The problem of Dark Matter searches

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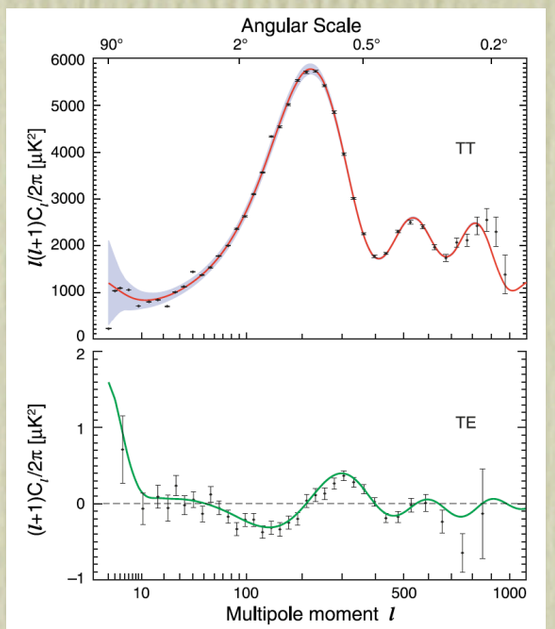
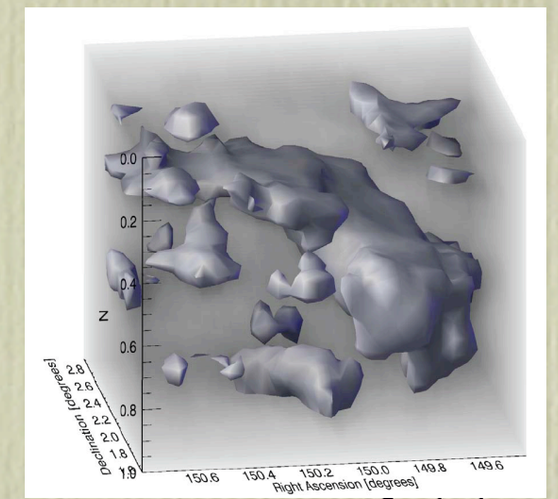
SciNeGHE 2010, Trieste, September 10, 2010

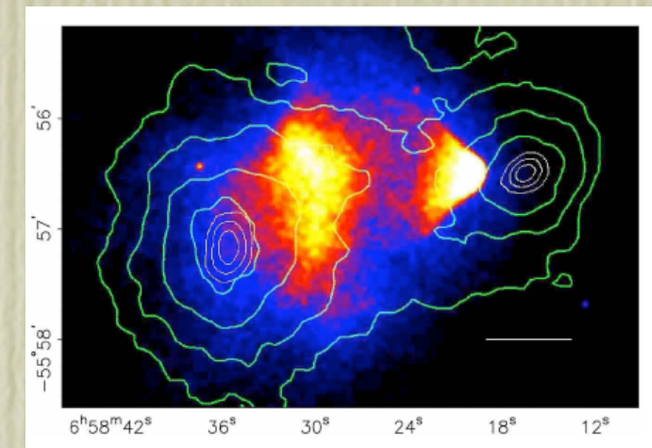
Overwhelming evidence for CDM as building block of all structures in the Universe, from the largest scales down to galactic dynamics:



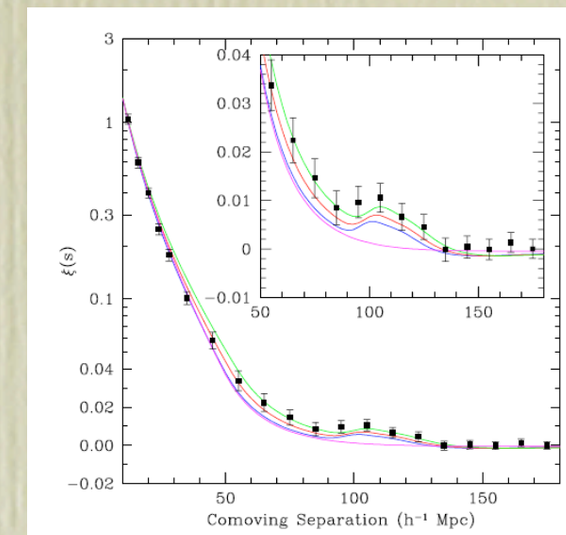
CMB



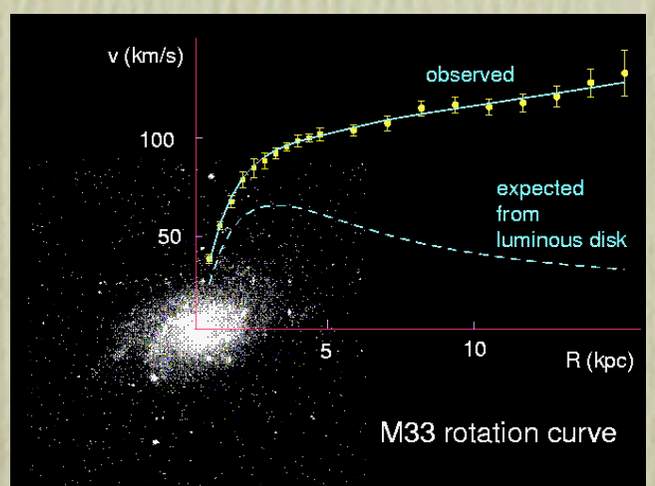
grav. scaffold



"Bullet" cluster



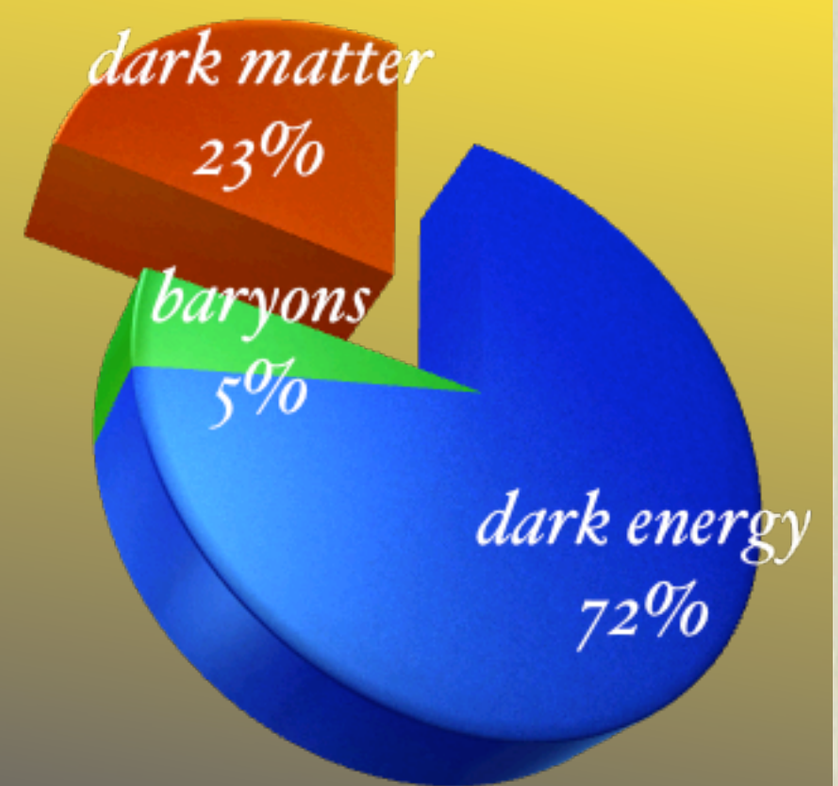
BAO



galaxies

+ many others:

All point to a single "concordance" model:



Cosmological and astrophysical observations suggest that dark matter is: an optically-dark (i.e. dissipation-less), collision-less, classical fluid with negligible free-streaming effects. This excludes some models, such as, e.g.:

~~Baryonic DM~~

~~Hot DM (e.g. SM neutrinos)~~

From the cosmologist perspective, Non-baryonic Cold DM is the preferred paradigm (i.e., for DM only gravity matters). Not helping much the particle physicist: there are only (weak) upper limits on the DM interaction strength, while other crucial properties (e.g., the mass scale) are missing.

"Particle Dark Matter", Cambridge U. Press, edited by G. Bertone

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The picture becomes slightly more focussed addressing the question: How was DM generated? The most beaten paths have been:

i) DM as a ***thermal relic product*** (or in connection to thermally produced species);

ii) DM as a ***condensate***, maybe at a phase transition; this usually leads to very light scalar fields;

iii) DM ***generated at large T***, most often at the end of (soon after, soon before) inflation; candidates in this scheme are usually supermassive.

CDM particles as thermal relics

Let χ be a stable particle, with mass M_χ, carrying a non-zero charge under the SM gauge group. Processes changing its number density are:

$$\chi\bar{\chi} \leftrightarrow P\bar{P}$$

with P some (lighter) SM state in thermal equilibrium. The evolution of the number density is described by the Boltzmann equation:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_A v\rangle_T \left[(n_\chi)^2 - \left(n_\chi^{eq}\right)^2\right]$$

dilution by Universe expansion

thermally averaged annihilation cross section

$P\bar{P} \to \chi\bar{\chi}$

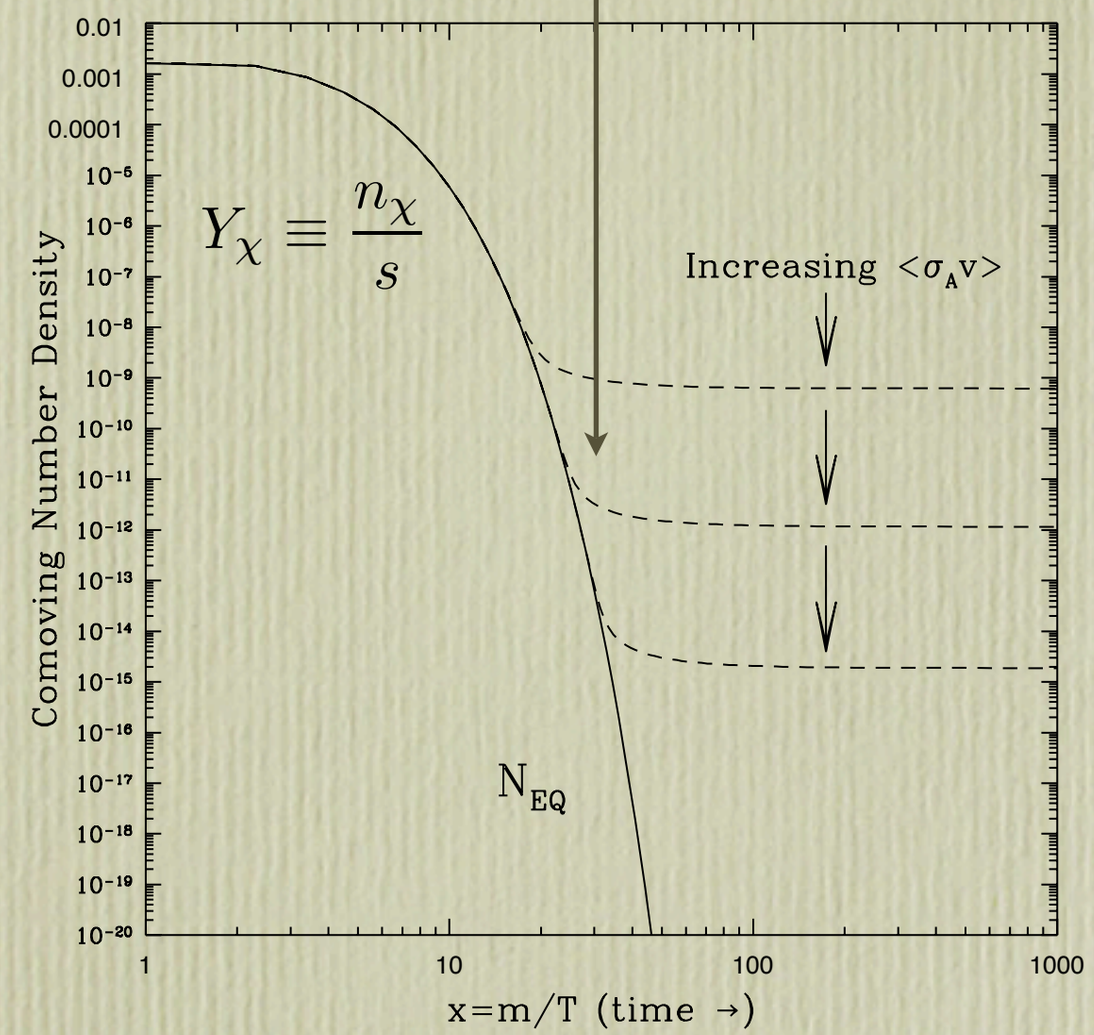
$\chi\bar{\chi} \to P\bar{P}$

χ in thermal equilibrium down to the freeze-out T_f , given, as a rule of thumb, by:

$$\Gamma(T_f) = n_\chi^{eq}(T_f)\langle\sigma_A v\rangle_{T=T_f} \simeq H(T_f)$$

After freeze-out, when $\Gamma \ll H$, the number density per comoving volume becomes constant. For a species which is non-relativistic at freeze-out:

$$\Gamma(T_f) \simeq H(T_f)$$



$$\Omega_\chi h^2 \simeq \frac{M_\chi\, s_0\, Y_\chi^{eq}(T_f)}{\rho_c/h^2}$$

(freeze-out + entropy conservation)

$$\simeq \frac{M_\chi\, s_0}{\rho_c/h^2}\,\frac{H(T_f)}{s(T_f)\langle\sigma_A v\rangle_{T_f}}$$

(standard rad. dominated cosmology)

$$\simeq \frac{M_\chi}{T_f}\,\frac{g_\chi^\star}{g_{\rm eff}}\,\frac{1\cdot 10^{-27}{\rm cm}^{-3}{\rm s}^{-1}}{\langle\sigma_A v\rangle_{T=T_f}}$$

with: $M_\chi/T_f \sim 20$

$$\Omega_\chi h^2 \simeq \frac{3\cdot 10^{-27}{\rm cm}^{-3}{\rm s}^{-1}}{\langle\sigma_A v\rangle_{T=T_f}} \longrightarrow \text{WIMP}$$

The WIMP recipe to embed a dark matter candidate in a SM extension: foresee an extra particle χ that is stable (or with lifetime exceeding the age of the Universe), massive (non-relativistic at freeze-out) and weakly interacting.

WIMP dark matter candidates:

A simple recipe in which maybe the most delicate point is the requirement of stability. You can enforce it via a discrete symmetry:

- R-parity in SUSY models
- KK-parity in Universal Extra Dimension models (Servant & Tait, hep-ph/0206071)
- T-parity in Little Higgs models (Bickedal et al., hep-ph/0603077)
- Z_2 symmetry in a 2 Higgs doublet SM extension (the "Inert doublet model", Barbieri et al. hep-ph/0603188)
- Mirror symmetry in 5D models with gauge-Higgs unification (Serone et al., hep-ph/0612286)
- ...

or via an accidental symmetry, such as a quantum number preventing the decay: [Mirror DM], DM in technicolor theories (Gudnason et al., hep-ph/0608055), "minimal" DM (Cirelli et al., hep-ph/0512090) , ...

