Status of Dark Matter searches

Piero Ullio
SISSA & INFN (Trieste)

MULTI^3, Padova, March 1, 2010

Outline

- Evidence for dark matter; the determination of the local halo density as sample case.

- Properties of dark matter particles from cosmological and astrophysical observations: deviations from the standard picture as guideline for dark matter identification?

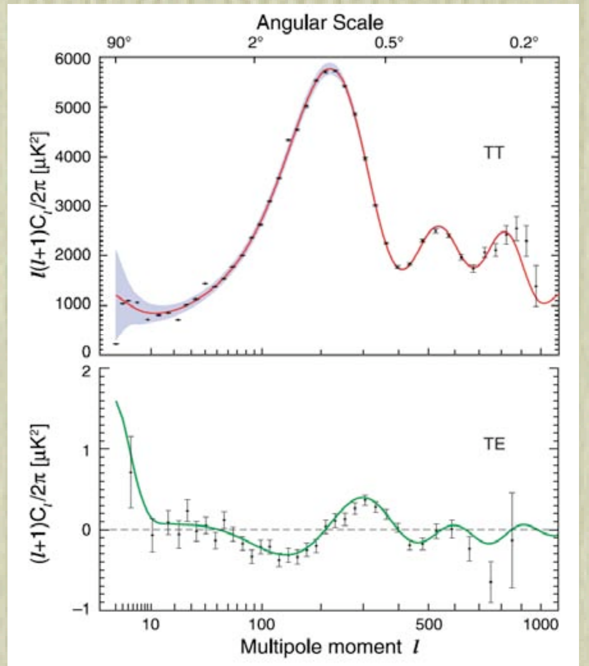
- Models for DM generation and the thermal relic picture (or slight variants) and the LHC connection.

- Direct versus indirect dark matter detection. Peculiar properties when interpreting recent (indications of) excesses in terms of dark matter induced effects.

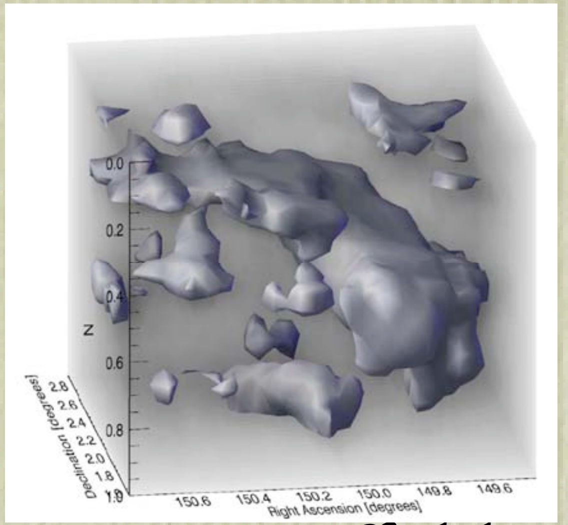
- The cross-correlation among DM signals as route to detection.

- Perspectives rather than conclusions.

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

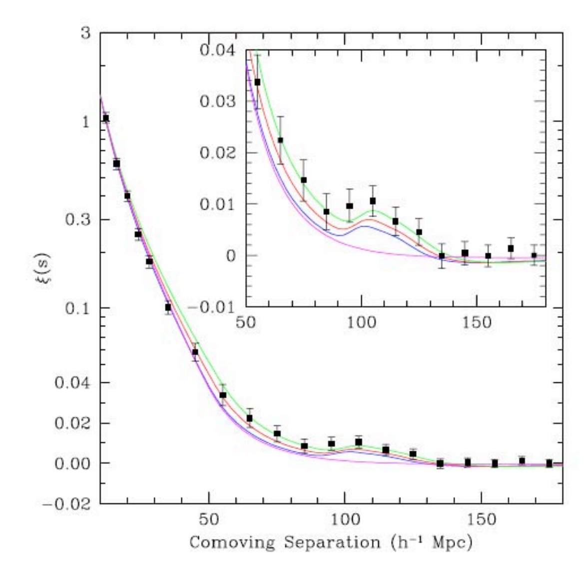


CMB

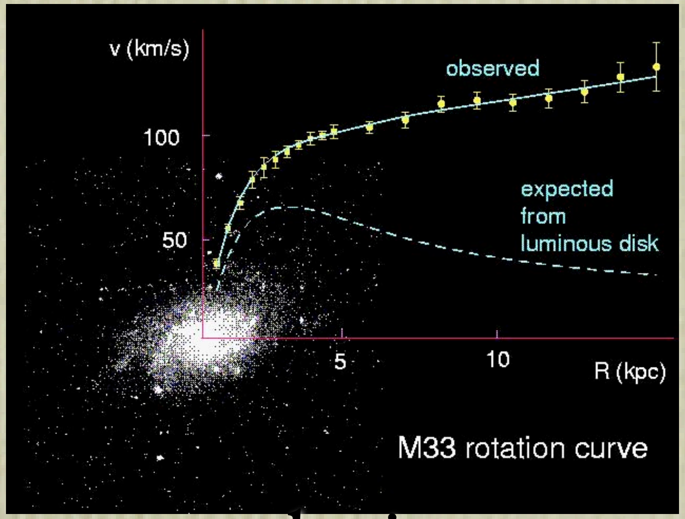


grav. scaffold

galaxy clusters



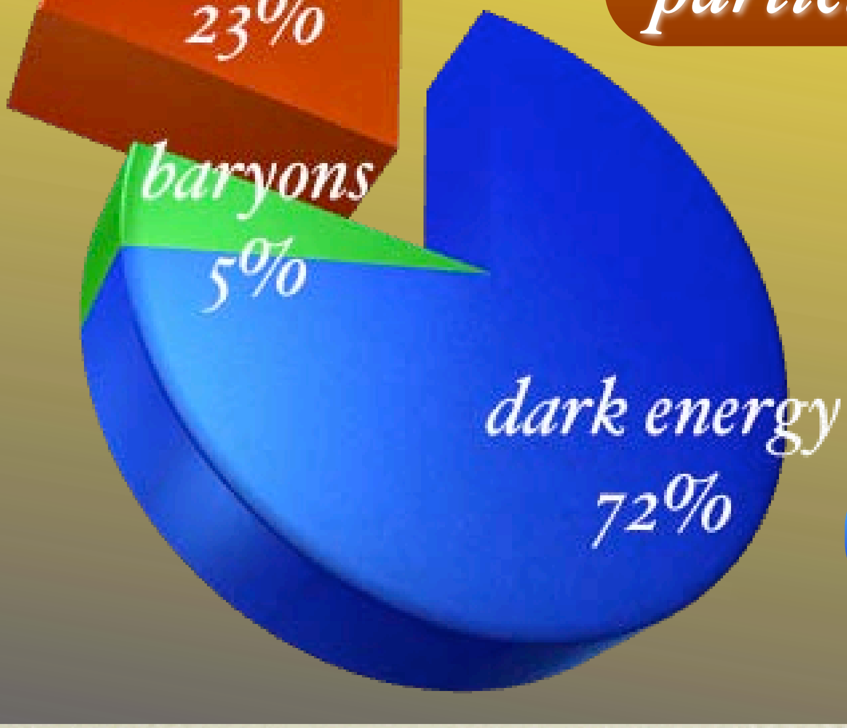
BAO



galaxies

+ many others:

All point to a single "concordance" model (assuming GR as the theory of gravity):



elementary particles?

???

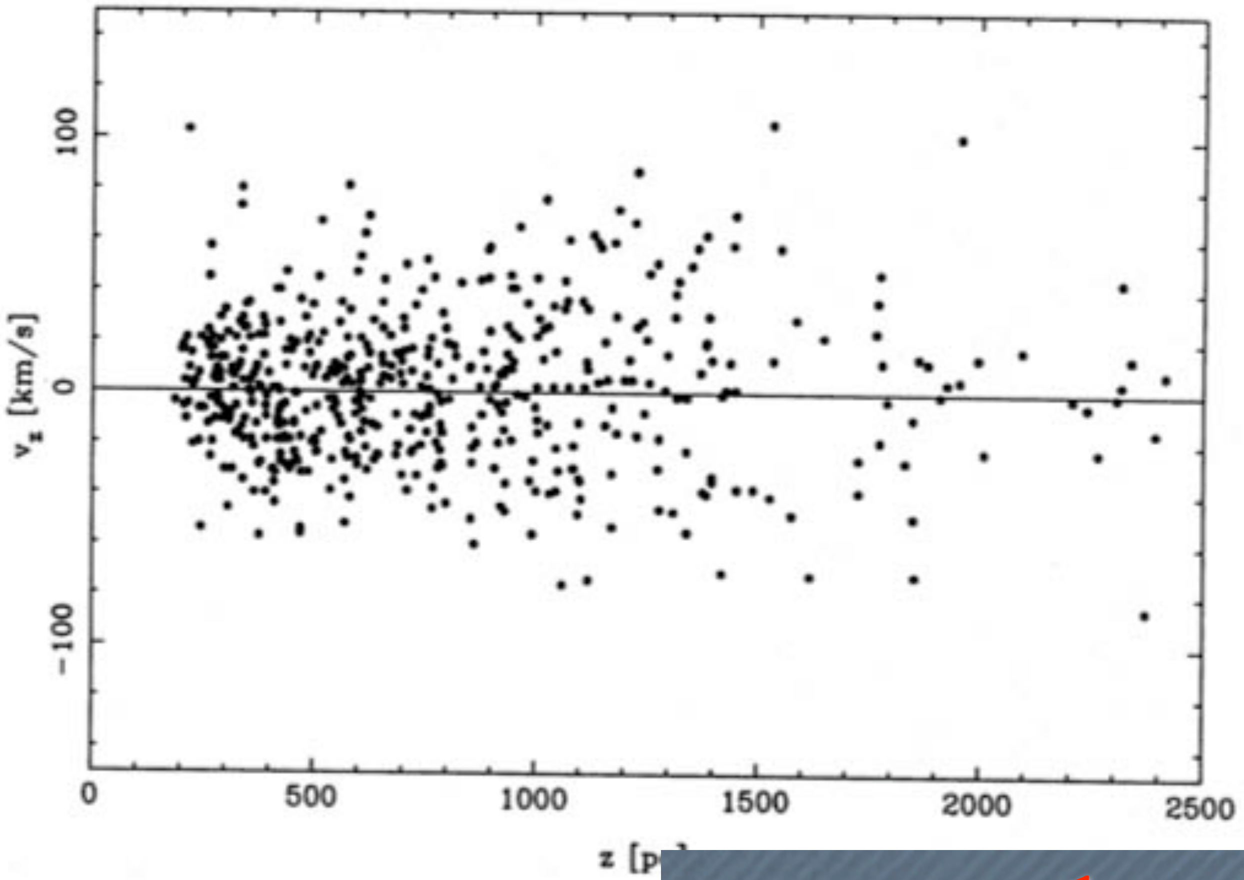
In each of these single probes the accuracy reached on the determination of the dark matter component is really remarkable. An example:

Determination of the local dark matter halo density

In principle this is a very difficult task since we are forced to a biassed perspective on our own Galaxy. However there is such a wealth of complementary dynamical tracers providing relevant informations:

Local surface mass densities:
local star velocity fields to infer the vertical motion of stars in the solar neighborhood

Kuijken & Gilmore, 1991



+ several more!

Determination of the local dark matter halo density

All dynamical tracers compared to a mass model for the Galaxy. The standard approach is to perform a decomposition into into axisymmetric or spherically symmetric terms. E.g.: Catena & P.U., arXiv:0907.0018

$$\rho_d(R,z) = \frac{\Sigma_d}{2z_d} e^{-\frac{R}{R_d}} \operatorname{sech}^2\left(\frac{z}{z_d}\right) \quad \text{with} \quad R < R_{dm}$$

stellar disc

$$\rho_{bb}(x,y,z) = \rho_{bb}(0)\left[s_a^{-1.85}\exp(-s_a) + \exp\left(-\frac{s_b^2}{2}\right)\right]$$

stellar bulge/bar

$$\rho_h(r) = \rho' f\,(r/a_h)$$

dark matter halo

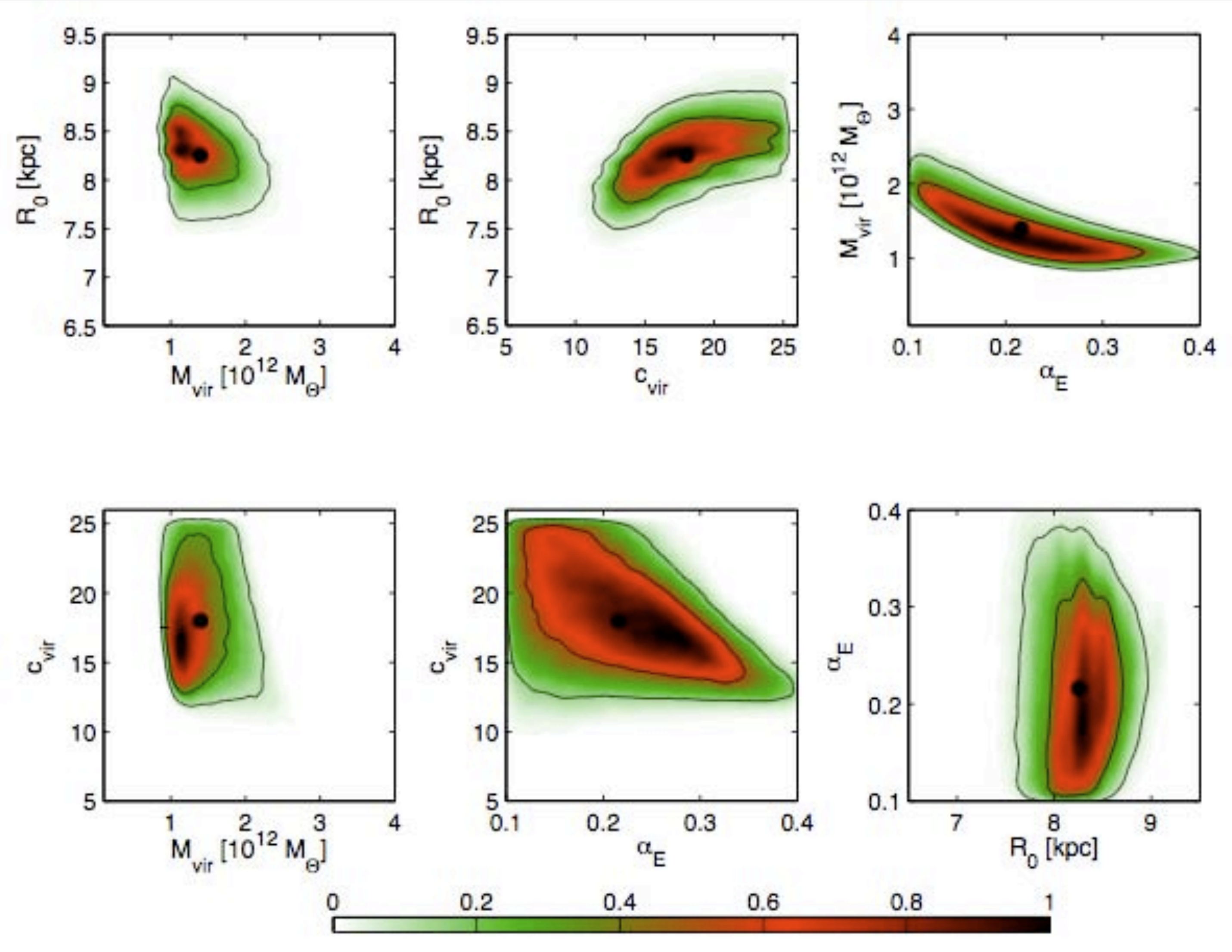
+ gas disc

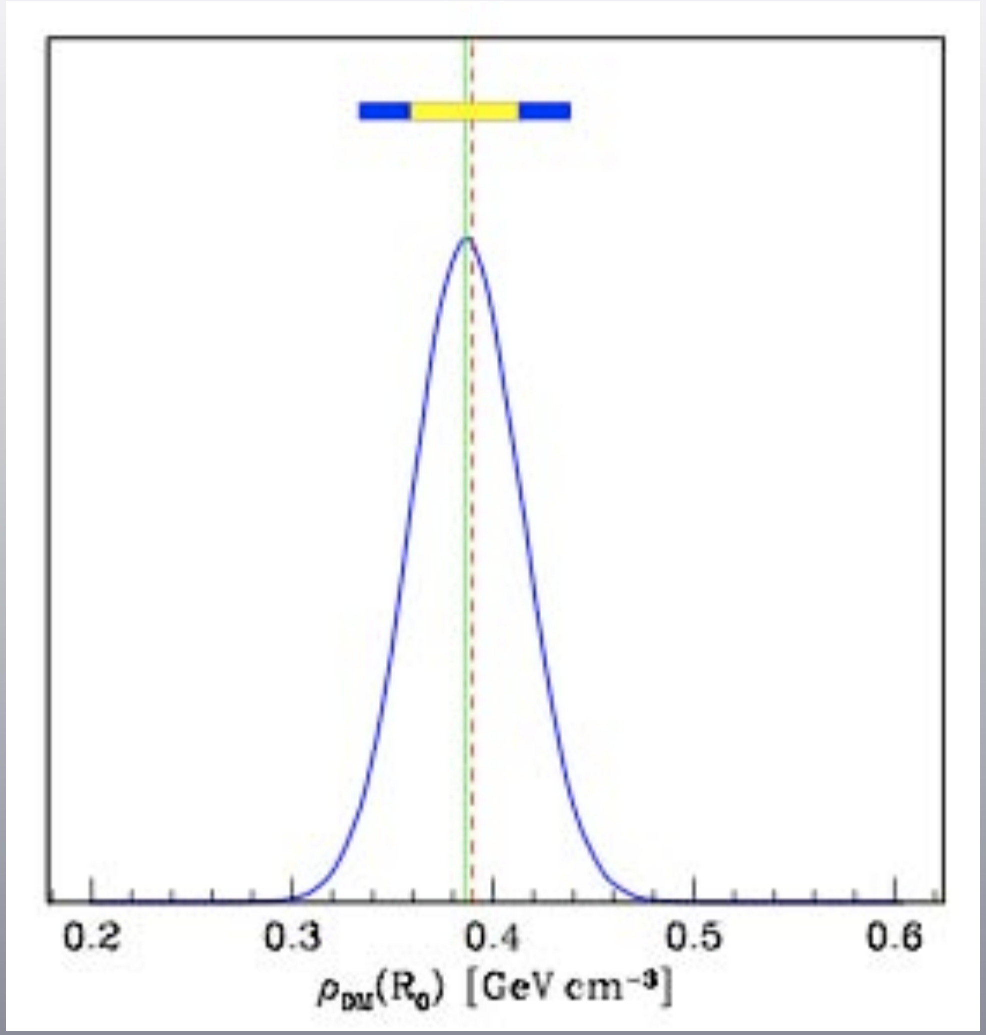
a **7 or 8 parameter model**, which, having defined an appropriate likelihood function, is studied in a **Bayesian approach** implementing a Markov chain Monte Carlo method:

Determination of the local dark matter halo density

Results of the fit and implications for the local halo density:

Einasto profile: $f_E(x) = \exp\left[-\frac{2}{\alpha_E}\left(x^{\alpha_E} - 1\right)\right]$





$$\rho_{DM}(R_0) = 0.385 \pm 0.027\,\mathrm{GeV\,cm^{-3}}$$

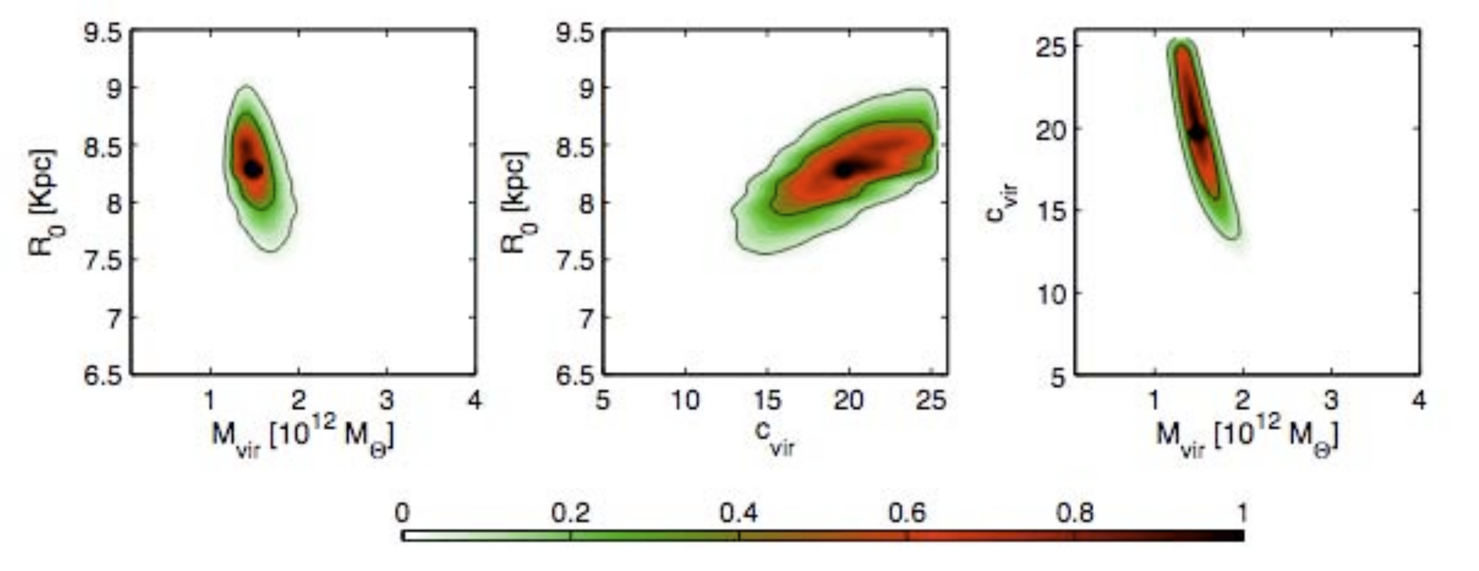
1-σ error of ~ 7%

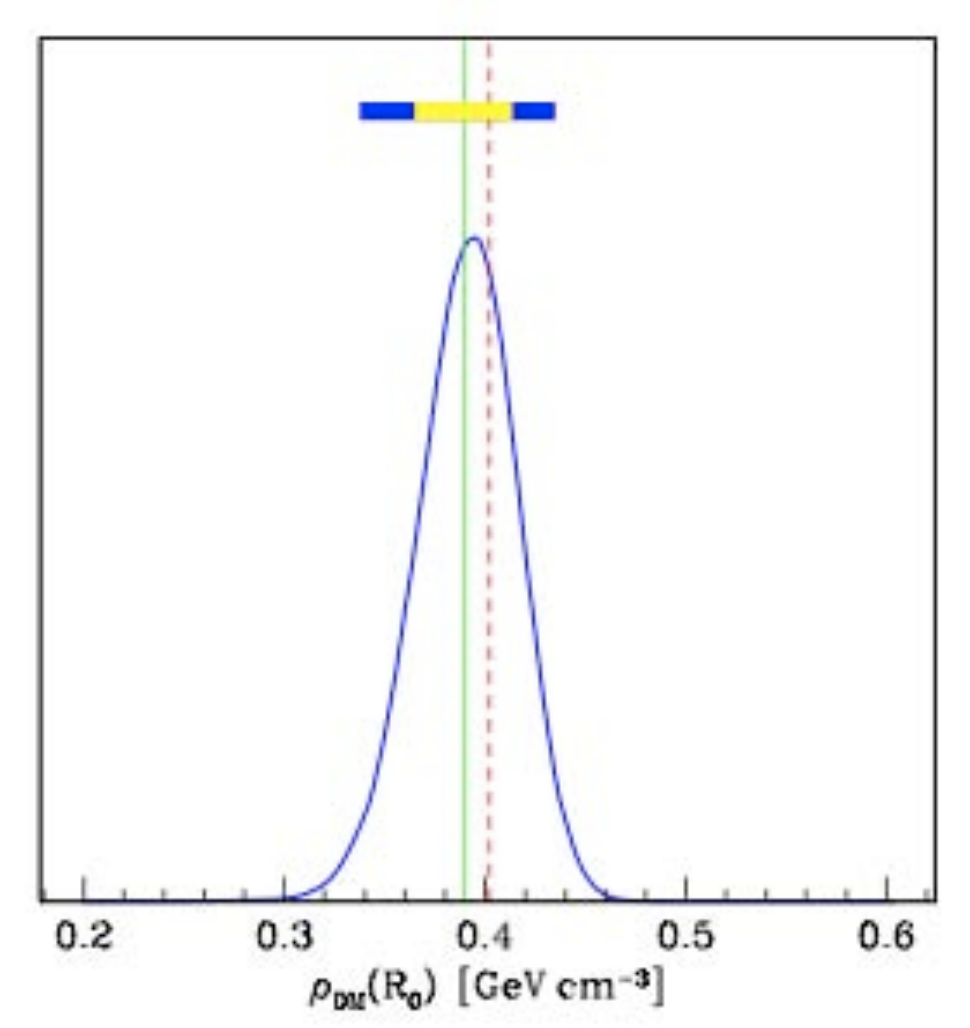
Determination of the local dark matter halo density

Results of the fit and implications for the local halo density:

NFW profile:

$$f_{NFW}(x) = \frac{1}{x(1+x)^2}$$





$$\rho_{DM}(R_0) = 0.389 \pm 0.025\,\mathrm{GeV\,cm^{-3}}$$

1-σ error of ~ 7%

Burkert profile:

$$f_B(x) = \frac{1}{(1+x)(1+x^2)}$$

$$\rho_{DM}(R_0) = 0.409 \pm 0.029\,\mathrm{GeV\,cm^{-3}}$$

What properties of DM particles can be deduced from cosmological and astrophysical observations?

