Dark Matter Decay and Cosmic Rays

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see arXiv:0903.3625 (accepted by JCAP) and arXiv:0906.1571

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I. Introduction

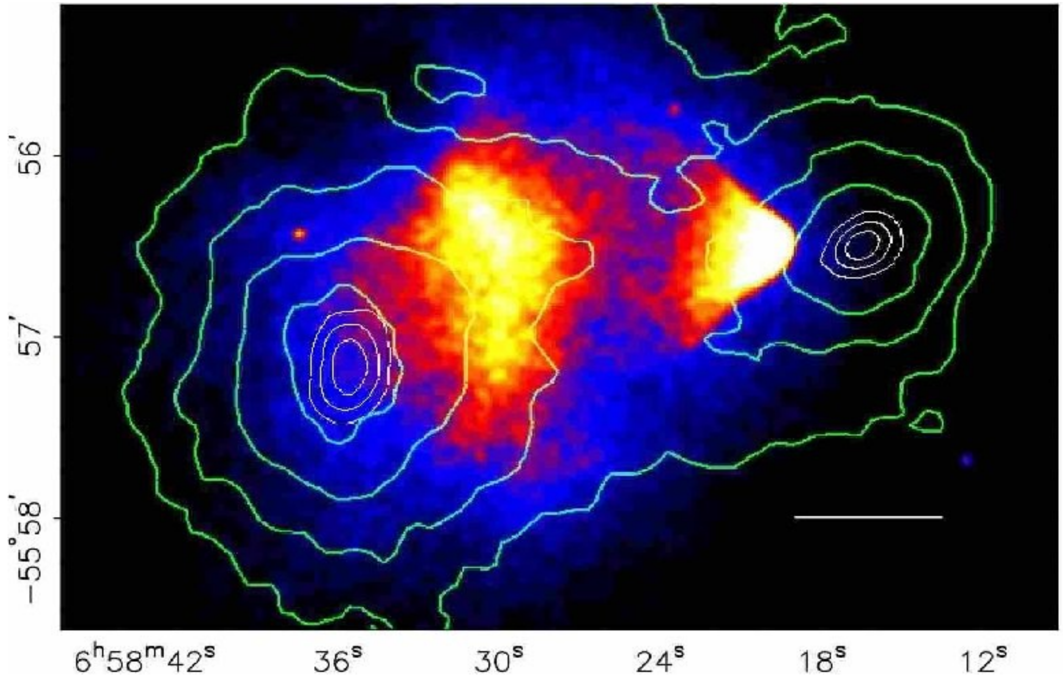
Evidence for Dark Matter

There is substantial evidence for the existence of non-baryonic dark matter

Dark Matter shows up **gravitationally** in

- Rotation curves of Galaxies
- X-Ray emission of intracluster gas
- Gravitational Lensing
- CMB + LSS

„Bullet" Cluster



[Clowe *et al.* (2006)]

Properties of Dark Matter

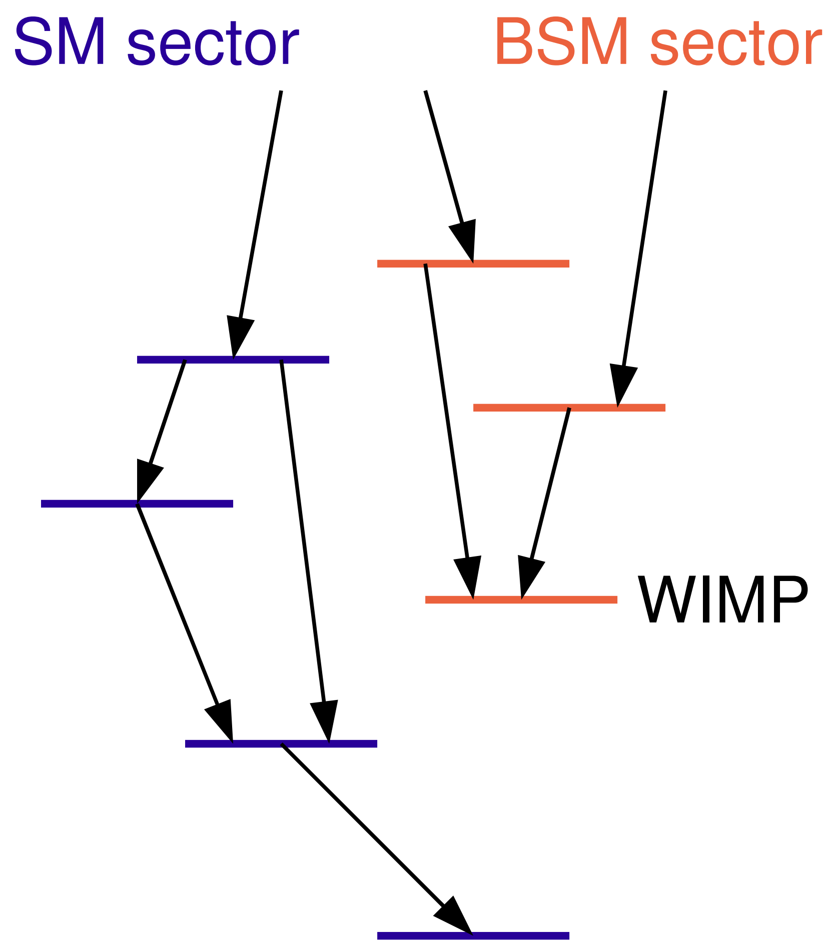
Dark Matter is

- **non-baryonic**: only weakly or super-weakly interacting with baryonic matter
- **cold (or warm)**: non-relativistic at onset of structure formation
- **cosmologically long-lived** or stable

A convincing dark matter candidate should be embedded in a consistent **thermal history** of the Universe, *i.e.*

- possess a mechanism that explains the observed **relic density**
- be compatible with
  - **Big Bang Nucleosynthesis**
  - **Baryogenesis** (*e.g.* Leptogenesis)
  - ...

Stable Dark Matter



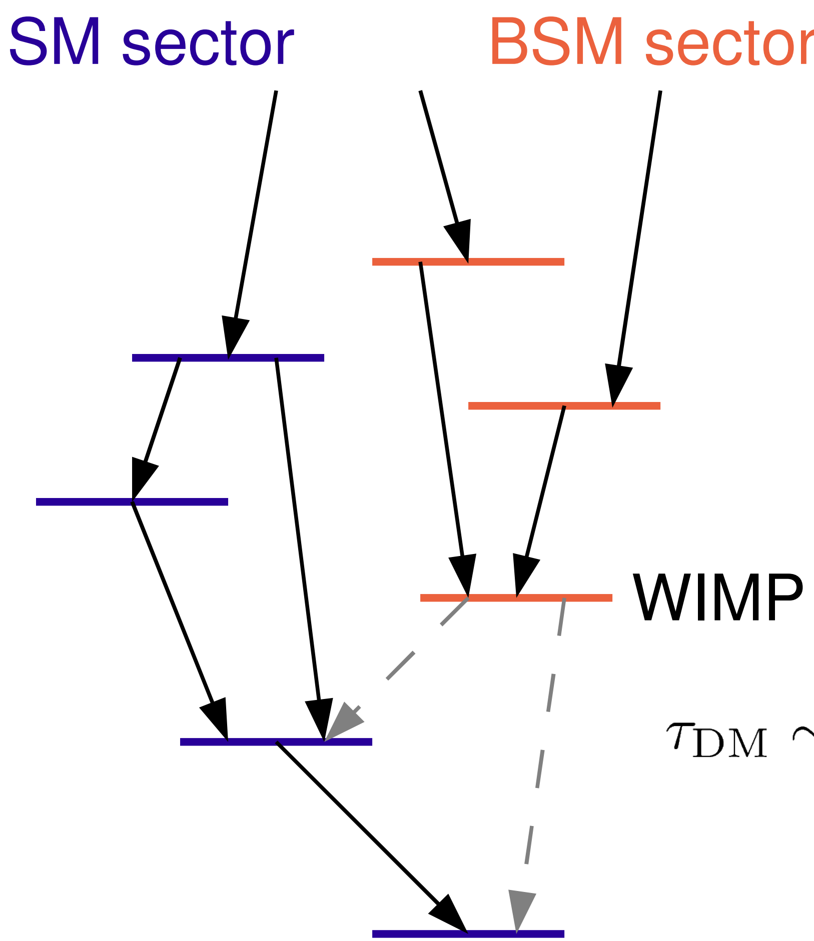
Standard scenario: **WIMPs**

- Some particle is stabilized by a **symmetry***
- If it is **weakly** interacting it can have naturally the right relic abundance to be Dark Matter, provided its mass lies in the GeV – TeV range

==> Stable DM

* Without this symmetry, the particle would have a lifetime around ~O(10^{-6} s)

Unstable DM: Symmetry Violation



e.g. GUT scale relics, hidden vector dark matter

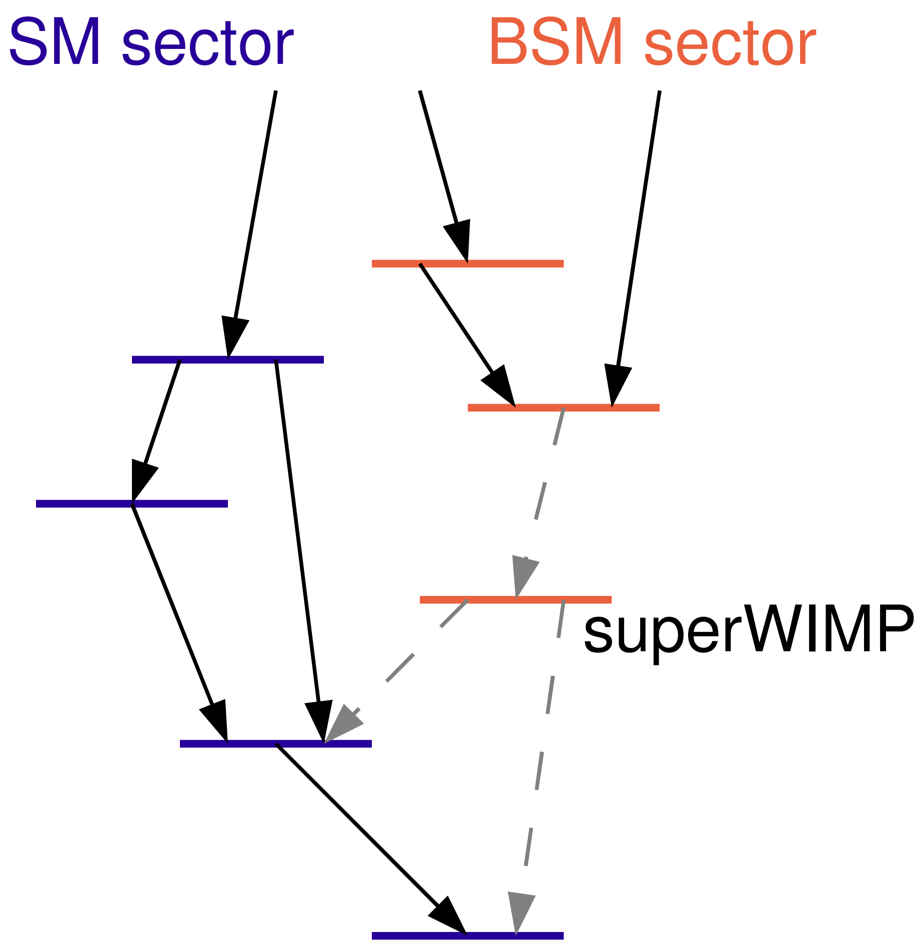
Symmetry can be **violated** at some high scale

- DM becomes **unstable**
- In case of *e.g.* **dim-6 operators** the lifetime is roughly given by

$$\tau_{\rm DM} \sim \mathcal{O}(10^{26}\ {\rm s}) \left(\frac{10^{15}\ {\rm GeV}}{M^*}\right)^4 \left(\frac{M_{\rm DM}}{100\ {\rm GeV}}\right)^5$$

==> Decay on cosmological time scales

Unstable DM: superWIMPs



e.g. Gravitino with mild R-parity violation, Sterile Neutrino

Dark Matter can be **superweakly** interacting.

