PAMELA, Fermi and Indirect Detection of Dark Matter

Michele Papucci

(IAS)

P.Meade, M.P., T.Volansky 0901.2925
P.Meade, M.P., A.Strumia, T.Volansky 0905.0480
M.P., A.Strumia 0912.0742

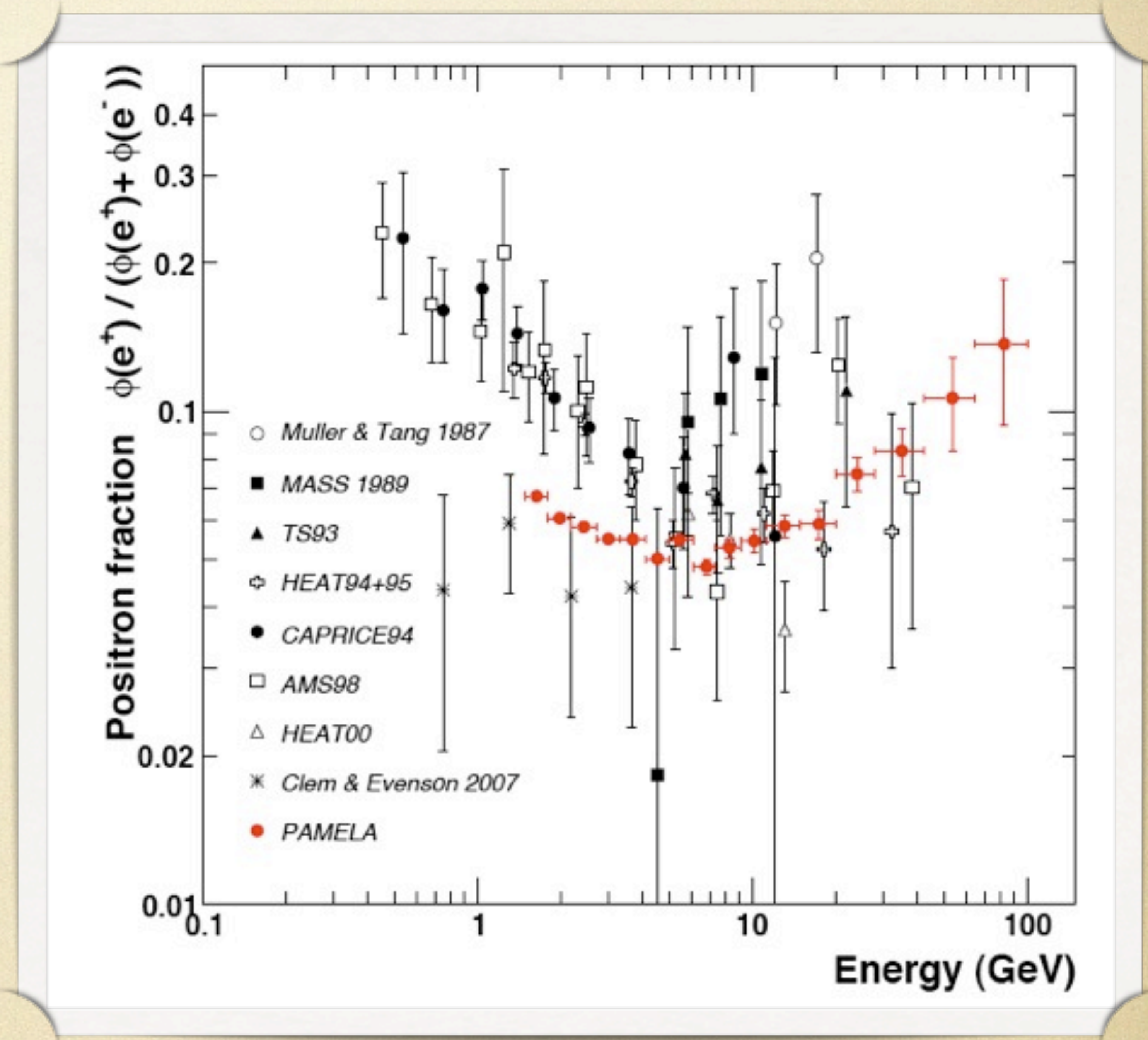
Cornell, Mar 10th 2010

Outline

- Review of PAMELA, Fermi and all that
- Dark Matter explanations (model indep′)
  - Which models fit the data?
  - Which models survive the γ constraints?
- Conclusions

Cosmic Rays Data - I

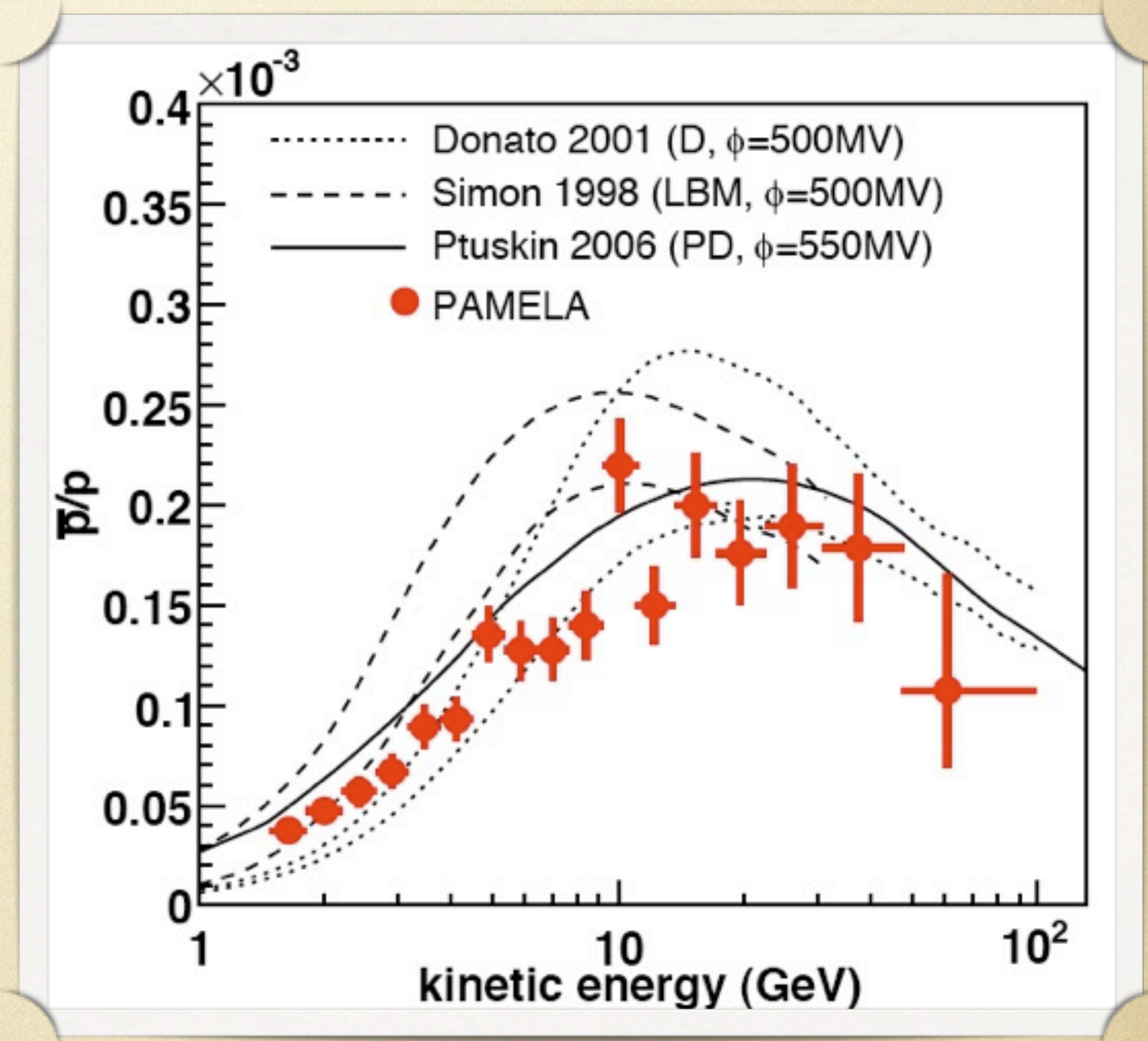
- The satellite PAMELA measured the positron fraction in the range 1-100 GeV
- The fraction increases by a factor ~3 in the 10-100 GeV range
- Naive expectation is e$^+$ fraction decreasing with energy (anomaly?)
- Proton rejection factor needed O(10^5)



☹ Presently no indep’ experiment to directly confirm it (FERMI will try to reproduce it, then wait for AMS02)

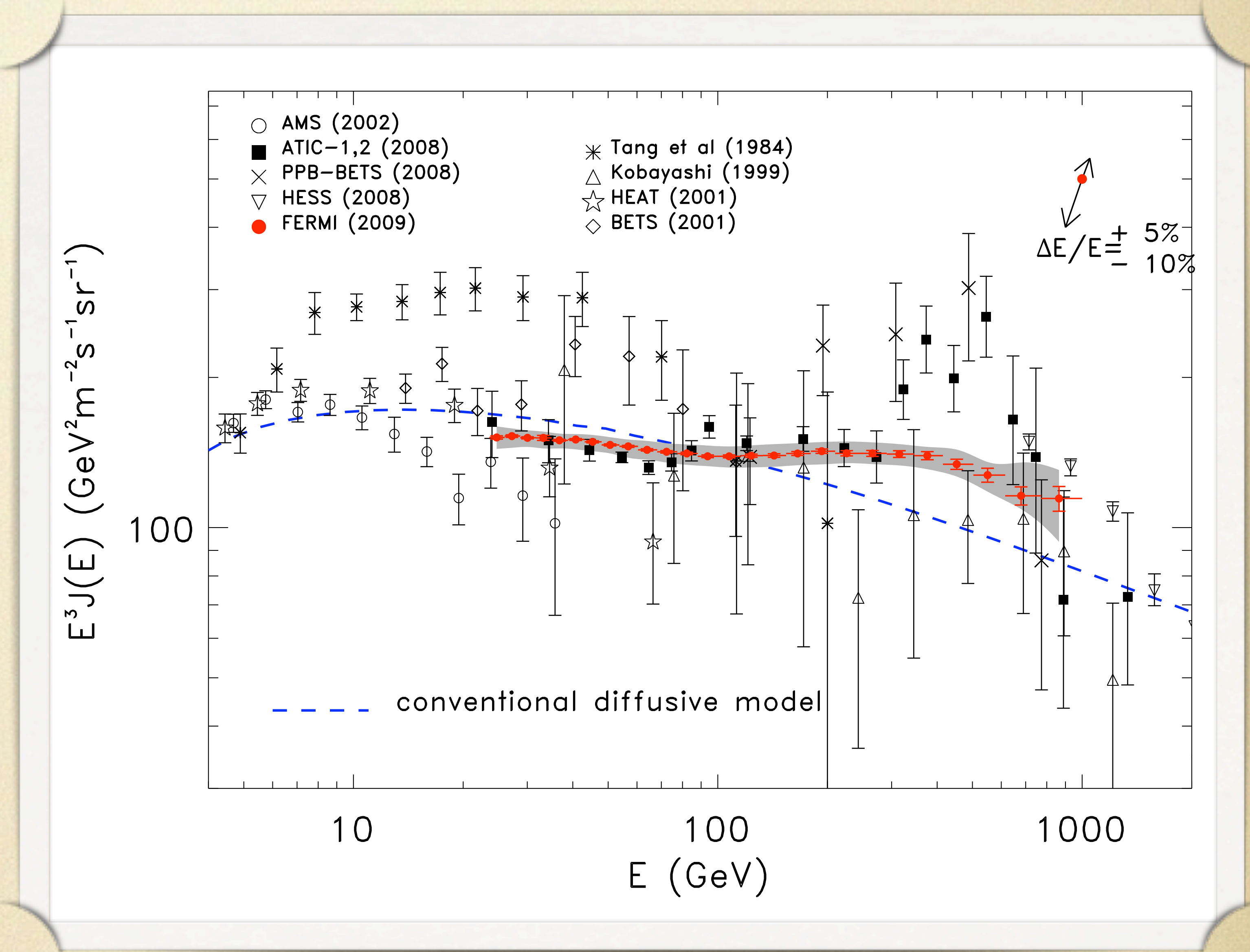
Cosmic Rays Data - II

- PAMELA also measured the antiproton/proton ratio in the range 1-100 GeV
- The ratio is consistent with the expectations
- No excess in hadronic CR activity



Cosmic Rays Data - III

- The satellite FERMI measured the $e^+ + e^-$ flux up to 1 TeV
- High statistics
- Spectrum is harder than previous low energy measurements
- Flux consistent with a power-law, but shallow feature visible

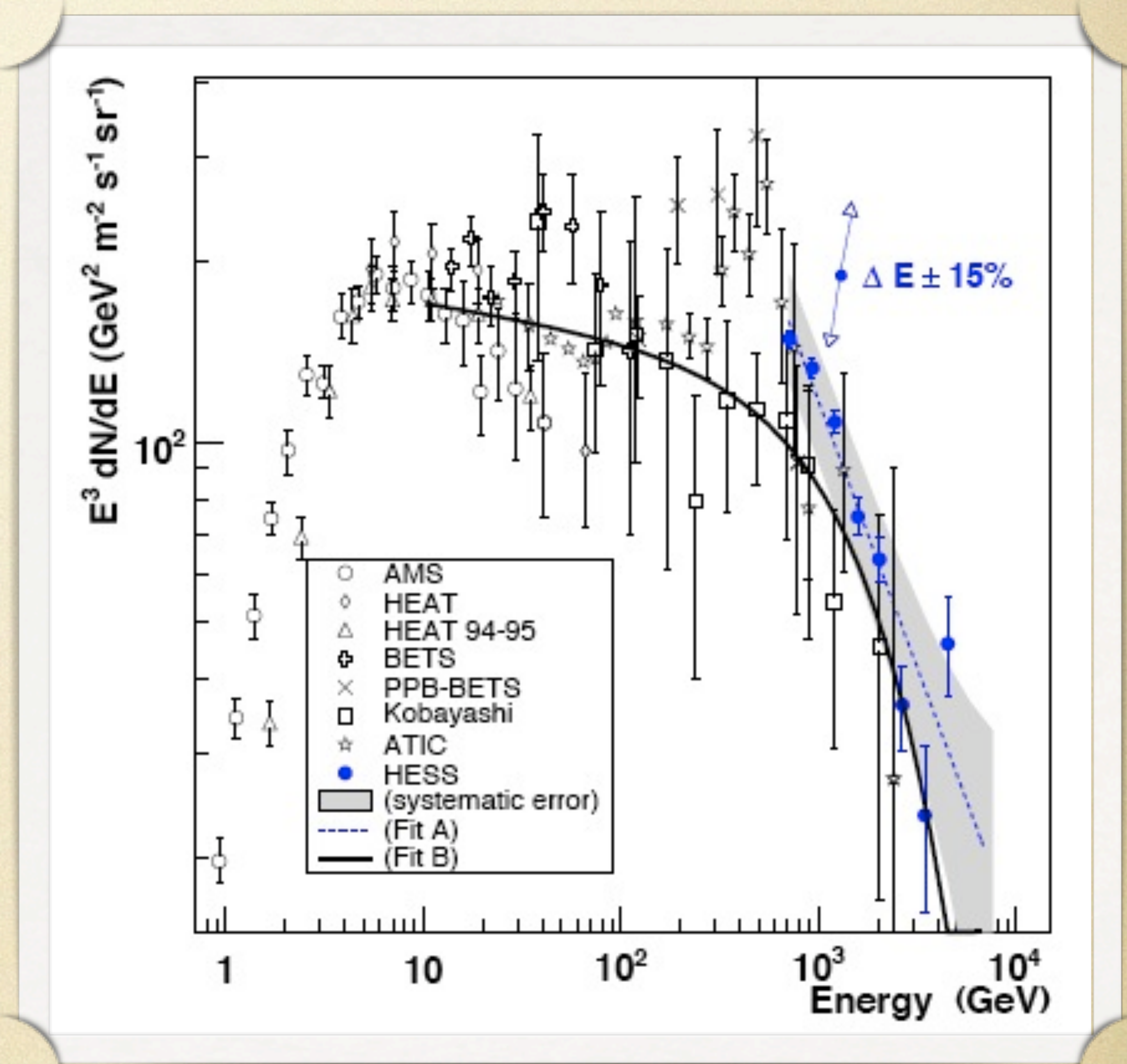


Does not confirm the ATIC bump!

