Title: You can hide but you have to run: new theory tools to unveil the mystery of dark matter

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Abstract: The origin and composition of 85% of the matter in the universe is completely unknown. Among several viable options, Weakly Interacting Massive Particles (WIMPs) are motivated dark matter candidates that can be tested by different and complementary search strategies. Crucially, different searches probe WIMP couplings at different energy scales, and such a separation of scales has striking consequences in connecting different experimental probes. This motivates the development of theoretical tools to properly connect the different energy scales involved in constraining WIMP models. I will introduce these tools and I will illustrate with several examples how crucial the inclusion of these effects in WIMP searches is.

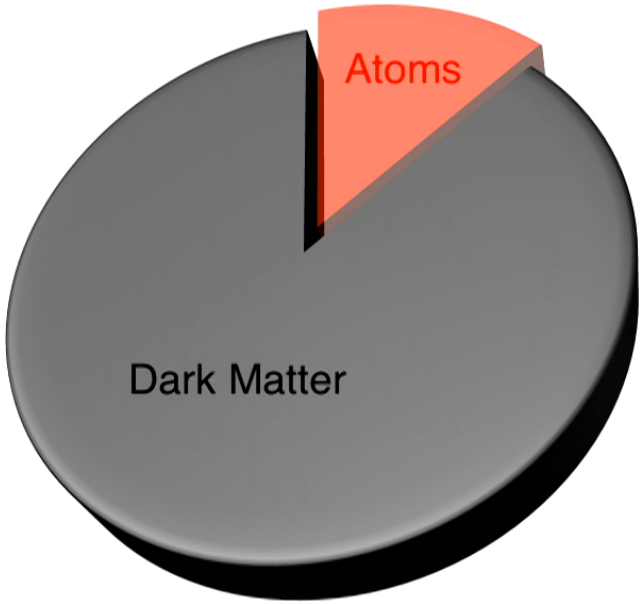
You can hide but you have to run: new theory tools to unveil the mystery of dark matter

Francesco D'Eramo

Santa Cruz Institute for Particle Physics
University of California, Santa Cruz

Perimeter Institute
5 May 2017

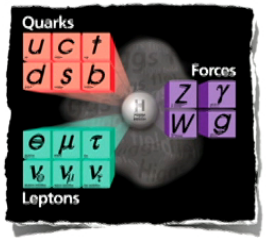
Dark Matter

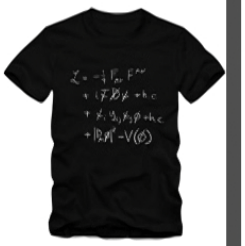


Composition of approximately
4/5 of matter *unknown*

What do we know?

Standard Model

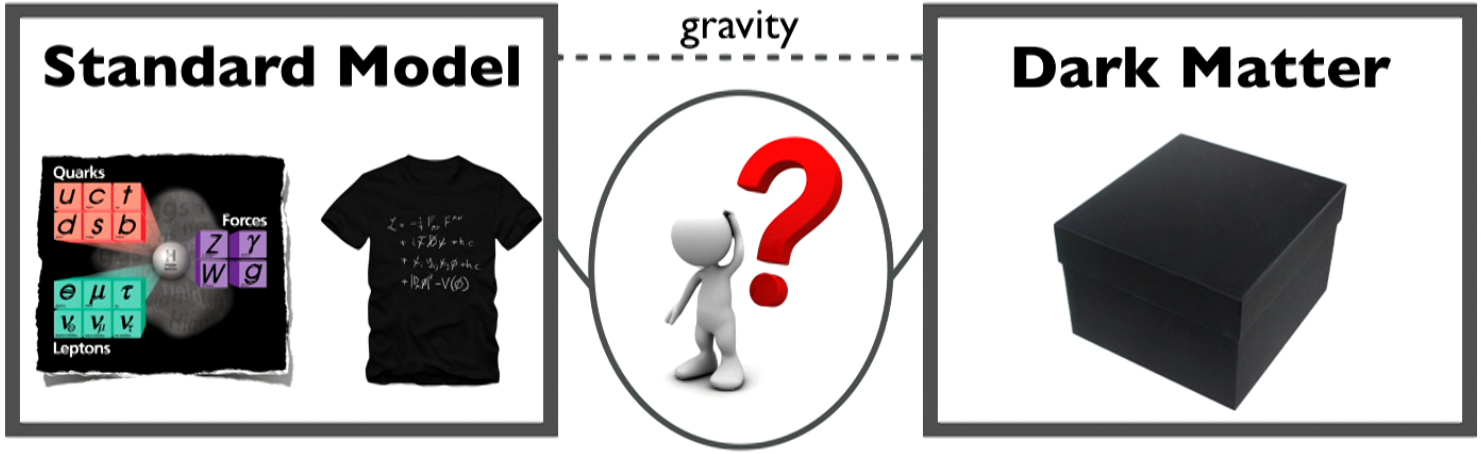




gravity

Dark Matter

What do we know?



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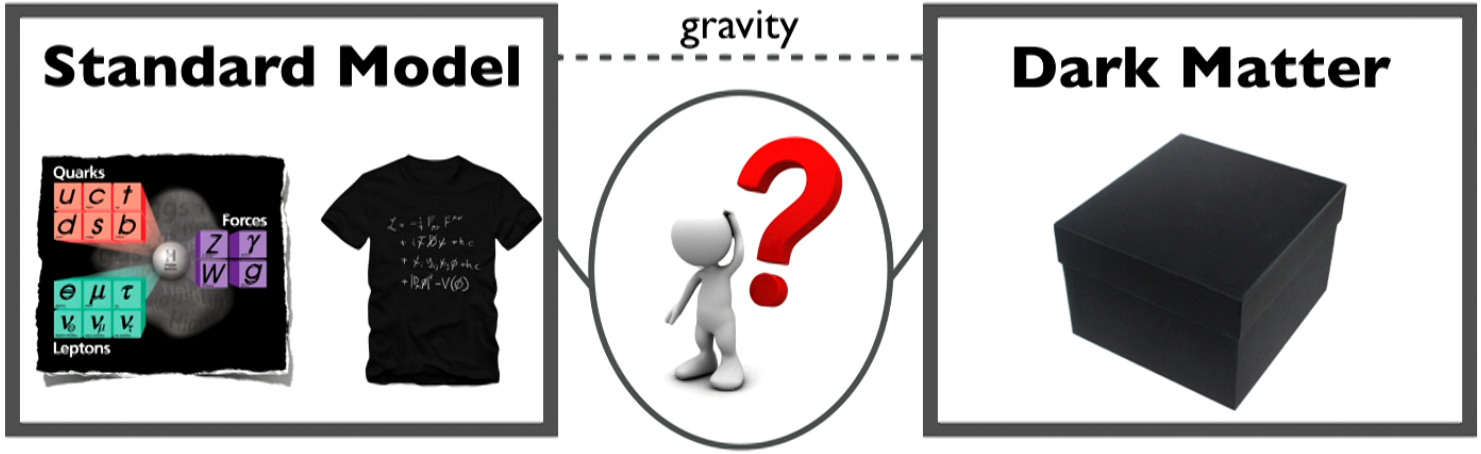
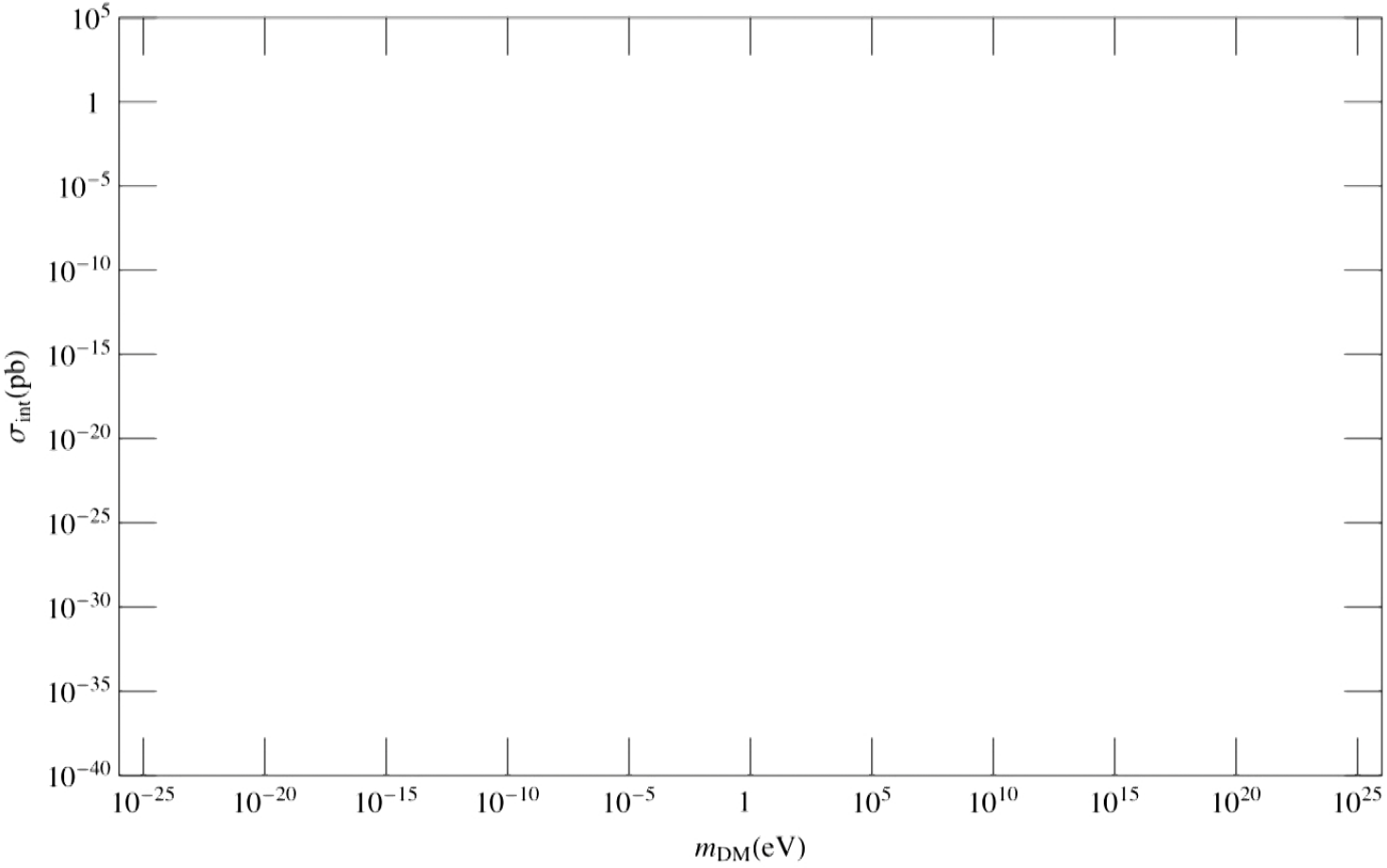


It cannot be arbitrary...

