Panel Discussion: Are WIMPs dead?

Tim M.P. Tait
University of California, Irvine

Cosmic Controversies
October 7, 2019


My Old Living Room Window…

New Controversy:

Is the Lake rising or is Chicago sinking?!

So, WIMPs…

INSIDE SCIENCE

Reliable news for an expanding universe

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Physicists Look Beyond WIMPs For Dark Matter

After top dark matter candidate fizzles out, physicists look to more exotic realms

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Meetings: WIMP Alternatives Come Out of the Shadows

May 14, 2018 • *Physics* 11, 48

At an annual physics meeting in the Alps, WIMPs appeared to lose their foothold as the favored dark matter candidate, making room for a slew of new ideas.

The Rencontres de Moriond (Moriond Conferences) have been a fixture of European high-energy physics for ov half a century. These meetings—typically held at an Alpine ski resort—have been the site of many big announcements, such as the first public talk on the top quark discovery in 1995 and important Higgs updates i 2013. One day, perhaps, a dark matter detection will headline at Moriond. For now, physicists wait. But they've gotten a bit anxious, as their shoo-in candidate, the WIMP, has yet to make an appearance—despite several ong searches. At this year's Moriond, held this past March in La Thuile, Italy, some of the limelight passed to other d matter candidates, such as axions, black holes, superfluids, and more.

MOTHERBOARD

More Negative Results in Hunt for Dark Matter WIMPs

But the search continues 2,500 meters underground at China's PandaX experiment.

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PHYSICS

In the Dark about Dark Matter

Recent disappointments have physicists looking beyond WIMPs for dark matter particles

By Lee Billings on October 1, 2016

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DARK MATTER

Dark Matter Recipe Calls for One Part Superfluid

17

A different kind of dark matter could help to resolve an old celestial conundrum.

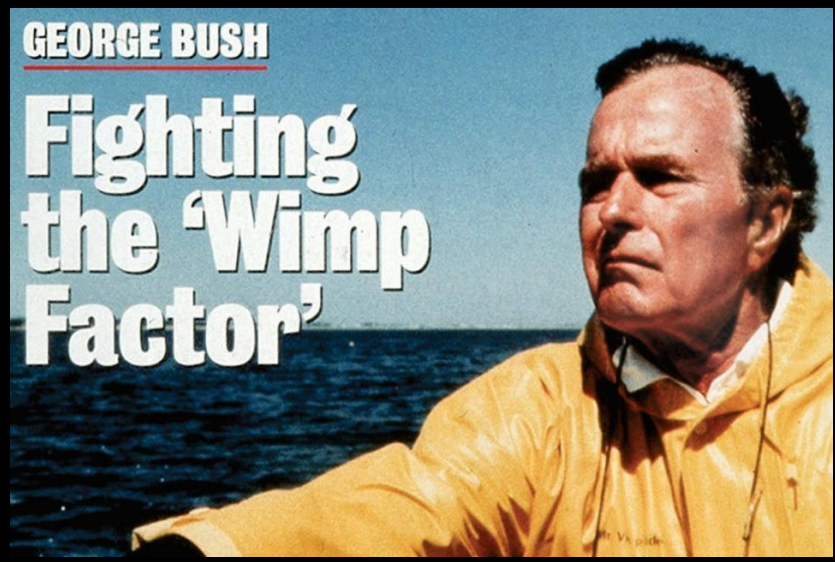
THIS WEEK 28 May 2014

It's crunch time for dark ma WIMPs don't show

If dark matter isn't made of WIMPs, could neutrinos or axions fit th particle at all but a strange modification of gravity?

By **Lisa Grossman**

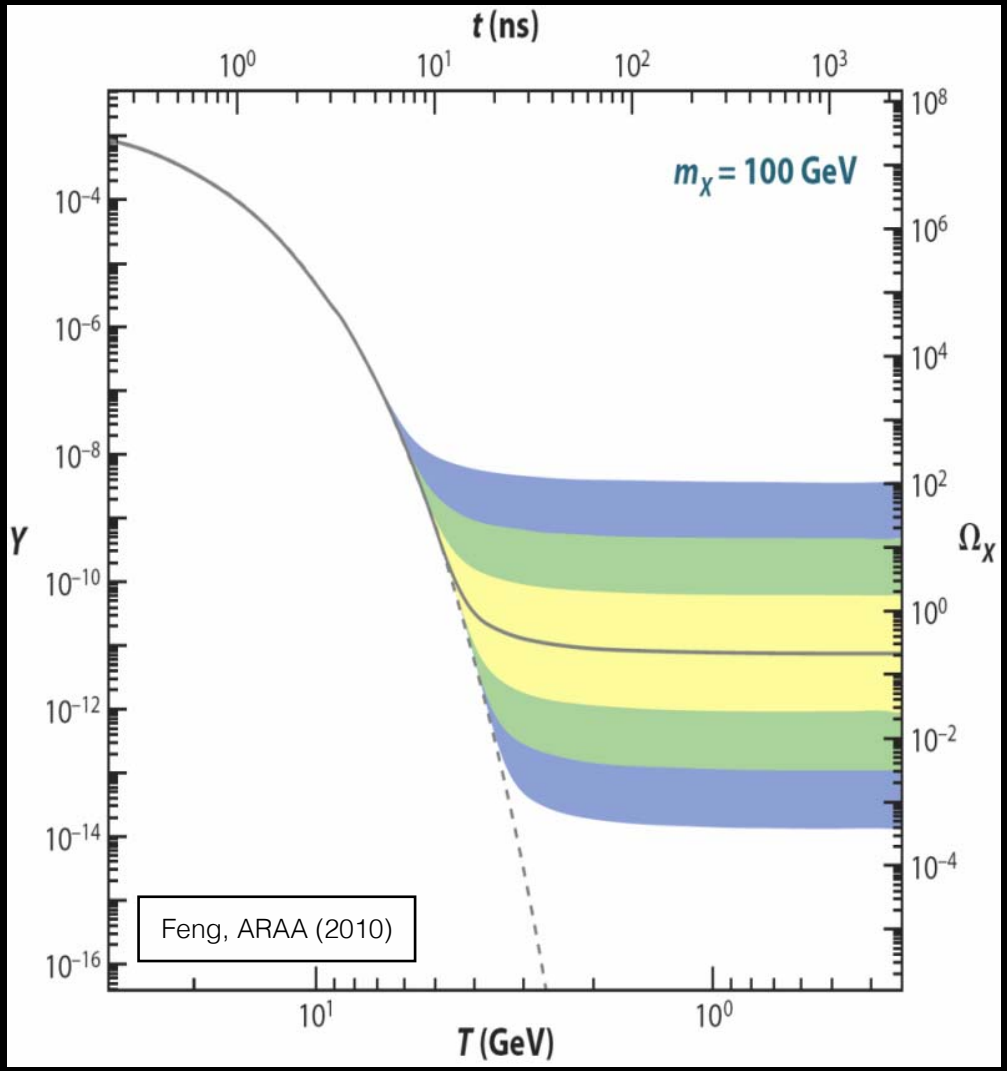
Fake News?



What is behind this Question?

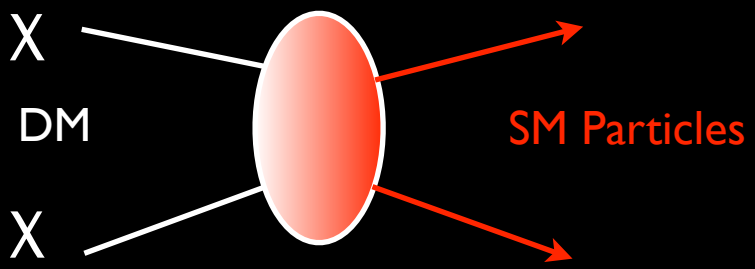
Relic Density

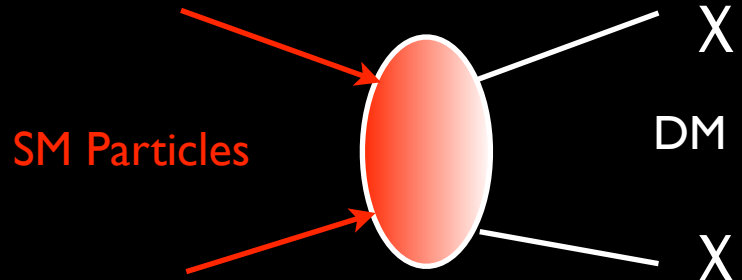
- Most of the statements about WIMPs are correlating null results for searches with the relic density.
- This is clearly a very attractive target, but it is worth remembering that typically freeze-out occurs at ~ $m_{DM}/20$ or so.
- For most masses of interest, these are times where we have no direct cosmological probes.
- My attitude is that this kind of standard cosmology is something we want to establish, not assume.