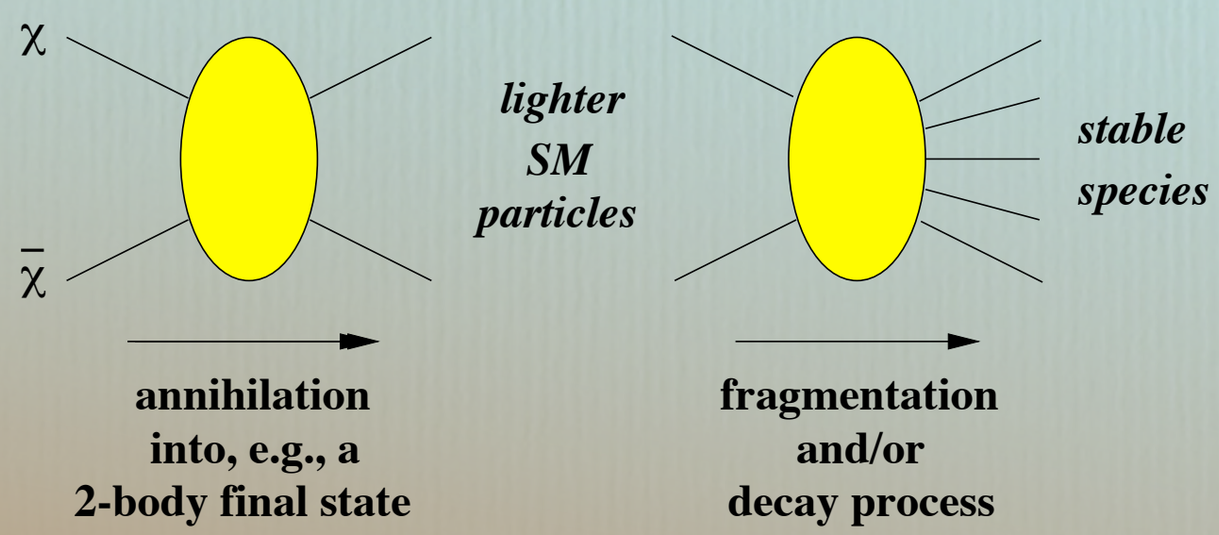
In most of these, DM appears as a by-product from a property considered to understand or protect other features of the theory.

Incomplete list of models and very incomplete list of references!

Indirect detection of WIMP dark matter

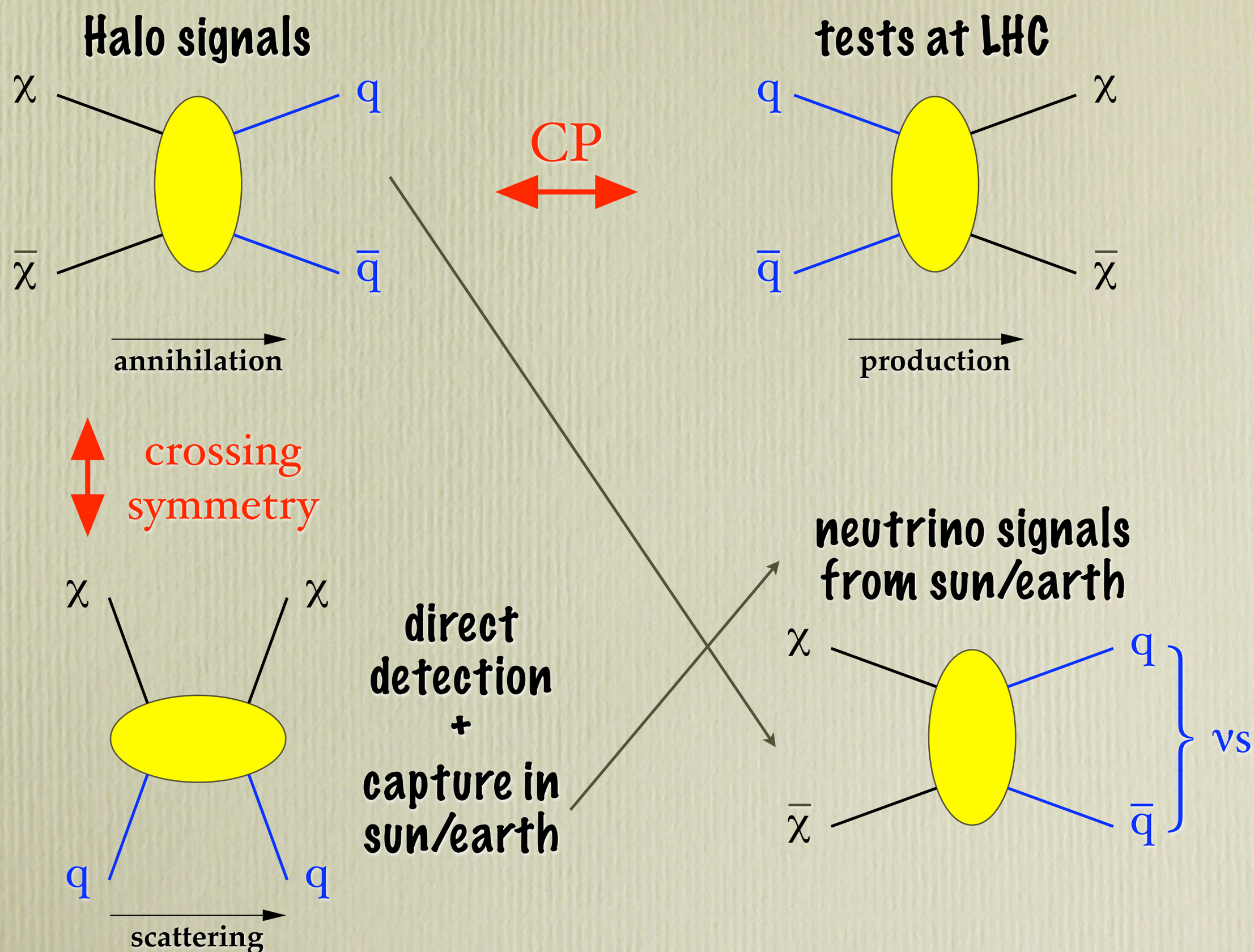
A chance of detection stems from the WIMP paradigm itself:

Pair annihilations of WIMPs in DM halos (i.e. at T≅0)

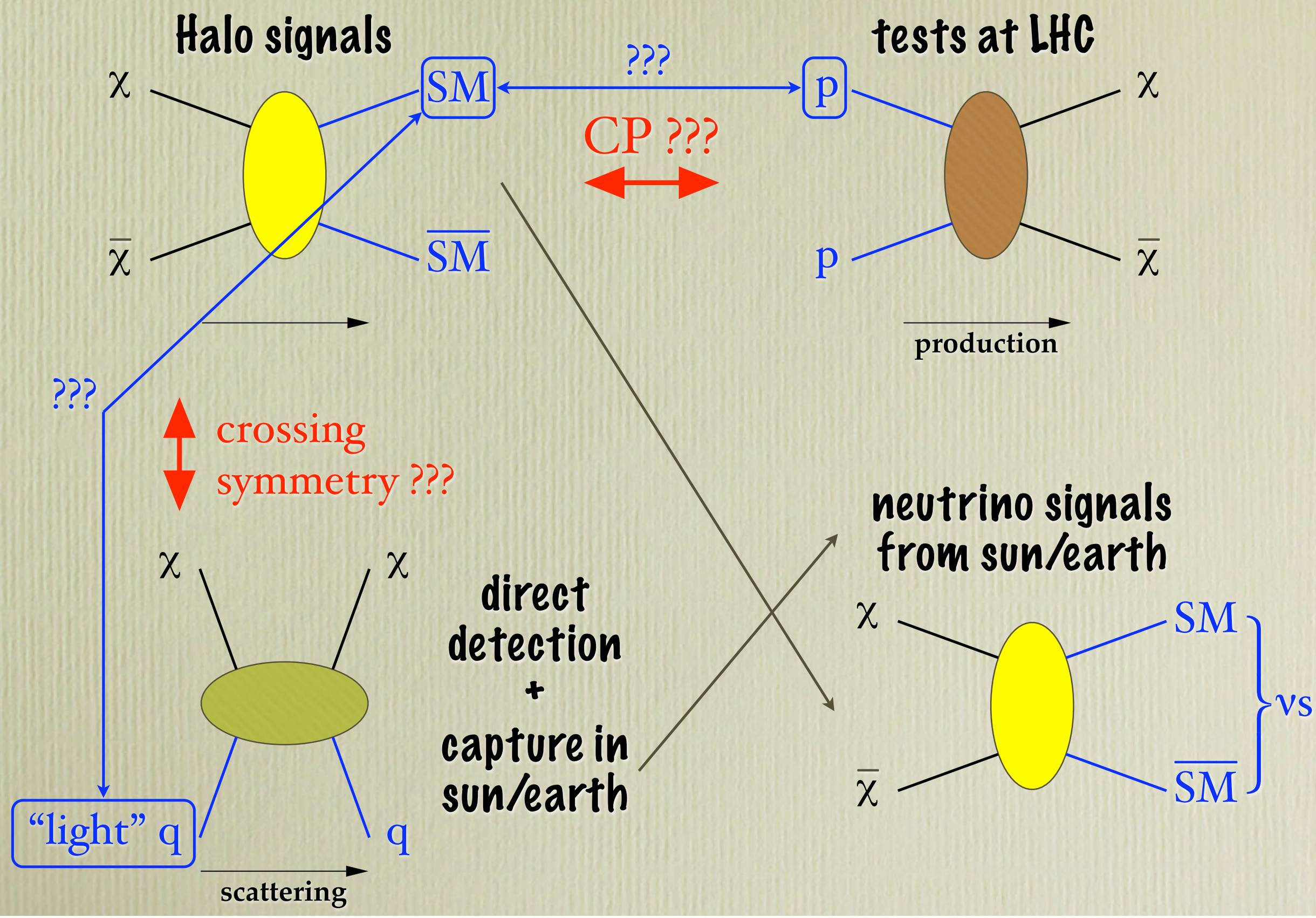


Focus on:
antiprotons,
positrons,
antideuterons,
gamma-rays,
(neutrinos)

WIMP coupling to ordinary matter



WIMP coupling to ordinary matter ???



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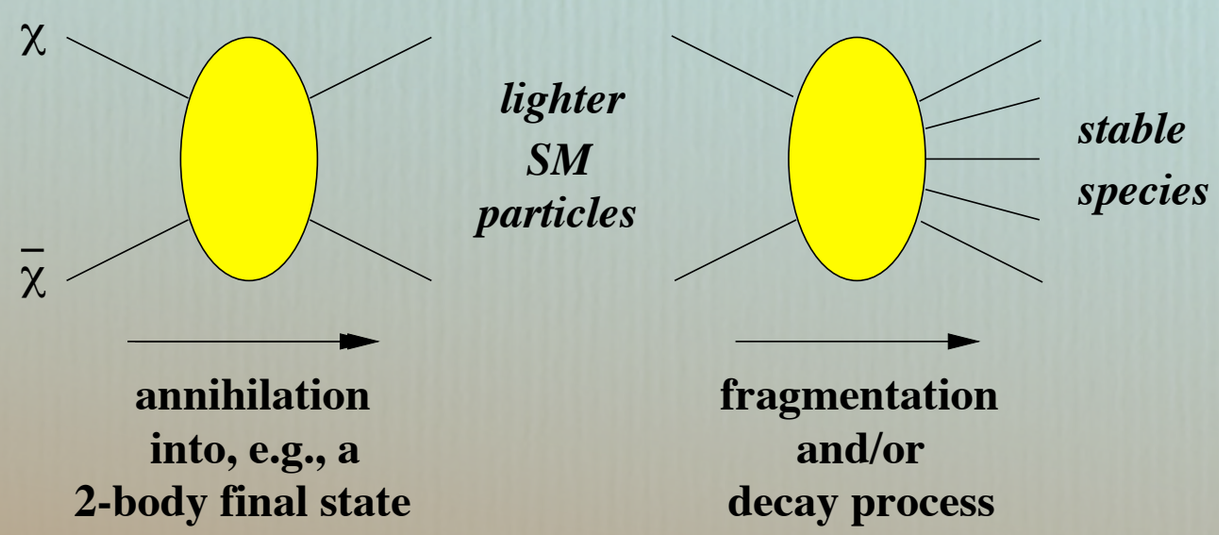

Focus on:
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(neutrinos)

- $(\sigma v)_{T\simeq 0} \overset{?}{\sim} \langle \sigma v \rangle_{T=T_f}$
- final state branching ratios
- $N_{\chi-\text{pairs}} \propto [\rho_\chi(r)]^2 \simeq [\rho_{\text{DM}}(r)]^2$

WIMP DM source function

Dynamical observations (?)/
N-body simulations (?)

