Status of the Inert Doublet Model (and the scalar portal)

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The Standard Model Scalar (SMS) as a Portal to New Physics

$$\mathcal{L}_{SM} \supset \mu^2 \, |H|^2$$

Unique! All others terms have Mass Dimension = 4

☞ Origin of Electroweak Symmetry Breaking

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$$\mathcal{L}_{SM} \supset \mu^2 \, |H|^2$$

Unique! All others terms have Mass Dimension = 4

☞ Origin of Electroweak Symmetry Breaking

☞ Portal* to renormalizable couplings to New Physics!

(Patt & Wilczek)

* this is not unique, e.g. $\mathcal{L}_{SM} \supset \bar{L}\tilde{H}N$

Simplest incarnation: a Singlet Scalar

$$\Delta\mathcal{L} \supset \frac{\lambda_S}{2} S^2 |H|^2$$

What is it good for?

☞ $\langle S^2 \rangle$ origin of Electroweak Symmetry Breaking?

☞ Z_2 symmetry? $S \to -S$

S as Dark Matter candidate

(Silveira & Zee; McDonald; Burgess, Pospelov & ter Veldhuis;...)

The Inert Doublet Model

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

$$\mathcal{L} \supset \mu_2^2 |H_2|^2 + \lambda_2 |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2$$

$$+\lambda_4 |H_1^\dagger H_2|^2 + \lambda_5 Re(H_1^2 H_2)^2$$

2 Doublets Model with Z_2 symmetry $H_2 \to -H_2$

No *vev* nor couplings to quarks ☞ no FCNC & H_0 dark matter

(Deshpande & Ma; Barbieri, Hall & Ryshkov)

Why the Inert Doublet Model?

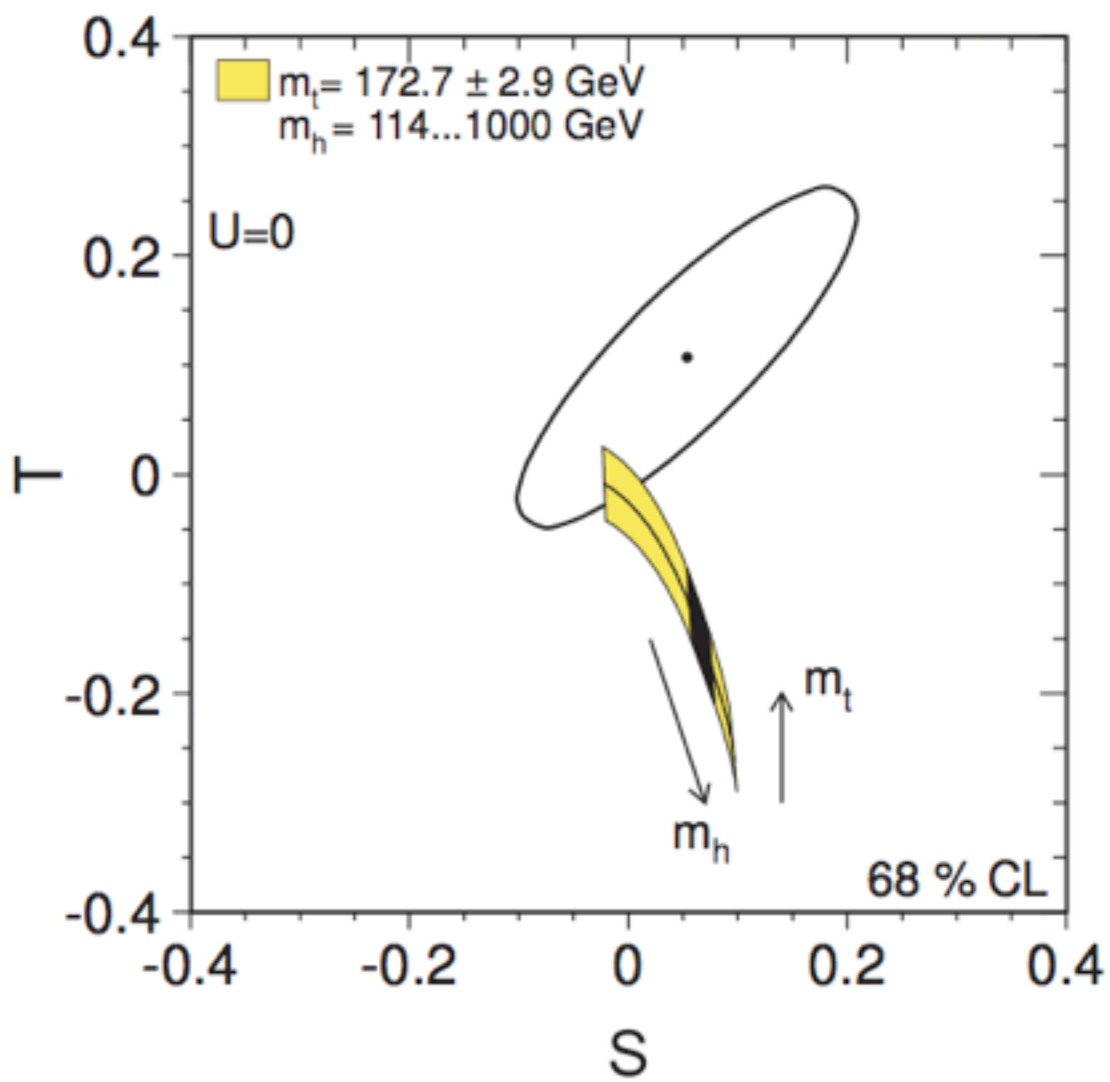
One of the simplest extensions of the SM

Yet rich and versatile (*i.e.* having many uses or applications)

☞ dark matter, radiative neutrino masses, EWSB,...

«Improved naturalness with a Heavy Higgs»

(Barbieri, Hall & Ryshkov, 2006)



LEP Electroweak Precision Tests

☞ light SMS

Inert Doublet contribution

$$\Delta T \approx \frac{1}{24\pi^2 \alpha v^2}(m_{H^+} - m_{A_0})(m_{H^+} - m_{H_0})$$

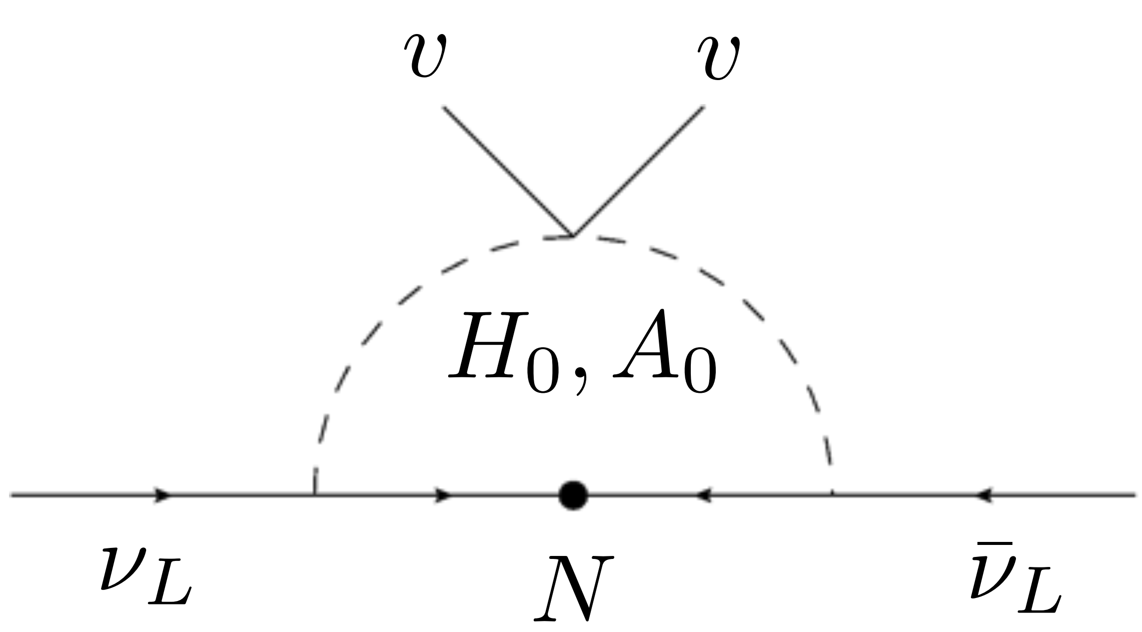
☞ M_h up to 500 GeV

«Verifiable radiative seesaw mechanism of neutrino mass and dark matter»

(Ma, 2006)

$$\Delta\mathcal{L} \supset y_l\,\bar{L}\,\tilde{H}_2\,N + M_N \bar{N}^c N$$

N is odd
(*i.e.* could be DM)

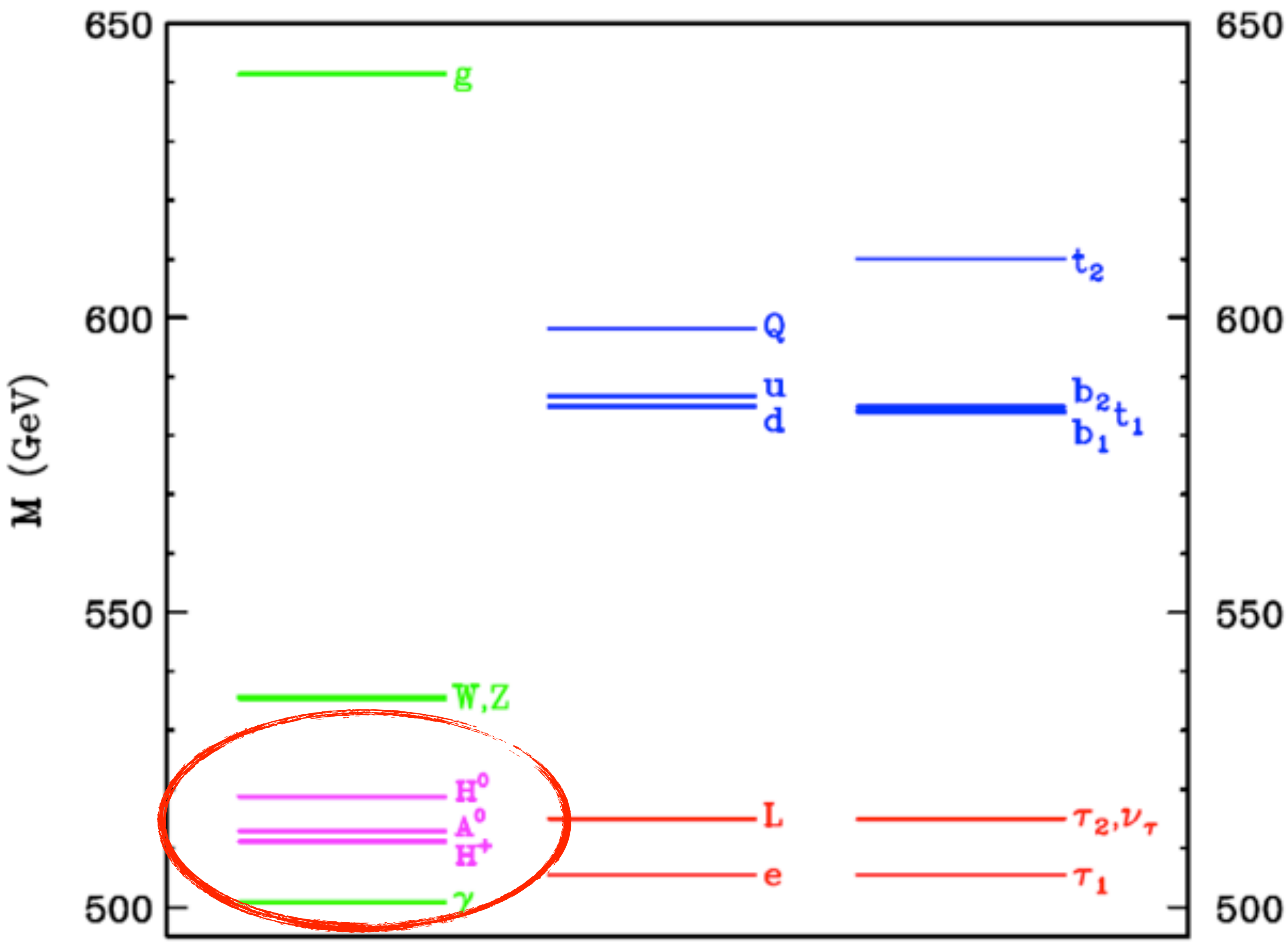


$$M_{\nu_L} \sim \frac{\lambda_5}{4\pi}\,\frac{y_l^2 v^2}{M_N}$$

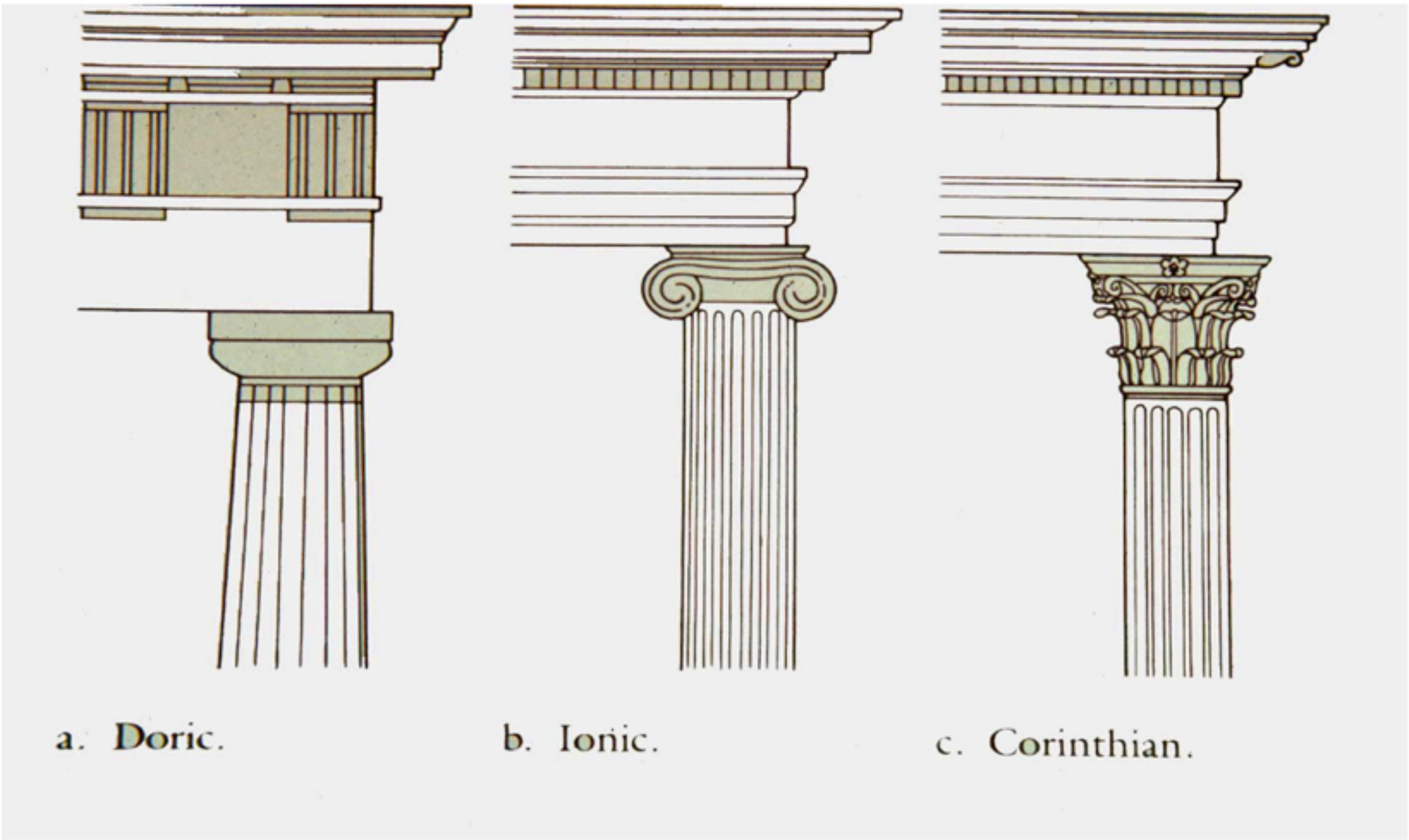
☞ $M_N \sim$ TeV range

Who ordered an Inert Doublet?