There are 5 golden rules (properties that are not strongly violated):

1) DM is **optically dark**:

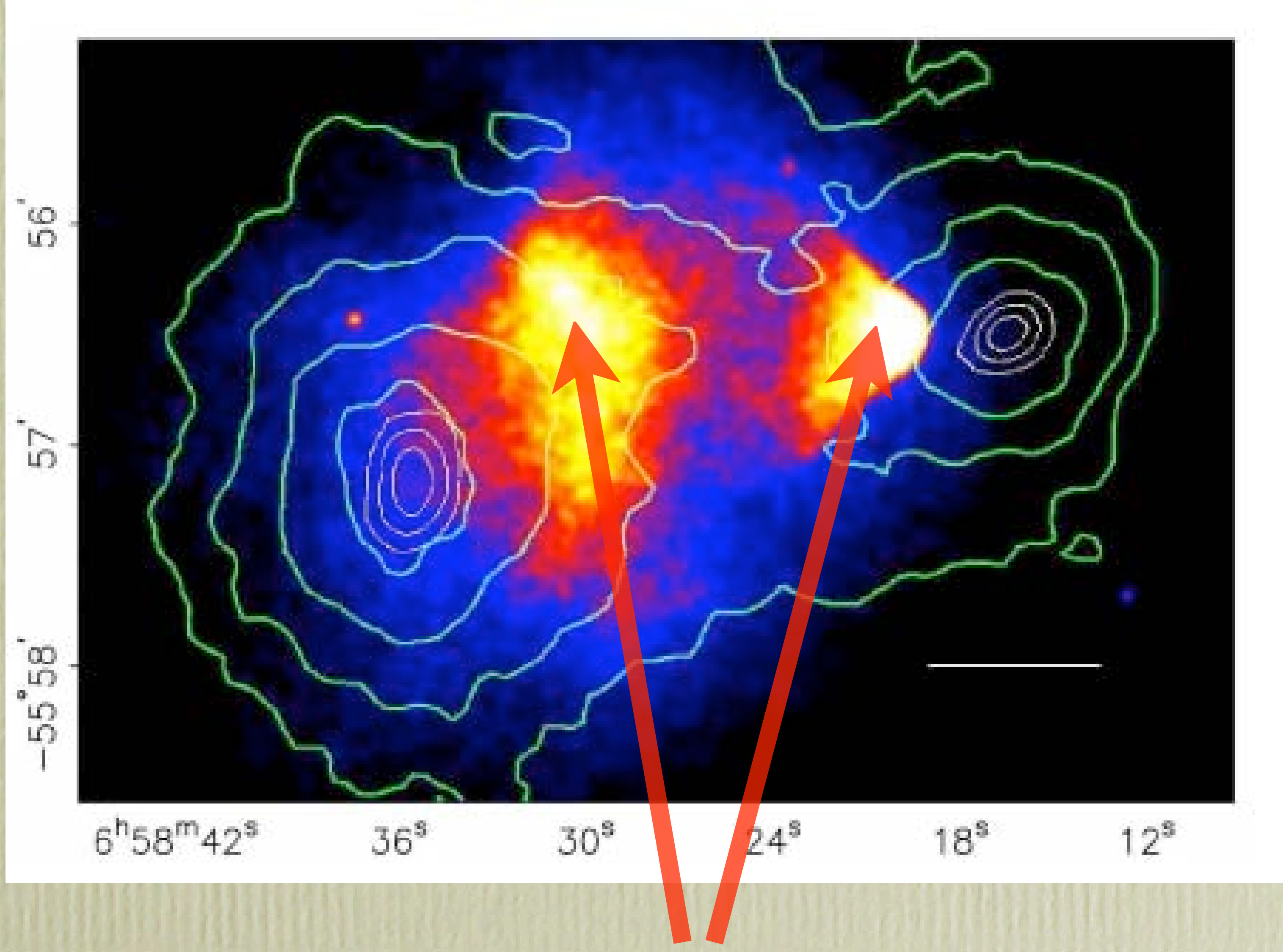
its electromagnetic coupling is suppressed since:
a) it is not coupled to photons prior recombination;
b) it does not contribute significantly to the diffuse extragalactic background radiation at any frequency;
c) it cannot cool radiating photons (as baryons do, when they collapse to the center of galaxies).
The last property applies to any cooling mechanism (radiative emission in some hidden or mirror sector?)

⇒ DM is **dissipation-less**

Tight limits for particles with a millicharge, or electric/magnetic dipole moment, see, e.g., Sigurdson et al., 2004

2) DM is **collision-less**:

Limits from the fact that you get spherical clusters as opposed to the observed ellipticity in real clusters (e.g. Miralda-Escude, 2000). More recently, limits from the morphology of the recent merging in the 1E0657-558 cluster ("Bullet" cluster):



Collisional hot gas
displaced from gravitational wells

Lensing map of the cluster superimposed on Chandra X-ray image, **Clowe et al. 2006**

Inferred limit of the self-interaction cross section per unit mass:

$$\sigma/m < 1.25 \text{ cm}^2 \text{ g}^{-1}$$

Radall et al., 2007

in the range:

$$\sigma/m \sim 0.5 - 5 \text{ cm}^2 \text{ g}^{-1}$$

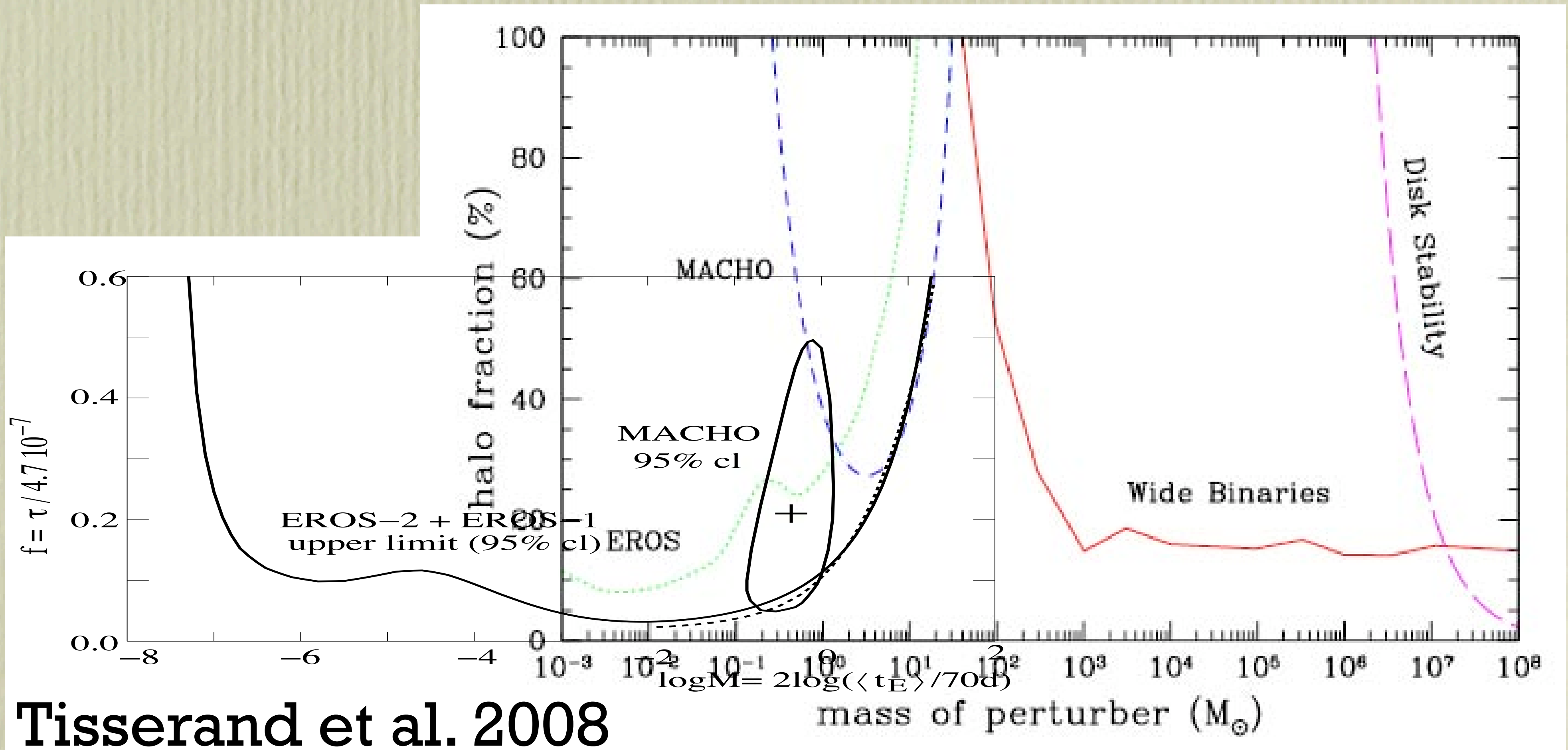
claimed for self-interacting DM **Spergel & Steinhardt, 2000**

1) + 2) constrain the interaction strength: what about implications for the mass of the dark matter particles?

3) DM is in a **fluid limit**:

we have not seen any discreteness effects in DM halos. Granularities would affect the stability of astrophysical systems. Limits from, e.g. the thickness of disks, globular clusters, Poisson noise in Ly-α, halo wide binaries :

Macho + Eros microlensing searches set limits on MACHOs in the Galaxy:



Tisserand et al. 2008

Yoo, Chaname& Gould, 2003

Hardly meaningful range in particle physics units: 1 M$_\odot$ ~ 10^{57} GeV

4) DM is **classical**:

it must behave classically to be confined on galactic scales, say 1 kpc, for densities ~ 1 GeV cm^{-3}, with velocities ~ 100 km s^{-1}. Two cases:

a) for ***bosons***: the associated De Broglie wavelength

$$\lambda < 1\,\mathrm{kpc} \quad \Rightarrow \quad M_p > 10^{-22}\,\mathrm{eV}$$

“Fuzzy” CDM ? **Hu, Barkana & Gruzinov, 2000**

b) for ***fermions***: Gunn-Tremaine bound (**PRL, 1979**):

the Pauli exclusion principle sets a maximum to phase space density f of a fermion fluid in this primordial configuration: $f_{\max}^{\rm ini} = \frac{g}{h^3}$.

f is conserved, while its coarse-grained version $\bar{f}$ (which is “observable”) may eventually only decrease:

$$\bar{f}_{\max} \leq f_{\max} \leq f_{\max}^{\rm ini}$$

For a DM isothermal sphere: $\bar{f}_{\max} = \frac{\rho_0}{M_p^4} \frac{1}{(2\pi\sigma^2)^{3/2}}$

$$\rho_0 \sim 1\,\mathrm{GeV\,cm}^{-3}$$

$$\sigma \sim 100\,\mathrm{km}\,s^{-1}$$

$$\Longrightarrow \quad \boxed{M_p \gtrsim 35\ \mathrm{eV}}$$

5) DM is **cold** (or better it is *not hot*):

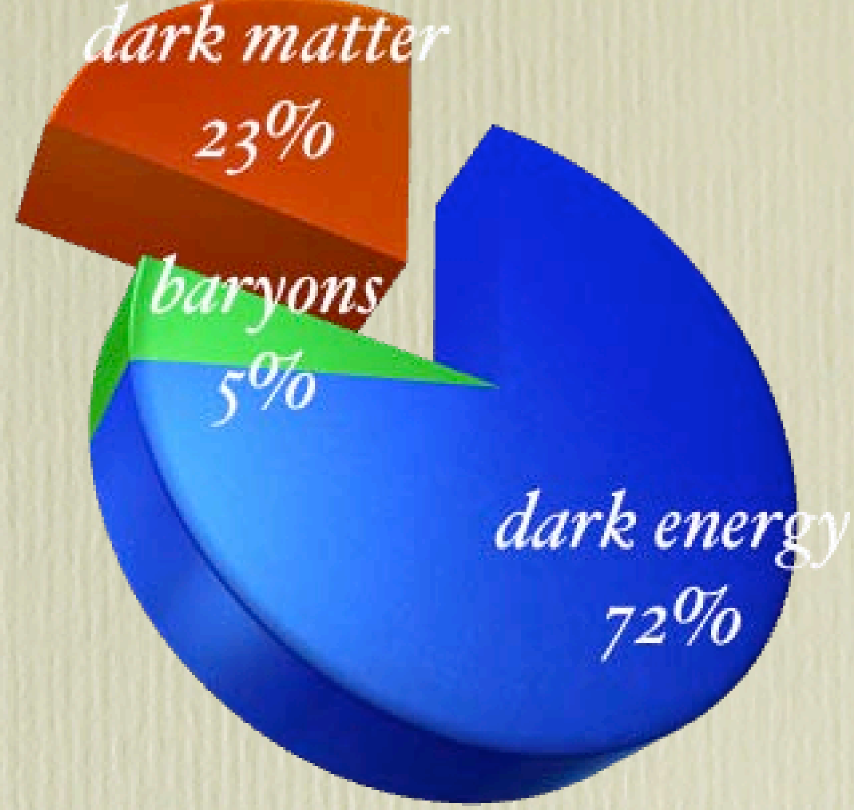
at matter-radiation equality perturbations need to growth. If kinetic terms dominates over the potential terms, free-streaming erases structures. The free-streaming scale is about:

$$\lambda_{FS} \simeq 0.4\,\mathrm{Mpc}\,(M_p/\mathrm{keV})^{-1}(T_p/T)$$

Top-down formation history excluded by observations, i.e. hot DM excluded. In the cold DM regime λ_{FS} is very small. Warm DM stands in between and needs some particle in the keV mass range (Lyα data place constraints on this range).

The 5 golden rules imply, e.g., that **Baryonic DM and Hot DM (SM neutrinos) are excluded,** and that **Non-baryonic Cold DM is the preferred paradigm**

Standard structure formation picture: Gaussian adiabatic primordial density perturbations, with nearly scale-invariant spectrum, evolving in a CDM cosmology (C→ only gravity matters) + Λ term.



Many spectacular successes of the theory, expecially on large scales, both at the level of analytical computations in the linear (or next to linear) regime, as well as with numerical N-body simulations

Challenges to the ΛCDM model?

There are possible areas of disagreement between theory (more exactly numerical N-body simulations of the theory in the non-linear regime) and observations, expecially on small scales:

- Mismatch in the number of satellites found in the simulations of Milky Way size halos and the number of those identified in real galaxies through their (faint) luminous counterparts.
- Simulations predict cuspy (singular) dark matter halo density profiles, a feature which is not clearly supported by dynamical tracers, possibly disfavored in case of small (faint) galaxies such as LSB and dwarf galaxies.
- Simulations tends to fail to produce realistic discs for spiral galaxies, with significant angular momentum mismatches.
- Difficulties with the morphology of galaxies, luminosity functions, age of stellar populations, and possibly other "baryonic observables".

Real issues or just calls for refinements in the simulations?

A particle physics solution to the satellite/cusp issues?

Goal: start with a scale invariant CDM power spectrum and then remove power on small scales. Mechanism: introduce a model mildly (i.e. at level of current bounds) violating one of the 5 golden rules listed above:

1) ~~Dissipation-less~~: e.g., DM with a electric/magnetic dipole moment, Sigurdson et al. 2004
2) ~~Collision-less~~: self interacting DM, Spergel & Steinhardt 2000
3) ~~Fluid limit~~: ...
4) ~~Classical~~: fuzzy DM, Hu, Barkana & Gruzinov 2000
5) ~~Cold~~: warm DM, Hogan & Dalcanton 2000

Another possibility: 2 phases for DM, i.e. the stable DM matter specie we seen in the Universe today is generated in the late decay (at an age of Universe up to few years) of another specie.(e.g. a charged particle or a neutral state slightly more massive, e.g., Profumo, Sigurdson, P.U. & Kamionkowski, 2005; Borgani,Masiero & Yamaguchi, 1996).

Could this be the key to identify dark matter?

Back to the standard lore...

The Non-baryonic Cold DM paradigm does not help 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.

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.

Example of case ii): axion dark matter. Example of case iii): Wimpzillas. The phenomenology for these models and their detection depends critically on the single scenarios.

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:

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

$P\bar{P} \rightarrow \chi\bar{\chi}$

$\chi\bar{\chi} \rightarrow P\bar{P}$

dilution by Universe expansion

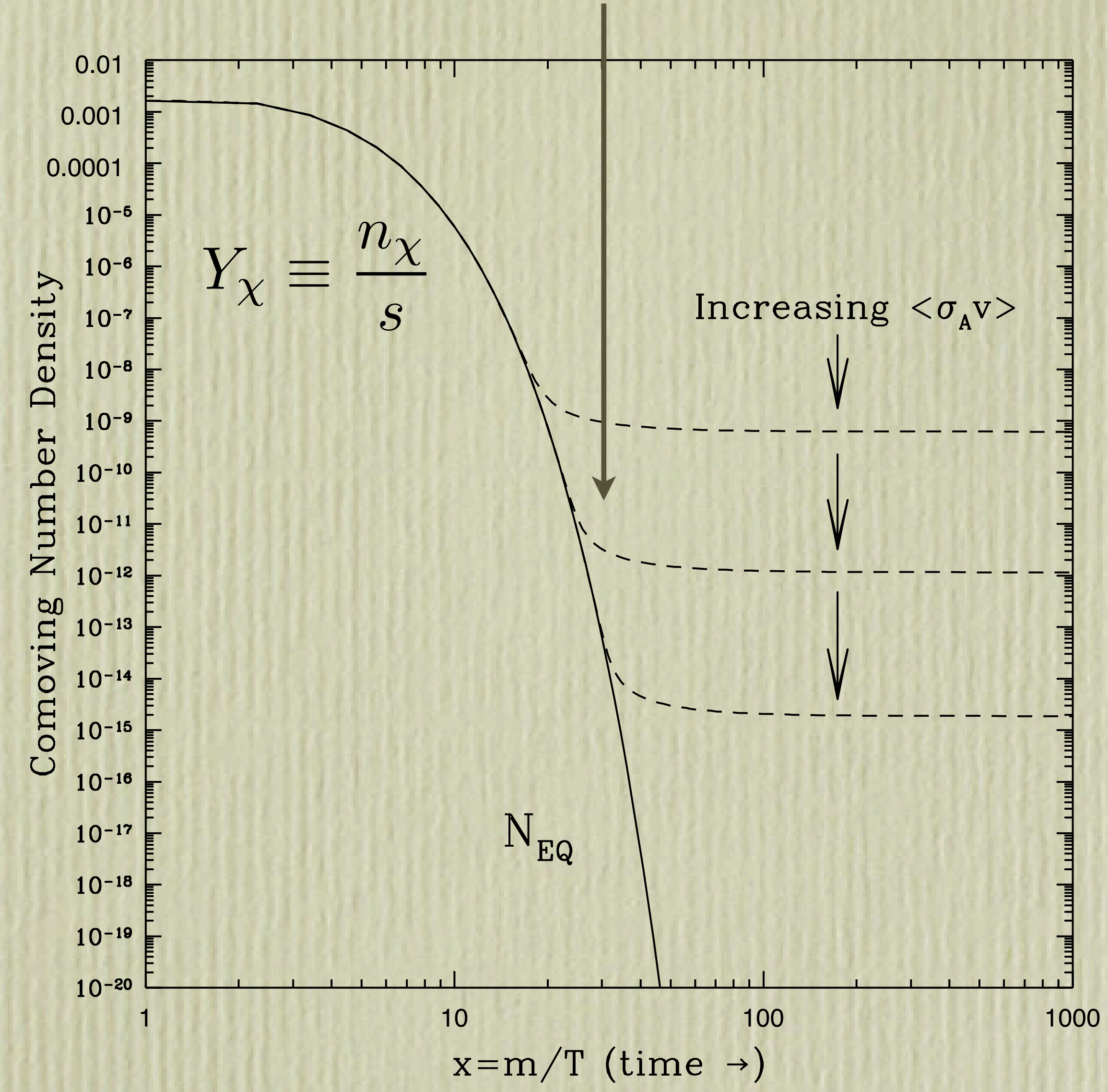
thermally averaged annihilation cross section

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:

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



$$Y_\chi \equiv \frac{n_\chi}{s}$$

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

(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)
- ...

