Discussion: Are WIMPs dead?

Tim M.P. Tait
University of California, Irvine

KITP CDM
April 30, 2018

INSIDE SCIENCE

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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

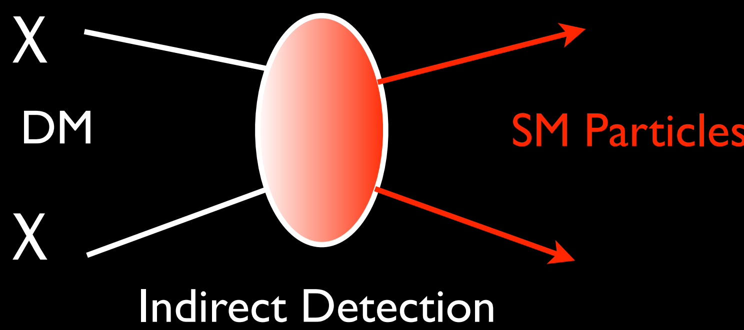
If dark matter isn't made of WIMPs, could neutrinos or axions fit th particle at all but a strange modification of gravity?

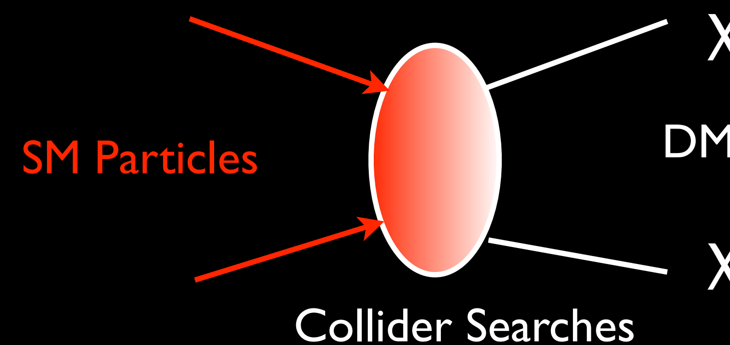
By Lisa Grossman

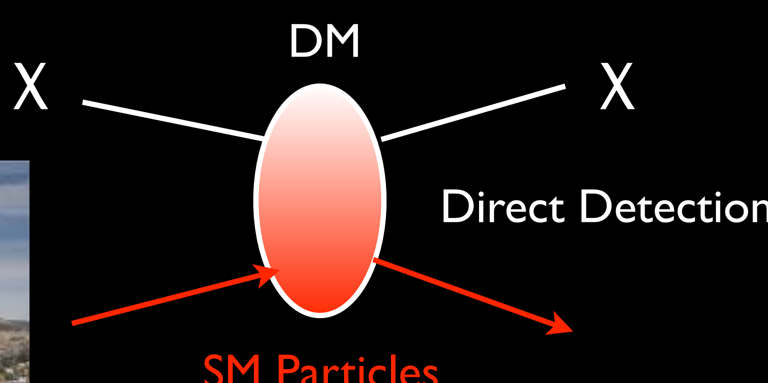
Fake News?

What is behind this Question?

WIMP Searches







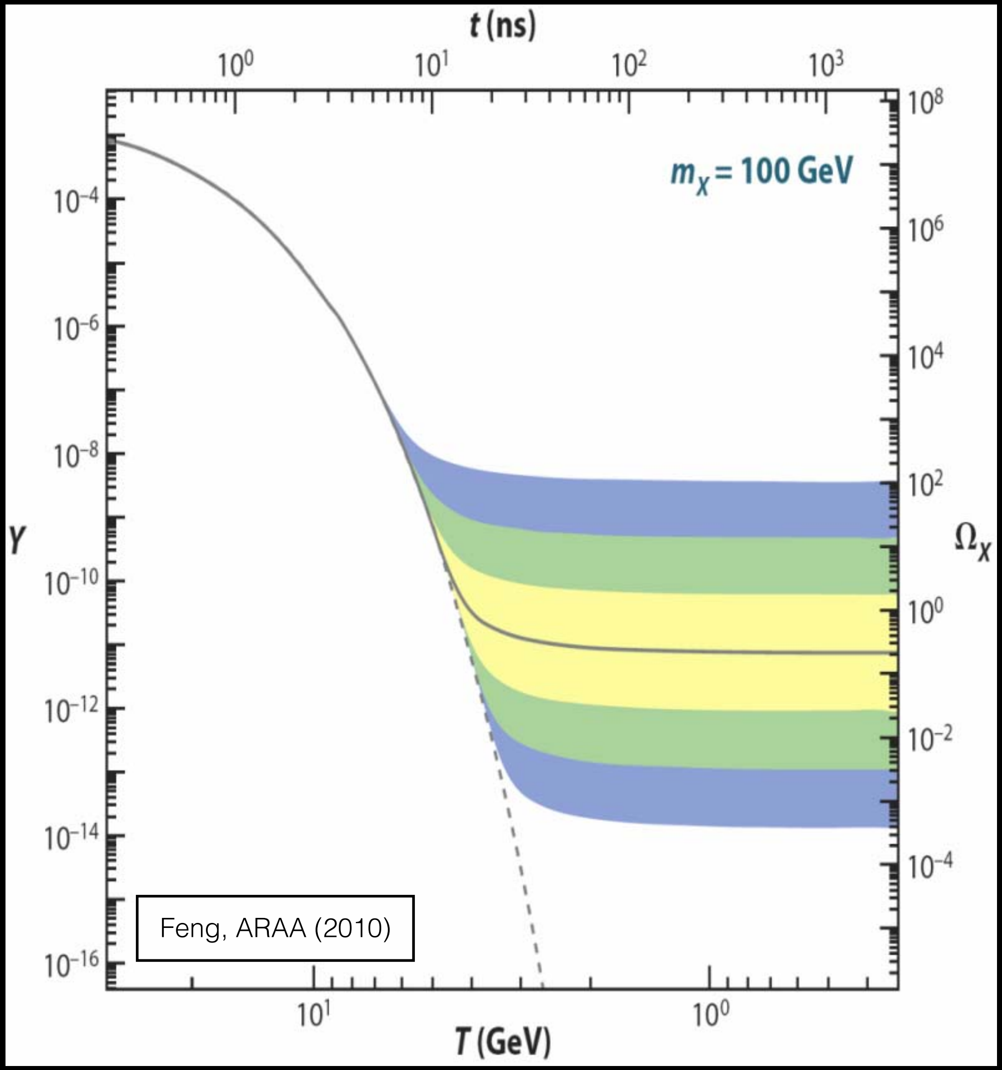
Relic Density

- The basic picture is:
  - We start out with dark matter in equilibrium with the SM plasma.
  - As the temperature falls, the number of WIMPs does too.
  - We track the equilibrium density until freeze-out:

$$n_{eq}\langle\sigma v\rangle \sim H$$

$$(mT)^{3/2}e^{-m/T} \qquad \frac{g^4}{m^2} \qquad \sim \frac{T^2}{M_{Pl}}$$

$$\frac{m}{T} \sim \log\left[\frac{M_{Pl}}{m}\right] \qquad m \sim 100\ \text{GeV} : \frac{m}{T} \sim 40$$



…which determines how many WIMPs are left over.

What IS a WIMP?

Weakly-interacting

Massive

Particle

What IS a WIMP?

Weakly-interacting → Electroweak interaction
SU(2) x U(1)
Z, W, Higgs?

Massive

Particle

What IS a WIMP?

Weakly-interacting → Electroweak interaction

$SU(2) \times U(1)$

Z, W, Higgs?

α_{EM}, $\sin\theta_W$?

Massive

Particle

What IS a WIMP?

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Z, W, Higgs?

α_{EM}, $\sin\theta_W$?

→ Random “weak interaction?”

Symmetries?

Mediator particles?

Massive

Particle

What IS a WIMP?

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SU(2) x U(1)

Z, W, Higgs?

α_{EM}, $\sin\theta_W$?

Massive

Random "weak interaction?"

Symmetries?

Mediator particles?

g < around 1

Freeze-out relic?

Particle

What IS a WIMP?

Weakly-interacting

Electroweak interaction

SU(2) x U(1)

Z, W, Higgs?

α_{EM}, sin θ_W ?

Random "weak interaction?"

Symmetries?

Mediator particles?

g < around 1

Freeze-out relic?

Massive

Anything cold?

Particle

What IS a WIMP?

Weakly-interacting → Electroweak interaction

$SU(2) \times U(1)$

Z, W, Higgs?

α_{EM}, $\sin\theta_W$?

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

What IS a WIMP?

Weakly-interacting → Electroweak interaction

$SU(2) \times U(1)$

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Particle → Yes?

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Weakly-interacting → Electroweak interaction

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Symmetries?

Mediator particles?

g < around 1

Freeze-out relic?

Massive → Anything cold?

Massive →

> 10 keV?

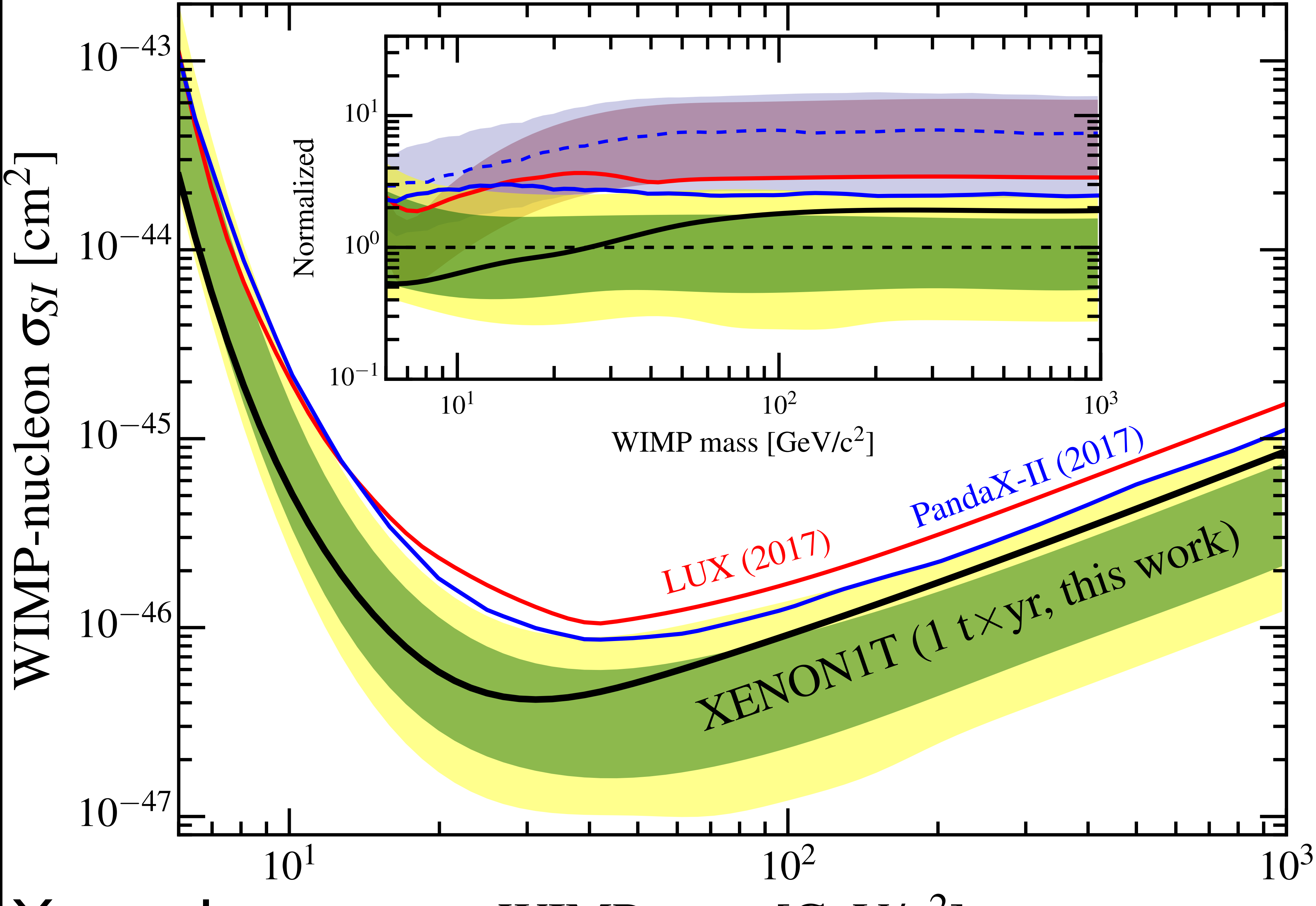
>1 GeV?

~ 100 GeV

< 100 TeV?

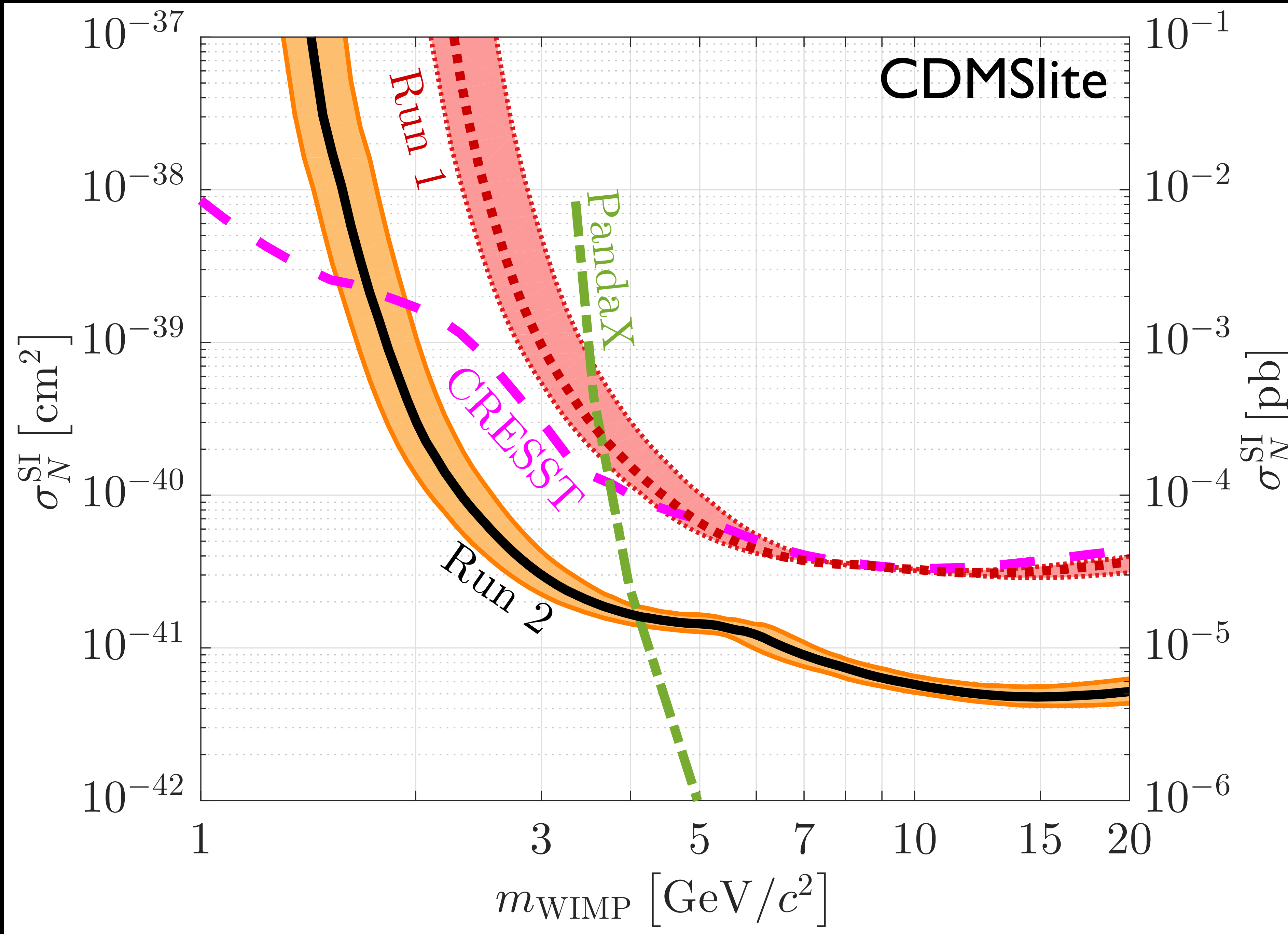
Particle → Yes?

Particle → Fields? Fuzzy? Superfluid?!



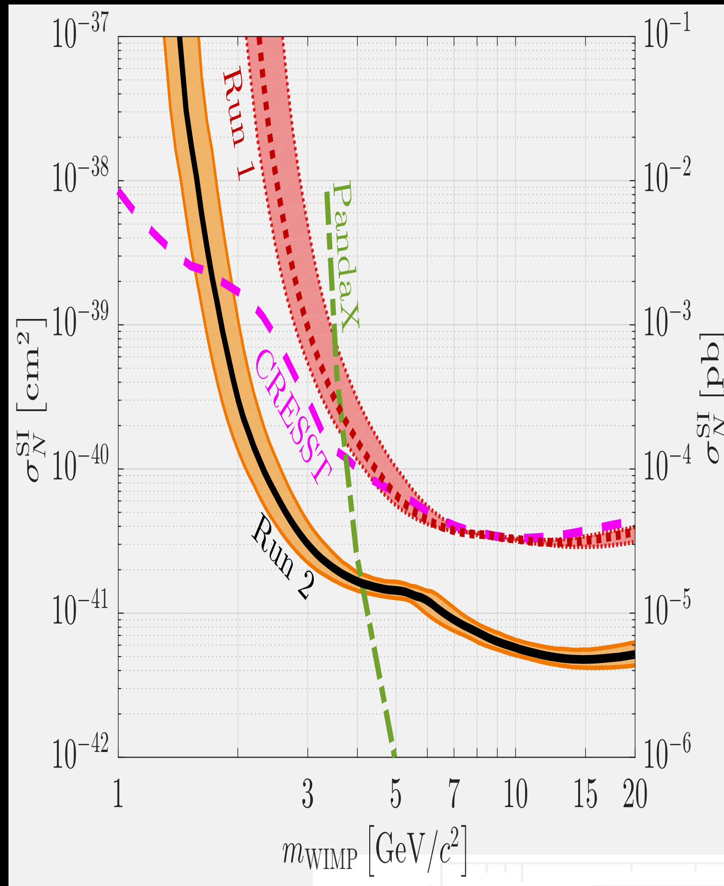
WIMP-nucleon σ_{SI} [cm^2]
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{1}
10^{2}
10^{3}
WIMP mass [GeV/c^2]
LUX (2017)
PandaX-II (2017)
XENON1T (1 t×yr, this work)
Normalized
10^{1}
10^{0}
10^{-1}
10^{1}
10^{2}
10^{3}
WIMP mass [GeV/c^2]

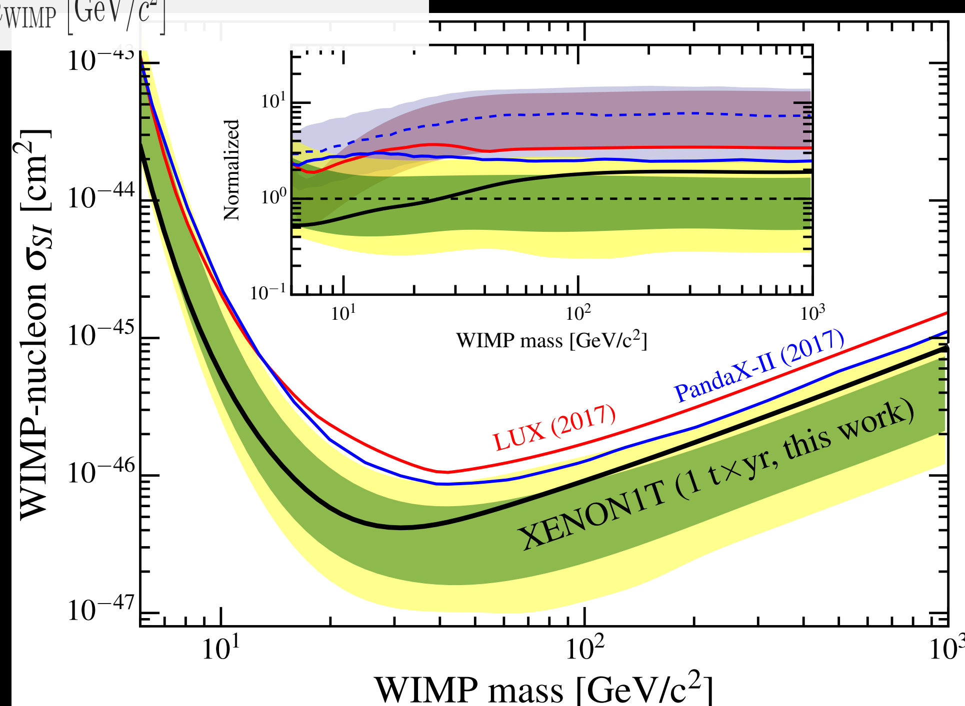
Xenon 1t



CDMSlite
Run 1
Run 2
PandaX
CRESST
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1
3
5
7
10
15
20
σ_N^{SI} [cm^2]
σ_N^{SI} [pb]
m_{WIMP} [GeV/c^2]

