SCALAR(WIMP)S 2015

with a focus on gamma-ray signatures

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Belgium

SCALARS 2015
Warsaw, Poland, 03-07 December 2015

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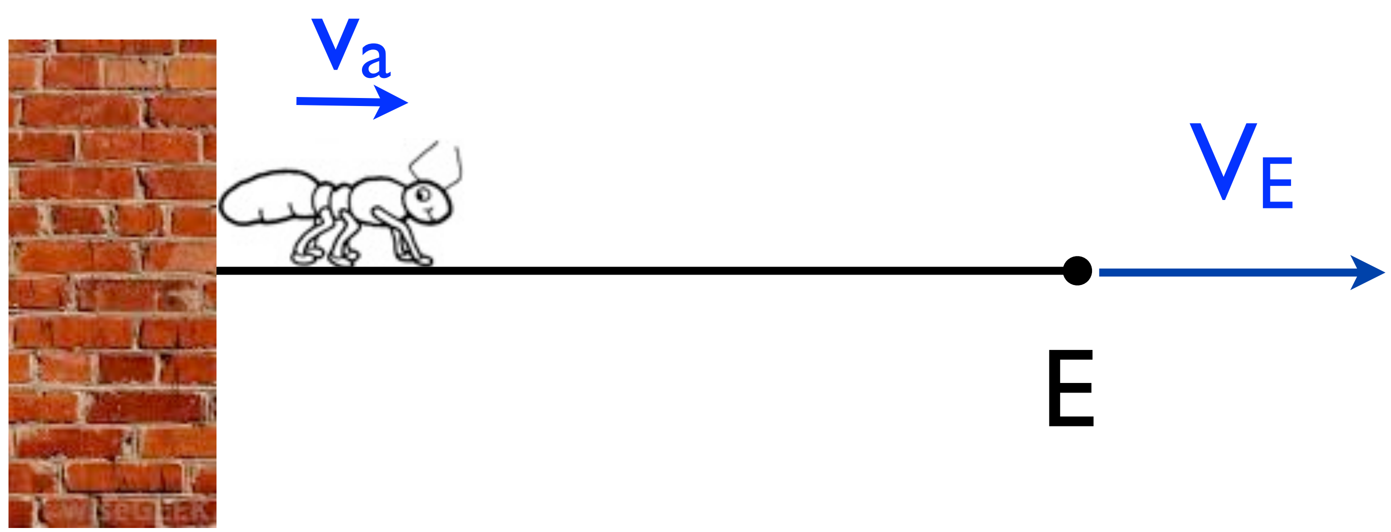
DARK ENERGY
DARK MATTER
BARYONS

About Lev Okun



Q1. Can the ant reach the end E of the string if $V_E > v_a$?

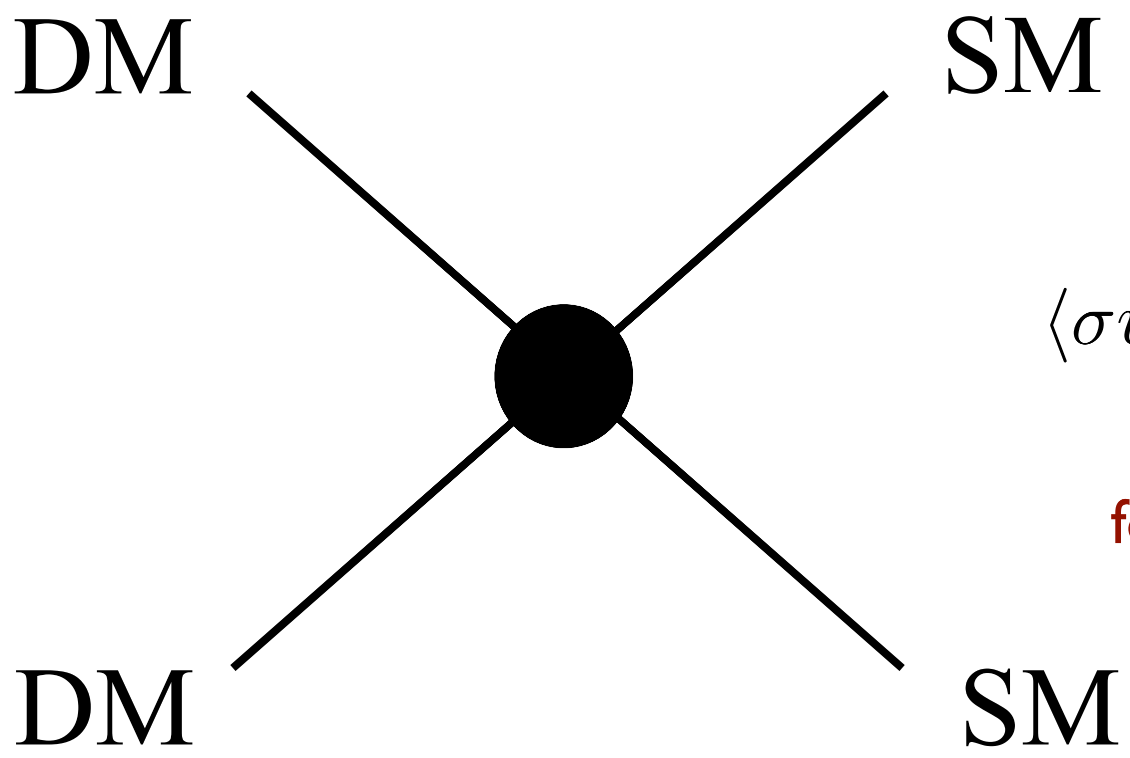
$V_E = const$

Q2. If so, how long would it take ?

Q3. What if $dV_E/dt > 0$?

Hint: the story goes, according to Lev Okun, that A. Sakharov gave the answer(s) in one second

DM AS A WIMP
(weakly interacting massive particle)



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

Benchmark value
for DM indirect detection

freeze-out in early universe

WHY WIMP MODELS?

Why not? We don't know what DM is made of

2 canonical DM candidates

The neutralino

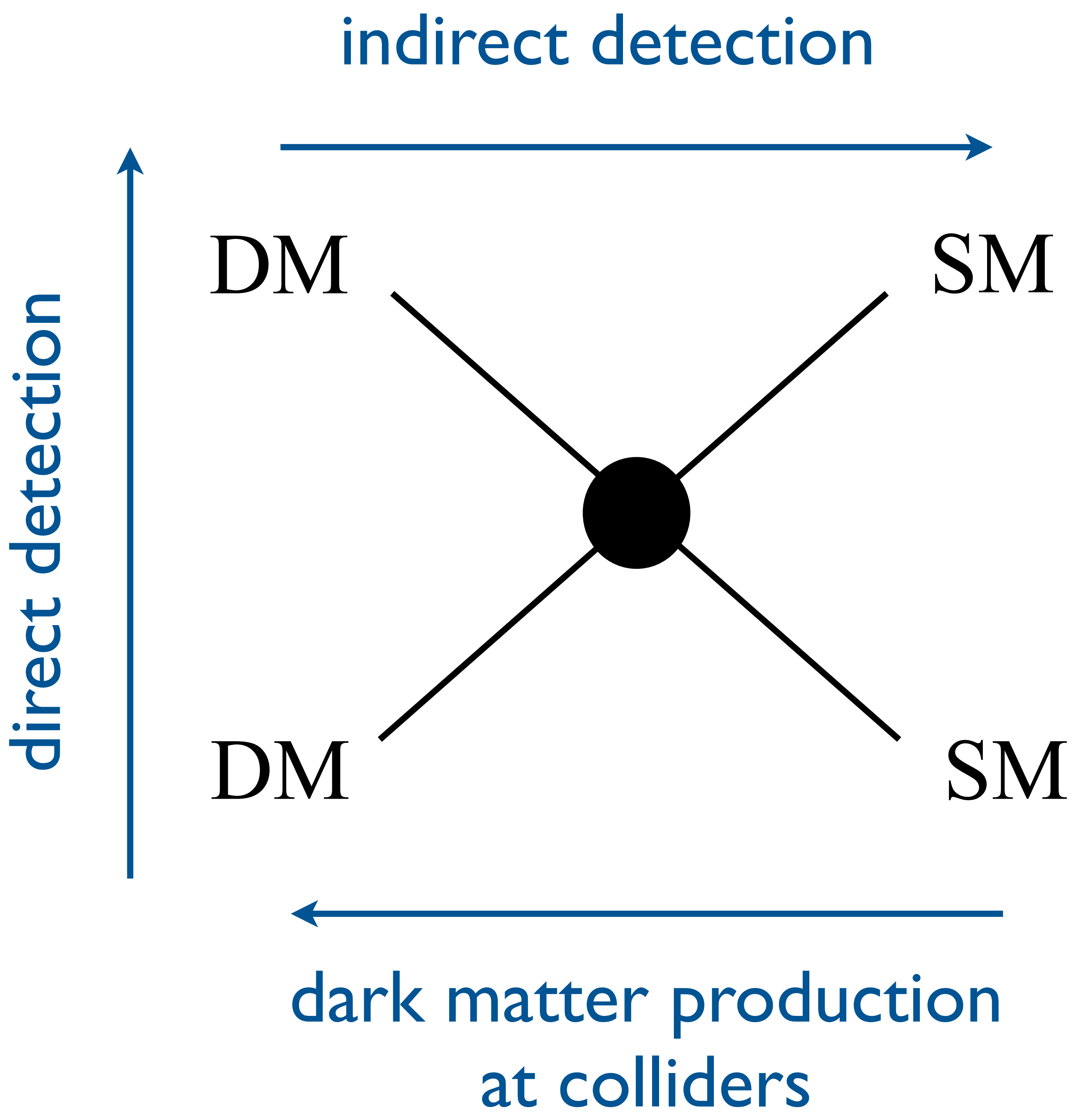
SUSY may not exist

The strong CP axion

Not a WIMP

May be subdominant DM

WHY WIMP MODELS?



WHY A SCALAR WIMP?

Possible relation to Higgs sector

$$\mathcal{L}_{\rm SM} \supset -\frac{\mu^2}{2}|H|^2$$

Dim 2

The Higgs Portal

See Gavela's talk

$$\mathcal{L} \supset -\lambda_{hs}|S|^2|H|^2$$

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

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 1.0 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)
...

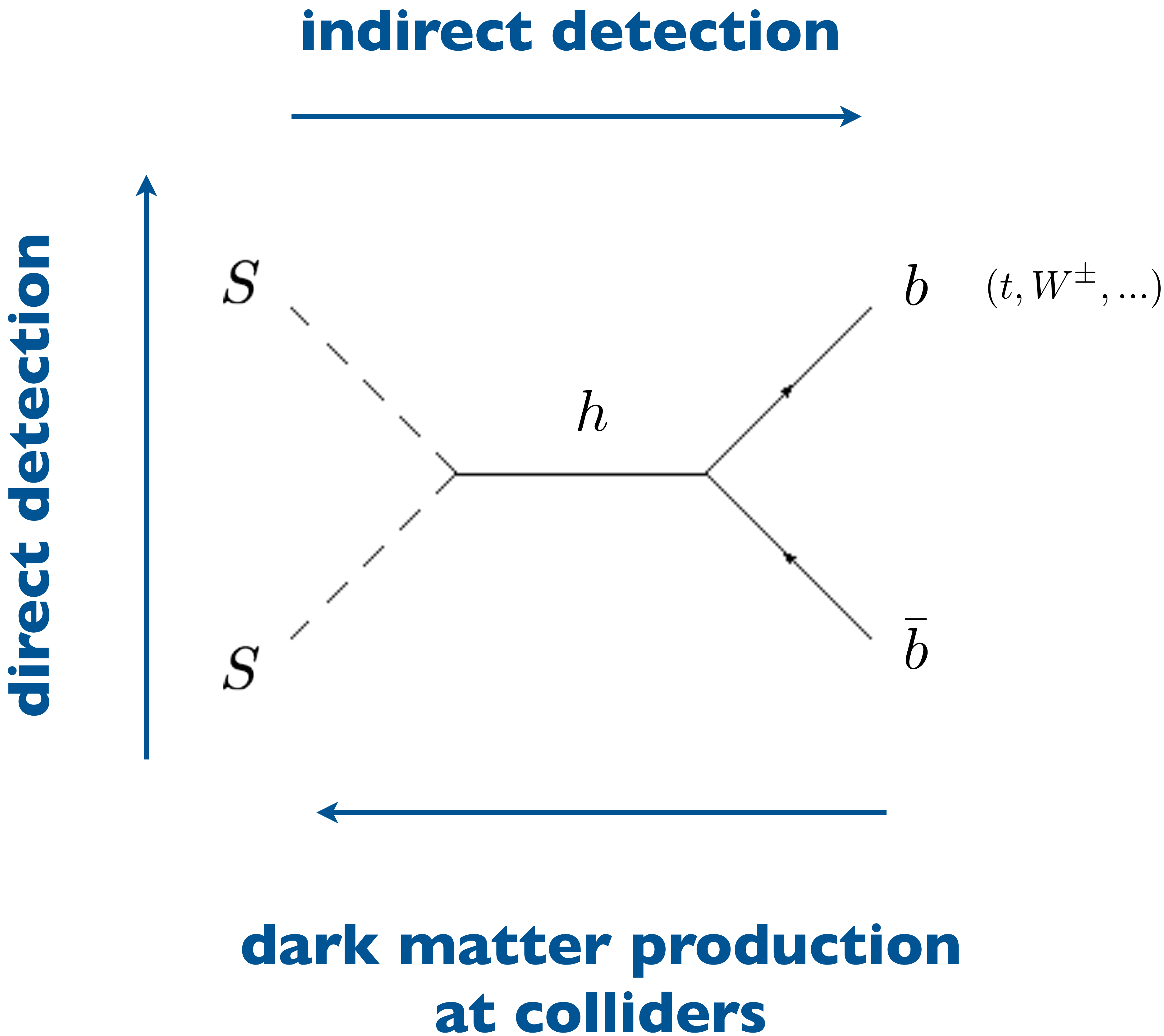
Remark: Z_2 may be a remnant of a gauge symmetry e.g. Matter Parity in SO(10)

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

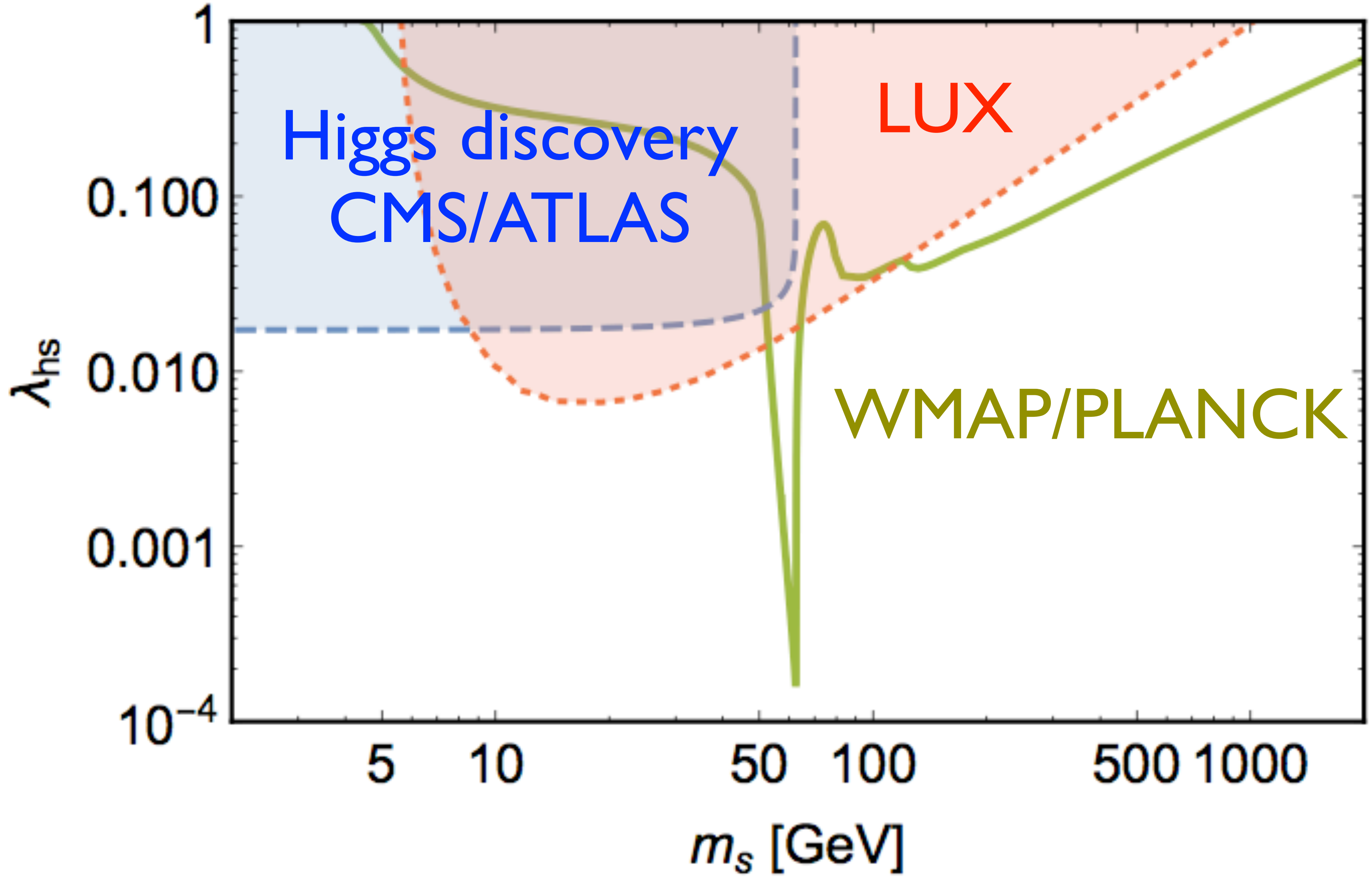
CAVEAT

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

Scalar DM at the EW scale (hierarchy problem)


indirect detection
direct detection
dark matter production
at colliders
S
S
h
b
$\bar{b}$
$(t, W^{\pm}, ...)$

Very simple and (by now) very constrained model



Plot from F. Kahlhoefer & McDonald, arXiv:1507.03600

WHY A SCALAR WIMP?

