CONFRONTING DIFFERENT MASS SCALES FOR DARK MATTER

Michel H.G. Tytgat
Université Libre de Bruxelles
Belgium

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«Would you be willing to give a talk on the possible different mass scales for DM? Tentative/illustrative title: "Confronting different scales for DM"...

I know we are asking something non-trivial, a kind of deep perspective talk.»

WHICH MASS SCALE?

Observations tell us that
dark matter is cold, stable ($\tau \gg \tau_U$)* and invisible

This leaves some freedom...

* Rem: $\tau_U \sim 10^{18}$ sec; $\tau \gtrsim 10^{26}$ sec from constraints on flux of e+, anti-proton, gamma-ray,...

WHICH MASS SCALE?

Observations tell us that
dark matter is cold, stable ($\tau \gg \tau_U$)* and invisible

This leaves some freedom...

A WIMP?
Probably still our best bet

An AXION?

A WIMPZILLA?

e.g. $\sim 10^{-6}$ eV

GeV to TeV

e.g. $\sim 10^{12}$ GeV

* Rem: $\tau_U \sim 10^{18}$ sec; $\tau \gtrsim 10^{26}$ sec from constraints on flux of e+, anti-proton, gamma-ray,...

WHY WIMPs?

Classy theories (SUSY, Xtra DIM’s, etc.) «predict» the existence of stable, weakly interacting massive particles.

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Classy theories (SUSY, Xtra DIM’s, etc.) «predict» the existence of stable, weakly interacting massive particles.

Stable, weakly interacting massive particles may be searched by:

Direct Detection, Indirect Detection and Collider Experiments

WHY WIMPs?

This experimental program by itself largely motivates (at times much) less classy constructions.

Indeed, it is easy to implement DM.

e.g. add a singlet scalar field S with a parity

$$S \to -S$$

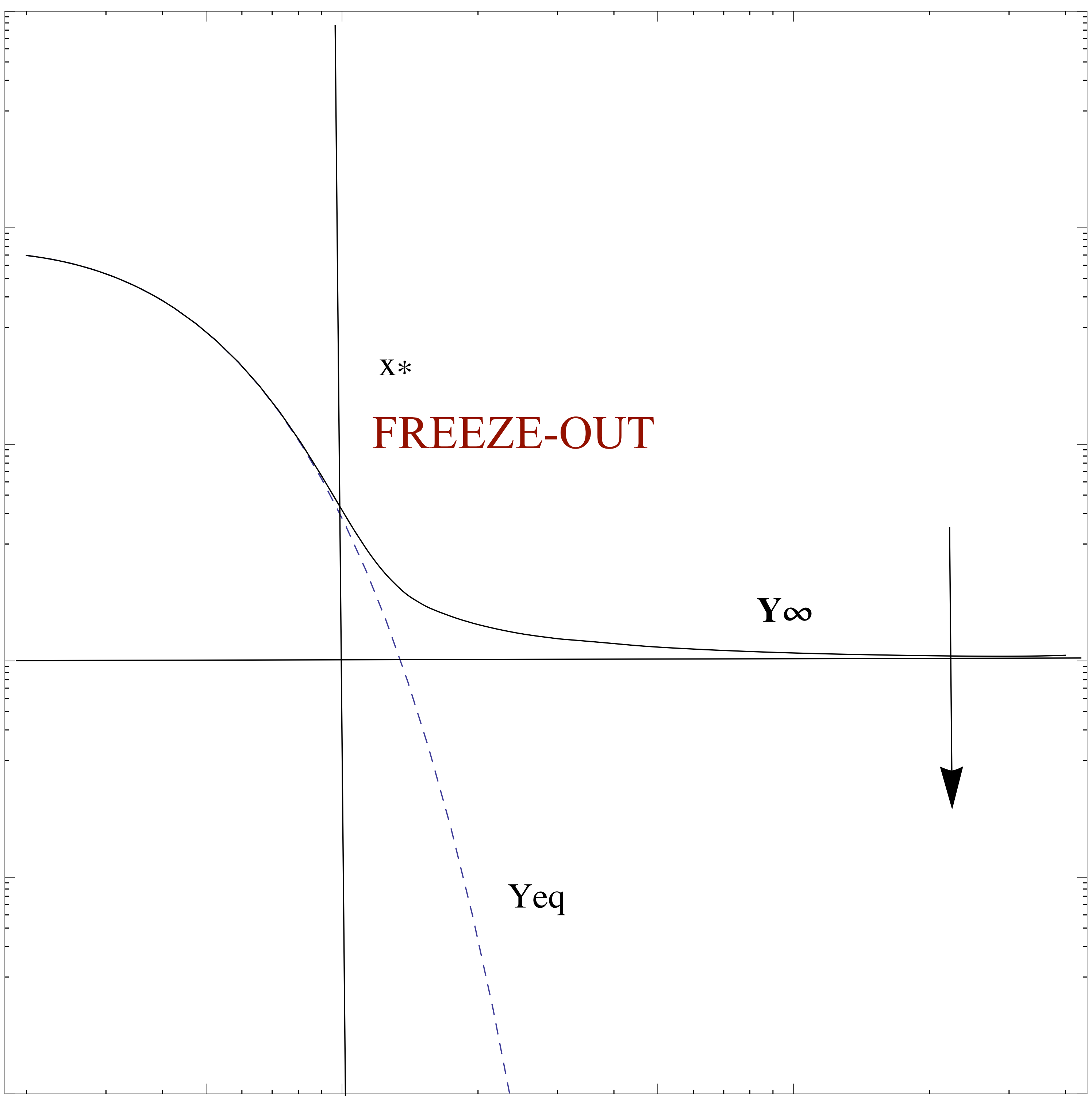
If $\langle S \rangle = 0$ then S is a DM candidate.

Silveira & Zee; Yndurain & Veltman; McDonald; Burgess, Pospelov & ter Veldhuis;...

THEN THERE IS THE WIMP MIRACLE

THERMAL ABUNDANCE

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



RELIC ABUNDANCE

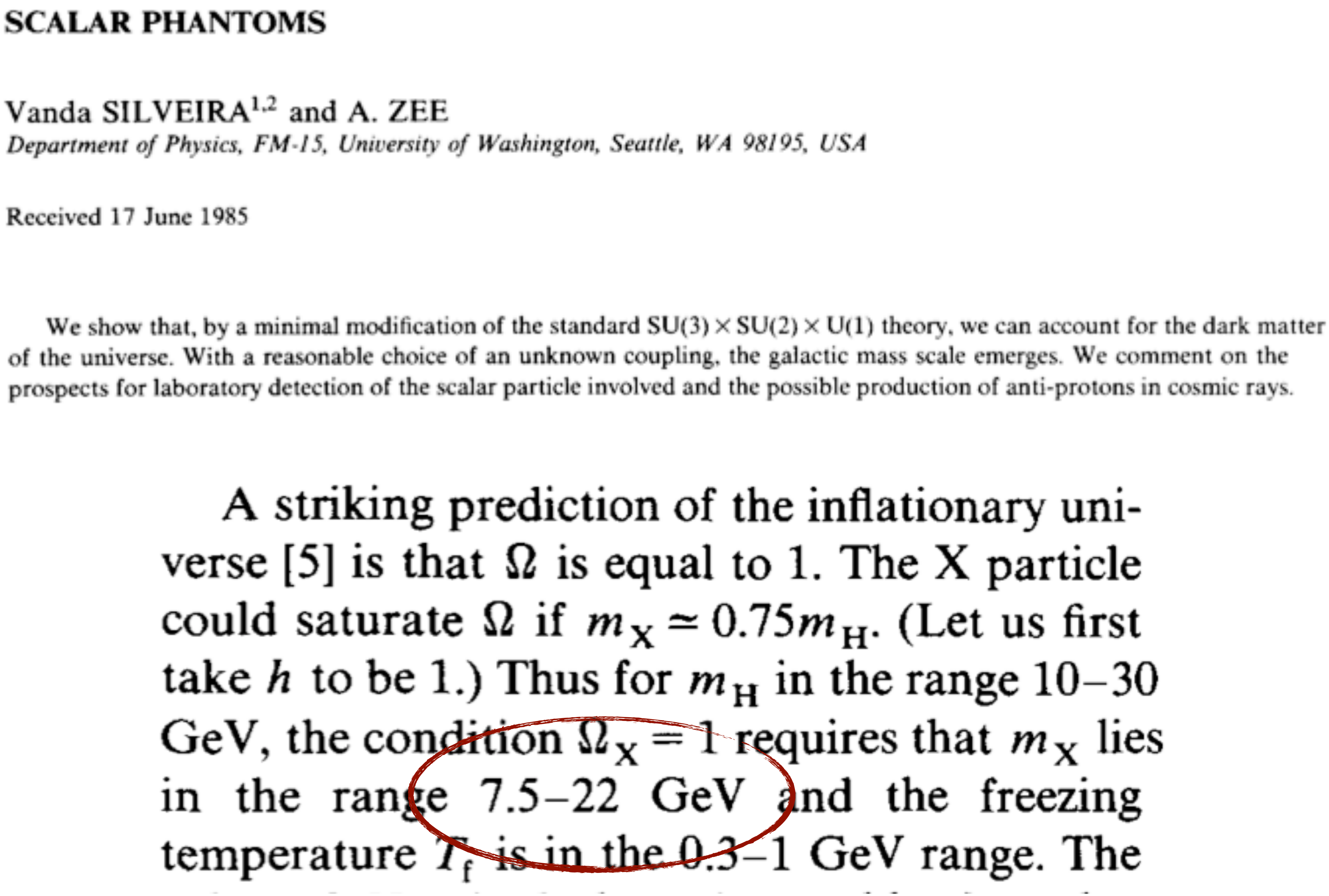
$$x = m/T$$

RELIC
ABUNDANCE

$$\frac{\Omega_{dm}}{\Omega_b} \approx 0.2\, x^* \left(\frac{\text{pbarn}}{\langle \sigma v \rangle}\right) \approx 5$$

FOR $x^* = \mathcal{O}(25)$ NEED $\langle \sigma v \rangle \sim 3 \cdot 10^{-26} \text{cm}^3 \cdot \text{s}^{-1}$

(FREEZE-OUT)



SCALAR PHANTOMS

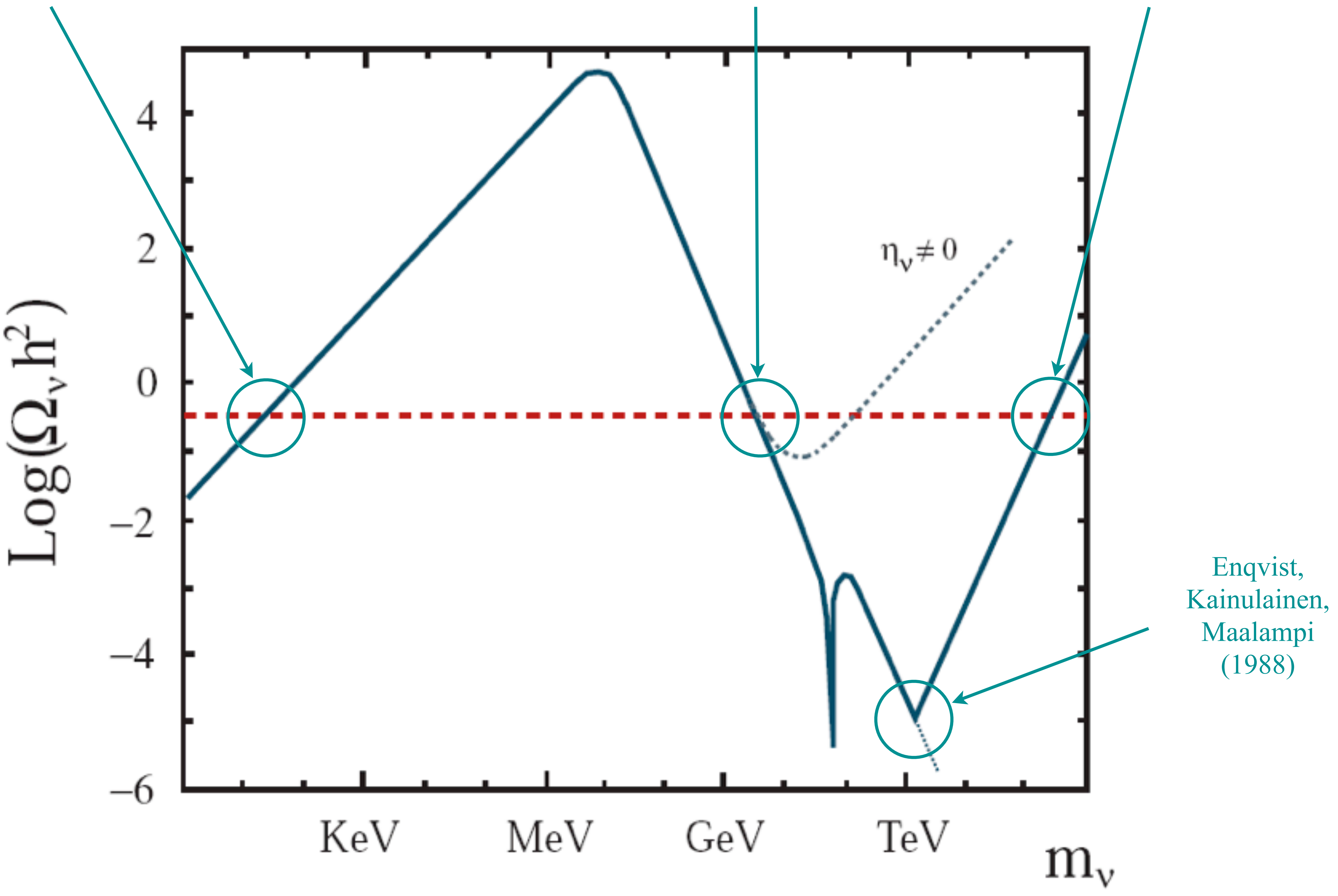
Vanda SILVEIRA[1,2] and A. ZEE
Department of Physics, FM-15, University of Washington, Seattle, WA 98195, USA

Received 17 June 1985

We show that, by a minimal modification of the standard SU(3) × SU(2) × U(1) theory, we can account for the dark matter of the universe. With a reasonable choice of an unknown coupling, the galactic mass scale emerges. We comment on the prospects for laboratory detection of the scalar particle involved and the possible production of anti-protons in cosmic rays.

A striking prediction of the inflationary universe [5] is that Ω is equal to 1. The X particle could saturate Ω if $m_X \simeq 0.75 m_H$. (Let us first take h to be 1.) Thus for m_H in the range 10–30 GeV, the condition $\Omega_X = 1$ requires that m_X lies in the range 7.5–22 GeV and the freezing temperature T_f is in the 0.3–1 GeV range. The

e.g. A HEAVY NEUTRINO



Cowsik-McLelland
(1972)

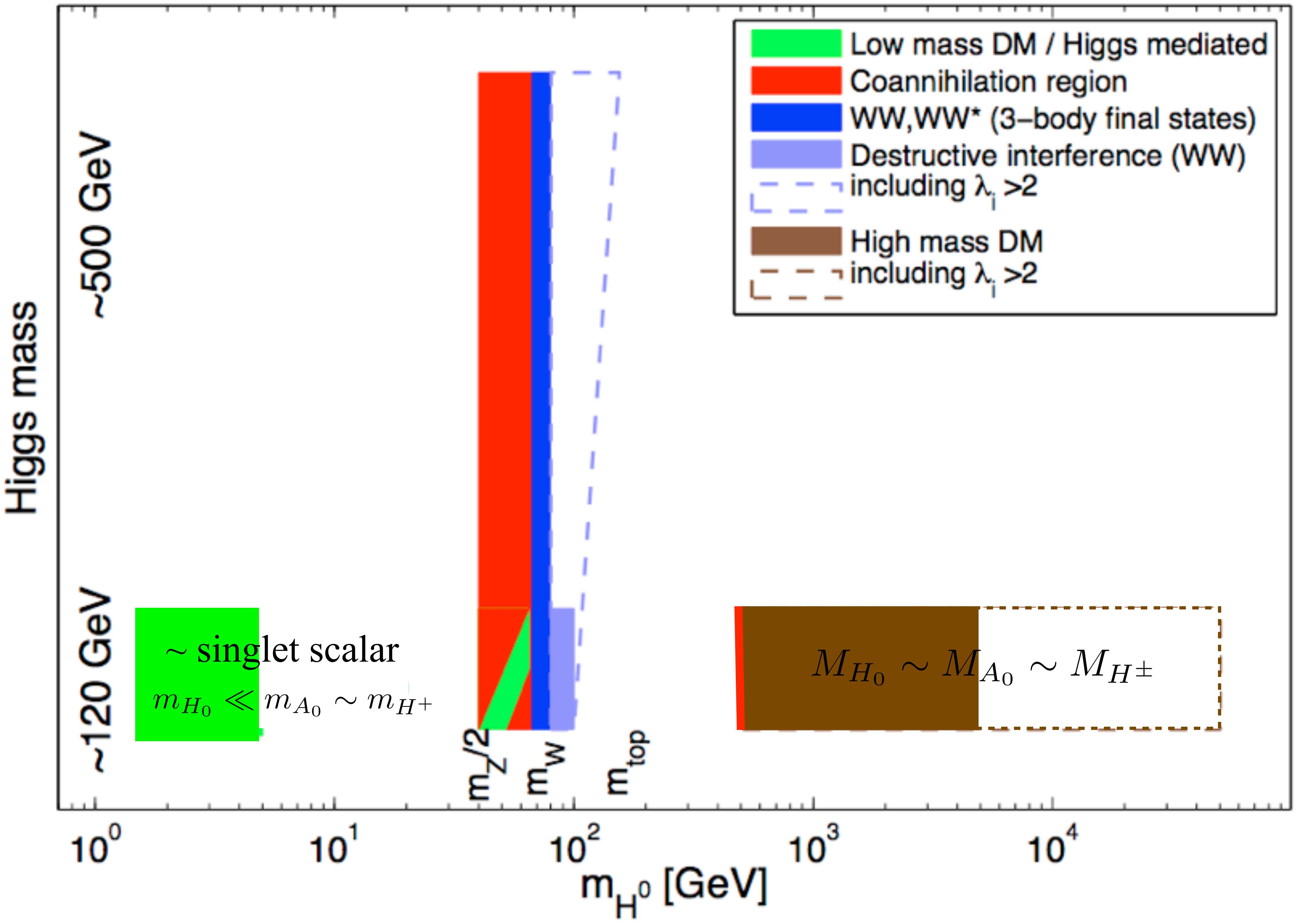
Lee-Weinberg
(1977)