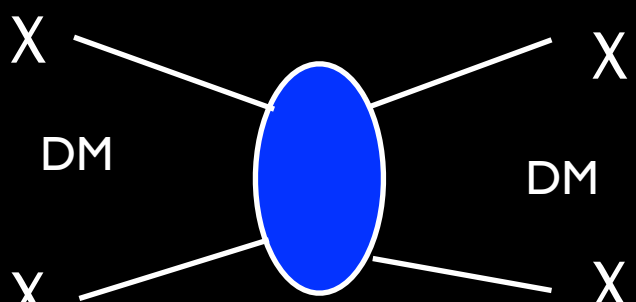
WIMP Searches

Indirect Detection

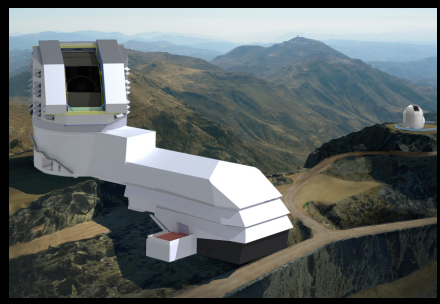




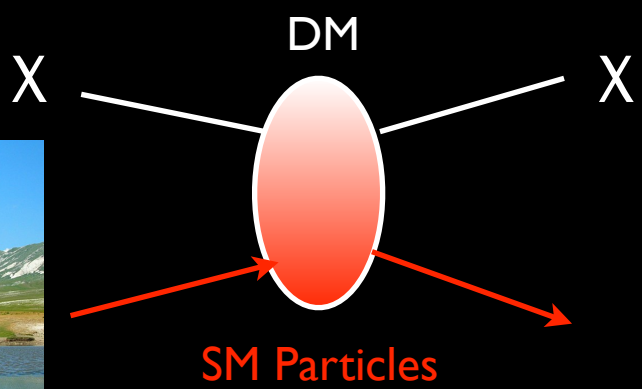
Collider Searches



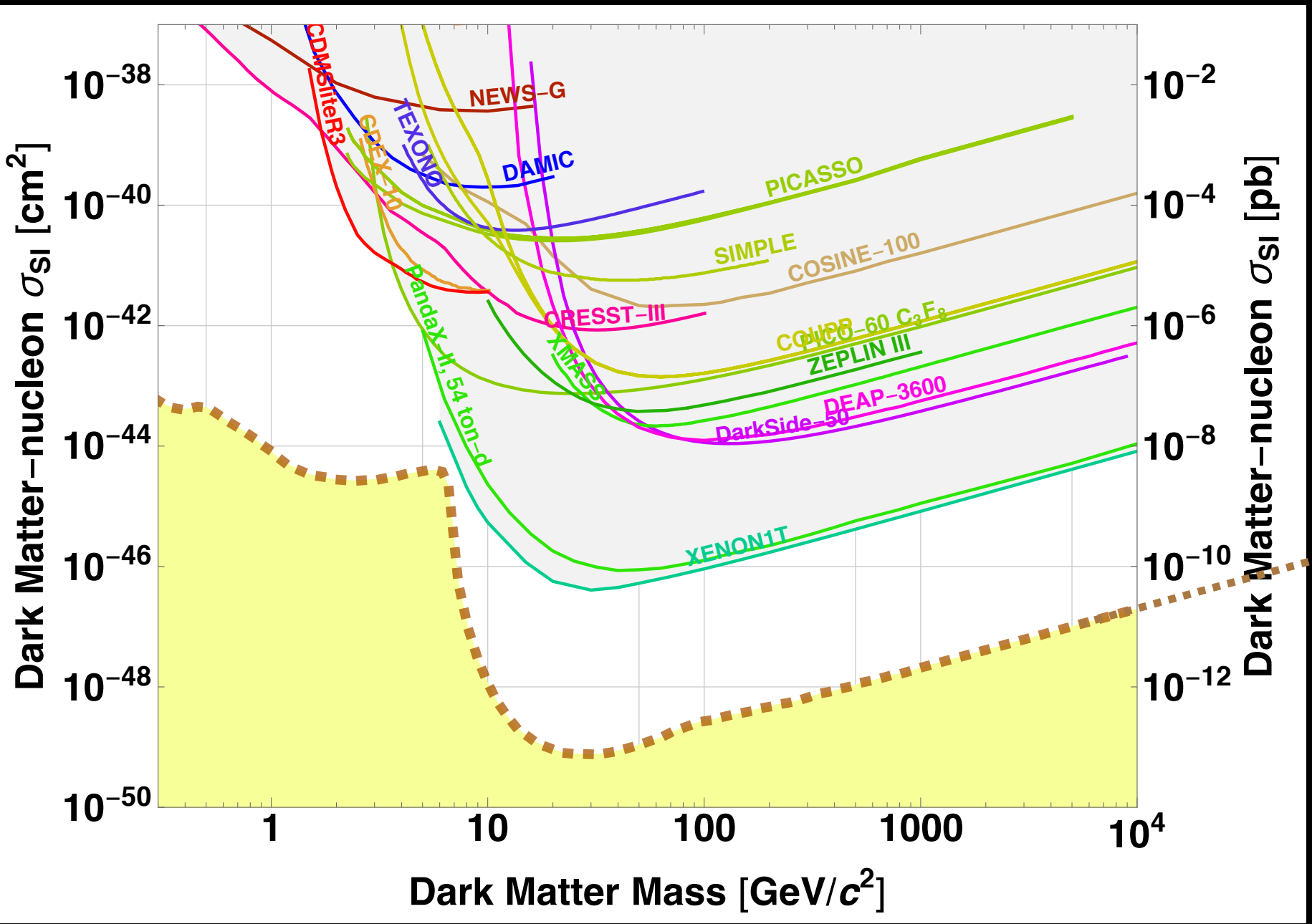
Self-Interactions



Direct Detection



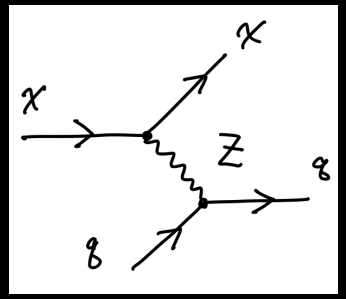
Ceiling:
These limits become ineffective around 10^{-33} cm^2

