Status of the Inert Doublet Model

Michel H.G. Tytgat
Université Libre de Bruxelles

«Higgs as a probe of New Physics 2013»
February 13-16, 2013, University of Toyama, Japan

The Model

SM Scalar (SMS) + extra Scalar Doublet

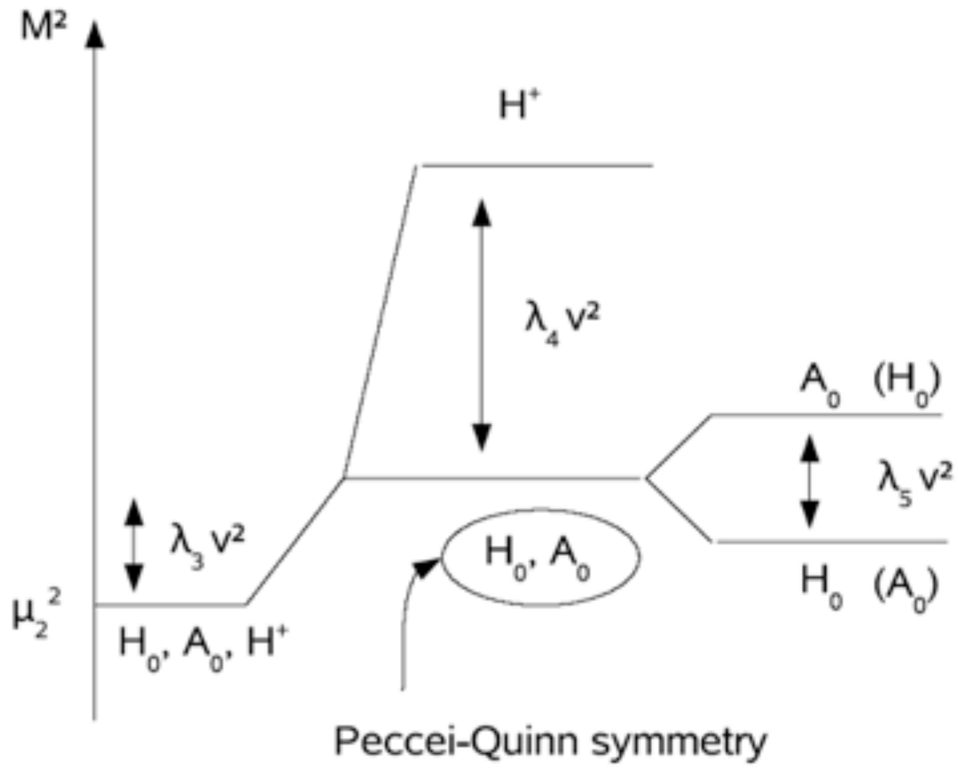
$$H_2 = \begin{pmatrix} H^+ \\ \frac{H_0 + iA_0}{\sqrt{2}} \end{pmatrix}$$

Unbroken Z_2 symmetry $\quad H_2 \to -H_2$

H_0 Dark Matter ~ WIMP

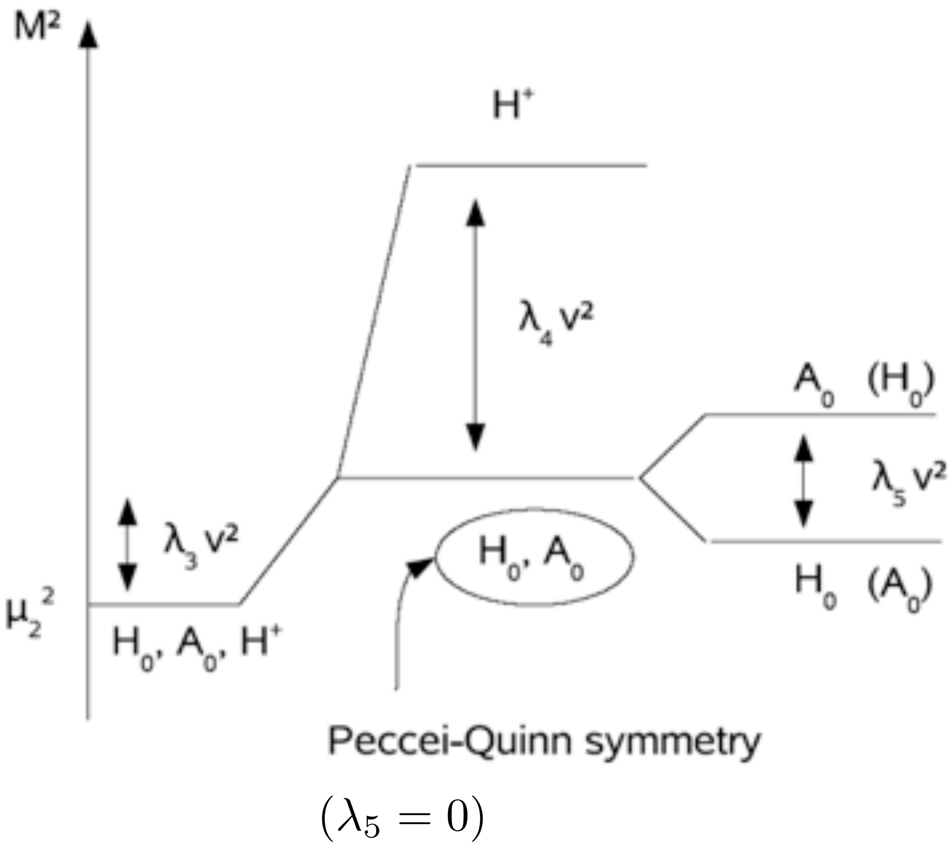
(Deshpande, Ma; Barbieri, Hall, Ryshkov)

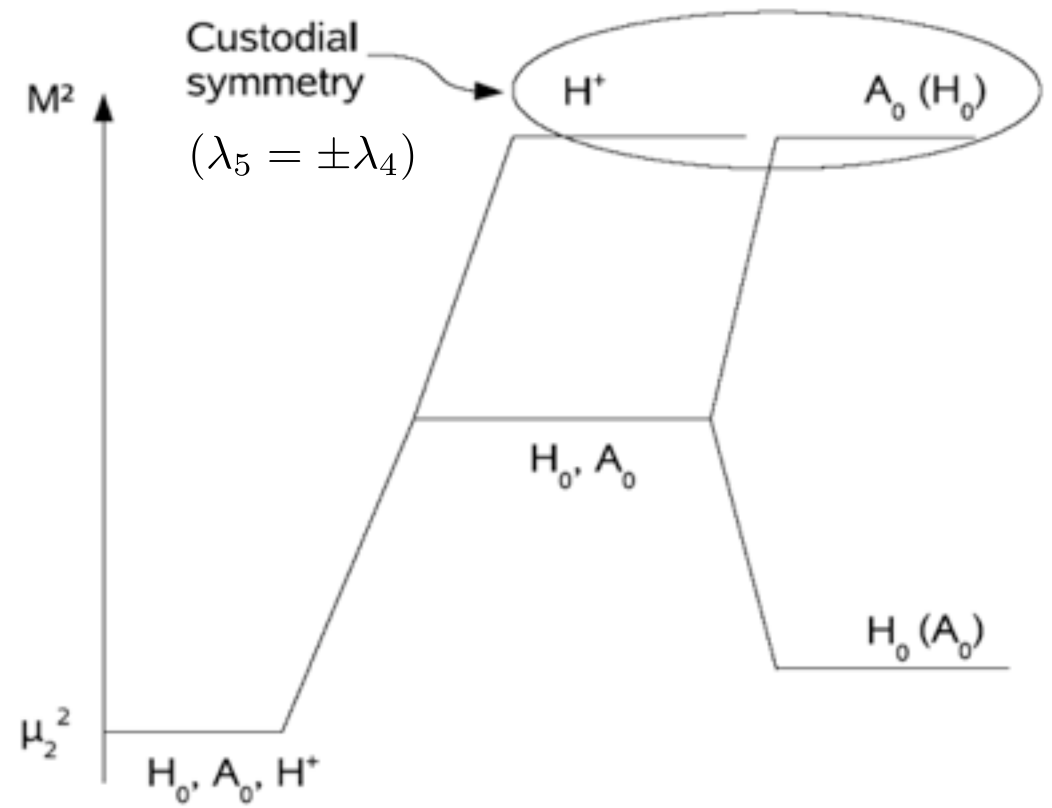
$$\mathcal{L} \supset \mu_2^2|H_2|^2 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2$$
$$+\lambda_4|H_1^\dagger H_2|^2 + \lambda_5 Re(H_1^2 H_2)^2$$



$(\lambda_5 = 0)$

$$\mathcal{L} \supset \mu_2^2|H_2|^2 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2$$
$$+\lambda_4|H_1^\dagger H_2|^2 + \lambda_5 Re(H_1^2 H_2)^2$$



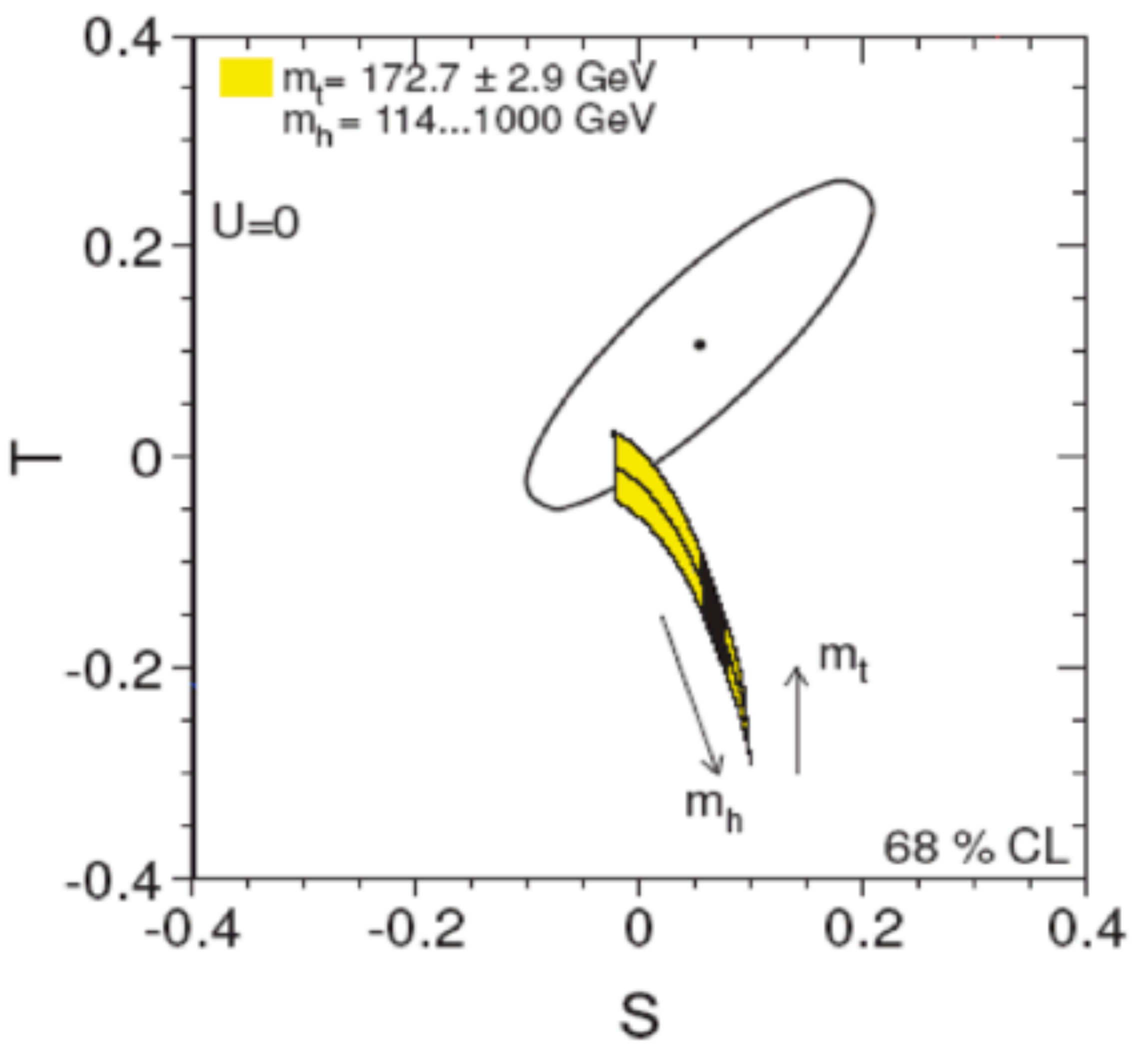


1. $$\mathcal{L} \supset -\frac{\lambda_2}{4} H_0^4 - \lambda_L H_0^2 H^\dagger H$$

Like a singlet scalar

(McDonald; Patt&Wilczek;...)

$$\Delta T \approx \frac{1}{24\pi^2 \alpha v^2}(m_{H^+} - m_A)(m_{H^+} - m_{H_0})$$ large ?



Large radiative corrections from the inert Higgs can 'screen' the SM Higgs contribution to ΔT.

Barbieri, Hall & Rychkov have explored the possibility of a Higgs with mass up to 500 GeV without conflict with LEP precision measurements

hep-ph/0603188

With the SMS @ 125 GeV, large custodial symmetry breaking is no longer an option

Z_2 parity of SM matter fields?

$$(Q_L, L, E_R, U_R, D_R) \to \pm(Q_L, L, E_R, U_R, D_R)$$

Both are possible since fermions come in pairs
No coupling to H_2, hence H_0 is stable

Rem: if odd SM fermions, «natural» embedding in SO(10)
Z_2 identified with Matter Parity $= (-1)^{3(B-L)}$
Fermions & Inert doublet in **16's** (unique)
SM Scalar in **10**

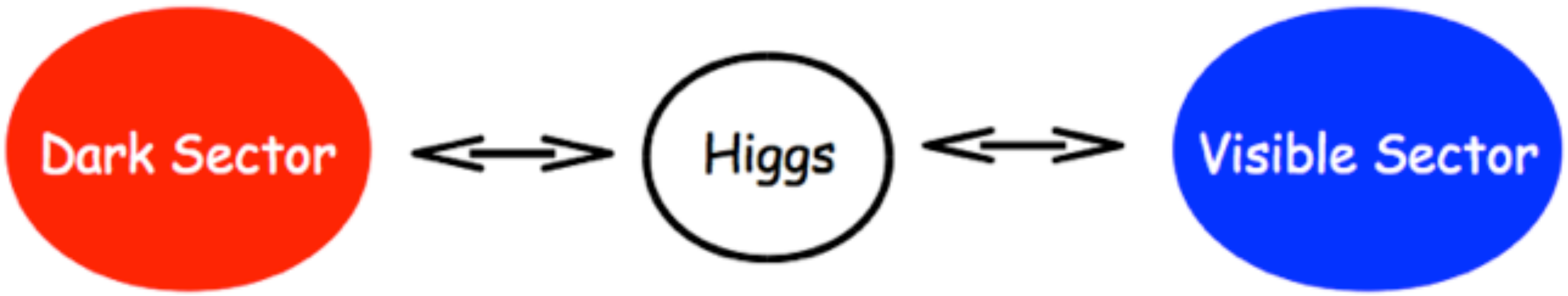
Why the Inert Doublet Model?

One of the simplest extensions of the SM

Yet, rich, specific phenomenology

Versatile (dark matter,
neutrino masses, EWSB,...)

e.g. The Higgs Portal *Patt & Wilczek (2006)*



$$\mathcal{L}_{SM} \supset -\mu^2 H^\dagger H + \lambda S^2 H^\dagger H$$

Simplest incarnation: S singlet scalar

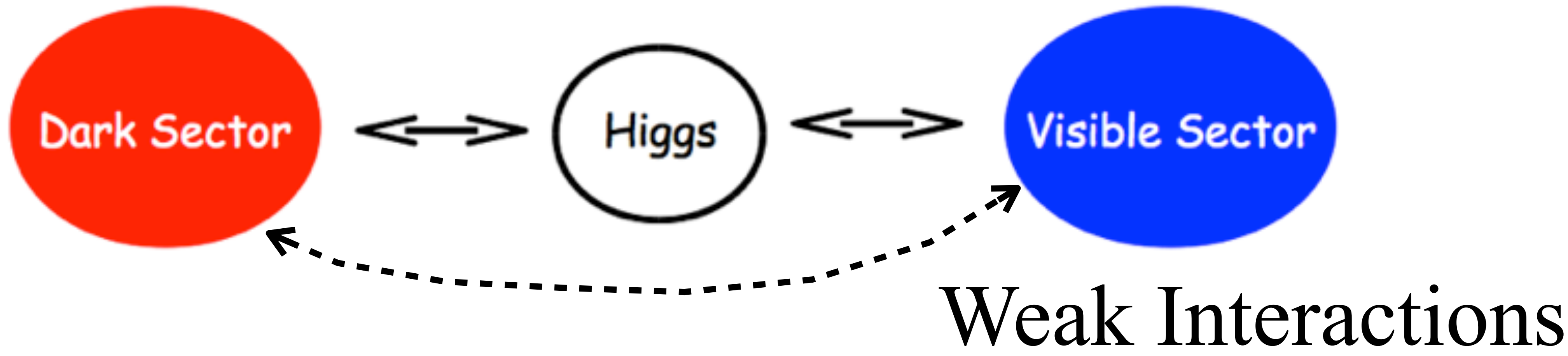
S -> -S symmetry

No <S> vacuum expectation

-> S stable and neutral

Silveira & Zee '85; McDonald '94; Burgess, Pospelov, ter Veldhuis '00; Patt,Wilczek '06; Barger et al '08; Andreas, Hambye, M.T. '08

e.g. The Higgs Portal *Patt & Wilczek (2006)*



$$\mathcal{L}_{SM} \supset -\mu^2 H^\dagger H + \lambda S^2 H^\dagger H$$

Simplest incarnation:
S singlet scalar

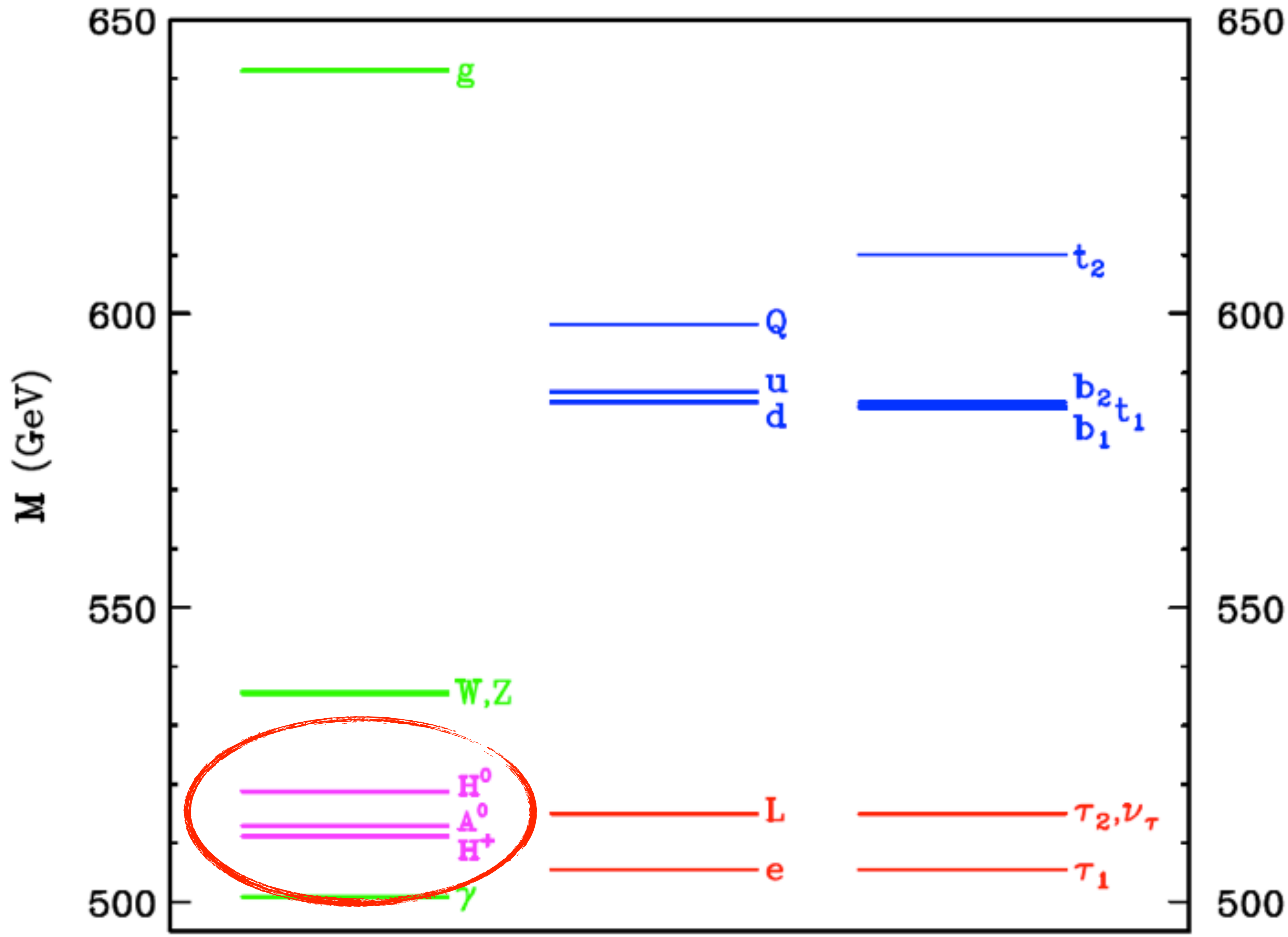
S -> -S symmetry

No <S> vacuum expectation

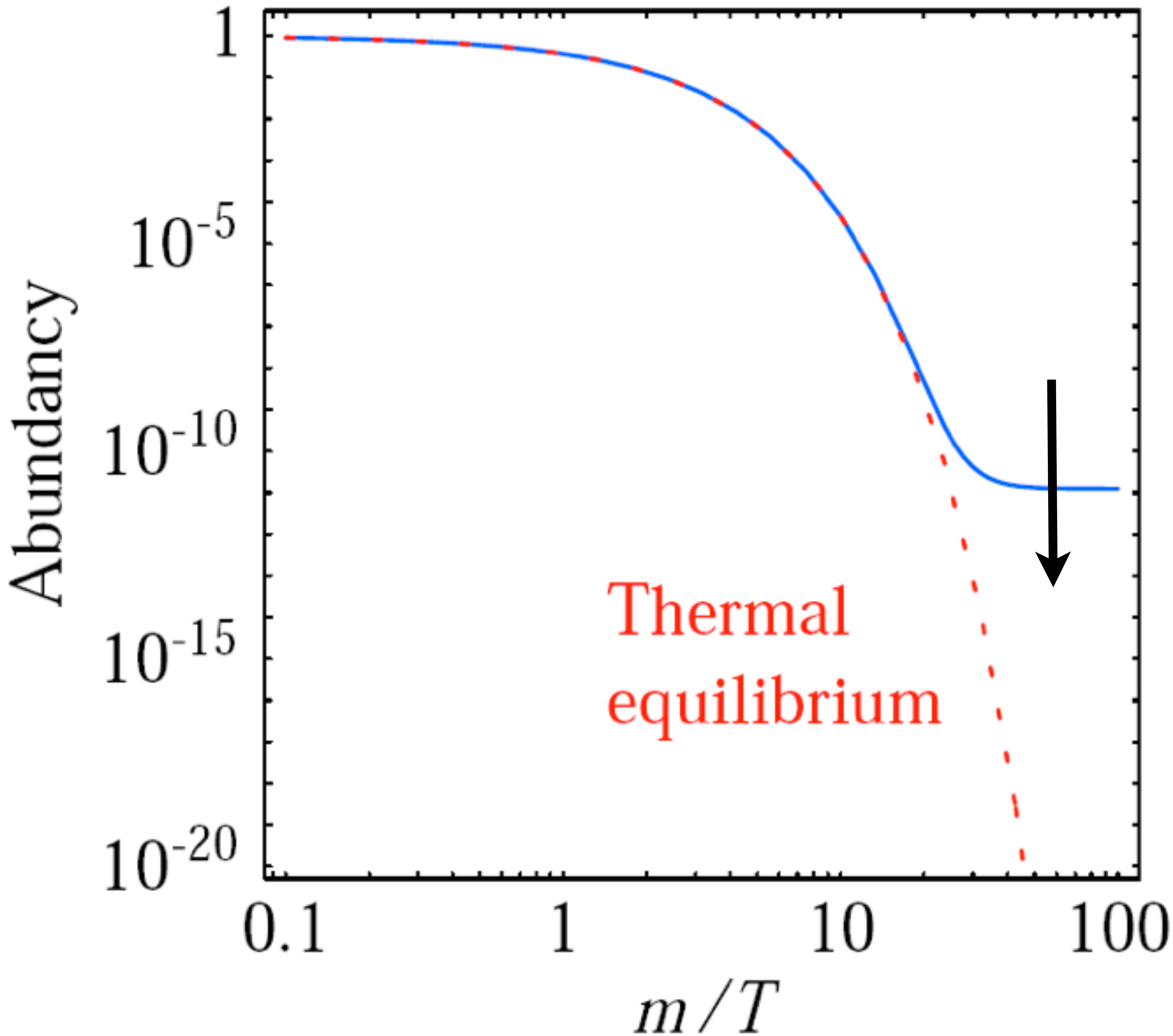
-> S stable and neutral

Silveira & Zee '85; McDonald '94; Burgess, Pospelov, ter Veldhuis '00; Patt,Wilczek '06; Barger et al '08; Andreas, Hambye, M.T. '08

