Decaying Dark Matter, Anisotropies, Lines, and the Fermi LAT Gamma-Ray Data

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JCAP 1003:024 (2010); arXiv:0912.4504 [astro-ph.HE]

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Outline

I. Introduction

II. Review: Positron Excess & Decaying DM

III. Gamma-Ray Anisotropies & Constraints

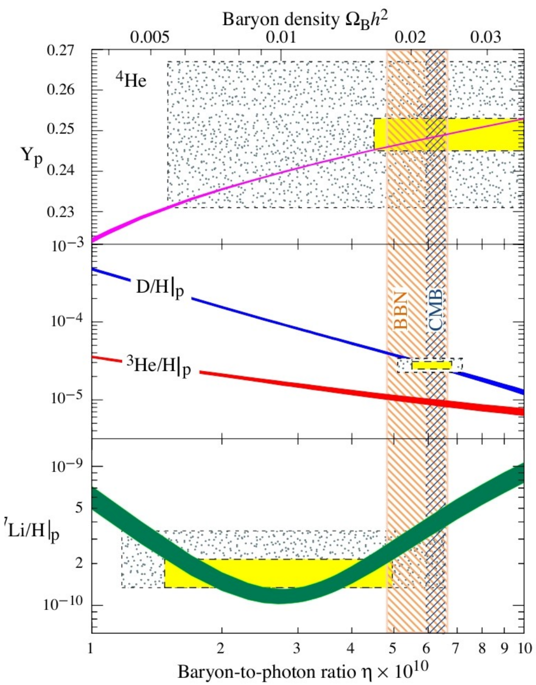
IV. Hidden SU(2) Vector Dark Matter & Gamma-Ray Lines

V. Conclusions

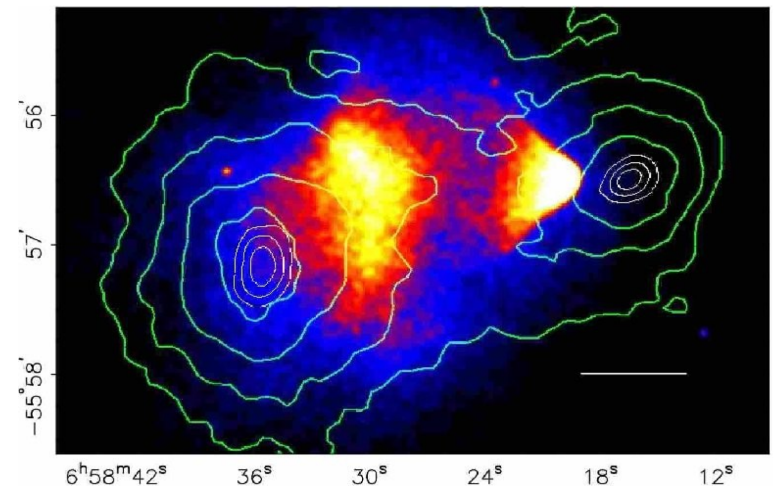
I. Introduction

Evidence for non-baryonic Dark Matter

Evidence for the existence of **non-baryonic** dark matter in the Universe comes from a combination of different observations:



Primordial Nucleosynthesis (the fusion of light elements 3-20 min after the Big Bang)



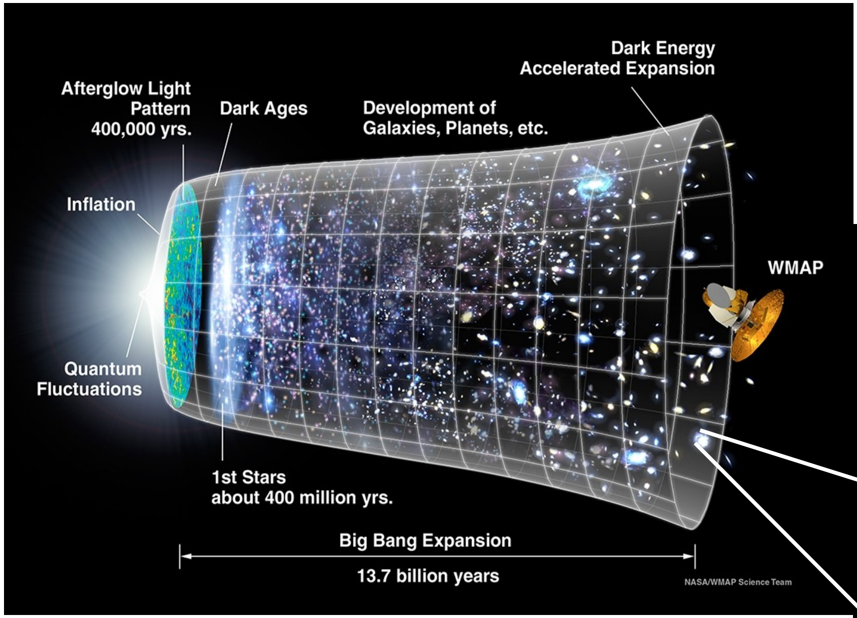
[Clowe et al. (2006)]

Total Mass on Galaxy Cluster scales measured via

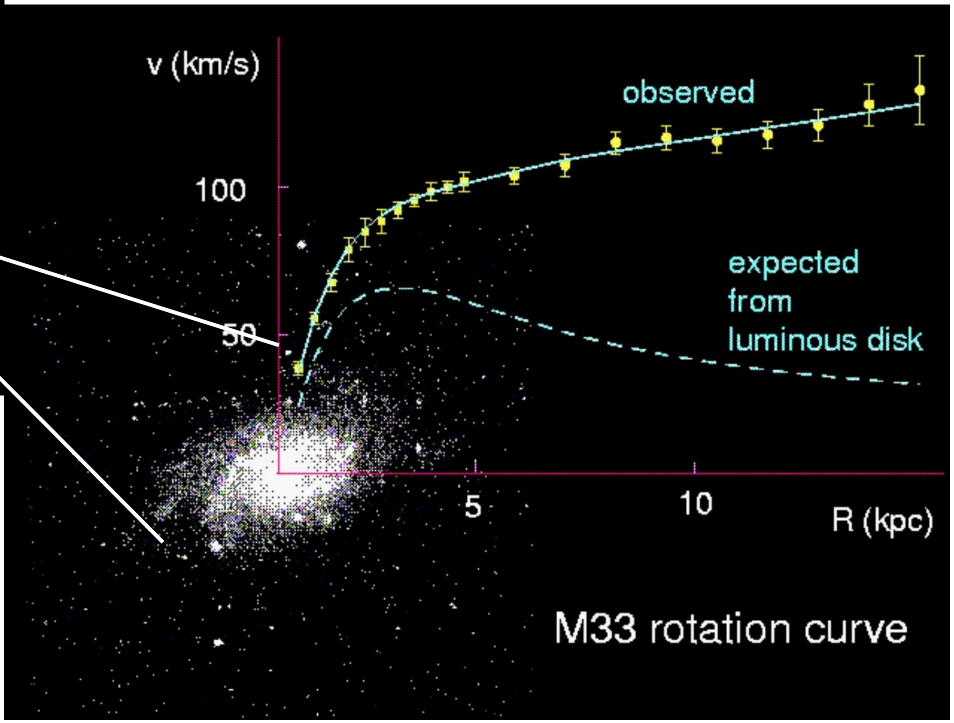
- Weak Gravitational Lensing
- X-ray measurements
- Velocity dispersions
- ...

$$\Omega_B \sim 0.04 \qquad \ll \qquad \Omega_{DM} \sim 0.2\text{–}0.4$$

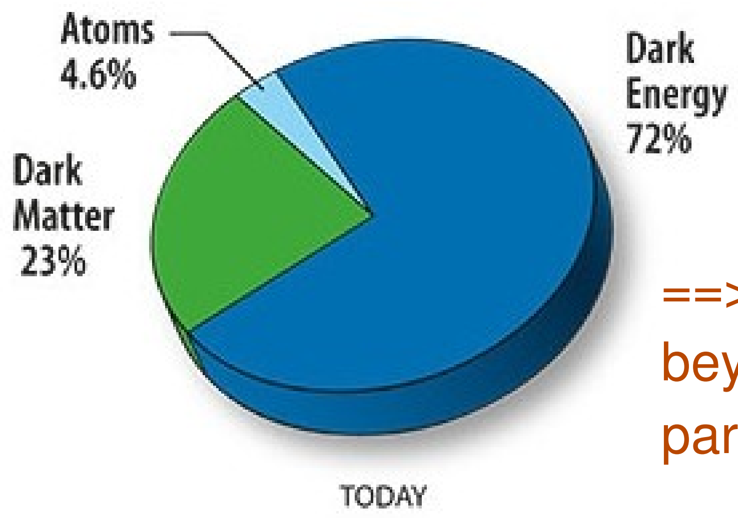
Evidence for non-baryonic Dark Matter



- CMB anisotropies vs LSS today
- Rotation curves in spiral galaxies



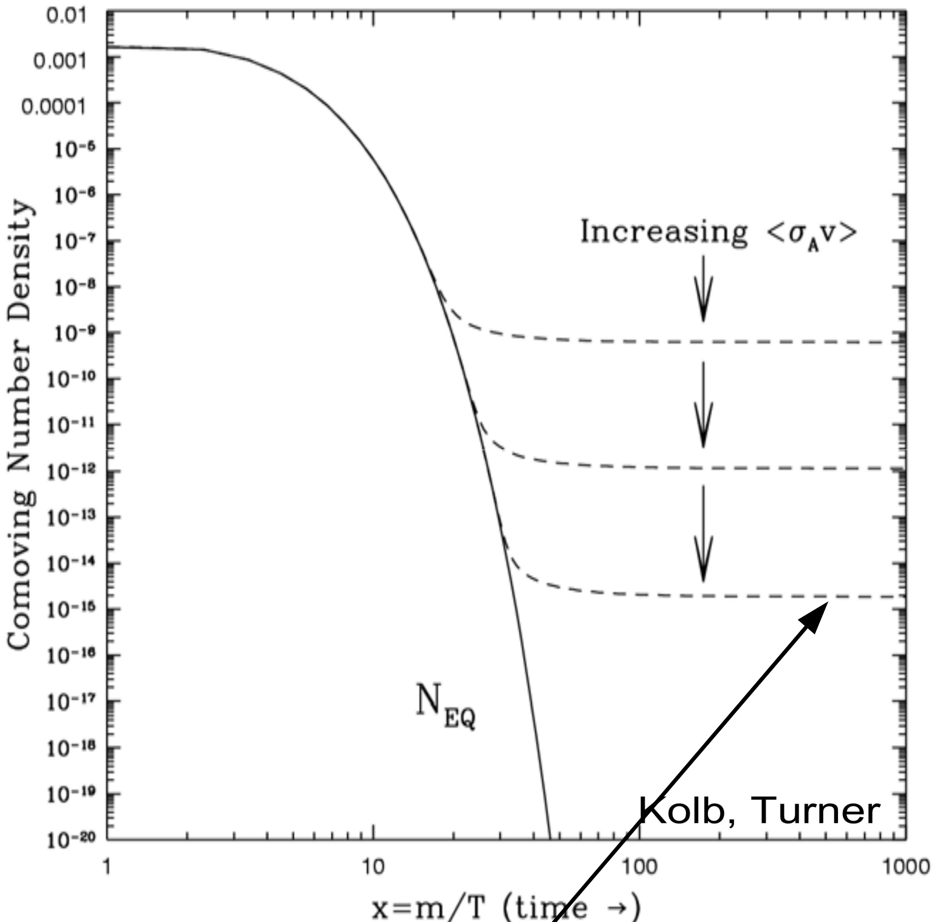
Total Energy in the Universe:



==> Suggests **new elementary particles**, beyond the realms of the Standard Model of particle physics

[see Amsler *et al.* (2009)]

WIMPs



A Weakly Interacting Massive Particle (WIMP), initially in thermal equilibrium with the rest of the Universe, freezes out with a relic density given by

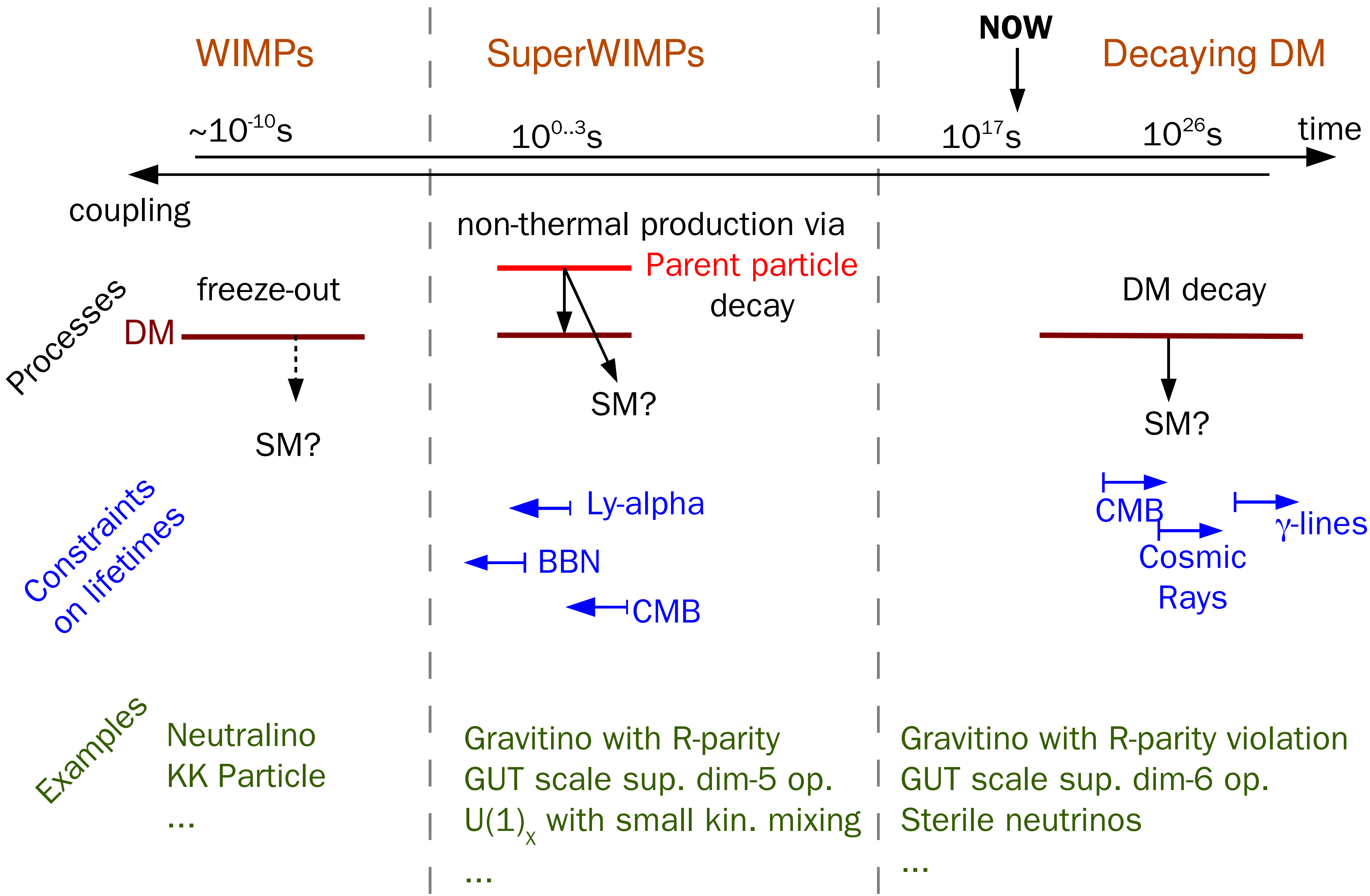
$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{M_X^2}{\alpha^2}$$

$$M_X \simeq 100 \text{ GeV} \Rightarrow \Omega_X \sim 0.1$$

==> WIMPs naturally reproduce the observed relic density.

Annihilation never stopped and is potentially observable in the cosmic-ray signals today $e.g.$ via $XX \to b\bar{b}$

"SuperWIMPs" and Decaying Dark Matter



Decaying DM: Reasons for $\tau_{DM} \sim 10^{26}$ s

Some models that predict lifetimes around this order of magnitude:

Gravitino dark matter with mild violation of R-parity

- R-parity violation allows gravitino dark matter to be consistent with BBN and Leptogenesis [Buchmüller *et al.* (2007), Bertone *et al.* (2008)]
- This implies the decay of gravitinos on cosmological time-scales

Sterile Neutrino Dark Matter

- Cosmological lifetime due to tiny Yukawa couplings (lives in the keV regime, however) [Dodelson and Widrow (1994), Shi and Fuller (1999), *e.g.* Boyarsky *et al. (2008)*]

Generic GUT scale physics

- Decay can be mediated by GUT-scale suppressed dim-6 operators ==> cosmological lifetimes [D. Eichler (1989), *e.g.* Arvanitaki *et al.* (2009)]

Example: Hidden SU(2) Vector Dark Matter

- Long lifetime due to GUT-suppressed dim-6 operator that breaks custodial symmetry –> tree-level gamma-ray lines [Arina, Hambye, Ibarra, CW (2009)]

...

