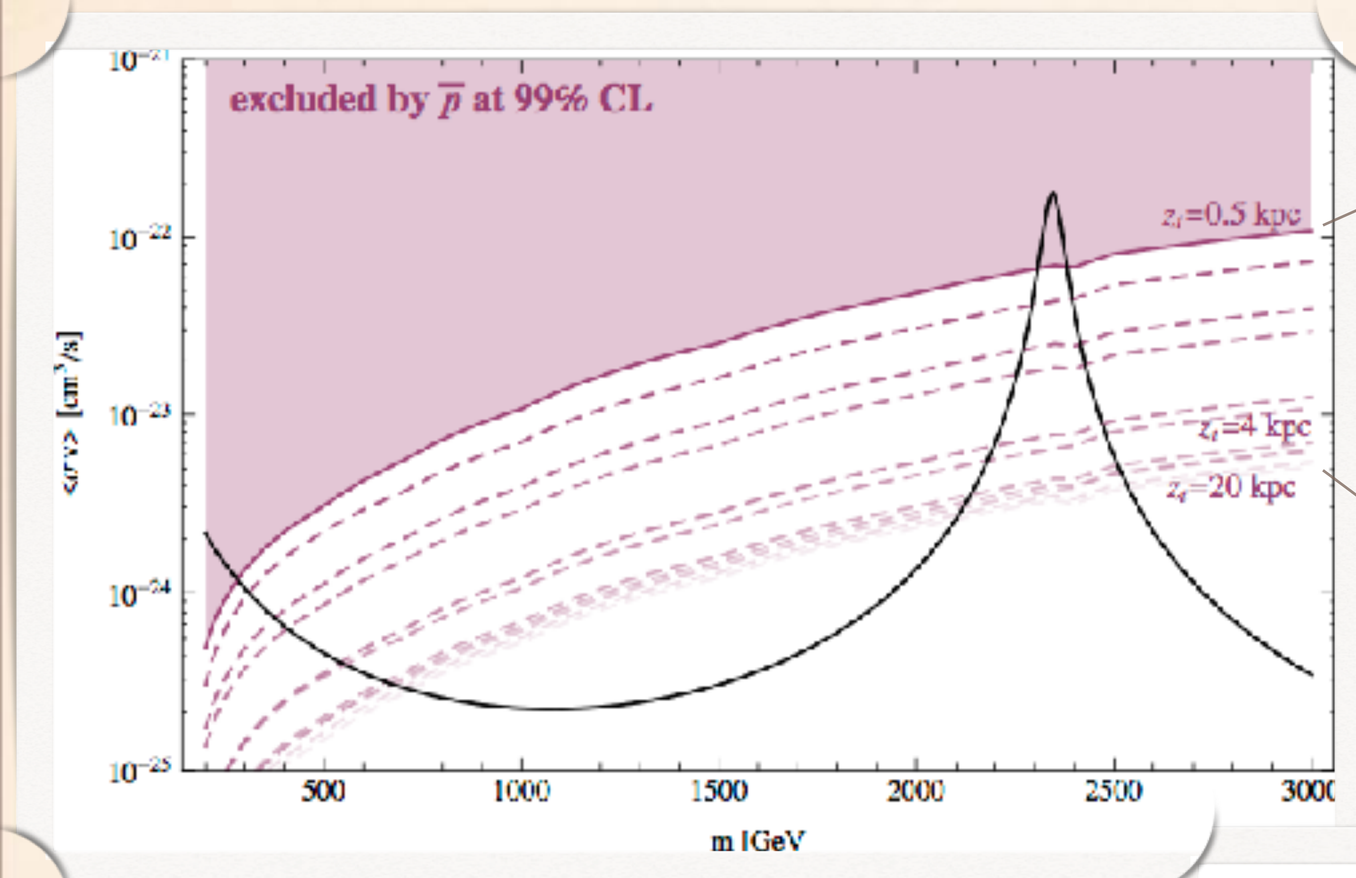
# SEARCH CHANNELS

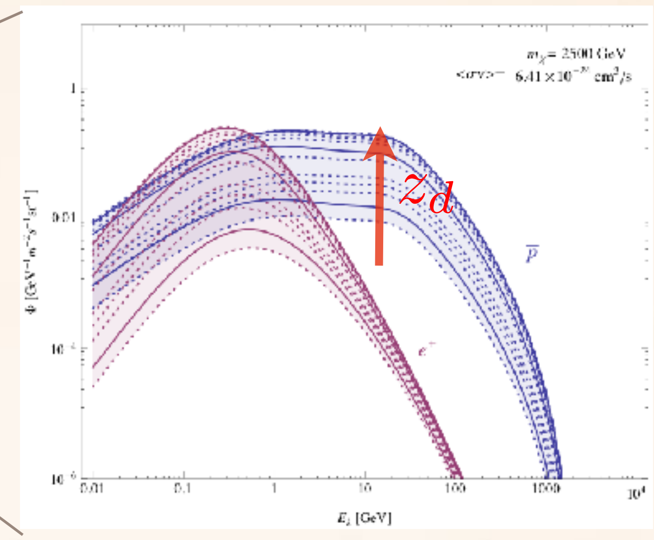


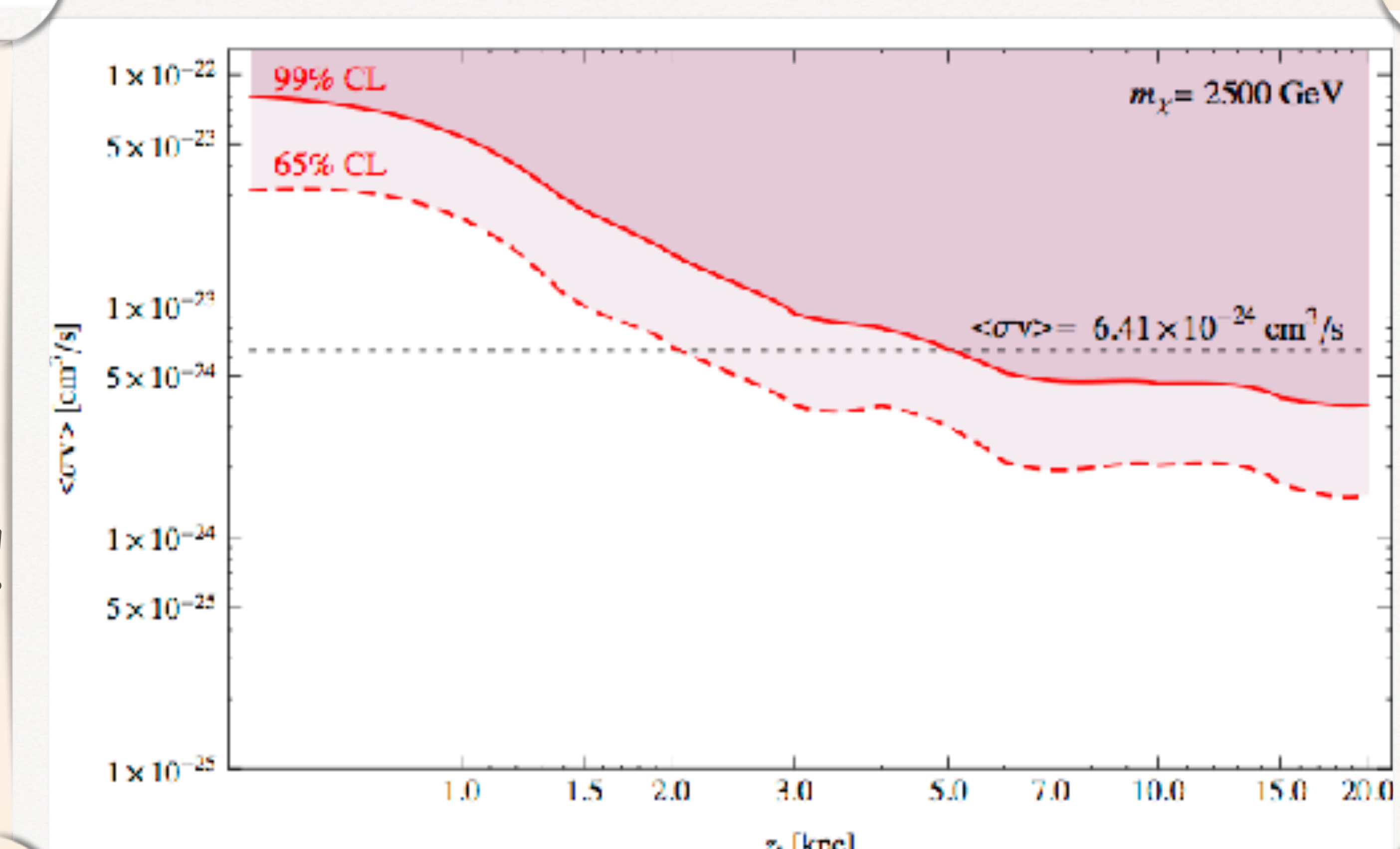
# ANTIPROTONS



# ANTIPROTONS




The thicker diffusion zone
the stronger the constraint!

