SIGNATURES FROM SCALAR DARK MATTER

WITH A FOCUS ON GAMMA-RAYS

Michel H.G. Tytgat
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6th International Workshop in High Energy Physics in the LHC Era
Universidad Técnica Federico Santa María, Valparaiso, Chile, 6-12 January 2016

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* EX UMBRA IN SOLEM

From the Shadow into the Light

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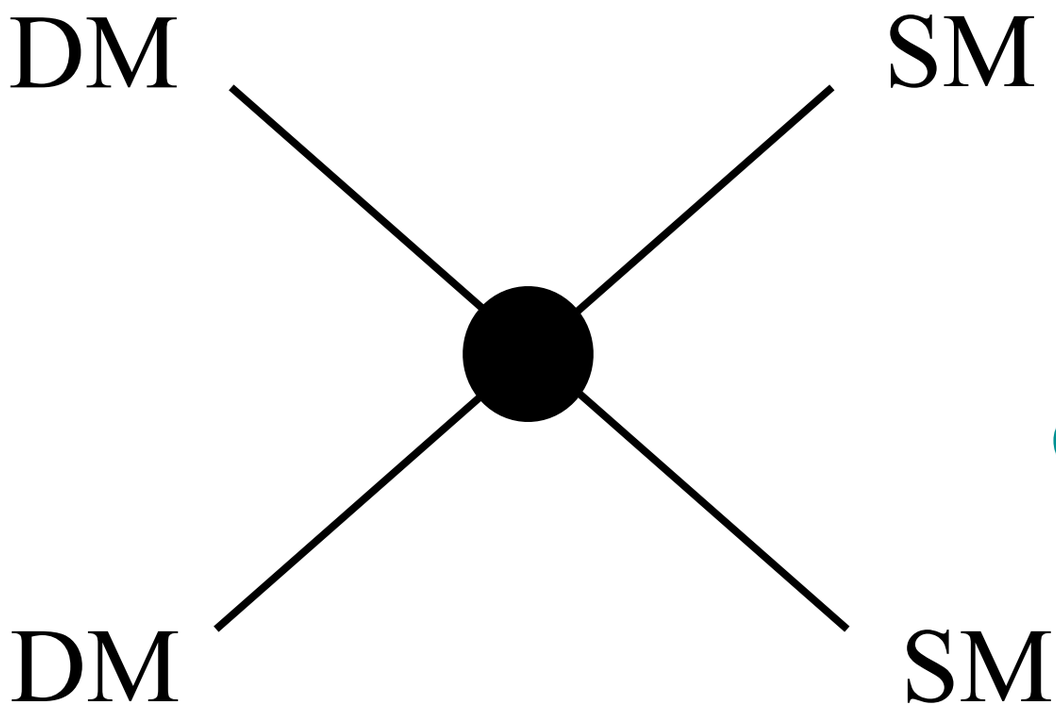
DARK ENERGY

DARK MATTER

BARYONS

DM AS A WIMP
(weakly interacting massive particle)

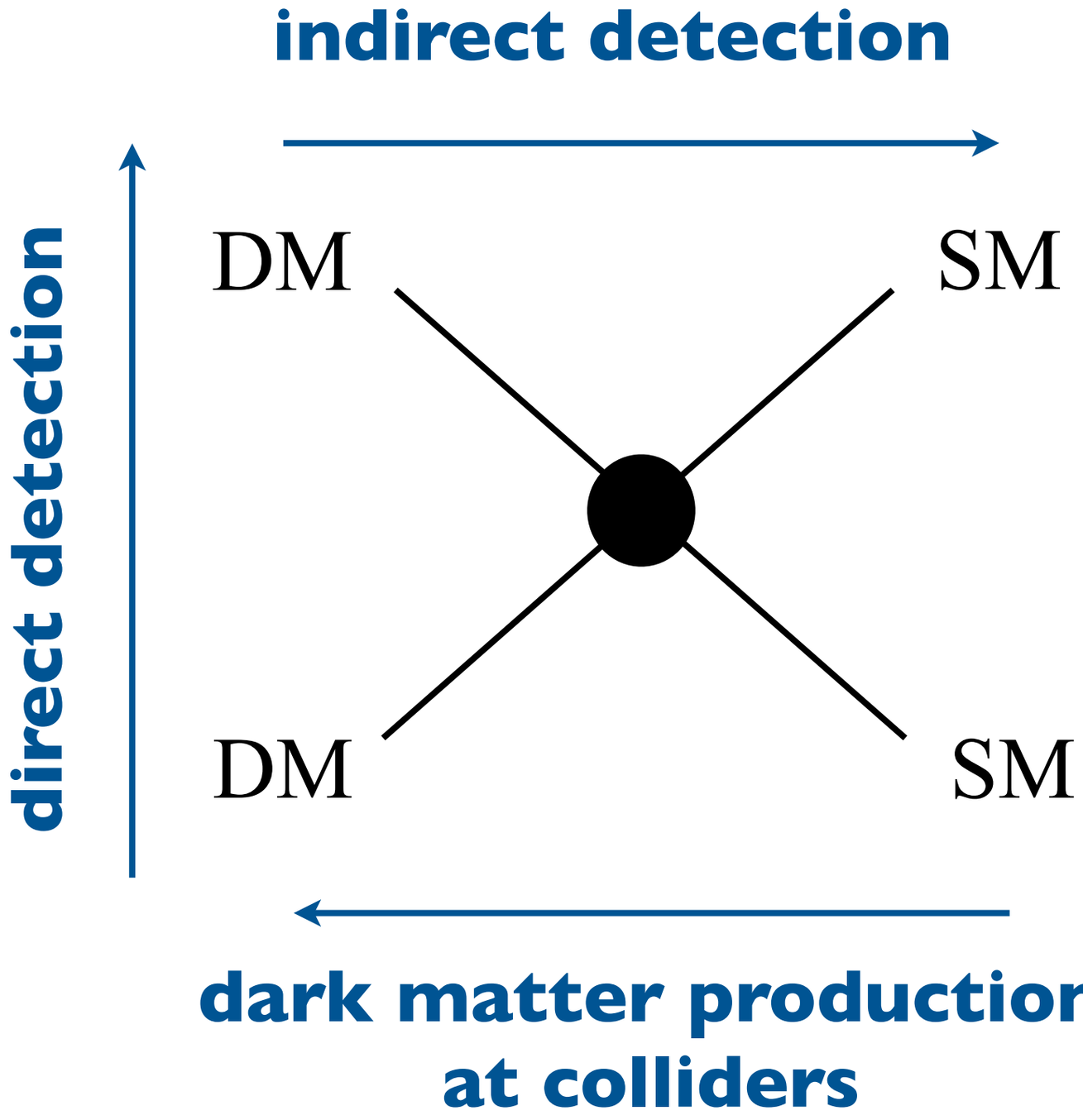


weak scale
dark matter?

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

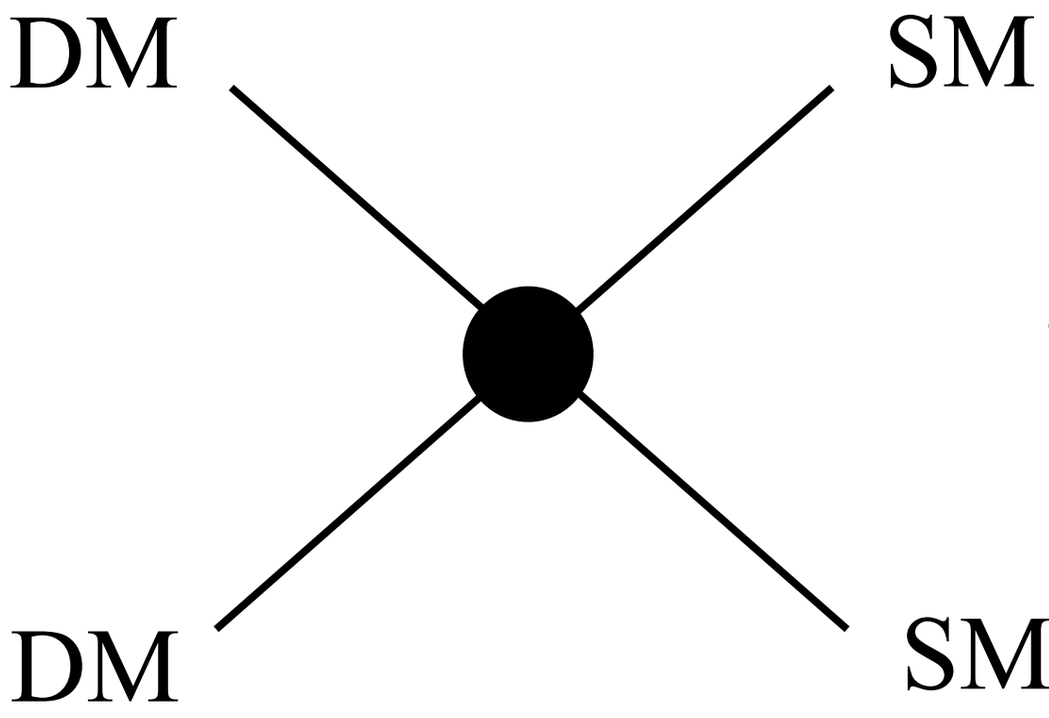
freeze-out in early universe

DM AS A WIMP
(weakly interacting massive particle)



DM AS A WIMP
(weakly interacting massive particle)

indirect detection



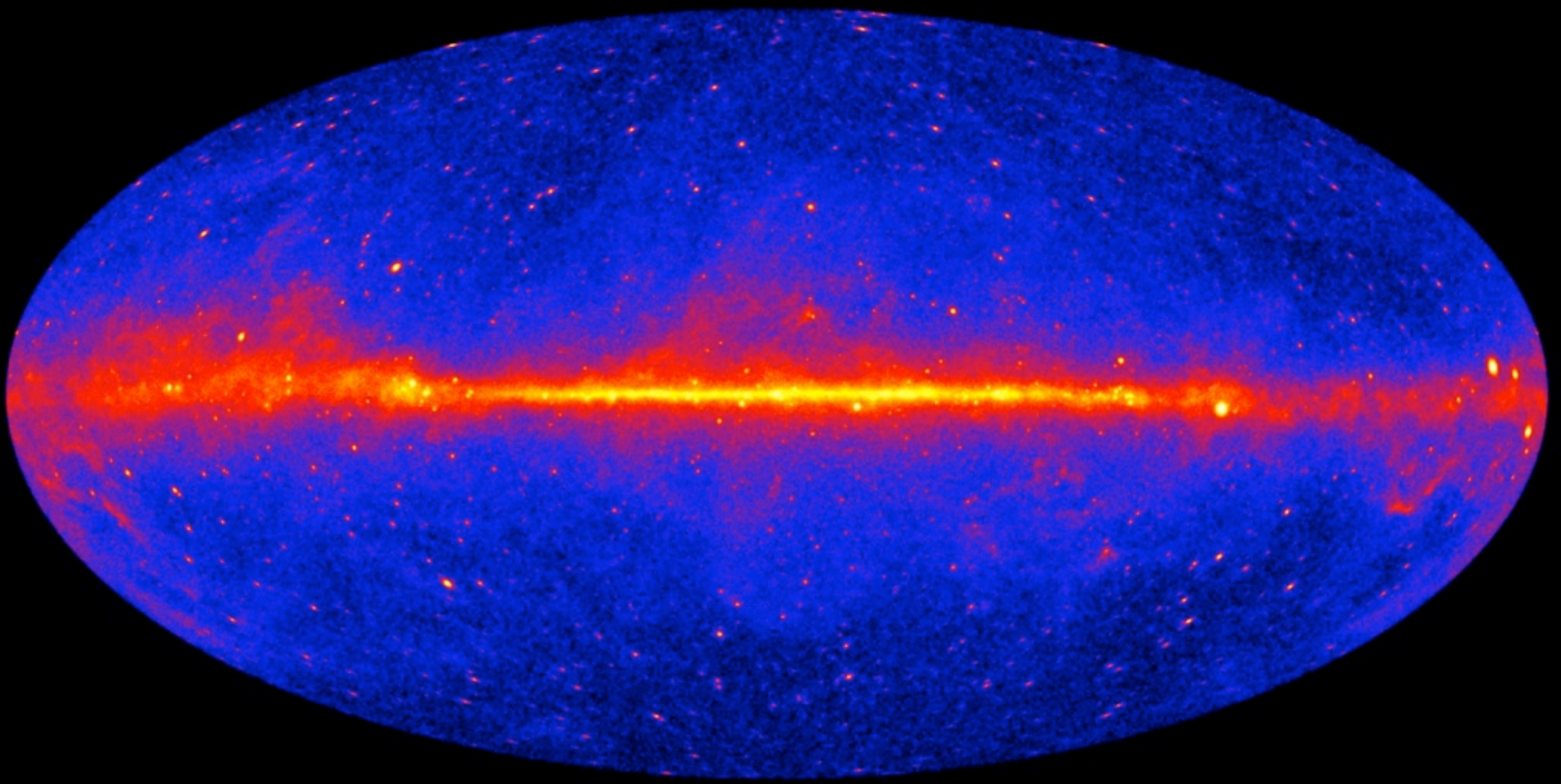
gamma-rays!

target value for indirect detection searches

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

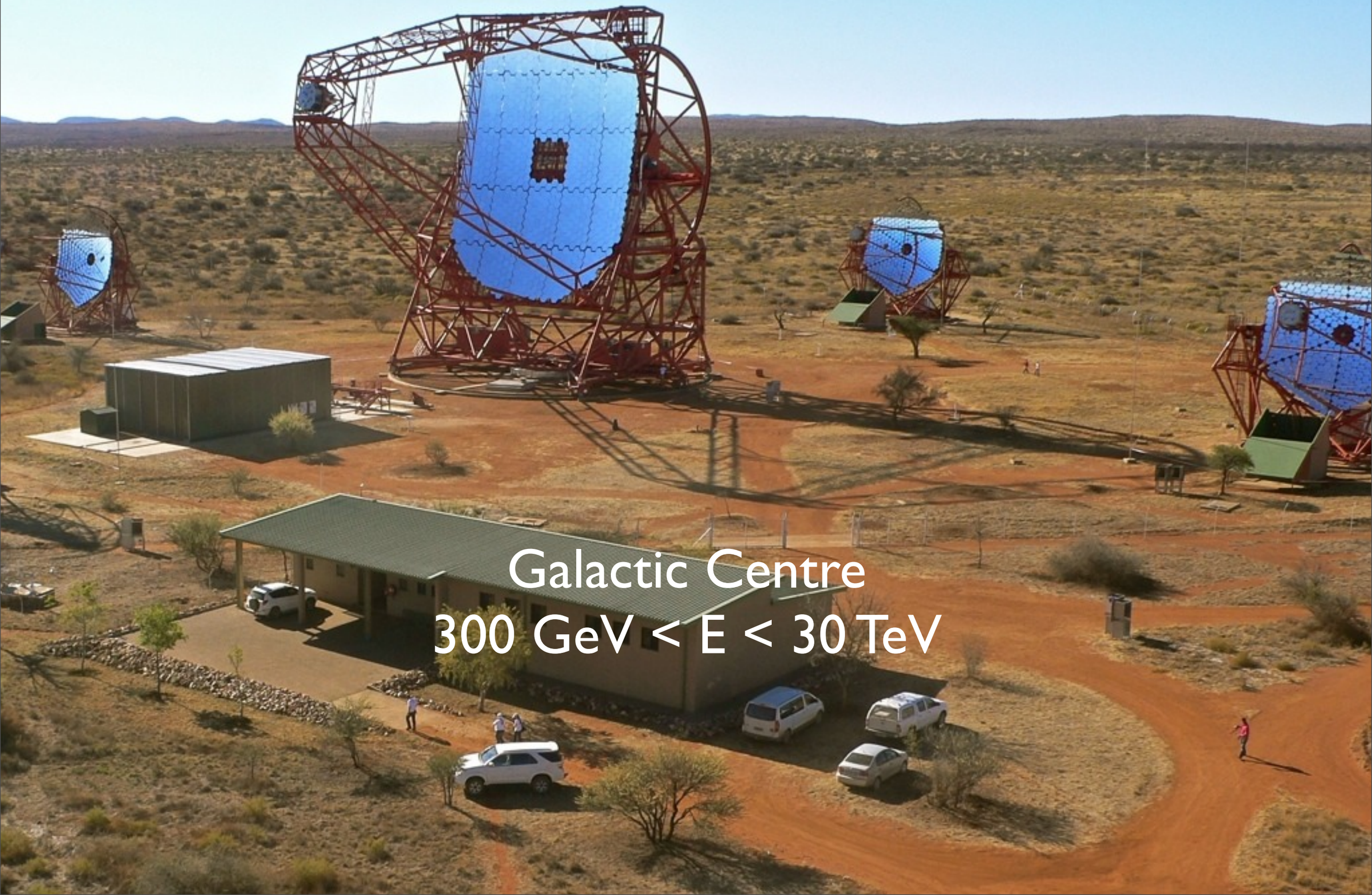
freeze-out in early universe

FERMI-LAT
(Fermi Large Area Telescope)