Minimality2.0

SU(2) multiplets

(aka Minimal Dark Matter)

Quantum numbers $SU(2)_L$	$U(1)_Y$	Spin	DM can 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	$(\chi\chi\chi H^\dagger H)$

Inert Doublet

~ Higgsino-like

~ Wino-like

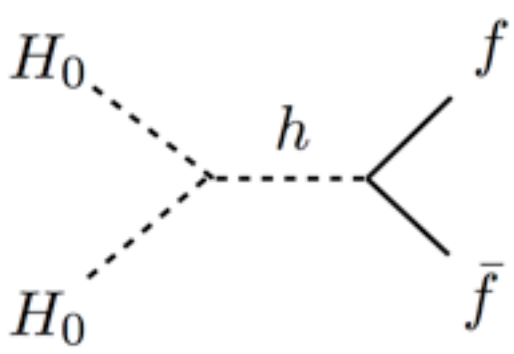
Fermionic 5-plet

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

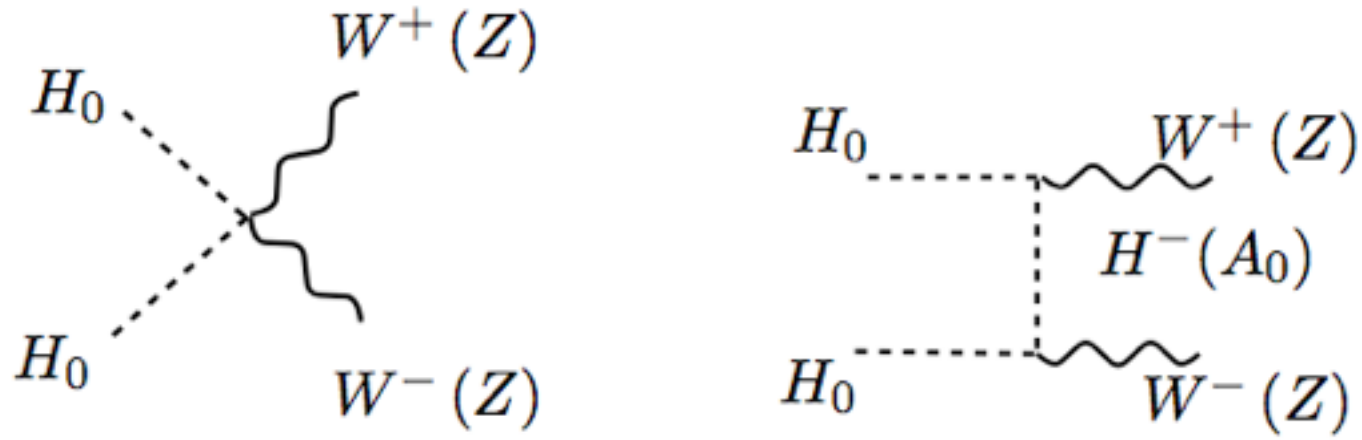
Scalar 7-plet

Cirelli, Fornengo & Strumia (2005) “Minimal Dark Matter”

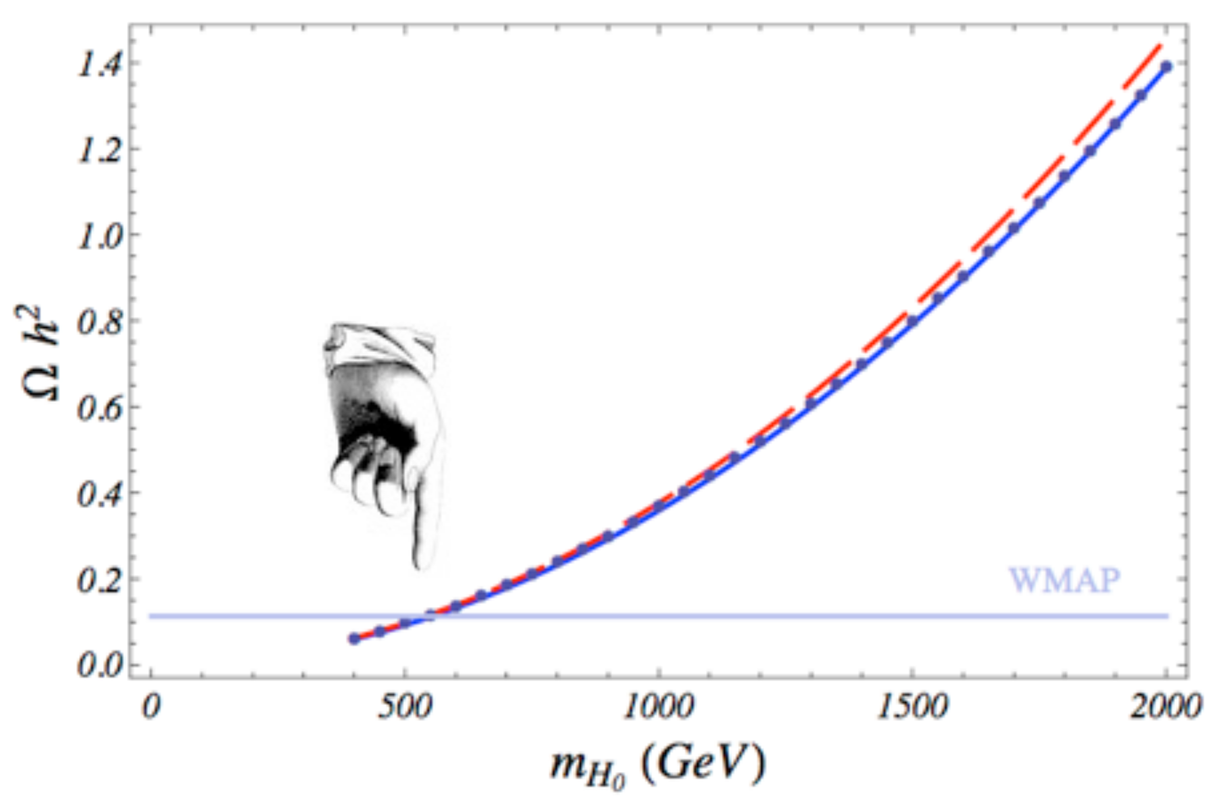
singlet



multiplet



Naturally Heavy ~ TeV WIMPs



Plot from Hambye, Ling, Lopez Honorez & Rocher (2009)

WHY A SCALAR WIMP?

The Devil is in the details

I. VECTOR LIKE PORTAL

Based on:

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

II. MDM SCALAR 7-PLET

Based on:

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

I. VECTOR-LIKE PORTAL*

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

real singlet scalar

vector-like lepton (or quark)

SM light lepton (or quark)

Z2 symmetry

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

S is our dark matter

* We call it the Vector-like Portal 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

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

See also Laura Covi's talk for a variation on this model

Appears in top-down scenarios

eg 6D model with spinless KK photon ~ S

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

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Appears in top-down scenarios

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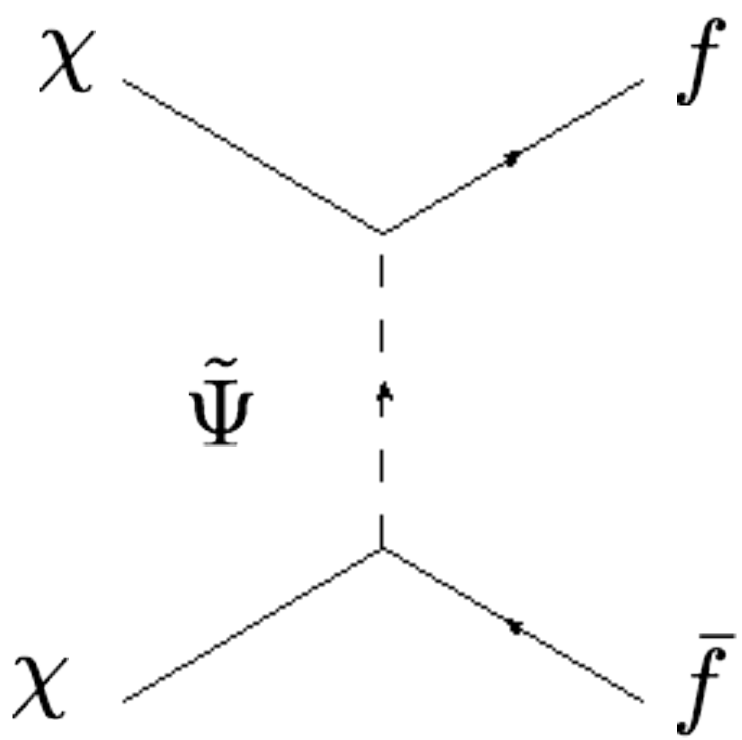
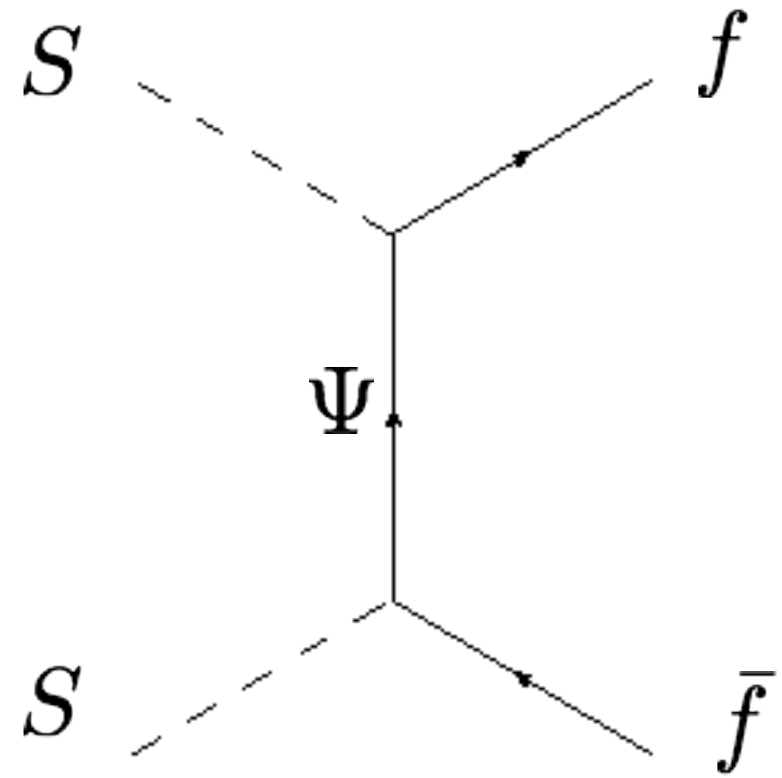
A benchmark dark matter model
with strong gamma ray spectral features

Majorana vs Real Scalar into light SM fermions



vs



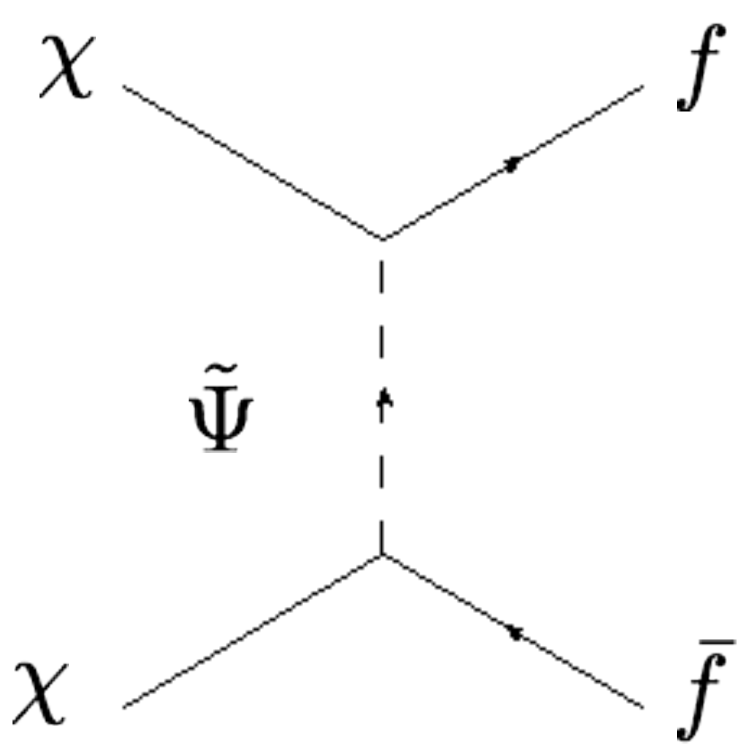
p-wave

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

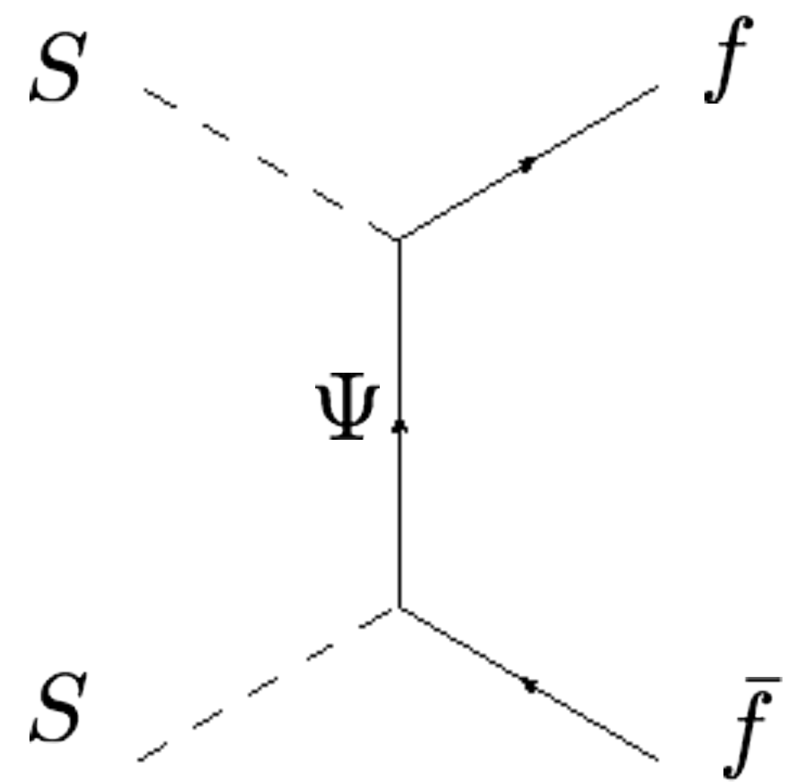
$$r = \frac{m_{\tilde{\Psi}}}{m_\chi} \geq 1$$

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

MAJORANA vs REAL SCALAR



vs



light SM fermions

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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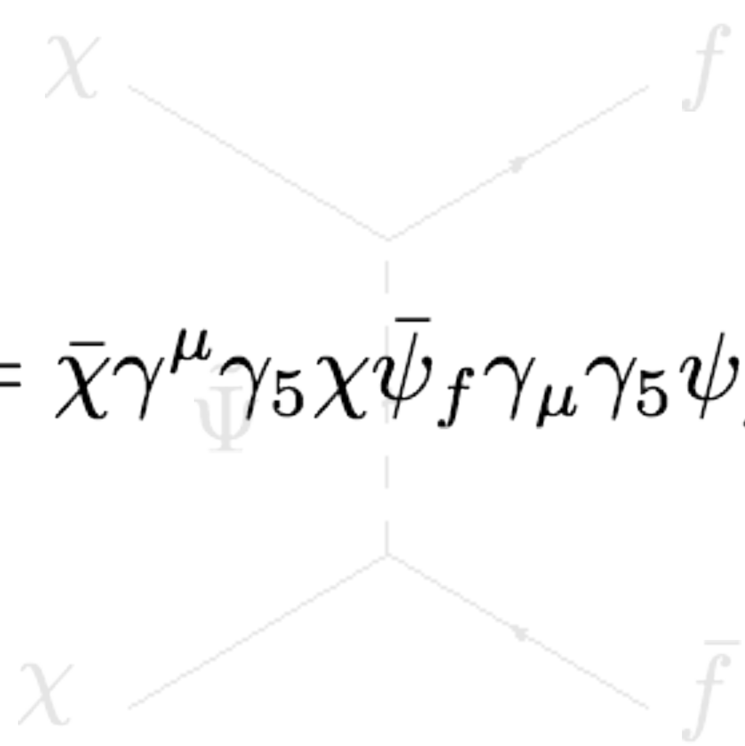
d-wave

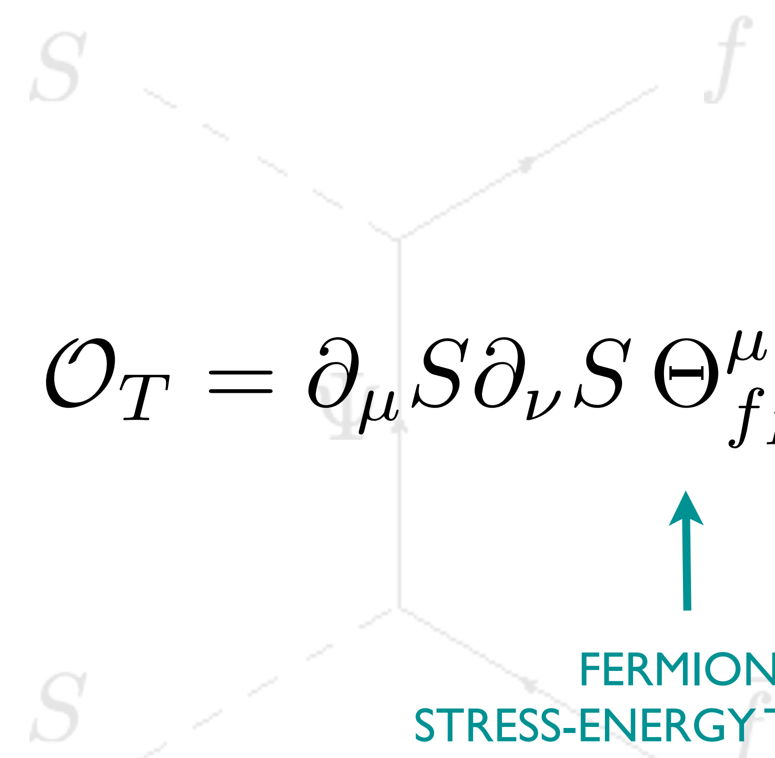
$$\sigma v(SS \to l\bar{l}) = \frac{y_l^4}{60\pi}\frac{v^4}{m_S^2}\frac{1}{(1+r^2)^4}$$

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

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

MAJORANA vs REAL SCALAR





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

vs

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

FERMION
STRESS-ENERGY TENSOR

p-wave

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

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

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

Consequences?

