Indirect Detection of Dark Matter: Recent Developments

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Outline

- Introduction – Indirect Detection
- Photons
- Neutrinos
- Antimatter (positrons, antiprotons)
- Enhancements from bremsstrahlung

Indirect Detection

Search for fluxes of DM annihilation or decay products from regions where the DM density is high:

- Annihilation in our Galaxy or in nearby galaxies
→ Photons, antimatter, neutrinos

- Annihilations in galaxies throughout the Universe
→ cosmic diffuse fluxes

- Annihilation in Sun/Earth
→ Neutrinos only

“WIMP Miracle“

❖ The thermal relic picture sets the “natural scale” for the dark matter annihilation cross section:

❖ $\Omega_{DM} \sim$ 0.2 implies $\langle \sigma_A v \rangle \sim 3 \times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$

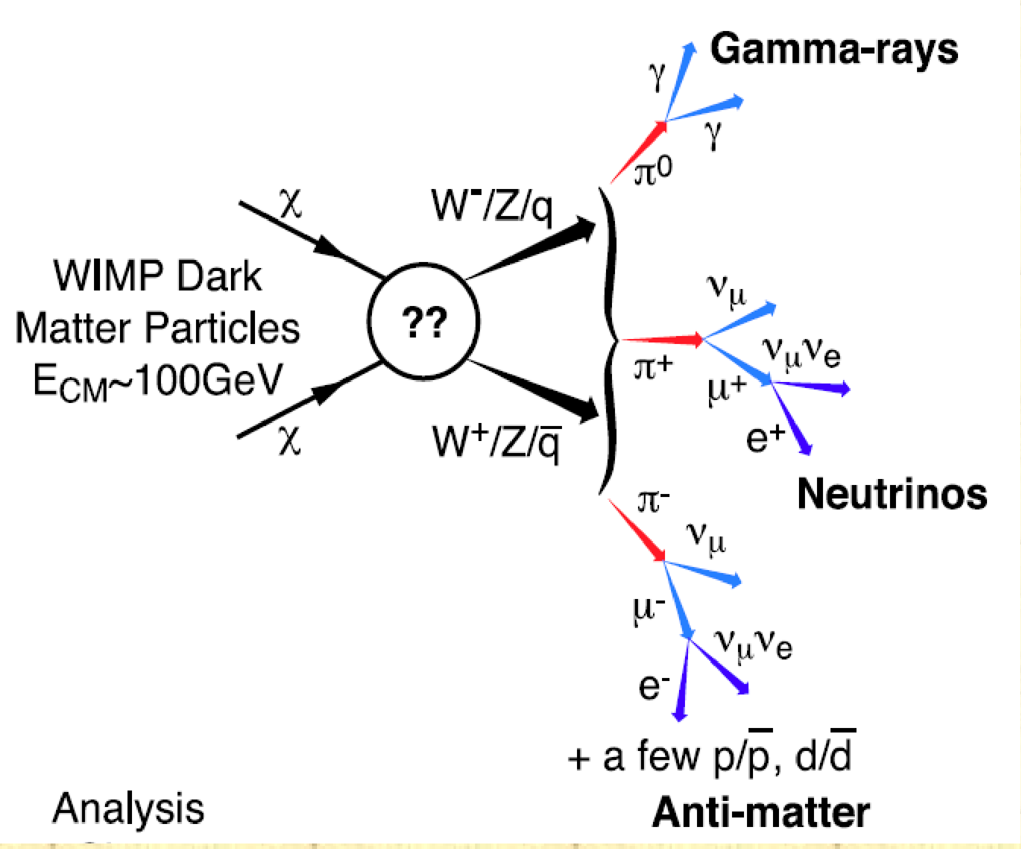
❖ Correct relic density for:

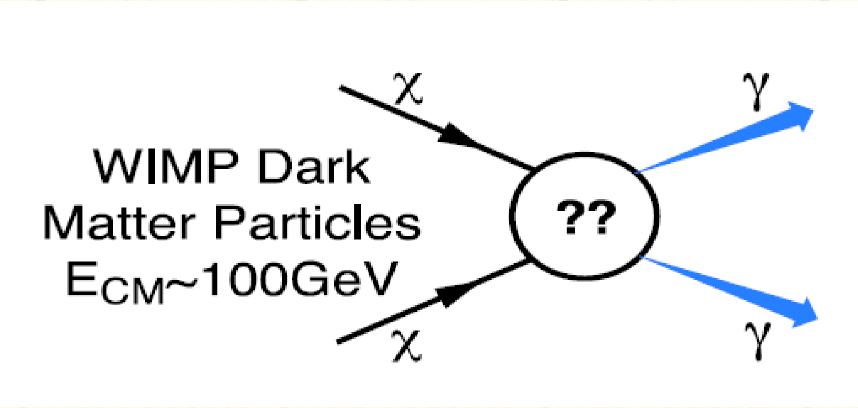
- electroweak strength couplings
- GeV – TeV masses

→ Realistic prospects of detecting annihilation signals!

(Indirect detection also sensitive to decaying DM, in some scenarios)

Annihilation to Gamma rays





Baltz et al., JCAP 2008

Annihilation - gamma rays

- Gamma ray lines from $\chi\chi \rightarrow \gamma\gamma$ or γX

→ "smoking gun" signal, present in most models but small rate due to loop suppression (See also parallel talk by P. Agrawal)

- Continuum gamma rays from fragmentation or decays of quarks and gauge bosons

→ good detection prospects, less distinct spectral info

- Internal bremsstrahlung gammas

→ QED correction to any annihilation process which produces charged particles. Dominates flux in some cases.

- Gammas from energy loss of charged particles

→inverse Compton scattering, bremsstrahlung

Annihilation in the Galaxy

Intensity of DM annihilation gamma ray signal:

$$\frac{d\Phi_\gamma}{dE} = \frac{\langle\sigma_A v\rangle}{2} \frac{\mathcal{J}_{\Delta\Omega}}{\mathrm{J}_0} \frac{1}{4\pi m_\chi^2} \frac{dN_\gamma}{dE}$$

Integral of square of DM density, along the line of sight:

$$\mathcal{J}(\psi) = \mathrm{J}_0 \int_0^{\ell_{max}} \rho^2 \left(\sqrt{R_{\mathrm{sc}}^2 - 2\ell R_{\mathrm{sc}} \cos\psi + \ell^2}\right) d\ell$$

where y is angle of observation w.r.t. to the Galactic Center.

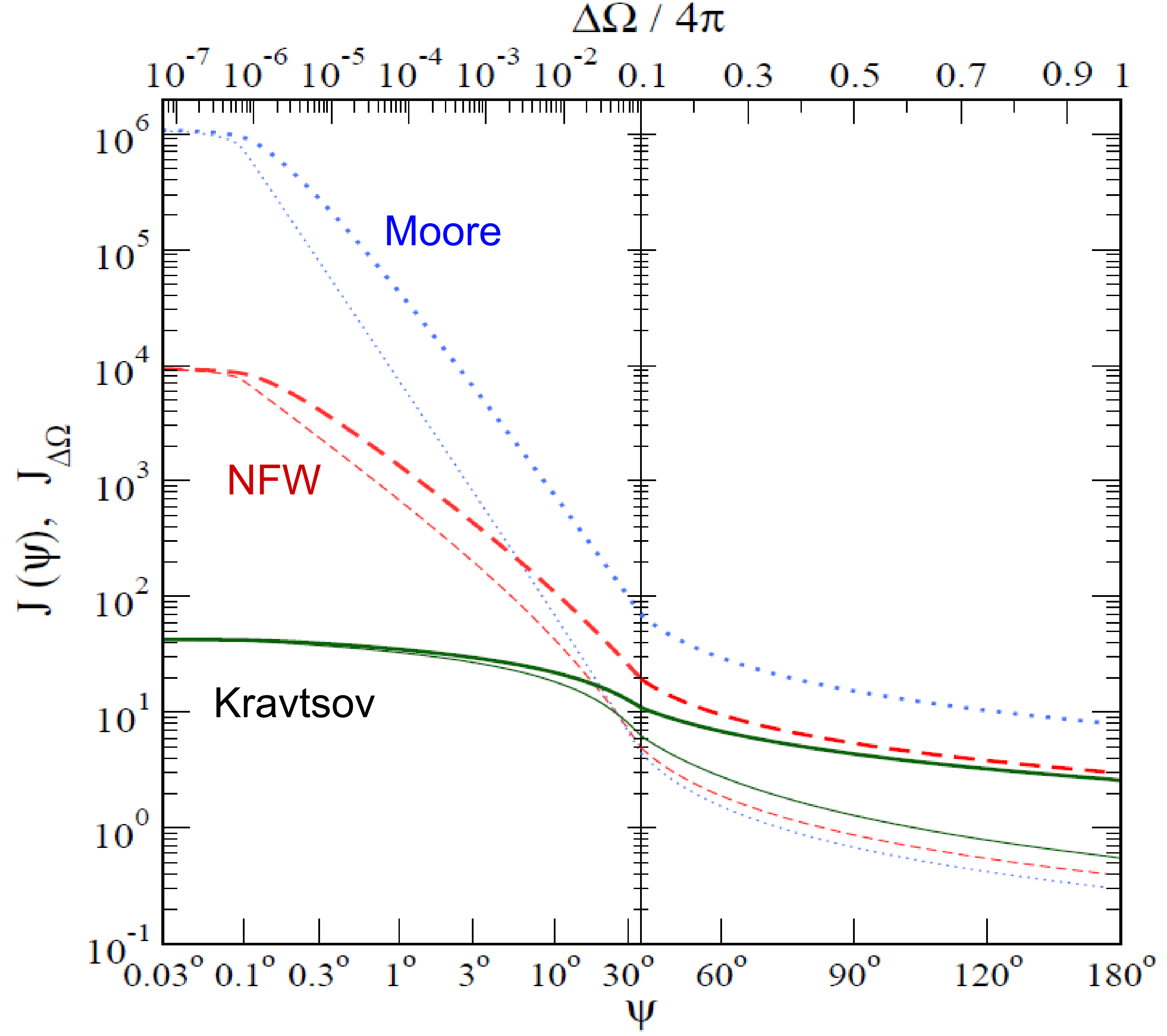
Average over solid angle of DW is:

$$\mathcal{J}_{\Delta\Omega} = \frac{2\pi}{\Delta\Omega} \int_0^{\psi} \mathcal{J}(\psi) \sin\psi d\psi$$

For $\chi\chi\rightarrow\gamma\gamma$, the gamma ray spectrum per annihilation is:

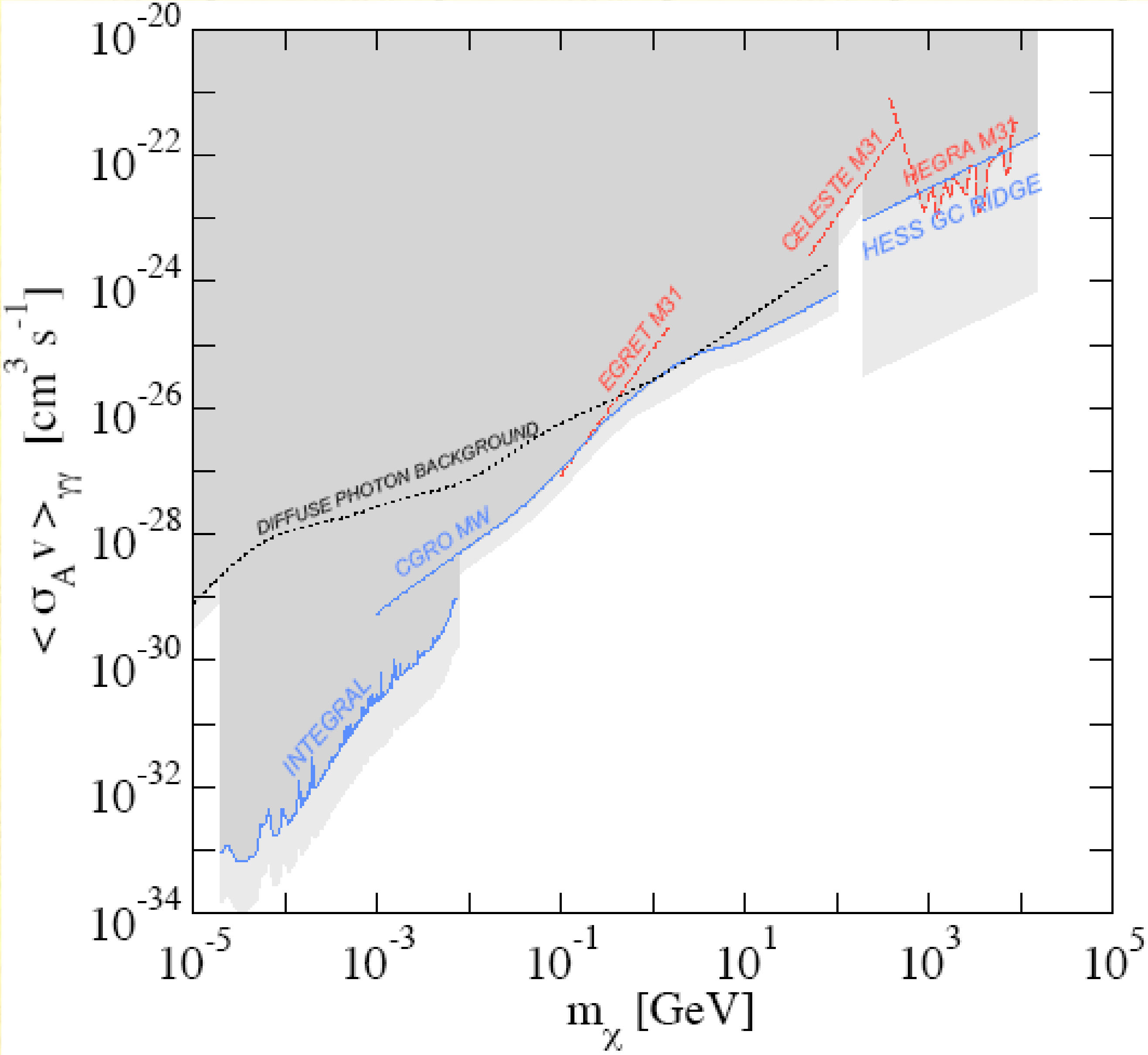
$$\frac{dN_\gamma}{dE} = 2\delta(m_\chi - E)$$

