NICPB KBFI

CONNECTING SCIENCES

Thermal loophole in the Higgs Portal

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NICPB, Tallinn

in collaboration with
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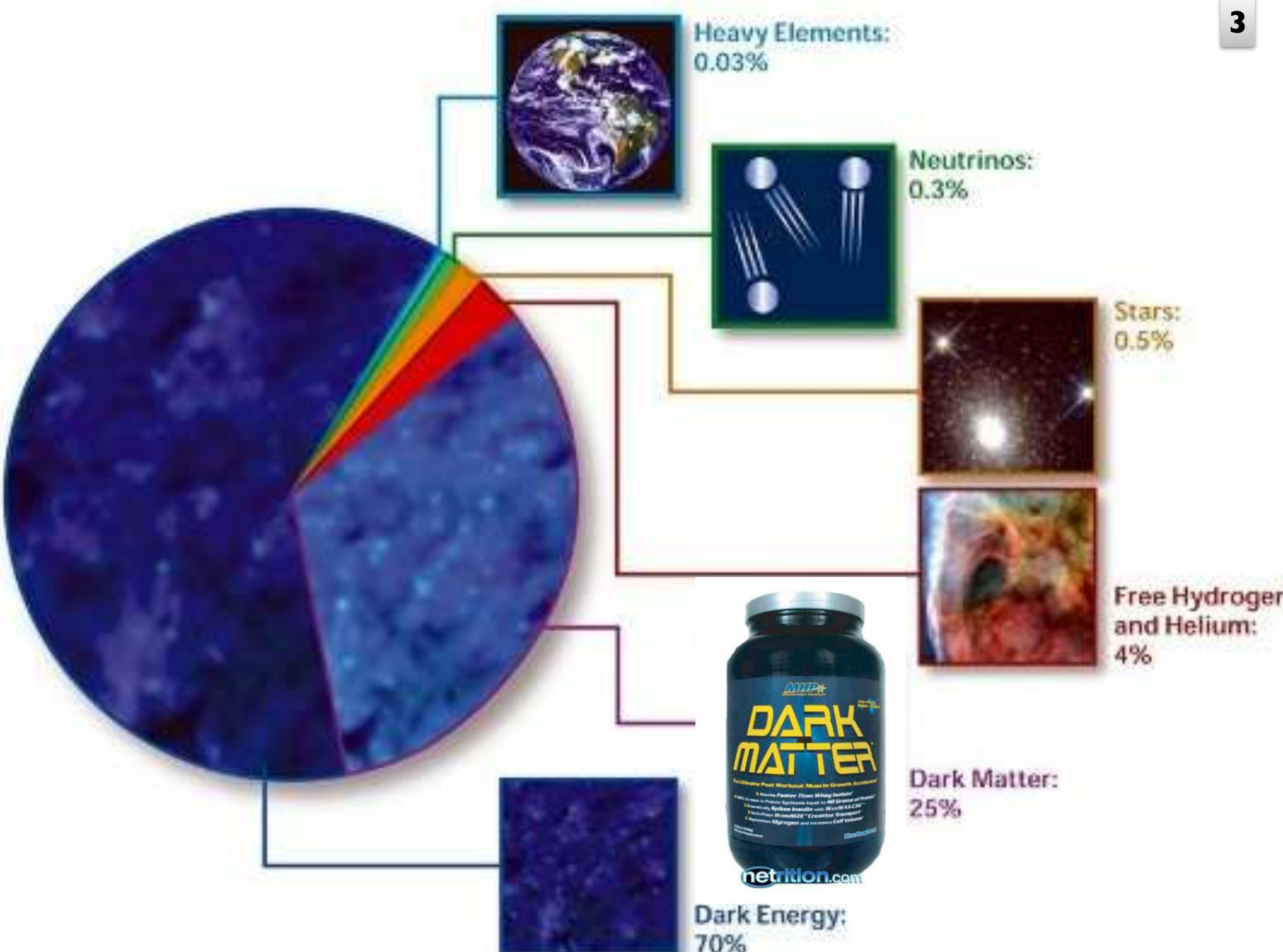
Helsinki ✧ 7/9/2017

Euroopa Liit
Euroopa
Regionaalarengu Fond

Eesti tuleviku heaks

Motivation & outlines

- Higgs Portal, rise and fall
- Escapes form the direct detection constraints:
  - ‘Pseudoscalar portal’
  - ‘Resonance portal’
- ‘Thermal portal’
- Thermal effects of primordial plasma at the freeze-out
- A minimal model
- Conclusions


Heavy Elements:
0.03%
Neutrinos:
0.3%
Stars:
0.5%
Free Hydrogen
and Helium:
4%
MHP
DARK
MATTER
netrition.com
Dark Matter:
25%
Dark Energy:
70%

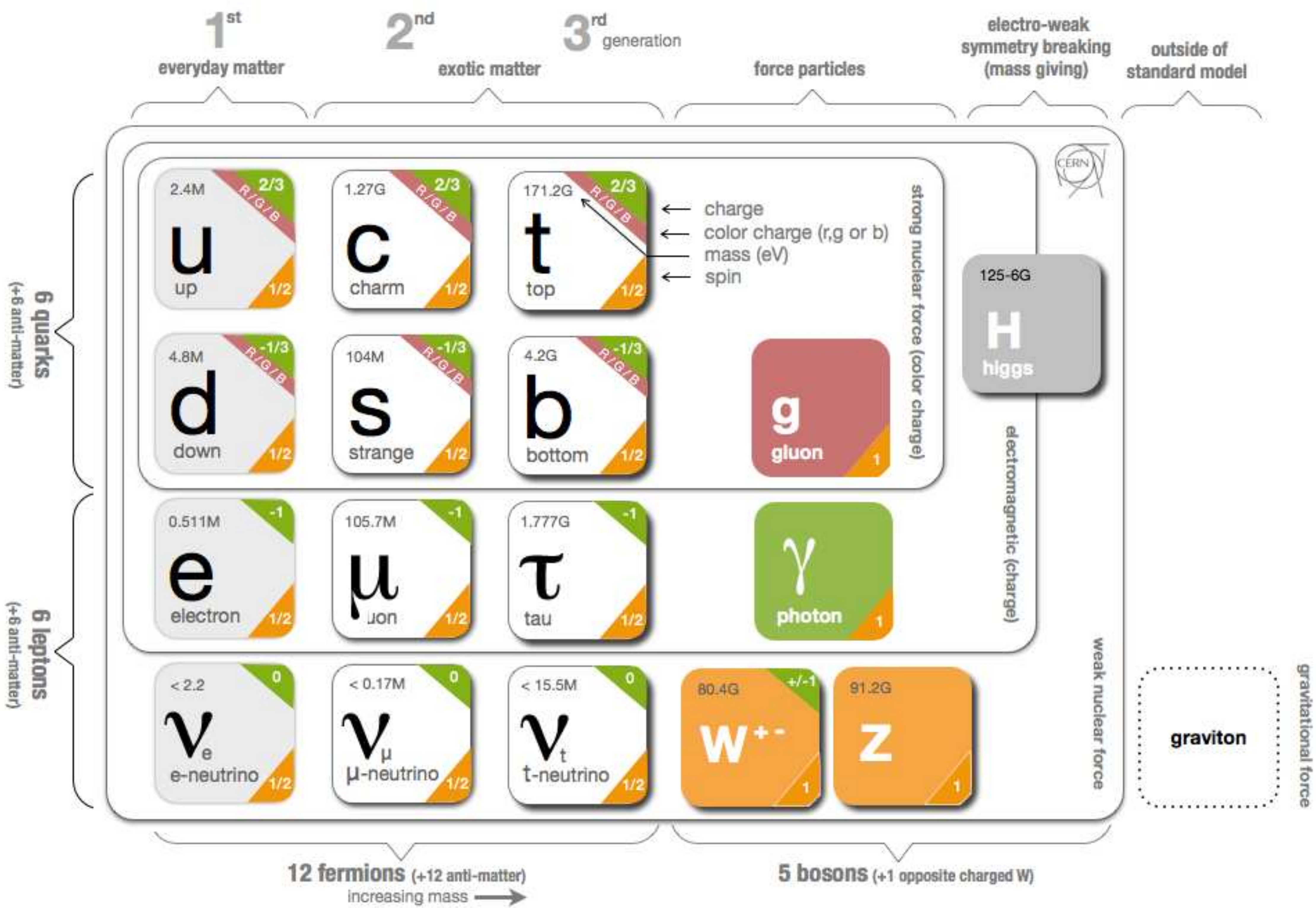
The Journal

Trump searches for the “dark matter” of politics

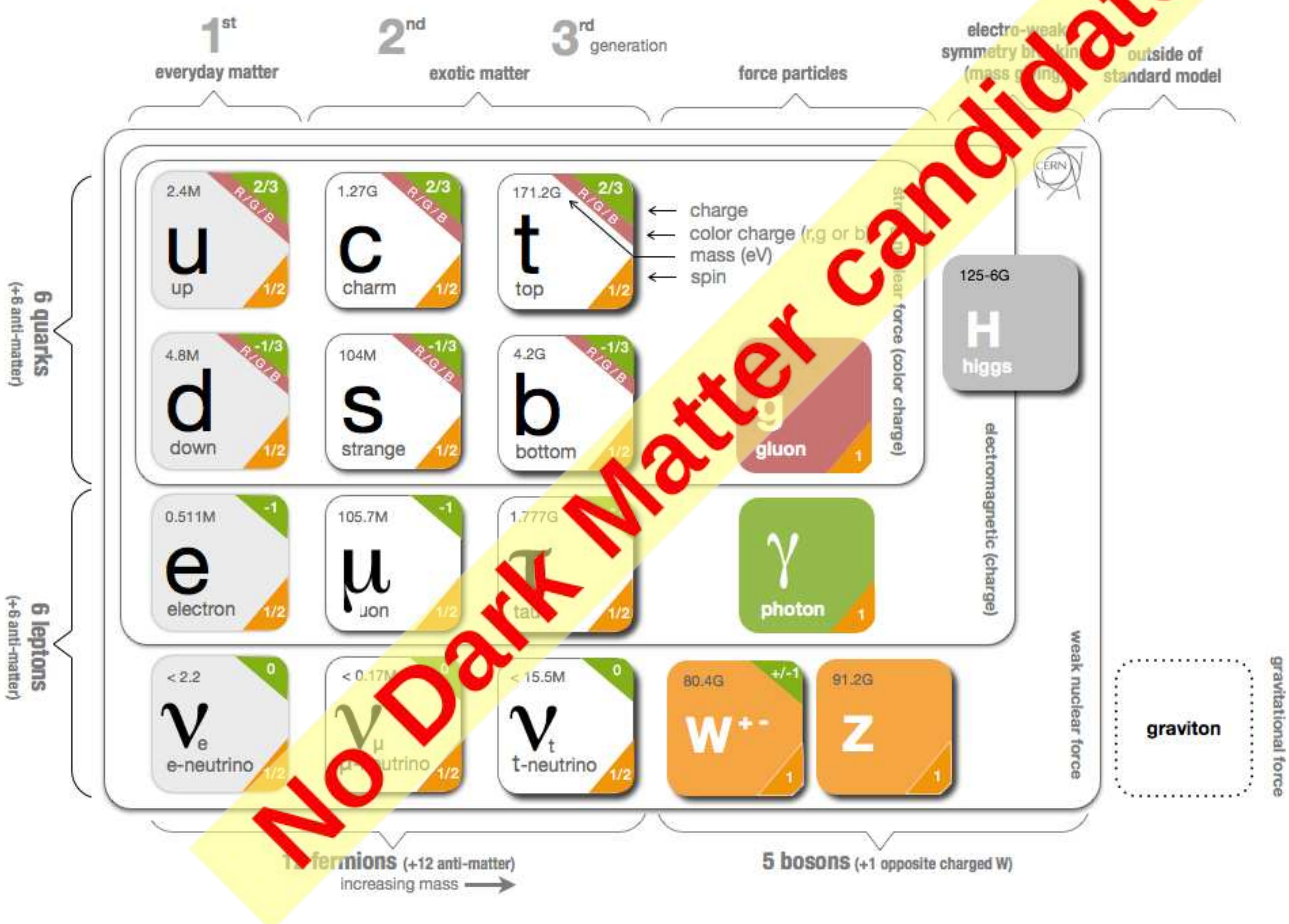
Details Last Updated on Tuesday, 14 June 2016 11:12
Published on Tuesday, 14 June 2016 11:12 Hits: 650

It exists mostly in theory and the realm of complicated mathematical equations. But, scientists know it's there. It's called “dark matter” and it makes up a substantial part of our universe. Politics, of course, isn't physics, but in the theater of American elections there is a sort of dark matter as well. We can't always trace its source, sometimes it's completely hidden, but on occasion, it's more evident than we would like to believe. And this year, the dark matter of American politics isn't hard to find at all. It's that undercurrent of hostility that stays just below the surface. Most of us, admit it, come on, have thought some of the outlandish things Donald

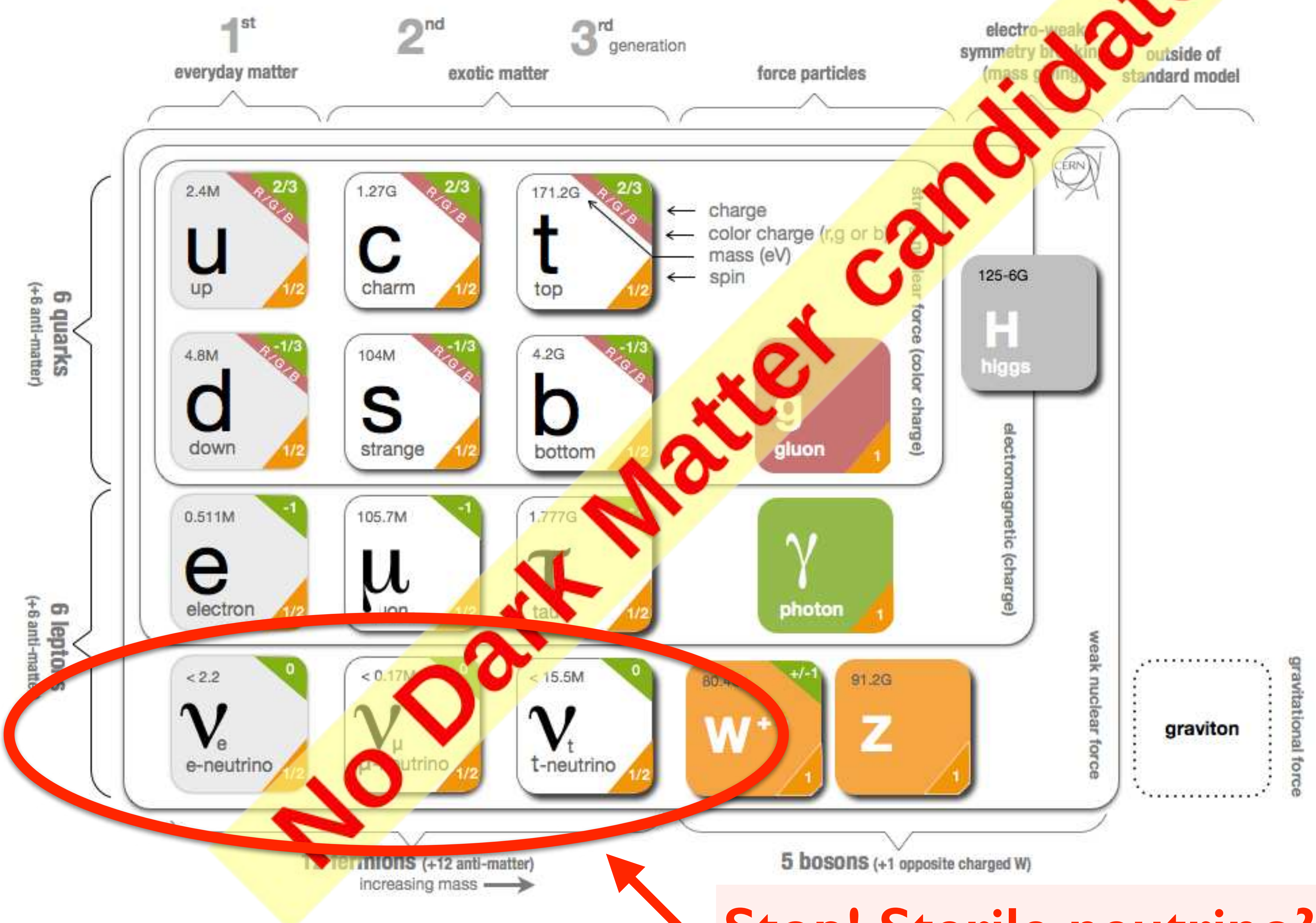
DM in the Standard Model?



DM in the Standard Model?



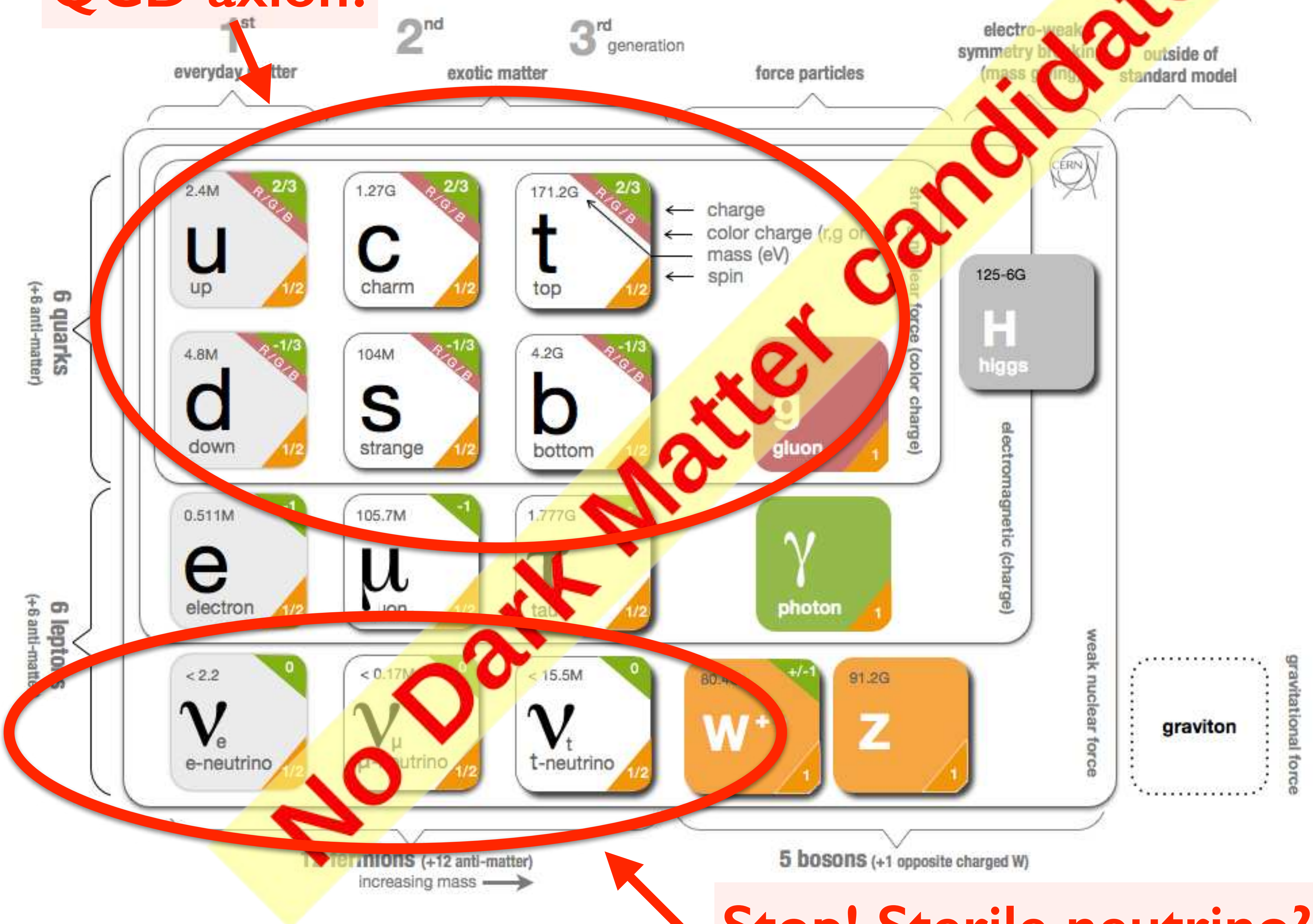
DM in the Standard Model?



Stop! Sterile neutrino?

DM in the Standard Model?

Stop! QCD axion?



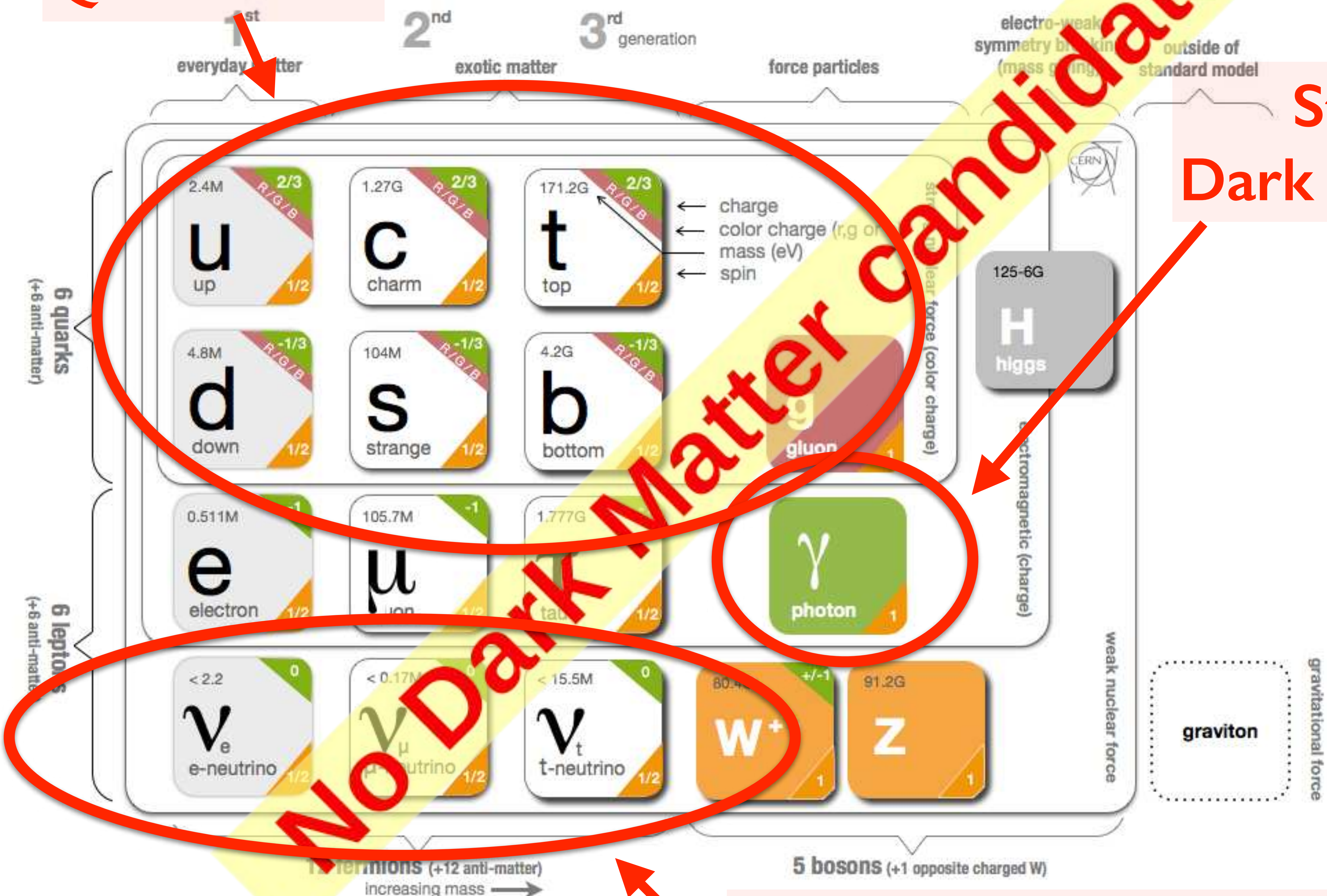
Stop! Sterile neutrino?

