Theories of Light Dark Matter and Their Connection to Intensity Experiments

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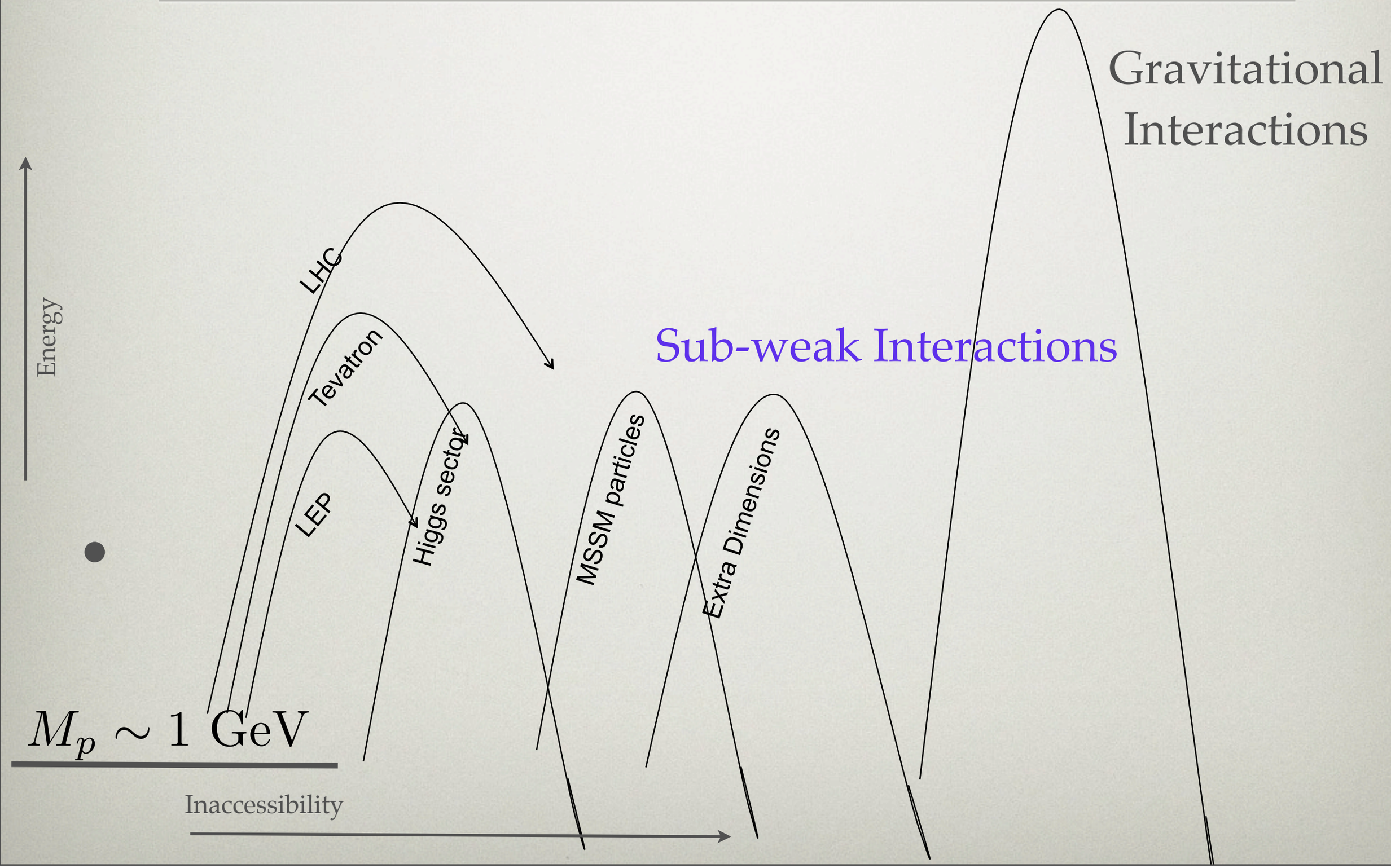
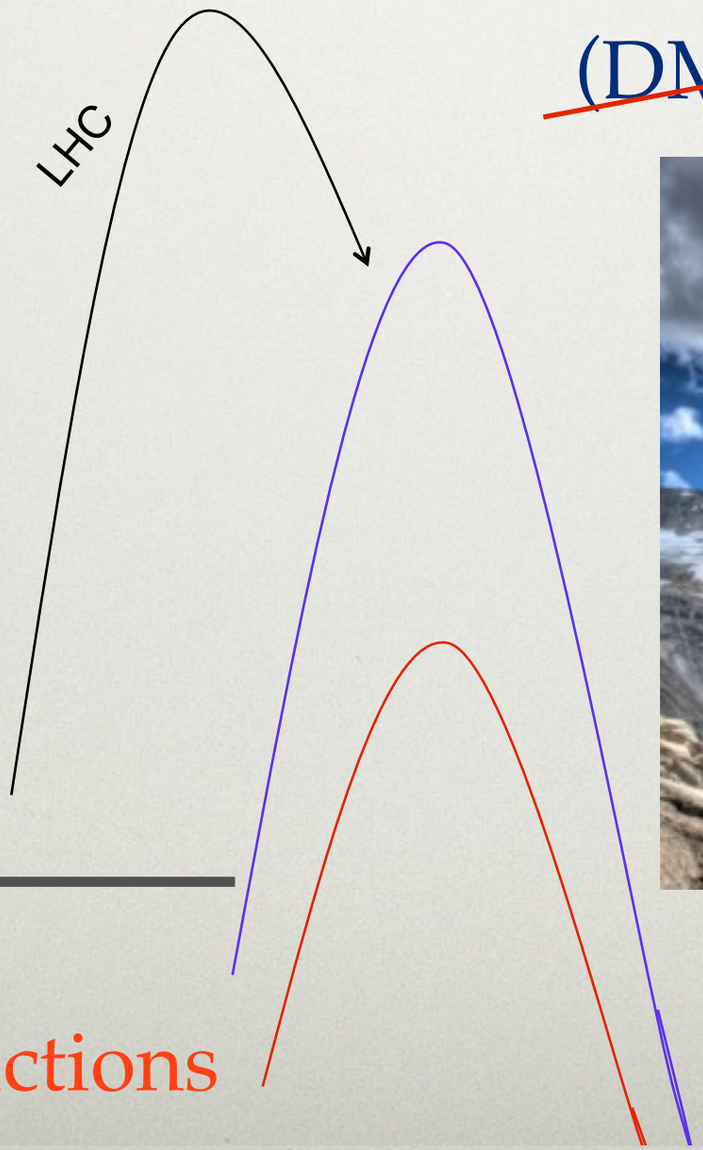
Focus on Weak Scale for New Physics



Paradigm Shift

Sub-weak Interactions

(DM ~~here.~~)



Standard Model

Weak Interactions

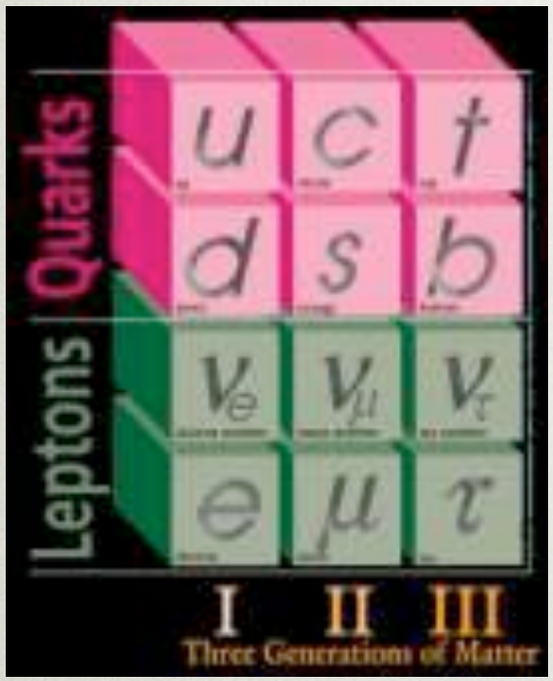
Torres del Paine

Dark World

Hidden Valley

Paradigm Shift

Our thinking has shifted



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

?

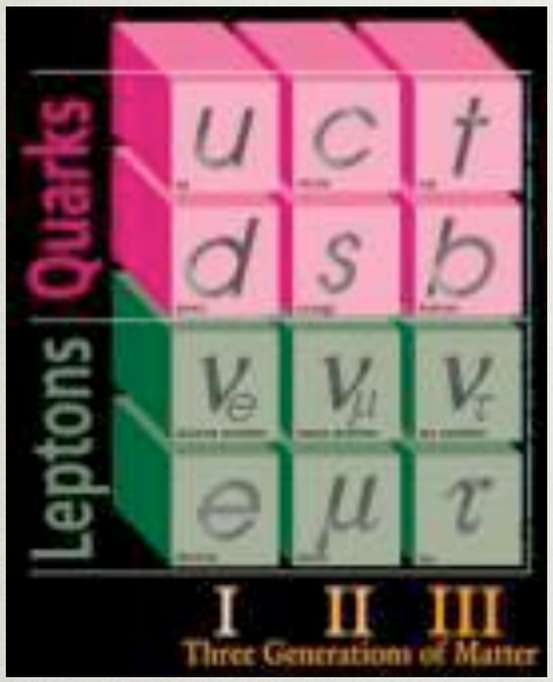
$M_p \sim 1$ GeV

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′

(Heavy Photon Search)

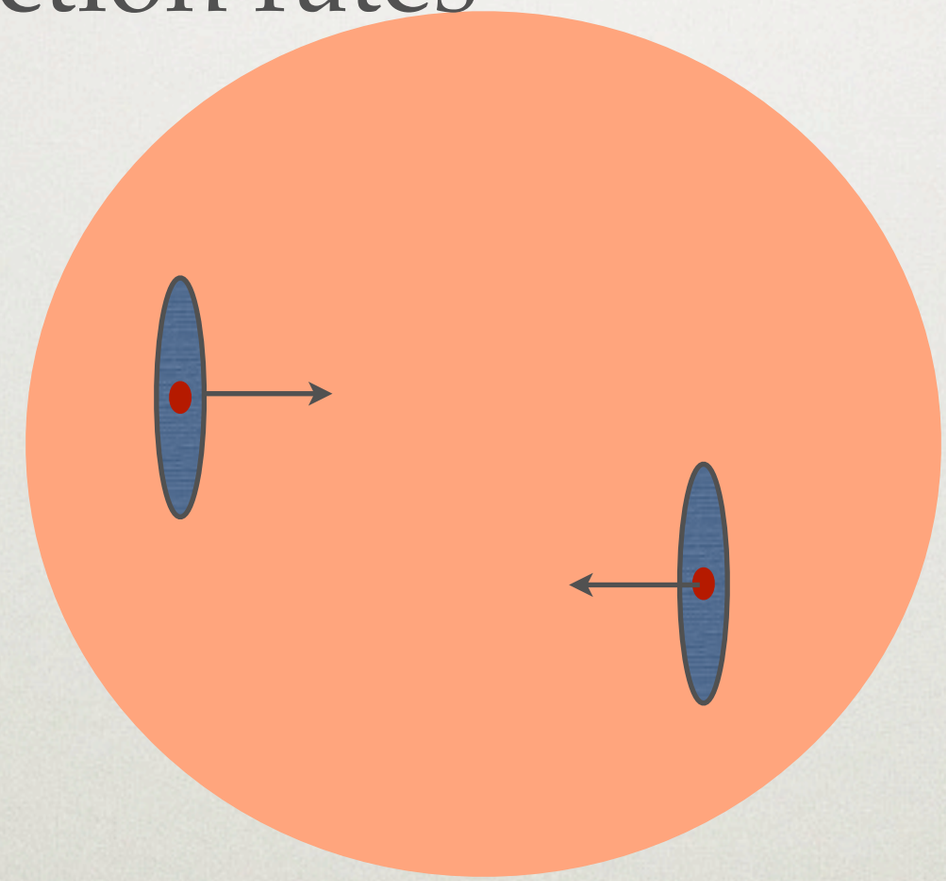
$M_p \sim 1$ GeV

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

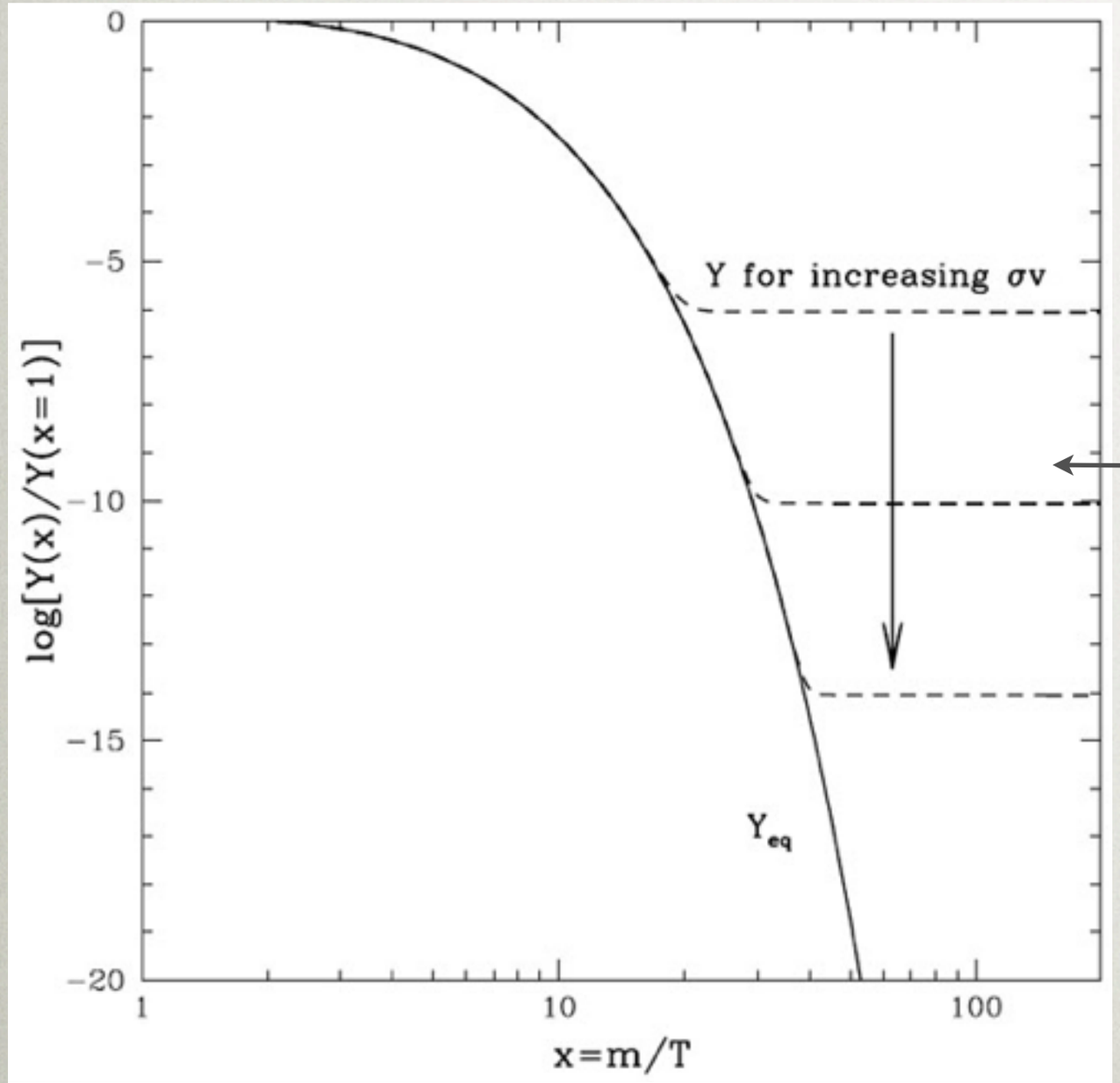


Freeze-out

Measured by WMAP + LSS

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

Why the Weak Scale is Compelling



Kolb and Turner

Meausured by CMB plus large scale structure

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

$$\simeq \frac{1}{(20\ \mathrm{TeV})^2}$$

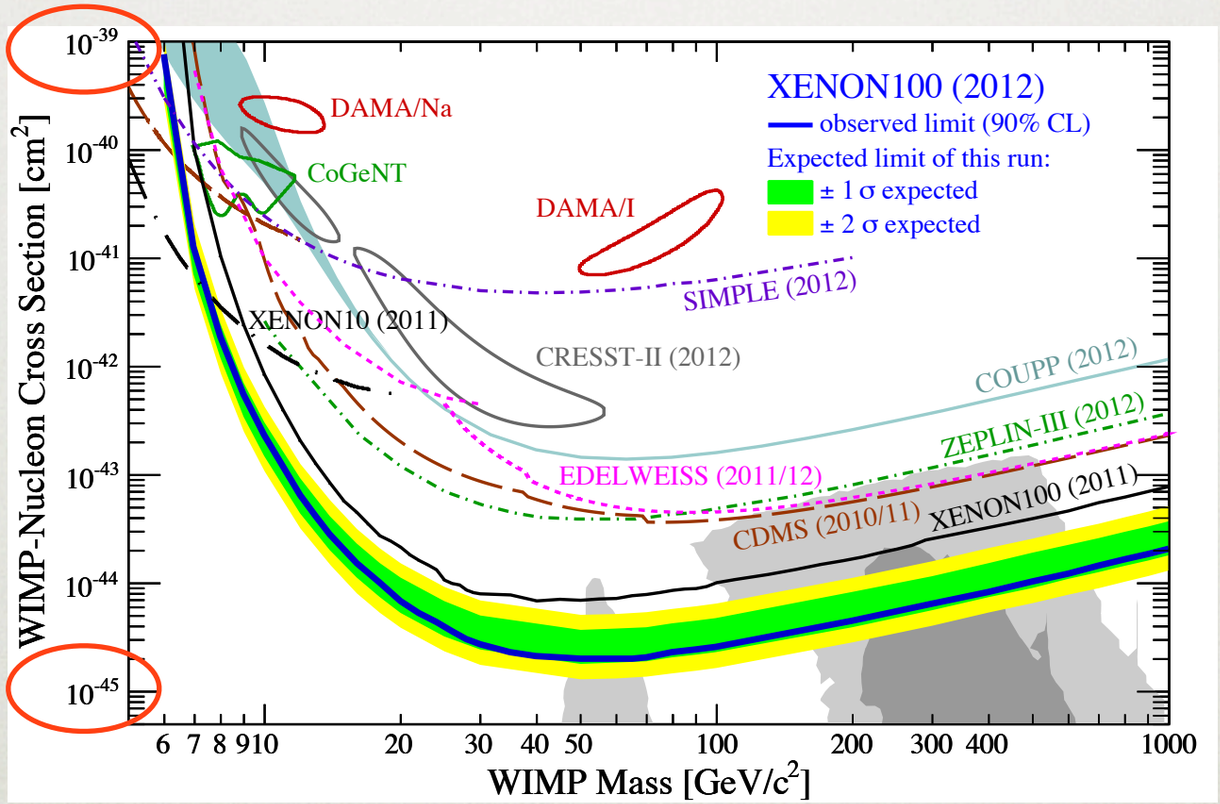
Idea Focus: Supersymmetry

- Provides sharp predictions
- Must be neutral $\tilde{\nu}$ $\tilde{B},\ \tilde{W}_3,\ \tilde{H}$
- Sneutrino scatters through Z
- Neutralino does not because operator vanishes identically for Majorana fermion $\bar{\chi}\gamma^\mu\chi\bar{N}\gamma_\mu N$

Sub-Weakly Interacting Massive Particles

Scattering through the Z boson: ruled out

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

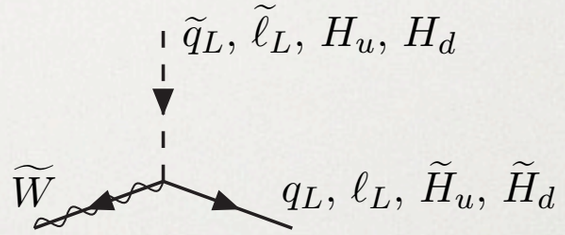


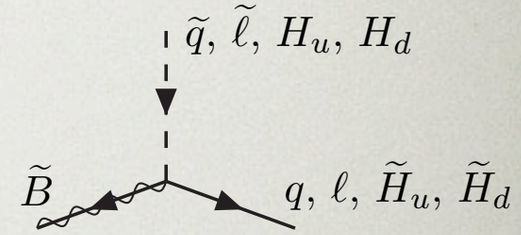
Next important benchmark:
Scattering through the Higgs

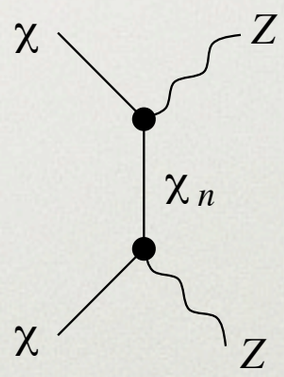
$$\sigma_n \sim 10^{-45-46}\ \mathrm{cm}^2$$

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





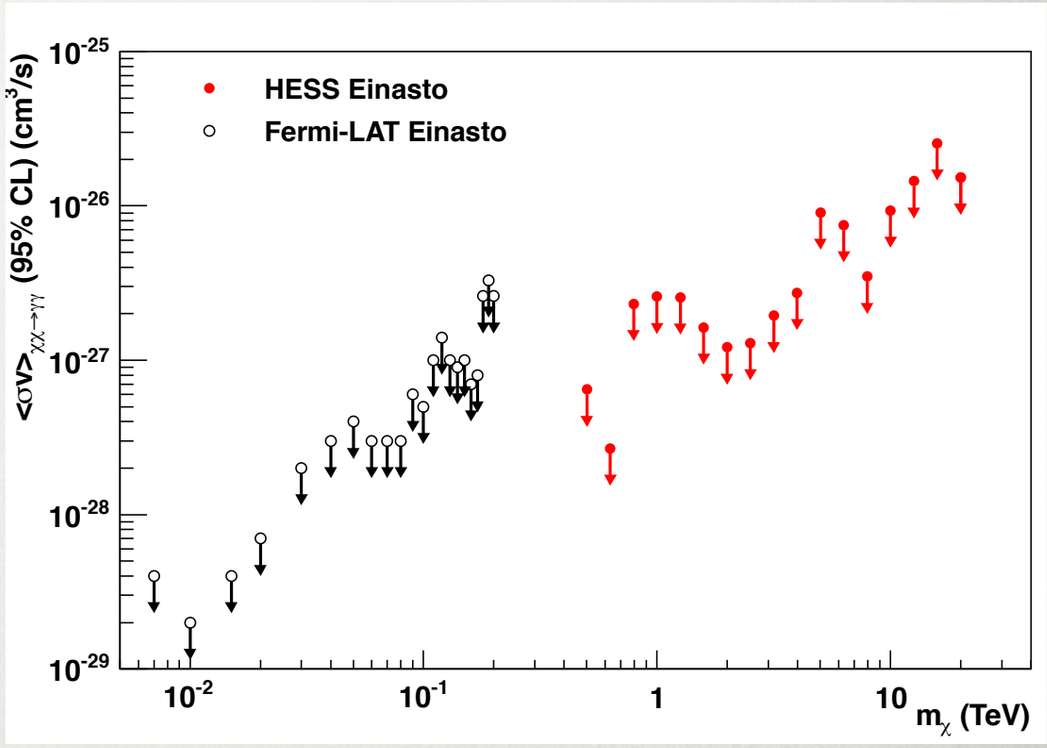


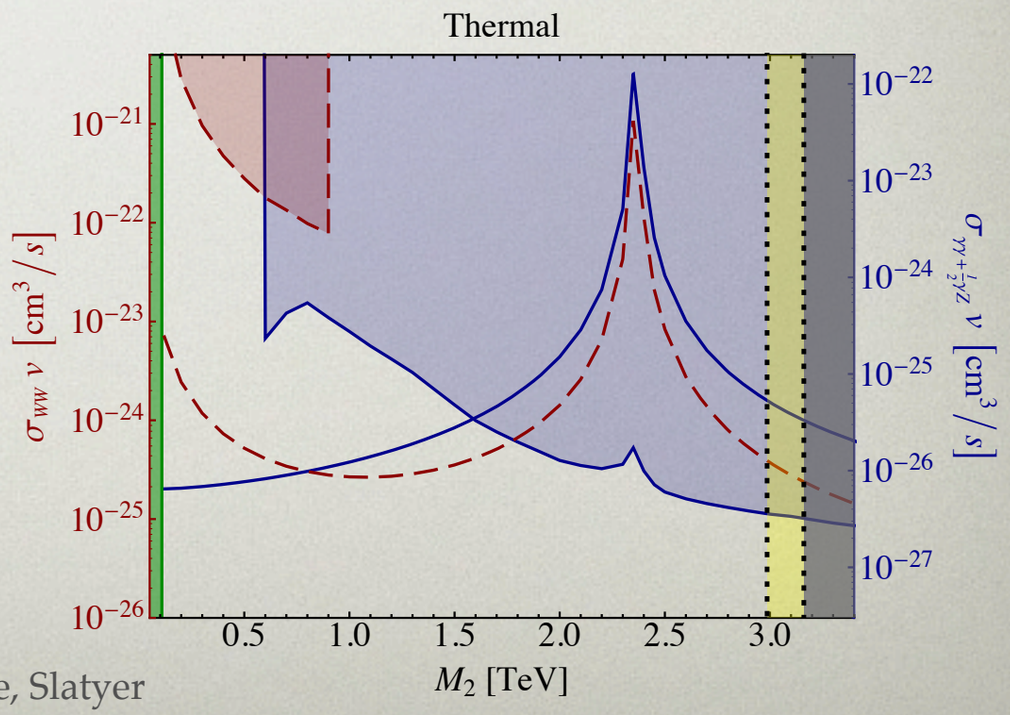
Large!

