Looking into the darkness:

old and new experiments to look for dark matter

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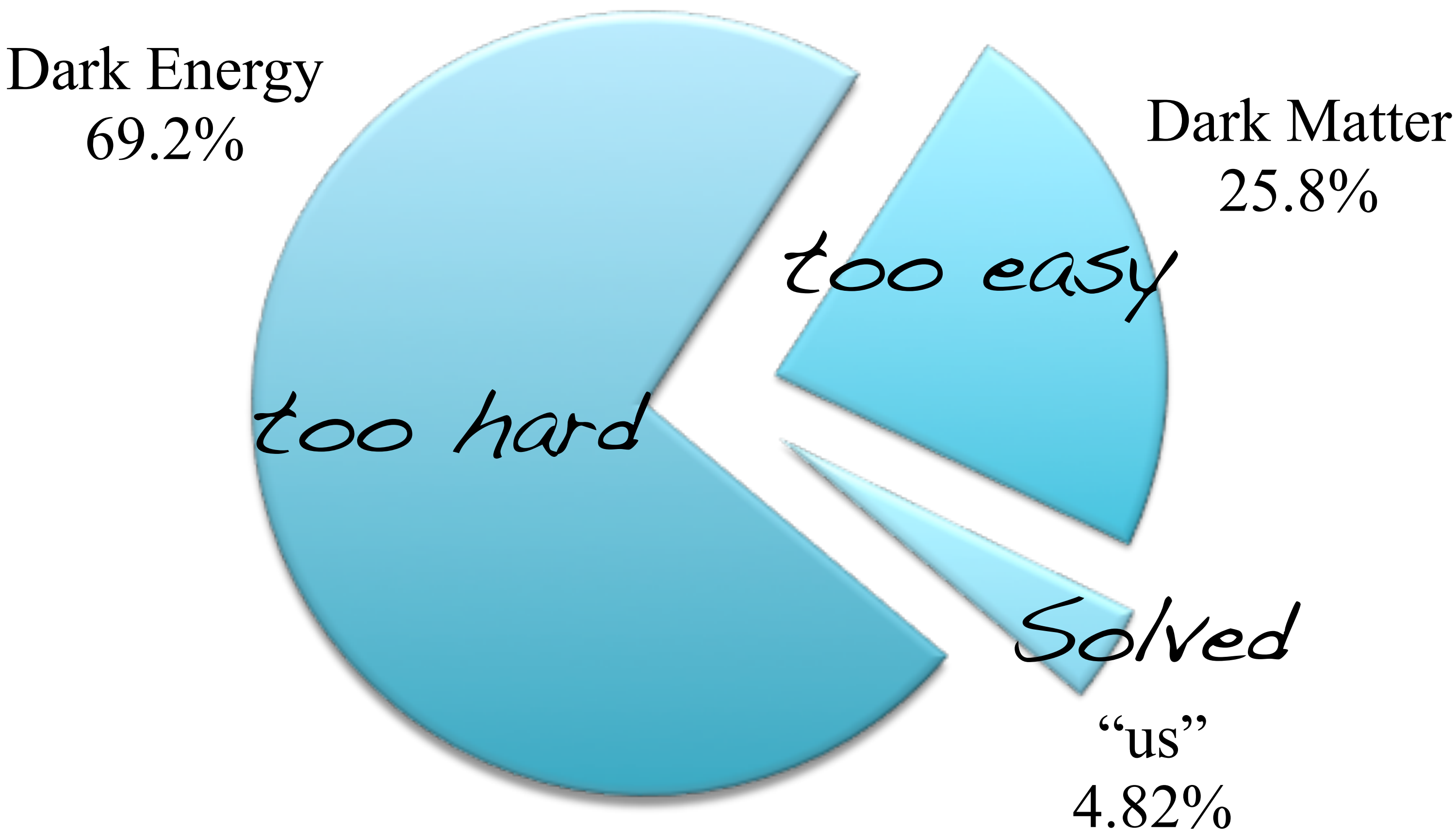
TRIUMF

Dec 9th, 2013

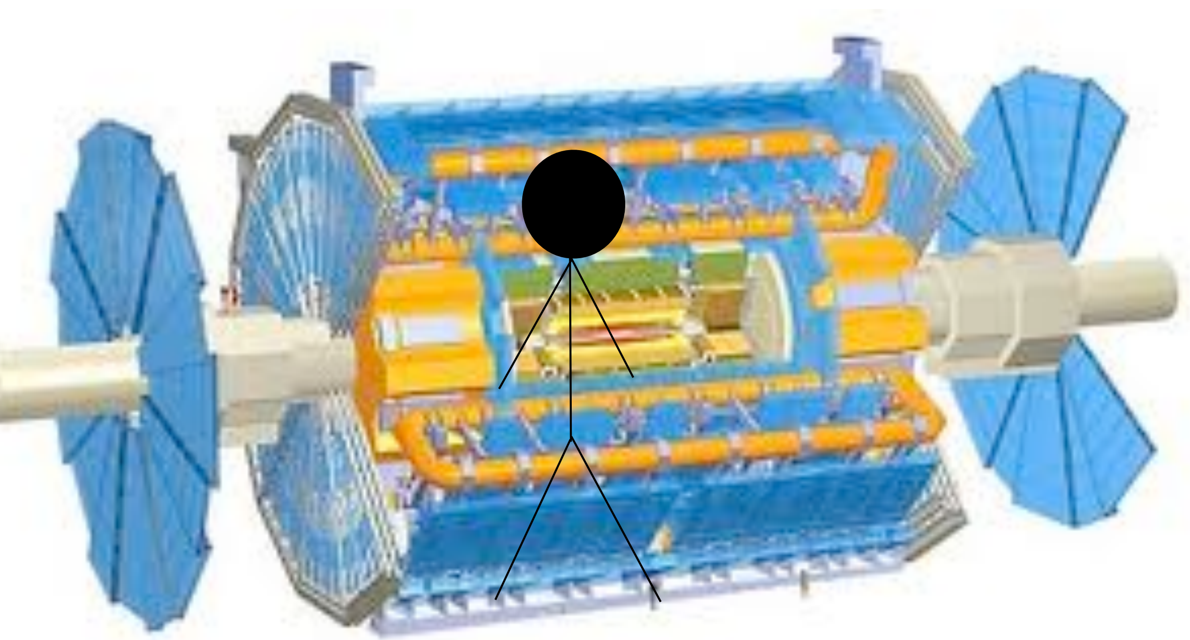
The Problem

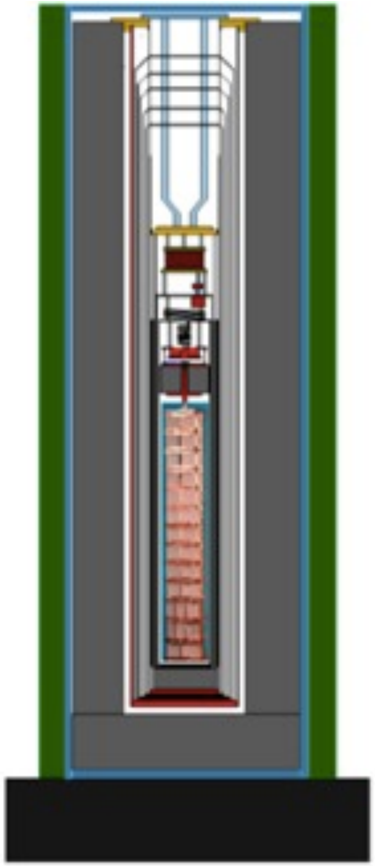


Recent results from PLANCK.

Thinking outside the SUSY box

(only one slide of philosophy, I promise . . .)





Road Map

1. Magnetic & Rayleigh Dark Matter

   (effective field theory)

2. New charged states and the FERMI line

   (the microscopic origin of the effective theory)

3. Dark Matter detection in two easy steps

   (looking for the de-excitation associated with MiDM)

Magnetic & Rayleigh Dark Matter

(effective field theory)

Dark, but not too dark

From Effective Field Theory point of view, a natural reason why DM is dark is that its interactions with light are all coming through irrelevant operators.

$$\mathcal{L} \quad = \quad \text{massive fermion } \chi$$

$$+ \quad \frac{1}{2}\mu_\chi \; \bar{\chi}\sigma_{\mu\nu}\chi B^{\mu\nu}$$

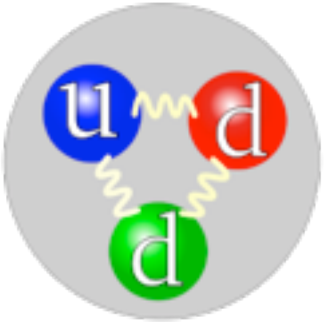
Chang, Weiner, and IY arXiv:1007.4200

Dark, but not too dark

We have many examples of neutral objects with a magnetic dipole:

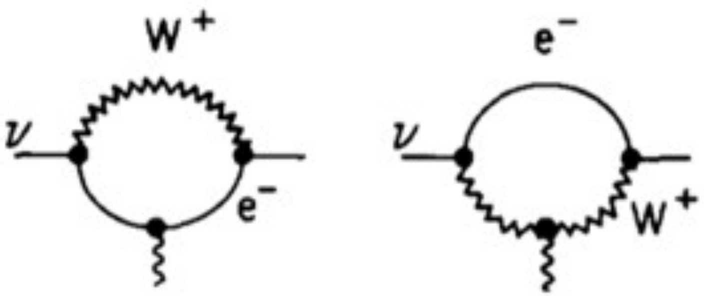
Neutrons

Charged constituents result in a magnetic dipole moment.