Solid bounds on masses and
couplings from dark matter searches

DM Theories Landscape



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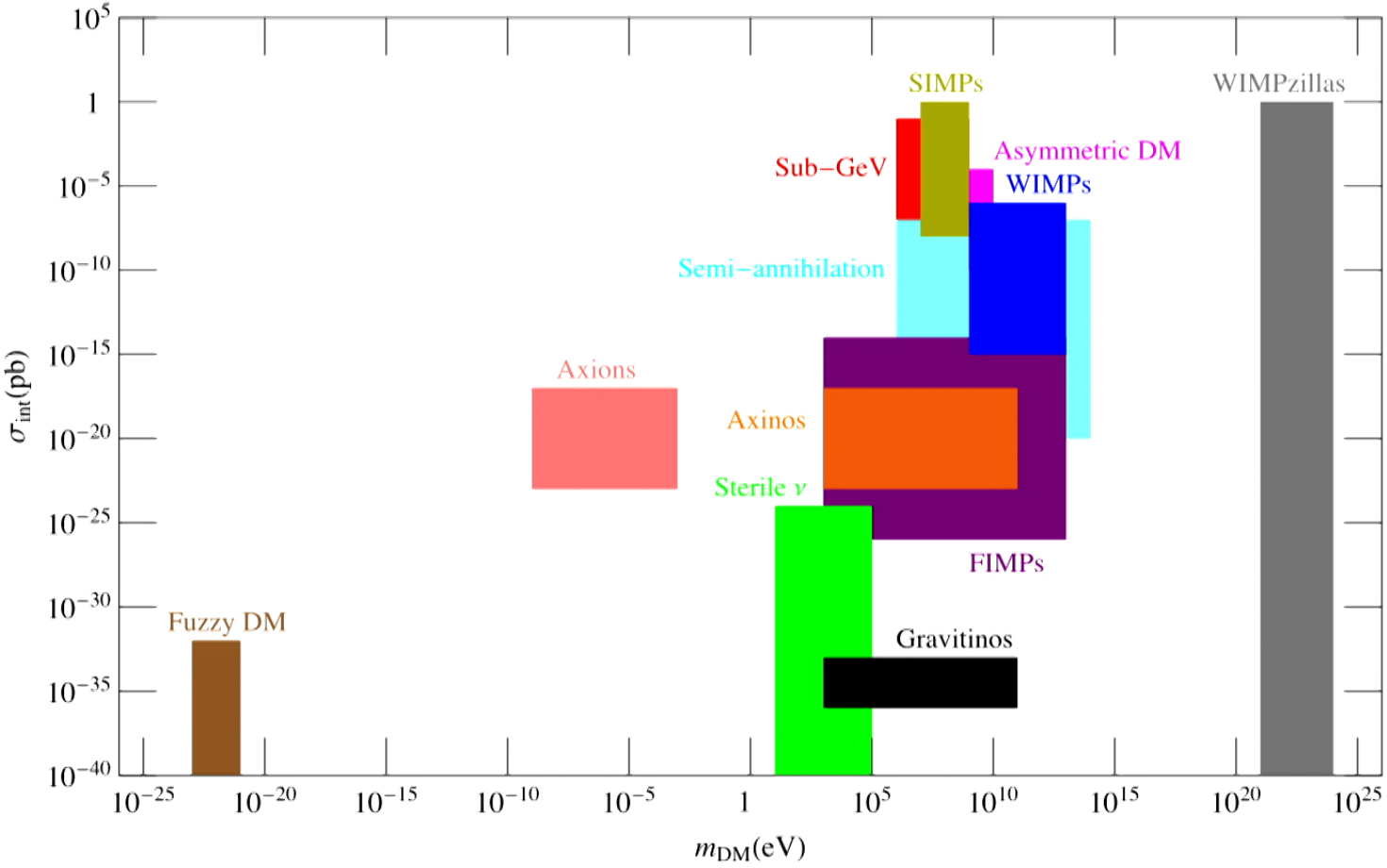

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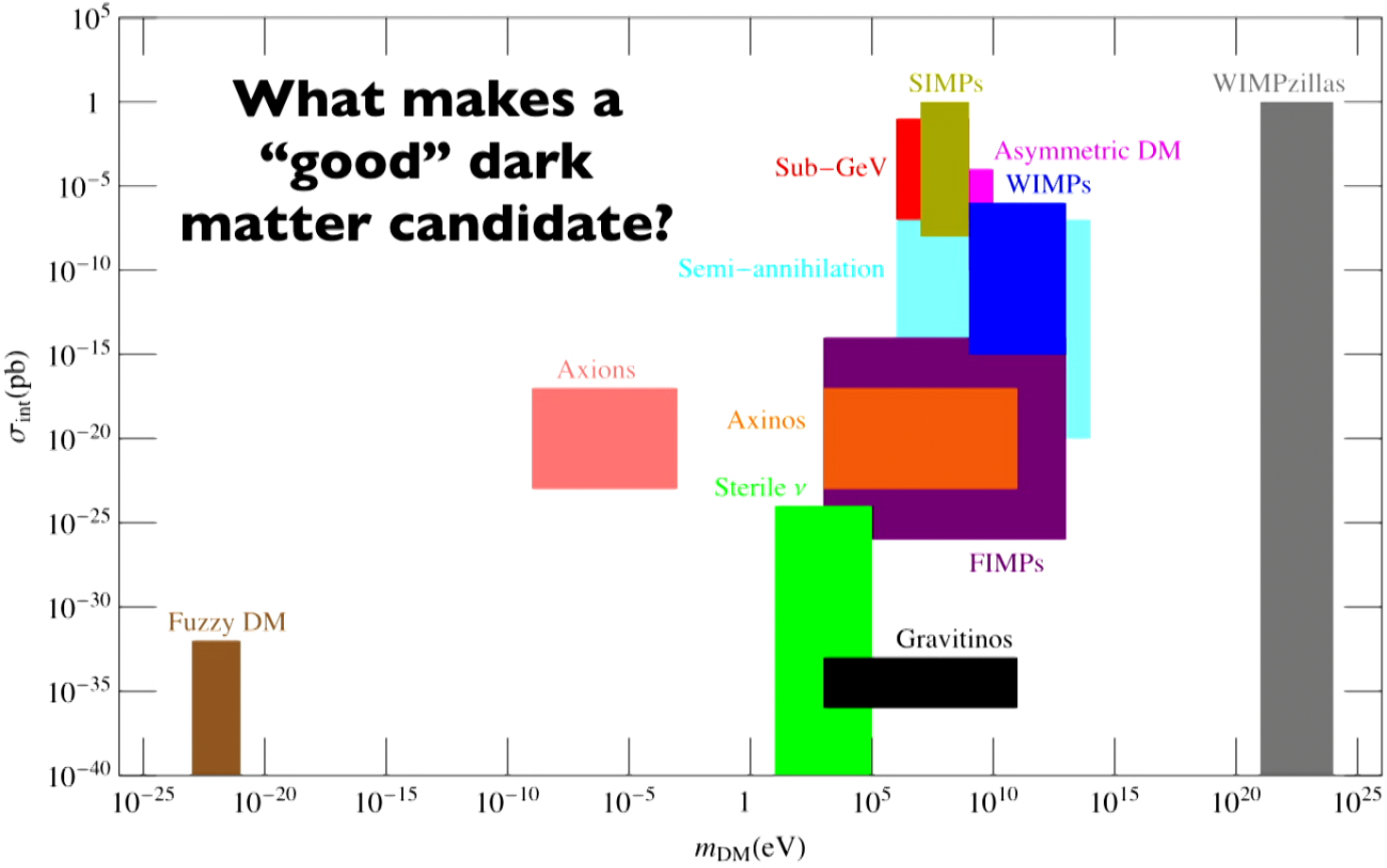
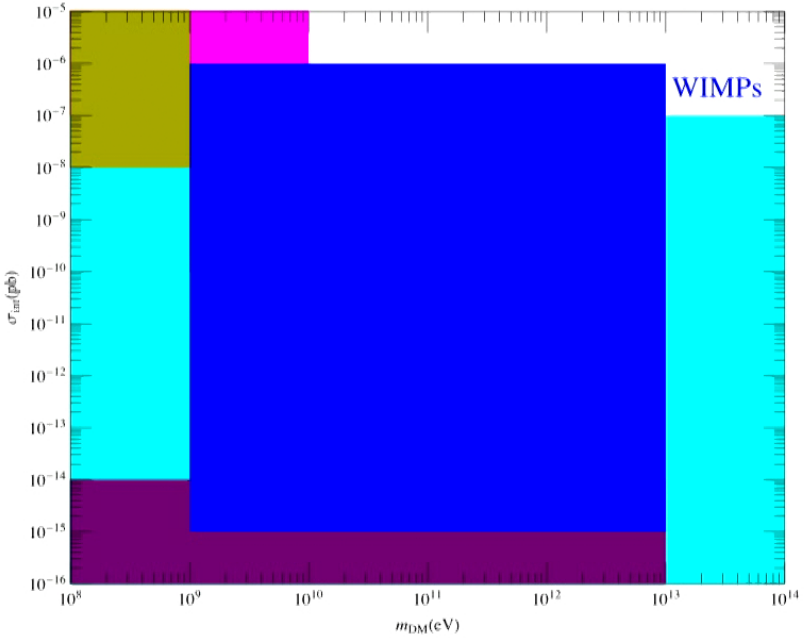


