Multi-messenger and multi-wavelength dark matter searches

Piero Ullio
SISSA & INFN (Trieste)

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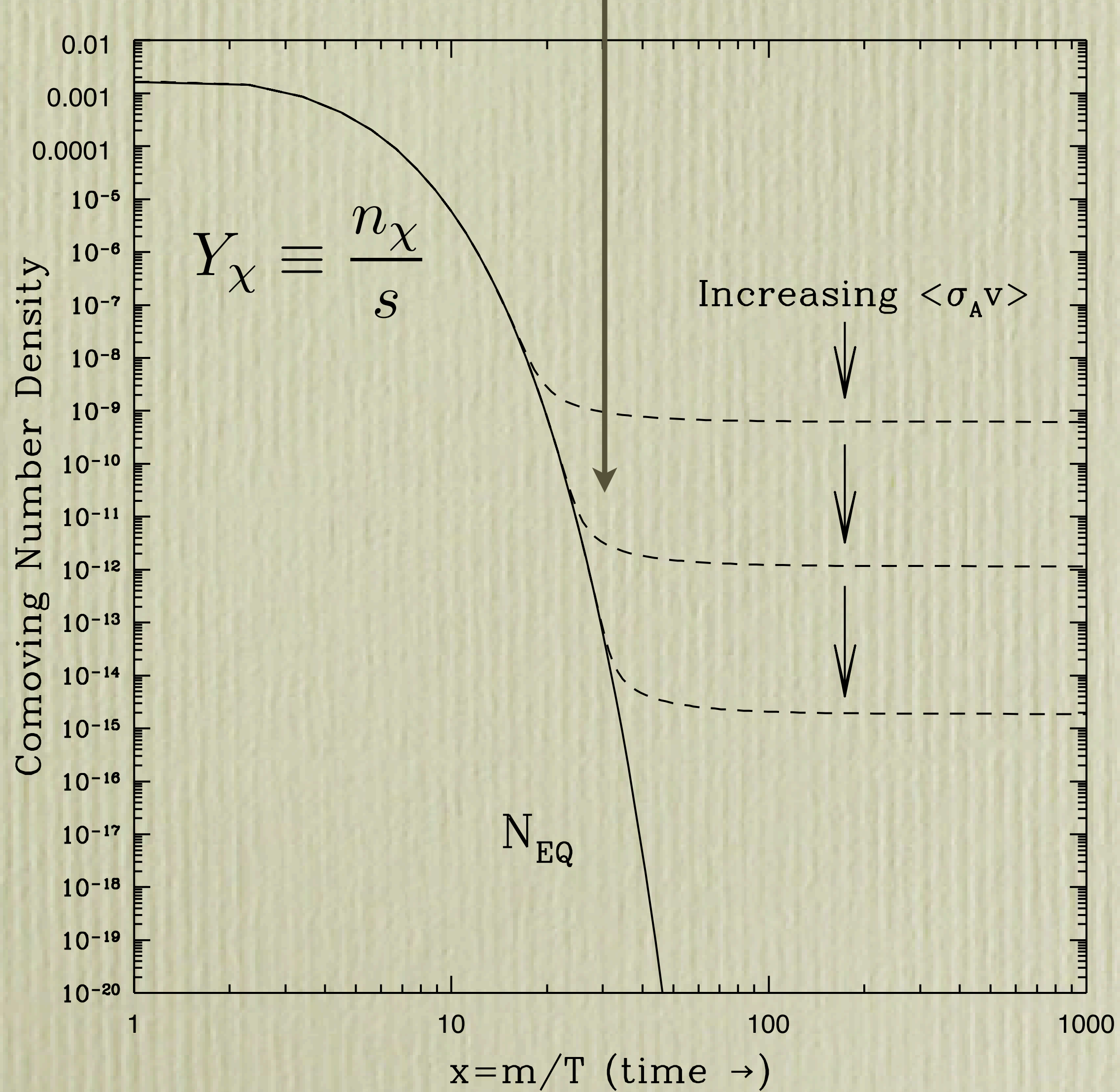
CDM particles as thermal relics

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.