- In this case, DM is naturally **long-lived**
- Depending on the couplings, it can have a **cosmological lifetime**

$$\tau_{\rm DM} \gg 10^{17}\ {\rm s}$$

==> Decay on cosmological time scales

Dark Matter Candidates

There exists a large number Dark Matter candidates. They include

Stable

- Neutralinos, Lightest KK particles, Axions, Sneutrinos, Gravitinos, WIMPzillas,...

Unstable

- Gravitino with mild R-parity violation
- Sterile Neutrinos
- Hidden Gauginos
- Right-handed sneutrinos
- Hidden U(1)' gauge bosons
- Hidden sector Mesons or Baryons
- Neutralinos with tiny R-parity violation
- ...

Overview

II.) Cosmic Rays from Dark Matter Decay

III.) Models for Decaying Dark Matter

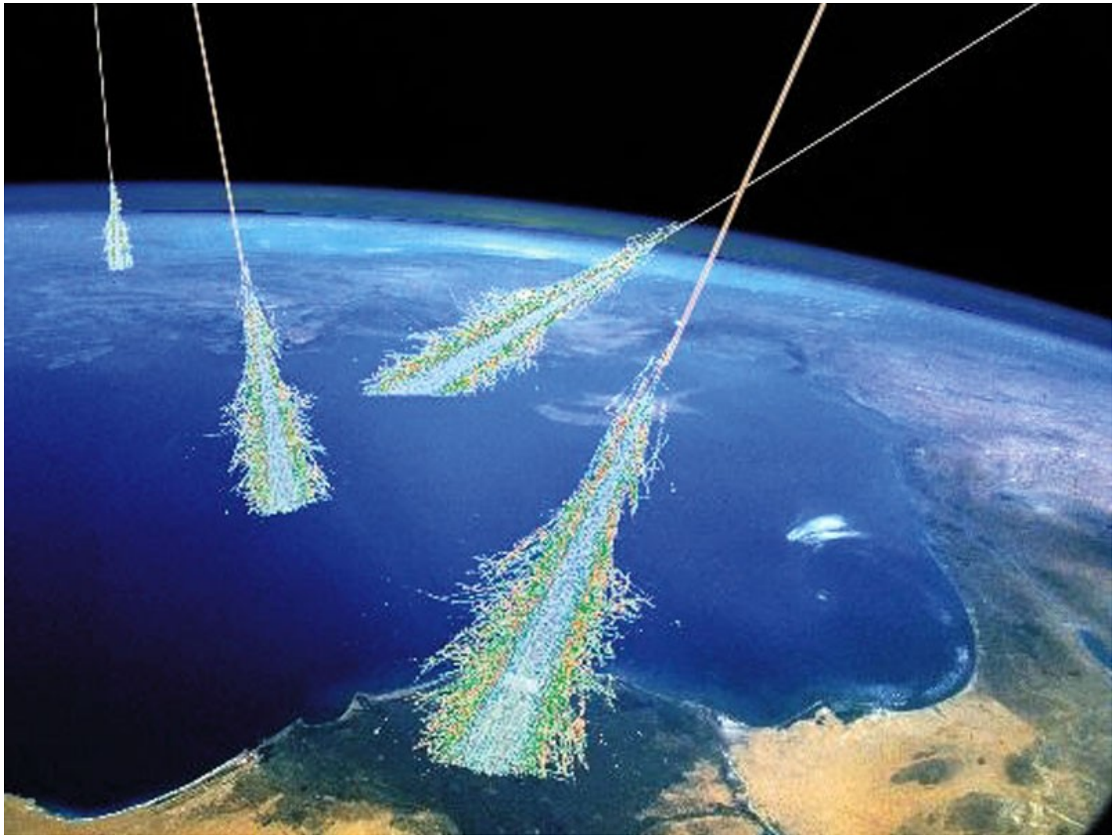
- Sterile Neutrinos
- Gravitino with R-parity violation

IV.) PAMELA & Fermi electron/positron data

- Interpretation in terms of decaying dark matter
- Prospects

V.) Conclusions

II. Cosmic Rays from Dark Matter Decay



Cosmic Rays from Dark Matter Decay

Decay of DM can be observable in **Cosmic Ray Fluxes**:

Photons
X- and Gamma-Rays

* Propagation trivial (light follows geodesics, galaxy transparent)
* Detection of sources possible

Positrons

* Excess observed in the GeV – TeV range
* Diffusive propagation
  ==> Flux isotropized
  ==> Source identification difficult

Anti-protons

* Background estimates compatible with measurements
* Diffusive propagation

Anti-deuterons

* Very low background expected compared to typical signals from DM decay
* Diffusive propagation

Photons: Signal Profile

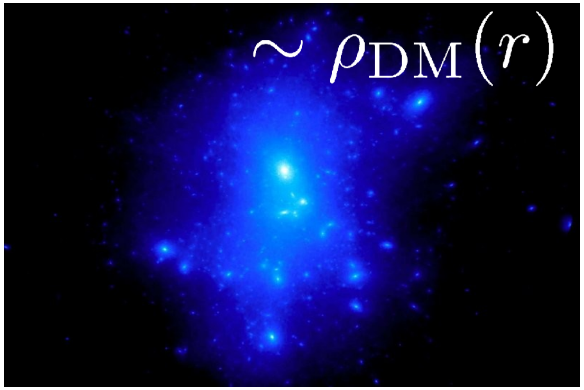
The Dark Matter Gamma-Ray signal is proportional to the **column density** of the Dark Matter distribution*

$$F = \frac{\Omega_{\text{FoV}}}{4\pi} \frac{N_\gamma(E)}{\tau_{\text{DM}} M_{\text{DM}}} \underbrace{\int_{\text{l.o.s.}} dr\ \rho_{\text{DM}}(r)}_{\equiv \mathcal{S}}$$

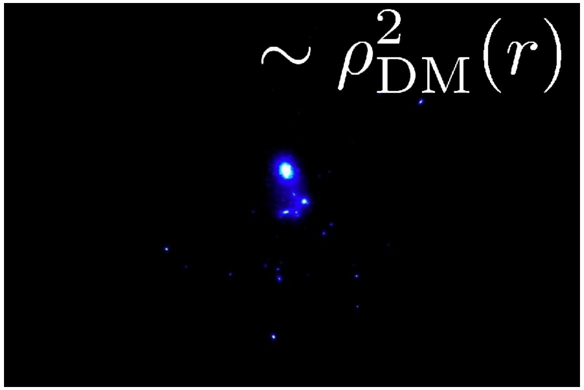
- **Signal** from decay is much **less peaked** than the signal from annihilation
  ==> No need to look at *e.g.* the galactic center (where the background is large)
- Signal does **not depend on details** of dark matter distribution

*as long as characteristic DM scale larger than Field of View; for small redshifts

Decay



Annihilation



[Moore, B. (2005)]

Photons: Targets for Decaying DM Searches

At low energies ~ O(10 keV): Look for **Extragalactic Sources**

$$\text{Flux} \sim \mathcal{O}(10^7)\,\frac{\text{photons}}{\text{year}\cdot\text{m}^2\cdot(1^\circ)^2}$$

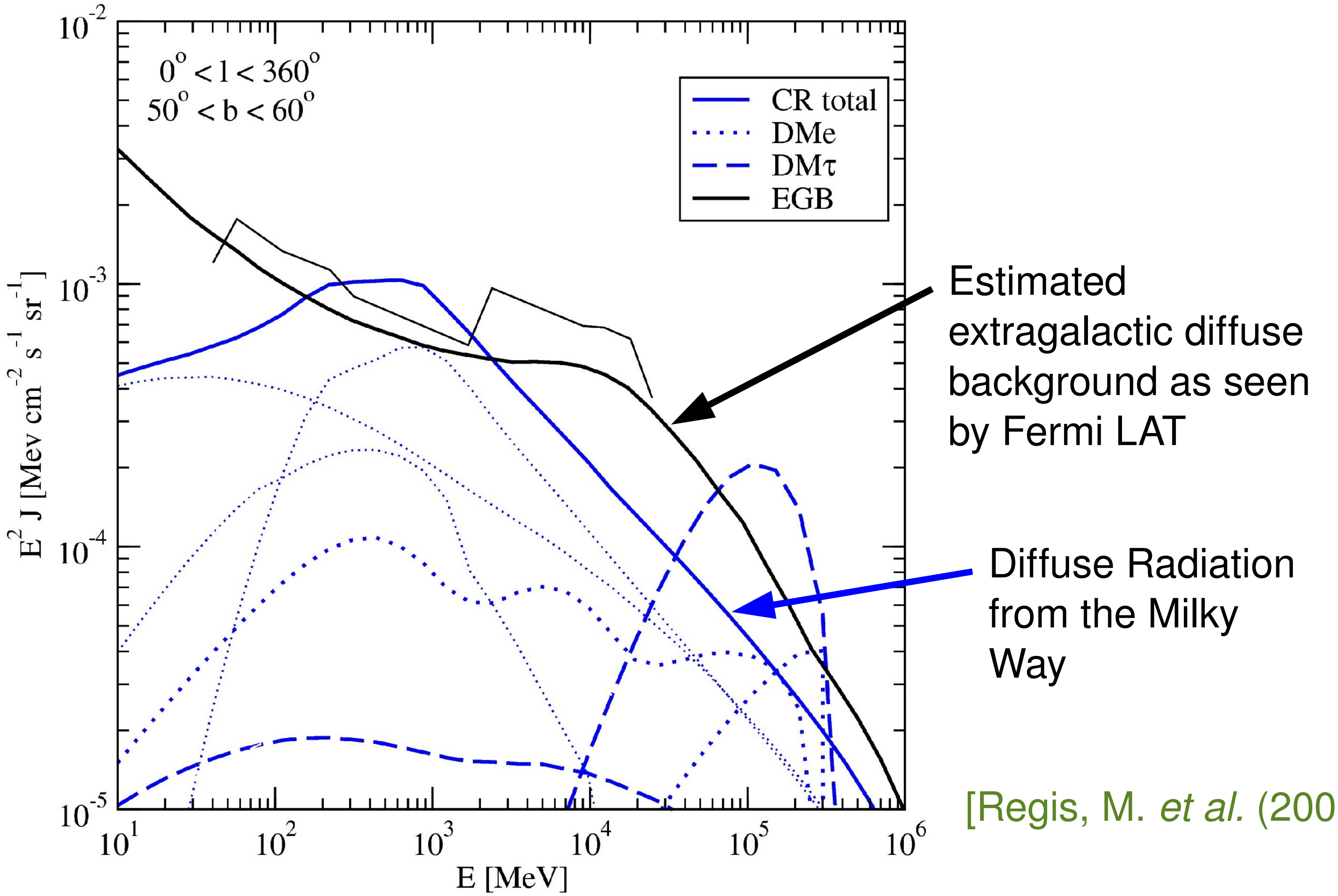
- Different extended objects (like satellite galaxies, galaxy clusters) possess **similar column densities** and give comparable fluxes
- Fluxes from different extragalactic objects only a few times larger than the flux from the Milky Way Halo [Boyarsky *et al.* (2008)]

At high energies ~ O(10 GeV): Look for the **Milky Way Halo**

$$\text{Flux} \sim \mathcal{O}(1)\,\frac{\text{photons}}{\text{year}\cdot\text{m}^2\cdot(1^\circ)^2}$$

- **Very small fluxes** at high energies
- Observation of point sources can only give marginally better results

Photons: The Halo Component



[Regis, M. *et al.* (2009)]

At **high latitudes** the **extragalactic background** dominates the diffuse flux.