WIMPs

Weakly Interacting Massive Particles

Ubiquitous in theories for the Fermi scale *(hierarchy problem)*

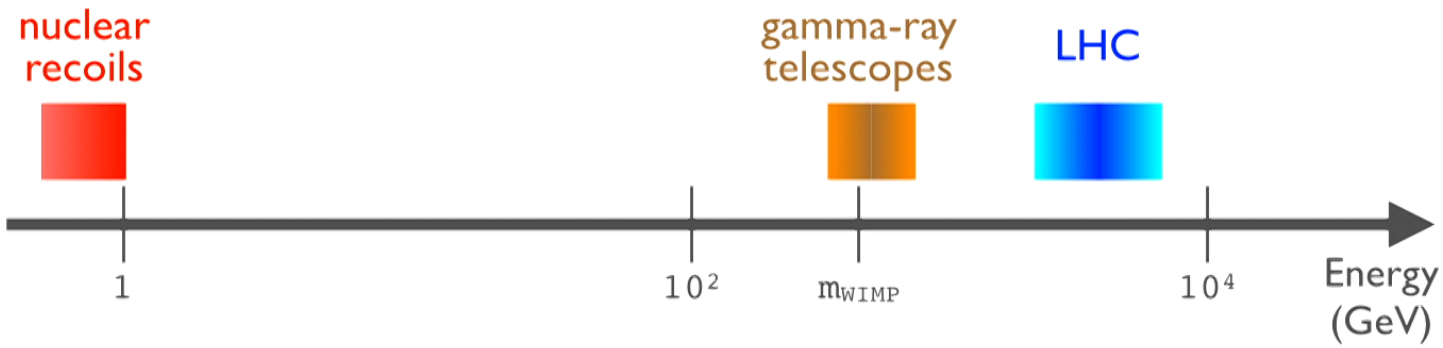
Produced through thermal freeze-out *("WIMP miracle")*



Testable with *multiple* and *complementary* strategies

Energy Scales and DM

WIMP Dark Matter searches probe couplings at widely different energies



Energy Scales and DM

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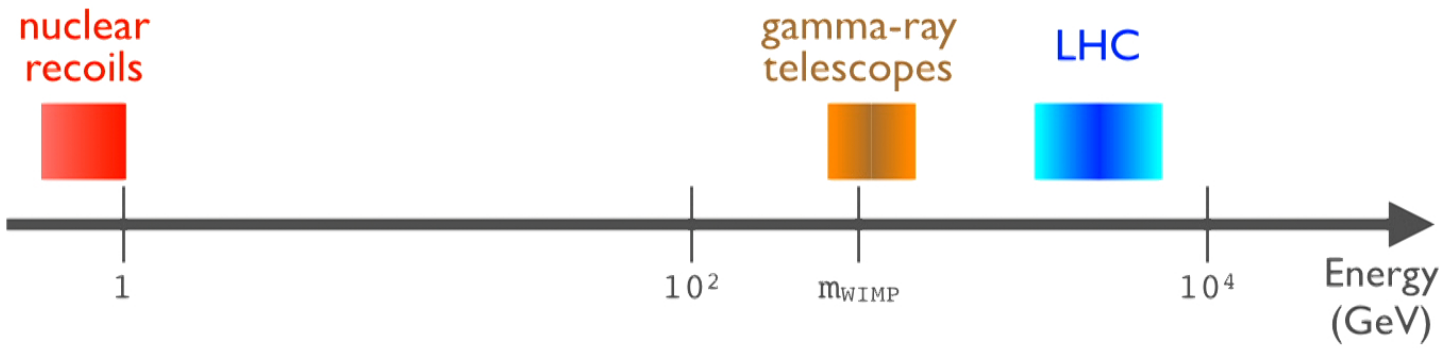

GOAL:

Build new theory tools to connect energy scales probed by DM searches

Energy Scales and DM

Standard Model drives Renormalization Group Evolution (RGE) of WIMP couplings

"You have to run"

GOAL:

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Energy Scales and DM

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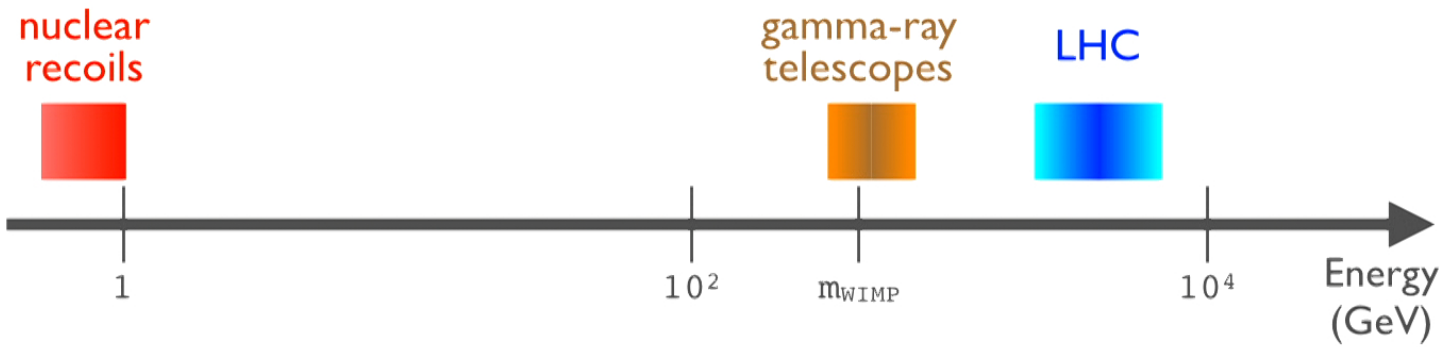
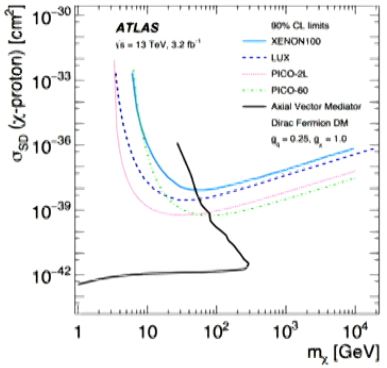


Comparison between LHC and nuclear recoils



Energy Scales and DM

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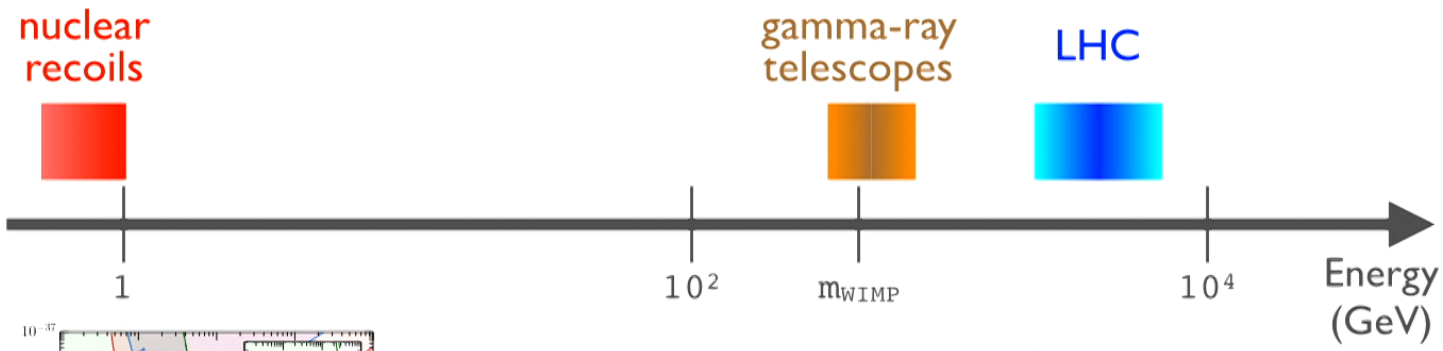
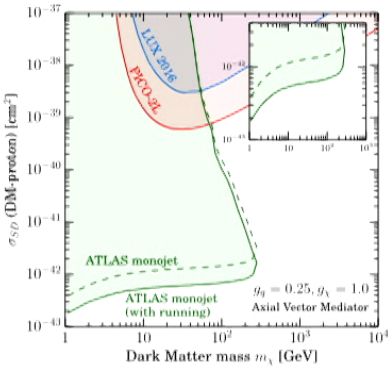
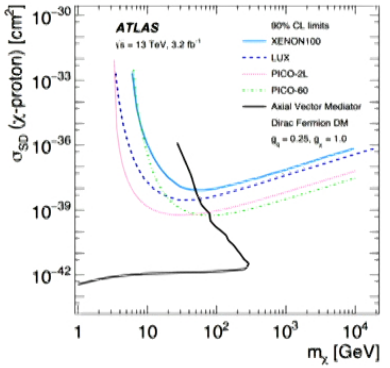


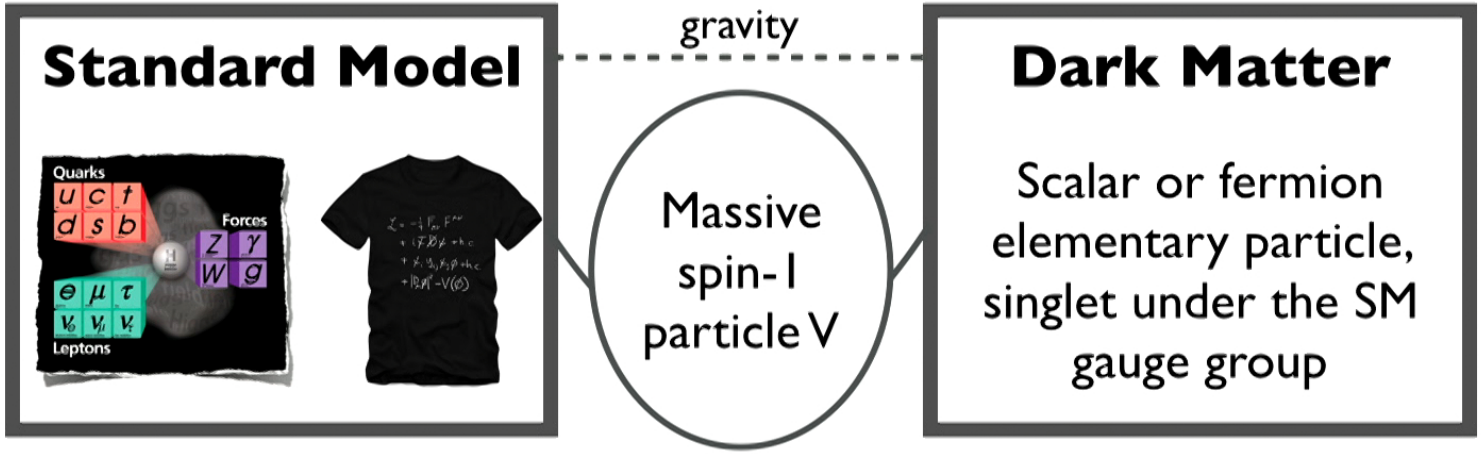


RGE

LHC bounds must be evolved to the nuclear scale



Vector Portals

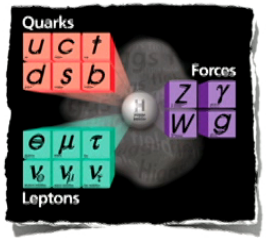


Motivated Extension of the Standard Model

Hewett, Rizzo, Phys.Rept. 183 (1989)
Cvetic, Godfrey, Barklow, T.L. (ed.) et al.: EWSB and new physics at the TeV scale (1995), (hep-ph/9504216)
Cvetic, Langacker, Adv.Ser.Direct.High Energy Phys. 18 (1998), (hep-ph/9707451)
Langacker, Rev.Mod.Phys. 81 (2009), (arXiv:0801.1345)