UED Spectrum

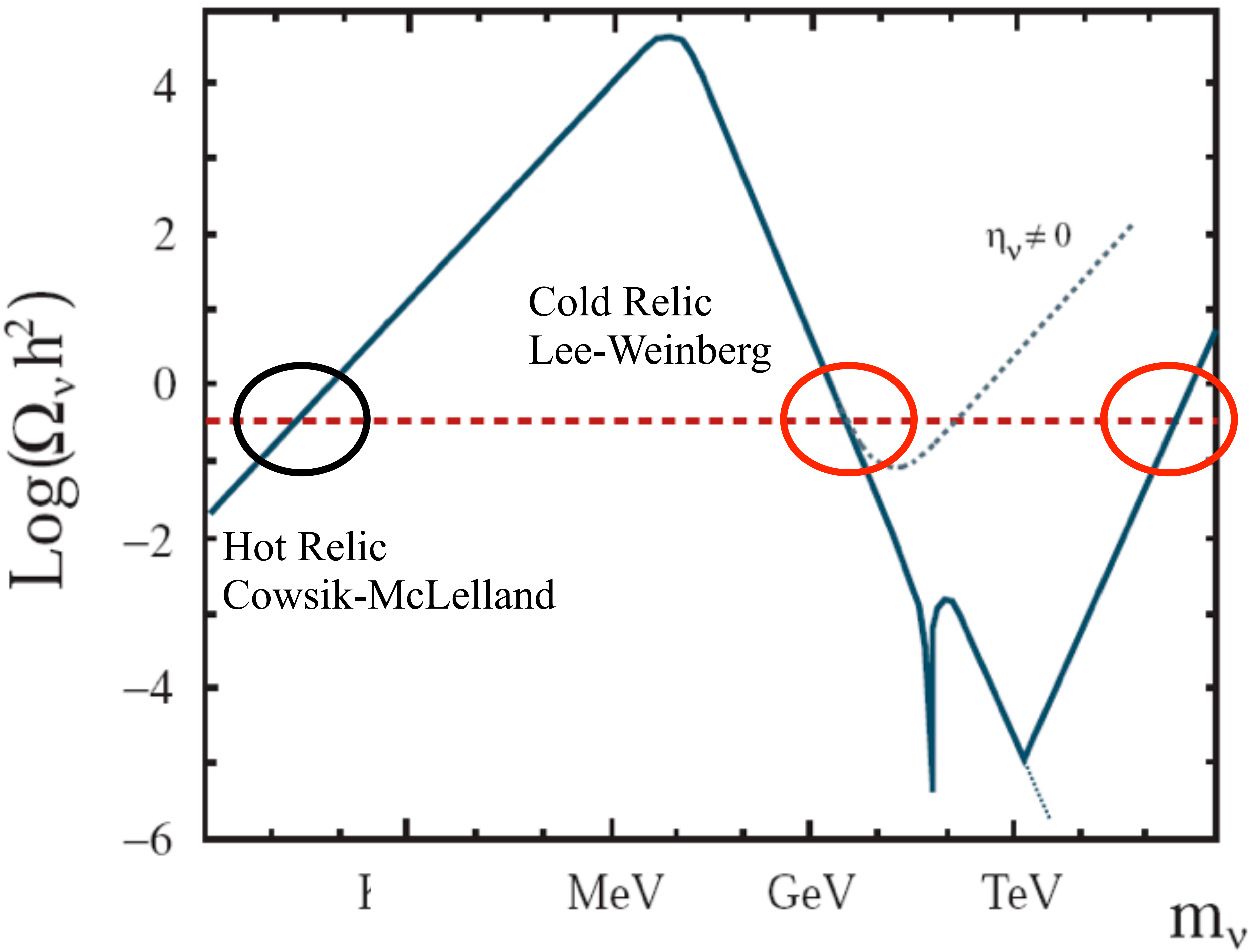


Inert Doublet Model Dark Matter Candidates



Increasing
Cross Section

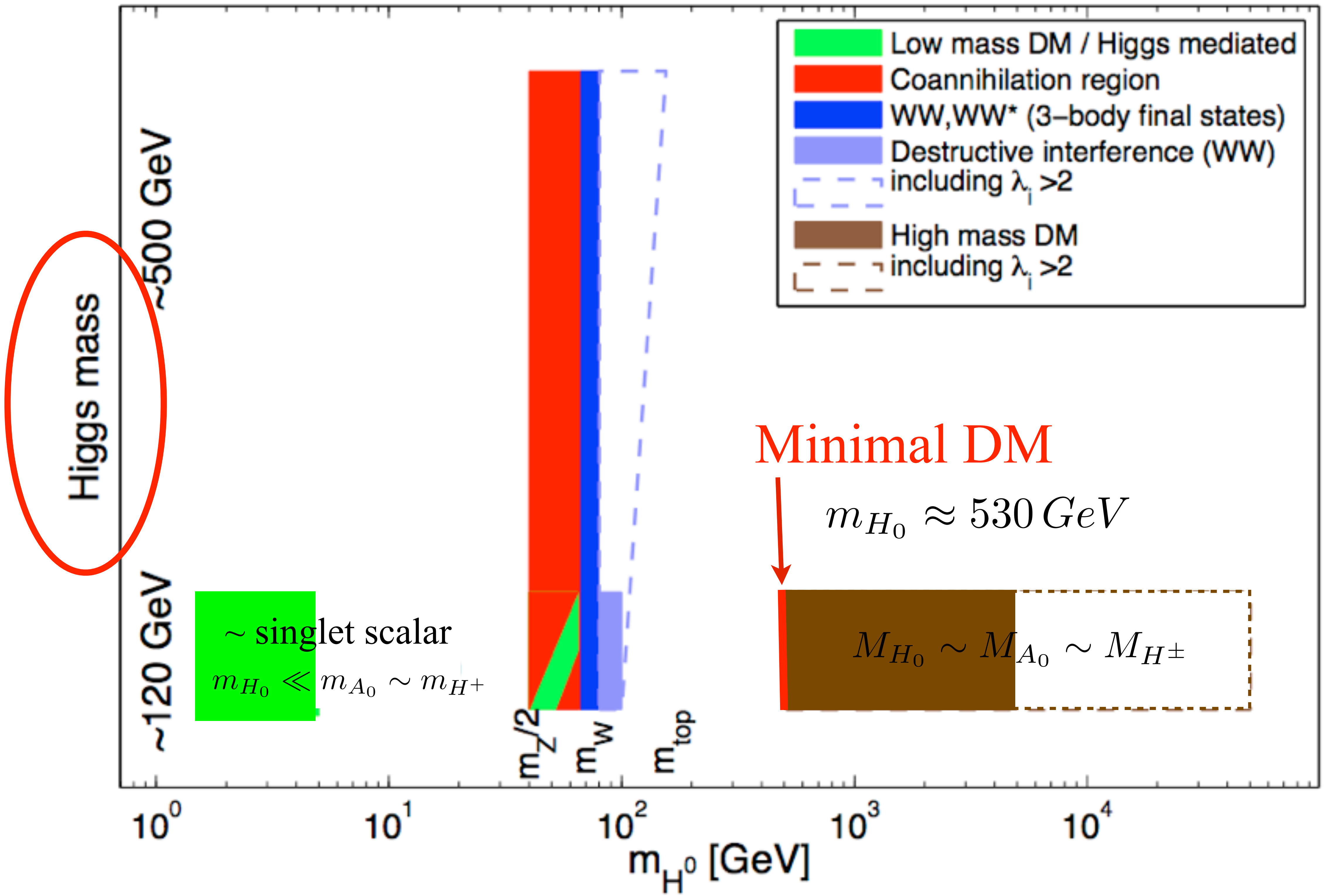
Instance : A massive Neutrino



Cold Relic
Griest-Kamionkowski

$$\sigma v \propto \frac{\alpha^2}{m_{DM}^2}$$

Possible H_0 Candidates?



(Courtesy M. Gustafsson)

Middle Mass
Range
~ 60-70 GeV

High Mass
Range
~ 0.5-50 TeV

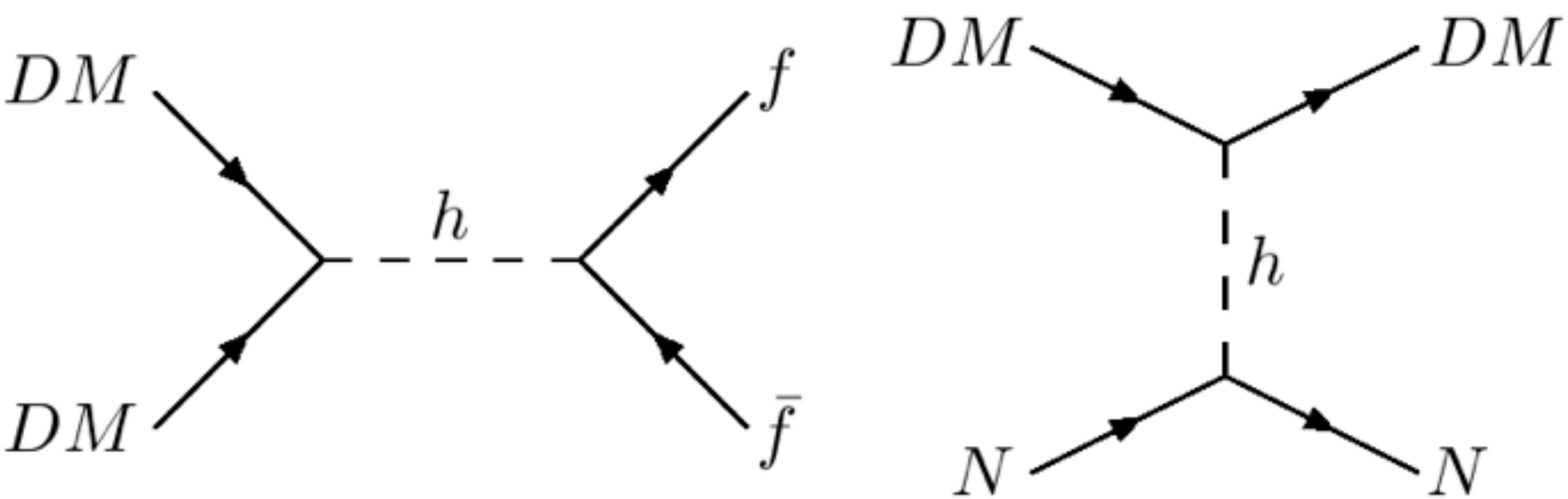
Low Mass
Range
~5-10 GeV

Middle Mass
Range
~ 60-70 GeV

High Mass
Range
~ 0.5-50 TeV

Low Mass
Range
~5-10 GeV

Possible H_0 Candidates : the «Ugly»



$$\sigma(SS \to \bar{f}f)v_{rel} = n_c \frac{\lambda_L^2}{\pi} \frac{m_f^2}{m_h^4 m_S^3} (m_S^2 - m_f^2)^{3/2}$$

$$\sigma(SN \to SN) = \frac{\lambda_L^2}{\pi} \frac{\mu_r^2}{m_h^4 m_S^2} f^2 m_N^2$$

$$R \equiv \sum_f \frac{\sigma(SS \to \bar{f}f)v_{rel}}{\sigma(SN \to SN)} = \sum_f \frac{n_c m_f^2}{f^2 m_N^2 \mu_r^2} \frac{(m_S^2 - m_f^2)^{3/2}}{m_S}$$

Low mass

Only parameters:

Coupling to SMS λ_L

DM mass $m_S \equiv m_{H_0}$

Relevant combination of parameters is $\frac{\lambda_L}{m_h^2}$

WMAP and perturbativity require a light SMS,

for $\lambda_L \sim 1$ if $m_h^2 = 125$

Also fine tuning is requested, for

$m_{H_0}^2 = \mu_2^2 + \lambda_L v^2$ implies $\mu_2^2 \sim -\lambda_L v^2$

in order to have a «light» WIMP

Why I ♥ Light Dark Matter

$$\Omega_{dm}/\Omega_b \approx 5$$

EW, SUSY,... ?

Freeze-out,... ?

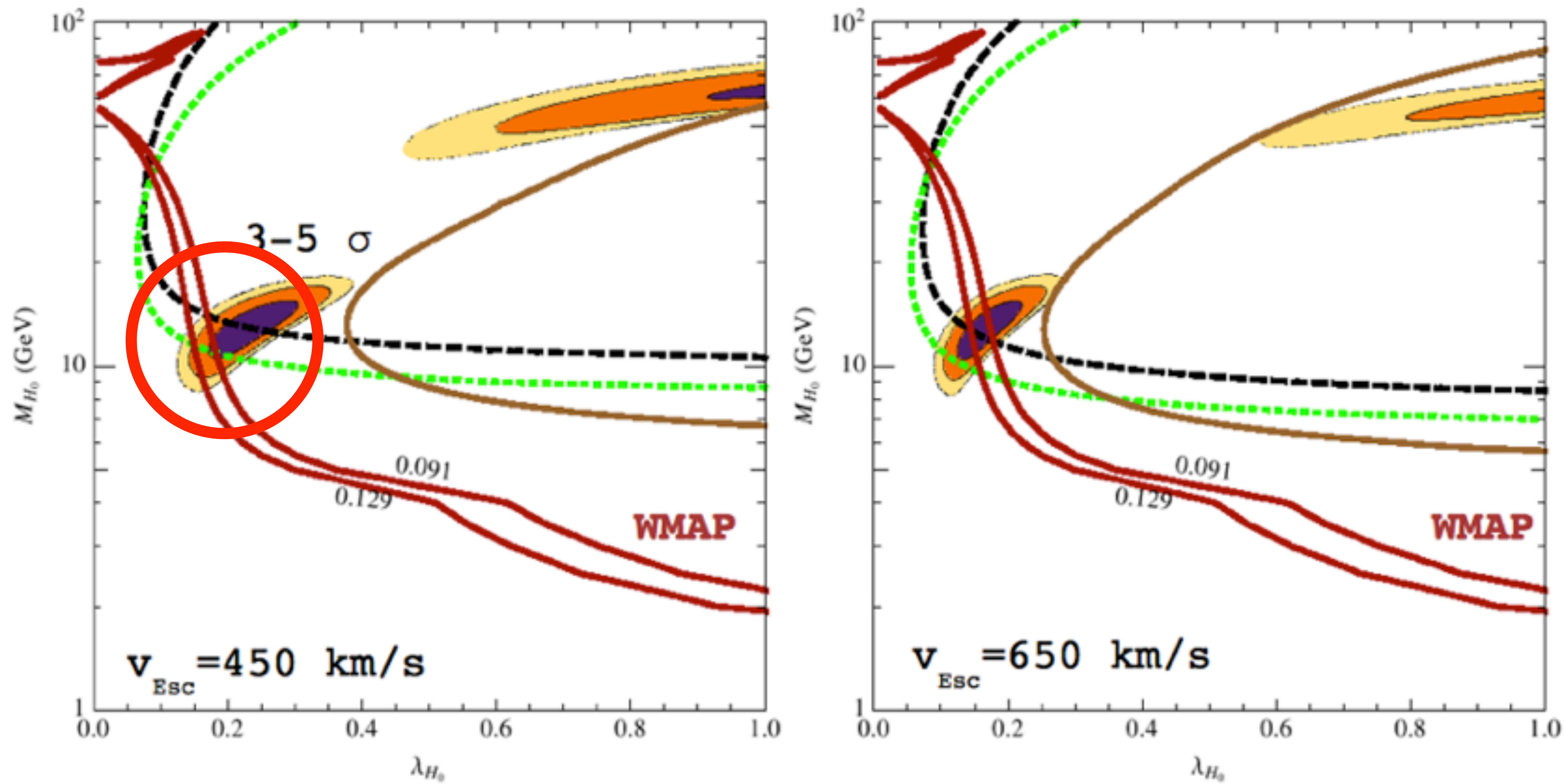
$$\frac{\text{Mass}_{dm} \times \text{Density}_{dm}}{\text{Mass}_b \times \text{Density}_b} = O(1)$$

QCD Dynamics

Baryogenesis (?)

Allowed DAMA region within the IDM

Back in 2009!



