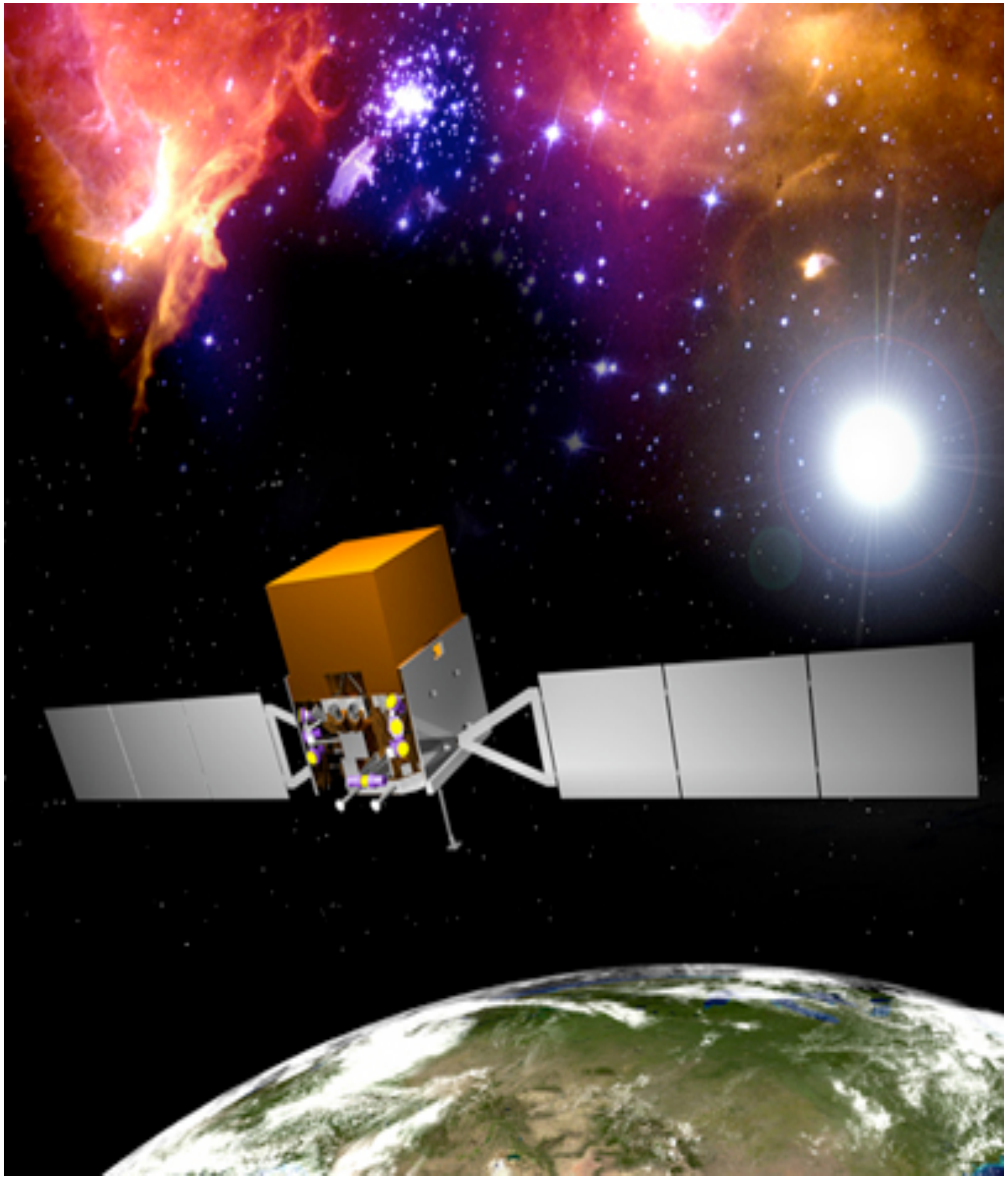


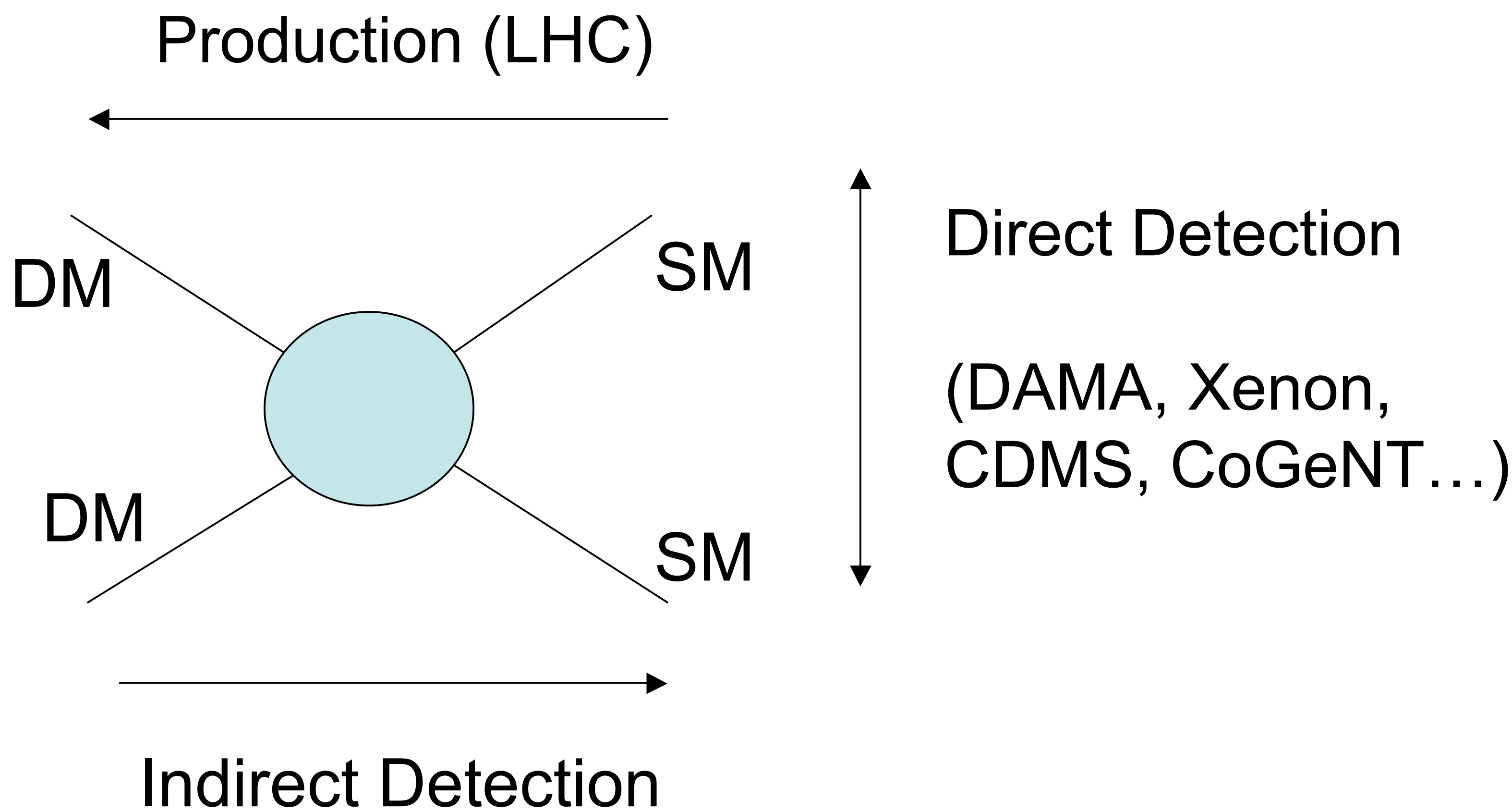
Interpreting Indirect Signatures of Dark Matter

Bibhushan Shakya
Cornell University

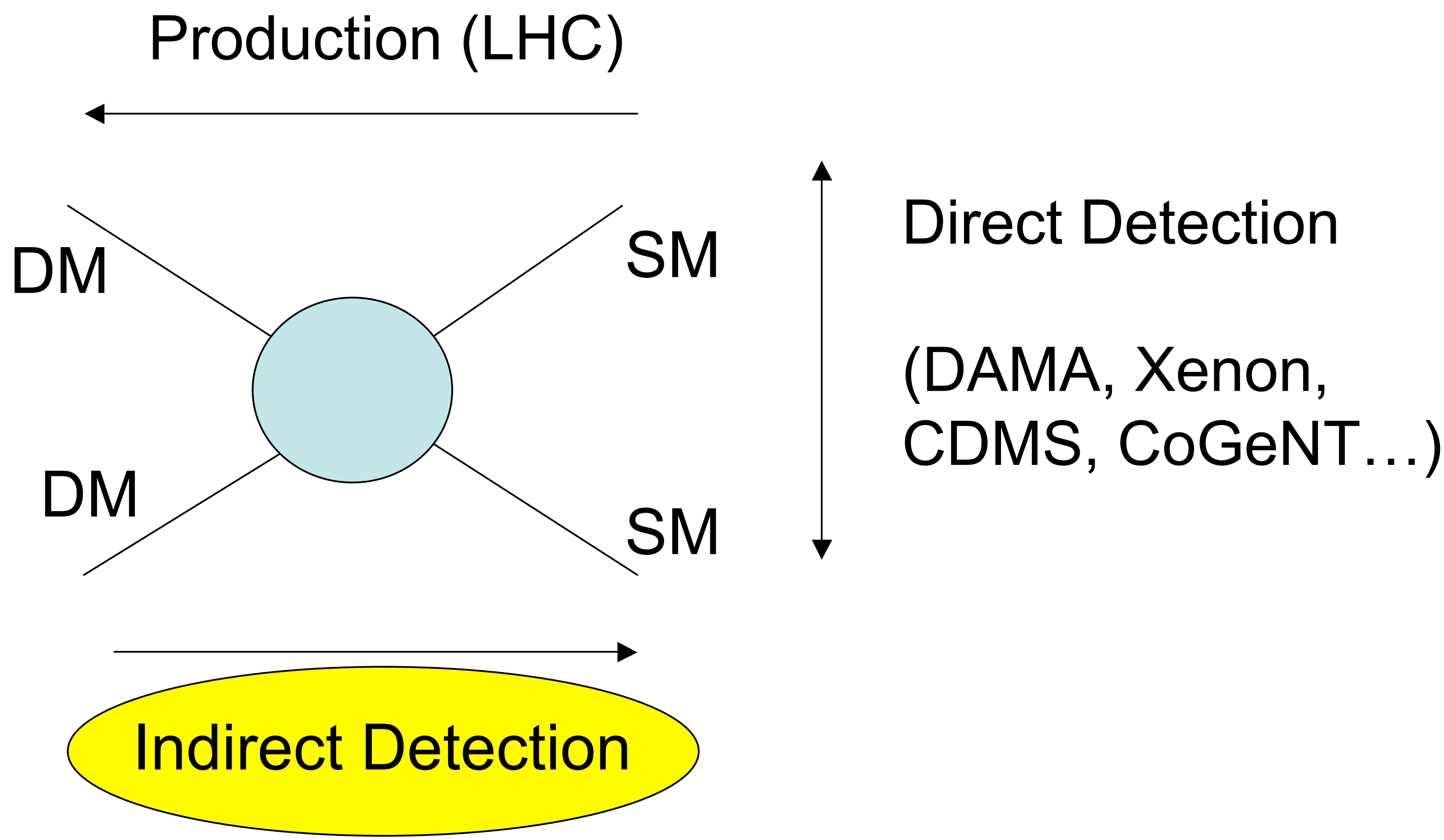
Cornell Particle Theory Seminar
February 25, 2011

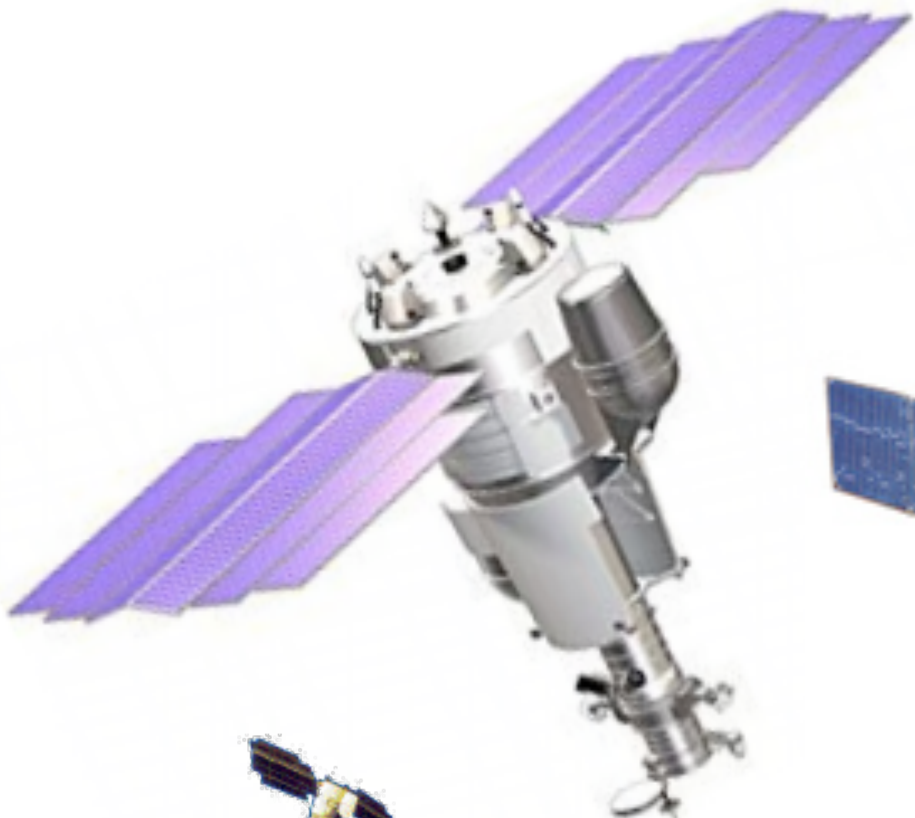
Based on arXiv:1002.4588, 1007.0018, 1012.3772 with Maxim Perelstein

Detecting Dark Matter



Detecting Dark Matter



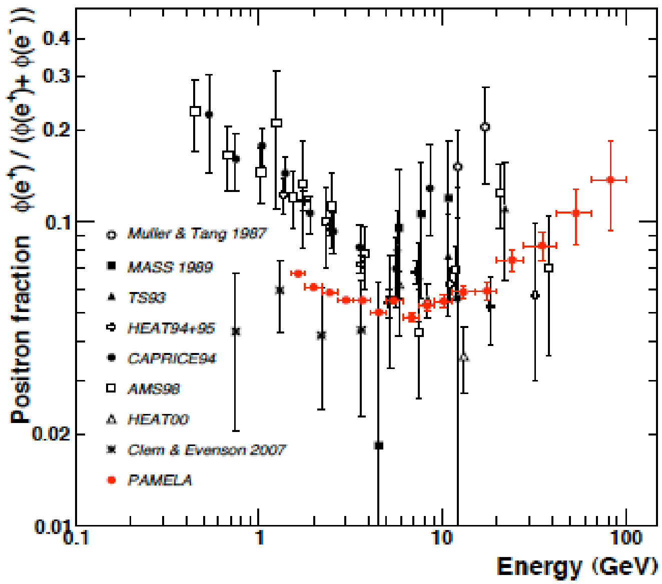


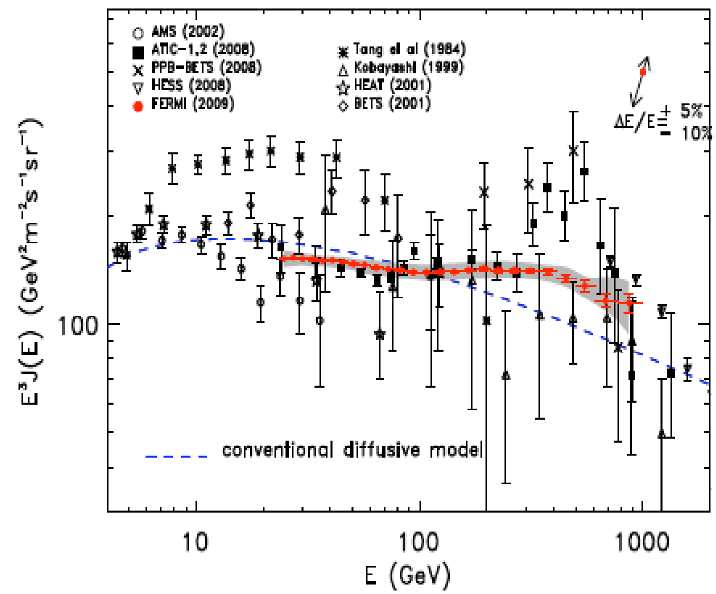
Fermi
Gamma-ray
Space Telescope

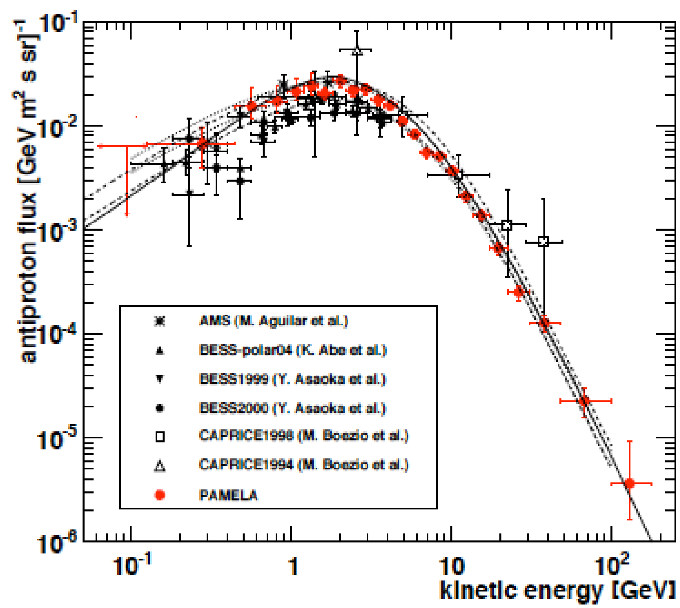
PaMeLa
a Payload for Antimatter Matter Exploration
and Light–nuclei Astrophysics

2008-09: data showed an excess of positrons at ~1-100GeV, inconsistent with conventional astrophysics

Indirect Evidence of Dark Matter?