DM in the Standard Model?

Stop!
QCD axion?

Stop!
Dark photon?

No Dark Matter candidate!



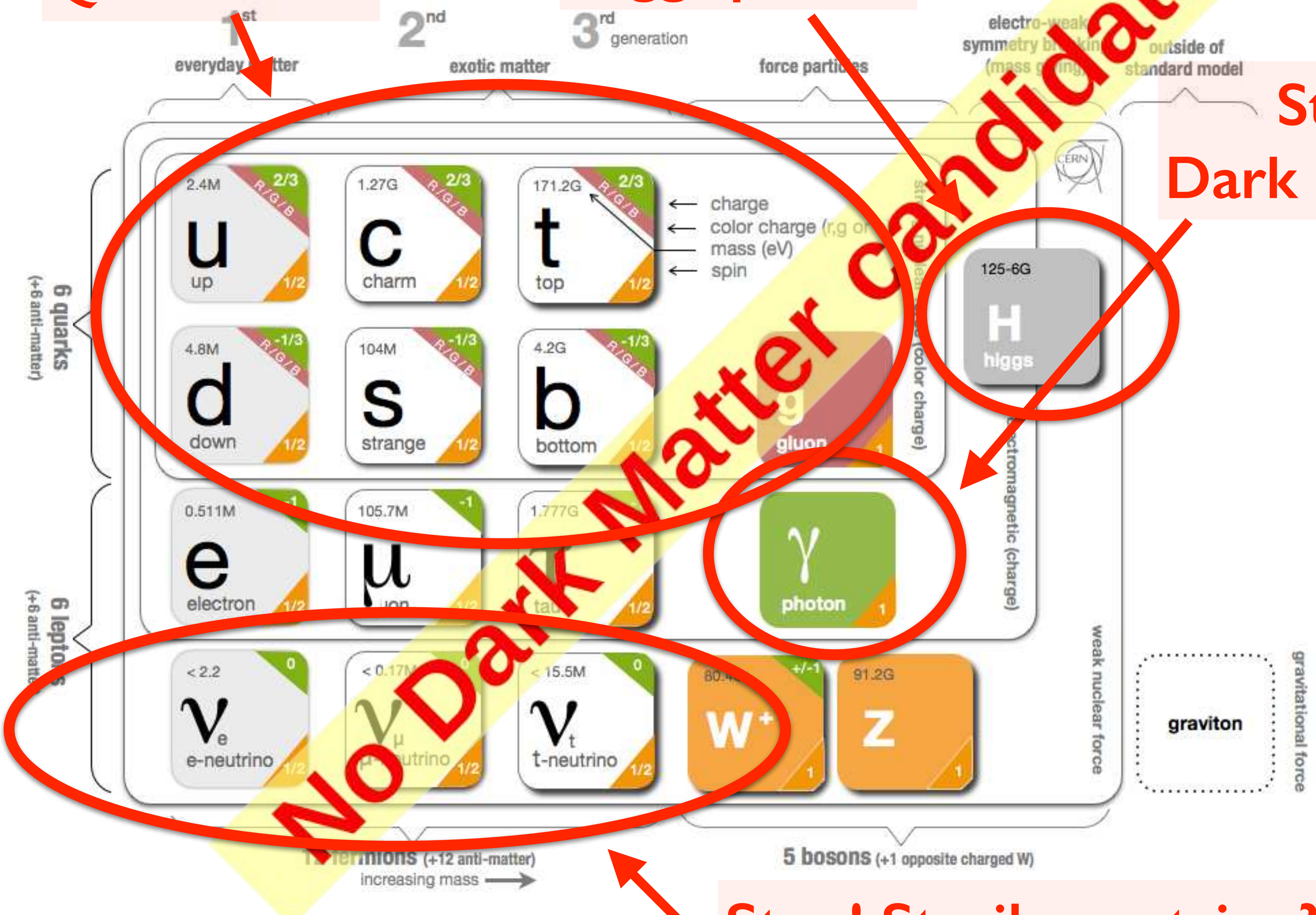
Stop! Sterile neutrino?

DM in the Standard Model?

Stop! QCD axion?

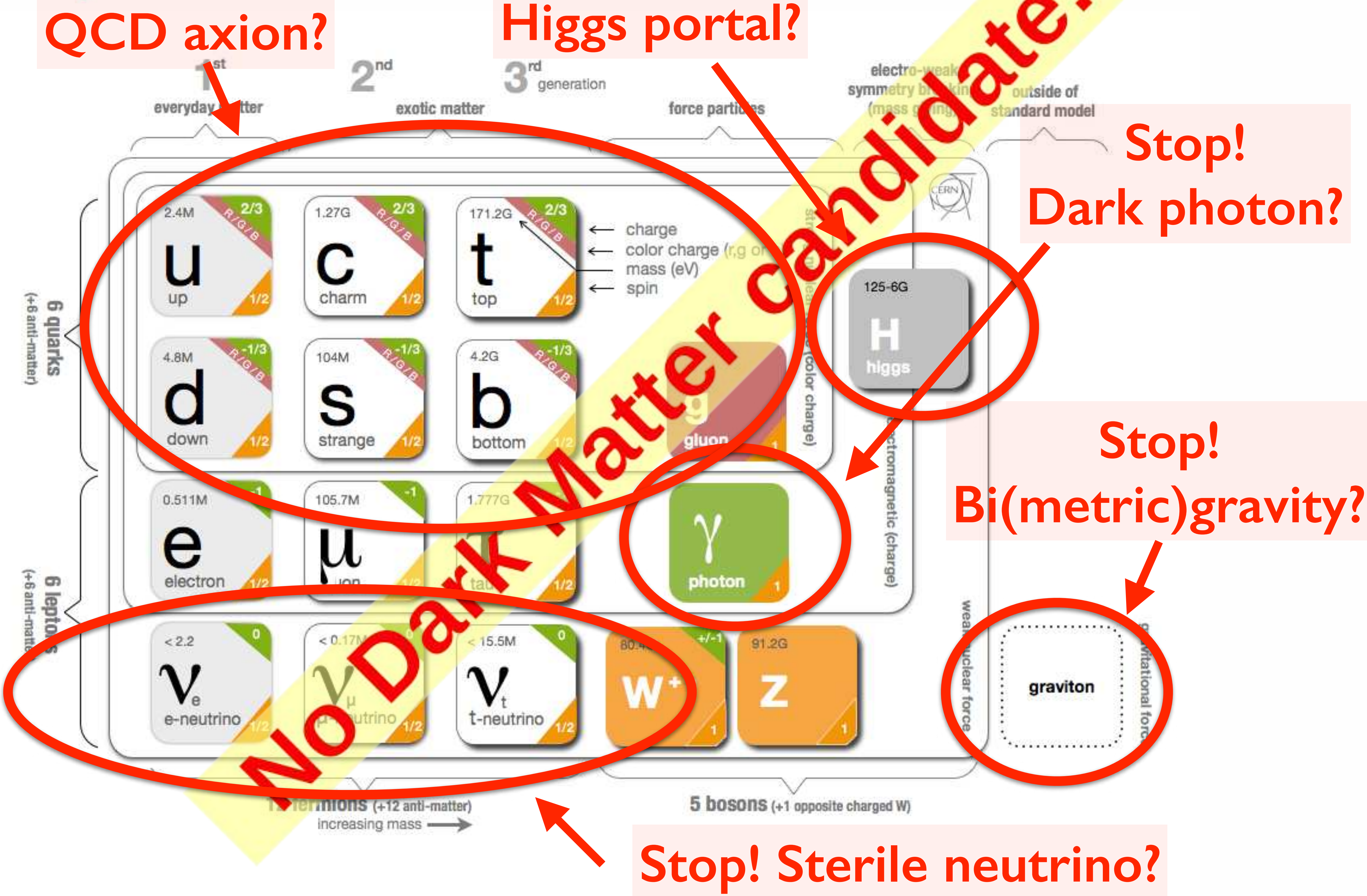
Stop! Higgs portal?

Stop! Dark photon?

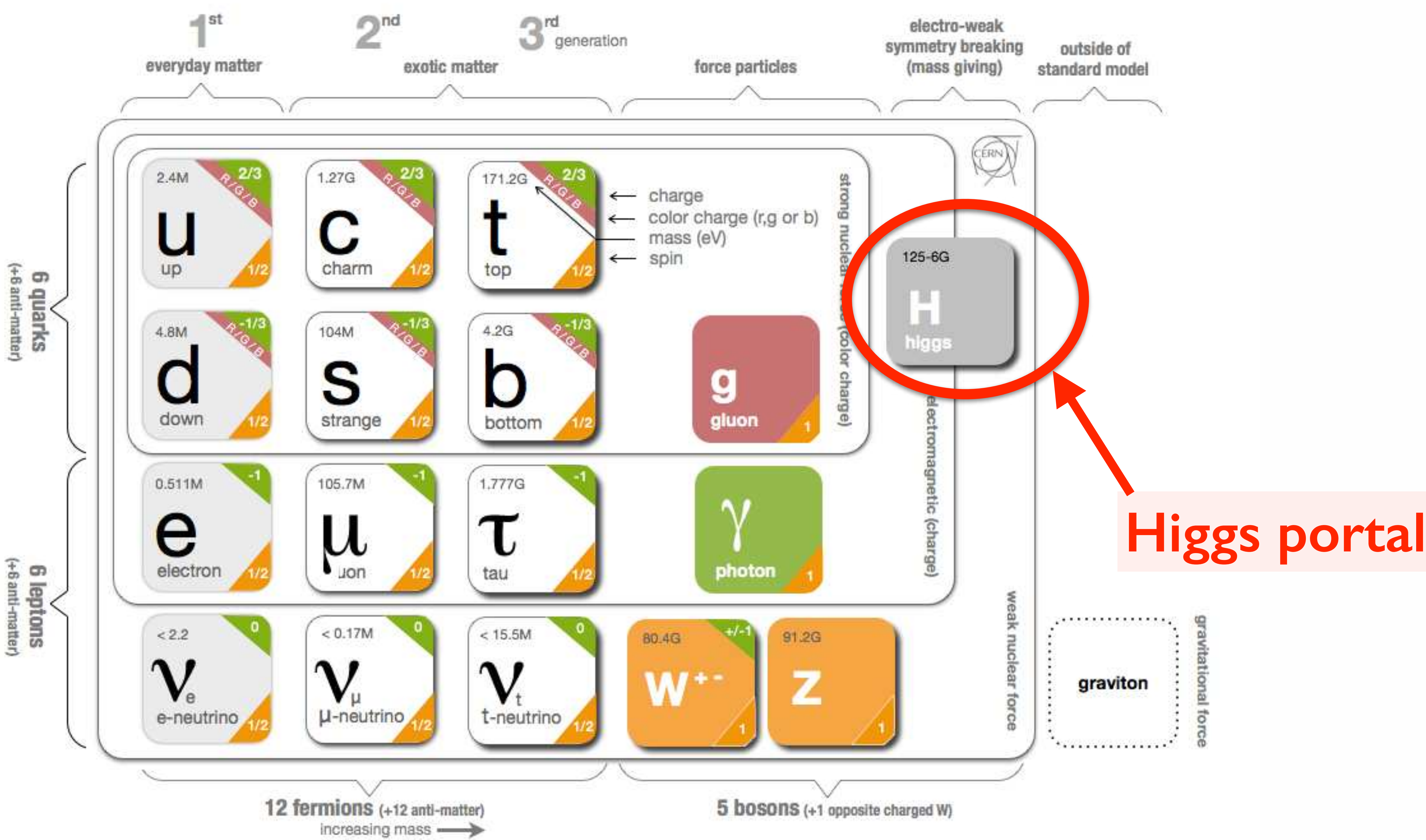


Stop! Sterile neutrino?

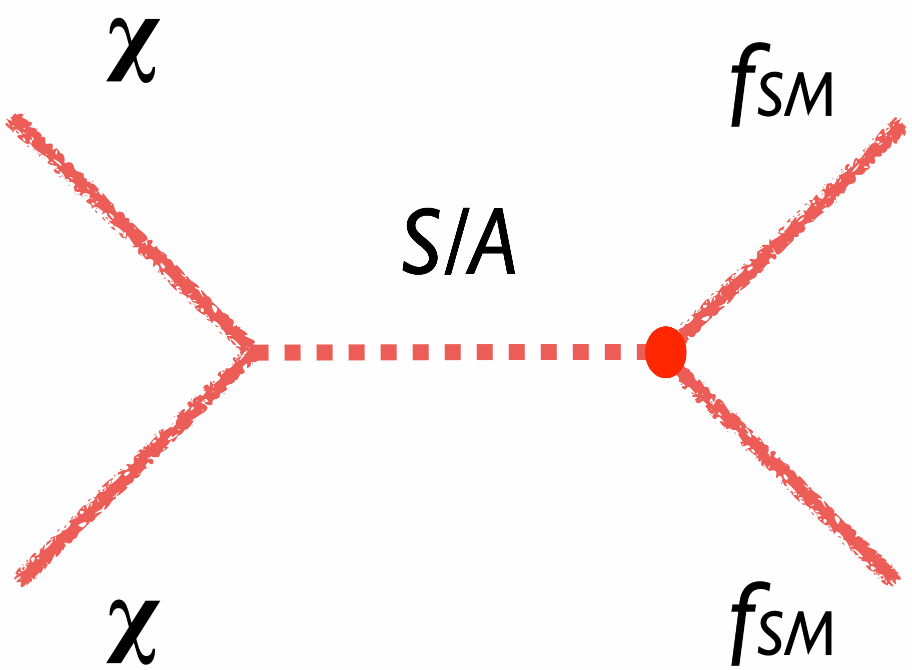
DM in the Standard Model?

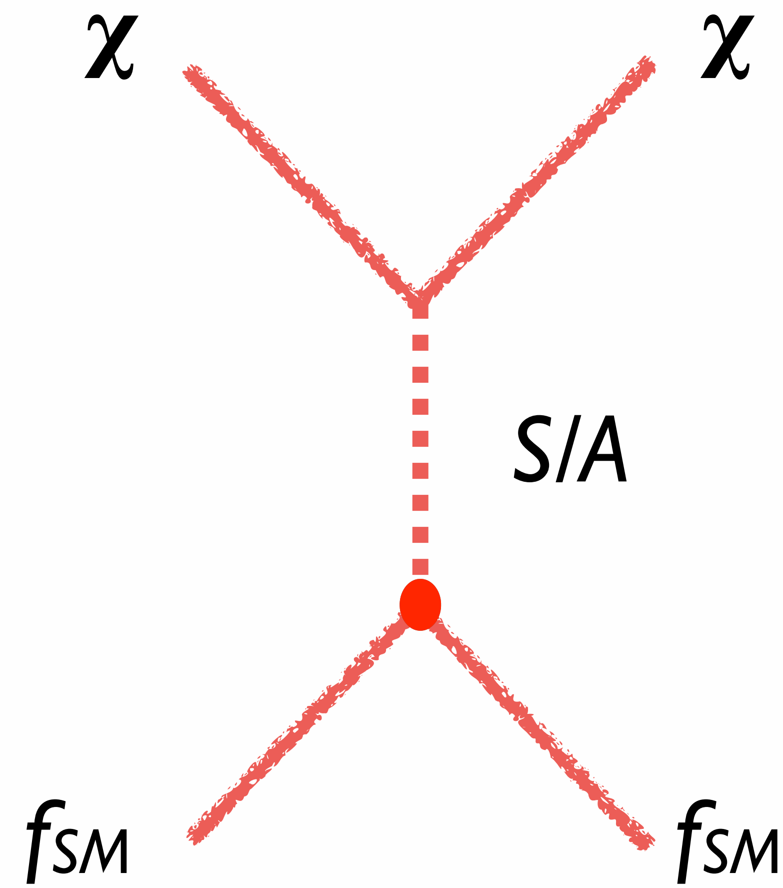


In this talk, the favourite is…



The (simplified) portal DM





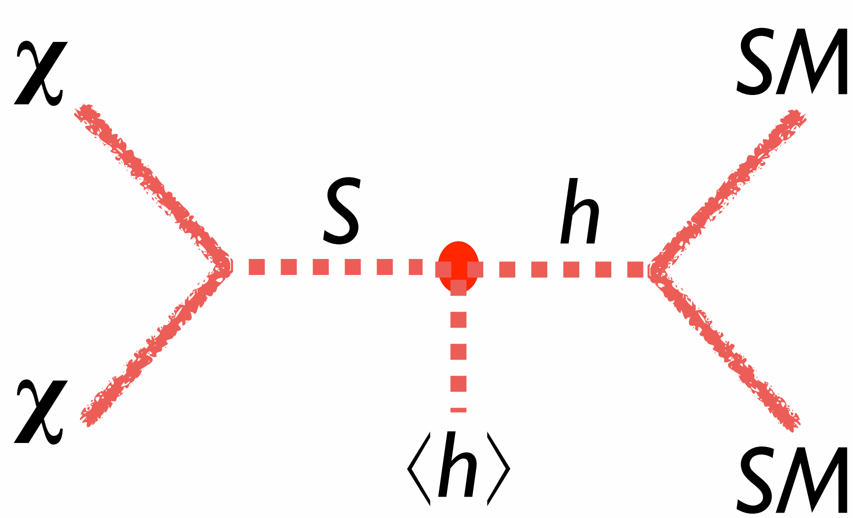
$$\mathcal{L}_{0_S s_{\frac{1}{2}}} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 + \bar{\chi}(i\not{\partial} - m_\chi)\chi - g_\chi S \bar{\chi}\chi - g_{\rm SM} S \sum_f \frac{y_f}{\sqrt{2}} \bar{f} f$$

$$\mathcal{L}_{0_A s_{\frac{1}{2}}} = \frac{1}{2}(\partial_\mu A)^2 - \frac{1}{2} m_A^2 A^2 + \bar{\chi}(i\not{\partial} - m_\chi)\chi - i g_\chi A \bar{\chi}\gamma^5\chi - i g_{\rm SM} A \sum_f \frac{y_f}{\sqrt{2}} \bar{f}\gamma^5 f$$

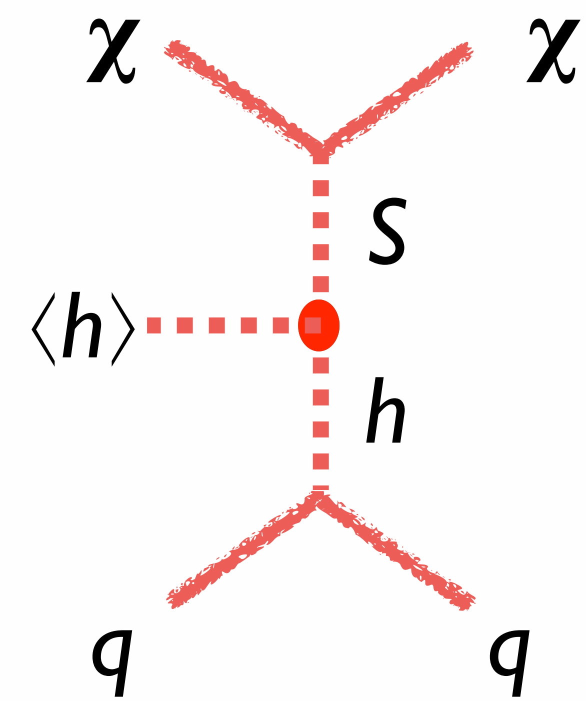
The portal provides
a good old WIMPy scenario!