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

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

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

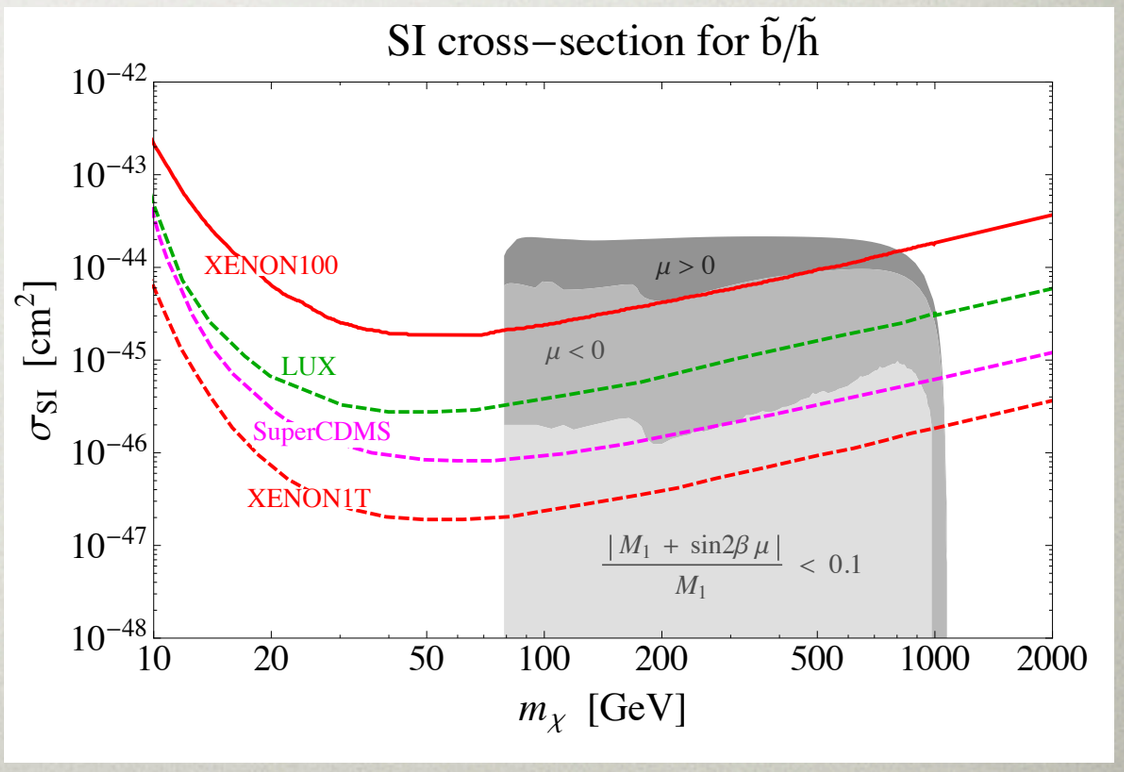
$$m_Z^2 = \frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1 - \sin^2(2\beta)}} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2$$

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

$\mathbf{m}_\chi$	**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



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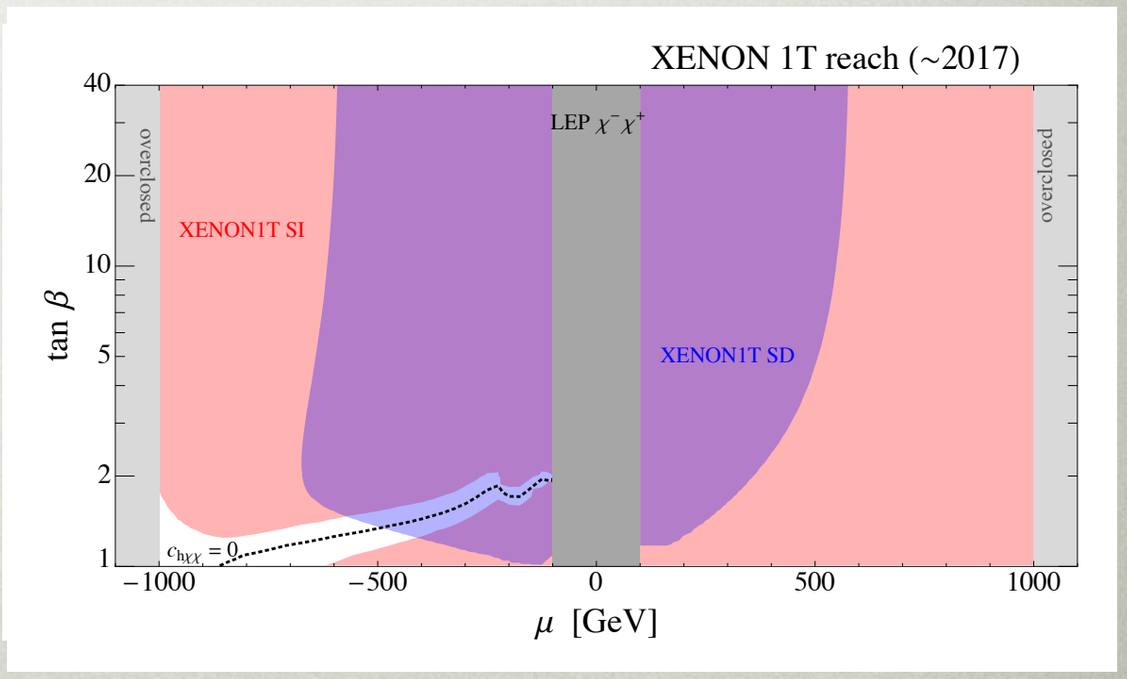
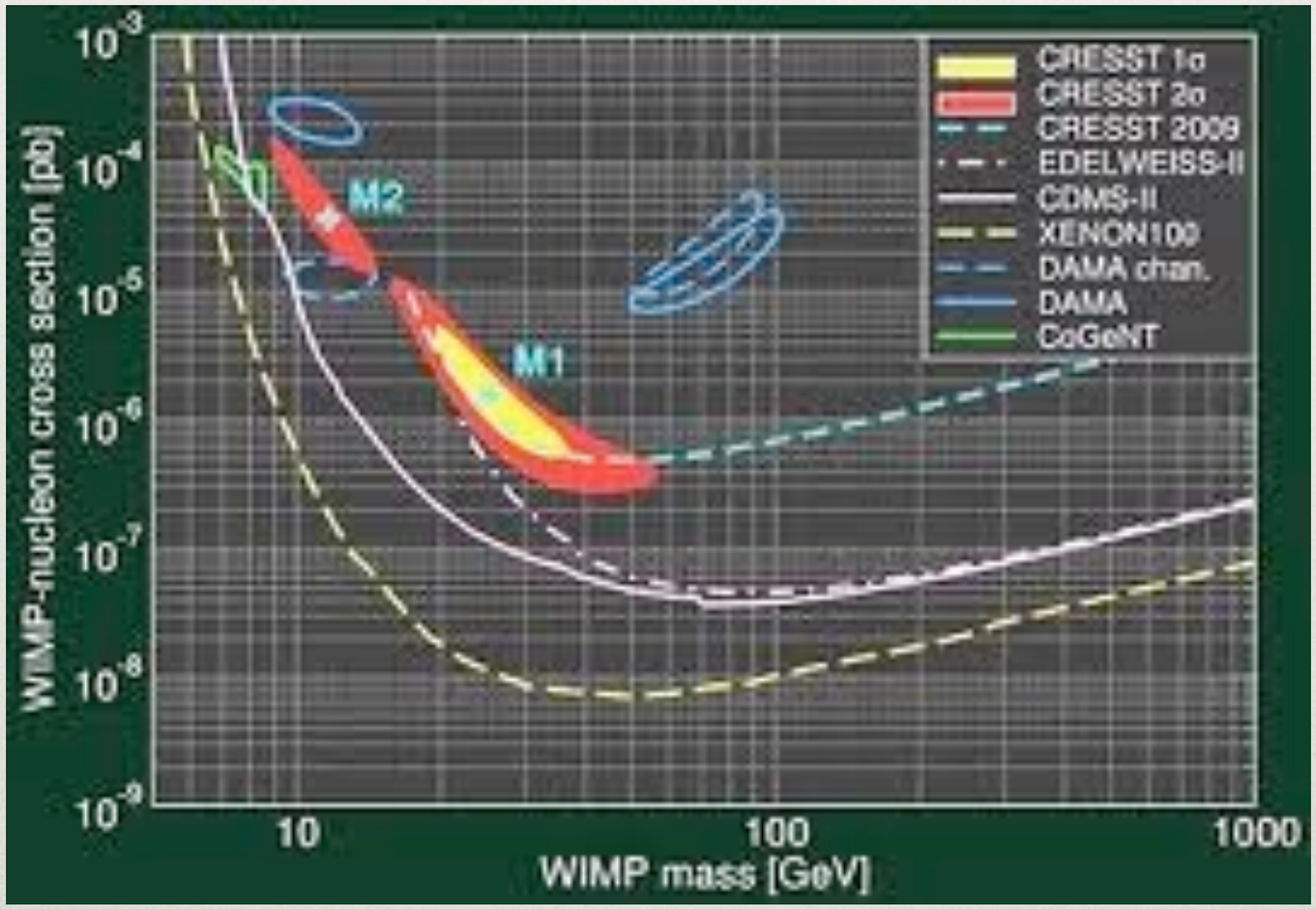


When Should We Start Looking Elsewhere?

- 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

Current Sensitivity Limited

CRESST 2011



DAMA

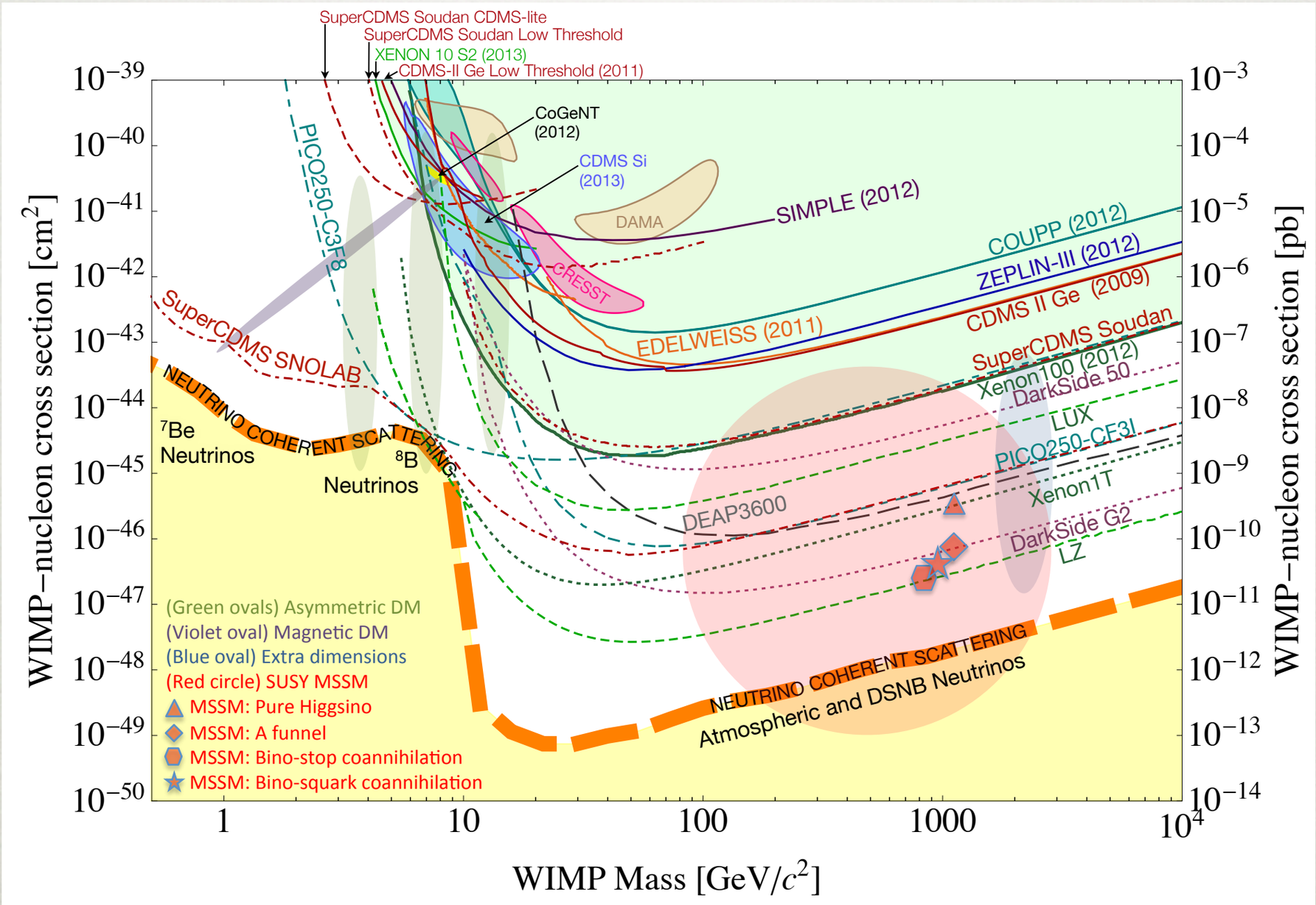
CoGeNT

CRESST

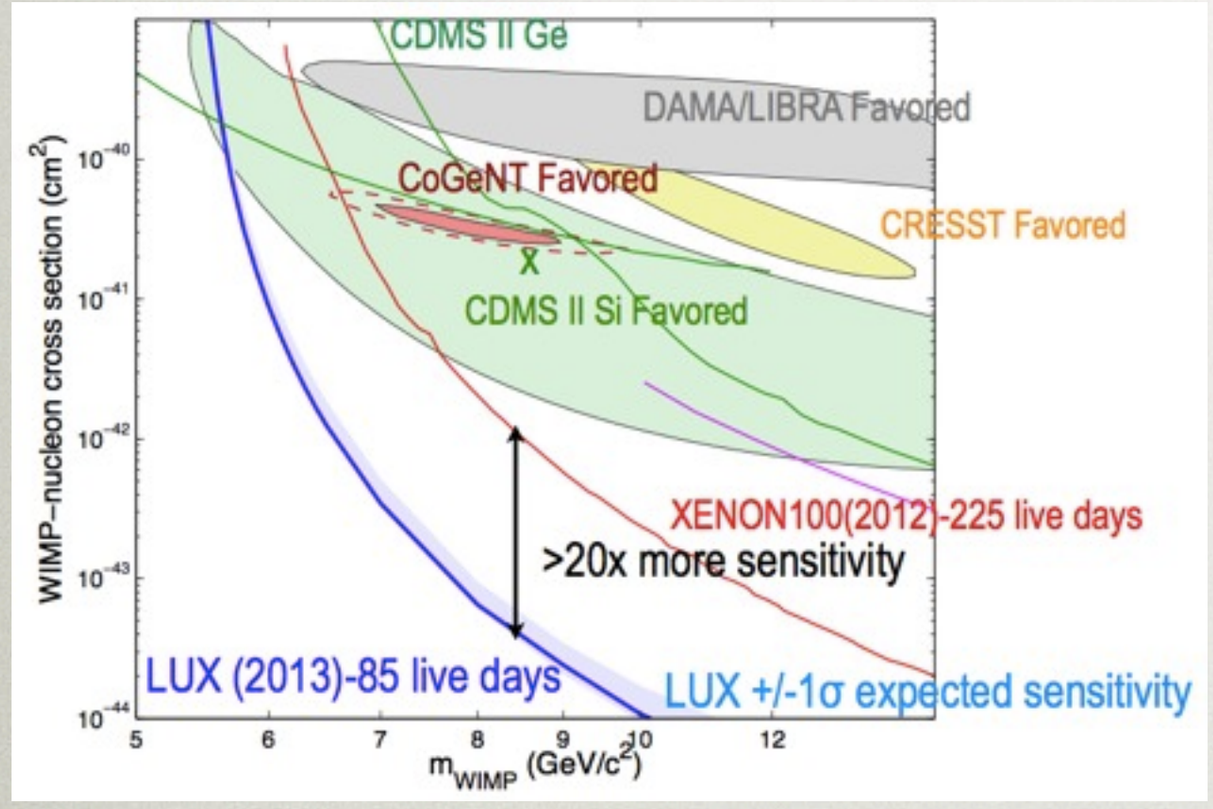
CDMS-Si

Terra Incognita

CF1 Snowmass report, 1310.8327



Cross-Sections May Be Mediated By A'

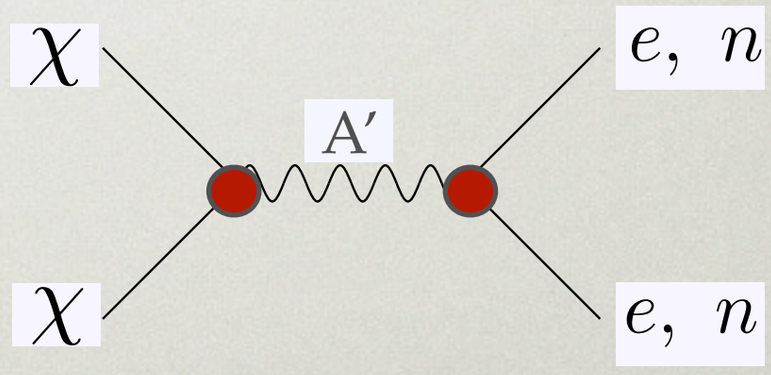


LUX talk

KZ, 0811.4429

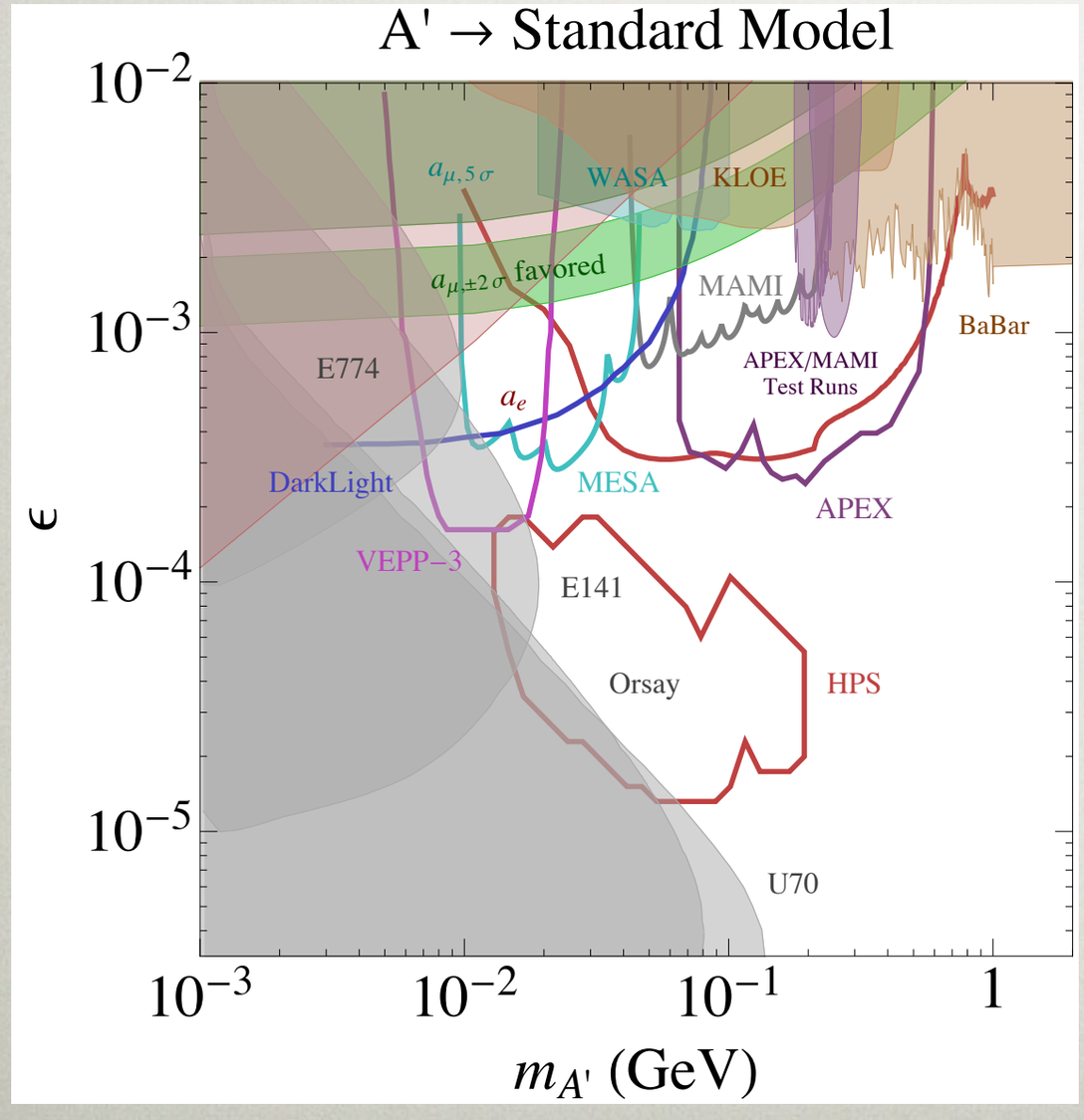
$$\sigma_{SI} \simeq \frac{g_n^2 g_\chi^2 m_r^2}{\pi m_{A'}^4}$$

$$\sim 10^{-40}\ \mathrm{cm}^2 \left(\frac{g_n g_\chi}{10^{-4}}\right)^2 \left(\frac{8\ \mathrm{GeV}}{m_{A'}}\right)^4$$