Consider first coupling to light leptons

It is simpler

It is relevant for indirect detection

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 ?

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

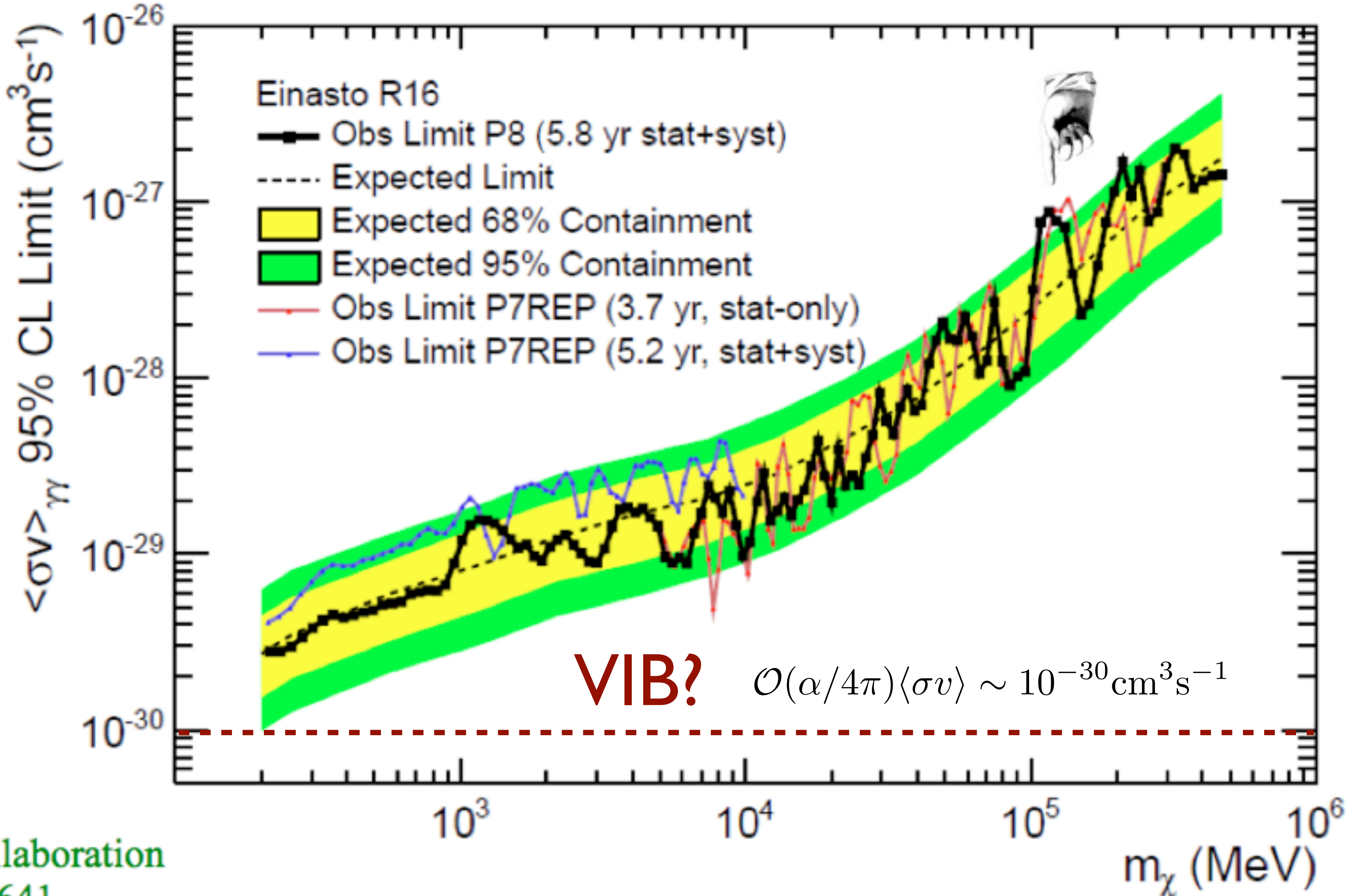
Digammas

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

Bremsstrahlung

both are s-wave (velocity independent) but expected to be small...

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



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

Fermi-LAT collaboration
arXiv:1503.02641

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

DM smoking gun signatures - digammas

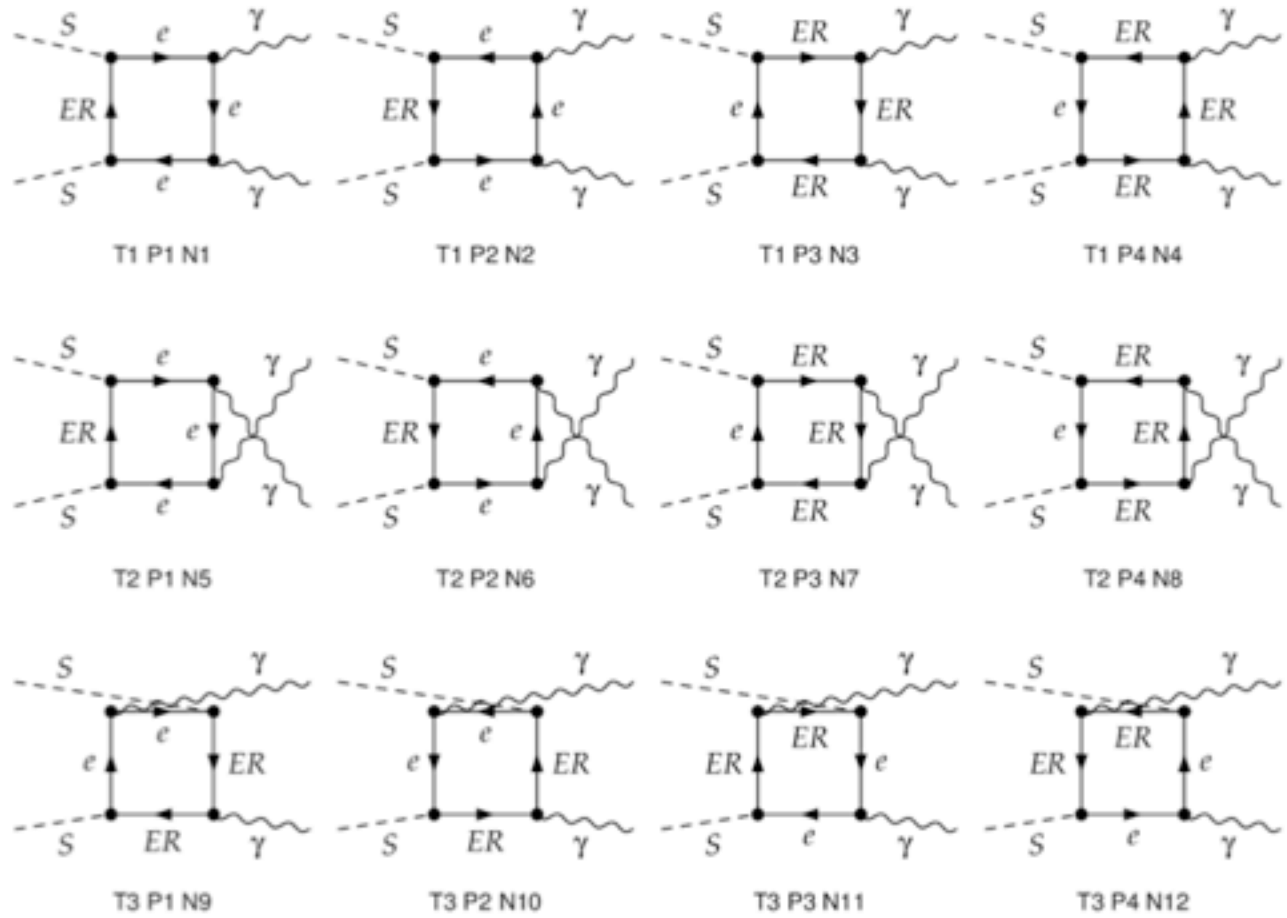
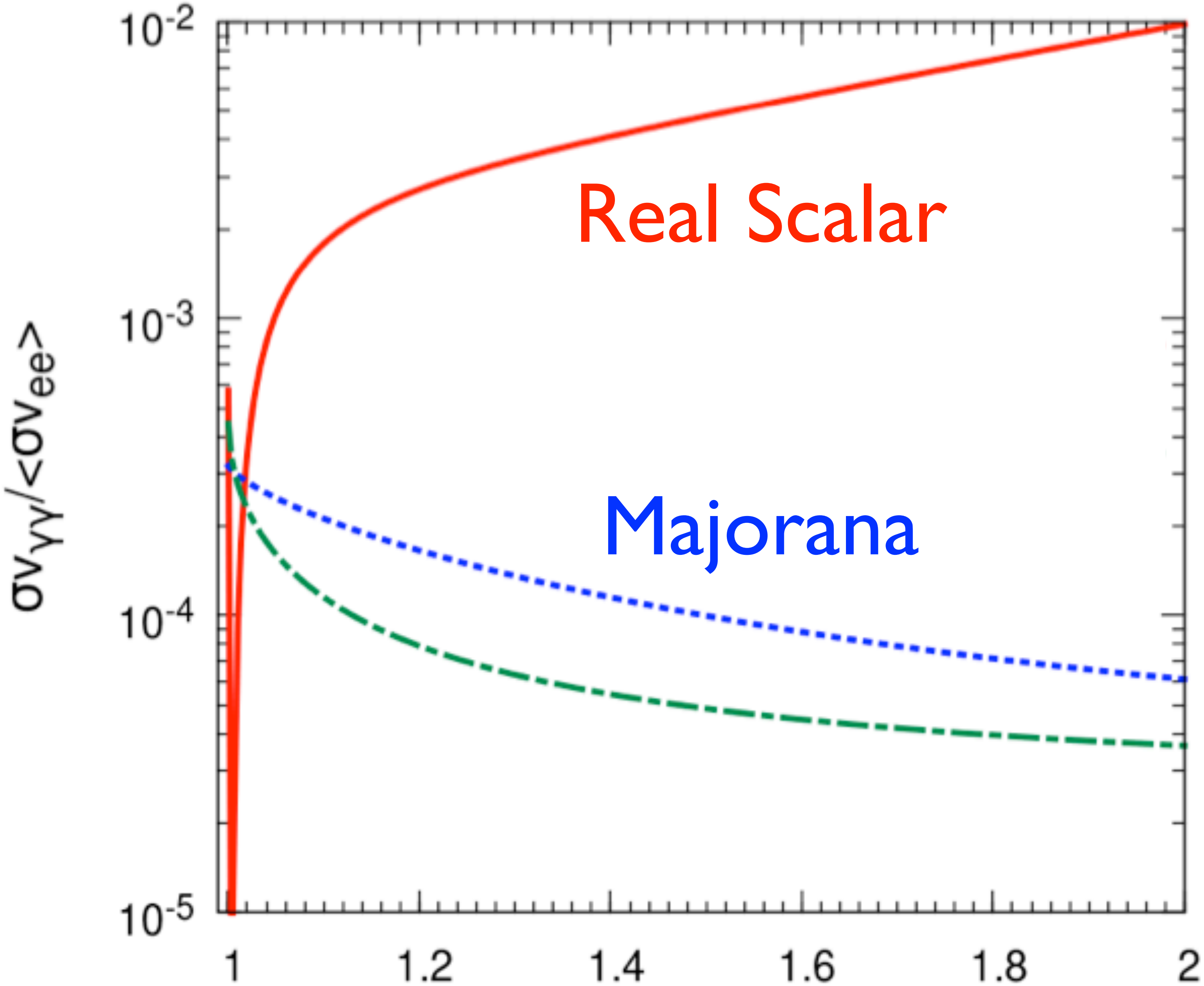


Figure 1: Box diagrams relevant for the $SS \to \gamma\gamma$ process

1. no astrophysical counterparts
2. $E_{\gamma} = M_{DM}$

DM smoking gun signatures - digammas



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

$\sim 10^{-28}\mathrm{cm}^3\mathrm{s}^{-1}$

O(100) larger than expected!

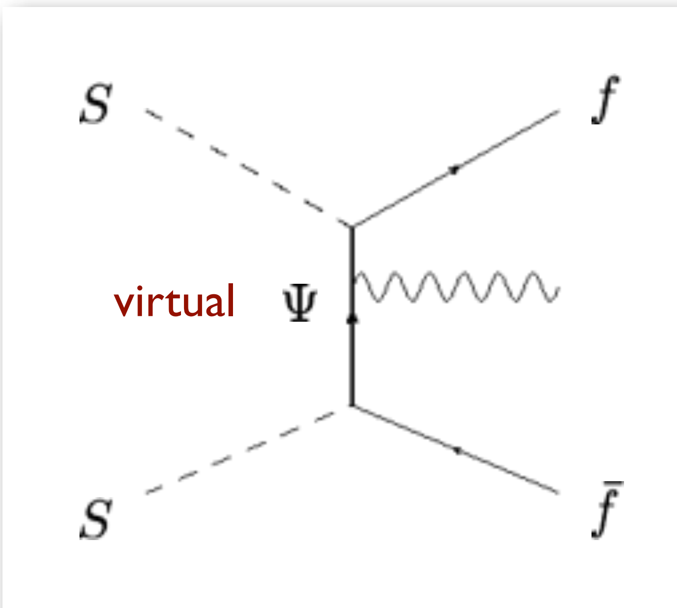
$\sim 10^{-31}\mathrm{cm}^3\mathrm{s}^{-1}$

$\mathcal{O}(\alpha^2/16\pi^2)\langle\sigma v\rangle$

Ibarra, Toma, Totzauer & Wild
arXiv:1405.6917
Giacchino, Lopez Honorez & MT
arXiv:1405.6921

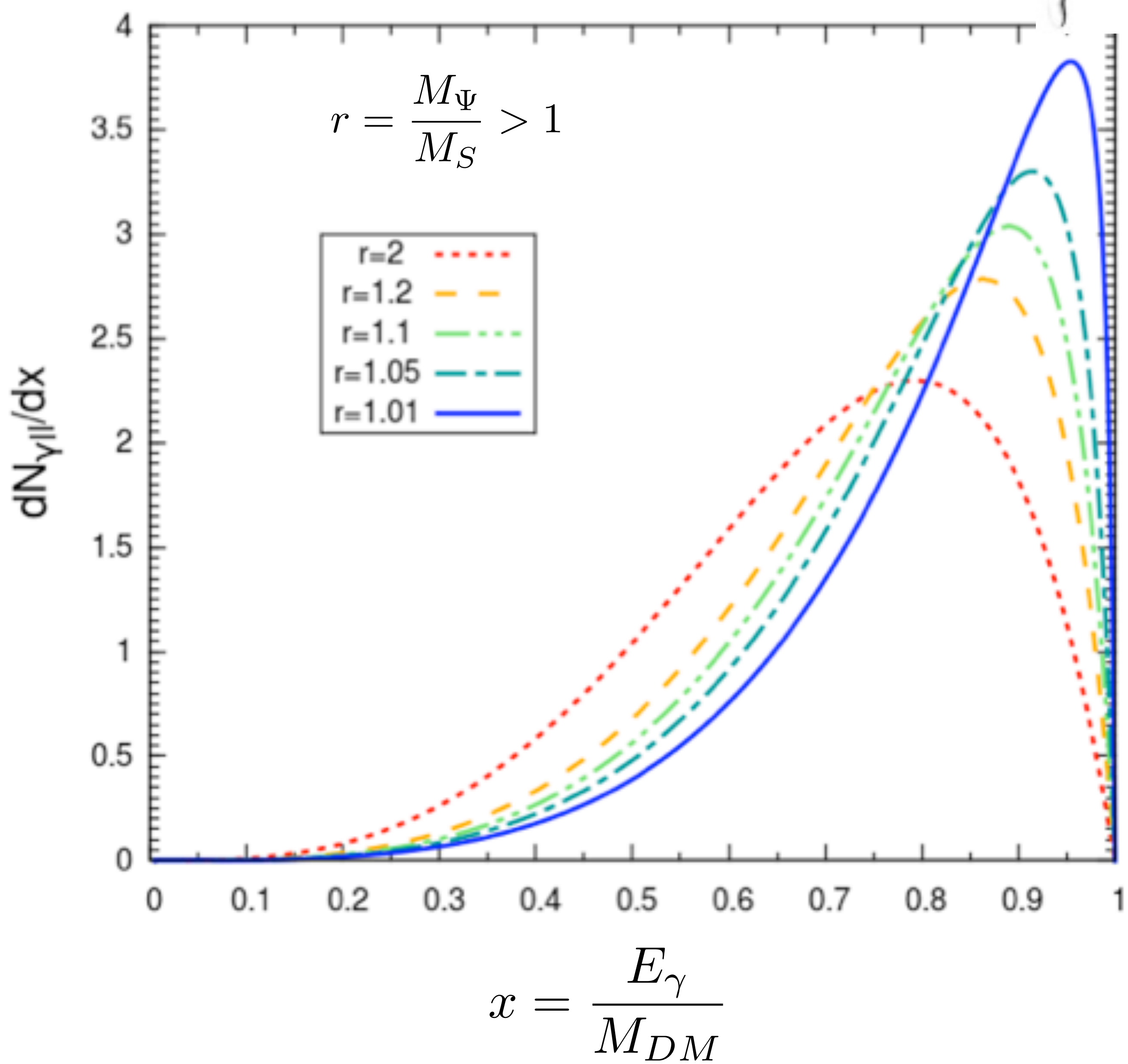
Smoking gun signatures - virtual internal Bremsstrahlung