Uncertainty in halo density



Yuksel, Horiuchi, Beacom & Ando, 2007

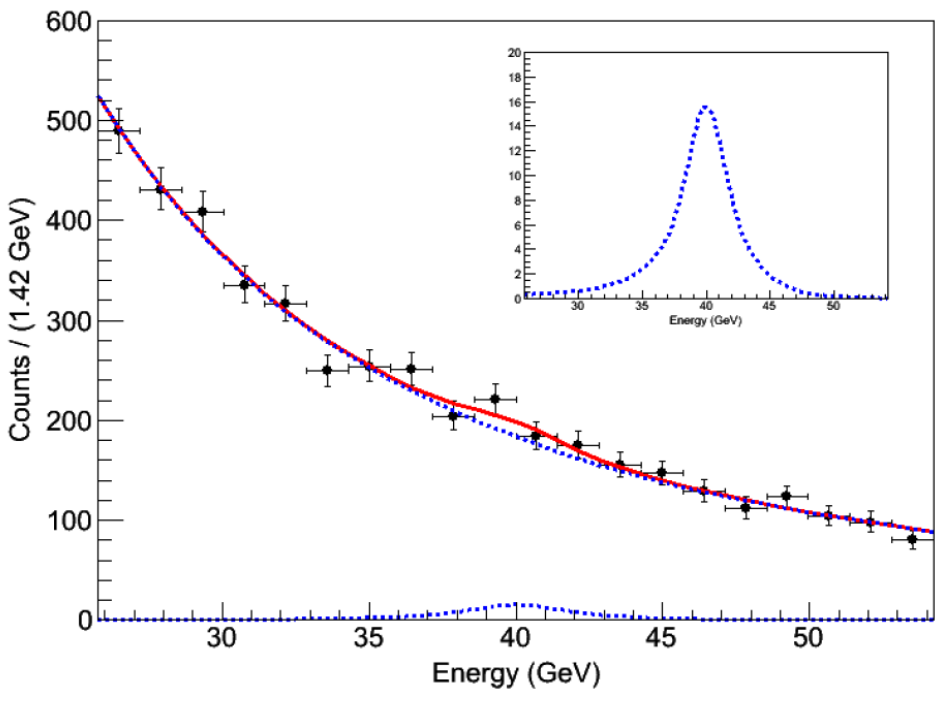
Cross-section limits for $\chi\chi \rightarrow \gamma\gamma$



Mack, Jacques, Beacom, Bell, Yuksel, PRD 2008.

Fermi gamma ray line limits

- ❖ Gamma ray line search from 30 – 200 GeV



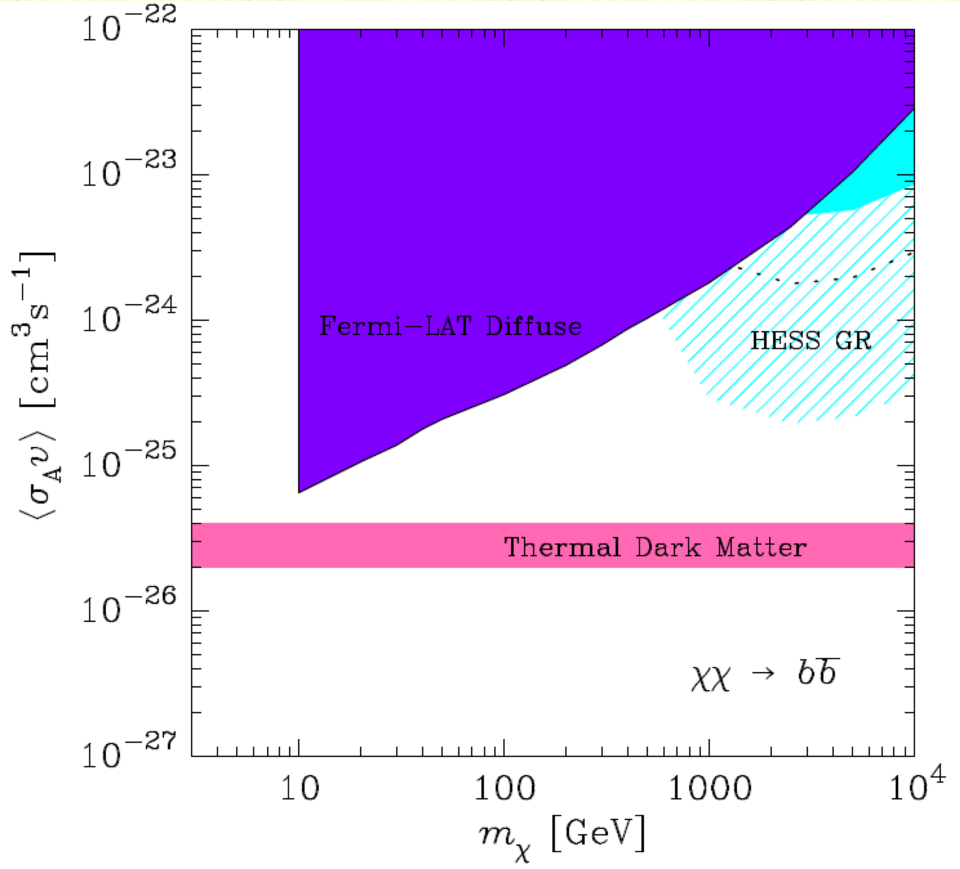
Fermi LAT, PRL 2010

→ no signal seen

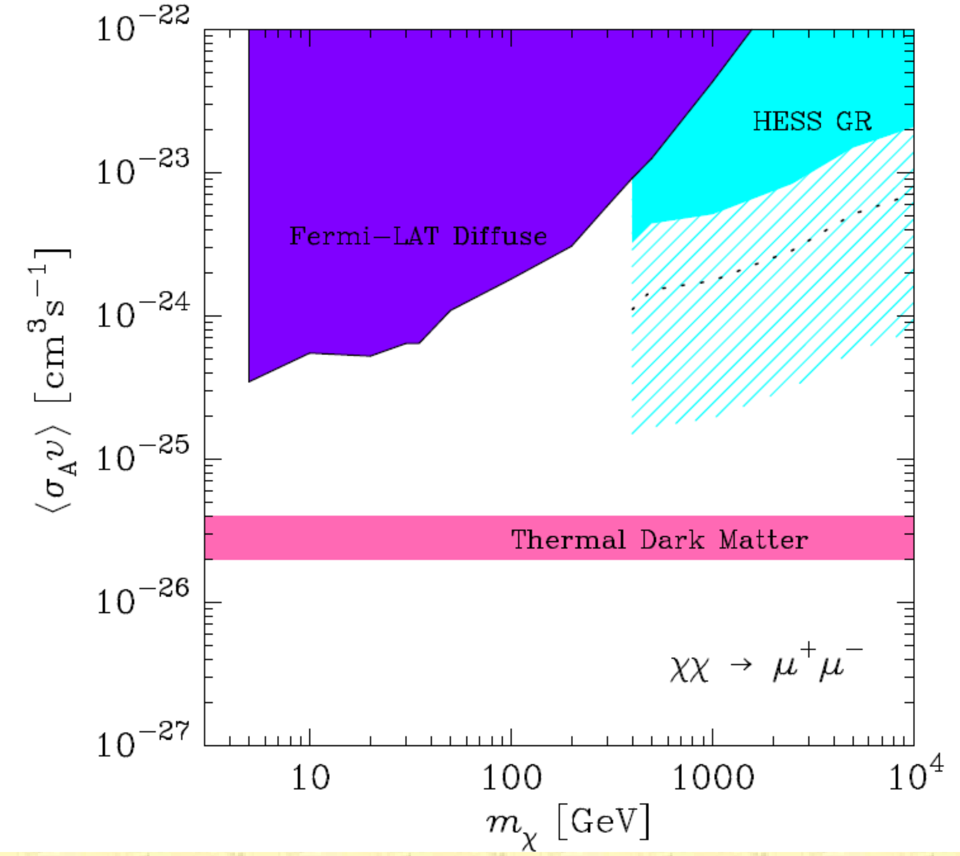
→ Translates to cross section limits an order of magnitude or more weaker than expected for a thermal relic WIMP.

See also talk by P. Agrawal → parallel session

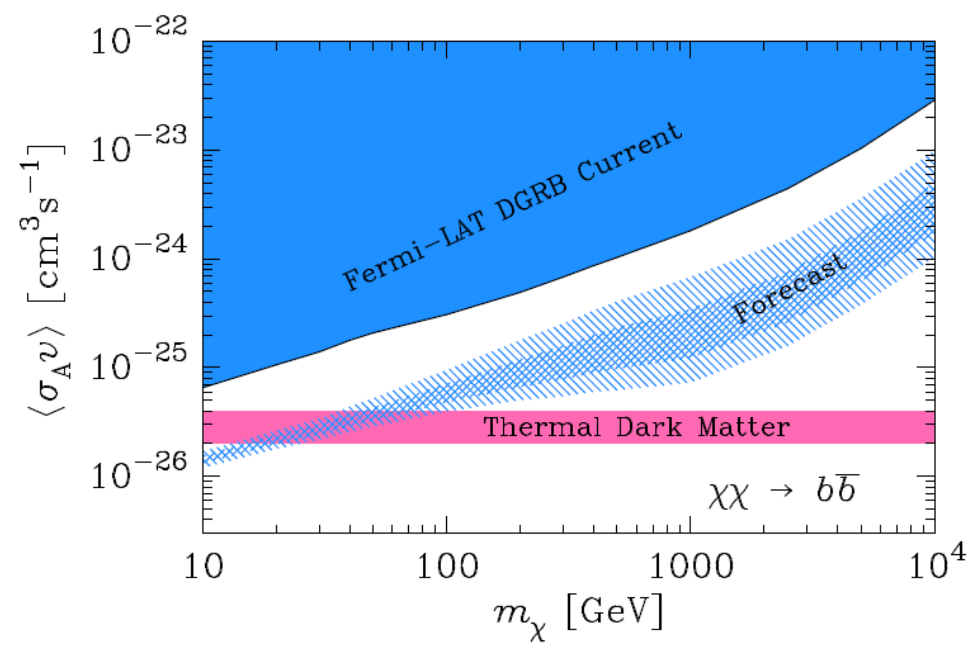
Gamma ray limits - continuum



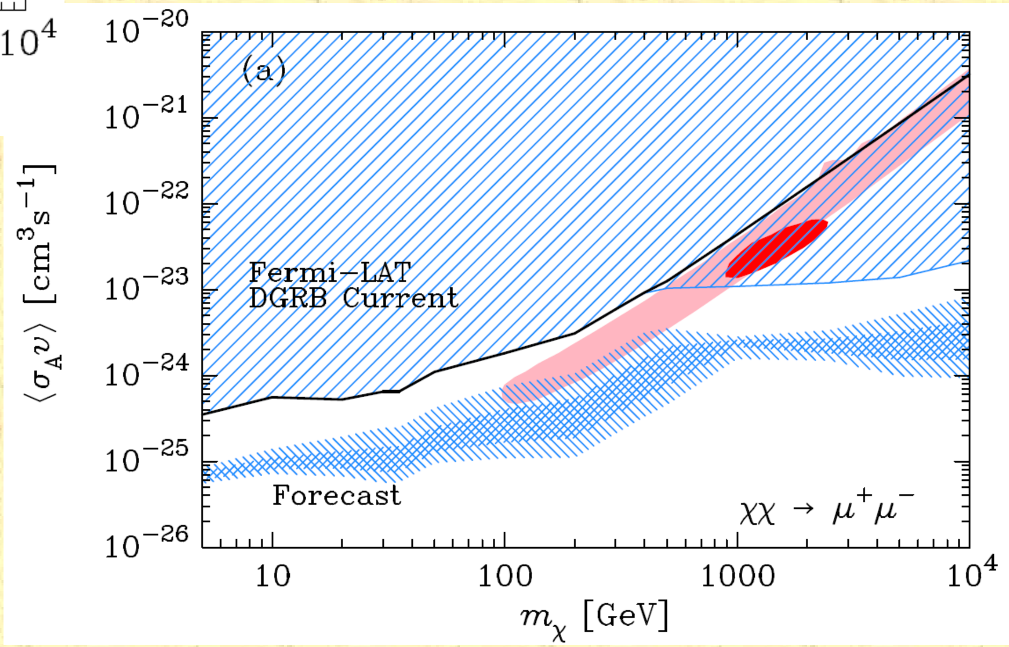
Abazajian, Agrawal and Chacko, 2010



Fermi limits and forecasts



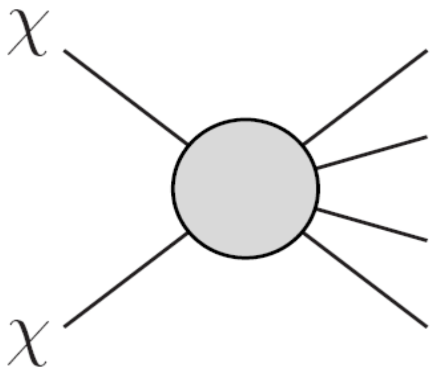
Diffuse gamma ray background



Abazajian, Blanchet and Harding, 2011

Annihilation to Neutrinos – galactic halo

If the dark matter is the lightest new particle:



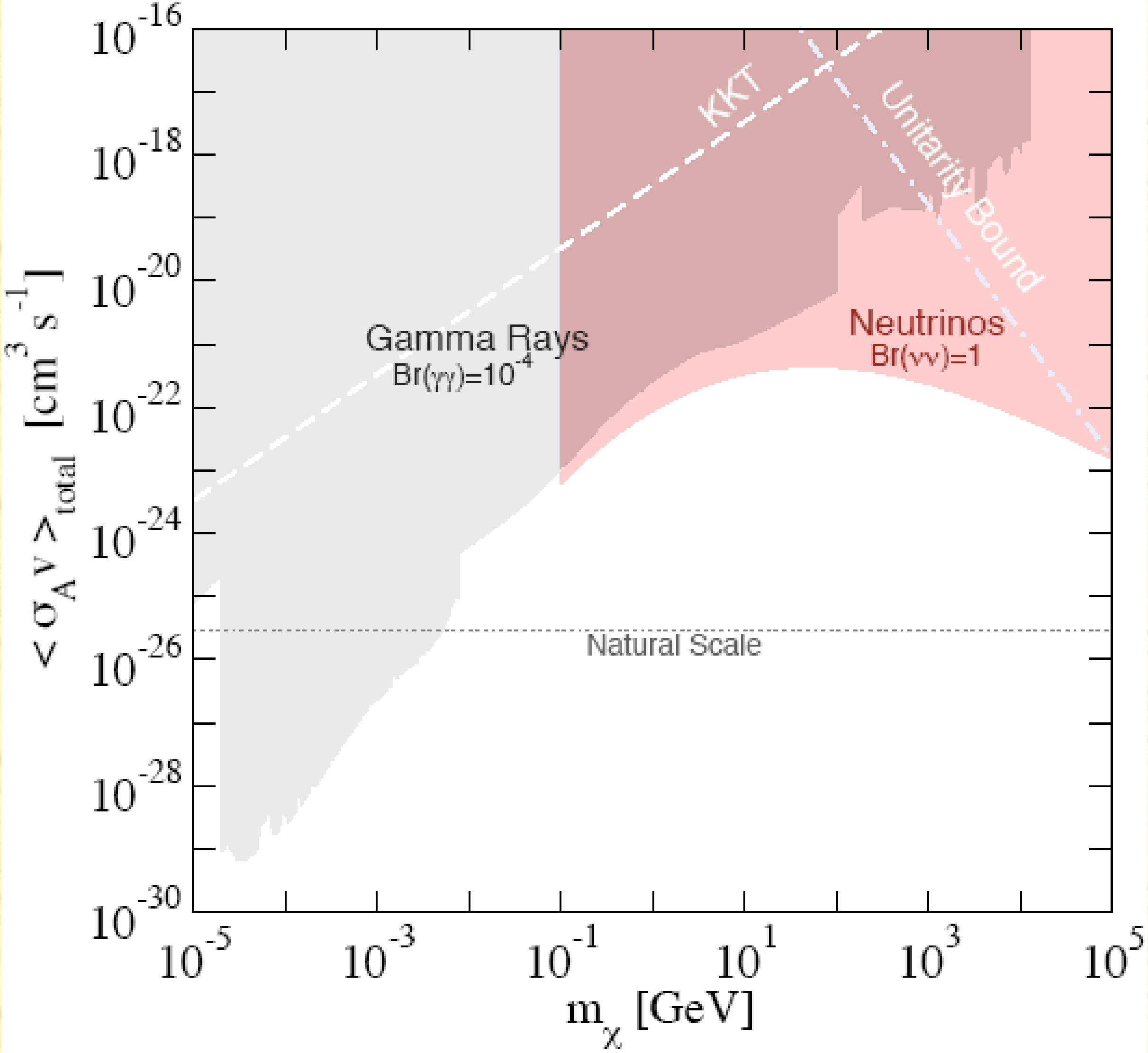
All Standard Model final states = "Visible" states: $\gamma\gamma,\ \overline{q}q,\ e^+e^-,\ \ldots$ + "Invisible" states: $\overline{\nu}\nu$

❖All final states except neutrinos produce gamma rays,

→Bound the *total* cross-section with the neutrino signal limit
i.e. Assume Br("hardest to detect") = 100%

Comparison of neutrino and photon limits on dark matter annihilation

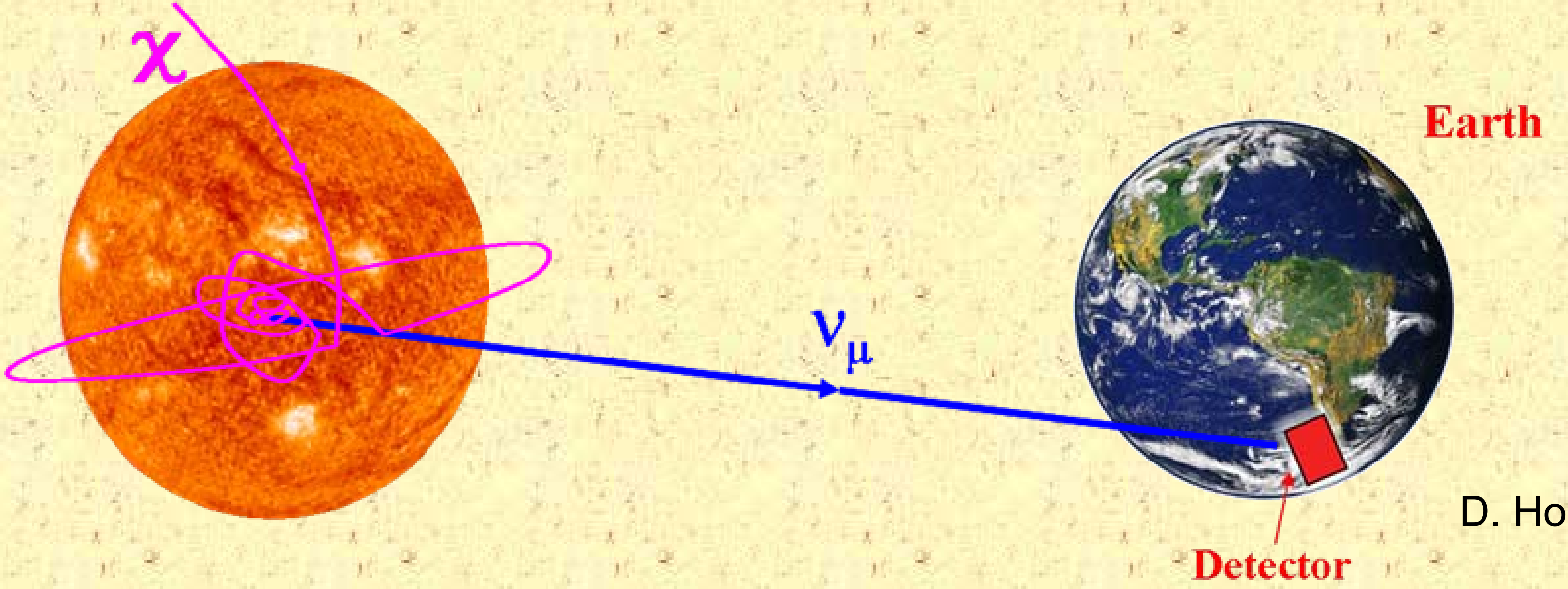
Br($\gamma\gamma$) = 10^{-4} assumed



Mack, Jacques, Beacom, Bell, Yuksel, 2008

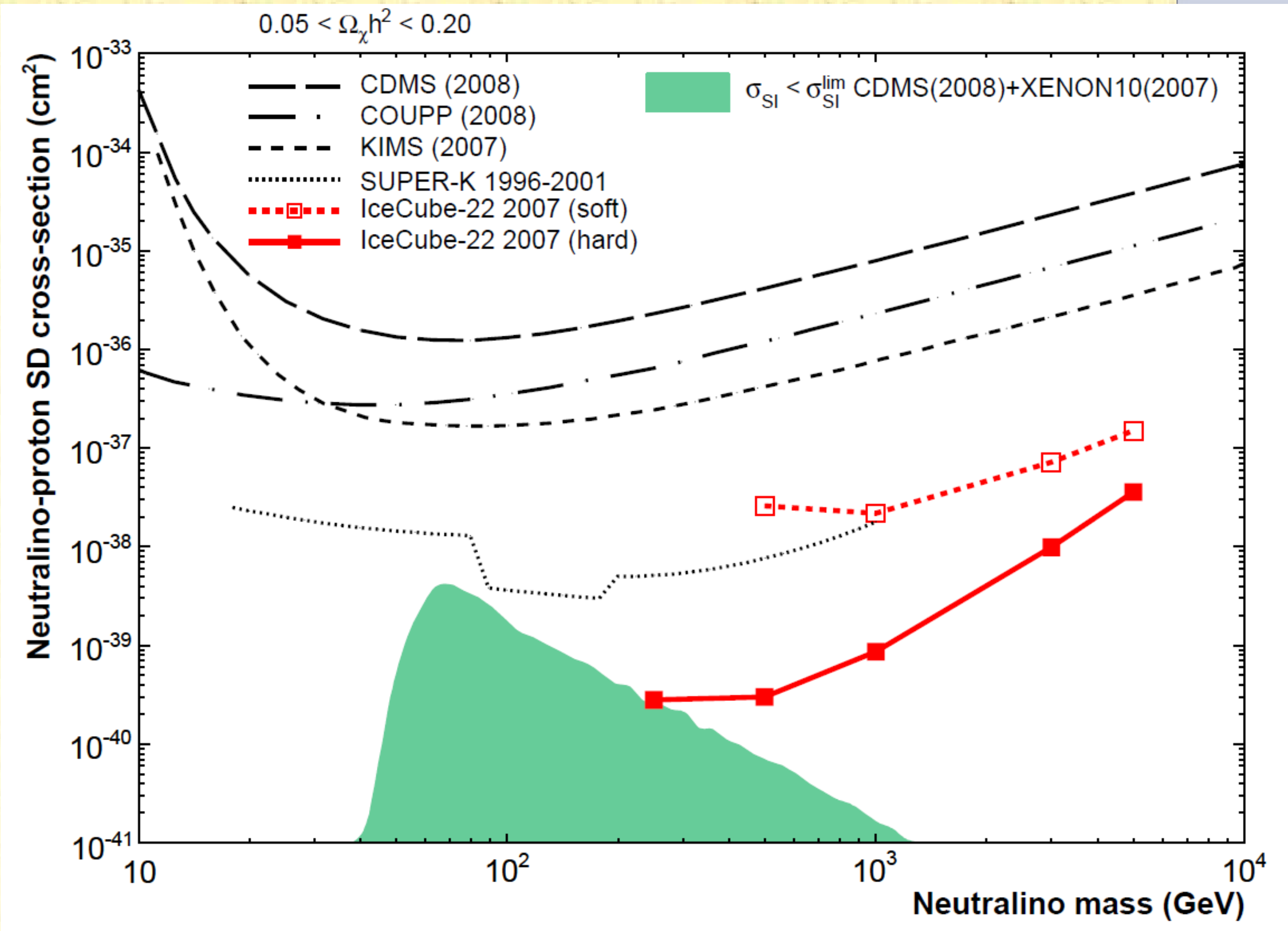
Neutrinos from the Sun

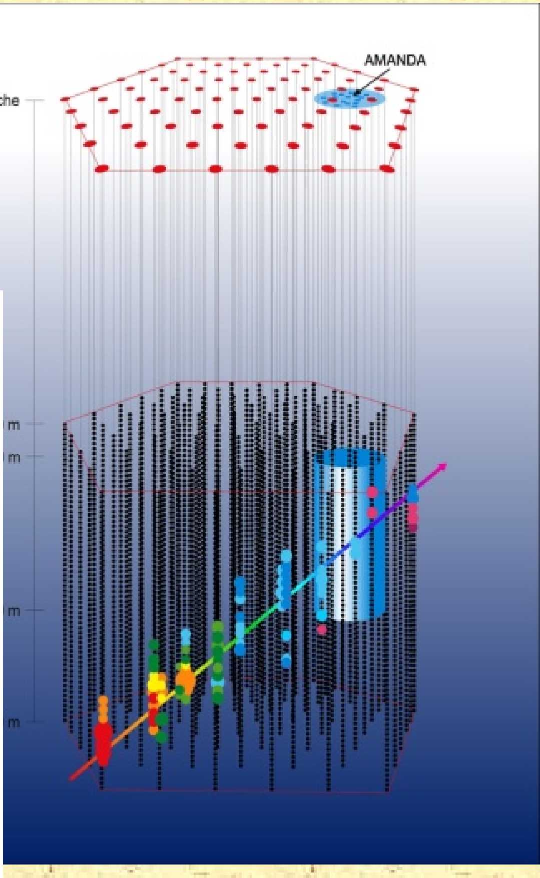
- Dark matter accumulates in the centre of Sun (and Earth)
- Neutrinos are the only annihilation products able to escape
- High energy neutrinos detected by IceCube, SuperK.
- Capture rate and (if in equilibrium) the annihilation rate controlled by WIMP-nucleon scattering cross section
- Competitive limits for spin-dependent cross sections



