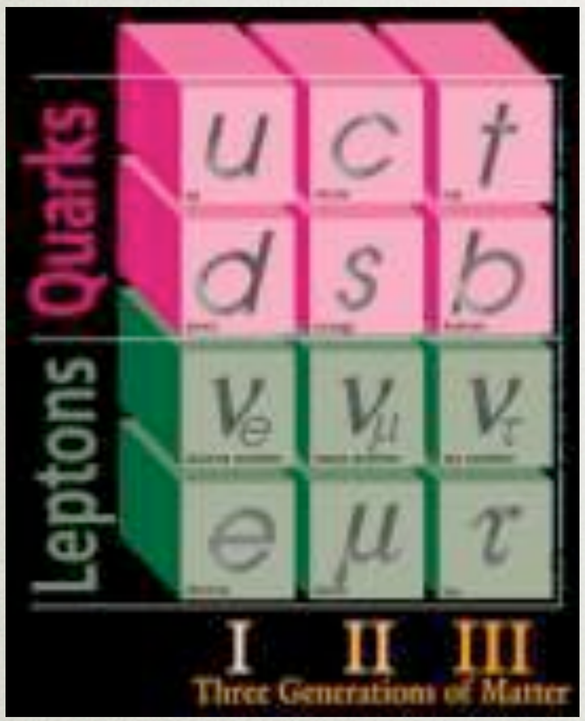
Direct Detection Update and Connection to Intensity Experiments

Kathryn M. Zurek
University of Michigan

Paradigm Shift

Our thinking has shifted



From a single, stable weakly interacting particle ..... (WIMP, axion)

?

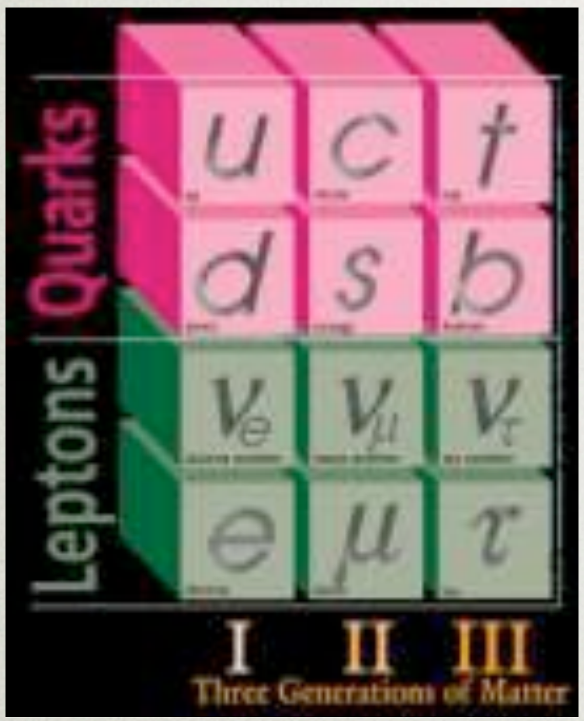
$M_p \sim 1$ GeV

Standard Model

...to a hidden world with multiple states, new interactions

Hidden Dark Worlds

Our thinking has shifted



From a single, stable weakly interacting particle .....
(WIMP, axion)

A′

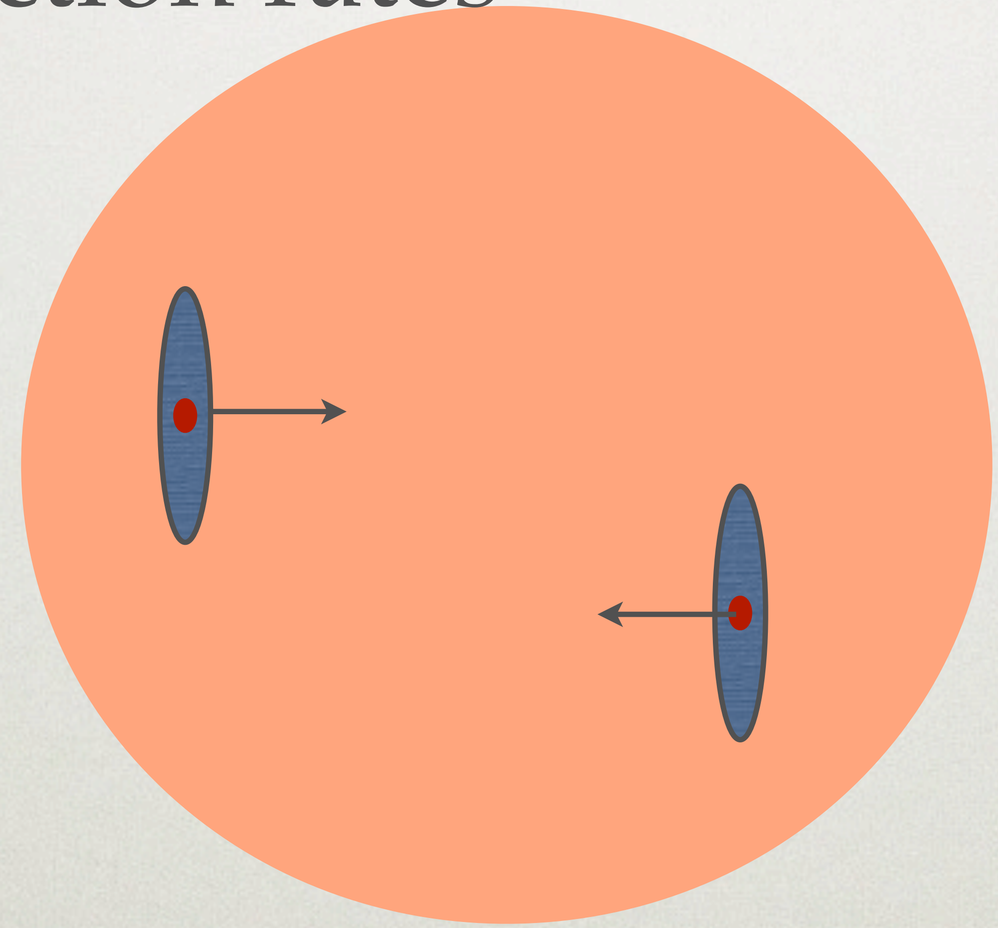
$M_p \sim 1$ GeV

Standard Model

...to a hidden world with multiple states, new interactions

Why the (sub-)Weak Scale is Compelling

- Abundance of new stable states set by interaction rates



Freeze-out

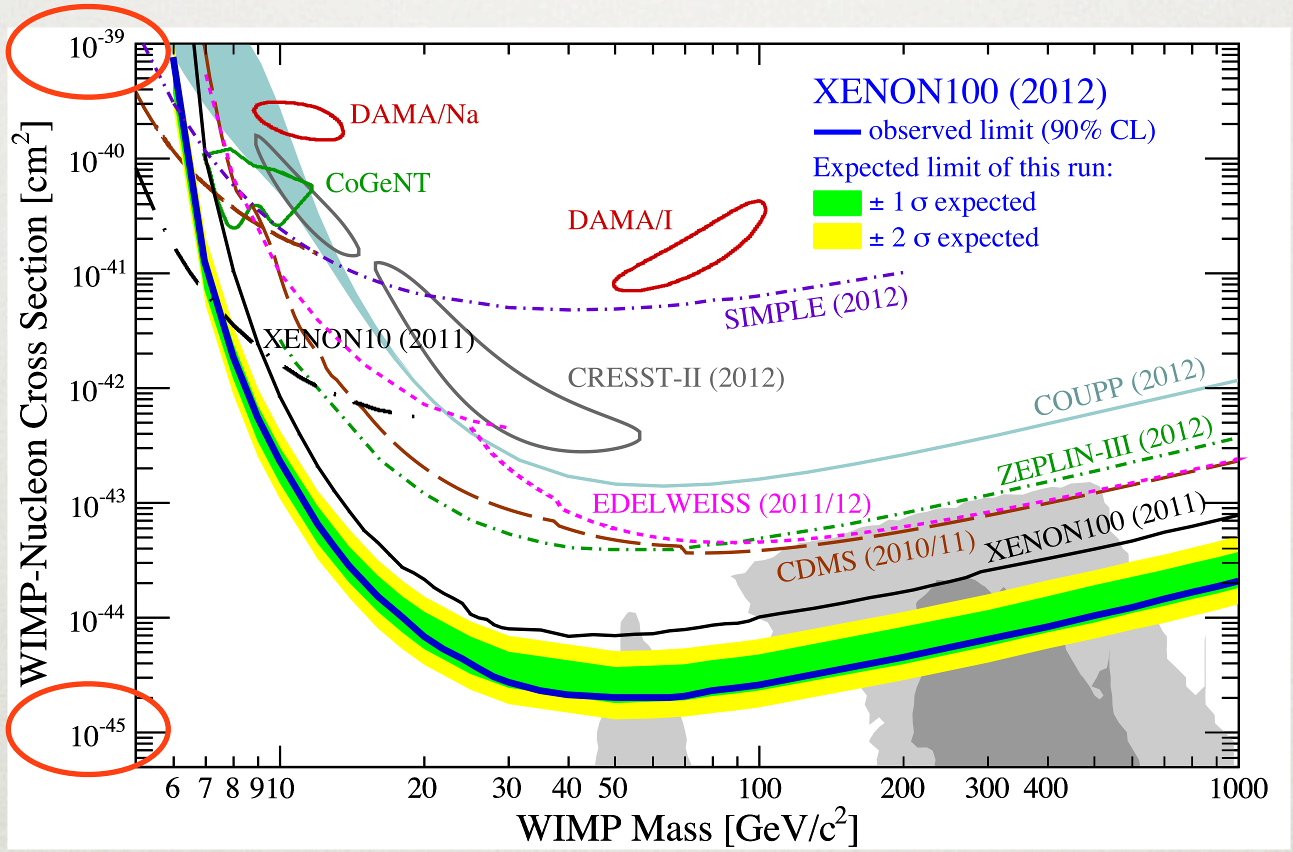
Measured by CMB + LSS

$$\Gamma = n\sigma v = H \qquad \rightarrow \sigma \sim \frac{1}{\text{few TeV}^2}$$

Sub-Weakly Interacting Massive Particles

Scattering through the Z boson: ruled out

$$\sigma_n \sim 10^{-39}\ \mathrm{cm}^2$$

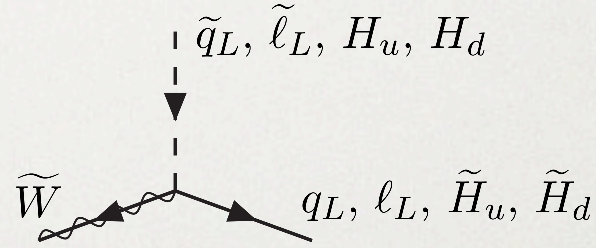


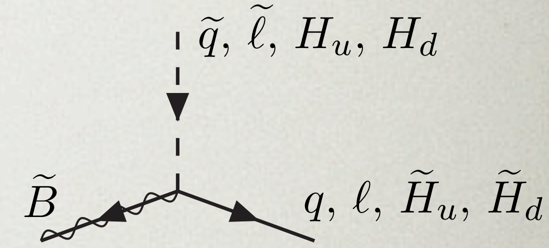
Next important benchmark:
Scattering through the Higgs

$$\sigma_n \sim 10^{-45-46}\ \mathrm{cm}^2$$

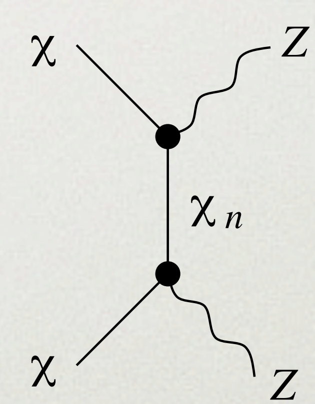
Are there ways around for the Neutralino?

- Make the Neutralino a pure state -- coupling to Higgs vanishes





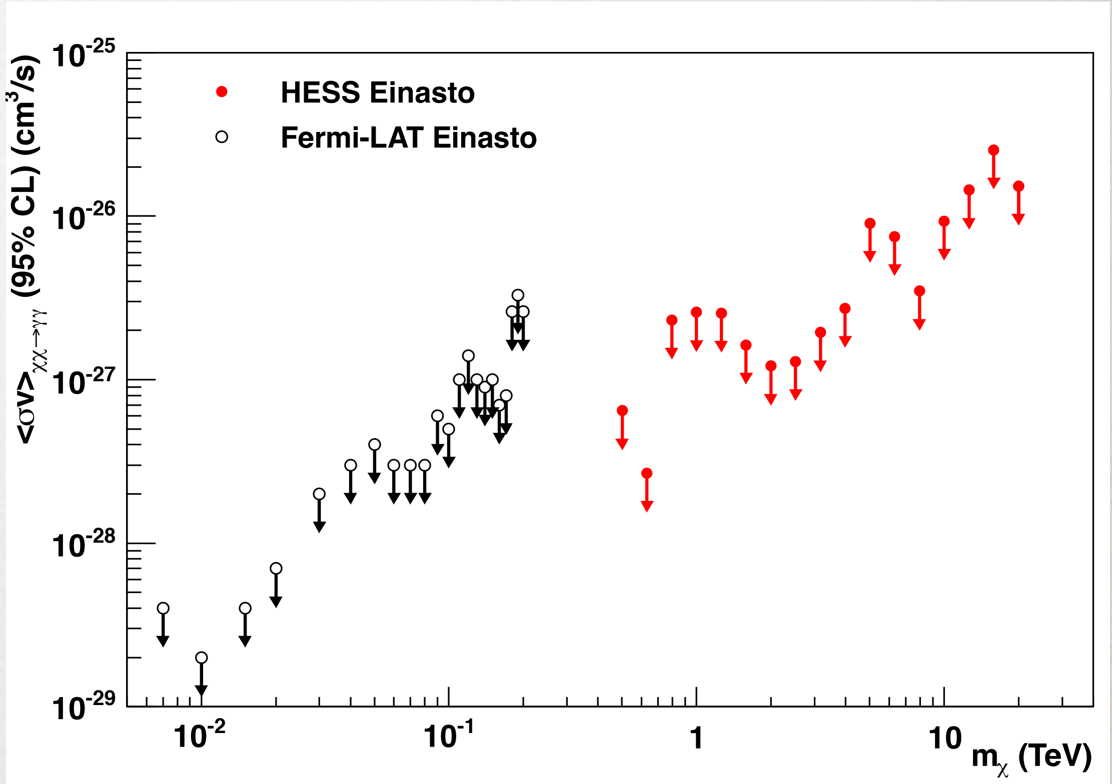
- However, Wino and Higgsino pure states can be probed by indirect detection



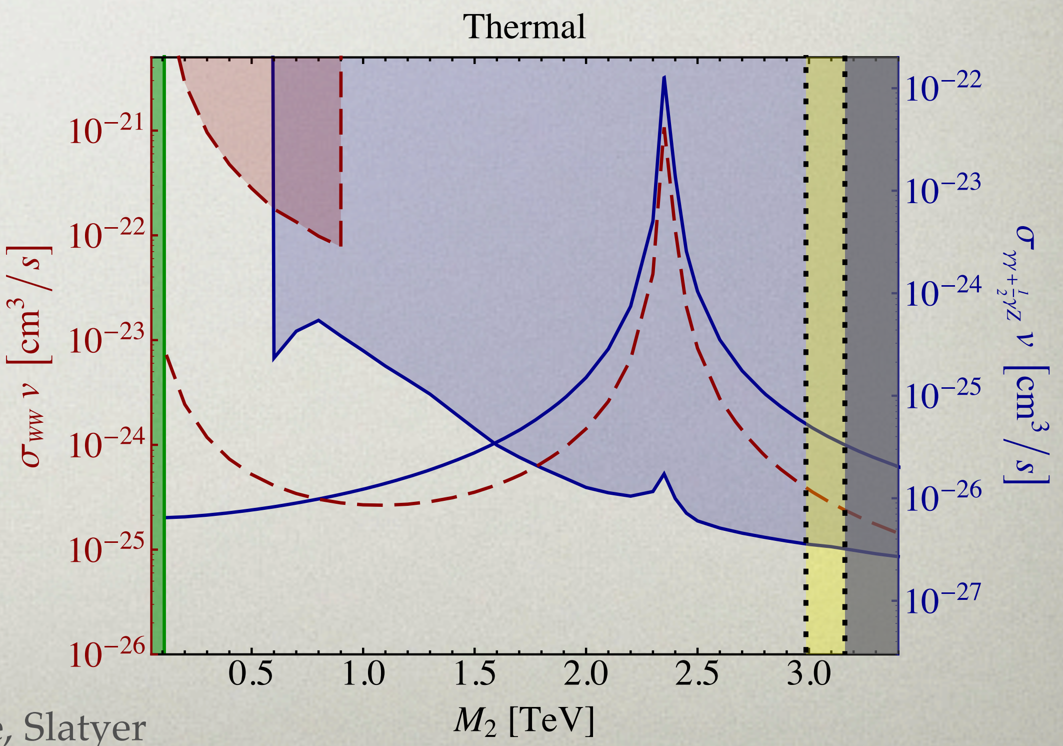
Large!

$$\langle \sigma v \rangle \sim \left(\frac{2\ \mathrm{TeV}}{m_\chi} \right)^2 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

ARE THERE WAYS AROUND FOR THE NEUTRALINO?