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



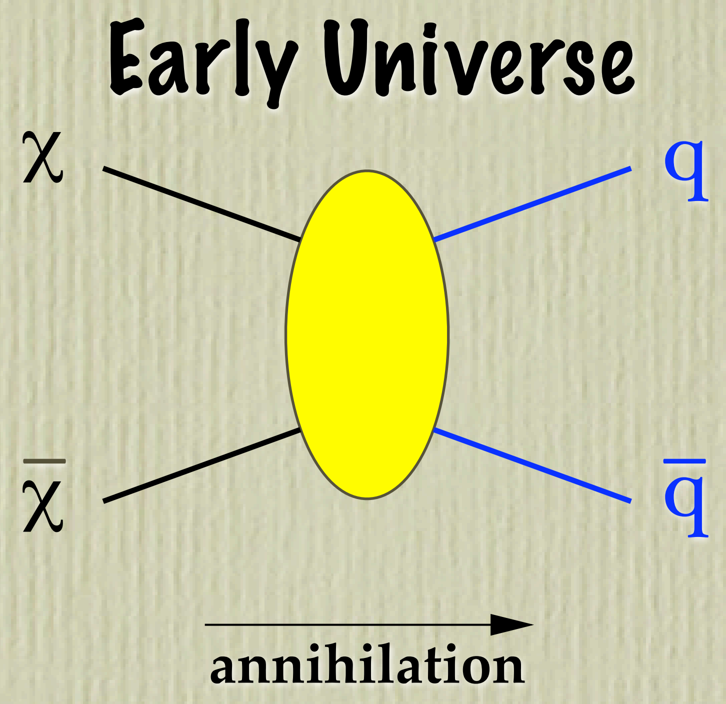
$$\Omega_\chi h^2 \simeq \frac{3 \cdot 10^{-27} \mathrm{cm}^{-3} \mathrm{s}^{-1}}{\langle \sigma_A v \rangle_{T=T_f}}$$

$\downarrow$

WIMPs

This production mechanism indicates the route to address the coupling of DM with ordinary matter, and hence how to search for DM.

WIMP coupling to ordinary matter



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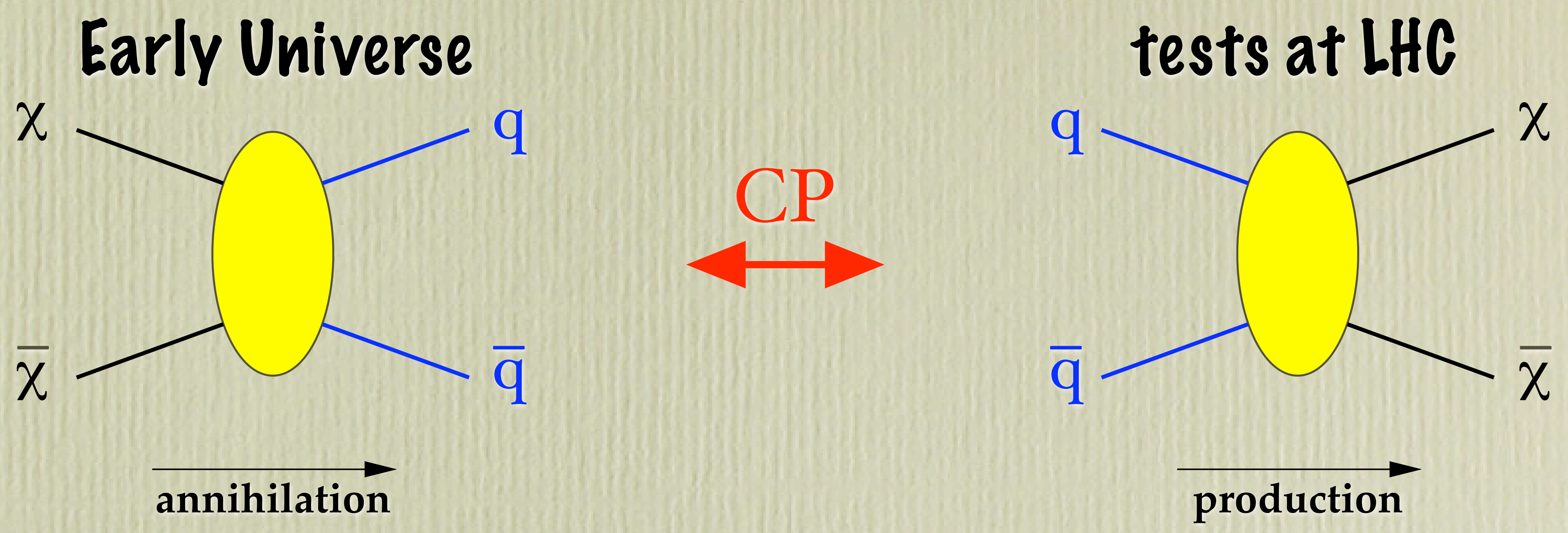