Higgs portal, a realization

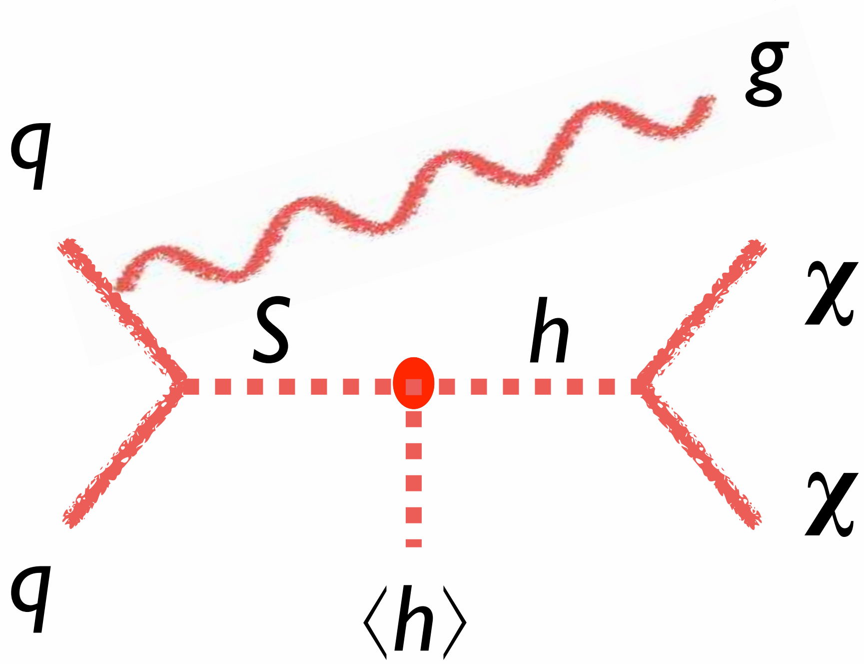
Freeze-out



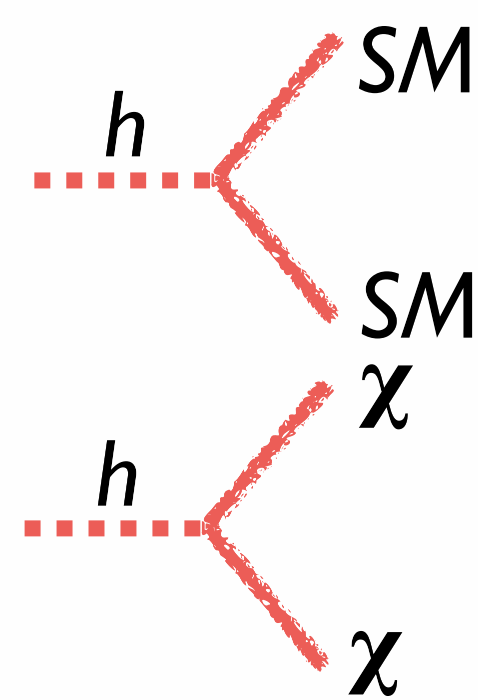
Direct detection



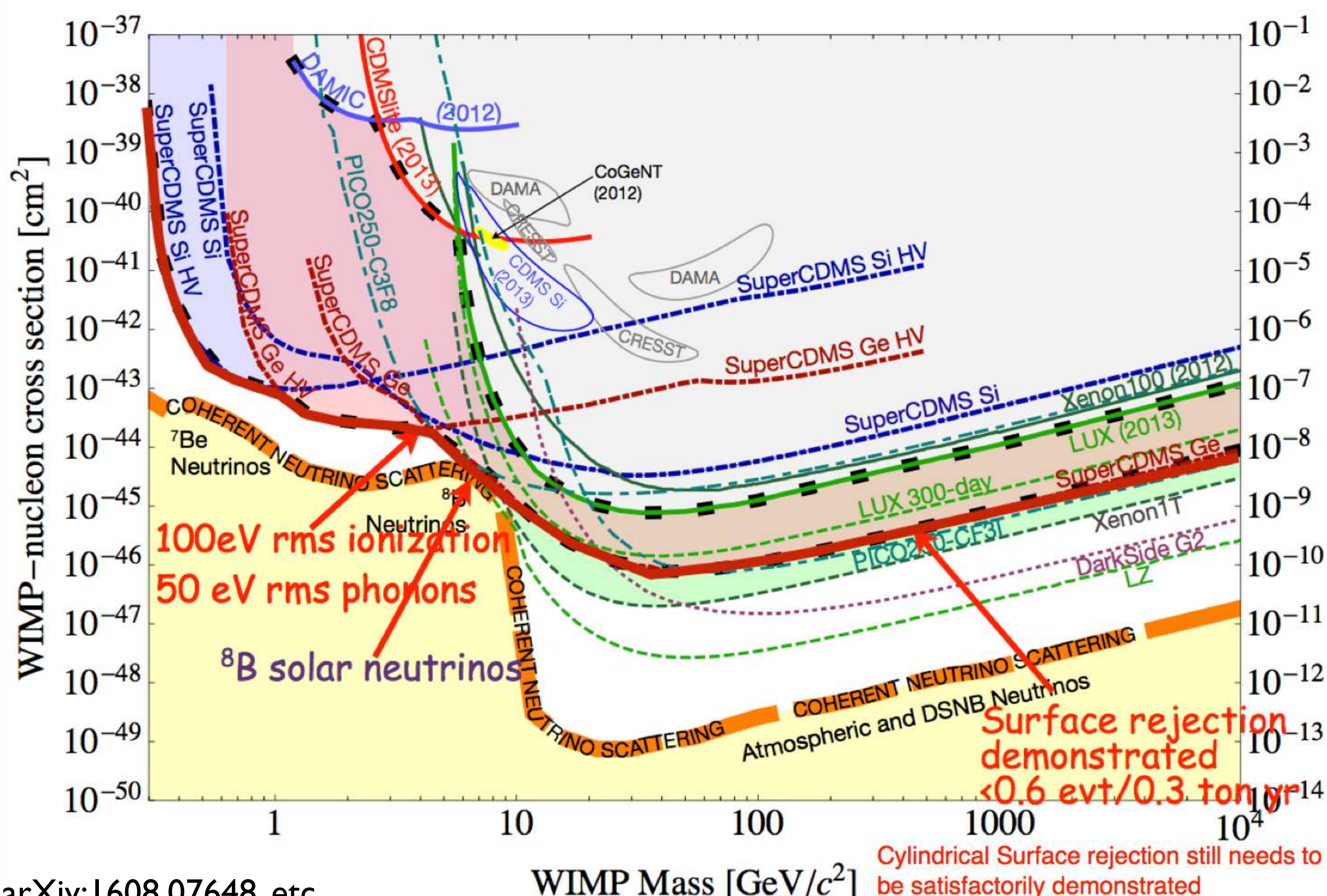
Accelerator: mono-jet



Accelerator: the Higgs width



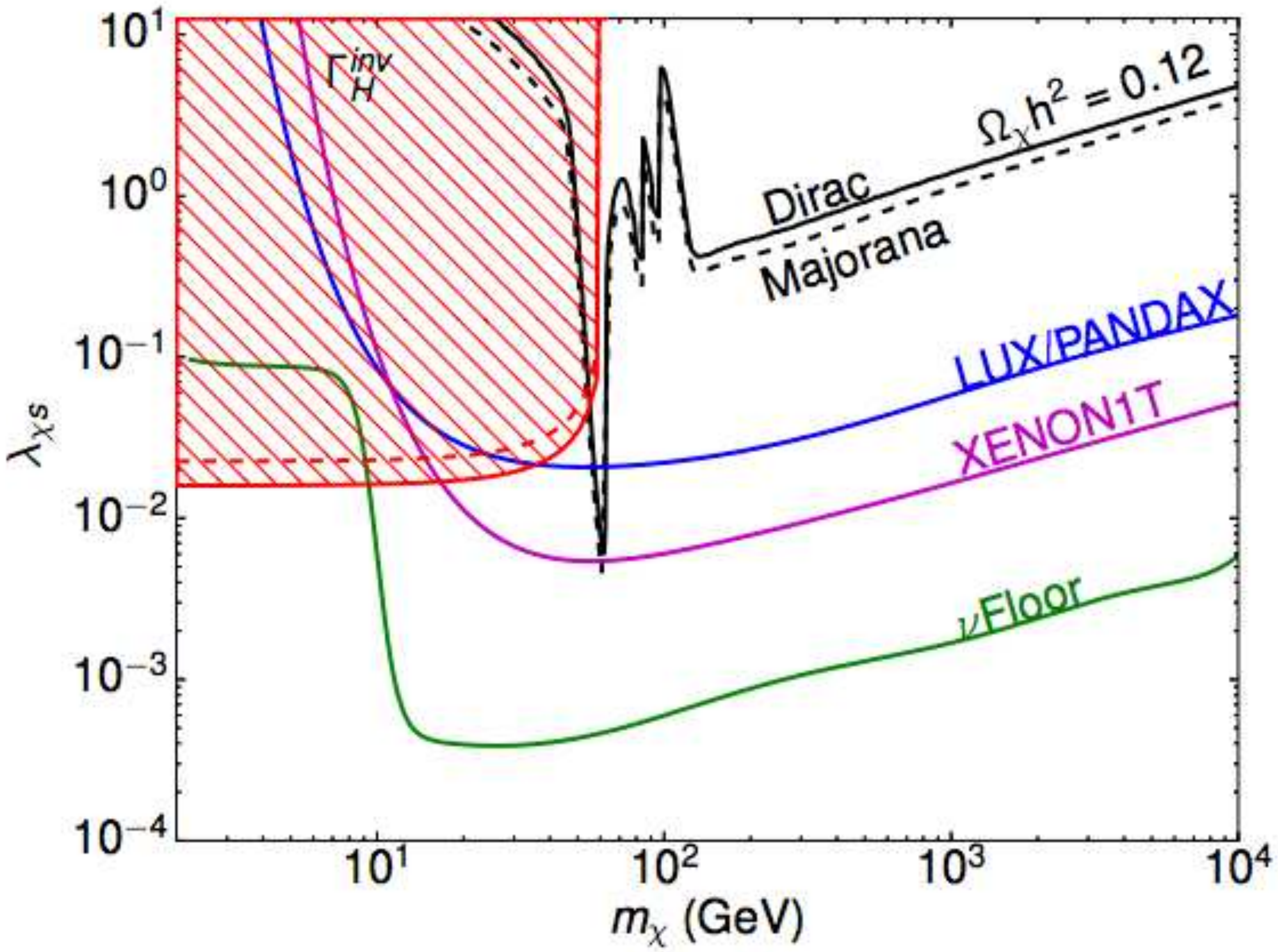
The model killer, Direct Detection



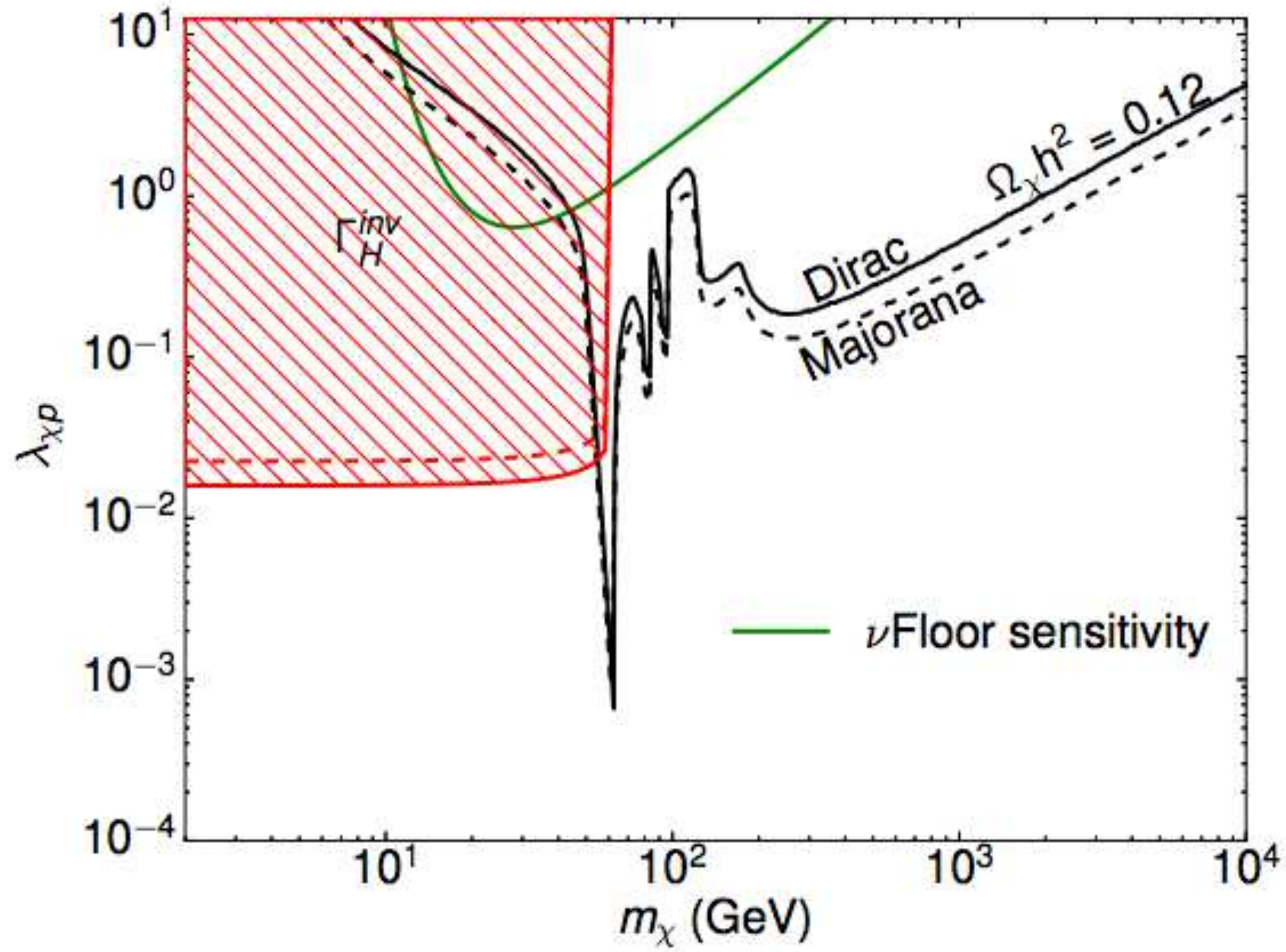
See arXiv:1608.07648, etc

So, after LUX/Pandax there is just one problem — the model is ruled out?

Scalar

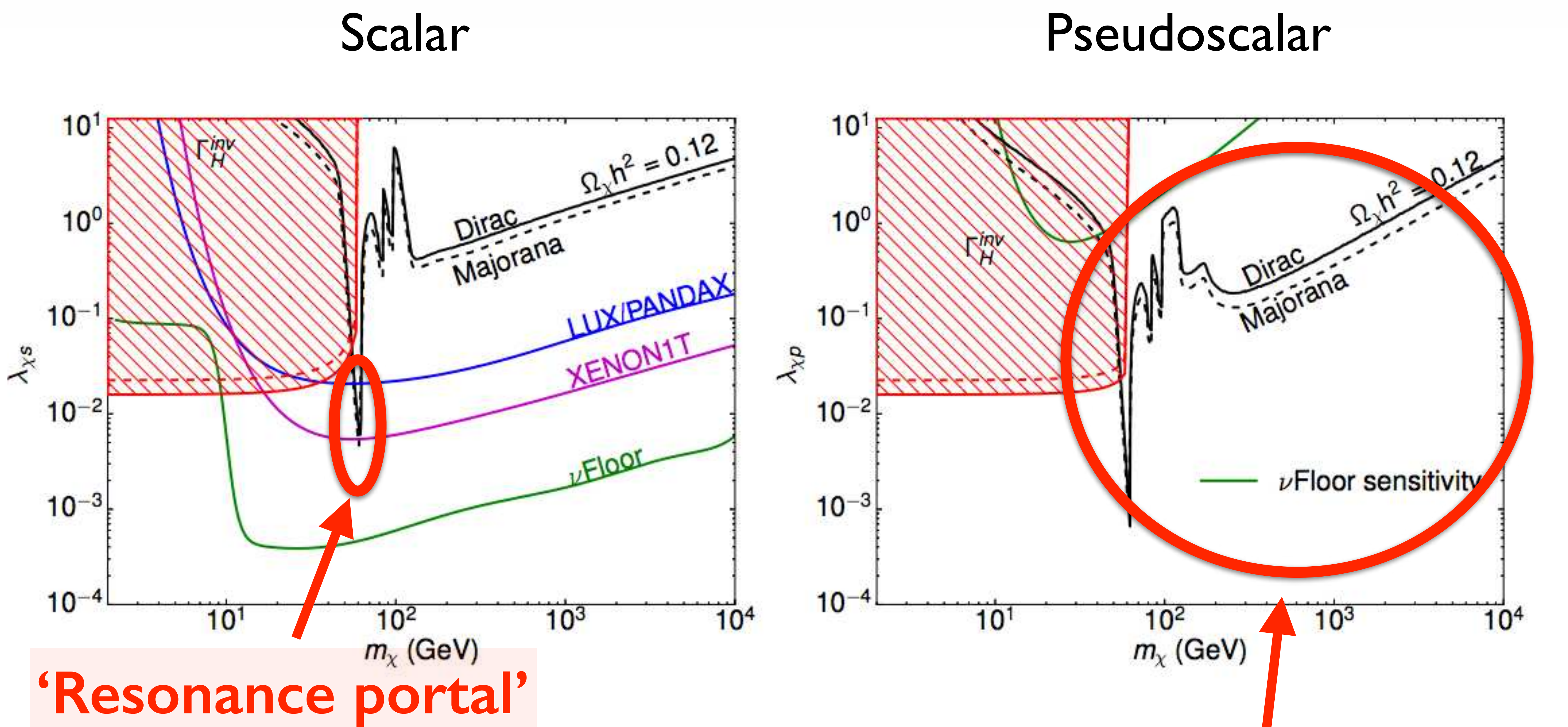


Pseudoscalar



Escudero et al, arXiv:1609.09079

So, after LUX/Pandax there is just one problem — the model is ruled out?

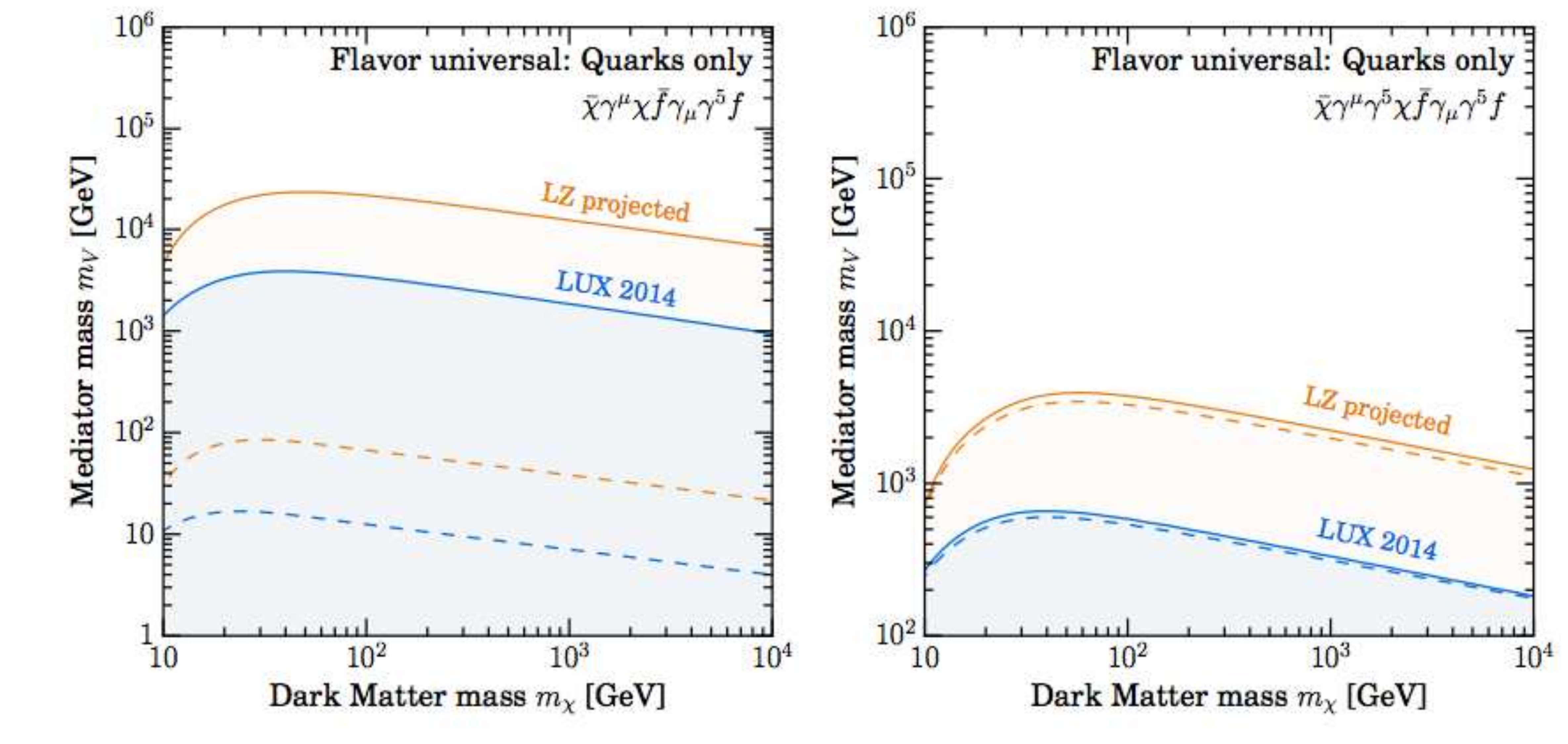


Escudero et al, arXiv:1609.09079

Escudero et al, arXiv:1609.09079

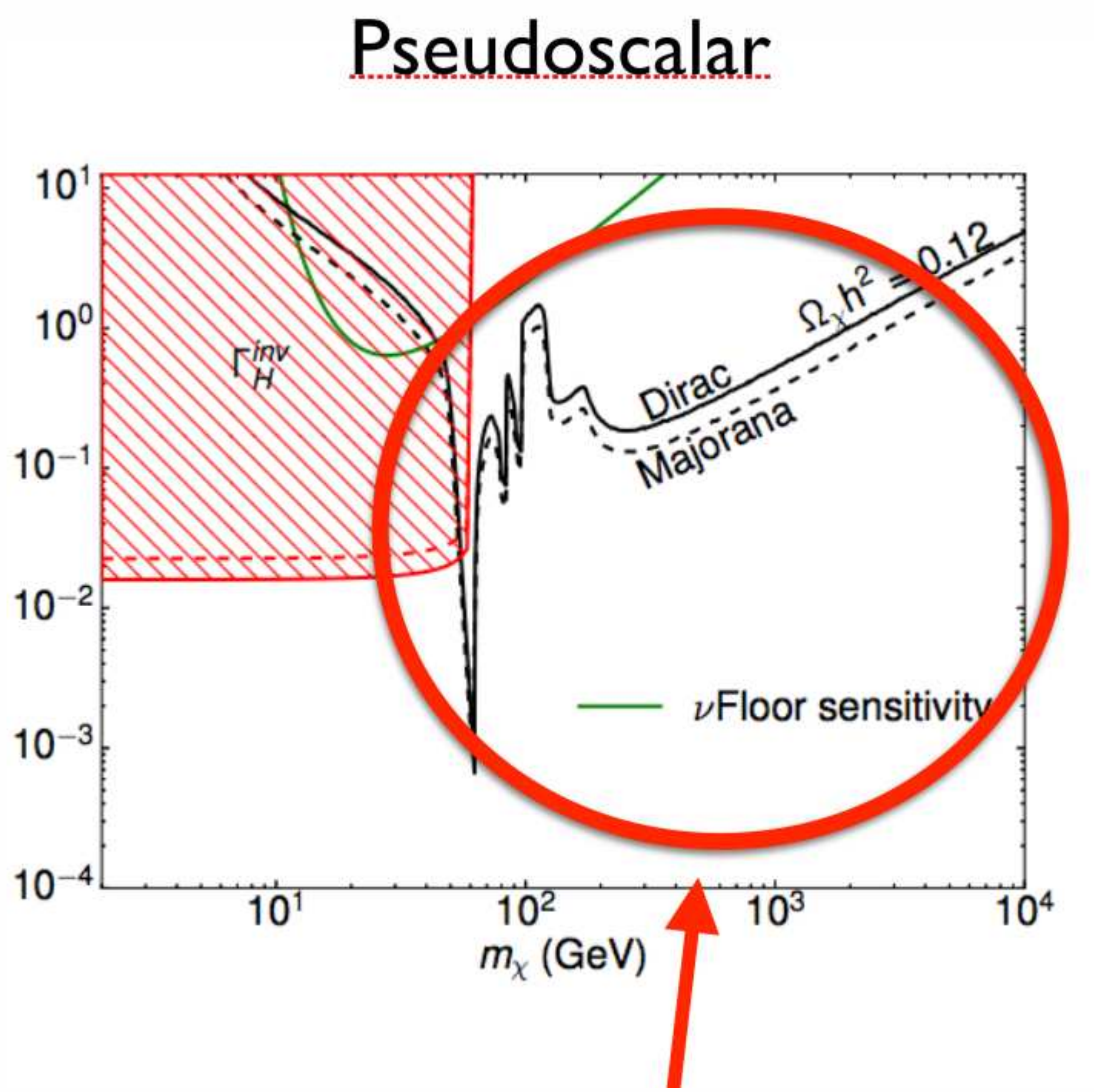
A note added

One has to be careful comparing very different energy scales — running!

