GAMMA RAY SPECTRAL FEATURES FROM SCALAR DARK MATTER

Michel H.G. Tytgat
Université Libre de Bruxelles
Belgium

Astroparticle Physics 2014 (TeVpa/IDM)
Amsterdam, June 23-27 2014

Based on works done in collaboration with

Federica Giacchino (ULB) and Laura Lopez Honorez (VUB)

arXiv:1307.6480, JCAP10(2013)025
arXiv:1405.6921

Closely related works by

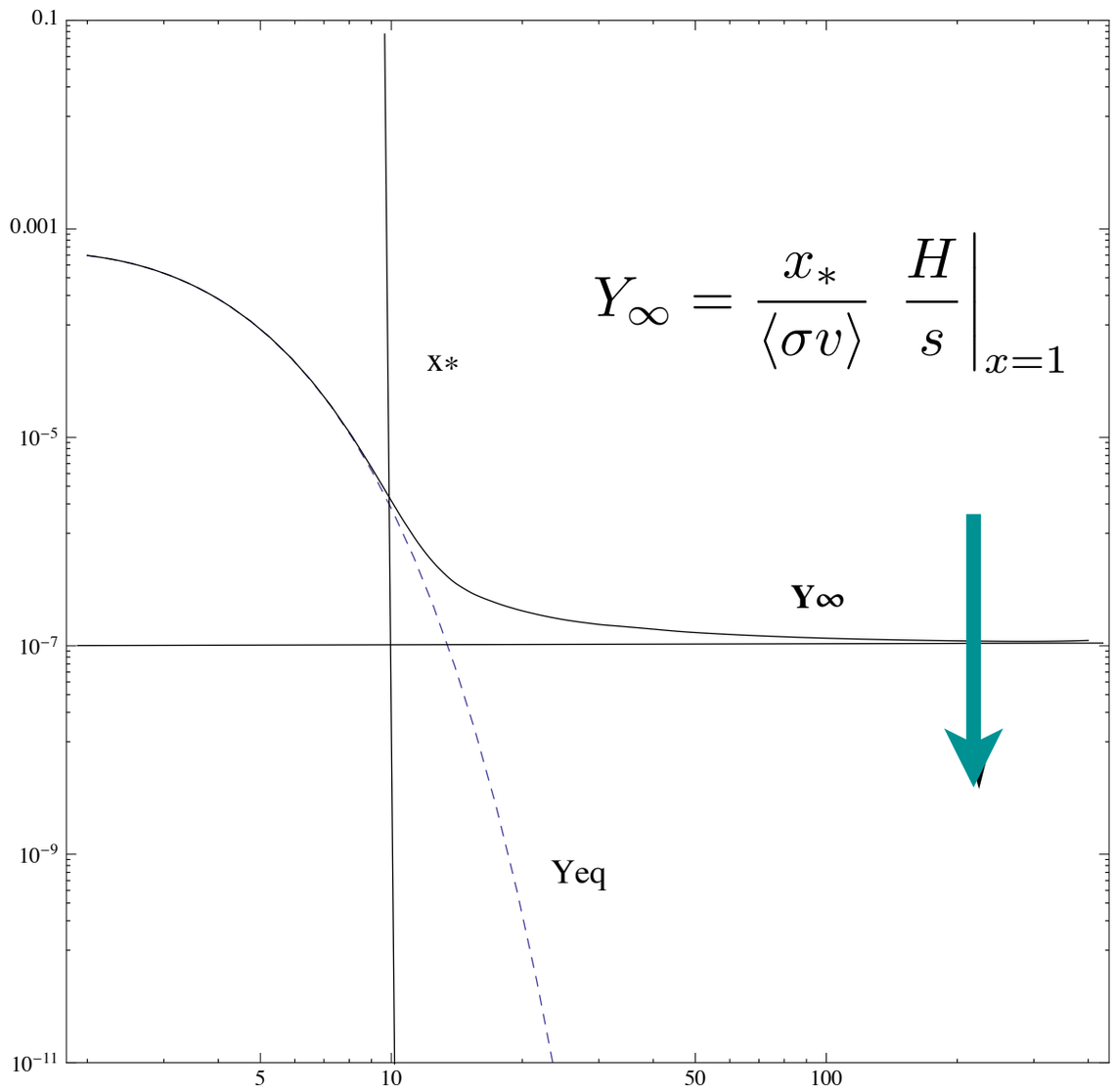
Takashi Toma
arXiv:1307.6181

Alejandro Ibarra, Takashi Toma, Maximilian Totzauer, Sebastian Wild
arXiv:1405.6917

ASSUME THAT DM IS A WIMP

(*i.e.* relic abundance from thermal freeze-out)

$$Y = \frac{n_X}{s}$$



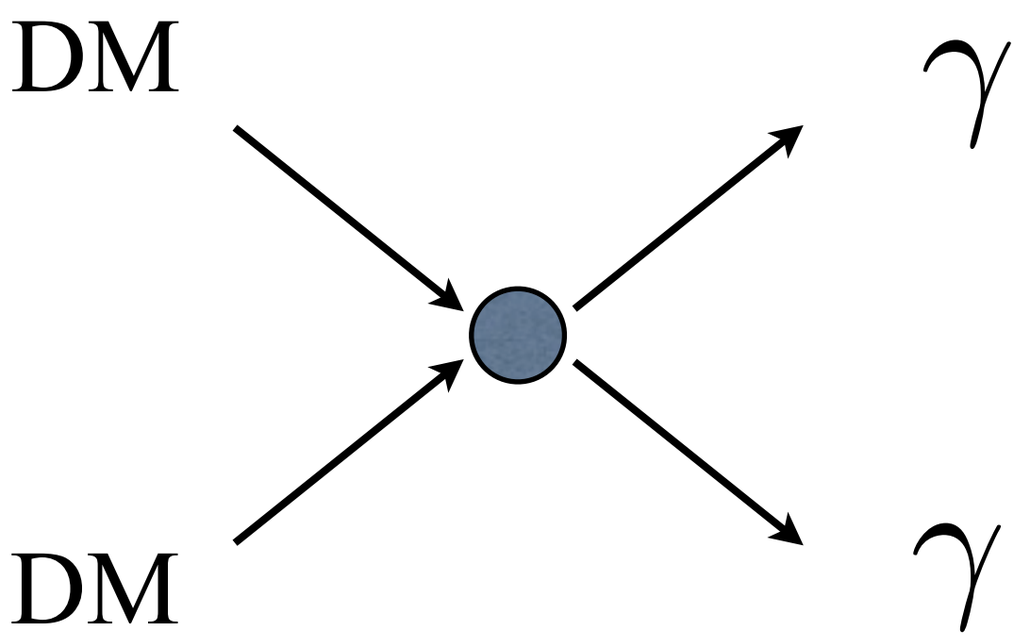
$$Y_\infty = \frac{x_*}{\langle \sigma v \rangle} \left. \frac{H}{s} \right|_{x=1}$$

$$x = \frac{m}{T}$$

WMAP/Planck require

$$\langle \sigma v \rangle \approx 3 \cdot 10^{-26} \mathrm{cm}^3 \cdot \mathrm{s}^{-1}$$

