Status of Indirect Dark Matter Searches

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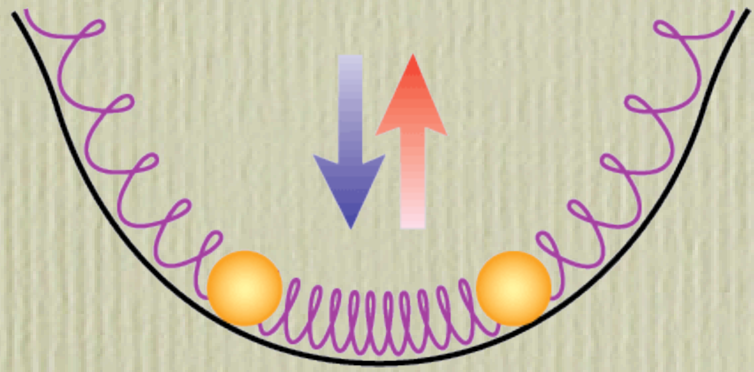
Dark Workshop @ GGI, Firenze, October 26, 2011

Dark matter indirectly detected

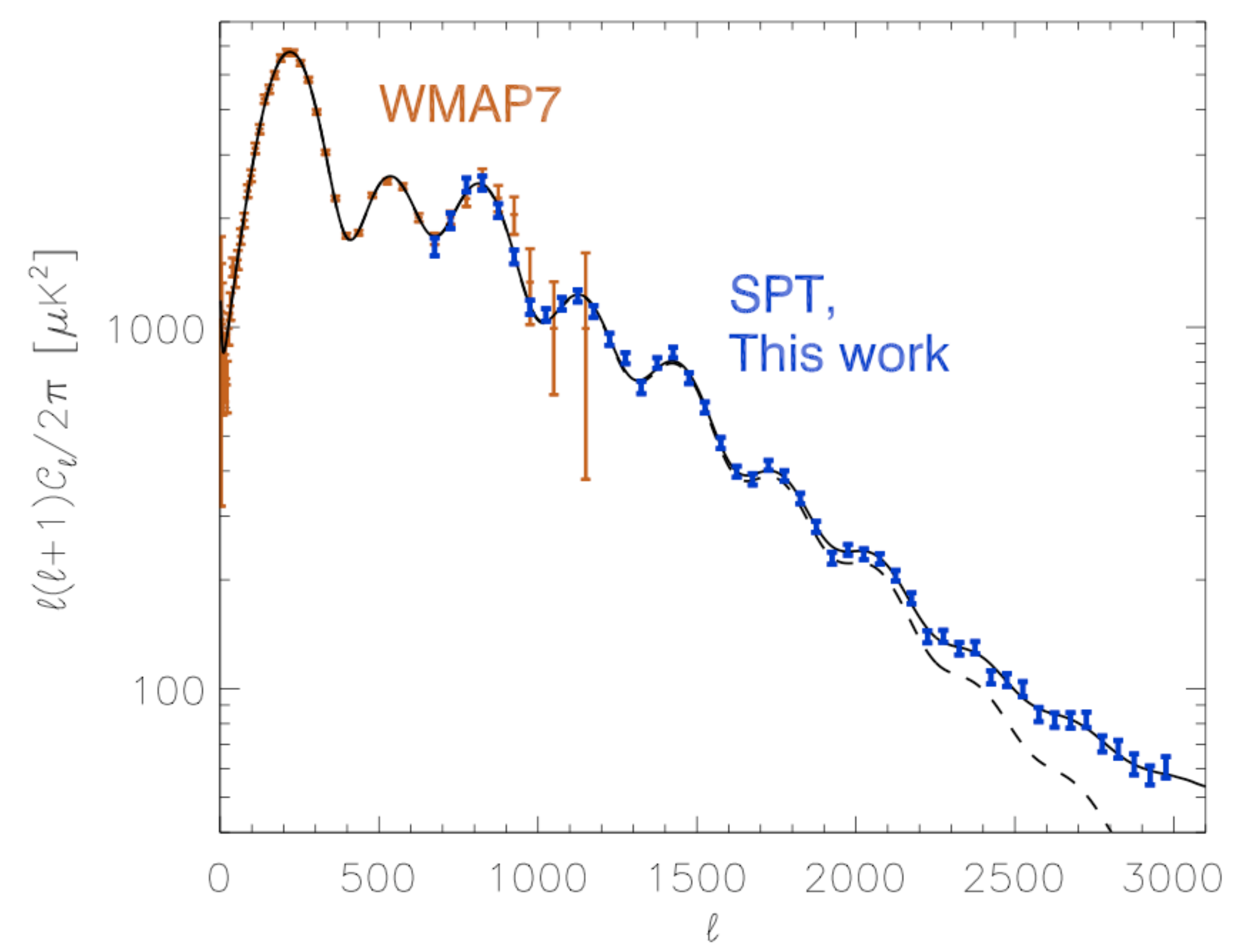
Plenty of indirect (gravitational) evidence for non-baryonic cold (or coldish - as opposed to hot) DM being the building block of all structures in the Universe. E.g.:

it accounts for the gravitational potential wells in which CMB acoustic oscillations take place:



Credit: W. Hu website

(7-yr WMAP, 2010 + STP, 2011)

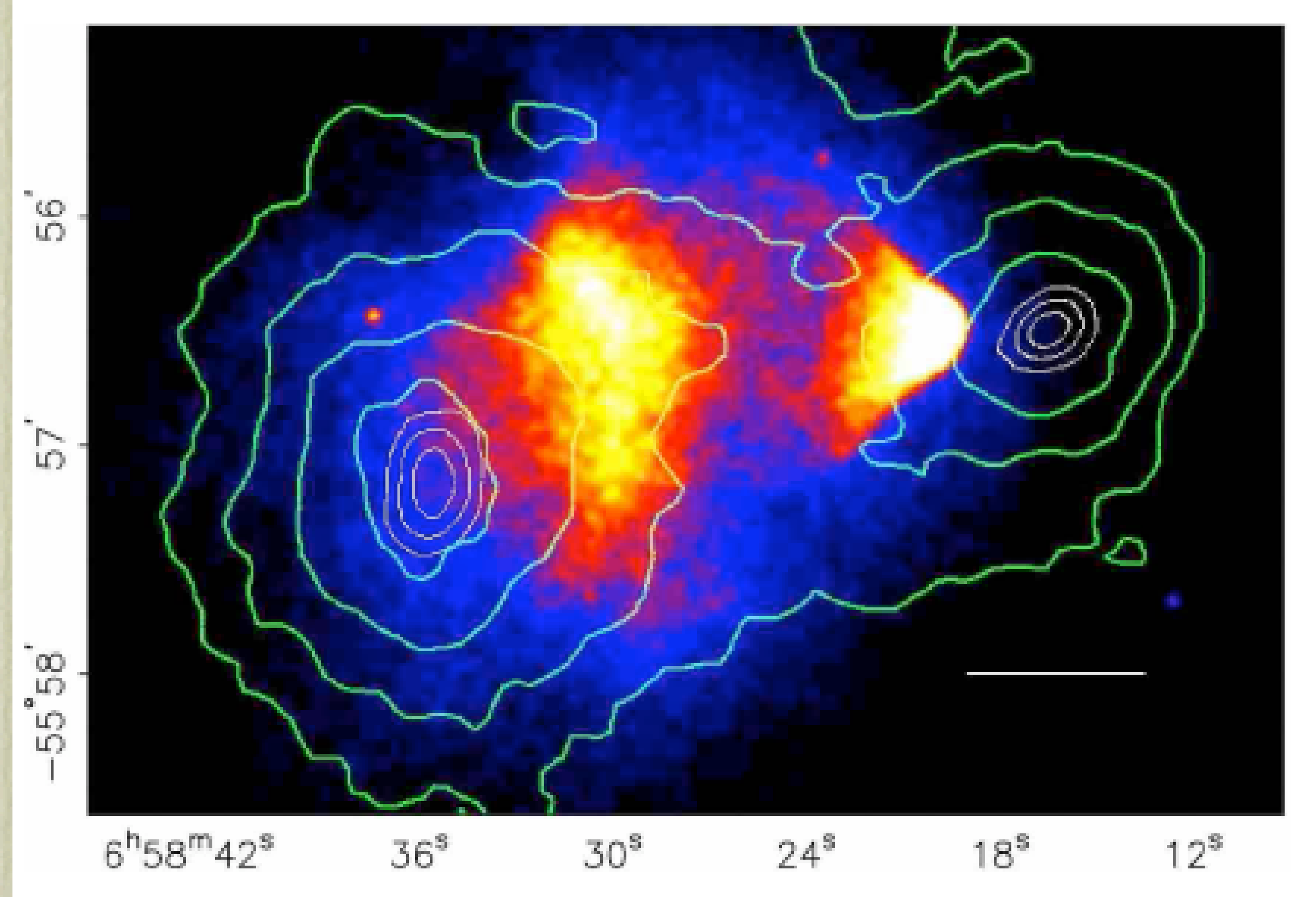


Dark matter indirectly detected

Plenty of indirect (gravitational) evidence for non-baryonic cold (or coldish - as opposed to hot) DM being the building block of all structures in the Universe. E.g.:

(Clowe e al., 2006)

1E0657-558 ("bullet") cluster observation: merging event with collision-less DM traced via gravitational lensing, and hot gas via X-ray imaging.



Very problematic to explain features like the prominence of the third peak in the CMB, or the segregation of mass in the bullet cluster, within a framework only with baryons & a modification of the theory of gravitation: some sort of DM is typically needed.

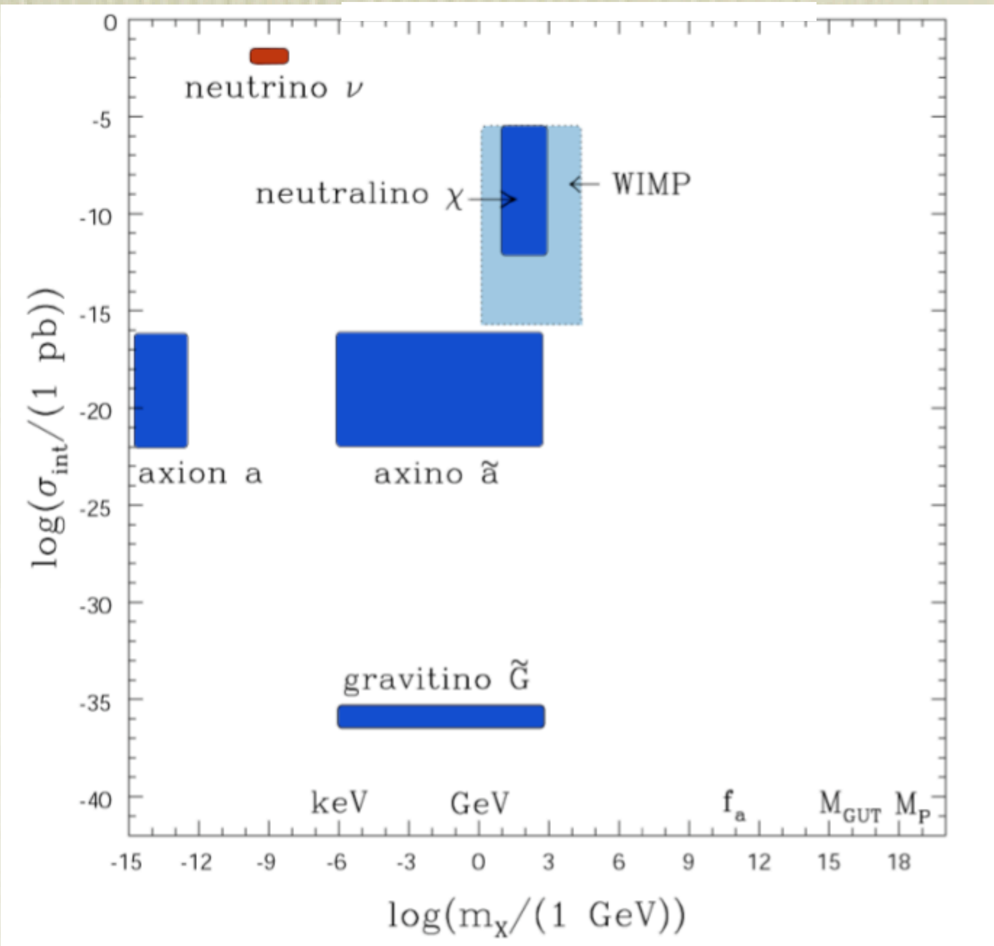
(Indirect) detection of dark matter particles

Dark matter as a beyond-SM particle yet to be discovered? 1001 models in 1001 different frameworks…

(recent review: Bertone, (ed.) e al., 2010)

(just a subset)

How to make the jump from the indirect (gravitational) evidence to the identification of the nature of the DM component?



Astrophysical and cosmological observations give very loose constraints on the properties of DM particles which are crucial for devising a detection strategy: the mass and coupling to ordinary matter.

Credit: L. Roszkowski

(Indirect) detection of dark matter particles

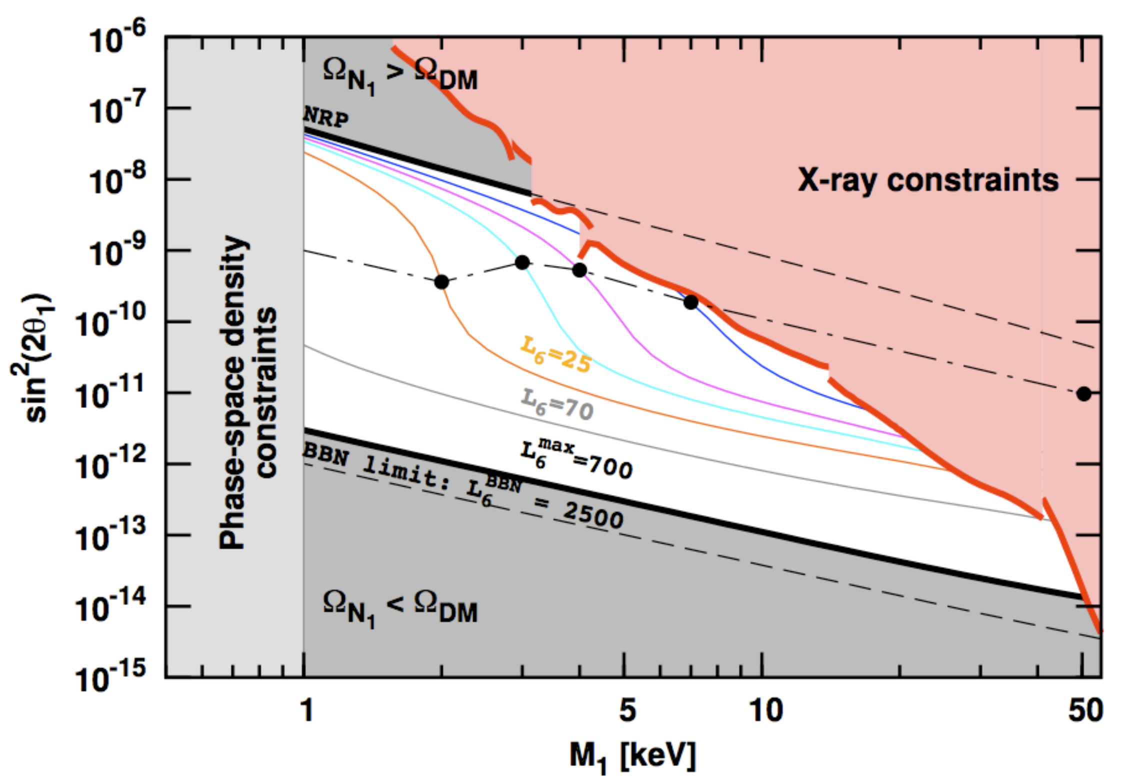
Identify the nature of dark matter particles addressing some of the (possible) shortcomings of the ΛCDM model for structure formation, loosely targeted as an excess of power on small scales? E.g.:

- Warm DM: imprint on the sky of the DM particle free streaming scale, approximately:

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

DM mass scale in, say, the keV - 100 keV range depending on the DM temperature T_p. Popular candidates: sterile neutrinos and gravitinos. Their detection depends on features in the specific model; e.g. for sterile neutrinos:

search for the decay into
1 photon & 1 neutrino
+ constraints from
production + constraints
from being a fermion



Boyarsky et al.,
arXiv:0901.0011

(Indirect) detection of dark matter particles

Identify the nature of dark matter particles addressing some of the (possible) shortcomings of the ΛCDM model for structure formation, loosely targeted as an excess of power on small scales? E.g.:

- Self Interacting DM (Spergel & Steinhardt, 2000): introduce a mean free path for DM-DM collision as a new scale in the model, in principle addressing the cusp problem - see however the limits one can derive from the observed non-spherical shapes of clusters. DM in the form, e.g., of baryon-like particles in a hidden sector may fall in this class.

- Fuzzy DM (Hu, Barkana & Gruzinov, 2000): the new scales comes in as the De Broglie wavelength associated to an ultra-light scalar DM particle. Very hard to find a particle physics candidate in this class.

In case astrophysics and cosmology do not provide a guideline, the only other option is to refer to a mechanism for generating dark matter particles. In this respect the most beaten paths have been to introduce DM as a condensate (e.g. axion DM), or as a thermal relic particle.

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

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

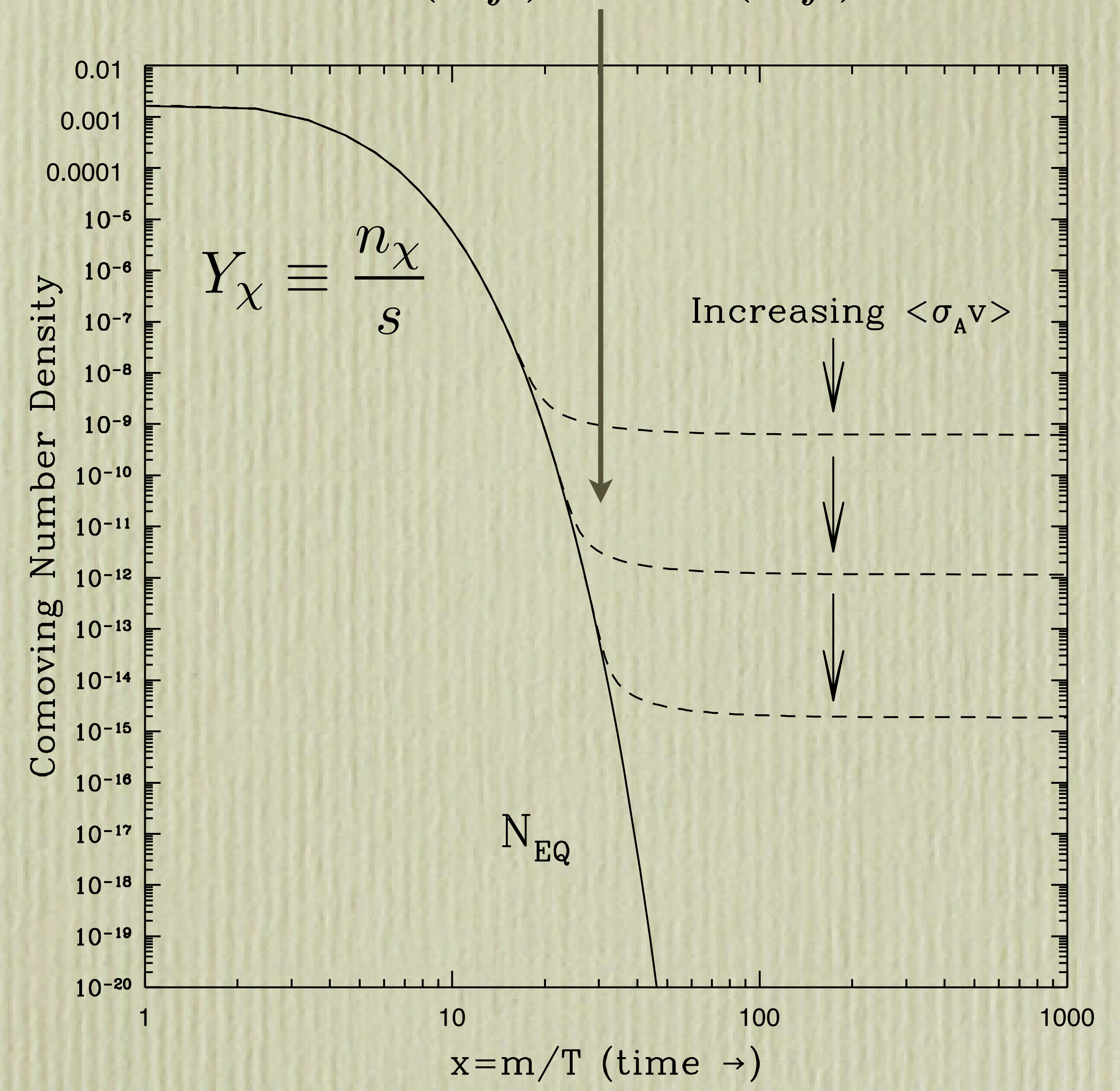
$\chi\bar{\chi} \rightarrow P\bar{P}$

χ in thermal (chemical) 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)

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

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

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

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. Plenty of frameworks in which it is viable to apply this recipe.

