Astrofisica: Rassegna teorica

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Incontri di Fisica delle Alte Energie, Roma, April 8, 2010

taking the liberty of focussing on:

Recent insights on the DM problem

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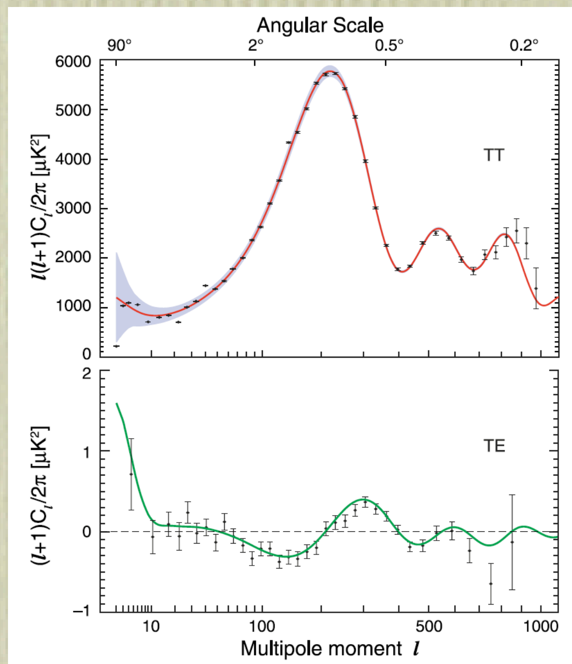
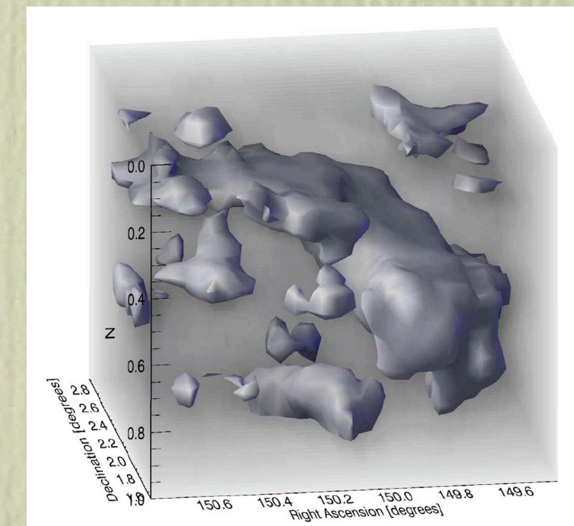
Outline:

- The appeal of the thermal relic picture (or slight variants) as a framework for the generation of the dark matter component.
- WIMP interactions with ordinary matter: model independent approaches and their limitations.
- Recent direct detection results: a light (few GeV) DM candidate? Complementarity with neutrino telescope searches.
- Halo annihilation signals: antiproton upper limits and antideuteron detection perspectives. The cosmic lepton puzzle: a heavy (few TeV) DM candidate?
- The cross-correlation among DM signals as route to DM detection.

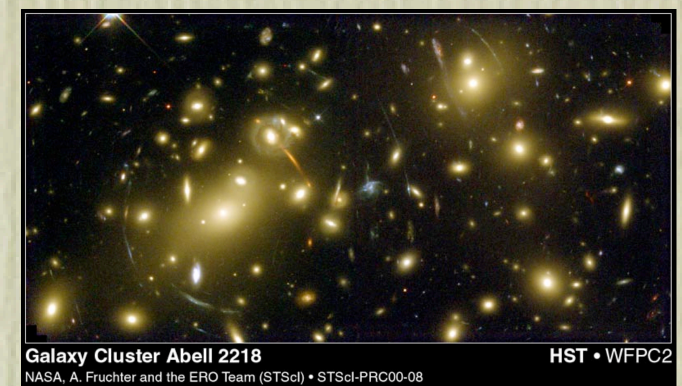
Overwhelming evidence for CDM as building block of all structures in the Universe, from the largest scales down to galactic dynamics:



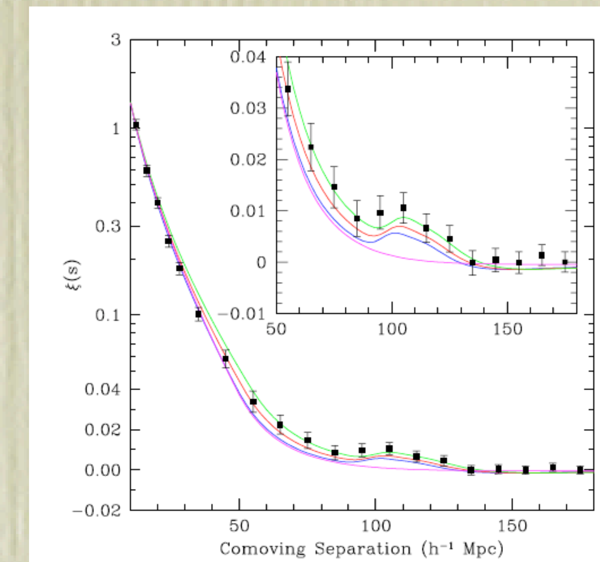
CMB



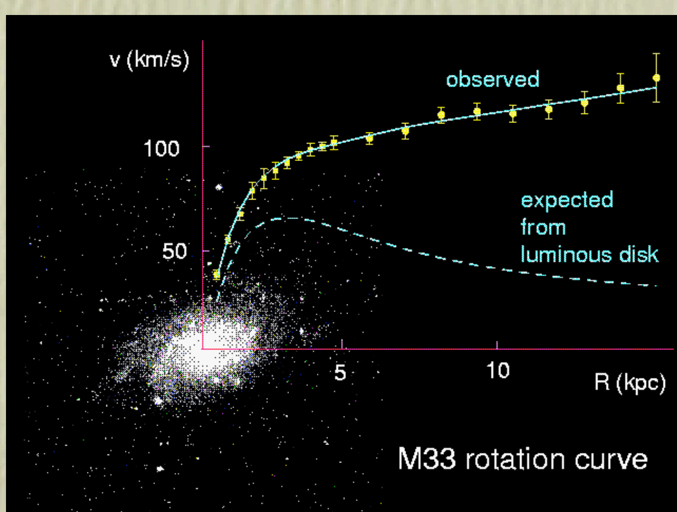
grav. scaffold



galaxy clusters



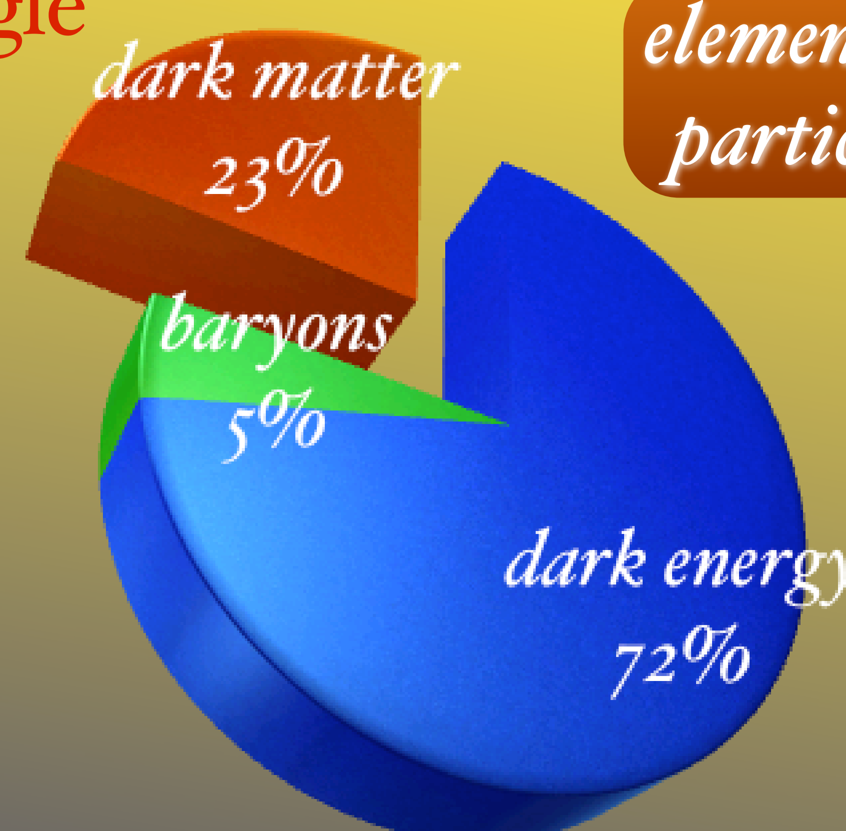
BAO



galaxies

+ many others:

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



elementary particles?

???

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:

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

$3Hn_\chi$: dilution by Universe expansion

$\langle\sigma_A v\rangle_T$: thermally averaged annihilation cross section

$(n_\chi)^2$: $\chi\bar{\chi} \rightarrow P\bar{P}$

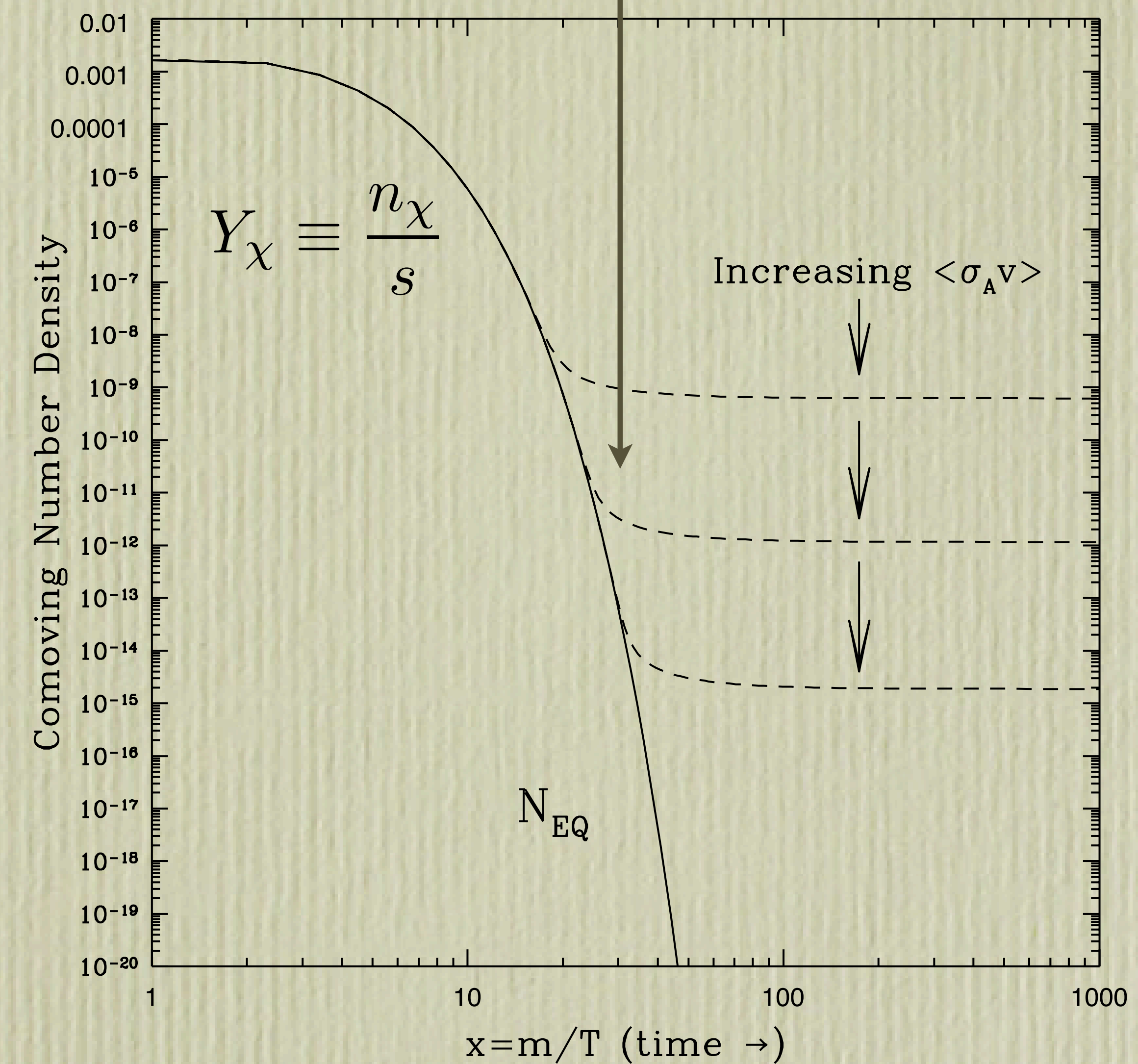
$\left(n_\chi^{eq}\right)^2$: $P\bar{P} \rightarrow \chi\bar{\chi}$

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) , ...

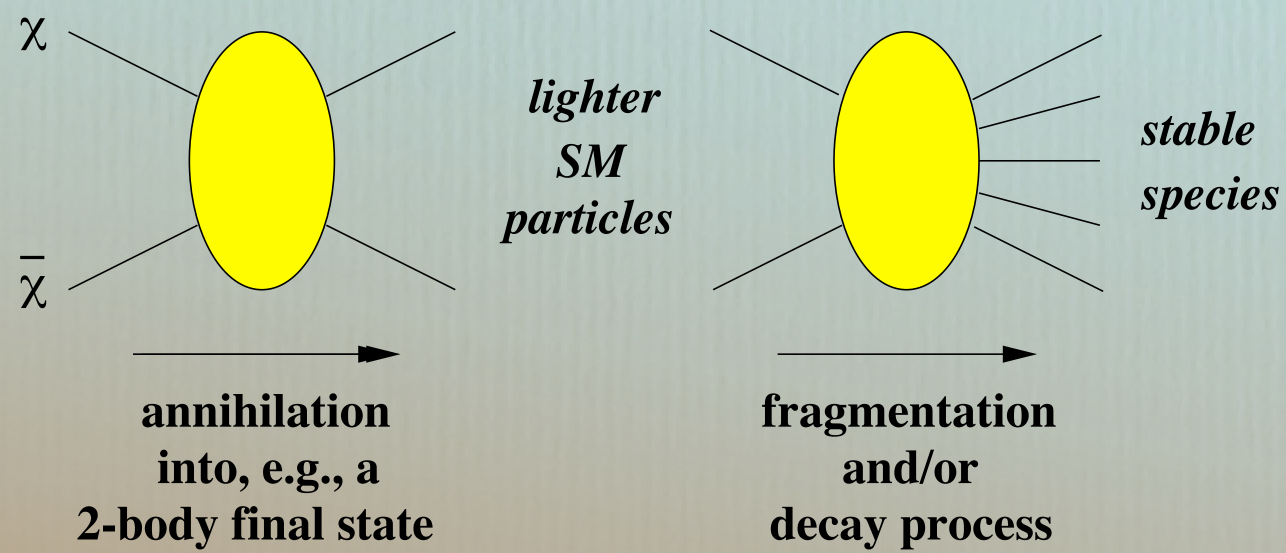
Incomplete list of models and very incomplete list of references!

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

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)



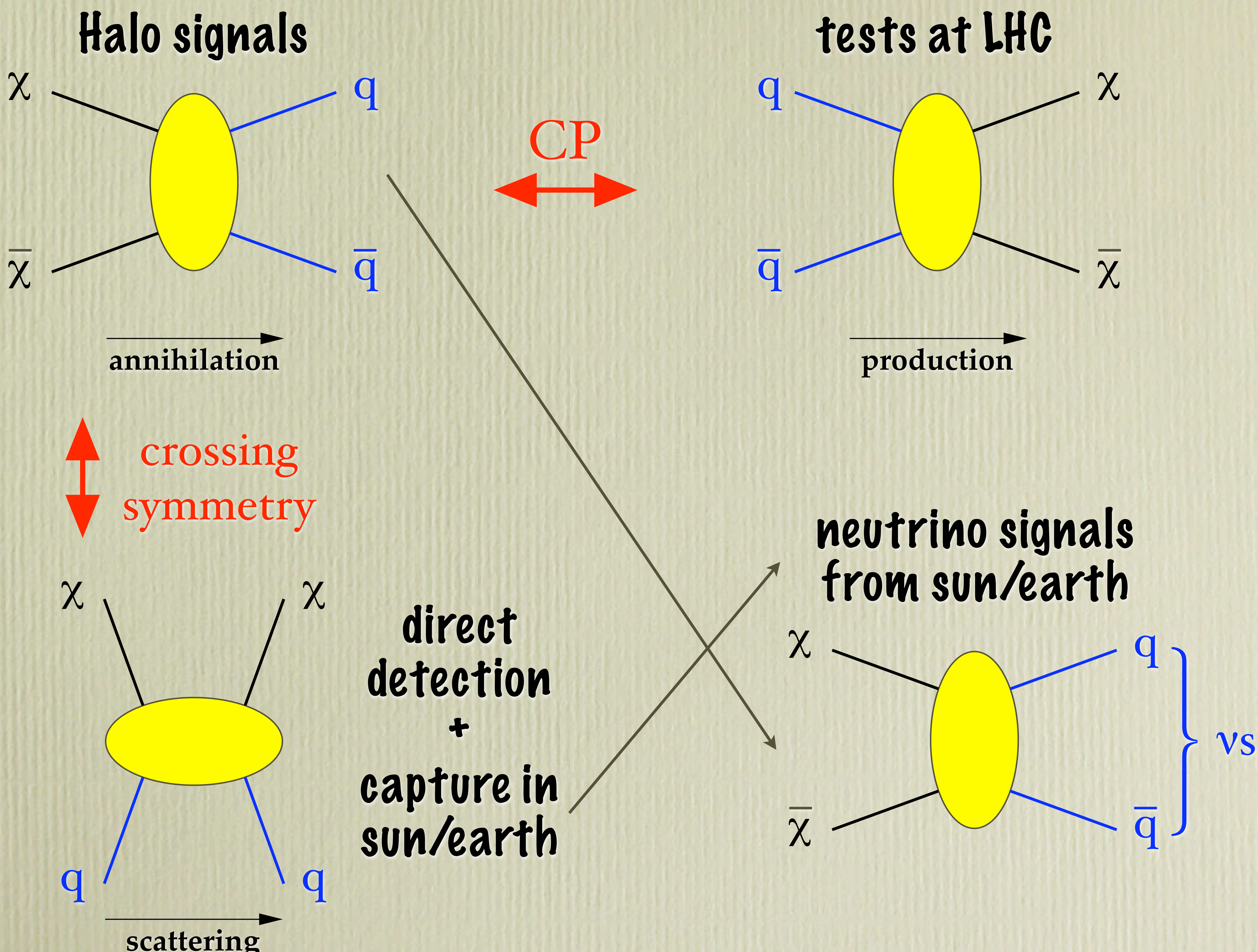
Focus on: antiprotons, positrons, antideuterons, gamma-rays, (neutrinos)

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

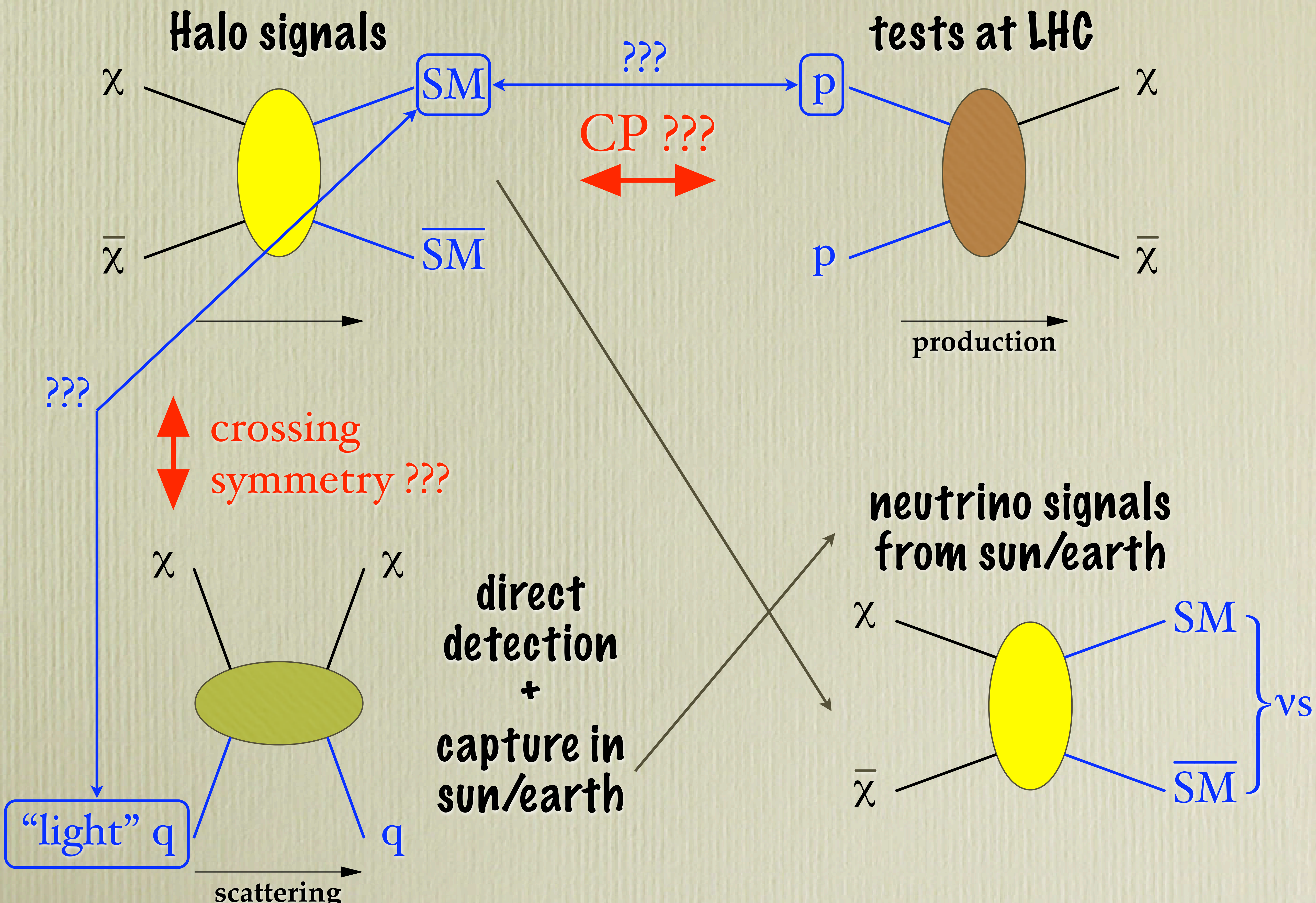
} WIMP DM source function

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

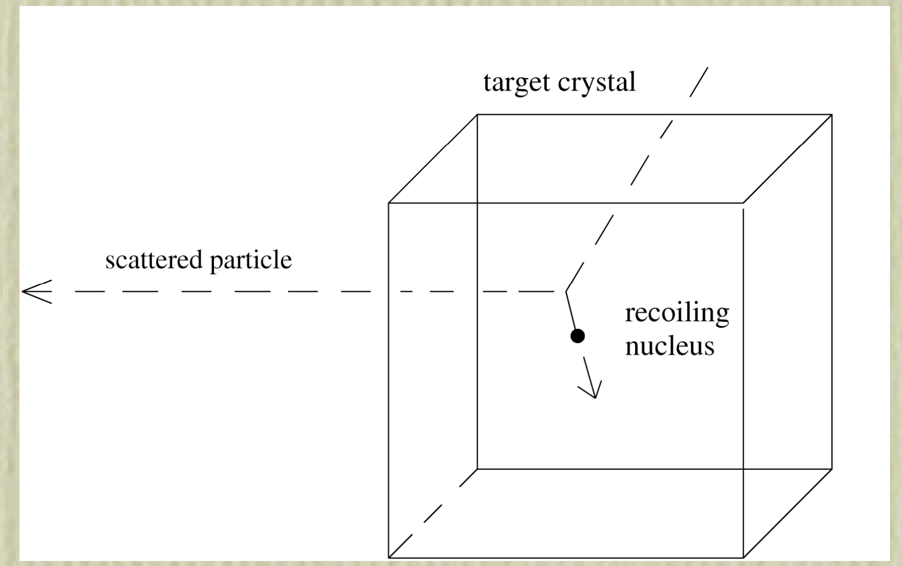
WIMP couplings to ordinary matter



WIMP coupling to ordinary matter ???