WIMP INDIRECT SEARCHES

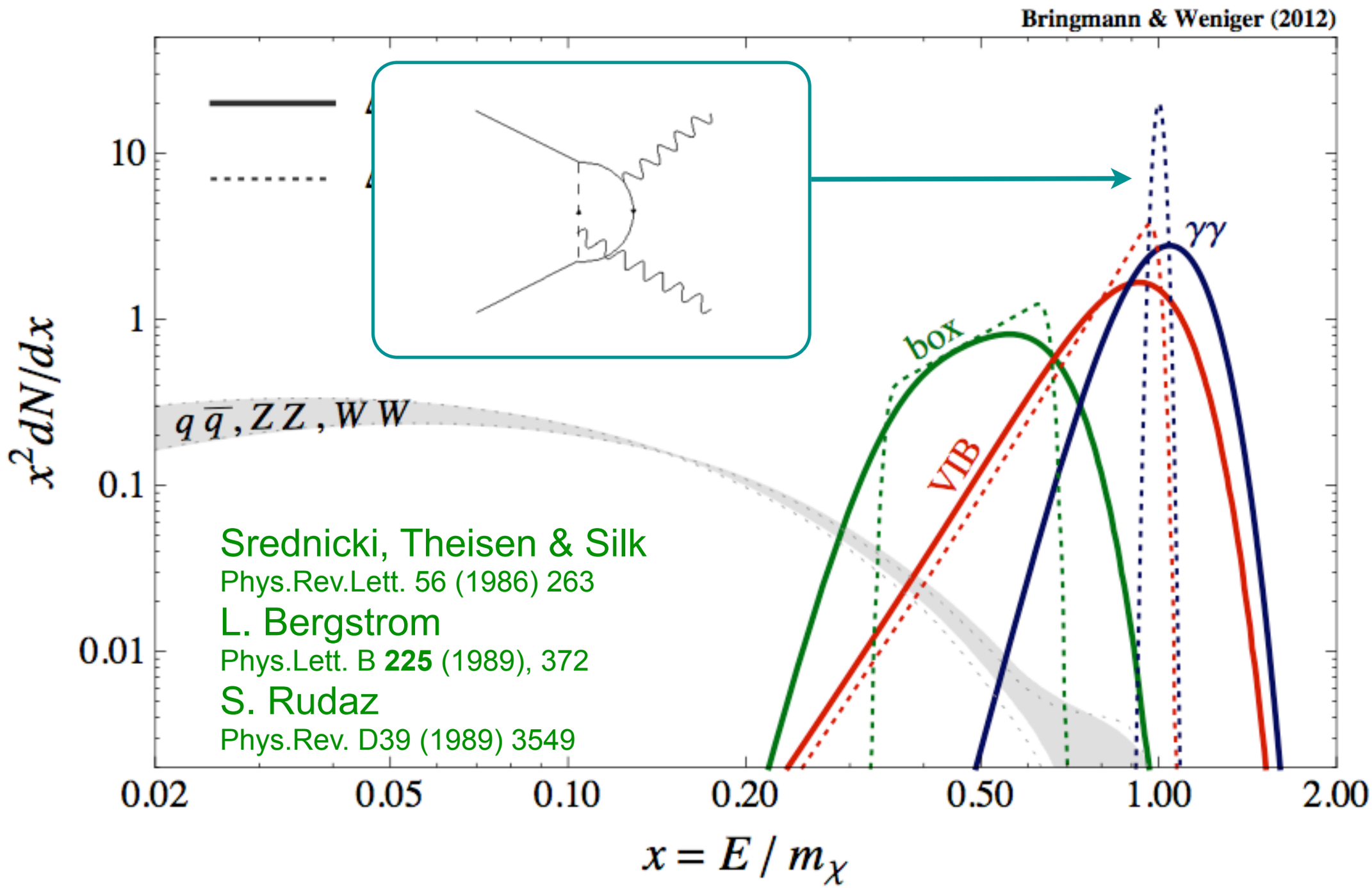


1. no astrophysical counterparts

2. $M_{DM} \sim E_{\gamma}$

More generally look for SPECTRAL FEATURES

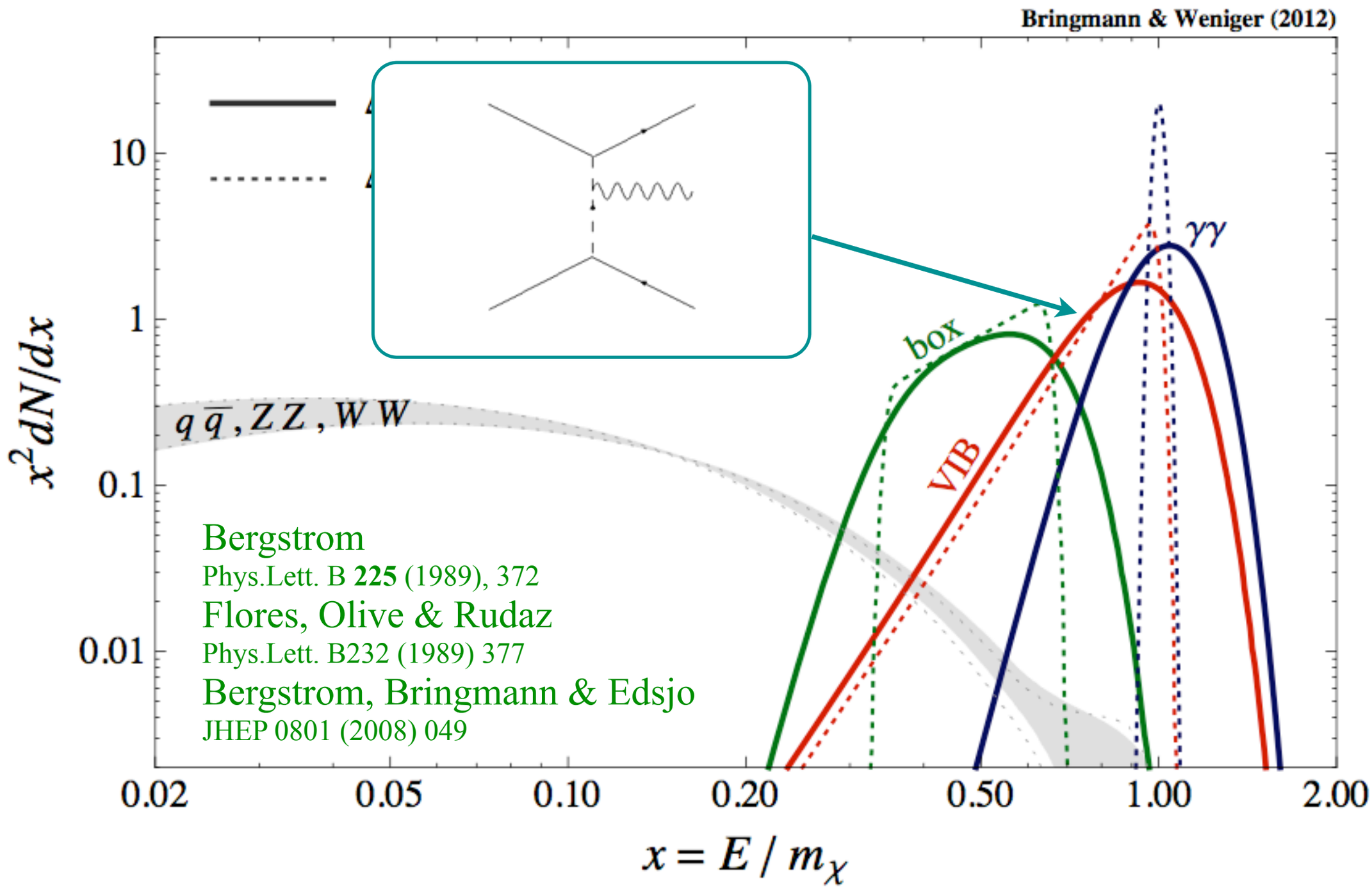
POSSIBLE GAMMA RAY FEATURES



Srednicki, Theisen & Silk
Phys.Rev.Lett. 56 (1986) 263
L. Bergstrom
Phys.Lett. B **225** (1989), 372
S. Rudaz
Phys.Rev. D39 (1989) 3549

MONO-CHROMATIC GAMMA RAYS

POSSIBLE GAMMA RAY FEATURES



VIRTUAL INTERNAL BREMSSTRAHLUNG

PROBLEM

HOW TO HAVE A SIGNIFICANT (>< FAINT) GAMMA RAY FEATURE?