WIMPs as non-thermal DM

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 plausible scenario (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 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:

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

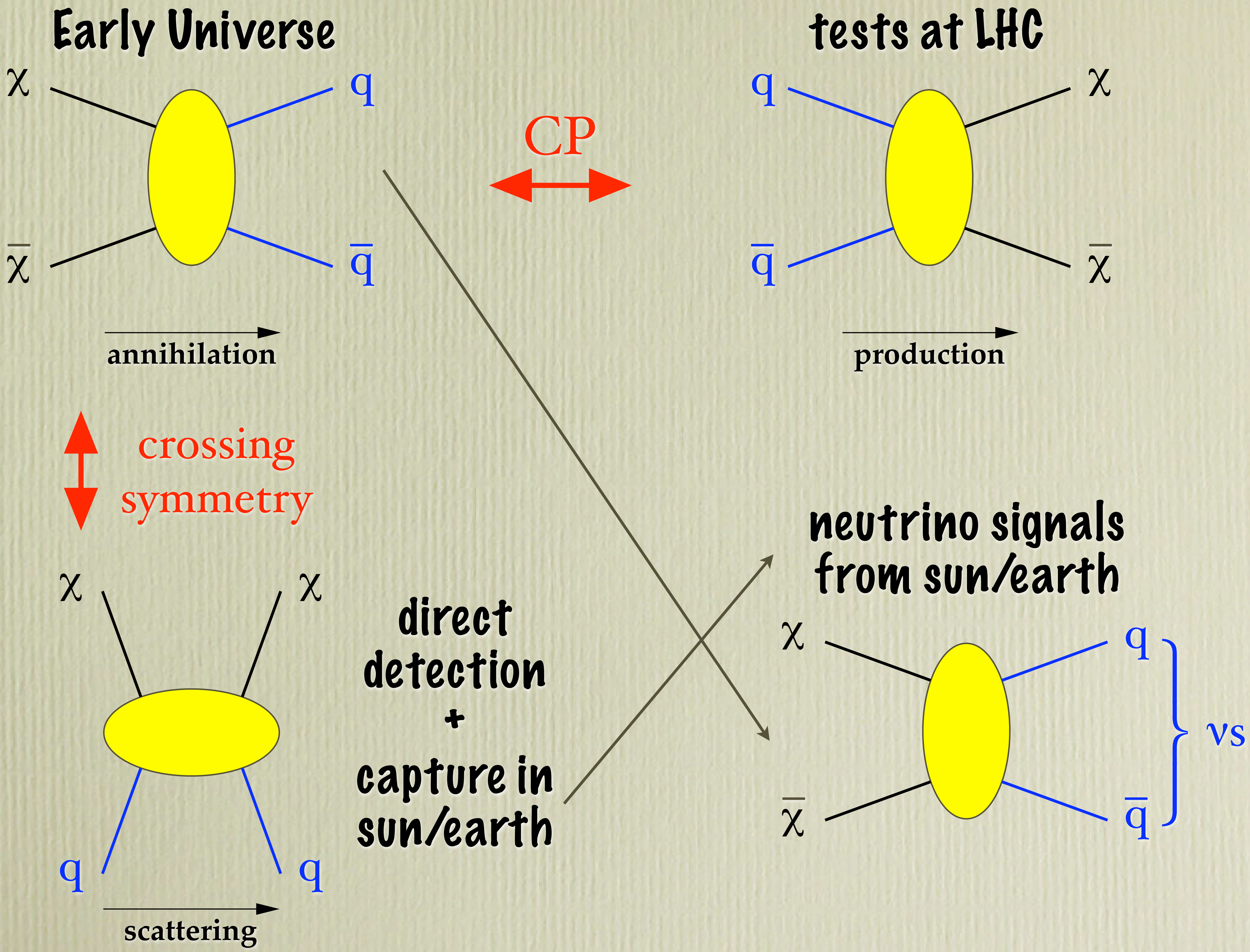
giving:

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

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

Note: in this scenario, WIMPs, which are relativistic at injection, can be Warm DM (or even Hot DM; Lin et al. astro-ph/0009003). One needs to compute the kinetic decoupling (when scattering processes go out of equilibrium, e.g., Bringmann & Hofmann hep-ph/0612238) as appropriate for a low temperature reaheating Universe, see, e.g., Arcadi & PU, arXiv: 1104.3591.

WIMP coupling to ordinary matter



Early Universe

CP

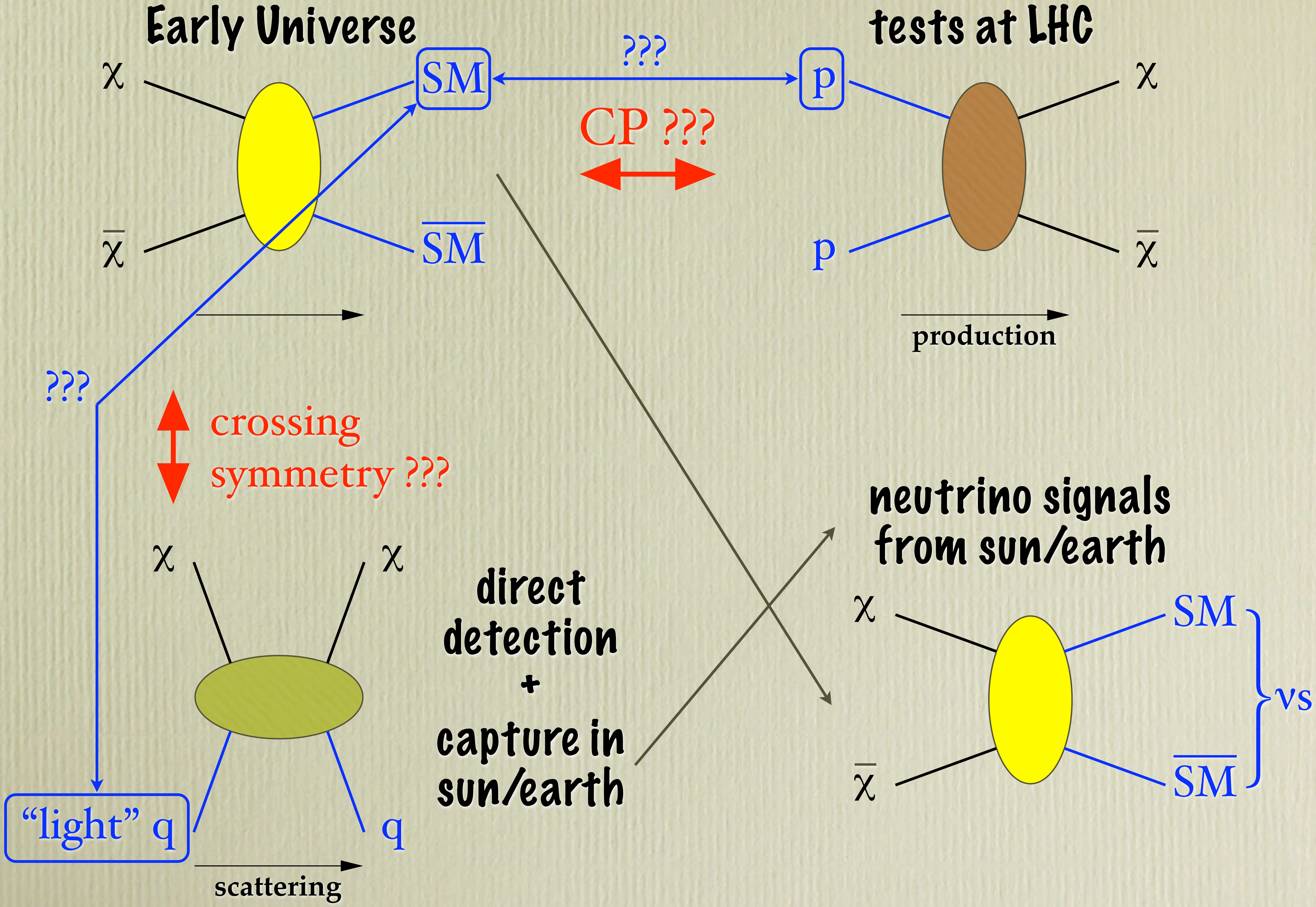
tests at LHC

crossing symmetry

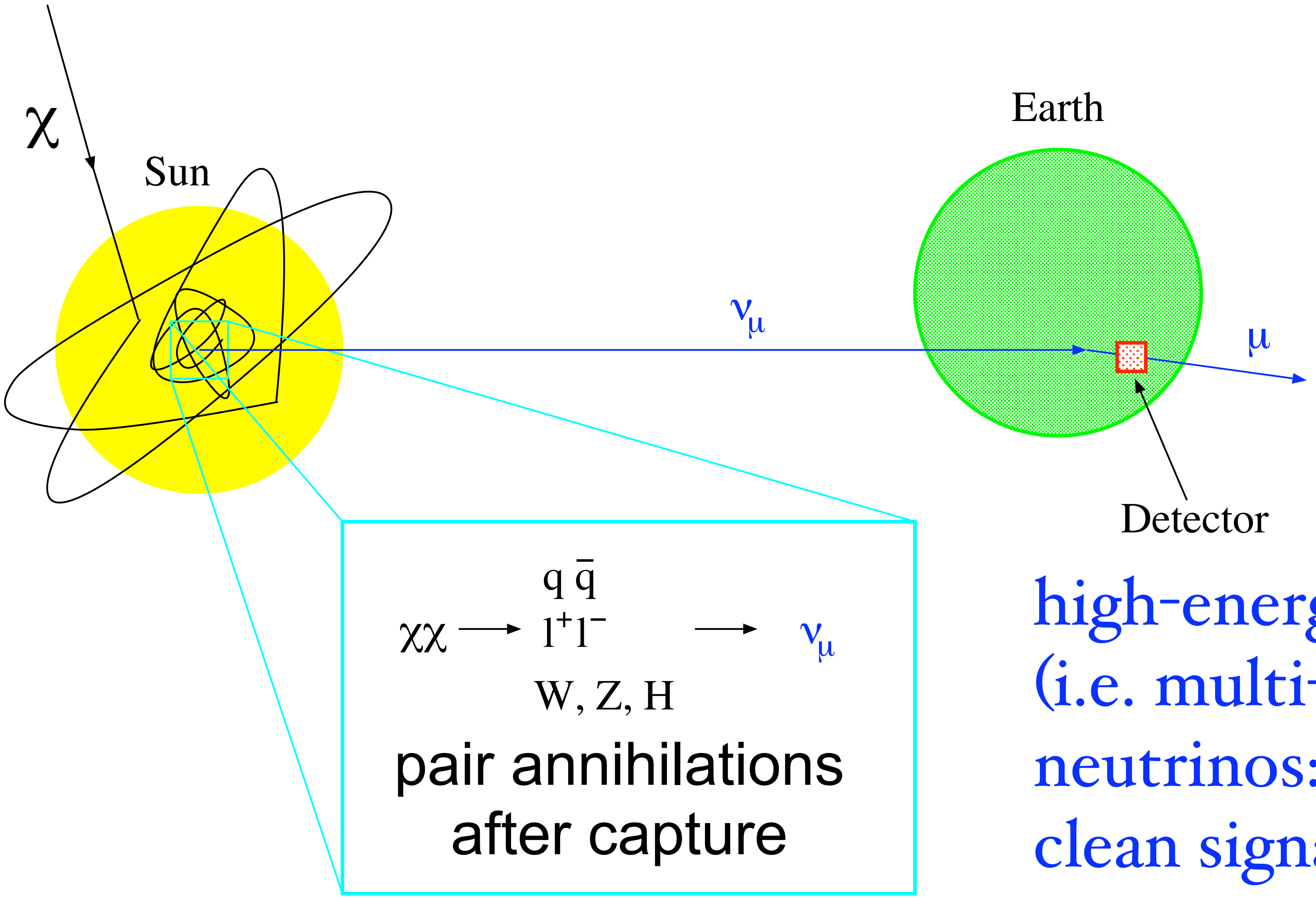
direct detection + capture in sun/earth

neutrino signals from sun/earth

WIMP coupling to ordinary matter ???



WIMP searches with neutrino telescopes



$$\chi\chi \longrightarrow \begin{array}{c} q\,\bar{q} \\ l^+l^- \\ W, Z, H \end{array} \longrightarrow \nu_\mu$$

pair annihilations after capture

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

Another possibility: $\chi\chi \to \phi\phi \to e^+e^-$ with Φ decaying outside the Sun (**Schuster et al., arXiv:0910.1839**). Recently tested by Fermi, setting competitive upper limits (**Ajello et al., arXiv:1107.4272**).

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

$$\frac{dN}{dt} = \underset{\text{capture}}{\boxed{C_c}} - \underset{\text{annihilation}}{\boxed{C_a}} N^2$$

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:

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

(??? - rarely in equilibrium)

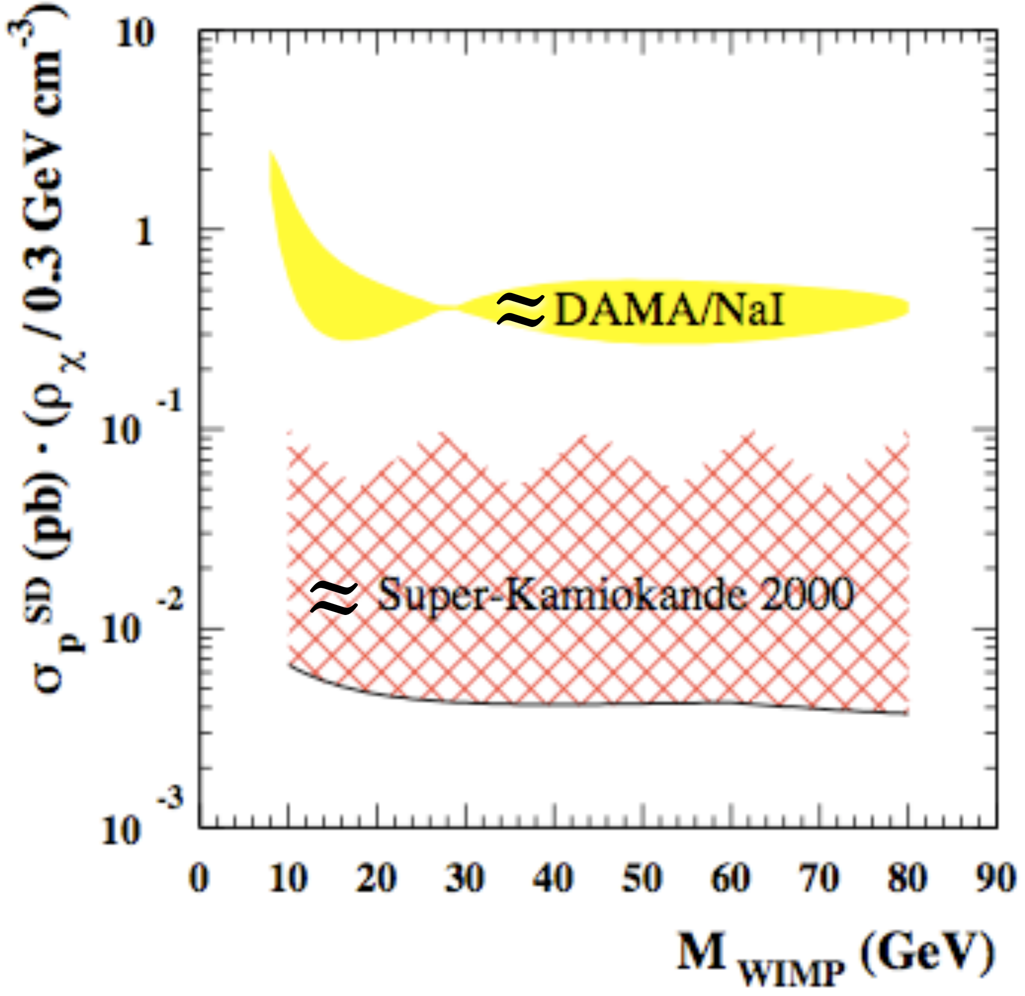
Direct detection versus neutrino telescopes

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;

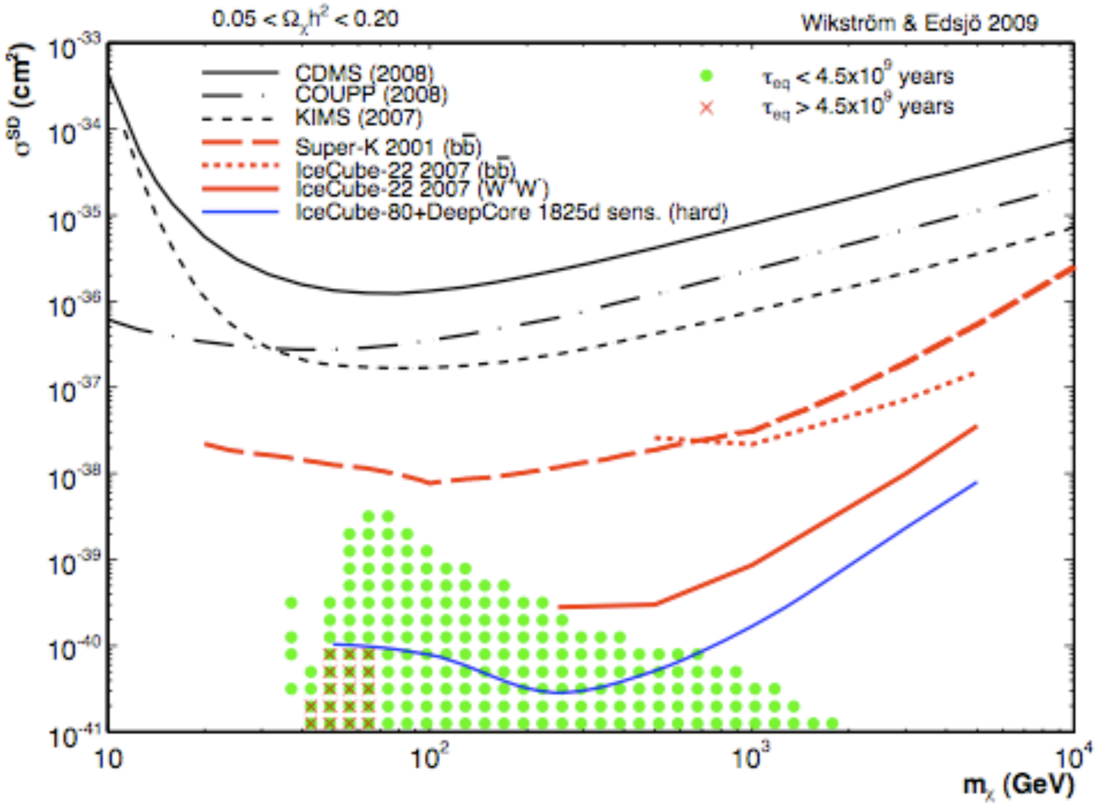
II) WIMP annihilation modes for which the ν yield is not suppressed.

