Indirect Probes of the Hidden Sector

February 2010

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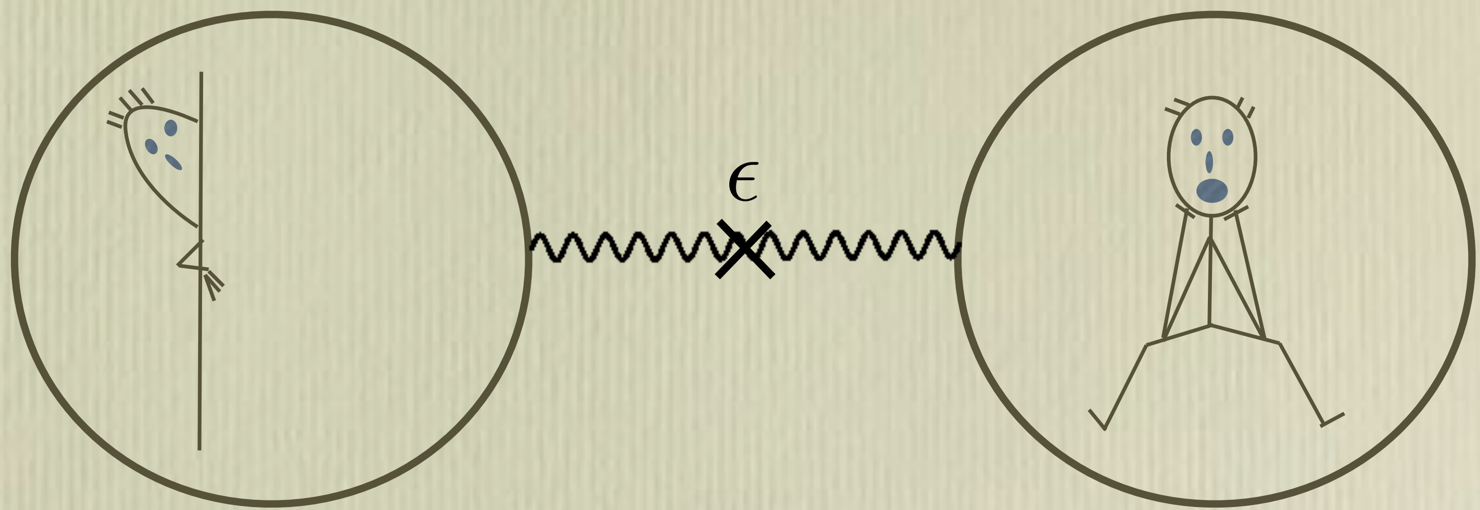
Based on:

P. Meade, M. Papucci, TV, {arXiv:0901,2925}.
P. Meade, M. Papucci, A. Strumia, TV, {arXiv:0905.0480}.
J.Ruderman, TV, {arXiv:0907.4373}.
J.Ruderman, TV, {arXiv:0908.1570}.
P. Meade, S. Nussinov, M. Papucci, TV, {0910.4160}.

Low Scale Hidden Sectors?



Intriguing idea. May be motivated by:

- Fine tuning in SUSY models (hidding the Higgs).
  [Falkowski,Ruderman,TV,Zupan, 2010]
- Recent cosmic-ray anomalies.
  [Cholis,Goodenough,Weiner, 2008; Arkani-Hamed,Finkbeiner,Slatyer,Weiner 2008...]
- Some string theory constructions.
- LHC phenomenology (hidden valleys). [Strassler,Zurek, 2006]
- ...

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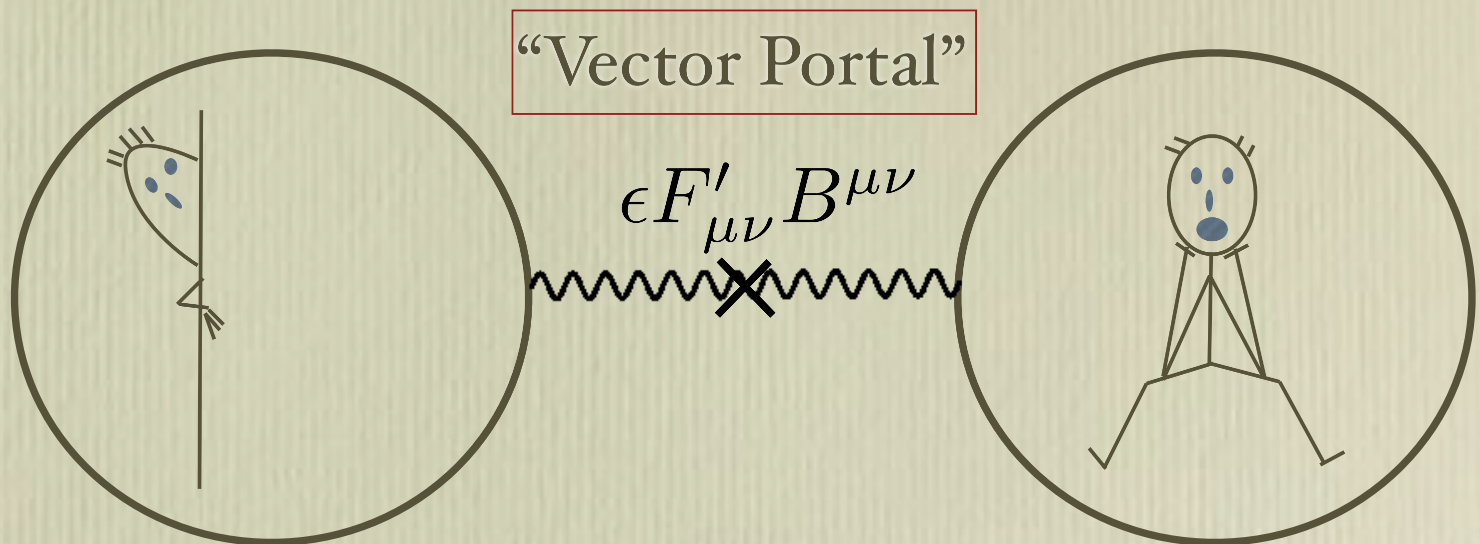

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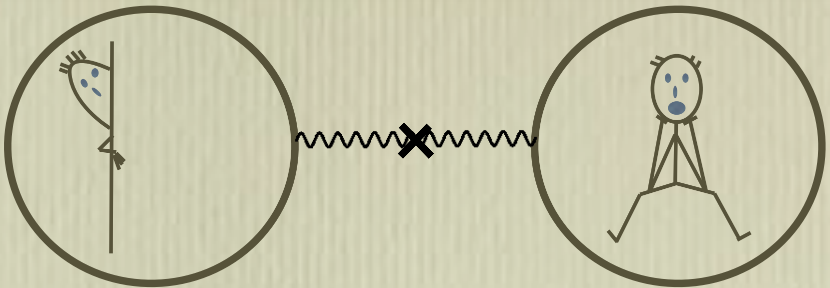
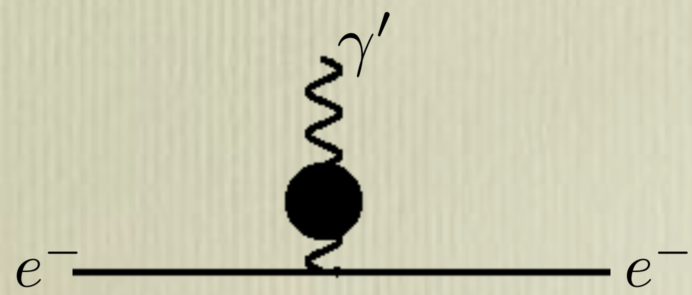
Vector Portal



- For concreteness, we'll assume that the hidden sector contains a new force (new, dark photon).
- Mass of dark photon ~ GeV.
- Then the SM fields are charged under new force:



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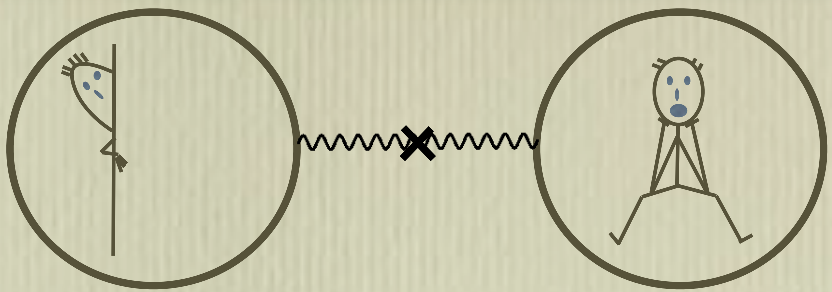

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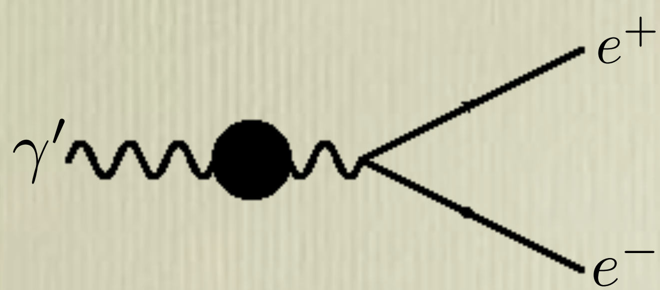
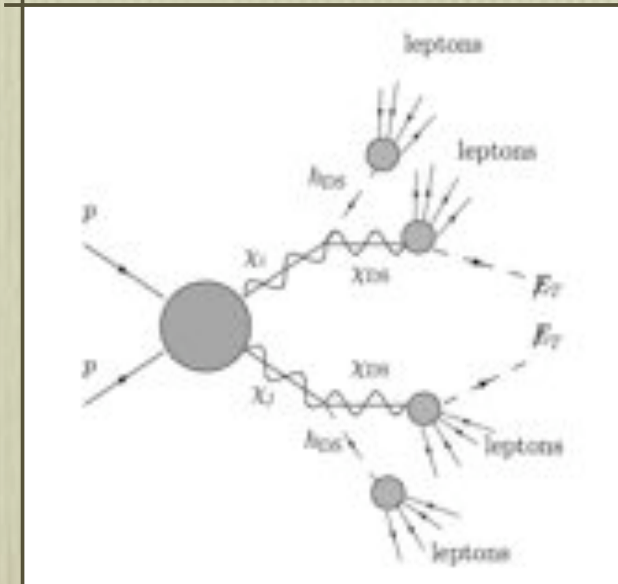


- The new photon can also decay into SM particles.

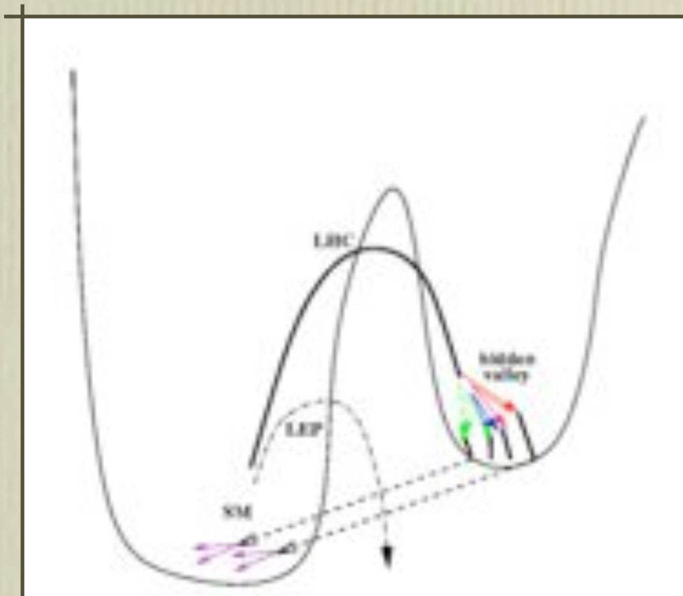
Experimental Probes: Direct

The hidden sector can be probed directly by various experiments:

- High-Energy colliders. $\epsilon \lesssim 10^{-6} - (10^{-9}?)$



Baumgart et. al. 2009



Strassler 2008

[Strassler,Zurek 2006, Arkani-Hamed,Weiner 2008, Baumgart et. al. 2009,..]

Experimental Probes: Direct

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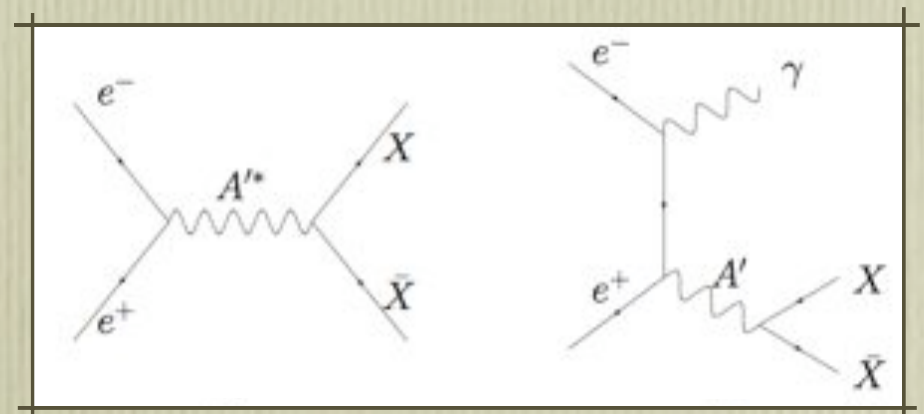

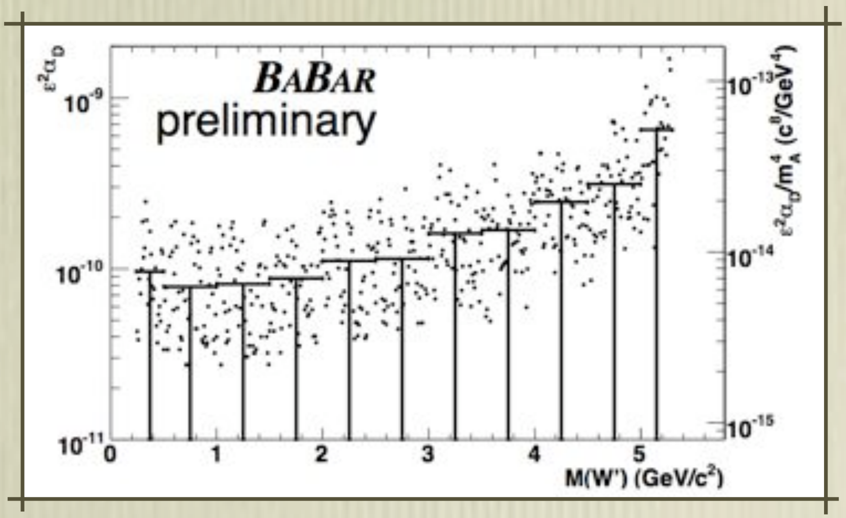

[Essig,Schuster,Toro 2009; Reece,Wang 2009; BaBar Collabration 2009; Freytsis,Ovanesyan,Thaler 2009;...]