ANNIHILATION OF REAL SCALAR DM INTO LIGHT FERMIONS

Toy model!

$$\mathcal{L} \supset y_l \, S \, \bar{\Psi} \, l_R + h.c.$$

real singlet scalar

vector-like charged lepton

SM light lepton

Z_2 symmetry

$$S \longrightarrow -S$$

$$\Psi \longrightarrow -\Psi$$

S dark matter

→ CALL IT THE VECTOR-LIKE PORTAL

following P. Fileviez Perez, M.B. Wise
arXiv:1303.1452

THE BASIC POINTS I REPORT

1. $\langle \sigma v \rangle (\chi\chi \to f\bar{f})$ IS D-WAVE

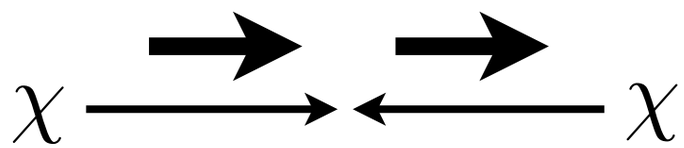
2. VIB ENHANCED
(compared to Majorana DM)

3. NEW RESULTS ON GAMMA RAY LINES

A DIGRESSION

ANNIHILATION OF MAJORANA DM INTO LIGHT FERMIONS

P-WAVE INITIAL STATE



$^3P_1(1^{++})$

FINAL STATE

$\bar{\psi}_f \gamma^k \gamma_5 \psi_f$

P-WAVE IN MASSLESS LIMIT

$$\sigma v \propto y_f^4 \frac{v^2}{M_\chi^2}$$

Goldberg
«Constraint on the Photino mass from cosmology»
Phys.Rev.Lett. 50 (1983) 1419

ANNIHILATION OF REAL SCALAR DM INTO LIGHT FERMIONS

D-WAVE IN MASSLESS LIMIT

$$\sigma v(SS \to l\bar{l}) = \frac{y_l^4}{60\pi} \frac{v^4}{M_S^2} \frac{1}{(1+r^2)^4}$$

$$r = \frac{M_\Psi}{M_S} > 1$$

Takashi Toma
arXiv:1307.6181
Giacchino, Lopez Honorez & M.T.
arXiv:1307.6480

MAJORANA vs SCALAR DARK MATTER

$$\frac{\langle \sigma v \rangle_S}{\langle \sigma v \rangle_\chi} = \frac{4 y_l^4 \langle v^4 \rangle}{5 g_l^4 \langle v^2 \rangle (1 + r^4)} < 0.16 \, \frac{y_l^4}{g_l^4}$$

for r =1

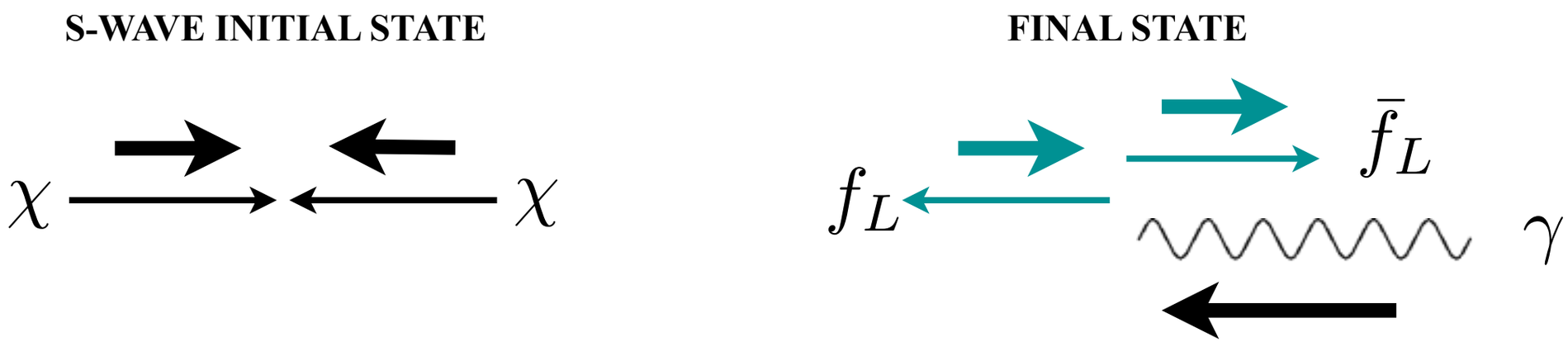
$$r = \frac{M_\Psi}{M_S} > 1$$

Mutatis mutandis a <u>larger coupling</u>
required for scalar DM to <u>match WMAP/Planck</u>

Takashi Toma
arXiv:1307.6181
Giacchino, Lopez Honorez & M.T.
arXiv:1307.6480

VIRTUAL INTERNAL BREMSSTRAHLUNG IS S-WAVE

$$\chi\chi \to f\bar{f}\gamma$$

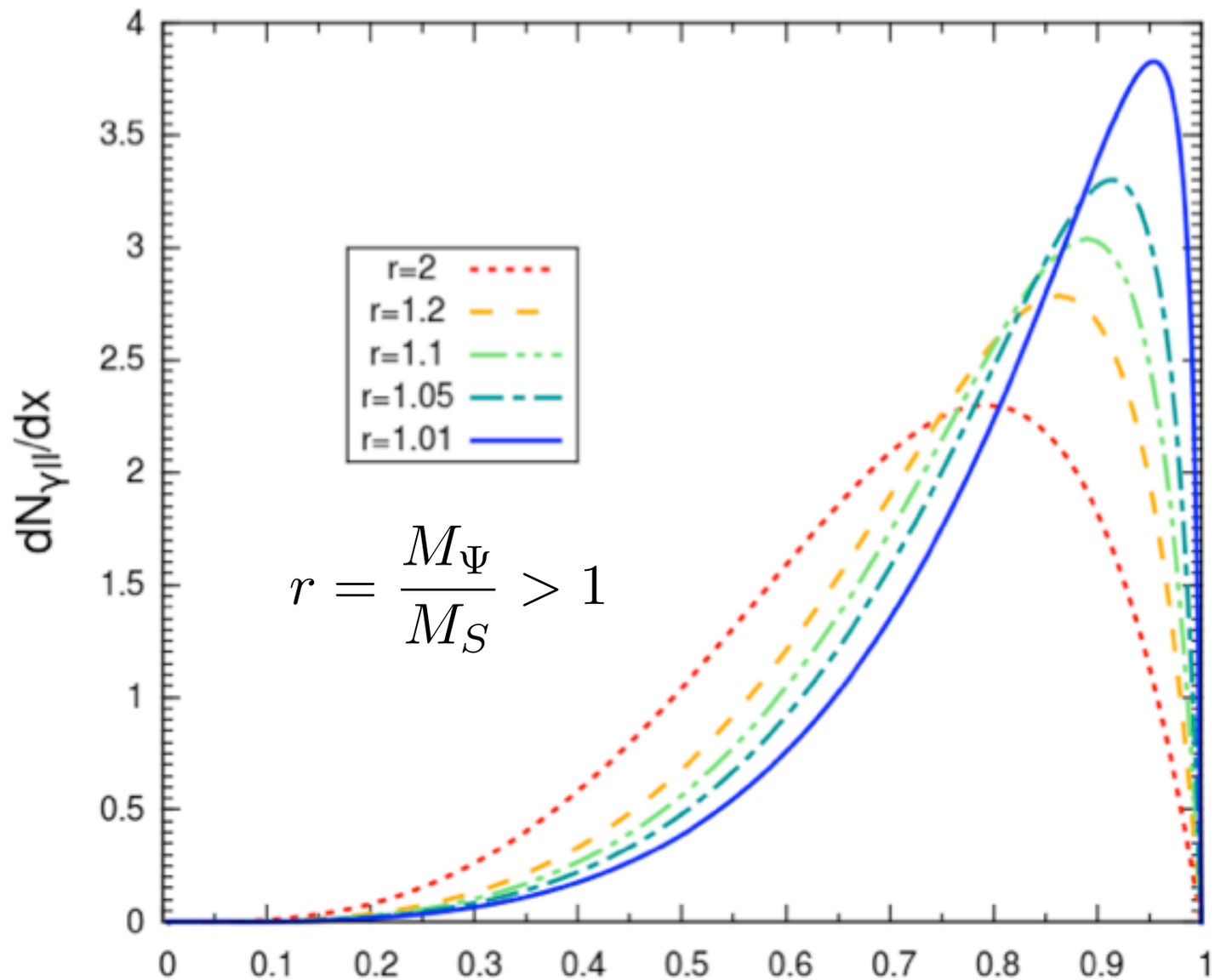


→ VIB <u>dominant</u> in the Galaxy!