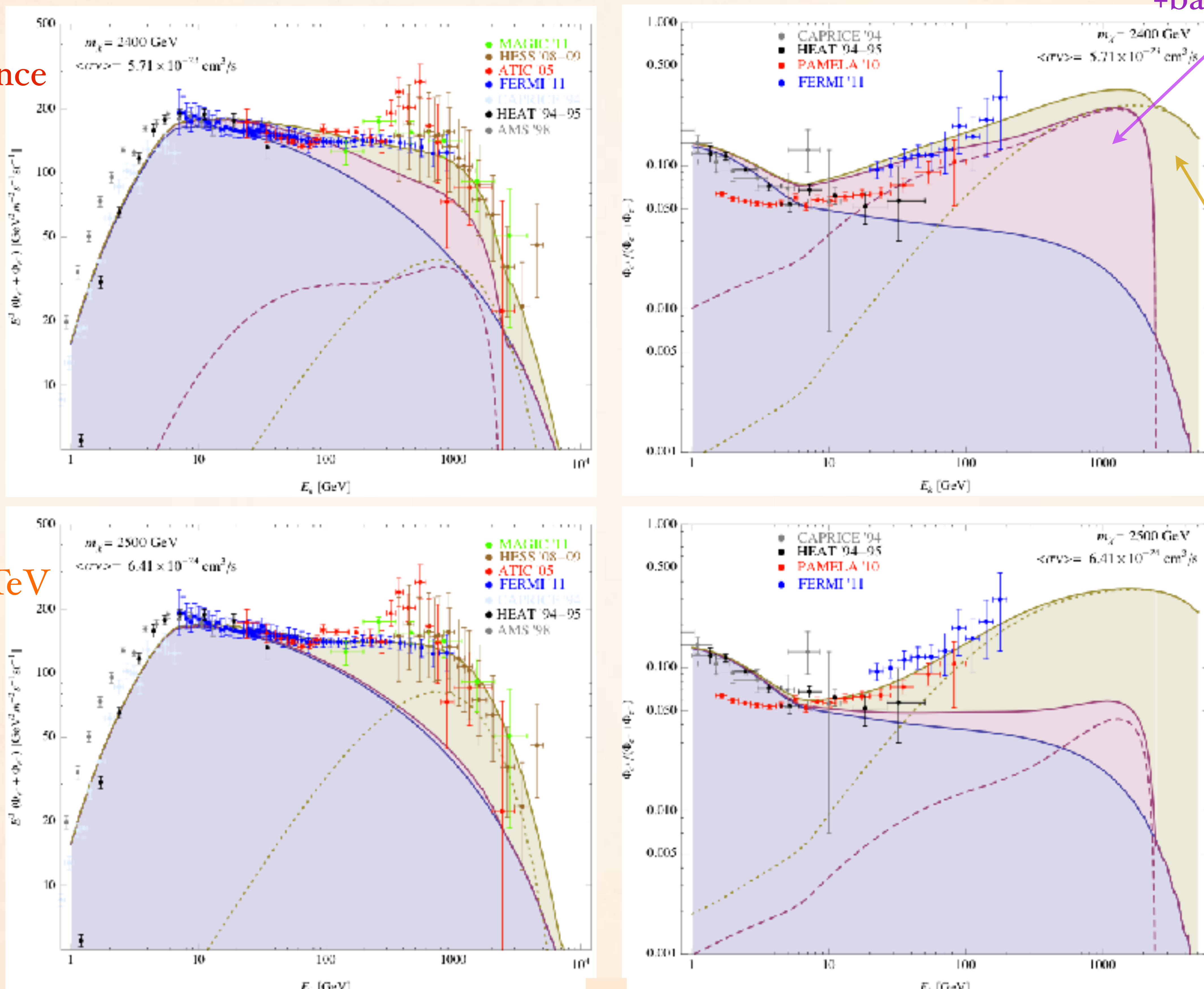
## $e^+ + e^-$      $e^+$ fraction

resonance

m=2.5 TeV

DM +background

DM +bckgr. +pulsars



# SUMMARY
## INDIRECT DETECTION

Wino DM is ruled out for

$m_\chi \lesssim 450$ GeV

antiprotons + diffuse gamma-rays

see also **Belanger *et al.*, arXiv:** 1208.5009

$2.2 \text{ TeV} \lesssim m_\chi \lesssim 2.5 \text{ TeV}$

leptons

antiprotons + diffuse gamma-rays

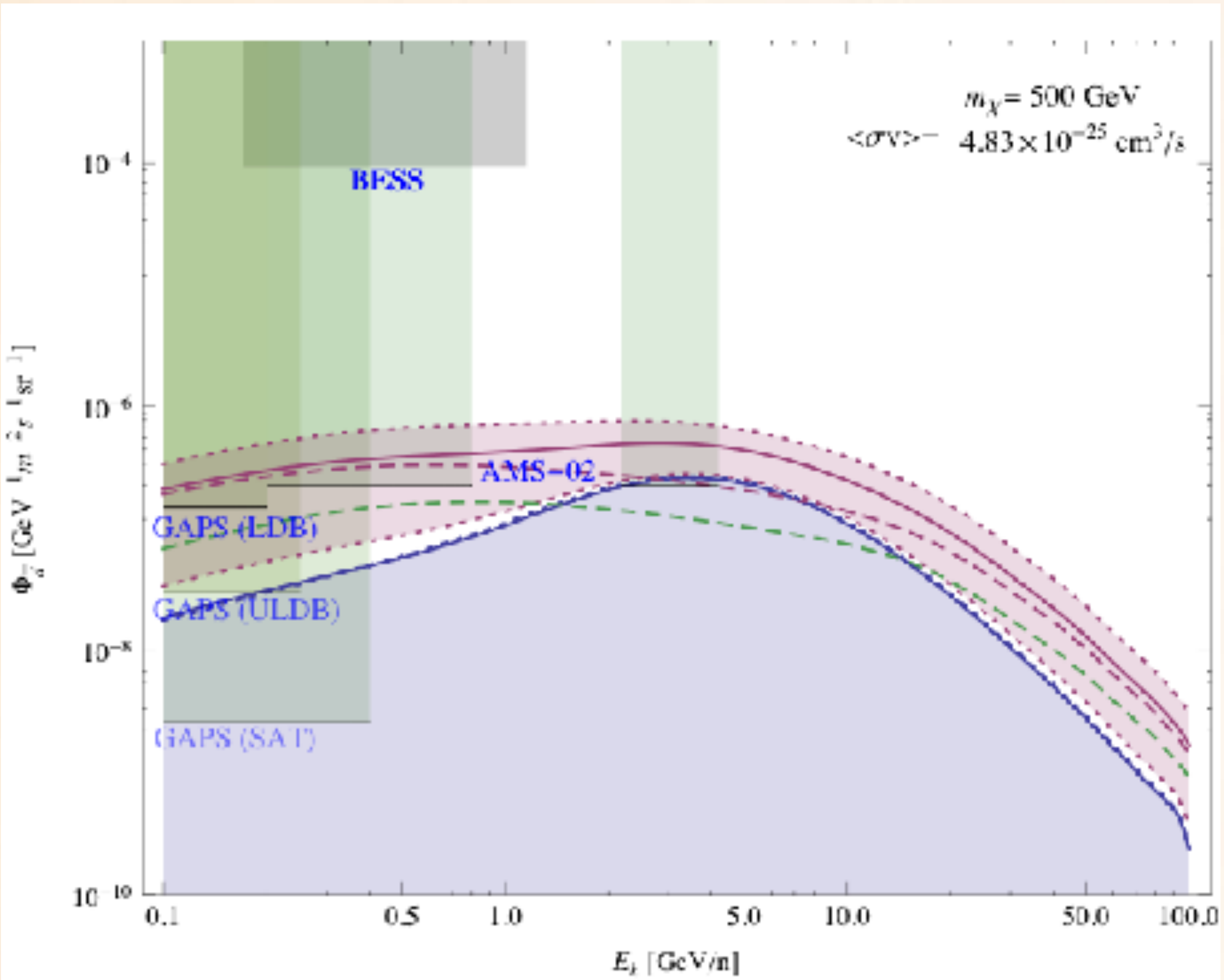
dSphs

GC

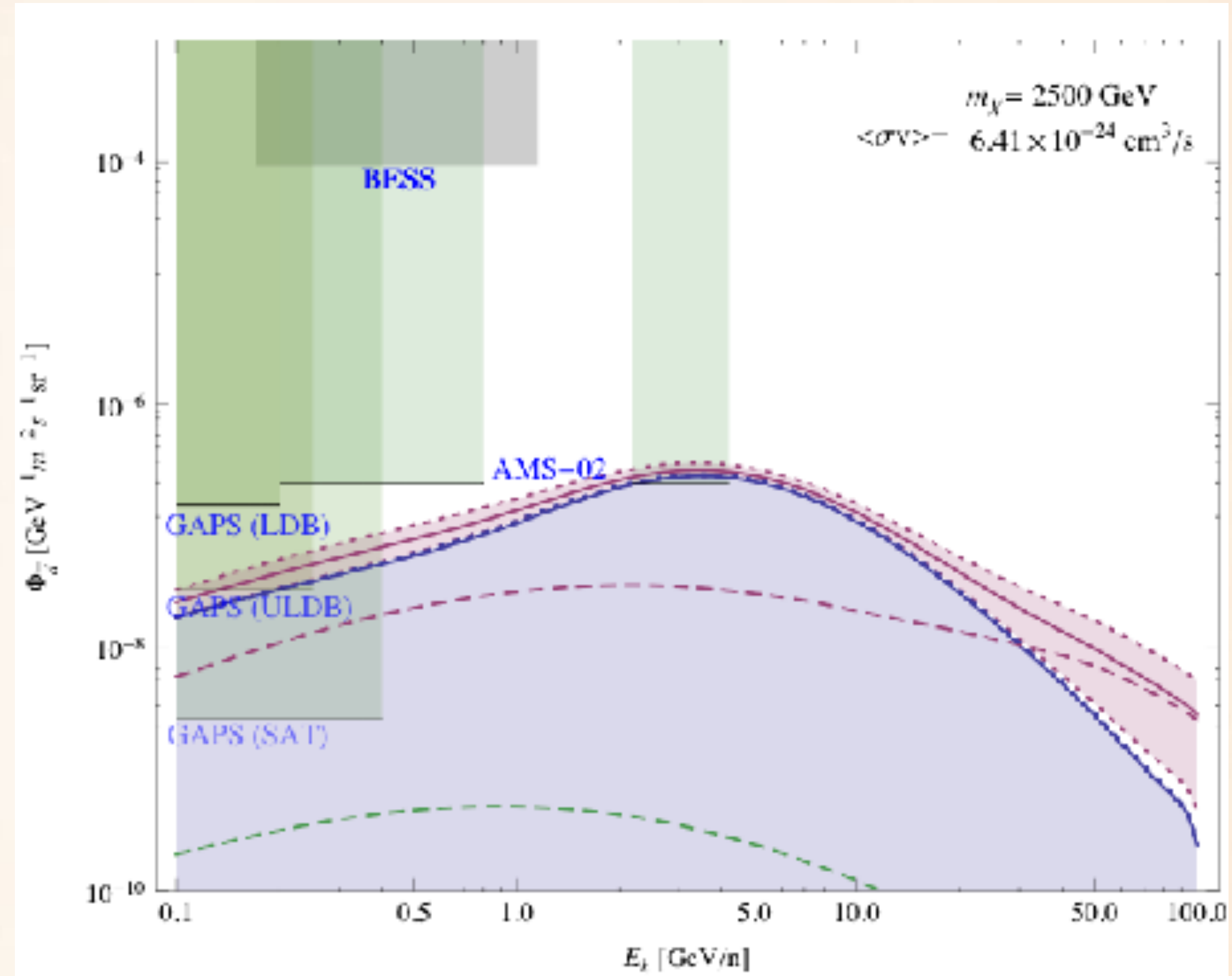
It cannot explain the lepton CR puzzle

Thermal Wino DM evades all ID constraints...