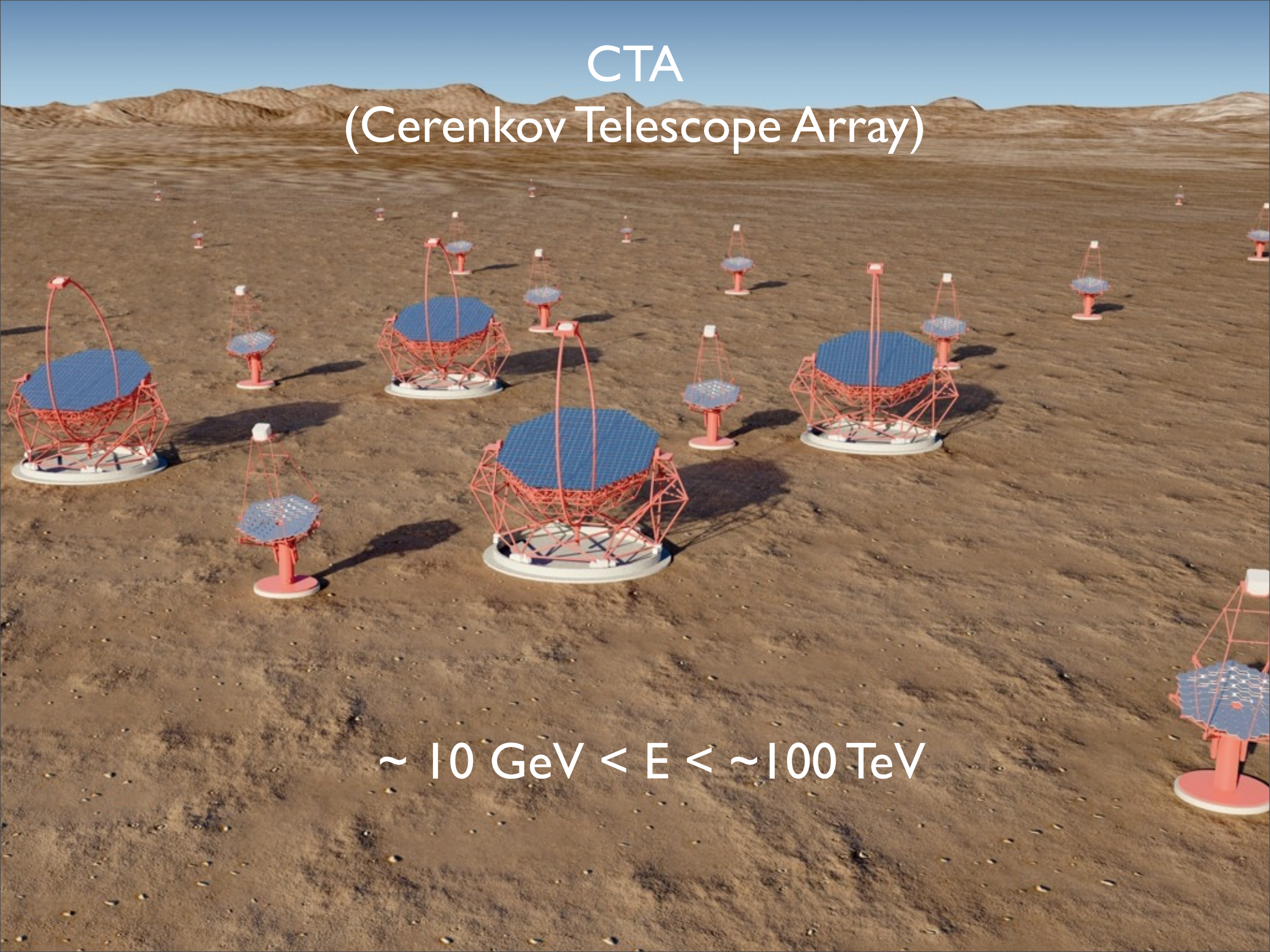
0.2 GeV < E < 300 GeV

H.E.S.S.
(High Energy Stereoscopic System)



Galactic Centre
300 GeV < E < 30 TeV

CTA
(Cerenkov Telescope Array)



~ 10 GeV < E < ~100 TeV

WIMPS THROUGH GAMMA RAYS

Problem:

strong/poorly understood astrophysical background

Strategy #1 Spatial morphology expected from DM annihilation

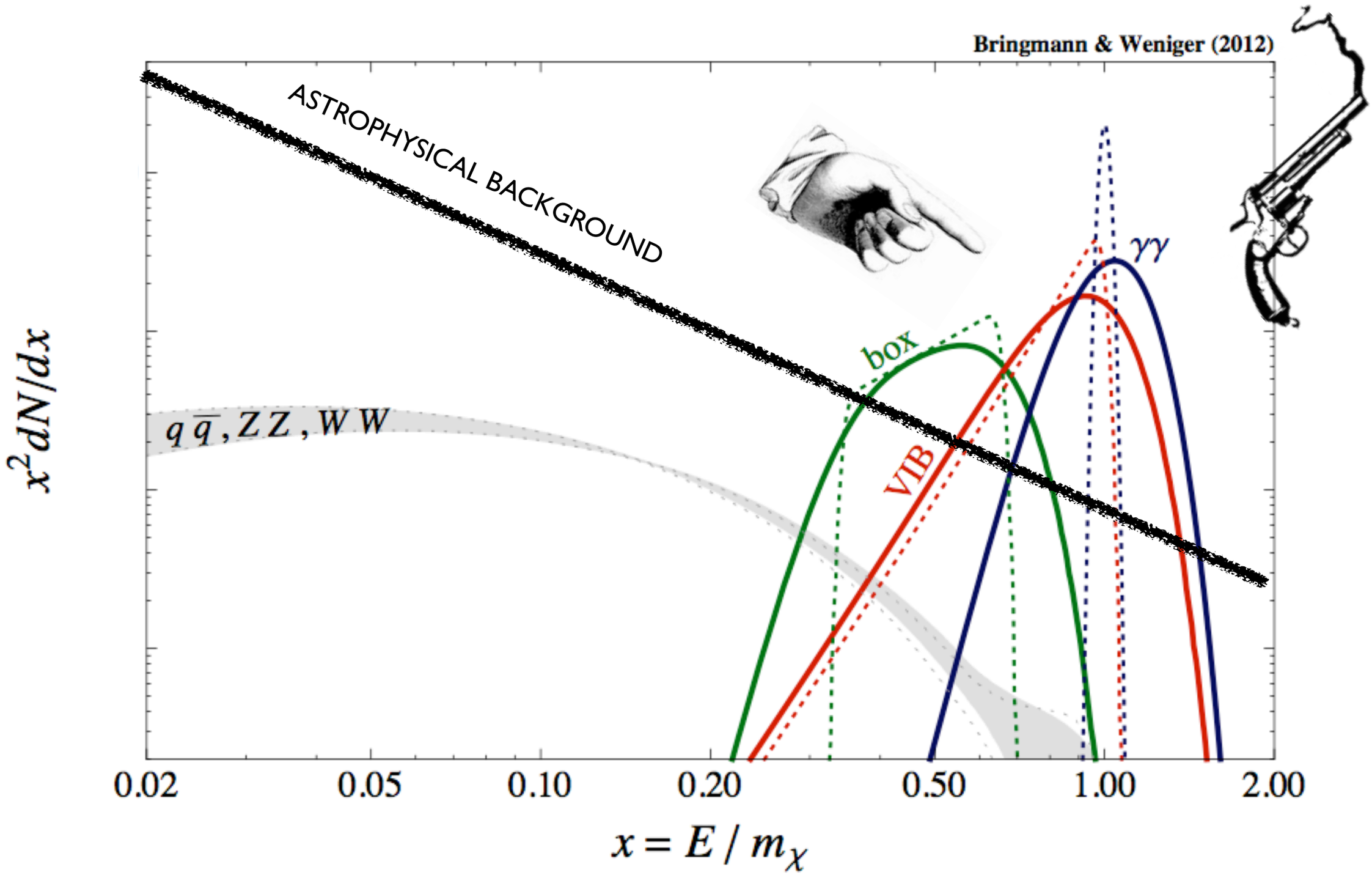
Promising targets: Dwarf Spheroidal galaxies
Galactic Centre

Strategy #2 Spectral signatures distinct from astrophysics background

Spectral features: Digammas
Virtual Internal Bremsstrahlung,...

GAMMA RAY SPECTRAL FEATURES

Digammas or Virtual Internal Bremsstrahlung (VIB)



No astrophysical background (smoking gun) (also $M_{DM} \sim E_\gamma$)

SMOKING GUN SIGNATURES - DIGAMMAS

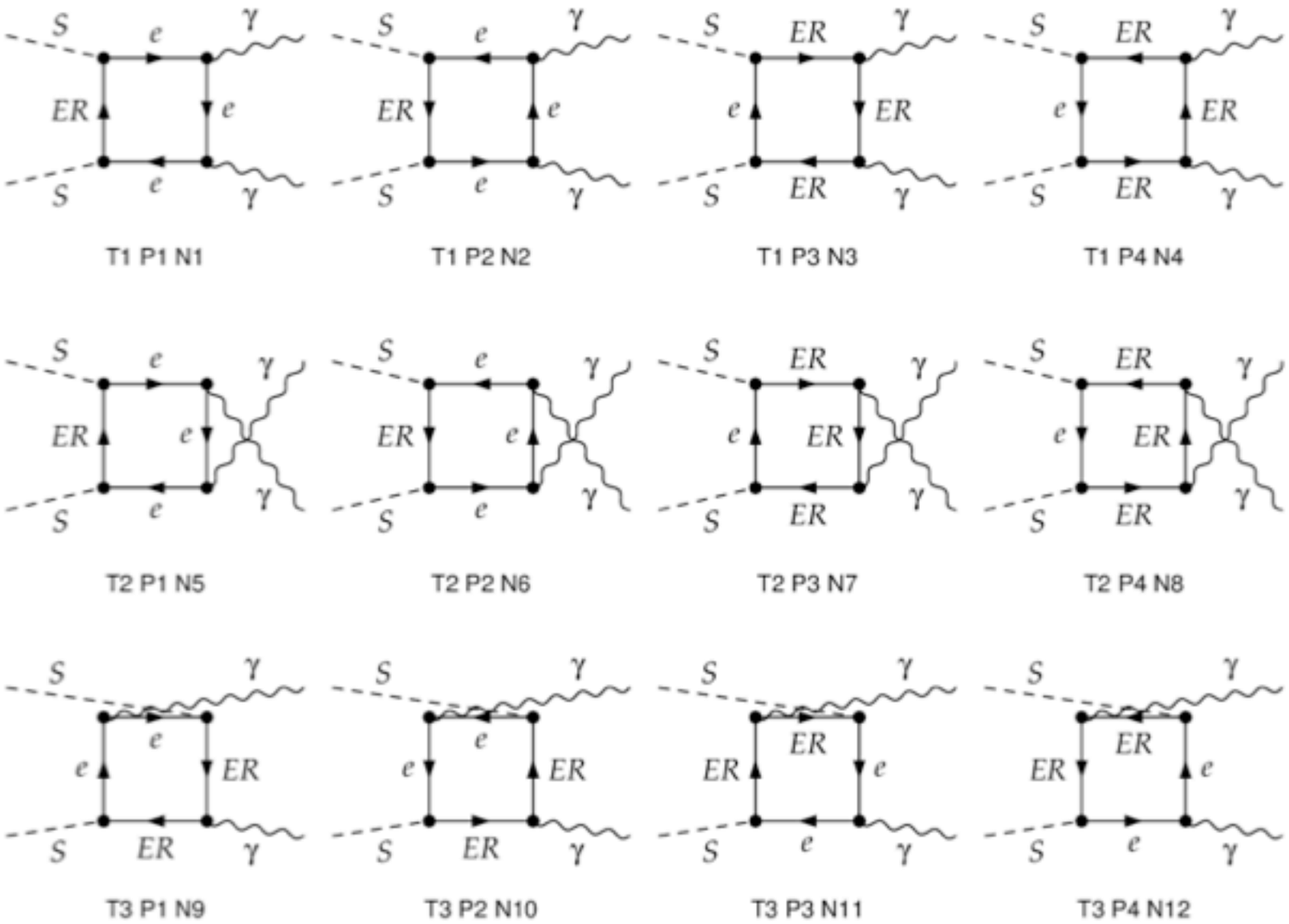


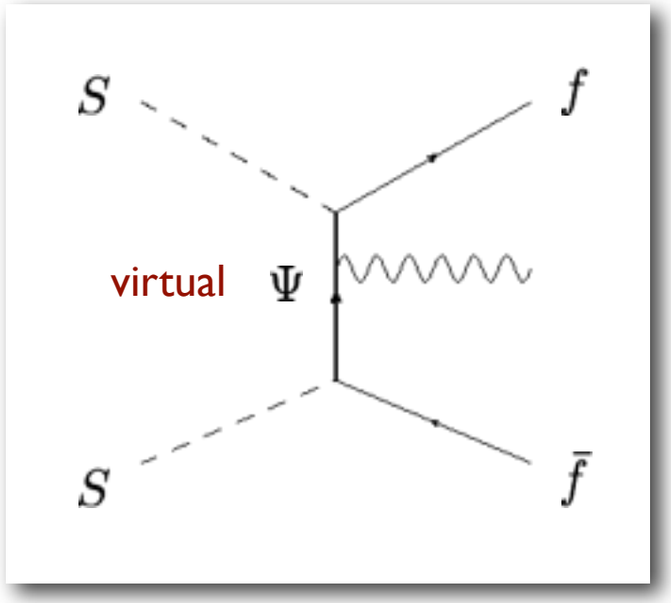
Figure 1: Box diagrams relevant for the $SS \to \gamma\gamma$ process

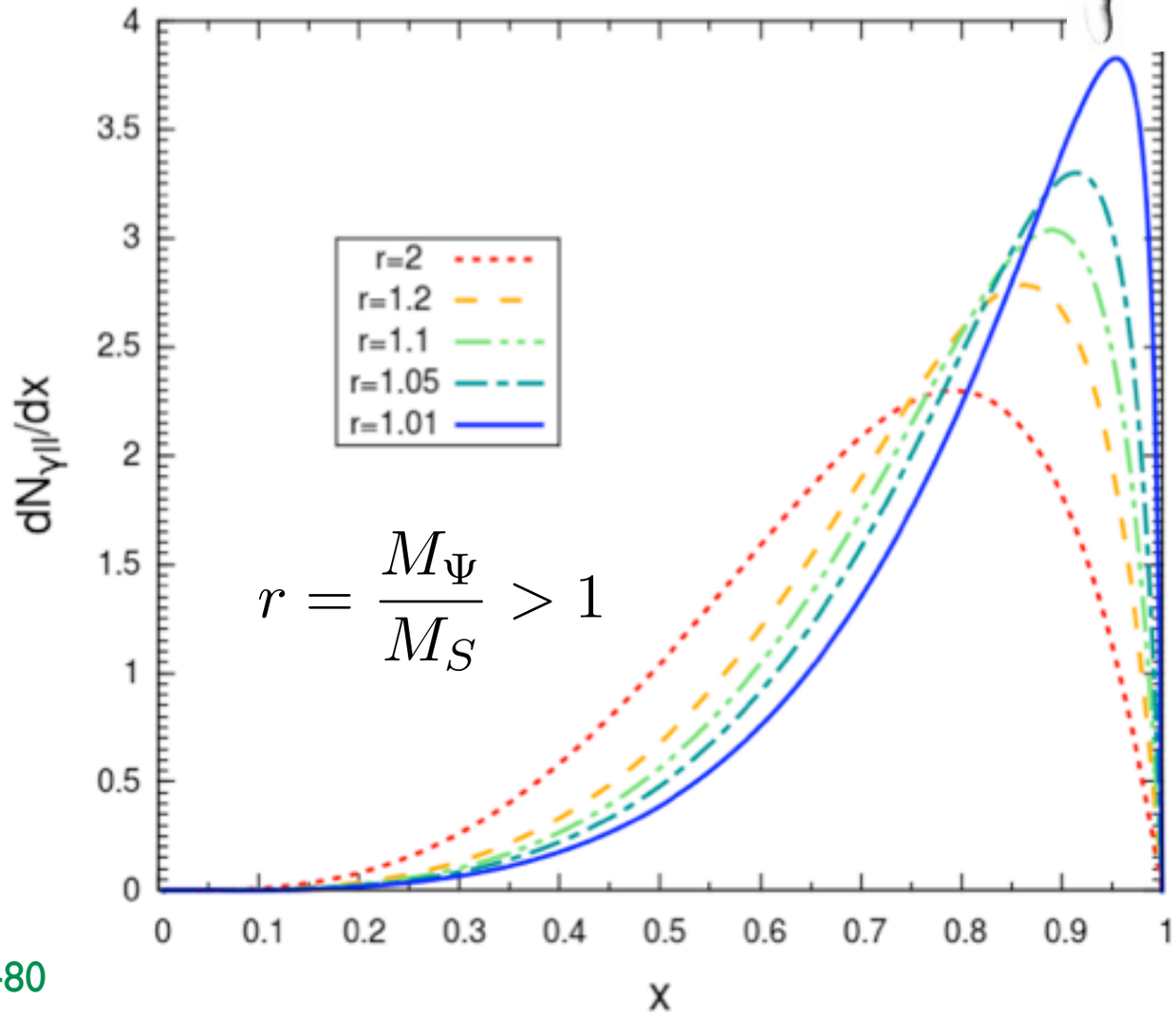
No astrophysical background (smoking gun) (also $M_{DM} \sim E_\gamma$)