Cosmic Rays from Dark Matter Decay

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

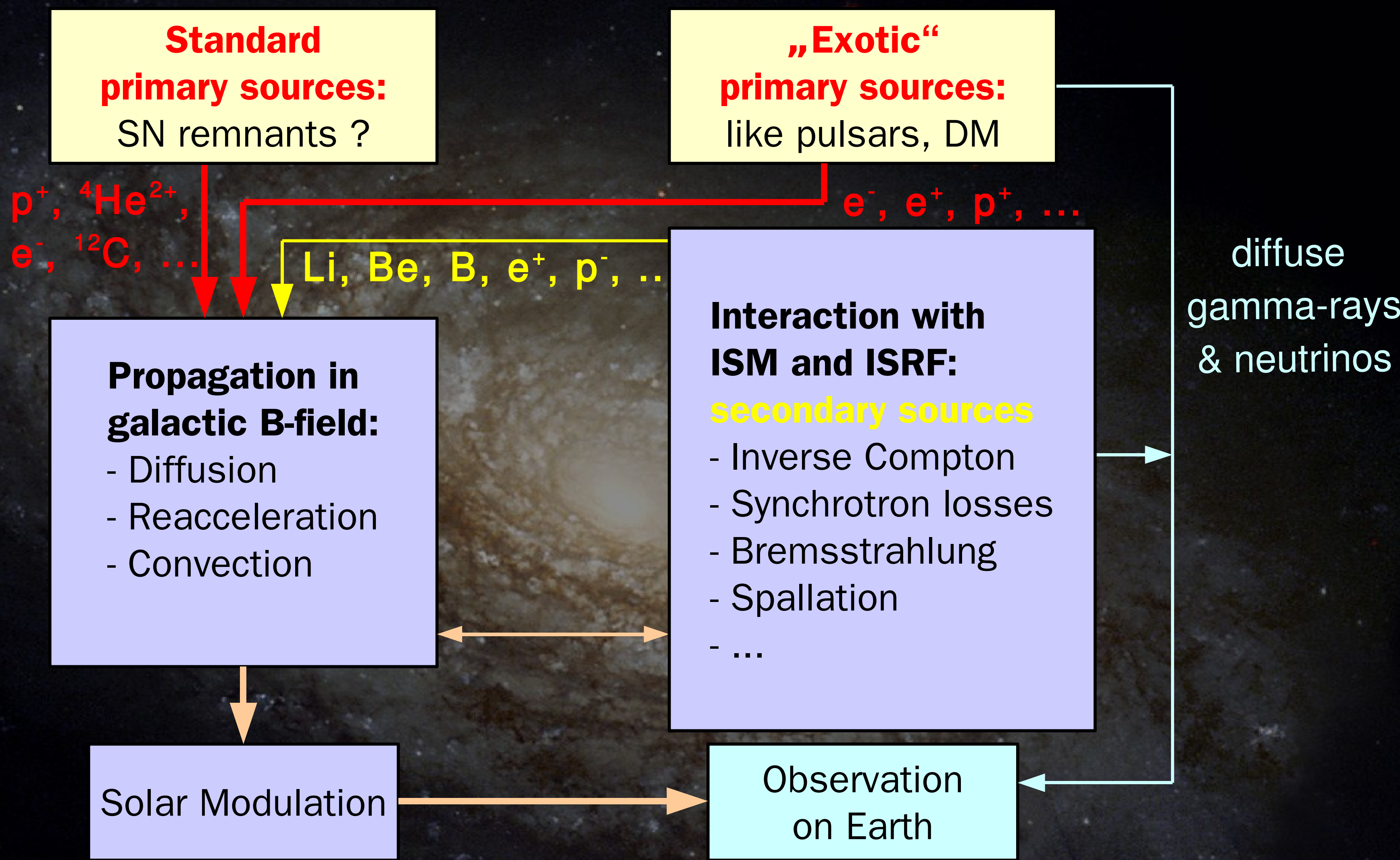
Positrons	* Diffusive propagation in Galactic magnetic field * Spatial information washed out & mainly **isotropic** * **Rise in positron fraction observed above 10 GeV**
Anti-protons	* Diffusive propagation * **Low astrophysical background**
Anti-deuterons	* Diffusive propagation * **Very low astrophysical background**
Gamma Rays	* No absorption on galactic scales * Carry **spatial information** about their **galactic** and **extragalactic** sources
Neutrinos	* Carry **spatial information** about their sources * Atmospheric background & Flavour Oscillation

firstly (Positrons, Anti-protons)

secondly (Gamma Rays)

II. The Positron Excess & Decaying Dark Matter

Cosmic Rays in the Galaxy



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

Propagation is <u>local</u> phenomena (~kpc scale) ==> Only mild difference between positron signals from pulsars or decaying or annihilating dark matter

CR Positrons and Dark Matter

Standard astrophysical picture:

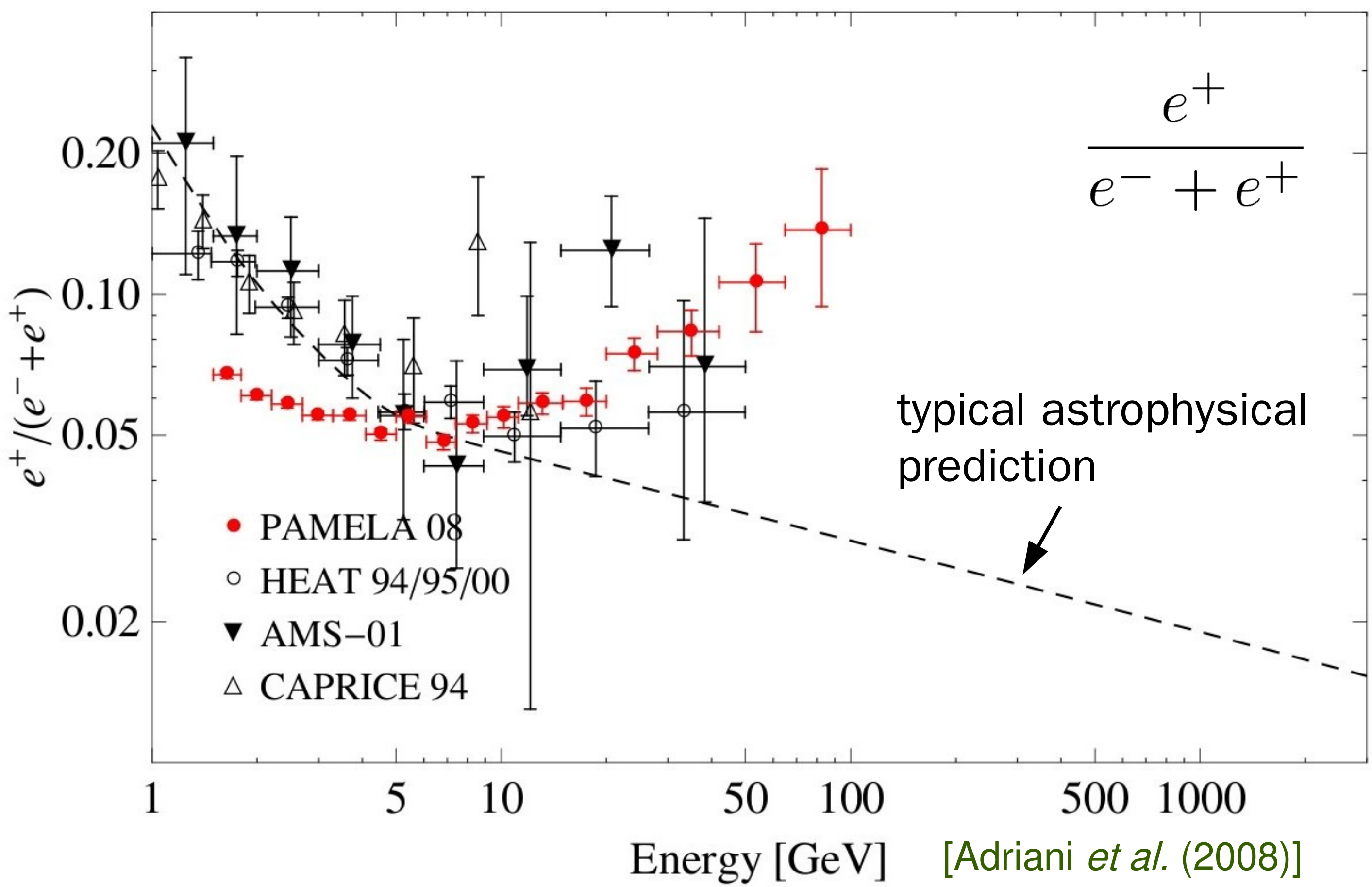
- Positron fraction in electron+positron flux should **decrease** with energy
- Measured positron fraction is **< 0.2 at GeV energies**
- Energy spectrum of electrons+positrons ~ E^-3

Dark Matter Decay/Annihilation:

- Dark Matter Decay/Annihilation products have **positron fraction = 0.5**
- Typically **harder energy spectrum** than E^-3

Dark Matter generically predicts a
rise in the positron fraction
(provided the fluxes are large enough)

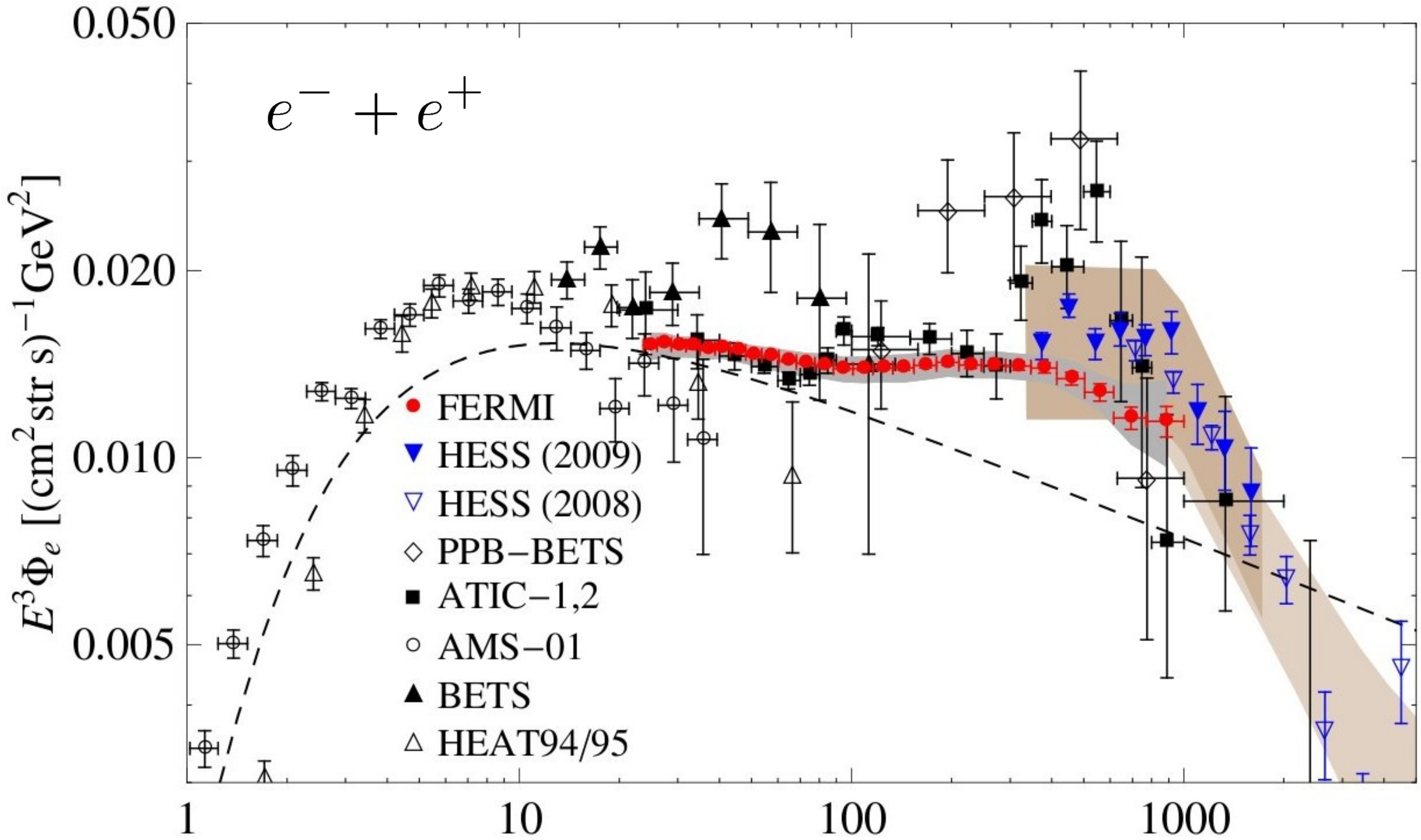
The Positron Fraction



[Adriani *et al.* (2008)]

- **Astrophysical models with only secondary positrons generically do not predict rise** in positron fraction as observed by PAMELA (secondary positrons have in general softer spectrum than primary electrons)

The Electron plus Positron Flux

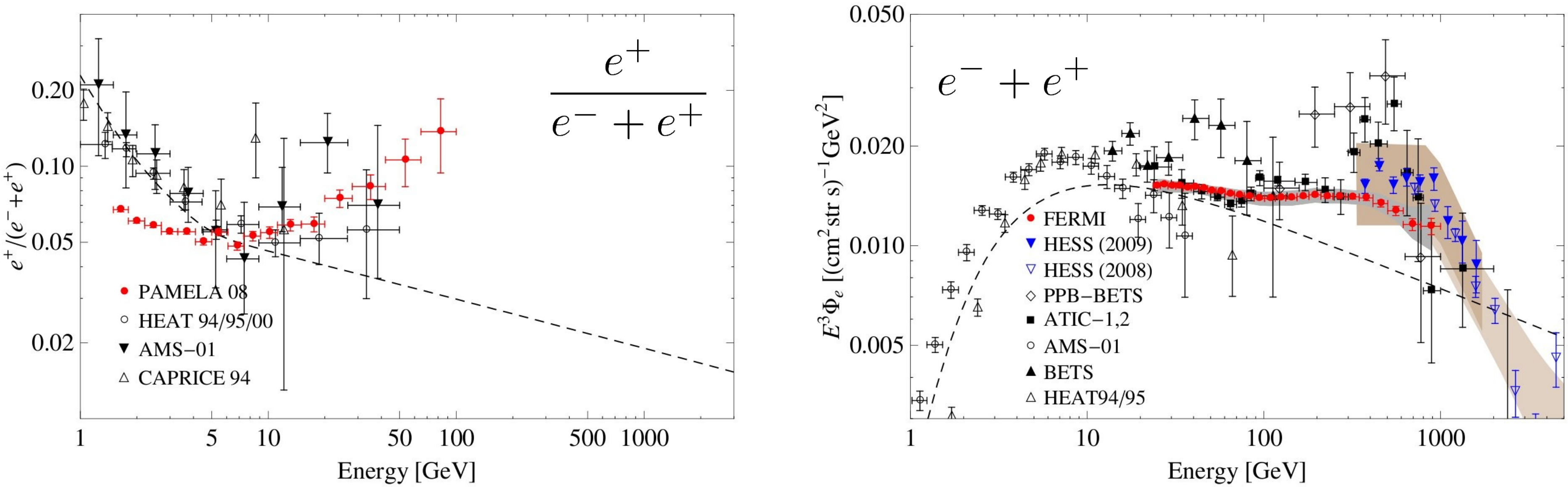


[Abdo *et al.* (2009)]

- **Fermi LAT** measured a **hard spectrum of electrons** up to 1 TeV, **H.E.S.S.** a **steepening** in the spectrum above energies of 1 TeV

The e^+/e^- excess of PAMELA/Fermi

PAMELA and Fermi LAT detected deviations from the astrophysical expectations

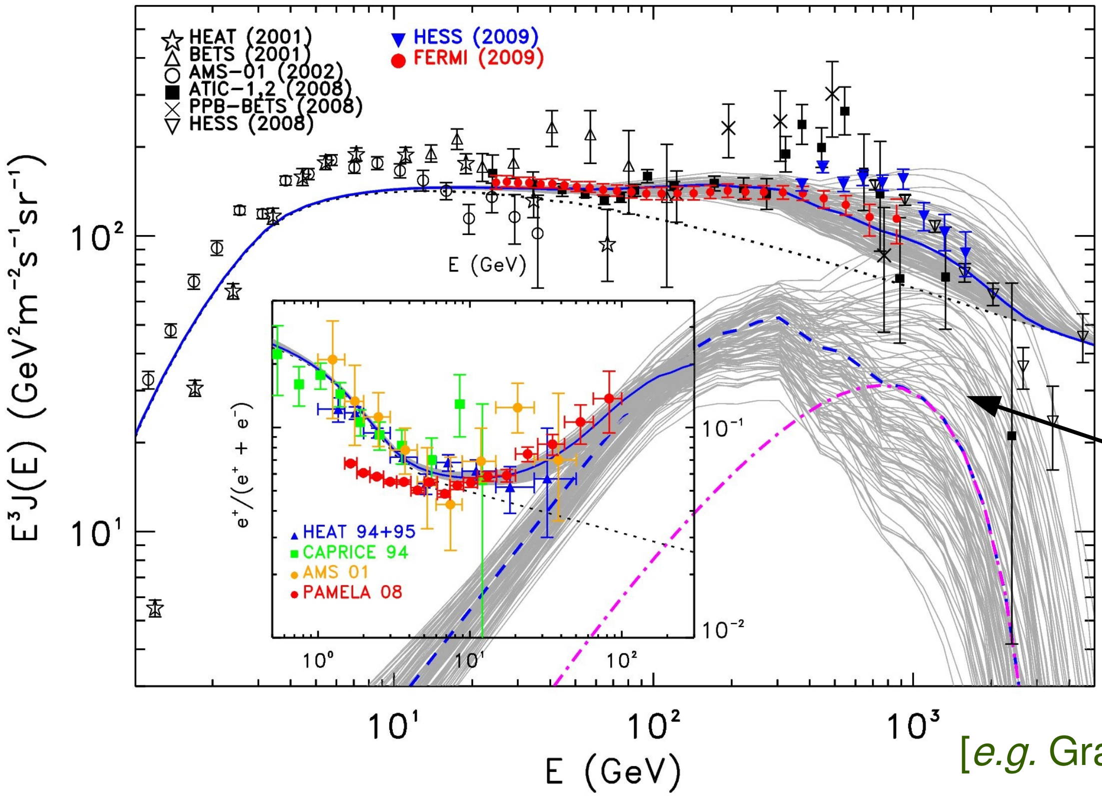


The PAMELA, Fermi and H.E.S.S. results together suggests the existence of **a local primary source of electrons and positrons** up to ~ 1 - 2 TeV

Pulsar Explanation

Observations may be explained by e^+/e^- emission of **nearby pulsars.**

- Pulsars are **highly magnetized rotating neutron stars** that emit beams of electromagnetic radiation
- They can **produce electron/positron pairs** by interaction of high-energetic photons



predictions for different sets of pulsar parameters

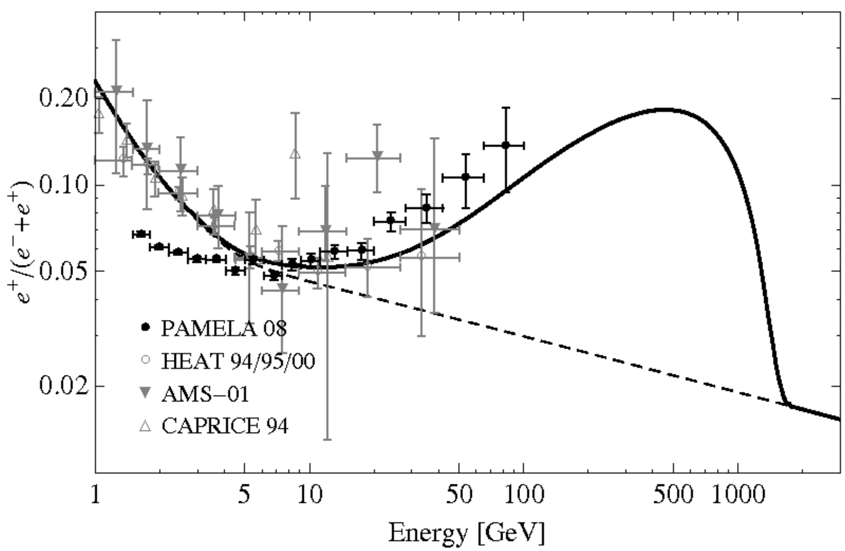
[*e.g.* Grasso *et al.* (2009)]

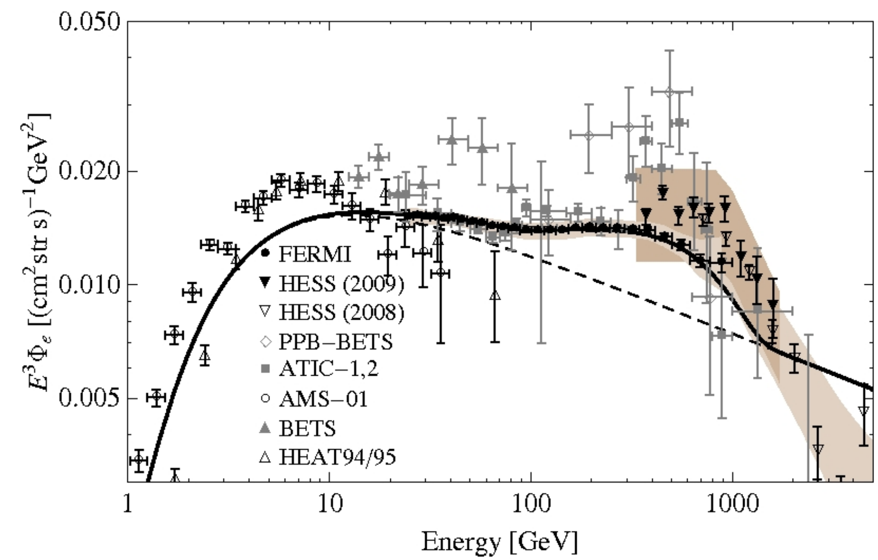
- If they emit a considerable fraction (10%-30%) of their spin-down power through the electron/positron channel, this can generate the observed fluxes