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

Spin-dependent versus spin-independent

For WIMP DM in the form of Majorana fermions, there are two terms contributing to the scattering cross section in the non-relativistic limit:

not coherent

Axial-vector
(spin-dependent)

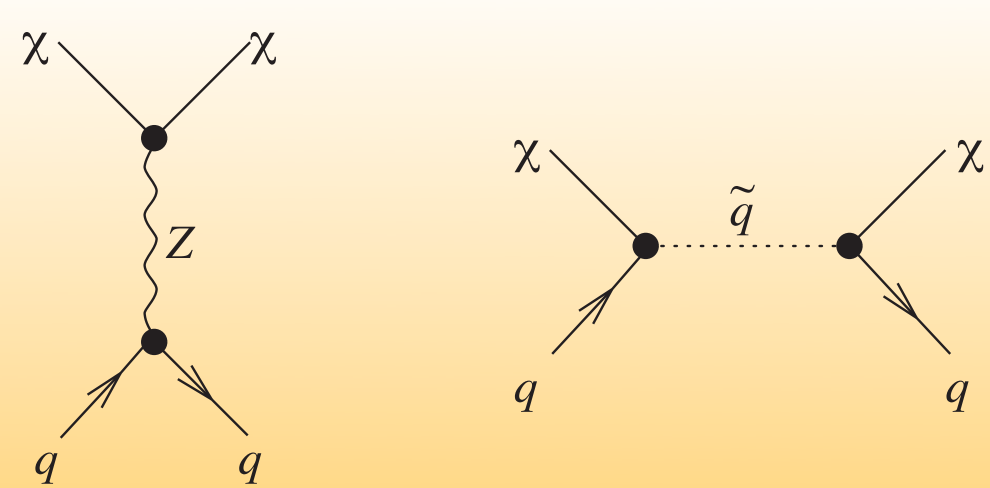
$$\mathcal{L}_A = d_q\ \bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu\gamma_5 q$$

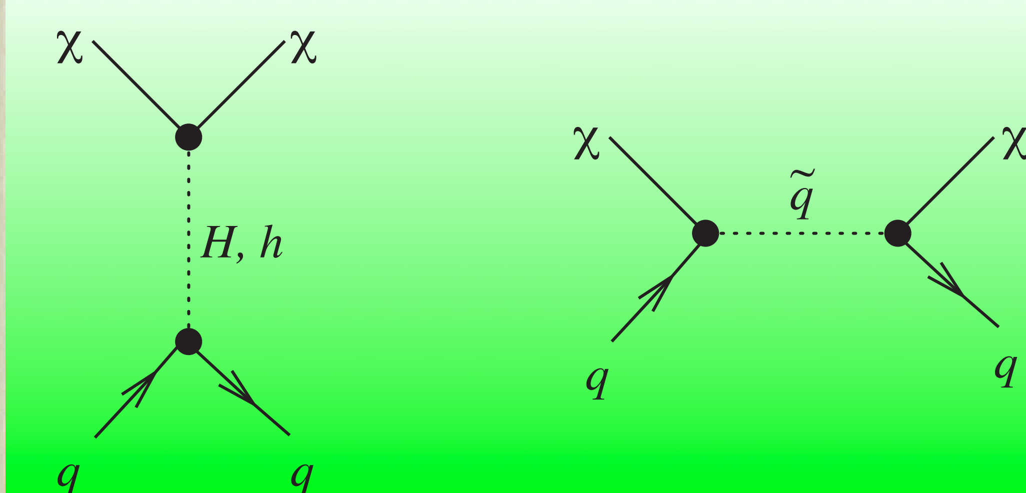
coherent

Scalar
(spin-independent)

$$\mathcal{L}_{\text{scalar}} = a_q\bar{\chi}\chi\bar{q}q$$

In case of neutralinos in the MSSM:





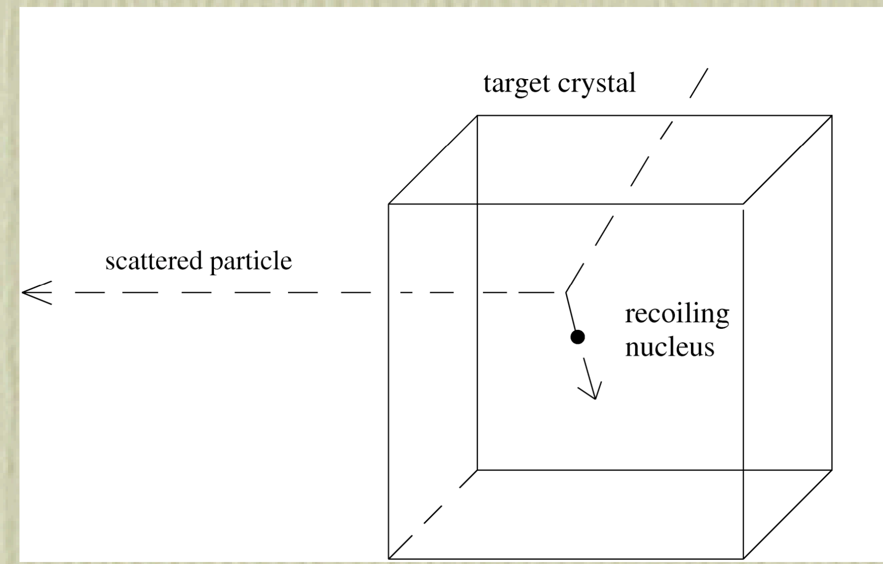
For dirac fermions also:

coherent

Vector: $\mathcal{L}^q_{vec} = b_q\ \bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$

For spin-0 or spin-1 WIMPs the discussion is analogous.

Direct detection:



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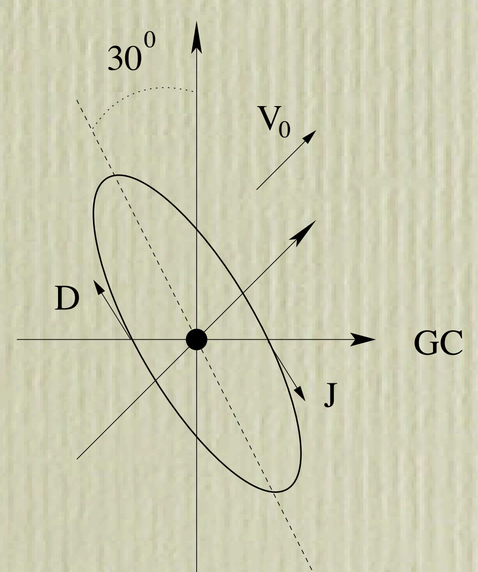
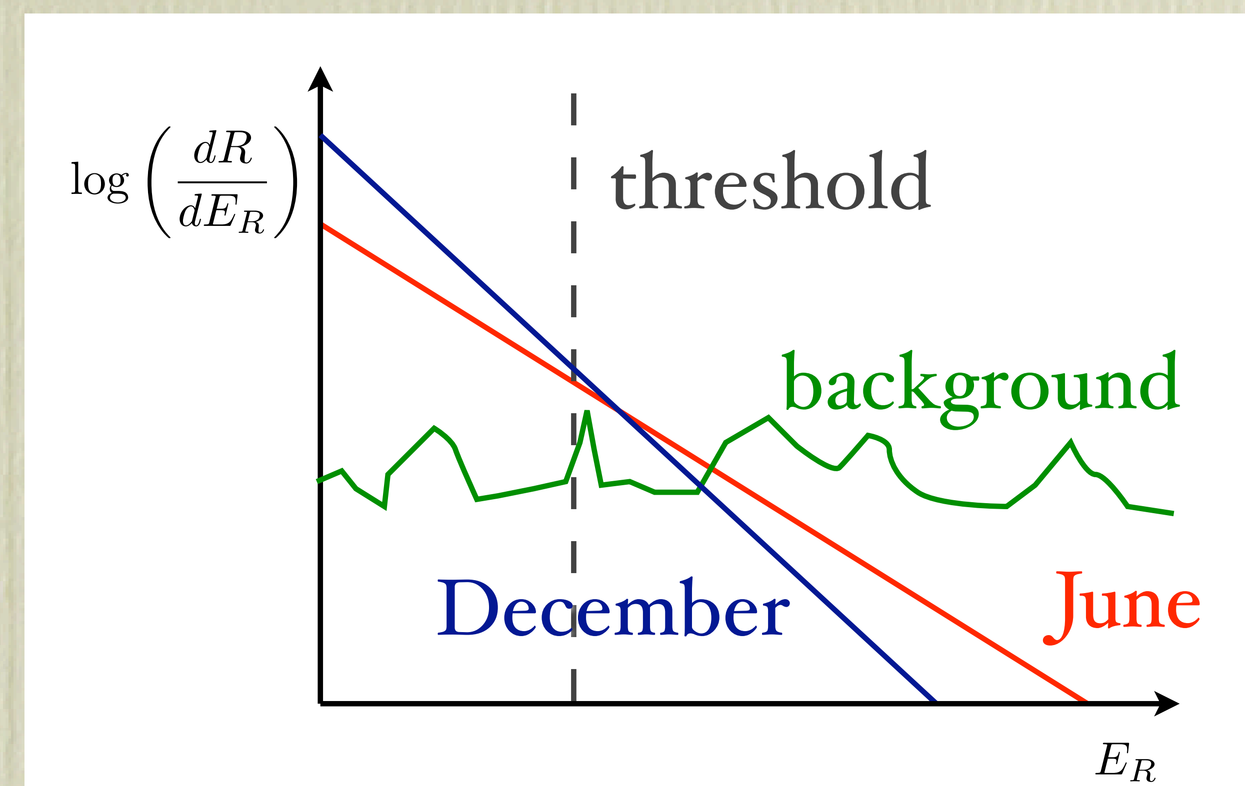
WIMP-nucleus cross section

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)

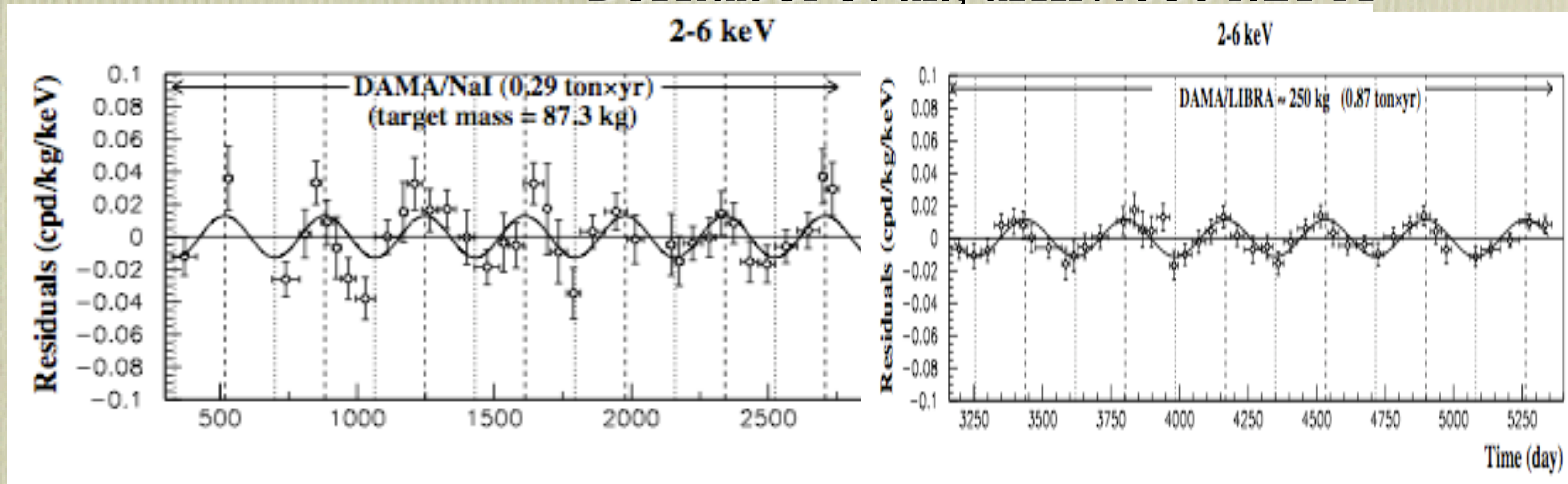




Annual modulation detected by DAMA/LIBRA

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



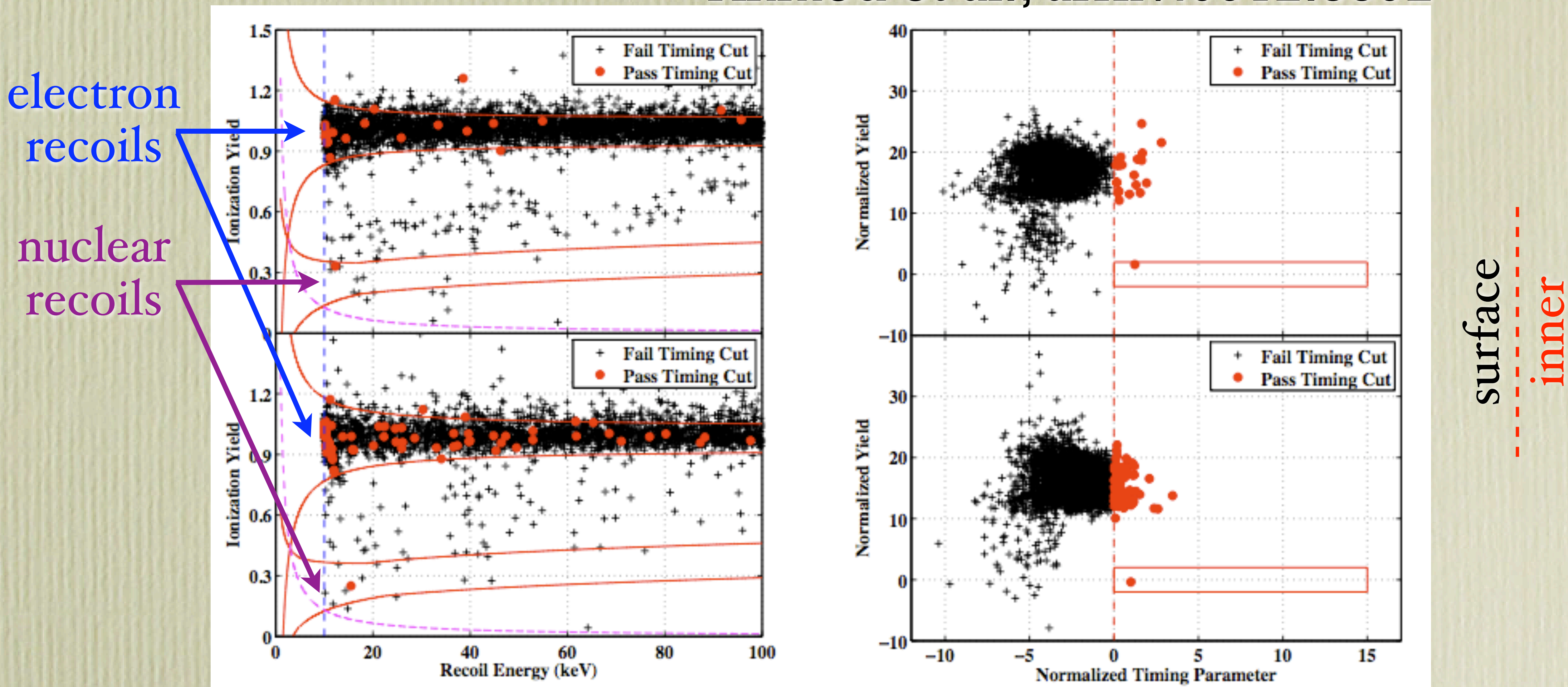
Bernabei et al., arXiv:1002.1028

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

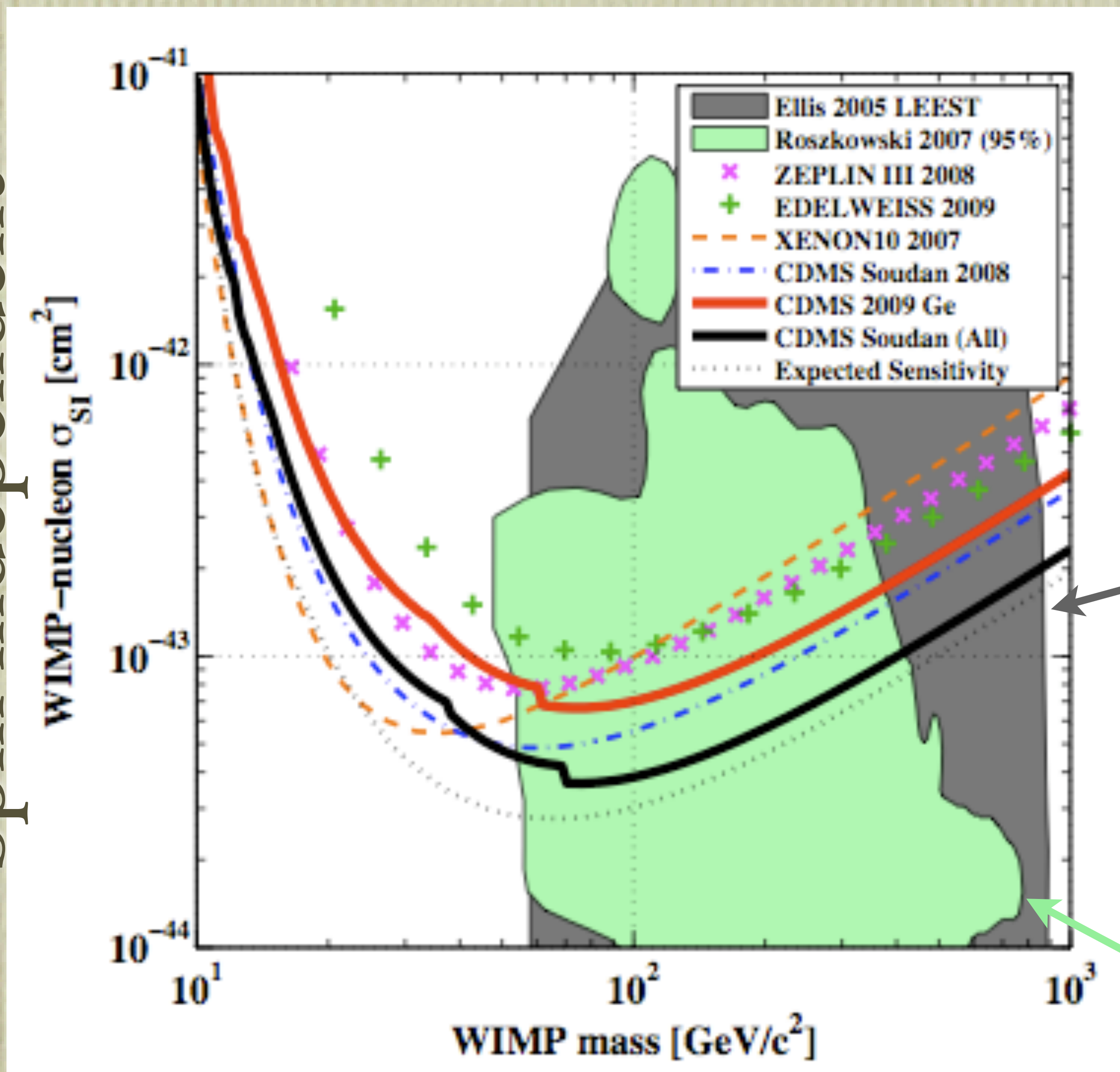


2 events survive all cuts; expected background: 0.9±0.2 events;
the probability to see ≥ 2 events is 23% ⇒ too little to claim a signal;
XENON-100 will clarify this within the summer!

CDMS II (+ competing experiments) bounds:

Ahmed et al., arXiv:0912.3592

Spin independent



Published upper limits are already setting relevant constraints on well-motivated particle physics models, such as:

Neutralino DM within the MSSM defined at low energy (but with gaugino mass unification) Ellis et al., hep-ph/0502001

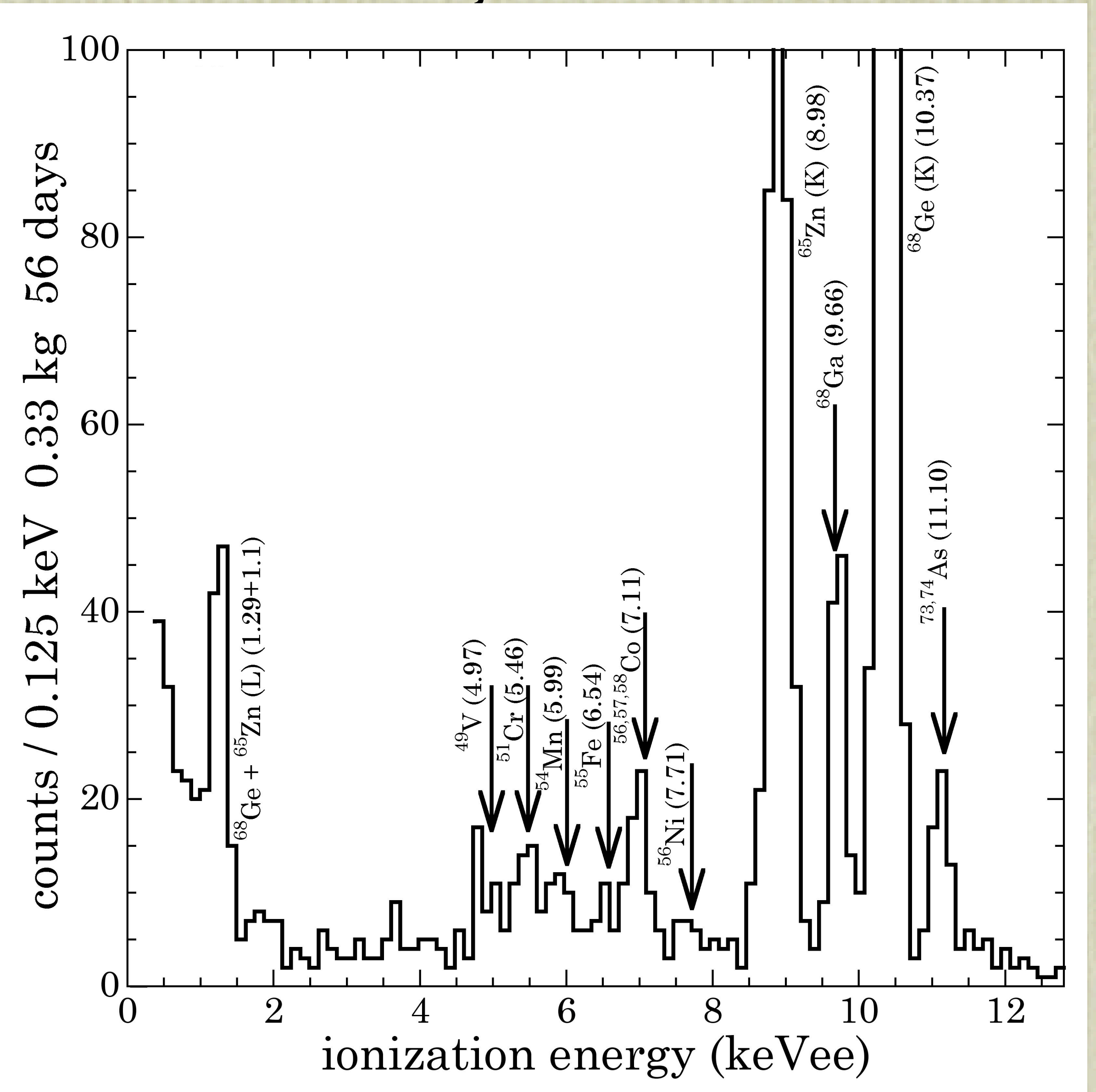
Neutralino DM within the CMSSM, Trotta et al., arXiv:0809.3792

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

CoGeNT "excess"

Small Ge detector with very low threshold, excellent energy resolution and extremely low noise: an exponential tail not straightforwardly identifiable as background; it is a DM signal ?

