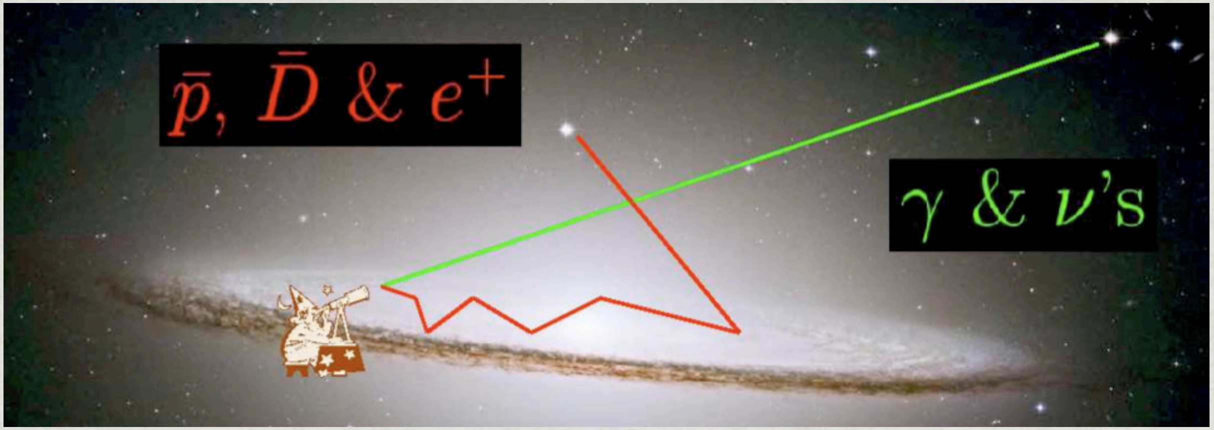
The cosmic electron/positron puzzle: dark matter interpretations

Gabrijela, GGI Florence, May 5th 2010.

The data



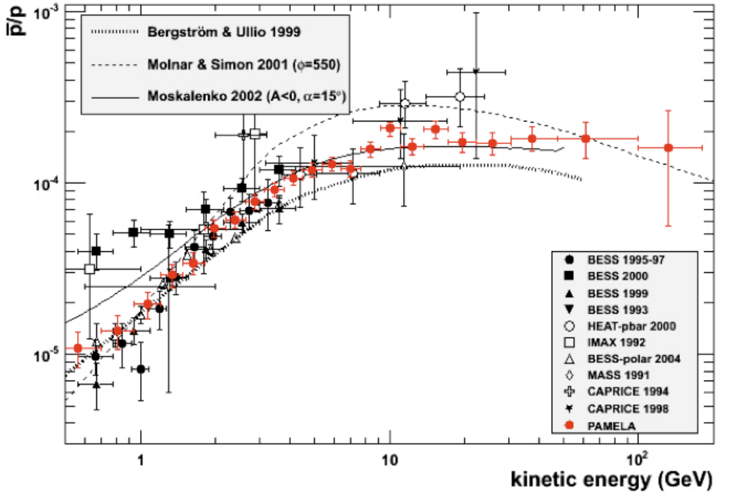
[courtesy P. Salati, from Julien's talk]

Gammas expected to be the clean channel (not affected by the Galaxy) --> high Fermi pre-launch expectations for DM detection; nothing unambiguously seen yet in this channel yet.

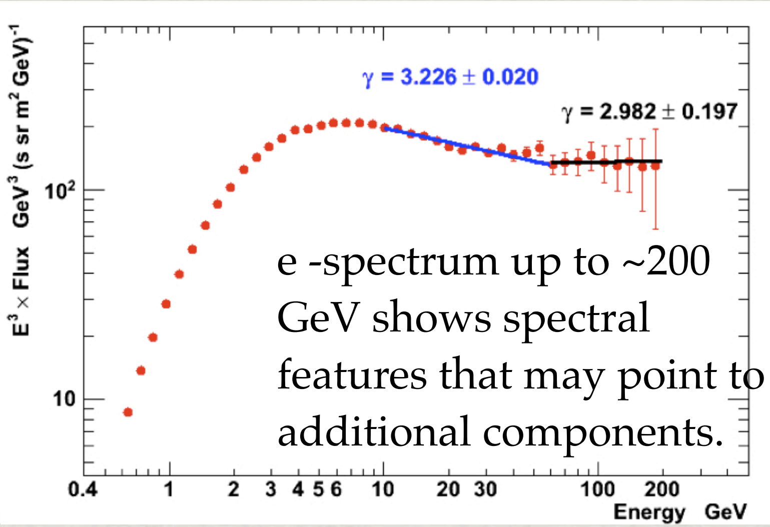
e+/e- diffuse from galactic sources and loose energy on radiation and magnetic fields - ***not the cleanest channel for DM detection.***

Yet, the *e+ e- high energy excess of PAMELA & FERMI has been claimed to be a first non gravitational signal of Dark Matter .*

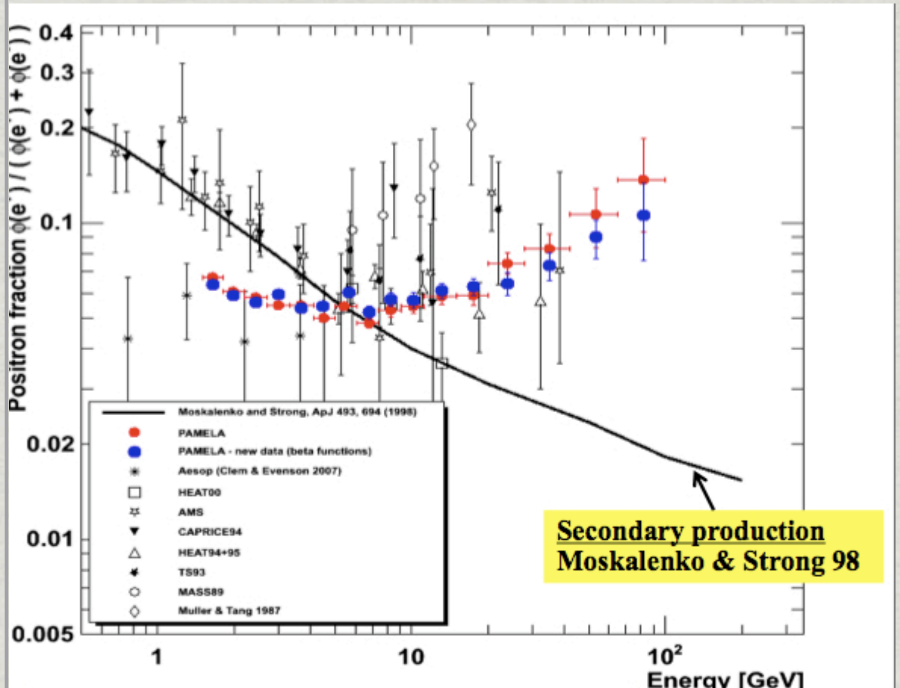
PAMELA



Antiprotons in CRs are in agreement with secondary production.



e -spectrum up to ~200 GeV shows spectral features that may point to additional components.

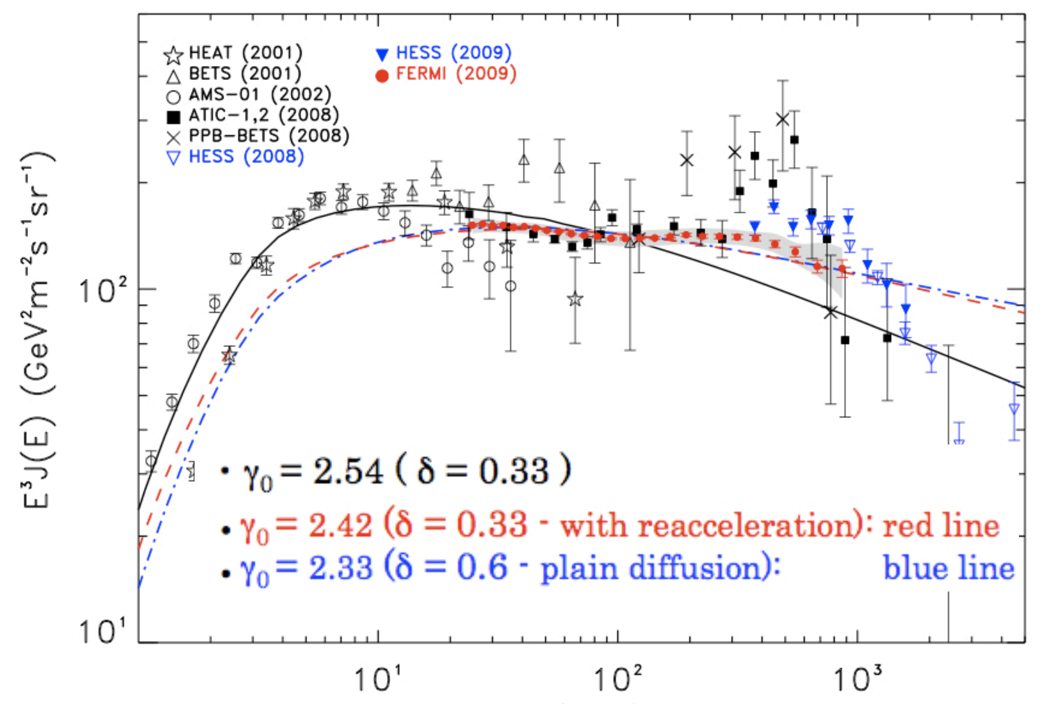


Secondary production
Moskalenko & Strong 98

Adriani et al, arXiv:1001.3522 [astro-ph.HE]

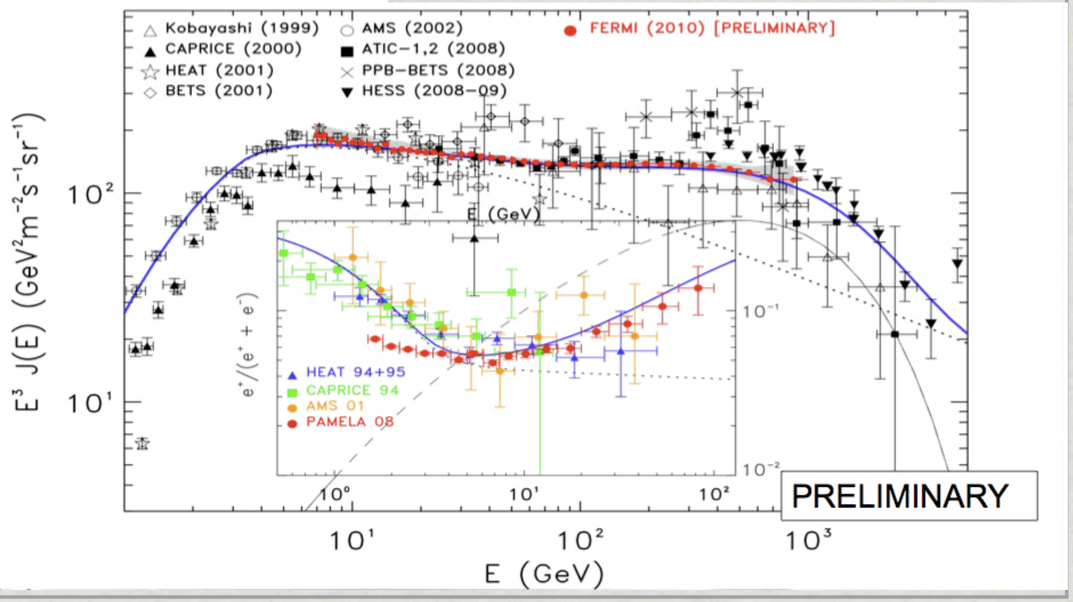
Puzzling rising positron fraction..., unlikely due to secondary production of e+ (Serpico, Phys.Rev.D79:021302,2009.)

FERMI

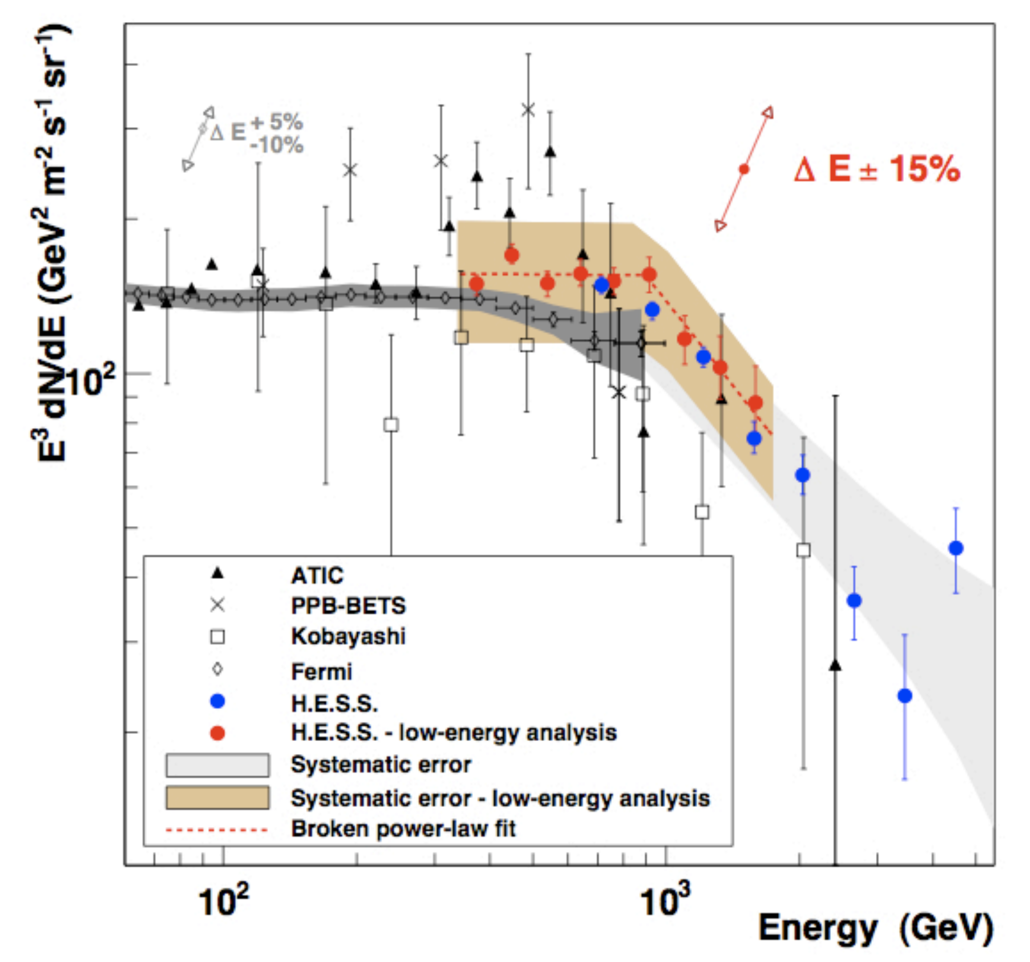


e+e- of Fermi could be explained by using a ***different electron injection index.*** But, that model does not fit the PAMELA ratio, neither fits low-energy Fermi spectrum.

an additional electron component seems to be needed...