Bergstrom
Phys.Lett. B **225** (1989), 372

Bergstrom, Bringmann & Edsjo
JHEP 0801 (2008) 049

SAME VIB SPECTRA FOR SCALAR AND MAJORANA



$$x = \frac{E_\gamma}{M_{DM}}$$

Barger, Keung & Marfatia
arXiv:1111.4523
Takashi Toma
arXiv:1307.6181
Giacchino, Lopez Honorez & M.T.
arXiv:1307.6480

SAME BUT CROSS SECTION DIFFER BY A FACTOR OF 8

$$\frac{\sigma(SS \to f\bar{f}\gamma)}{\sigma(\chi\chi \to f\bar{f}\gamma)} = \frac{8y_l^4}{g_l^4}$$

«VIB enhanced»

while

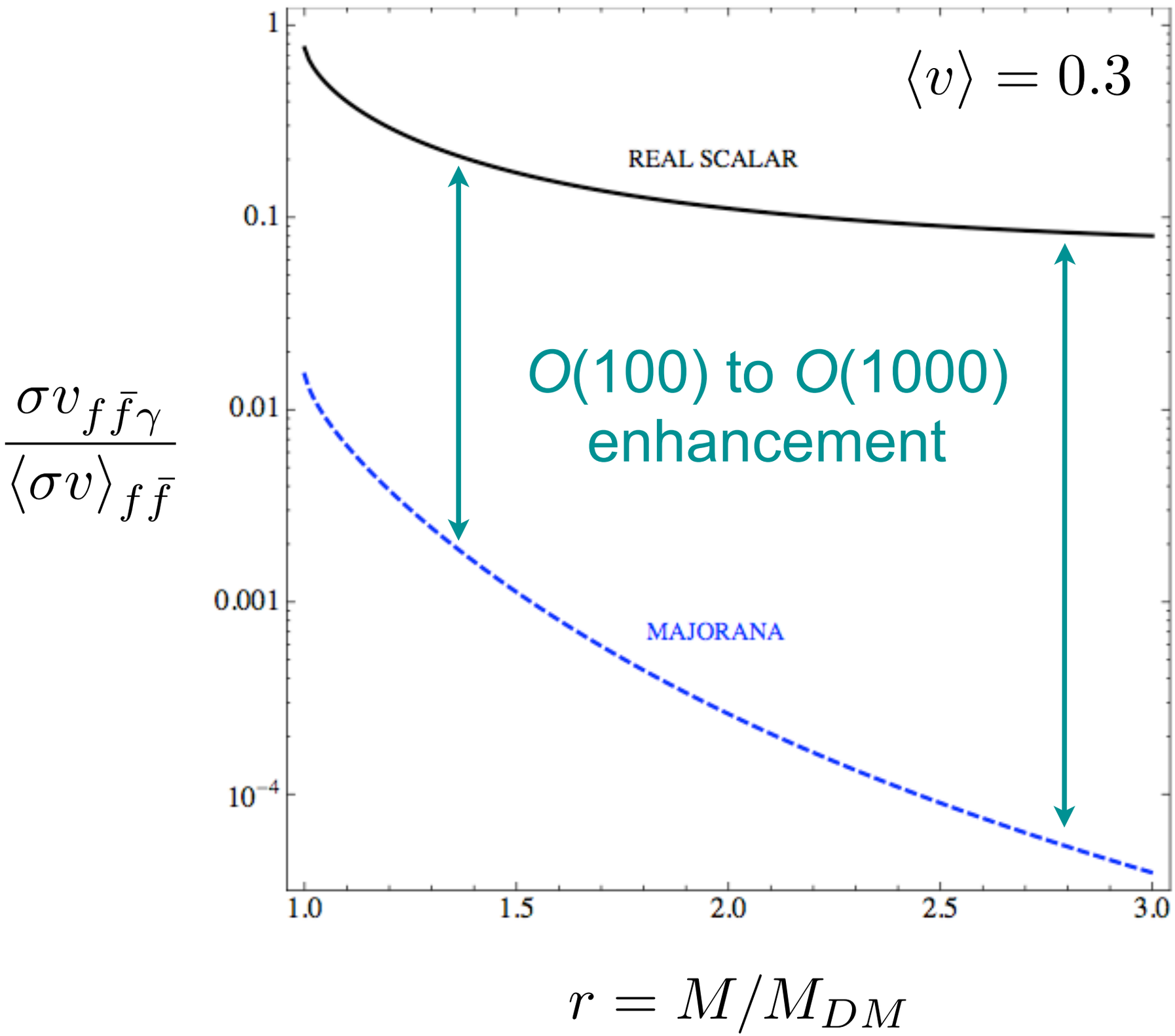
$$\frac{\langle\sigma v\rangle(SS \to f\bar{f})}{\langle\sigma v\rangle(\chi\chi \to f\bar{f})} < 0.16\frac{y_l^4}{g_l^4}$$

«2-body suppressed»

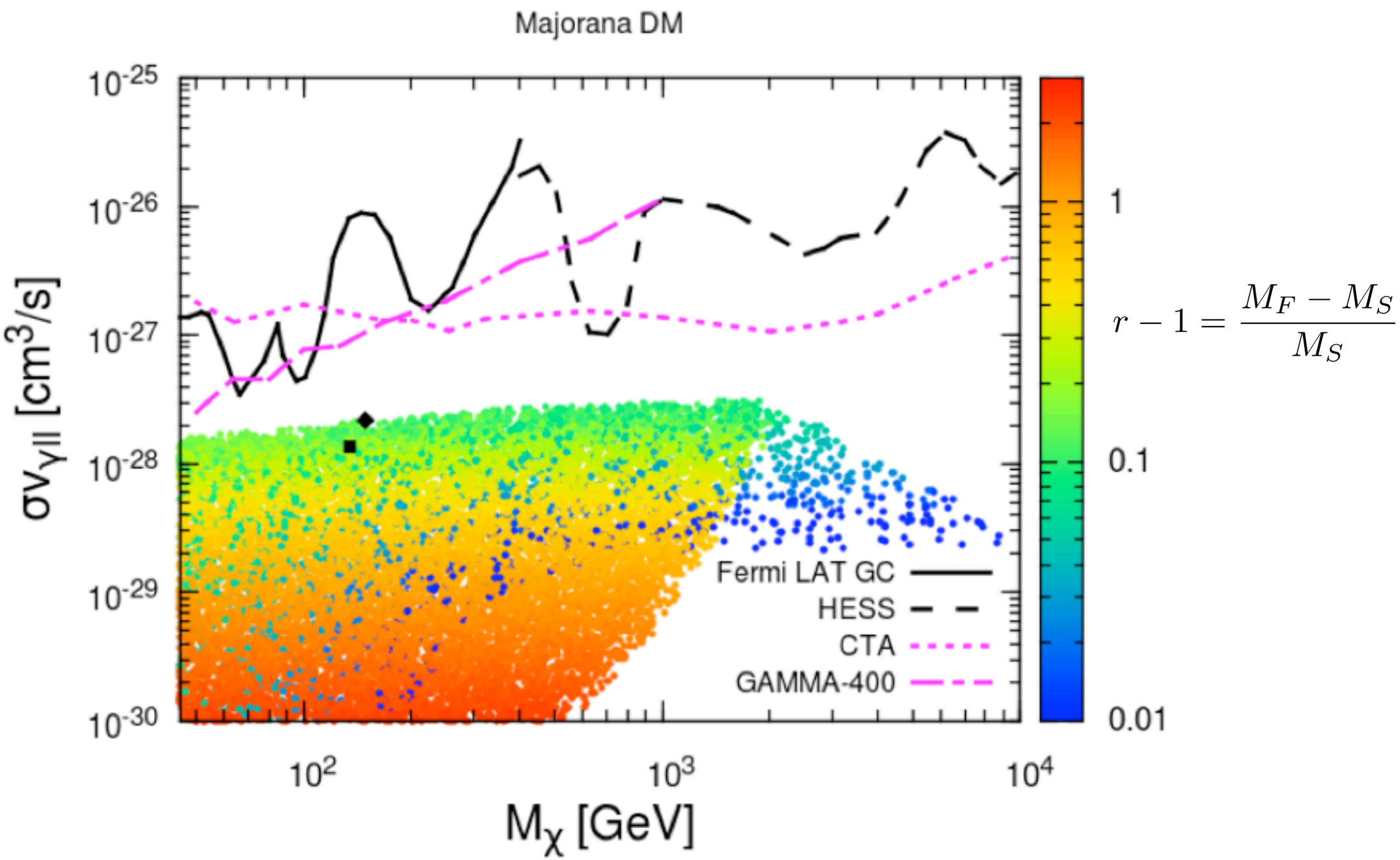
→ large enhancement of VIB for scalar DM