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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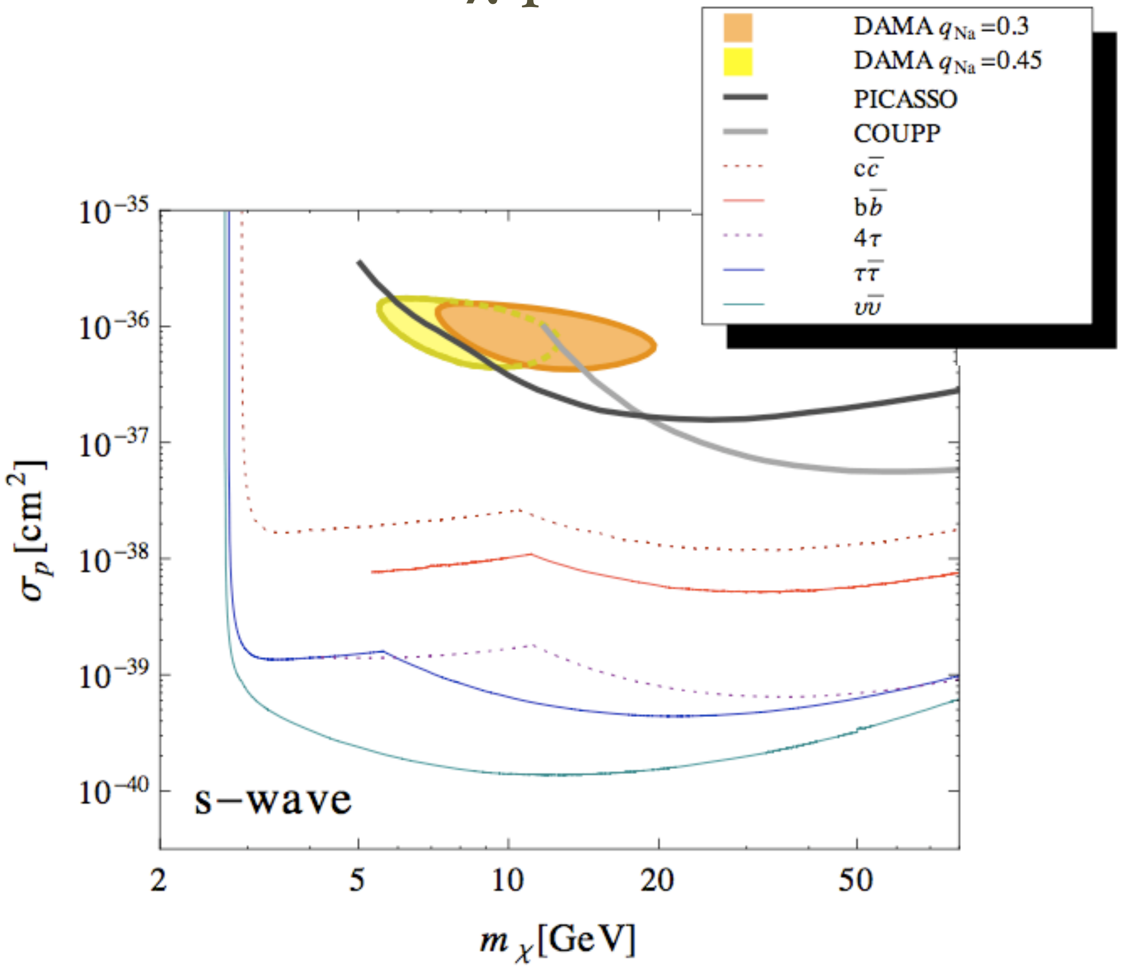

Knappl & Winkler, 2011

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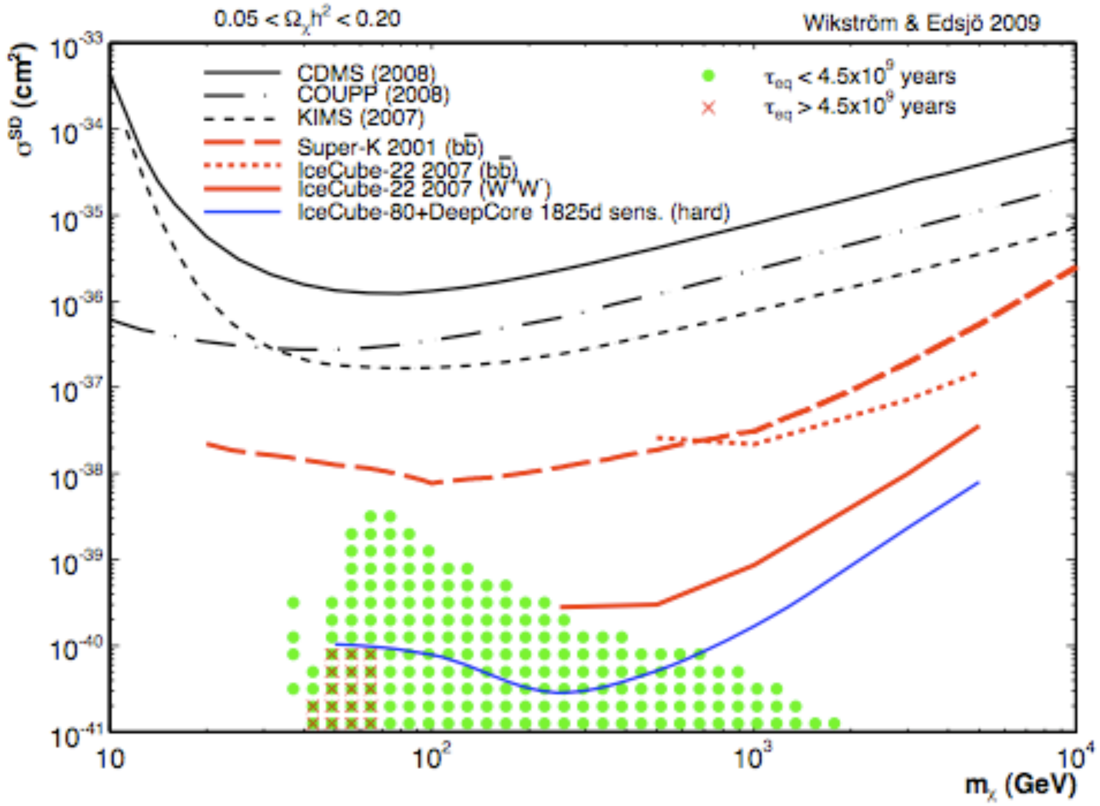

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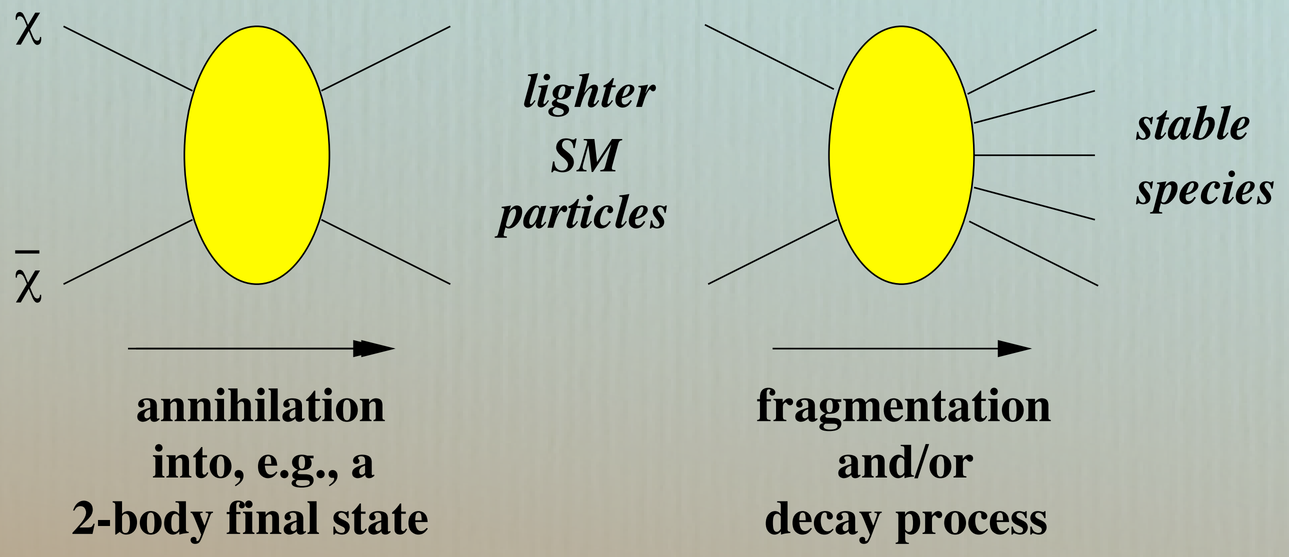
Indirect detection of WIMP dark matter

The chance of detection stems from the WIMP paradigm itself:

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



lighter SM particles

stable species

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

fragmentation and/or decay process

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

WIMP DM source function:

$$Q_i(E,r) = (\sigma v)_0 \sum_f B_f \frac{dY_i^f}{dE}(E)\, \mathcal{N}_{\text{pairs}}(r)$$

total rate

branching ratios

yield spectra

density of WIMP pairs

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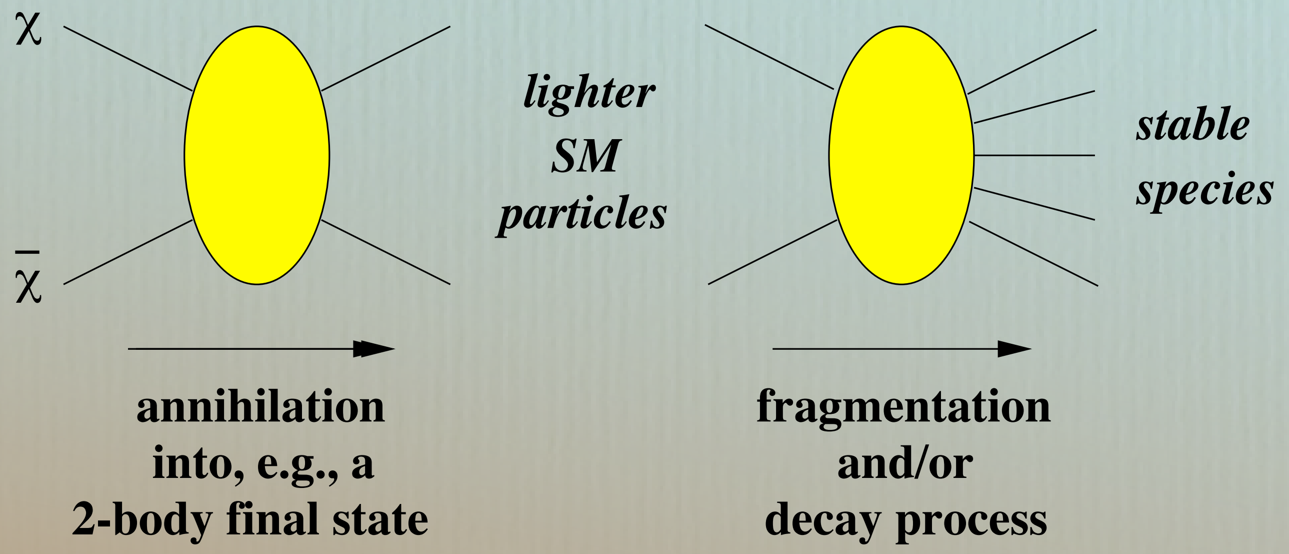


Focus on:
antiprotons,
positrons,
antideuterons,
gamma-rays,
(neutrinos)

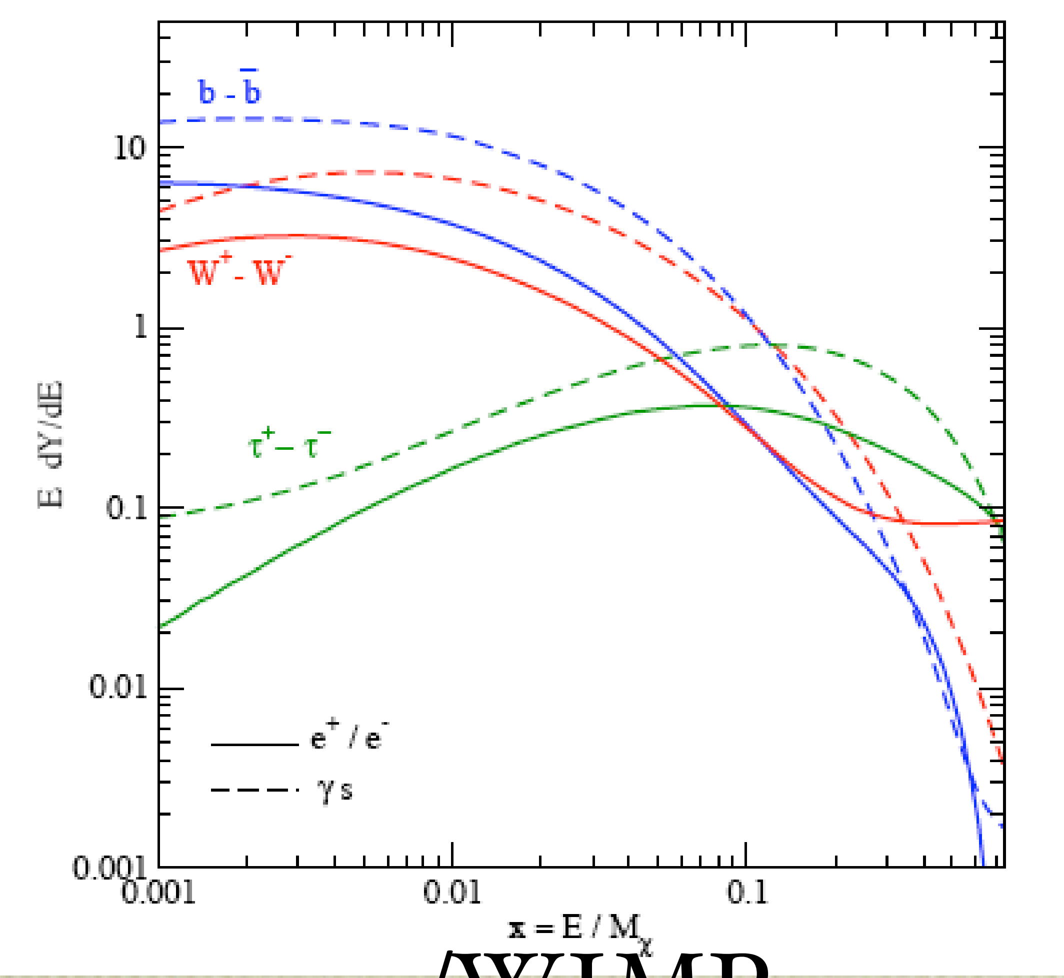
WIMP DM source function:

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

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

Definite patterns linking WIMP source functions

E.g.: the $e^{\pm}$ and γ yields have in most cases analogous spectral features:



energy/WIMP mass

$$\frac{dY^f_{e^\pm}}{dE}(E) \quad \text{from } \pi^{\pm} \text{ decays}$$

$$\frac{dY^f_{\gamma}}{dE}(E) \quad \text{from } \pi^{0} \text{ decays}$$

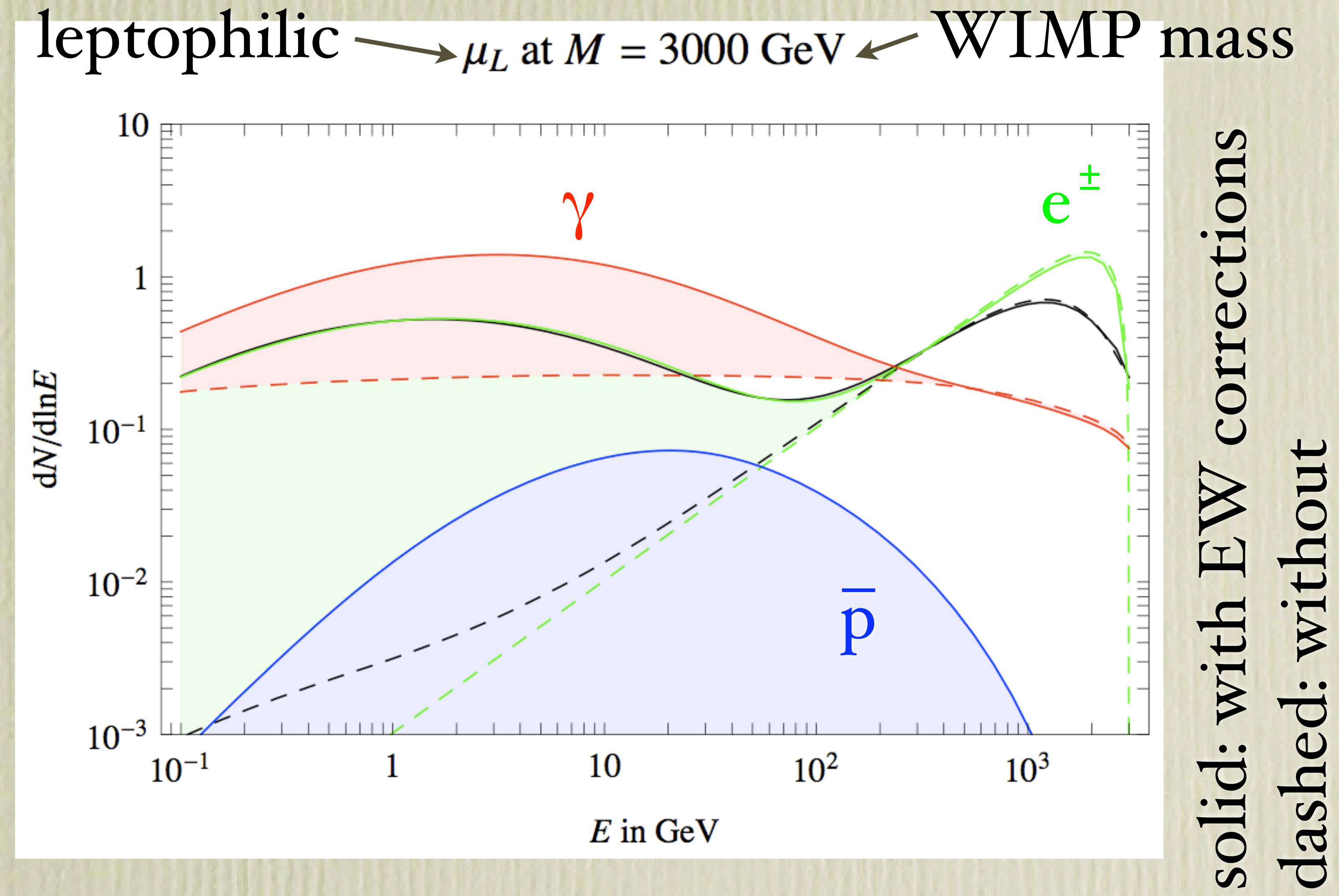
twin processes with comparable relative multiplicities in both hard (e.g. $\tau^+ \tau^-$) and soft (e.g. $b\,\bar{b}$) 2-body annihilation channels

For leptophilic models annihilating into $\mu^+ \mu^-$ or $e^+ e^-$, final state radiation (FSR) is very important: the γ yield is suppressed but peaks at the threshold, a very important spectral feature.