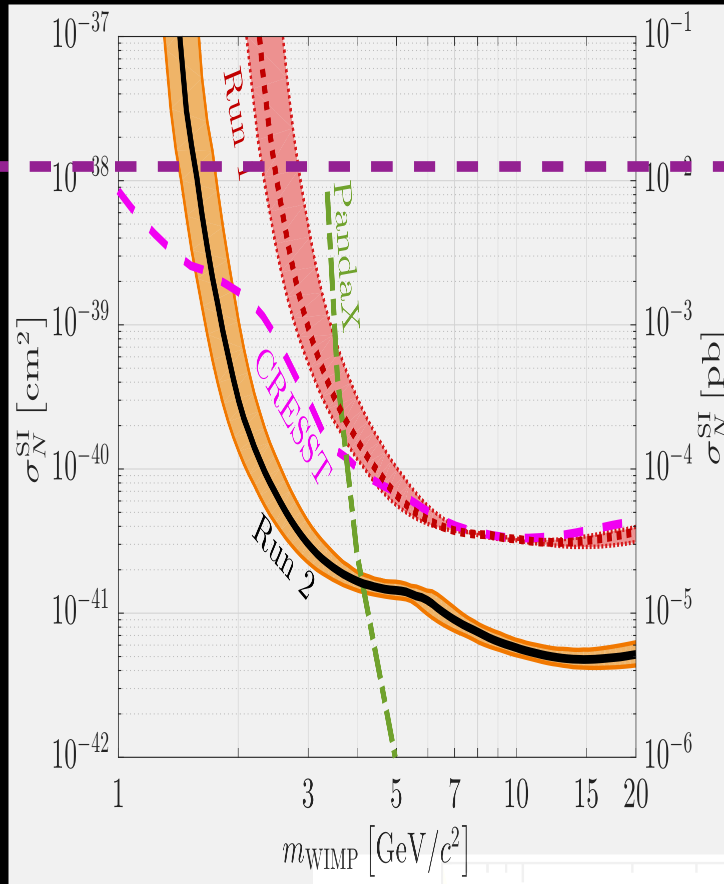
Ceiling:
These limits become ineffective around 10^{-33} cm^2

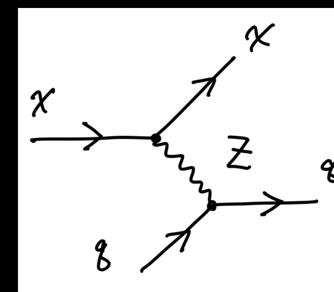




Freeze-out σ is model-dependent in this parameter space

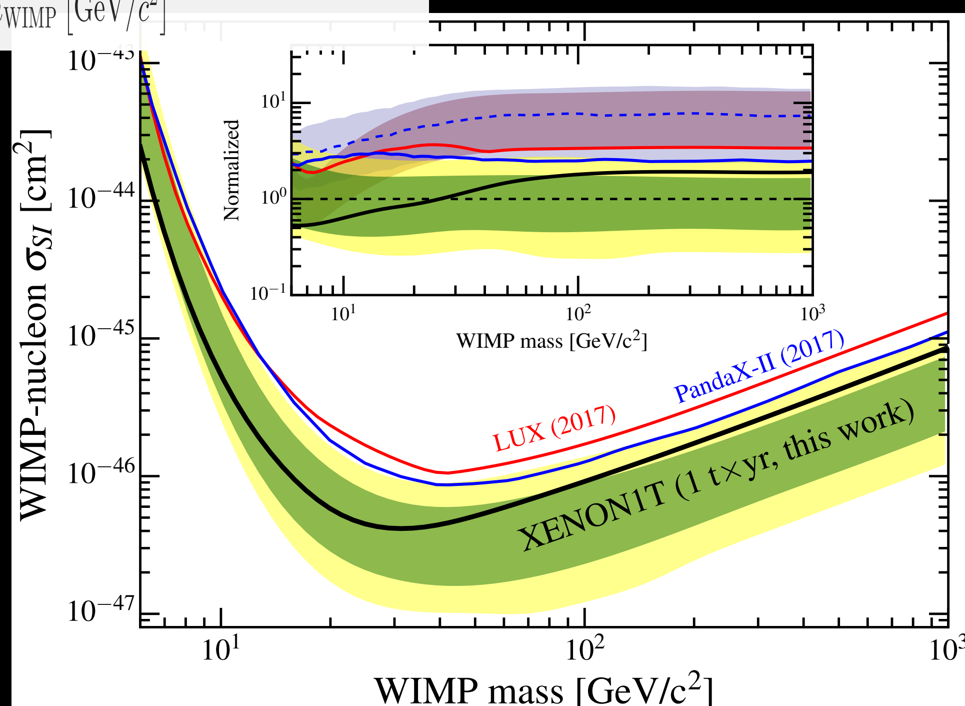
“Electroweak” Cross section



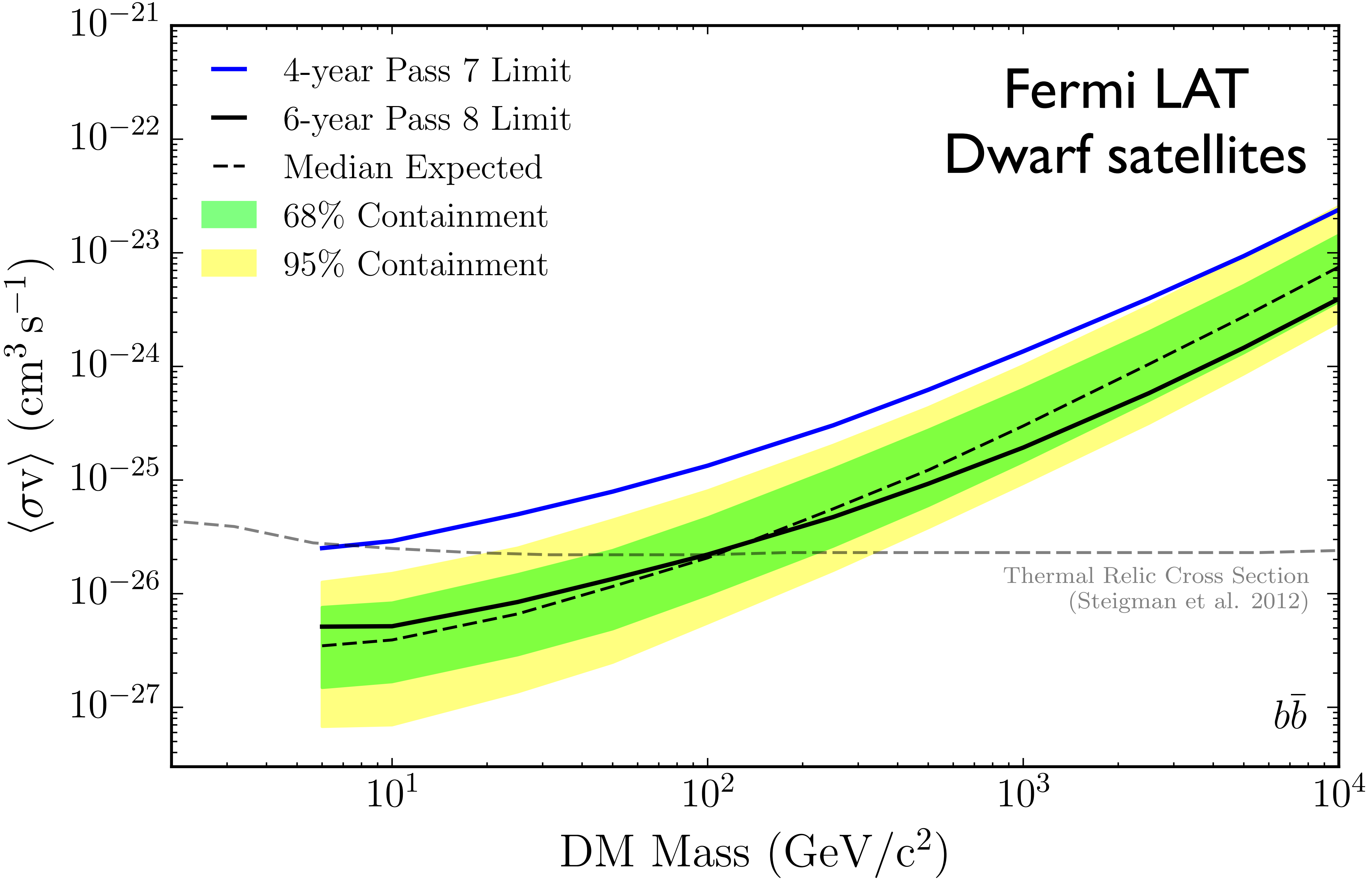


(excluded by CDMS ~2000 for a wide range of masses)

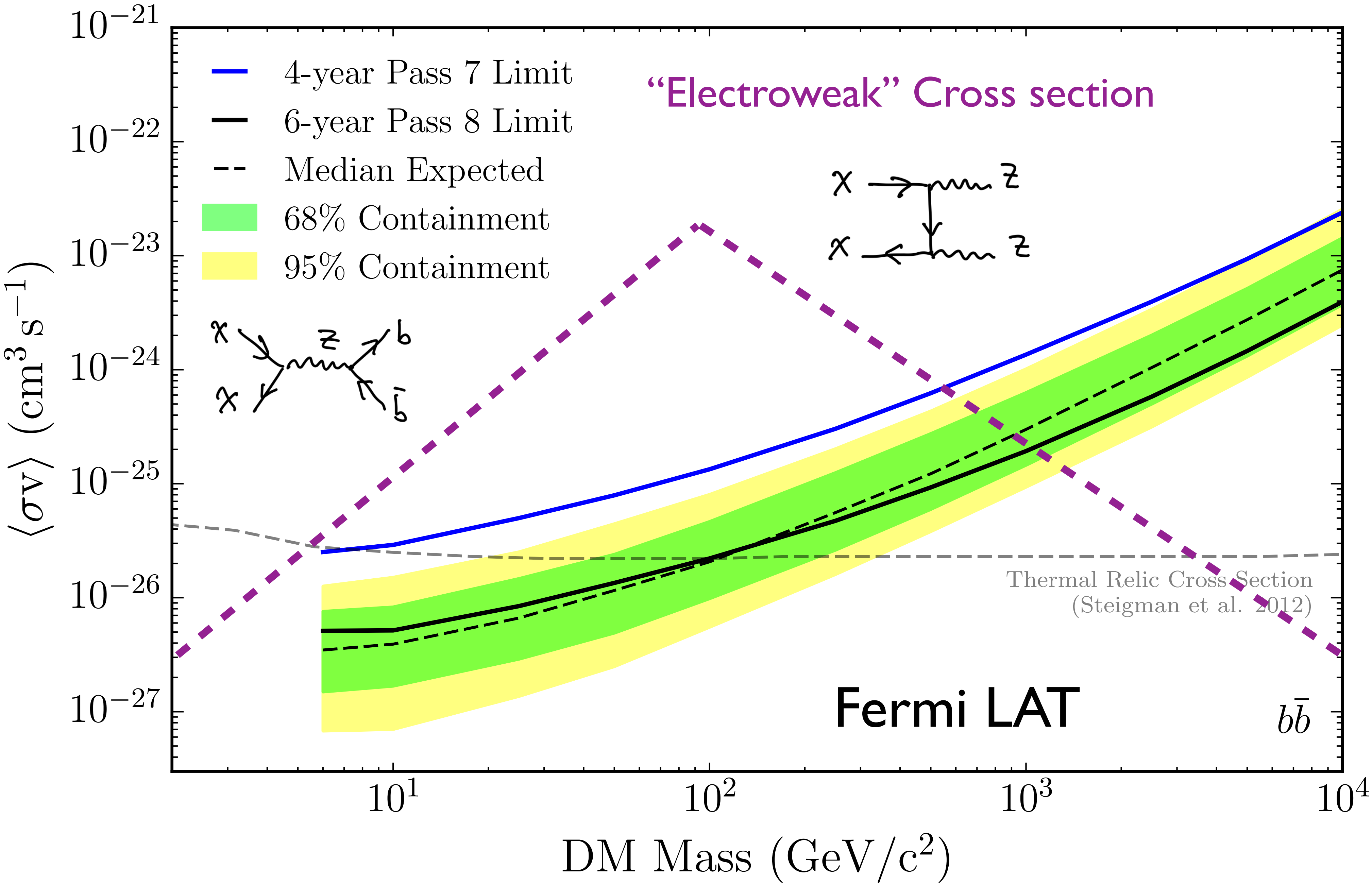
Now: 2 GeV to ~10^7 GeV



Warning:
Lots of “back of the envelope” estimates in these slides



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



"Electroweak" Cross section
4-year Pass 7 Limit
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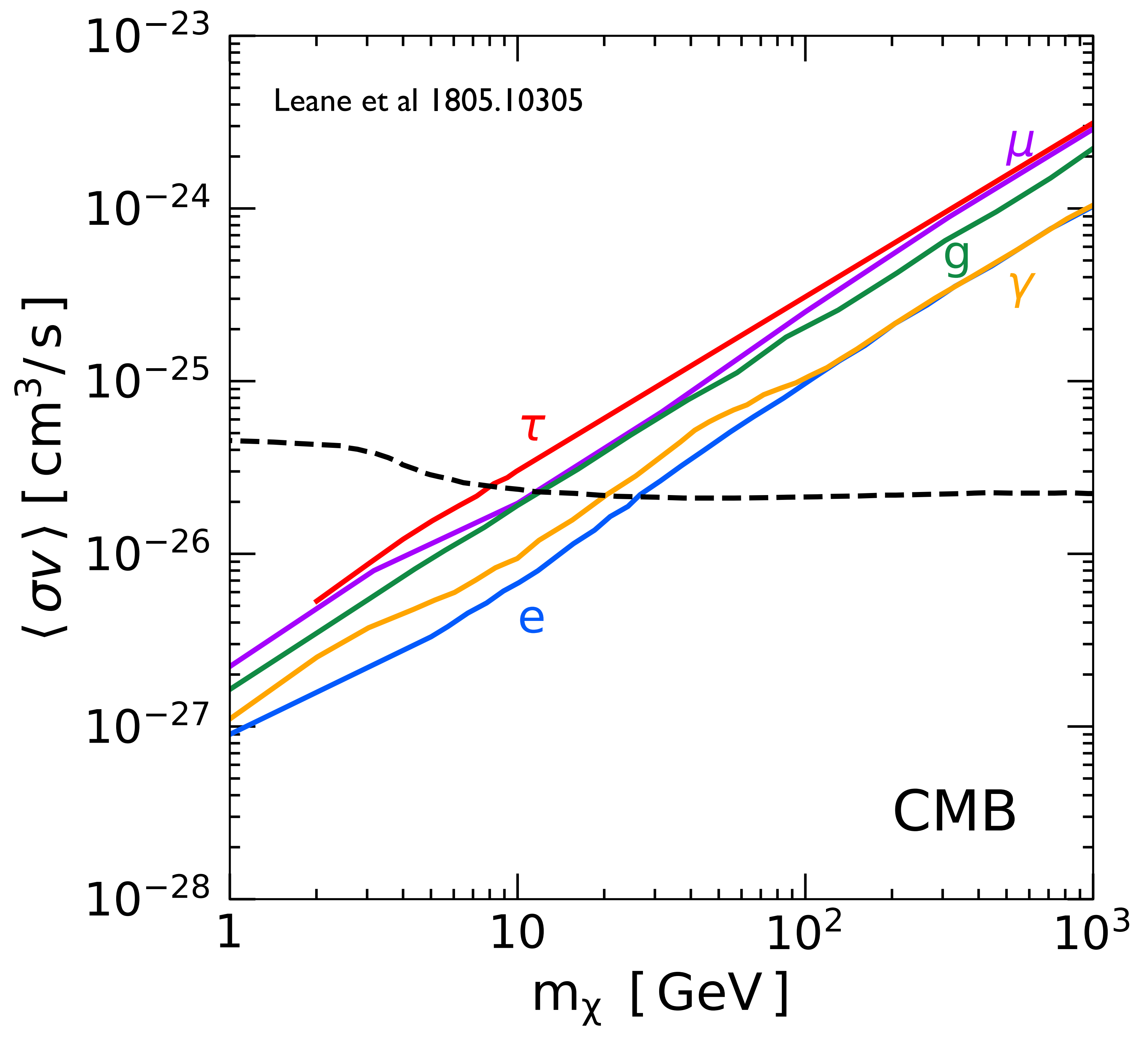
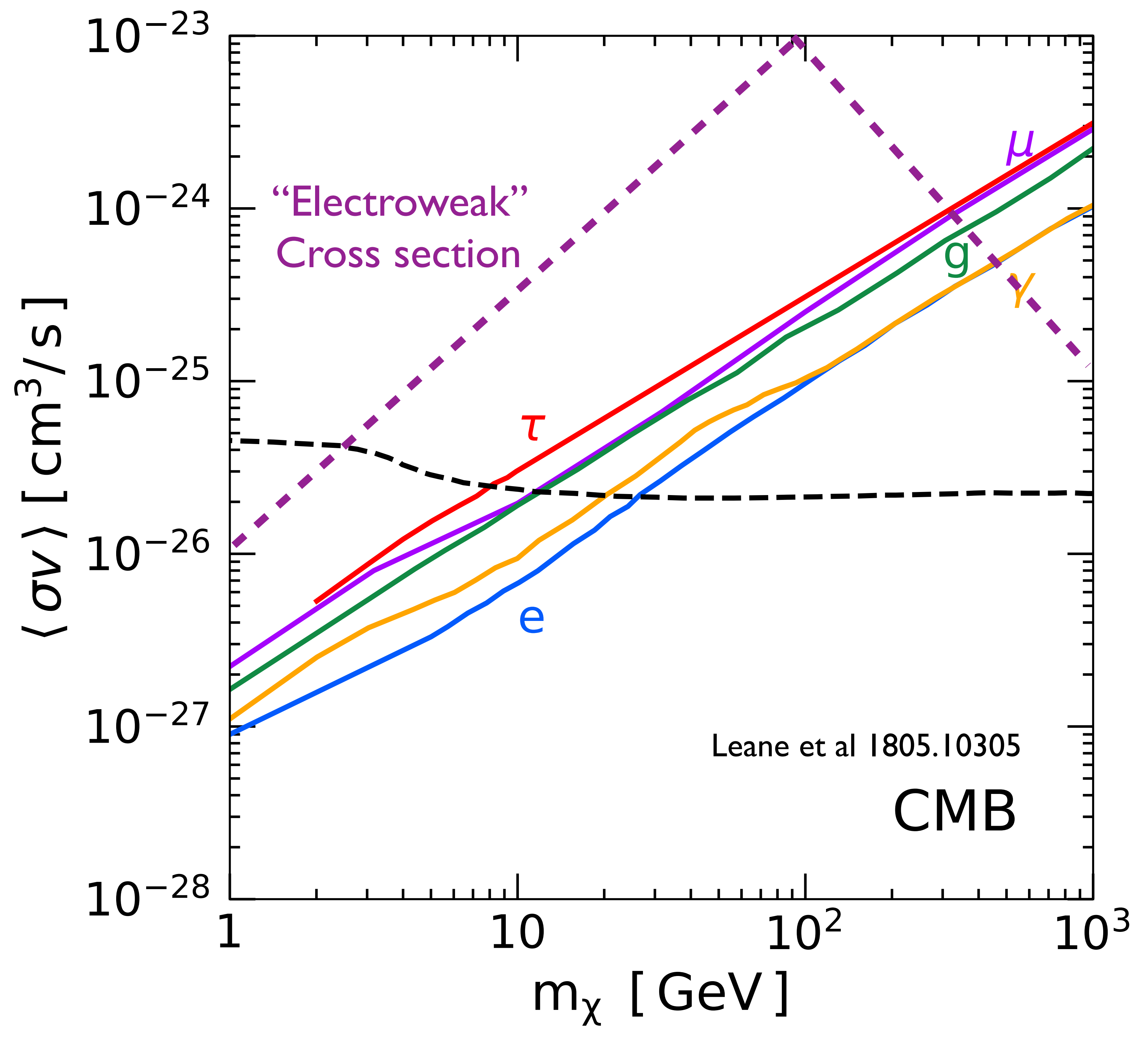
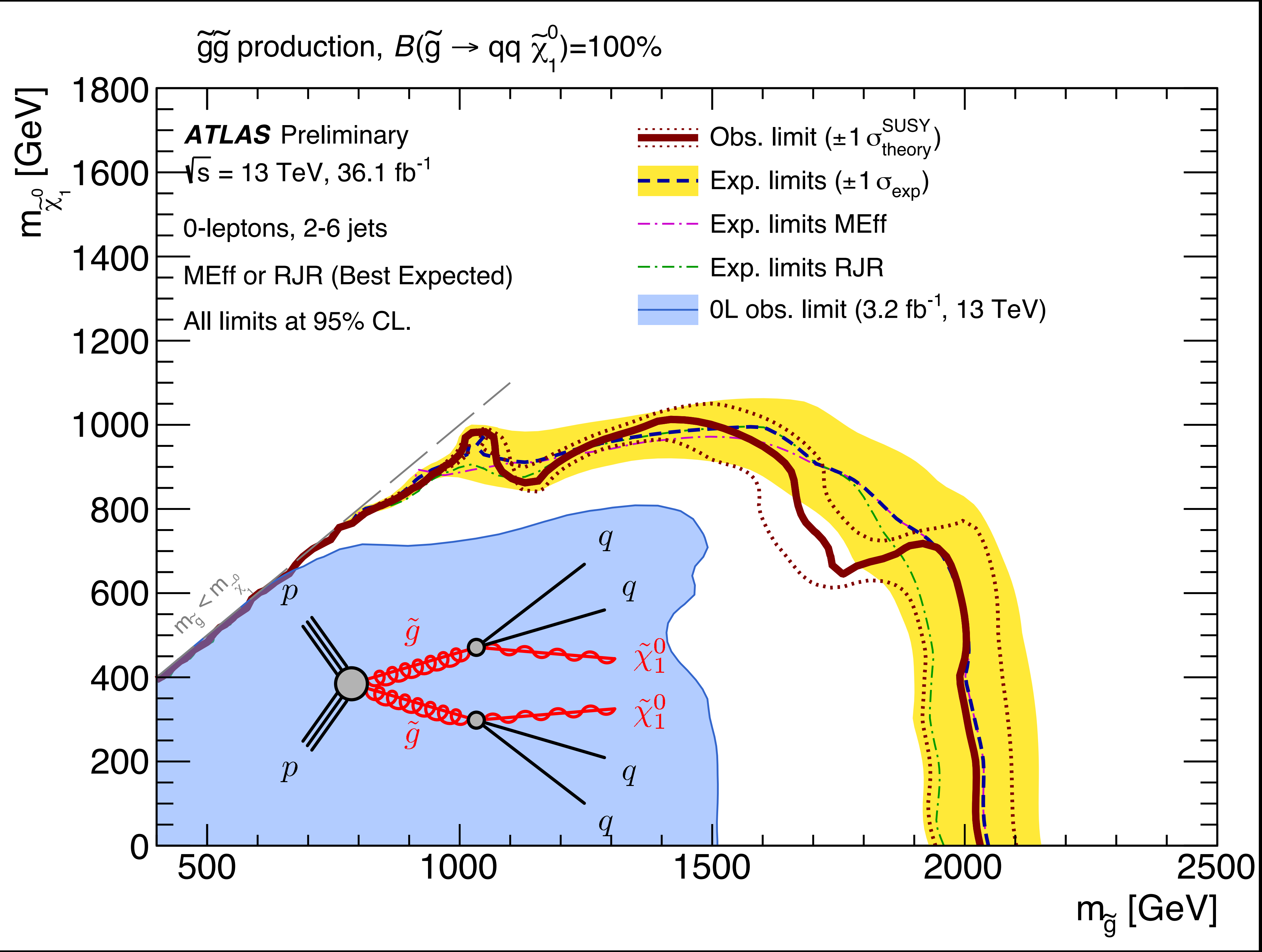
DM Mass (GeV/c^2)



