

RAPPORTEUR'S REPORT:  
SEARCHES FOR **DARK**  
PHOTONS AT JEFFERSON LAB

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NYU  
January 12, 2011

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- 4 total itineraries to get here
  - Suggests that the impact could be high!

# THE COPERNICAN EVOLUTION

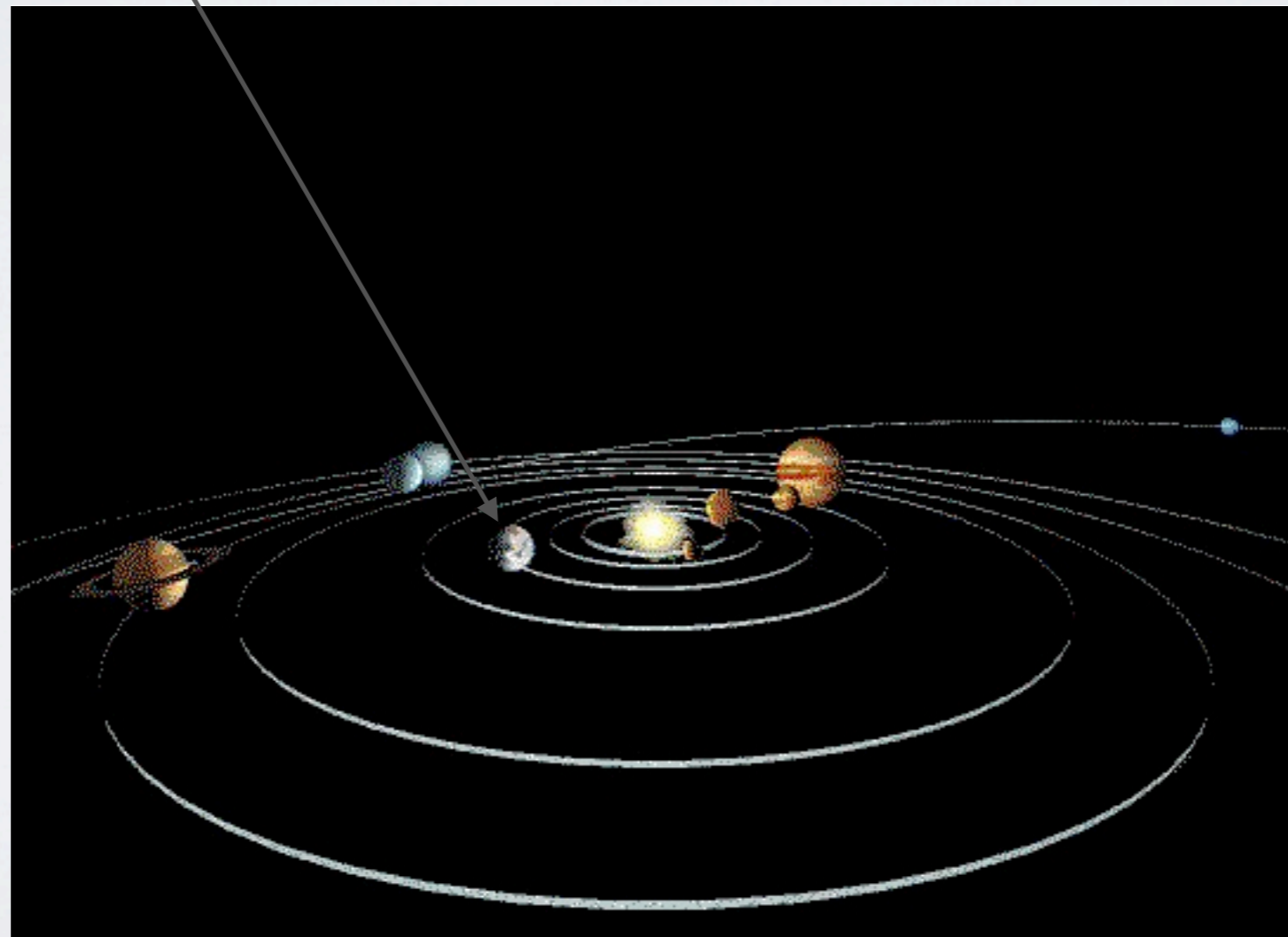
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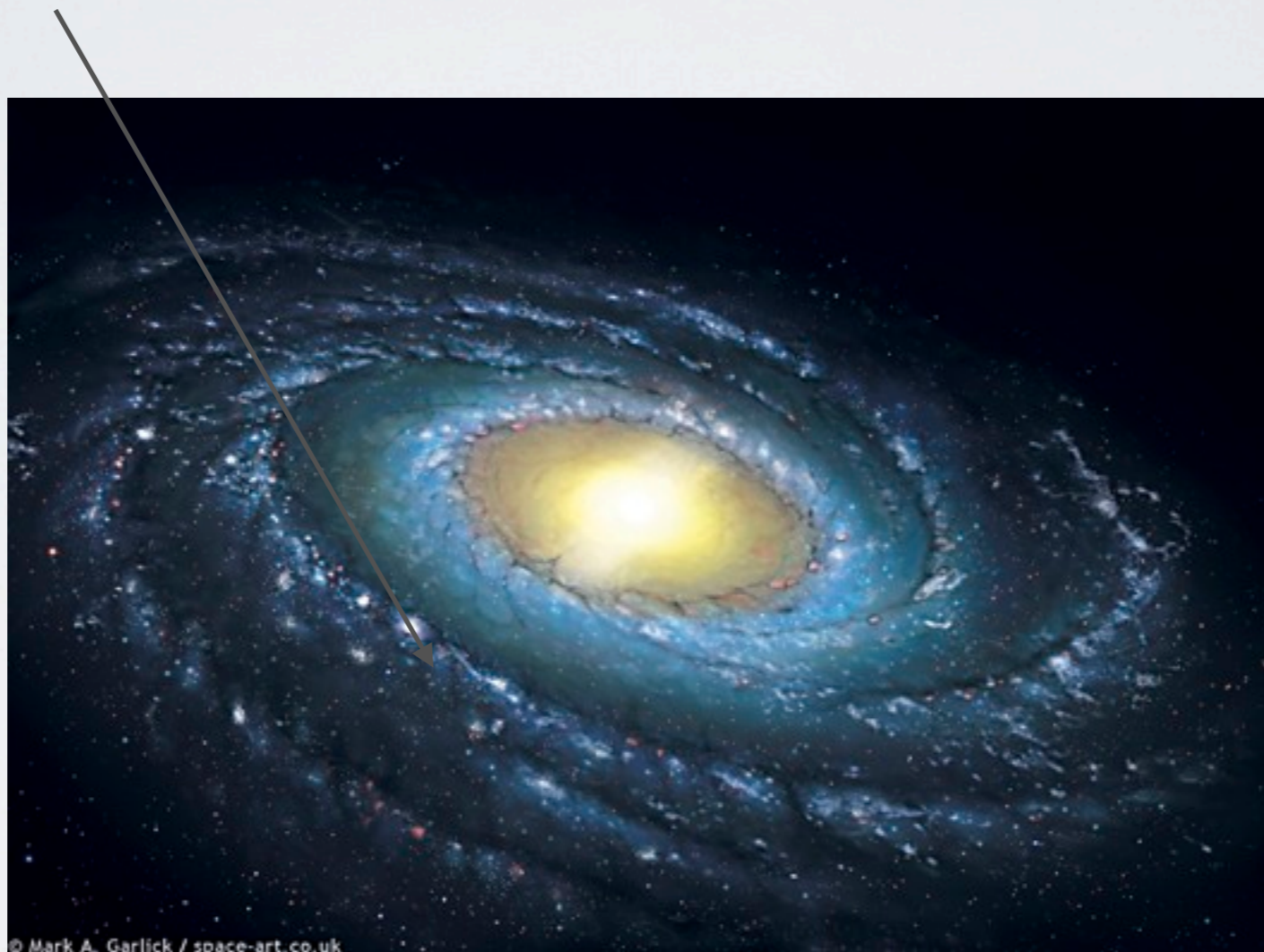
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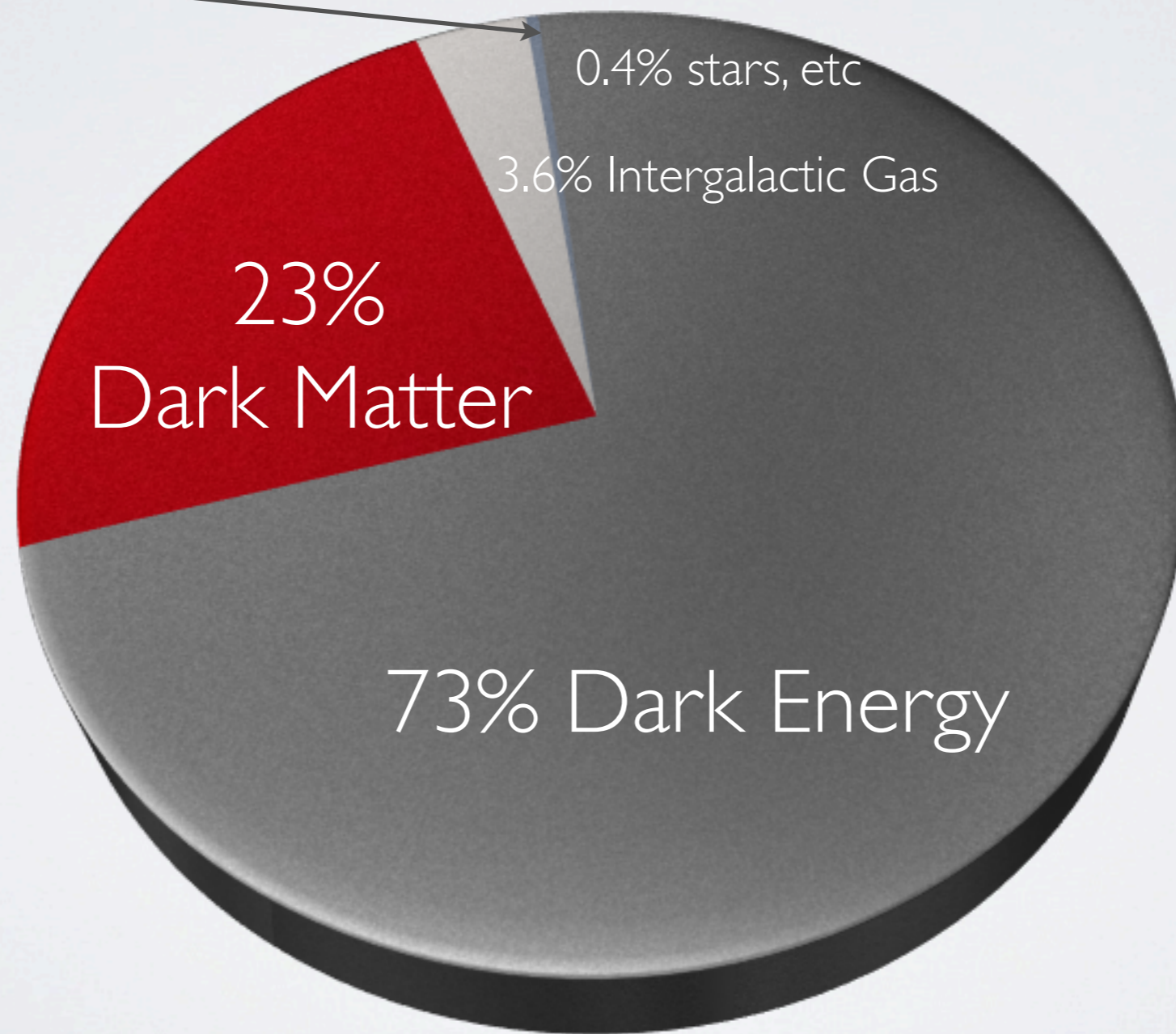
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## Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

### FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c <sup>2</sup>	Electric charge	Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
$\nu_e$ electron neutrino	<1.0 × 10 <sup>-8</sup>	0	u up	0.003	2/3
e <sup>-</sup> electron	0.000511	-1	d down	0.006	-1/3
$\nu_\mu$ muon neutrino	<0.0002	0	c charm	1.3	2/3
$\mu^-$ muon	0.106	-1	s strange	0.1	-1/3
$\nu_\tau$ tau neutrino	<0.02	0	t top	175	2/3
$\tau^-$ tau	1.7771	-1	b bottom	4.3	-1/3

**Spin** is the intrinsic angular momentum of particles. Spin is given in units of  $\hbar$ , which is the quantum unit of angular momentum, where  $\hbar = h/2\pi = 6.58 \times 10^{-22}$  GeV s =  $1.05 \times 10^{-34}$  J s.

**Electric charges** are given in units of the proton's charge. In SI units the electric charge of the proton is  $1.60 \times 10^{-19}$  coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c<sup>2</sup> (remember  $E = mc^2$ ), where  $1 \text{ GeV} = 10^9 \text{ eV} = 1.60 \times 10^{-10}$  joule. The mass of the proton is  $0.938 \text{ GeV}/c^2 = 1.67 \times 10^{-27}$  kg.

### Structure within the Atom

If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

### BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1			Strong (color) spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge	Name	Mass GeV/c <sup>2</sup>	Electric charge
$\gamma$ photon	0	0	g gluon	0	0
W <sup>-</sup>	80.4	-1	<b>Color Charge</b>		
W <sup>+</sup>	80.4	+1	Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons, just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and W and Z bosons have no strong interactions and hence no color charge.		
Z <sup>0</sup>	91.187	0	<b>Quarks Confined in Mesons and Baryons</b>		

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons**  $q\bar{q}$  and **baryons**  $qqq$ .

**Residual Strong Interaction**  
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

### PROPERTIES OF THE INTERACTIONS

Property	Gravitational	Weak (Electroweak)	Electromagnetic	Strong	
				Fundamental	Residual
Acts on:	Mass - Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W <sup>+</sup> W <sup>-</sup> Z <sup>0</sup>	$\gamma$	Gluons	Mesons
Strength relative to electromagnetism for two u quarks at:	10 <sup>-41</sup>	0.8	1	25	Not applicable to quarks
	10 <sup>-41</sup>	10 <sup>-4</sup>	1	60	
	10 <sup>-36</sup>	10 <sup>-7</sup>	1	Not applicable to hadrons	20

#### Baryons $qqq$ and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons. There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c <sup>2</sup>	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1	0.938	1/2
n	neutron	udd	0	0.940	1/2
$\Lambda$	lambda	uds	0	1.116	1/2
$\Omega^-$	omega	sss	-1	1.672	3/2

**Matter and Antimatter**  
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z<sup>0</sup>,  $\gamma$ , and  $\eta$ , and  $\eta_c = c\bar{c}$ , but not K<sup>0</sup> = d $\bar{s}$ ) are their own antiparticles.

**Figures**  
These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W<sup>-</sup> boson. This is neutron  $\beta$  decay.

An electron and positron (antiparticle) colliding at high energy can annihilate to produce  $\gamma$  and Z<sup>0</sup> bosons. These bosons then decay via a virtual Z boson or a virtual photon.

Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

#### Mesons $q\bar{q}$

Mesons are bosonic hadrons. There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c <sup>2</sup>	Spin
$\pi^+$	pion	u $\bar{d}$	+1	0.140	0
K <sup>-</sup>	kaon	s $\bar{u}$	-1	0.494	0
$\rho^+$	rho	u $\bar{d}$	+1	0.770	1
B <sup>0</sup>	B-zero	d $\bar{b}$	0	5.279	0
$\eta_c$	eta-c	c $\bar{c}$	0	2.980	0

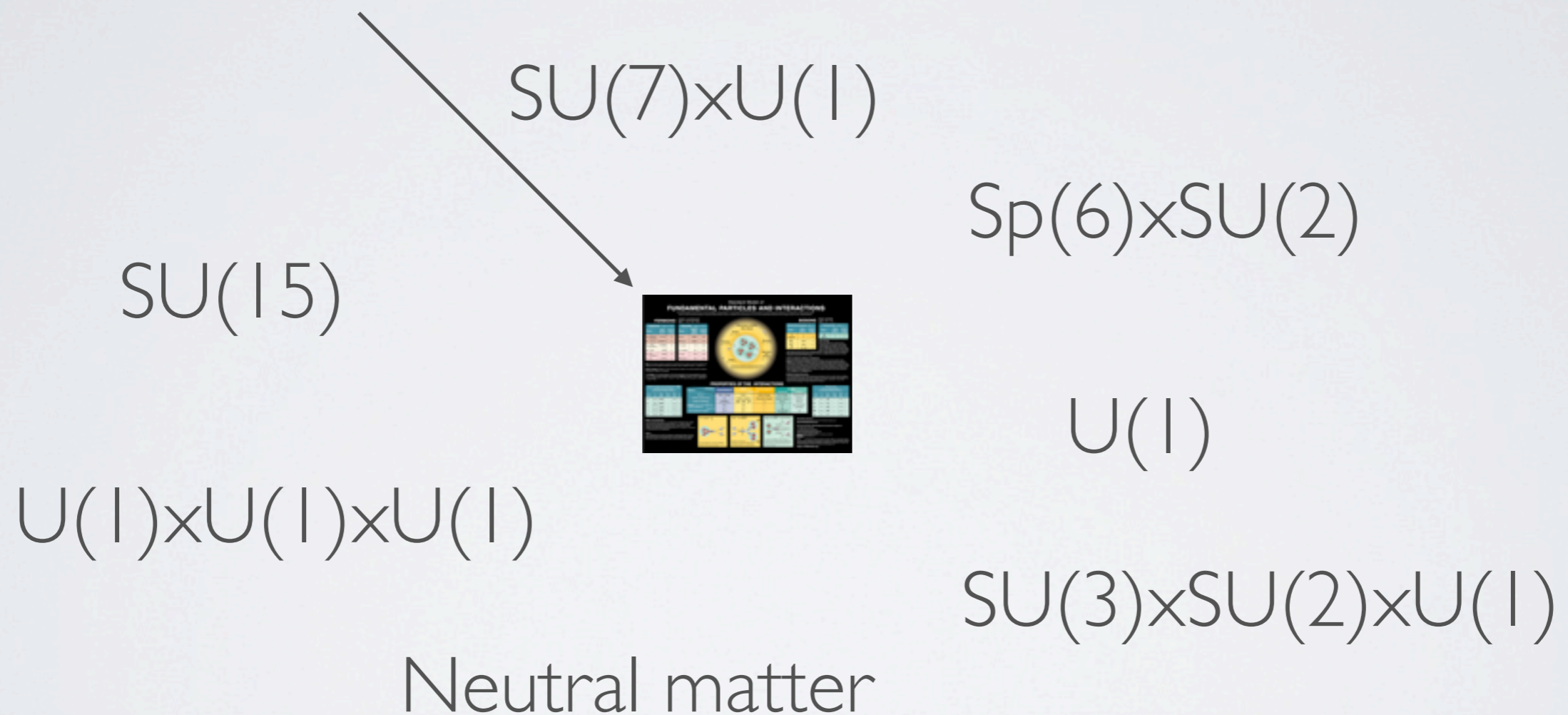
**The Particle Adventure**  
Visit the award-winning web feature The Particle Adventure at <http://ParticleAdventure.org>

This chart has been made possible by the generous support of:  
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Stanford Linear Accelerator Center  
American Physical Society, Division of Particle and Field  
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# THE COPERNICAN EVOLUTION

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# PORTALS TO A HIDDEN SECTOR

- Suppose there is matter uncharged under the SM
- How do we couple to it?

# PORTALS TO A HIDDEN SECTOR

$$\underbrace{(\bar{L}H)}_{\text{Standard Model}} \times \underbrace{(N)}_{\text{Hidden Sector}} \quad \text{Neutrino Portal}$$

$$\underbrace{(F_{\mu\nu})}_{\text{Standard Model}} \times \underbrace{(F_d^{\mu\nu})}_{\text{Hidden Sector}} \quad \text{Vector (photon) Portal}$$

$$\underbrace{(h^\dagger h)}_{\text{Standard Model}} \times \underbrace{(a\phi)}_{\text{Hidden Sector}} + \text{h.c.} \quad \text{Scalar (Higgs) Portal}$$

\*NB: Non-renormalizable portals, e.g., axion portal also can be important



$$\underbrace{(\bar{L}H)}_{\text{Standard Model}} \times \underbrace{(N)}_{\text{Hidden Sector}}$$

# Neutrino Portal

- Requires complete gauge singlet  $N$
- Would naturally be heavy
- If charged, has coupling  $\frac{\phi_d}{\Lambda} \sim \text{small}$
- Dominant signal  $\Rightarrow$  neutrino mass

$$\underbrace{(h^\dagger h)}_{\text{Standard Model}} \times \underbrace{(a\phi)}_{\text{Hidden Sector}} + \text{h.c.} \quad \text{Scalar (Higgs) Portal}$$

- Requires complete gauge singlet  $\phi$ , or  $\langle \phi \rangle = a$
- Would naturally have mass  $m_\phi = a$
- Has mixing with the Higgs  $\sim m_\phi/m_W \sim \text{small}$
- Dominant effect: rare meson decays, non-standard Higgs decays



$$\epsilon \times \underbrace{(F_{\mu\nu})}_{\text{Standard Model}} \times \underbrace{(F_d^{\mu\nu})}_{\text{Hidden Sector}} \quad \text{Vector (photon) Portal}$$

- Requires Hidden sector has an effective U(1) (can arise from breaking of non-Abelian sector)
- Natural mass scales/couplings shortly
- Mixes with the photon (if  $< \text{GeV}$ ) or Z boson (if  $\sim M_W$ )
- Dominant effect is to give coupling of charged matter to new, dark photon,  $q = \epsilon e$

$$\epsilon \times \underbrace{(F_{\mu\nu})}_{\text{Standard Model}} \times \underbrace{(F_d^{\mu\nu})}_{\text{Hidden Sector}} \quad \text{Vector (photon) Portal}$$

$$\alpha, \alpha_{EM}$$

Fine structure constant

$$\epsilon, \alpha' = \epsilon^2 \alpha$$

Coupling of dark photon to EM

$$\alpha_D$$

dark sector coupling



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- Natural range of  $1 > \epsilon > 10^{-8}$  (approximately)



# WHAT IS A NATURAL MASS FOR $A'$ ?

- SM Fields should not couple to a new, massless  $A'$ 
  - (NB: If entirety of new physics is  $A'$ , mixing is not a physical effect)
- What is natural mass scale?