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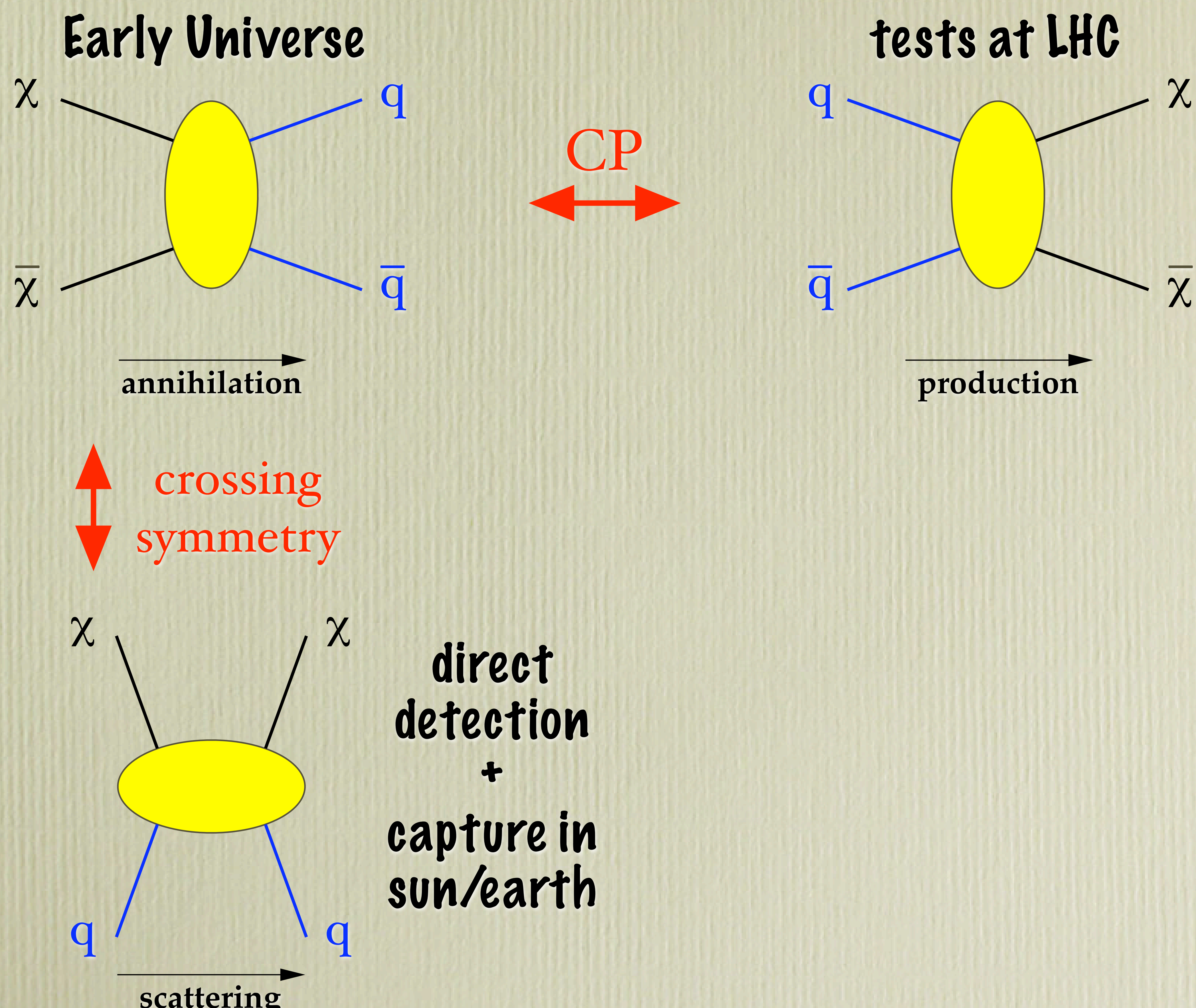