(two experiments inconsistent with each other, need to resolve who's right)

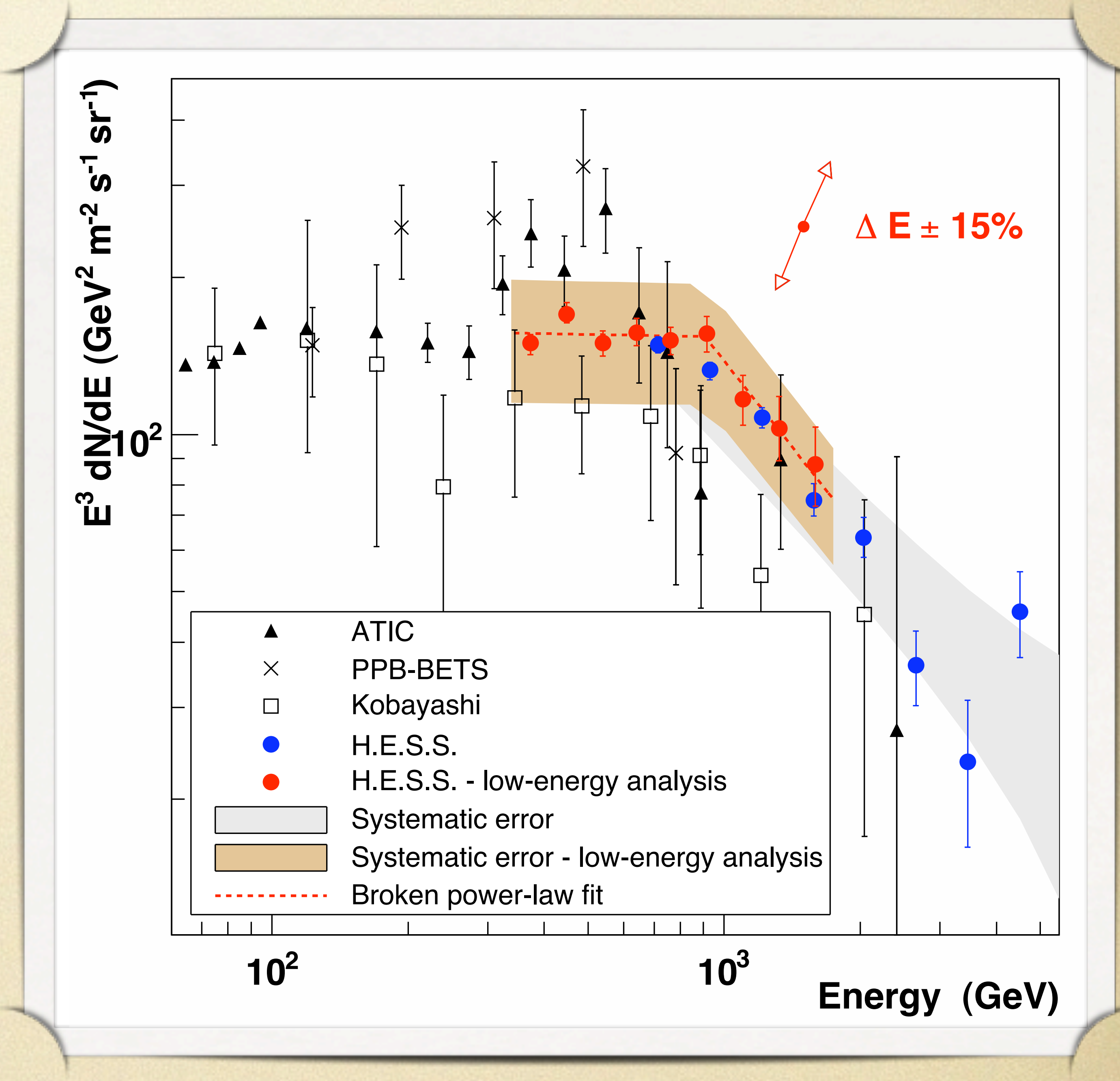
Cosmic Rays Data - IV

- The Air-Shower Cherenkov Telescope HESS measured also the $e^+ + e^-$ flux
- Measurement at higher energies than FERMI
- Break at 700-800 GeV: significant steepening of the spectrum observed



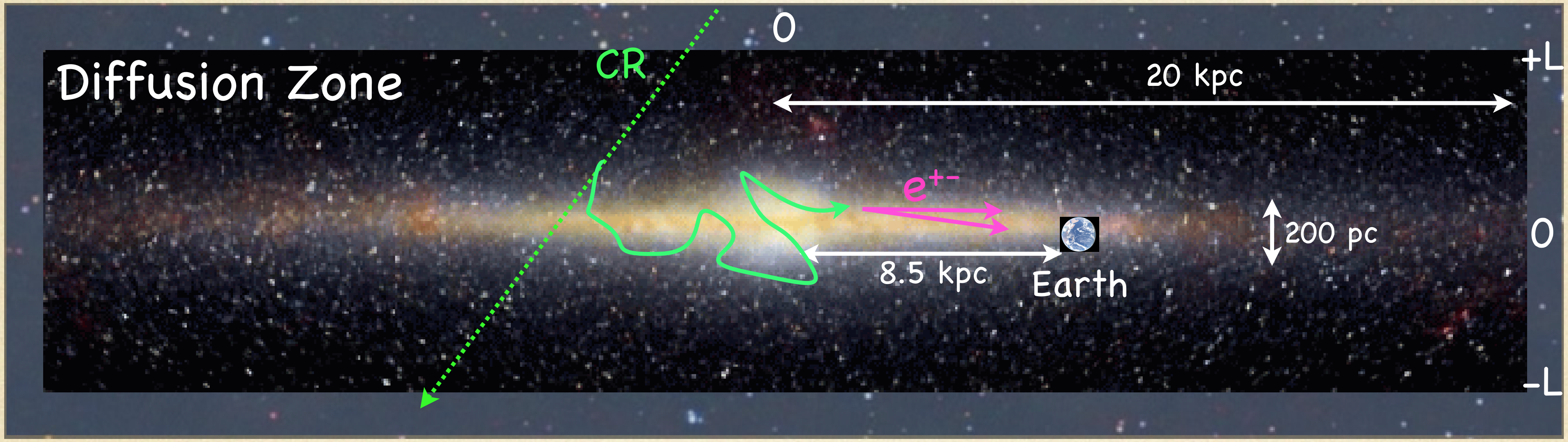
Cosmic Rays Data - IV

- The Air-Shower Cherenkov Telescope HESS measured also the $e^+ + e^-$ flux
- Measurement at higher energies than FERMI
- Break at 700-800 GeV: significant steepening of the spectrum observed



HESS later extended their measurement to lower energy to probe the break → no ATIC peak...

Cosmic Rays Propagation 101



- Cosmic Rays are diffused by magnetic field inhomogeneities
- CRs loose energy by interacting with the interstellar medium
  (electrons: synchrotron radiation and Inverse Compton Scattering onto starlight, IR and CMB photons)
- Electrons and protons are primary cosmic rays and are originated by astrophysical sources (SN remnants)

$$-K(E,x)\nabla^2 n_p(E,x) = Q_p(E,x)$$

$$-K(E,x)\nabla^2 n_{e^-}(E,x) - \frac{\partial}{\partial E}\left(b(E,x)n_{e^-}(E,x)\right) = Q_{e^-}(E,x)$$

Cosmic Rays Propagation 101

- Positrons (and antiprotons) are secondary cosmic rays and originate in collisions of cosmic rays with interstellar gas:

$$-K(E,x)\nabla^2 n_{e^+}(E,x) - \frac{\partial}{\partial E}\left(b(E,x) n_{e^+}(E,x)\right) = Q_{e^+}(E,x)$$

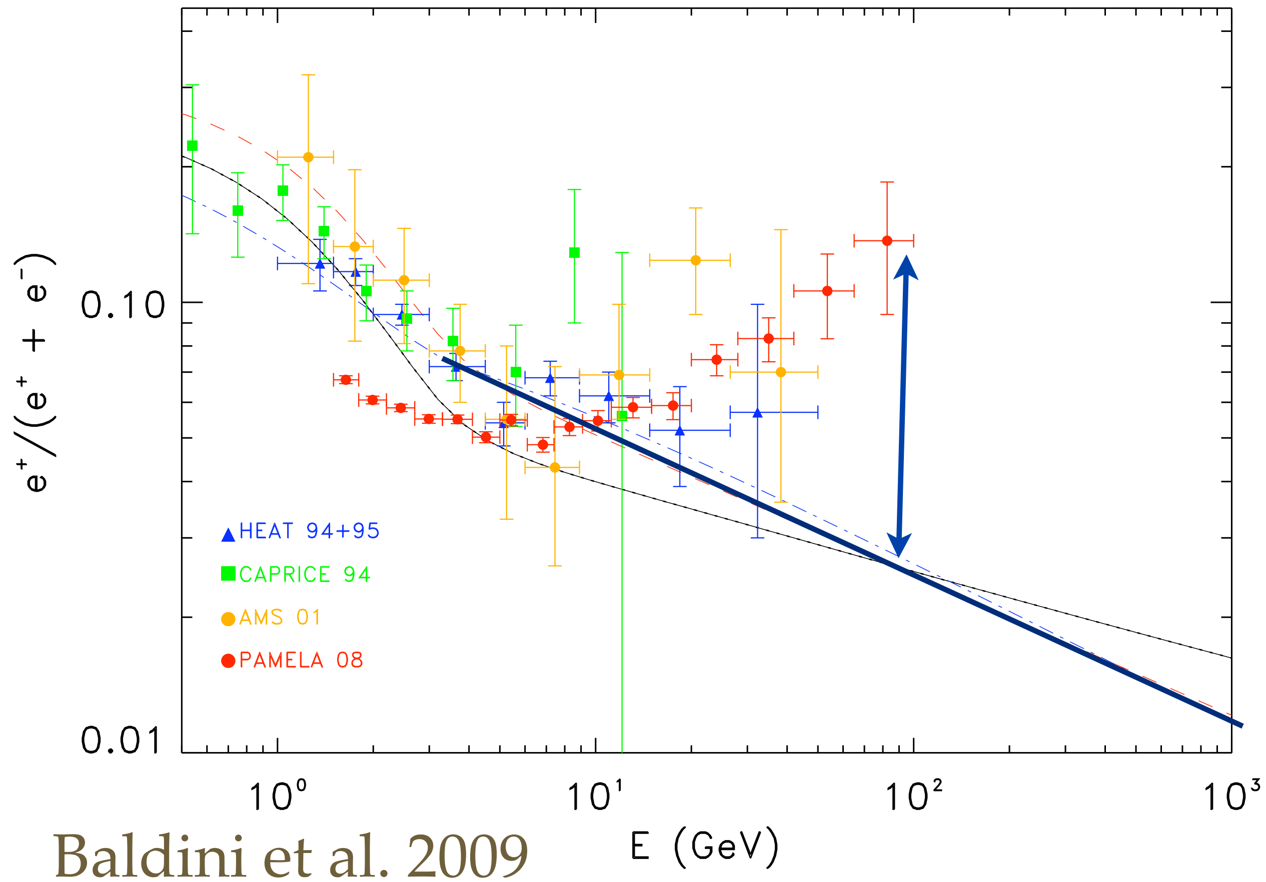
$$Q_{e^+} = \int d^3x\, dE\, n_p(E,x)\, n_{H,He}(x)\, \sigma_{p\to\pi^+ + X}(E)$$

$K(E,x) \propto E^{\delta}$, $\delta > 0$ → diffusion softens spectra

$K(E,x) \propto E^{\delta}$ + energy loss → high E $e^{\pm}$ come from nearby

K(E,x) and $Q_e(E,x)$ sufficiently omogeneous around us (few kpc) → positrons are softer than electrons ← Standard assumption!

Cosmic Rays Propagation 101



Baldini et al. 2009

- FERMI measurement → the denominator in the positron fraction is under control
- PAMELA clearly observe a deviation from the standard picture

Why?

What can explain the excess?

- It's just Cosmic Ray Propagation:
  - Some of the assumptions about homogeneity of K_0, L, $Q_{p,e}$ (or energy indep' of L) are not good approx' at these energies (Katz, Waxman; Piran et al.)
- Positrons have also a primary component
  - New source(s) are needed...

What can explain the excess?

- New Astrophysical sources:
  - Positrons are created and accelerated in surroundings of pulsars (Pulsar Winds Nebulae) or in secondary accel' of Supernova Remnants
  - Some nearby Pulsar may explain PAMELA and FERMI
  - HESS explanation: spectrum expected to be $E^a \exp(-E/E_c)$
  - Plausible but not clear how positrons can escape to the Interstellar Medium

What can explain the excess?

- New Astrophysical sources
- Indirect signal of Dark Matter:
    - Dark Matter in the Galactic Halo may annihilate or decay (on cosmological timescales)
    - Positrons (and electron excess) are DM products

☞ Explore this possibility in the rest of the talk....

(Model indep') Analysis

- DM annihilations involving SM particles end up in electrons/positrons, (anti-)protons, photons, neutrinos.
- Electron, positrons, (anti-)protons are constrained by PAMELA & FERMI & HESS
- Photons are always present
- Neutrinos may or may not be present

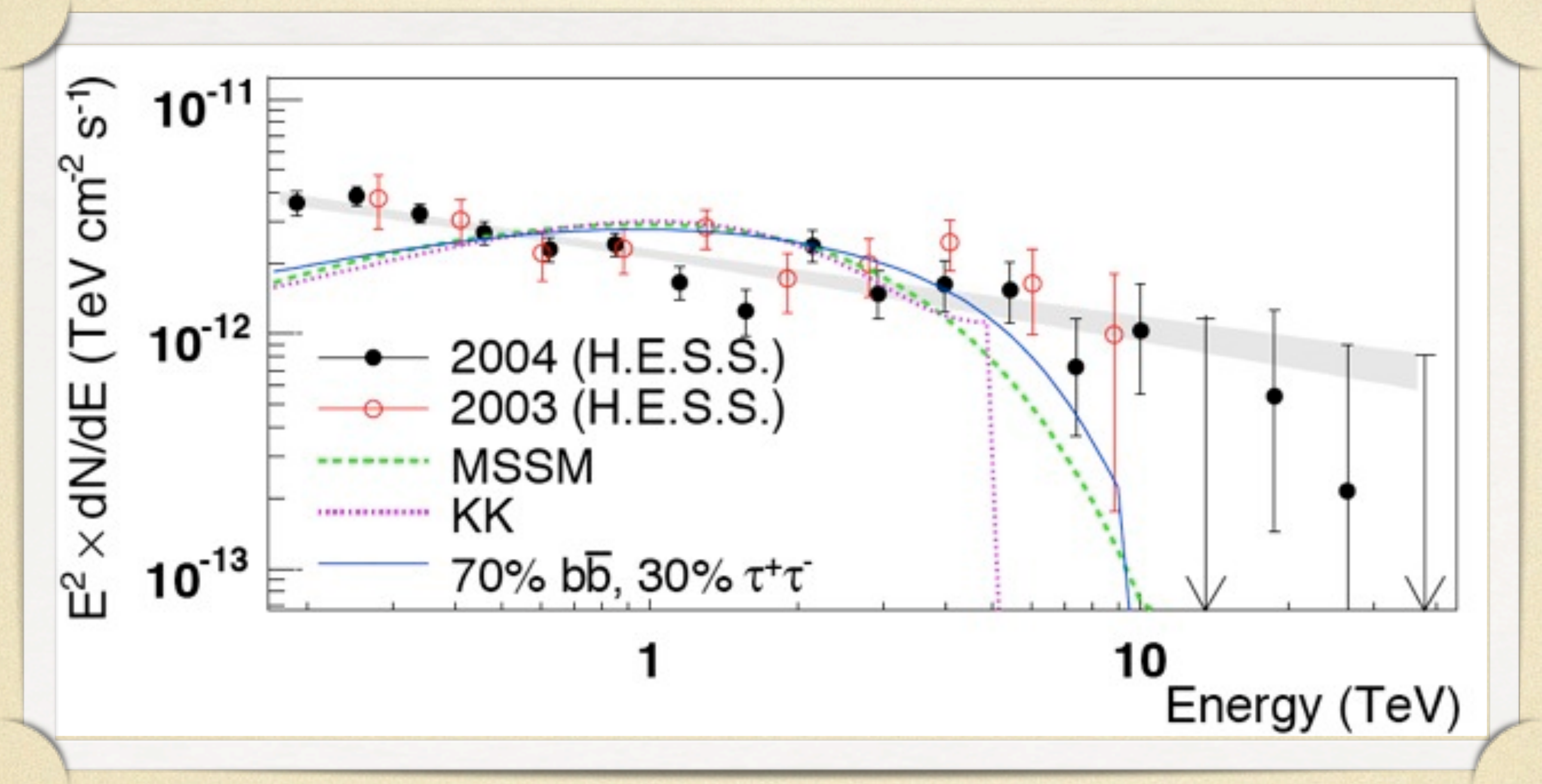
➠ Fit PAMELA+FERMI+HESS and then look at gamma and neutrino observatories!