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

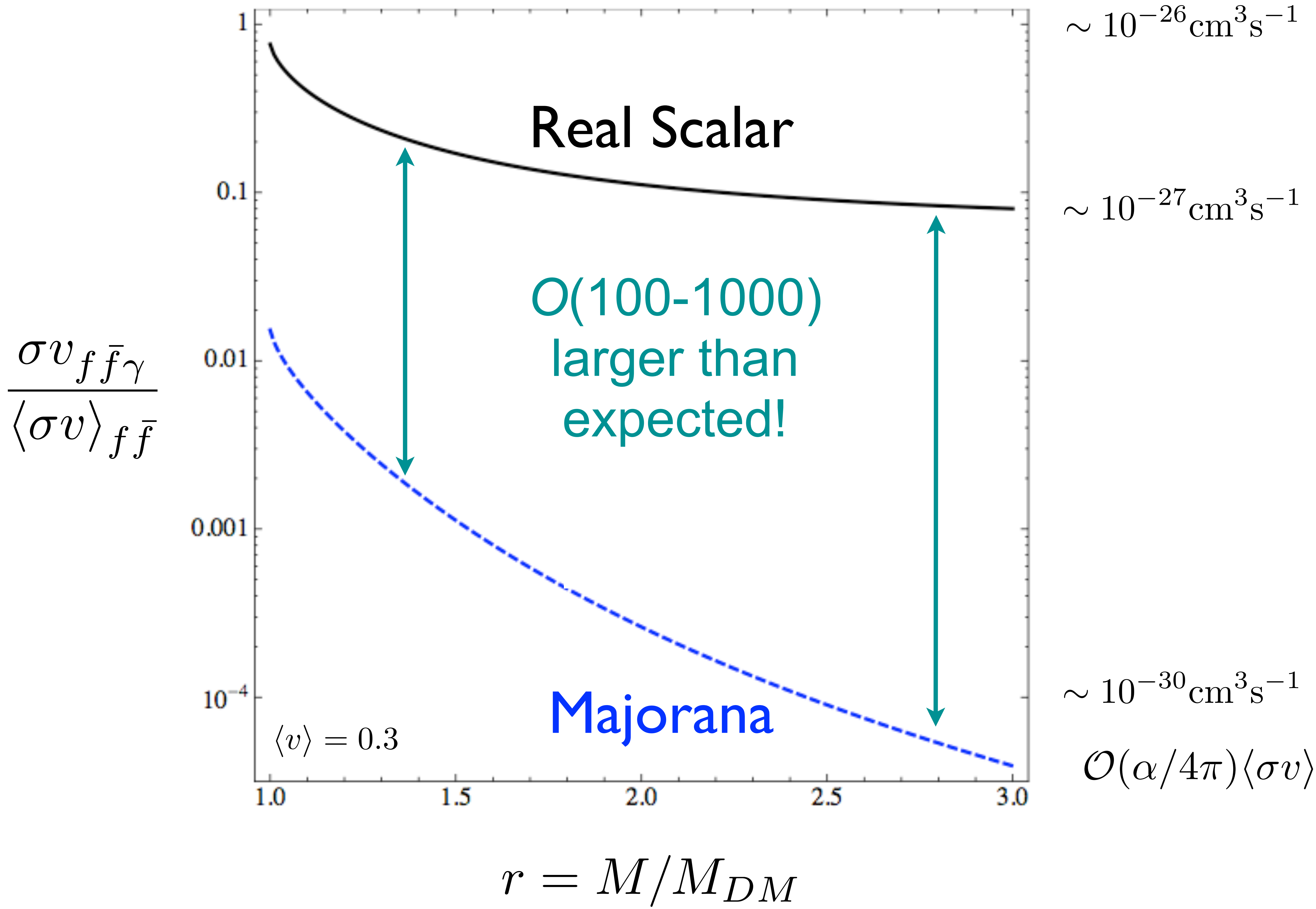


Barger, Keung & Marfatia
arXiv:1111.4523
Takashi Toma
arXiv:1307.6181
Giacchino, Lopez Honorez & M.T.
arXiv:1307.6480

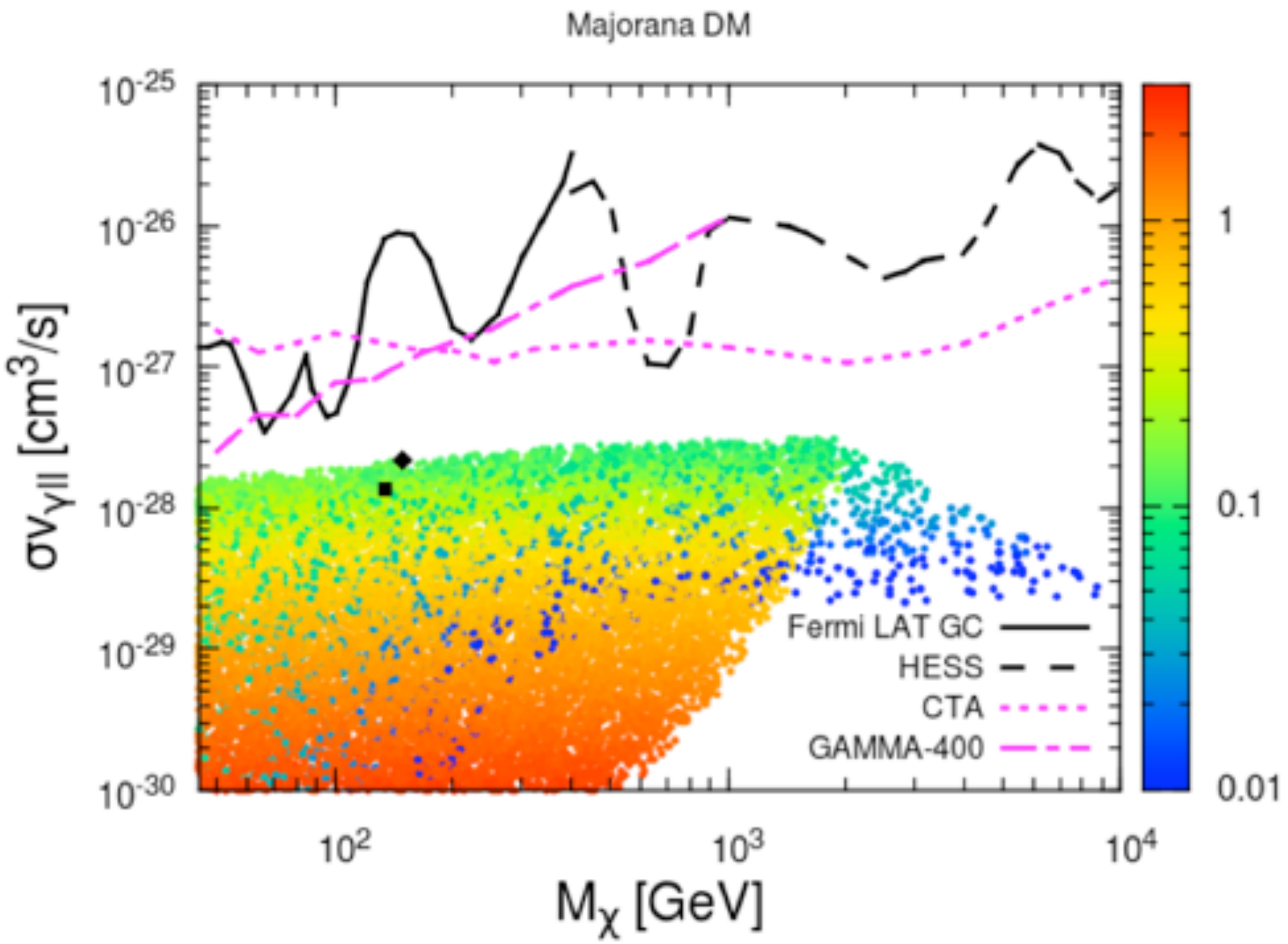
$E_\gamma \sim M_{DM}$



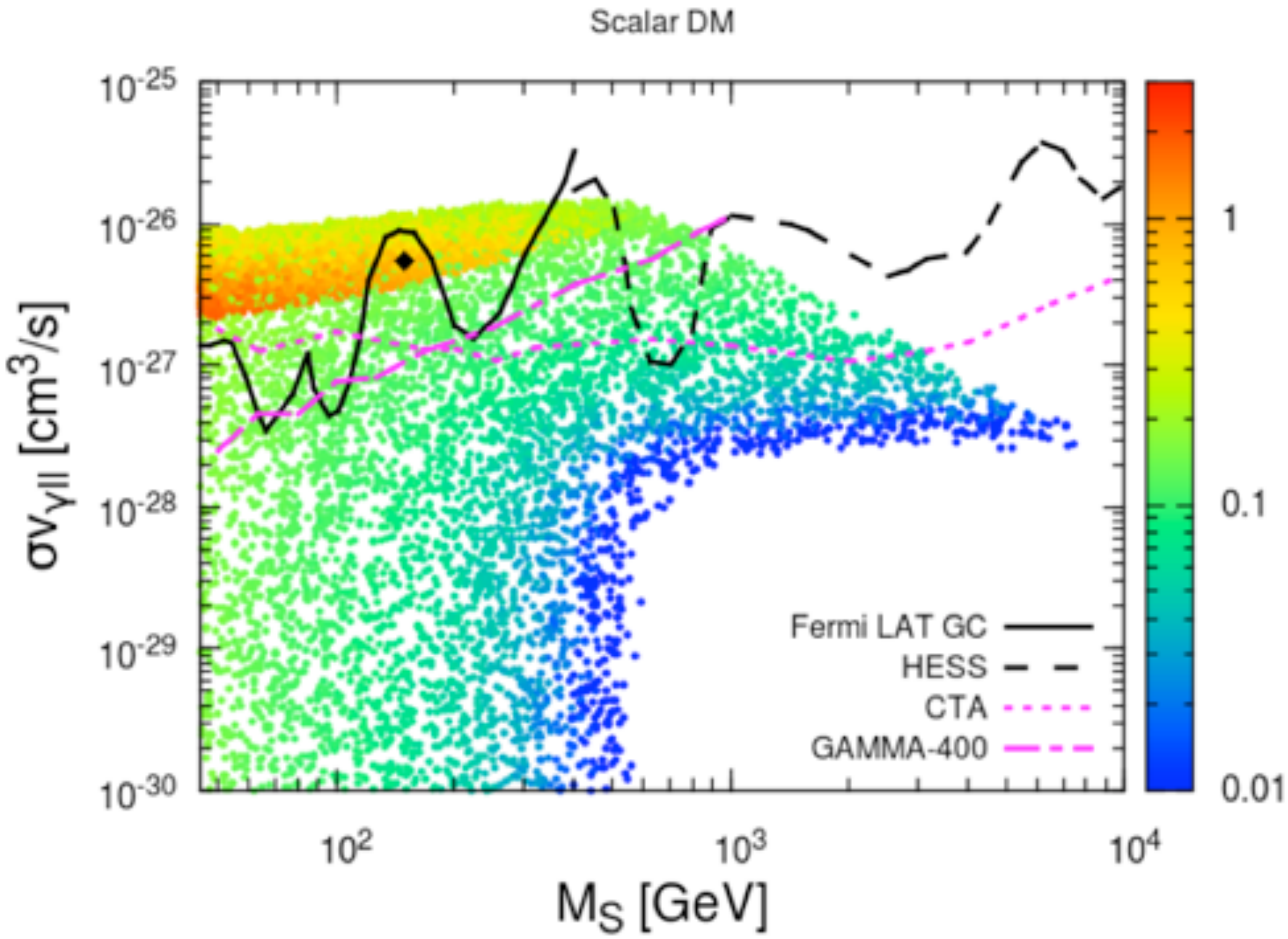
Smoking gun signatures - virtual internal Bremsstrahlung



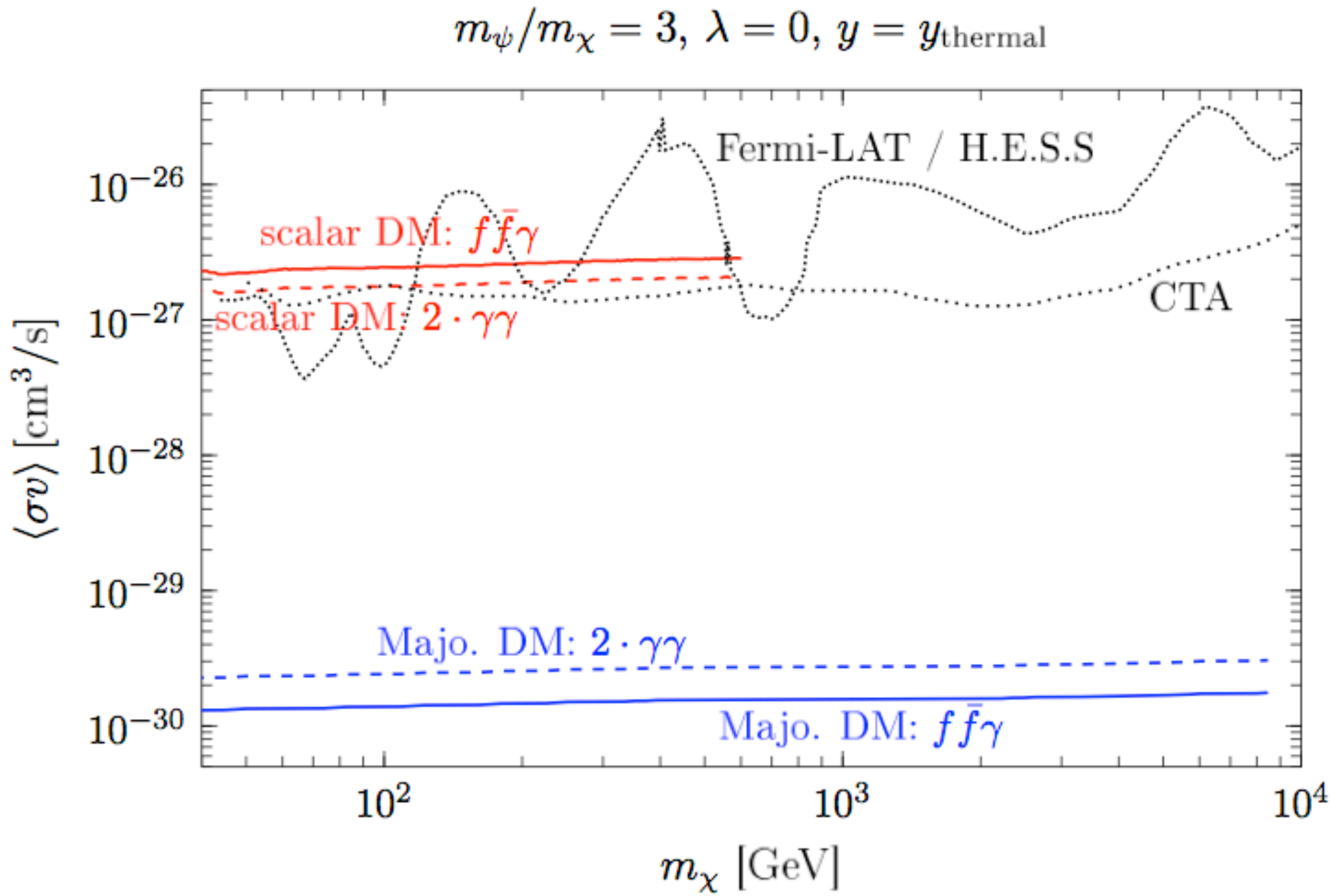
Majorana DM



Real scalar DM



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



Ibarra, Toma, Totzauer & Wild
arXiv:1405.6917

Gluon Bremsstrahlung?