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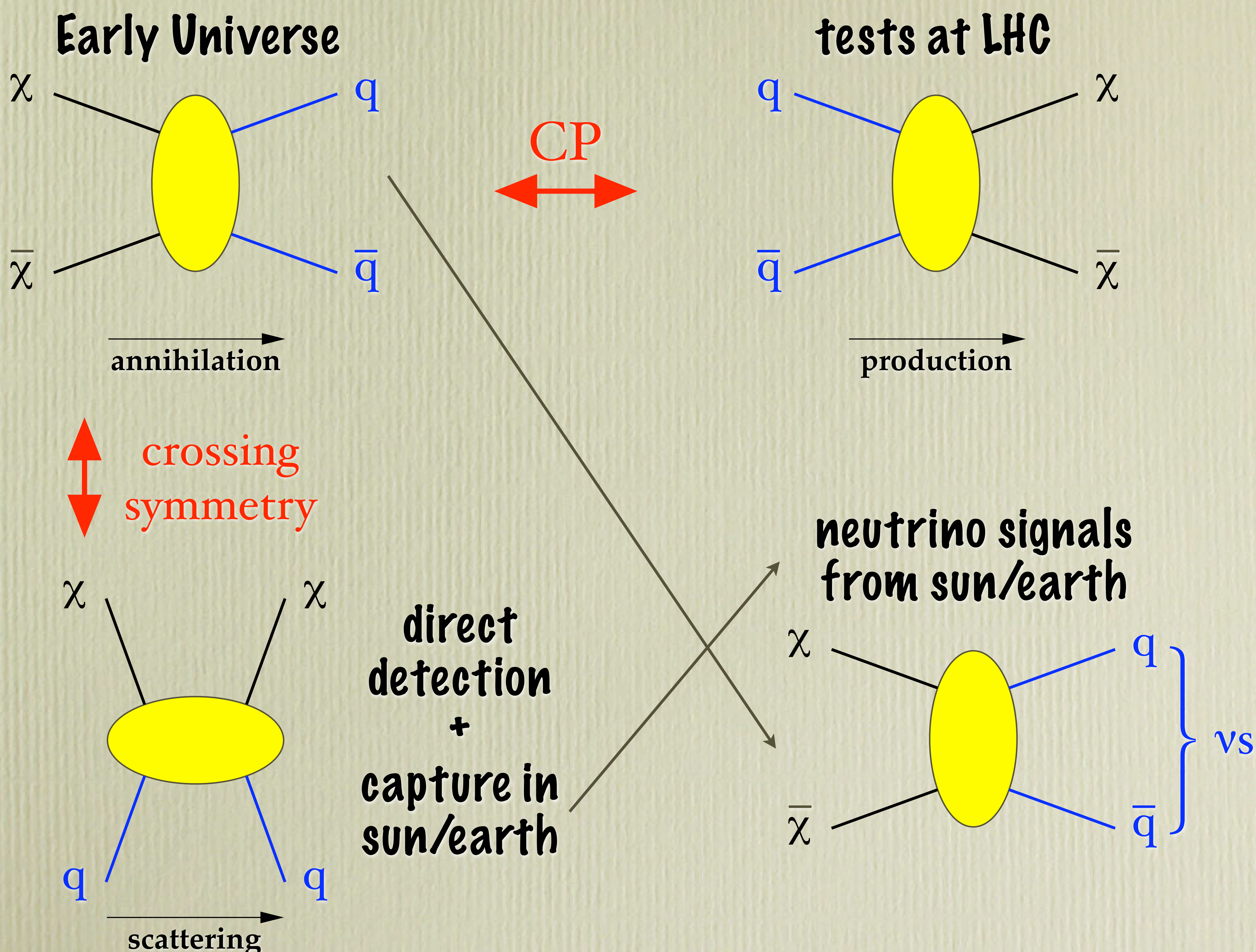
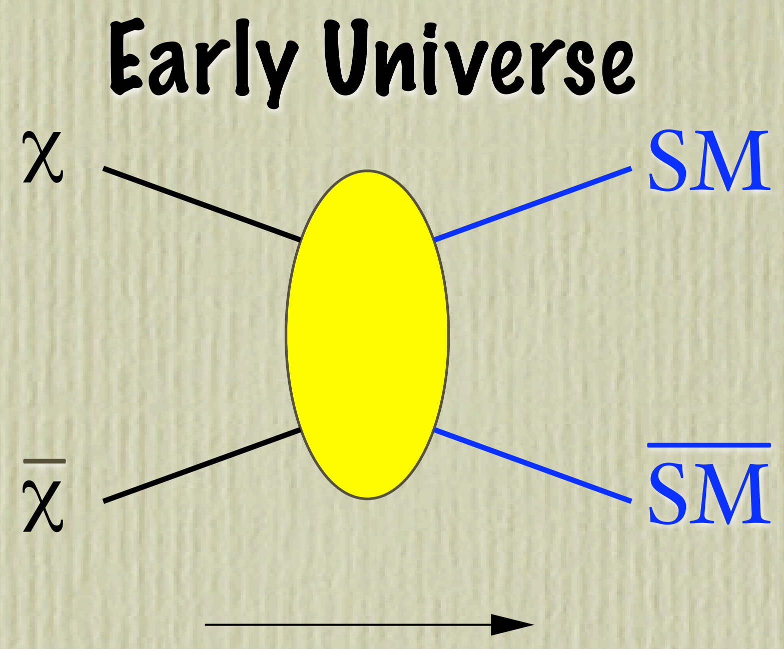