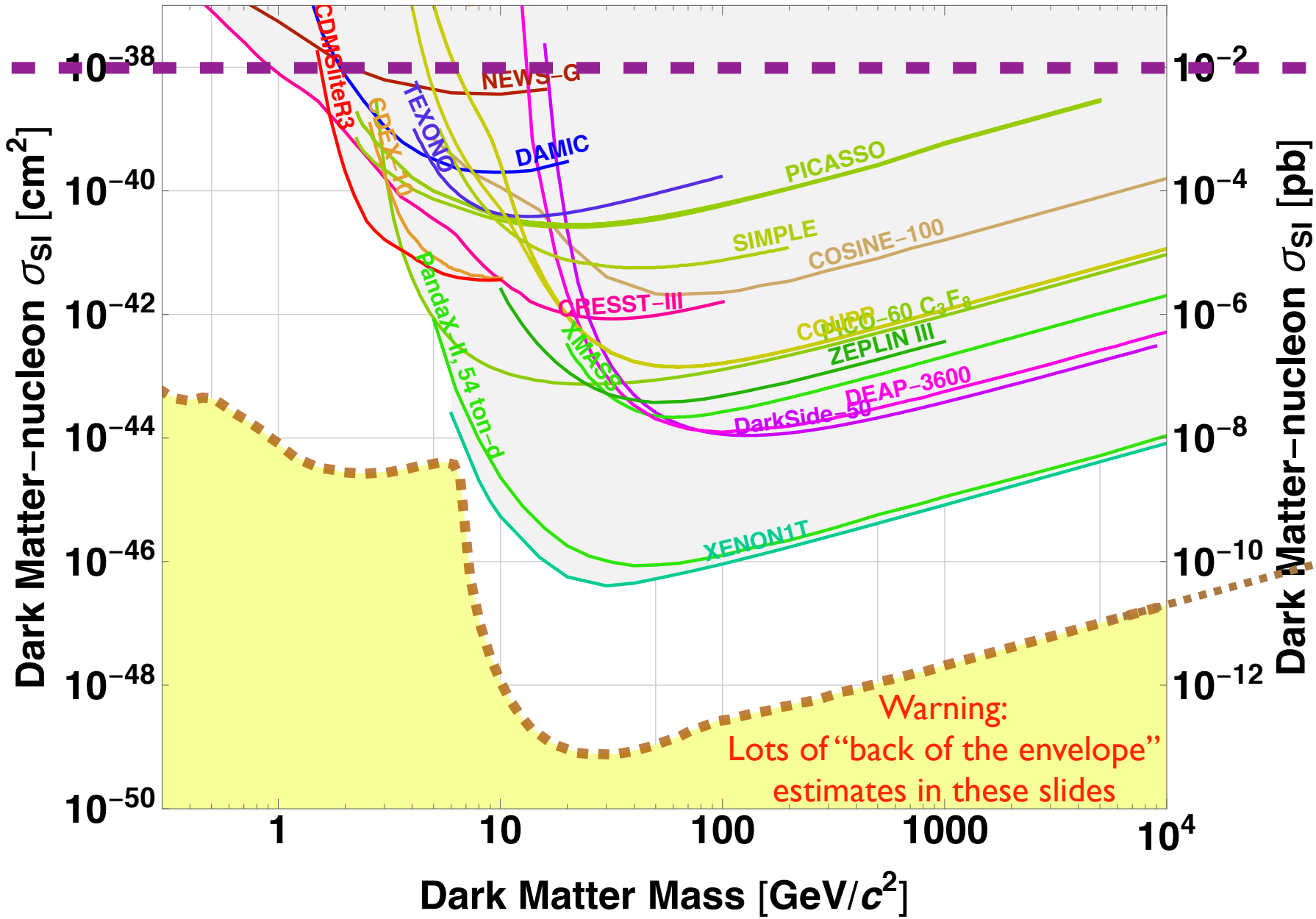


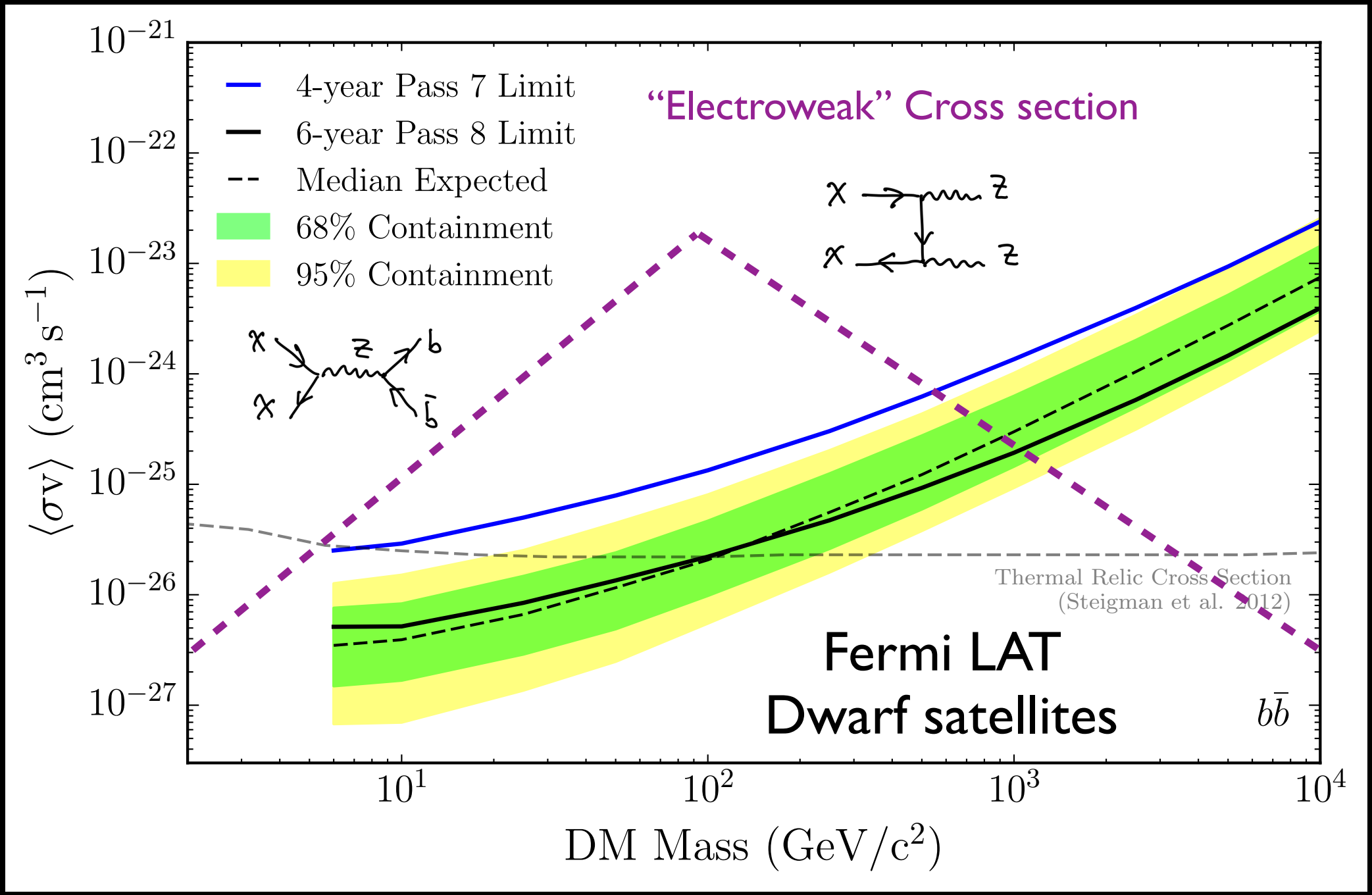
"Electroweak" Cross section

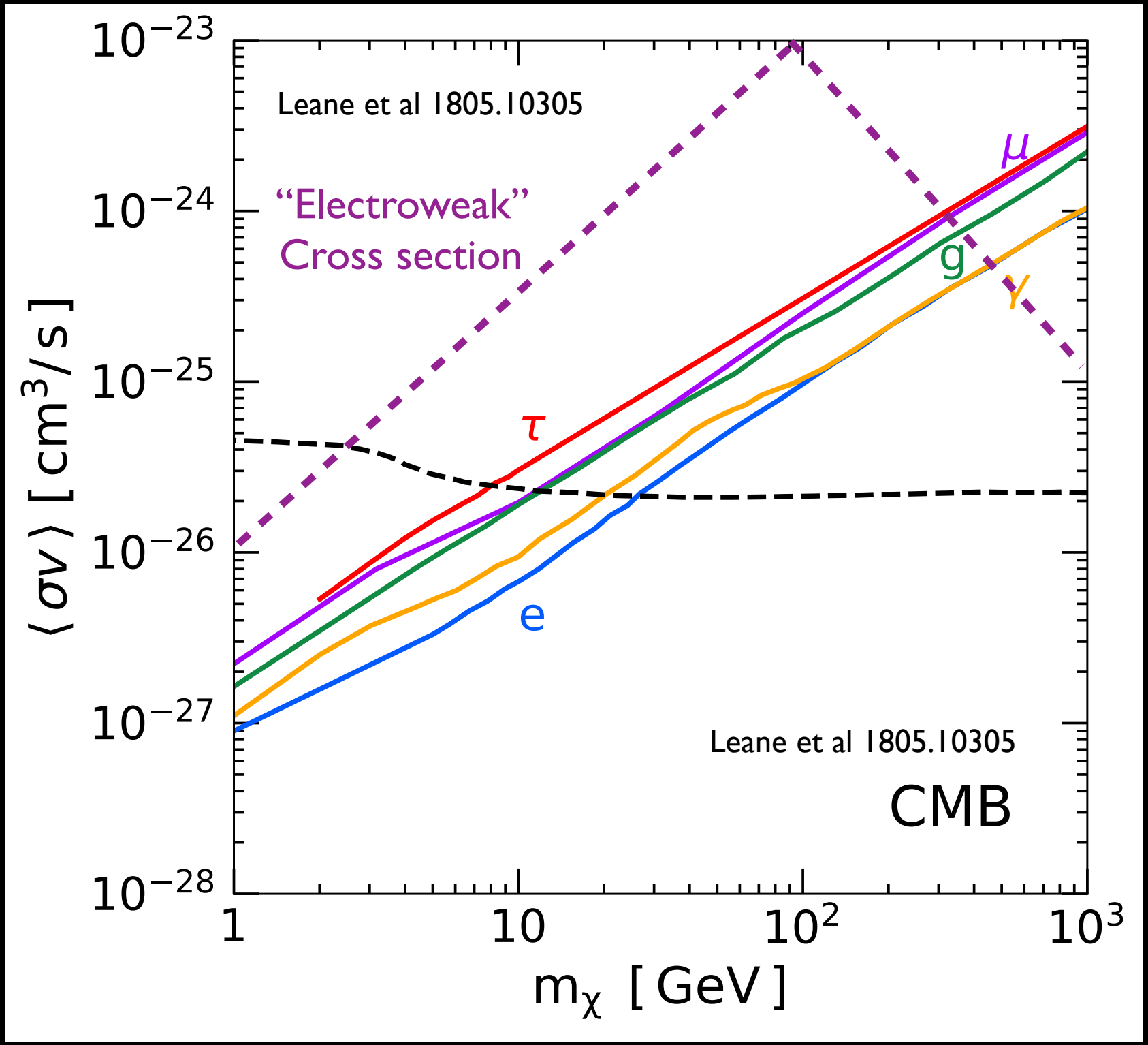
(excluded by CDMS ~2000
for a wide range of masses)

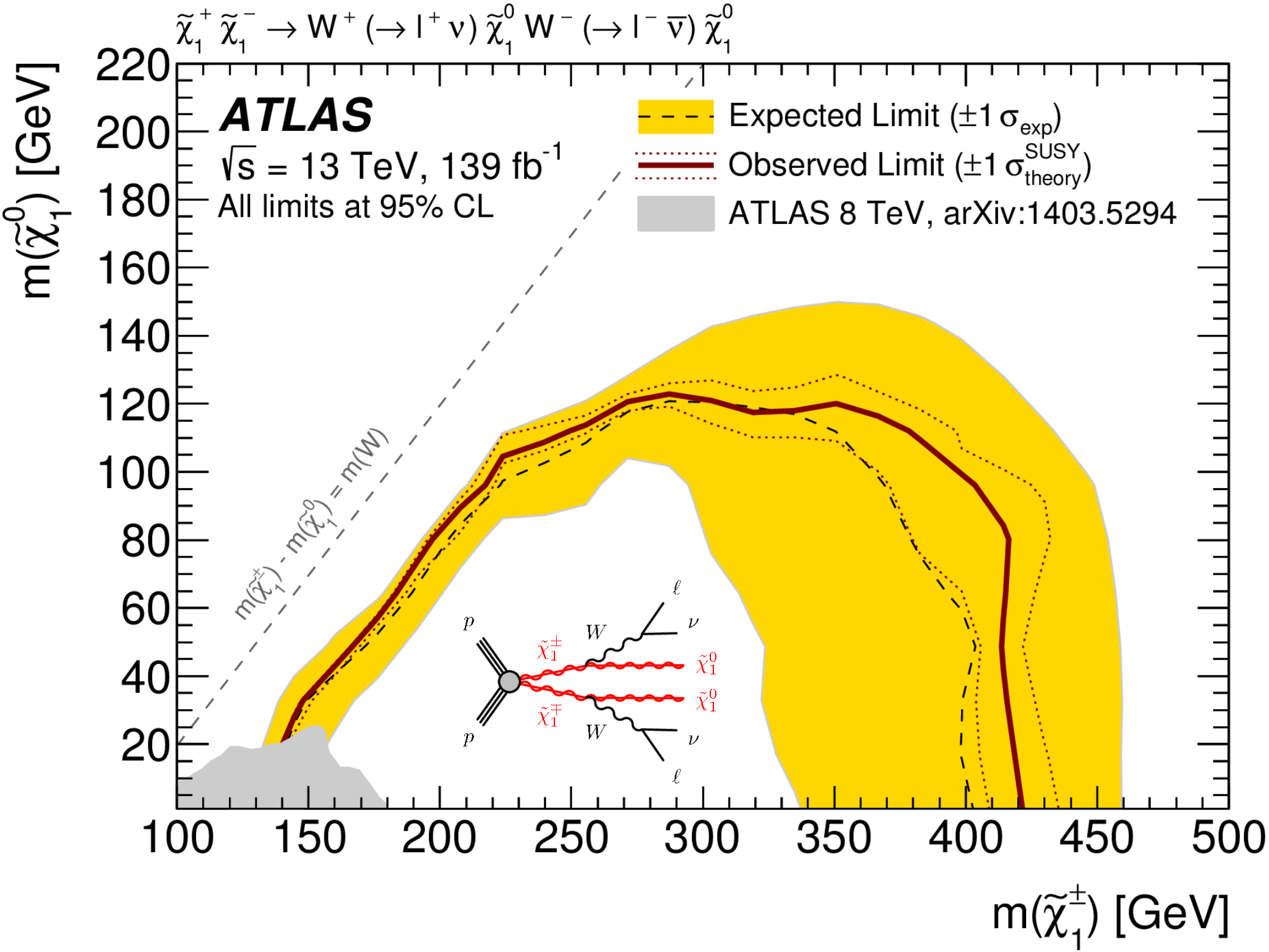
Now: ~1 GeV to ~10^7 GeV






4-year Pass 7 Limit
6-year Pass 8 Limit
Median Expected
68% Containment
95% Containment
"Electroweak" Cross section
Thermal Relic Cross Section
(Steigman et al. 2012)
Fermi LAT
Dwarf satellites
$b\bar{b}$
$\langle \sigma v \rangle$ (cm^3 s^{-1})
DM Mass (GeV/c^2)
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^1
10^2
10^3
10^4

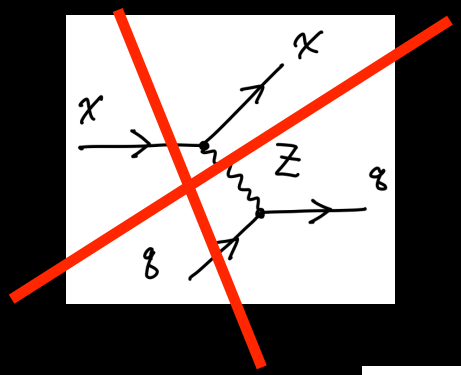

Leane et al 1805.10305
"Electroweak"
Cross section
μ
g
γ
τ
e
Leane et al 1805.10305
CMB
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$\langle \sigma v \rangle$ [cm^3/s]
1
10
10^2
10^3
m_χ [GeV]


$\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow W^+ (\rightarrow l^+ \nu) \tilde{\chi}_1^0 W^- (\rightarrow l^- \bar{\nu}) \tilde{\chi}_1^0$
ATLAS
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
All limits at 95% CL
Expected Limit ($\pm 1\,\sigma_{exp}$)
Observed Limit ($\pm 1\,\sigma_{theory}^{SUSY}$)
ATLAS 8 TeV, arXiv:1403.5294
$m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = m(W)$
$m(\tilde{\chi}_1^0)$ [GeV]
$m(\tilde{\chi}_1^\pm)$ [GeV]
p
p
$\tilde{\chi}_1^\pm$
$\tilde{\chi}_1^\mp$
W
W
ℓ
ν
ℓ
ν
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
20
40
60
80
100
120
140
160
180
200
220
100
150
200
250
300
350
400
450
500

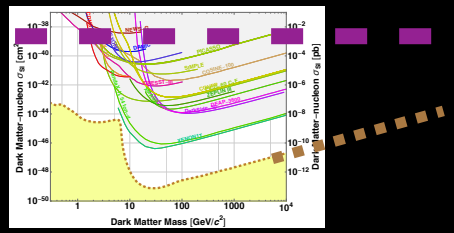
So what does this mean for WIMPs?