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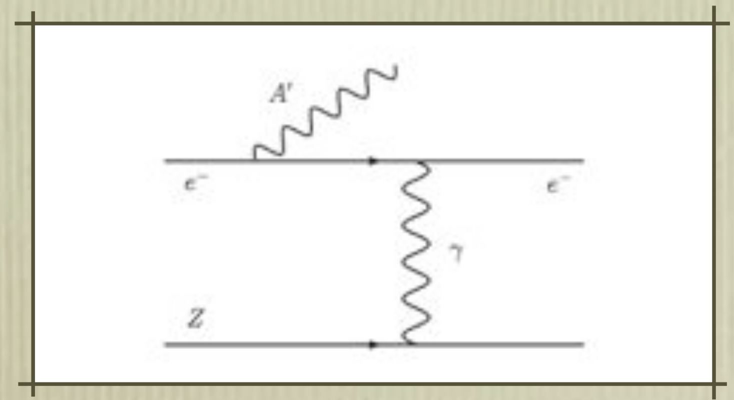

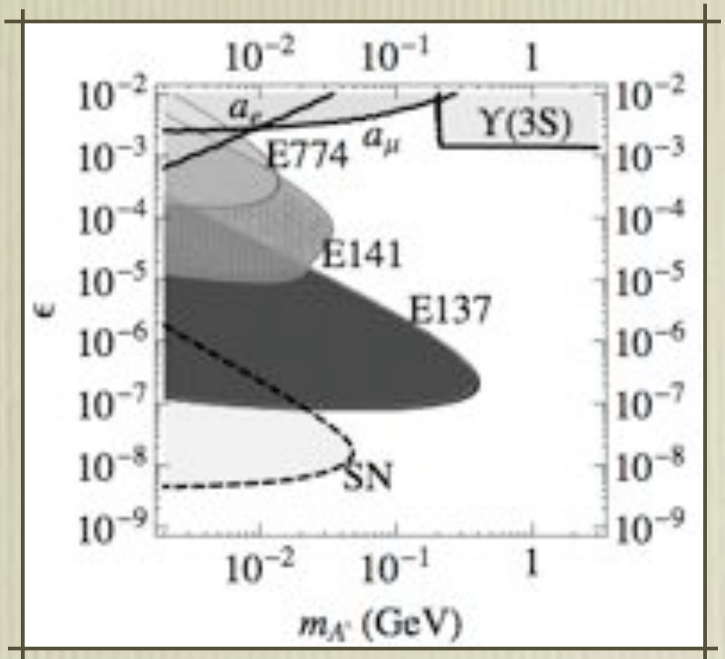

[Bjorken,Essig,Schuster,Toro 2009; Reece,Wang 2009; Batell,Pospelov,Ritz 2009;]

Experimental Probes: Direct

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- Low-Energy e^+e^- and e^-p colliders. $\epsilon \lesssim 10^{-4}$
- Fixed-target experiments. $\epsilon \lesssim 10^{-7}$
- Meson decays. $\epsilon \lesssim 10^{-3}$

$X \to YU$	n_X	$m_X - m_Y$ (MeV)	BR$(X \to Y + \gamma)$	BR$(X \to Y + \ell^+\ell^-)$	$\epsilon \leq$
$\eta \to \gamma U$	$n_\eta \sim 10^7$	547	$2 \times 39.8\%$	6×10^{-4}	2×10^{-3}
$\omega \to \pi^0 U$	$n_\omega \sim 10^7$	648	8.9%	7.7×10^{-4}	5×10^{-3}
$\phi \to \eta U$	$n_\phi \sim 10^{10}$	472	1.3%	1.15×10^{-4}	1×10^{-3}
$K_L^0 \to \gamma U$	$n_{K_L^0} \sim 10^{11}$	497	$2 \times (5.5 \times 10^{-4})$	9.5×10^{-6}	2×10^{-3}
$K^+ \to \pi^+ U$	$n_{K^+} \sim 10^{10}$	354	-	2.88×10^{-7}	7×10^{-3}
$K^+ \to \mu^+ \nu U$	$n_{K^+} \sim 10^{10}$	392	6.2×10^{-3}	7×10^{-8a}	2×10^{-3}
$K^+ \to e^+ \nu U$	$n_{K^+} \sim 10^{10}$	496	1.5×10^{-5}	2.5×10^{-8}	7×10^{-3}

[Reece,Wang 2009;]

Experimental Probes: Indirect

- Hidden sector can be probed indirectly by searching for sources that produce the light hidden states.
- An attractive possibility:

DM ⟷ *Hidden Sector*

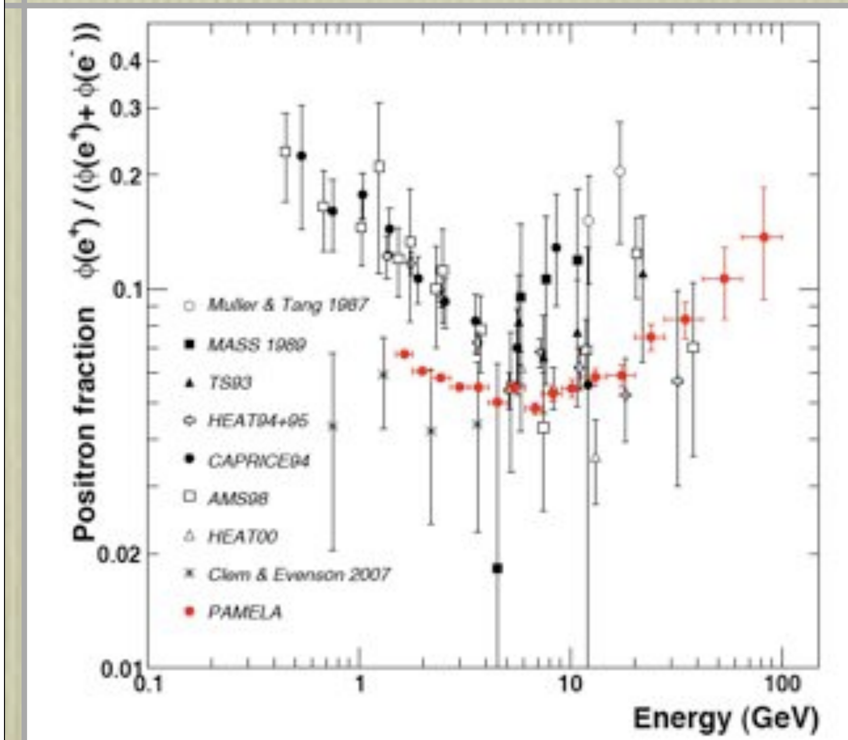
- Motivated by recent CR anomalies.
- In this talk we concentrate on two new probes:
  - Photon measurements. $\epsilon \lesssim 10^{-9}$
  - Neutrino Telescopes. $\epsilon \lesssim 10^{-15}$

Outline

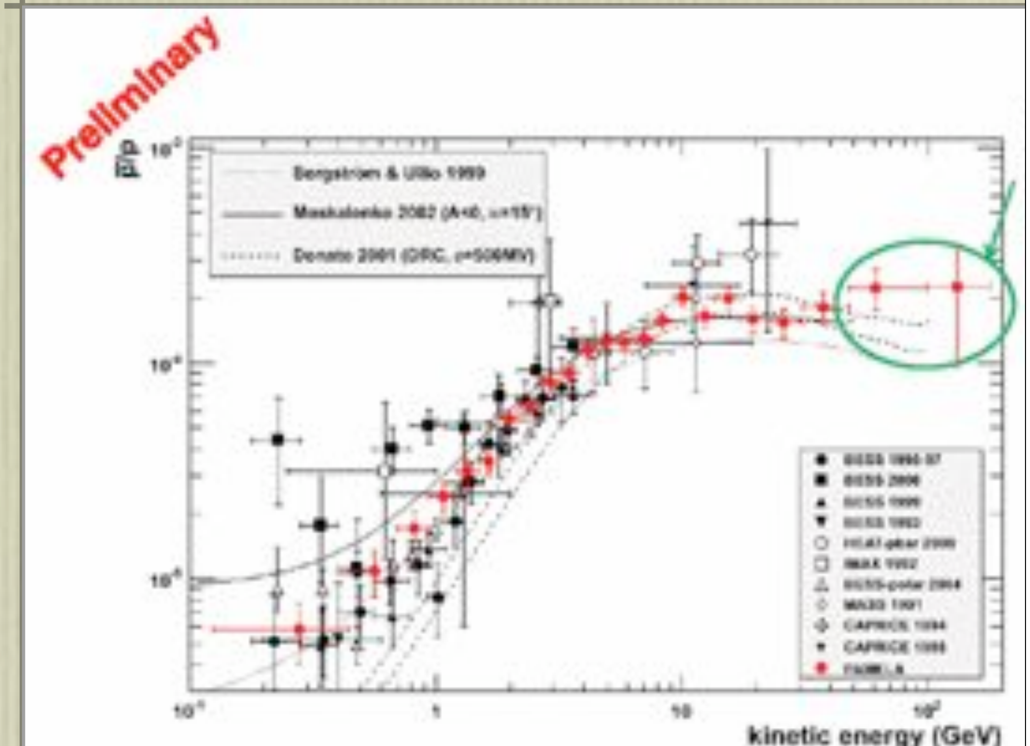
- The Cosmic Ray Anomalies
- Model Independent Analysis
- Decaying DM: Probing a Hidden Sector
  - A Model
  - Predictions
- Seeing the Hidden Sector in Neutrino Telescopes
- Conclusions

The Cosmic Ray Anomalies

PAMELA

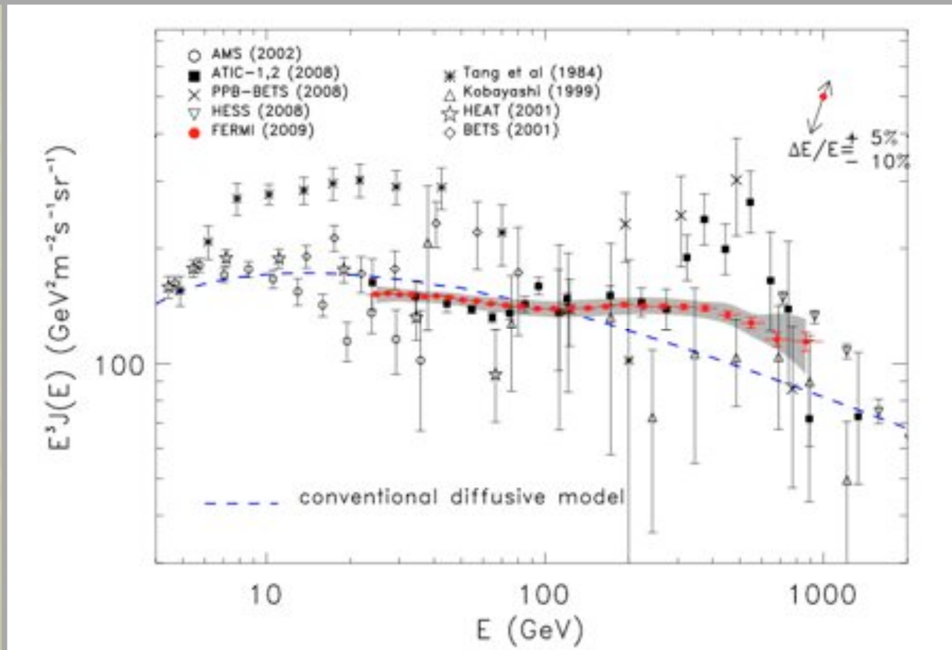


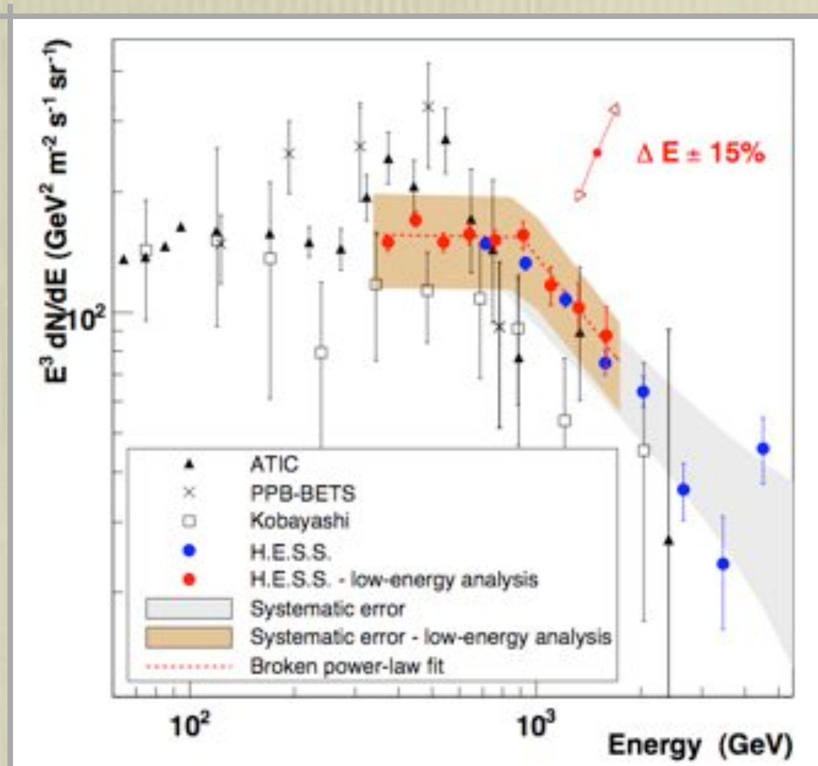
Positron fraction φ(e⁺) / (φ(e⁺)+ φ(e⁻))
0.4
0.3
0.2
0.1
0.02
0.01
0.1
1
10
100
Energy (GeV)
Muller & Tang 1987
MASS 1989
TS93
HEAT94+95
CAPRICE94
AMS98
HEAT00
Clem & Evenson 2007
PAMELA



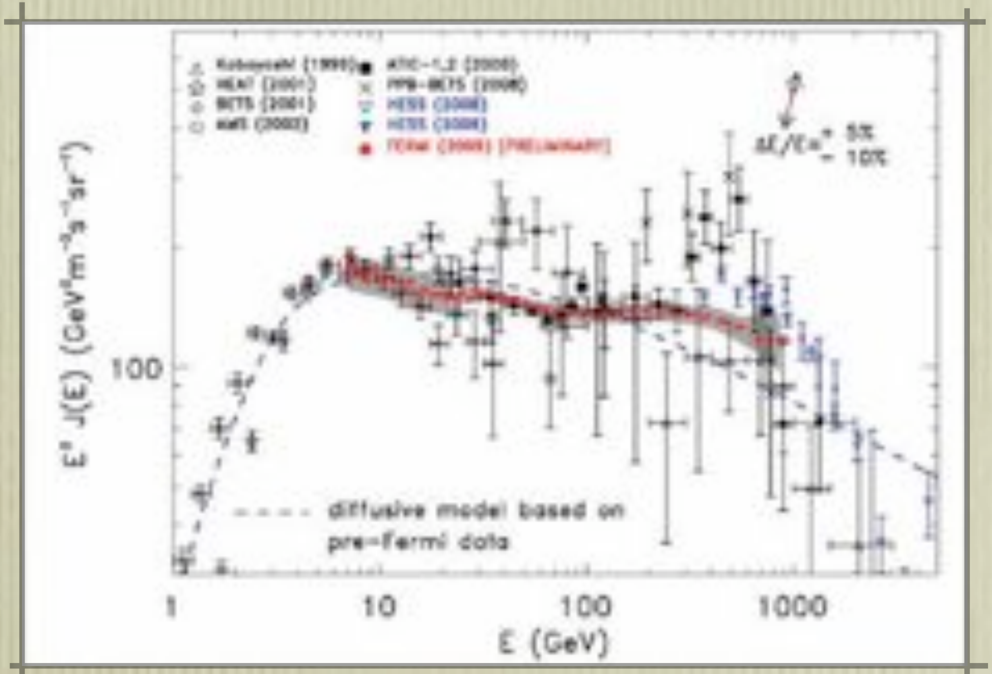
Preliminary
p̄/p
Bergstrom & Ullio 1999
1
10
kinetic energy (GeV)

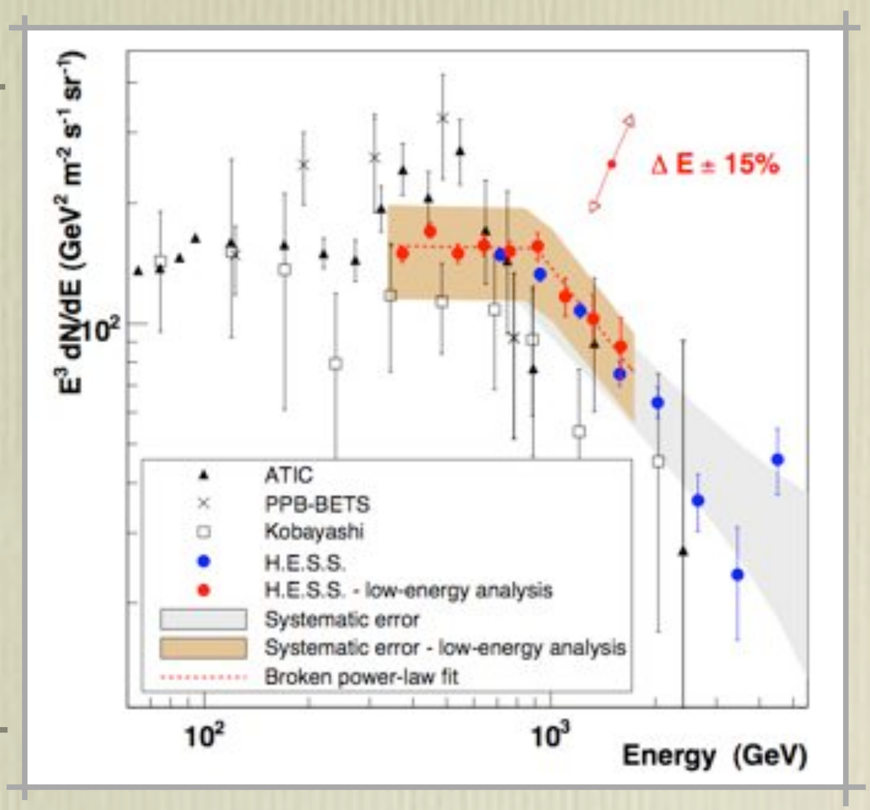
FERMI and HESS





FERMI and HESS





What can it be?