WIMP coupling to ordinary matter ???



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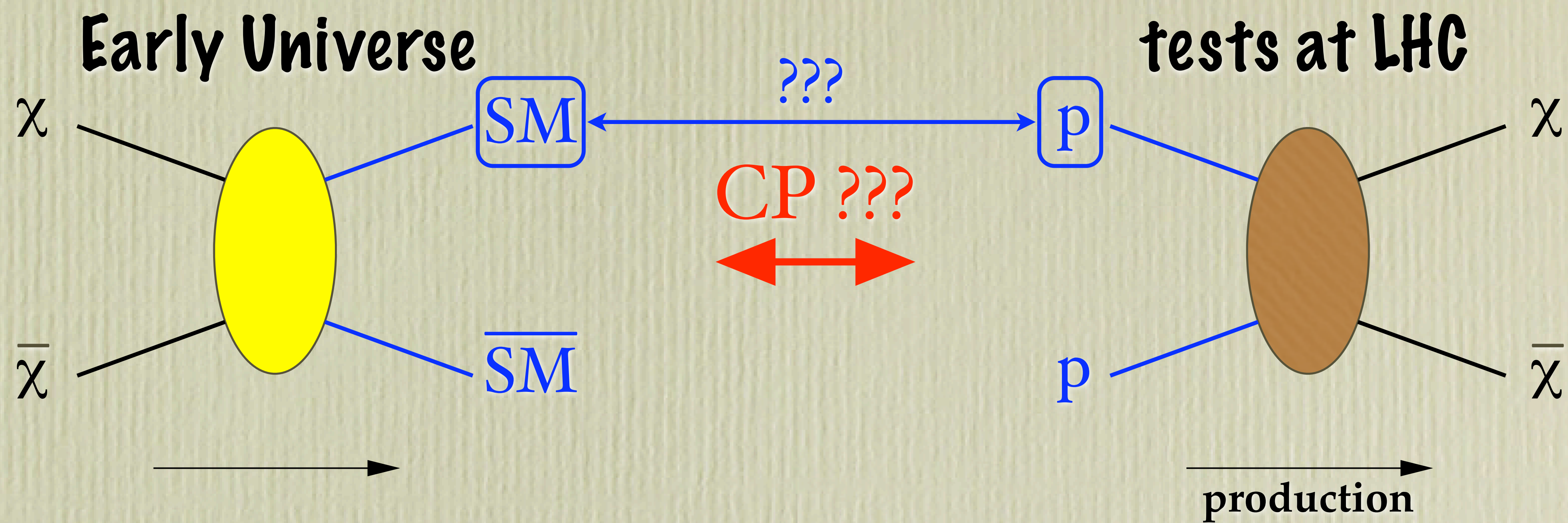