Neutrinos

Virtual cloud of charged matter results in magnetic dipole.



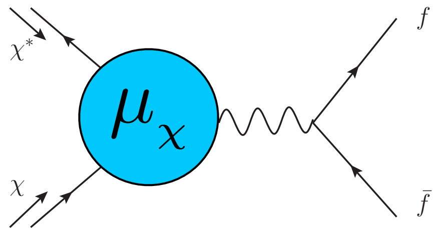
From Duncan, Grifols, Mendez, and Uma Sankar, Phys.Lett.B 191 (1987) 304

Notice that the mass difference of neutrinos may allow one neutrino to decay to another via a photon emission.

Phenomenology

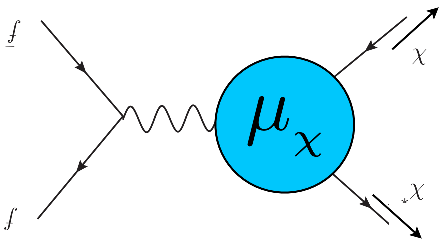
This single vertex contributes to a variety of observable processes

Annihilation



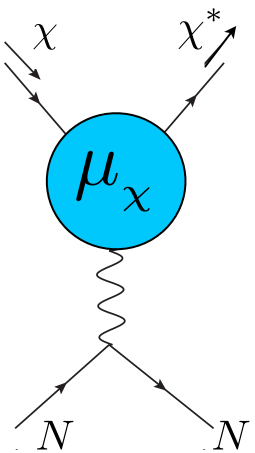
This process in the early universe can lead to the correct relic abundance of dark matter.

Production



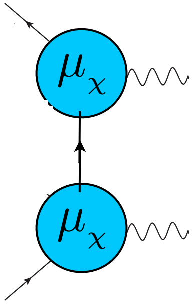
Dark matter in colliders

Direct detection



This process can be searched for in direct detection experiments looking for dark matter in the lab.

Gamma-rays



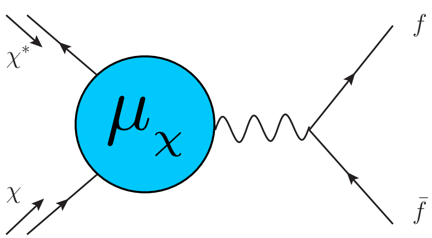
This process can be searched for in gamma-ray lines in astrophysical observations (e.g. galactic center).

Scaling Relations

For thermally produced MiDM, the direct and gamma-ray line indirect signatures are roughly independent of the size of the dipole

Duda, Gelmini, & Gondolo arXiv:hep-ph/0102200, Weiner and IY arXiv:1206.2910

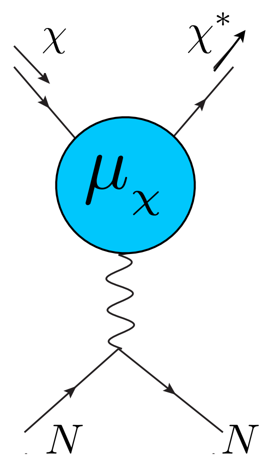
annihilation



$$\rho_{\rm MiDM} = \rho_0 \times \frac{\mu^2_{\rm thermal}}{\mu^2_\chi}$$

numerical value required for dark matter to be a thermal relic

direct detection

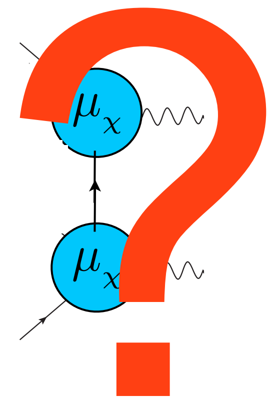


$$R_{DD} \propto n_\chi \mu^2_\chi =$$

$$\frac{\rho_0}{m_\chi} \frac{\mu^2_{\rm thermal}}{\mu^2_\chi} \times \mu^2_\chi =$$

$$\frac{\rho_0}{m_\chi} \mu^2_{\rm thermal}$$

gamma-rays



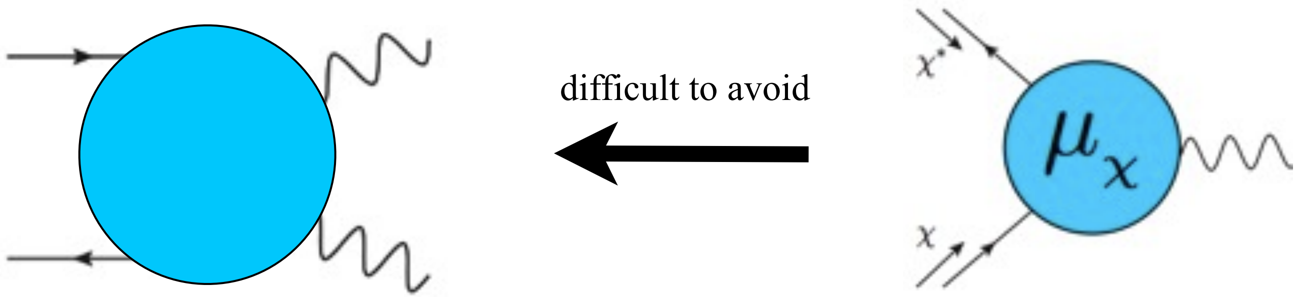
$$R_{\gamma\gamma} \propto n^2_\chi \mu^4_\chi =$$

$$\frac{\rho^2_0}{m^2_\chi} \frac{\mu^4_{\rm thermal}}{\mu^4_\chi} \times \mu^4_\chi =$$

$$\frac{\rho^2_0}{m^2_\chi} \mu^4_{\rm thermal}$$

Rayleigh Dark Matter

Neutral particles also have two-photon interactions leading to Rayleigh scattering (the blue sky. . .) Weiner and IY arXiv:1206.2910



$$\mathcal{L}_{\mathrm{MiDM}} = \left(\frac{\mu_\chi}{2}\right) \bar{\chi}^* \sigma_{\mu\nu} B^{\mu\nu} \chi + c.c.$$