SMOKING GUN SIGNATURES
VIRTUAL INTERNAL BREMSSTRAHLUNG

MAJORANA DM

Bergstrom (1989)
Flores, Olive & Rudaz (1989)
Bergstrom, Bringmann & Edsjo (2008)





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

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

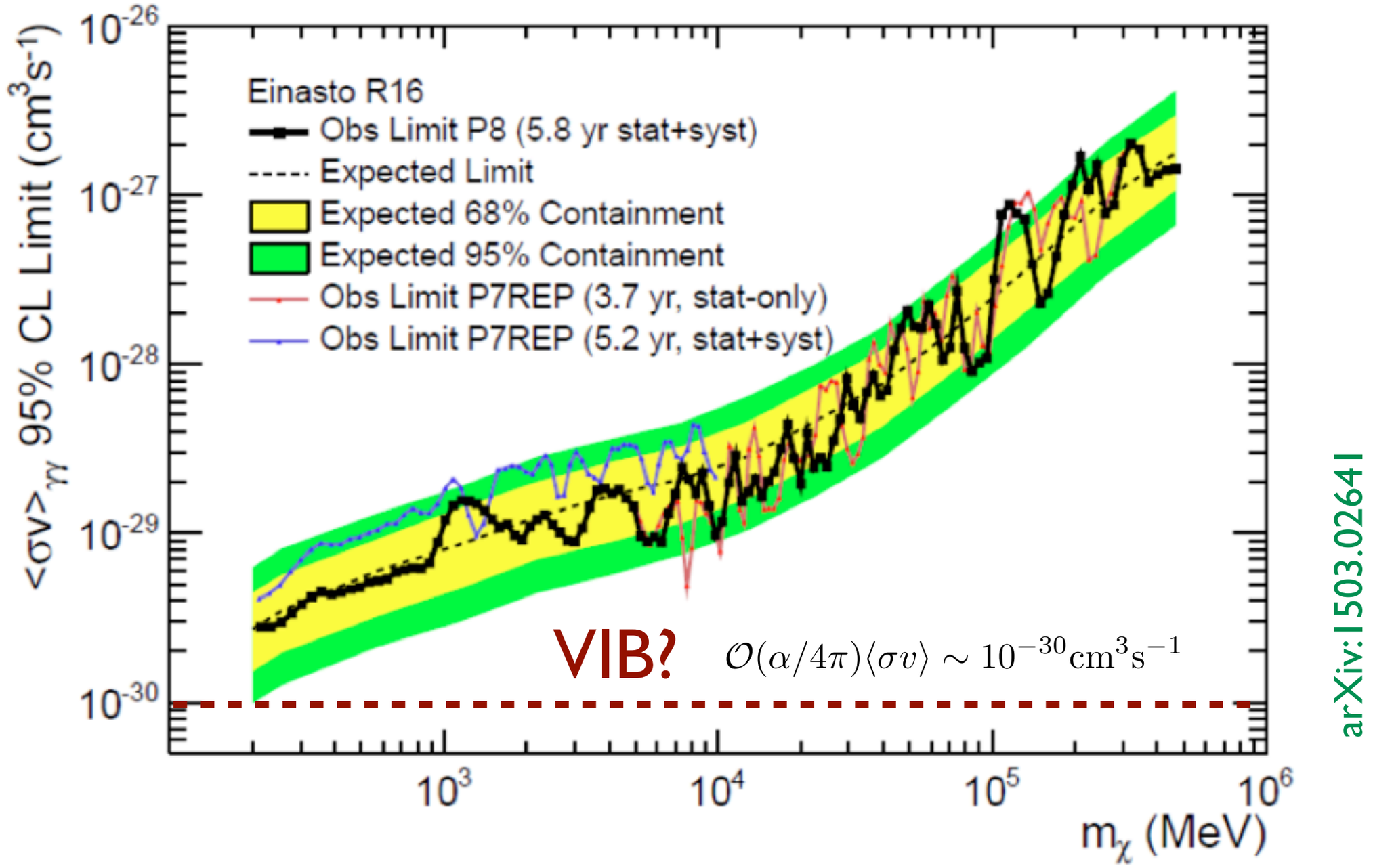
SCALAR DM

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

No astrophysical background (smoking gun) (also $M_{DM} \sim E_\gamma$)

FERMI LIMITS ON GAMMA RAY LINES

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



VIB? $\mathcal{O}(\alpha/4\pi)\langle\sigma v\rangle \sim 10^{-30}\mathrm{cm}^3\mathrm{s}^{-1}$

digammas? $\mathcal{O}(\alpha^2/16\pi^2)\langle\sigma v\rangle \sim 10^{-32}\mathrm{cm}^3\mathrm{s}^{-1}$

arXiv:1503.02641

SIMPLE (SCALAR) WIMP MODELS WITH STRONG GAMMA RAY FEATURES

I. Relating digammas to digluons (loops dominate)

X. Chu, Th. Hambye, T. Scarna & MT arXiv:1206.2279

II. A vector-like portal (enhanced VIB)

F. Giacchino, L. Lopez Honorez & MT arXiv:1307.6480 & arXiv:1405.6921
A. Ibarra, F. Giacchino, L.Lopez Honorez, MT & S. Wild, arXiv:1511.04452

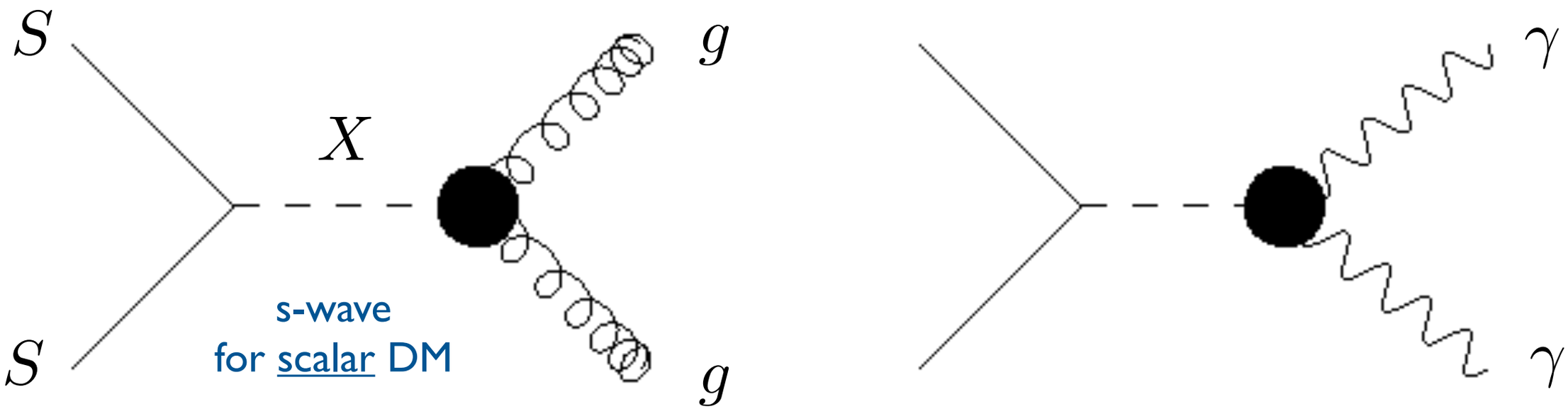
III. Heavy Minimal Dark Matter (Sommerfeld effects)

C. Garcia-Cely, A. Ibarra, A. Lamperstorfer & MT, arXiv:1507.05536

1. A GAMMA RAY LINE FROM DIGLUON ?

relic abundance

indirect detection



$$\frac{\sigma v_{gg}}{\sigma v_{\gamma\gamma}} = \frac{\sum_{vlq} 2\alpha_s^2}{\sum_{vlq} N_c^2 \alpha^2 Q_q^4 + \sum_{vll} \alpha^2 Q_l^4} = \mathcal{O}(10 - 1000)$$

e.g. vector-like
quarks/leptons in the loops

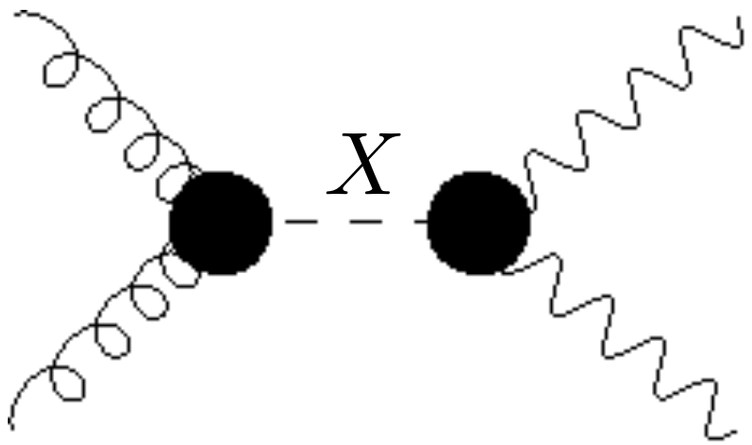
Chu, Hambye, Scarna & M.T.
arXiv:1206.2279

What if Dark Matter Gamma-Ray Lines come with Gluon Lines?

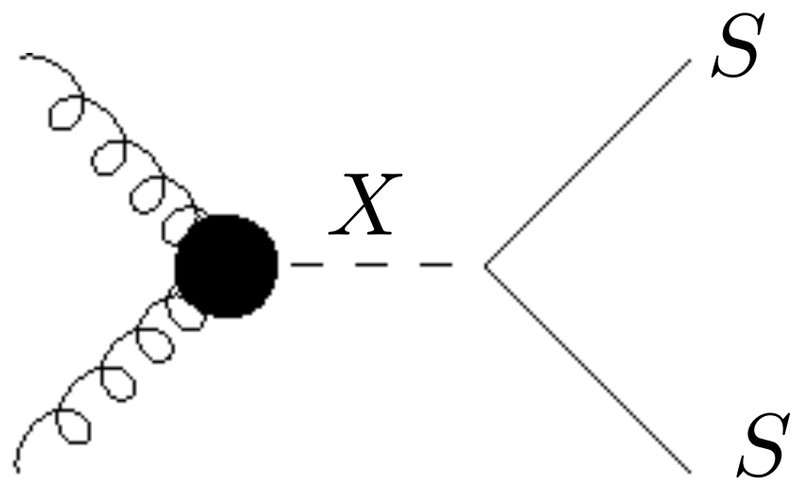
Xiaoyong, Chu,[1] Thomas Hambye,[1,2] Tiziana Scarna,[1] and Michel H.G. Tytgat[1,*]

arXiv:1206.2279

"This brings another possible signature at colliders, which is the production at the LHC of an on-shell messenger particle through gluon-gluon fusion, followed by its decay into a pair of gammas."



diphotons



(potentially large) invisible branching

II. VECTOR-LIKE PORTAL*

F. Giacchino, L. Lopez Honorez & MT, arXiv:1307.6480 & arXiv:1405.6921
A. Ibarra, F. Giacchino, L.Lopez Honorez, MT & S.Wild, arXiv:1511.04452

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

real singlet <u>scalar</u>

<u>vector-like</u> lepton or quark

SM light lepton or quark

Z_2 symmetry

$$S \xrightarrow{Z_2} -S$$
$$\Psi \xrightarrow{Z_2} -\Psi$$

S is our dark matter

*We call it the <u>Vector-like Portal</u> following Fileviez Perez & Wise, arXiv:1303.1452

IT'S A TOY MODEL

(aka simplified model)

Scalar cousin of bino-like DM

Majorana DM
with slepton or squark mediator

$\chi \tilde{l}^\dagger l_R \quad \chi \tilde{q}^\dagger q_R$

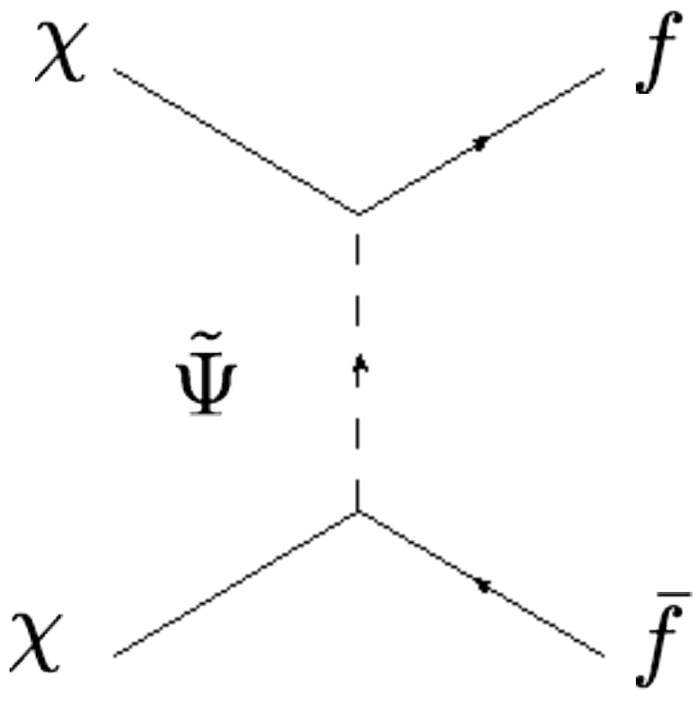
Appears in top-down scenarios

eg 6D model with spinless KK photon ~ S

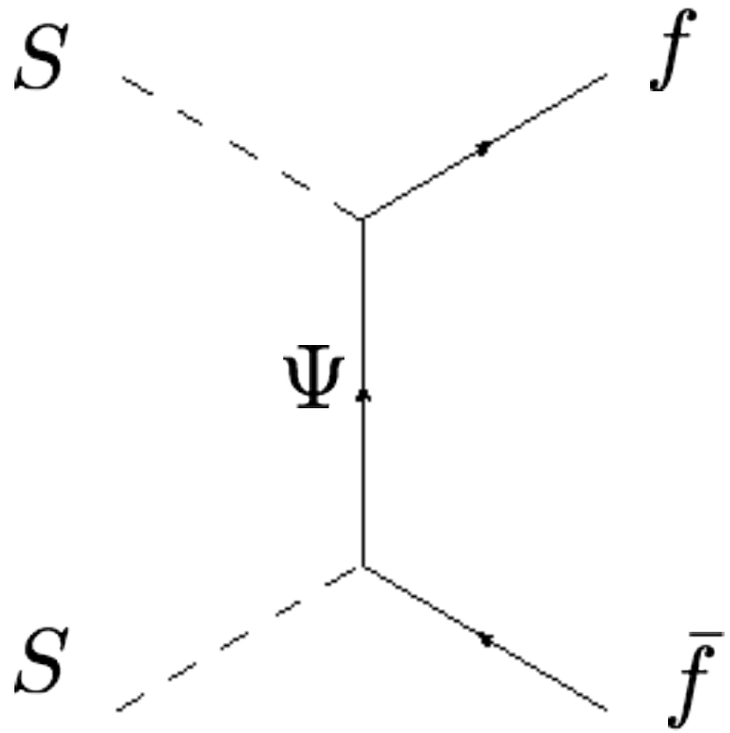
eg Dobrescu & Ponton, arXiv:hep-th/0401032

A benchmark dark matter model
with strong gamma ray spectral features

MAJORANA vs REAL SCALAR into light SM fermions



vs



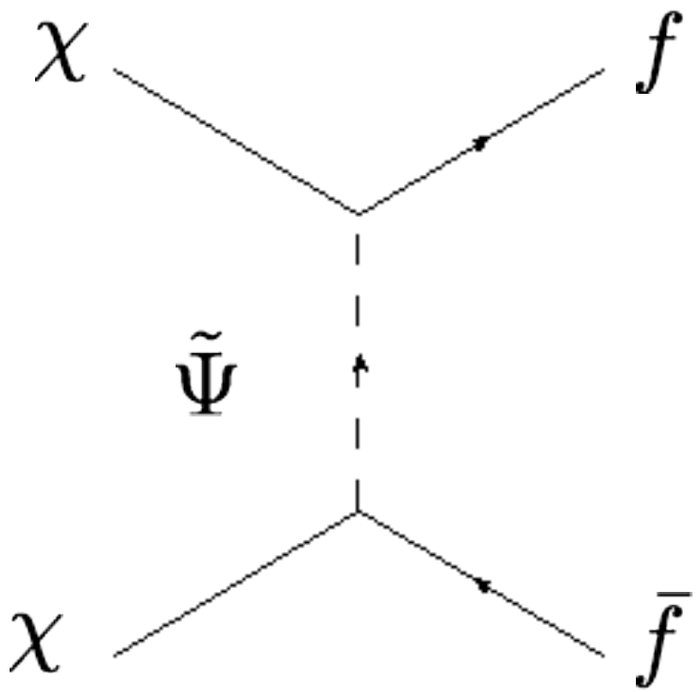
p-wave

$$\sigma v(\chi\chi \to l\bar{l}) = \frac{g_l^4}{48\pi}\frac{v^2}{m_\chi^2}\frac{1+r^4}{(1+r^2)^4}$$