Griest-Kamionkowski
(1989)

Enqvist,
Kainulainen,
Maalampi
(1988)

(Figure by Kimmo Kainulainen)

e.g. THE INERT DOUBLET



(Fig. by Michael Gustafsson)

ONLY EXPERIMENTS CAN TELL

Singlet Scalar through the ~~Higgs~~ SMS Portal

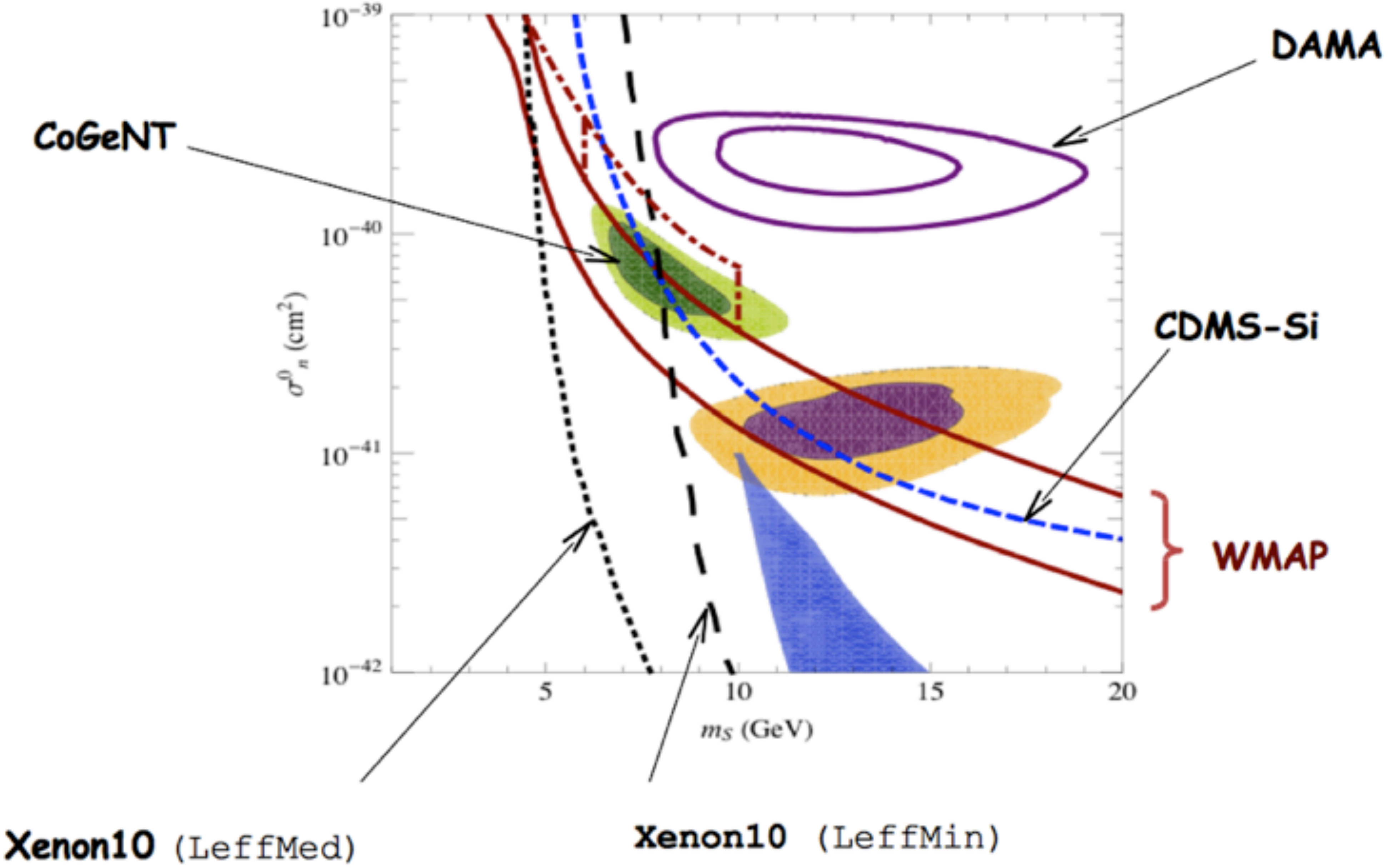
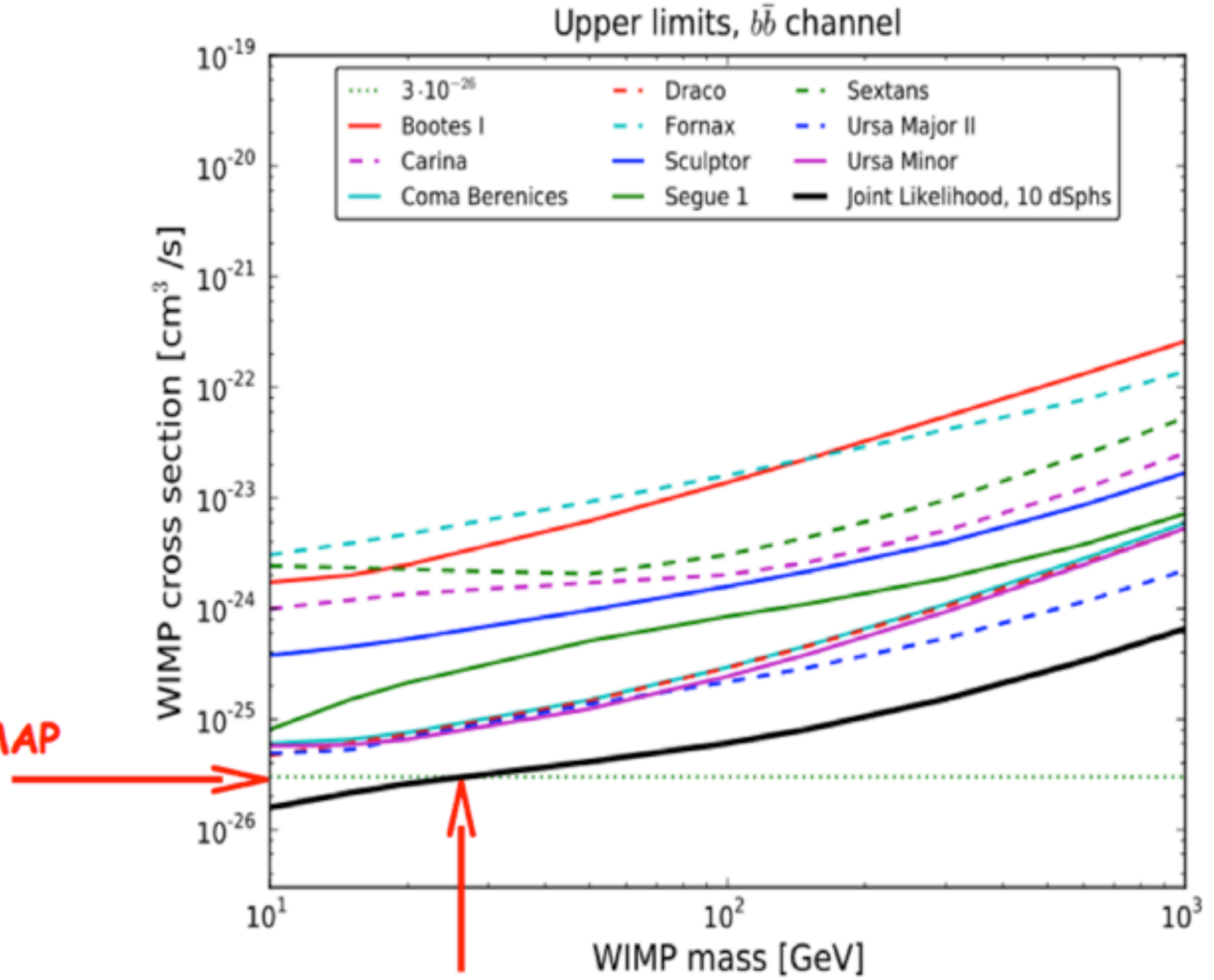


Figure from Andreas, Arina, Hambye, Ling & M.T. arXiv:1003.2595

ONLY EXPERIMENTS CAN TELL

Limits from nearby dwarf spheroidal galaxies (Fermi-LAT)



WMAP

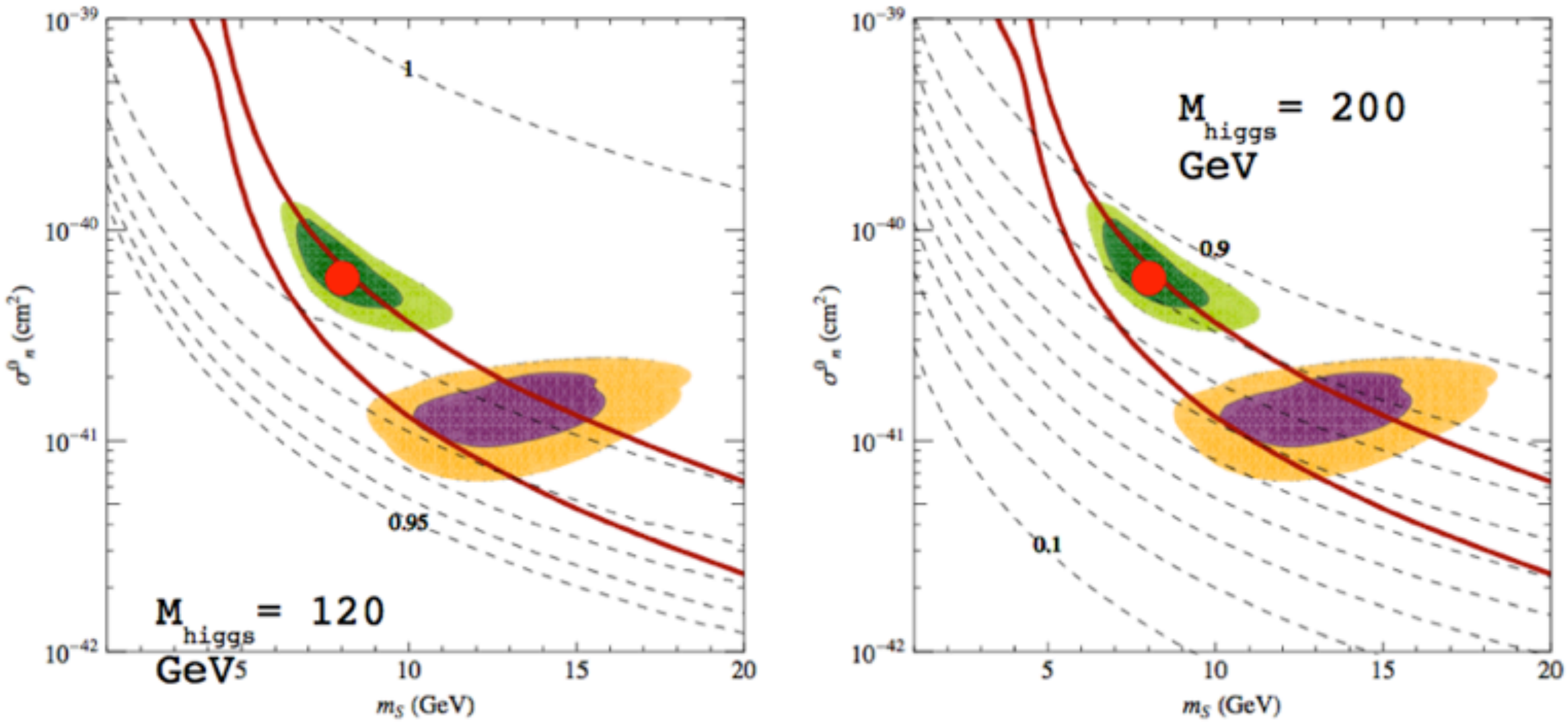
M_{dm} < 25 GeV

Fermi-LAT (1108.3546)

ONLY EXPERIMENTS CAN TELL

Light Scalar = Very Invisible ~~Higgs~~ Scenario

SMS



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)

ONLY EXPERIMENTS CAN TELL

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SO, WHICH MASS SCALE?

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The Baryon-Dark Matter Coincidence

Low Mass WIMP, $M_{DM} \sim$ few GeV?

Dark Matter and Electroweak Symmetry Breaking

Medium Mass WIMP, $M_{DM} \sim M_H$?

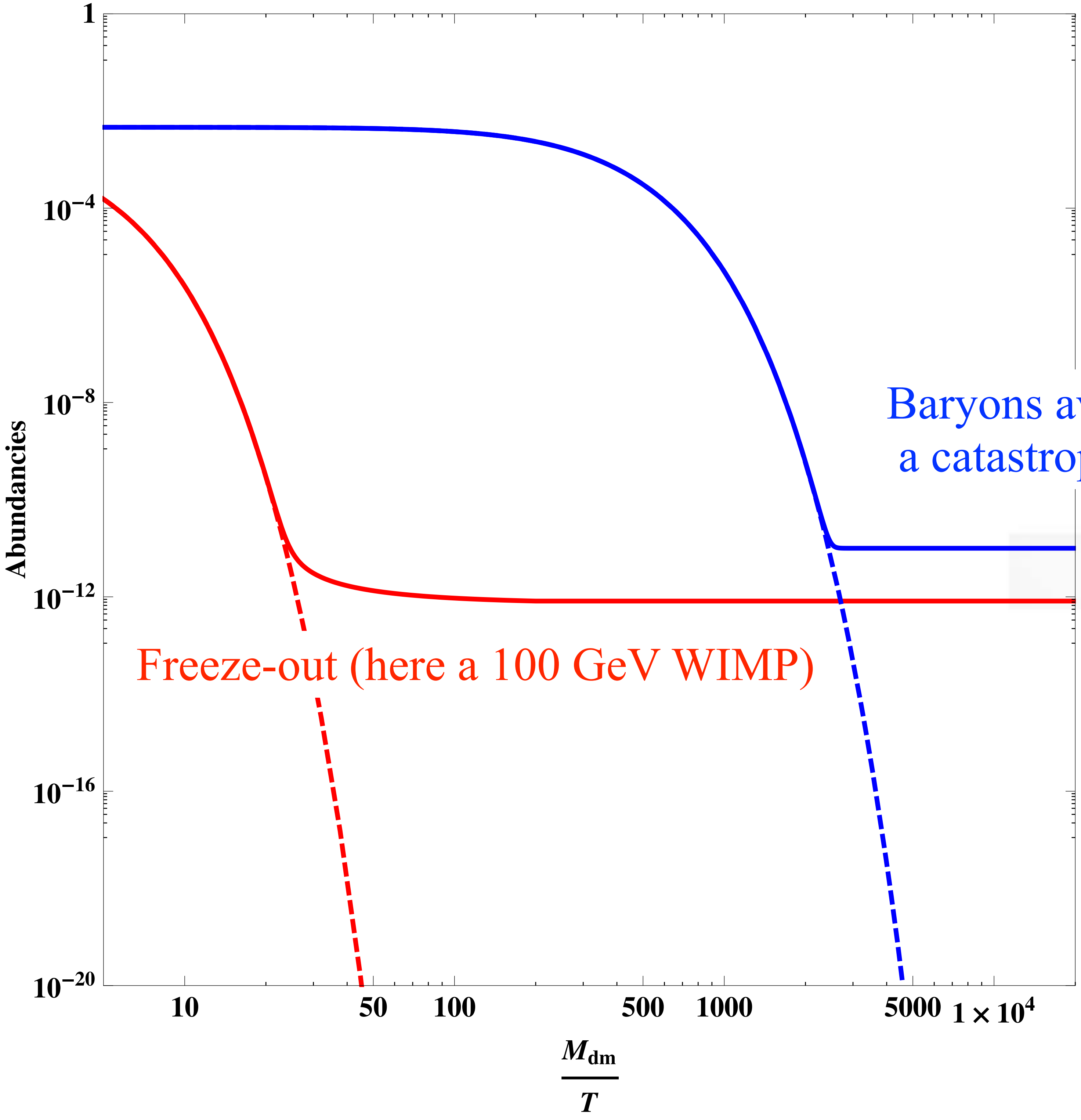
Minimal Dark Matter & Siblings

Large Mass WIMP, $M_{DM} \sim$ few TeV?

SO, WHICH MASS SCALE?

- Standard
  ~ 100 GeV
- Heavy
  ~ TeV
- Light
  ~1-10 GeV

1. BARYON - DARK MATTER COINCIDENCE



A miracle, indeed...

1. BARYON - DARK MATTER COINCIDENCE

$$\frac{\Omega_{DM}}{\Omega_B} = \frac{M_{DM}}{M_p} \times \frac{Y_{DM}}{Y_B} = \mathcal{O}(5)$$

1. BARYON - DARK MATTER COINCIDENCE

BARYON ASYMMETRY ⟶ ASYMMETRIC DM?

$$\frac{\Omega_{DM}}{\Omega_B} = \frac{M_{DM}}{M_p} \times \frac{\cancel{Y_{DM}}}{\cancel{Y_B}} = \mathcal{O}(5)$$

A LIGHT WIMP?