e.g. UED Spectrum

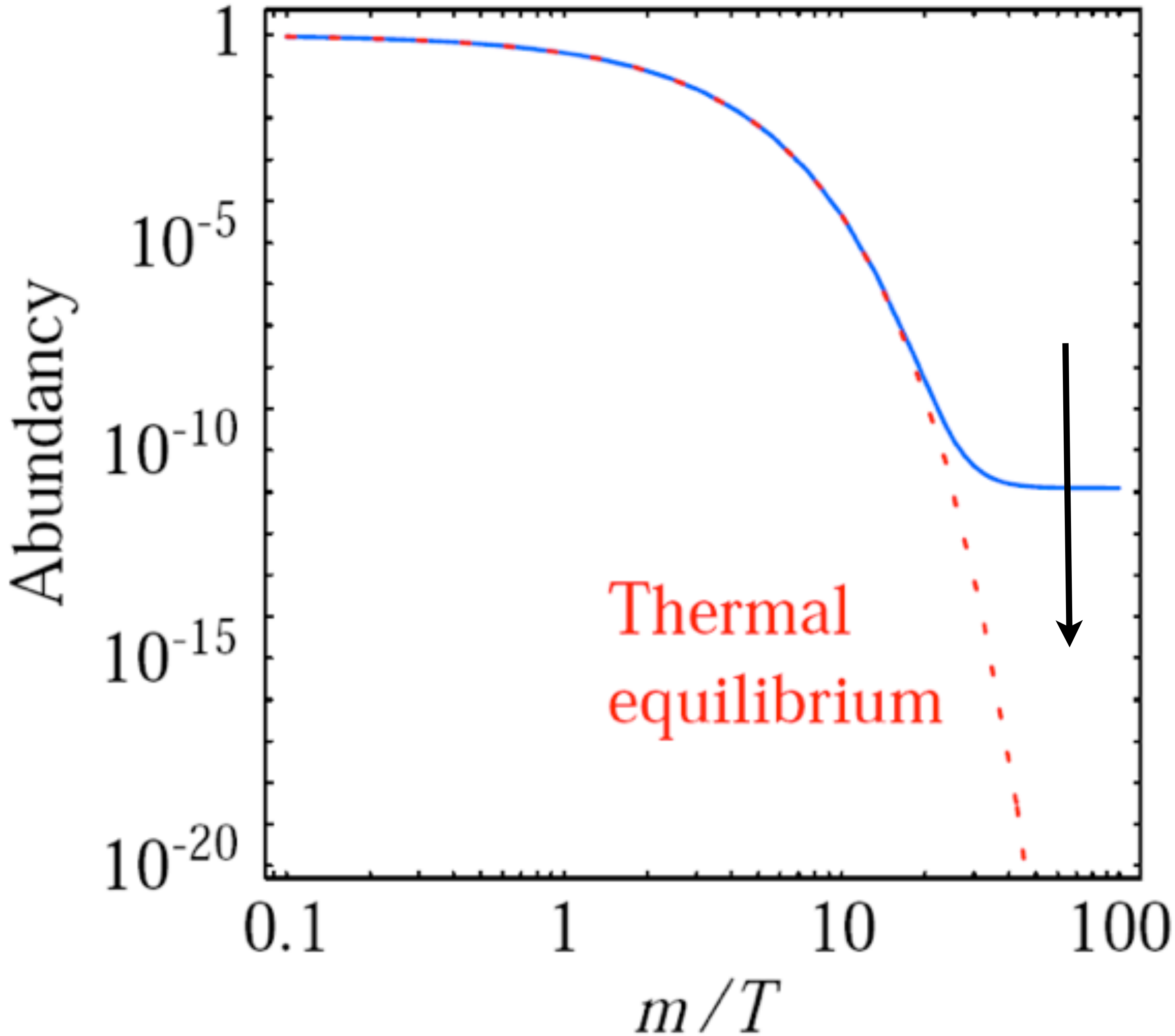


WIMP ARCHETYPES



Spin 0	Spin 1/2	Spin 1
Inert Doublet	Neutralino	KK photon

The WIMP Paradigm



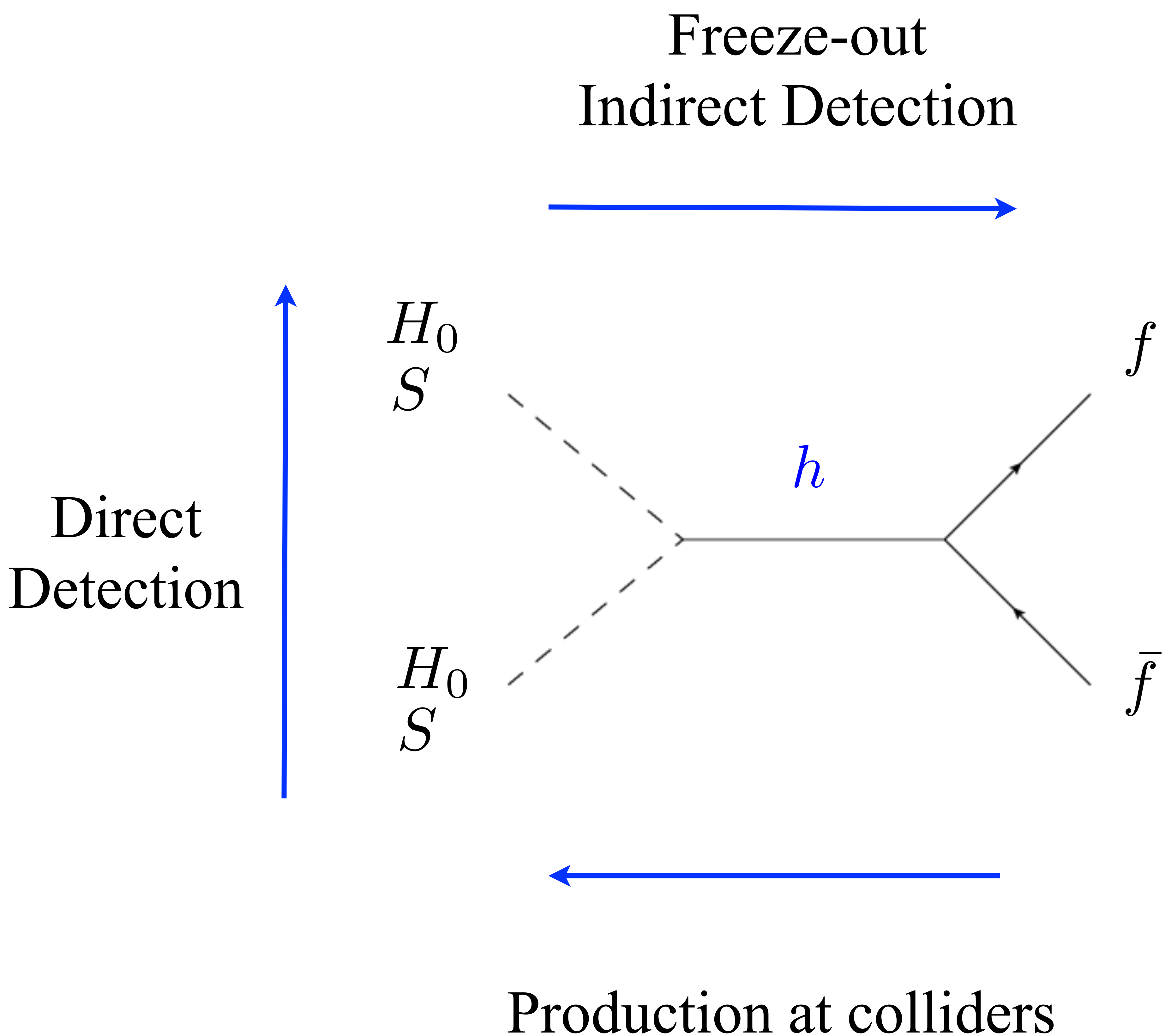
$\langle \sigma v \rangle$ ↗

abundance ↘

Freeze-out

WMAP abundance

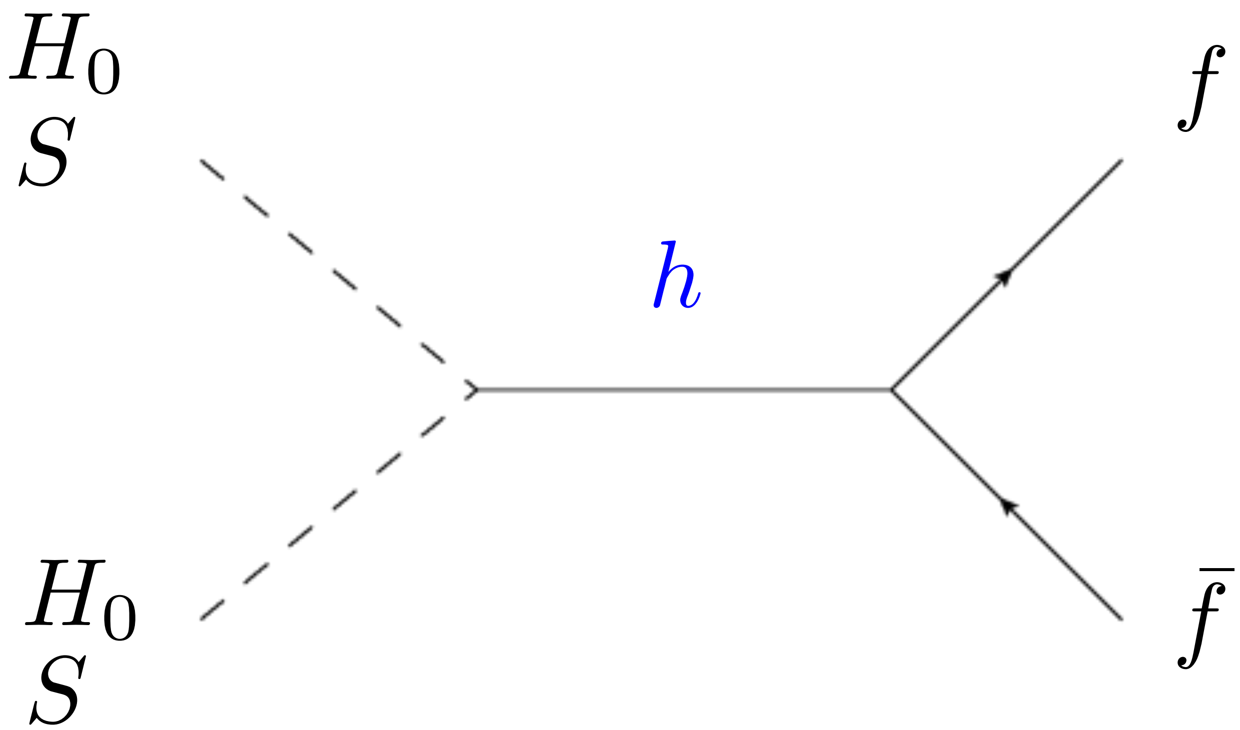
☞ $\langle \sigma v \rangle \sim 10^{-26}$ $cm^3 s^{-1}$


Freeze-out
Indirect Detection
H_0
S
f
h
Direct
Detection
H_0
S
$\bar{f}$
Production at colliders

Freeze-out

Indirect Detection

Direct Detection



☞ Resonance

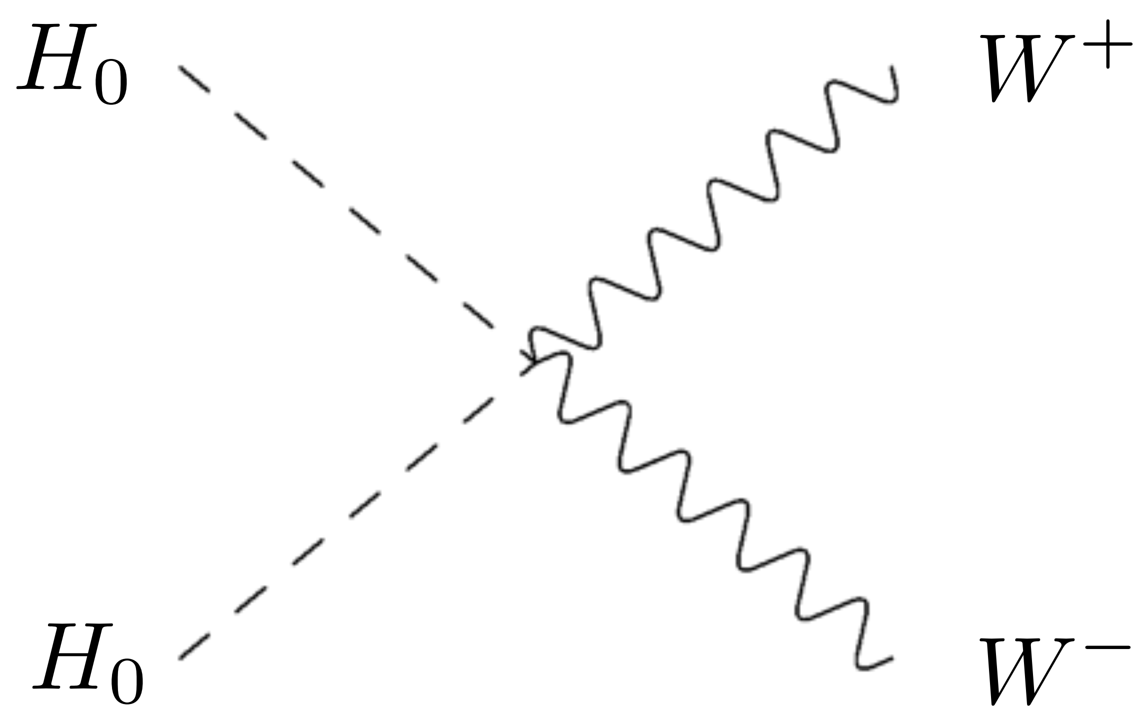
if $M_H \sim M_h/2$

Production at colliders

Freeze-out

Indirect Detection

Direct Detection



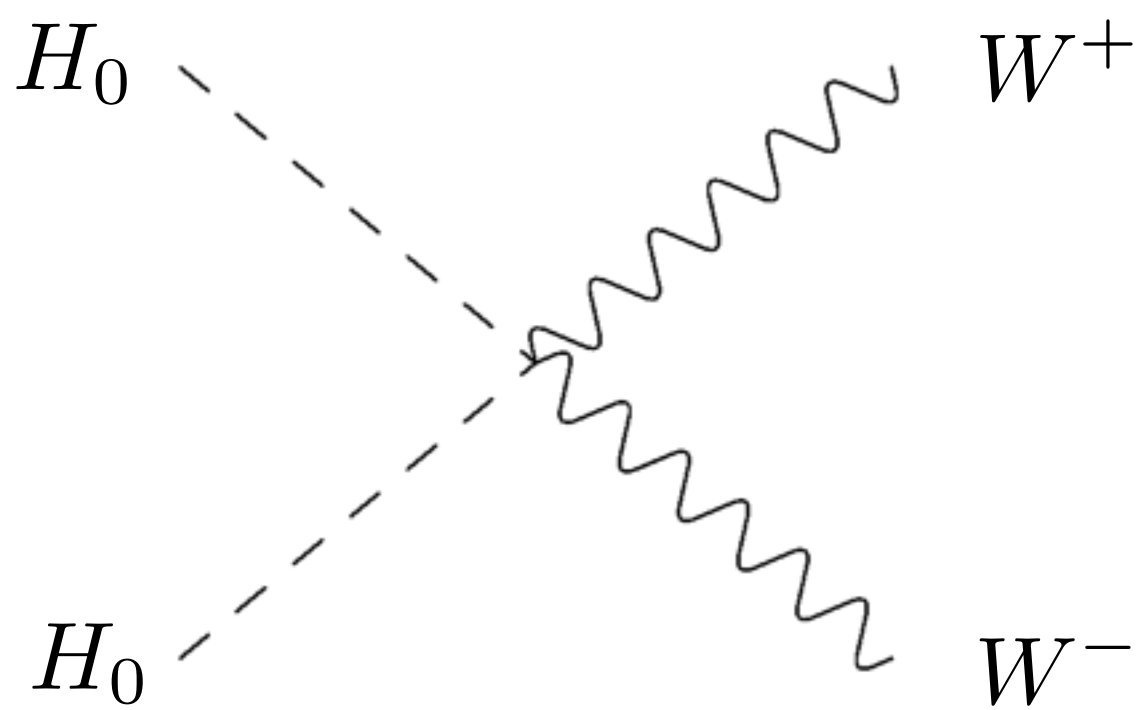
Large $\langle \sigma v \rangle$
for $M_H > M_W$
☞ $\Omega_H < 0.1$ (WMAP)

$\langle \sigma v \rangle \sim 1/M_H^2$
for $M_H \gg M_W$
☞ $\Omega_H > 0.1$

Production at colliders

Freeze-out
Indirect Detection

Direct
Detection



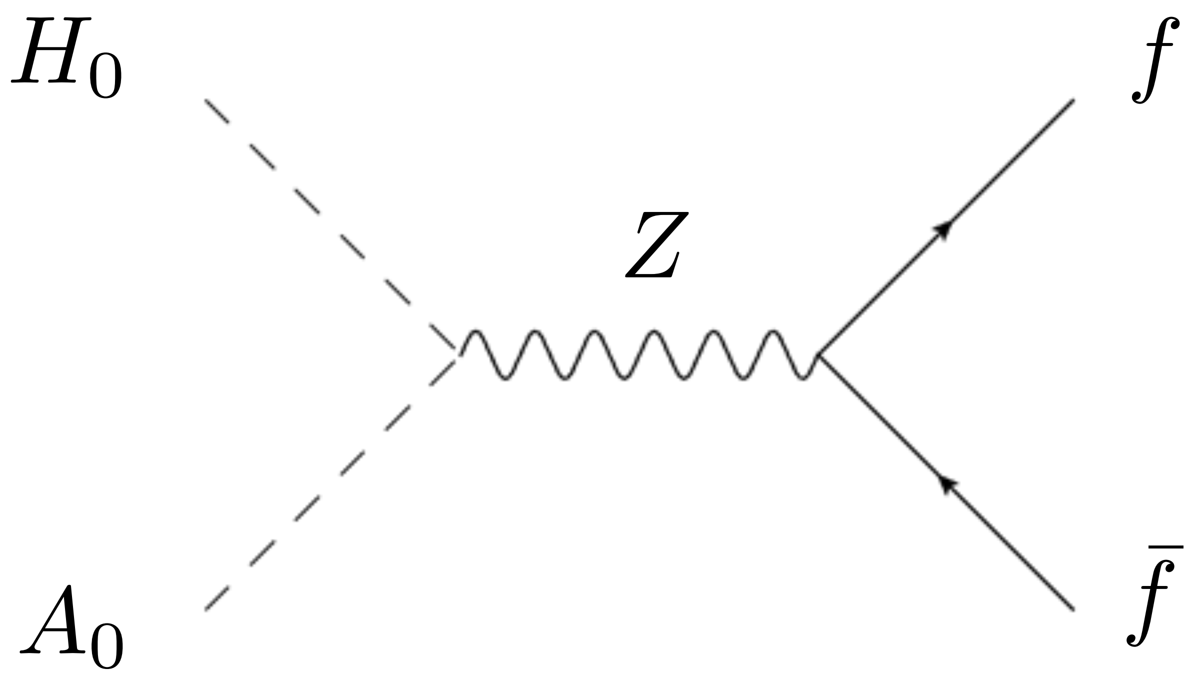
☞ scattering on nucleons @ 1-loop

Production at colliders

Freeze-out

Indirect Detection

Direct Detection



☞ Co-annihilation

if $M_H \lesssim M_A$

Production at colliders

Inert Doublet WIMP Candidates

- Middle Mass WIMP ~ 60-70 GeV
- Heavy WIMP ~ 0.5-50 TeV
- Light WIMP ~5-10 GeV

(Lopez Honorez, Nezri, Oliver & MT, 2006)