Mh = 120 GeV

Higgs-nucleon coupling
fn = 0.3

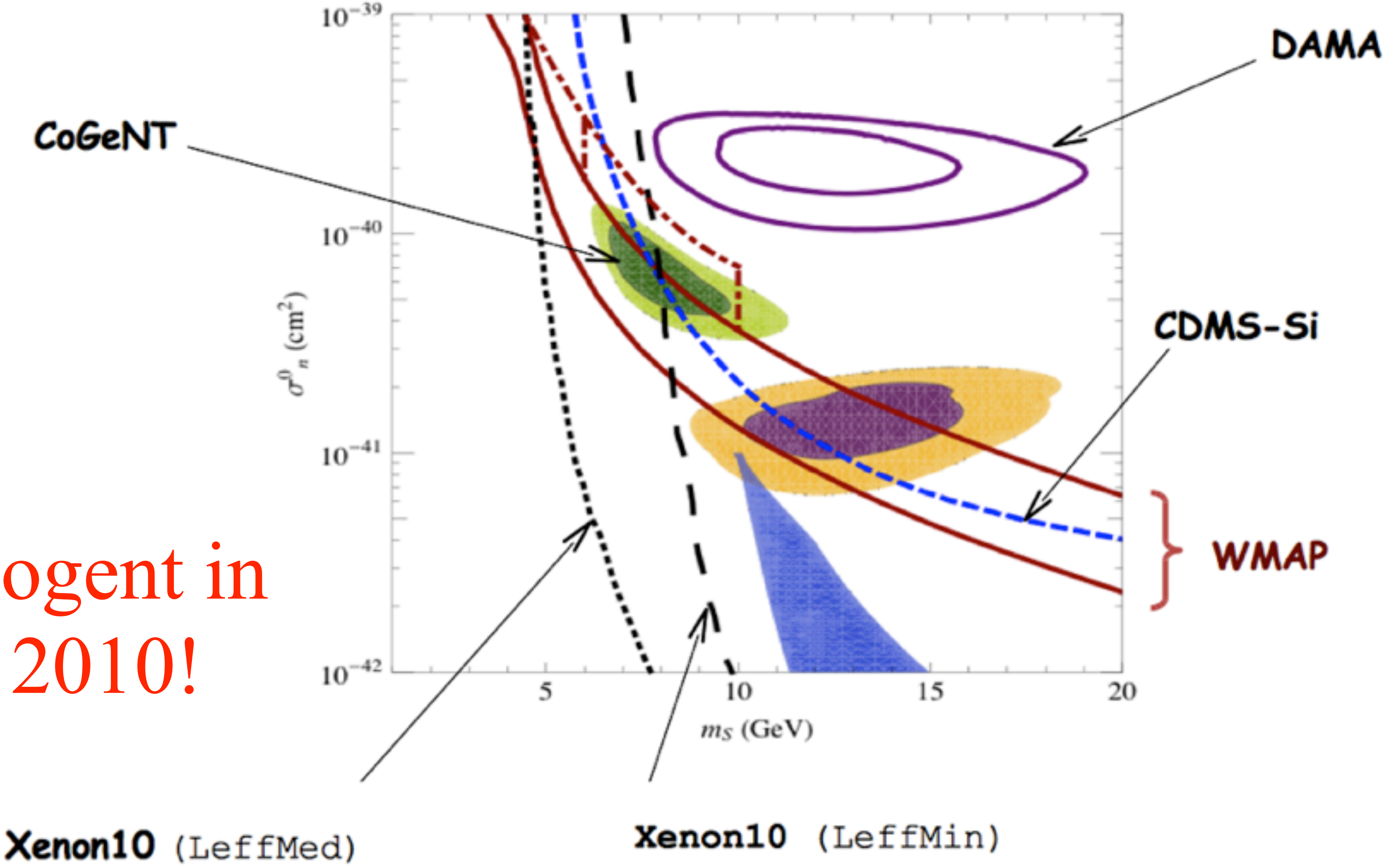
XENON10 95 CL

CDMS 95 CL

exclusion limit from total cumulative rate

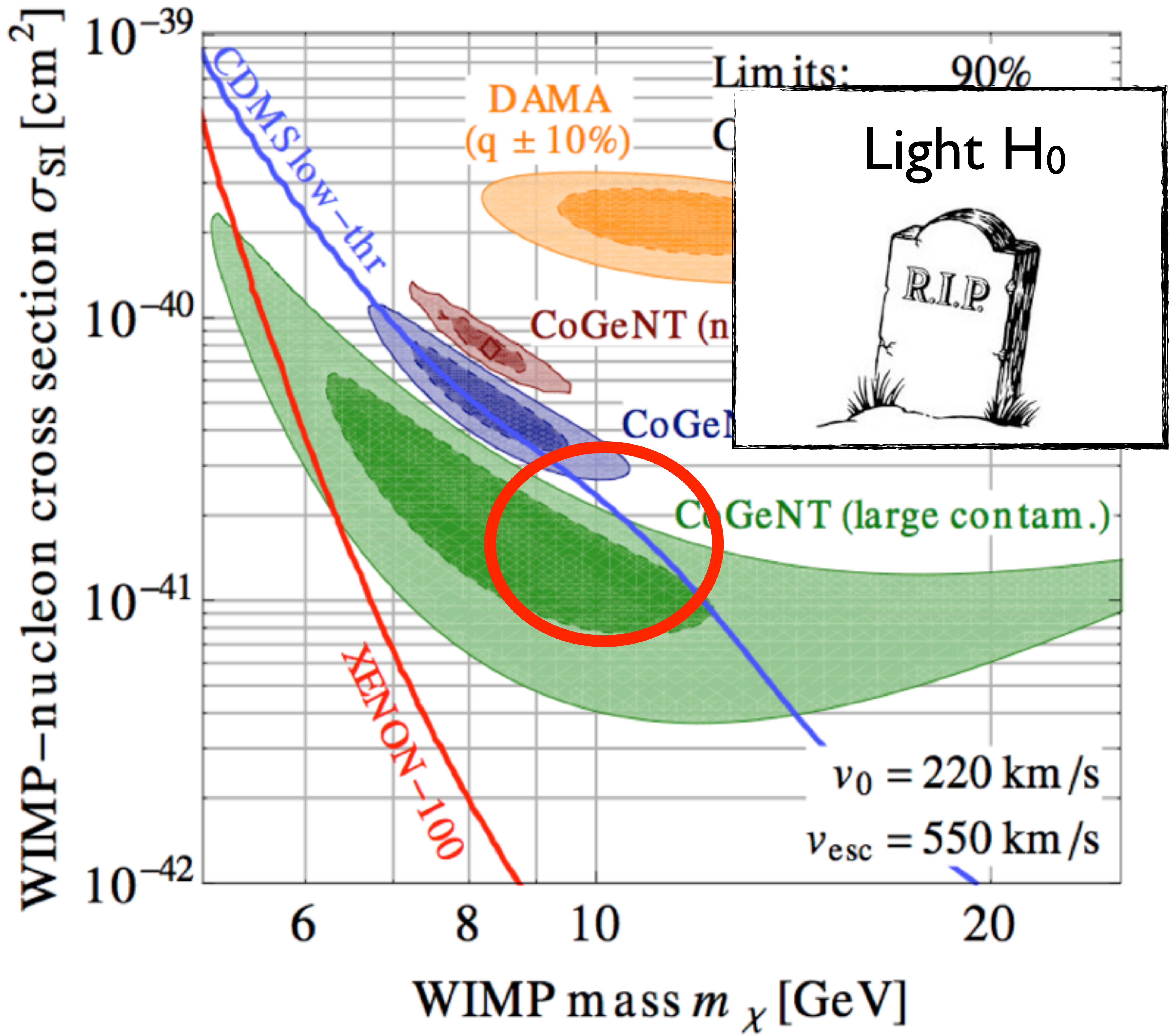
Andreas, Hambye, M.T.; Arina, Ling, MT

Singlet Scalar through the Higgs Portal



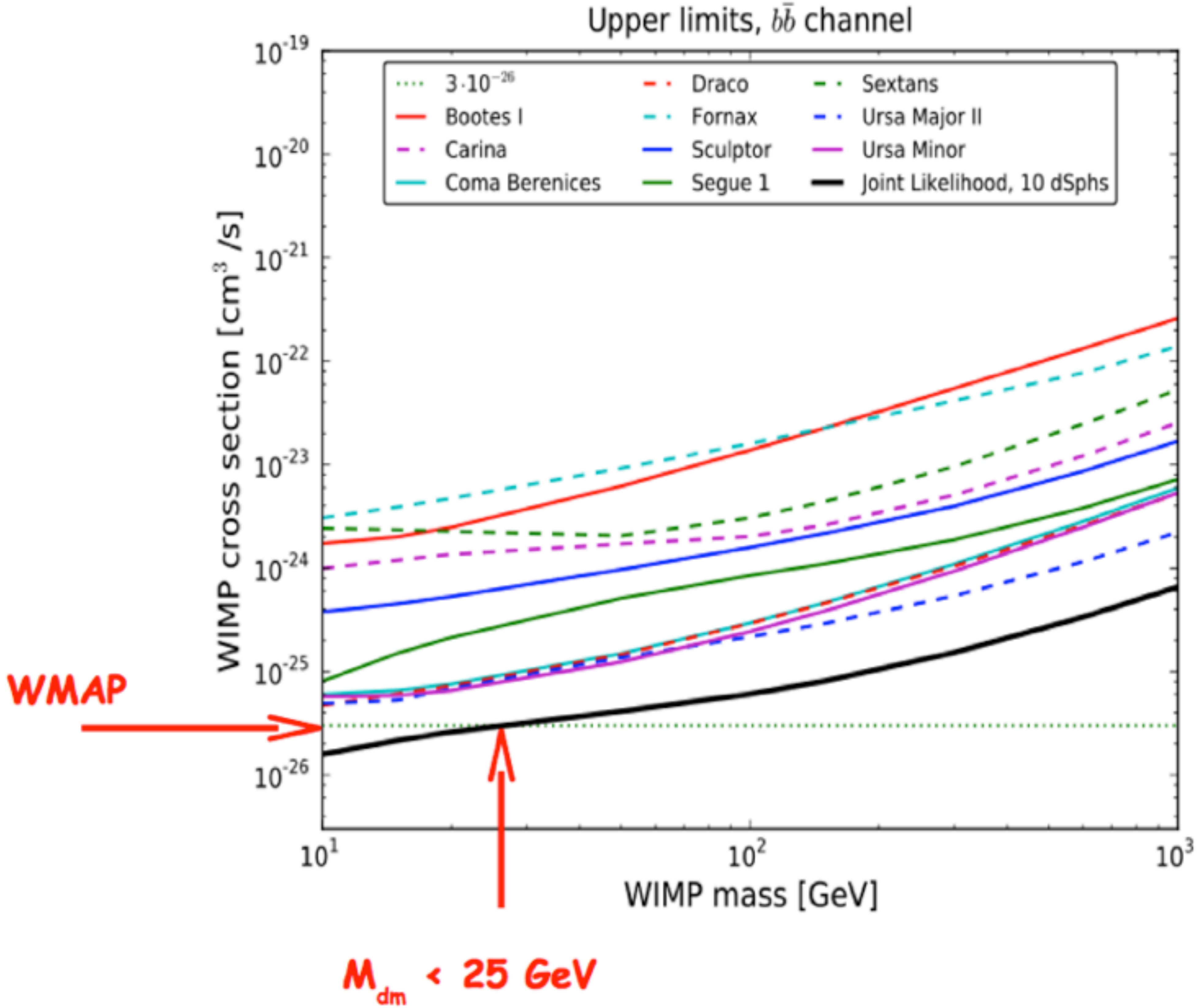
Cogent in 2010!

Figure from Andreas, Arina, Hambye, Ling & M.T. arXiv:1003.2595



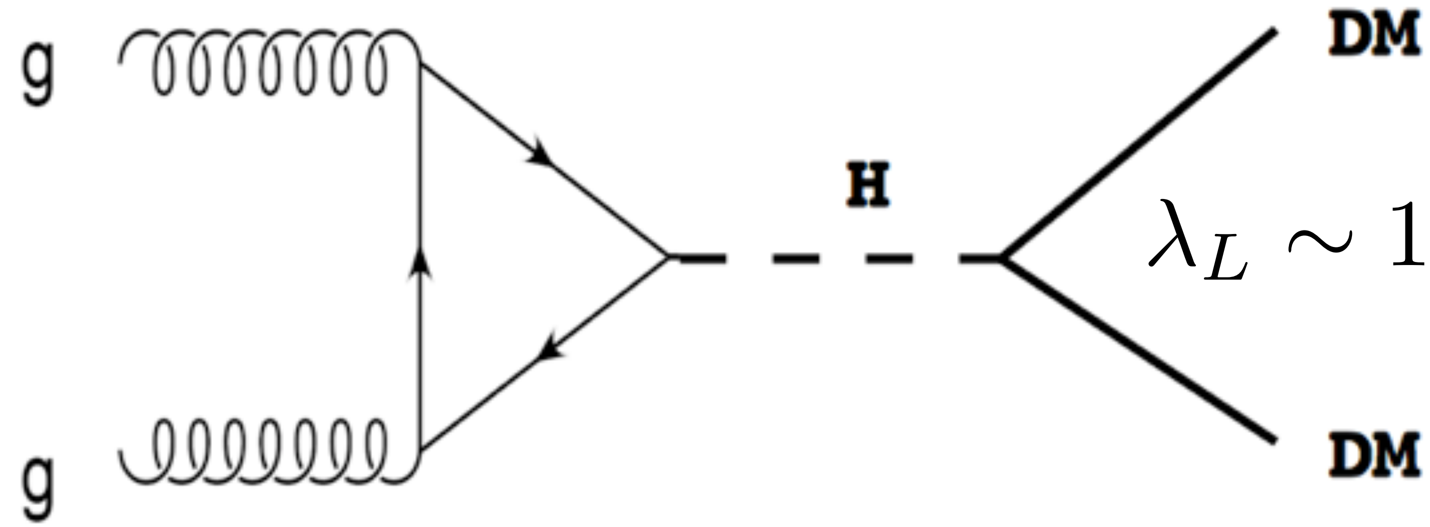
Kopp, Schwetz & Zupan (2011)

Limits from nearby dwarf spheroidal galaxies (Fermi-LAT)

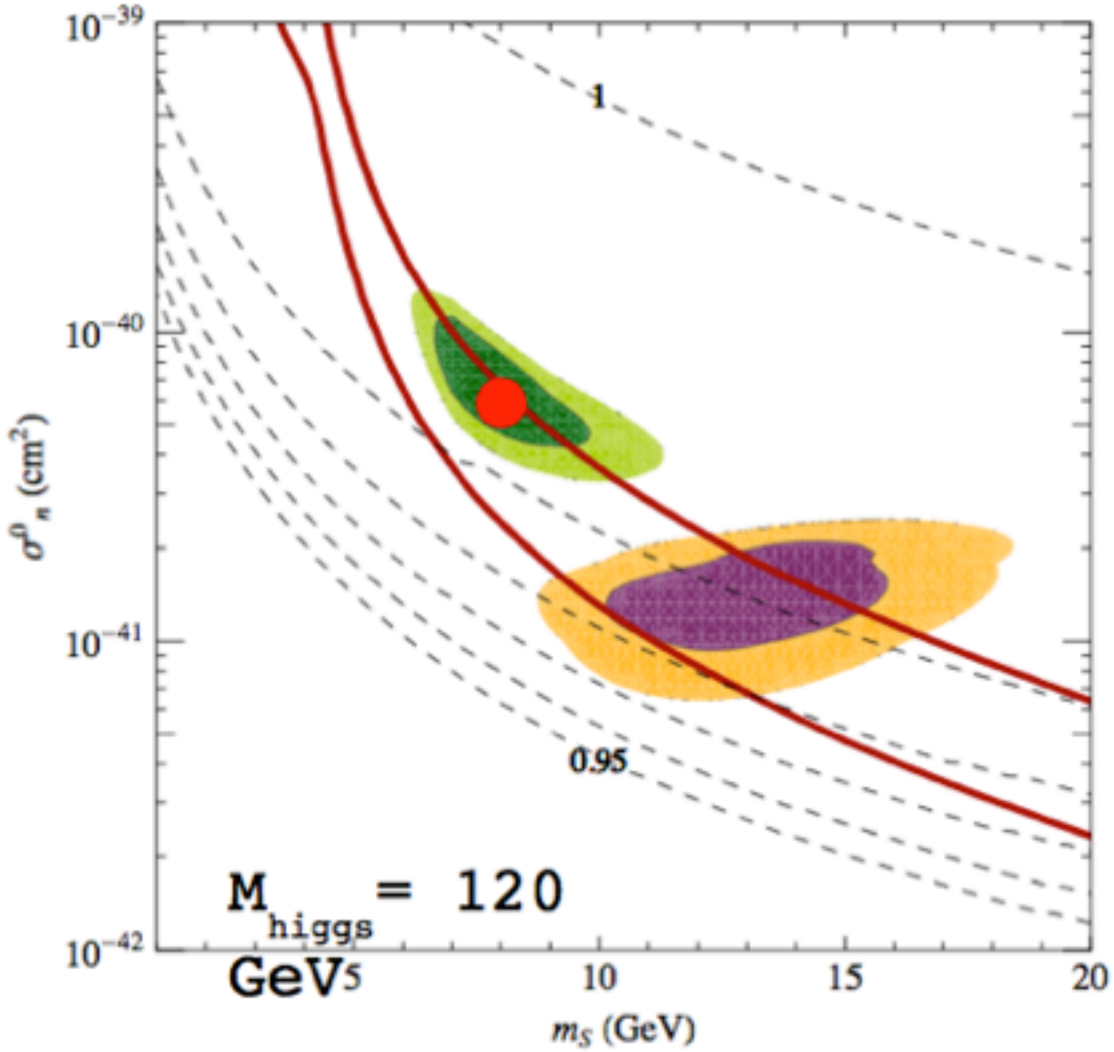


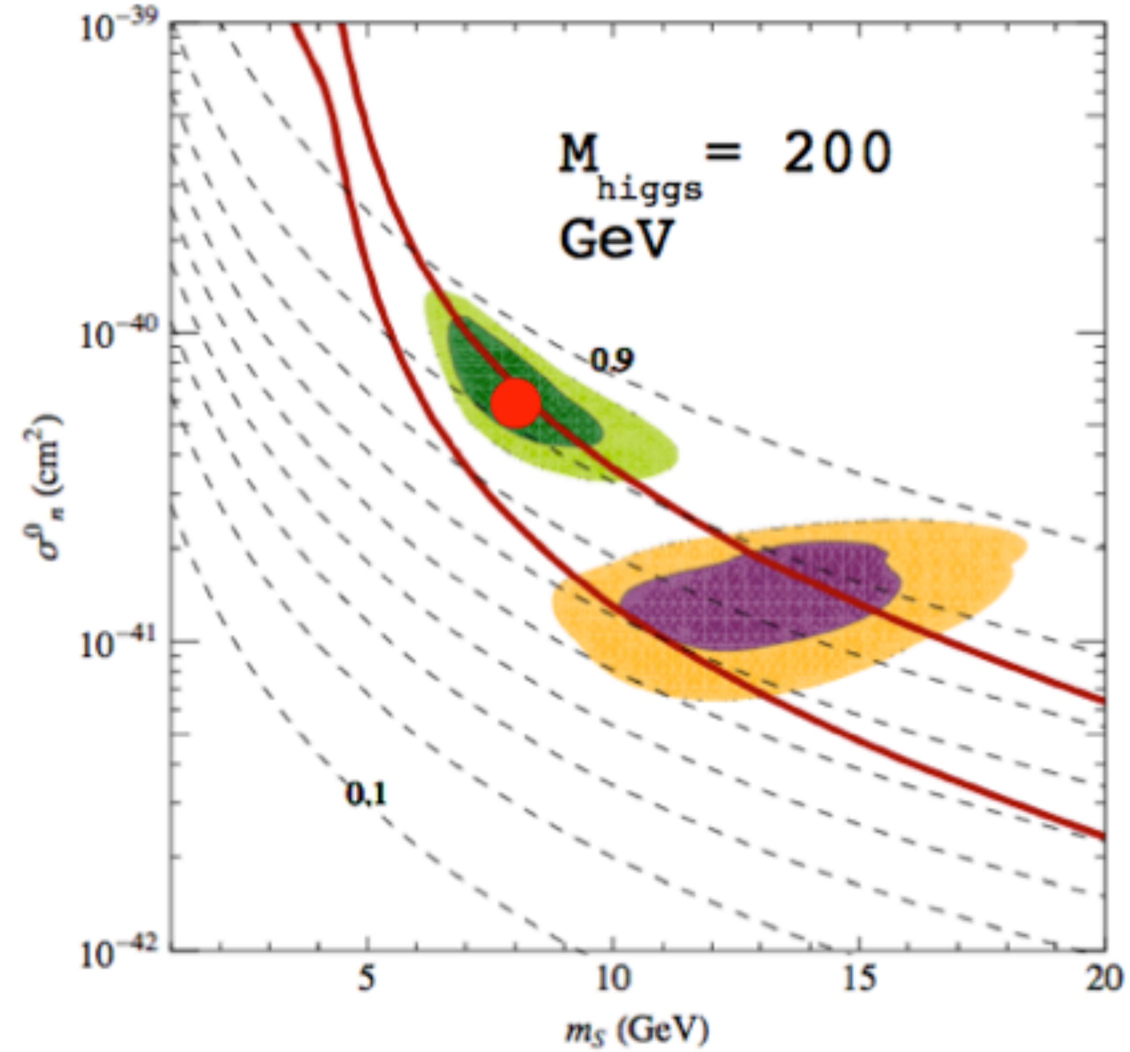
Fermi-LAT (1108.3546)

Last nail in the coffin is the observation of the SMS at 125 GeV



Light Scalar = Very Invisible ~~Higgs~~ SMS Scenario





For M_{DM} = 8 GeV

M_{higgs} = 120 GeV BR(h → SS) = 99.5%

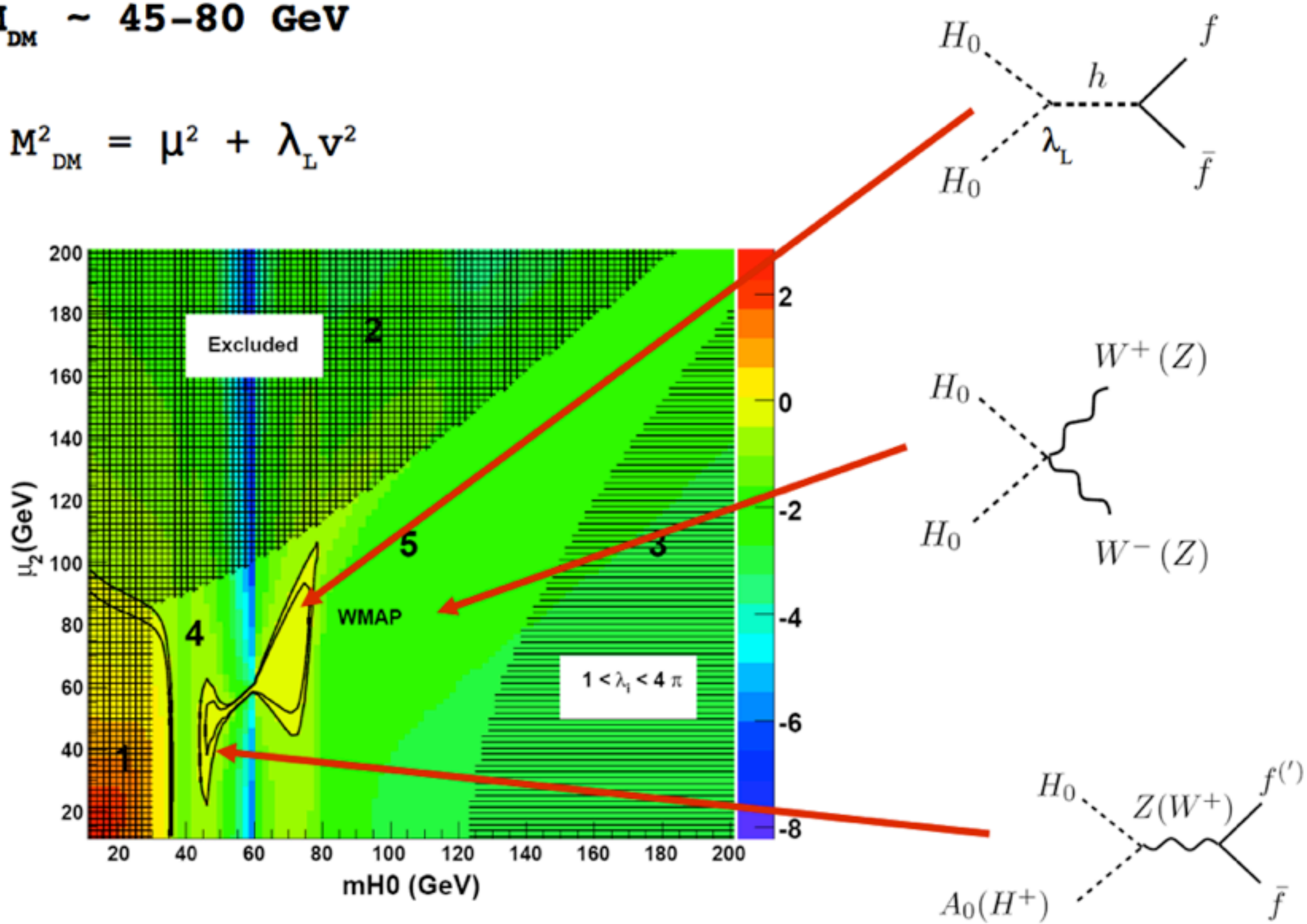
M_{higgs} = 200 GeV BR(h → SS) = 70%

Andreas, Arina, Ling, Hambye, MT (2010)

Middle Mass Range ~ the «Good»

Middle mass solutions
M_{DM} ~ 45-80 GeV

$$M^2_{DM} = \mu^2 + \lambda_L v^2$$



Coannihilation effects

Barbieri, Hall, Ryckhov;
L. Lopez Honorez, E. Nezri, J. Oliver, M.T.

m_{H^0}	m_{A^0}	$m_{H^\pm}$	μ_2^2	λ_{H^0}	λ_{A^0}	$\lambda_{H^\pm}$	$\sigma v_{\rm tot/3-body}$	$\sigma v_{\gamma\gamma/\gamma Z}$	$\sigma^{\rm SI}$	$\Omega_{H^0}h^2$	Br($h \to$inv)
53.0	120	130	2100	0.023	0.39	0.47	0.097/0.0089	1.8/0.095	1.5	0.115	26%
54.0	140	110	2500	0.013	0.54	0.31	0.056/0.016	2.3/0.17	0.50	0.107	11%
60.0	160	160	3624	$-7.6 \cdot 10^{-4}$	0.70	0.70	0.16/0.15	4.5/0.14	0.0015	0.110	0.02%
65.0	72.9	120	4200	$8.0 \cdot 10^{-4}$	0.036	0.32	0.40/0.38	5.7/3.1	0.0013	0.109	0
65.0	120	150	3640	0.019	0.34	0.60	3.1/1.9	20/14	0.69	0.110	0
75.5	130	98.0	6900	-0.038	0.32	0.086	1.0/0.91	4.5/3.8	2.1	0.104	0

TABLE VII: Benchmark models with m_h=126.0 GeV. Masses are given in units of GeV. Annihilation cross sections, at relative impact velocity $v \to 10^{-3}c$, are in units of 10^{-26} cm^3/s for $\sigma v_{\rm tot,3-body}$ and in units of 10^{-29} cm^3/s for $\sigma v_{\gamma\gamma,\gamma Z}$. Spin-independent cross sections $\sigma^{\rm SI}$ are in units of 10^{-45} cm^2. $\lambda_2 = 0.01$ for all models.