- Thermal Wino ruled out
- Thermal Higgsino still allowed, but can be ruled out in the future



Cohen, Lisanti, Pierce, Slatyer

Are there ways around for the Neutralino?

- Bino escapes
- Pay a fine-tuning price

$$\mu \gg M_1 \sim m_{wk}$$

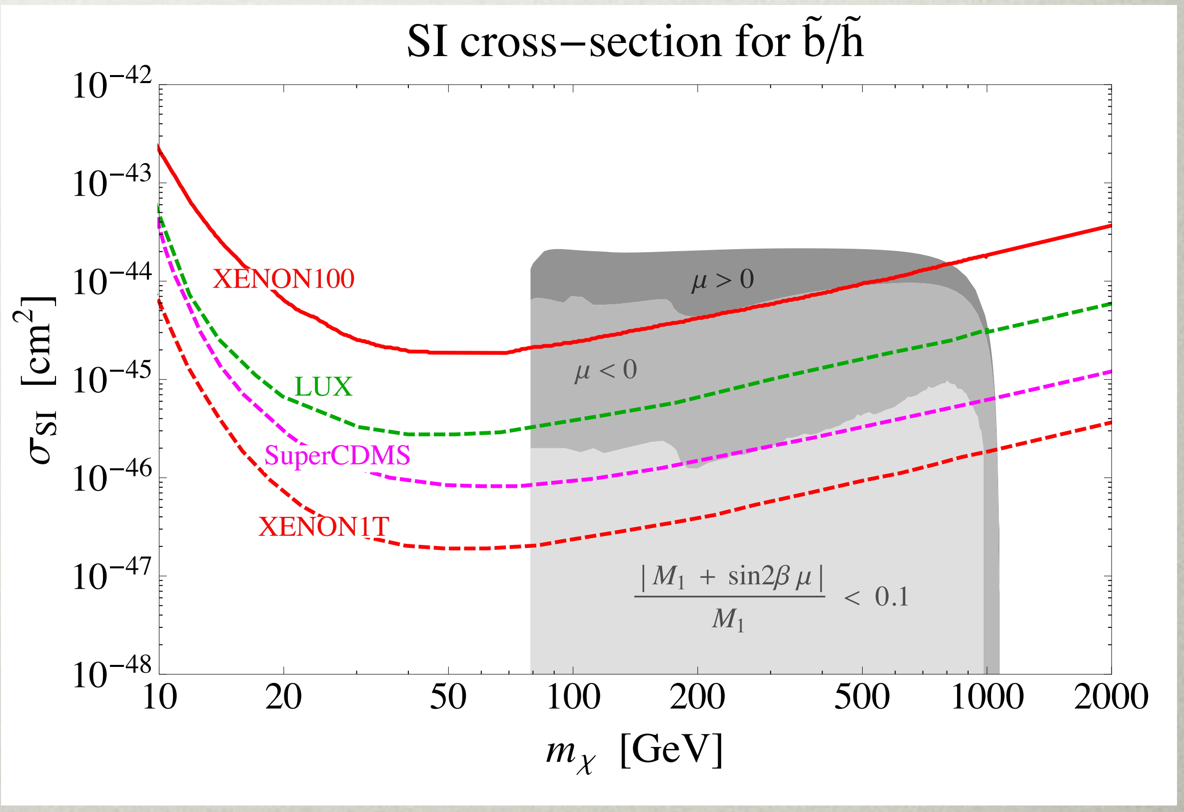
$$m_Z^2 \quad = \quad \frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1-\sin^2(2\beta)}} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2$$

ARE THERE WAYS AROUND FOR THE NEUTRALINO?

- Tune away the coupling to the Higgs
- Smaller cross-sections correspond to more tuning in the neutralino components

m_χ	condition
M_1	$M_1 + \mu \sin 2\beta = 0$
M_2	$M_2 + \mu \sin 2\beta = 0$
$-\mu$	$\tan\beta = 1$
M_2	$M_1 = M_2$

Cheung, Hall, Pinner, Ruderman

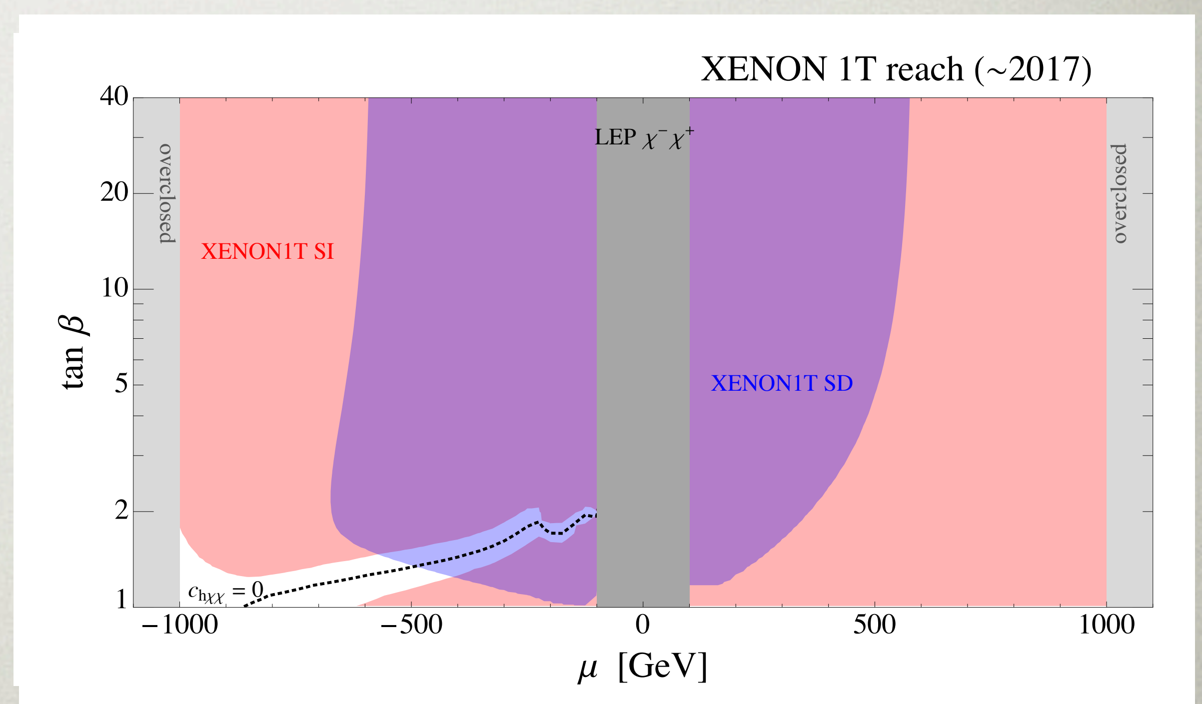


Are there ways around for the Neutralino?

- Tune away the coupling to the Higgs
- Smaller cross-sections correspond to more tuning in the neutralino components

m_χ	condition
M_1	$M_1 + \mu \sin 2\beta = 0$
M_2	$M_2 + \mu \sin 2\beta = 0$
$-\mu$	$\tan\beta = 1$
M_2	$M_1 = M_2$

Cheung, Hall, Pinner, Ruderman

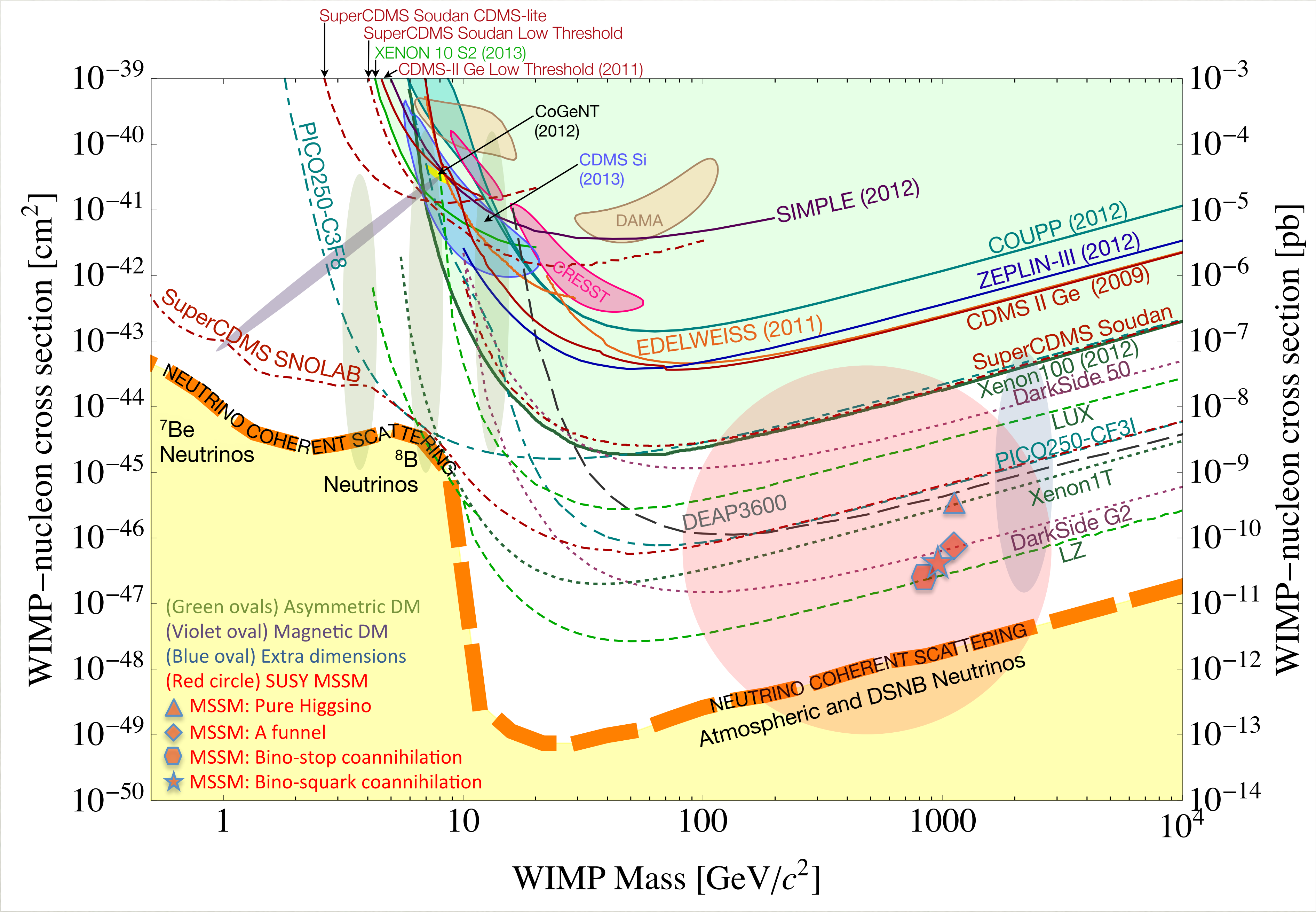


When Should We Start Looking Elsewhere?

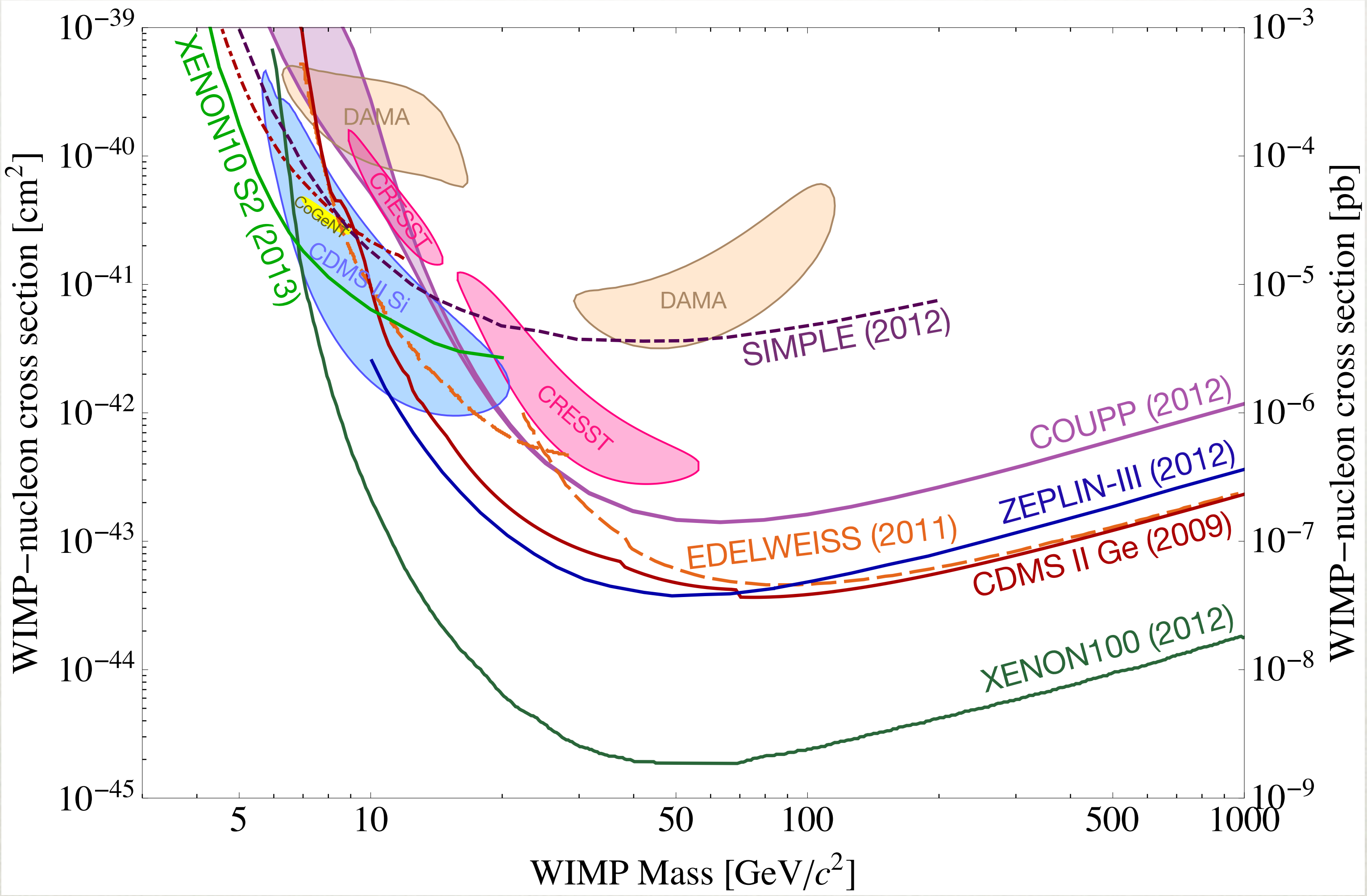
- Cannot kill neutralino DM, but paradigm does become increasingly tuned
- Somewhat below Higgs pole -- Neutrino background?
- Well-motivated candidates that are much less costly to probe
- Light WIMPs