Low Mass Candidate

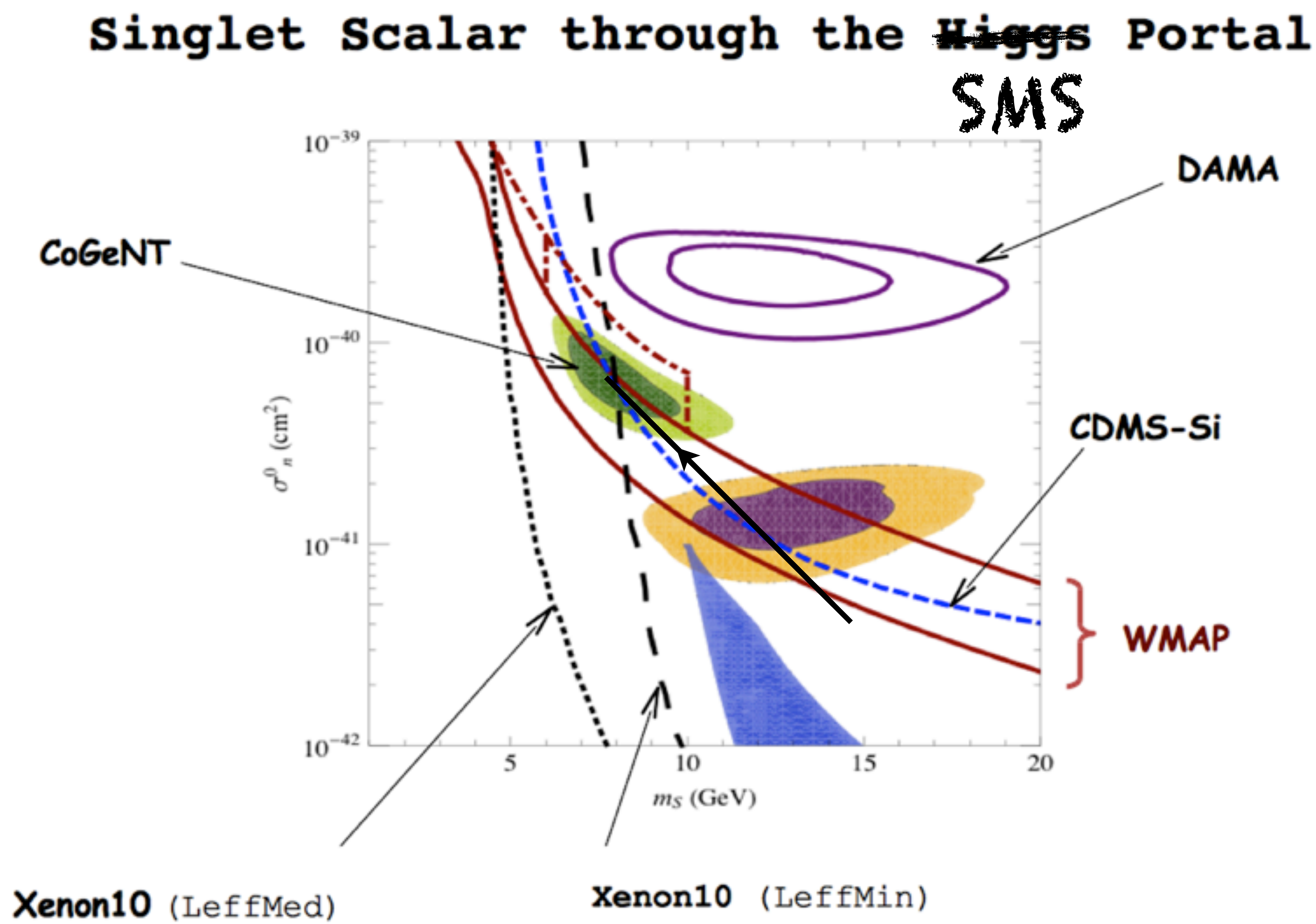


Figure from Andreas, Arina, Hambye, Ling & M.T. Moriond 2011

Low Mass Candidate

Singlet Scalar through the ~~Higgs~~ SMS Portal

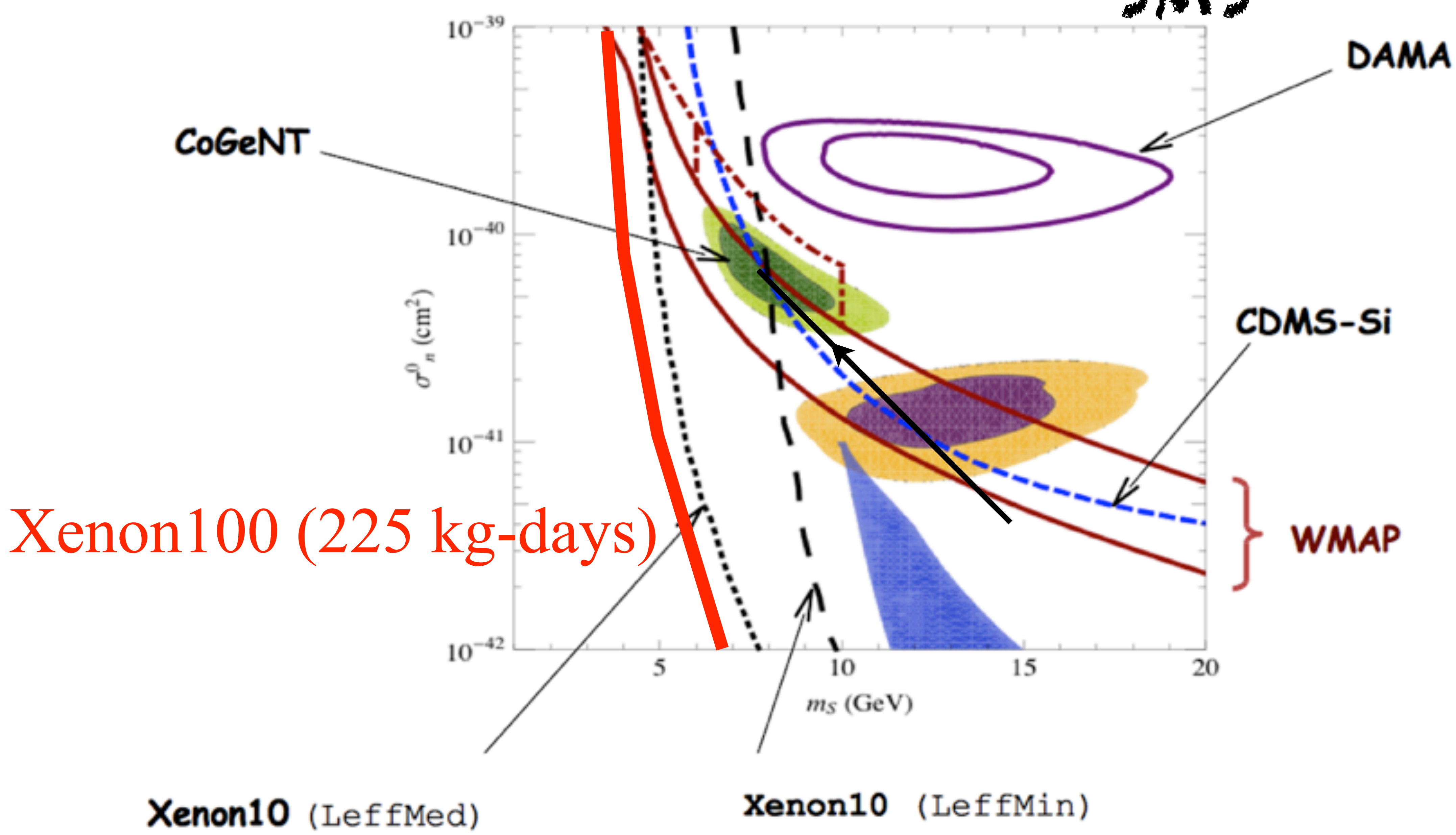
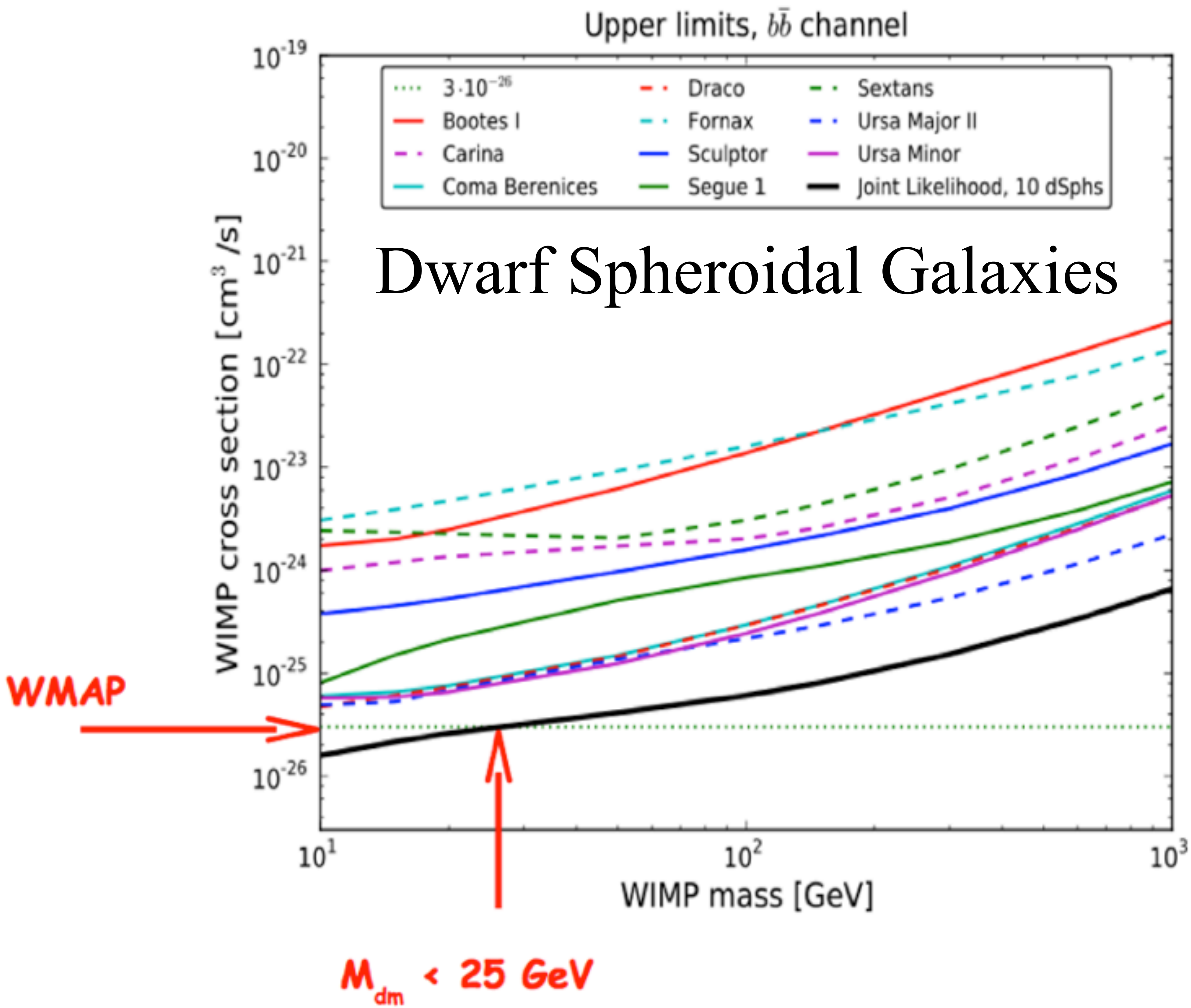


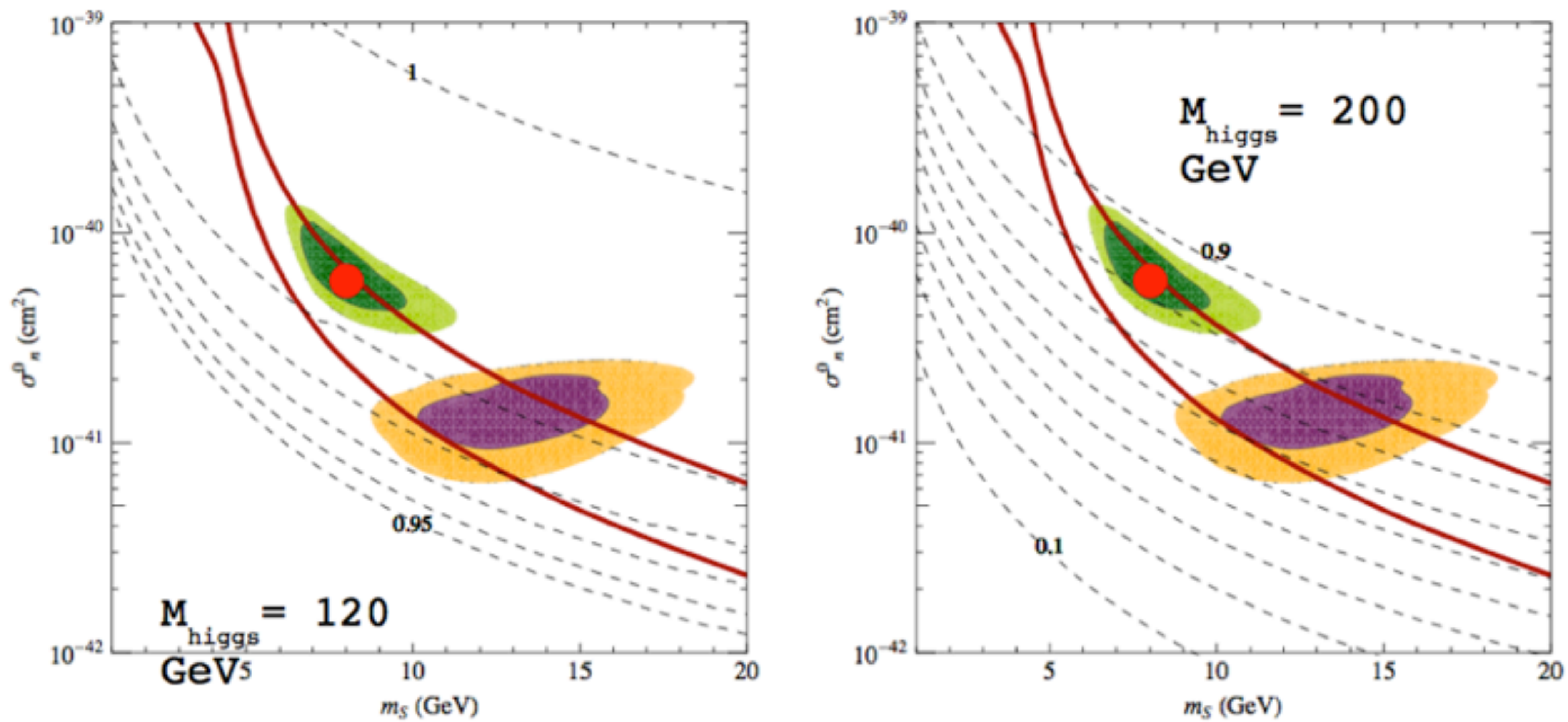
Figure from Andreas, Arina, Hambye, Ling & M.T. Moriond 2011

Low Mass Candidate



Fermi-LAT (1108.3546)

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)