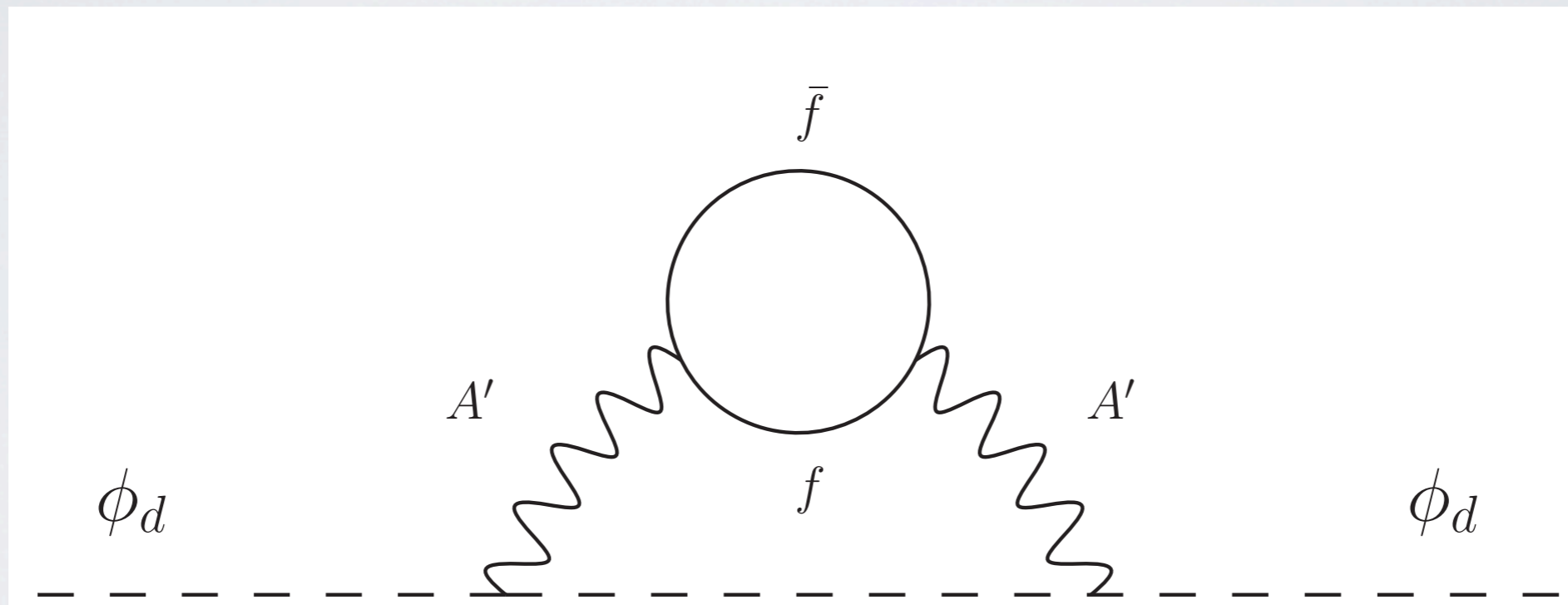
# WHAT IS A NATURAL MASS FOR A'?

- If strong dynamics (similar to QCD) drive  $U(1)_d$  breaking, mass scale can be anything (theoretically)



# WHAT IS A NATURAL MASS FOR A'?

- If  $U(1)_d$  breaking is driven by a scalar, there is a *lower* bound on the mass from two-loop effects



$$m_{\phi}^2 \approx \epsilon^2 \left( \frac{\alpha_d}{4\pi} \right)^2 m_W^2$$

# WHAT IS A NATURAL MASS FOR A'?

- In supersymmetric theories, there is an additional effect

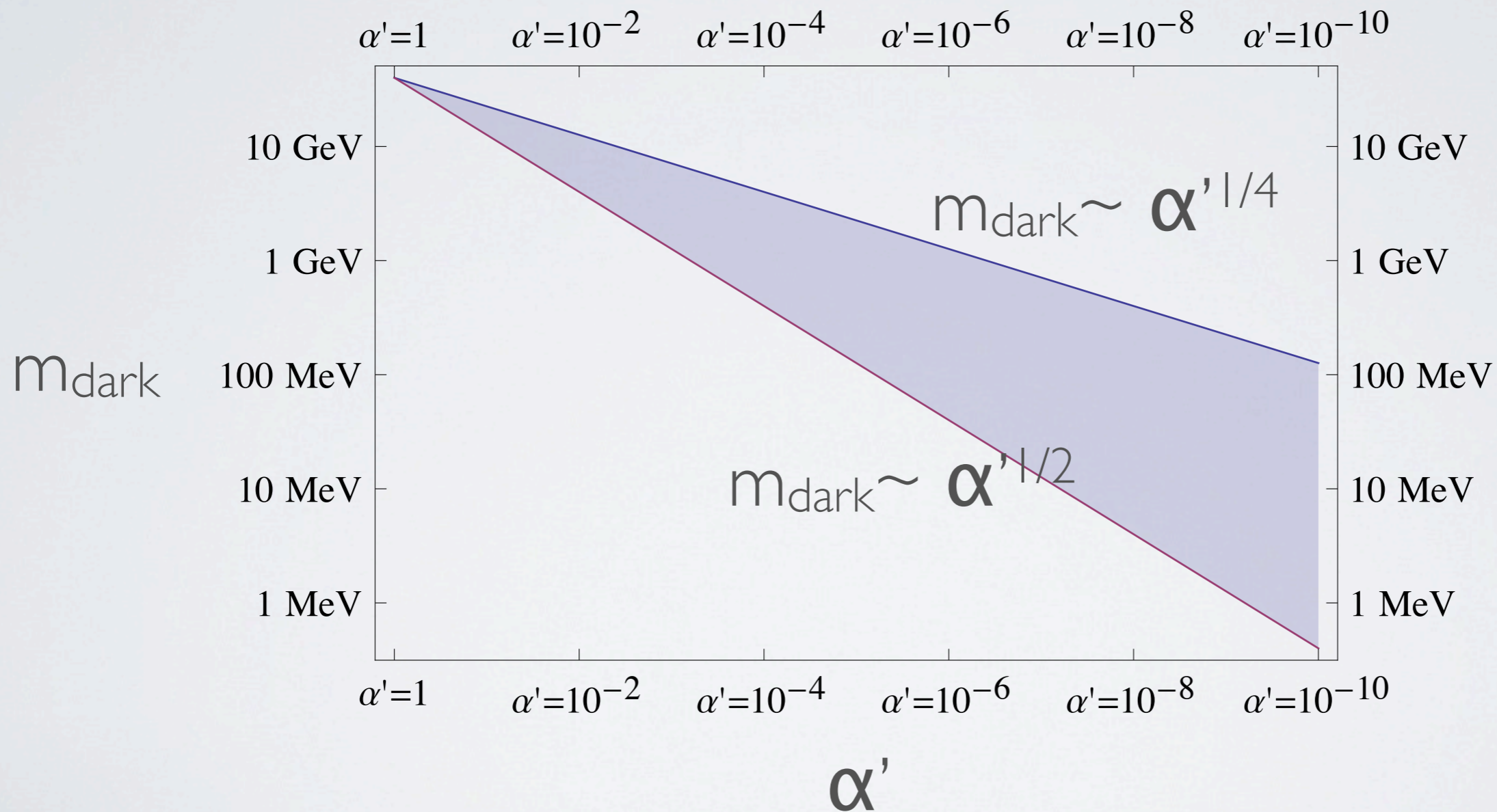
$$\epsilon F_{\mu\nu} F_d^{\mu\nu} \Rightarrow \epsilon \int d^2\theta W_\alpha W_d^\alpha$$

$$V \supset \epsilon D_Y D_d = \epsilon g_Y \frac{v^2}{4} \cos(2\beta) \times (\phi_d^2 - \tilde{\phi}_d^2)$$

$$m_\phi^2 \approx \epsilon \alpha_Y m_W^2 \sim \sqrt{\alpha' \alpha_d} m_W^2$$

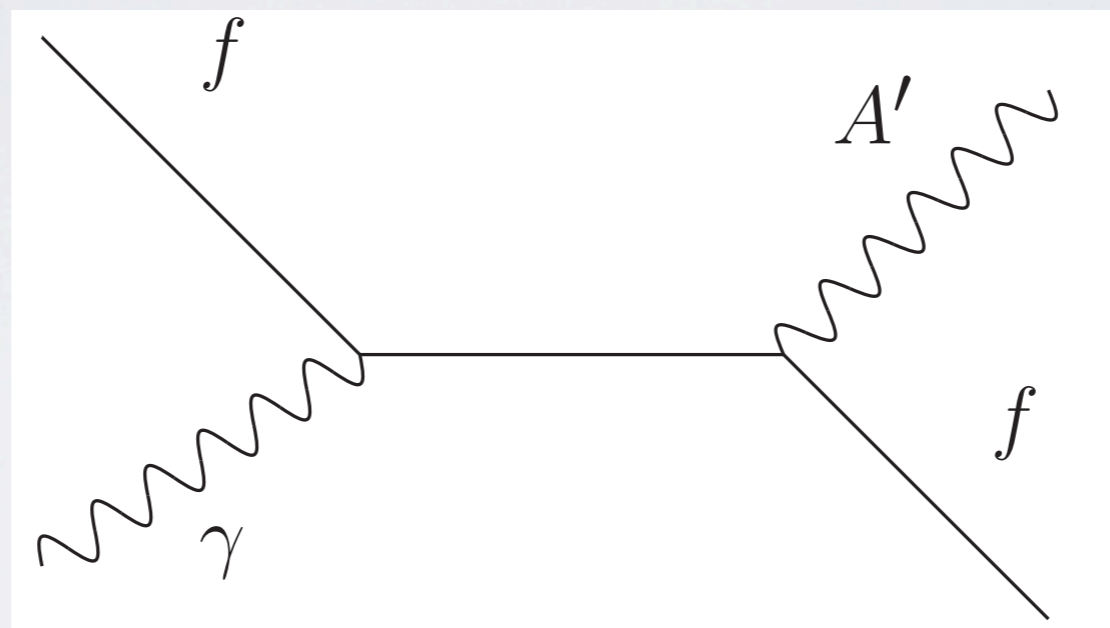


# WHAT IS A NATURAL MASS FOR A'?



(Note: boundaries are approximate)

# A BRIEF COSMIC HISTORY



Depending on mass,  $A'$  will generally thermalize for

$$\epsilon > 10^{-9} \div -8 \text{ (i.e., } \alpha' > 10^{-18} \div -20)$$

Should be  $> 1$  MeV to avoid problems with BBN



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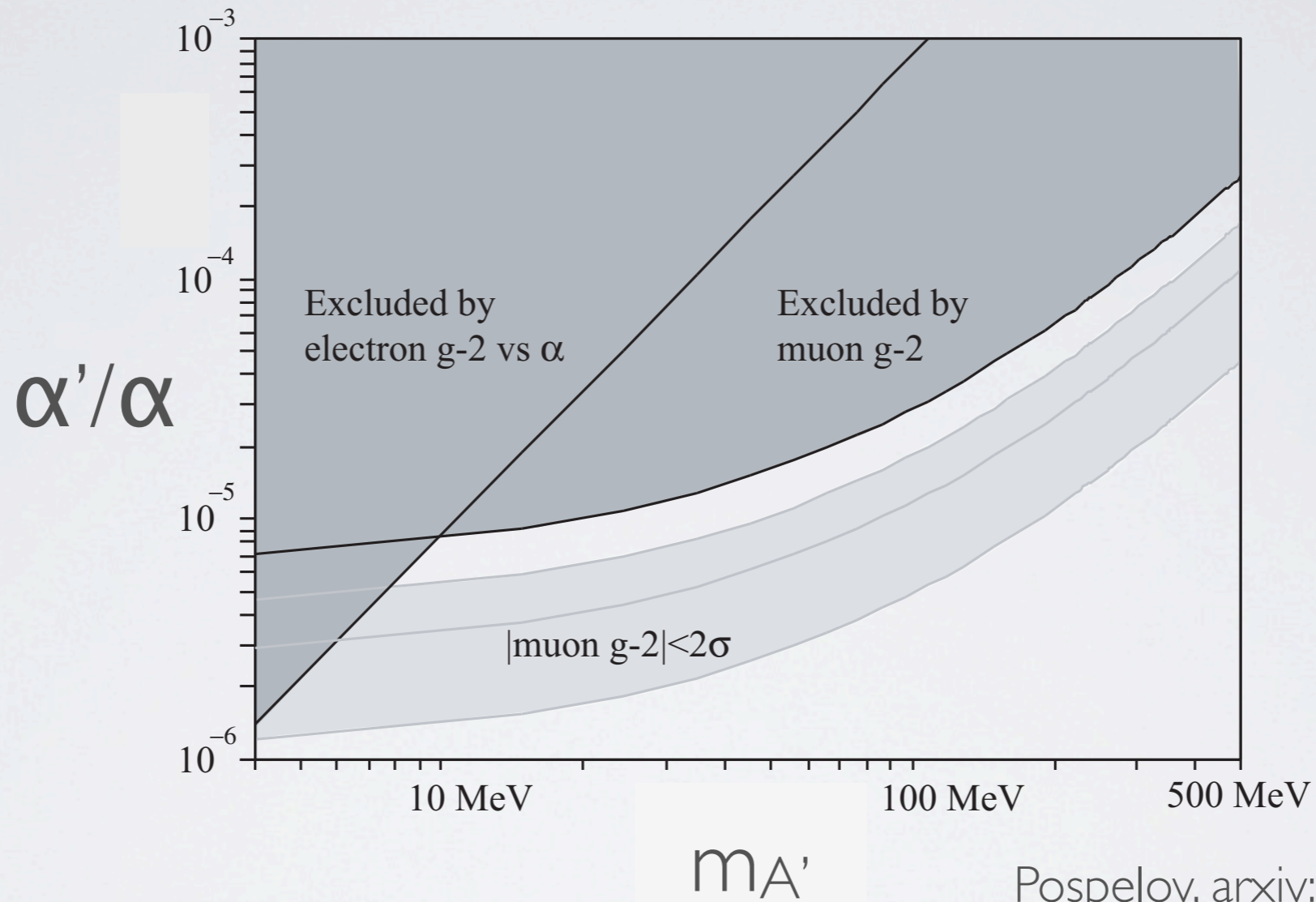
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- Are any regions particularly motivated?
- A dark photon would influence particle physics at the GeV scale



# $g_{\mu-2}$



$g-2$  for the muon  $3.6\sigma$  deviation from SM prediction

# STILL A BROAD PARAMETER SPACE

- $m_\chi > 1 \text{ MeV}$ ,  $\alpha' > 10^{-12}$  would be a natural part of particle physics landscape
- Are any regions particularly motivated?
- Dark matter charged under a dark force has been motivated by a variety of DM anomalies



# DM WITH A DARK U(I)

# DM WITH A DARK $U(1)$

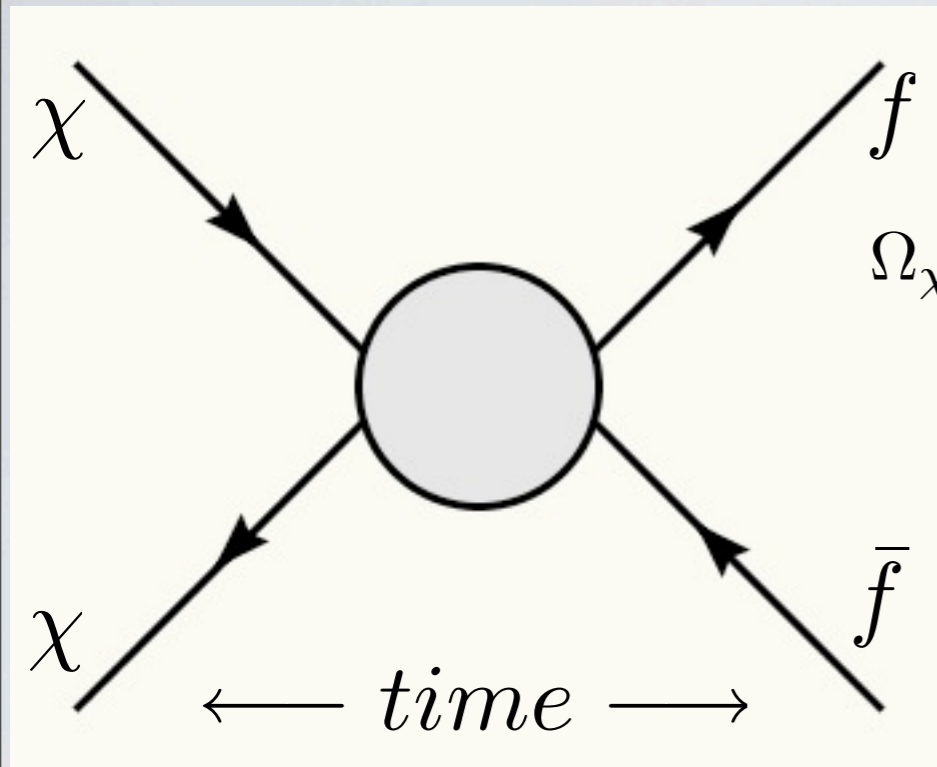
- The presence of a dark  $U(1)$  would very likely be accompanied by stable particles
- Thus dark matter would naturally be charged millicharged for a massless force [Holdom, '84]
- Dark matter can annihilate into the dark photon
- Dark matter can scatter via the dark photon



# FREEZEOUT INTO A DARK

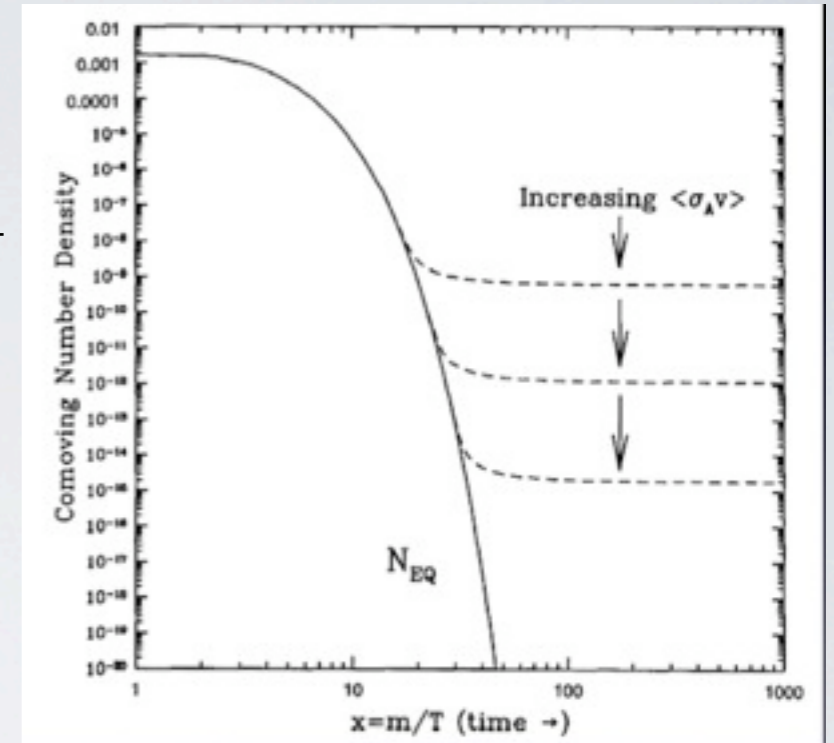
“Classic” WIMP

# PHOTON



$$\Omega_{\chi} h^2 \approx 0.1 \times \frac{3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle}$$

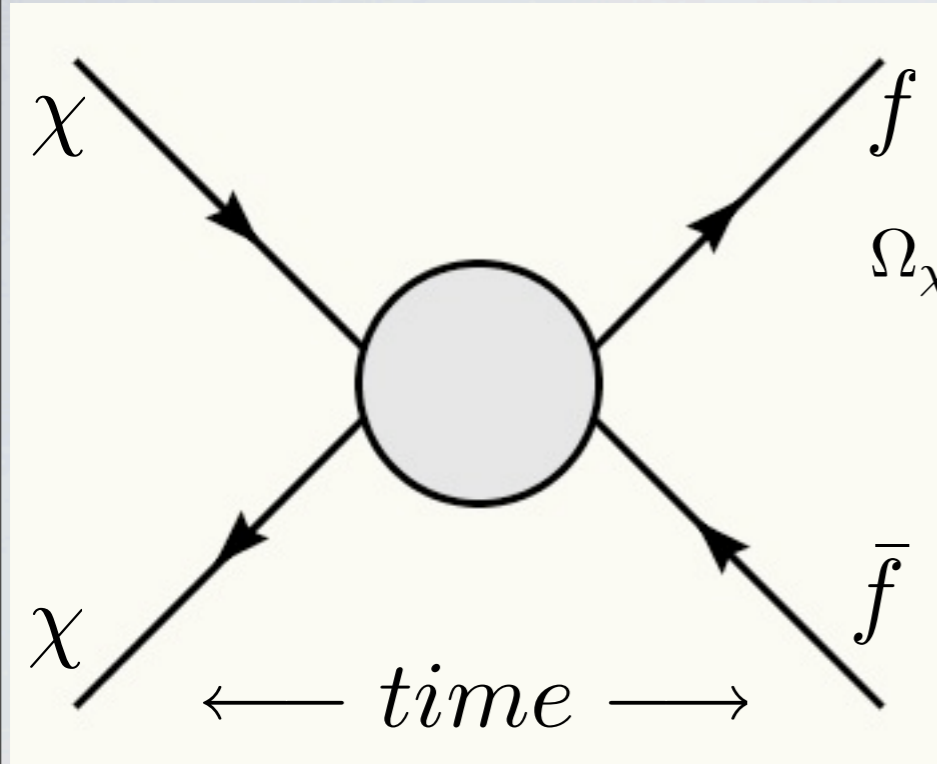
$$\Rightarrow \langle \sigma v \rangle \approx \frac{\alpha^2}{M_W^2}$$