Nussinov (1985); Barr; Kaplan; Gudnasson *et al*; Dodelson *et al*; Kitano *et al*; Farrar & Zaharijas; Lopez Honorez *et al*; Zurek *et al*; etc...

Some recent models: aidogenesis, cogenesis, xogenesis, baryomorphosis, darkogenesis,... (I personally prefer «Matter Genesis»)

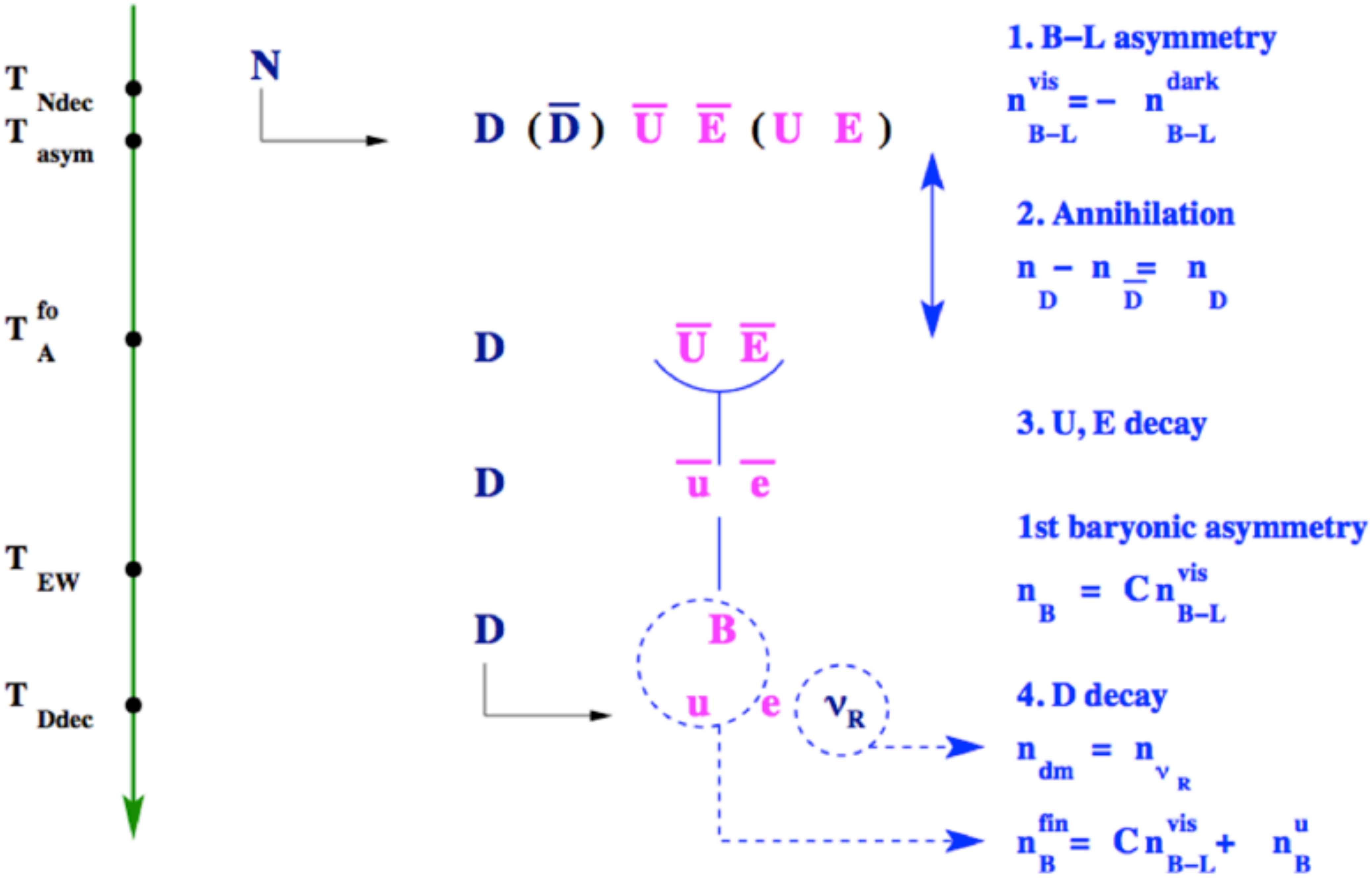
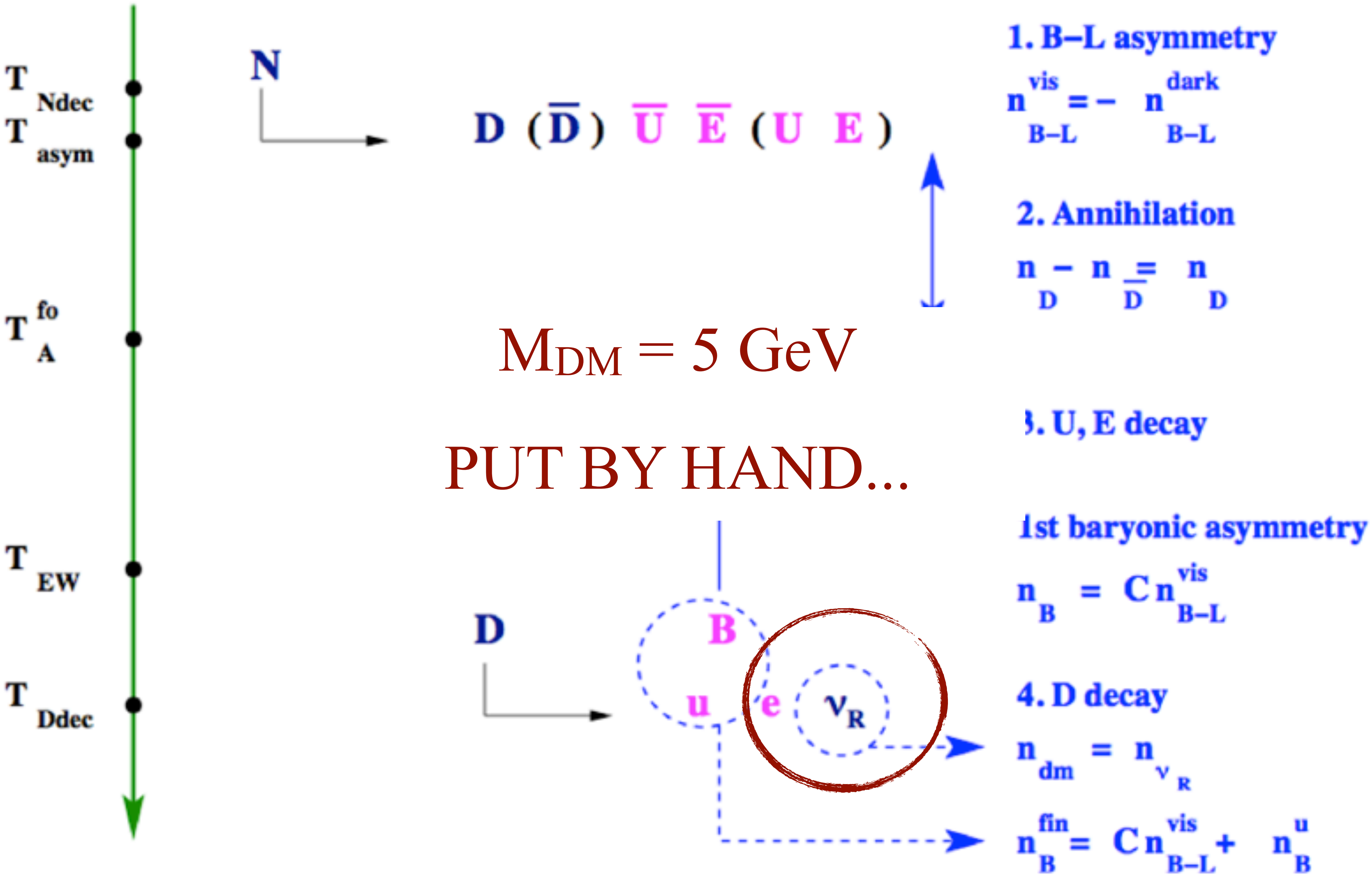


Figure 1: Steps of Matter Genesis

Figure from Lopez Honorez, Cosme and M.T. (2005)



$M_{DM} = 5$ GeV

PUT BY HAND...

Figure 1: Steps of Matter Genesis

Figure from Lopez Honorez, Cosme and M.T. (2005)

NEED A REALLY GREAT WATCHMAKER

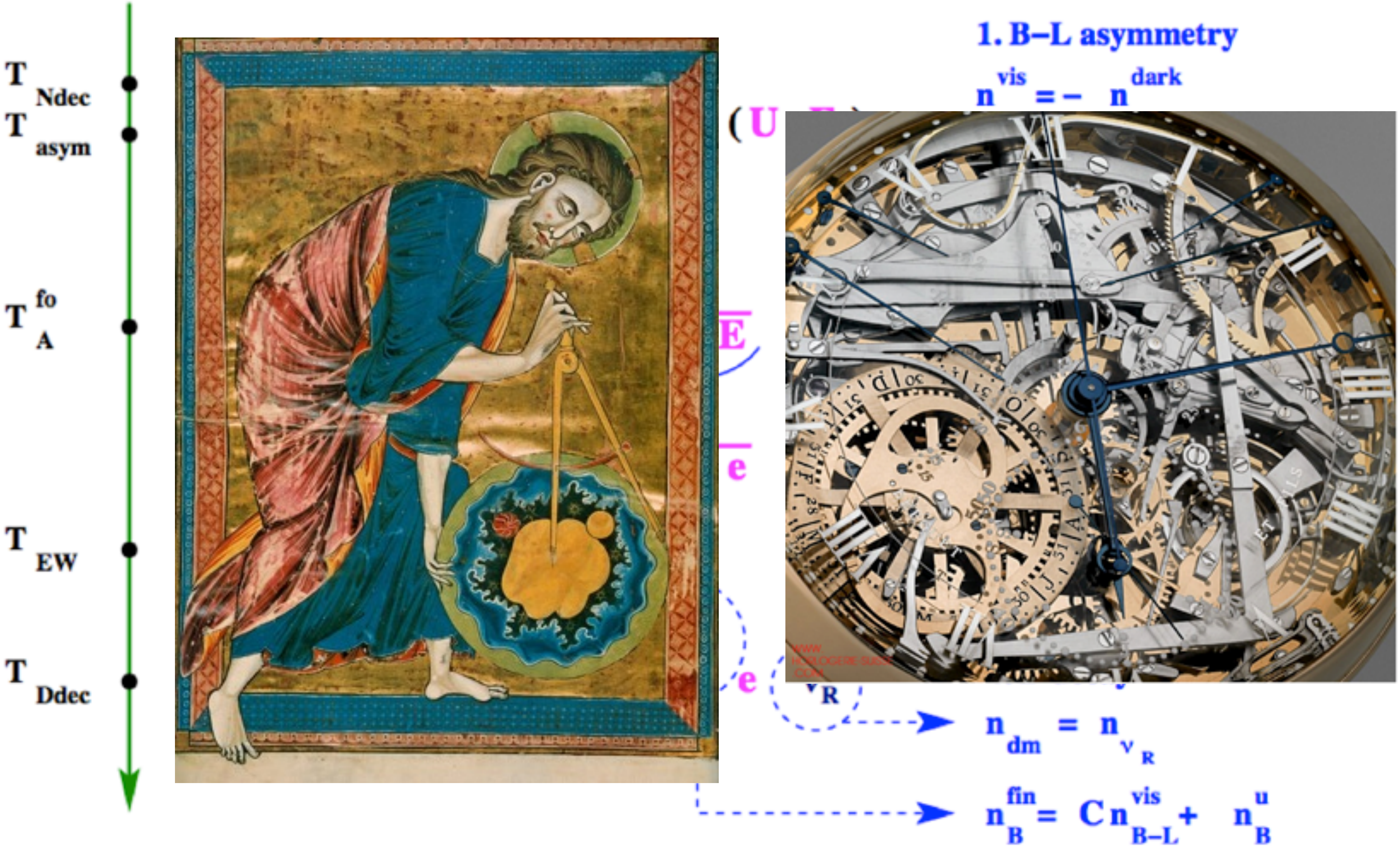
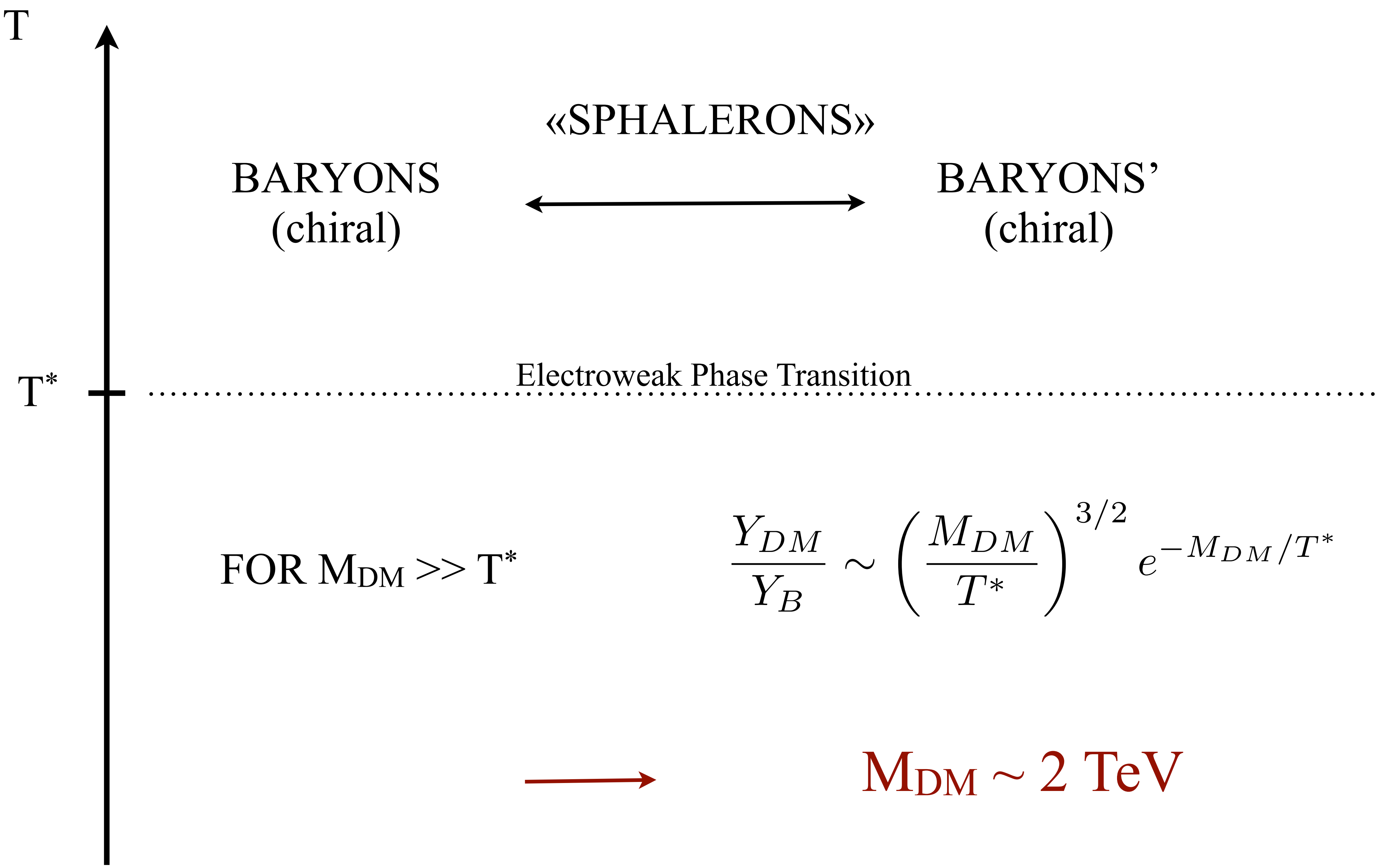


Figure 1: Steps of Matter Genesis

ANYWAY, ASYMMETRIC DM DOES NOT MEAN LIGHT DM



T

«SPHALERONS»

BARYONS
(chiral)

BARYONS'
(chiral)

T^*

Electroweak Phase Transition

FOR $M_{DM} >> T^*$

$$\frac{Y_{DM}}{Y_B} \sim \left(\frac{M_{DM}}{T^*}\right)^{3/2} e^{-M_{DM}/T^*}$$

$\longrightarrow$ $M_{DM} \sim 2$ TeV

Nardi, Sannino & Strumia (2008)