HESS



HESS observed a cut-off in the e+e- spectra, at ~1 TeV.

$dN/dE = k\ (E/E_b)^{-\Gamma_1}\ (1 + (E/E_b)^{1/\alpha})^{-(\Gamma_2 - \Gamma_1)\alpha}$

k = (1.5 ± 0.1) × 10−4 TeV−1 m−2 sr−1 s−1 ,

and a break energy **Eb = 0.9 ± 0.1 TeV**, where the transition between the two spectral indices **Γ1 = 3.0 ± 0.1** and **Γ2 = 4.1 ± 0.3** occurs.

...a signal in electrons and positrons, and nothing in anti-protons or gammas, quite unexpected for DM candidates.

Possible explanations for the excess:

- The local astrophysical sources (pulsars, re-acceleration at SNR, localized SNR, ...) give a contribution?
- Dark matter annihilations give a contribution?
- There is no excess (non-standard diffusion)
- ...

Is the e+ e- high energy excess of PAMELA & FERMI caused by Dark Matter annihilation?

Standard (simple) diffusion assumed from now on...

1. What kind of dark matter?

Model independent/phenomenological approach (i.e. blind fit to the data...):

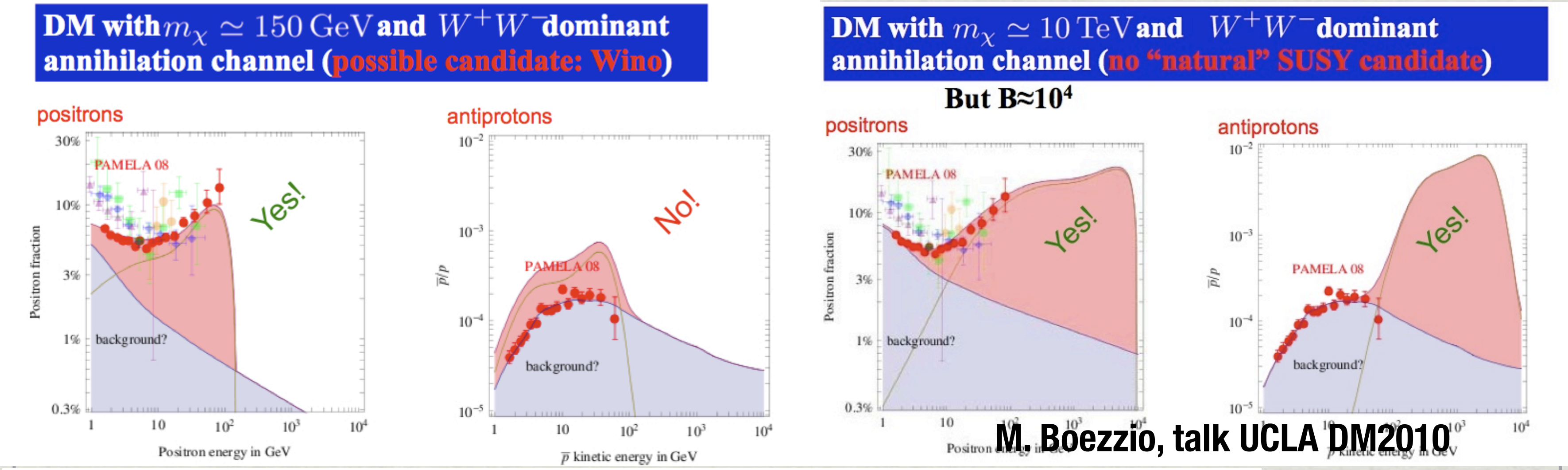
- match the annihilation cross section to the normalization of the signal.

- the annihilation channel to the spectral shape;

- and DM mass to the threshold of the excess;

- ***while respecting PAMELA antiproton measurement***

[from Piero's talk in Stockholm]

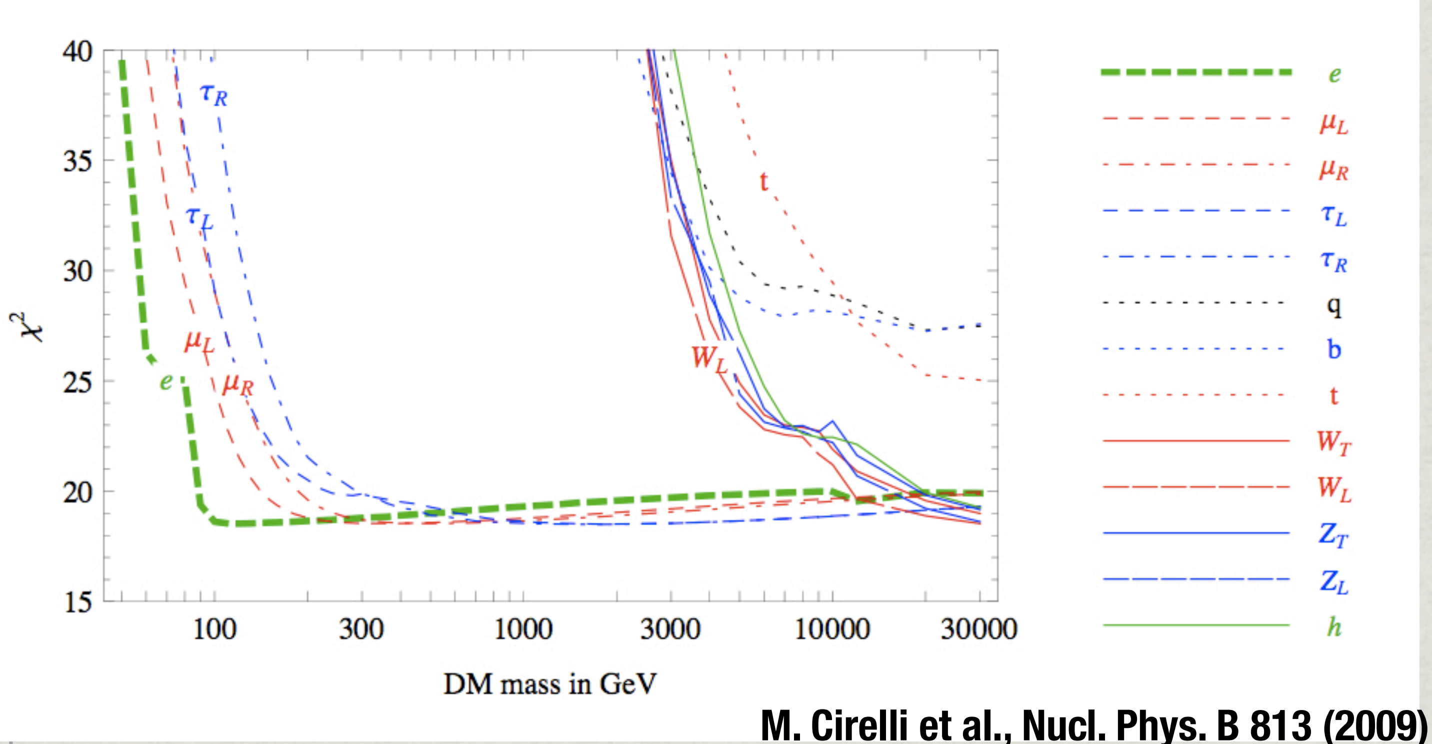


DM with $m_\chi \simeq 150$ GeV and W^+W^- dominant annihilation channel (possible candidate: Wino)

DM with $m_\chi \simeq 10$ TeV and W^+W^- dominant annihilation channel (no "natural" SUSY candidate)

But B≈10^4

M. Boezzio, talk UCLA DM2010



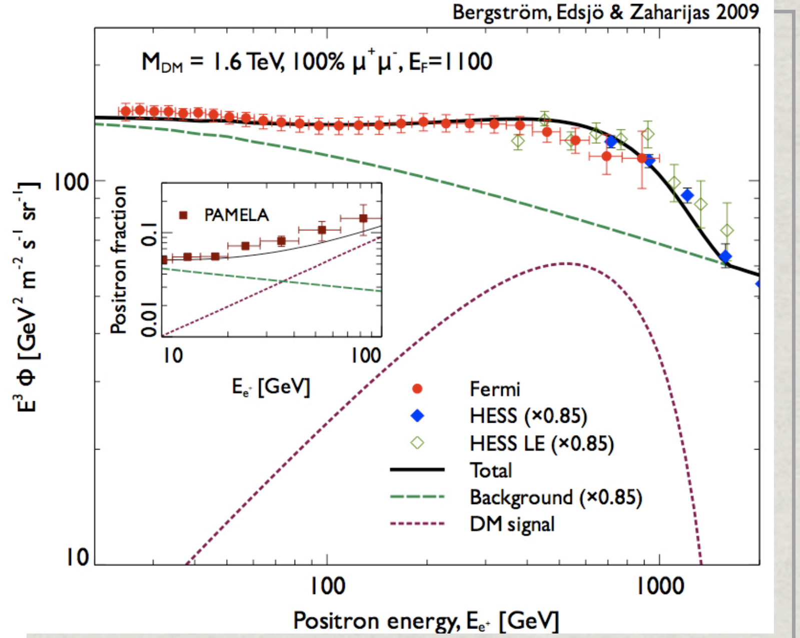
M. Cirelli et al., Nucl. Phys. B 813 (2009)

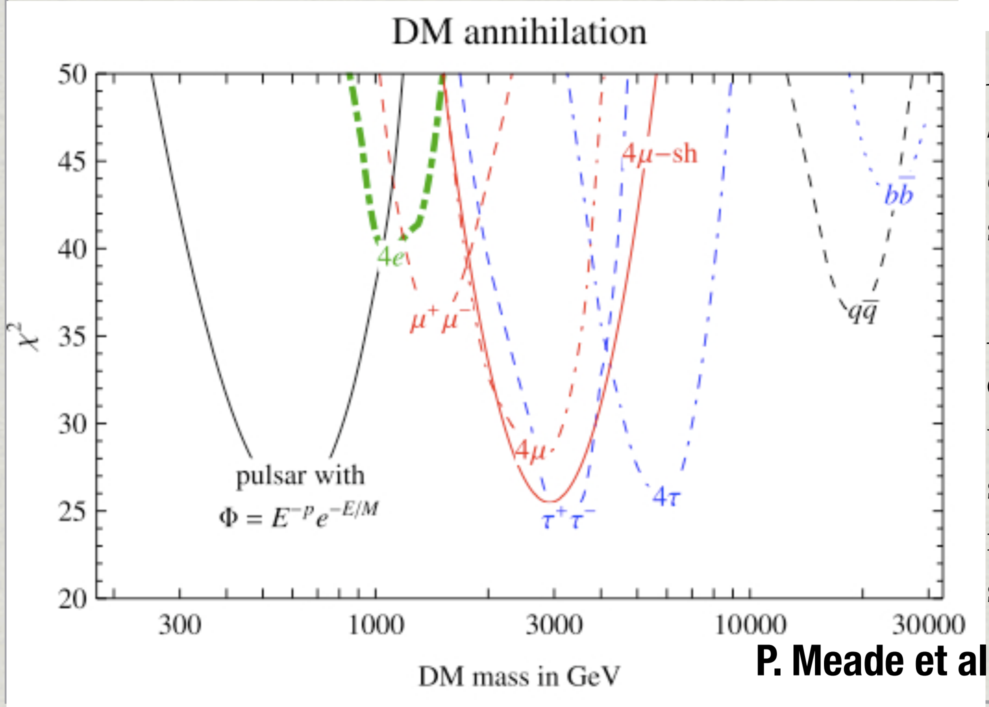
Fit only to PAMELA data.

annihilation channel & mass

Fit all PAMELA & FERMI &HESS data.

annihilation channel & mass


Bergström, Edsjö & Zaharijas 2009



HESS e- measurement limits the mass at a high end. Also, it disfavors ***non-leptonic channels*** (since e± excess terminates in a sharp way).