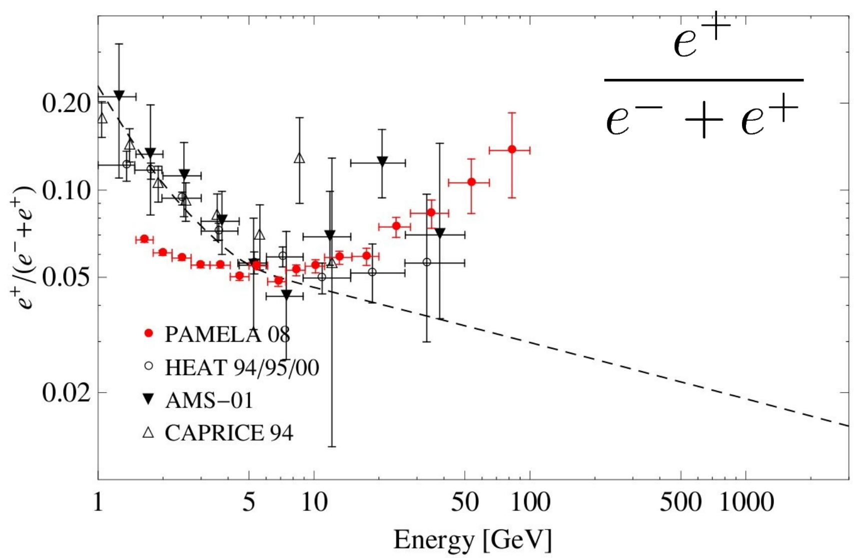
Cosmic Rays from Dark Matter Decay

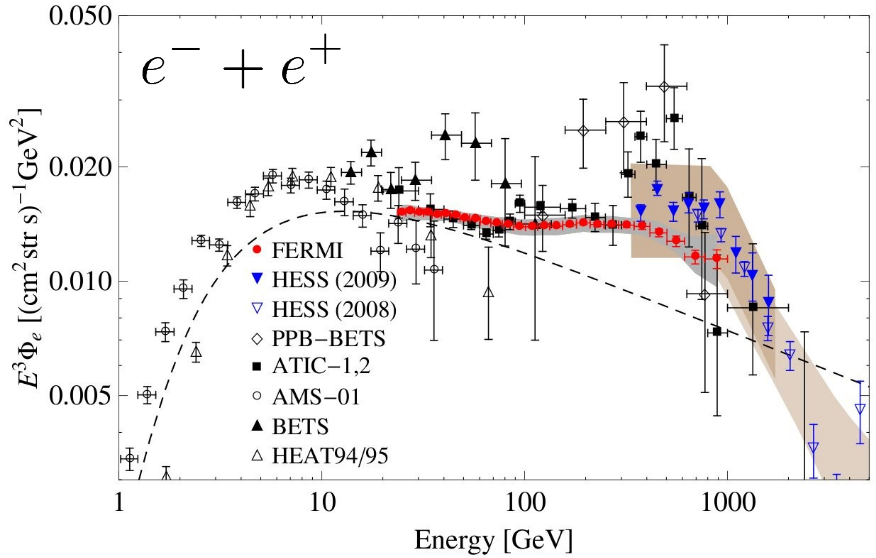
Decay of DM can be observable in **Cosmic Ray Fluxes**:

Photons X- and Gamma-Rays	* Propagation trivial (light follows geodesics, galaxy transparent) * Detection of sources possible
Positrons	* Excess observed in the GeV – TeV range * Diffusive propagation ==> Flux isotropized ==> No direct Source detection possible
Anti-protons	* Background estimates compatible with measurements * Diffusive propagation
Anti-deuterons	* Very low background expected compared to typical signals from DM decay * Diffusive propagation

PAMELA and Fermi LAT Data

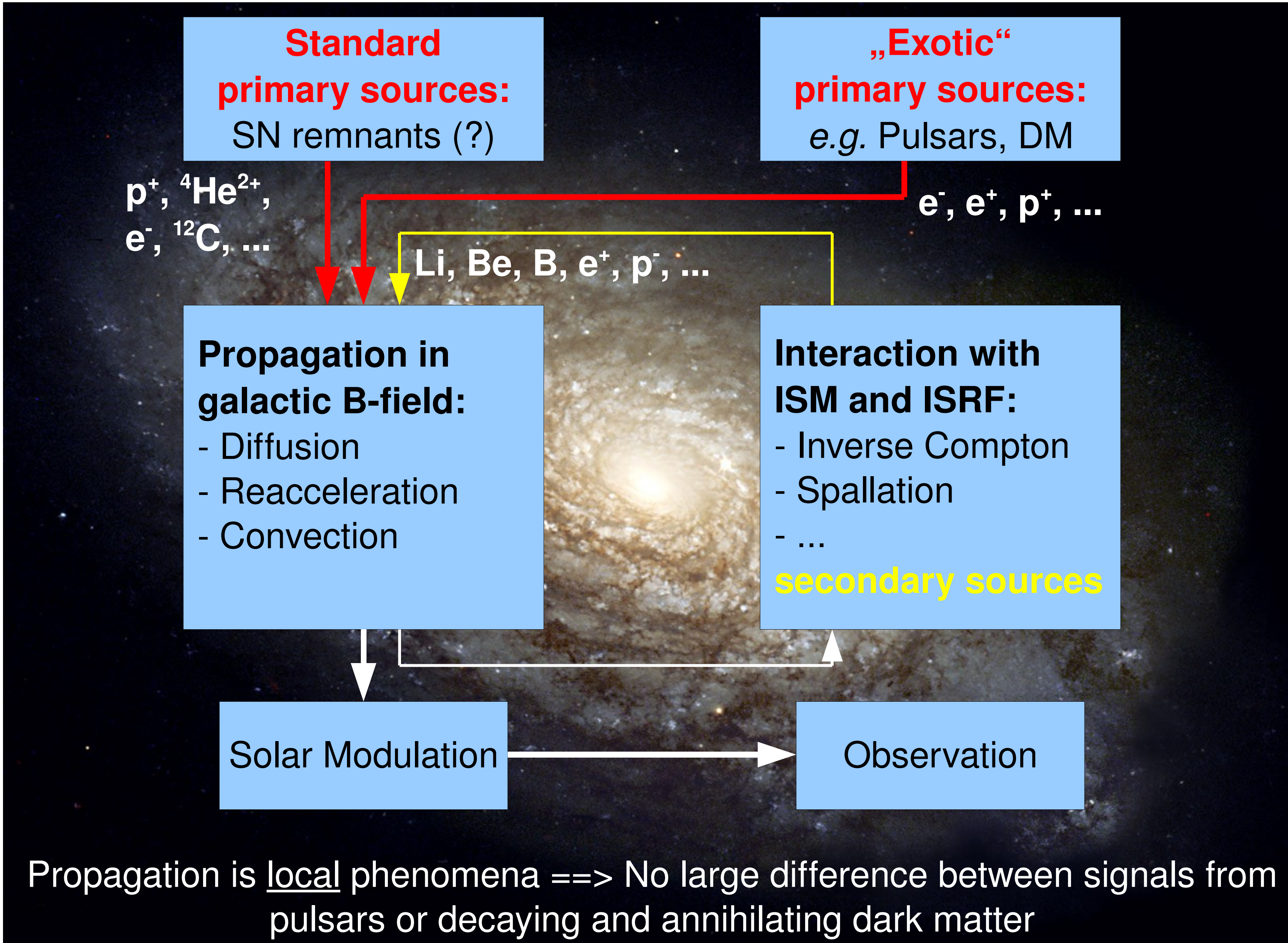
PAMELA and Fermi LAT detected deviations from the astrophysical expectations [Adriani *et al.* (2008), Abdo *et al.* (2009)]





- Standard propagation models **do not predict rise** in positron fraction as observed by PAMELA
- The Fermi results for the electron+positron flux, together with the H.E.S.S. results, point to **an excess up to ~ 1 - 2 TeV**
- Interpretation difficult since observations measure only the **local flux** ==> difficult to distinguish source distribution

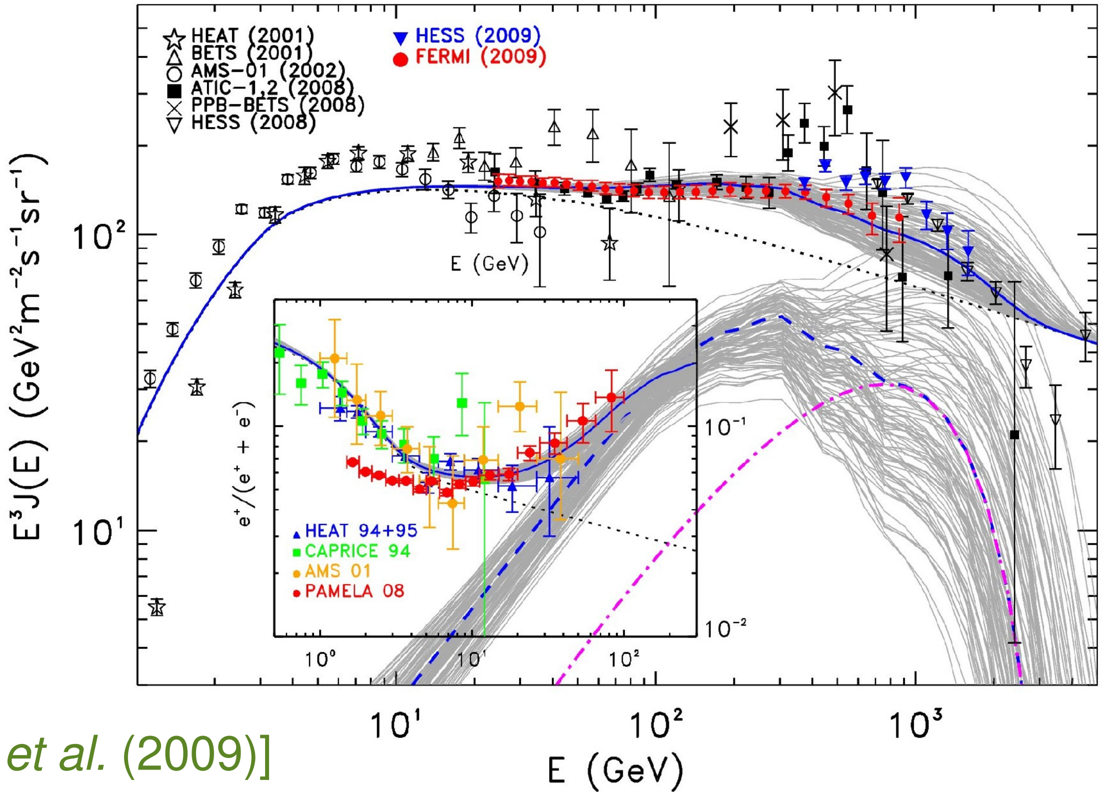
Propagation of Charged Particles in the Galaxy



[*e.g.* Strong, Moskalenko and Ptuskin (2007)]

Pulsar Interpretation of positron excess

The observed excesses may be explained by e^+/e^- emission of **nearby pulsars**.