Definite patterns linking WIMP source functions

If kinematically allowed, the p̄ yield plays always a major role. E.g.: for the W^+W^- final state, about 4% of the total energy released goes into p̄, as opposed to about 18% going into $e^\pm$. On the other hand, in general, the signal to background ratio in the p̄ searches is much larger than than for CR leptons.

Even for leptophilic models, designed to prevent large p̄ yields, in case of heavy WIMPS, there is a non-negligible p̄ component due to radiative emission of EW gauge bosons.



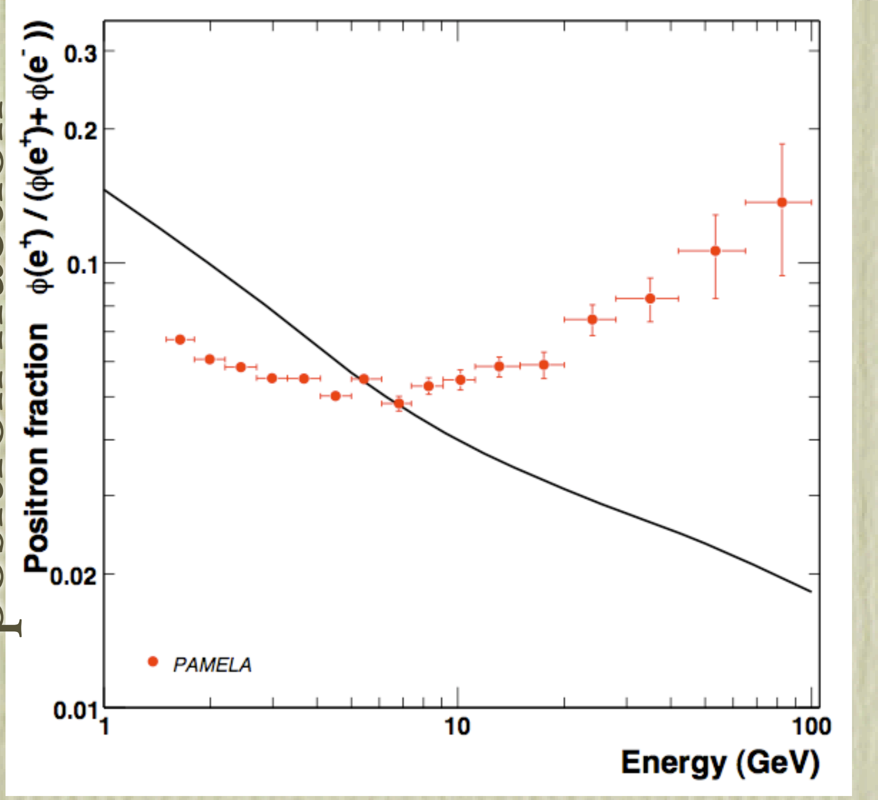
Ciafaloni et al., arXiv: 1009.0224

To be or not to be … leptophilic

Focus on leptophilic models driven by recent CR lepton data:

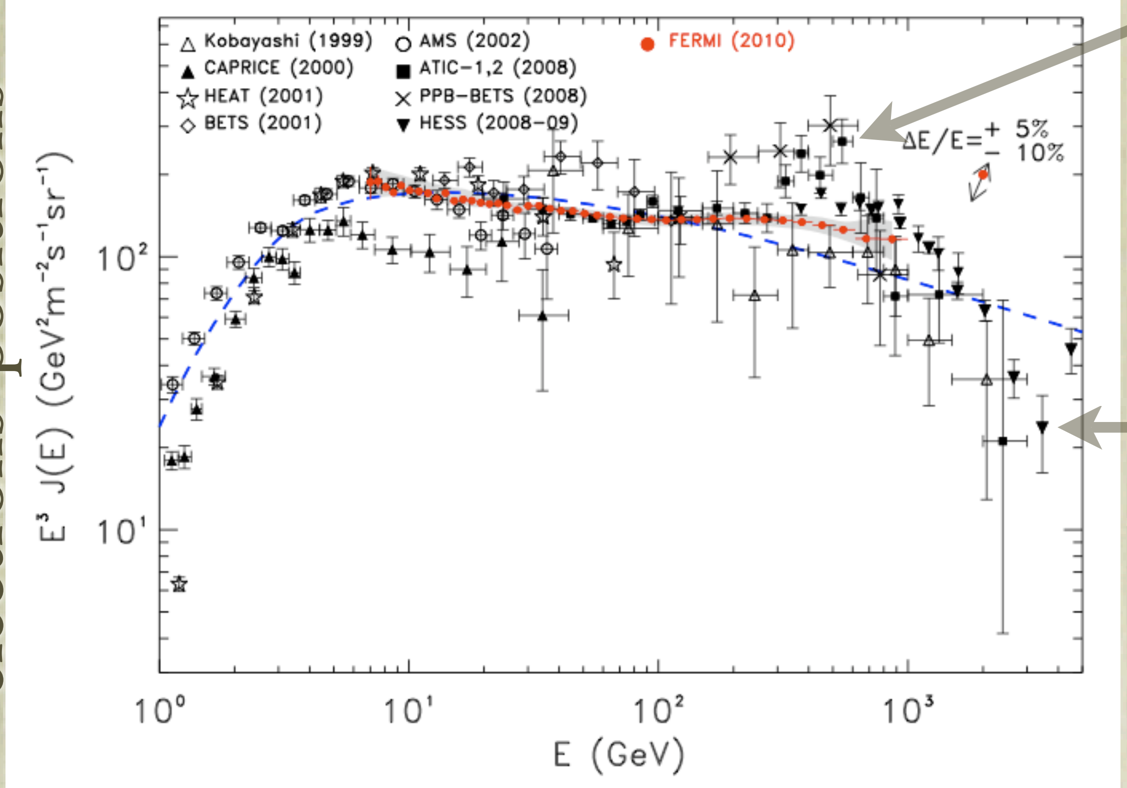
2008: PAMELA

positron fraction



2009-2010: Fermi GRT

electrons+positrons

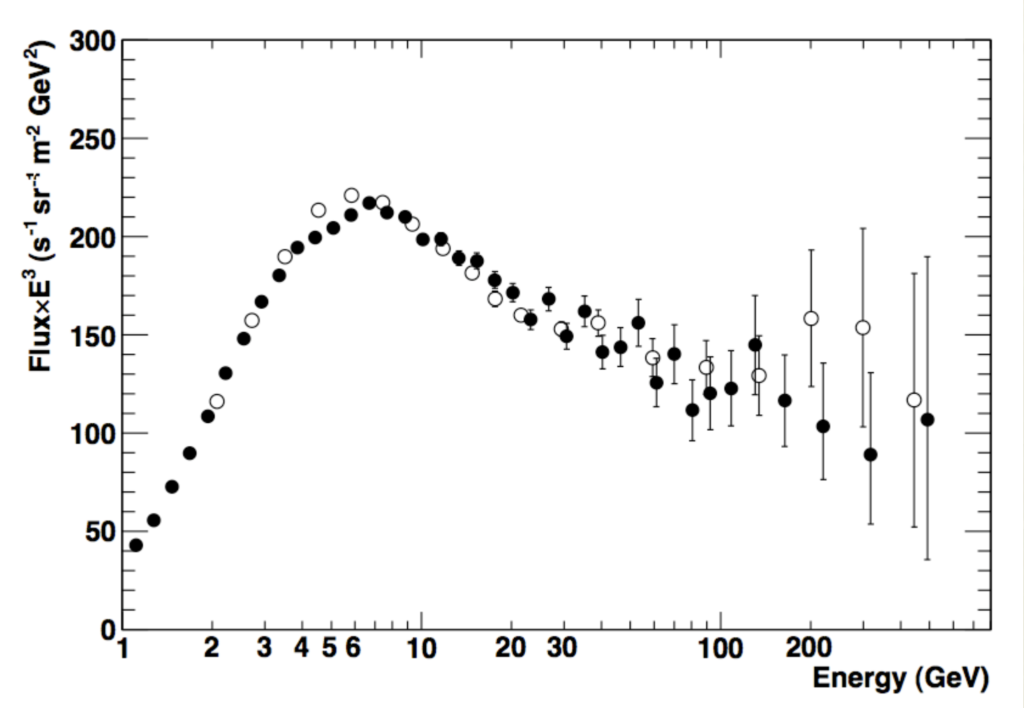


2008: ATIC

2008/9: HESS

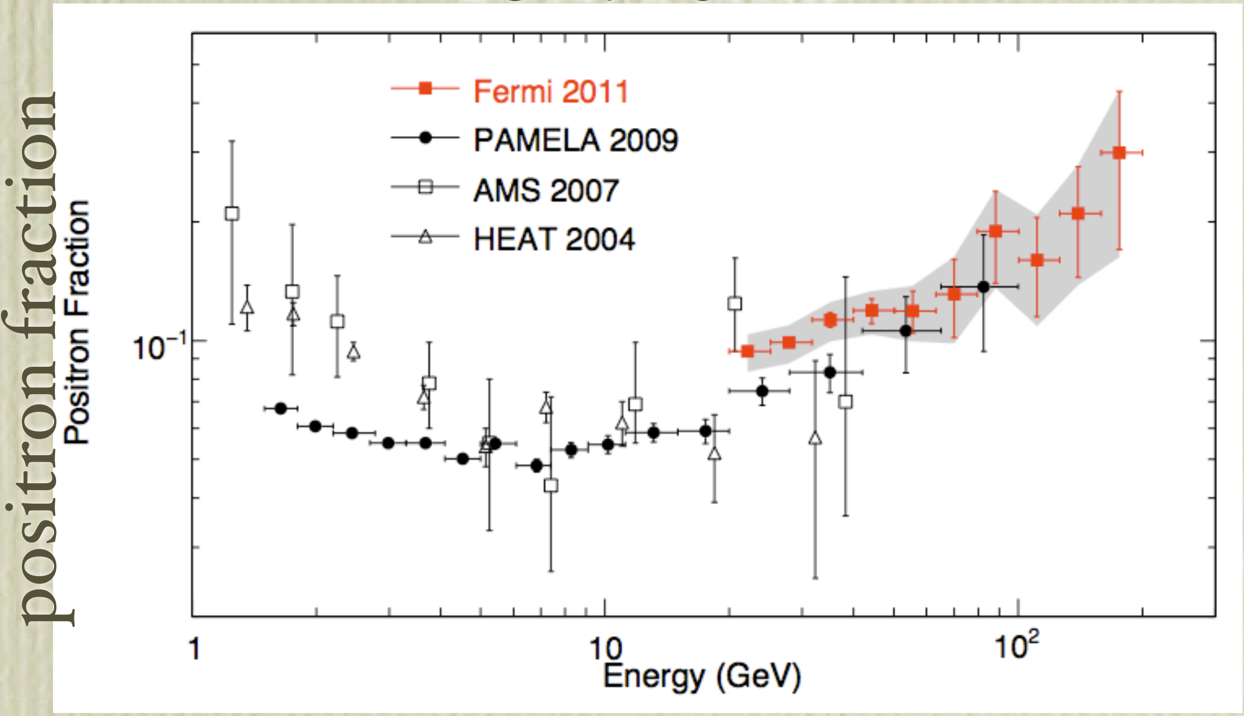
2011: PAMELA

electrons



2011: Fermi

positron fraction



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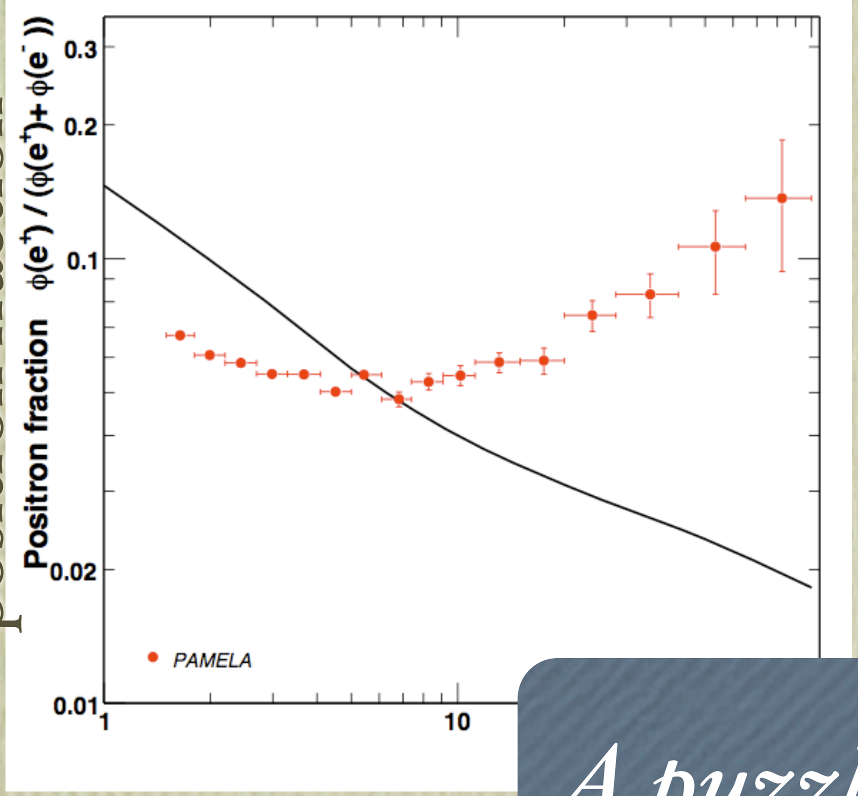

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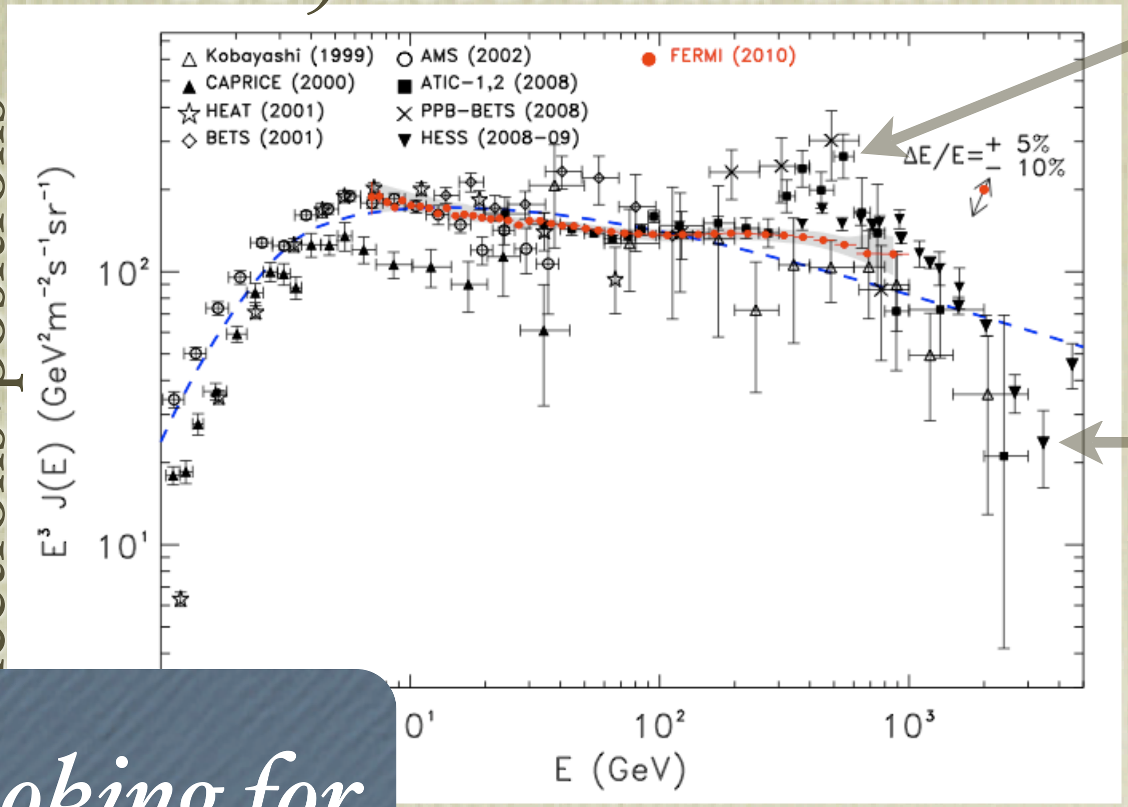
lectrons+positrons



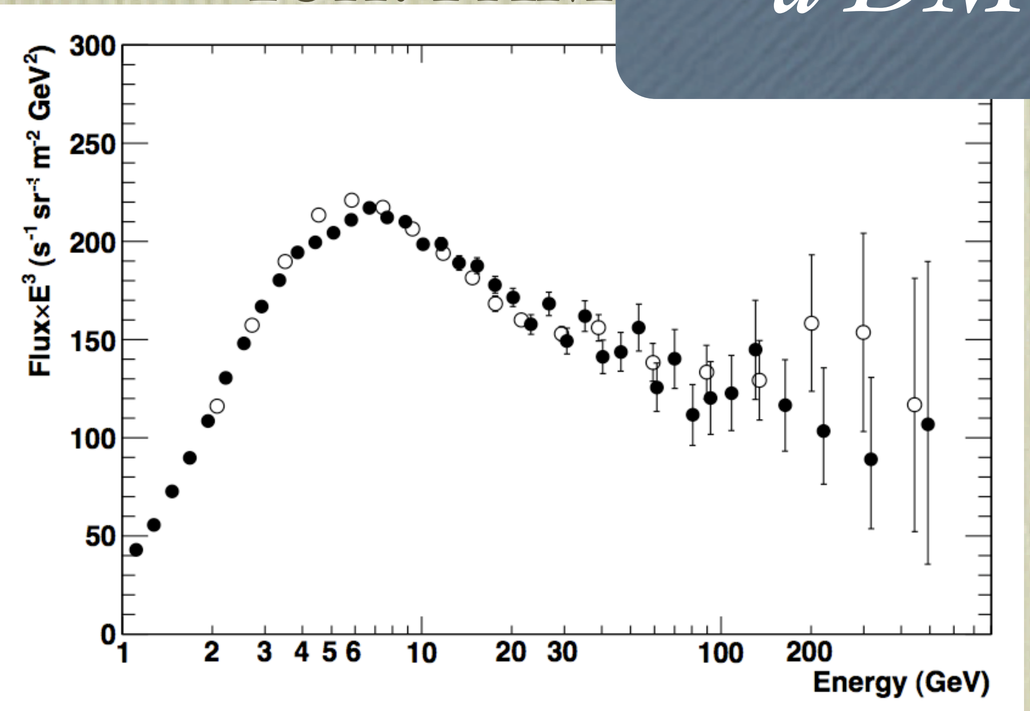
2008: ATIC

2008/9: HESS

A puzzle invoking for a DM solution?