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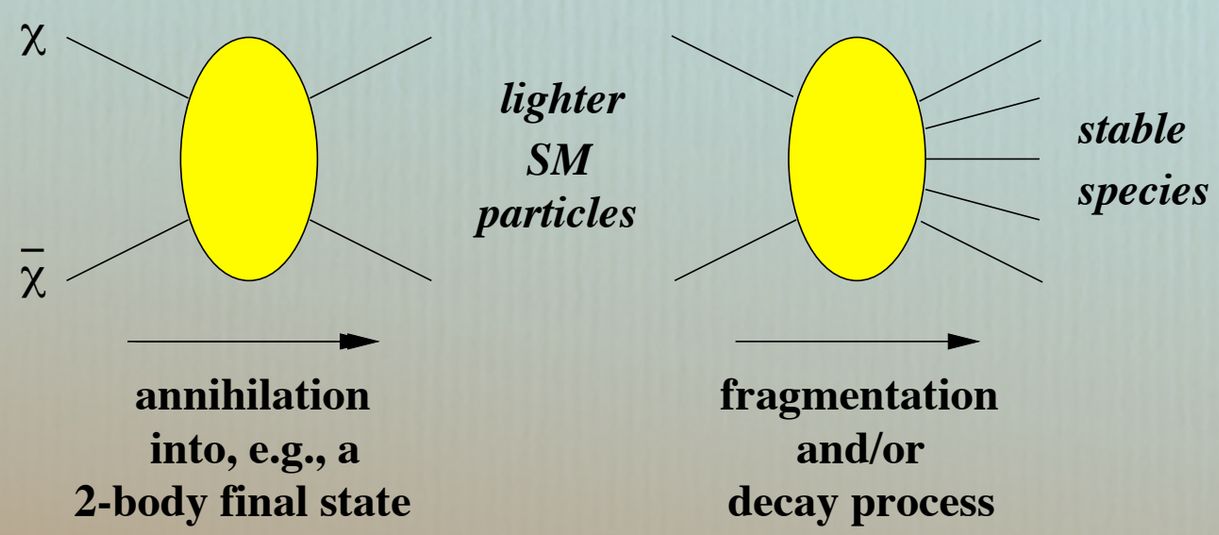

Focus on:
antiprotons,
positrons,
antideuterons,
gamma-rays,
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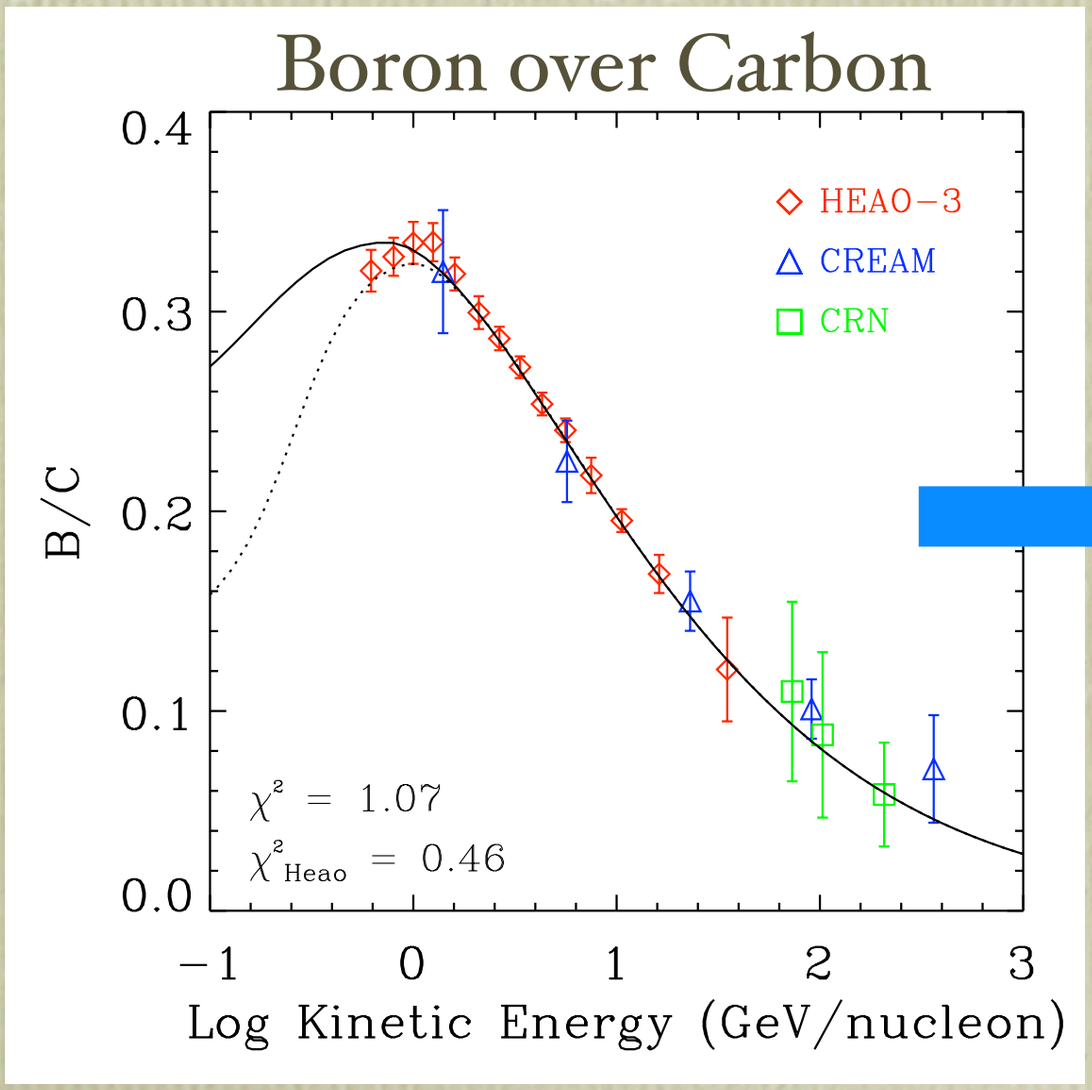
Search for the species with low or well understood backgrounds from other known astrophysical sources.

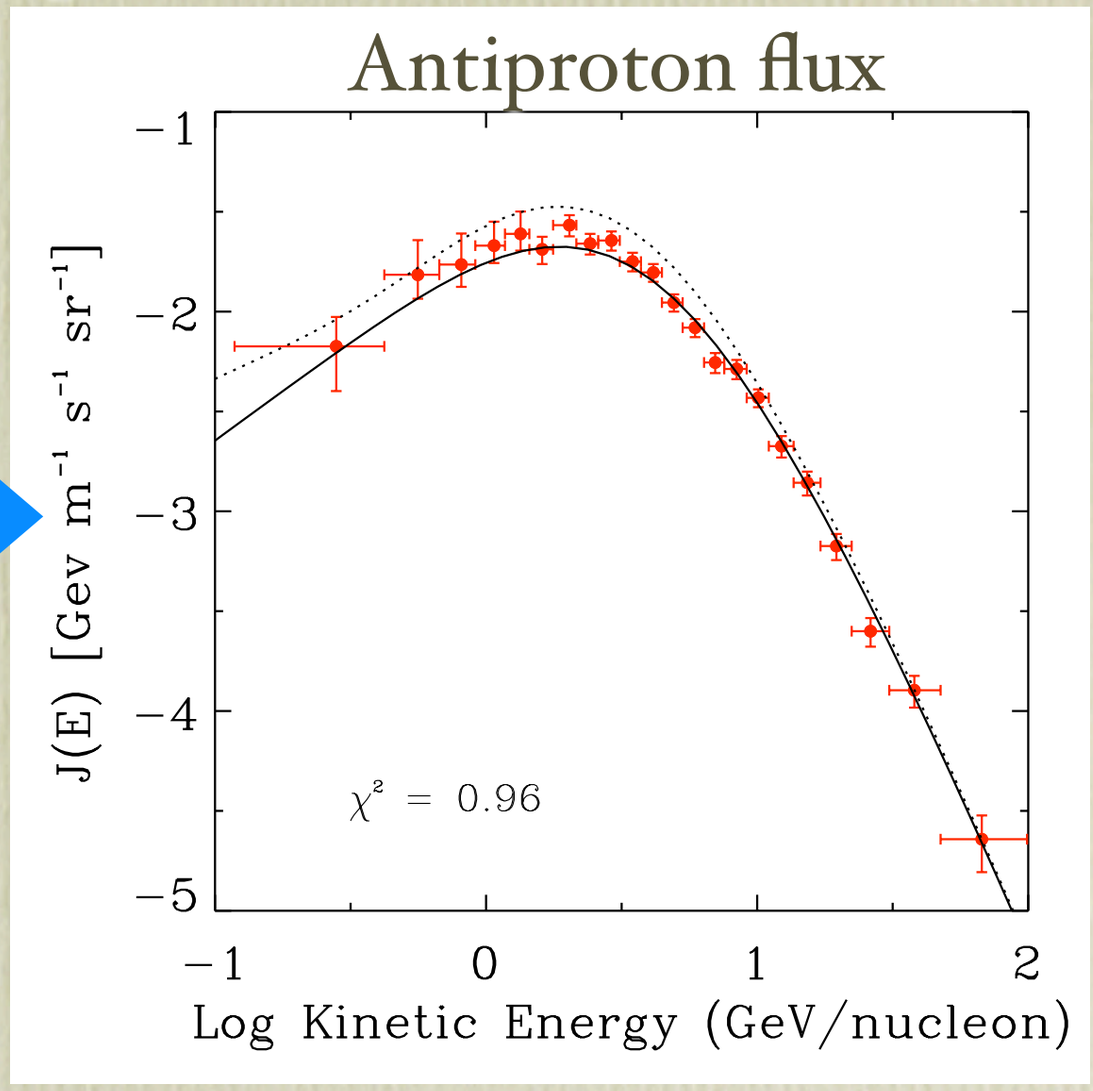
For "standard" annihilation rates, final states and DM density profiles, the ratio signal over background is the largest for antiprotons (antideuterons), can be sizable for gamma-rays, is fairly small for positrons and very small for neutrinos.

The $\bar{p}$ measurements are consistent with secondaries:

Antiprotons are generated in the interaction of primary proton and helium cosmic rays with the interstellar gas (hydrogen and helium), e.g., in the process: $p + H \rightarrow 3\,p + \bar{p}$

Use the parameter determination from the B/C ratio, to extrapolate the prediction for the $\bar{p}$/p ratio: excellent agreement for secondaries only!

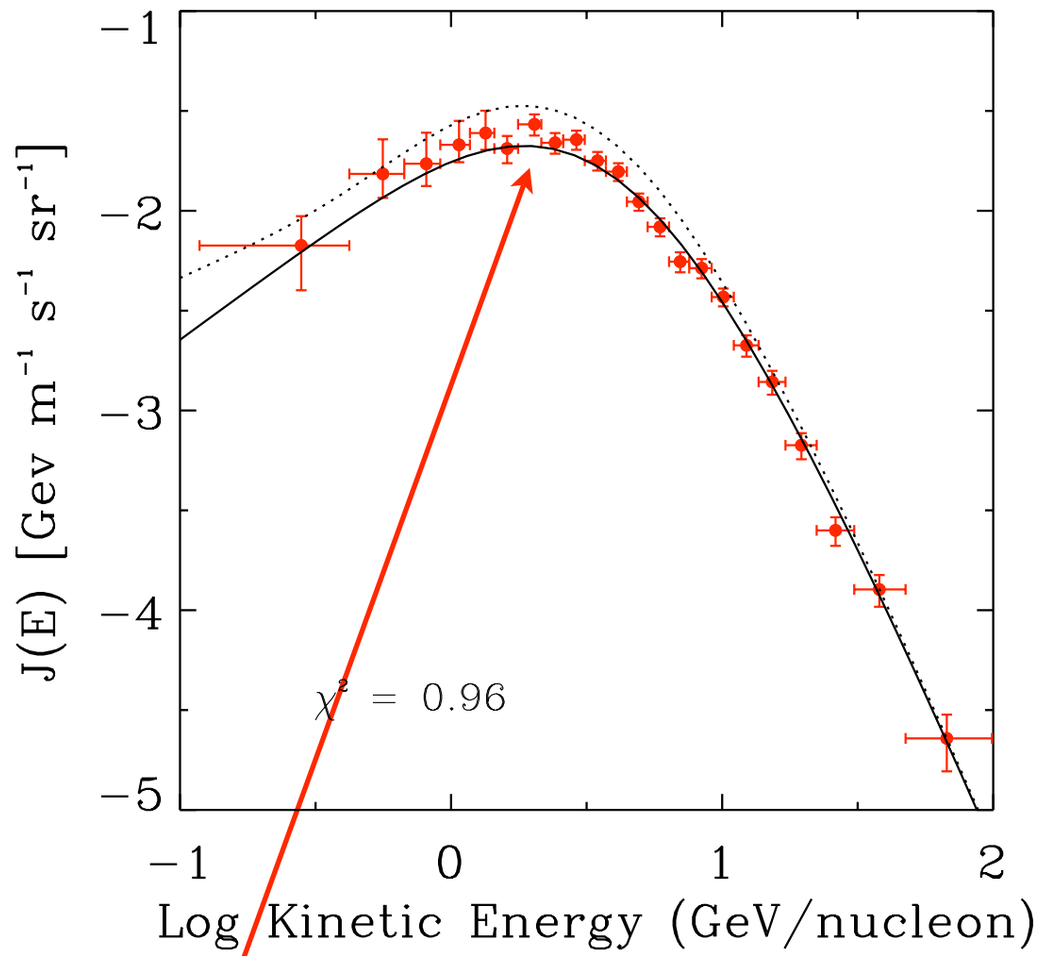




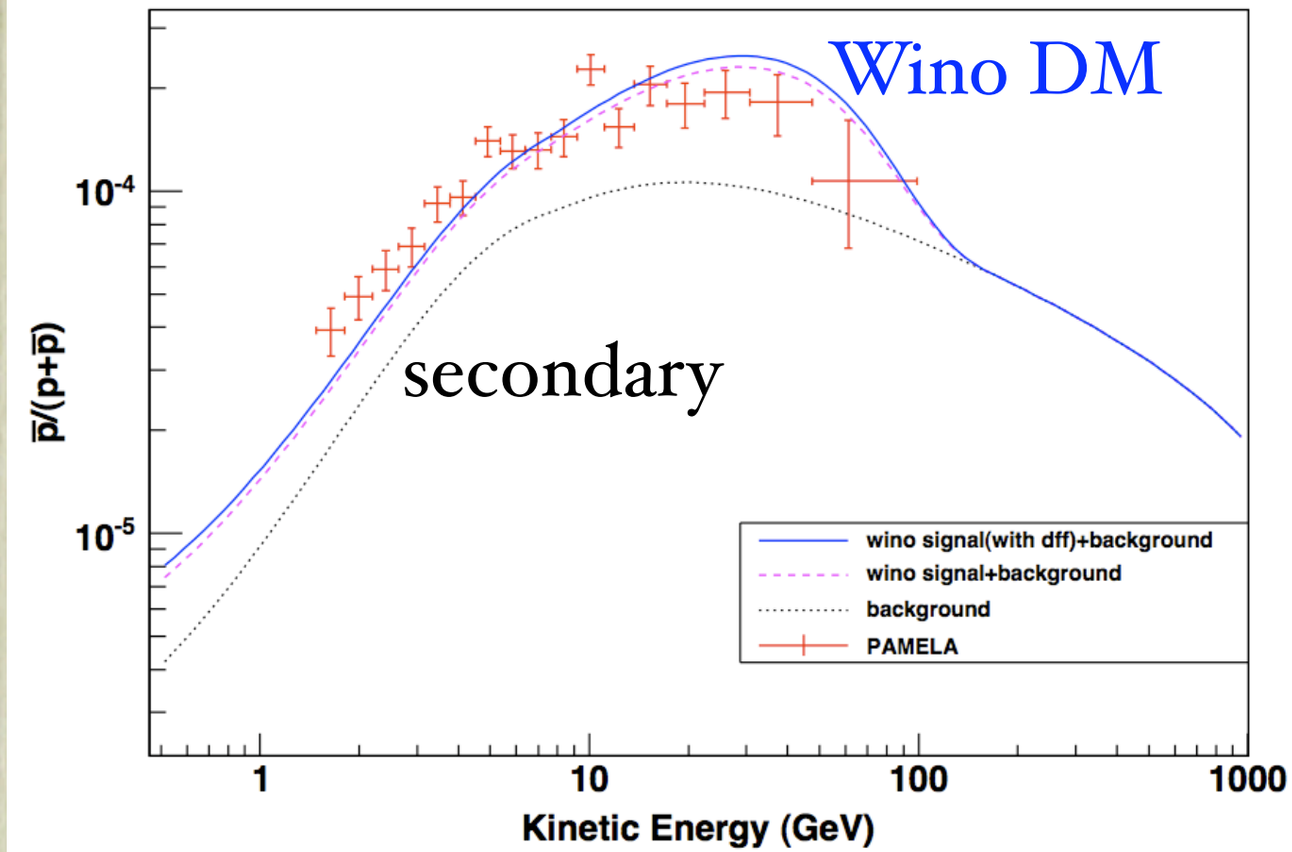
PAMELA data: Adriani et al., arXiv:1007.0821

Predictions obtained with the Dragon propagation code (Evoli et al., 2010); specular results with Galprop, semi-analytic models, ect. ect.