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


"Electroweak"
Cross section
μ
g
γ
τ
e
Leane et al 1805.10305
CMB
$\langle \sigma v \rangle$ [cm³/s]
m_χ [GeV]
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
1
10
10^2
10^3

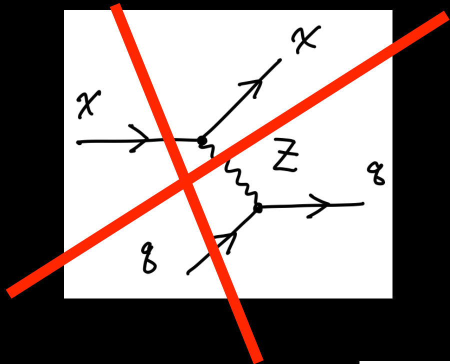


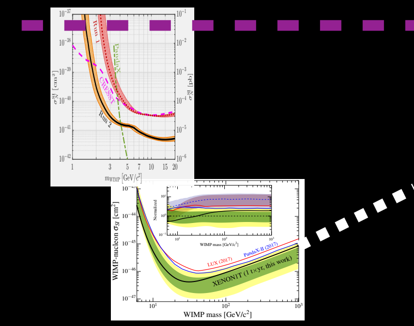
g̃g̃ production, B(g̃ → qq χ̃₁⁰)=100%
ATLAS Preliminary
√s = 13 TeV, 36.1 fb-1
0-leptons, 2-6 jets
MEff or RJR (Best Expected)
All limits at 95% CL.
Obs. limit (±1 σ theory SUSY)
Exp. limits (±1 σ exp)
Exp. limits MEff
Exp. limits RJR
0L obs. limit (3.2 fb-1, 13 TeV)
m g̃ < m χ̃₁⁰
m χ̃₁⁰ [GeV]
m g̃ [GeV]
1800
1600
1400
1200
1000
800
600
400
200
0
500
1000
1500
2000
2500
p
p
g̃
g̃
q
q
q
q
χ̃₁⁰
χ̃₁⁰

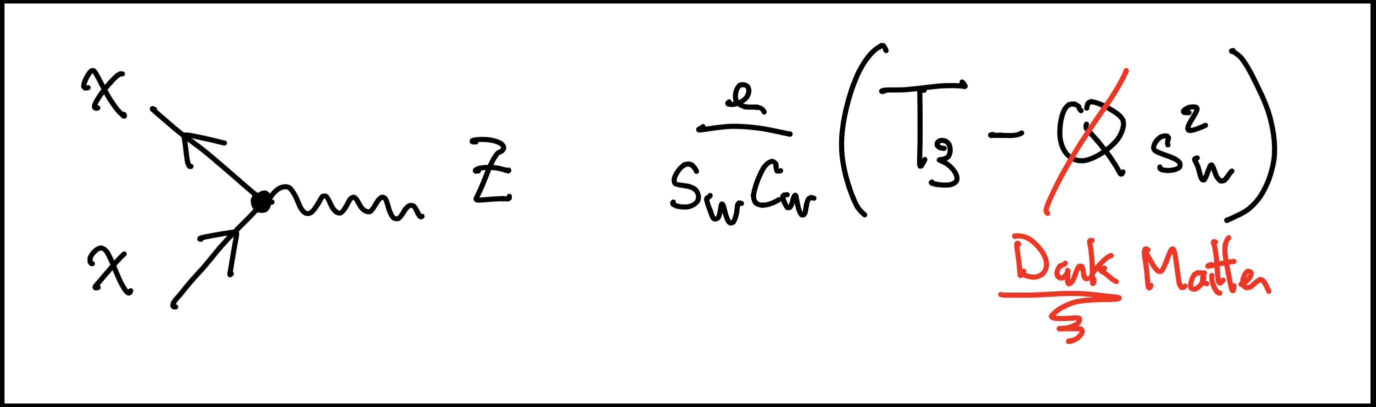
So what does this mean for WIMPs?

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
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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	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$

Goodman et al, 1008.1783

Nonrelativistic EFT

1. P-even, S_χ-independent

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

Spin Independent

2. P-even, S_χ-dependent

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

Spin Dependent

3. P-odd, S_χ-independent

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

4. P-odd, S_χ-dependent

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

5. P-odd, S_χ-independent:

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

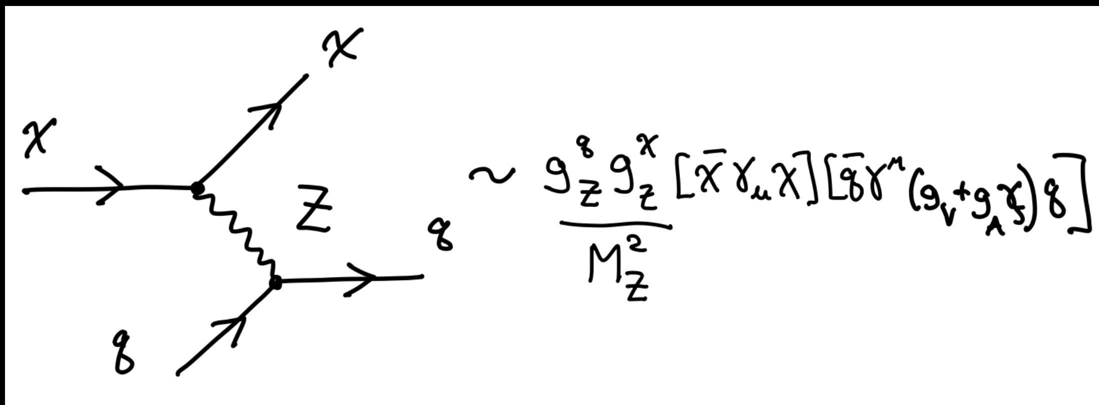
6. P-odd, S_χ-dependent

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

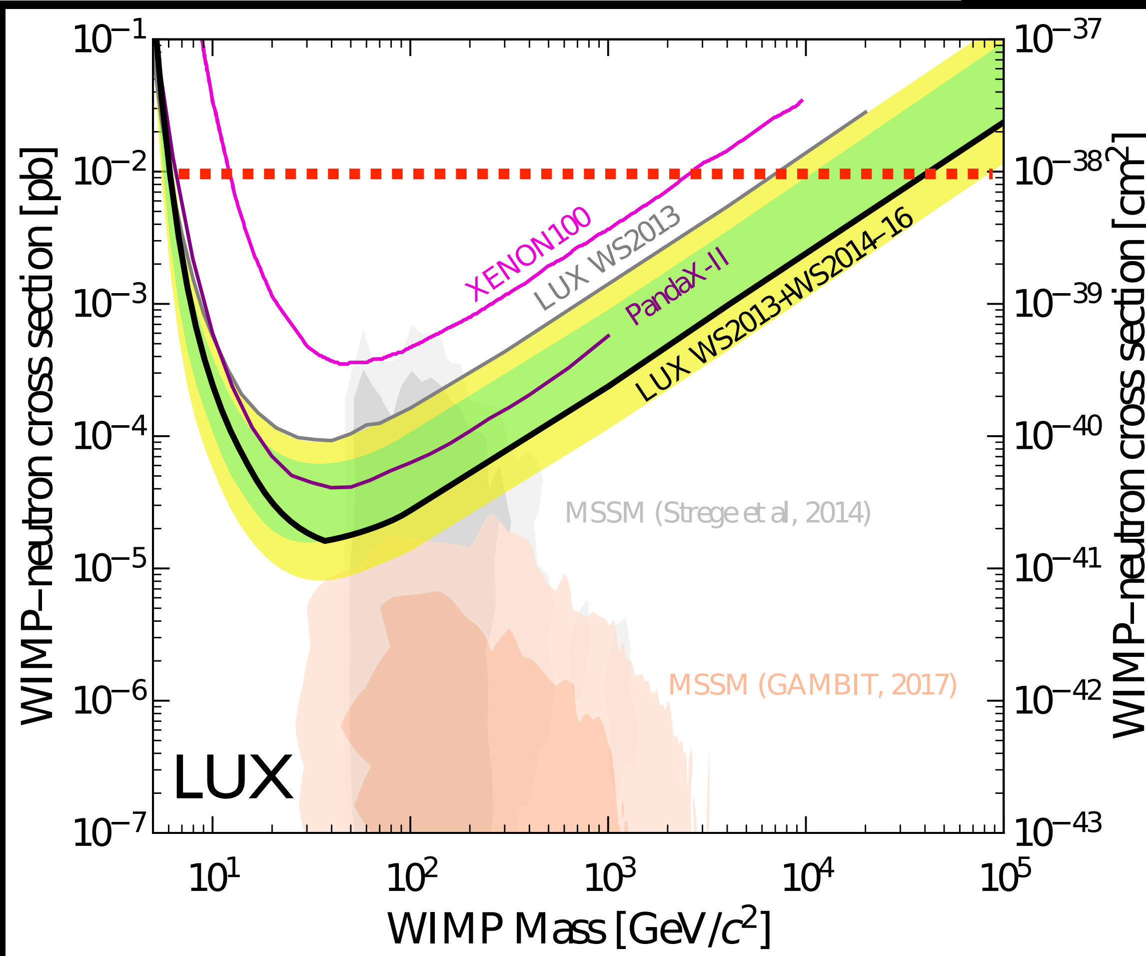
Fitzpatrick et al, 1203.3542

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

Majorana DM



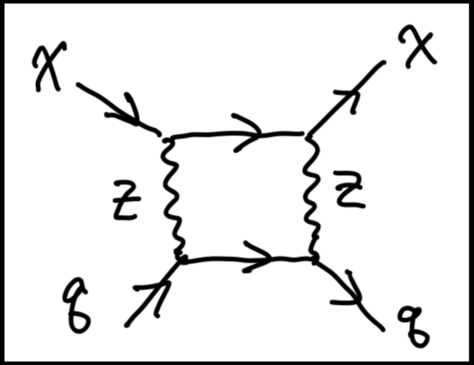
The vector interaction vanishes (identically) for a Majorana particle. That leaves behind spin-dependent (and v-suppressed) terms.



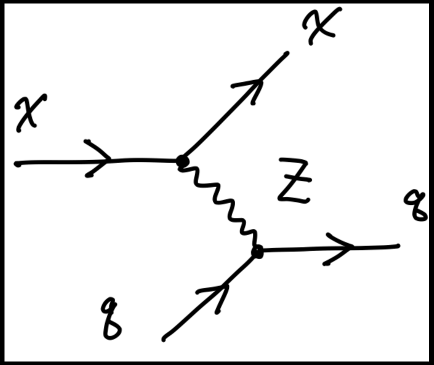
That suggests another strategy for EW-charged WIMPs:
Majorana particles are less constrained than Dirac, even if they carry hyper-charge.

…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 $\sim 10^{-3}$.

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

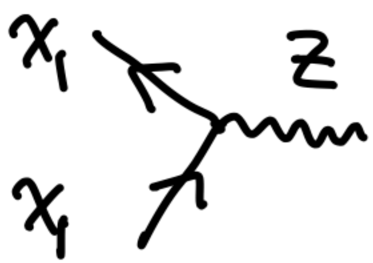
Mixed DM

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.

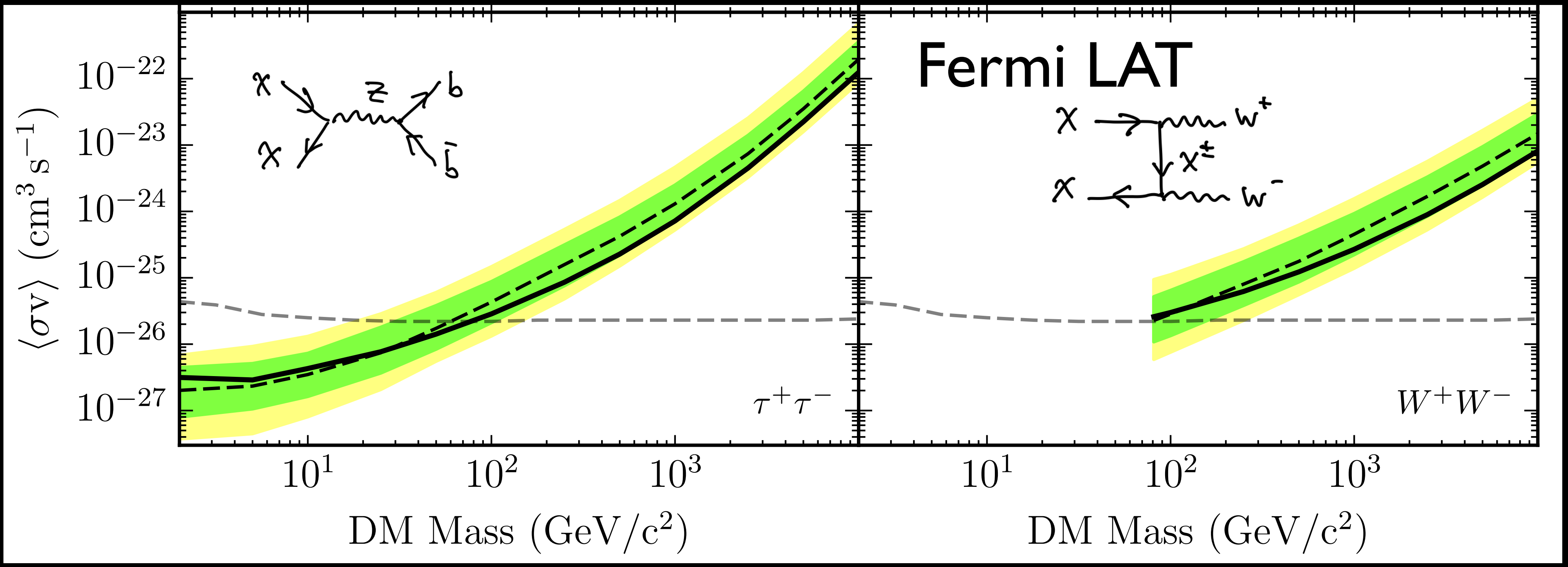
$$\chi_1 = N_{11} S_1 + N_{12} S_2 + N_{13} S_3 + \dots$$



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

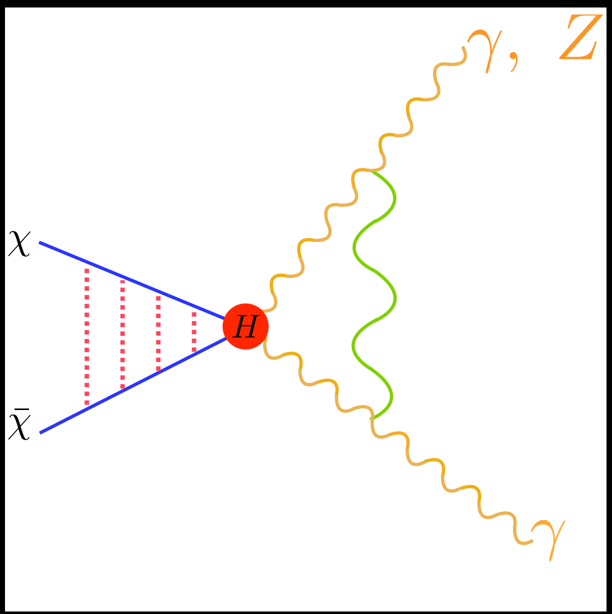
Indirect Constraints

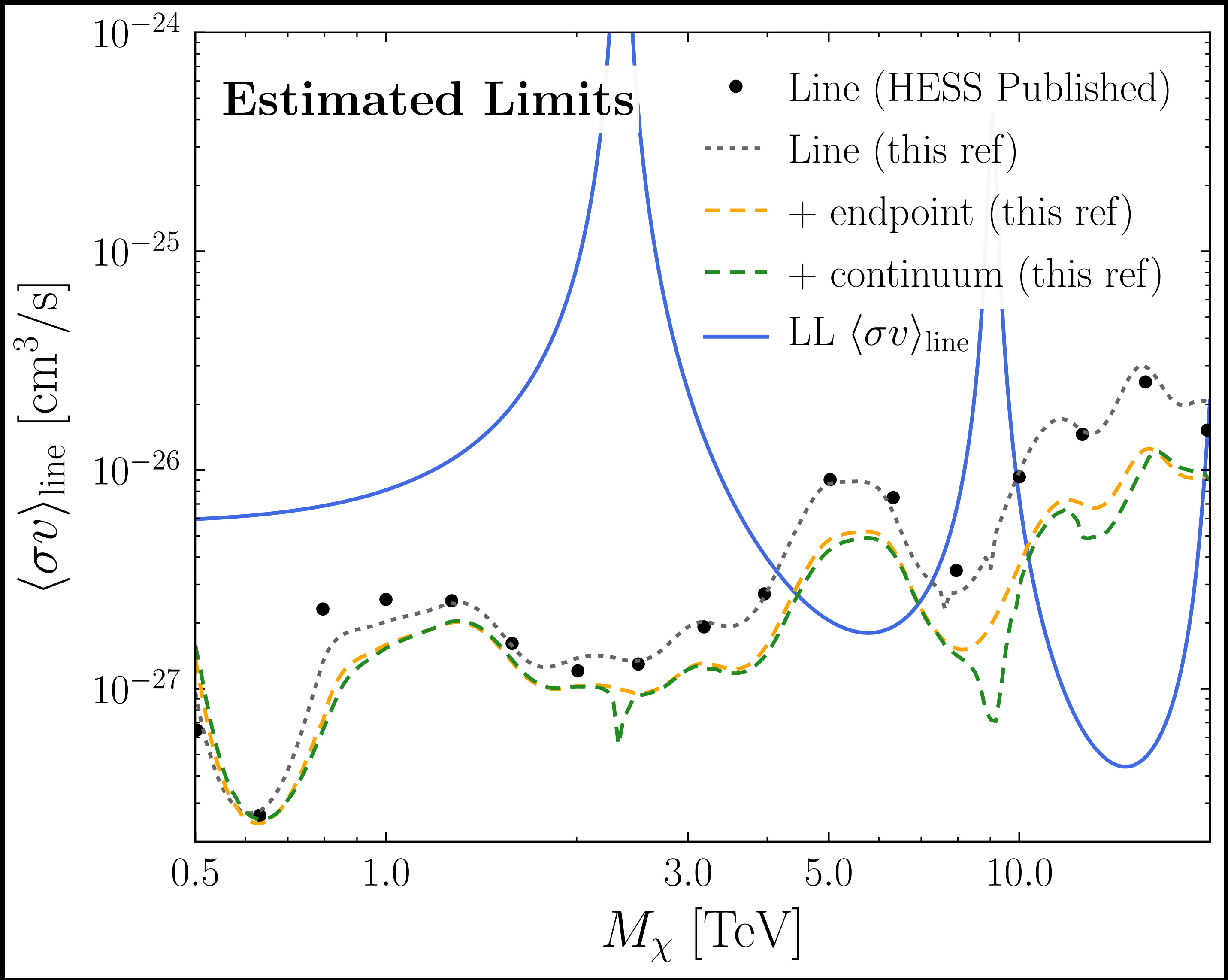
It isn't enough to engineer away scattering with nuclei. There are also important constraints from indirect detection too.