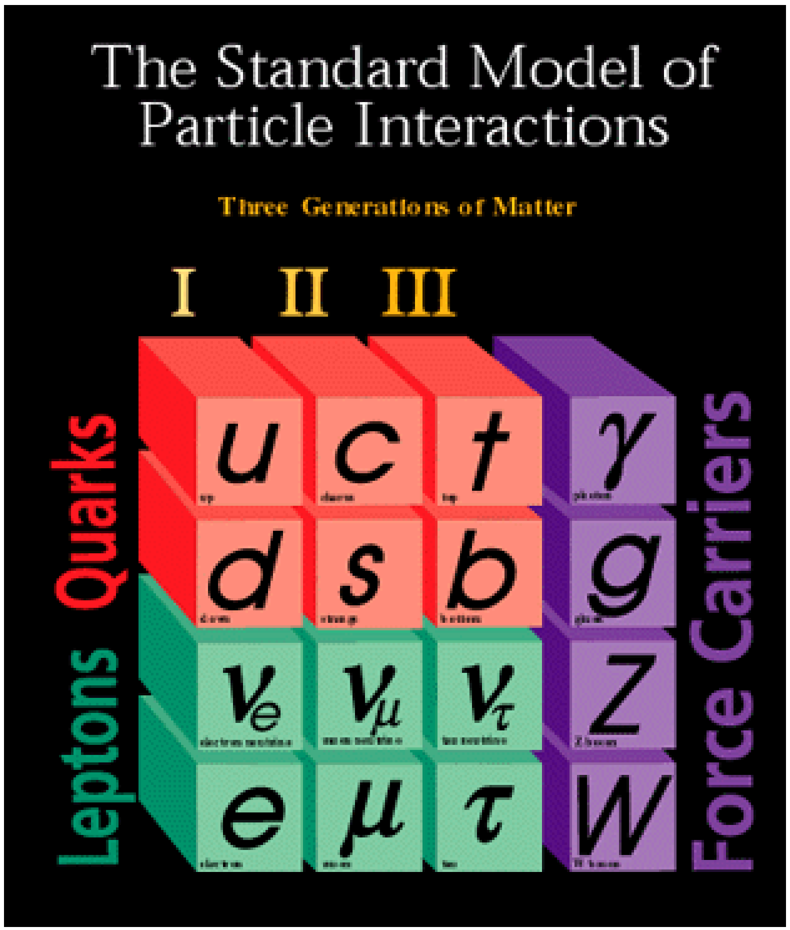


[*e.g.* Grasso *et al.* (2009)]

- If fraction of spin-down energy that goes into e^+/e^- emission and spectral cutoffs are adjusted appropriately, the observations can be reproduced

III. Models for Decaying Dark Matter

Sterile Neutrino Dark Matter



$+ \ 3\ \nu_R$

Sterile Neutrinos as DM

Standard Model + three **right-handed neutrinos.**

[Dodelson and Widrow (1994), Shi and Fuller (1999)]

With

- Majorana mass terms around 1 keV – 100 GeV
- appropriately chosen Yukawa couplings

this model can explain different beyond SM phenomena:

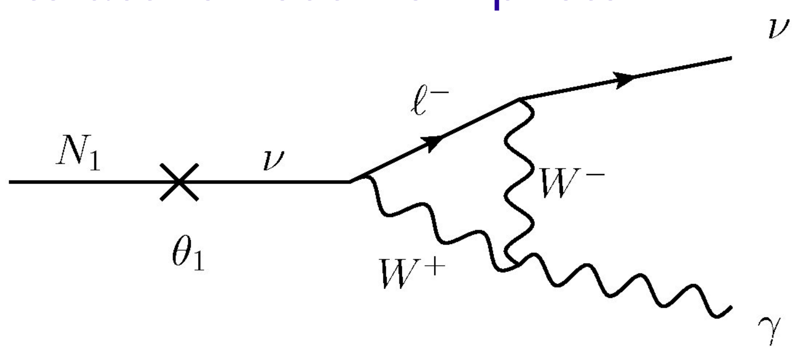
- **Neutrino Oscillations,**
- **Dark Matter,**
  - which is identified with the lightest sterile neutrino, N_1,
- **Baryon Asymmetry** of the Universe,
  - produced via CP-violating oscillation of active neutrinos and sphaleron processes at energies above 100 GeV,
- and can accomodate Inflation & Dark Energy

[see *e.g.* Boyarsky, Ruchayskiy and Shaposhnikov (2008)]

Sterile Neutrino as DM: Gamma Ray Line

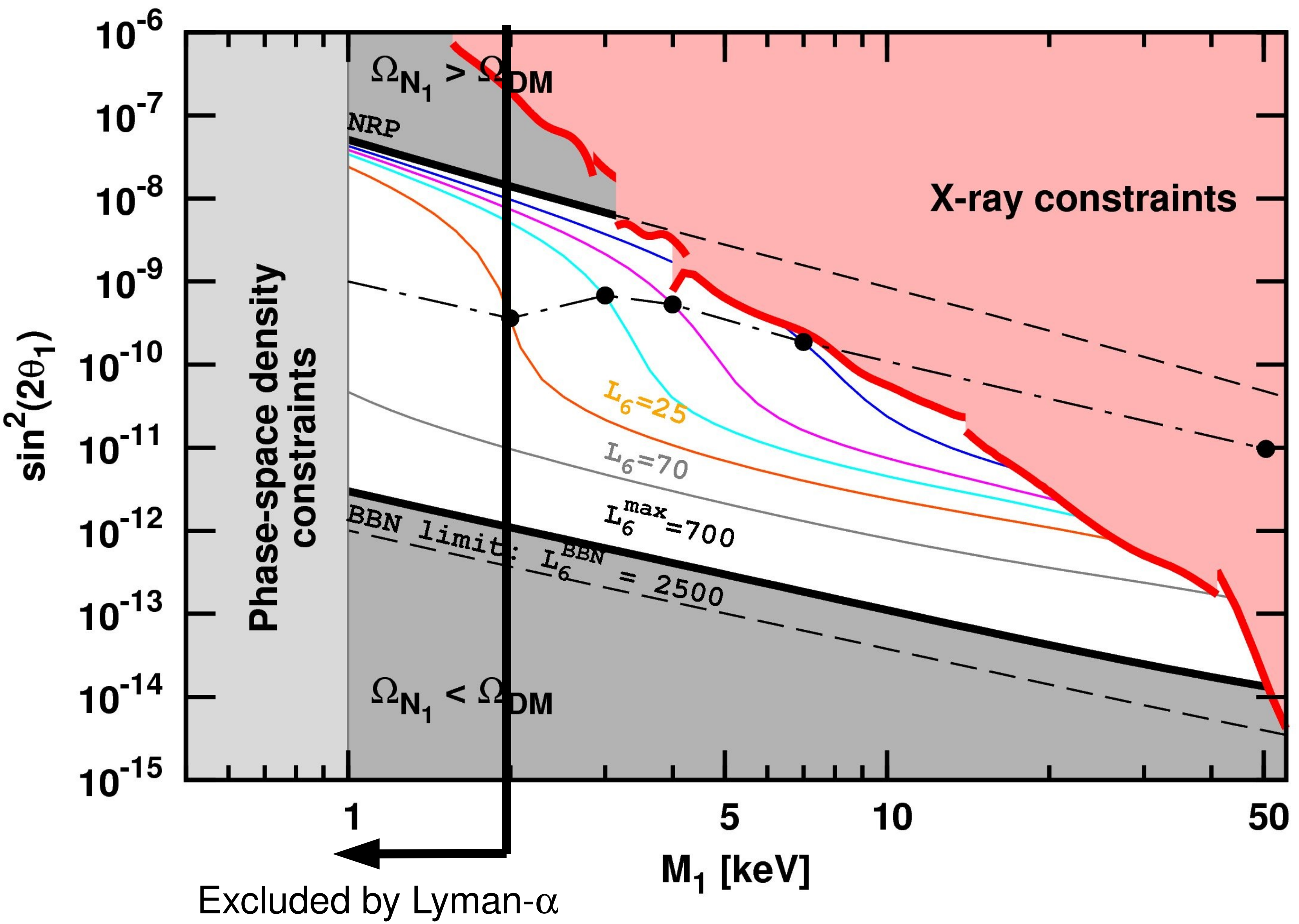
The **lightest sterile neutrino**, N_1, is Dark Matter

- Long DM lifetime implies very **small Yukawa couplings**, $Y < O(10^{-11})$ for N_1, and hence a small Majorana mass ~ O(keV)
- N_1 is **produced due to mixing with active neutrinos** in the early Universe (either resonantely or non-resonantely)
- **X-ray observations** can detect sterile neutrino dark matter due to two-body decay into active neutrino + photon:



- Line searches have been performed for
  - M31, galaxy clusters, dwarf spheroidal galaxies
  - Extra-galactic X-ray background

Sterile Neutrinos as DM: Constraints



[A. Boyarsky, O. Ruchayskiy and M. Shaposhnikov (2008)]

Gravitino Dark Matter

Gravitino Dark Matter: NLSP bottleneck

MSSM + **Gravitino** (+ right-handed neutrinos).

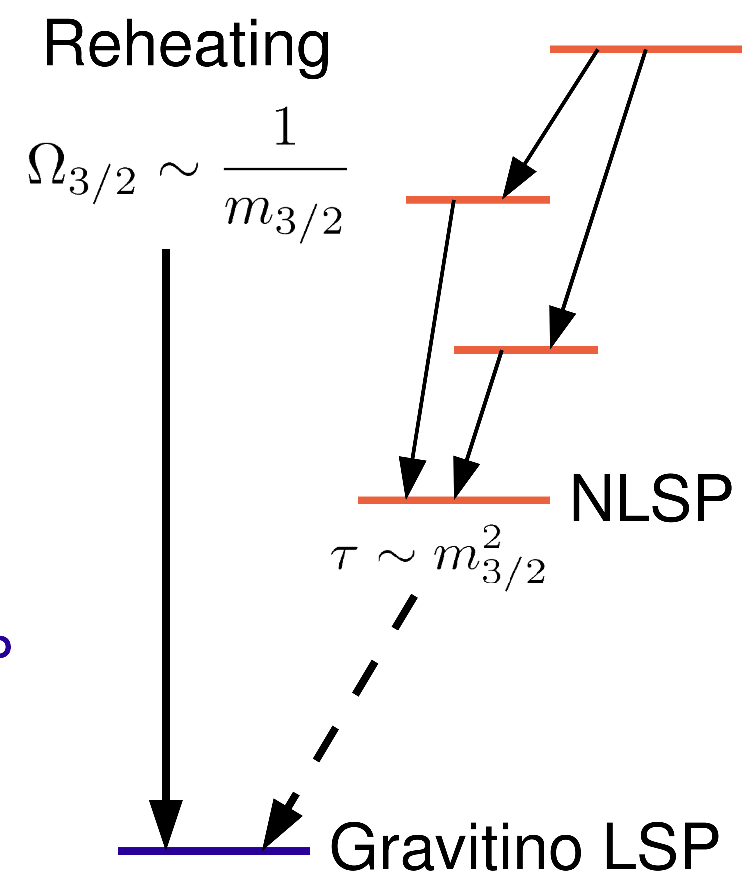
- **Gravitino is LSP** and Dark Matter
- It is produced
  - during reheating
  - in the late decay of NLSPs
- If baryon asymmetry is generated by **Leptogenesis**