Aalseth et al., arXiv:1002.4703



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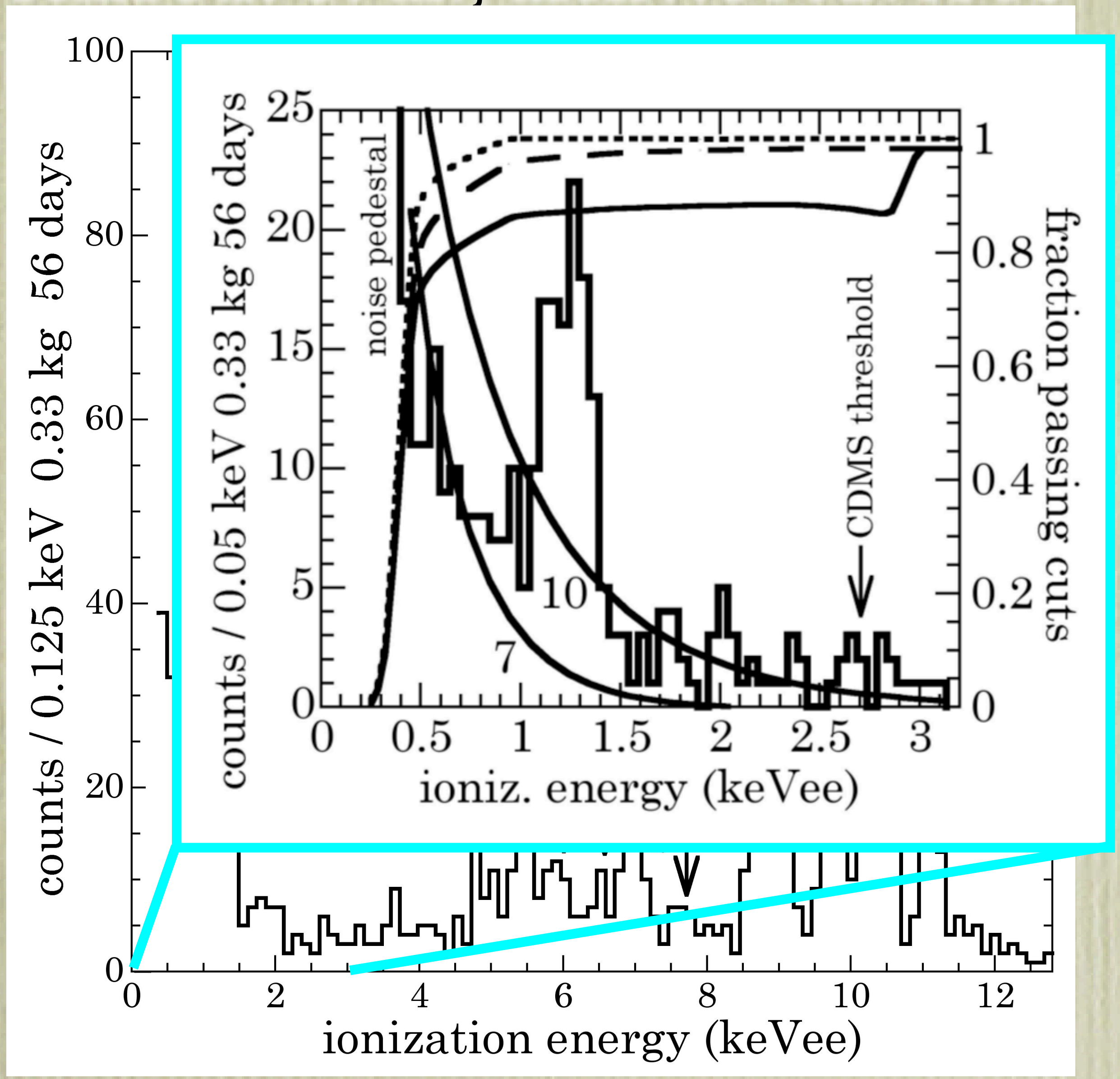
Aalseth et al., arXiv:1002.4703



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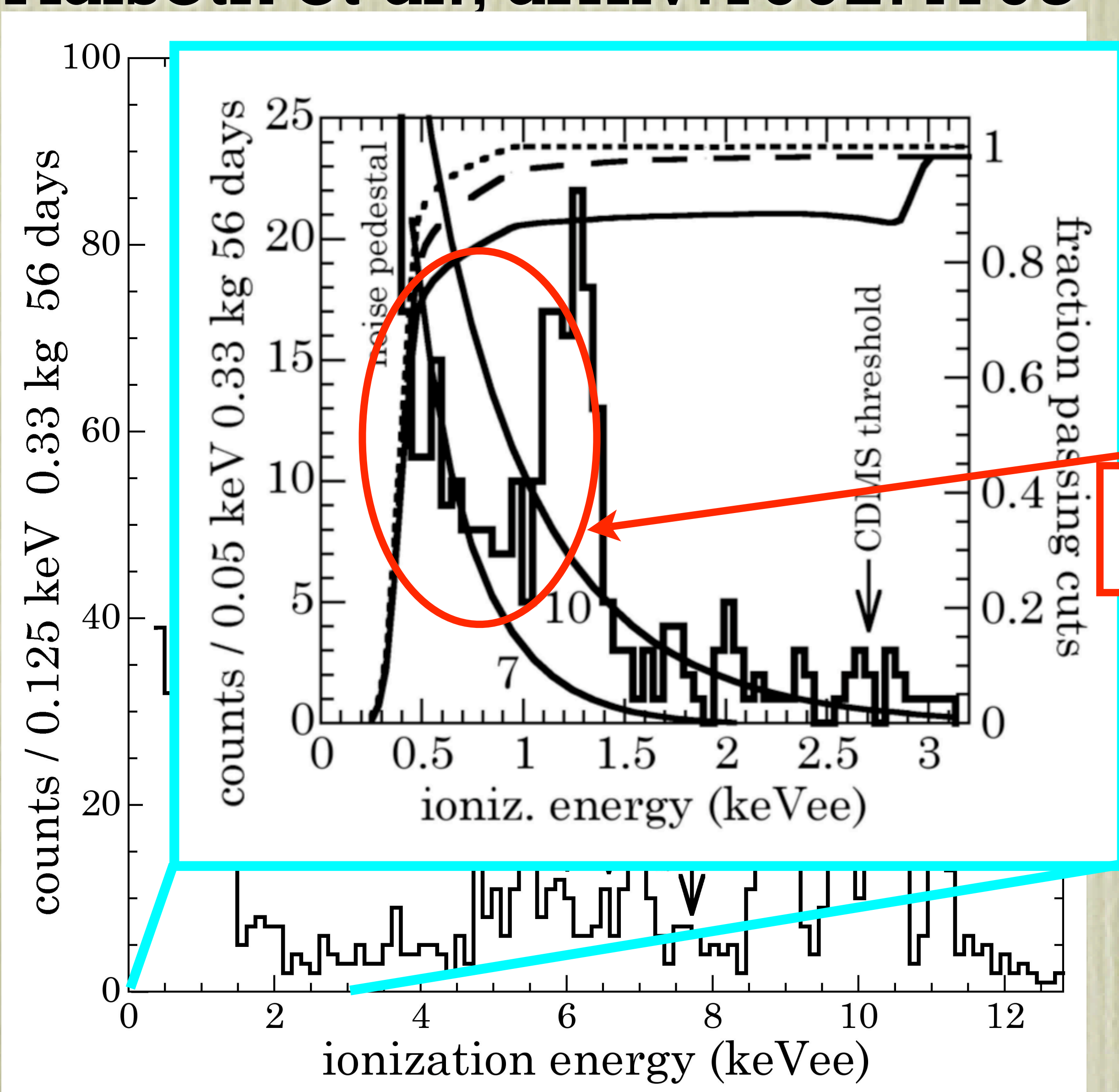
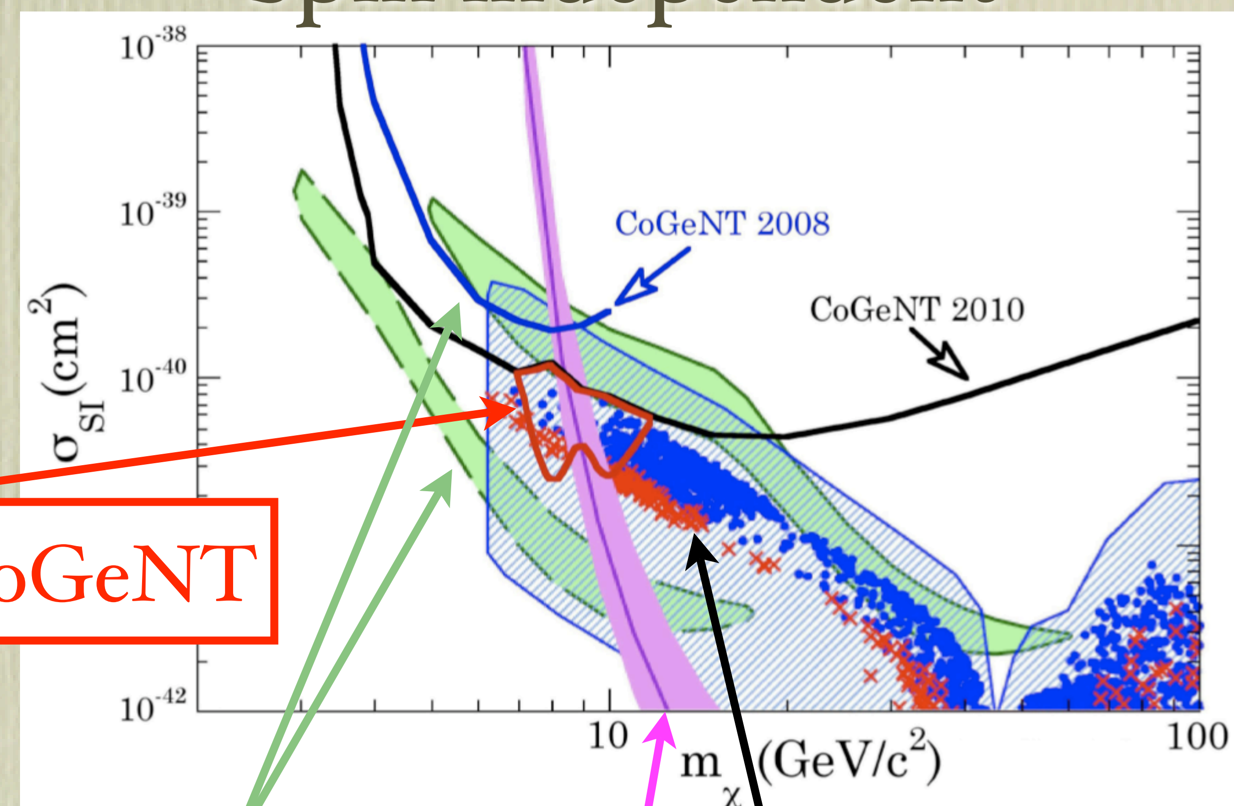


Spin independent



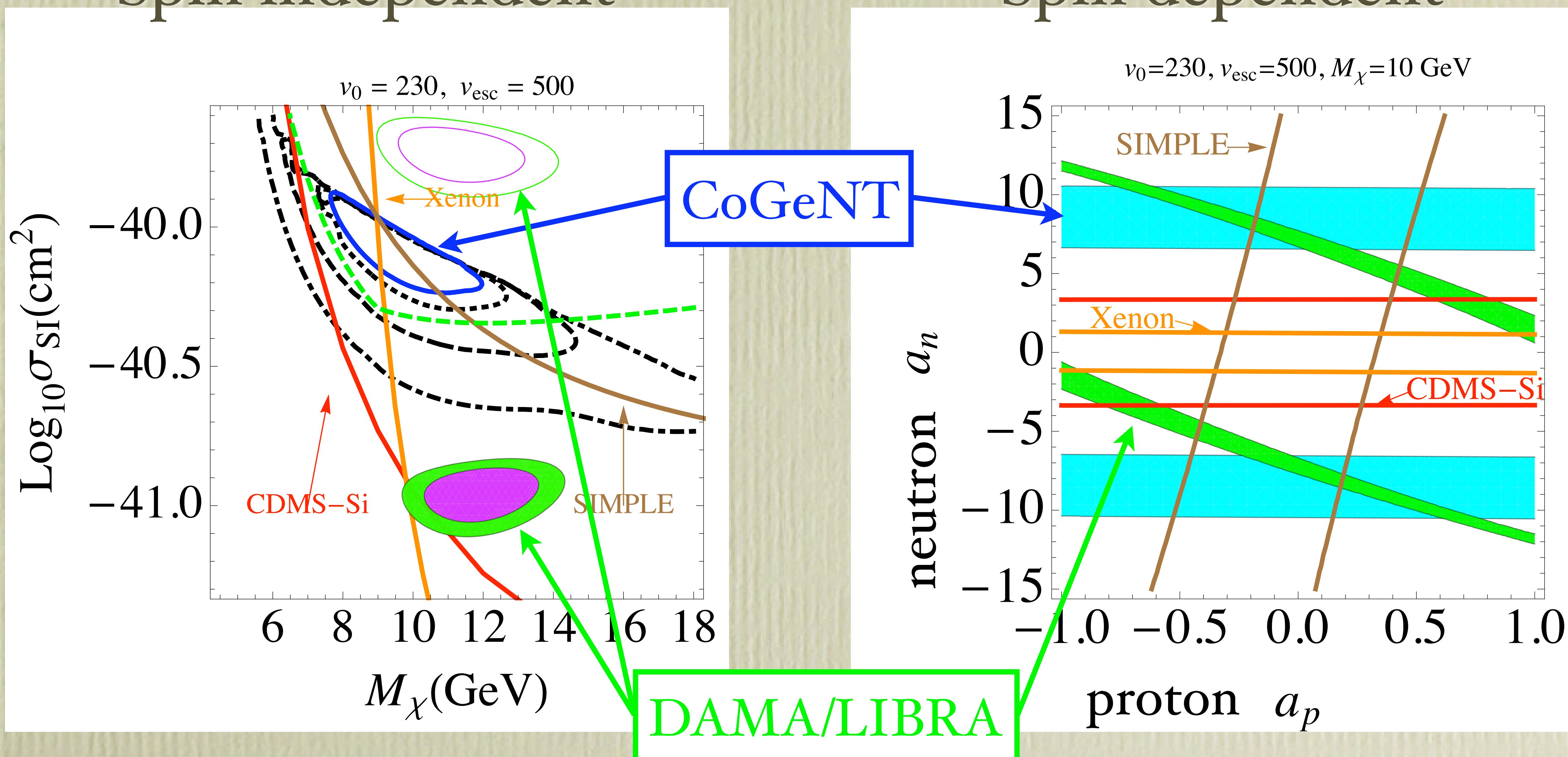
A common interpretation (???) in terms of a light DM particle (mass ~ 9 GeV)

DAMA & CoGeNT within the WIMP framework:

Several recent analyses comparing the different results (at "face value") with slightly different results, e.g.: Chang et al., arXiv:1004.0697

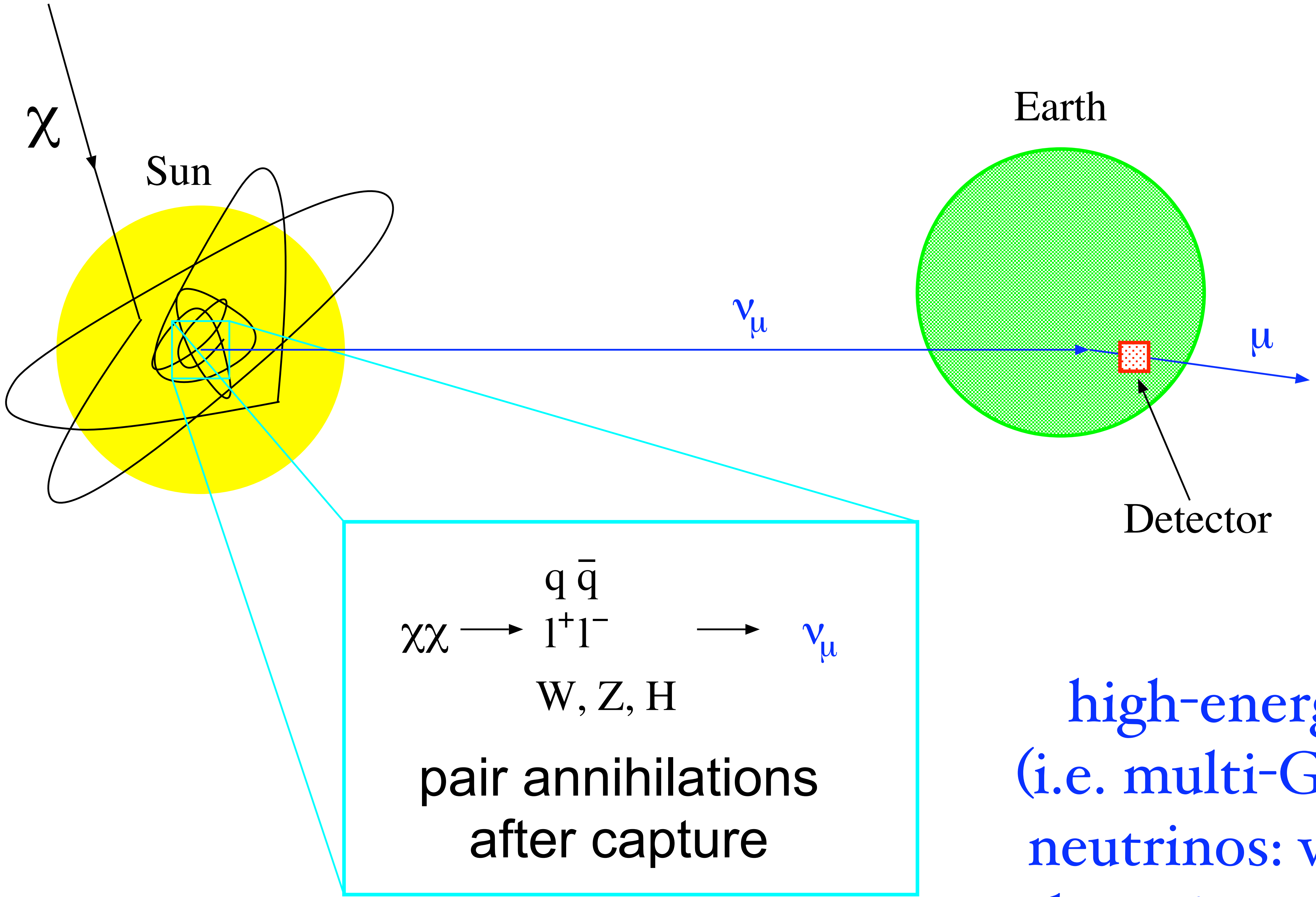
Spin independent

Spin dependent



(Very) little room for a solution in case of a light WIMP (mass between, say, 2 and 10 GeV). Should we trust "face values"?

WIMP searches with neutrino telescopes



high-energy (i.e. multi-GeV) neutrinos: very clean signature!

The WIMP number density inside the Sun/Earth obeys the equation:

$$\frac{dN}{dt} = C_c - C_a N^2$$

capture annihilation

which gives the WIMP annihilation rate:

$$\Gamma_a \equiv \frac{1}{2} C_a N^2 = \frac{1}{2} C_c \tanh^2(t/\tau)$$

with: $t = t_\odot \simeq 4.5 \cdot 10^9$ years & $\tau \equiv 1/\sqrt{C_c C_a}$.

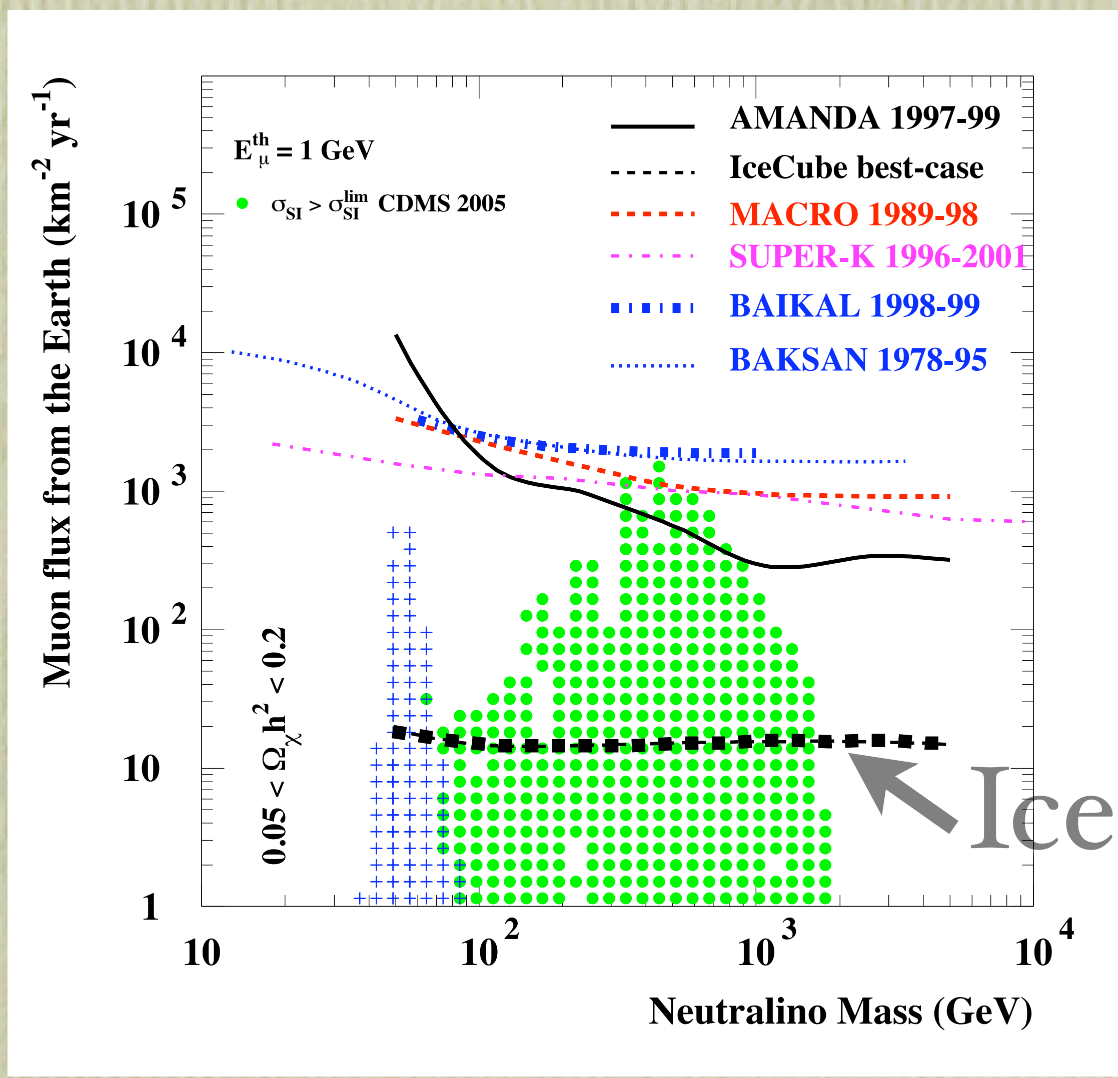
For $\tau \ll t_\odot$ capture and annihilation have reached equilibrium:

$$\Gamma_a = \frac{1}{2} C_c \longrightarrow \Phi_\mu \begin{cases} \propto\!\!\!\sim \ \sigma_{\chi\, p}^{SD} & \text{Sun} \\ \propto \ \sigma_{\chi\, p,n}^{SI} & \text{Earth} \end{cases}$$