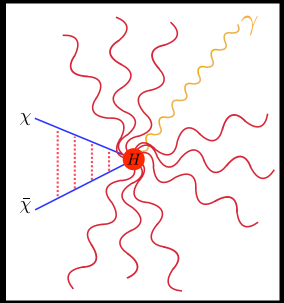
The Majorana and T3=0 options work here as well, below the threshold for ZZ and WW annihilation. Z-exchange is suppressed by either the velocity or the mass of the final fermions.

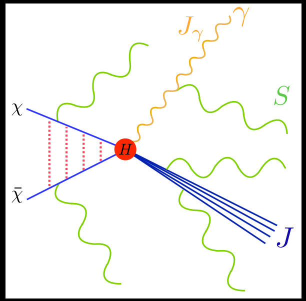
Heavy EW WIMPs



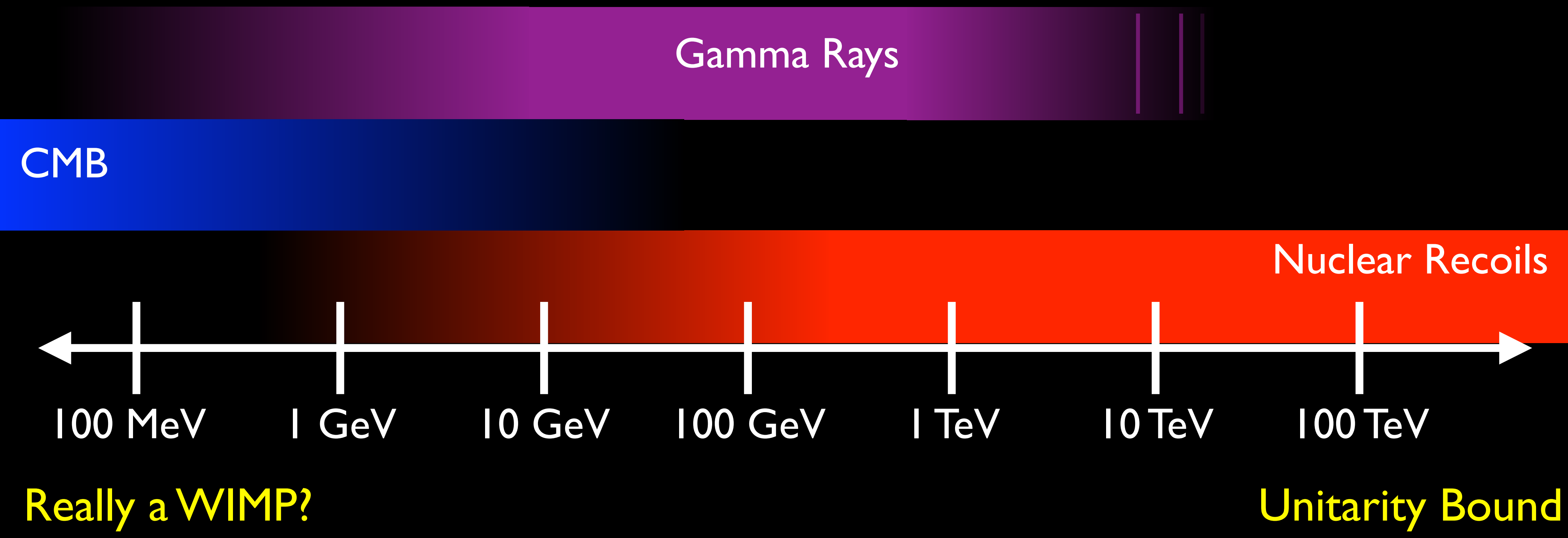


Baumgart, Cohen, Mouilt, Rodd, Slatyer, Solon, Stewart, Vaidya. 1712.07656

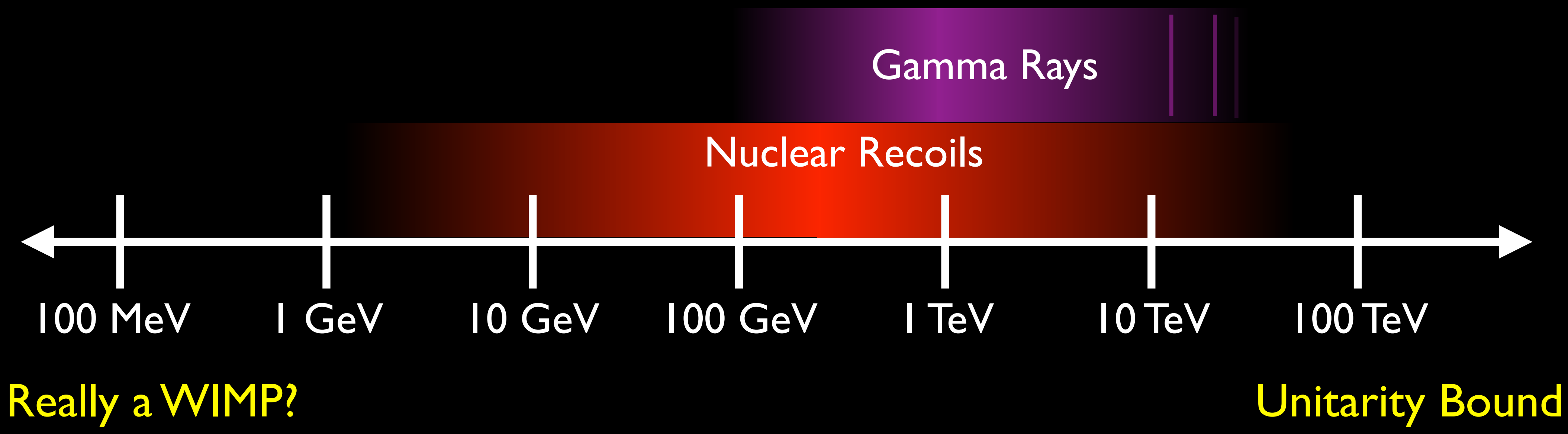




Dirac EW-Charged WIMP Scorecard



Majorana EW-Charged WIMP Scorecard



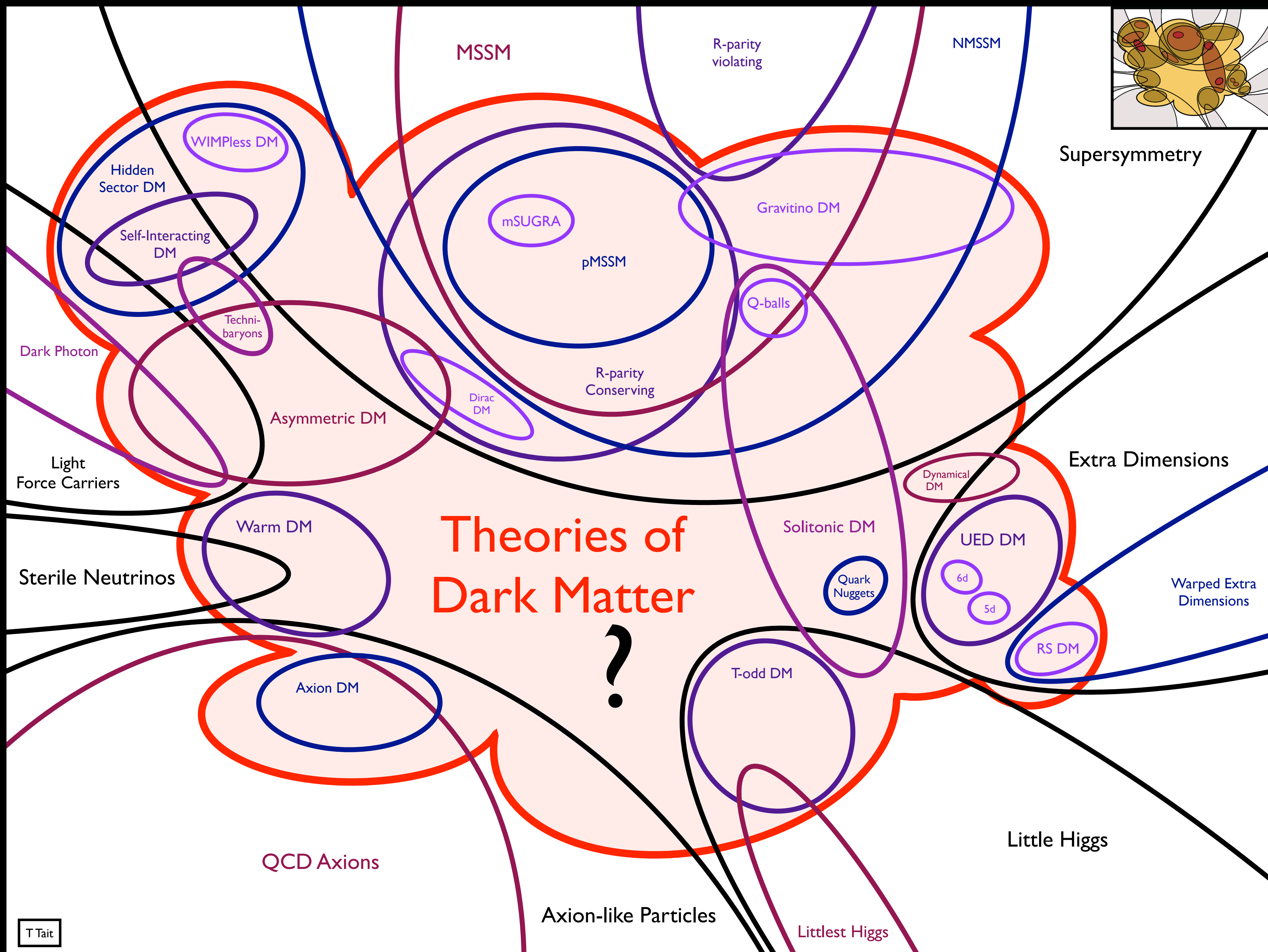
“Kinda-weakly” Interacting Massive Particles

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.

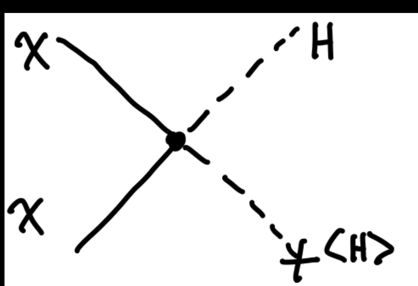
Things become much more model-dependent. Let’s just consider a few strategies one can use to engineer viable models.


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

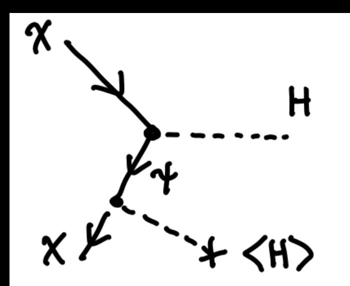
Higgs

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

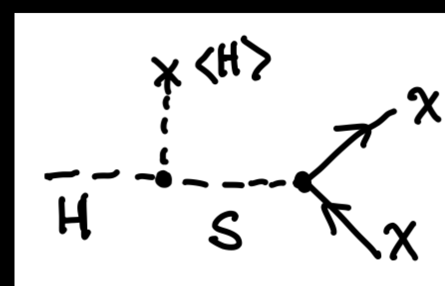
It is very unlikely that the Higgs is the source of mass for the dark matter in the same way that it is for the SM particles.



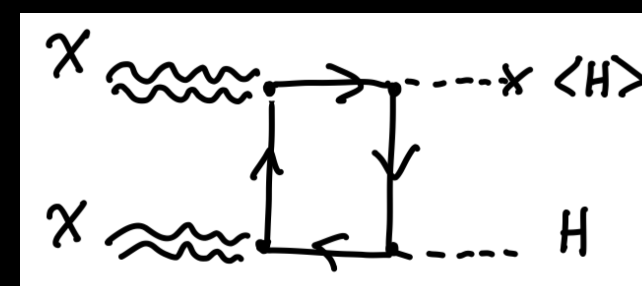
Classic Scalar DM
Higgs portal



Mixed fermions
(MSSM-like)



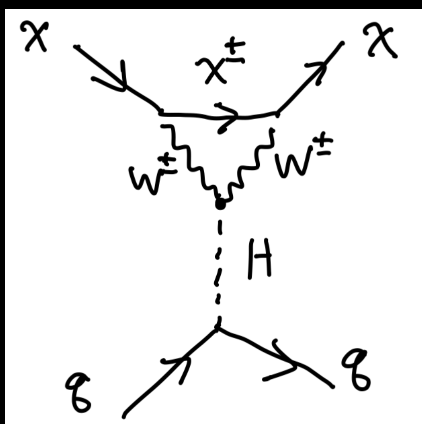
Mixed scalar
mediator

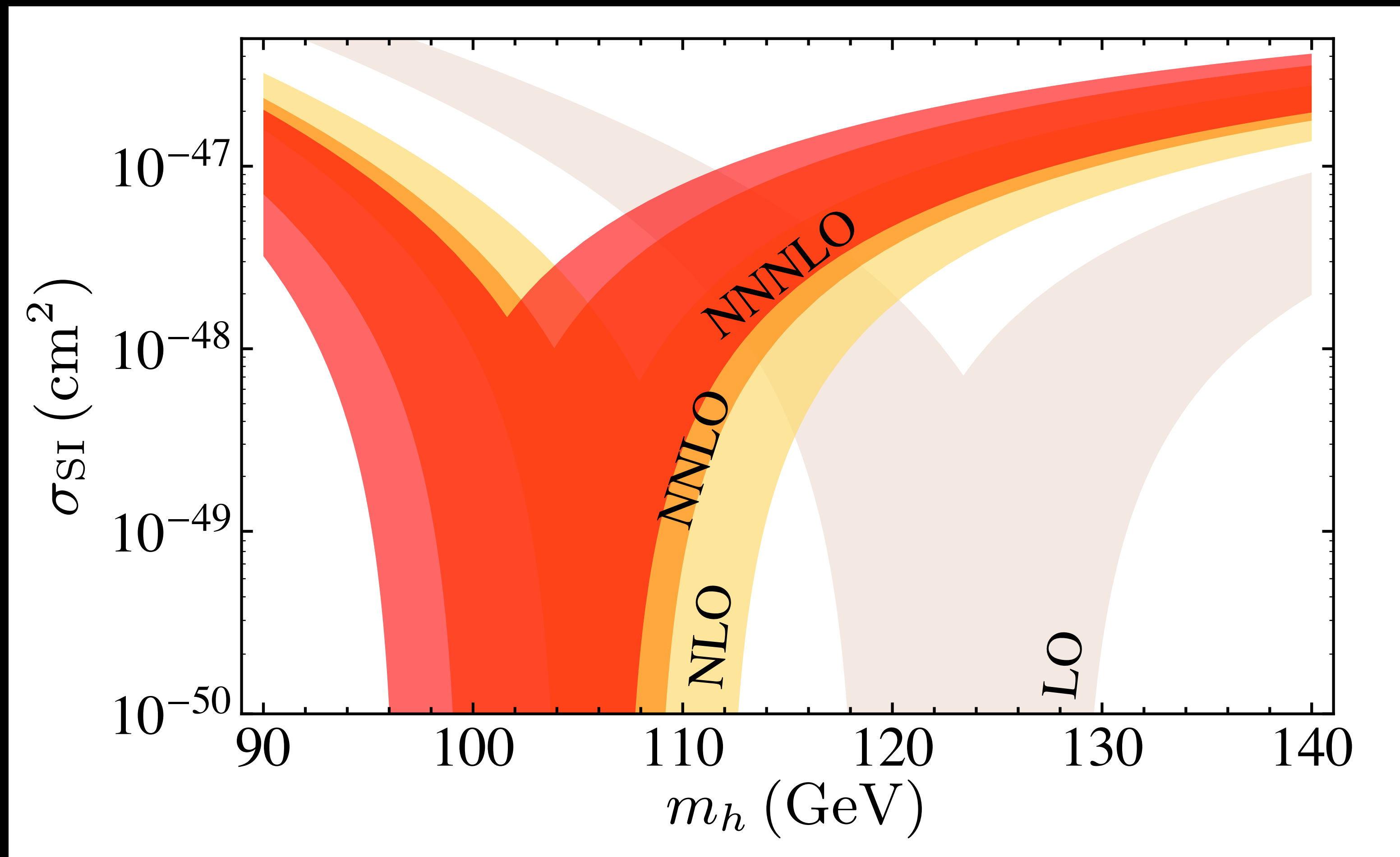


Vector dark matter,
radiative portal

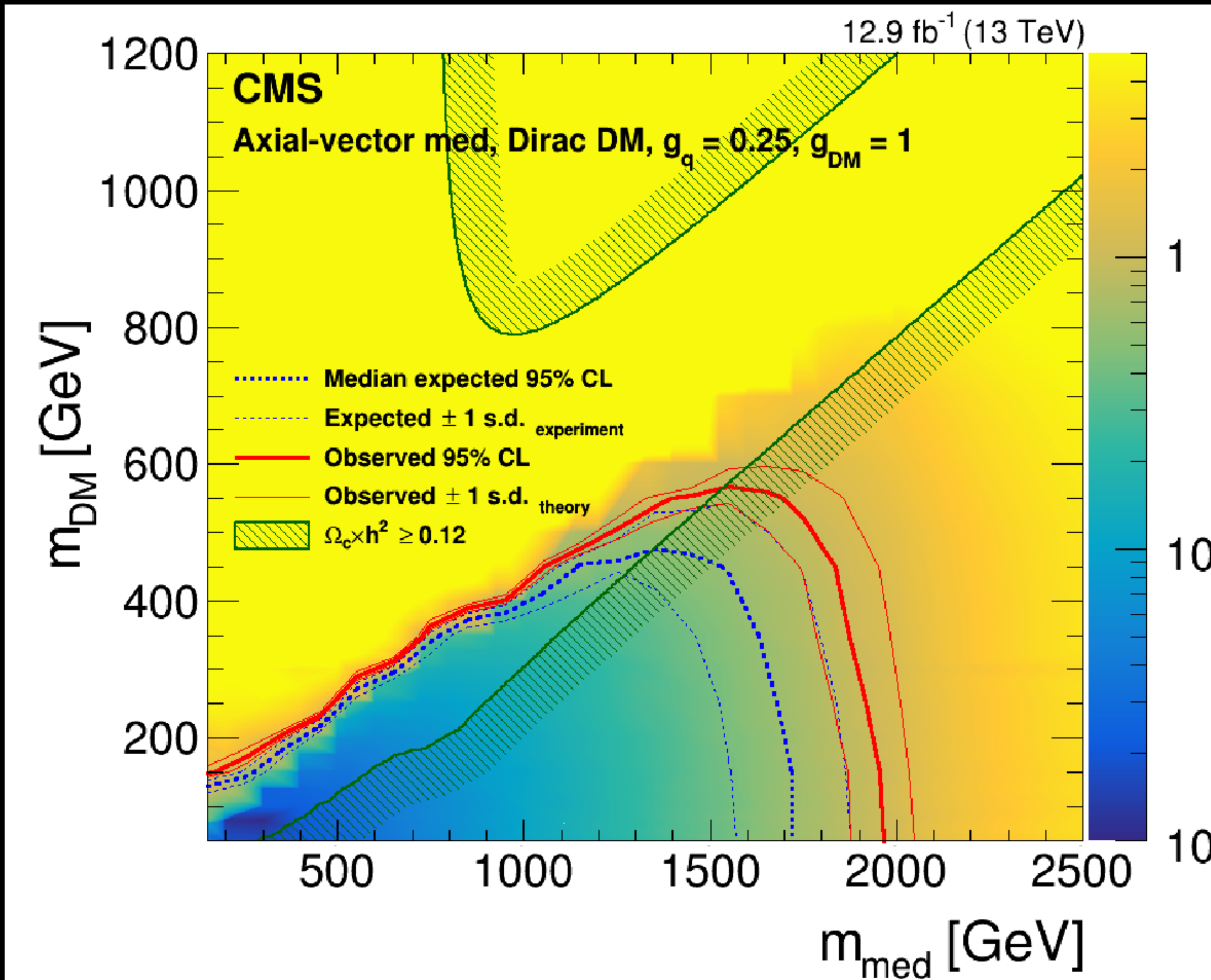
EW Higgs Exchange

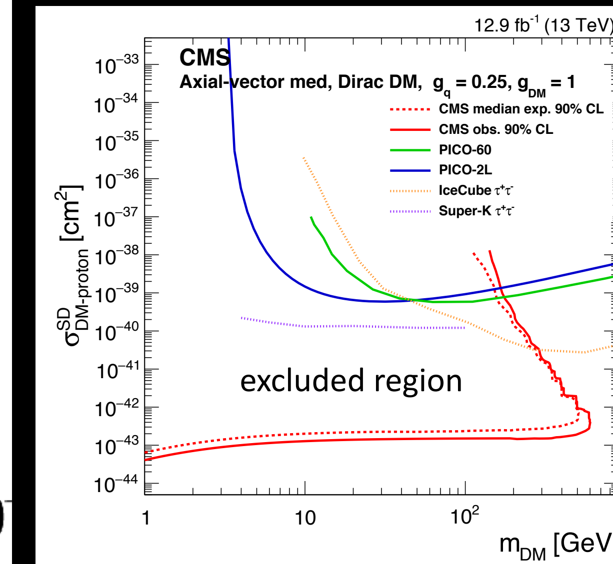
Hill, Solon 1309.4092

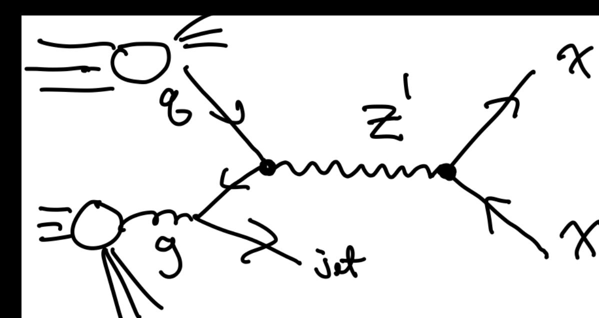




Even without a tree level coupling to the Higgs, an EW-charged WIMP picks up a coupling at one loop.