  ==> lower bound on gravitino mass

  $m_{3/2} > O(5\text{ GeV})$
- This gives a lower bound on the NLSP lifetime

  $\tau_{NLSP} > O(10^5\text{ s})$

  ==> **NLSP decays during BBN**

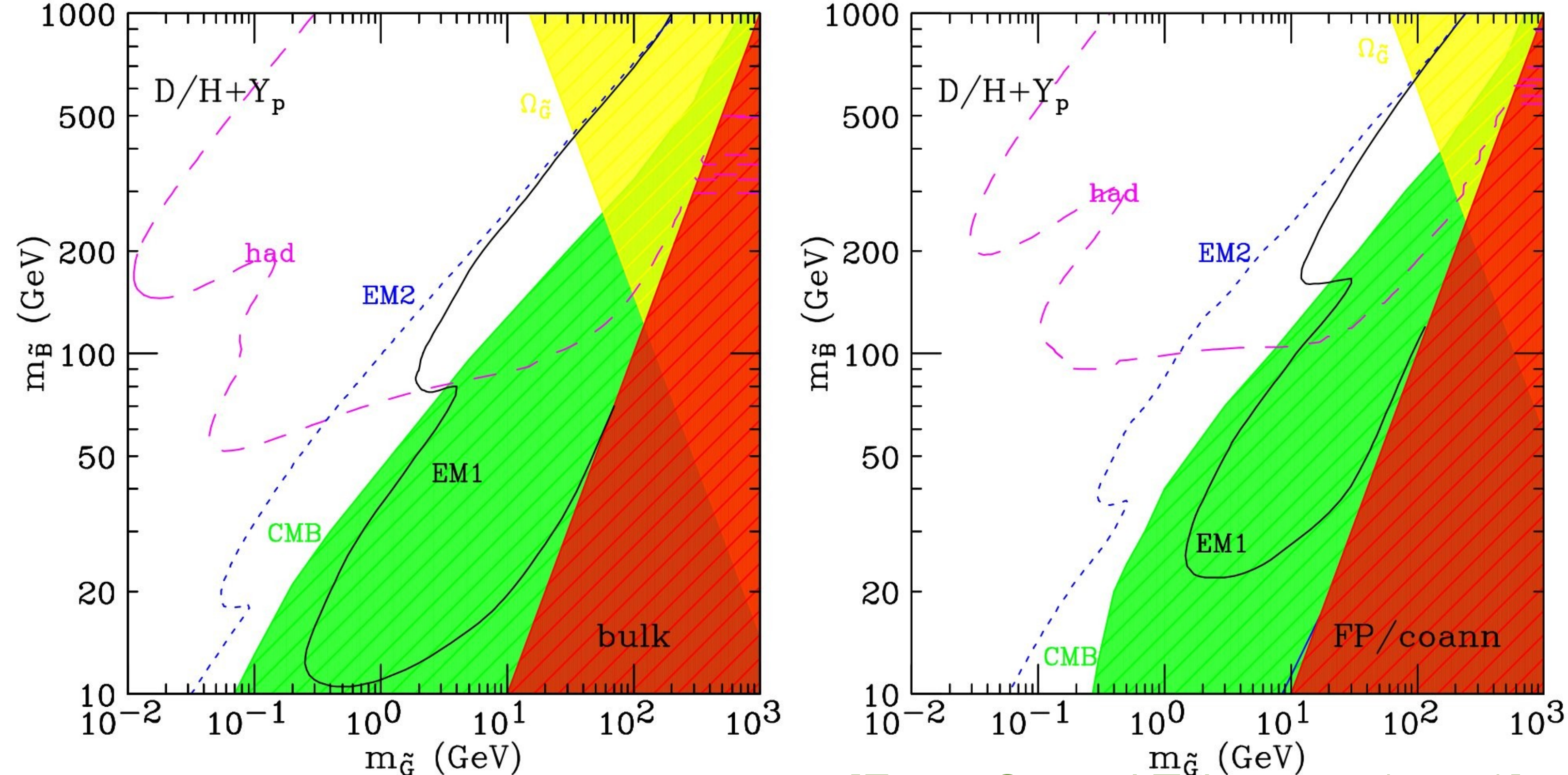


see [Buchmueller, Covi, Hamaguchi, Ibarra and Yanagida (2007)]

Gravitino Dark Matter

Problem: Long-lived NLSPs in general spoil BBN

e.g. Bino NLSP:



[Feng, Su and Takayama (2004)]

Solution: Get rid of NLSP before BBN by allowing mild violation of R-parity

Gravitino Dark Matter with R-parity Violation

R-parity can be violated by a term $\sim \lambda_{ijk} L_i L_j e^c_k$

- **BBN** and **Leptogenesis** give lower and upper bound on size of breaking

$$10^{-14} \lesssim \lambda \lesssim 10^{-7}$$

- As a consequence the **gravitino becomes <u>unstable</u>** with a long lifetime (due to Planck-mass suppression and smallness of λ)

$$\tau_{3/2} \gtrsim \mathcal{O}(10^{23}\ \mathrm{s})$$

The gravitino decays via the following **decay channels**:

(Branching ratios become model-independent for large gravitino masses)

$$\psi_{3/2} \to \gamma\nu \qquad \psi_{3/2} \to Z^0\nu$$

$$\psi_{3/2} \to W^{\pm}\ell^{\mp} \qquad \psi_{3/2} \to h^0\nu$$

- Decay products are potentially visible in Cosmic Rays

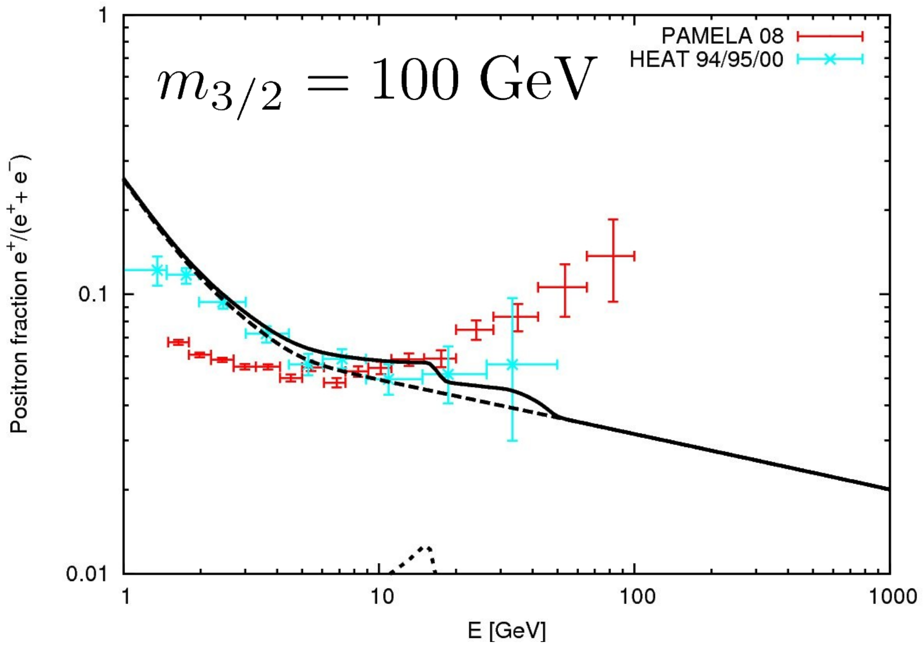
Note: naturalness suggests an **upper bound** $m_{3/2} < 600$ GeV

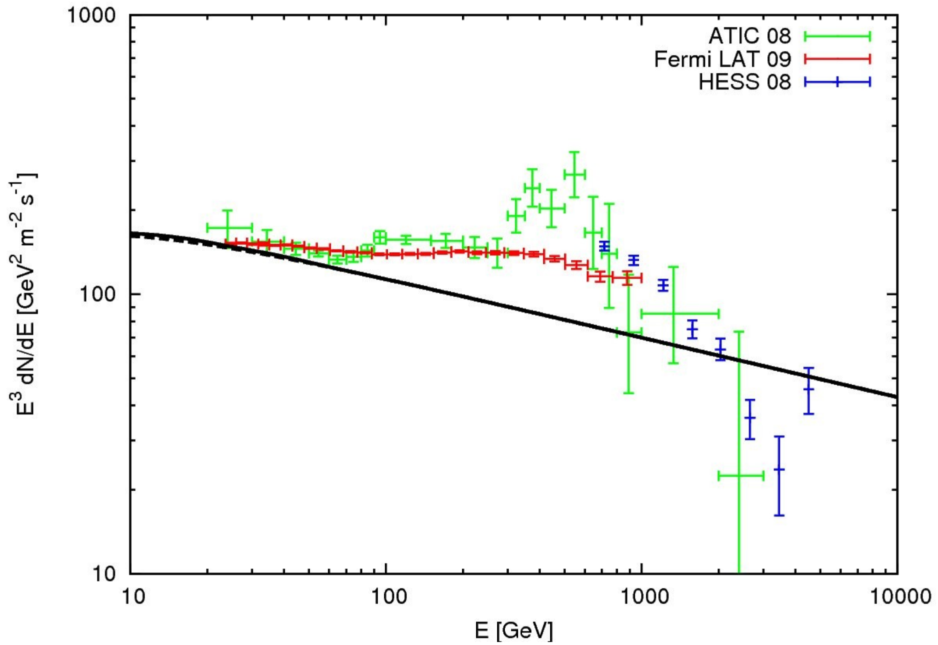
[Buchmueller, Endo and Shindou (2008)]

e^+/e^- Flux from Gravitino DM

Comparison with Cosmic Ray positron and electron data

- **Decaying Gravitinos** are **unlikely the cause** for the PAMELA/Fermi excesses, since this requires TeV masses.
- However: lower bounds on life-time can be extracted from data

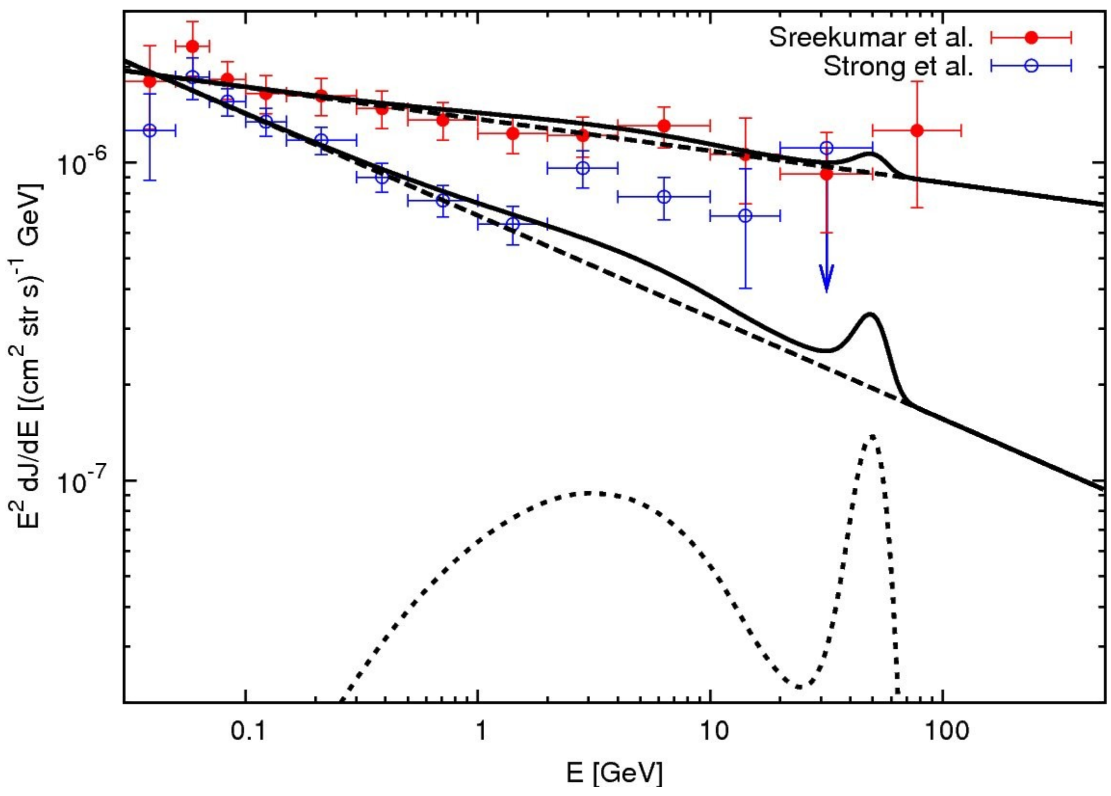




[Buchmueller, Ibarra, Shindou, Takayama and Tran (2009)]

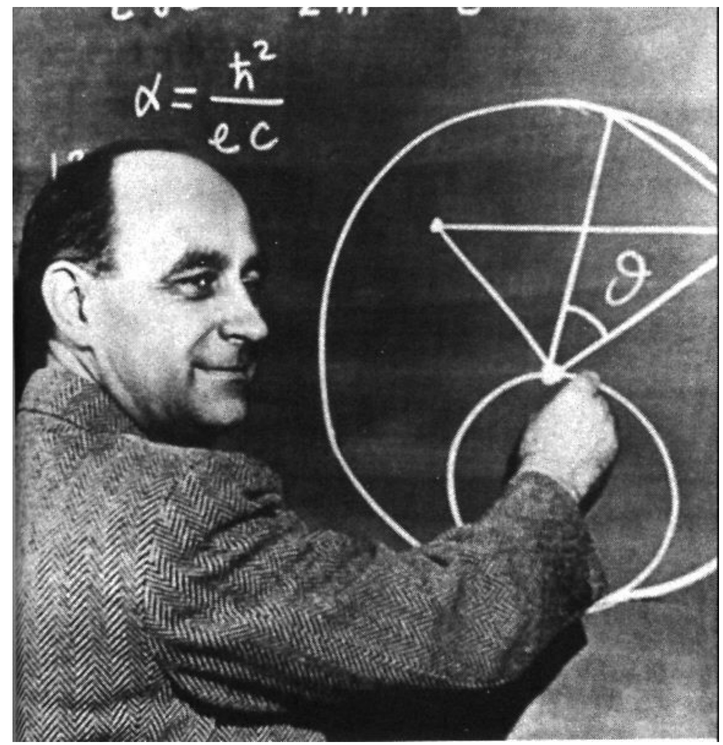
Gamma Ray Flux from Gravitino DM

- The Fermi/PAMELA observations still allow an **observable impact** on the extragalactic gamma-ray background
- Prominent feature is a **gamma-ray line** at half of the gravitino mass