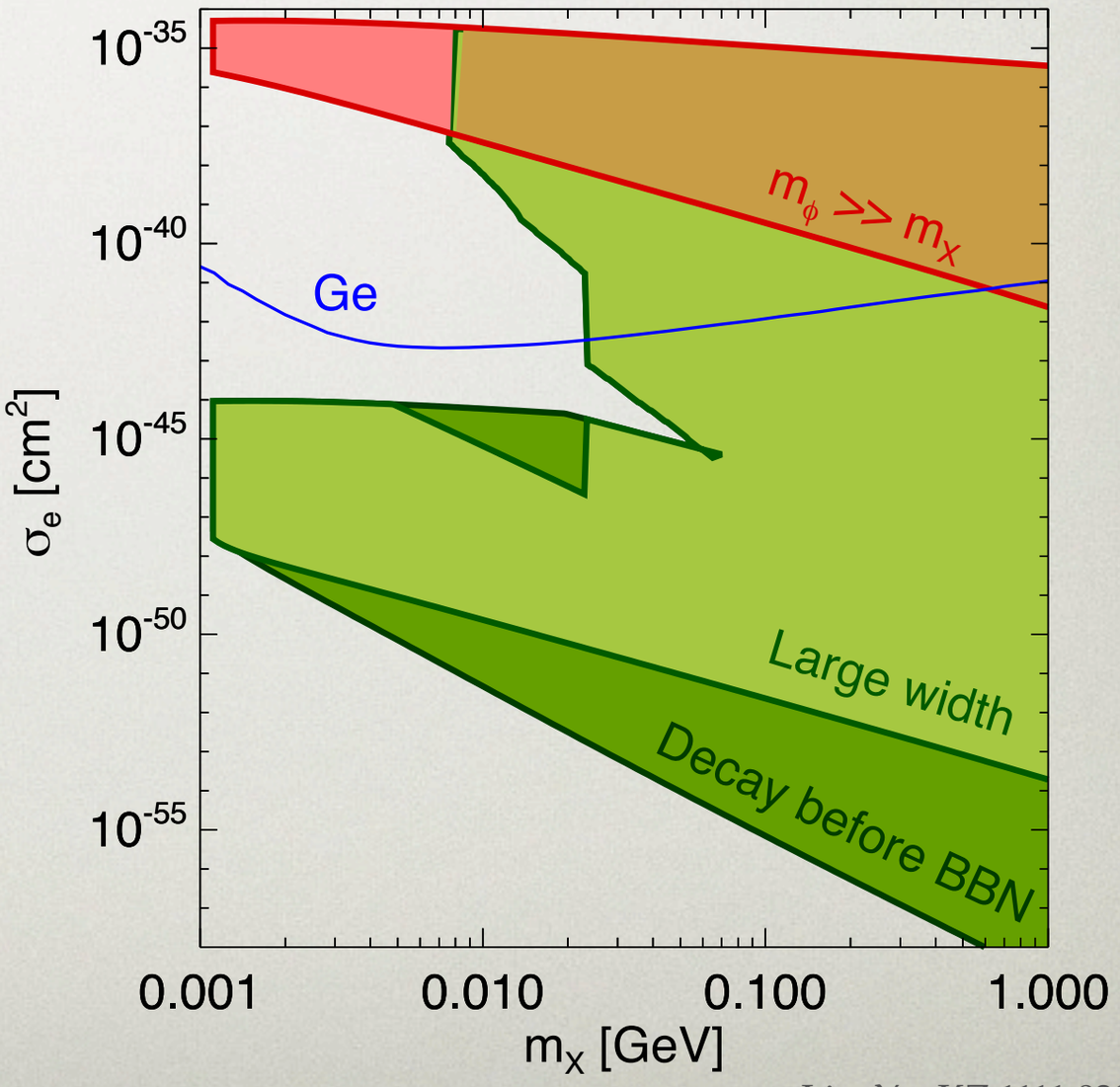


Connection to Dark Forces

- A′ searches can constrain this parameter space



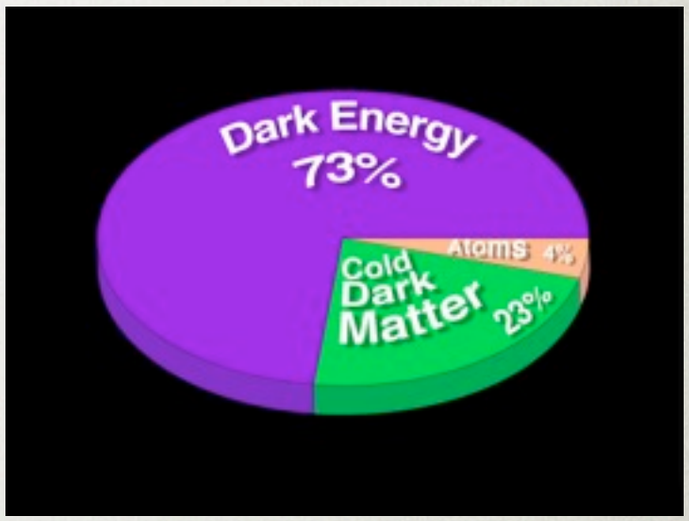
1311.0029



Lin, Yu, KZ 1111.0293

Light WIMPs: Asymmetric Dark Matter

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

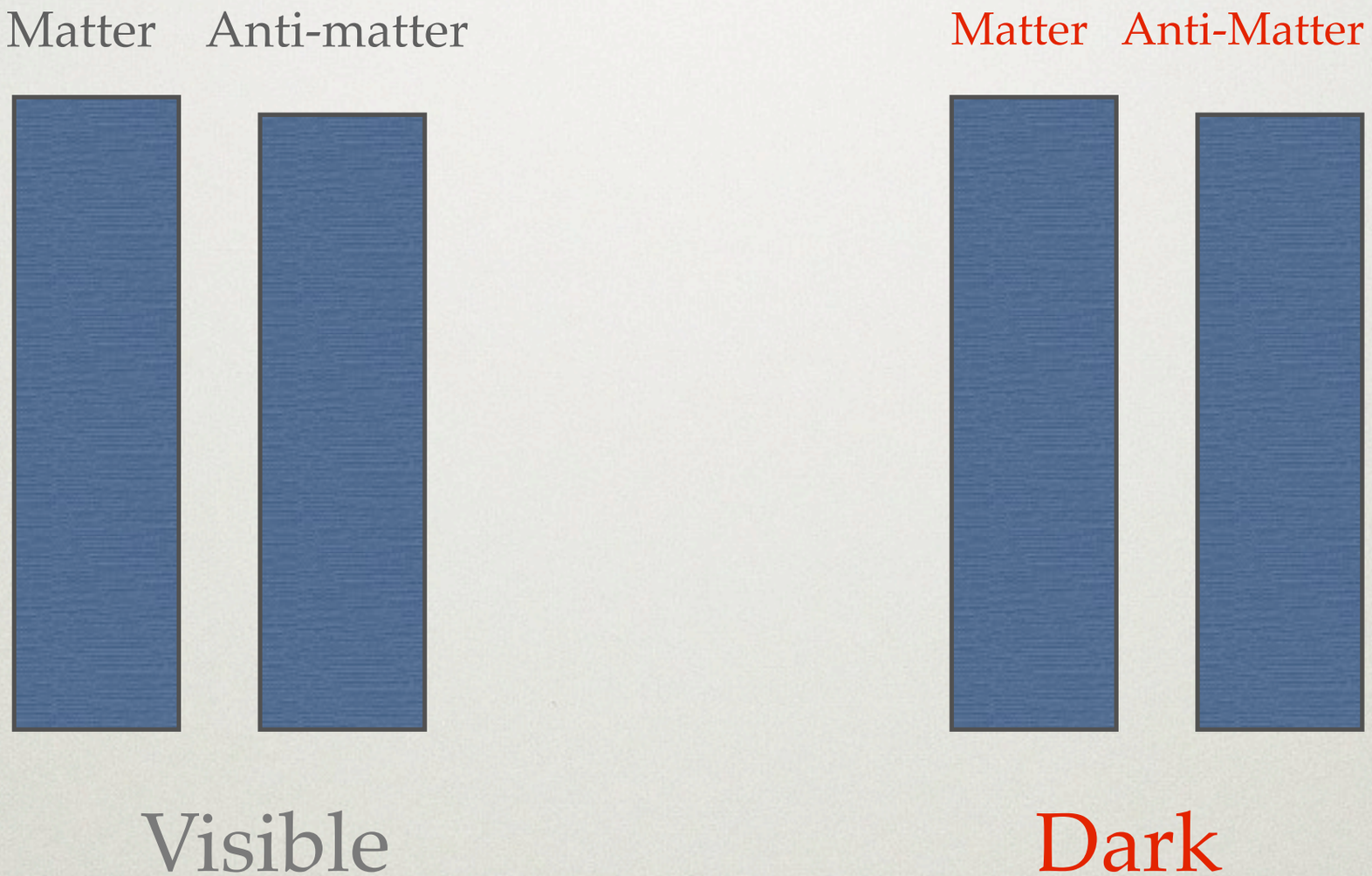


Experimentally, $\Omega_{DM} \approx 5\Omega_b$

Mechanism $n_{DM} \approx n_b$

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

Chemical Potential Dark Matter



Baryon and DM Number Related?

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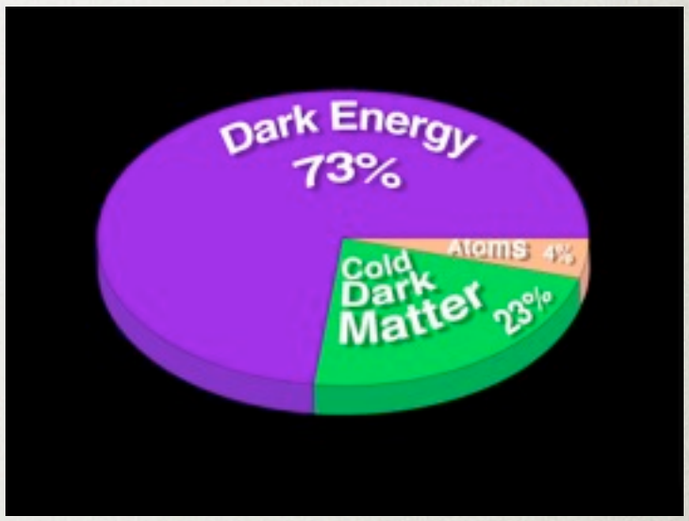

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Nussinov,
Hall, Gelmini,
Barr, Chivukula, Farhi,
D.B. Kaplan

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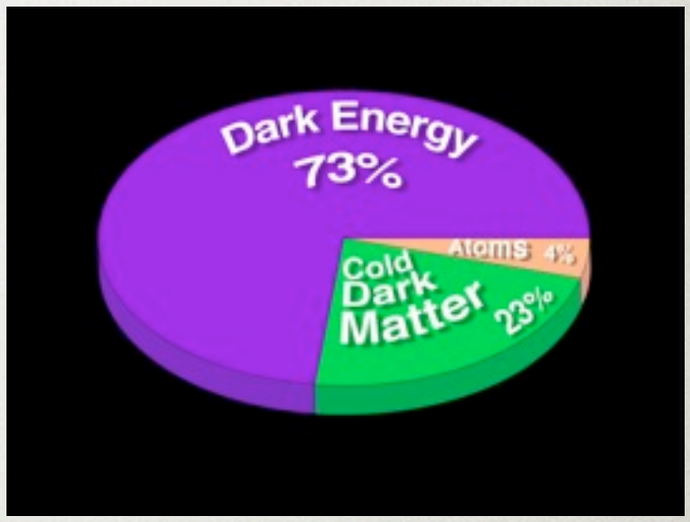
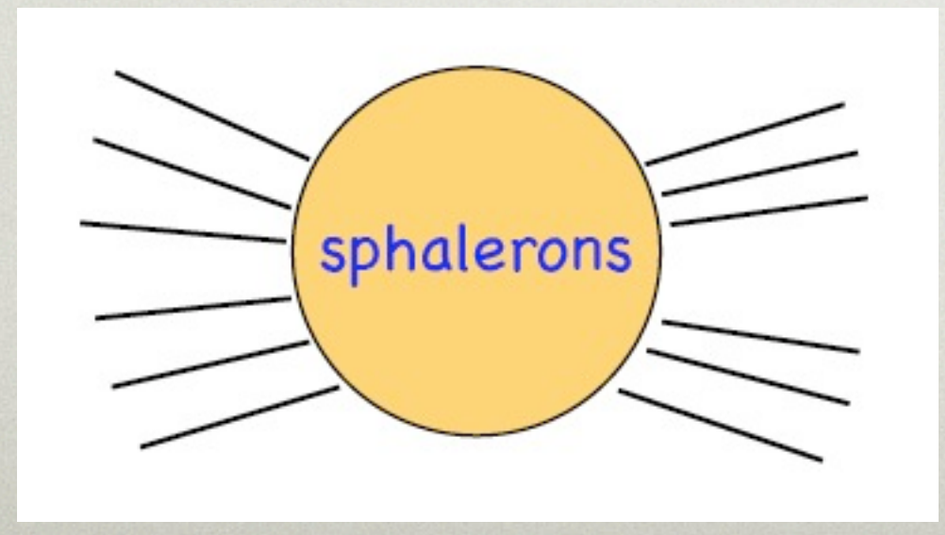


Use:

B, L



X

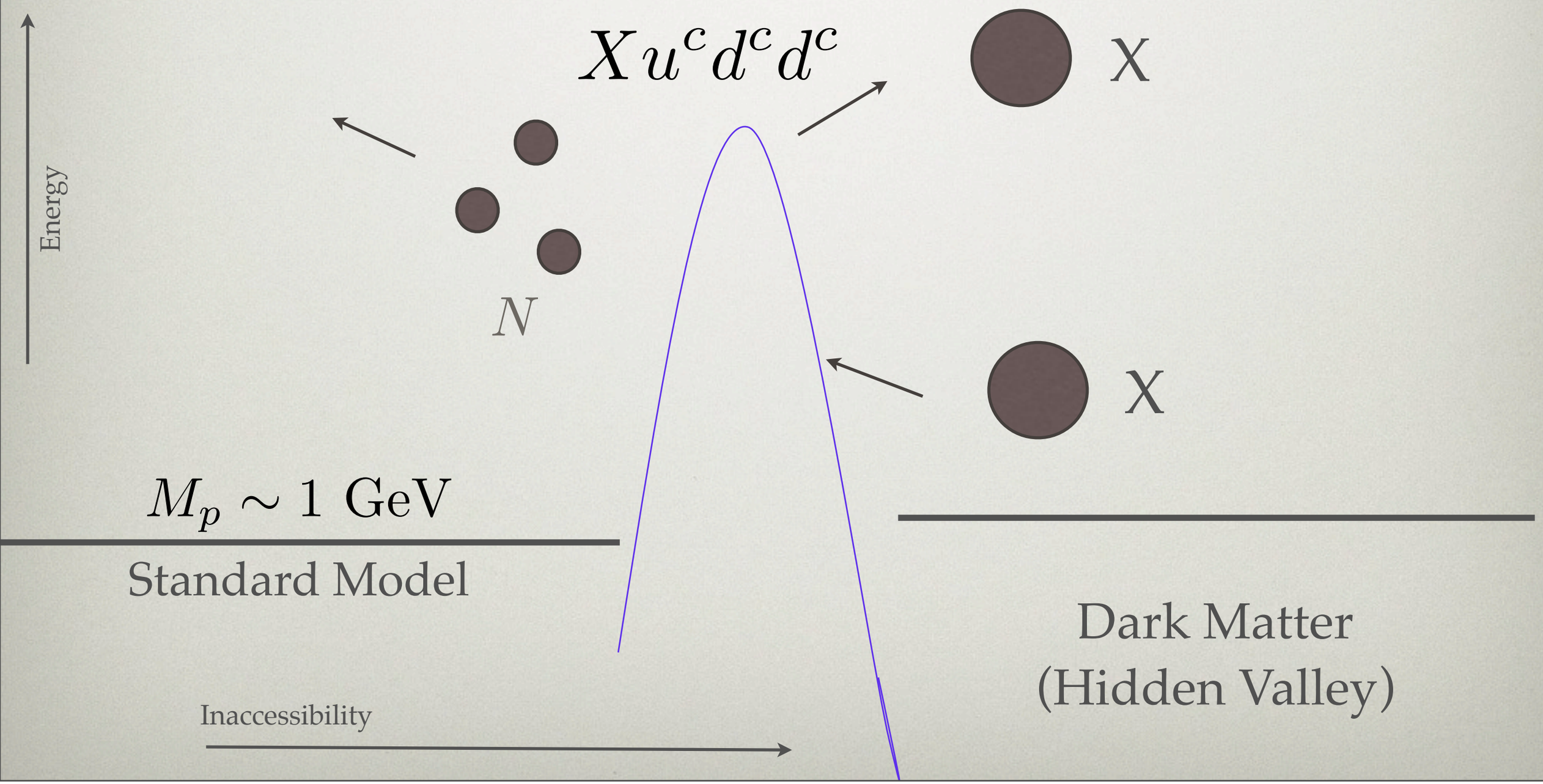
LEP and Precision EW tend to result in problematic models

Asymmetric DM

"Integrate out" heavy state
Higher dimension operators:

Luty, Kaplan, KZ
0901.4117

$$X u^c d^c d^c$$



Asymmetric DM

Luty, Kaplan, KZ
0901.4117

$$\mathcal{O}_{B-L}\mathcal{O}_X$$

Energy

$\mathcal{O}_{B-L} = LH_u, LLE^c, QLD^c, U^cD^cD^c$

$\mathcal{O}_X = X,\ X^2$

$M_p \sim 1$ GeV

Standard Model

Dark Matter

Inaccessibility

What Does an ADM Model Do?

KZ, 1308.0338

1. *Share* an asymmetry between the visible and dark sectors

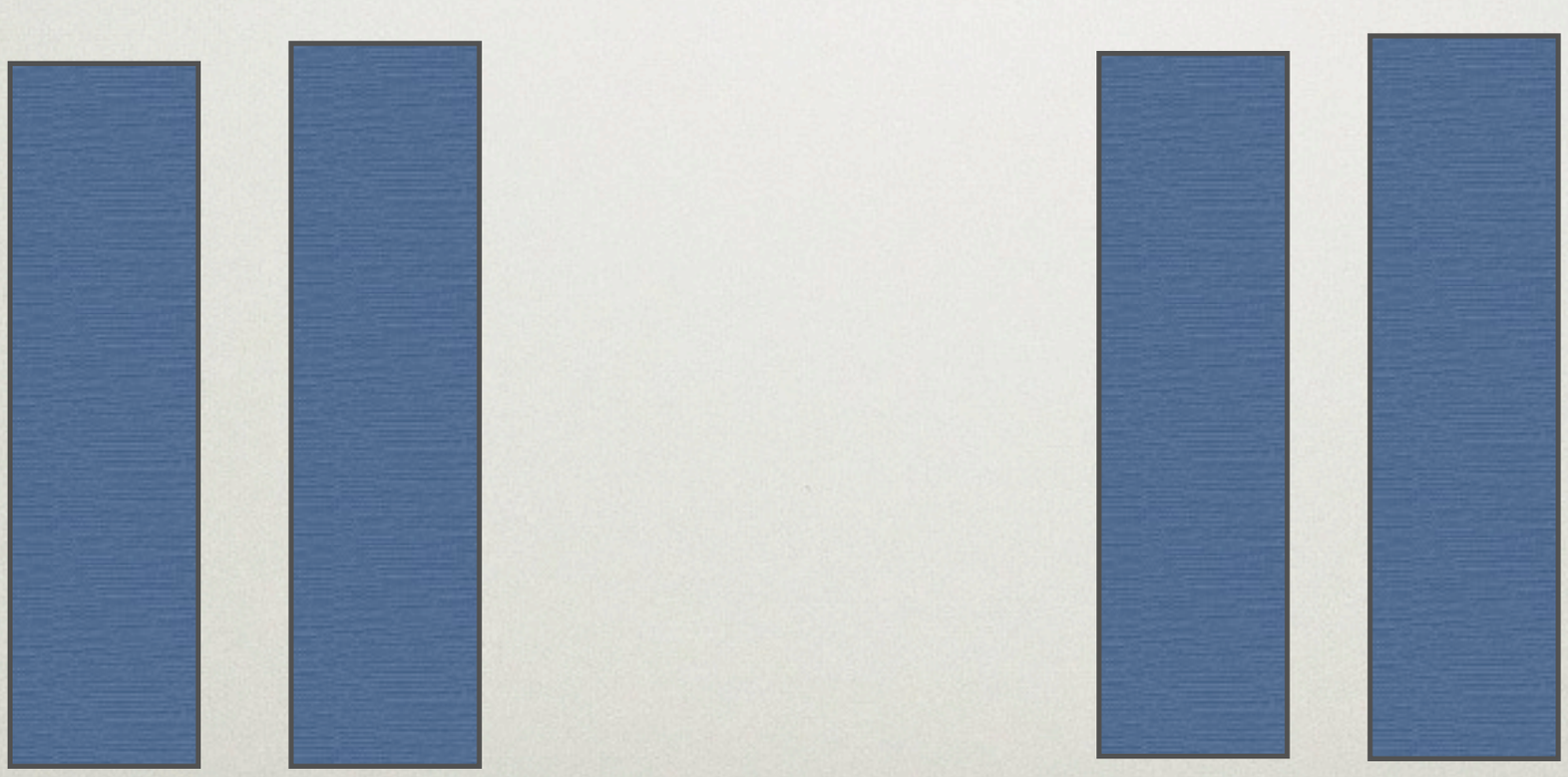
2. *Decouple* transfer mechanism to separately freeze-in the asymmetries in both sectors

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.