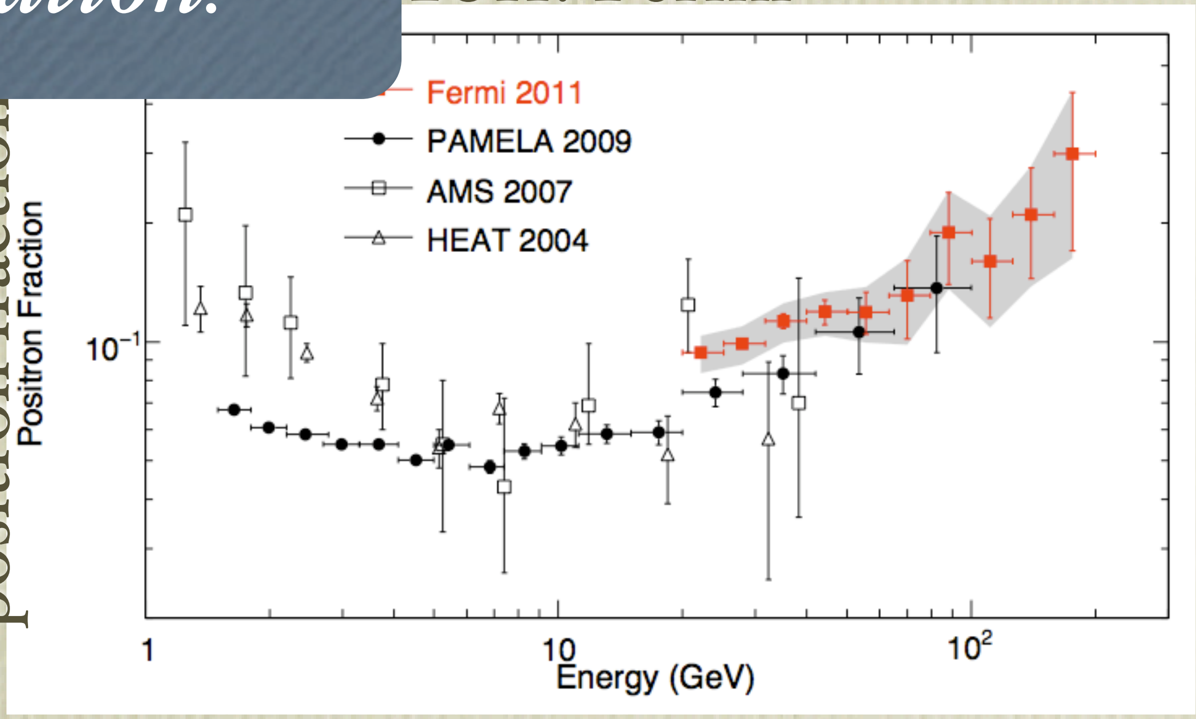
2011: PAM

electrons



2011: Fermi

positron fraction



Charged particles in the Galaxy

A random walk (maybe with a preferred drift direction) in turbulent & regular magnetic fields, modeled through a diffusion equation:

$$\frac{\partial n_i(\vec{r},p,t)}{\partial t} = \vec{\nabla}\cdot\left(D_{xx}\vec{\nabla} n_i - \vec{v}_c\, n_i\right) + \frac{\partial}{\partial p}\, p^2 D_{pp} \frac{\partial}{\partial p}\, \frac{1}{p^2}\, n_i - \frac{\partial}{\partial p}\left[\dot{p}\, n_i - \frac{p}{3}\,(\vec{\nabla}\cdot\vec{v}_c)\, n_i\right] + q(\vec{r},p,t) + \frac{n_i}{\tau_f} + \frac{n_i}{\tau_r}$$

spatial diffusion

reacceleration

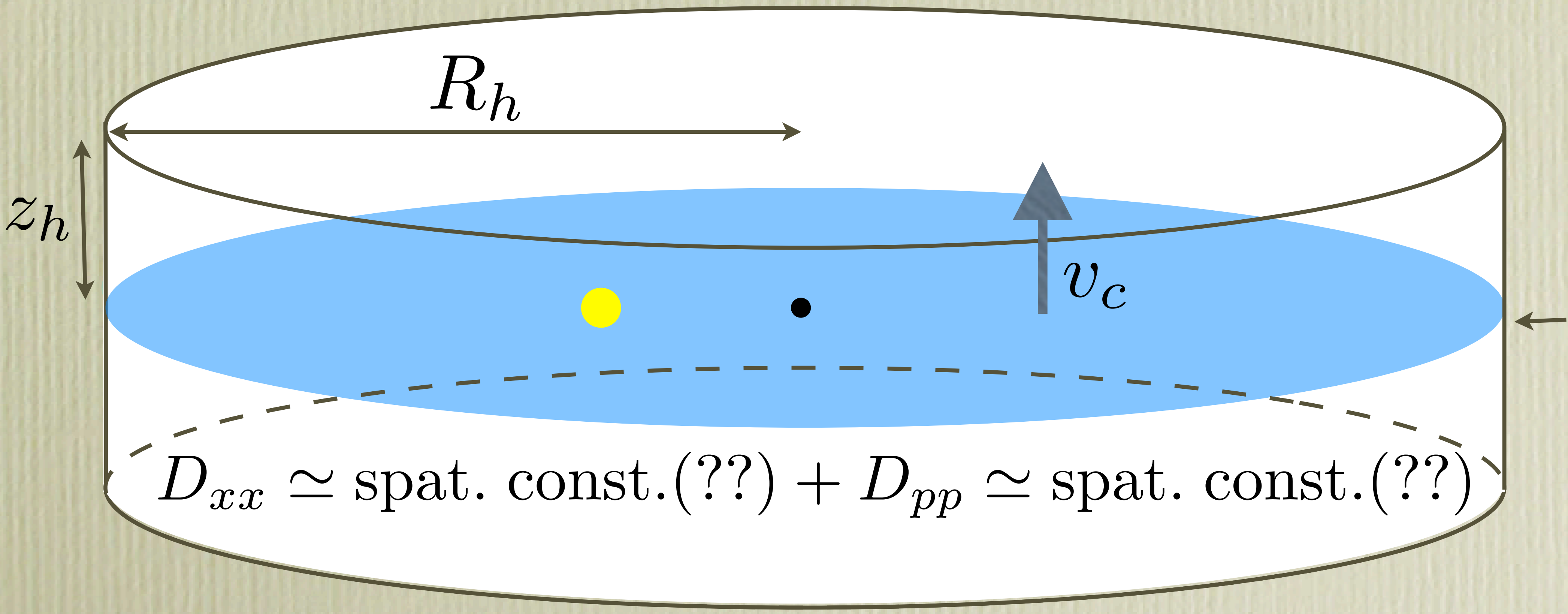
energy loss

source

decay, fragmentation

convection

usually solved in steady state (l.h.s. put to zero) and applied to some schematic picture of the Galaxy :



thin gas layer, primary + secondary sources

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:

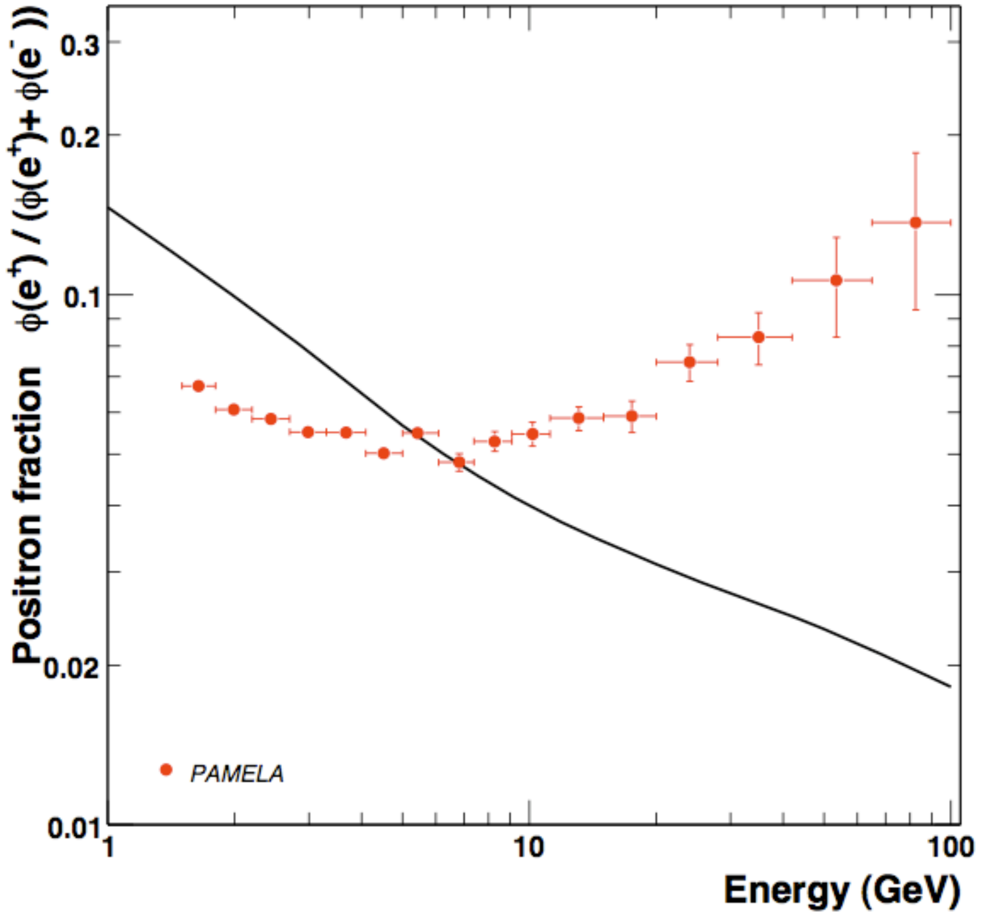
$$\frac{\phi_{e^+}}{\phi_{e^-}} \propto p^{-(\beta_{inj,p}-\beta_{inj,e}+\alpha)}$$

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



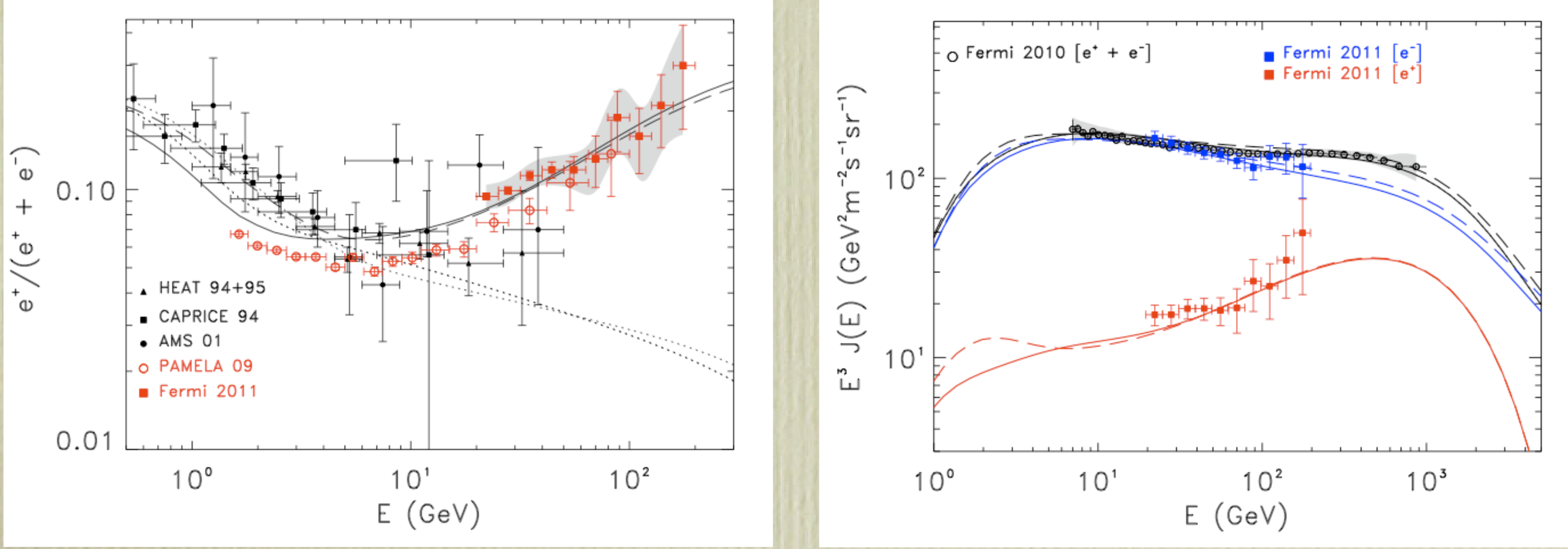
Adriani et al., arXiv:0810.4995

Fixing the CR lepton puzzle:

- A set of proposals blame the standard lore for CR propagation invoking extra energy loss effects affecting leptons (but not nuclei), or discreteness effects in sources, or ...; set of early references include, e.g., **Piran et al., arXiv:0905.0904; Katz et al., arXiv:0907.1686** (??? - probably ad hoc)

- Secondary species produced and reaccelerated within the sources, e.g., **Blasi, arXiv:0903.2794; Mertsch & Sarkar, arXiv:0905.3152** (? - maybe and testable with higher energy data on nuclei)

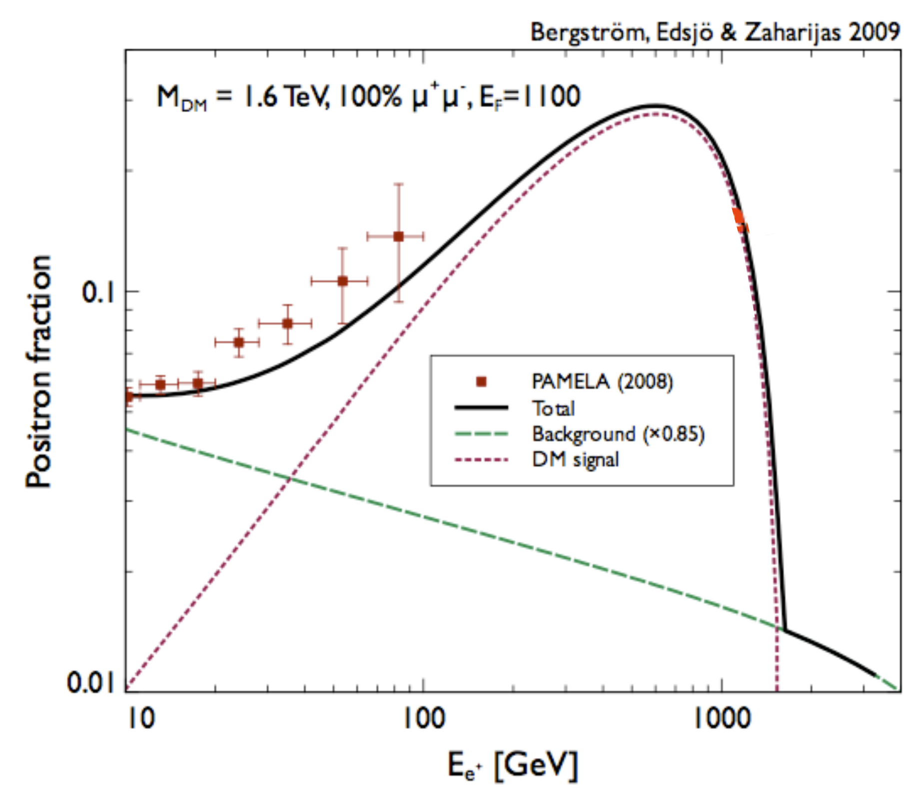
- Pulsars as additional primary source of leptons (! - pulsar do exist and the energetics and injection rates possibly ok):

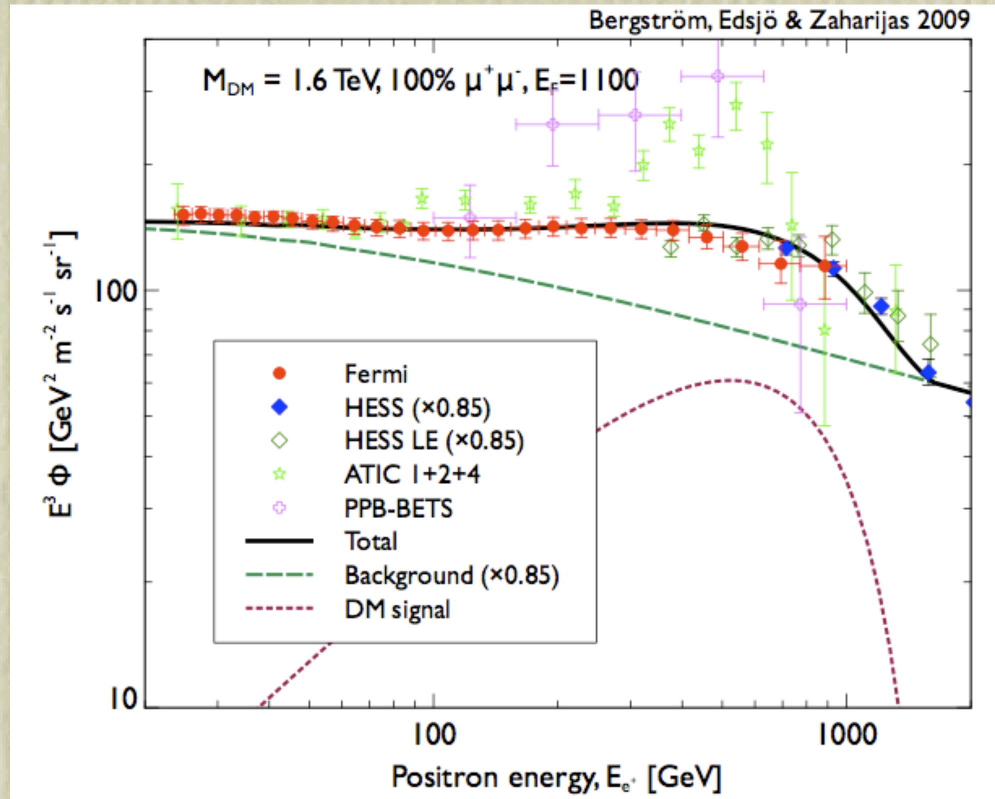


Grasso & Gaggero for Fermi Coll., arXiv:1110.2591

To be or not to be … leptophilic

- An additional primary lepton source from DM annihilations, e.g.:





Bergström et al., arXiv:0905.0333

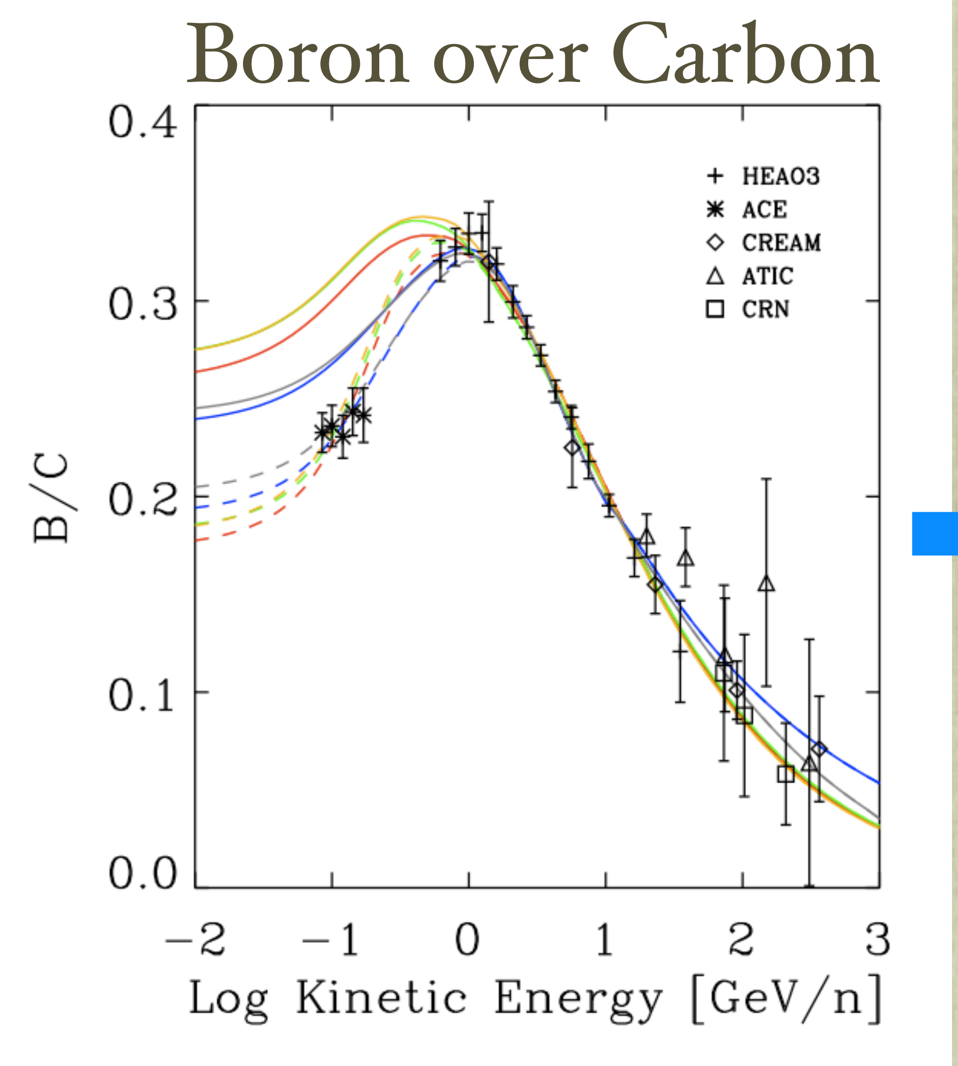
within however a model not fitting within a standard WIMP “miracle” case, since the DM particles need: **to be heavy** (above the 1 TeV scale); **to have a very large enhancement in the source**, either in the rate (non-thermal WIMP? Sommerfeld effect? a resonance effect?) or in the WIMP pair density because of small scale inhomogeneities (DM clumps? -- hardly plausible within the ΛCDM setup); **to hide themselves in other annihilation channels**, especially antiprotons → leptophilic DM.