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

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

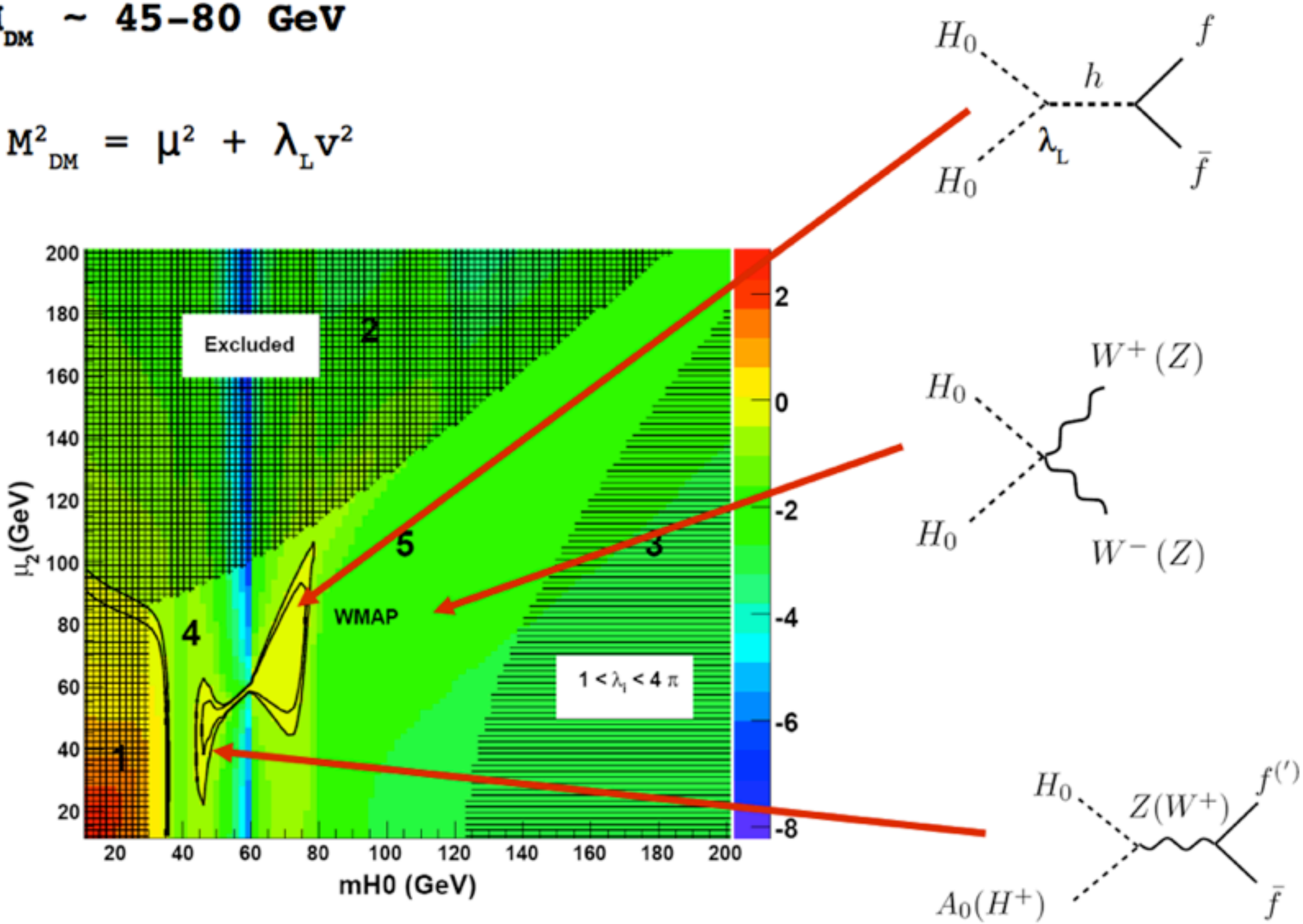
M_{higgs} = 200 GeV   BR(h → SS) = 70%

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

Middle Mass Candidate

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

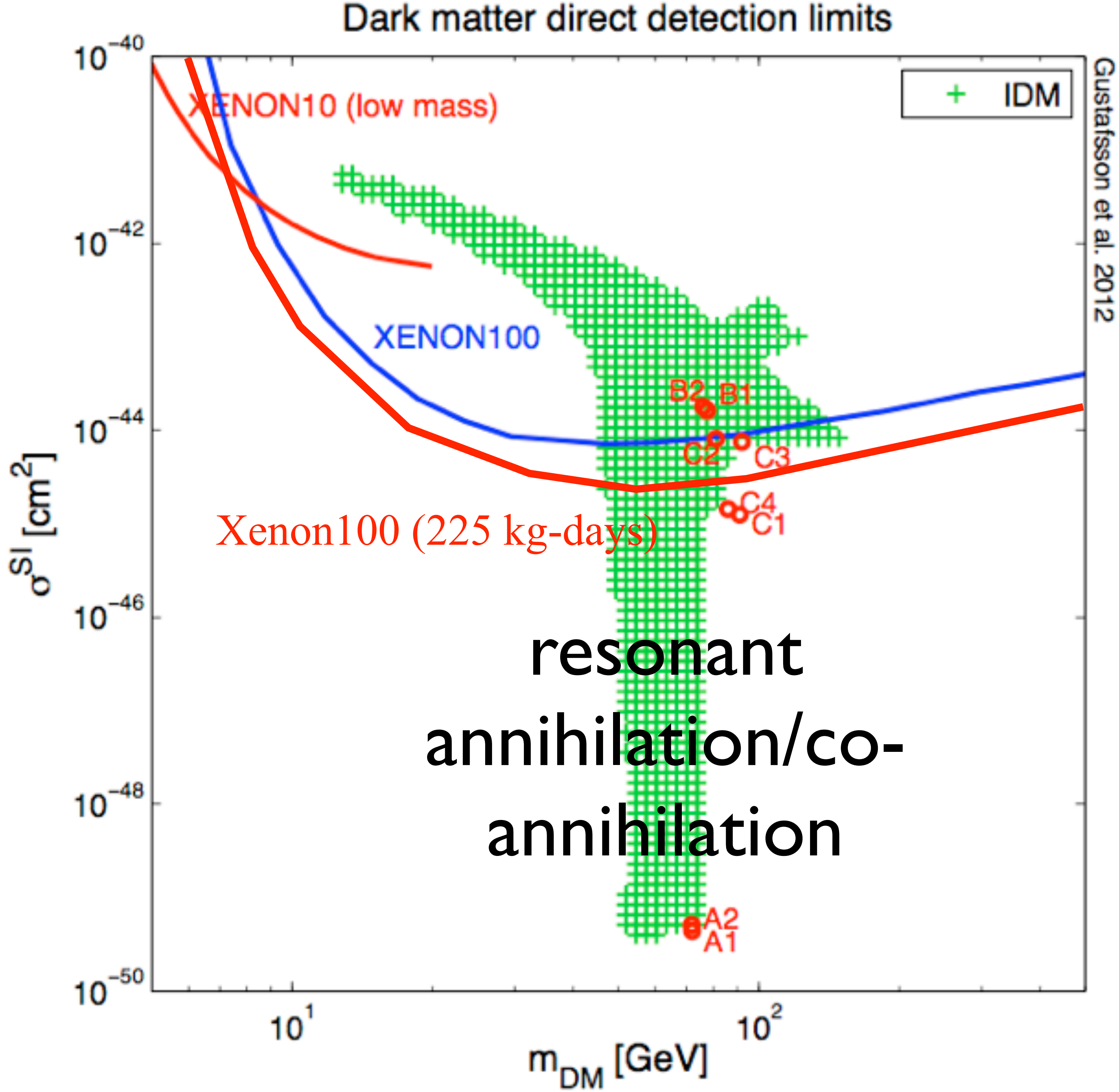
$$M^2_{DM} = \mu^2 + \lambda_L v^2$$



Coannihilation effects

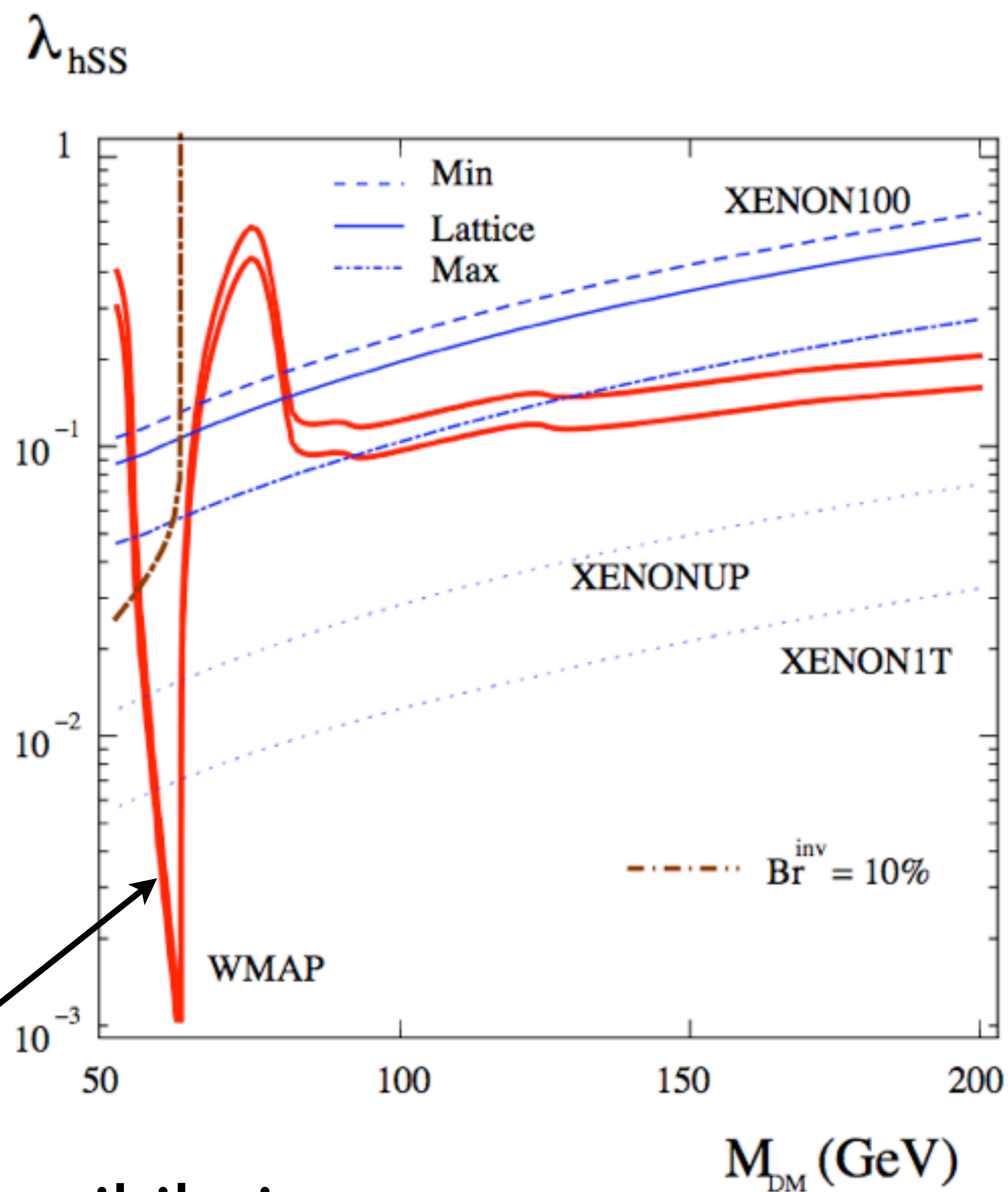
Barbieri, Hall, Ryckhov;
L. Lopez Honorez, E. Nezri, J. Oliver, M.T.

Middle Mass Candidate



(Gustafsson, Lopez Honorez, Rydbeck & Lundstrom)

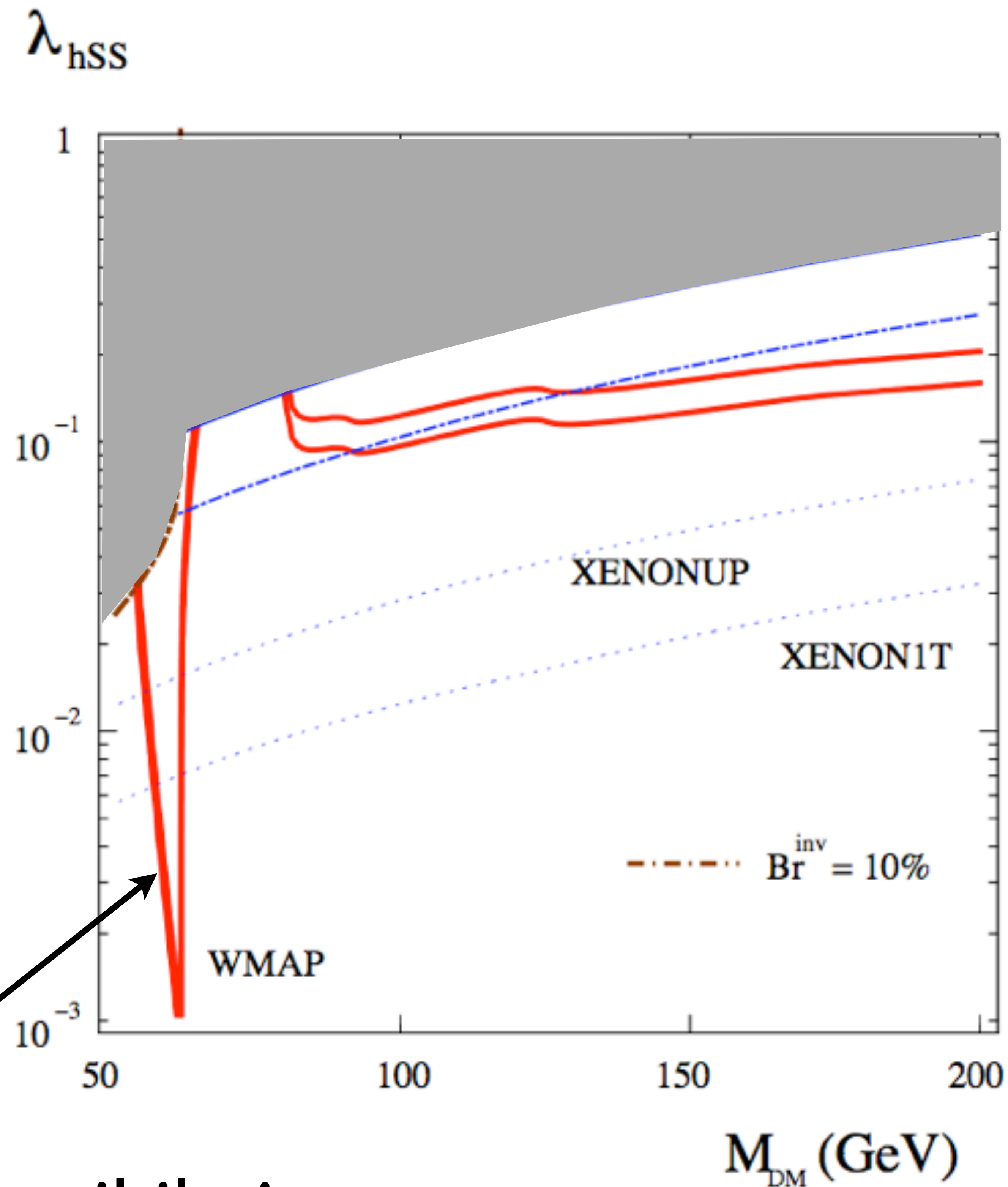
Digression: Singlet Candidate



resonant annihilation

(Djouadi, Lebedev, Mambrini & Quevillon)

Digression: Singlet Candidate



resonant annihilation

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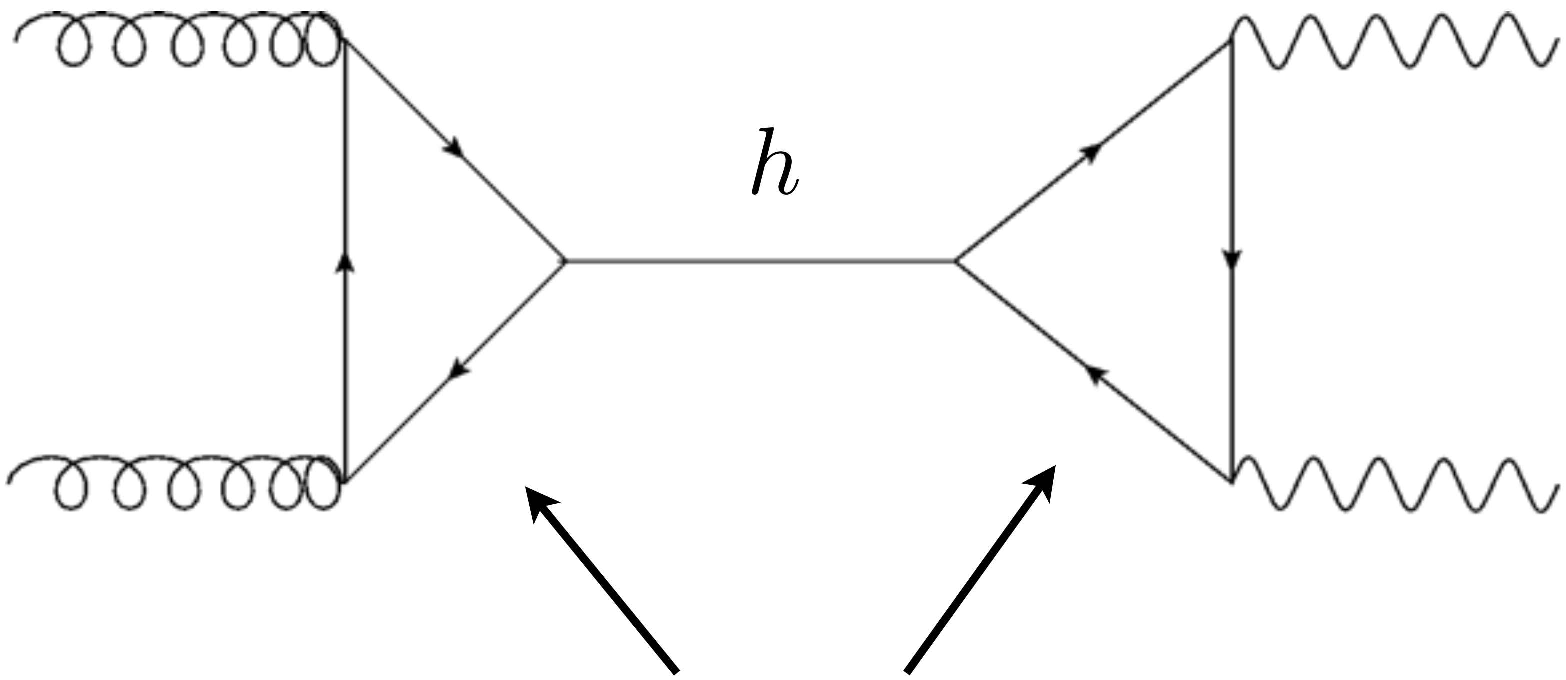
SMS diphoton decay

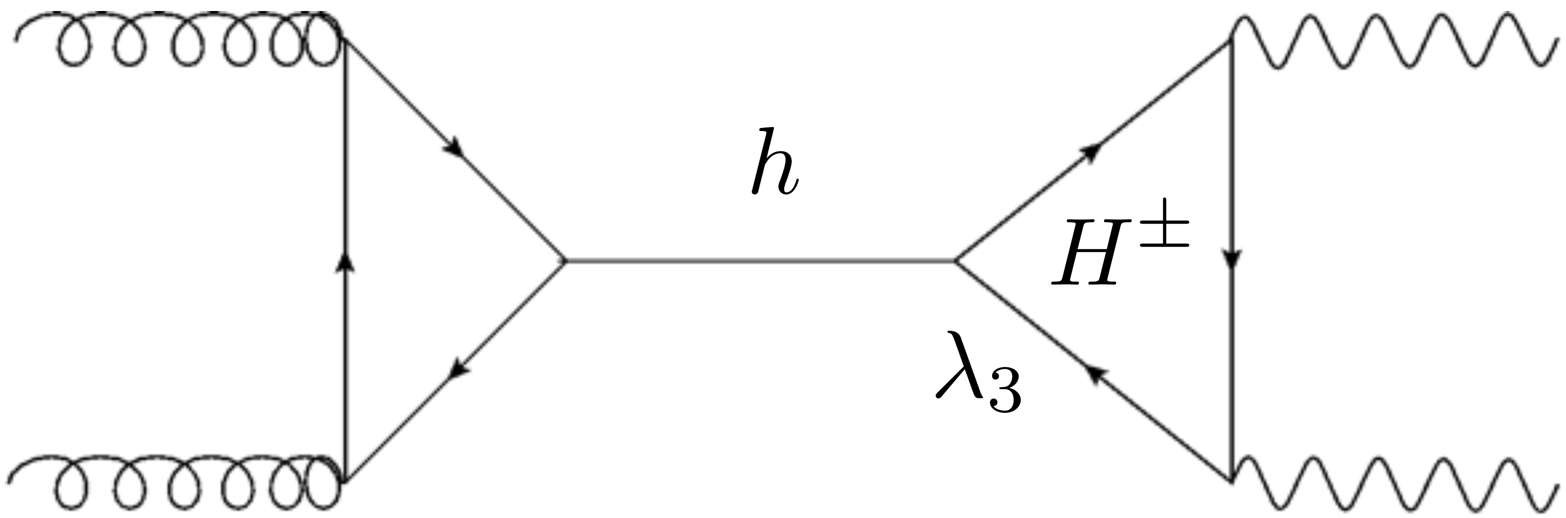


New Physics?