D. Hooper

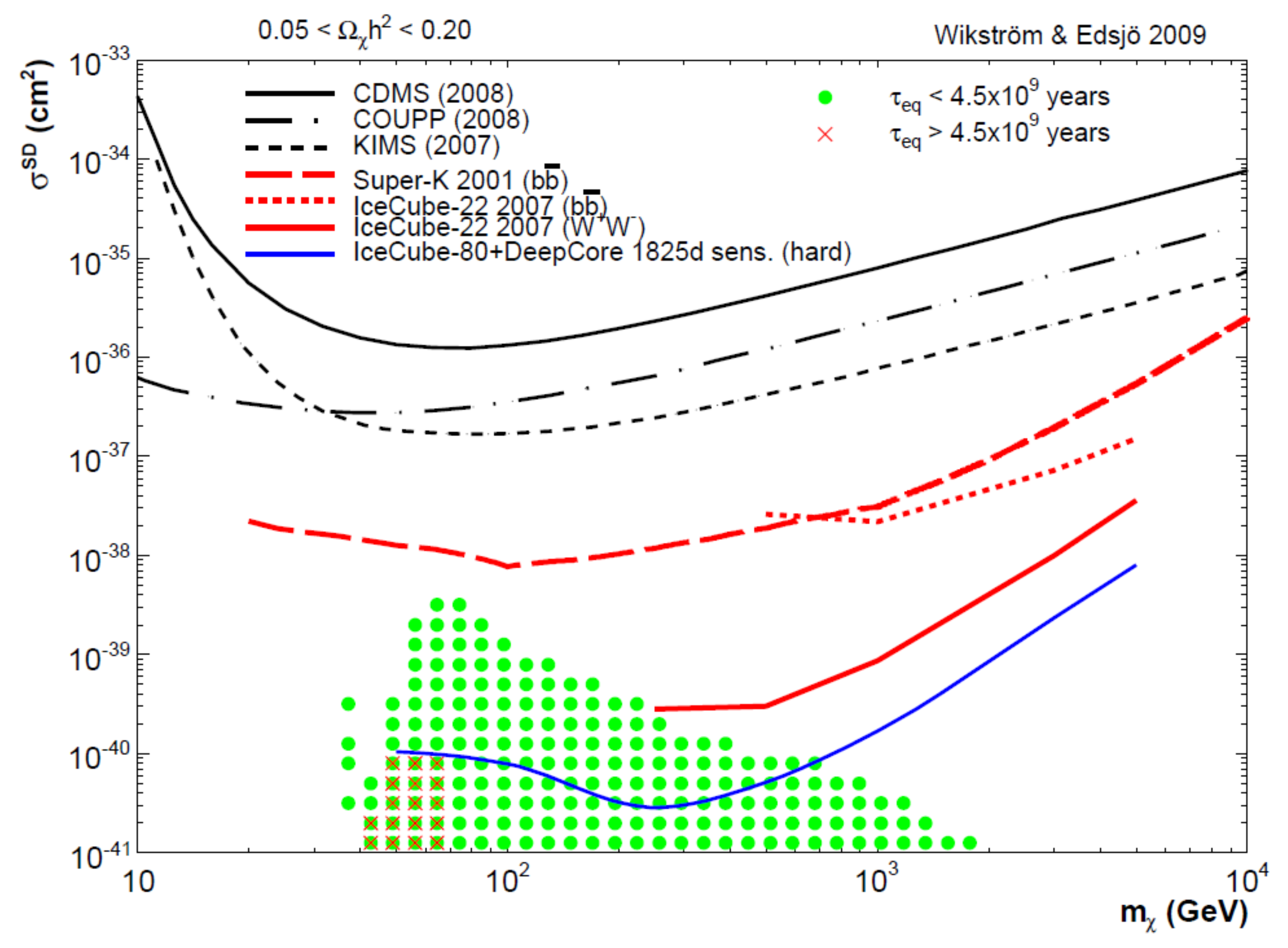
IceCube limits on Neutralinos





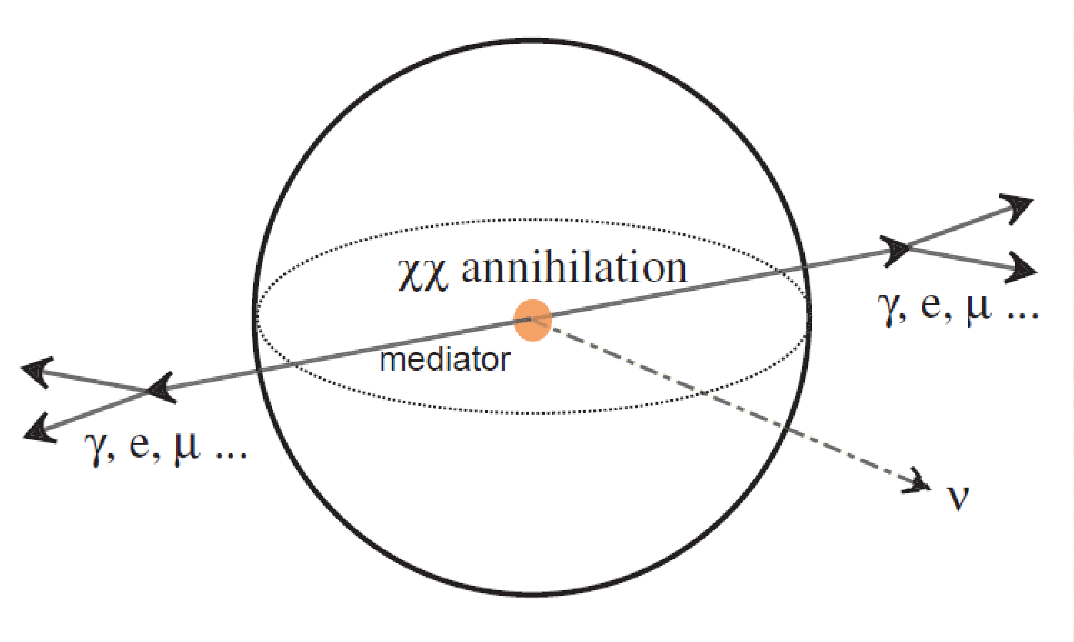
IceCube, PRL 2010; Limits with 22 string detector.

Full IceCube Sensitivity - Forecast



Wilkstrom and Edsjo, JCAP 2009

Annihilation in the Sun - secluded dark matter



Batell,
Pospelov, Ritz
and Shang,
PRD 2010

- Annihilation via metastable mediators, V

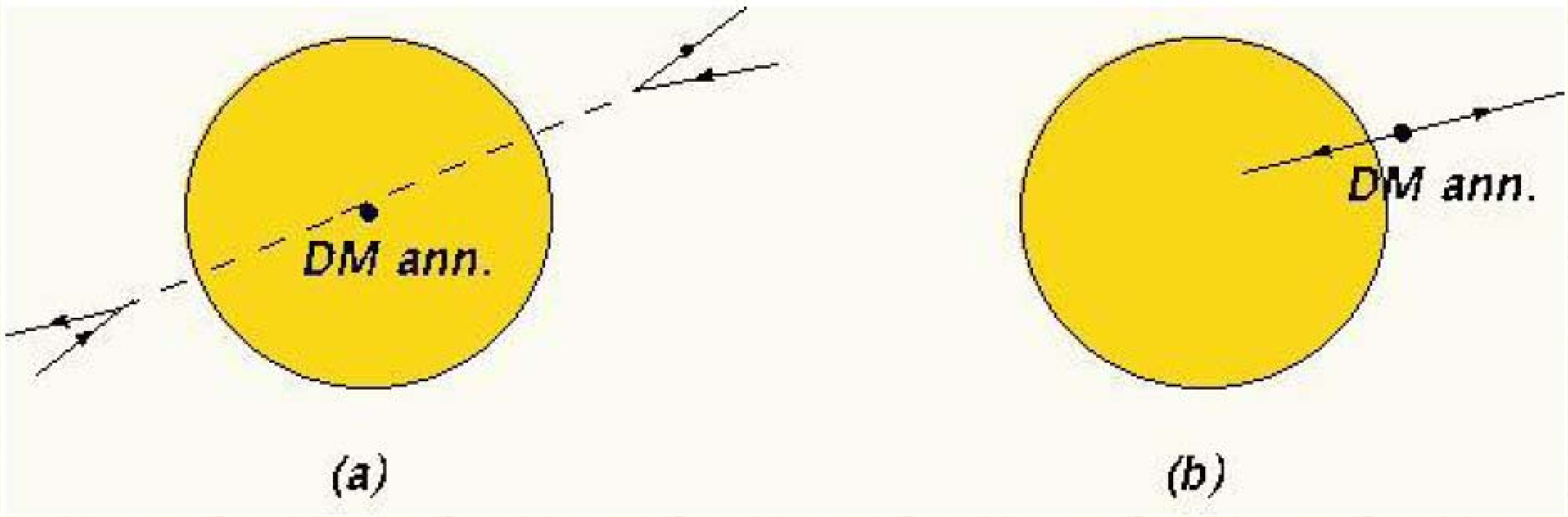
$$\chi\chi \to VV \to \text{SM particles}$$

- The mediators propagate before decaying:

$$L = c\tau_V\gamma_V = 3\times10^6\,\mathrm{km}\times\frac{\tau_V}{0.01\ \mathrm{s}}\times\frac{\gamma_V}{10^3}$$

→ Can decay outside the Sun → solar gamma rays

Schuster, Toro, Weiner and Yavin, PRD 2010



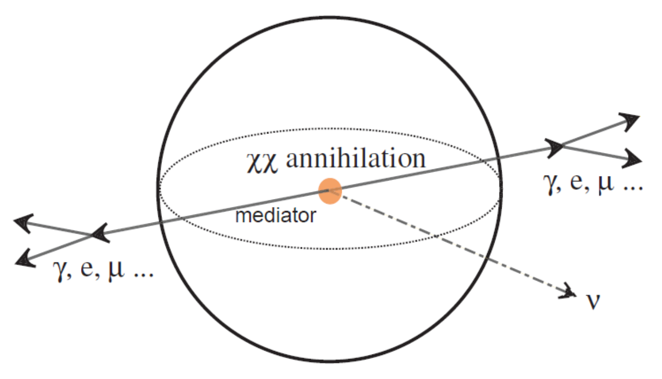
- ❖ Annihilation to long lived force carriers which escape the Sun before decaying

- ❖ Inelastically interacting dark matter forms halo of dark matter outside the Sun

→ gamma rays or charged particles from the Sun

→ Test with Fermi data in near future

Neutrino signal enhanced for secluded DM



- High energy neutrinos produced at the solar core undergo significant absorption in the Sun, for E > O(100) GeV.

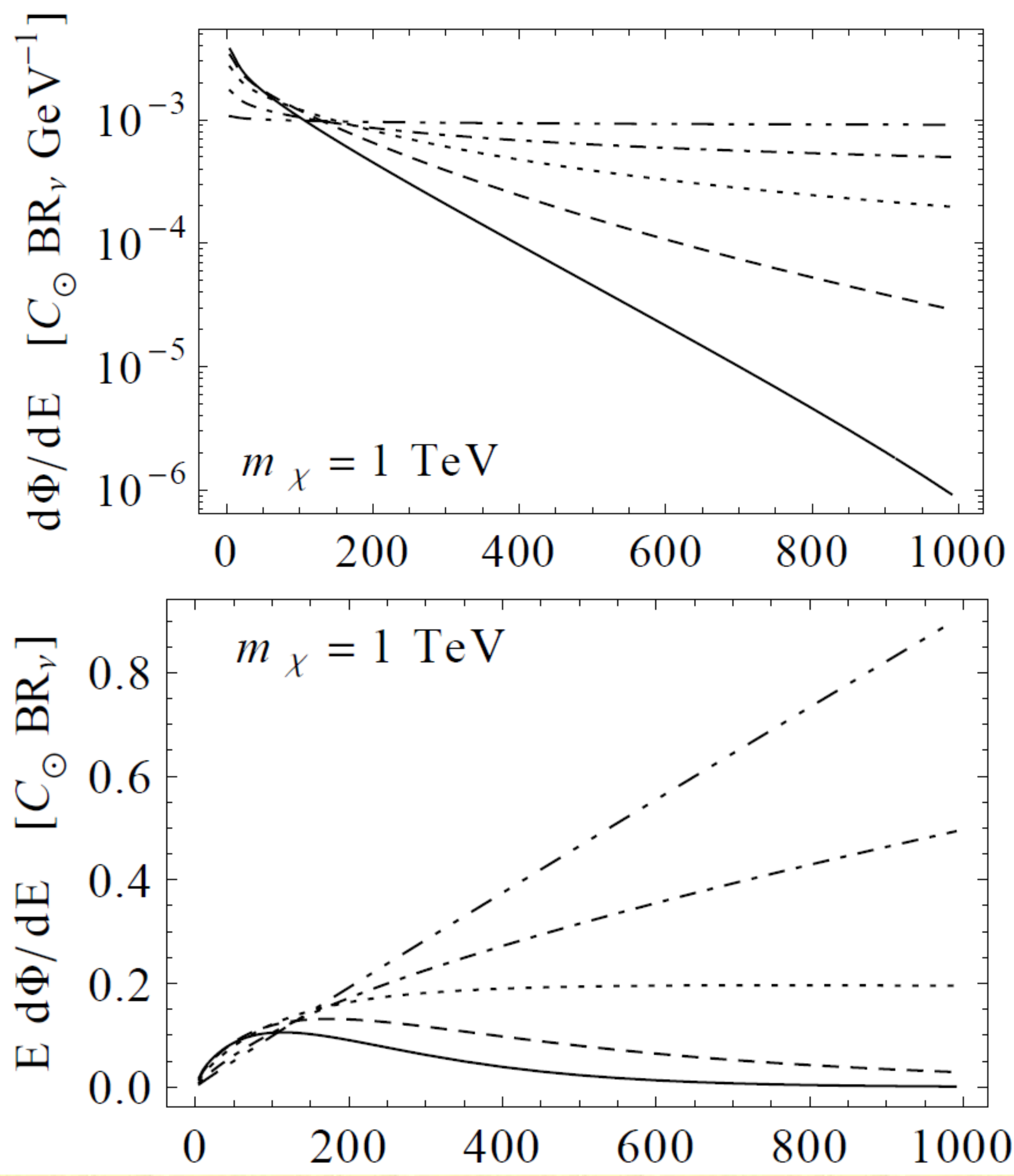
$$\rho = \rho_{\mathrm{inj}} e^{-\frac{E}{\varepsilon}\Delta x}$$

ε~100 GeV,
Δx=optical depth in Sun

- If mediators propagate out of the dense core before decaying → neutrino signal greatly enhanced

- Since the solar density falls exponentially with radius, this can have a large effect, even for short mediator lifetimes.