The measured antiproton flux has the spectral shape and normalization as predicted in vanilla secondary models:



kinematic peak expected for secondaries, not for a primary exotic component



Kane et al., arXiv:0906.4765

introduce a DM model + a cosmic ray propagation model such that the DM signal mimics the background (?!?!?)

Antiproton data are useful to set limits on DM models. These limits will slightly improve with upcoming data on antiproton, but especially with new data on other cosmic ray species, needed to refine propagation models.

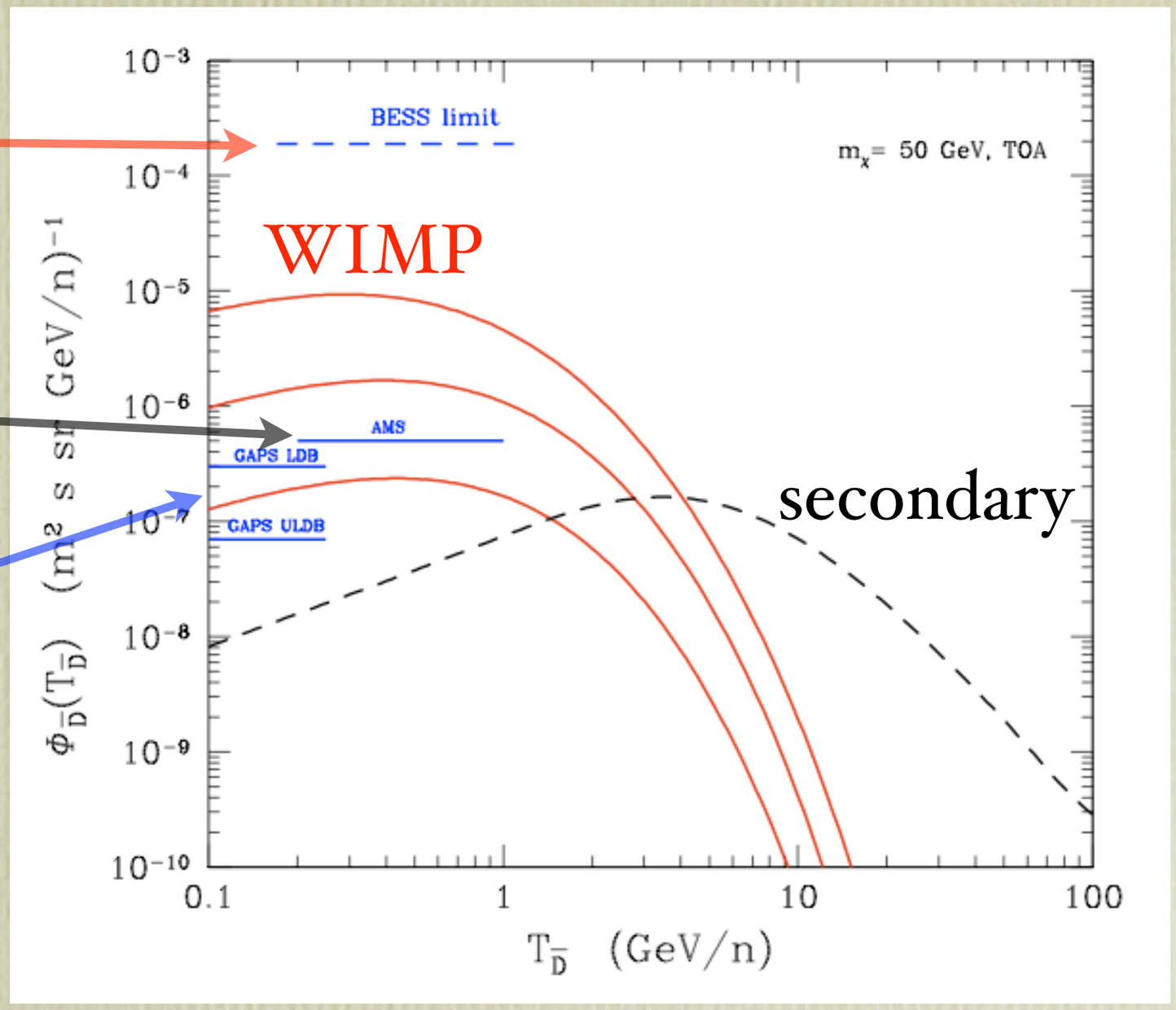
Antideuteron fluxes

Possibly a large $\bar{D}$ flux for WIMP models whose $\bar{p}$ flux is consistent with current data. A promising target for future measurements?

today

AMS

GAPS

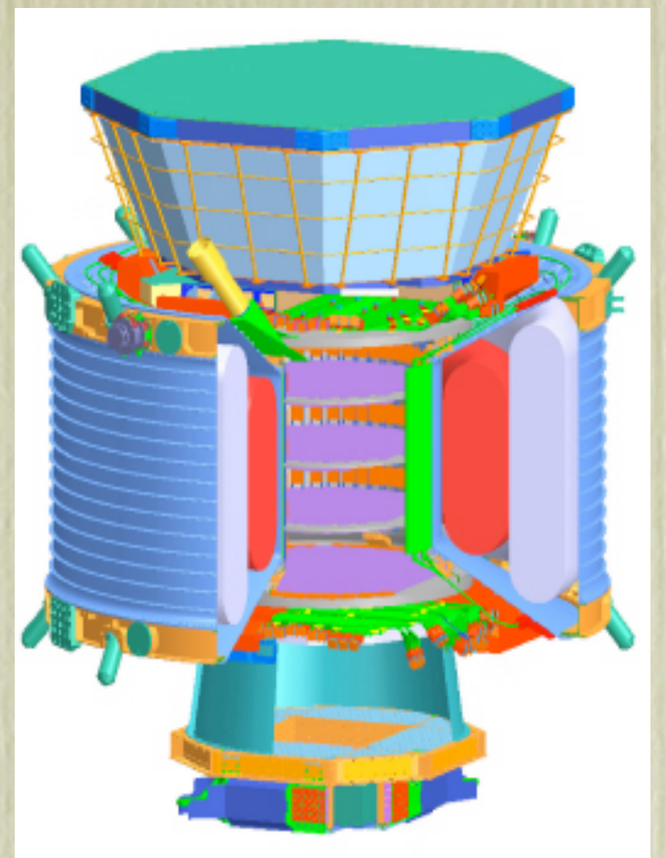


Donato, Fornengo & Maurin, 2008

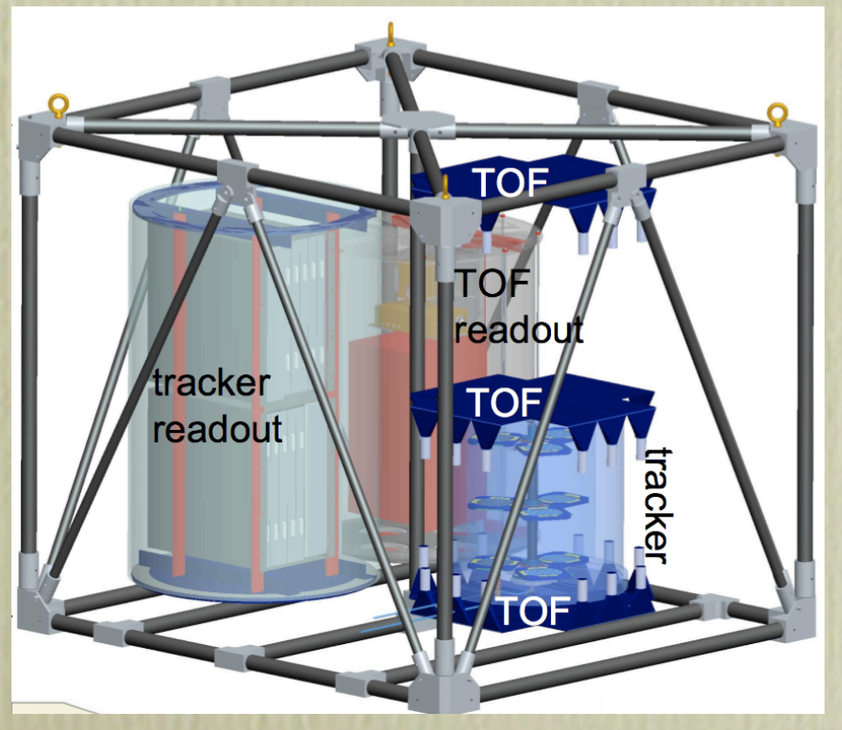
NOTE: much cleaner DM signature compared to $\bar{p}$

Steady progresses in the field, with a very rich program upcoming:

Pamela mission extended



AMS-02 on the ISS in 2011

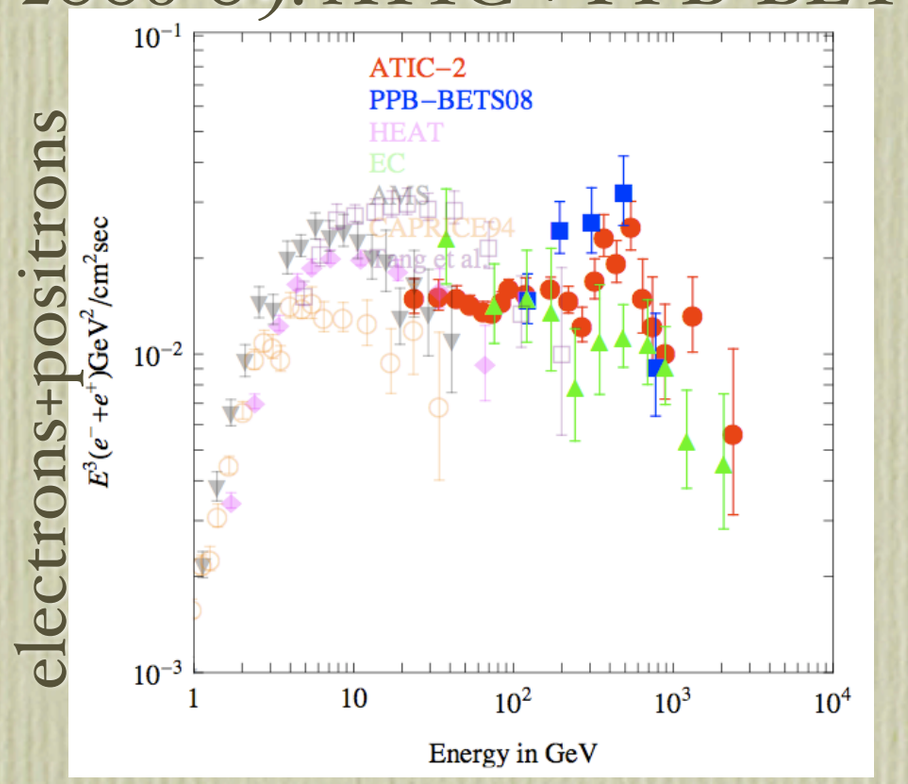


GAPS prototype test in 2011

BESS Polar II flight a solar min.

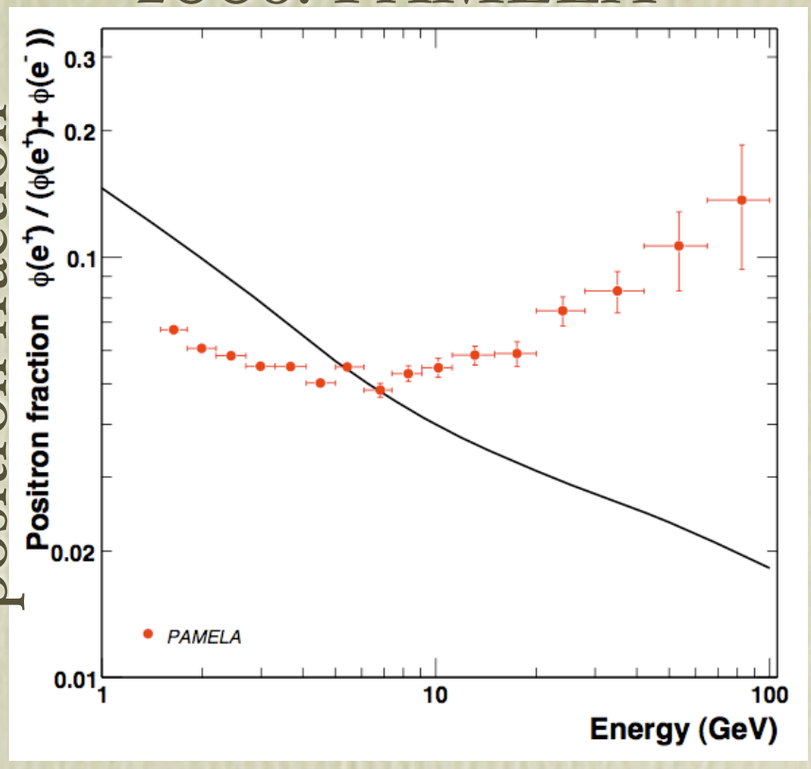
In the last 2-3 years electrons and positrons has gained the rank # 1 in cosmic-ray studies:

2008-09: ATIC + PPB-BETS



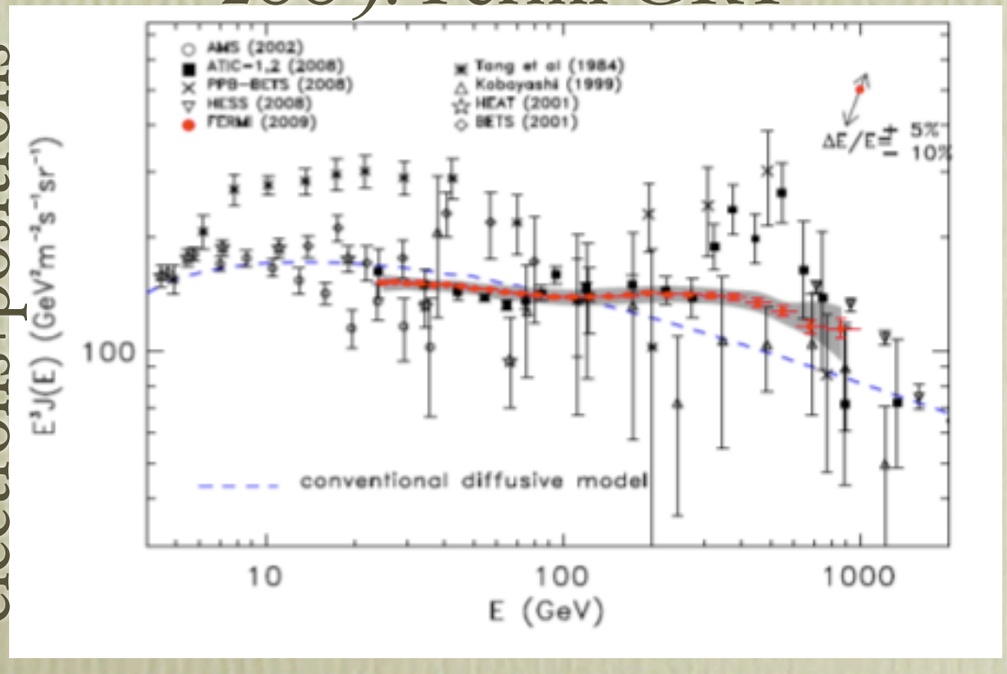
electrons+positrons

2008: PAMELA



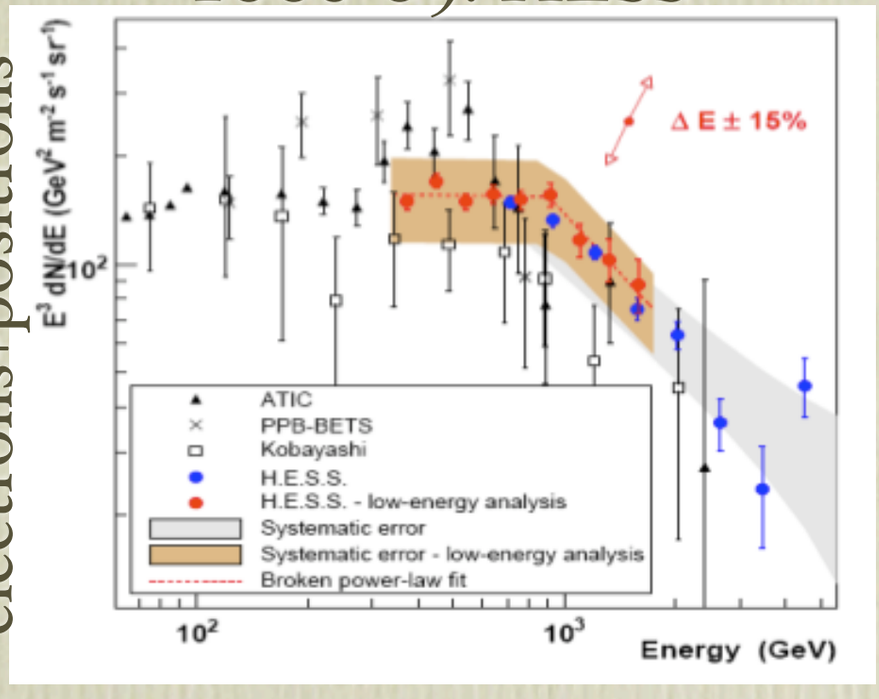
positron fraction

2009: Fermi GRT



electrons+positrons

2008-09: HESS



electrons+positrons

The rising positron fraction detected by PAMELA?

- The standard propagation models are wrong: there are extra energy-dependent effects which affect secondary positrons (or primary electrons) but not the secondary to primary ratios for nuclei (at least at the measured energies), e.g.: **Piran et al., arXiv:0905.0904; Katz et al., arXiv:0907.1686**

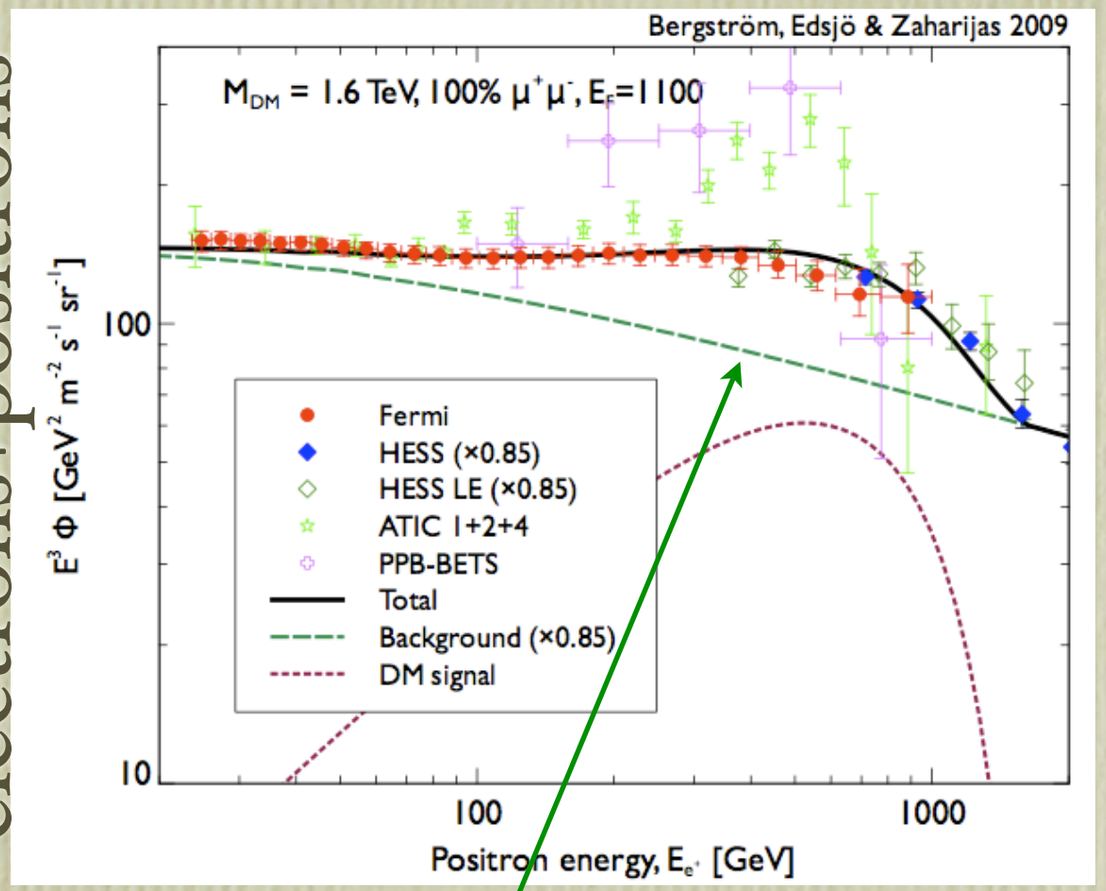
- There is production of secondary species within the CR sources with a mechanism giving a sufficiently hard spectrum (reacceleration at SN remnants?), e.g.: **Blasi, arXiv:0903.2794; Mertsch & Sarkar, arXiv: 0905.3152**

- There are additional astrophysical sources producing primary positrons and electrons: pulsars are the prime candidate in this list, e.g.: **Grasso et al., arXiv:0905.0636**

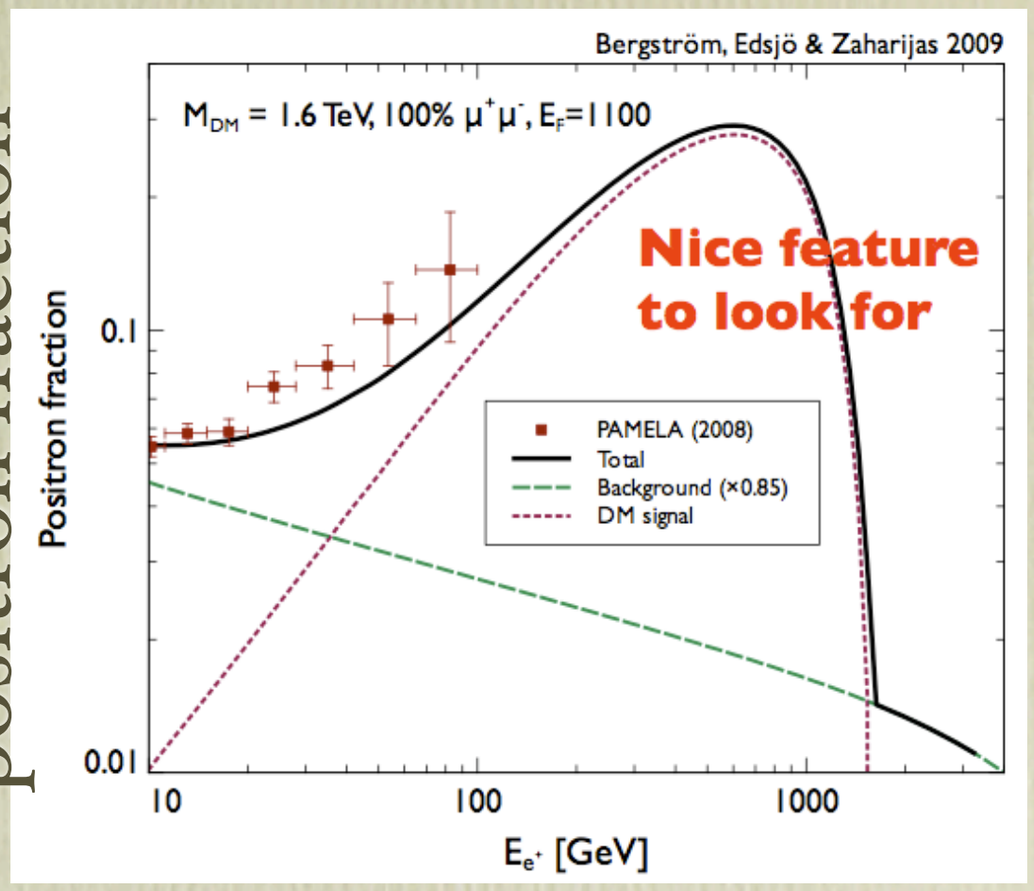
- There is an exotic extra source of primary positrons and electrons: a dark matter source is the most popular option in this class.

A blind fit of the PAMELA/Fermi/HESS positron/electron data with a generic WIMP model (defined by WIMP mass and dominant annihilation channel), taking into account limits, e.g., from antiproton data, is possible:

electrons+positrons



positron fraction



Bergström et al., arXiv:0905.0333

background ?!?

This "solution":

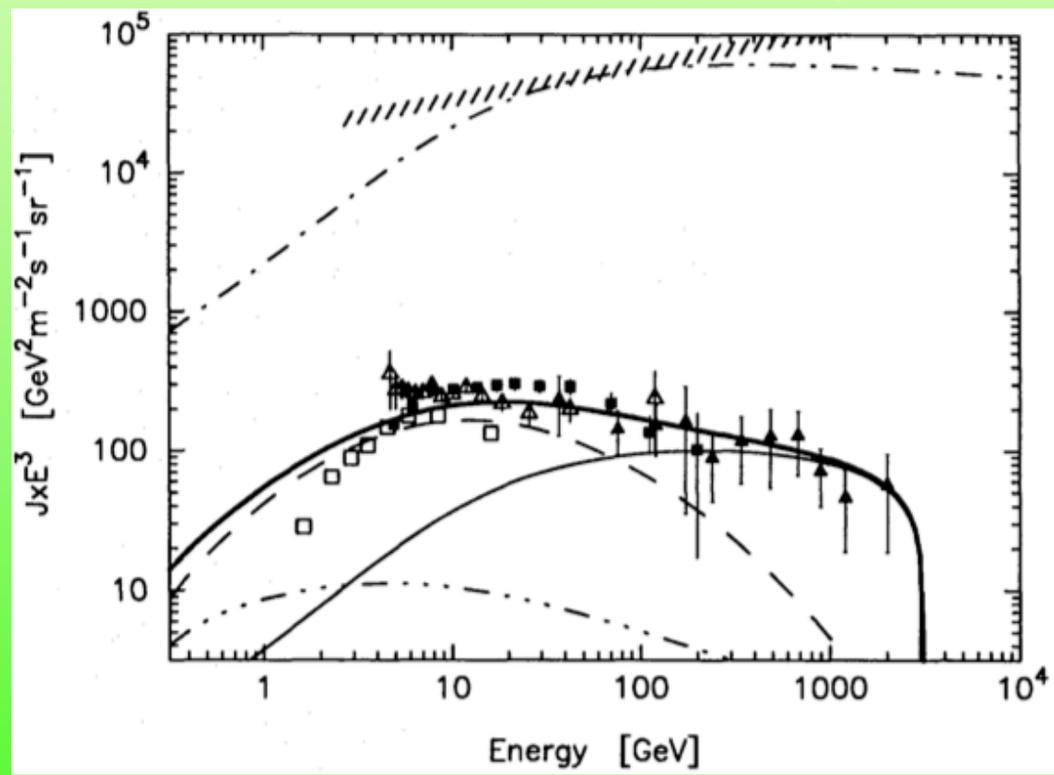
a heavy WIMP (mass above 1 TeV), with a large "enhancement factor" in the source function (Sommerfeld effect? non-thermal WIMP? clumps?), annihilating with a hard spectrum into leptons only (leptophilic)!

Anything but a vanilla WIMP model!

Very important caveat: we may have seen a DM signal, but have not seen a DM signature.

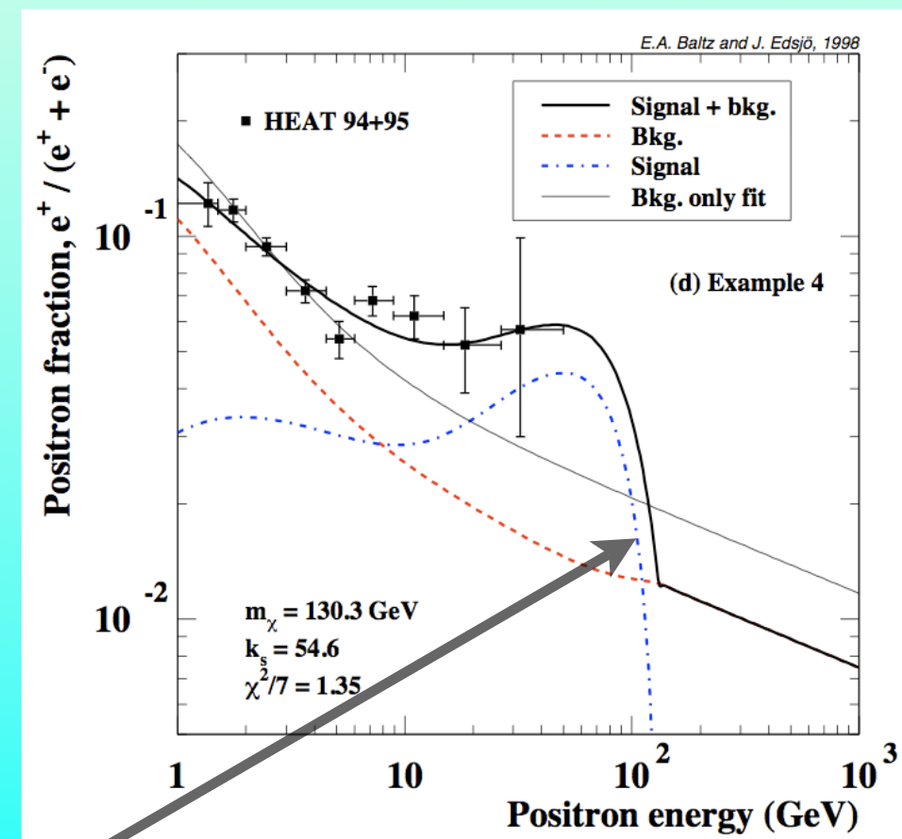
The sample fit of the data with a DM signal matches very nicely the signal foreseen more than a decade ago:

Aharonian et al., 1995



except that this is a pulsar signal

The predicted WIMP DM signature (in some cases, not a general feature) was not the rise in the positron fraction, but rather its rise + its sharp decrease at the WIMP mass scale.