Incomplete list of models and very incomplete list of references!

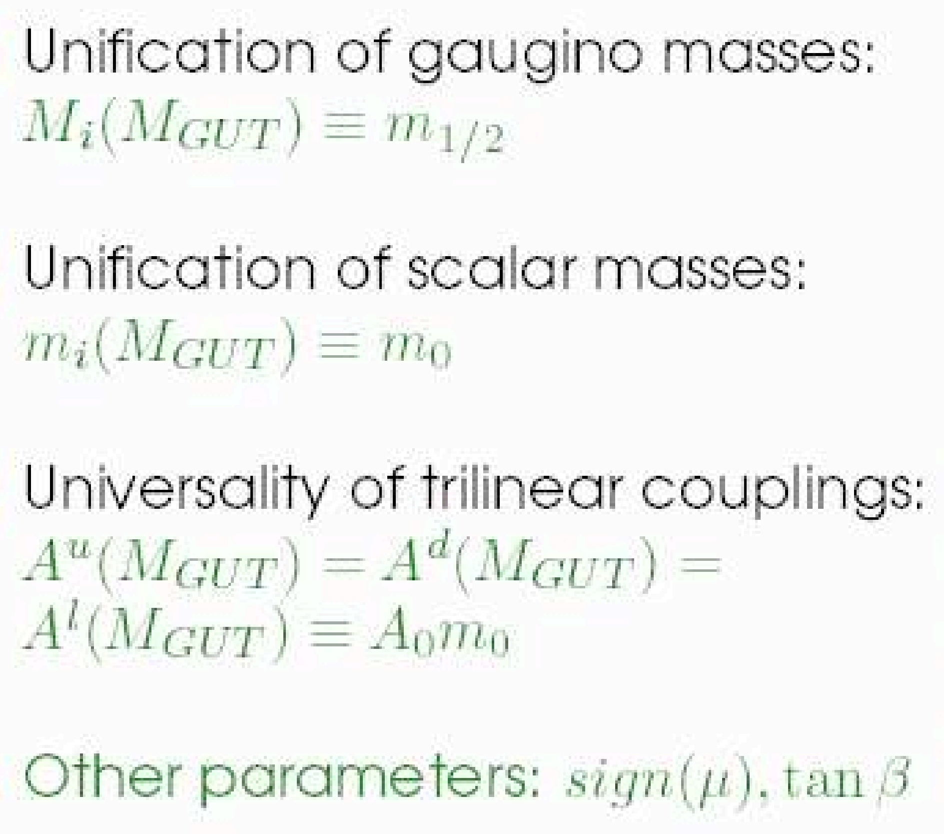
or via an accidental symmetry, such as a quantum number preventing the decay: [Mirror DM], DM in technicolor theories (Gudnason et al., hep-ph/0608055), "minimal" DM (Cirelli et al., hep-ph/0512090) , ...

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

E.g.: neutralino LSP in the CMSSM

Minimal scheme,
but general enough to
illustrate the point.

Set of assumptions:

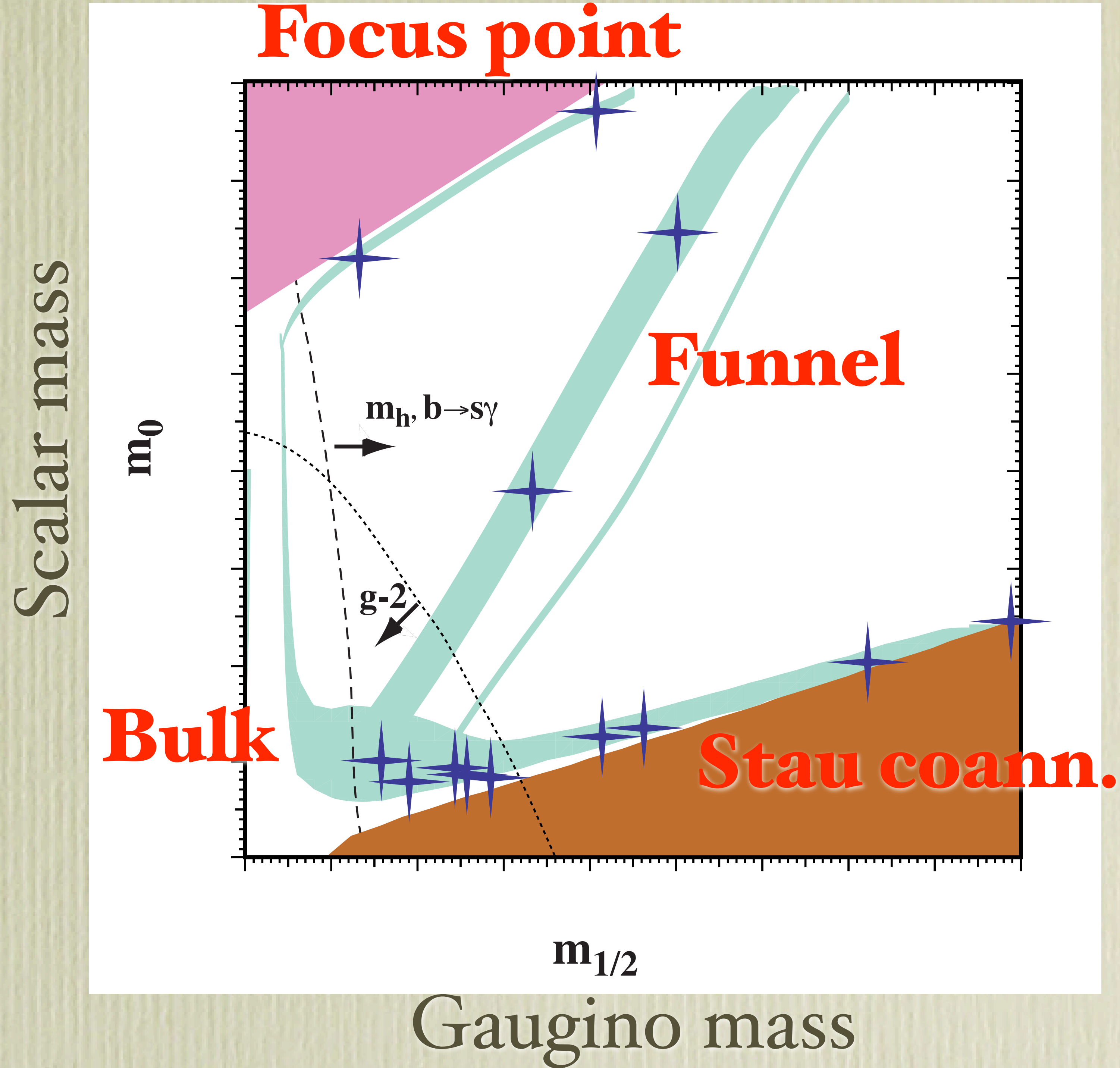


Unification of gaugino masses:
$M_i(M_{GUT}) \equiv m_{1/2}$

Unification of scalar masses:
$m_i(M_{GUT}) \equiv m_0$

Universality of trilinear couplings:
$A^u(M_{GUT}) = A^d(M_{GUT}) =$
$A^l(M_{GUT}) \equiv A_0 m_0$

Other parameters: $sign(\mu), \tan\beta$



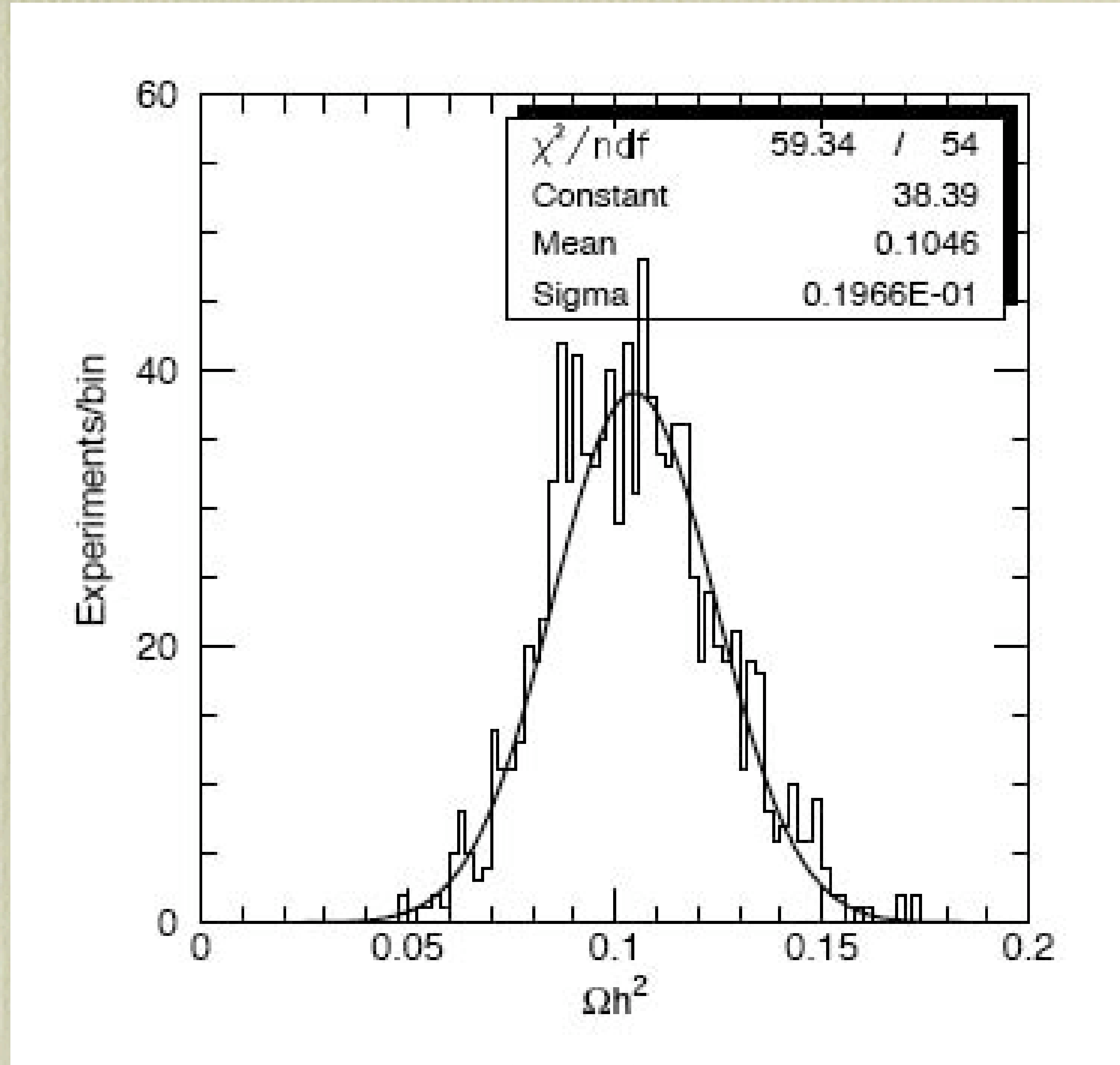
Battaglia et al. 2001

WIMPs at the LHC time. A few possibilities.

There are favourable case, such as for the **bulk region**, in which you would reconstruct the relic density:

Most superpartners are light and detected at LHC (only heaviest stop, stau and neutralino are not seen in example displayed):

fairly accurate prediction for the relic density



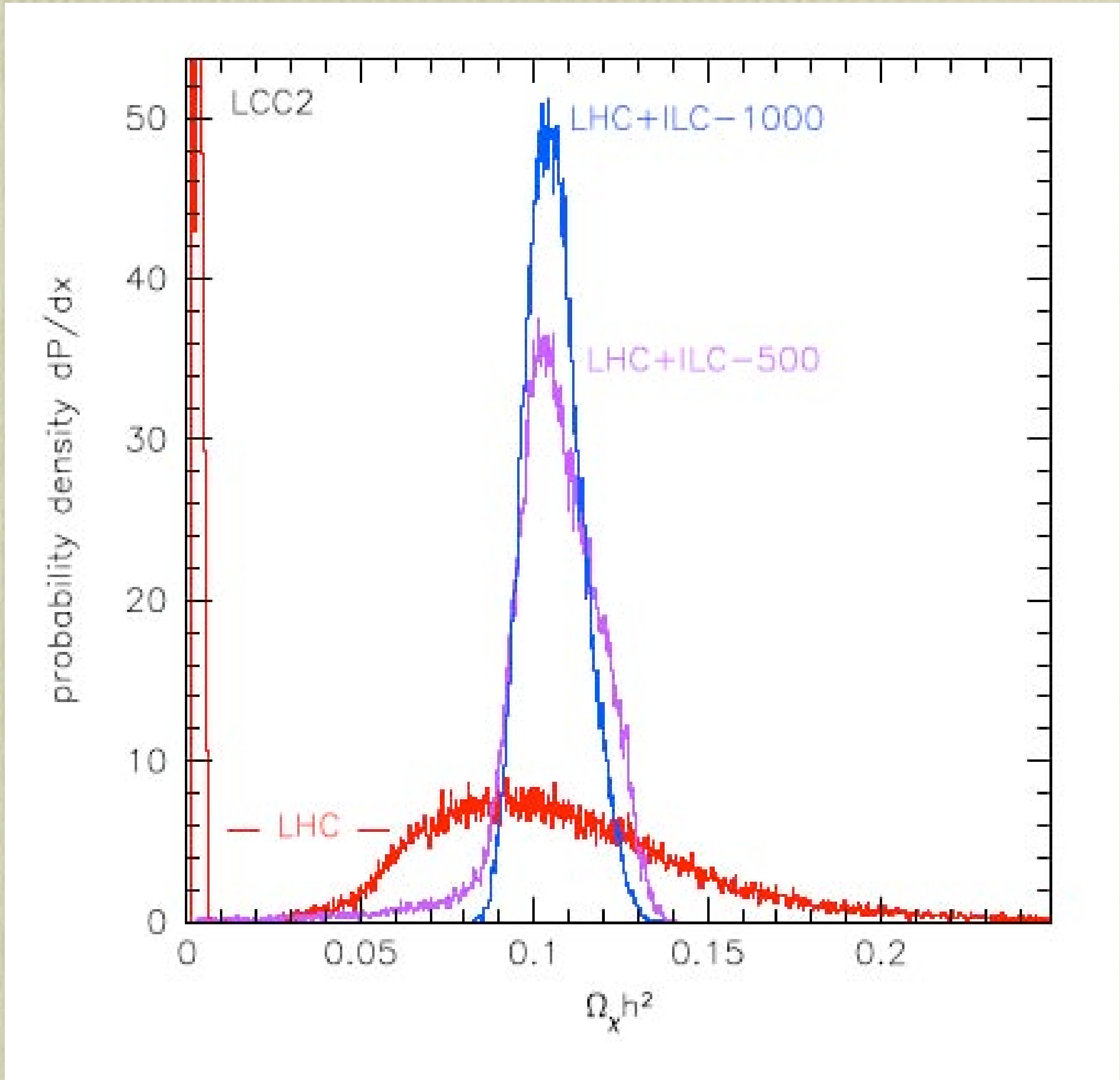
Relic density

Nojiri, Polesello & Tovey, 2006

… and much less favourable cases, such as for the **focus-point region**:

Even assuming a light $M_{1/2}$ (300 GeV), LHC finds only the gluino and 3 neutralinos:

the relic density value is poorly reconstructed



Relic density

Baltz, Battaglia, Peskin & Wizansky, 2006

Non-thermal contributions to the relic density

The thermal relic picture is valid within an extrapolation of the early Universe from the epoch at which it is well tested, the onset of BBN:

$$T_{BBN} \simeq 1\,\mathrm{MeV} \quad \text{or:} \quad t(T_{BBN}) \simeq 1\,\mathrm{s}$$

assuming that: a) there is no entropy injection, b) the Universe is radiation dominated, and c) there is no extra χ source, up to, at least:

$$T_f \simeq M_\chi/20 \sim 5 - 50\,\mathrm{GeV} \quad \text{or:} \quad t(T_f) \sim 10^{-7} - 10^{-9}\,\mathrm{s}$$

However, all three conditions may be violated in theories containing at heavy states extremely weakly (e.g.: gravitationally) coupled to matter, such as the gravitino or moduli in SUSY theories. These states are not in thermal equilibrium in the early Universe, possibly dominate the Universe energy density prior BBN, are long-lived and may inject a large amount of entropy and/or χ particles.

A perfectly viable scenario as long as their lifetime is:

$$\tau_\phi < t(T_{BBN})$$

or that Universe is "re-heated" to a temperature:

$$T_{RH} > T_{BBN}$$

The prediction for the relic density of χ is model dependent, there are however a few definite scenarios. One attractive possibility (e.g., Moroi & Randall, hep-ph/9906527):

There is one heavy modulus, driving the Universe to a matter dominated phase, decaying with a large entropy injection (the number density of early thermal relics is totally diluted) and a non-negligible branching ratio into χ, reheating the Universe at a temperature:

$$T_{RH} \sim \text{few MeV} \; - \; 100\,\text{MeV}$$

At the modulus decay the χ number density is comparable to the number density of light SM states, however pair annihilations instantaneously reduce it to the level at which annihilations become inefficient:

$$n_\chi \sim \frac{H(T_{RH})}{\langle \sigma v \rangle}$$

If the annihilation cross-section is not strongly dependent on temperature:

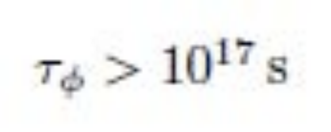
$$\Omega_\chi^{NT} h^2 \sim \Omega_\chi^T h^2 \, \frac{T_f}{T_{RH}} \sim \frac{3 \cdot 10^{-27}\,\text{cm}^3\,\text{s}^{-1}}{\langle \sigma v \rangle} \, \frac{T_f}{T_{RH}}$$

i.e., compared to the thermal relic case, an increase in the annihilation cross-section is needed for χ to match the dark matter density level.

Is this testable at the LHC?

Decaying dark matter

Among the extra massive, super-weakly interacting states there is one whose lifetime is comparable or longer than the present age of the Universe:



$$\tau_\phi > 10^{17}\ \mathrm{s}$$

E.g.: gravitinos in R-parity breaking vacua (Takayama & Yamaguchi, hep-ph/0005214), hidden sector gauge bosons/gauginos (Chen, Takahashi & Yanagida, arXiv:0809.0792), right-handed sneutrinos (Pospelov & Trott, arXiv:0812.0432), ...

The (extremely) long-lived state is playing the role of the dark matter candidate (different production mechanisms invoked in different models)

The interaction of dark matter with ordinary matter is totally negligible, however the scenario could be testable through the search of dark matter decay products.

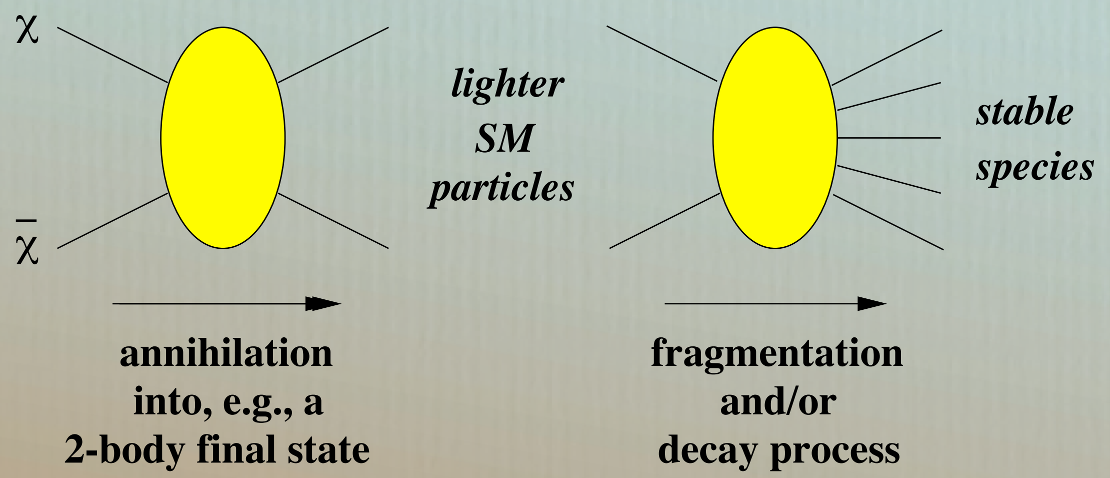
Possible LHC tests of the scenario could be the detection of long-lived charged states (the lightest beyond-SM state with ordinary coupling to ordinary matter)

Detection of WIMP dark matter

A chance for **indirect detection** stems from the WIMP paradigm itself:

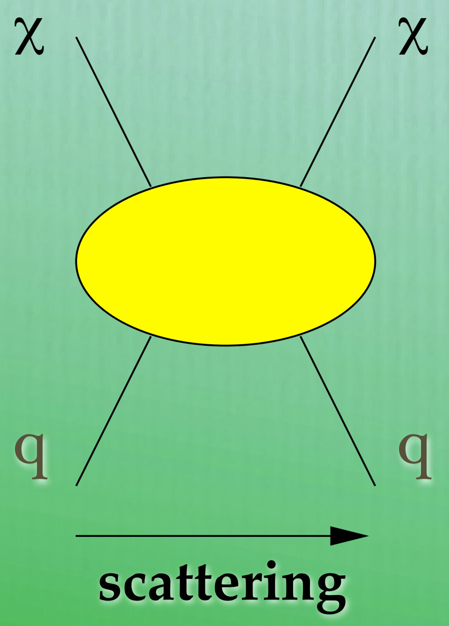
Pair annihilations of WIMPs in DM halos (i.e. at T≅0)

$$(\sigma v)_{T\simeq 0} \;\sim\; \langle \sigma v \rangle_{T=T_f}$$



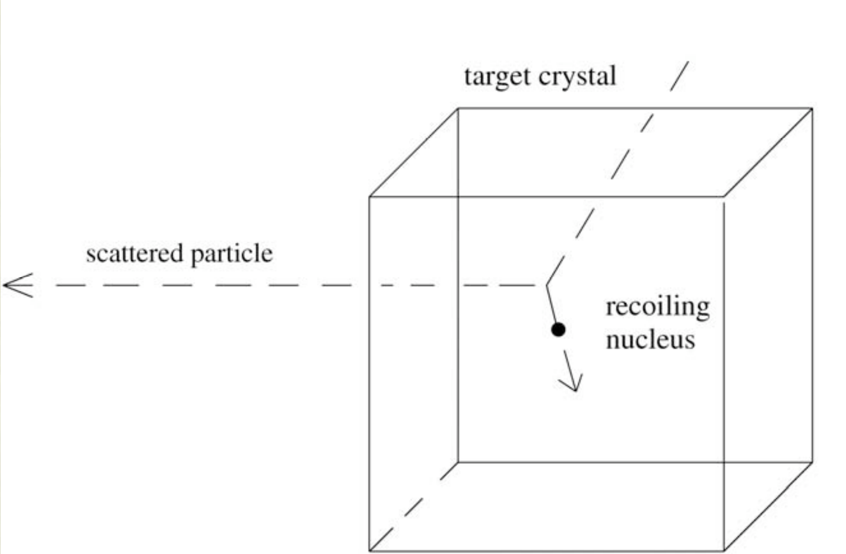
Focus on:
antiprotons,
positrons,
antideutrons,
gamma-rays,
(neutrinos)

By crossing symmetry (???) there is also a (small but finite) interaction with ordinary matter



allowing for **direct detection** by measuring nuclear recoils, and the capture into massive bodies (Earth/Sun) and detection via neutrino emission in pair annihilations therein

Direct detection:



The attempt to measure the recoil energy from elastic scattering of local DM WIMPs with underground detectors (cosmic-ray shielded).