Terra Incognita

CF1 Snowmass report, 1310.8327

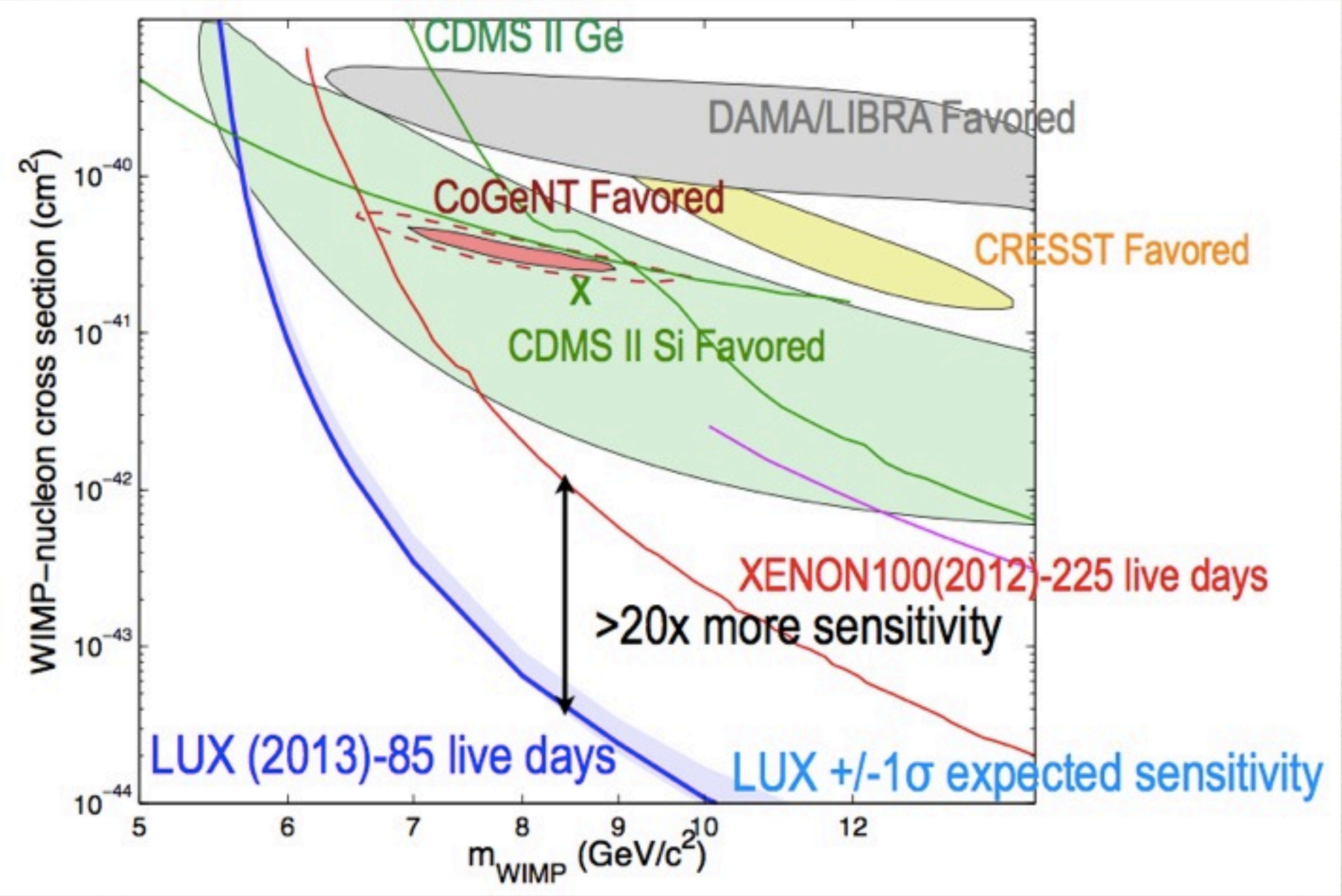


Current Sensitivity Limited



CF1 Snowmass report, 1310.8327

Anomalies and LUX

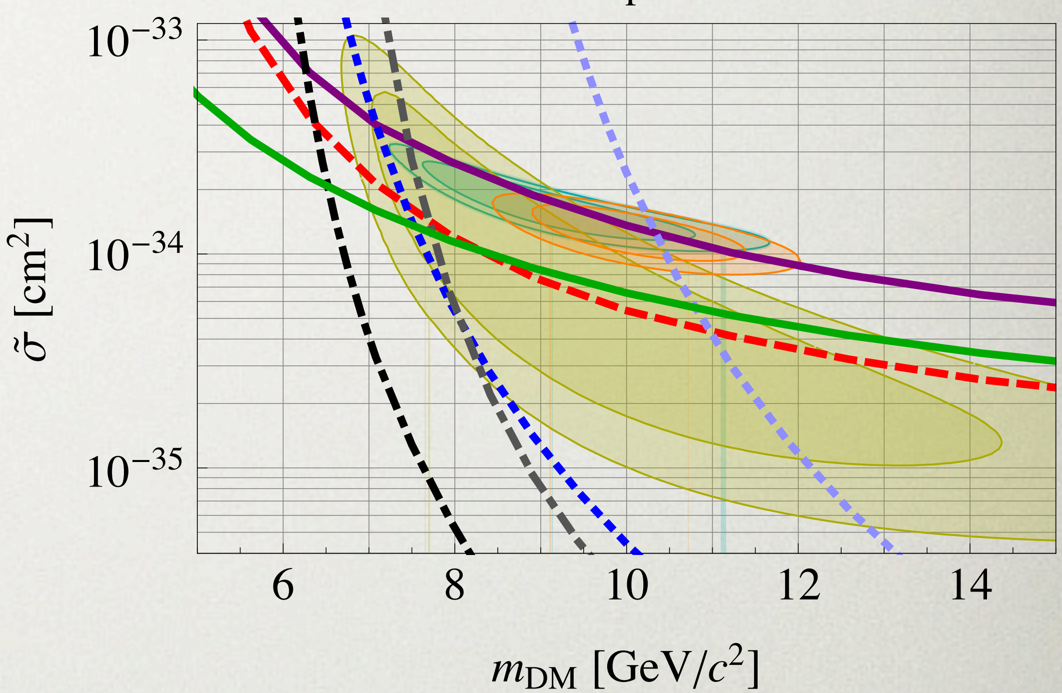


Uncertainties

- Experiment: Result assumes a particular choice of the energy calibration
- Theory: Also assumes spin-independent, momentum-independent scattering
- How do the results fare under more general assumptions?

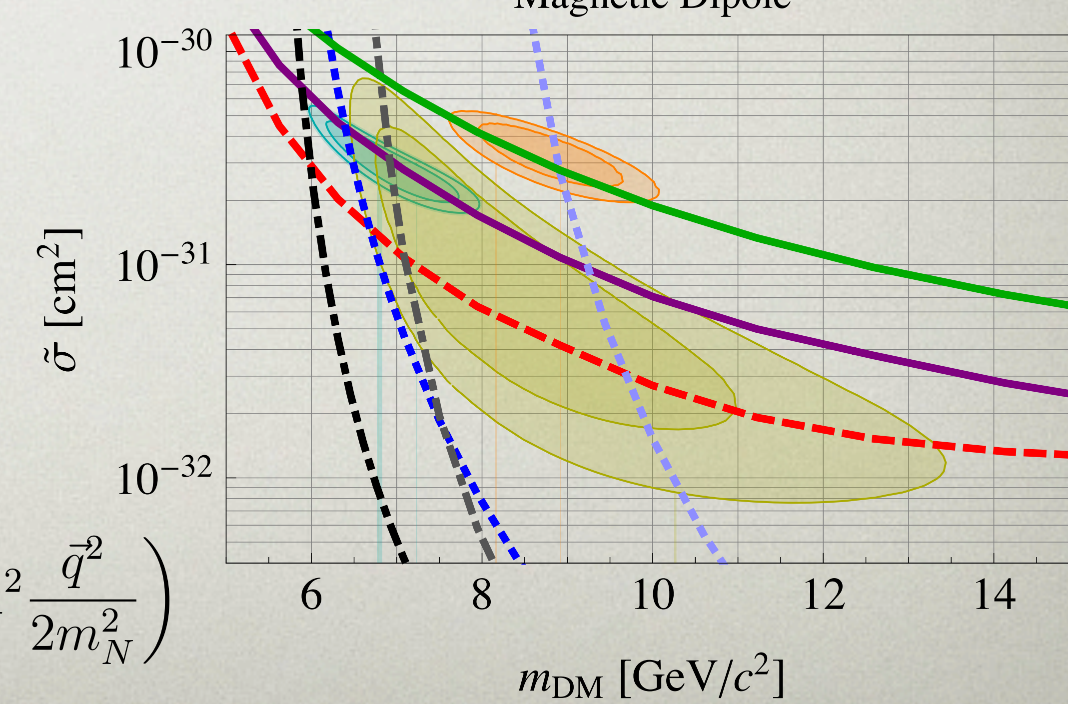
Operator Uncertainties

Gresham, KZ 1311.2082



- Anapole and Dipole operators do best job, but neither escapes constraints

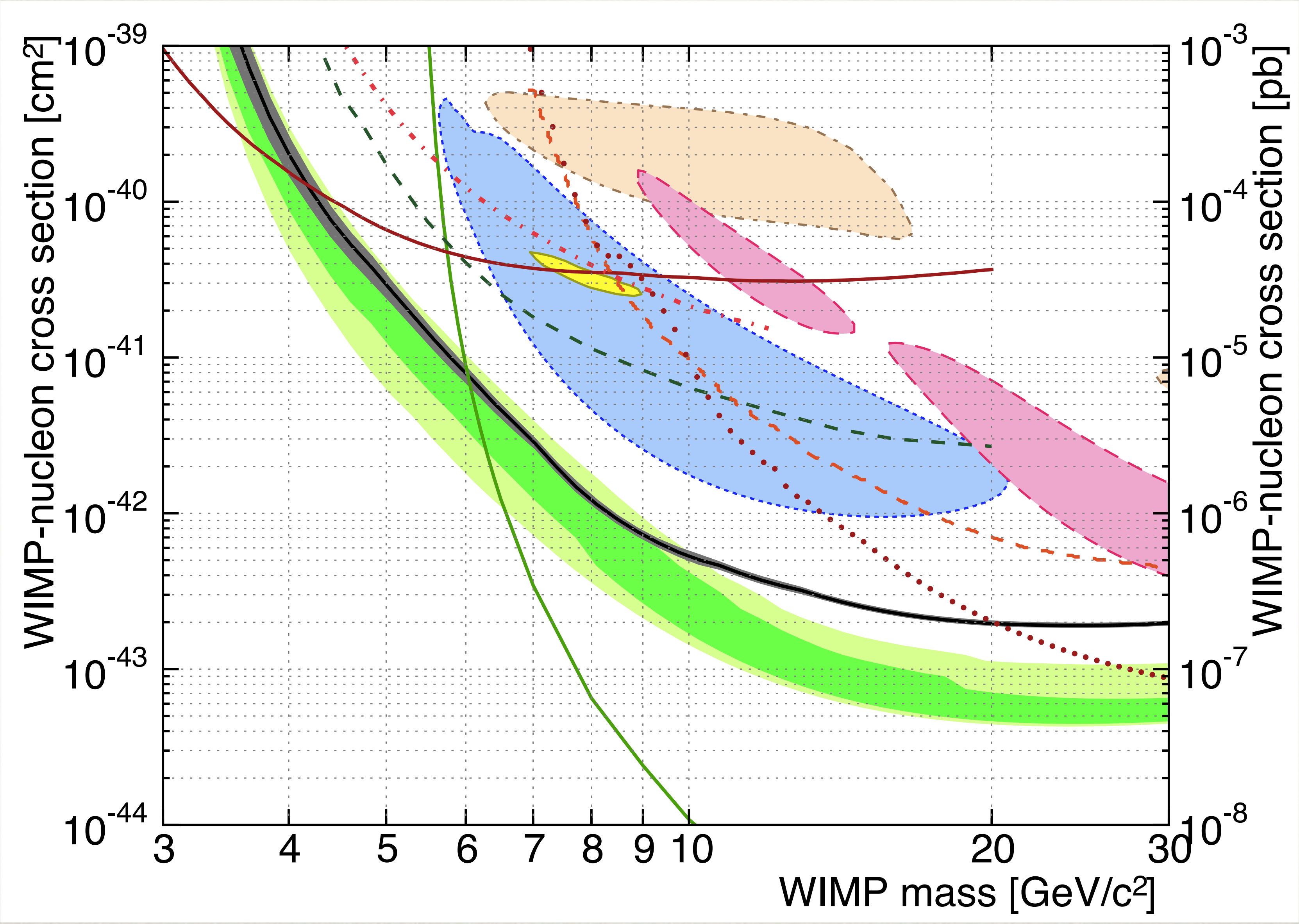
$$\mathcal{O}_a = \bar{\chi}\gamma^\mu\gamma_5\chi A_\mu$$
$$\mathcal{O}_d = \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}/\Lambda$$



$$\sigma_N^a = f_a^2 \frac{\mu_N^2}{\pi M^4}\left(Z^2F^2(A;\vec{q}^2)\left(\vec{v}^2 - \frac{\vec{q}^2}{4\mu_N^2}\right) + \frac{J+1}{3J}g_N^2A^2\frac{\vec{q}^2}{2m_N^2}\right)$$
$$\sigma_N^d = f_d^2 \frac{\mu_N^2}{\pi M^4}\frac{\vec{q}^2}{\Lambda^2}\left(Z^2F^2(A;\vec{q}^2)\left(\vec{v}^2 - \frac{\vec{q}^2}{4\mu_N^2} + \frac{\vec{q}^2}{4m_{\rm DM}^2}\right) + \frac{J+1}{3J}g_N^2A^2\frac{\vec{q}^2}{2m_N^2}\right)$$