Takashi Toma
arXiv:1307.6181
Giacchino, Lopez Honorez & M.T.
arXiv:1307.6480

2. VIB ENHANCEMENT

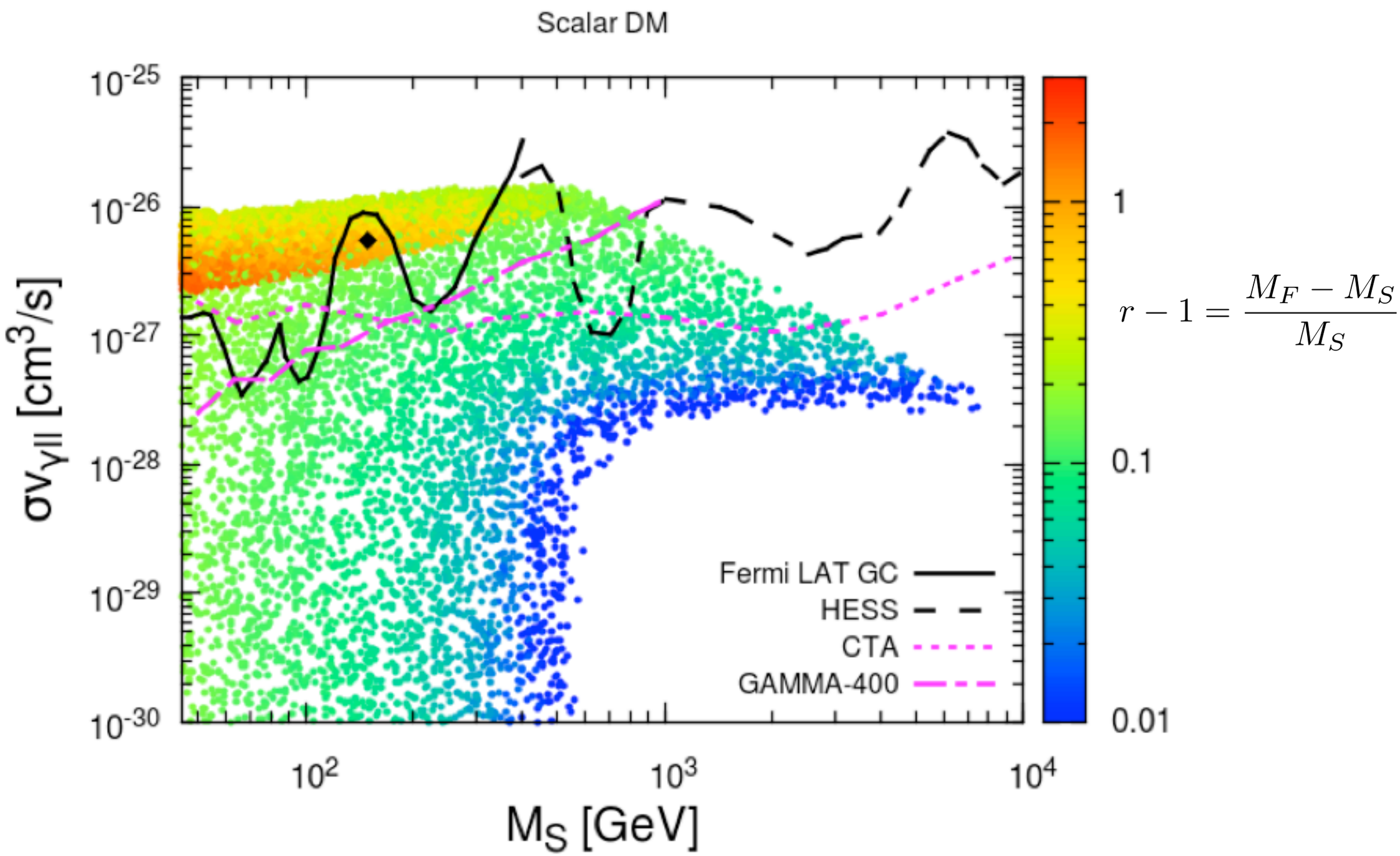


PARAMETER SCAN - MAJORANA



Giacchino, Lopez Honorez & M.T.
arXiv:1307.6480

PARAMETER SCAN - SCALAR



Giacchino, Lopez Honorez & M.T.
arXiv:1307.6480

e.g. 130 GeV FERMI-LAT EX-EXCESS

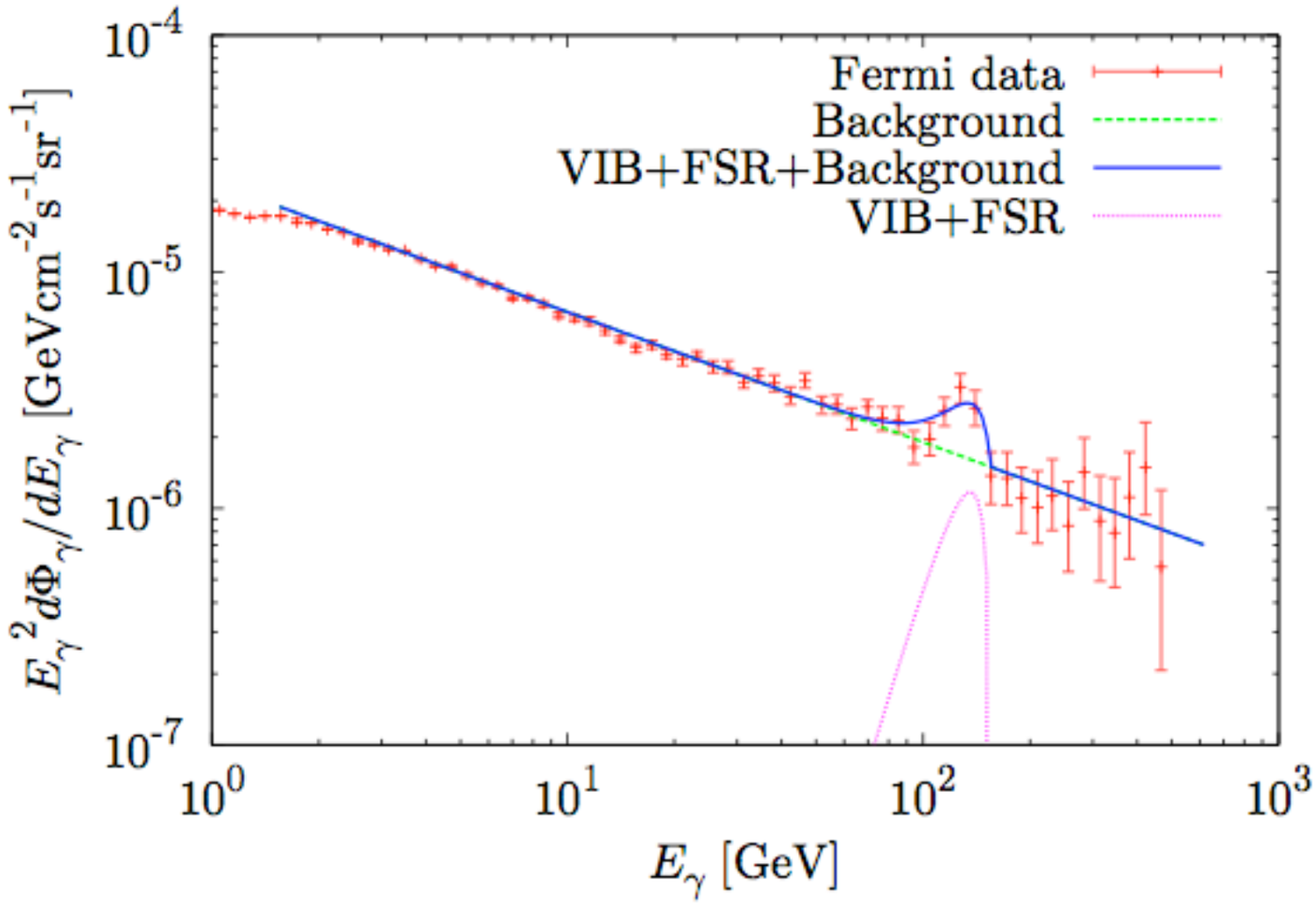


FIG. 3: Fitting to the gamma-ray excess via the VIB process. We use the best fit parameters found here. The data are taken from ref. [43]. Note that the energy dispersion of the Fermi instrument is included; it is approximately 10% at $E_\gamma =$ 100 GeV. This may alter the fit region.