Data:
excess in e+ fraction and e^+e^- flux, no excess in antiprotons

Fit well to leptophilic dark matter annihilation with boosted cross sections in the galaxy

Connecting Theory to Observation

Spectrum observed experimentally

Annihilation cross section predicted by theory

$$\frac{d\phi}{dE} = \int_{E_{min}}^{m_\chi} dE' (\text{astrophysical correction}) \times \frac{d\sigma}{dE'}$$

Connecting Theory to Observation

Spectrum observed experimentally

Annihilation cross section predicted by theory

$$\frac{d\phi}{dE} = \int_{E_{min}}^{m_\chi} dE' \boxed{(\text{astrophysical correction})} \times \frac{d\sigma}{dE'}$$

Spatial distribution of dark matter sources, propagation effects, interaction with interstellar matter….

Three ideas

1. If the positron excess is from dark matter, contribution from all dark matter sources in the galaxy must be properly included in the fits

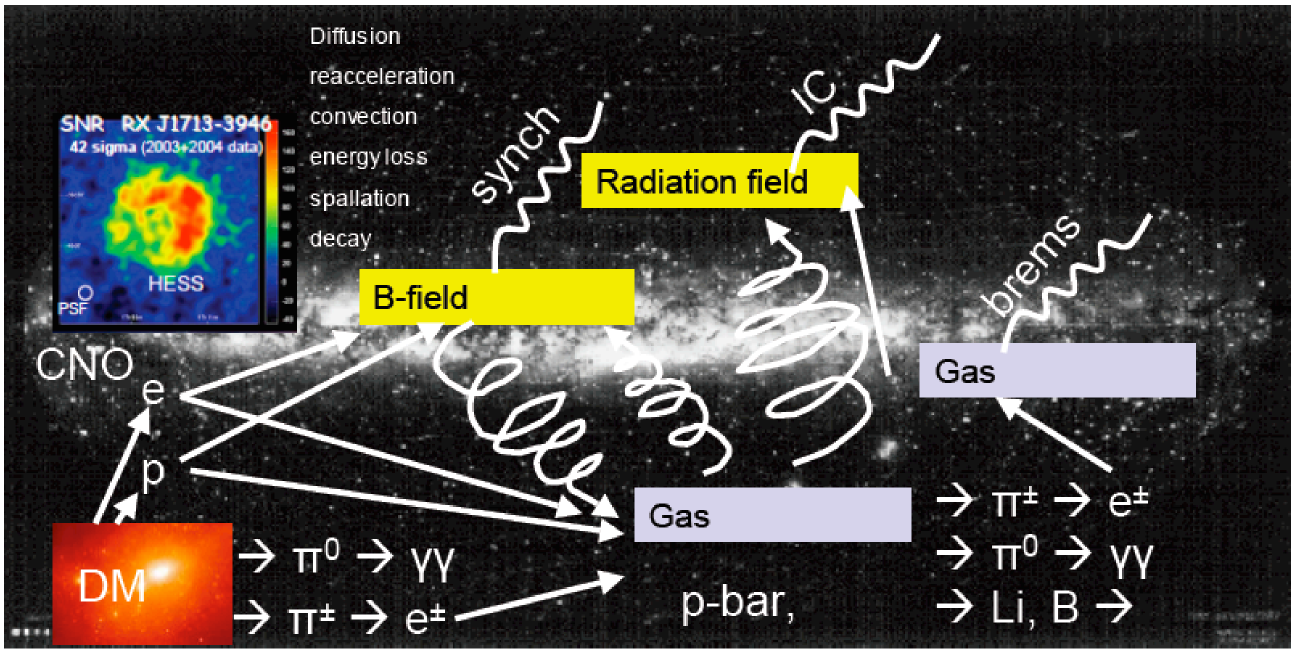
2. The lack of excess in antiprotons can be used to place constraints on dark matter parameters, but similar contributions need to be likewise included

3. If the excess is from dark matter, accompanying signals are expected in the form of energetic gamma rays


Part
I
e^+

(Nontrivial) Cosmic ray propagation in the galaxy

A mess! Electrons, positrons from dark matter annihilation interact with the galactic interstellar medium, losing energy and directional information.



From Jan Conrad's 08/07/09 talk at the SLAC Summer Institute

Galactic propagation significantly alters the spectrum

Solving for Positron Spectrum : the Conventional Formalism

- Analytically, by solving the steady-state diffusion equation:

Positron density per unit volume per unit energy

$$-\nabla\left[K(\mathbf{x},E)\,\nabla\psi\right]-\frac{\partial}{\partial E}\left[b(E)\psi\right]=q(\mathbf{x},E)$$

Source term

position independent

Diffusion coefficient

$$K(E)=K_0\epsilon^\delta$$

Energy loss rate

$$b(E)=\frac{E_0}{\tau_E}\,\epsilon^2$$

$$\epsilon=E/E_0,\ E_0=1\ \mathrm{GeV}$$

$$\tau_E=10^{16}\ \mathrm{sec}$$

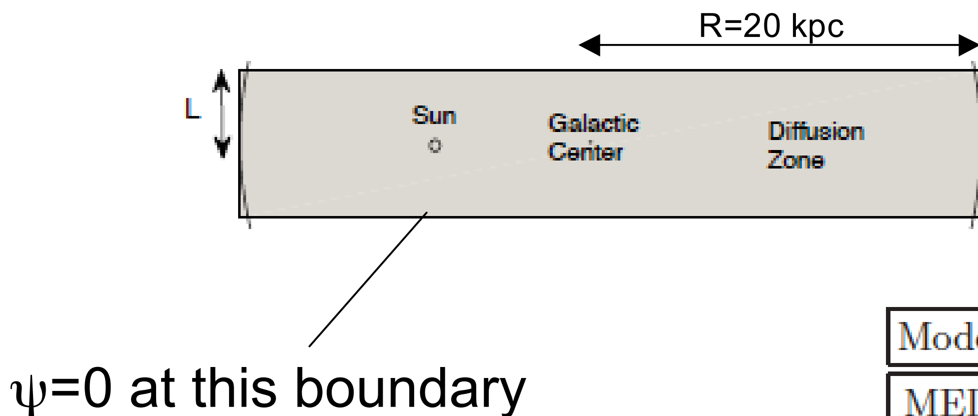
Parameters defining a propagation model:

K, δ, L (size of region in which transport equation solved)

Model	δ	K_0 [kpc^2/Myr]	L [kpc]
MED	0.70	0.0112	4
M1	0.46	0.0765	15
M2	0.55	0.00595	1

- Numerically, eg. with GALPROP

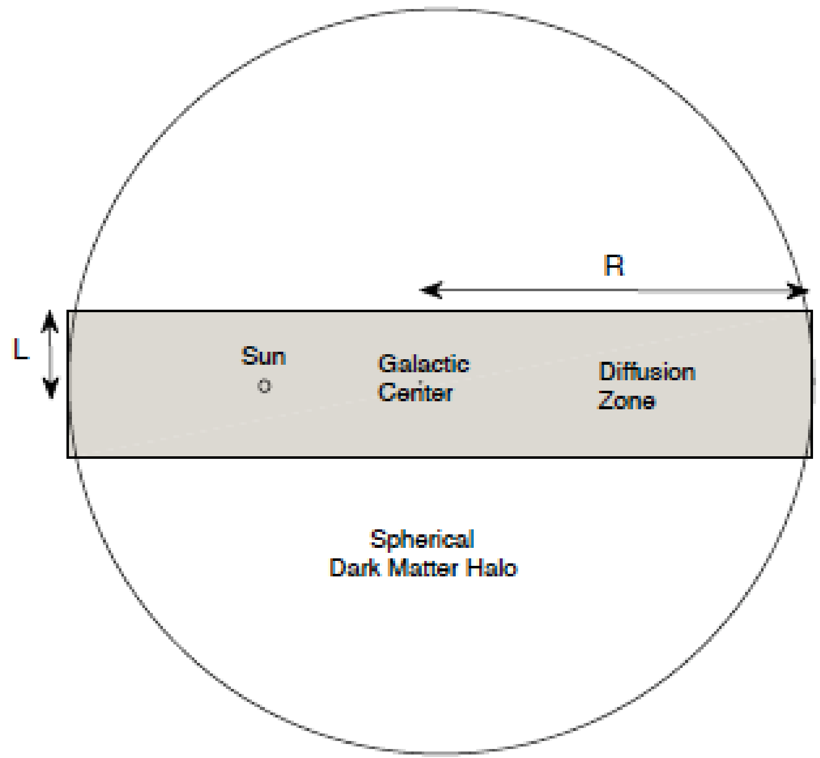
Conventional approach: solve transport equation in a thin cylindrical disk (half-thickness L, radius R = 20kpc), the *diffusion zone,* where galactic magnetic fields confine positrons. Outside this region, positrons are assumed to propagate freely and escape.



Model	δ	K_0 [kpc^2/Myr]	L [kpc]
MED	0.70	0.0112	4
M1	0.46	0.0765	15
M2	0.55	0.00595	1

Obtained from fits to cosmic ray isotope ratios

Problem: the dark matter halo extends significantly beyond this disk. eg. for L=1 kpc and dark matter with an isothermal profile, the diffusion zone contains only ~10% of the dark matter mass



Positrons produced in the extended halo can enter the diffusion zone and contribute to the positron density there !

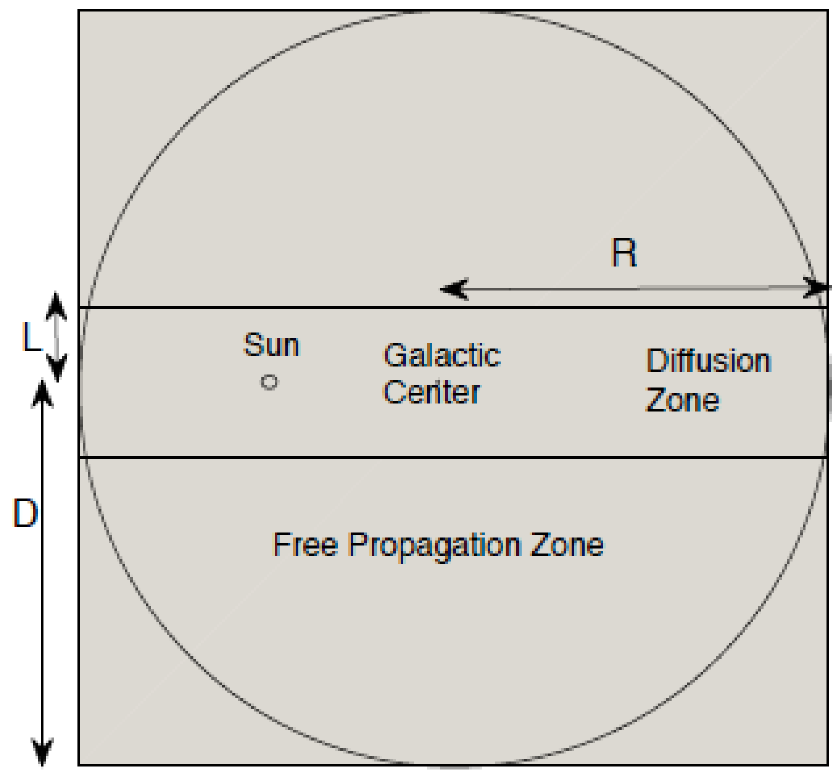
The (wrong) way to fix it:

Switch to a propagation model with larger half-thickness L

Problems with this:

1. Need to rescale diffusion coefficient K with L to remain consistent with cosmic ray data.
2. Positrons coming in from far away lose most of their energy on the way; not the behavior we want in the free propagation zone outside the diffusion zone.

Fix: solve transport equation in this extended *free propagation zone* while maintaining the distinction between diffusion and free propagation zones.



Conventional Formalism

[T. Delahaye, R. Lineros, F. Donato, N. Fornengo and P. Salati, Phys. Rev. D 77, 063527 (2008)]

1. Write positron density as a Bessel-Fourier series

$$\psi(z,r,\epsilon) = \sum_i \sum_n P_{i,n}(\epsilon) J_0\left(\frac{\alpha_i r}{R}\right) \sin\left(\frac{n\pi(z+L)}{2L}\right)$$

2. Change variables as $t = \frac{\tau_E \epsilon^{\delta-1}}{1-\delta}\,, \quad \tilde{P}_{i,n} = \epsilon^2 P_{i,n}$

and take Bessel and Fourier transforms of the transport equation:

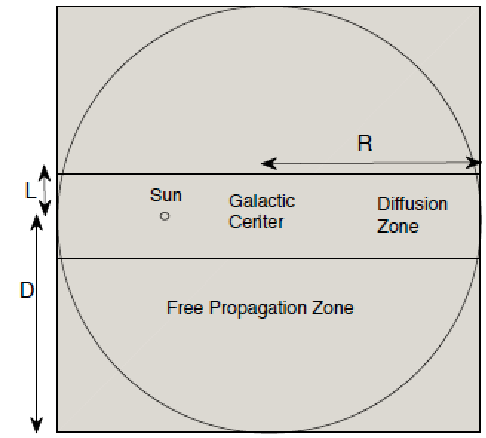
$$\frac{d\tilde{P}_{i,n}}{dt} + K_0\left(\left(\frac{\alpha_i}{R}\right)^2 + \left(\frac{n\pi}{2L}\right)^2\right)\tilde{P}_{i,n} = \epsilon^{2-\delta} Q_{i,n}$$

($Q_{i,n}$: Bessel-Fourier transform of source term q)

3. Solve to get: $$\tilde{P}_{i,n}(t) = \int_0^t \tilde{Q}_{i,n}(t_S)\, \exp\left[-\omega_{i,n}(t-t_S)\right] dt_S$$

where $\tilde{Q}_{i,n} = \epsilon^{2-\delta} Q_{i,n}$ and $\omega_{i,n} = K_0\left[\left(\frac{\alpha_i}{R}\right)^2 + \left(\frac{n\pi}{2L}\right)^2\right]$

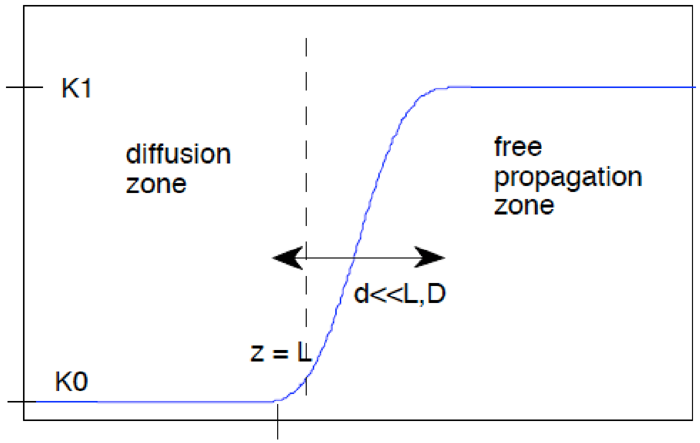
Extended Formalism: Modifications



1. Set boundary condition at |z|=D, not |z|=L.

2. Make diffusion coefficient position dependent to incorporate different behavior in diffusion and free propagation zones

$$K(z,\epsilon) = \left(K_0 + \tilde{K}(z)\right)\epsilon^{\delta}$$



The transport equation now has an extra term

$$-\nabla K \cdot \nabla \psi - K\,\Delta\psi - \frac{\partial}{\partial E}[b(\mathbf{x},E)\psi] = q(\mathbf{x},E)$$

Taking the Bessel and Fourier transforms gives…

Extended Formalism

$$
\begin{aligned}
&- \sum_n \tilde{P}_{i,n} \left(\frac{n\pi}{2D^2}\right) \int_{-D}^{D} \frac{d\tilde{K}}{dz} \cos\left(\frac{n\pi(z+D)}{2D}\right) \sin\left(\frac{m\pi(z+D)}{2D}\right) dz \\
&+ \frac{1}{D} \sum_n \tilde{P}_{i,n} \left(\left(\frac{\alpha_i}{R}\right)^2 + \left(\frac{n\pi}{2D}\right)^2\right) \int_{-D}^{D} \tilde{K}(z) \sin\left(\frac{n\pi(z+D)}{2D}\right) \sin\left(\frac{m\pi(z+D)}{2D}\right) dz \\
&+ K_0 \left(\left(\frac{\alpha_i}{R}\right)^2 + \left(\frac{m\pi}{2D}\right)^2\right) \tilde{P}_{i,m} + \frac{d}{dt}\tilde{P}_{i,m} = \tilde{Q}_{i,m}
\end{aligned}
$$

} same as from conventional formalism

Different modes mix, equations no longer decoupled.