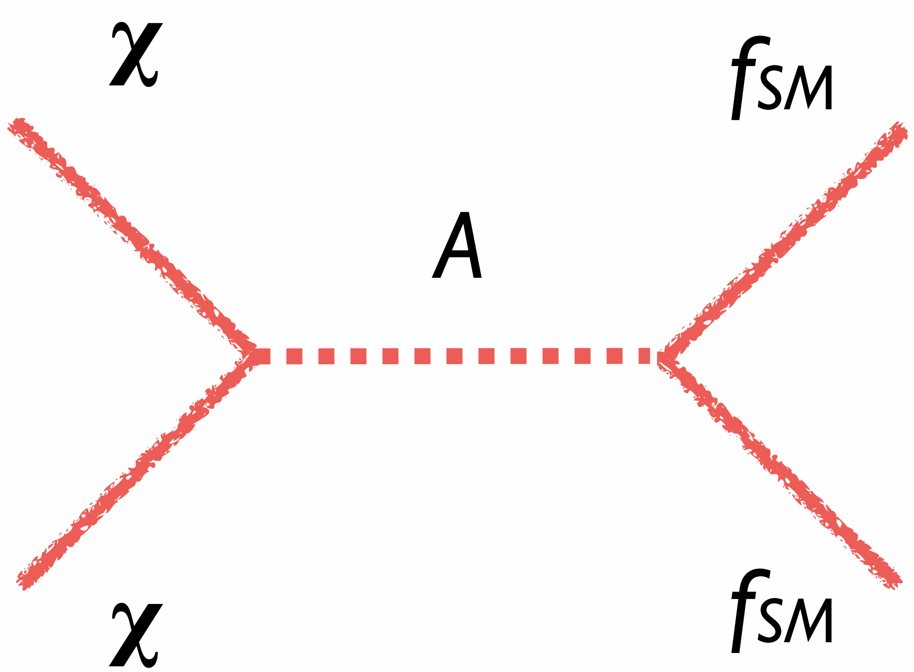


D'Eramo, Kavanaghc & Panci, arXiv:1609.09079

‘Pseudoscalar portal’



Pseudoscalar portal



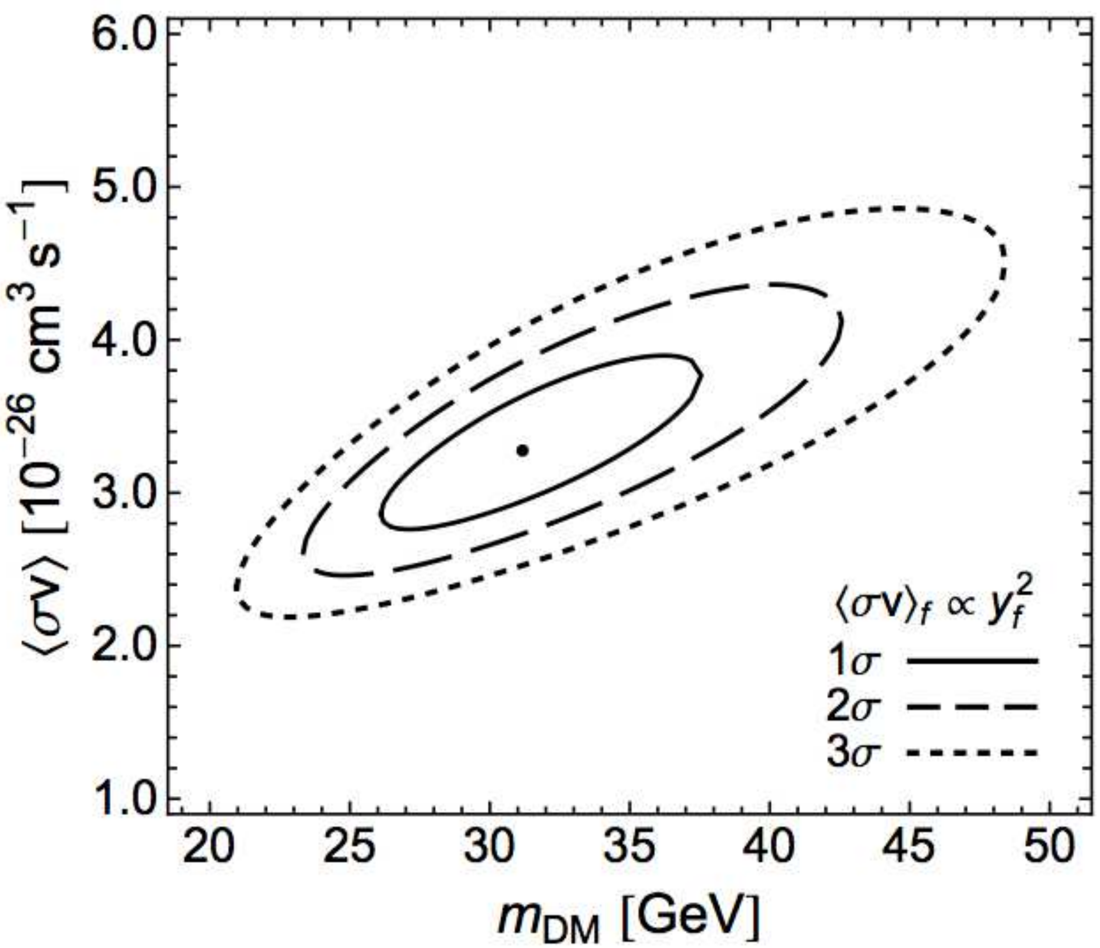
$\sigma_{SI} \propto v^2$

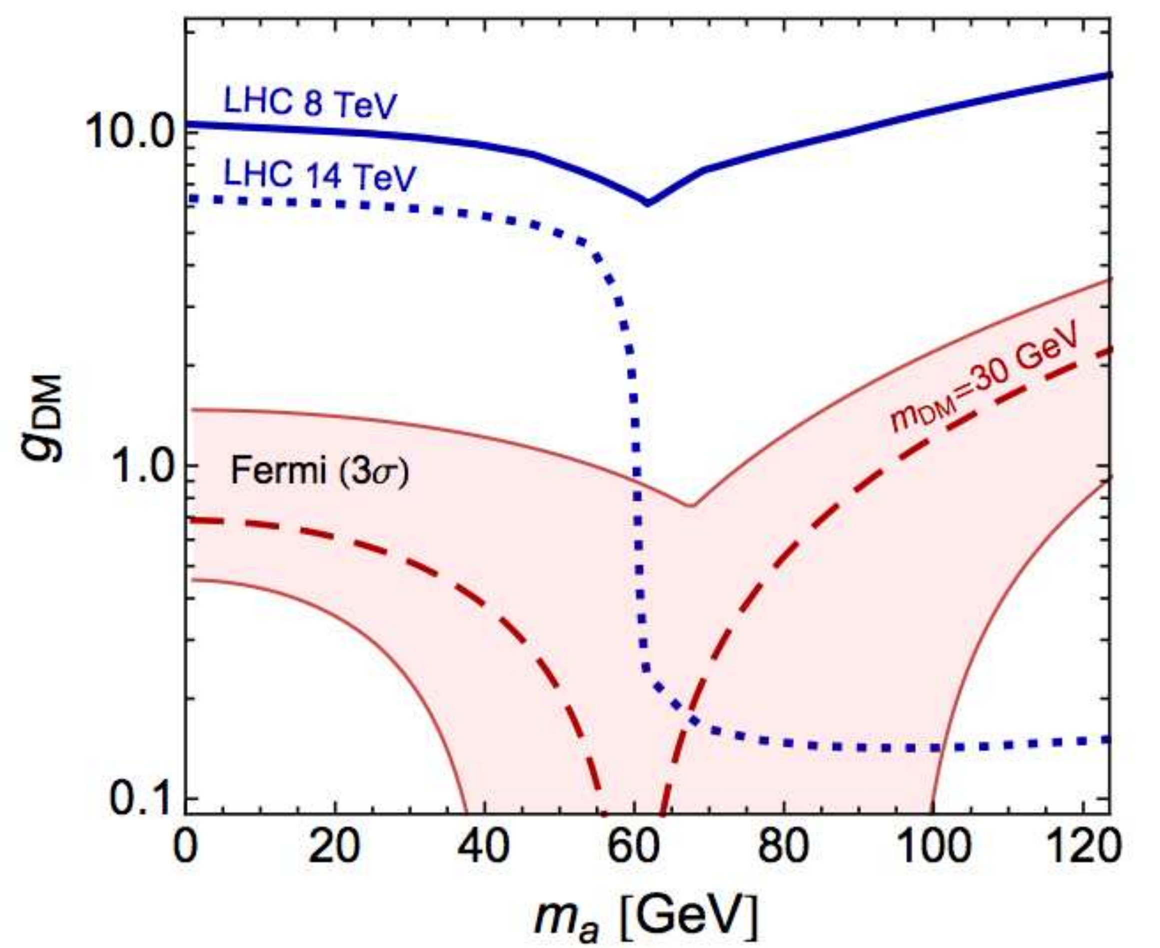
$$\mathscr{L}_{0_A s \frac{1}{2}} = \frac{1}{2}(\partial_\mu A)^2 - \frac{1}{2} m_A^2 A^2 + \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi - i g_\chi A \bar{\chi}\gamma^5 \chi - i g_{\rm SM} A \sum_f \frac{y_f}{\sqrt{2}} \bar{f}\gamma^5 f$$

Galactic Centre Excess — Bohm et al, 1401.6458; Berlin et al, 1404.0022;
Constraints from flavour physics — Dolan et al, 1412.5174

Pseudoscalar portal

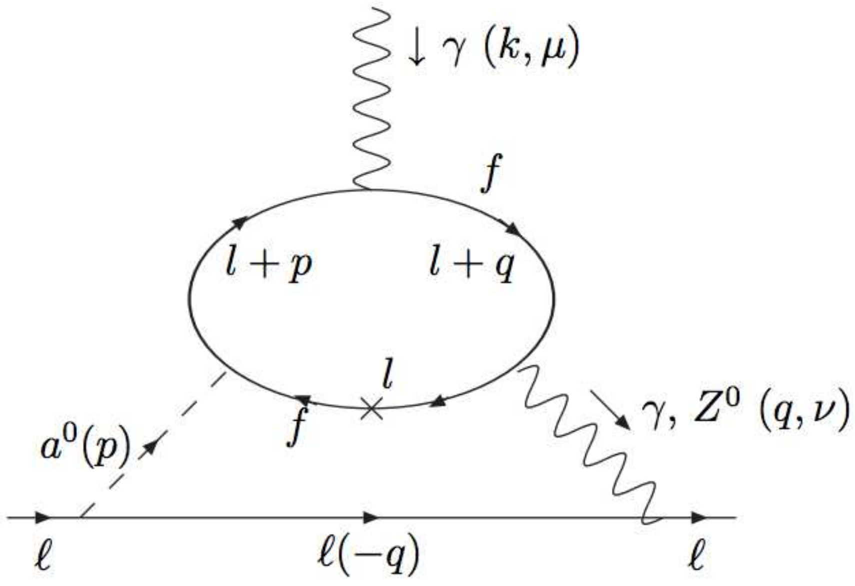
- Fits the 2-5 GeV gamma-ray excess at GC





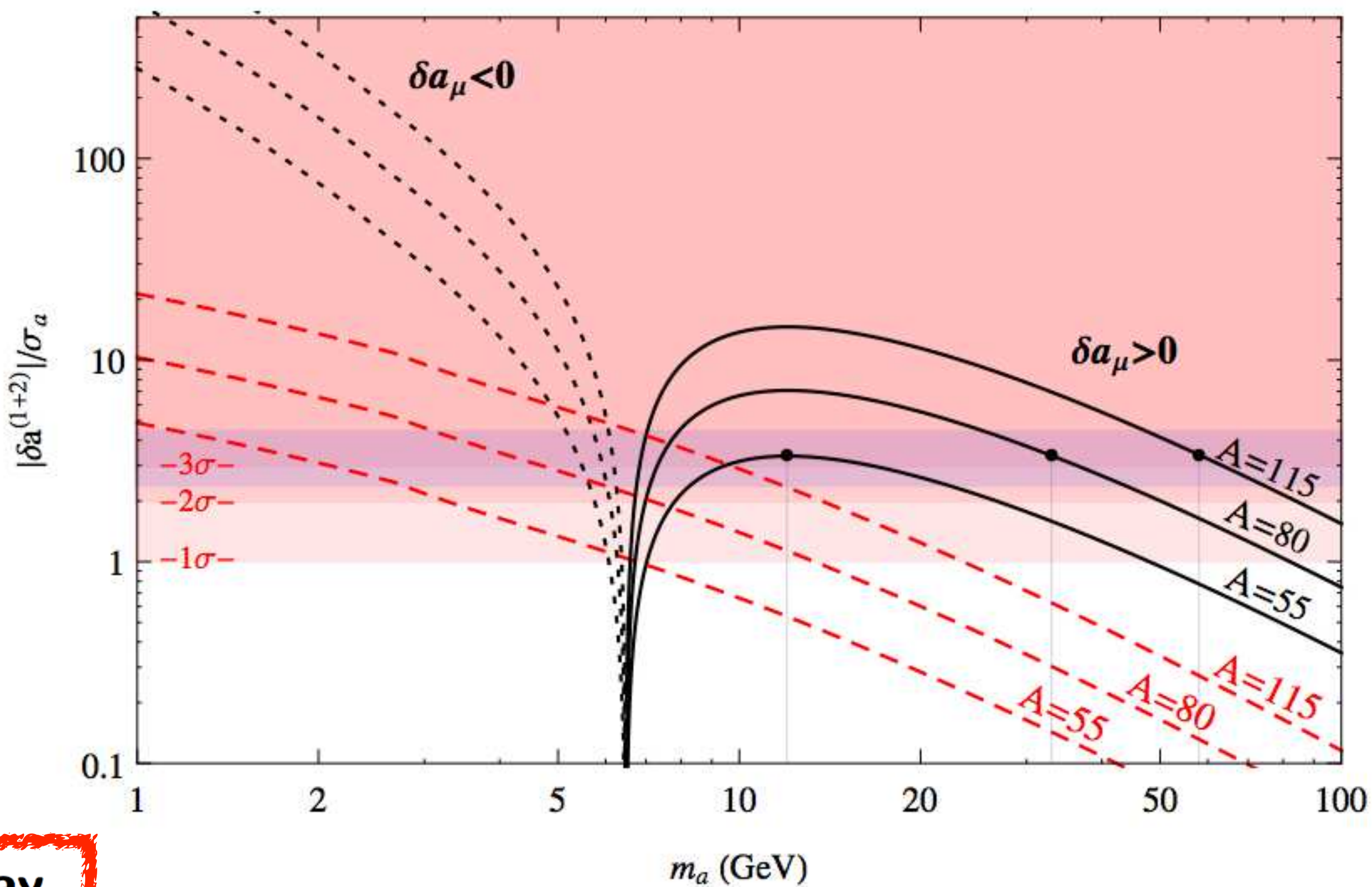
Bohm et al, 1401.6458

Pseudoscalar portal & muon g-2



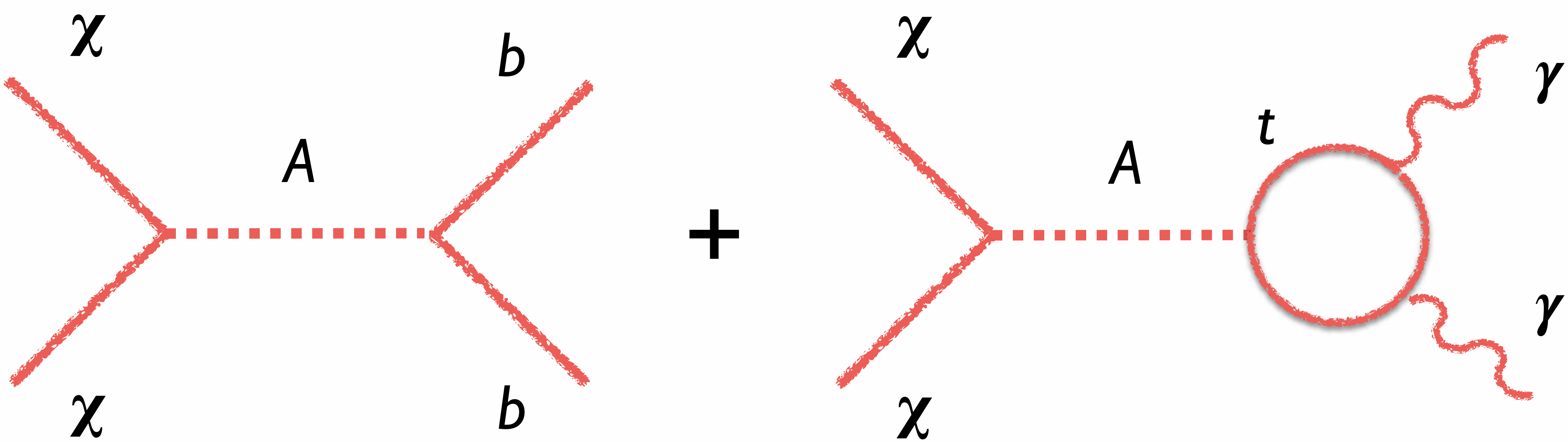
[Chang et al, hep-ph/0009292]

‘Leptophilic’ Coy DM,
Hektor & Marzola, arXiv:1403.3401



Muon g − 2 and Galactic Centre γ-ray excess in a scalar extension of the 2HDM type-X
arXiv:1507.05096
Andi Hektor,[a,1] Kristjan Kannike[a] and Luca Marzola[a,b]

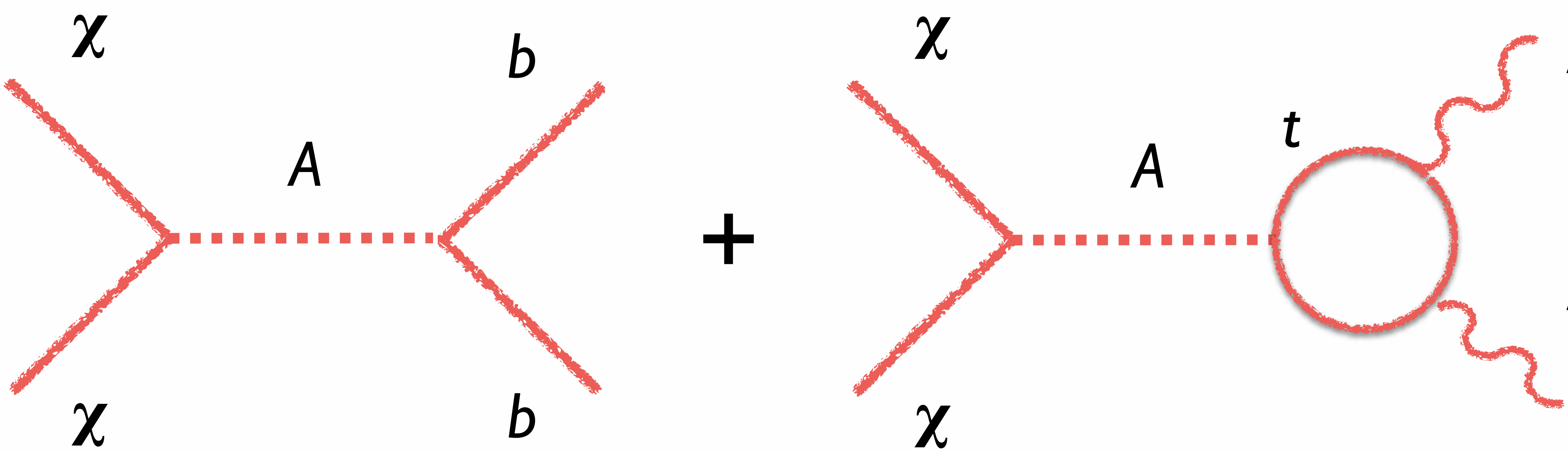
Pseudoscalar portal & γ-ray line



$$m_\chi < m_t$$

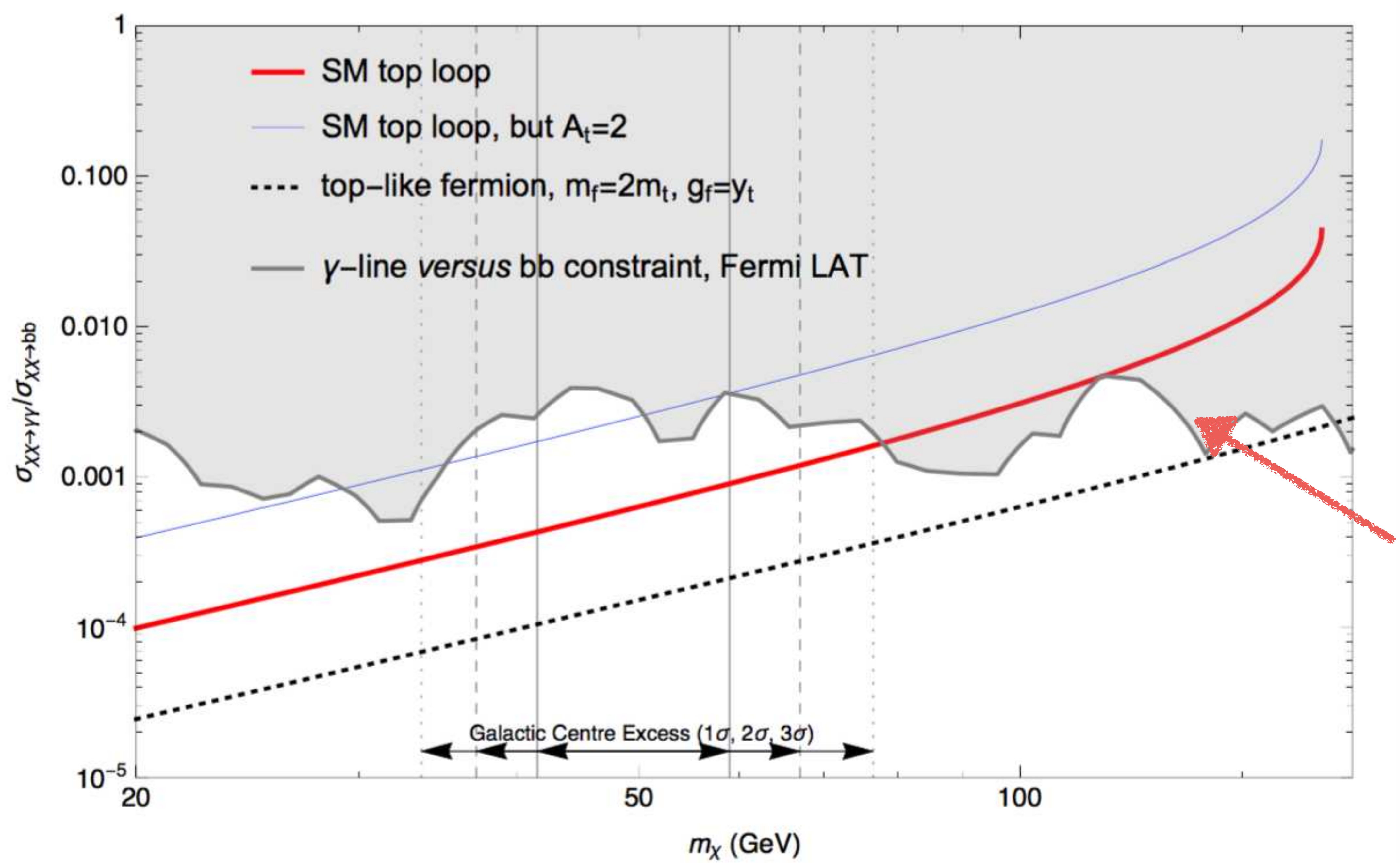
$$\mathcal{L}_{0_A s_{\frac{1}{2}}} = \frac{1}{2}(\partial_\mu A)^2 - \frac{1}{2} m_{\mathrm{A}}^2 A^2 + \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi - i g_\chi A \bar{\chi}\gamma^5\chi - i g_{\mathrm{SM}} A \sum_f \frac{y_f}{\sqrt{2}} \bar{f}\gamma^5 f$$

Pseudoscalar portal & γ-ray line



- Loop suppression, ~10^{-2}…10^{-3}
- Sensitivity of line/broader distribution search, ~10^{2}

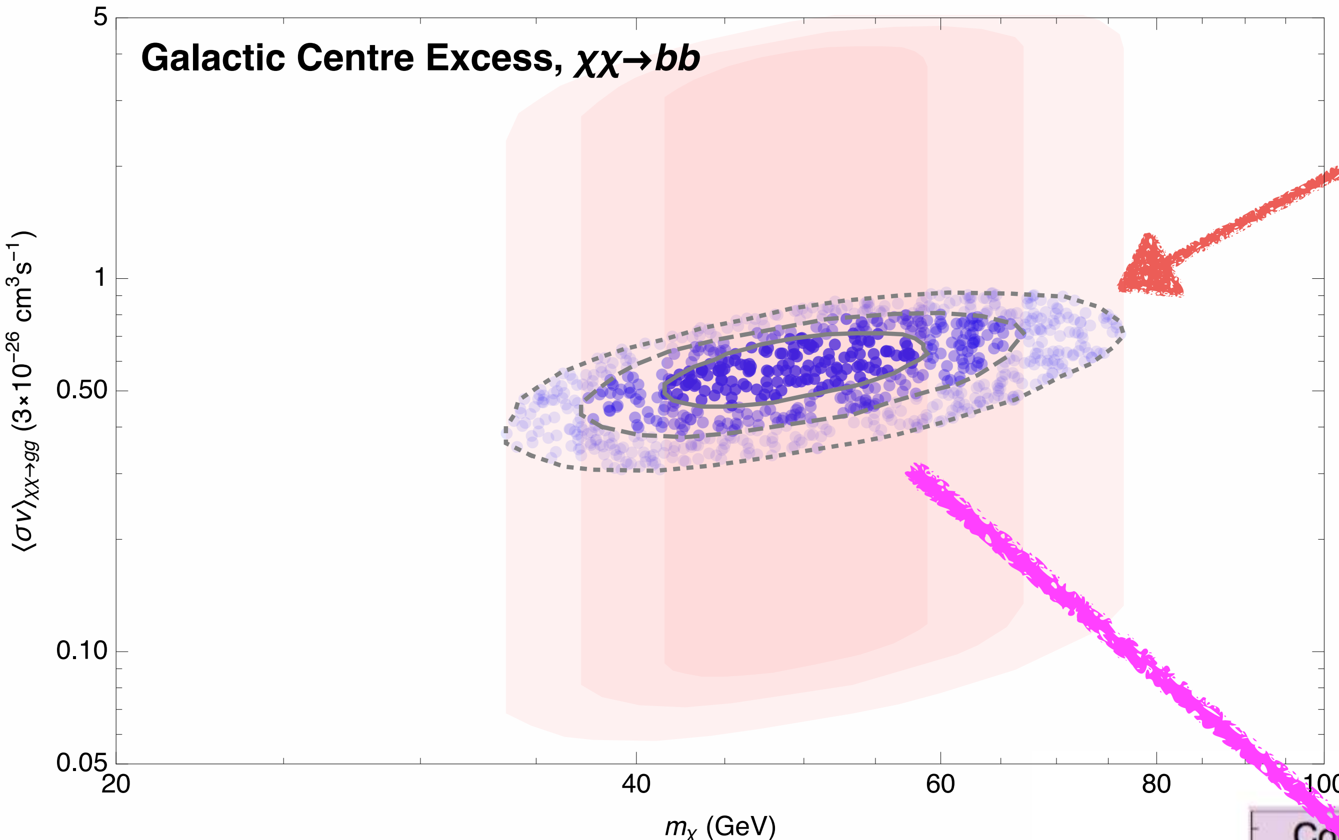
Ratio of the γ-ray line and *bb* signal



Fermi-LAT
1506.00013,
1503.02641

$$R = \frac{(N_c^t \alpha Q_t y_t)^2}{2\pi^2 N_c^b y_b^2} \frac{m_t^2}{m_\chi^2 \sqrt{1 - \frac{m_t^2}{m_\chi^2}}} \left| \arcsin^2\left(\frac{m_\chi}{m_t}\right) \right|^2$$