Vector Portals

Standard Model



gravity

Massive spin-1 particle V

Dark Matter

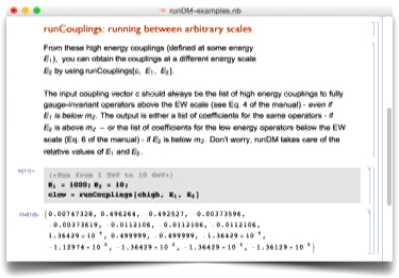
Scalar or fermion elementary particle, singlet under the SM gauge group

RGE known for this class of models

$$\frac{d\,c}{d\ln\mu} = \gamma_{\mathrm{SM}_X}\, c$$

Crivellin, FD, Procura, PRL112 (2014), (arXiv:1402.1173)
FD, Procura, JHEP1504 (2015), (arXiv:1411.3342)

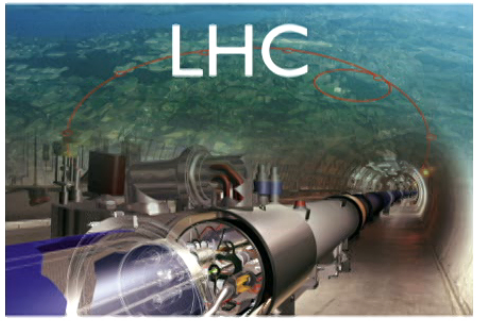
Procedure automated by runDM



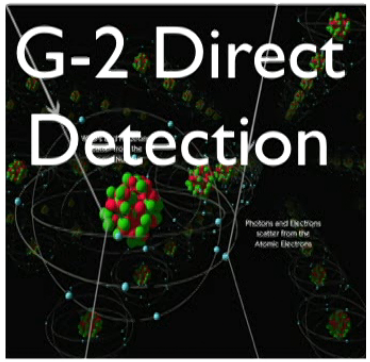
FD, Kavanagh, Panci (https://github.com/bradkav/runDM/)

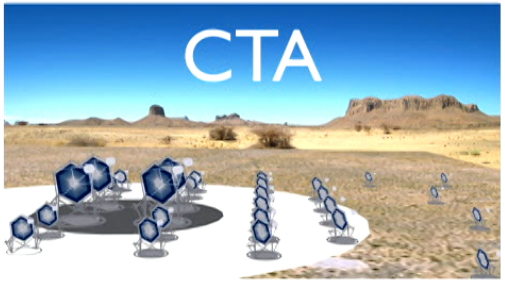
Searching for WIMPs

Impressive Results by Current Experiments

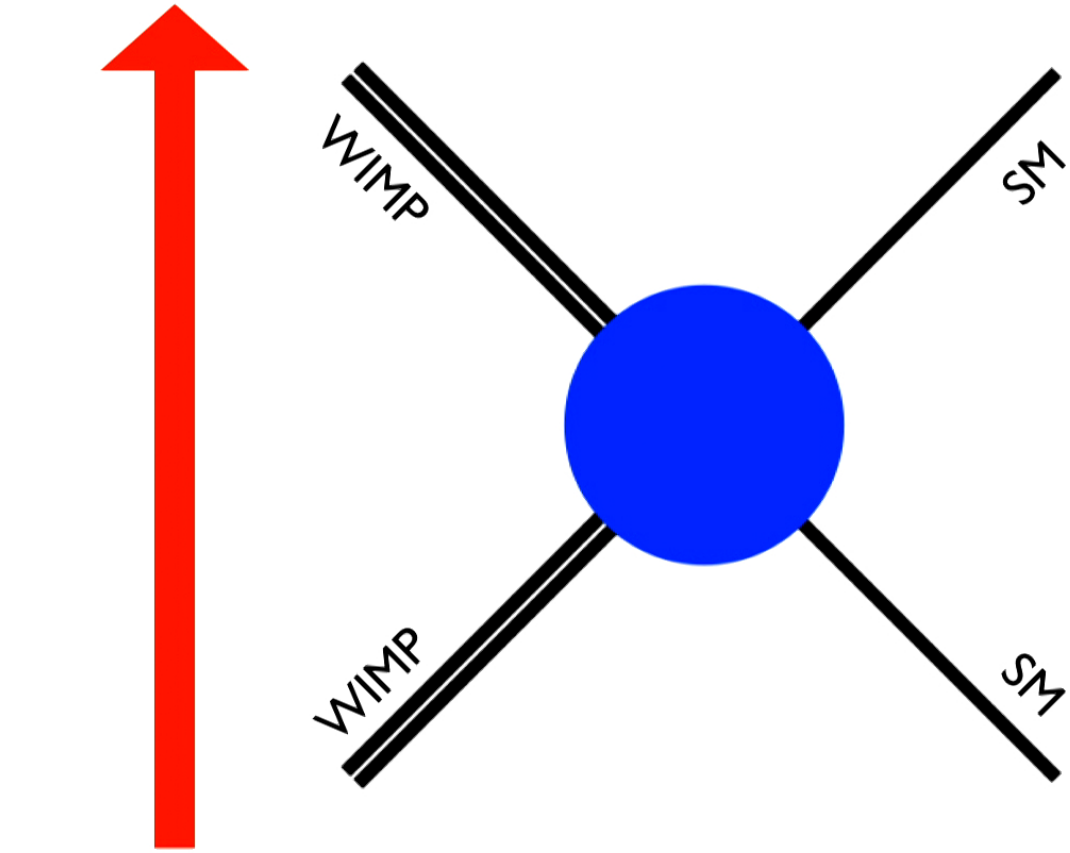


We will learn much more soon (next 5-10 years)





Direct Searches



Direct Searches

Flux of WIMPs:

10^5 cm^{-2} s^{-1}

(m_{WIMP} = 100 GeV)

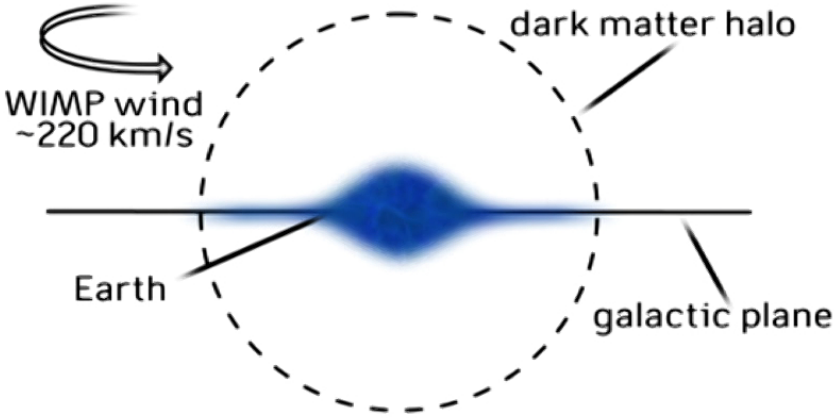


Image credit: https://www.learner.org/courses/physics/visual/img_full/wimp_signal.jpg

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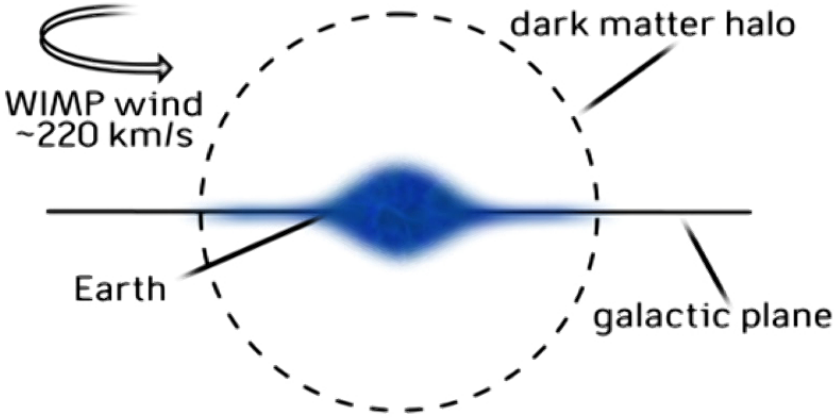

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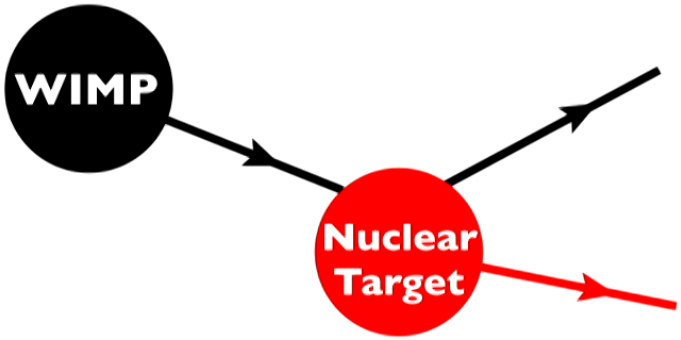

Typical recoil energy:
1-100 keV

Goodman and Witten, PRD31 (1985)
Primack, Seckel, Sadoulet, Ann.Rev.Nucl.Part.Sci. 38 (1988)