Takashi Toma
arXiv:1307.6181

MONOCHROMATIC GAMMA RAYS

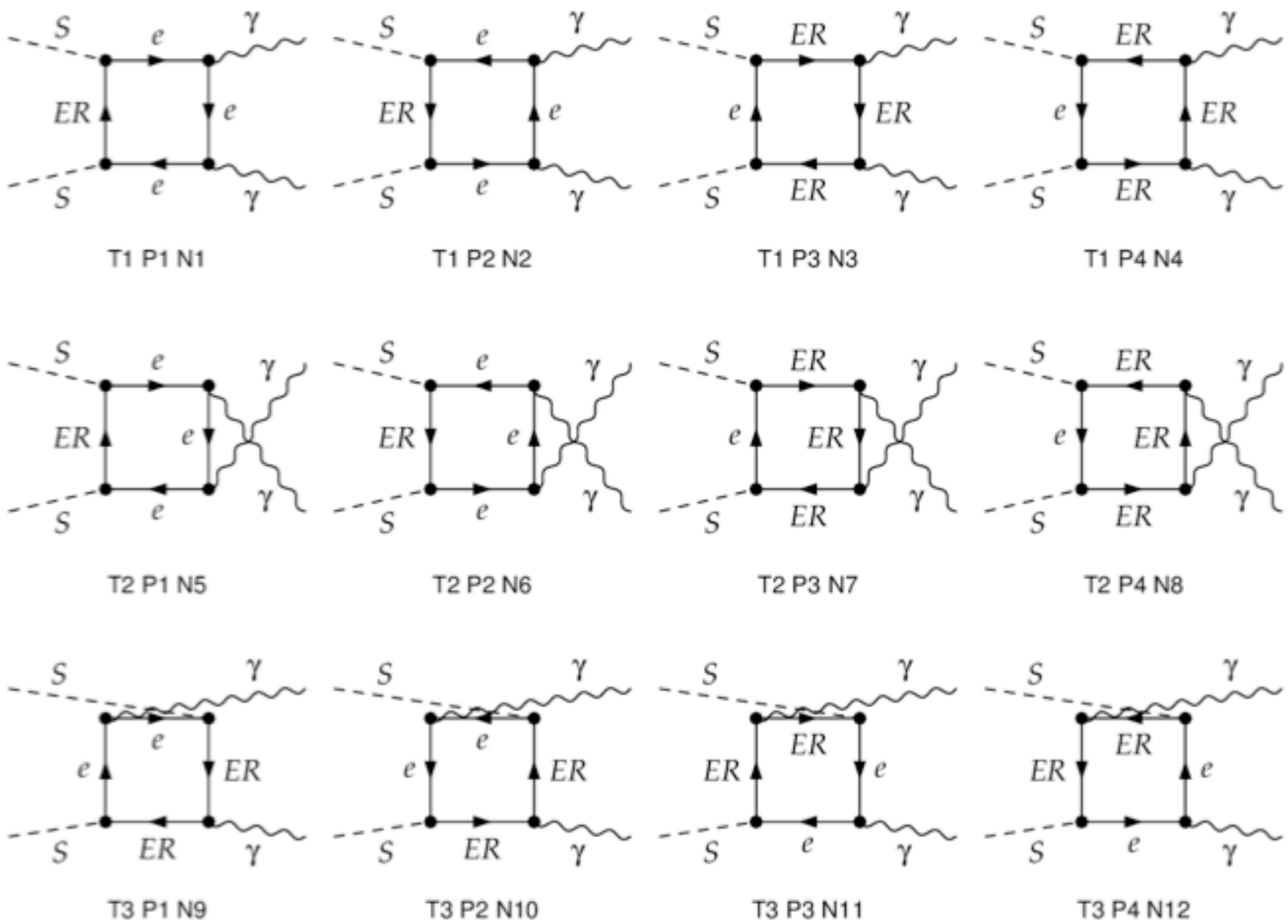


Figure 1: Box diagrams relevant for the $SS \to \gamma\gamma$ process

MONOCHROMATIC GAMMA RAYS

$$\langle \sigma v \rangle (SS \to \gamma\gamma) = \frac{2\, y_S^4 \alpha^2}{64\pi^3 M^2} |\mathcal{A}|^2$$

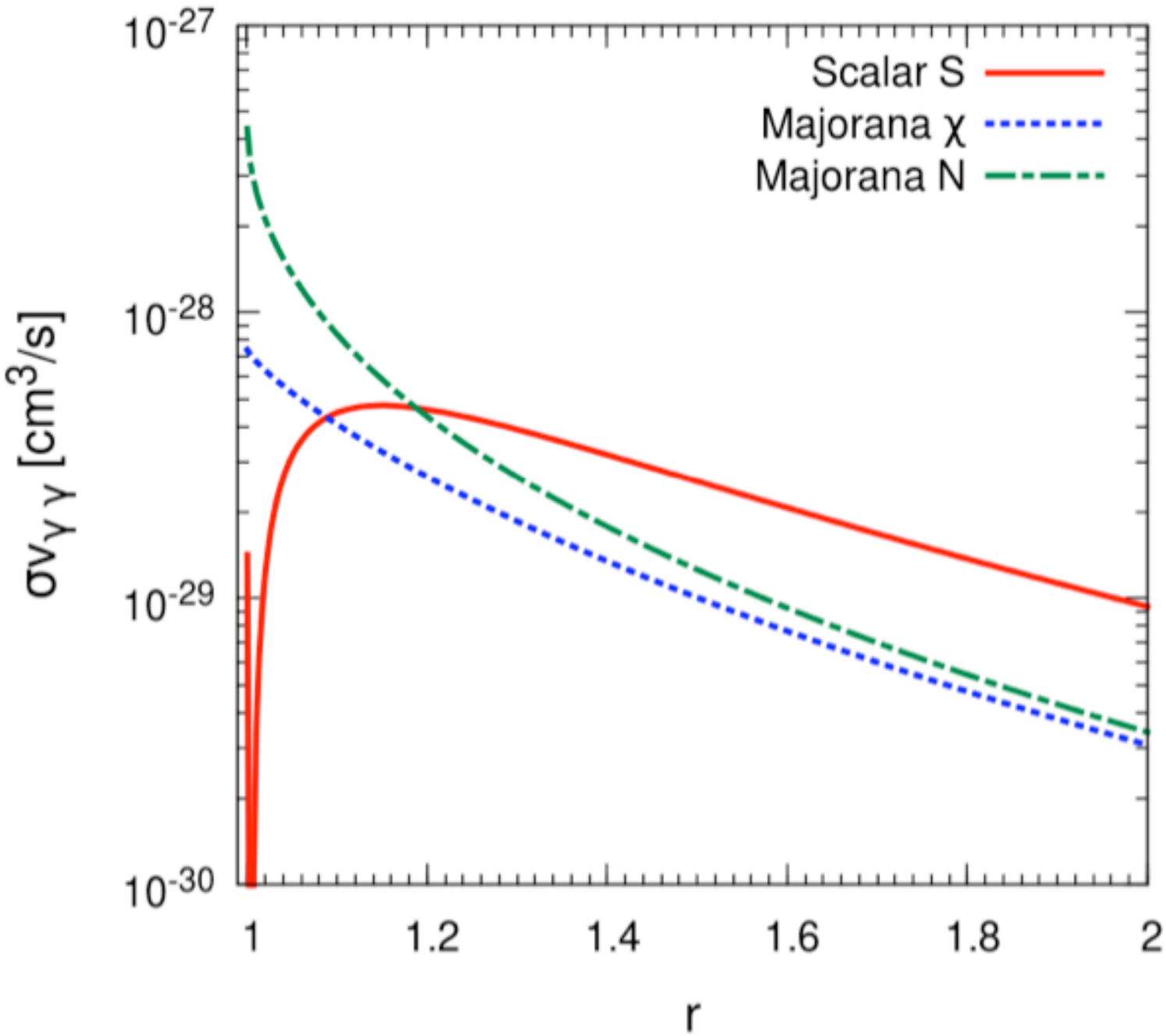
$$\begin{aligned}\mathcal{A} = 2 &- 2M^2 C_0(-M^2, M^2, 0, r^2M^2, 0, r^2M^2) \\ &+ 4r^2M^2 C_0(4M^2, 0, 0, r^2M^2, r^2M^2, r^2M^2)\,.\end{aligned}$$