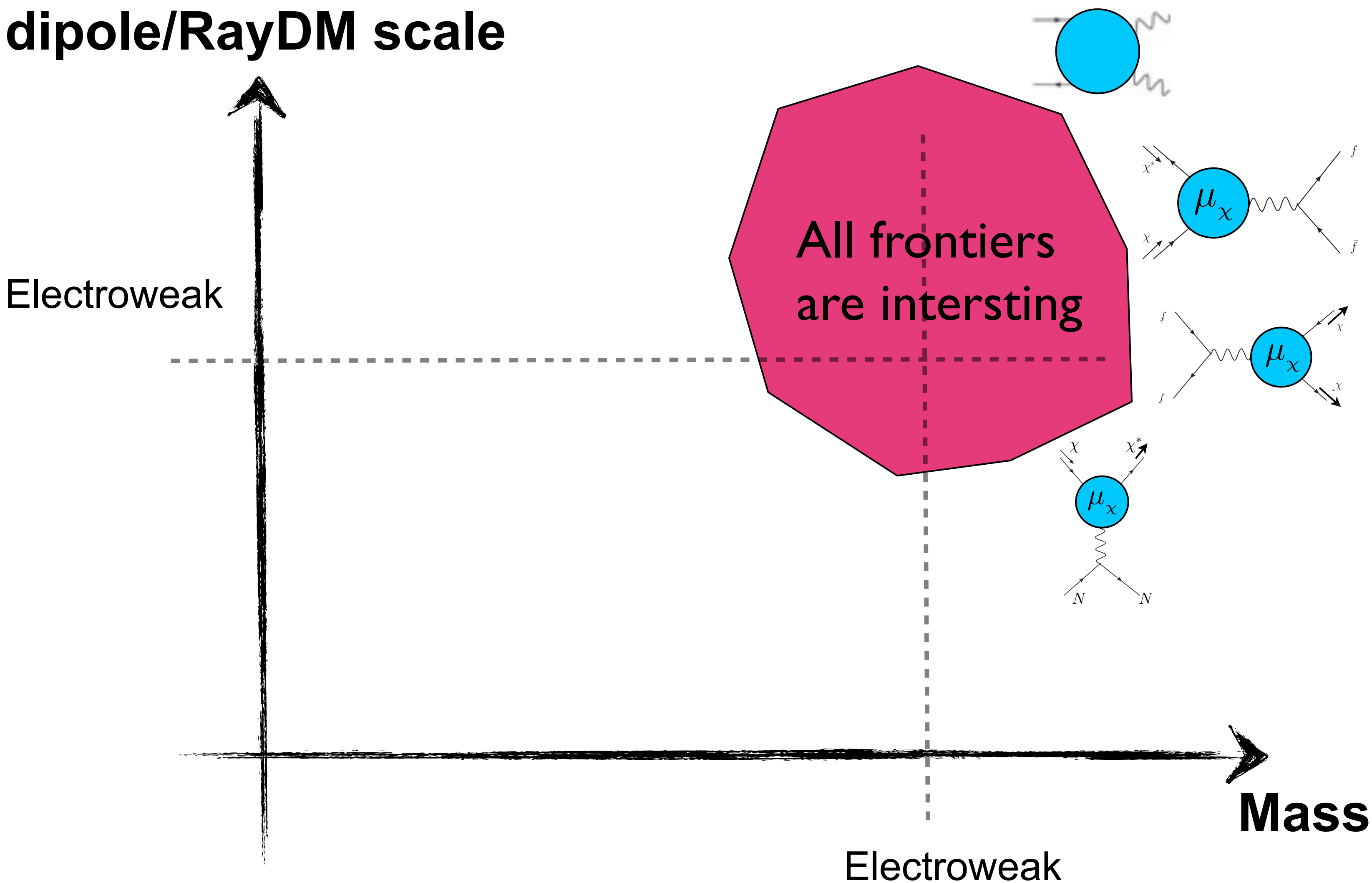
Magnetic (inelastic) Dark Matter

$$\mathcal{L}_{\mathrm{RayDM}} = \frac{1}{4\Lambda_R^3} \bar{\chi}\chi \left(\cos\theta_\chi B_{\mu\nu} B^{\mu\nu} + \sin\theta_\chi \mathrm{Tr} W_{\mu\nu} W^{\mu\nu}\right)$$

Rayleigh Dark Matter

$$+ \frac{i}{4\tilde{\Lambda}_R^3} \bar{\chi}\gamma_5\chi \left(\cos\theta_\chi B_{\mu\nu} \tilde{B}^{\mu\nu} + \sin\theta_\chi \mathrm{Tr} W_{\mu\nu} \tilde{W}^{\mu\nu}\right)$$

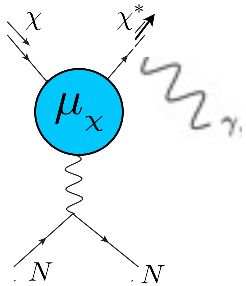
Interesting Parameter Space



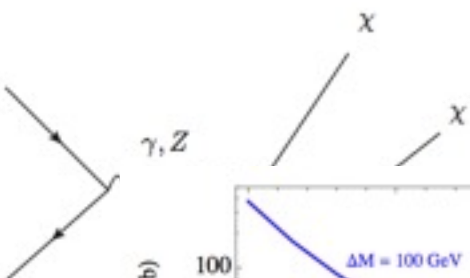
Other Searches

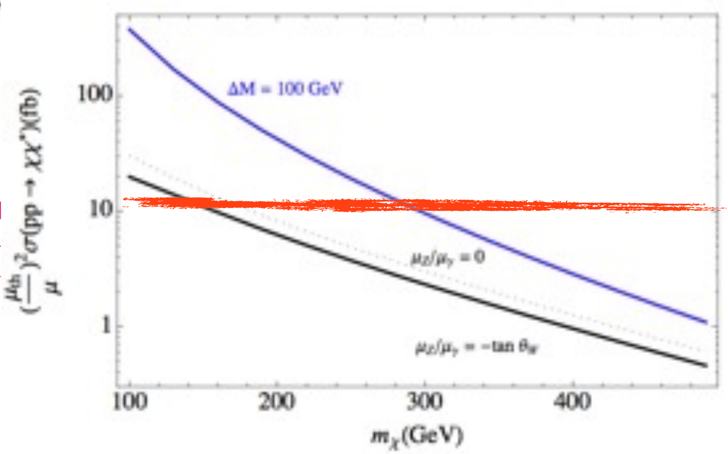
Is there any other testable phenomenology? More in the next section, but

MiDM (one-photon vertex)



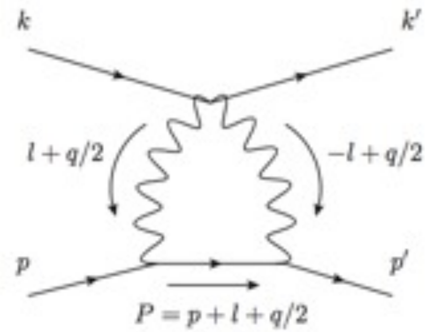
Excited state will decay.
Look for x-ray lines.



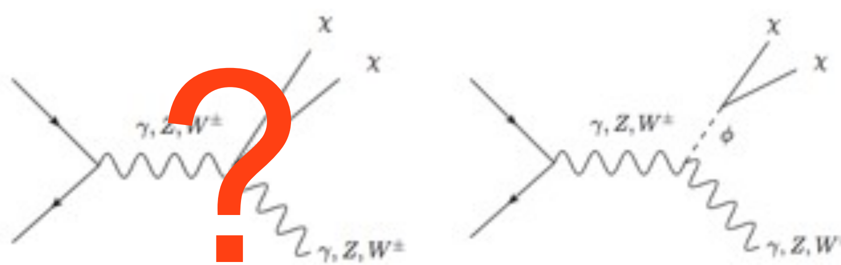


Produ
monop

RayDM (two-photon vertex)



Seems difficult, but forced us to find new ways (ala HQET) to calculate these effects.



Motivates mono-W searches

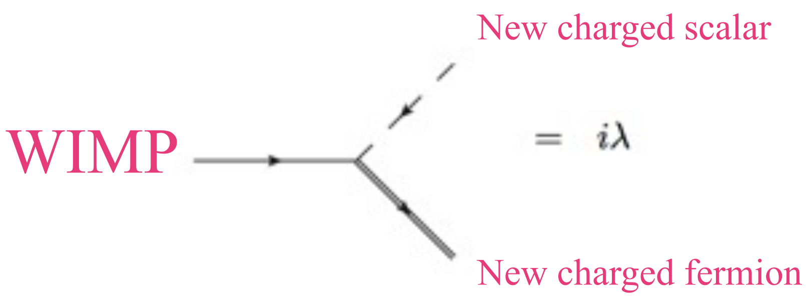
New charged states

(the microscopic origin of these interactions)

New Charged States

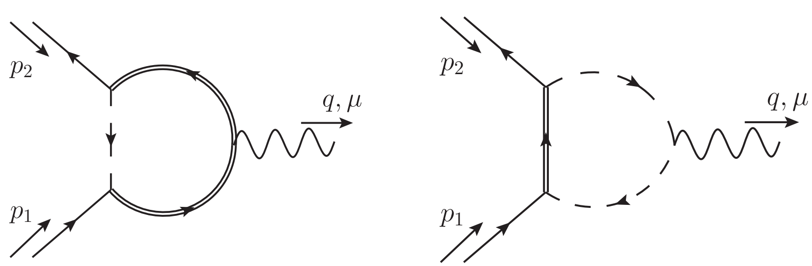
The MiDM and RayDM operators arise from integrating out charged matter that couples to the WIMP. Charged matter at the electroweak scale is necessary, N. Weiner & IY arXiv:1209.1093

J. Cline, A. Frey, G. Moore for strongly coupled version

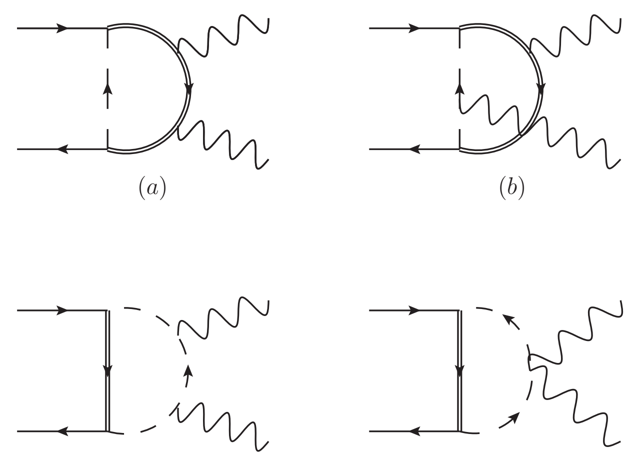


$$\begin{aligned}\mathcal{L} = &\bar{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \bar{\psi}\left(iD\!\!\!\!/ - M_f\right)\psi \\ &+ \left(D^\mu\varphi\right)^\dagger D_\mu\varphi - M_s^2\varphi^\dagger\varphi \\ &+ \lambda\bar{\psi}\chi\varphi\end{aligned}$$