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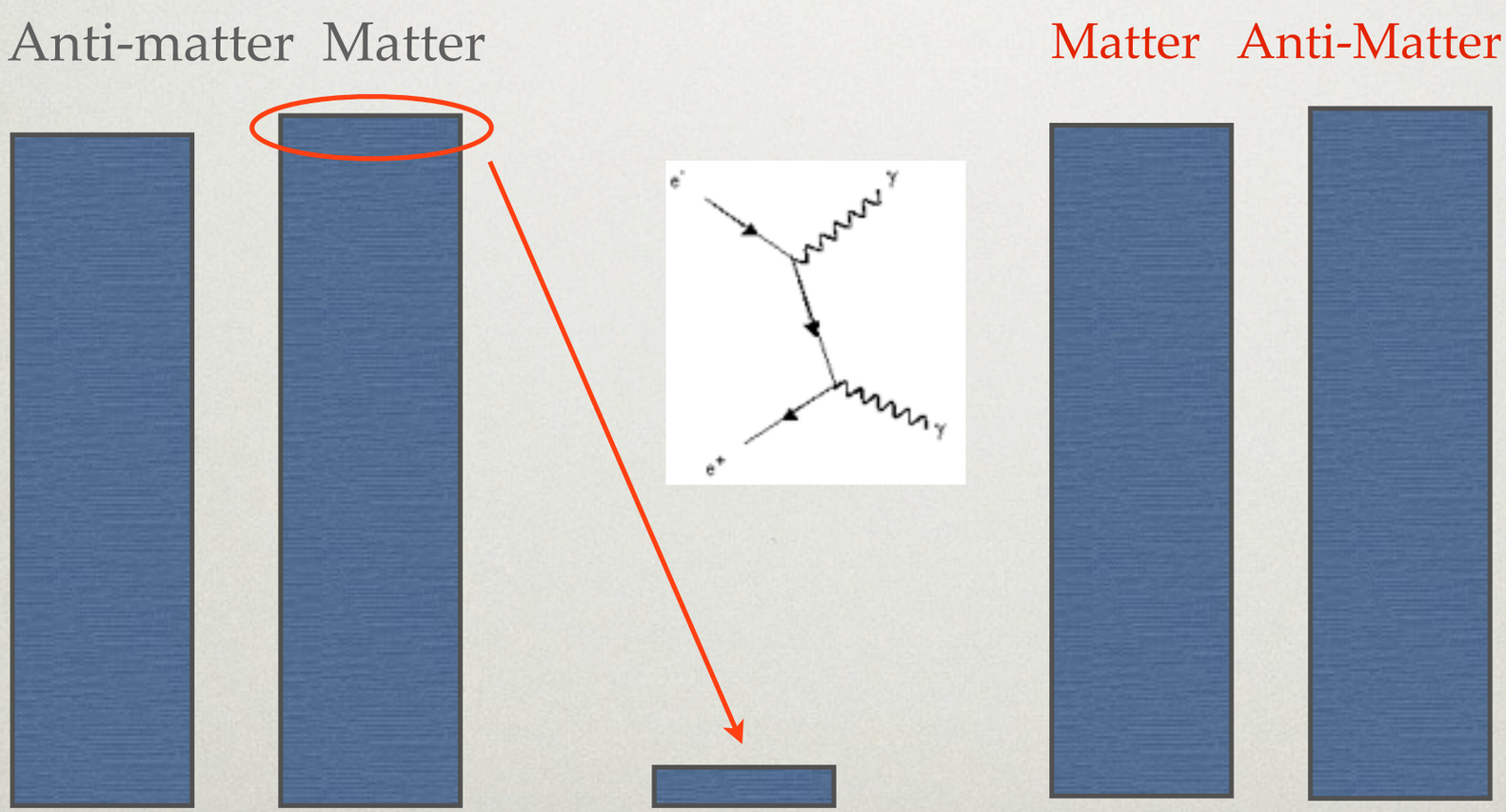

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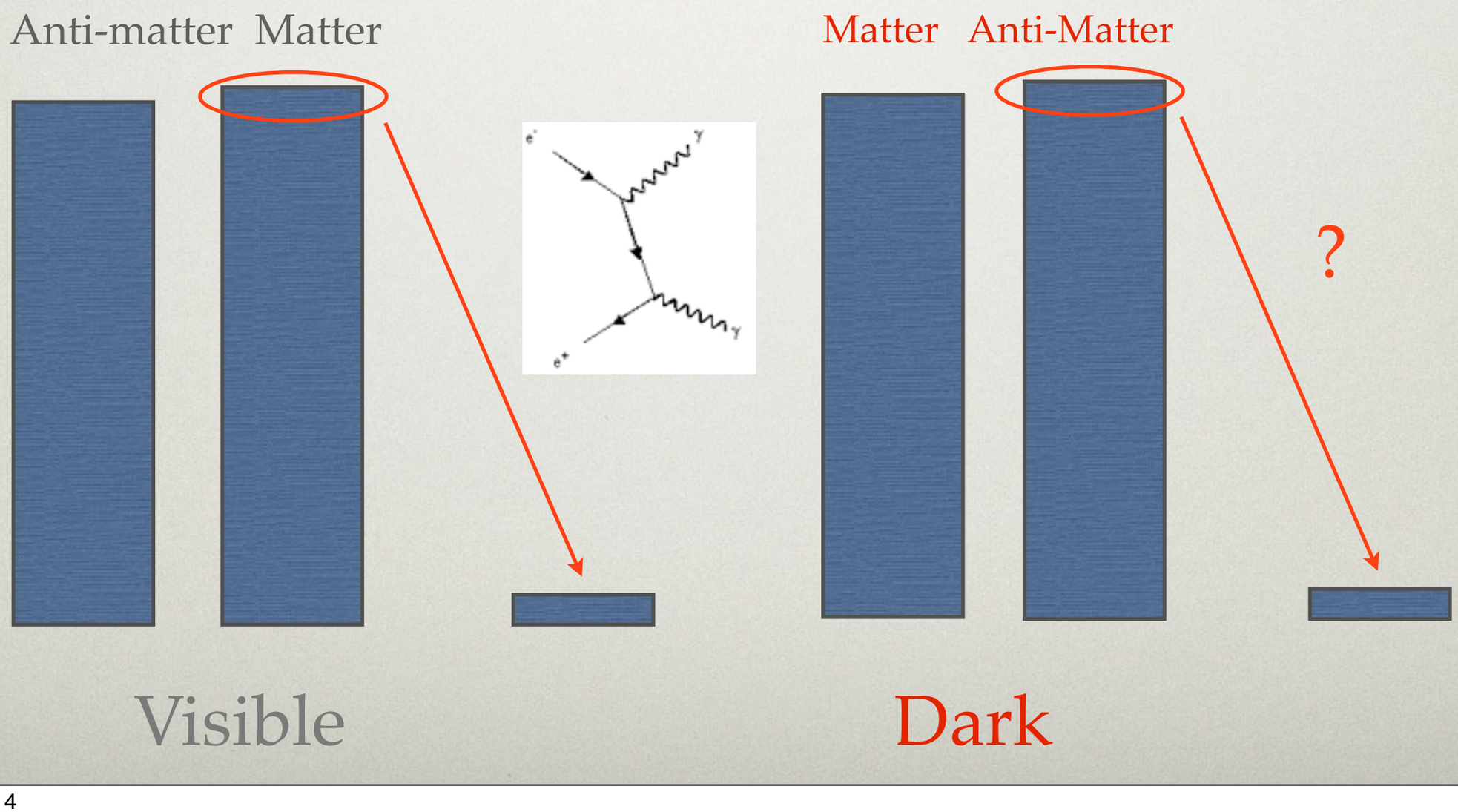
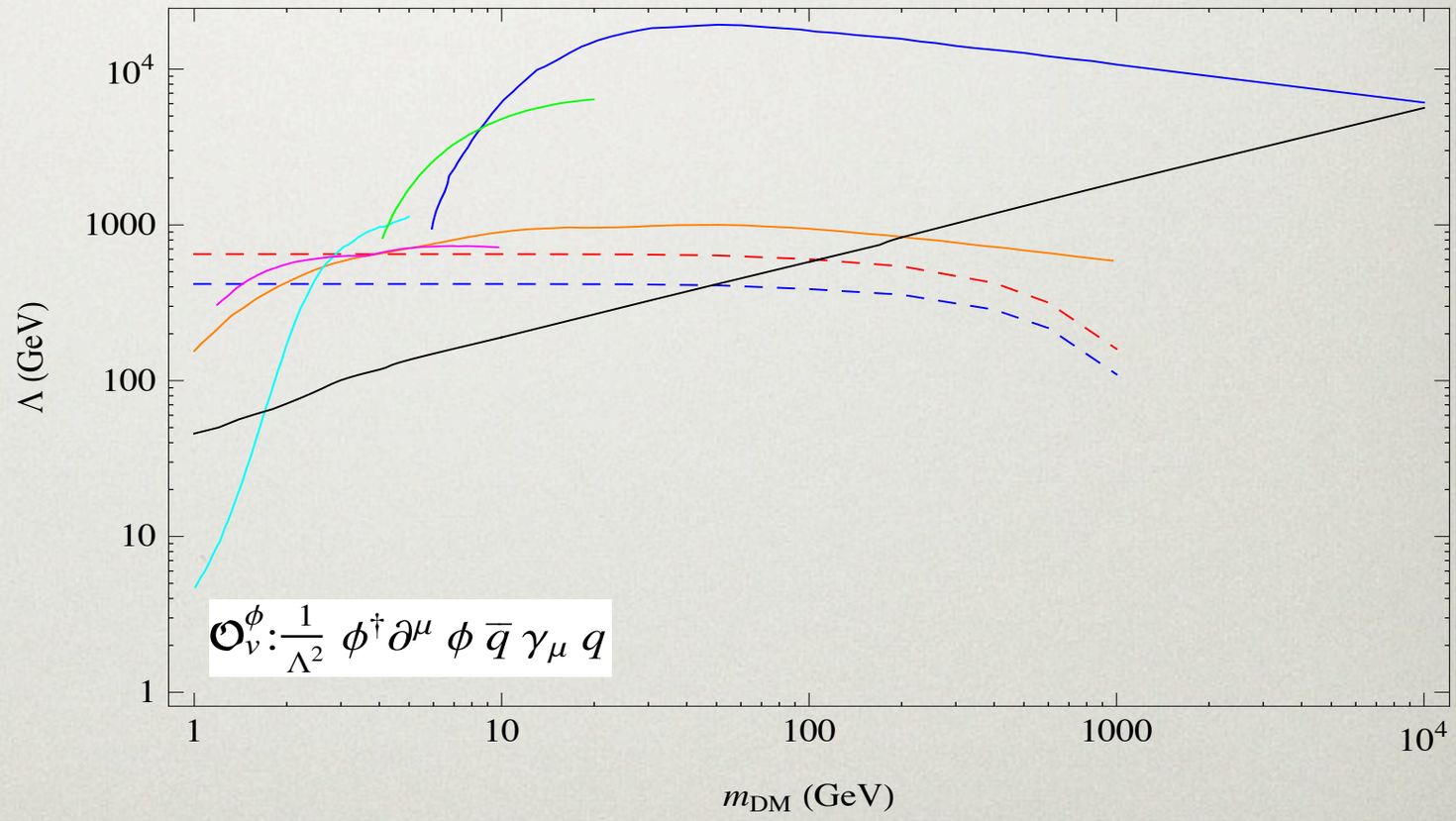


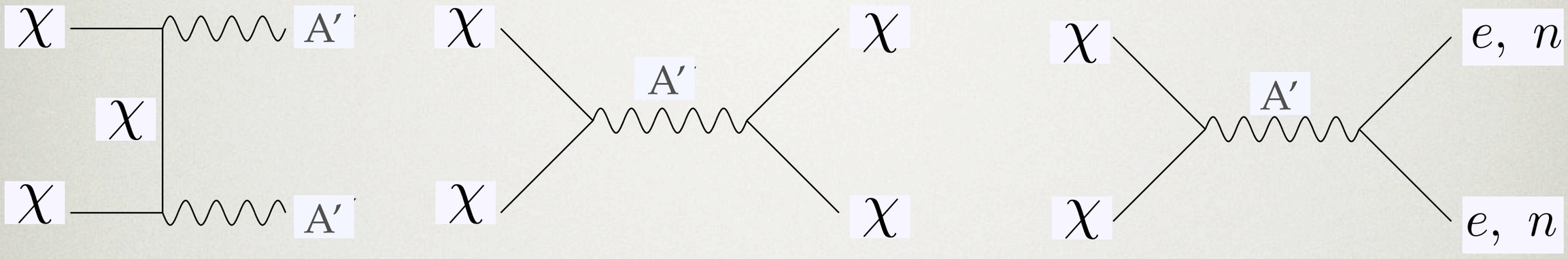
Annihilating through weak scale states ...

- doesn't really work ....

March-Russell
et al 1203.4854

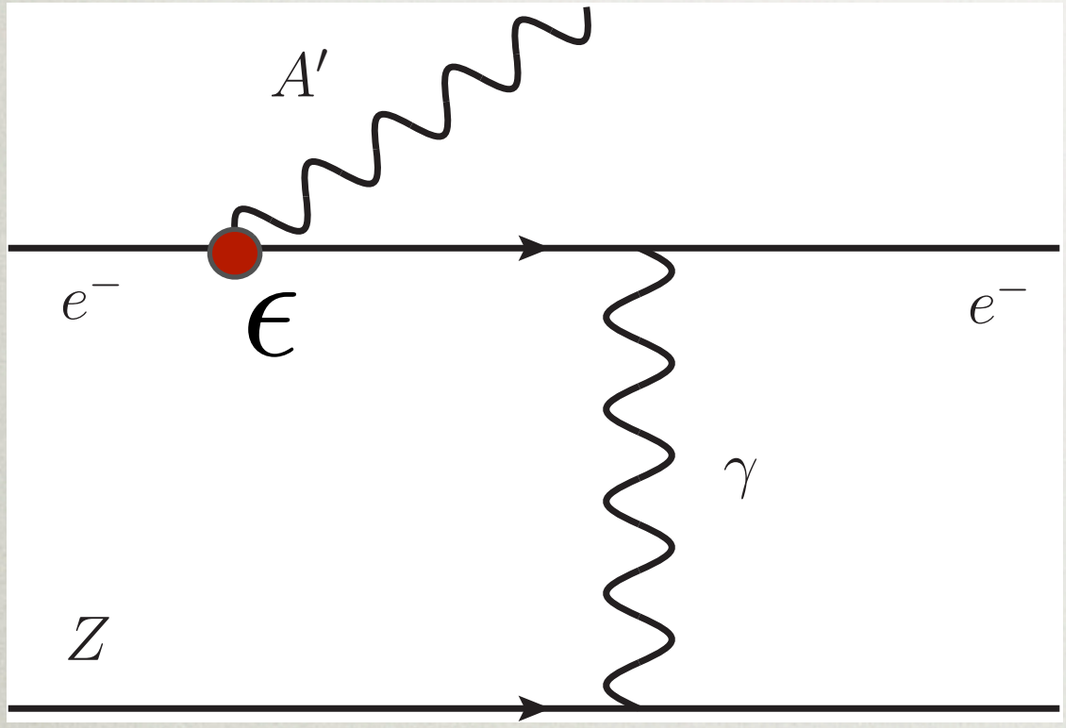


Dark Forces and DM Interactions

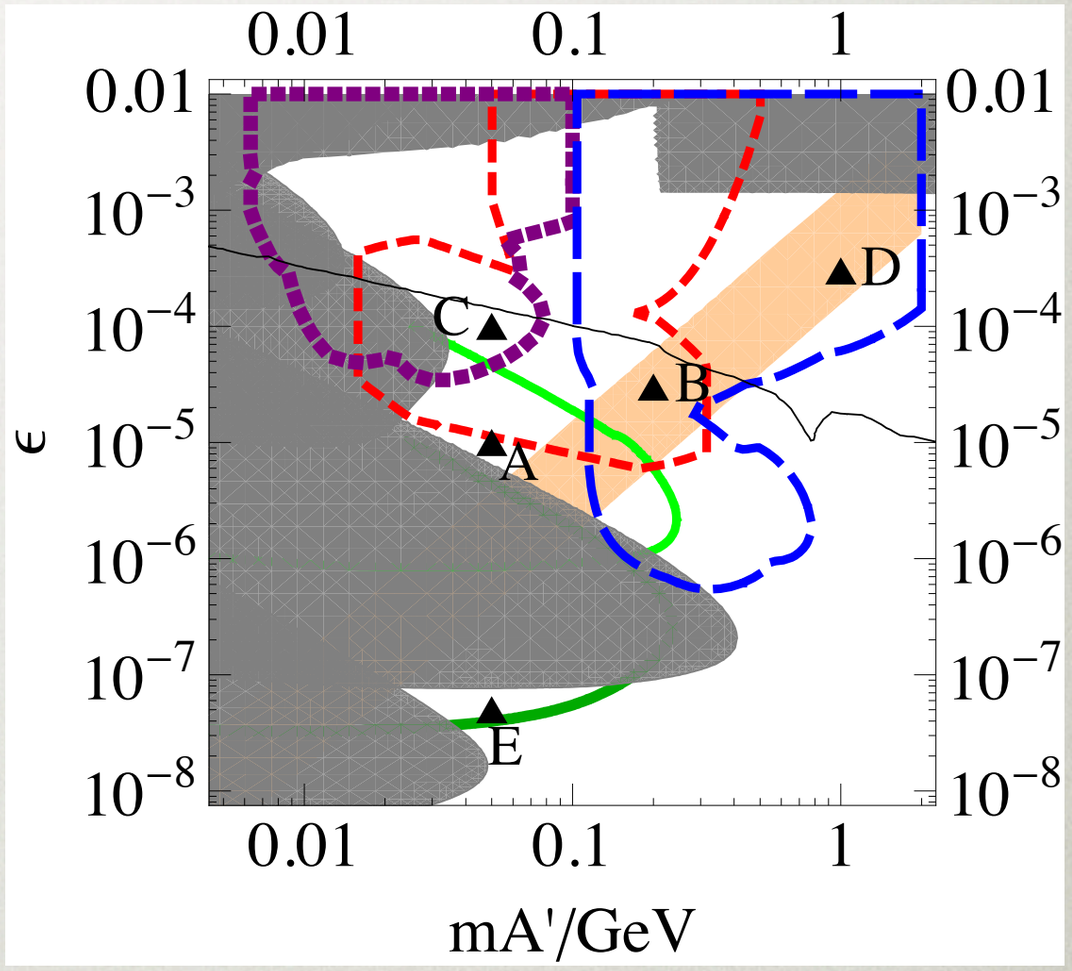


- Dark Forces Very Important for Asymmetric Dark Matter!
- May also be important for structure of DM halos
- May be important for DM direct detection and collider searches

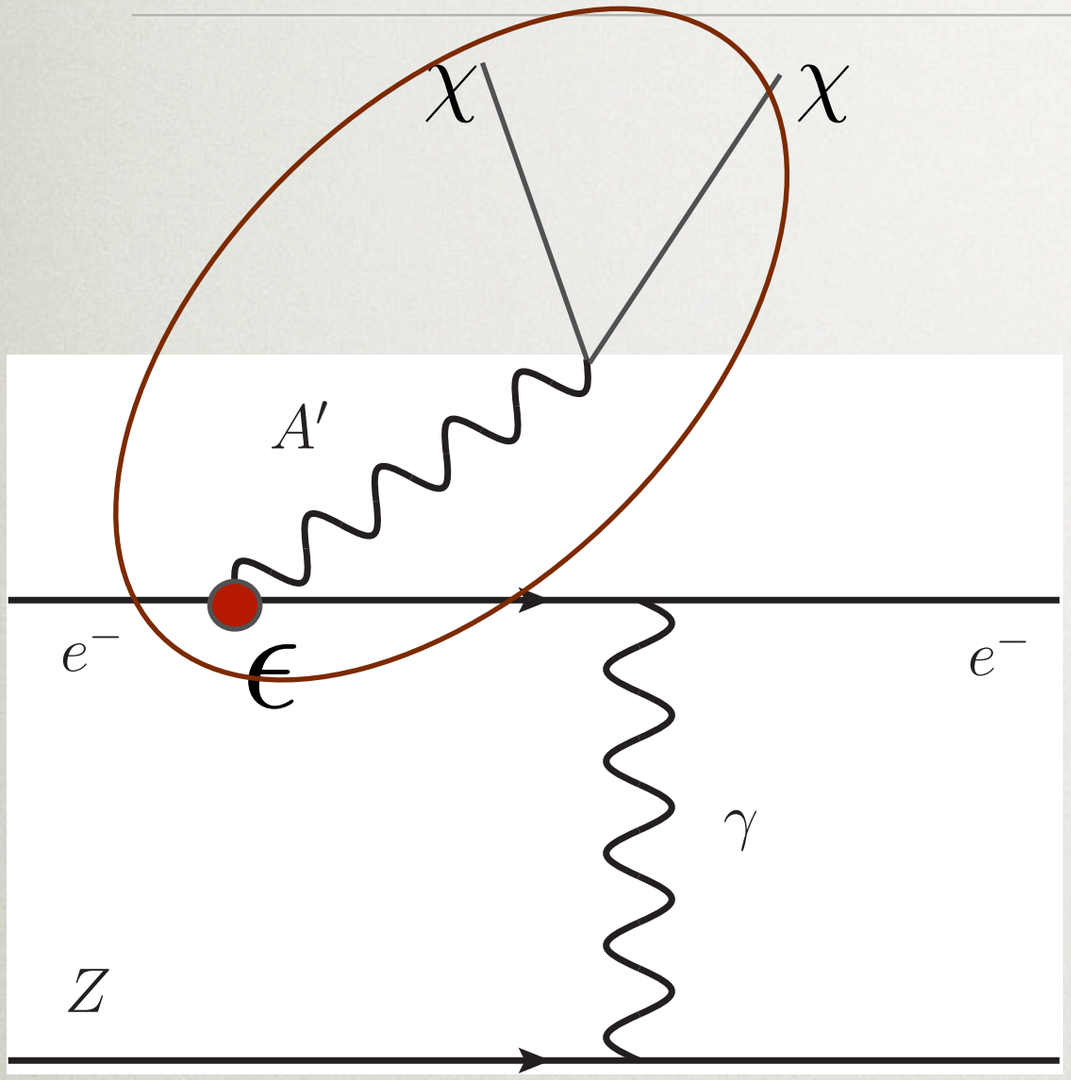
Low Energy Accelerator Constraints



Bjorken, Essig, Schuster, Toro



Translate to Direct Detection



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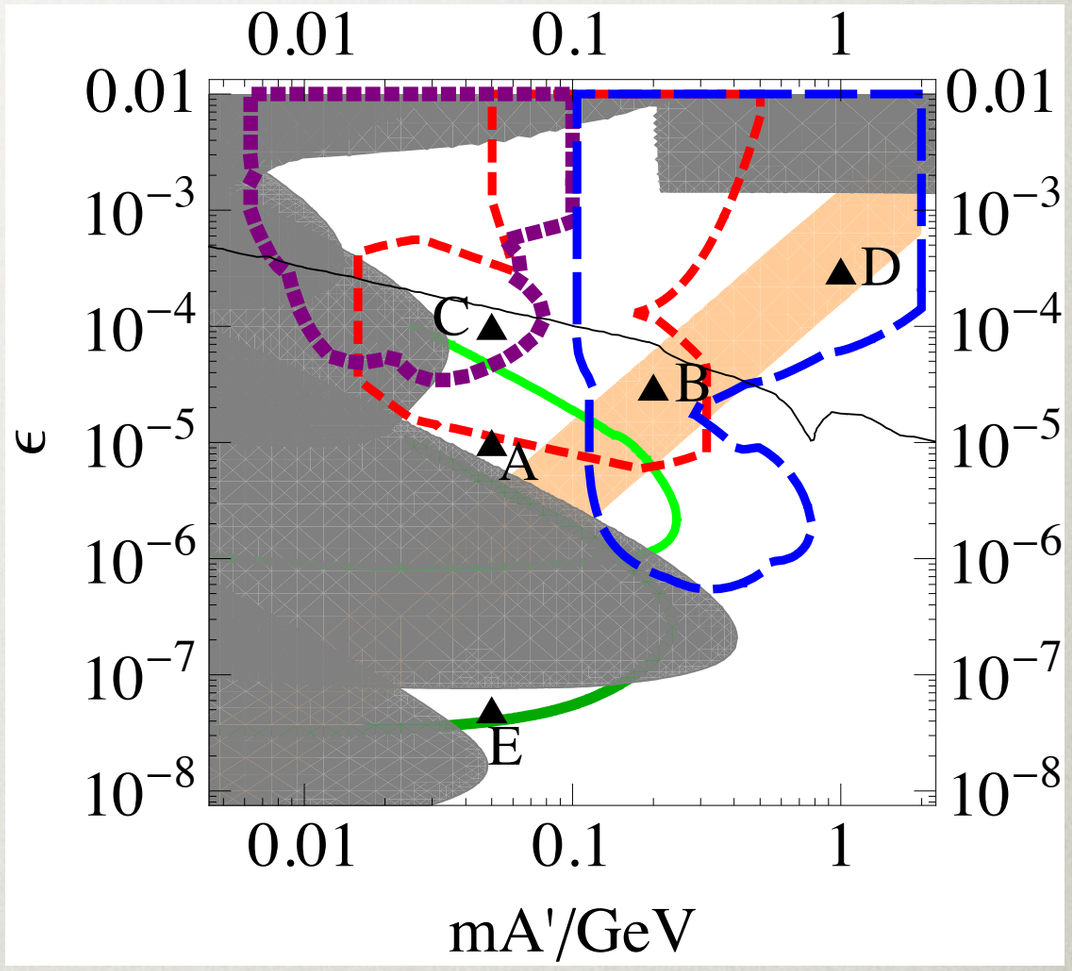