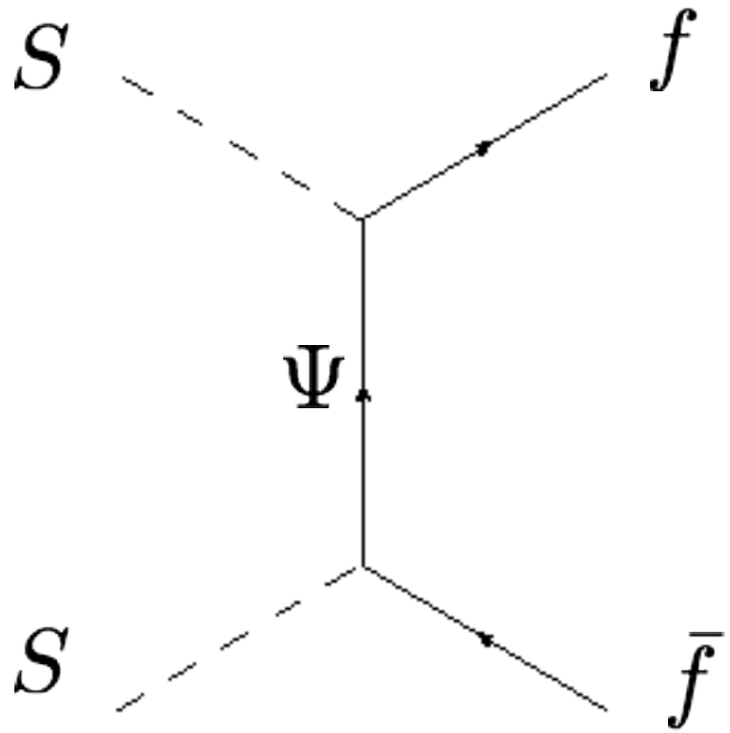
$$r = \frac{m_{\tilde{\Psi}}}{m_\chi} \geq 1$$

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

MAJORANA vs REAL SCALAR into light SM fermions



vs



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Goldberg
«Constraint on the Photino mass from cosmology»
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d-wave

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

$$r = \frac{m_\psi}{m_S} \geq 1$$

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

MAJORANA vs REAL SCALAR into light SM fermions

$$\mathcal{O} = \bar{\chi}\gamma^\mu\gamma_5\chi\bar{\psi}_f\gamma_\mu\gamma_5\psi_f \quad \text{vs} \quad \mathcal{O}_T = \partial_\mu S \partial_\nu S\, \Theta^{\mu\nu}_{f_R}$$

FERMION
STRESS-ENERGY TENSOR

p-wave

$$\sigma v(\chi\chi \to l\bar{l}) = \frac{g_l^4}{48\pi}\frac{v^2}{m_\chi^2}\frac{1+r^4}{(1+r^2)^4}$$

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d-wave

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$$r = \frac{m_\psi}{m_S} \geq 1$$

Toma, arXiv:1307.6181
Giacchino, Lopez Honorez & MT, arXiv:1307.6480

I. Annihilation in early universe $v \sim 0.3$

→ $\mathrm{DM\ DM} \to f\bar{f}$ more suppressed for scalar DM than for Majorana

II. Annihilation at Galactic Centre ? $v_{\mathrm{GC}} \sim 10^{-3}$

$\mathrm{DM\ DM} \to f\bar{f}$ completely irrelevant

→ Radiative corrections relevant!

$\mathrm{DM\ DM} \to \gamma\gamma$

Digammas

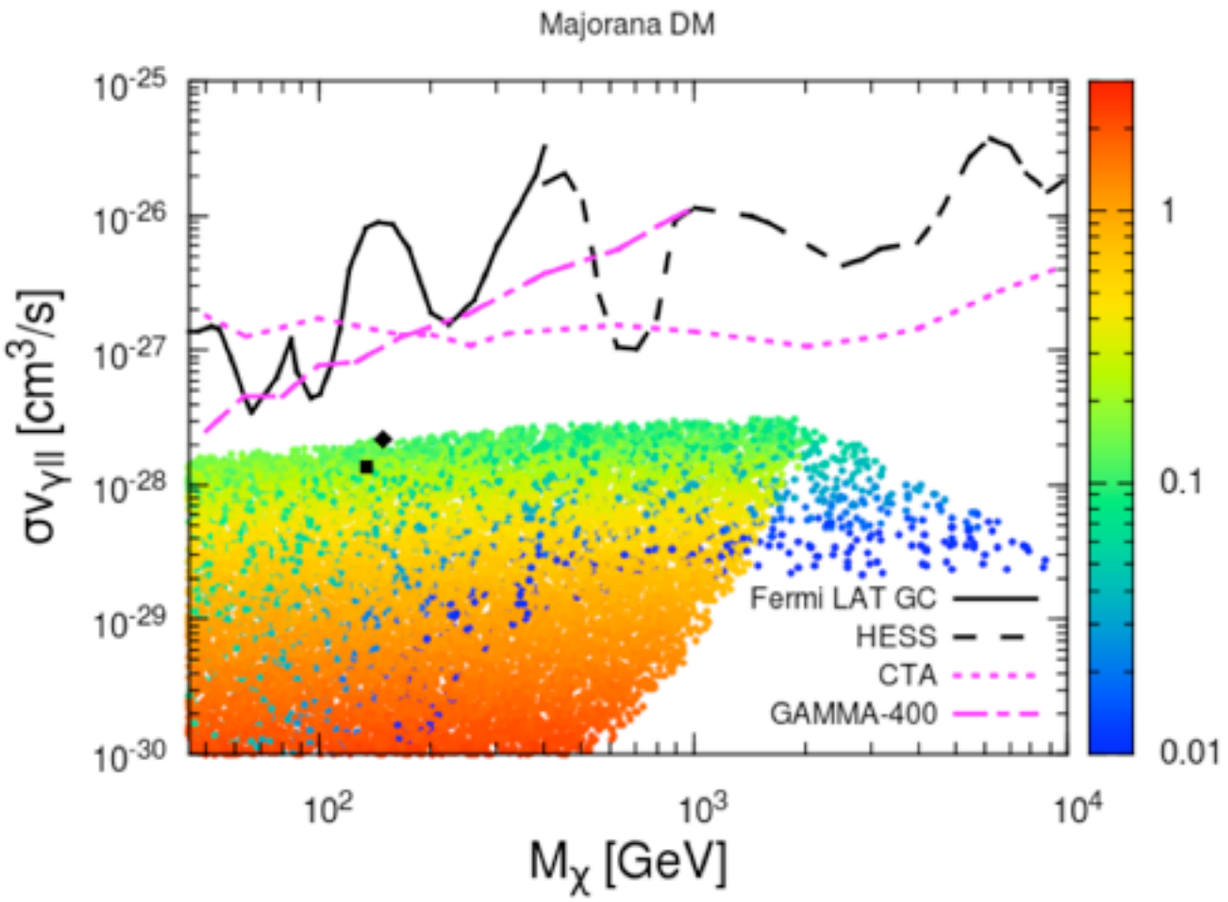
$\mathrm{DM\ DM} \to f\bar{f}\gamma$

Bremsstrahlung

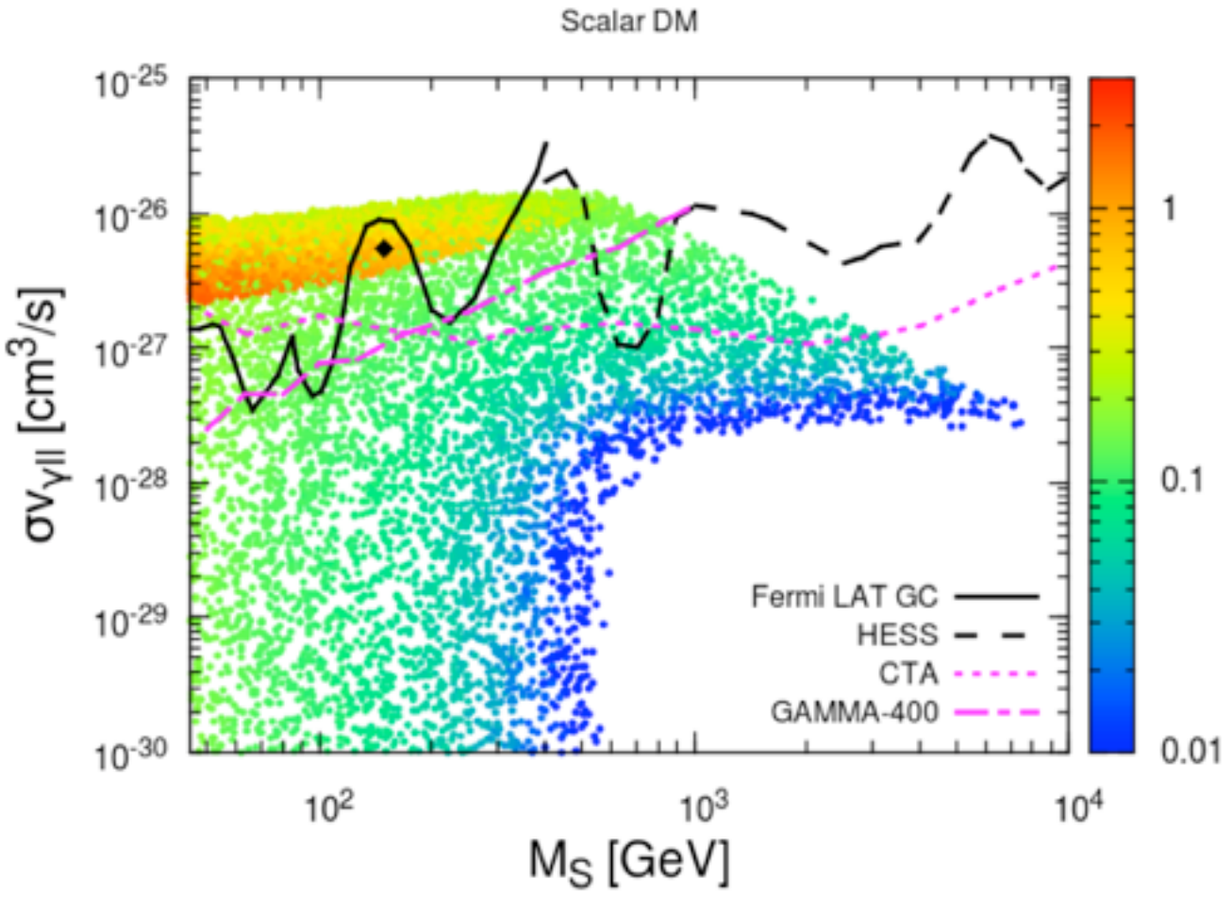
Both are s-wave and very strong for a scalar DM particle!

COUPLING TO VECTOR-LIKE LEPTONS

Majorana DM

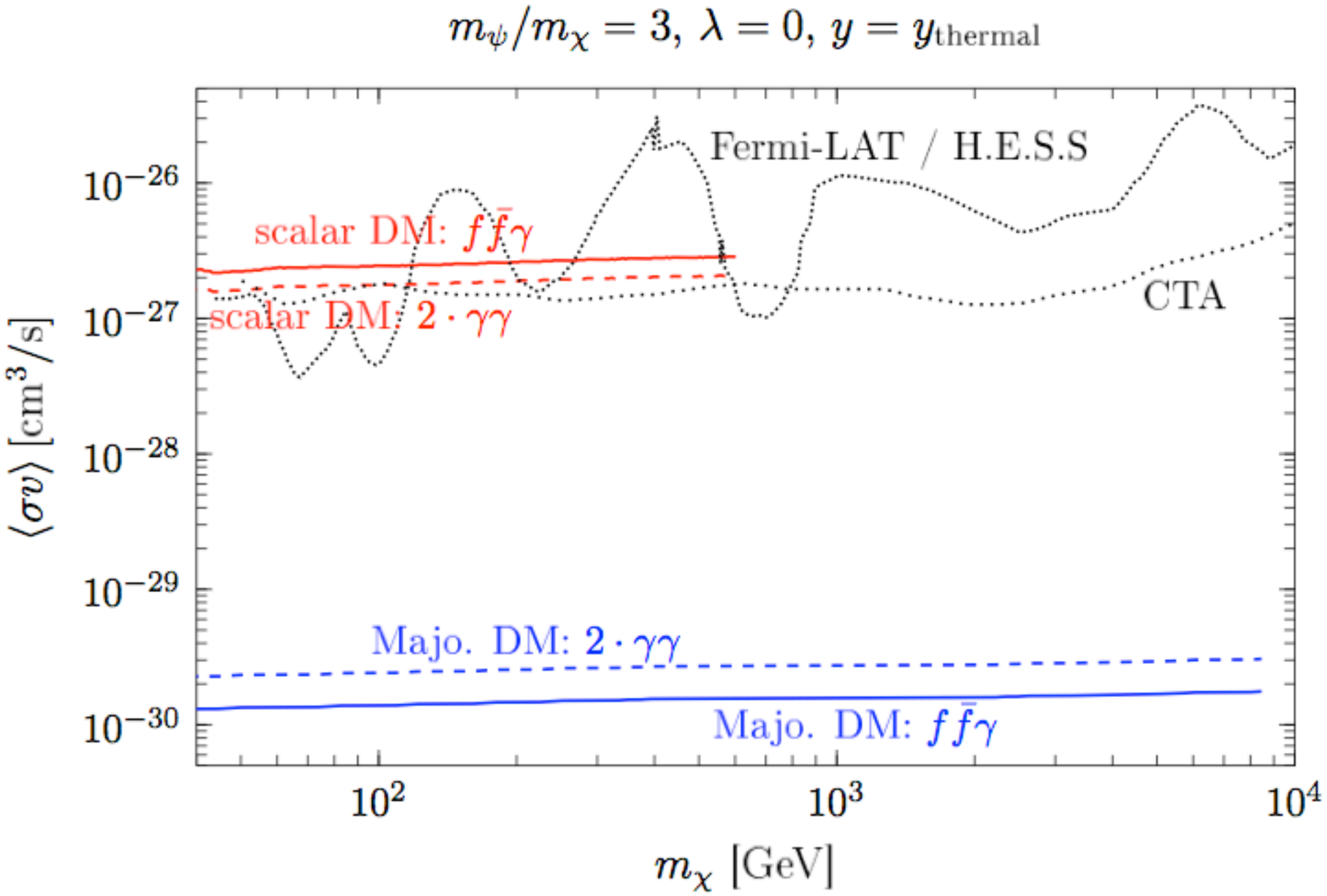


Real scalar DM



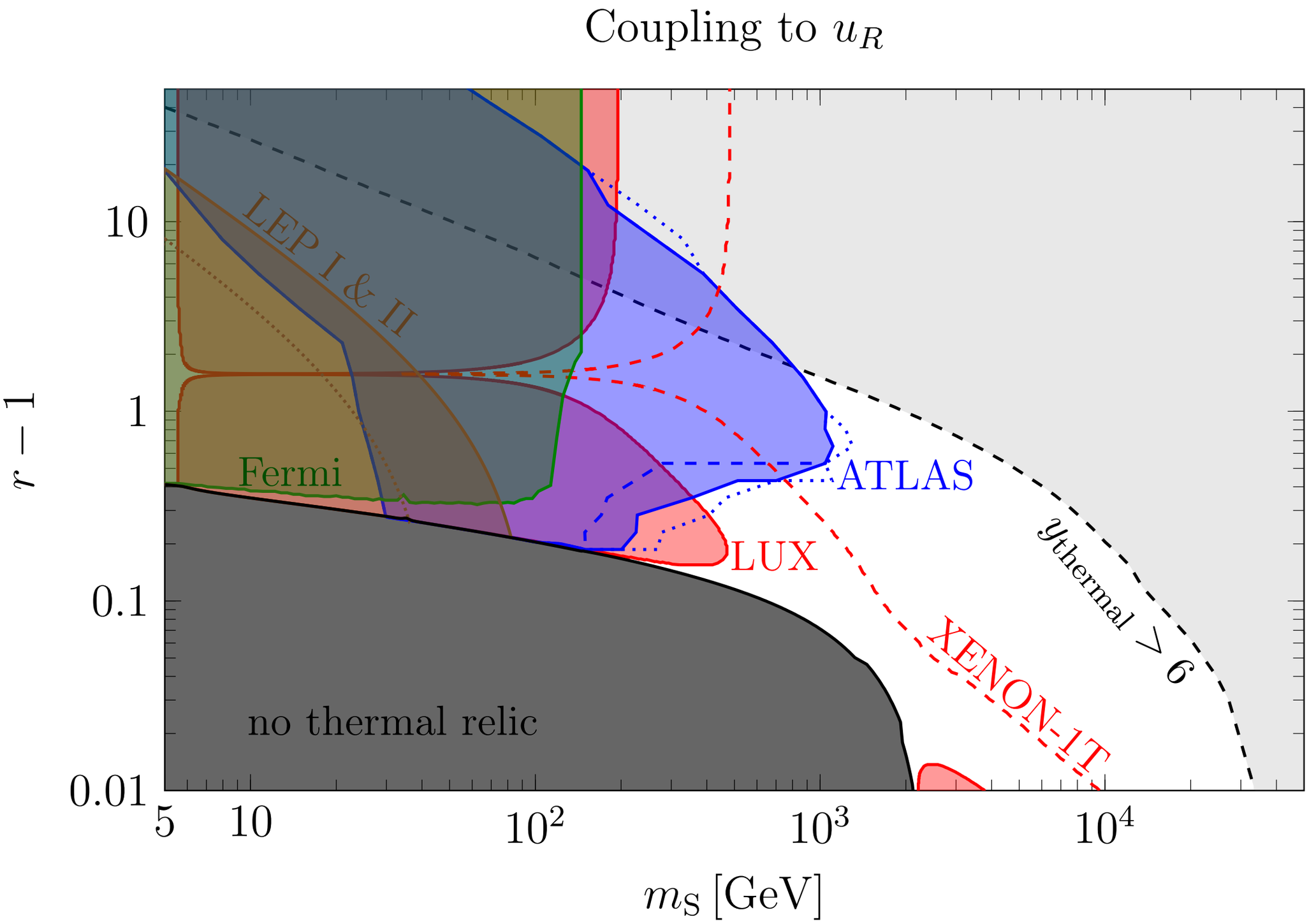
Giacchino, Lopez Honorez & MT, arXiv:1307.6480
See also
Takashi Toma, arXiv:1307.6181