IV. PAMELA & Fermi

Las Pamelas

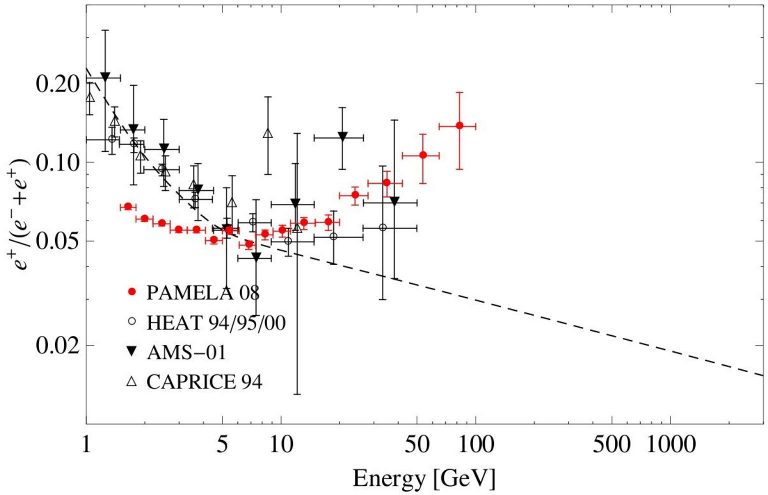


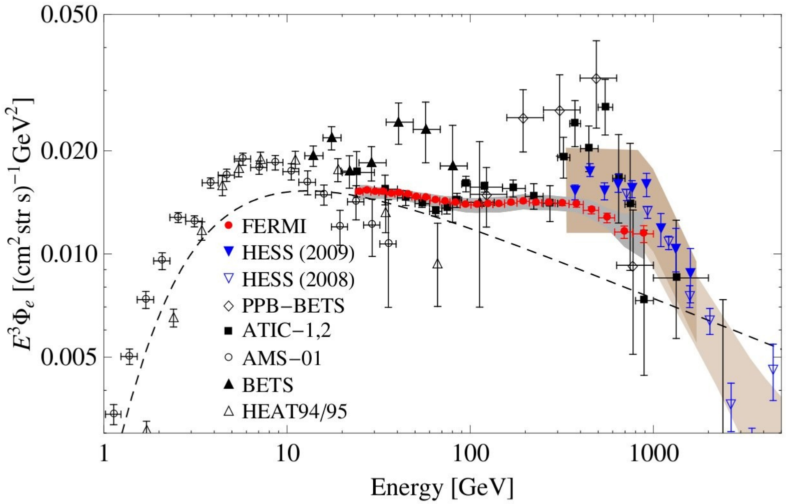
Enrico Fermi

PAMELA/Fermi excess from DM Decay

Model-independent analysis in terms of **Decaying DM**, concentrating on <u>two- and three-body decay</u> channels

see [Ibarra, Tran and CW, arXiv:0906.1571]





- Taking standard propagation model (analytical) [Donato *et al.* (2004)]
- Using Pythia Monte-Carlo for decay & fragmentation calculation
- Using Galprop „Model 0“ background fluxes
- Looking for qualitatively good fits
- Neglecting finite energy resolution of Fermi

There exist related analyses: [Cirelli *et al.* (2008), Meade *et al.* (2009), Grasso *et al.* (2009), Bergstrom *et al.* (2009)]

Search Strategy and good Decay Channels

List of decay channels that we looked at closer:

- Fermior

  ψ_{DN}

  ψ_{DN}

  ψ_{DN}

Decay Channel	M_{DM} [GeV]	τ_{DM} [10^{26}s]
$\psi_{DM} \to \mu^+\mu^-\nu$	3500	1.1
$\psi_{DM} \to \ell^+\ell^-\nu$	2500	1.5
$\psi_{DM} \to W^\pm\mu^\mp$	3000	2.1
$\phi_{DM} \to \mu^+\mu^-$	2500	1.8
$\phi_{DM} \to \tau^+\tau^-$	5000	0.9

- Bosonic

  ϕ_{DN}

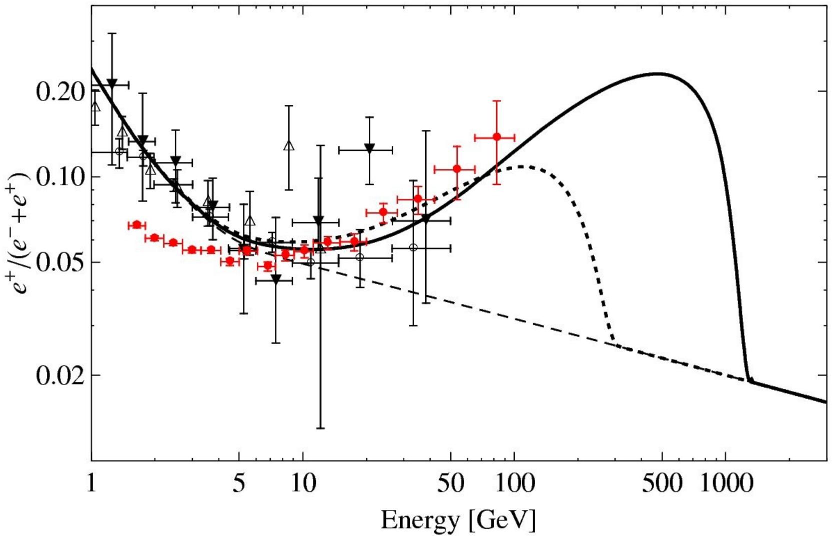
  ϕ_{DN}

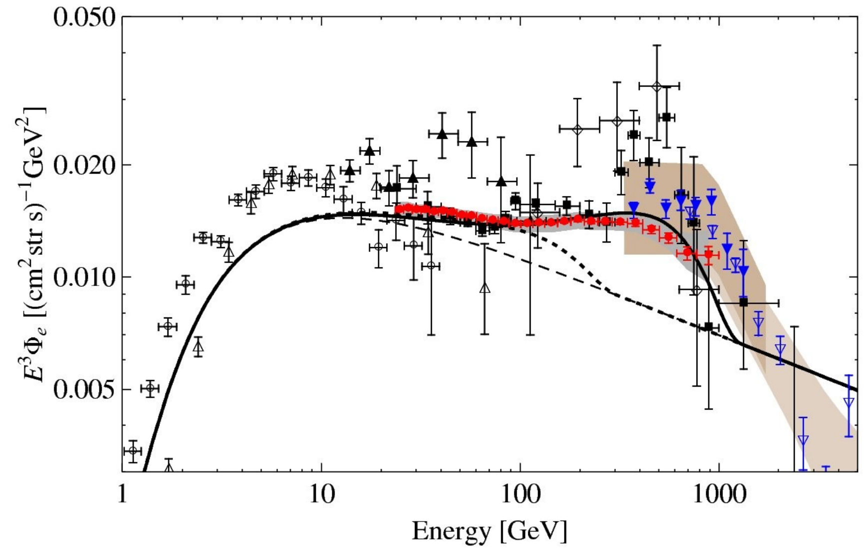
  ϕ_{DN}

- Note: Decay into quarks similar to decay into heavy gauge bosons

Decay Channels that fit the data

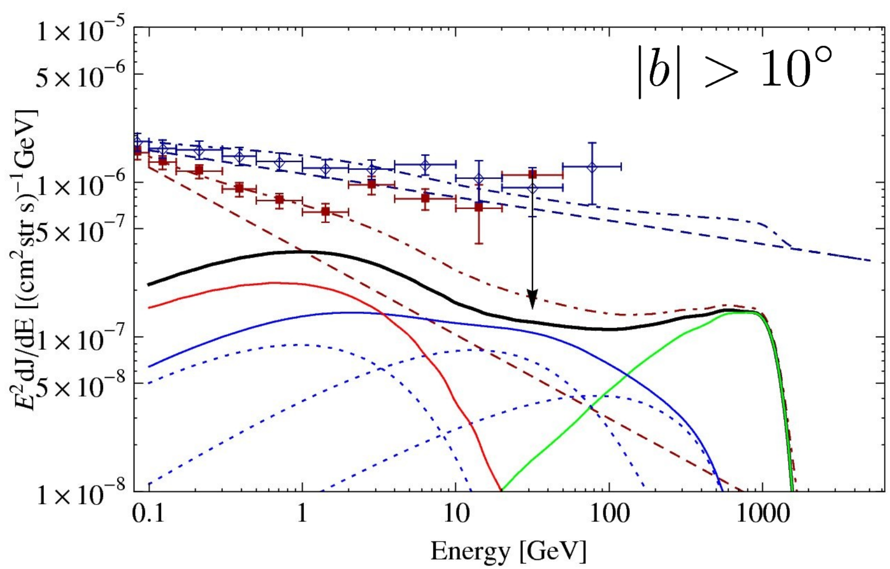
$$\phi_{\rm DM} \to \mu^+ \mu^-$$





Gamma Rays come from:

- Prompt radiation
- Galactic Inverse Compton
- Extragalactic Inverse Compton



Decay Channels that fit the data

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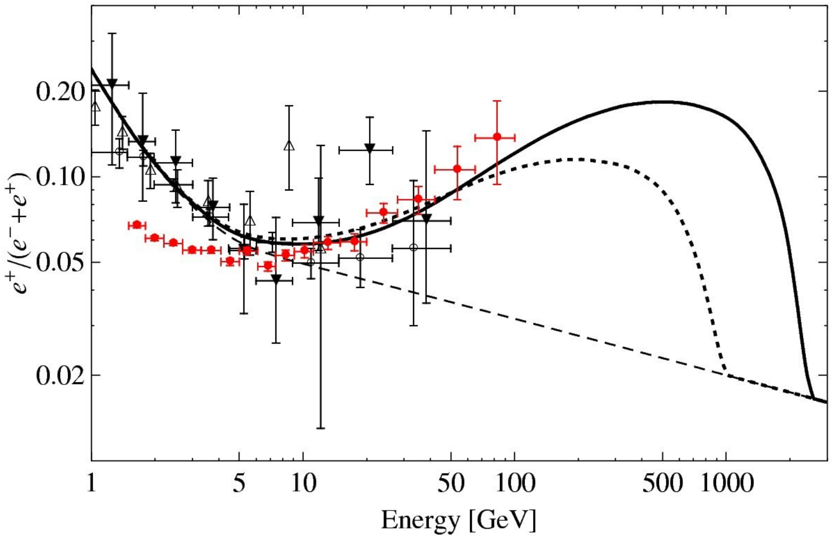