Direct Searches

Example mediators:

- Z boson: $\sigma \sim 10^{-39}$ cm^2
- Higgs boson: $\sigma \sim 10^{-44}$ - 10^{-47} cm^2

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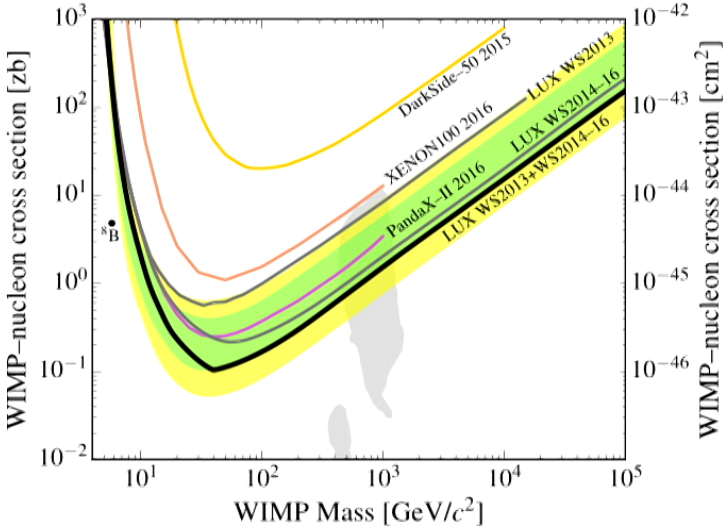

LUX Collaboration, PRL118 (2017) (arXiv:1608.07648)

Impressive results from current searches

Higgs portal under investigation…

… and motivated candidates, such as vector portals

Why RGE matters?

- changing size of the effective couplings
- generating new interactions (operator mixing)

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DM-Nucleus scattering:

only through couplings to light SM degrees of freedom

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very sensitive to the details of the interactions

Goodman and Witten, PRD31 (1985)

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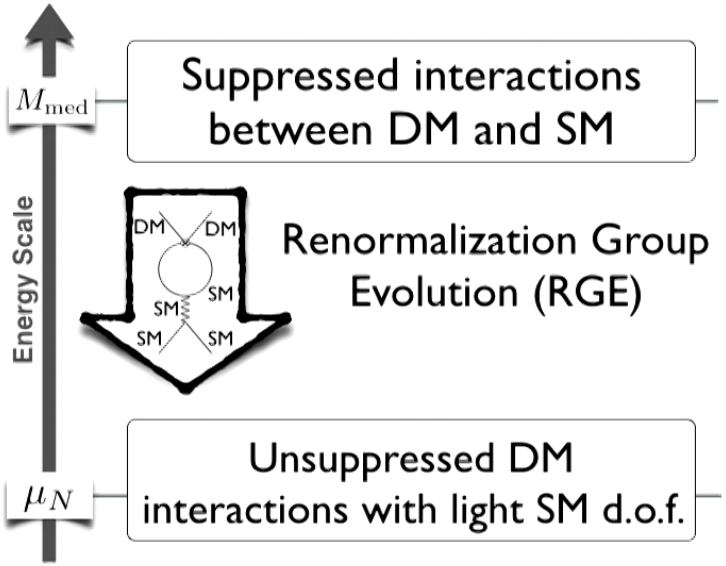
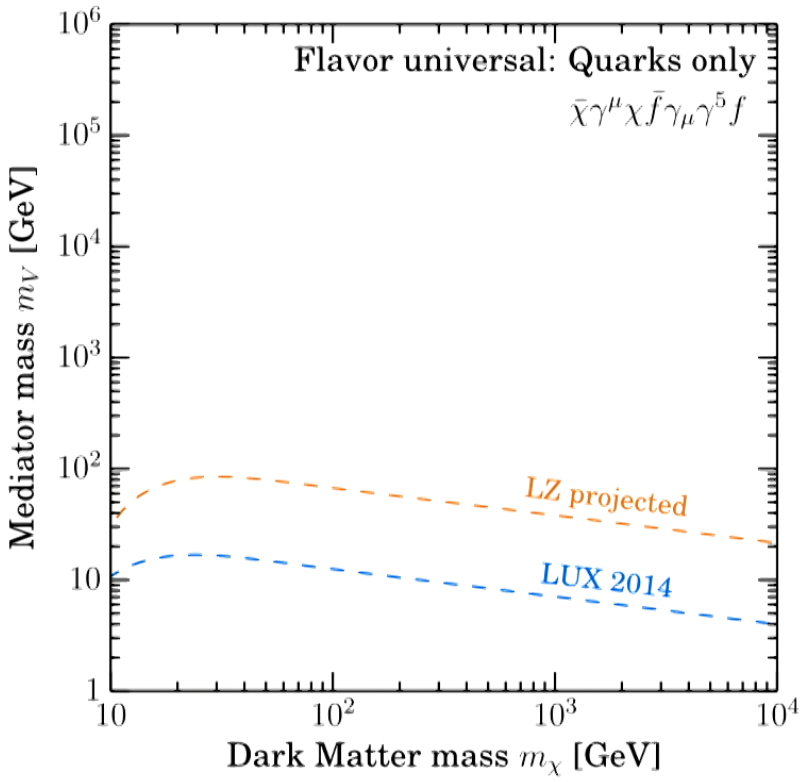
What if...



RGE in DD - I

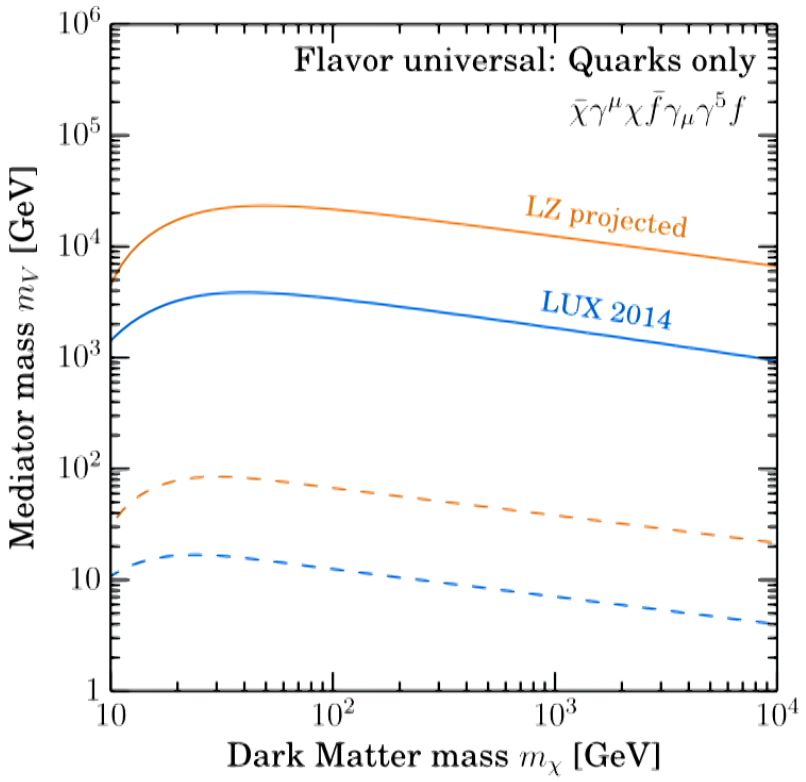


without RGE

with RGE

FD, Kavanagh, Panci, JHEP1608 (2016), arXiv:1605.04917

RGE in DD - I

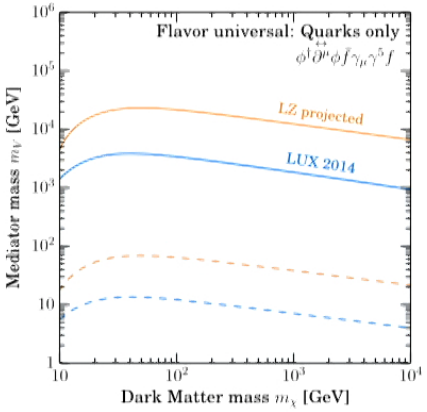


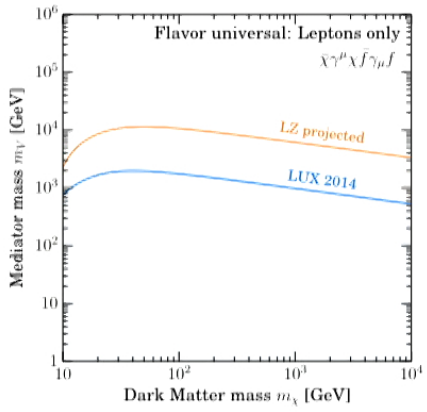
without RGE

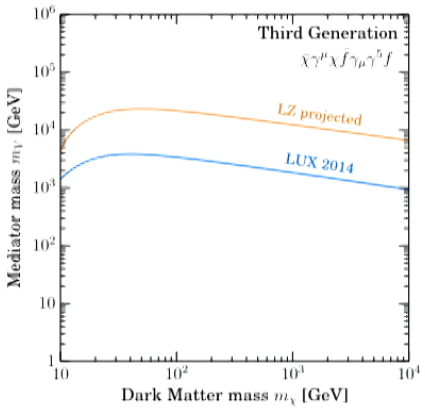
with RGE

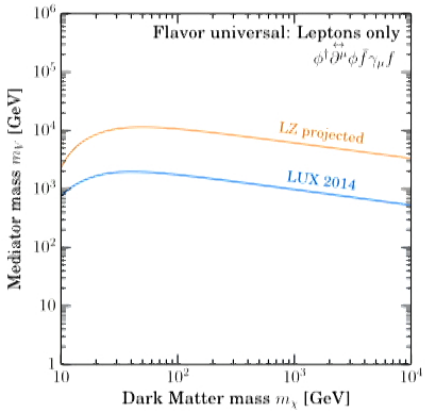
FD, Kavanagh, Panci, JHEP1608 (2016), arXiv:1605.04917