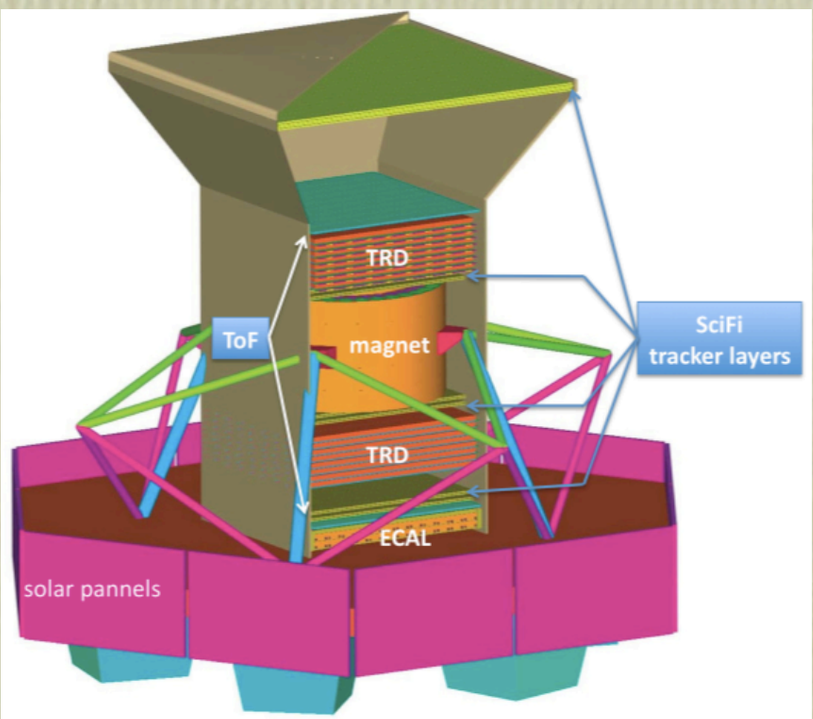


Baltz & Edsjö, 1998

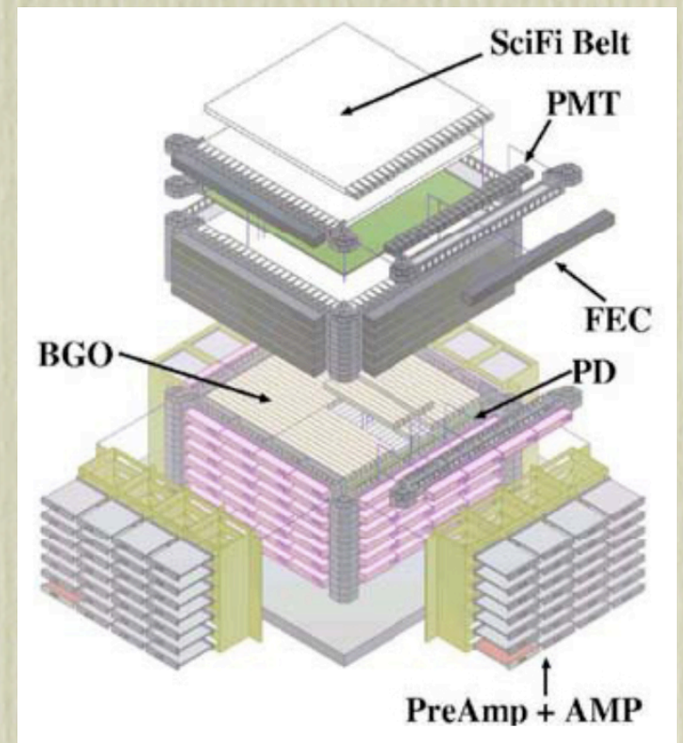
WIMP mass (e.g. 100-300 GeV ???), hopefully at an energy scale different from the cutoff scale in the electrons.

Learning more about the lepton cosmic-ray puzzle:

- PAMELA keeps taking data and will measure the positron fraction up to 200-300 GeV. Will they see at decrease in the positron ratio?
- Fermi will improve its statistics. Will this allow to identify features in the spectrum to be associated to single sources, say a few nearby pulsars? Will Fermi see a spatial anisotropy, say a 1% effect to be associated to a single nearby source?
- AMS-02 will improve further on statistics and energy coverage.
- Other experiments in R&D phases, e.g.:



PEBS: in 2014 positron fraction up to 2 TeV



CALET: on the ISS in 2013, all electrons up to 20 TeV

+ cross-correlations of the PAMELA excess with other DM signals!

DM annihilations and gamma-ray fluxes:

Prompt emission of γ-rays associated to three components:

i) Continuum: i.e. mainly from $f \to ... \to \pi^0 \to 2\gamma$

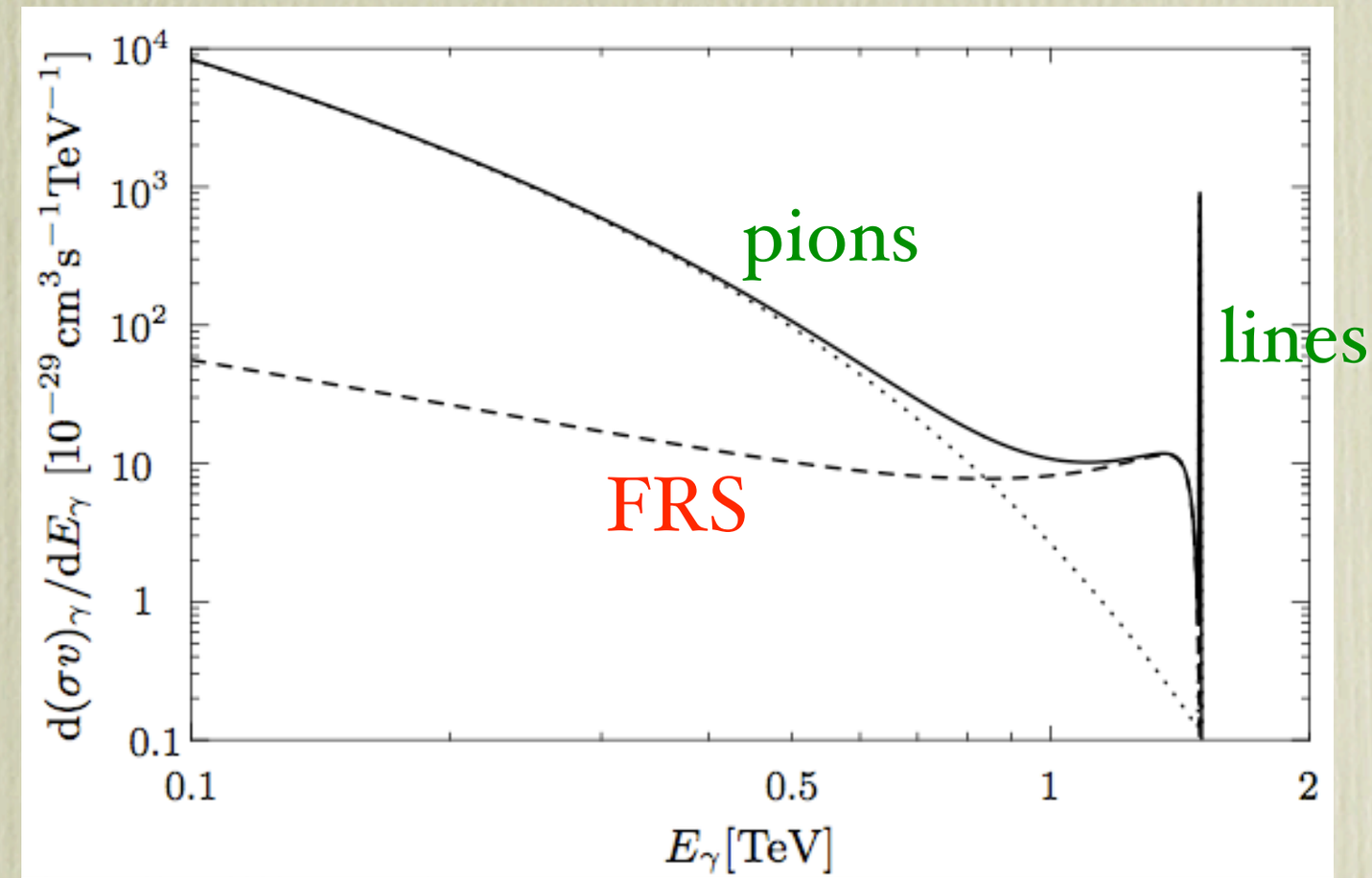
ii) Monochromatic: i.e. the 1-loop induced $\chi\chi \to 2\gamma$ and $\chi\chi \to Z^0\gamma$
(in the MSSM, plus eventually others on other models)

iii) Final state radiation (internal Bremsstralungh), especially relevant for:

$$\chi\chi \to l^+ l^- \gamma$$

For a model for which all three are large (e.g. pure Higgsino):

Bergström et al., astro-ph/0609510



The induced gamma-ray flux can be factorized:

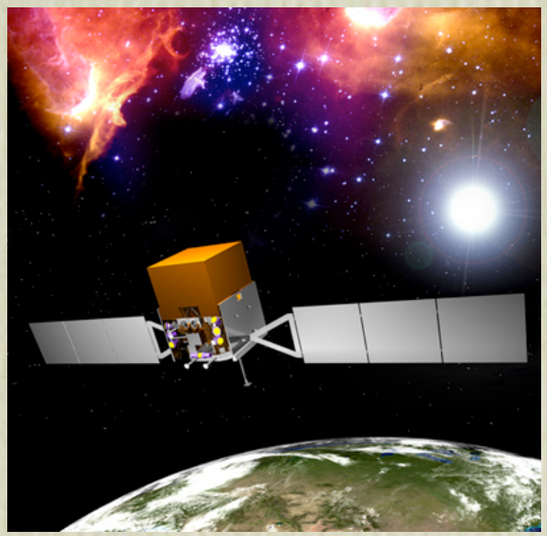
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\theta,\phi) = \frac{1}{4\,\pi}\boxed{\frac{\langle\sigma v\rangle_{T_0}}{2\,M_\chi^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f}\cdot\boxed{\int_{\Delta\Omega(\theta,\phi)} d\Omega' \int_{l.o.s.} dl\ \rho_\chi^2(l)}$$

Particle Physics DM distribution

Targets which have been proposed:

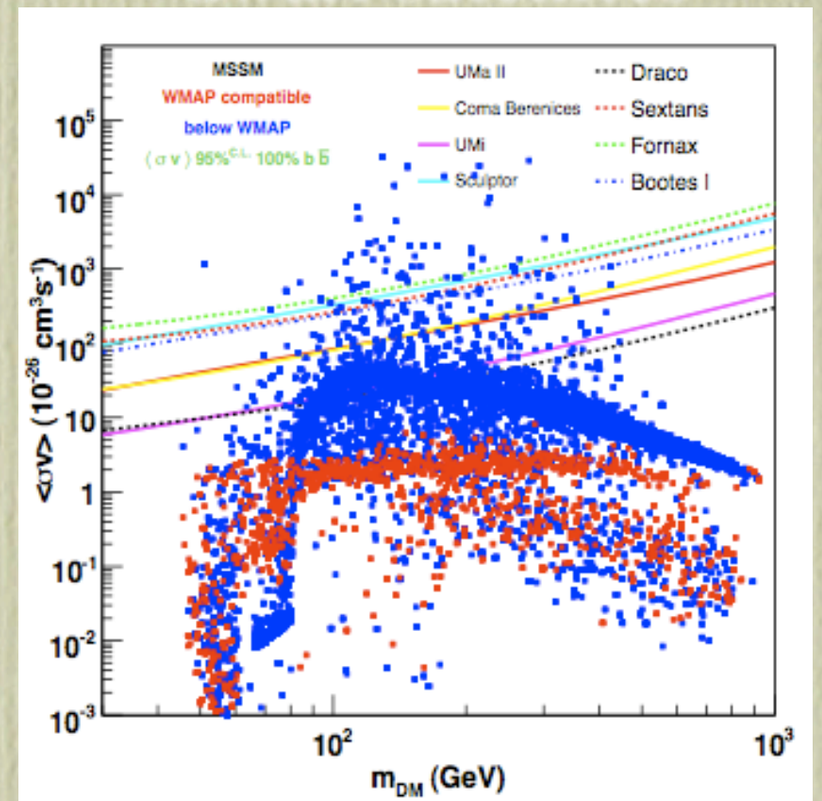
- The Galactic center (largest DM density in the Galaxy)
- The diffuse emission from the full DM Galactic halo
- Dwarf spheroidal satellites of the Milky Way
- Single (nearby?) DM substructures without luminous counterpart
- Galaxy clusters
- The diffuse extragalactic radiation
- ...

All of these are targets for FERMI.