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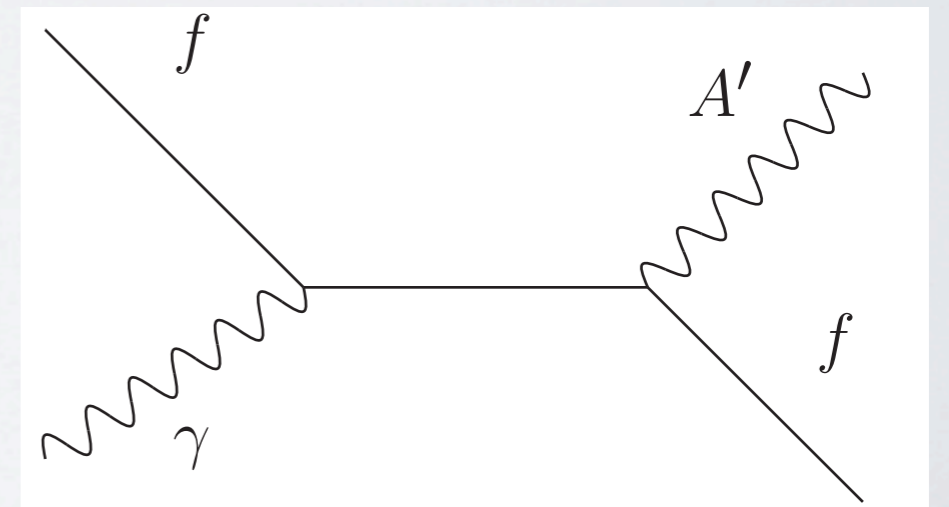
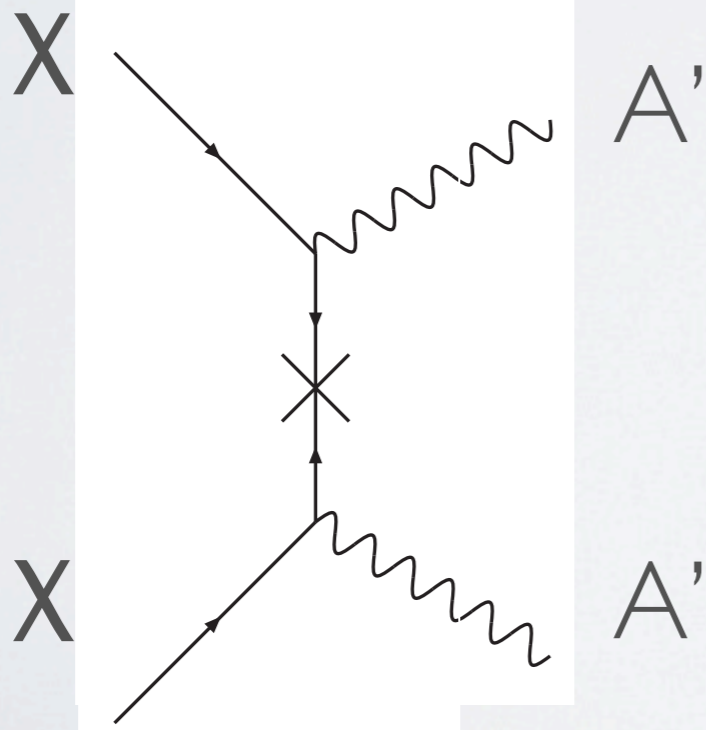
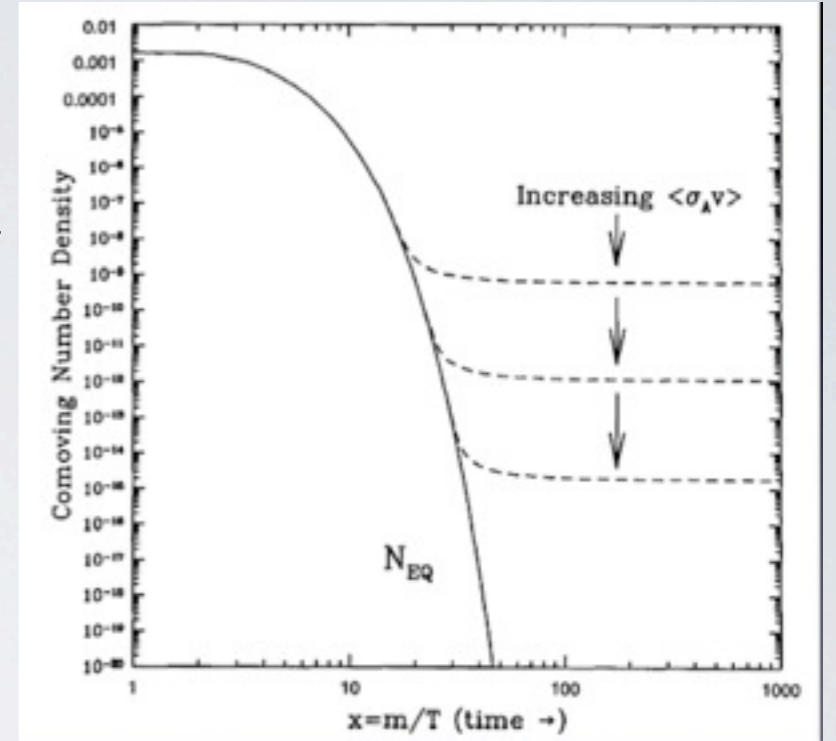
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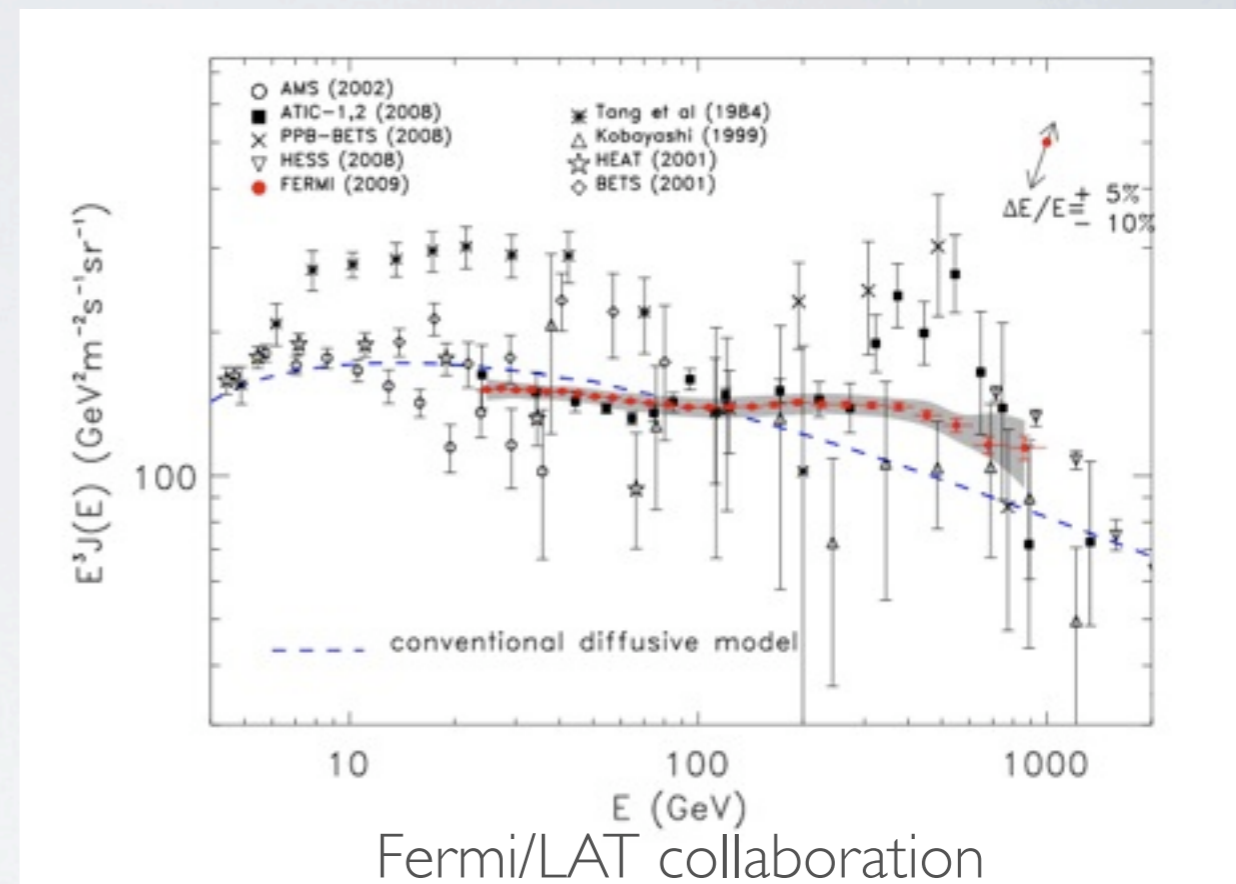
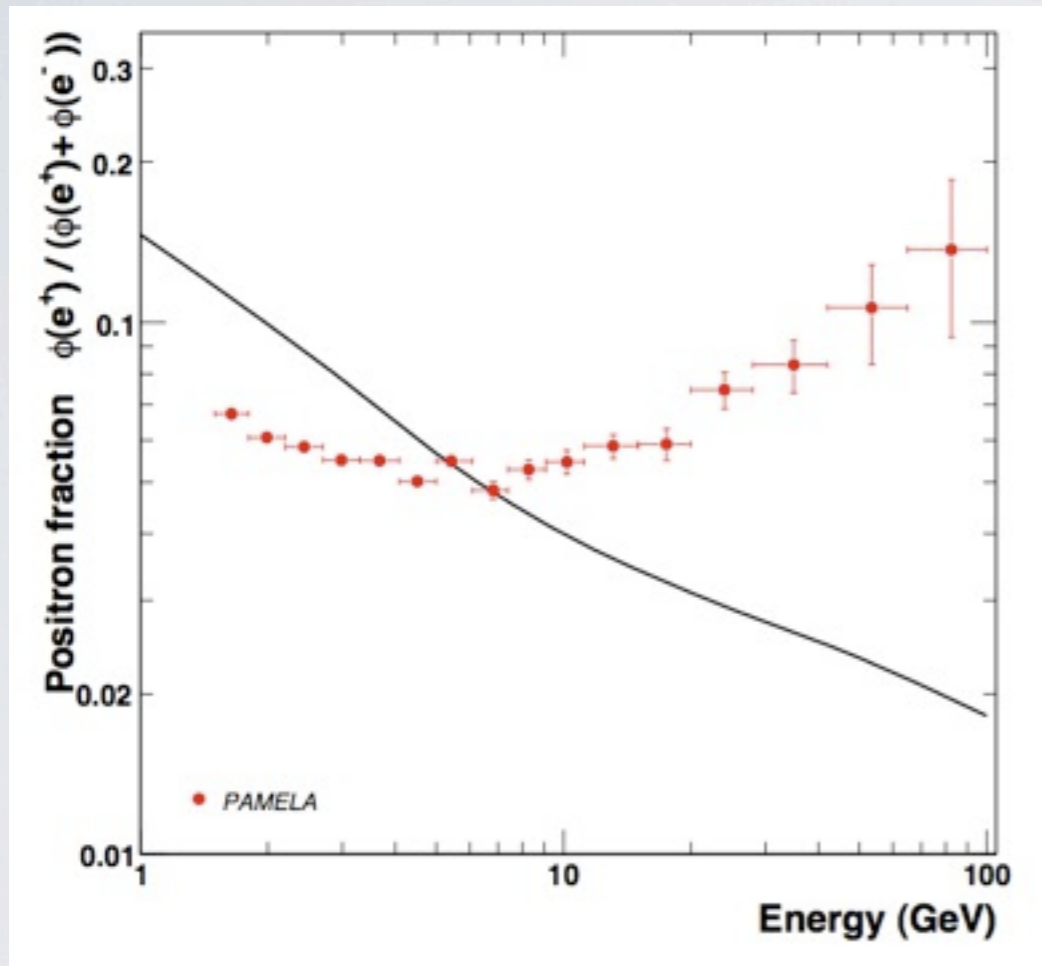
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Finkbeiner, NW astro-ph 0702587v2; Pospelov, Ritz, Voloshin arxiv 0711.4866



# COSMIC RAYS: PAMELA/FERMI



DM?

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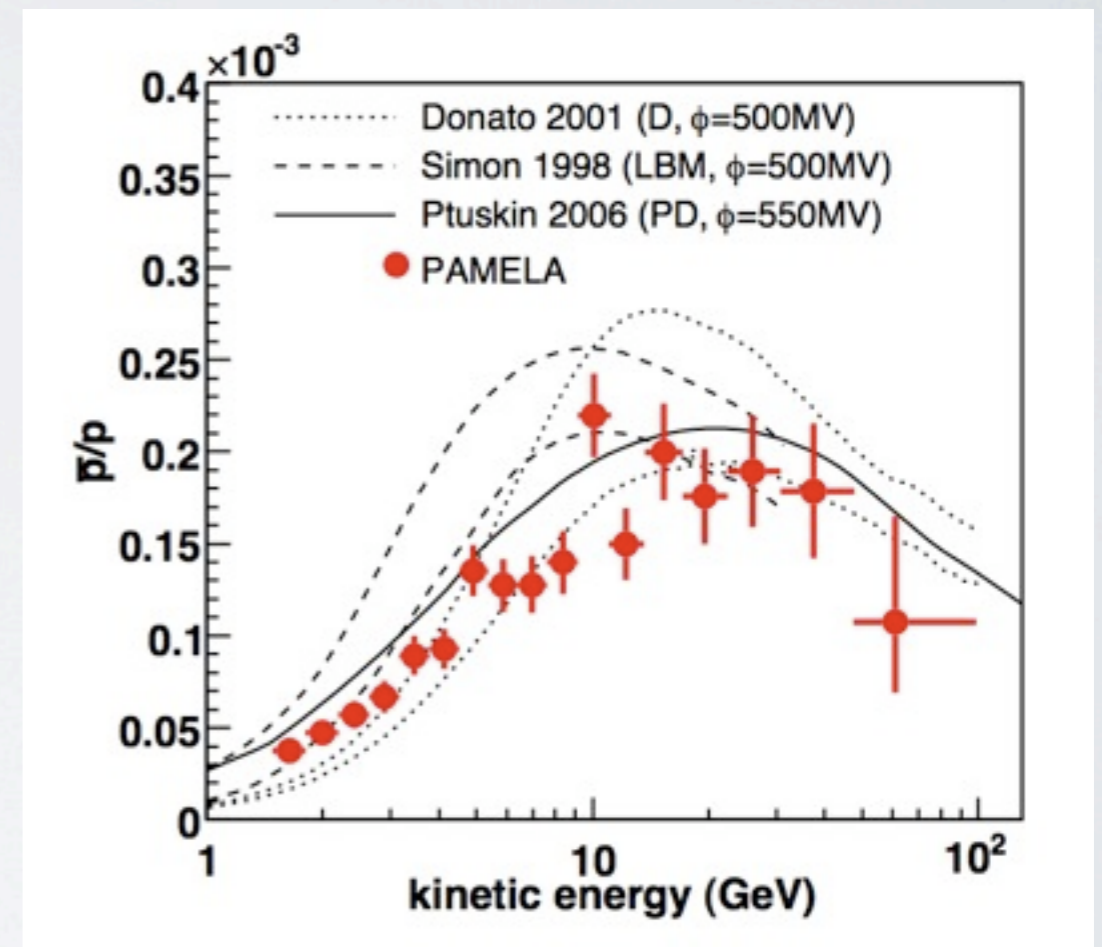


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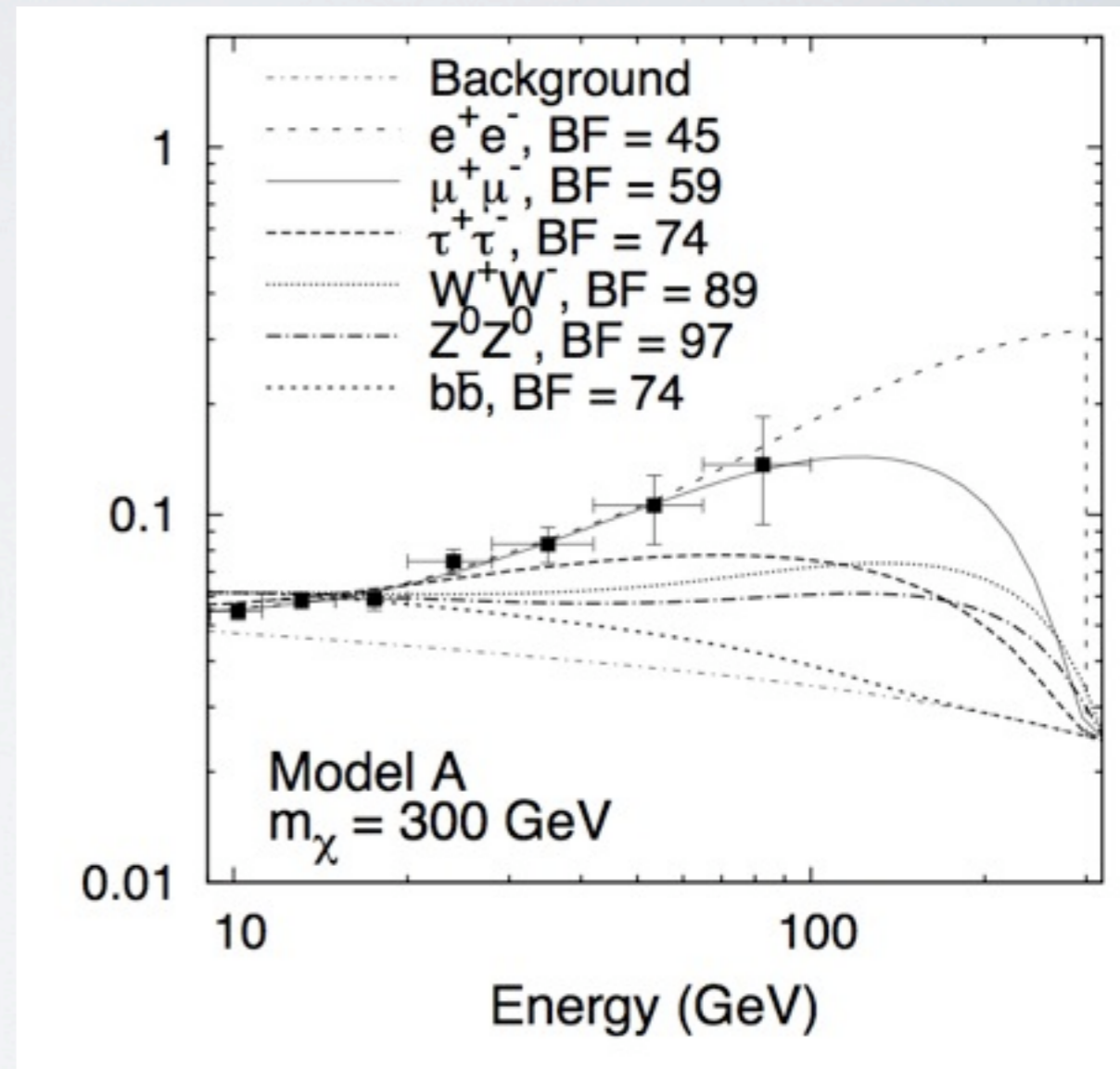
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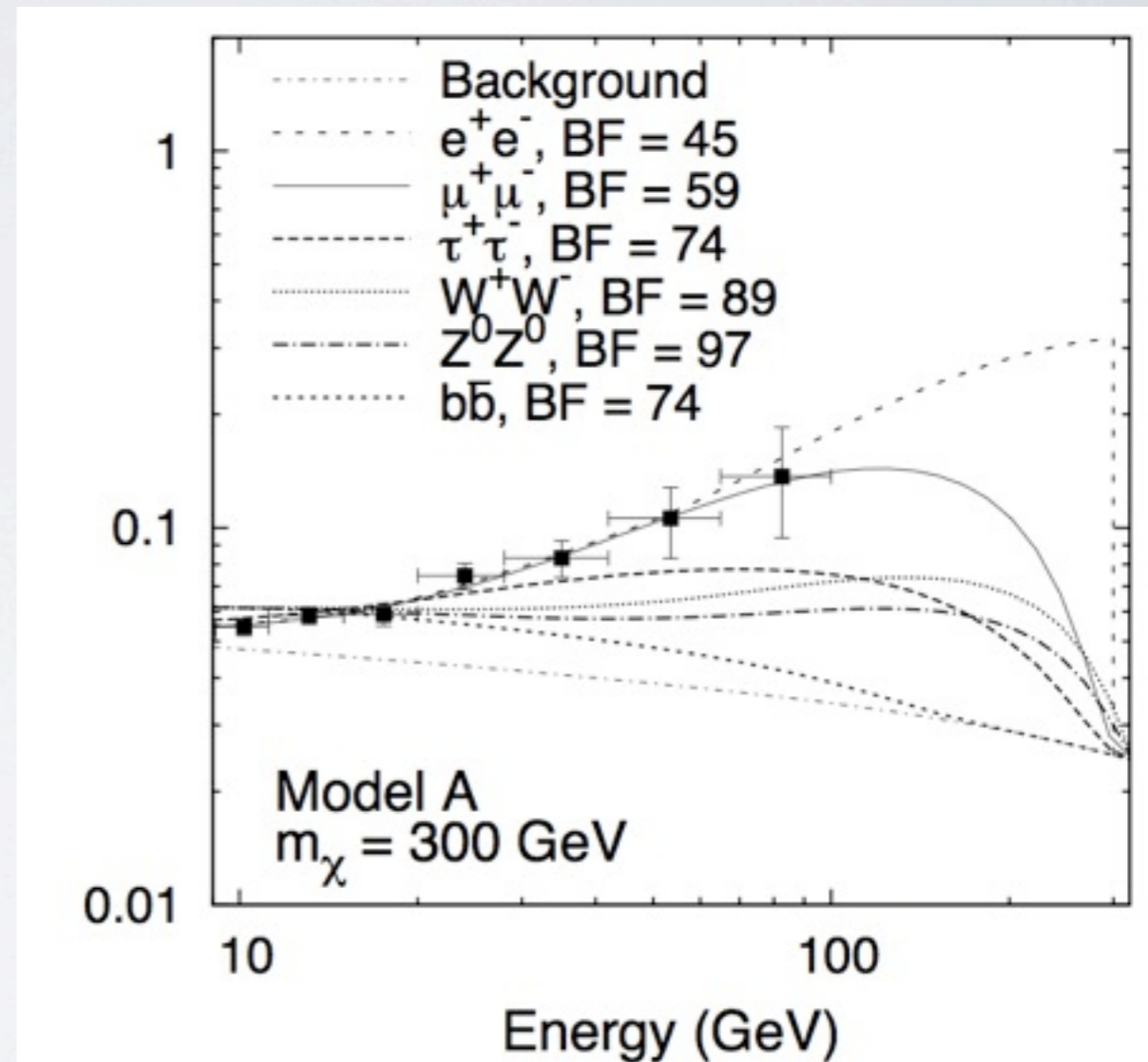