This is in the form $\frac{d\mathbf{P}_i}{dt} + \mathbf{A}_i \cdot \mathbf{P}_i = \mathbf{Q}_i$

The solution is $\mathbf{P}_i(t) = \int_0^t dt_S \exp\left[-(t-t_s)\mathbf{A}_i\right] \mathbf{Q}_i$

The P_i's can be worked out by numerically diagonalizing the A matrix.

can compute positron flux, which can be compared to the solution from the conventional formalism.

Dark Matter and Galactic Propagation Models

Dark matter halo profile

$$\rho(r) = \rho_{\odot} \left(\frac{r_{\odot}}{r}\right)^{\gamma} \left(\frac{1 + (r_{\odot}/r_s)^{\alpha}}{1 + (r/r_s)^{\alpha}}\right)^{(\beta-\gamma)/\alpha}$$

Model	α	β	γ	r_s(kpc)
Cored isothermal	2	2	0	5
NFW	1	3	1	20
Moore	1.5	3	1.3	30

Propagation parameters

Model	δ	K_0 [kpc^2/Myr]	L [kpc]
MED	0.70	0.0112	4
M1	0.46	0.0765	15
M2	0.55	0.00595	1

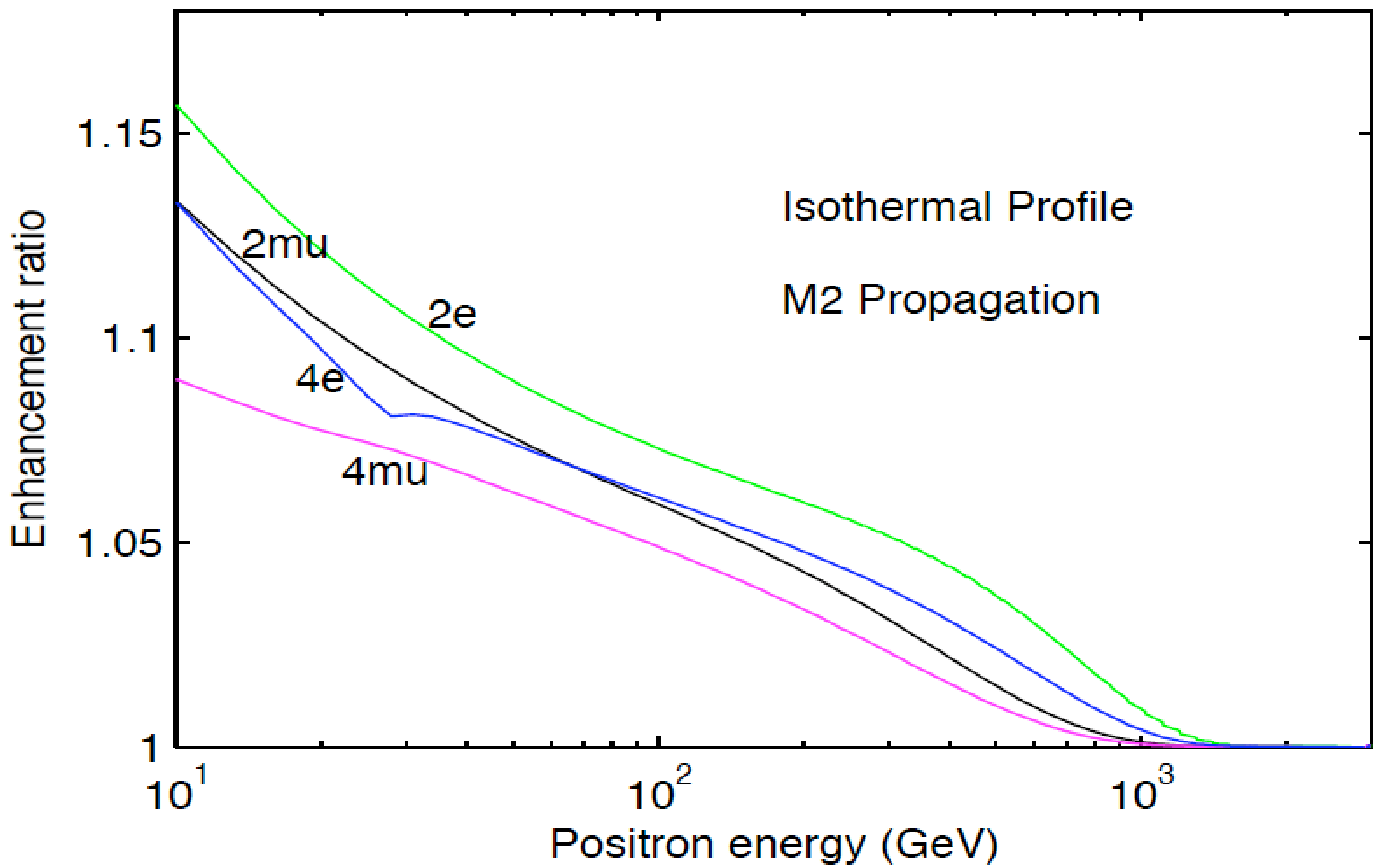
Annihilation channels

1. $\chi\chi \to e^+e^-$
2. $\chi\chi \to \mu^+\mu^-$
3. $\chi\chi \to \phi\phi \to 4e$
4. $\chi\chi \to \phi\phi \to 4\mu$

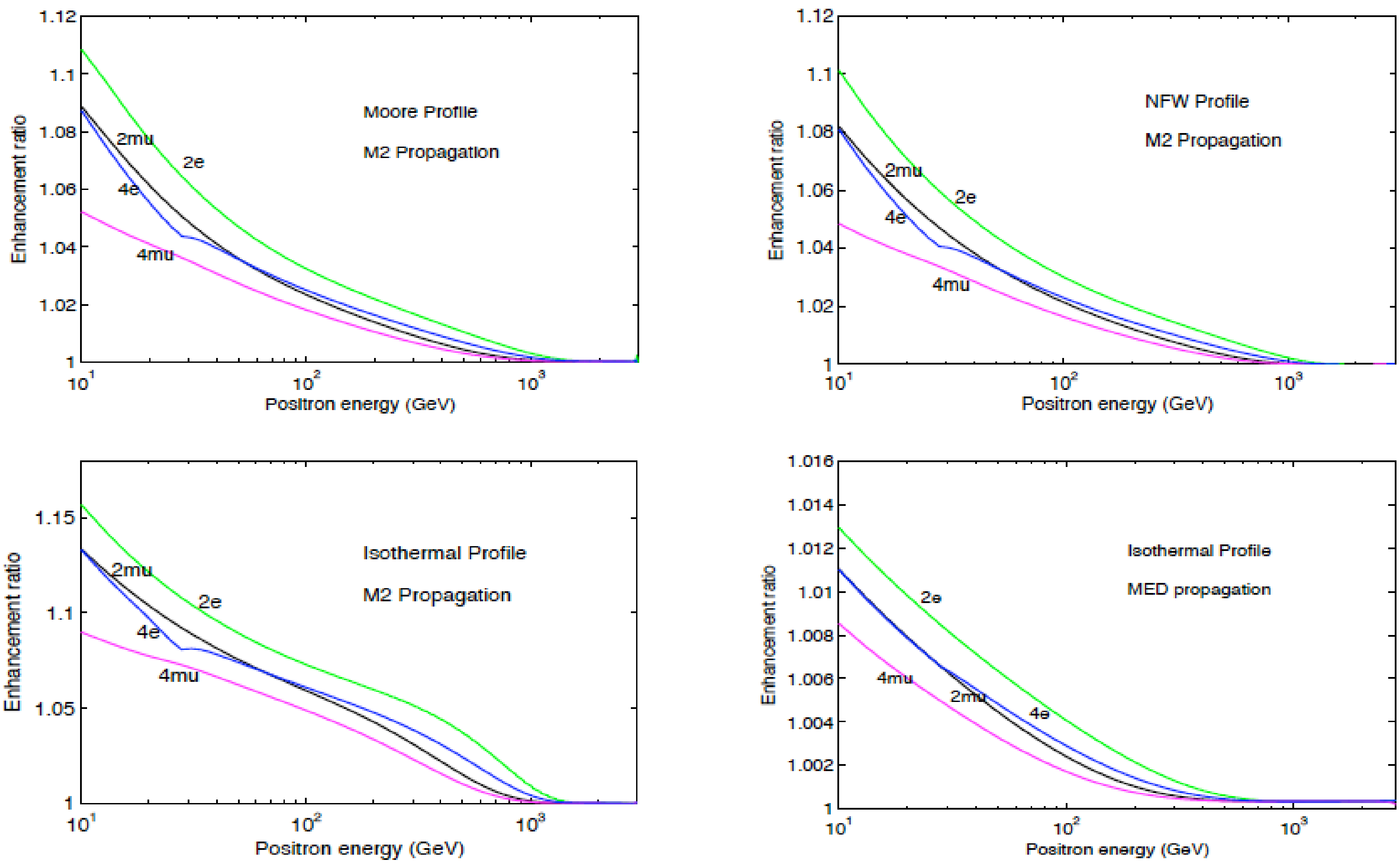
} Favored by PAMELA / Fermi data

- Annihilating vs decaying dark matter
- Consider dark matter mass of 3 TeV (6 TeV for decaying dark matter)

Results: Positron Flux at Earth

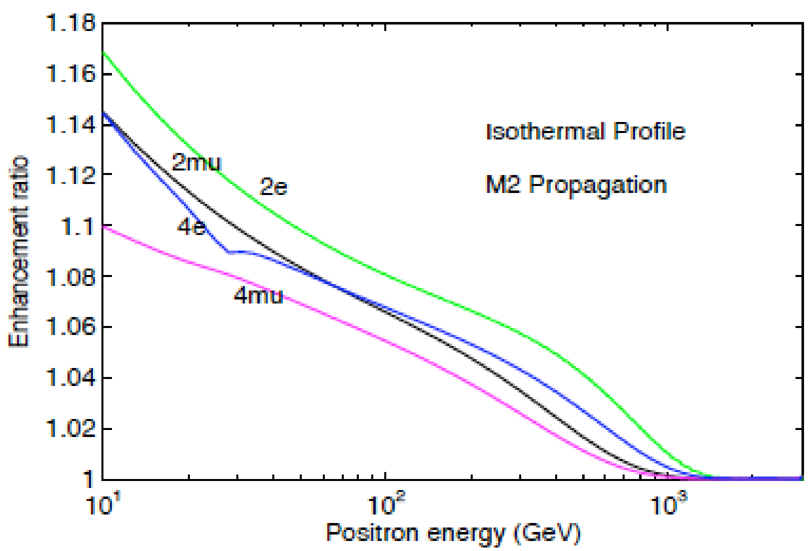


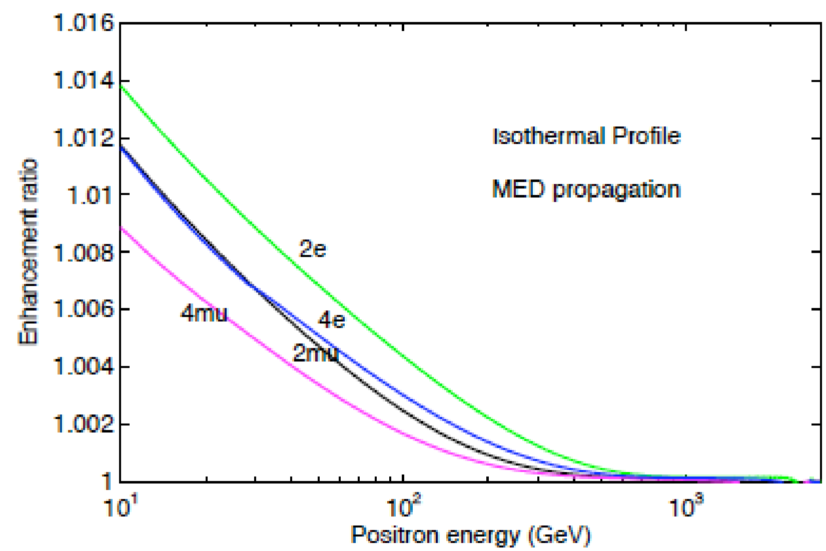
Results: Positron Flux at Earth



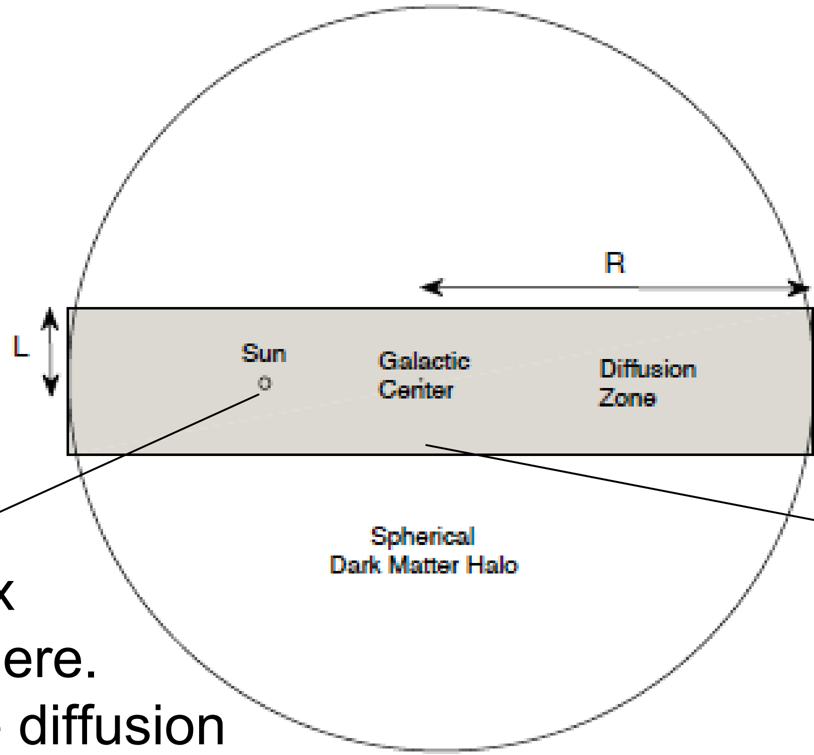
Results: Positron Flux at Earth (decaying dark matter)

Source term $\propto \rho_{DM}$ ($\propto \rho_{DM}^2$) for decaying (annihilating) dark matter, so the enhancement is expected to be greater for decaying DM since the diffusion zone contains a smaller fraction of the source.





Larger corrections elsewhere…



Positron flux measured here. Deep inside diffusion zone, so only small corrections expected.

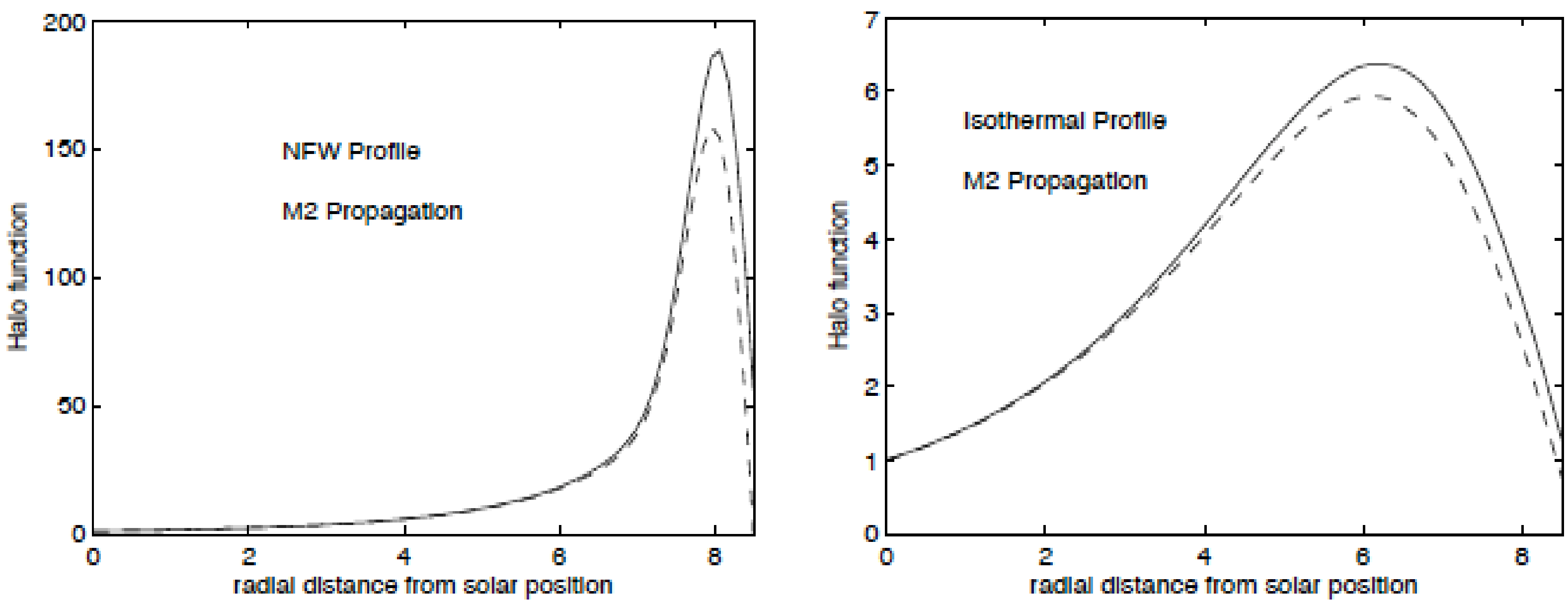
Largest corrections occur close to the diffusion zone boundary.