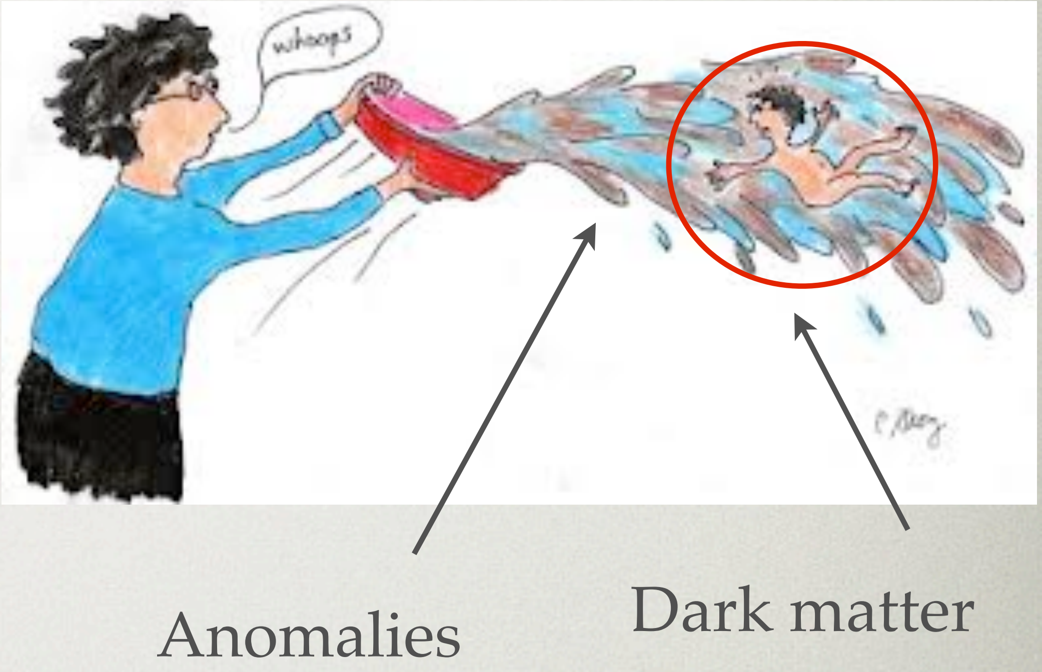
SuperCDMS: the nearly final word

1402.7137



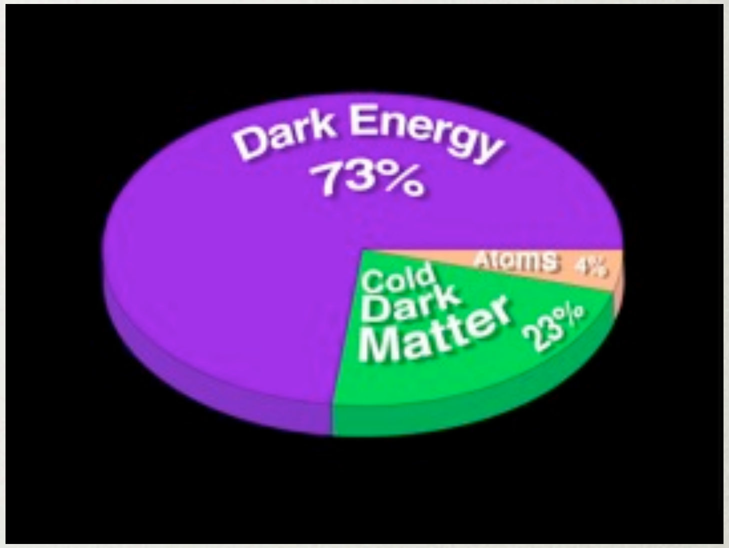
Anomalies probably not due to DM ....

- But must be careful not to throw baby out with bath water
- Low mass DM is motivated theoretically, and does not necessarily predict excluded cross-sections



Light WIMPs: Asymmetric Dark Matter

- Standard picture: freeze-out of annihilation; baryon and DM number unrelated
- Accidental, or dynamically related?



Experimentally, $\Omega_{DM} \approx 5\Omega_b$

Mechanism $n_{DM} \approx n_b$

$\Rightarrow$ $m_{DM} \approx 5m_p$

Chemical Potential Dark Matter

WHAT DOES AN ADM MODEL DO?

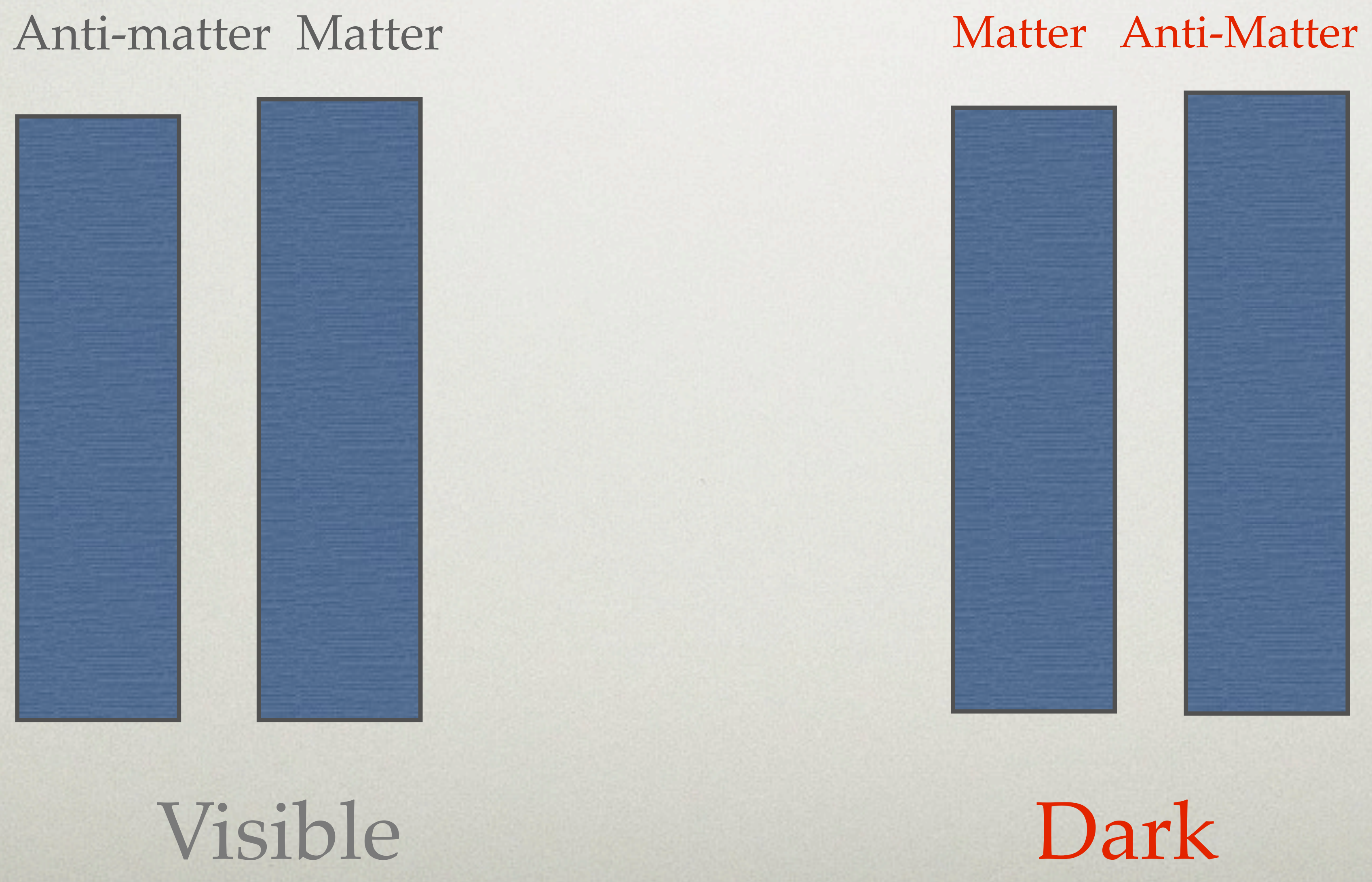
KZ, 1308.0338

1. *Share* an asymmetry between the visible and dark sectors
2. *Decouple* transfer mechanism to separately freeze-in the asymmetries in both sectors
3. *Annihilate* the symmetric abundance

$$n_X - n_{\bar{X}} \sim n_b - n_{\bar{b}} \quad \Rightarrow \quad m_X \sim 5 m_p \simeq 5 \text{ GeV}$$

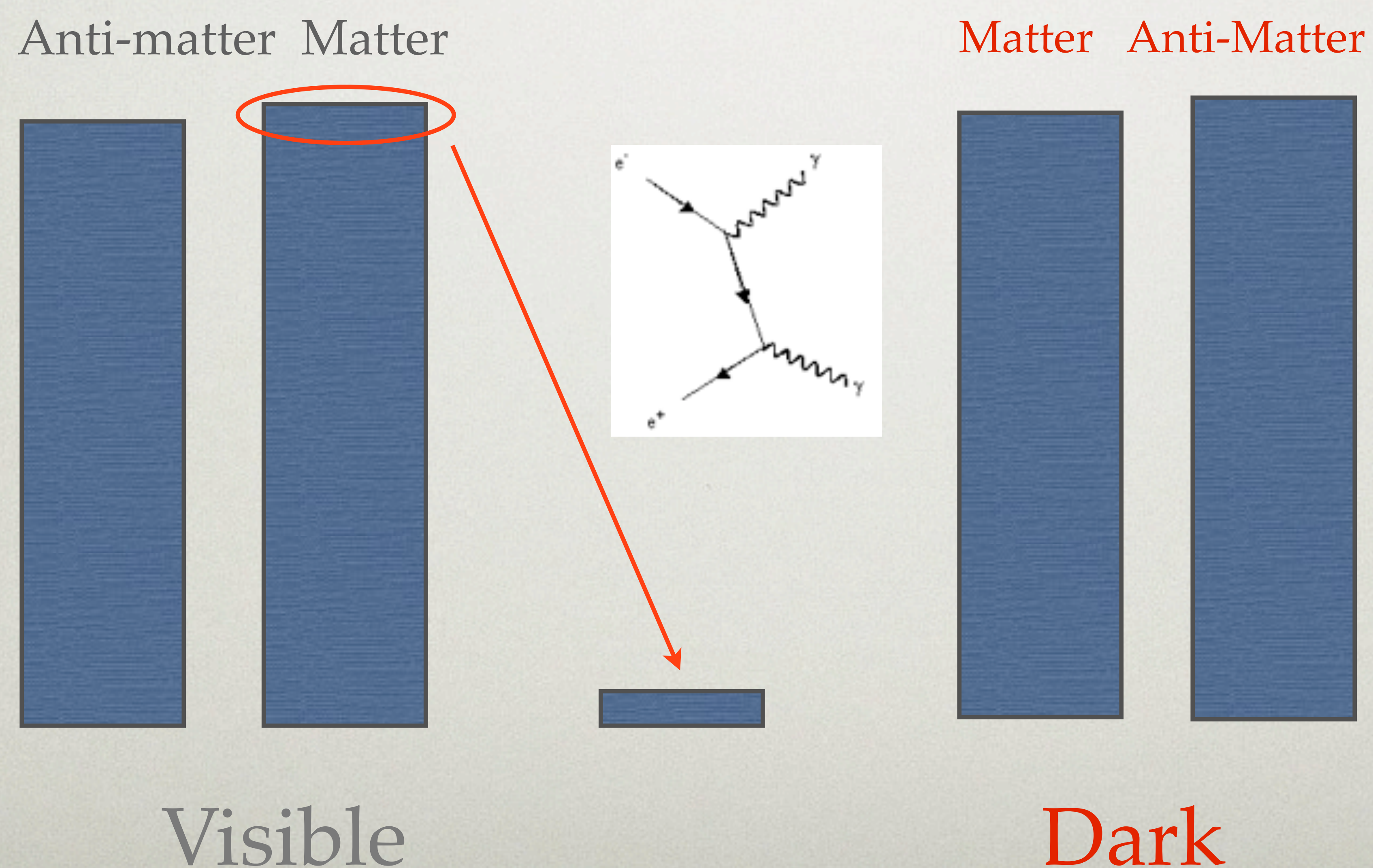
3. Annihilating

- While it doesn't directly probe the asymmetry mechanism, it is more likely this physics is at a low scale which we can probe.



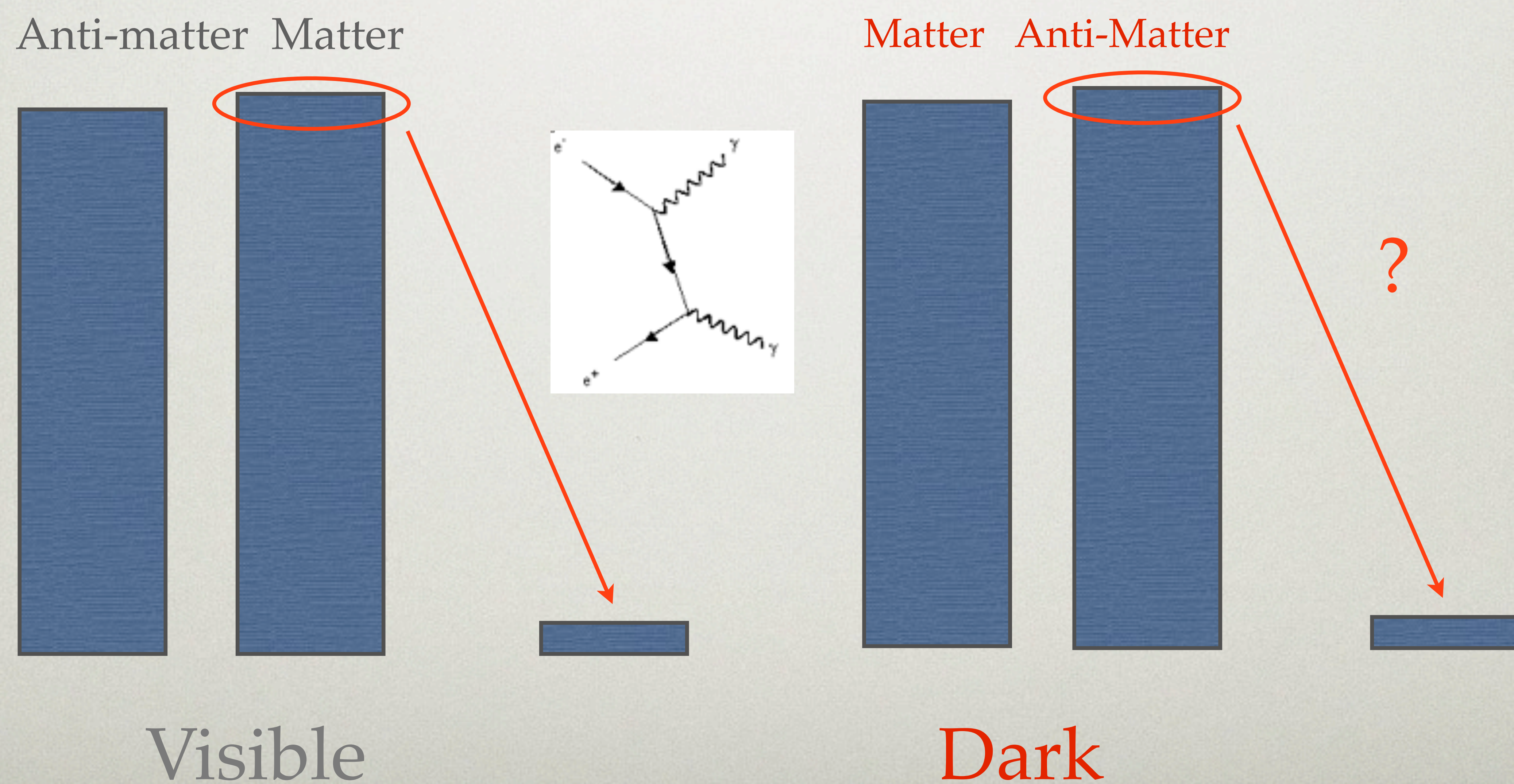
3. Annihilating

- While it doesn't directly probe the asymmetry mechanism, it is more likely this physics is at a low scale which we can probe.