Relevant γ & ν data

- HESS measurements:
  - γ's from Galactic Center: $\vartheta < 0.1°$
  - γ's from Galactic "Ridge": $|b| < 0.3°$, $|l| < 0.8°$
- SuperKamiokande: ν's in cone up to 30° around Gal Center
- WMAP*
- Fermi: all sky gamma ray data

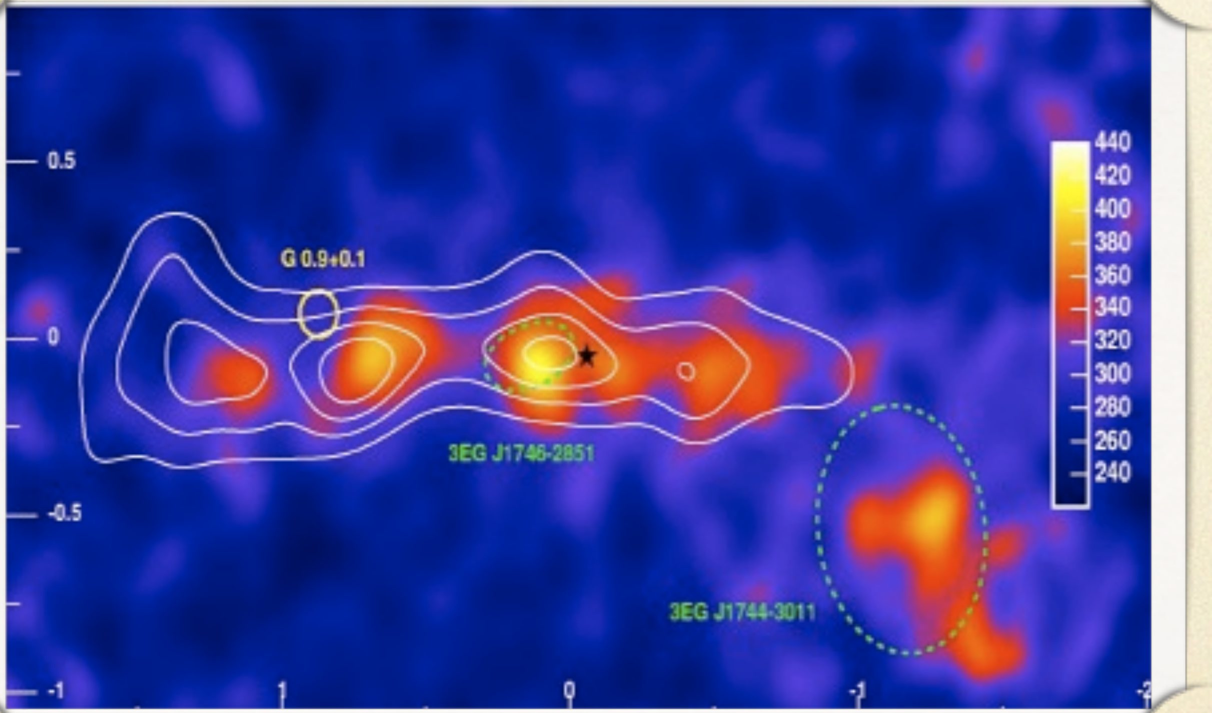
→ Strongest constraints!

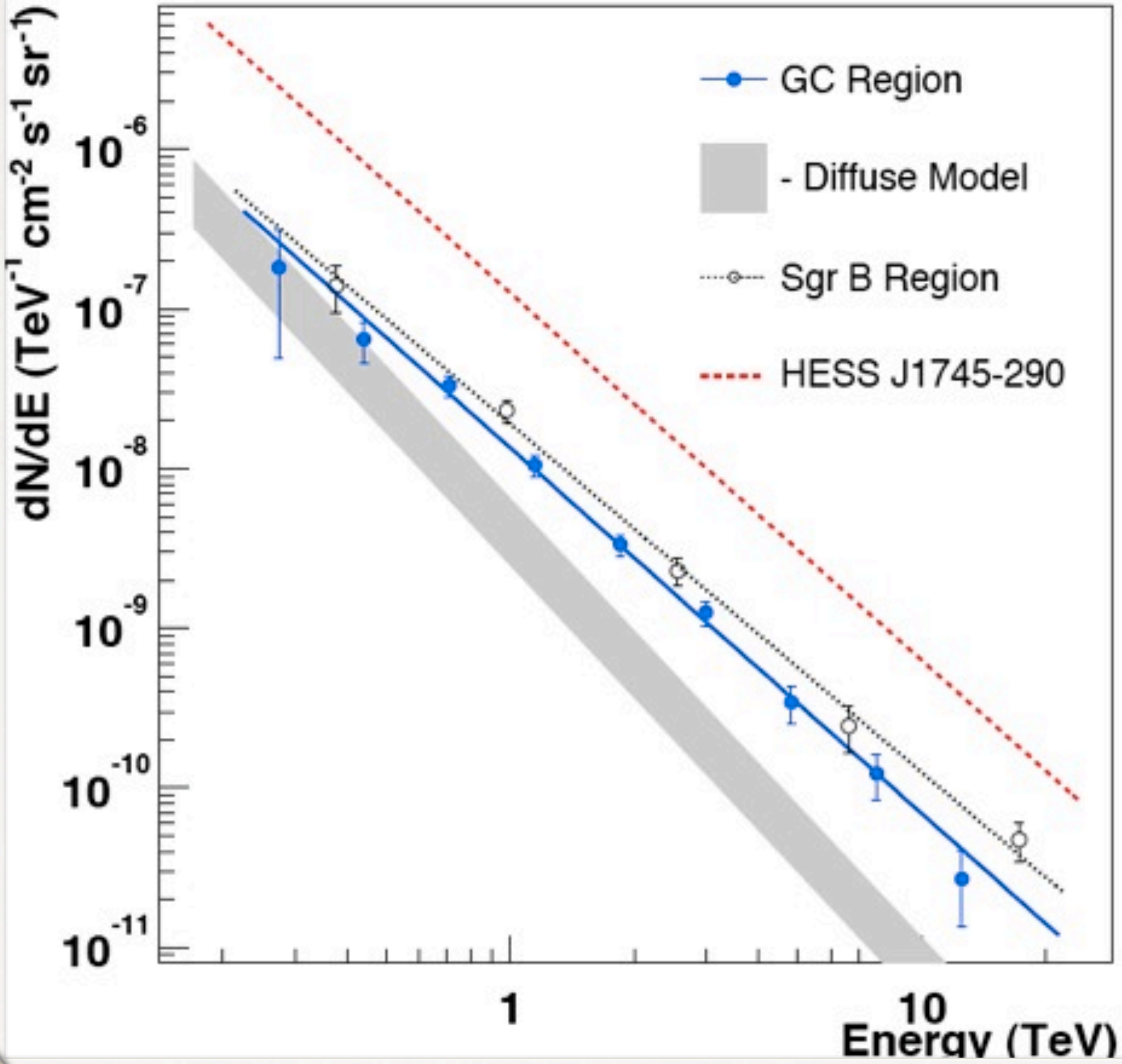
HESS: Galactic Center



- HESS observes a region of $d\Omega = 2\ 10^{-5}$ around the Galactic Center
- A powerful source of gamma rays with a spectrum well fitted by a power law in the energy range of 200 GeV-30 TeV
- An astrophysical source → DM signal should be much smaller
- Powerful to constrain very cuspy DM profiles, but looking in a larger area may be better...

HESS: Galactic Ridge



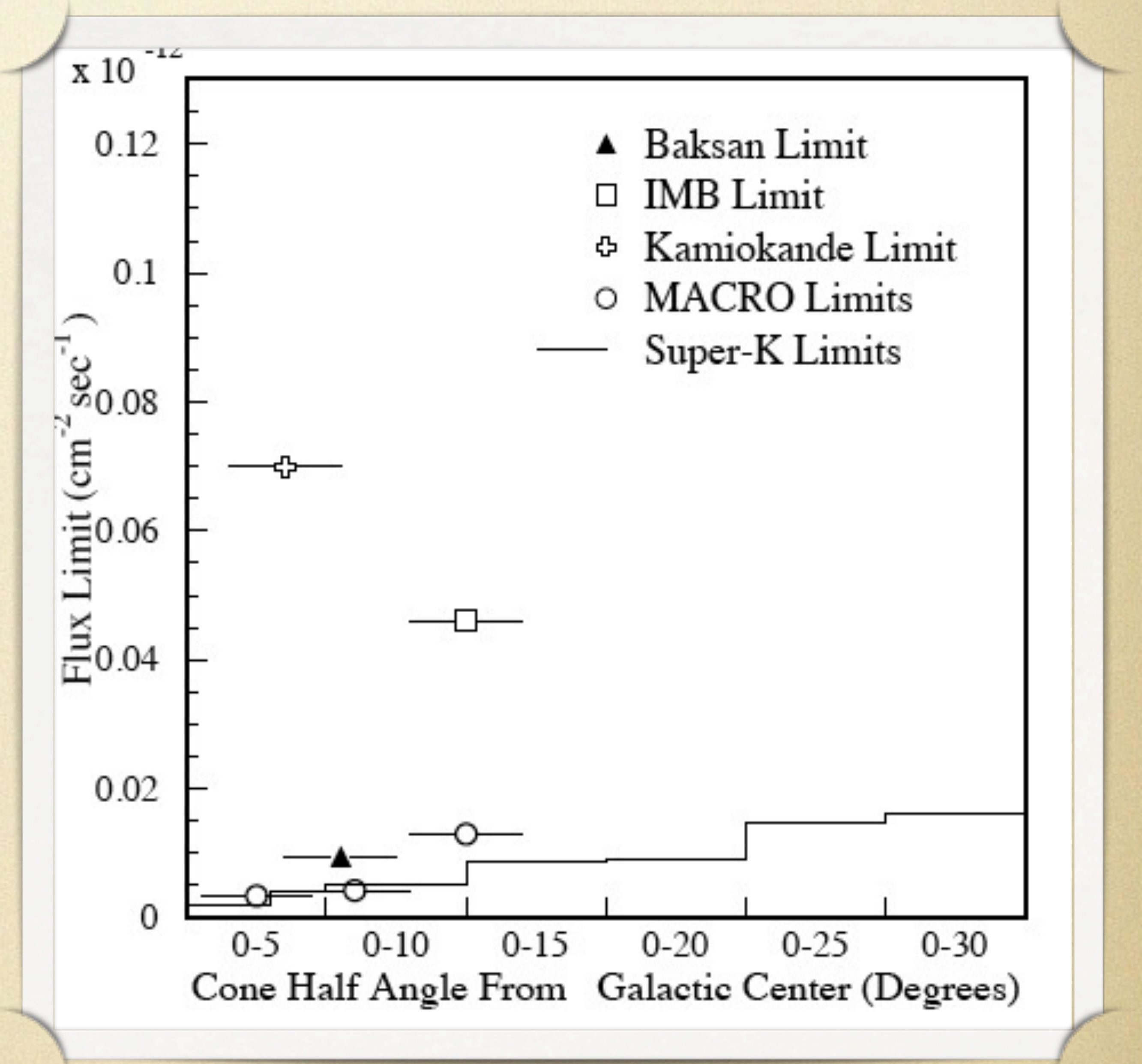


- A rectangle of 0.6°x1.6° around the Galactic Center
- After subtracting point sources it reveals areas of diffuse gamma ray emission
- Power-law spectrum extending to 10 TeV → astrophysical

Larger area and smaller flux detected → stronger constraints!

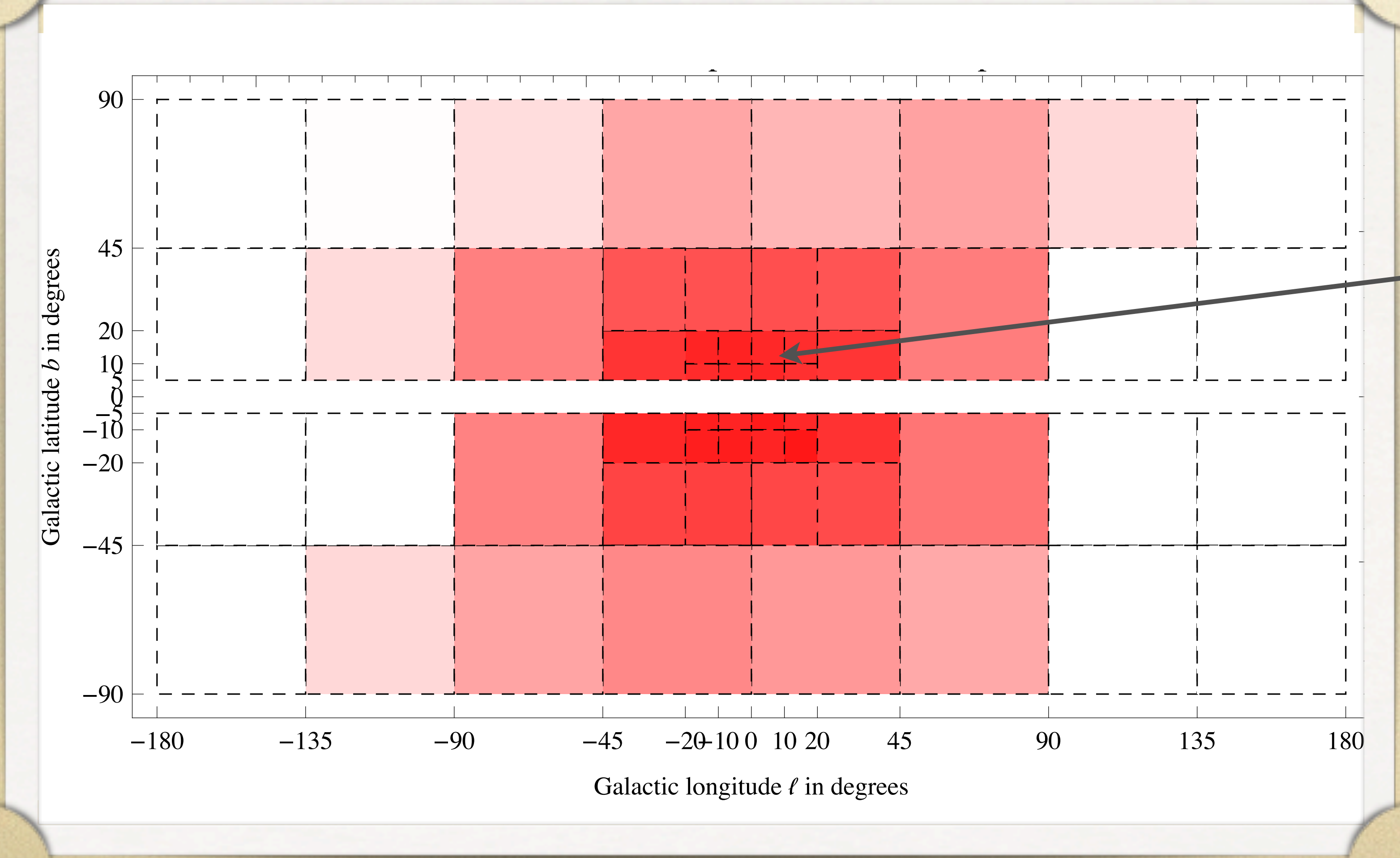
SuperK upgoing muons

- Neutrinos coming from the Galactic Center show up as up-going muons in detectors in the northern hemisphere (SuperK, Antares, ...)
- Best bounds to date from SuperK
- Very low signals from annihilations in the Sun and Earth in these models → IceCUBE less interesting



Fermi γ ray data

- Full dataset released (~16M events, covering all sky)
- Analysis software available
  - Divide the sky in different regions (exclude Gal plane)
  - Extract the differential γ flux in each region



Stronger constraints from inner 10°<|b|<20°

Fermi γ ray data

- Combine all the regions (and all energy bins) in one fit:

$$\chi^2 = \sum_i \frac{(\Phi_i^{\rm DM}(E_i(1+e)) - \Phi_i^{\rm exp})^2}{\delta\Phi^2}\Theta(\Phi_i^{\rm DM} - \Phi_i^{\rm exp}) + \frac{e^2}{\delta e^2} \ ,$$

δe/e → energy scale uncert.