The $\bar{p}$ flux is consistent with secondaries:

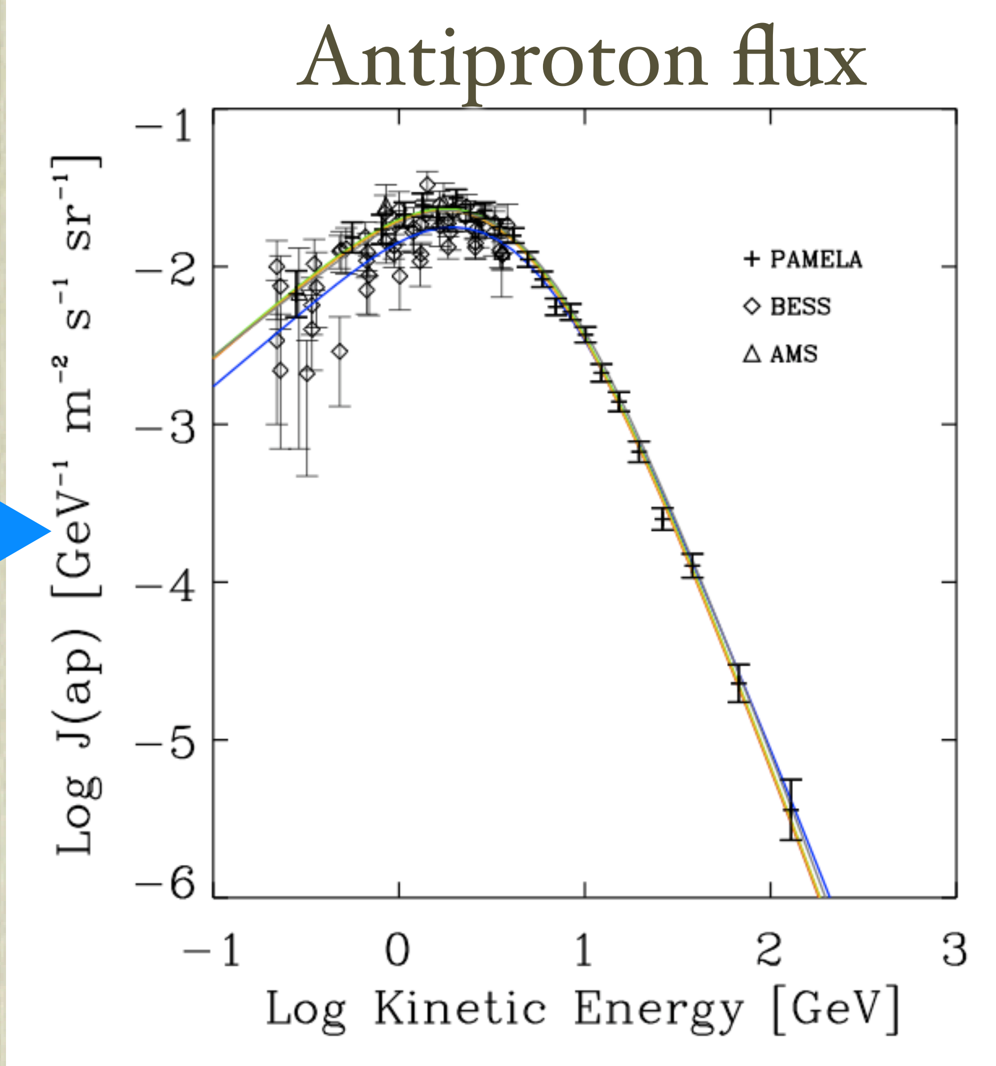
Antiprotons are generated in the interaction of primary proton and helium cosmic rays with the interstellar gas (hydrogen and helium), e.g., in the process:

$$p + H \rightarrow 3\,p + \bar{p}$$

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



Boron over Carbon

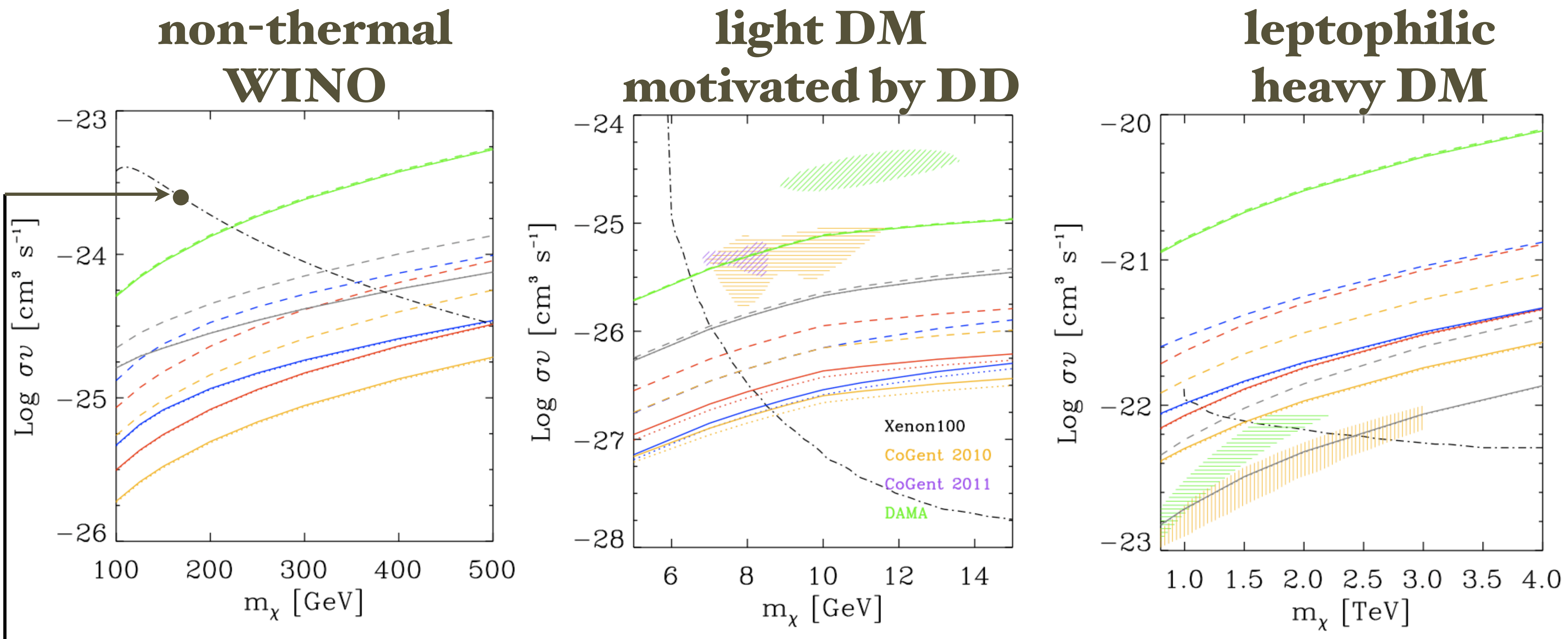


Antiproton flux

Evoli, Cholis, Grasso, Maccione & PU, arXiv:1108.0664

A set of very different propagation models: Kraichnan , Kolmogorov, thick (z_h = 10 kpc), thin (z_h = 0.5 kpc), convective (dv /dz = 50 km/s/kpc); analogous mapping.

Use the background information to extrapolate limits on DM models contributing to the local antiproton flux. E.g.:



Limits depending on propagation model & (mildly) on DM profile:

—— Kraichnan

—— Kolmogorov

—— thick (z_t= 10 kpc)

—— thin (z_t= 0.5 kpc)

—— convective (dv_c/dz = 50 km/s/kpc)

—— Einasto

········ NFW

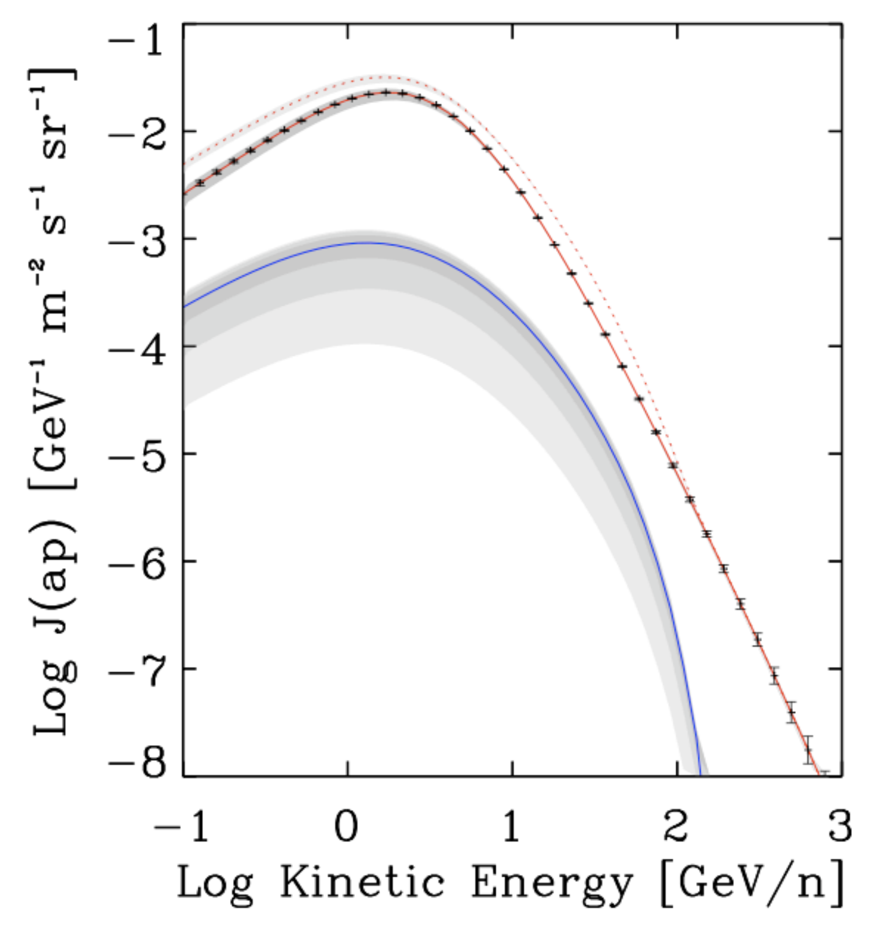
– – – – Burkert

180 GeV Wino explaining Pamela positron fraction data in **Kane et al., arXiv: 0906.4765** is clearly excluded

Improving limits and/or detecting DM with $\bar{p}$ & $\bar{D}$?

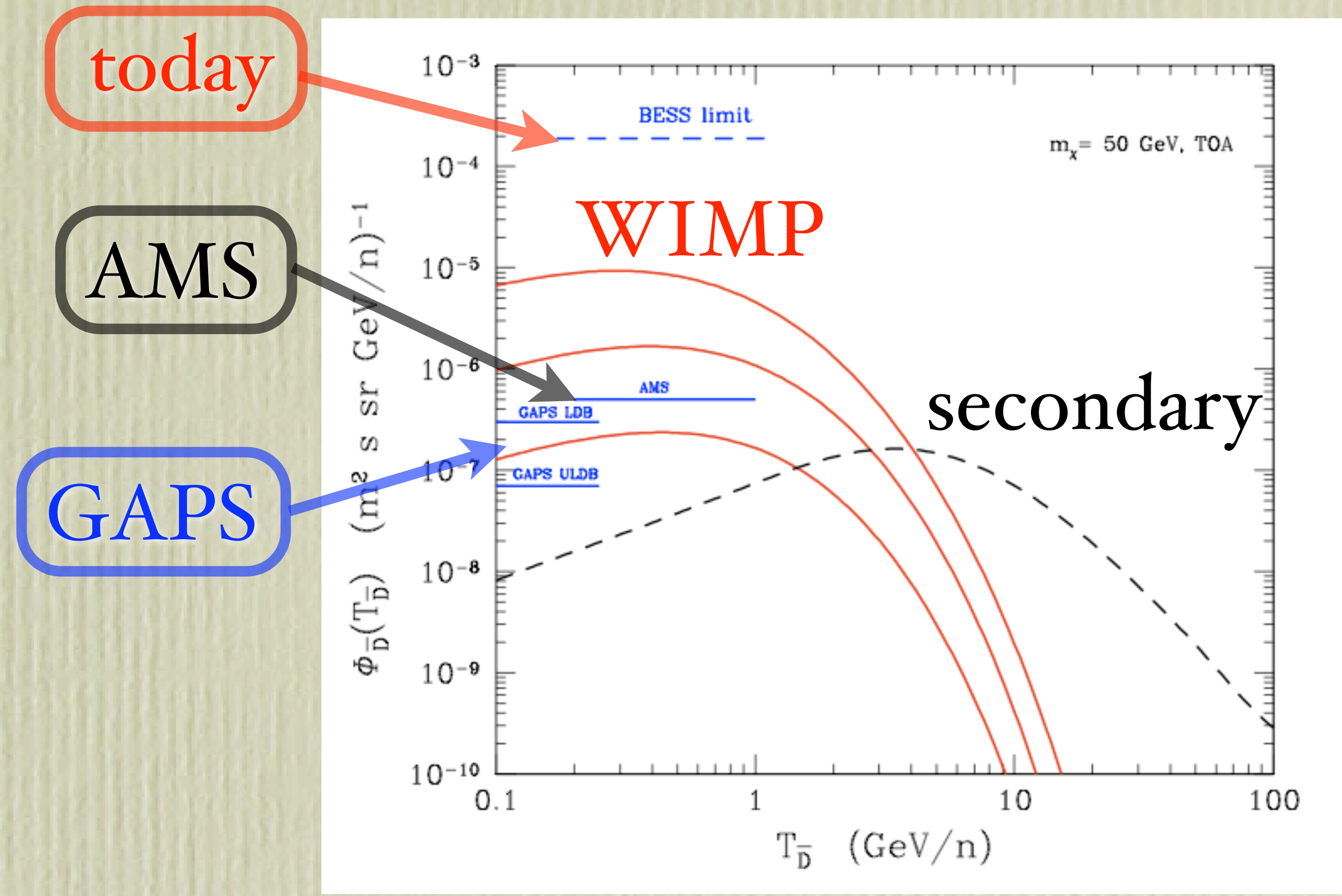
With the upcoming AMS data on nuclei, our understanding of the CR propagation model will be refined. A window for singling out DM?

Tough, but not inconceivable, in the $\bar{p}$ channel with AMS:



Evoli, Cholis, Grasso, Maccione & PU, arXiv:1108.0664

Possibly more promising in the $\bar{D}$ channel:



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

Donato, Fornengo & Maurin, 2008

Leptons from DM & Multi-wavelength signals

Having identified DM annihilations as a copious source of **non-thermal electrons** (even when DM is not leptophilic), there are potentially signals associated to the **radiative emissions** of such electrons on ambient backgrounds and fields, such as starlight, CMB, gas and magnetic fields:

synchrotron

inv. Compton

Ionization

Coulomb

bremsstrahlung

↓

A flux extending over 10 decades in energy, from the radio to the gamma-ray bands, stemming from a single energy scale, the WIMP mass

Cross-correlate the different wavebands with multiwave-length observations!