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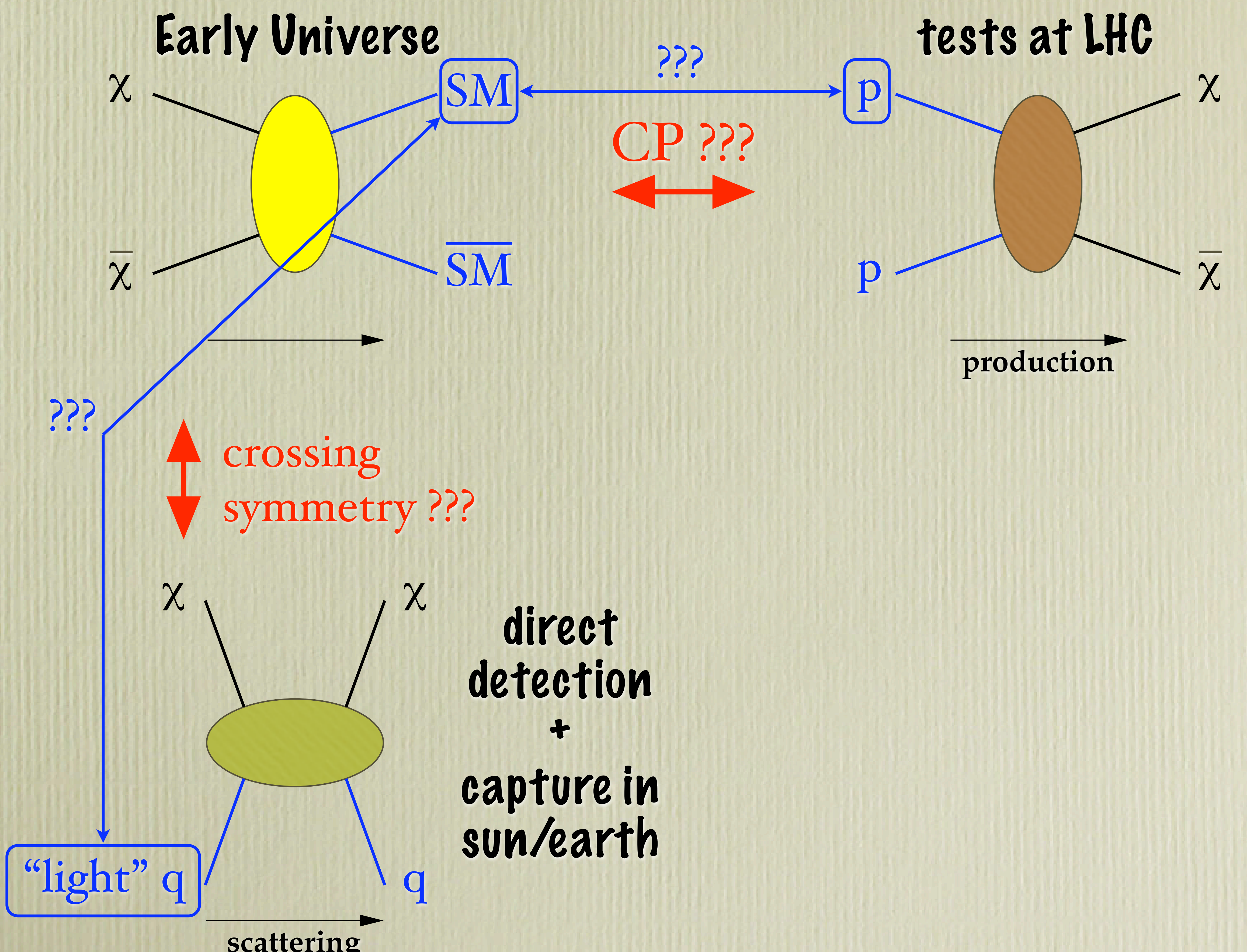