(Reduced dependence on the choice of the sky division/energy binning)

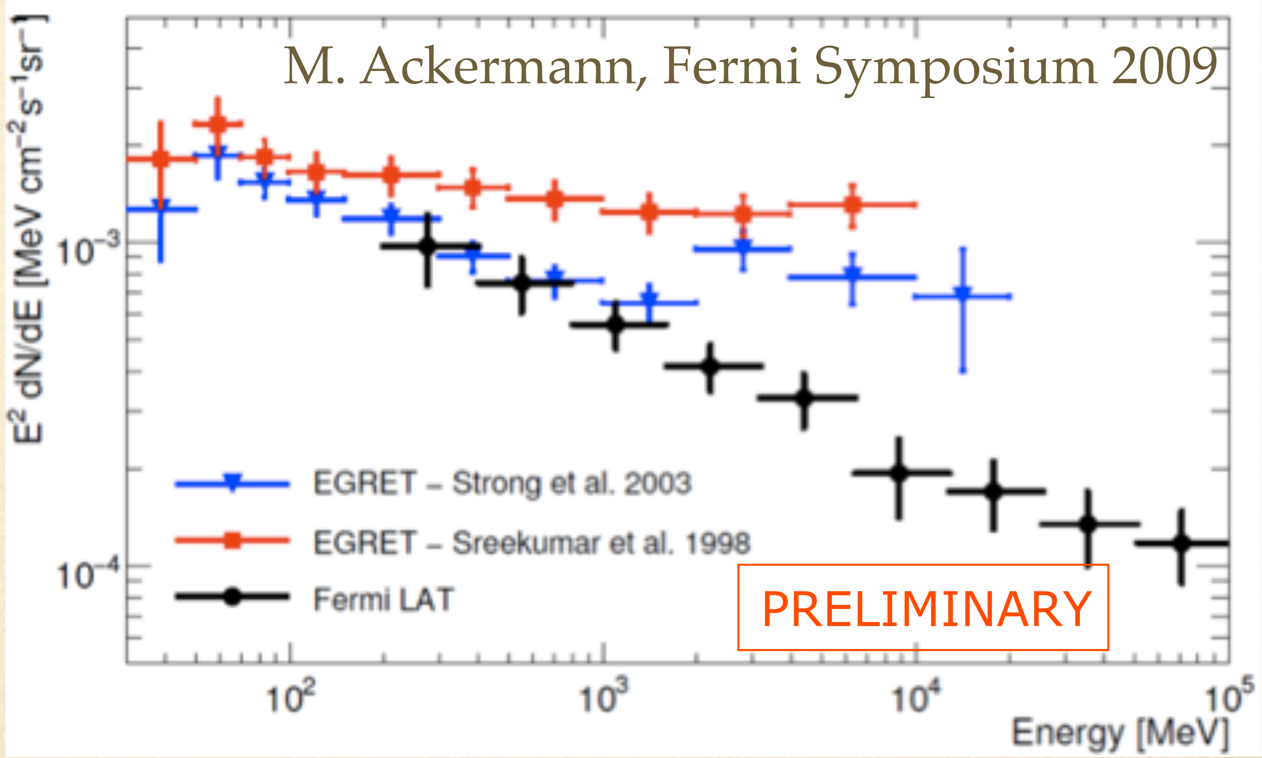
- Require that DM contrib' does not exceed the measured flux @ 3σ

- Do not try to subtract anything (be conservative)

Fermi γ ray data

Fermi: extragalactic isotropic emission

(after removing foregrounds, more model dep')

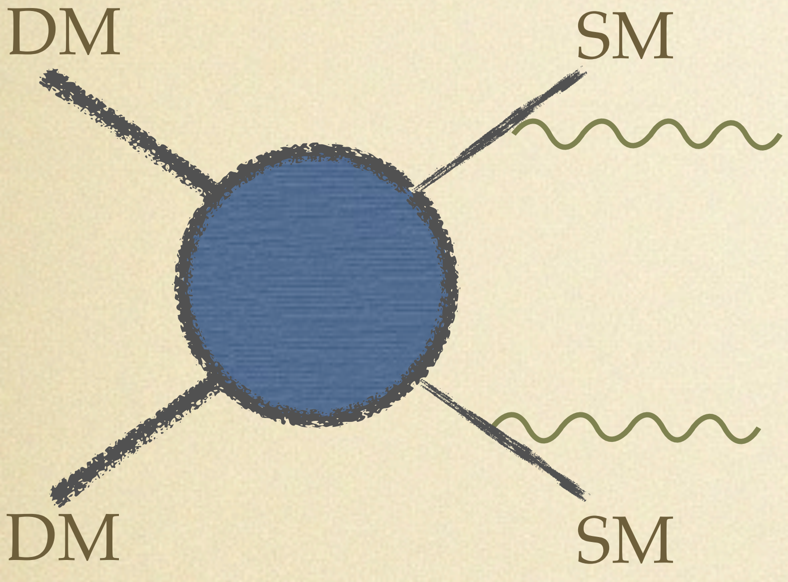


→ constrain DM extragal' contrib (MP, A.Strumia 2009; M.Cirelli et al. 2009)

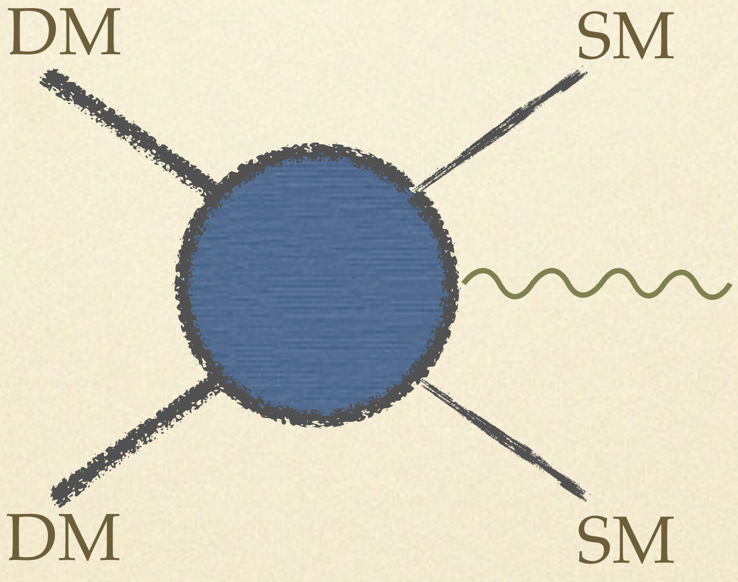
$$\frac{\Phi_{\rm cosmo}}{\Phi_{\rm galactic}} \sim \frac{\rho_{\rm cosmo} R_{\rm cosmo}}{\rho_\odot R_\odot} \sim 1$$

relevant for decaying DM (and may probe models with γ peaks beyond Fermi energy reach thru redshift)

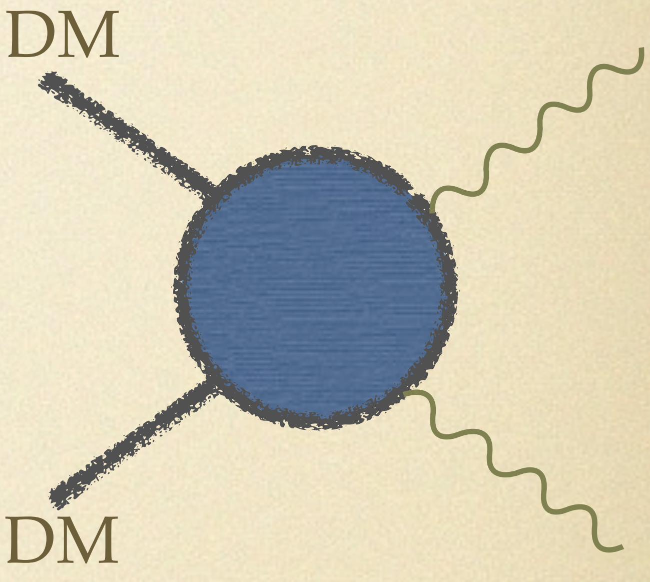
Many photons to consider



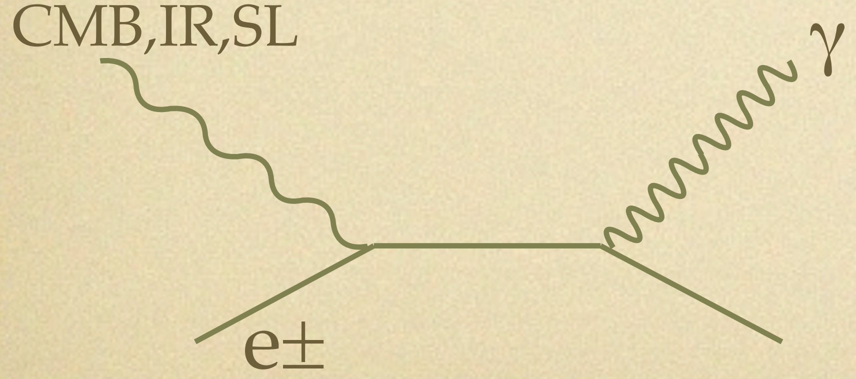
Final State Rad′
(soft+collinear)



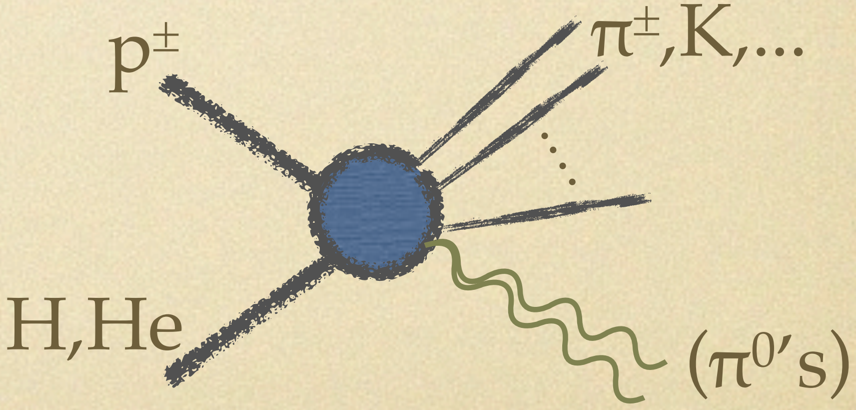
Hard emission



Higher order processes

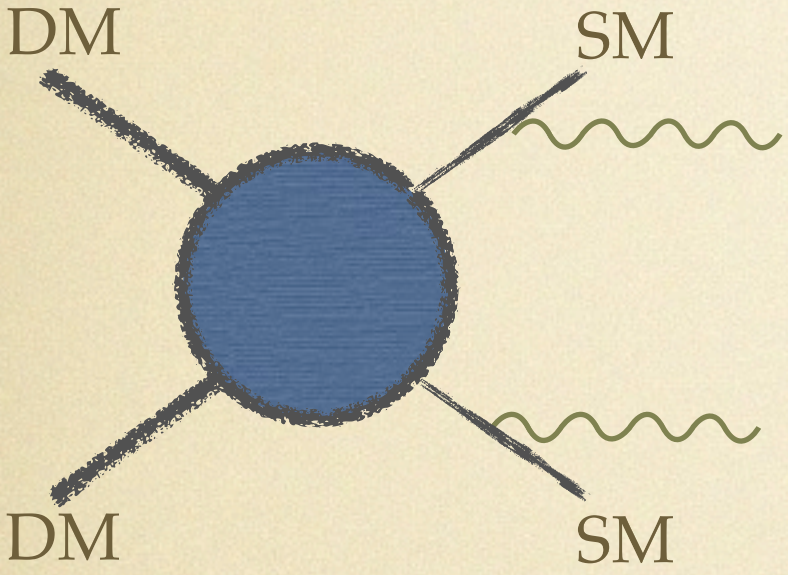


Inverse Compton



γ′s from proton int′ with ISM

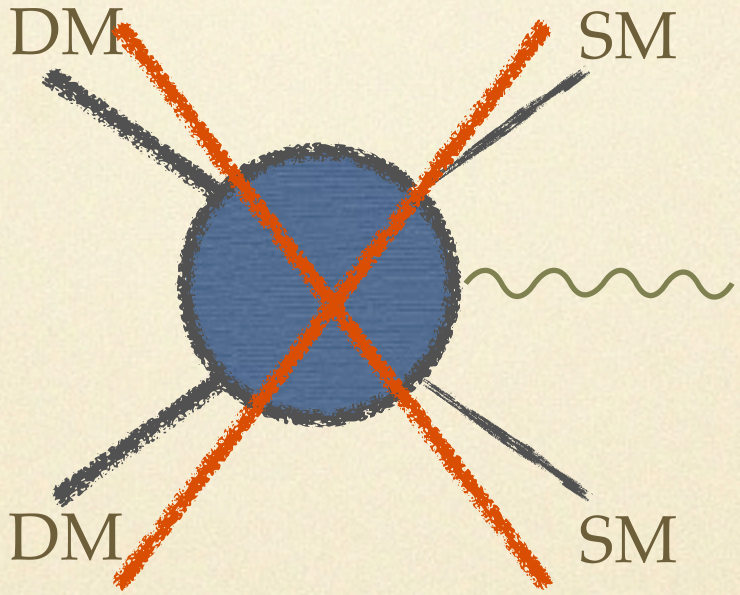
Many photons to consider



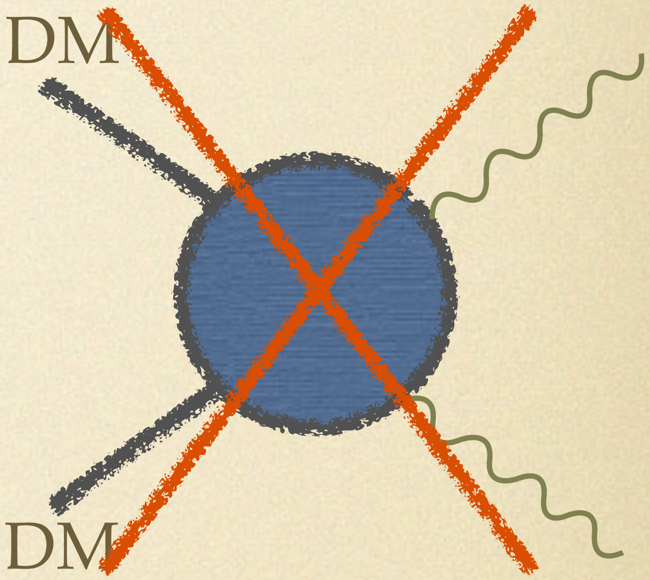
Final State Rad′

(soft+collinear)