FERMI e- limits the low mass end
e+ fraction ~15%; if that drops >~200 GeV it would cause a drop in the e+e- spectra at similar level level, while the error on this measurement is -~ 5%> positron fraction should plateau or continue rising.

P. Meade et al., Nucl.Phys.B831:178-203,2010.

Fit all PAMELA & FERMI &HESS data.

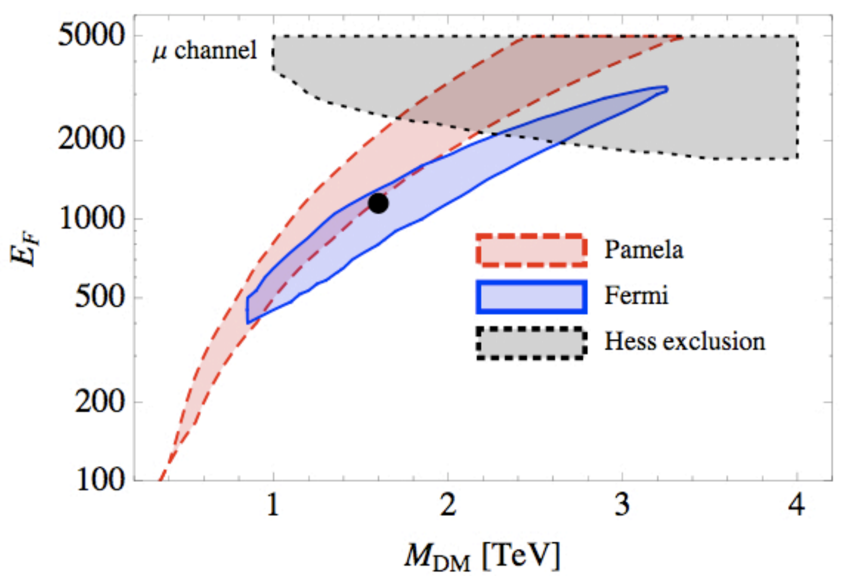
normalization/cross section:

$$E_F = \left(\frac{\rho_0}{0.3\ \mathrm{GeV\,cm^{-3}}}\right)^2 \left(\frac{\tau_0}{10^{16}\ \mathrm{s\,GeV^{-2}}}\right) B_F$$

High energy ~1 TeV electrons originate from within ~1 kpc. Diffusion in the local volume can be neglected and e signal determined by energy losses.

$$\left(\frac{dn_e}{dE}\right)_{nsd}(r,E) = \frac{1}{b(E)}\int_E^{M_\chi} dE'\ Q_e(r,E')\ .$$

$$b(E) \ = \ b_{IC}(E) + b_{syn}(E) + b_{Coul}(E) + b_{brem}(E)$$



enhancement factors ~10^3 needed.

Substructure boost, BF_{SS}

$$E_F = \left(\frac{\rho_0}{0.3\ \mathrm{GeV\,cm^{-3}}}\right)^2 \left(\frac{\tau_0}{10^{16}\ \mathrm{s\,GeV^{-2}}}\right) B_F$$

$$B_F = BF_{CS} BF_{SS}$$

* average boost due to the presence of all substructures ~1 [Lavalle,]

* single, nearby clump (~2-5kpc) needs to be ~$10^{11}M_{sun}$, very unlikely...
[Bringmann, Lavalle, Salati, Phys.Rev.Lett.103:161301,2009.]

Julien, Lidia?

Uncertainty in determination of $E_{F,}$ BF_{CS} ?

$$E_F = \left(\frac{\rho_0}{0.3\ \mathrm{GeV\,cm^{-3}}}\right)^2 \left(\frac{\tau_0}{10^{16}\ \mathrm{s\,GeV^{-2}}}\right) B_F$$

✴ The value for local DM density is likely higher than the one assumed:
Catena et al, ‘09 find 0.385 ± 0.027 GeV/cm3. (for Einasto profile, but holds also for cored profiles). Rescaling the E_F for higher local DM density would lower the value of actual BF_{CS} by a factor of **(0.3/0.4)2~1/2**. ***(would not affect searches in our Galaxy...)***

✴ The commonly assumed effective value of tau into account **synchrotron** (assuming 3μG random magnetic fields in the diffusion zone -> 0.2 eV/cm^3) and **IC** losses on CMB and starlight, with energy densities of 0.3 and 0.6 eV/cm^3, respectively.

✴BF_{SS}?

$$B_F = BF_{CS} BF_{SS}$$

Constrained quantity BF_{CS}, could be lower than E_F (needed to explain local e+e-) by a factor of a few...

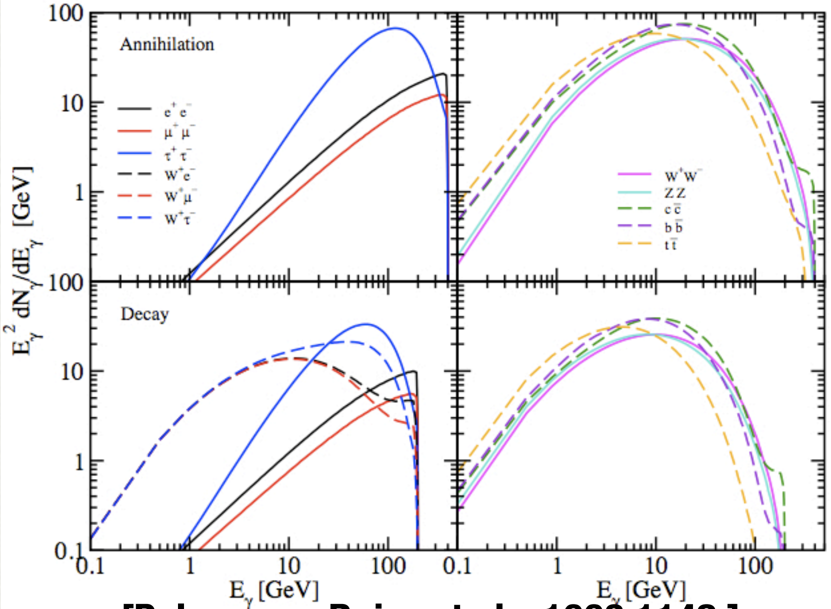
In general this fit can be performed for ***four distinct signatures***:

✶***annihilating*** or ***decaying*** DM: mainly just a switch in the source term (rho vs rho^2 dependence)

$$\rho^2 \langle \sigma v \rangle / 2M^2 \leftrightarrow \rho \Gamma / M$$

✶***2l*** or ***4l*** final states (softer electron spectra, lower FSR).

more on this later...



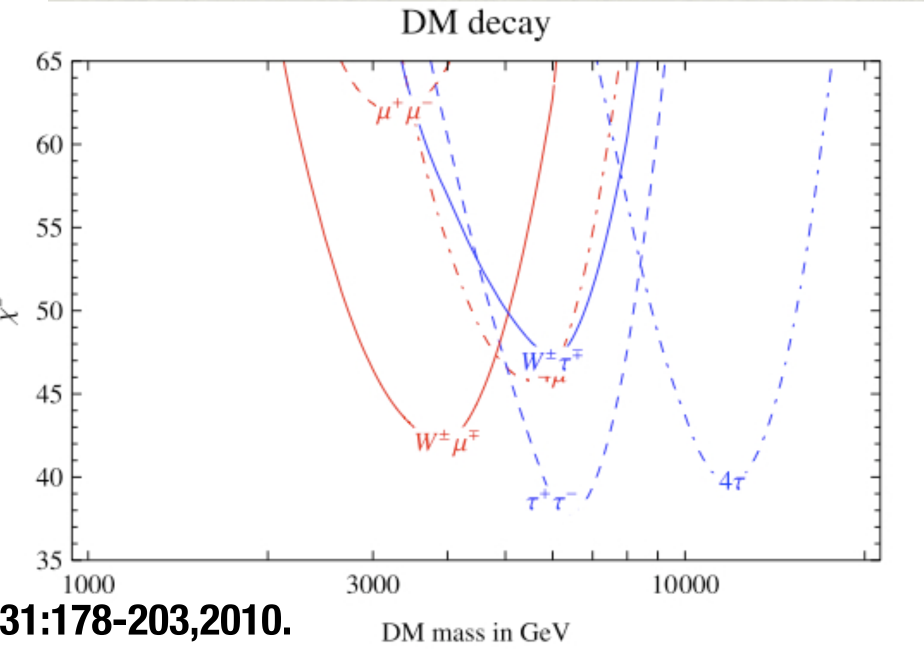
[Palomares-Ruiz,, et al. , 1003.1142.]

Fit all PAMELA & FERMI &HESS data.

decay channel & mass

Annihilation vs decay: a simple switch in the rate & different mass deendence

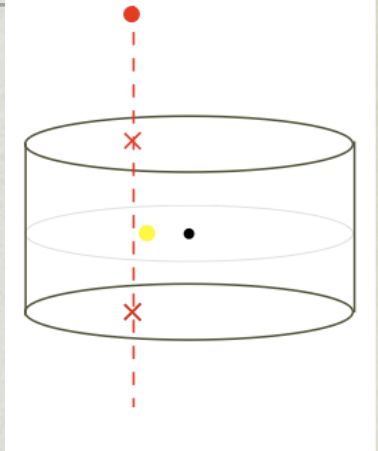
\+ some minor differences (only in the DM annihilation case a sizable amount of lower-energy e± can reach us from the Galactic Center, giving rise to a smoother e± energy spectrum)



P. Meade et al., Nucl.Phys.B831:178-203,2010.

Caution:

Regis et al, Phys.Rev.D79:123517,2009.



For example: if signal dominated by a near-by moving clump...
spectra, normalization... different -- different set of conclusions

∗ the energy threshold can be drastically shifted for a substructure which is far away from the observer;
∗the spectral shape is mostly determined by the transient, and is sensitive to the specific transient one considers;
∗the normalization depends mainly on the dark matter density within the substructure.

An extreme case, however it illustrates that fact that derived quantities should be considered with care.

however, we stick to the baseline model in this talk...

Piero?

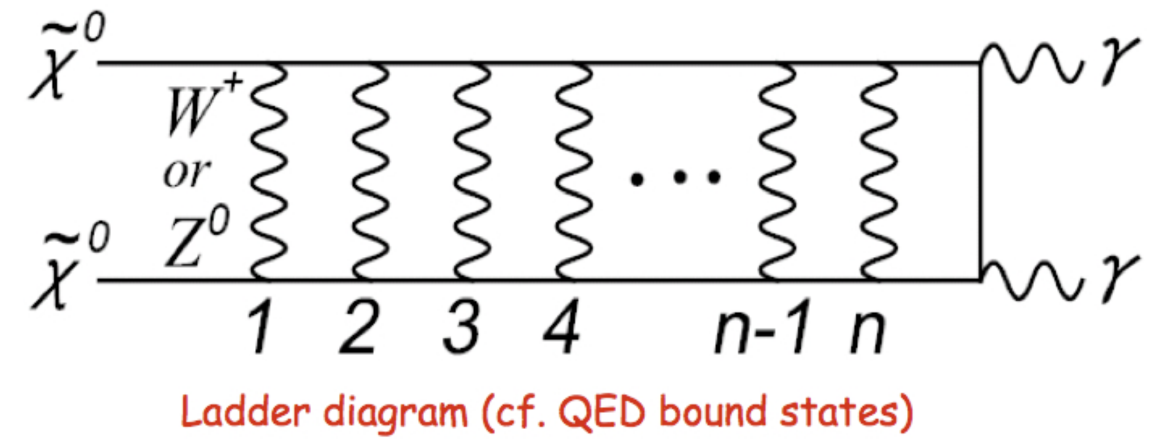
2. Particle physics models

PAMELA&FERMI&HESS fits -> ***leptophilic final states, large "event rates" in our galaxy and a high mass scale (O(TeV)).***

Ways to to get a high boost factor:
1. Nearby Dark Matter clump(unlikely)
2. Non-thermal production (decay of heavy DM ...)
3. Sommerfeld enhancement

$$B = \left(\frac{\langle n^2 \rangle_{\Delta V}}{\langle n^2_{NFW} \rangle_{\Delta V}} \right) \times \left(\frac{\langle \sigma v \rangle_{v_{halo}}}{\langle \sigma_0 v \rangle_{v_F}} \right)$$

Sommerfeld enhancements: a new interaction in the dark sector, with a force carrier $m_\phi < \alpha M_{DM}$ (i.e. dark matter bound states are present in the spectrum of the theory).



Ladder diagram (cf. QED bound states)

freeze-out unaffected, T~m/20->v/c~.3

Hisano, Matsumoto and Nojiri, 2003; Hisano, Matsumoto, Nojiri and Saito, 2004, expandingon the 2gamma calculationof L.B. and P. Ullio(1998)

notice:

Sommerfeld effect natural for ~TeV DM (for a mediator of ~<m_Z).

if ϕ light -> leptophilic final states (from kinematic suppression)

A problem of naturalness: ***we must have massive degrees of freedom, which are naturally light, while still coupling significantly to the darkmatter.***

Solution: we can have a coupling to spin-1 gauge fields arising from some dark gauge symmetry. Because that ***scalar need not couple directly to the dark matter,*** it is sufficiently sequestered that its small mass is technically natural...