Magnetic (inelastic) Dark Matter

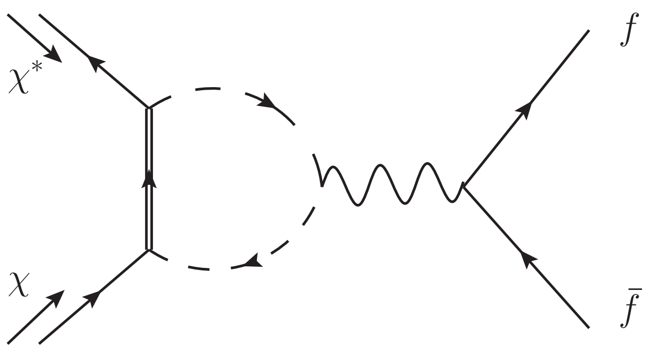


Rayleigh Dark Matter

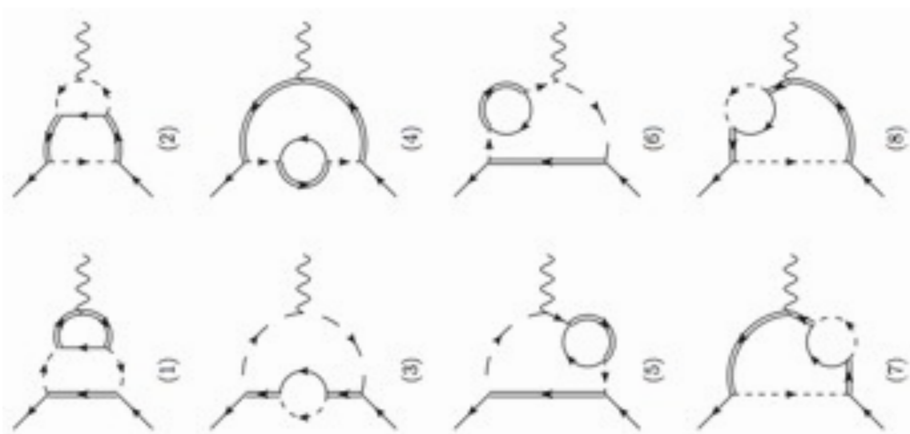


Relic Abundance

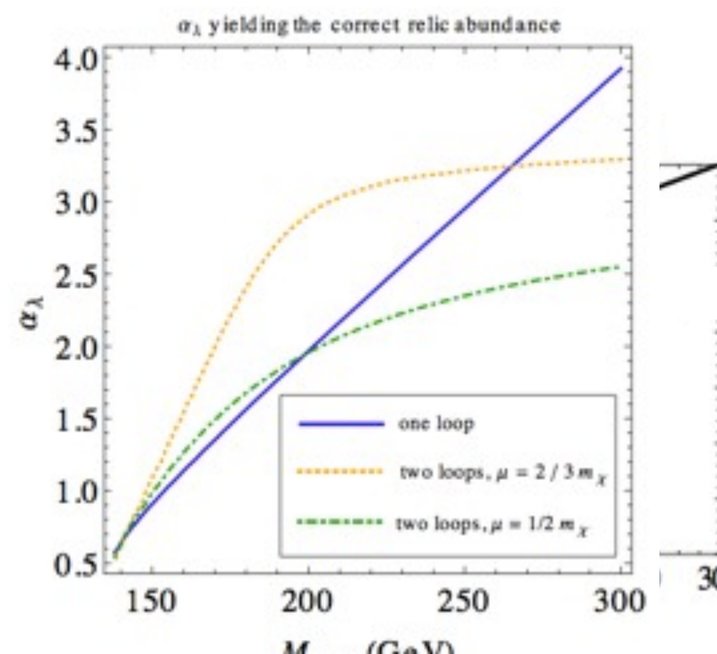
The dark matter density observed today is determined by the annihilation of DM into charged pairs through the dipole operator in the early Universe, N. Weiner & IY arXiv:1209.1093



$$
\begin{aligned}
\mathcal{L} = {} & \bar{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \bar{\psi}\left(iD\!\!\!\!/ - M_f\right)\psi \\
& + \left(D^\mu\varphi\right)^\dagger D_\mu\varphi - M_s^2\varphi^\dagger\varphi \\
& + \lambda\bar{\psi}\chi\varphi - \frac{\kappa}{4}\left|\varphi^\dagger\varphi\right|^2 + \text{h.c.}
\end{aligned}
$$

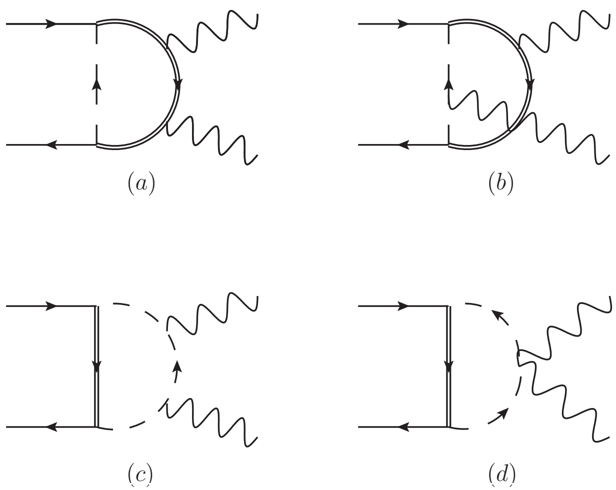


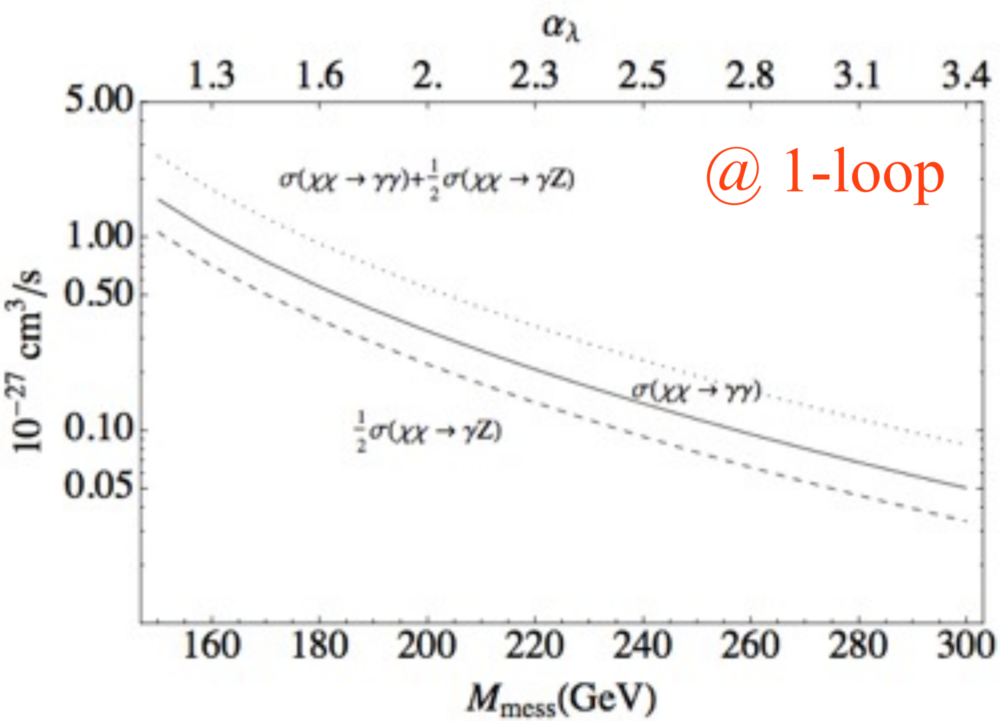
C. Tamarit & IY arXiv:1305.2951



Gamma Rays

Annihilation today is dominated by the Rayleigh operator (no excessive continuum),



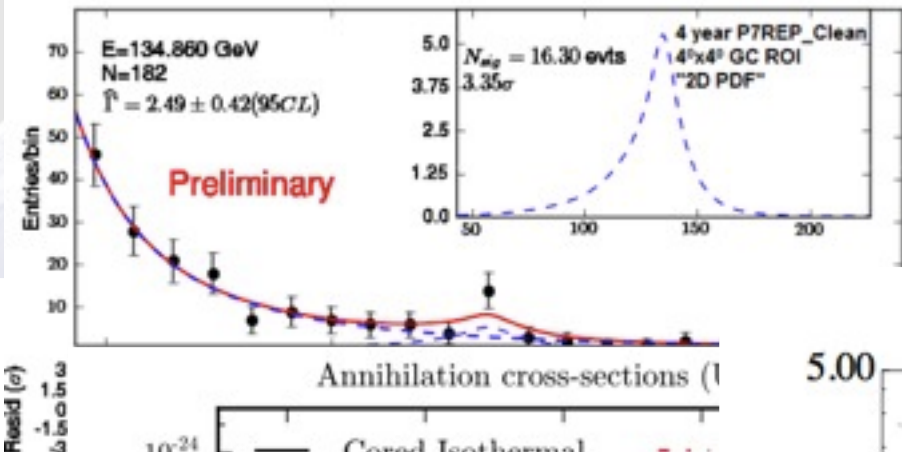


By electroweak gauge invariance we expect annihilations into photons as well as Z-bosons.