- Systematics?
  - PAMELA: sufficient proton rejection?
  - PAMELA and FERMI electron measurements consistent?
- Propagation?
  - e^+ created through interactions of CR-p's with interstellar matter.
  - Propagation of positrons to us is model dependent and unknown.
  - PAMELA may encode information of the propagation model. Indicates a more significant energy loss at lower energies.

    [Blum, Katz, Waxman, 2009]
- Astrophysical Source?
  - Positrons from Pulsars

    [Hooper et al., 2008; Yuksel et al., 2008; Zhang, Cheng 2001; Profumo 2008]
  - Acceleration in SNR

    [Blasi, 2009]
  - Inhomogeneities of sources

    [Nakar, Piran, Shaviv, 2009]
  - ...

For the rest of the talk:

Assume anomalies are indirect evidence for DM

Model Independent Analysis

Identifying Dark Matter

DM is required to address:

- Significant excess in $e^{\pm}$: Electronic activity.
- No excess in $\bar{p}$: No hadronic activity.
- No feature in FERMI:DM mass must be $\gtrsim 1$ TeV.
- For annihilating DM: In the absence of large local overdensity (boost factor), annihilation cross-section is $\mathcal{O}(1000)\times$ WIMP.

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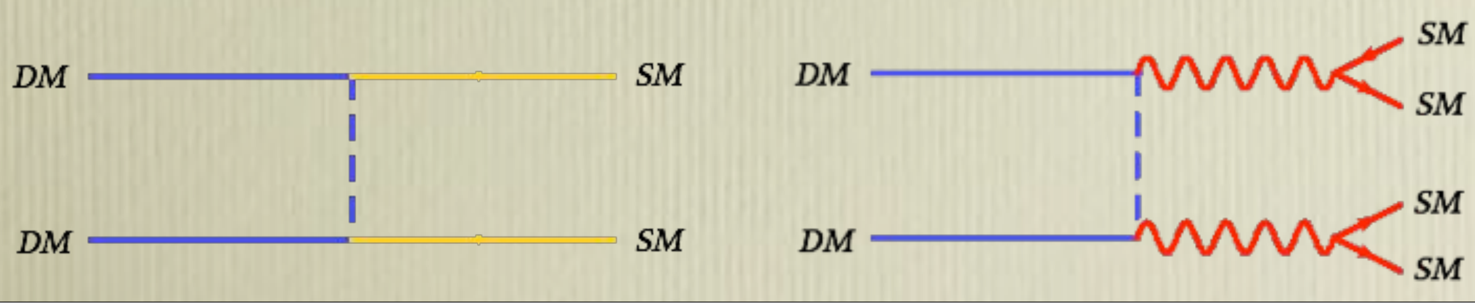
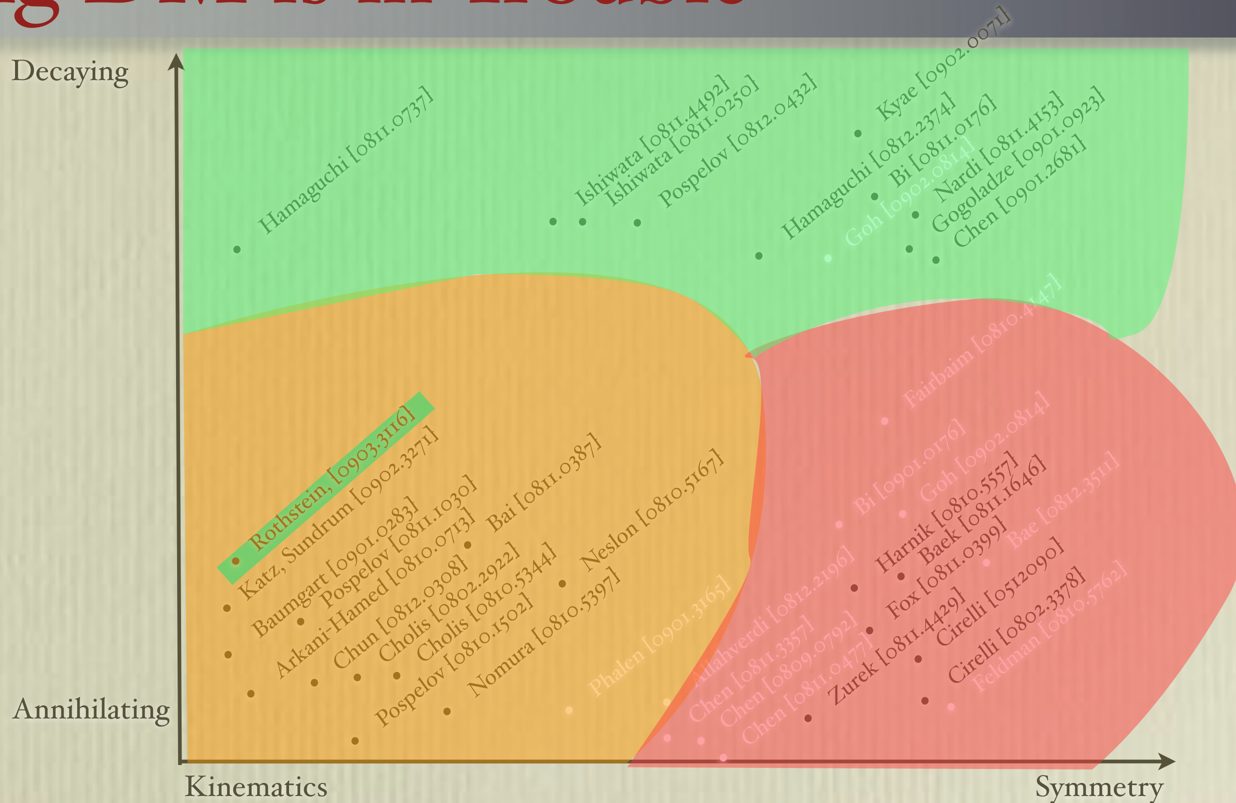
- For annihilating DM: In the absence of large local overdensity (boost factor), annihilation cross-section is $\mathcal{O}(1000)\times$ WIMP.

- Models of DM bifurcate into annihilating or decaying DM.
- Those that further explain absence of hadronic activity assume symmetry or kinematical constraint.



Annihilating DM is in Trouble



- Tension with measurements from Galactic Center.
- Tension with CMB Measurements.
- Tension with Extra-galactic photon measurements.
- Required enhancement of annihilation rate, O(few x 1000), hard to achieve.

Disclaimer

Astrophysics uncertainties do not allow for a robust statement. Annihilating models cannot be excluded definitively.

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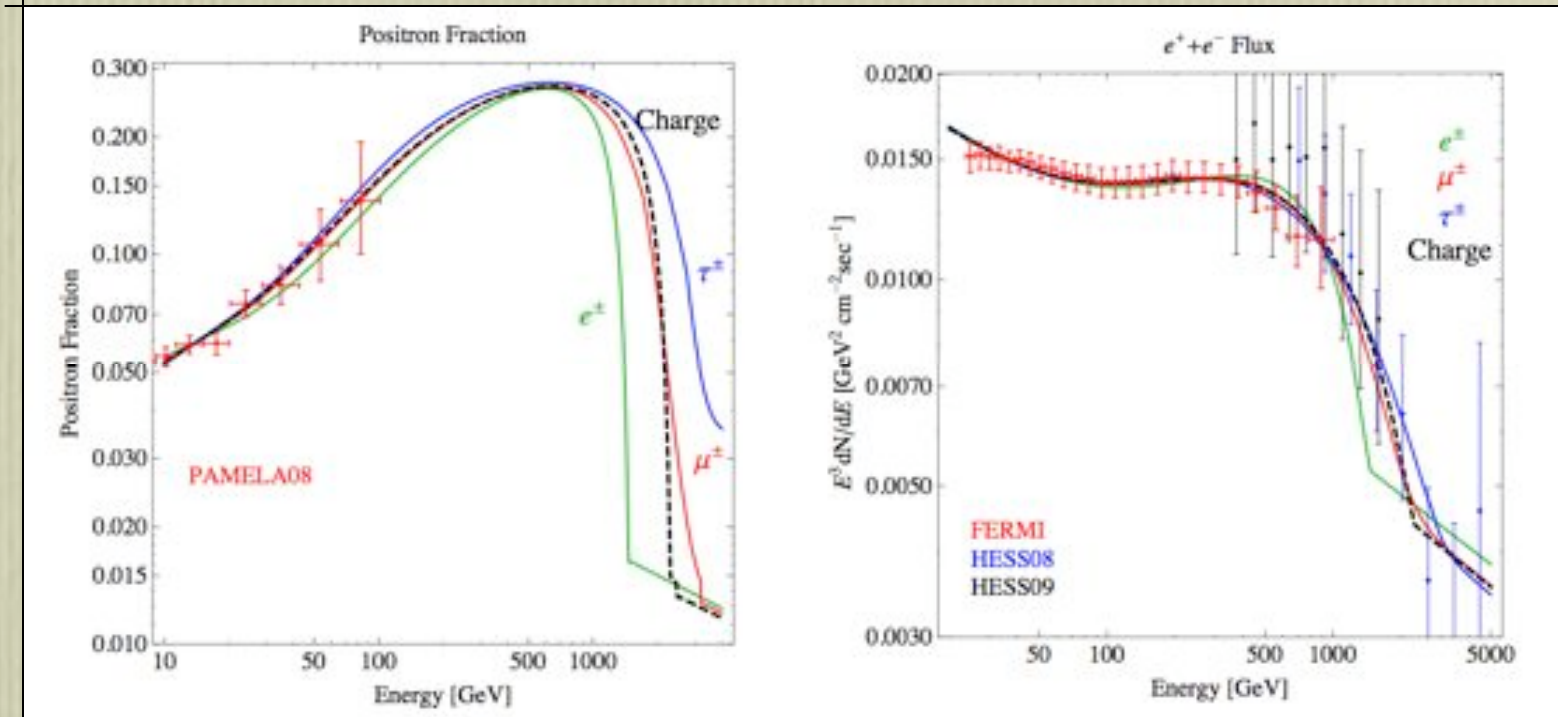
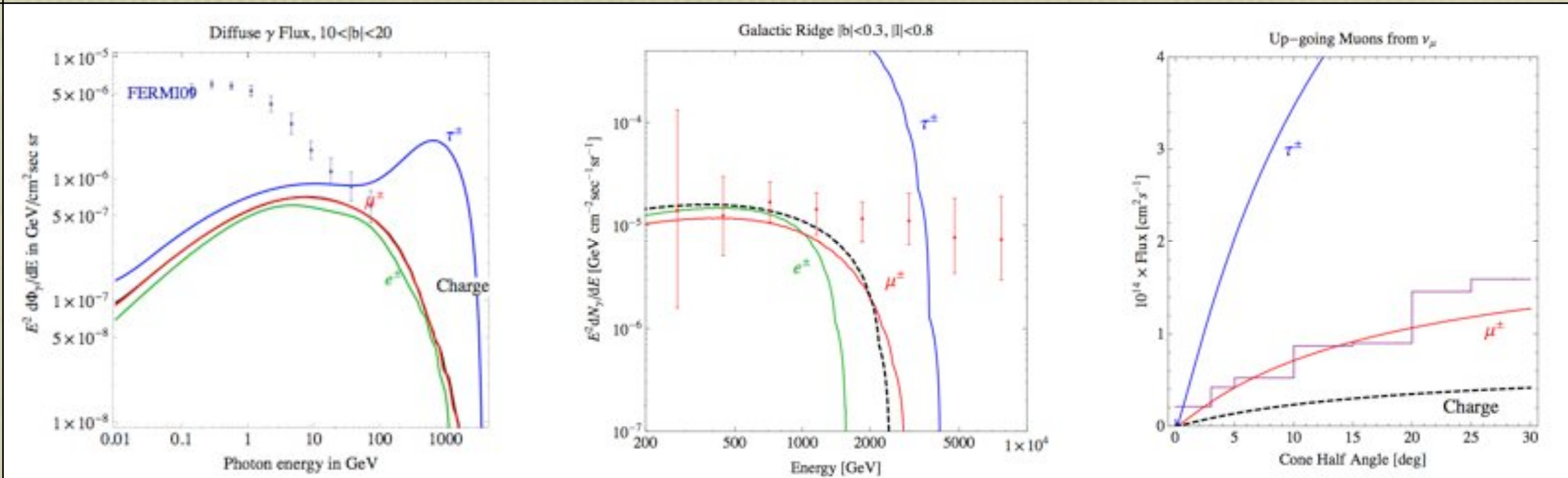
Constraints: Ann’ into 4l



[Meade,Papucci,Strumia,TV 2009]

- All 4-leptonic channels fit well.
- Positron faction expected to rise.

Constraints: Ann' into 4l



- Diffuse photons provide (relatively) robust prediction. Should be measured at $\sim$ 100 GeV.

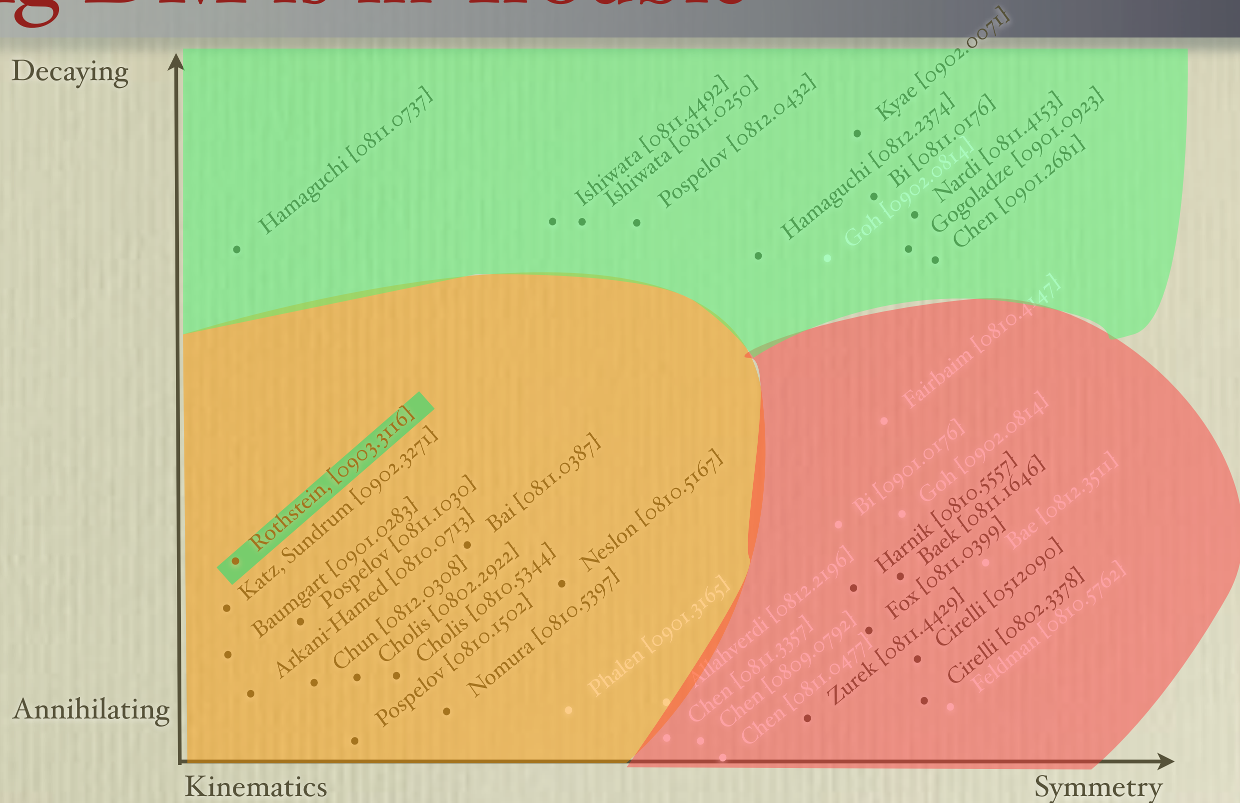
- Ann' modes that produce π^0's are disfavored by GC/GR.

- Ann' modes that produce many ν's are disvafored by SuperK.

- $\tau^{\pm}$ channel predict a bump (due to π^0's) in diffuse gamma, but is excluded by GC/GR and SuperK.

- All annihilation channels are in tension with measurements in GC/GR. Together with background they are excluded, unless DM profile is shallower.