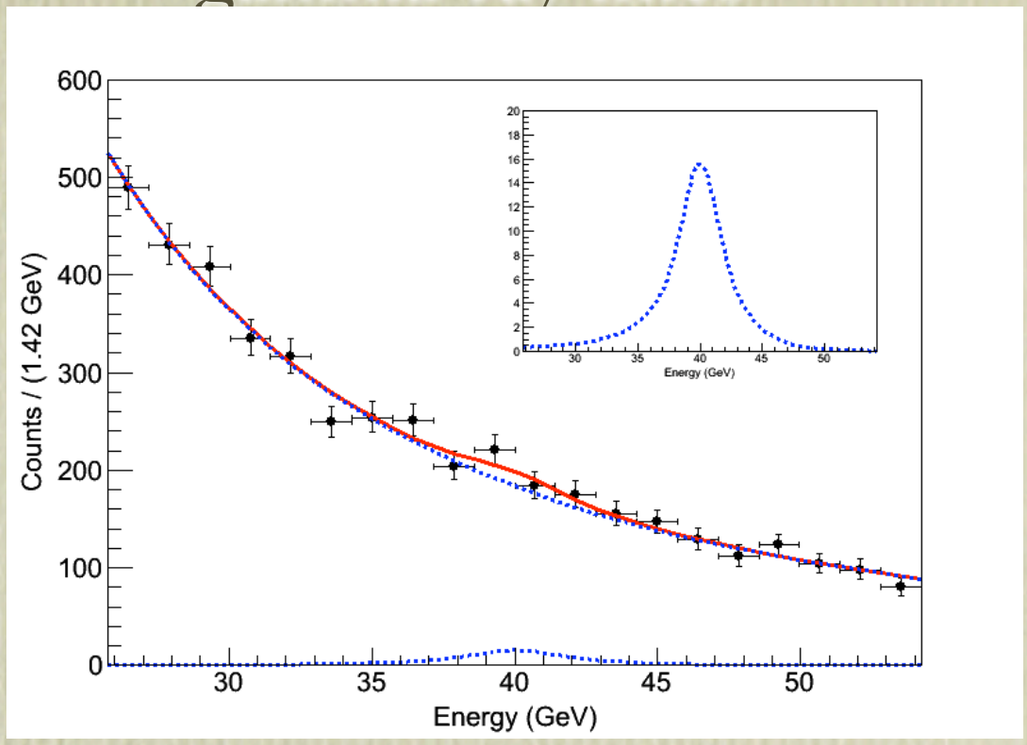
The first upper limits on DM gamma-ray fluxes from Fermi:

dwarf satellites



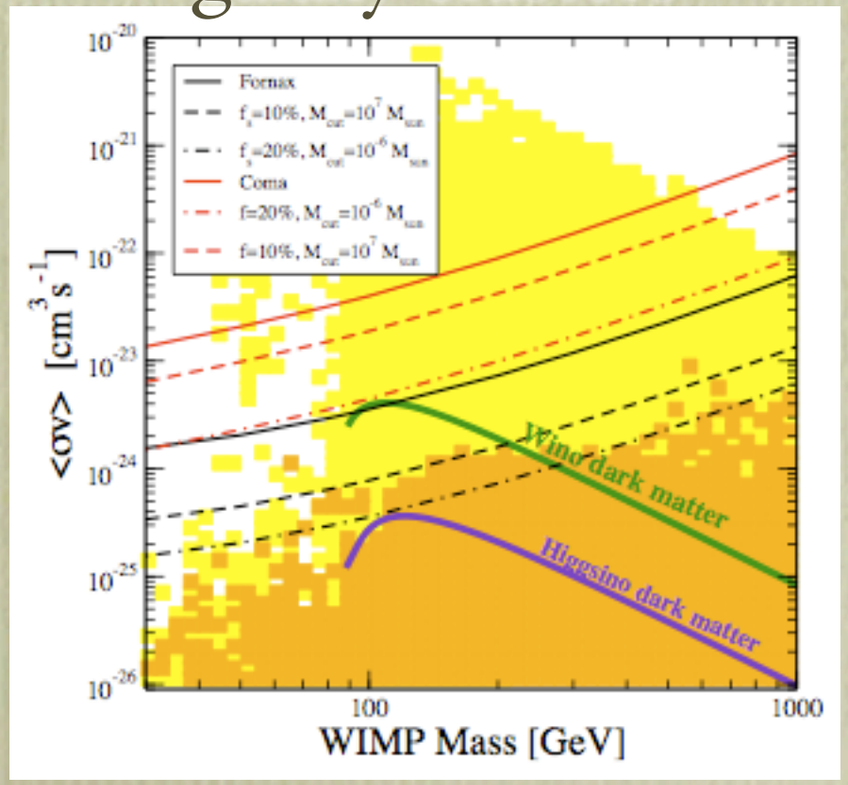
arXiv: 1001.4531

gamma-ray lines



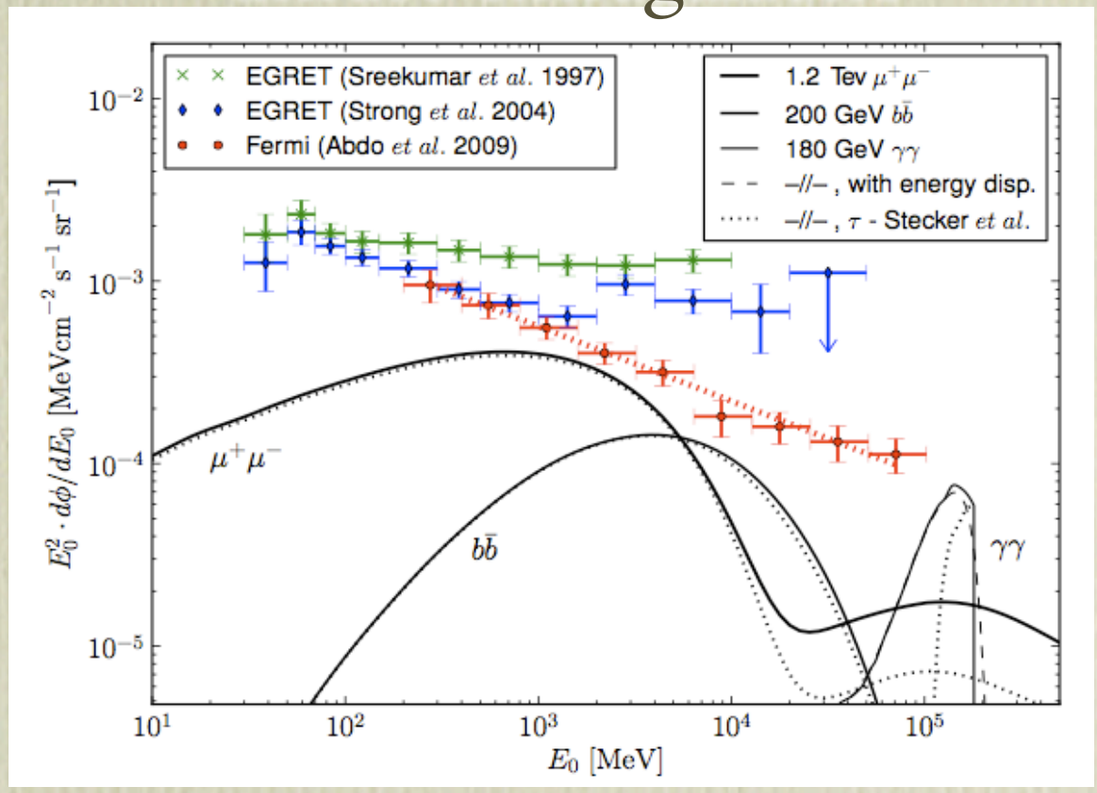
arXiv: 1001.4836

galaxy clusters



arXiv: 1002.2339

diffuse extragalactic



arXiv: 1002.4415

DM annihilations and radiative emission:

The annihilation yields give rise to a multicomponent spectrum:

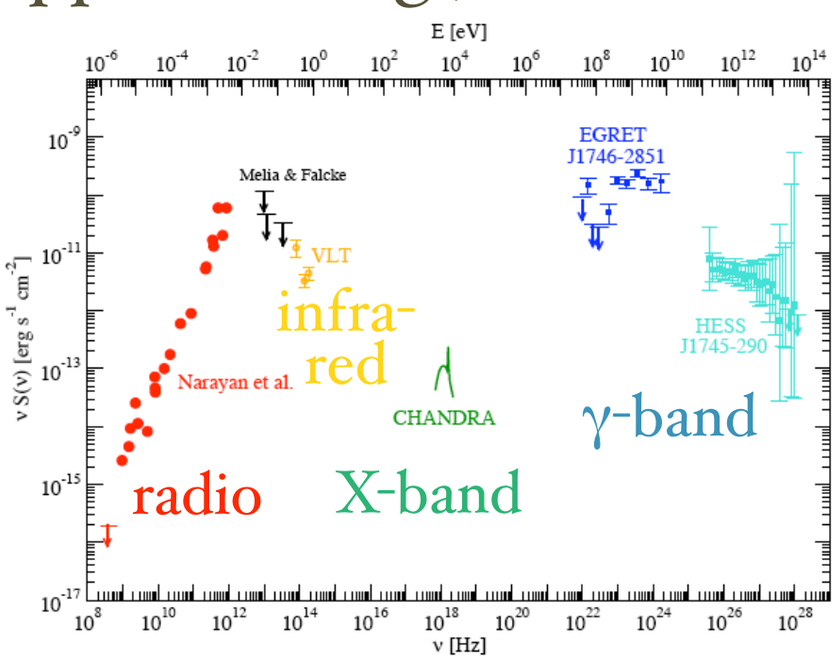
$$\chi\,\bar{\chi} \rightarrow \begin{cases} e^+ e^- \\ l^+ l^- \text{ or } \phi\,\phi \rightarrow \ldots + e^+ e^- \\ P\,\bar{P} \rightarrow \ldots + \pi^\pm \rightarrow \ldots + e^\pm \end{cases}$$

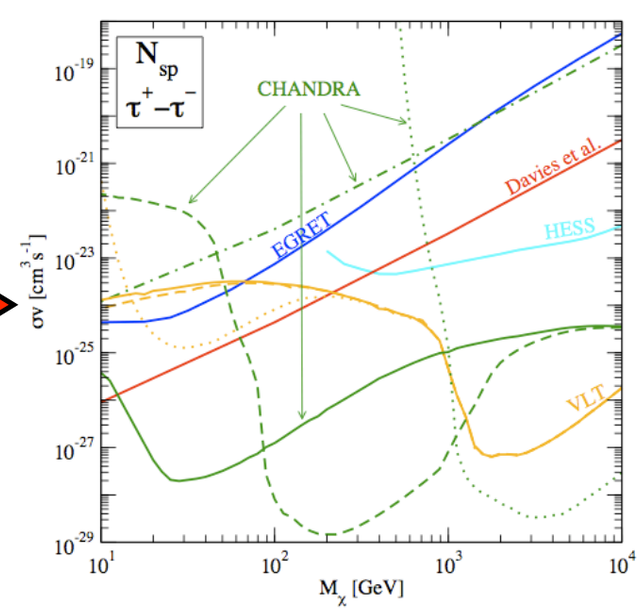
ambient backgrounds and fields

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

- radio
- IR
- X-rays
- Υs

For certain DM sources is a very powerful (although model dependent) approach. E.g., the Galactic center (Sgr A*) has a well-measured seed:

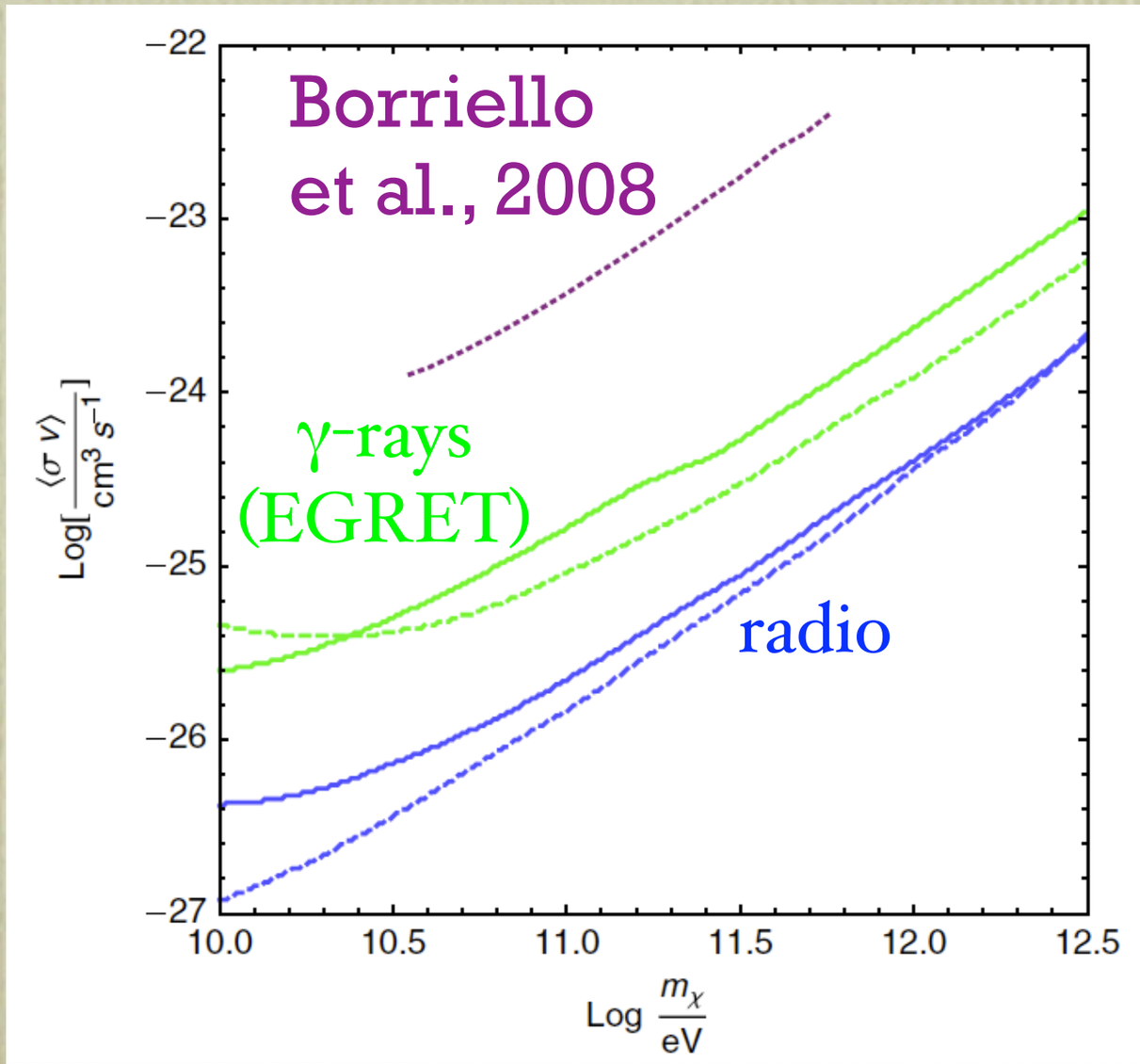




significant limits on WIMP models at any wavelength, unlikely the most stringent from the γ-band (even with Fermi)

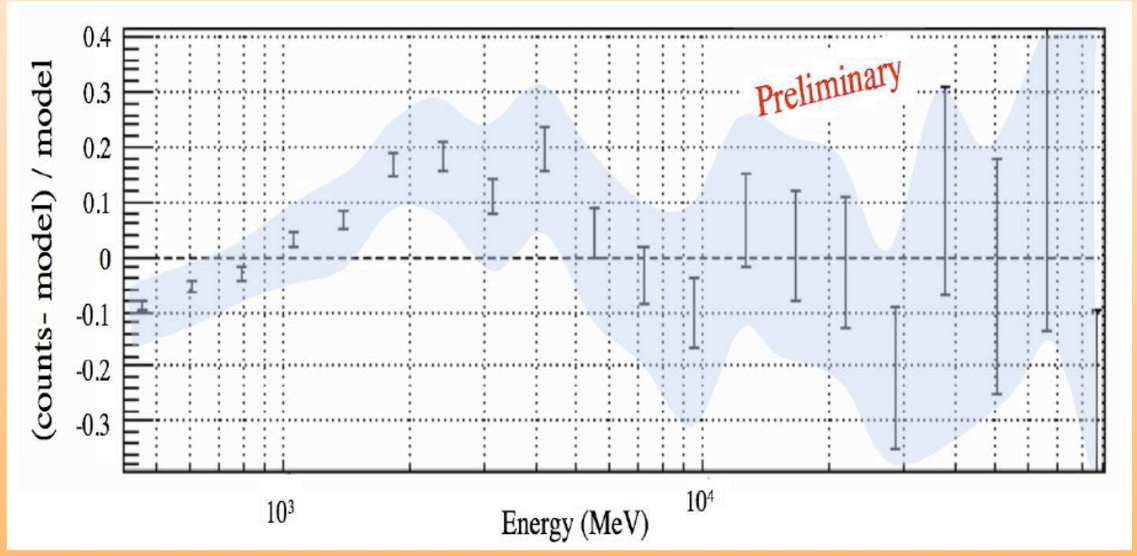
Regis & P.U., arXiv: 0802.0234

Looking at a slightly larger angular region, depending on the magnetic fields and models for the distribution of DM, one can extrapolate the limits: **Crocker et al., 2010**



solid and dashed curves represent a loop over viable magnetic fields

What will Fermi say about the diffuse emission at the GC? Early reports of an "excess":