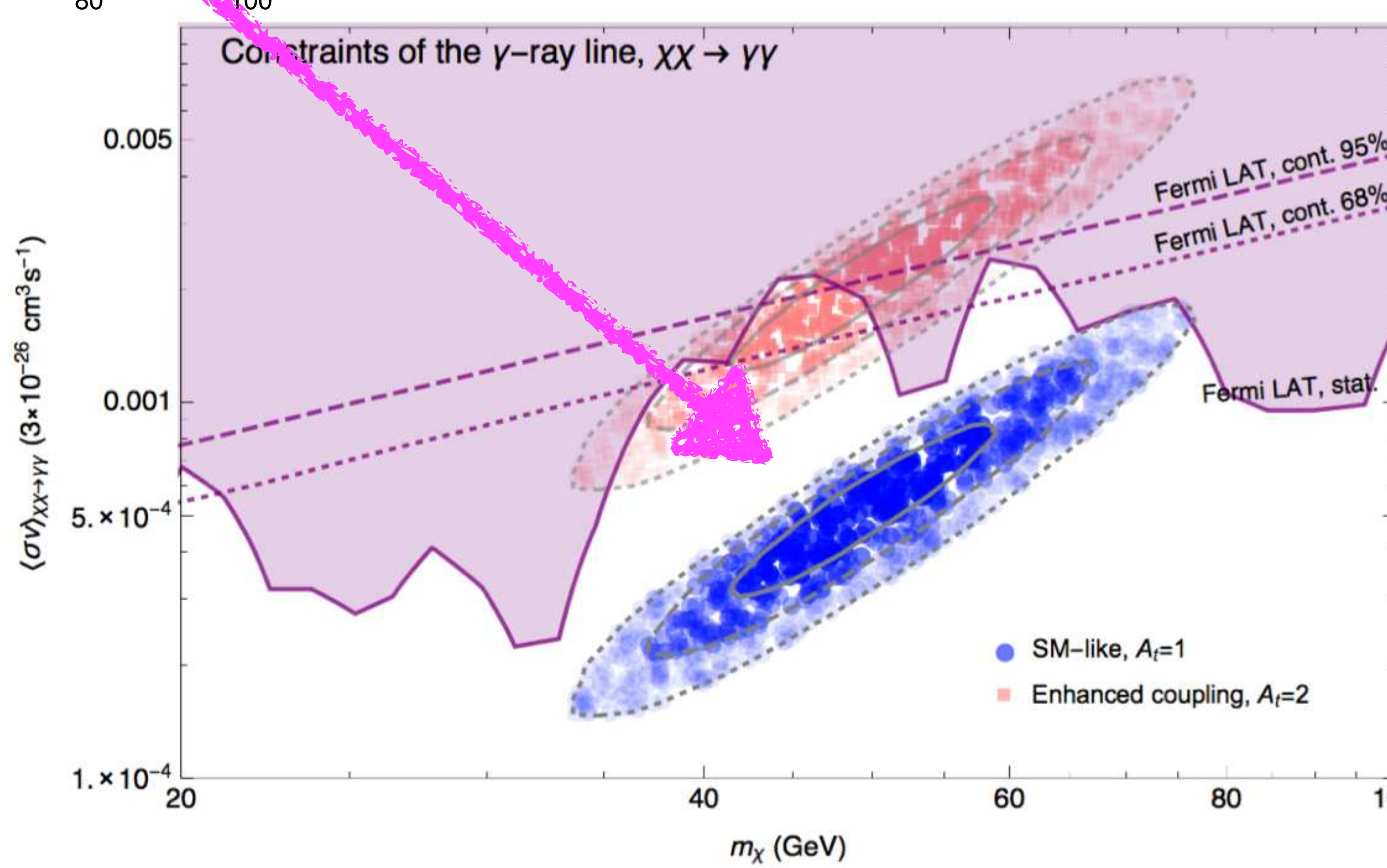
The γ-ray line and the Galactic Centre Excess



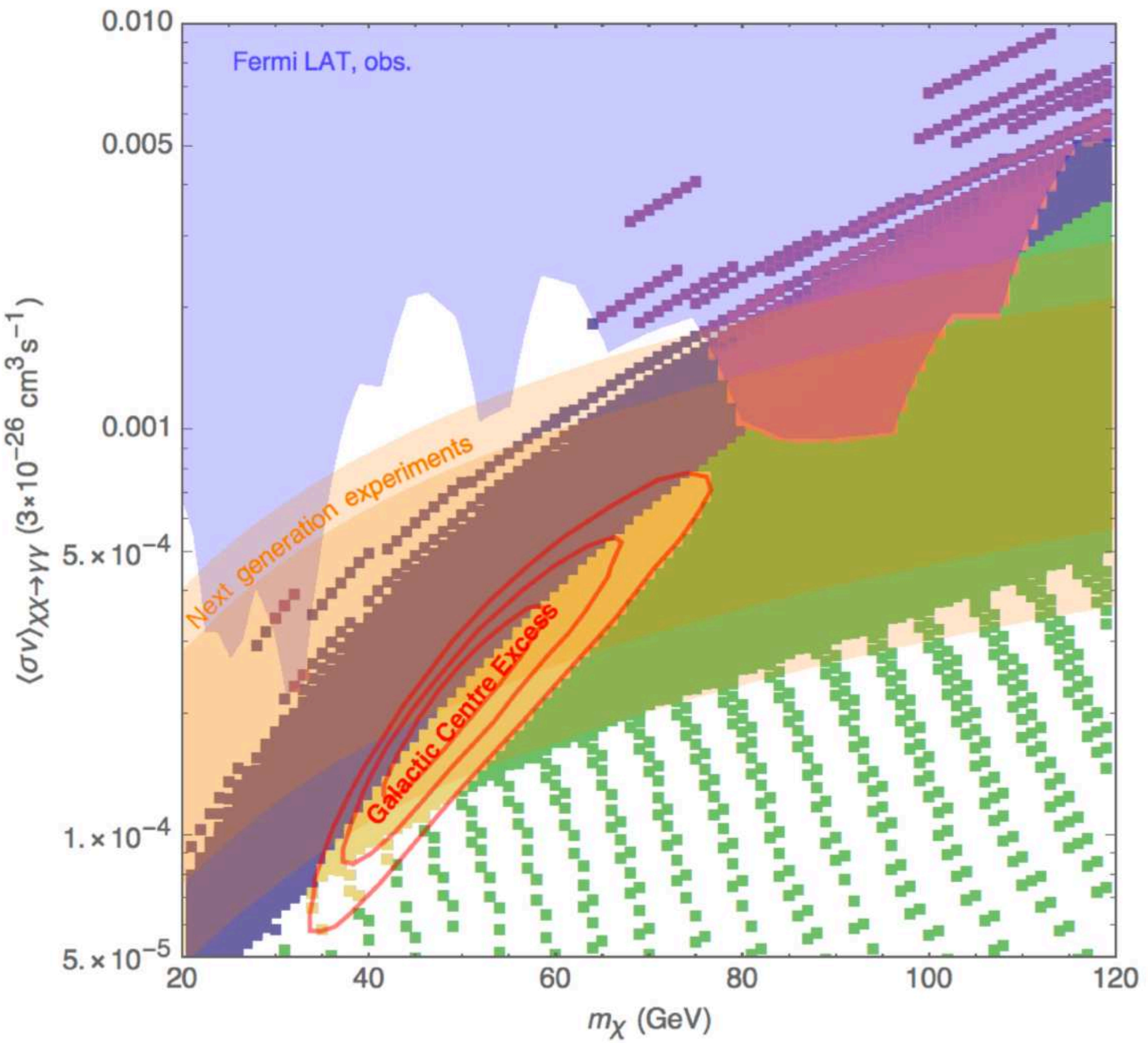
Calore et al,

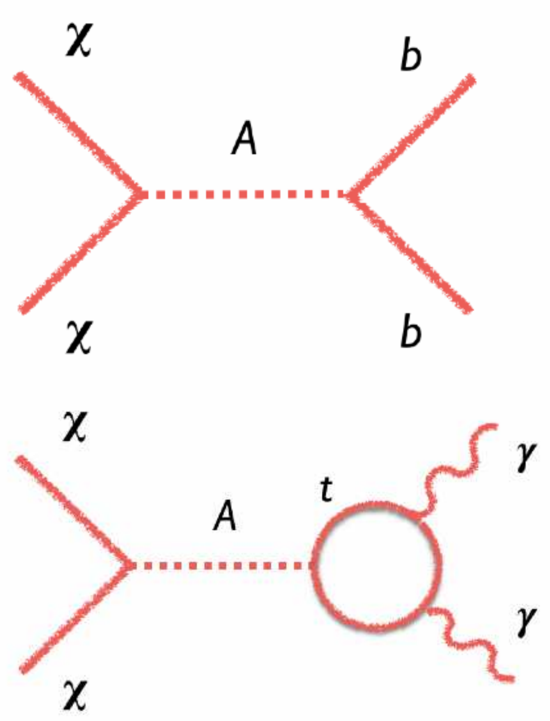
1411.4647

$$R = \frac{(N_c^t \alpha Q_t y_t)^2}{2\pi^2 N_c^b y_b^2} \frac{m_t^2}{m_\chi^2 \sqrt{1 - \frac{m_t^2}{m_\chi^2}}} \left| \arcsin^2 \left(\frac{m_\chi}{m_t} \right) \right|^2$$



The γ-ray line and the Galactic Centre Excess



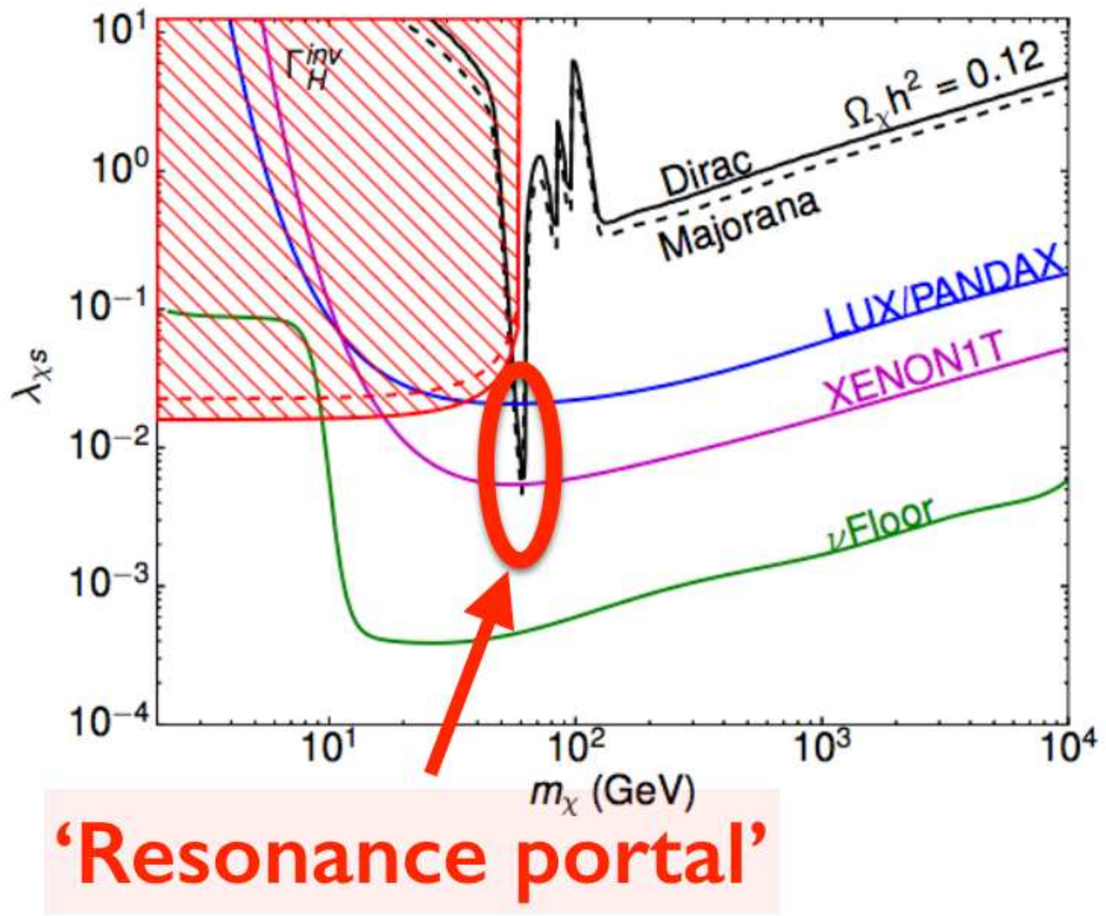


Gamma-ray line constraints on coy dark matter

Andi Hektor, Luca Marzola, and Taavi Tuvi
Phys. Rev. D **95**, 121301(R) – Published 16 June 2017

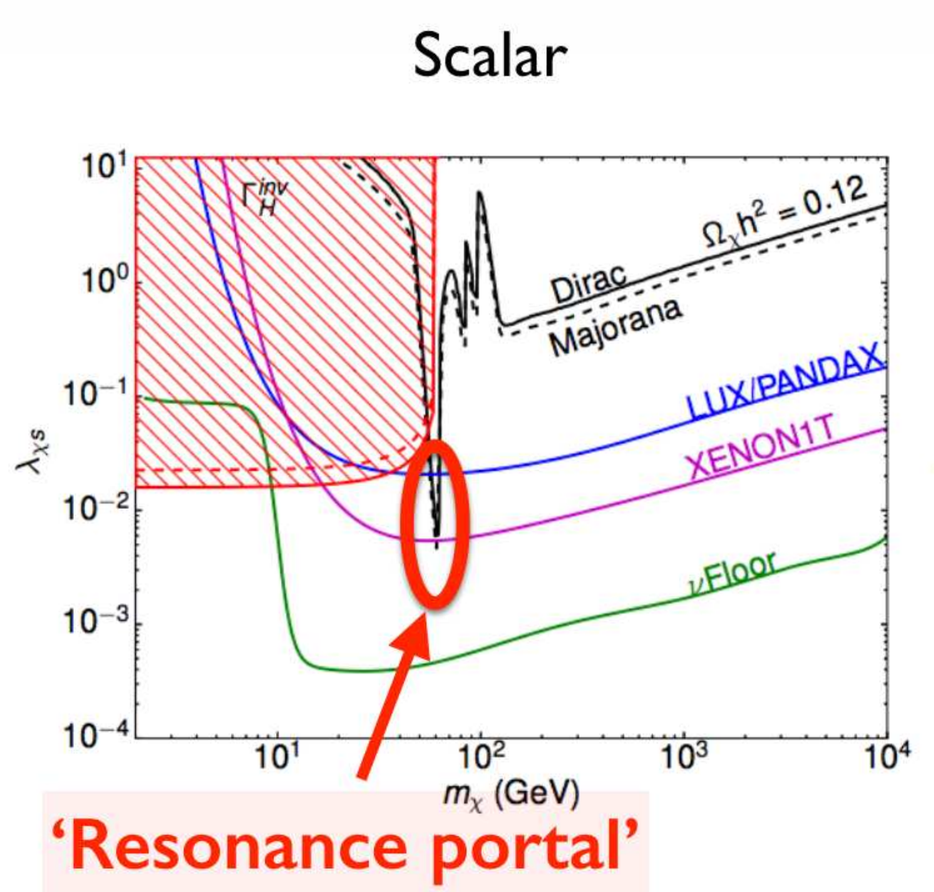
‘Resonance portal’

Scalar



Is ‘Resonance Portal’ very tuned?

1. Yes
2. No. There can be theoretical motivation, e.g. hep-ph/9207234, hep-ph/9704403, hep-ph/9804231



Interesting phenomenology for indirect section!

$$\sigma_{\chi\chi\to S\to ff} = \frac{N_c\,(g_\chi\,A\,y_f)^2}{16\,\pi}\,\frac{m^2\left(1-\frac{m_f{}^2}{m^2}\right)^{3/2}}{(M^2 - s[m^2, v_{rel}])^2 + M^2\,\Gamma^2}\,v_{rel}$$

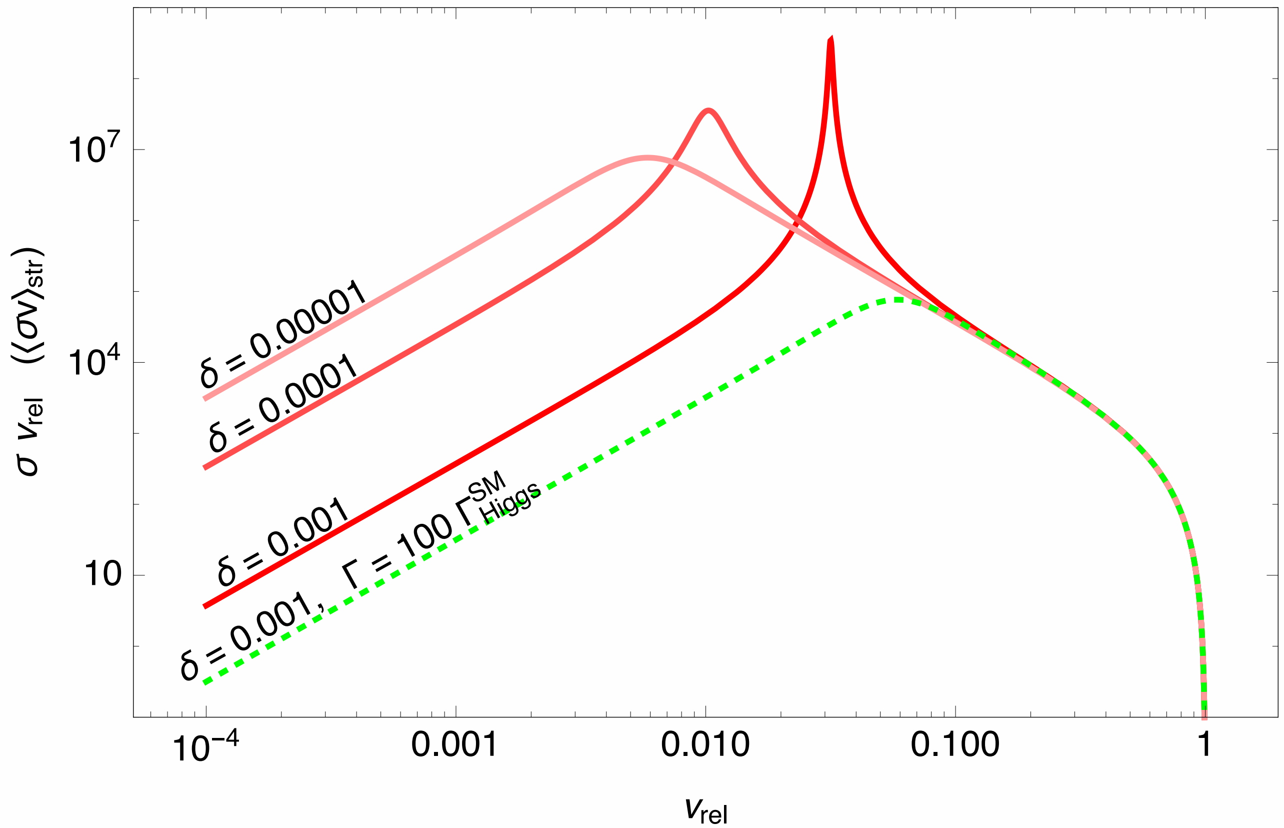
$$\sigma_{\chi\chi\to A\to ff} = \frac{N_c\,(g_\chi\,A\,y_f)^2}{16\,\pi}\,\frac{m^2\left(1-\frac{m_f{}^2}{m^2}\right)^{1/2}}{(M^2 - s[m^2, v_{rel}])^2 + M^2\,\Gamma^2}\,v_{rel}{}^{-1}$$