Annihilating DM is in Trouble



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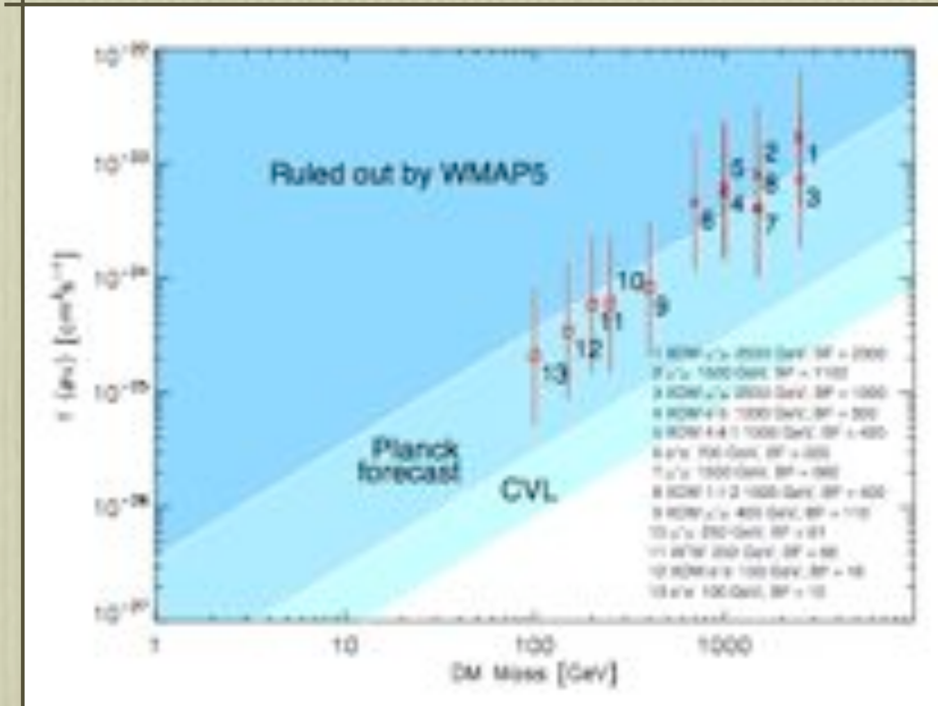
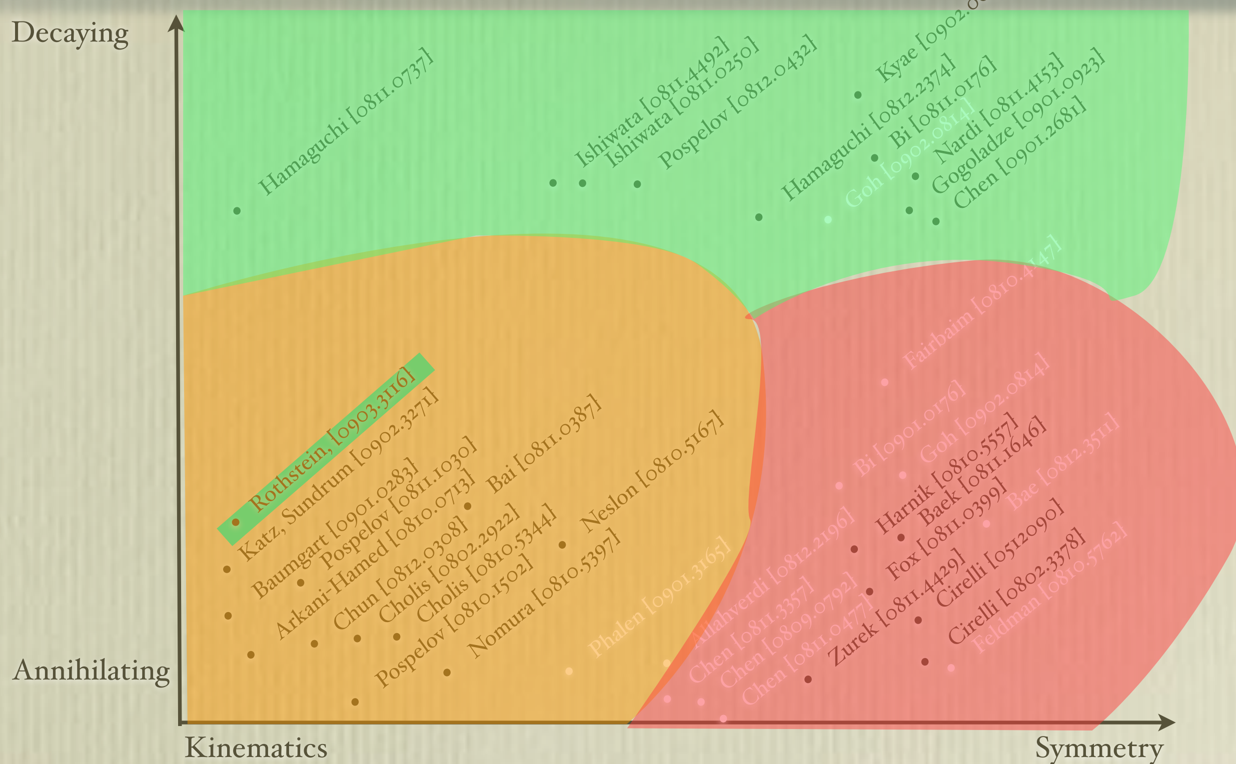
CMB Constraints



[Finkbeiner et. al. 2009;]

Annihilating DM is in Trouble



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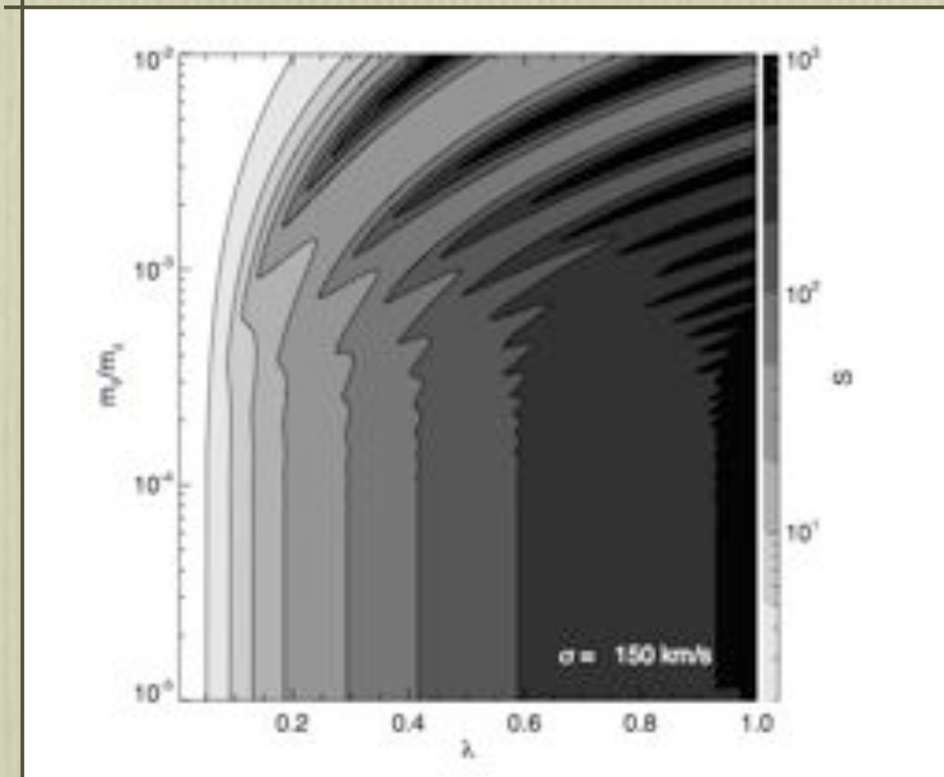
Sommerfeld



[Arkani-Hamed et. al. 2008;]

- Requires large coupling to force carrier, $\lambda \gtrsim 1$.
- Same coupling λ sets the relic abundance.
- In practice, hard to write models that generate sufficient enhancement and the correct relic abundance.

Decaying DM works better...

- Correct lifetime to explain PAMELA+FERMI+HESS is obtained if DM decays through dimension-6 operators suppressed by the GUT scale:

$$\tau \simeq \left(\frac{M_{\rm DM}^5}{16\pi^2 M_{\rm GUT}^4}\right)^{-1} \simeq 10^{26}\ {\rm sec}\left(\frac{M_{\rm DM}}{1{\rm TeV}}\right)^{-5}\left(\frac{M_{\rm GUT}}{5\times 10^{15}\ {\rm GeV}}\right)^4$$

[Eichler, 1989]

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- To ensure longevity: In $M_{\rm GUT} \to \infty$ limit, DM is completely stable due to a global (discrete) symmetry.
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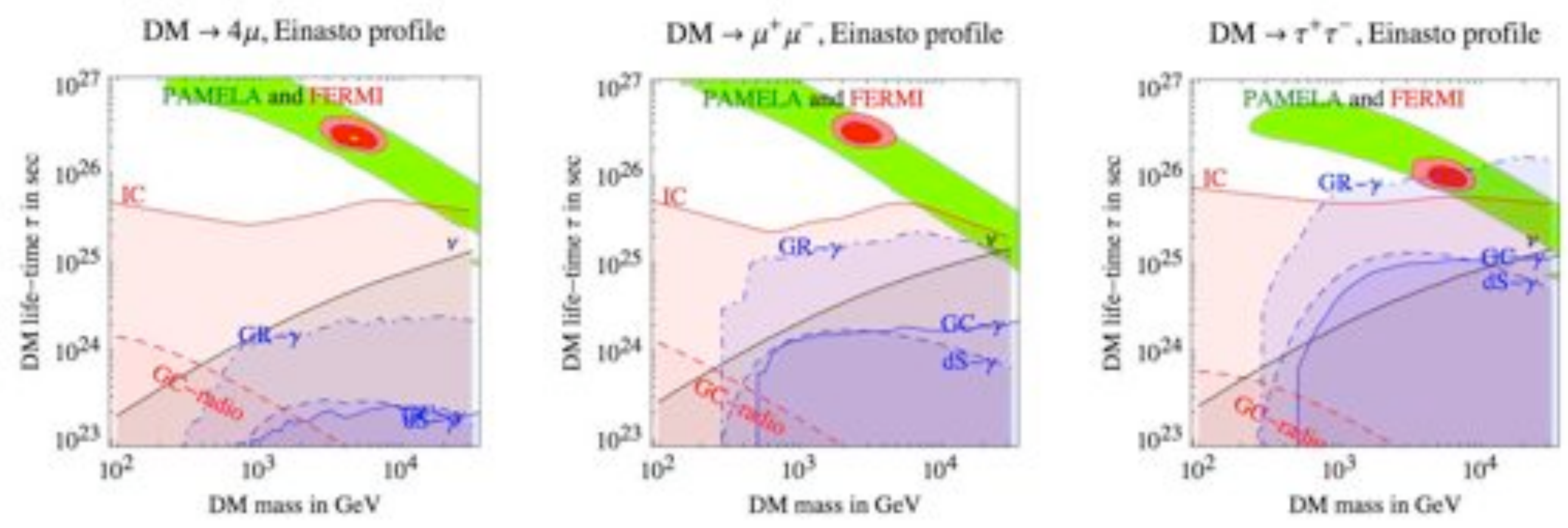
- Simpler than annihilating: does not require large enhancement of thermal cross-section.
- Usual WIMP cosmology apply: Thermal relic.

Decaying DM: Constraints



[Meade,Papucci,Strumia,TV 2009]

- Dependence on DM density is weaker at the Galactic Center.
- Decaying DM fits well and is not constrained by photons or neutrinos.
- May be probed by FERMI as in the annihilating case.
- Can, in principle, be differentiated from annihilating case if hard spectrum is measured. This is excluded for annihilating models.

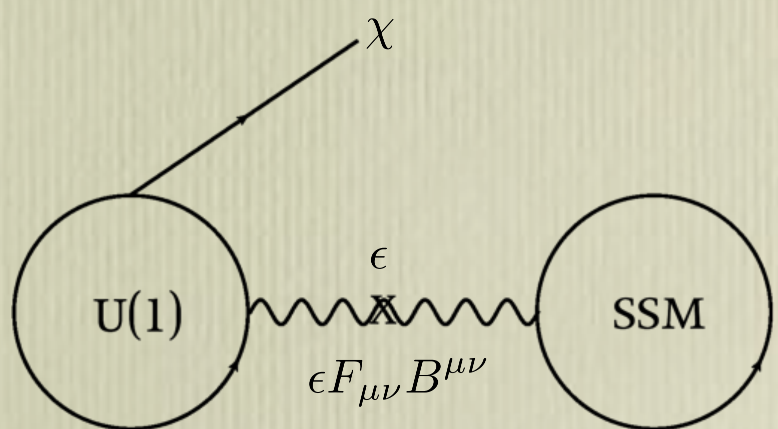
We now argue:

Low energy spectrum of hidden sector can be probed in the decaying DM case.

Models of Decaying Dark Matter

Decaying into Hidden Valleys

- Models of decaying DM have problems explaining the absence of anti-protons and photons from the GC.
- Typically require significant fine tuning or complicated and ad hoc structure.
- Can be naturally achieved if DM decays into a hidden "dark" sector.



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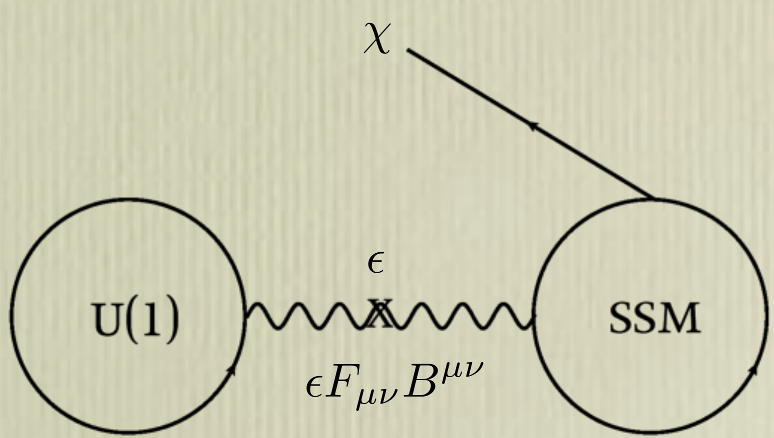
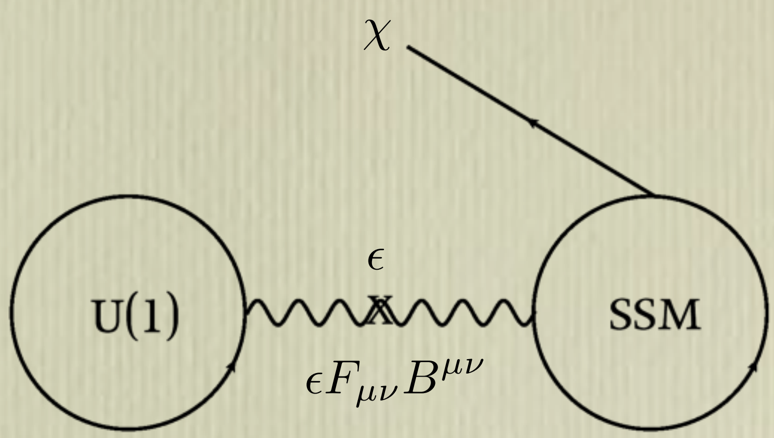


- The DM, χ, does not have to be charged under the dark sector.
- GeV scale explains the leptonic activity, through kinematics.