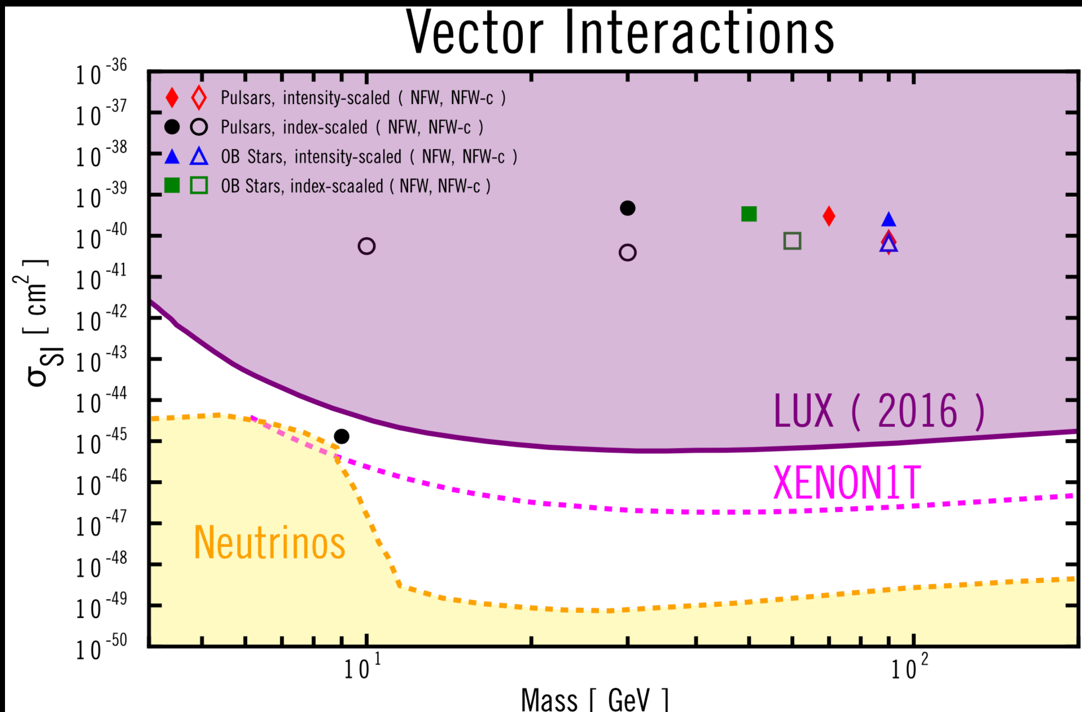


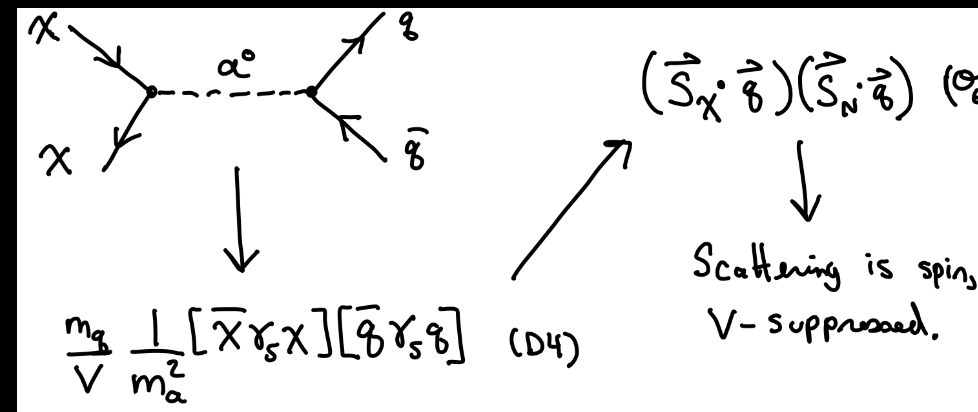




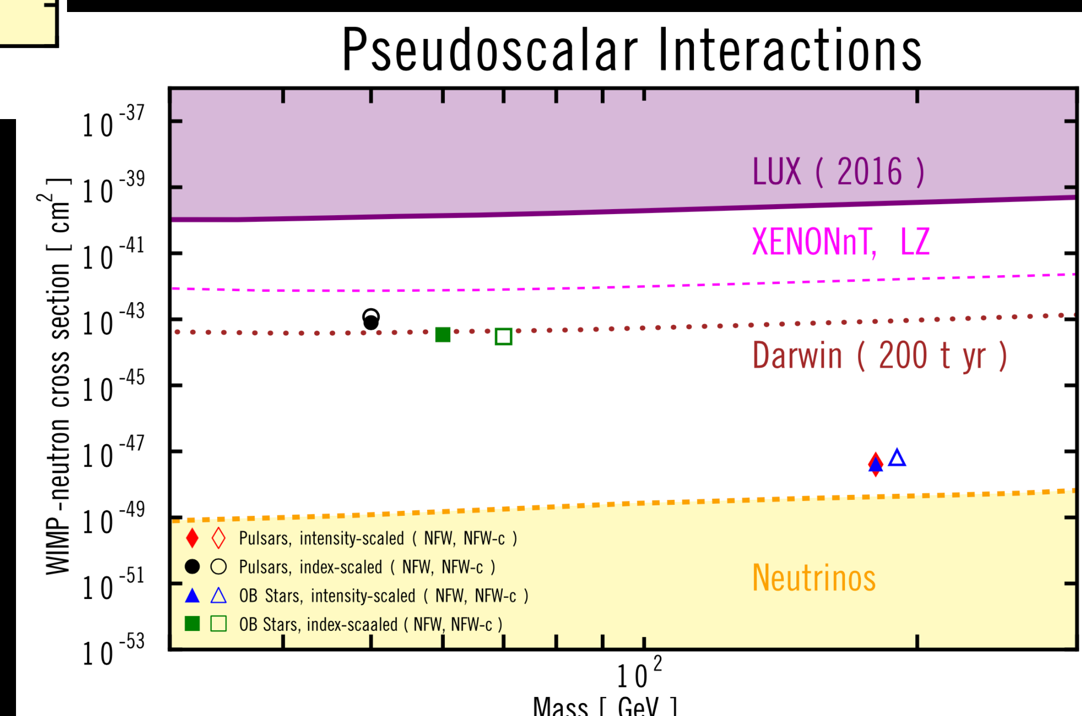
Axial vector — SD at tree level.
Note the choice of DM and quark couplings.

Pseudo-scalar Mediator



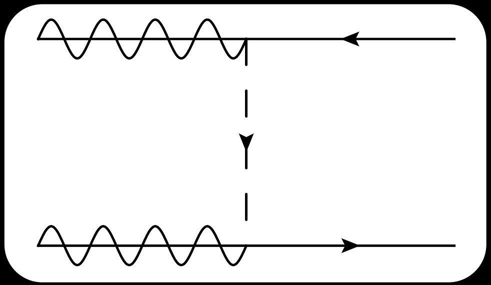


Karwin et al 1612.05687

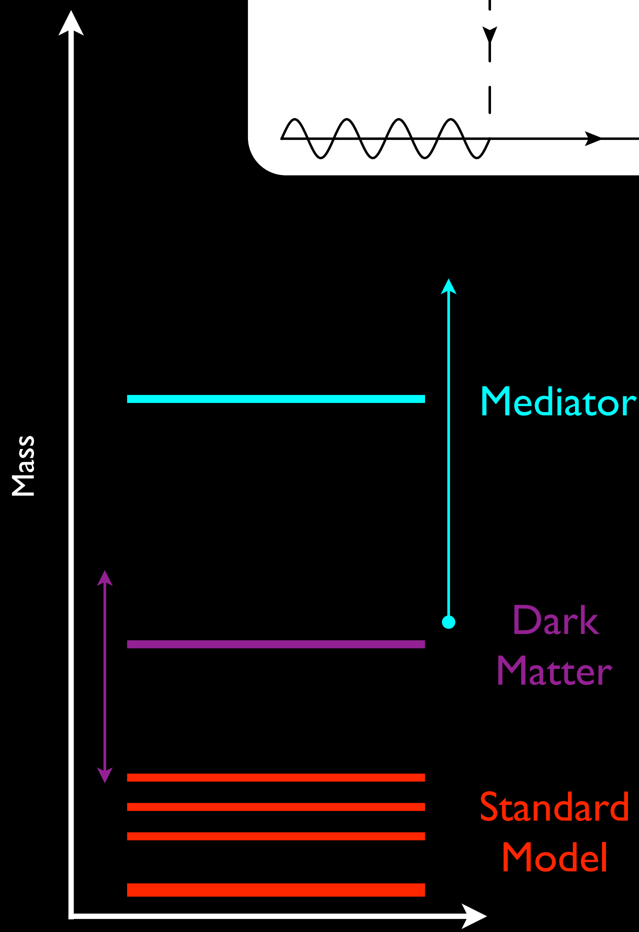


A pseudo-scalar mediator leads to scattering which is both SD and v-suppressed, but annihilation is not suppressed.

Colored Scalar

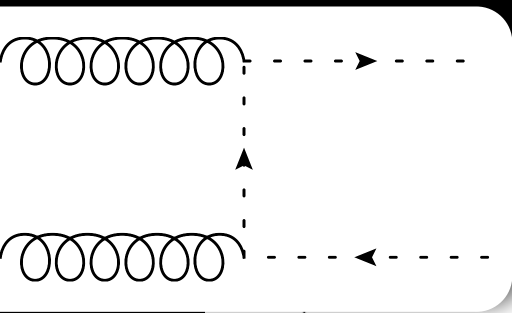


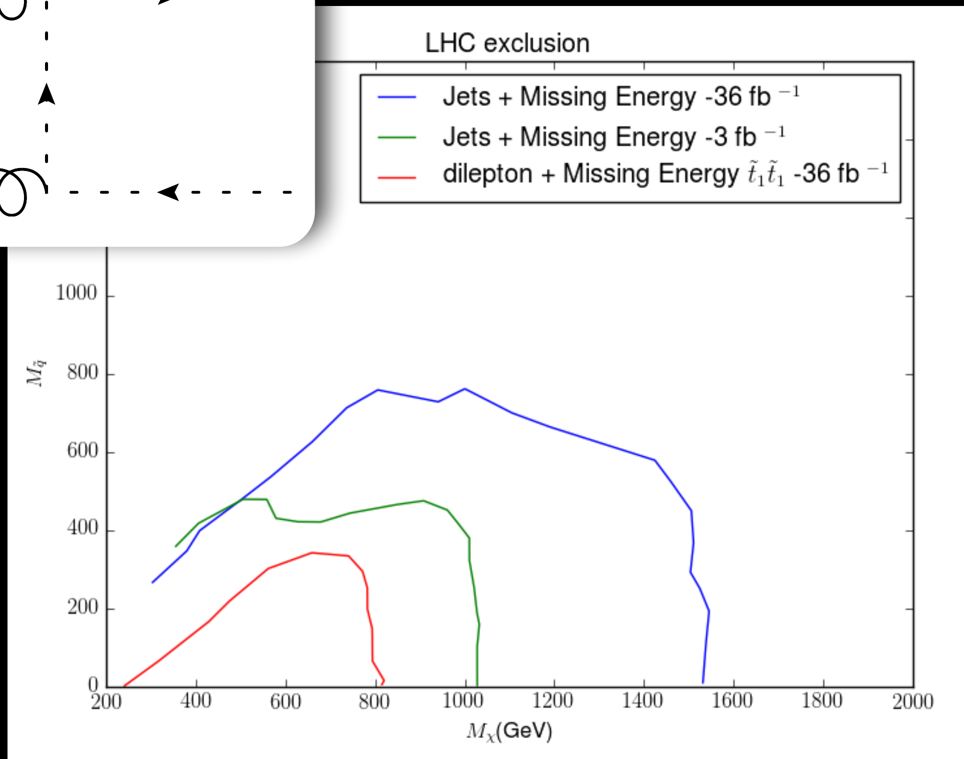
- Another construction has dark matter interacting with quarks via a colored scalar mediator.
- Minimal flavor violation suggests we consider mediators with a flavor index corresponding to {uR,cR,tR}, {dR,sR,bR}, {Q1,Q2,Q3} and/or combinations.
- This theory looks kind of like a little part of a SUSY model, but has more freedom in terms of choosing couplings, masses, etc.
- There are basically three parameters to this model: the mass of the dark matter, the mass of the mediator, and the coupling strength with quarks.

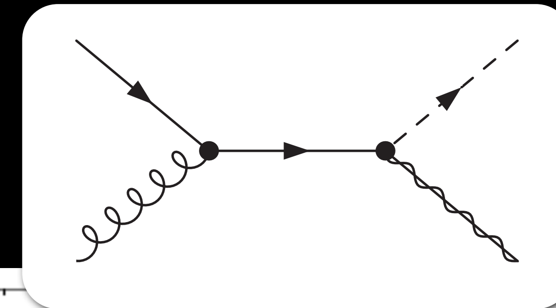


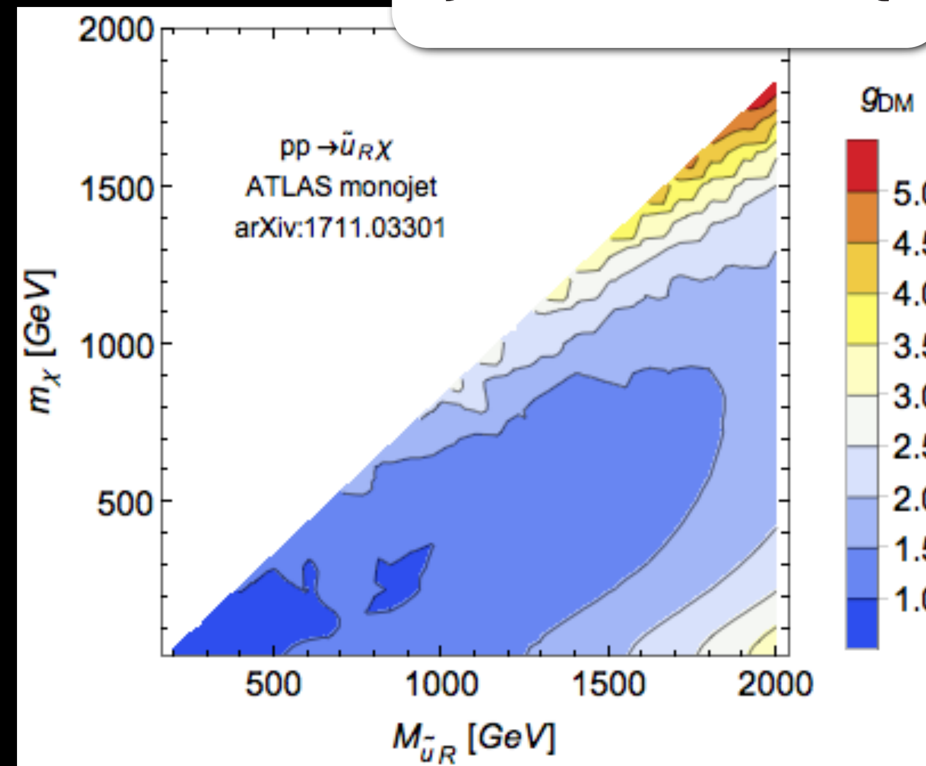
Chang, Edezhath, Hutchinson, Luty 1307.8120
An, Wang, Zhang1308.0592
Berger, Bai 1308.0612
Di Franzo, Nagao, Rajaraman, TMPT 1308.2679