The detection rate takes the form:

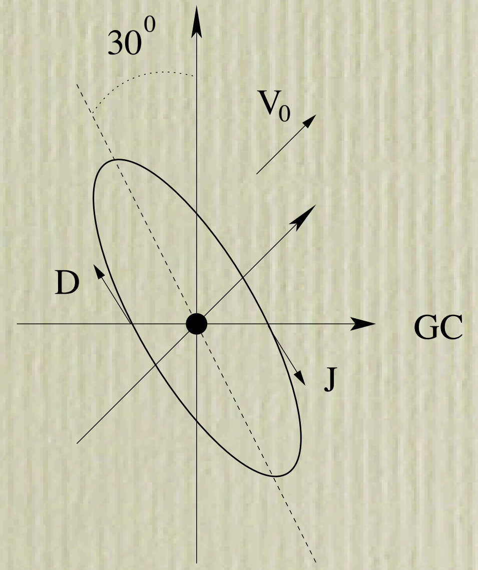
$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int_{vmin}^{v_{max}} d\vec{v} f(\vec{v})|\vec{v}| \frac{d\sigma(\vec{v},E_R)}{dE_R}$$

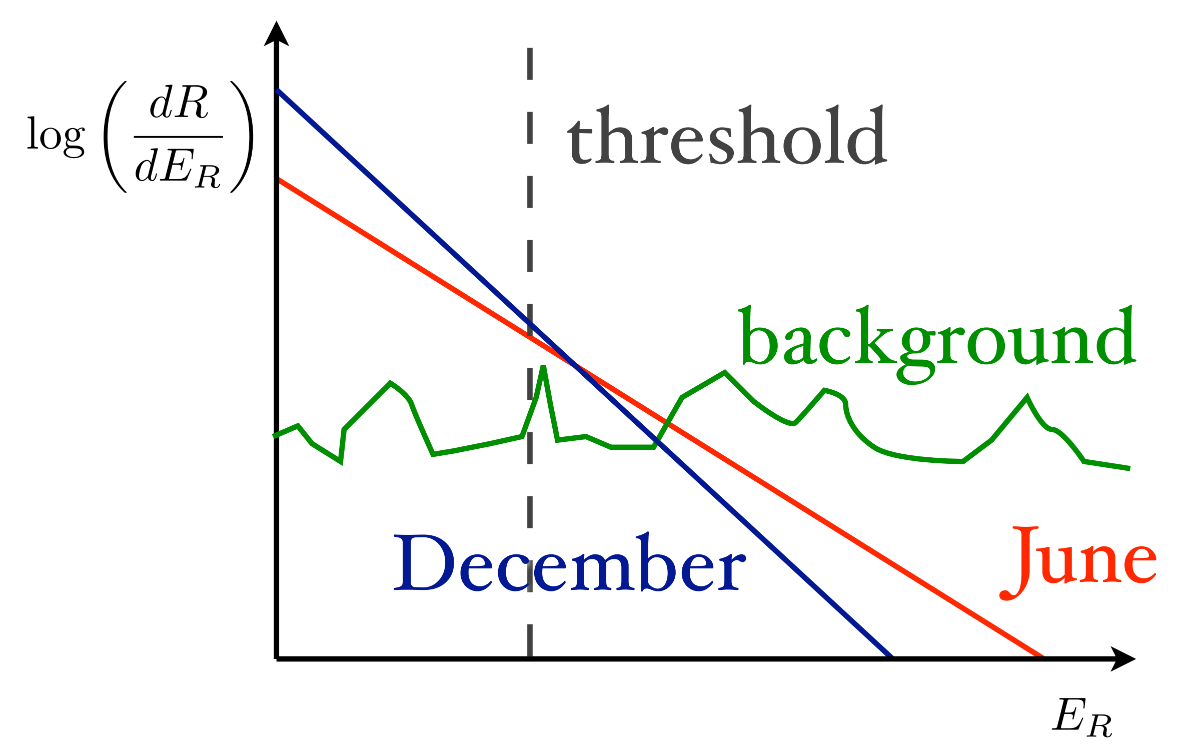
WIMP-nucleus cross section

WIMP DF

Integral on the WIMP velocity in the detector frame → directional signals & temporal modulation effects:

annual modulation: an effect on the total event rate of few % (depending on the WIMP DF)

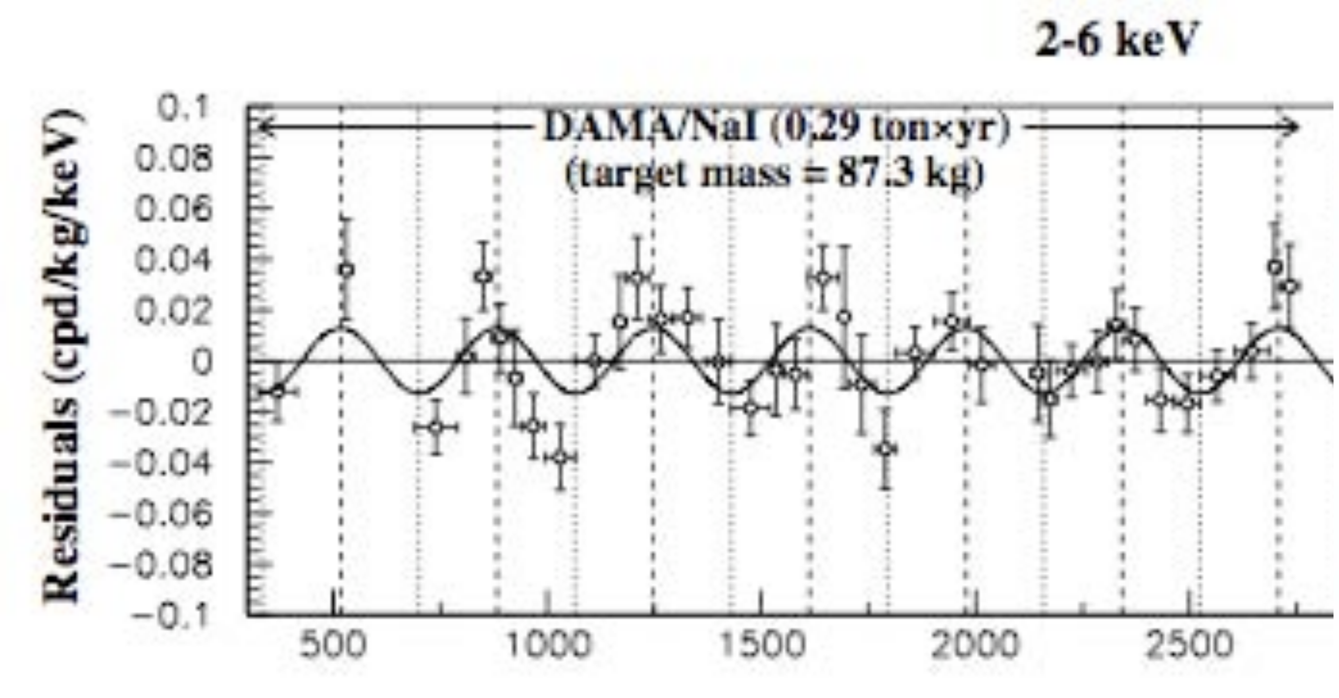


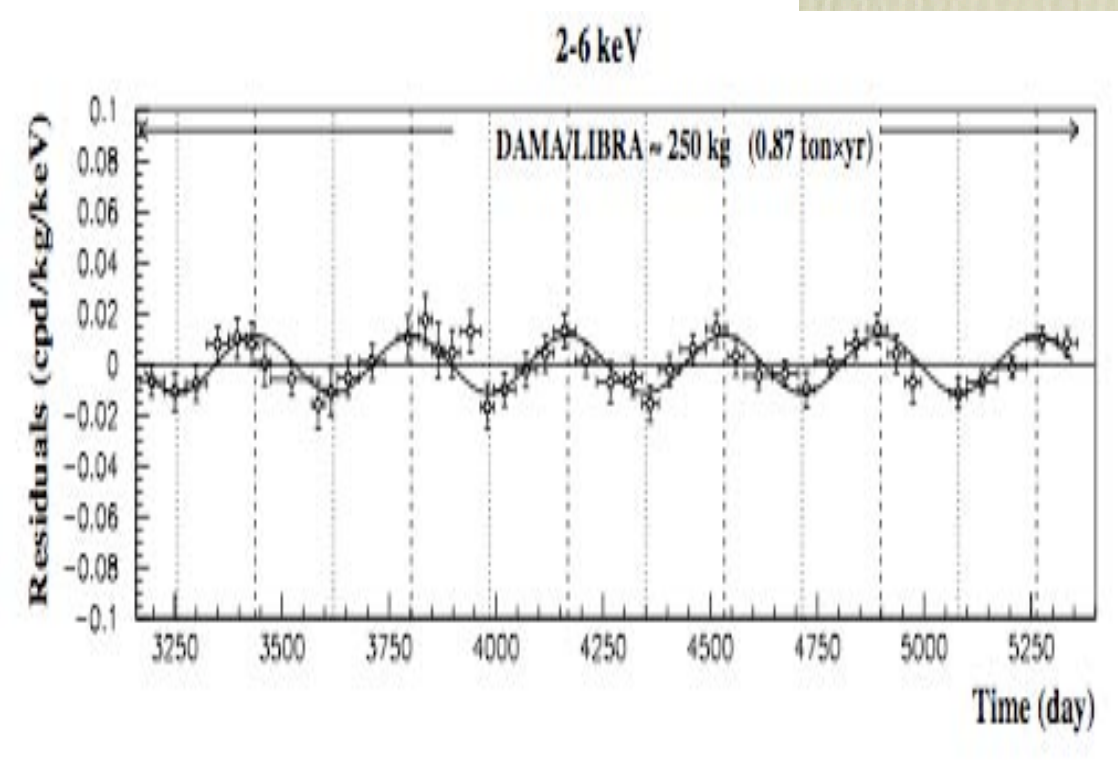


Annual modulation detected by DAMA/LIBRA

Large mass NaI detector, not discriminating between background and signal events but looking at temporal variation of the total event rate in different energy bins:

Bernabei et al., arXiv:0804.2741





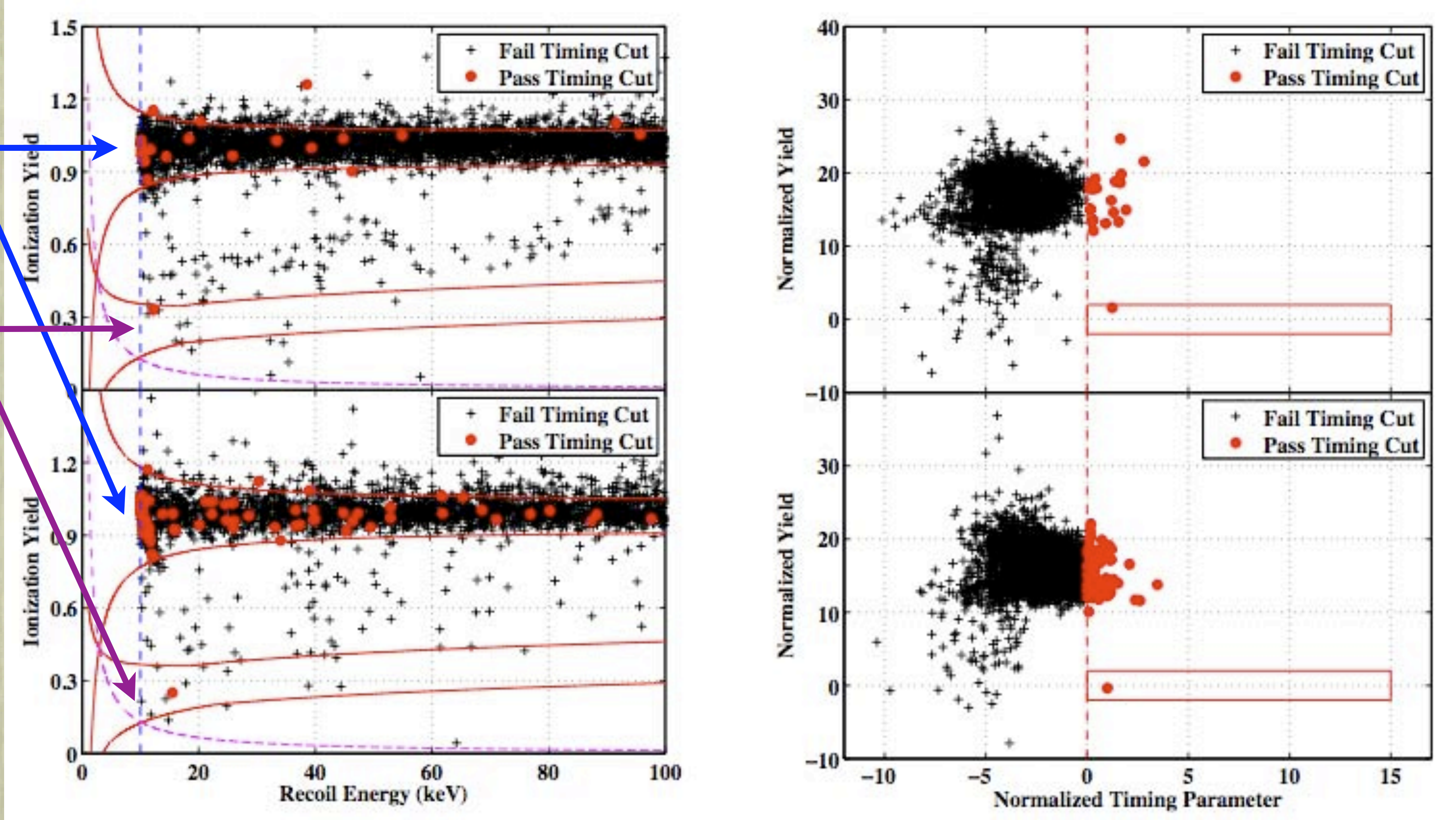
Bernabei et al., arXiv:1002.1028

By now 12 annual cycles, huge statistics and modulation effect solidly detected. Regarding its interpretation, the phase of the modulation and its amplitude are compatible and suggestive of WIMP DM scatterings; however converting the effect into a WIMP event rate, there is tension with other direct detection experiments.

CDMS II final result

Small mass Ge detector with heavy discrimination between background and signal events:

Ahmed et al., arXiv:0912.3592



electron recoils

nuclear recoils

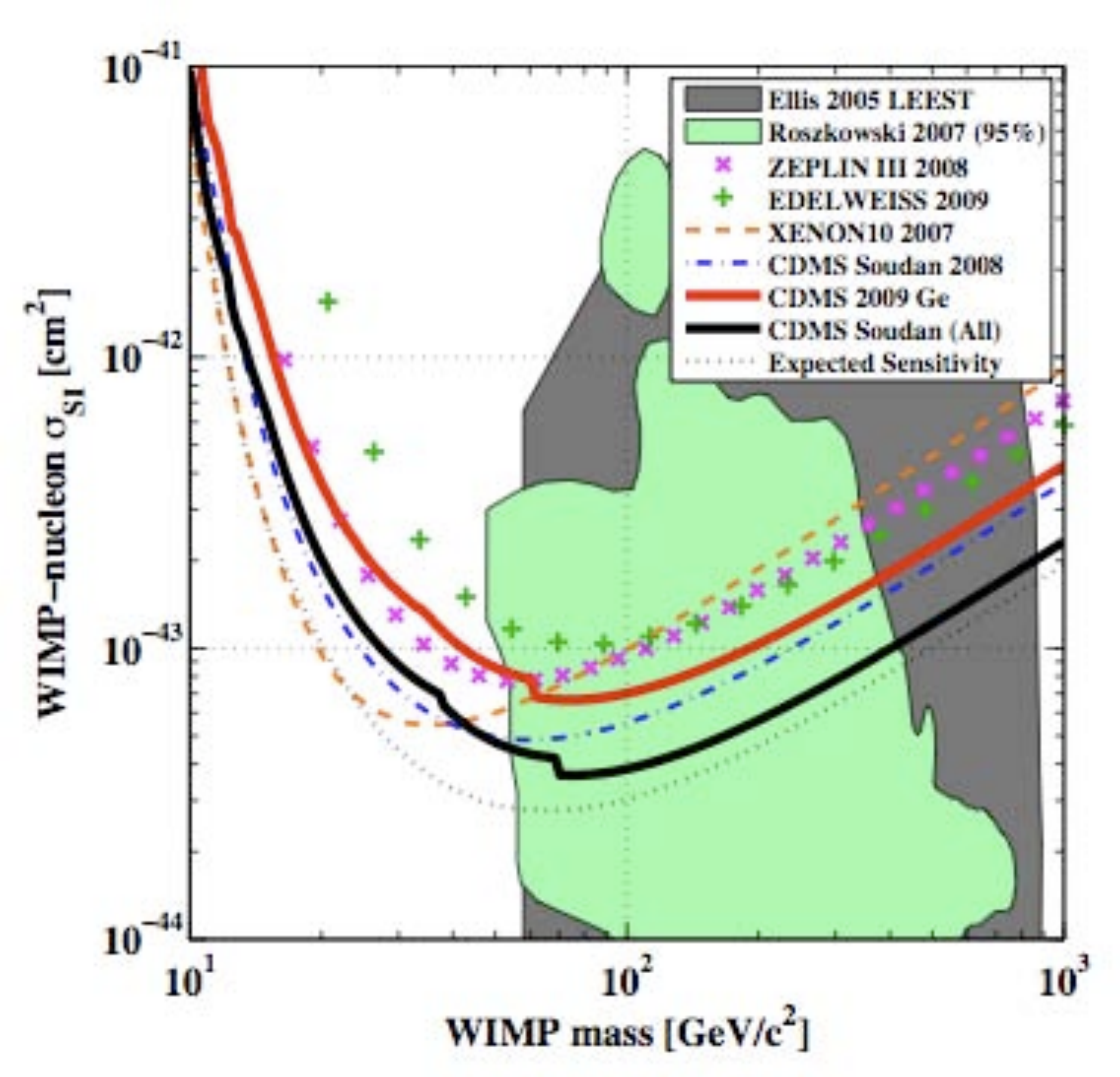
surface

inner

2 events survive all cuts; expected background: 0.9±0.2 events;
the probability to see ≥ 2 events is 23% ⇒ too little to claim a signal;
XENON-100 will clarify this within the summer!

CDMS II (+ competing experiments) bounds:

Ahmed et al., arXiv:0912.3592



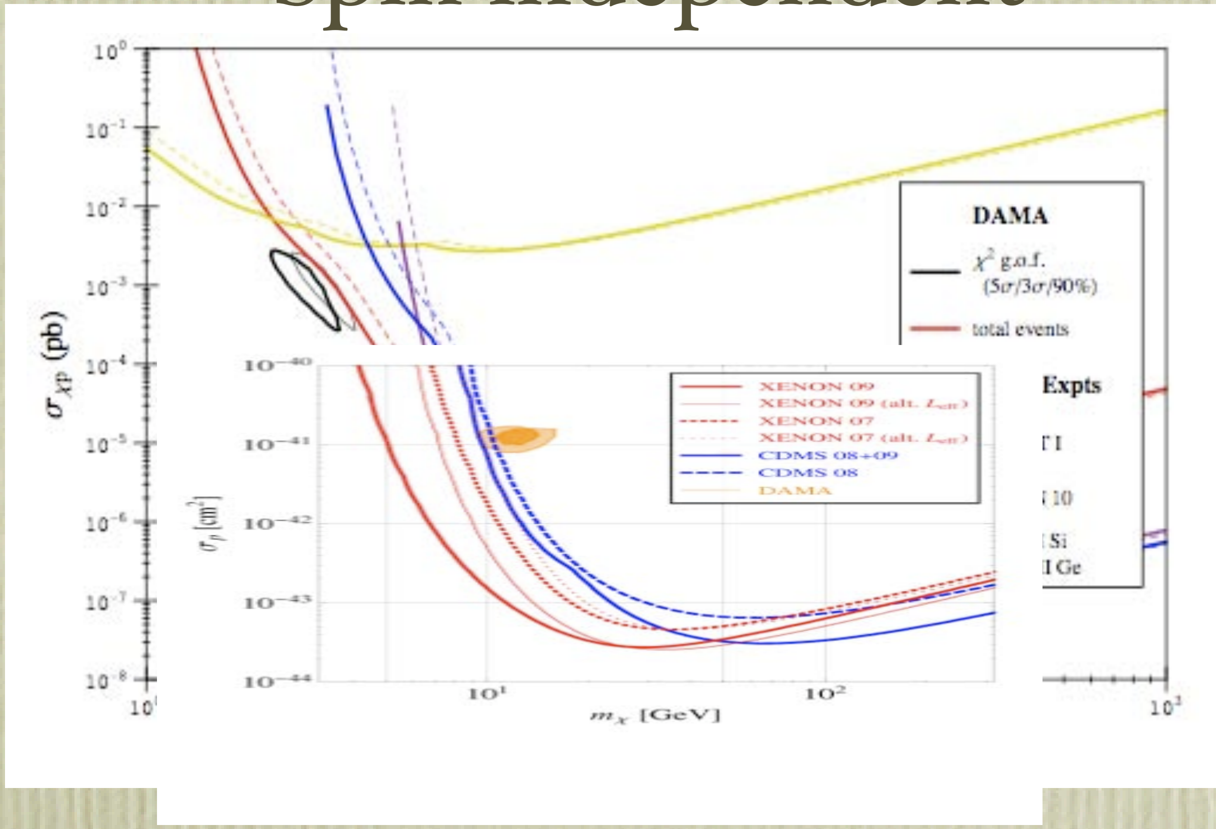
Several experiments have published upper limits, improving of a factor of (a) few every year; these are already setting relevant constraints on well-motivated particle physics models, such as SUSY DM within the MSSM

Final goal: ton-scale detectors increasing the present sensitivities of a factor of 100 (1000???)