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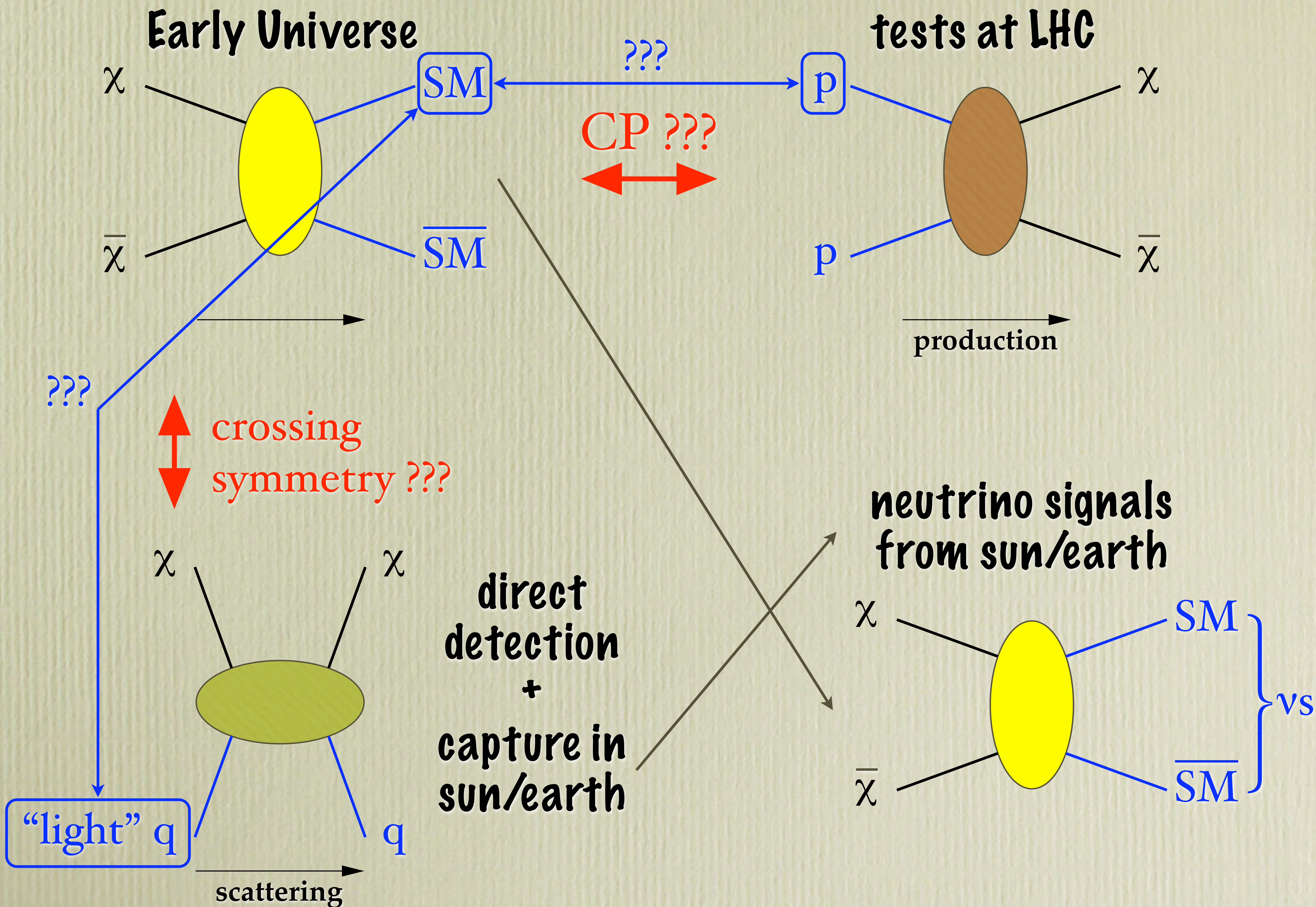
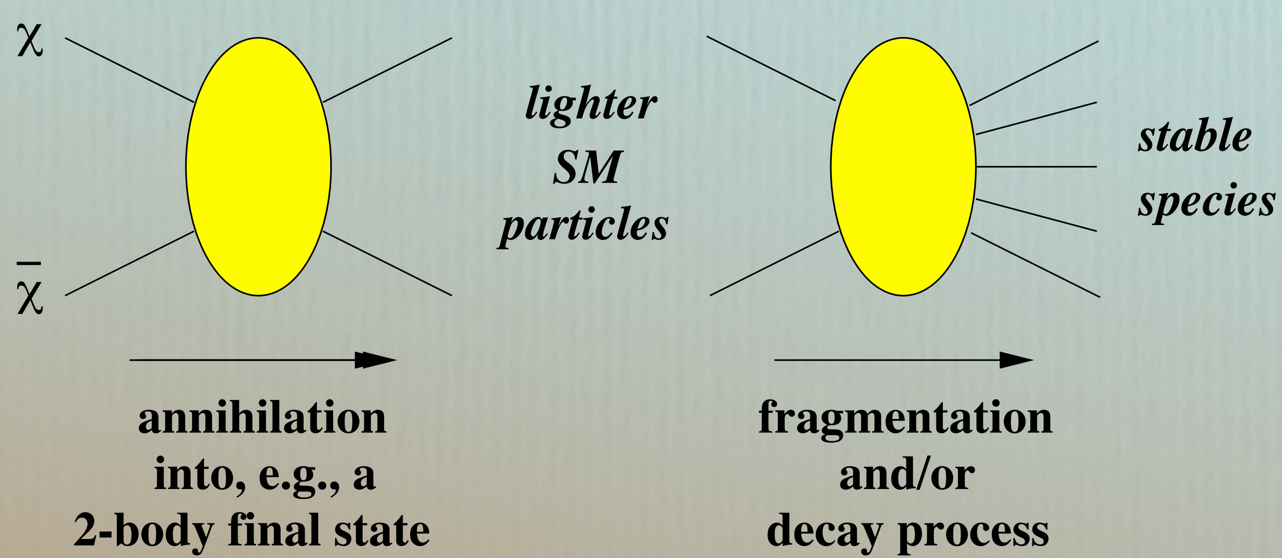