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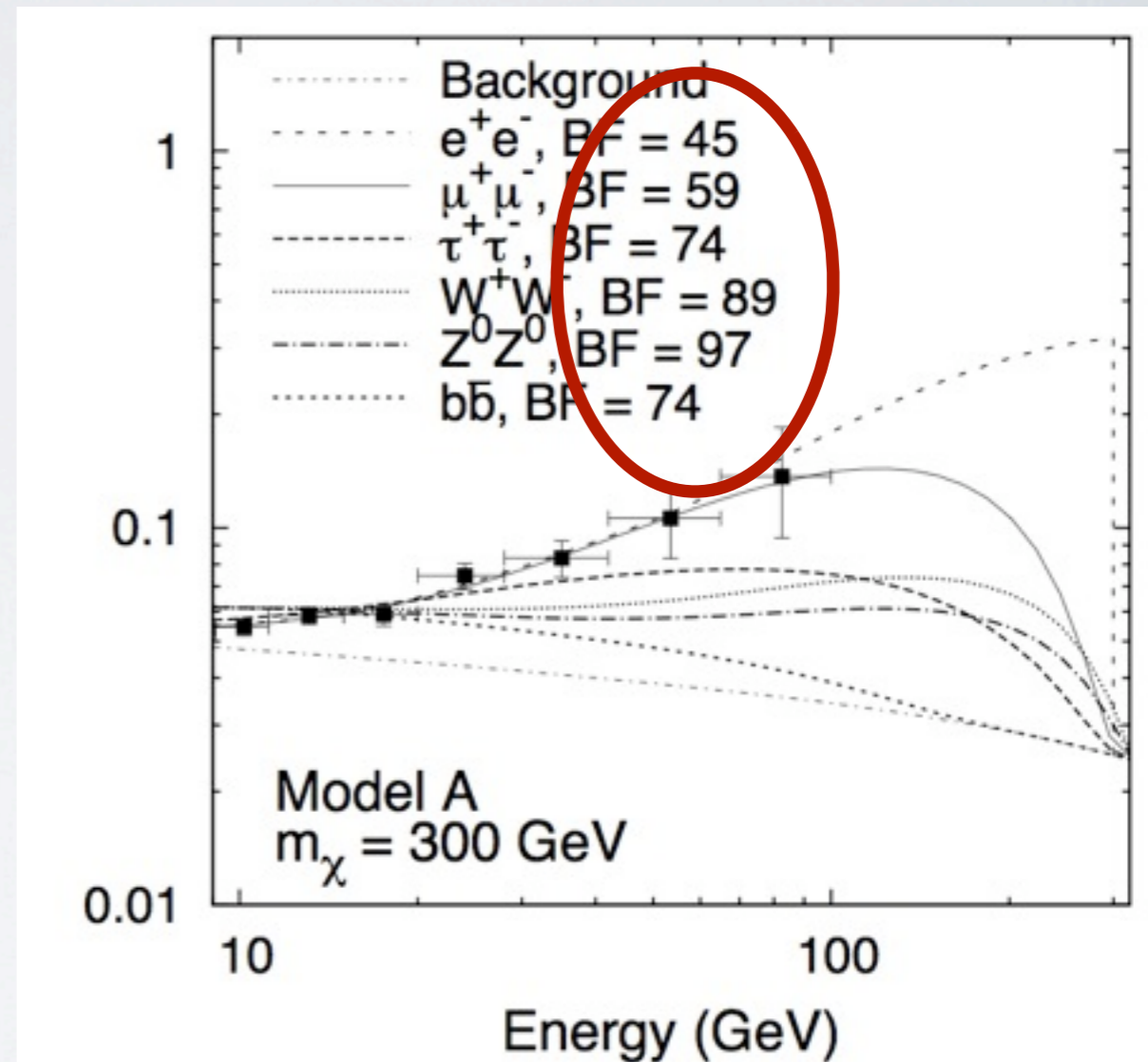


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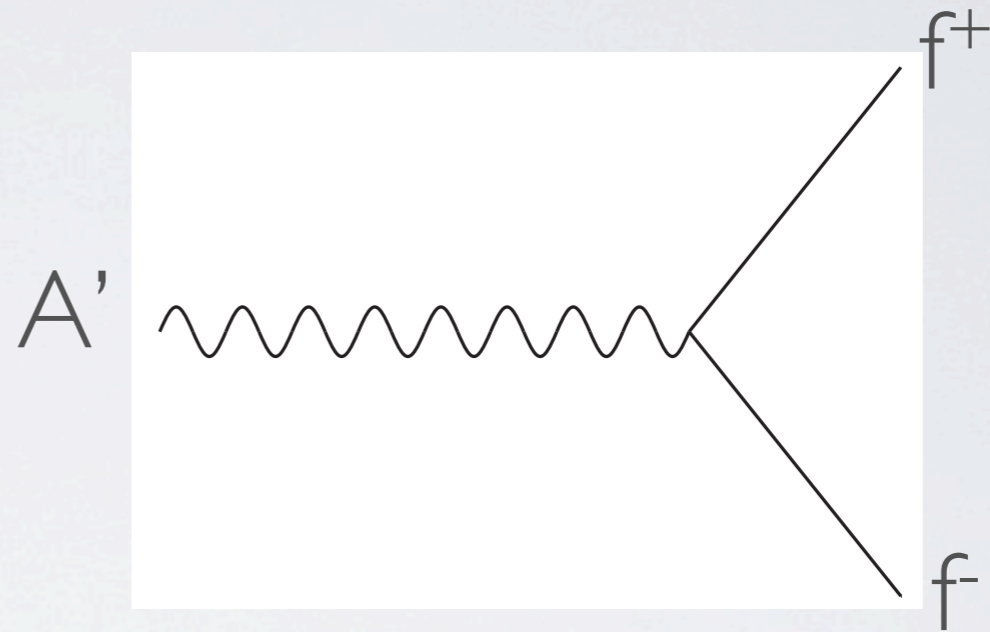
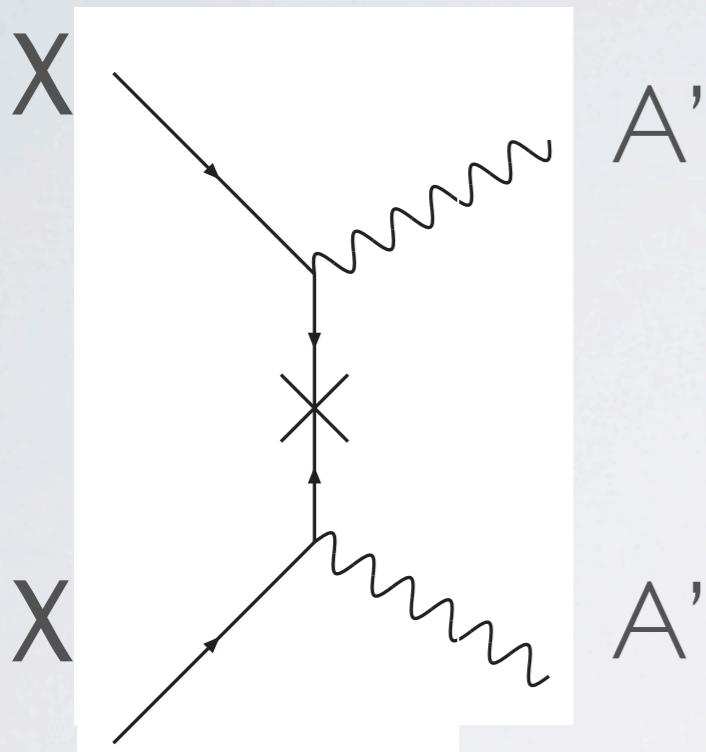
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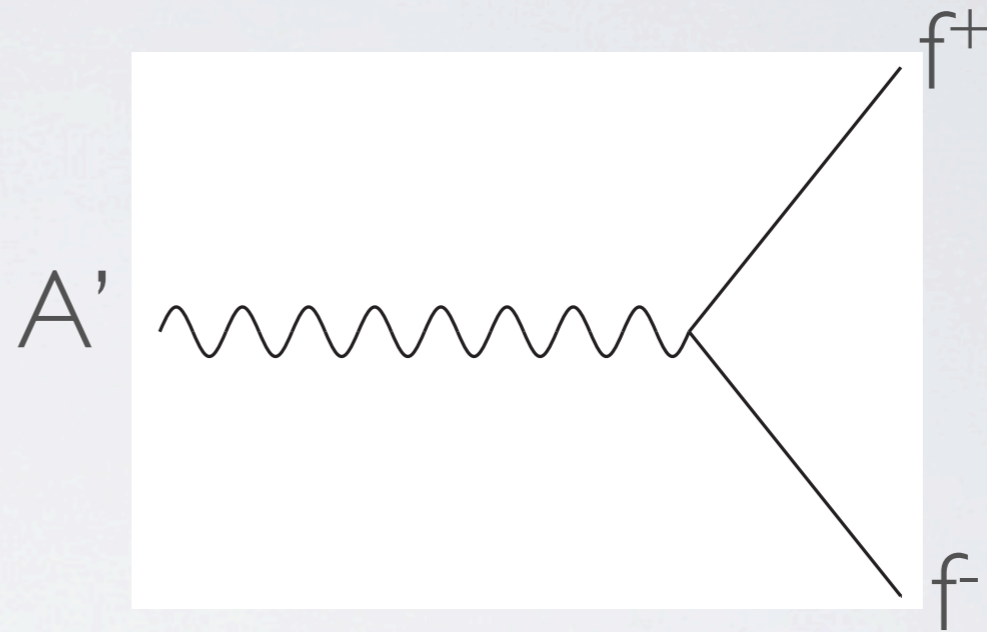
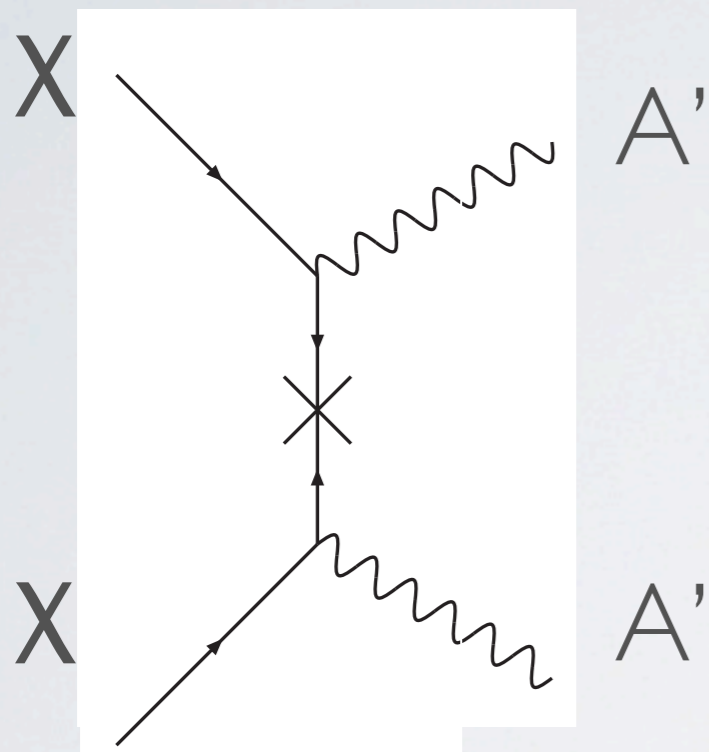


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(Finkbeiner, NW, arxiv 0702587v2; Cholis, Goodenough, NW arxiv 0802.2922)



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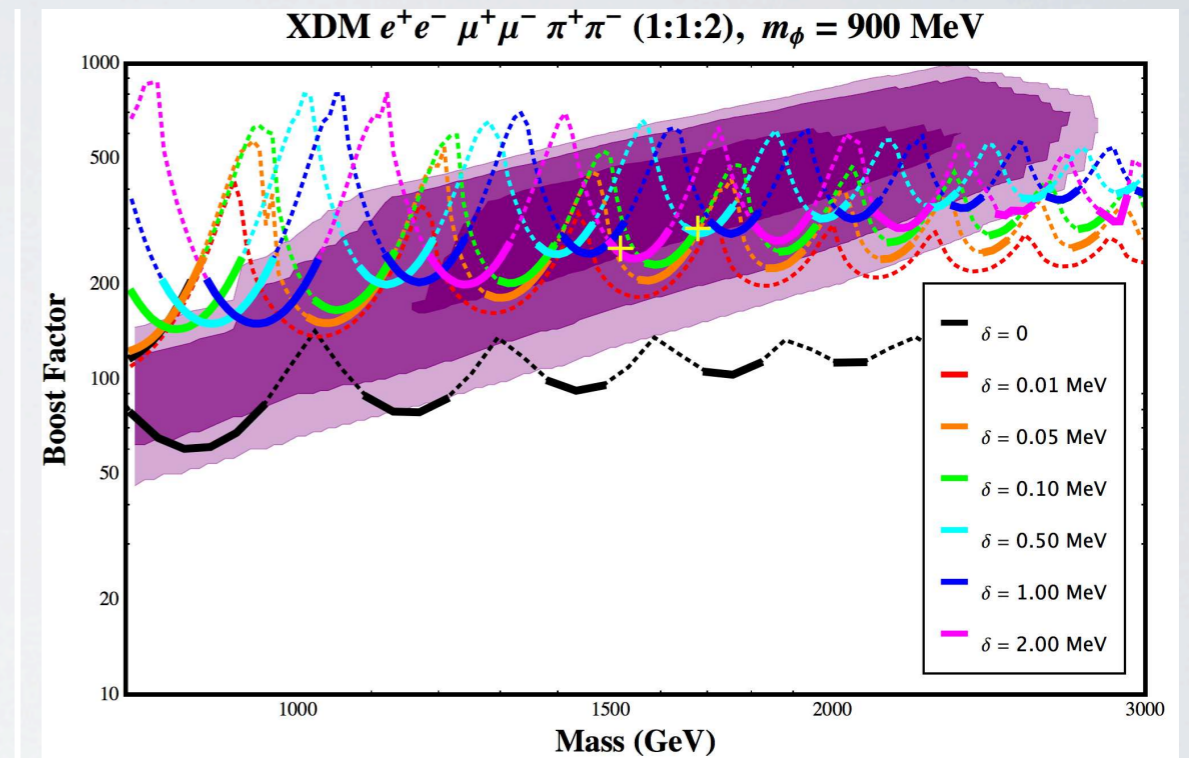
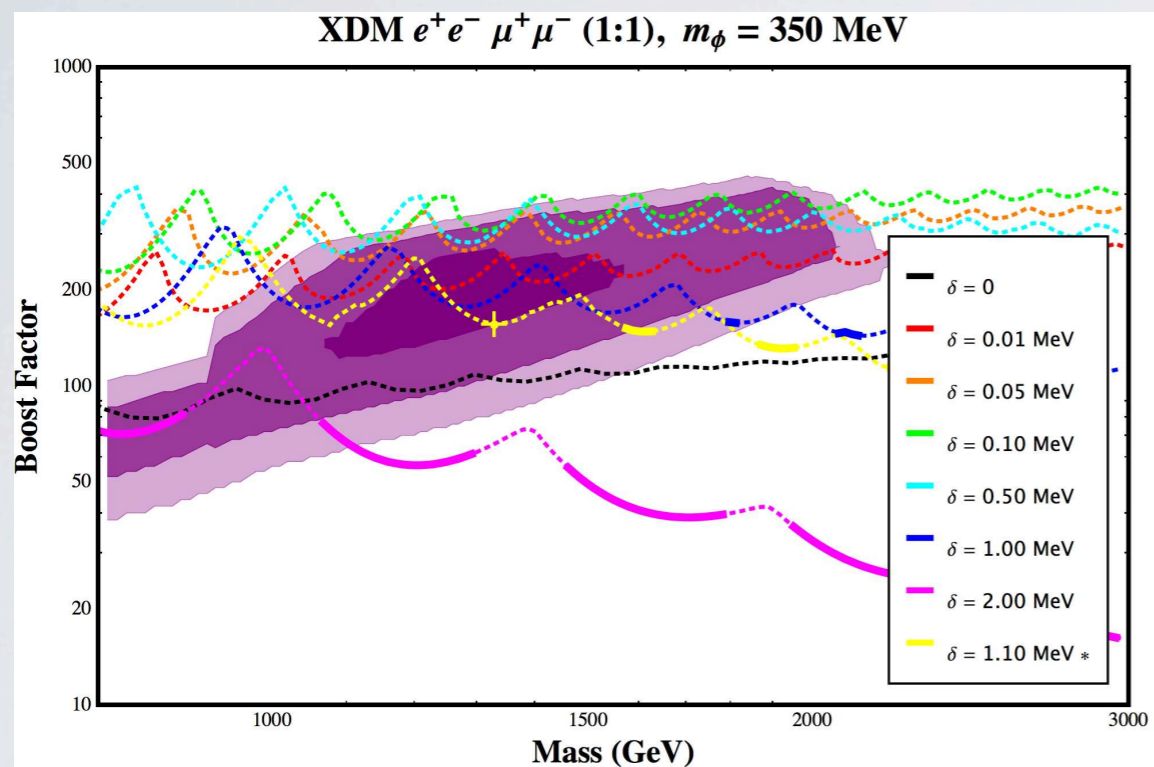


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Large cross section from Sommerfeld enhancement

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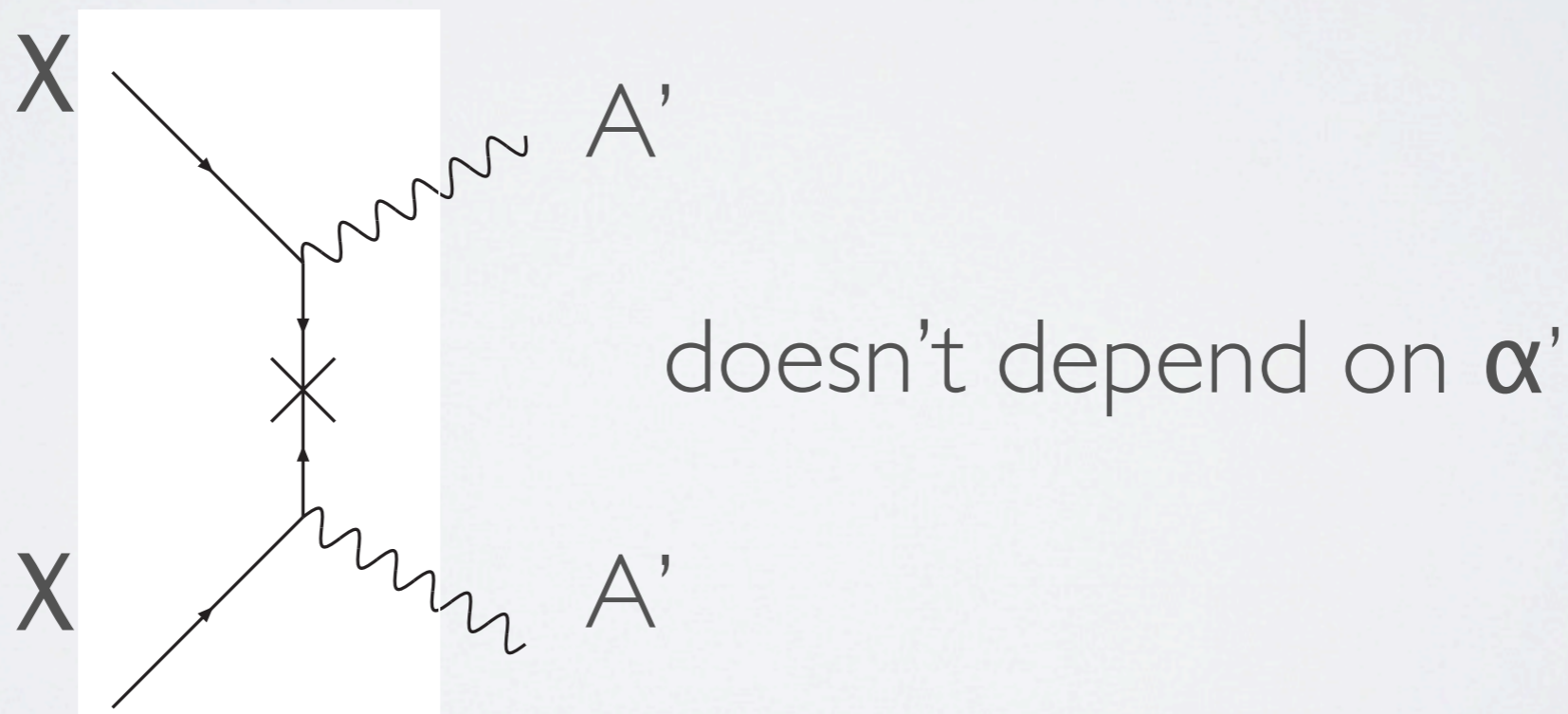
Finkbeiner et al, arxiv1011.3082

- Provides a consistent and testable DM interpretation

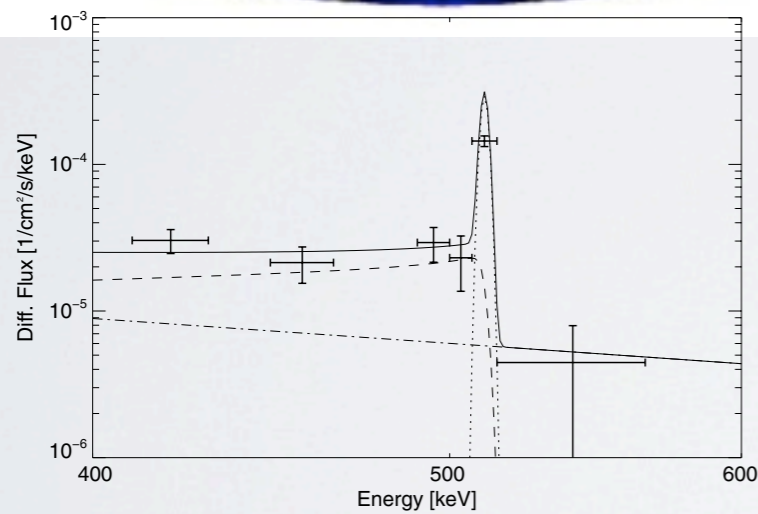
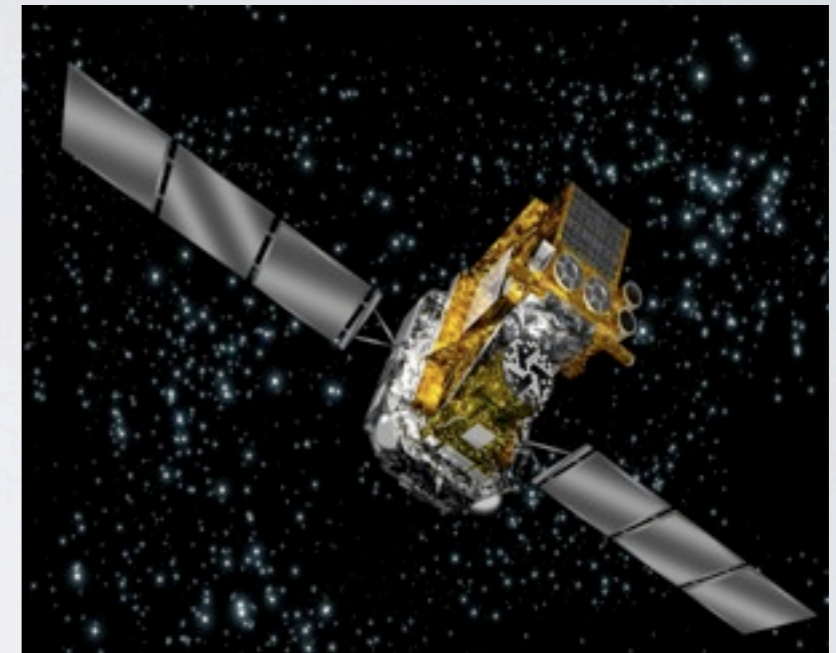
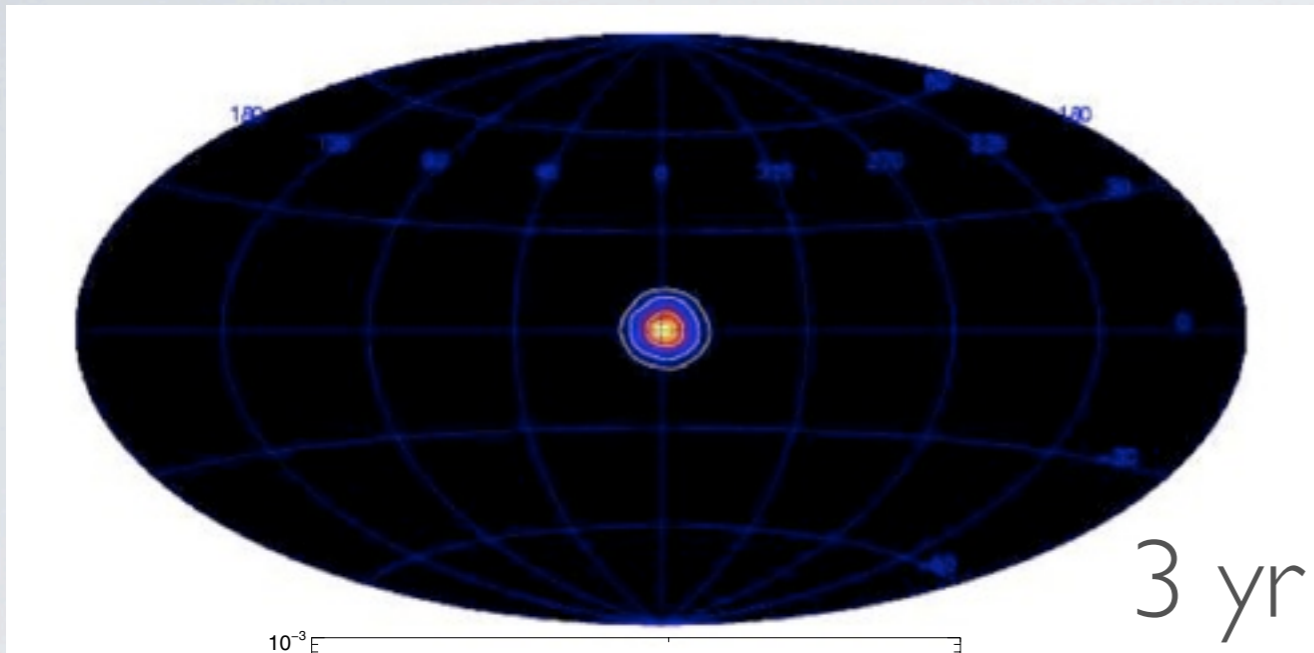