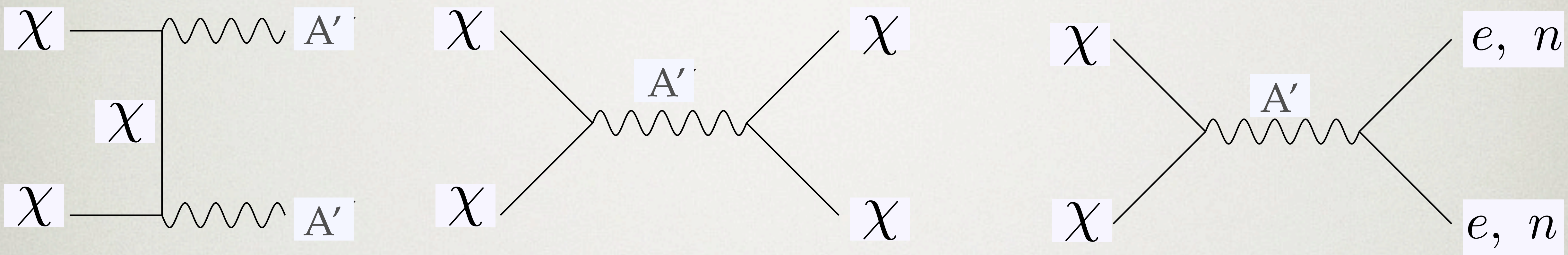


3. Annihilating

- While it doesn't directly probe the asymmetry mechanism, it is more likely this physics is at a low scale which we can probe.

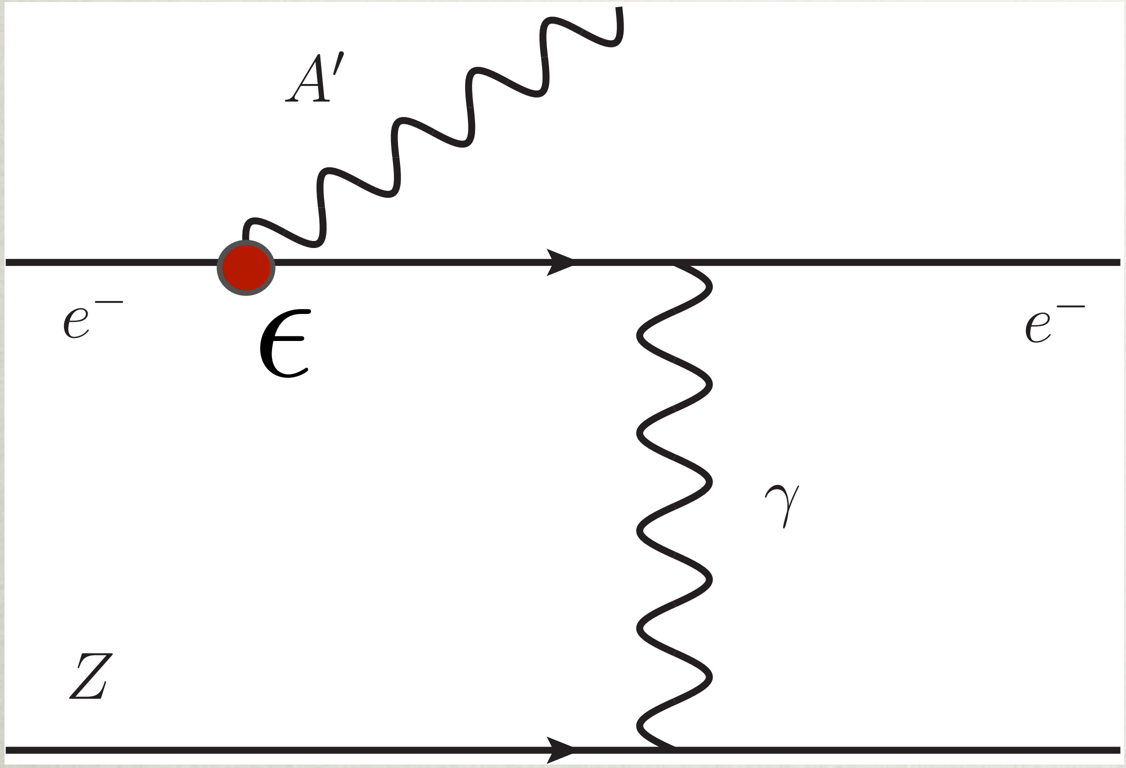


Dark Forces and DM Interactions

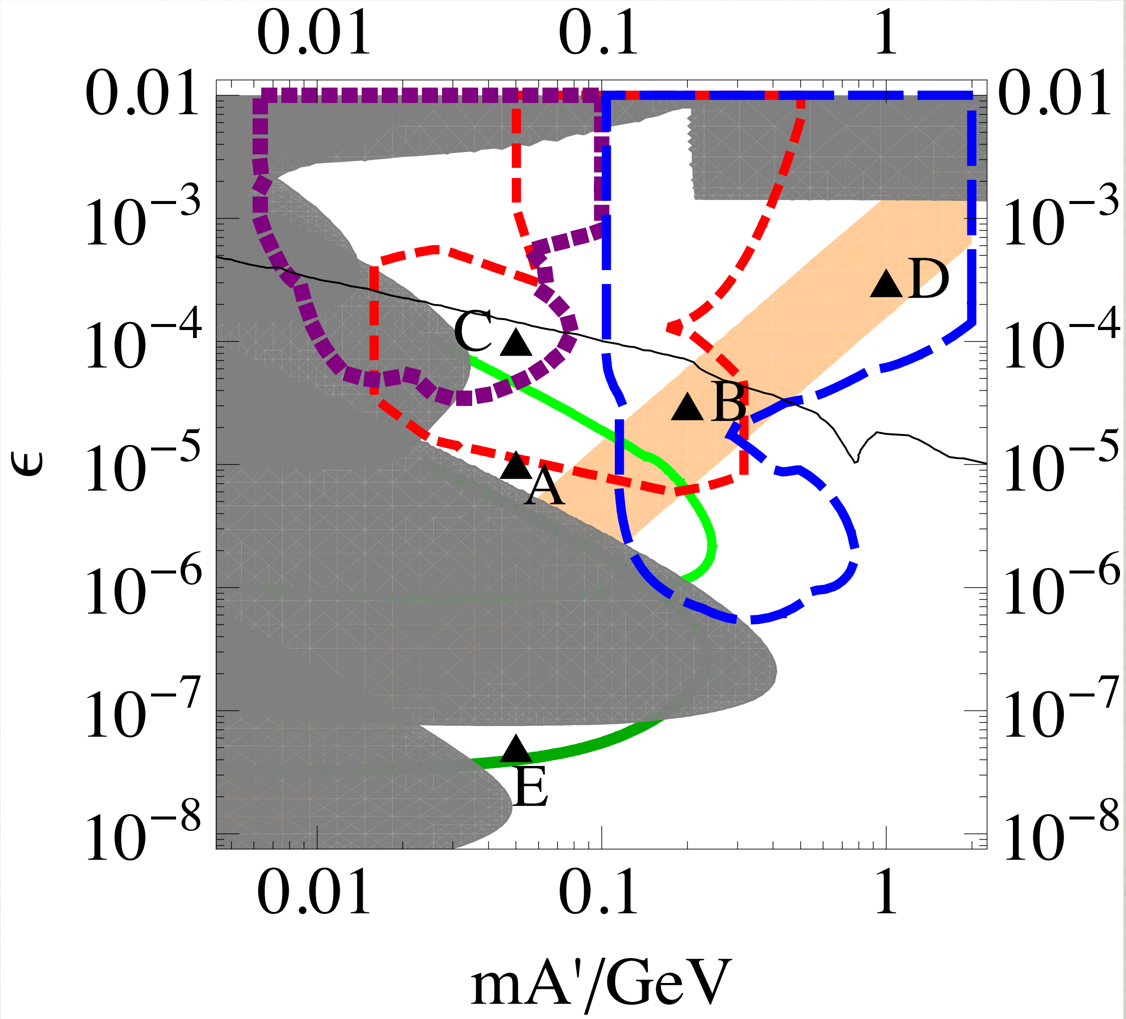


- Dark Forces Very Important for Light Dark Matter!
- May also be important for structure of DM halos
- May be important for DM direct detection and collider searches