$$C_0(4M^2, 0, 0, r^2M^2, r^2M^2, r^2M^2) = \frac{-1}{2M^2}\left(\arctan\frac{1}{\sqrt{r^2-1}}\right)^2$$

$$C_0(-M^2, M^2, 0, r^2M^2, 0, r^2M^2) = \frac{-1}{2M^2}\left(Li_2\left(\frac{1}{r^2}\right) - Li_2\left(\frac{-1}{r^2}\right)\right)$$

Ibarra, Toma, Totzauer & Wild
arXiv:1405.6917
Giacchino, Lopez Honorez, M.T.
arXiv:1405.6921

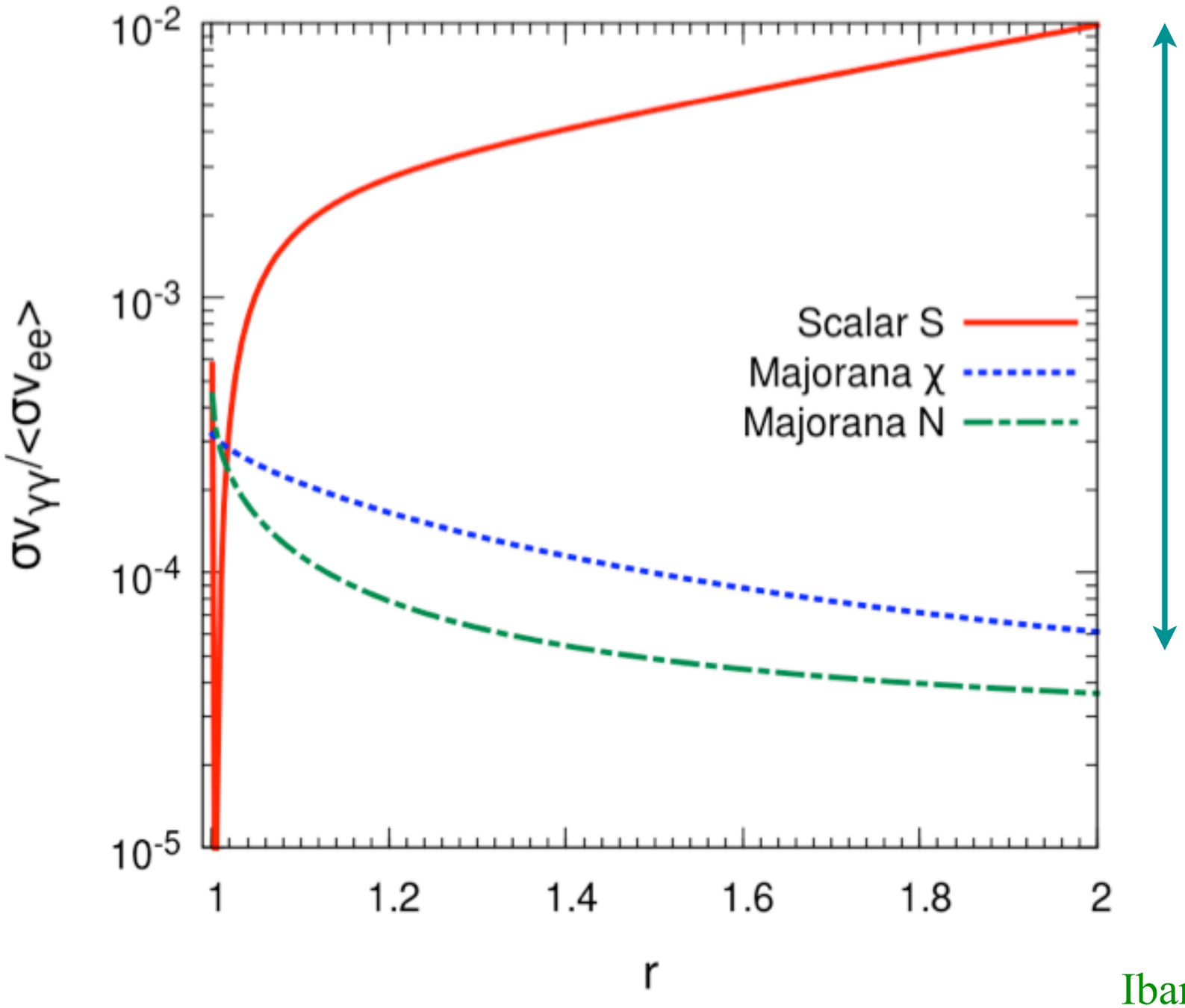
MONOCHROMATIC GAMMA RAYS



NEW
(and correct)

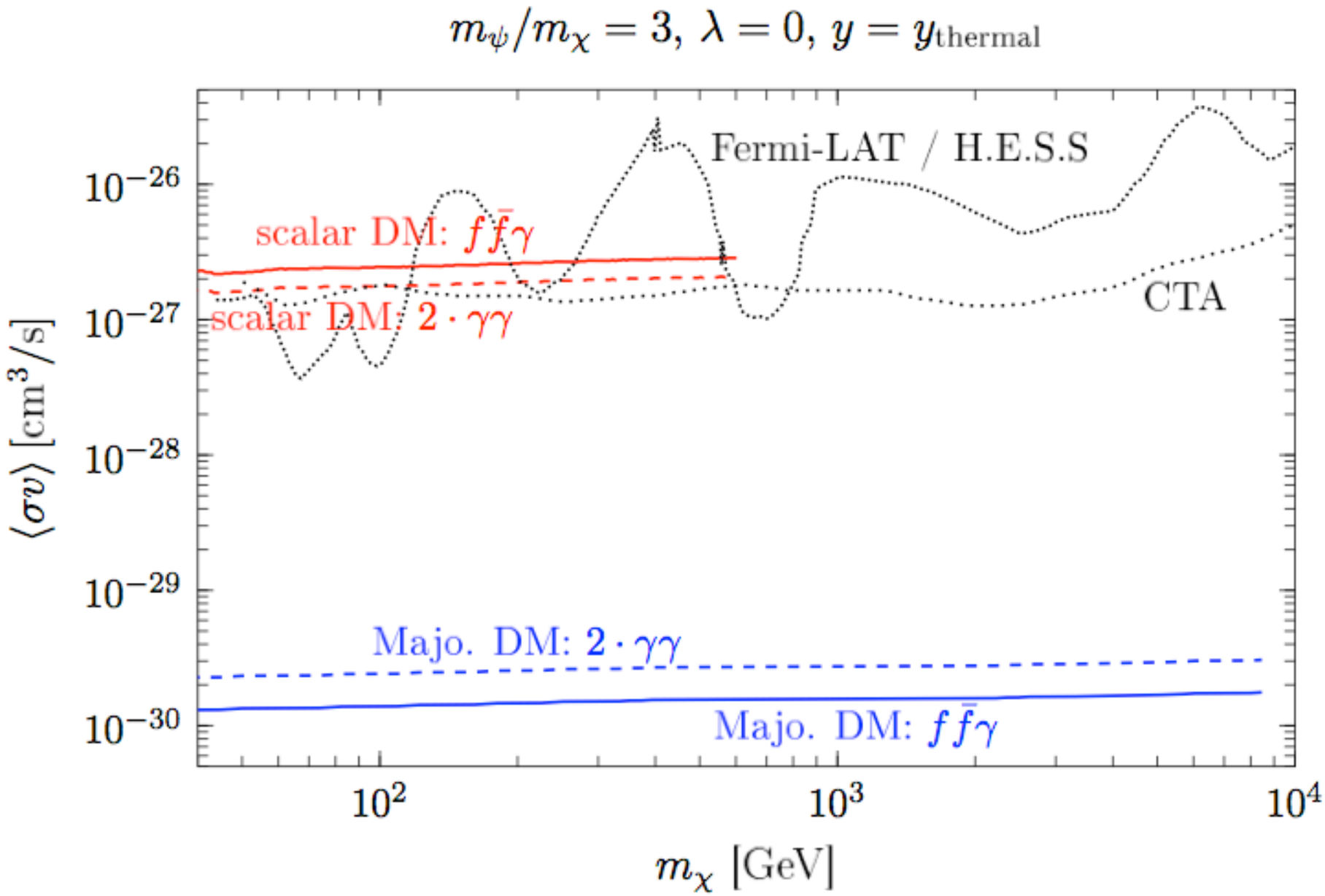
Ibarra, Toma, Totzauer & Wild
arXiv:1405.6917
Giacchino, Lopez Honorez, M.T.
arXiv:1405.6921