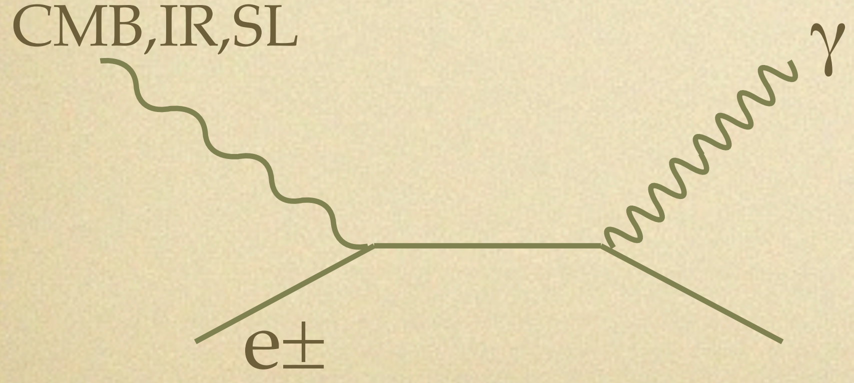
+ γ′s from hadro decays



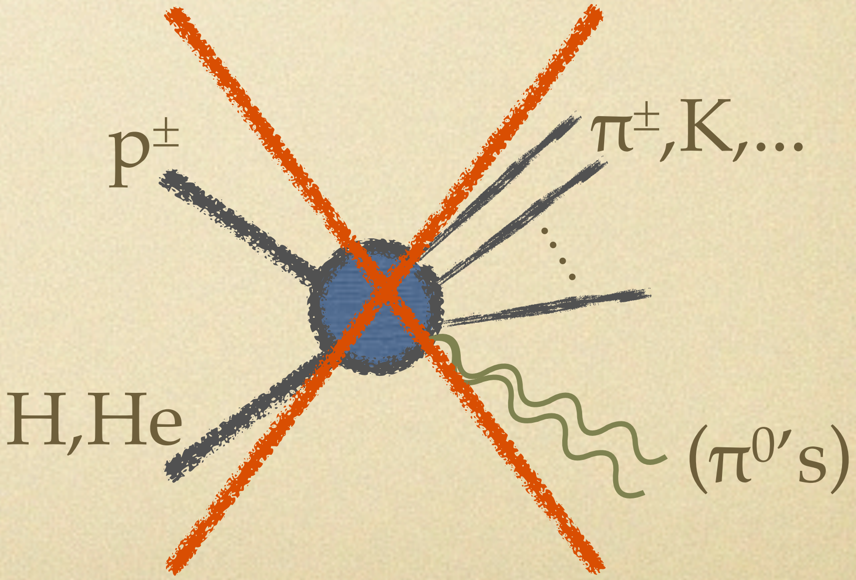
Hard emission



Higher order processes

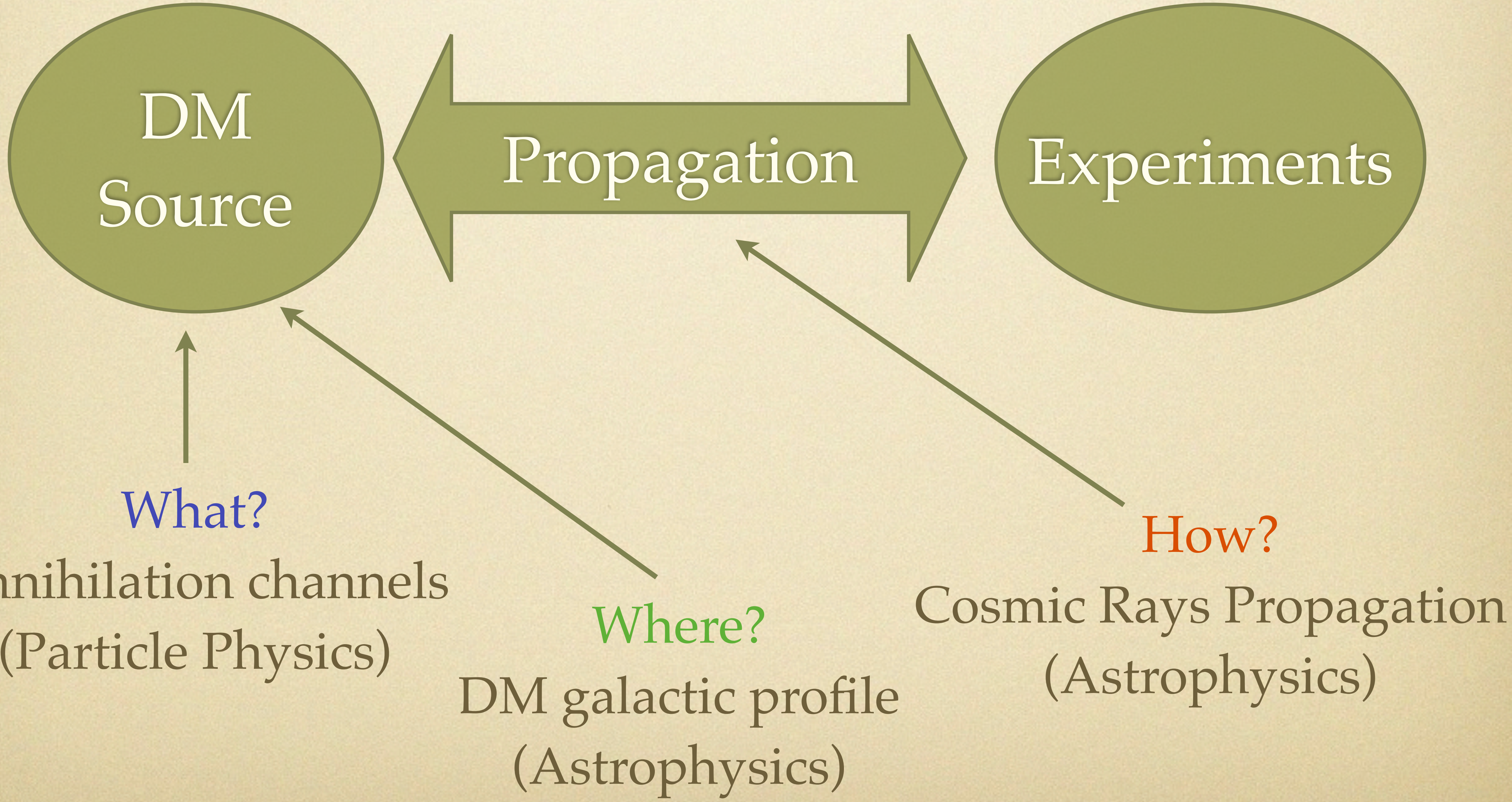


Inverse Compton



γ′s from proton int′ with ISM

Working out the signals



DM Source

Propagation

Experiments

What?

Annihilation channels

(Particle Physics)

Where?

DM galactic profile

(Astrophysics)

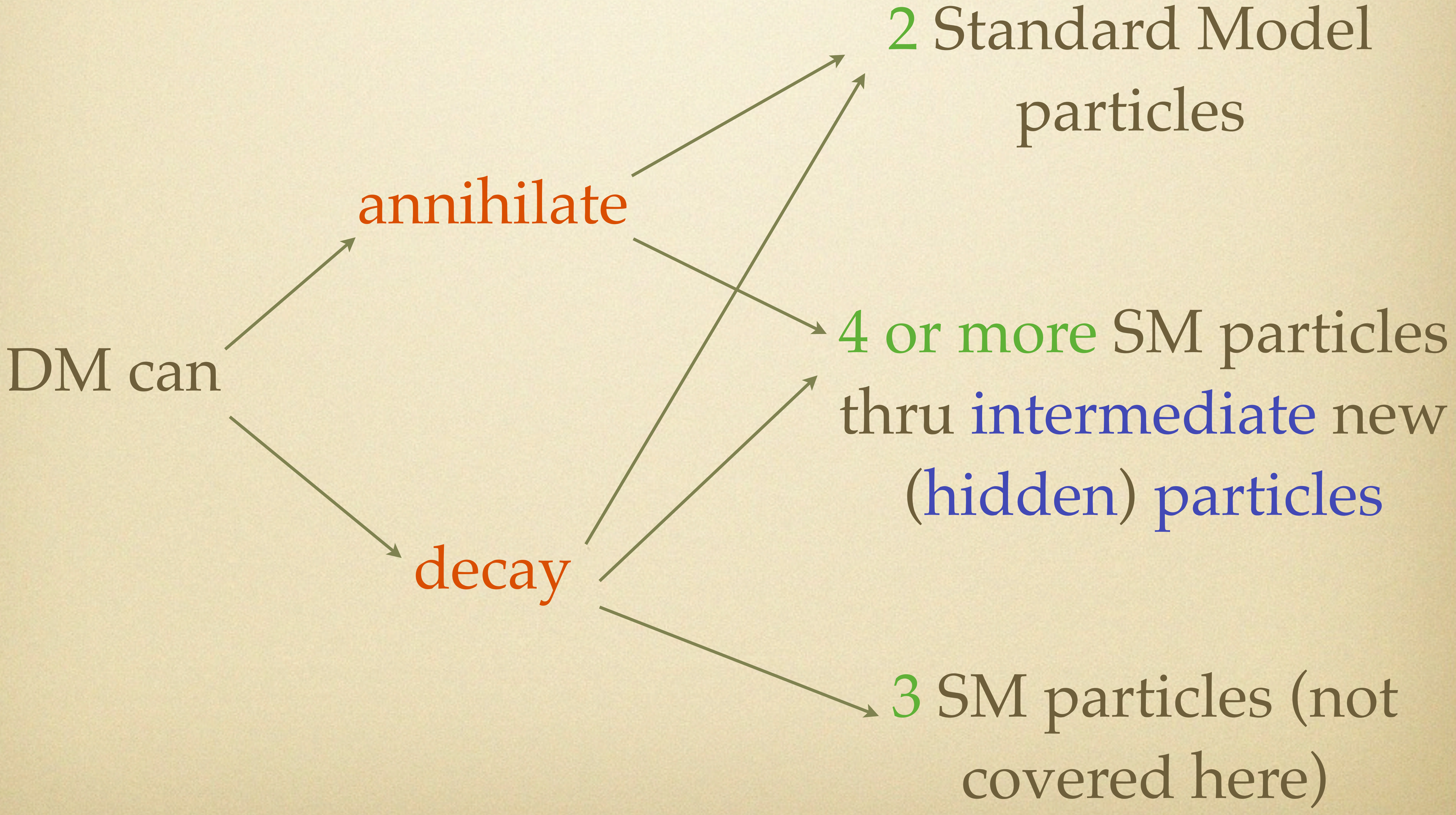
How?

Cosmic Rays Propagation

(Astrophysics)

- What? (Particle Physics Module)
- Where? (Dark Matter Profile)
- How? (Cosmic Rays Propagation)

Particle Phys' Module



DM can

annihilate

decay

2 Standard Model particles

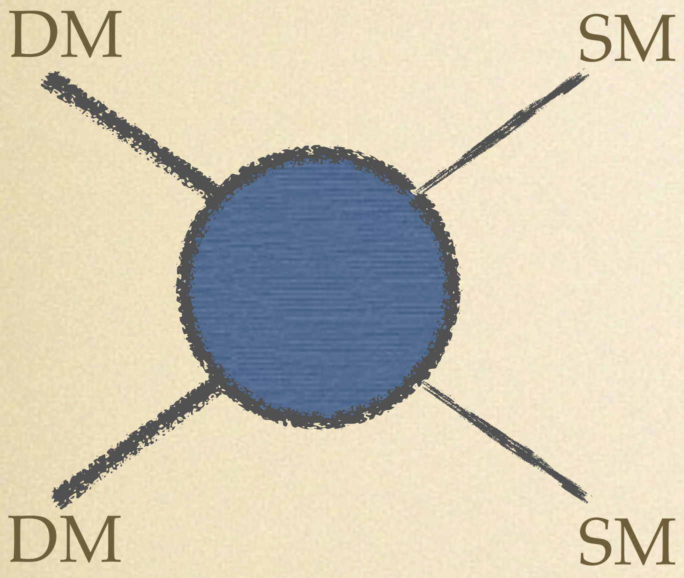
4 or more SM particles thru intermediate new (hidden) particles

3 SM particles (not covered here)

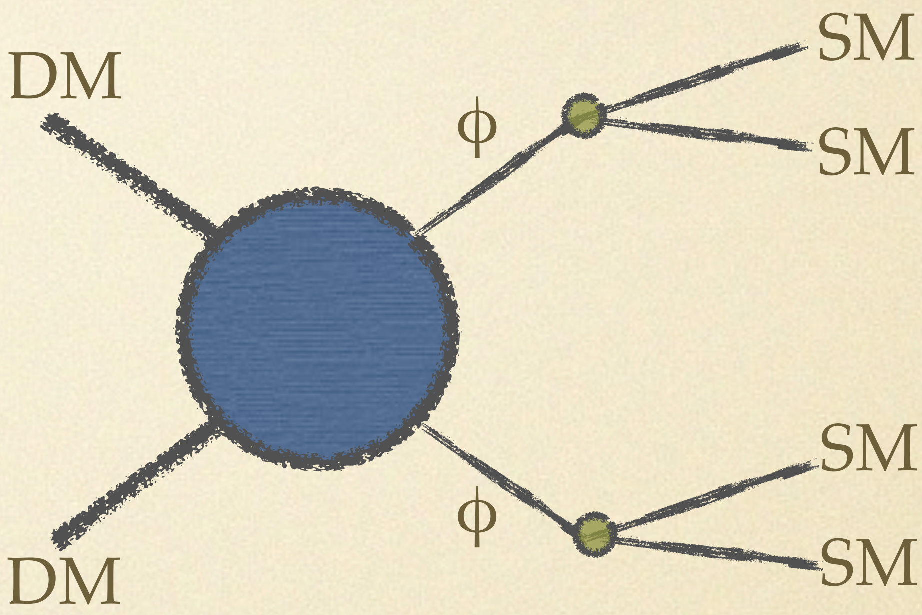
Particle Phys' Module

- Fit specified by M_{DM}, $<\sigma v>$ and final states
- For 2-body final states → look at all SM final states
- For 4-body (or more) → a (hidden) light new particle ϕ required:
    - Generically ϕ can decay back to the SM via Higgs or photon mixing (spin 0 or 1)
    - Look at ϕ coupling to a single type of SM particle (e.g. 2τ) or ϕ coupling proportionally to electric charge

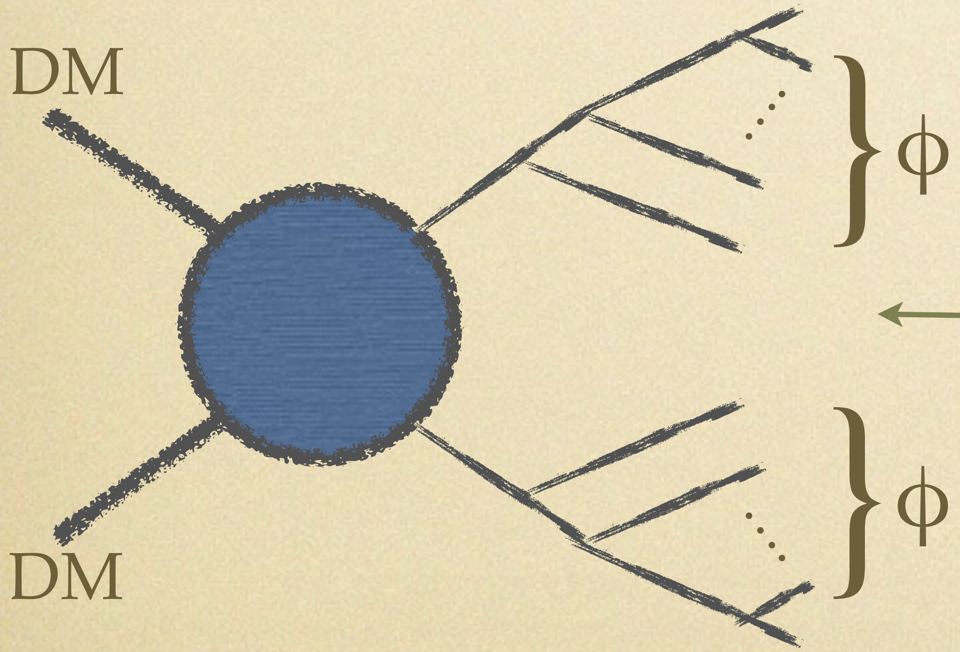
Particle Phys' Module



All SM final states



Leptons and pions
(motivated by PAMELA)



"Hidden" shower, softer spectra
(e.g. ϕ spin 1 in non-Abelian gauge group)

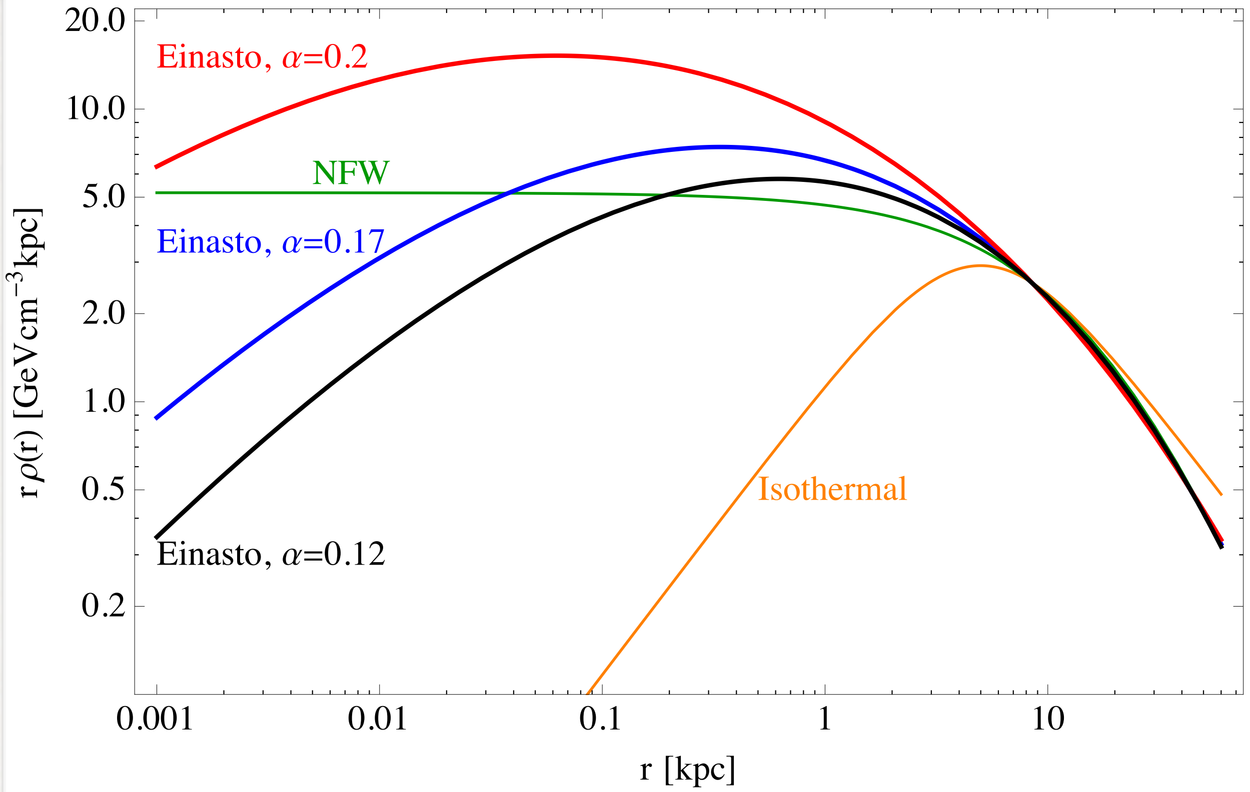
And the same for decaying DM...

- What? (Particle Physics Module)
- Where? (Dark Matter Profile)
- How? (Cosmic Rays Propagation)

Dark Matter Profile

- Dark Matter Profile inferred from N-body simulations
- Current hi-res simulations have resolutions of O(0.1 kpc)
- Best fit is for Einasto profile: $\rho(r) = \rho_\odot \exp\left[\frac{-2}{\alpha}\left(\left(\frac{r}{r_s}\right)^{\alpha} - 1\right)\right]$

- α=0.12-0.2, here 0.17
- No baryonic components in the simulations: may drastically change the results!
- Study also a cored IsoThermal as a shallower profile



(BBN?)

Rothstein et al.