COUPLING TO VECTOR-LIKE LEPTONS



Ibarra, Toma, Totzauer & Wild
arXiv:1405.6917

COUPLING TO VECTOR-LIKE QUARKS



Giacchino, Ibarra, Lopez Honorez, M.T. & Wild, arXiv:1511.04452

III. HEAVY MINIMAL DARK MATTER

Inert Doublet

Ma & Deshpande (1978)
Barbieri, Hall & Rychkov (2006)
Lopez Honorez, Nezri, Oliver & MT (2007)
...
See Kraml, Swiezewska, Robens,... talks

Quantum numbers			DM can
$SU(2)_L$	$U(1)_Y$	Spin	decay into
2	1/2	0	EL
2	1/2	1/2	EH
3	0	0	HH^*
3	0	1/2	LH
3	1	0	HH, LL
3	1	1/2	LH
4	1/2	0	HHH^*
4	1/2	1/2	(LHH^*)
4	3/2	0	HHH
4	3/2	1/2	(LHH)
5	0	0	(HHH^*H^*)
5	0	1/2	–
7	0	0	$(\chi\chi\chi H^\dagger H)$

~ Higgsino-like

~ Wino-like

Fermionic 5-plet

Scalar 7-plet

Cirelli, Fornengo & Strumia (2005) "Minimal Dark Matter"

HEAVY SCALAR 7-PLET

A benchmark for multi-TeV dark matter with strong gamma-ray features

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\left(|D_\mu \chi|^2 - M^2|\chi|^2\right)$$

$$\chi = \begin{pmatrix} \mathrm{DM}^{3+} \\ \mathrm{DM}^{2+} \\ \mathrm{DM}^{+} \\ \mathrm{DM} \\ -\mathrm{DM}^{-} \\ \mathrm{DM}^{2-} \\ -\mathrm{DM}^{3-} \end{pmatrix}$$

Mass splitting
through loop corrections

$$M_Q - M_{Q'} \approx (Q^2 - Q'^2)\,\Delta$$

$$\Delta \equiv \alpha_2 \sin^2\left(\frac{\theta_W}{2}\right) M_W \approx 166 \text{ MeV}$$

Cirelli, Fornengo & Strumia (2005)

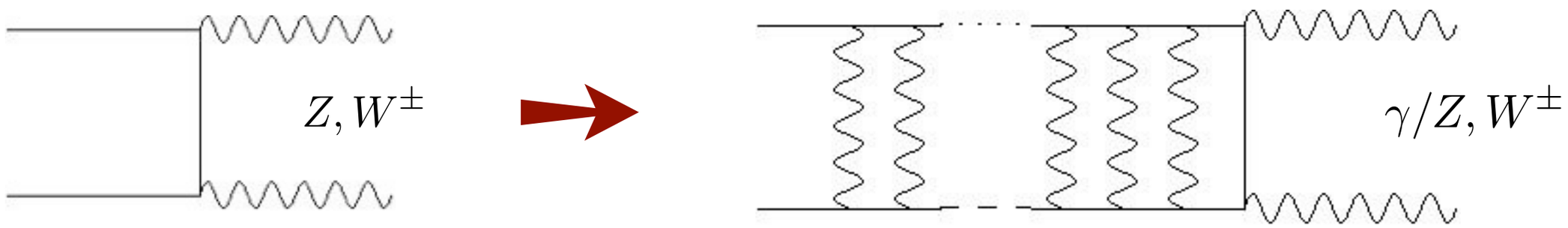
HEAVY SCALAR 7-PLET

A benchmark for multi-TeV dark matter with strong gamma-ray features

$$M_7 \sim 25 \text{ TeV}$$ Cirelli, Strumia & Tamburini (2007)

1. CO-ANNIHILATION
2. SOMMERFELD EFFECTS

} σ_{eff} ⇗

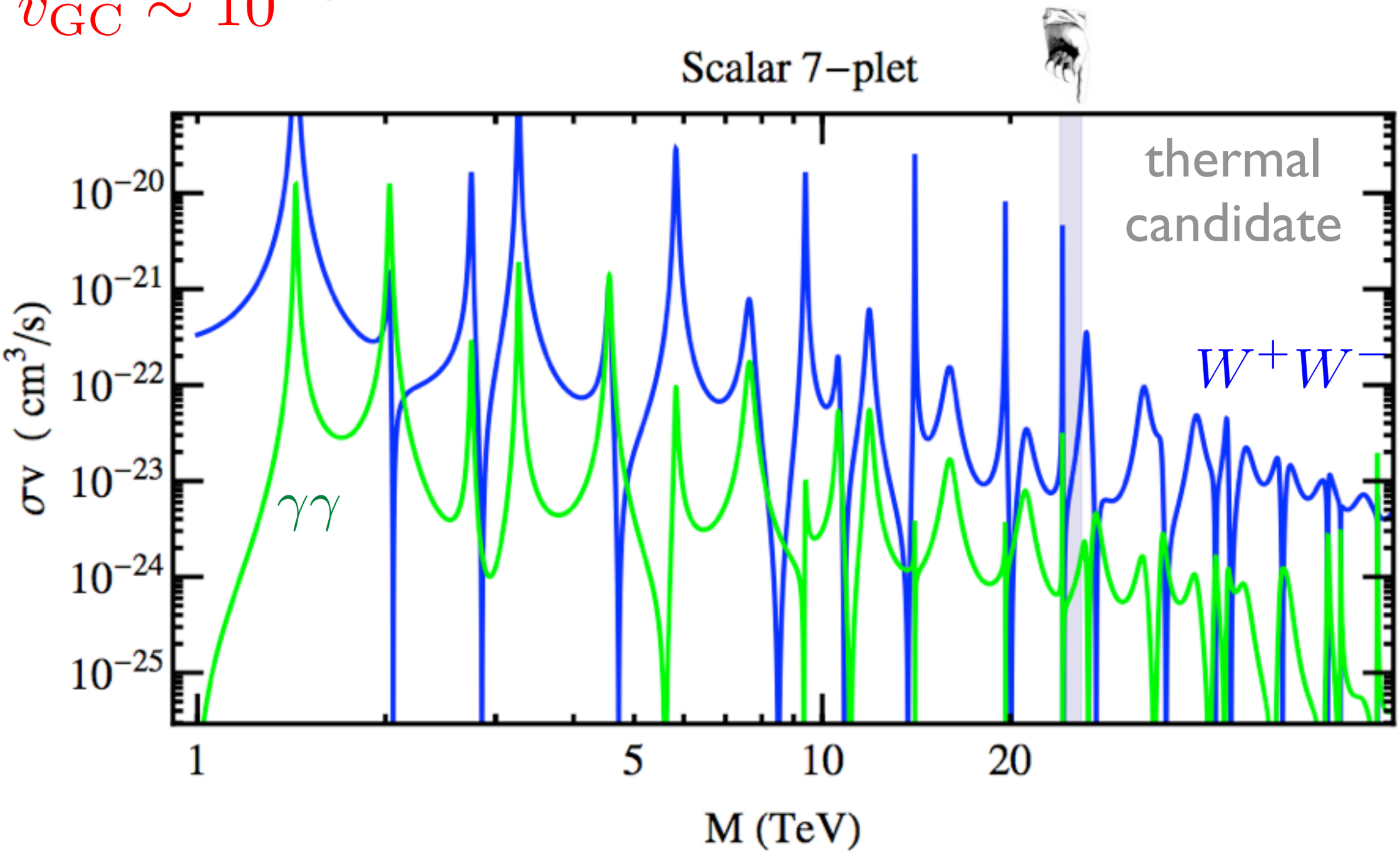


$$M_7 \gg M_{W/Z}$$

PEAKS AND DIPS IN ANNIHILATION CROSS SECTIONS

Strumia, Cirelli & Tambirini (2007)

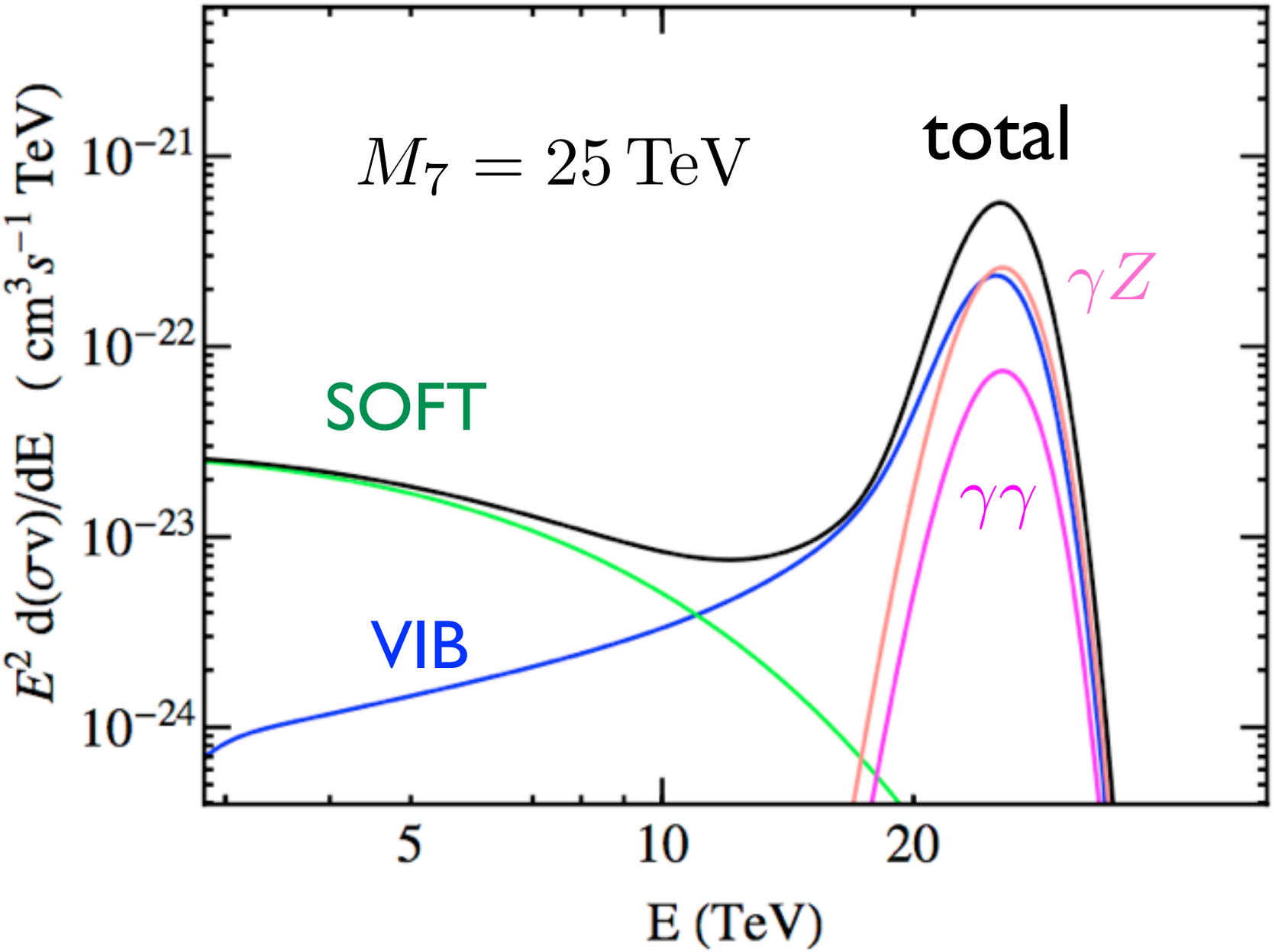
$v_{\rm GC} \sim 10^{-3}$



Garcia-Cely, Ibarra, Lamperstorfer & MT, arXiv:1507.05536

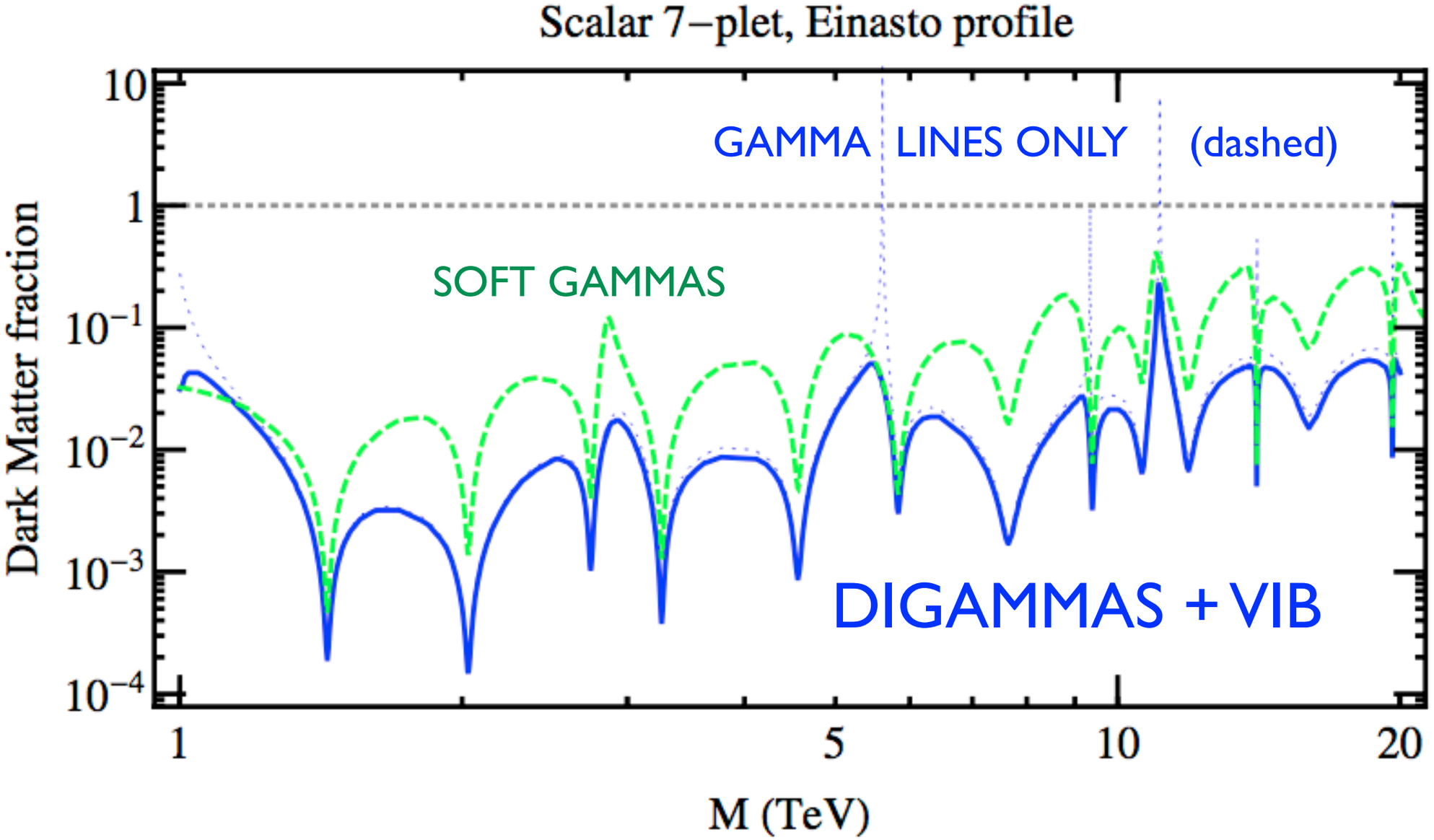
See also Cirelli, Hambye, Panci, Sala & Taoso, arXiv:1507.05519 (fermionic 5-plet)