# ANTIDEUTERONS




m=0.5 TeV




m=2.5 TeV

**Dal** and **Kachelriess, arXiv:** 1207.4560

Large uncertainties: propagation, fragmentation model, cross-sections

→ prospective channel in (not immediate) future

# Conclusion

In order to obtain robust predictions for dark matter relic density and indirect detection one is forced to look beyond the tree level

and also

study different detection channels simultaneously.

# Thank you

# Relic density
## with the SE

$$\langle \sigma_{\rm eff} {\rm v} \rangle = \sum_{ij} S_{ij}(T, {\rm v}) \langle \sigma_{ij} {\rm v}_{ij} \rangle \frac{n_i^{\rm eq} n_j^{\rm eq}}{n_{\rm eq}^2}$$

Why temperature dependence?

- Higgs VEV

$$v(T) = v \cdot \Re \left(1 - \frac{T^2}{T_c^2}\right)^{1/2} \qquad T_c \approx m_h$$

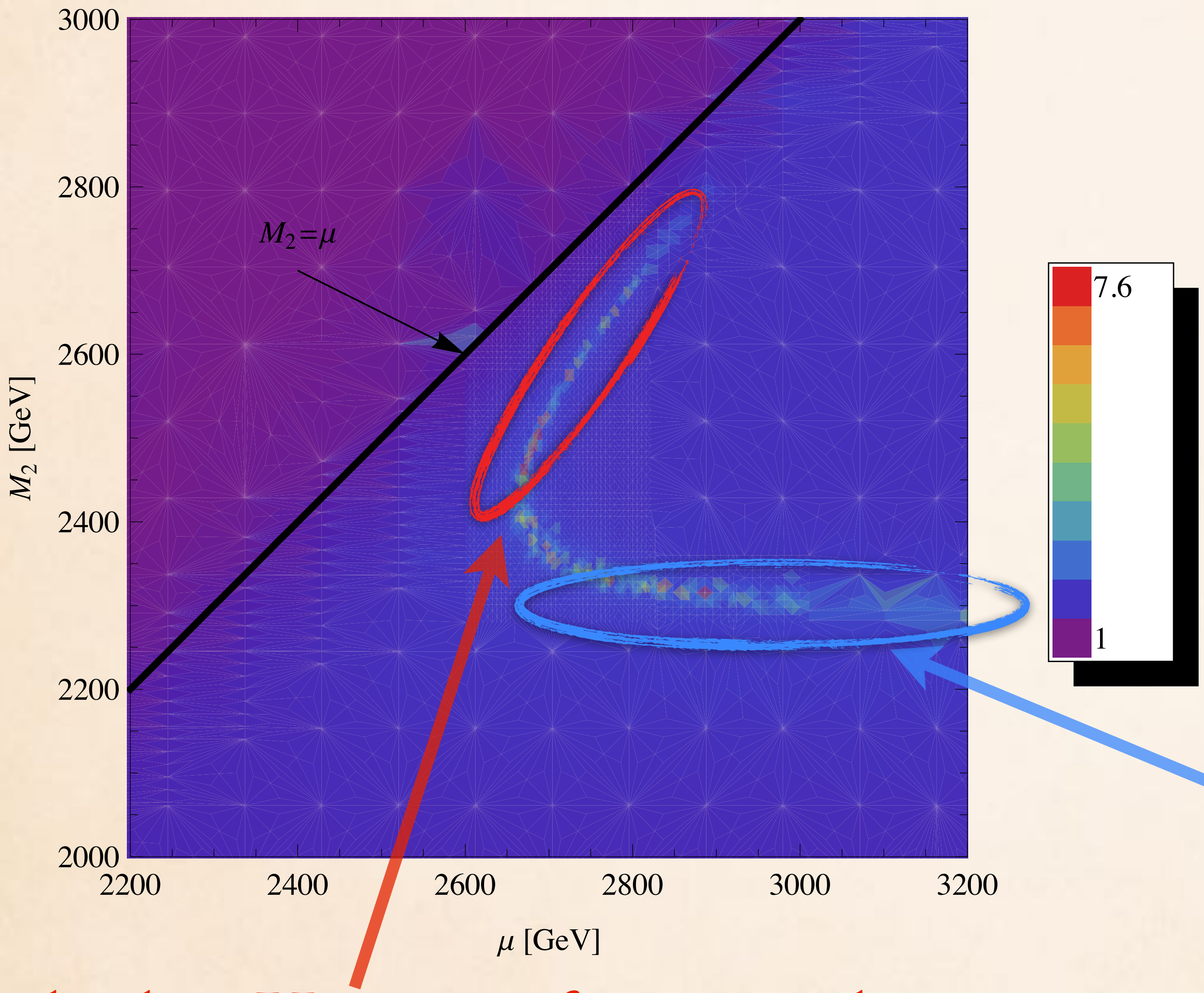
- Debye masses

$$\Delta m_\gamma^2 = \frac{11}{6} g_Y^2 T^2 \qquad \Delta m_{W,Z}^2 = \frac{11}{6} g_2^2 T^2 \qquad \Delta m_g^2 = \frac{3}{2} g_s^2 T^2$$

Strumia *et al.*, Nucl. Phys. B787 (2007) 152

# RESULTS

## WINO-HIGGSINO




higher Higgsino fraction - larger mass needed

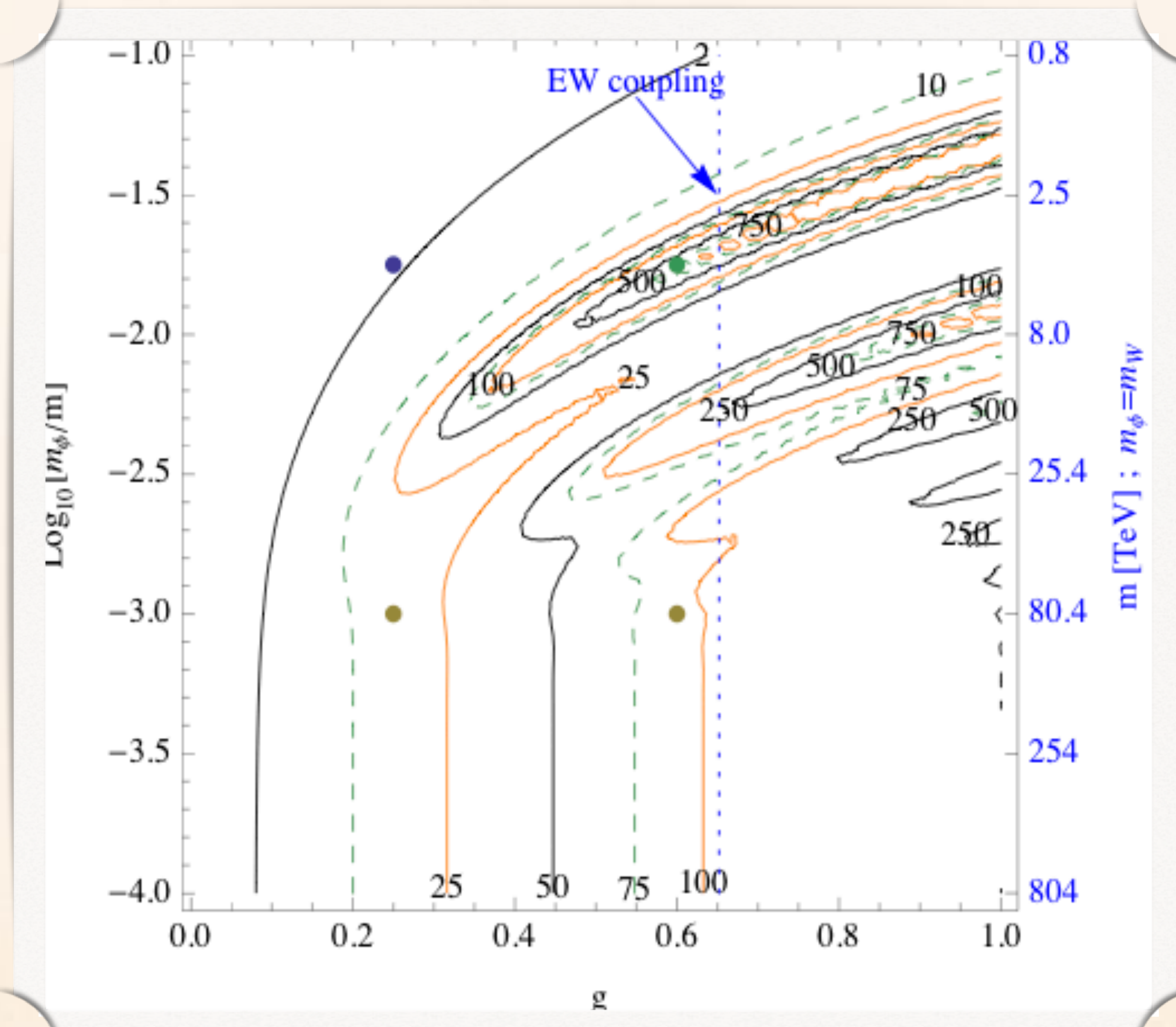
Zoom on the resonance effect on relic density

$$\frac{1}{m_W} \approx \frac{1}{\alpha m_\chi}$$

which gives:

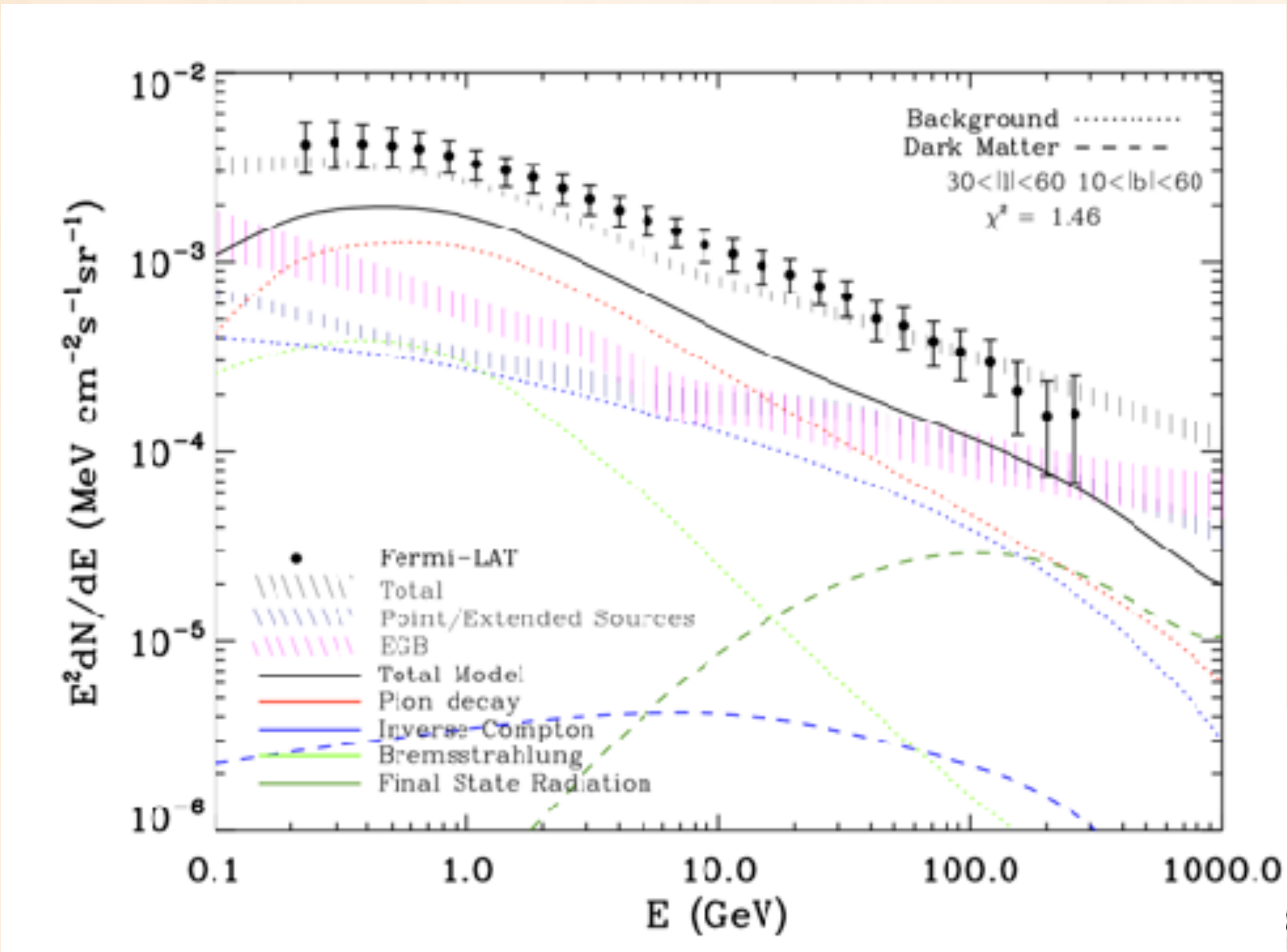
$$m_\chi \approx 2.3 \text{ TeV}$$

# THE SOMMERFELD EFFECT
## WITH A DARK FORCE

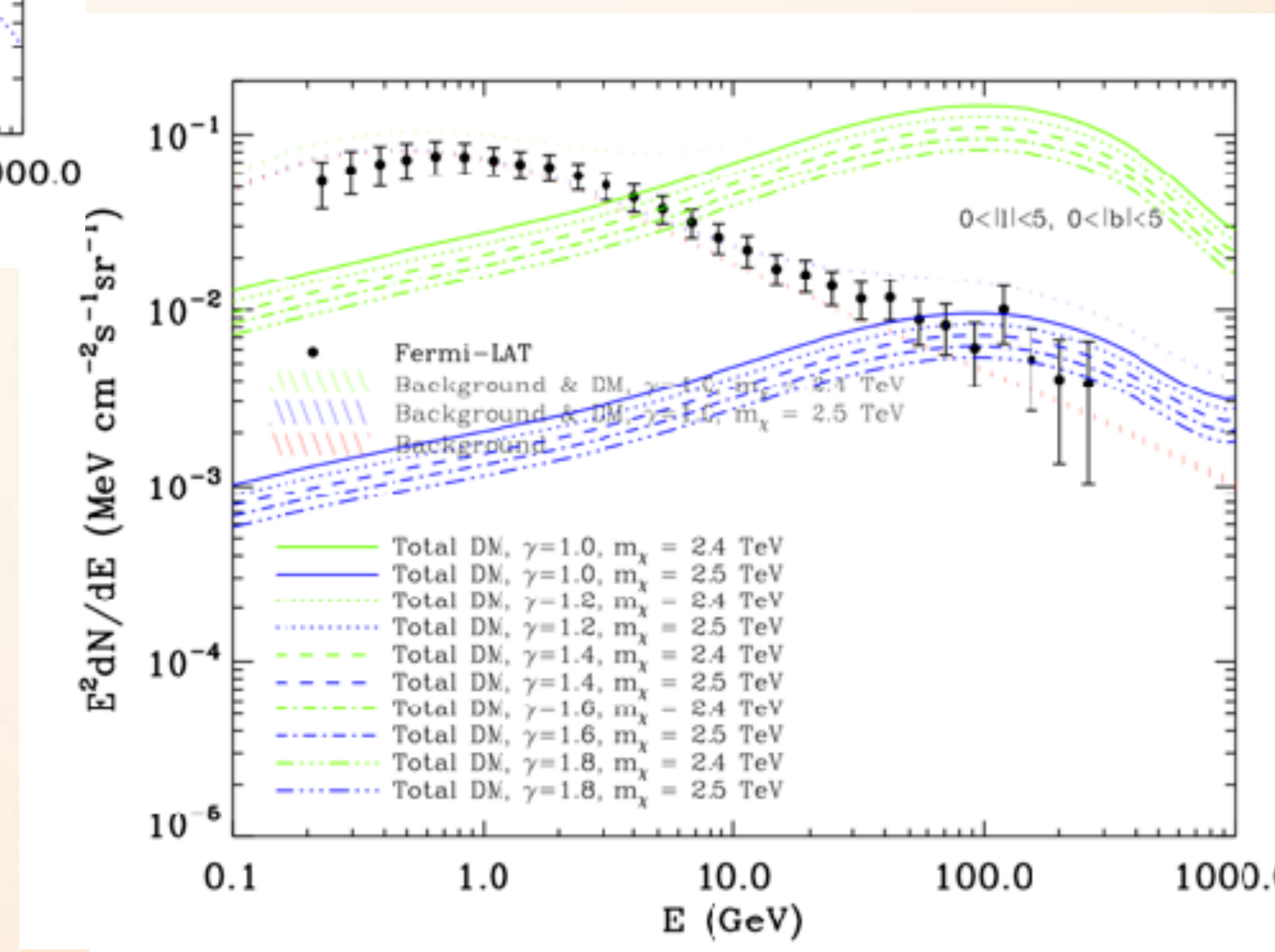



rich resonance structure, with very large enhancements

# GAMMA-RAYS



Background
Dark Matter
30<|l|<60 10<|b|<60
χ² = 1.46
Fermi-LAT
Total
Point/Extended Sources
EGB
Total Model
Pion decay
Inverse Compton
Bremsstrahlung
Final State Radiation
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
0.1
1.0
10.0
100.0
1000.0
E (GeV)
E²dN/dE (MeV cm⁻²s⁻¹sr⁻¹)

0<|l|<5, 0<|b|<5
Fermi-LAT
Background
Total DM, γ=1.0, mχ = 2.4 TeV
Total DM, γ=1.0, mχ = 2.5 TeV
Total DM, γ=1.2, mχ = 2.4 TeV
Total DM, γ=1.2, mχ = 2.5 TeV
Total DM, γ=1.4, mχ = 2.4 TeV
Total DM, γ=1.4, mχ = 2.5 TeV
Total DM, γ=1.6, mχ = 2.4 TeV
Total DM, γ=1.6, mχ = 2.5 TeV
Total DM, γ=1.8, mχ = 2.4 TeV
Total DM, γ=1.8, mχ = 2.5 TeV
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
0.1
1.0
10.0
100.0
1000.0
E (GeV)
E²dN/dE (MeV cm⁻²s⁻¹sr⁻¹)

# SOMMERFELD FACTORS

## RESULTS: SCALARS

scalar - scalar → $S$, scalar - fermion → $F$

$$c_{ij,i'j'} = g^{\phi}_{ii'} g^{\phi}_{jj'} N^{S,F}_{ij,i'j'} A^{S,F}_{\phi}(m_i, m_j, m_{i'}, m_{j'})$$

with:

$$A^S_V = A^S_A = \frac{1}{2}\left(1 + \frac{m_i}{2m_{i'}} + \frac{m_j}{2m_{j'}}\right)$$