Dark Matter Explanation

OR: Decaying (or annihilating) **dark matter** with TeV masses could be responsible for the PAMELA and Fermi LAT observations.

$$e.g. \;\; \psi_{\rm DM} \to \mu^+ \mu^- \nu$$





$$M_{\rm DM} \simeq 3.5 \text{ TeV}$$

$$\tau_{\rm DM} \simeq 1.1 \times 10^{26} \text{ s}$$

In the plots we adopted

- a standard propagation model ("**MED model**")
- a standard astrophysical background ("**Model 0**")

Decay Channels that explain the data

List of different reference two- and three-body decay channels:

- **Fermionic** Dark Matter:

~~$\psi_{\rm DM} \to Z^0 \nu$~~

$\psi_{\rm DM} \to W^\pm \ell^\mp$ with **muon** flavour

$\psi_{\rm DM} \to \ell^\pm \ell^\mp \nu$ with **muon** flavour, or flavour democratic

- **Bosonic** Dark Matter:

~~$\phi_{\rm DM} \to Z^0 Z^0$~~

~~$\phi_{\rm DM} \to W^\pm W^\mp$~~

$\phi_{\rm DM} \to \ell^\pm \ell^\mp$ with **muon** flavour, or tau flavour

Decay Channels that explain the data

List of different reference two- and three-body decay channels:

- **Fermionic** D

  ψ_{DM}

  ψ_{DM}

  ψ_{DM} ... tic

- **Bosonic** Da

  ϕ_{DM}

  ϕ_{DM}

  ϕ_{DM}

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
$\phi_{DM} \to \tau^+\tau^-$	5000	0.9
$\phi_{DM} \to \mu^+\mu^-$	2500	1.8
$\psi_{DM} \to W^\pm\mu^\mp$	3000	2.1

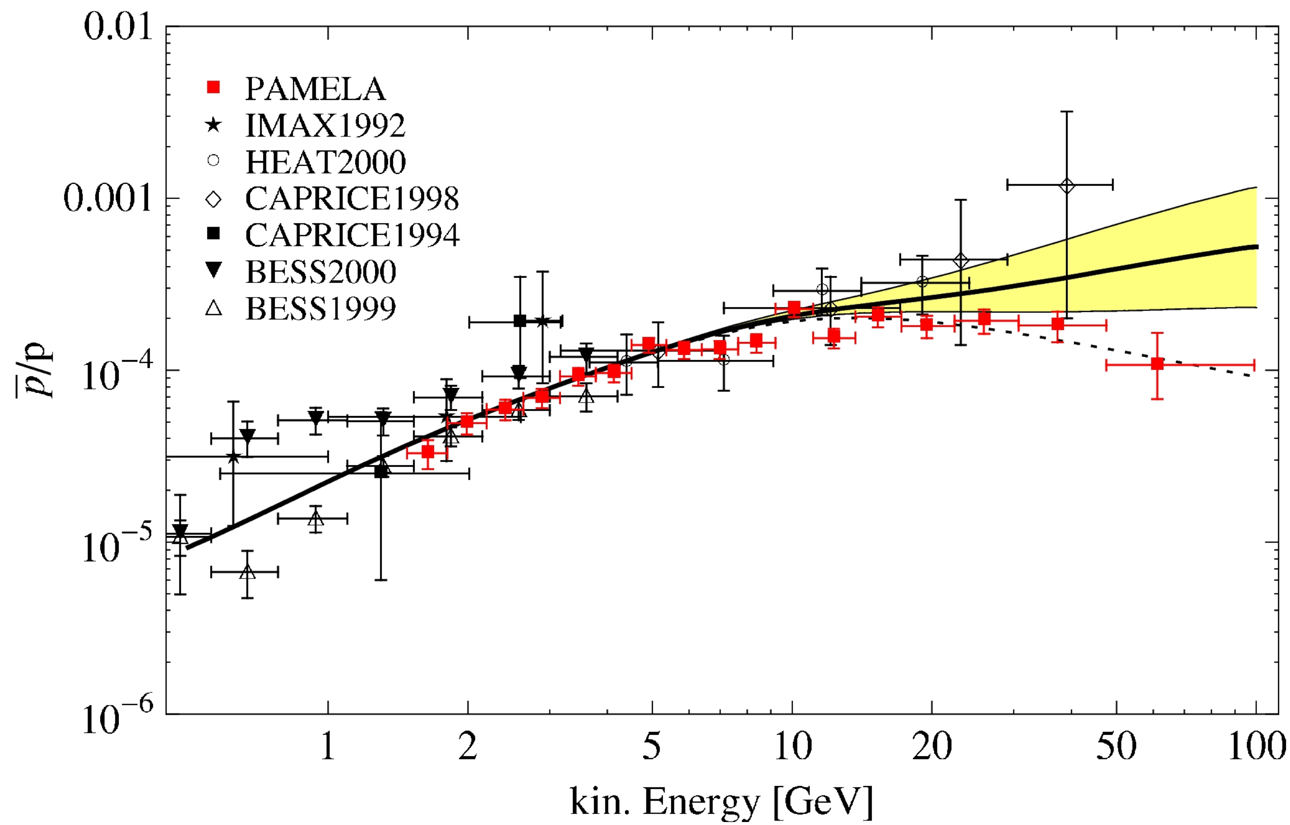
[Ibarra, Tran and CW (2009)]

Related work: [Cirelli *et al.* (2008), Meade *et al.* (2009), Grasso *et al.* (2009), Bergstrom *et al.* (2009), ...]

Antiprotons from $W^{\pm}$-decay

$W^{\pm}$ fragmentation yields a problematic abundance of antiprotons

$$\psi_{\mathrm{DM}} \rightarrow W^{\pm}\mu^{\mp}$$



- Propagated spectrum is **not** consistent with measurements of antiproton-to-proton ratio by PAMELA

==> Leptonic decay favored by data

DM Annihilation vs Decay

Annihilation signals scale like	**Decay** signals scale like
$\propto \rho_{\rm dm}(\vec{r},z)^2$	$\propto \rho_{\rm dm}(\vec{r},z)$
(times boost factor)	(no boost factor)

==> **Annihilation signal** is in general **stronger** than decaying signal at **high redshifts** and in **peaked structures**.

Emission in the **early Universe**:

- *Interference with reionization* [Zhang *et al.* (2007); Hütsi *et al.* ; Cirelli *et al.* (2009)]
- Extragalactic Prompt/*Inverse Compton Scattering Radiation* [Ishiwata *et al.*; Profumo *et al.* (2009)]

Emission at the **Galactic Center**:

- ***Inverse Compton Scattering/Prompt Radiation*** (HESS, Fermi LAT)
- ***Radio Emission***
- Neutrino Emission (superKamiokande)

[Meade *et al.*; Papucci *et al.*; Cirelli *et al.*; Covi *et al.*, Mandal *et al.* (2009)...]

Decaying Dark Matter Interpretation more difficult to exclude

~O(100) Models Proposed to Explain Excess

„TeV Particles as Weakly Unstable Dark Matter“

Long Liftime due to dim-6 operator at GUT scale [D. Eichler, **1989**]

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

Sky

Lo

sma

De

lon

All models predict a more or less intense amount of prompt and ICS gamma-rays

--> Observations by **Fermi LAT**

Here: only minimal fluxes from reference channels

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

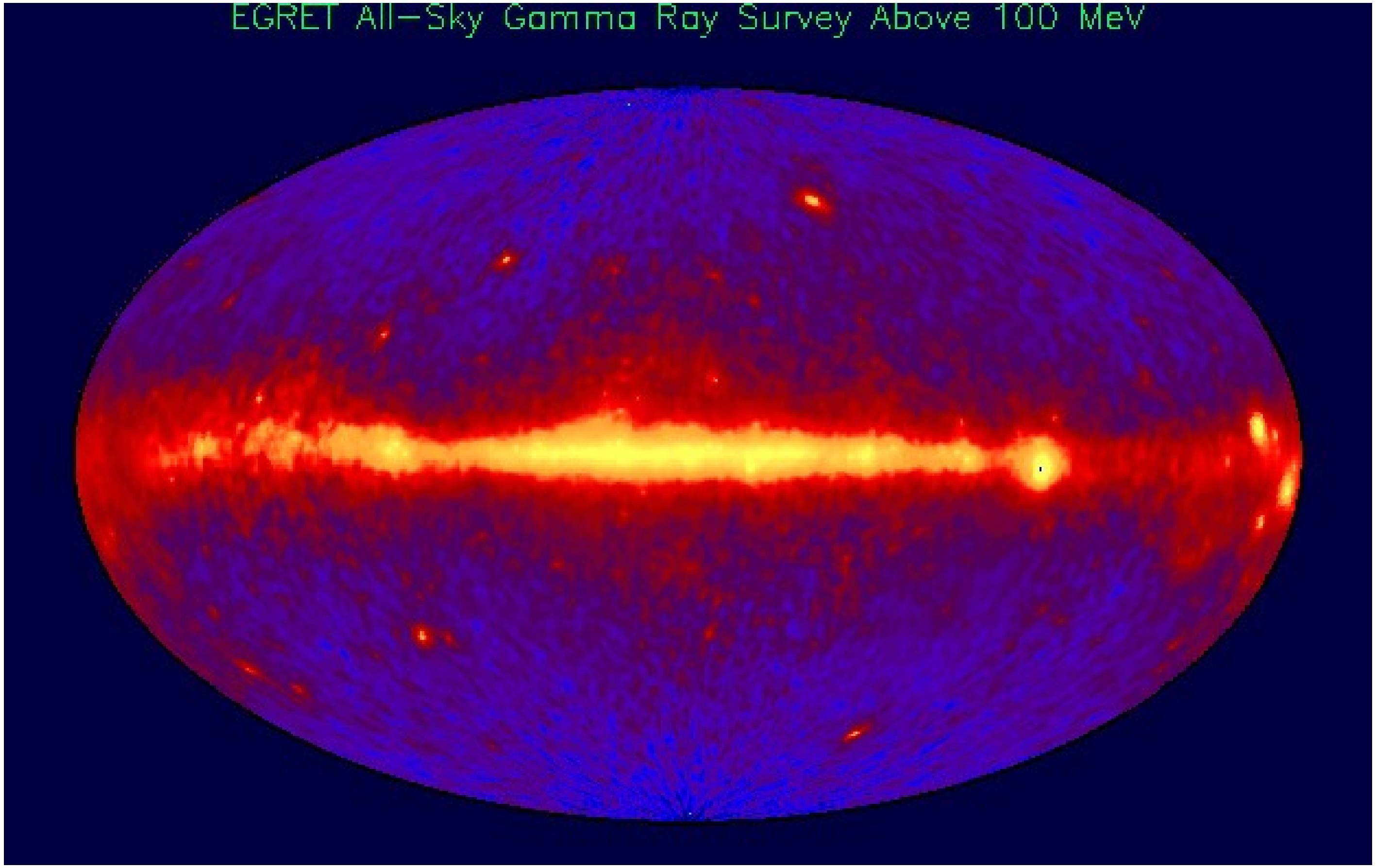
long lifetime due to small Dirac-mass Yukawas

Hidden Gaugino Dark Matter [Ibarra, Ringwald, CW (2009), Shirai, Takahashi, Yanagida (2009), ...]

long lifetime due to tiny kinetic mixing

and many more...

III. Gamma-Ray Anisotropies & Constraints



Gamma-ray signal from Dark Matter Decay

The gamma-ray signal from dark matter decay has **two main components**:

Prompt Radiation

- produced in the decay itself (final state radiation, pion decay...)
- may contain spectral lines, sharp spectral features.

Inverse Compton Scattering Radiation

- of electrons/positrons that are produced in the dark matter decay
- always smooth energy spectrum

The Prompt Radiation

The prompt gamma-ray flux from DM splits again in two components: gamma-rays can be produced **inside** or **outside** of the Milky Way halo

$$\frac{dJ}{dE_\gamma}(\Omega) = \frac{dJ_{\rm halo}}{dE_\gamma}(\Omega) + \frac{dJ_{\rm eg}}{dE_\gamma}$$

Halo component

- depends on **dark matter profile** (Einasto, NFW, isothermal, ...?)
- Even if profile is spherically symmetric, flux is **anisotropic**, due to the offset between sun and galactic center

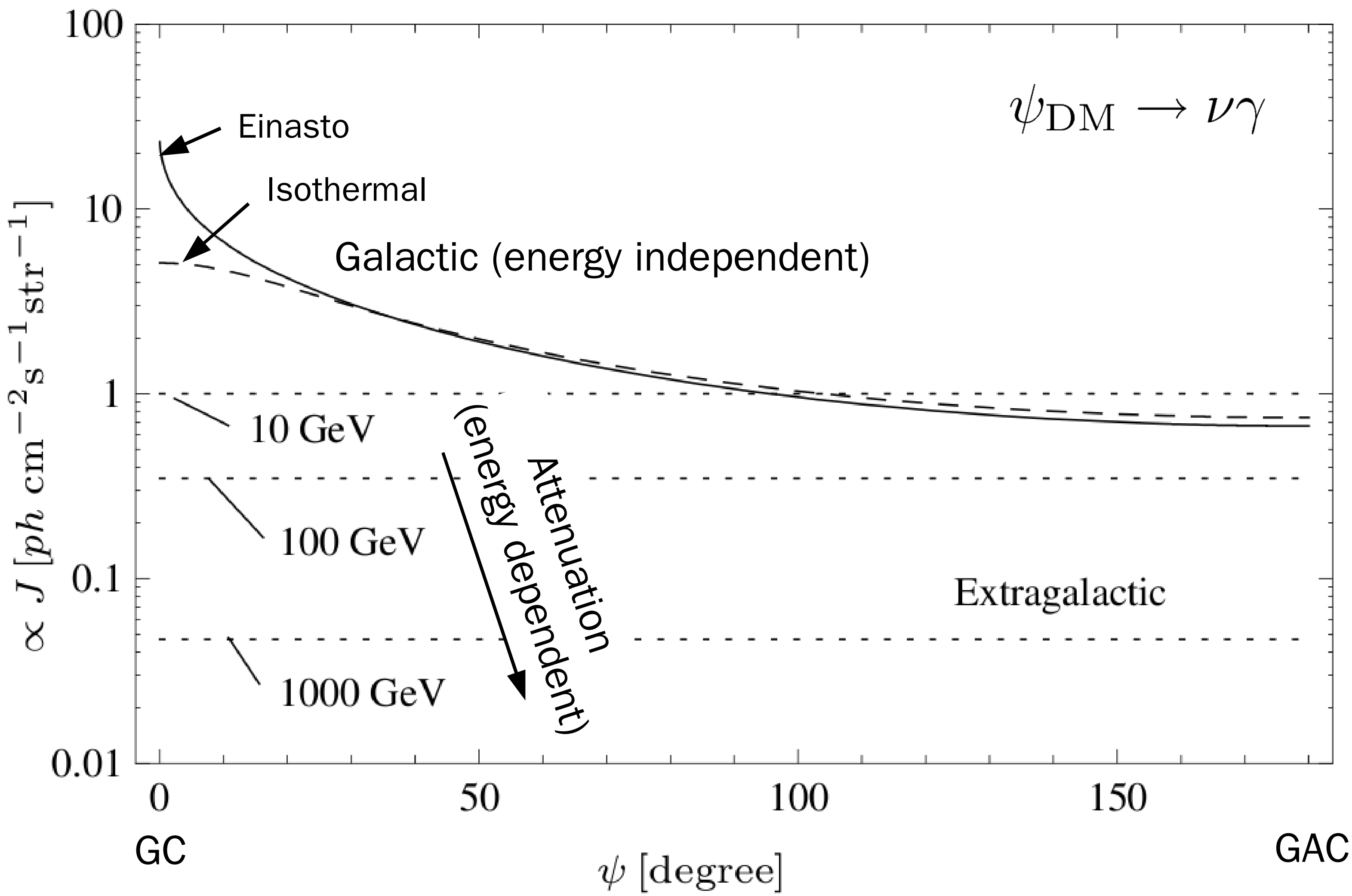
Extragalactic component

- is mainly **isotropic**
- At high energies, **attenuation effects** due to scattering with the **intergalactic background light** must be taken into account

[Stecker *et al.* (2006)]

The Prompt Radiation

Galactic and extragalactic prompt gamma-ray flux as function of the angle to the galactic center.



Inverse Compton Scattering Radiation

Inverse Compton scattering of electrons/positrons from dark matter decay with the interstellar and extragalactic radiation field produces gamma-rays

$$e^{\pm} + \gamma \rightarrow e^{\pm} + \gamma^{*}$$

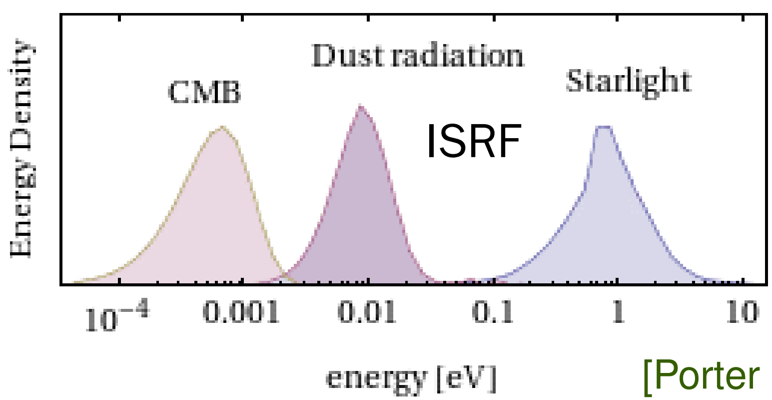
dark matter decay products

$$E_e = \mathcal{O}(1 - 1000\,\mathrm{GeV})$$

Upscattered Photon

$$E_{\gamma^*} \leq 4 \left(\frac{E_e}{m_e}\right)^2 E_\gamma$$

Galactic: Interstellar Radiation Field (ISRF)
Extragalactic: CMB only

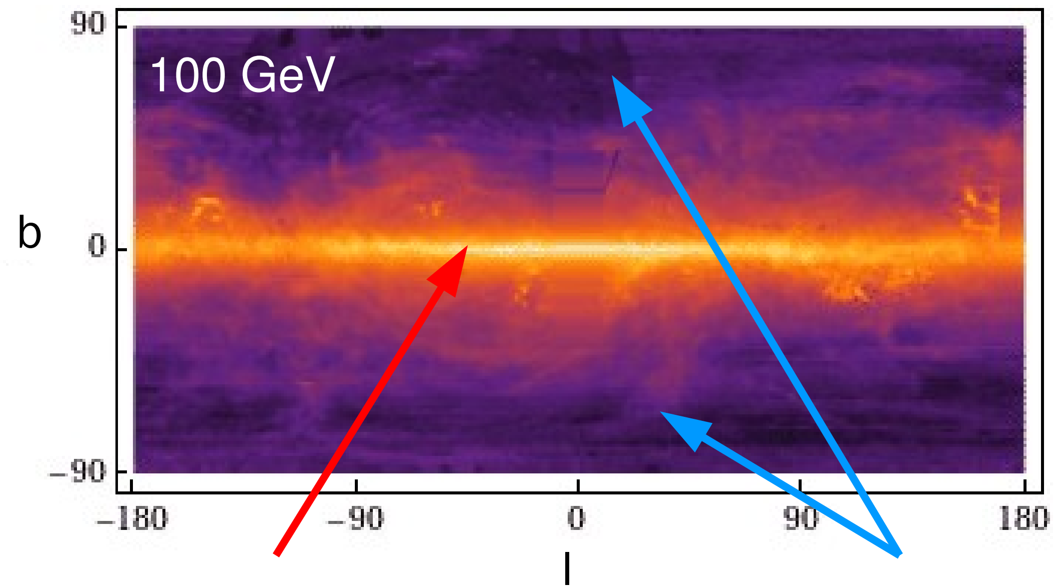


[Porter *et al.* (2005)]

This produces gamma rays up to O(100 GeV)

The Background: Galactic Foreground + EGBG

The Galactic Foreground as predicted by GalProp:



[Strong *et al.* (2004)]

Galactic Foreground (highly anisotropic)

- from cosmic ray interactions, it receives contributions from
  - Pion Decay
  - Inverse Compton Scattering
  - and Bremsstrahlung
- It dominates in galactic disk region

Extragalactic fluxes (highly isotropic)

- Away from the galactic disk, <u>at high latitudes</u>, the **E**xtragalactic **G**amma-ray **B**ack**g**round (EGBG) becomes relevant and can dominate the galactic foreground
- Produced by unresolved extragalactic point sources, like Blazars

Where to look for Decaying Dark Matter?