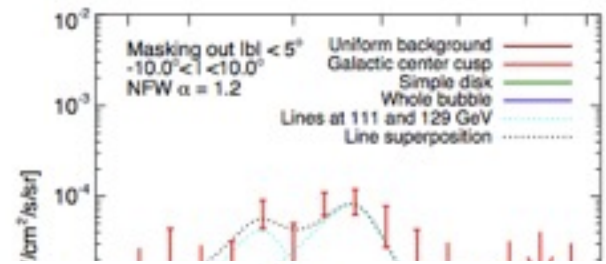
The Fermi Line

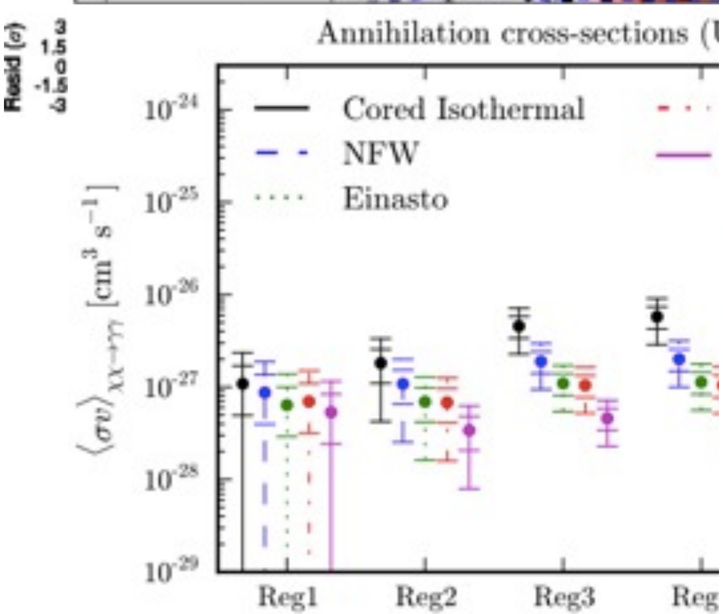
FERMI data reveals an excess at 135 GeV that can be interpreted as Dark Matter annihilation.

Albert for FERMI

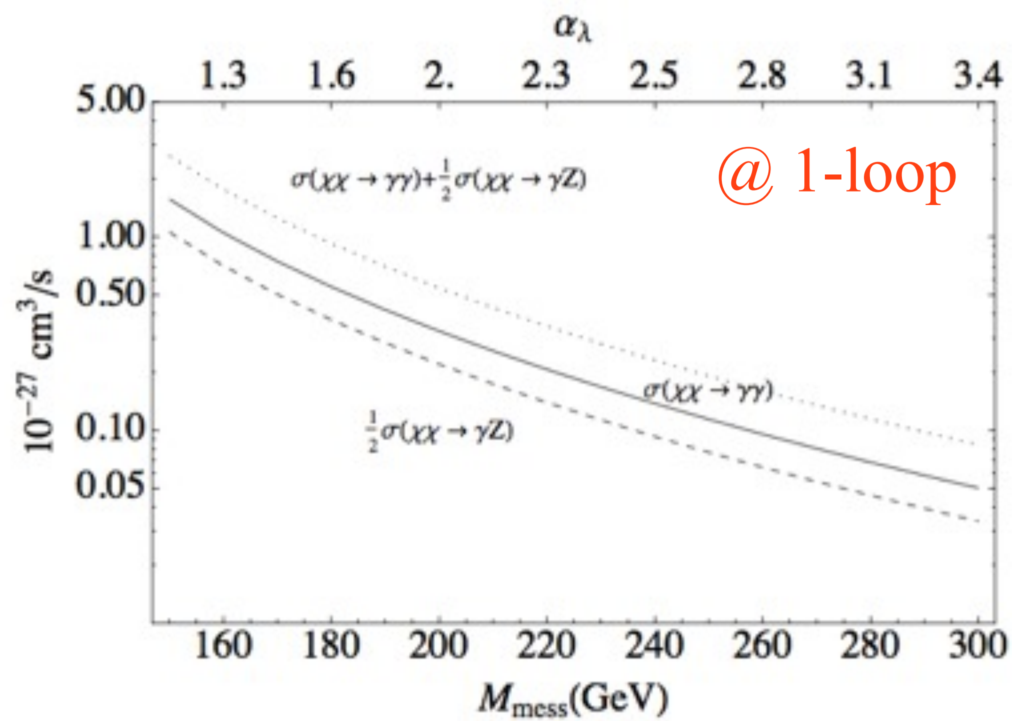


Finkbeiner & Su arXiv:1206.1616





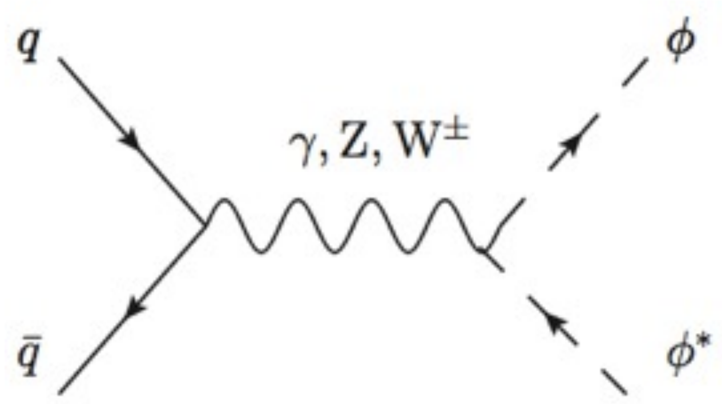
Weniger arXiv:1204.2797

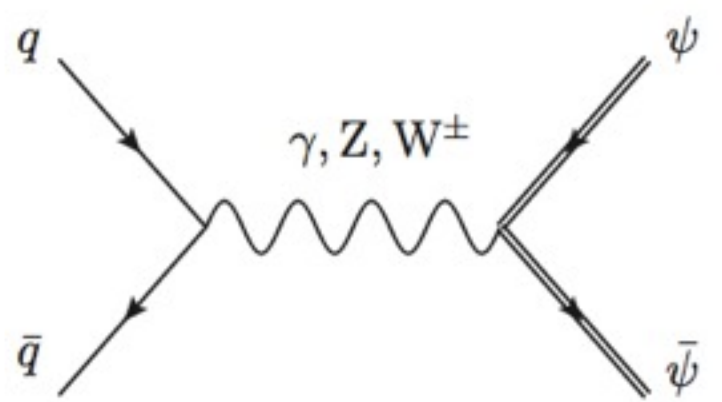


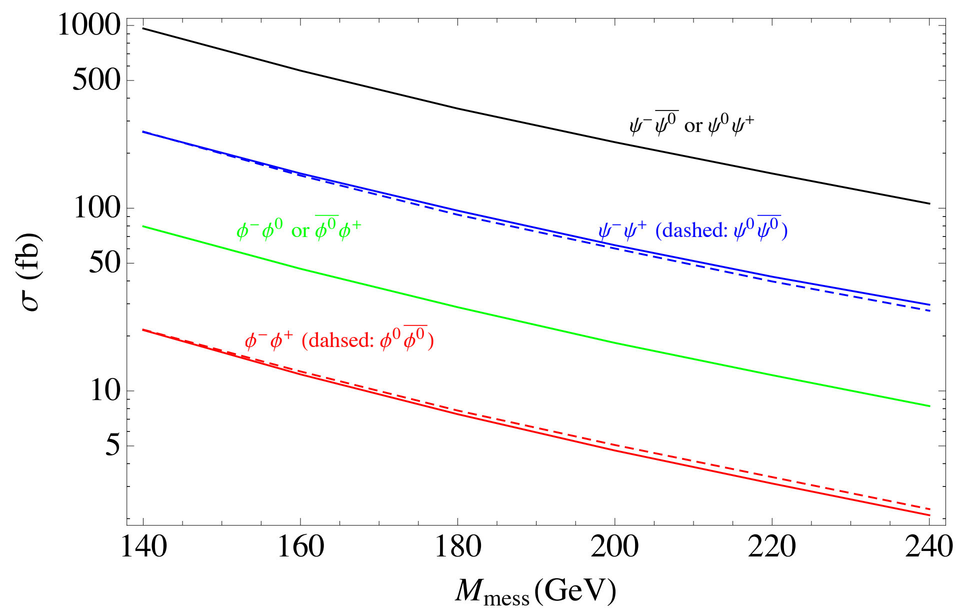
Already Produced at the LHC

These charged states were already produced at the LHC through their gauge interactions:

(Liu, Shuve, Weiner, IY arXiv:1303.4404)



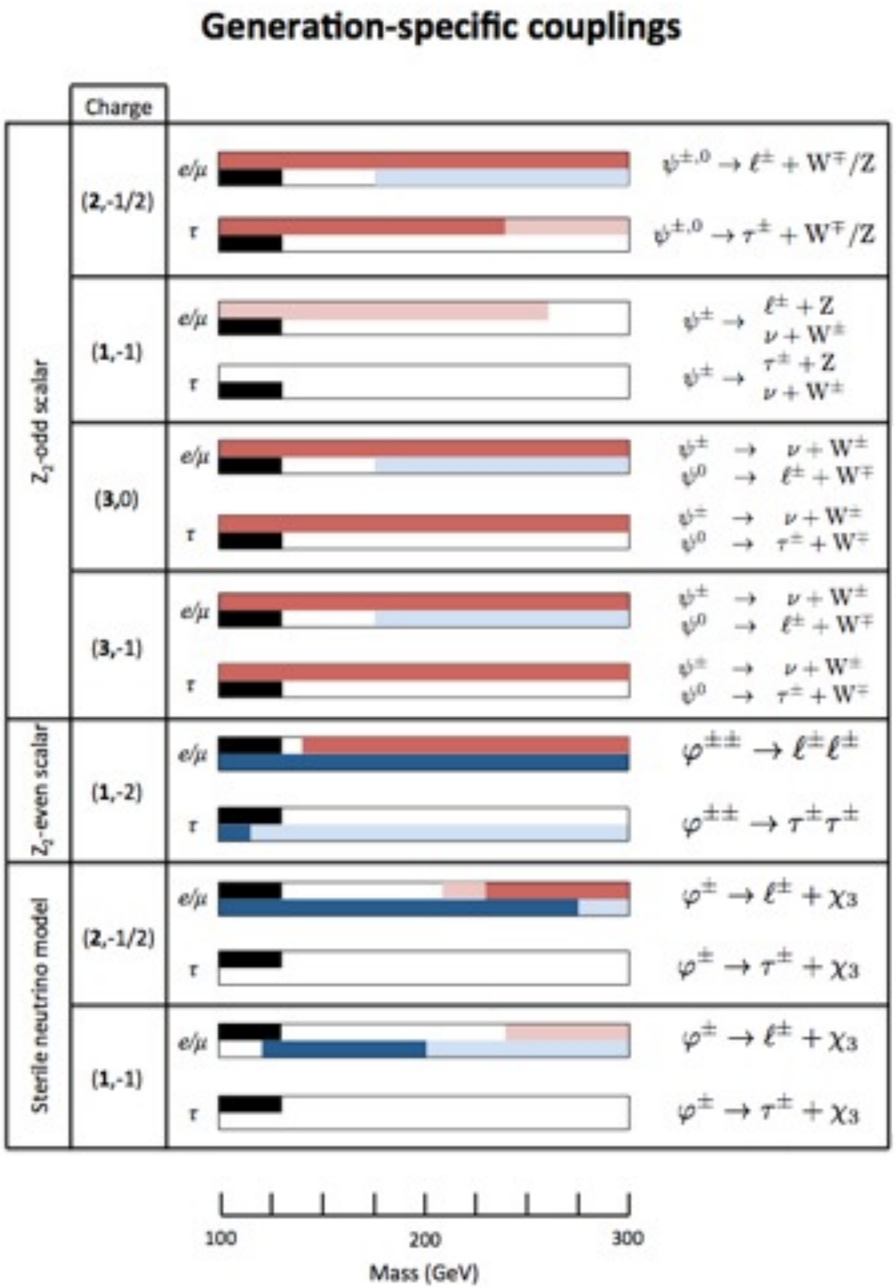




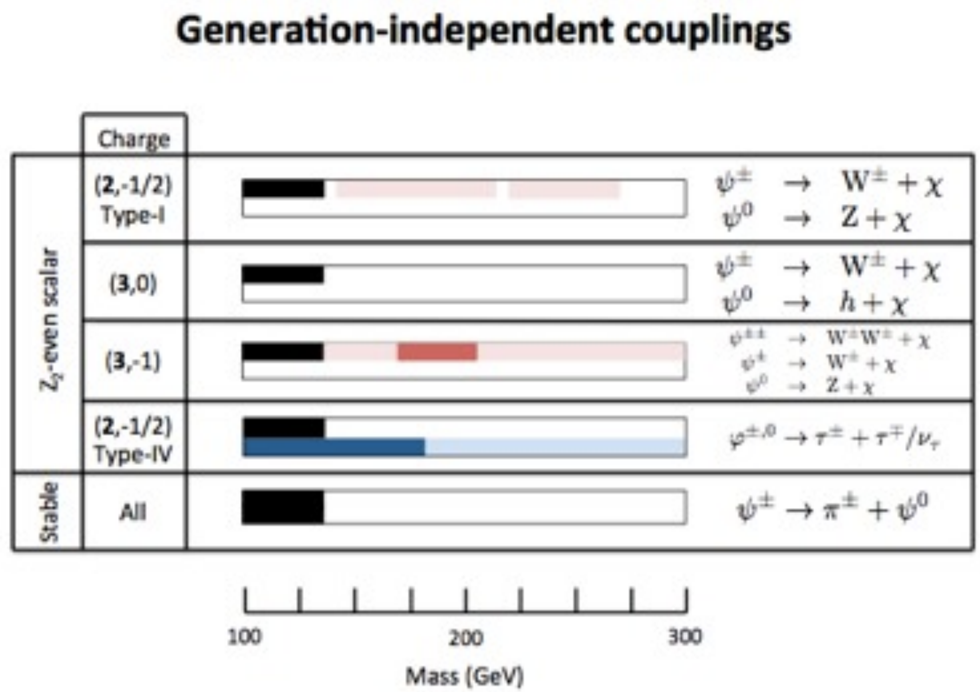
The production cross-section for the fermionic states is a lot larger.

These cross-sections are now being probed at the LHC.

The discovery prospects really depend on how they decay.



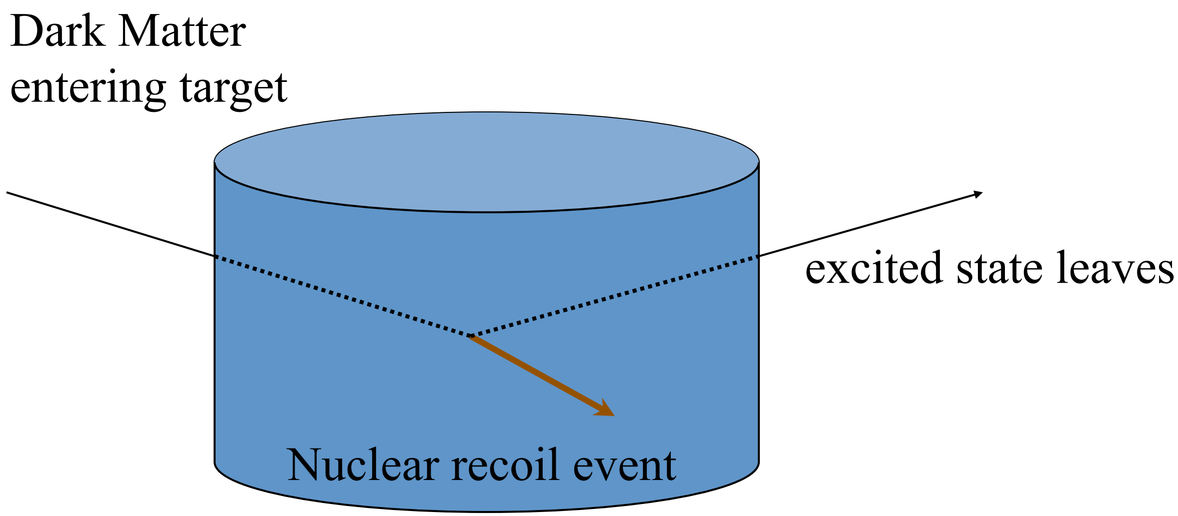
The charged states should not remain stable. How to search for these states depends on their decays.