(Courtesy L. Lopez Honorez)

Vanilla candidate but challenged by constraints on SMS invisible width

m_{H^0}	m_{A^0}	m_{H^+}	μ_2^2	λ_{H^0}	λ_{A^0}	λ_{H^+}	$\sigma v_{tot/3-body}$	$\sigma v_{\gamma\gamma/\gamma Z}$	σ^{SI}	$\Omega_{H^0}h^2$	Br($h \to$inv)
53.0	120	130	2100	0.023	0.39	0.47	0.097/0.0089	1.8/0.095	1.5	0.115	26%
54.0	140	110	2500	0.013	0.54	0.31	0.056/0.016	2.3/0.17	0.50	0.107	11%
60.0	160	160	3624	$-7.6 \cdot 10^{-4}$	0.70	0.70	0.16/0.15	4.5/0.14	0.0015	0.110	0.02%
65.0	72.9	120	4200	$8.0 \cdot 10^{-4}$	0.036	0.32	0.40/0.38	5.7/3.1	0.0013	0.109	0
65.0	120	150	3640	0.019	0.34	0.60	3.1/1.9	20/14	0.69	0.110	0
75.5	130	98.0	6900	−0.038	0.32	0.086	1.0/0.91	4.5/3.8	2.1	0.104	0

TABLE VII: Benchmark models with m_h=126.0 GeV. Masses are given in units of GeV. Annihilation cross sections, at relative impact velocity $v \to 10^{-3}c$, are in units of 10^{-26} cm^3/s for $\sigma v_{tot,3-body}$ and in units of 10^{-29} cm^3/s for $\sigma v_{\gamma\gamma,\gamma Z}$. Spin-independent cross sections σ^{SI} are in units of 10^{-45} cm^2. $\lambda_2 = 0.01$ for all models.

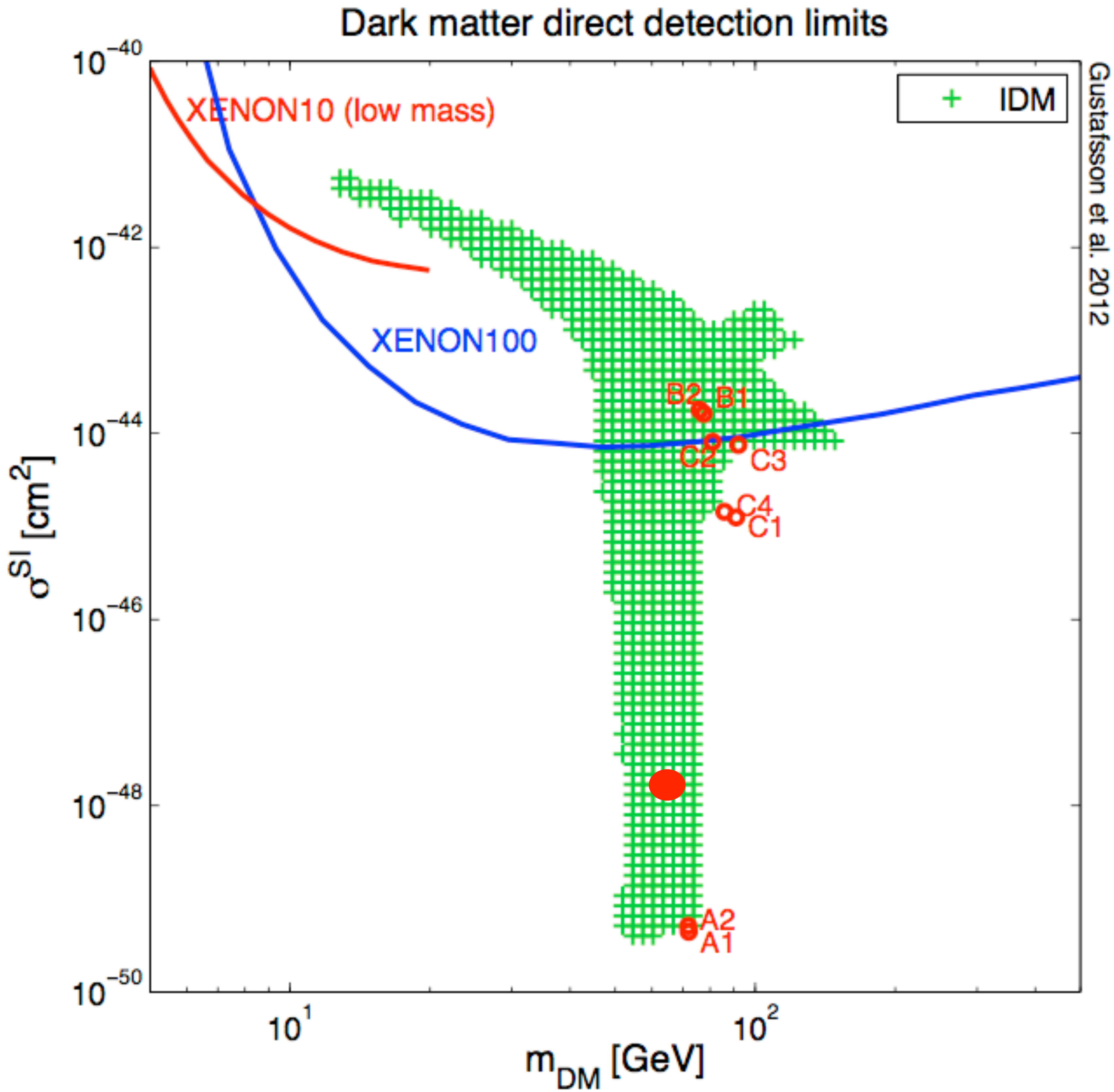
(Courtesy L. Lopez Honorez)

SMS resonance for relic abundance - No direct detection

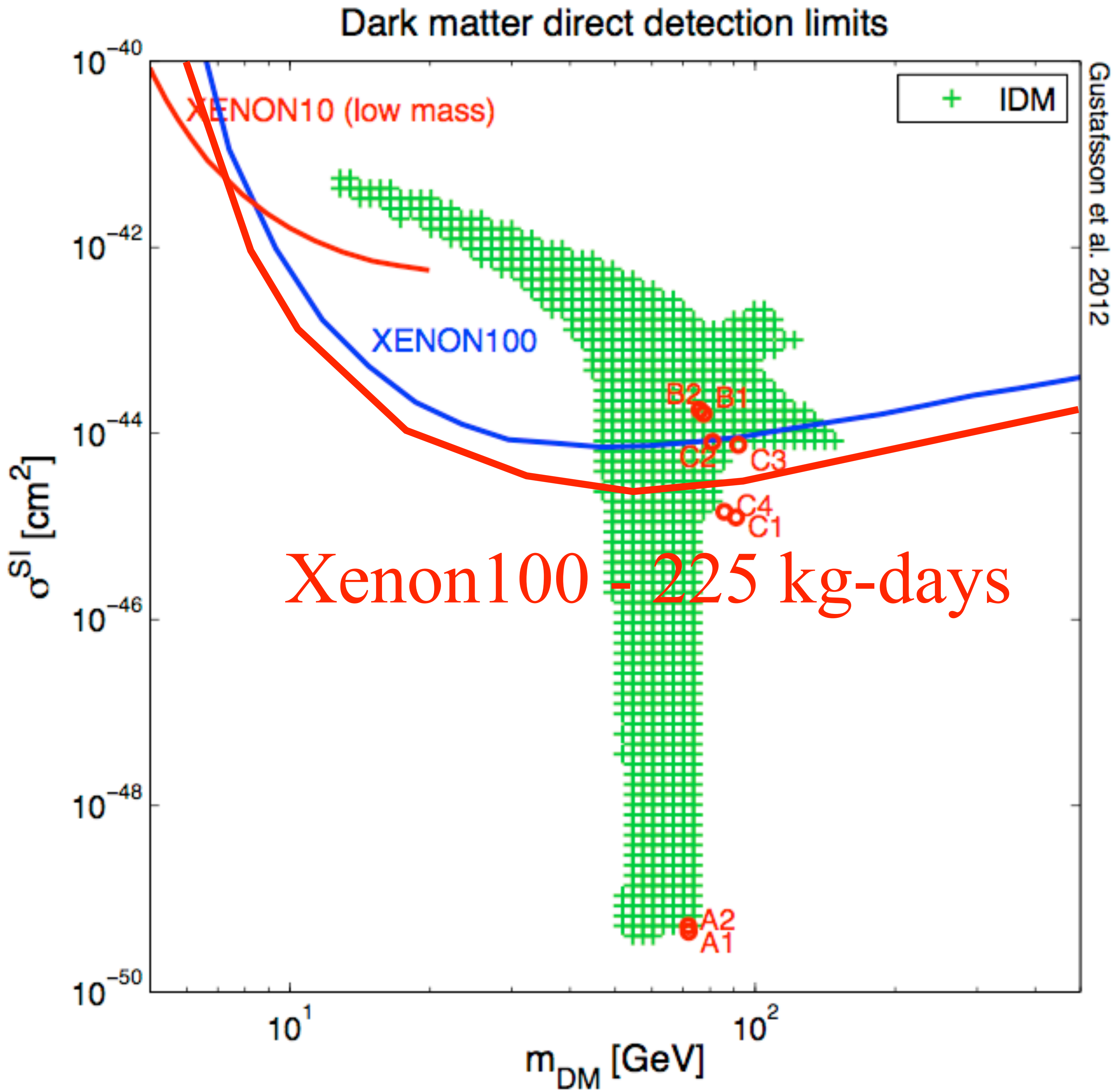
m_{H^0}	m_{A^0}	$m_{H^\pm}$	μ_2^2	λ_{H^0}	λ_{A^0}	$\lambda_{H^\pm}$	$\sigma v_{\text{tot}/3-\text{body}}$	$\sigma v_{\gamma\gamma/\gamma Z}$	σ^{SI}	$\Omega_{H^0} h^2$	Br($h \to$inv)
53.0	120	130	2100	0.023	0.39	0.47	0.097/0.0089	1.8/0.095	1.5	0.115	26%
54.0	140	110	2500	0.013	0.54	0.31	0.056/0.016	2.3/0.17	0.50	0.107	11%
60.0	160	160	3624	$-7.6 \cdot 10^{-4}$	0.70	0.70	0.16/0.15	4.5/0.14	0.0015	0.110	0.02%
65.0	72.9	120	4200	$8.0 \cdot 10^{-4}$	0.036	0.32	0.40/0.38	5.7/3.1	0.0013	0.109	0
65.0	120	150	3640	0.019	0.34	0.60	3.1/1.9	20/14	0.69	0.110	0
75.5	130	98.0	6900	-0.038	0.32	0.086	1.0/0.91	4.5/3.8	2.1	0.104	0

TABLE VII: Benchmark models with m_h=126.0 GeV. Masses are given in units of GeV. Annihilation cross sections, at relative impact velocity $v \to 10^{-3}c$, are in units of 10^{-26} cm^3/s for $\sigma v_{\text{tot},3-\text{body}}$ and in units of 10^{-29} cm^3/s for $\sigma v_{\gamma\gamma,\gamma Z}$. Spin-independent cross sections σ^{SI} are in units of 10^{-45} cm^2. $\lambda_2 = 0.01$ for all models.

(Courtesy L. Lopez Honorez)



Dark matter direct detection limits
XENON10 (low mass)
XENON100
IDM
Gustafsson et al. 2012
B2
B1
C2
C3
C4
C1
A2
A1
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
10^{1}
10^{2}
σ^{SI} [cm^2]
m_{DM} [GeV]


Dark matter direct detection limits
IDM
Gustafsson et al. 2012
XENON10 (low mass)
XENON100
B2
B1
C2
C3
C4
C1
A2
A1
Xenon100 - 225 kg-days
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
σ^{SI} [cm^2]
10^1
10^2
m_{DM} [GeV]

SMS resonance/Co-annihilation for relic abundance

No direct detection either

m_{H^0}	m_{A^0}	$m_{H^\pm}$	μ_2^2	λ_{H^0}	λ_{A^0}	$\lambda_{H^\pm}$	$\sigma v_{\text{tot}/3-\text{body}}$	$\sigma v_{\gamma\gamma/\gamma Z}$	σ^{SI}	$\Omega_{H^0}h^2$	Br($h \to$inv)
53.0	120	130	2100	0.023	0.39	0.47	0.097/0.0089	1.8/0.095	1.5	0.115	26%
54.0	140	110	2500	0.013	0.54	0.31	0.056/0.016	2.3/0.17	0.50	0.107	11%
60.0	160	160	3624	$-7.6 \cdot 10^{-4}$	0.70	0.70	0.16/0.15	4.5/0.14	0.0015	0.110	0.02%
65.0	72.9	120	4200	$8.0 \cdot 10^{-4}$	0.036	0.32	0.40/0.38	5.7/3.1	0.0013	0.109	0
65.0	120	150	3640	0.019	0.34	0.60	3.1/1.9	20/14	0.69	0.110	0
75.5	130	98.0	6900	-0.038	0.32	0.086	1.0/0.91	4.5/3.8	2.1	0.104	0

TABLE VII: Benchmark models with m_h=126.0 GeV. Masses are given in units of GeV. Annihilation cross sections, at relative impact velocity $v \to 10^{-3}c$, are in units of 10^{-26} cm^3/s for $\sigma v_{\text{tot},3-\text{body}}$ and in units of 10^{-29} cm^3/s for $\sigma v_{\gamma\gamma,\gamma Z}$. Spin-independent cross sections σ^{SI} are in units of 10^{-45} cm^2. $\lambda_2 = 0.01$ for all models.

(Courtesy L. Lopez Honorez)

3-body annihilation through W W* for relic abundance

(L. Lopez Honorez, C. Yaguna)

m_{H^0}	m_{A^0}	$m_{H^\pm}$	μ_2^2	λ_{H^0}	λ_{A^0}	$\lambda_{H^\pm}$	$\sigma v_{\text{tot}}/_{3-\text{body}}$	$\sigma v_{\gamma\gamma/\gamma Z}$	σ^{SI}	$\Omega_{H^0}h^2$	Br($h \to$inv)
53.0	120	130	2100	0.023	0.39	0.47	0.097/0.0089	1.8/0.095	1.5	0.115	26%
54.0	140	110	2500	0.013	0.54	0.31	0.056/0.016	2.3/0.17	0.50	0.107	11%
60.0	160	160	3624	$-7.6 \cdot 10^{-4}$	0.70	0.70	0.16/0.15	4.5/0.14	0.0015	0.110	0.02%
65.0	72.9	120	4200	$8.0 \cdot 10^{-4}$	0.036	0.32	0.40/0.38	5.7/3.1	0.0013	0.109	0
65.0	120	150	3640	0.019	0.34	0.60	3.1/1.9	20/14	0.69	0.110	0
75.5	130	98.0	6900	−0.038	0.32	0.086	1.0/0.91	4.5/3.8	2.1	0.104	0

TABLE VII: Benchmark models with m_h=126.0 GeV. Masses are given in units of GeV. Annihilation cross sections, at relative impact velocity $v \to 10^{-3}c$, are in units of 10^{-26} cm^3/s for $\sigma v_{\text{tot},3-\text{body}}$ and in units of 10^{-29} cm^3/s for $\sigma v_{\gamma\gamma,\gamma Z}$. Spin-independent cross sections σ^{SI} are in units of 10^{-45} cm^2. $\lambda_2 = 0.01$ for all models.

(Courtesy L. Lopez Honorez)

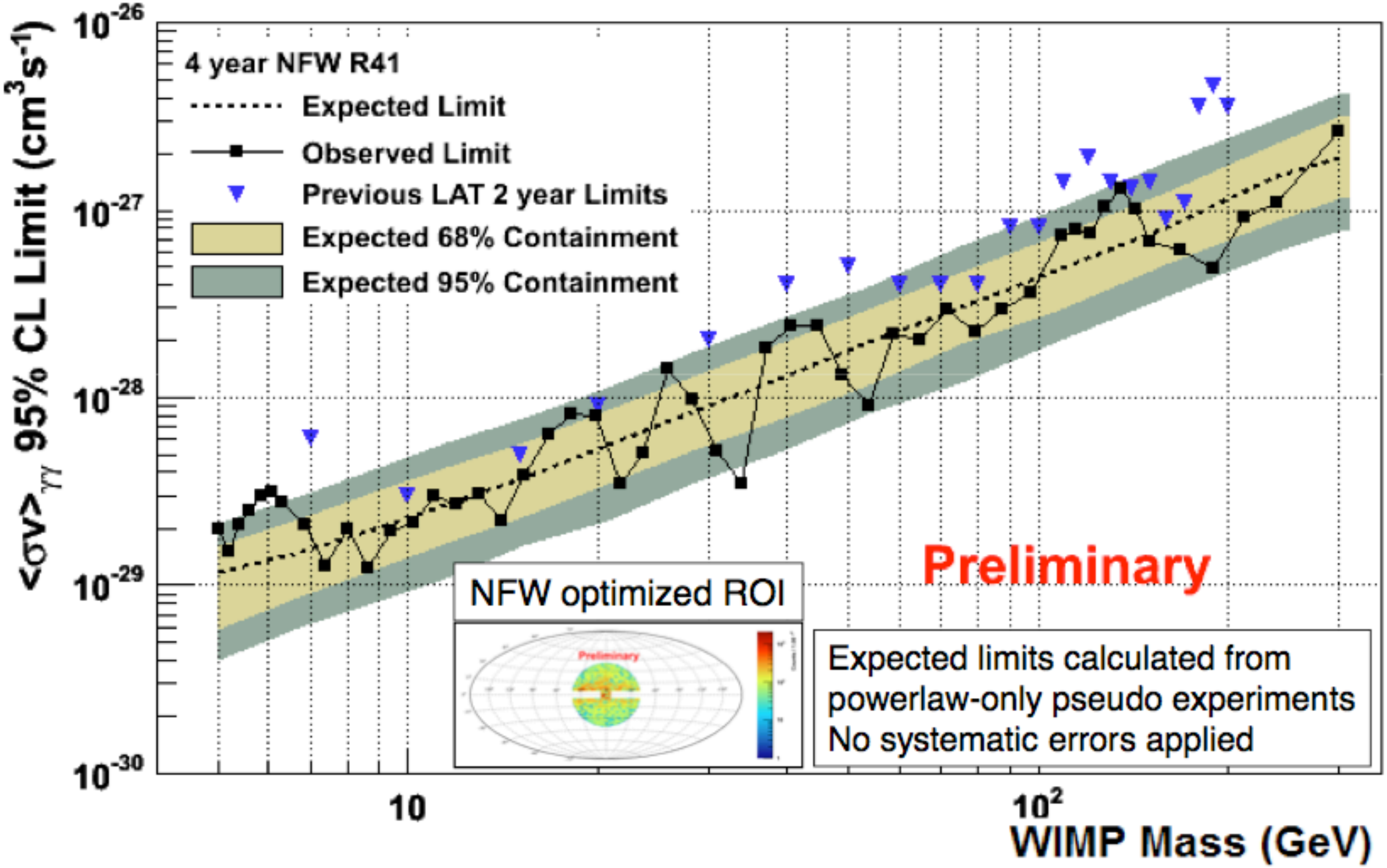
Gamma-ray spectral features?

m_{H^0}	m_{A^0}	$m_{H^\pm}$	μ_2^2	λ_{H^0}	λ_{A^0}	$\lambda_{H^\pm}$	$\sigma v_{\text{tot}/3-\text{body}}$	$\sigma v_{\gamma\gamma/\gamma Z}$	σ^{SI}	$\Omega_{H^0} h^2$	Br($h \to$inv)
53.0	120	130	2100	0.023	0.39	0.47	0.097/0.0089	1.8/0.095	1.5	0.115	26%
54.0	140	110	2500	0.013	0.54	0.31	0.056/0.016	2.3/0.17	0.50	0.107	11%
60.0	160	160	3624	$-7.6 \cdot 10^{-4}$	0.70	0.70	0.16/0.15	4.5/0.14	0.0015	0.110	0.02%
65.0	72.9	120	4200	$8.0 \cdot 10^{-4}$	0.036	0.32	0.40/0.38	5.7/3.1	0.0013	0.109	0
65.0	120	150	3640	0.019	0.34	0.60	3.1/1.9	20/14	0.69	0.110	0
75.5	130	98.0	6900	−0.038	0.32	0.086	1.0/0.91	4.5/3.8	2.1	0.104	0