SMS diphoton decay

This is unchanged

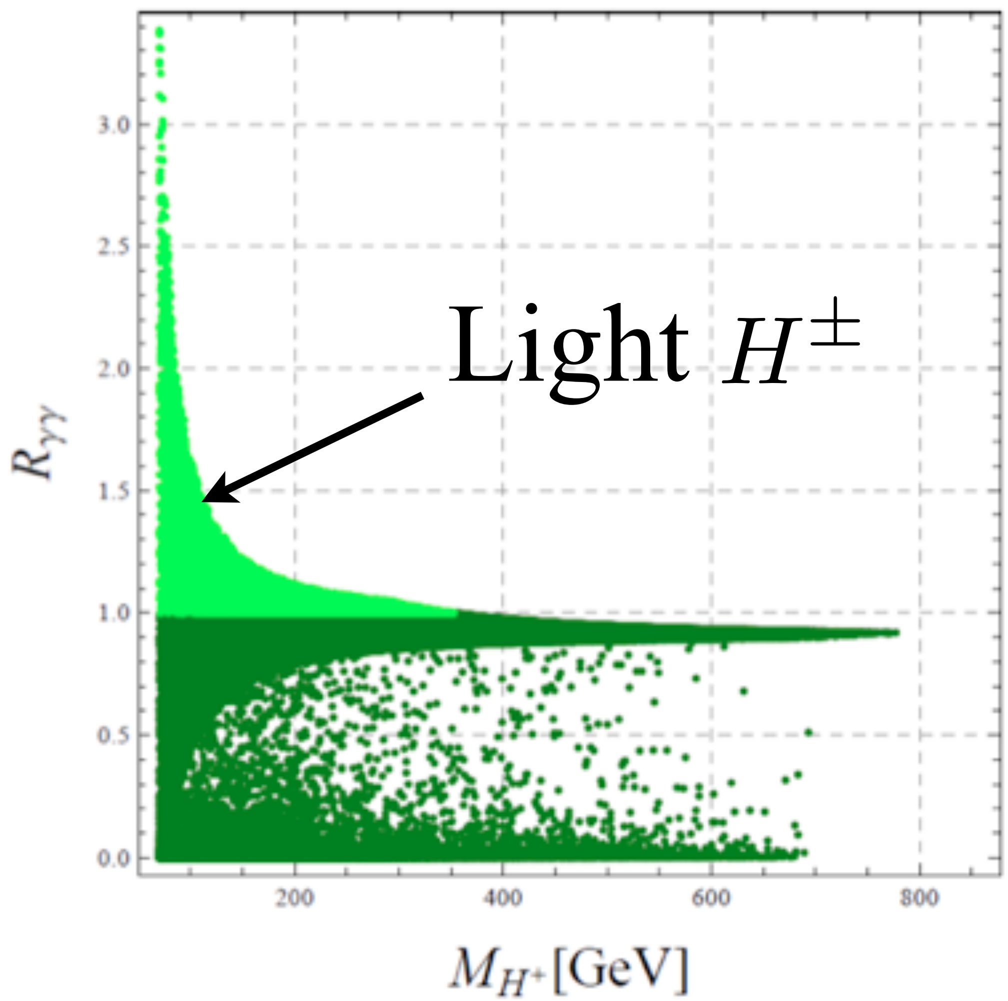
☞ Positive/Negative interference

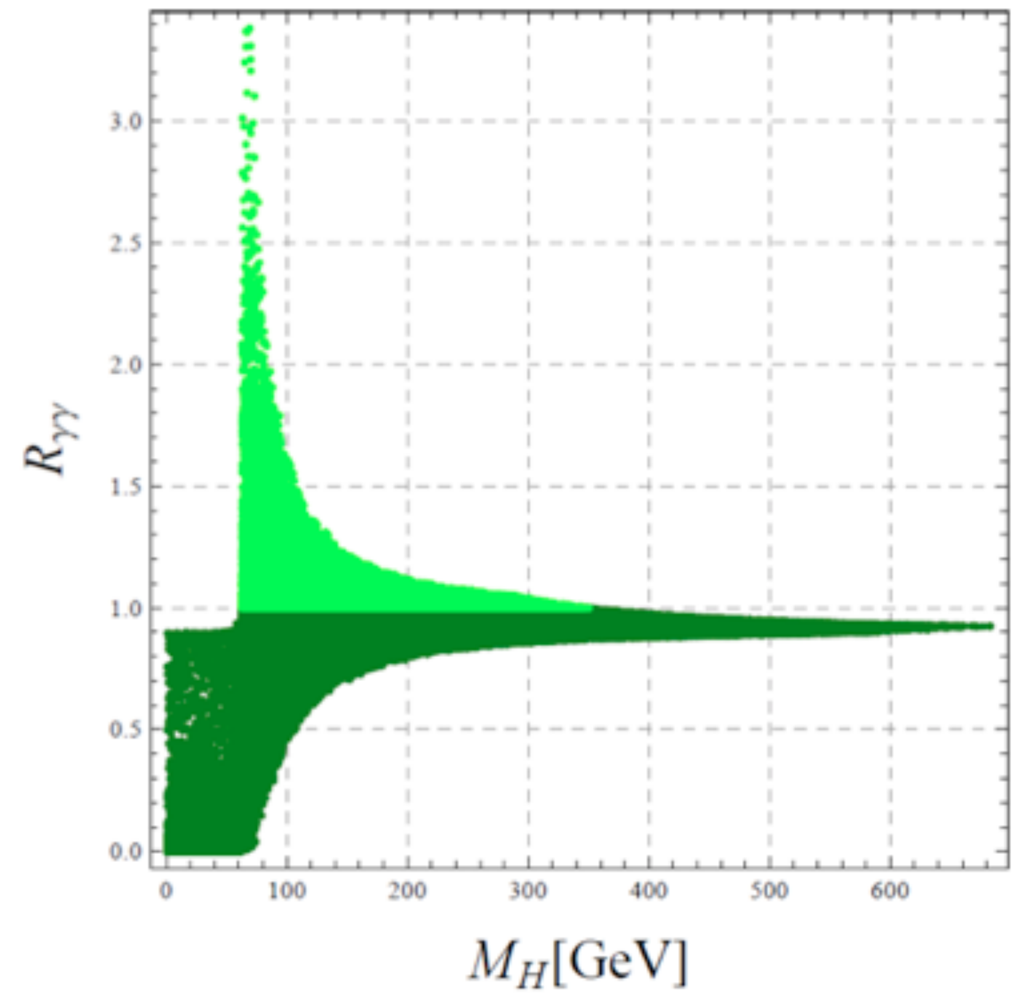


$$\Gamma = \frac{G_F \alpha^2 m_h^3}{128\sqrt{2}\pi^3} \left| A_{SM} + A_{H^{\pm}} \right|^2$$

SMS diphoton decay

(cf talk by Bogumila Swiezewska on Tuesday)

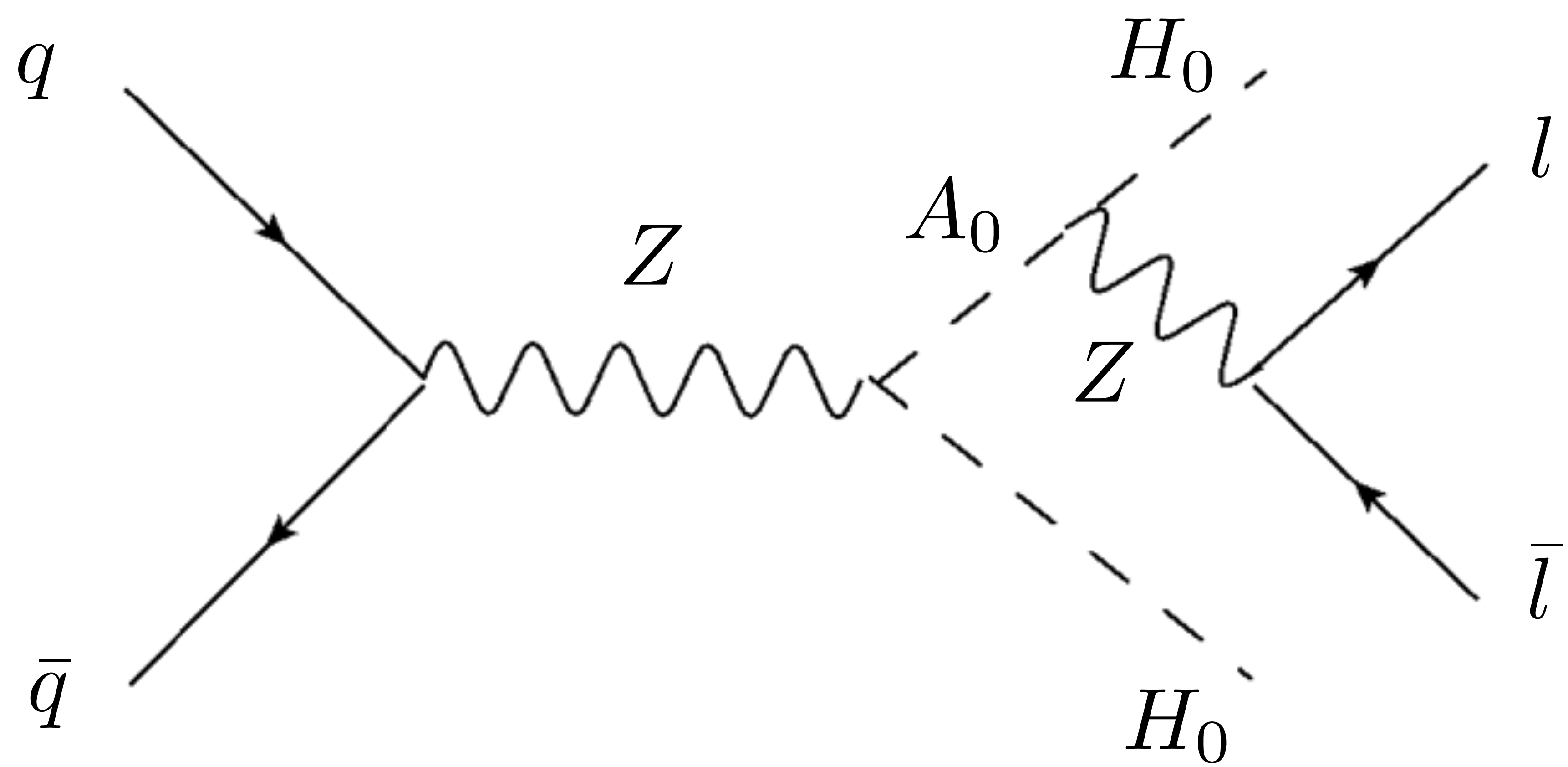




$$\frac{\Gamma_{\gamma\gamma}(IDM)}{\Gamma_{\gamma\gamma}(SM)} >\sim 1.3 \quad \text{for} \quad 62.5\text{GeV} < M_{H_0} < 135\text{GeV}$$

(Swiezewksa & Krawczyk
see also Arhrib, Benbrik & Gaur)

Multi-leptons @ LHC

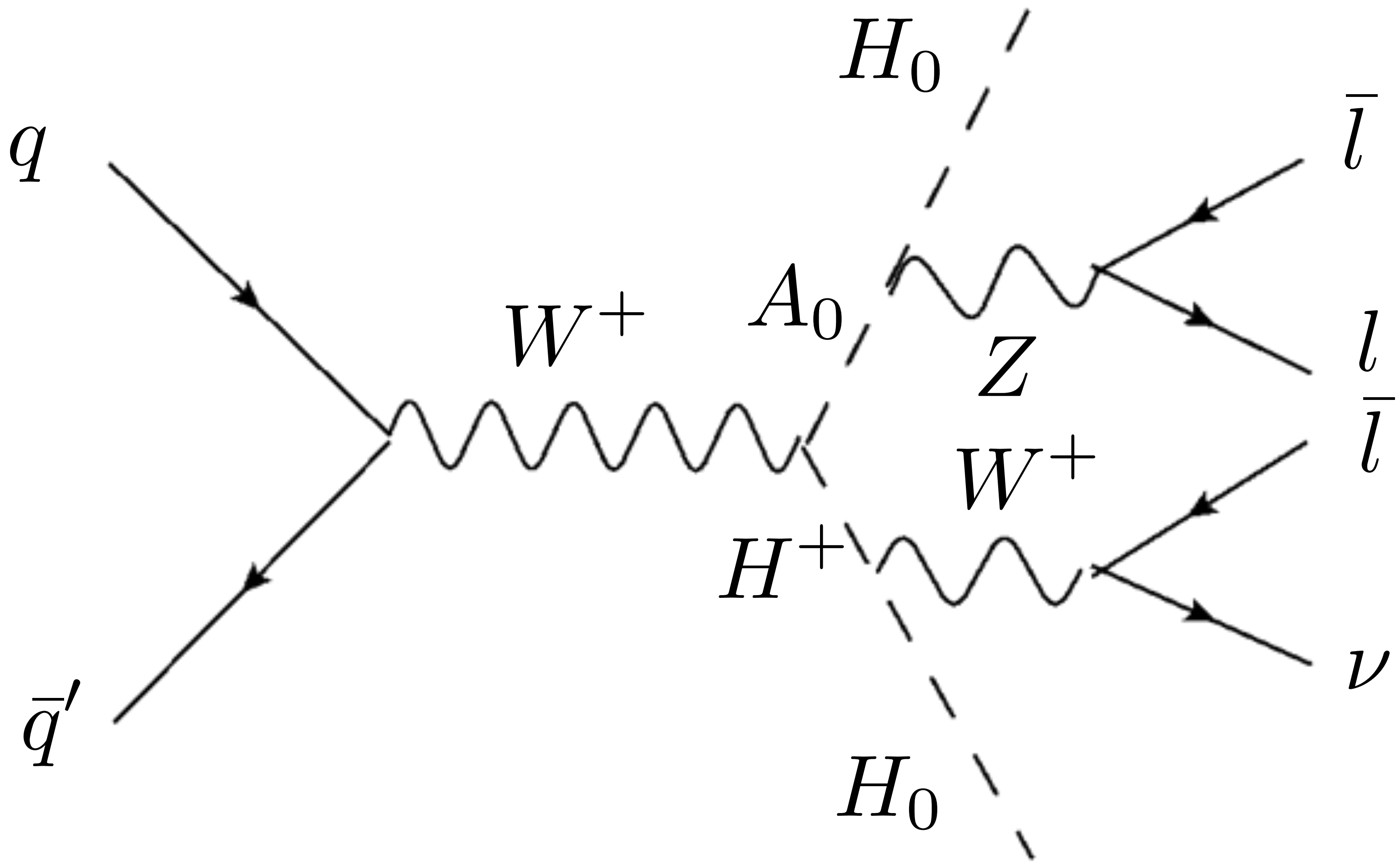


dileptons + $\not{E}$

Typically 3σ evidence possible 100 fb^{-1} @ 14 TeV

(Cao, Ma & Rajasekaran ; Dolle, Miao, Su & Thomas)

Multi-leptons @ LHC

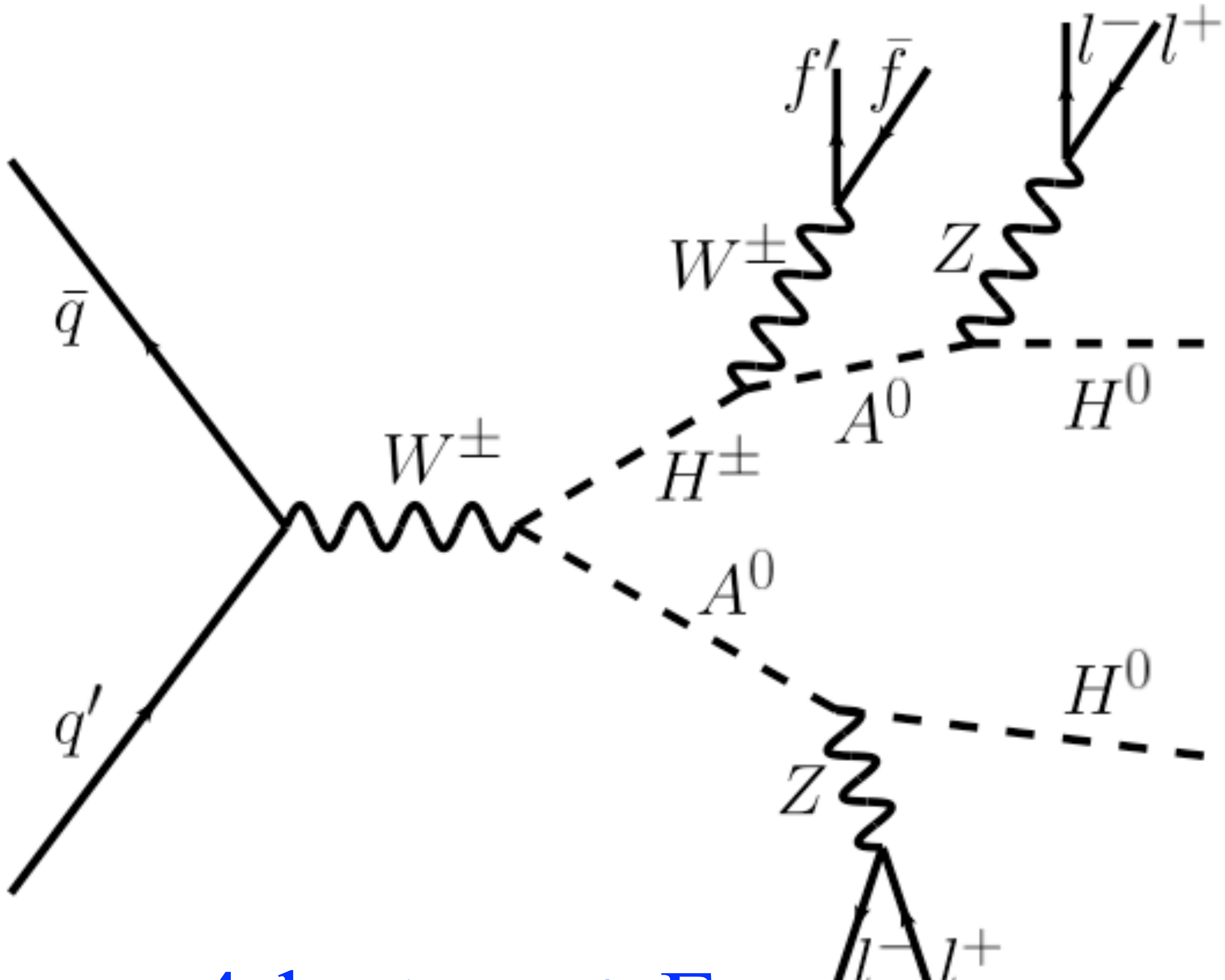


trileptons + $\not{E}$

Typically 3σ evidence possible 100 fb^{-1} @ 14 TeV

(Miao, Su & Thomas)