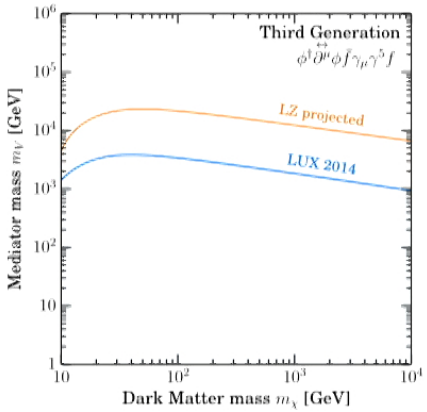
RGE in DD - more…





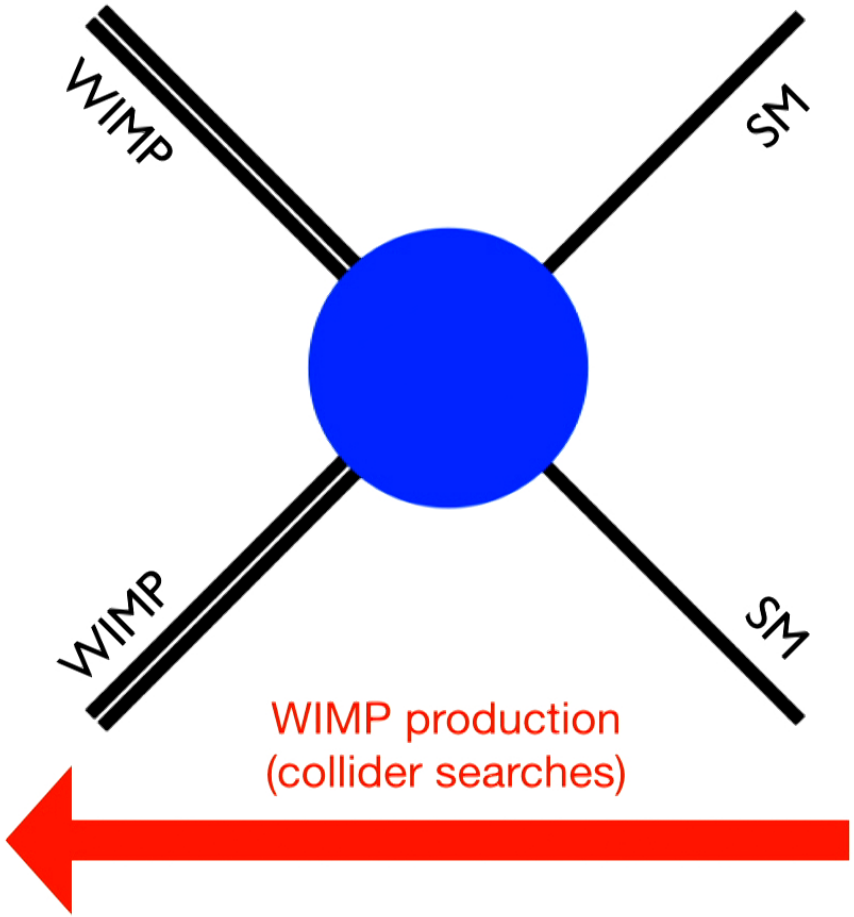






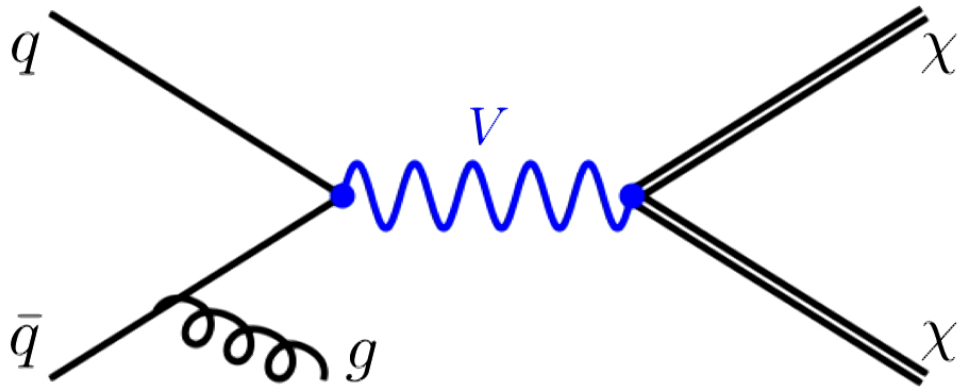
FD, Kavanagh, Panci, JHEP1608 (2016), arXiv:1605.04917

Collider Searches



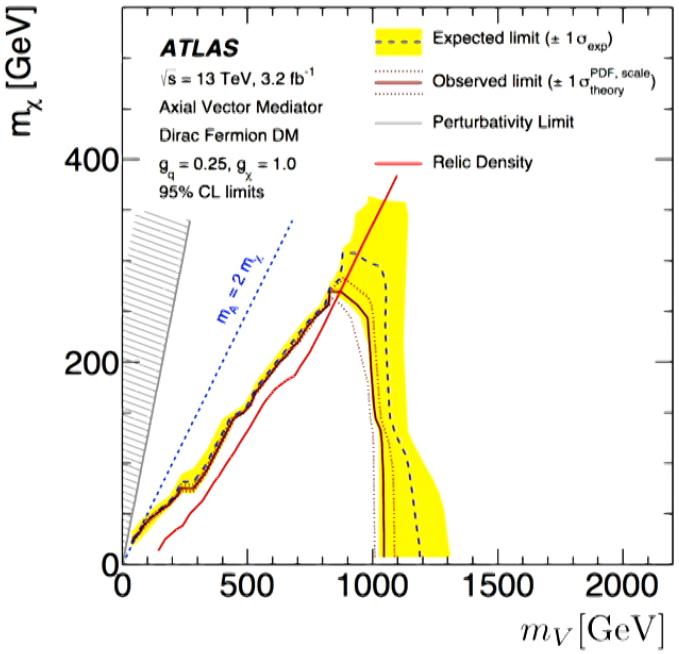
Vector Mediators @ LHC

Contact interactions not justified



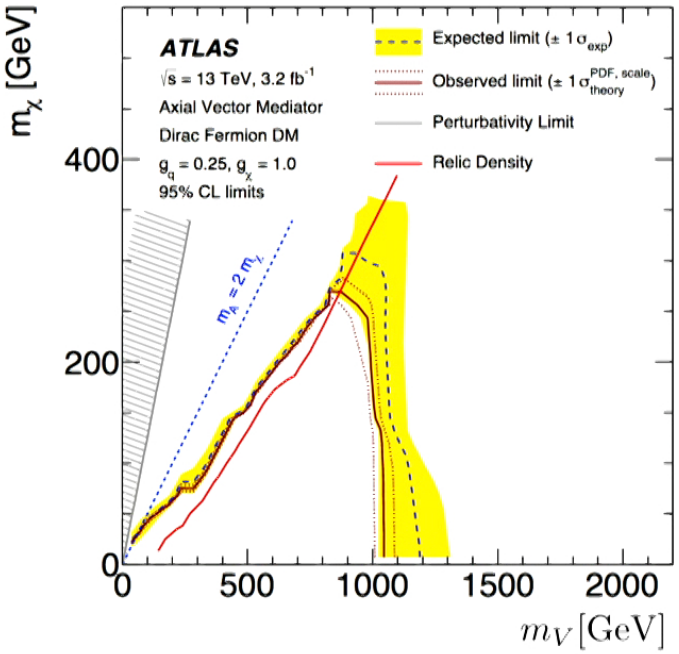
"Mono-jet" event

Vector Mediators @ LHC



ATLAS, PRD94 (2016), (arXiv:1604.07773)

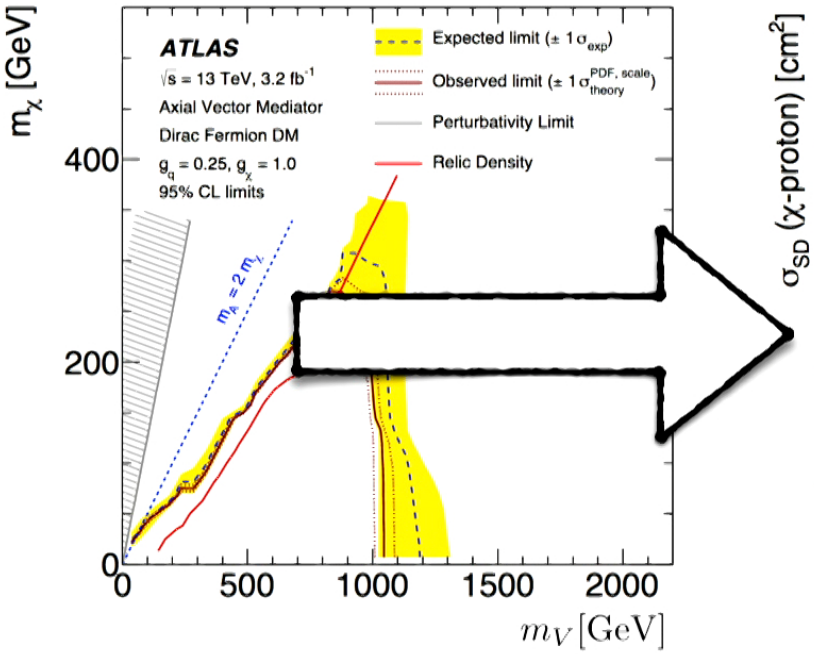
Vector Mediators @ LHC



ATLAS, PRD94 (2016), (arXiv:1604.07773)