Corrections along this line of sight

$$\psi(r,z,\epsilon) = \frac{\tau_E}{\epsilon^2} \int_{\epsilon}^{\epsilon_{\max}} d\epsilon_S \, f(\epsilon_S) \, I(r,z,\epsilon,\epsilon_S)$$

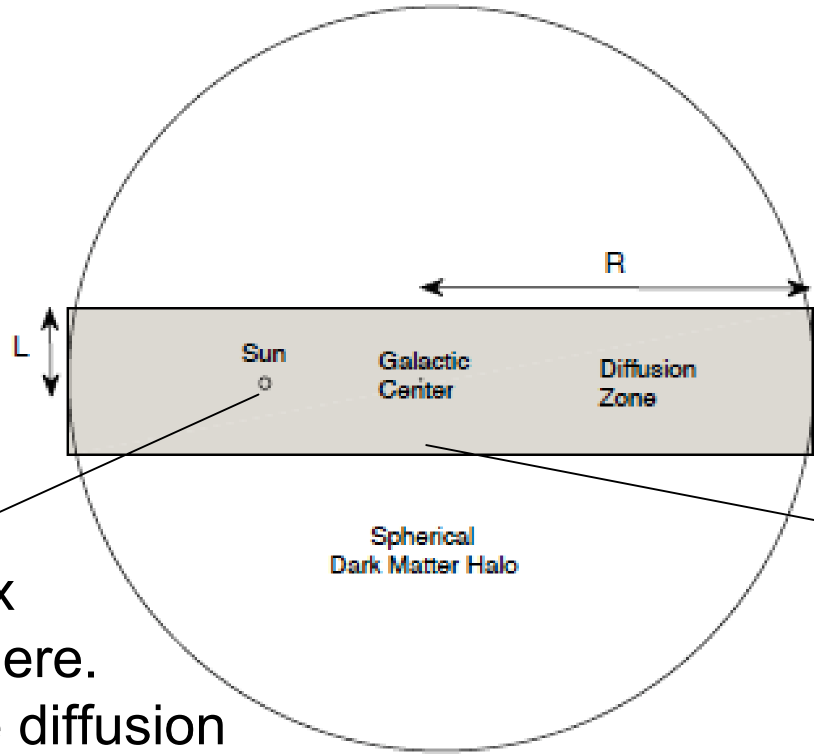
Injection spectrum at source

Halo function:
corrects for
propagation effects



dotted: conventional; solid: extended formalism

Larger corrections elsewhere…



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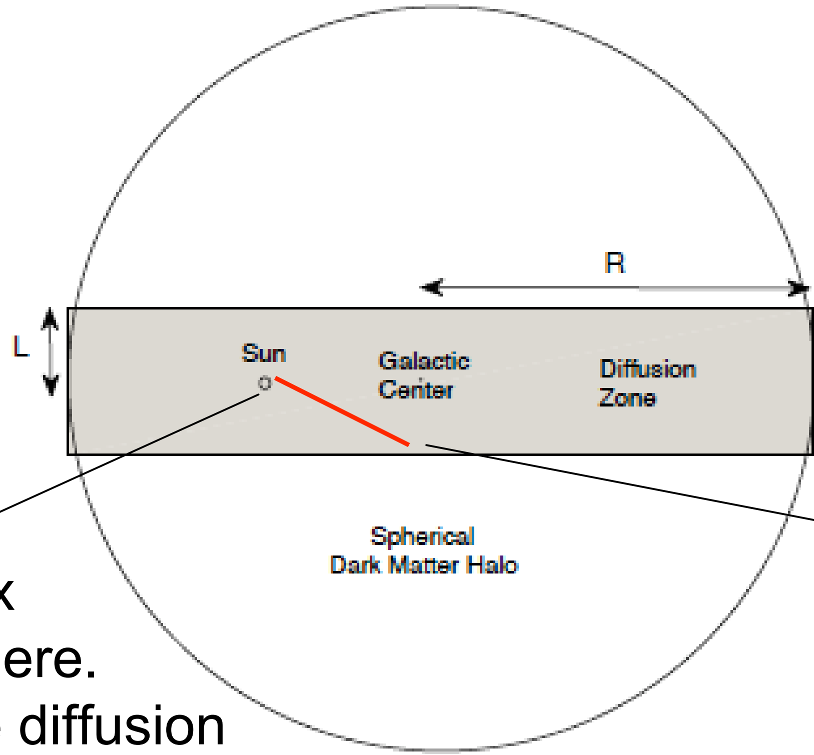
Larger corrections elsewhere…

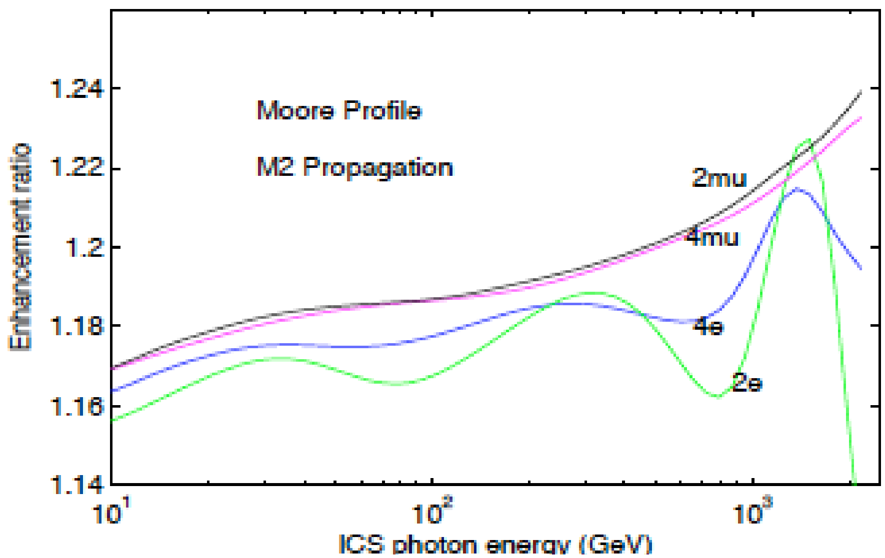


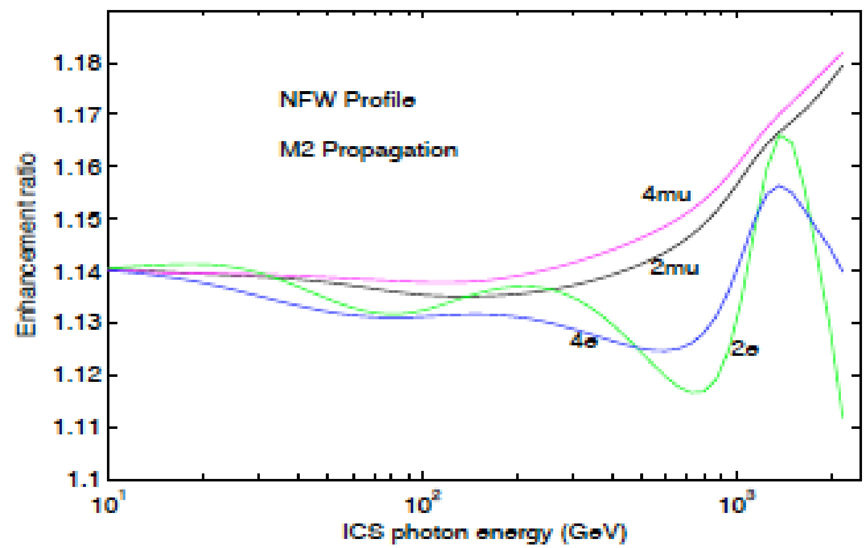
Positron flux measured here. Deep inside diffusion zone, so only small corrections expected.

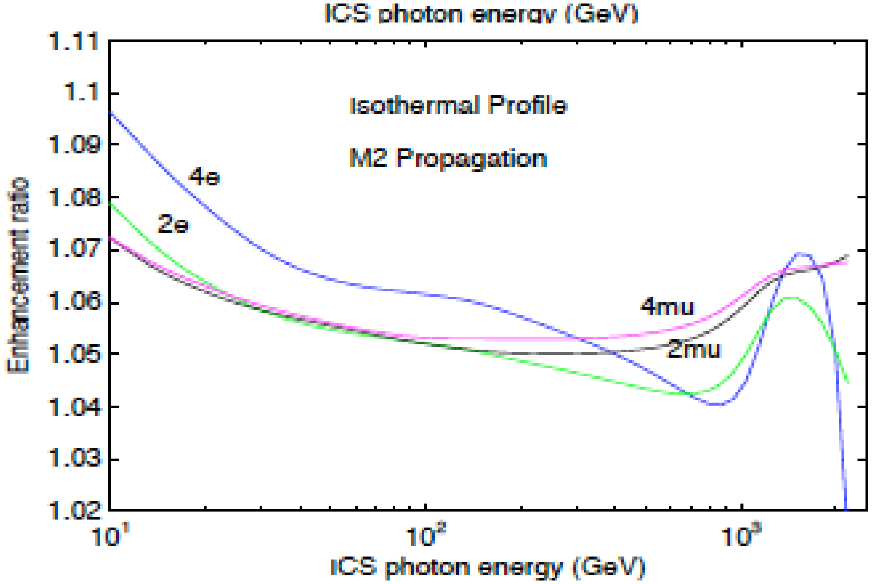
Largest corrections occur close to the diffusion zone boundary.

Look at gamma rays that inverse Compton scatter off positrons and travel towards the Earth from this direction.

Gamma Rays from ICS







The three 'bumps' in the figures correspond to three different components of galactic light that can scatter off positrons: CMB, starlight, and starlight rescattered by dust.

Summary of results

• Up to 10-15% enhancement in positron flux and up to 20-25% enhancement in ICS gamma ray flux expected from contributions from the dark matter halo beyond the diffusion zone.

• Enhancement in positron flux decreases with energy (not necessarily true for ICS gamma ray flux).

• Enhancements significant for M2 propagation model (L=1kpc), negligible for MED propagation.

• Smaller than other astrophysical, experimental uncertainties at present, should be considered when accuracy to better than ~20% is needed.


Part
II
$\bar{p}$

Solving for antiproton flux

Diffusion equation for antiprotons:

Omitted: energy loss term (negligible for the more massive antiprotons)

Convective wind term

$$-\nabla\,[K(\mathrm{x},E)\,\nabla n_{\bar{p}}]+\frac{\partial}{\partial z}(V_C(z)n_{\bar{p}}(E,\mathrm{x}))+2h\delta(z)\Gamma_{ann}n_{\bar{p}}(E,\mathrm{x})=\,q_{\bar{p}}(\mathrm{x},E)$$

Antiproton interaction with interstellar medium, confined to galactic plane

Conventional Solution

Expand antiproton density as a Bessel series

$$n_{\bar{p}}(\rho, z, E) = \sum_i N_i(z, E) J_0\left(\frac{\zeta_i \rho}{R}\right)$$

Assuming position independent K and V and solving the diffusion equation in the cylindrical disk, the solution is

$$N_i(z) = e^{a(|z|-L)} \frac{y_i(L)}{B_i \sinh(S_i L/2)} \left[\cosh(S_i z/2) + A_i \sinh(S_i z/2)\right] - \frac{y_i(z)}{K S_i}$$

where

$$S_i = 2\left(a^2 + \frac{\zeta_i^2}{R^2}\right)^{1/2}, \quad A_i = \frac{V_C + 2h\Gamma_{ann}}{K S_i}; \quad B_i = K S_i \left[A_i + \coth(S_i L/2)\right]$$

$$y_i(z) = 2\int_0^z e^{a(z-z')} \sinh\left[S_i(z-z')/2\right] q_i(z') dz' .$$

$a = V_C/(2K)$

suffers from the same problem as the positron density : sharp boundary cutoff at |z|=L, ignores sources outside

Can do better: A more realistic setup

position independent diffusion coefficient with a sharp cutoff at L : a very crude approximation

Diffusion: charged particles getting confined by galactic magnetic fields $\longrightarrow$ diffusion coefficient should follow spatial variations of the galactic magnetic field strength

$$B(\rho, z) \approx (11\mu\mathrm{G}) \times \exp\left(-\frac{\rho}{10\ \mathrm{kpc}} - \frac{|z|}{2\ \mathrm{kpc}}\right) \Longrightarrow K(E, z) = K_e(E)\exp(|z|/z_t)$$

Has been studied numerically, have best fit parameters

If the convective wind term has a similar exponential profile (or can be neglected), CAN solve the diffusion equation analytically!

New Solution

$$N_i(z) = e^{a(|z|-L)} \frac{y_i(L)}{B_i \sinh(S_i L/2)} \left[\cosh(S_i z/2) + A_i \sinh(S_i z/2)\right] - \frac{y_i(z)}{K_e S_i}$$

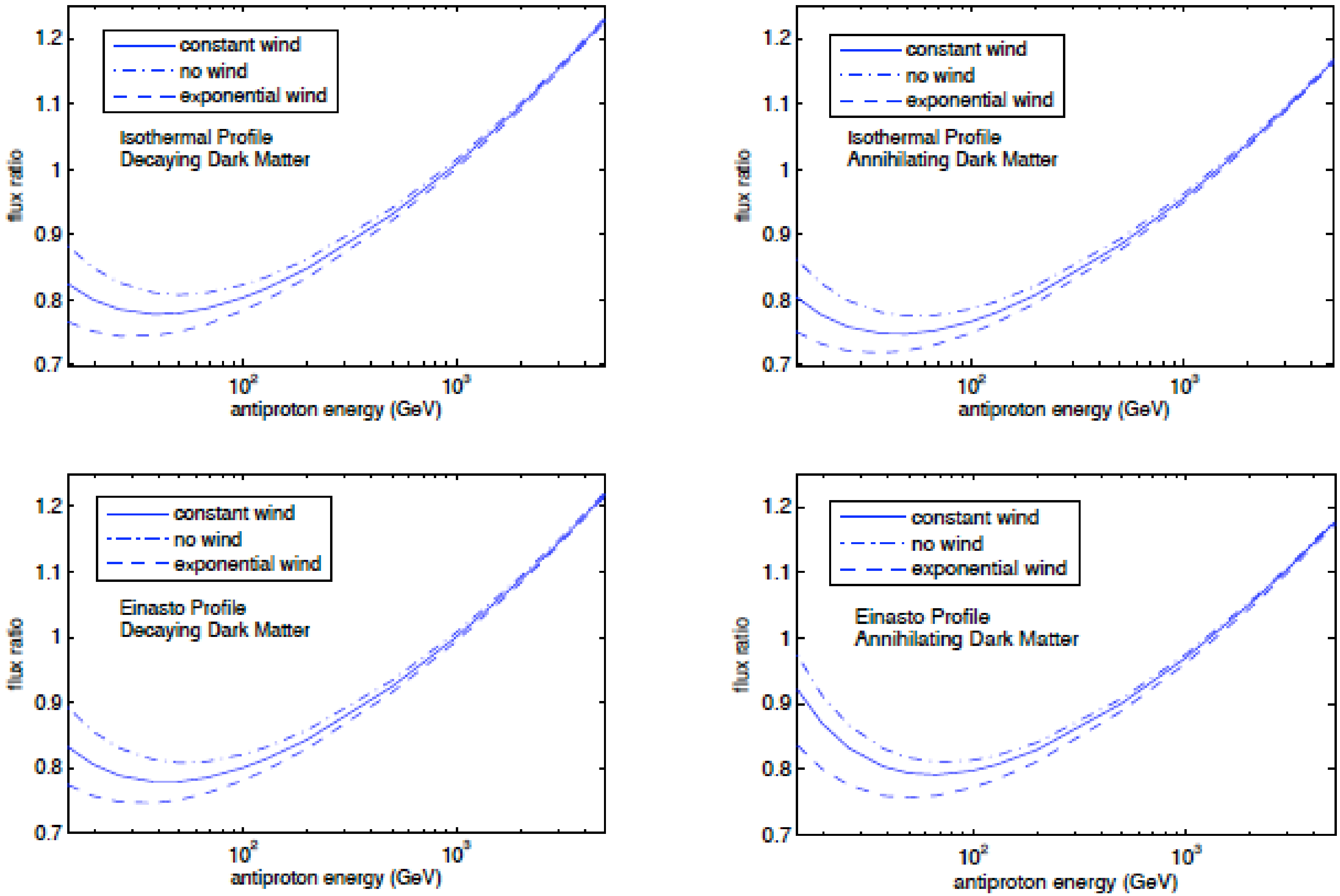
same form as the conventional solution, with slightly different definitions

$$\begin{aligned}
a &= \frac{V_e}{2K_e} - \frac{1}{2z_t}, \quad S_i = 2\left(a^2 + \frac{\zeta_i^2}{R^2} + \frac{V_e}{z_t K_e}\right)^{1/2}, \\
A_i &= \frac{V_e + 2h\Gamma_{ann}}{K_e S_i} + \frac{1}{z_t S_i}; \quad B_i = K_e S_i \left[A_i + \coth(S_i L/2)\right] \\
y_i(z) &= 2\int_0^z e^{a(z-z')} \sinh\left[S_i(z-z')/2\right] q_i(z')\, e^{-z'/z_t}\, dz'.
\end{aligned}$$