Multi-leptons @ LHC



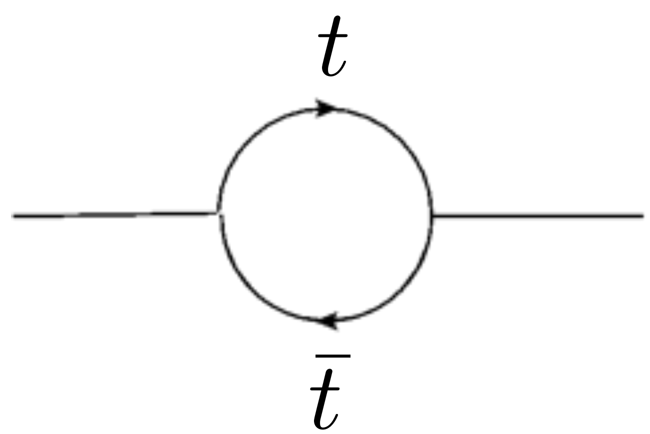
4-leptons + $\not{E}$

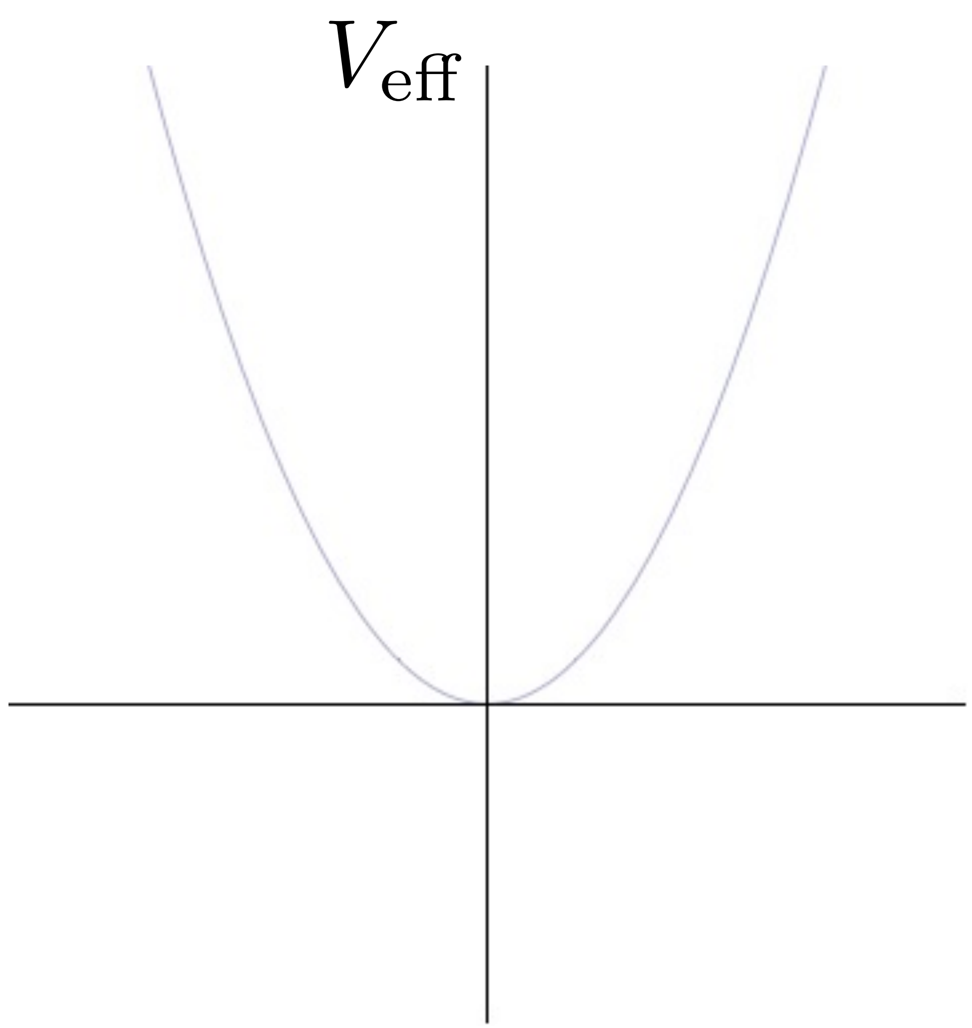
Studied but beyond the reach of LHC
(for standard SMS)

(Gustafsson, Rydbeck, Lopez Honorez &Lundstrom, arXiv:1206.6316)

EWSB & EWPT

$\Delta V_{\text{eff}}(H) \supset$





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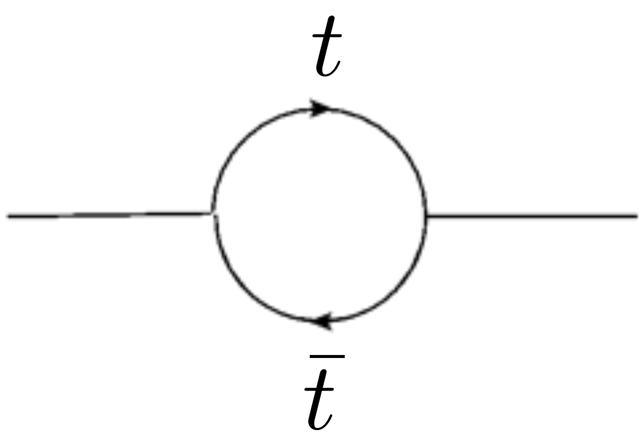
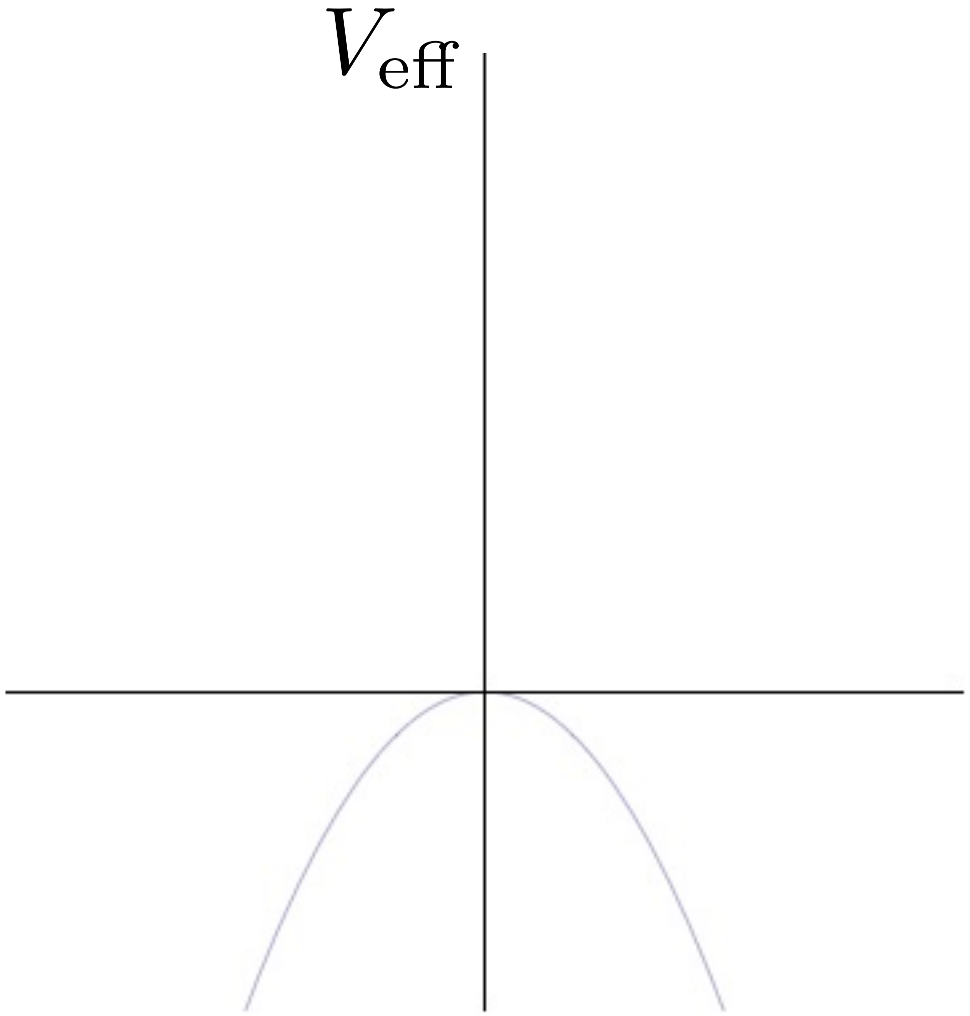
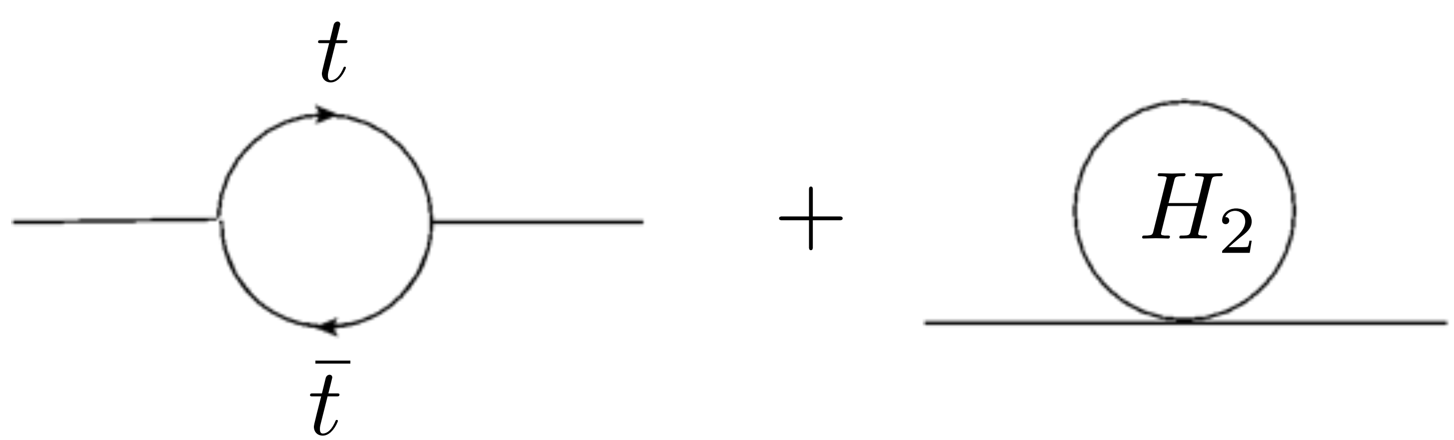


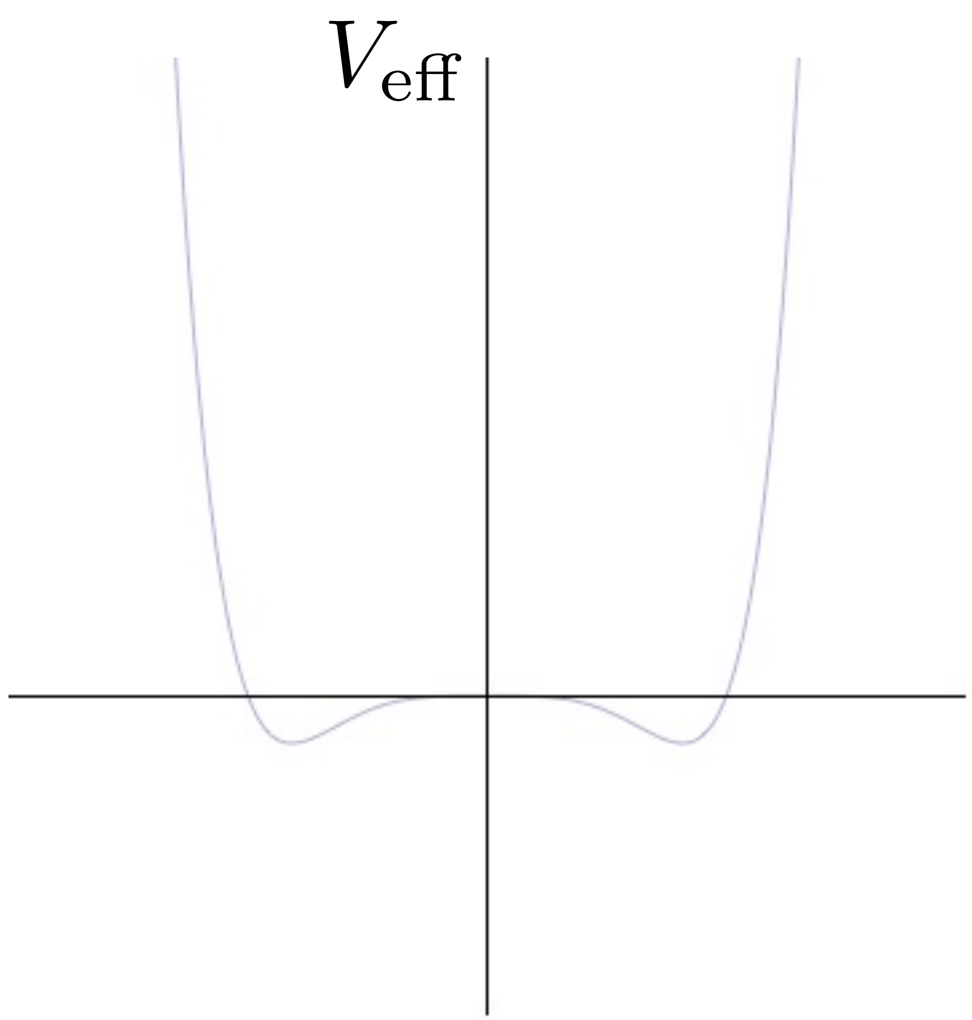


Instability due to top quarks in loops

EWSB & EWPT

$\Delta V_{\rm eff}(H) \supset$





Electroweak Symmetry Breaking by Dark Matter (à la Coleman-Weinberg)

Roughly speaking $M_H \sim \mu$

(Quiros & Espinosa; Hambye & MT)

EWSB & EWPT

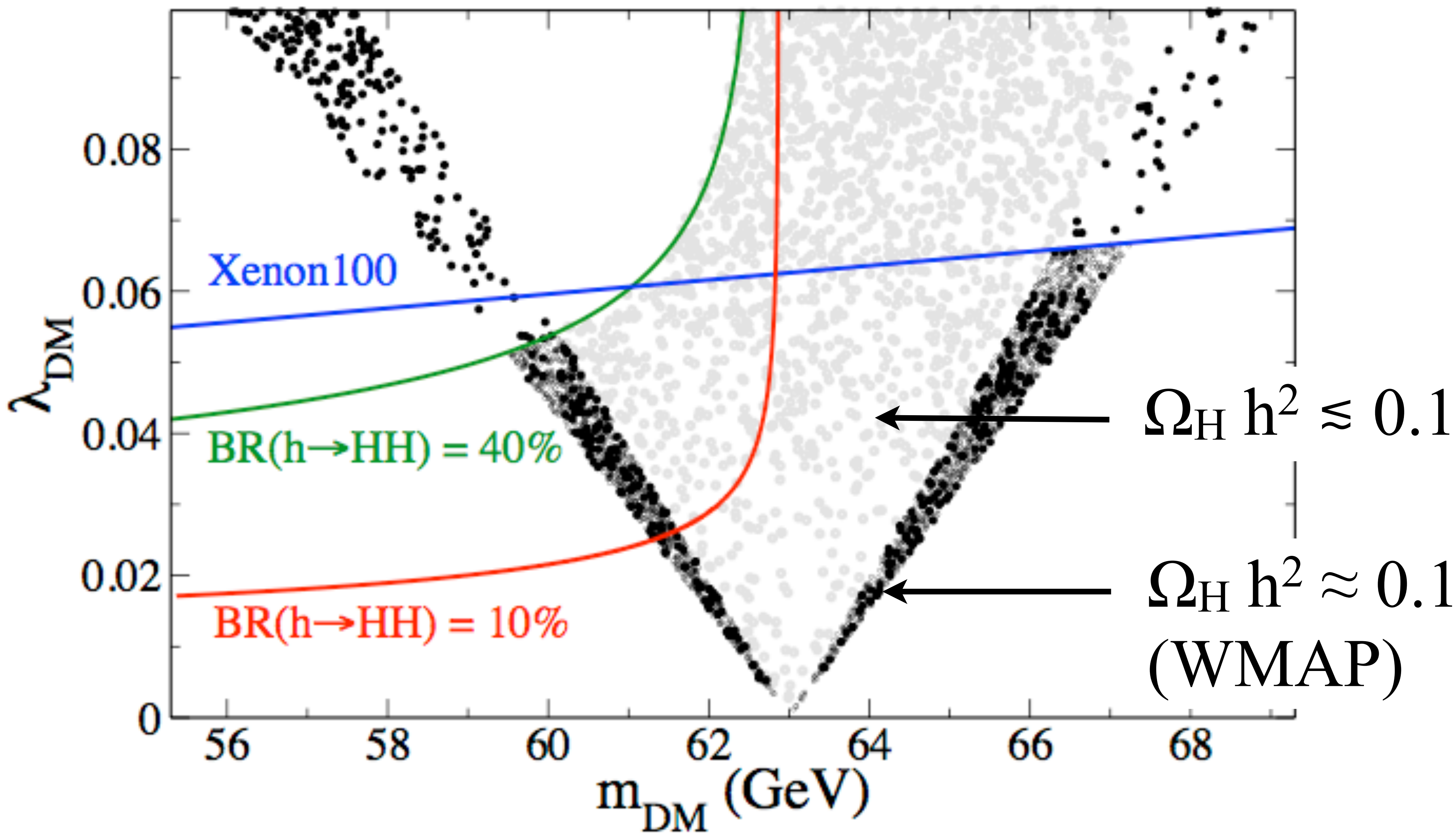
By the same token, H_2 may induce a
Strongly First Order
Electroweak Phase Transition *