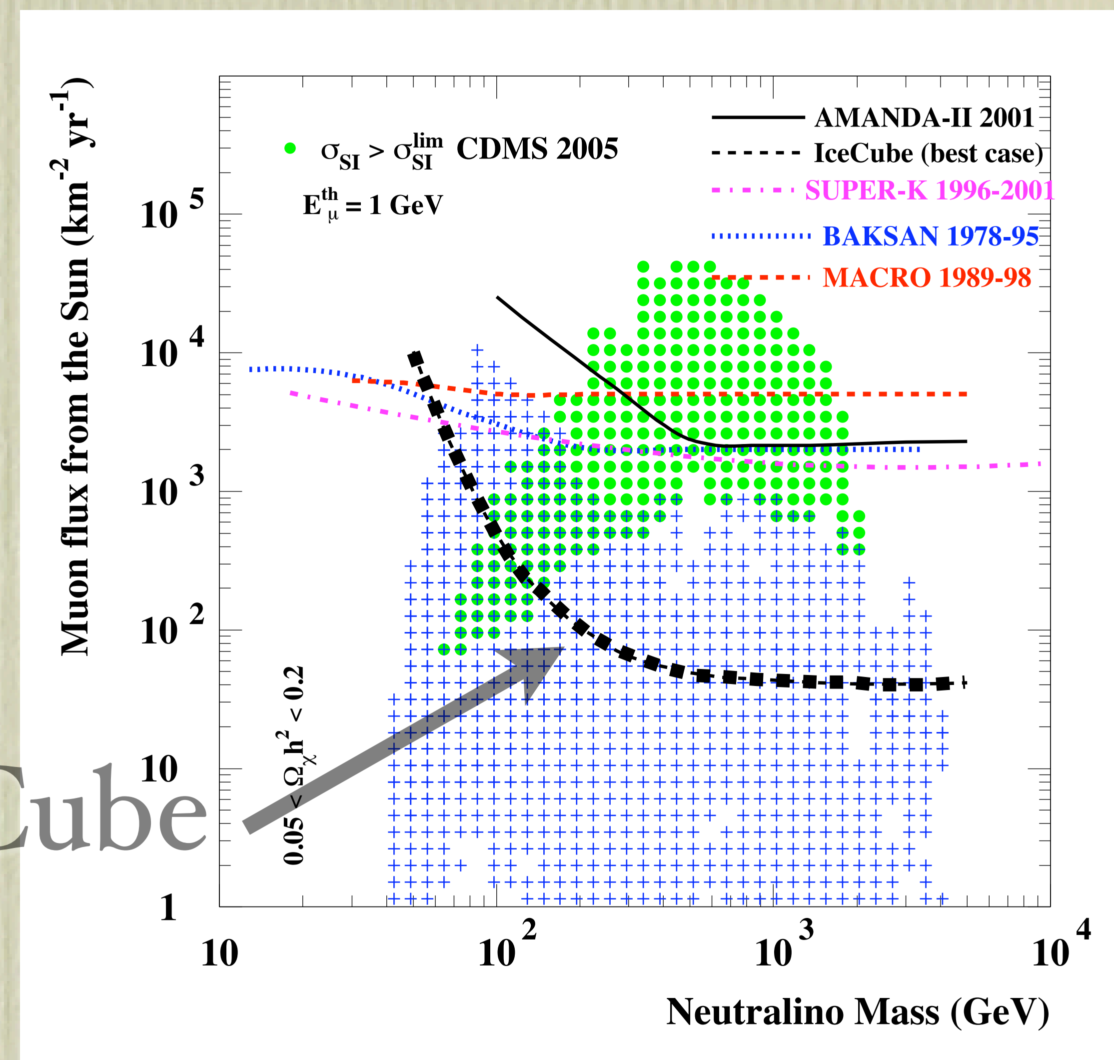
(??? - rarely in equilibrium)

The ν signal from the Earth versus the ν signal from the Sun, keeping in mind direct detection results: the standard lore is that the Sun wins. E.g. a general scan for neutralino dark matter candidates within the MSSM:

Flux from the Earth



Flux from the Sun



IceCube

● model excluded by the 2005 CDMS SI limit

Icecube Collaboration & DarkSUSY, 2007

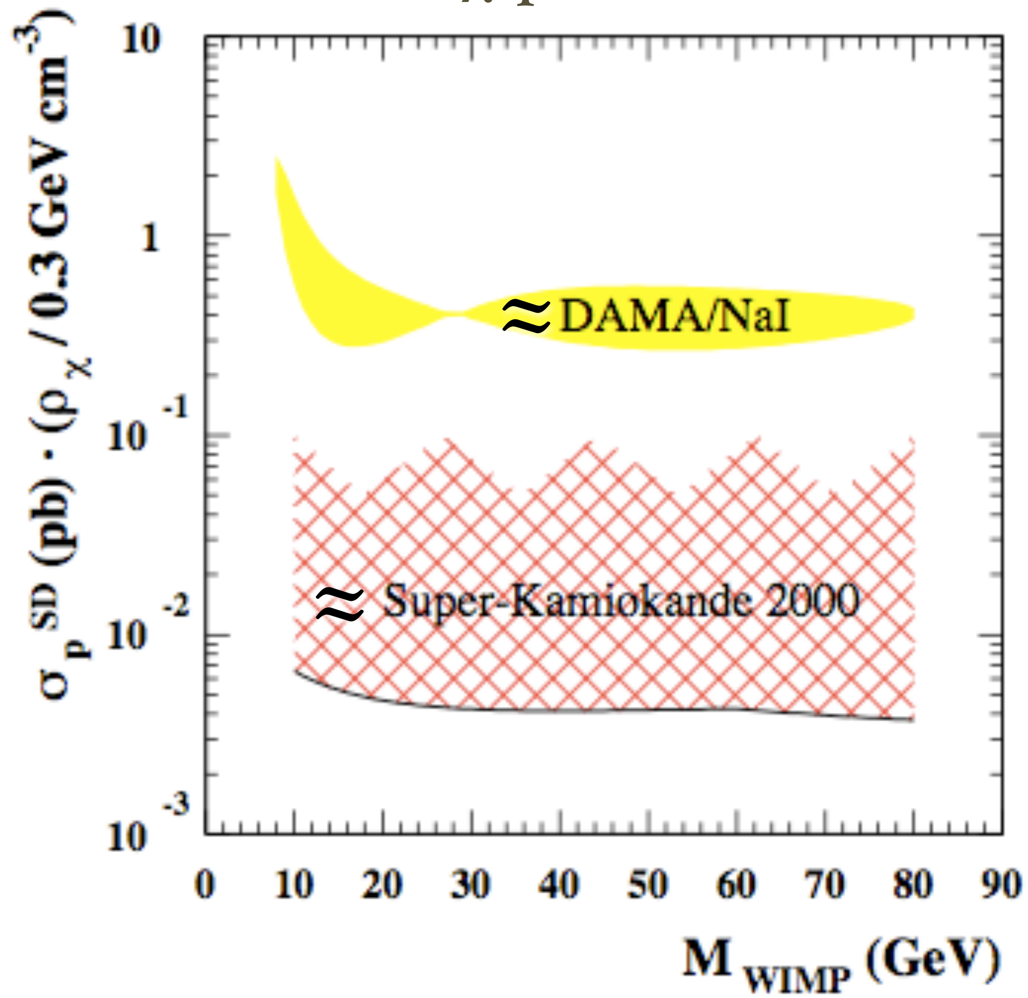
Direct detection versus neutrino telescopes

Test a given a positive signal in a direct detection experiment searching for a ν signal from the Sun, assuming (**Kamionkowski et al., 1995**):

I) equilibrium between capture and annihilation in the Sun;

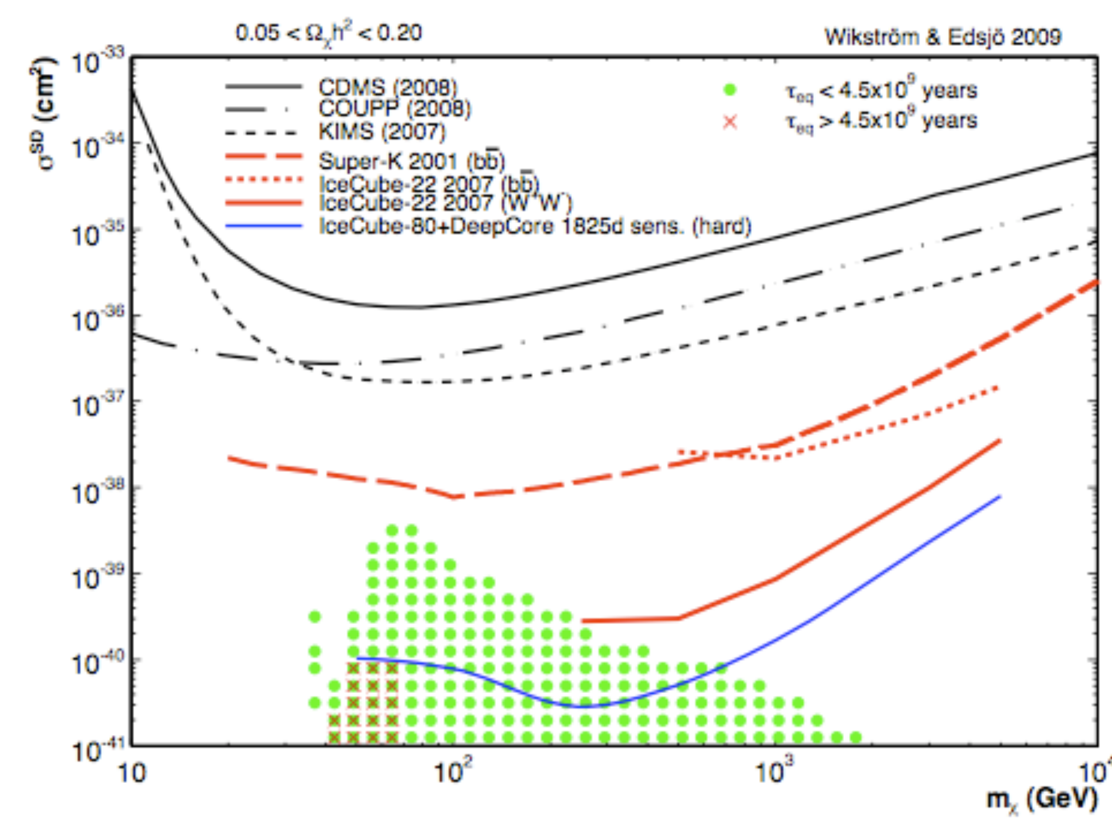
II) WIMP annihilation modes for which the ν yield is not suppressed.

DAMA/LIBRA annual modulation effect and χ-p SD interactions



P.U., Kamionkowski & Vogel,2001

comparison with recent χ-p SD searches



Wikström & Edsjo, 2009

WARNING: there are loopholes in these arguments

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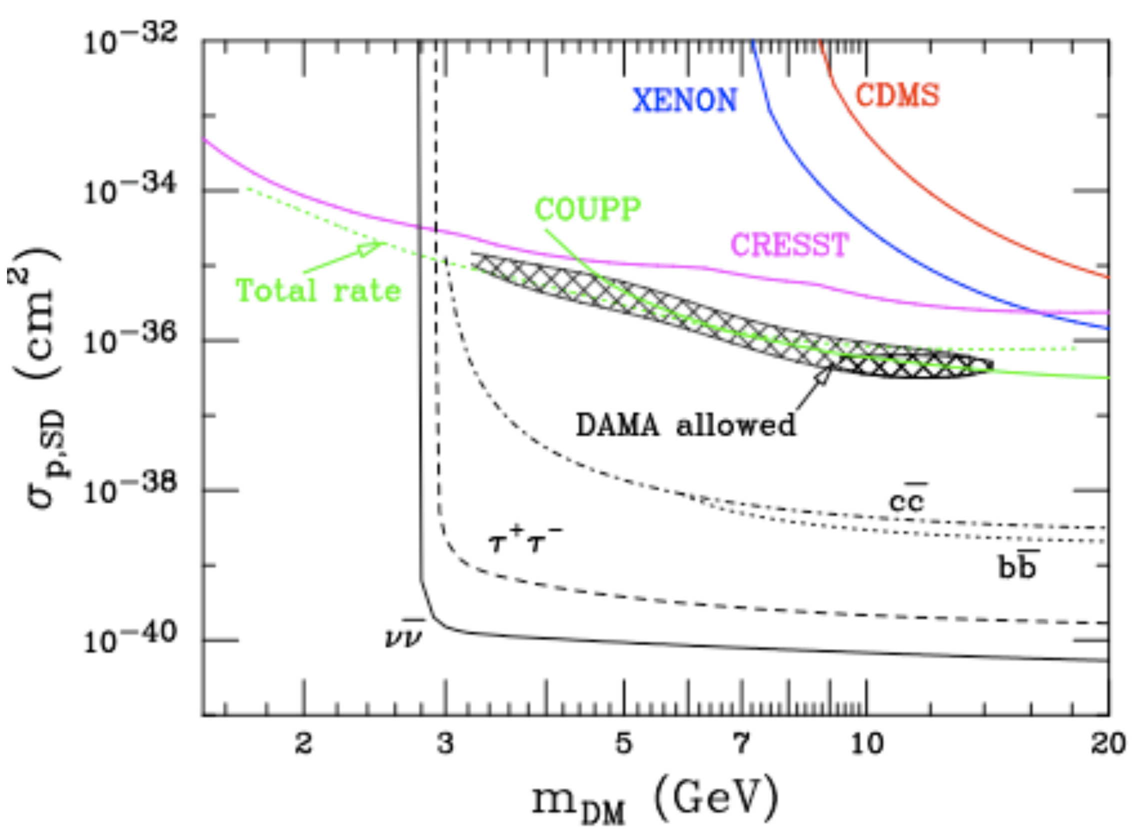
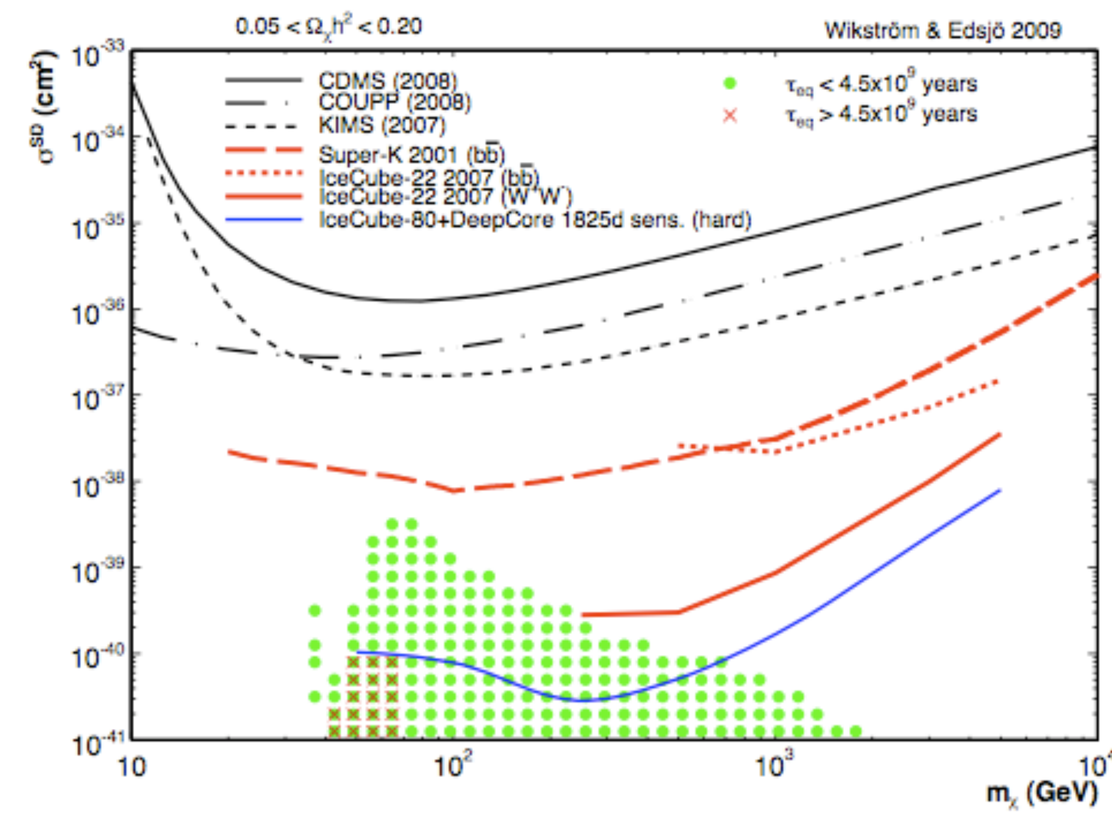


Hooper et al., 2008

comparison with recent χ-p SD searches



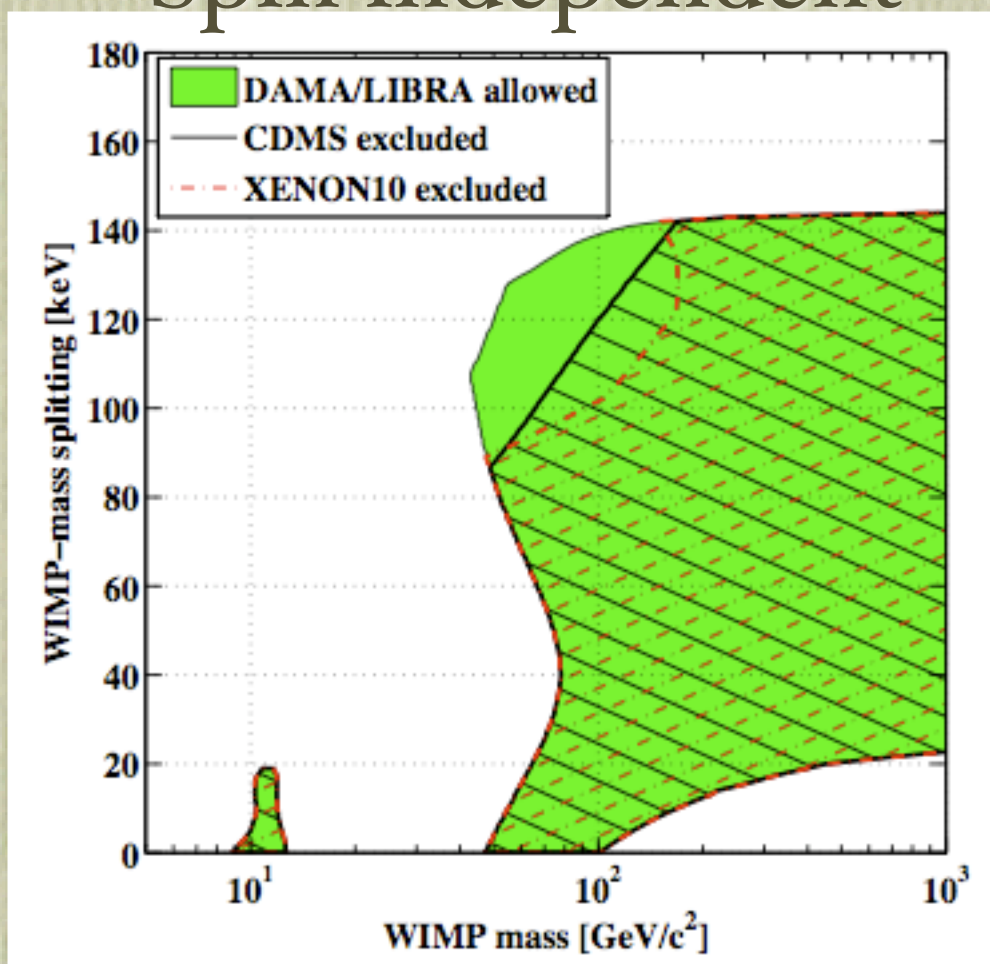
Wikström & Edsjo, 2009

WARNING: there are loopholes in these arguments

What the DAMA (CoGeNT) signal out of the WIMP framework?