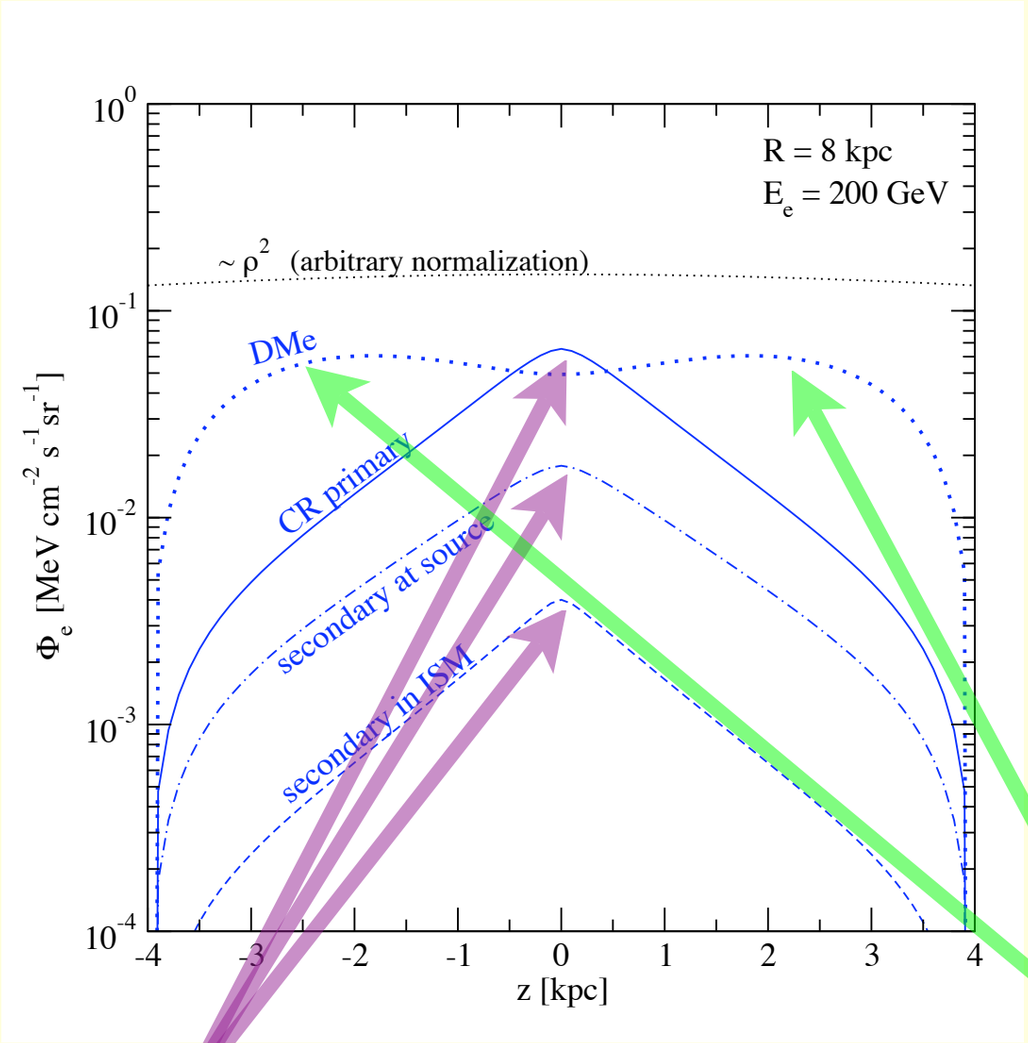
Vitale et al., arXiv:0912.3828

Multi-wavelength tests of an eventual DM component should be rather powerful.

Galactic diffuse γ-rays and the e^+/e^- CR puzzle

Fermi should also contribute to address the issue of whether the local positron excess is due to primary sources located in the disc or to a leptophilic DM component distributed in a much thicker halo (forgetting now other explanations proposed so far):

Regis & P.U., 2009



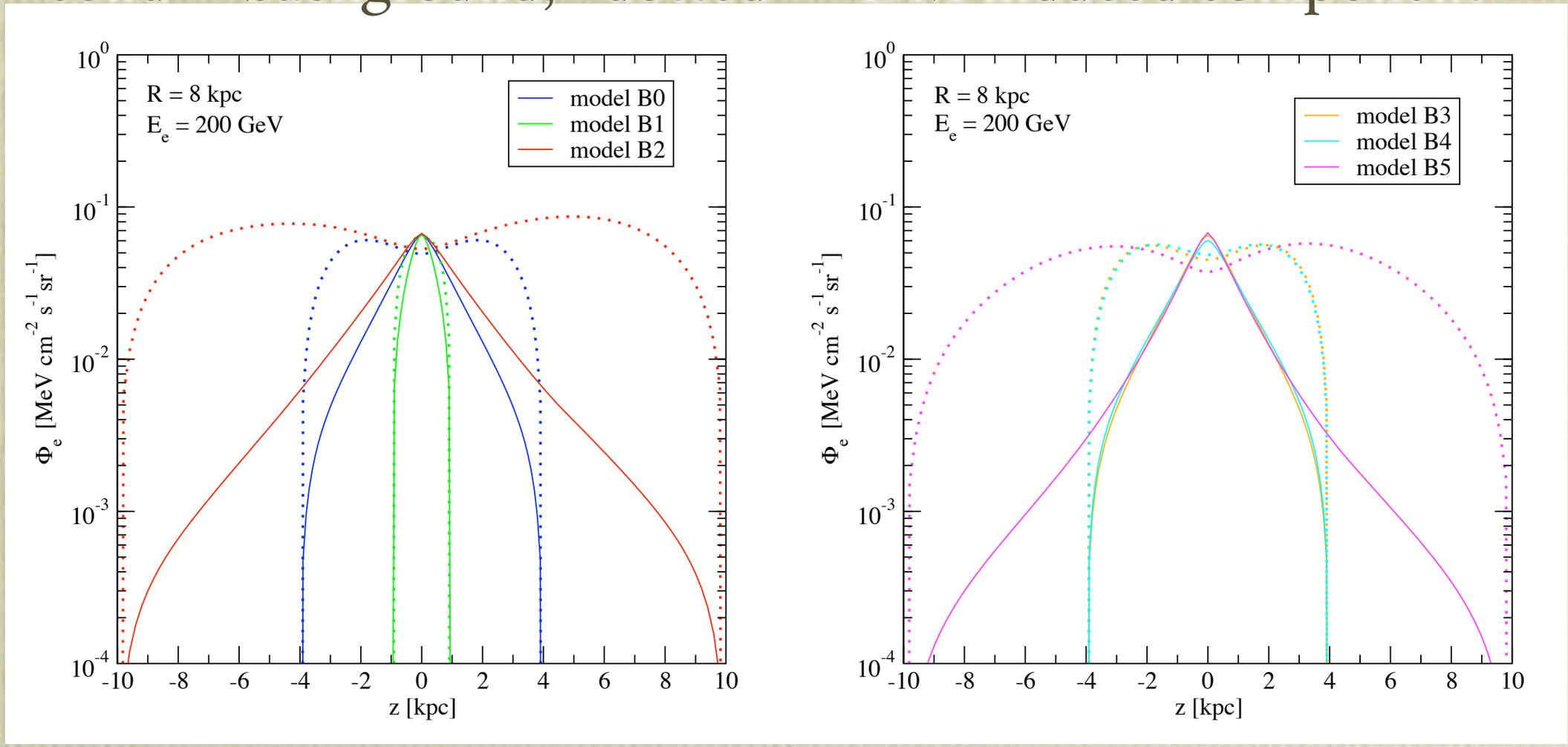
Equilibrium number density profile of "all-electrons", at the local Galacto-centric distance and as a function of height over the disc - a "reference" propagation model for CR in the Galaxy implemented (the old "standard" Galprop)

Primary/secondary sources located in the disc

DM sources extending in the halo

Similar picture for other sample prop. models (thin halo, thick halo, convective, kraichnan, vertically varying D), except if you force the halo to be thin (and with sharp truncation):

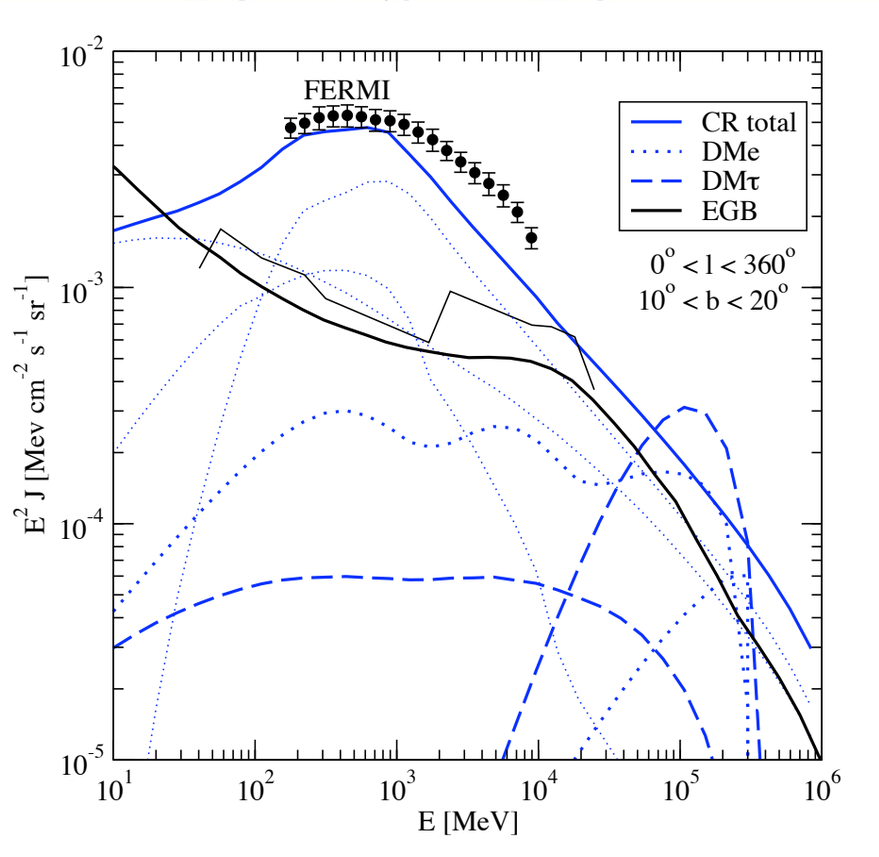
solid→ background; dotted → DM induced component



IC on a 1 μm starlight photon from 100 GeV (1 TeV) electrons gives a gamma-ray of 50 GeV (5 TeV); synchrotron emission on a 1 μG magnetic field 50 GHz (5000 GHz) radiation. Possibly a handle on this from Fermi and Planck.

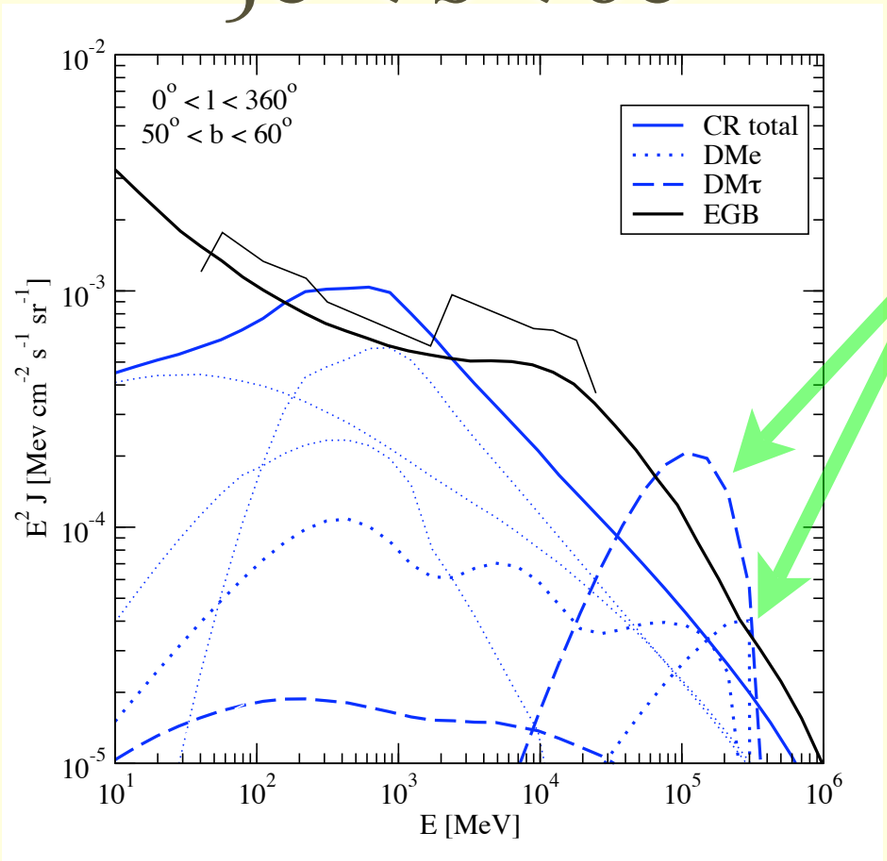
A prediction for the IC term (plus final state radiation or pion decay terms) for two sample (leptophilic) models fitting the Pamela excess in the positron ratio:

$10^\circ < b < 20^\circ$



cross checked against Fermi data at intermediate latitudes

$50^\circ < b < 60^\circ$



DM spectral feature at E≥ 100 GeV (?)

a prediction independent on propagation at high latitudes

Note also: the prediction is insensitive to the halo model (since it is well away from the GC), and to whether it is related to decaying or annihilating DM (since it is normalized to the locally measured electron/positron flux)

Conclusions:

- The WIMP framework has a very rich phenomenology; it offers definite patterns to link direct and indirect detection, although model independent approaches have some limitations.
- Steady progresses in DM indirect detection from the dramatic improvement in the quality of cosmic-ray data. The DM interpretation of the cosmic lepton puzzle convergences on models with peculiar properties, and it is not the most plausible scenario to explain data at this stage.
- We are learning and will learn a lot from the wealth of data Fermi is delivering; several examples for which the multi-wavelength approach to DM indirect detection is very powerful.
- The cross-correlation among DM signals is the main route to DM identification.