For example, light hiden gauge group could couple through kinetic mixing of e charge in our sector with the hidden kinetic term or throug mass mixing through the Higgs.

$$\epsilon F_{\mathrm{DM}}^{\mu\nu} F_{\mu\nu} \quad \text{and} \quad \epsilon h^2 h_{\mathrm{DM}}^2$$

For Yukawa potential:

$$S_k \rightarrow \frac{\pi\alpha}{v}$$

At low velocity, when de broglie wave length of DM becomes larger than the force range $m_{\phi}^{-1,}$ S saturates to the value $S \sim \alpha\ m_{dm}/m_{\phi}$, at a saturation velocity $v_{min}/c \sim m_{\phi}/m_{dm}$

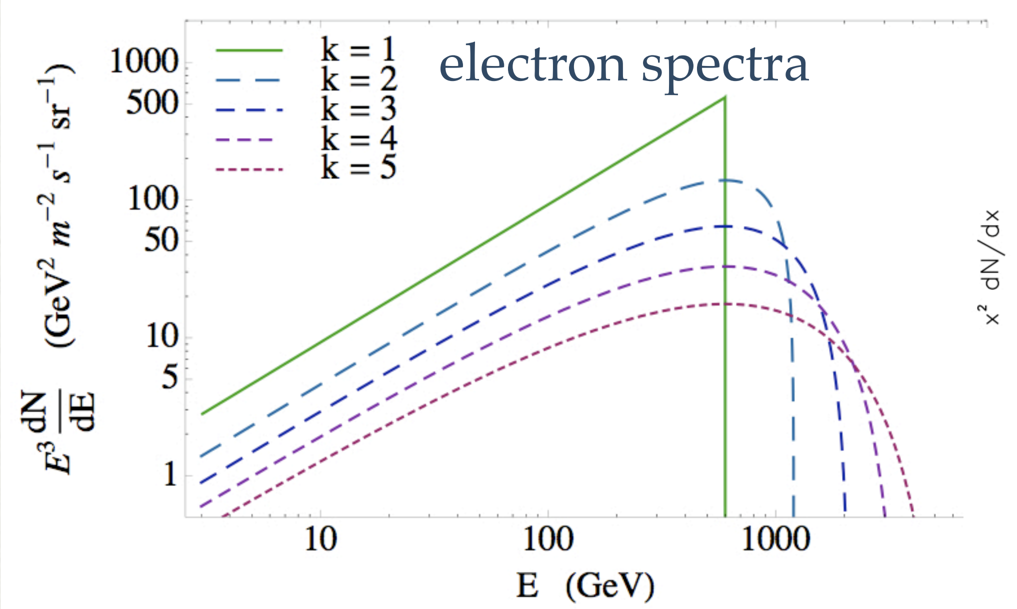
For specific values of, Yukawa potential develops threshold bound states, resulting in resonant enhancements of the Sommerfeld enhancement

Since model dependent, typically not taken into account when deriving the constraints (conservative approach).

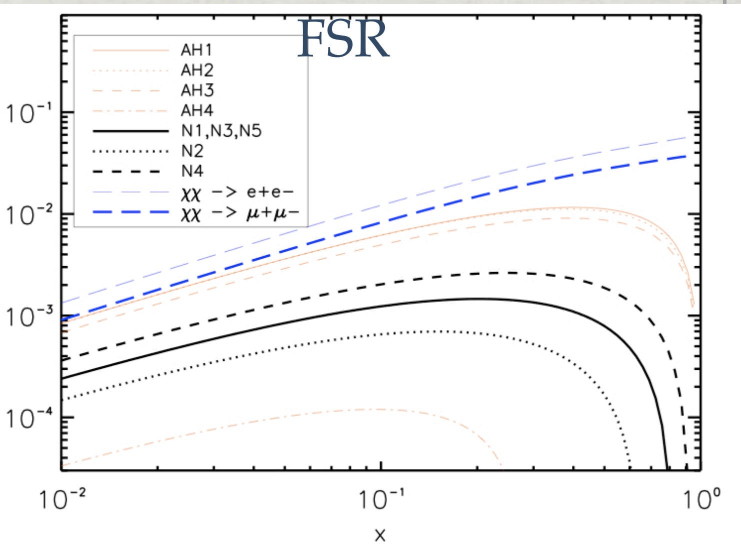
Note: DM annihilations into two light hidden sector particles produce at least 4 body final states of SM particles.

More generally, the e+ e– flux gets softer on the number of steps, and FSR gets weaker, compared to the ***2l*** spectra.

$$2\chi \rightarrow 2\phi_1 \rightarrow 4\phi_2 \rightarrow \ldots \rightarrow 2^{k-1}e^{+}+2^{k-1}e^{-}$$

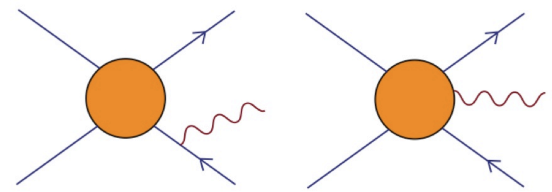


Kuhlen et al, Phys.Rev.D79:123517,2009.

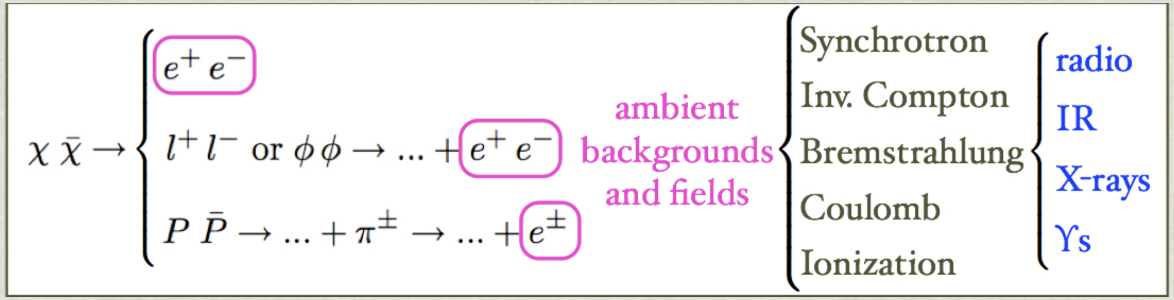


Signatures in photons

Photons produced directly, through FSR:



Or through radiative processes:



$$\chi\,\bar{\chi} \rightarrow \begin{cases} \boxed{e^+\,e^-} \\ l^+\,l^- \text{ or } \phi\,\phi \rightarrow \ldots + \boxed{e^+\,e^-} \\ P\,\bar{P} \rightarrow \ldots + \pi^\pm \rightarrow \ldots + \boxed{e^\pm} \end{cases}$$

ambient
backgrounds
and fields

- Synchrotron
- Inv. Compton
- Bremstrahlung
- Coulomb
- Ionization

- radio
- IR
- X-rays
- γs

IC emission of a 100 GeV to 1 TeV electron on 1eV starlight photons gives gamma-rays with energies peaked in about the range 50 GeV to 5 TeV;

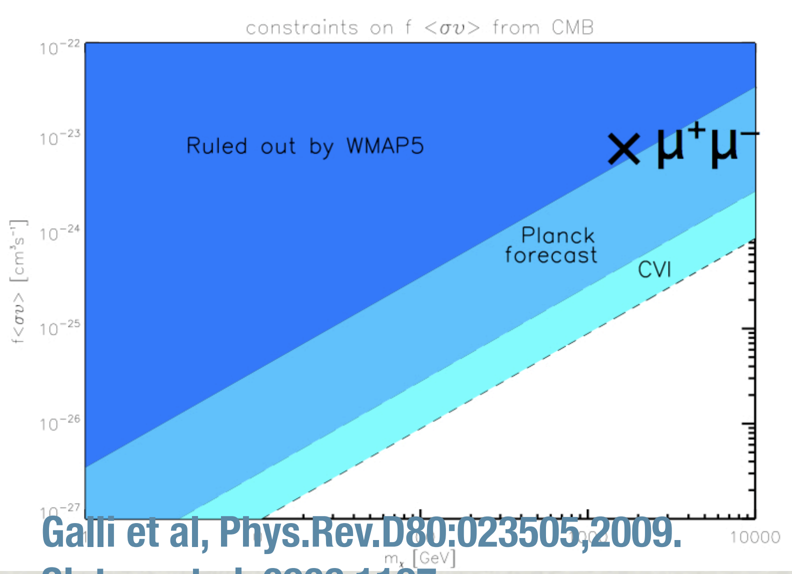
$$E_{\gamma'} \sim E_\gamma (E_e/m_e)^2 \sim 10\ \mathrm{GeV}$$

the associated ***synchrotron*** emission on a 1 microG magnetic field is peaked between 50 to 5000 GHz (scaling linearly with the magnetic field)

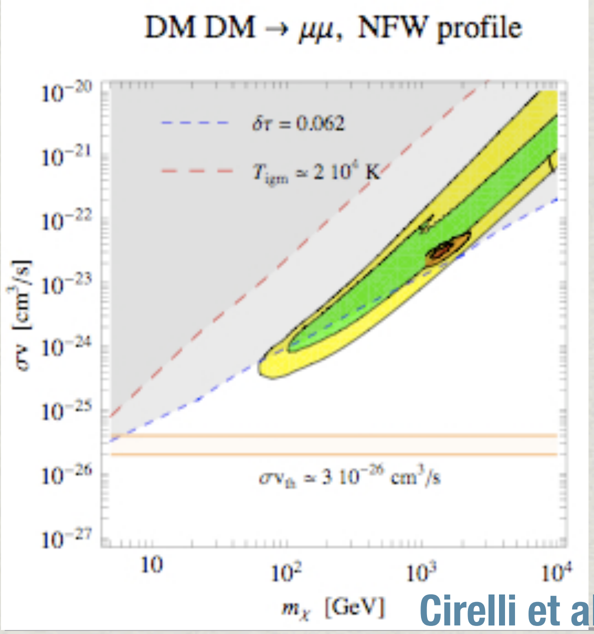
3. Constraints: early Universe:

BBN: **Hisano et al,PhysRevD.79.083522**

Epoch of recombination (effect on CMB): z~1000. DM annihilation products ionize plasma, heat plasma and excite H... affecting the way recombination proceeds and therefore the angular power of CMB.



Galli et al, Phys.Rev.D80:023505,2009.
Slatyer et al. 0906.1197



reionization: $6 < z < 20$; DM annihilations products reionize the medium, freeing more electrons, that contribute to the optical depth (determined by WMAP) and also changing the temperature of the gas (measured via observations of the Ly-α forest).

Fabio?

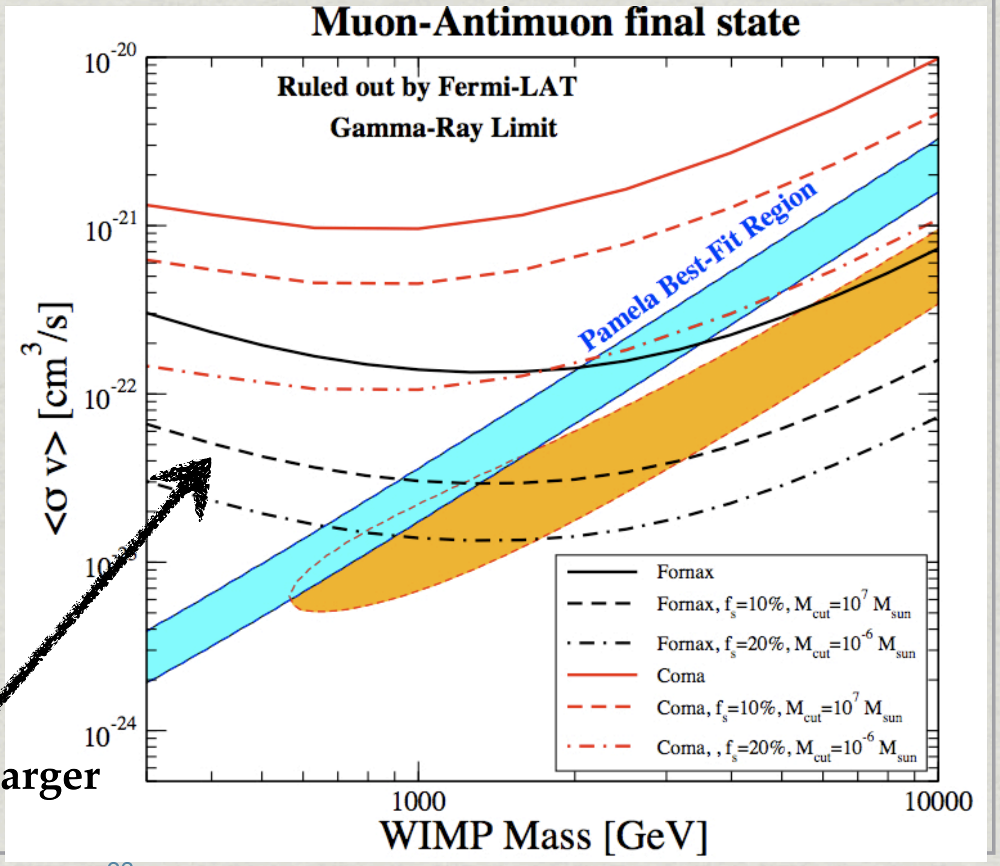
Cirelli et al,JCAP 0910:009,2009.; Hutsi et al. 0906.4550.

Galaxy Clusters

FERMI-LAT COLLABORATION, ARXIV: 1002.2239, JCAP.

Galaxy Clusters: The most massive halos formed in the Universe. Dark matter dominated objects, but, ***expected to be sources of high energy gamma rays***, due to a population of cosmic rays accelerated in merger and accretion shocks.

Selected 6 clusters (observed in X rays) expected to have the brightest DM gamma ray emission-> no Galaxy cluster discovery in gamma rays.