RGE effects mild for mono-jet searches at the LHC

Vector Mediators @ LHC



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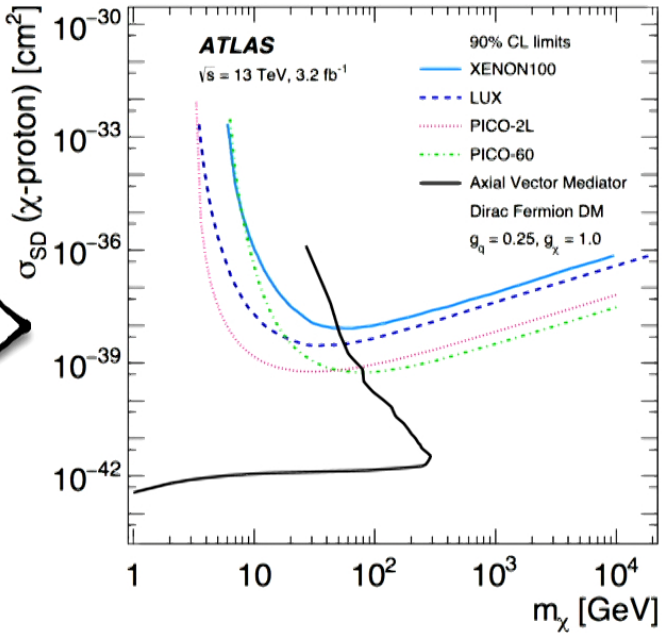
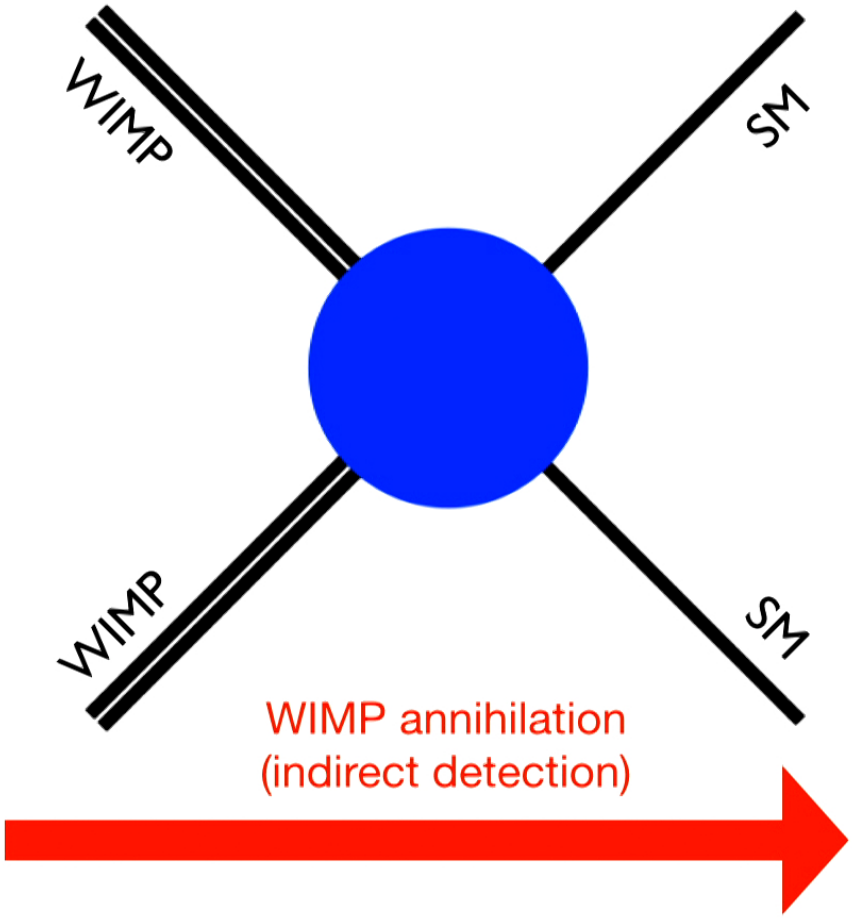


LUX, PRL116 (2016), (arXiv:1602.03489)
PICO-2L, PRD93 (2016), (arXiv:1601.03729)

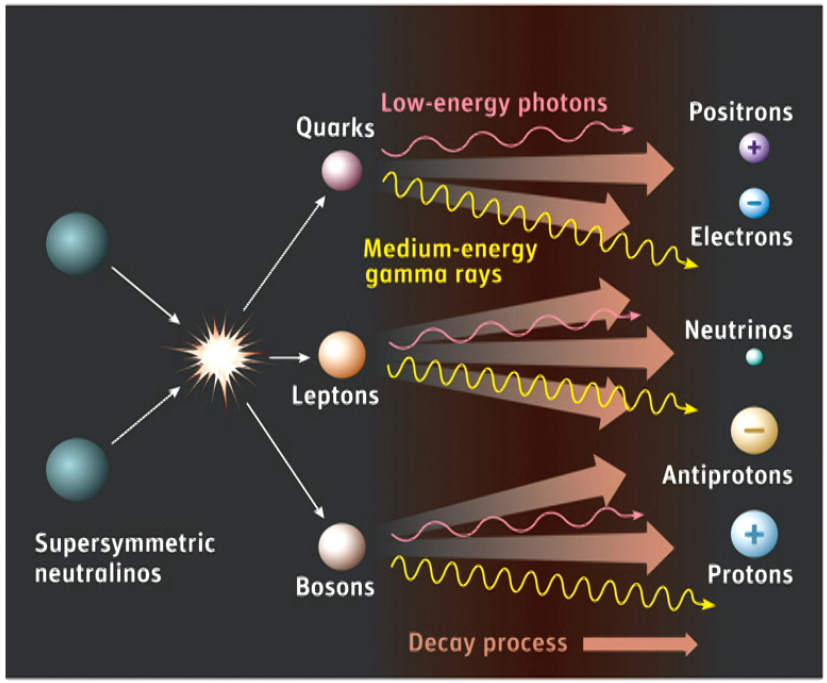
LHC limits on mediator mass translated into direct detection cross section (without RGE)

Indirect Searches



Indirect Searches

Look for DM annihilation products



Photons

☹ Astrophysical background

☺ Direction information

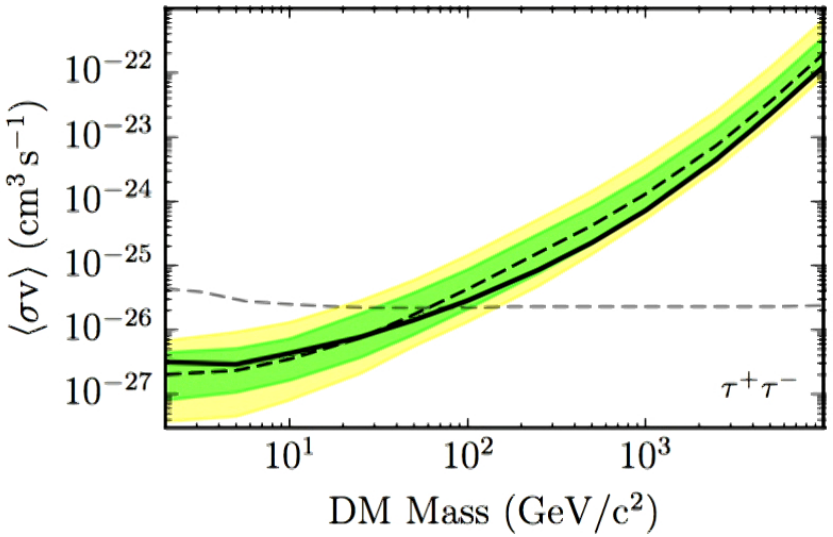
☺ No energy loss

Image credit: http://2.bp.blogspot.com/_mazRoHLuLI0/S8vDDnfah1I/AAAAAAAAAaQ/1Cxtj7Zs6DA/s1600/188434main_DkMatter_lg.jpg

Gamma Rays

Benchmark (Thermal) Annihilation Cross Section:

$\sigma v_{rel} \sim 3 \times 10^{-26}$ cm^3 s^{-1}



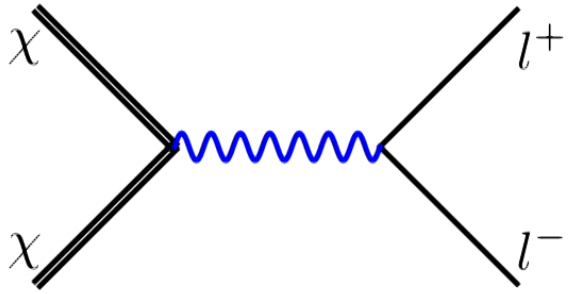
Fermi-LAT Collaboration, PRL115 (2015) (arXiv:1503.02641)

Thermal relic lighter than 100 GeV excluded by Fermi

The Cherenkov Telescope Array (CTA) will probe higher masses

DM on Leptons

How to probe these models?



- No coupling to nuclei (no direct detection)
- No couplings to protons (no events at the LHC)
- DM annihilation to leptons (signals in gamma rays)

DM on Leptons

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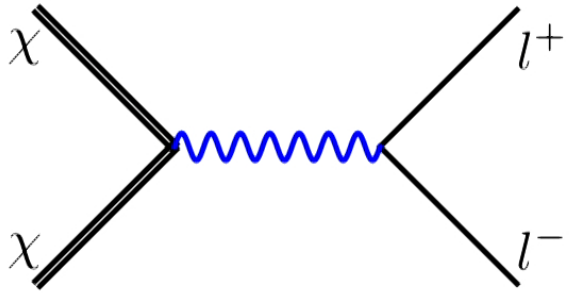

- No coupling to nuclei (no direct detection) ?
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- DM annihilation to leptons (signals in gamma rays)

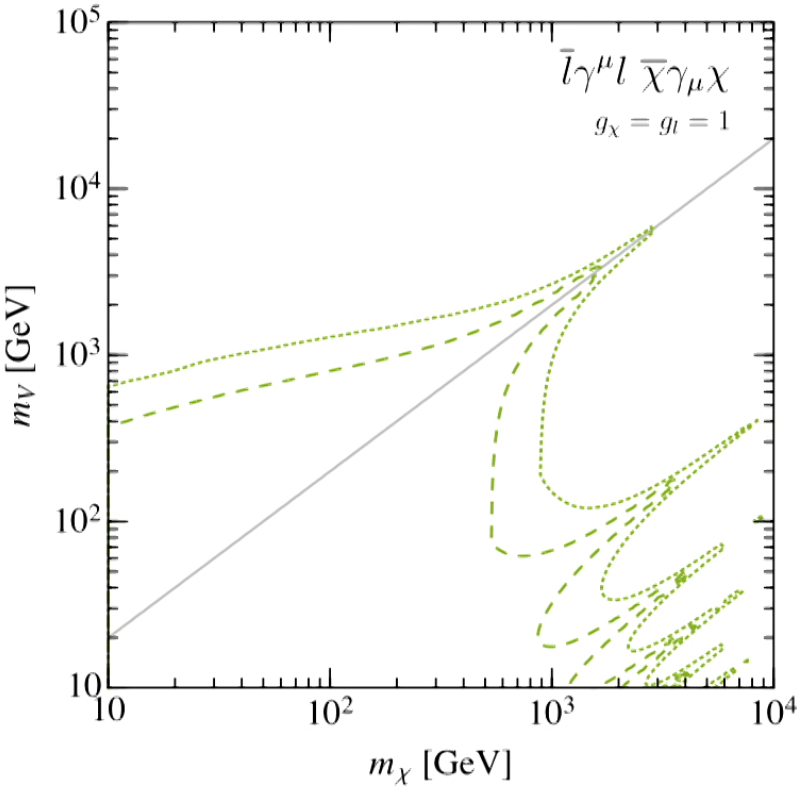
Are we sure?