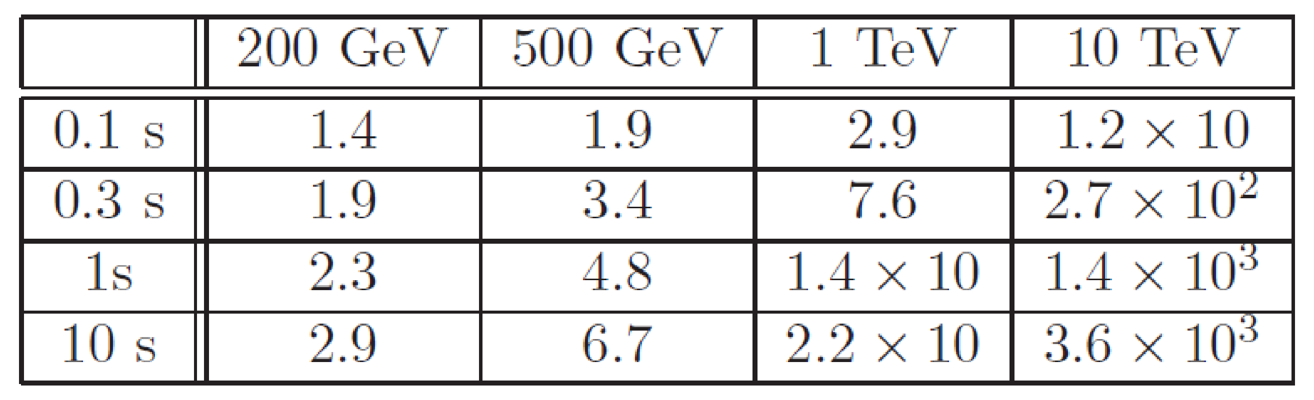
Enhanced HE neutrino fluxes from Sun



Bottom to top: mediator lifetimes of $\gamma\tau$ = 0.001 s, 0.1 s, 0.3 s, 1 s, and 10 s.

Note: solar radius ~ 2.2s

Bell and Petraki,
JCAP 2011



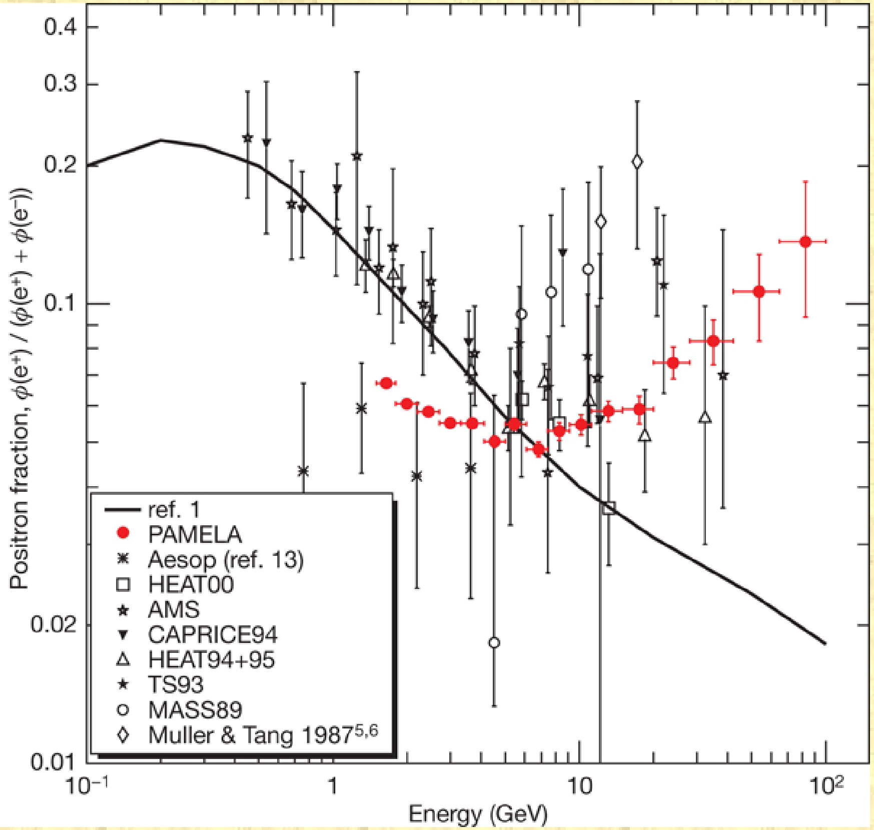
	200 GeV	500 GeV	1 TeV	10 TeV
0.1 s	1.4	1.9	2.9	1.2×10
0.3 s	1.9	3.4	7.6	2.7×10^2
1s	2.3	4.8	1.4×10	1.4×10^3
10 s	2.9	6.7	2.2×10	3.6×10^3

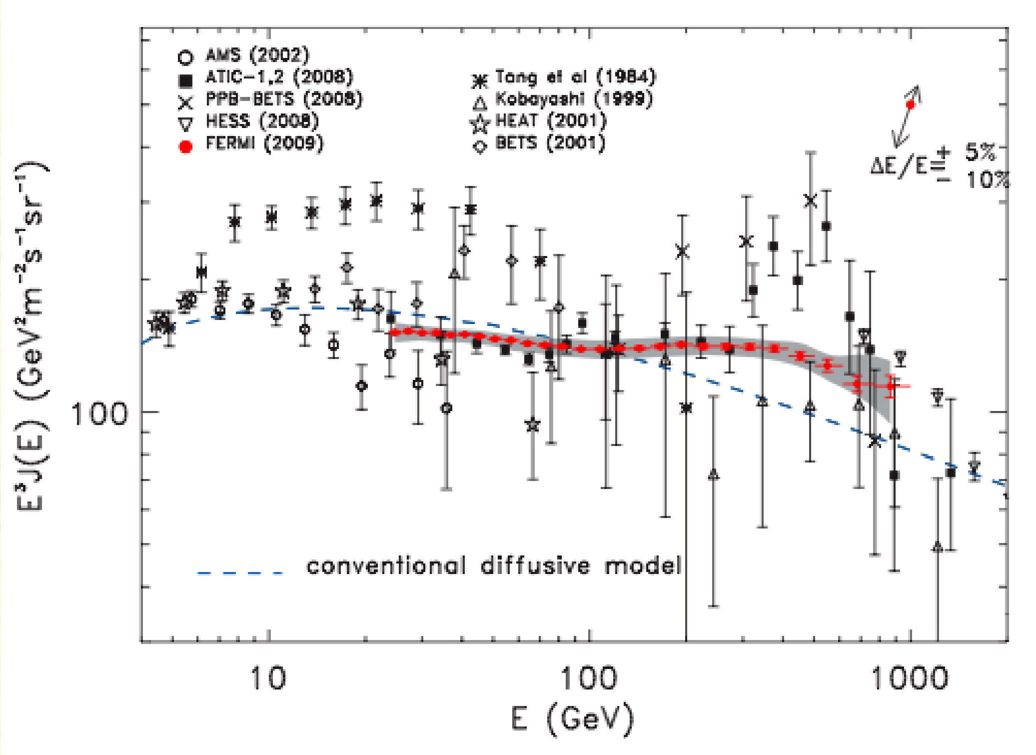
The ratio of $\mu^\pm$ events observable at IceCube in the presence of mediators of lifetime $\gamma\tau$ over those in the absence of metastable mediators, integrated over muon energies $E > 100$GeV

Bell and Petraki,
JCAP 2011

Annihilation to Antimatter

Positrons





PAMELA e+ excess

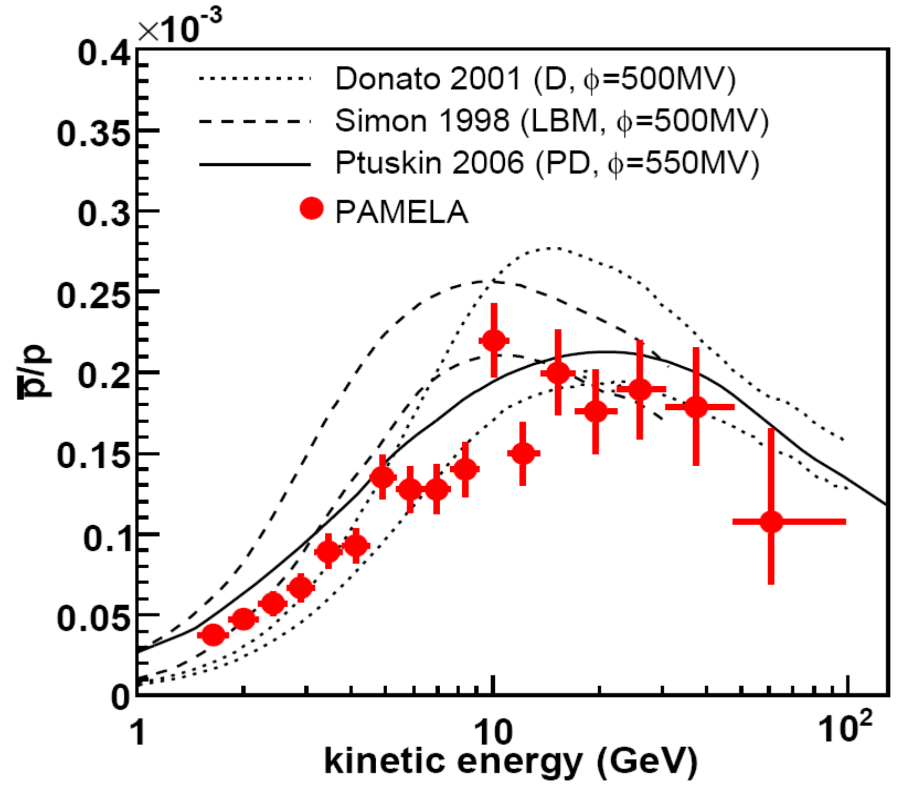
Nature 458, 607-609

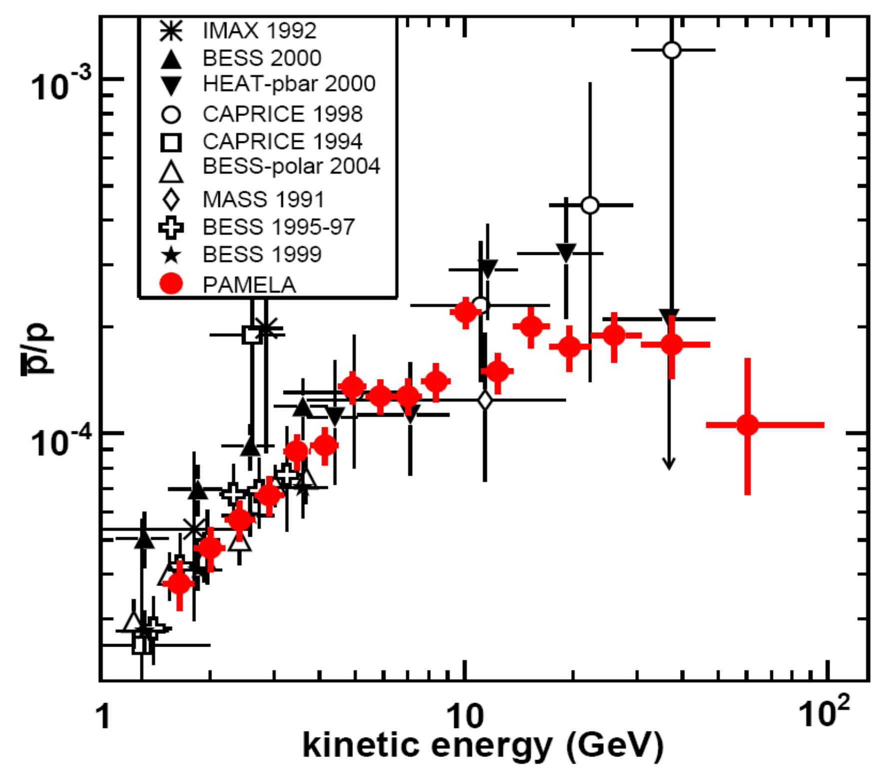
Fermi $e^+ + e^-$ excess

Phys. Rev. Lett. 102, 181101 (2009)

Annihilation to Antimatter

Antiprotons





Antiproton data consistent with theory expectation (for secondary production of antiprotons via cosmic ray propagation in the Galaxy).