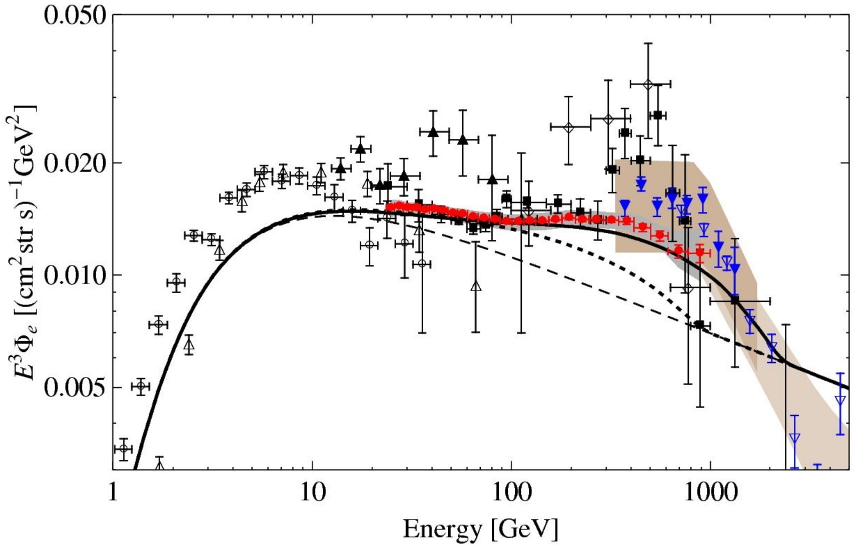

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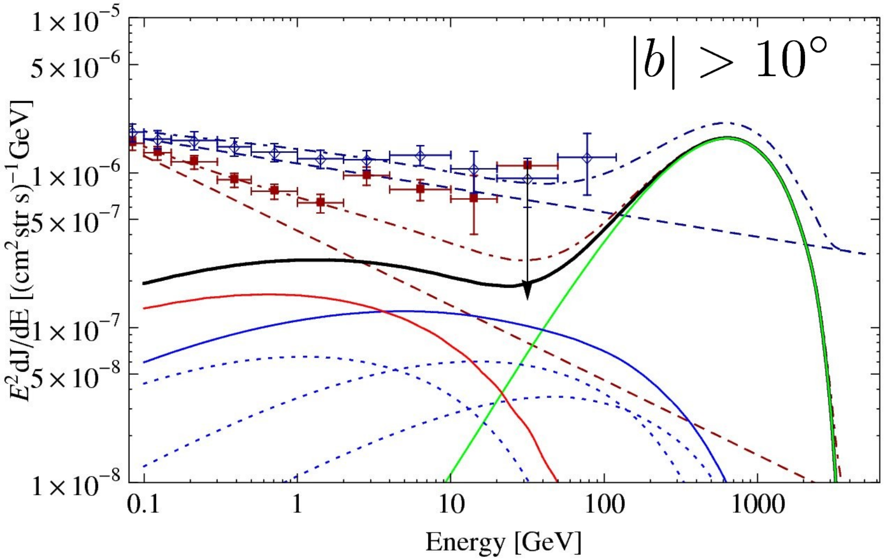
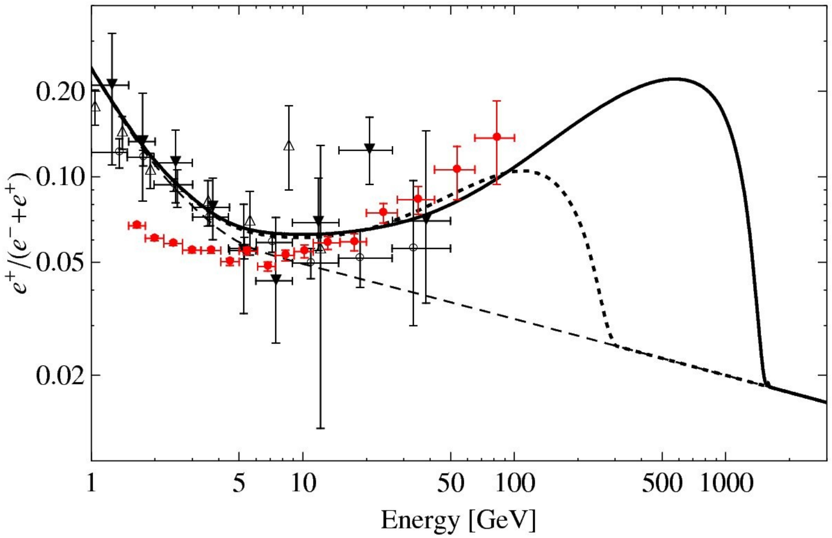
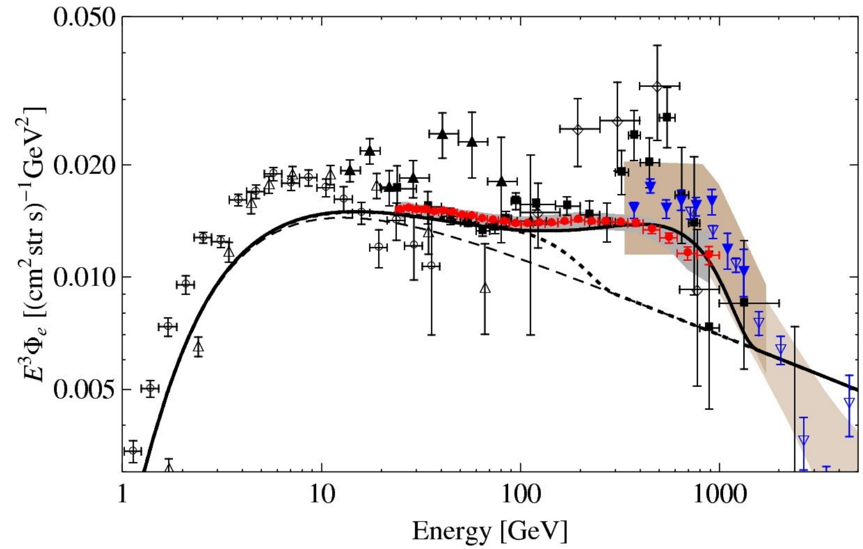


Decay Channels that fit the data

$$\psi_{\rm DM} \to W^{\pm}\mu^{\mp}$$





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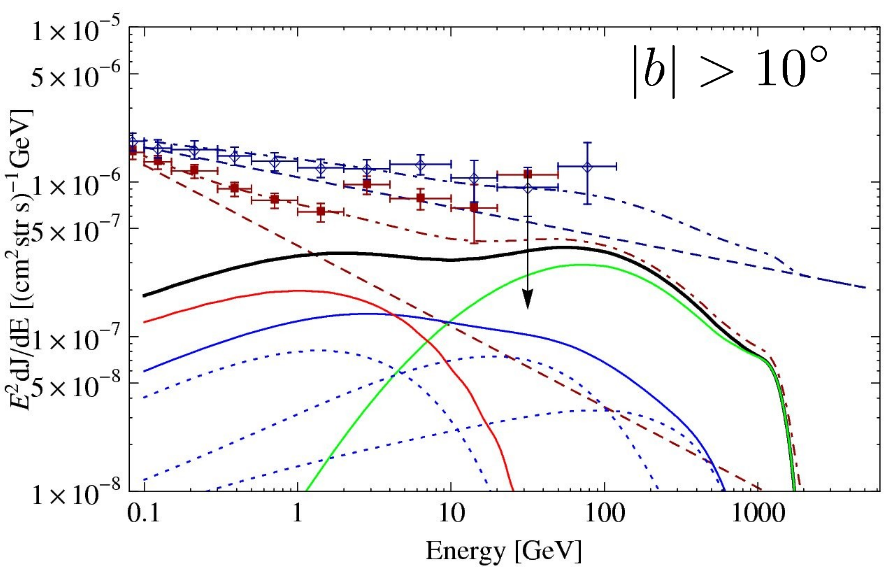
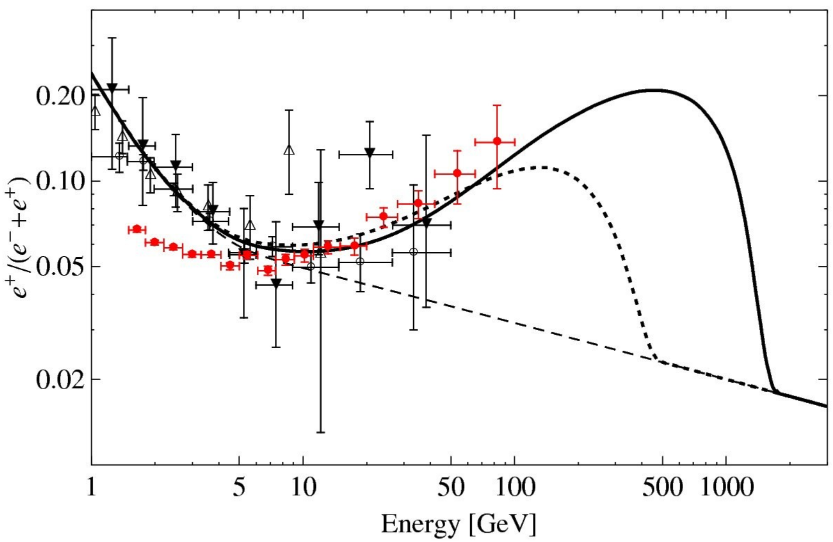
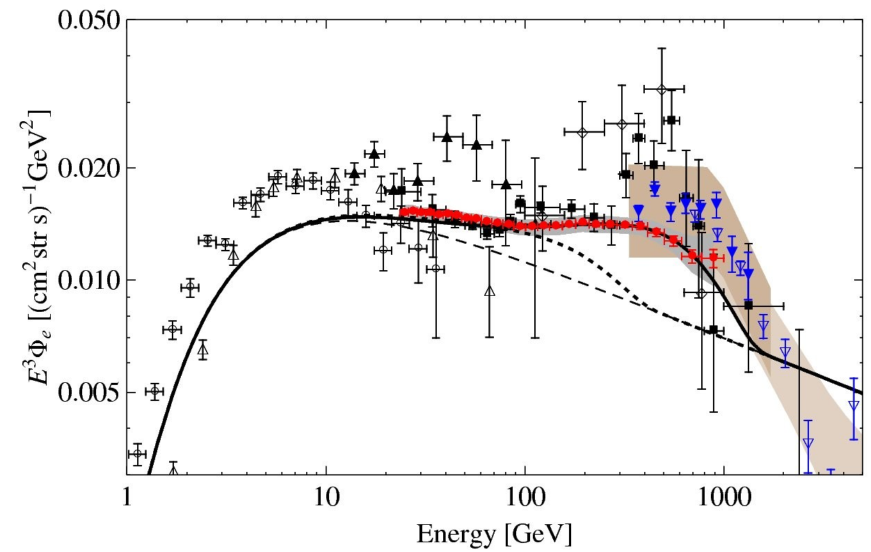


Decay Channels that fit the data

$$\psi_{\mathrm{DM}} \rightarrow \mu^+ \mu^- \nu$$





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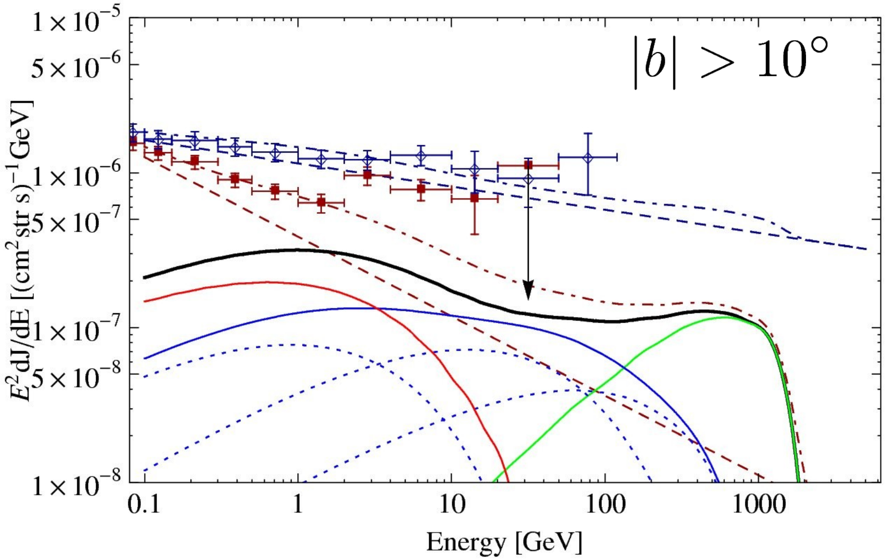
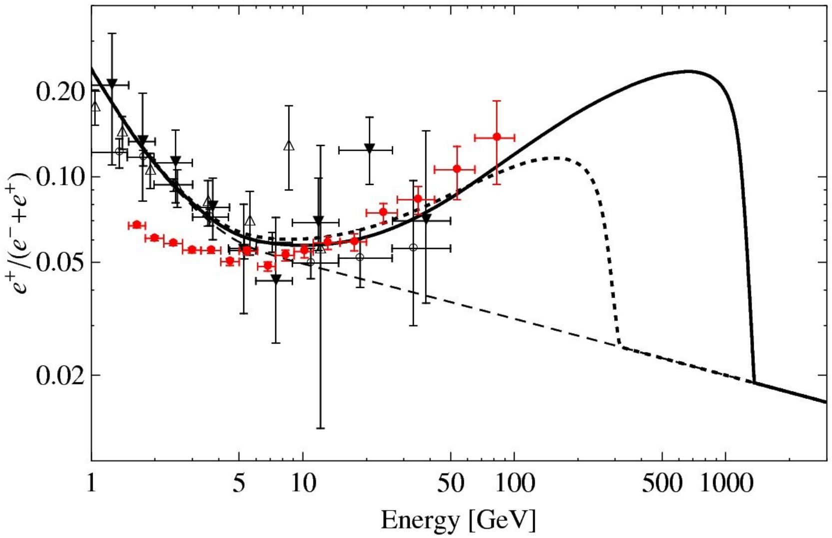
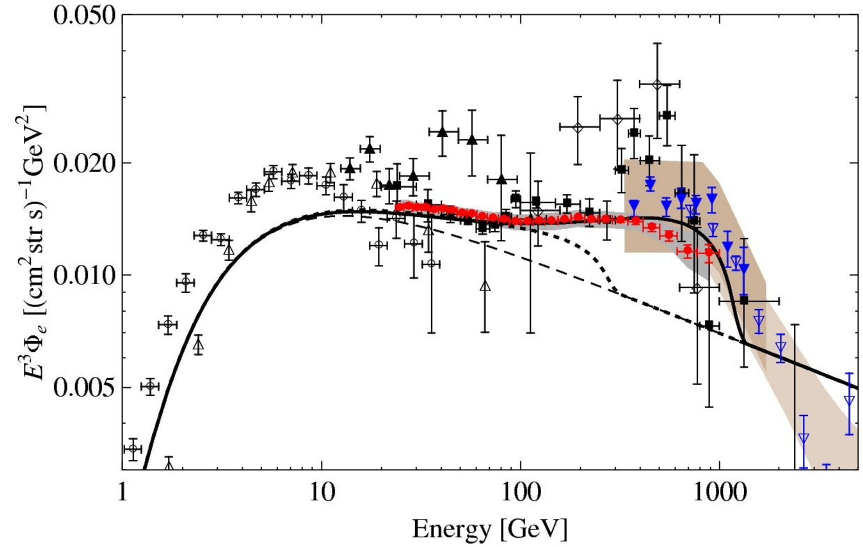