[Cholis,Goodenough,Weiner 2008]

A Model

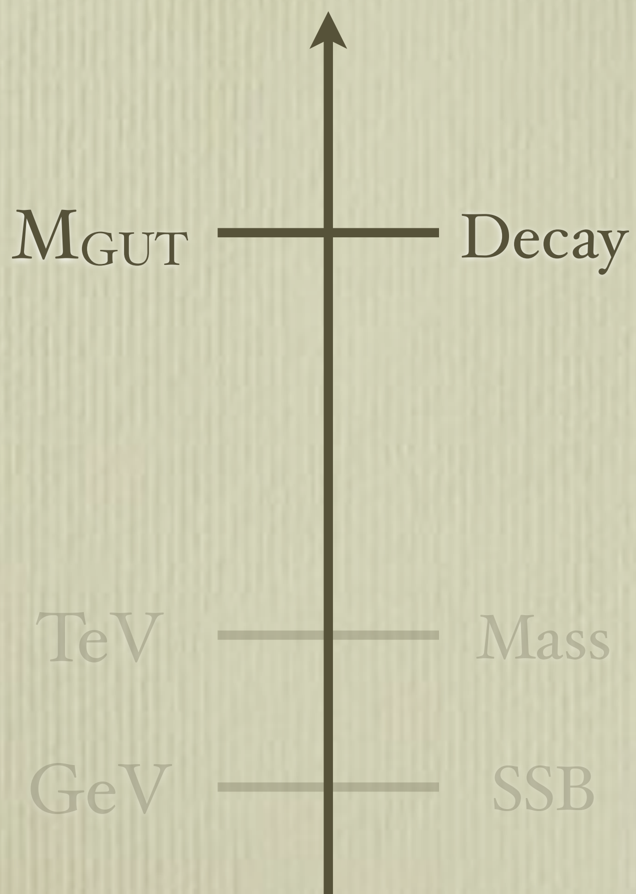


- Assume:
  - GUT.
  - SUSY (natural with GUT and stable GeV scale).
  - Gauge mediation.
- To demonstrate:

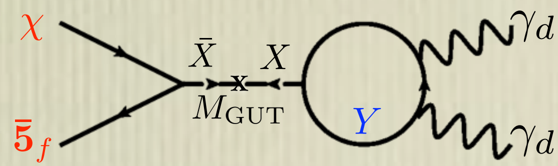
$$G_{\text{dark}} \times G_{SM} = U(1)_d \times SU(5)$$

$$\chi + \bar{\chi} = (0, \mathbf{5} + \bar{\mathbf{5}})$$

Scales

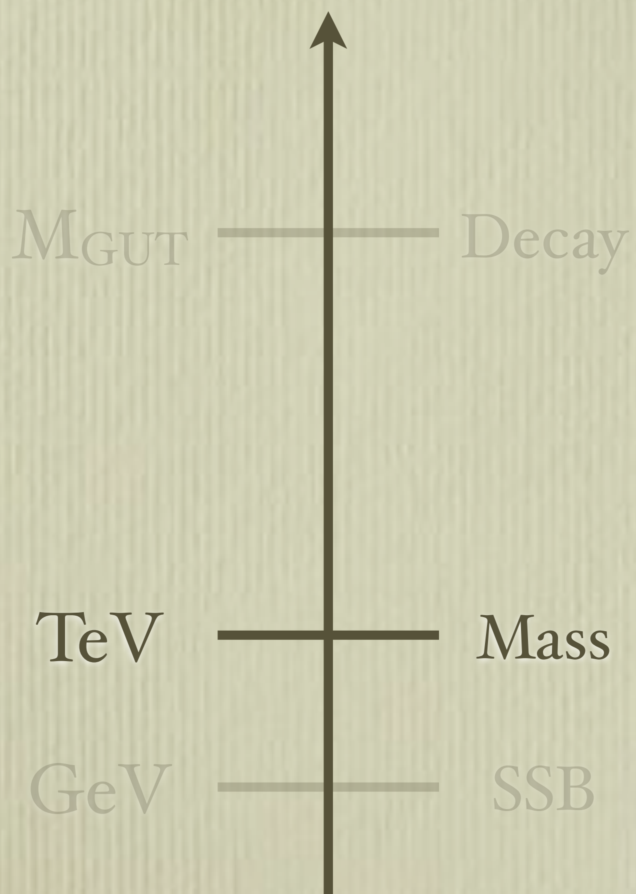


$$W_{\text{decay}} = (M_{\text{GUT}} + X)Y\bar{Y} + M_{\text{GUT}}X\bar{X} + \bar{X}\chi\bar{\mathbf{5}}_f$$



$$\frac{\alpha_d}{4\pi M_{\text{GUT}}^2}\int d^2\theta\ \chi\bar{\mathbf{5}}_f\mathcal{W}_d^2$$

Scales



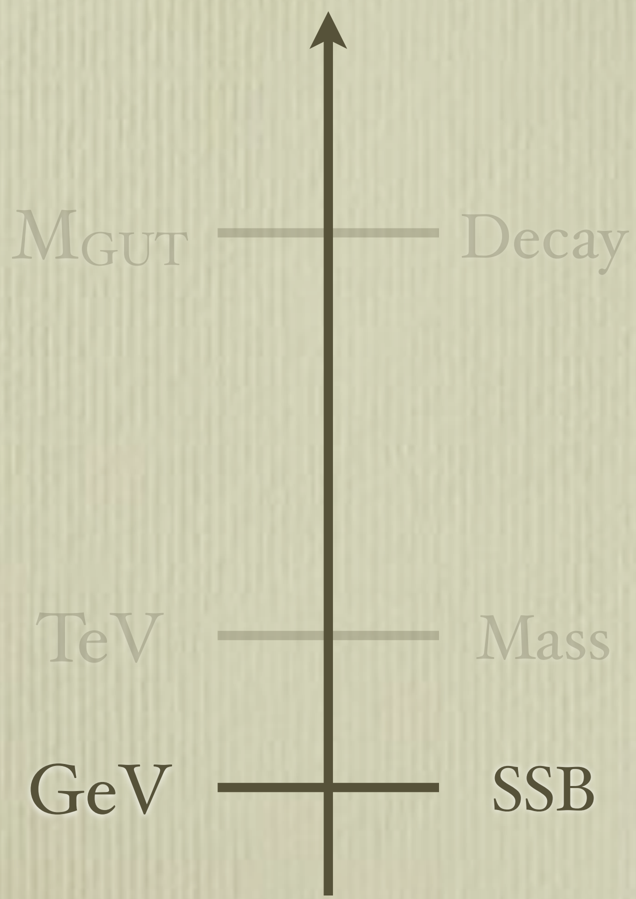
$$\frac{\alpha_d}{4\pi M_{\rm GUT}^2}\int d^2\theta\ \chi\bar{\mathbf{5}}_f\mathcal{W}_d^2$$

$$W_{\rm DM} = S\chi\bar{\chi}$$

$$\langle S\rangle = M_{\rm DM}$$

$$M_{\rm DM}\chi\bar{\chi}$$

Scales



$$\frac{\alpha_d}{4\pi M_{\mathrm{GUT}}^2}\int d^2\theta\, \chi\bar{\mathbf{5}}_f\mathcal{W}_d^2$$

$$M_{\mathrm{DM}}\chi\bar{\chi}$$

$$\mathcal{L}\supset -\frac{\epsilon}{2}\int d^2\theta\mathcal{W}_d\mathcal{W}_Y \Rightarrow \epsilon F_{\mu\nu}B^{\mu\nu} + \epsilon D_d D_Y$$

$$\langle D_Y\rangle \qquad \epsilon\sim 10^{-4}$$

$$m_{\gamma_d}^2 \sim \epsilon M_{\mathrm{EW}}^2$$

[Dienes et. al. 1996; Baumgard et. al. 2009]

Supersymmetry Breaking

- Simplest mechanism to break SUSY without destabilizing the GeV scale: gauge mediation.
- SUSY breaking spectrum is model dependent.

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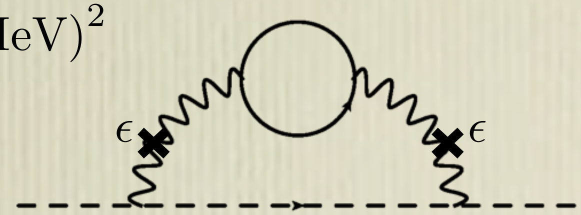
- If D-term mixing is the dominant mechanism for generating GeV scale $\Rightarrow$ Dark sector is approximately supersymmetric,

$$\delta m_h^2 \simeq \epsilon^2 \frac{g_d^2}{g_Y^2} M_{\tilde{E}}^2 = (100\ \mathrm{MeV})^2$$

$$\delta m_{\tilde{\gamma}_d}^2 \ll \delta m_h^2$$



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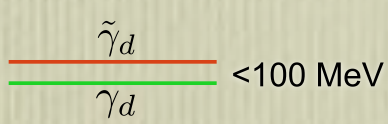
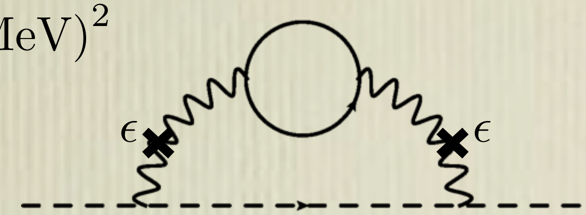
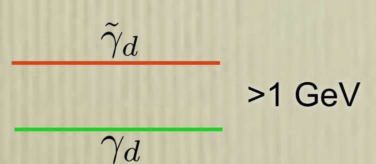


- If D-term mixing is the dominant mechanism for generating GeV scale $\Rightarrow$ Dark sector is approximately supersymmetric,

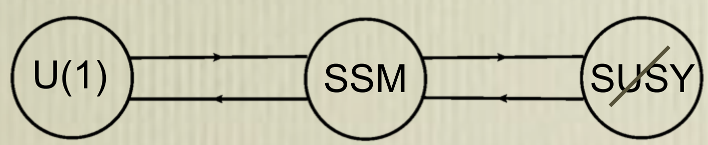
$$\delta m_h^2 \simeq \epsilon^2 \frac{g_d^2}{g_Y^2} M_{\tilde{E}}^2 = (100 \text{ MeV})^2$$

$$\delta m_{\tilde{\gamma}_d}^2 \ll \delta m_h^2$$



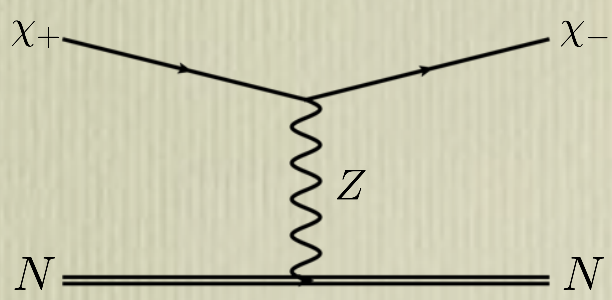


- If there are bi-fundamentals at the TeV (messengers), SUSY breaking is large (of order GeV).



Direct Detection

- There are also strong limits from direct detection (CDMS, XENON) on DM that couples elastically to the Z.
- Mass eigenstates, $\chi_\pm = (\chi \pm \bar{\chi})/\sqrt{2}$ couple to Z:



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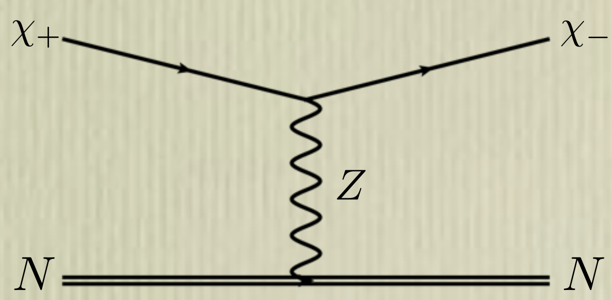


- As is, above model is excluded by 2-3 orders of magnitude.
- Bounds can easily be evaded by splitting the DM multiplets:

$$W_{\text{split}} = MN^2 + \chi H_d N \;\Rightarrow \delta M_{\text{DM}} = \frac{v^2}{M} \sim 10 \text{ GeV}$$

- DM interacts inelastically, thereby evading bounds.

Triplet Decay

- The triplet which resides in the DM multiplet must decay fast to evade constraints from exotic atom searches and BBN.
- Dimension 5 operators can induce fast decay, $\tau_3 \sim 1$ sec:

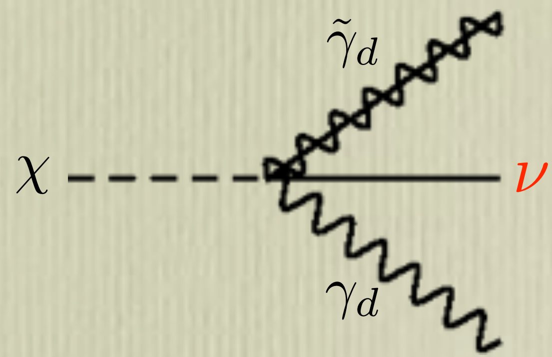
$$\frac{1}{M_{\rm GUT}} \int d^2\theta \, \chi^2 \bar{\mathbf{5}}_f^2 \qquad \frac{1}{M_{\rm GUT}} \int d^2\theta \, \chi \mathbf{10}_f^2 s \qquad \frac{1}{M_{\rm GUT}} \int d^4\theta \, \bar{\chi} \bar{\mathbf{5}}_f^\dagger s$$

- s is a singlet, $m_{\chi_{\mathbf{2}}} < m_s < m_{\chi_{\mathbf{3}}}$.
- Assumes $m_{\chi_3} > m_{\chi_2}$ which is typically true due to RG running.

Decay Modes

- The operator: $\int d^2\theta\ \chi \bar{\mathbf{5}}_f \mathcal{W}_d^2$ has several decay modes, with branching fractions depending on whether the DM is fermion or scalar.

- Example:



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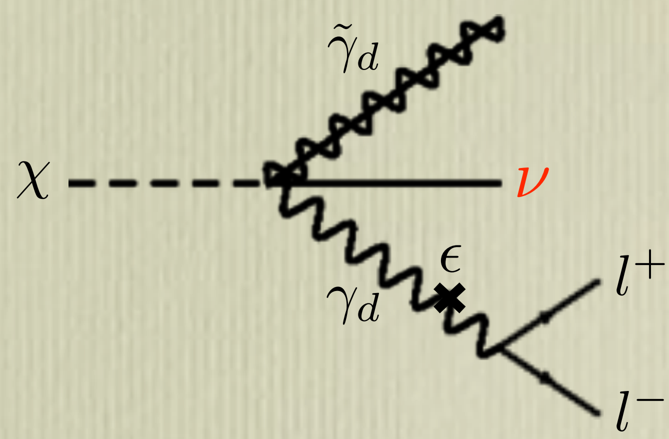

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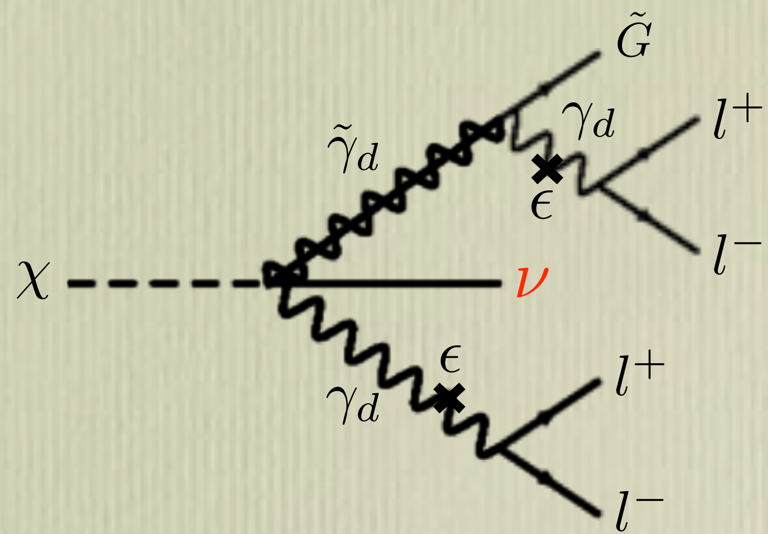

Dark Sector:
GeV Scale ~~SUSY~~.

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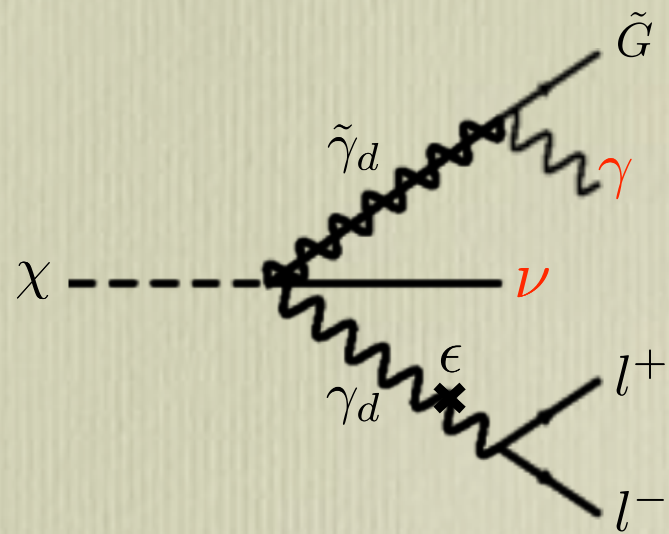

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Approximate SUSY.