$$A^S_S = \frac{1}{4m_{i'}m_{j'}} \qquad A^F_A = 0$$

$$A^F_S = \frac{1}{2m_{j'}} \qquad A^F_V = \frac{m_{j'} + m_j}{2m_{j'}}$$

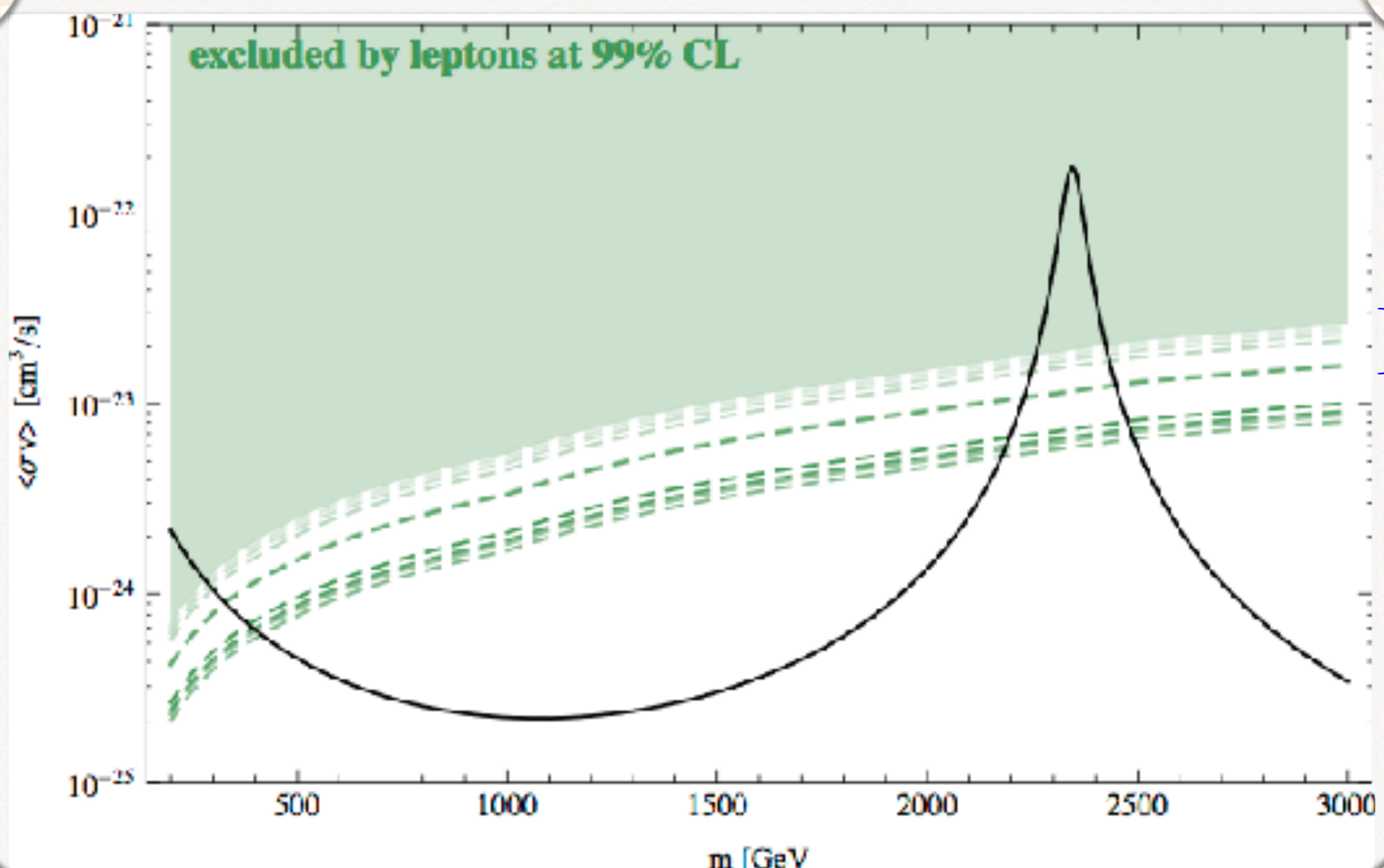
equal masses →

$$A^S_V = A^S_A = 1$$

$$A^S_S = \frac{1}{4m^2} \qquad A^F_A = 0$$

$$A^F_S = \frac{1}{2m} \qquad A^F_V = 1$$

# LEPTONS (PRELIMINARY)



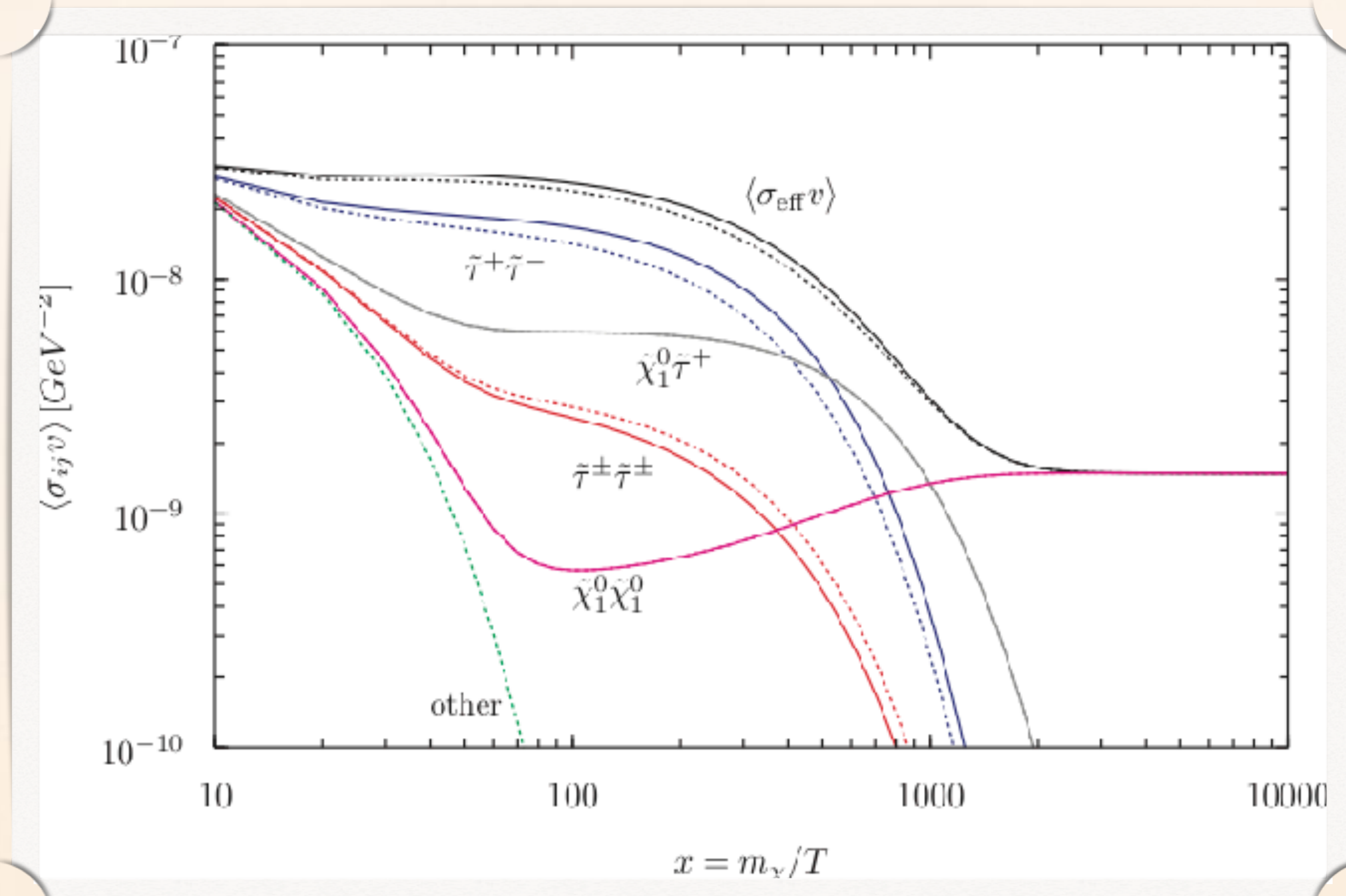

} thick
} thin

Leptons = combined:
electrons
$e^+$ fraction
$e^+ + e^-$

The thiner diffusion zone gives stronger constraint
other way around than for antiprotons!