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

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

~ 40 (up-like quarks)

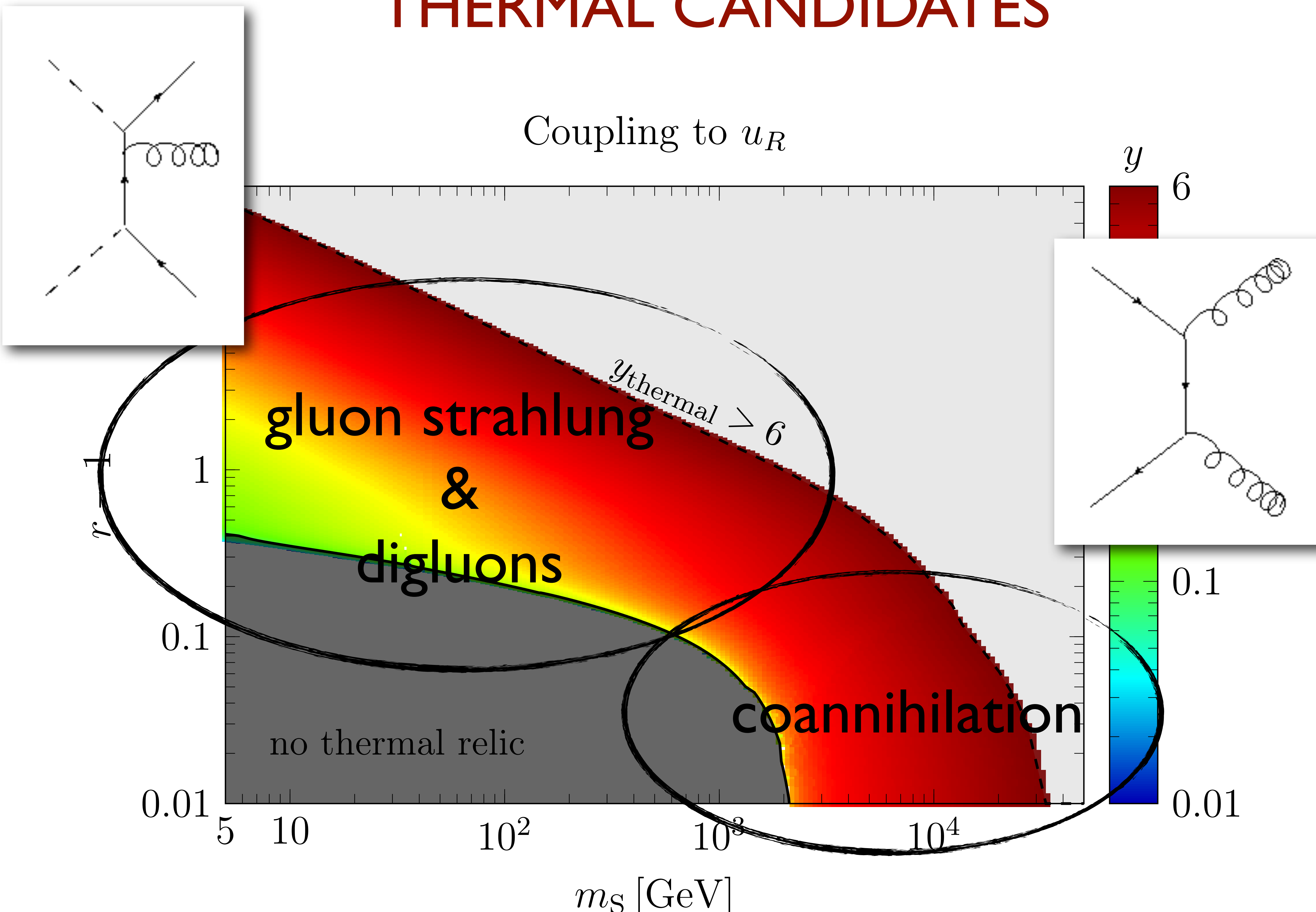
~ 150 (down-like quarks)

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

EVEN IN EARLY UNIVERSE

RELIC ABUNDANCE FROM GLUON BREMSSTRAHLUNG AND/OR DI-GLUONS!!!

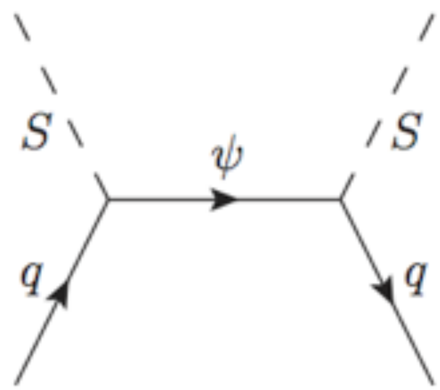
THERMAL CANDIDATES



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

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

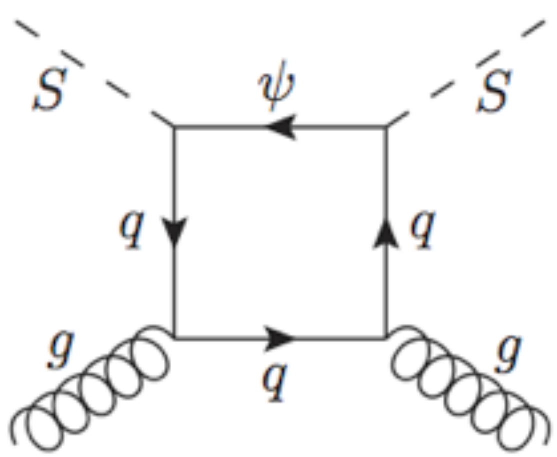
DIRECT DETECTION



$$\mathcal{L}_q = C_S^q\, m_q S^2 \bar{q} q \;+\; C_T^q\, (\partial_\mu S)(\partial_\nu S)\mathcal{O}^{\mu\nu}_{q,\text{twist-2}}$$

$$\mathcal{O}^{\mu\nu}_{q,\text{twist-2}} \equiv \frac{i}{2}\left(\bar{q}\gamma^\mu\partial^\nu q + \bar{q}\gamma^\nu\partial^\mu q - \frac{g^{\mu\nu}}{2}\bar{q}\partial\!\!\!/ q\right)$$

Drees & Nojiri (Majorana case, '93)
Giacchino, Ibarra, Lopez Honorez, MT & Wild '15



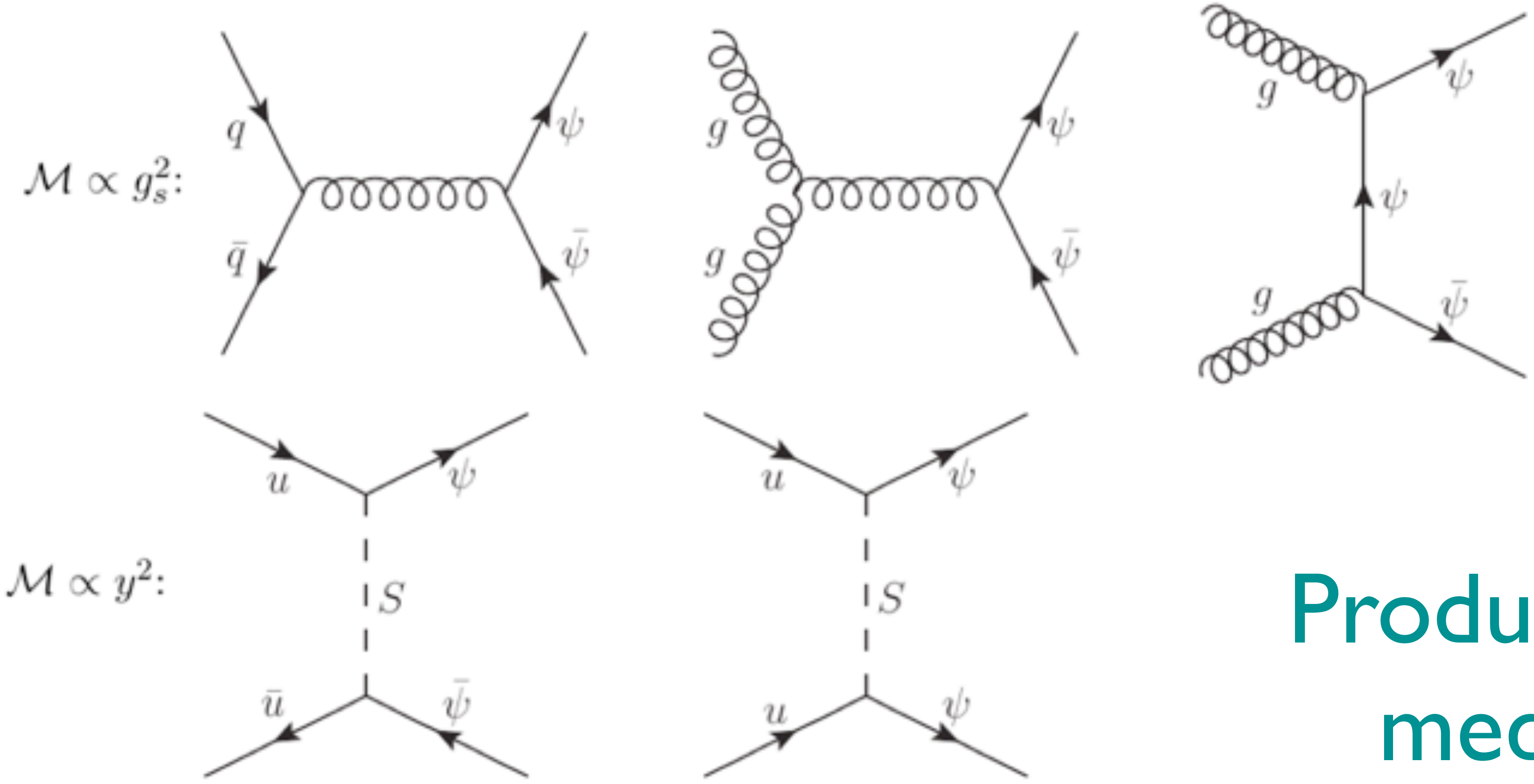
$$\mathcal{L}_g = C_S^g\, \frac{\alpha_S}{\pi} S^2\, G^{\mu\nu} G_{\mu\nu}$$

Hisano, Nagai & Nagata, arXiv:1502.02244

Drees & Nojiri (Majorana case, '93)

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

CONSTRAINTS FROM LHC

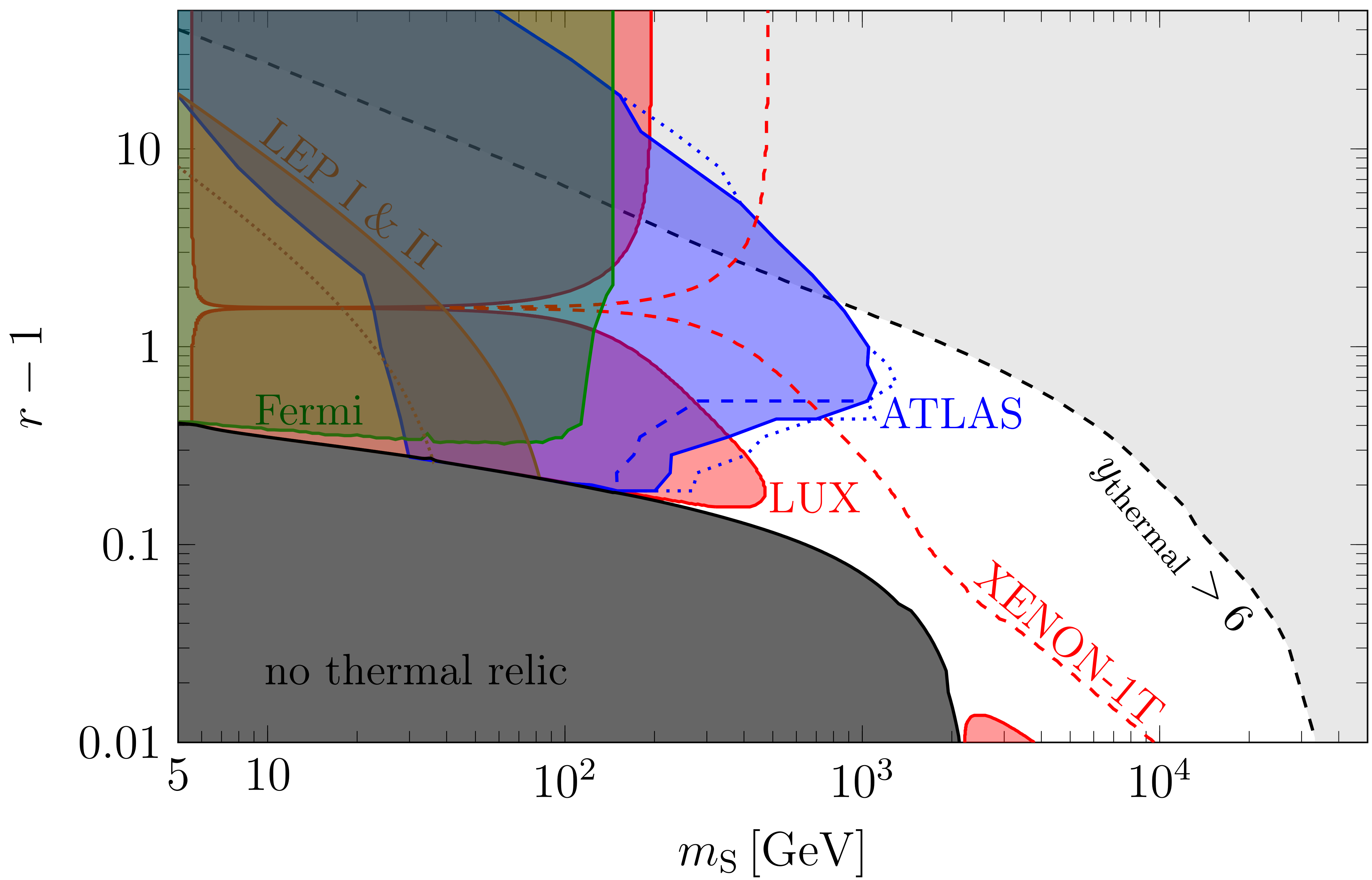


Production of colored mediator @ LHC

Signal = n jets + missing E_T

Small r: extra jets alleviate softness
Large r: extra jets improve S/B

Coupling to u_R



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

II. MDM SCALAR 7-PLET

A benchmark for multi-TeV dark matter

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

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

Mass splitting
through loop corrections

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

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

Cirelli, Fornengo & Strumia (2005)

II. MDM SCALAR 7-PLET

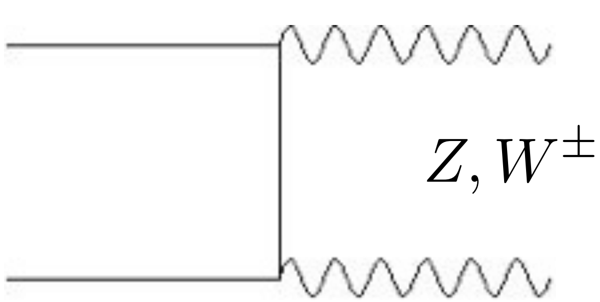
A benchmark for multi-TeV dark matter

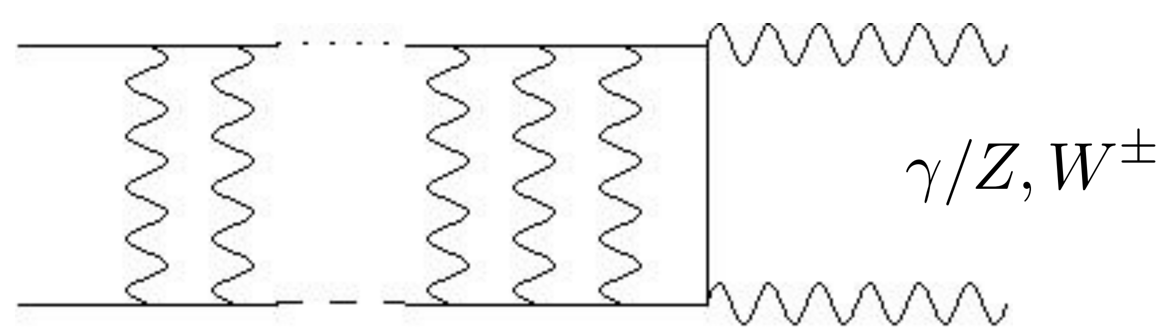
$$M_7 \sim 25 \text{ TeV}$$

Cirelli, Strumia & Tamburini (2007)