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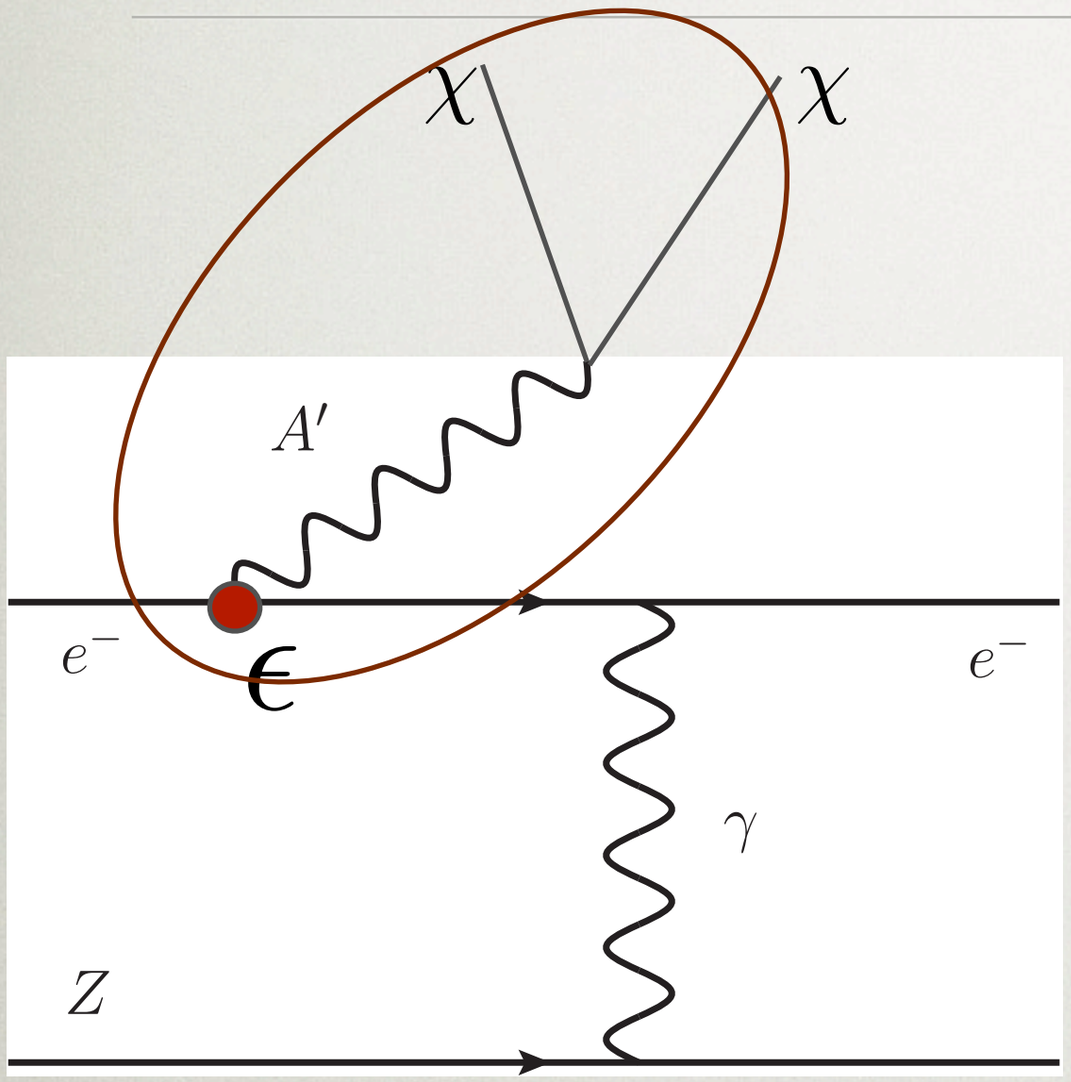


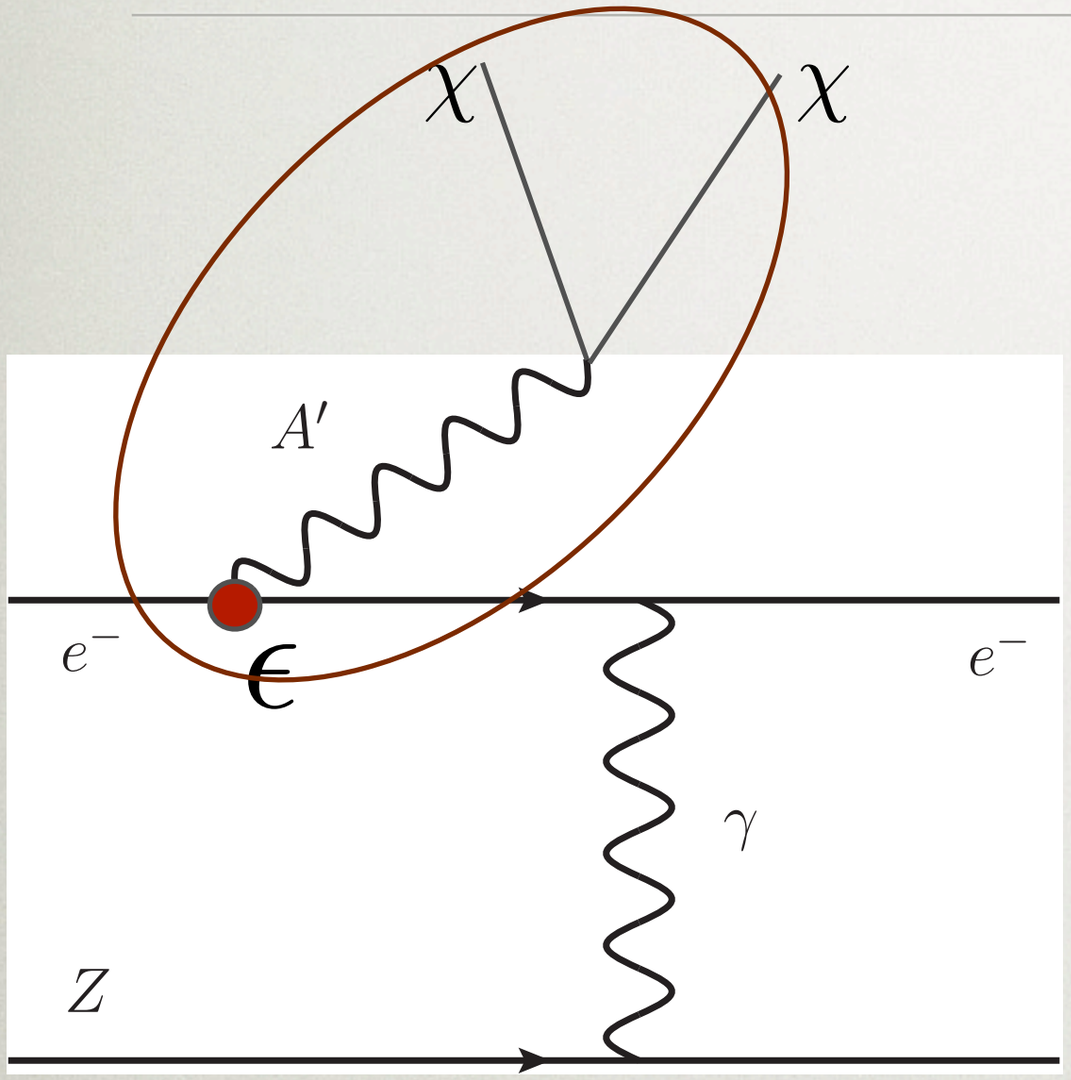
Ingredients:

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

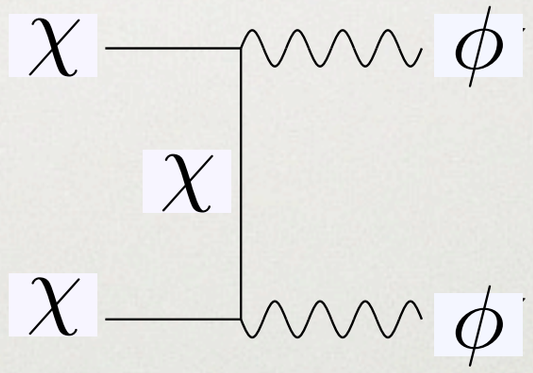
Constrained by HPS

Other complementary searches for other two parameters?

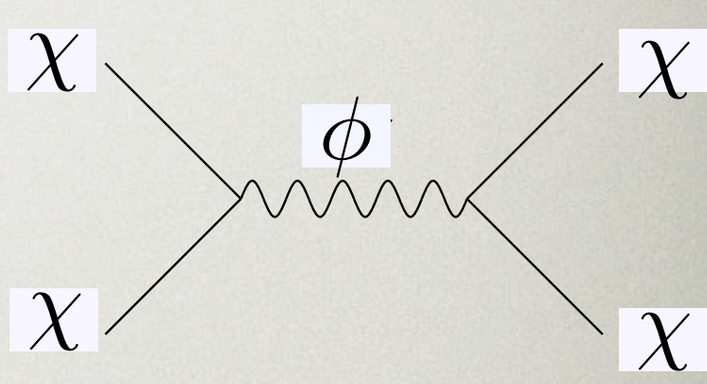
Translate to Direct Detection



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



DM Relic Abundance

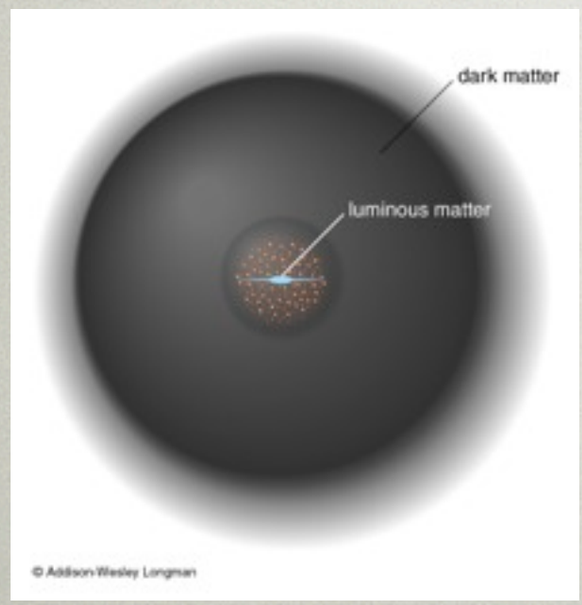


DM self-scattering

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

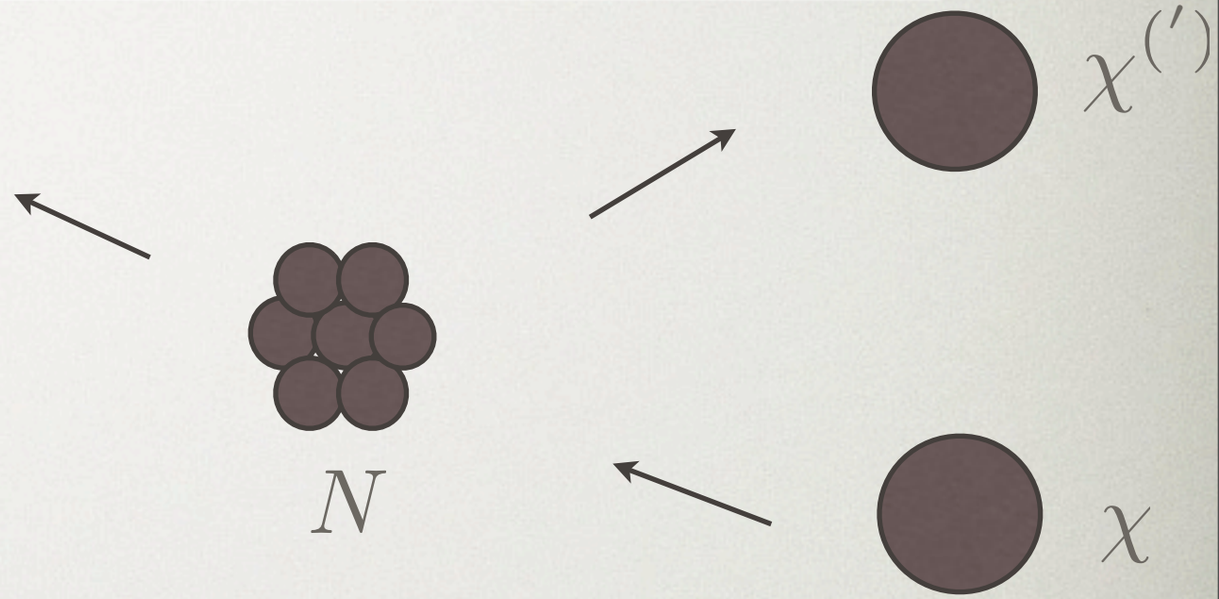


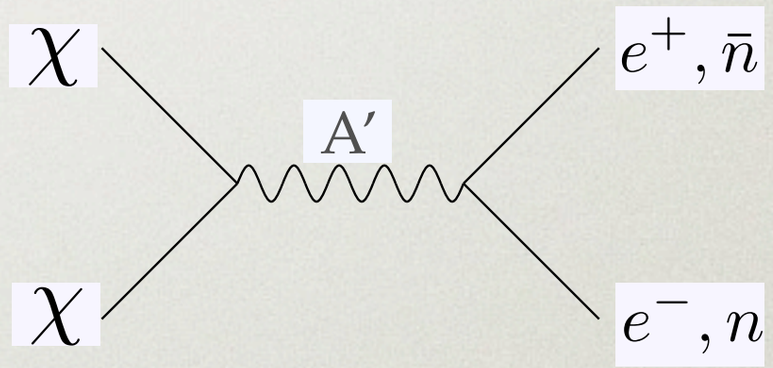
$$\sigma_{\chi\chi} \approx \frac{g_\chi^4 m_\chi^2}{4\pi m_{A'}^4} \lesssim 4.4 \times 10^{-27}\ \mathrm{cm}^2 \left(\frac{m_\chi}{1\ \mathrm{GeV}}\right)$$

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



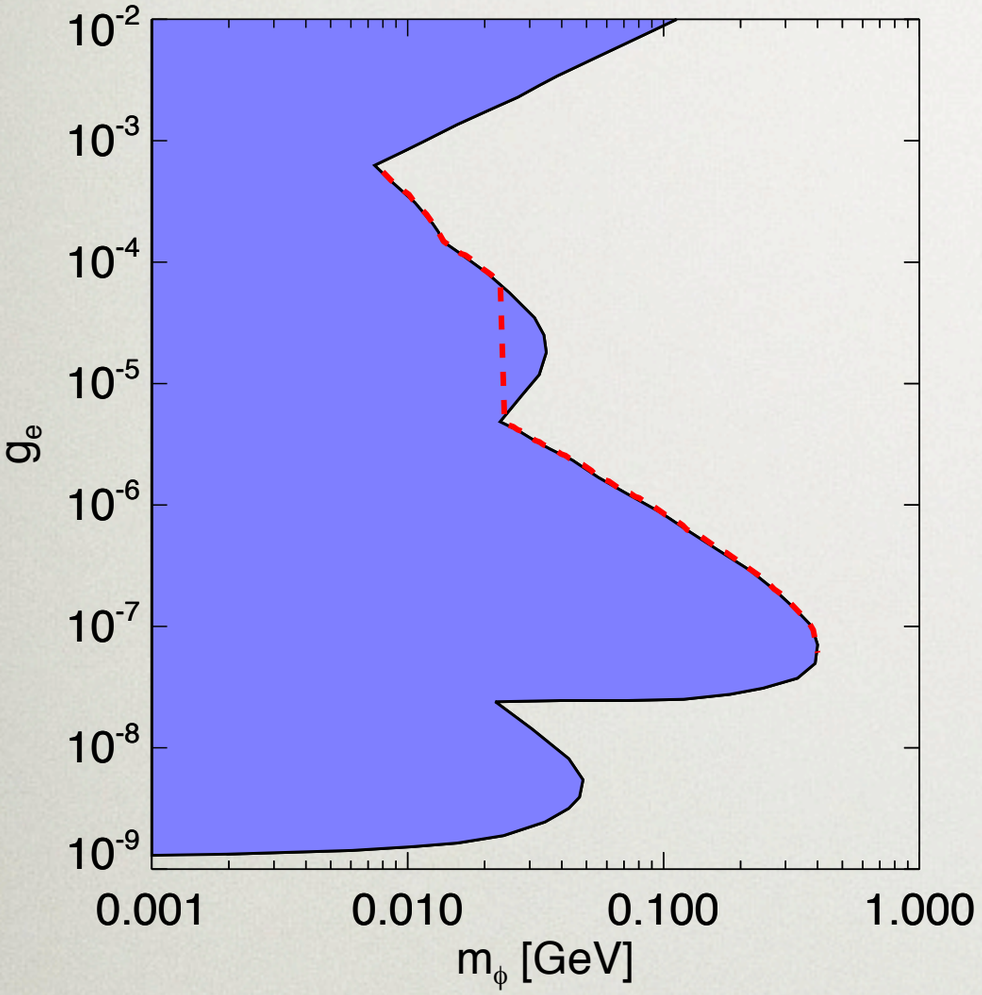


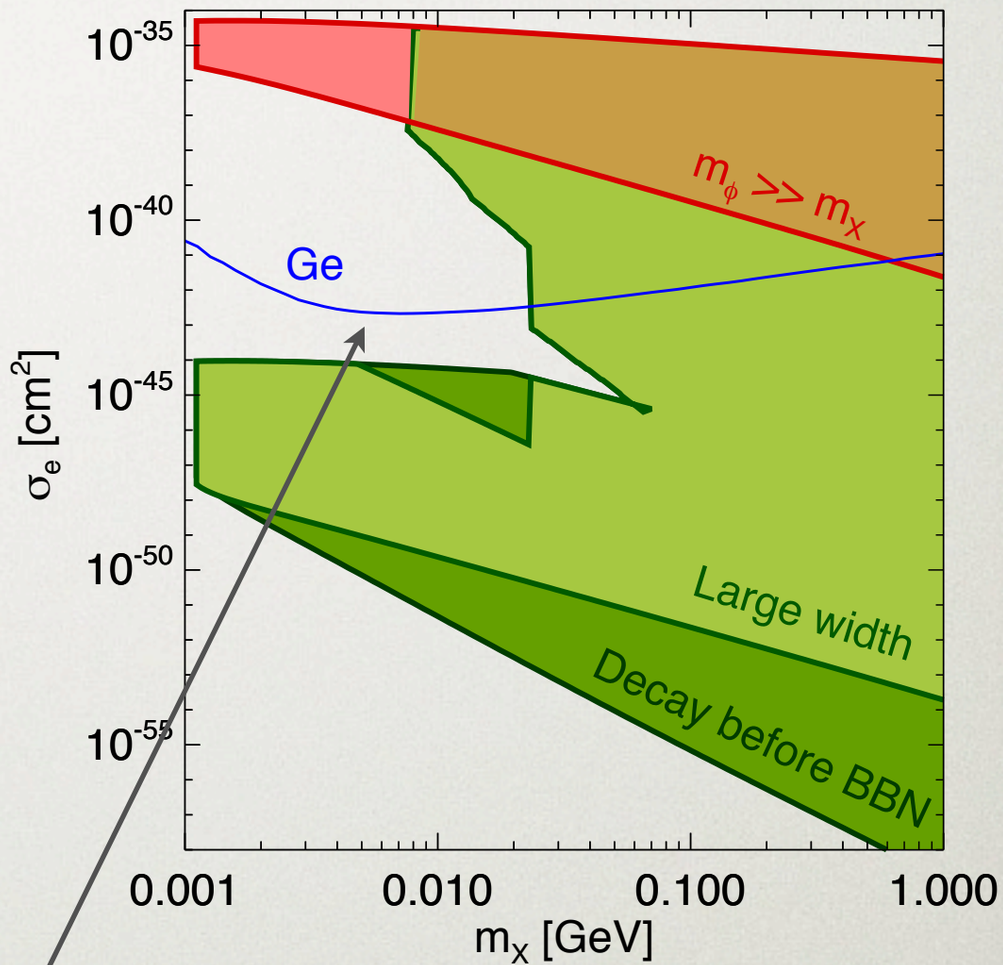
Constrained by halo shapes

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

Constrained by heavy photon search

Map into Direct Detection Plane





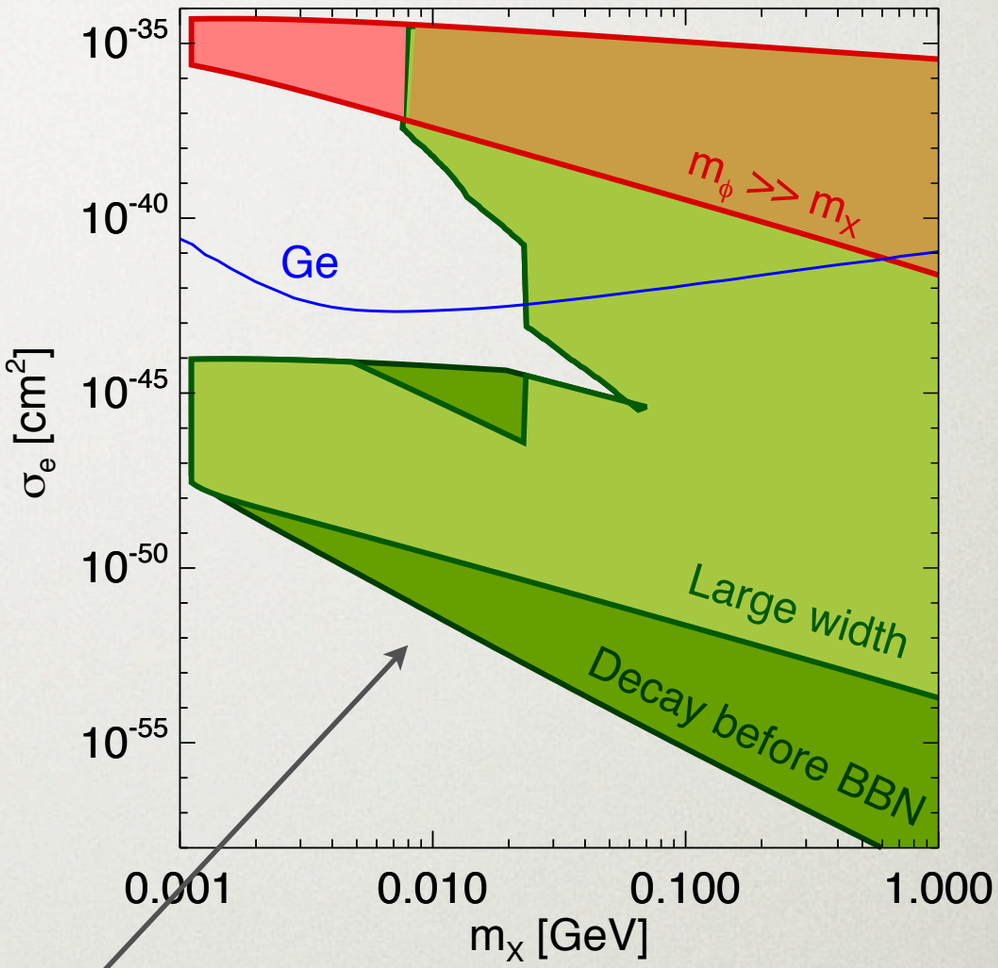
Lin, Yu, KZ 1111.0293

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?



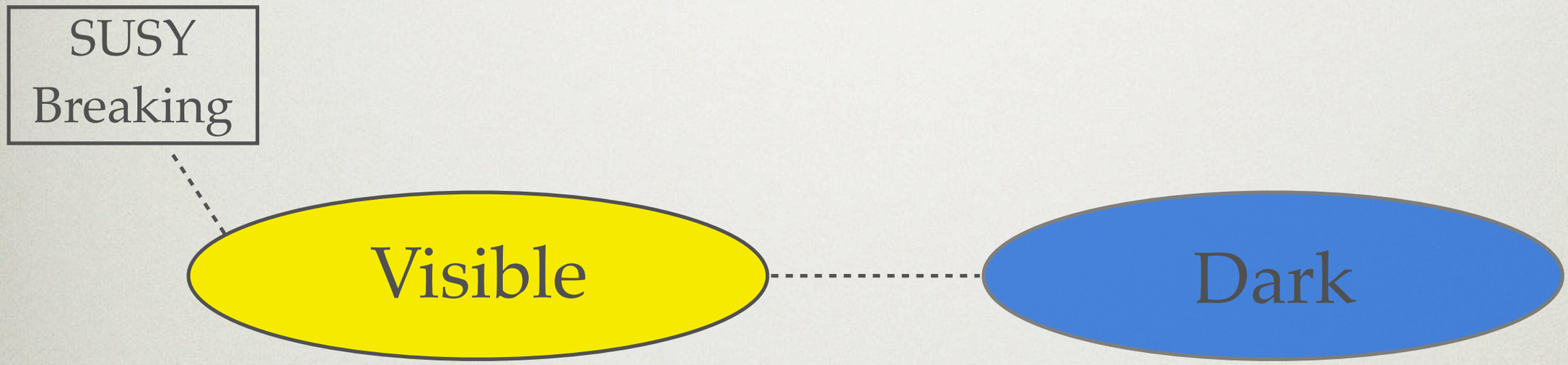
Lin, Yu, KZ 1111.0293

Require A′ to decay before BBN

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

Particular Models Can be MUCH More Predictive!