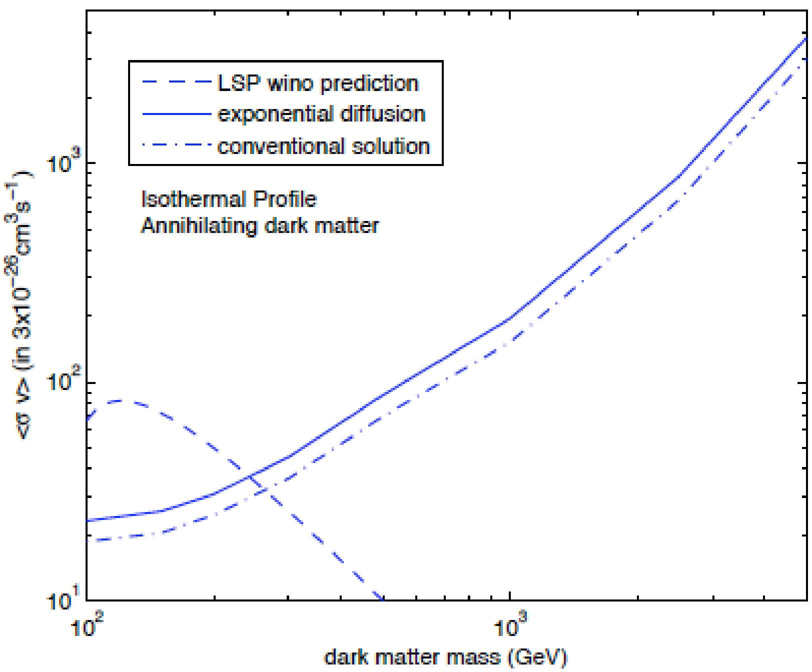
$$V_C(z) = V_e \exp(|z|/z_t)$$

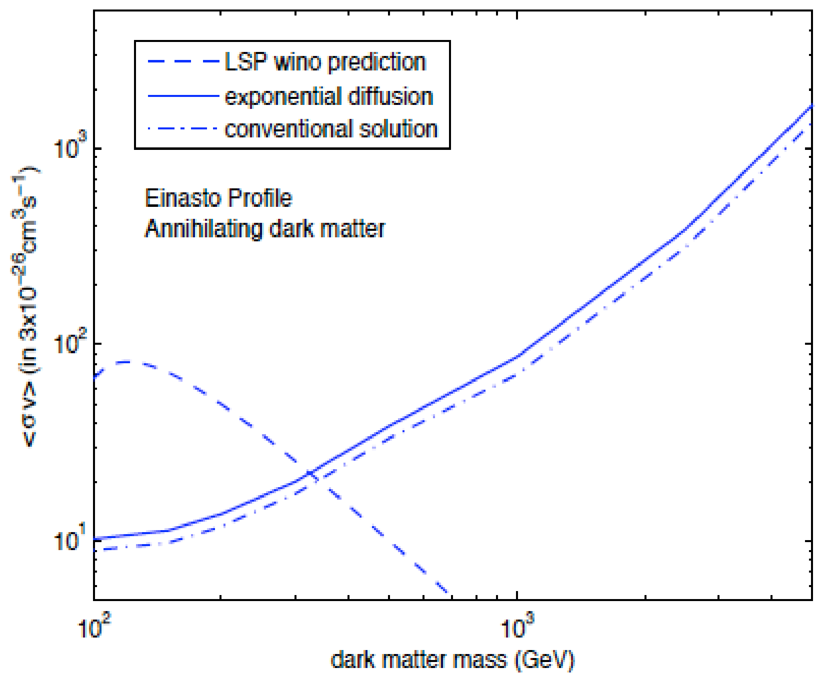
As simple to evaluate as the conventional solution!

Comparison with conventional solution



Antiproton bounds for WIMP dark matter



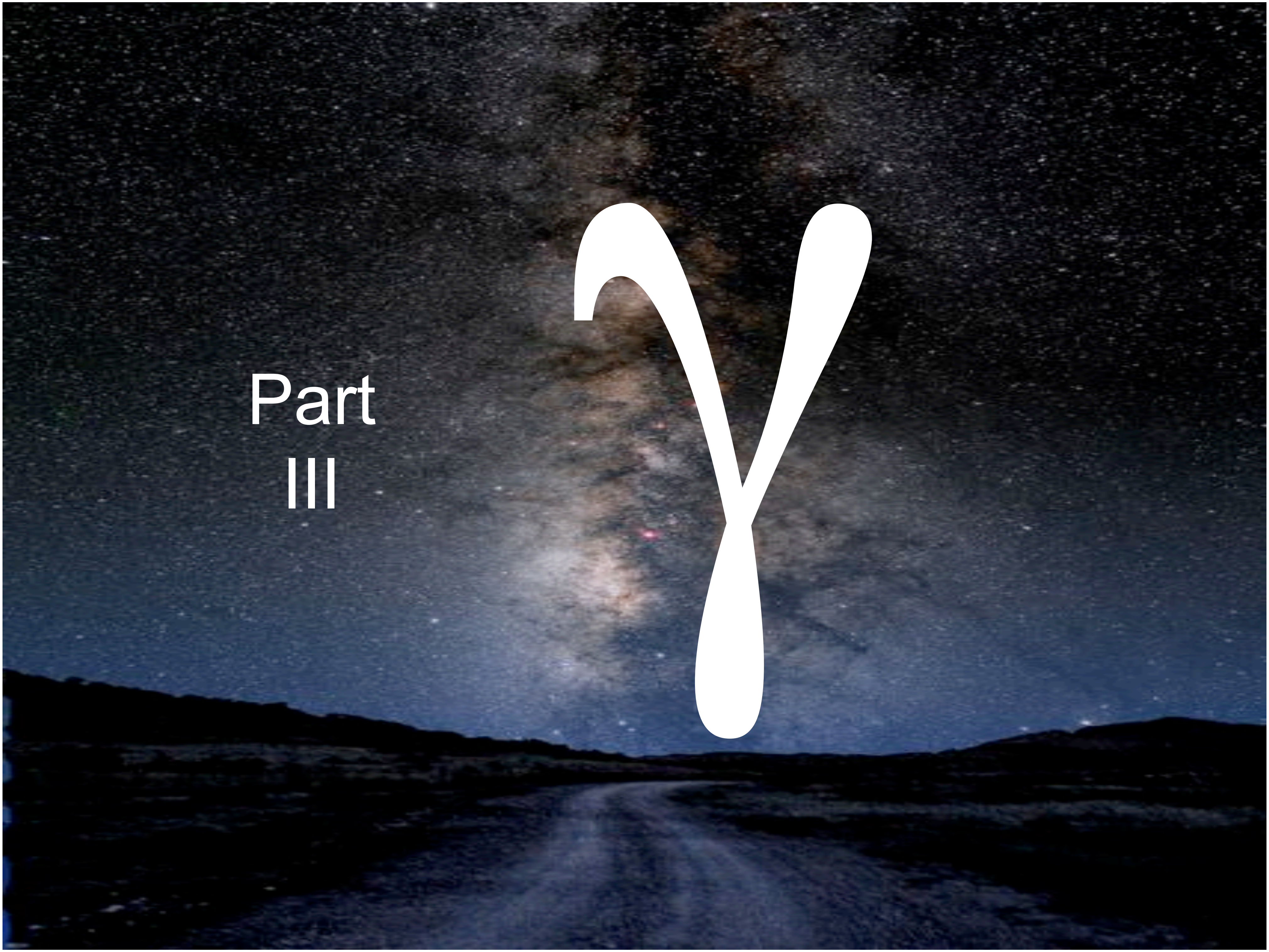


Assume stable dark matter pair annihilating into W^+W^-

Bounds from conventional and new solutions agree to within ~20%

Summary

- New, analytic, easy-to-use solution to antiproton flux from dark matter (valid at energies higher than several hundred GeV) in a more realistic propagation model, includes contributions from the full dark matter halo
- deviates from conventional solution by ~25% for realistic parameters


Part
III
γ

Gamma ray signals from dark matter

- What kind of gamma rays?

  Inverse Compton scattering, final state radiation

- Look at:

  Galactic center

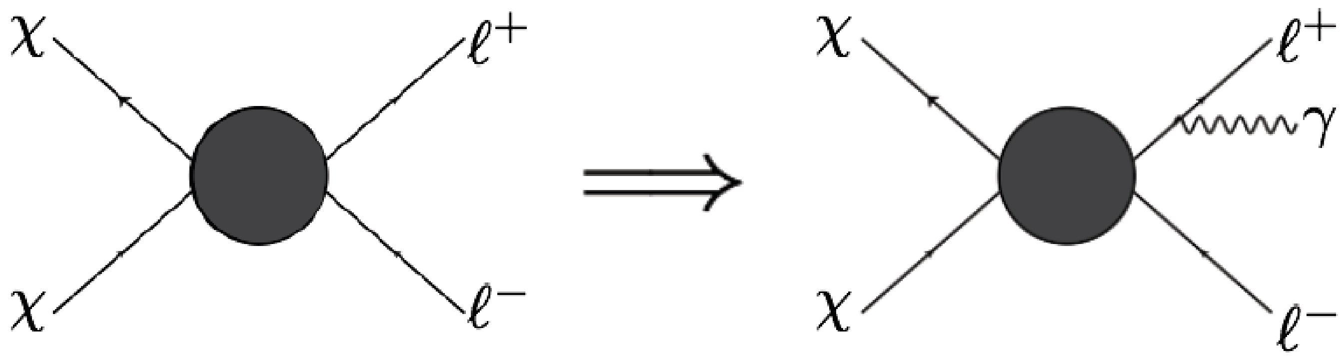
(region of greatest dark matter density, expect the strongest gamma ray signals)

- Use:

  Fermi Gamma-ray Space Telescope

(free of atmospheric background, excellent energy and angular resolution and range, can cover the whole sky continuously)

Gamma Rays from Final State Radiation (FSR)



(Birkedal, Matchev, Perelstein, Spray, 2005)

- guaranteed in leptophilic (or any charged) annihilation channels
- dominant close to dark matter mass, has a sharp “edge” feature at this cutoff for 2-body final states
- spectrum independent of astrophysical uncertainties
- independent of details of the particle physics model; model-independent predictions can be made

Dwarf Galaxies

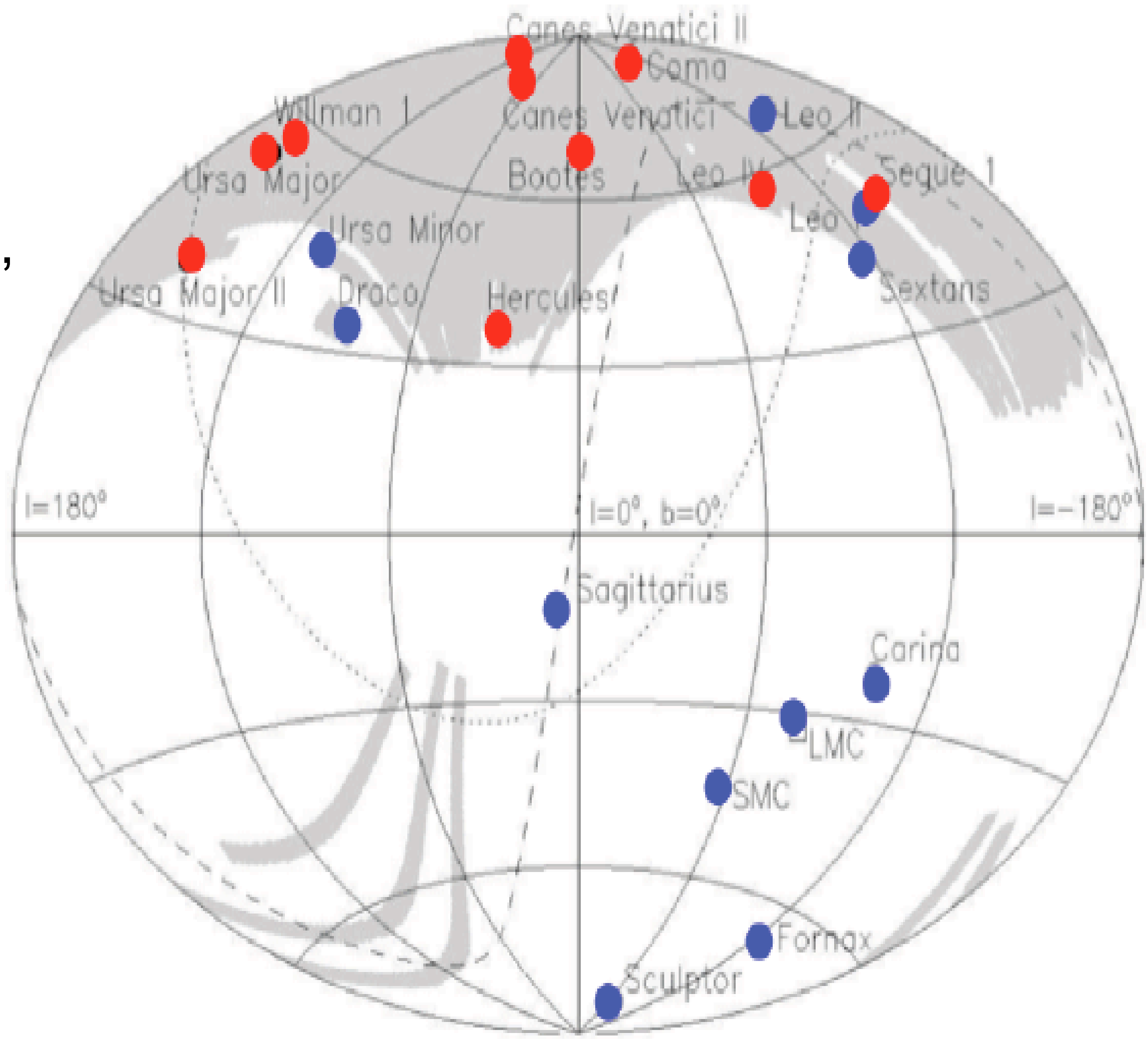
• dark matter dominated

• low background: no detected gas, minimal dust, no magnetic fields, little or no recent star formation activity

• lie away from galactic center

• velocity distribution lower than in Milky Way

halo: possible Sommerfeld enhancement increase by an order of magnitude !



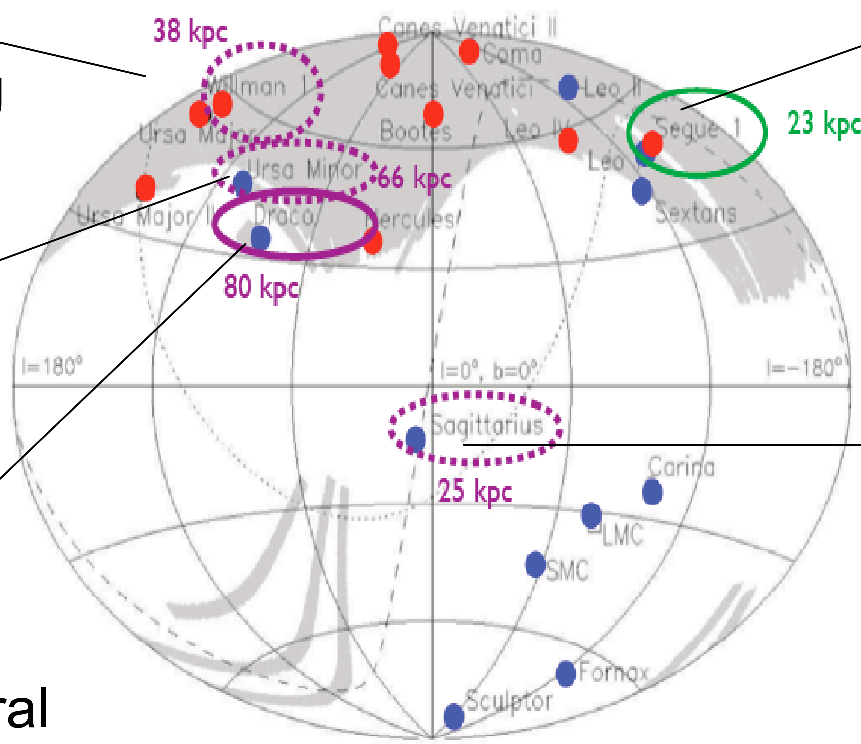
Belokurov et al. (2006)

Dwarf Galaxies: Promising Candidates

Willman 1:
Strongest existing
constraint

Ursa Minor

Draco:
Observed several
times



Segue 1:
recently discovered,
very promising
candidate

Sagittarius:
direction close to
galactic center,
being tidally
disrupted by the
Milky Way

many new dwarfs expected to be discovered in the future.

FSR flux

$$\frac{d\Phi_{FSR}}{dx} = \Phi_0 \left(\frac{\langle\sigma v\rangle}{1pb}\right)\left(\frac{100\ \mathrm{GeV}}{m_\chi}\right)^3 F(x)\,\log\left(\frac{4m_\chi^2(1-x)}{m_l^2}\right)\, J$$

Separates into particle physics factor x astrophysical factor.

F(x): splitting function $F(x) = \frac{1+(1-x)^2}{x}$ $\quad 2\frac{2-x+2x\log x - x^2}{x}$

2-body annihilation 4-body annihilation

J: astrophysical factor. For annihilating dark matter,

$$J = \frac{1}{8.5\ \mathrm{kpc}}\left(\frac{1}{0.3\ \mathrm{GeV/cm^3}}\right)^2 L, \qquad L = \int d\Omega \int_{l.o.s.} \rho^2 dl$$

Dwarf	$\log_{10}(L\times \mathrm{GeV^{-2}cm^5})$
Sagittarius	19.35 ± 1.66
Draco	18.63 ± 0.60
Ursa Minor	18.79 ± 1.26
Willman 1	19.55 ± 0.98
Segue 1	20.17 ± 1.44

R. Essig, N. Sehgal and L. E. Strigari
Phys. Rev. D **80**, 023506 (2009)

For comparison, for the Galactic center with an Einasto profile, the corresponding number is ~ 21 ± 3.