(while being consistent with Mh ≈ 126 GeV and $\Omega_H h^2 \approx 0.085$)

* This is a necessary condition for Baryogenesis at the Electroweak Scale

By the way, needs also CP violation, but this is beyond the realm of the IDM

EWSB & EWPT



(Borah & Cline: arXiv:1204.4722)

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

EWSB & EWPT

$$\Gamma = \frac{G_F \alpha^2 m_h^3}{128\sqrt{2}\pi^3} \left| A_{SM} + A_{H^\pm} \right|^2$$

Strong EWPT requires

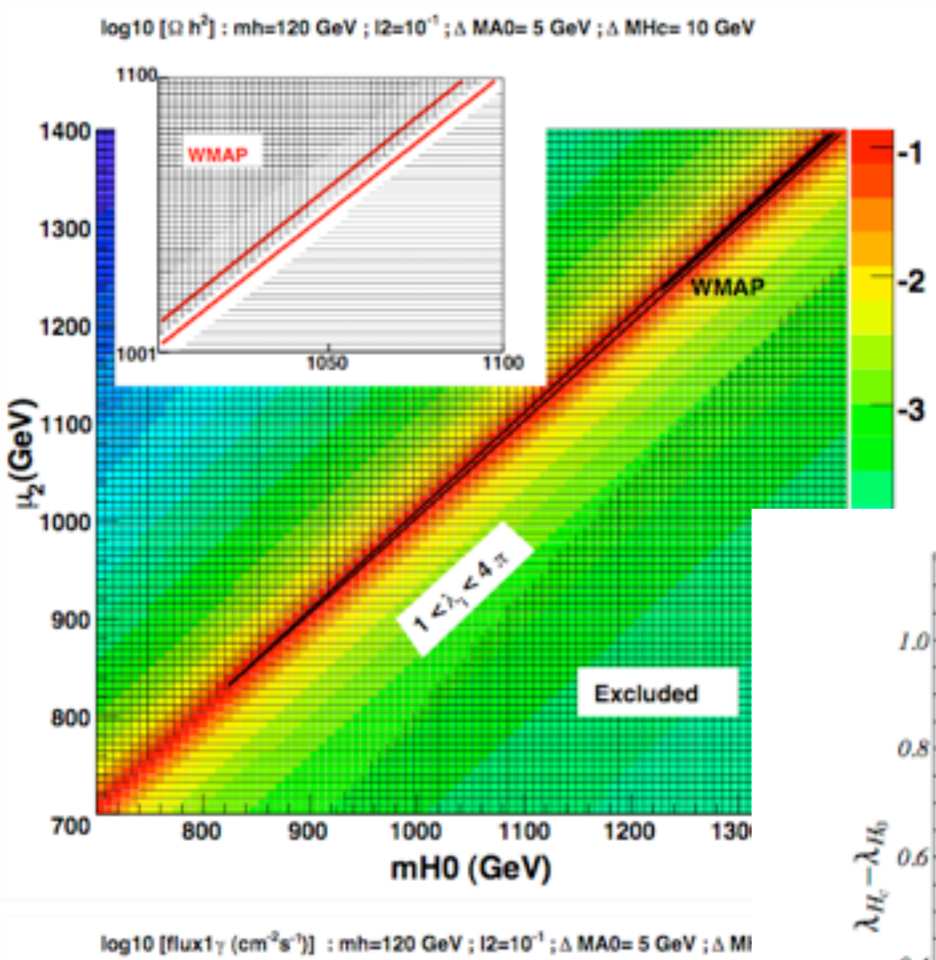
$$M_{H^\pm} \sim M_{A_0} \sim 200\,\mathrm{GeV}$$

which gives*

$$\Gamma \approx 1.1 \times \Gamma_{SM}$$

* for $M_H >$ $M_h/2$

High Mass Candidate



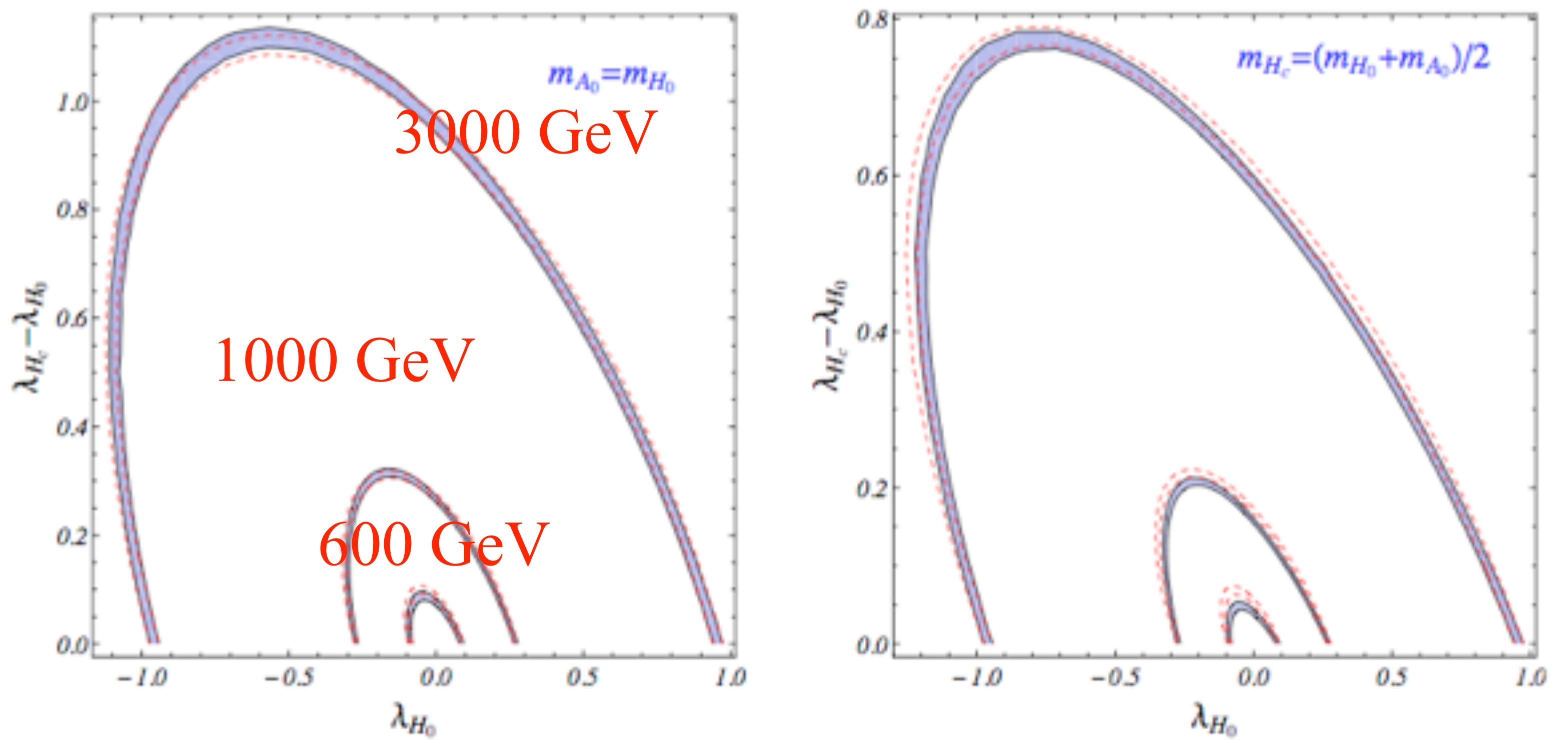
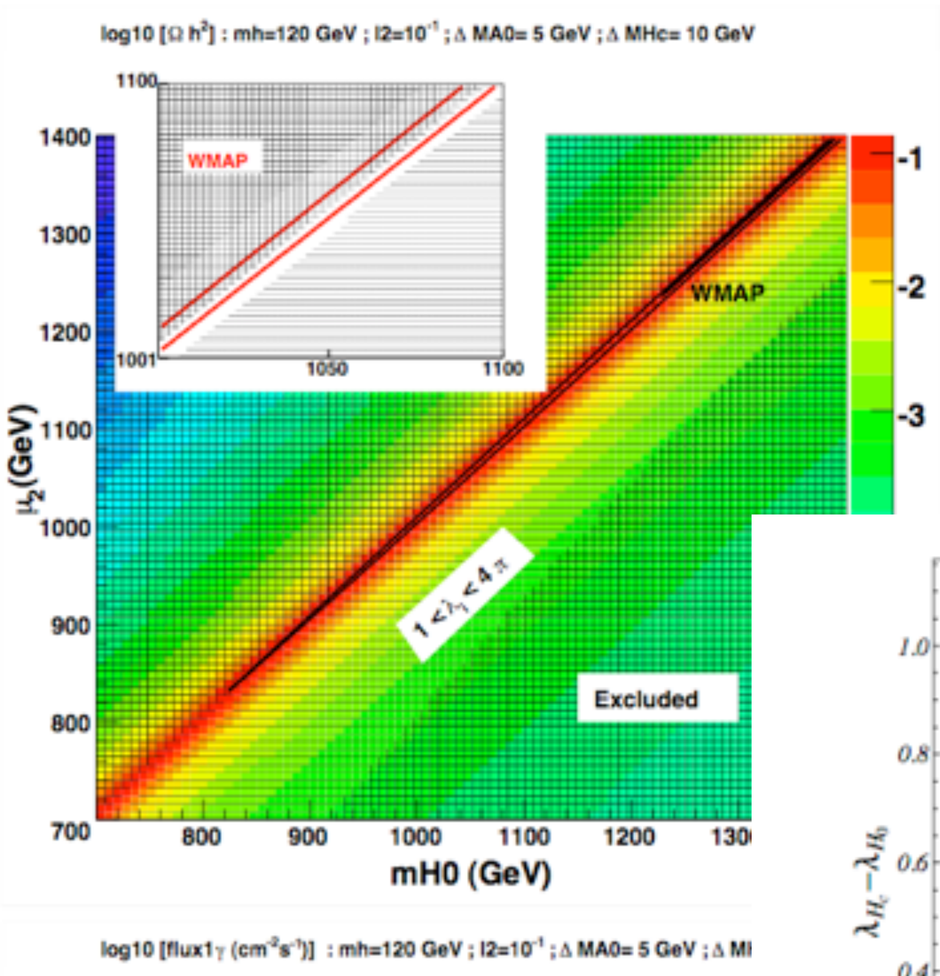


Figure 3: *Contours of λ for the WMAP value $\Omega_{DM}h^2 = 0.1131 \pm 0.0034$ for $m_{H_0} = 600$ (interior), 1000, 3000 (exterior) GeV, with $m_{A_0} = m_{H_0}$ (left panel) and $m_{H_c} = (m_{H_0} + m_{A_0})/2$ (right panel). Dashed curve corresponds to the approximate ellipsoid.*

(Lopez Honorez, Nezri, Oliver & M.T.)

(Hambye, Ling, Lopez Honorez &Rocher)

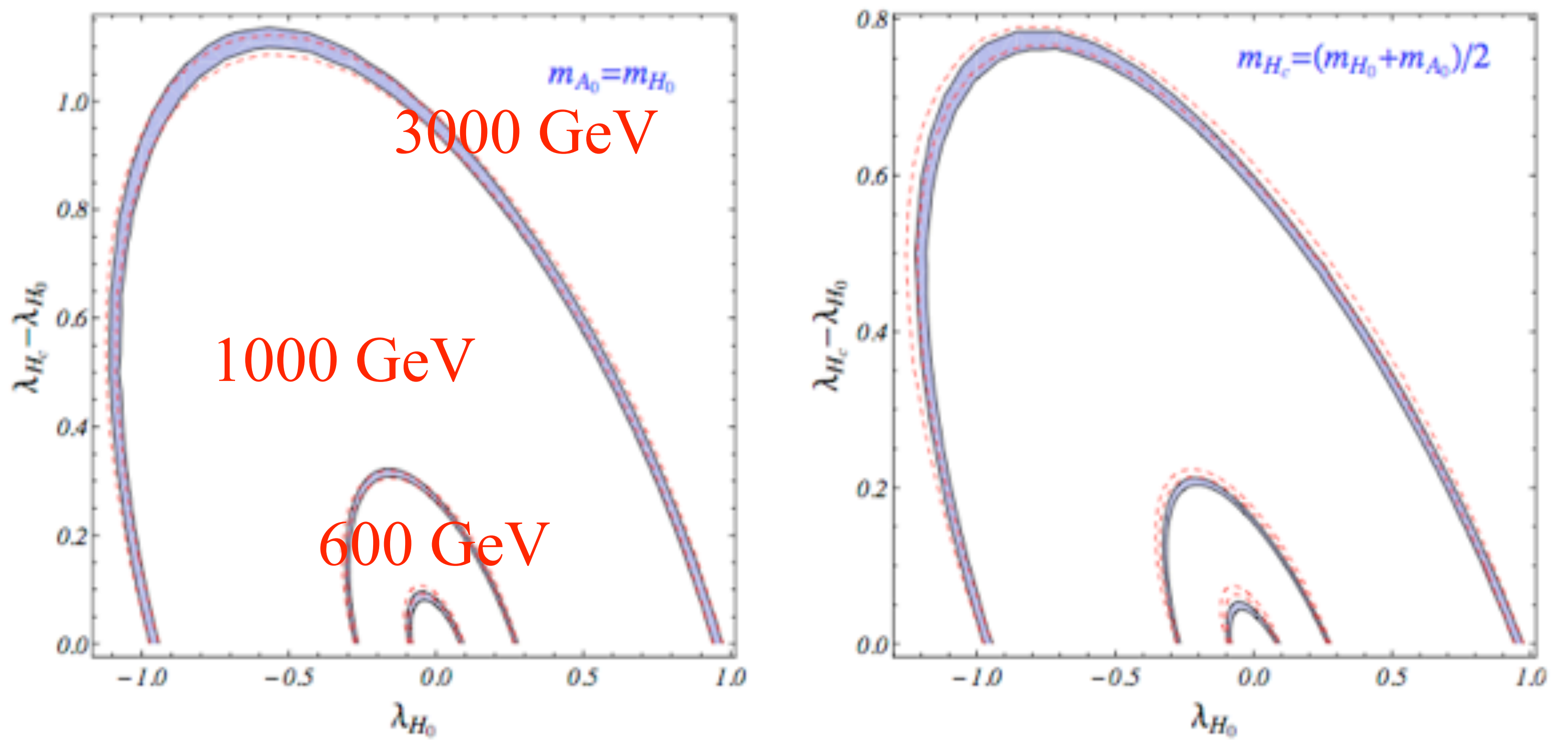
High Mass Candidate



Minimal Dark Matter ($\lambda = 0$)

$M_H \approx 500$ GeV

(Cirreli, Fornengo & Strumia)



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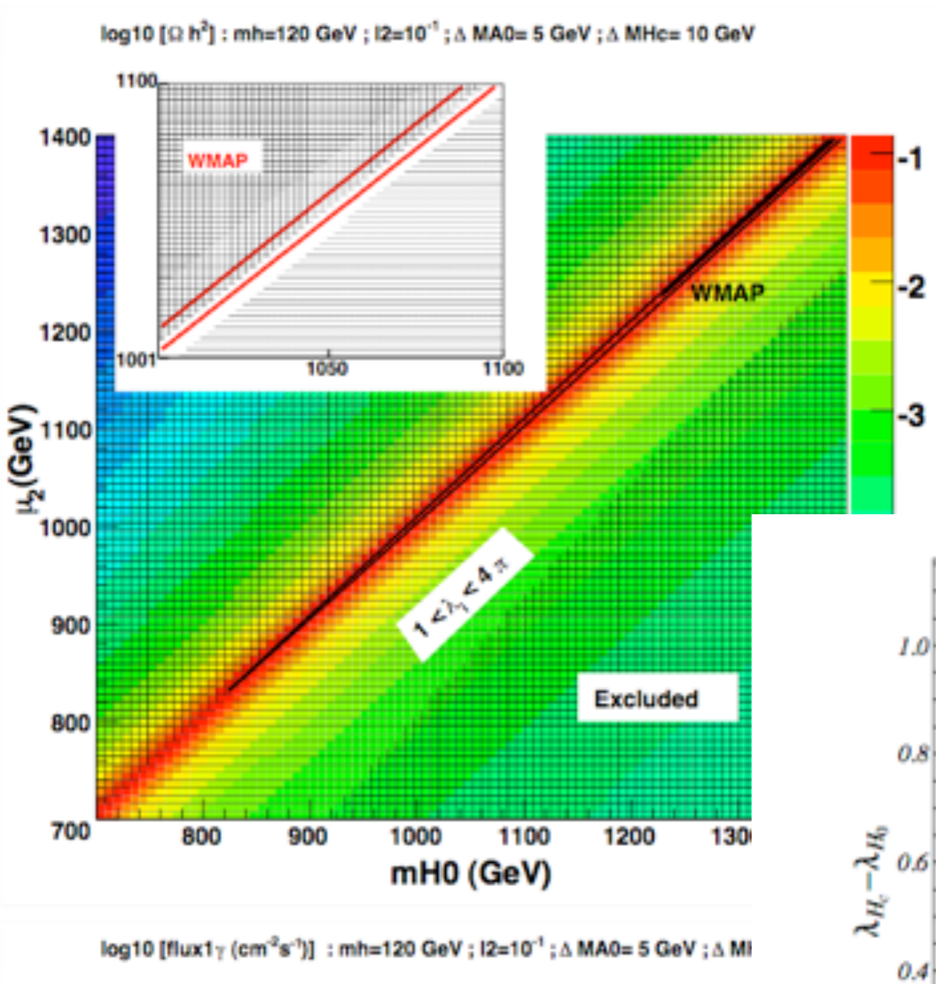
High Mass Candidate