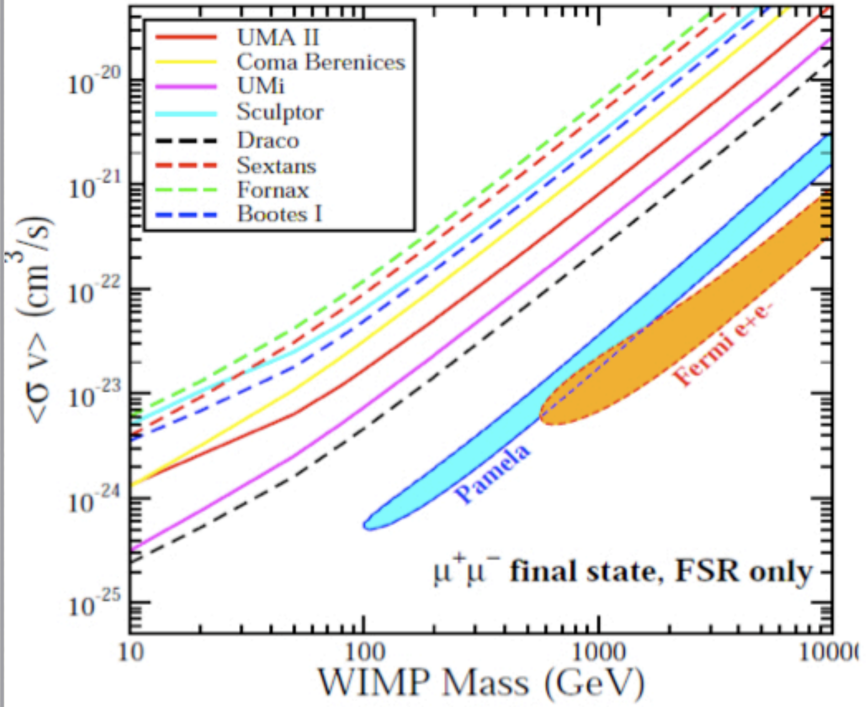


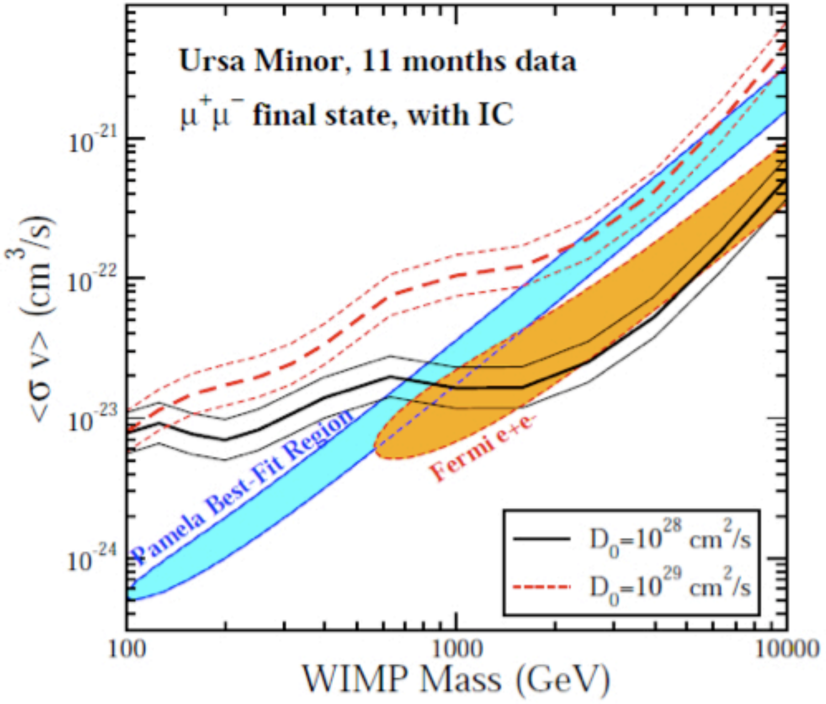
dSpH size substructure and larger

FERMI-LAT COLLABORATION, APJ, 712, 147 (2010).

Limits on DM annihilation set based on:

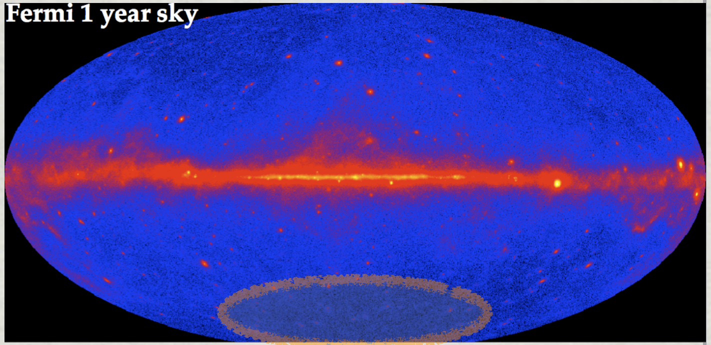
- *background: point sources from Fermi Catalog (within 10 deg from dSph) + galactic and isotropic diffuse emission.*
- *DM signal calculated assuming NFW profile, and modeling of stellar kinematic data (Keck observatory, Martinez, Bullock and Kaplinghat).*


$\mu^+\mu^-$ final state, FSR only


$\mu^+\mu^-$ final state, FSR + IC

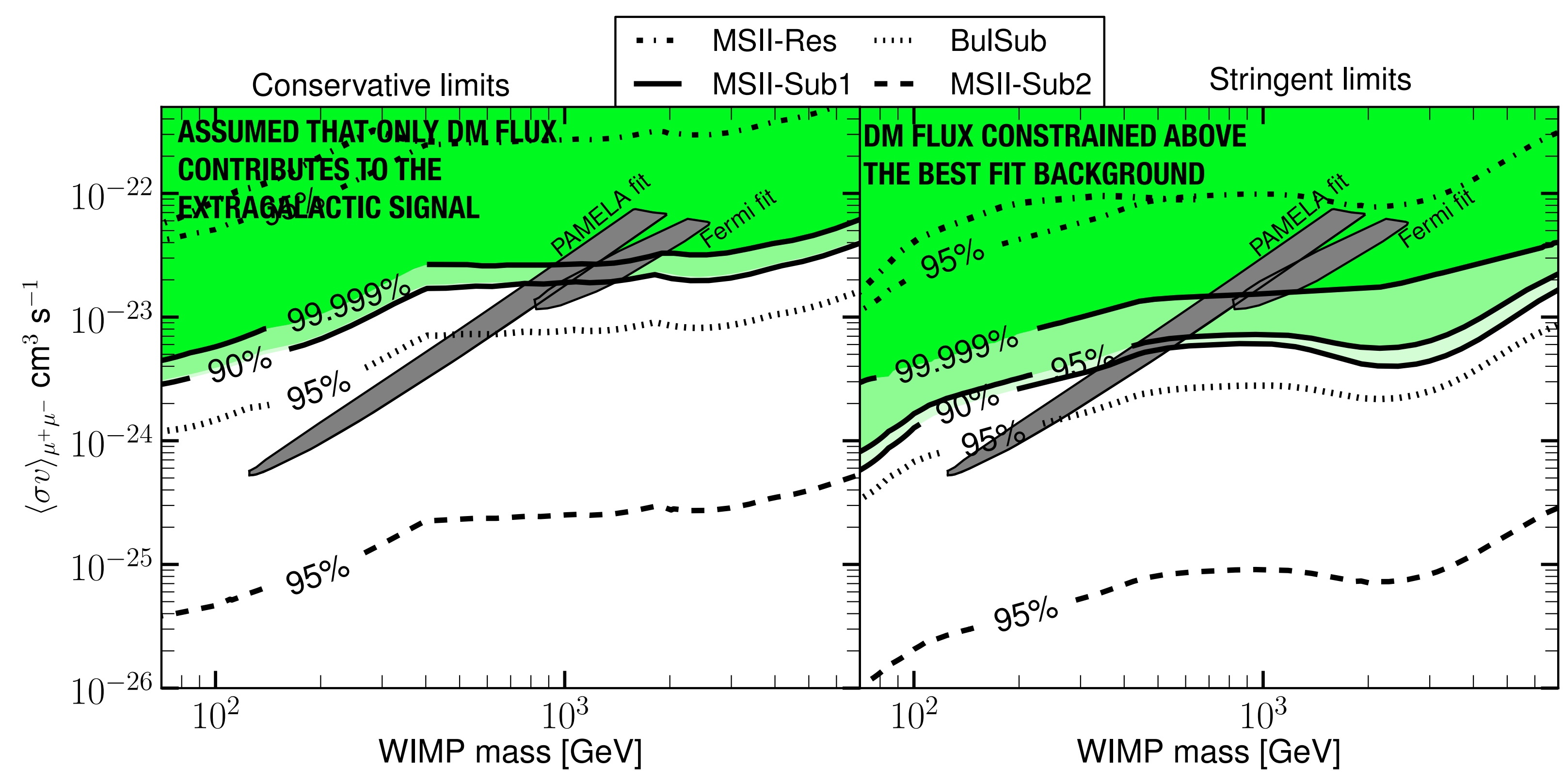
Inverse Compton spectra depends on the diffusion parameter assumed, MODEL DEPENDENT. Dwarfs are not the best place to constrain leptonic channels, they are small objects electrons potentially diffuse out before IC scatter.

all halos/all redshifts



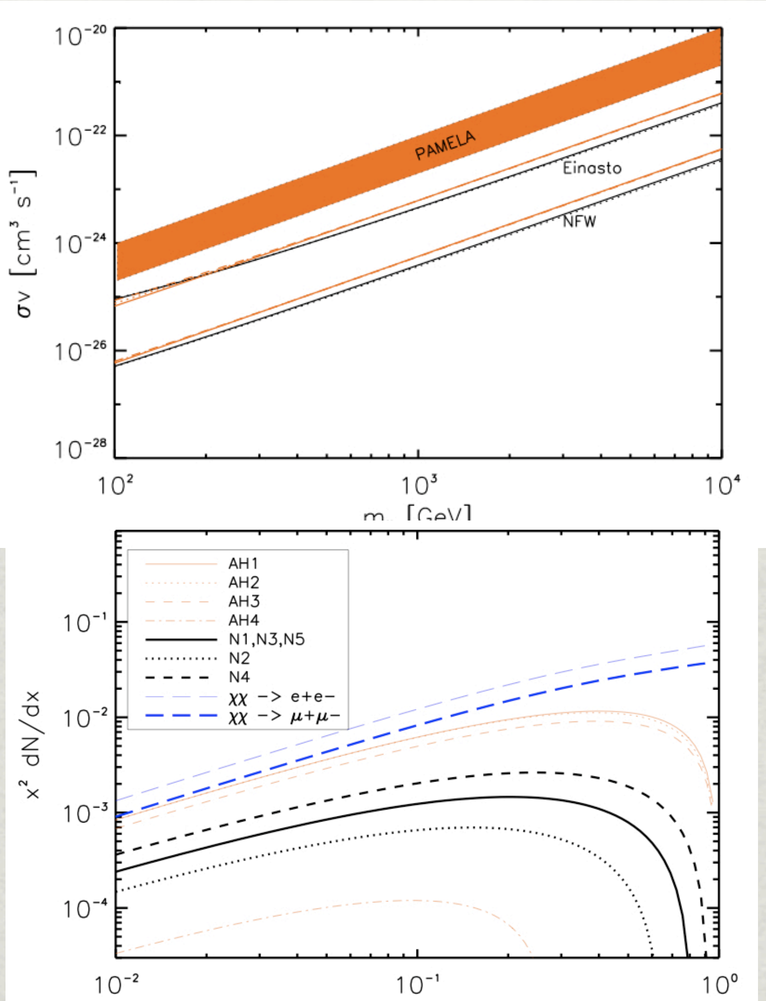
Fermi-LAT collaboration, arxiv:1002.4415, JCAP.

limits depend on modeling of halo formation (N-body simulations).



Our Galaxy (typically depend strongly on the DM profile):

Radio: High energy electrons emit radio to microwave photons via synchrotron radiation on the Galactic magnetic fields.
The upper limit on the radio emission from a cone with half-aperture of 4′′ (O (1)pc) towards Sgr A* at ν = 0.408 GHzH.



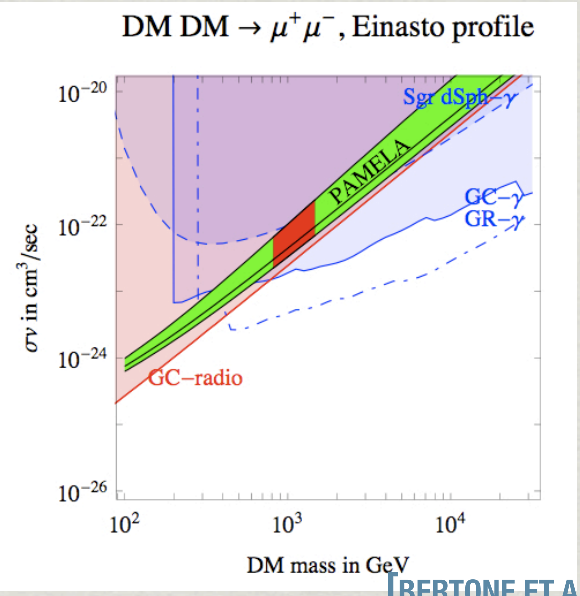
Bergstrom et al., Phys.Rev.D79:081303,2009.