Updated value: 19.0 ± 0.6

Atmospheric Cherenkov Telescopes (ACTs)

• Signals from dwarf galaxies expected to be too weak for Fermi LAT to detect: need larger collection areas

⇒ ACTs! (typical effective areas ~10^4 times larger than Fermi)

• typical energy threshold: 200 GeV

• energy resolution: 10-30%

• major disadvantage: large atmospheric (cosmic ray) backgrounds (hadronic and leptonic)

• several ACTs currently operational: MAGIC, HESS, VERITAS, CANGAROO

• future telescopes being planned: CTA (Cherenkov Telescope Array). Will provide an order of magnitude improvement over current instruments.

Gamma ray signals from dark matter : An alternative

- What kind of gamma rays?

  Final State Radiation

(dominates at high energies, model-independent and independent of astrophysical uncertainties)

- Look at:

  Dwarf galaxies

(negligible background, clear direction)

- Use:

  Atmospheric Cherenkov Telescopes

(large effective areas of observation)

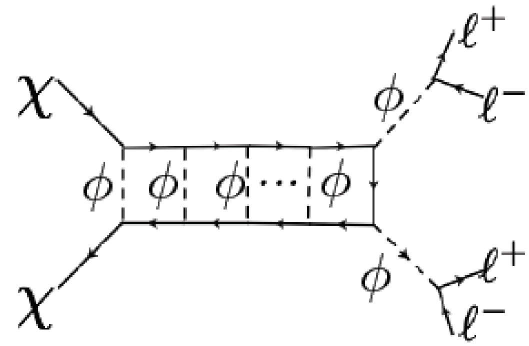
Leptophilic dark matter "models", favored by current PAMELA, Fermi data.

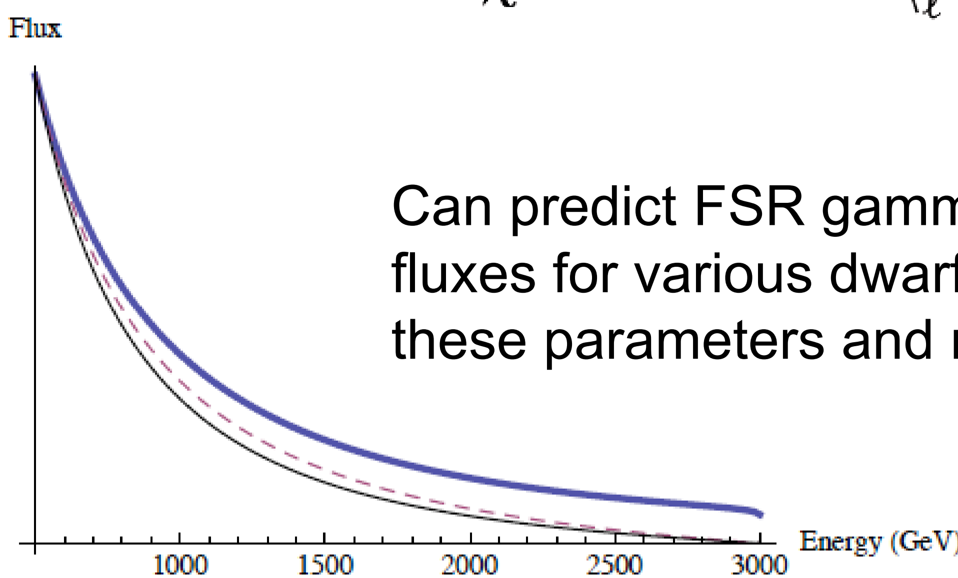
$\chi\chi \rightarrow \mu+\mu-$

$\chi\chi \rightarrow \phi\phi \rightarrow 4e$

$\chi\chi \rightarrow \phi\phi \rightarrow 4\mu$

ϕ : new, intermediate particle with GeV scale mass, provides Sommerfeld enhancement

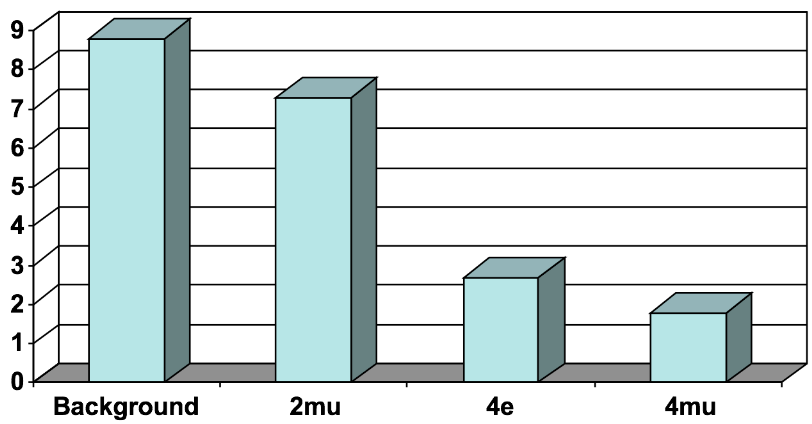




Take
m_χ= 3 TeV,
m_ϕ = 1 GeV
$<\sigma_0 v> = 3x10^{-23}\ cm^3s^{-1}$

Can predict FSR gamma ray fluxes for various dwarfs for these parameters and models.

Backgrounds



Background and signals fluxes for Segue 1 (in $10^{-12} cm^{-2} s^{-1}$)

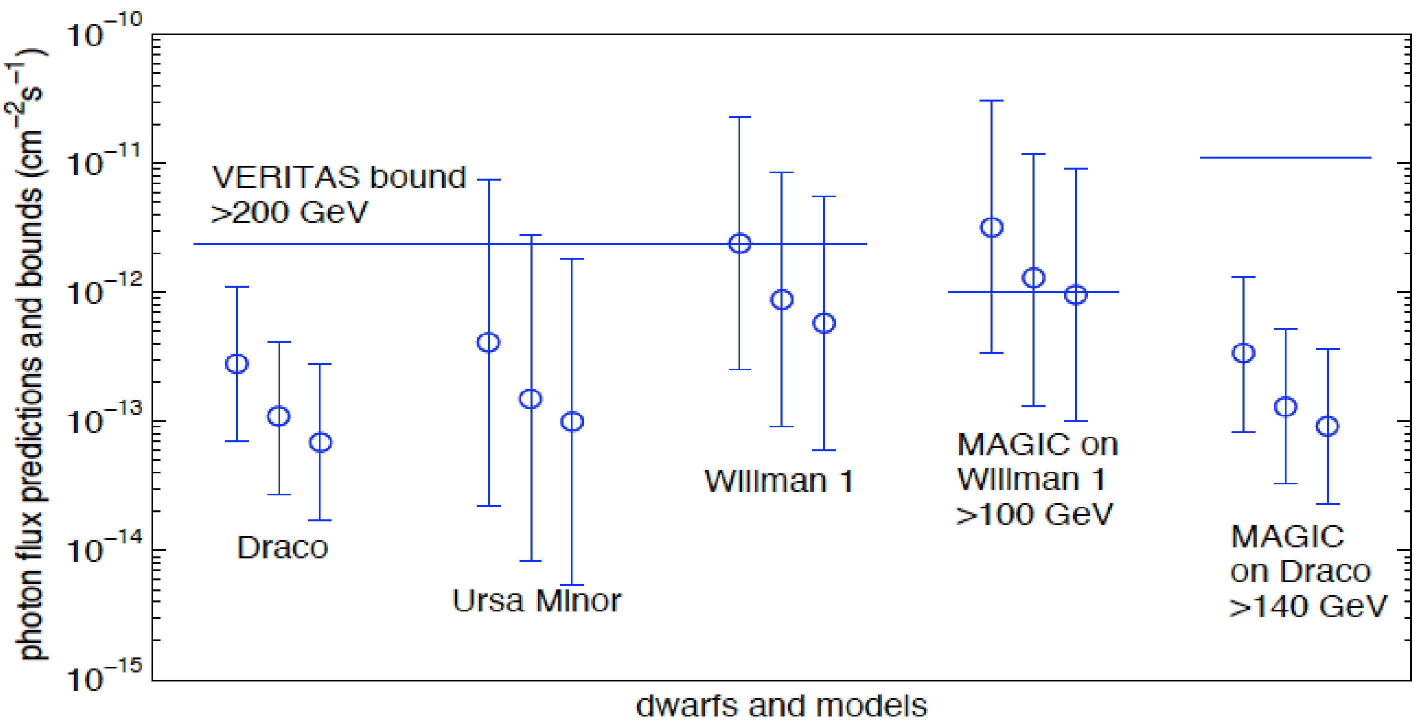
- Cosmic ray background: misidentifying hadronic and leptonic events in the atmosphere as gamma ray signals
- Can “subtract” this background away up to statistical fluctuations (ON region - OFF region)

DM backgrounds from inside the galaxy (FSR and invserse Compton scattering) are negligible because of a narrow region of focus and the direction of dwarfs (away from galactic center).

Previous Observations and Upper Bounds

- No significant signals observed

- Large uncertainty in dark matter distribution in all dwarfs, predictions consistent with experimental bounds up to these uncertainties

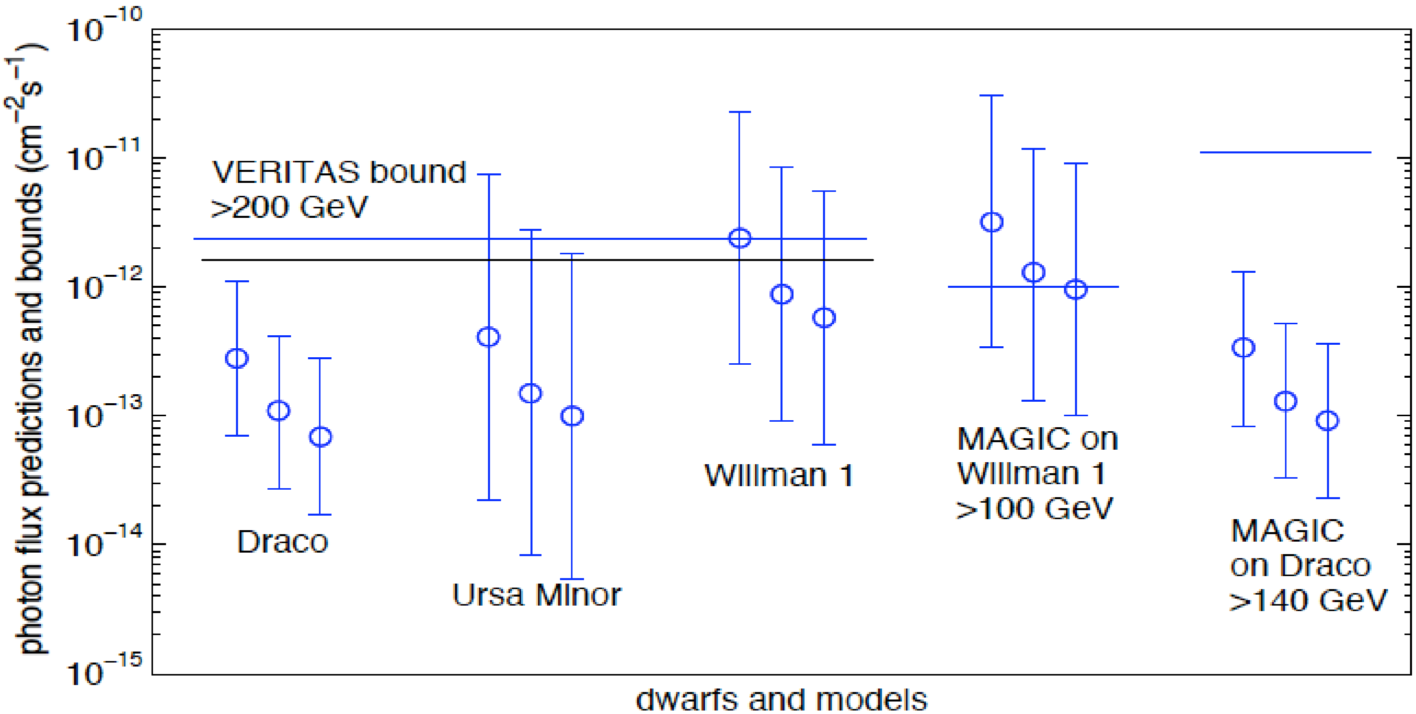


(Left to right: 2mu, 4e, 4mu predictions for each dwarf)

Previous Observations and Upper Bounds: Updated

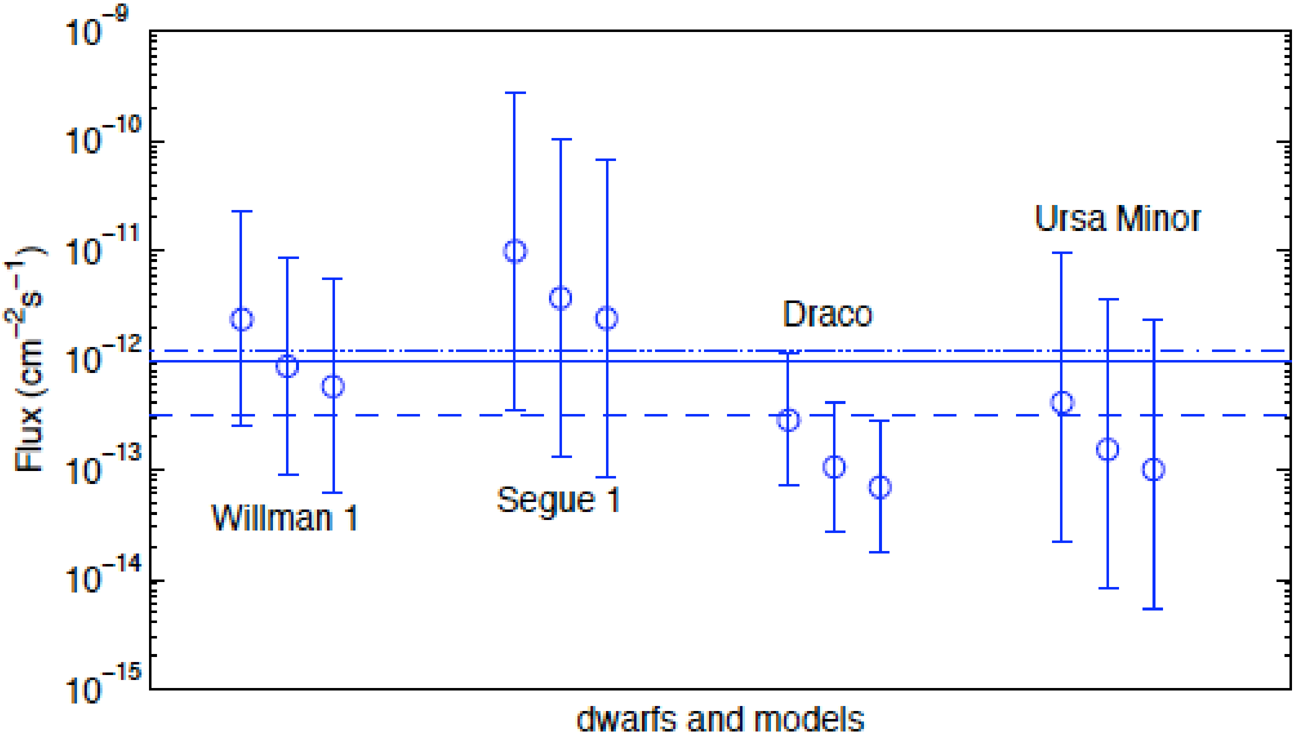
- No significant signals observed

- Large uncertainty in dark matter distribution in all dwarfs, predictions consistent with experimental bounds up to these uncertainties



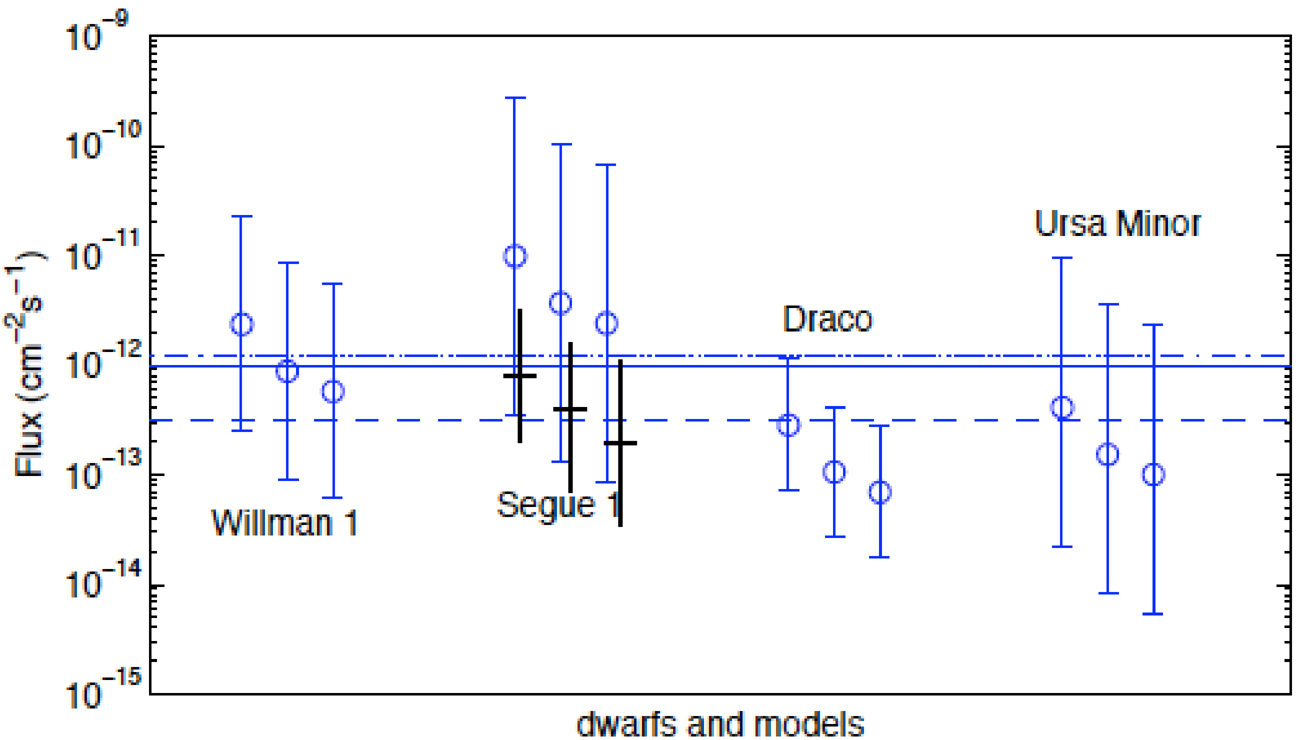
(Left to right: 2mu, 4e, 4mu predictions for each dwarf)

Detection Prospects



Integrated flux above 200 GeV. Dot-dashed, solid, and dashed lines: 3σ sensitivities of VERITAS, MAGIC, and CTA in 50 hours.