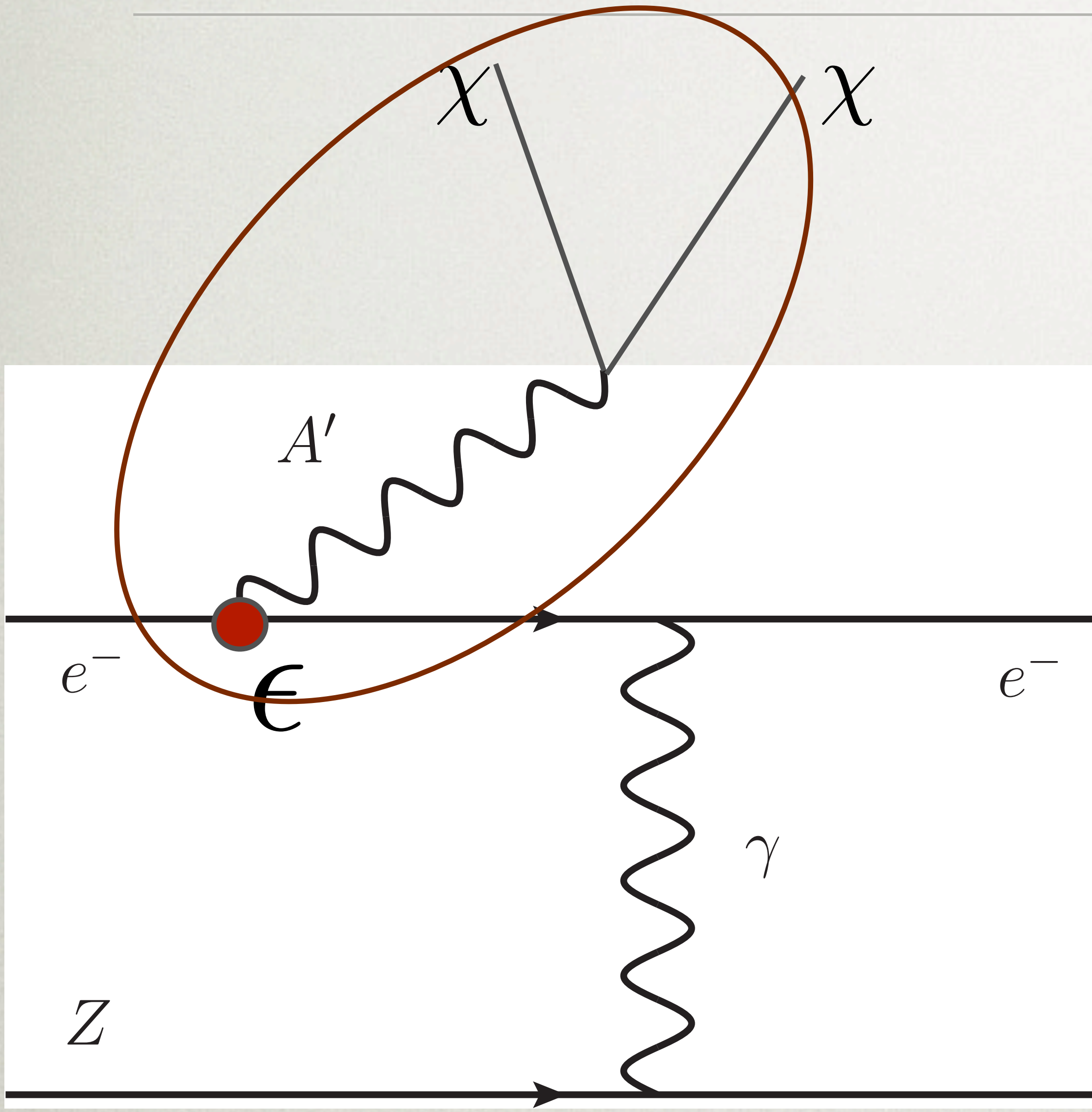
Low Energy Accelerator Constraints



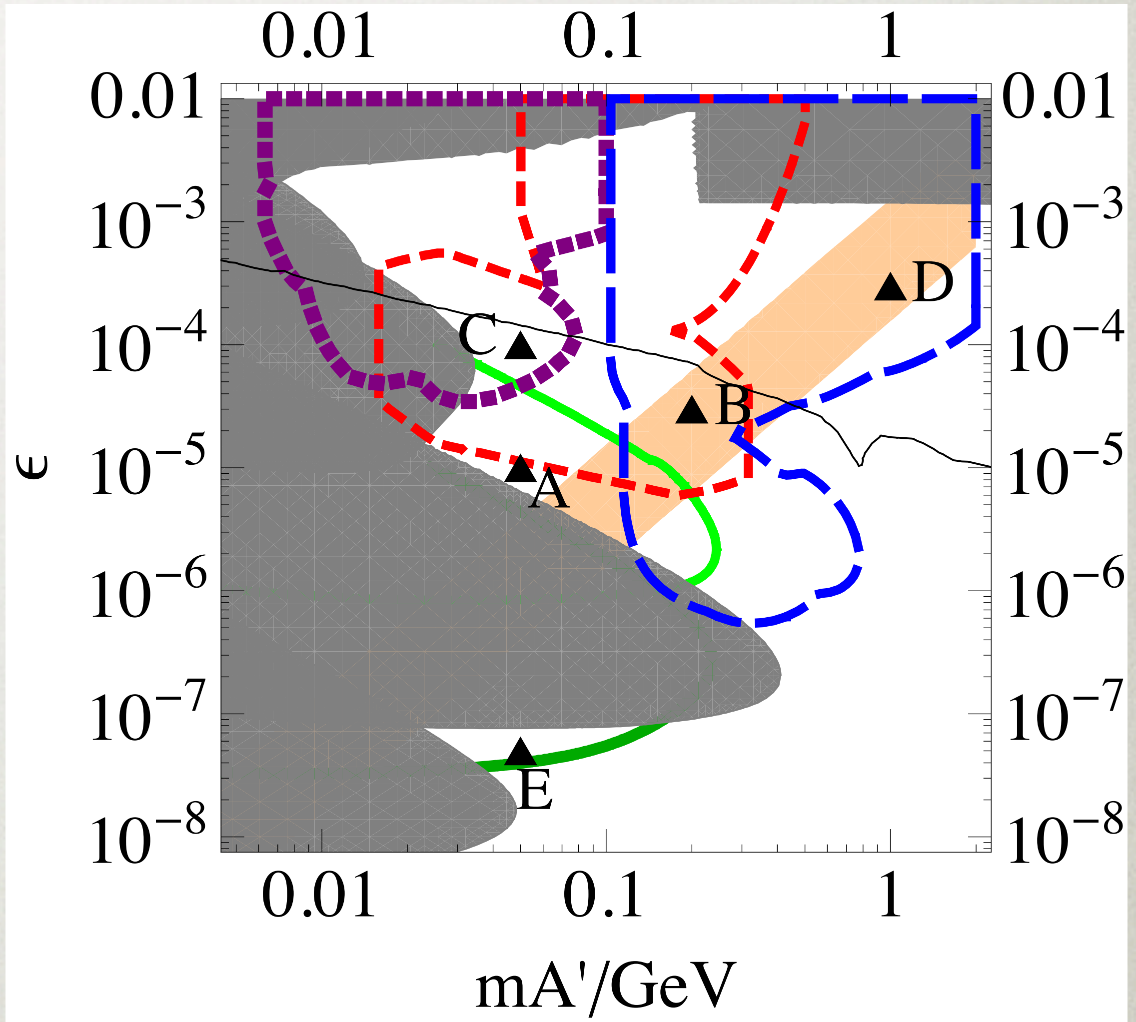
Bjorken, Essig, Schuster, Toro



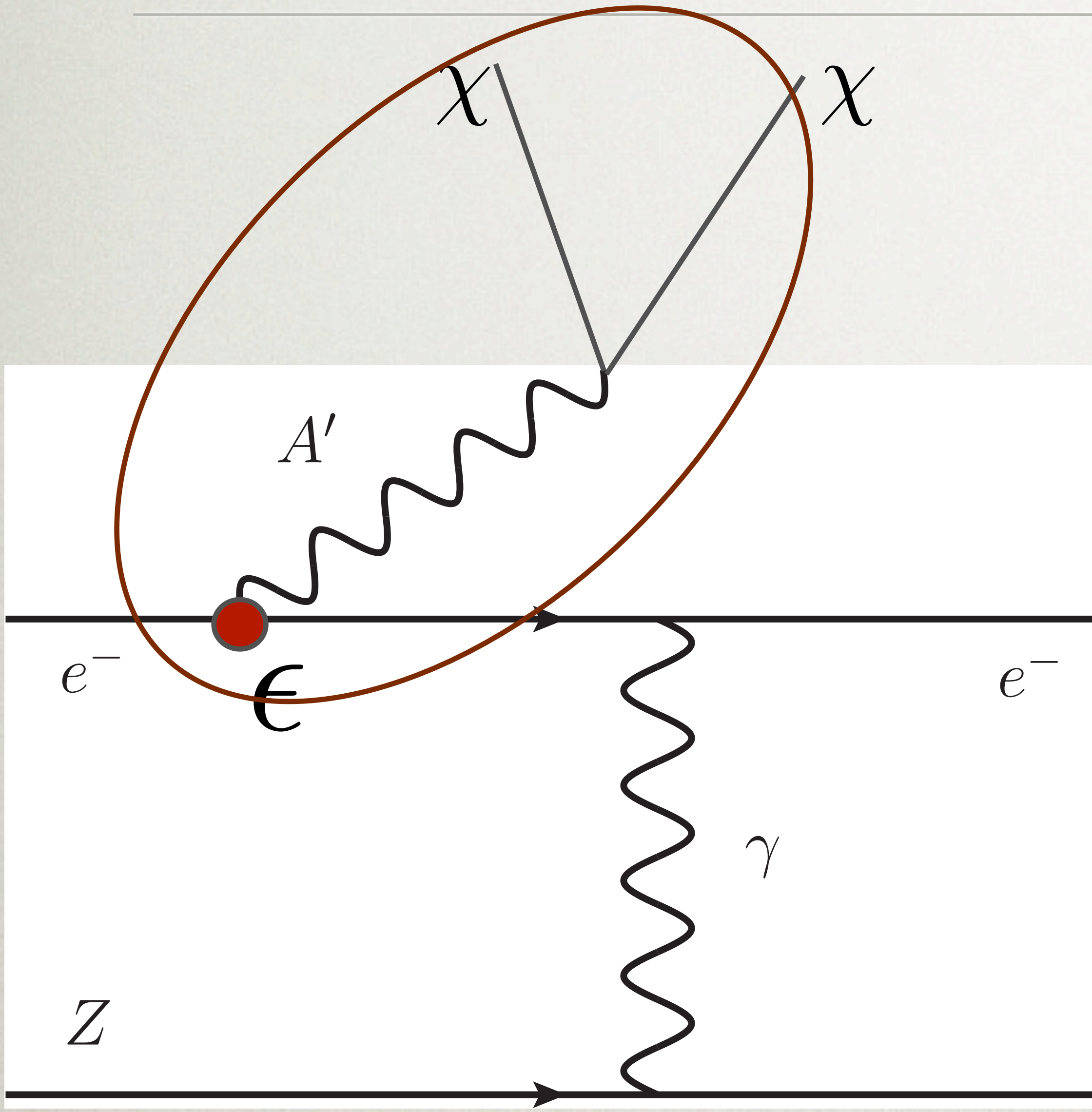
Translate to Direct Detection



Bjorken, Essig, Schuster, Toro



Translate to Direct Detection



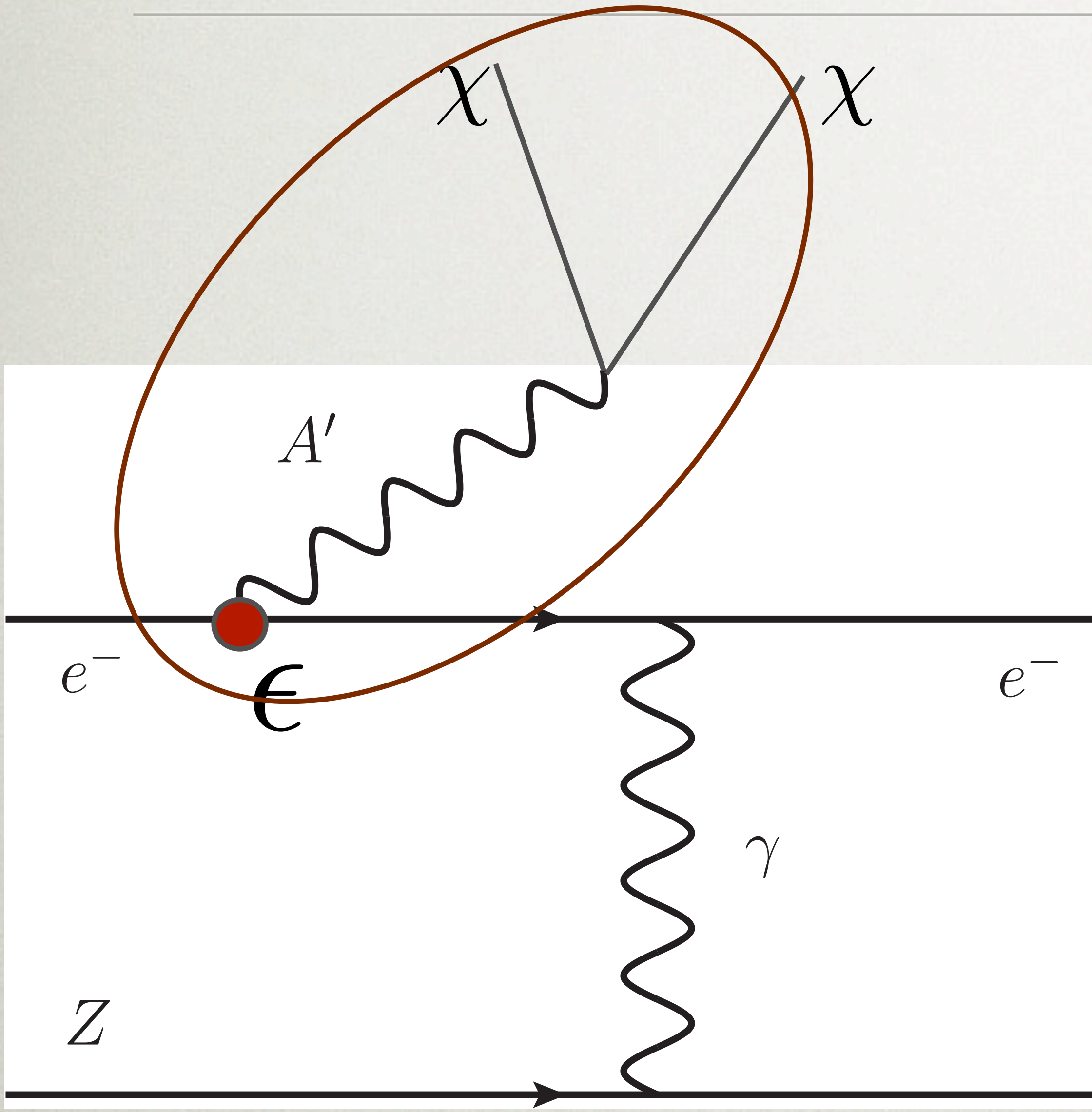
Ingredients:

$$m_\chi, \ m_{A'}, \ g_e, \ g_\chi$$

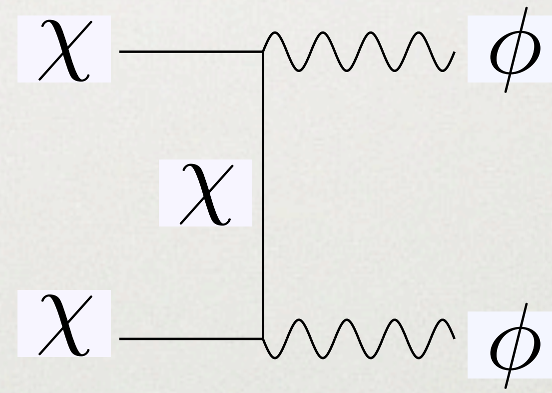
Constrained by intensity experiments

Other complementary searches for other two parameters?

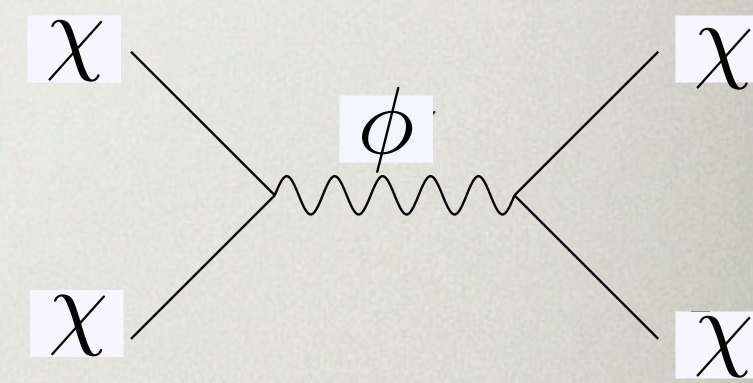
Translate to Direct Detection



$$m_\chi,\ m_{A'},\ g_e,\ g_\chi$$



DM Relic Abundance

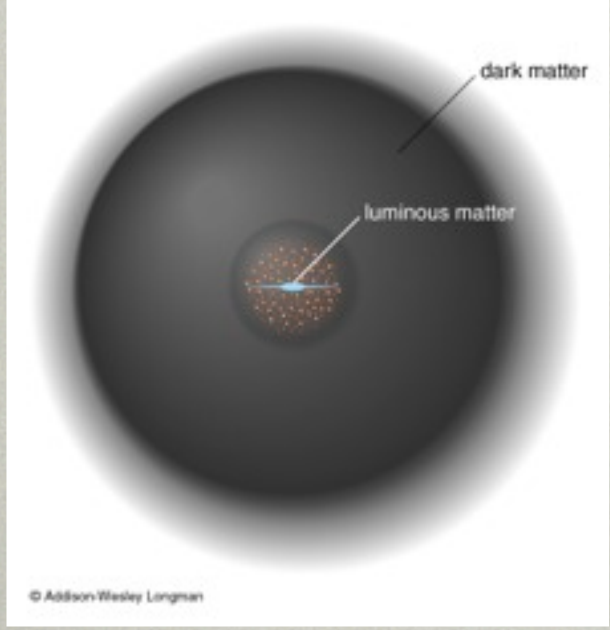


DM self-scattering

Can we connect dark photon searches to direct detection and other astrophysical observables?

Dark Matter Self-Scattering

- Dark matter self-coupling changes the shape of a dark matter halo (such as the milky way halo) - we can extract constraints on coupling g_χ

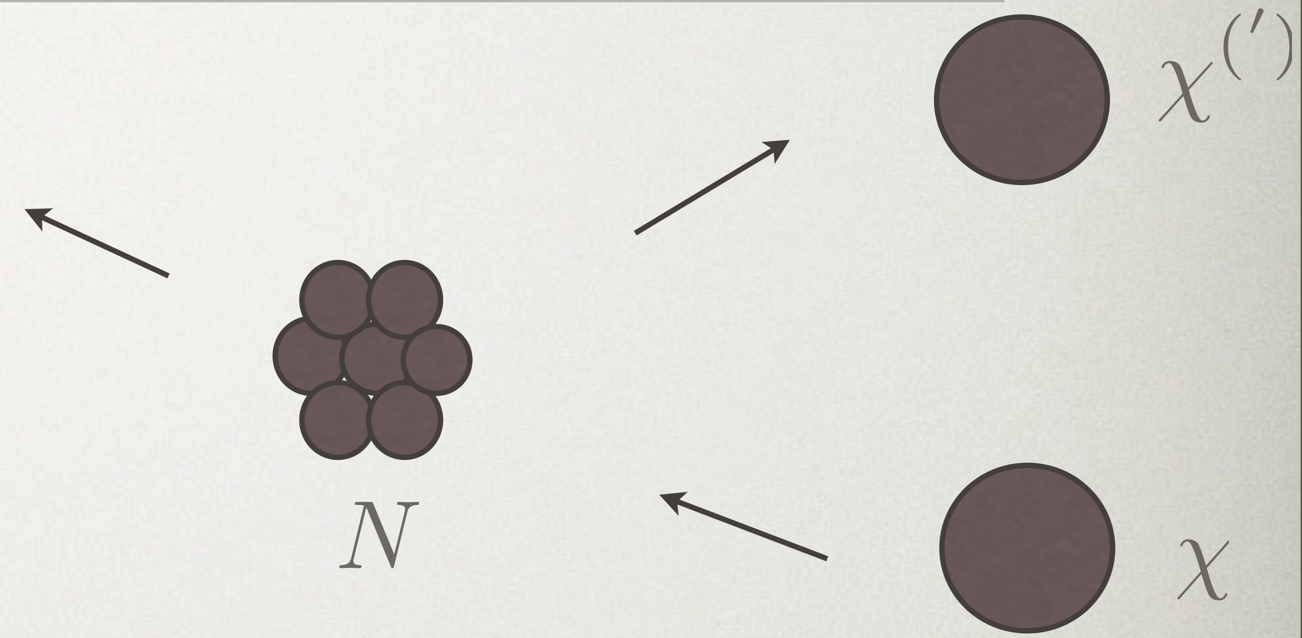


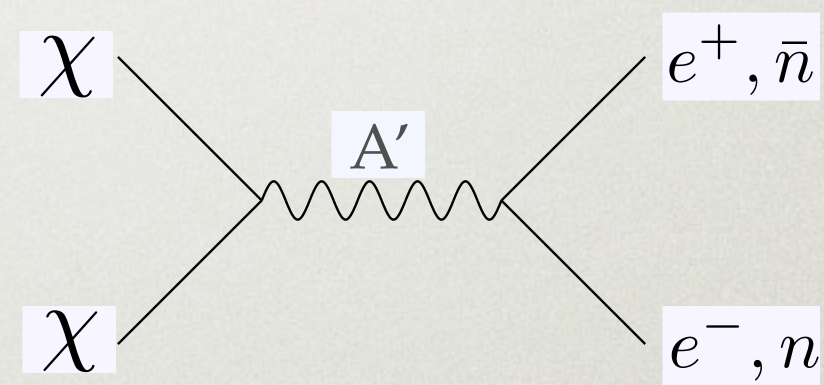
$$\sigma_{\chi\chi} \approx \frac{g_\chi^4 m_\chi^2}{4\pi m_{A'}^4} \lesssim 4.4 \times 10^{-27}\ \mathrm{cm}^2 \left(\frac{m_\chi}{1\ \mathrm{GeV}}\right)$$