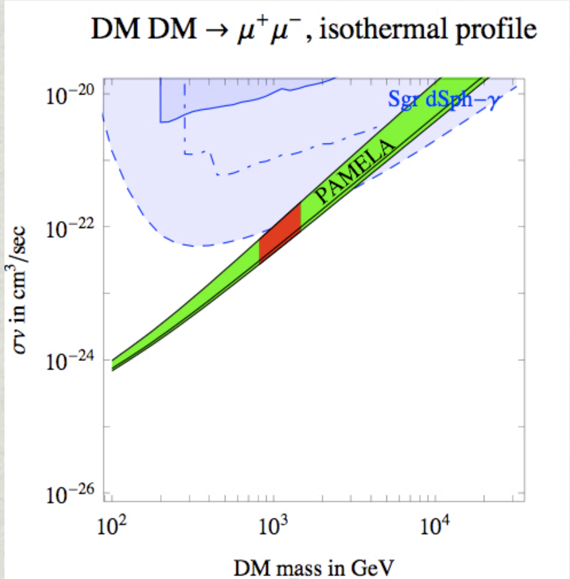
Our Galaxy:

gamma rays:

Galactic Center: HESS source (HESS J1745-290) lying within 7″ ± 14″ ± 28″ from the supermassive black hole Sgr A*, and compatible with a point source of size less then 1.2′. energy spectrum dΦ / dE ∝ E−2.25 ±0.04

Galactic ridge: a complex of giant molecular clouds in the central 200 pc of the Milky Way. the reconstructed gamma-ray spectrum for the region with galactic longitude −0.8○ < l< 0.8○ and latitude ∣b∣ < 0.3○ is well described by a power law with photon index Γ = 2.29 ± 0.07stat ± 0.20syst .

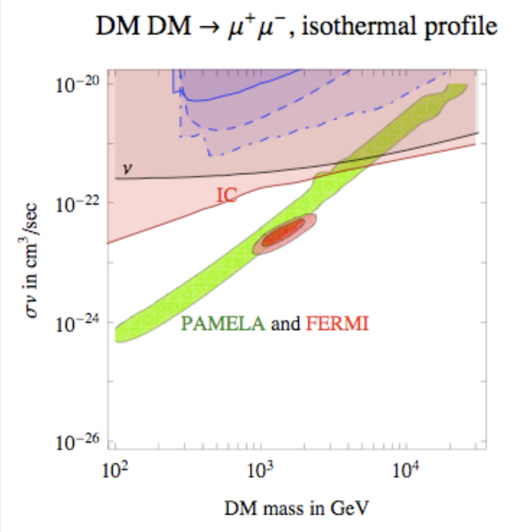


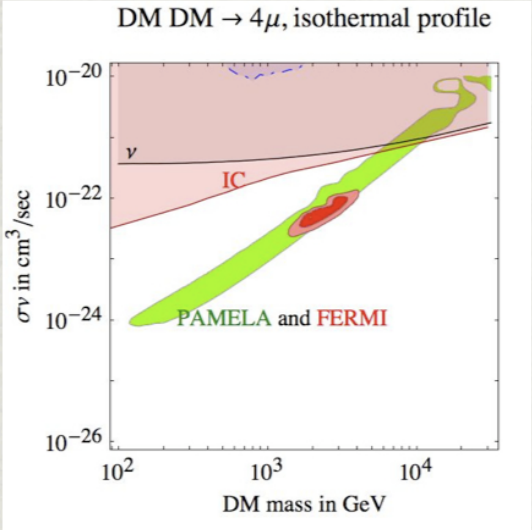


[BERTONE ET AL. JCAP 0903:009,2009,]

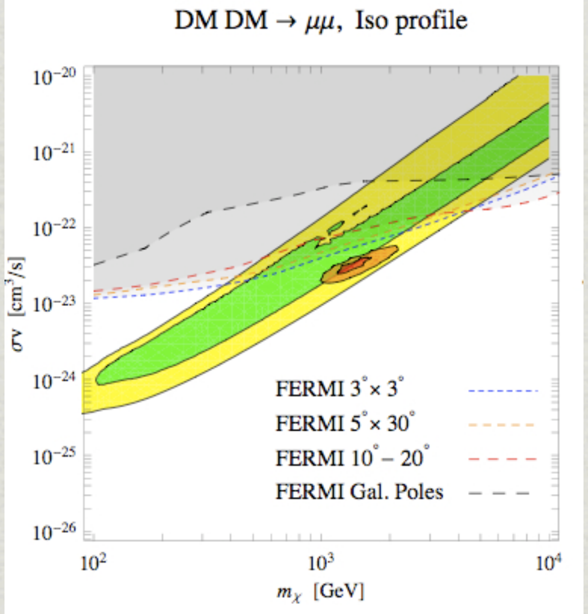
Our Galaxy:

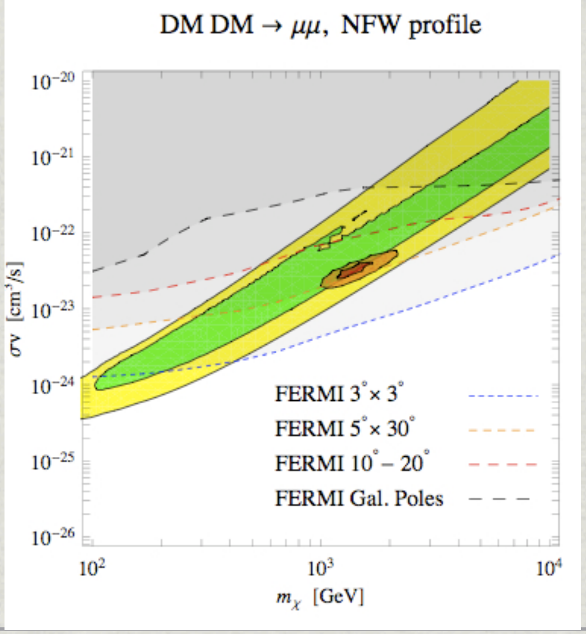
diffuse: based on the preliminary Fermi data: 10-20 deg, or:





P. Meade et al., Nucl.Phys.B831:178-203,2010.



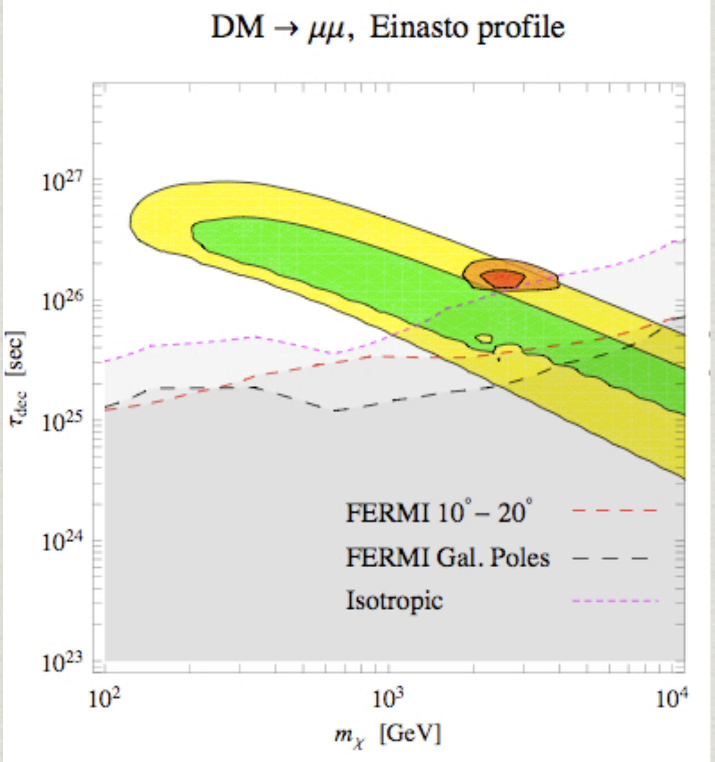


[Cirelli, et al,0912.0663v1]

Our Galaxy:

Isotropic diffuse: based on the preliminary Fermi data: ***Decaying DM.***

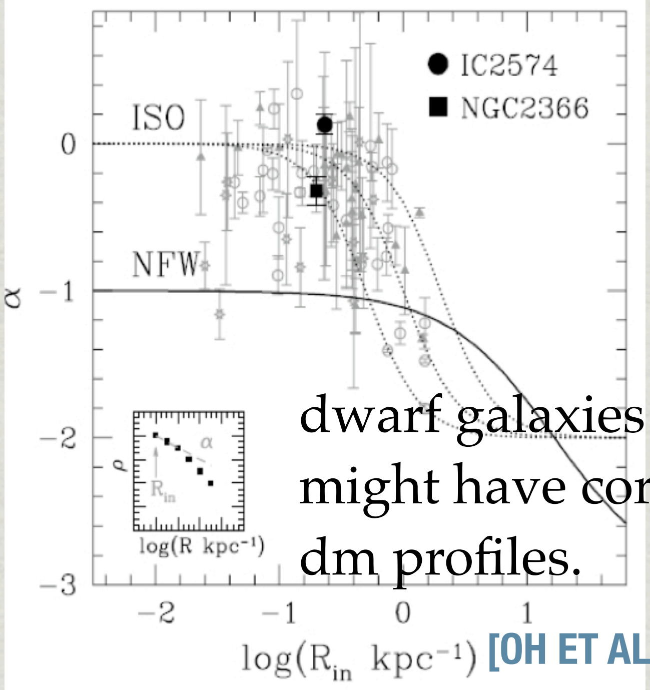
$$\frac{d\Phi^{\rm dec}_{\rm isotropic}}{d\epsilon} = \frac{d\Phi^{\rm dec}_{\rm cosm}}{d\epsilon} + 4\pi \left.\frac{d\Phi^{\rm dec}_{\rm halo}}{d\epsilon\, d\Omega}\right|_{\rm anti-GC}$$



[CIRELLI, ET AL, ARXIV:0912.0663V1]

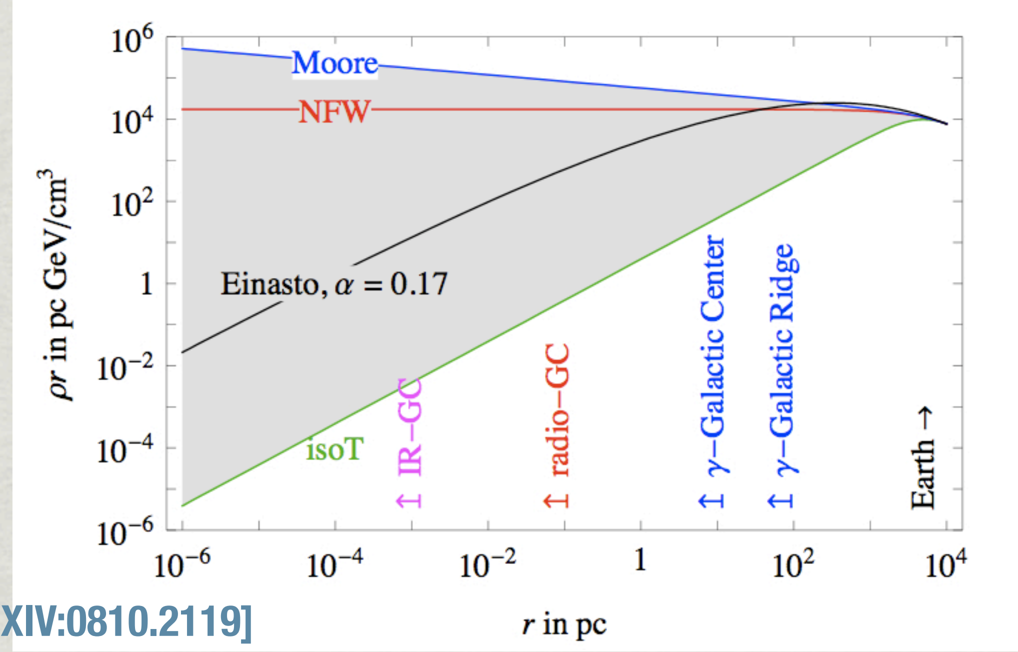
Summary so far:

These models are in tension with (too) many types of constraints. But, not convincingly ruled out yet (arguably still within existing uncertainties). ***Constraints somewhat weaker for 4l final states?*** *NFW (and steeper) in our Galaxy strongly disfavored* (if DM explanation of excess correct).