# COSMIC RAYS: PAMELA/FERMI

- Motivates sub-GeV dark photon (determined by spectrum of positrons); typically  $210 \text{ MeV} < m_{A'} < \sim \text{GeV}$



# COSMIC RAYS: INTEGRAL

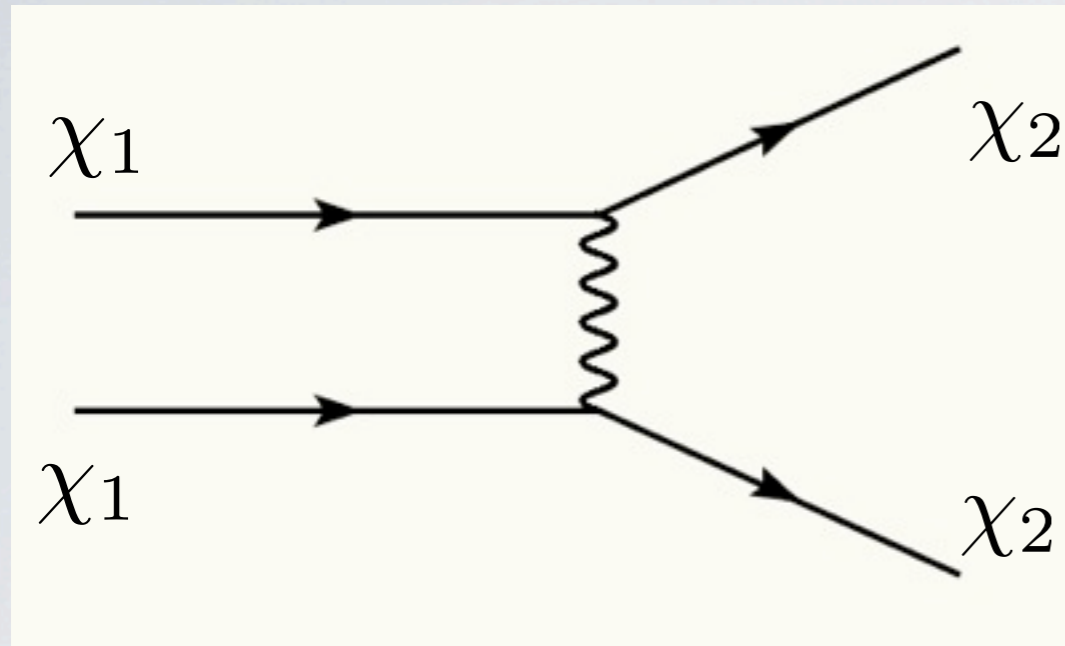


**Fig. 2.** A fit of the SPI result for the diffuse emission from the GC region ( $|l|, |b| \leq 16^\circ$ ) obtained with a spatial model consisting of an  $8^\circ$  FWHM Gaussian bulge and a CO disk. In the fit a diagonal response was assumed. The spectral components are: 511 keV line (dotted), Ps continuum (dashes), and power-law continuum (dash-dots). The summed models are indicated by the solid line. Details of the fitting procedure are given in the text.

Large excess of cosmic ray positrons (low energy)

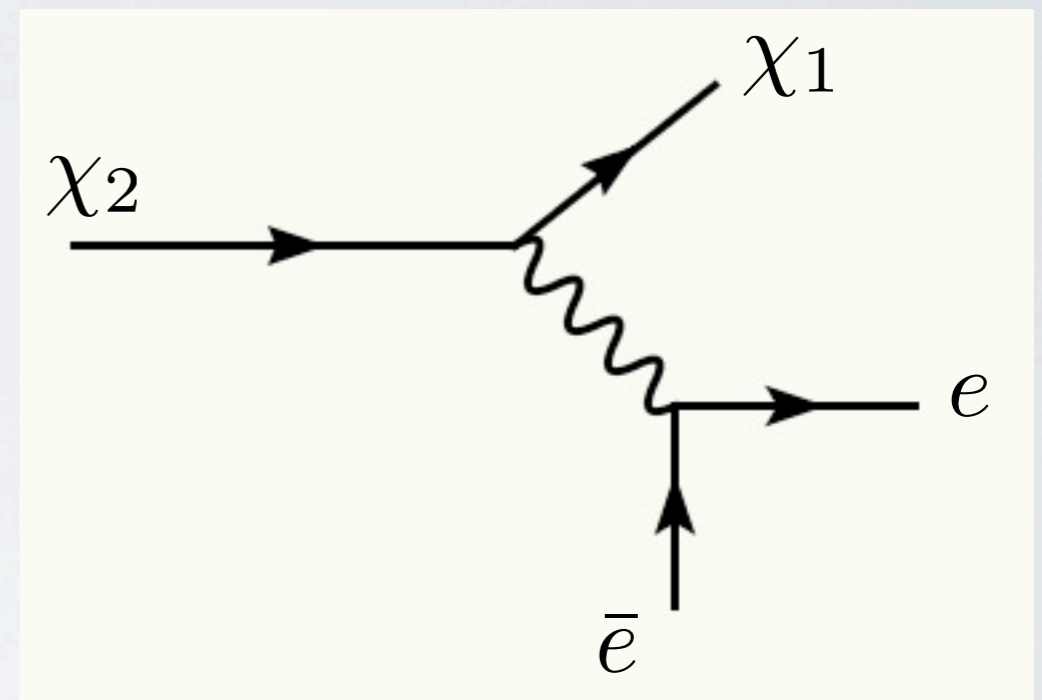


# COSMIC RAYS: INTEGRAL



WIMP-WIMP should induce  
WIMP excitations

subsequent decays should  
produce  $e^+e^-$  pairs

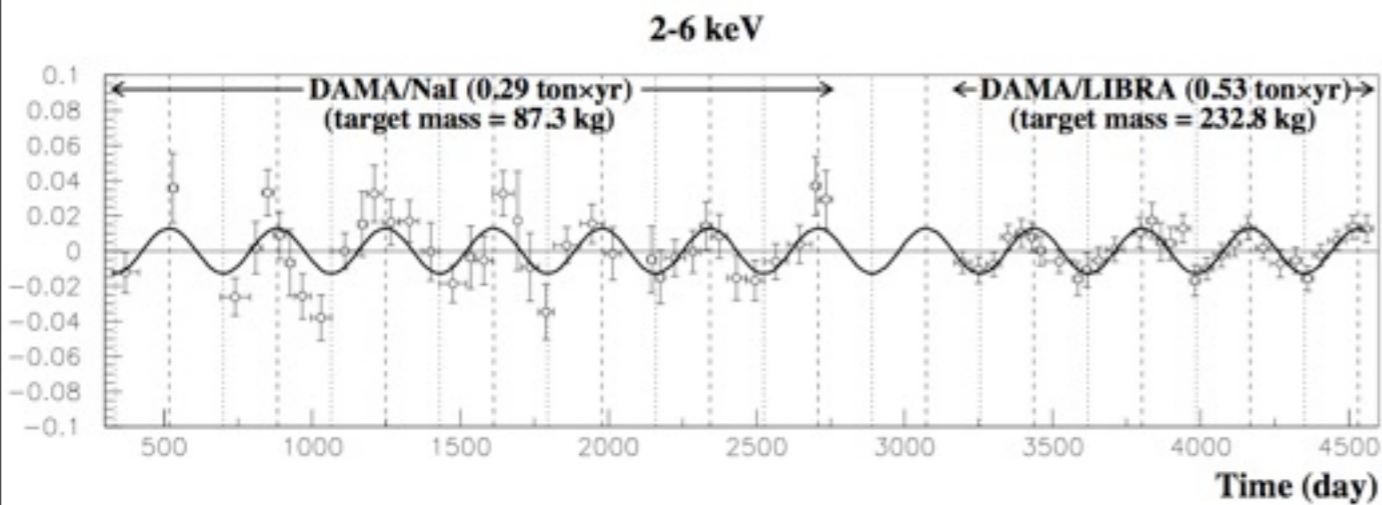


Possible origin for INTEGRAL  
positron excess

D.Finkbeiner, NW, 0702587v2

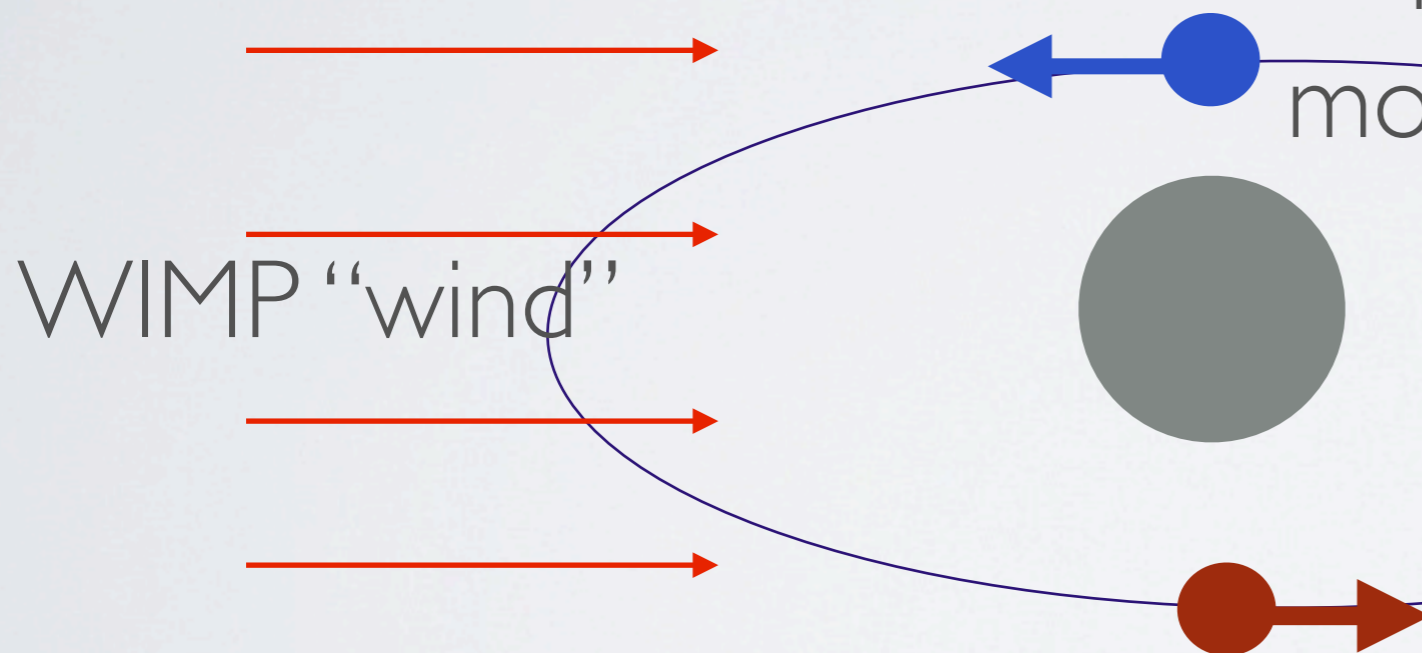
Also no dependence on  $\alpha'$

# DIRECT DETECTION: DAMA



in the summer,  
moving against wind

expect an annual  
modulation in signal!

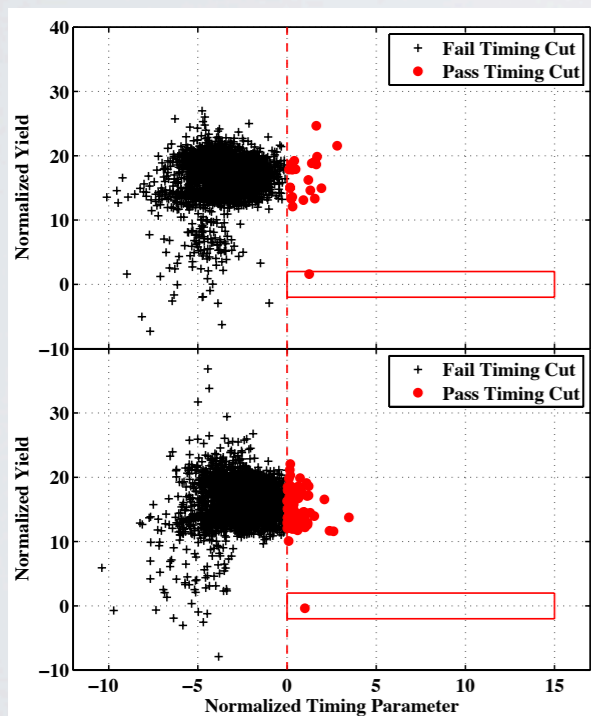
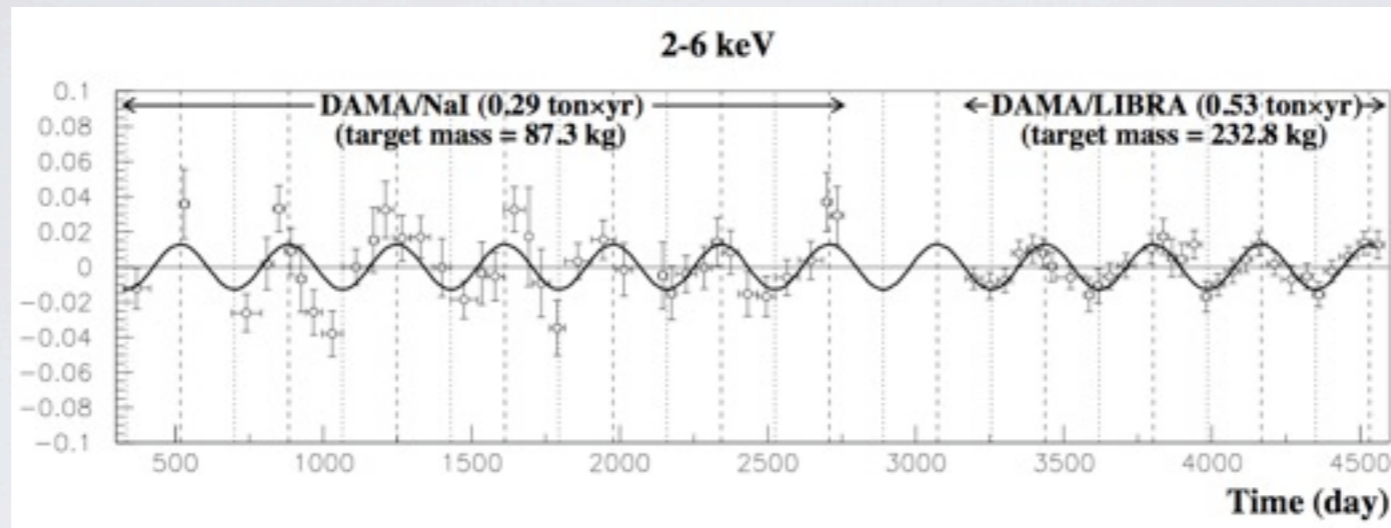