$\tilde{u}_R$ Model





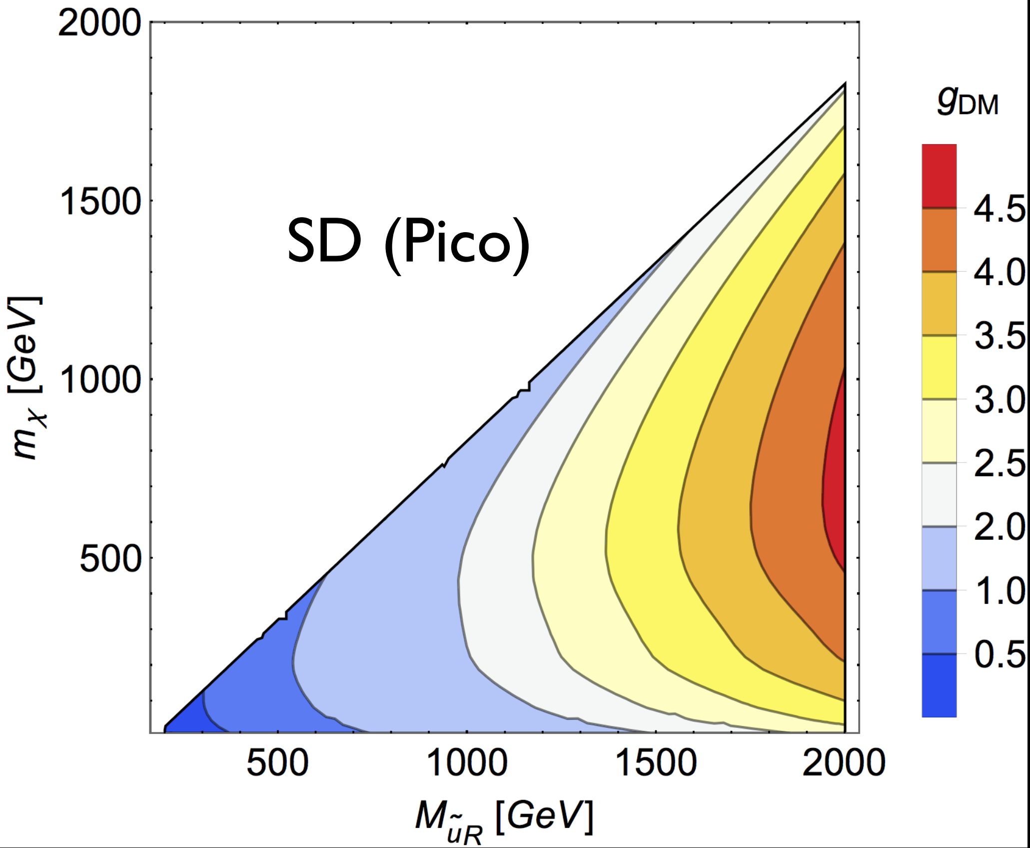


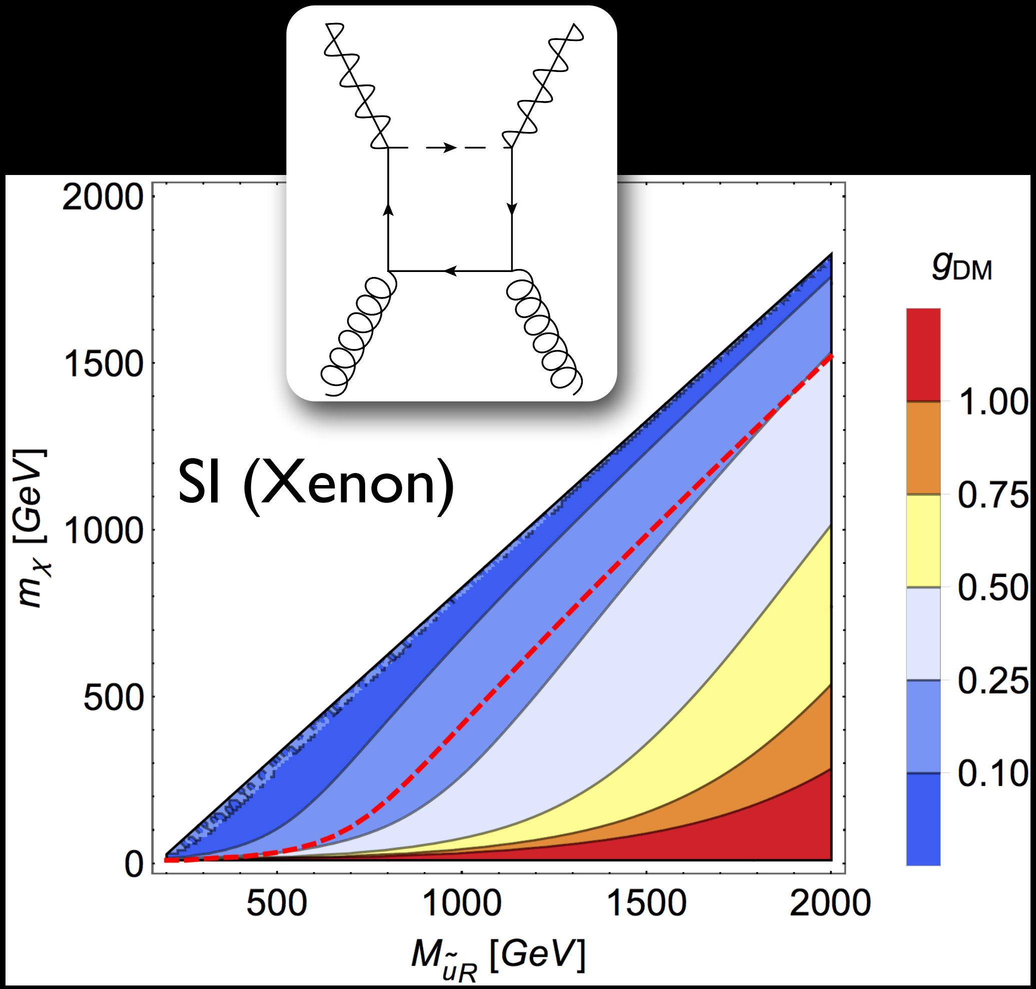


Mohan, Sengupta, TMPT, Yan, Yuan in progress

- For example, we can look at a model where a Majorana DM particle couples to right-handed up-type quarks.
- At colliders, the fact that the mediator is colored implies we can produce it at the LHC using the strong nuclear force or through the interaction with quarks.
- Once produced, the mediator will decay into an ordinary quark and a dark matter particle.

Direct Detection





Mohan, Sengupta, TMPT, Yan, Yuan in progress

- At tree level, the fact that Majorana particles have vanishing vector current implies that the scattering with nuclei is spin-dependent..
- But at one loop, the scattering is spin-independent, and these are the dominant constraint- the smaller rate is compensated by the stronger experimental bounds.

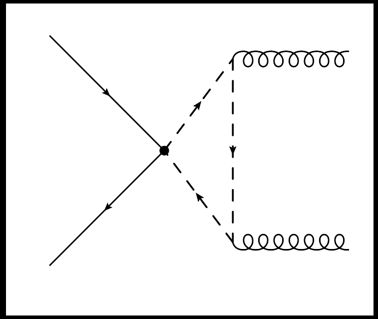
Dark Matter Coupled to Gluons

Godbole, Mendiratta, TMPT 1506.01408 & JHEP
+Shivaji 1605.04756 & JHEP
Bai, Osborne 1506.07110 & JHEP

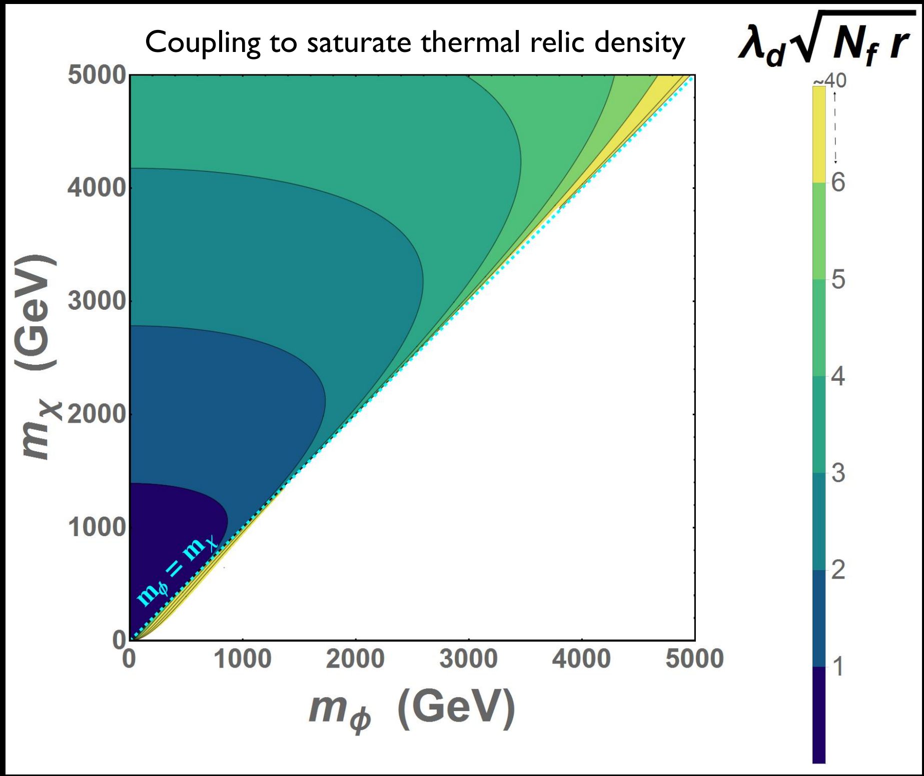
- Another possibility is to engineer the coupling to the SM to occur at loop level.
- In that case, a quartic interaction can connect the two.

$$\lambda_d \; |\chi|^2 |\phi|^2$$

- This interaction does not require the scalar to be Z_2-stabilized, and (given an appropriate choice of EW charges) it can decay into a number of quarks, looking (jn some cases) more like an R-parity violating squark.
- The color and flavor representations (r, Nf) of the mediator are free to choose.
- For perturbative λ, a thermal relic actually favors $m_\varphi < m_\chi$ so annihilation into $\varphi\varphi^*$ is open.



The dominant coupling to the SM is at one loop to gluons!

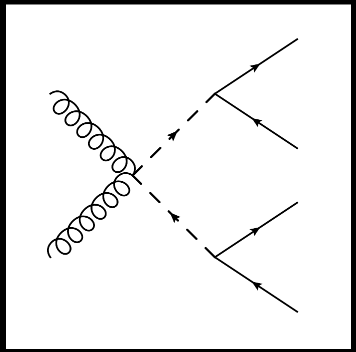


Mediator Searches

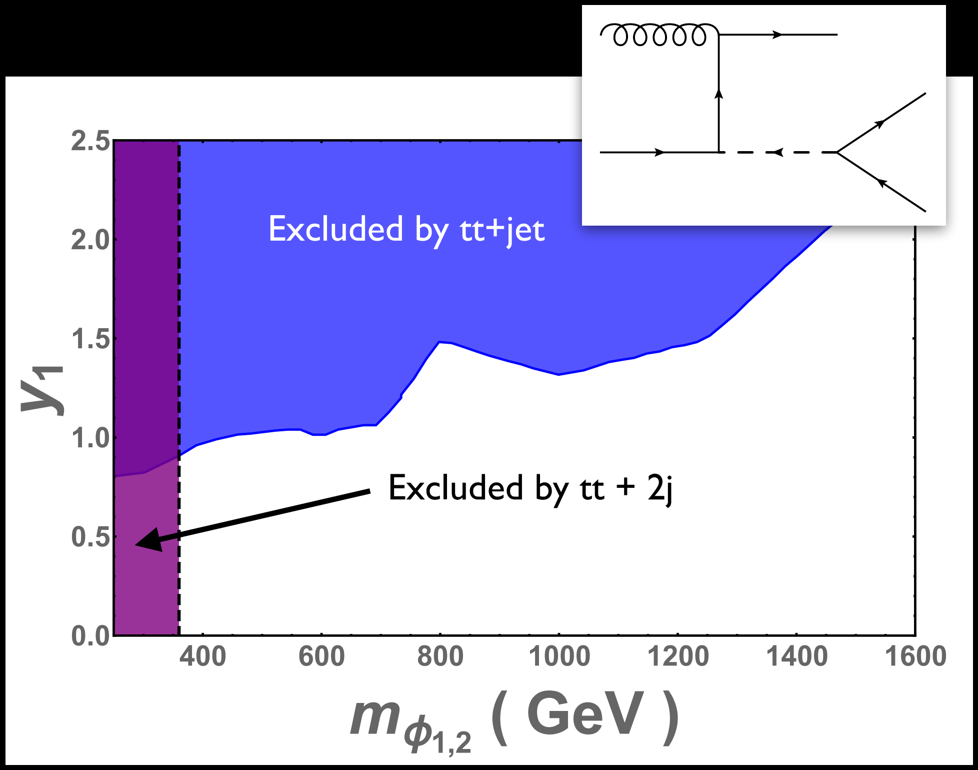
- The physics of the mediators is model-dependent, depending on the color and EW representation.
- As a starting point, we considered mediators of charge 4/3 coupling to 2 uR quarks.
- In this case, a MFV theory can be obtained by coupling anti-symmetrically in flavor indices:

$$y\epsilon^{ijk}\phi_i\bar{u}_j u^c_k + h.c.$$

- There are interesting searches for pairs of dijet resonances and also potential impacts on top quark physics.
- All of these constraints are rather weak.

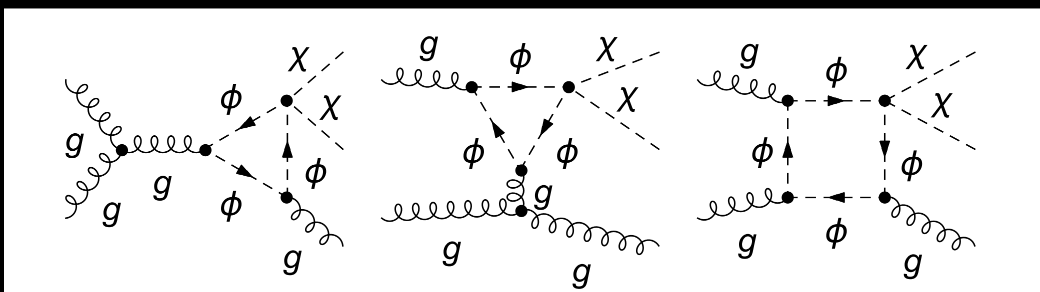


Decays into unflavored jets are bounded by m_φ > 350 GeV.

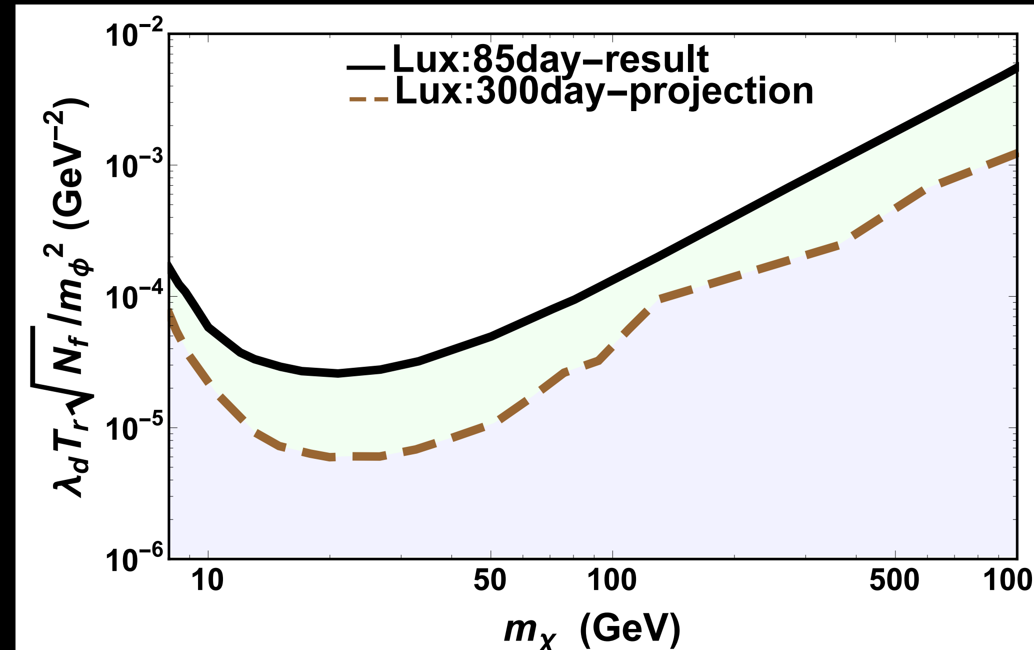


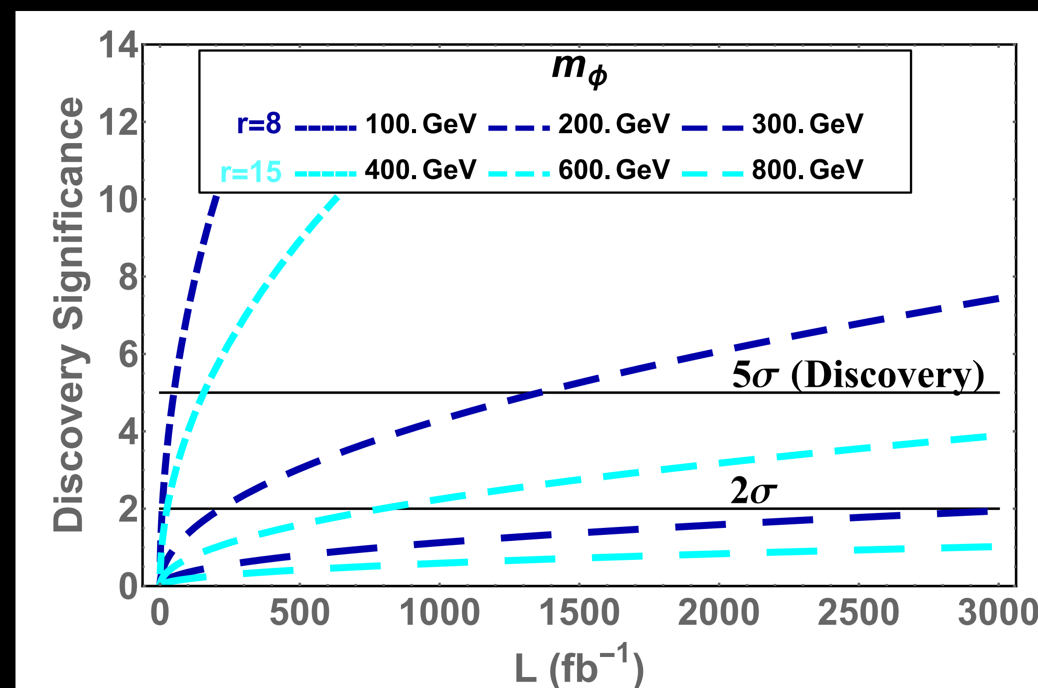
DM Searches

- Direct detection generally provides a strong bound unless the dark matter mass is particularly small.
- At a hadron collider, the mono-jet signature occurs at one loop.



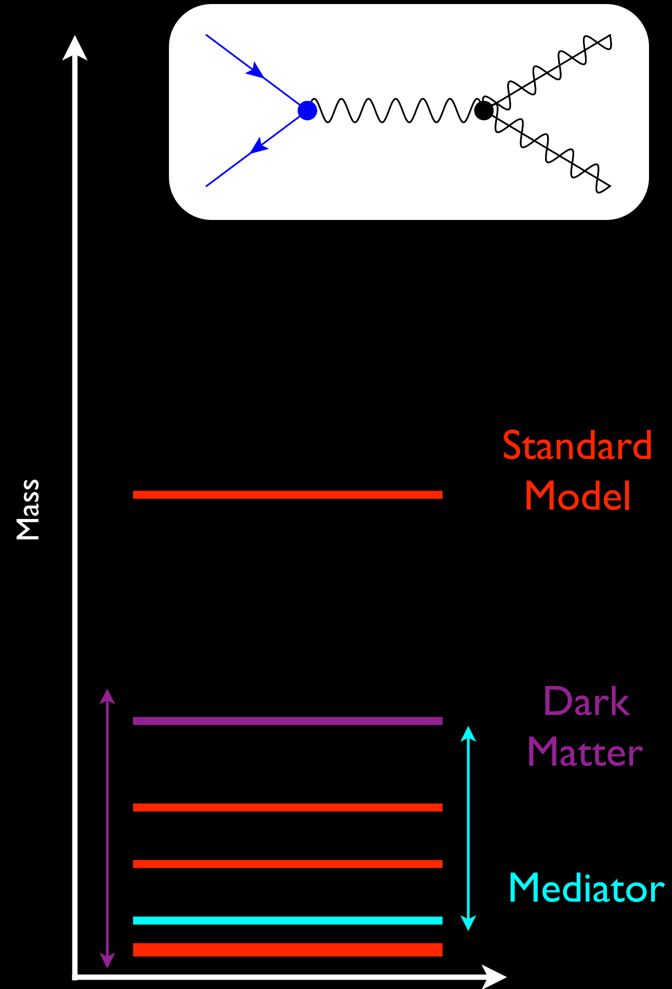
- As a result, prospects at the LHC are not particularly hopeful, though for large enough r and λ, it is possible to see something with a very large data set.
- A 100 TeV pp collider would do better…





Light Dark Matter

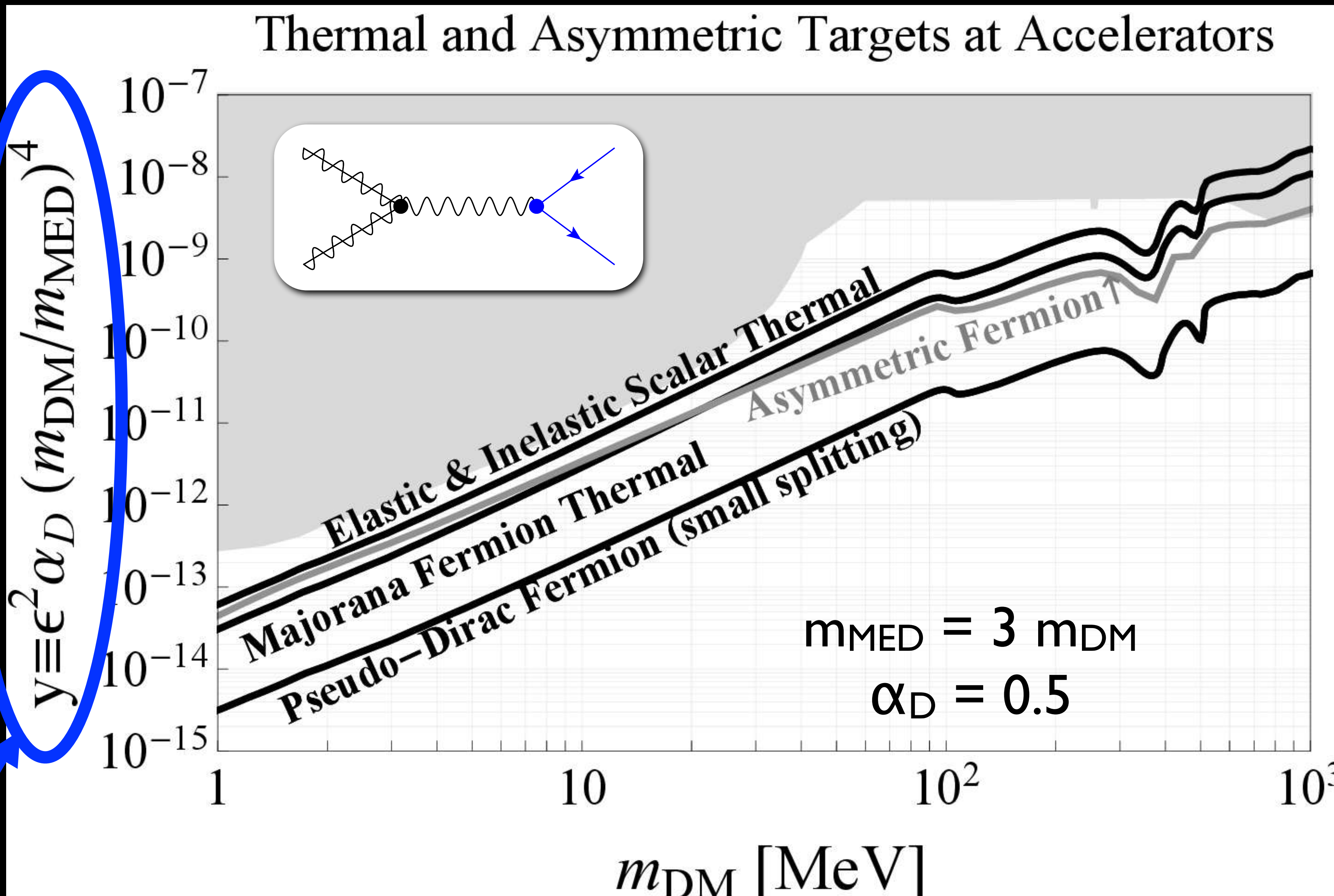
- One can construct theories where the DM is light enough that direct bounds become rather weak.
- This typically requires light mediators as well.
- A nice picture is a light vector boson whose coupling to the SM comes from kinetic mixing with $U(1)_Y$.
- In this limit, the couplings of the mediator to the SM look like photon couplings scaled down by ε. The mediator in this case is often referred to as a "dark photon".
- There are other variations with scalars, pseudo-scalars, or vectors with chiral interactions.