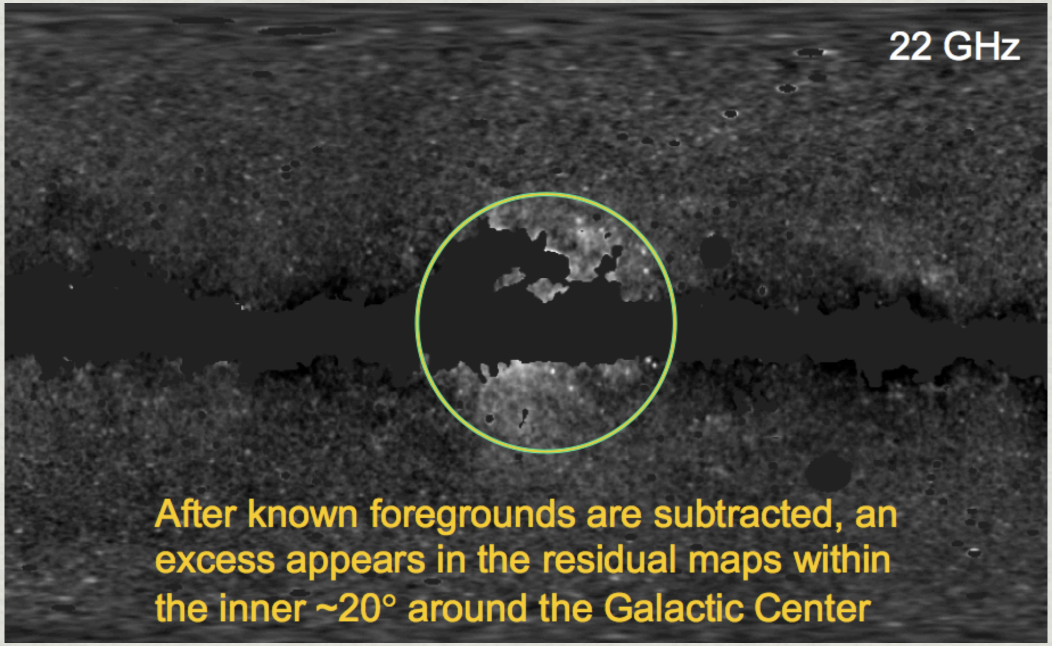


dwarf galaxies might have cored dm profiles.

[OH ET AL. ARXIV:0810.2119]



however, some measurements might hint in favor of leptophillic DM models...



After known foregrounds are subtracted, an excess appears in the residual maps within the inner ~20° around the Galactic Center

- hazes (WMAP, Fermi?) and/or INTEGRAL: claims of an extra electron population towards the galactic center...

- Is WMAP haze signal consistent with PAMELA/Fermi interpretation? (see Alessandro's talk on Friday)

Alex?

Particle physics models that could evade (some) of constraints: Asymmetric DM

[COHEN ET AL. PHYS.REV.LETT.104:101301,2010]

A way to evade early universe constraints (annihilating DM):

$$(n_X - n_{\bar{X}}) \sim (n_\ell - n_{\bar{\ell}}) \sim (n_b - n_{\bar{b}}),$$

$$m_X \sim \frac{\Omega_{\rm DM}}{\Omega_b} m_p$$

Main idea: baryon asymmetry transfered to dark sector through interactions which violate lepton number -- Explains similarity in Ωb and ΩDM

$$\mathcal{L}_{\rm asym} = \frac{1}{M'^4_{ij}} \bar{X}^2 (L_i H)(L_j H) + \text{h.c.},$$

$$\bar{X}\,\bar{X} \leftrightarrow \bar{\nu}\,\bar{\nu}$$

$$\mathcal{L}_{\rm sym} = \frac{1}{M^2_{ij}} \bar{X}\,X\,\bar{L}_i\,L_j + \text{h.c.},$$

$$\mathcal{L}_M = m_M\,\bar{X}\,\bar{X},$$

After Lasym freezes out, X and Xbar anihilate till there are no only Xbar left. At late times, Xbar anihilate back to X through majorana mass term, and self-annihilation recommence.

Particle physics models that could evade (some) of constraints: Long lived intermediate state

[ROTHSTEIN, ET AL. JCAP 0907:018,2009.]

A way to evade constraints from the Galactic Center: DM annihilates into ***long lived*** particles (Gamma ray signature which can interpolate between the signatures of DM decays and annihilation.
The long lifetime disperses the production zone of the SM particles away from the galactic center and hence, relaxes constraints from gamma ray observations on canonical annihilation scenarios.
The typical decay length l~10 kpc six operator suppressed by a scale 10^13 GeV, which is roughly the see saw scale for neutrino masses.

$$\chi\chi \to \phi\phi \to 2\,\mathrm{SM}\,2\,\overline{\mathrm{SM}}\,.$$

$$\tau = \frac{\lambda}{c\beta\gamma} \simeq \frac{10^{12}\,\mathrm{s}}{\beta\gamma}\left(\frac{\lambda}{10\,\mathrm{kpc}}\right).$$

Problems: with late time decays (light element abundances))? diffuse gamma ray signal...

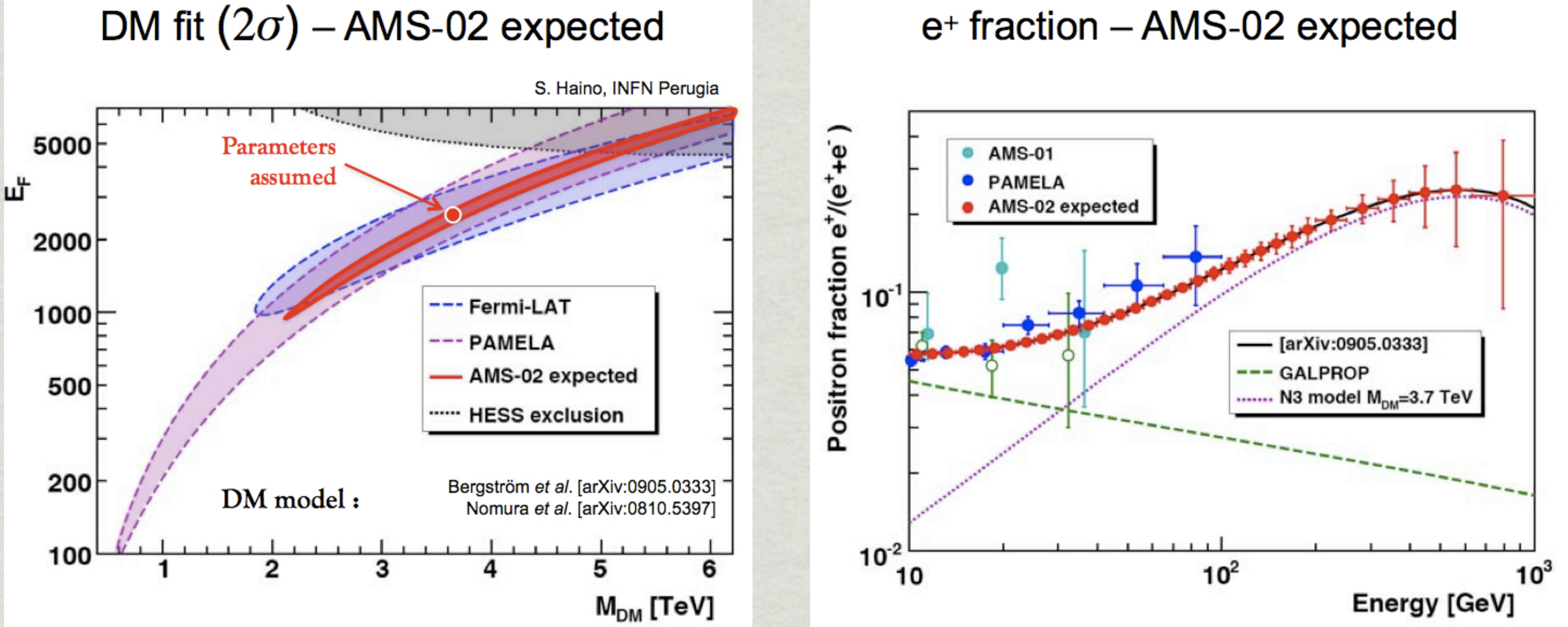
decaying DM?

- some of constraints evaded by considering decaying DM.
- Decaying DM models have a lot more freedom. The e± excesses can be accommodated by choosing the DM decay rate, which unlike the thermal DM annihilation rate, is not linked to cosmology
- Unfortunately, the lifetime ~ O(10^26) s required to fit the data is not predicted in these scenarios, rather obtained a posteriori.
- Example:gravitino dark matter which is unstable due to a small breaking of R-parity; Since R-parity is broken, gravitinos can decay into a photon and a neutrino, although with a lifetime that, being suppressed both by the Planck mass and by the small R-parity breaking parameters, is naturally much longer than the age of the Universe

A. Ibarra and D. Tran, Phys. Rev. Lett. 100, 061301

Further test:

Electron spectra: does it show signature of several components (bumpiness)? **AMS** should be able to tell (modulo magnet problems ?)



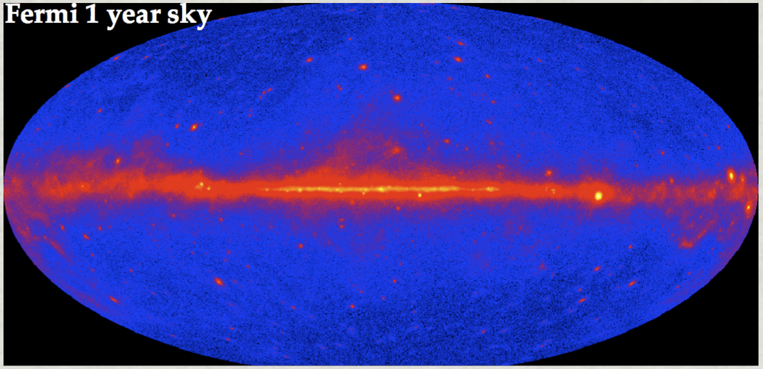
Sensitivity prediction by AMS-02 collaboration, Haino. s.

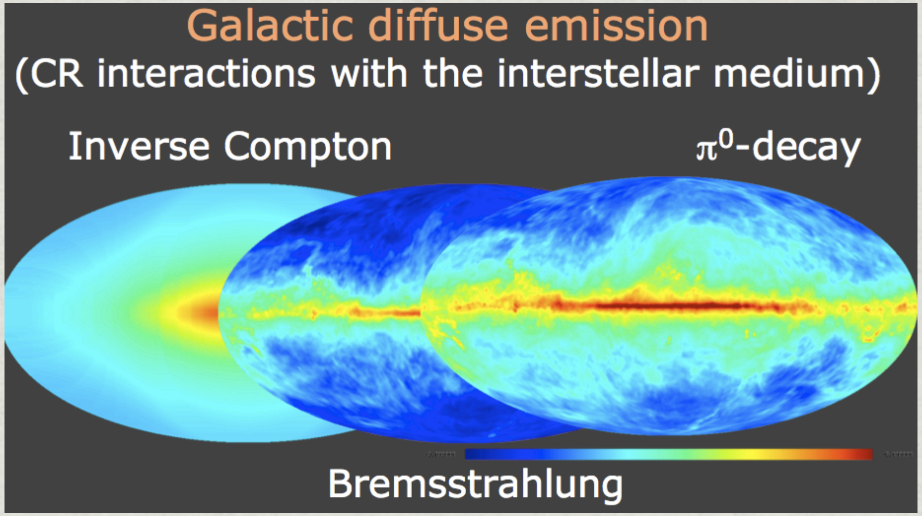
Further test:

Fermi diffuse data: ***The DM ICS spectrum is well predicted***.

(i) Far away (10 deg) from the Galactic Center, the DM uncertainties are relatively mild.

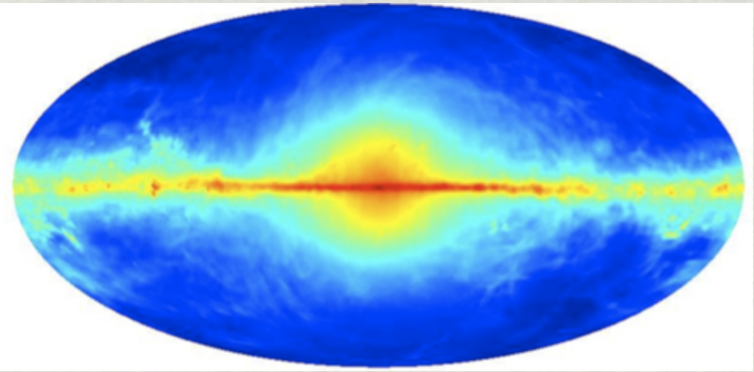
(ii) all DM models that fit the data predict roughly the same e± spectrum.

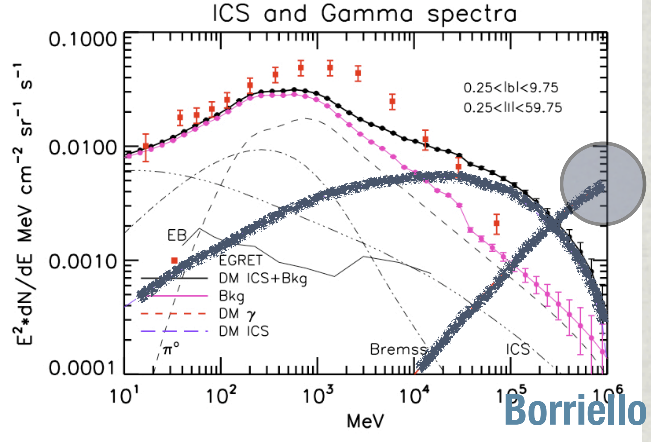




The full sky fit to the Galactic diffuse can probe DM efficiently, by exploiting both, spatial and spectral information.

But a rigorous fit to the astrophysical signal is needed: depends on cosmic ray propagation, gas column densities, interstellar radiation field...





Borriello et al, 0903.1852.