Drukier, Freese, Spergel Phys.Rev.D33:3495-3508, 1985

in the winter, moving with wind

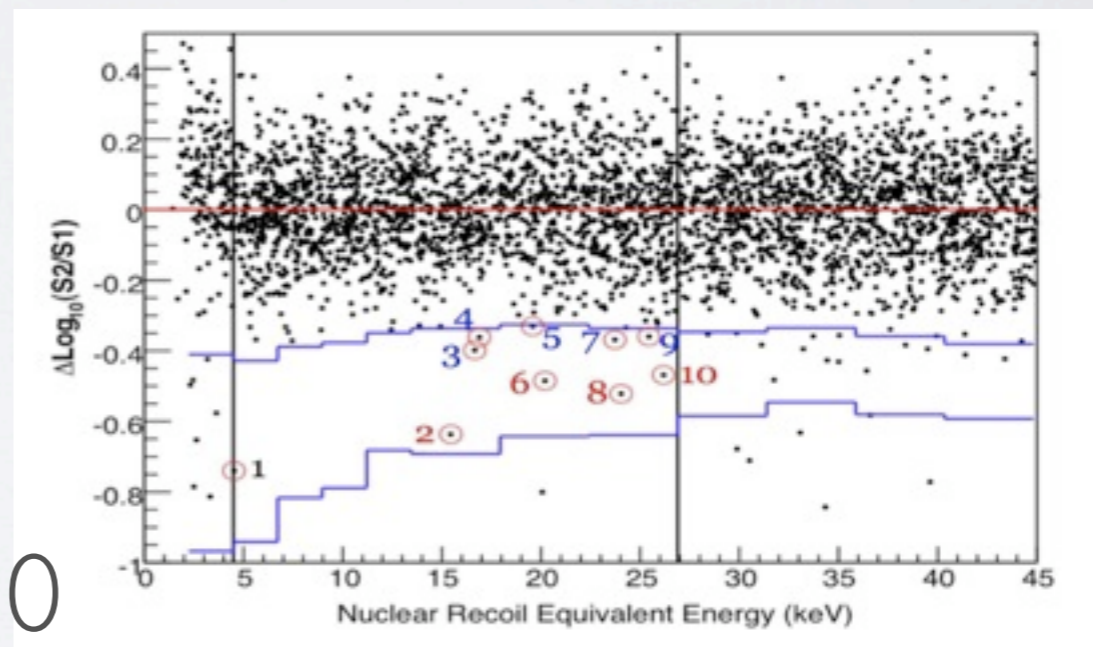


# DIRECT DETECTION: DAMA

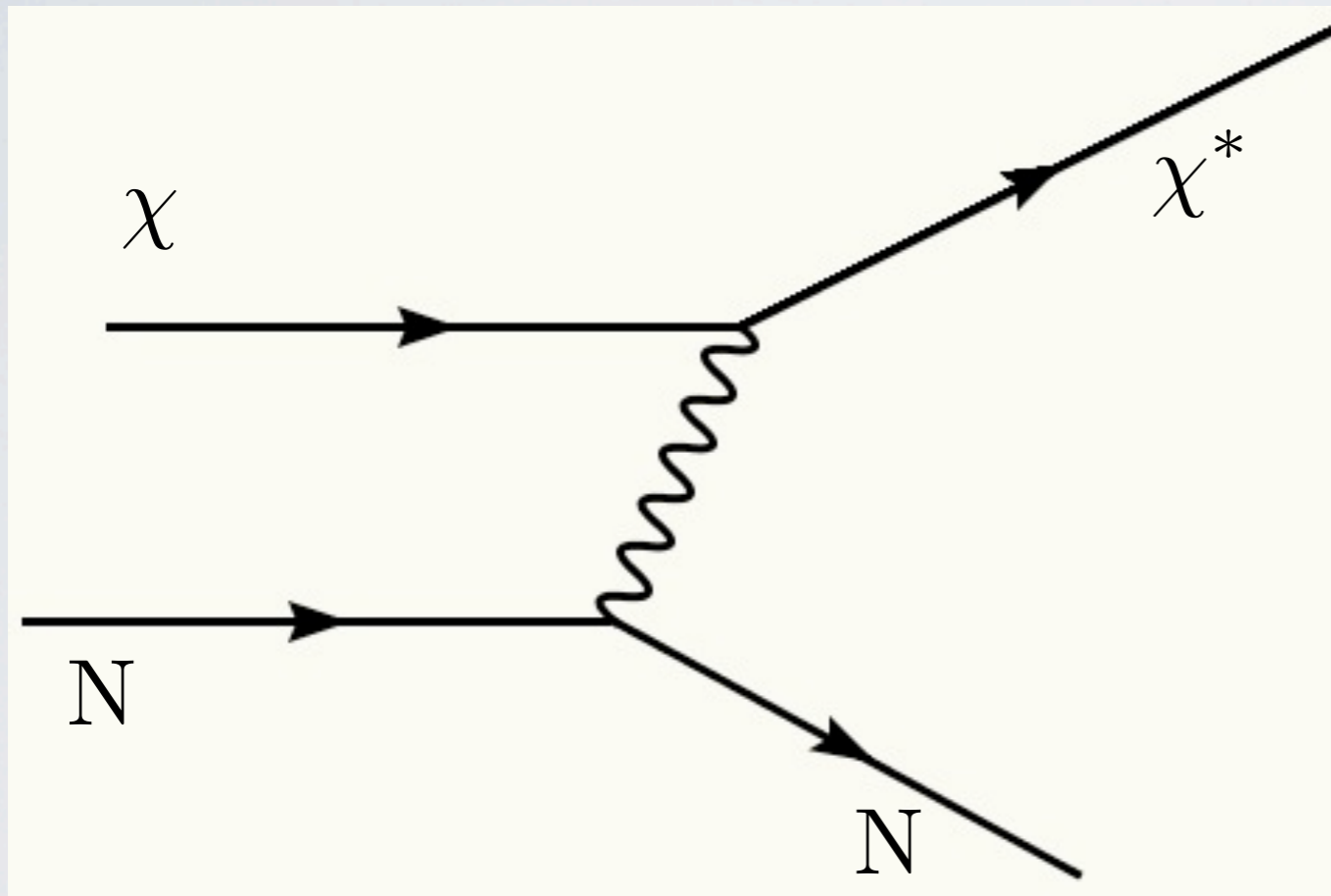


CDMS

XENON10



# DIRECT DETECTION: DAMA

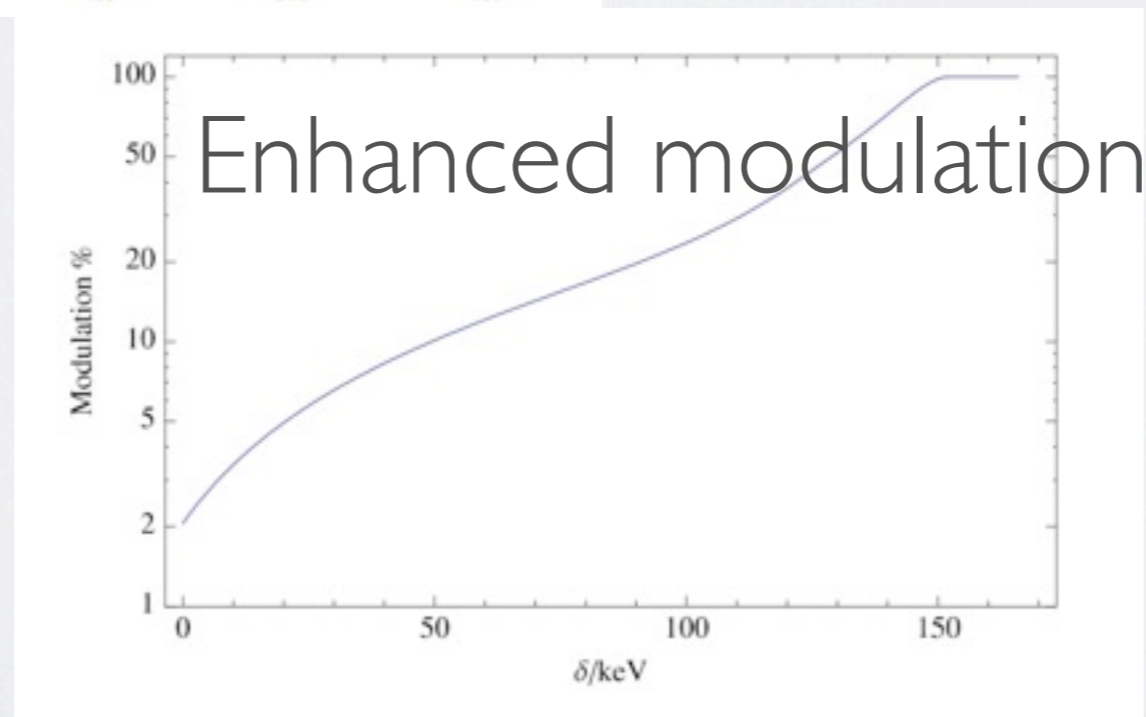
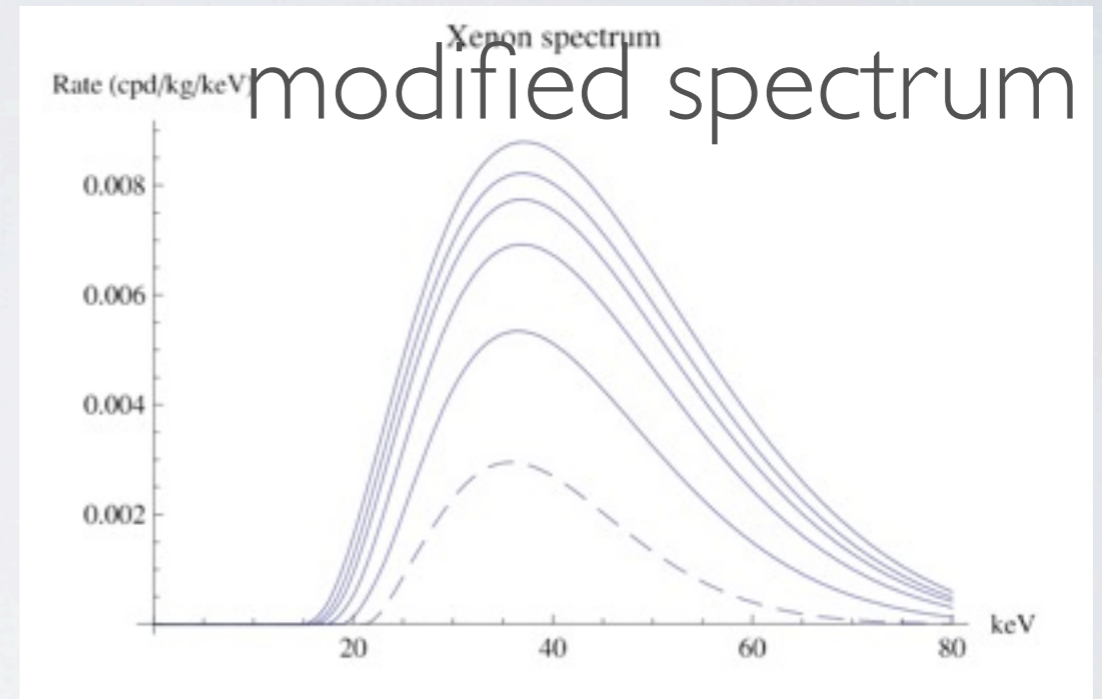
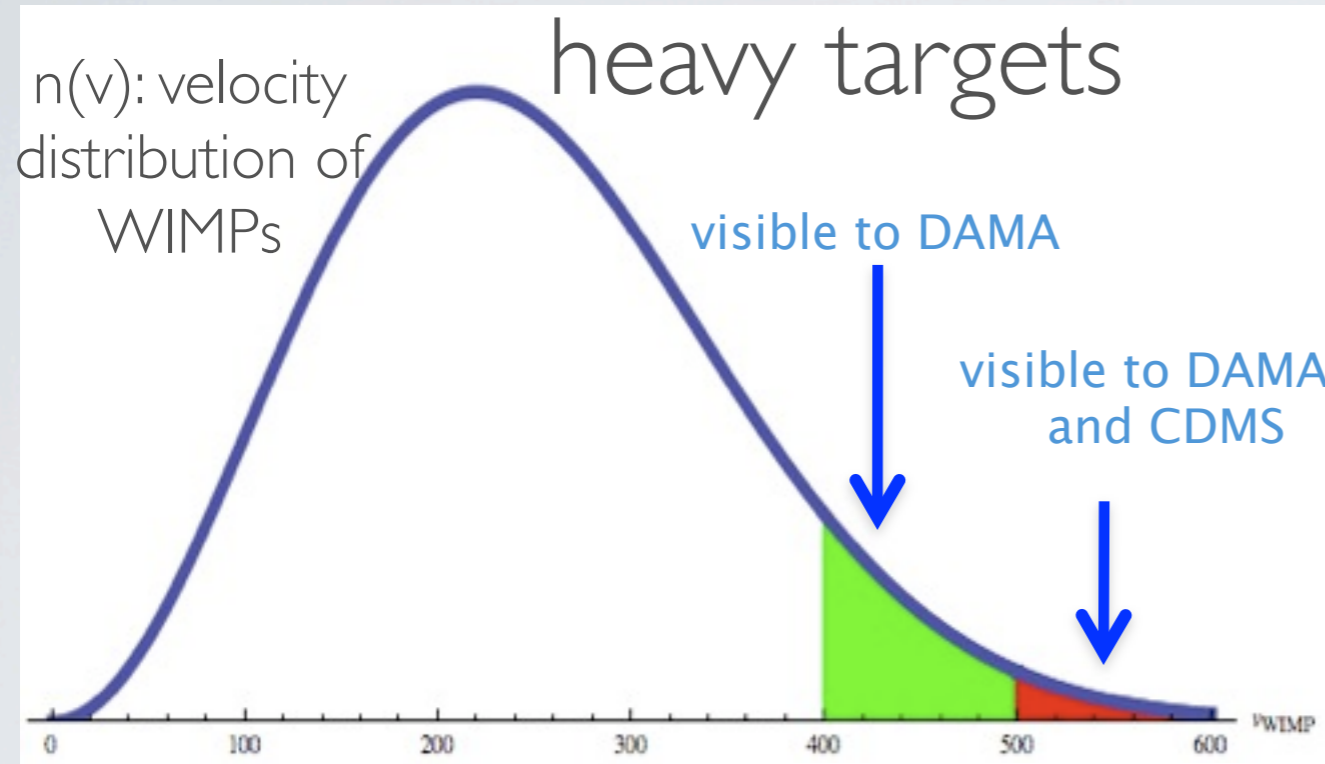


$$\frac{\mu_{\chi N} v^2}{2} > \delta$$

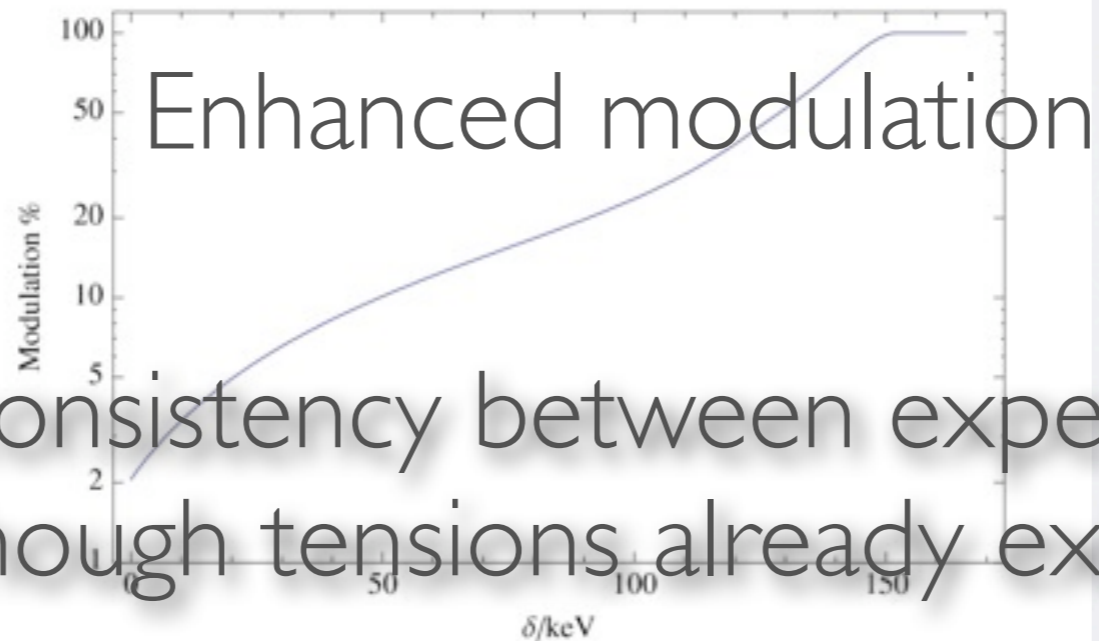
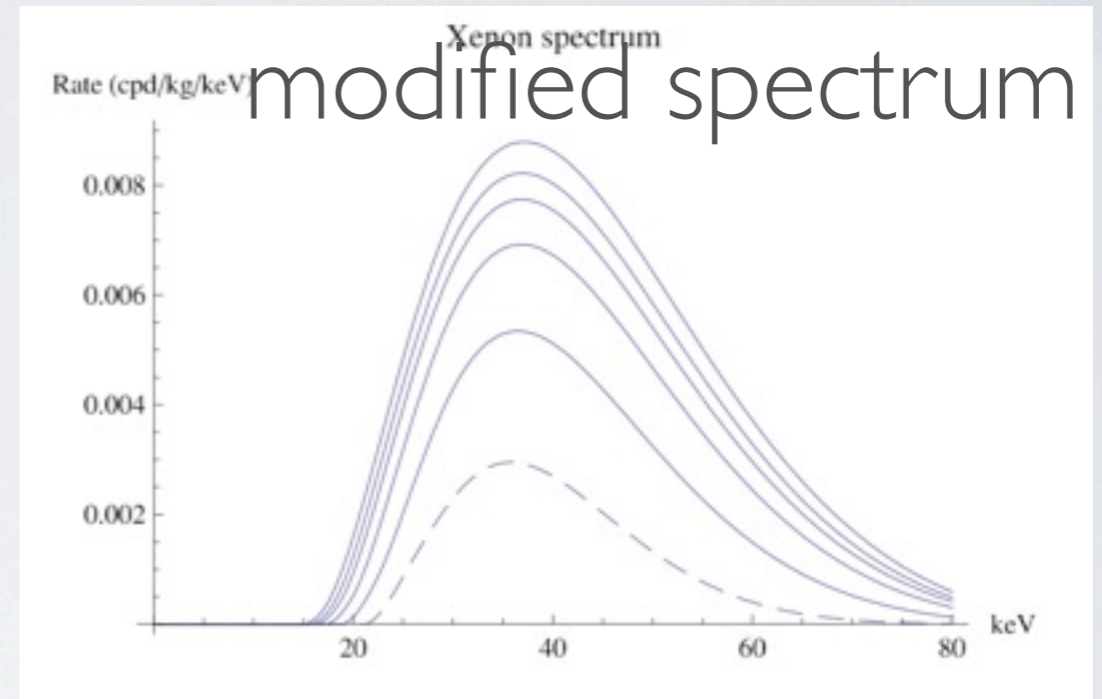
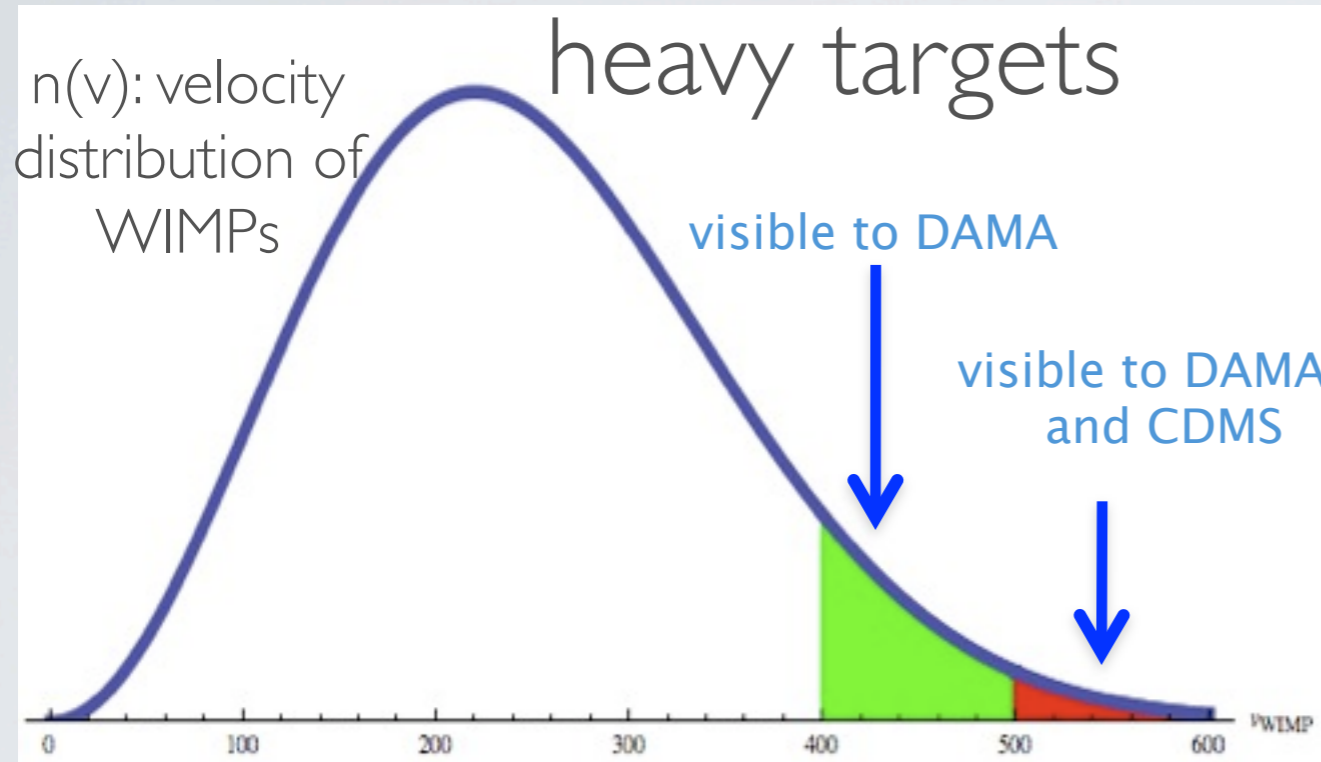
Scattering via dark photon naturally off-diagonal - realization of “inelastic dark matter”



# DIRECT DETECTION: DAMA



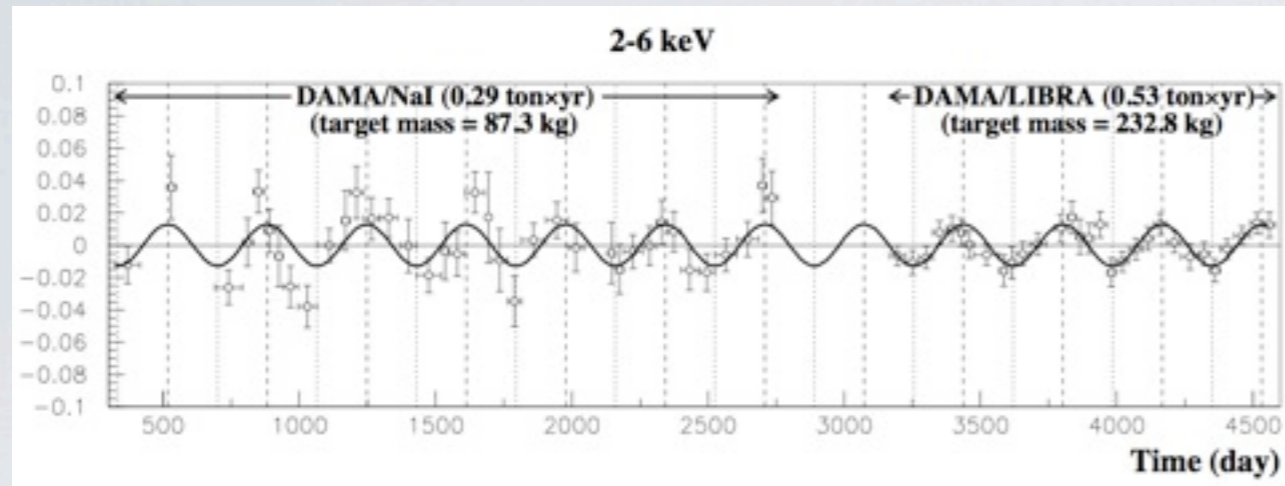
# DIRECT DETECTION: DAMA



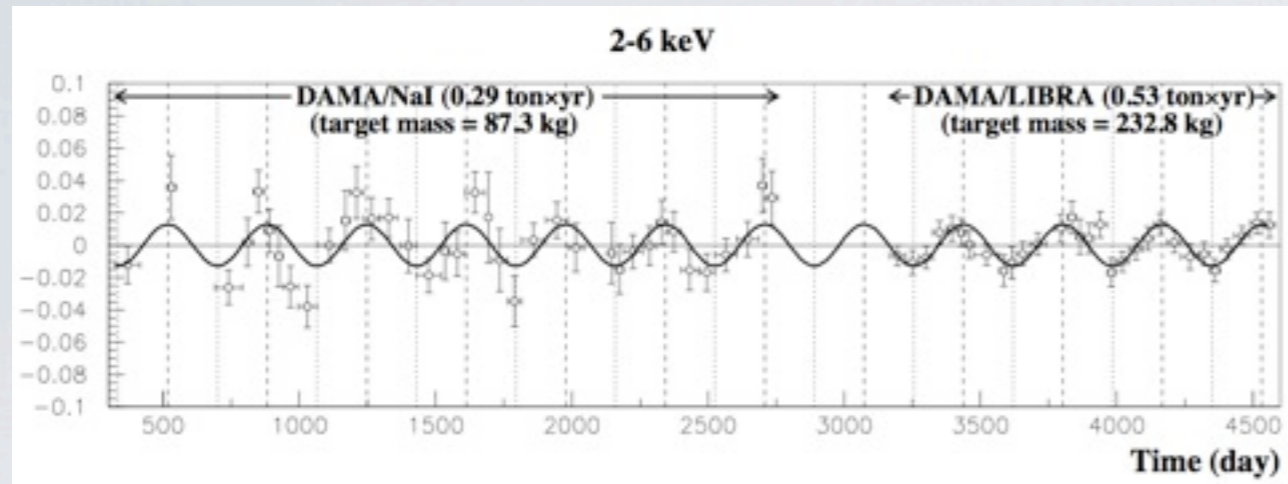
Allows consistency between experiments  
(although tensions already exist)