The Signal-to-Background Ratio

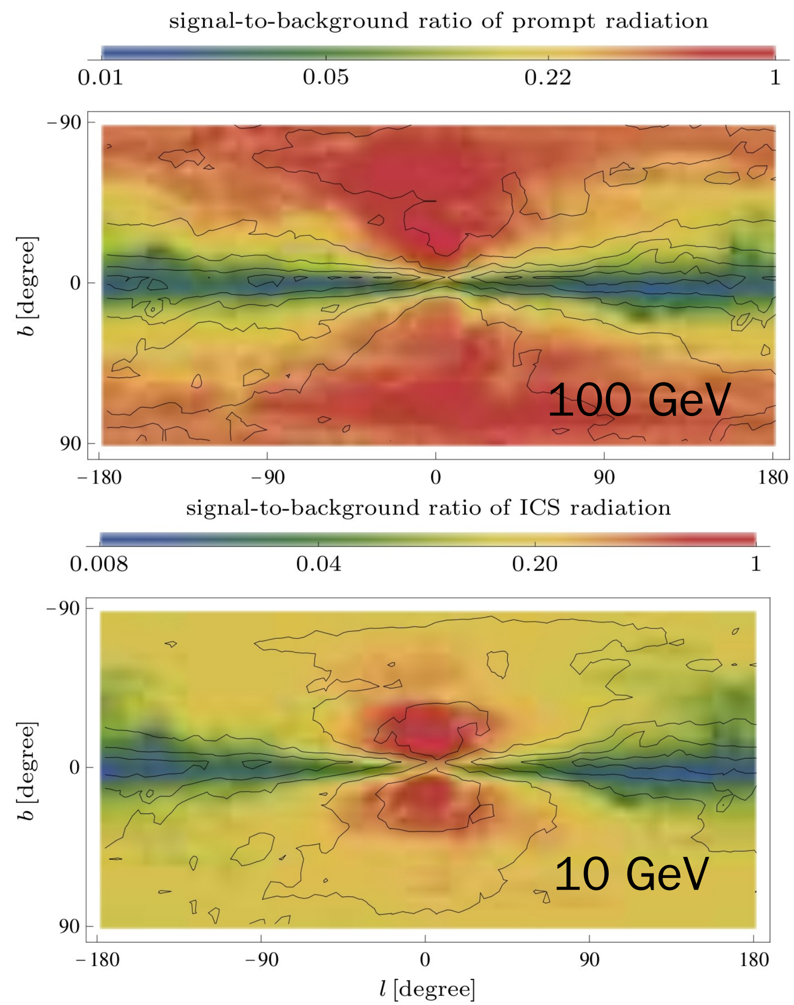
(Dark Matter Signal) / (Background Fluxes)

Prompt Radiation:

- Dominates Galactic Foreground at high latitudes
- **<u>Can be misidentified as extragalactic gamma-ray background</u>**, which also dominates at high latitudes

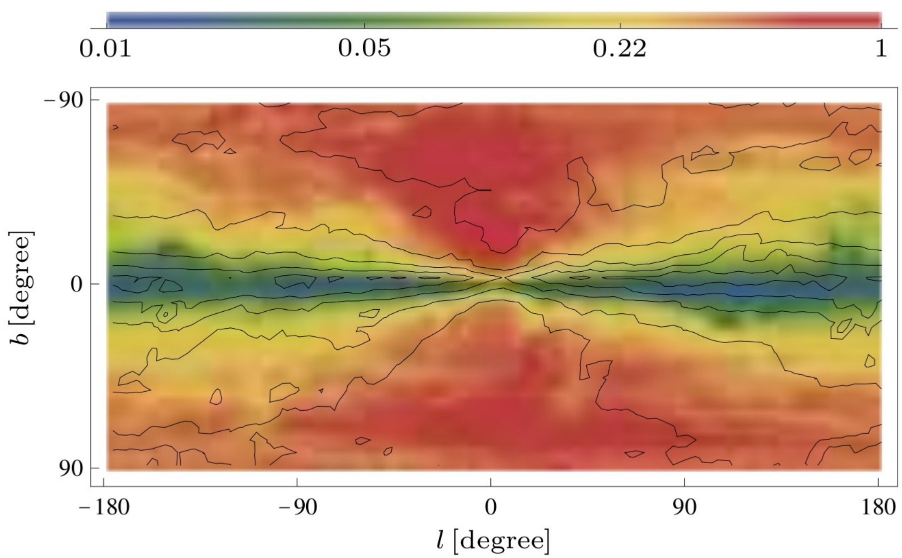
ICS Radiation:

- Dominates Galactic Foreground above and below the galactic center
- Flux in the Galactic Center region itself is small compared with foreground ==> requires special treatment
- **Minimal Flux implied by Dark Matter Interpretation of Positron Excess**

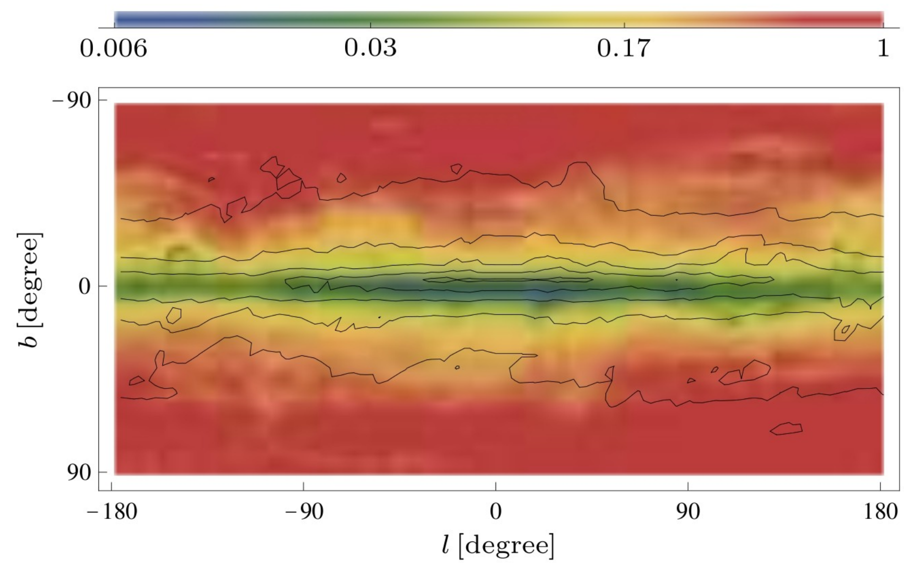


EGBG vs Prompt DM Signal

Prompt Dark Matter Signal/
Galactic Foreground



EGBG/
Galactic Foreground



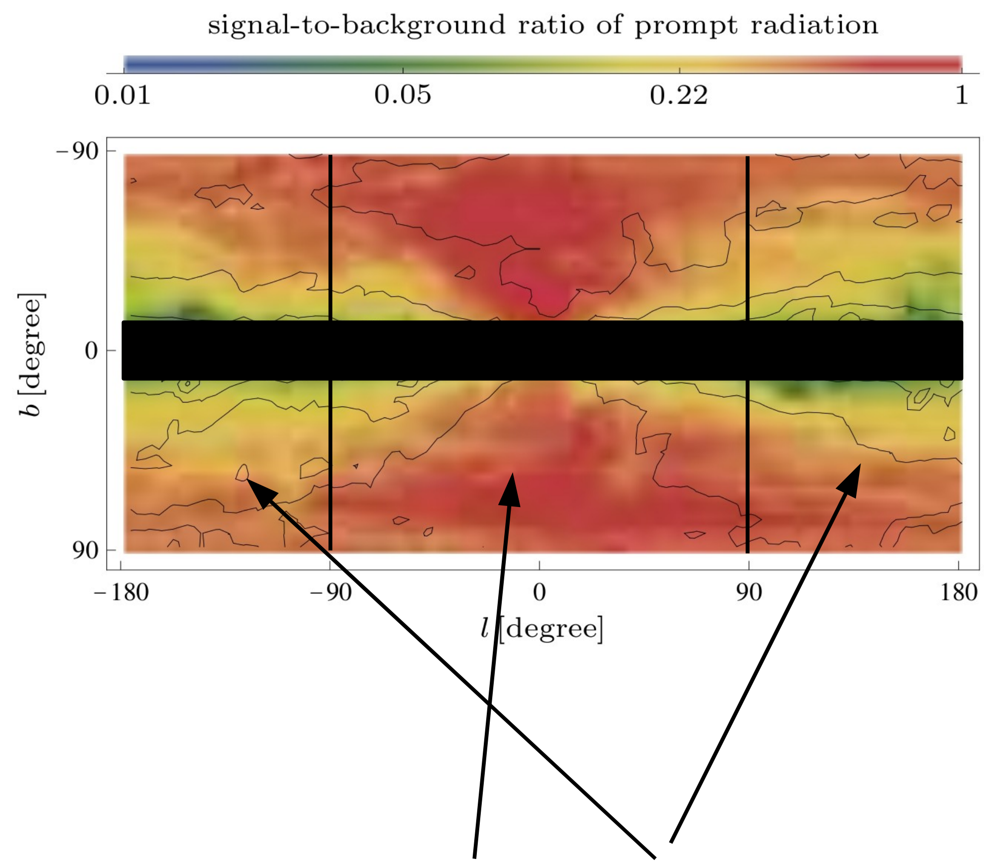
==> Decaying dark matter and extragalactic radiation can be in principle distinguished by their
anisotropy as function of the galactic longitude

The Anisotropy Parameter *A*:

- *A* is related to the **difference between the fluxes** from the hemisphere in direction of the galactic center (GC) and the hemisphere in direction of galactic anticenter (GAC)
- **Galactic disk region** is with

$$|b| \leq 10^\circ$$

is **excluded** to avoid too large contamination by galactic foreground



$$A = \frac{J_{\mathrm{GC}} - J_{\mathrm{GAC}}}{J_{\mathrm{GC}} + J_{\mathrm{GAC}}}$$

Typical Anisotropy Parameter Values

- **Extragalactic Gamma-Ray Background**: $A = 0$

- The **Galactic Foreground** (conventional GALPROP model tuned to local CR fluxes), also compatible with EGRET data up to 10 GeV: $A \lesssim 0.1$

- **Dark Matter, prompt** radiation: (depends mildly on dark matter profile) $A \simeq 0.20 - 0.36$

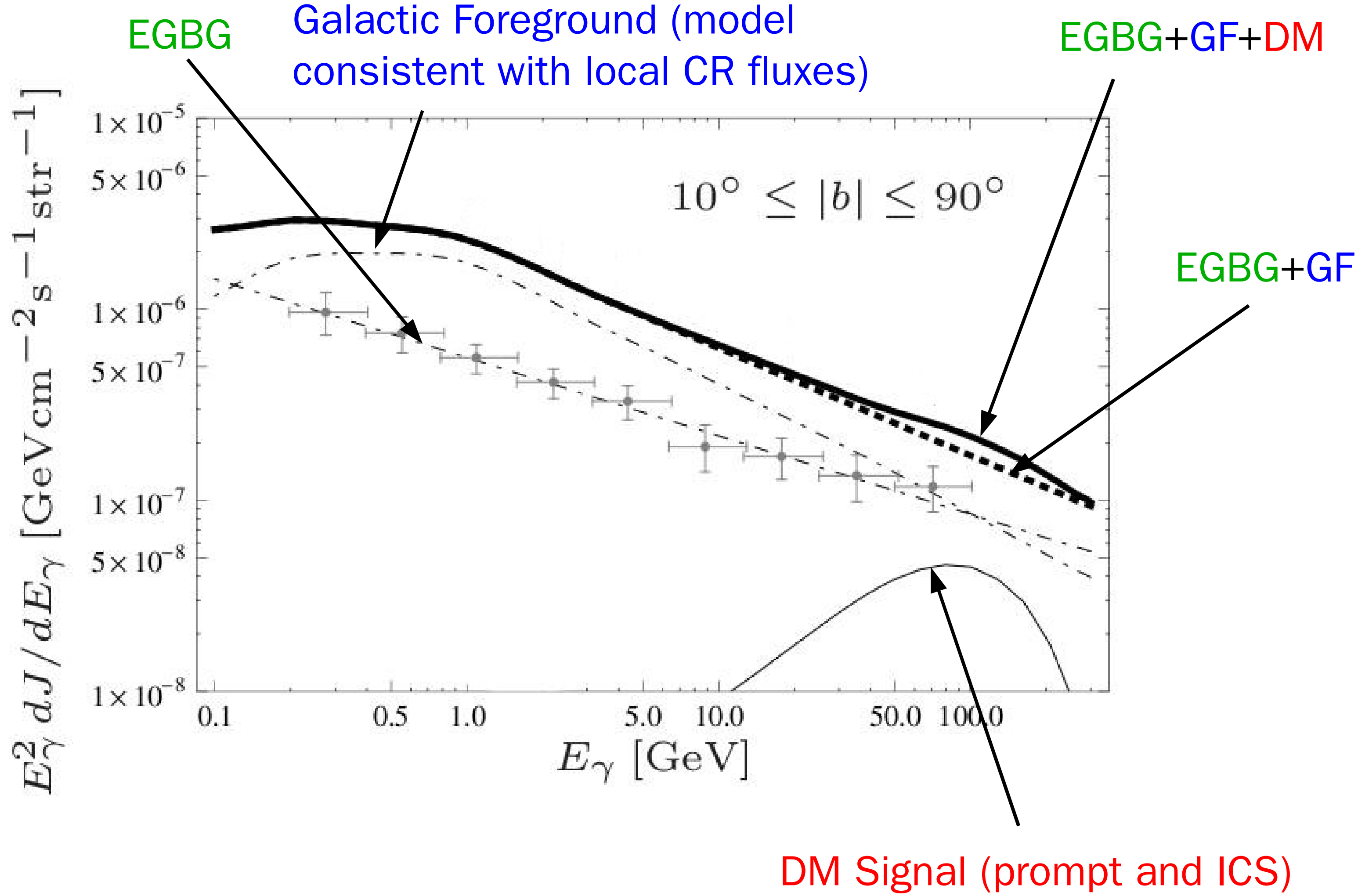
  lower (0.20), higher (0.36) gamma-ray energies

- **Dark Matter, ICS** radiation: $A \simeq \mathcal{O}(0.5)$

Example: Decay into $\tau^+\tau^-$ pairs

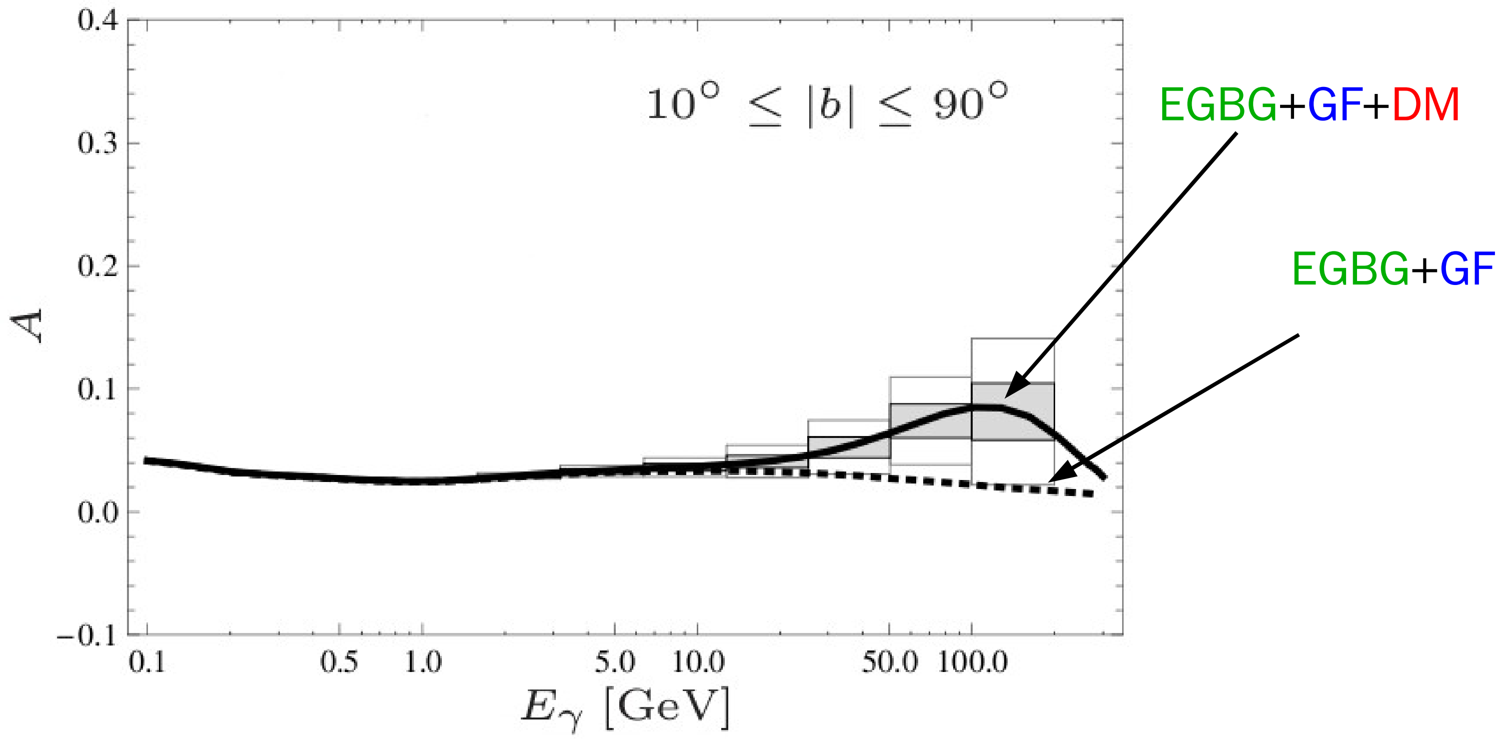
$$M_{\mathrm{DM}} = 600\,\mathrm{GeV} \quad \tau_{\mathrm{DM}} = 3.5 \times 10^{27}\,\mathrm{s}$$

All-sky averaged diffuse gamma-ray flux (excluding galactic disk)