Resolution of positron anomalies?

- Positrons from astrophysics?

Re-examine the expected positron flux from:
→pulsars
→supernova remnants
→modified cosmic ray propagation/acceleration

- Positrons from Dark Matter? Challenging because:

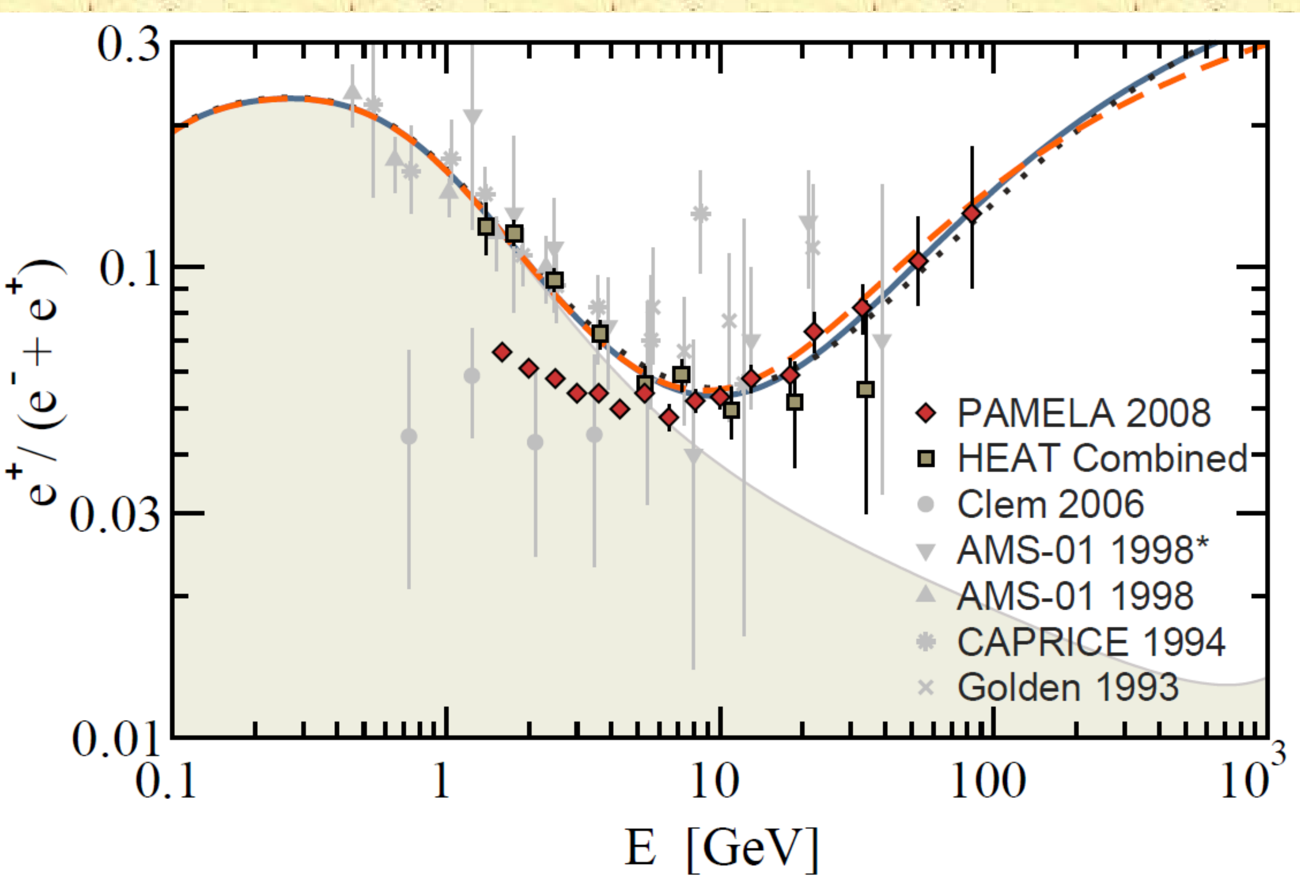
→ Must produce enough e+e- without overproducing pbar or gamma ray, or radio fluxes

→ Need big cross sections!

  - Boost via DM clumping/substructure or enhanced cross sections→"Sommerfeld", non-thermal DM, …
  - ***But annihilation to leptons is often suppressed……***

Pulsars?

Possible contribution from Geminga pulsar to positron fraction:



Yuksel, Kistler and Stanev, PRL 2009

Annihilation cross section

Parameterize the annihilation cross section as:

$$\langle \sigma v \rangle = a + b v^2 + \ldots$$

a -- from s-wave (*L*=0) annihilation
b -- both s-wave and p-wave (*L*=1) contributions

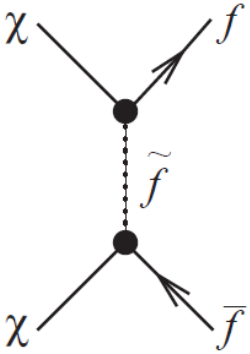
The L^{th} partial wave contribution is suppressed as v^{2L}

In galactic halos, v~ 10^{-3}c, so only the s-wave contribution will be significant.

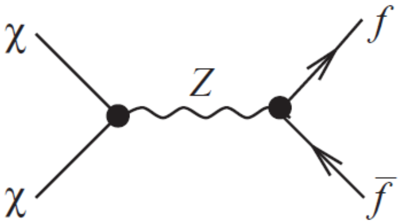
However, in many models, s-wave annihilation to a fermion pair is helicity suppressed by a factor of $(m_f / m_{DM})^2$

Example: SUSY

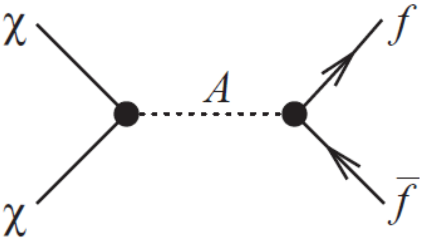
Majorana neutralinos annihilate to a fermion pair via:



- t- and u-channel exchange of sfermions
  → helicity suppressed



- s-channel exchange of Z
  →helicity suppressed



- s-channel exchange of higgs
  → suppressed by yukawa couplings

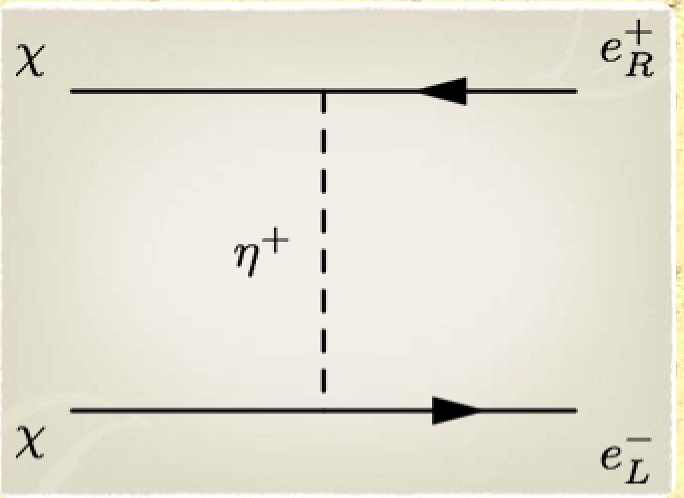
$$(m_f/\mathrm{vev})^2$$

Example: leptophillic model

- Cao, Ma, Shaughnessy, PLB 2009.

Dark matter = gauge-singlet Majorana fermion = χ

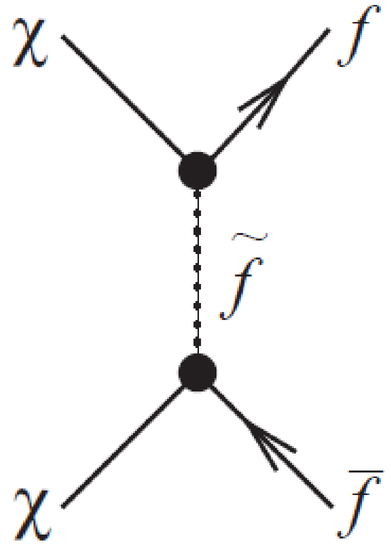
$$\mathcal{L} = f(\nu_L \eta^0 - \ell_L \eta^+)\chi + h.c.$$



$$v\,\sigma = \frac{f^4 v^2}{24\pi\, m_\chi^2}\,\frac{1+\mu^2}{(1+\mu)^4}$$

$$\mu = m_\eta^2 / m_\chi^2$$

SUSY analogue

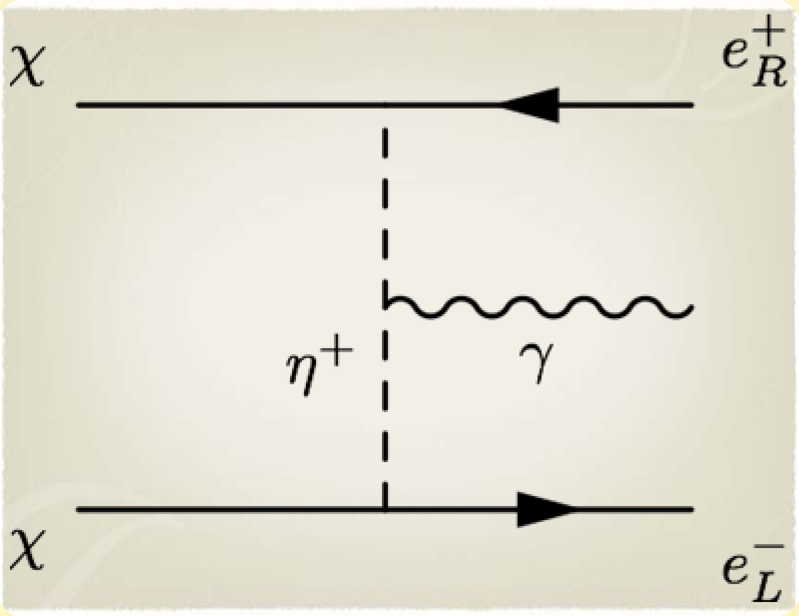


Annihilation of bino dark matter to fermions via exchange of sfermions

Lifting the suppression (photons)

Emission of a photon can lift this suppression:

Bergstrom, PLB 225, 372, 1989;
Flores, Olive, Rudaz, PLB 232, 377, 1989;
Bringmann, Bergstrom, Edsjo, 2008;
Barger, Gao, Keung, Marfatia, 2009,
…

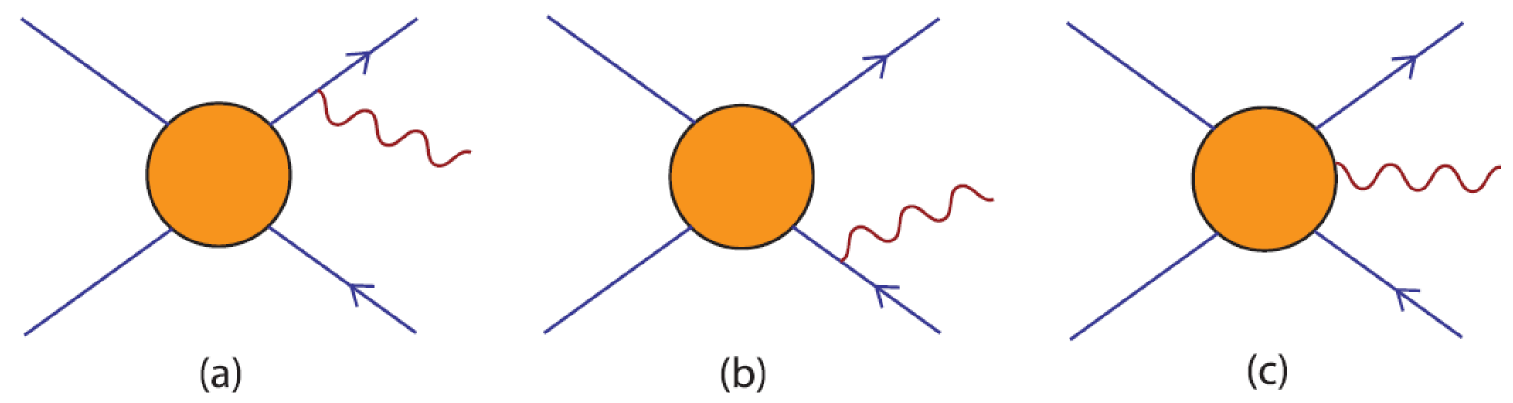


The photon carries away a unit of angular momentum
→no longer helicity suppressed.

$$\chi\chi \to f\bar{f}\gamma \gg \chi\chi \to f\bar{f}$$

Lifting the suppression (photons)