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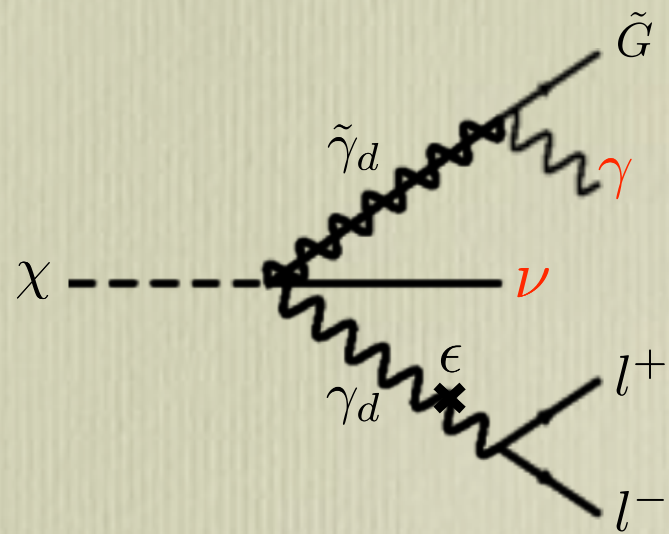
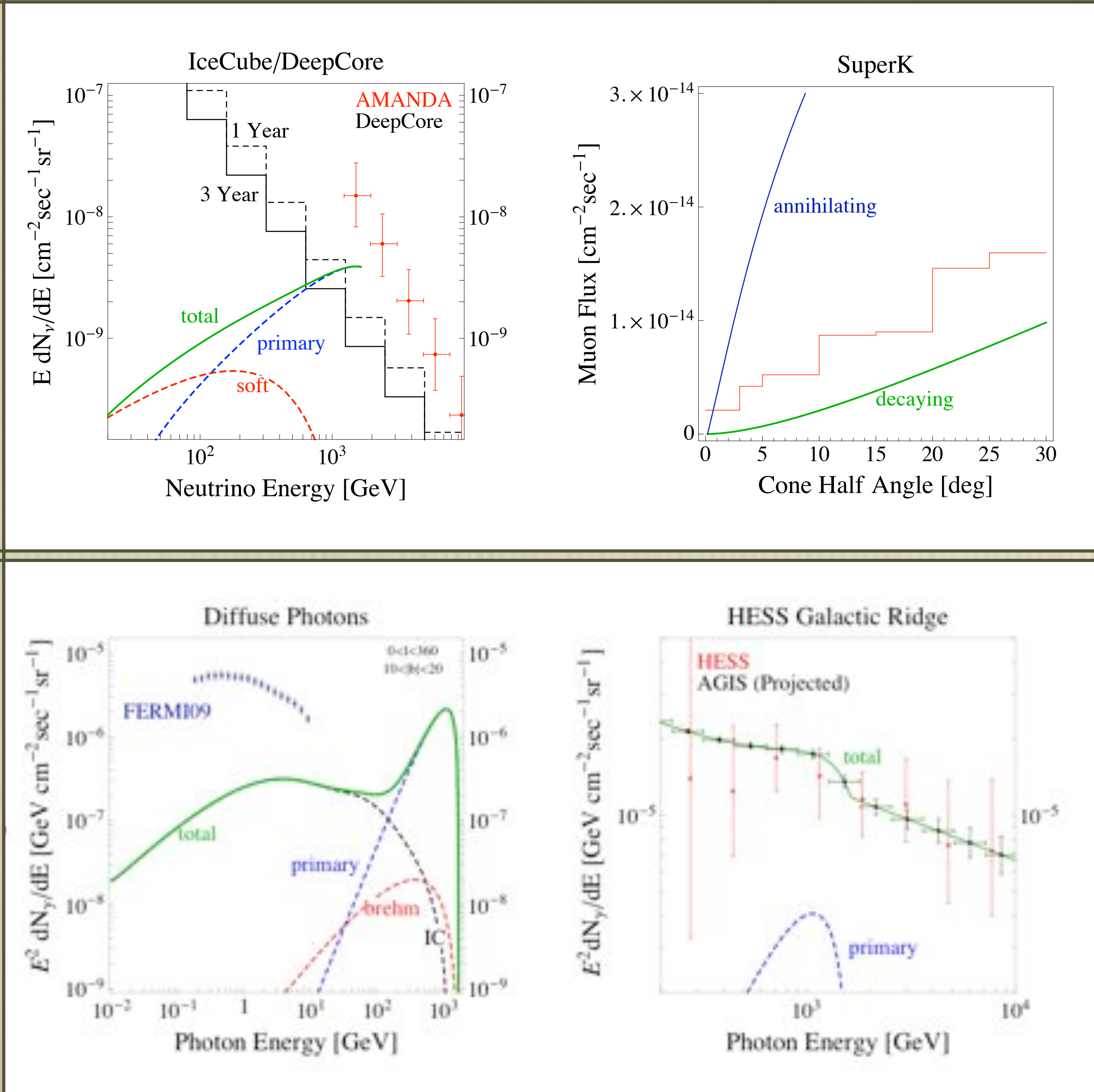


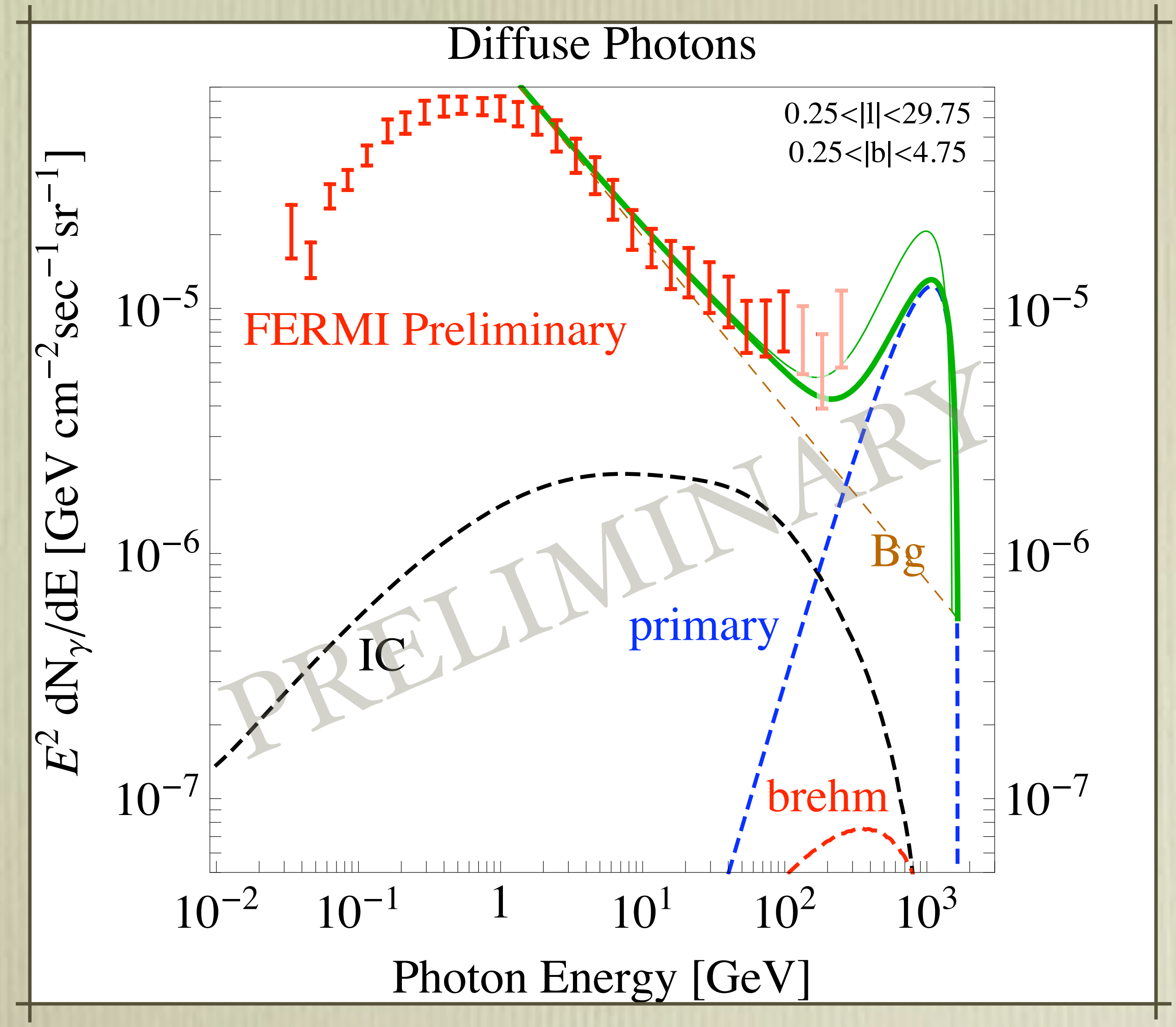
Dark Sector: Approximate SUSY.

- If DM is charged under SM, there is always a primary (hard) spectrum of neutrinos.
- If dark sector is approximately supersymmetric, there is a primary (hard) spectrum of photons.
- Primary photons will be generically produced if the lightest state in the dark sector is a fermion.

Smoking Gun Signatures

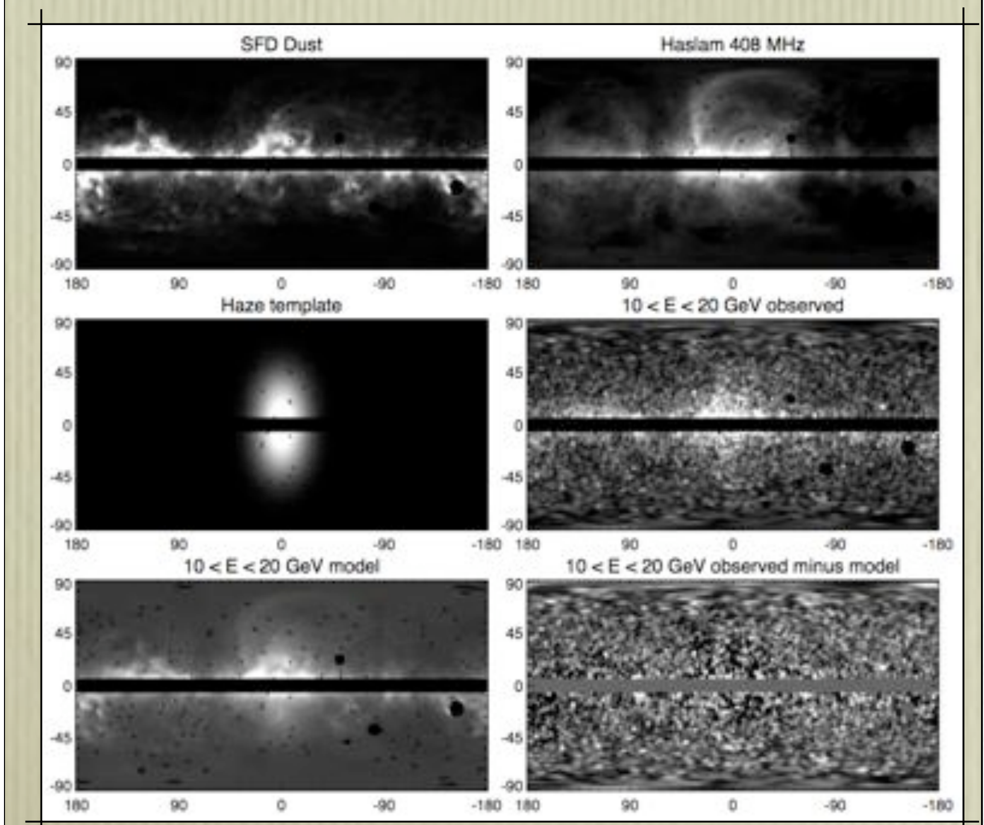


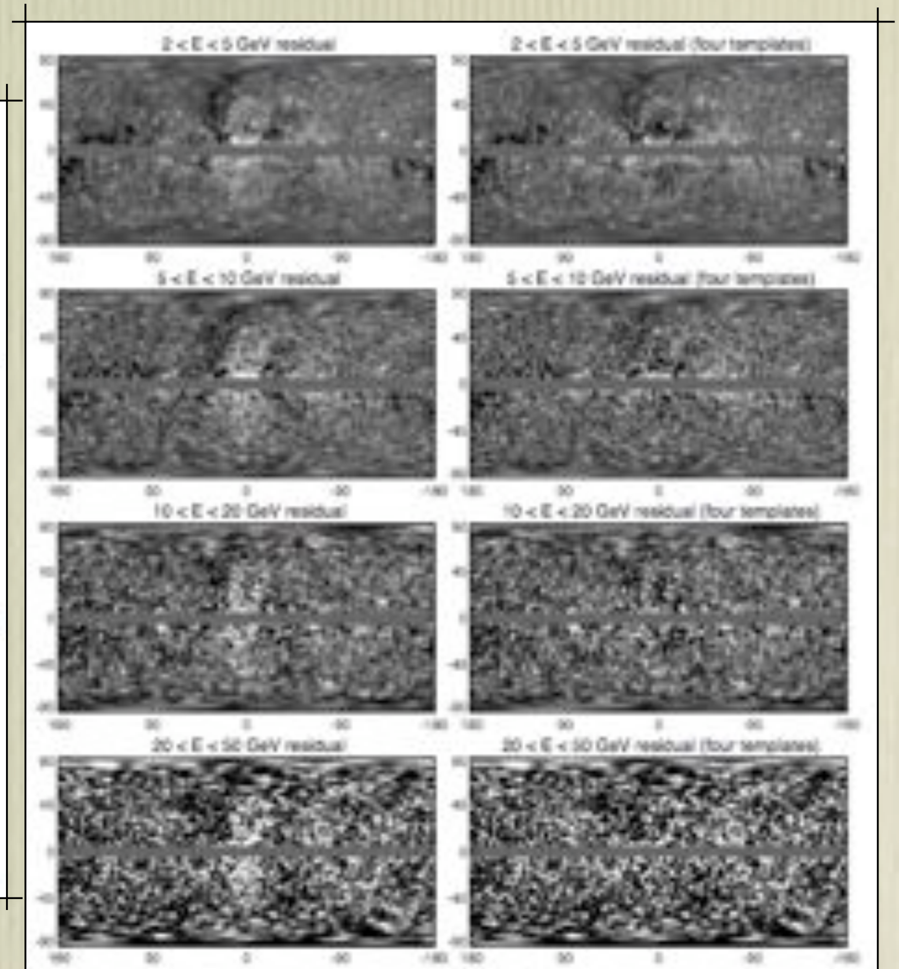
Is FERMI Seeing Decaying DM?



Is FERMI Seeing Decaying DM?

- Fermi released a 1-year sky map.
- A template analysis shows an excess of photons at the center of the Galaxy.