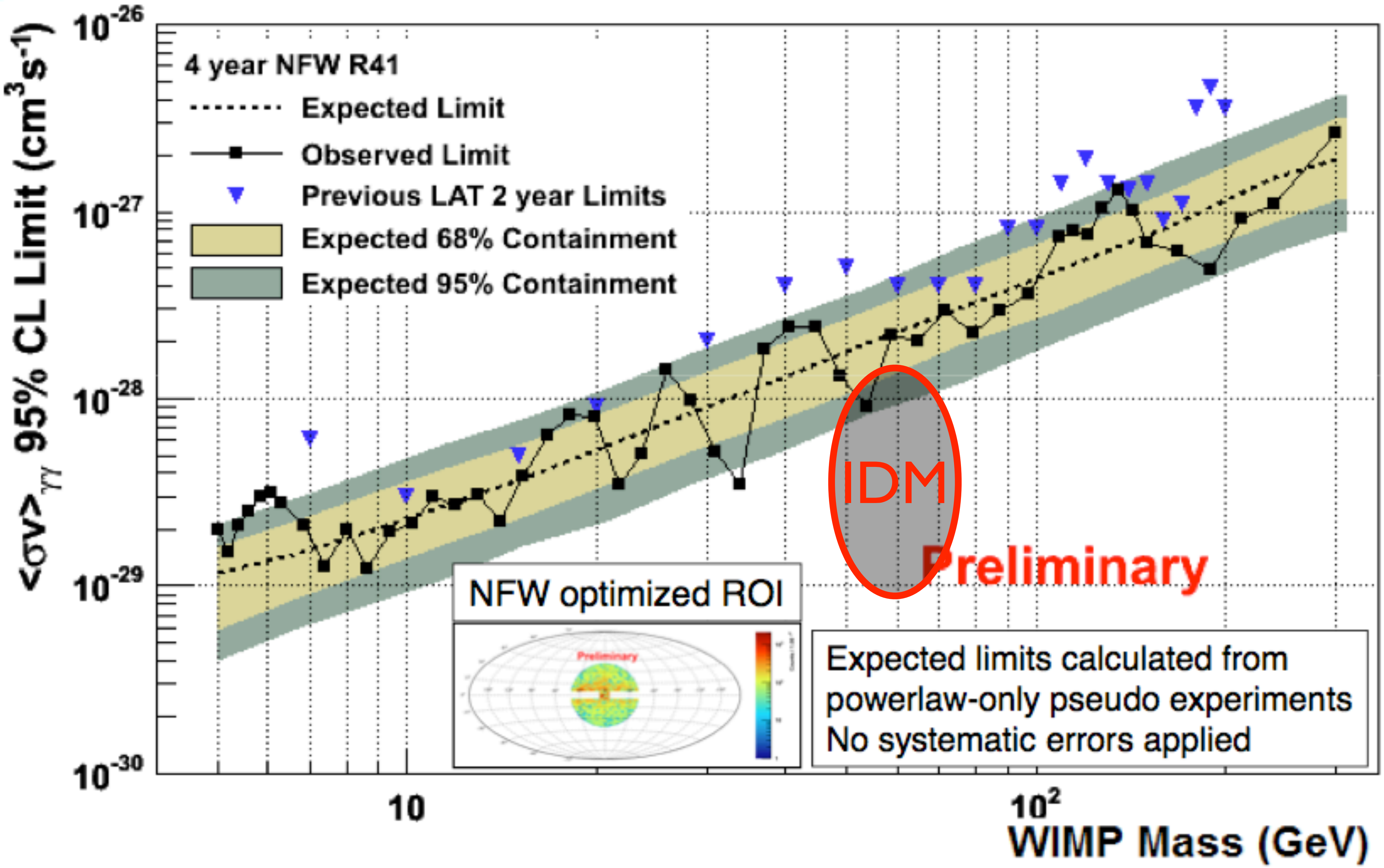
TABLE VII: Benchmark models with m_h=126.0 GeV. Masses are given in units of GeV. Annihilation cross sections, at relative impact velocity $v \to 10^{-3}c$, are in units of 10^{-26} cm^3/s for $\sigma v_{\text{tot},3-\text{body}}$ and in units of 10^{-29} cm^3/s for $\sigma v_{\gamma\gamma,\gamma Z}$. Spin-independent cross sections σ^{SI} are in units of 10^{-45} cm^2. $\lambda_2 = 0.01$ for all models.

(Courtesy L. Lopez Honorez)

95% CL $\langle\sigma v\rangle_{\gamma\gamma}$ NFW Upper Limit R41



95% CL $\langle\sigma v\rangle_{\gamma\gamma}$ NFW Upper Limit R41



Significant Gamma-Ray lines from IDM?

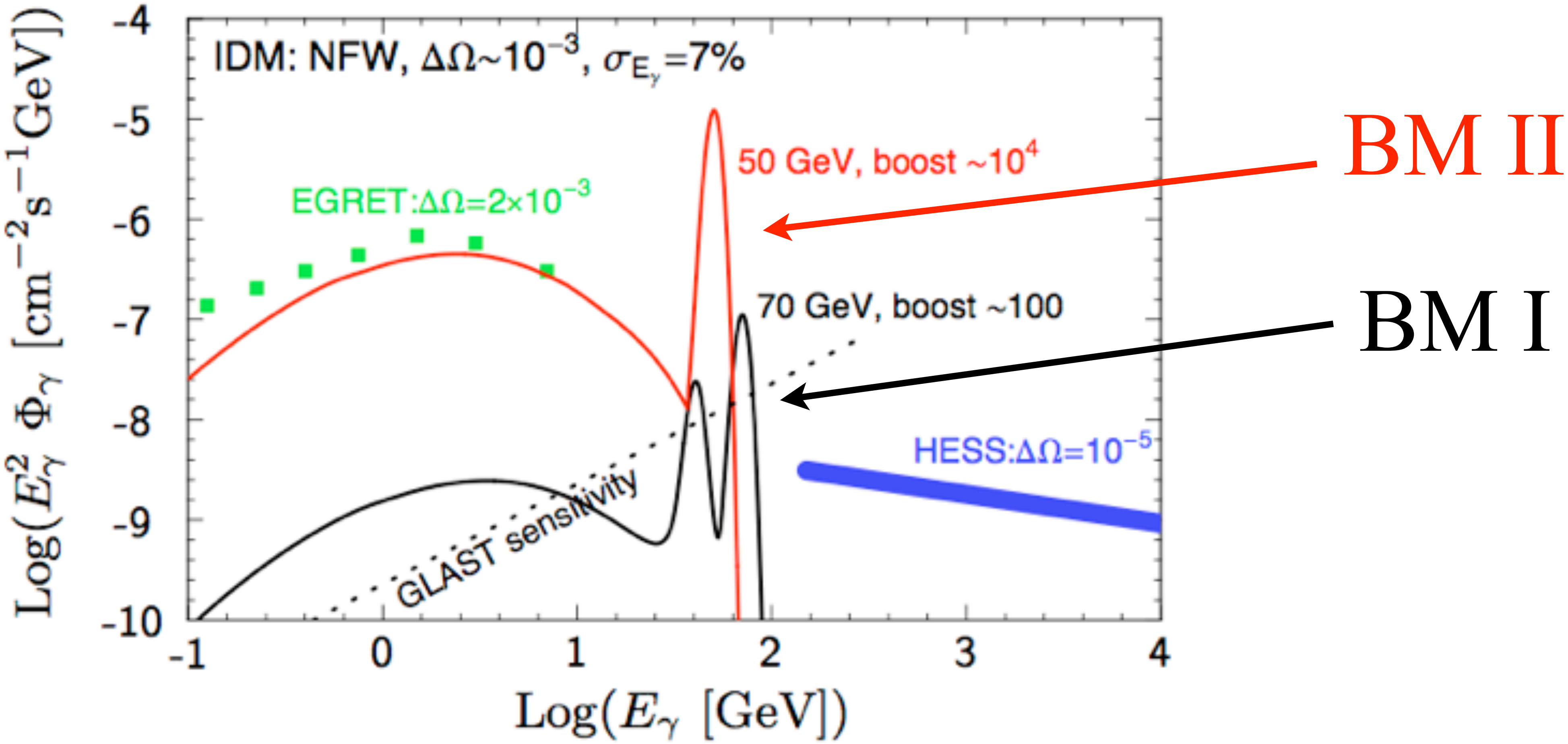


TABLE I: *IDM benchmark models. (In units of GeV.)*

Model	m_h	m_{H^0}	m_{A^0}	$m_{H^\pm}$	μ_2	$\lambda_2 \times 1$ GeV
I	500	70	76	190	120	0.1
II	500	50	58.5	170	120	0.1
III	200	70	80	120	125	0.1
IV	120	70	80	120	95	0.1

TABLE II: *IDM benchmark model results.*

$v\sigma_{tot}^{v\to 0}$ [cm^{3}s^{-1}]	Branching ratios [%]: $\gamma\gamma$	$Z\gamma$	$b\bar{b}$	$c\bar{c}$	$\tau^+\tau^-$	$\Omega_{\rm CDM}h^2$
1.6×10^{-28}	36	33	26	2	3	0.10
8.2×10^{-29}	29	0.6	60	4	7	0.10
8.7×10^{-27}	2	2	81	5	9	0.12
1.9×10^{-26}	0.04	0.1	85	5	10	0.11

Gustafsson, Lundstrom, Bergstrom, Edsjo, arXiv:astro-ph/0703512

Significant Gamma-Ray lines from IDM?

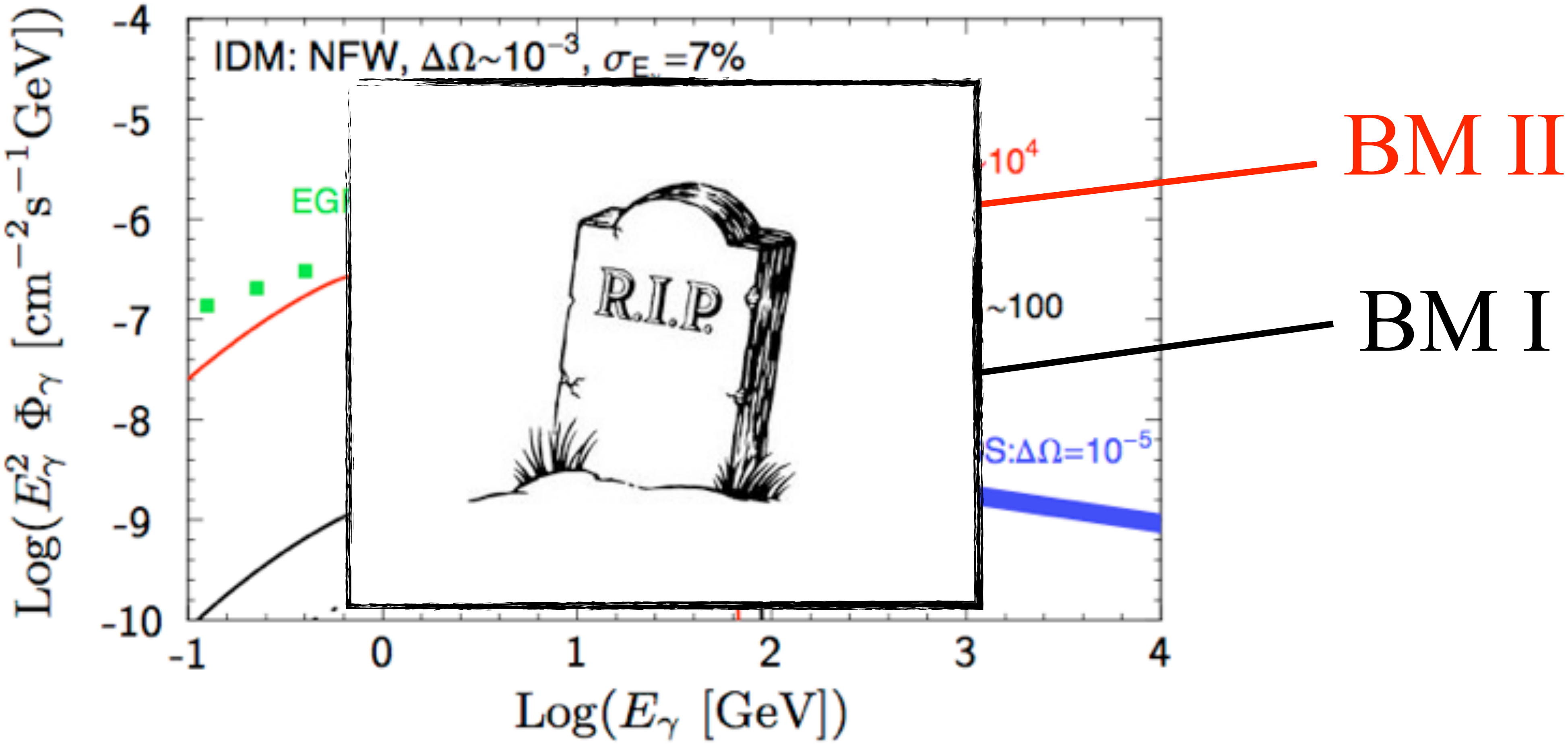


TABLE I: *IDM benchmark models. (In units of GeV.)*

Model	m_h	m_{H^0}	m_{A^0}	$m_{H^\pm}$	μ_2	$\lambda_2 \times 1$ GeV
I	500	70	76	190	120	0.1
II	500	50	58.5	170	120	0.1
III	200	70	80	120	125	0.1
IV	120	70	80	120	95	0.1

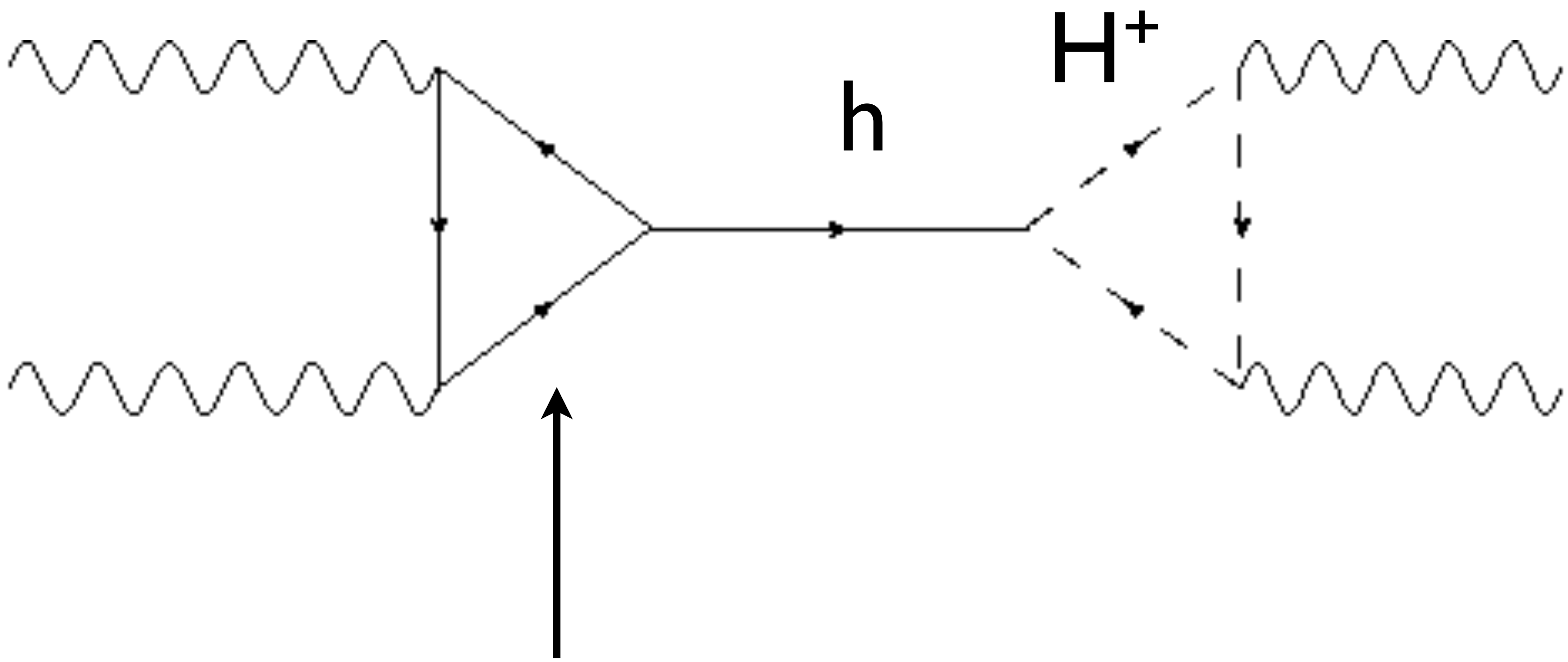
TABLE II: *IDM benchmark model results.*

$v\sigma_{tot}^{v\to 0}$ [cm^{3}s^{-1}]	Branching ratios [%]: $\gamma\gamma$	$Z\gamma$	$b\bar{b}$	$c\bar{c}$	$\tau^+\tau^-$	$\Omega_{CDM}h^2$
1.6×10^{-28}	36	33	26	2	3	0.10
8.2×10^{-29}	29	0.6	60	4	7	0.10
8.7×10^{-27}	2	2	81	5	9	0.12
1.9×10^{-26}	0.04	0.1	85	5	10	0.11

Gustafsson, Lundstrom, Bergstrom, Edsjo, arXiv:astro-ph/0703512

SMS diphoton decay rate?

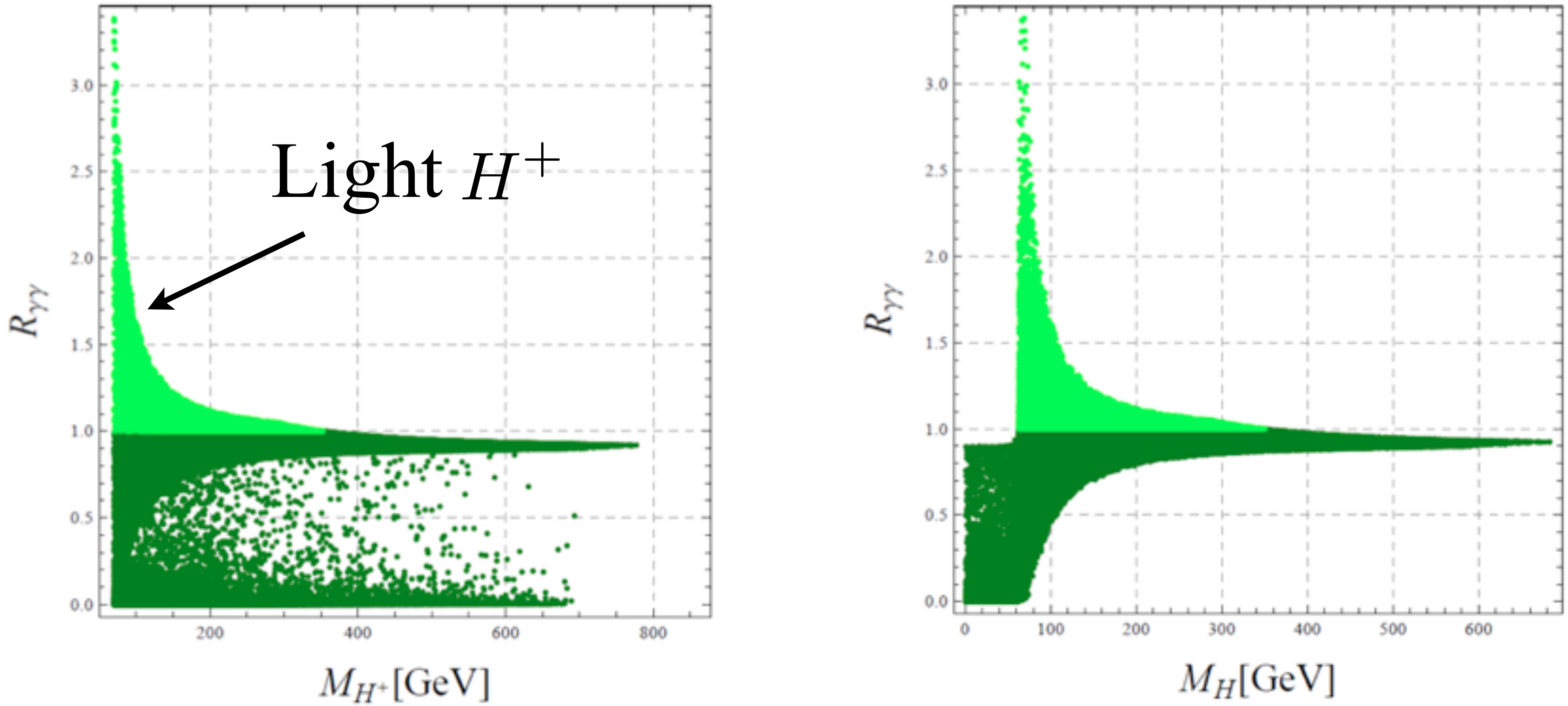
(cf talk of Maria Krawczyk)



Unchanged

SMS diphoton decay rate?

(cf talk of Maria Krawczyk)



$$\frac{\Gamma_{\gamma\gamma}(IDM)}{\Gamma_{\gamma\gamma}(SM)} >\sim 1.3 \quad \text{for} \quad 62.5\text{GeV} < M_{H_0} < 135\text{GeV}$$

Swiezewksa & Krawczyk arXiv:1212.4100

Multi-leptons signals @ LHC

di-leptons

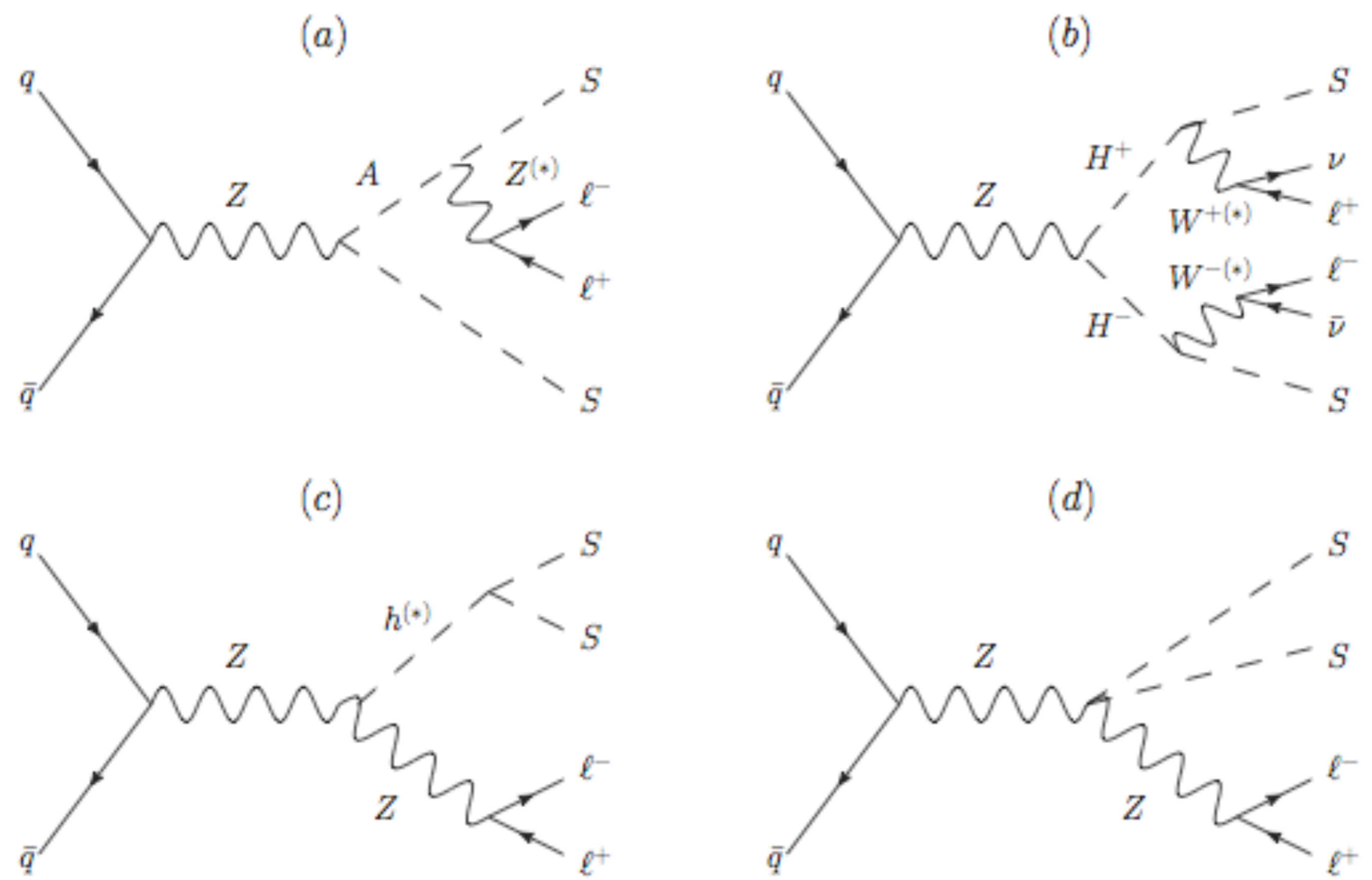


FIG. 1: Diagrams corresponding to the contributions to the $pp \to \ell^+\ell^- \not{E}_T$ in the IDM discussed in the text.