FD, Kavanagh, Panci, (arXiv:1702.00016)

RGE for “Leptophilic” - I

- – Valid for μ only
- ····· Valid for τ only
- — Valid for μ or τ

Fermi (dSphs)



FD, Kavanagh, Panci, (arXiv:1702.00016)

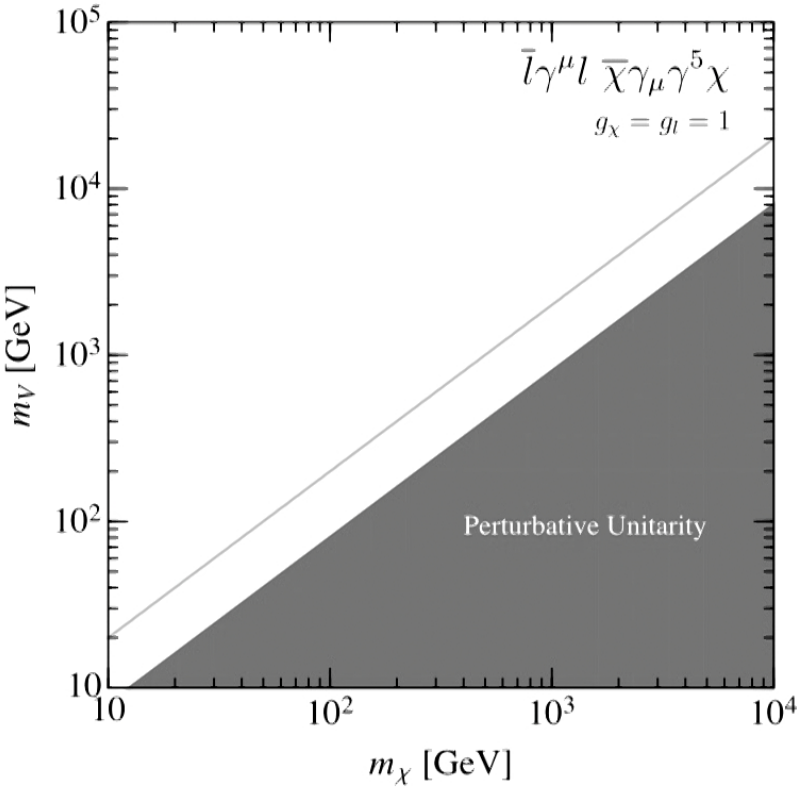
RGE for "Leptophilic" - II

- - Valid for μ only

····· Valid for τ only

— Valid for μ or τ

Fermi (dSphs)



FD, Kavanagh, Panci, (arXiv:1702.00016)

Spectra for “Leptophilic”

Radiative corrections alter cosmic ray spectra for leptophilic models

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High DM mass range ($m_{DM} > m_Z$):
final state radiation of EW gauge bosons lead to hadronic final states

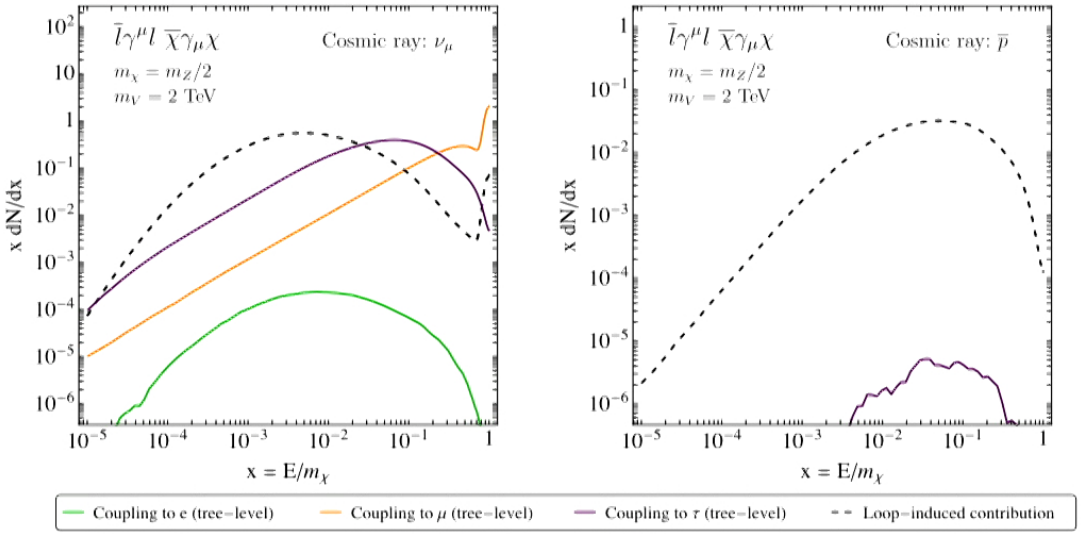
Kachelriess, Serpico, Solberg, PRD 80 (2009), arXiv:0911.0001

Spectra for “Leptophilic”

Radiative corrections alter cosmic ray spectra for leptophilic models

Low DM mass range ($m_{DM} < m_Z$):
new final states due to RG induced DM - Z boson interaction

Crivellin, FD, Procura, PRL112 (2014), (arXiv:1402.1173)
FD, Procura, JHEP1504 (2015), (arXiv:1411.3342)



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Outlook

A proper handling of energy scales crucial to connect different DM searches

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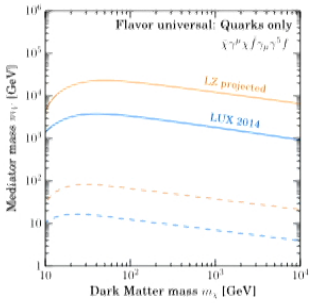
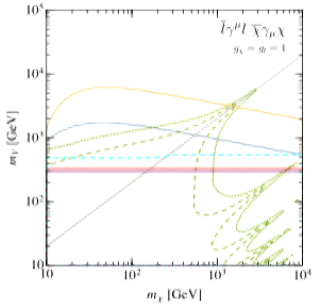
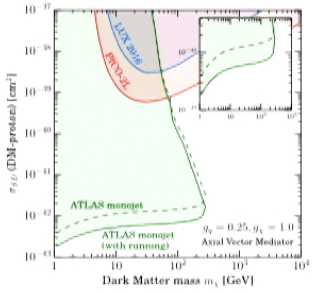
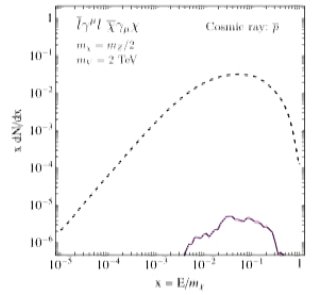
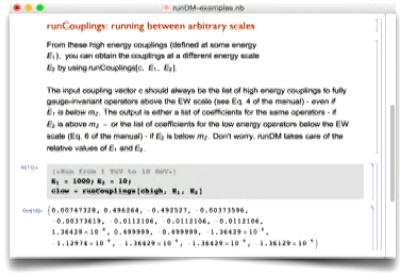








Procedure automated by runDM


runCouplings: running between arbitrary scales

From these high energy couplings (defined at some energy E_1), you can obtain the couplings at a different energy scale E_2 by using runCouplings[c, E_1, E_2].

The input coupling vector c should always be the list of high energy couplings to fully gauge-invariant operators above the EW scale (see Eq. 4 of the manual) - even if E_1 is below m_Z. The output is either a list of coefficients for the same operators - if E_2 is above m_Z - or the list of coefficients for the low energy operators below the EW scale (Eq. 6 of the manual) - if E_2 is below m_Z. Don't worry, runDM takes care of the relative values of E_1 and E_2.

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(*Run from 1 TeV to 10 GeV*)
E1 = 1000; E2 = 10;
clow = runCouplings[chigh, E1, E2]
```

```
{0.00747328, 0.496564, -0.492527, -0.00373596,
 -0.00373619, -0.0112106, -0.0112106, -0.0112106,
 1.36429×10^-6, 0.499999, 0.499999, -1.36429×10^-6,
 -1.12974×10^-5, 1.36429×10^-6, -1.36429×10^-6, 1.36129×10^-6}
```

FD, Kavanagh, Panci (https://github.com/bradkav/runDM/)

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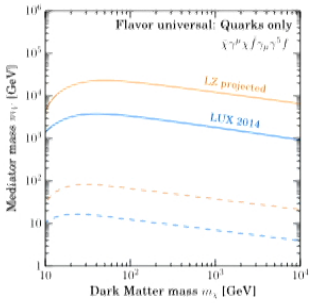

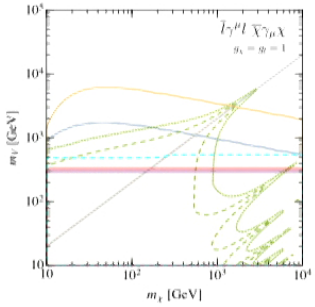

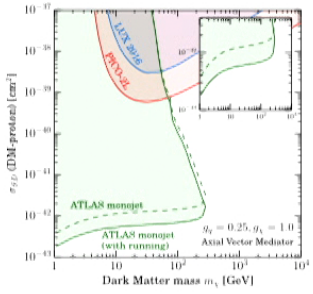

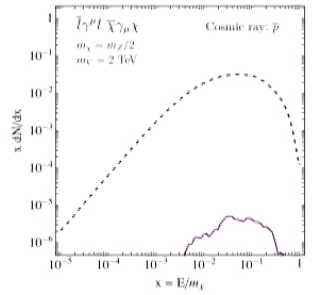

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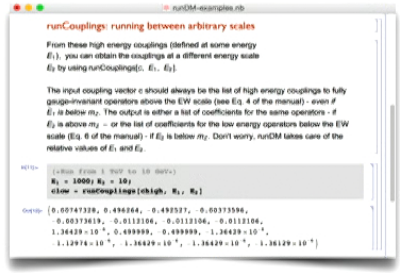
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Thank you!