[Dobler et. al. 2009]

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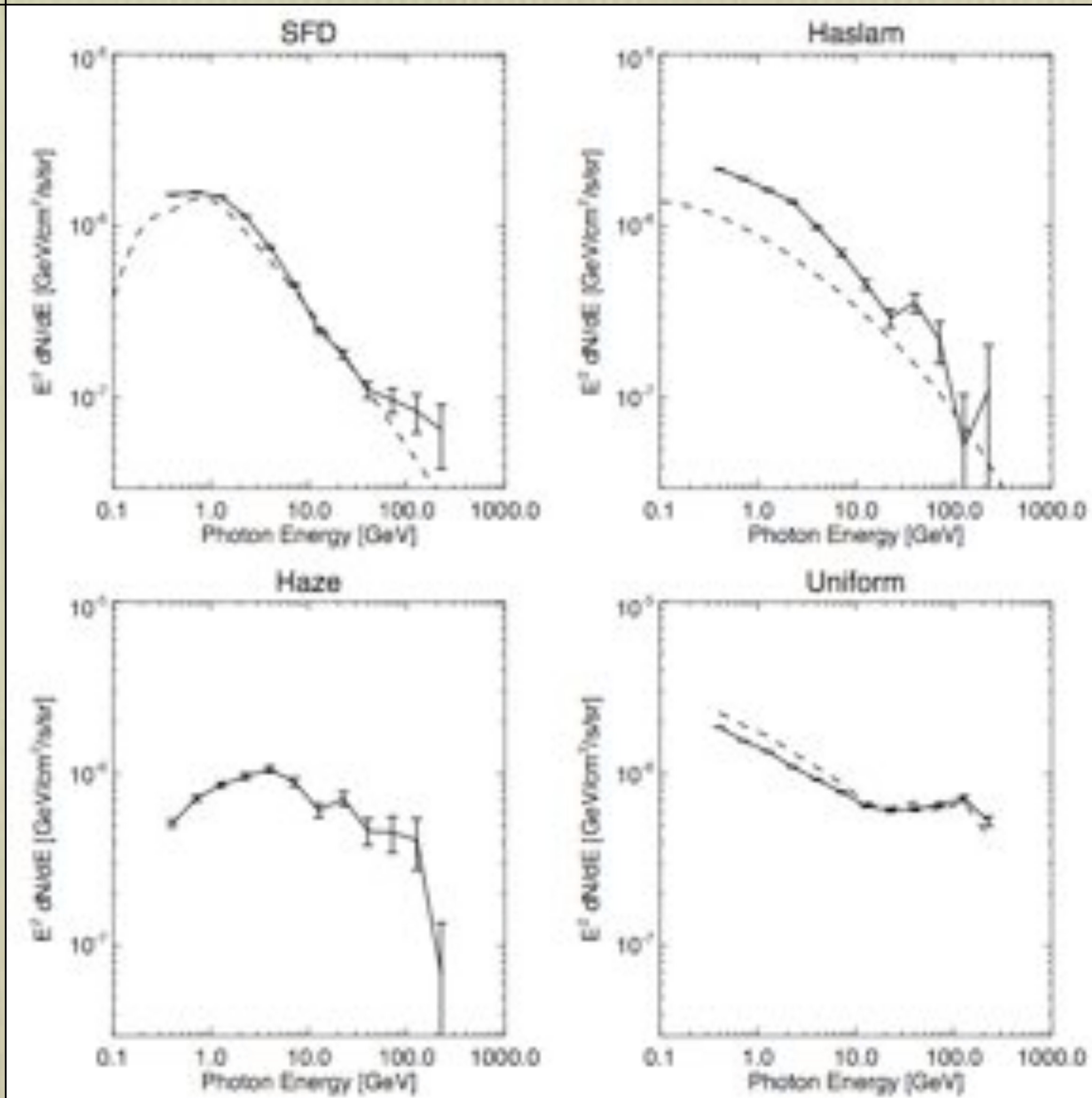

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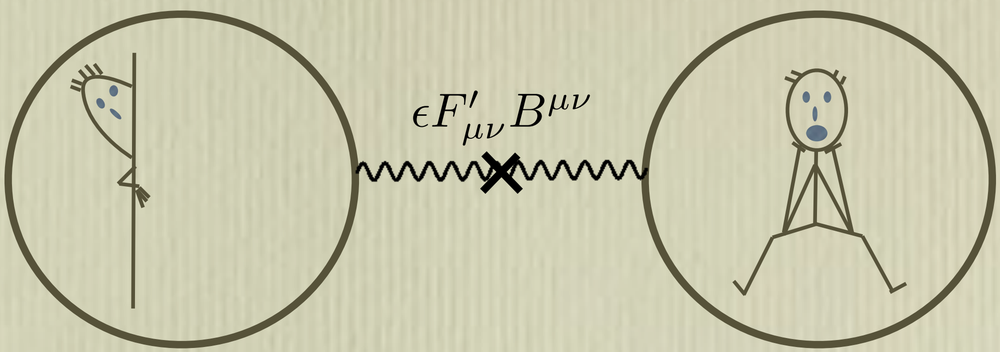
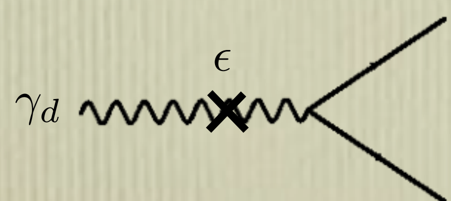
The Hidden Sector at Neutrino Telescopes

Long Lived Particles (LOLIPs)

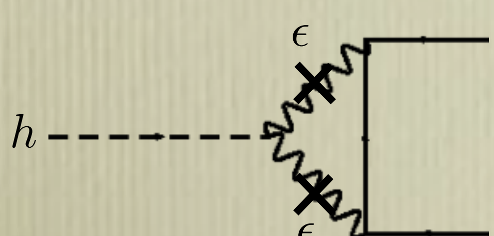


- For sufficiently small ϵ, hidden sector is expected to have long lived particles which decay to SM.

- Examples:



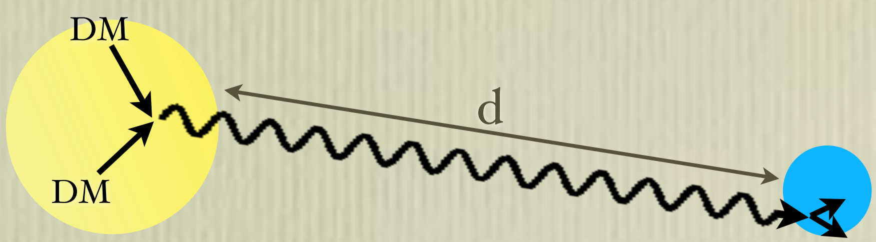
$$c\tau \sim (\epsilon^2 \alpha_{\mathrm{EM}} m_{\gamma_d})^{-1} \sim 1\ \mathrm{km} \left(\frac{\epsilon}{10^{-8}}\right)^{-2} \left(\frac{m_{\gamma_d}}{1\ \mathrm{GeV}}\right)^{-1}$$



$$c\tau \sim \left(\frac{\epsilon^4 \alpha_d \alpha_{\mathrm{EM}}^2 m_h}{2\pi^2} \frac{m_f^2}{m_{\gamma_d}^2}\right)^{-1} \sim 10^7\ \mathrm{km} \left(\frac{\epsilon}{10^{-4}}\right)^{-4} \left(\frac{m_{\gamma_d}}{1\ \mathrm{GeV}}\right)$$

Production of LoLiPs

- If DM annihilates into hidden sector, signals can be measured at regions with high DM densities: Sun, Earth.



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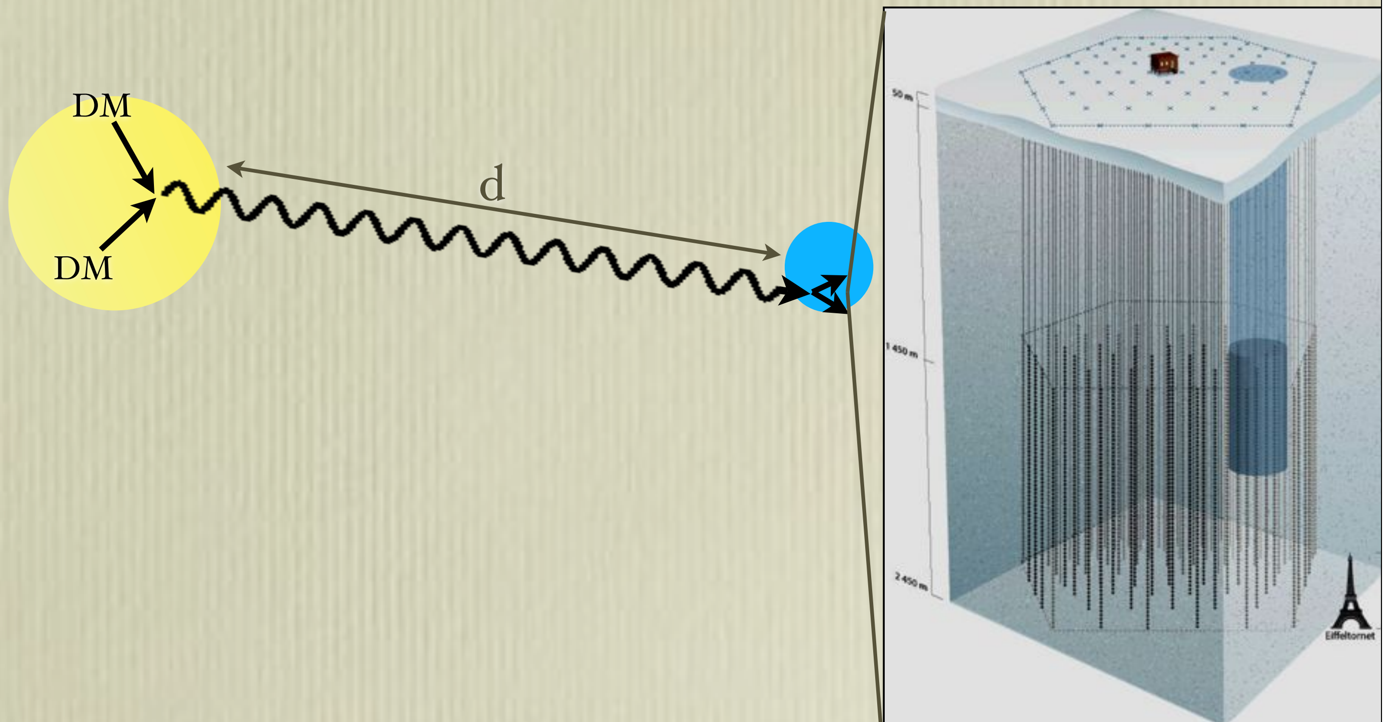

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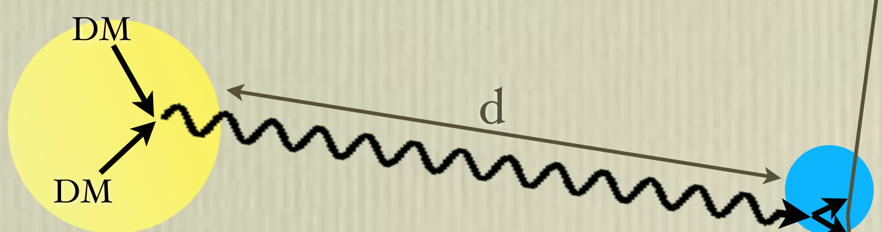
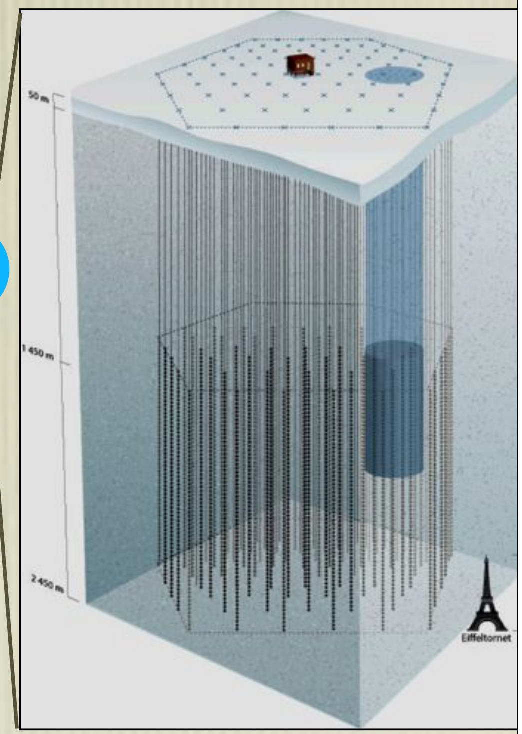




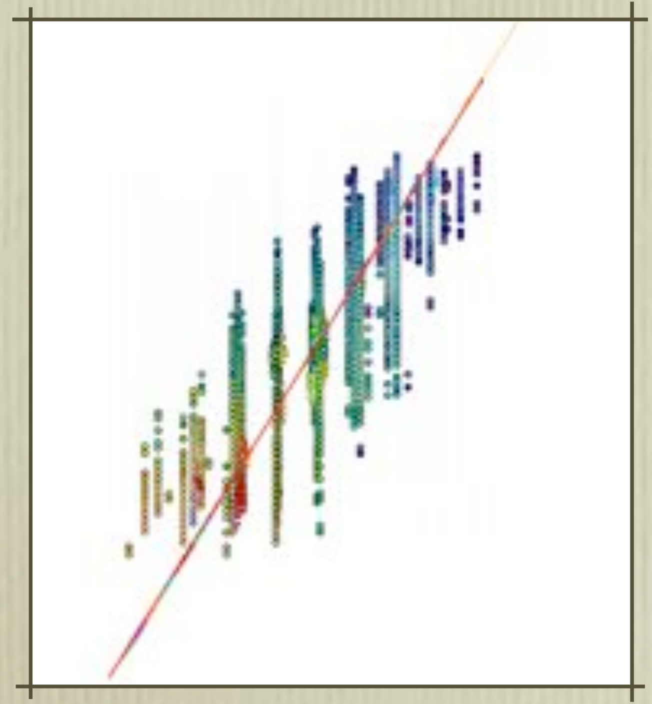
- Probability to decay inside detector:

$$P_{\text{decay}} = e^{-d/L}\left(1 - e^{-s/L}\right) \simeq \begin{cases} \frac{s}{L} & L \gtrsim d \\ e^{-d/L} & L \ll d \end{cases}$$

$L = \gamma c \tau$.
$s =$ Size of detector.

Event Types

- Neutrino telescopes are typical arrays of photomultiplier tubes.
- Roughly two types of signatures:
    1. Track-like signature, mostly Cherenkov radiation. (Mostly $\mu^{\pm}$).
    2. Localized source of light (e.g. $e^{\pm}$ or γ).



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- Roughly two types of signatures:
  1. Track-like signature, mostly Cherenkov radiation. (Mostly $\mu^{\pm}$).
  2. Localized source of light (e.g. $e^{\pm}$ or γ).
- Decay from LOLIPs may produce highly boosted di-muons. Typical separation is a few meters at most.
- Cherenkov radiation is doubled.
- Monte-Carlo simulations show an increase of $\times 3$ in effective area.
- Thus di-muons are recognized as single muons above critical energy (which is $\mathcal{O}(700 \text{ GeV})$ in water).
- Good handle for background:
  - Atmospheric neutrino flux is drops rapidly.
  - Differential light yield along track is different.

Event Rate

- Rate of events depends on:

$$\# \text{ of events} \simeq \Gamma_{\rm ann} \times d\Omega \times P_{\rm decay}(c\tau)$$

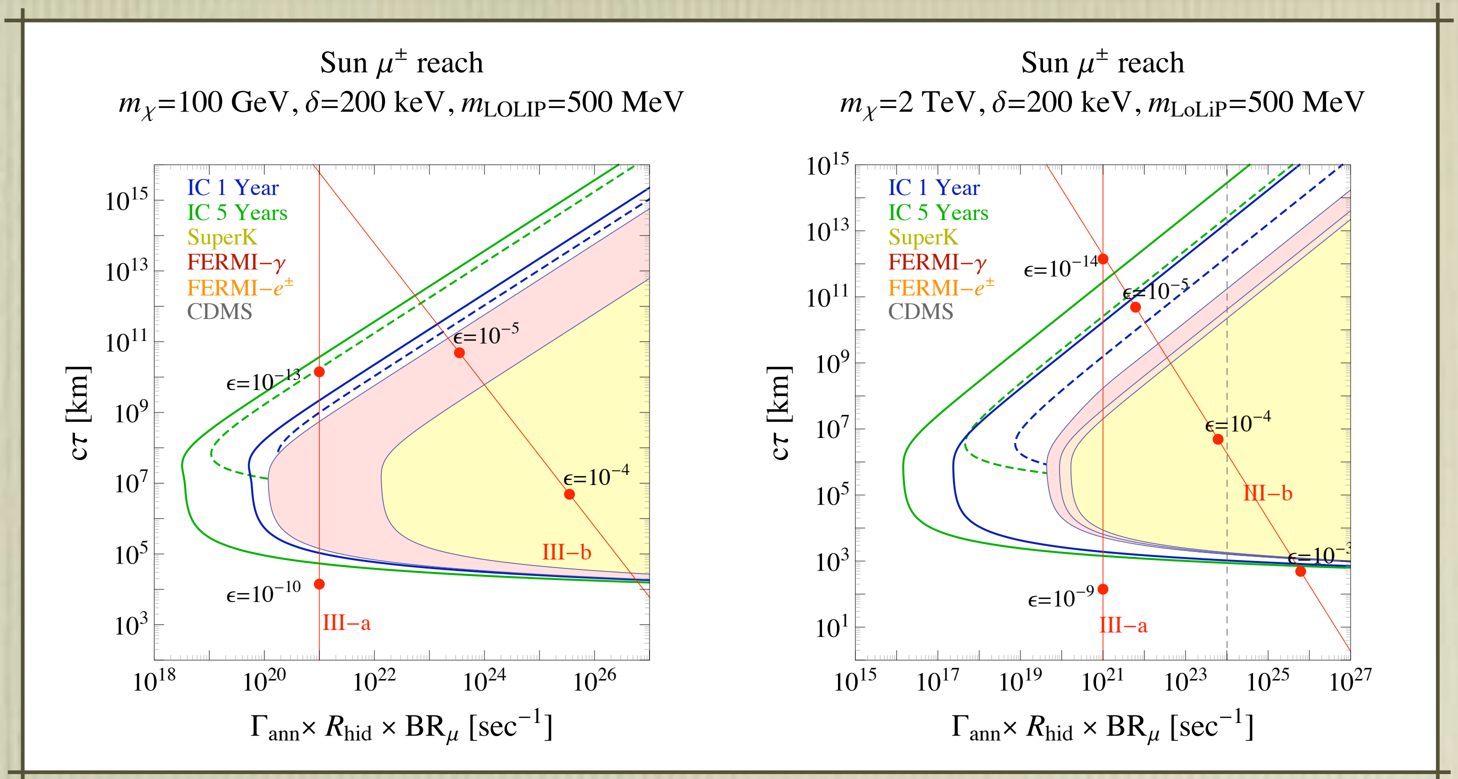
$$\Gamma_{\rm ann} \simeq \frac{1}{2} C \qquad\qquad \text{(equilibrium)}$$