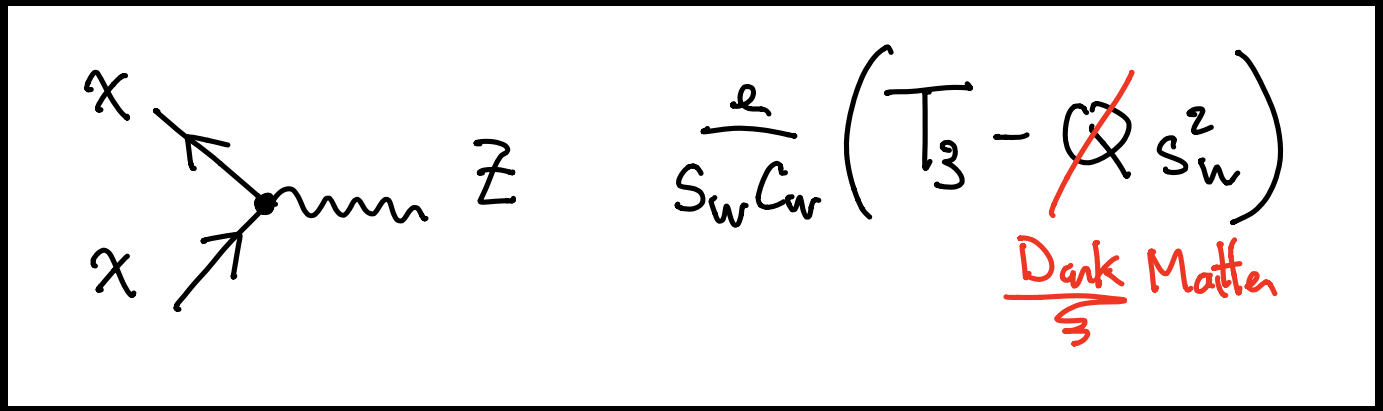
It depends what you mean by WIMP.

Electroweakly Interacting Massive Particles



Z Interactions





To be EW-charged, but avoid full strength Z interactions, DM could have T3=0.

This happens for odd-dimensional representations (triplet, quintuplet, …)
It doesn't work for doublets, quadruplets, etc..

Another way to say it: Dark Matter should not carry hypercharge (Q=T3+Y).

This implies EW-charged dark matter comes with electrically charged EW siblings whose masses differ by O(<H> ~ 100 GeV).

EFTs

(For illustration: just quarks and gluons)

Relativistic EFT

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Goodman et al, 1008.1783

More Realistic

v -> 0

Nonrelativistic EFT

1. P-even, S_χ-independent

$$\mathcal{O}_1 = \mathbf{1}, \qquad \mathcal{O}_2 = (v^\perp)^2, \qquad \mathcal{O}_3 = i\vec{S}_N \cdot (\vec{q} \times \vec{v}^\perp),$$

2. P-even, S_χ-dependent

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N, \qquad \mathcal{O}_5 = i\vec{S}_\chi \cdot (\vec{q} \times \vec{v}^\perp), \qquad \mathcal{O}_6 = (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q}),$$

3. P-odd, S_χ-independent

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp,$$

4. P-odd, S_χ-dependent

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp, \qquad \mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q})$$

5. P-odd, S_χ-independent:

$$\mathcal{O}_{10} = i\vec{S}_N \cdot \vec{q},$$

6. P-odd, S_χ-dependent

$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \vec{q}.$$

More general

Fitzpatrick et al, 1203.3542

This description knows that physics respects special relativity.

This description is the natural language for the scattering problem.

EFTs

Relativistic EFT

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Goodman et al, 1008.1783

Nonrelativistic EFT

1. P-even, S_χ-independent

$$\mathcal{O}_1 = \mathbf{1}, \qquad \mathcal{O}_2 = (v^\perp)^2, \qquad \mathcal{O}_3 = i\vec{S}_N \cdot (\vec{q} \times \vec{v}^\perp),$$

Spin Independent

2. P-even, S_χ-dependent

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N, \qquad \mathcal{O}_5 = i\vec{S}_\chi \cdot (\vec{q} \times \vec{v}^\perp), \qquad \mathcal{O}_6 = (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q}),$$

Spin Dependent

3. P-odd, S_χ-independent

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp,$$

4. P-odd, S_χ-dependent

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp, \qquad \mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q})$$

5. P-odd, S_χ-independent:

$$\mathcal{O}_{10} = i\vec{S}_N \cdot \vec{q},$$

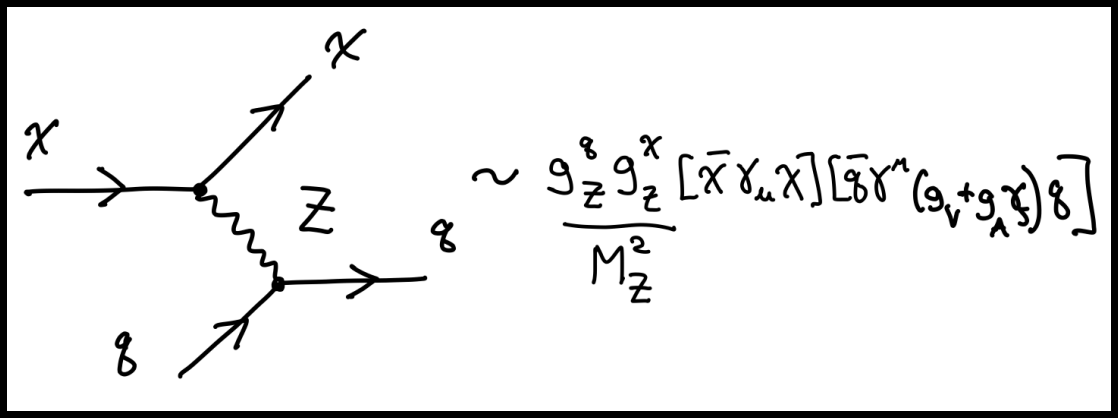
6. P-odd, S_χ-dependent

$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \vec{q}.$$

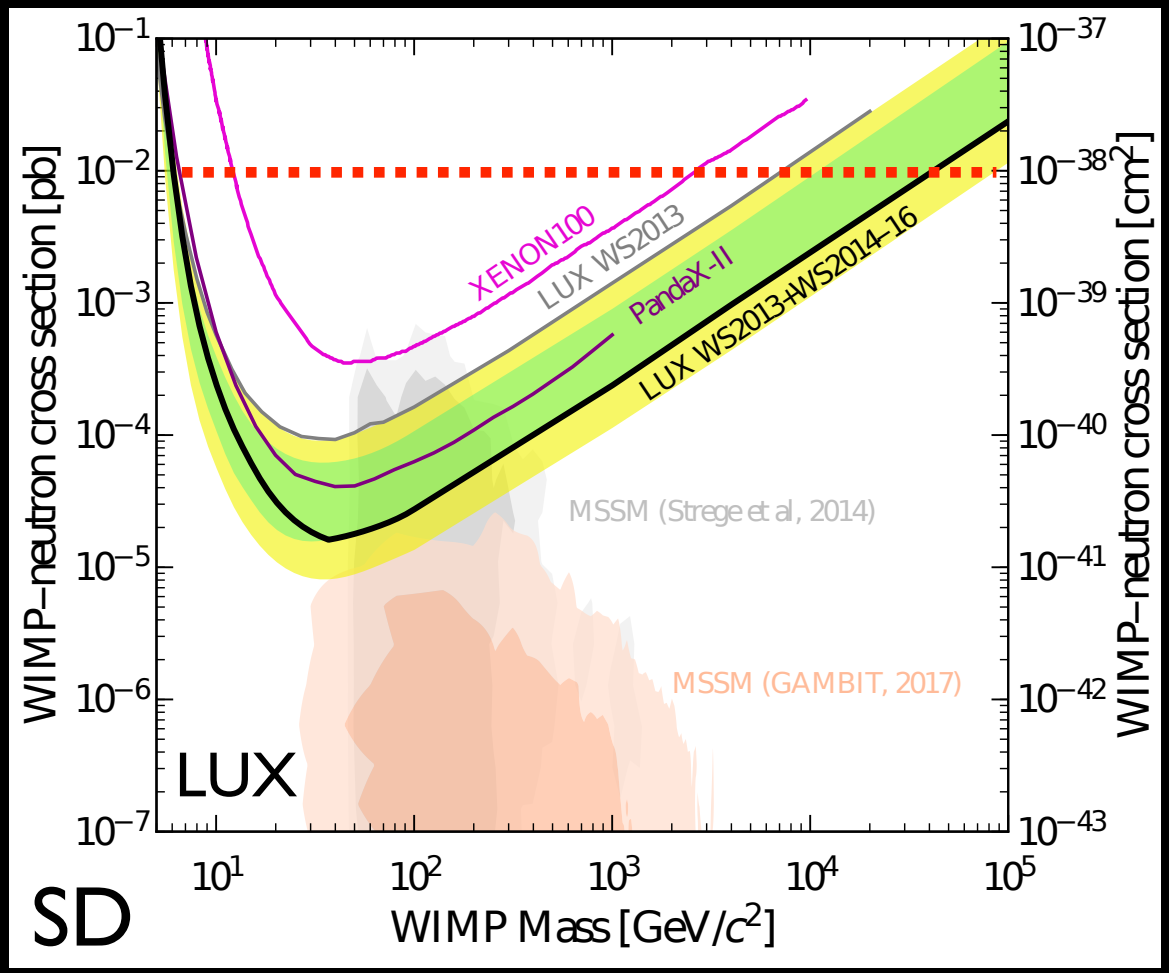
Fitzpatrick et al, 1203.3542

The Z boson is a problem because it switches on relativistic operator D5 which maps to O_1 (SI).

Majorana DM



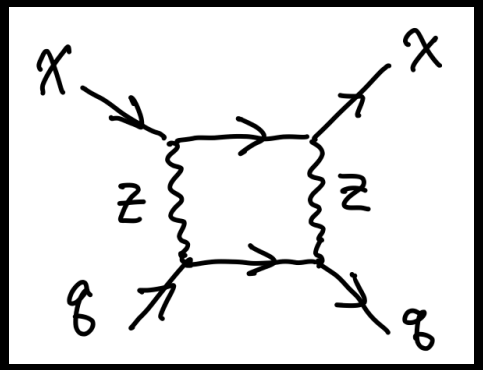
The vector interaction vanishes (identically) for a Majorana particle. That leaves behind spin-dependent (and v-suppressed) terms.



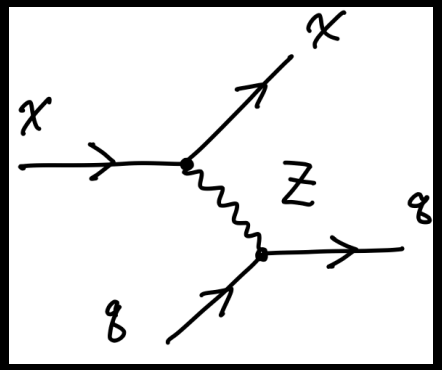
That suggests another strategy for EW-charged WIMPs:
Majorana particles are less constrained than Dirac, even if they carry hyper-charge.