Explain DAMA within the WIMP framework:

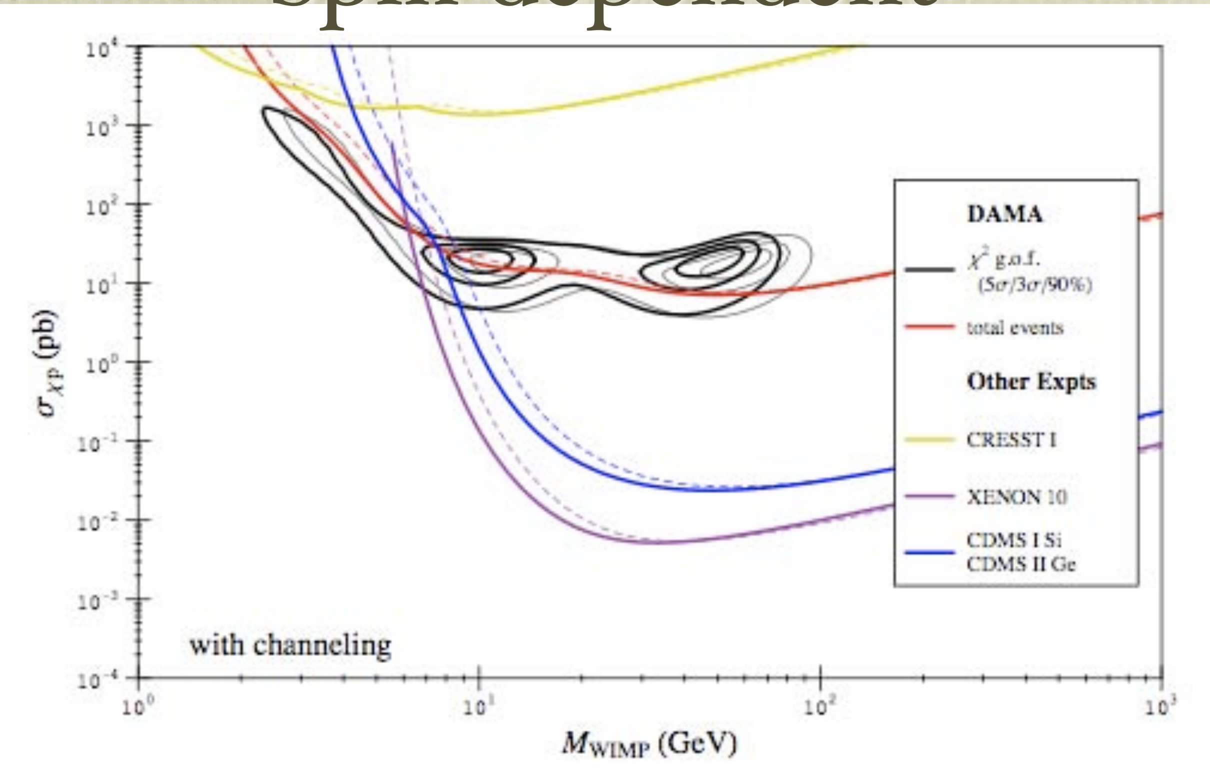
Several analyses on the WIMP elastic scattering interpretation in the latest years, comparing DAMA against other experiments (not totally trivial since DAMA is the only NaI detector, competitors run with Ge, Si, Xe, Ar, ...). Lately the discussion has been on ion channeling or not channeling, and different circular velocities for the Sun.

Spin independent



Kopp et al., arXiv:0912.4262

Spin dependent

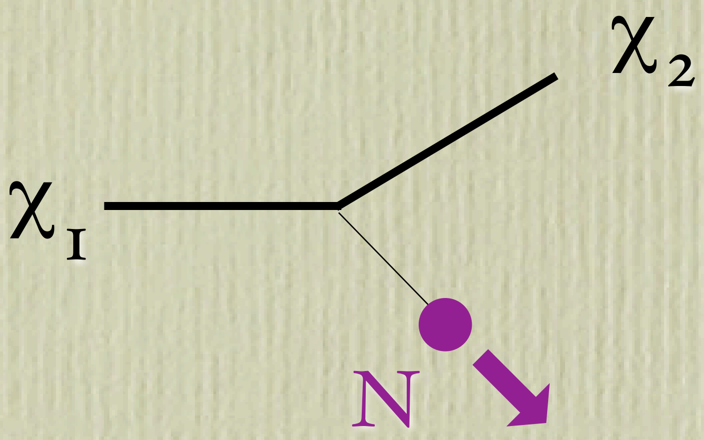


Savage et al., arXiv:0901.2713

There is (very little) room for a solution in case of light WIMPs (masses between, say, 2 and 10 GeV)

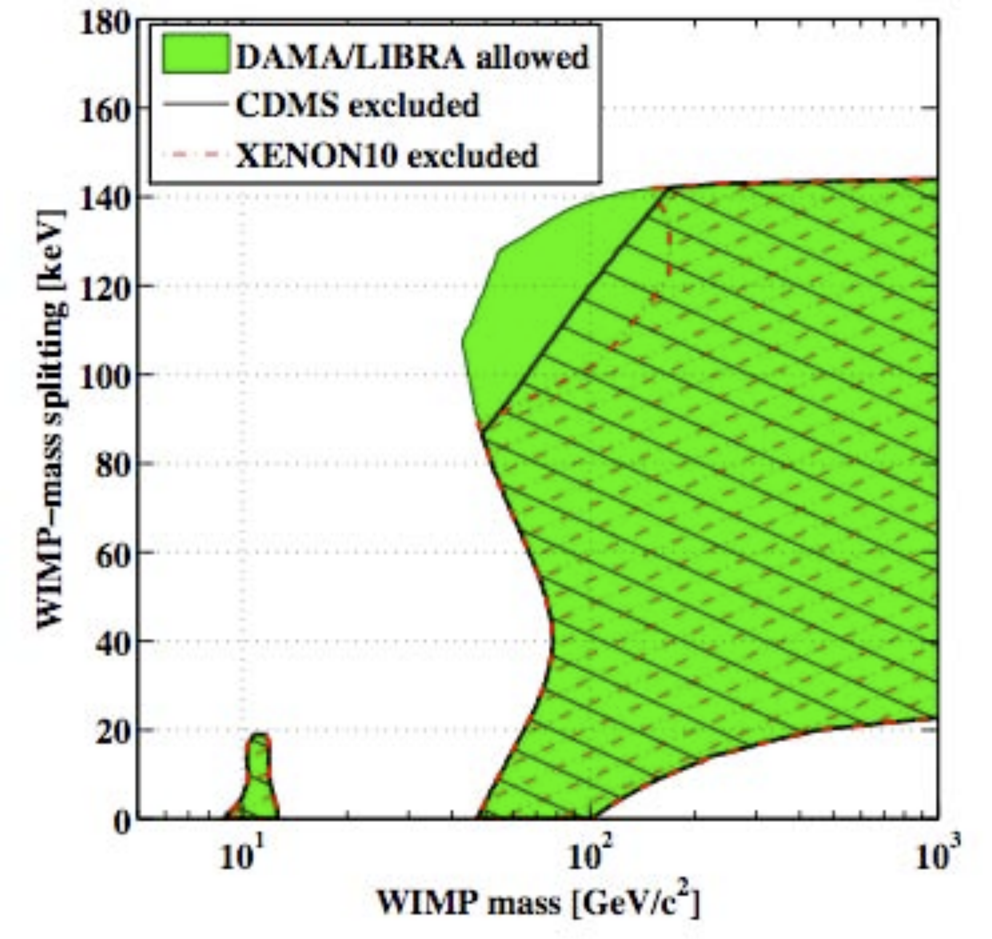
... or explain DAMA out of the WIMP framework:

The most popular scenario advocate **Inelastic Dark Matter** (**Smith & Weiner, 2001**), assuming the existence of two (or more) dark states with mass splittings of the order of 100 keV and imposing only inelastic scattering:



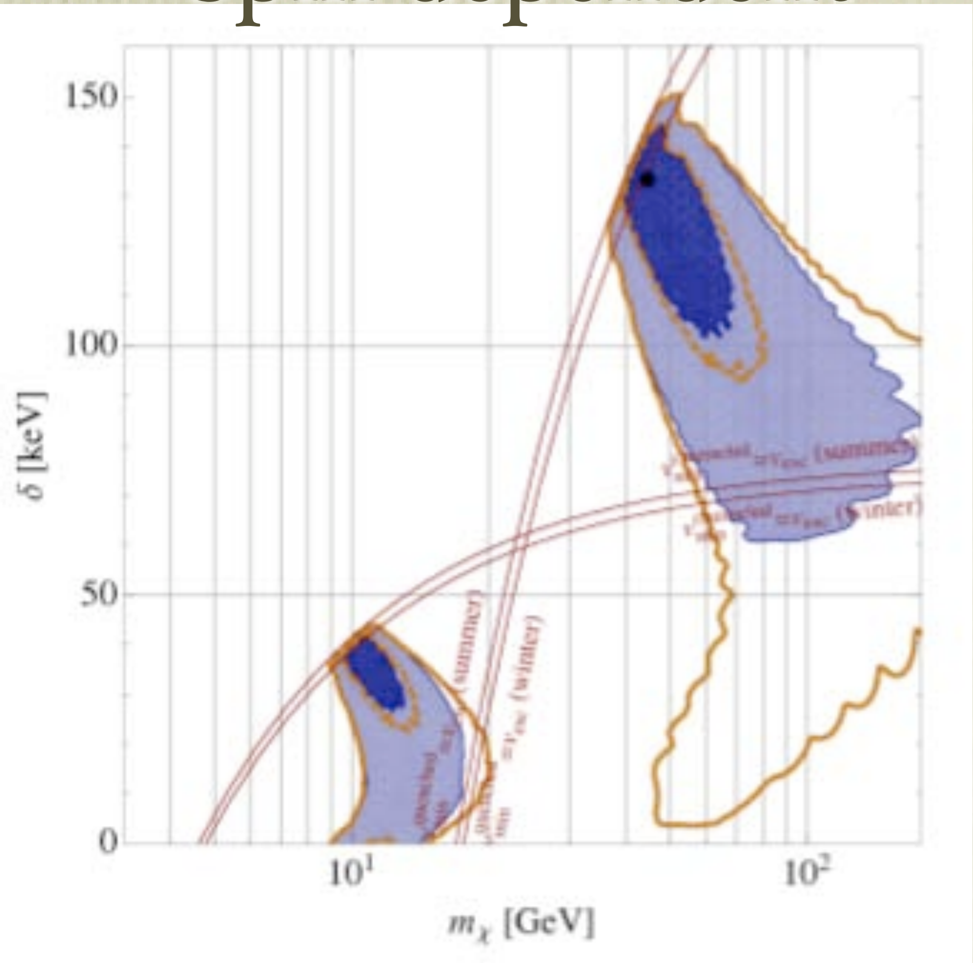
with the minimum velocity for the incoming particle depending on the target nucleus N:

Spin independent



Ahmed et al., arXiv:0912.3592

Spin dependent



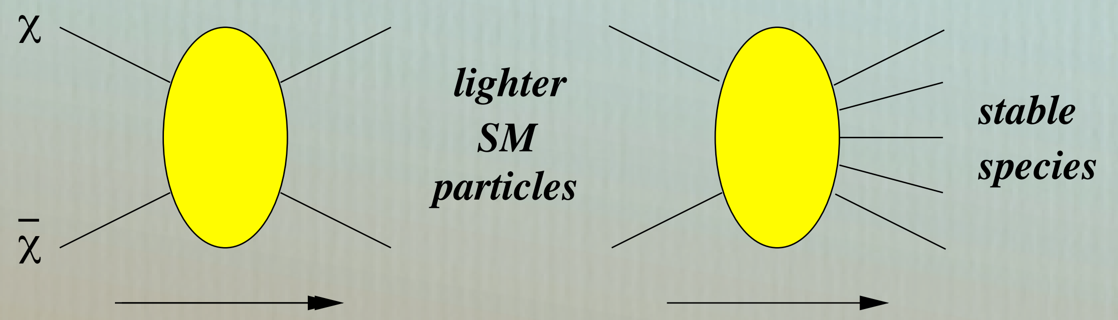
Kopp et al., arXiv:0912.4262

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)

$$(\sigma v)_{T\simeq 0} \sim \langle \sigma v \rangle_{T=T_f}$$



lighter SM particles

stable species

annihilation into, e.g., a 2-body final state

fragmentation and/or decay process

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

Signatures:

I) in energy spectra: One single energy scale in the game, the WIMP mass, rather then sources with a given spectral index; edge-line effects?

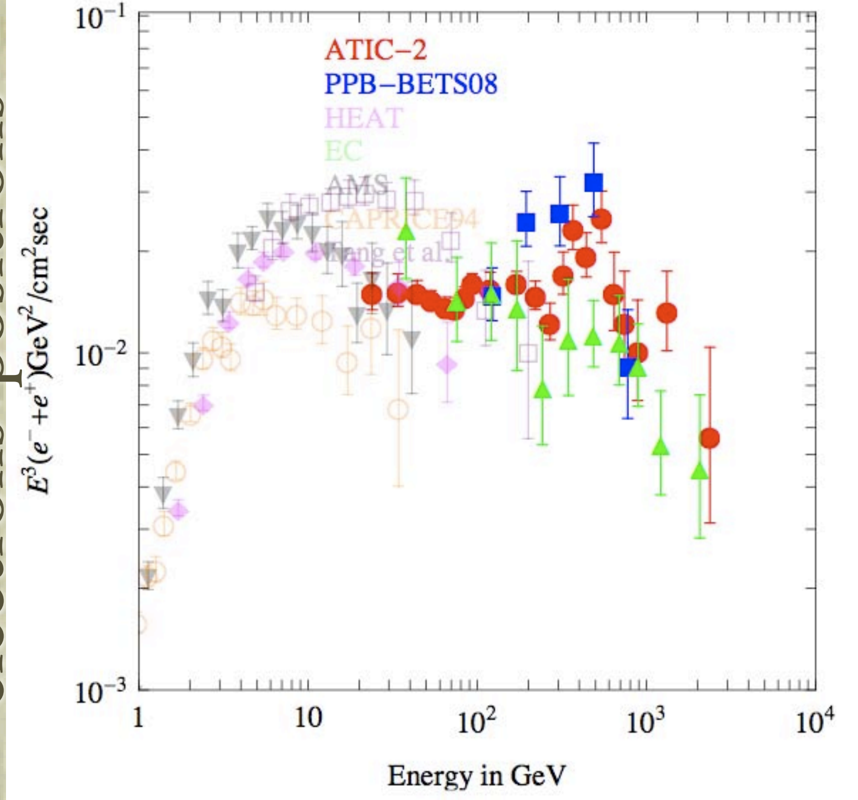
II) angular: flux correlated to DM halo shapes and with DM distributions within halos: central slopes, rich substructure pattern.

A fit of a featureless excess may set a guideline, but will be inconclusive.

The focus on electrons and positrons because of recent experimental results:

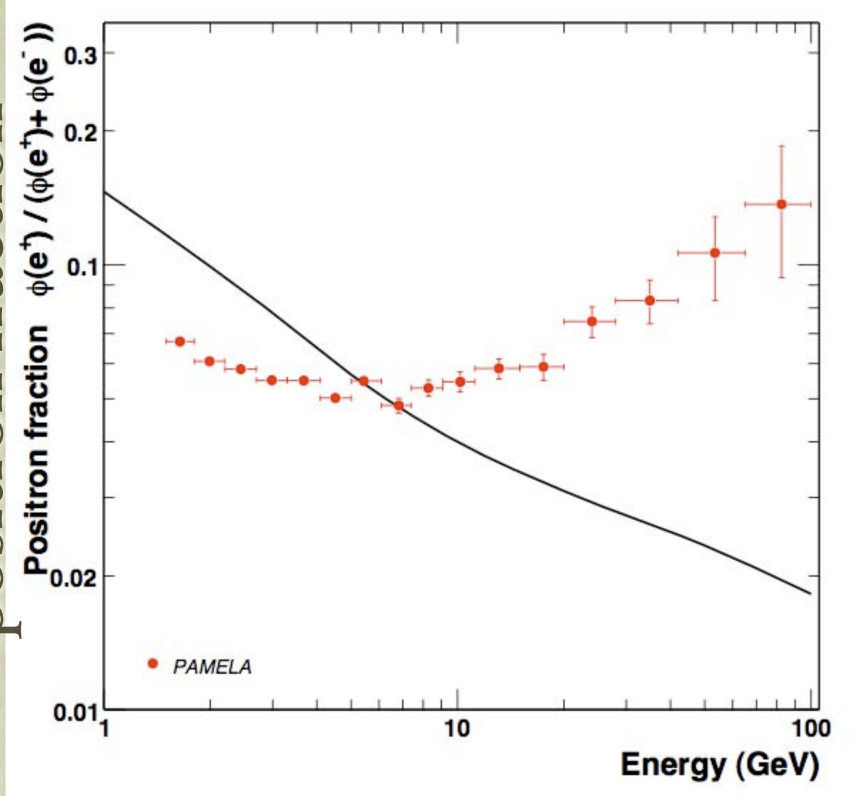
2008-09: ATIC + PPB-BETS

electrons+positrons



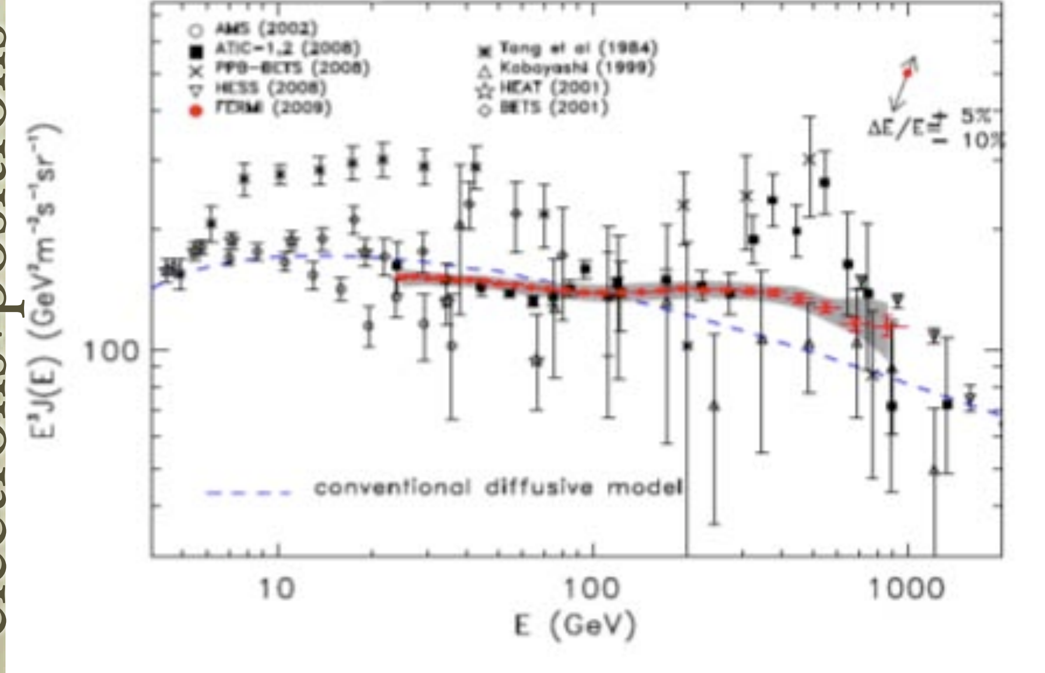
2008: PAMELA

positron fraction



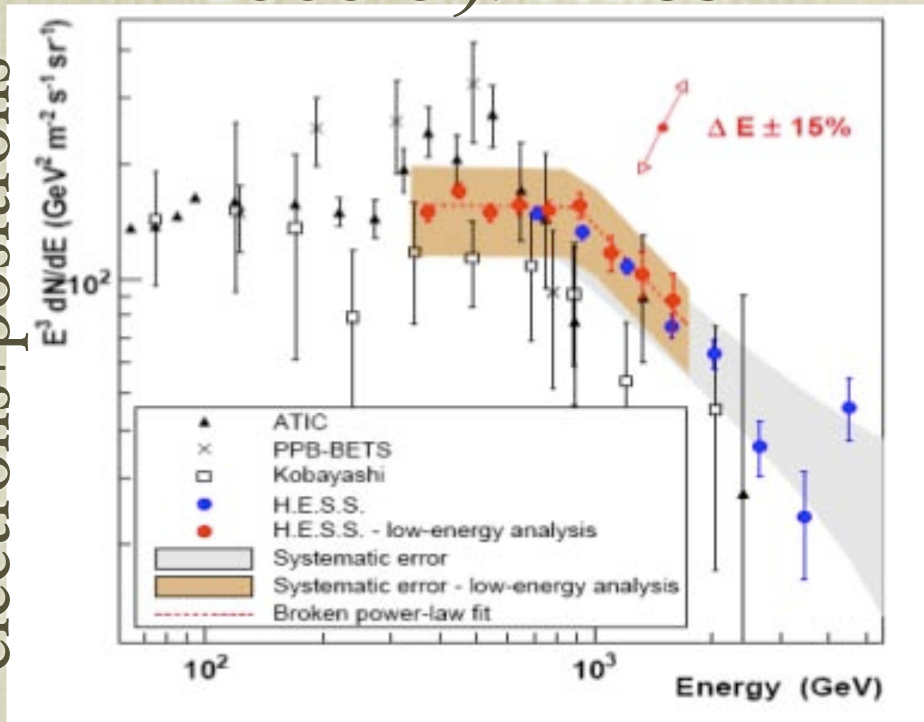
2009: Fermi GRT

electrons+positrons



2008-09: HESS

electrons+positrons



Electrons/positrons and the standard CR lore:

"Primary" CRs from SNe, "secondary" CRs generated in the interaction of primary species with the interstellar medium in "spallation" processes. Example: secondary Boron from the primary Carbon. Experimental data used to tune cosmic propagation parameters such as the spatial diffusion coefficient: $D_{xx}(p) \propto p^{\alpha}$

Looking at the ratio between the (secondary only) positron flux to the (mostly primary) electron flux, you expects it to scale like:

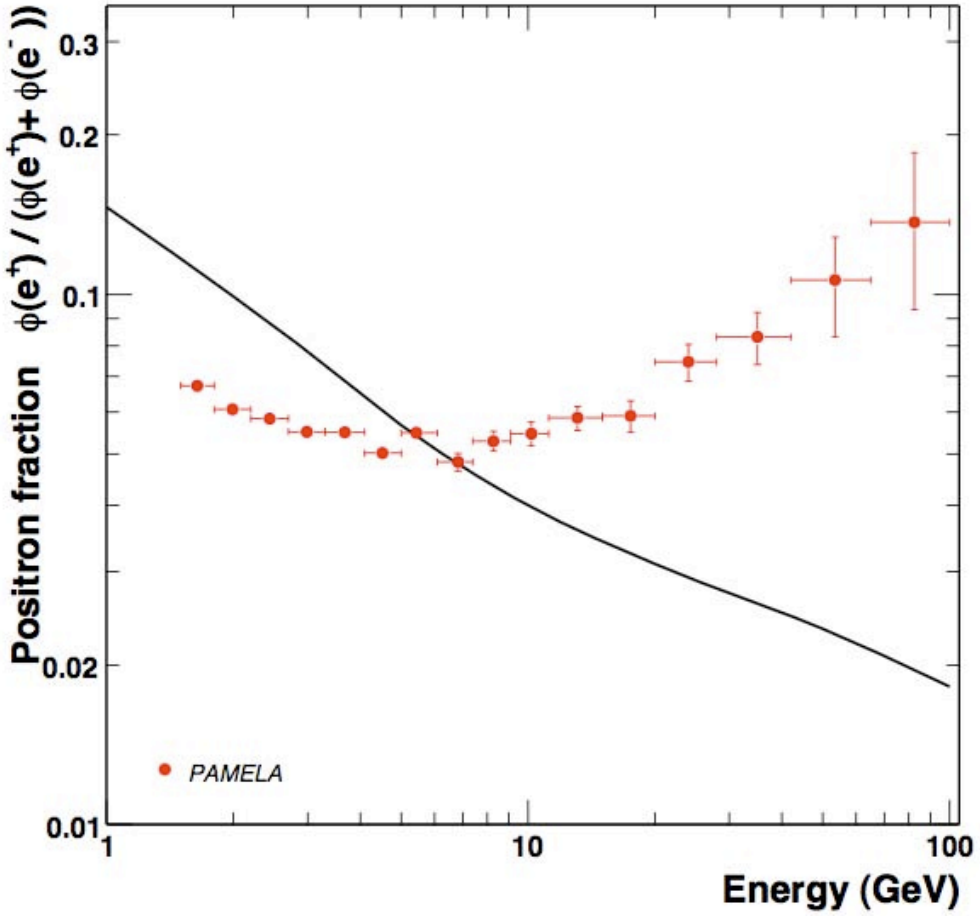
$$\frac{\phi_{e^+}}{\phi_{e^-}} \propto p^{-(\beta_{inj,p}-\beta_{inj,e}+\alpha)}$$

i.e. decreasing with energy since it would be hard to find a scheme in which:

$$\beta_{inj,p} - \beta_{inj,e} + \alpha$$

is negative.

PAMELA measured a rising positron fraction



Adriani et al., arXiv:0810.4995

How to explain a rising positron fraction?

- The propagation model is 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.

Primary electrons/positrons from DM WIMPs:

The relevant process is the pair annihilations of non-relativistic WIMPs in the DM halo, proceeding mostly through two-body final states:

$$\chi\bar{\chi} \to f\bar{f}$$

(the energy of f is equal to the WIMP mass) corresponding to the source function:

$$Q_i(r,E) = \langle\sigma v\rangle_0 \sum_f \boxed{\frac{dN_i^f}{dE}(E)}\, B_f\, \boxed{\mathcal{N}_{\rm pairs}(r)}$$

total rate

branching ratio into f

density of WIMP pairs

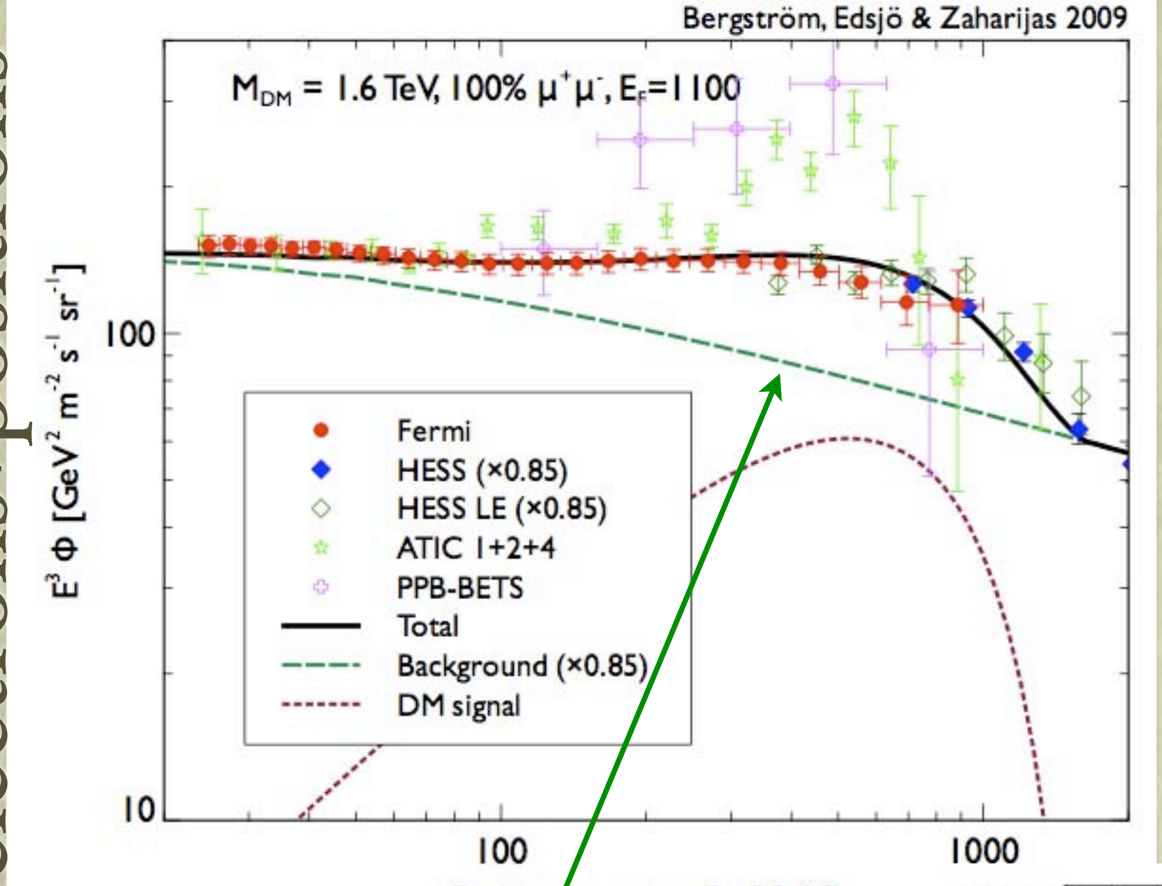
e^+/ e^- energy spectra of two kinds:

Soft spectra from, e.g., quark final states which produce charged pions decaying into leptons;

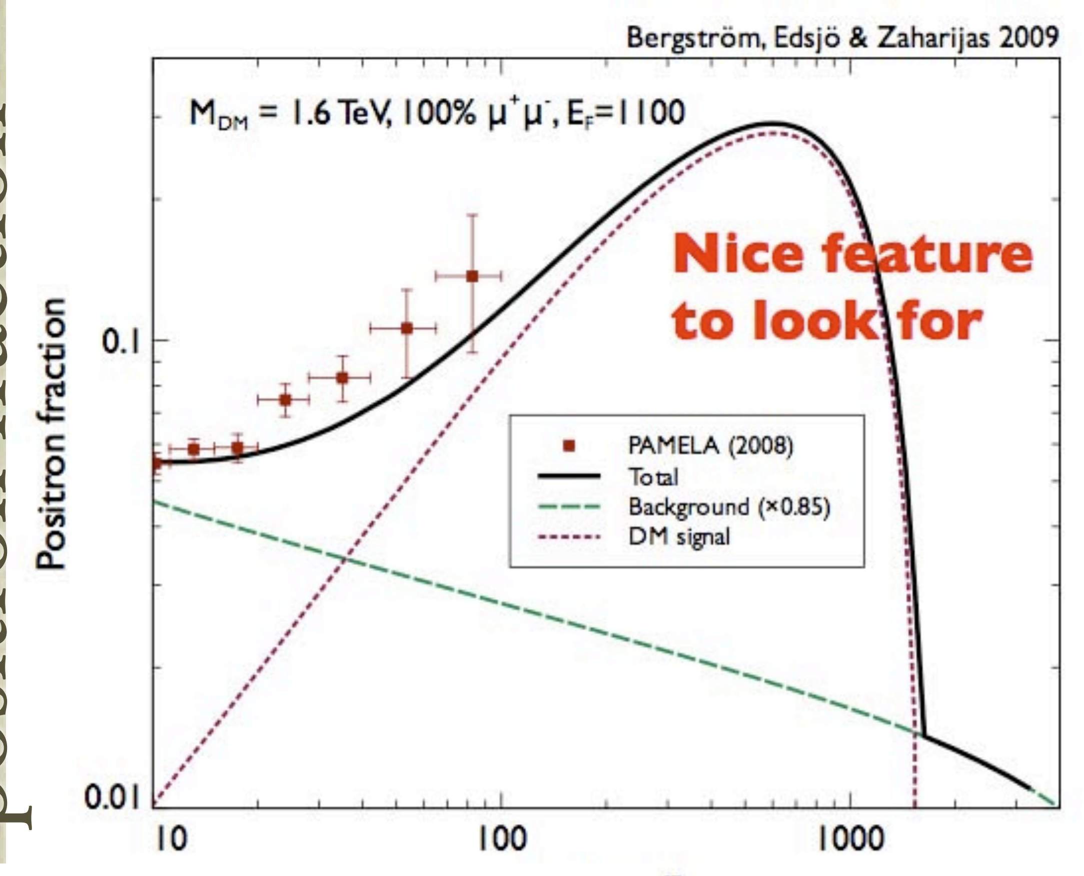
Hard spectra from, e.g., lepton or gauge boson final states, in which electrons and positrons are produced promptly or in a short decay chain.

Blind fit of Pamela/Fermi with a generic WIMP model (defined by WIMP mass and dominant annihilation channel), taking into account limits, e.g., from antiproton data:

electrons+positrons

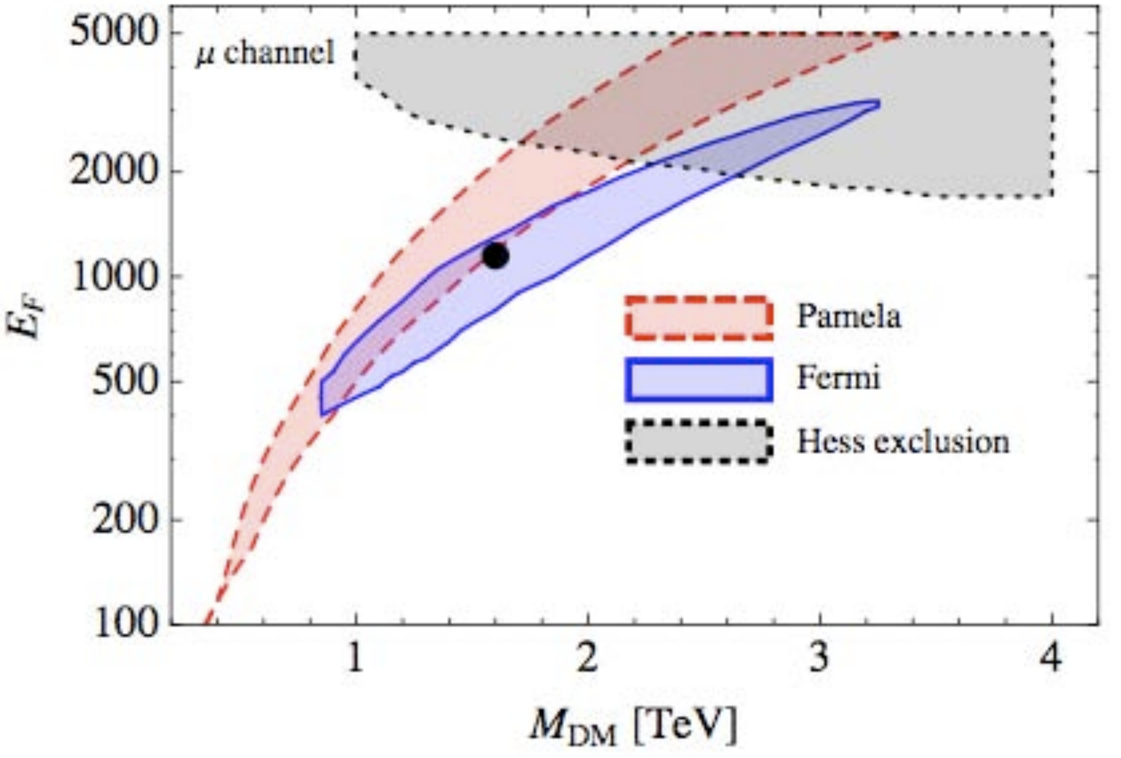


positron fraction



Nice feature to look for

Bergström et al., arXiv:0905.0333



background ?!?

This “solution”:

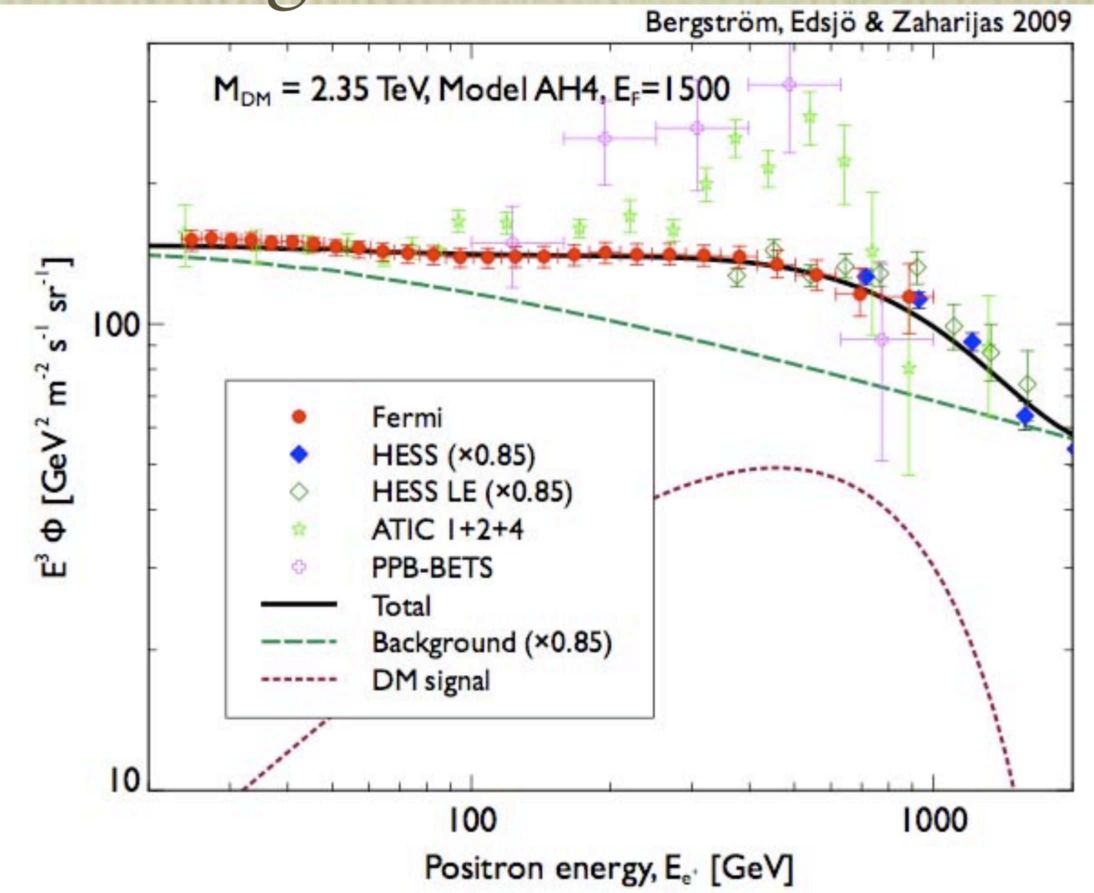
annihilation into muons, heavy WIMPs, large “enhancement factors”

Slightly different results among the numerous fits to the recent data, but convergence on models which are very different from “conventional” WIMP models (e.g. neutralinos in the MSSM). DM seems to be:

- **heavy**, with WIMP masses above the 1 TeV scale;
- **leptophilic**, i.e. with pair annihilations with hard spectrum and into leptons only, or into light (pseudo)scalars which for kinematical reasons can decay into leptons only (there is very little room to accommodate a hadronic component which would manifest in the antiproton data - this point has been disputed by, e.g., Grajek et al., arXiv:0812.4555);
- with a **large** (order 1000 or more) **“enhancement factor”** in the source function, either: i) in the annihilation rate because $\langle \sigma v \rangle_{T_0} \gg \langle \sigma v \rangle_{T_{f.o.}}$ (non-thermal DM or decaying DM? Sommerfeld effect? a resonance effect?, or: ii) in the WIMP pair density because $\langle \rho_\chi^2 \rangle \gg \langle \rho_\chi \rangle^2$.

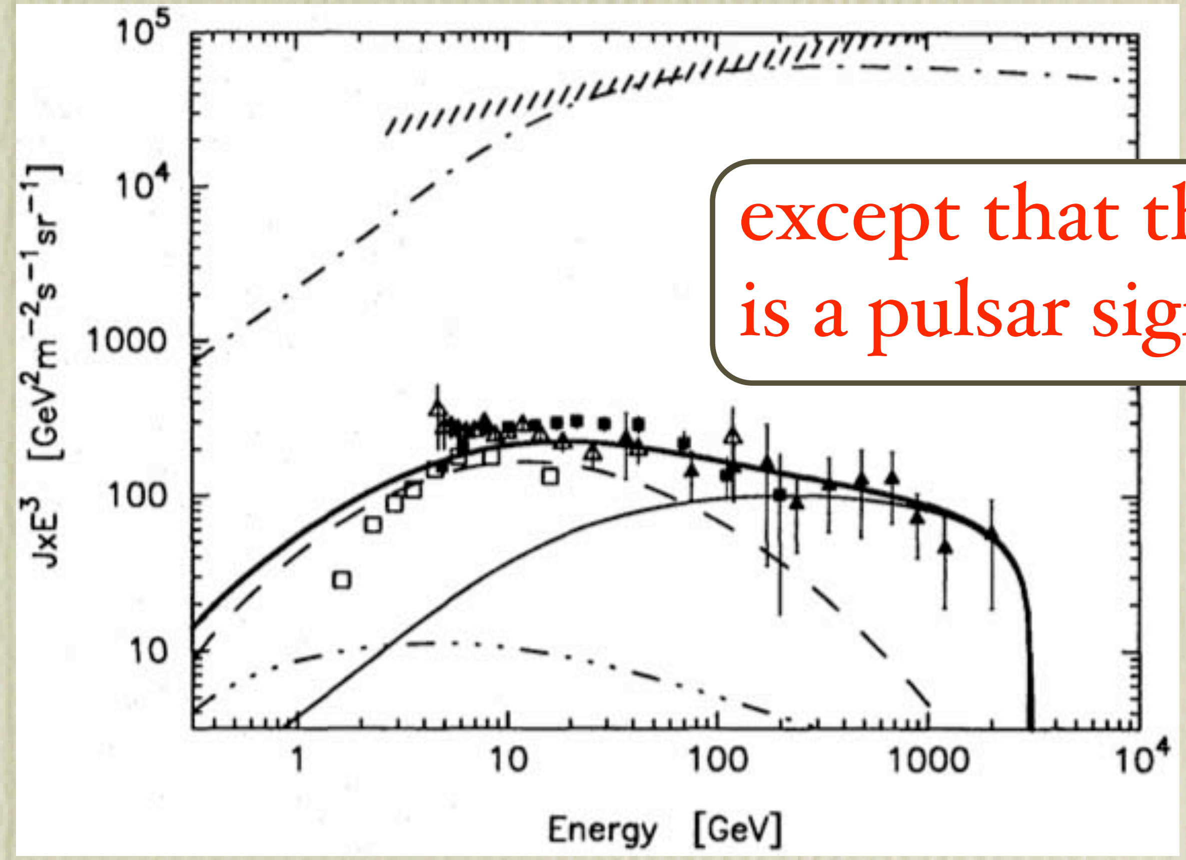
Caveat: we may have seen a DM signal, but have not seen a DM signature.

The sample fit of the data with a DM signal:


Bergström, Edsjö & Zaharijas 2009

Bergström et al. on model by **Arkani-Hamed et al.**

is analogous to the signal foreseen in models of more than a decade ago:



except that this is a pulsar signal

Aharonian et al., 1995

Cleaner spectral features in upcoming higher statistics measurements (???). Pay attention to cross correlations with other DM detection channels.