Example: Decay into tau/antitau pairs

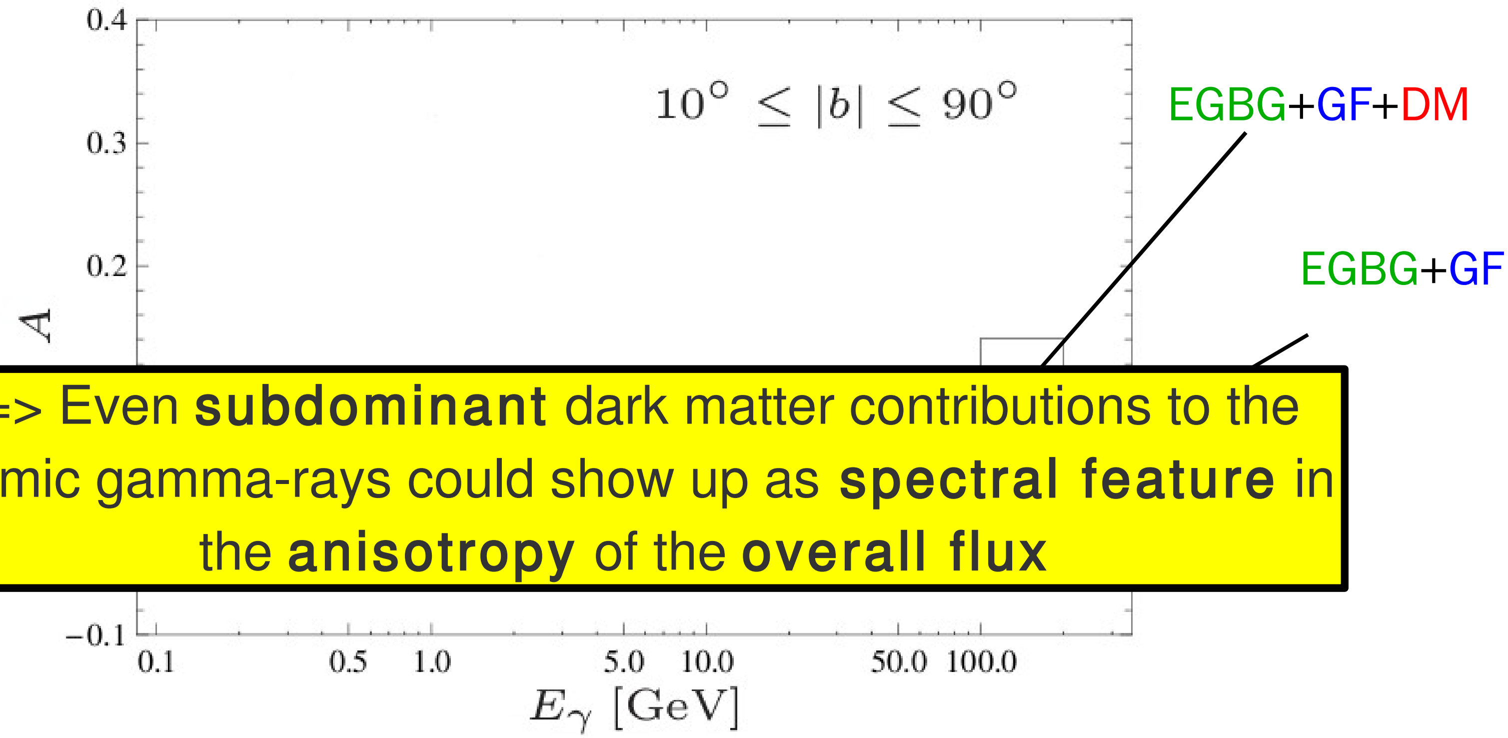
Anisotropy of overall flux (with and without dark matter signal)



- The anisotropy of the background is always much smaller than 0.1 and does not exhibit strong spectral features
- Error bars show the predicted one- and five-year *statistical* error of Fermi LAT

Example: Decay into tau/antitau pairs

Anisotropy of overall flux (with and without dark matter signal)

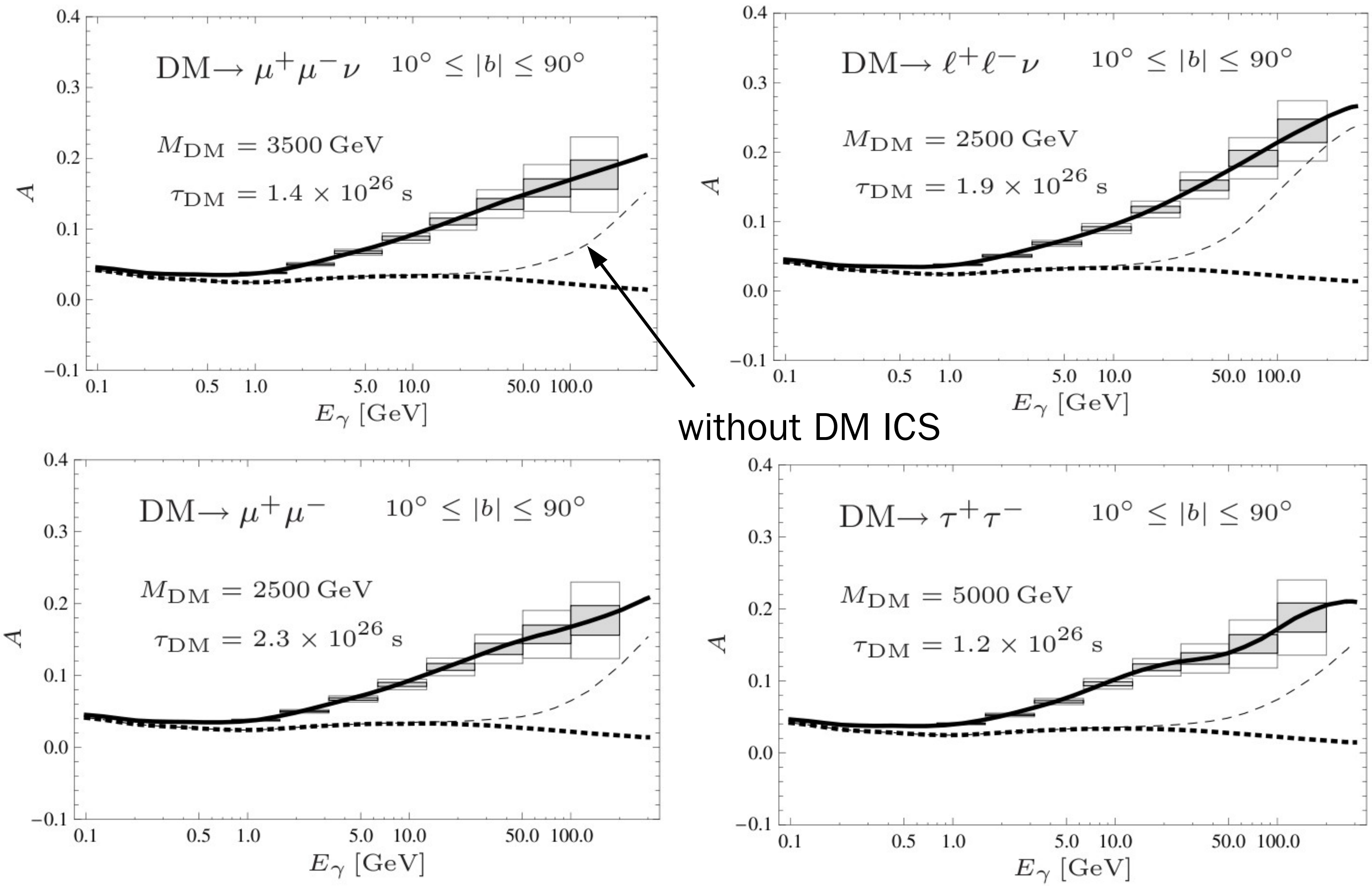


==> Even **subdominant** dark matter contributions to the cosmic gamma-rays could show up as **spectral feature** in the **anisotropy** of the **overall flux**

- The anisotropy of the background is always much smaller than 0.1 and does not exhibit strong spectral features
- Error bars show the predicted one- and five-year *statistical* error of Fermi LAT

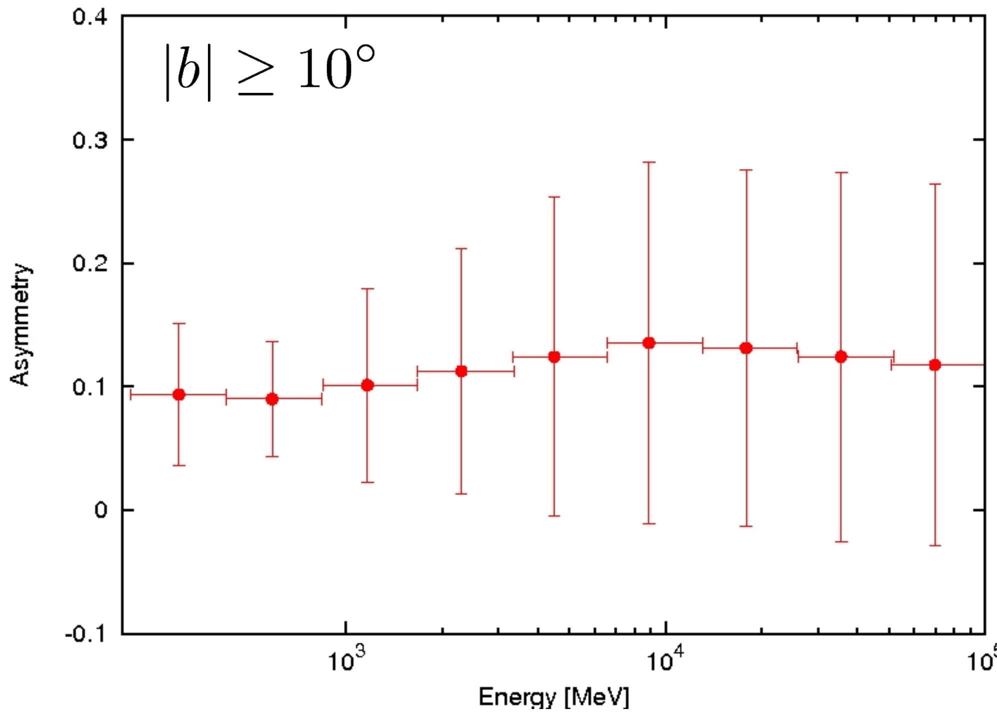
PAMELA/Fermi positron excess

Our predictions for the some decay channels that are motivated by the dark matter interpretation of the PAMELA/Fermi positron excess



Measured Anisotropy

Anisotropy as derived from published data points for GC and GAC hemisphere fluxes up to 100 GeV

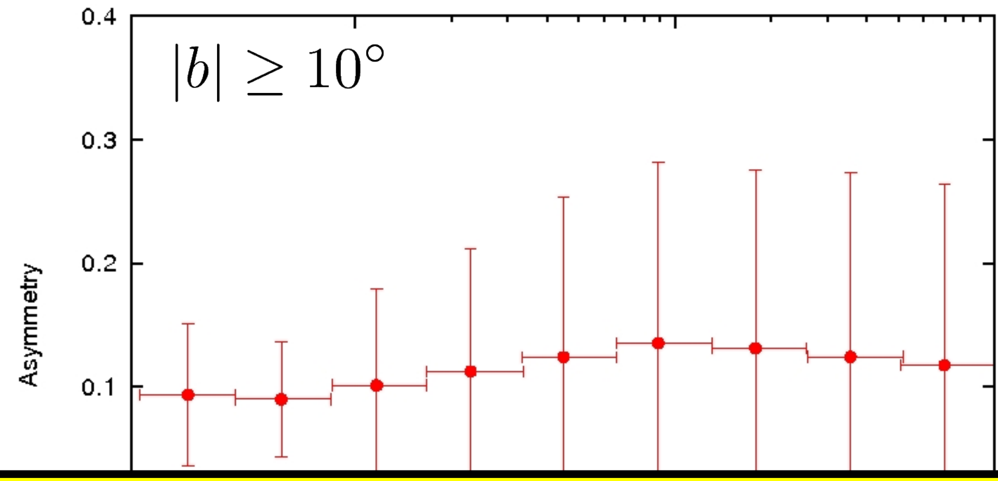


[from Fig. 7 in Abdo *et al.* (2010)]

- Error-bars are very large, but systematic errors are very likely overestimated in our calculation
- **Anisotropy around 10%** (larger than expected) with weak energy dependence
- Note: also the observed diffuse fluxes are larger than expected
- Modeled by Fermi LAT collaboration by increasing ICS radiation from astrophysical electrons normalized to local fluxes by 50% ad-hoc
  <–> "Fermi Haze" (?)

Measured Anisotropy

Anisotropy as derived from published data points for GC and GAC hemisphere fluxes up to 100 GeV



[from Fig. 7 in Abdo *et al.* (2010)]

Observations of overall flux inconclusive.

Using the dipole-anisotropy to constrain DM models requires better understanding of Galactic foreground.

our calculation

- **Anisotropy around 10%** (larger than expected) with weak energy dependence
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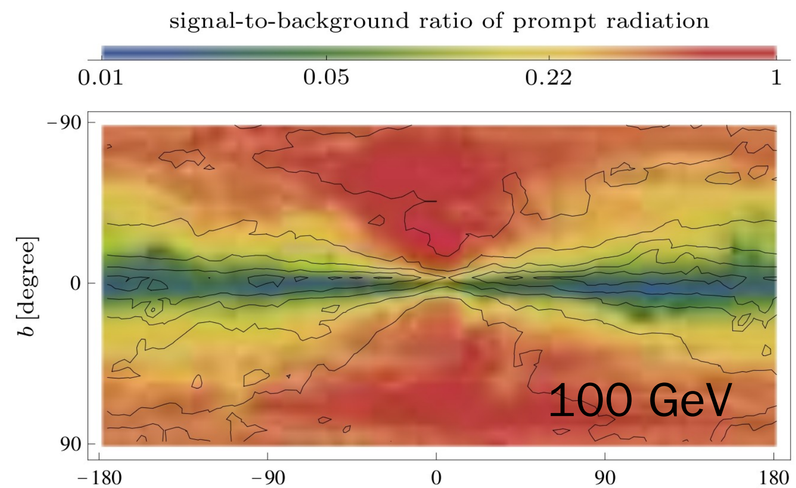

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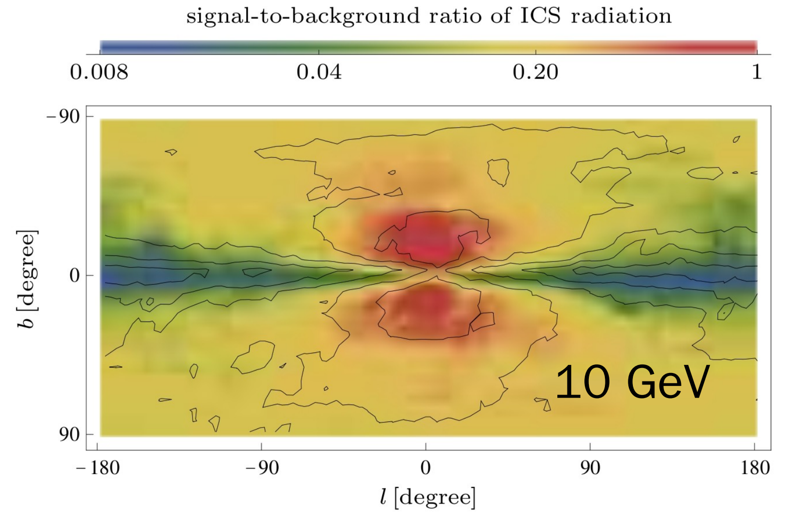


Deriving bounds from the Gamma-Ray Data

1) Bounds from the Fermi LAT gamma-ray **Skymaps** (as derived from public event lists):

- **Pro**: Allows looking for **optimal point in the sky**
- **Pro**: Public data goes up to **300 GeV**
- **Con**: Public **data** comes without point source subtraction, but **large CR contamination** at energies above ~ O(50) GeV (concerning only diffuse fluxes)

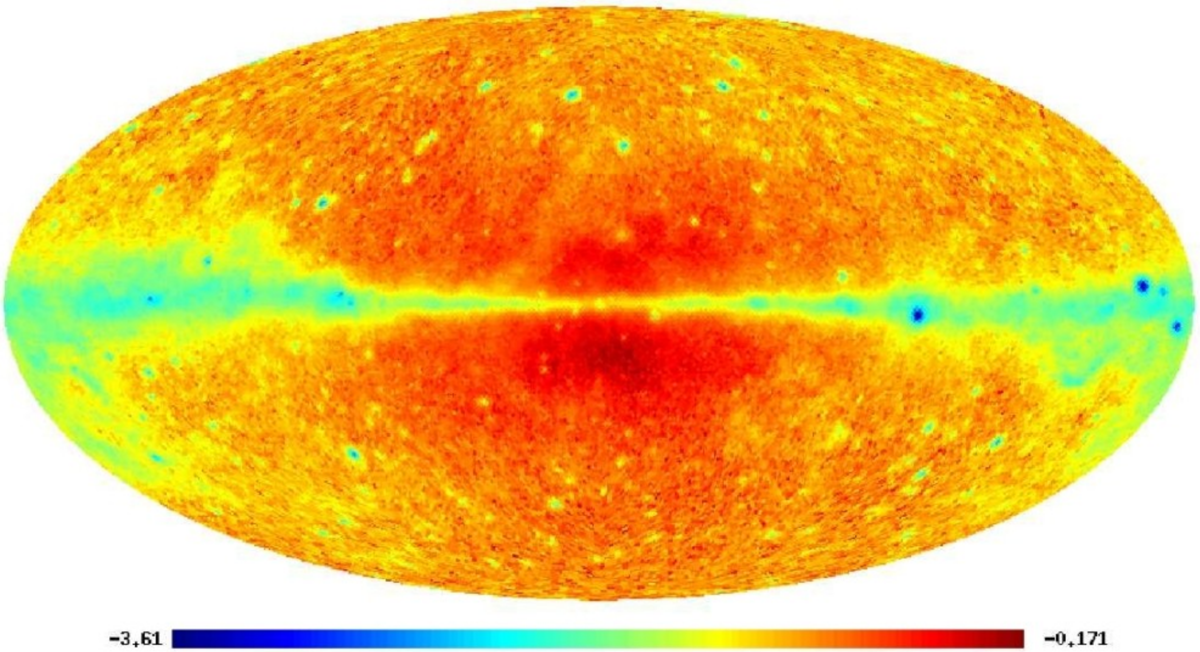
2) Bounds from published Fermi LAT results for **Extragalactic Gamma-Ray Background**

- **Pro**: Is based on data with **better background rejection** (not public up to now)
- **Pro/Con (?)**: Is based on **foreground subtraction**, which induces systematics
- **Con**: goes only up to **100 GeV**
- **Con**: just **isotropic flux**, no "optimal patch" possible

1) Bounds from Skymaps

DDM ICS Signal / Fermi Data @ 0.5 - 1 GeV

$M_{\rm DM} = 200\,{\rm GeV} \quad \phi_{\rm dm} \to e^+ e^-$



Input:

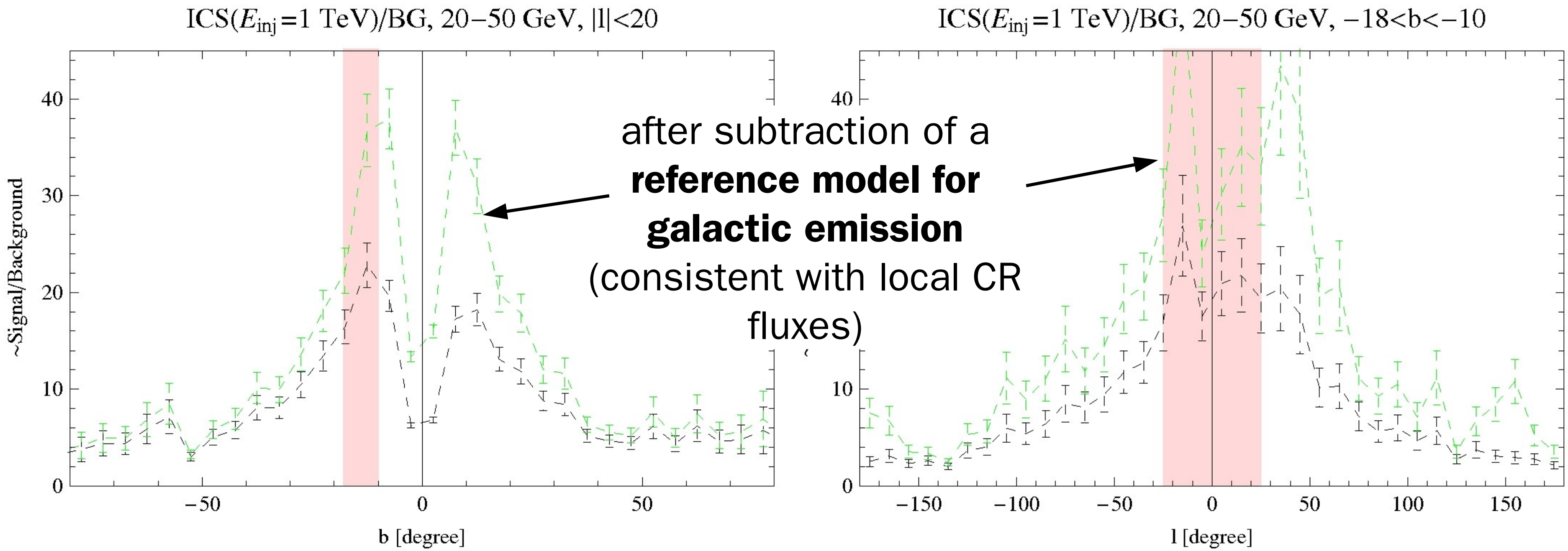
- ISRF from GalProp (2005)
- Diffusion-Reacceleration model with L=4kpc
- Extragalactic ICS from scattering with CMB included

- ==> Highest Signal-to-Background close to and south of the galactic center, as long as Galactic ICS dominates extragalactic

S/B as function of Galactic Coordinates

DDM ICS / Fermi Data @ 20 - 50 GeV

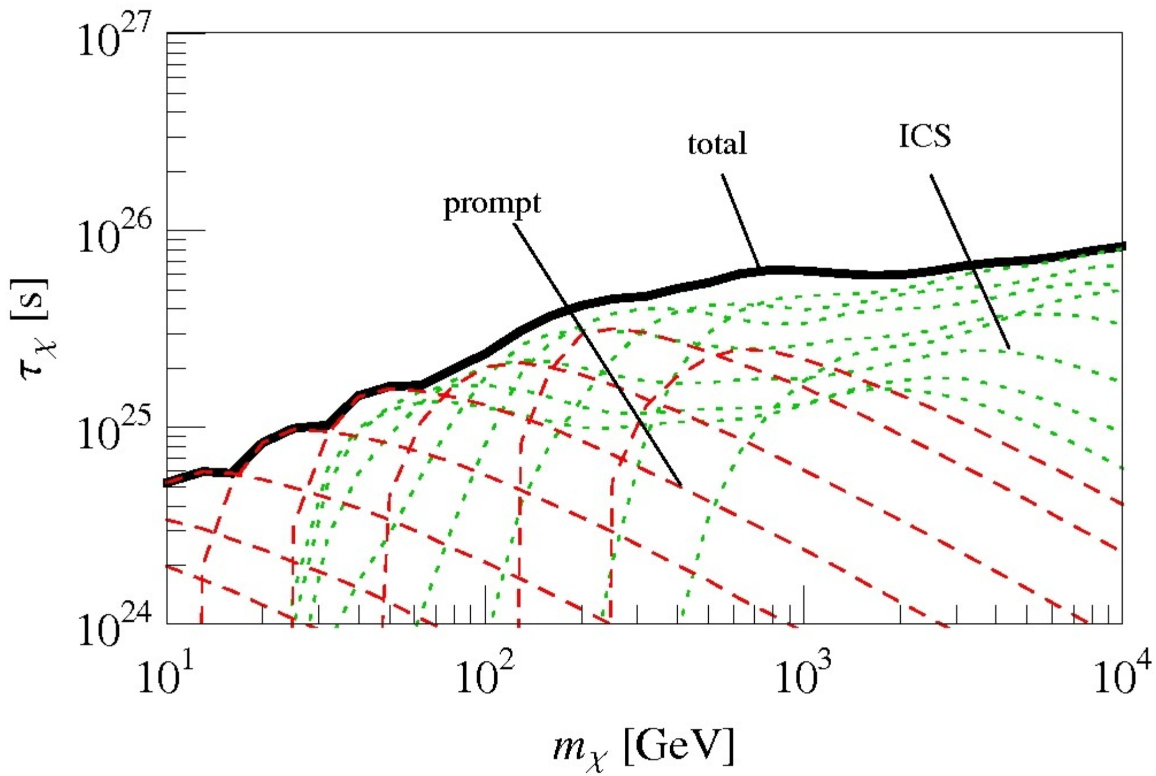
$$M_{\rm DM} = 1\,{\rm TeV} \qquad \phi_{\rm dm} \to e^+ e^-$$



- At higher gamma-ray energies, ICS mainly produced close to the galactic center --> best region is south of the galactic center with **-18°<b<-10° and -20°<l<20°**
- We don't use a global adaptive method to **avoid statistical bias effects**

Constraints on decay into muon pairs

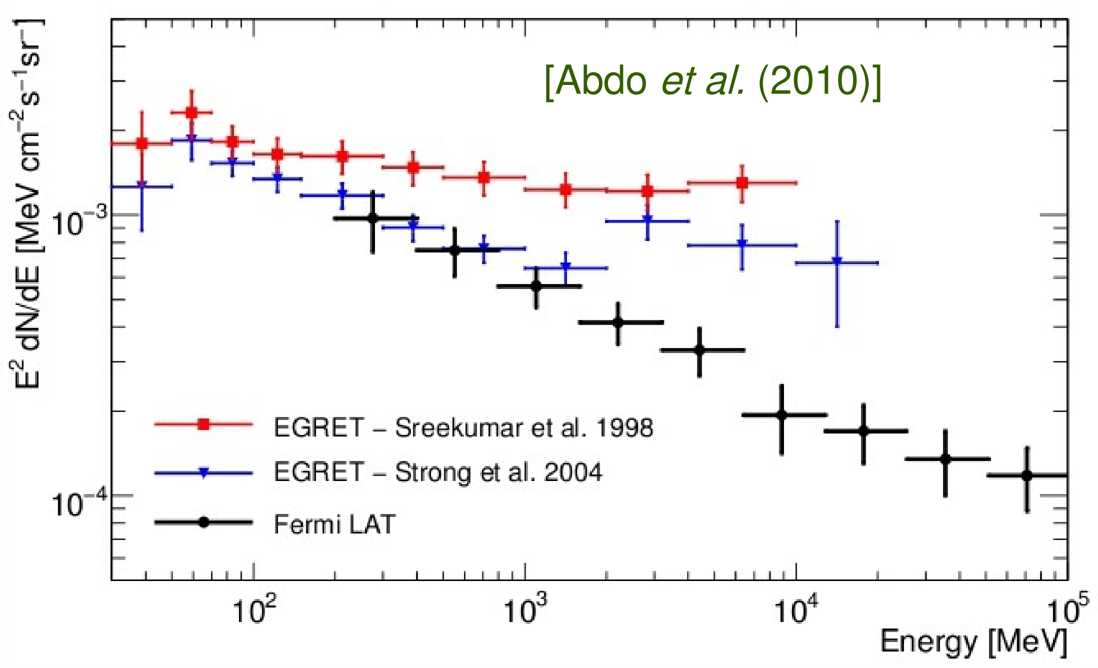
$$\phi_{\rm dm} \to \mu^+\mu^-$$



- Constraints from ICS radiation dominate for high DM masses, prompt bounds dominate at lower DM masses
- Gamma-ray energy bands: 0.5-1, 1-2, 2-5, 5-10, 10-20, 20-50, 50-100, 100-300 GeV [Dobler *et al.* (2009)]
- Uncertainties: DM Profile +30%/-10%, Magnetic fields ~15%, Diffusion Zone height ~O(1), if L considerably smaller than 4 kpc

2) Bounds from EGBG

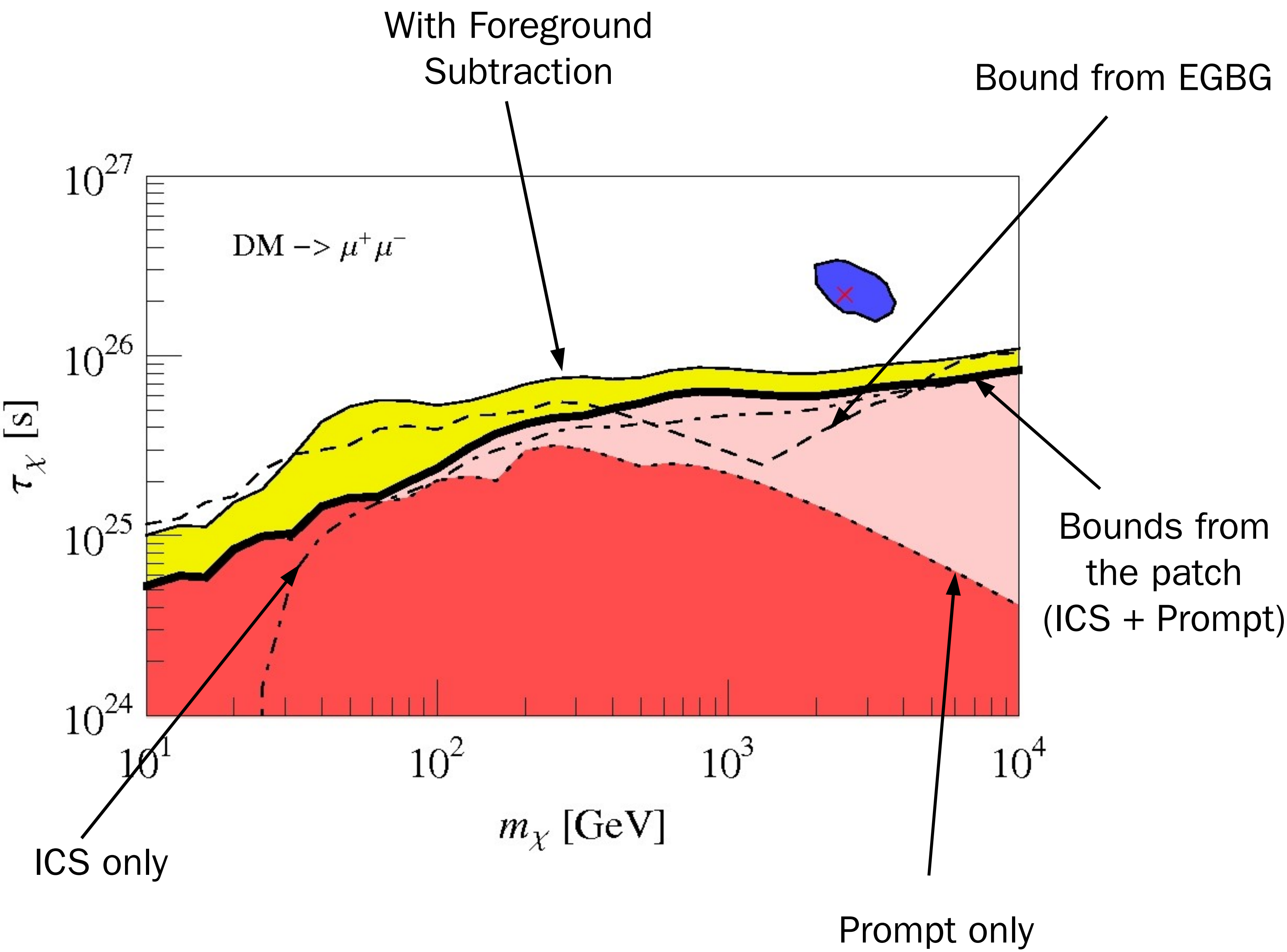
Fermi LAT analysis reveals power law without the “EGRET excess”



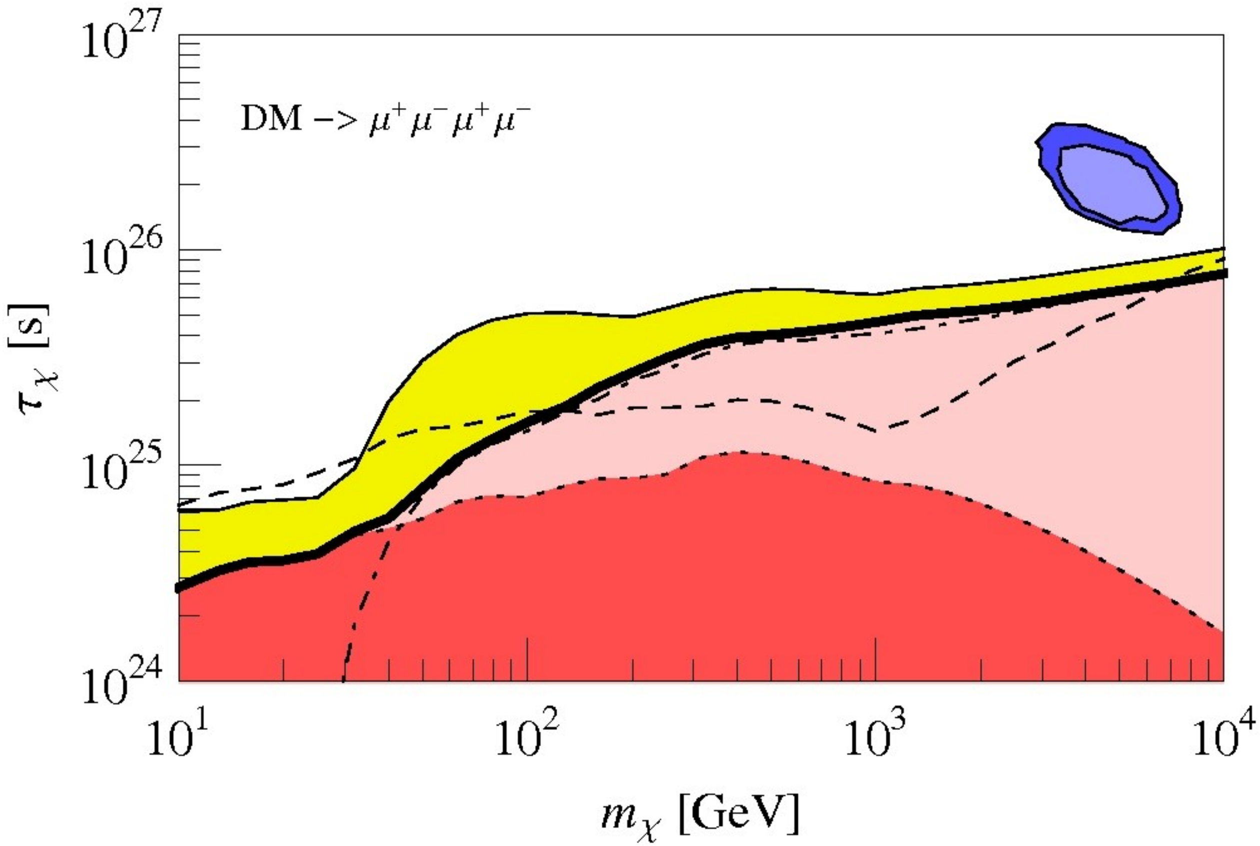
Can be compared with **isotropic part of decaying dark matter prediction**

= **Extragalactic ICS** radiation from electrons/positrons with dark matter origin scattering on CMB
+ **Extragalactic prompt** radiation from dark matter decay
+ Isotropic component of **Galactic prompt** radiation (identical with flux from Galactic anti-center)

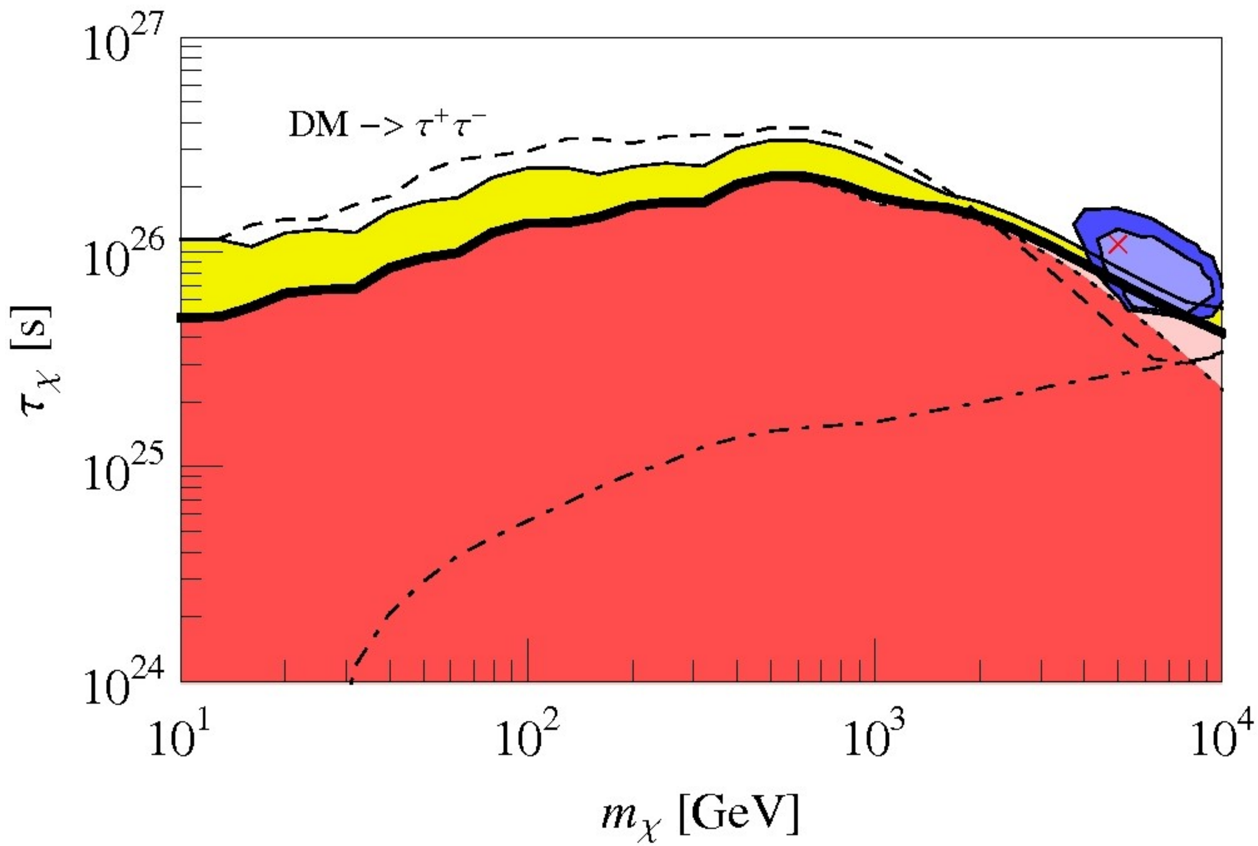
Our Results: DM -> mu+ mu-



DM -> a a -> mu+ mu- m+ mu-



DM -> tau+ tau-



DM −> $\tau^+\tau^-$
10^{27}
10^{26}
10^{25}
10^{24}
τ_χ [s]
10^1
10^2
10^3
10^4
m_χ [GeV]