Lin, Yu, KZ 1111.0293

Connection to Direct Detection

- Can now take constraints from heavy photon searches + halo shapes to map to direct detection experiments



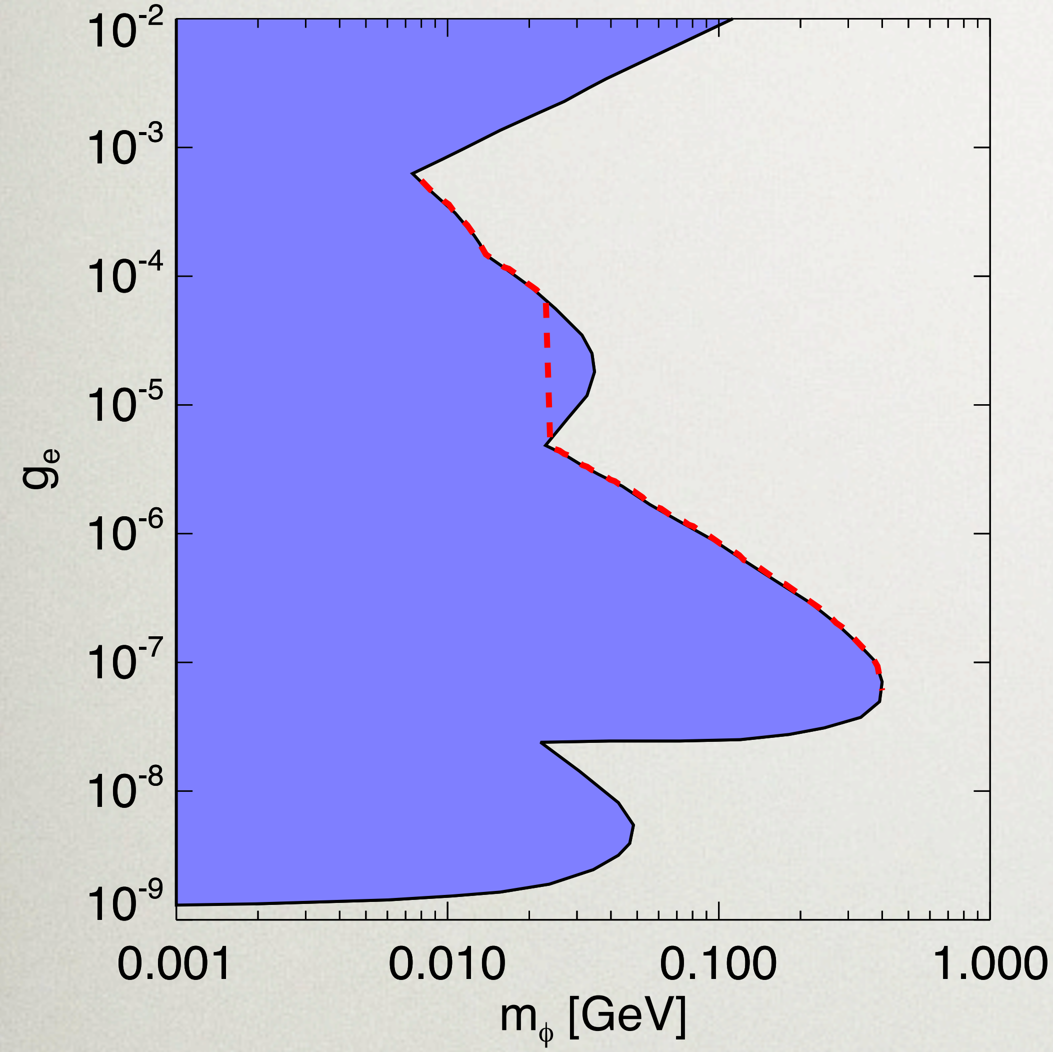


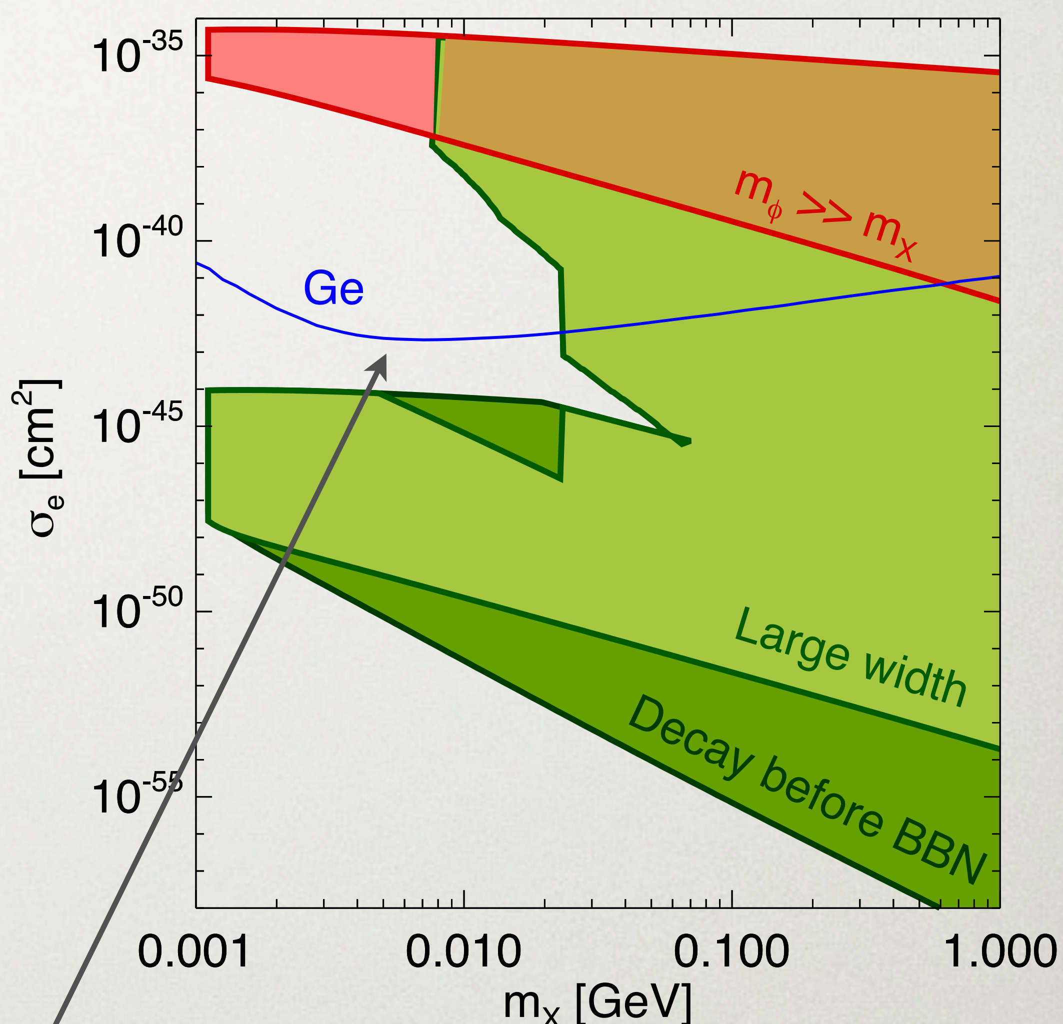
Constrained by halo shapes

$$\sigma_n \approx \frac{g_\chi^2 g_n^2 \mu_n^2}{\pi m_{A'}^4} \qquad \sigma_e \approx \frac{g_\chi^2 g_e^2 \mu_e^2}{\pi m_{A'}^4}$$

Constrained by heavy photon search

Map into Direct Detection Plane





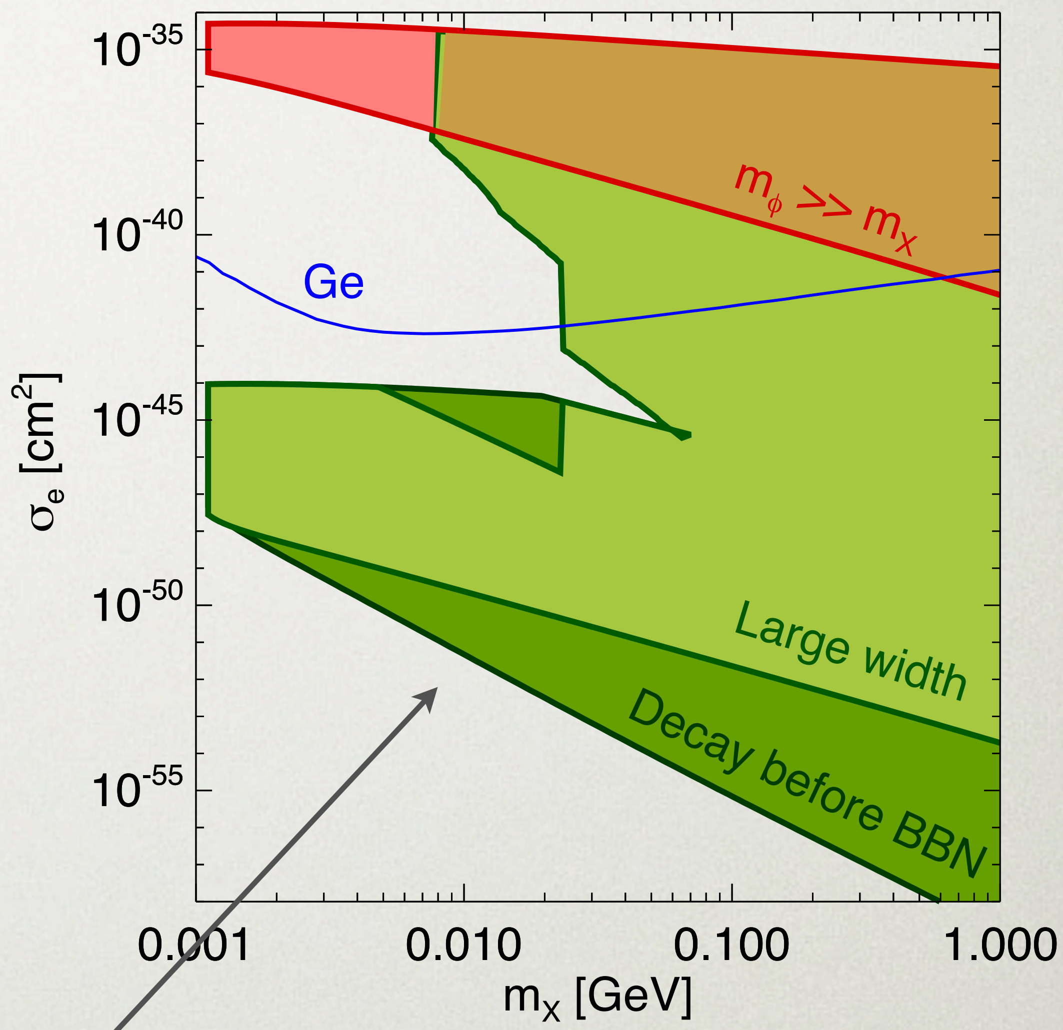
Lin, Yu, KZ 1111.0293

Projected maximum sensitivity of direct detection experiment

Cut-out gives combined constraints of beam dump + supernova + g-2

Map into Direct Detection Plane

Note that the lower bound of the theory parameter space is totally out of reach of any experiment! Can we do better?



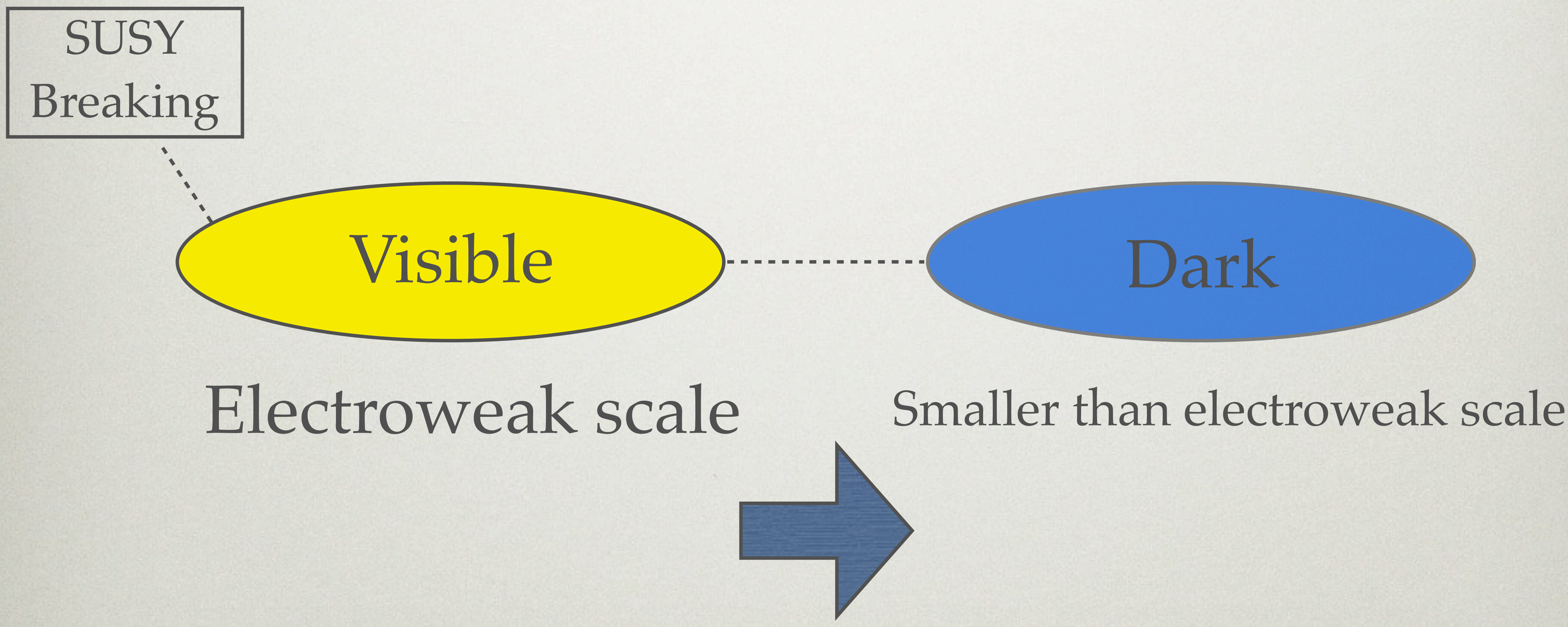
Lin, Yu, KZ 1111.0293

Require A′ to decay before BBN

$$g_e \gtrsim 5 \times 10^{-11} \sqrt{10\ \mathrm{MeV}/m_{A'}}$$

Particular Models Can be MUCH More Predictive!