# LIGHT DARK MATTER



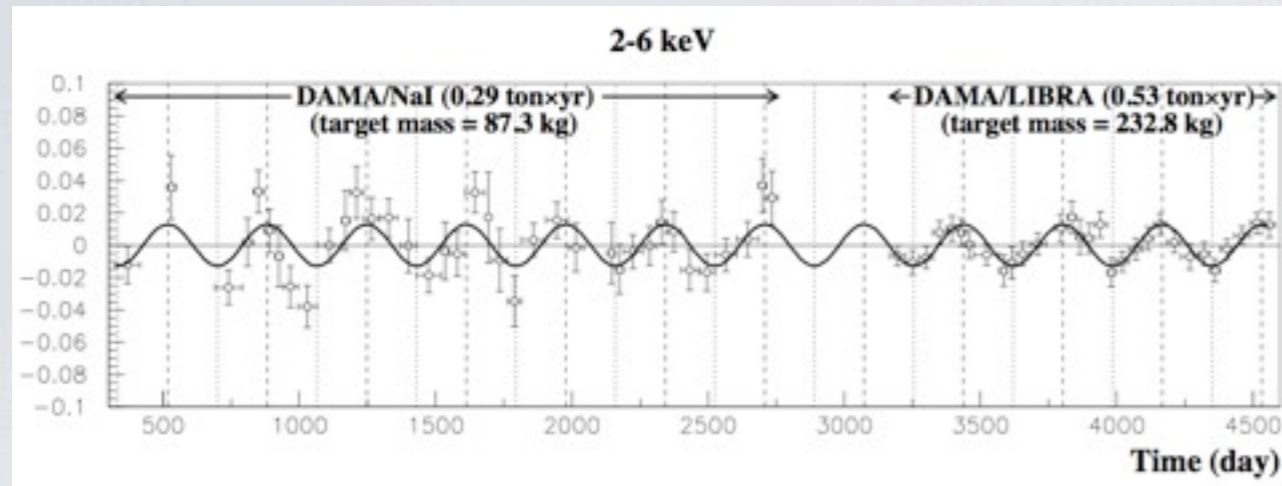
# LIGHT DARK MATTER



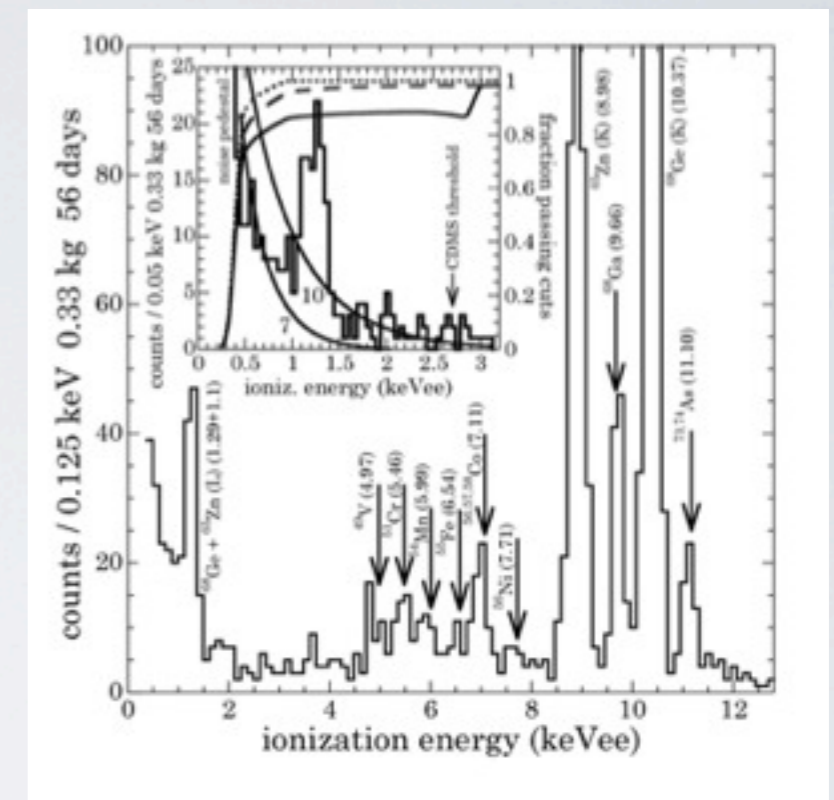
DM Interpretation: variation in WIMP scattering as Earth moves around sun (with and against galactic motion)



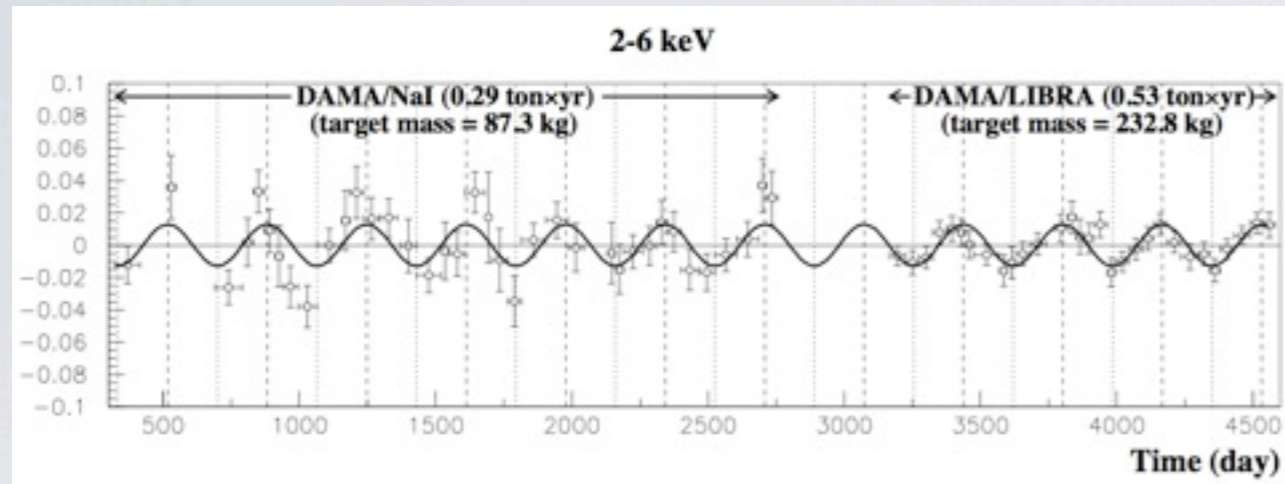
# LIGHT DARK MATTER



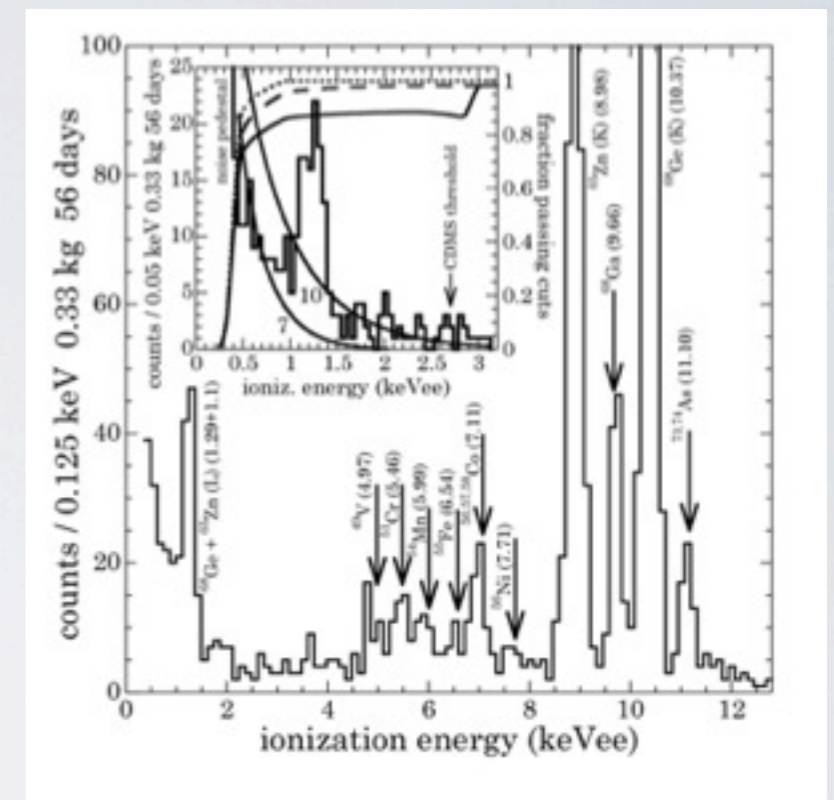
DM Interpretation: variation in WIMP scattering as Earth moves around sun (with and against galactic motion)



# LIGHT DARK MATTER



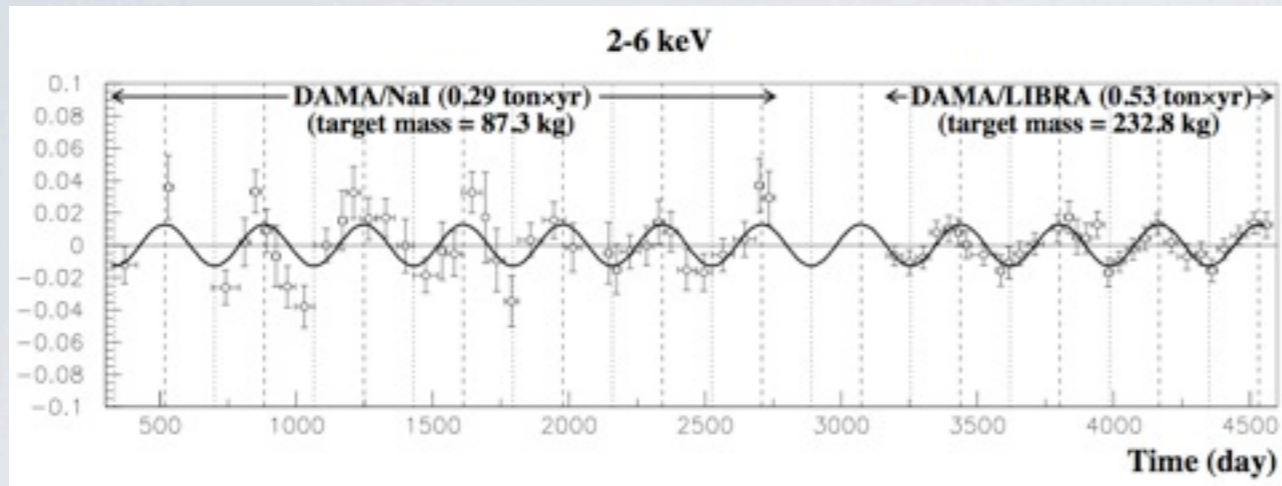
DM Interpretation: variation in WIMP scattering as Earth moves around sun (with and against galactic motion)



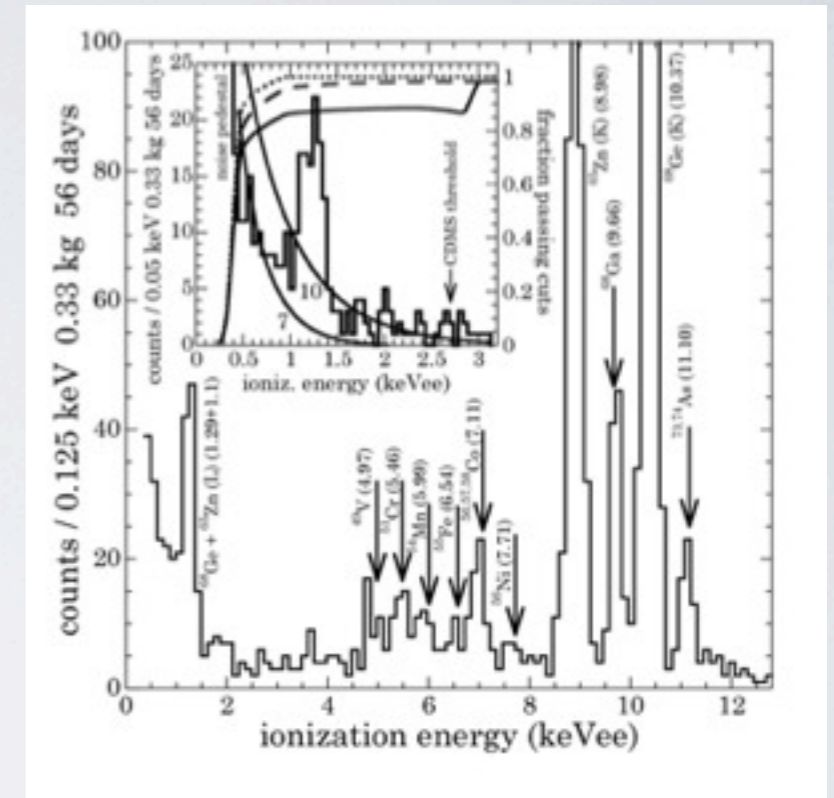
DM Interpretation: elastic scattering of  $\sim 7\text{GeV}$  WIMP



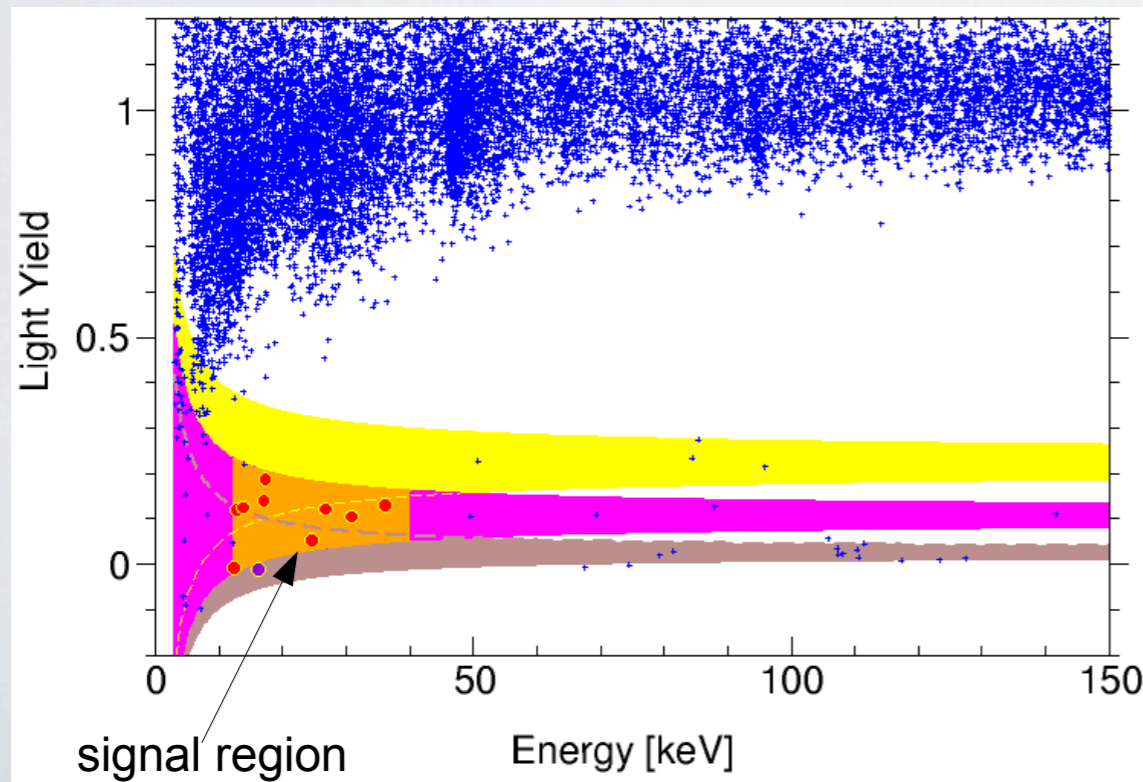
# LIGHT DARK MATTER



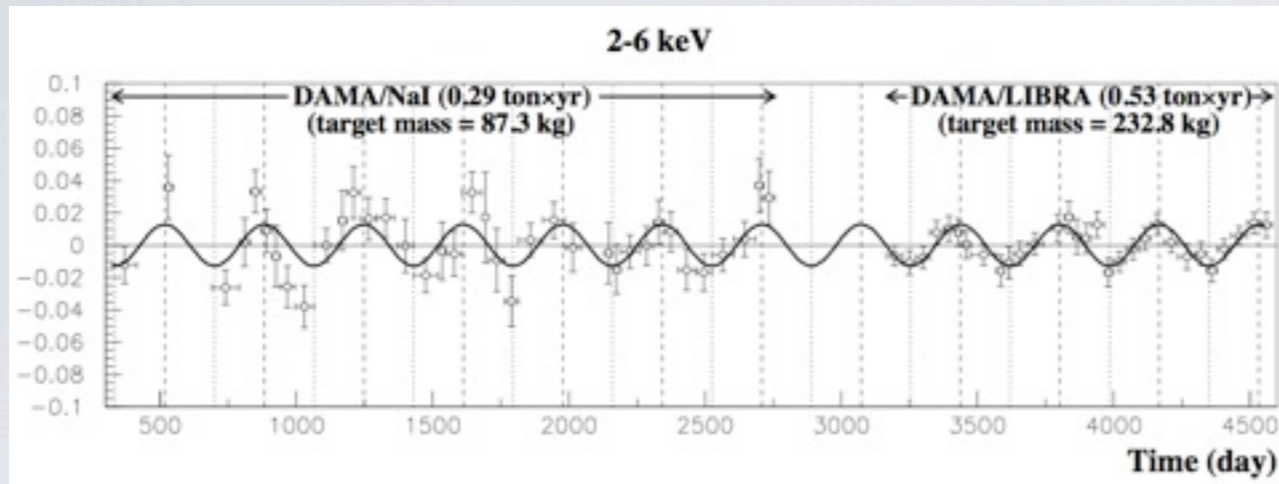
DM Interpretation: variation in WIMP scattering as Earth moves around sun (with and against galactic motion)



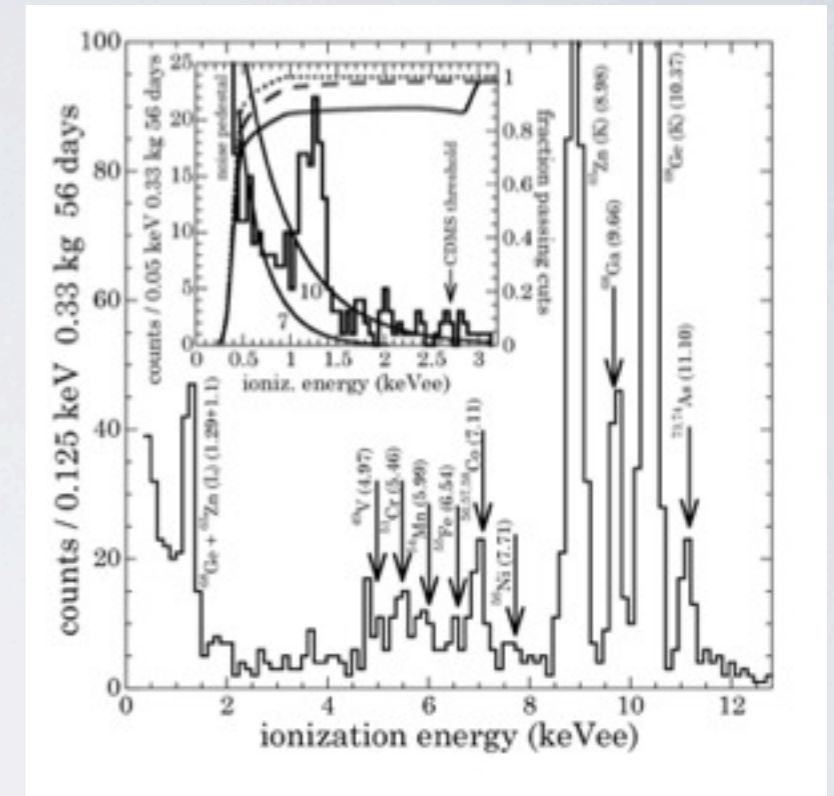
DM Interpretation: elastic scattering of  $\sim 7\text{GeV}$  WIMP



# LIGHT DARK MATTER

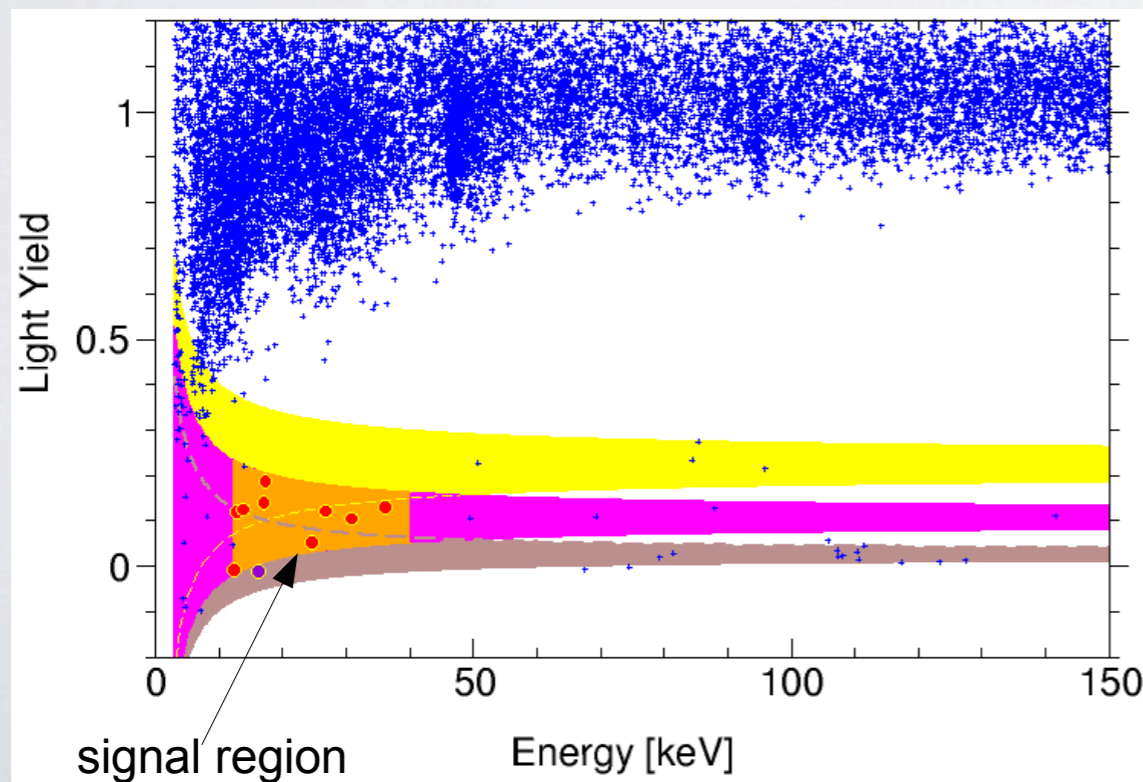


DM Interpretation: variation in WIMP scattering as Earth moves around sun (with and against galactic motion)