Detection Prospects : Updated

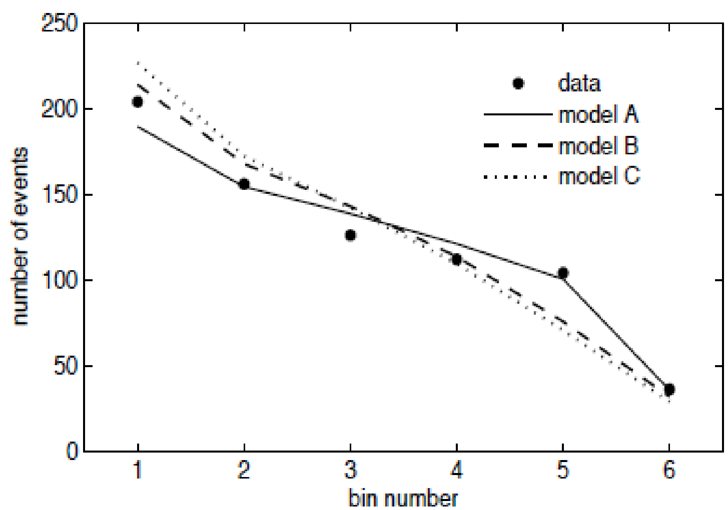


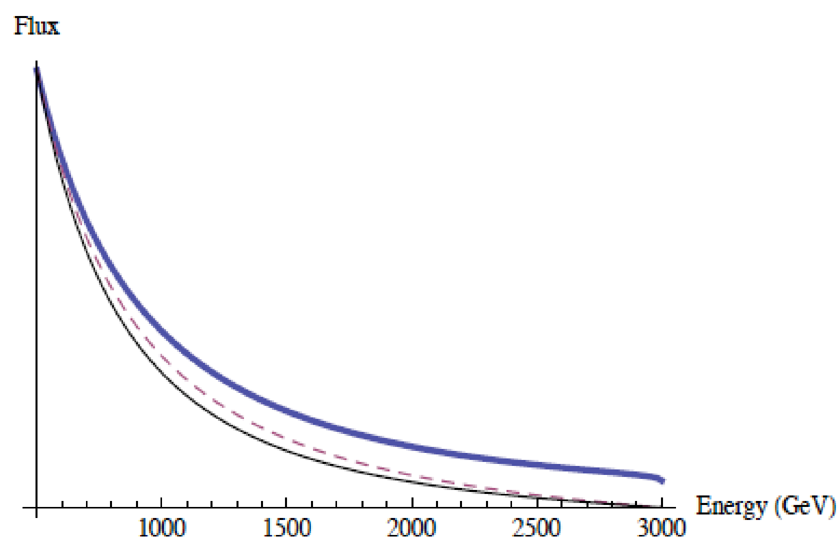
Integrated flux above 200 GeV. Dot-dashed, solid, and dashed lines: 3σ sensitivities of VERITAS, MAGIC, and CTA in 50 hours.

What can we learn from a signal?

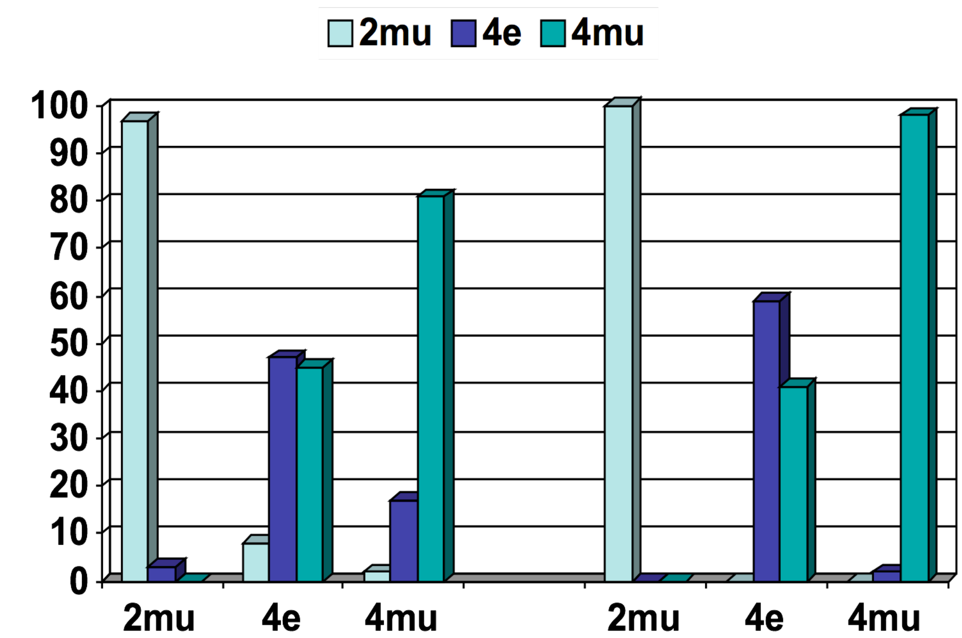
• Once a positive signal is detected, what information can be extracted from it? Can the underlying model and parameters be identified?

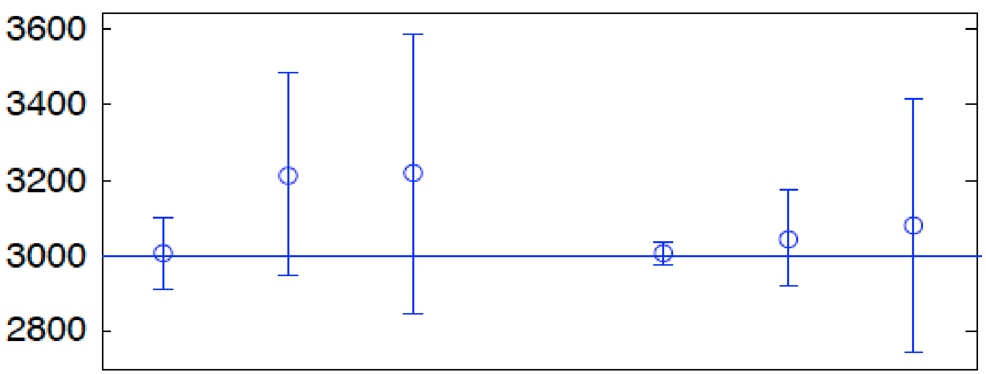
• Simulate observation (including background subtraction) and fits to theory for different scenarios:





Model Identification
Benchmark case: Observation of Segue 1





Threshold energy: 500 GeV

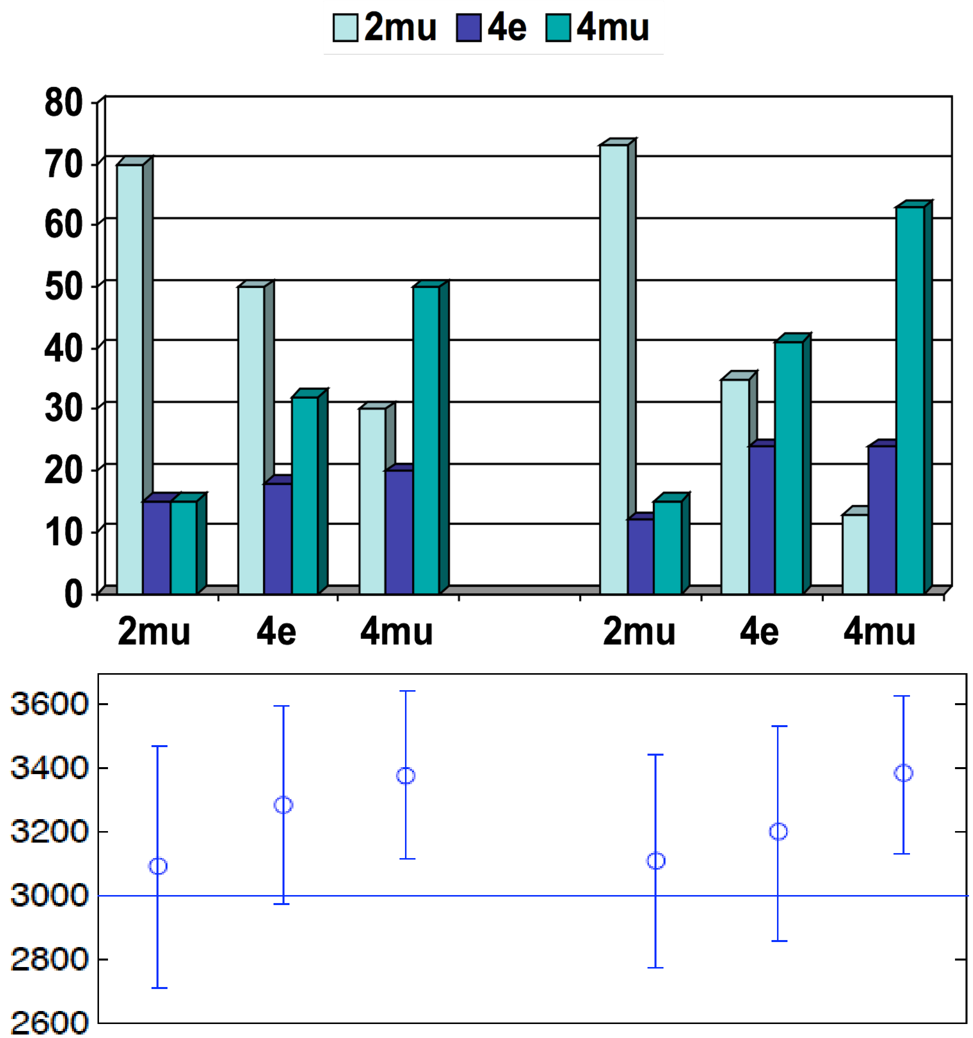
Top plot: Frequency with which model used to generate data (x-axis) was best fit to the three channels (color coded).

Results for current instrument parameters on left, future parameters on right.

Bottom: best fit masses, in GeV

Overall success rate:
75% for current telescope parameters,
86% for future ones

Case 2: 3σ or 5σ detection



Left: 3σ detection
Right: 5σ detection

Success rates now lower:
46% for 3σ, 53% for 5σ

Success rate for discriminating between 2 and 4 body channels:
63% and 75% respectively.

Robustness

Can look at variations in:

- Dark matter mass
- Energy binning
- Energy threshold
- Hadron rejection capability

No significant change in model identification success rate or best fit dark matter mass

Summary

• Prospects of indirect detection of dark matter via FSR from dwarf galaxies using current and near-future ACTs are excellent.

• Large uncertainty in distribution of dark matter in dwarf galaxies.

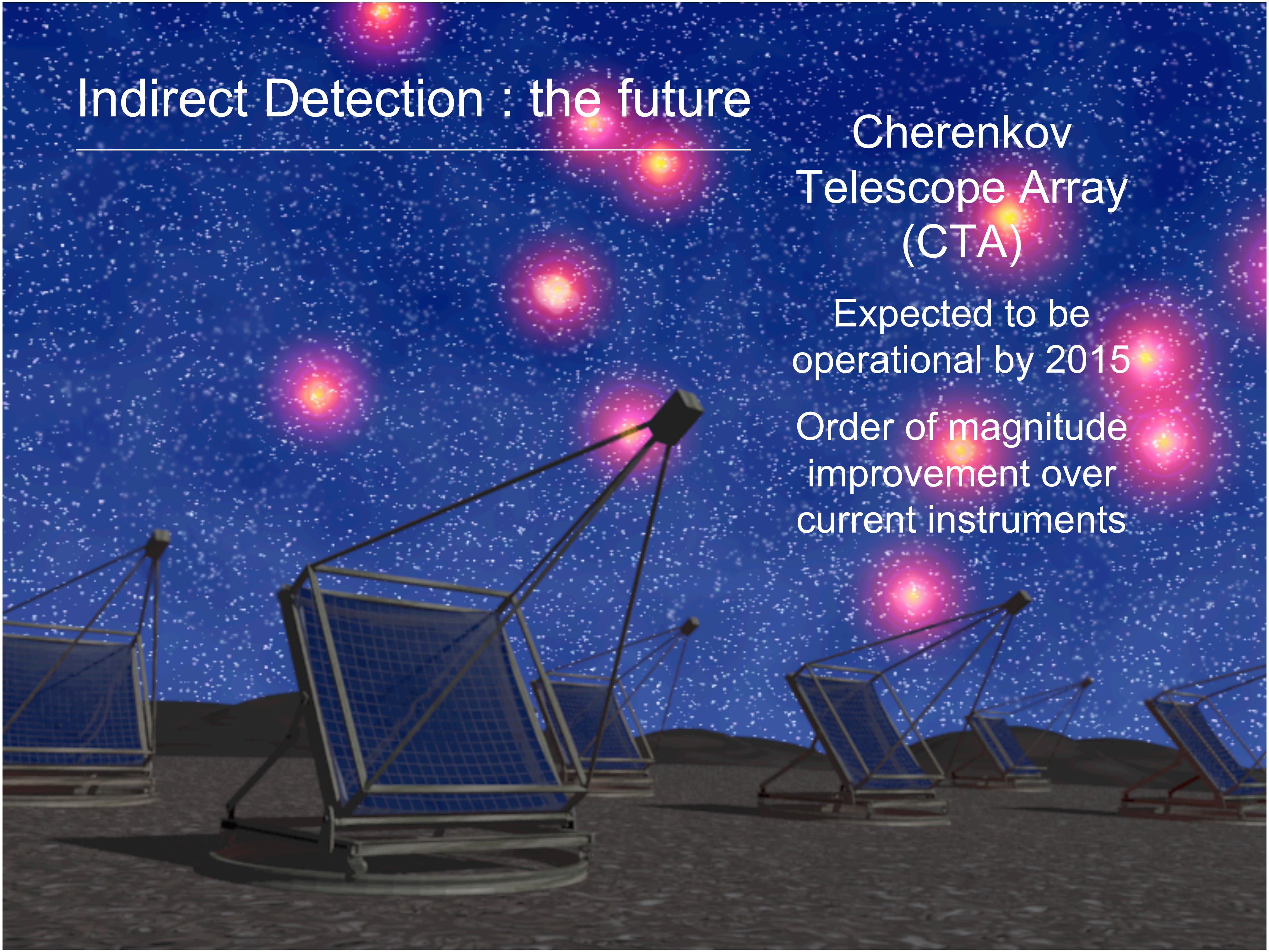
• Fits to observed signals can identify the dark matter mass to ~10-20% accuracy, and correctly identify the annihilation channel with ~60-80% probability.

• Success rate for mass and annihilation channel identification is robust with respect to changes in energy threshold, WIMP mass, energy resolution, and hadron rejection capabilities.