Decay Channels that fit the data

$$\psi_{\rm DM} \to \ell^- \ell^+ \nu$$





Gamma Rays come from:

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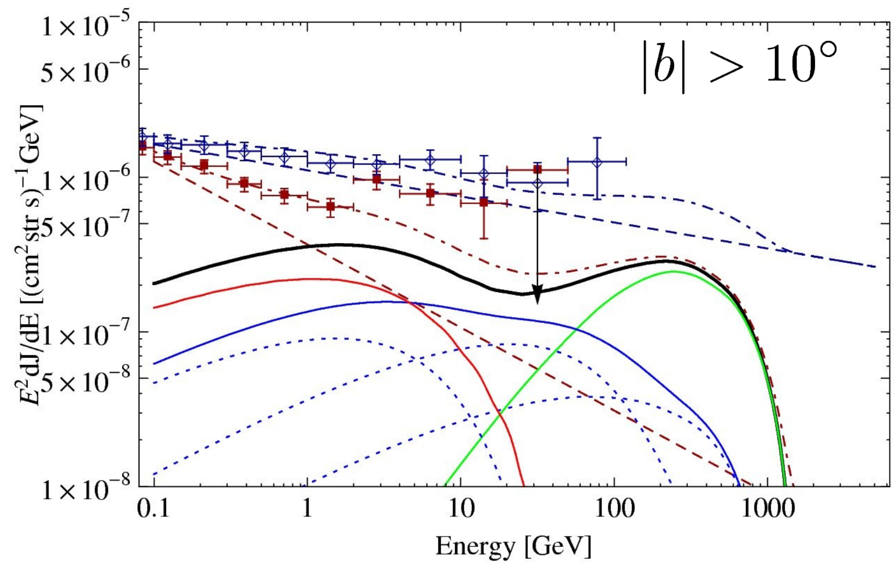
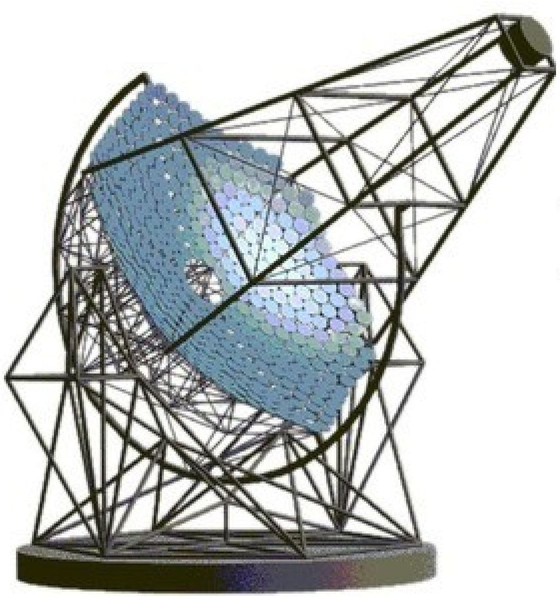
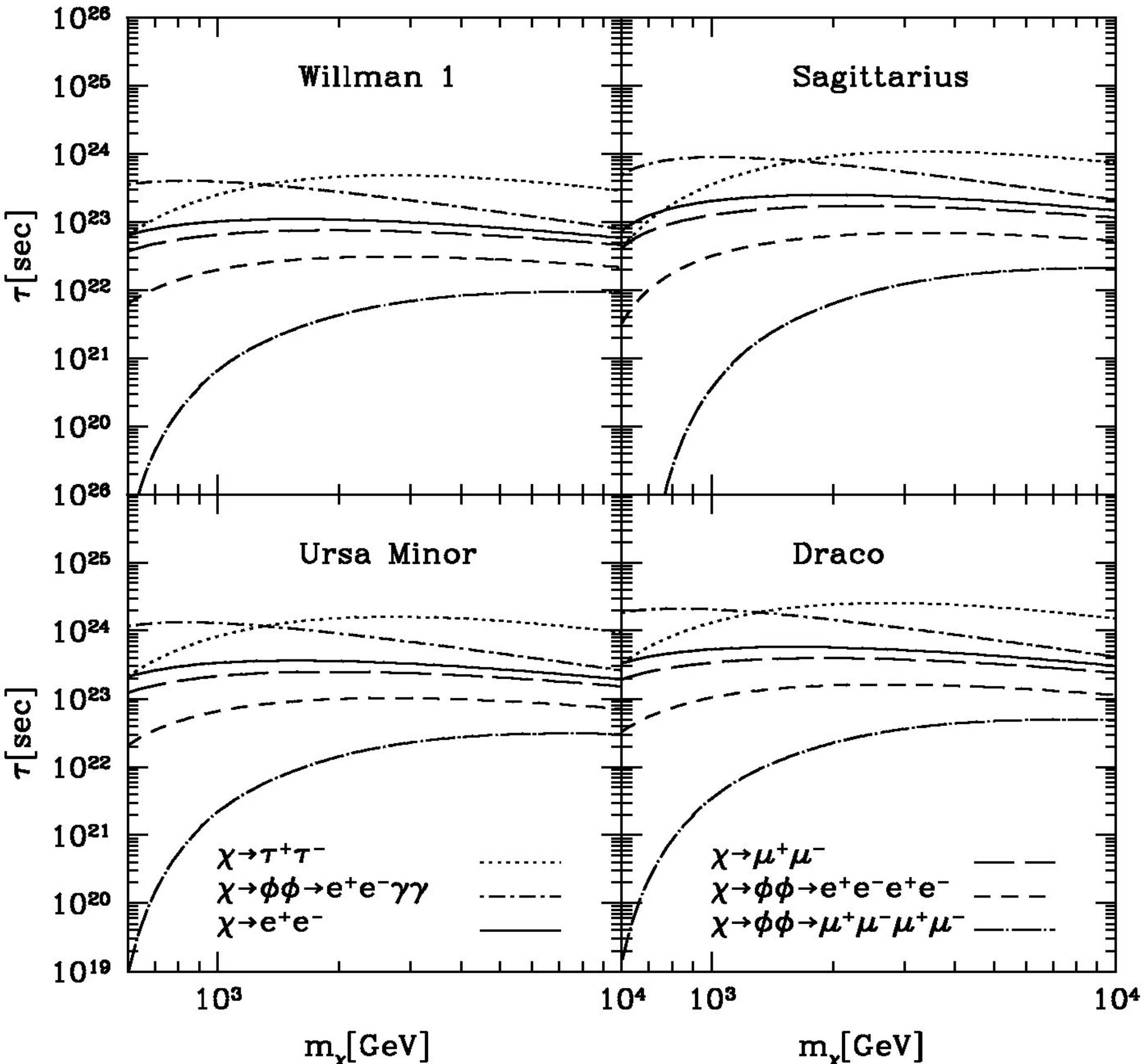


Dwarf Galaxy bounds on Decaying DM

Atmospheric Cherenkov Telescope observations (H.E.S.S. and VERITAS) of Milky Way dwarf galaxies give **only weak bounds** on Dark Matter lifetime.





[Essig *et al.* (2009)]

Selection of Models that fit PAMELA and Fermi

Split SUSY with R-parity violation
[Chen *et al.*, 2009]

Neutralino decay mediated by heavy sleptons

Topological Dark Matter
[Murayama *et al.*, 2009]

Skyrmion decay via dim-6 operators

Long-lived Kaluza-Klein Dark Matter
[Okada *et al.*, 2009]

small curvature in UED models

Decaying Mesons in Hidden Sectors
[Mardon *et al.*, 2009]

long lifetime due to dim-6 operators

Sneutrino Dark Matter
[Demir *et al.*, 2009]

long lifetime due to small Dirac-mass Yukawas

Hidden Gaugino Dark Matter
[Ibarra, Ringwald, Tran and CW 2009, accepted by JCAP]

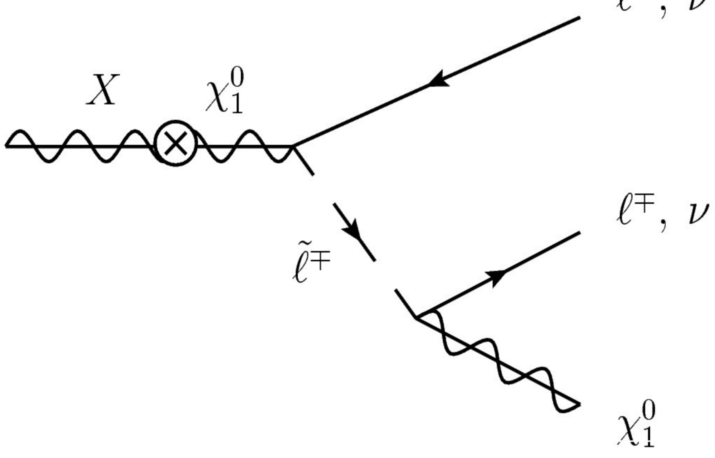
long lifetime due to tiny kinetic mixing

Hidden Gaugino Dark Matter

Setup: **MSSM** & **Hidden Gaugino** of unbroken **U(1)'**

[Ibarra, Ringwald, Tran and CW, accepted by JCAP 2009]

- Long lifetime due to **tiny kinetic mixing** ~ O(10^{-22}) between hidden U(1)' and hypercharge $U(1)_Y$ (motivated by scenarios with warped extra dimensions)
- Only two free parameters, but exact branching ratios depend on MSSM mass spectrum
- In certain cases (light enough sleptons, large mu-term), **three-body decay** into charged leptons can be dominant
  ==> Fits Fermi/PAMELA



V. Conclusions

Conclusions

- Sterile Neutrinos and Gravitinos with R-parity violation are well motivated models for beyond the Standard Model physics that implicate the Decay of Dark Matter
- With typical search strategies for annihilation signals one could miss their signals
- Dark Matter Decay can explain the Fermi/PAMELA excess
- This interpretation will be tested soon by the upcoming Fermi LAT Observations of the high latitude diffuse Gamma Rays

THANK YOU