ANYWAY, ASYMMETRIC DM DOES NOT MEAN LIGHT DM

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BARYC
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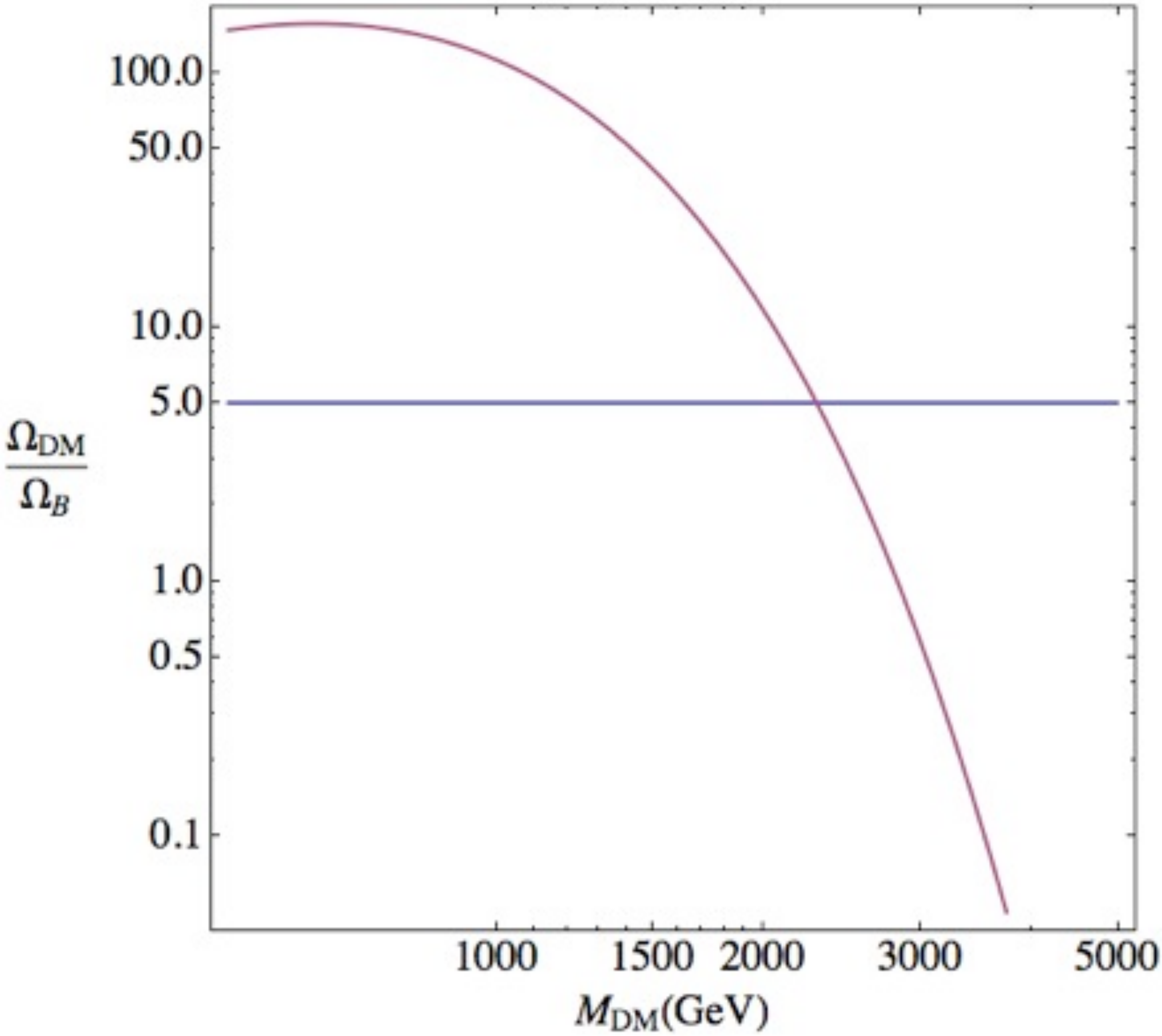
NB:
Superficially like a WIMP, but dependence on M_{DM} is really exponential!

(*ie* instead of a power-law for a WIMP)

ak Phase Transition



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$M_{DM} \sim 2$ TeV

Nardi, Sannino & Strumia (2008)

2. DARK MATTER AND ELECTROWEAK SYMMETRY BREAKING?

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

Unique!

☞ Origin of Electroweak Symmetry Breaking

☞ Portal to renormalizable couplings to New Physics!

2. DARK MATTER AND ELECTROWEAK SYMMETRY BREAKING?

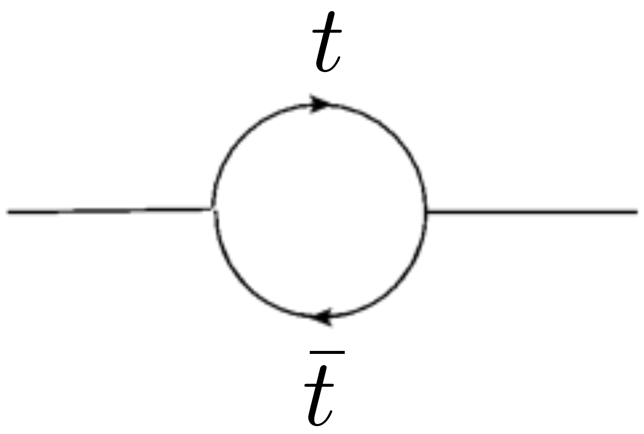
$$\mathcal{L} \supset S^2 |H|^2$$

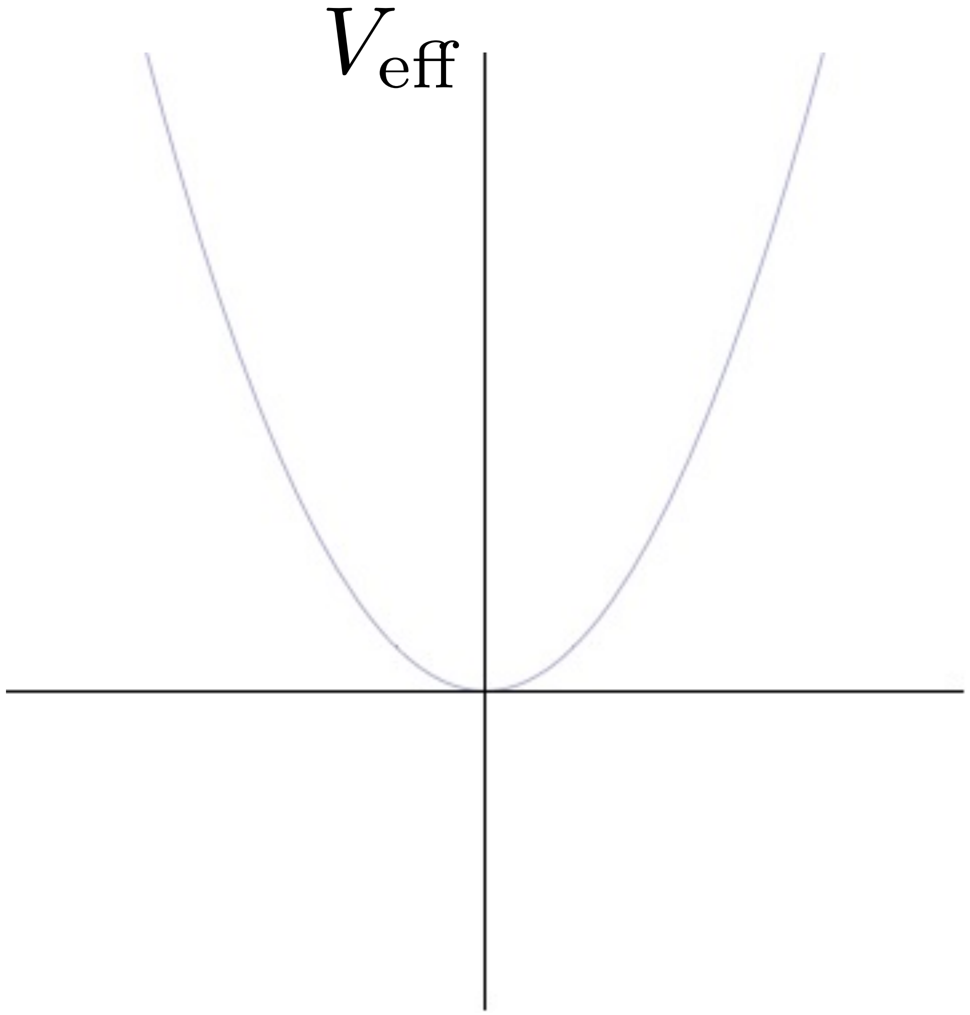
- ☞ Origin of Electroweak Symmetry Breaking
- ☞ Portal to renormalizable couplings to New Physics!
- ☞ All of the above?

(Patt & Wilczek; Quiros & Espinosa; Hambye & MT;...)

2. DARK MATTER AND ELECTROWEAK SYMMETRY BREAKING?

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





DARK MATTER AND ELECTROWEAK SYMMETRY BREAKING?

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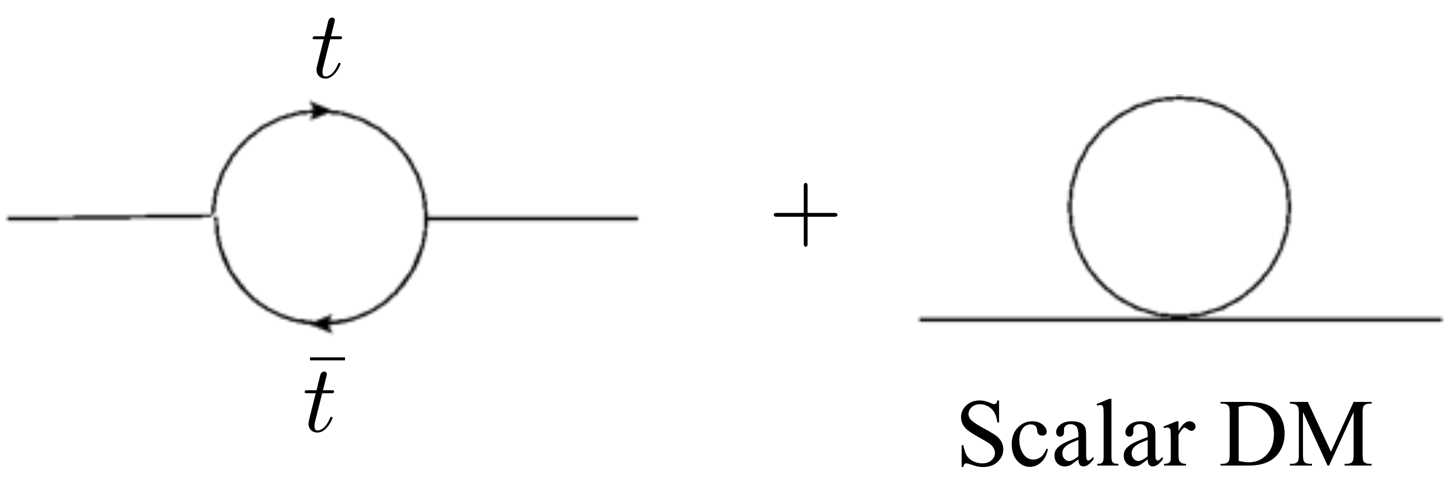

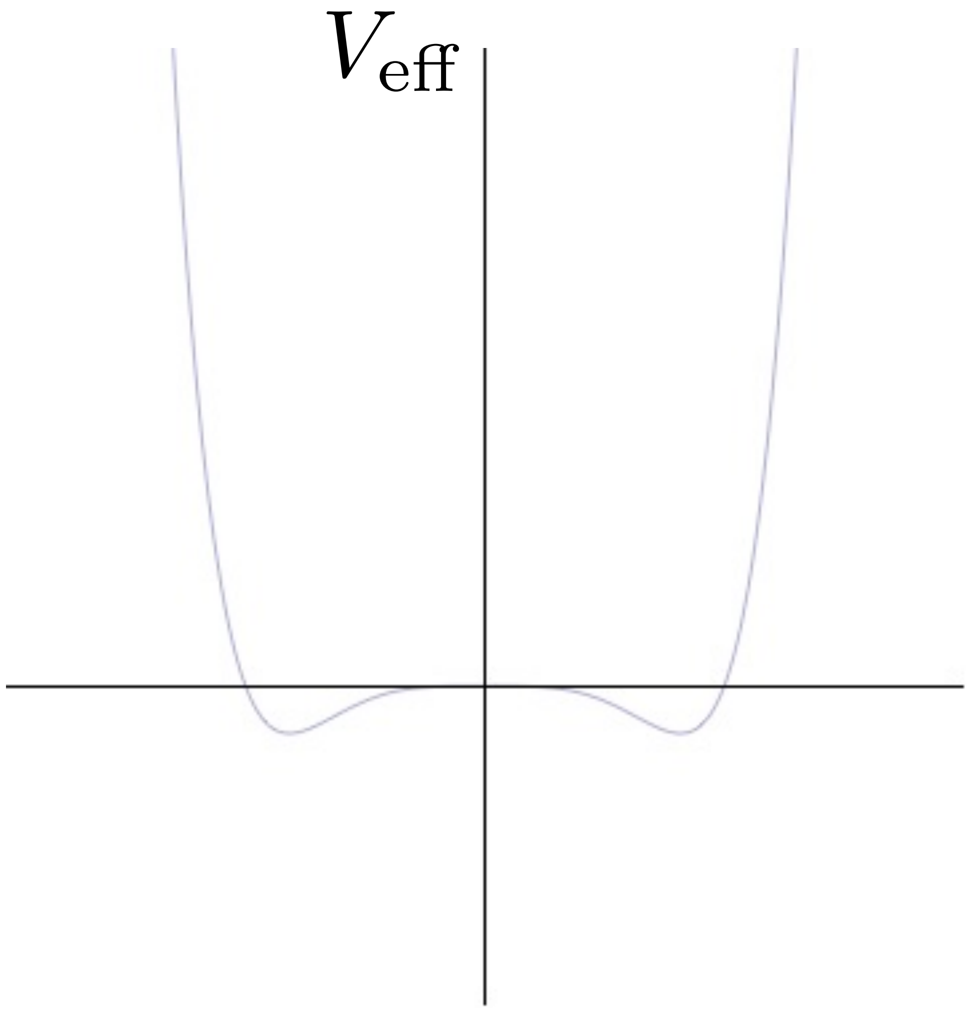

Electroweak Symmetry Breaking induced by DM (i.e. à la Coleman-Weinberg)

Roughly expect $M_{DM} \sim M_H$

(Quiros & Espinosa; Hambye & MT)

2. DARK MATTER AND ELECTROWEAK SYMMETRY BREAKING?

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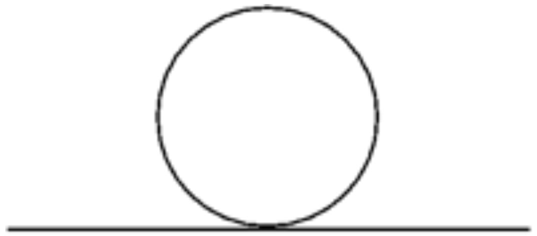

Scalar DM

ectroweak Symmetry
reaking induced by DM
e. à la Coleman-Weinberg)

—

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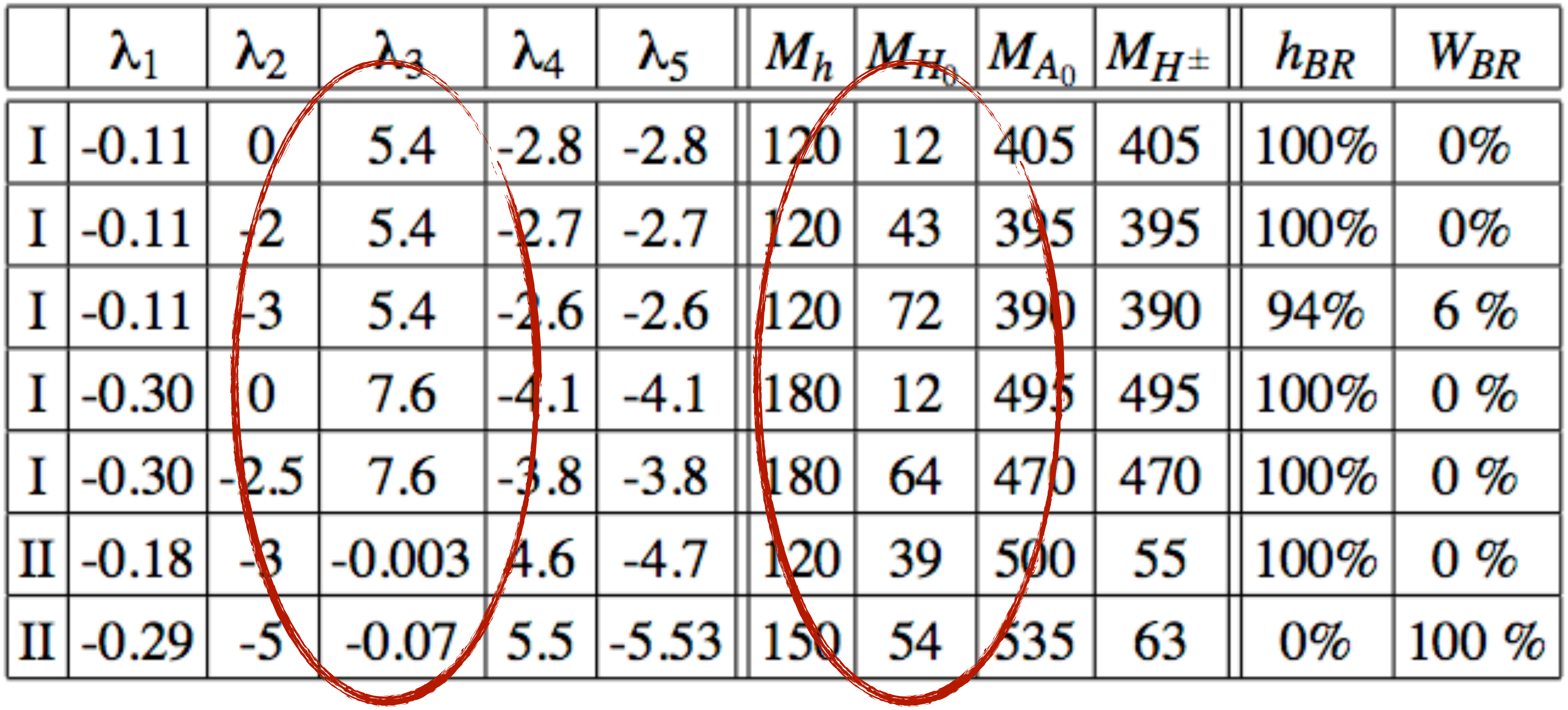
DARK MATTER AND ELECTROWEAK SYMMETRY BREAKING