- What? (Particle Physics Module)
- Where? (Dark Matter Profile)
- How? (Cosmic Rays Propagation)

Cosmic Rays Propagation

- Galaxy is transparent to gamma rays and neutrinos:

$$\Phi_{\gamma,\nu} \propto Q_{\gamma,\nu} \bar{J} \Delta\Omega$$

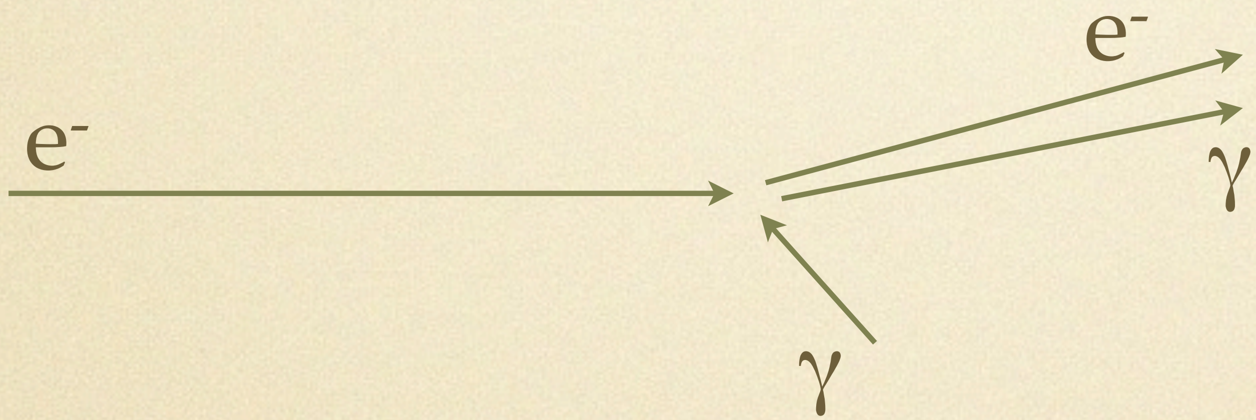
$$\bar{J} = \frac{1}{\Delta\Omega} \int d\Omega \int_{\mathrm{line-of-sight}} \frac{dl}{r_\odot} \left(\frac{\rho(r)}{\rho_\odot} \right)^2$$

(single power of density if decaying DM)

- Valid for prompt γ produced in annihilation/decay
- No uncert' from propagation, not too large uncertainties from DM Profile if not looking at the Center of the Galaxy

Inverse Compton

- Electrons and positrons can up-scatter ambient light to gamma rays thru Compton scattering:



$E'_{\gamma} \approx (E_e/m_e)^2 E_\gamma$

$$\frac{d\Phi_{\gamma'}}{dE_{\gamma'}d\Omega} = \frac{1}{2}\alpha_{\rm em}^2 \int_{\rm l.o.s.} ds \iint \frac{dn_e}{dE_e}\frac{du_\gamma}{dE_\gamma}\frac{dE_e}{E_e^2}\frac{dE_\gamma}{E_\gamma^2} f_{\rm IC}.$$

DM profile

diffusion

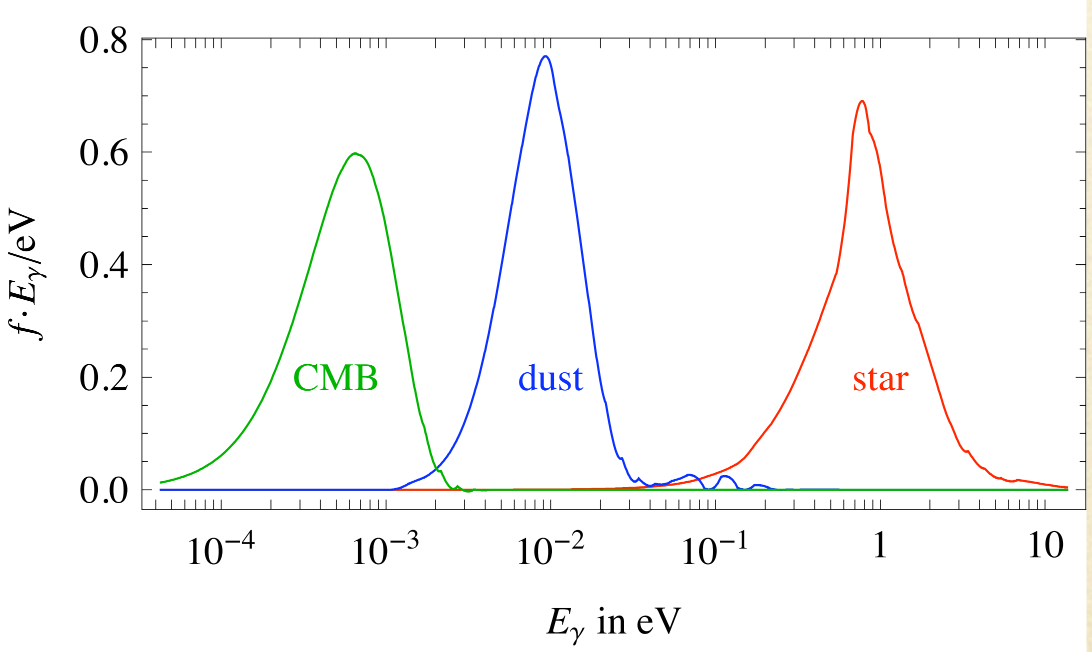
B field

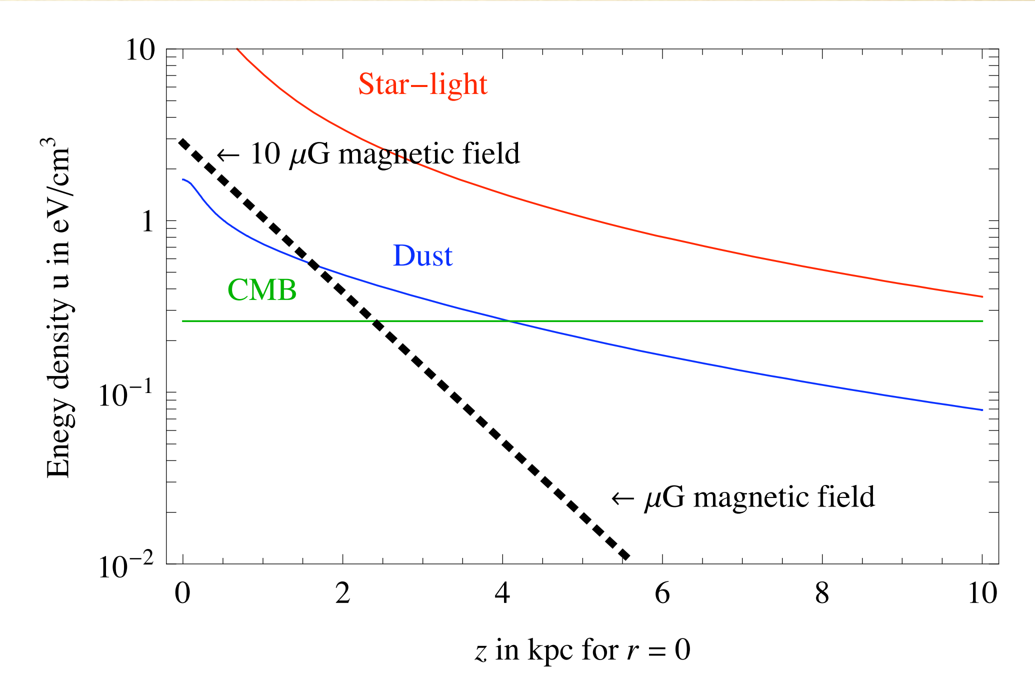
Interstellar Rad' Field

(factor ~ O(1) uncert' on the result from each)

Inverse Compton

Interstellar photons are from CMB, starlight and IR emission from dust





Magnetic field can be relevant in the inner part of the Galaxy (r < 1÷2 kpc)

@ high latitudes CMB dominates

Inverse Compton

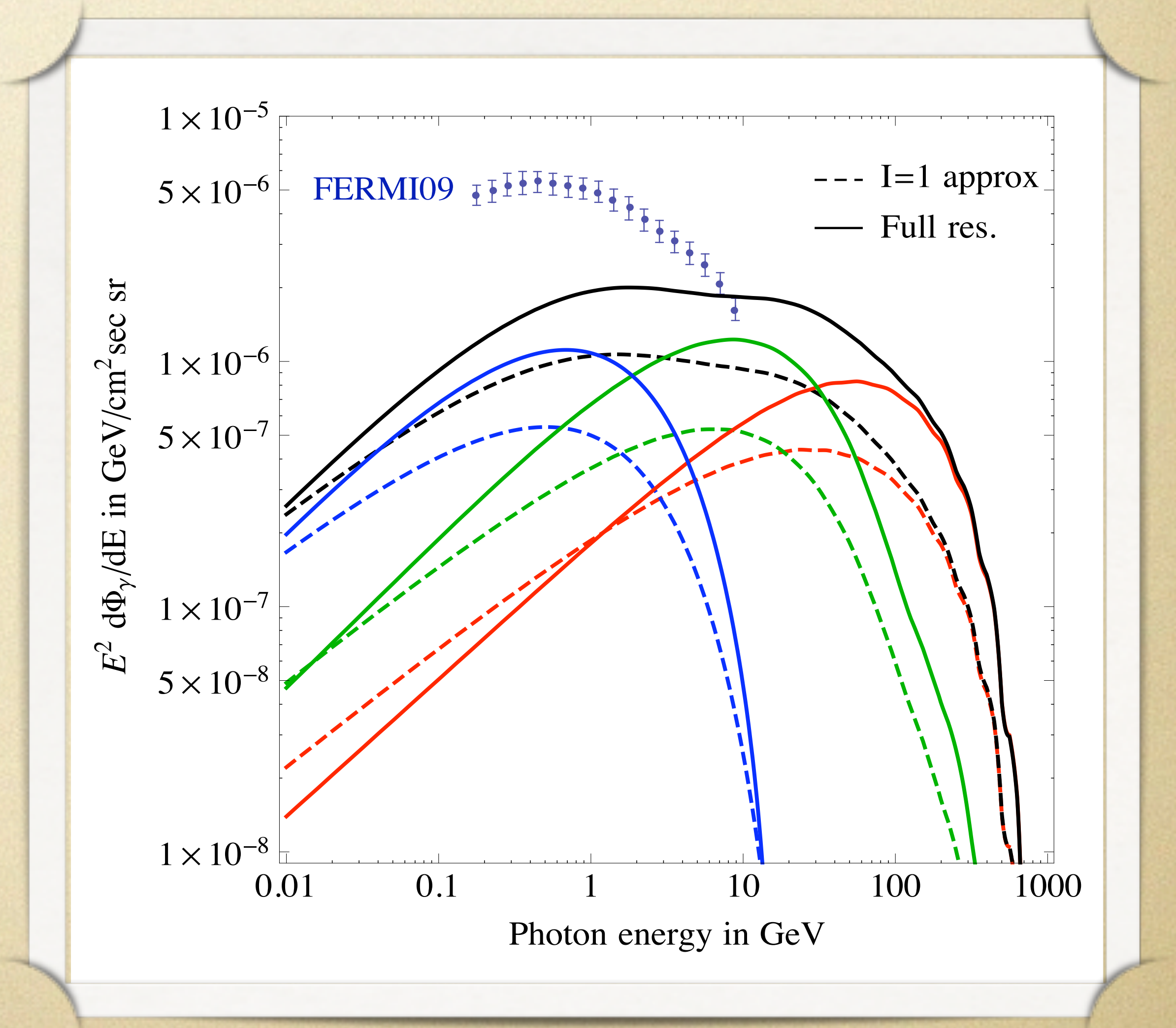
In principle one should propagate e± first, but...

Simple formula if energy loss dominates over diffusion (good up to factor of 2)

$$\frac{d\Phi_{\gamma'}}{dE_{\gamma'}} = \sum_i G_{i\mathrm{IC}}(E'_\gamma) J_{i\mathrm{IC}} \frac{9 r_\odot \langle\sigma v\rangle}{64\pi \langle E_{\gamma i}\rangle} \left(\frac{\rho_\odot}{M}\right)^2$$

$$J_{i\mathrm{IC}} = \int d\Omega \int_{\mathrm{l.o.s.}} \frac{ds}{r_\odot} \left(\frac{\rho(r)}{\rho_\odot}\right)^2 \frac{u_{\gamma i}}{u_{\mathrm{tot}}},$$

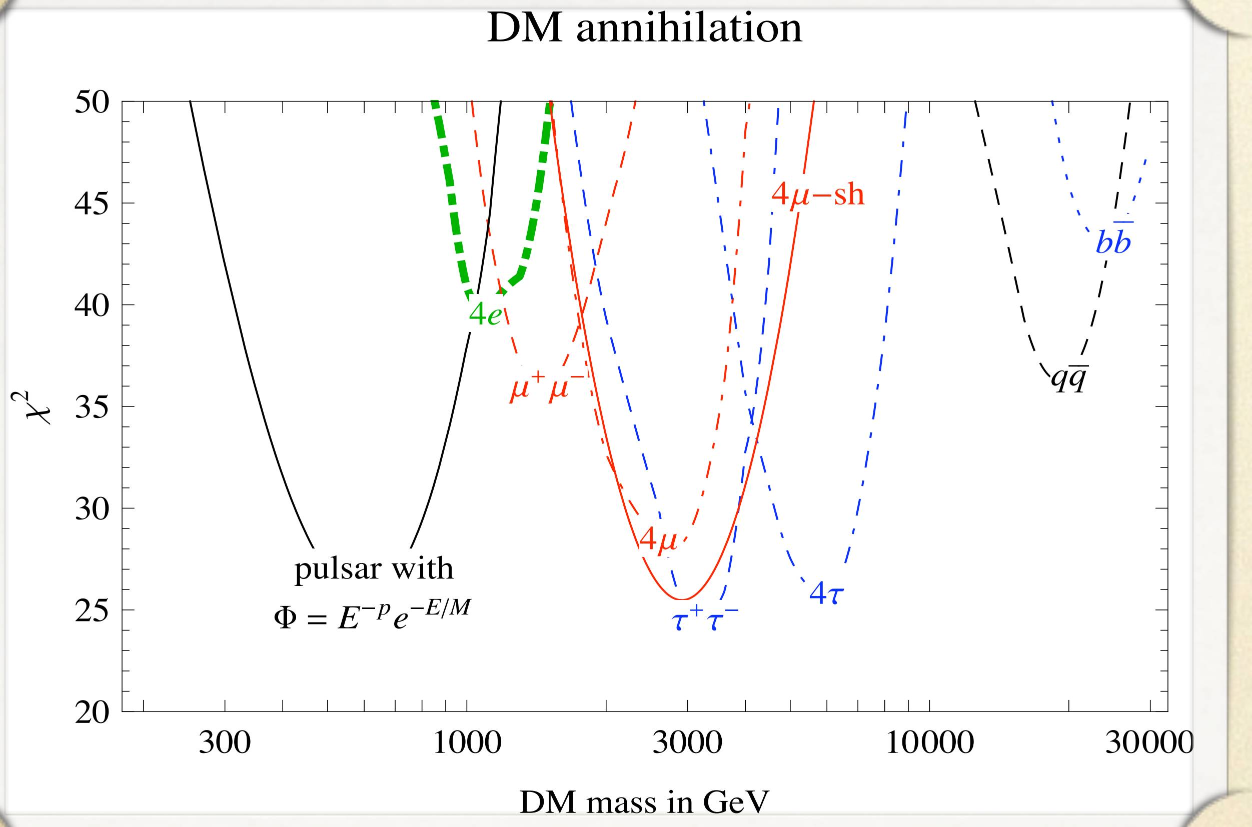
$$G_{i\mathrm{IC}} = m_e^4 \iint N_e(E_e) f_{\gamma i}(E_\gamma) \frac{dE_e}{E_e^4} \frac{dE_\gamma}{E_\gamma} \frac{f_{\mathrm{IC}}}{R(E_e)}.$$



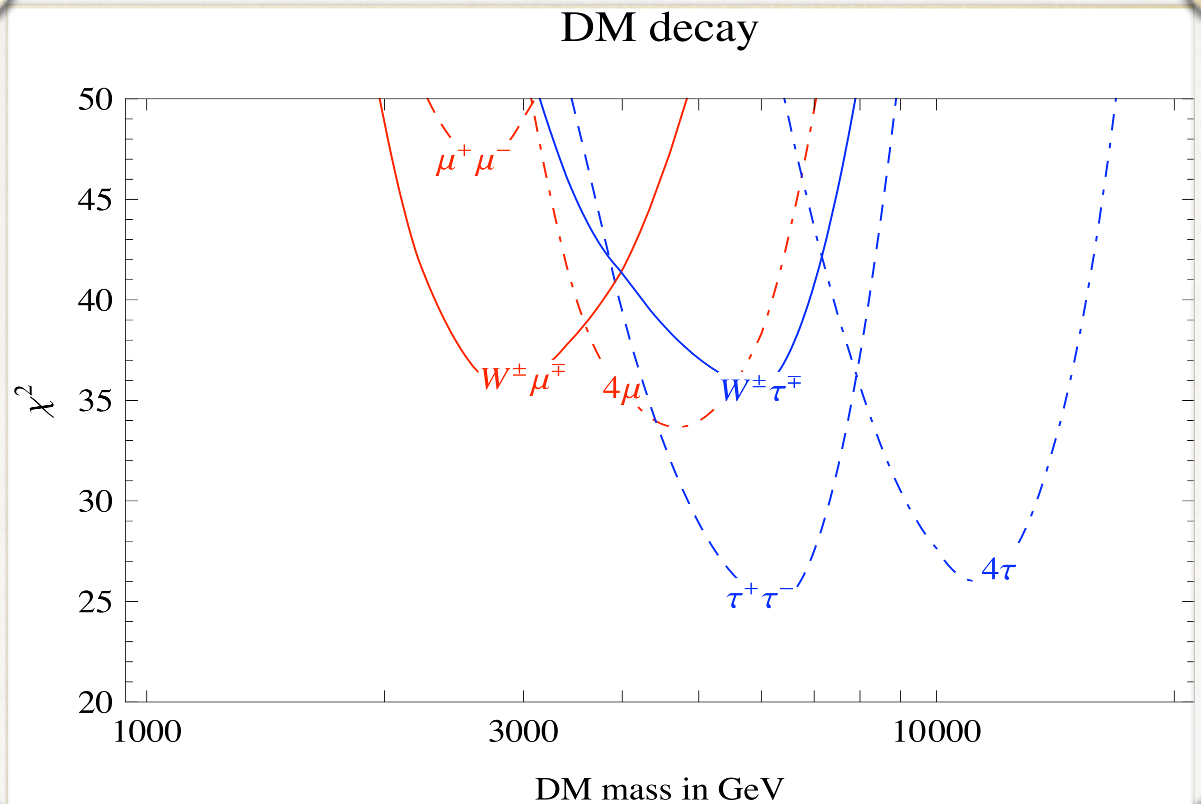
Results

(some highlights...)