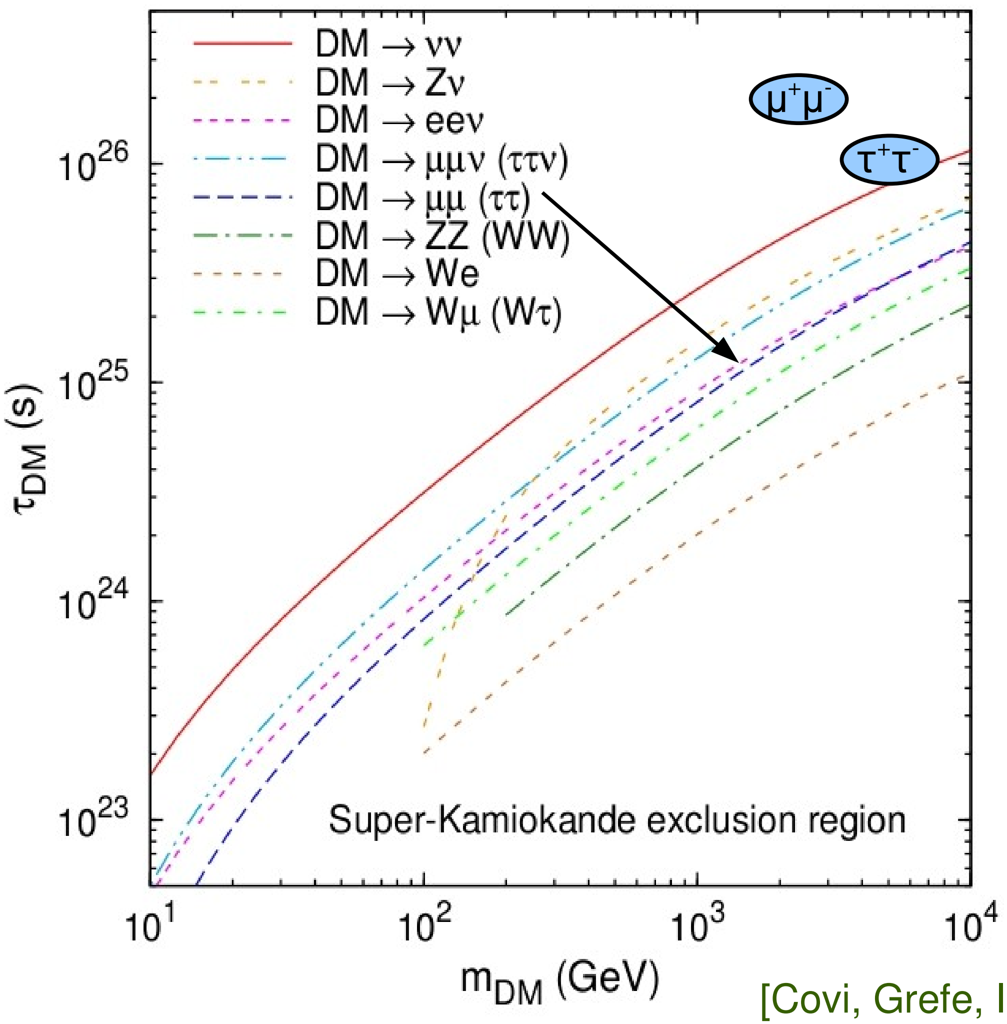
Results

Non of the three reference channels is excluded in our analysis of the present Fermi LAT gamma-ray data.

What could improve the bounds?

- Better Fermi LAT gamma-ray skymaps (**new event class**)
  (also fits to the gamma-ray maps are possible)
- Future **Neutrino Observations** with IceCube/DeepCore
- Looking for loop-induced **gamma-ray lines**...

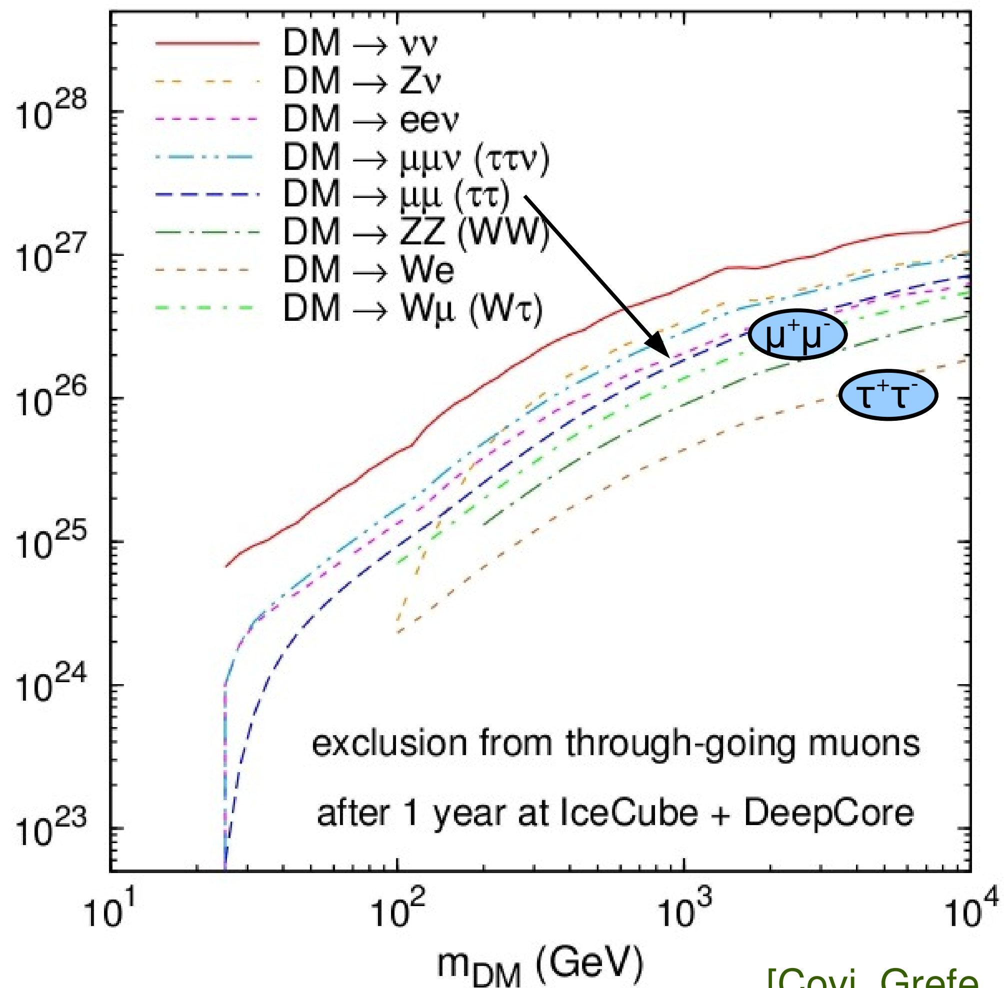
Bounds from Super-Kamiokande



[Covi, Grefe, Ibarra, Tran (2009)]

- Decay into muons and taus also produces large number of neutrinos
- Current Super-K observations do not constrain the DDM interpretation

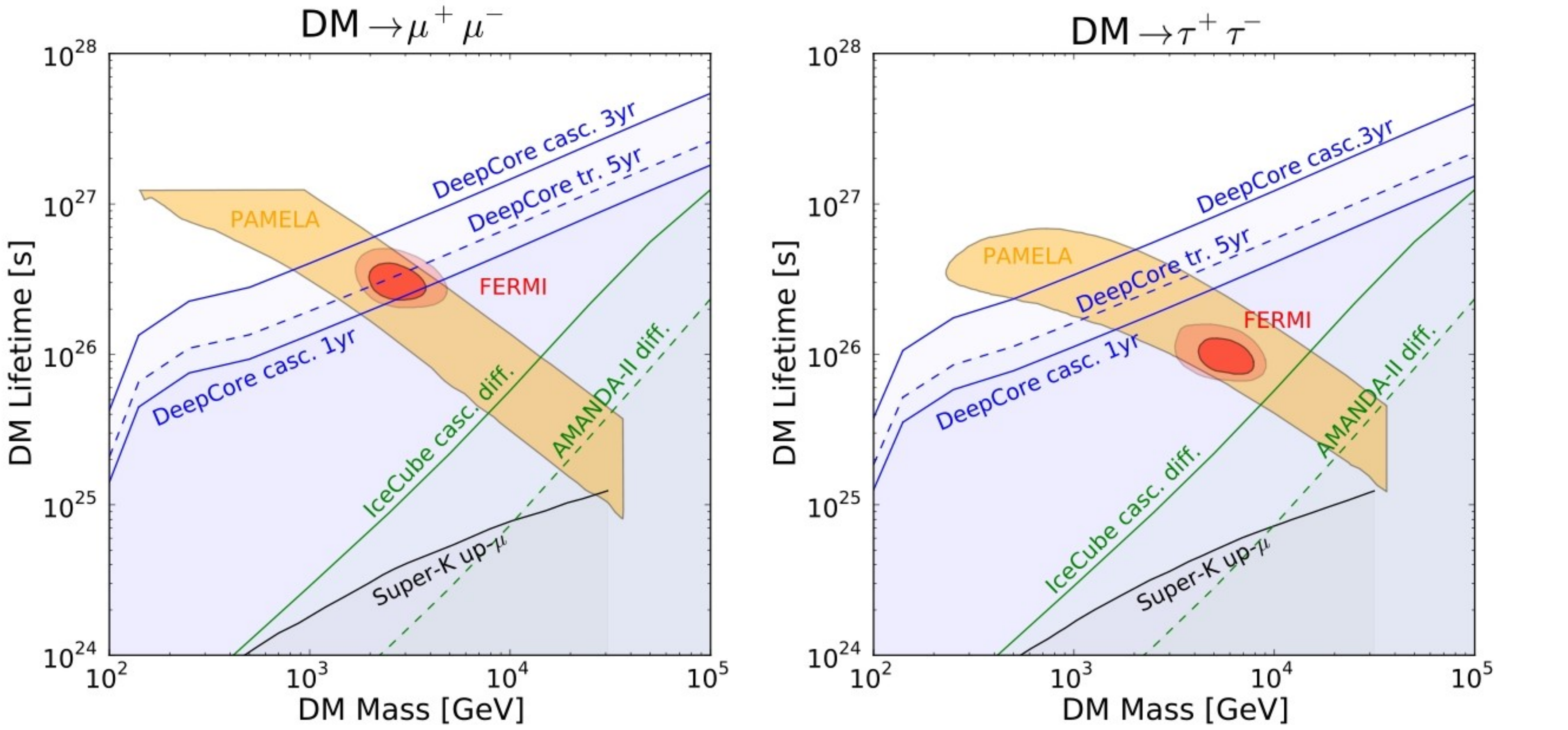
Prospects for IceCube+DeepCore



[Covi, Grefe, Ibarra, Tran (2009)]

- BUT: This will likely change with IceCube+DeepCore in the near future due to increased effective area and statistics

Prospects for IceCube+DeepCore



[Mandal, Buckley, Freese,
Spolyar, Murayama (2009)]

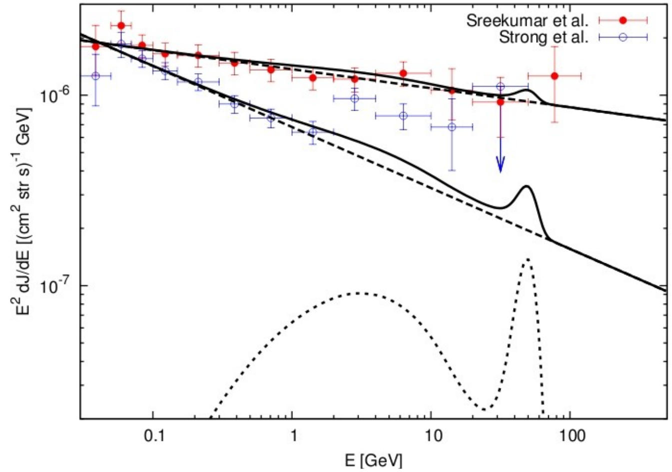
- Looking at cascade events can increase sensitivity due to better signal-to-background ratio with respect to track-like events

IV. Gamma-ray lines

Different DM models predict gamma-ray lines

R-parity violation & Gravitino

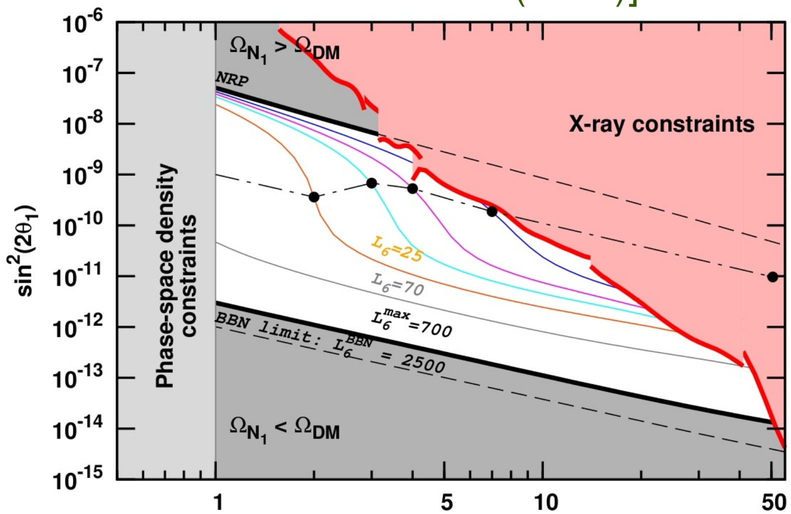
[Buchmüller *et al.* (2009)]



Sterile Neutrinos

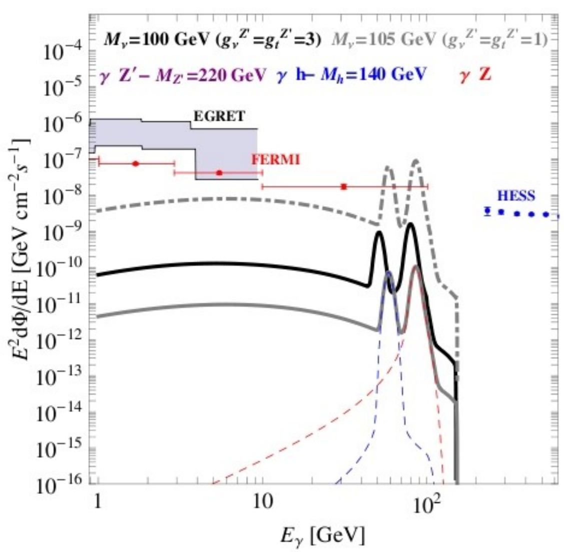
[Boyarsky *et al.* (2009),

Loewenstein & Kusenko (2009)]

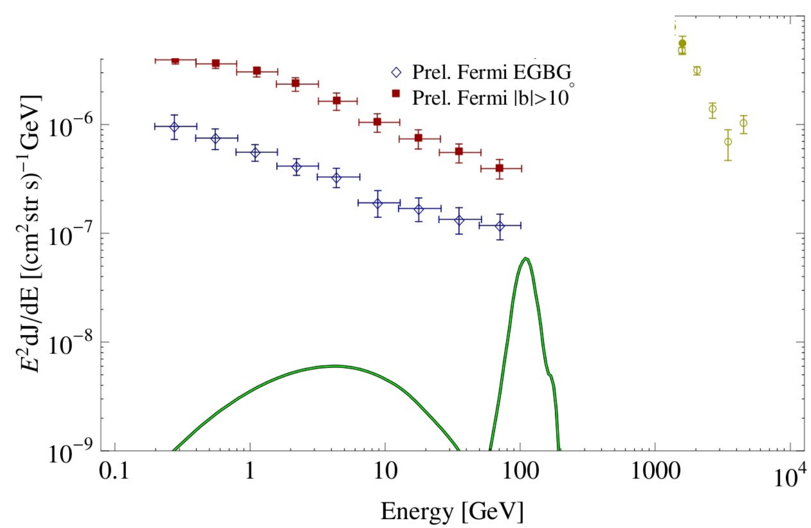


"Higgs in Space!"

[Jackson, Servant *et al.* (2009)]



–> Hidden SU(2) vector DM



Hidden Vector Dark Matter

Standard Model + hidden SU(2) gauge group with hidden higgs

$$\mathcal{L} = \mathcal{L}^{SM} - \frac{1}{4g_\phi^2} F^{\mu\nu} \cdot F_{\mu\nu} + (\mathcal{D}_\mu \phi)^\dagger (\mathcal{D}^\mu \phi) - \lambda_m \phi^\dagger \phi H^\dagger H - \mu_\phi^2 \phi^\dagger \phi - \lambda_\phi (\phi^\dagger \phi)^2$$

- The hidden SU(2) breaks down completely when $\mu_\phi^2 < 0$
- The resulting Lagrangian exhibits a **custodial SO(3) symmetry** in the component space $A_\mu^i \, , \quad i = 1, 2, 3$

  --> The **hidden vectors cannot decay**

- After EWSB, the hidden higgs η mixes with the SM higgs h

$$h' = \cos\beta \; h + \sin\beta \; \eta$$
$$\eta' = -\sin\beta \; h + \cos\beta \; \eta$$