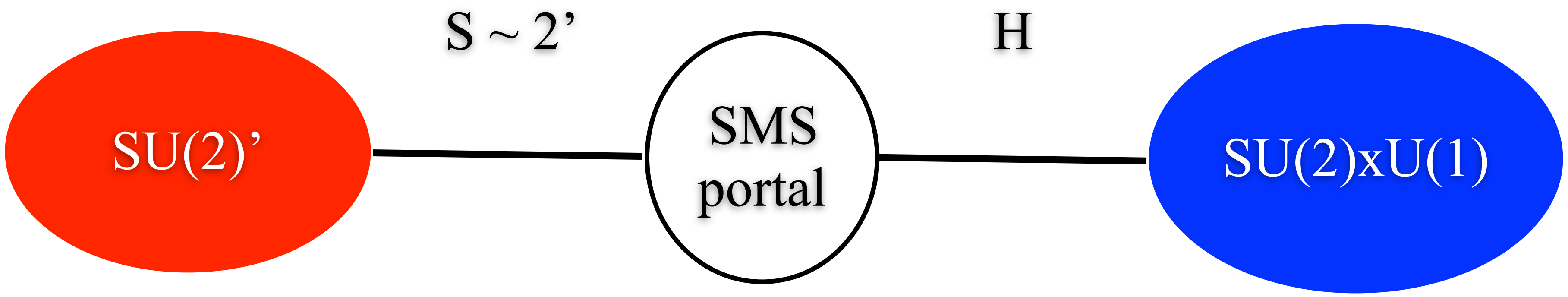
	λ_1	λ_2	λ_3	λ_4	λ_5	M_h	M_{H_0}	M_{A_0}	$M_{H^\pm}$	h_{BR}	W_{BR}
I	-0.11	0	5.4	-2.8	-2.8	120	12	405	405	100%	0%
I	-0.11	-2	5.4	-2.7	-2.7	120	43	395	395	100%	0%
I	-0.11	-3	5.4	-2.6	-2.6	120	72	390	390	94%	6 %
I	-0.30	0	7.6	-4.1	-4.1	180	12	495	495	100%	0 %
I	-0.30	-2.5	7.6	-3.8	-3.8	180	64	470	470	100%	0 %
II	-0.18	-3	-0.003	4.6	-4.7	120	39	500	55	100%	0 %
II	-0.29	-5	-0.07	5.5	-5.53	150	54	535	63	0%	100 %

VANILLA WIMPs,
BUT (EMBARRISSINGLY) LARGE
COUPLINGS
(MAINLY DUE TO ⟨S⟩ = 0)

rs with WMAP DM abundance.
bution of Higgs mediated annihi-
W_{BR}).

Hambye & M.T. (2007);...

2. DARK MATTER AND ELECTROWEAK SYMMETRY BREAKING



SU(2)’

S ~ 2’

SMS portal

H

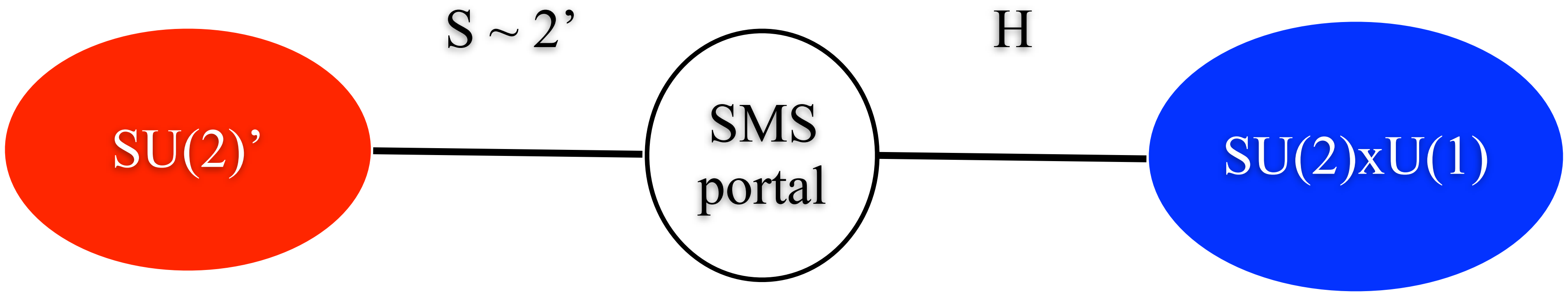
SU(2)xU(1)

DM = Hidden Gauge Bosons
(Stability from a global
custodial SO(3) symmetry)

IF NO FURTHER ASSUMPTION, M_{DM} ~ 1 MeV to 120 TeV

Hambye (2009); Hambye, M.T. (2009)

DARK MATTER AND ELECTROWEAK SYMMETRY BREAKING


S ~ 2’

H

SU(2)’

SMS portal

SU(2)xU(1)

DM = Hidden Gauge Bosons
(Stability from a global
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$$\lambda_{HS}|S|^2|H|^2 \rightarrow \lambda_{HS}\Lambda_{HS}^2|H|^2$$

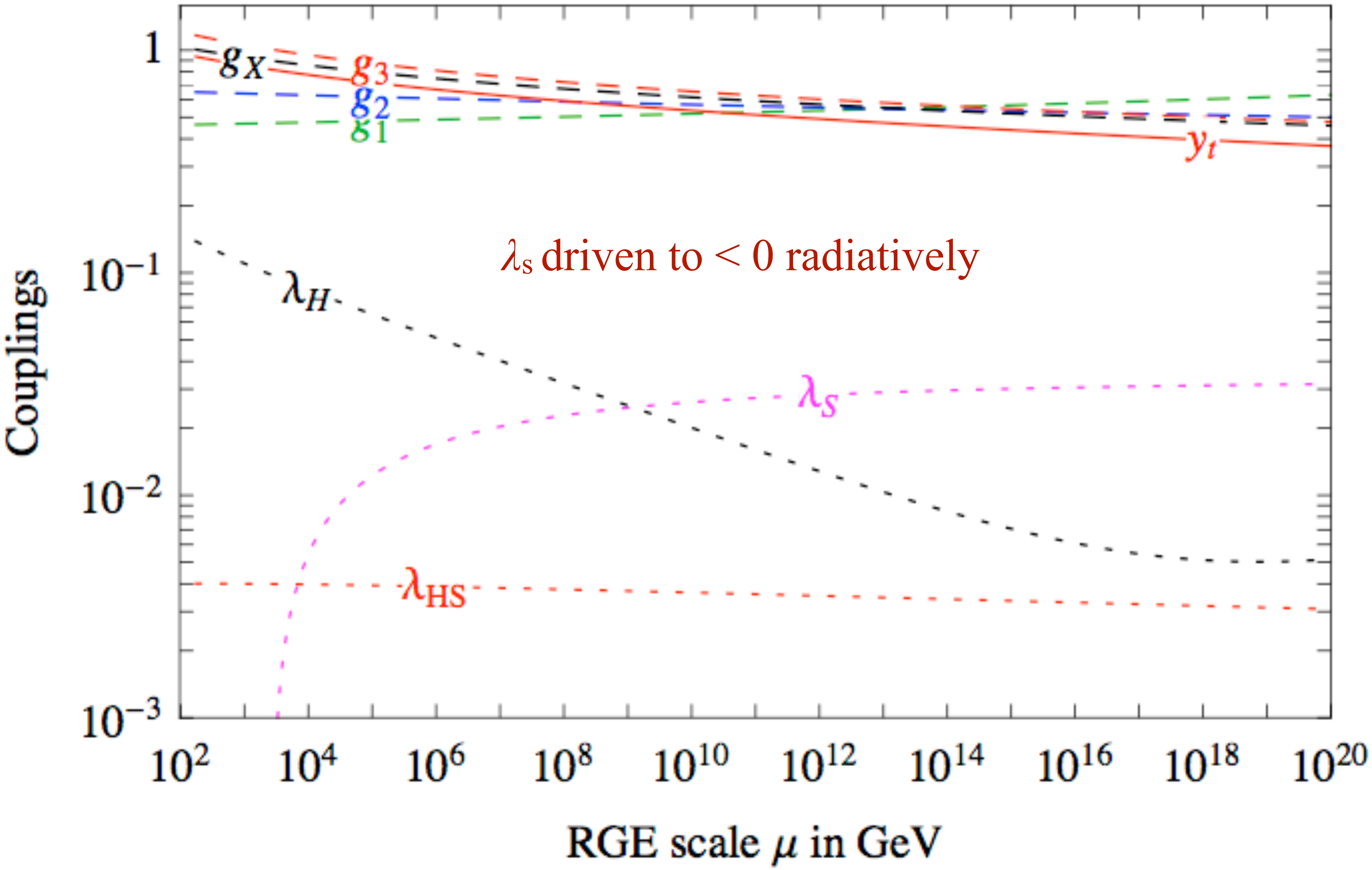
Coleman-Weinberg
SU(2)’ in confined phase

$M_{DM} \sim$ FEW TeV

Hambye, M.T. (2009)

2. DARK MATTER AND ELECTROWEAK SYMMETRY BREAKING

$$V = \lambda_H |H|^4 - \lambda_{HS} |SH|^2 + \lambda_S |S|^4$$



λ_s driven to < 0 radiatively

Hambye, Strumia (2013)

4 parameters = 4 couplings

3 fixed by M_h, *vev* and relic abundance

Only 1 free parameter e.g. M_{DM}

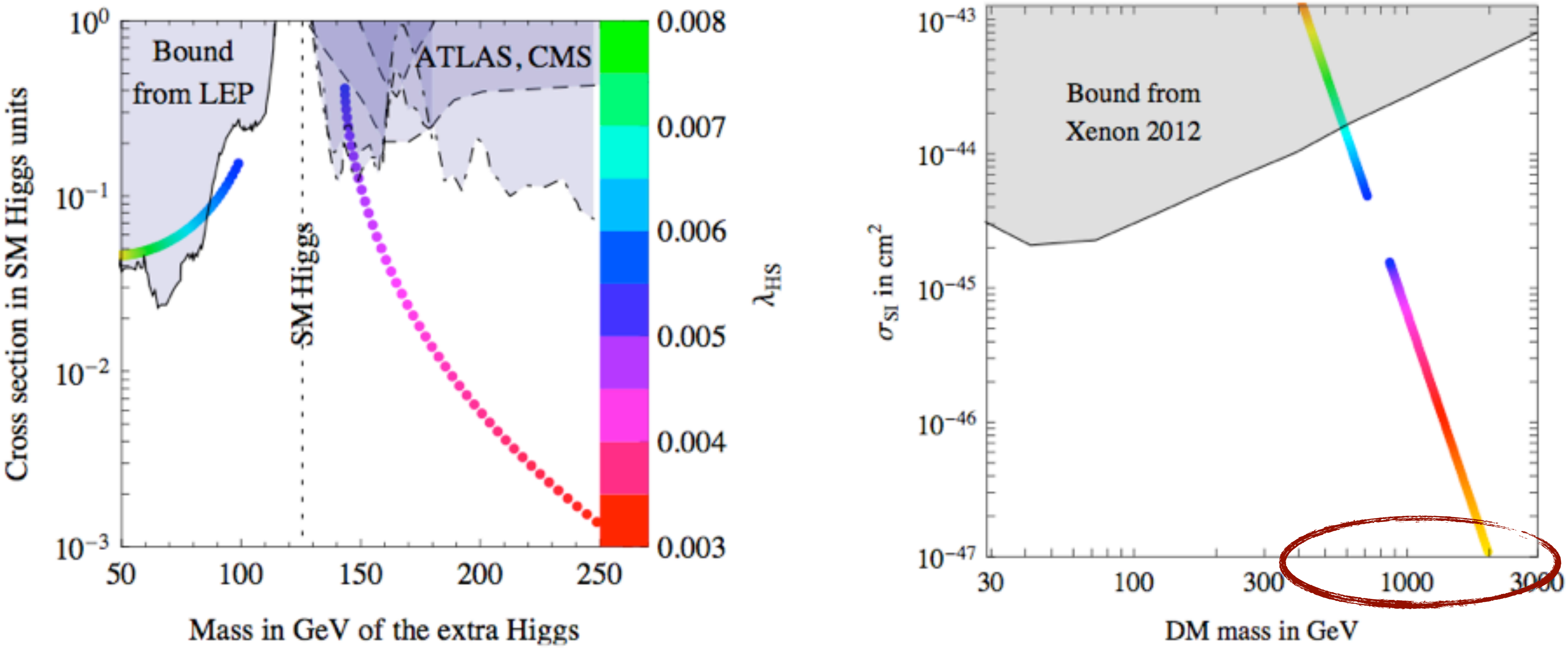


Figure 1: *Predicted cross sections for the extra scalar boson (left) and for DM direct detection (right) as function of the only free parameter of the model* λ_{HS}*, varied as shown in the colour legend.*

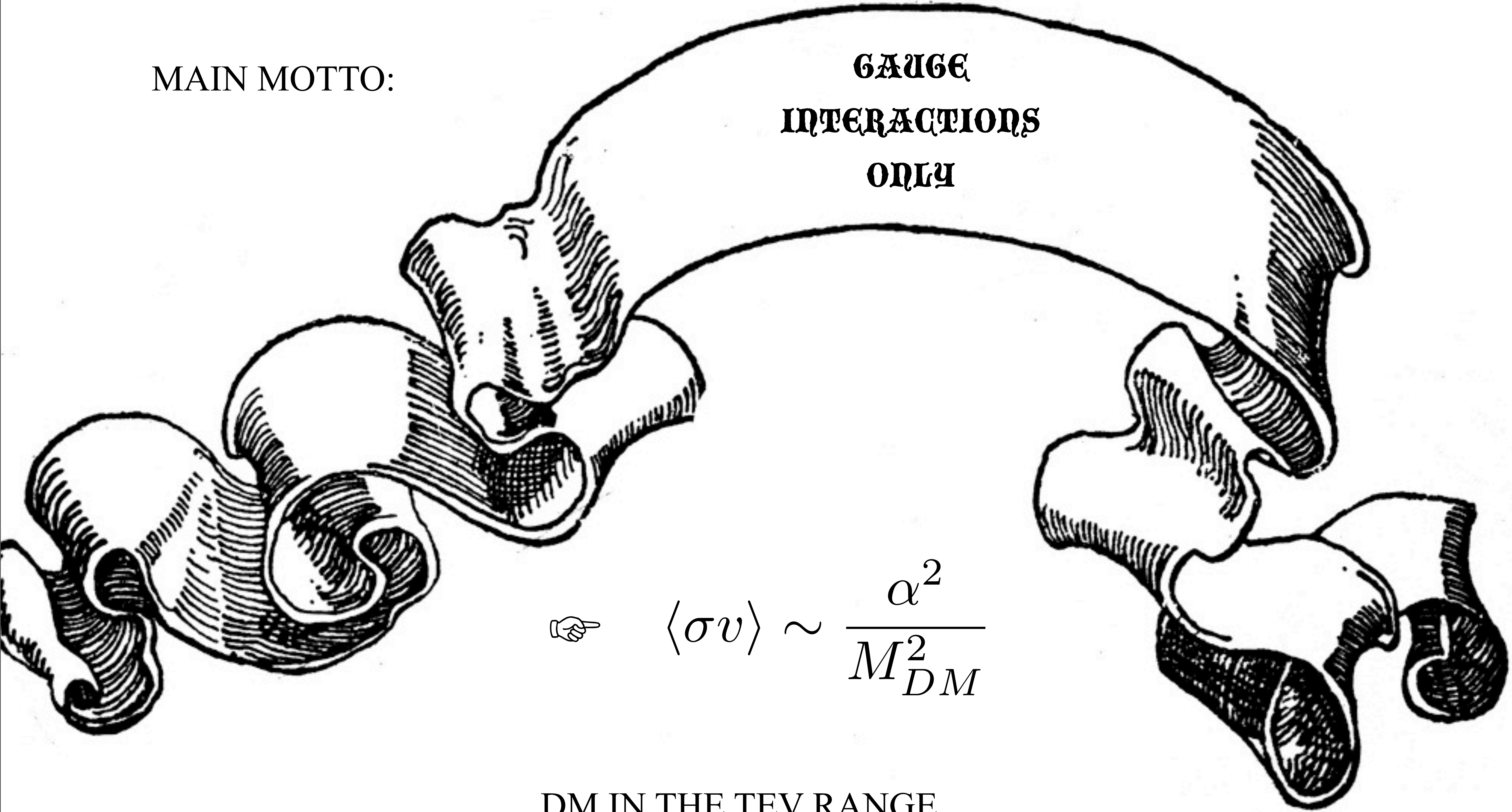
Hambye, Strumia (2013)

3. MINIMAL DARK MATTER & SIBLINGS

(Cirreli, Fornengo & Strumia)

3. MINIMAL DARK MATTER & SIBLINGS

MAIN MOTTO:

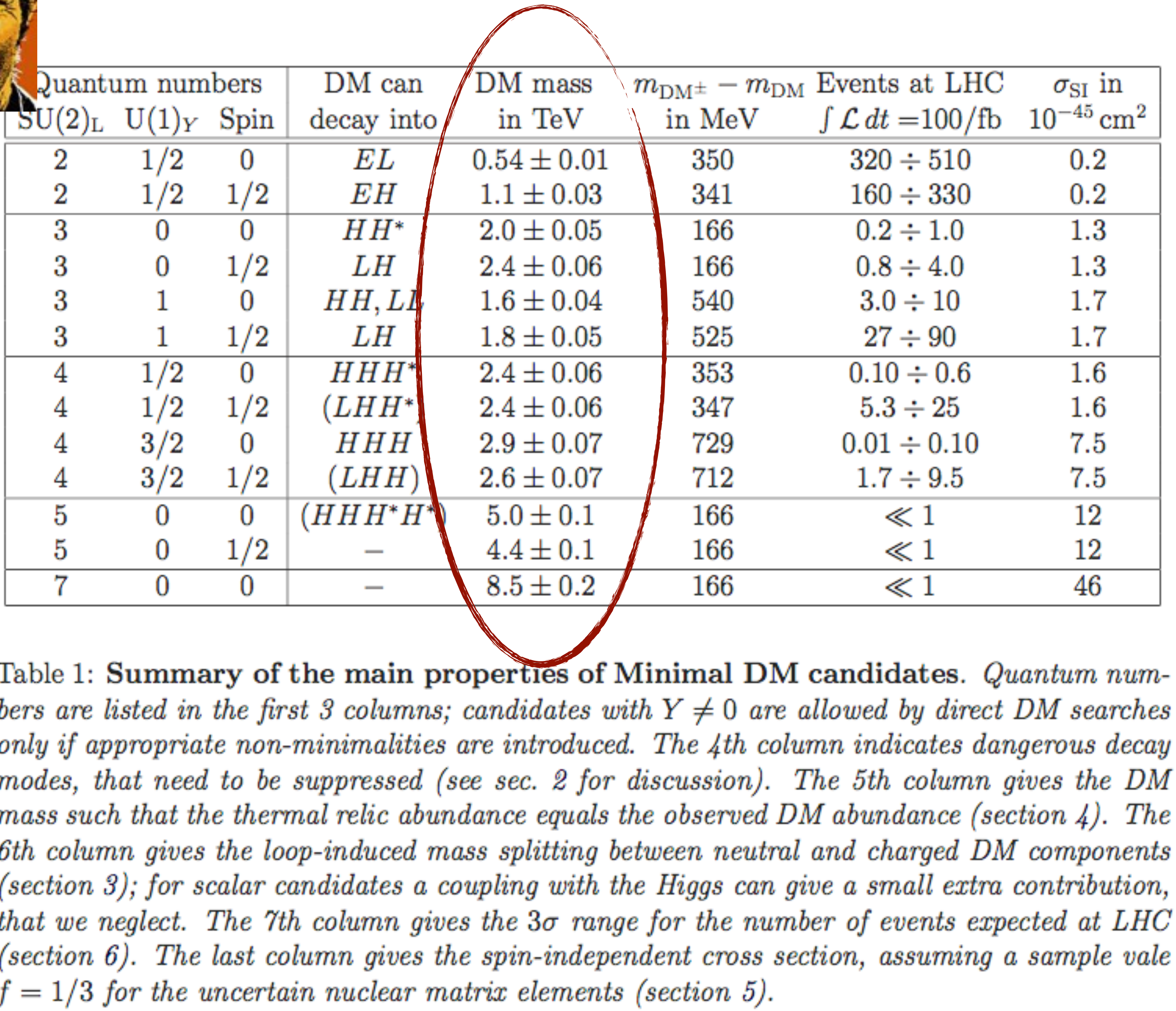


GAUGE
INTERACTIONS
ONLY

☞ $$\langle \sigma v \rangle \sim \frac{\alpha^2}{M_{DM}^2}$$

DM IN THE TEV RANGE

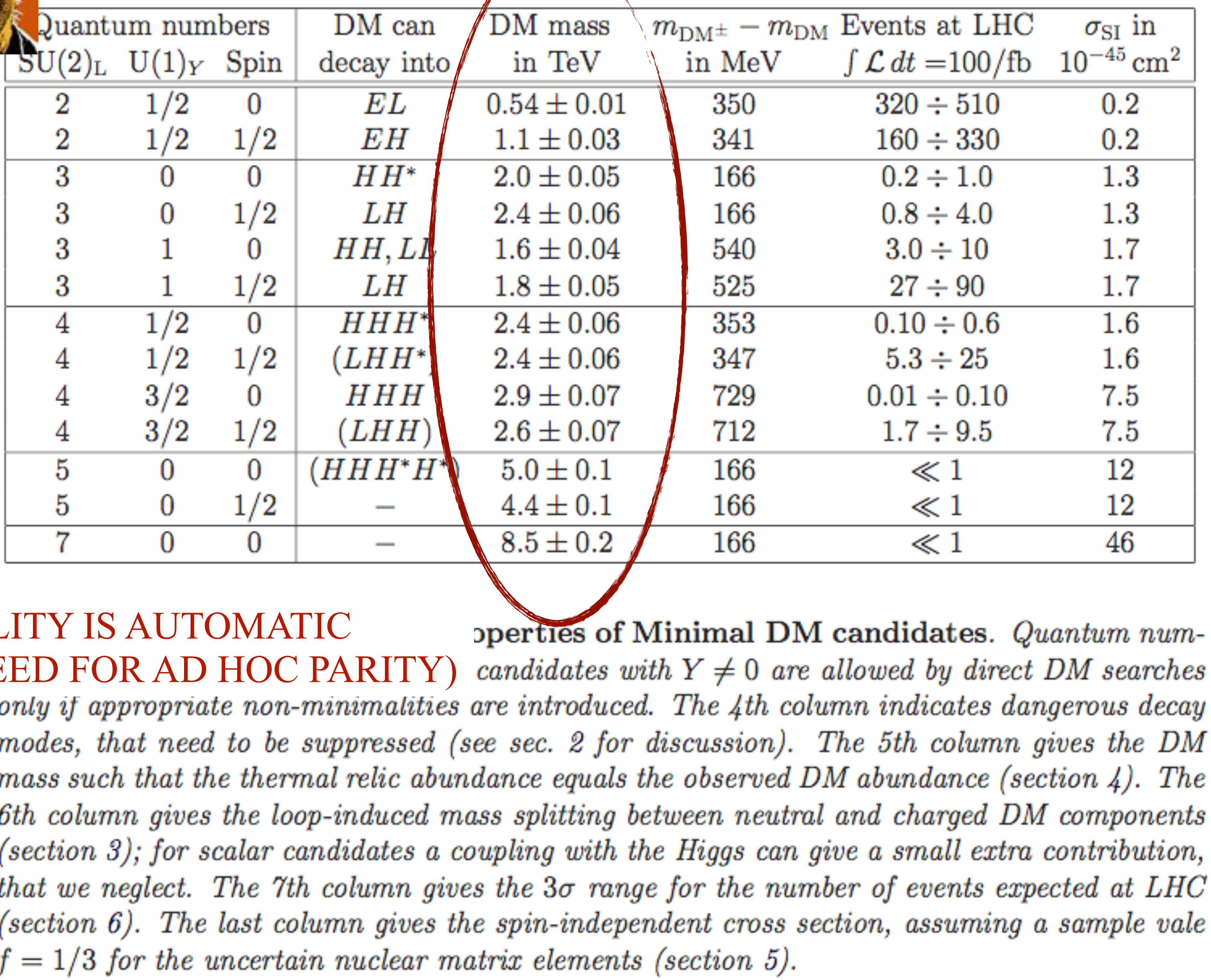
(Cirreli, Fornengo & Strumia)



Quantum numbers			DM can decay into	DM mass in TeV	$m_{DM^\pm} - m_{DM}$ in MeV	Events at LHC $\int \mathcal{L}\, dt = 100/\text{fb}$	σ_{SI} in $10^{-45}\,\text{cm}^2$
$SU(2)_L$	$U(1)_Y$	Spin					
2	1/2	0	EL	0.54 ± 0.01	350	$320 \div 510$	0.2
2	1/2	1/2	EH	1.1 ± 0.03	341	$160 \div 330$	0.2
3	0	0	HH^*	2.0 ± 0.05	166	$0.2 \div 1.0$	1.3
3	0	1/2	LH	2.4 ± 0.06	166	$0.8 \div 4.0$	1.3
3	1	0	HH, LL	1.6 ± 0.04	540	$3.0 \div 10$	1.7
3	1	1/2	LH	1.8 ± 0.05	525	$27 \div 90$	1.7
4	1/2	0	HHH^*	2.4 ± 0.06	353	$0.10 \div 0.6$	1.6
4	1/2	1/2	(LHH^*)	2.4 ± 0.06	347	$5.3 \div 25$	1.6
4	3/2	0	HHH	2.9 ± 0.07	729	$0.01 \div 0.10$	7.5
4	3/2	1/2	(LHH)	2.6 ± 0.07	712	$1.7 \div 9.5$	7.5
5	0	0	(HHH^*H^*)	5.0 ± 0.1	166	$\ll 1$	12
5	0	1/2	–	4.4 ± 0.1	166	$\ll 1$	12
7	0	0	–	8.5 ± 0.2	166	$\ll 1$	46

Table 1: **Summary of the main properties of Minimal DM candidates.** *Quantum numbers are listed in the first 3 columns; candidates with $Y \neq 0$ are allowed by direct DM searches only if appropriate non-minimalities are introduced. The 4th column indicates dangerous decay modes, that need to be suppressed (see sec. 2 for discussion). The 5th column gives the DM mass such that the thermal relic abundance equals the observed DM abundance (section 4). The 6th column gives the loop-induced mass splitting between neutral and charged DM components (section 3); for scalar candidates a coupling with the Higgs can give a small extra contribution, that we neglect. The 7th column gives the 3σ range for the number of events expected at LHC (section 6). The last column gives the spin-independent cross section, assuming a sample vale $f = 1/3$ for the uncertain nuclear matrix elements (section 5).*

(Cirreli, Fornengo & Strumia)



Quantum numbers			DM can	DM mass	$m_{DM^\pm} - m_{DM}$	Events at LHC	σ_{SI} in
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☞ {

STABILITY IS AUTOMATIC
(NO NEED FOR AD HOC PARITY)

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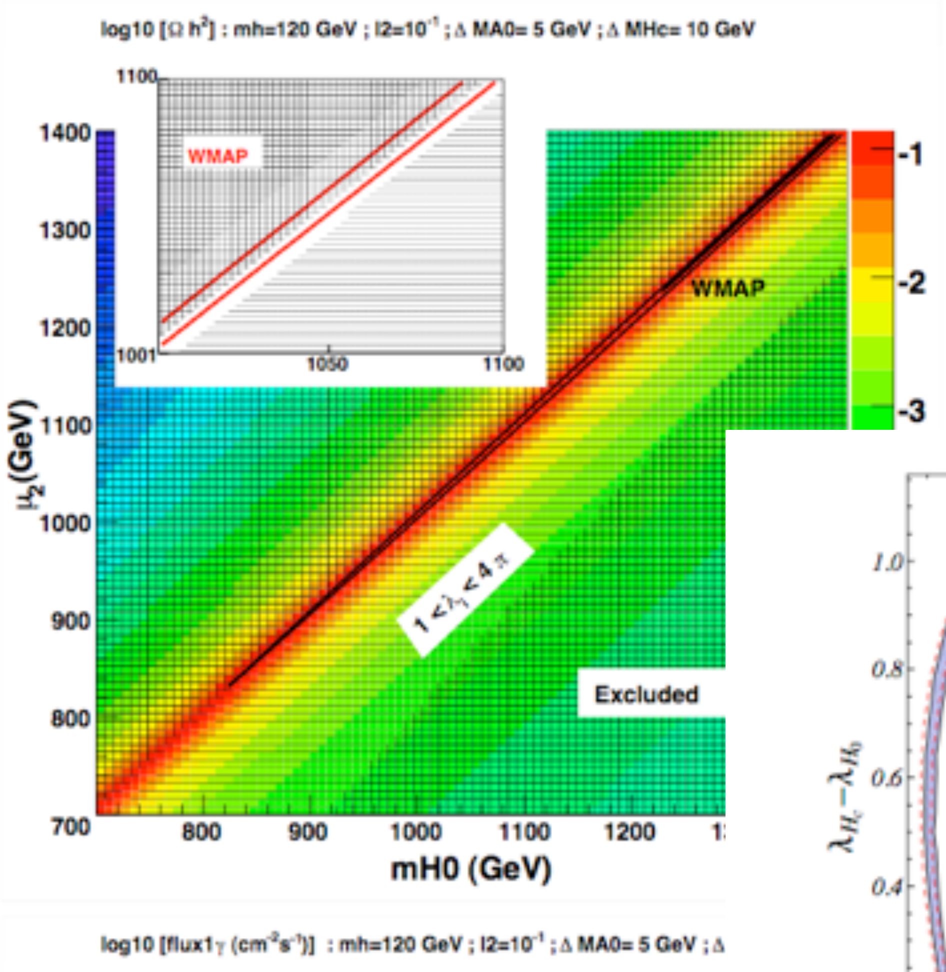
(Cirreli, Fornengo & Strumia)

3. MINIMAL DARK MATTER & SIBLINGS

ADD OTHER INTERACTIONS (ie quartic couplings for scalar doublet DM)