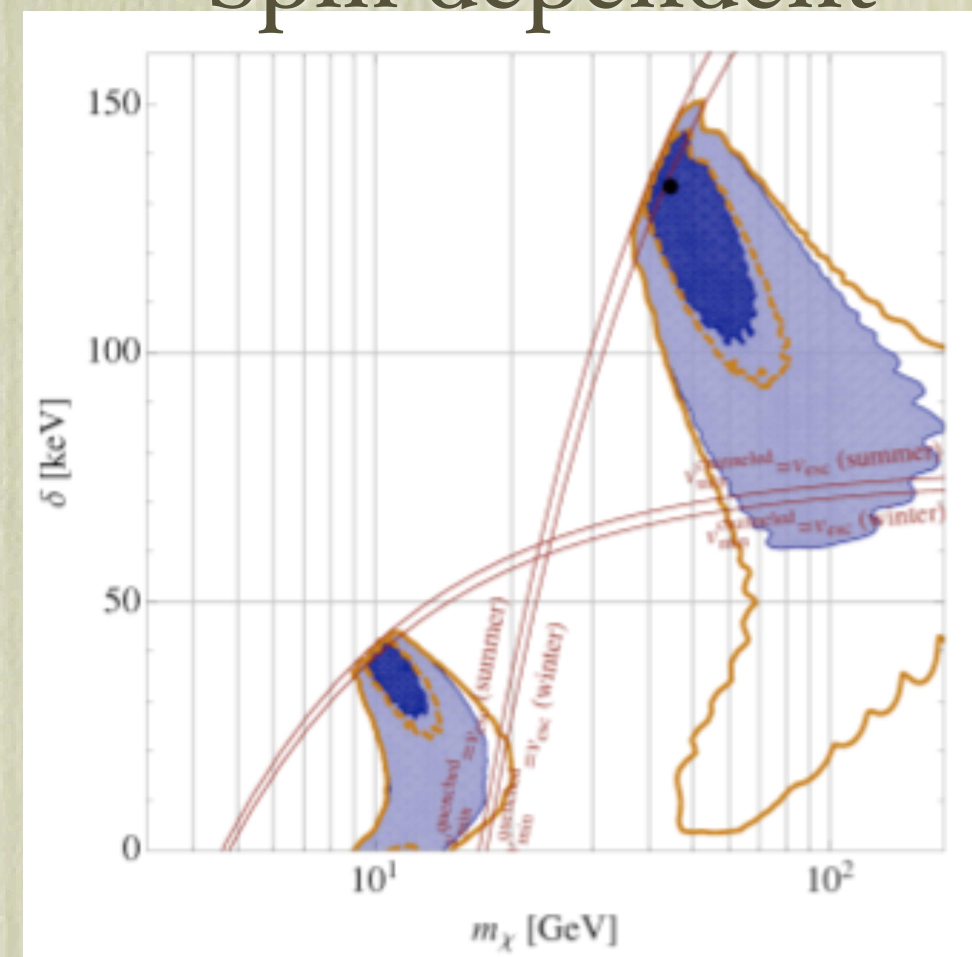
Advocate, e.g., **Inelastic Dark Matter** (Smith & Weiner, 2001), assuming the existence of two (or more) dark states with mass splittings of the order of 10-100 keV and imposing only inelastic scattering:

Spin independent

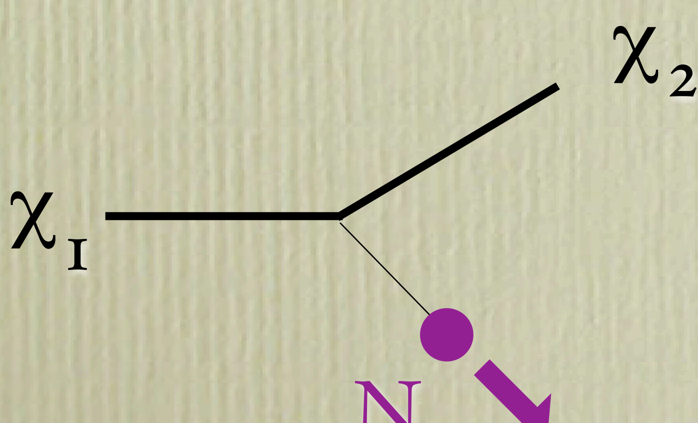


Ahmed et al., arXiv:0912.3592

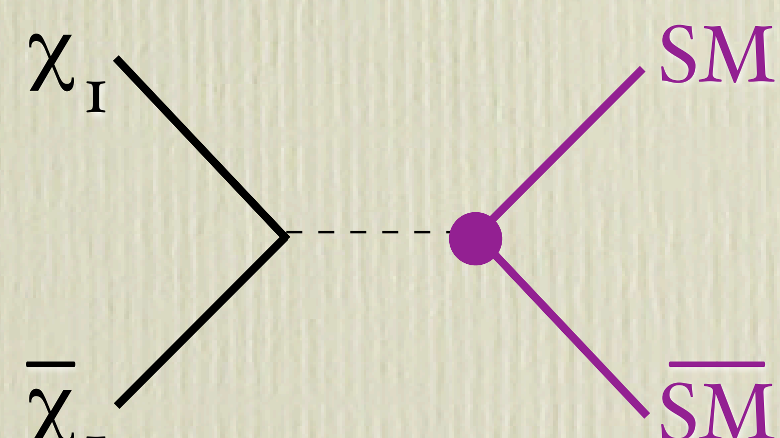
Spin dependent



Kopp et al., arXiv:0912.4262



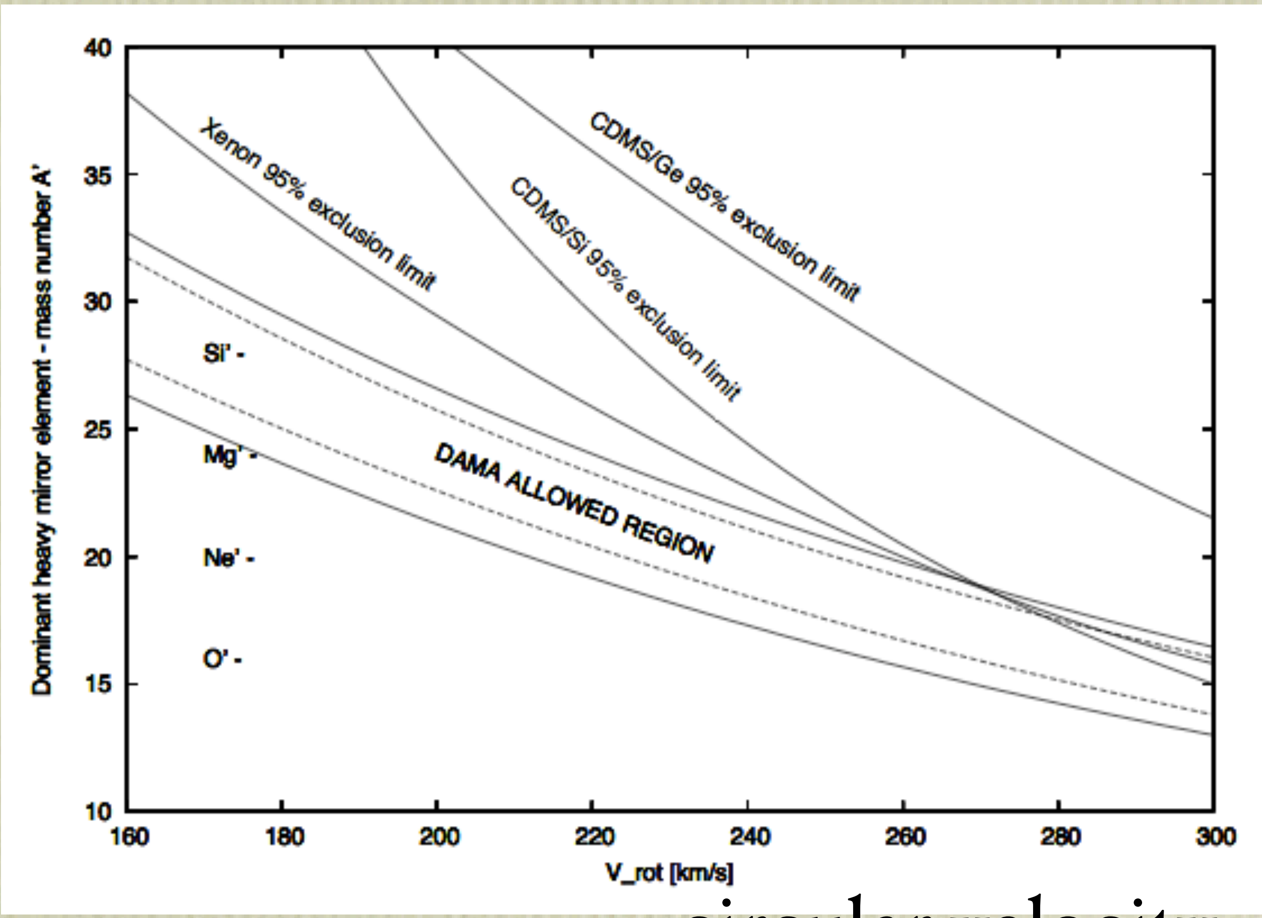
tunable on direct detection results but with feeble connections to the pair annihilation process:



What the DAMA (CoGeNT) signal out of the WIMP framework?

Advocate, e.g., **Mirror Dark Matter** (Foot et al., 1991; Berezhiani et al., 2001), assuming the existence of mirror baryons interacting with ordinary matter via a sizable photon-mirror photon kinetic mixing:

atomic number for mirror element



circular velocity

Foot, arXiv:0804.4518

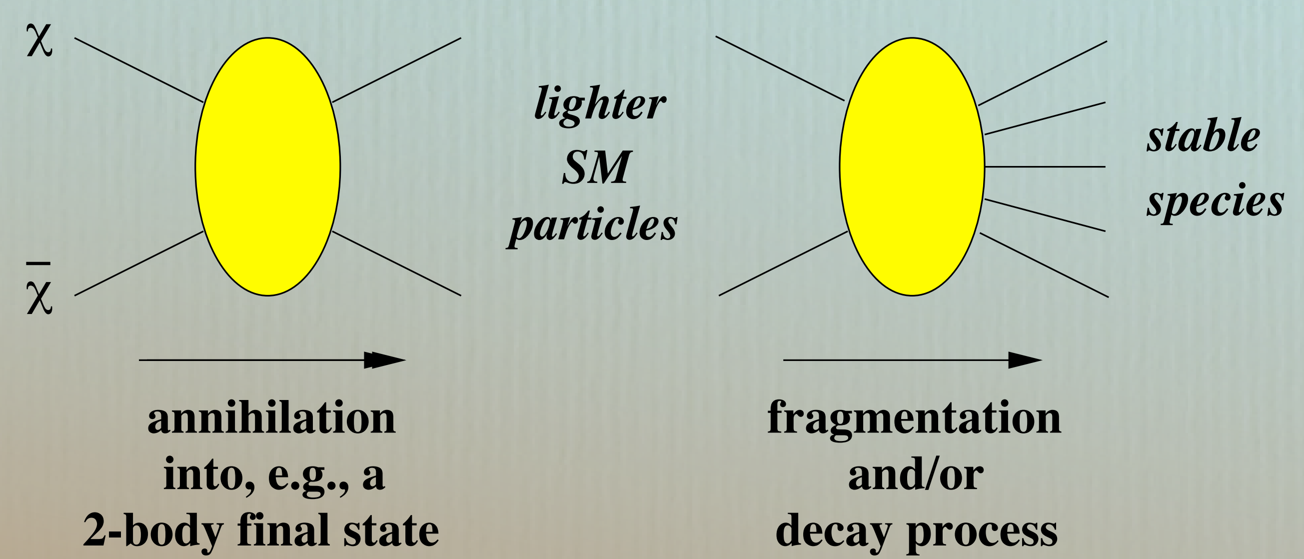
In this model the dark matter component does not contain antiparticles, hence there are no pair annihilation signals, including the ν signals.

Analogous picture for **Asymmetric Dark Matter** (Kaplan, 1992).

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 $T \cong 0$)



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

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.

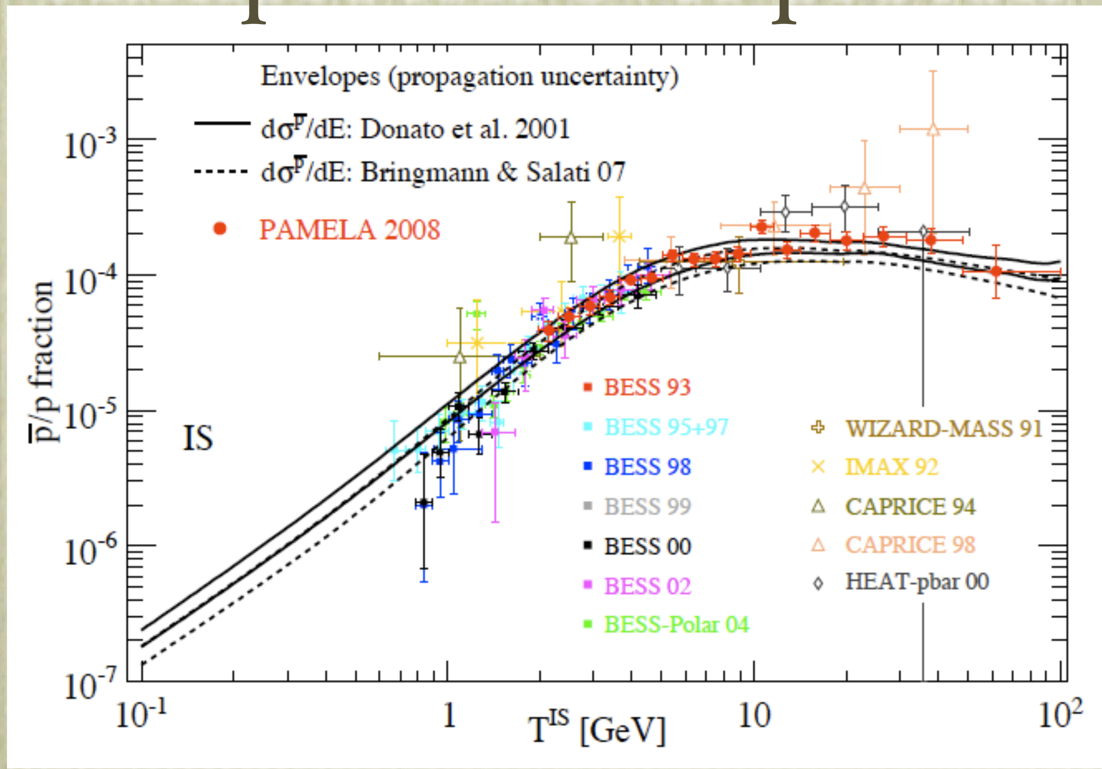
The $\bar{p}$ measurements are consistent with secondaries:

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!

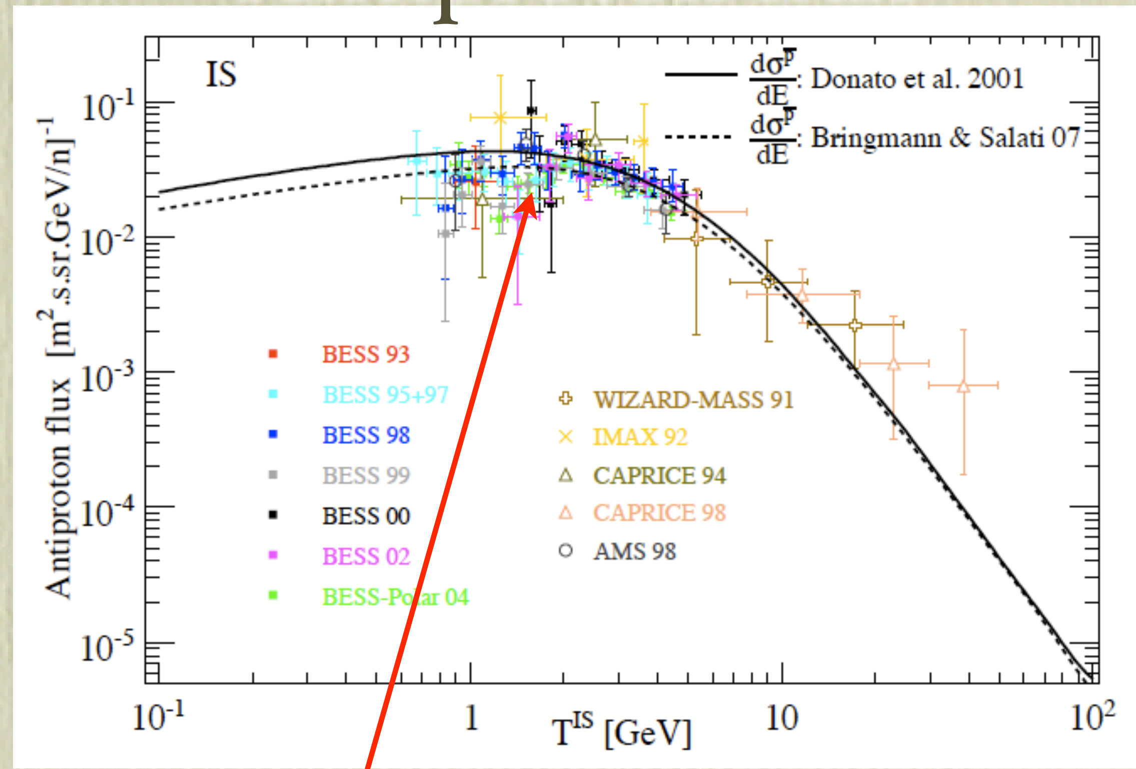
Antiproton over proton



Donato et al., arXiv:0810.5292

Latest Pamela data: Adriani et al., arXiv:0810.4994

Antiproton flux



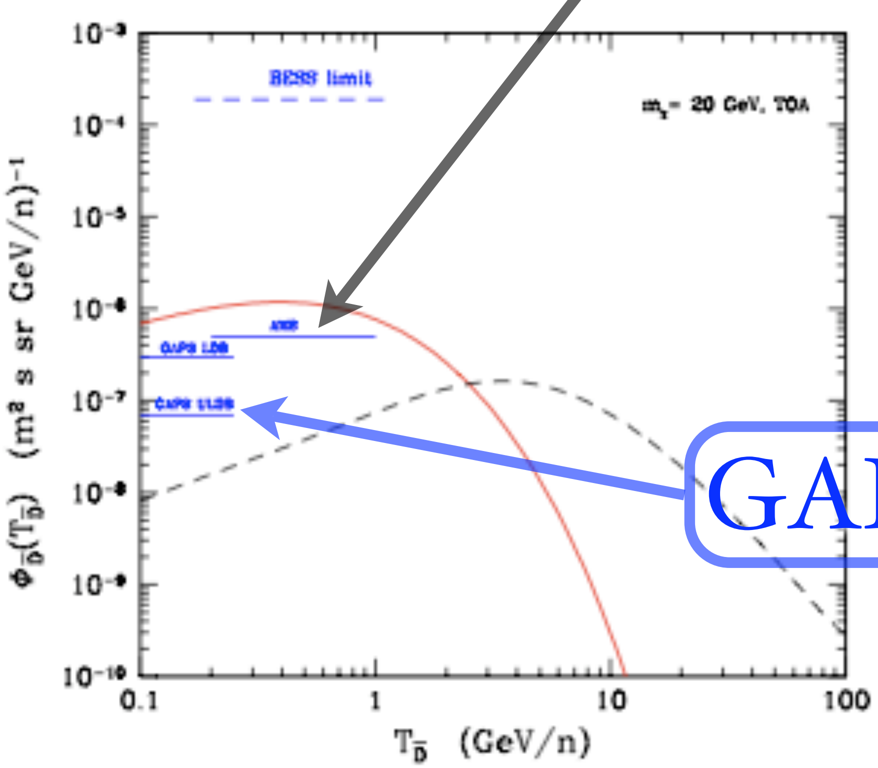
kinematic peak expected for secondaries, not for a primary component

Antideuteron fluxes (& direct detection)

E.g., for light neutralinos in the MSSM (no gaugino mass unification) large $\bar{D}$ fluxes and a tight correlation with direct searches - this is not fully general.

AMS

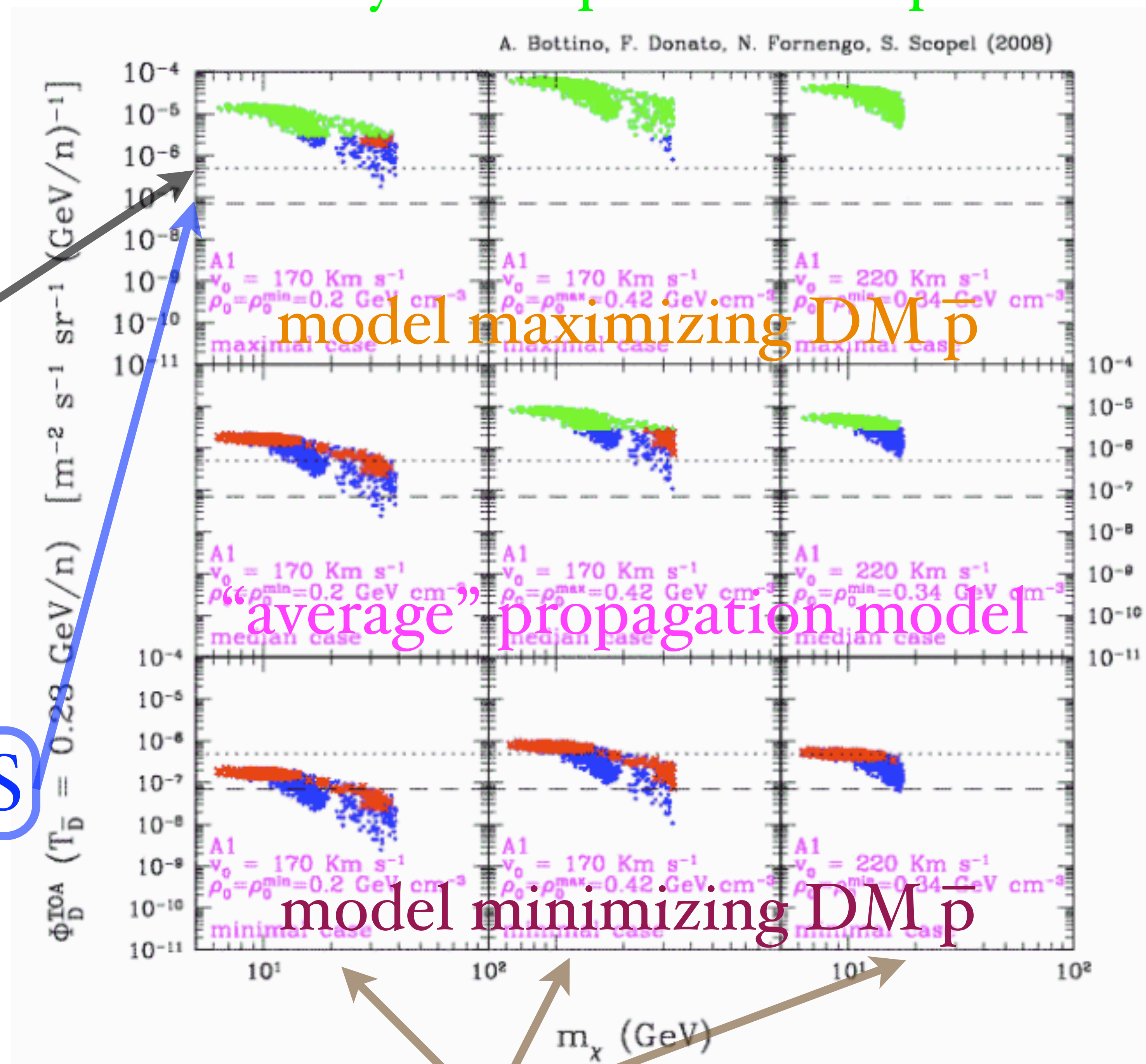
GAPS



Red: compatible with DAMA and WMAP

Blue: compatible with DAMA but low Ω

Green: already incompatible with $\bar{p}$



three different halo models

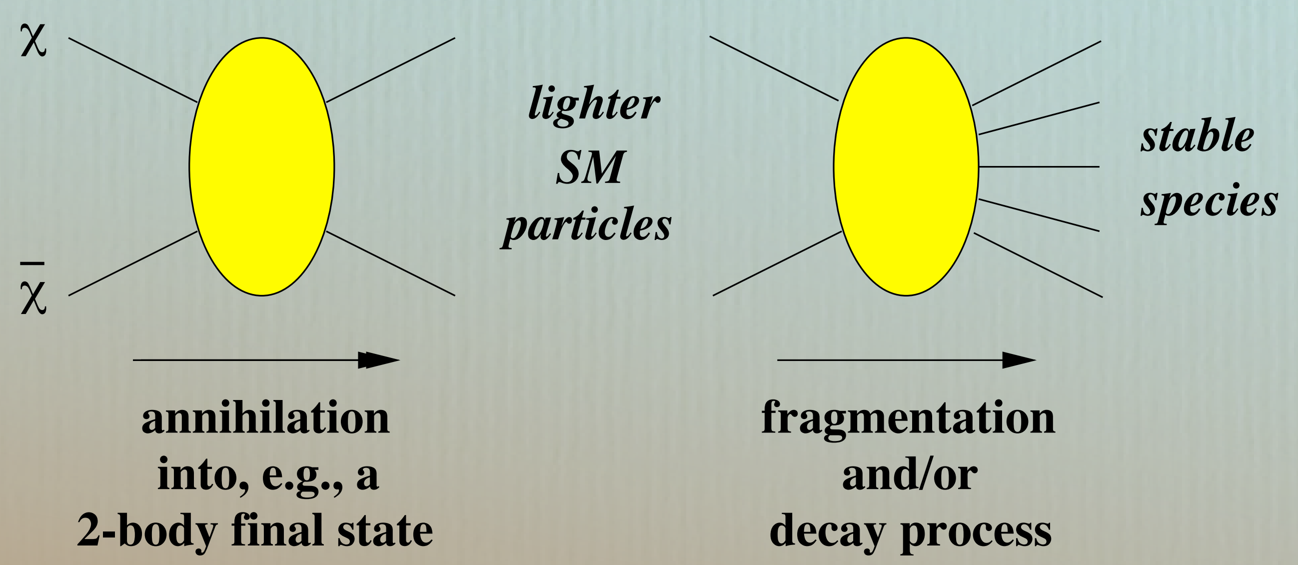
NOTE: much cleaner signature compared to $\bar{p}$

Bottino, Donato, Fornengo & Scopel, 2008

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)

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?