STRONG GAMMA-RAY SPECTRAL FEATURES



Garcia-Cely, Ibarra, Lamperstorfer & MT, arXiv:1507.05536

H.E.S.S. LIMITS



Garcia-Cely, Ibarra, Lamperstorfer & MT, arXiv:1507.05536

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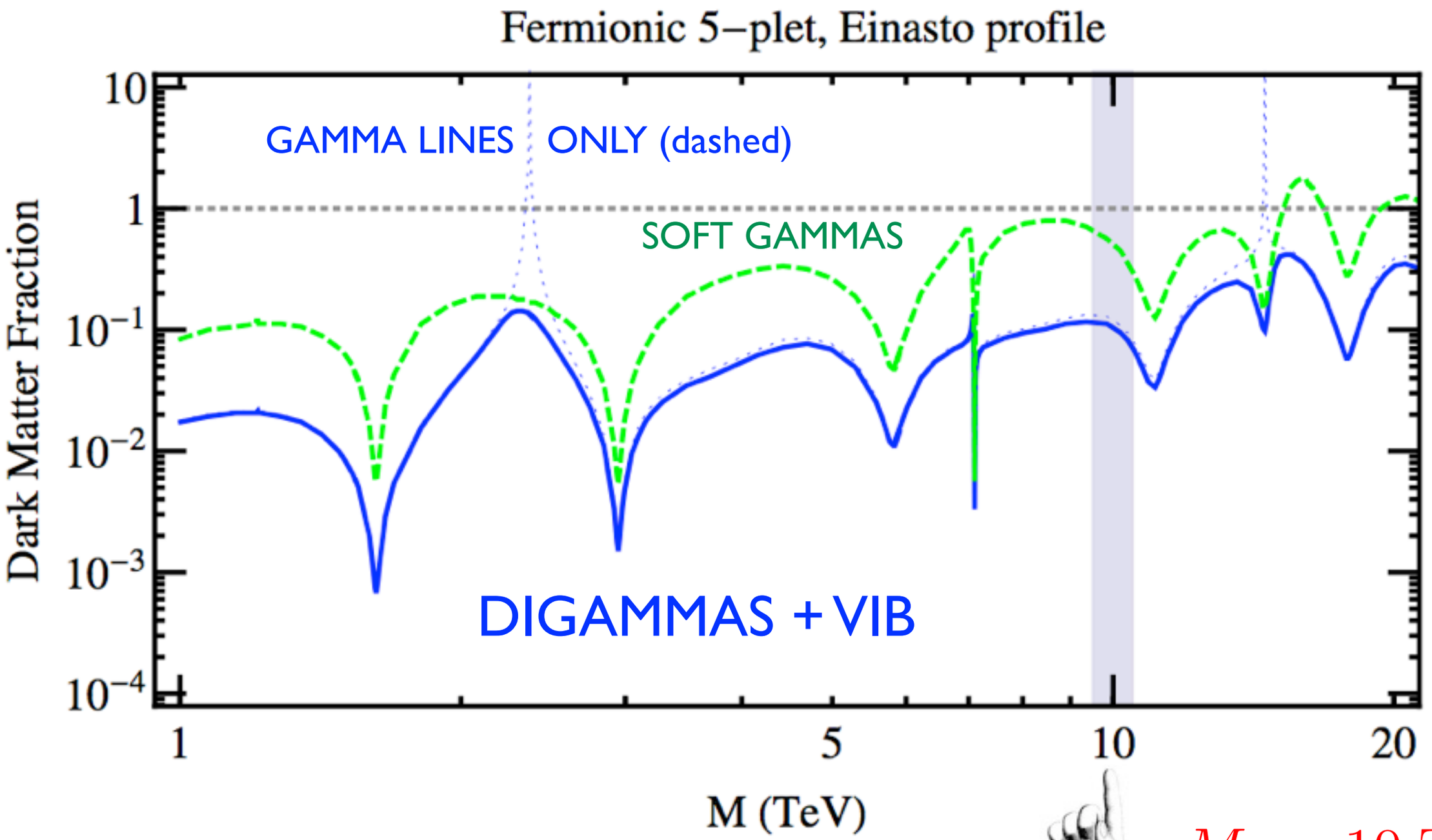
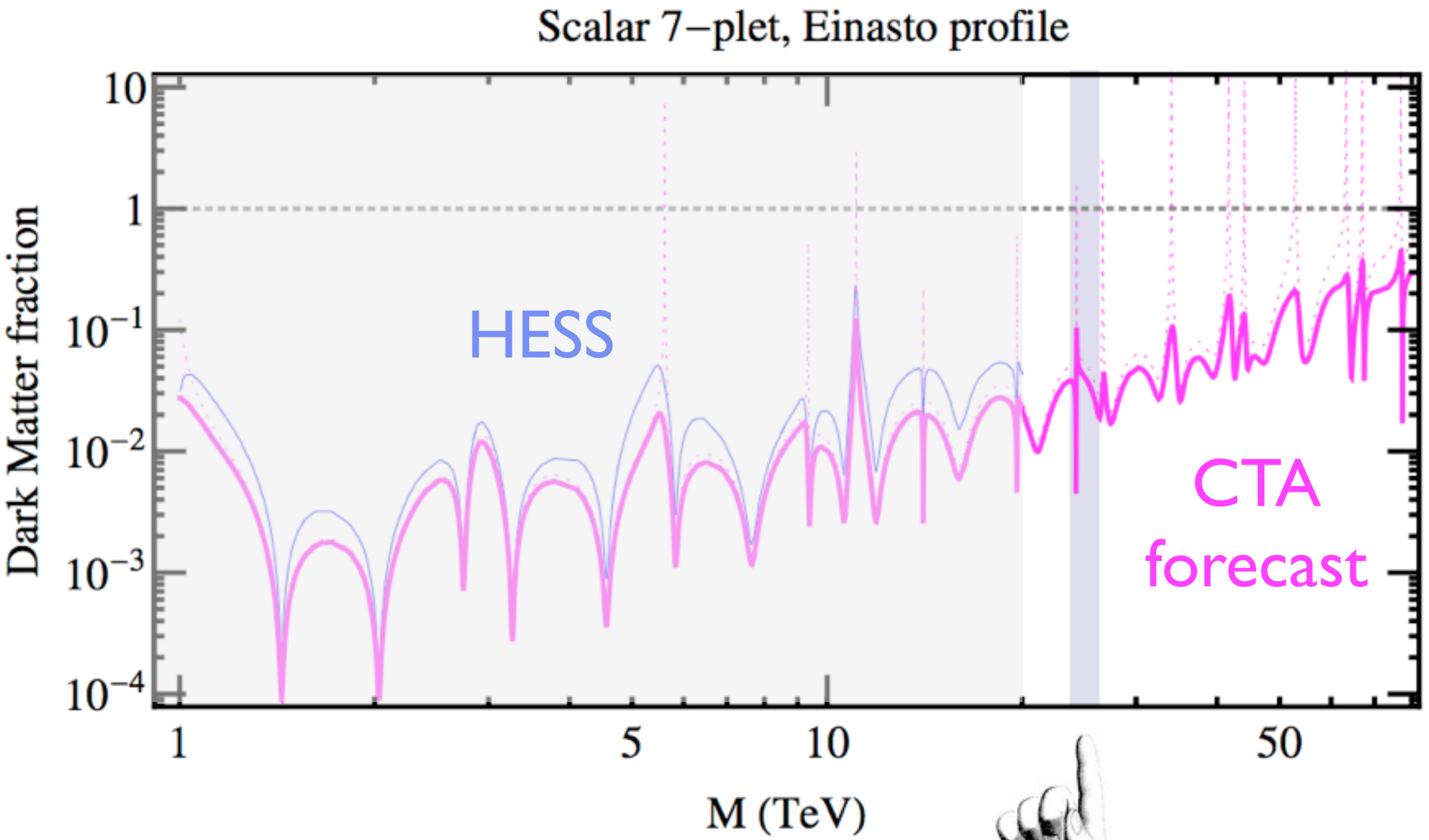


$M_5 \sim 10$ TeV

Thermal fermionic 5-plet candidate constrained by H.E.S.S.

Garcia-Cely, Ibarra, Lamperstorfer & MT, arXiv:1507.05536
Cirelli, Hambye, Panci, Sala & Taoso, arXiv:1507.05519

H.E.S.S. LIMITS vs CTA FORECAST



CTA can test a thermal scalar 7-plet

(rem: it's a ~ 200 million € project)

$M_7 \sim 25$ TeV

Garcia-Cely, Ibarra, Lamperstorfer & MT, arXiv:1507.05536

CONCLUSIONS

Spectral features smoking gun signatures for WIMPs

Expect faint signals...

But there are remarkable, yet simple, exceptions!

I discussed 3 scenarios based on scalar WIMPs

Scalar Weakly Interacting Massive Particle

SWIMP

SWIMP the Simple

SWIMP

To stay true and loyal to once's friends even though times might be rough

urban DICTIONARY

Backup slides

WHY A SCALAR WIMP?

Possible relation to Higgs sector

The Higgs Portal

See Gavela's talk

$$\mathcal{L}_{\rm SM} \supset -\frac{\mu^2}{2}|H|^2 \quad \rightarrow \quad \mathcal{L} \supset -\lambda_{hs}|S|^2|H|^2$$

Dim 2

$$\sim -\lambda_{\rm hs}\frac{v^2}{2}|S|^2$$

weak scale mass?

Patt & Wilczek (2006) "The Higgs portal"
Hempfling (1996)
Espinosa & Quiros (2007)
Hambye & MT (2007)
....

See also Lindner's talk

WHY A SCALAR WIMP?

Minimality I .0 DM as SM scalar singlet

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{m_S^2}{2} S^2 - \frac{\lambda_S}{4} S^4 - \frac{\lambda_{hs}}{2} S^2 |H|^2$$

$$S \xrightarrow{Z_2} -S$$

$$H \xrightarrow{Z_2} H$$

Zee & Silveira (1985) “Phantom matter”
Veltman & Yindurain (1989)
Mc Donald (1994)
Burgess, Pospelov & ter Veldhuis (2001)
...

Remark: Z_2 may be a remnant of a gauge symmetry e.g. Matter Parity in SO(10)

Krauss & Wilczek (1986)
Kadastik, Kannike & Raidal, arXiv:0902.2475
...

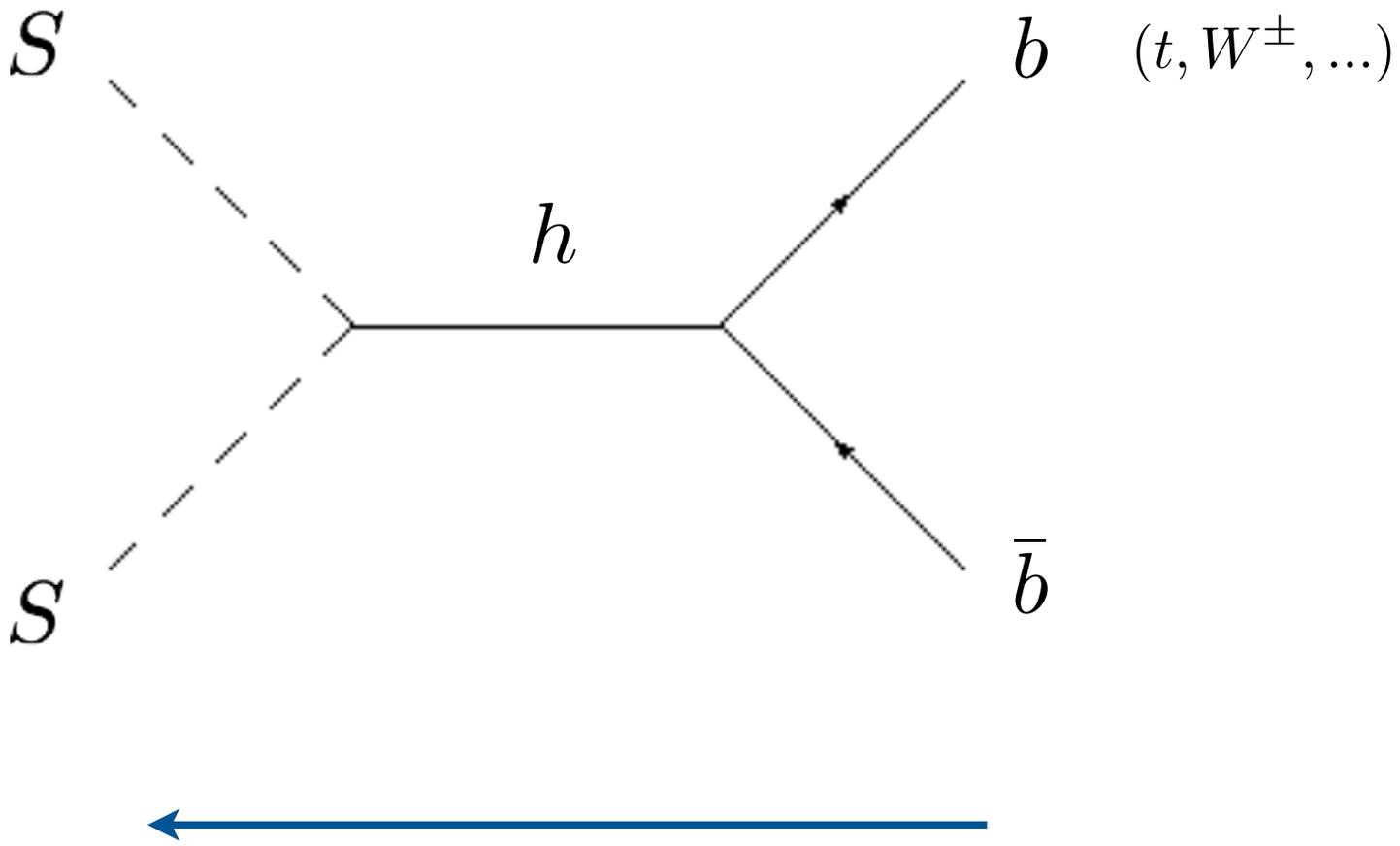
CAVEAT

$\langle S \rangle = 0$ (unbroken Z_2 symmetry)

Scalar DM at the EW scale (hierarchy problem)