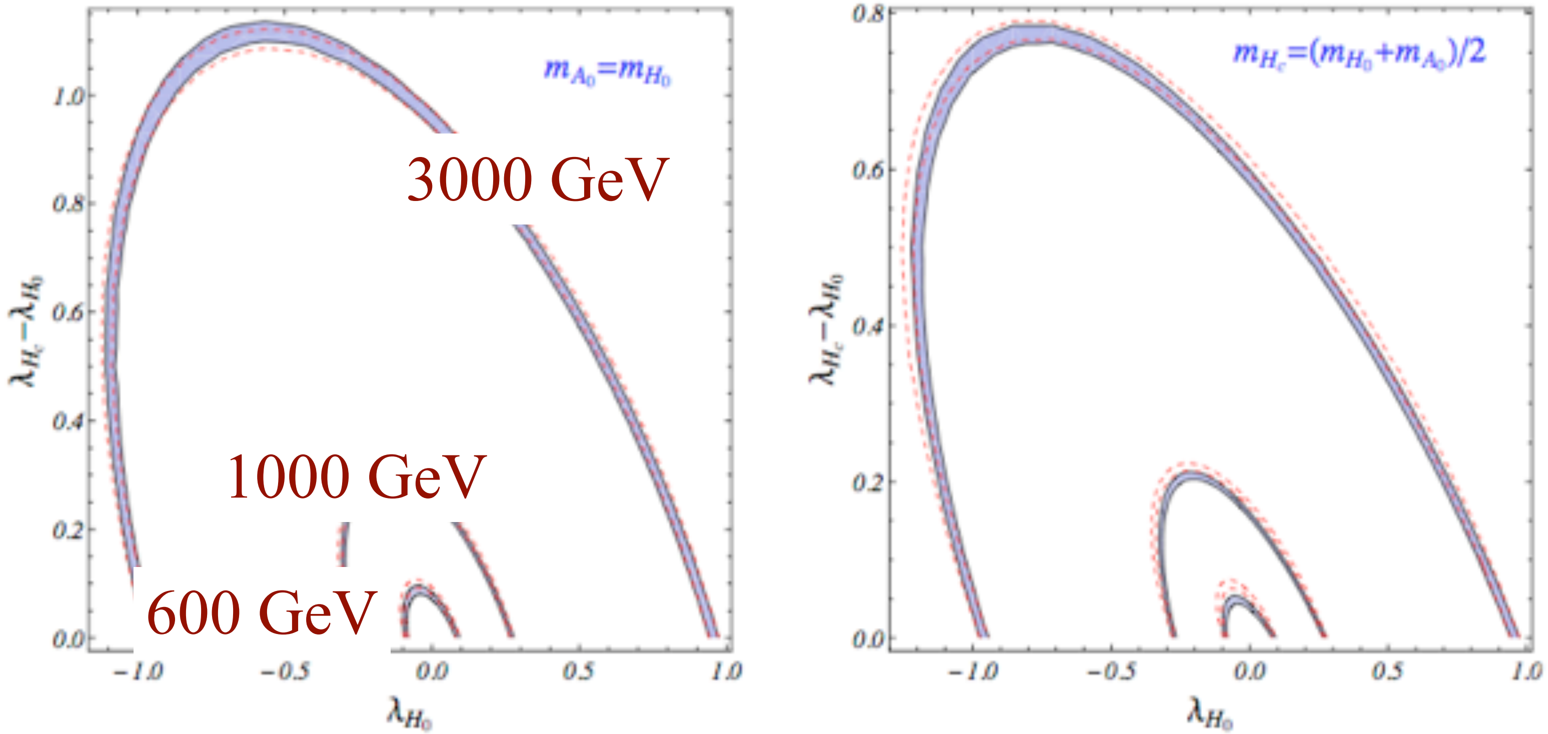


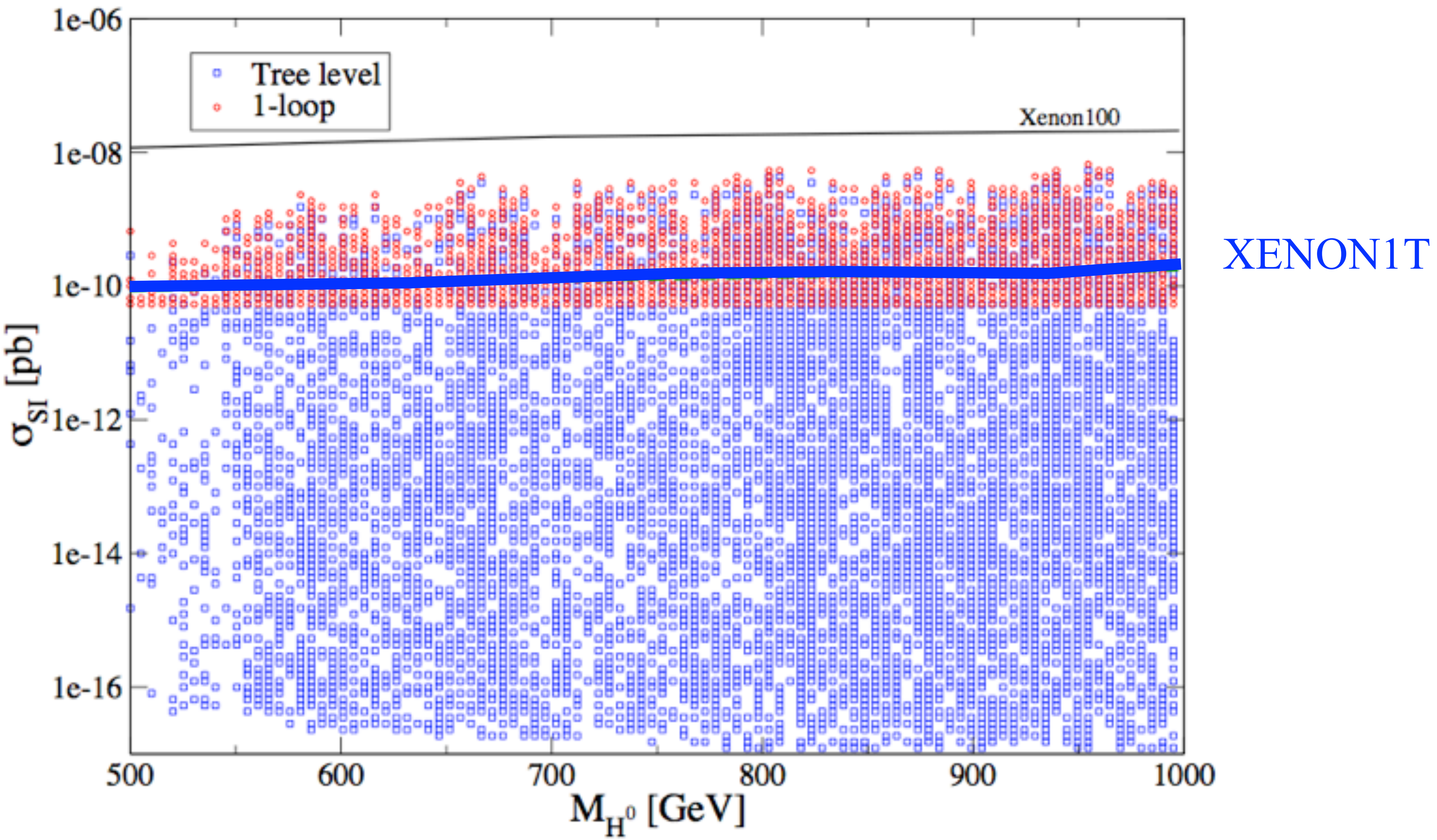
Figure 3: *Contours of* λ *for the WMAP value* $\Omega_{\rm DM}h^2 = 0.1131 \pm 0.0034$ *for* $m_{H_0} = 600$ *(interior),* 1000, 3000 *(exterior) GeV, with* $m_{A_0} = m_{H_0}$ *(left panel) and* $m_{H_c} = (m_{H_0} + m_{A_0})/2$ *(right panel). Dashed curve corresponds to the approximate ellipsoid.*

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

(Hambye, Ling, Lopez Honorez & Rocher)

3. MINIMAL DARK MATTER & SIBLINGS

TOO HEAVY FOR LHC BUT WITHIN REACH OF
FUTURE DIRECT DETECTION EXPERIMENTS



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

TENTATIVE CONCLUSION

DIFFICULT TO MAKE DEFINITIVE STATEMENTS REGARDING DM MASS SCALE.
(IE COULD BE ANYTHING...)

YET, SIMPLE MODELS POINT TO THE TEV SCALE
(NO SURPRISE HERE)

PERHAPS BAD FOR LHC, BUT NOT DESPERATE FOR DIRECT DETECTION.

$$\tau_p \sim \frac{M_{\mathrm{GUT}}^4}{m_p^5} \sim 10^{41}\,\mathrm{sec} \qquad\qquad p \rightarrow \pi^0 e^+$$

$$\tau_p \sim \frac{M_{\rm GUT}^4}{m_p^5} \sim 10^{41}\,{\rm sec} \qquad\qquad p \to \pi^0 e^+$$

$$\tau_p \sim \frac{M_{\rm GUT}^4}{M_{\rm DM}^5} \sim 10^{26}\,{\rm sec}$$

IN THE BALL PARK OF INDIRECT SEARCHES
(antimatter, gamma rays, ...)

BACKUP SLIDES

MORE ON HIDDEN SECTORS

The hypothesis of thermal equilibrium basically fixes the moment (time/temperature) of decoupling

$$x = x^*$$

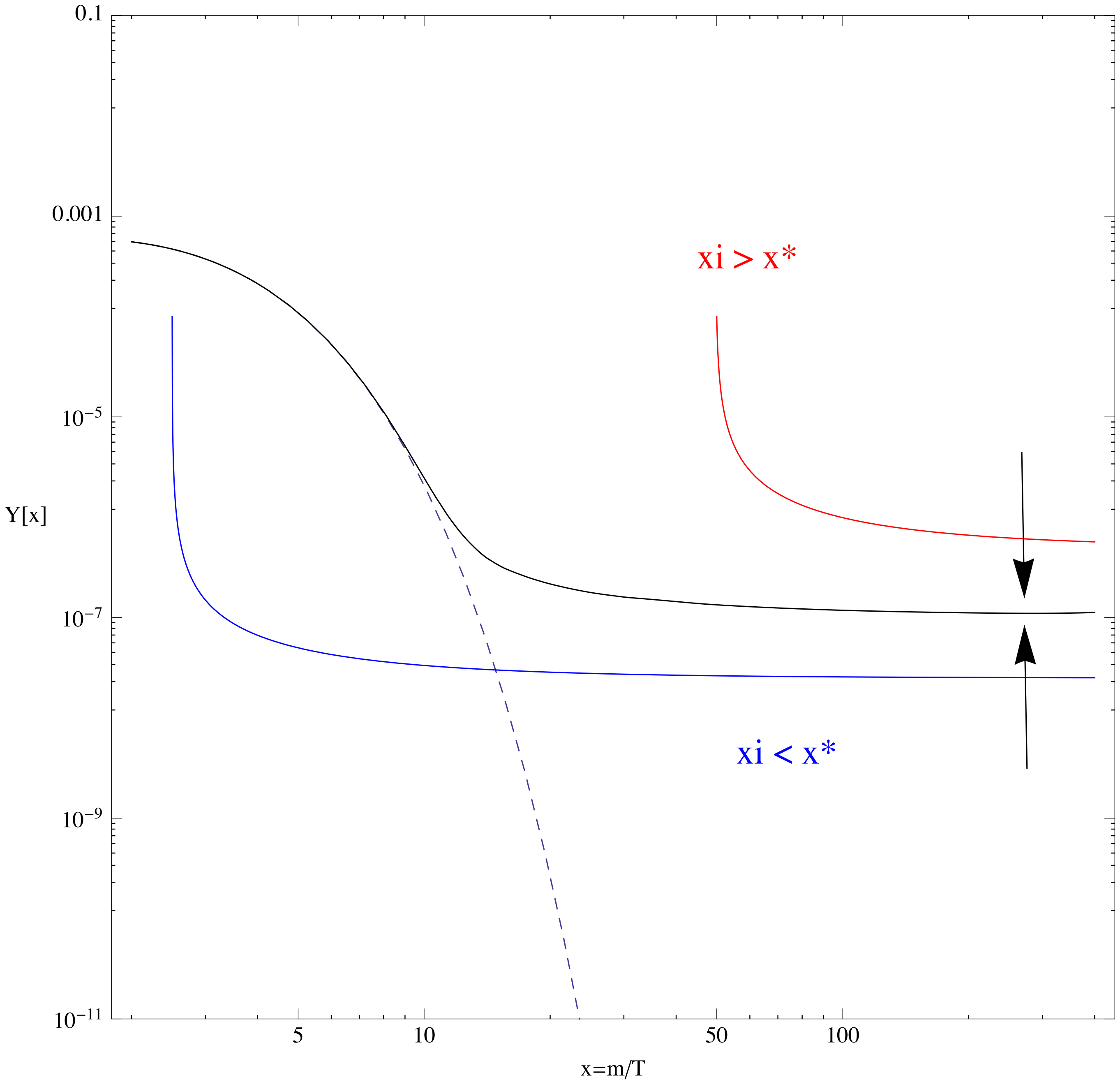
A WIMP-like behaviour may occur in more generic scenarios*

$$Y_\infty|_{\mathrm{non-thermal}} = \frac{x_i}{x^*}\, Y_\infty|_{\mathrm{thermal}} \propto \frac{x_i}{\langle \sigma v \rangle}$$

in which x_i is the characteristic time of DM release/production

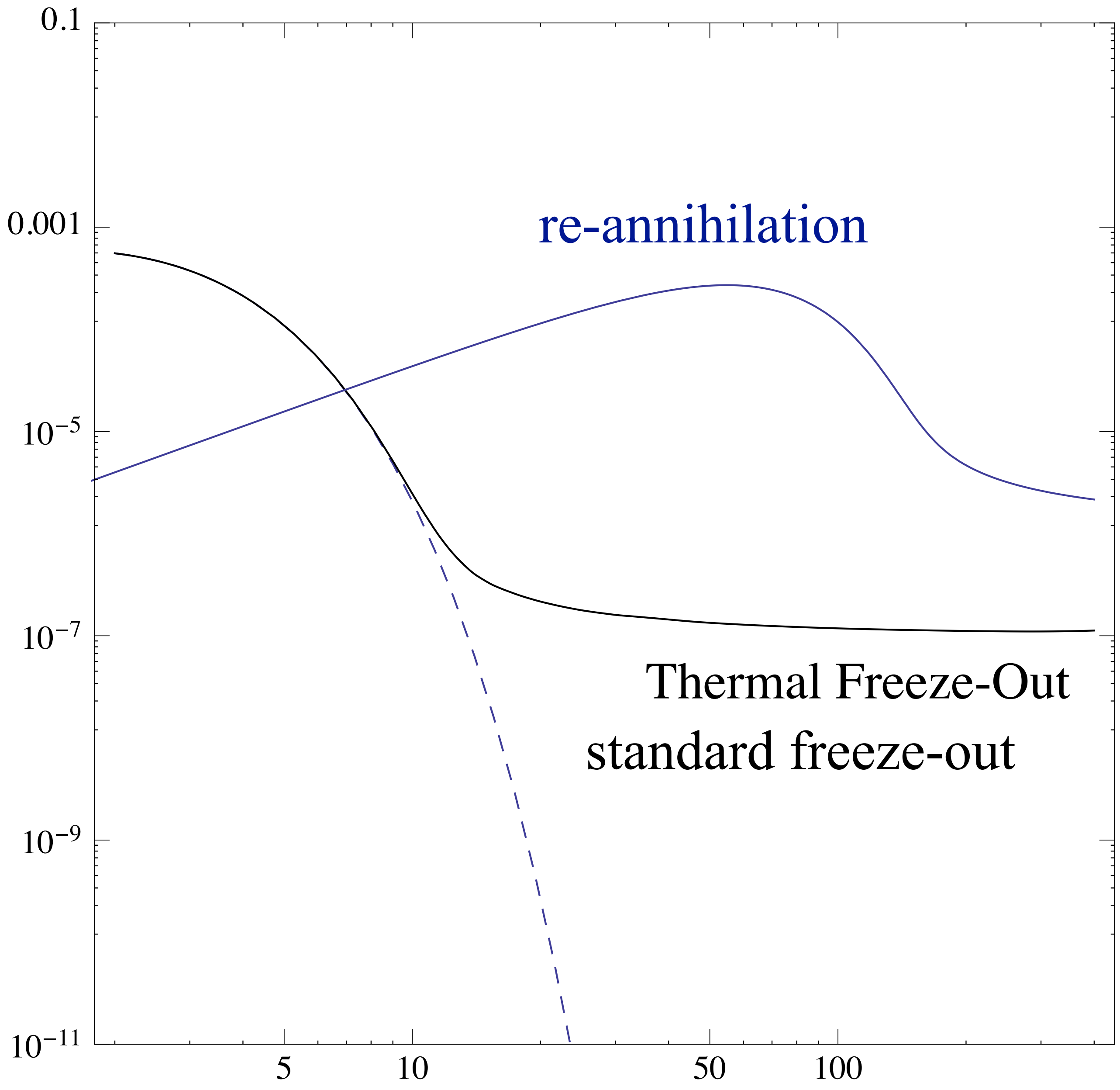
* T. Moroi and L. Randall; B.S. Acharya, G. Kane, S. Watson, P. Kumar;...

For instance $x_i > x^*$ requires $\langle\sigma v\rangle$ to be larger than 1 pbarn to reach the same relic abundance



e.g. Production of DM (e.g. scattering $SM + \Sigma \rightarrow X + SM'$)

followed by annihilation $X + X \longrightarrow SM + SM$

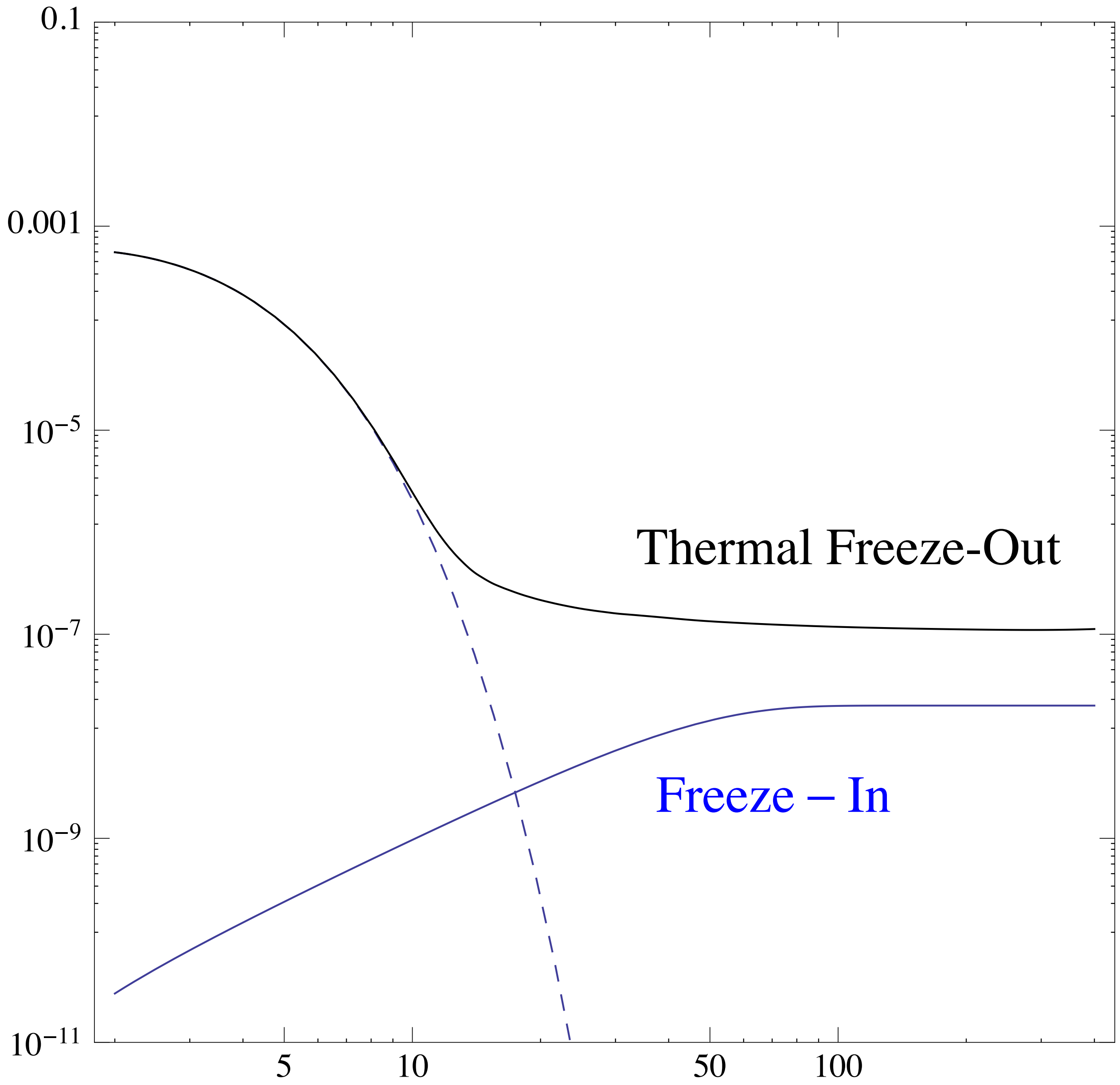


This is called a re-annihilation regime.*

* Cheung, Elor, Hall and Kumar

Now, if $$Y(x_i) \lesssim Y_\infty|_{\mathrm{thermal\,freeze-out}}$$

there is no re-annihilation. Instead $Y_\infty = Y(x_i).$



This is called freeze-in *

* Mc Donald (02); Hall, Jedamzik, March-Russell and West (09)