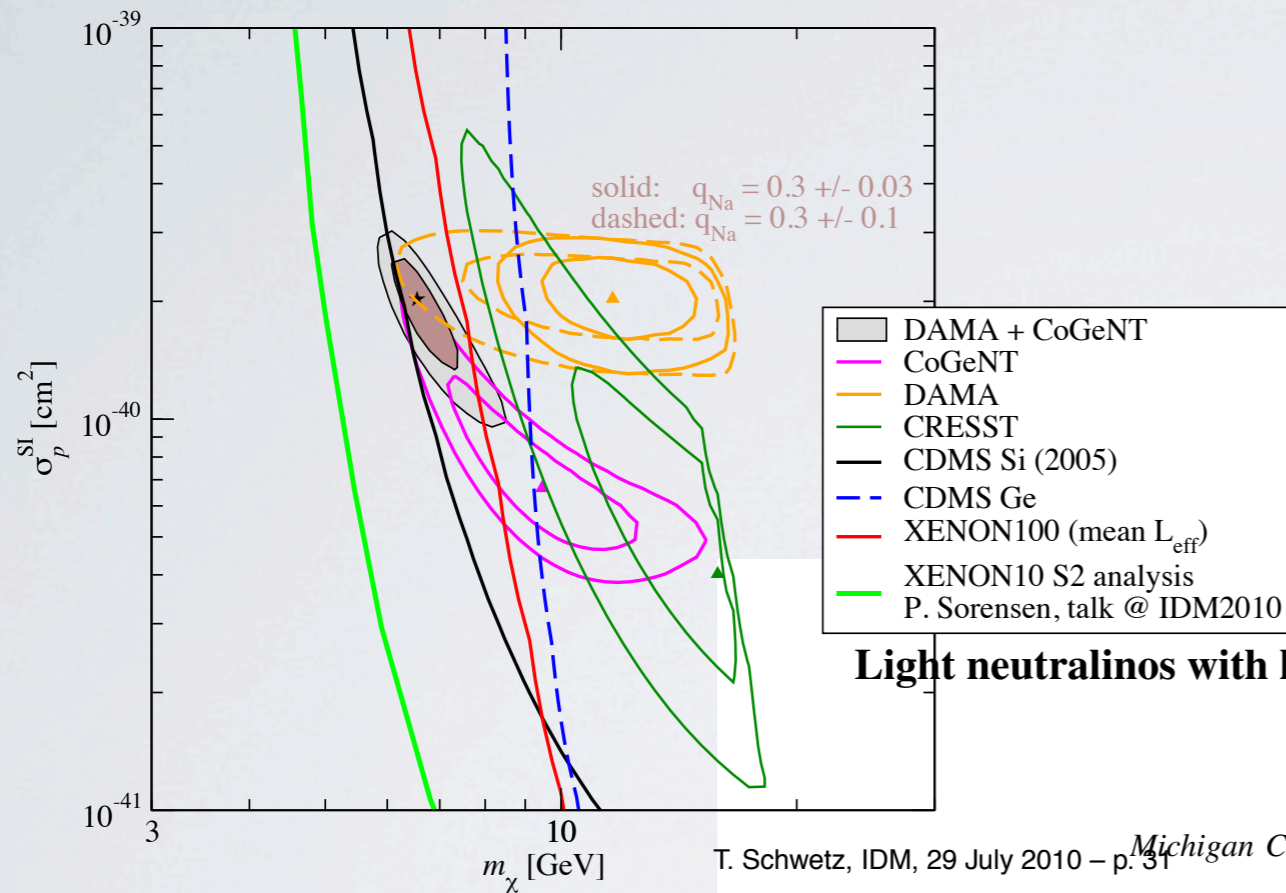
DM Interpretation: elastic scattering of  $\sim 7\text{GeV}$  WIMP

DM Interpretation: unquantified (**pre-announced March 2010**) "Light" WIMP





# LIGHT DARK MATTER



## Light neutralinos with large scattering cross sections in the minimal supersymmetric standard model

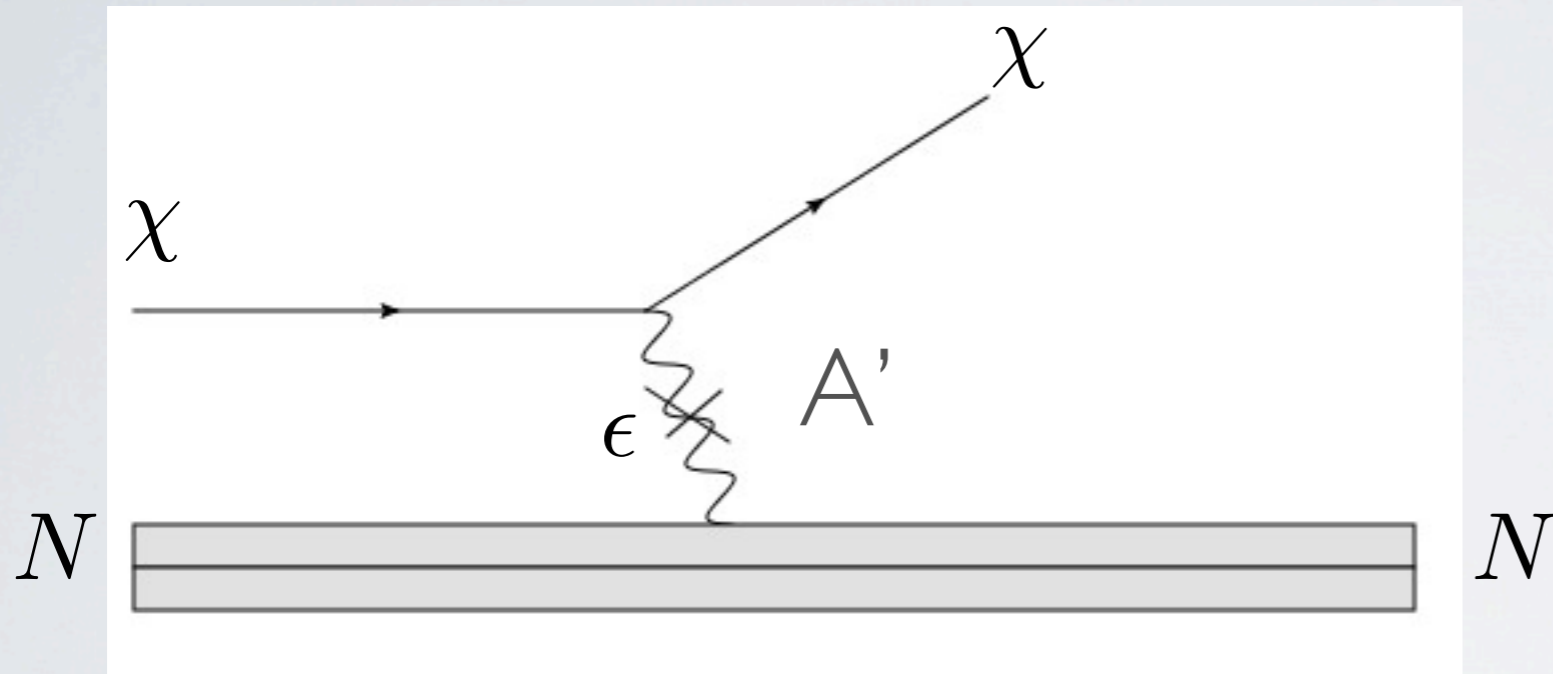
Eric Kuflik, Aaron Pierce, and Kathryn M. Zurek

Michigan Center for Theoretical Physics, University of Michigan, Ann Arbor, MI 48109

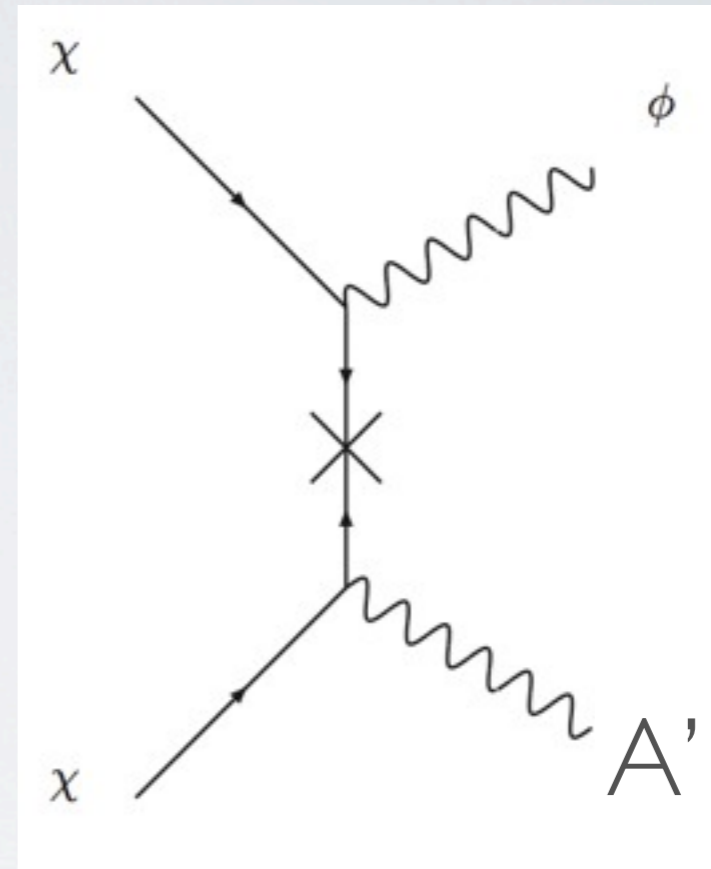
(Dated: July 20, 2010)

Motivated by recent data from CoGeNT and the DAMA annual modulation signal, we discuss collider constraints on minimal supersymmetric standard model neutralino dark matter with mass in the 5-15 GeV range. The lightest superpartner (LSP) would be a bino with a small Higgsino admixture. Maximization of the dark matter-nucleon scattering cross section for such a weakly interacting massive particle requires a light Higgs boson with  $\tan \beta$  enhanced couplings. Limits on the invisible width of the  $Z$  boson, combined with the rare decays  $B^\pm \rightarrow \tau \nu$ , and the ratio  $B \rightarrow D \tau \nu / B \rightarrow D \ell \nu$ , constrain cross sections to be below  $\sigma_n \lesssim 5 \times 10^{-42} \text{ cm}^2$ . This indicates a higher local Dark Matter density than is usually assumed by a factor of roughly six would be necessary to explain the CoGeNT excess. This scenario also requires a light charged Higgs boson, which can give substantial contributions to rare decays such as  $b \rightarrow s \gamma$  and  $t \rightarrow b H^+$ . We also discuss the impact of Tevatron searches for Higgs bosons at large  $\tan \beta$ .

# LIGHT DARK MATTER



$$\sigma \approx \frac{\alpha_d \alpha_{EM} \epsilon^2}{m_\phi^4}$$

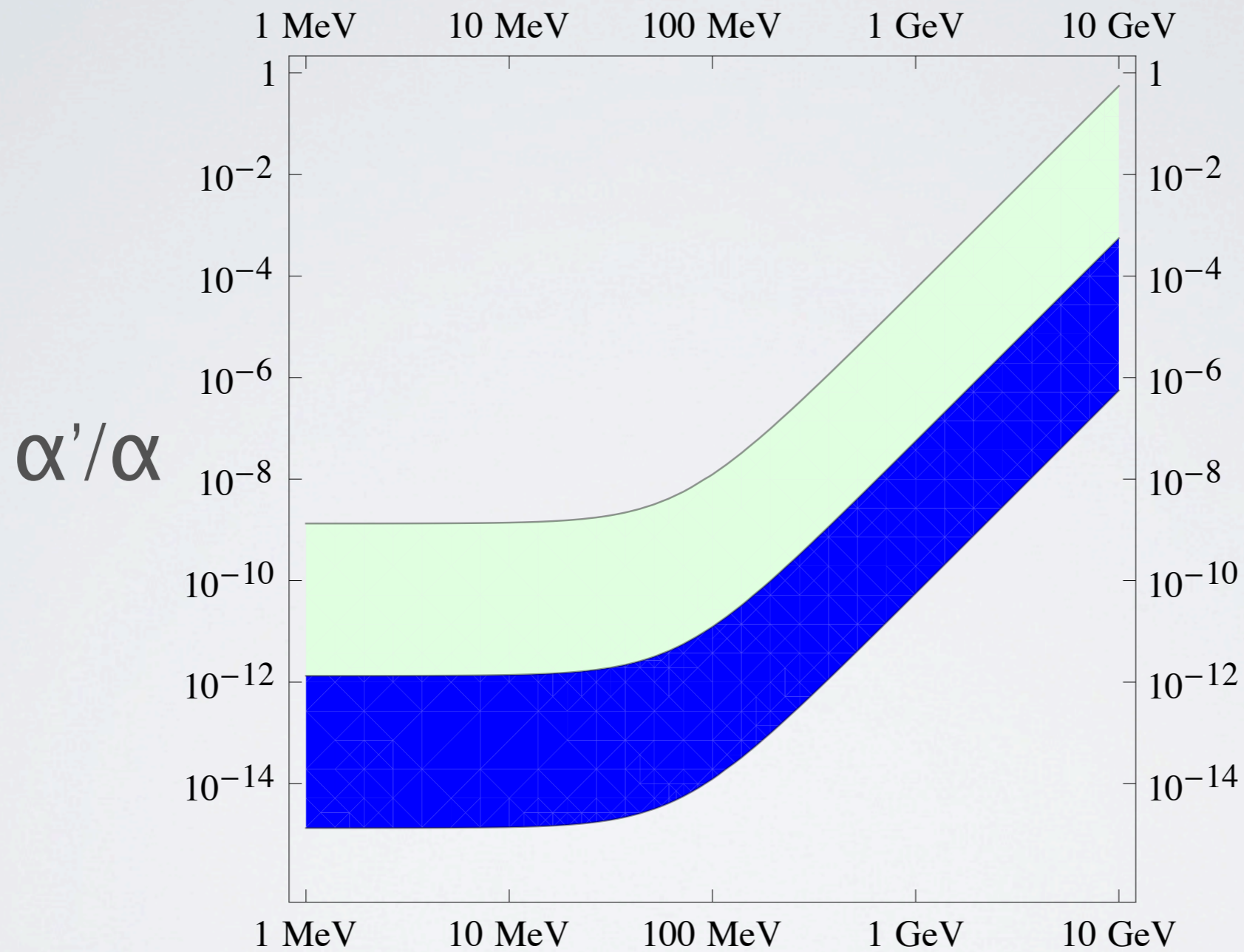


$$\sigma \approx \frac{\alpha_d^2}{m_\chi^2}$$

allows large cross section with reasonable relic abundance



# DARK MATTER



NB:  $\text{rate} \sim \frac{\rho}{m_\chi} \sigma \sim \frac{m_\chi}{\alpha_d^2} \times \frac{\alpha_d \alpha'}{m_{A'}^4}$

# HOW TO FIND A DARK PHOTON



# HOW TO FIND A DARK PHOTON

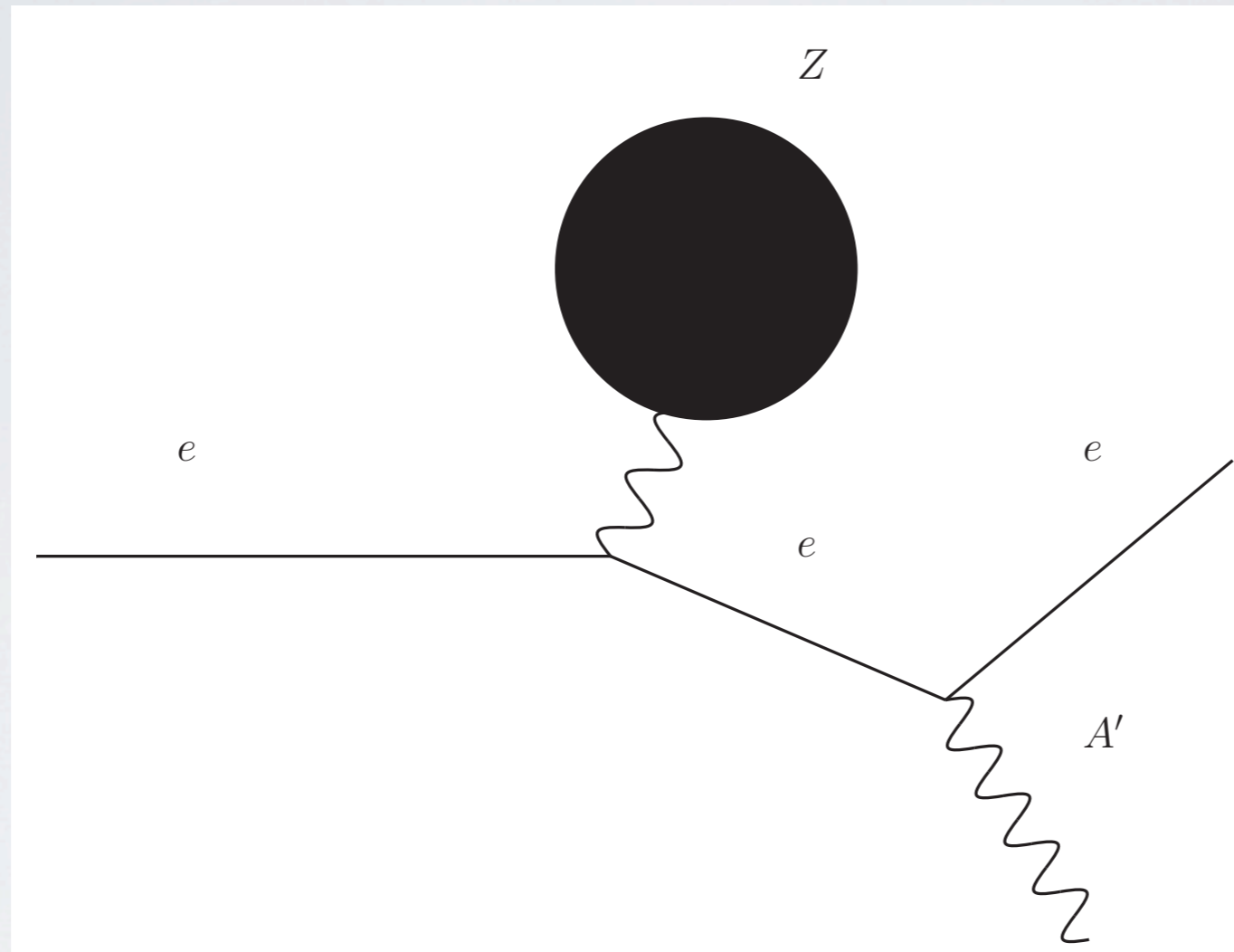
- Rare process
  - High luminosity
  - Extremely low backgrounds

# HOW TO FIND A DARK PHOTON

- Rare process
  - High luminosity
  - Extremely low backgrounds
- LHC complementary as produceable in SUSY cascade decays
  - Cascades fairly unique to SUSY
  - Much harder to directly discover



# HOW TO FIND A DARK PHOTON



Find  $A'$  via spectrometry, vertexing ( $A'$  decays), or  
“MET” (target recoil)

# HOW TO FIND A DARK PHOTON



# HOW TO FIND A DARK PHOTON

- Additional complications:

# HOW TO FIND A DARK PHOTON

- Additional complications:
  - decay modes?



# HOW TO FIND A DARK PHOTON

- Additional complications:
  - decay modes?
- Even when motivated by cosmic rays, don't know that strongest coupled  $A'$  decays to charged pairs

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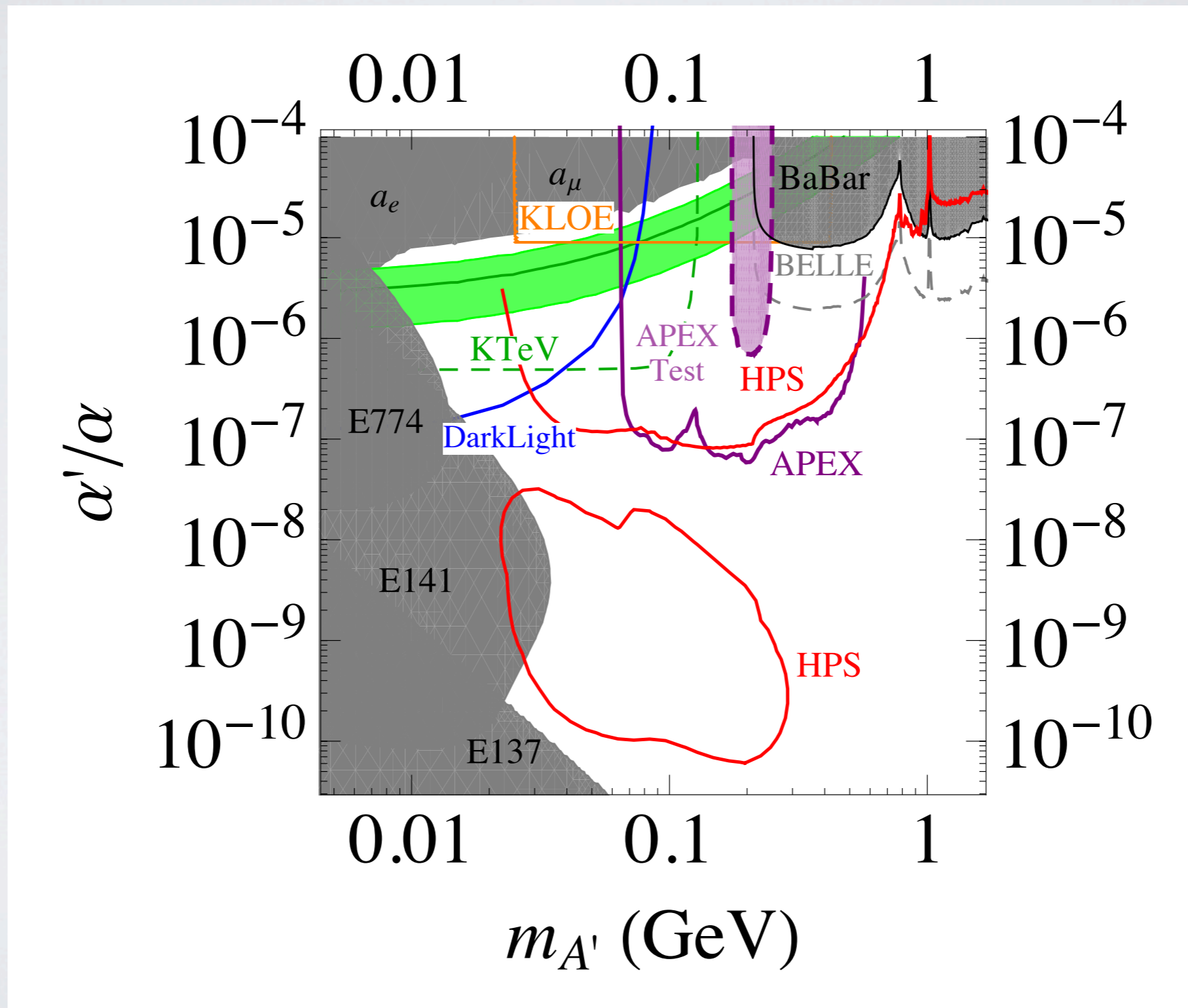
- Additional complications:
  - decay modes?
- Even when motivated by cosmic rays, don't know that strongest coupled  $A'$  decays to charged pairs
- Non-Abelian models can be very complicated



# HOW TO FIND A DARK PHOTON

- Additional complications:
  - decay modes?
- Even when motivated by cosmic rays, don't know that strongest coupled  $A'$  decays to charged pairs
- Non-Abelian models can be very complicated
- Important to develop general approaches for the future

# NEAR TERM REACH OF JLAB





# WHAT WOULD HAPPEN IF IT WERE FOUND

- The discovery of the “Theory Space Landscape”
- immediate need for confirmation/redundancy

# COPERNICUS 2011



# COPERNICUS 2011

- Jefferson Lab has the opportunity to be the LHC of weakly coupled physics

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- Accessible parameter space is motivated, but not converse



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# COPERNICUS 2011

- Jefferson Lab has the opportunity to be the LHC of weakly coupled physics
- Accessible parameter space is motivated, but not converse
- Need redundant experiments - multiple decay modes
- This is only the beginning: need development of future techniques
- Potential impact - while speculative - to rival LHC