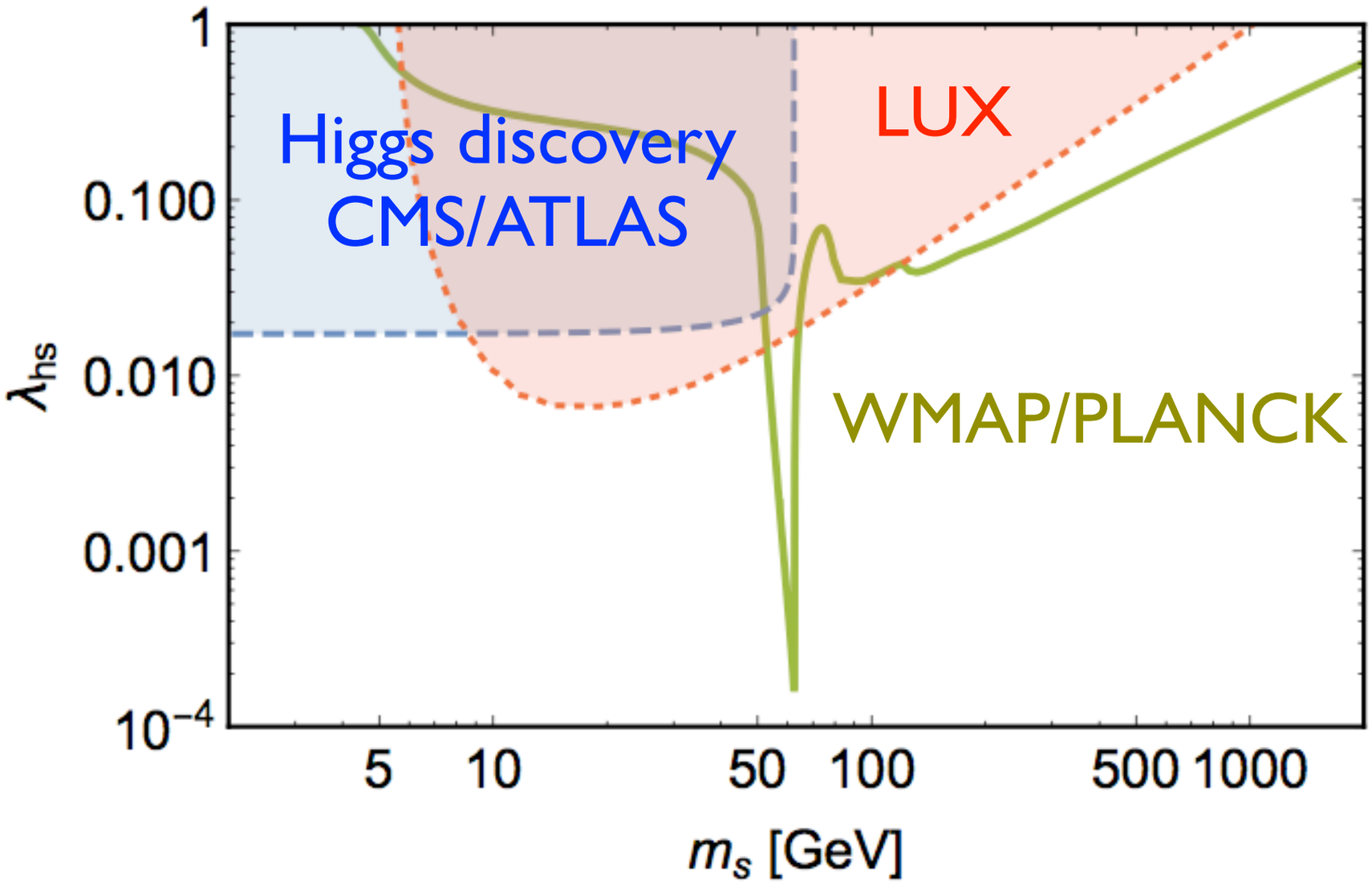
indirect detection

direct detection



dark matter production at colliders

Very simple and (by now) very constrained model



Plot from F. Kahlhoefer & McDonald, arXiv:1507.03600

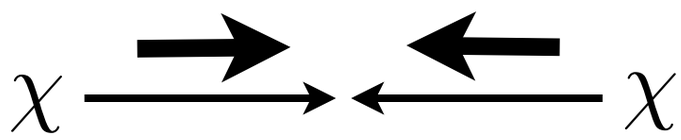
1st: MAJORANA

1. S-WAVE ANNIHILATION IS MASS SUPPRESSED

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

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

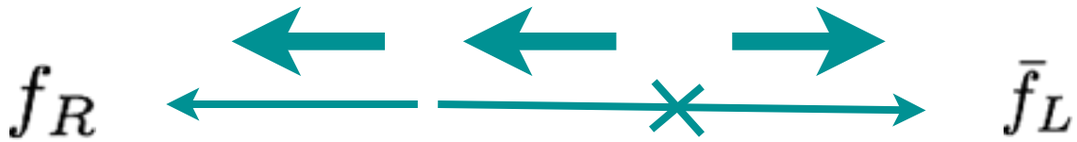
S-WAVE INITIAL STATE



$$^{2S+1}L_J(J^{PC}) = {}^1S_0(0^{-+})$$

$$|S=0\rangle = \frac{1}{2}\left(|\downarrow\rangle|\uparrow\rangle - |\uparrow\rangle|\downarrow\rangle\right)$$

FINAL STATE



$$\bar{\psi}_f \gamma_5 \psi_f$$

$$\mathcal{O}_{\mathrm{s-wave}} = m_f \bar{\chi}\gamma_5\chi\, \bar{\psi}_f\gamma_5\psi_f$$

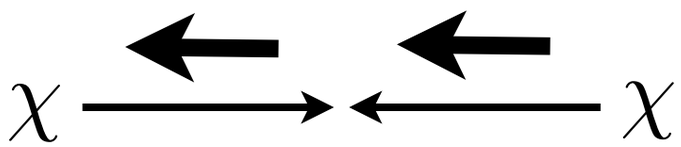
1st: MAJORANA

II. P-WAVE IN CHIRAL LIMIT

$$\sigma v(\chi\chi \to l\bar{l}) = \frac{g_l^4}{48\pi}\frac{v^2}{m_\chi^2}\frac{1+r^4}{(1+r^2)^4}$$

$$r = \frac{m_{\tilde{l}}}{m_\chi} \geq 1$$

P-WAVE INITIAL STATE



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

FINAL STATE

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

$$\mathcal{O} = \bar{\chi}\gamma^\mu\gamma_5\chi\bar{\psi}_f\gamma_\mu\gamma_5\psi_f$$

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

2nd: REAL SCALAR

D-WAVE IN CHIRAL LIMIT

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

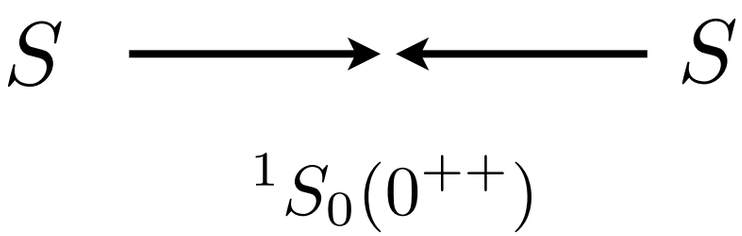
$$r = \frac{m_\psi}{m_S} \geq 1$$

Rem: I don't know of any other instance

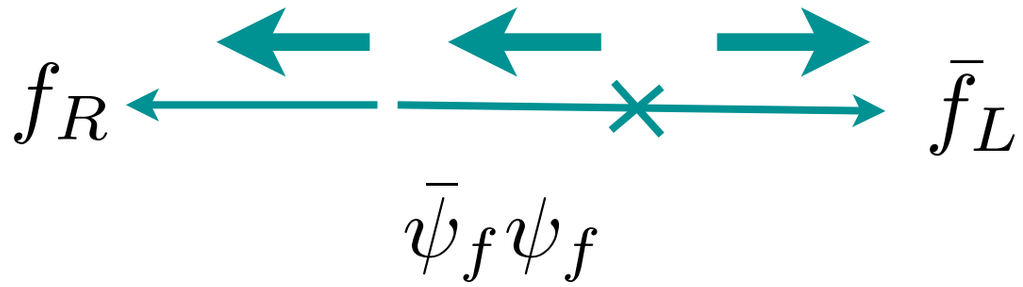
Takashi Toma
arXiv:1307.6181
Giacchino, Lopez Honorez & M.T. arXiv:1307.6480

WHY D-WAVE SUPPRESION?

S-WAVE INITIAL STATE



FINAL STATE

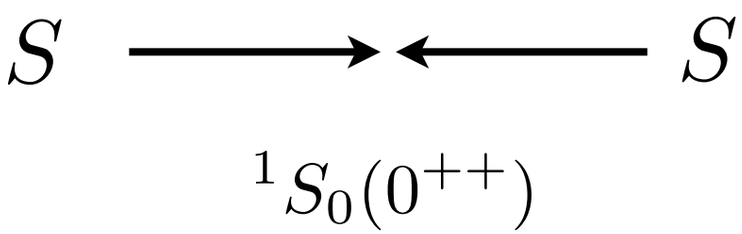


chirally suppressed

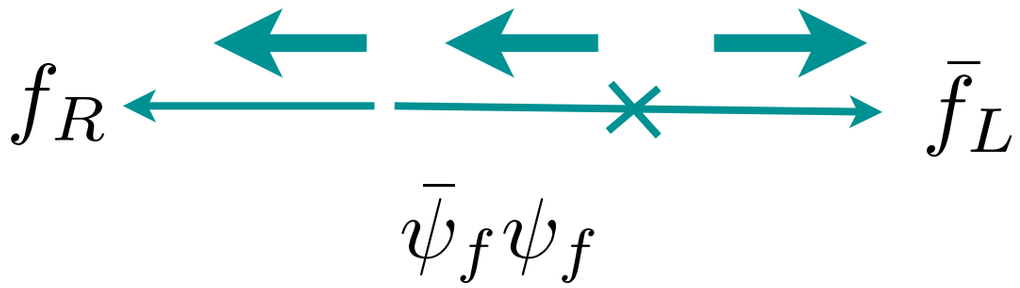
$$\mathcal{O}_S = m_f \, S^2 \, \bar{\psi}_f \psi_f$$

WHY D-WAVE SUPPRESSION?

S-WAVE INITIAL STATE



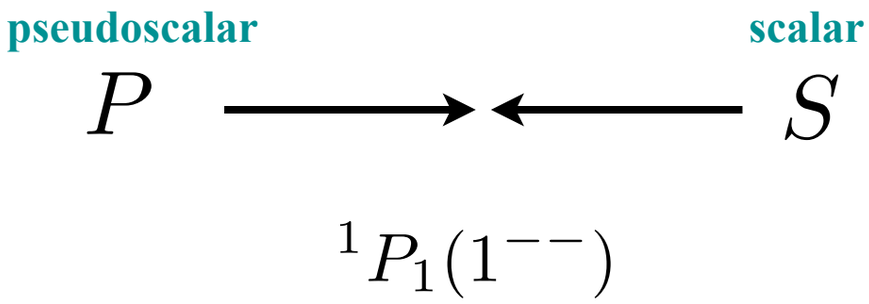
FINAL STATE



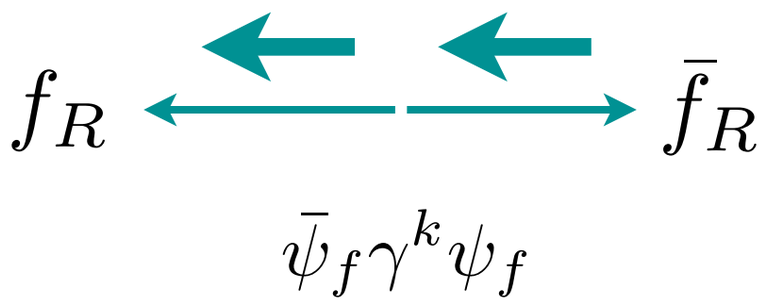
chirally suppressed

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

P-WAVE INITIAL STATE



FINAL STATE

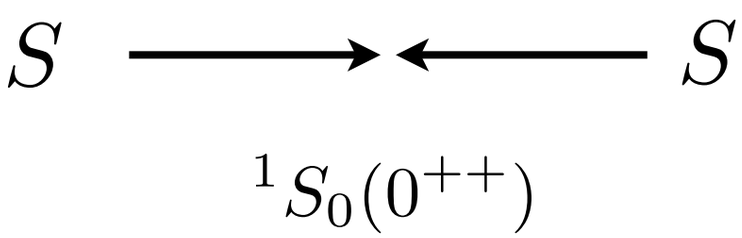


a complex scalar could
have p-wave annihilation

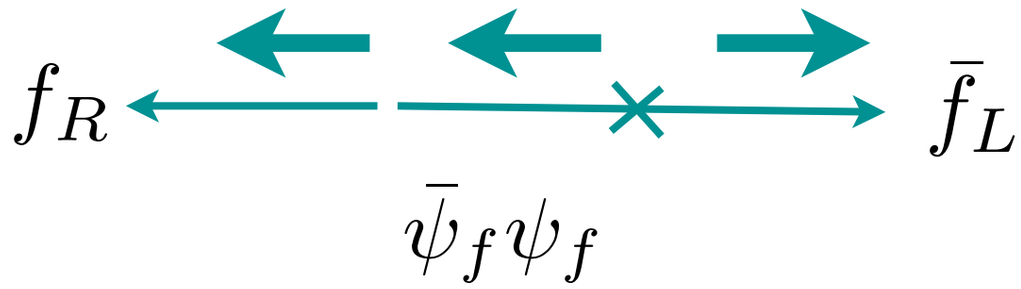
$$\mathcal{O} = P \overleftrightarrow{\partial_\mu} S \; \bar{\psi}_f \gamma^\mu \psi_f$$

WHY D-WAVE SUPPRESION?

S-WAVE INITIAL STATE



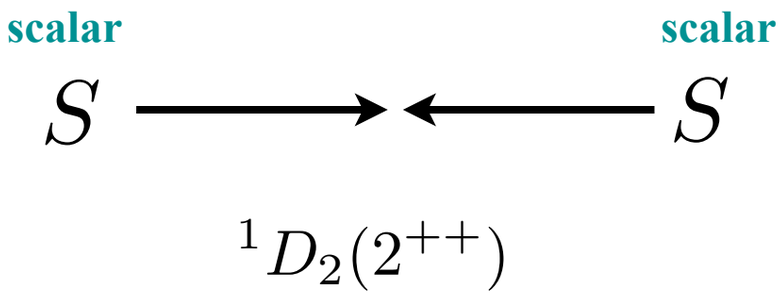
FINAL STATE



chirally suppressed

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

D-WAVE INITIAL STATE



FINAL STATE

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

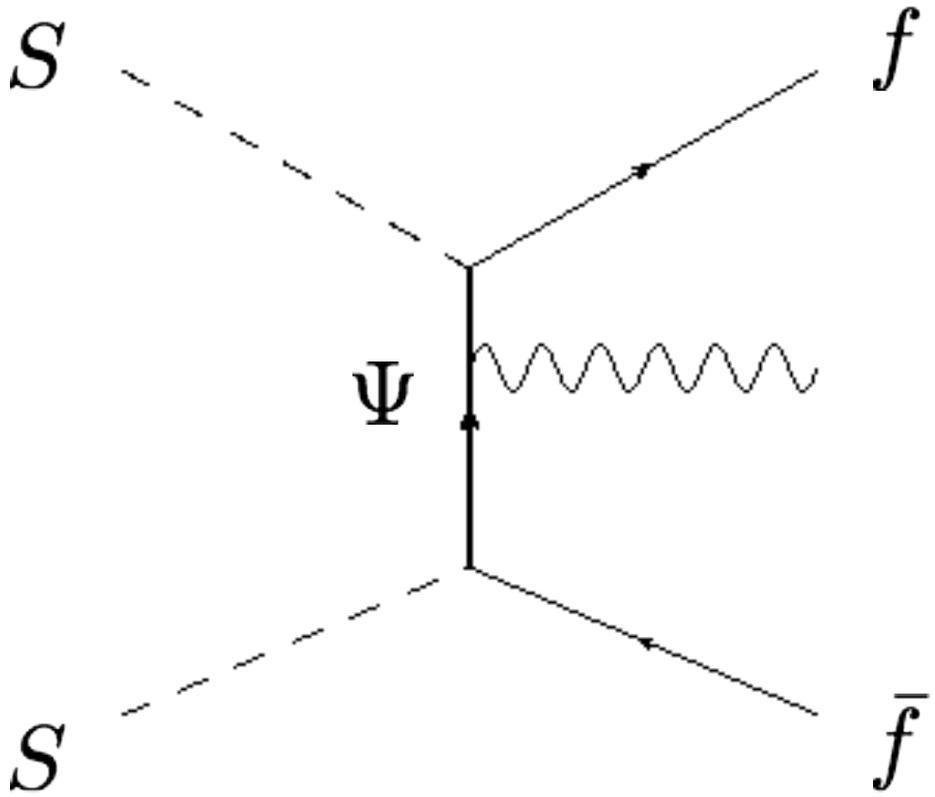
d-wave
in chiral limit

$$\mathcal{O}_T = \partial_\mu S \partial_\nu S \, \Theta^{\mu\nu}_{f_R}$$

FERMION
STRESS-ENERGY TENSOR

WHY VIRTUAL INTERNAL BREMSSTRAHLUNG?