1. Many co-annihilation channels
2. Sommerfeld effects $M_7 \gg M_{W/Z}$

} σ_{eff} ↗↗

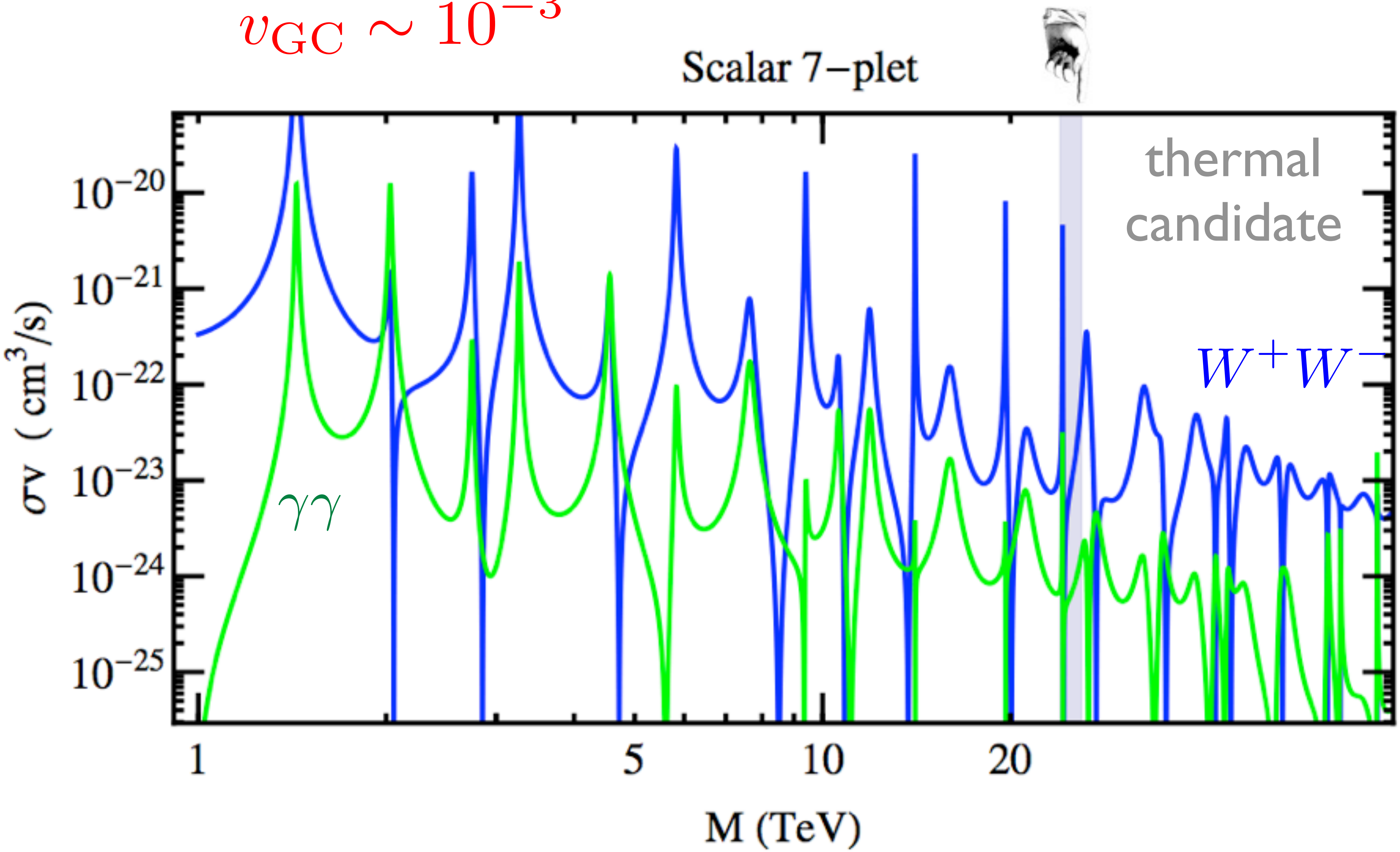




Sommerfeld leads to peaks and dips in the annihilation cross sections

Strumia, Cirelli & Tambirini (2007)

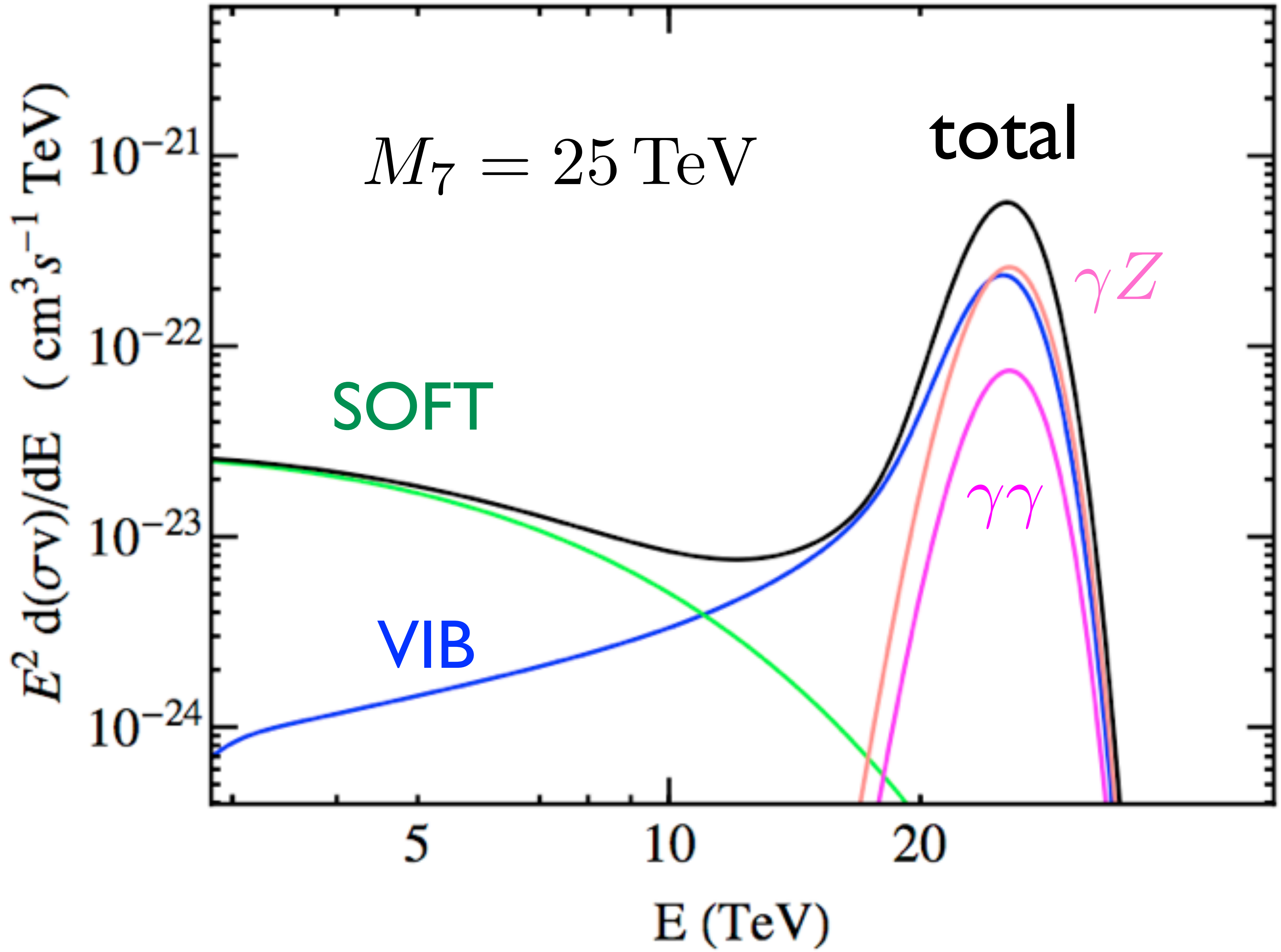
$v_{\rm GC} \sim 10^{-3}$



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

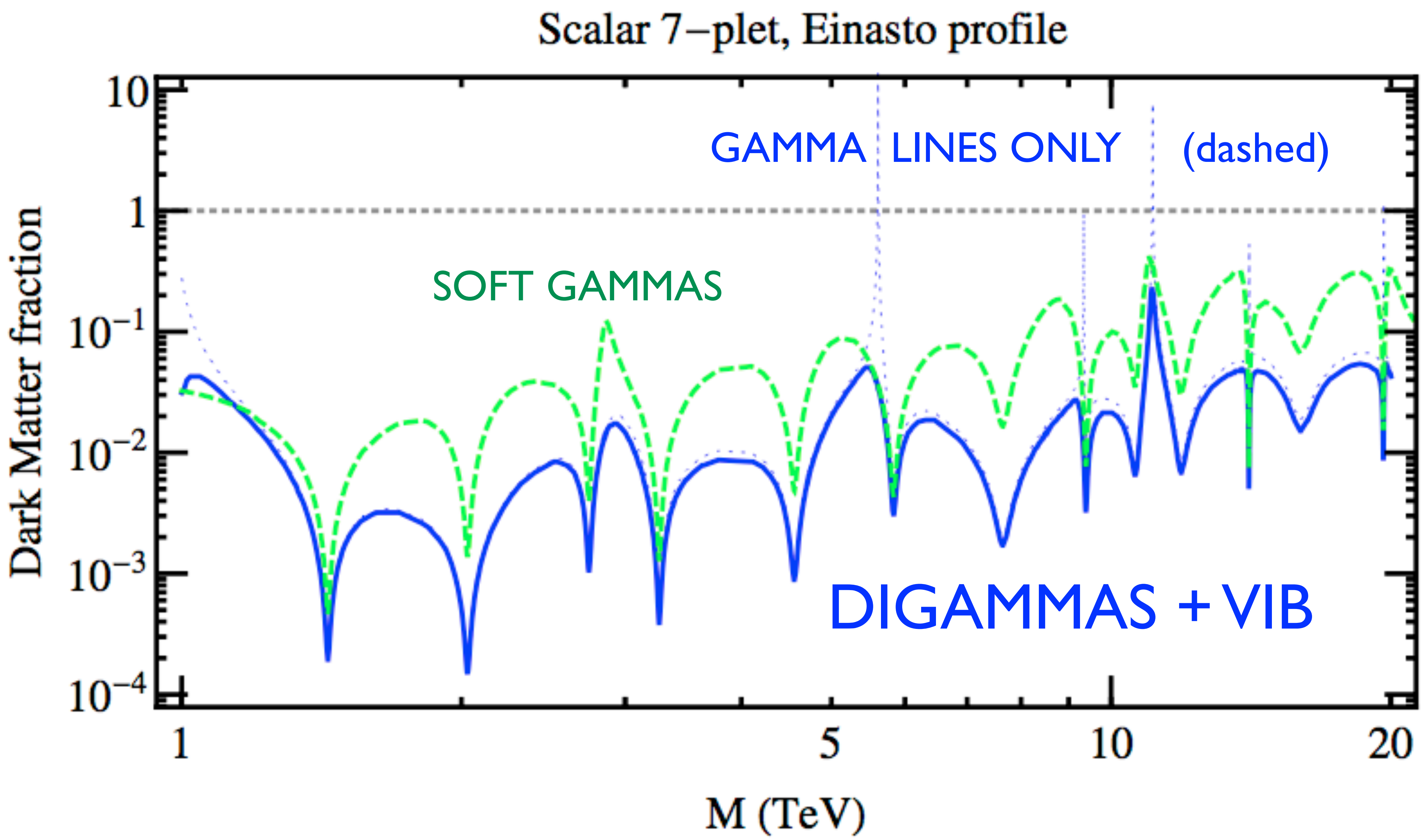
See also Cirelli, Hambye, Panci, Sala & Taoso, arXiv:1507.05519 (fermionic 5-plet)

7-plet components are nearly degenerate so VIB is also important



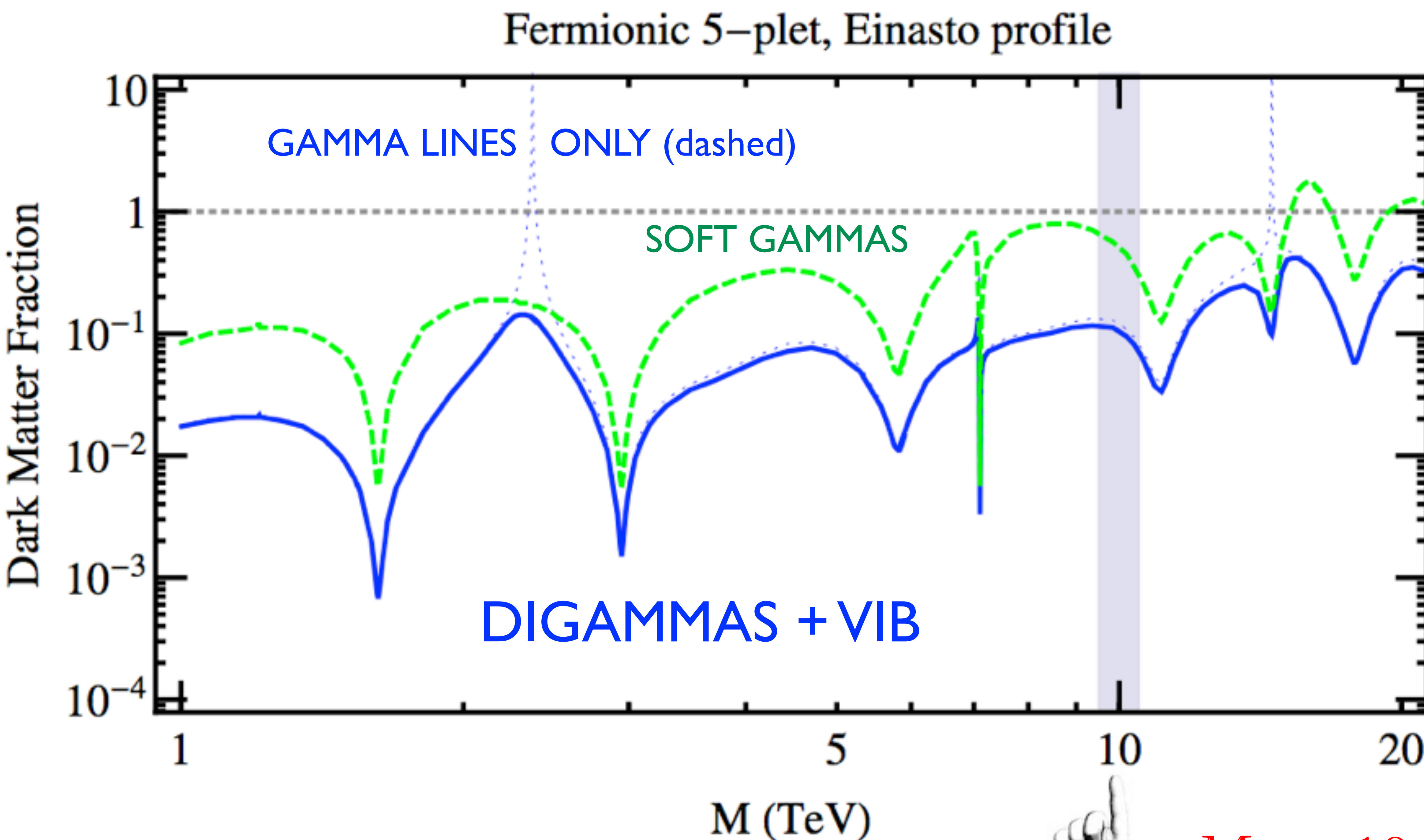
Garcia-Cely, Ibarra, Lamperstorfer & MT, arXiv:1507.05536