…this is not really enough at this point…

SD vs SI



vs



But…at loop level, what was spin-dependent at tree level can turn out to be spin-independent.

At weakly coupled loop costs ~10^{-3}.

At maximum sensitivity, the Xe limits on SI scattering are something like A^2 ~10^5 better than SD.

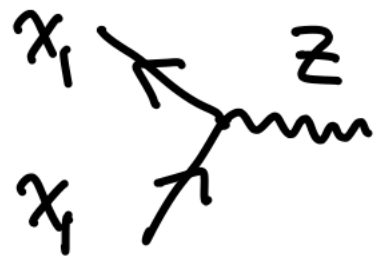
Mixed DM

Another strategy is to construct a dark matter which is a mixed state of more than one EW-charged object.

There can be cancellations between the different contributions to the the coupling (though this may not be generic).

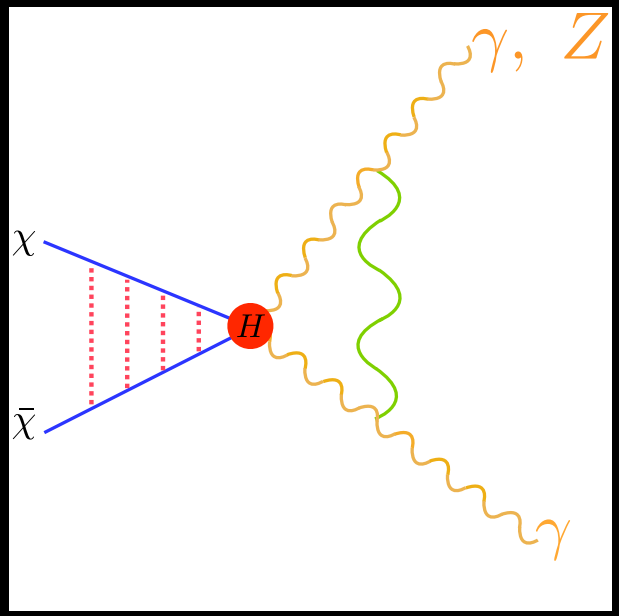
I don't know of any theory where this is the dominant scheme to avoid constraints, though the MSSM benefits from it to some degree. Mostly, the MSSM survives by having a large component without EW charge.

$$\chi_1 = N_{11} S_1 + N_{12} S_2 + N_{13} S_3 + \ldots$$

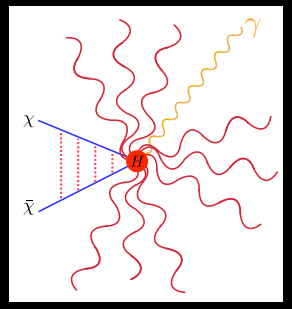


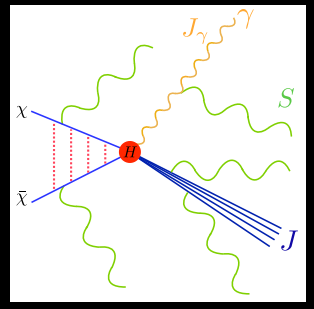
$$N_{11} T_3^{(1)} + N_{12} T_3^{(2)} + N_{13} T_3^{(3)} + \ldots$$

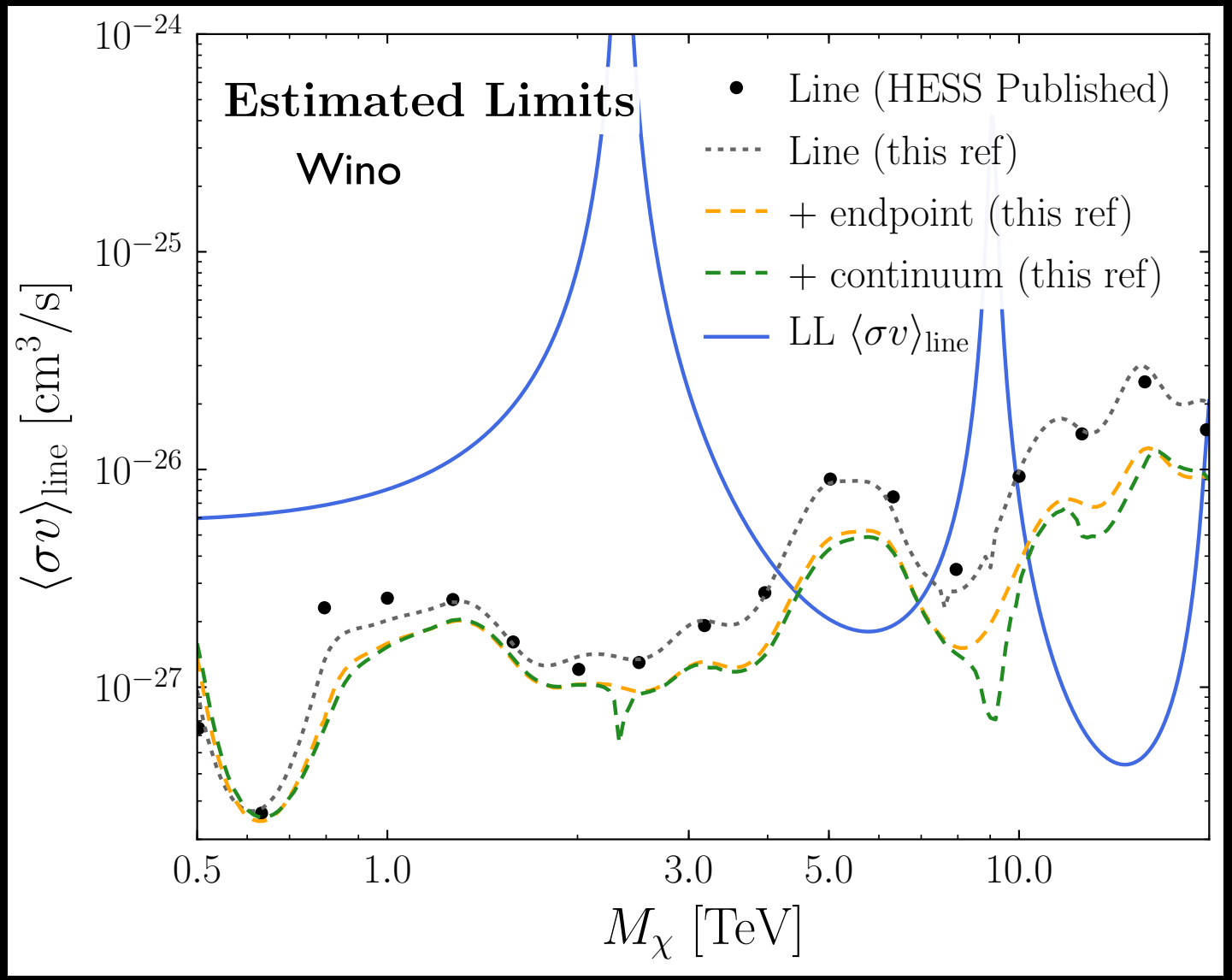
Heavy EW WIMPs



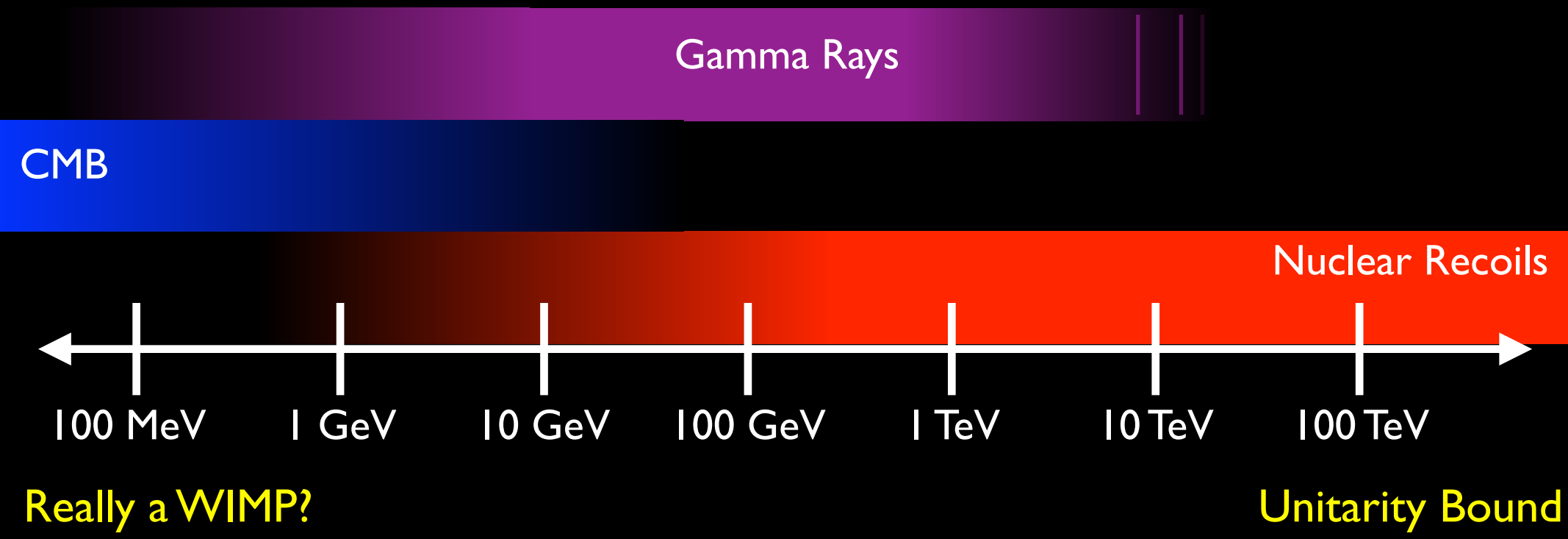
Baumgart, Cohen, Mouilt, Rodd, Slatyer, Solon, Stewart, Vaidya. 1712.07656