- Goal: explain why GeV? Dynamically generate DM mass



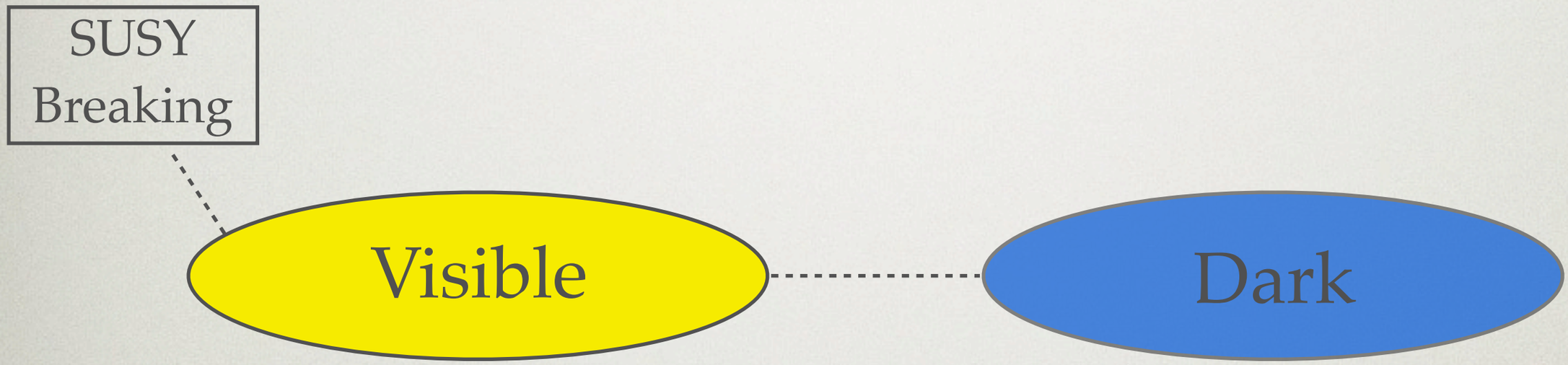
Electroweak scale

Smaller than electroweak scale

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

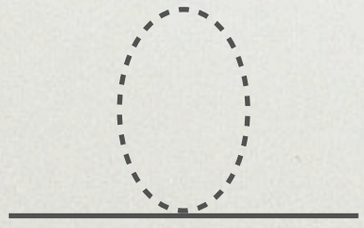
Particular Models Can be MUCH More Predictive!

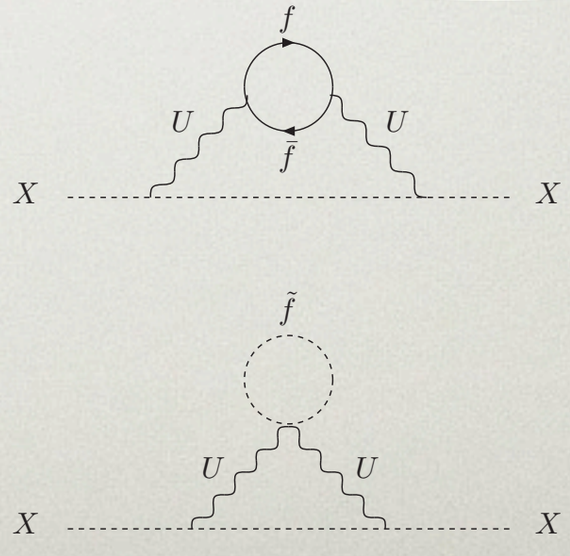
- Goal: explain why GeV? Dynamically generate DM mass



Yukawa

$$m_X^2 \simeq \frac{y^2 m_{SUSY}^2}{16\pi^2}$$





Gauge

$$m_X^2 \simeq \frac{g_{vis}^2 g_X^2 m_{SUSY}^2}{16\pi^2}$$

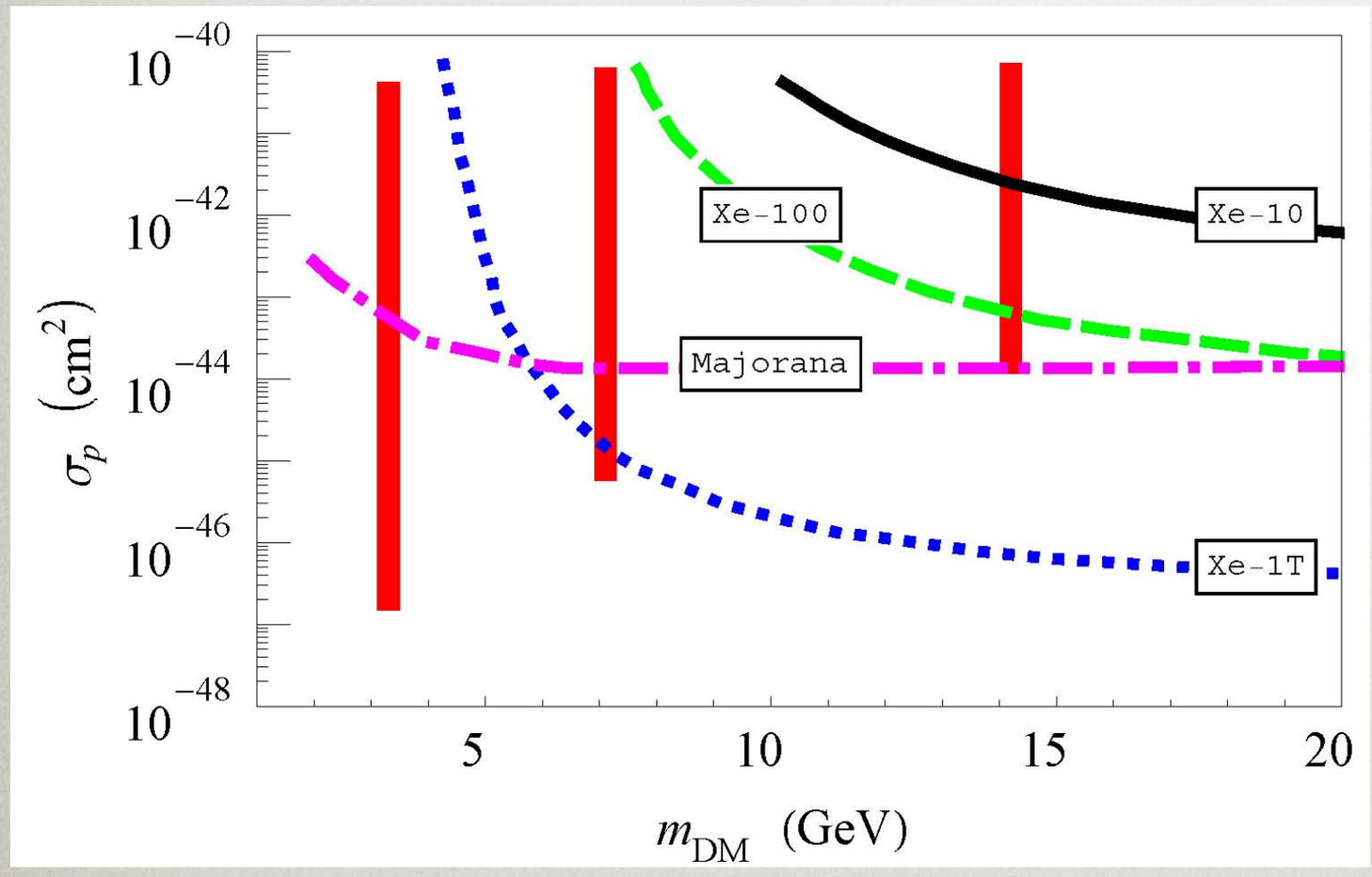
$$\sigma v \simeq \frac{g_{vis}^2 g_X^2}{16\pi m_X^2}$$

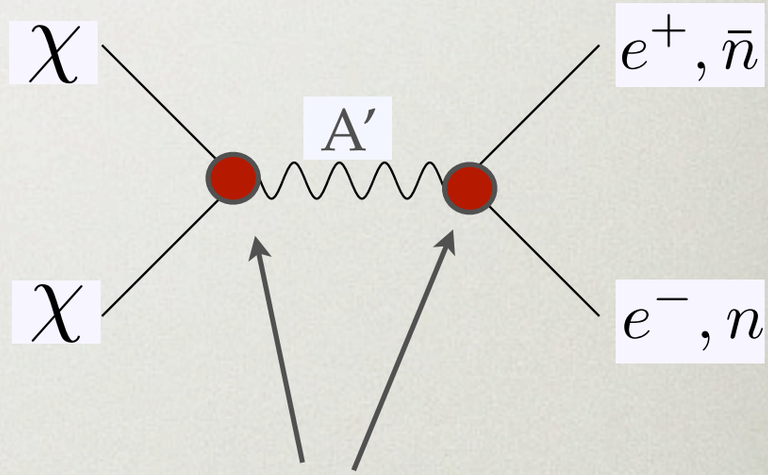
Nelson, Weiner '04, KZ '08

Hooper, KZ '08, Feng, Kumar '08, Arkani-Hamed, Finkbeiner, Slatyer, Weiner '08

Particular Models Can be MUCH More Predictive!

- Predict DD cross-section for Asymmetric Dark Matter!

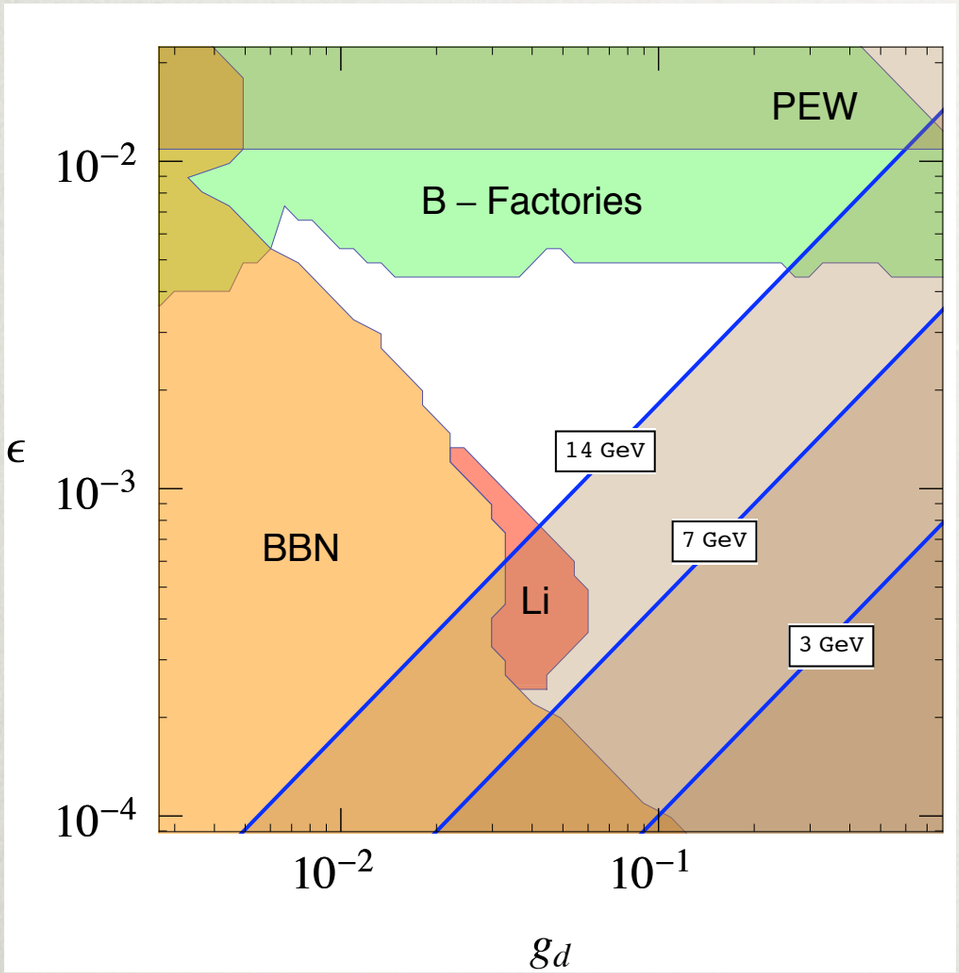




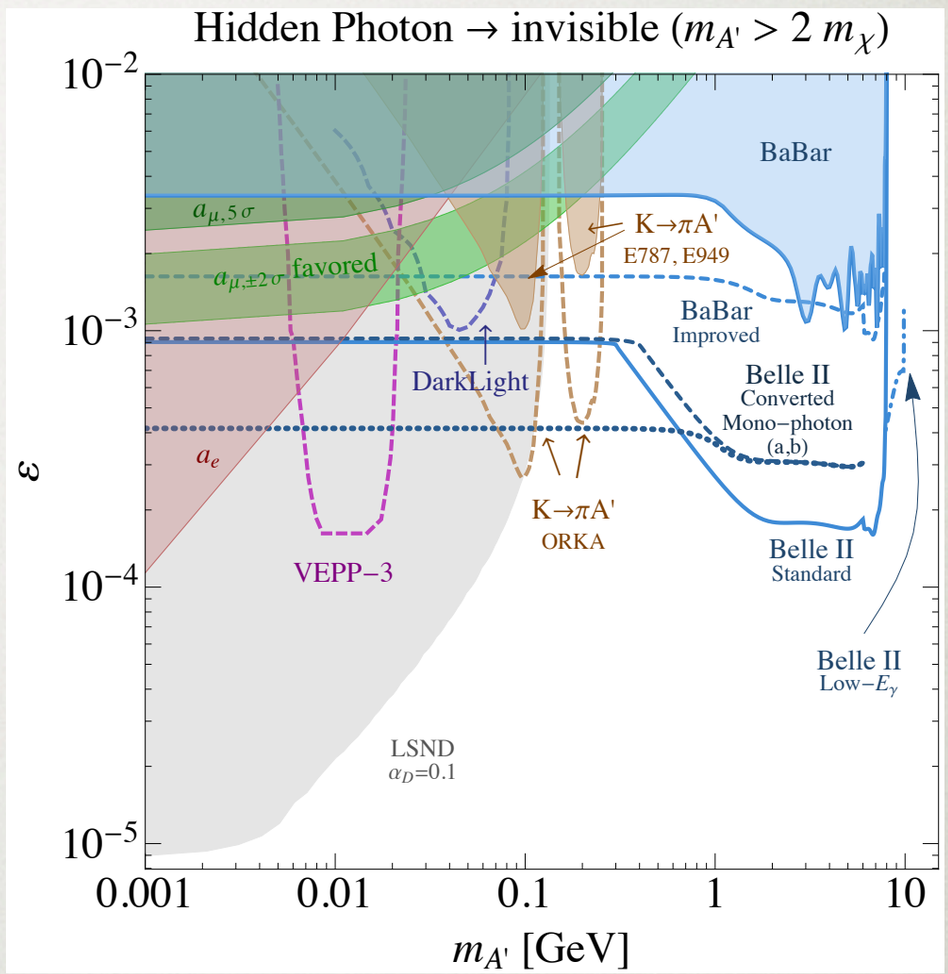
Coupling predicted by setting mass scale in DM sector!

Cohen, Phalen, Pierce, KZ 1005.1655

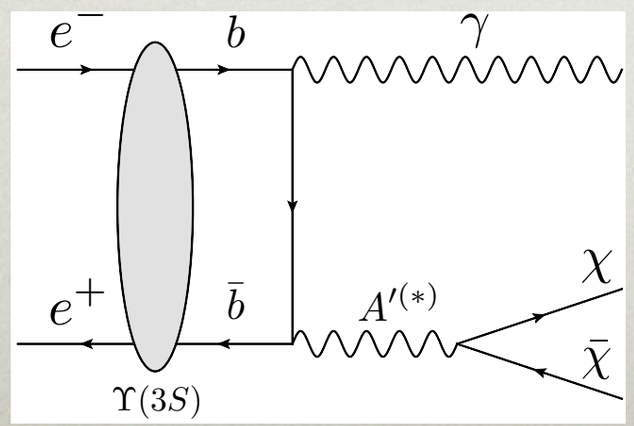
Also Probed by Intensity Experiments

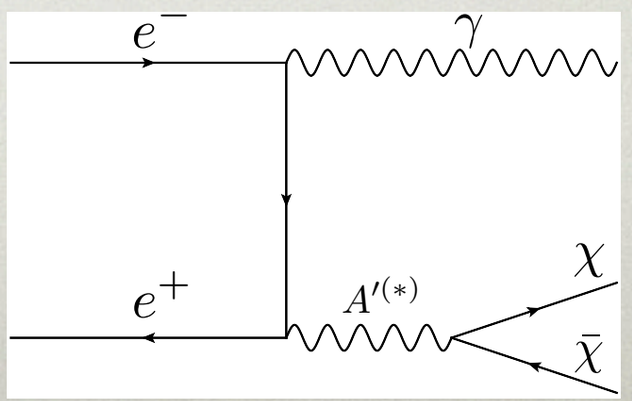


Cohen, Phalen, Pierce, KZ 1005.1655



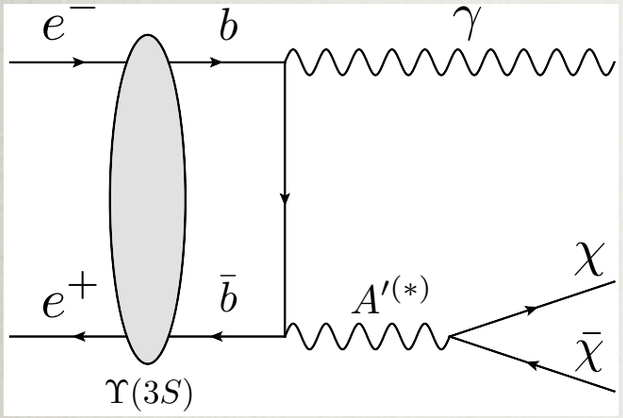
Essig, Mardon, Papucci, Volansky, Zhong 1309.5084