H.E.S.S. LIMITS



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

H.E.S.S. LIMITS

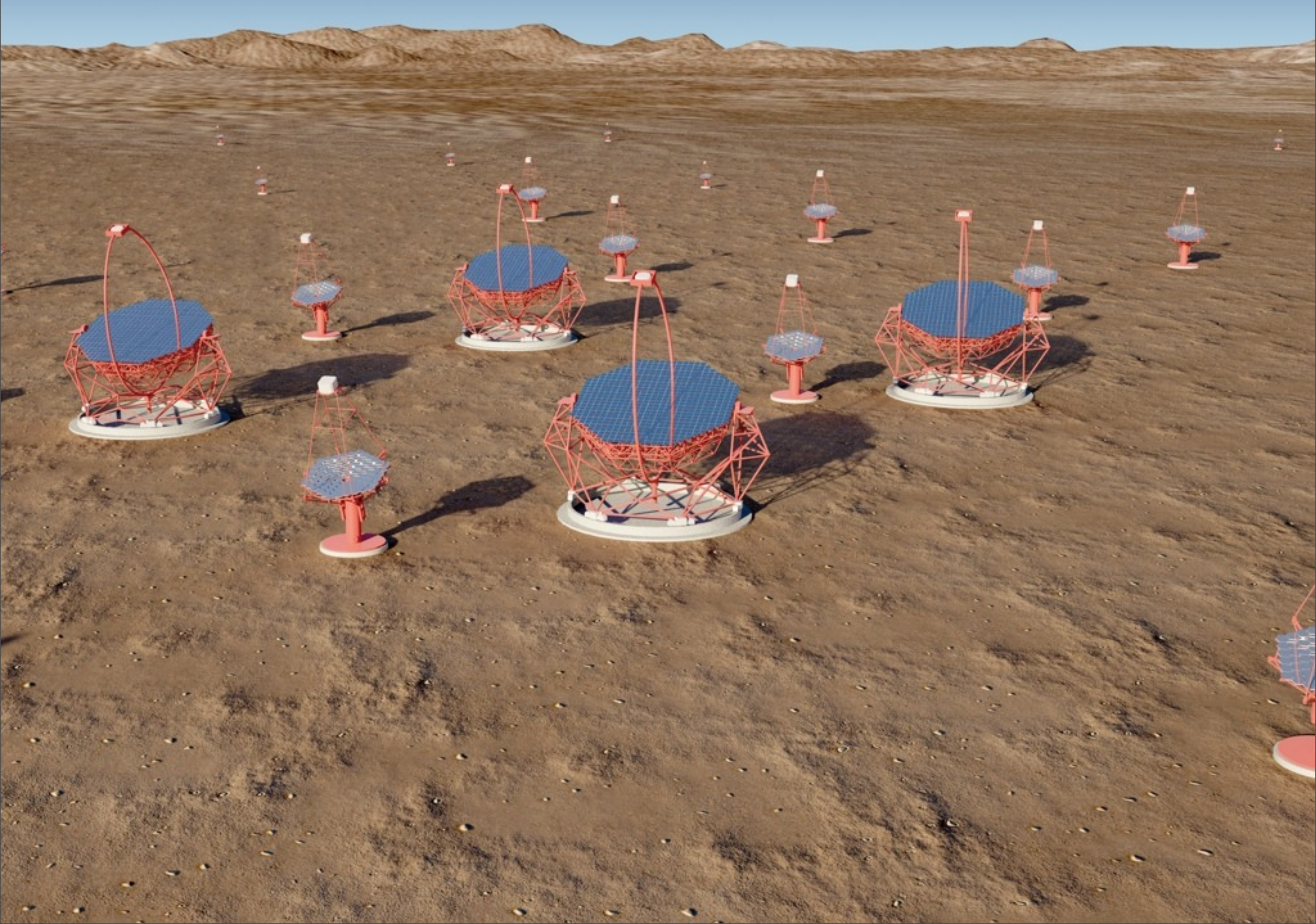


$M_5 \sim 10$ TeV

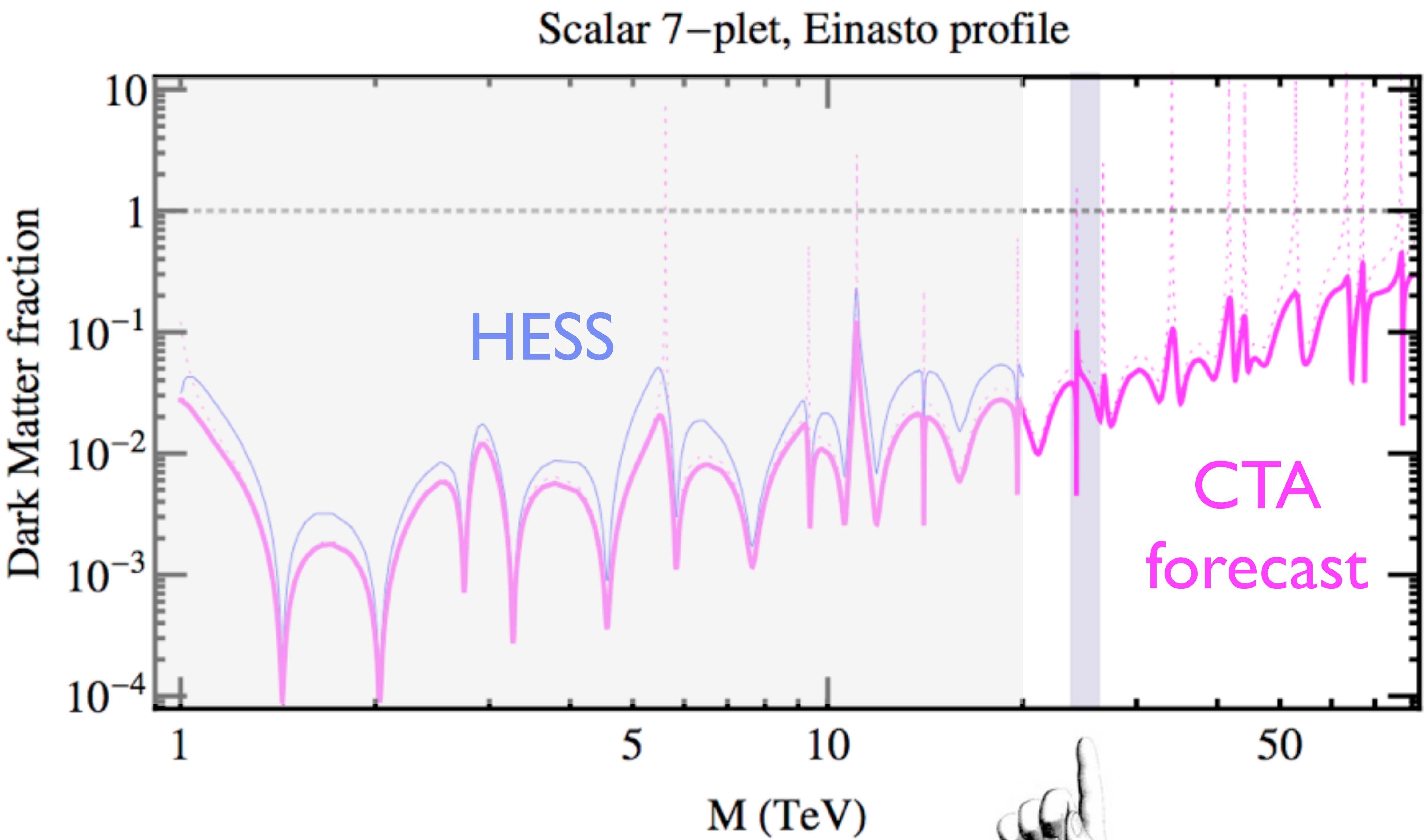
Thermal fermionic 5-plet candidate constrained by H.E.S.S.

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

CERENKOV TELESCOPE ARRAY



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



$M_7 \sim 25$ TeV

Thermal scalar 7-plet needs CTA

(a 200 million € project)

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

SWIMP

Super Weakly Interacting Massive Particle (Laura Covi's talk)

or

Scalar Weakly Interacting Massive Particle ;-)

www.wino.org.pl
SWiMP
Stowarzyszenie Winiarzy i Miodosytników Polskich

SWIMP the Simple

SWIMP

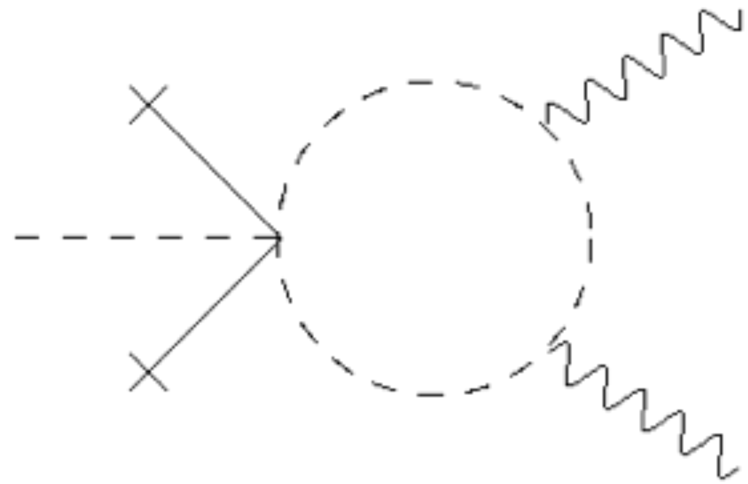
To stay true and loyal to once's friends even though times might be rough

urban DICTIONARY

Backup slides

II. MDM SCALAR 7-PLET

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



$$\Lambda \sim 10^{15}\mathrm{GeV}$$
$$M_\chi \sim \mathrm{TeV}$$
$$\longrightarrow \tau_\chi \sim 10^{-8}\mathrm{s}$$

$$\chi \underset{Z_2}{\longrightarrow} -\chi$$

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

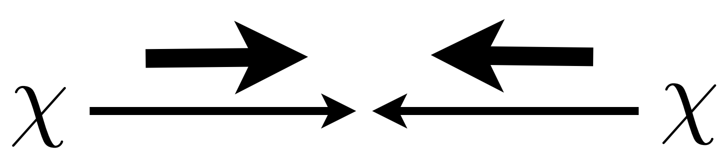
1st: MAJORANA

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

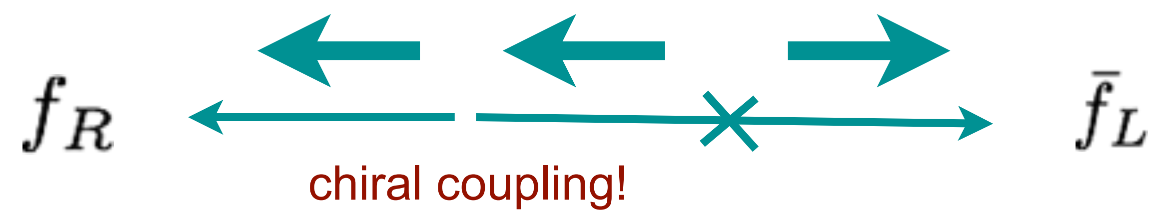
S-WAVE INITIAL STATE



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

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

FINAL STATE



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

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

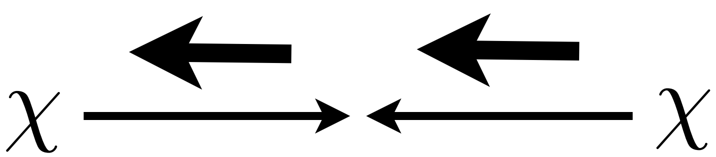
1st: MAJORANA

II. P-WAVE IN CHIRAL LIMIT ➔

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

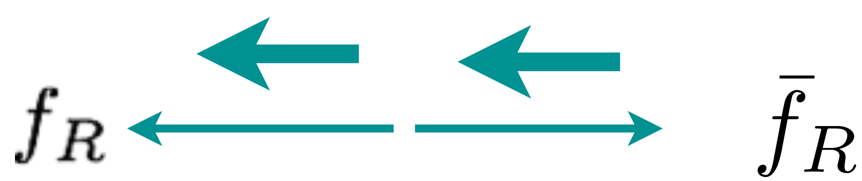
$$r = \frac{m_{\tilde{l}}}{m_\chi} \geq 1$$

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 →

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

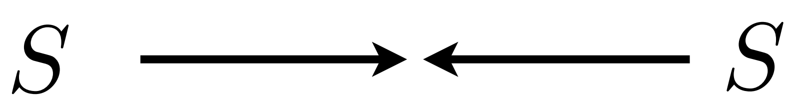
$$r = \frac{m_\psi}{m_S} \geq 1$$

Rem: I don't know of any other instance

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

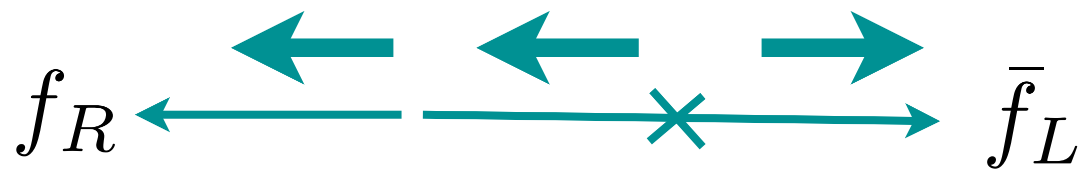
WHY D-WAVE SUPPRESION?

S-WAVE INITIAL STATE



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

FINAL STATE

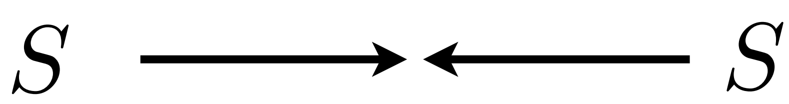


$$\bar{\psi}_f \psi_f$$

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

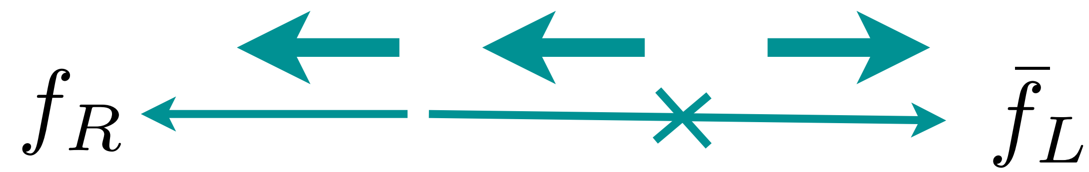
WHY D-WAVE SUPPRESSION?

S-WAVE INITIAL STATE



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

FINAL STATE

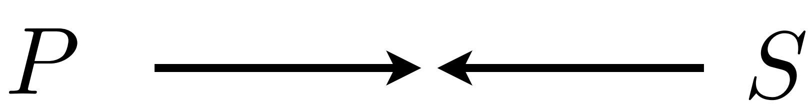


$\bar{\psi}_f \psi_f$

chirally suppressed

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

P-WAVE INITIAL STATE



$^1P_1(1^{--})$

FINAL STATE

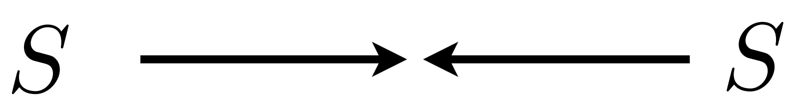
$\bar{\psi}_f \gamma^k \psi_f$

a complex scalar could have p-wave annihilation

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

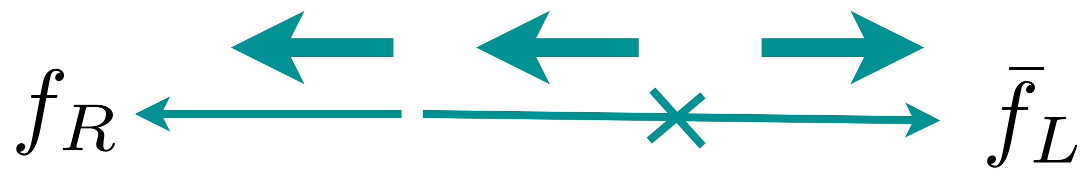
WHY D-WAVE SUPPRESION?

S-WAVE INITIAL STATE



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

FINAL STATE

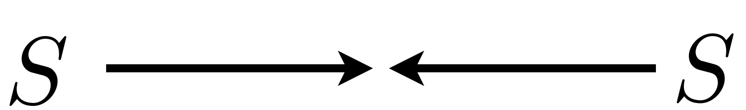


$\bar{\psi}_f \psi_f$

chirally suppressed

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

D-WAVE INITIAL STATE



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

FINAL STATE

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

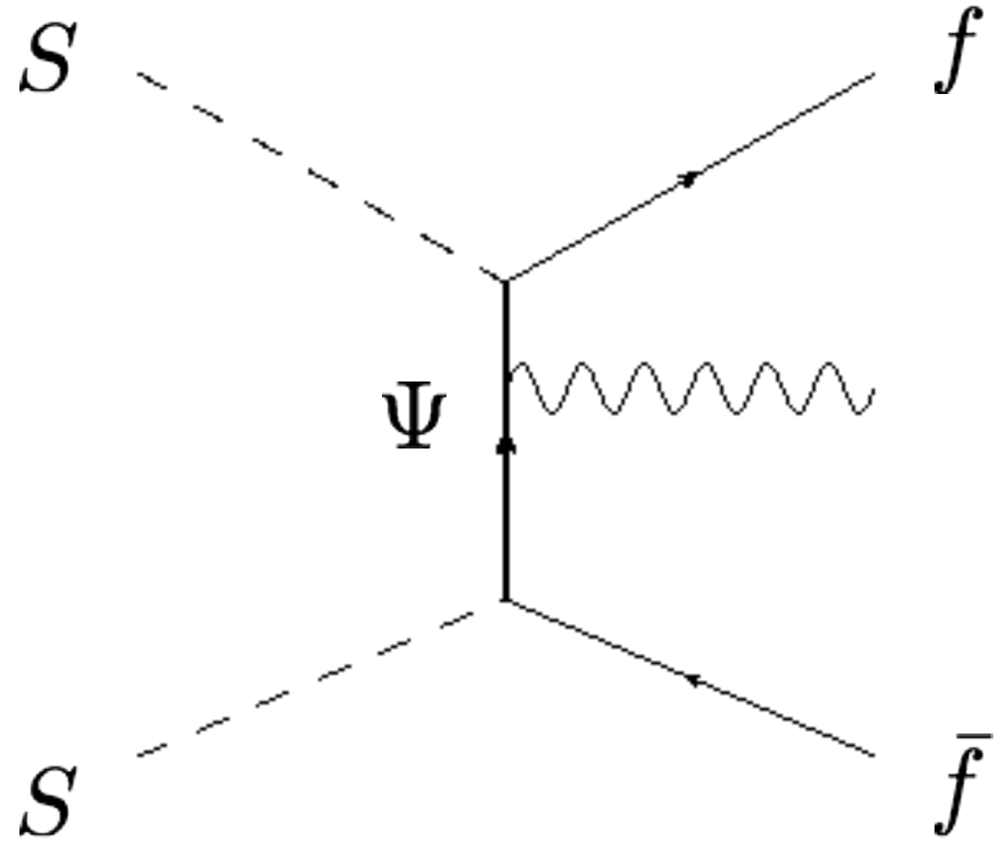
d-wave
in chiral limit

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

FERMION
STRESS-ENERGY TENSOR

WHY VIRTUAL INTERNAL BREMSSTRAHLUNG?