γ_D **Parameters:**

$$\{m_\chi, m_{A'}, \alpha_D, \epsilon\}$$

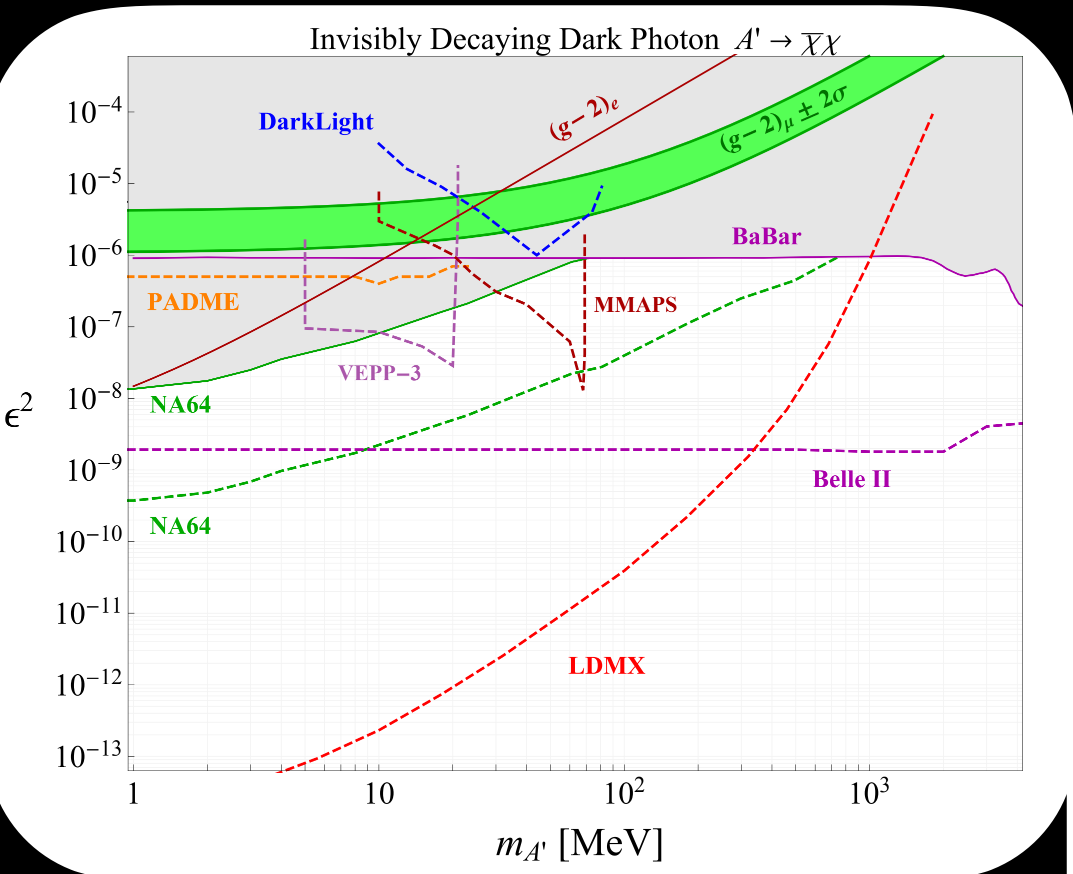
MeV Relic Dark Matter



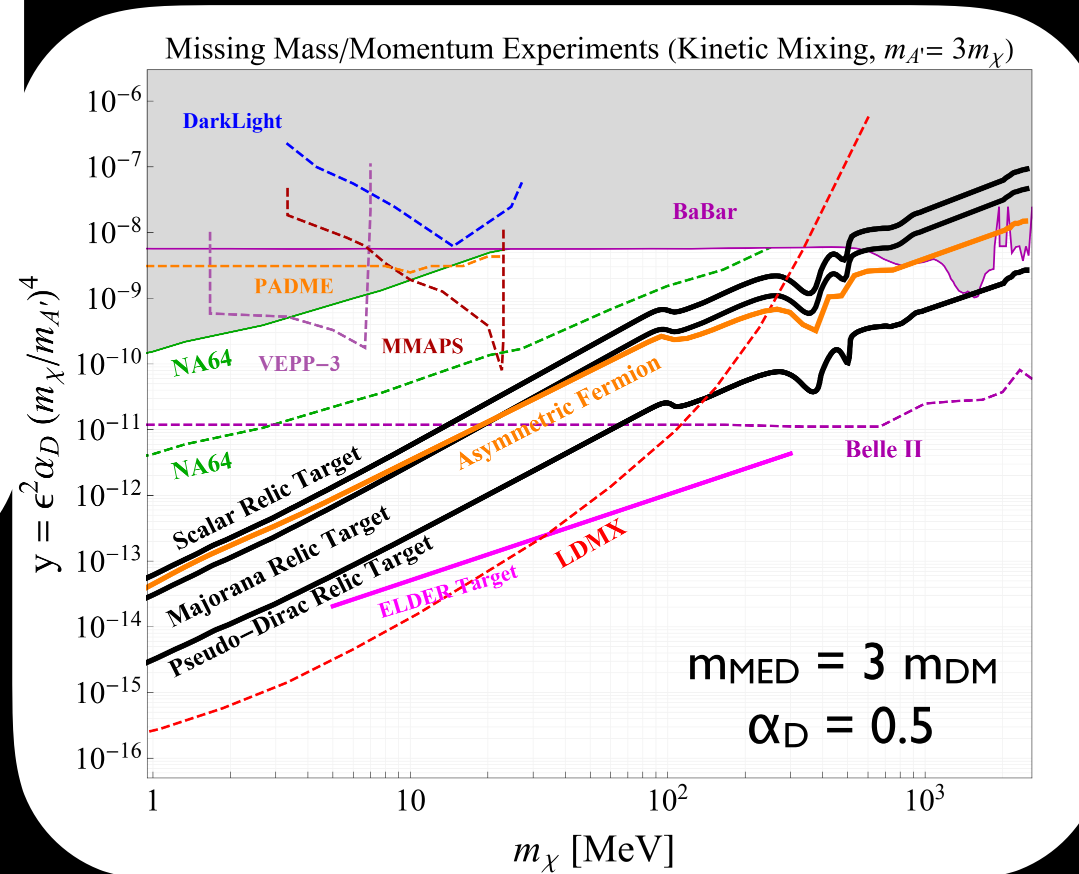
The y parameter is the combination that controls the relic density in this regime.

US Cosmic Visions Report
arXiv:1707.04591

Invisible Searches



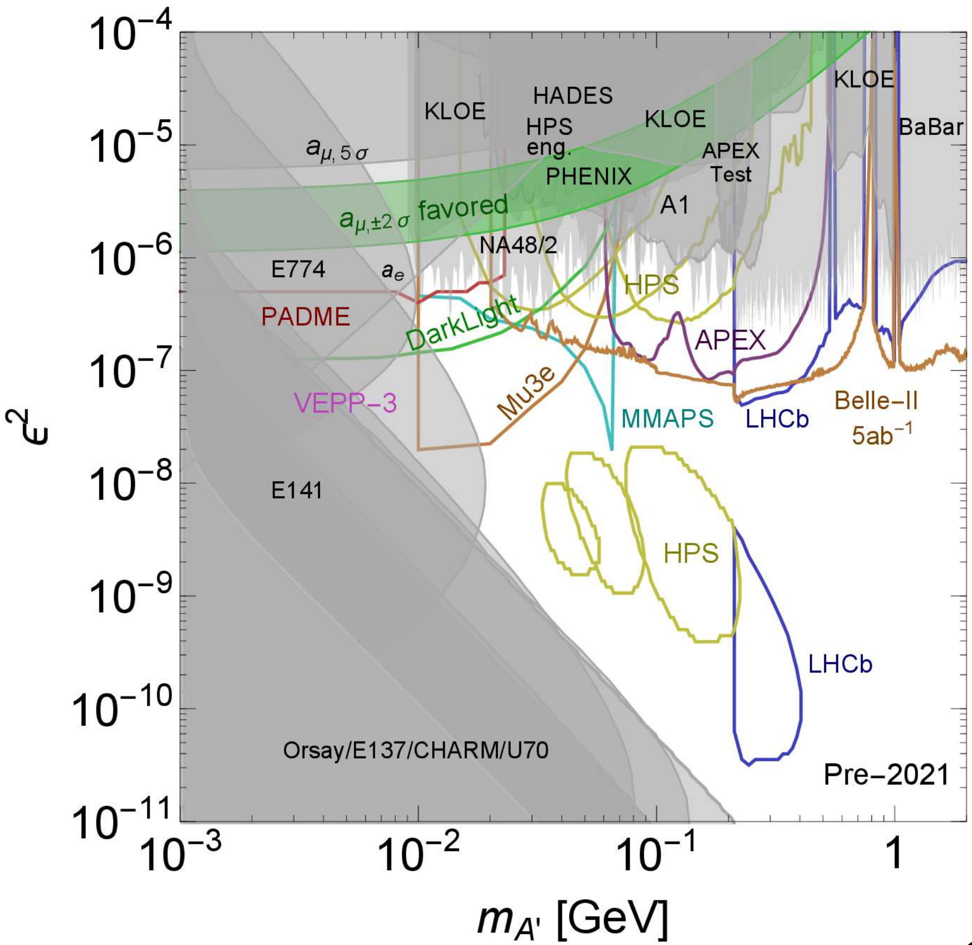
US Cosmic Visions Report
arXiv:1707.04591



~100% BR into invisible channels.

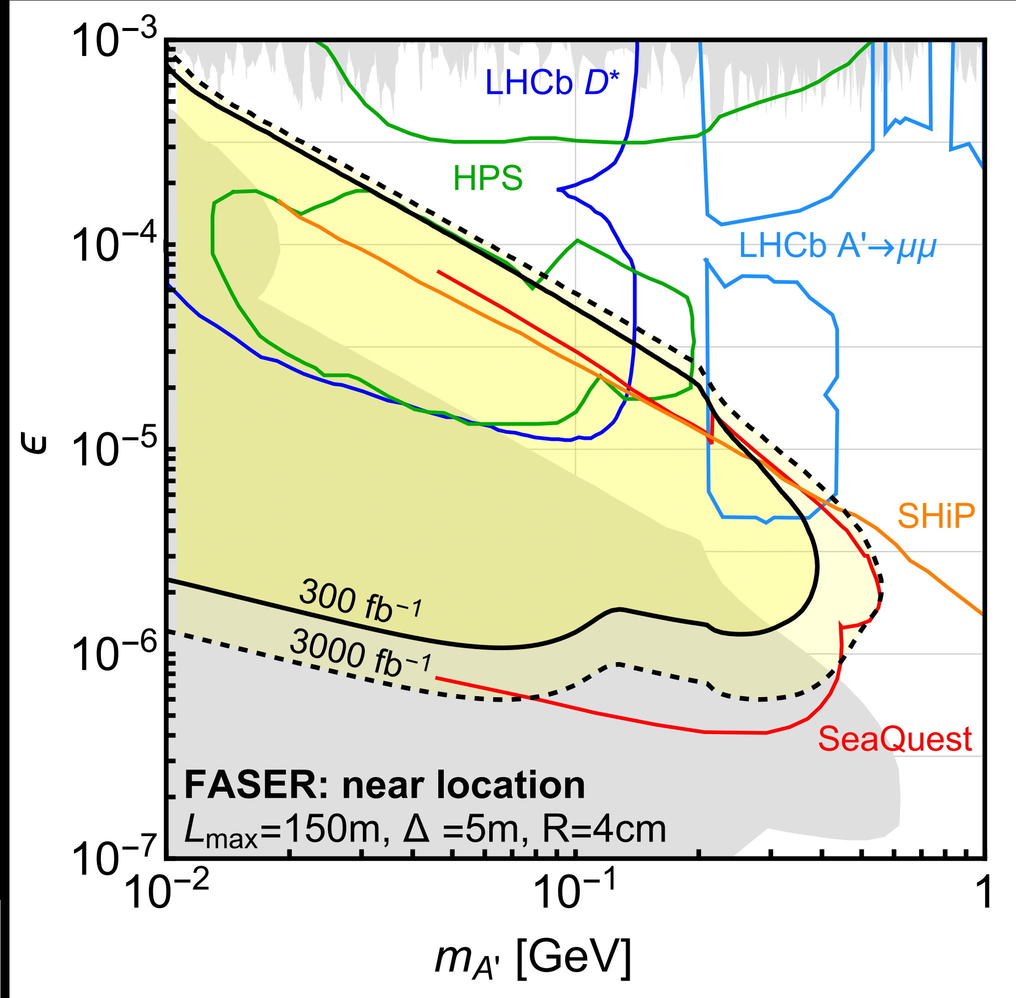
Many projects both underway and proposed can search for mediators decaying (dominantly) invisibly.

Visible Searches



US Cosmic Visions Report
arXiv:1707.04591

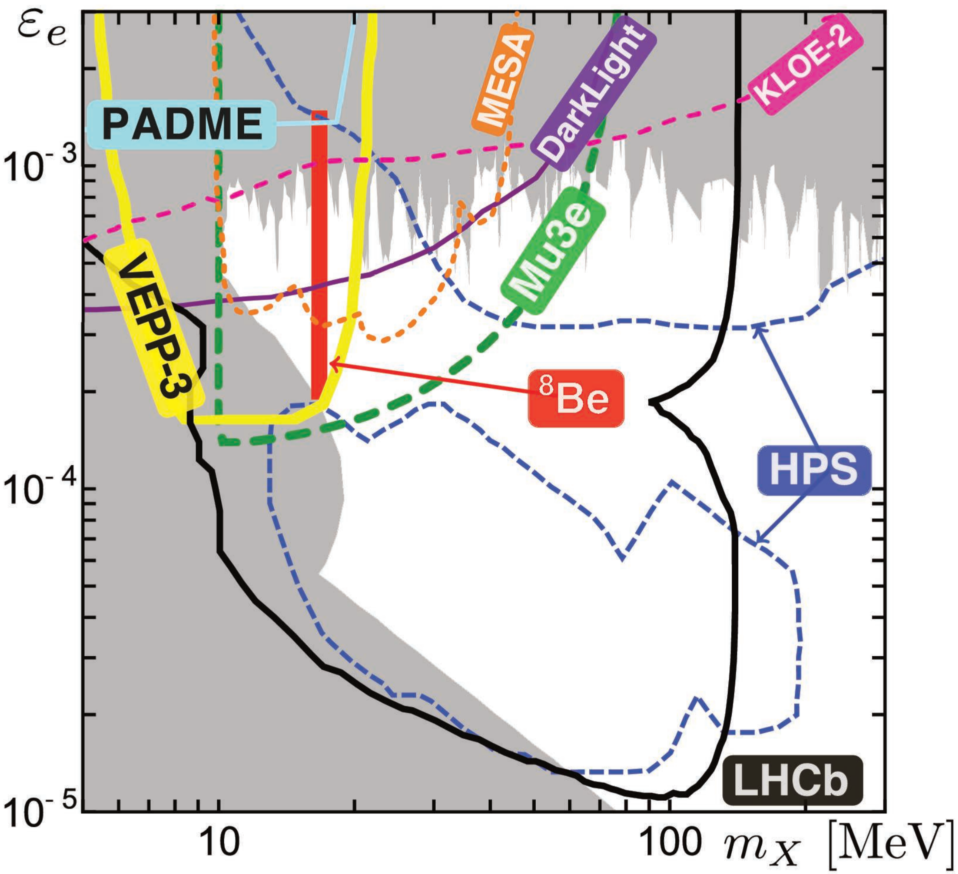
When the dark matter is too heavy, the mediator largely decays visibly into SM states.



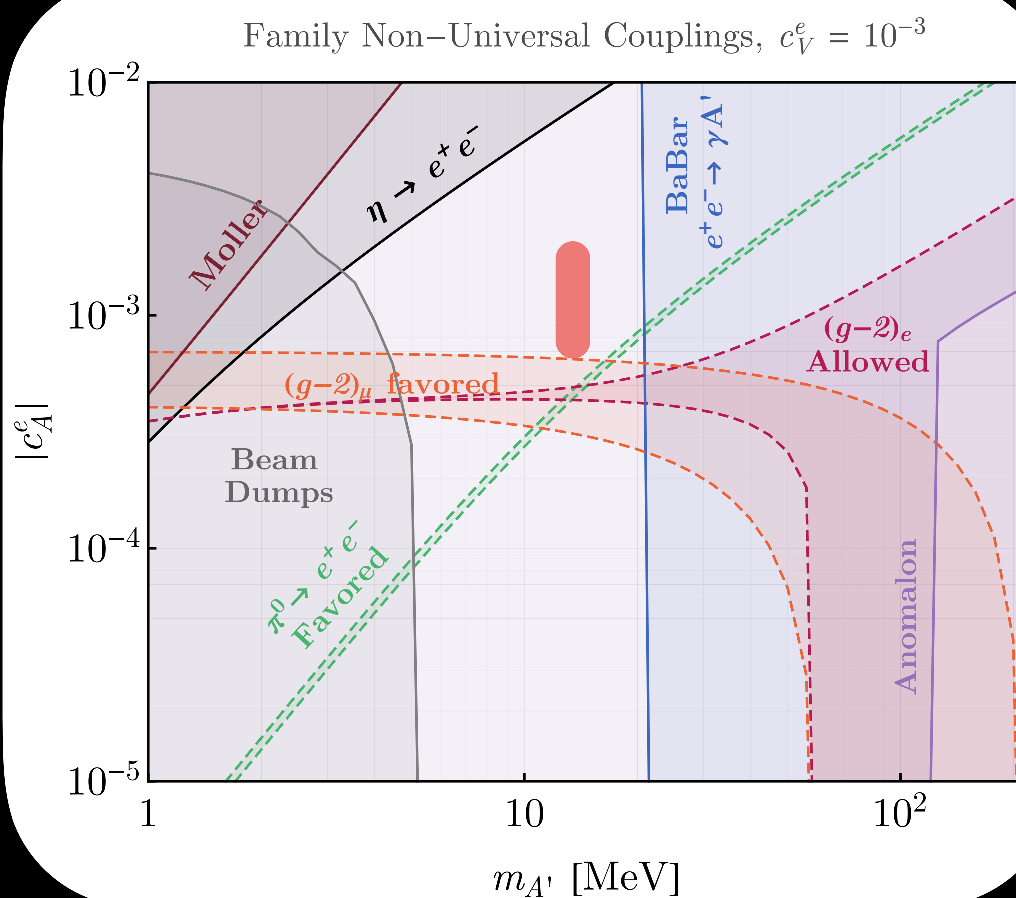
Feng, Galon, Kling, Trojanowski
arXiv:1707.04591

Beyond Dark Photons

Proto-phobic vector couplings to address the Be-8 anomaly.