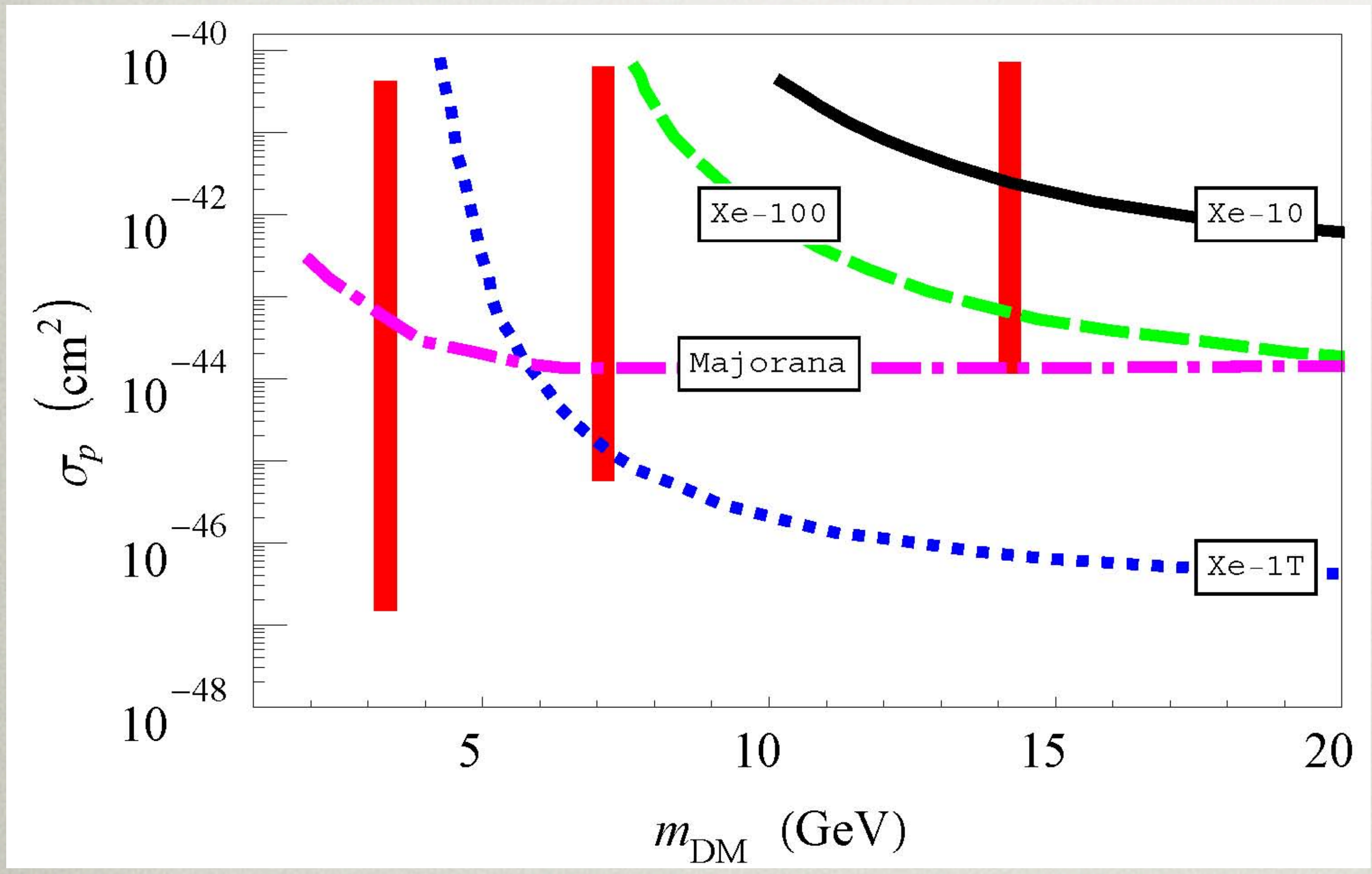
- Goal: explain why GeV? Dynamically generate DM mass

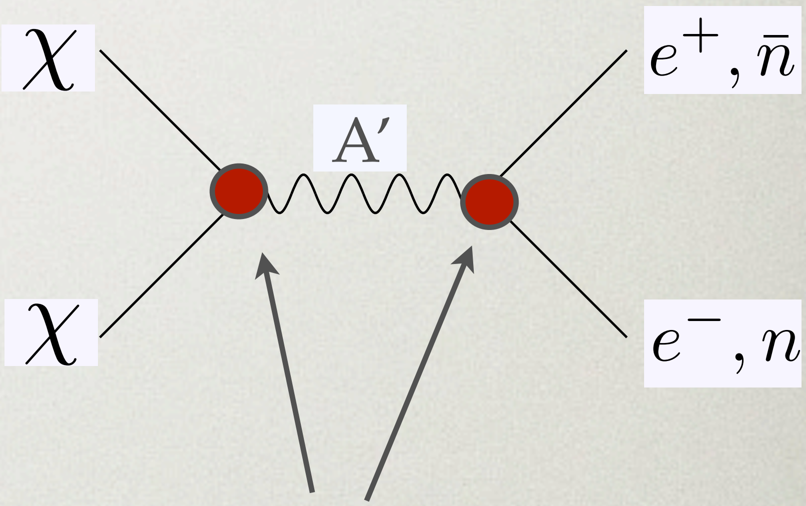


$$m_X \sim \sqrt{\epsilon} m_{SUSY}$$

Particular Models Can be MUCH More Predictive!

- Predict DD cross-section for Asymmetric Dark Matter!

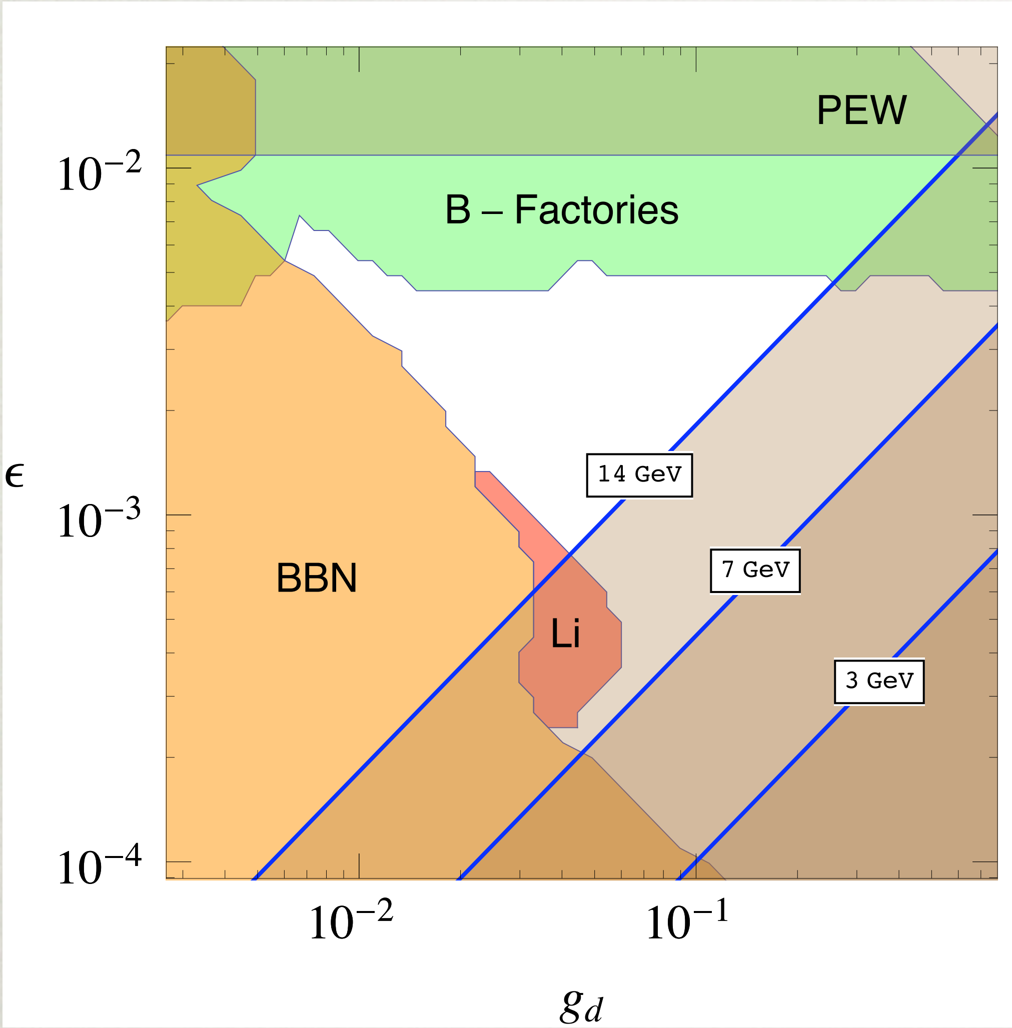


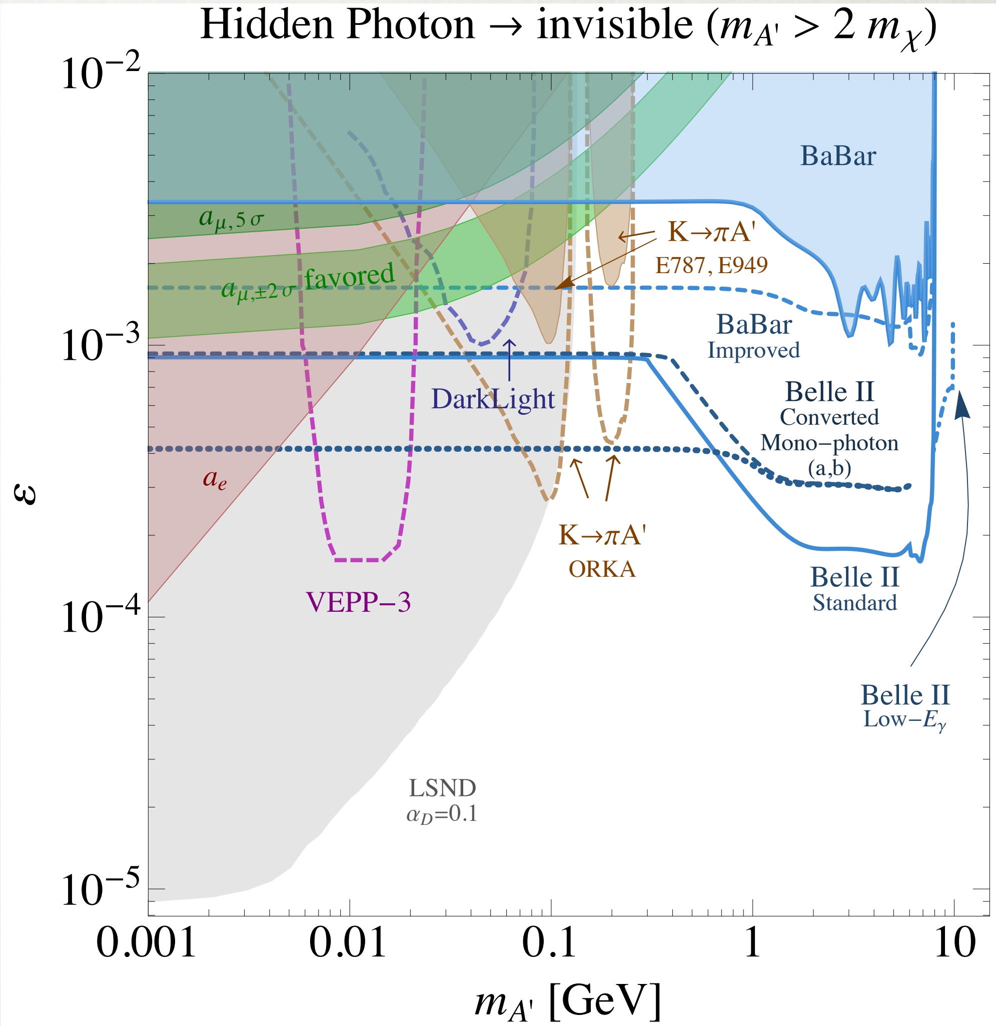


Coupling predicted by setting mass scale in DM sector!

Cohen, Phalen, Pierce, KZ 1005.1655

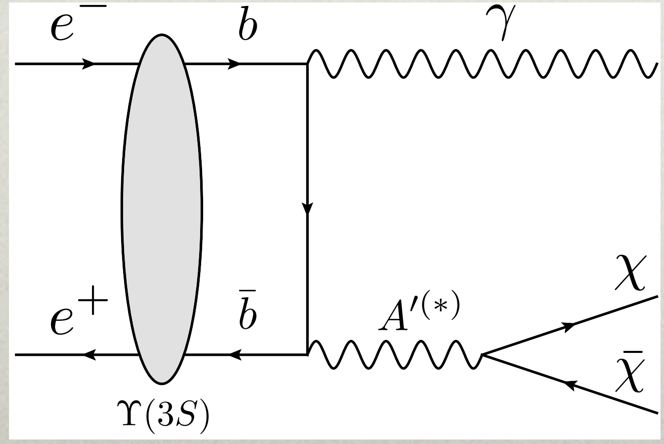
Also Probed by Intensity Experiments

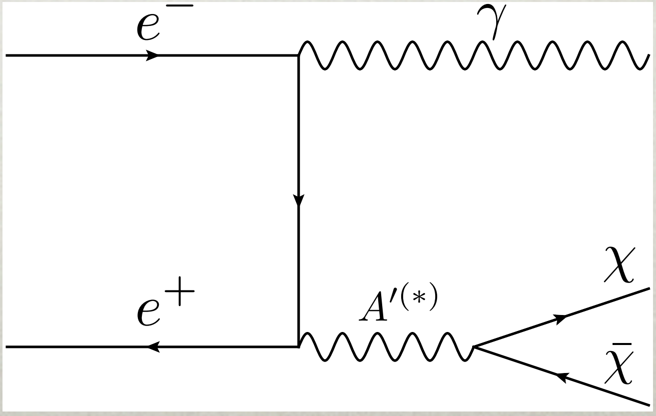




Cohen, Phalen, Pierce, KZ 1005.1655

Essig, Mardon, Papucci, Volansky, Zhong 1309.5084





Summary

- In the last 7-10 years, particle theory has undergone a paradigm shift from sole focus on weak scale processes
- A key aspect of this paradigm shift is towards searching for light hidden sectors
- This light hidden sector may play a key role in the dynamics of the DM

Summary

- Well-motivated models -- Asymmetric Dark Matter in particular
- Intensity experiments are complementary to direct detection and astrophysical probes
- Many probes coming online in next years