Bringmann, Bergstrom, Edsjo, 2008



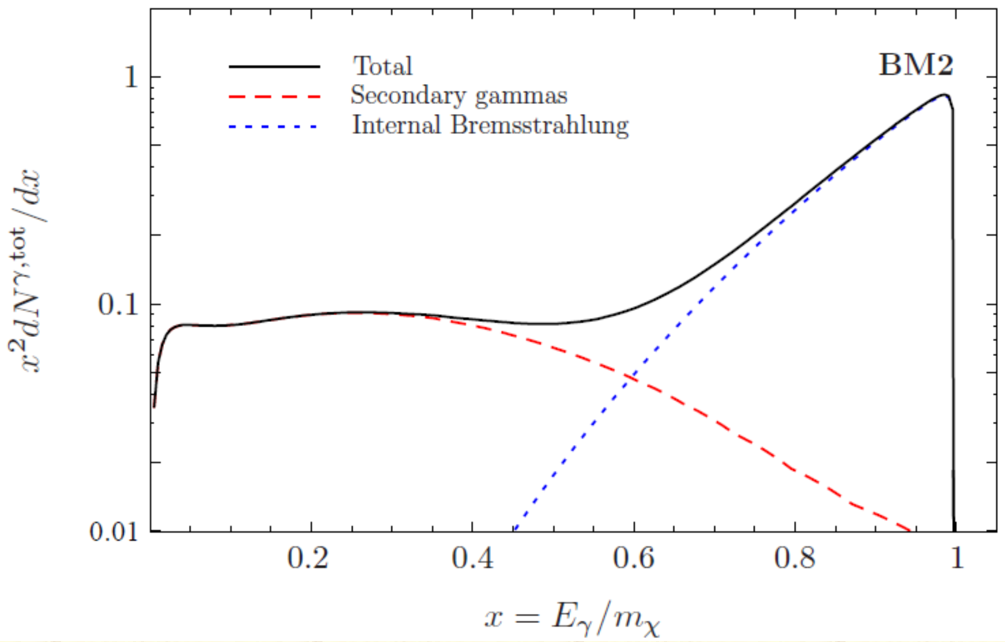
Final state radiation (FSR)

"Virtual internal bremsstrahlung" (VIB)

- Effect most pronounced for near-degenerate χ and η (i.e. coincides with the co-annihilation region)

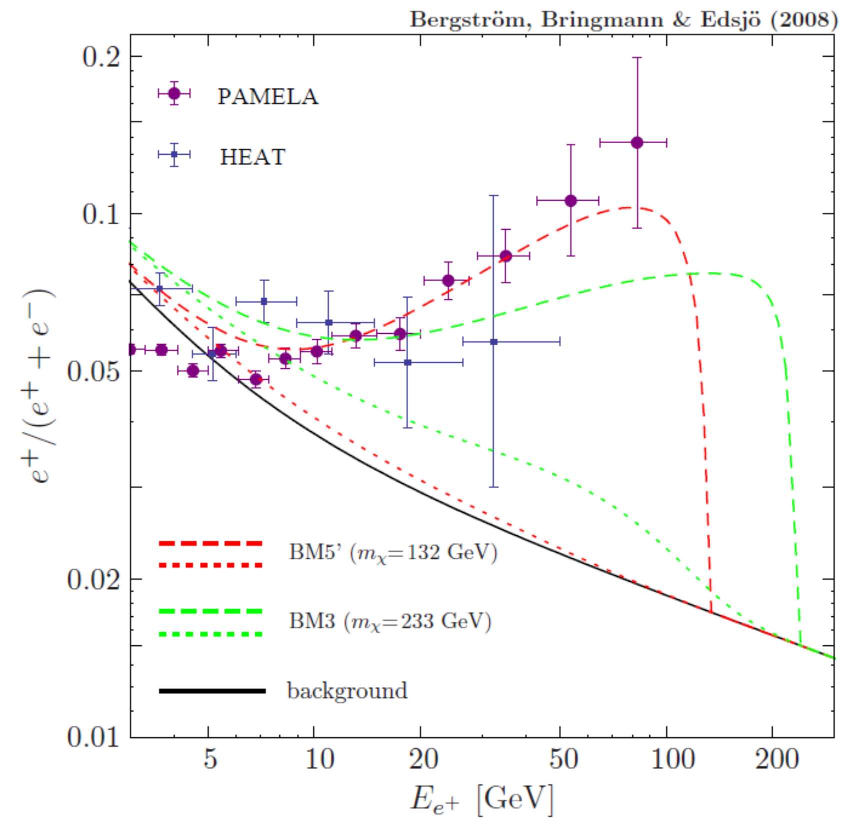
e+e-γ signals in SUSY models

Gamma rays



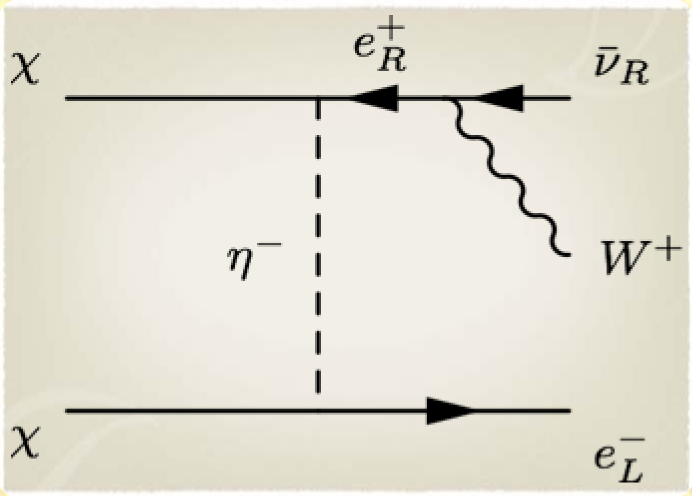
Bringmann, Bergstrom, Edsjo, JHEP 2008

Positrons



Bergstrom, Bringmann, Edsjo, PRD 2008

Lifting the suppression: electroweak (W,Z) bremsstrahlung



Bell, Dent, Jacques & Weiler, 2010.

Bell, Dent, Galea, Jacques, Krauss & Weiler, 2011

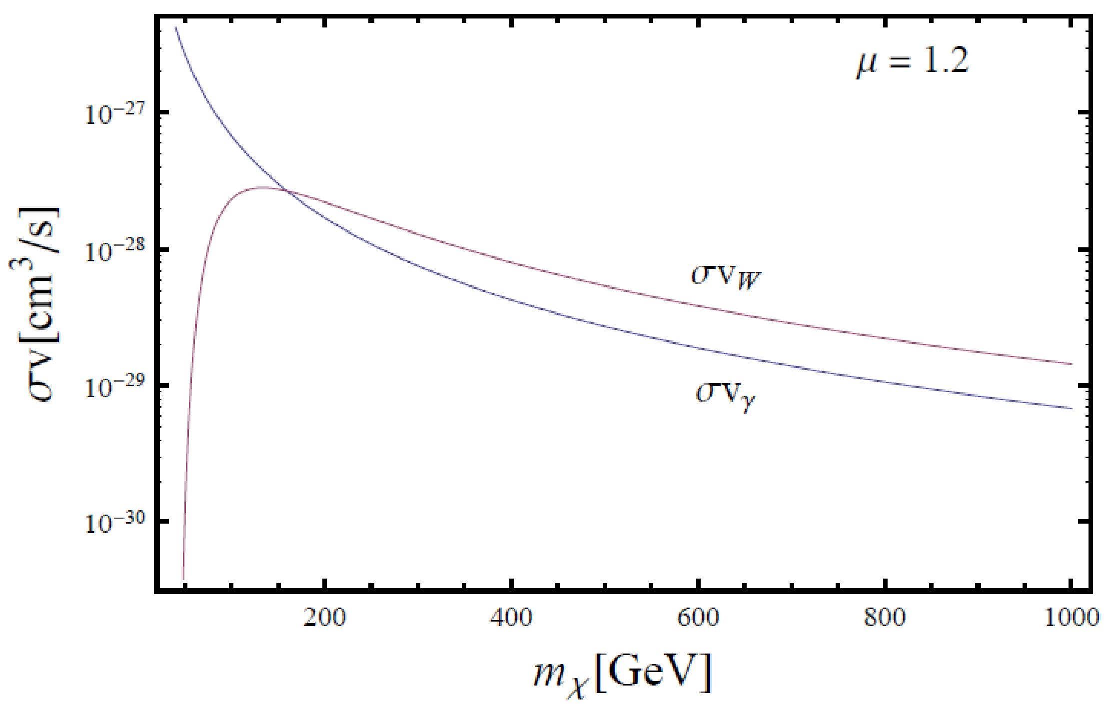
Ciafaloni, Cirelli, Comelli, De Simone, Riotto & Urbano, 2011

- Radiating a W or Z boson can also lift the suppression
- Both VIB and FSR are important
- similar to γ brem, except for W/Z mass effects.

- distinct phenomenology: W and Z bosons decay to charged leptons, neutrinos, gammas, and hadrons

→ hadron production even for "leptophillic" models

W brem rate larger than photon brem rate, except near threshold



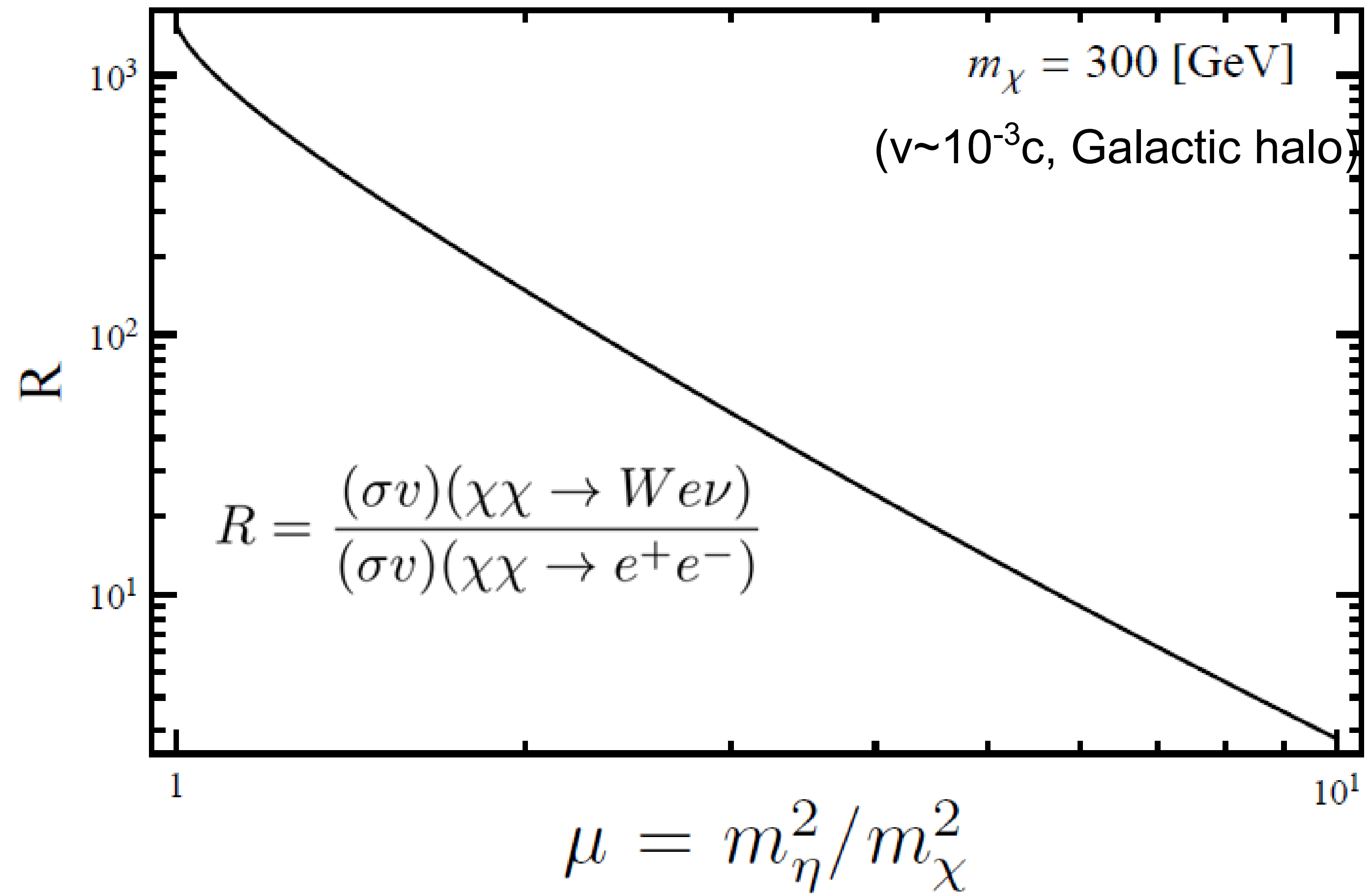
Bell, Dent, Galea, Jacques, Krauss and Weiler, arXiv:1104.3823

Adding all the bremsstrahlung processes:

$$\sigma_{\text{brem, total}} = \sigma_{e^+\nu W^-} + \sigma_{\bar{\nu}e^-W^+} + \sigma_{\bar{\nu}\nu Z} + \sigma_{e^+e^-Z} + \sigma_{e^+e^-\gamma} = 7.16\,\sigma_{e^+e^-\gamma}.$$

(in the limit where the W/Z mass is negligible)