E.g.: a DM point source accounting for the PAMELA excess would be detected by the Fermi GST looking at the associated γ-ray flux

DM annihilations and gamma-ray fluxes:

The source function has exactly the same form as for positrons:

$$Q_i(r,E) = \langle\sigma v\rangle_0 \sum_f \boxed{\frac{dN_i^f}{dE}(E)} B_f \boxed{\mathcal{N}_{\text{pairs}}(r)}$$

total rate

branching ratio into f

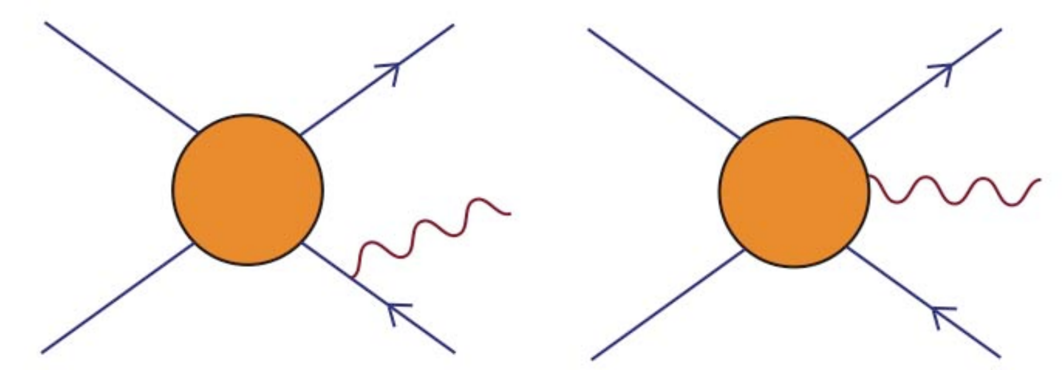
\# density of WIMP pairs

Prompt emission of γ-rays associated to three components:

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

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

III) Final state radiation (internal Bremsstralungh)

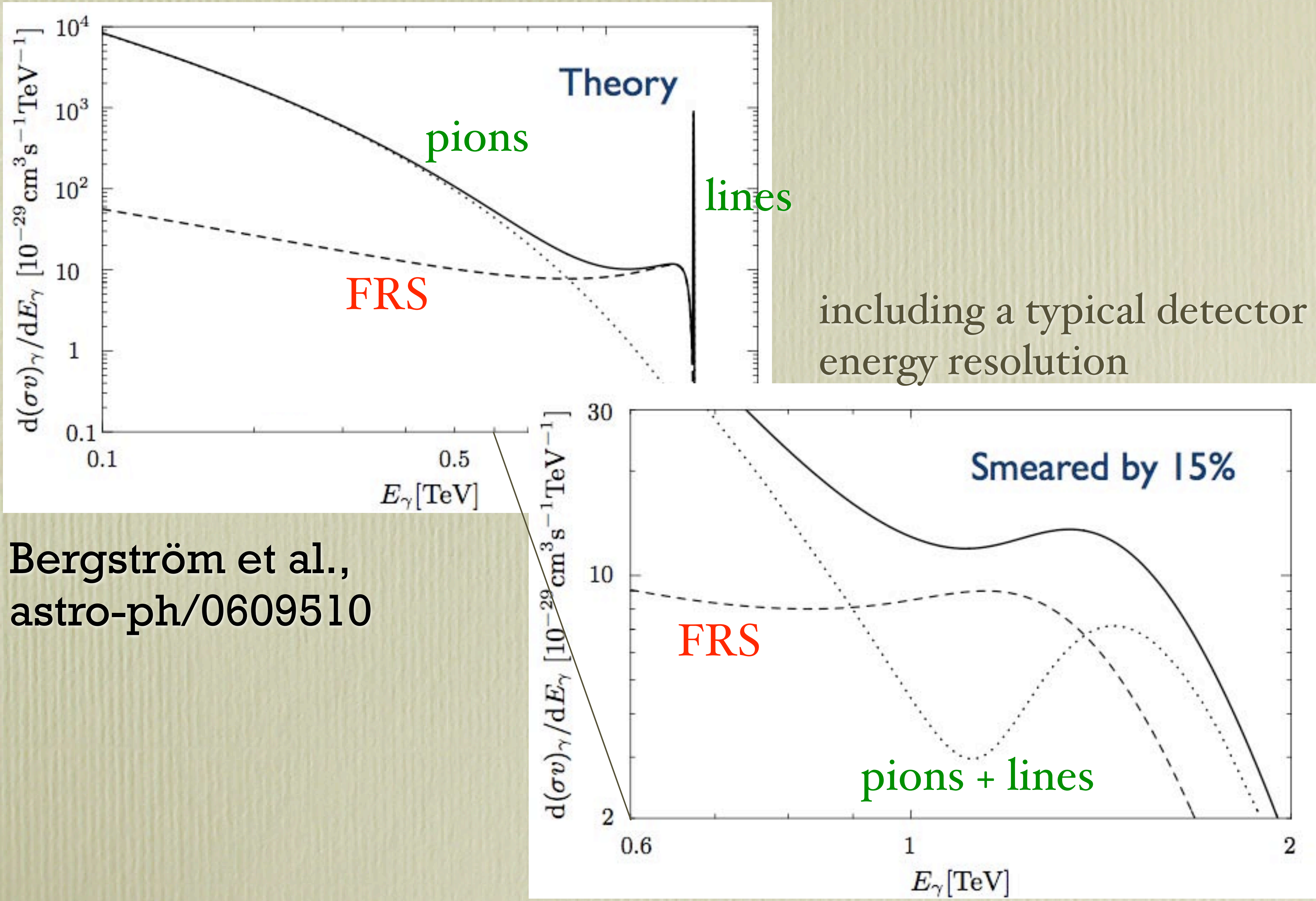


especially relevant for:

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

in case of Majorana fermions

Then for a model for which all three are relevant (e.g. pure Higgsino)The source function has exactly the same form as for positrons:



including a typical detector energy resolution

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

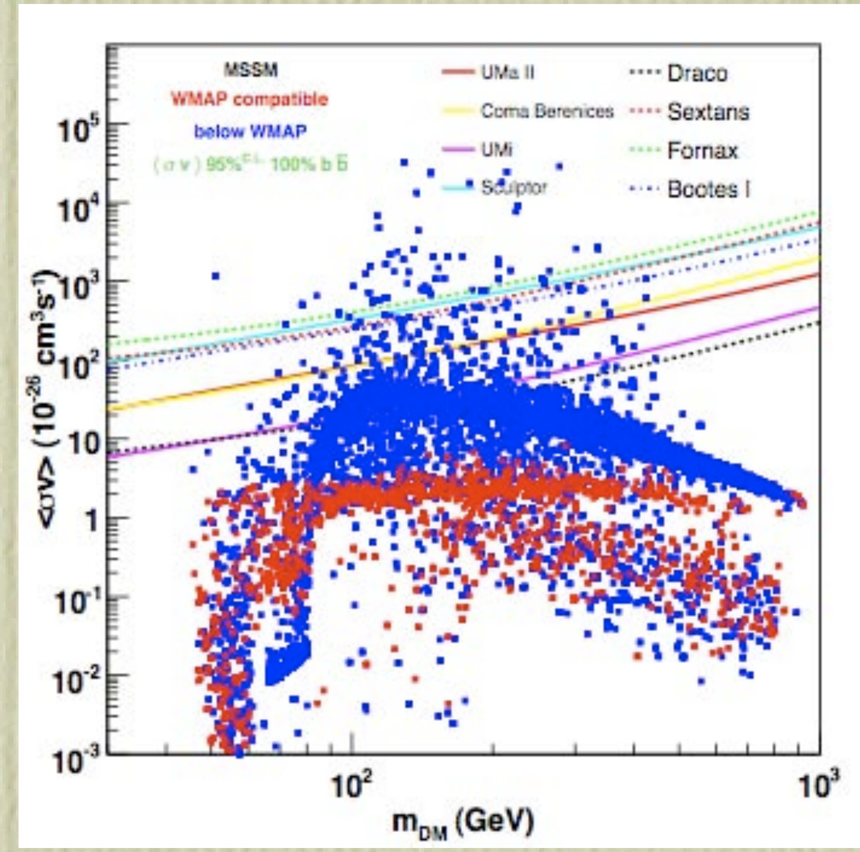
Targets which have been proposed:

- 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 suitable for the Fermi GRT. A number of "excesses" claimed in recent years; Fermi will allow for much firmer on them. Unfortunately only upper limits have been reported as first results.

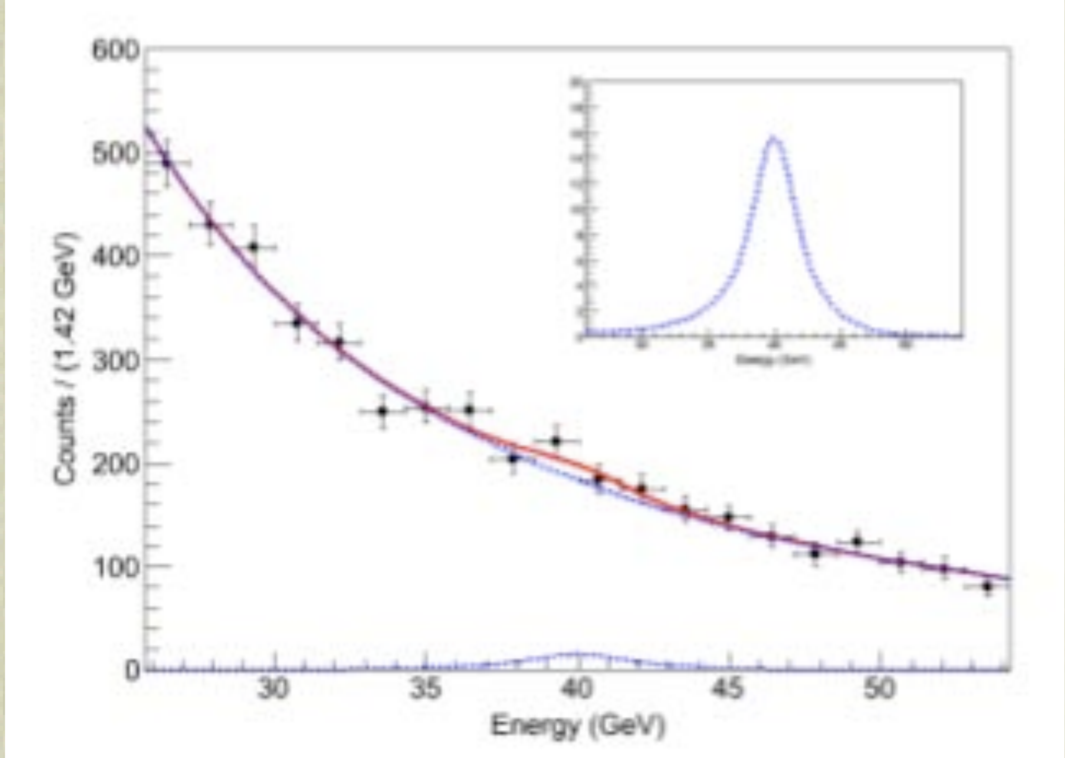
The first upper limits on DM gamma-ray fluxes from Fermi:

dwarf satellites



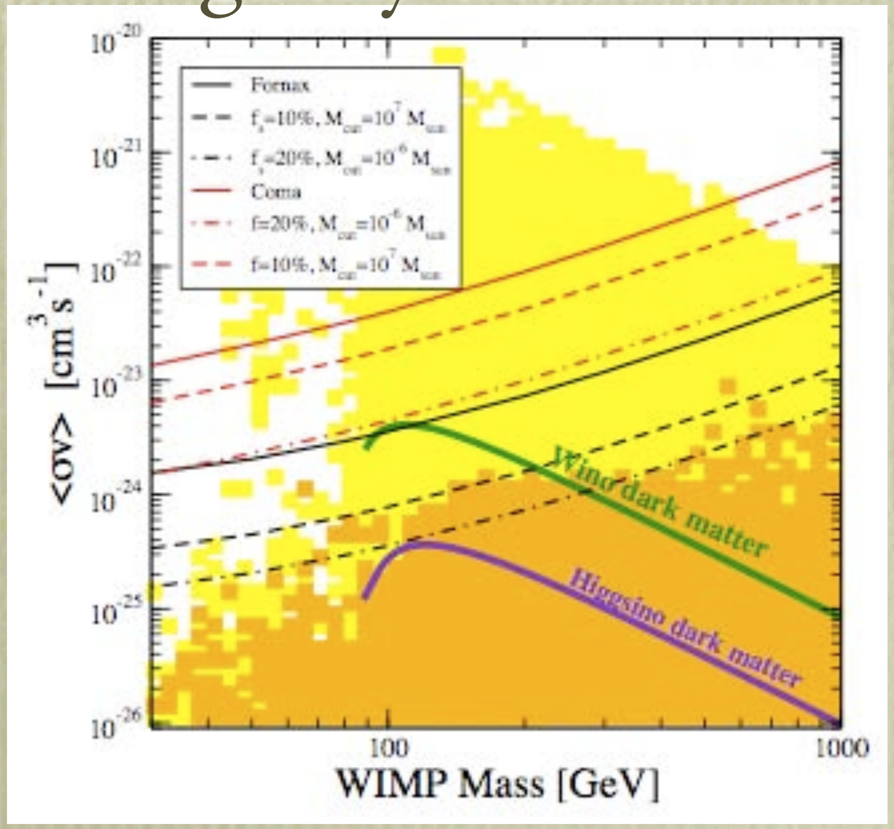
arXiv: 1001.4531

gamma-ray lines



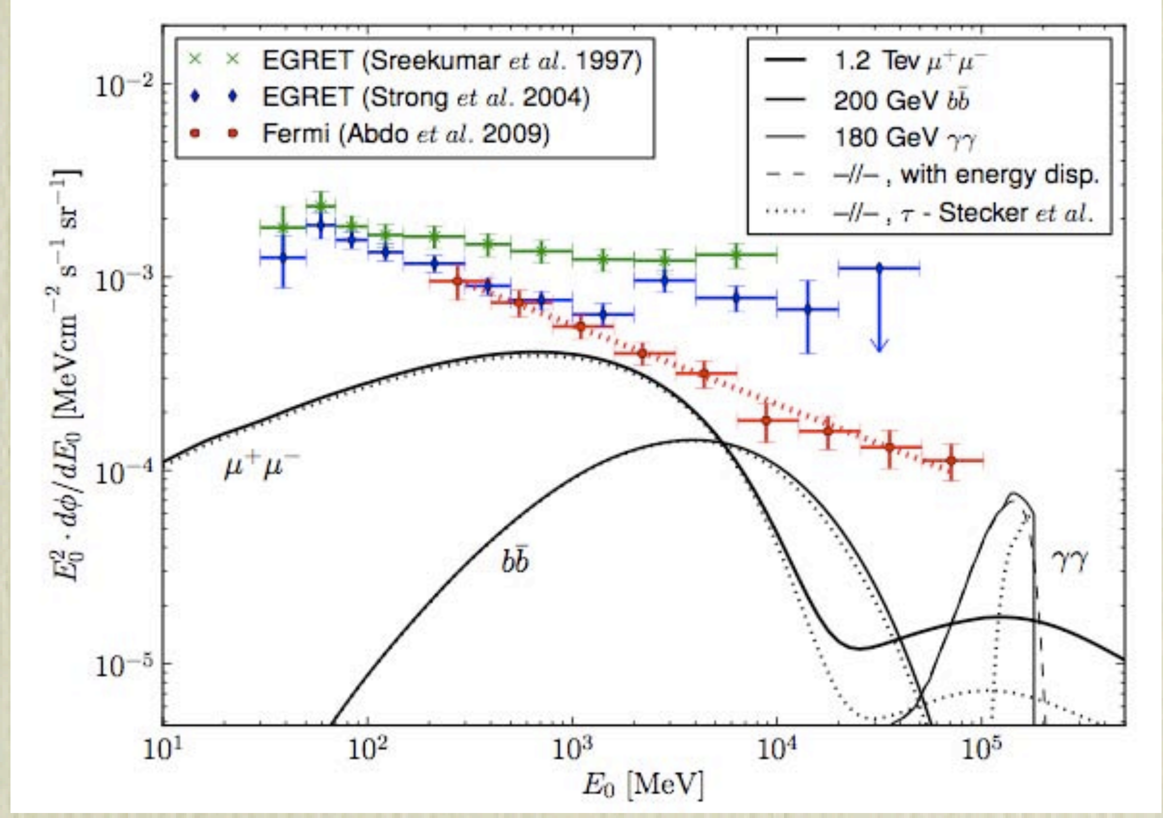
arXiv: 1001.4836

galaxy clusters



arXiv: 1002.2339

diffuse extragalactic



arXiv: 1002.4415

DM annihilations and radiative emission:

The annihilation yields give rise to a multicomponent spectrum:

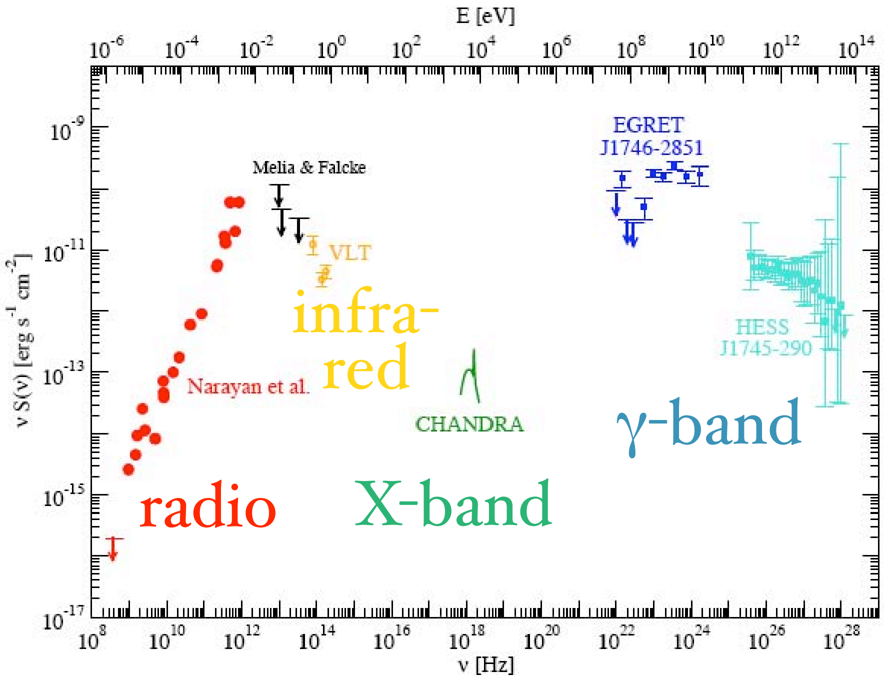
$$\chi\,\bar{\chi} \to \begin{cases} \boxed{e^+ e^-} \\ l^+ l^- \text{ or } \phi\,\phi \to \ldots + \boxed{e^+ e^-} \\ P\,\bar{P} \to \ldots + \pi^\pm \to \ldots + \boxed{e^\pm} \end{cases}$$

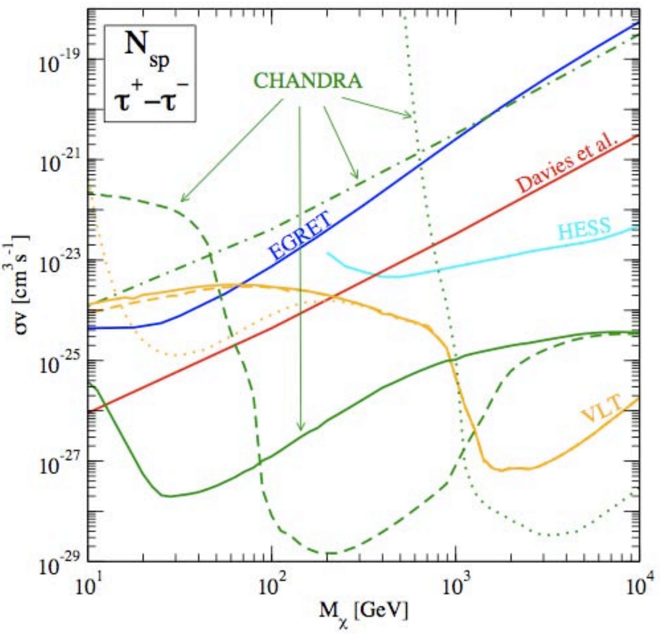
ambient backgrounds and fields

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

- radio
- IR
- X-rays
- γs

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)

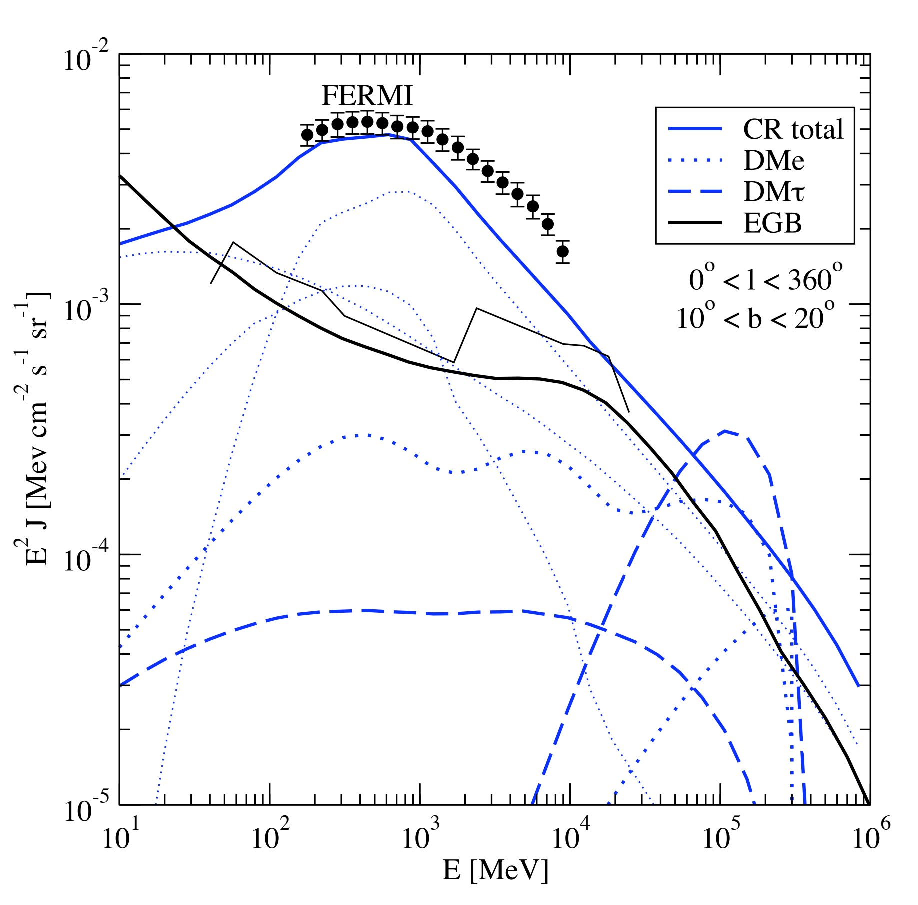
Regis & P.U., arXiv: 0802.0234

Multifrequency approach to test local e^+/e^- excesses:

An excess from standard astrophysical sources would be confined to the galactic disc, one from DM annihilation would be spread out to a much larger scale, leading to different predictions for the IC radiation.