# RESULTS

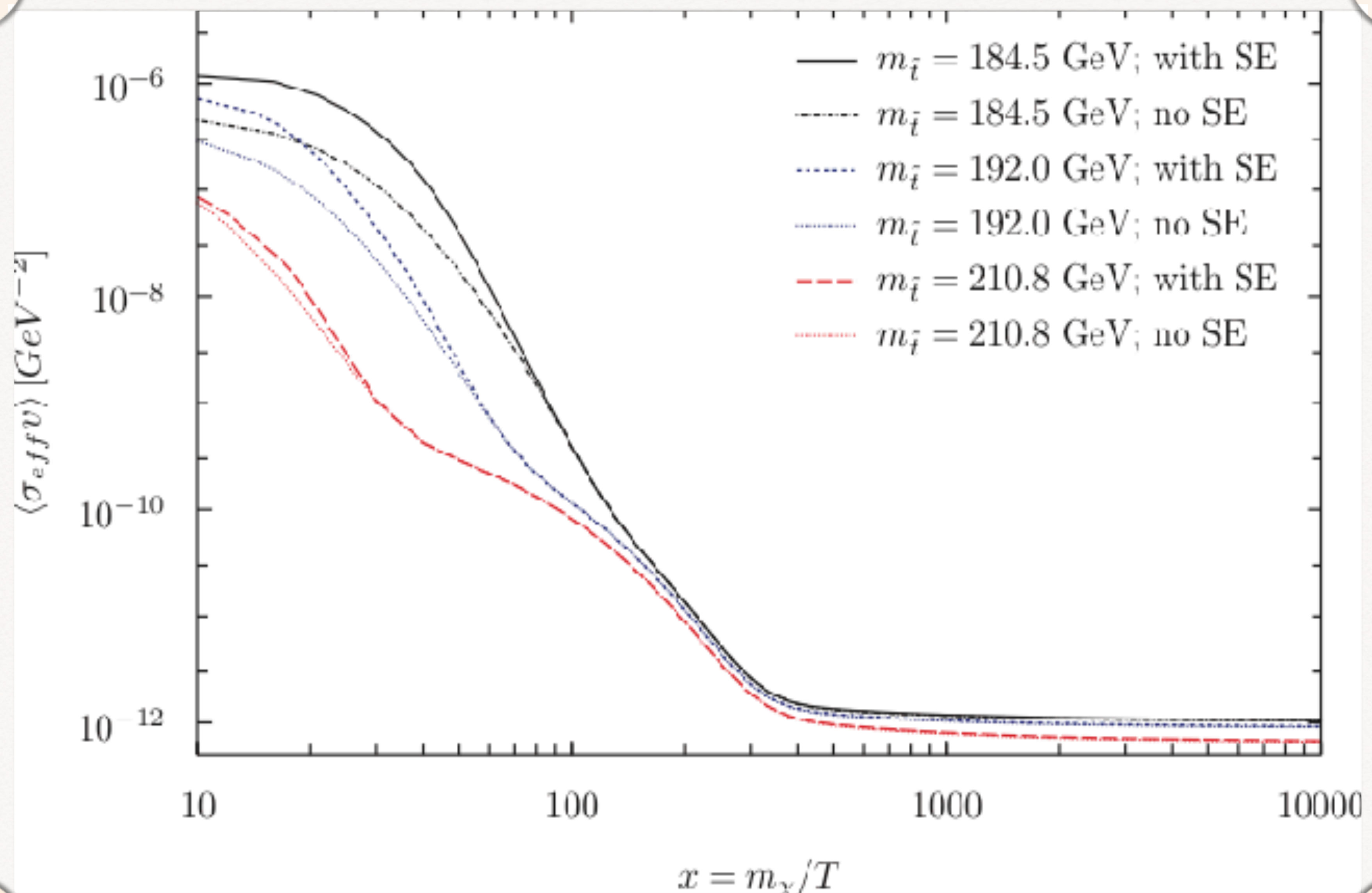
## $\tilde{\tau}$ CO-ANNIHILATION




Effect smeared out: both attractive and repulsive channels

# Results

## $\tilde{t}$ co-annihilation

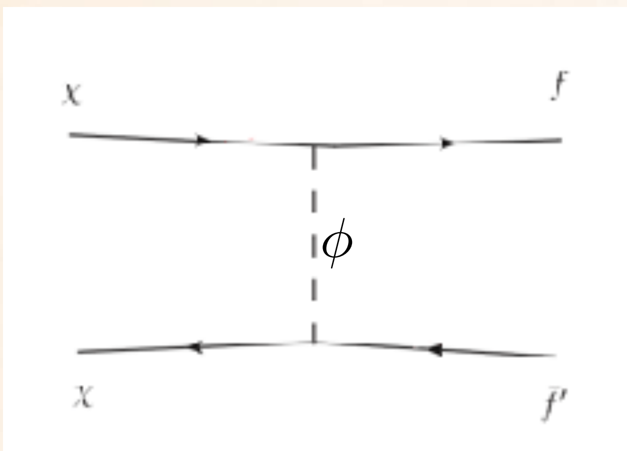



Large effect at early times

# Effect of EW corrections

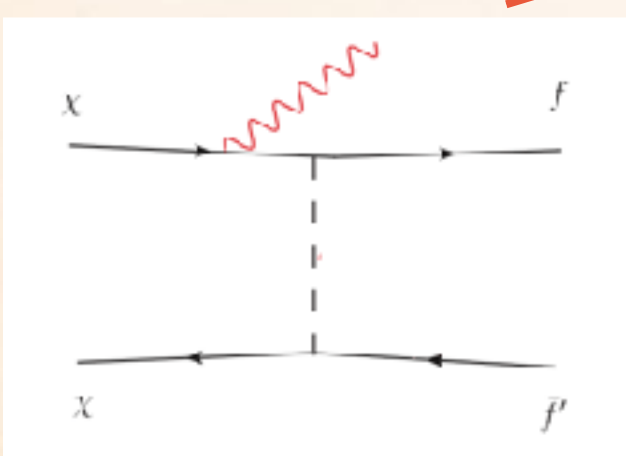
## 1. Modification of $\langle \sigma v \rangle$

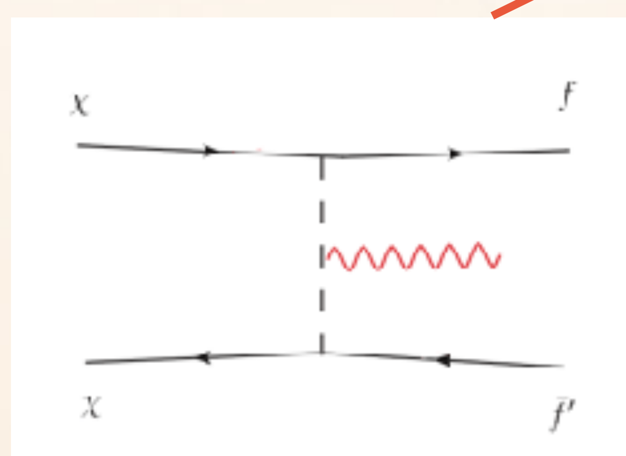
$$\sigma v \approx a + b v^2 \qquad v \sim 10^{-3}$$

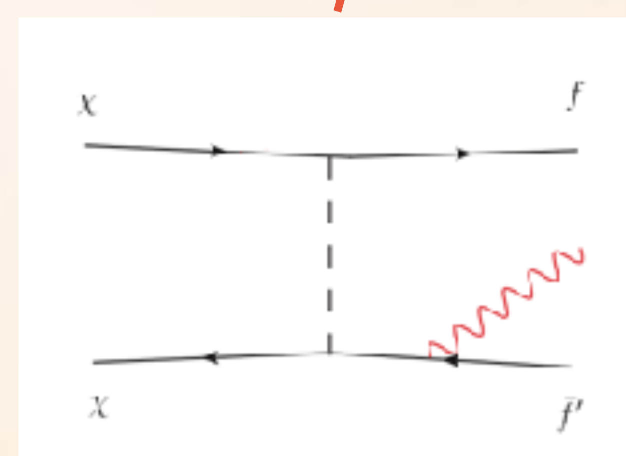



$$\propto \frac{m_f^2}{m_\chi^2} \quad + \mathcal{O}(v^0) \left[ \mathcal{O}\left(\frac{m_\chi^2}{m_\phi^2}\right)_{\text{ISR}} + \mathcal{O}\left(\frac{m_\chi^4}{m_\phi^4}\right)_{\text{VIB+FSR}} \right]$$

helicity suppression



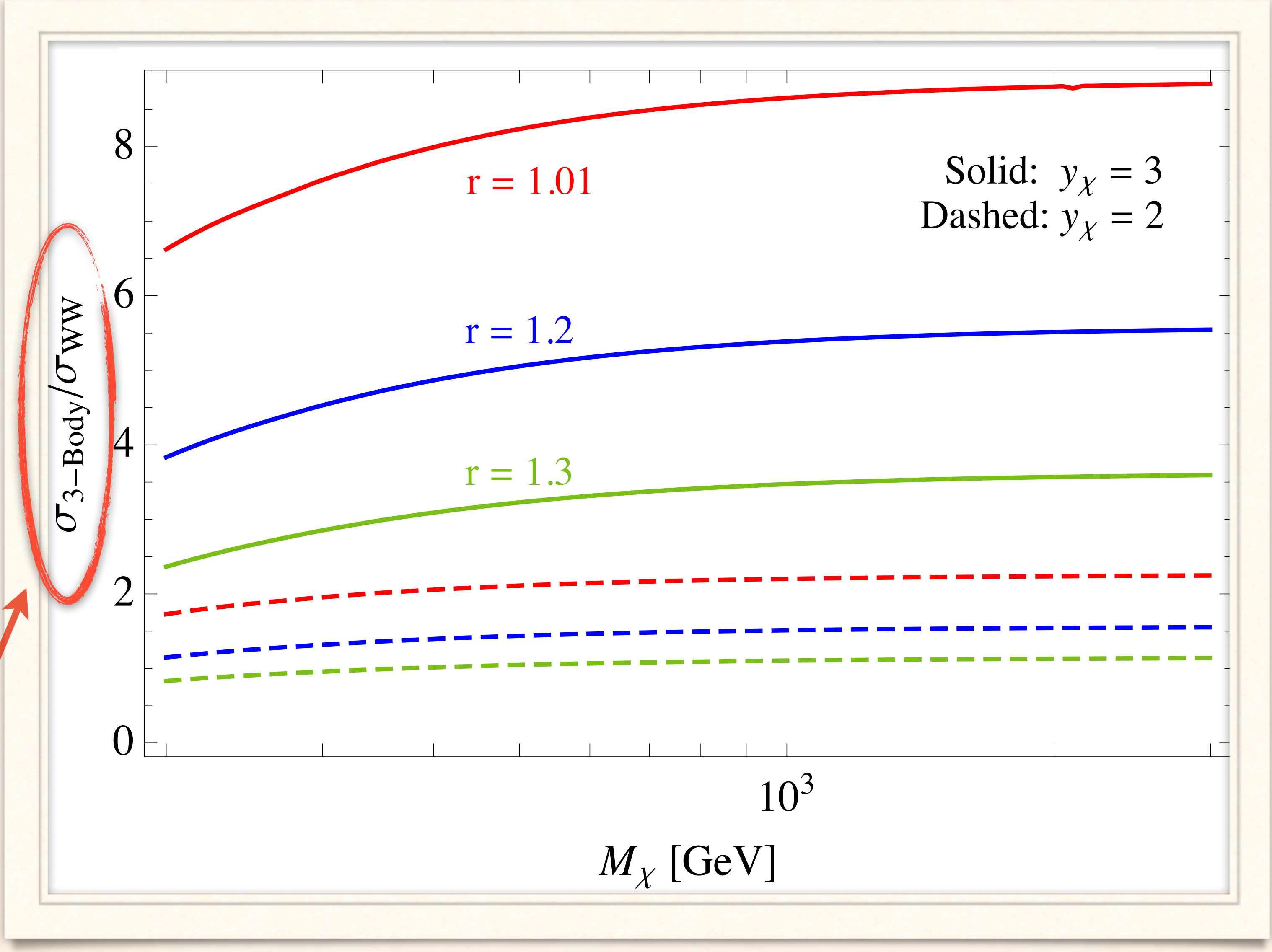




Lifting of the helicity suppression!