Typically 3σ discovery for 100 fb^{-1}

Dolle, Miao, Su & Thomas arXiv:0909.3094

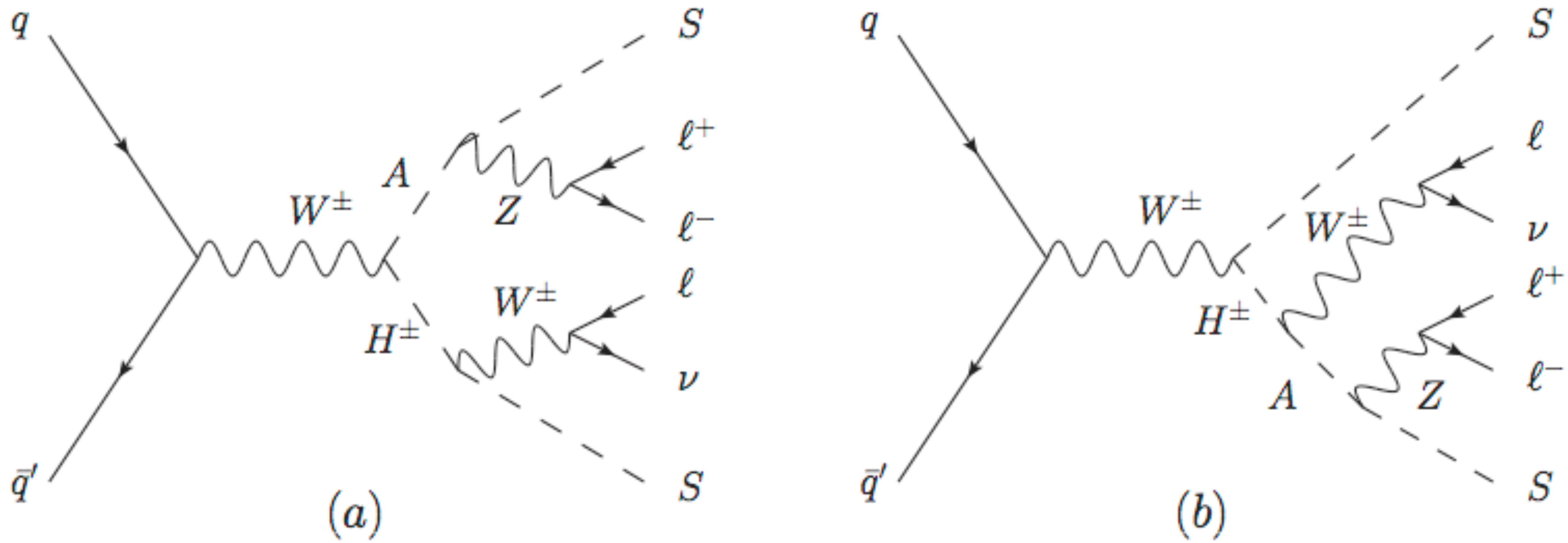


FIG. 1: Diagrams corresponding to the processes which provide the leading contributions to the $\ell^+\ell^-\ell^\pm + \not{E}_T$ cross-section in the IDM.

tri-leptons

Miao, Su & Thomas arXiv:1005.0090

4 to 6-leptons

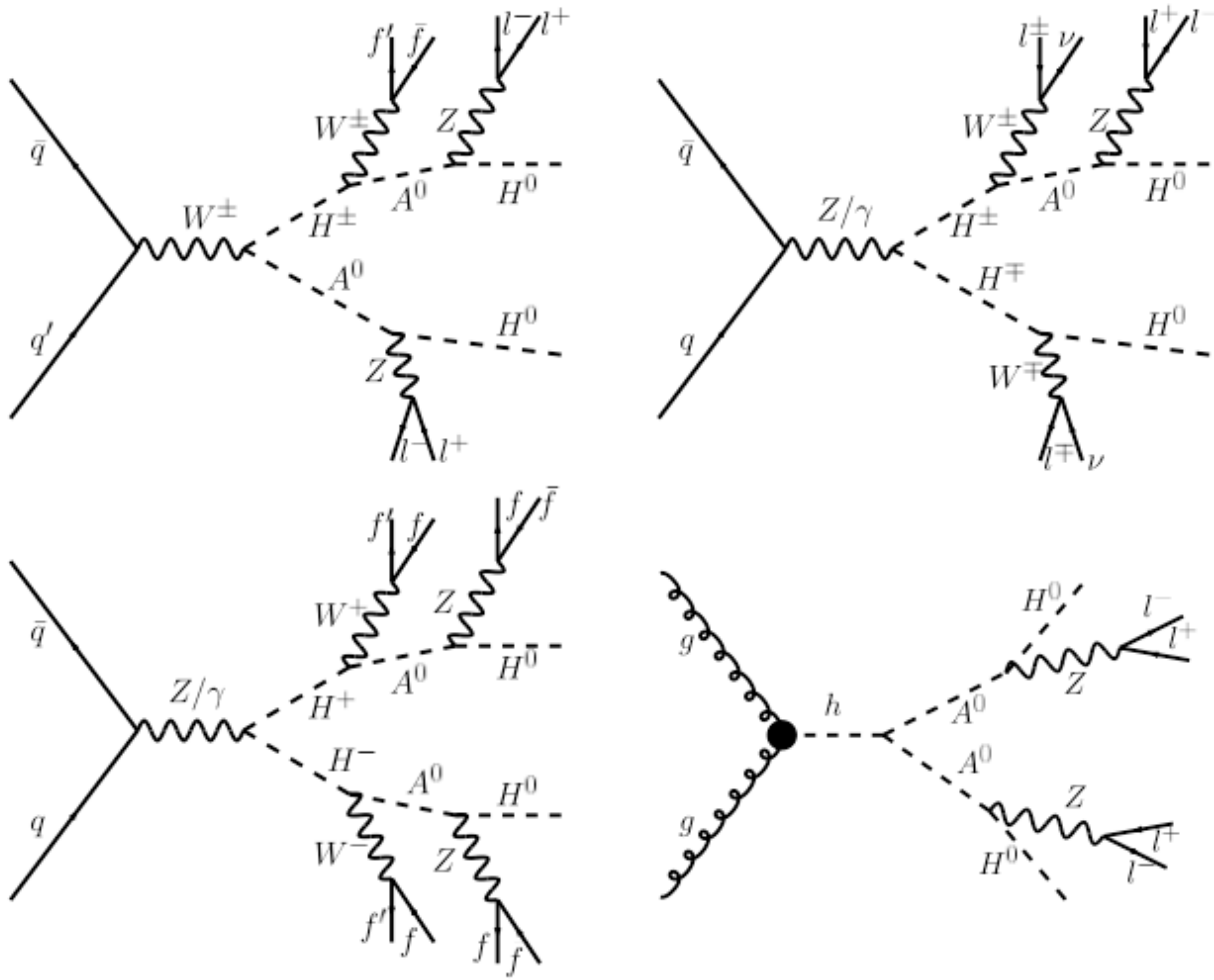


FIG. 4: Feynman diagrams contributing to $pp \to 4l + \not{E}_T$ in the IDM.

Gustafsson, Rydbeck, Lopez Honorez, Lundstrom arXiv:1206.6316

High Mass Range ~ the «Bad»

$\lambda's \to 0$ Minimal Dark Matter

Cirelli, Fornengo & Strumia hep-ph/0512090

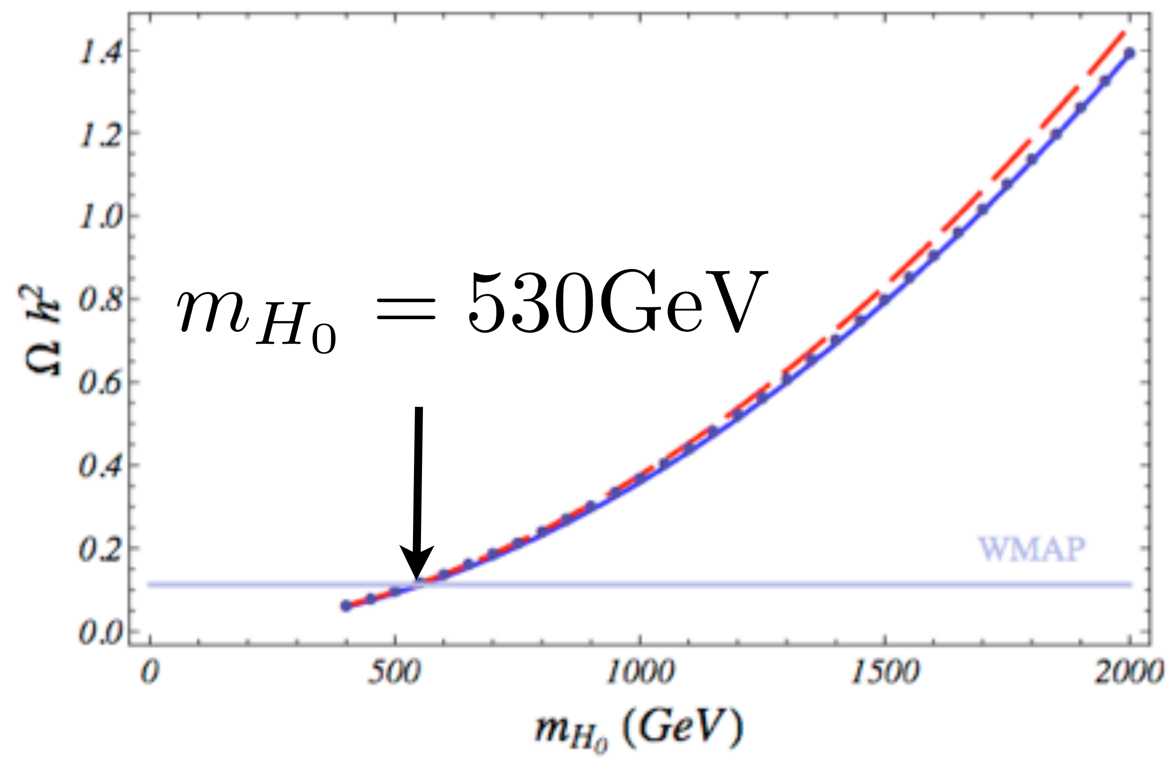
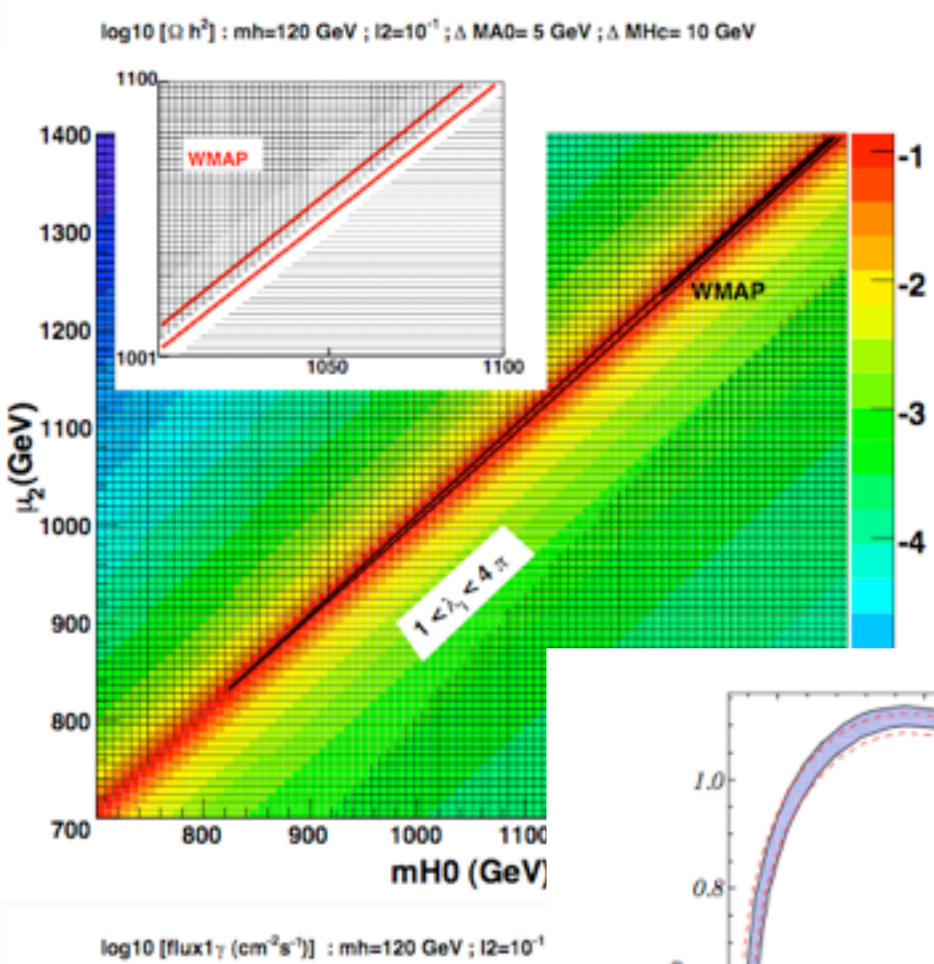


Figure 1: *Dark matter relic abundance in the pure gauge limit as a function of the DM mass. Dashed (Solid) curve : Instantaneous freeze-out approximation without (with) velocity-dependent terms in σv. Points : Output from MicrOMEGAs*

Hambye, Ling, Lopez Honorez, Rocher arXiv:0903.4010



Lopez Honorez, Nezri, Oliver, M.T. hep-ph/06122275

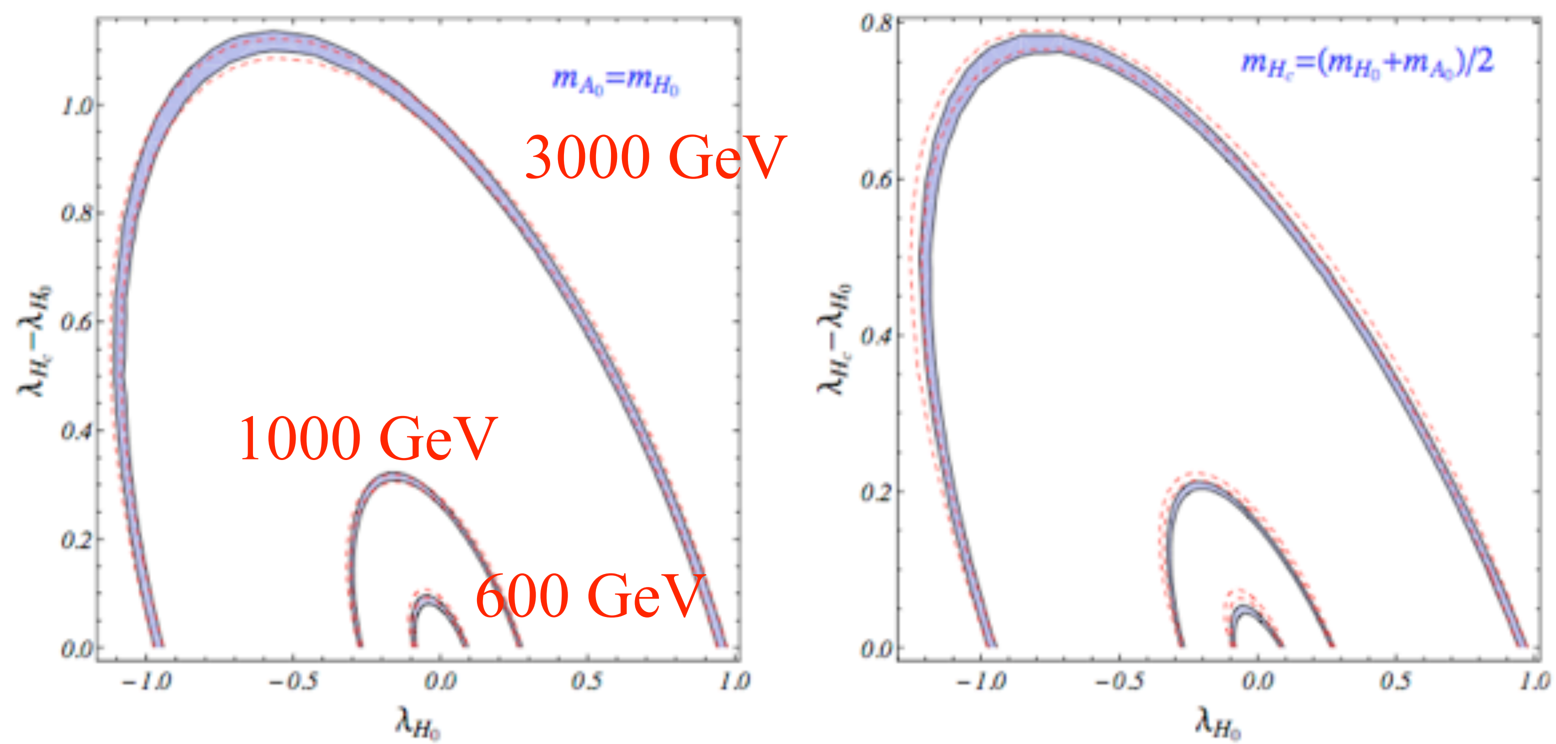
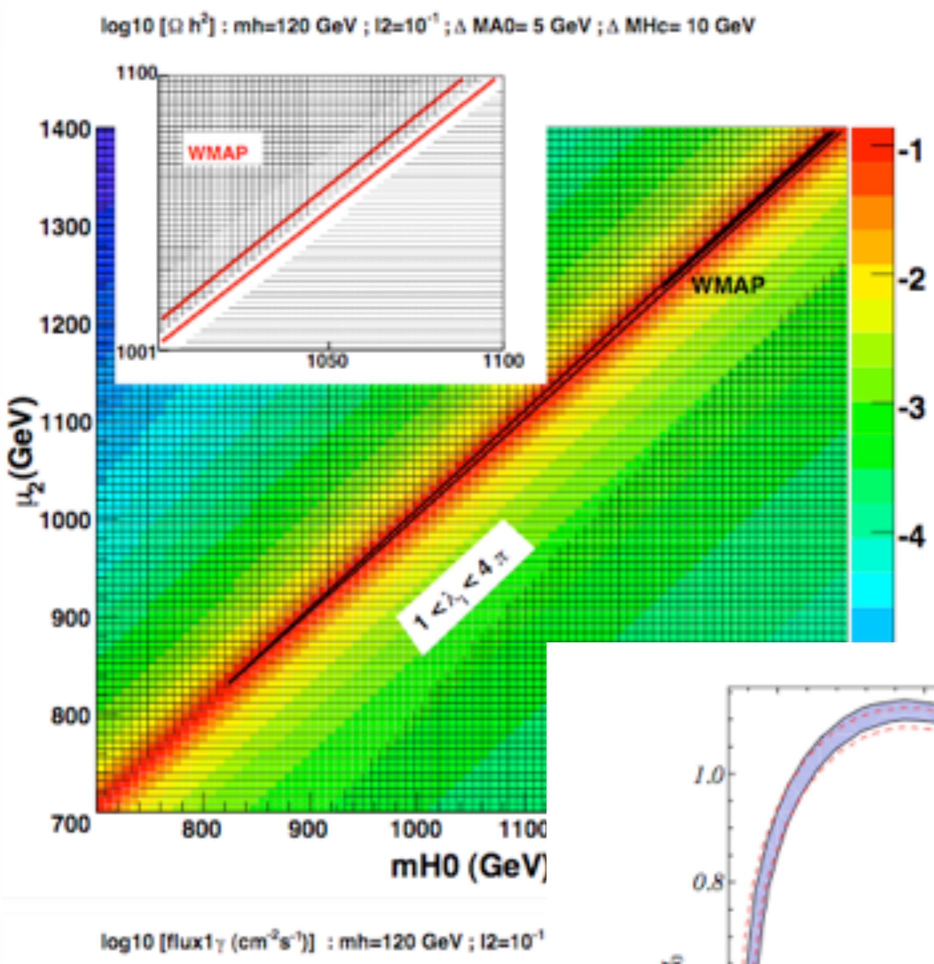


Figure 3: *Contours of λ for the WMAP value $\Omega_{\rm DM}h^2 = 0.1131 \pm 0.0034$ for $m_{H_0} = 600$ (interior), 1000, 3000 (exterior) GeV, with $m_{A_0} = m_{H_0}$ (left panel) and $m_{H_c} = (m_{H_0} + m_{A_0})/2$ (right panel). Dashed curve corresponds to the approximate ellipsoid.*

Hambye, Ling, Lopez Honorez, Rocher arXiv:0903.4010



Lopez Honorez, Nezri, Oliver, M.T. hep-ph/06122275

Unitarity bound ($\lambda's < 4\pi$)