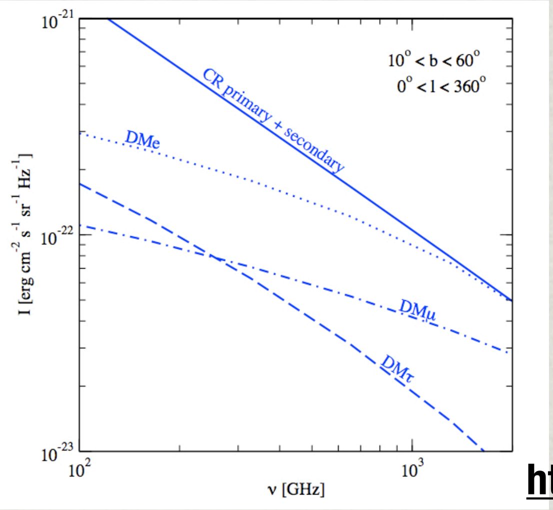
Further test:

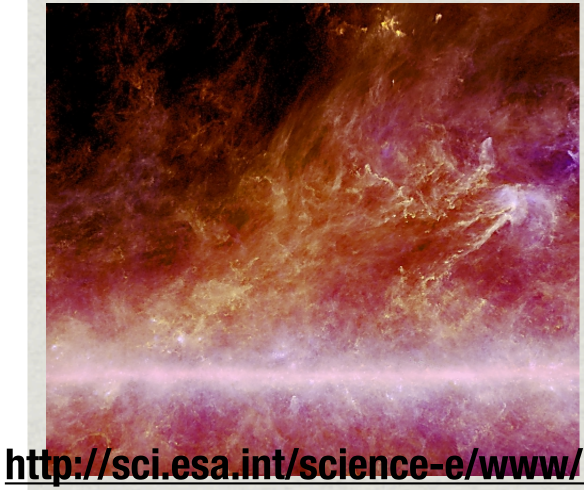
Plank?

The injection of high energetic electrons (Ee~100GeV) induce a signal peaked at frequencies 100GHz. Above the WMAP range, but within PLANCK's sensitivity, (up to 850GHz).

thermal emission rather than synchrotron is expected to dominate the foreground. Focusing the analysis on the spatial distribution

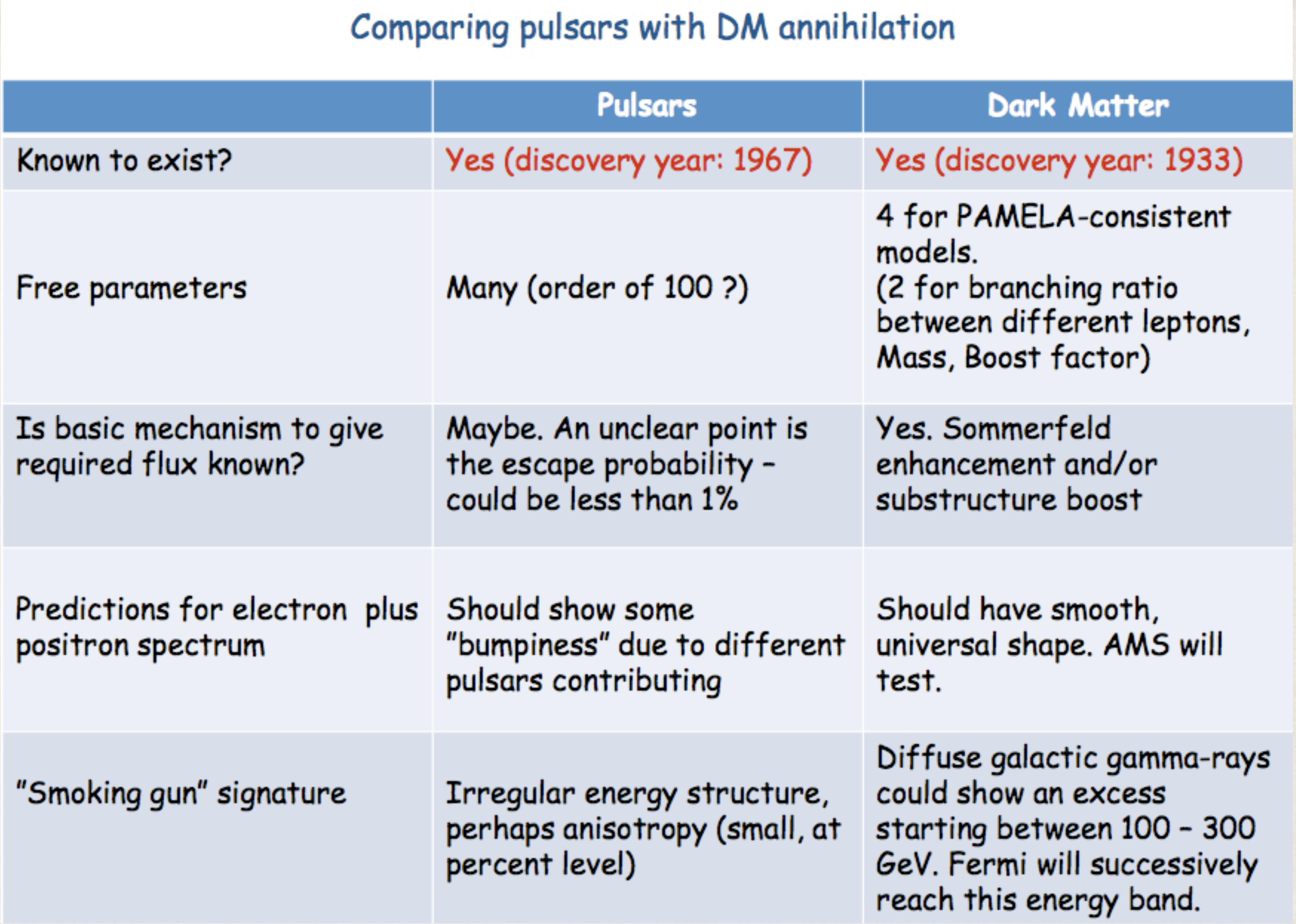
and on polarization data could, however, help to disentanglea DM-induced synchrotron signal.





angular resolution 5", Planck traces cold dust.

http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=46706



Comparing pulsars with DM annihilation

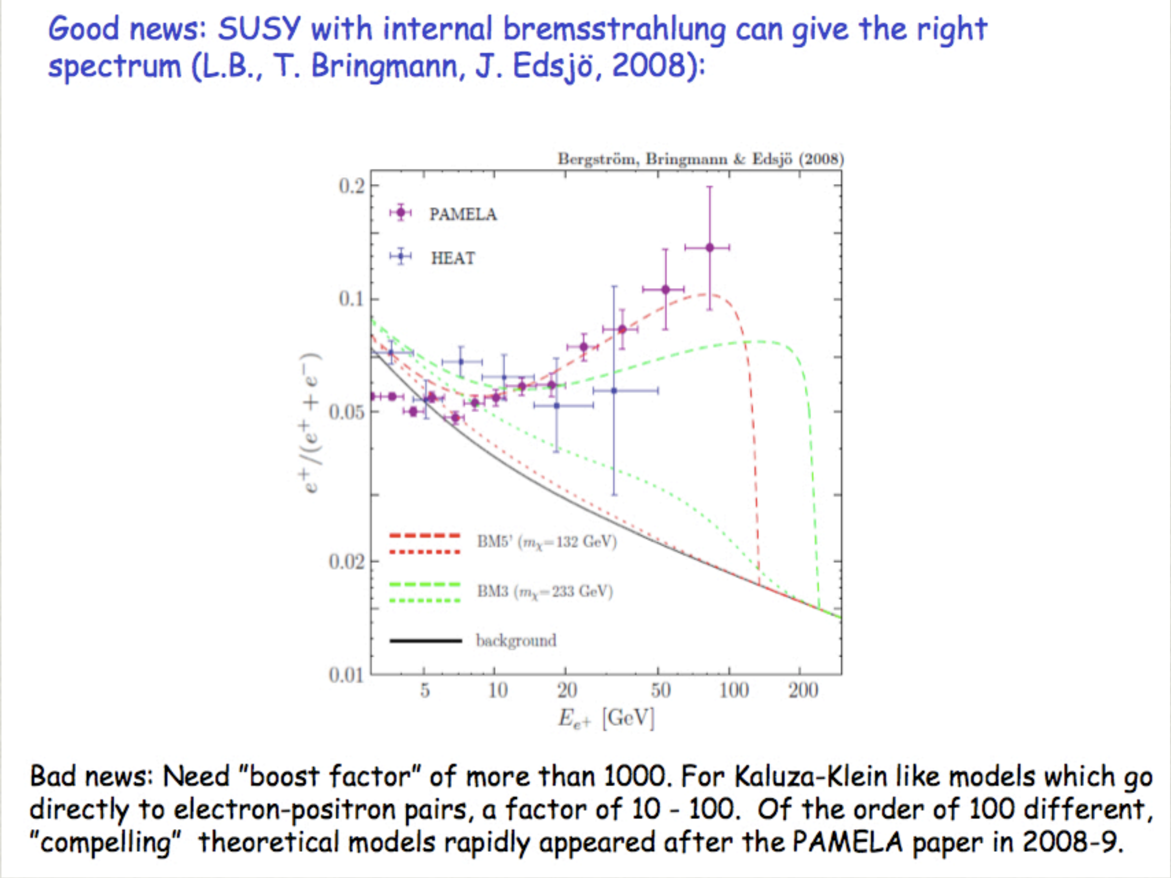
	Pulsars	Dark Matter
Known to exist?	Yes (discovery year: 1967)	Yes (discovery year: 1933)
Free parameters	Many (order of 100 ?)	4 for PAMELA-consistent models. (2 for branching ratio between different leptons, Mass, Boost factor)
Is basic mechanism to give required flux known?	Maybe. An unclear point is the escape probability – could be less than 1%	Yes. Sommerfeld enhancement and/or substructure boost
Predictions for electron plus positron spectrum	Should show some "bumpiness" due to different pulsars contributing	Should have smooth, universal shape. AMS will test.
"Smoking gun" signature	Irregular energy structure, perhaps anisotropy (small, at percent level)	Diffuse galactic gamma-rays could show an excess starting between 100 – 300 GeV. Fermi will successively reach this energy band.

[Bergstrom, L., talk at UCLA DM2010]

what have we learned (was this excersise of any use)

2. Particle physics models

PAMELA fits -> *could come from mssm; IB, stau coanhihilation regio. B~10^4 and light DM.*



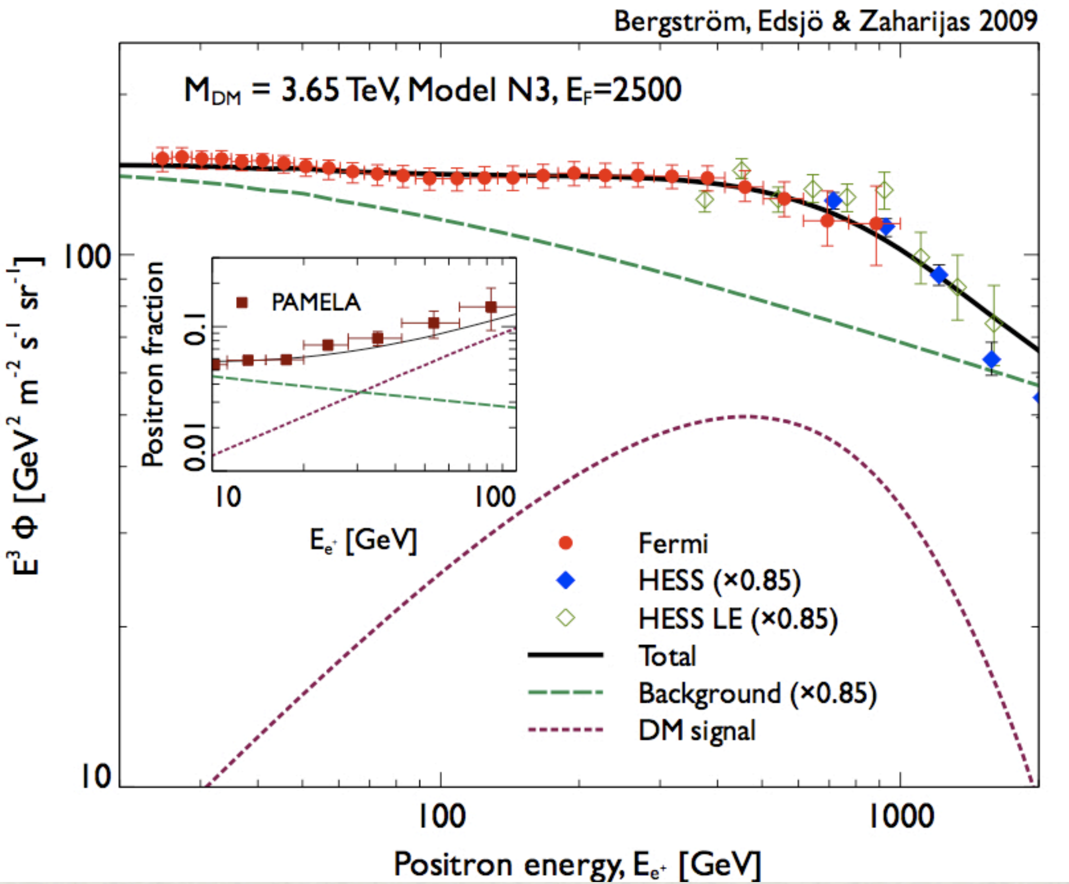
Good news: SUSY with internal bremsstrahlung can give the right spectrum (L.B., T. Bringmann, J. Edsjö, 2008):

Bad news: Need "boost factor" of more than 1000. For Kaluza-Klein like models which go directly to electron-positron pairs, a factor of 10 - 100. Of the order of 100 different, "compelling" theoretical models rapidly appeared after the PAMELA paper in 2008-9.

or, maybe a 4 particle final state?

Fit to PAMELA & FERMI &HESS data

From particle physics side 21 states are rather unnatural. More on the particle physics motivation for this choice, later...


Bergström, Edsjö & Zaharijas 2009