Bergstrom, Phys. Lett. B225 (1989) 372

# EFFECT OF EW CORRECTIONS

## 1. MODIFICATION OF $\langle \sigma v \rangle$



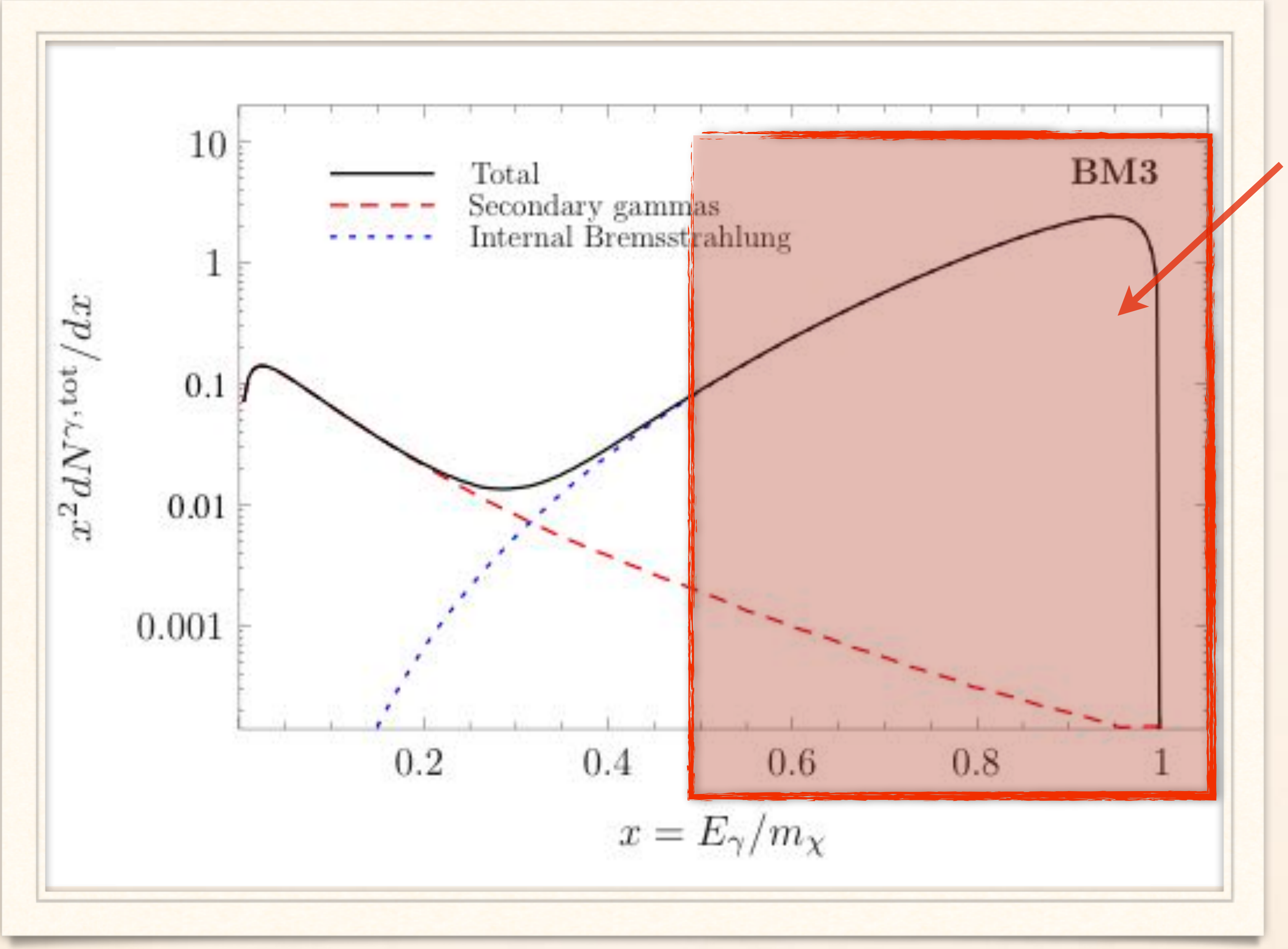

$$r \equiv \frac{m_\phi^2}{m_\chi^2}$$

large EW „corrections"

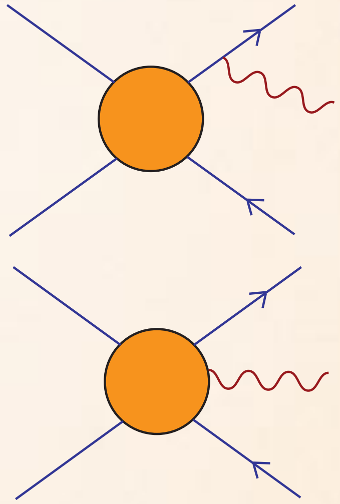
Ciafaloni *et al.*, JCAP 1206 (2012) 016