Freeze-out & Relic Density

Correct relic density is generated by annihilation, e.g. via

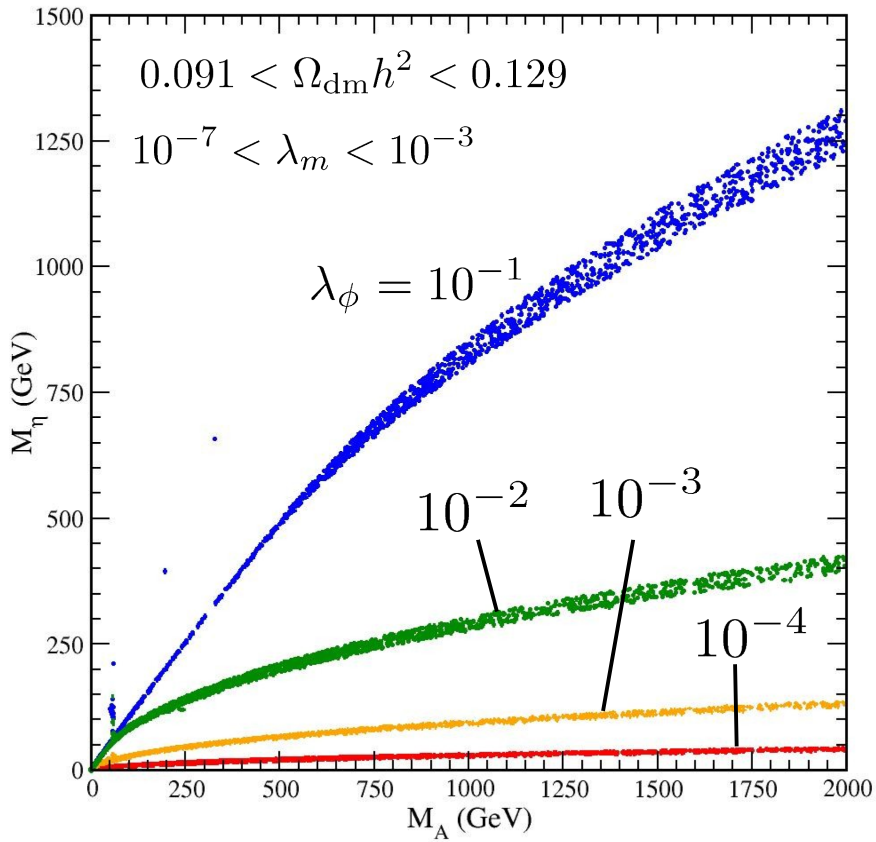
$$A_i A_i \to \eta\eta$$

no DM particle in final state

$$A_i A_j \to \eta A_k$$

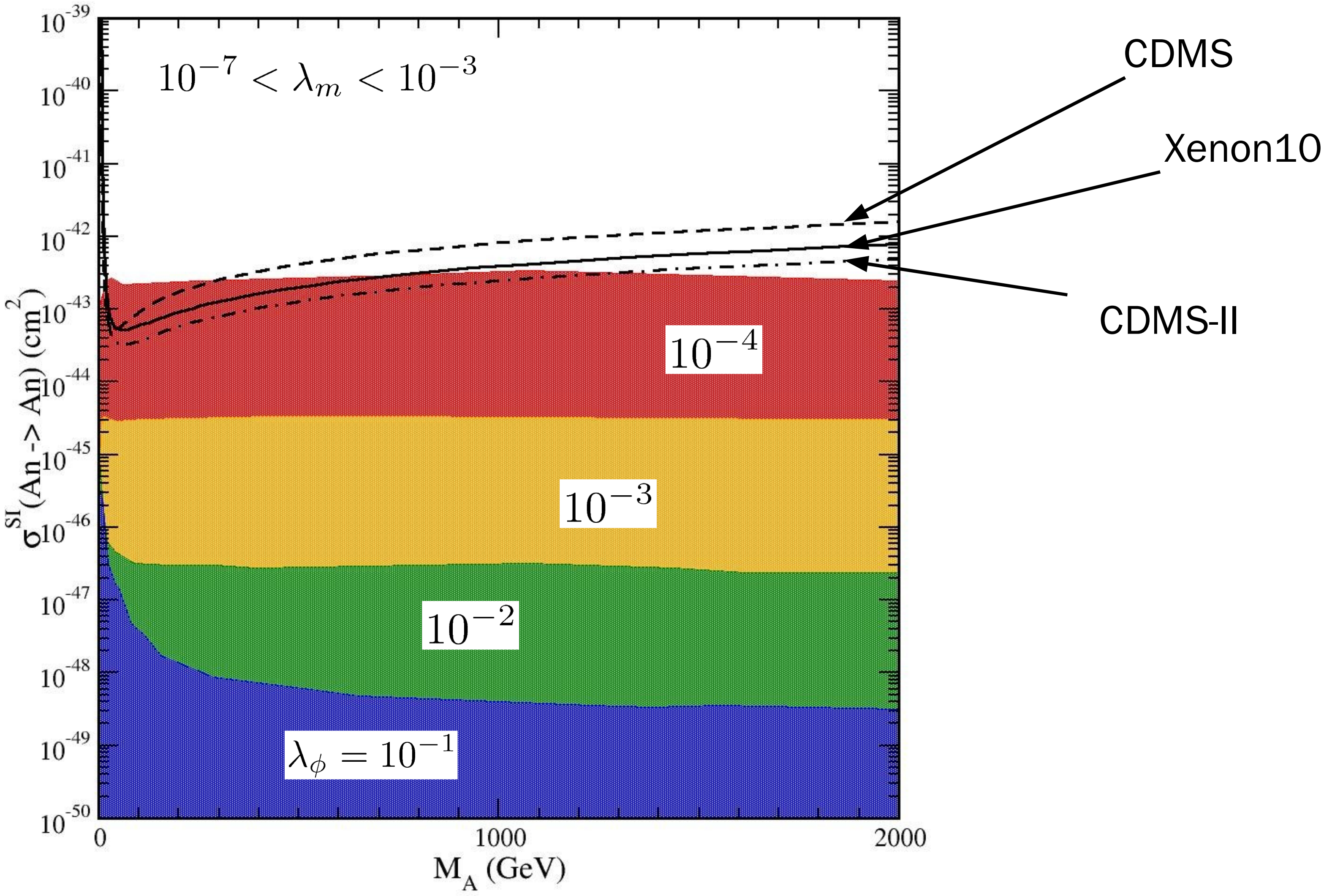
"**trilinear**" annihilation with one DM particle in the final state

Small Higgs portal:



Direct Detection Bounds / Prospects

Elastic scattering of vector dark matter is mediated by Higgs particles and spin-independent --> Allows for direct detection



Stability of Hidden Vector DM

SO(3) symmetry accidental

--> typically violated by higer dimensional operators

- Complete list of dim-5 and dim-6 operators that lead to decay of hidden vector bosons
  (no contribution from dim-5 operators!)

$$\frac{1}{\Lambda^2}\,\mathcal{D}^\mu\phi^\dagger\phi\;\mathcal{D}_\mu H^\dagger H \qquad A_i \to h\eta,\ hh,\ \gamma\eta,\ Z\eta,\ \gamma h,\ Zh$$

$$\frac{1}{\Lambda^2}\,\mathcal{D}_\mu\phi^\dagger\mathcal{D}_\nu\phi\;F^{\mu\nu Y} \qquad A_i \to \gamma\eta,\ Z\eta,\ \gamma h,\ Zh$$

$$\frac{1}{\Lambda^2}\,\phi^\dagger F^a_{\mu\nu}\frac{\tau^a}{2}\phi F^{\mu\nu Y} \qquad A_i \to Z\eta,\ Zh,\ \gamma\eta,\ W^+W^-,\ \nu\bar{\nu},\ e^+e^-,\ u\bar{u},\ d\bar{d}$$

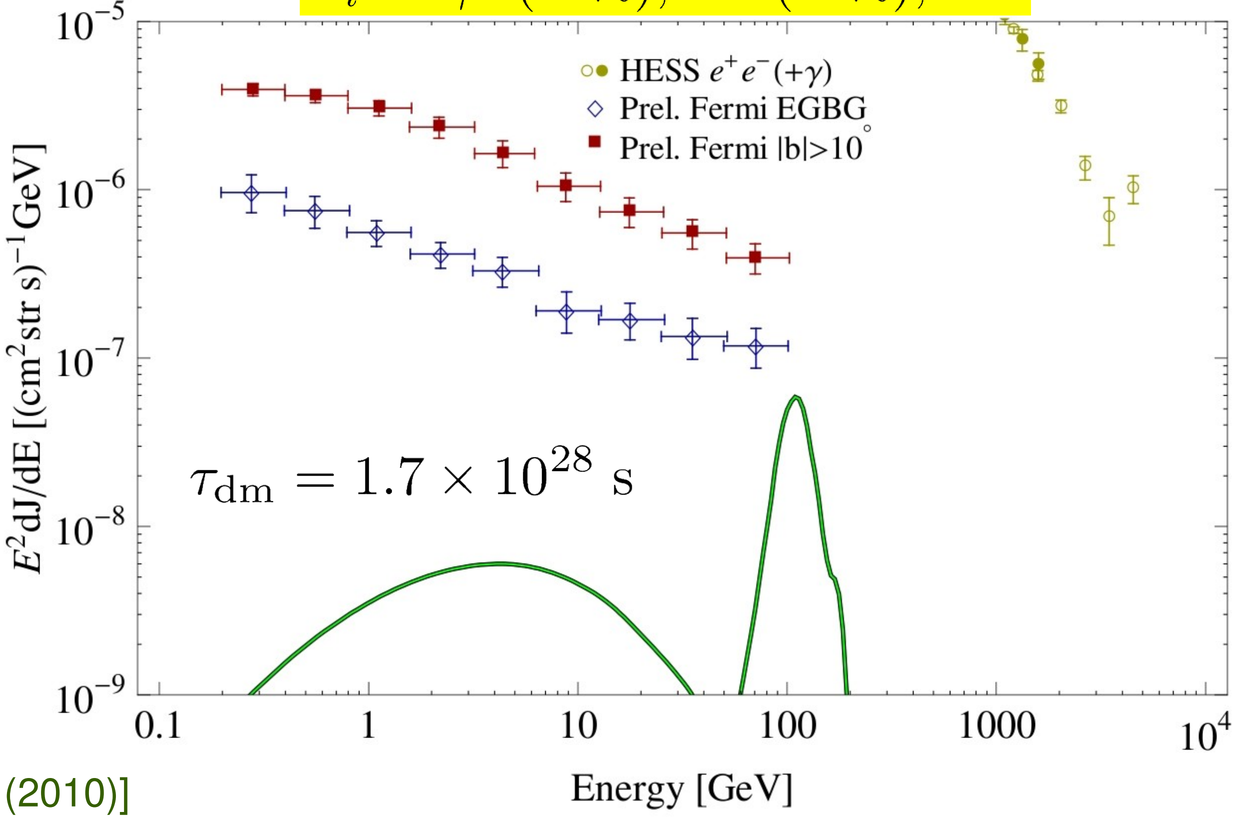
- Cosmic-ray observations can provide bounds on the energy scale of custodial symmetry breaking –> probes very high energies
- With luck, one could observe the produced fluxes in the CRs

Decay into lines

Decay due to $\frac{1}{\Lambda^2}\, \mathcal{D}^\mu \phi^\dagger \phi\, \mathcal{D}_\mu H^\dagger H$

$$M_A = 300\,\mathrm{GeV} \quad M_\eta = 30\,\mathrm{GeV} \quad M_h = 150\,\mathrm{GeV} \quad \sin\beta \simeq 0$$

$$A_i \to \gamma h\,(65\%),\ Zh\,(20\%),\ \ldots$$



[Abdo *et al.* (2010)]

- non-observation of gamma-ray line with Fermi LAT @100 GeV implies for the scale of custodial symmetry breaking:

$$\tau_{\rm dm} \gtrsim 10^{29}\ \mathrm{s}$$

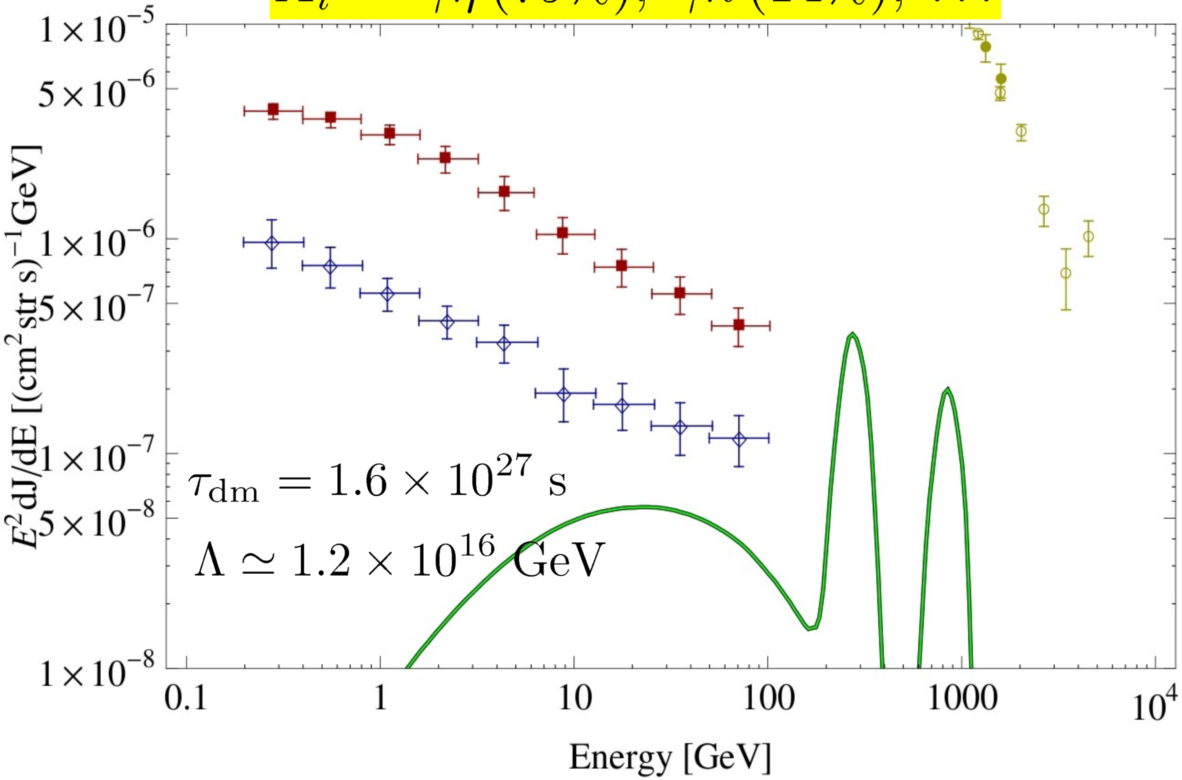
$$\Rightarrow \Lambda \gtrsim 6 \times 10^{15}\ \mathrm{GeV}$$

Two Lines

Decay due to $\frac{1}{\Lambda^2}\, \mathcal{D}_\mu \phi^\dagger \mathcal{D}_\nu \phi \; F^{\mu\nu Y}$

$$M_A = 1550\,\mathrm{GeV} \quad M_\eta = 1245\,\mathrm{GeV} \quad M_h = 153\,\mathrm{GeV} \quad \sin\beta \approx 0.25$$

$$A_i \to \gamma\eta\,(79\%),\ \gamma h\,(14\%),\ \ldots$$



- Fermi LAT limits go up to 200 GeV, above H.E.S.S. electron+gamma measurements translate into [Meyer, Zechlin, Horns (2009)]

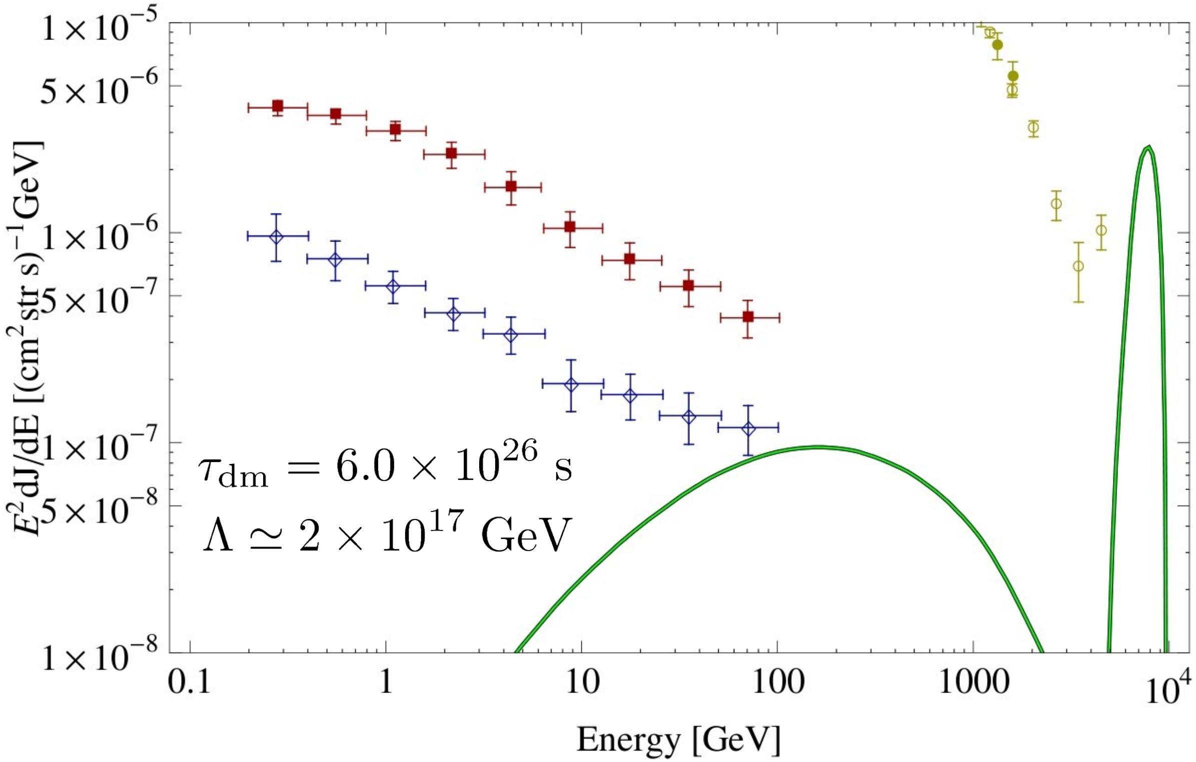
$$\tau_{\rm dm} \gtrsim \mathcal{O}(10^{27}\ \mathrm{s}) \qquad 400\ \mathrm{GeV} \lesssim E_\gamma \lesssim 4\ \mathrm{TeV}$$

Line at 7 TeV

Decay due to $\frac{1}{\Lambda^2} \mathcal{D}_\mu \phi^\dagger \mathcal{D}_\nu \phi \; F^{\mu\nu Y}$

$$M_A = 14\,\mathrm{TeV} \quad M_\eta = 500\,\mathrm{GeV} \quad M_h = 145\,\mathrm{GeV} \quad \sin\beta \simeq 0$$

$$A_i \to \gamma\eta\,(77\%),\; Z\eta\,(23\%)$$



- In extreme cases, the line could even be at TeV energies

Line at 7 TeV

Decay due to $\frac{1}{\Lambda^2}\, \mathcal{D}_\mu \phi^\dagger \mathcal{D}_\nu \phi \; F^{\mu\nu Y}$

$$M_A = 14\,\mathrm{TeV} \quad M_\eta = 500\,\mathrm{GeV} \quad M_h = 145\,\mathrm{GeV} \quad \sin\beta \simeq 0$$

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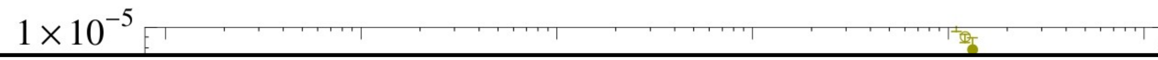
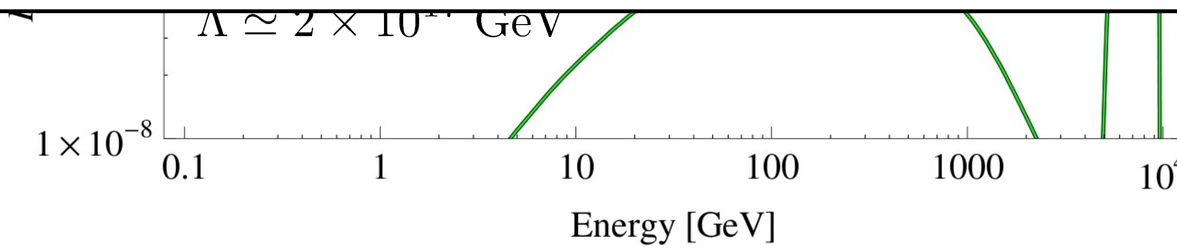


Prospects

- **H.E.S.S.** analysis on lines from decaying/annihilating dark matter
- Future Imaging Atmospheric Cherenkov Telescopes like **CTA** and **AGIS** (with energy ranges 50 GeV - 50 TeV) are planned to have ~100 times larger sensitivities to DM searches



- In extreme cases, the line could even be at TeV energies

V. Conclusions

Conclusions

- Decaying Dark Matter leads to peculiar cosmic-ray signatures that differ from annihilation signals
- The prompt radiation from decaying dark matter exhibits a dipole-like anisotropy which makes it distinguishable from the EGBG
- Leptonically decaying dark matter could be the explanation for the positron/electron fluxes observed by PAMELA, Fermi LAT & H.E.S.S.
- If this interpretation is true, a large anisotropy in the overall signal is predicted for *a-priori* foreground models
- Currently available data points to a larger overall anisotropy without spectral features, but error-bars are large --> Inconclusive
- ICS radiation doesn't constrain decaying dark matter interpretation at the moment, wait for neutrinos...
- Hidden SU(2) vector dark matter predicts in many cases intense GeV-TeV gamma-ray lines that could be observed in the future

-> THANK YOU <-