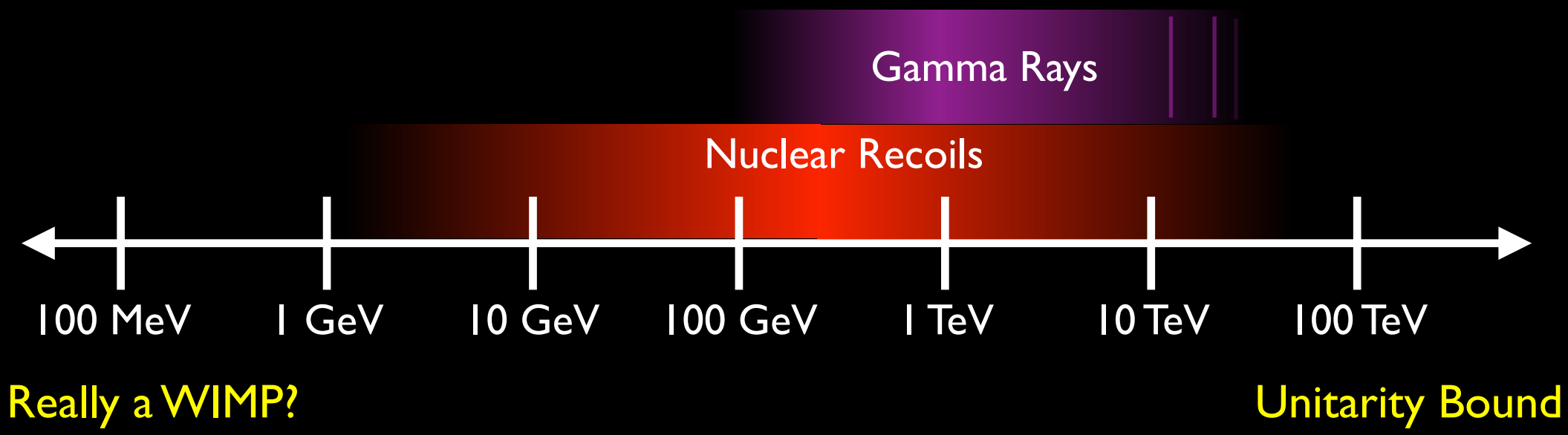




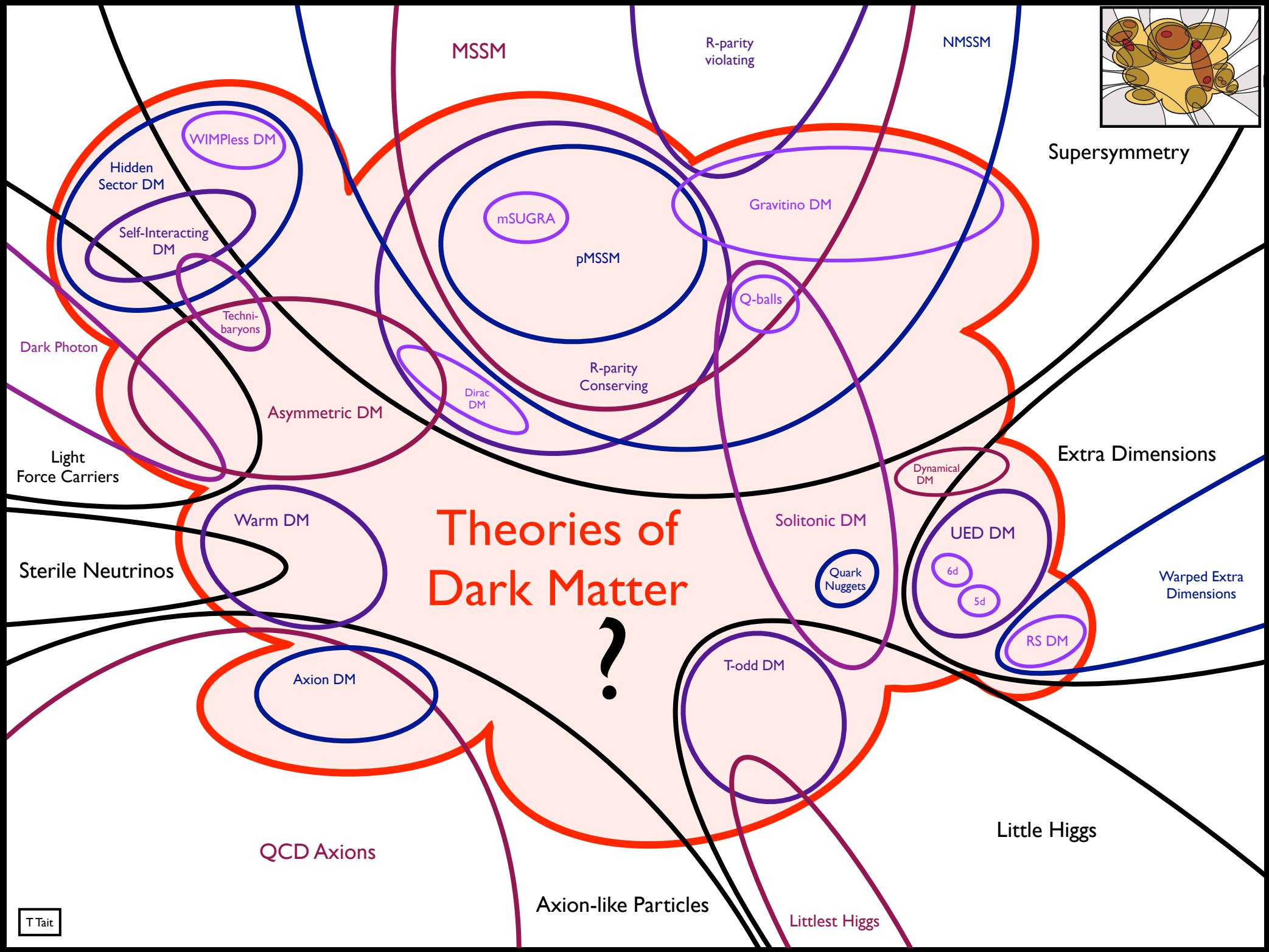
Dirac EW-Charged WIMP Scorecard



Majorana EW-Charged WIMP Scorecard



“Kinda-weakly” Interacting Massive Particles


Theories of Dark Matter
?
MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
T-odd DM
Axion DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

Non-EW Mediators

Without the weak interaction itself to provide a scale, focus shifts to the relic density through freeze-out.

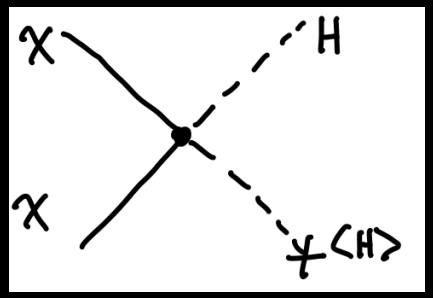
Though the couplings are typically free parameters, a general issue remains. The constraints from direct detection are very strong. Unless something mitigates them, they often rule out the cross sections necessary for freeze-in.

Things become much more model-dependent. Let's just consider a few strategies one can use to engineer viable models.

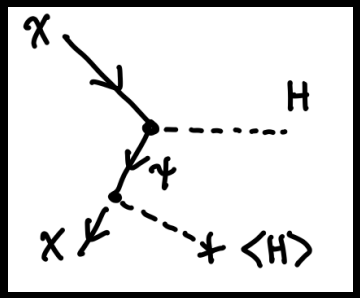
Higgs

Unlike the weak bosons, the Higgs coupling to dark matter is not specified in terms of parameters we've already measured.

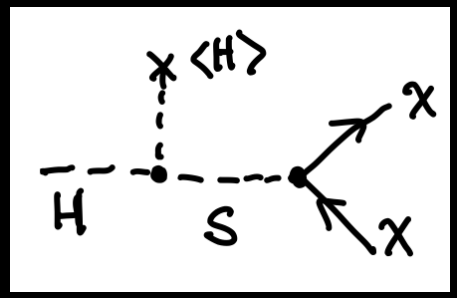
It is very unlikely that the Higgs is the source of mass for the dark matter in the same way that it is for the SM particles.



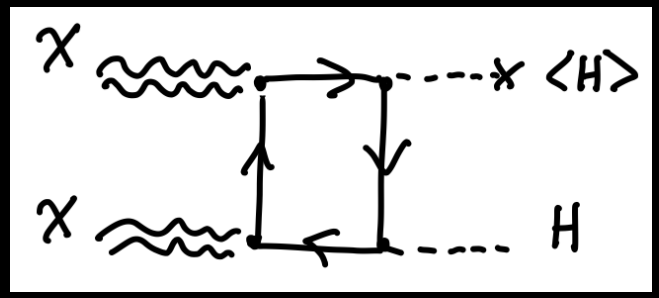
Classic Scalar DM
Higgs portal



Mixed fermions
(MSSM-like)