Indirect Detection : the future

PAMELA, Fermi, ACTs still operational, actively looking for dark matter signals

Indirect Detection : the future



Cherenkov Telescope Array (CTA)

Expected to be operational by 2015

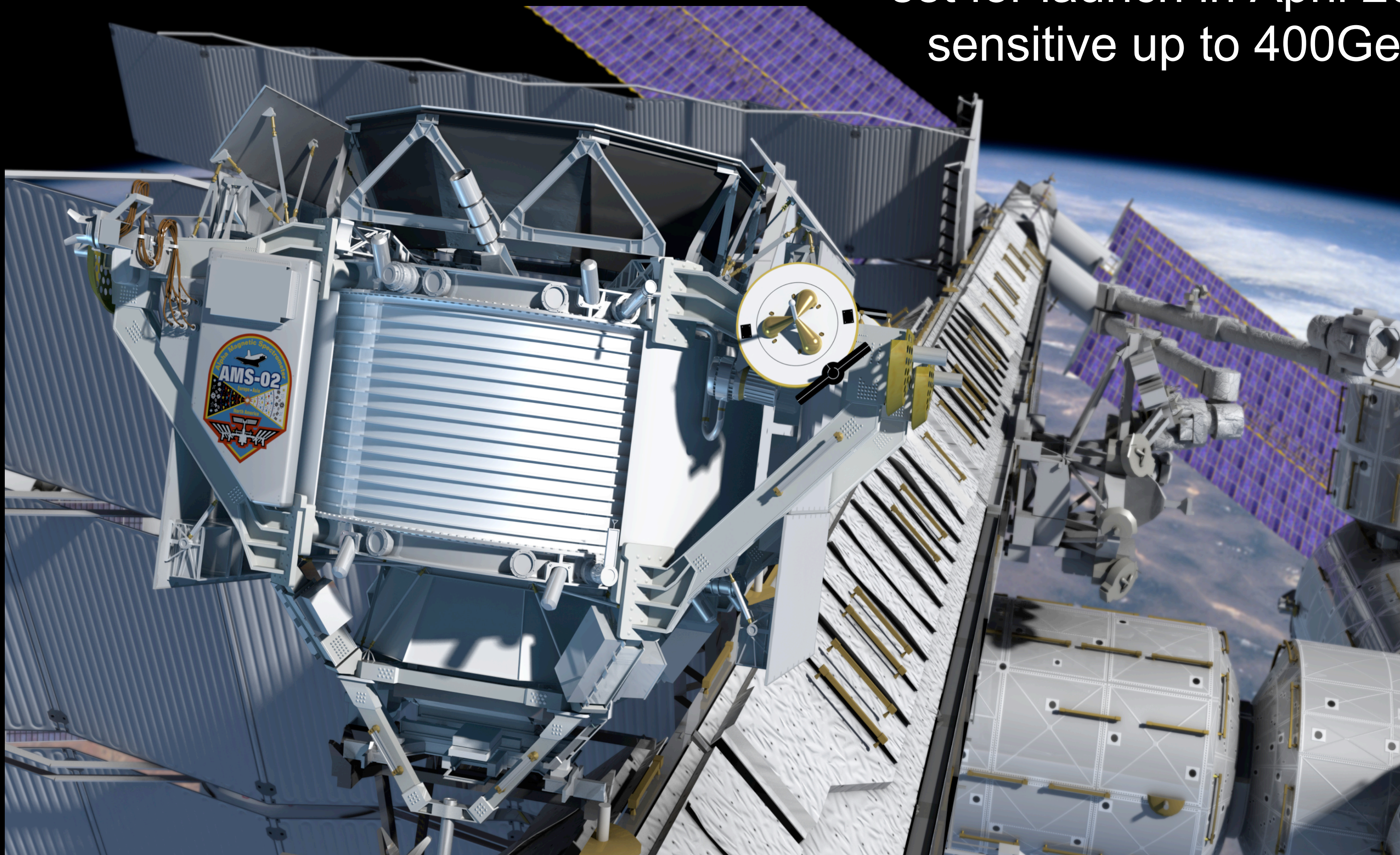
Order of magnitude improvement over current instruments

Indirect Detection : the future

AMS-02 :

set for launch in April 2011

sensitive up to 400GeV

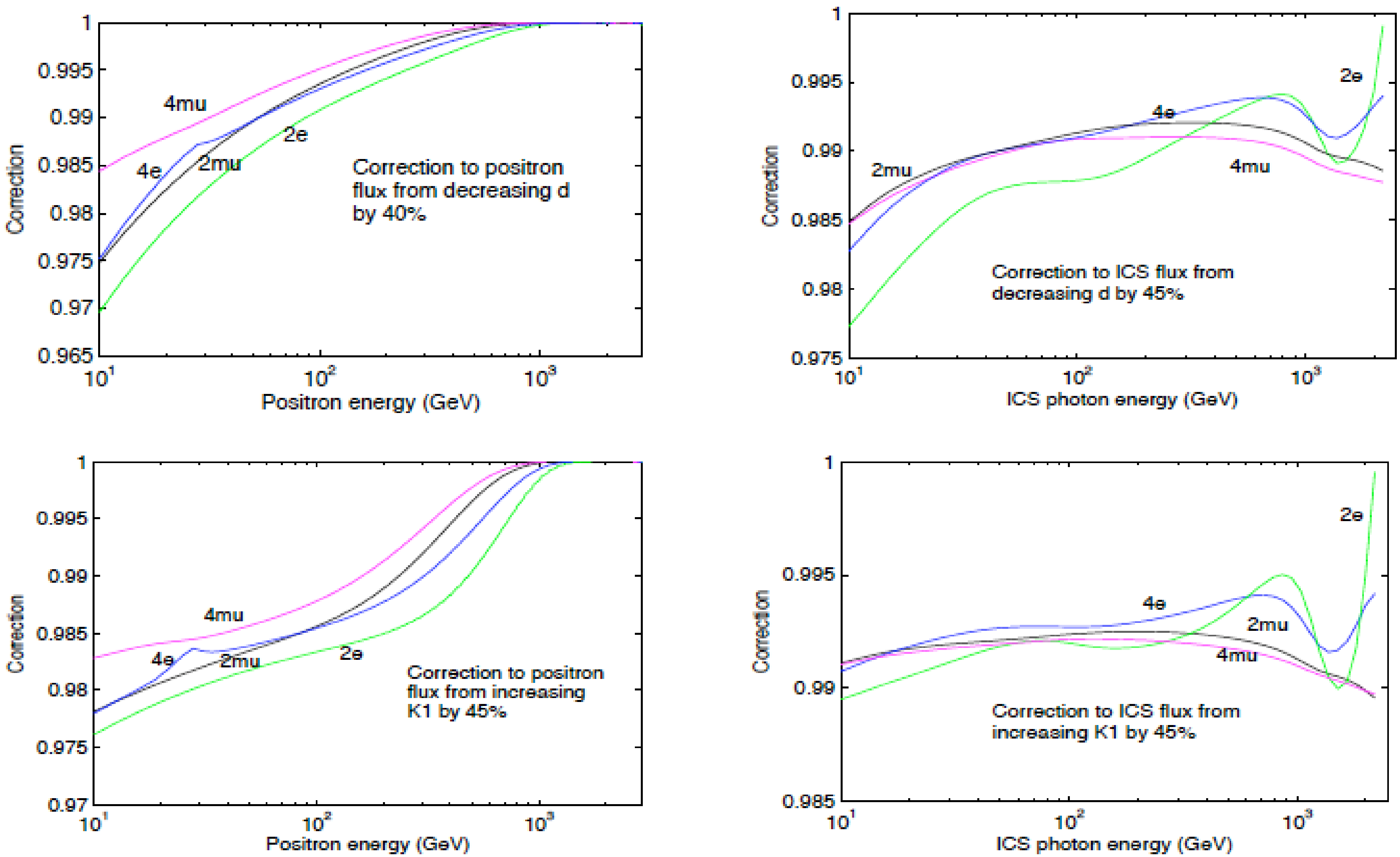


"When is science going to explain the dark matter I find in my belly button every morning?"

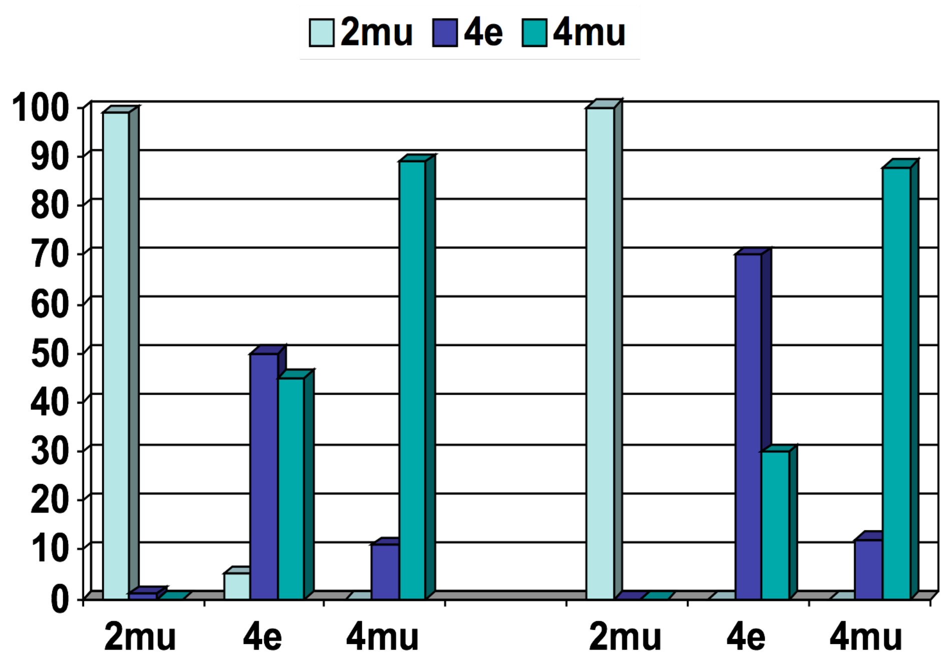
?

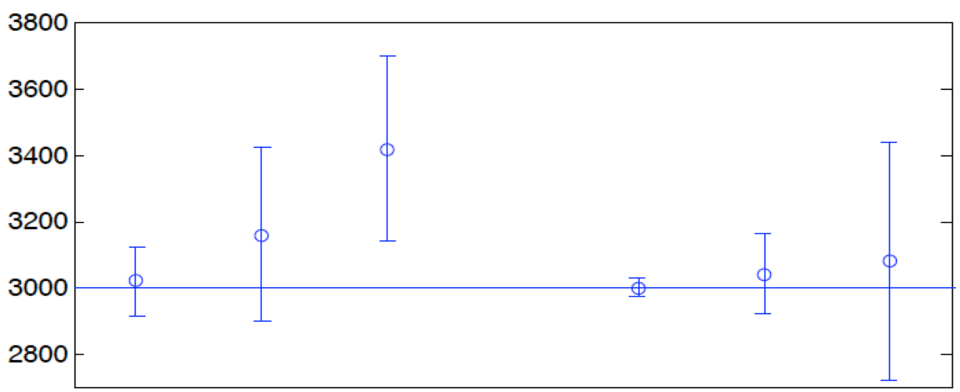
Questions

Convergence of Solutions



Case 3: A Lower Threshold





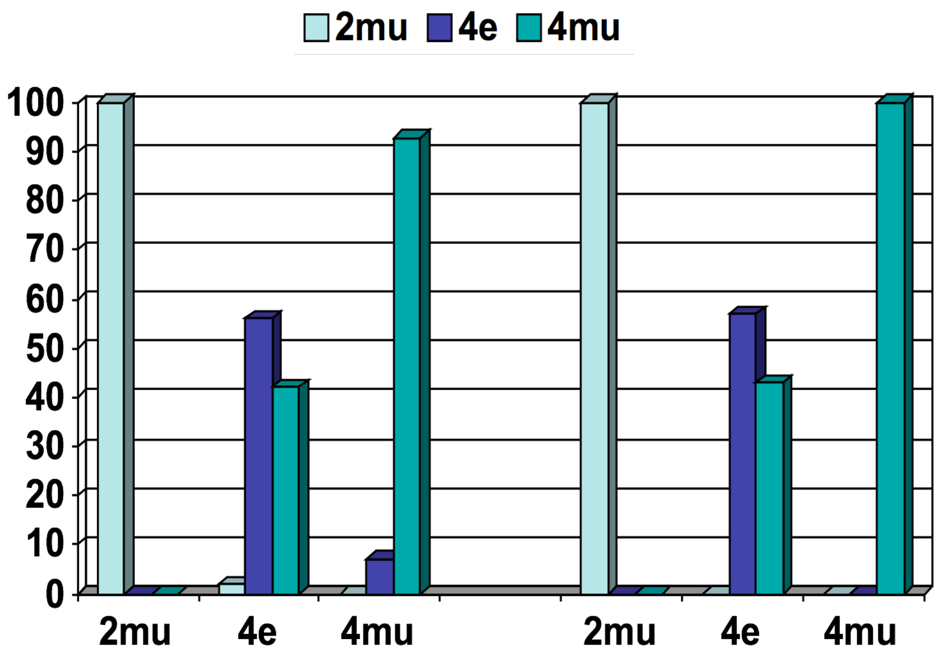
Threshold 200 GeV instead of 500 GeV.

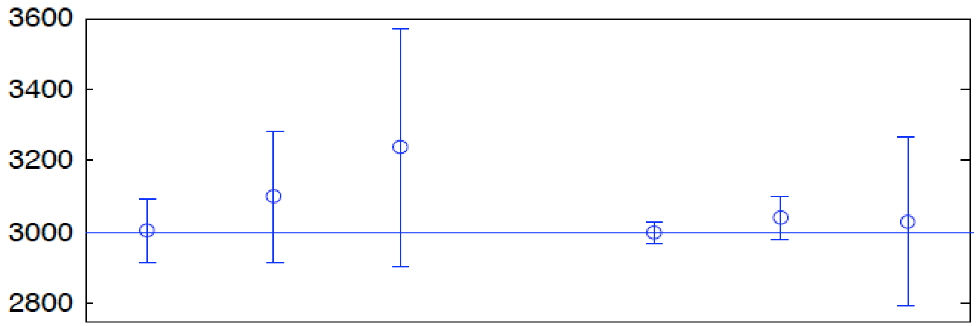
More statistics, but background also rises faster than signal at lower energies.

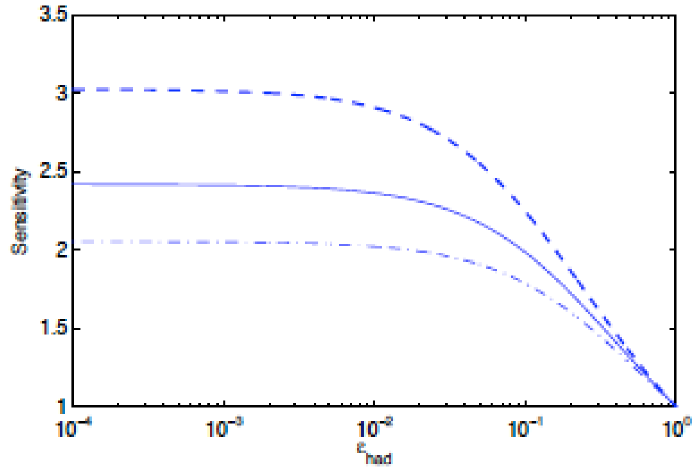
Success rates:
79% (current)
86% (future)

No significant improvement.

Case 4: Improved Hadron Rejection

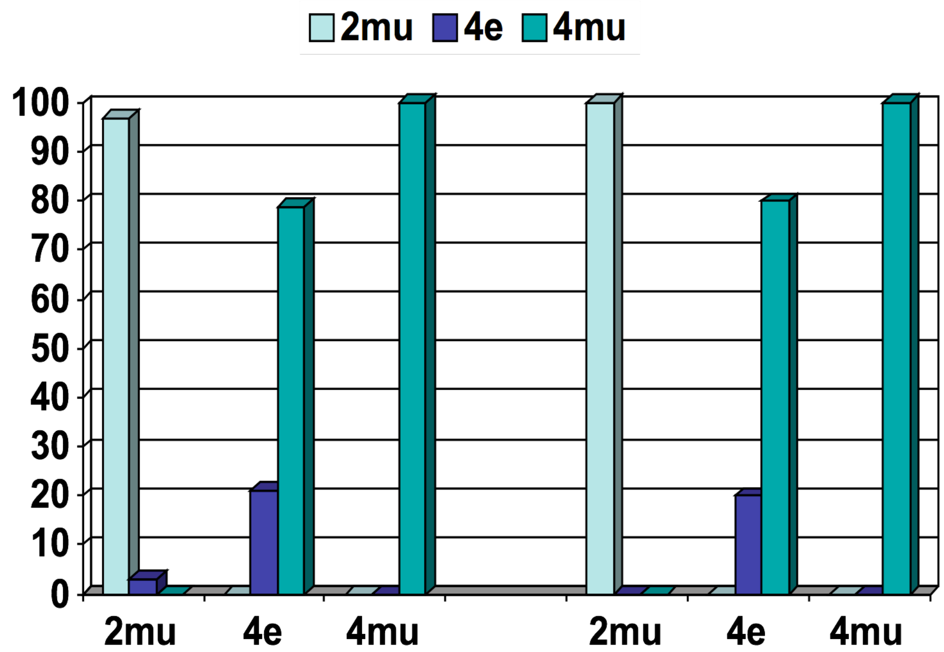


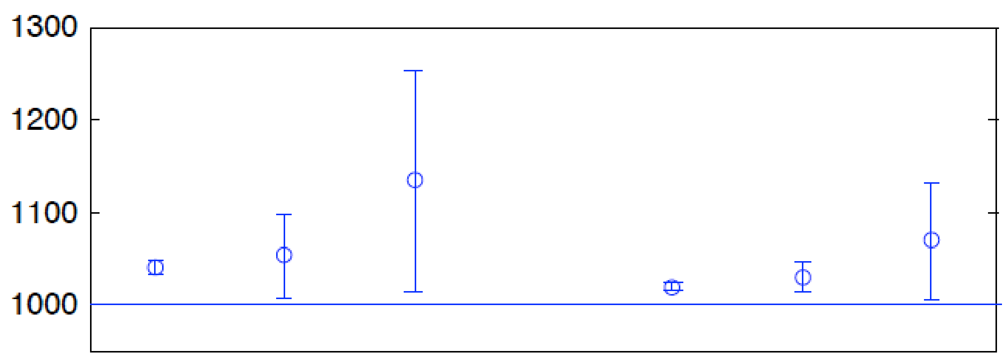




Have been using ε_{had}=1. Try ε_{had}=0.01. Fit quality significantly better, slight improvement in model identification.

Case 5: Lighter dark matter





Use m_χ= 1 TeV instead of m_χ= 3 TeV.

Signal has m_χ^{-3} dependence, but will have fewer energy bins.

Fits favor 4mu channel when annihilation is into 4 leptons.