$m_{H_0} < 58$ TeV

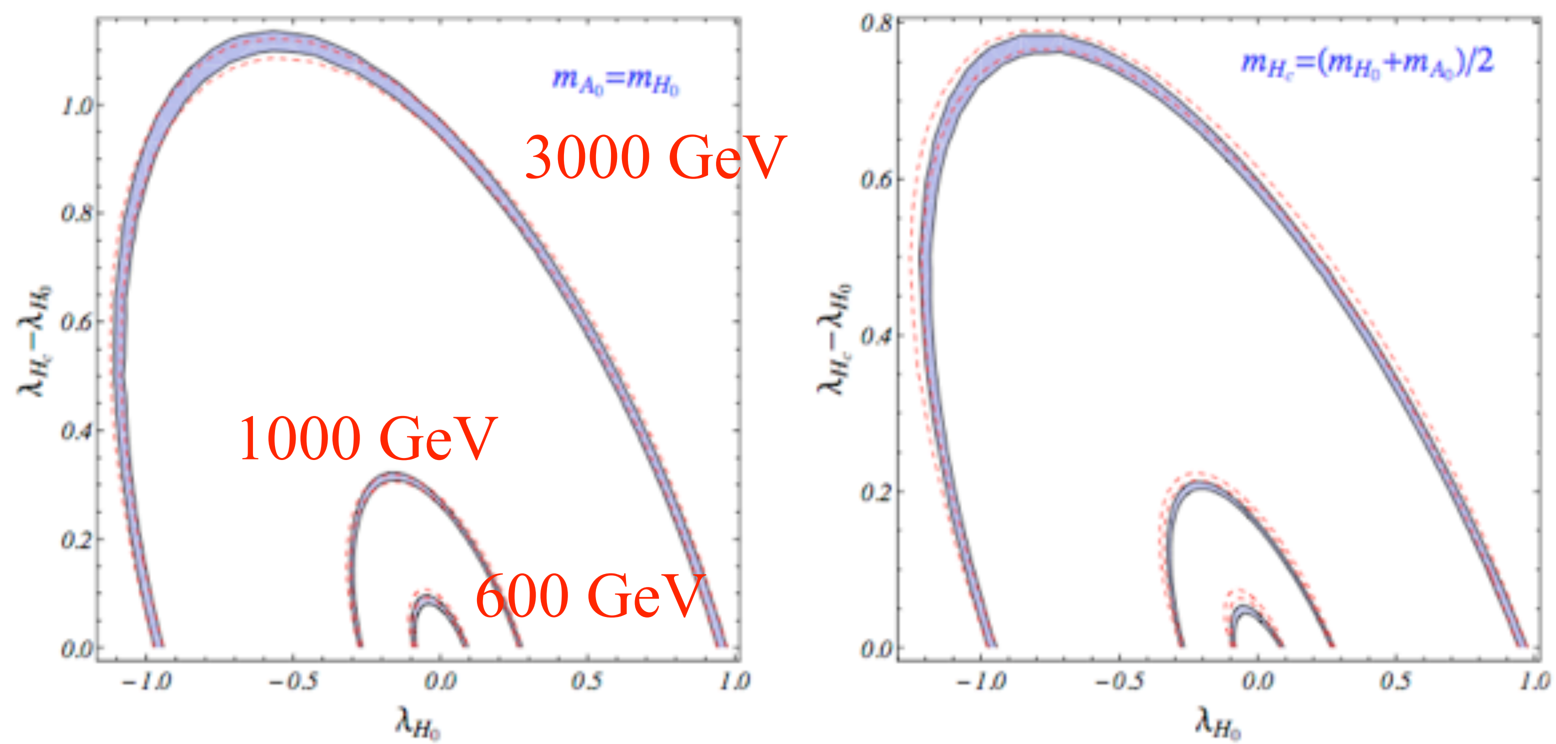
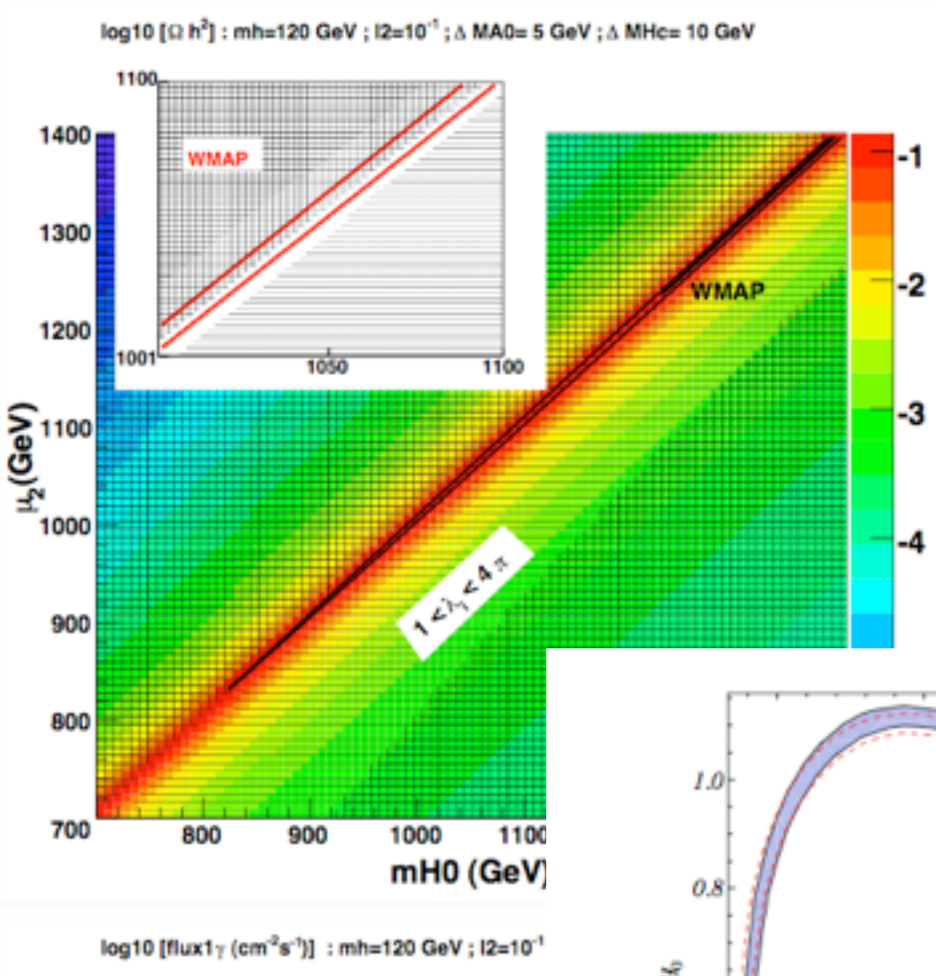


Figure 3: *Contours of* λ *for the WMAP value* $\Omega_{\rm DM}h^2 = 0.1131 \pm 0.0034$ *for* $m_{H_0} = 600$ *(interior),* 1000, 3000 *(exterior) GeV, with* $m_{A_0} = m_{H_0}$ *(left panel) and* $m_{H_c} = (m_{H_0} + m_{A_0})/2$ *(right panel). Dashed curve corresponds to the approximate ellipsoid.*

Hambye, Ling, Lopez Honorez, Rocher arXiv:0903.4010

Lopez Honorez, Nezri, Oliver, M.T. hep-ph/06122275



Small mass splittings

EWPT $\longrightarrow$ light SMS

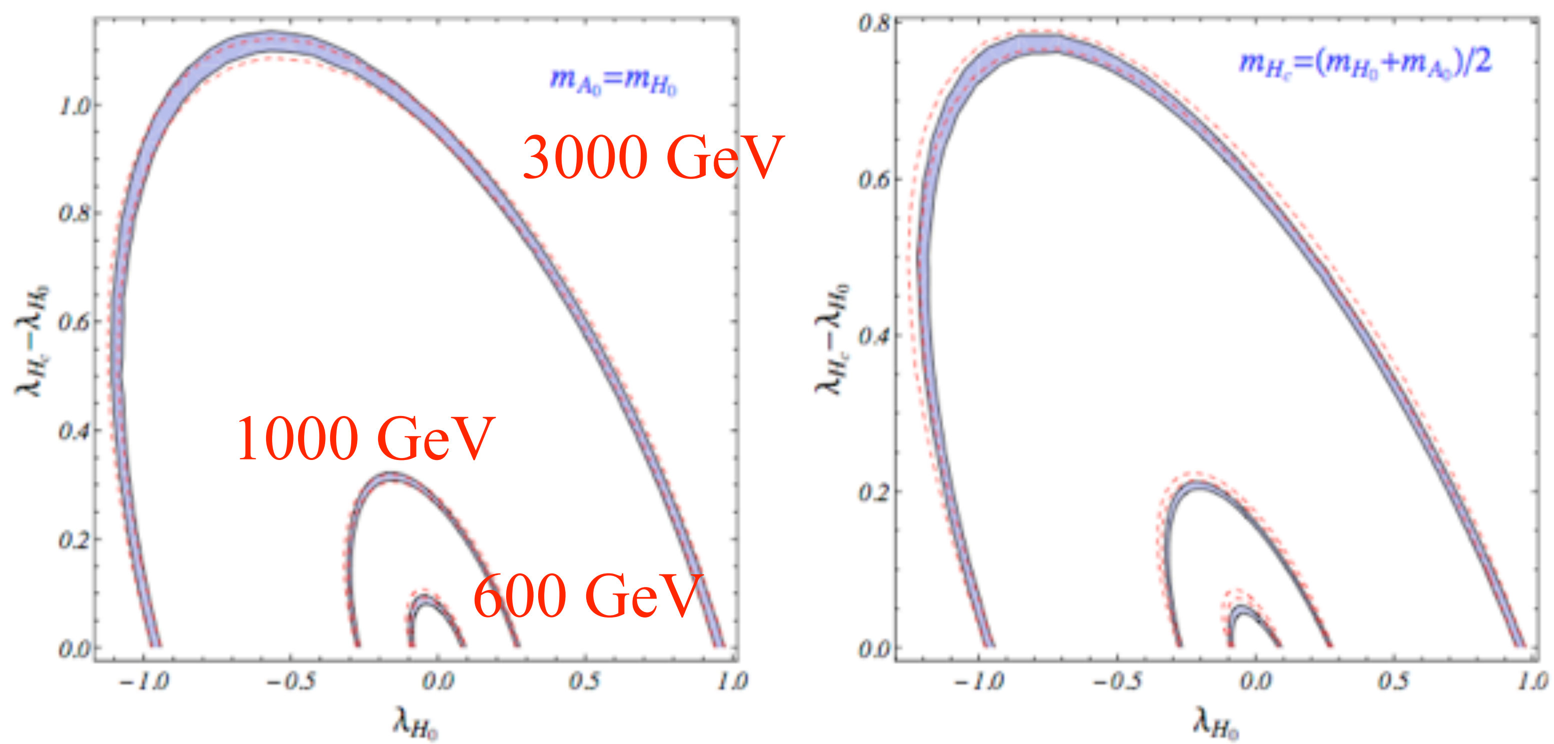
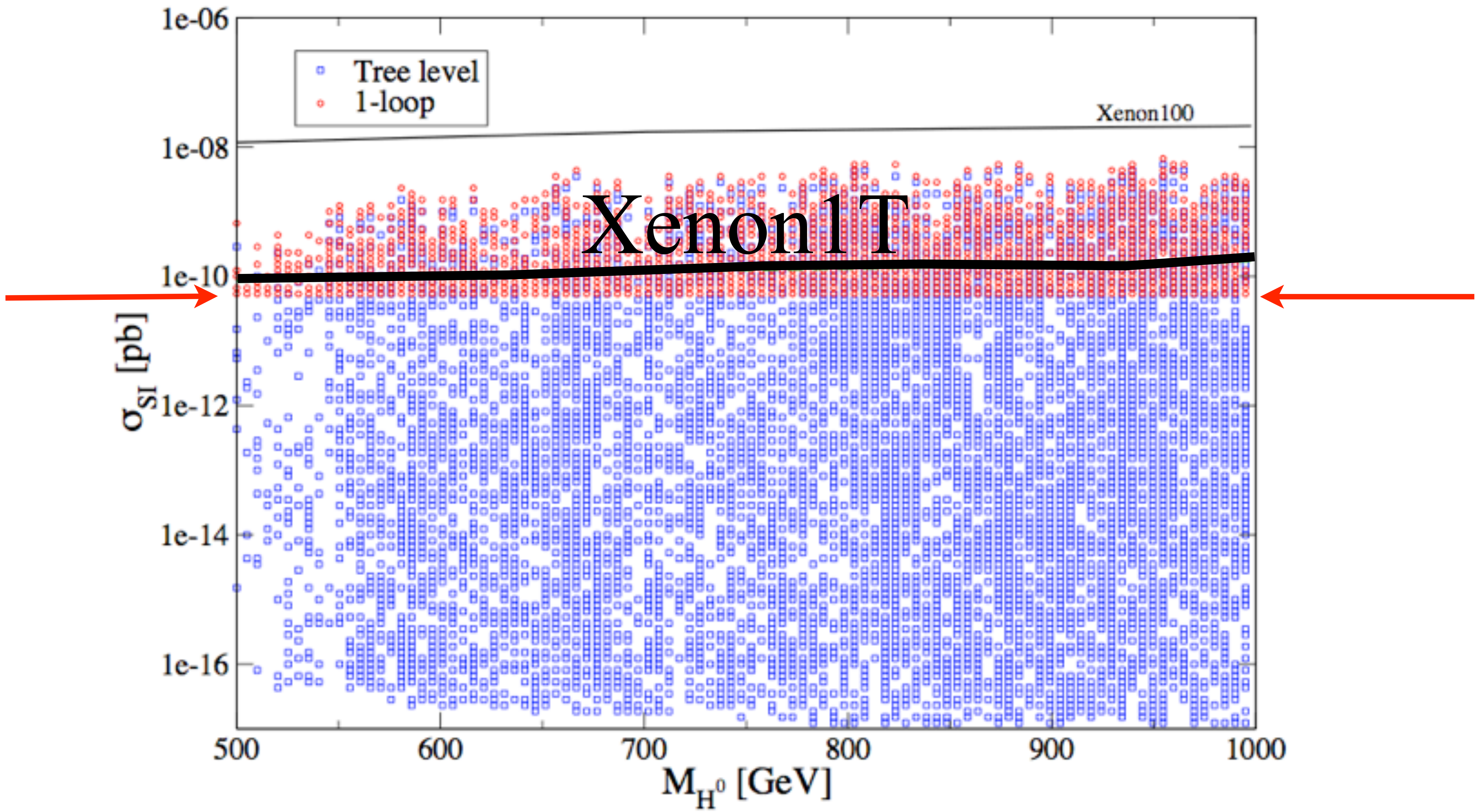


Figure 3: *Contours of* λ *for the WMAP value* $\Omega_{\rm DM}h^2 = 0.1131 \pm 0.0034$ *for* $m_{H_0} = 600$ *(interior),* 1000, 3000 *(exterior) GeV, with* $m_{A_0} = m_{H_0}$ *(left panel) and* $m_{H_c} = (m_{H_0} + m_{A_0})/2$ *(right panel). Dashed curve corresponds to the approximate ellipsoid.*

Hambye, Ling, Lopez Honorez, Rocher arXiv:0903.4010

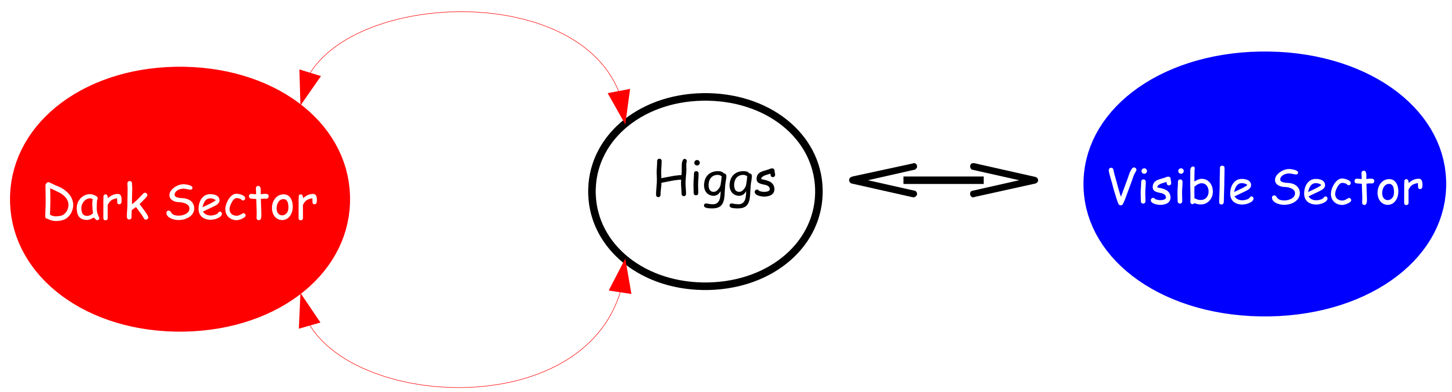
1-loop contributions to Direct Detection make it within reach of Xenon1T!



Klasen, Yaguna, Ruiz-Alvarez arXiv:1302.1657

A Versatile Model...

Radiative Electroweak Symmetry Breaking by DM ?



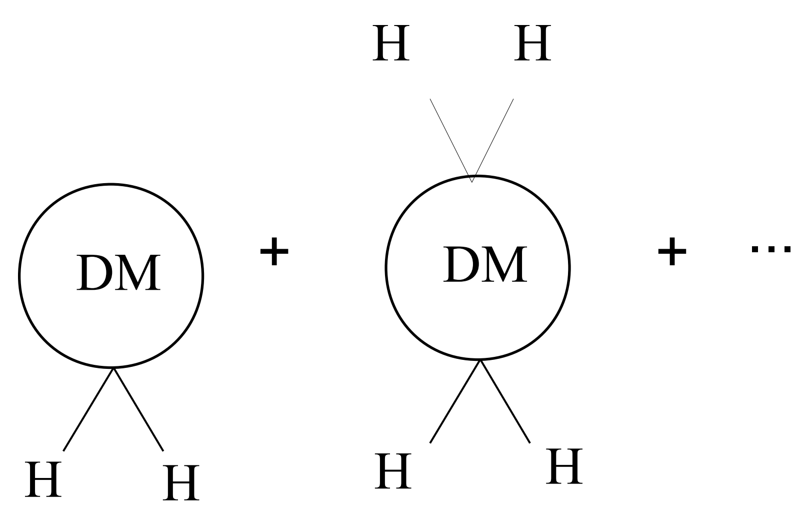
$M^2_{DM} \sim \lambda\, v^2$

e.g.

EWSB through loop corrections with DM

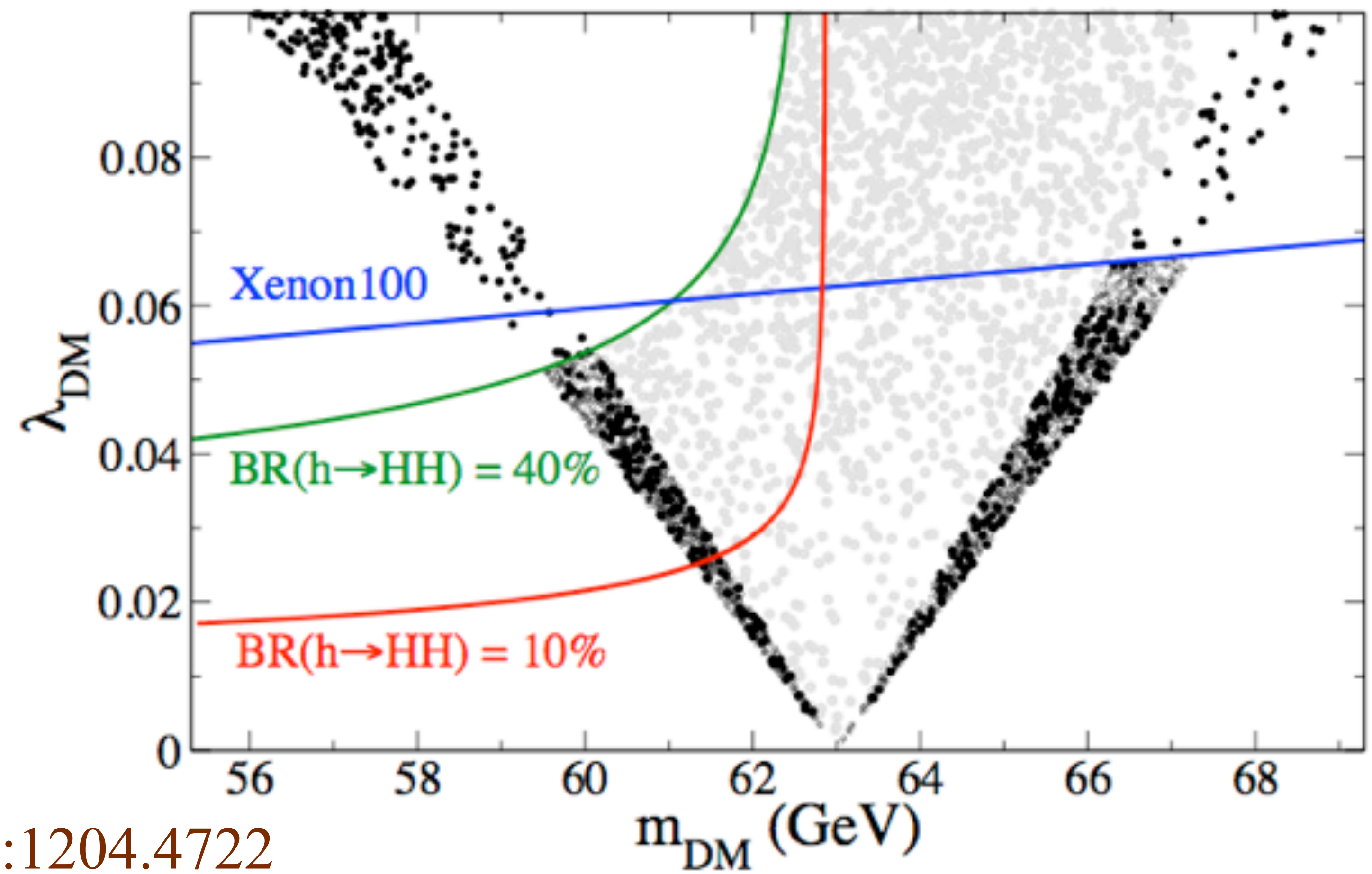
(à la Coleman-Weinberg)

scalar DM right sign for EWSB (ie opposite to top contribution)



Pratt & Wilczek; Espinosa & Quiros; Hambye & M.T. (2007);...