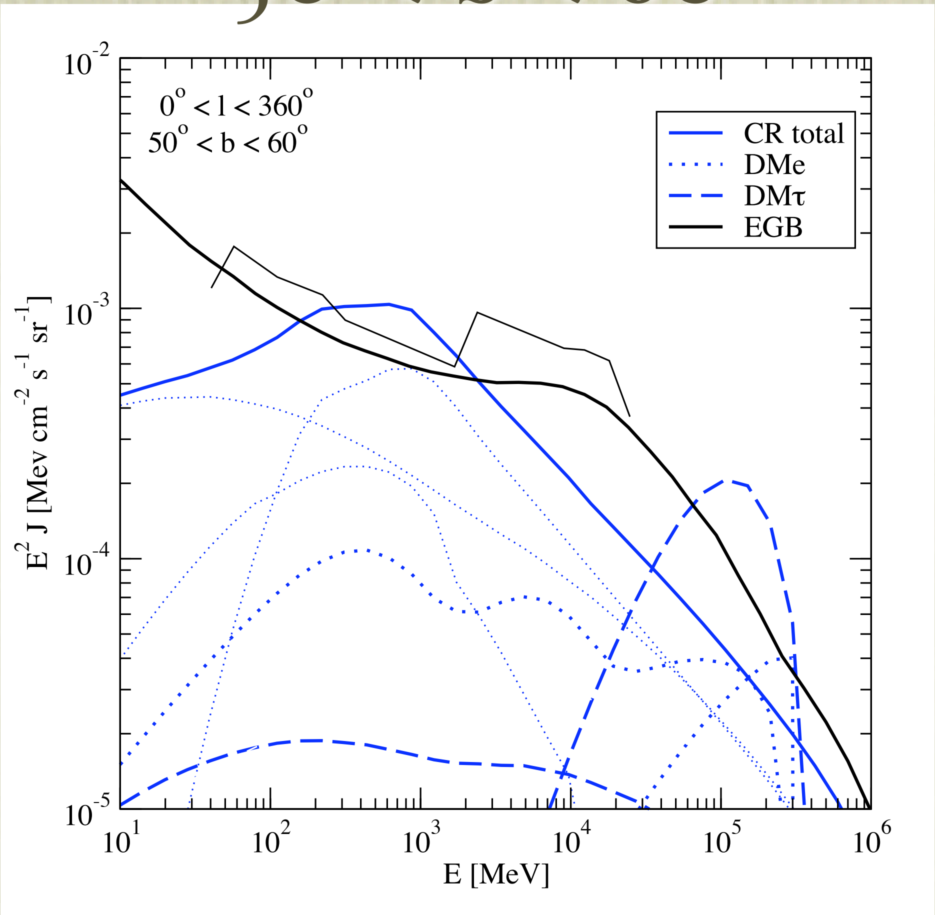
IC terms (plus FSR or pion terms) for two sample (leptophilic) models fitting the Pamela excess in the positron ratio:

10°< b < 20°



cross checked against Fermi preliminary data at intermediate latitudes

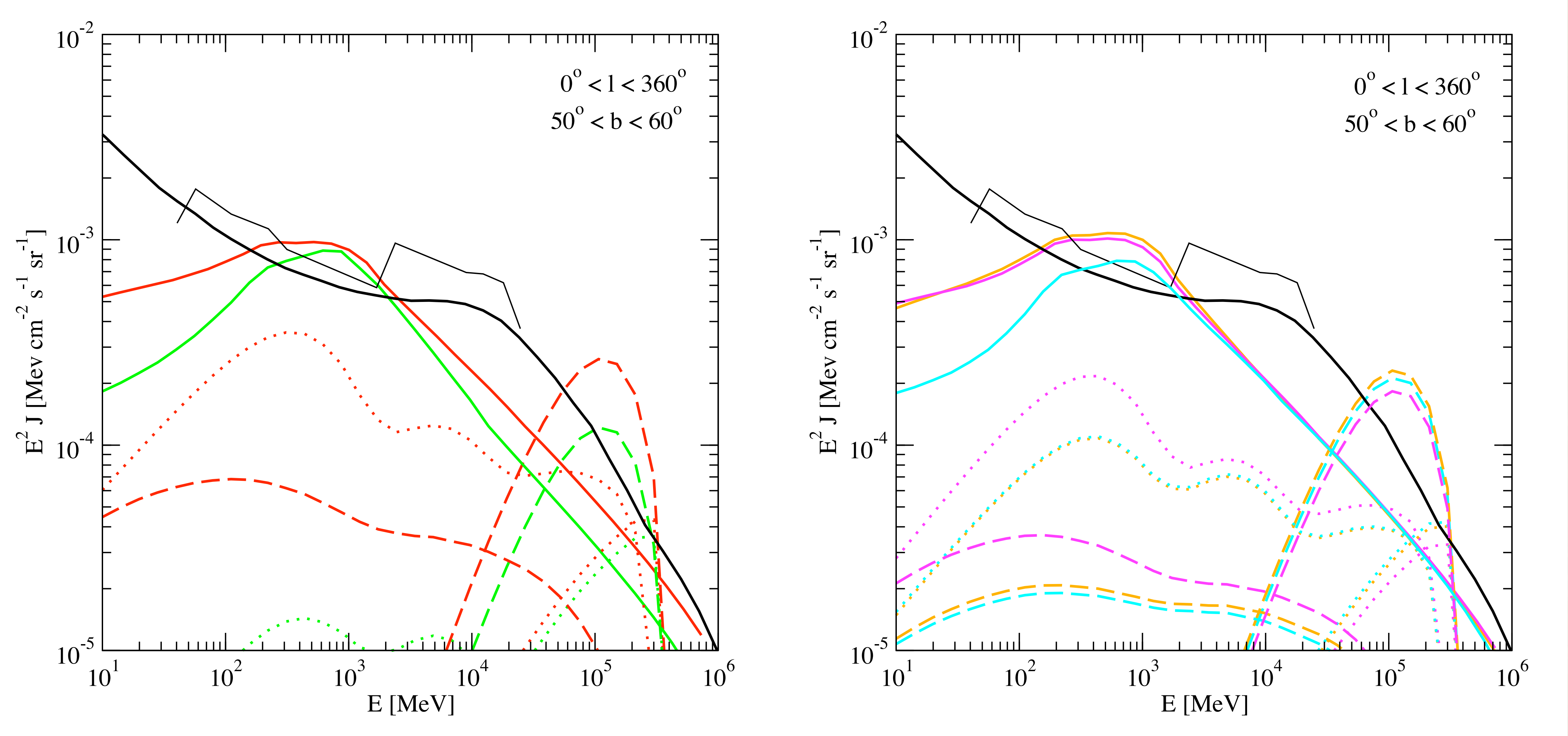
50°< b < 60°



a more solid prediction when looking at high latitudes ...

Regis & P.U., arXiv: 0904.4645

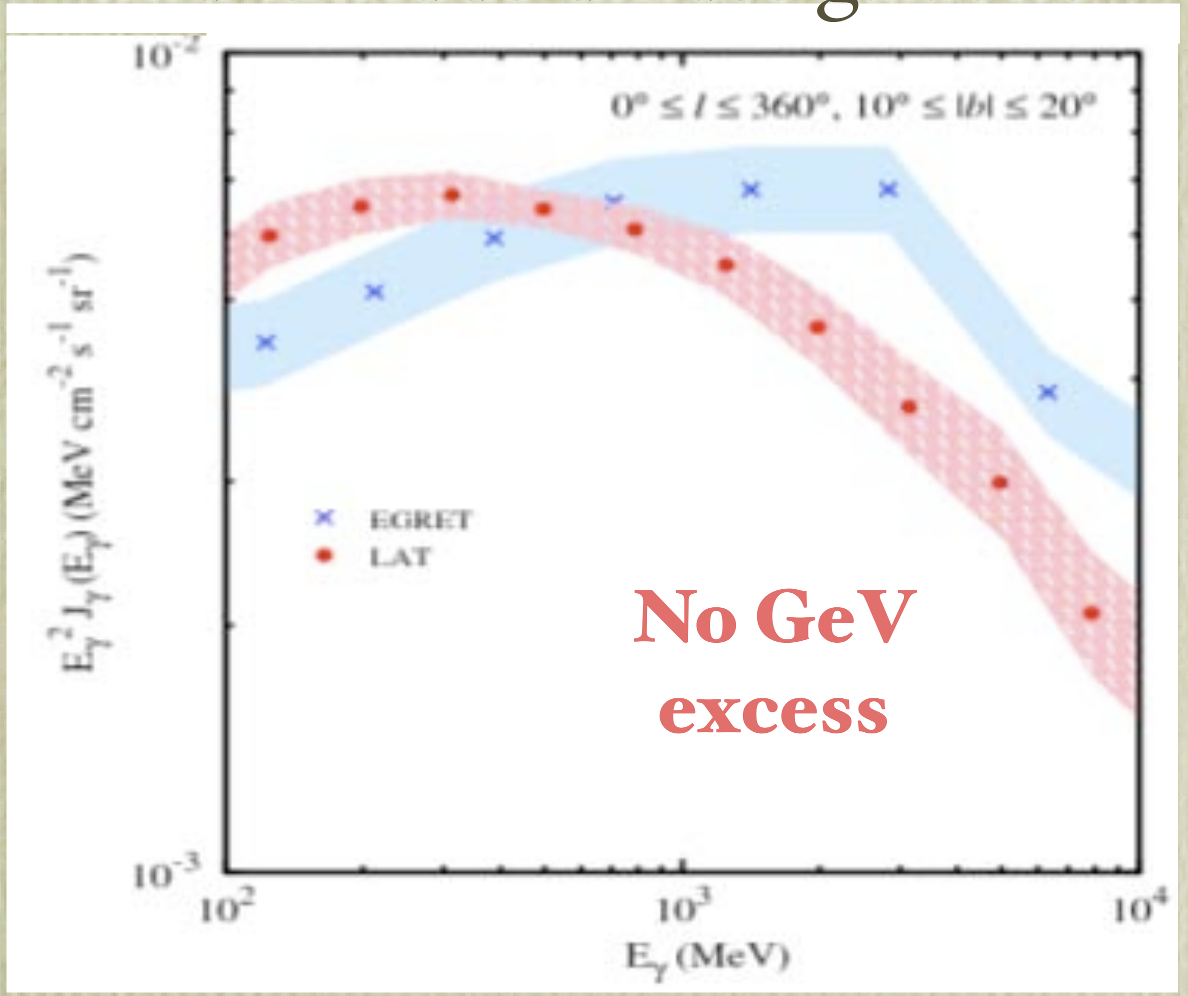
A result which is solid against uncertainties in the propagation model: the previous model extrapolated to a few sample setups consistent with B/C



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 annihilating or decaying DM (since it is normalized to the locally measured electron/positron flux)

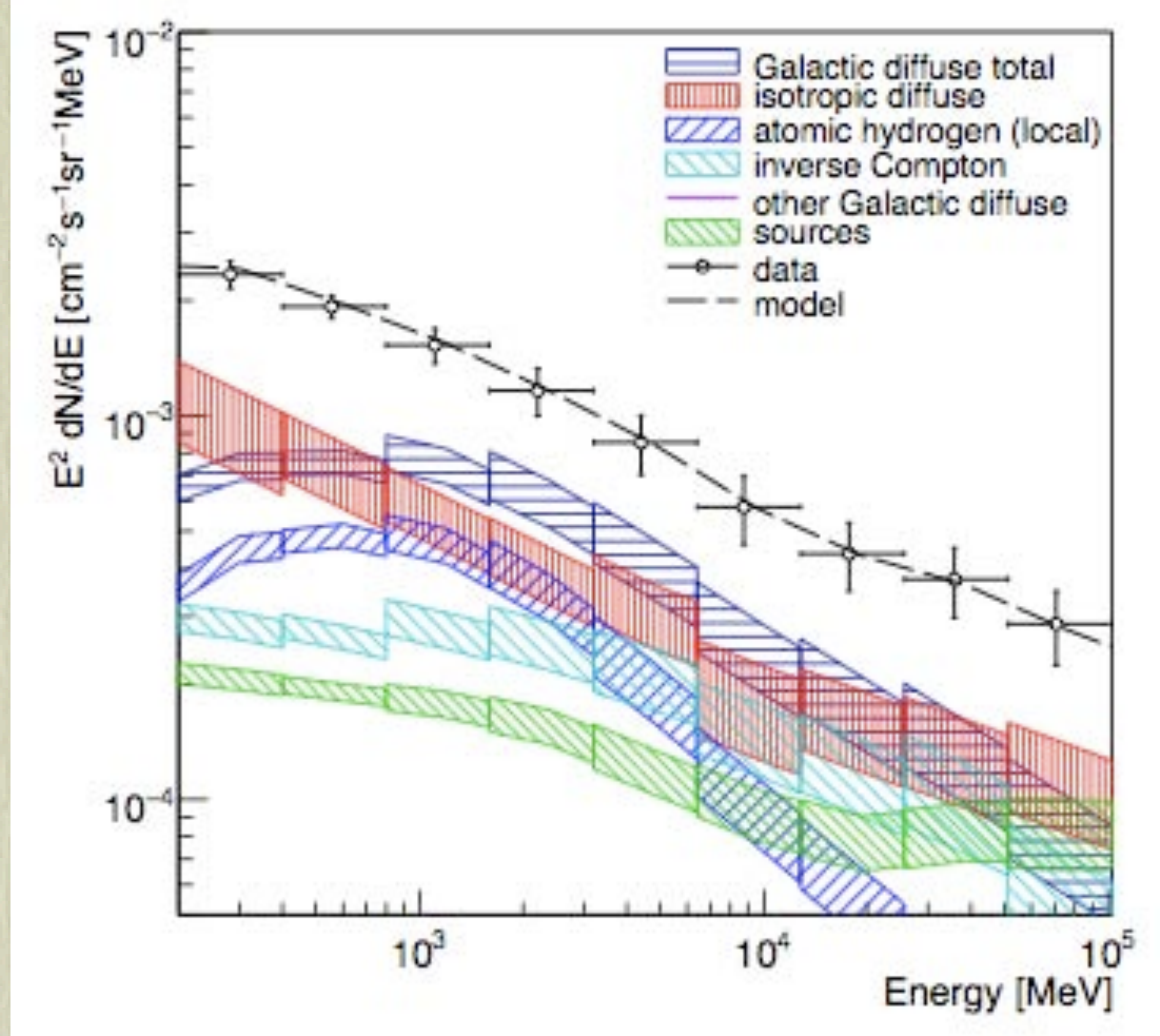
A result to be checked against data on the diffuse gamma-ray radiation at energies above 100 GeV which will soon be available. At present, Fermi has already excluded the EGRET GeV excess:

mid-latitude diffuse galactic



No GeV excess

diffuse, | b | > 60°



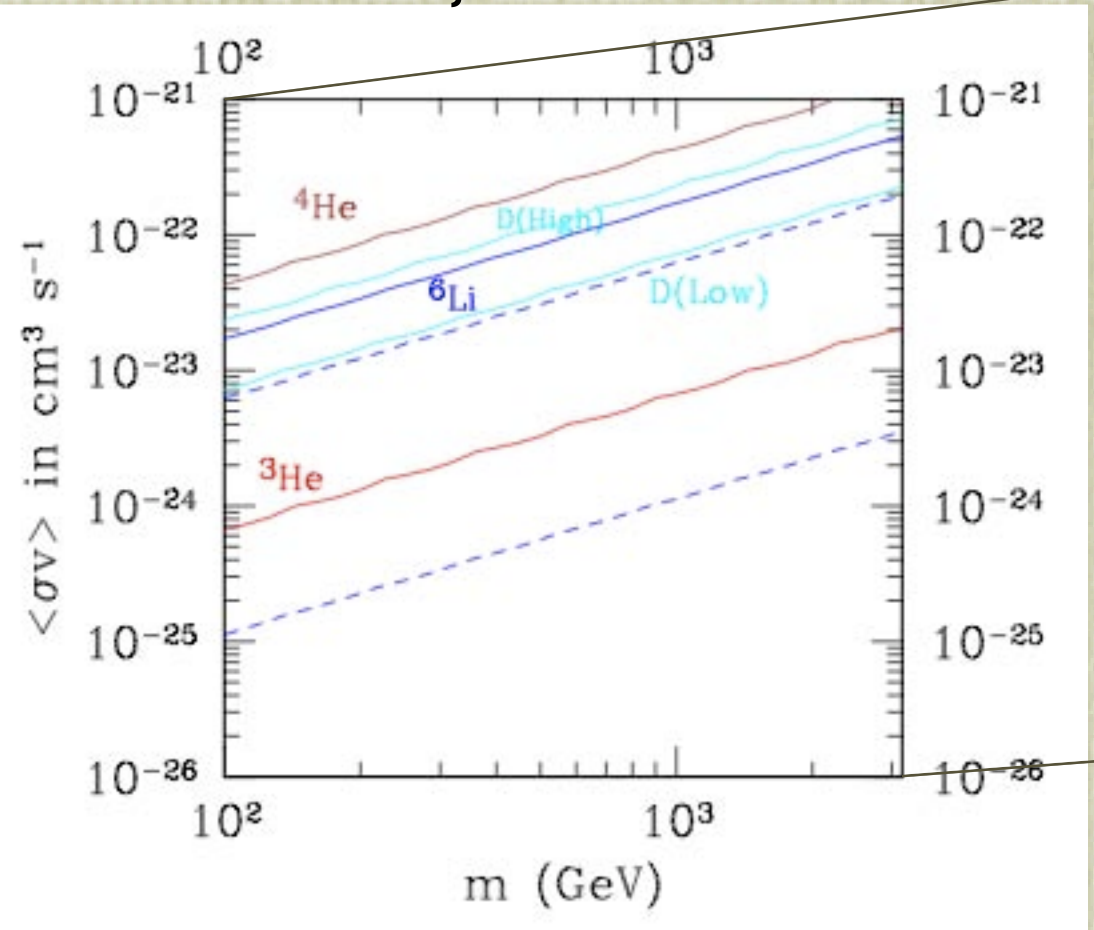
arXiv: 1002.3603

What about an excess in the central region of the Galaxy - the Fermi gamma-ray “haze”? What about connections to the WMAP haze?

DM annihilations at early stages of the Universe:

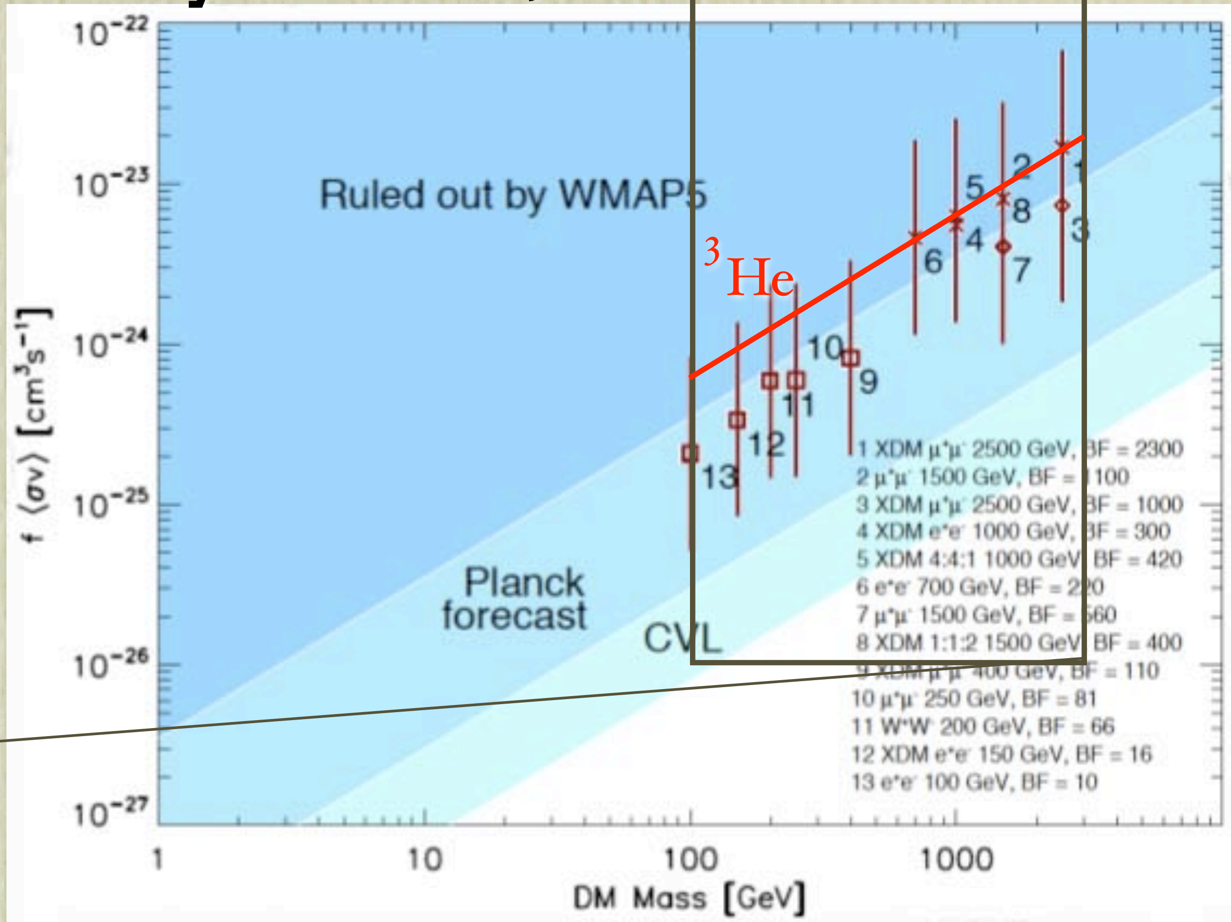
The very large annihilation cross sections has lead to several reanalyses of the limits from “polluting” the early Universe with DM yields. E.g.:

Hisano et al., arXiv: 0901.3582



BBN limits: mainly from photo- and hadro-dissociation of light elements, and changes in the neutron to proton ratio

Slatyer et al., arXiv: 0906.1197



CMB limits: mainly from ionization of the thermal bath, Ly-α excitation of Hydrogen and heating of the plasma

These limits do not depend on the poorly-known fine graining of the local DM halo; note also that the velocity is different ($v \approx 10^{-8}$ at the LSS)

Perspectives:

- Good discovery prospects at LHC
- Upcoming new results for direct detection experiments - what about a cross-check of DAMA?
- The cosmic lepton puzzle clarified?
- Surprises from the gamma-ray sky?