DM annihilations and gamma-ray fluxes:

Prompt emission of γ-rays associated to three components:

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

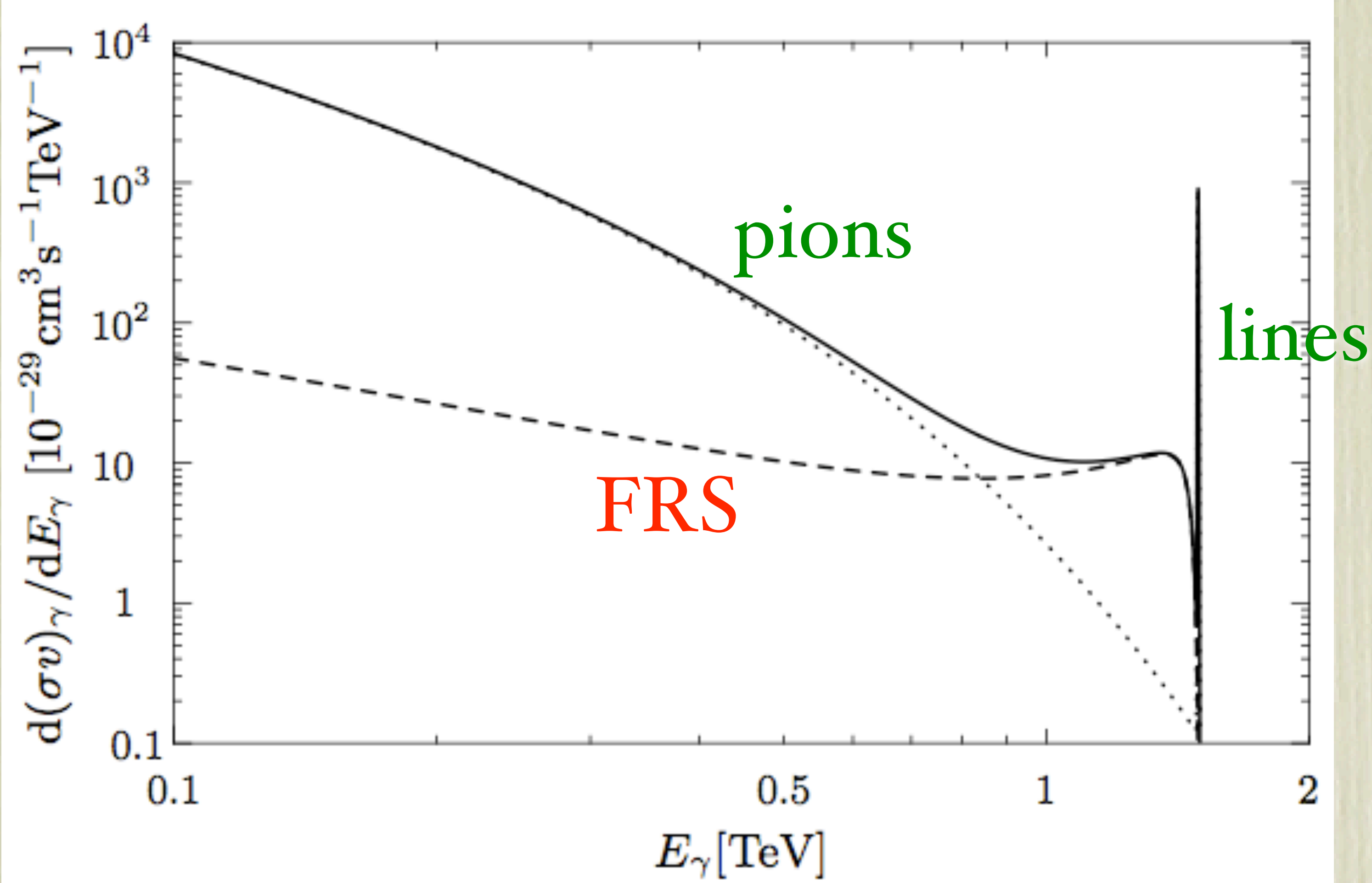
II) Monochromatic: i.e. the 1-loop induced $\chi\chi \to 2\gamma$ and $\chi\chi \to Z^0\gamma$ (in the MSSM, plus eventually others on other models)

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

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

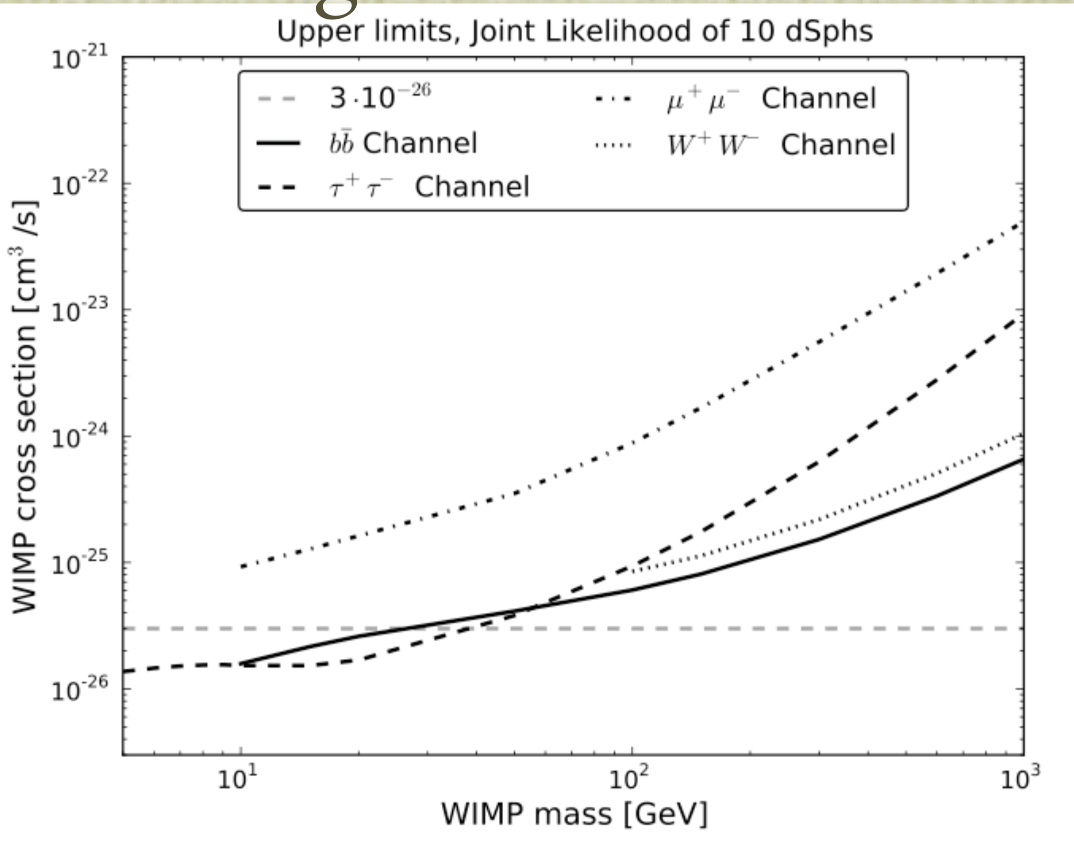
E.g. in a model for which all three terms are large (e.g. pure Higgsino):

Bergström et al., astro-ph/0609510



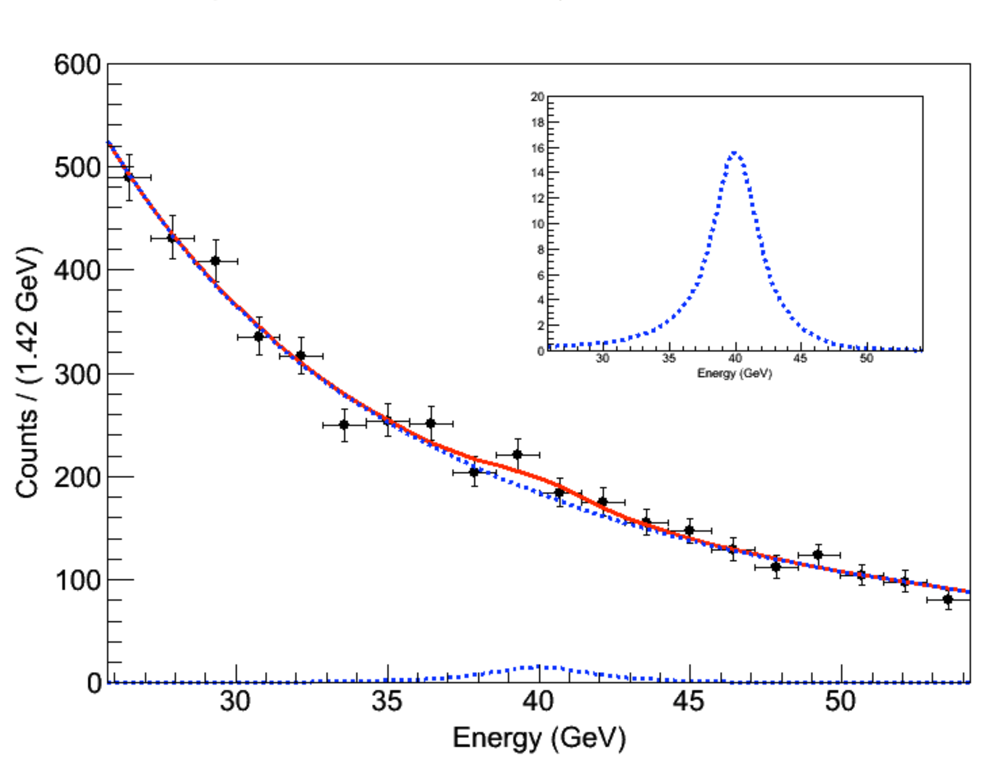
The first upper limits on DM gamma-ray fluxes from Fermi, e.g.:

stacking of dwarf satellites



arXiv: 1108.3546

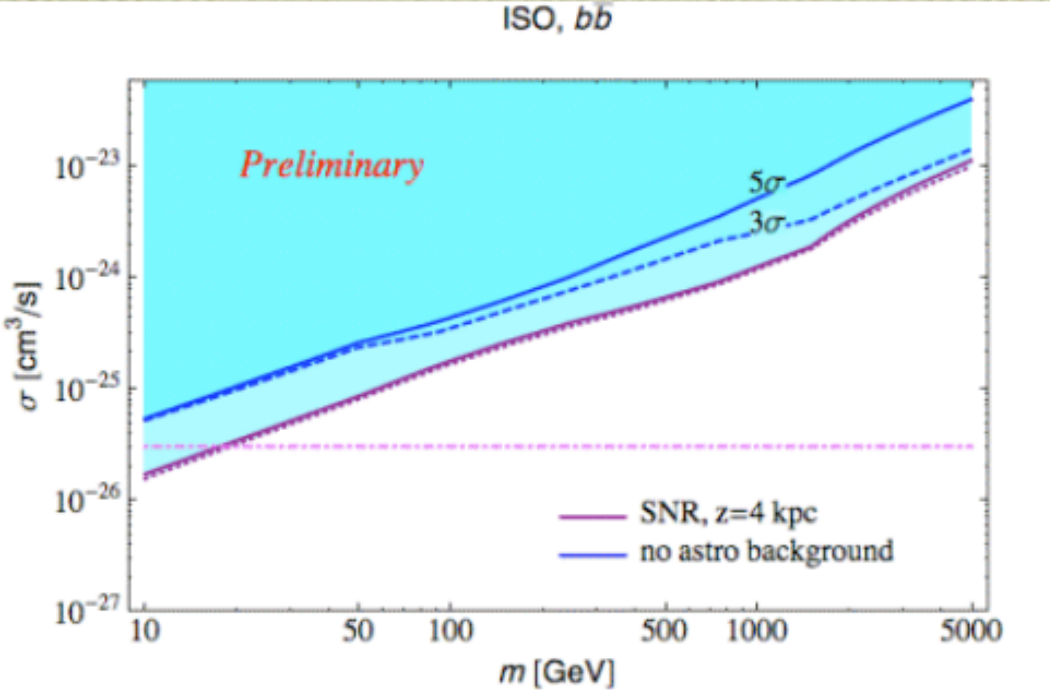
gamma-ray lines



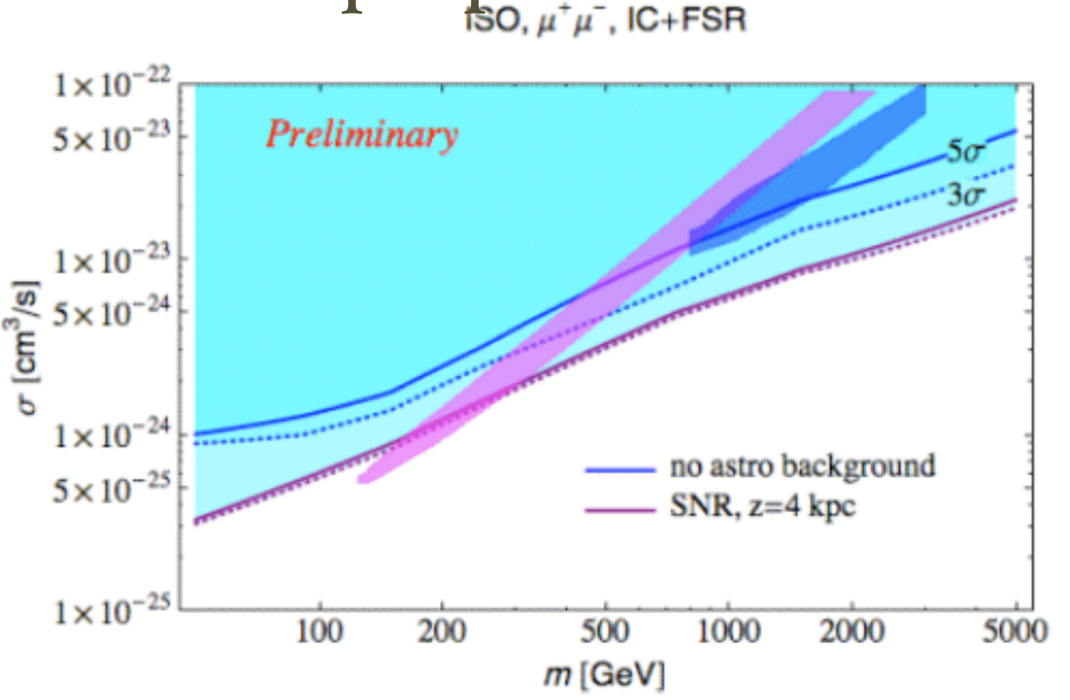
arXiv: 1001.4836

galactic diffuse emission for:

DM hadronic channel



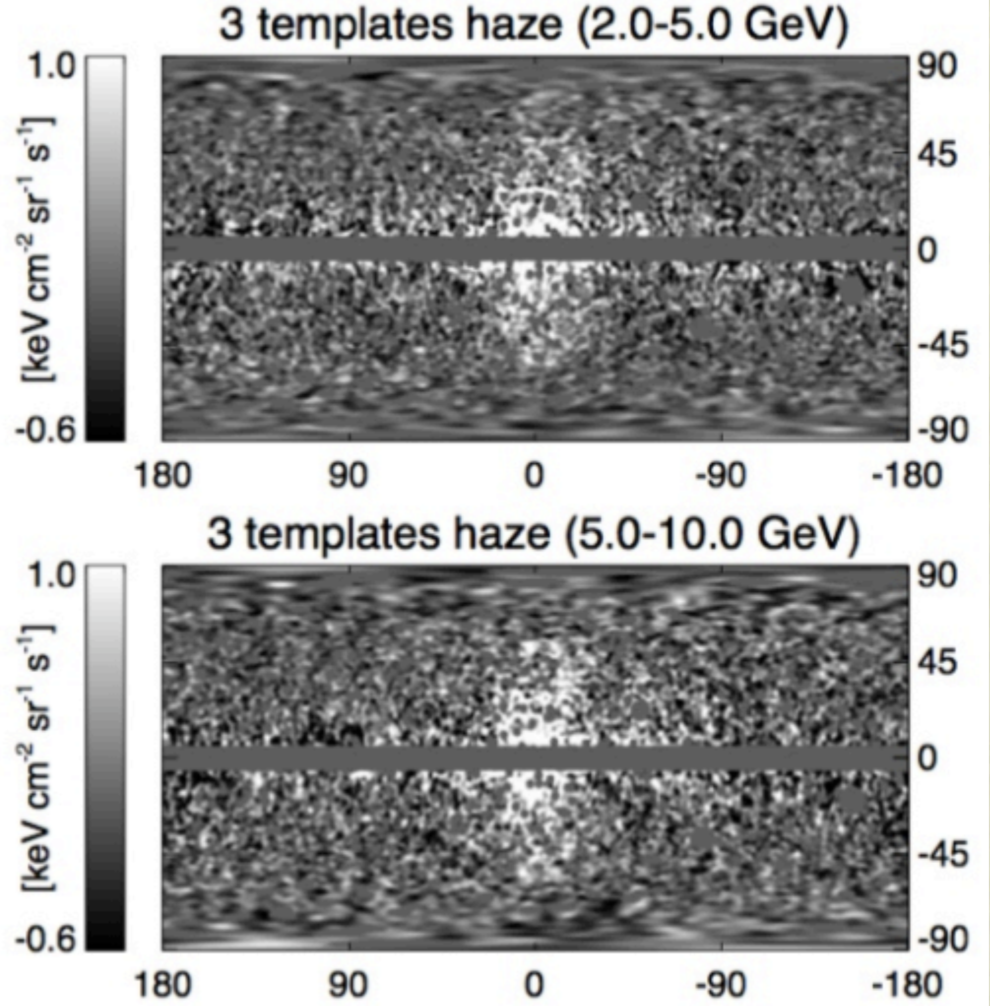
DM leptophilic channel



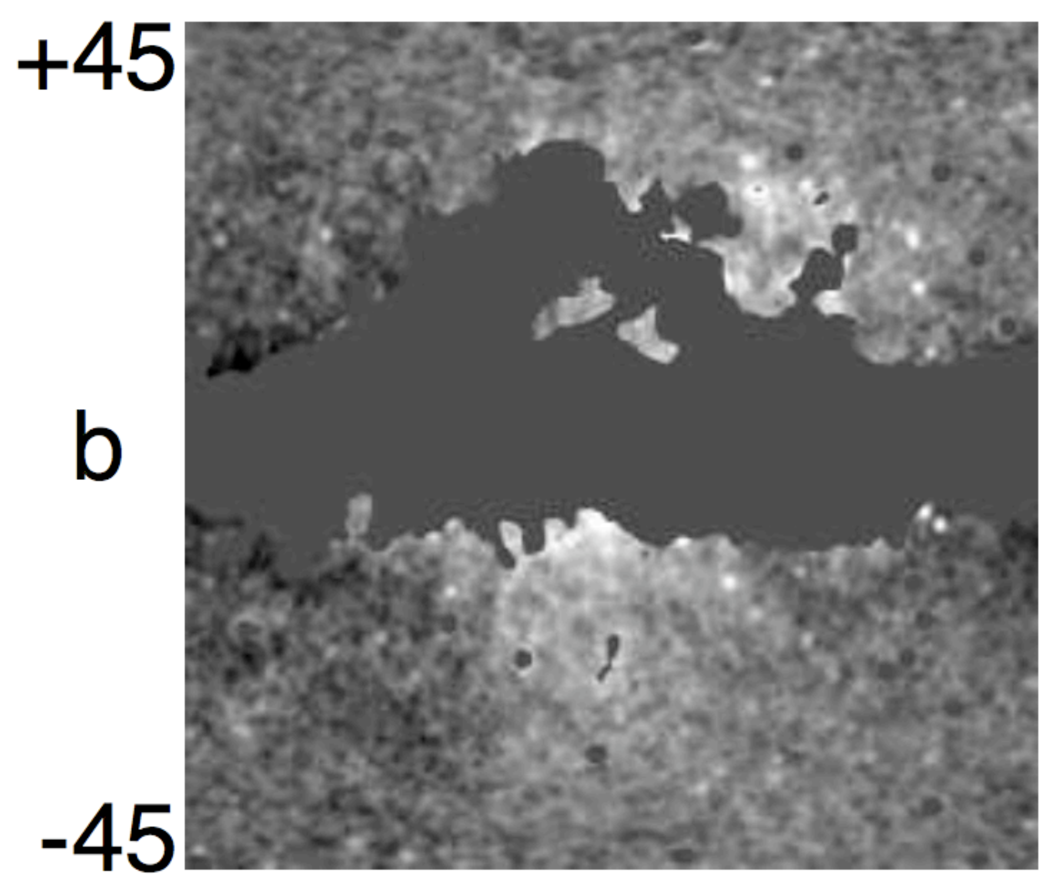
arXiv: 1012.0588

The first detection claims of DM gamma-ray fluxes from Fermi (following previous claims based on data from EGRET, Integral, ... , which however faded away), e.g.:

FERMI haze $\overset{?}{\Leftrightarrow}$ WMAP haze



Dobler, Cholis & Weiner, 2011



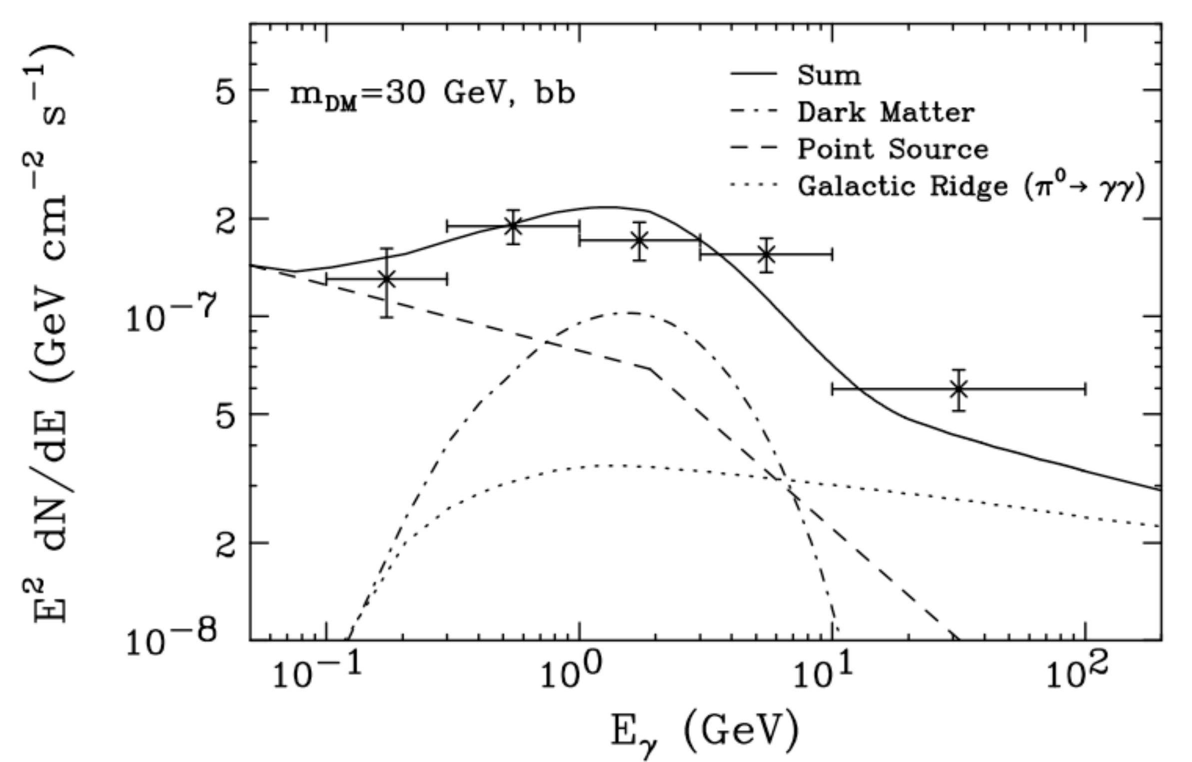
Finkbeiner, 2004

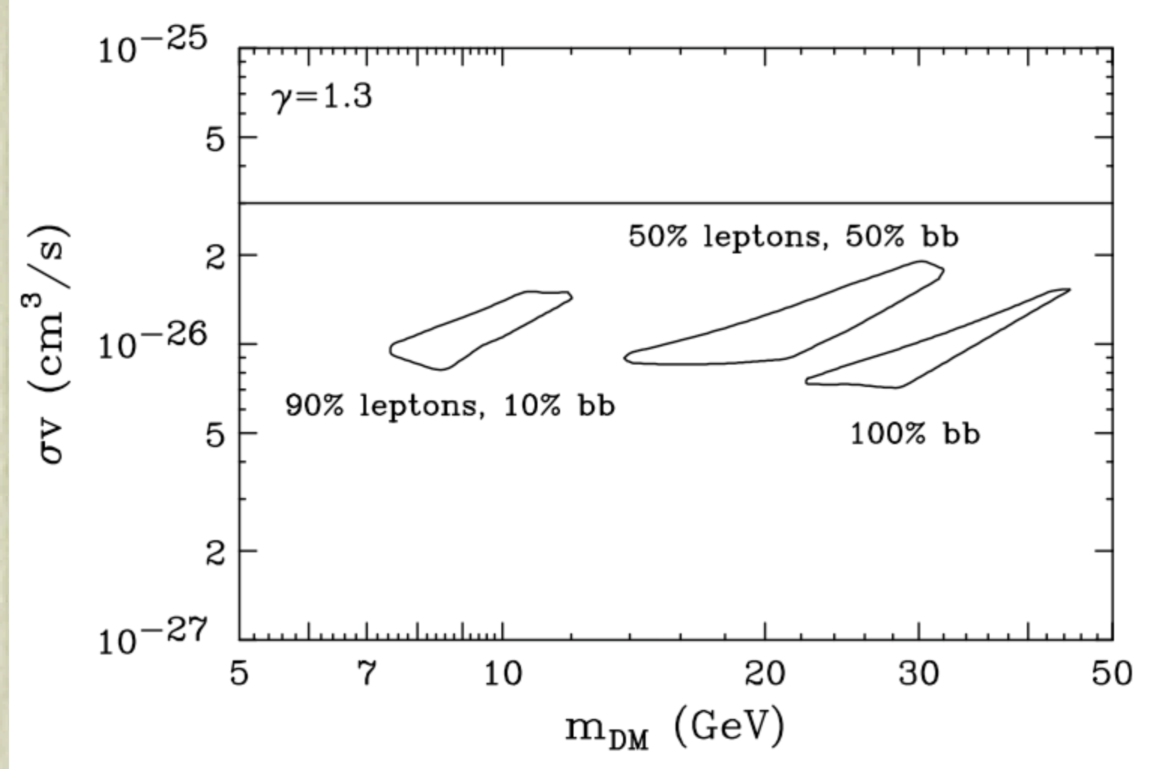
FERMI & WMAP hazes can be fitted with leptophilic DM with 1.2 TeV mass and EF of 30, assuming a prolate halo and anisotropic diffusion

Caveats: haze or bubbles? Sharp edges for a DM signal. Several contenders, such as additional sources and or variants to the propagation/acceleration model

The first detection claims of DM gamma-ray fluxes from Fermi (following previous claims based on data from EGRET, Integral, ... , which however faded away), e.g.:

The Galactic center region (<5 deg)





Hooper & Linden, arXiv:1110.0006

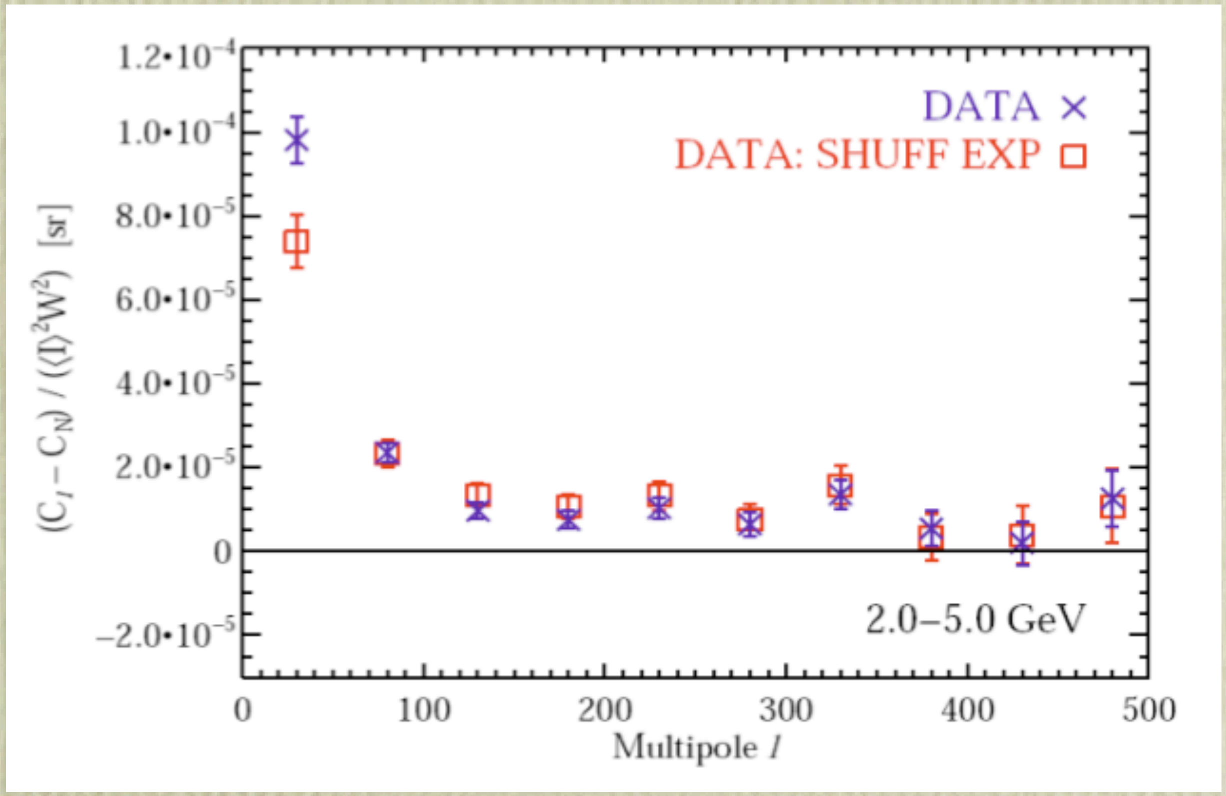
Room (or maybe even need) for a component from a light DM WIMP; no EF and cuspy DM profile.

Caveat: the interpretation relies heavily on what you are assuming (extrapolating) for the background component. The GC is a busy spot, difficult to model.

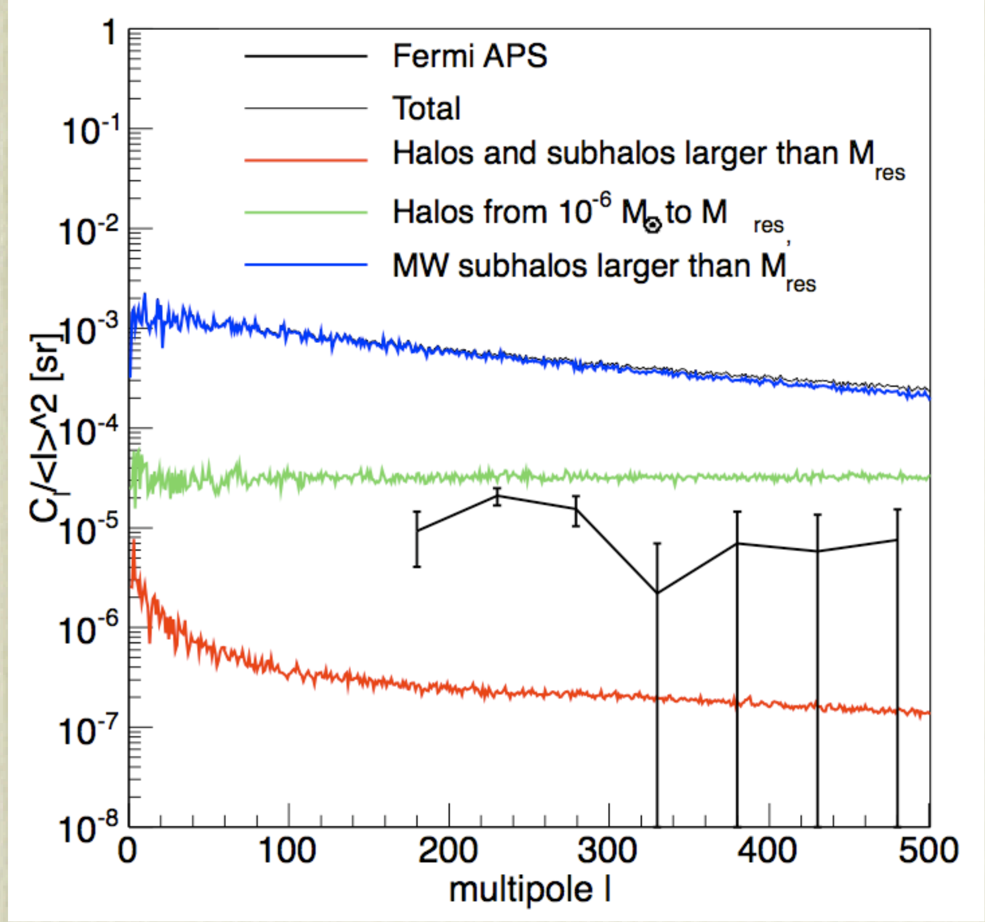
There is still room for improving on limits and possibly to clean out signals, as well to tag other targets. E.g.: is there a DM component in the extragalactic gamma-ray background? The answer to this question may come from the analysis of the angular anisotropies:

The Fermi Collaboration has preliminary results with evidence for angular power

The anisotropy pattern can be compared to what one finds in numerical simulations



Cuoco et al., arXiv:1110.1047

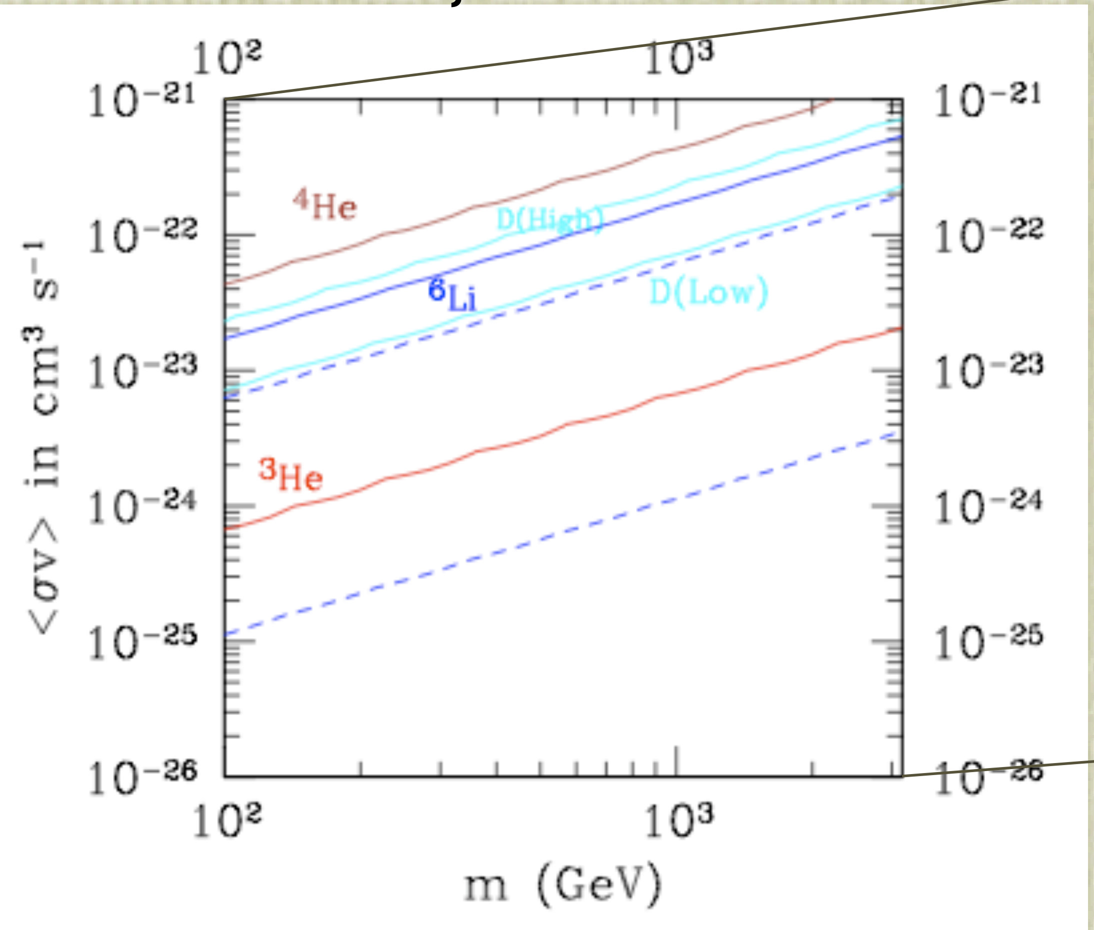


Fornasa et al., arXiv:1110.0324

DM annihilations at early stages of the Universe:

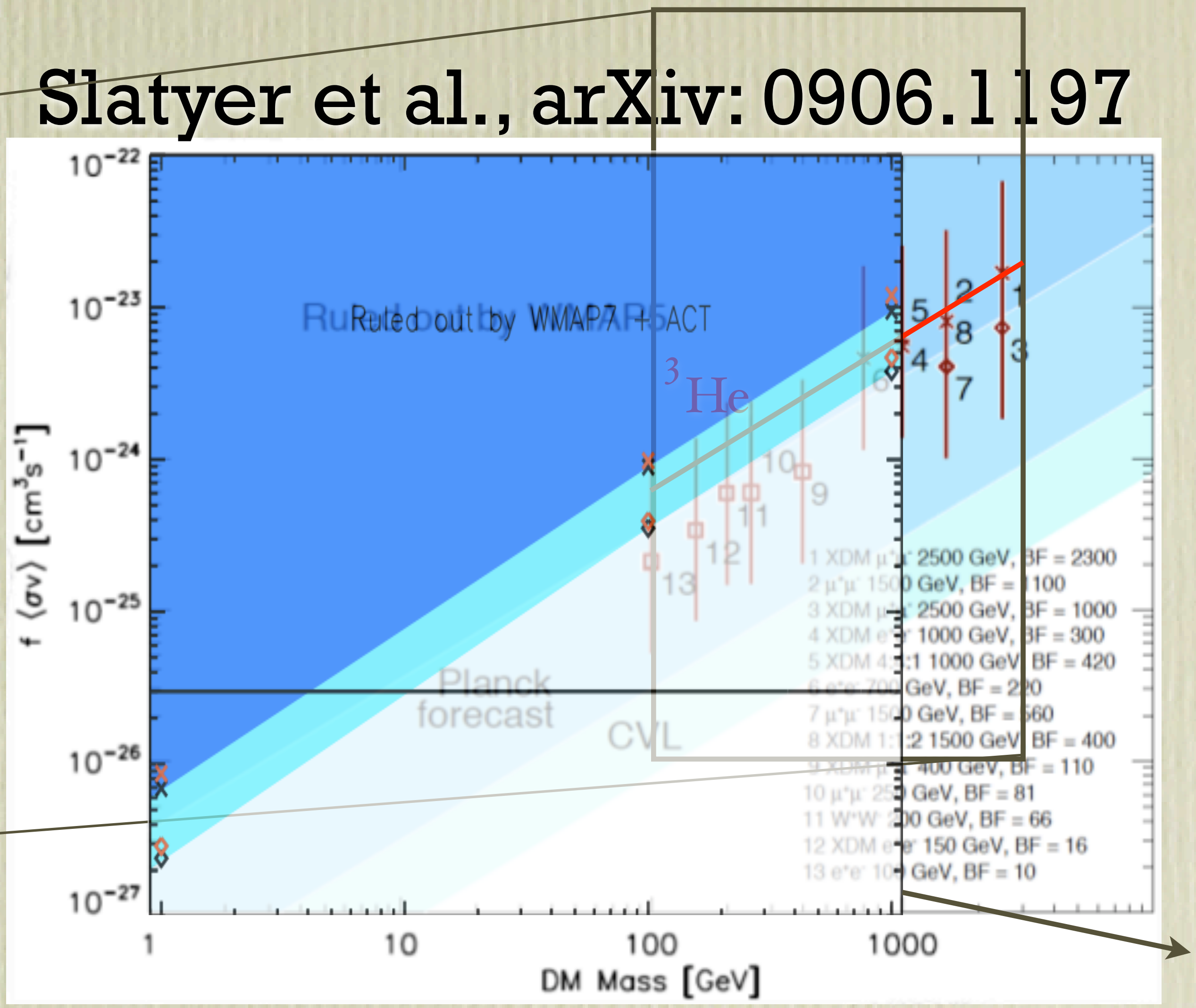
Several recent reanalyses of the limits from “polluting” the early Universe with DM yields. E.g.:

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



Galli et al., arXiv:1106.1528

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:

Astrophysical and cosmological observations give plenty of evidence for non-baryonic (cold?) DM; do they also give hints on its nature?

The emphases on indirect detection is stemming from the (almost) direct link between the mechanism of DM generation in an attractive scenario and the signals one searches for.

No clean case in which a DM annihilation yield has emerged as a signal prominent over astrophysical backgrounds (it would have been too good to be true...).

There is still the possibility of identifying clean signatures in the upcoming future; the multi-wavelength/multi-messenger approach to DM detection is at hand and very powerful.

The field has been recently driven the spectacular progresses on the experimental side, with a dramatic improvement in the quality of available data (and a few surprises). New results are expected soon, hence the excitement for the field is not going to fade away soon!