- Capture rate can vary by many orders of magnitude, depending on whether DM interacts elastically or inelastically with nucleons, as well as on DM-nucleon cross-section and DM mass. For elastic case:

$$C_\odot = 3 \times 10^{19} s^{-1} \left(\frac{\rho_\odot}{0.3 \text{ GeV cm}^{-3}}\right) \left(\frac{v_{\rm disp}}{270 \text{ km s}^{-1}}\right)^{-3} \left(\frac{\sigma_{\chi n}}{10^{-43} \text{ cm}^2}\right) \left(\frac{m_\chi}{100 \text{ GeV}}\right)^{-2}$$

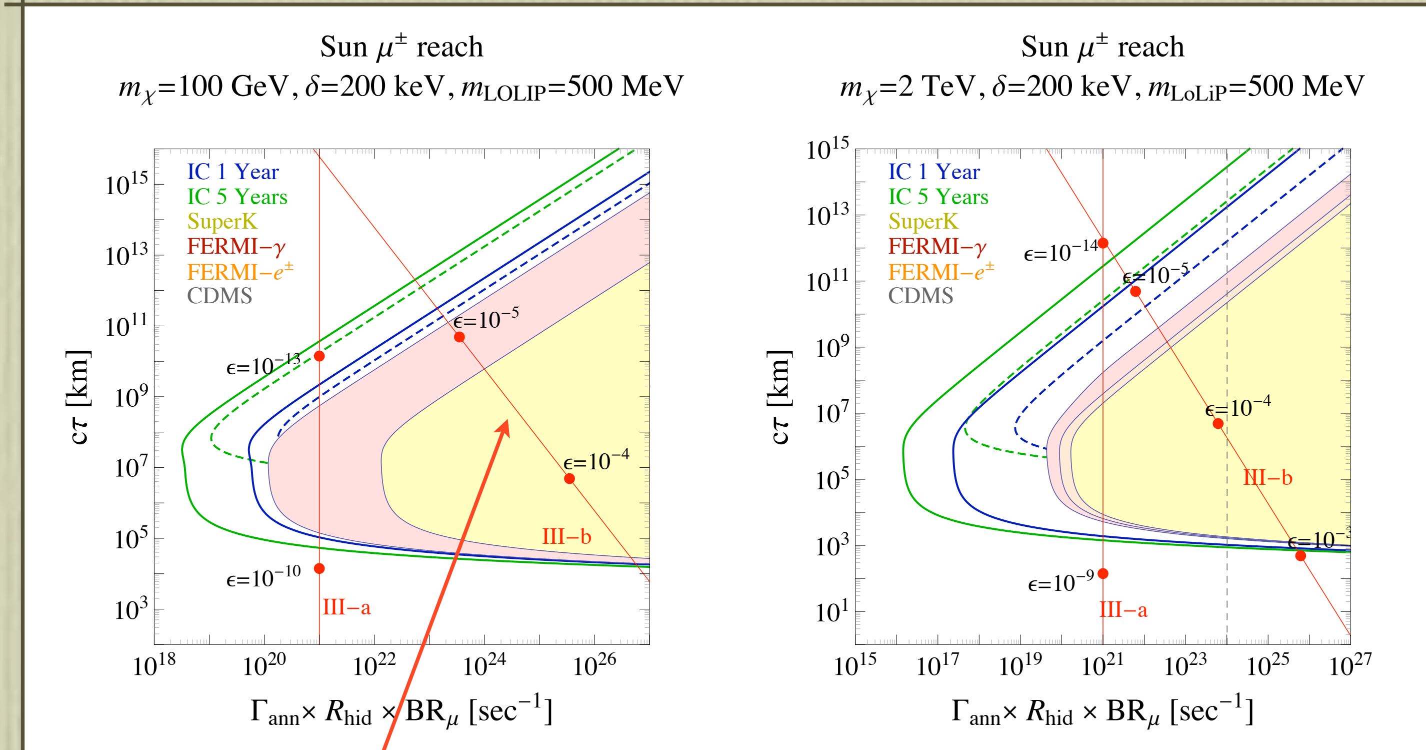
- Measurement is therefore sensitive to $c\tau, \sigma_{\chi n}, m_\chi$.

IceCube Reach



Model lines: Inelastic DM, $\delta = 200$ keV

IceCube Reach

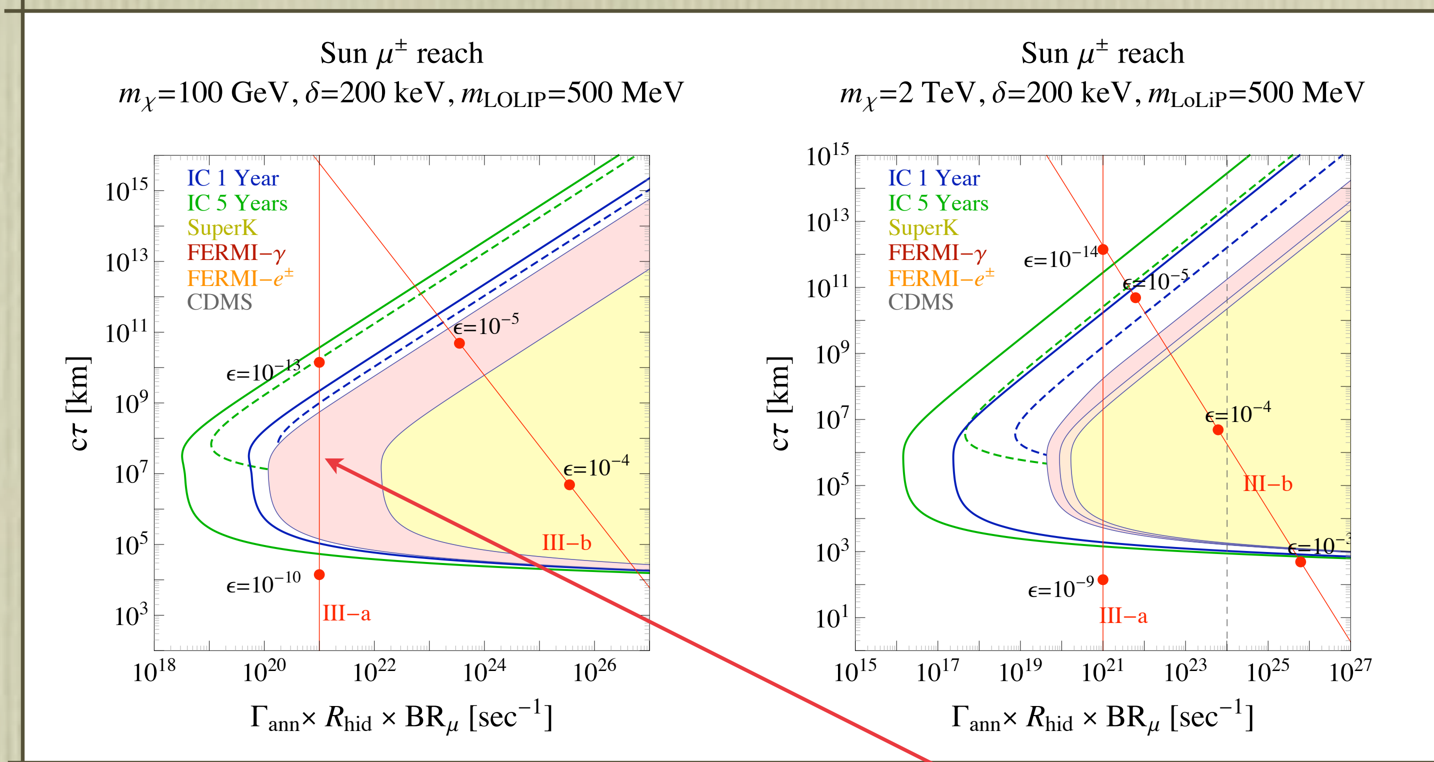


Model lines: Inelastic DM, $\delta = 200$ keV

IIIa:

- Lightest state is scalar, h.
- $\sigma_{\chi n} \propto \frac{\epsilon^2}{m_{\gamma_d}^4}$
- $c\tau \propto \left(\epsilon^4 m_h\right)^{-1}$

IceCube Reach



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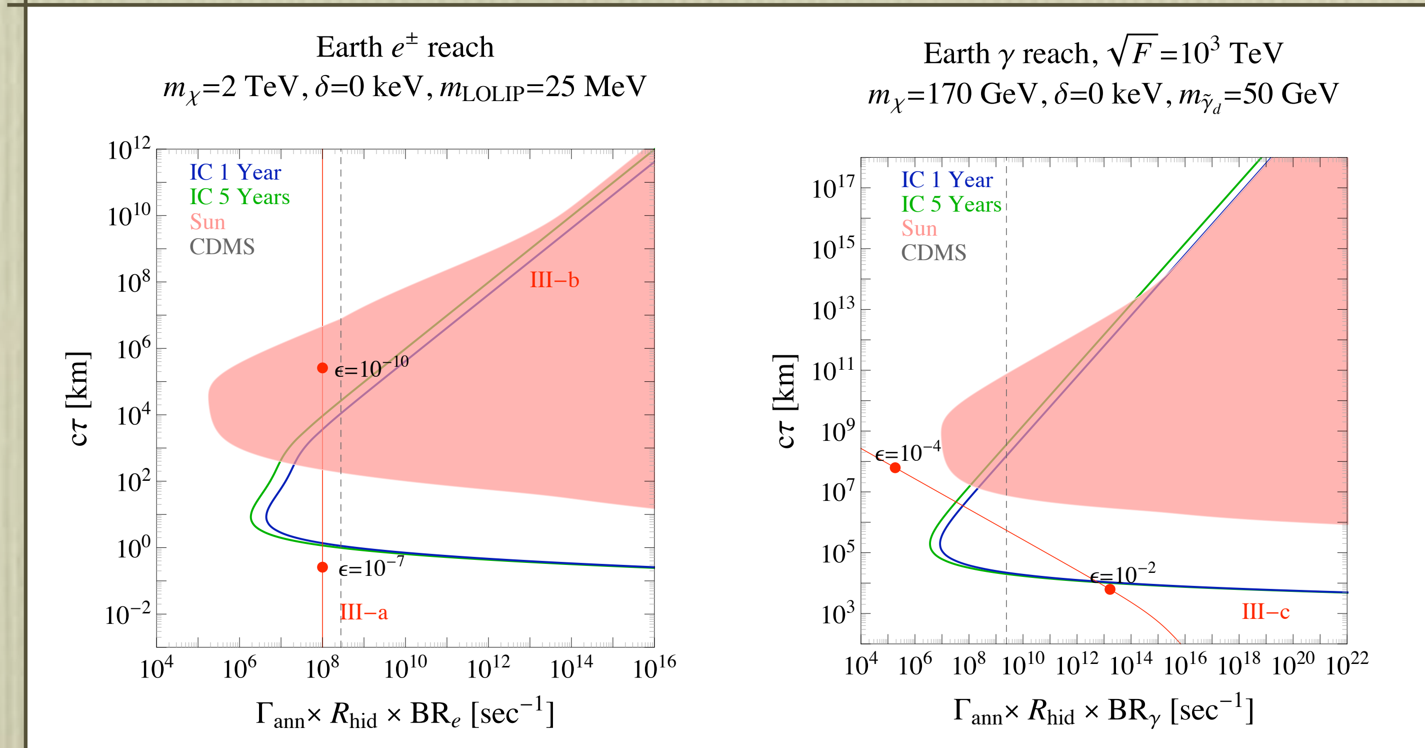
IIIb:

- Lightest state is the vector, γ_d.
- Interacting with SM and dark sector.
- $\sigma_{\chi n} \propto \epsilon^0$
- $c\tau \propto \left(\epsilon^2 m_{\gamma_d}\right)^{-1}$

IceCube Reach



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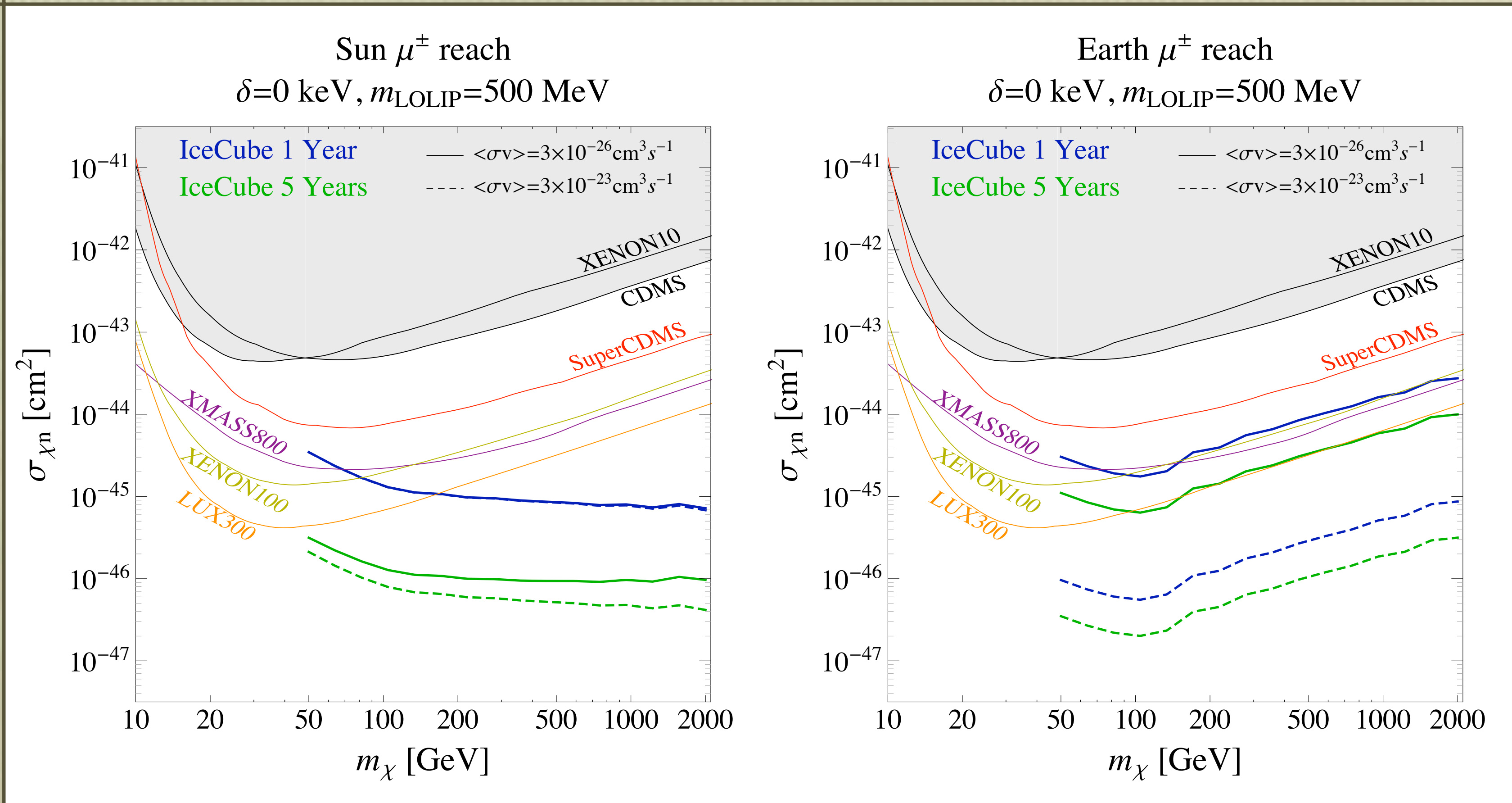

Conclusions

- Exciting time for DM physics!
- Motivates the existence of low scale hidden sectors.
- Hidden sectors could be probed in the near future.
- If related to DM, indirect measurements are very sensitive to such sectors: $\epsilon \gtrsim 10^{-15}$.
- Photon measurement can also differentiate between DM models.
- To be continued...