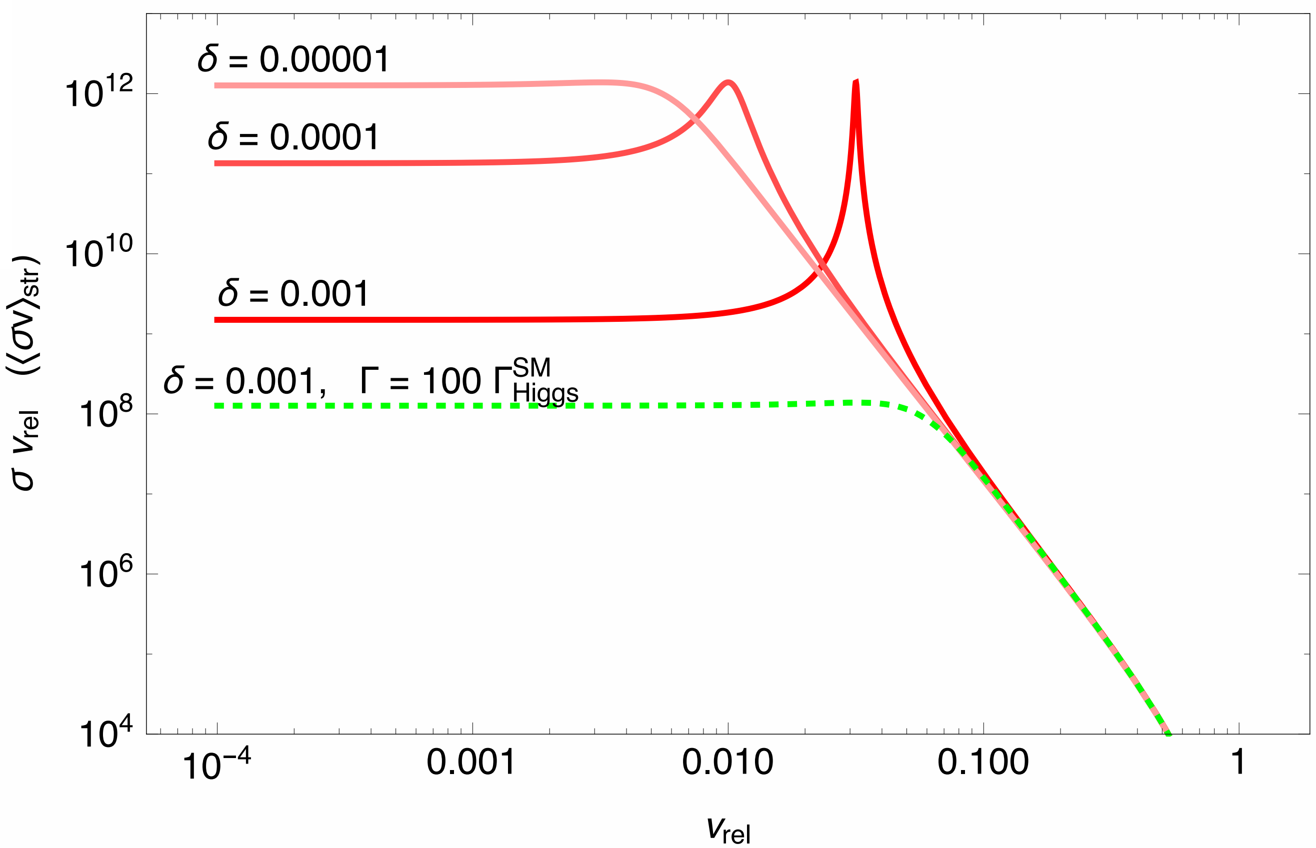
$$m^2 = \frac{M^2}{4\,(1+\delta)}, \quad s[m^2, v_{rel}] = \frac{4\,m^2}{1 - v_{rel}{}^2}$$

$$M = m_{higgs}, \;\; g_\chi = 1$$

$$A = 1, \;\; y_f = 1$$

$$\Gamma = \Gamma_{higgs}$$





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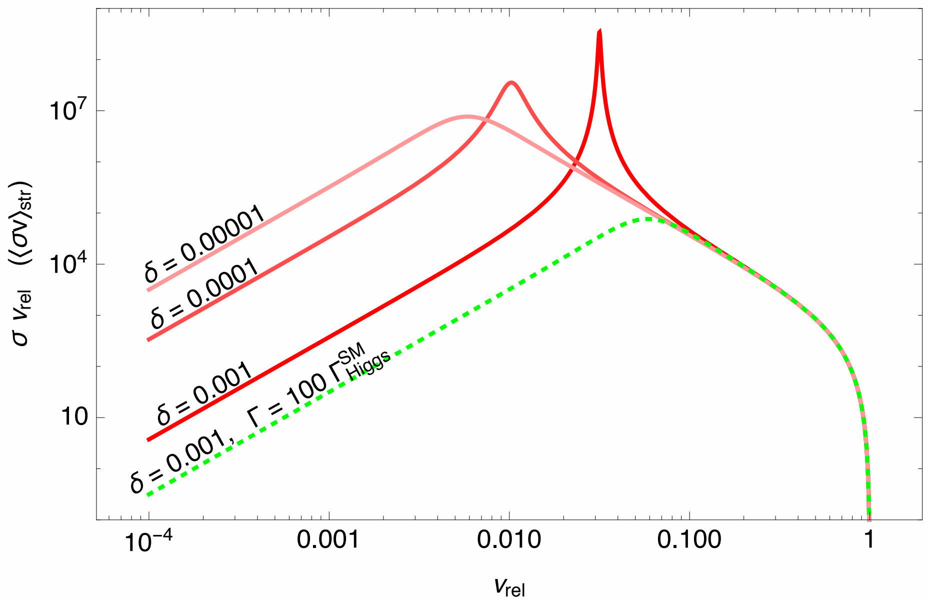
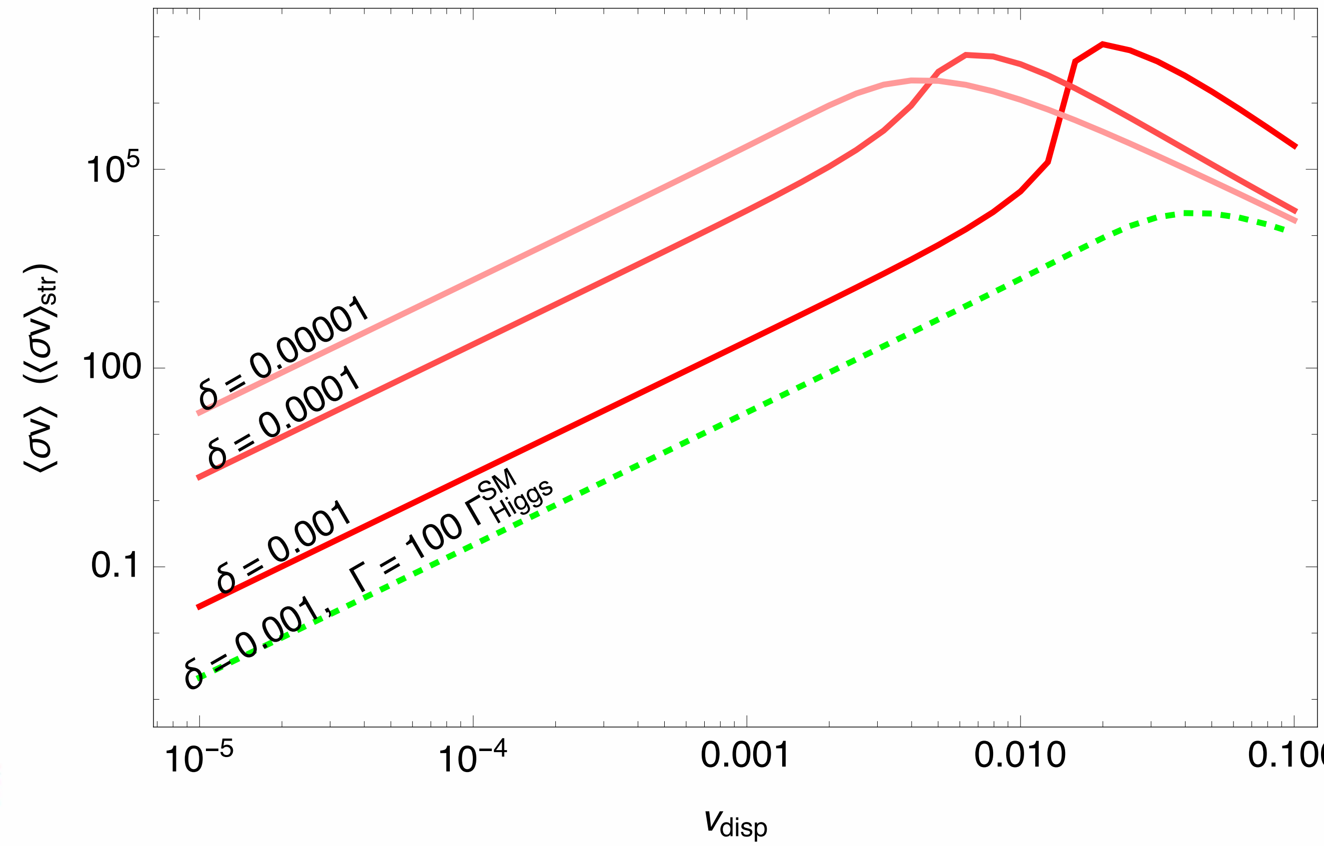
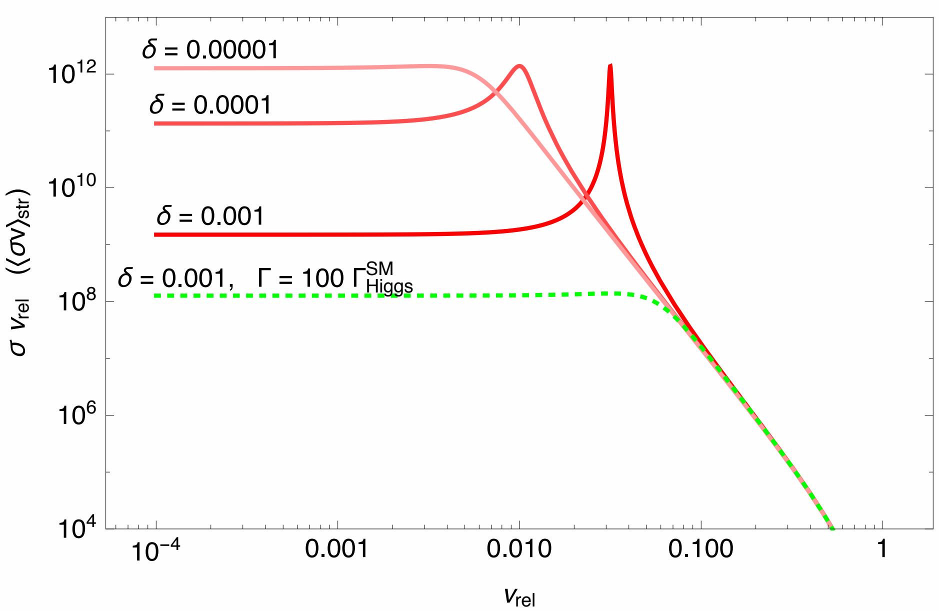
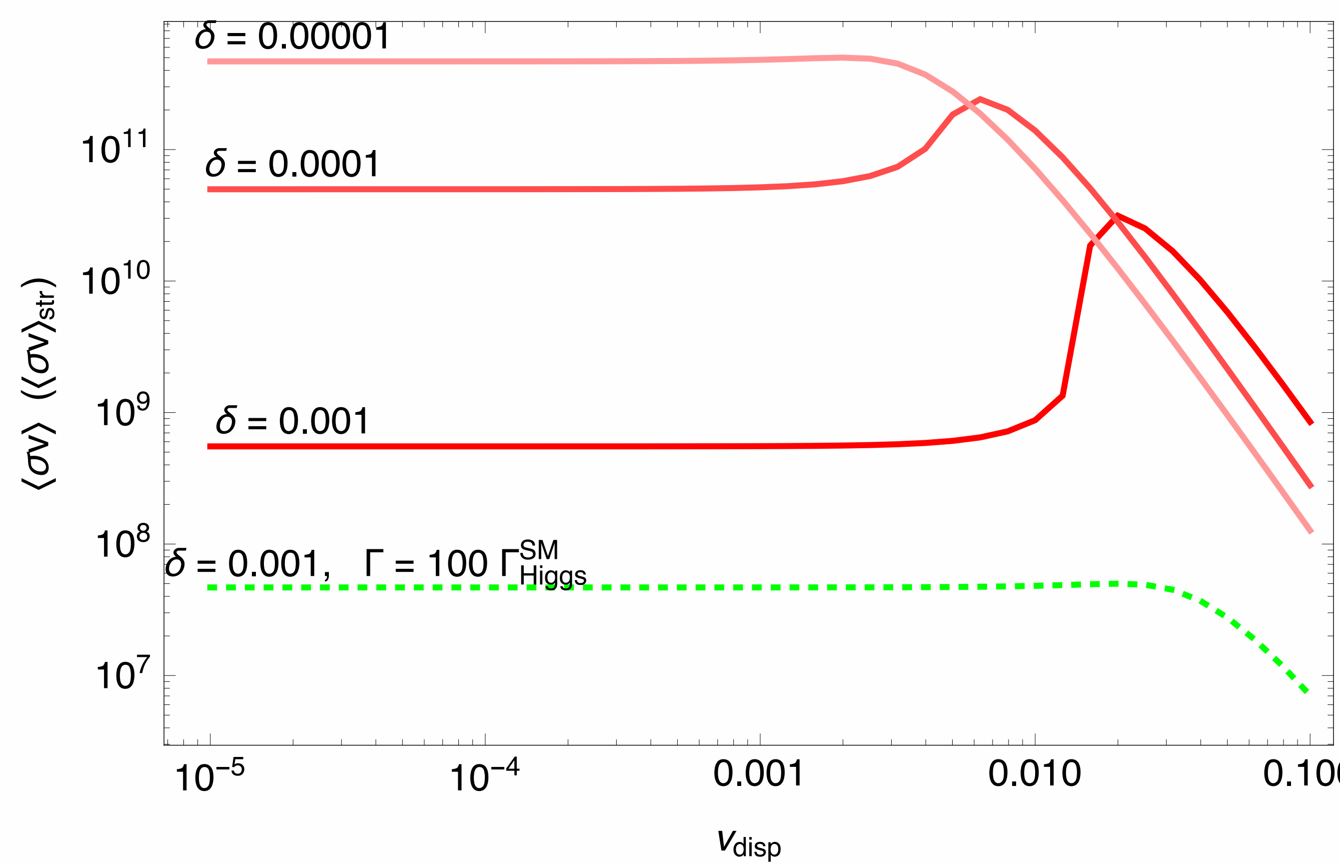




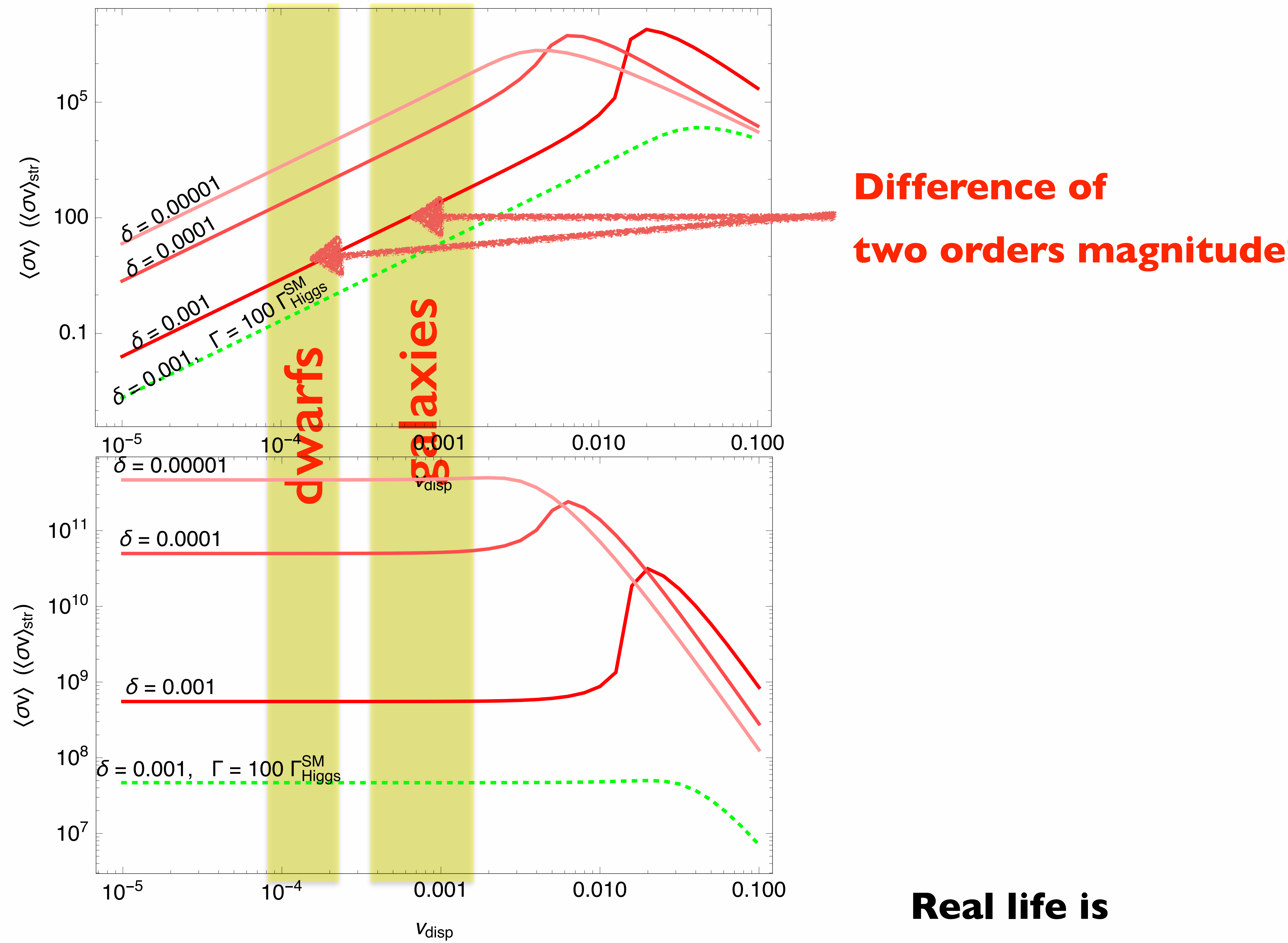




Interesting phenomenology for indirect section!

scalar

pseudo-scalar



Real life is more complicated!

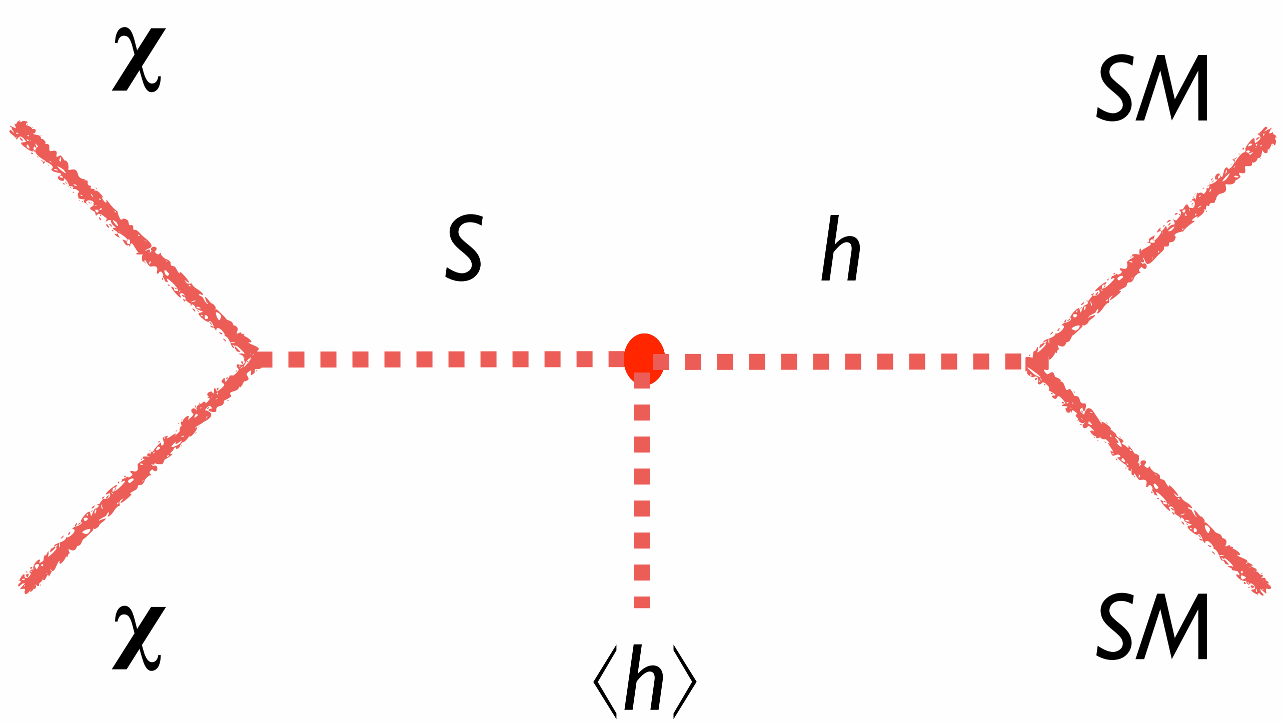
‘Thermal portal’

Thermal effects on the DM production

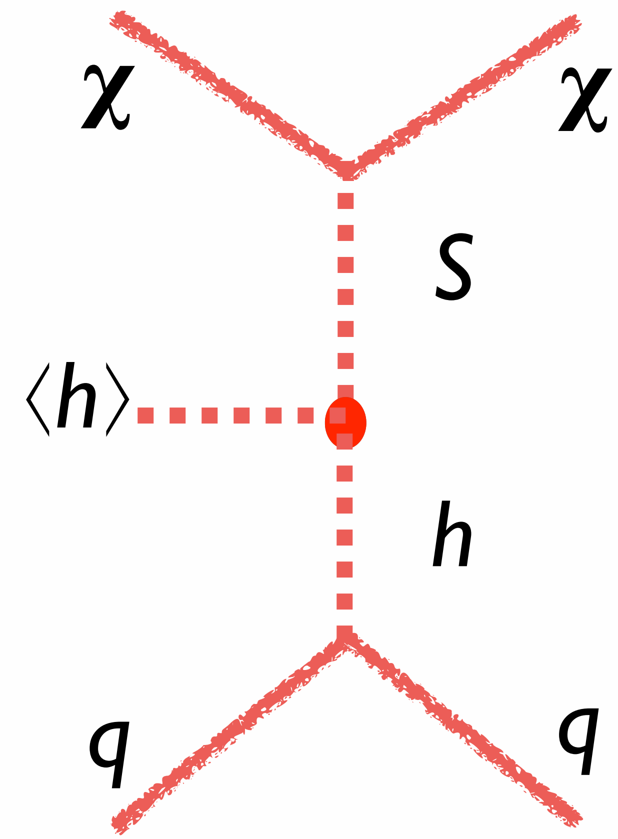
Recent interest in thermal effects on dark matter:
'forbidden' channels, D'Agnolo & Ruderman 1505.07107
cannibal DM, Pappadopulo, Ruderman & Trevirsan 1602.04219
VEV flip-flop Baker & Kopp 1608.07578

Thermal effects of the portal?

Higgs-scalar mixing, the freeze-out diagram



Direct detection



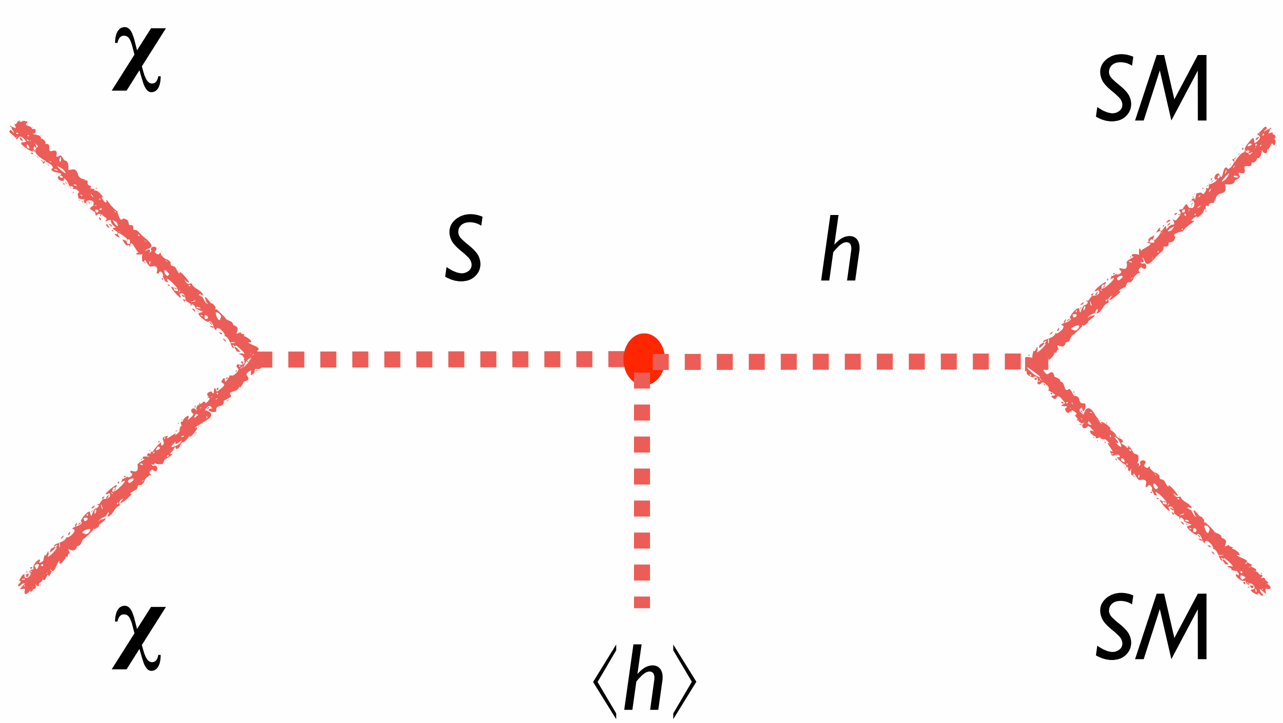
Typical assumptions at the freeze-out:

$\langle h \rangle \simeq$ *const(vacuum)* > 0

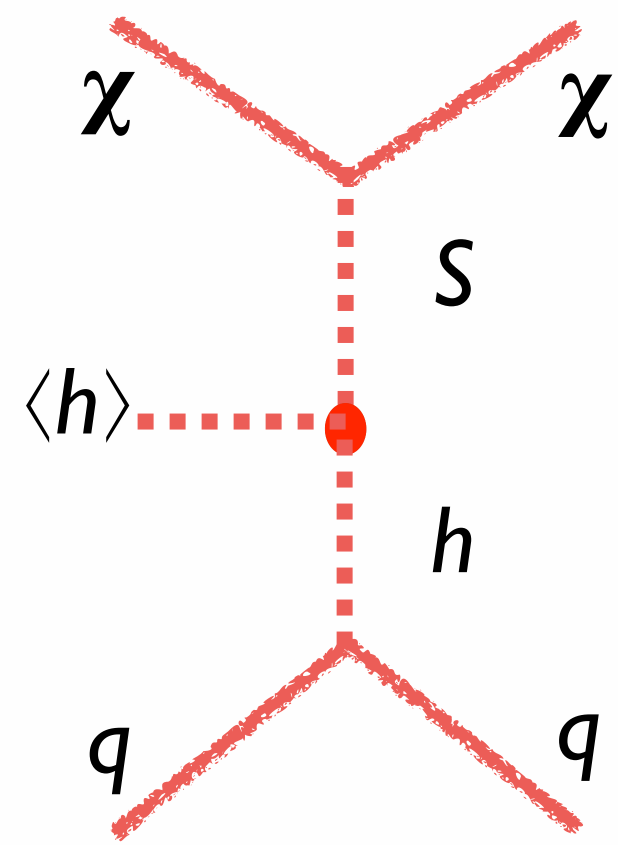
$\langle S \rangle \simeq$ *const(vacuum)* > 0 *or* $=0$

Thermal effects of the portal?