Dark Matter detection in two easy steps

(Looking for the de-excitation associated with MiDM)

MiDM and Direct Detection



Can be looked for with the usual dark matter detectors (LUX, CDMS, XENON, etc.), but:

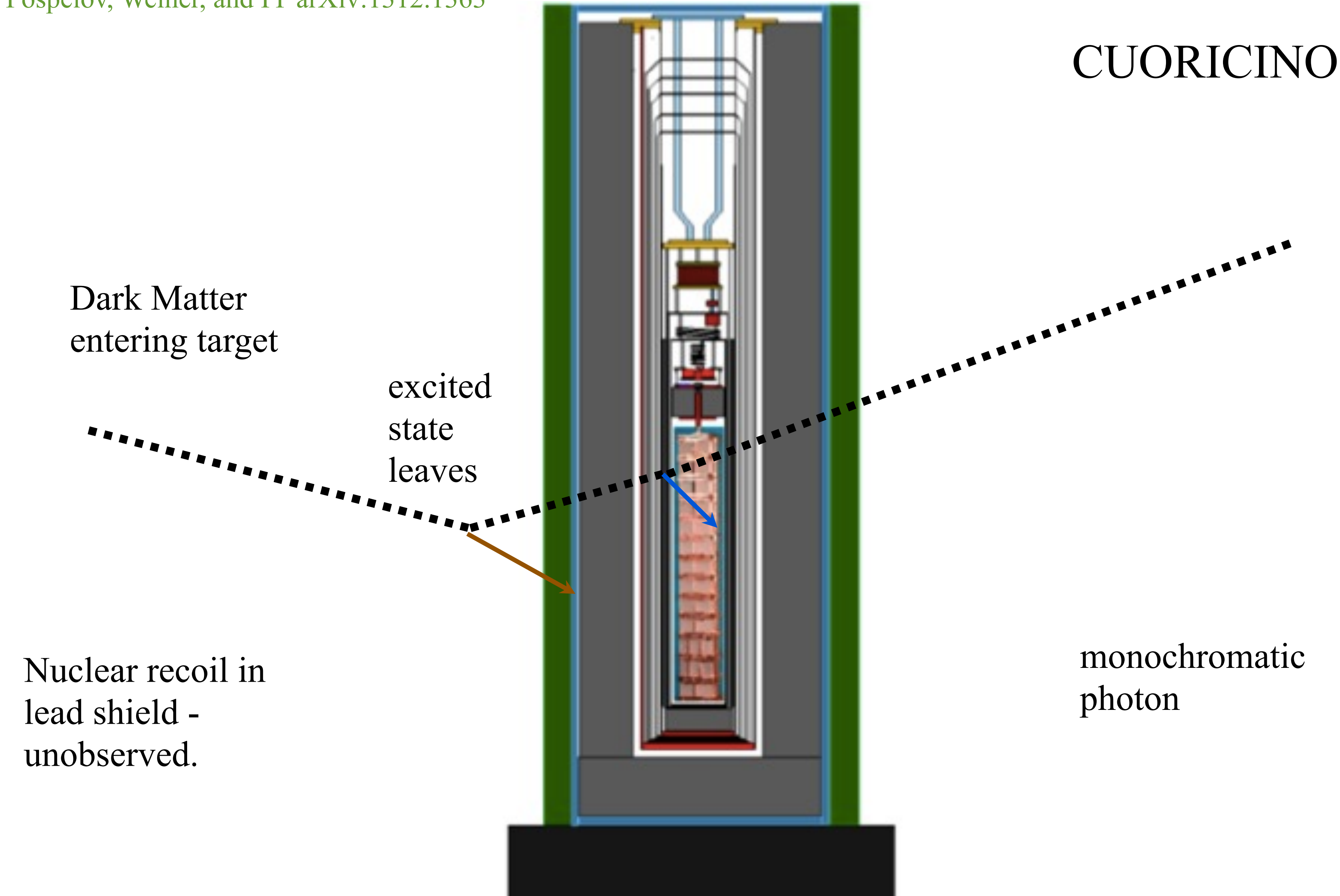
1) Excitation energy might be too large to overcome.

2) De-excitation might contaminate the signal with light.

3) De-excitation might result in double-coincidence (will then be vetoed).

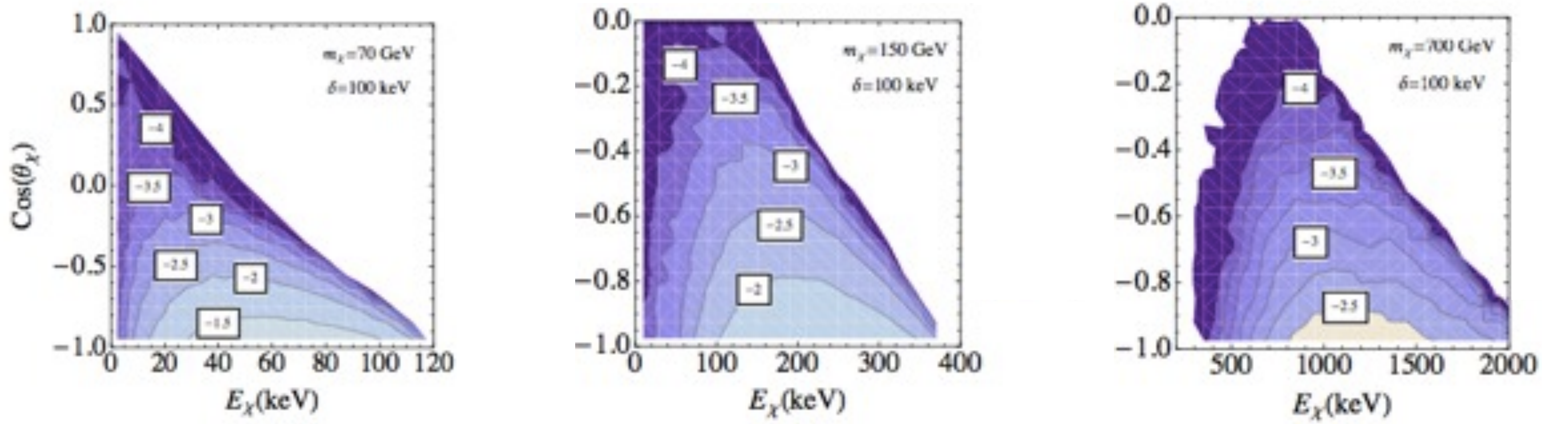
It turns out there is another, very different way to look for such transitions by using the shield of the detector. . .

Pospelov, Weiner, and IY arXiv:1312.1363

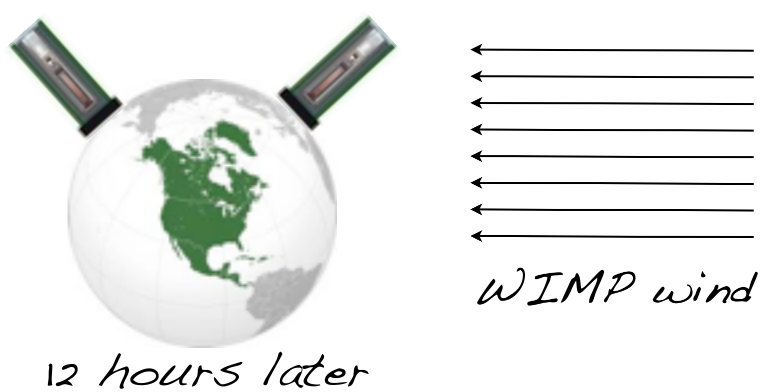


Directional Information

The excited state mostly scatters in the same direction as it arrived. This is becomes more so the heavier the WIMP is,

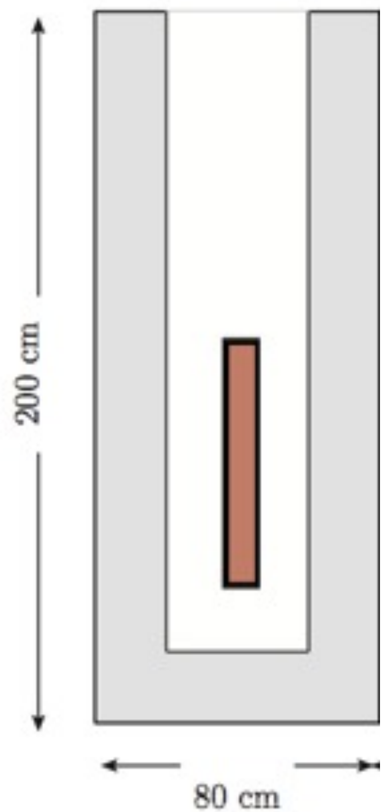


This has a surprising and useful side-effect: daily sidereal modulations of the event rate,