Unitarity bound ($\lambda \lesssim 4\,\pi$)

$M_H \lesssim 58$ TeV

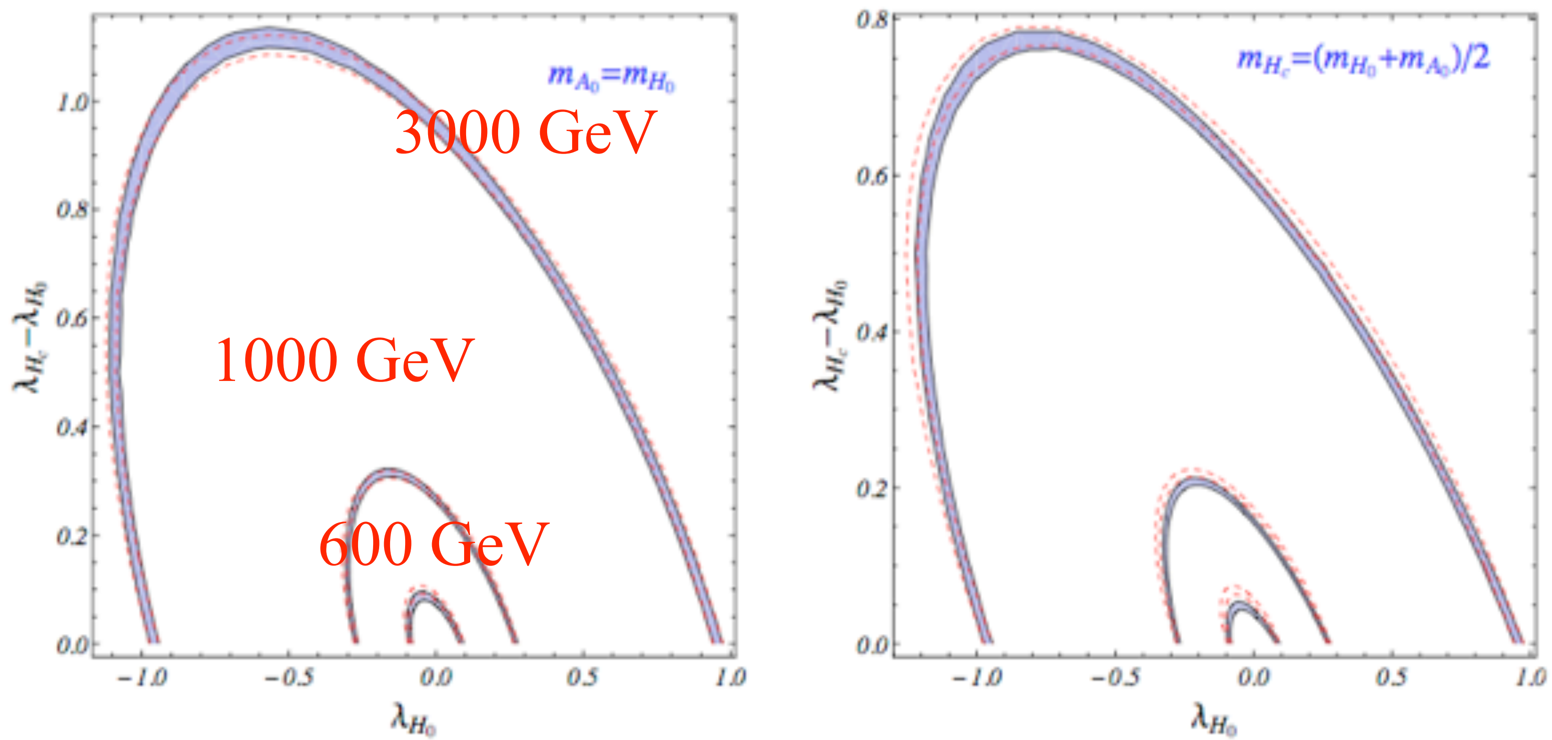


Figure 3: *Contours of* λ *for the WMAP value* $\Omega_{\rm DM}h^2 = 0.1131 \pm 0.0034$ *for* $m_{H_0} = 600$ *(interior),* 1000, 3000 *(exterior) GeV, with* $m_{A_0} = m_{H_0}$ *(left panel) and* $m_{H_c} = (m_{H_0} + m_{A_0})/2$ *(right panel). Dashed curve corresponds to the approximate ellipsoid.*

(Lopez Honorez, Nezri, Oliver & M.T.)

(Hambye, Ling, Lopez Honorez &Rocher)

Higher Scalar Multiplets?

Perturbativity of $SU(2)_L$ up to M_{Planck} ☞ $n \leq 8$

No Z coupling (*i.e.* no direct detection) ☞ $n = 3,5,7$

Heavy WIMPs ☞ M_{dm} from ~ 0.5 TeV

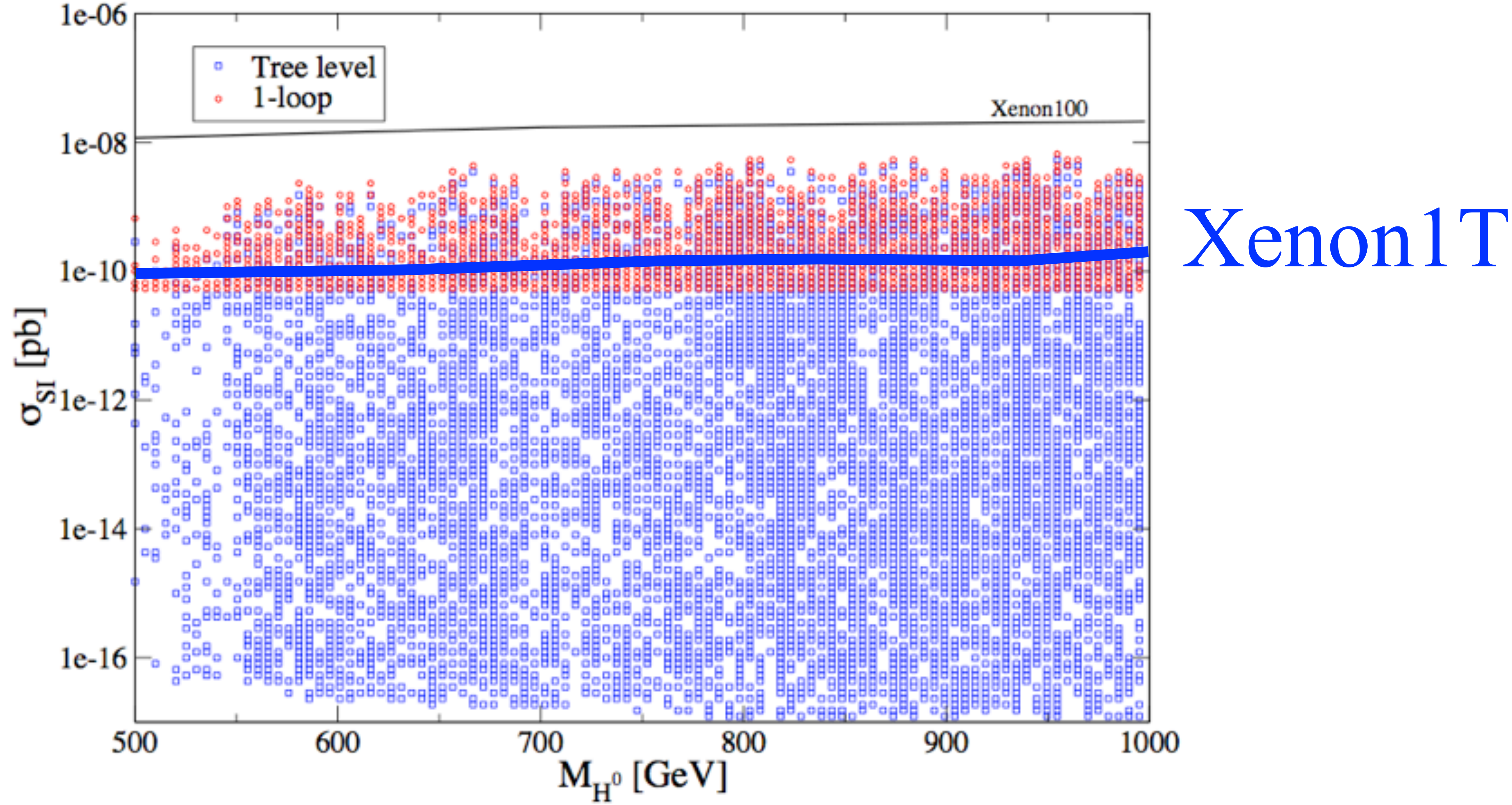
(Minimal Dark Matter: Cirreli, Fornengo &Strumia)

to up to ~ 50 TeV

(Unatirity bound: Hambye, Ling, Lopez Honorez & Rocher)

High Mass Candidate

Too heavy for LHC searches but direct detection within reach of Xenon1T



(Klasen, Yaguna & Ruiz-Alvarez: arXiv:1302.1657)

Conclusions

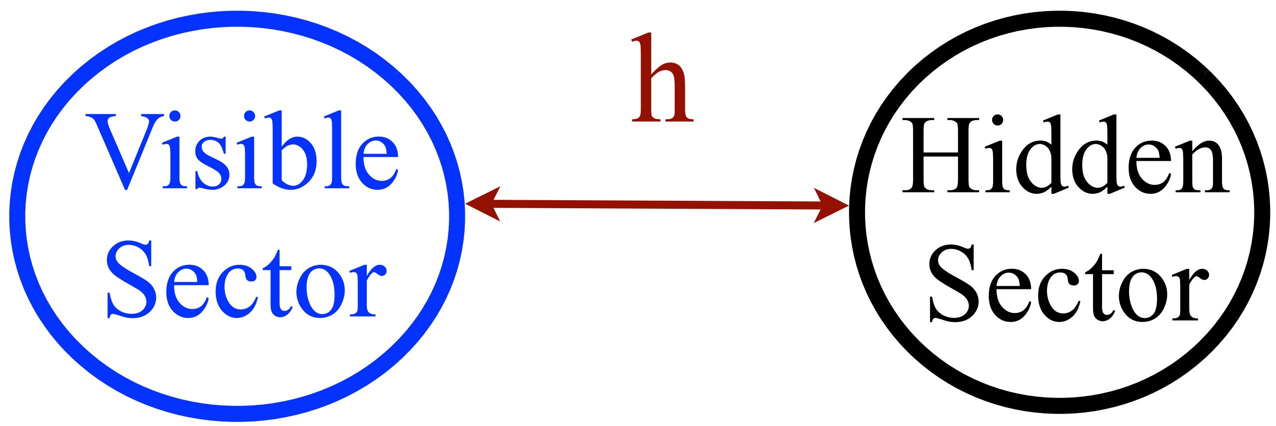
IDM is one of the simplest extensions of the SM

Yet rich and versatile (*i.e.* having many uses or applications)

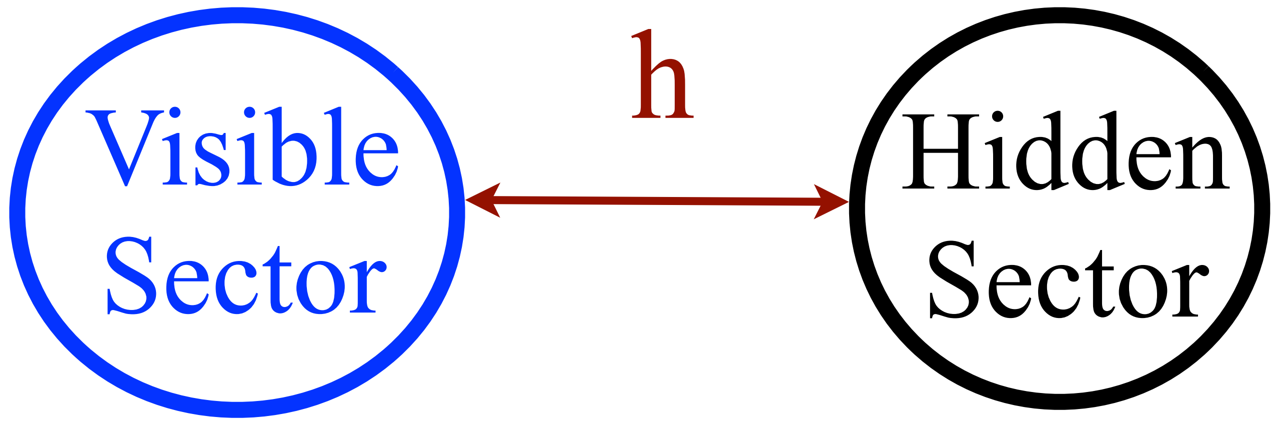
☞ dark matter, radiative neutrino masses, EWSB,...

All the parameter space will be probed eventually (expect for very fine tuned regions)

The Scalar sector as a Portal to New Physics



The Scalar sector as a Portal to New Physics



$$\Delta\mathcal{L} \supset \lambda_S\, |S|^2\, |H|^2 + |D'_\mu S|^2 - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu}$$

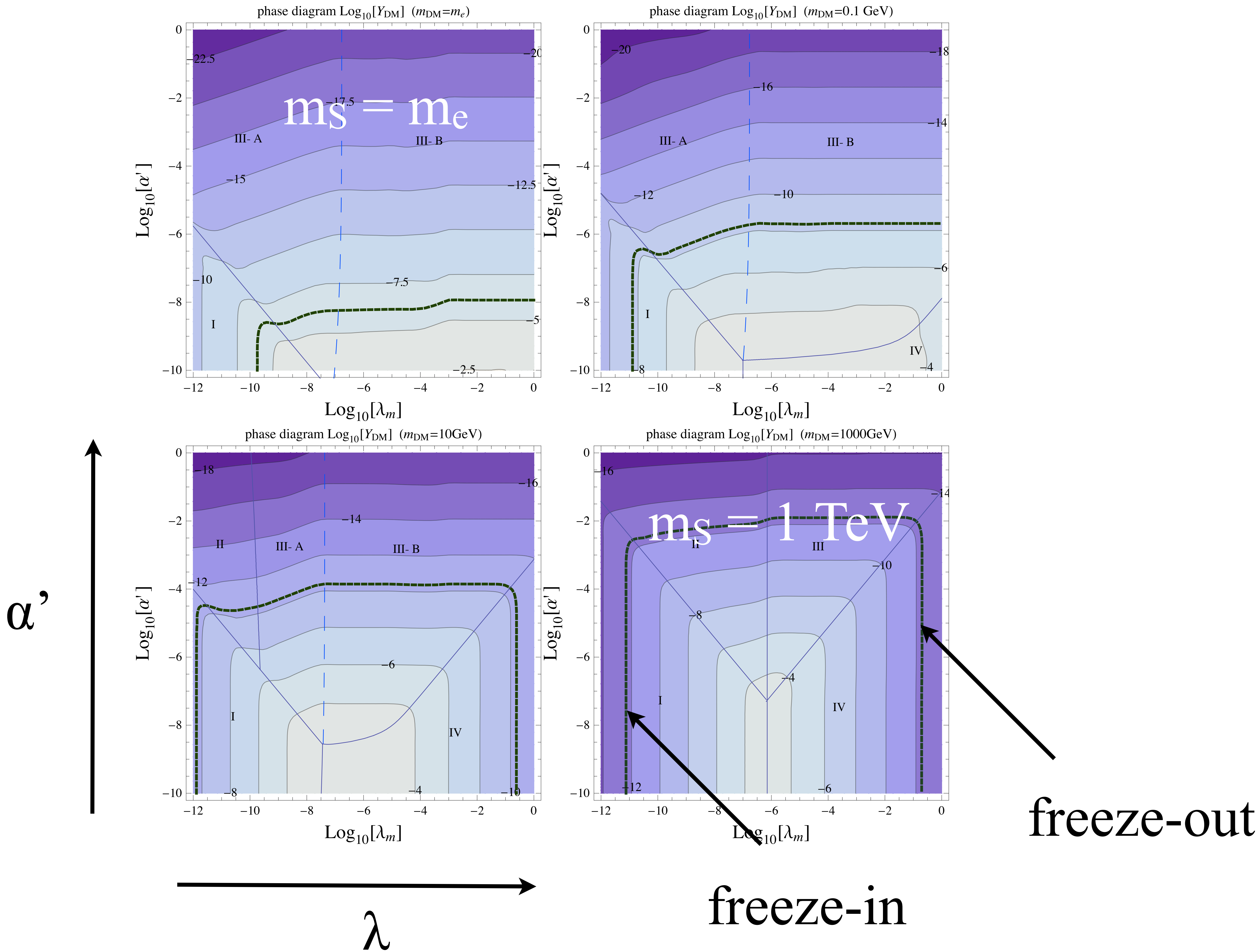
↑

hidden photon
(aka dark radiation)

☞ Stability from (gauged) $U(1)_{Q'}$

☞ 4 basic ways for DM creation through the SMS

(Chu, Hambye & MT: arXiv:1112.1657)


phase diagram Log10[YDM] (mDM=me)
phase diagram Log10[YDM] (mDM=0.1 GeV)
phase diagram Log10[YDM] (mDM=10GeV)
phase diagram Log10[YDM] (mDM=1000GeV)
Log10[α']
Log10[λm]
mS = me
mS = 1 TeV
I
II
III- A
III- B
III
IV
α'
λ
freeze-out
freeze-in

Low Mass Candidate

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 - That's ugly