Higgs-scalar mixing,
the freeze-out diagram



Direct detection



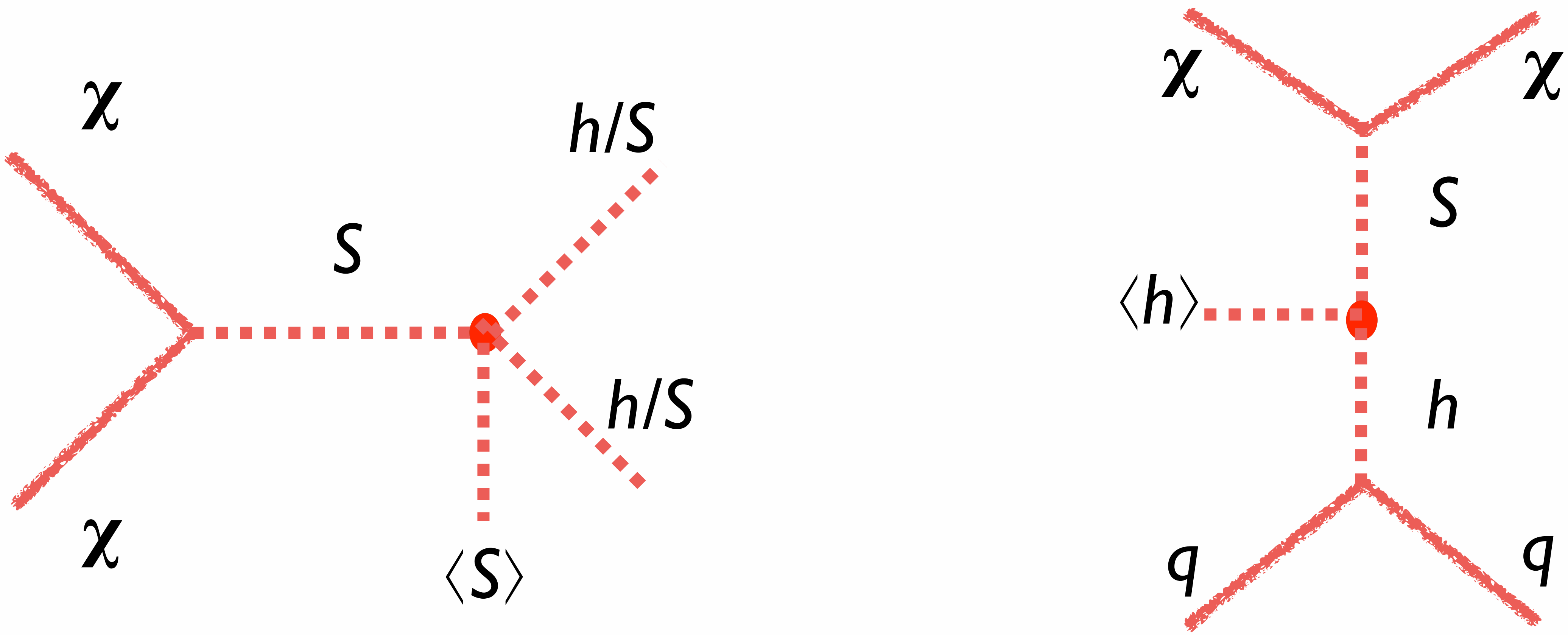
Typical assumptions at the freeze-out:
$\langle h \rangle \simeq$ const(vacuum) > 0
$\langle S \rangle \simeq$ const(vacuum) > 0

But $\langle h \rangle$ and $\langle S \rangle$ are not constants,
they are the functions of temperature!

What is '*thermal portal*'?

What about this?

But the direct detection remains same!

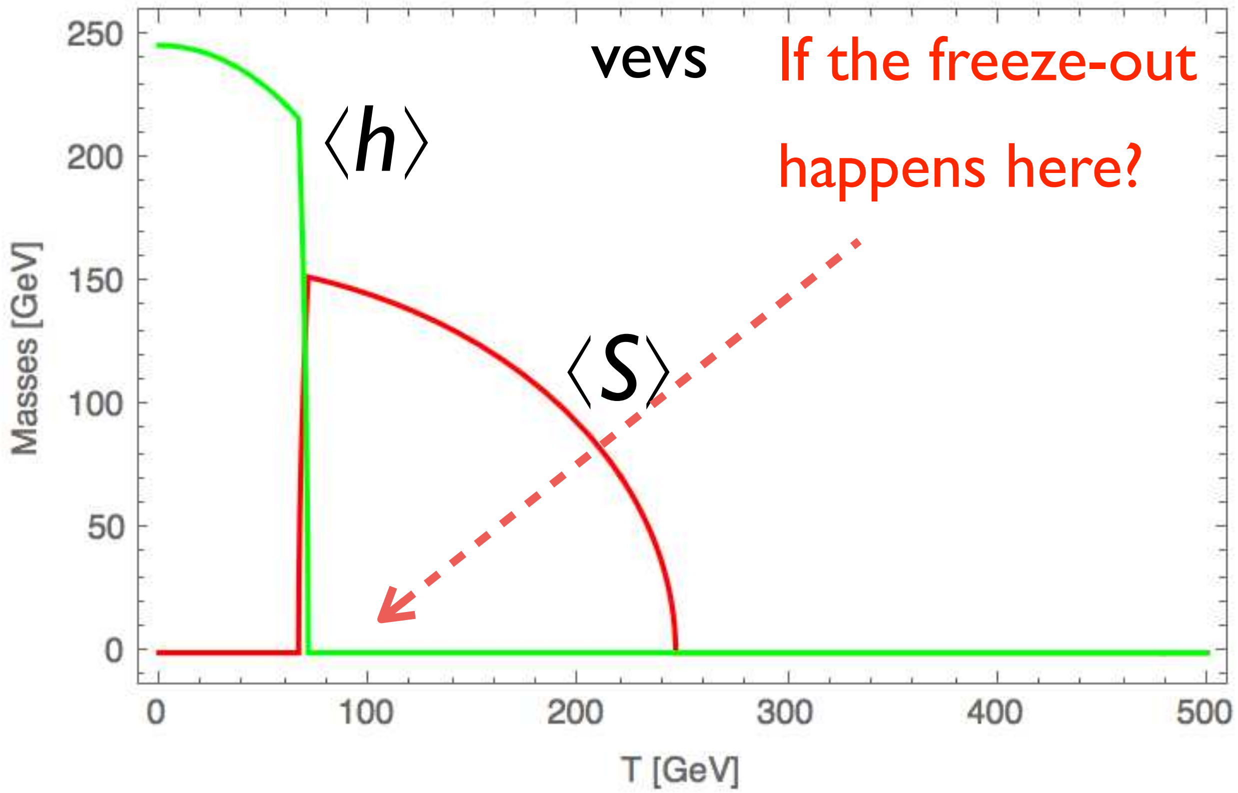


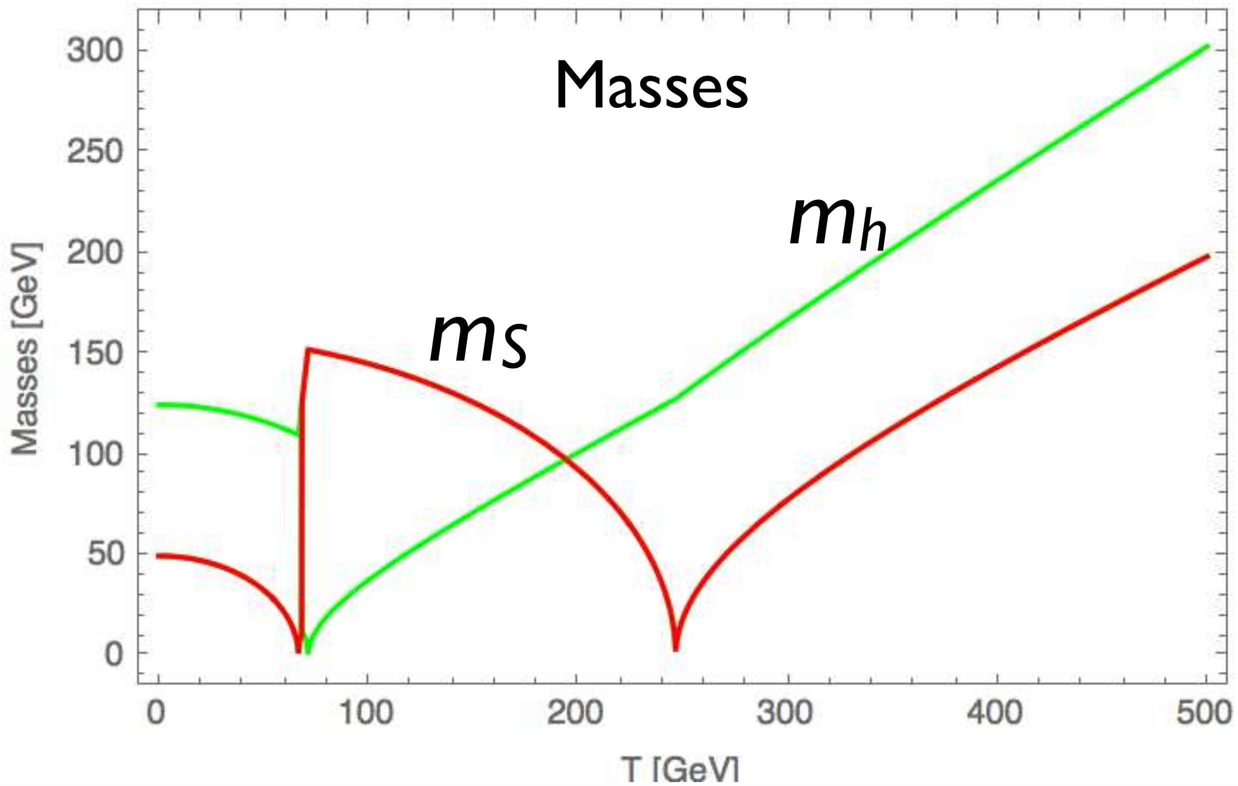
Due to thermal corrections ($T >\sim m_h, m_S$)

NB! $\langle h \rangle_T =\sim 0$, $\langle S \rangle_T > 0$

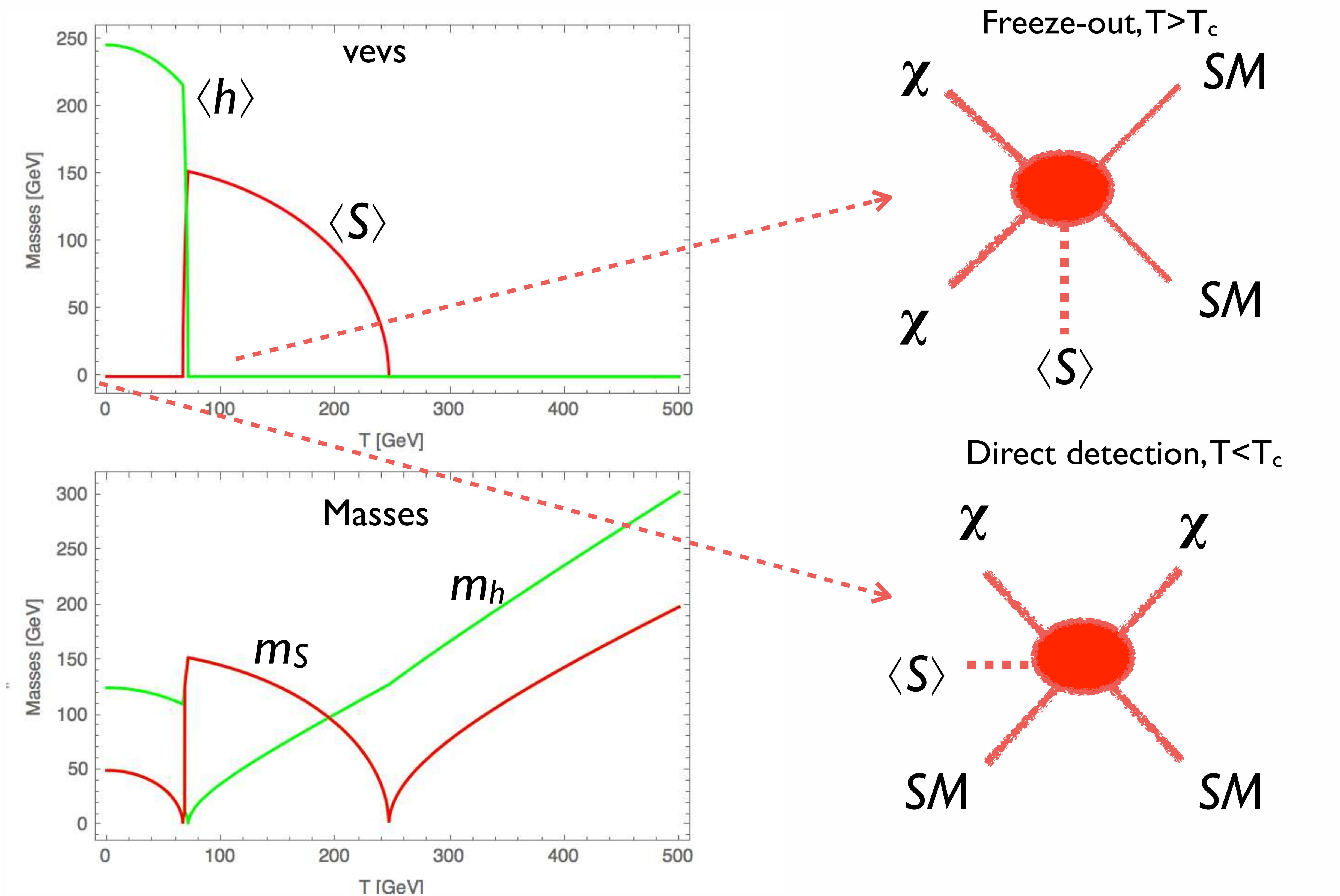
(but in vacuum: $\langle h \rangle_{T=0} > 0$, $\langle S \rangle_{T=0} = 0$)

Thermal running of the masses and vevs





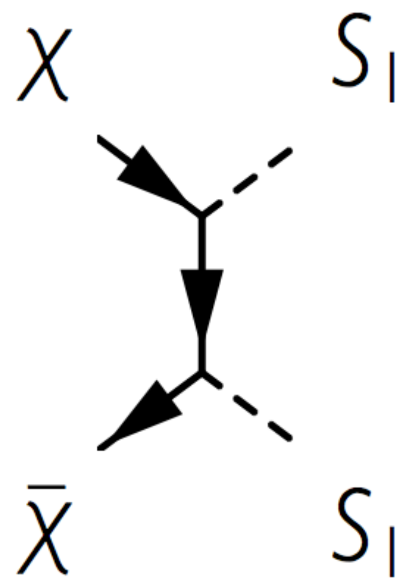
Thermal running of the masses and vevs



Let’s build a ‘thermal portal’ model

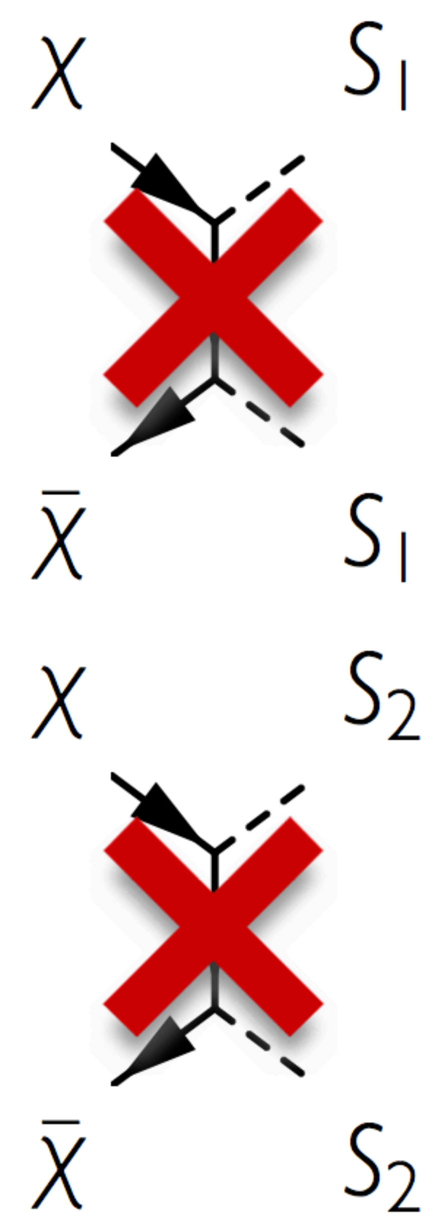
Considerations

- Dark matter itself cannot be thermal due to its freeze-out: $m_{\rm DM} \gg T$
- Fermion dark matter with a thermal scalar
- Only one scalar does not work: *t*-channel annihilation works in any phase



Considerations

- Dark matter itself cannot be thermal: it has to freeze out: $m_{\mathrm{DM}} \gg T$
- Fermion dark matter with a thermalised scalar singlet
- Only one scalar does not work: t-channel annihilation works in any phase
- Must have two scalars: light S_1 with $y_1 = 0$ and heavy S_2 ($m_2 > m_\chi$)



The minimal model

$$\mathcal{L} \supset \bar{\chi}\not\partial\chi + |D_\mu H|^2 + \frac{1}{2}(\partial_\mu S_1)^2 + \frac{1}{2}(\partial_\mu S_2)^2 - m_\chi\bar{\chi}\chi - y_1 S_1\bar{\chi}\chi - y_2 S_2\bar{\chi}\chi - V,$$

where

$$V = \mu_H^2|H|^2 + \frac{1}{2}\mu_{20}^2 S_1^2 + \frac{1}{2}\mu_{11}^2 S_1 S_2 + \frac{1}{2}\mu_{02}^2 S_2^2 + \lambda_H|H|^4 + \lambda_{H20}|H|^2 S_1^2 + \lambda_{H11}|H|^2 S_1 S_2 + \lambda_{H02}|H|^2 S_2^2 + \lambda_{40}S_1^4 + \lambda_{31}S_1^3 S_2^1 + \lambda_{22}S_1^2 S_2^2 + \lambda_{13}S_1 S_2^3 + \lambda_{04}S_2^4$$

The thermal corrections

Thermal corrections to mass terms are given by

$$\delta m_{ij}^2 \approx \sum_k \frac{g_k}{24} \frac{\partial m_k^2}{\partial \phi_i \partial \phi_j} T^2,$$

where $g_k = n_k$ for bosonic degrees of freedom

The thermal corrections

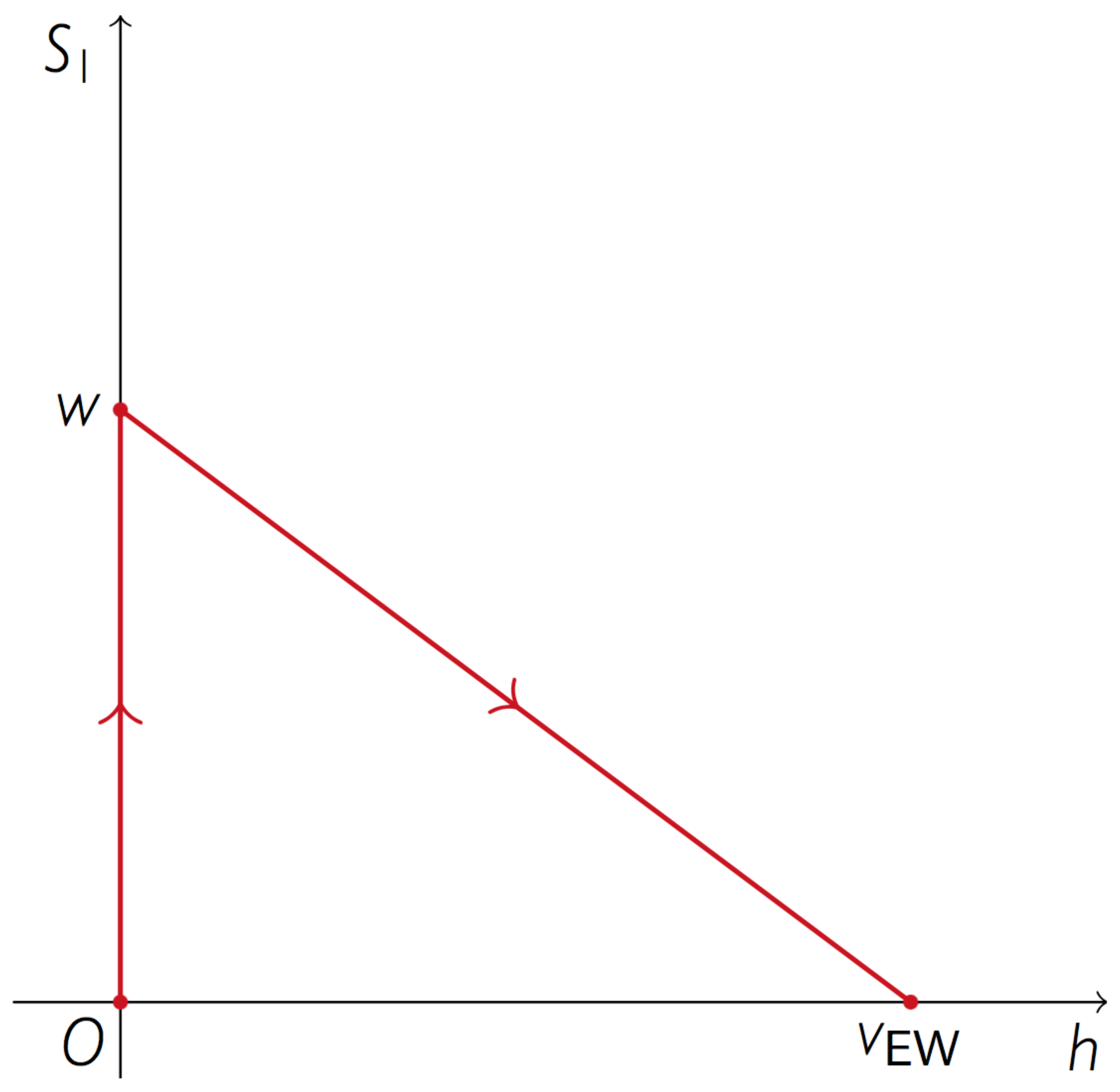
$$\mu_H^2 \to \mu_H^2 + c_H T^2,$$
$$\mu_{20}^2 \to \mu_{20}^2 + c_{20} T^2,$$

where

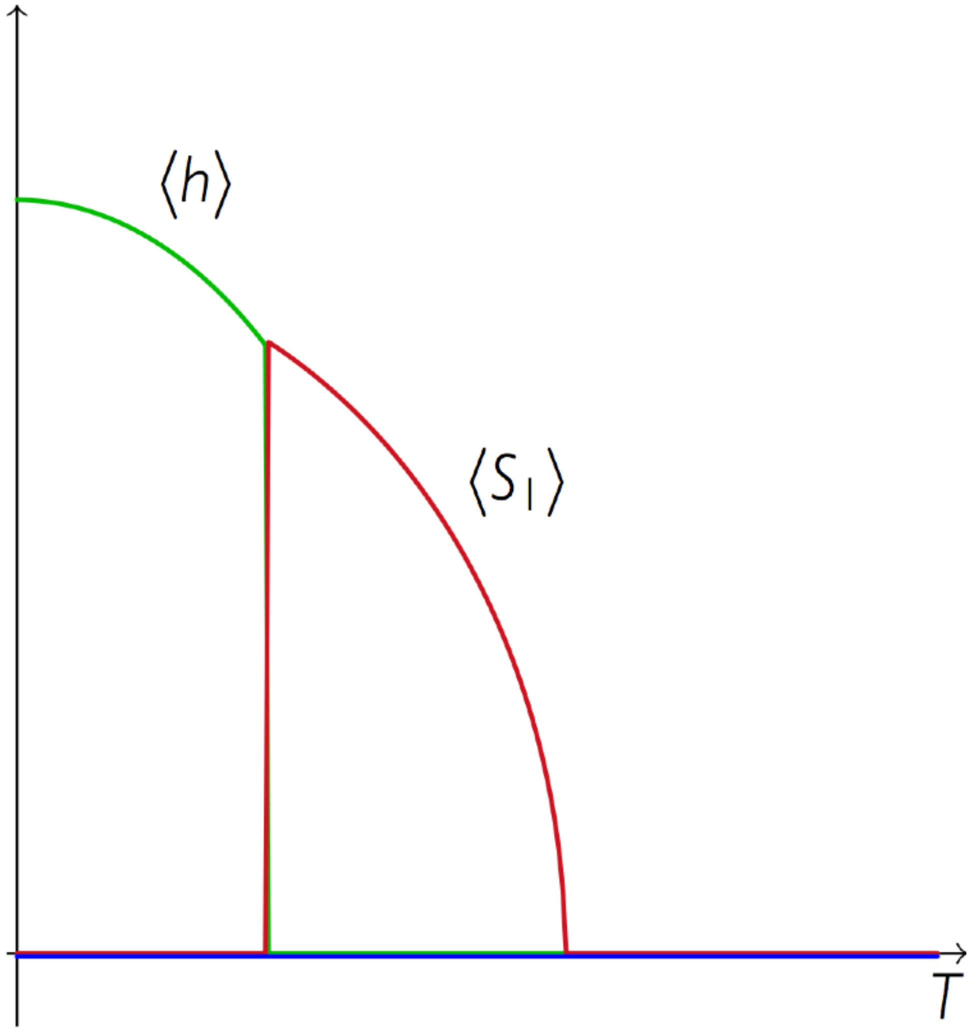
$$c_H = \frac{1}{48}(24\lambda_H + 3g'^2 + 9g^2 + 12y_t^2 + 4\lambda_{H20}),$$
$$c_{20} = \lambda_{40} + \frac{1}{3}\lambda_{H20}$$