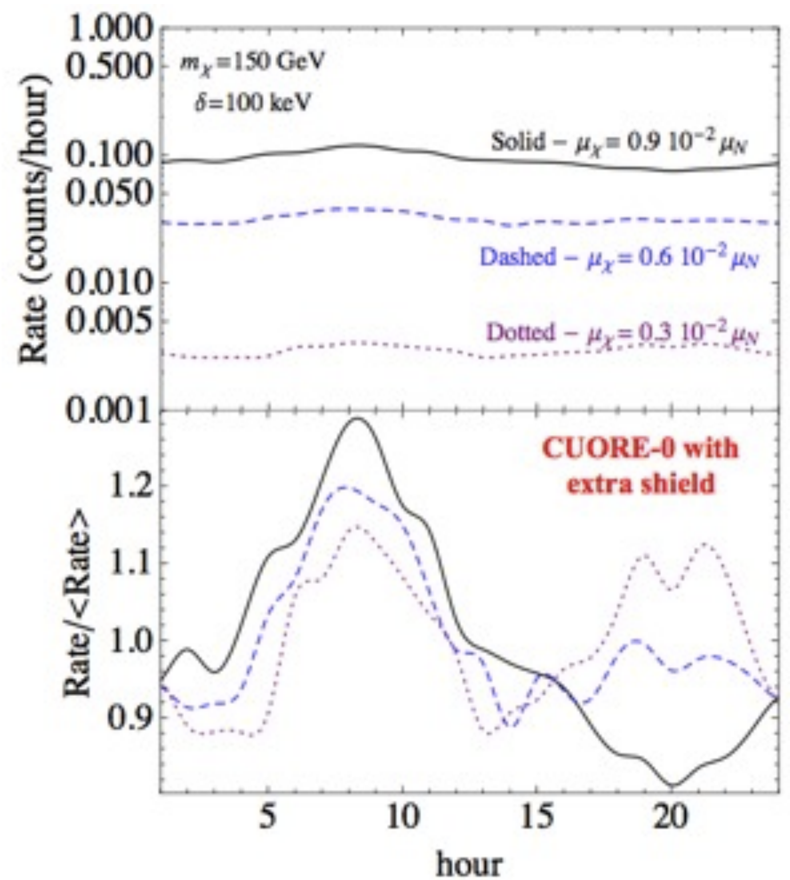


Daily Modulations

We simulated the expected rate and modulations for two experimental setups inspired by the CUORICINO and CUORE detectors,

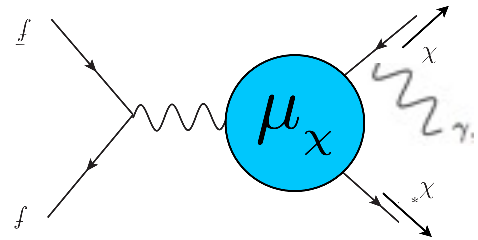


CUORICINO



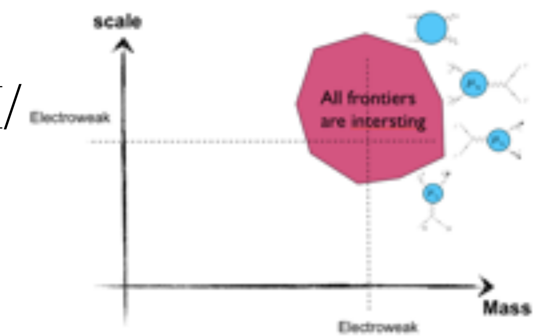
Future progress

1) Missing energy events with electroweak cross-sections are very difficult to search for at the LHC. Any progress on this front will be useful.

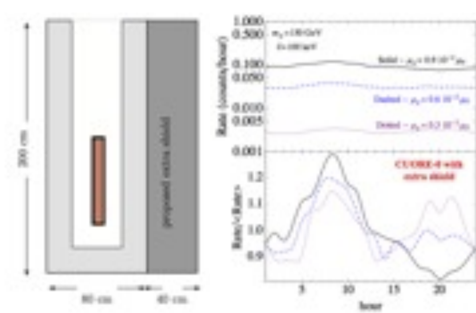


Dark matter in colliders

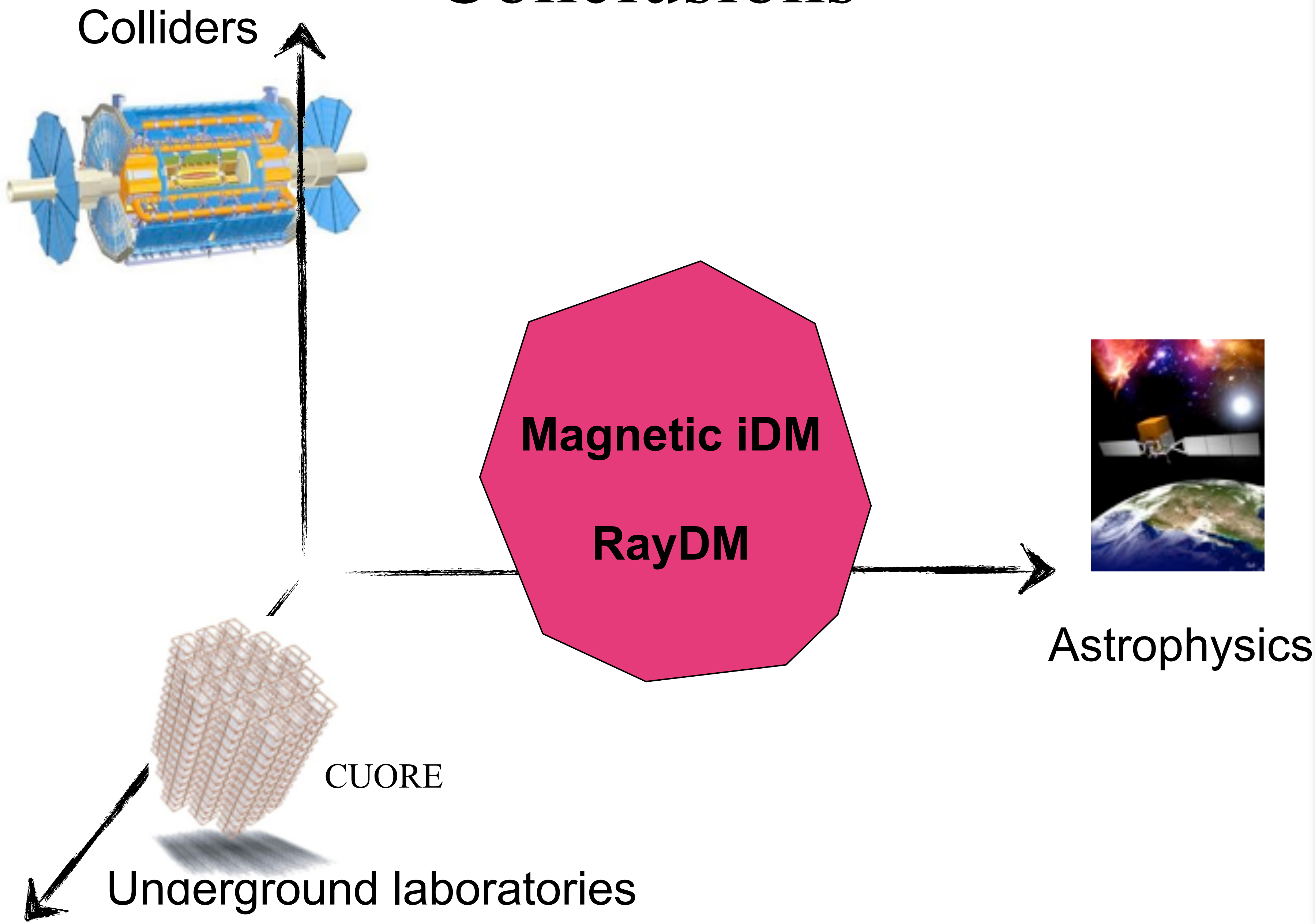
2) Other interesting regions in the MiDM/RayDM space?



3) Can be seen in direct-detection experiments (possibly accompanied by a characteristic x-ray), e.g. DAMA



Conclusions



Thank You

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So what is this all good for?

Concentrating on the leading operators, MiDM (dim-5) and RayDM (dim-7), motivates a variety of searches,

1) New electroweak states produced at the LHC with characteristic decays

2) New types of searches for dark matter at colliders

3) Gamma-ray lines from galactic center

4) Gamma-rays from celestial objects

5) Can be seen in direct-detection experiments (possibly accompanied by a characteristic x-ray), e.g. DAMA