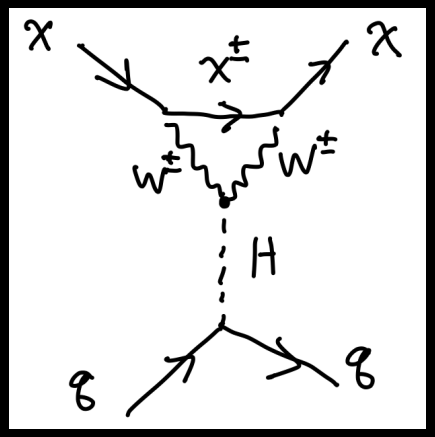
Mixed scalar
mediator

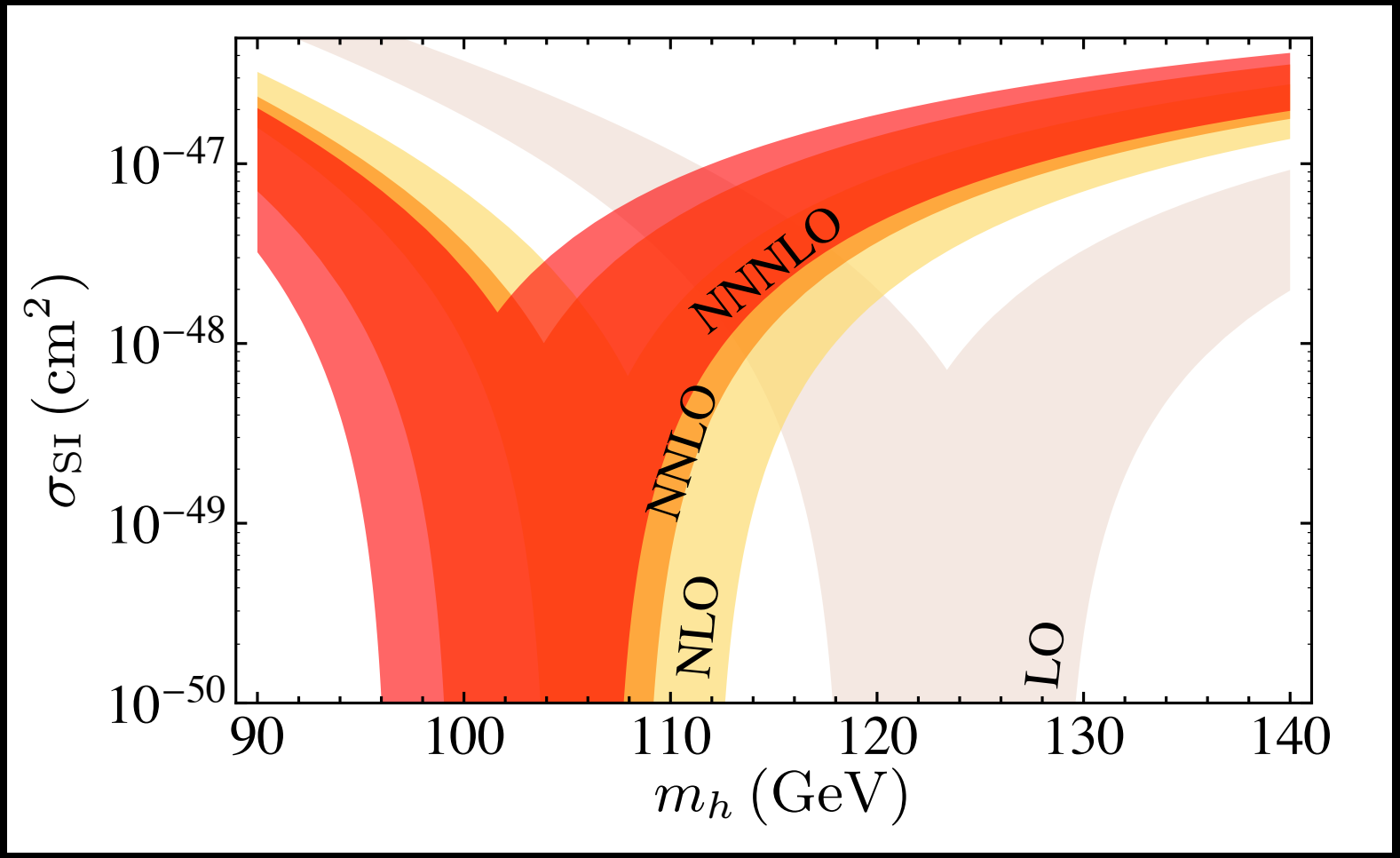


Vector dark matter,
radiative portal

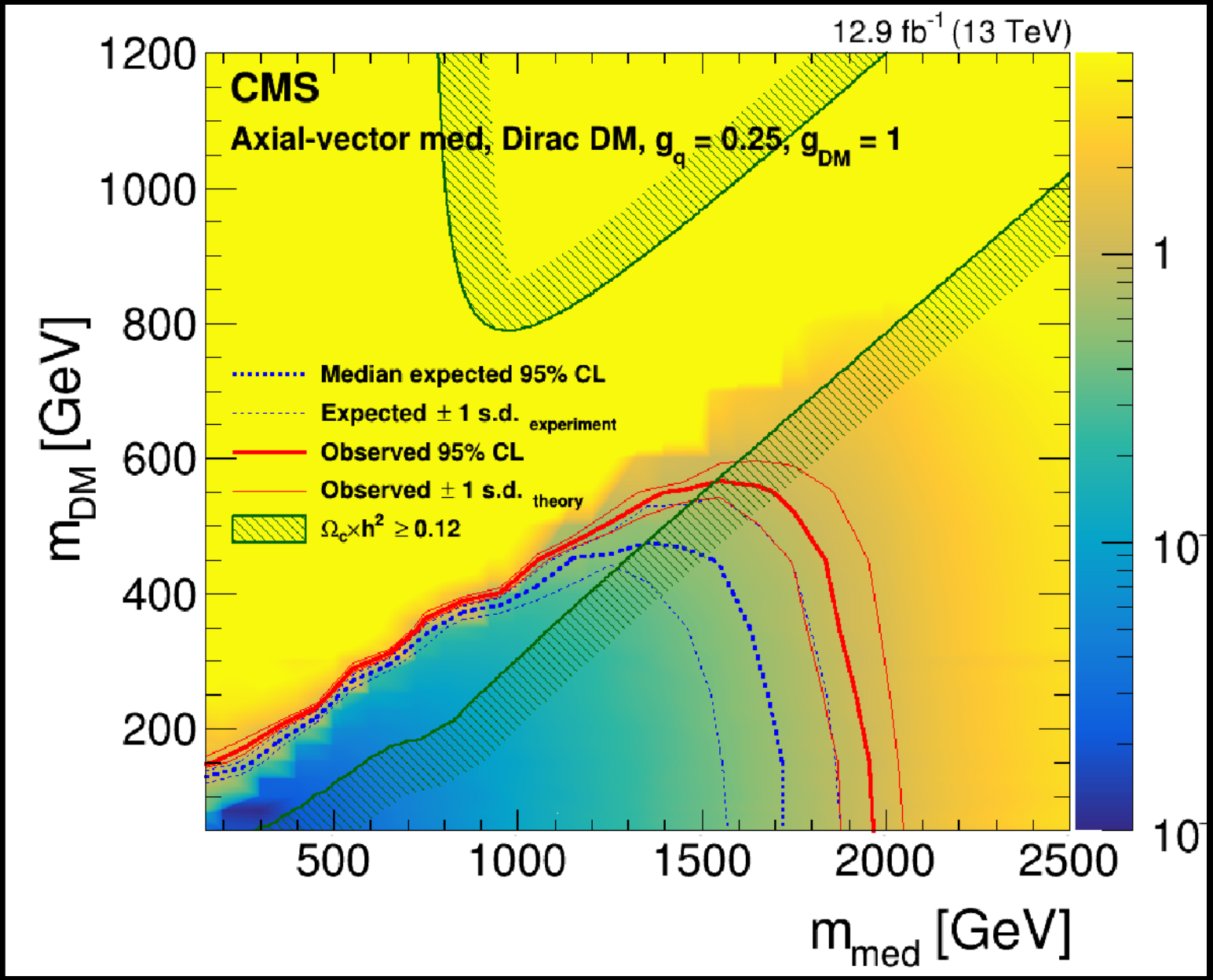
EW Higgs Exchange

Hill, Solon 1309.4092

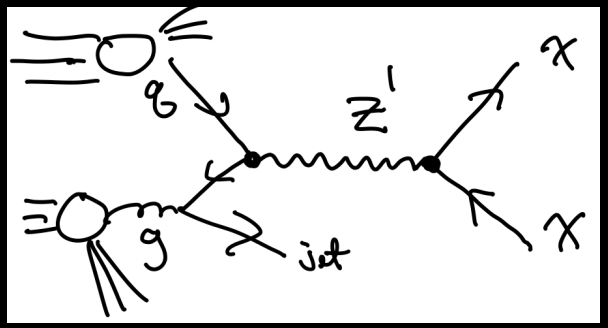




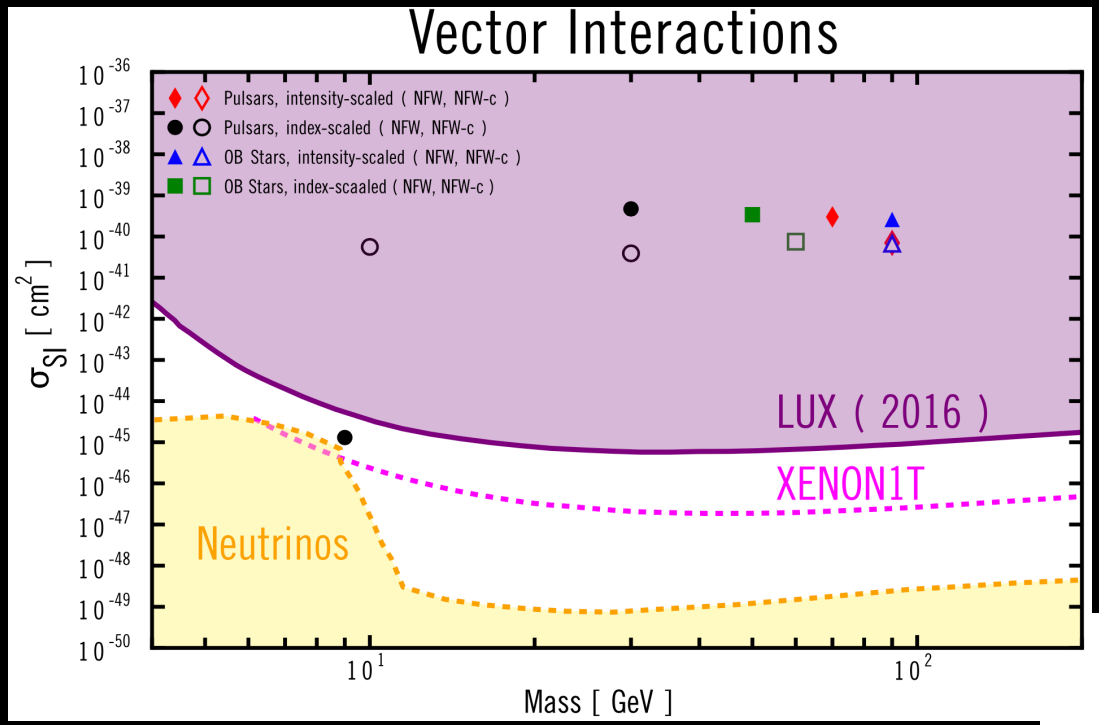
Even without a tree level coupling to the Higgs, an EW-charged WIMP picks up a coupling at one loop.

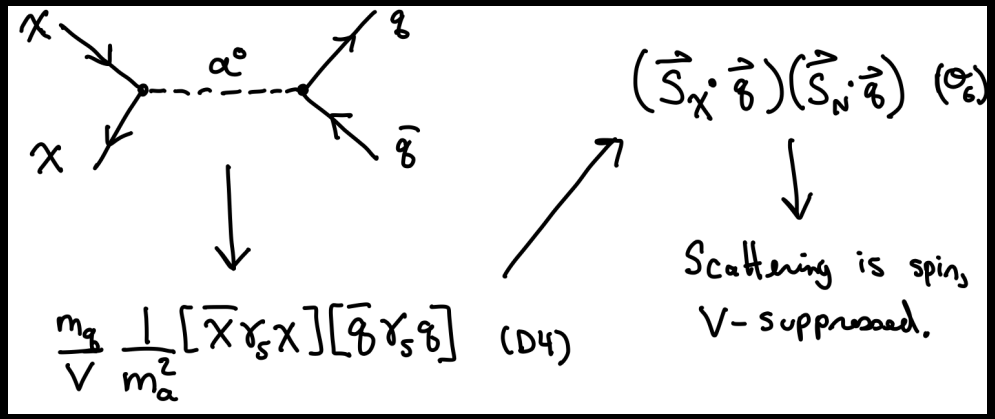


Axial vector — SD at tree level.
Note the choice of DM and quark couplings — the plot is totally different for other choices.