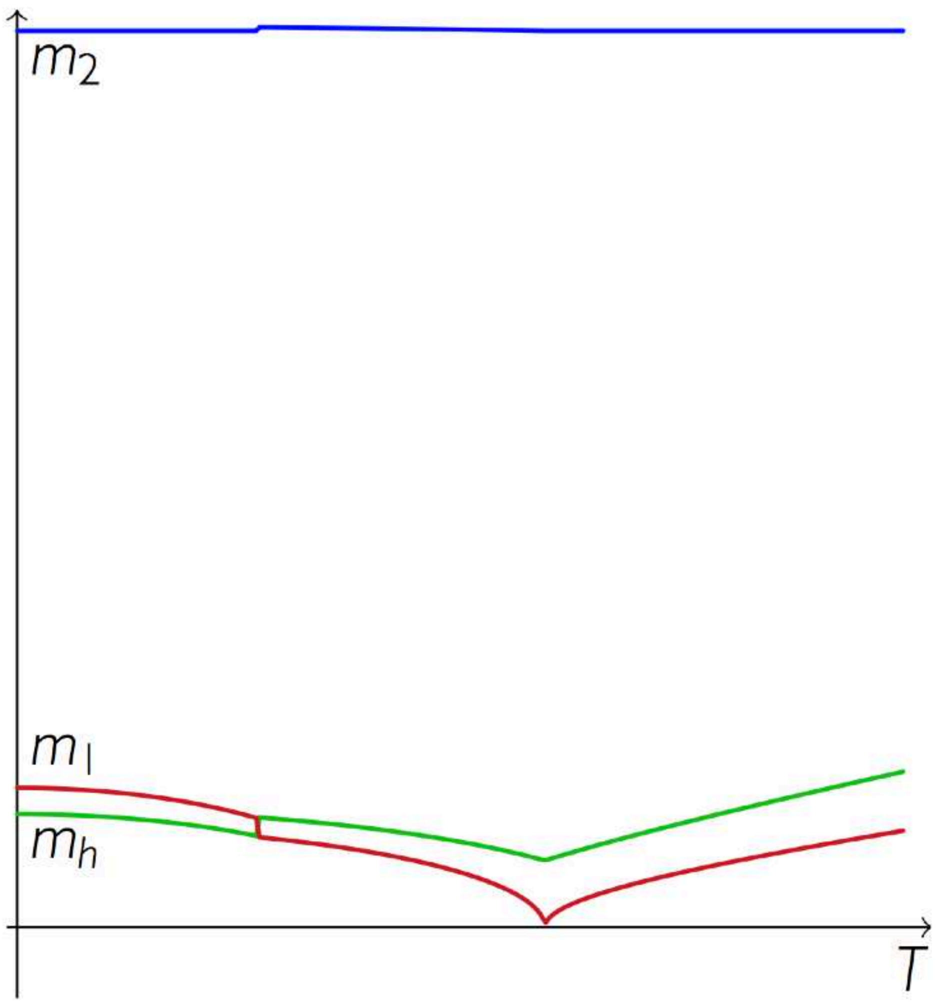
- The contributions to the terms $\mu_{11}^2 S_1 S_2$ and $\frac{1}{2}\mu_{02}^2 S_2^2$ are approximately zero due to the high mass of S_2

Phase transition

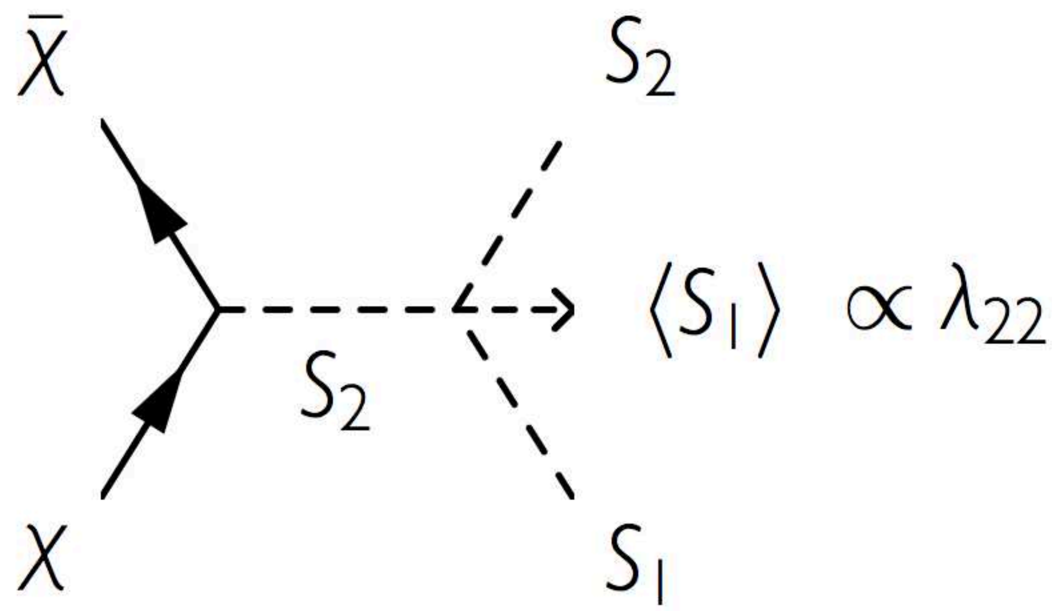


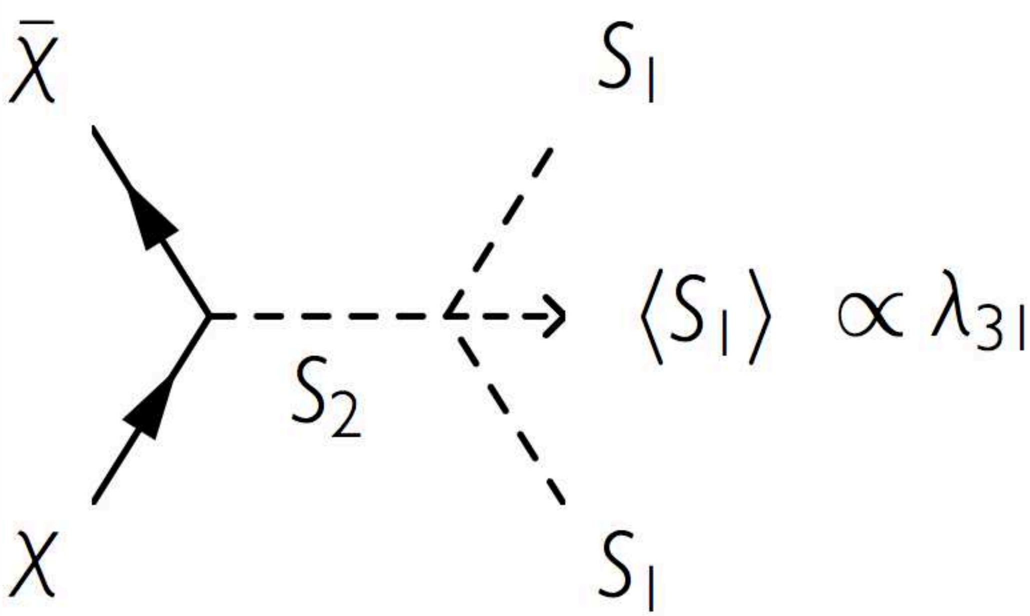
Phase transition

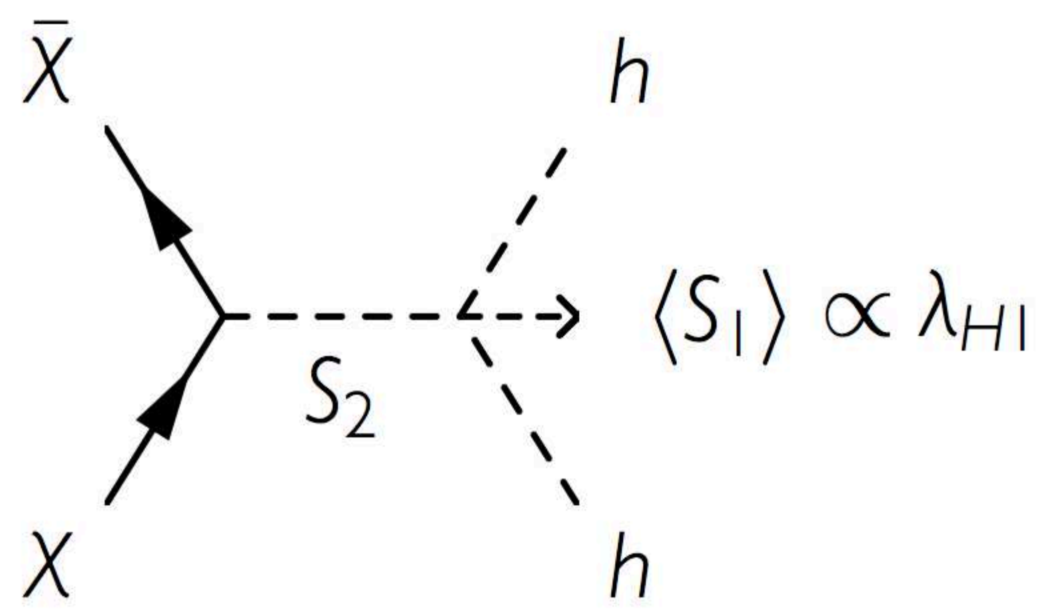




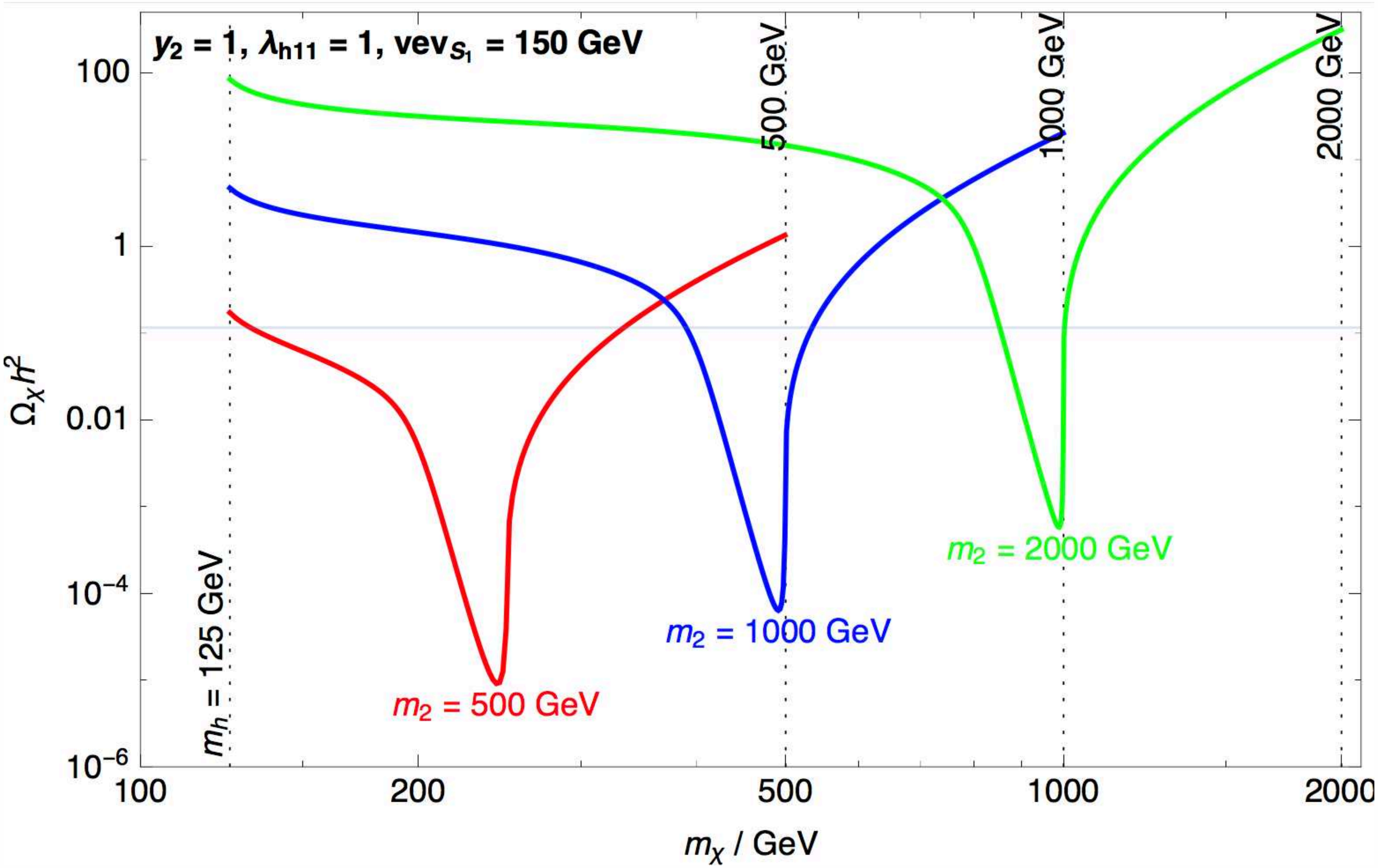
Annihilation channels



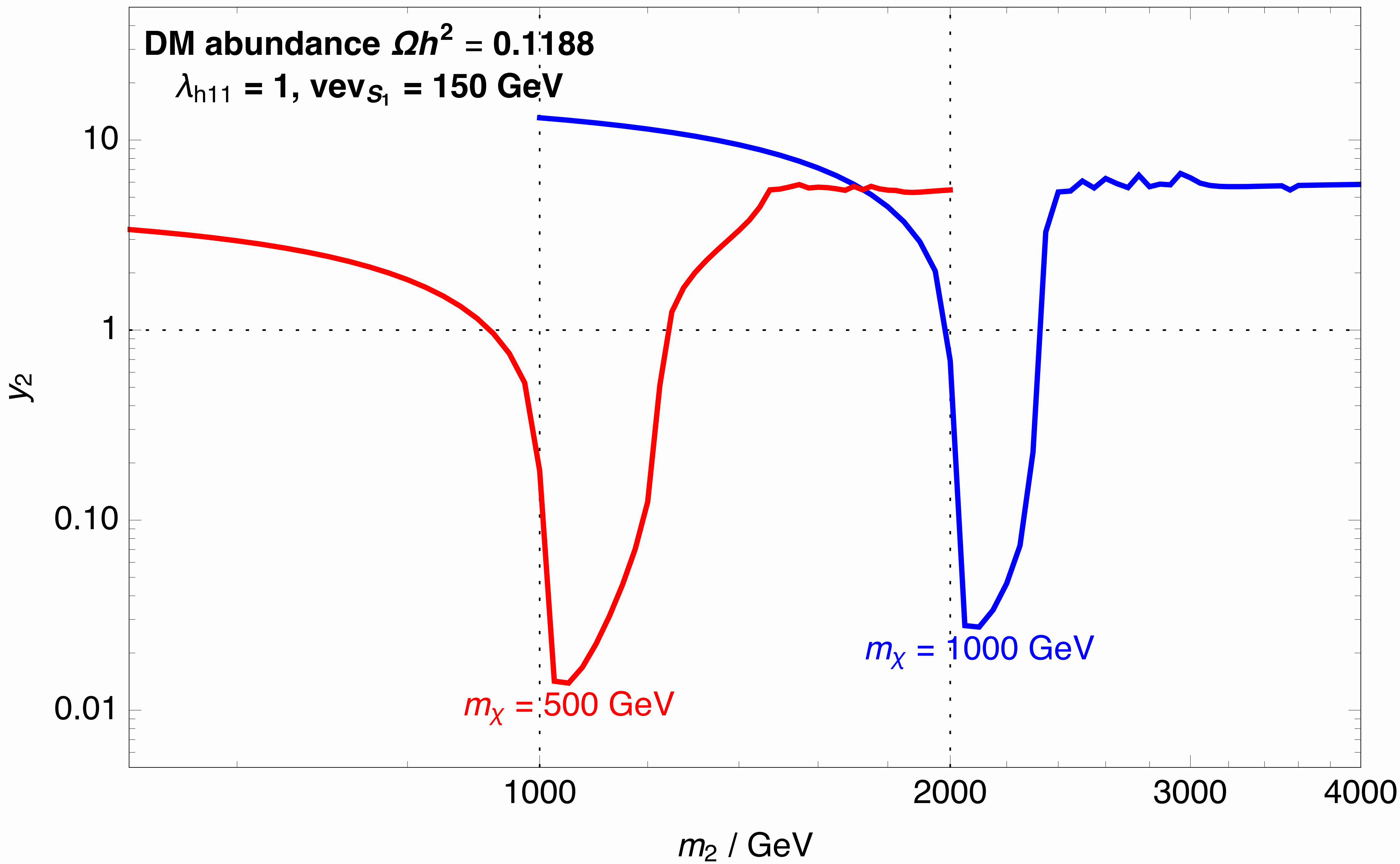




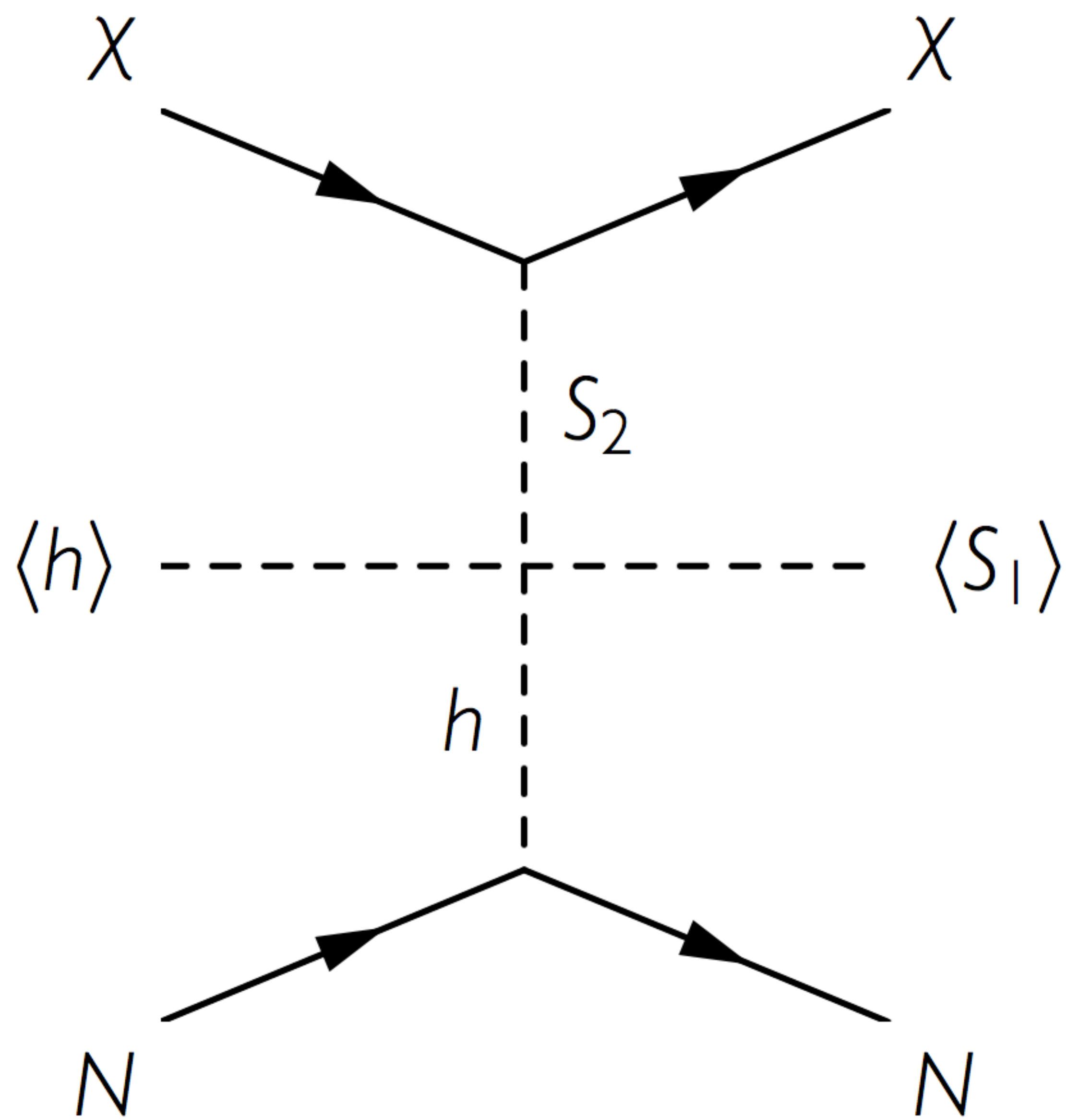
Relict density & parameter space



Relict density & parameter space



Direct detection



Gravitational waves

- Gravitational wave production similar to the model of the SM with an EW singlet
  Vaskonen 1611.02073 — work in progress

Barogenesis

?

Takeaway messages

- Non-zero temperature can have effect on dark matter freeze-out
- We have constructed a minimal model with freeze-out before phase transition
- While direct detection cross-section is negligible, there can be a gravitational wave signal

Thank you!