IDM dark matter with Strong EW phase transition



Borah & Cline arXiv:1204.4722

FIG. 2: Scatter plot of λ_{DM} versus m_{DM} for models with strong EWPT, correct relic density (dark points), and m_h = 126 GeV. The 90% c.l. upper bound on λ_{DM} from XENON100 is shown by the slanted line. The light shaded points denote models whose relic density is subdominant, $\Omega_H h^2 < 0.085$, but which still satisfy the correspondingly relaxed XENON100 limit. The other curves indicate the upper limit on λ_{DM} from requiring that the branching ratio for the invisible decay $h \to HH$ not exceed 10% or 40%, respectively.

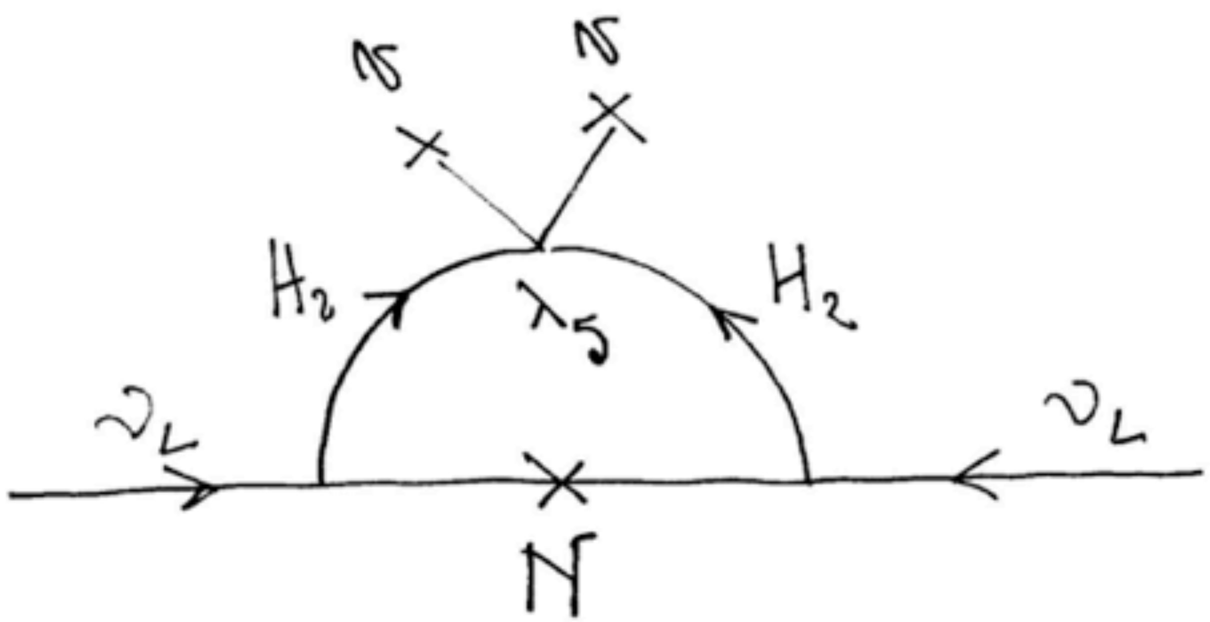
See also Chowdhury, Nemevsek, Senjanovic & Zhang arXiv:1110.5334

An interesting application : neutrino masses from radiative corrections

Ma (2006)

$$\mathcal{L} \supset f \bar{L} H_2 N + M_N \bar{N}^c N$$

with N RH Majorana, **odd** under Z_2



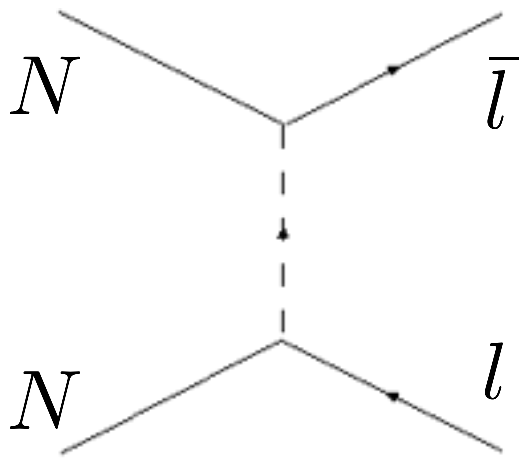
if $M_N >> M_{H2}$

$$m_{\nu_L} \sim \lambda_5 \frac{v^2}{M_N}$$

See Schmidt, Schwetz & Toma arXiv:1201.0906 for an update

Gamma-ray spectral feature from Leptonic WIMP

$\mathcal{L} \supset y_l \bar{L} H_2 N + M_N N^T C N + h.c.$



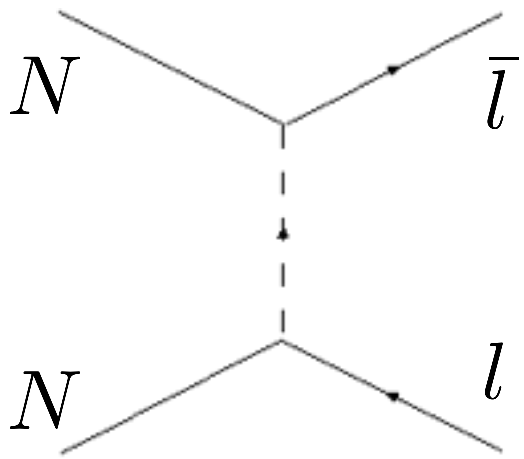
- Annihilation in lepton pairs is p-wave suppressed

$$\sigma v \propto \frac{y_l^4}{M_H^4} \left(m_l^2 + 2/3 M_N^2 \beta^2 \right)$$

$\beta \sim 0.3$ at Freeze-Out, but $\sim 10^{-3}$ @ GC

Bergstrom & Baltz, 2002

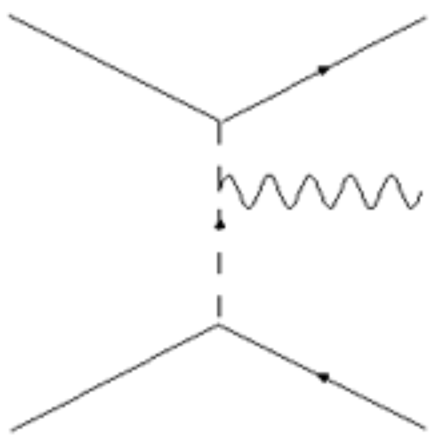
$$\mathcal{L} \supset y_l \bar{L} H_2 N + M_N N^T C N + h.c.$$



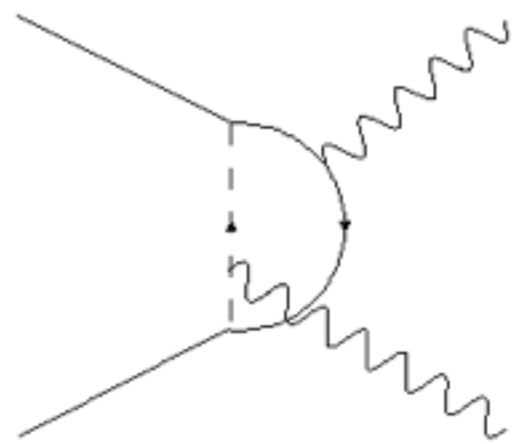
- Annihilation in lepton pairs is p-wave suppressed

$$\sigma v \propto \frac{y_l^4}{M_H^4}\left(m_l^2 + 2/3 M_N^2 \beta^2\right)$$

$\beta \sim 0.3$ at Freeze-Out, but $\sim 10^{-3}$ @ GC



- Annihilation through emission of photons (IB) dominant @ Galactic Centre



- Both $\gamma\,\gamma$ and γZ @ 1-loop

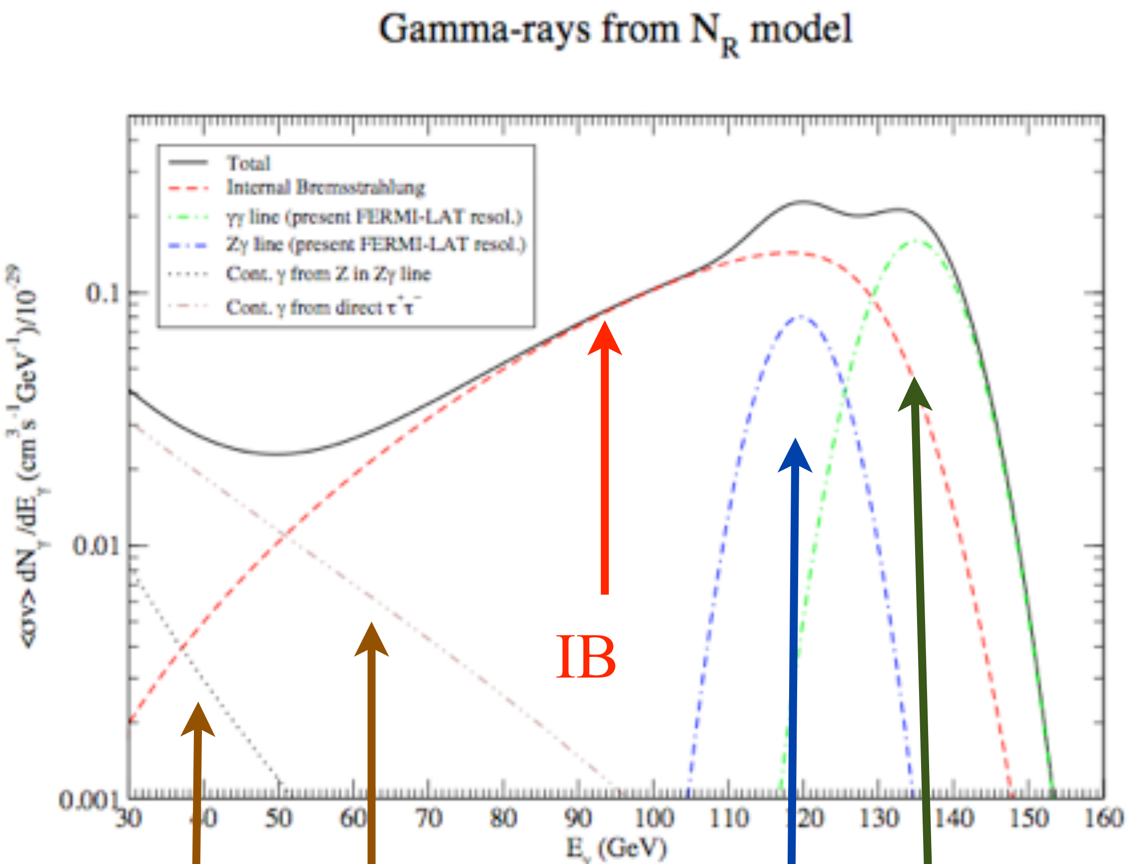
$\langle \sigma v \rangle \approx 6.7 \cdot 10^{-29} \mathrm{cm}^3 \mathrm{s}^{-1}$

$\langle \sigma v \rangle \approx 2.3 \cdot 10^{-29} \mathrm{cm}^3 \mathrm{s}^{-1}$

Rem: direct detection impossible

Bergstrom & Baltz, 2002

«The 130 GeV Fingerprint of Right-handed Neutrino Dark Matter»



IB

from $\tau^+\tau^-$

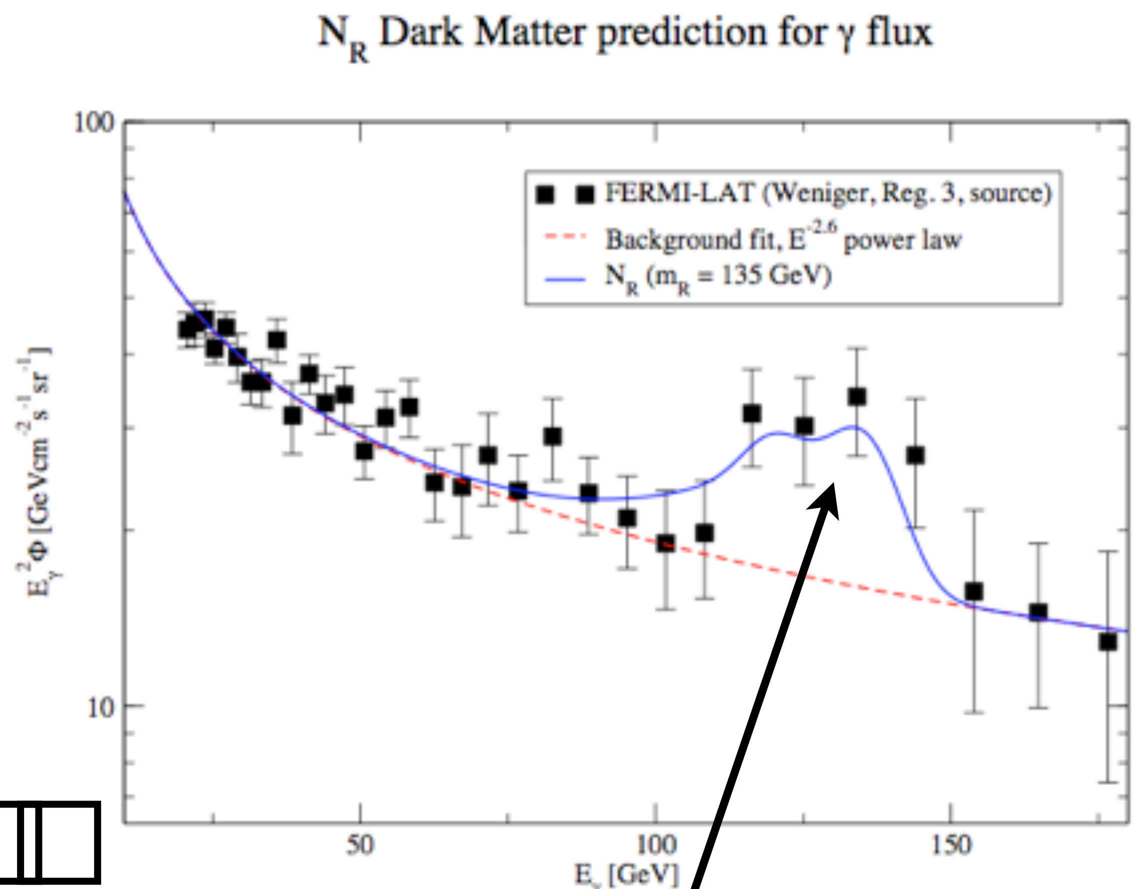
$\gamma\,\gamma$

continuum from Z in γZ

γ from γZ

Continuum
(negligible)

M_N ~135 GeV «fingerprint»



Einasto profile; Need a boost factor (~10)
to match the data (Weniger's)

Bergstrom, arXiv:1208.6082

A not-so-inert Doublet

$$\mathcal{L} \supset y' \bar{Q}\, H_2\, D_H + \ldots \;\; + m_{D_H} \bar{D}_H D_H$$

Even (SM)

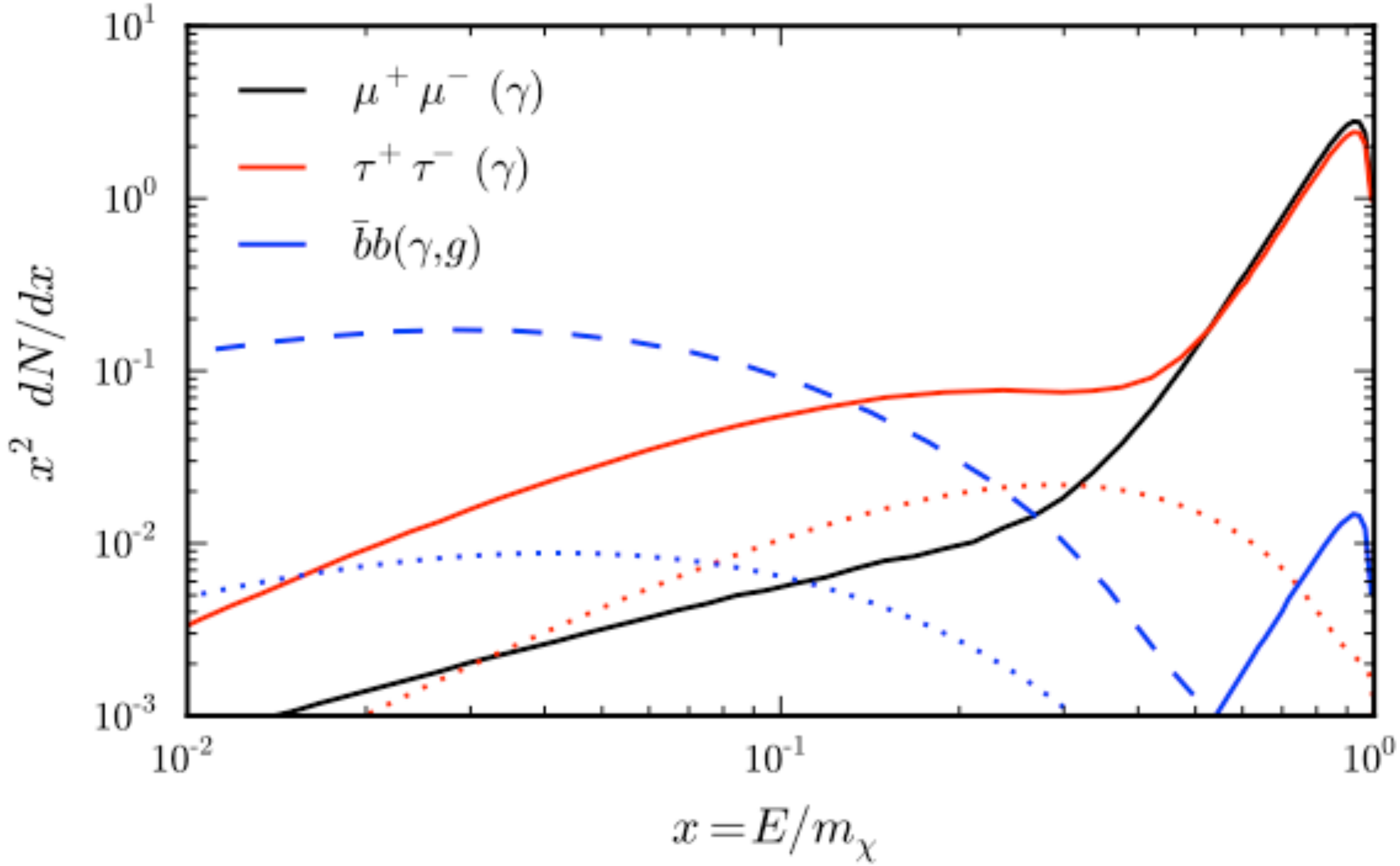
Odd

Vector-like heavy quarks

$$\longrightarrow \qquad \mathcal{O}_{\rm eff} \sim \frac{m_q}{m_{Q_H}^2} \bar{q}q\, H_0^2$$

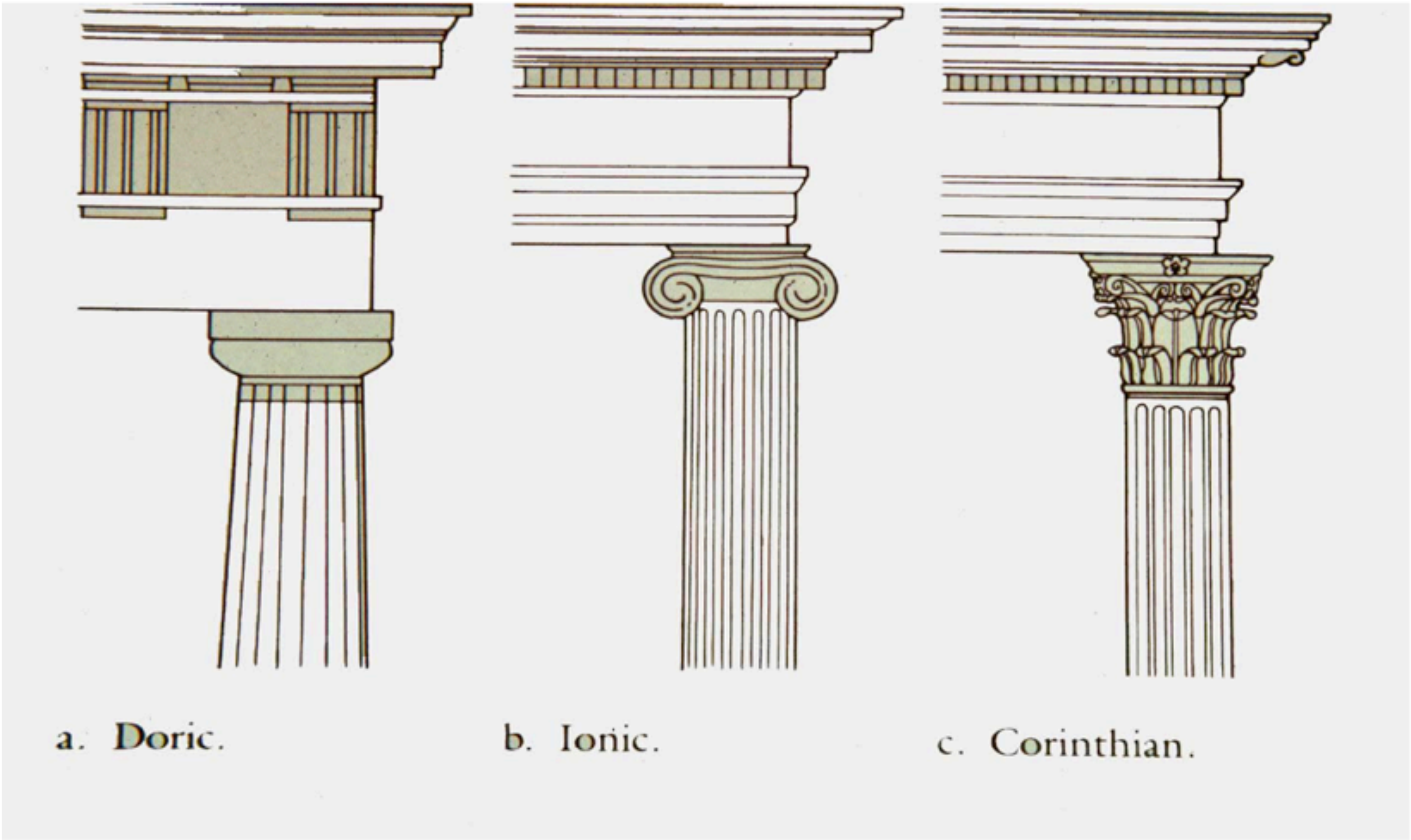
Giacchino, Lopez Honorez, M.T., work in progress

H_0 with a gamma-ray spectral feature



Conclusions

A nice WIMP archetype?



Spin 0	Spin ½	Spin 1
Inert Doublet	Neutralino	Heavy photon