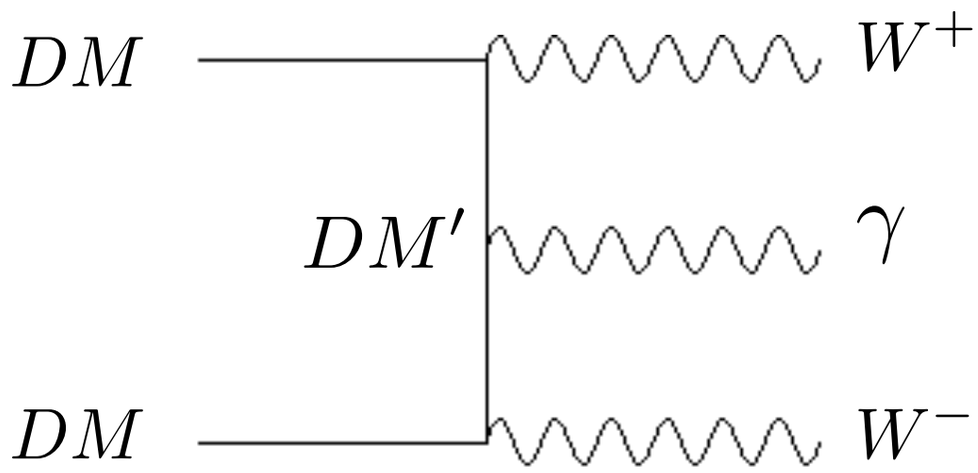
non-relativistic



$$\mathcal{M} \propto ((p_S - p_f)^2 - M_\Psi^2)^{-1} \sim (M_S^2 - 2E_f M_S - M_\Psi^2)^{-1}$$

if $M_S \sim M_\Psi$ peaks for $E_f \sim 0$

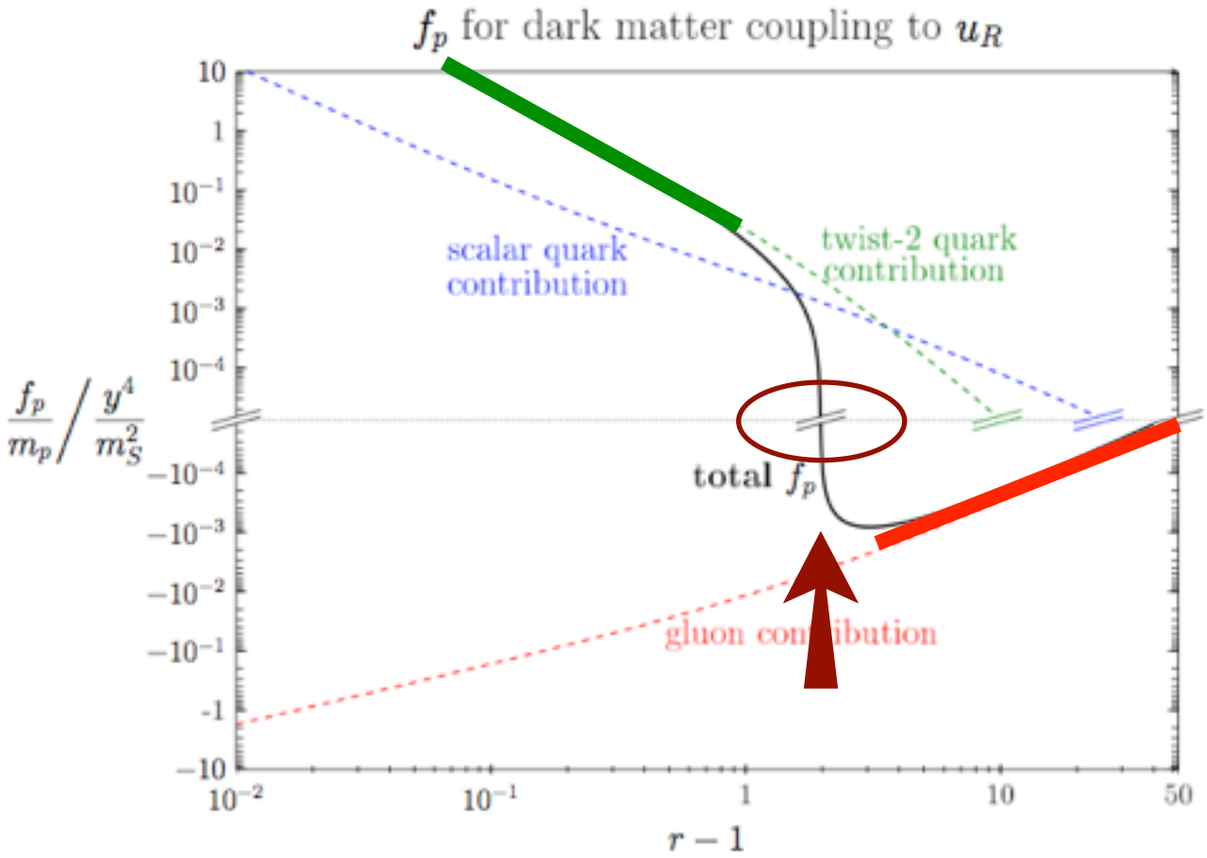
VIB = VIRTUAL INTERNAL BREMSSTRAHLUNG

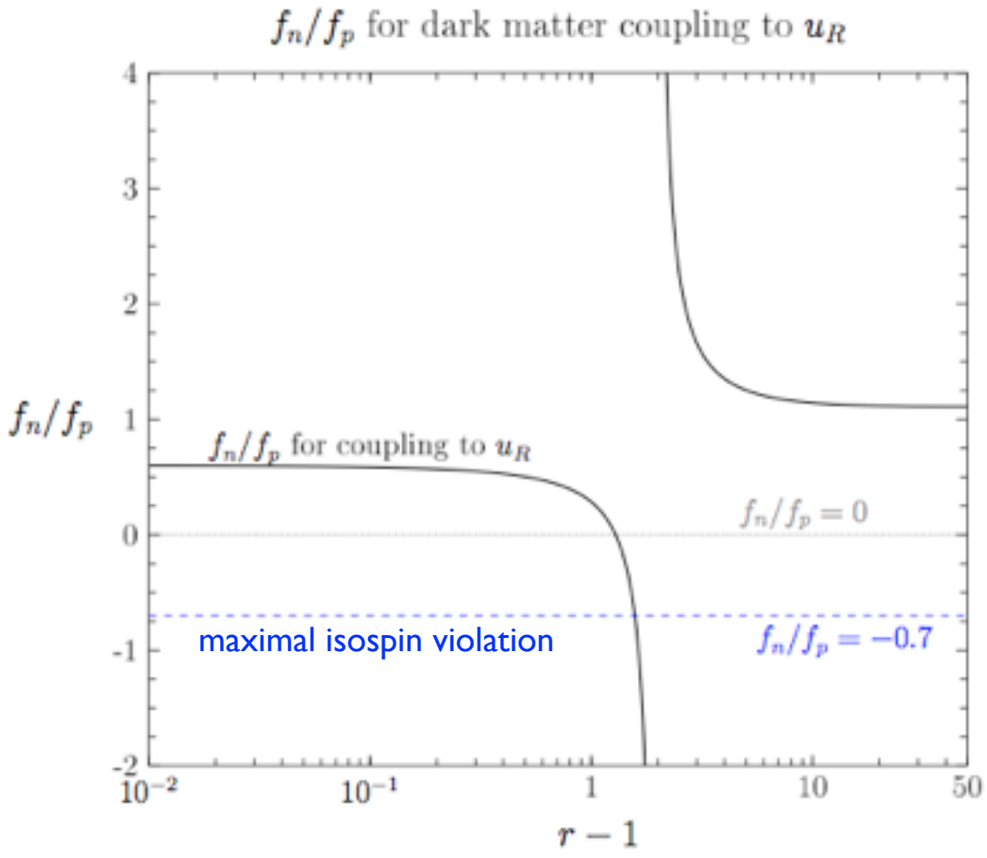


$$\mathcal{M} \propto \frac{1}{(p_{\rm DM} - p_W)^2 - M^2_{\rm DM'}} \sim \frac{1}{M^2_{DM} - 2E_W M_{\rm DM} - M^2_{DM'}} \sim \frac{1}{E_W}$$

Effectively $\sigma_{W^+W^-\gamma} \sim \sigma_{W^\pm\gamma}$

DIRECT DETECTION
isospin violation effects





destructive interference

$$\frac{f_N}{m_N} = C_S^q f_{T_q}^{(N)} + \frac{3}{4} C_T^q m_S^2 (q^{(N)}(2) + \bar{q}^{(N)}(2)) - \frac{8}{9} C_S^g f_{T_G}^{(N)}$$

twist-2 gluons

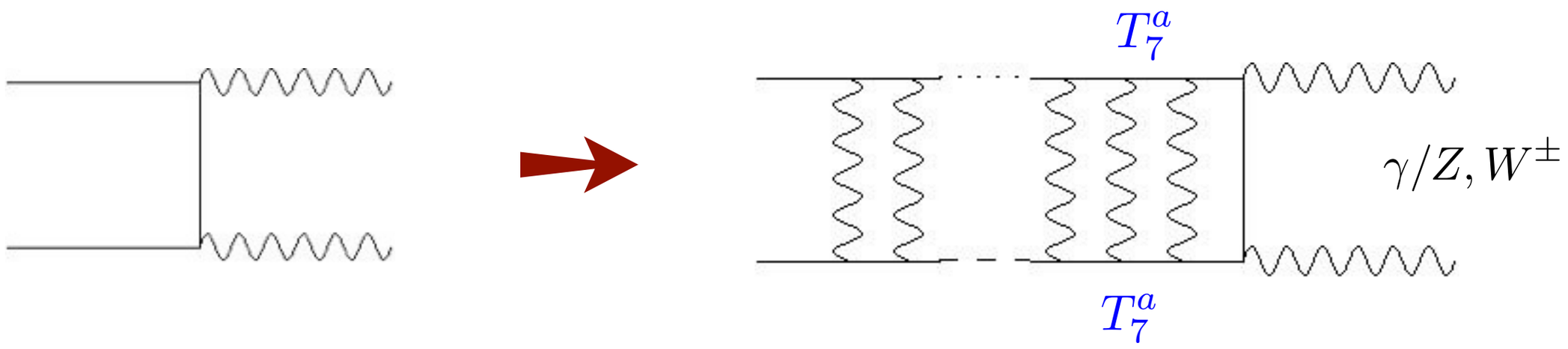
II. MDM SCALAR 7-PLET

a benchmark for multi-TeV dark matter

$$M_7 \sim 25 \text{ TeV}$$ Cirelli, Strumia & Tamburini (2007)

1. Many co-annihilation channels.

2. Sommerfeld effects $M_7 \gg M_{W/Z}$

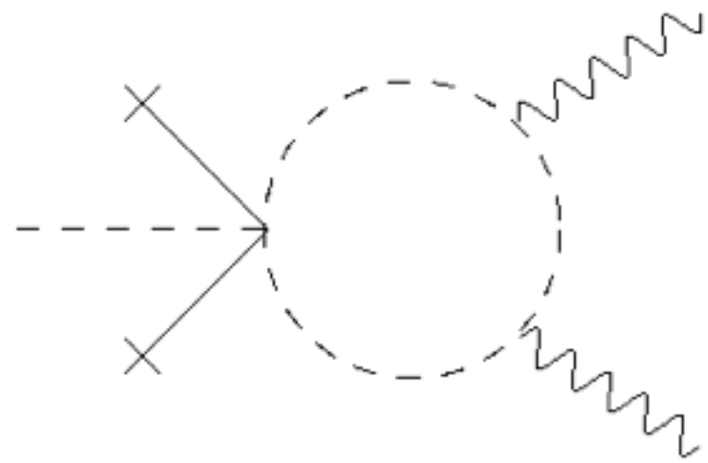


$$7 \otimes 7 = \ldots \oplus 5_s \oplus \cancel{3}_A \oplus 1_s$$

$$V_{5/1}(r) \approx \frac{g_2^2}{r} T_7^a \otimes T_7^a|_{5/1} = \frac{g_2^2}{2r}\left(T_{5/1}^2 - 2\,T_7^2\right) = \begin{cases} V_5(r) = -\frac{9g_2^2}{r} \\ V_1(r) = -\frac{12g_2^2}{r} \end{cases}$$

II. MDM SCALAR 7-PLET

$$7 \otimes 7 \otimes 7 = \ldots \oplus 3_S \oplus \ldots\ldots \quad \rightarrow \quad \mathcal{O}_5 = \frac{1}{\Lambda}(\chi_7^3)^a(\tilde{H}^\dagger \tau^a H)$$

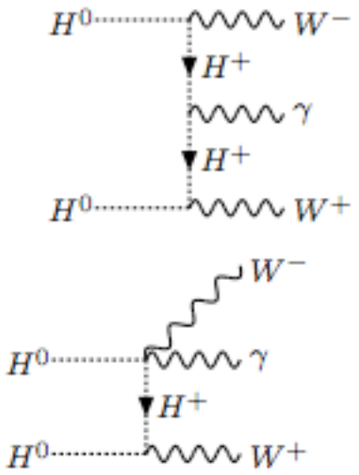


$$\Lambda \sim 10^{15}\mathrm{GeV}$$
$$M_\chi \sim \mathrm{TeV}$$

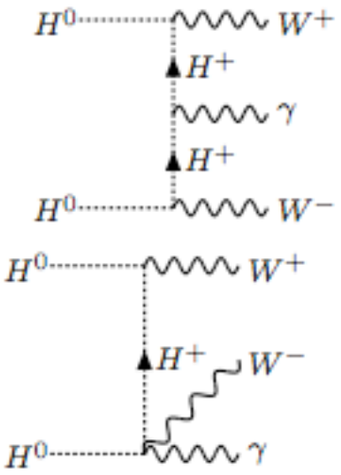
$$\rightarrow \quad \tau_\chi \sim 10^{-8}\mathrm{s}$$

$$\chi \longrightarrow -\chi$$
$$Z_2$$

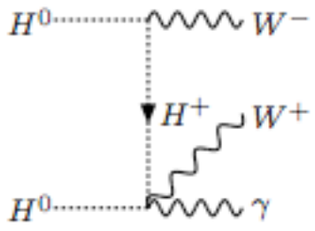
Di Luzio, R. Grober, J. F. Kamenik, and M. Nardecchia
arXiv:1504.00359

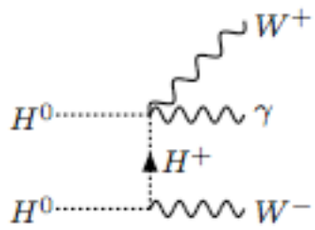

H^0
W^-
H^+
γ
H^+
H^0
W^+

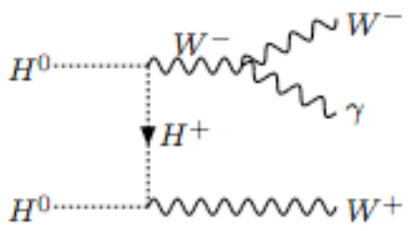
W^-
H^0
γ
H^+
H^0
W^+

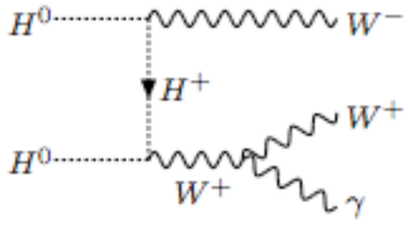

H^0
W^+
H^+
γ
H^+
H^0
W^-

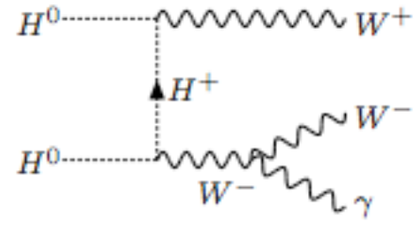
H^0
W^+
H^+
W^-
H^0
γ

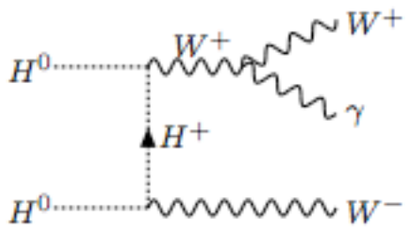

H^0
W^-
H^+
W^+
H^0
γ

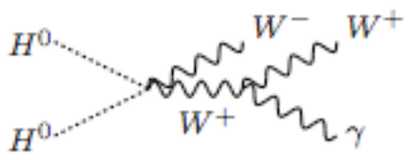

W^+
H^0
γ
H^+
H^0
W^-

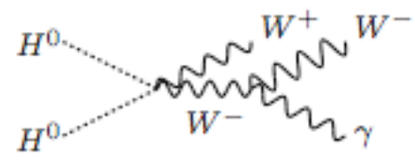

W^-
W^-
H^0
γ
H^+
H^0
W^+

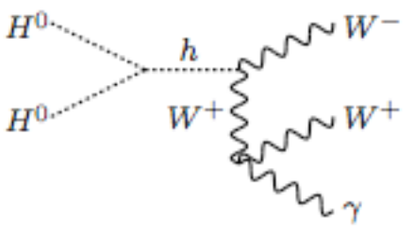

H^0
W^-
H^+
W^+
H^0
W^+
γ

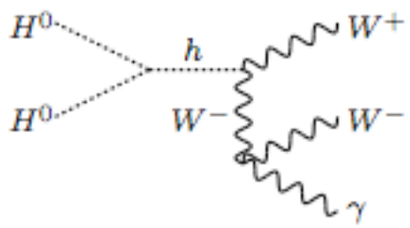

H^0
W^+
H^+
W^-
H^0
W^-
γ


W^+
W^+
H^0
γ
H^+
H^0
W^-


H^0
W^-
W^+
H^0
W^+
γ


H^0
W^+
W^-
H^0
W^-
γ


H^0
h
W^-
H^0
W^+
W^+
γ


H^0
h
W^+
H^0
W^-
W^-
γ