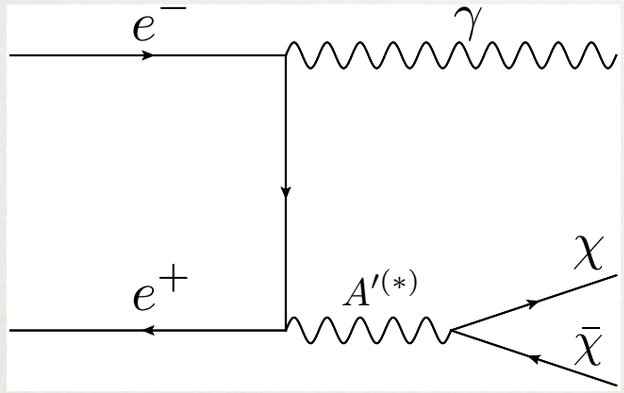


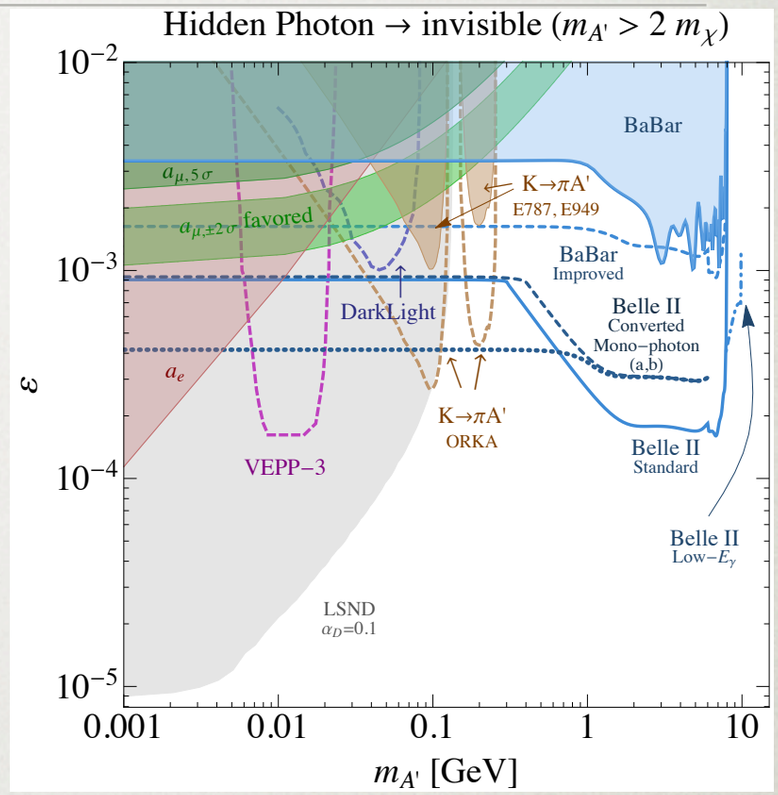


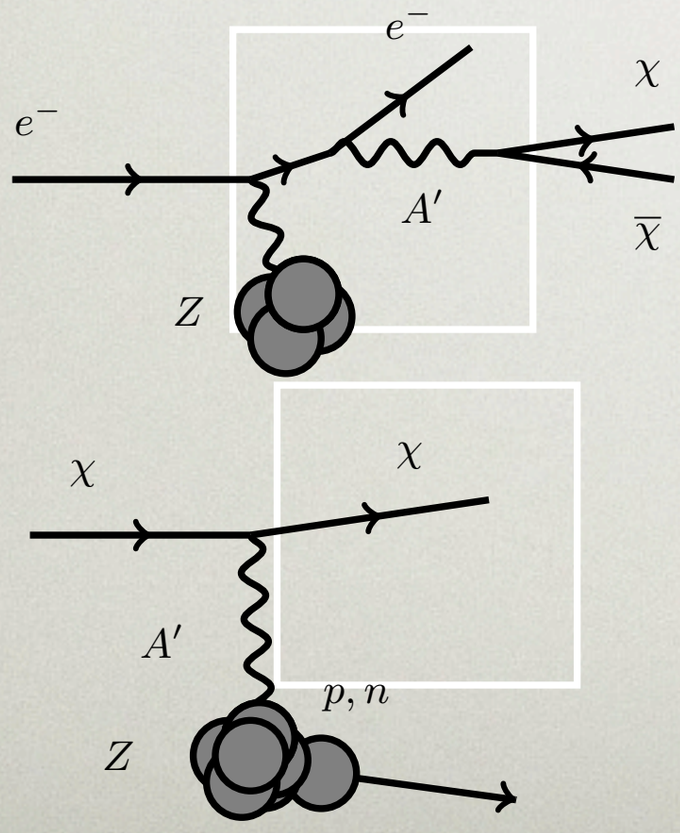
Low Energy Accelerator Constraints

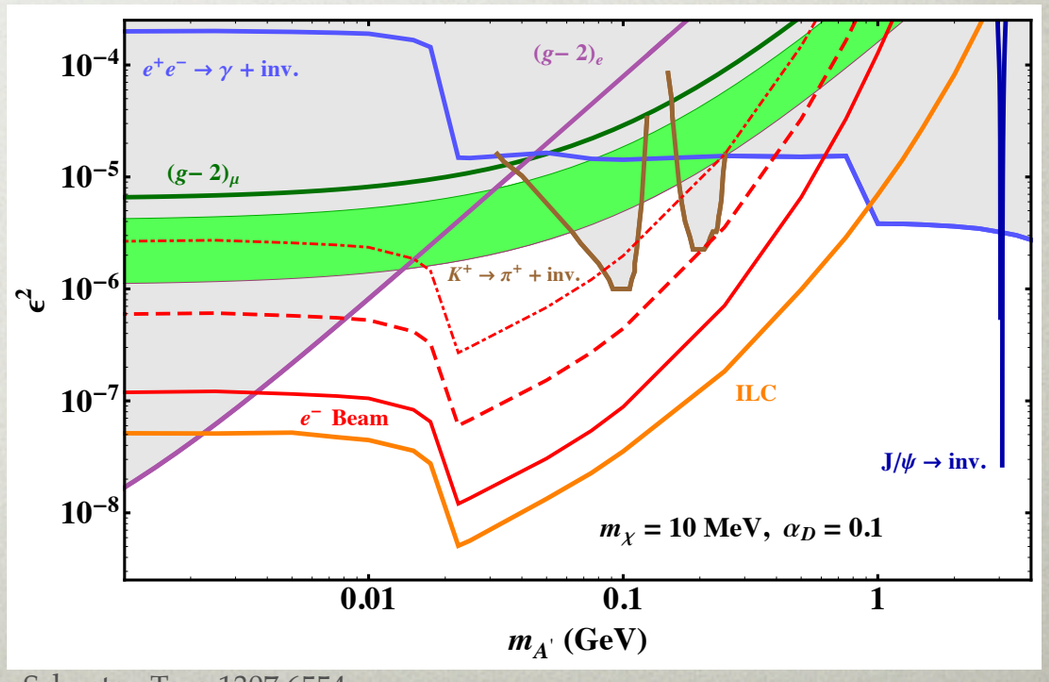
Essig, Mardon, Papucci, Volansky, Zhong





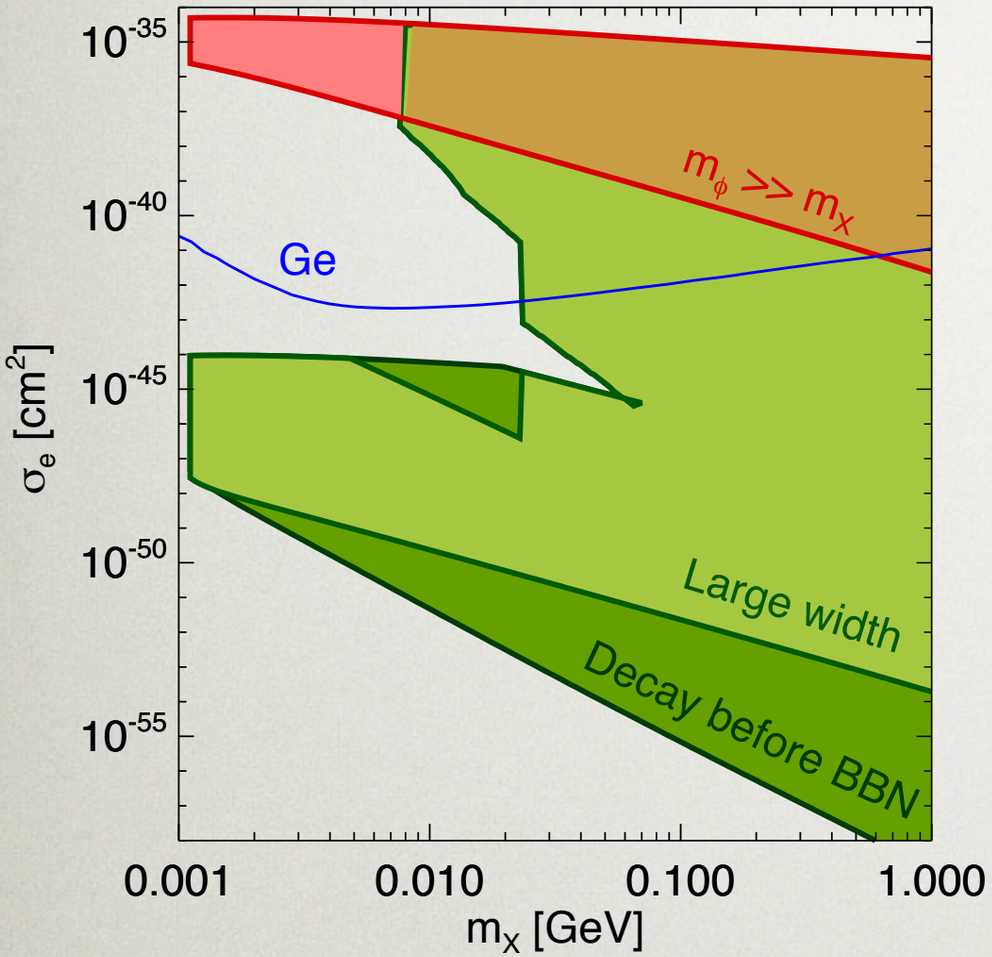




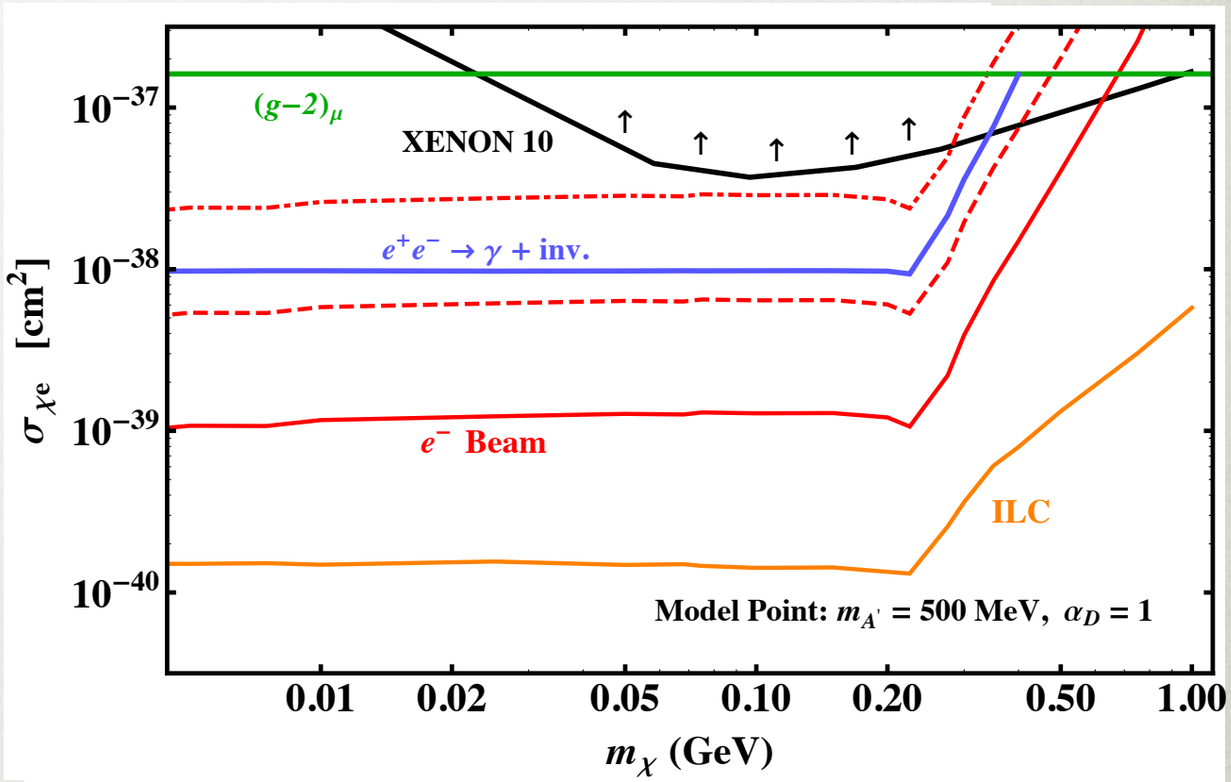


Izaguirre, Krnjaic, Schuster, Toro 1307.6554

Intensity Experiments Complement ....



Lin, Yu, KZ 1111.0293

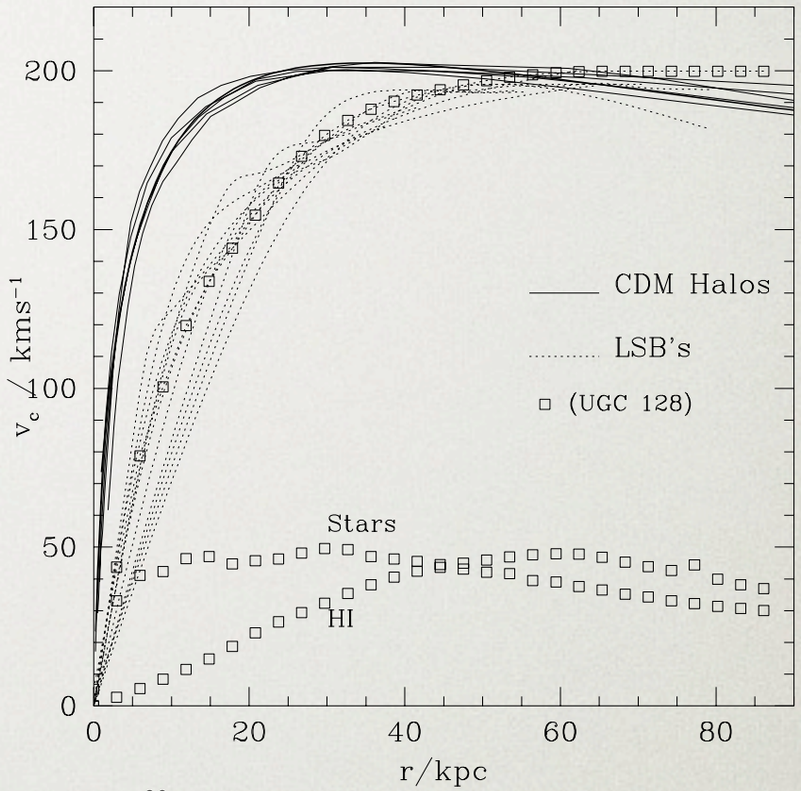


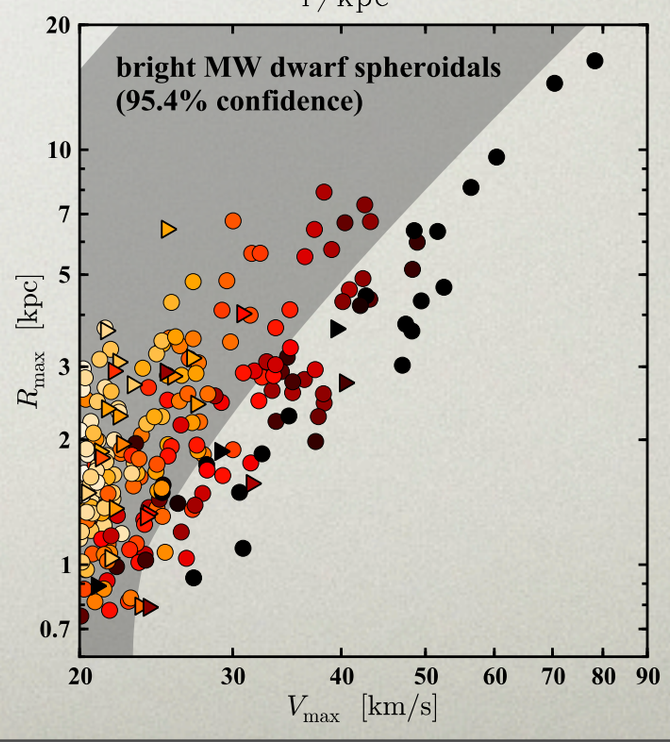
Izaguirre, Krnjaic, Schuster, Toro 1307.6554

These Dark Forces May Solve ...

- the core/cusp problem of dark matter halos (newer incarnation: "too big to fail" problem)

Moore, Quinn, Governato, Stadel, Lake



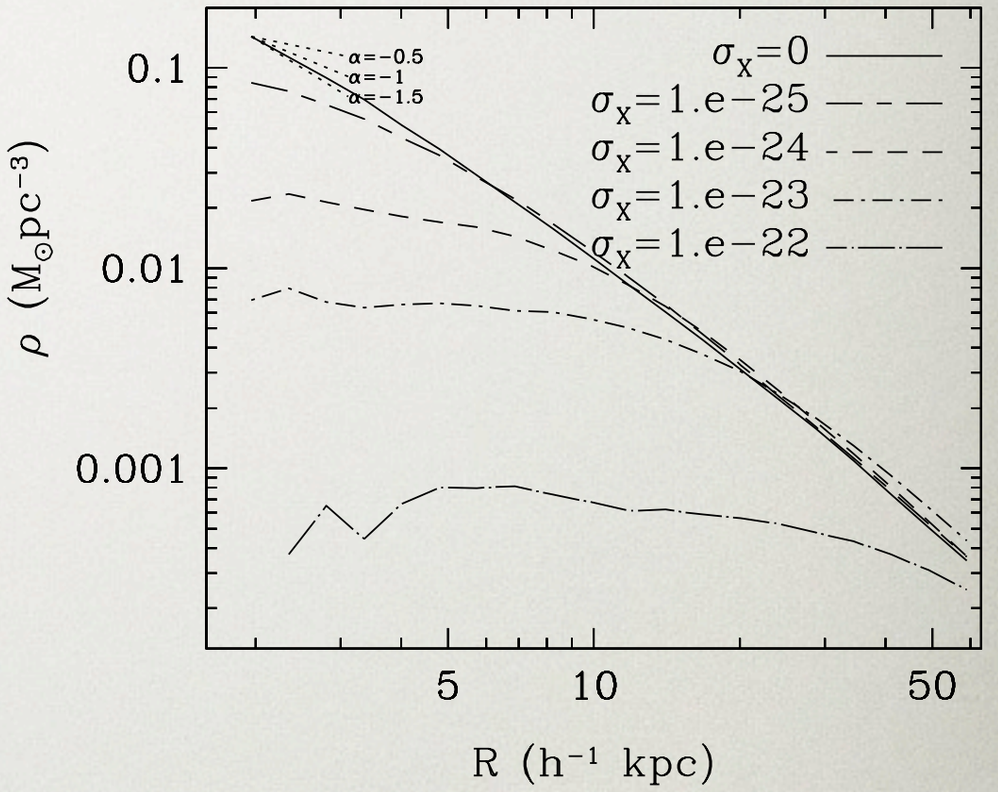


Boylan-Kolchin et al, 1103.0007

DM Interactions and DM Halos

- Dark matter self-interactions randomize momenta and isotropize halos
- Lead to lower density dark matter halo cores
- Dark matter halos (including baryon poor dwarf galaxies) seem to have cores rather than cusps (still controversy as to cause)

Dave, Spergel, Steinhardt, Wandelt



Implies Dark Forces!

- Very **big** scattering cross-sections

$$\sigma/m_X \sim 0.1\ \mathrm{cm}^2/\mathrm{g} \simeq 0.2 \times 10^{-24}\ \mathrm{cm}^2/\ \mathrm{GeV} \quad (\sigma_{weak} \sim 10^{-39}\ \mathrm{cm}^2)$$

- Fits well with our new models of DM!

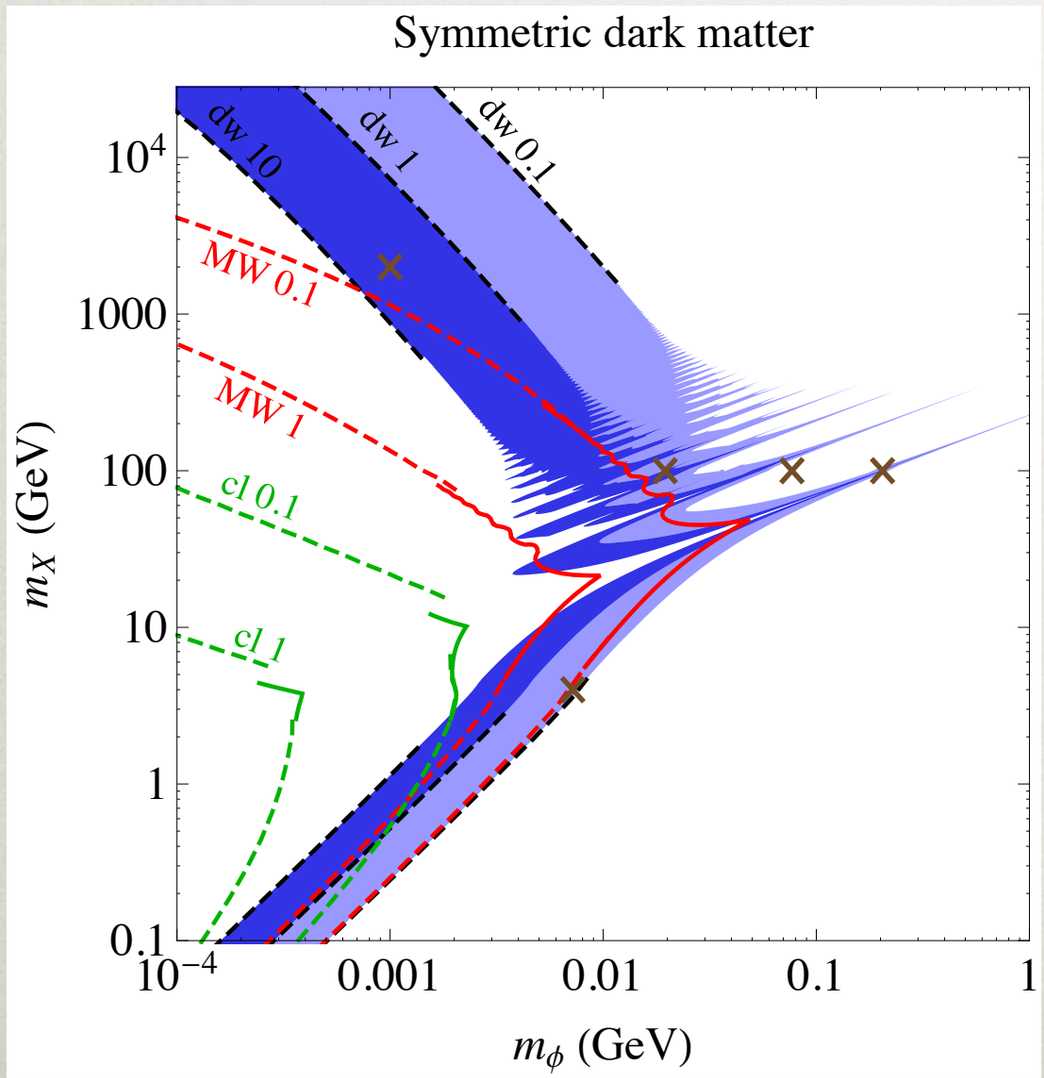
$$\sigma_T \approx 5 \times 10^{-23}\,\mathrm{cm}^2 \left(\frac{\alpha_X}{0.01}\right)^2 \left(\frac{m_X}{10\,\mathrm{GeV}}\right)^2 \left(\frac{10\,\mathrm{MeV}}{m_\phi}\right)^4$$

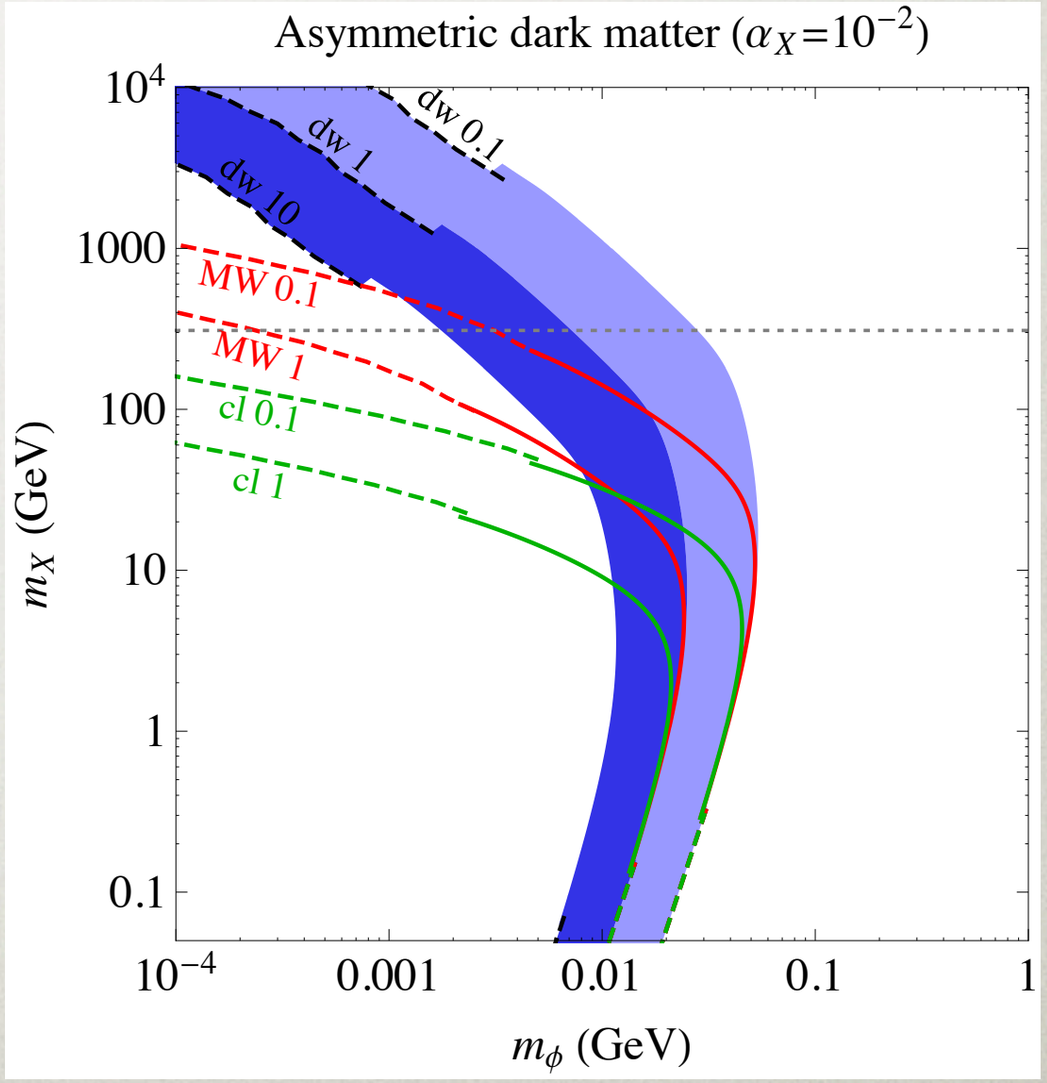
- Range of dynamics much bigger than previously thought
- Particle imprints on DM halos

Resonances are Generic for Thermal DM!