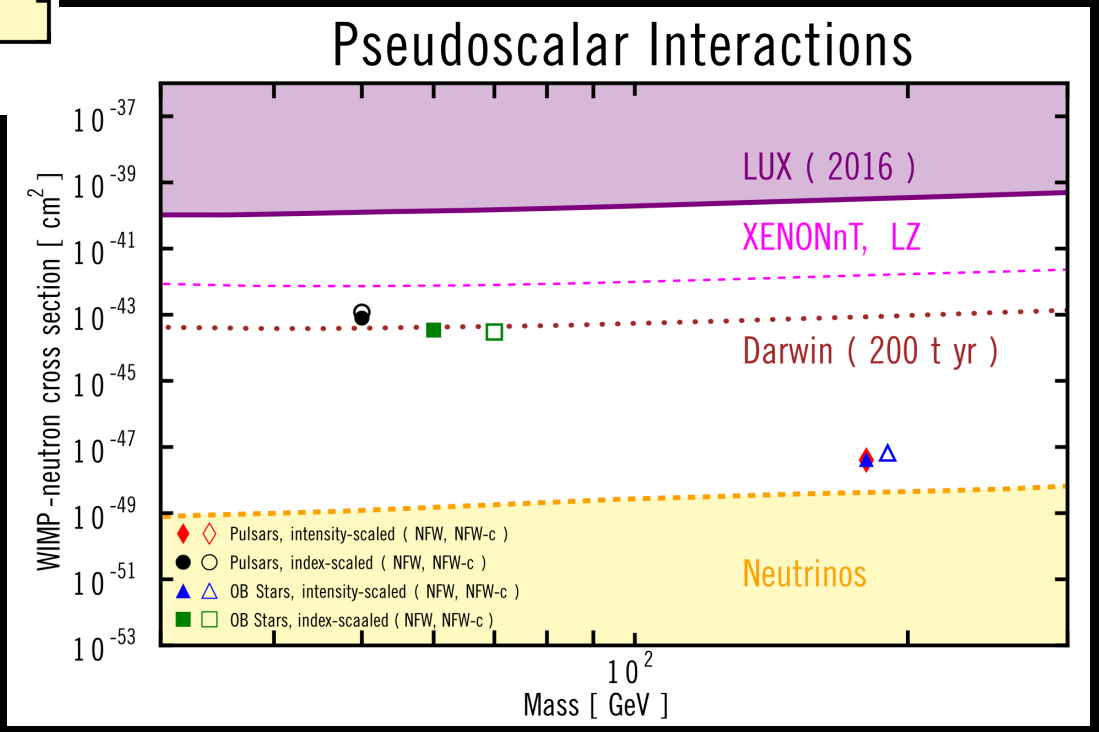
Pseudo-scalar Mediator





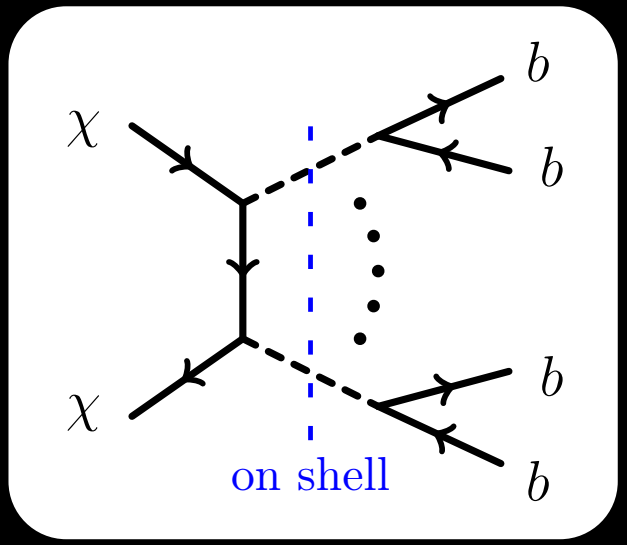
Karwin et al 1612.05687
(Points are fits to the GC Gamma ray excess)

A pseudo-scalar mediator leads to scattering which is both SD and v-suppressed, but annihilation is not suppressed.

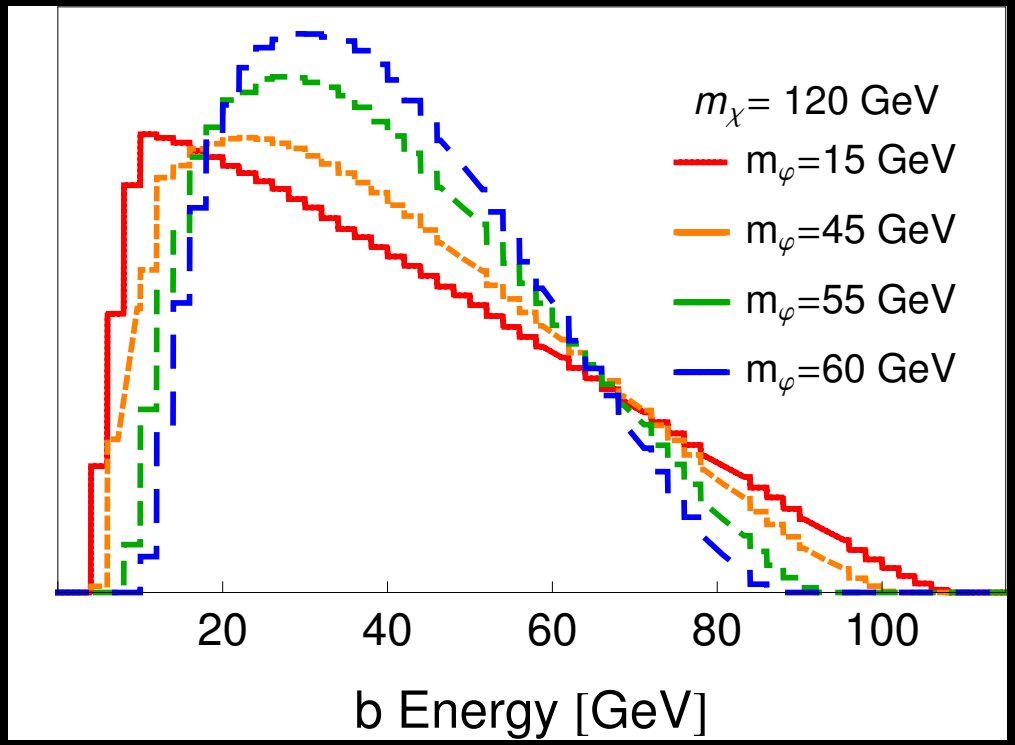


Secluded Dark Matter

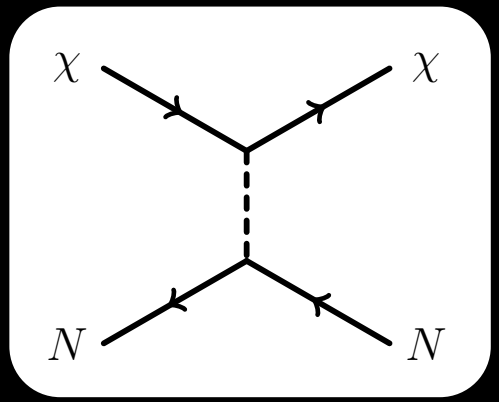
- If the dark matter annihilates primarily into an on-shell mediator which has tiny couplings to the SM, the annihilation rate may be effectively uncorrelated with the scattering with nuclei or production at atom smashers.



$$\sigma_{\rm ann} \propto g^2$$



Abdullah et al 2014



$$\sigma_{\rm direct} \propto \epsilon^2 g^2$$

Outlook

- Are WIMPs dead?
  - The answer really depends on how you frame the question.
  - Some are…
    - Electroweakly charged particles are rather constrained.
    - Some options survive by making choices of EW representation / spin.
  - Others not so much.
    - Freeze-out relics can exist for a wide variety of masses.
    - Engineering may be required on the theory side, but this could just be how nature works.
  - We have learned a lot about what WIMPs aren't.
  - Where do you put <u>your</u> effort?

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Yes.

Bonus Material

What IS a WIMP?

Weakly-interacting → Electroweak interaction

SU(2) x U(1)

Z, W, Higgs?

α_{EM}, sin θ_W ?

Weakly-interacting → Random "weak interaction?"

Symmetries?

Mediator particles?

g < around 1

Freeze-out relic?

Massive → Anything cold?

Massive → > 10 keV?

>1 GeV?

~ 100 GeV

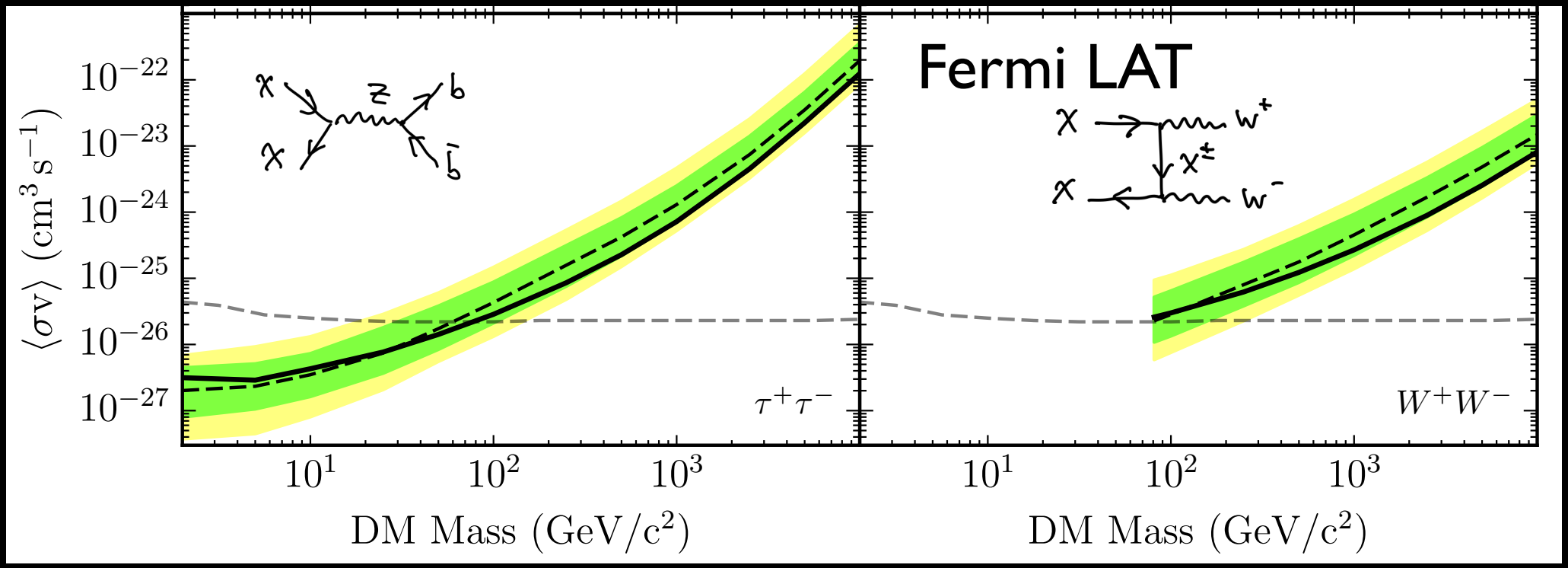
< 100 TeV?

Particle → Yes?

Particle → Fields? Fuzzy? Superfluid?!

Indirect Constraints

It isn't enough to engineer away scattering with nuclei. There are also important constraints from indirect detection too.



The Majorana and T3=0 options work here as well, below the threshold for ZZ and WW annihilation. Z-exchange is suppressed by either the velocity or the mass of the final fermions.