# EFFECT OF EW CORRECTIONS

## 2. NEW SPECTRAL FEATURES

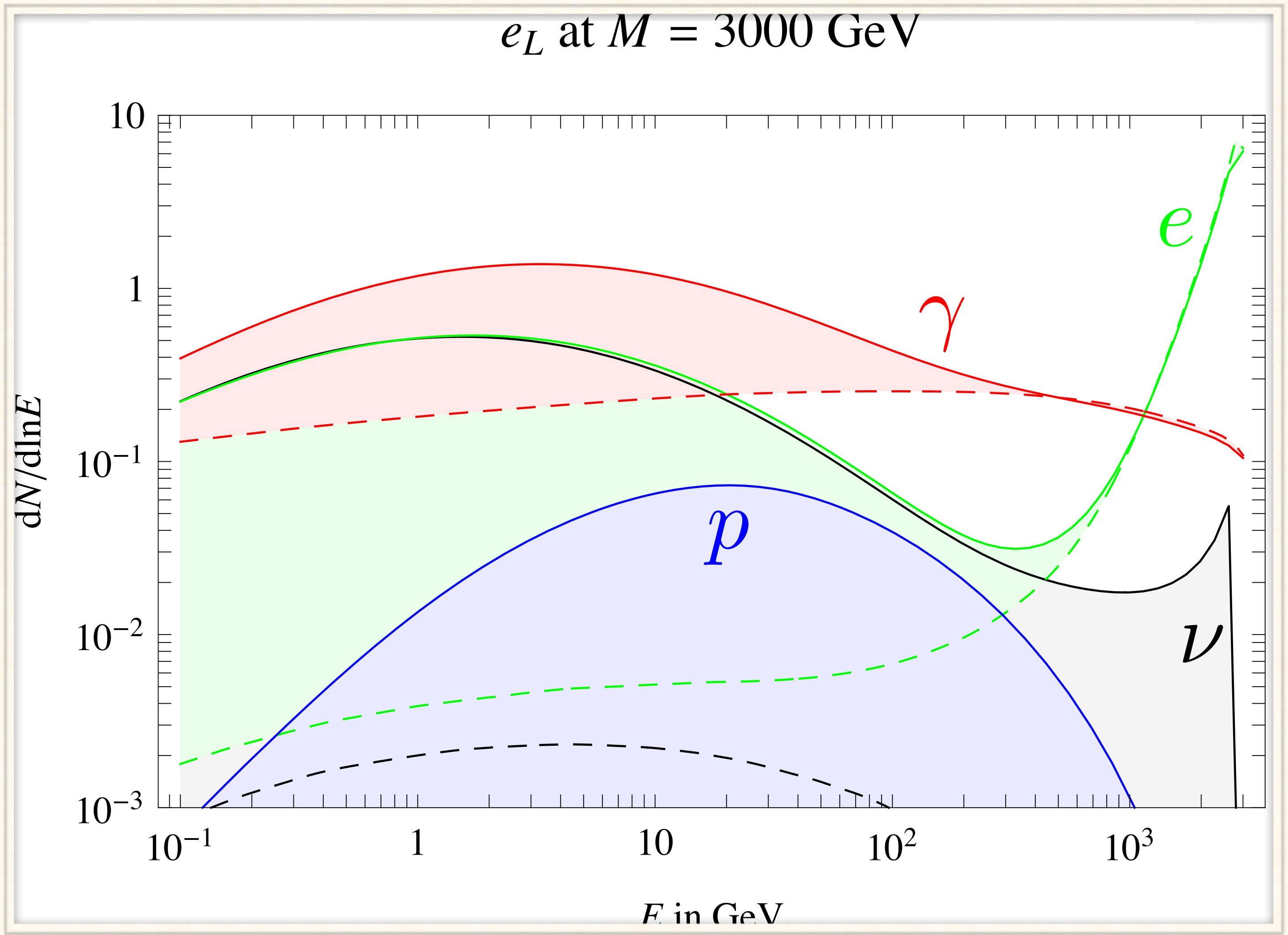



IB „bump" in photons



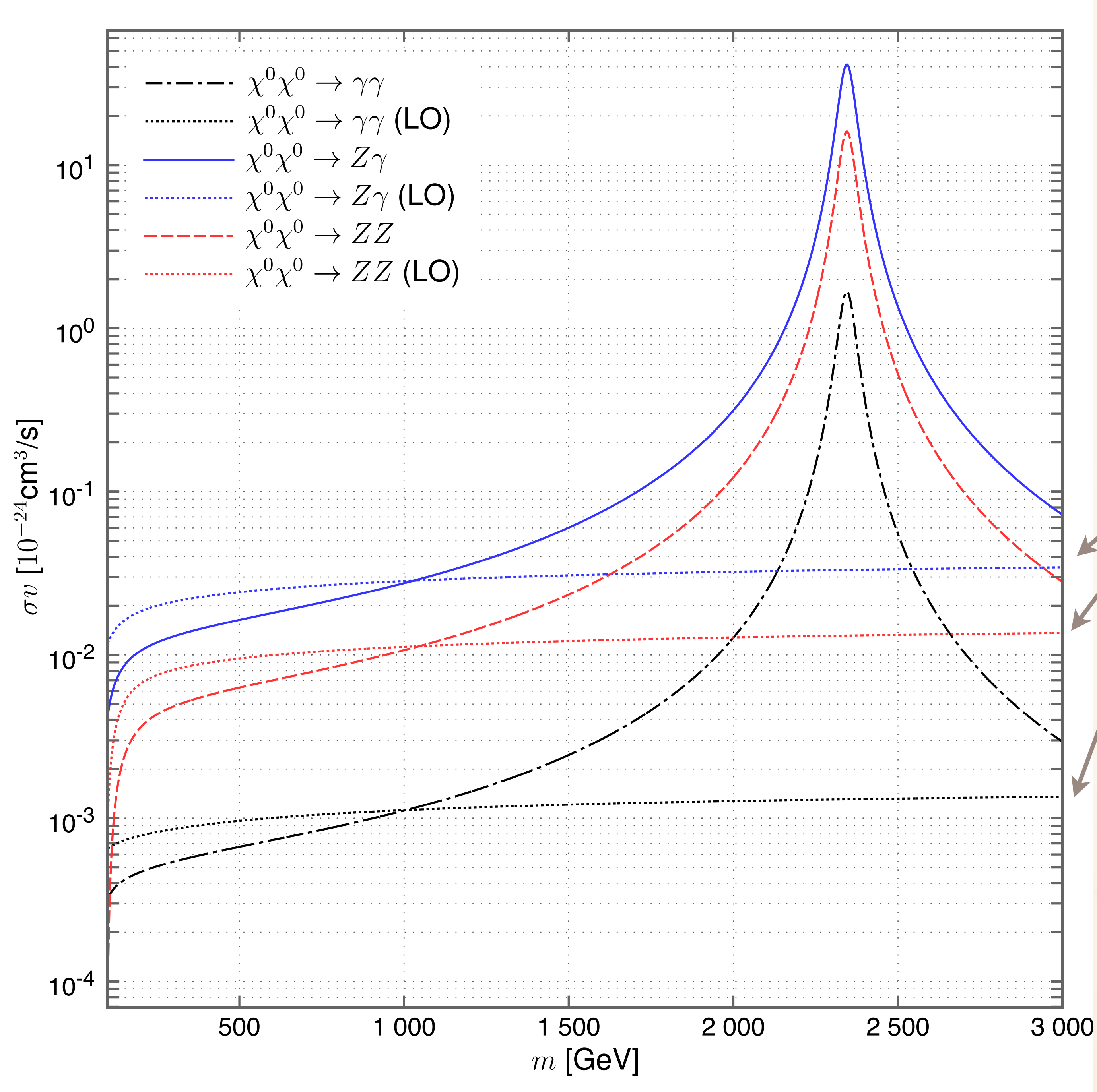
Bringmann *et al.*,JHEP 0801 (2008) 049

# Effect of EW corrections
## 3. softer spectra + more final SM states

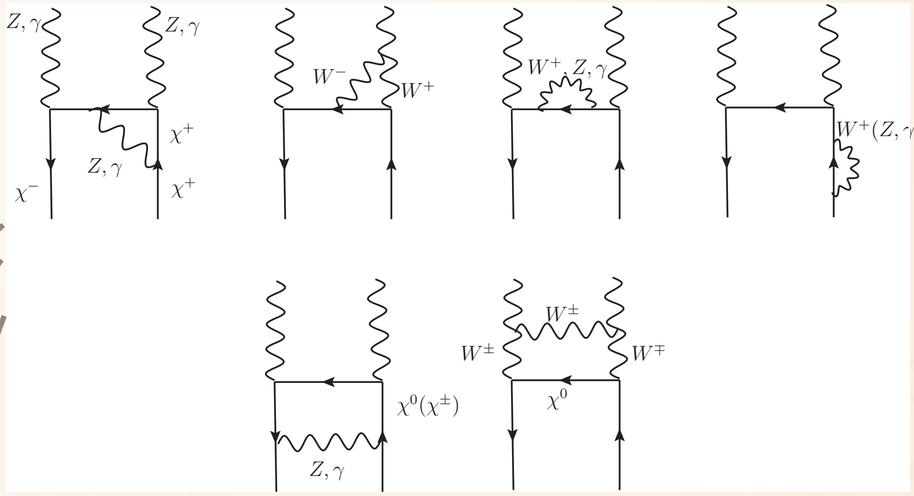



Ciafaloni *et al.*, JCAP 1103 (2011) 09

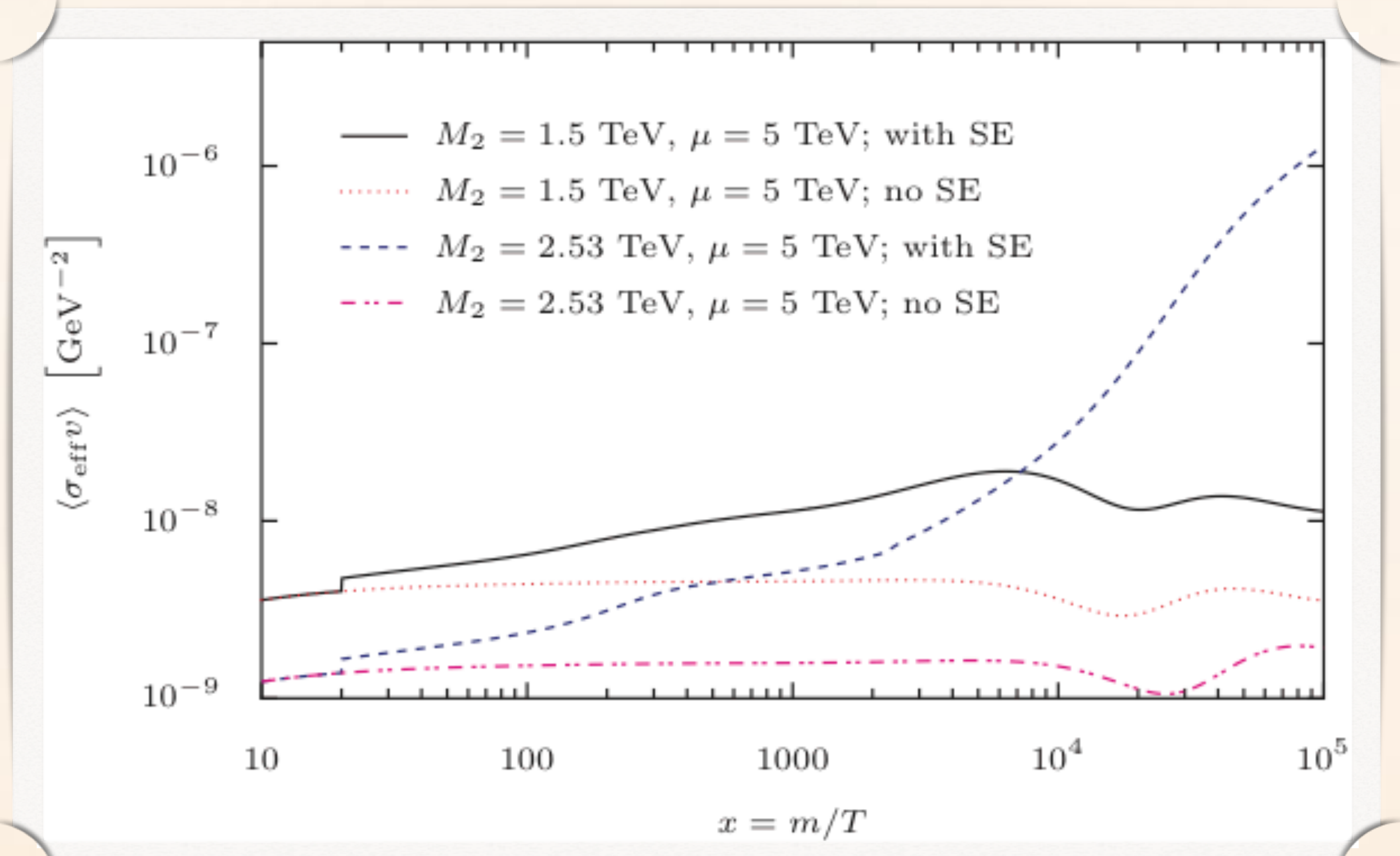
# CROSS-SECTION
## TO NEUTRAL GAUGE BOSONS




At the LO annihilation to $ZZ$, $Z\gamma$, $\gamma\gamma$ occurs at $\mathcal{O}(g^8)$ level

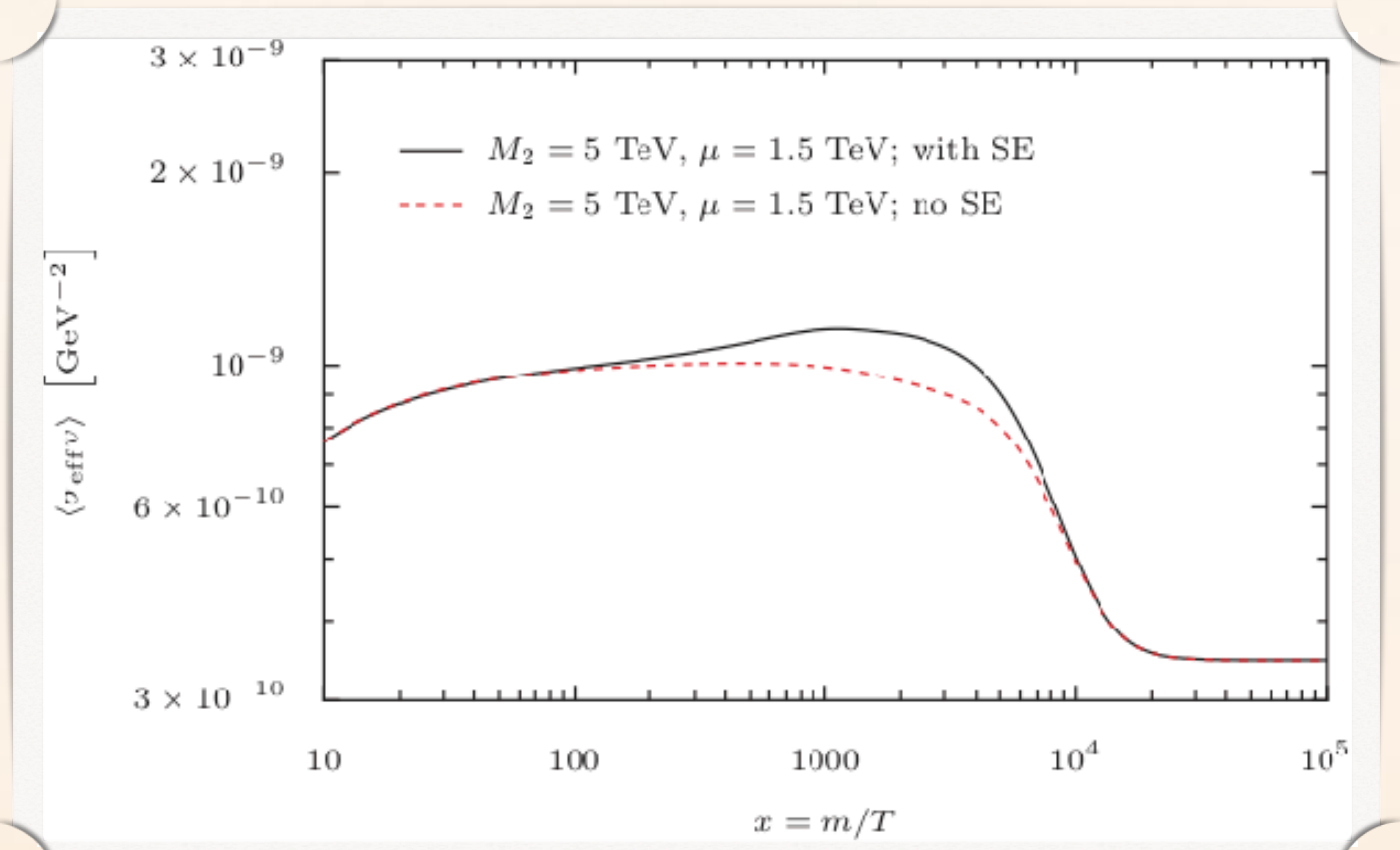


# RESULTS
## WINO-HIGGSINO




Wino-like: large effect on $\langle \sigma_{\rm eff} v \rangle$

# Results
## WINO-HIGGSINO




Higgsino-like: mild effect on $\langle \sigma_{\rm eff} v \rangle$