How well can DM fit?



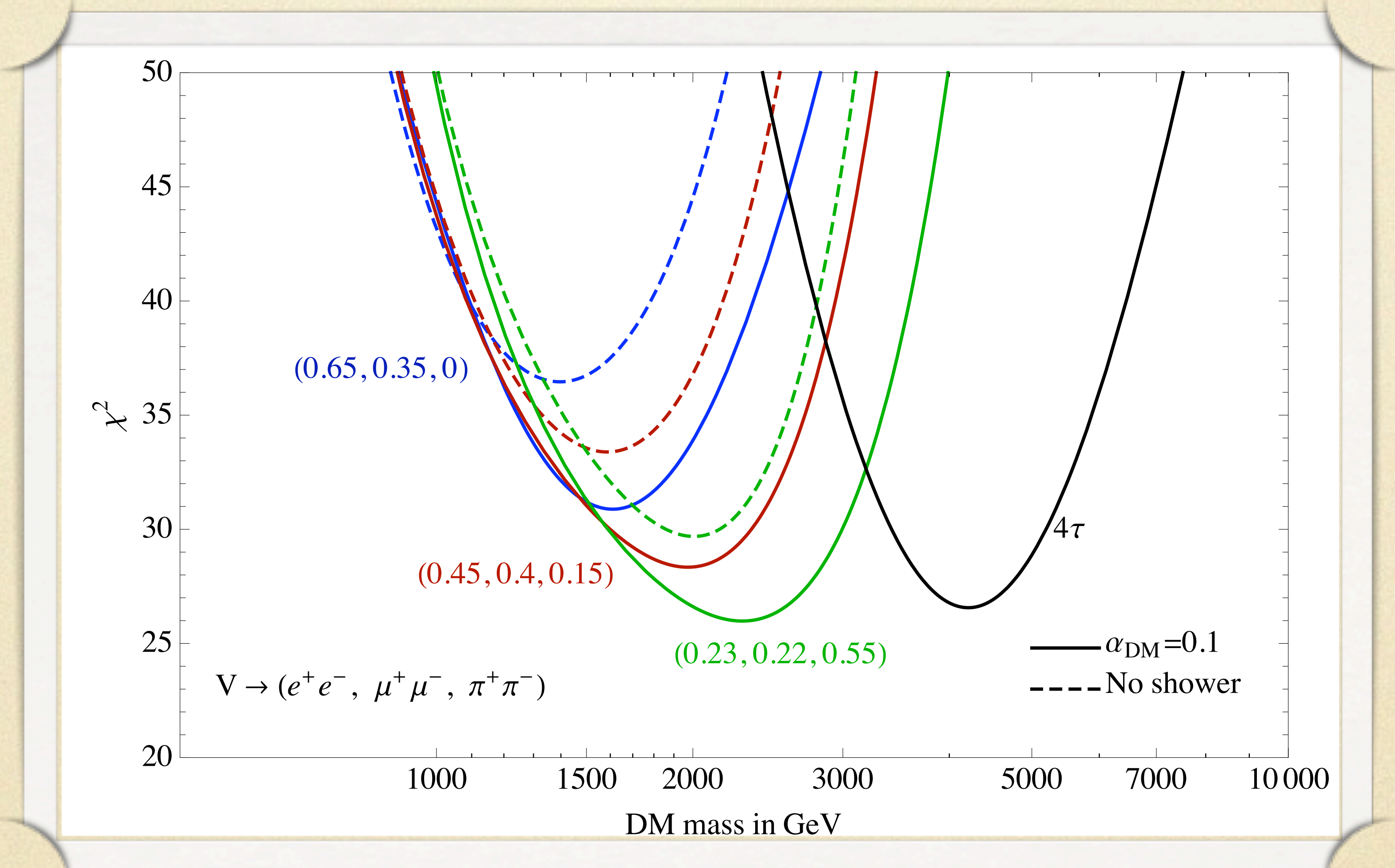
DM annihilation



DM decay

- 2τ, 4μ , 4τ produce very good fits
- 2e disfavored (too sharp peak: good fit of ATIC, bad fit of FERMI)
- Gauge bosons and quarks disfavored by the HESS electron meas’ (require 20 TeV mass)
- DM Mass in 1-5 TeV range

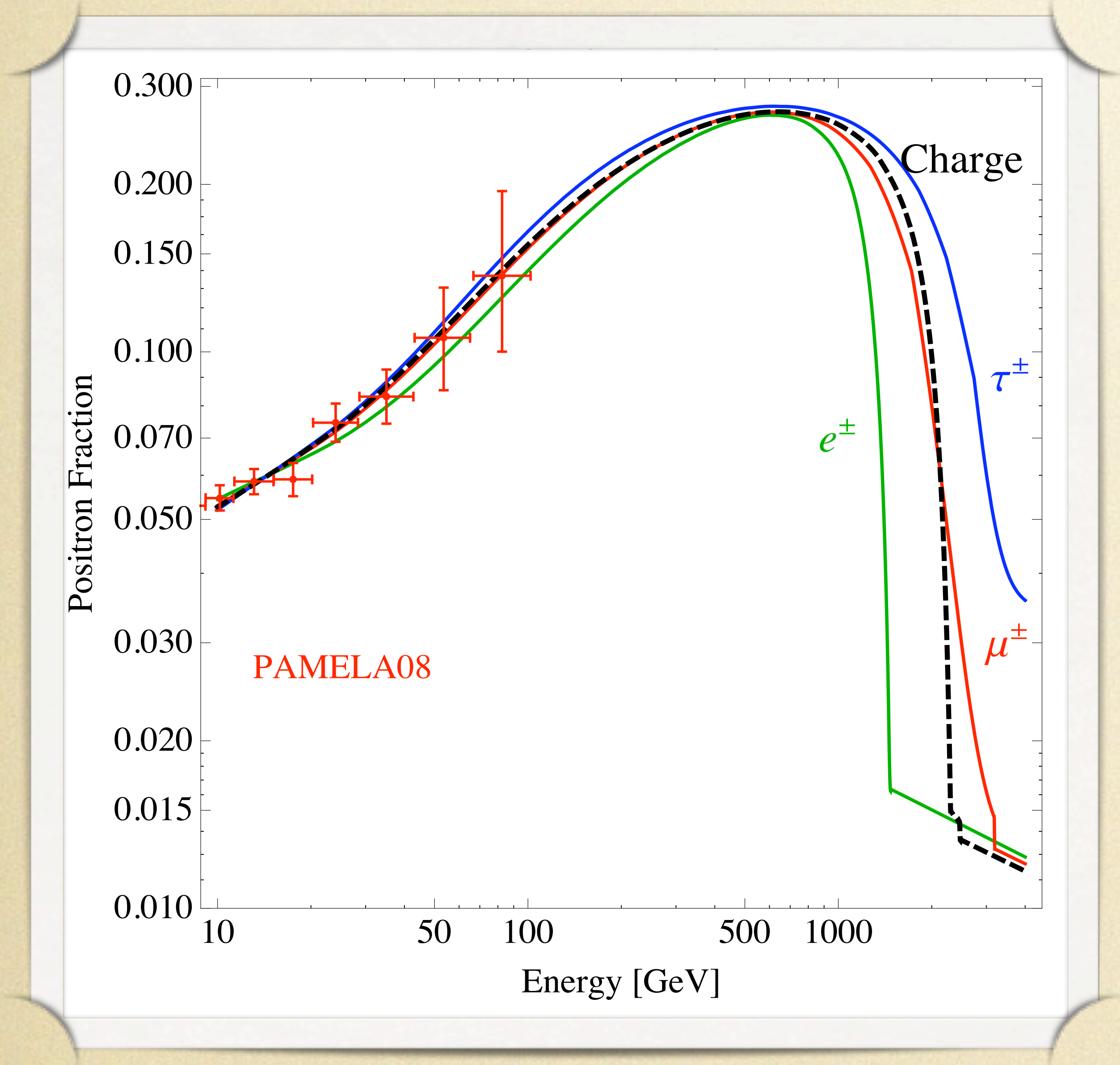
How well can DM fit?

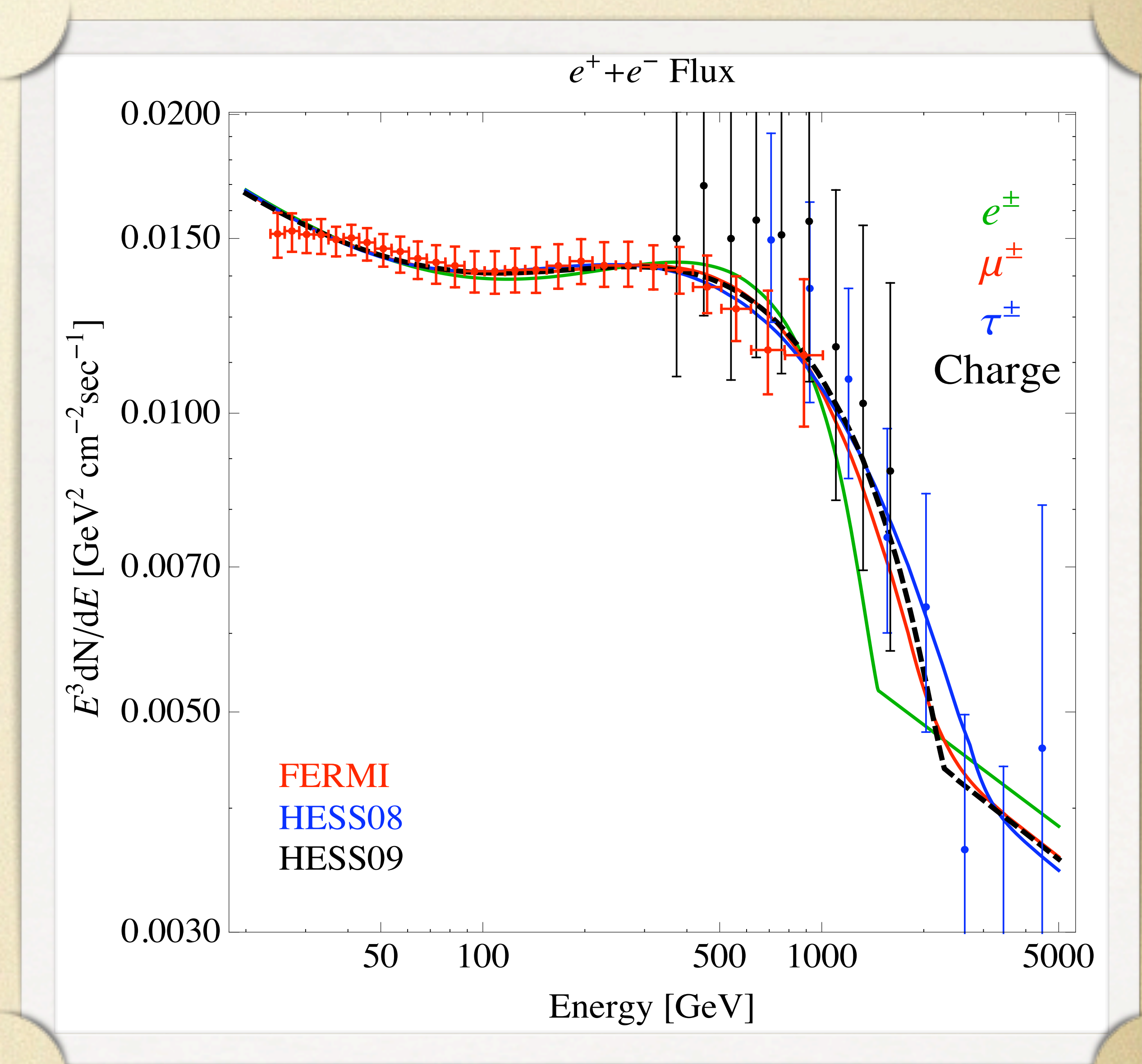


- Hidden sector shower always improves the fit
- Combinations of e±,μ±,π± (hidden spin-1 intermediate particles that mixes with photon) provide good fits