$$\langle \sigma v \rangle_{\rm ann} \approx \pi \alpha_X^2 / m_X^2$$

Tulin, Yu, KZ



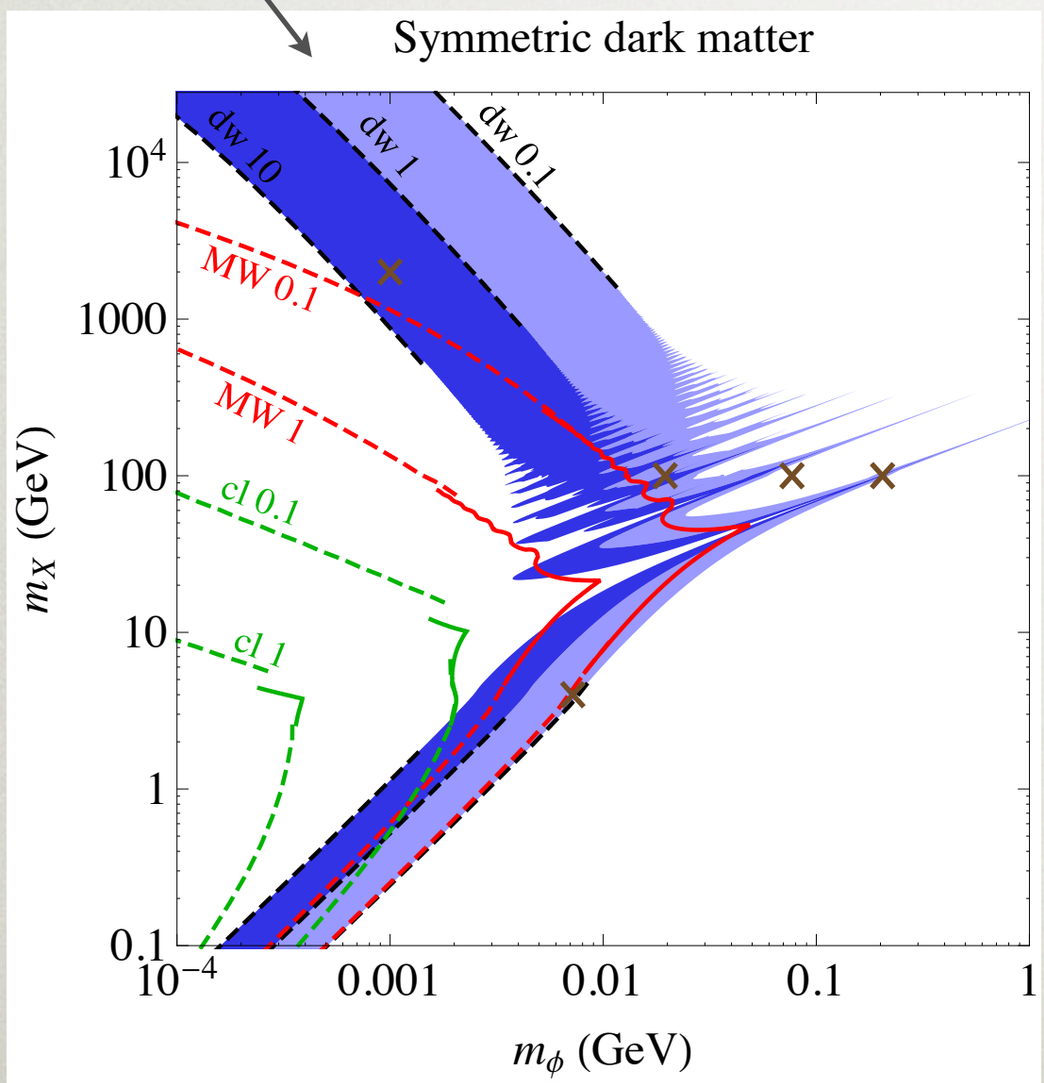


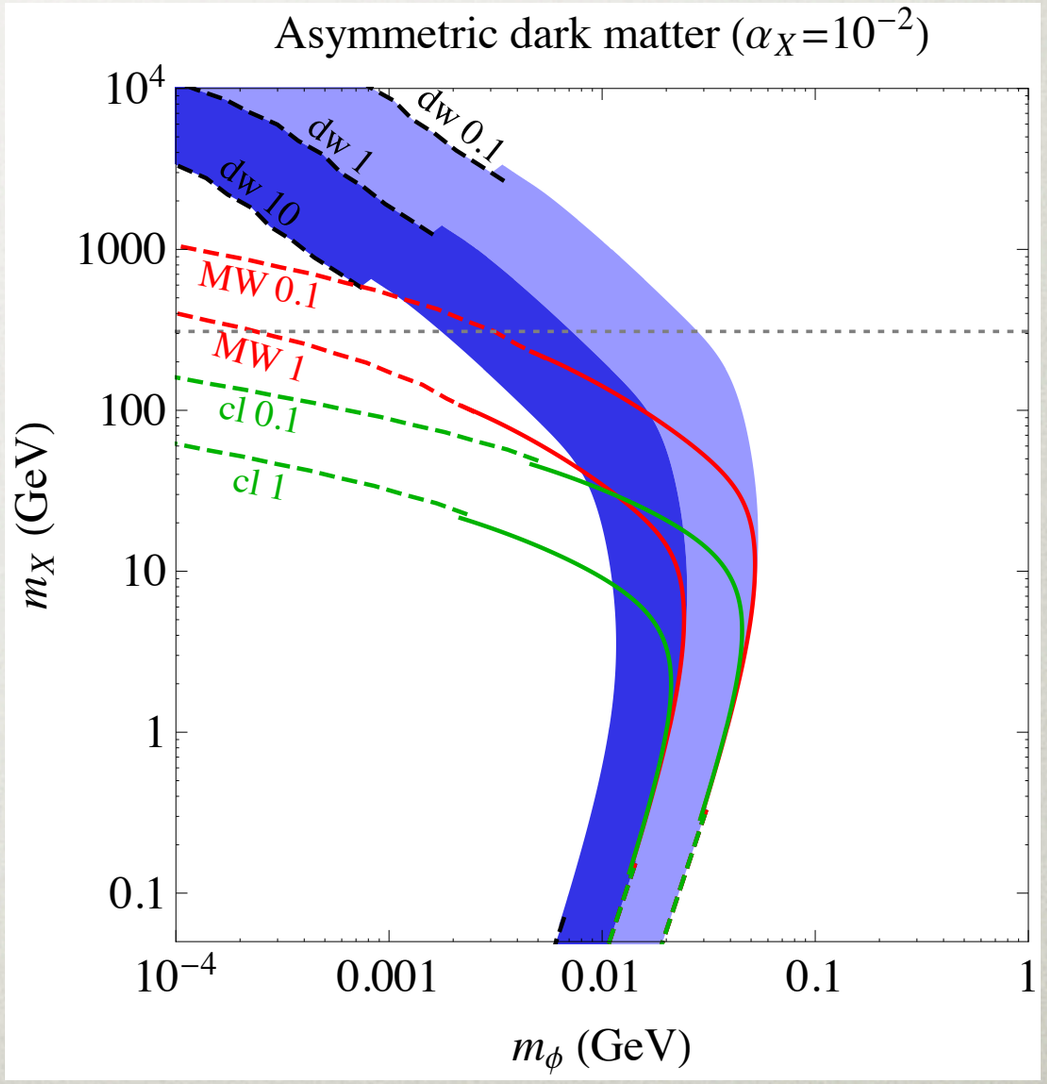
Resonances are Generic for Thermal DM!

Regions to solve dwarf structure

$$\langle \sigma v \rangle_{\rm ann} \approx \pi \alpha_X^2 / m_X^2$$

Tulin, Yu, KZ





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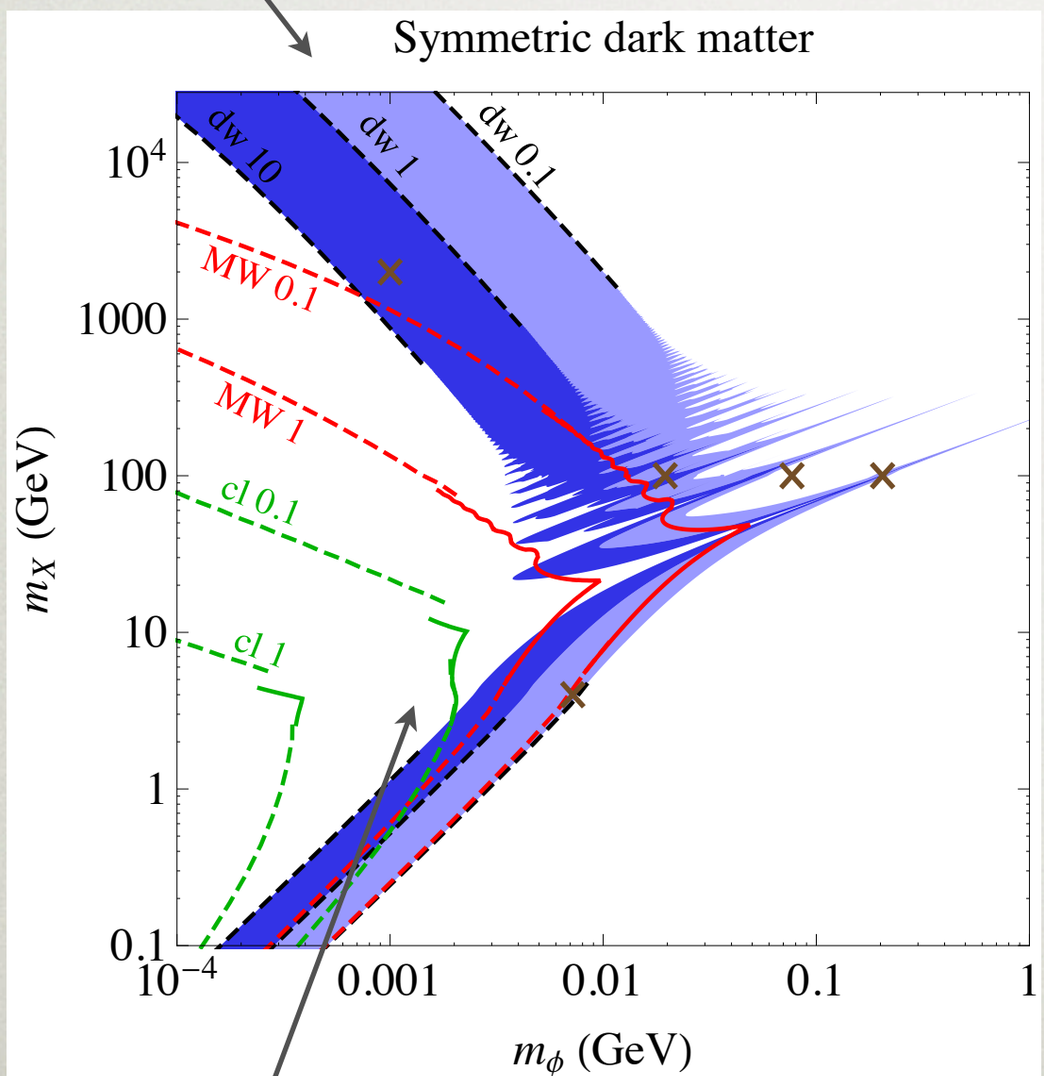
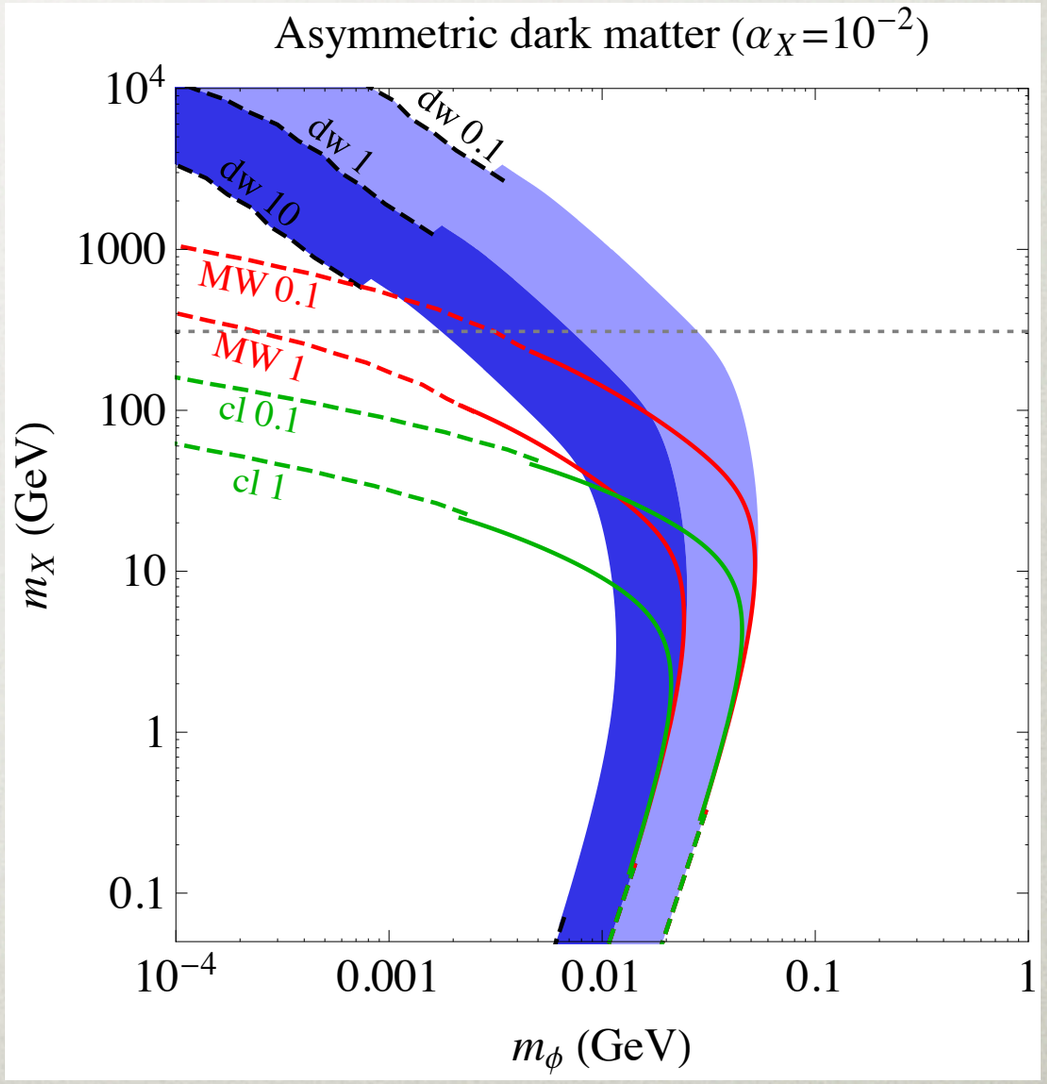
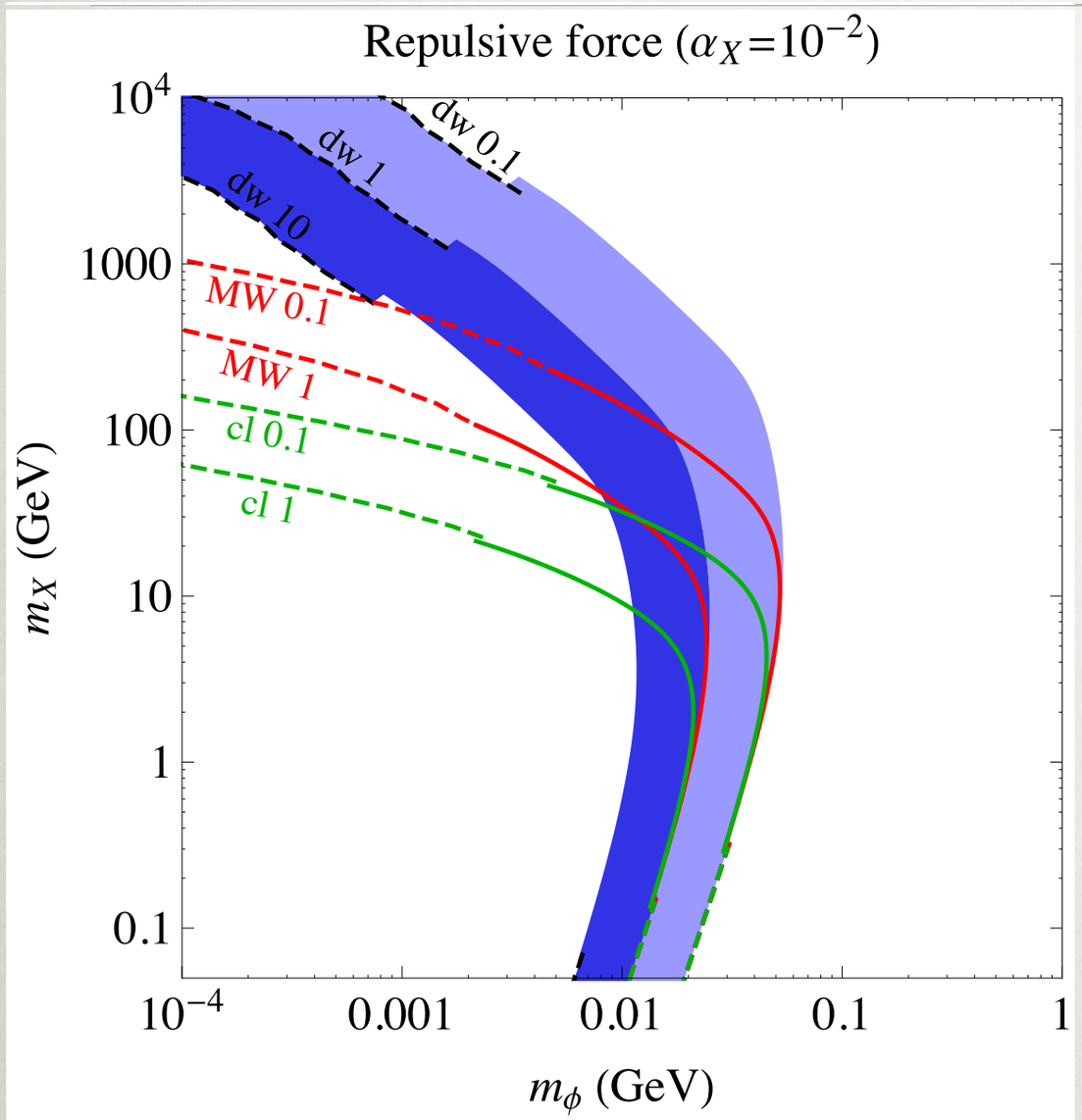
Tulin, Yu, KZ



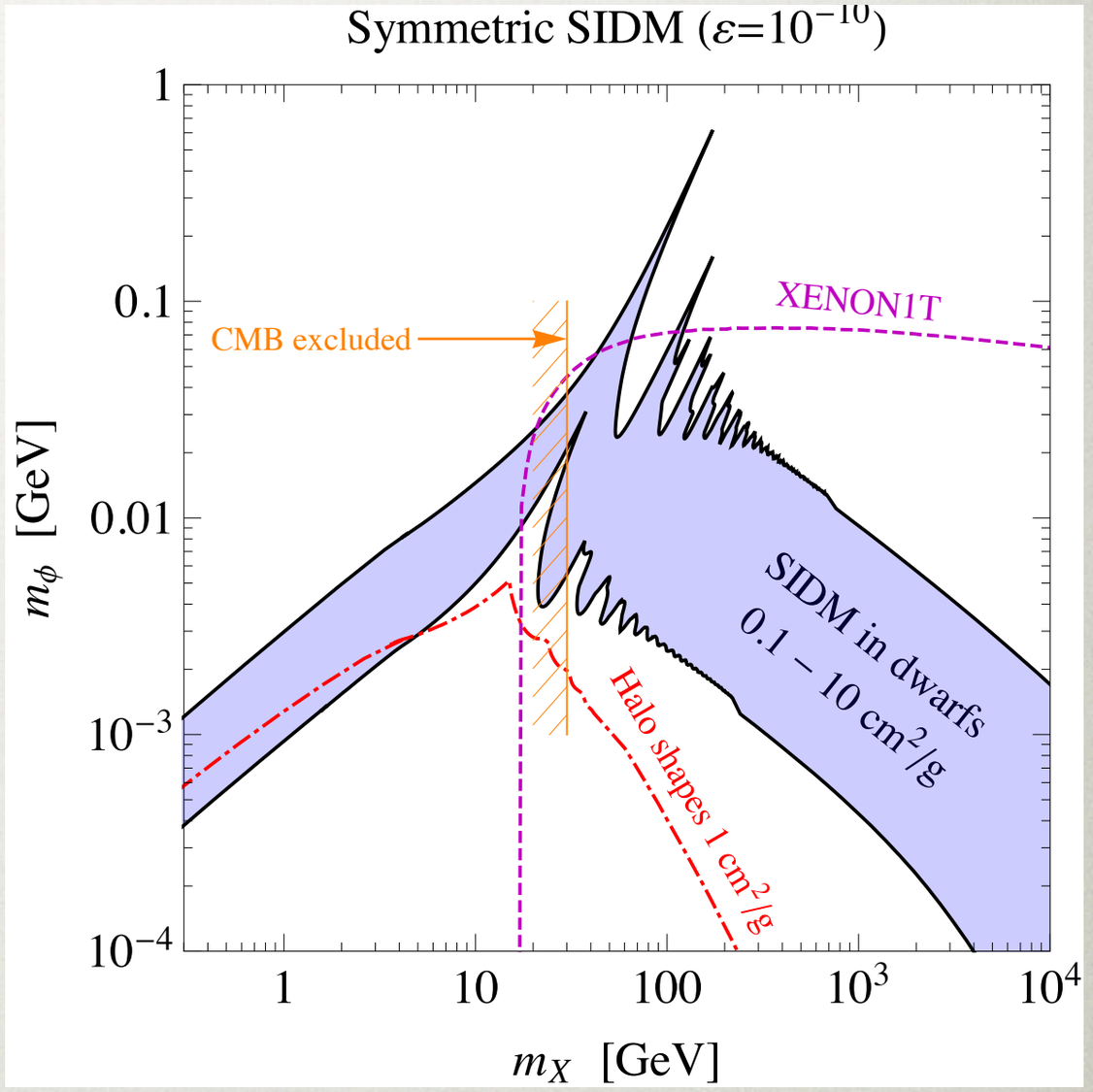


Constraints from MW and clusters

Implications for Direct Detection



Tulin, Yu, KZ



Kaplinghat, Tulin, Yu

$$\epsilon = 10^{-10}$$

$$g_q \gtrsim 1.6 \times 10^{-11} \sqrt{1\ \mathrm{GeV}/m_\phi}$$ from BBN

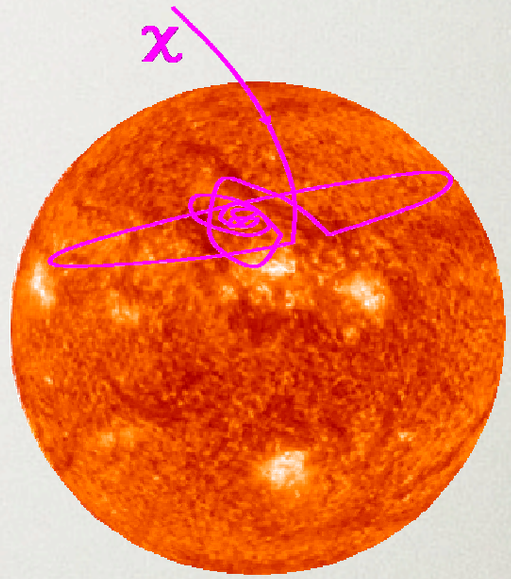
Lin, Yu, KZ

Reachable scattering cross-sections!

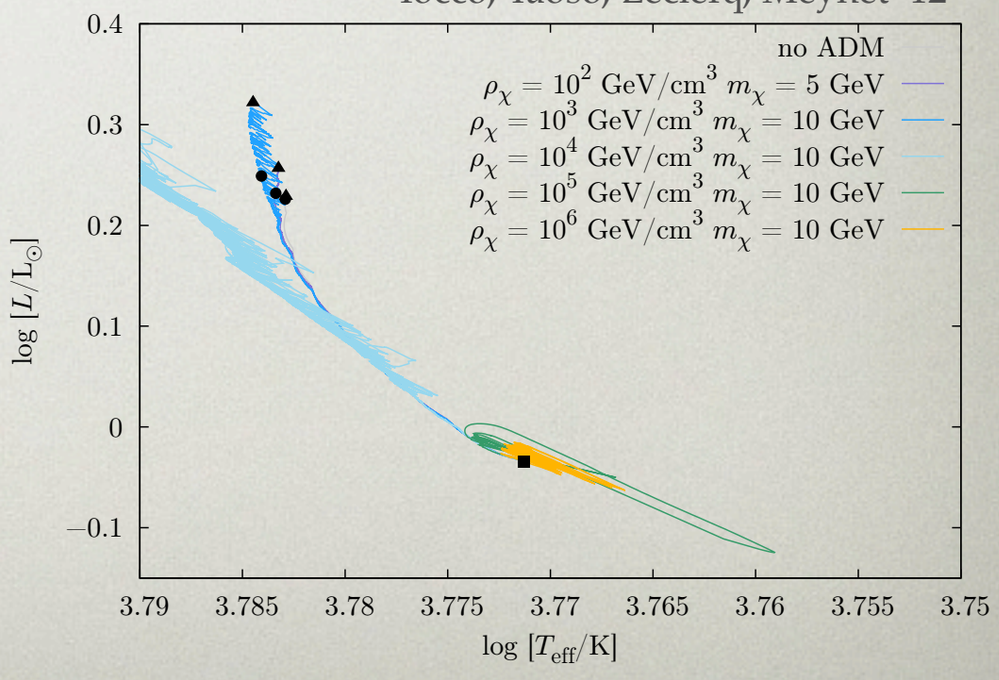
Astrophysical Implications

- DM does not annihilate
- It can accumulate in the center of stars
- Notable case: neutron stars
- Elastically scatter, come to rest in core
- High density!

McDermott, Yu, KZ '11



Iocco, Taoso, Leclerq, Meynet '12



Review: KZ, 1308.0338

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 such as the heavy photon search are complementary to direct detection and astrophysical probes
- Bright future!