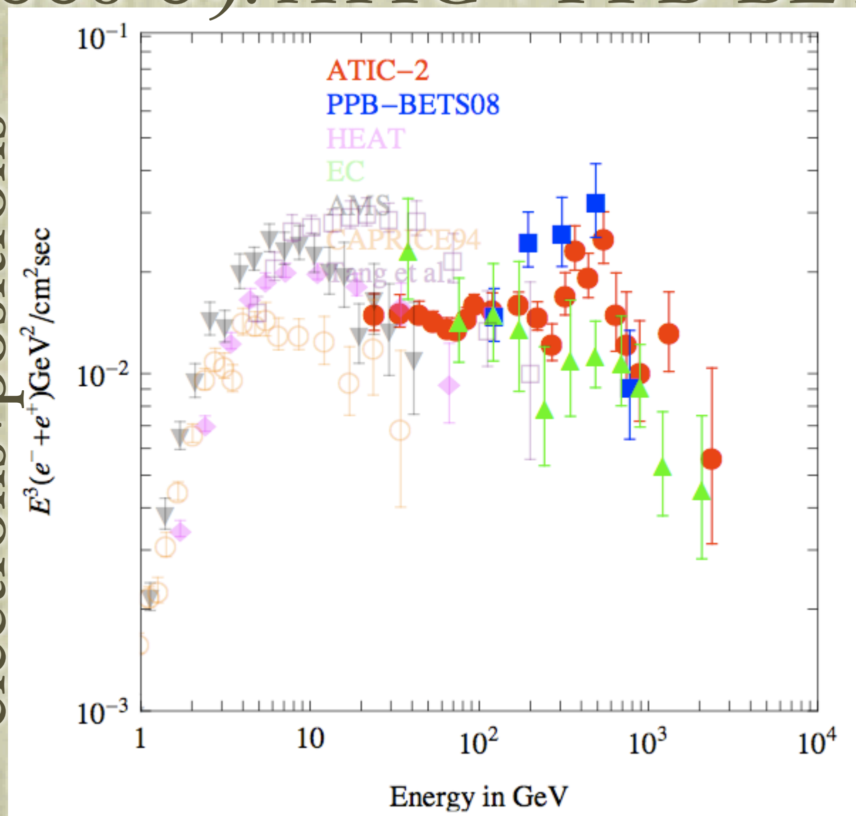
II) angular: flux correlated to DM halo shapes and with DM distributions within halos: central slopes, rich substructure pattern.

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:

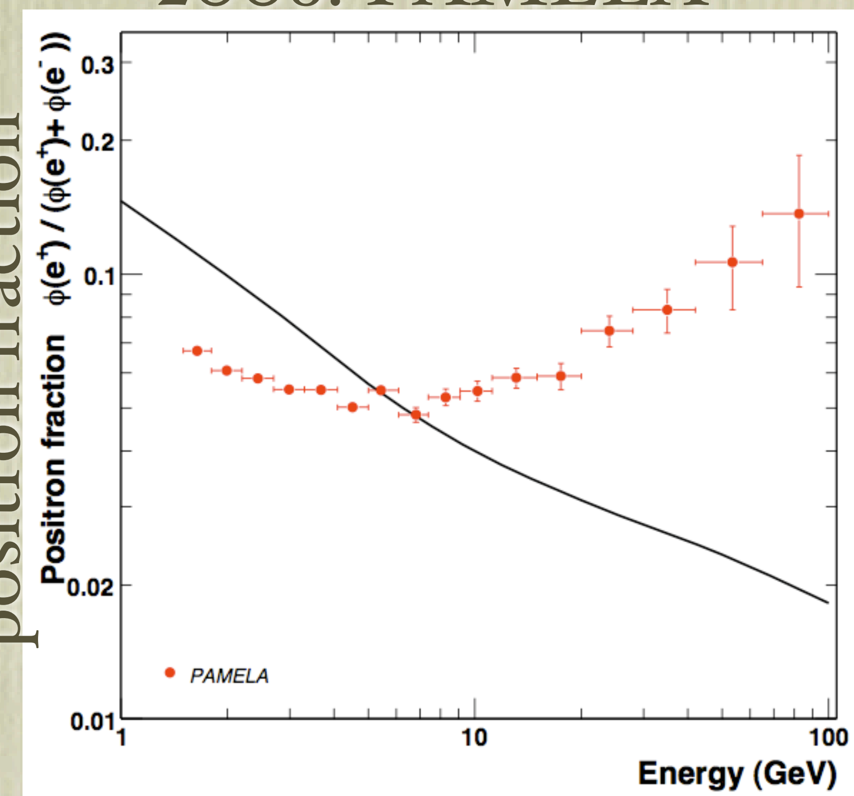
2008-09: ATIC + PPB-BETS

electrons+positrons



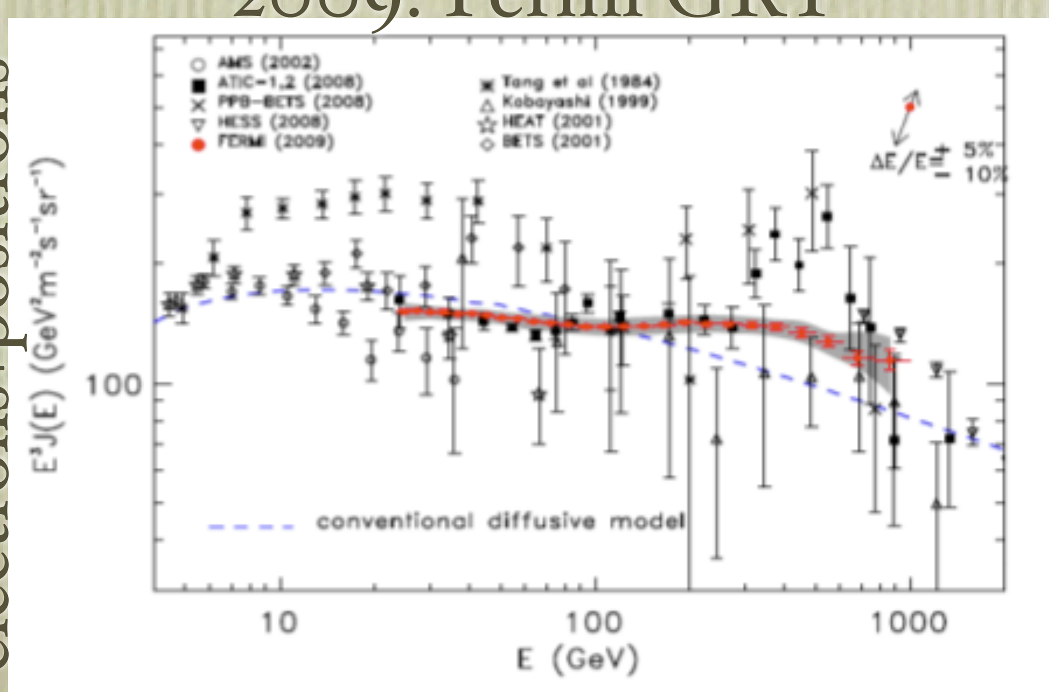
2008: PAMELA

positron fraction



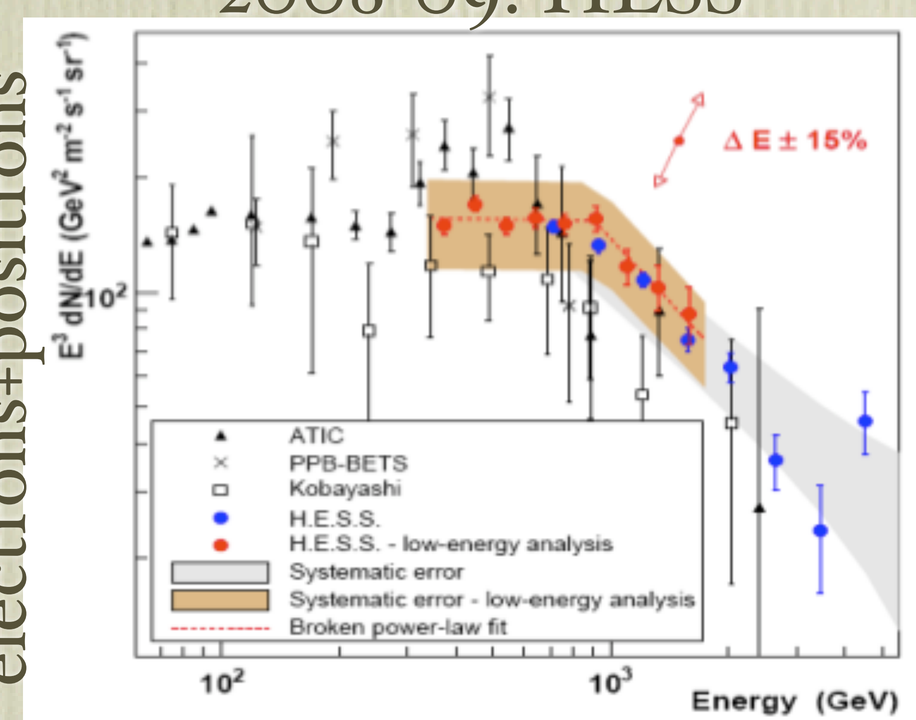
2009: Fermi GRT

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:

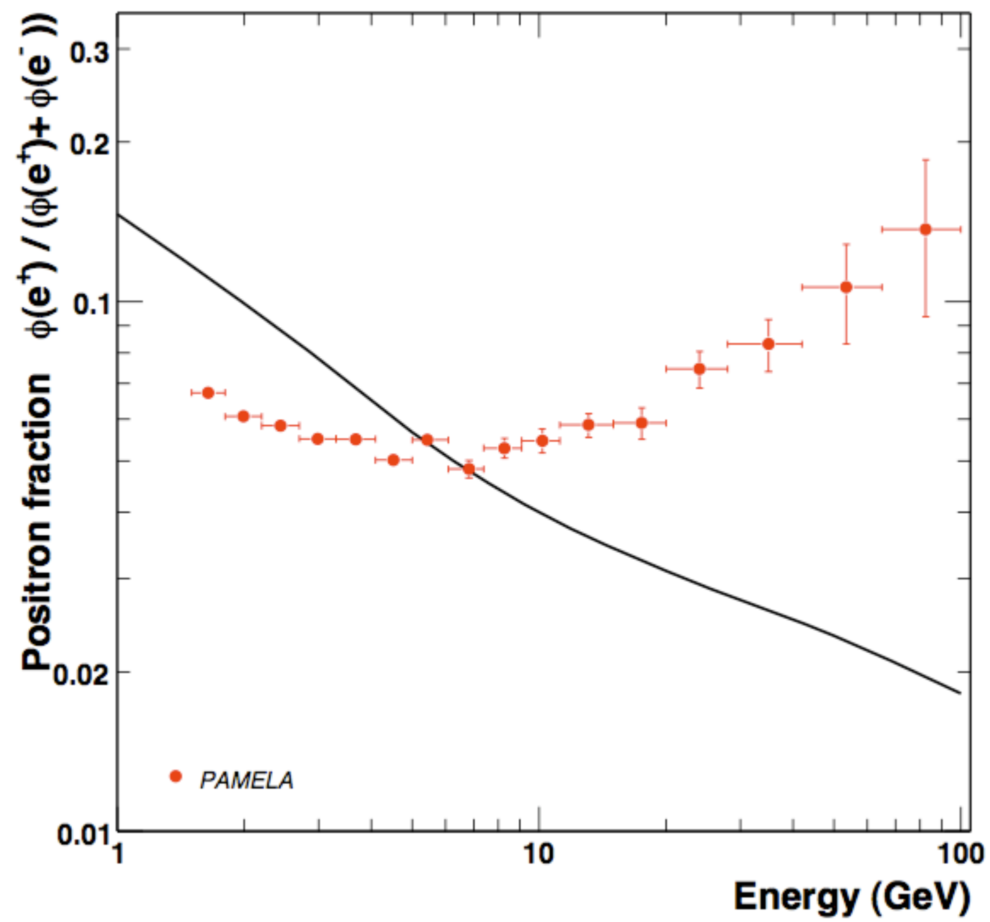
$$\frac{\phi_{e^+}}{\phi_{e^-}} \propto p^{-(\beta_{inj,p}-\beta_{inj,e}+\alpha)}$$

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

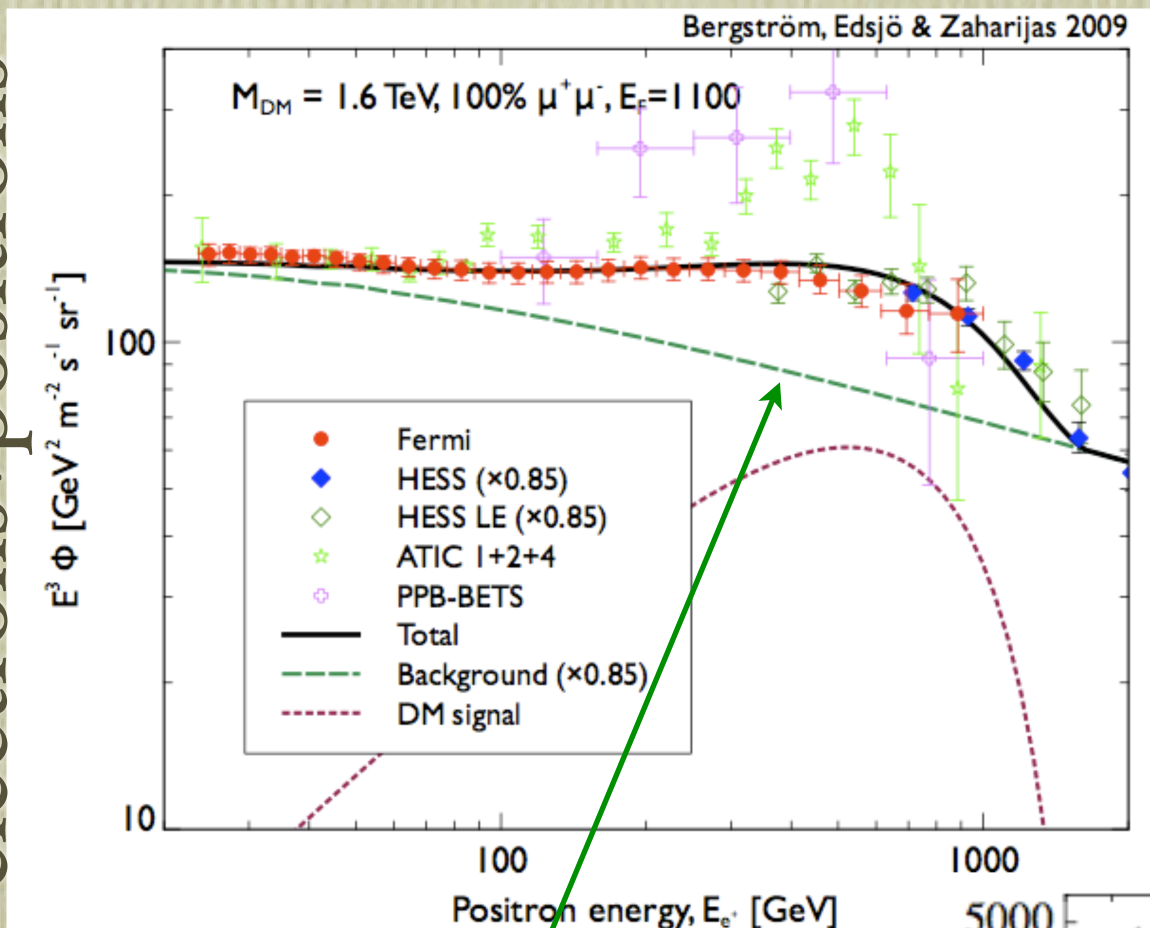
- There is production of secondary species within the CR sources with a mechanism giving a sufficiently hard spectrum (reacceleration at SN remnants?), e.g.: Blasi, arXiv:0903.2794; Mertsch & Sarkar, arXiv:0905.3152

- 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

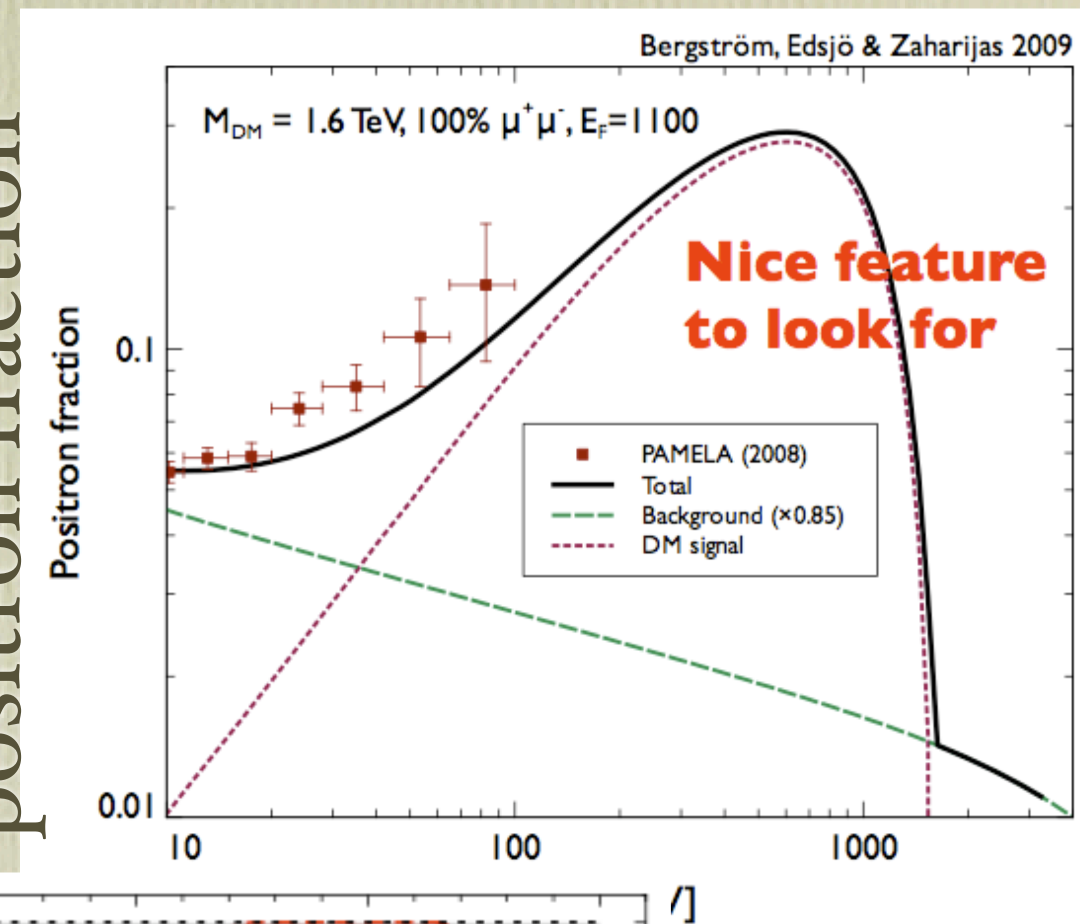
- There is an exotic extra source of primary positrons and electrons: a dark matter source is the most popular option in this class.

Blind fit of the Pamela/Fermi 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:

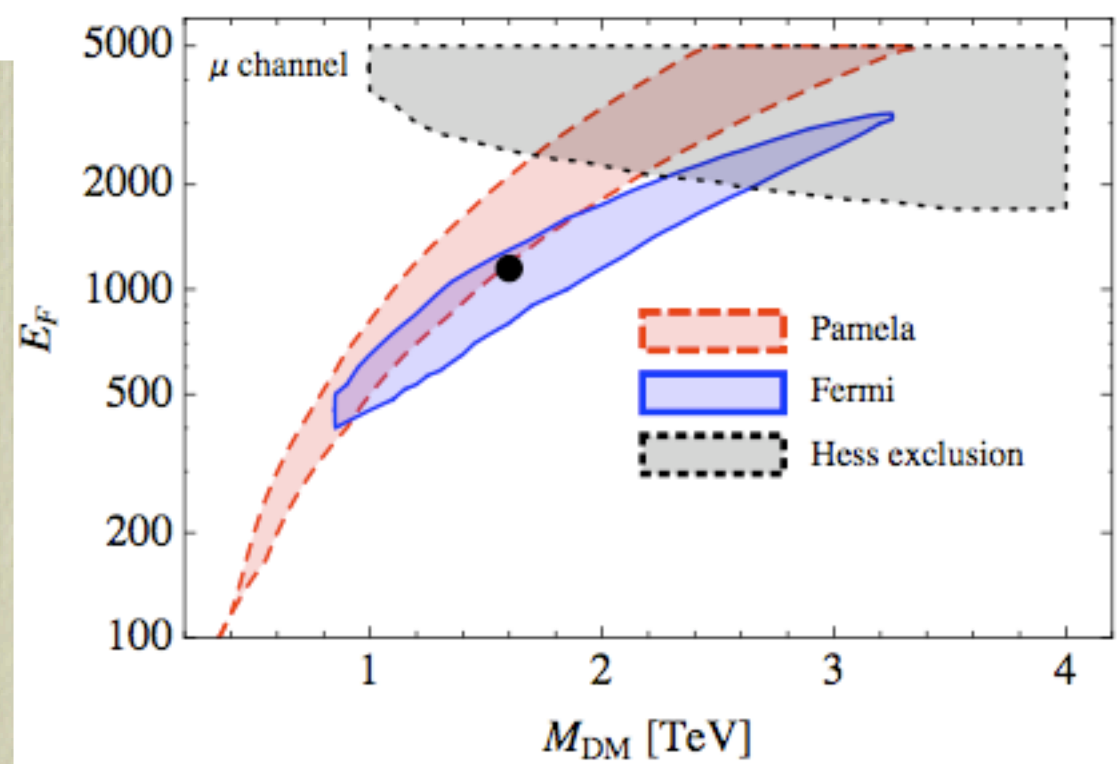
electrons+positrons



positron fraction



background ?!?



This "solution":

annihilation into muons, heavy WIMPs, large "enhancement factors"

Bergström et al., arXiv:0905.0333

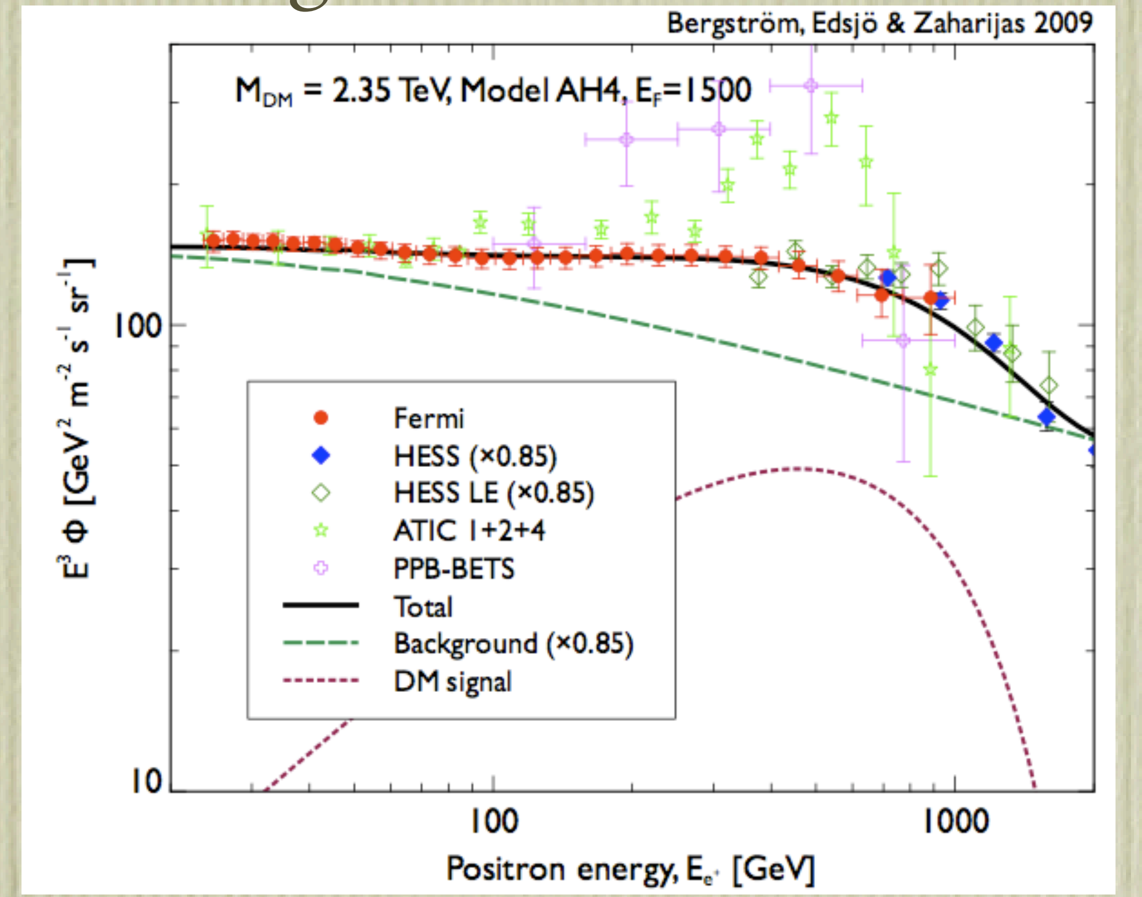
Slightly different results among the numerous fits to the recent data, but convergence on models which are very different from "conventional" WIMP models (e.g. neutralinos in the MSSM). DM seems to be:

- **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 $\langle \rho_\chi^2 \rangle \gg \langle \rho_\chi \rangle^2$.