Best fits

4body ann′, Einasto

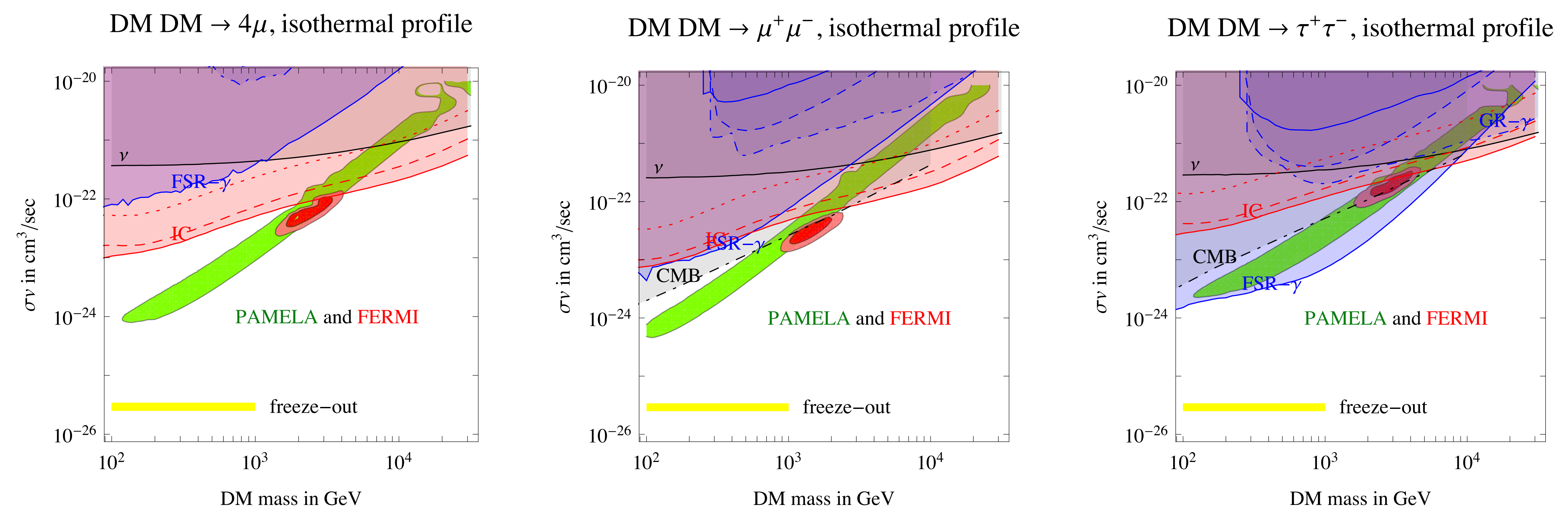


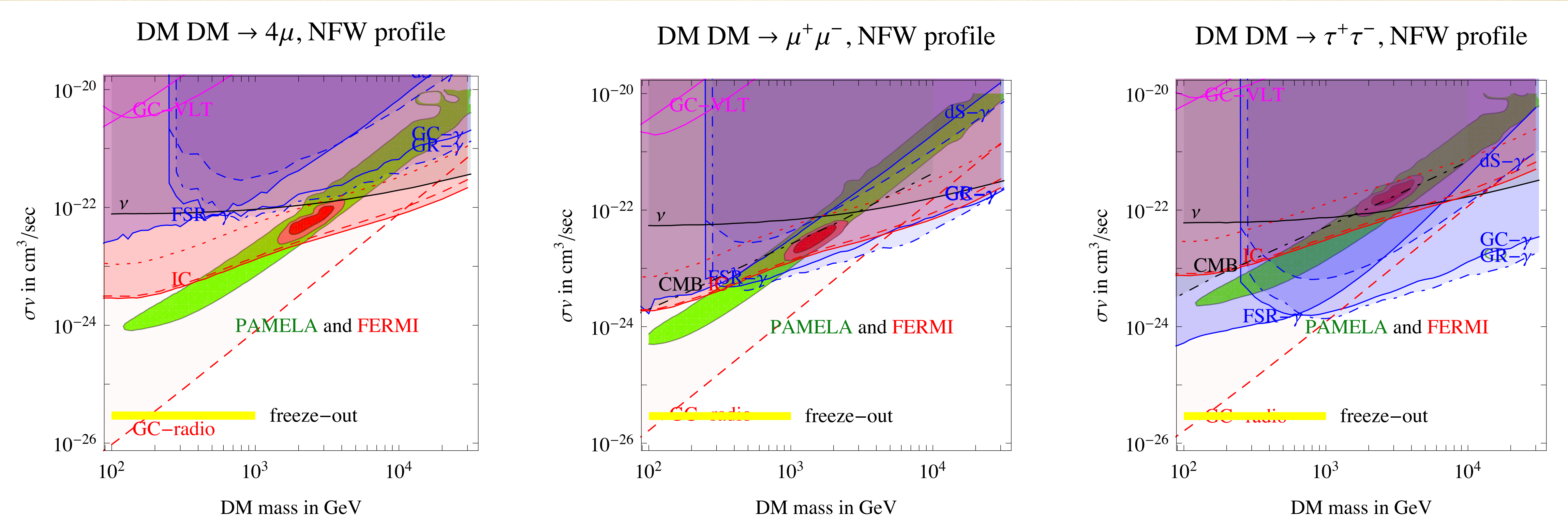


Charge = (0.23,0.22,0.55) in e±,μ±,π±

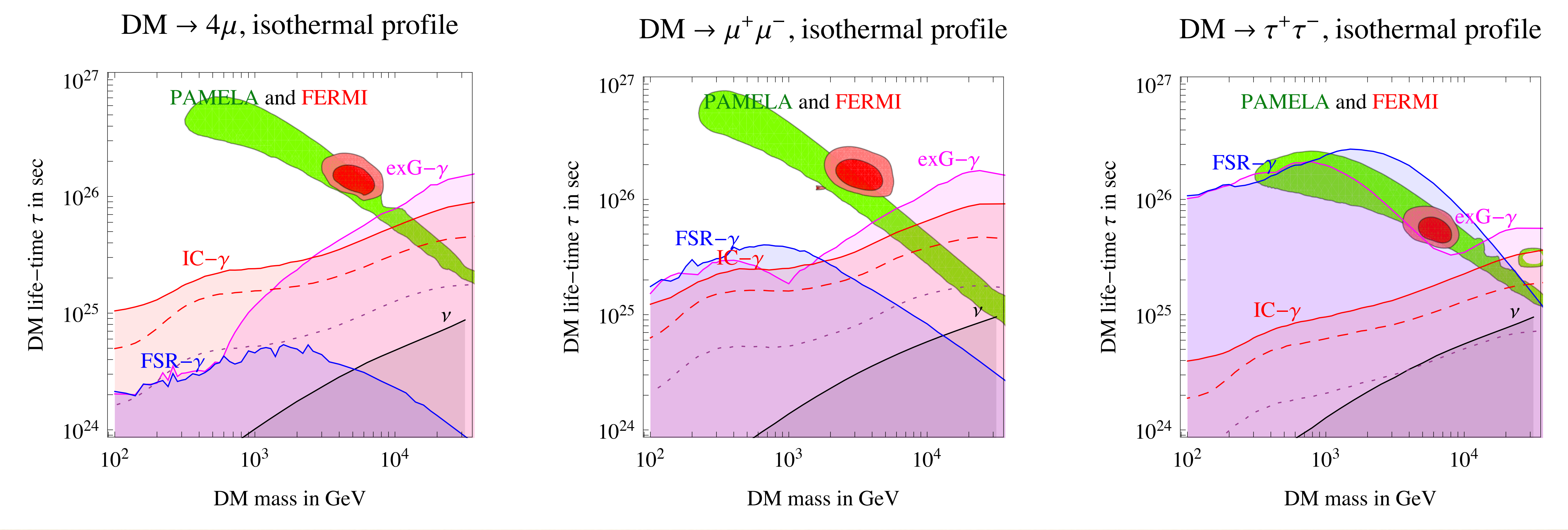
- Xsec required → O(1000) larger than thermal freeze-out xsec
- Particle Physics explanation: Sommerfeld enhancement (ok with 4 body final states)

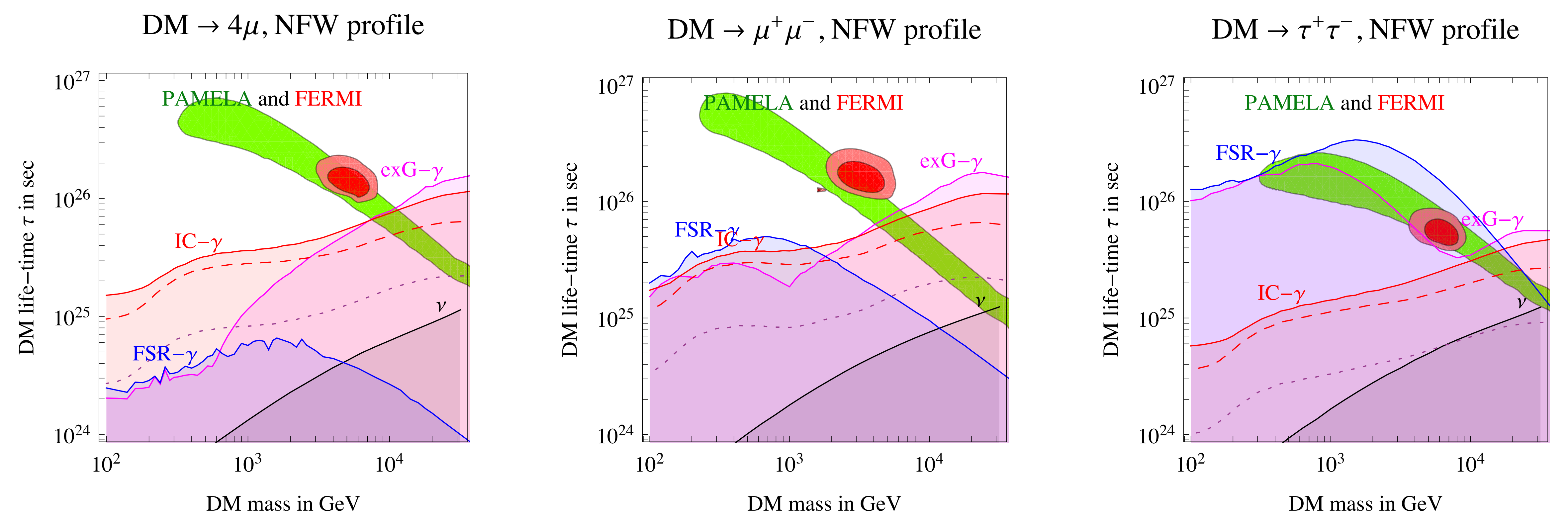
Fits vs γ bounds (annihilation)





Fits vs γ bounds (decay)





Robustness of the bounds?

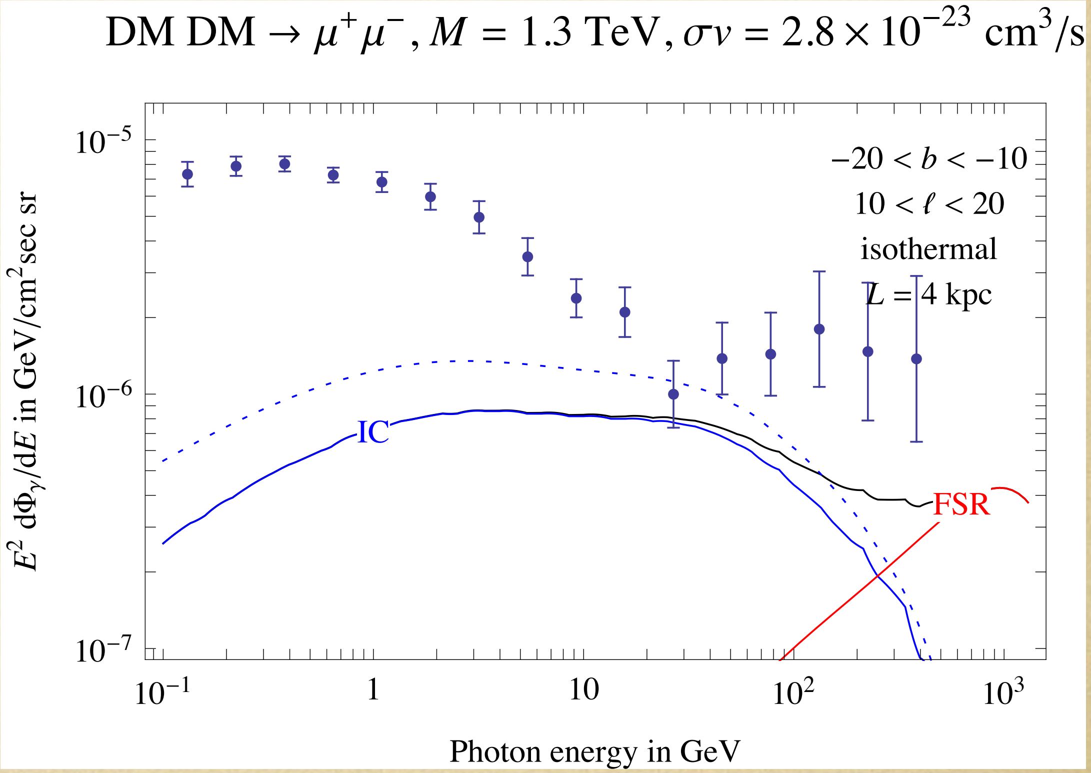
- Bounds come from intermediate latitudes → smaller DM profile uncertainties!
- Main uncertainties coming from:
    - Magnetic field in the Inner Galaxy (if factor of 2 larger may relax bounds up to factor of 1.5÷2)
    - Size of the diffusion halo: small effects except in very unrealistic cases (L~1kpc terminating abruptly)
    - Disk-like component for DM (Dark Disk): small effect unless O(1) fraction of local DM is stored in disk (effectively making profile shallower)

Fermi γ constraints

- Final states with too much hard radiation (π^0's in τ's) are now excluded both in annihilating and decay models
    - No way to hide signals with the Annihilating vs. Decay (ϱ^2 vs ϱ "trick" that worked for the Galactic Center)
- Other leptonic 4-body final states are in tension in annihilating models for cuspy profiles (~ factor of 2. Uncert' larger)
- But...

Fermi γ constraints

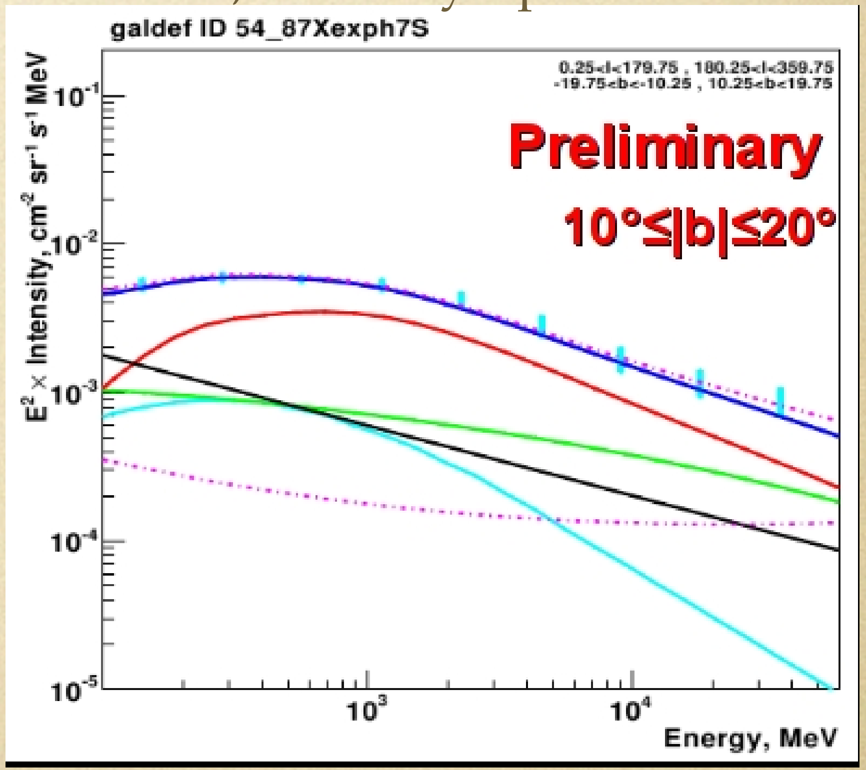
- Final states with too much hard radiation (π^0's in τ's) are now excluded both in annihilating and decay models
  - No way to hide signals with the Annihilating vs. Decay (ϱ^2 vs ϱ "trick" that worked for the Galactic Center)
- Other leptonic 4-body final states are in tension in annihilating models for cuspy profiles (~ factor of 2. Uncert' larger)
- But...
  - Less contaminated events will strengthen the bounds



Fermi γ constraints

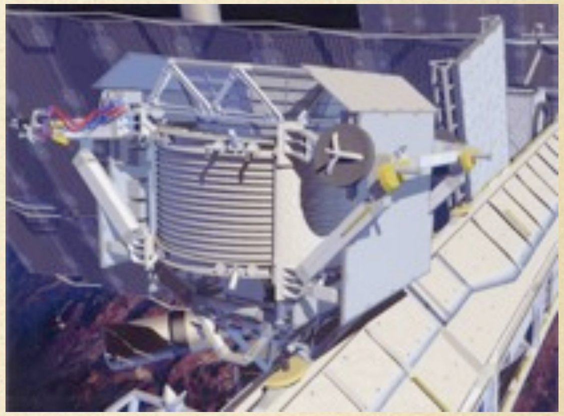
- Final states with too much hard radiation (π^0's in τ's) are now excluded both in annihilating and decay models
    - No way to hide signals with the Annihilating vs. Decay (ϱ^2 vs ϱ "trick" that worked for the Galactic Center)
- Other leptonic 4-body final states are in tension in annihilating models for cuspy profiles (~ factor of 2. Uncert' larger)
- But...
    - Less contaminated events will strengthen the bounds
    - Galactic emission models fit γ data reasonably well without DM

T.Porter, Fermi Symposium 2009



☞ DM should give O(1) fraction of γ emission at high energy

Making Progress

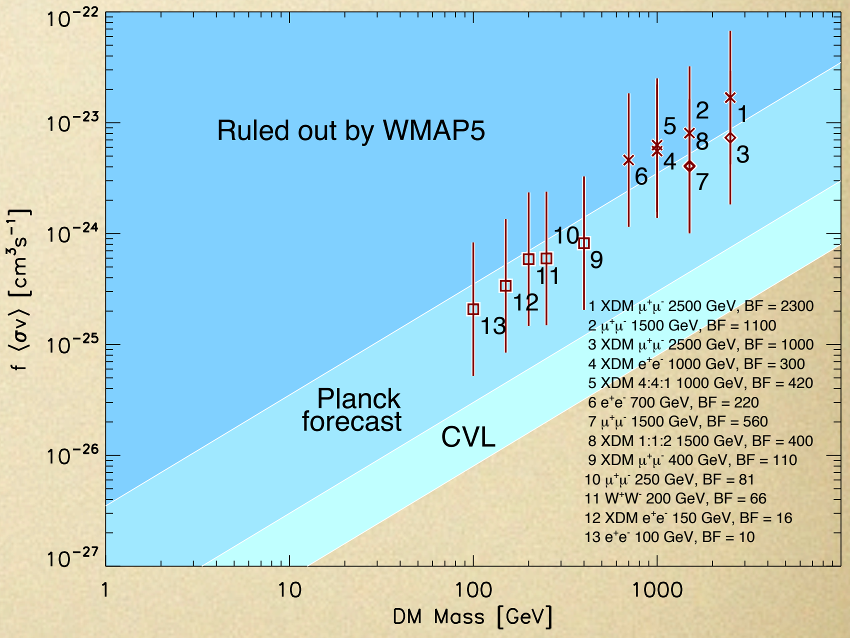


- AMS02: can tell whether positron fraction will continue to increase or not (necessary if DM is heavy); will drastically reduce CR propagation uncert'; will test some of the astro explanations

- FERMI: Better bounds from less contaminated γ events and/or higher energy. Possible detection of DM subhalos → Crucial to test the DM hypothesis, both for annihilating and for decay

- Planck: very robust bounds from energy injection at recombination time can close the window for annihilating DM (Finkbeiner et al. 2009, Bertone et al. 2009)

- Xenon/Lux: DM direct detection may have the chance to clarify the whole picture



Conclusions

- Present data does not exclude DM annihilations or decays as an explanation for PAMELA & FERMI results (but bounds are tight and DM should give O(1) fraction of γ emission at high energy)
- τ's final states are now excluded both for annihilating and decaying
- Annihilations into many ($e^\pm$), $\mu^\pm$, $\pi^\pm$ and high DM mass (~2-5TeV) are required