MONOCHROMATIC GAMMA RAYS



O(100) enhancement

Ibarra, Toma, Totzauer & Wild
arXiv:1405.6917
Giacchino, Lopez Honorez, M.T.
arXiv:1405.6921



Ibarra, Toma, Totzauer & Wild
arXiv:1405.6917

CURRENT CONSTRAINTS

FUTURE (CTA) CONSTRAINTS

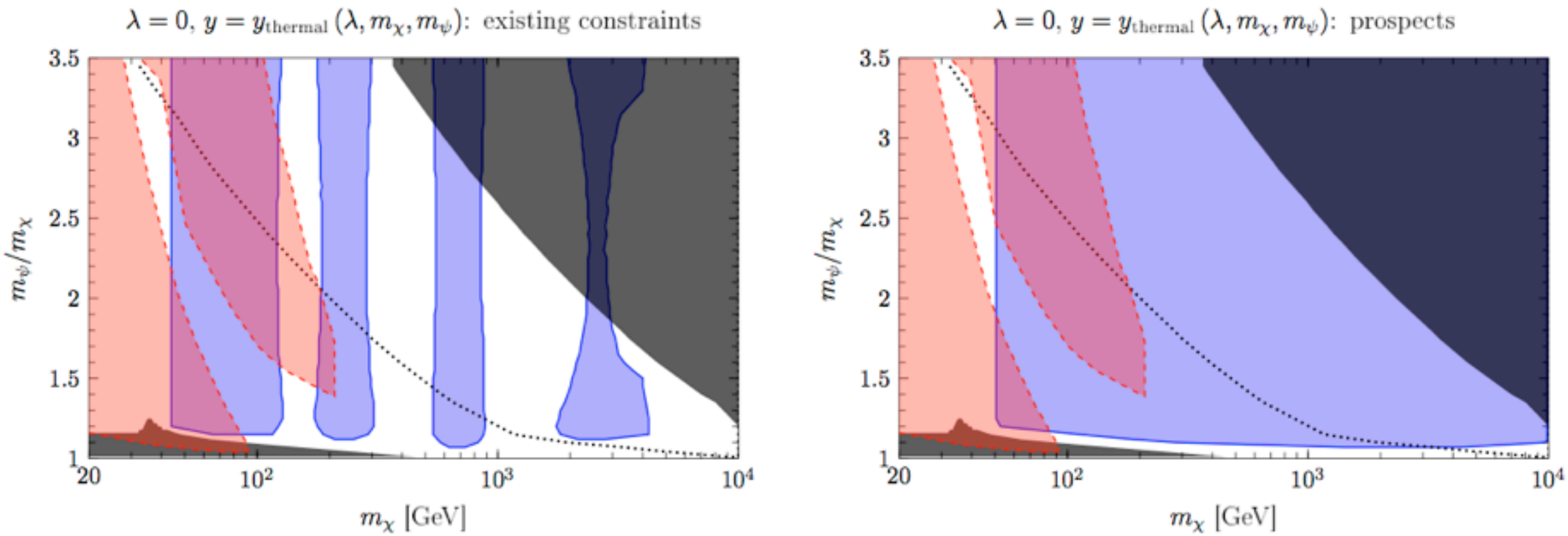


FIG. 11: Left plot: constraints from Fermi-LAT and H.E.S.S (blue shaded regions surrounded by solid lines), from LEP and LHC (red shaded regions enclosed by dashed lines), setting at each point of the parameter space the Yukawa coupling in order to reproduce the observed dark matter abundance via thermal production. We assume in the plots $\lambda = 0$. The dark gray shaded regions extending to the right upper corner correspond to scenarios violating the conservative perturbativity requirement $y > 4\pi$, while the dotted black line corresponds to scenarios with $y = \sqrt{4\pi}$. The gray shaded regions in the lower left corner show the values of the parameters for which the dark matter abundance is below the observed value due to coannihilations. Right plot: same as left plot, but here the blue shaded region (enclosed by the solid line) is the prospected reach of CTA.

Ibarra, Toma, Totzauer & Wild
arXiv:1405.6917

CONCLUSIONS

PROS

* SIMPLE MODEL

* STRONG GAMMA RAY FEATURES (quite uncommon)

CONS

* STRONG GAMMA RAY FEATURES (strong constraints)

* FINE TUNING

* MANY NEW PARAMETERS

CONCLUSIONS

CONS

* SIMPLE MODEL

* STRONG GAMMA RAY FEATURES (quite uncommon)

PROS

* STRONG GAMMA RAY FEATURES (strong constraints)

* FINE TUNING

* MANY NEW PARAMETERS

BACKUP SLIDES

WHY?

S-WAVE INITIAL STATE

$S \longrightarrow \longleftarrow S$

$^1S_0(0^{++})$

FINAL STATE

$f_R \longleftarrow \times \longrightarrow \bar{f}_L$

$\bar{\psi}_f \psi_f$

mass suppressed $\longrightarrow$ $\mathcal{O}_S = m_f\, S^2\, \bar{\psi}_f \psi_f$

D-WAVE INITIAL STATE

$S \longrightarrow \longleftarrow S$

$^1D_2(2^{++})$

FINAL STATE

$f_R \longleftrightarrow \bar{f}_R$

$$\Theta^{ij} = \frac{i}{2}\bar{\psi}_f(\gamma^i \overrightarrow{\partial}^j - \gamma^j \overleftarrow{\partial}^i)\psi_f$$

d-wave in chiral limit $\longrightarrow$ $\mathcal{O}_T = \partial_\mu S \partial_\nu S\, \Theta^{\mu\nu}_{f_R}$

FERMION STRESS-ENERGY TENSOR

A POSSIBLE EXTENSION

$$\mathcal{L} \supset y_l \, S \, \bar{\Psi} \, l_R + h.c.$$

A SINGLET SCALAR WITH VL LEPTONS

$$\mathcal{L} \supset y_q \, S \, \bar{\Psi} q_R + h.c.$$

THE SAME WITH VL QUARKS

$$\frac{\langle \sigma v \rangle_{g\bar{q}q}}{\langle \sigma v \rangle_{\gamma\bar{q}q}} = \frac{N_c^2 - 1}{2N_c} \frac{\alpha_s}{Q^2 \alpha}$$

~ 40 (up-like quarks)

~ 150 (down-like quarks)

$$\langle \sigma v \rangle_{q\bar{q}} \ll \langle \sigma v \rangle_{q\bar{q}g}$$

Even in early universe

→ ABUNDANCE FROM (GLUON) BREMSSTRAHLUNG

+ DIRECT DETECTION
+ CONSTRAINTS FROM CR ANTI-PROTONS
+ LHC constraints
etc...