Feng, Fornal, Galon, Gardner, Smolinsky, Tanedo, TMPT arXiv:1707.04591



Vector particle with chiral interactions

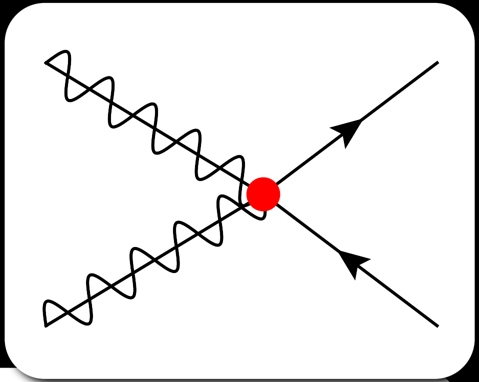
Kahn, Krnjaic, Mishra-Sharma, TMPT arXiv:1609.09072

Outlook

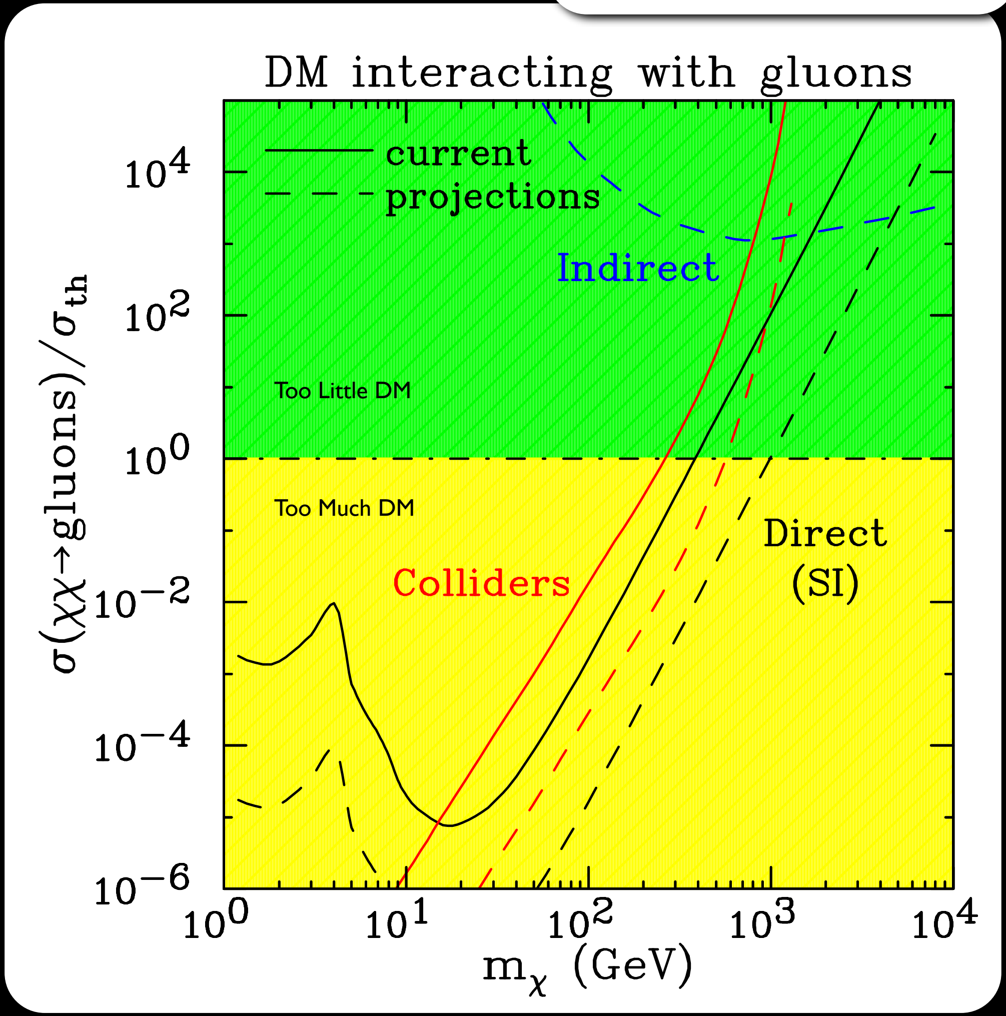
- Are WIMPs dead?
  - The answer really depends on how you frame the question.
  - Some are…
    - Electroweakly charged particles are rather constrained.
    - Some options survive by making choices of EW representation / spin.
  - Others not so much.
    - Freeze-out relics can exist for a wide variety of masses.
    - Engineering may be required on the theory side, but this could just be how nature works.
  - I think the only argument I can take away is that we need to keep looking everywhere we can.

Bonus Material

Annihilation

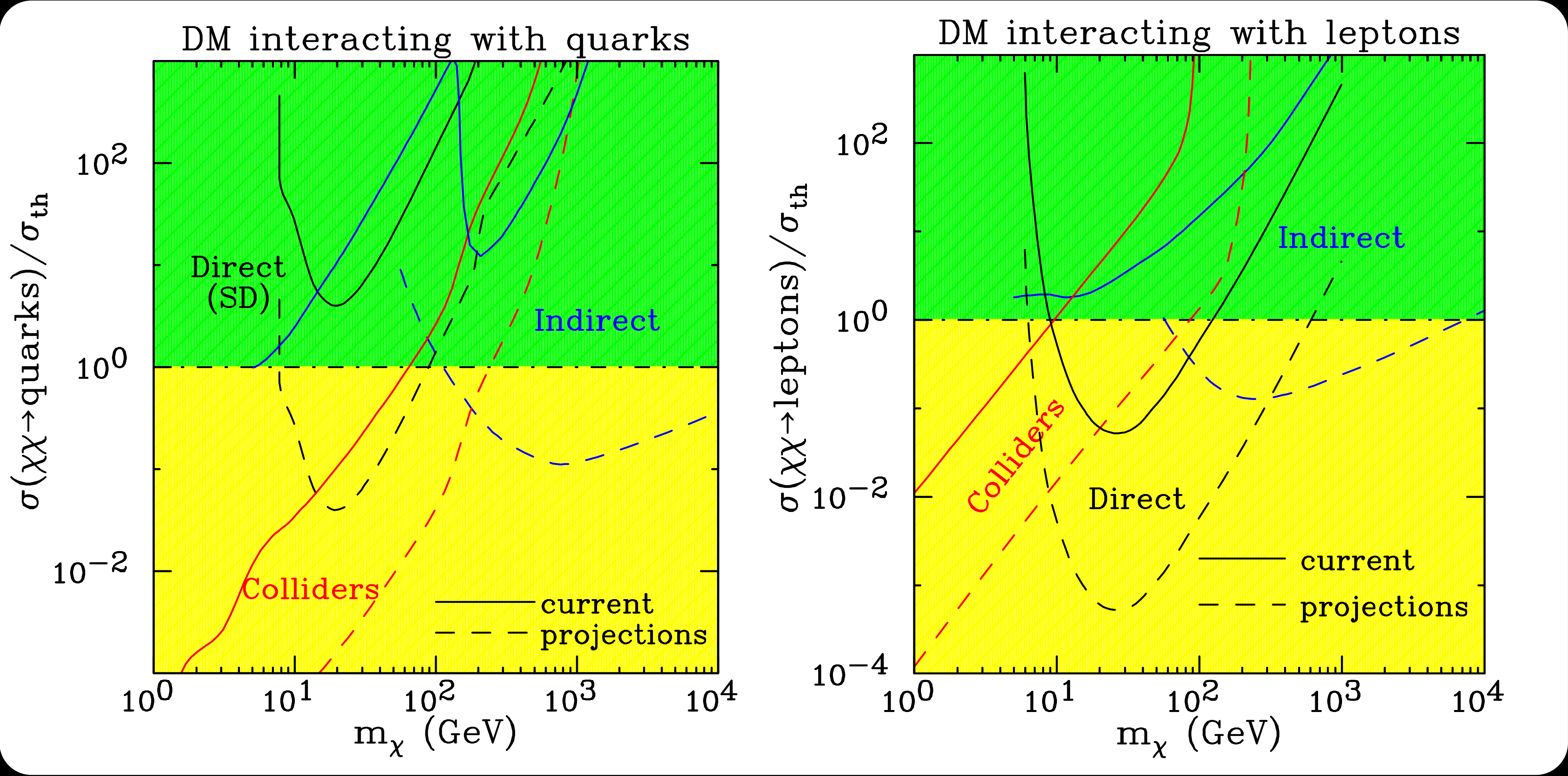


- We can also map interactions into predictions for WIMPs annihilating.
- This allows us to compare with cross sections leading to a thermal relic density through freeze out.
- This example is for dark matter interacting with gluons. The cross section has been normalized to the thermal cross section for a thermal relic at a given mass.
- The LHC does better for lighter WIMPs or p-wave annihilations whereas direct detection is more sensitive for heavy WIMPs.



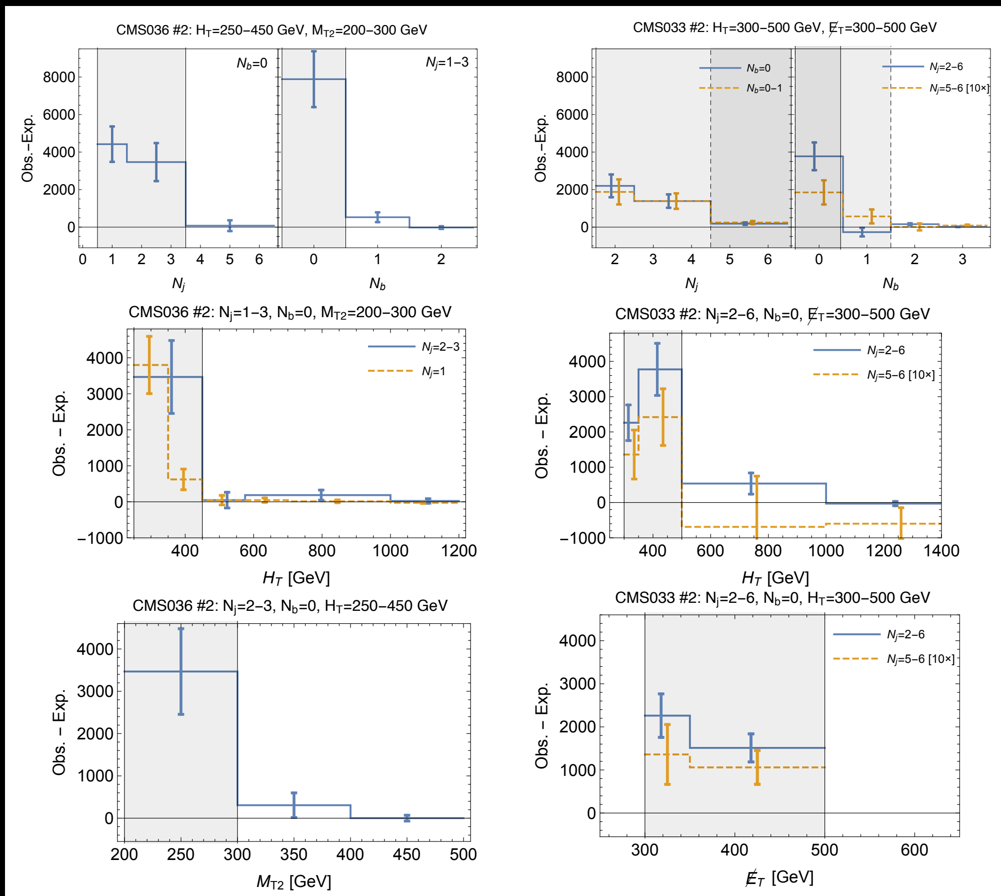
DM Complementarity, arXiv:1305.1605

Quarks & Leptons

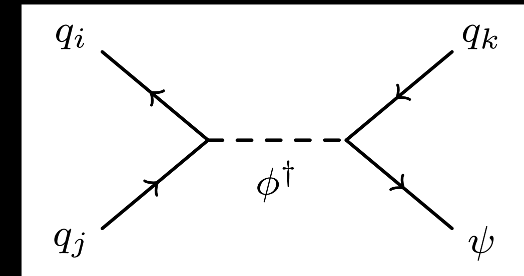


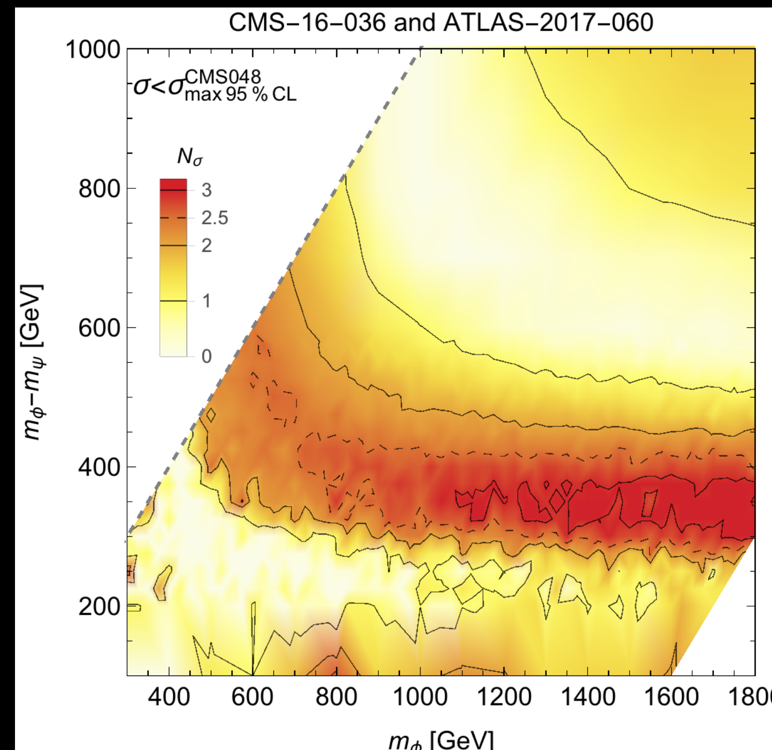
DM Complementarity, arXiv:1305.1605

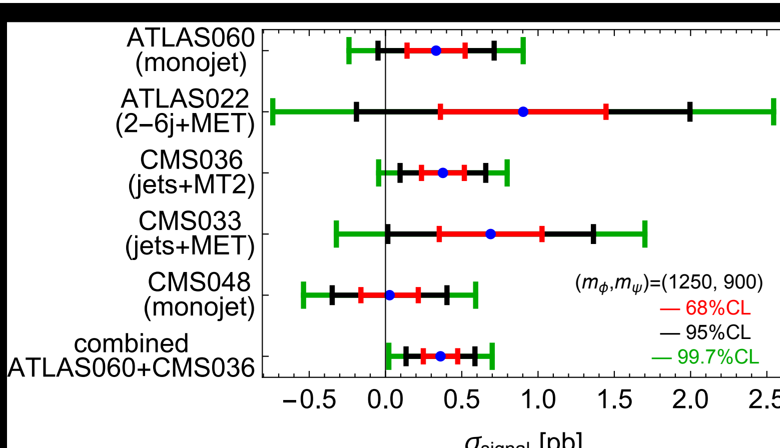
Excess?



Asadi, Buckley, DiFranzo, Monteux, Shih
arXiv:1707.05783 &1712.04939

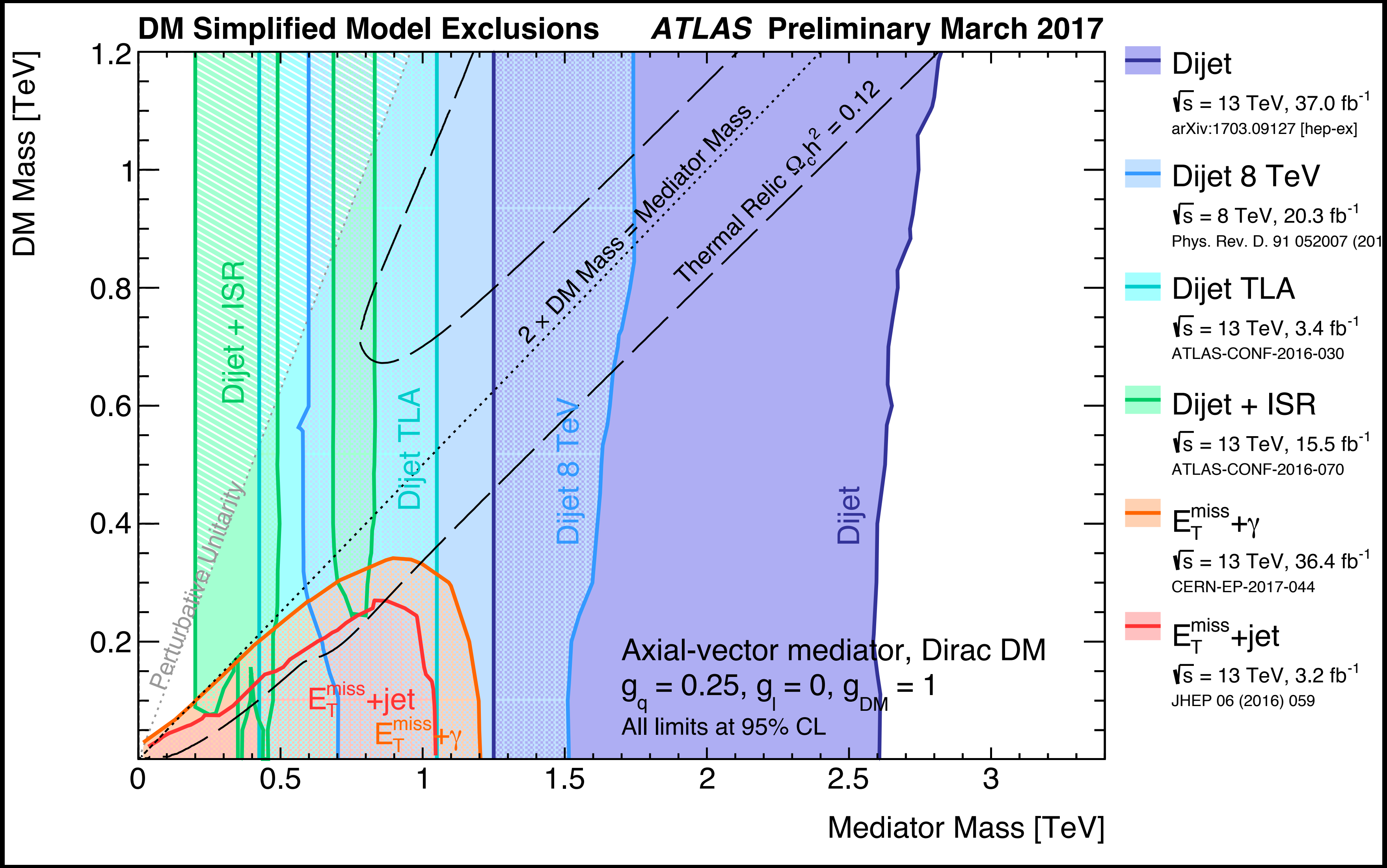


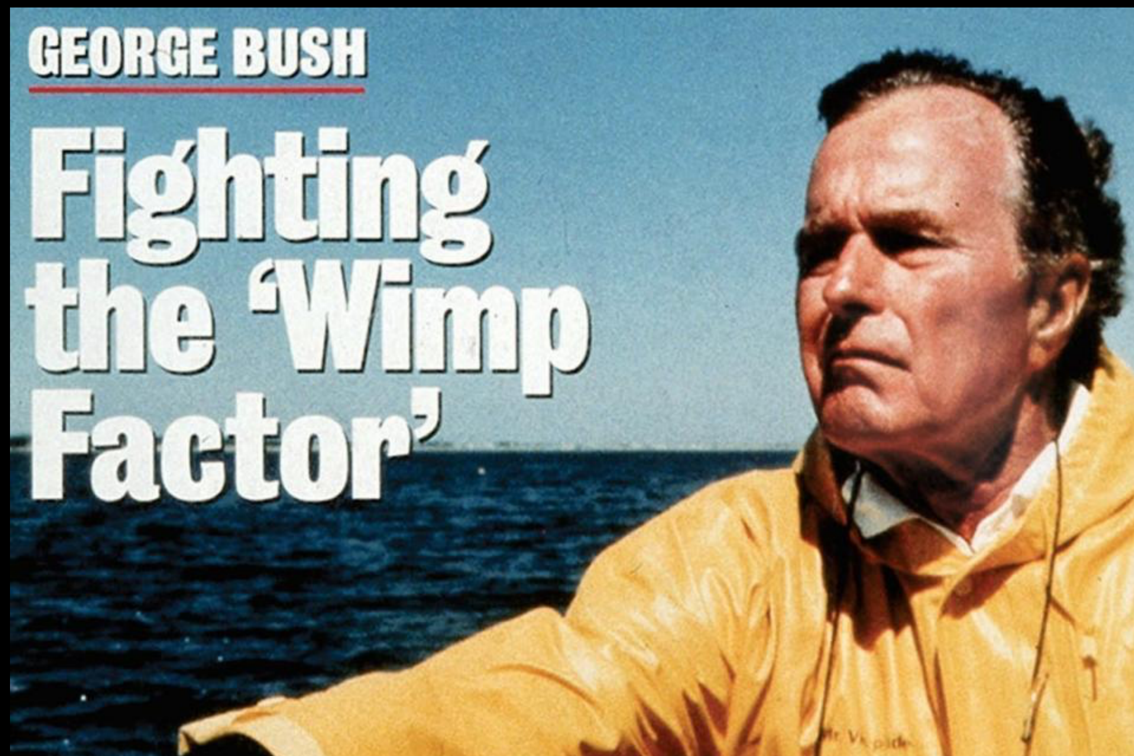




There is a theoretical recast of the jets + MET data that indicates ~2.5σ excesses over backgrounds.

Dijet Searches




GEORGE BUSH
Fighting the 'Wimp Factor'