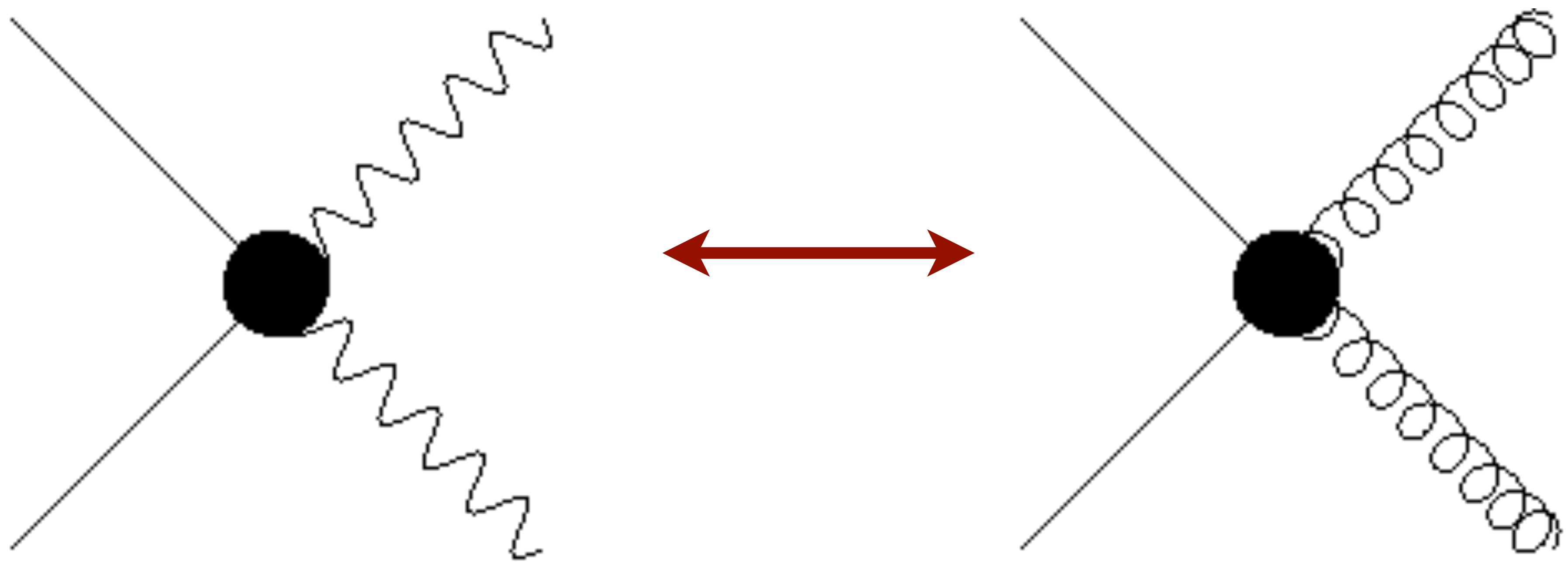
non-relativistic



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

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

indirect detection | relic abundance

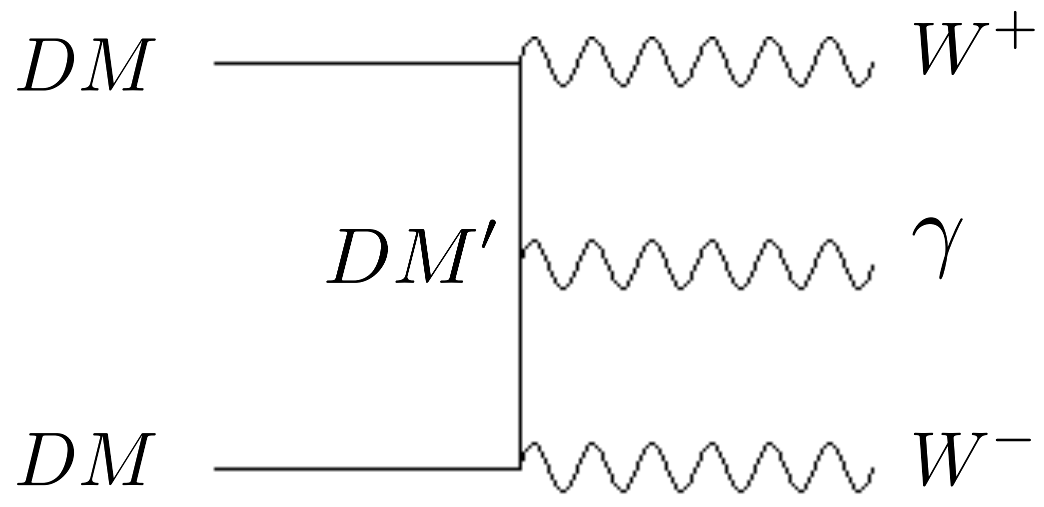


$$\frac{\sigma v_{gg}}{\sigma v_{\gamma\gamma}} = \mathcal{O}(100)$$

naturally strong digamma lines!

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

VIB = VIRTUAL INTERNAL BREMSSTRAHLUNG

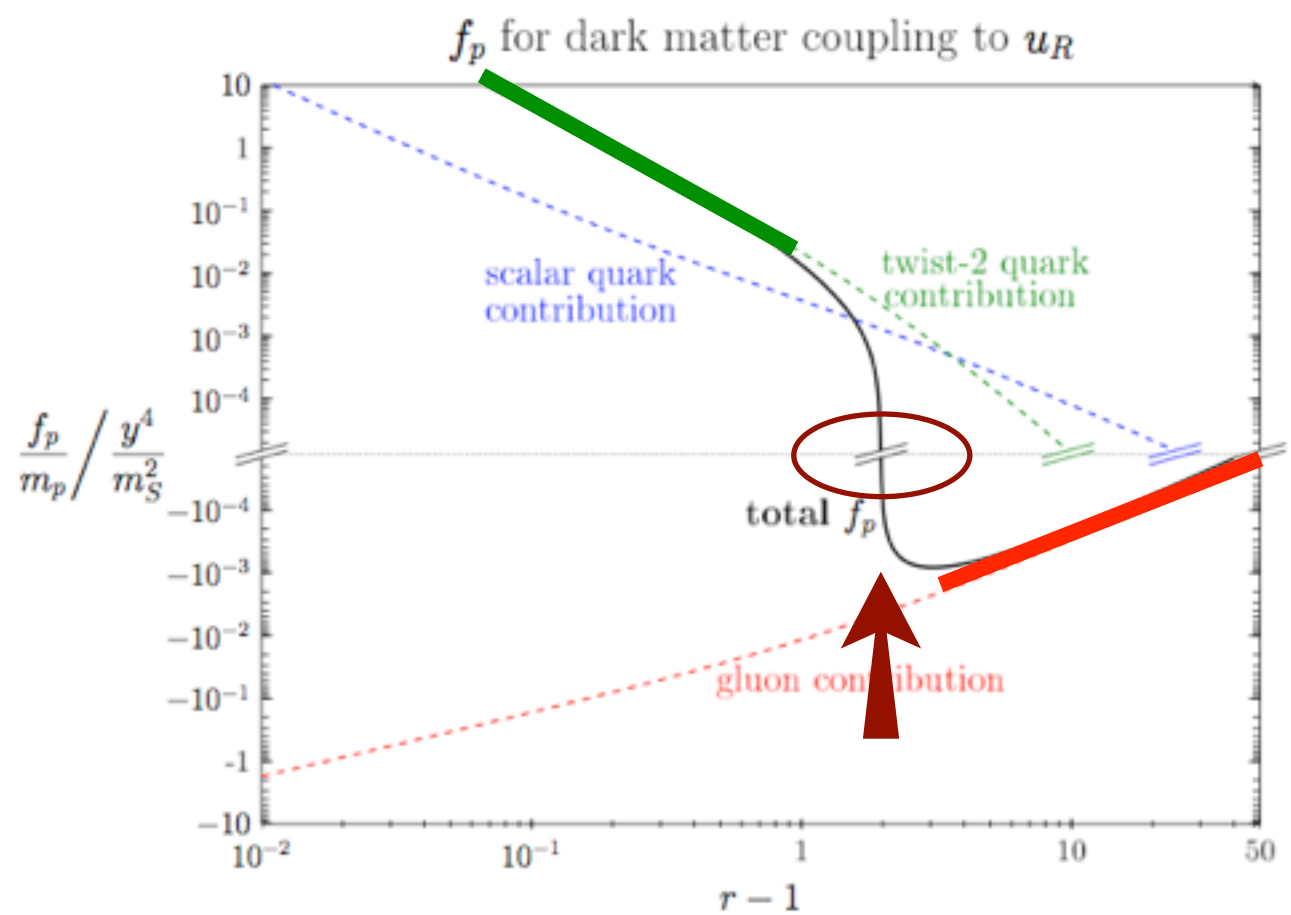


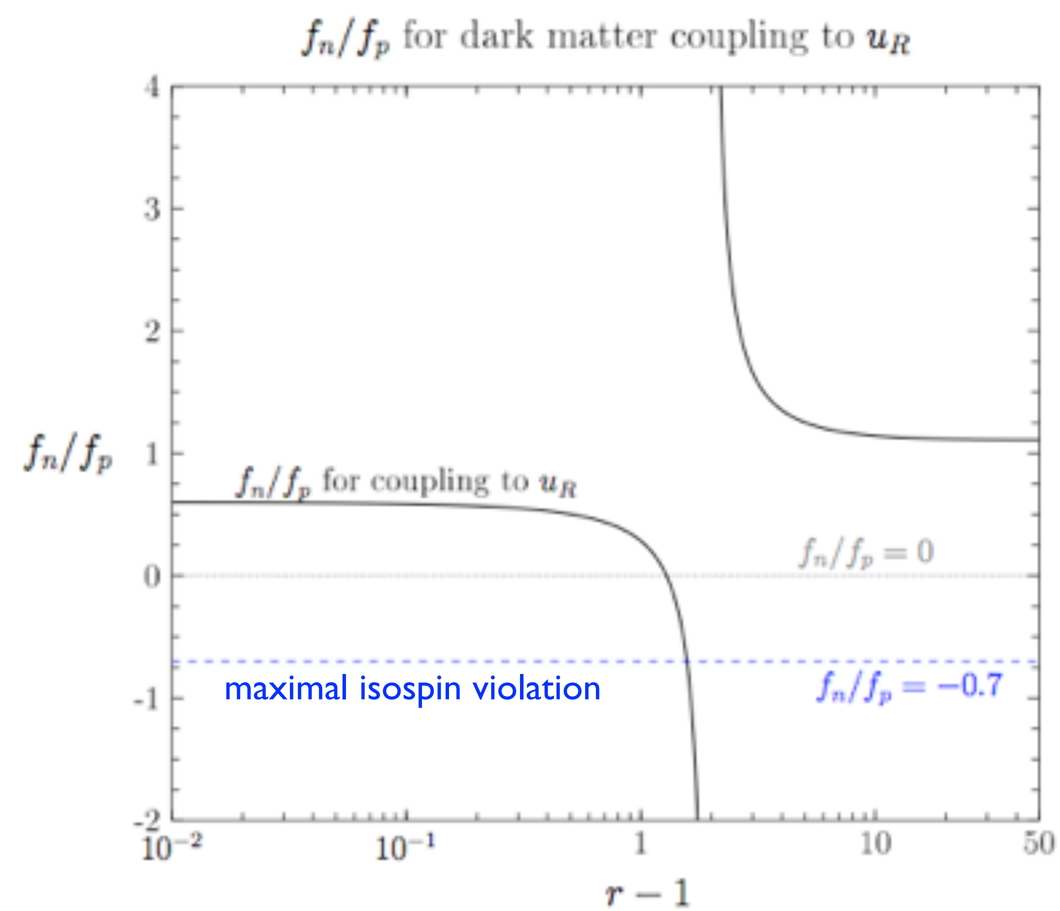
$$\mathcal{M} \propto \frac{1}{(p_{\rm DM} - p_W)^2 - M^2_{\rm DM'}} \sim \frac{1}{M^2_{DM} - 2E_W M_{\rm DM} - M^2_{DM'}} \sim \frac{1}{E_W}$$

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

DIRECT DETECTION

isospin violation effects





destructive interference

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

twist-2 gluons

II. MDM SCALAR 7-PLET

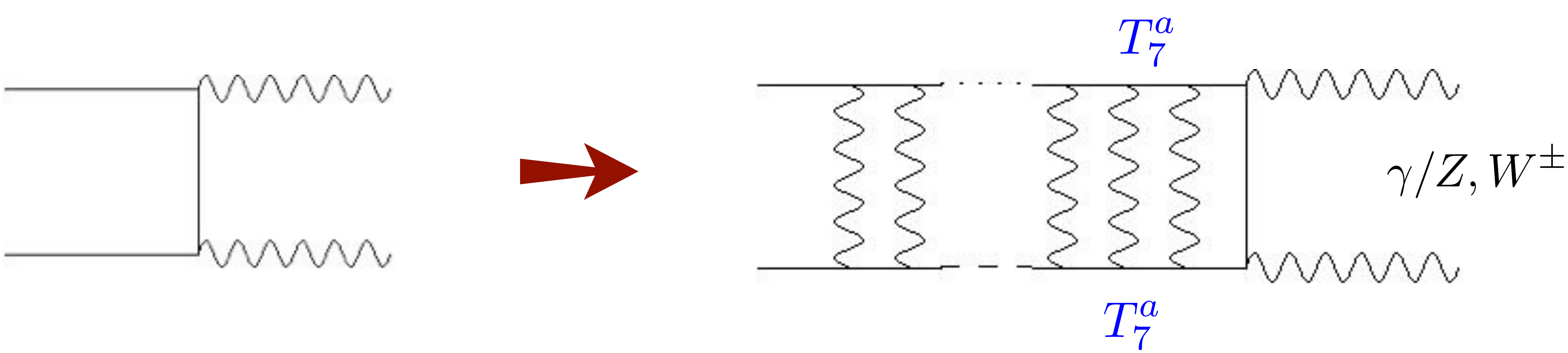
a benchmark for multi-TeV dark matter

$$M_7 \sim 25 \text{ TeV}$$

Cirelli, Strumia & Tamburini (2007)

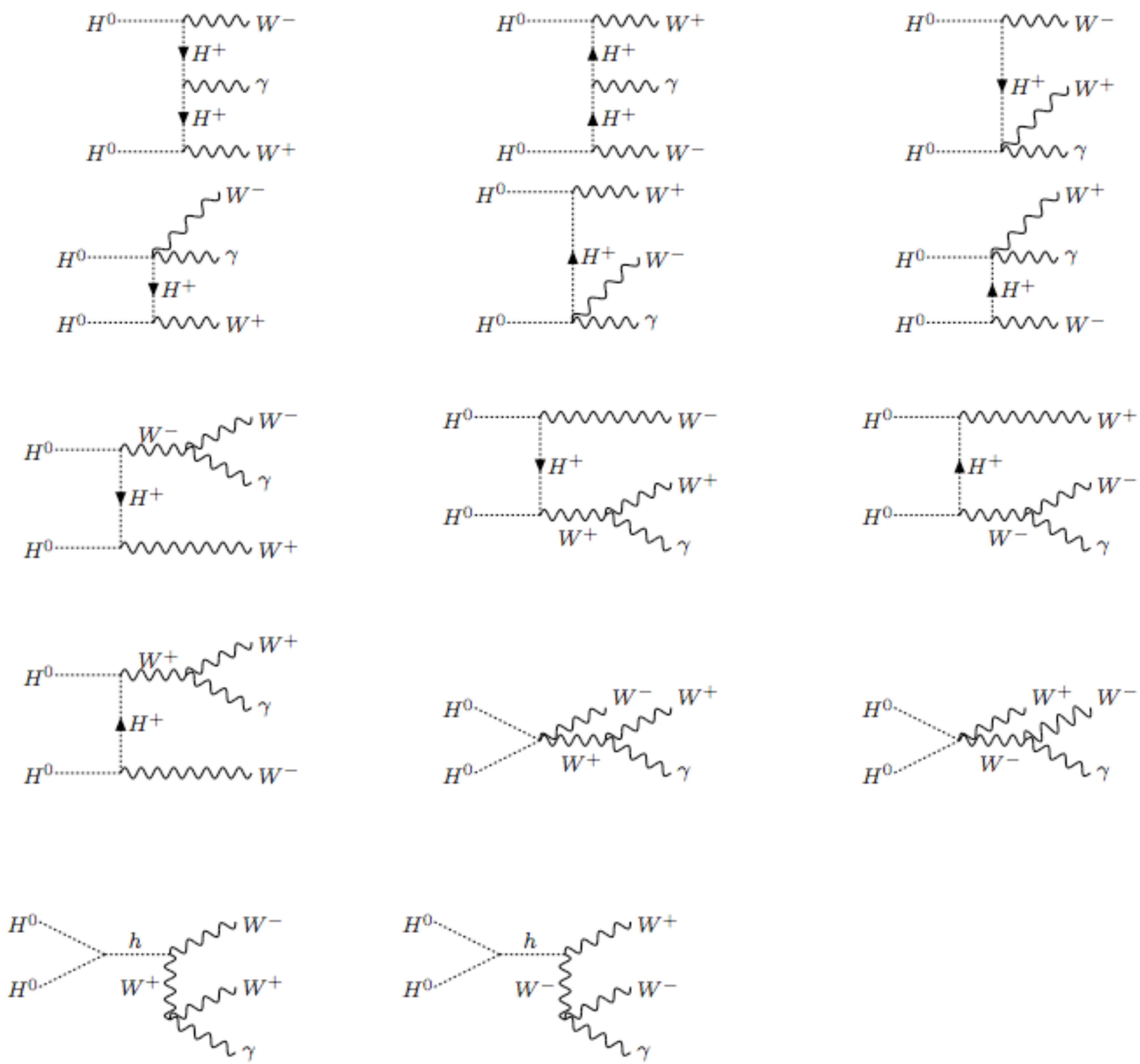
1. Many co-annihilation channels.

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



$$7 \otimes 7 = \ldots \oplus 5_s \oplus \not{3}_A \oplus 1_s$$

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



H^0 W^- H^+ γ H^+ H^0 W^+
H^0 W^+ H^+ γ H^+ H^0 W^-
H^0 W^- H^+ W^+ H^0 γ
W^- H^0 γ H^+ H^0 W^+
H^0 W^+ H^+ W^- H^0 γ
W^+ H^0 γ H^+ H^0 W^-
H^0 W^- W^- γ H^+ H^0 W^+
H^0 W^- H^+ W^+ H^0 W^+ γ
H^0 W^+ H^+ W^- H^0 W^- γ
H^0 W^+ W^+ 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