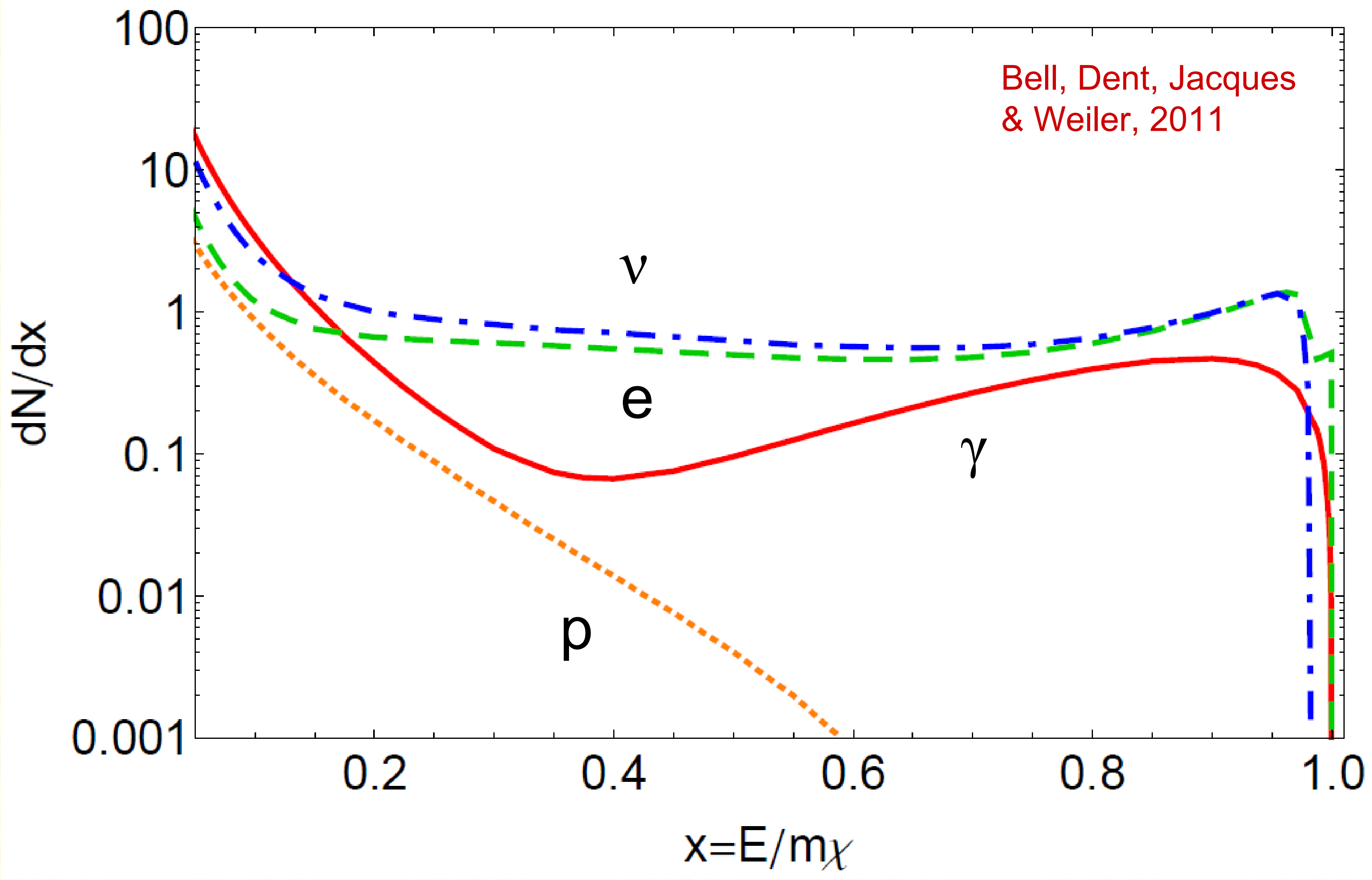
Ratio of eνW and e+e- cross sections



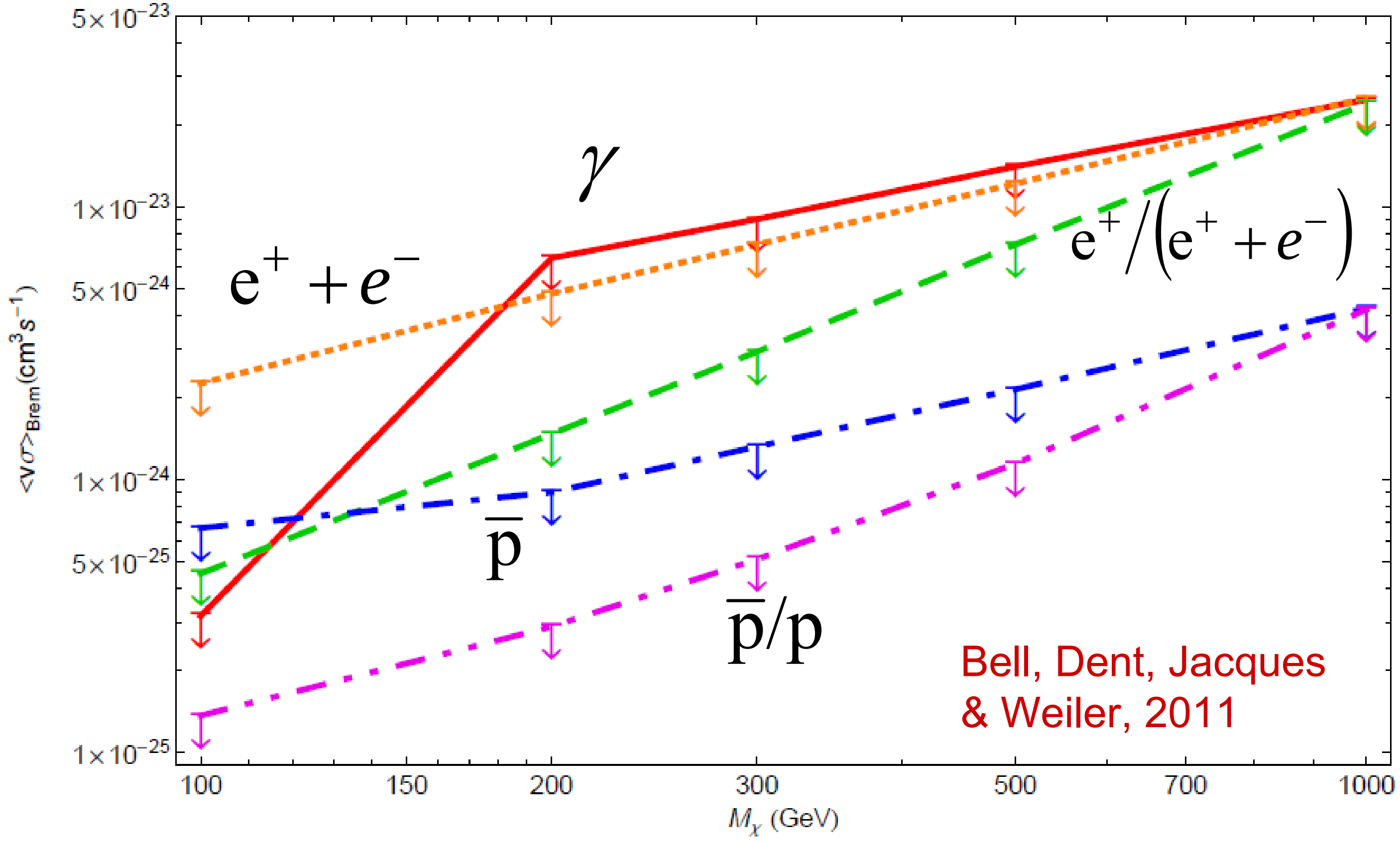
Bell, Dent, Galea, Jacques, Krauss and Weiler, arXiv:1104.3823

- Annihilation to e+e-γ, e+e-Z & eνW dominates over e+e-
- Enhancement by up to three orders of magnitude!

Annihilation spectra: γ / W/ Z brem



Maximum allowed brem cross sections



Bell, Dent, Jacques & Weiler, 2011

FIG. 4. Upper limits on $\langle v\sigma\rangle_{\mathrm{brem}}$. Shown are constraints based on gamma rays (solid, red), $e^+ + e^-$ flux (dots, orange), $e^+/(e^+ + e^-)$ ratio (dashes, green), $\bar{p}$ flux (dash-dots, blue), and $\bar{p}/p$ ratio (dot-dot-dashed, purple).

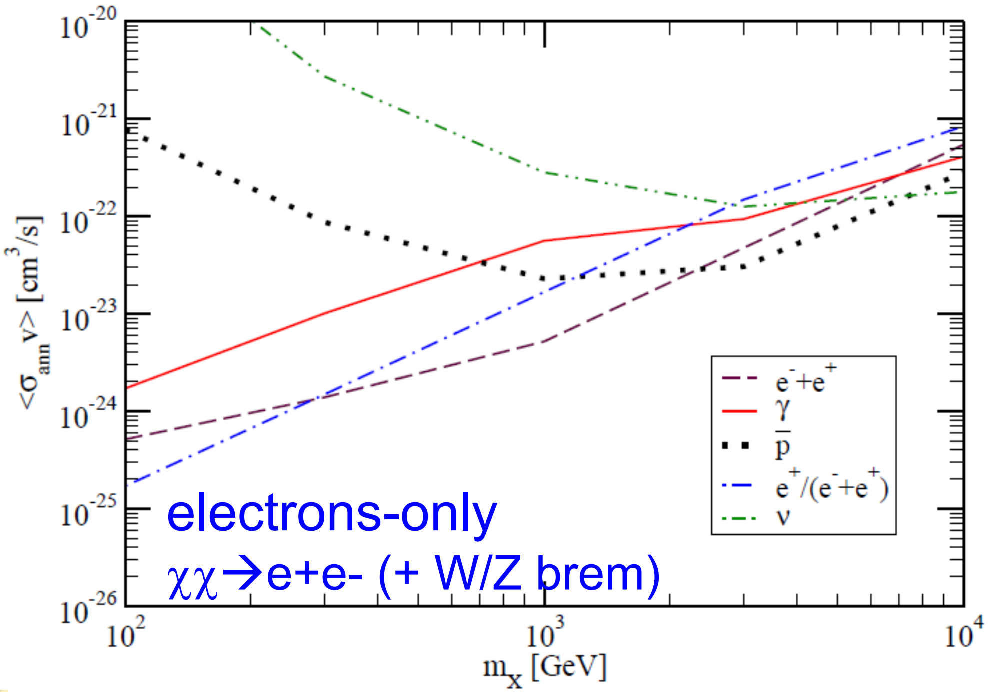
→Bremsstrahlung can’t make significant contribution to e+ flux, without overproducing pbar

Models with no helicity suppression

→EW-brem still occurs, but is subdominant

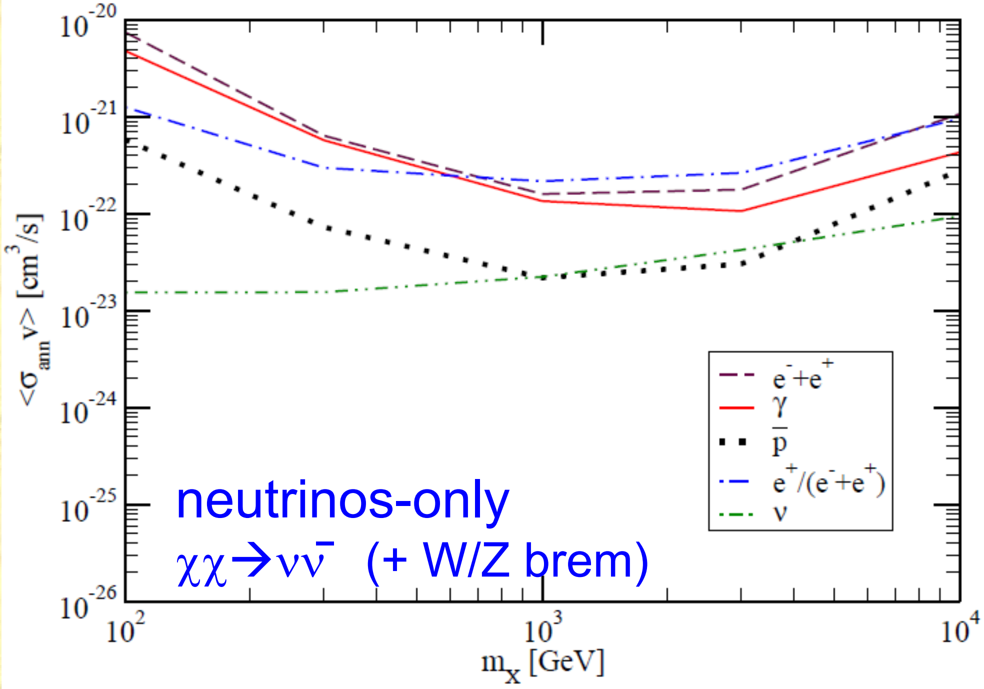
→W/Z decays ensures there is at least a minimal yield of hadrons, photons, charged leptons and neutrinos.

Kachelriess, Serpico and Solberg PRD 2009.



electrons-only

$\chi\chi \rightarrow e^+e^-$ (+ W/Z brem)



neutrinos-only

$\chi\chi \rightarrow \nu\bar{\nu}$ (+ W/Z brem)

Conclusions / Outlook

- Some suggestive signals identified, but, as yet, no definite dark matter indirect detection

- Sensitivity of gamma ray techniques is being pushed down toward the thermal relic values … thus realistic detection prospects

- Some models of new physics (e.g. light force carriers) give large indirect detection signals → can test in short term future

- Internal bremstrahlung of γ, W & Z enhances annihilation yields, and gives interesting multi-messenger signals