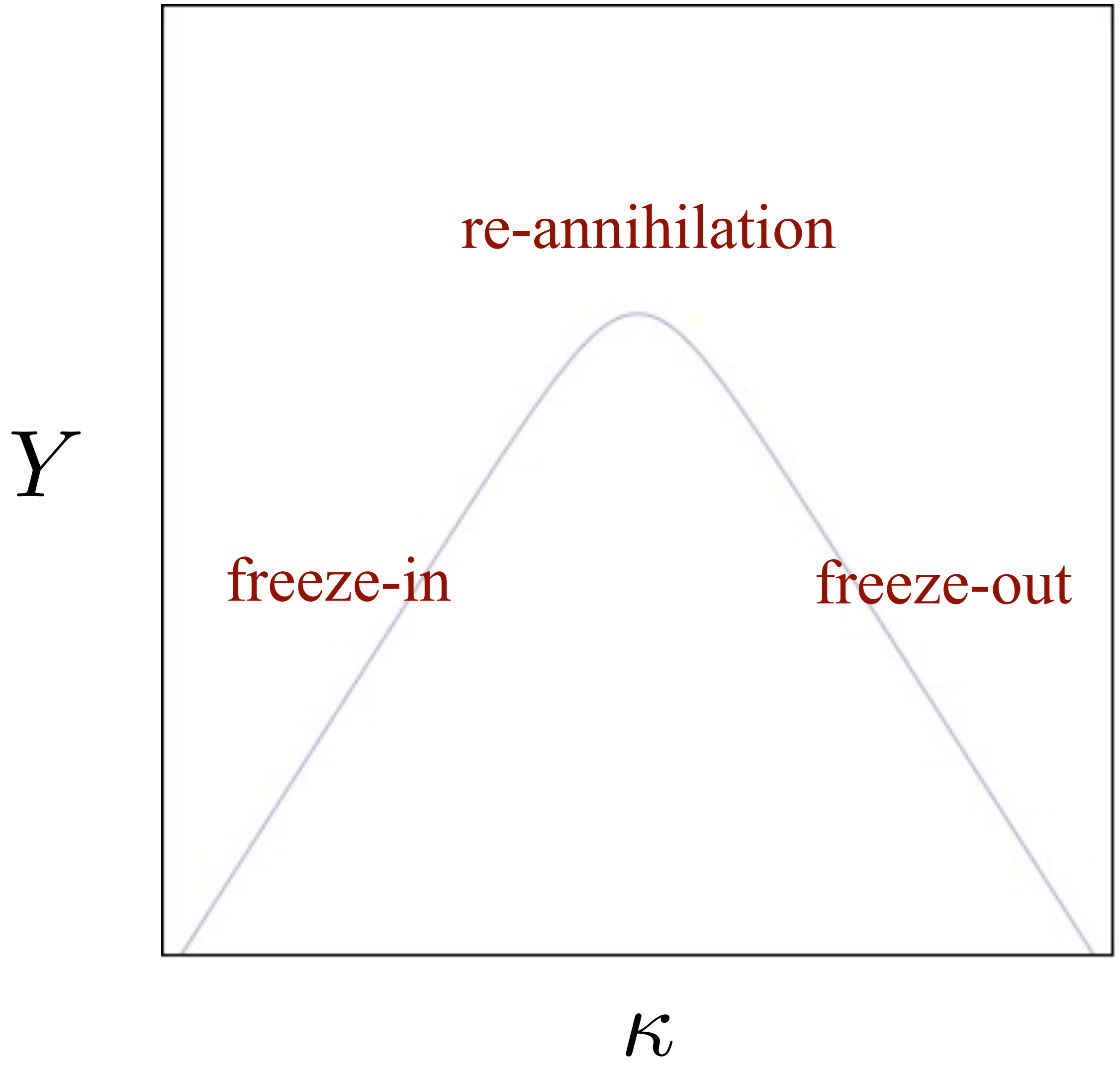
Typically freeze-in leads to

$$Y_{FI} \sim \kappa^2 \times M \times t_U$$

Some small coupling (the time scale t_U depends on process)

To be compared to

$$Y_{F0} \sim \frac{1}{\kappa^2 \times M \times t_U}$$



A VERY SIMPLE HIDDEN SECTOR

$$\mathcal{L}_{HS} = i\bar{\chi}\not{D}'\chi - m_\chi\bar{\chi}\chi + \ldots$$

χ is a Dirac fermion, charged under a massless U(1)' gauge field B'_μ

Stable simply because it is assumed to be the lightest charged particle in the HS *

*Feldman, Kors, Nath (06); Pospelov, Ritz, Voloshin (08) Mambrini (10);... Rem: for a massive Z′.

Interaction with the Visible Sector is through the Kinetic Portal *

$$\mathcal{L} \supset -\frac{\epsilon}{2} B^{\mu\nu} B'_{\mu\nu}$$

* Bob Holdom (86)

MOTIVATION?

Among the simplest models for DM.

Only 3 parameters (4 if A’ is made massive, say, à la Stueckelberg).

$$(m_\chi, e', \epsilon \to \kappa = \epsilon e'/e)$$

Some very natural features (stability from charge conservation, tiny mixing).

Visible Sector = Standard Model Only !

Yet very rich phenomenology (both for cosmology and particle physics).

New long range interactions and dark radiation *

Broad range of DM candidates (from sub-MeV to TeV)

Archetype for many VS-HS structures : 4 regimes for DM creation.

[*] Dark Radiation studied in details, but with no mediator, by Ackerman, Buckley, Carroll, Kamionkovski (08); Feng, Kaplinghat, Tu, Yu (09); Feng, Tu, Yu (08); see also Foot *et al* (06-10)

RELIC DENSITY IN **κ-α’** PLANE

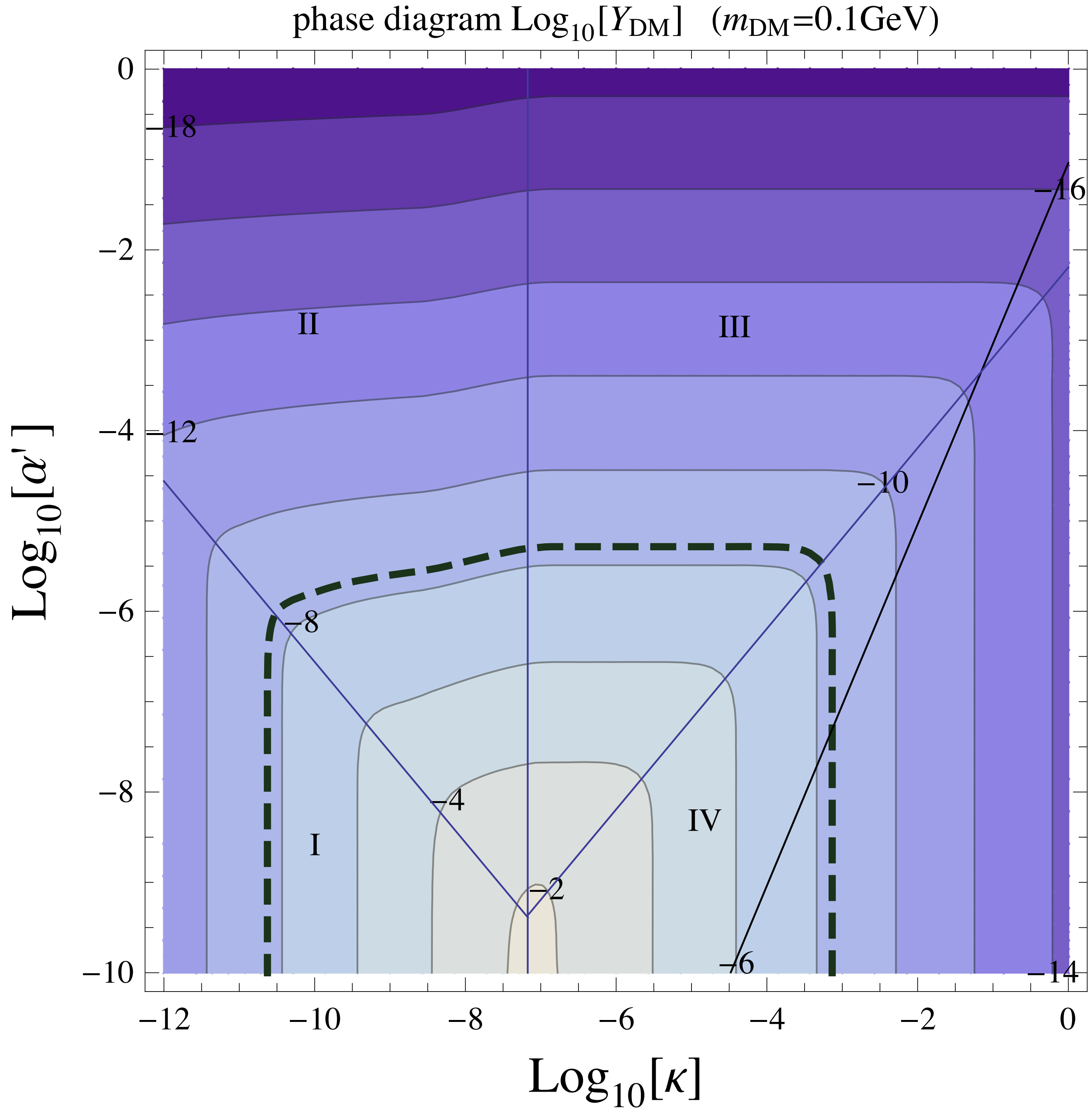
4 regimes:

I. Freeze-in

II. Reannihilation

IV. Freeze-out with thermalization of HS

V. Freeze-out without thermalization of HS



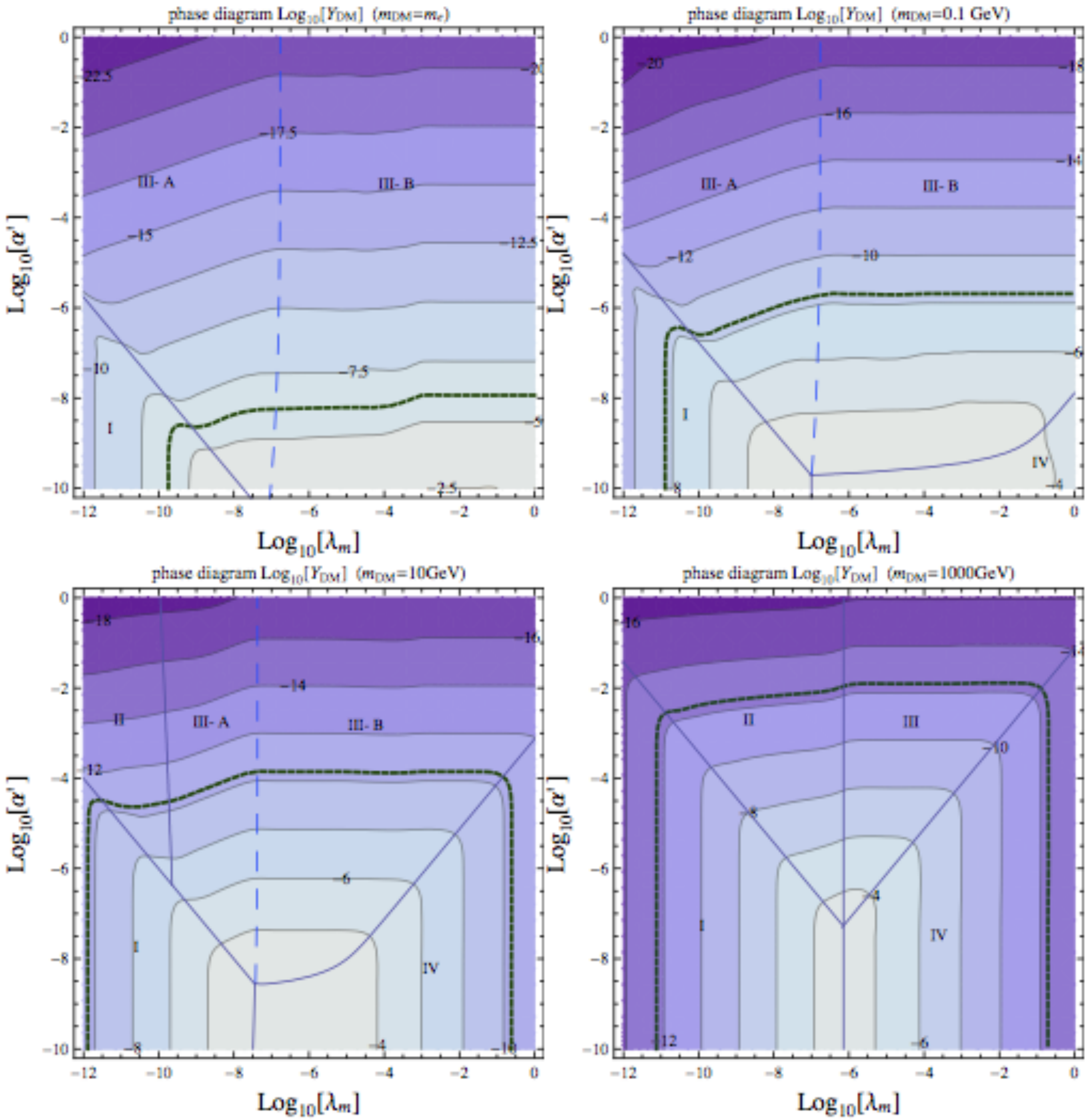
In the figure, the levels correspond to Ω_{dm}
The dashed line is $\Omega_{\mathrm{dm}} = 0.23$
(here for $m_{\mathrm{dm}} = 100$ MeV)

This structure is generic

(Here shown for Higgs portal)

$m_{DM} = m_e$

$m_{DM} = 0.1\,\mathrm{GeV}$

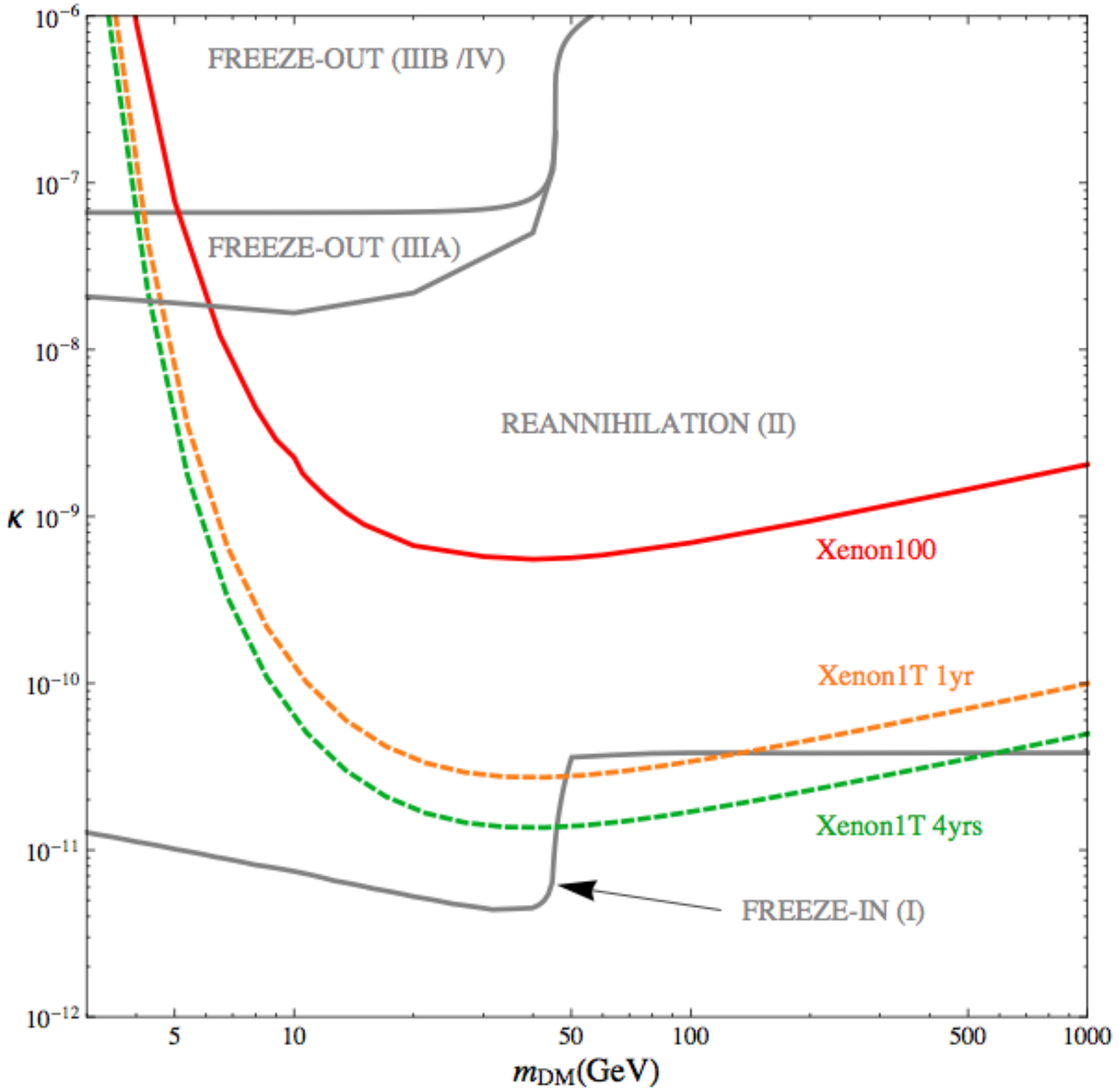


$m_{DM} = 10\,\mathrm{GeV}$

$m_{DM} = 1\,\mathrm{TeV}$

More about Direct Detection (kinetic portal)

Here, we assume that the local abundance (ie at the Sun's location) is 0.3 GeV/cm^3



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

LET $\langle \sigma v \rangle \sim \frac{\alpha^2}{M_{DM}^2}$ THEN $M_{DM} \sim \mathrm{TeV}$

GRIEST-KAMIONKOWSKI UNITARITY BOUND:

$\langle \sigma_{\max} v \rangle \approx \frac{4\pi(2J+1)}{M_{DM}^2 v}$ → $M_{DM} \lesssim 340$ TeV