Hard to extrapolate a connection between this scenario and the direct detection picture. A multi-component dark matter?

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

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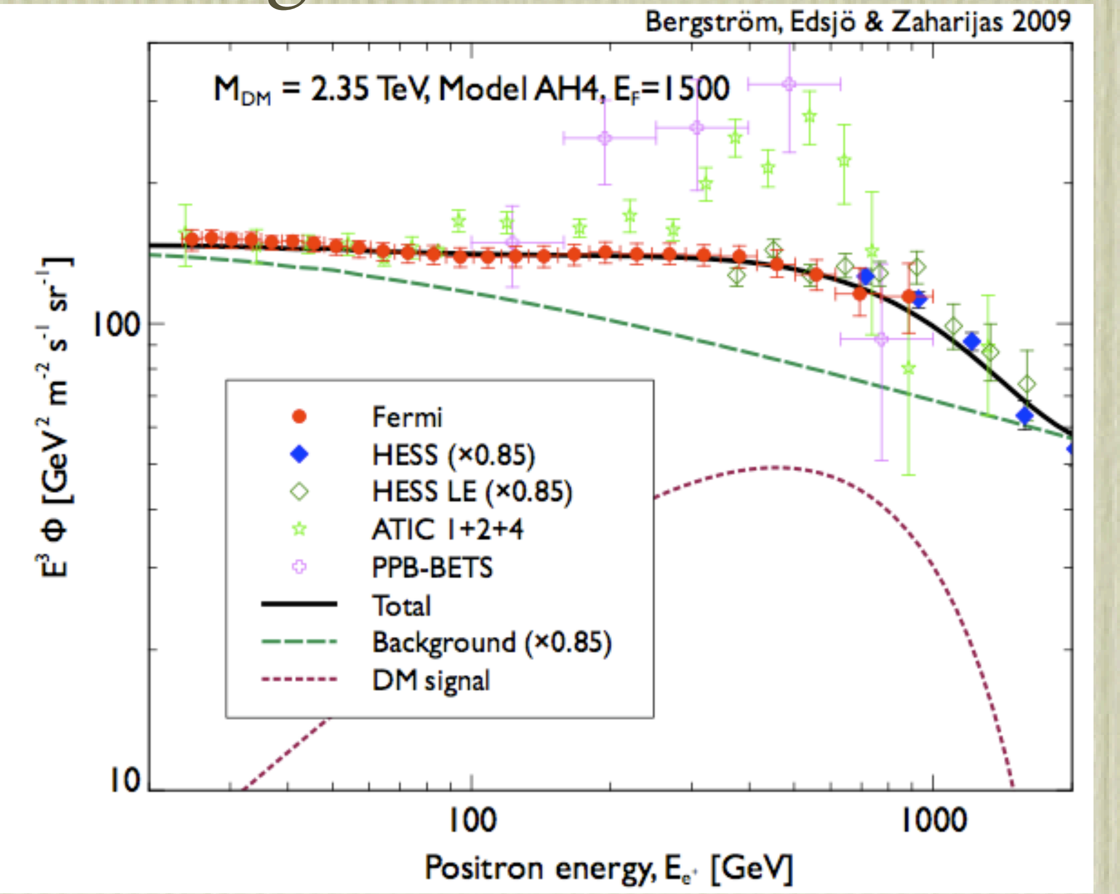
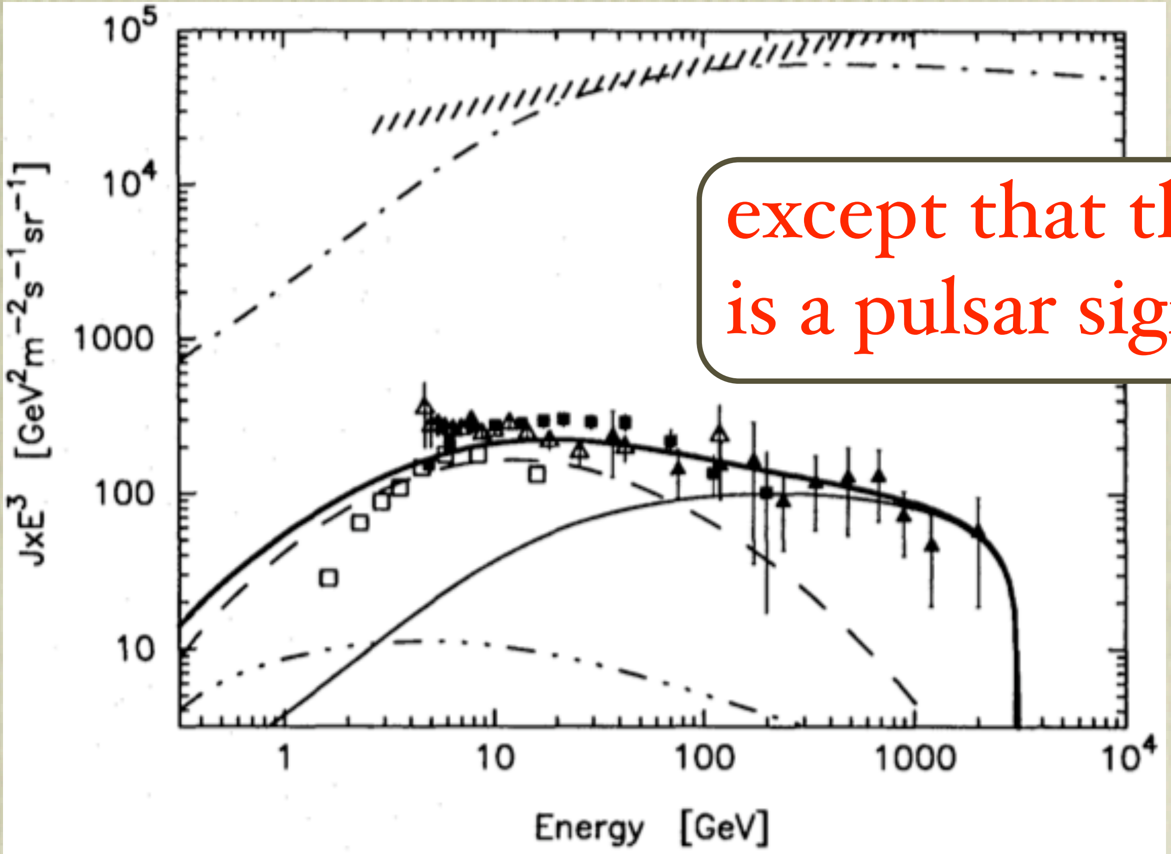


Bergström et al. on model by Arkani-Hamed et al.

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:

Prompt emission of γ-rays associated to three components:

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

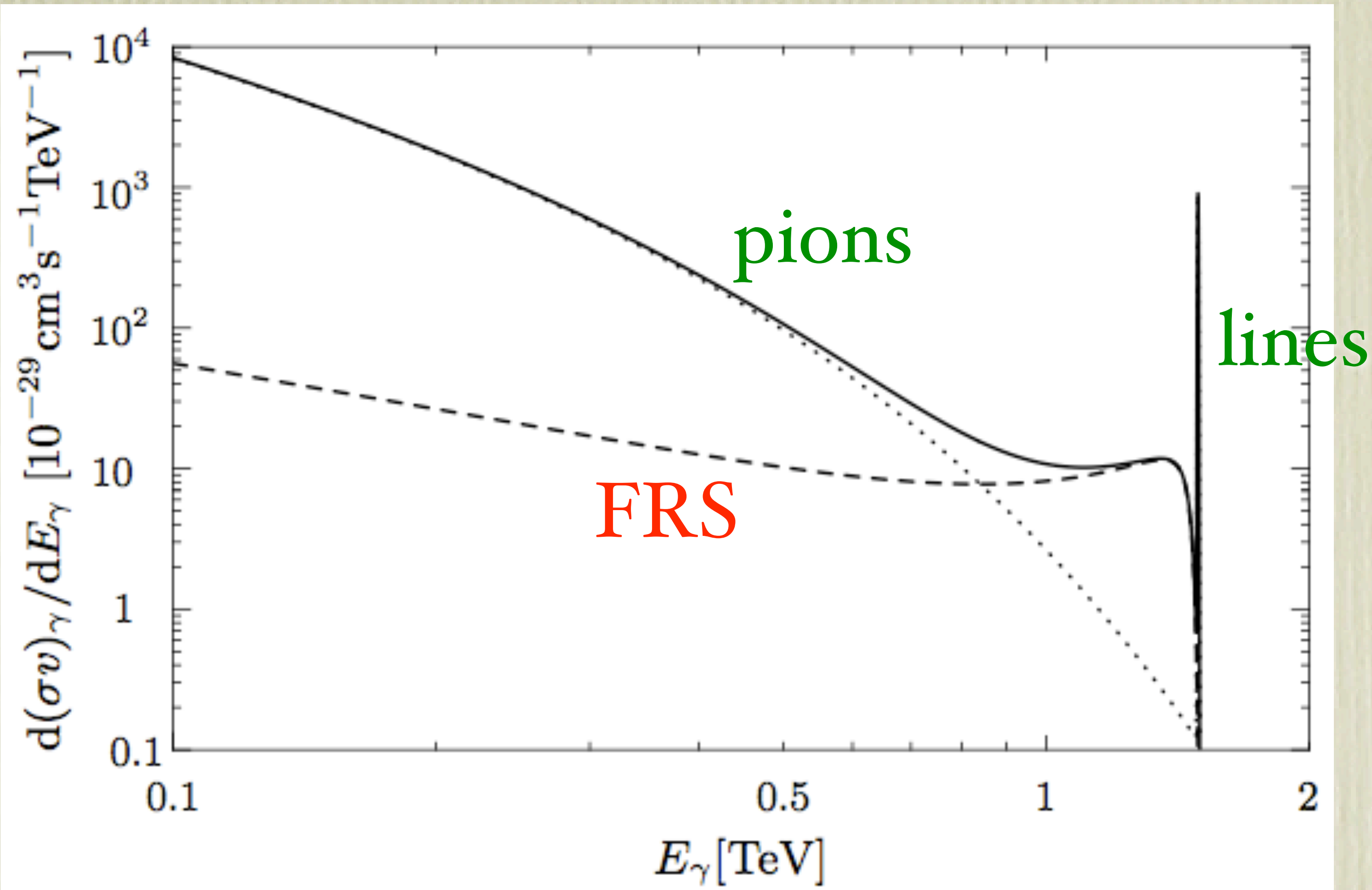
II) Monochromatic: i.e. the 1-loop induced $\chi\chi \to 2\gamma$ and $\chi\chi \to Z^0\gamma$ (in the MSSM, plus eventually others on other models)

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

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

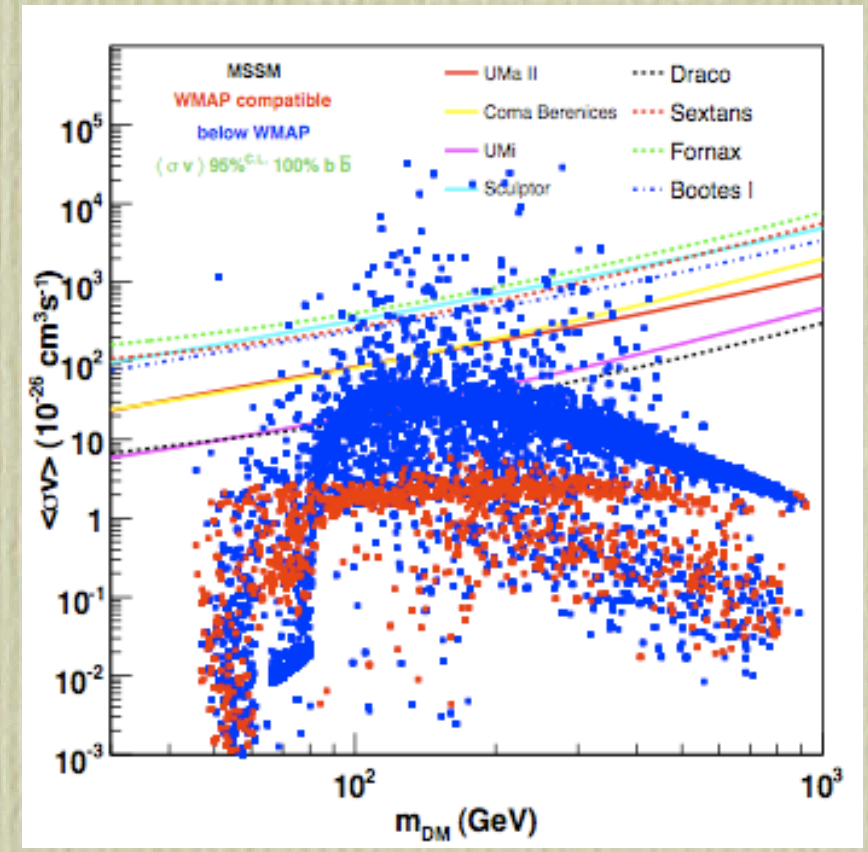
For a model for which all three are large (e.g. pure Higgsino):

Bergström et al., astro-ph/0609510



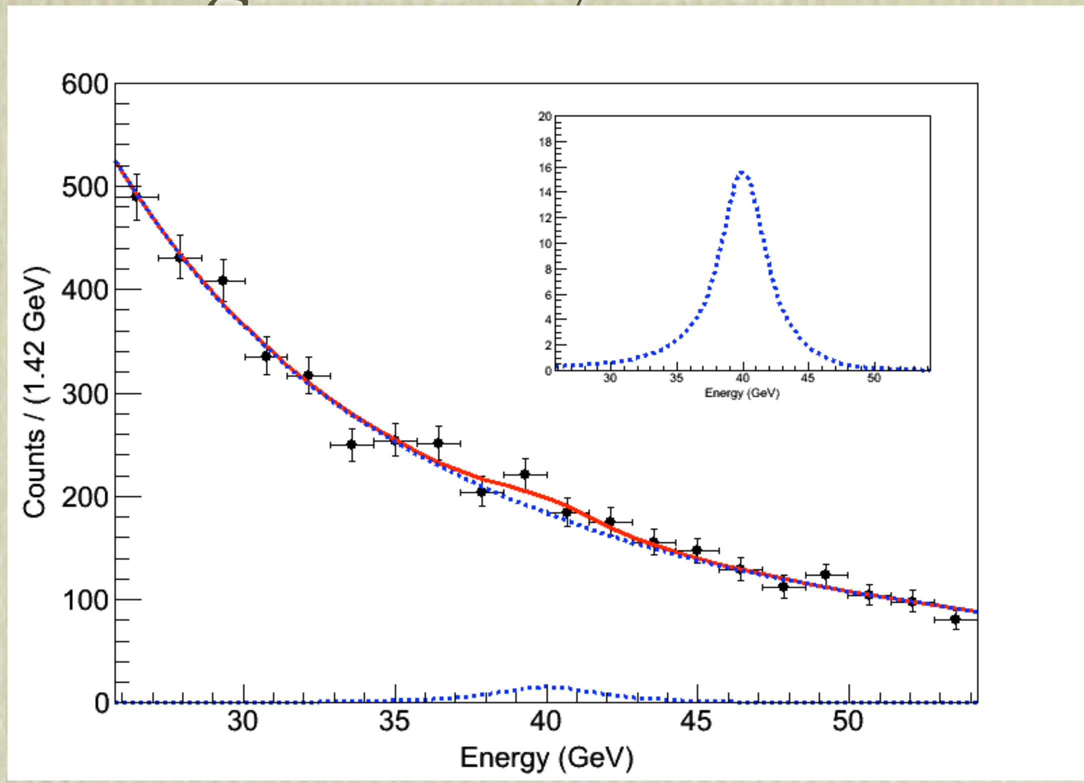
The first upper limits on DM gamma-ray fluxes from Fermi:

dwarf satellites



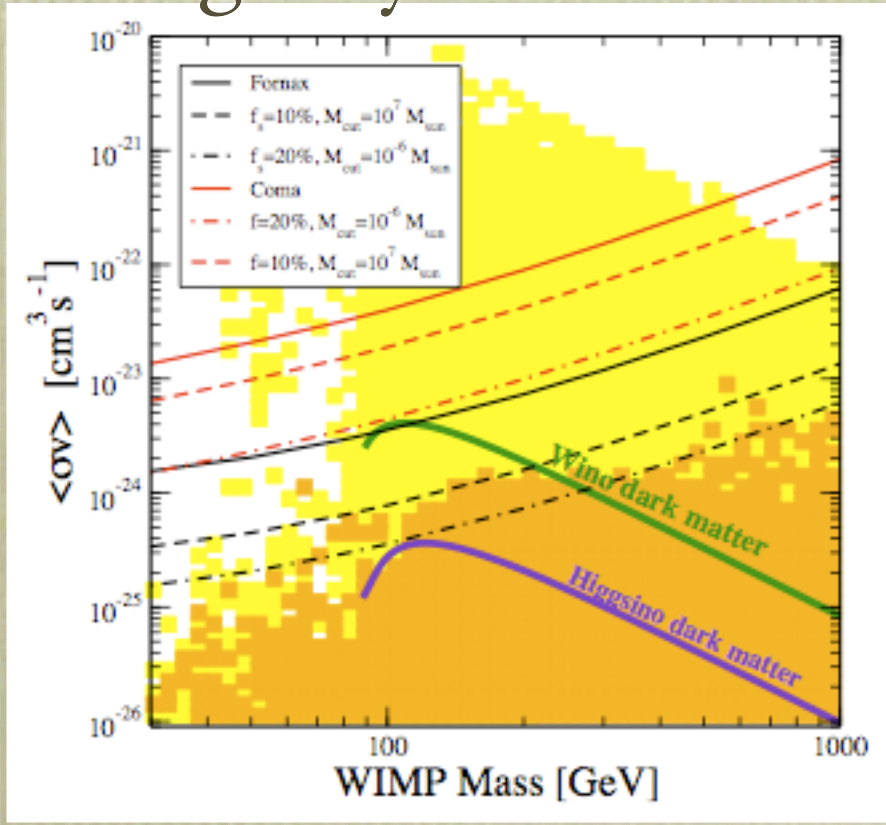
arXiv: 1001.4531

gamma-ray lines



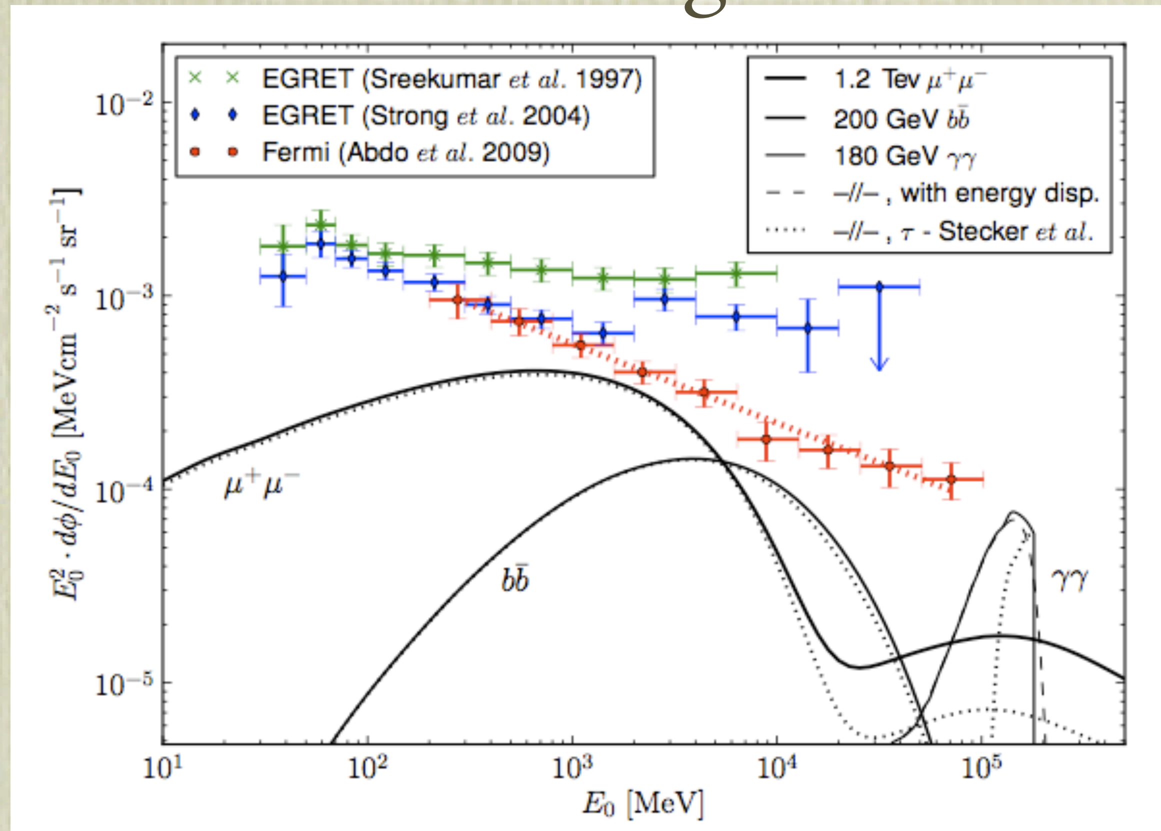
arXiv: 1001.4836

galaxy clusters



arXiv: 1002.2339

diffuse extragalactic



arXiv: 1002.4415

DM annihilations and radiative emission:

The annihilation yields give rise to a multicomponent spectrum:

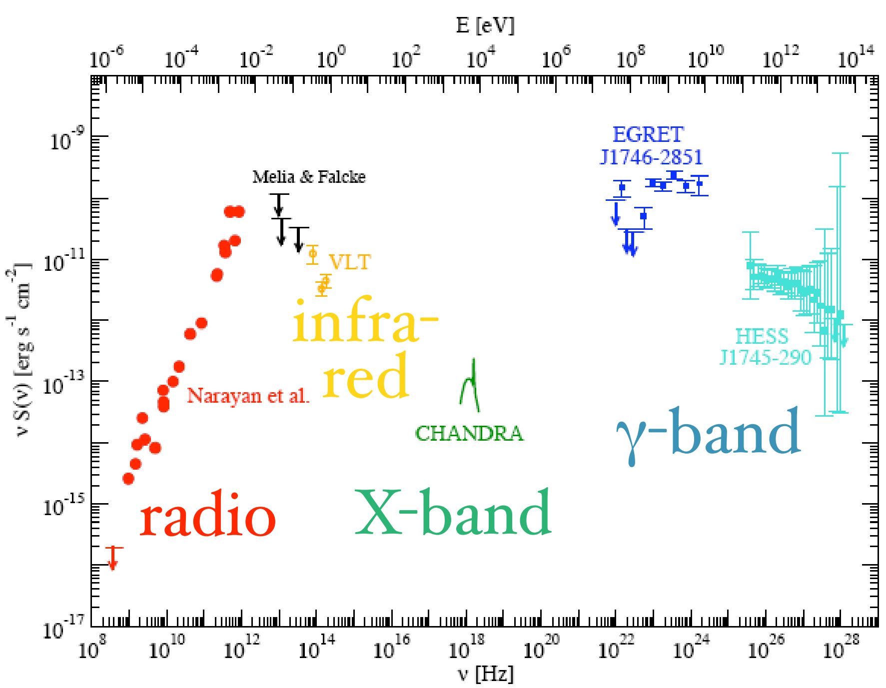
$$\chi\,\bar{\chi} \rightarrow \begin{cases} e^+\,e^- \\ l^+\,l^- \text{ or } \phi\,\phi \rightarrow \ldots + e^+\,e^- \\ P\,\bar{P} \rightarrow \ldots + \pi^\pm \rightarrow \ldots + e^\pm \end{cases}$$

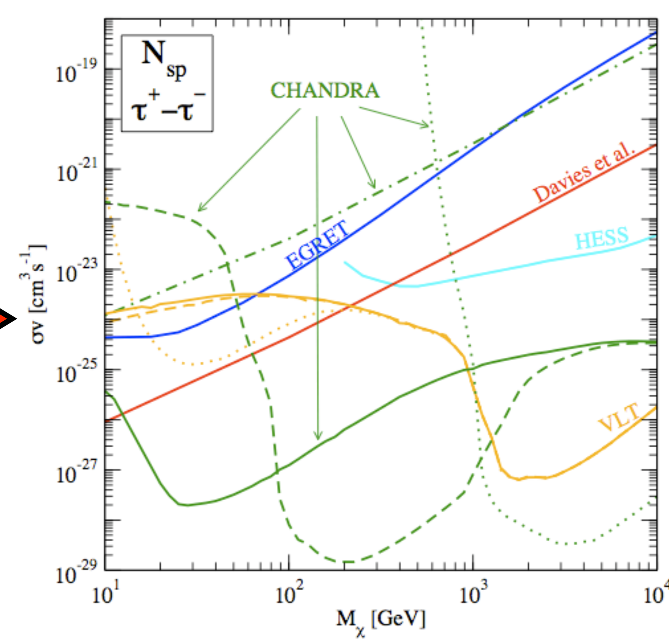
ambient backgrounds and fields

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

→ radio, IR, X-rays, 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:





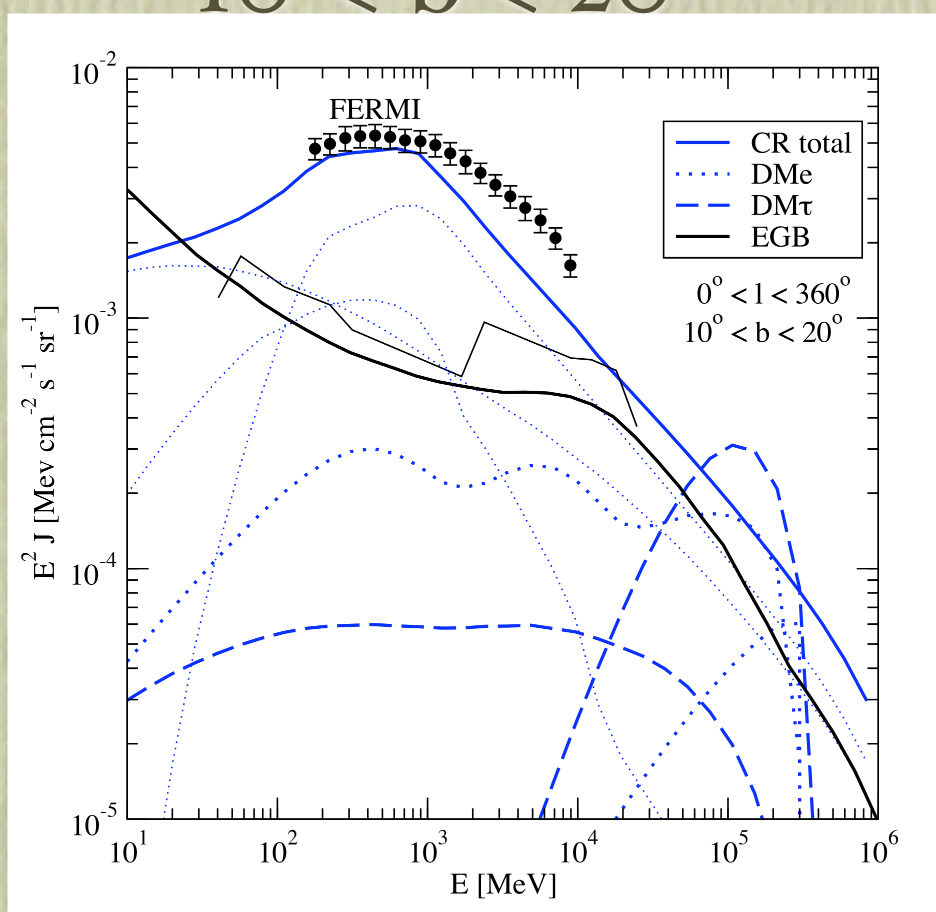
significant limits on WIMP models at any wavelength, unlikely the most stringent from the γ-band (even with Fermi)

Regis & P.U., arXiv: 0802.0234

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

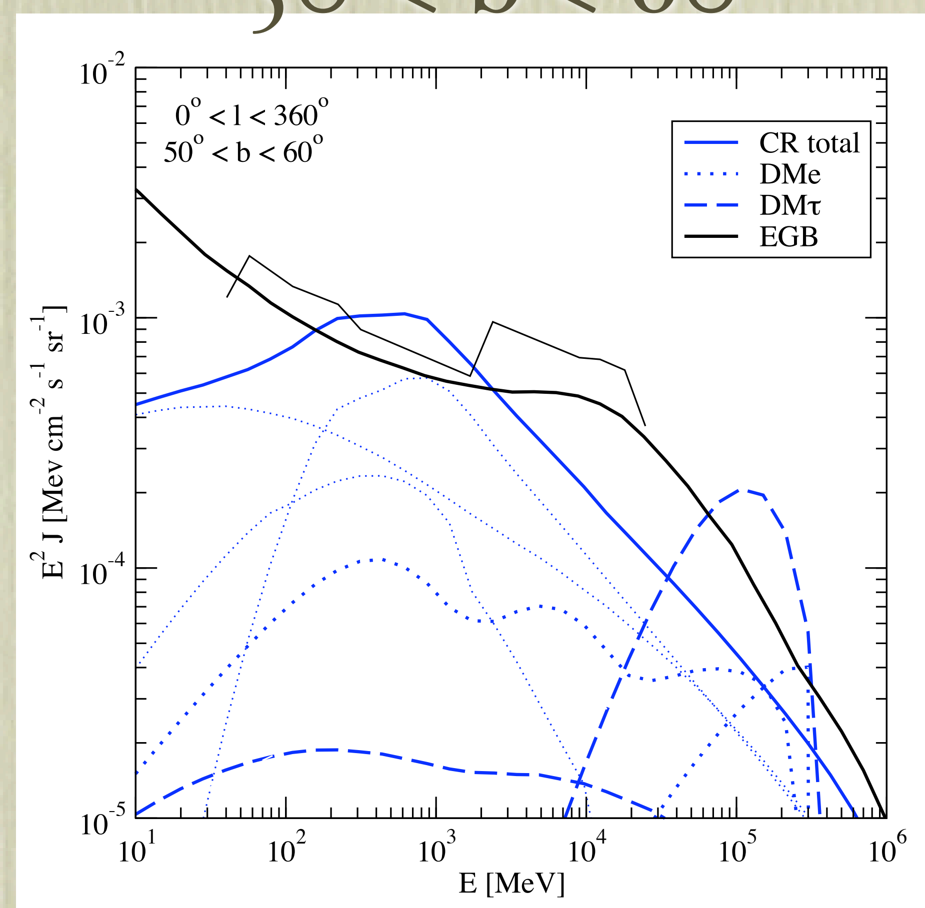
An excess from standard astrophysical sources would be confined to the galactic disc, one from DM annihilation would be spread out to a much larger scale, leading to different predictions for the IC radiation.
IC terms (plus FSR or pion terms) for two sample (leptophilic) models fitting the Pamela excess in the positron ratio:

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



cross checked against Fermi preliminary data at intermediate latitudes

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

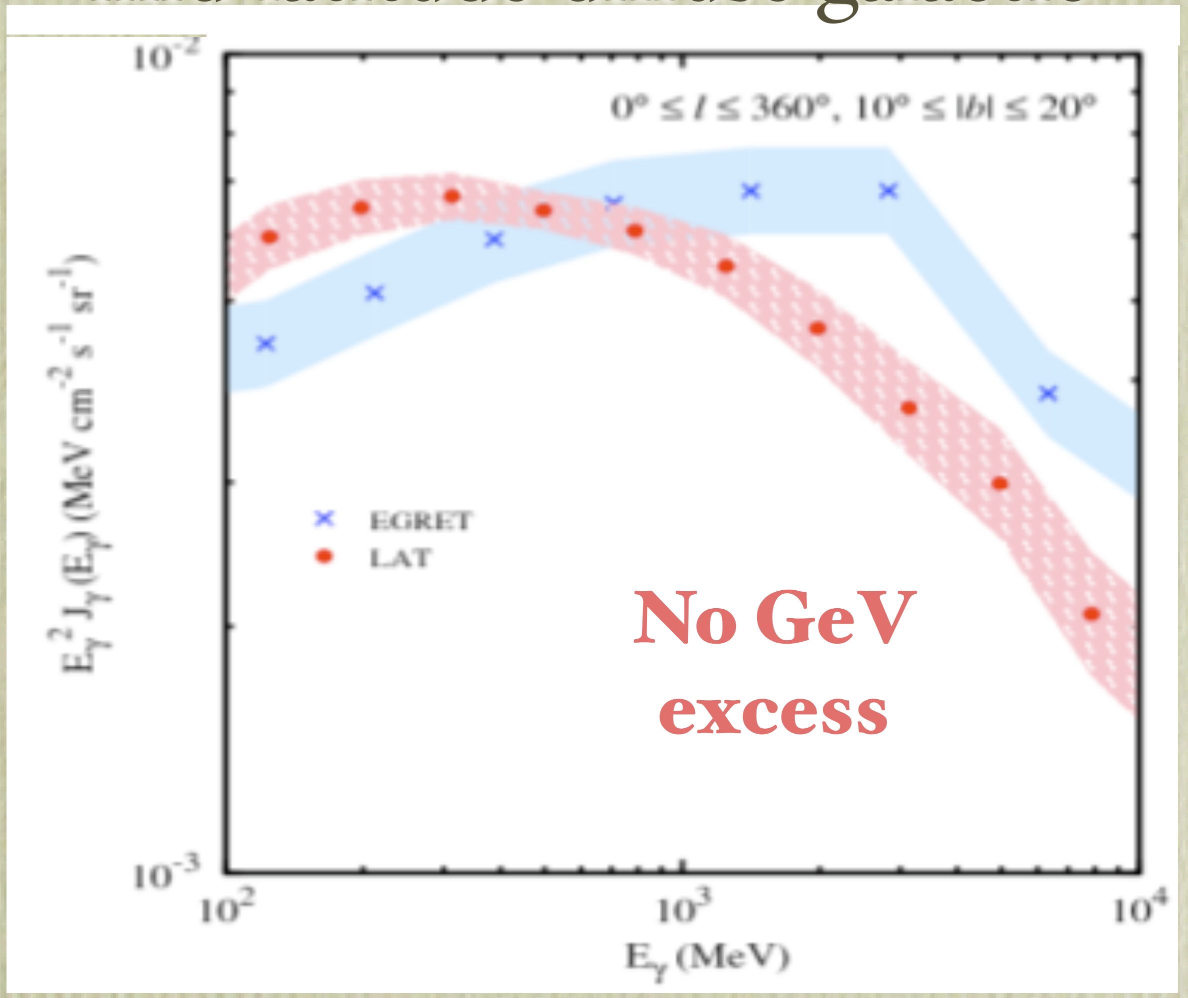


a more solid prediction when looking at high latitudes ...

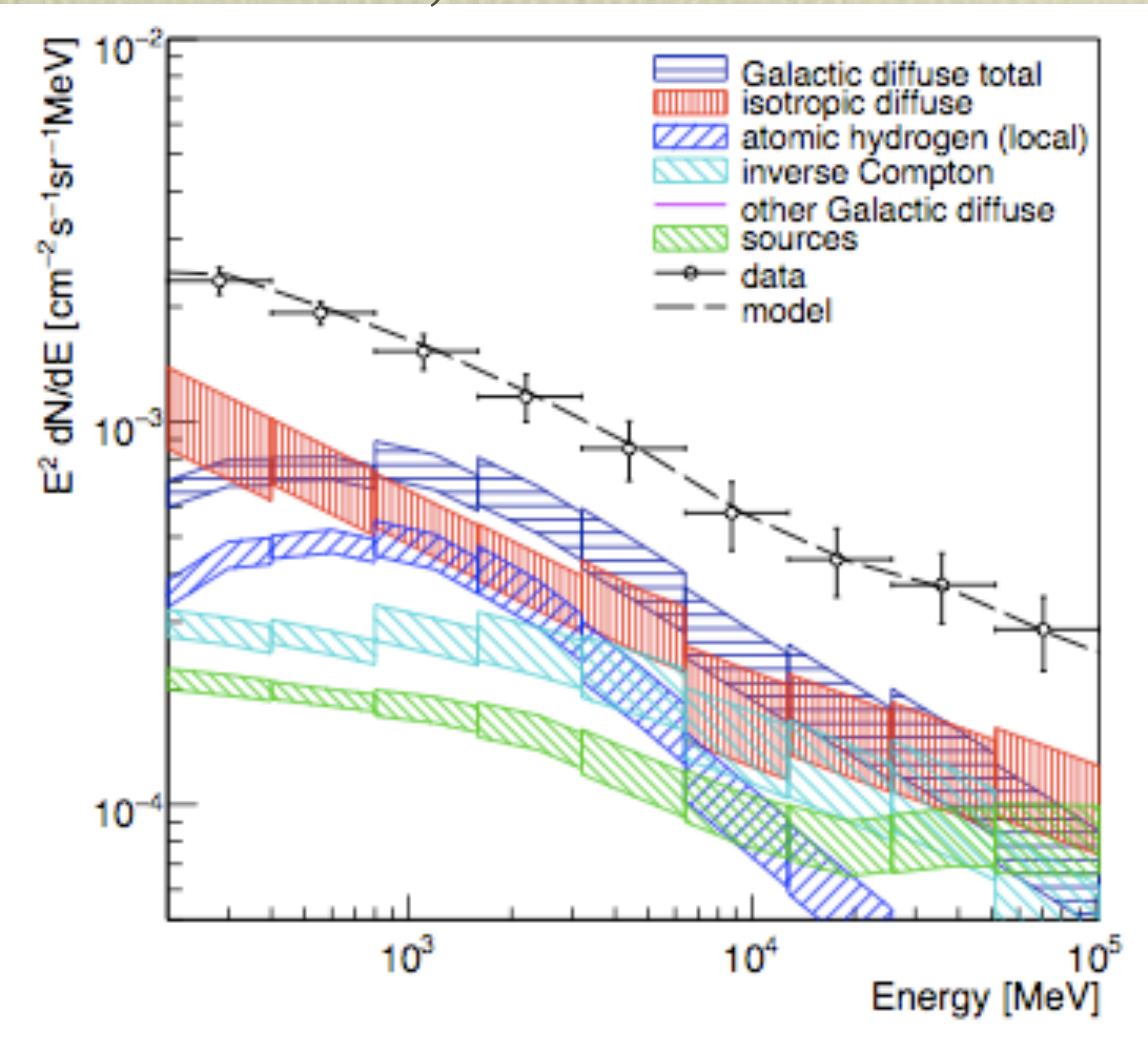
Regis & P.U., arXiv: 0904.4645

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



diffuse, |b| > 60°



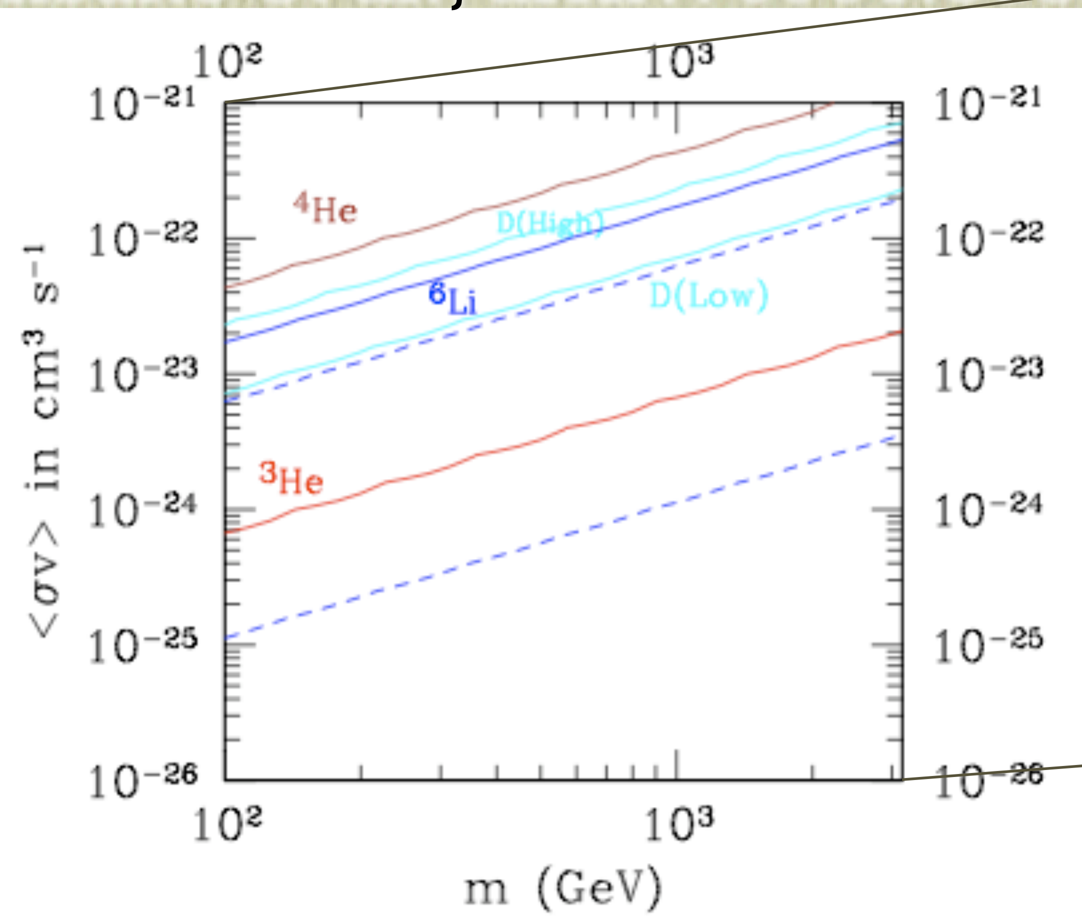
arXiv: 1002.3603

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

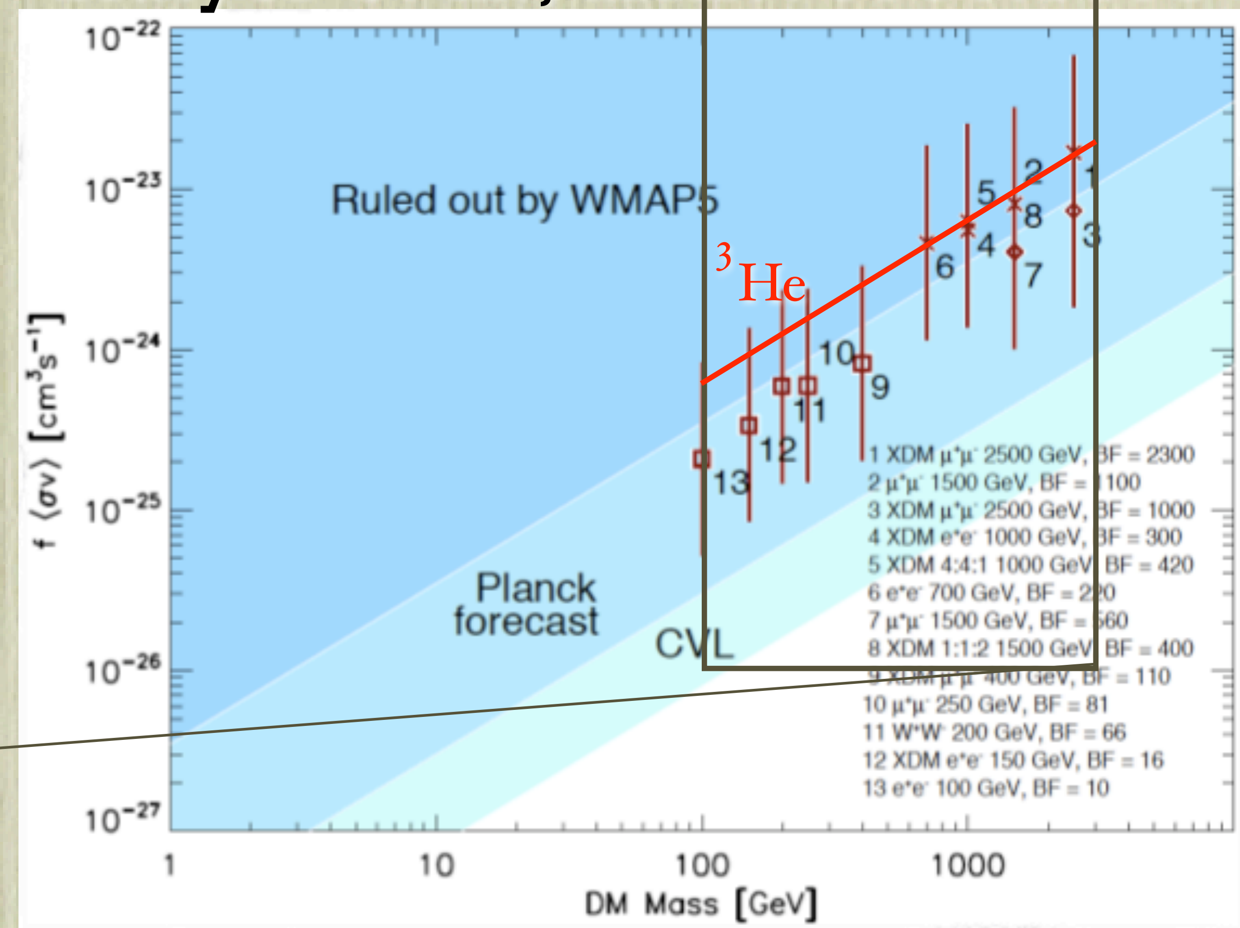
DM annihilations at early stages of the Universe:

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



Slatyer et al., arXiv: 0906.1197



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

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)

Conclusions:

- There have been rapid progresses in experimental tests for the WIMP dark matter framework (or its slight variants).
- The pattern emerging from direct detection seems to favor a light DM particle, say in the mass range between 2 and 10 GeV.
- The DM interpretation of the cosmic lepton puzzle convergences on models with peculiar properties, with heavy (few TeV) DM particles, hard to reconcile with direct detection unless a multicomponent DM picture is invoked.
- The cross-correlation among DM signals as route to DM detection.