Indirect detection of WIMP dark matter

The chance of detection stems from the WIMP paradigm itself:

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



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

WIMP DM source function:

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

total rate

branching ratios

yield spectra

\# density of WIMP pairs

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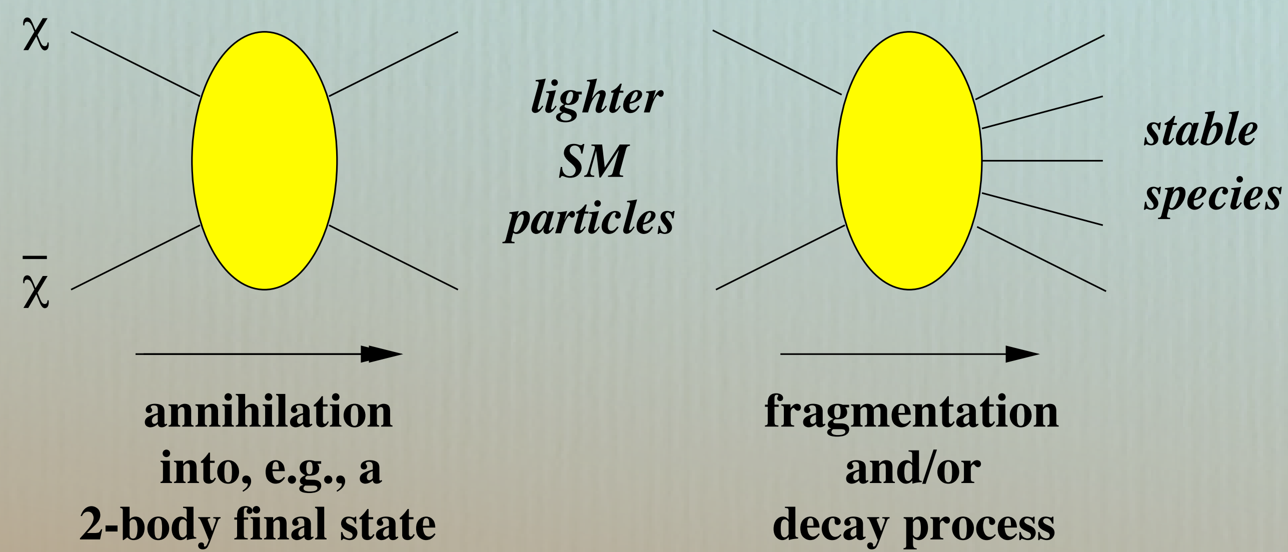


Focus on:
antiprotons,
positrons,
antideuterons,
gamma-rays,
(neutrinos)

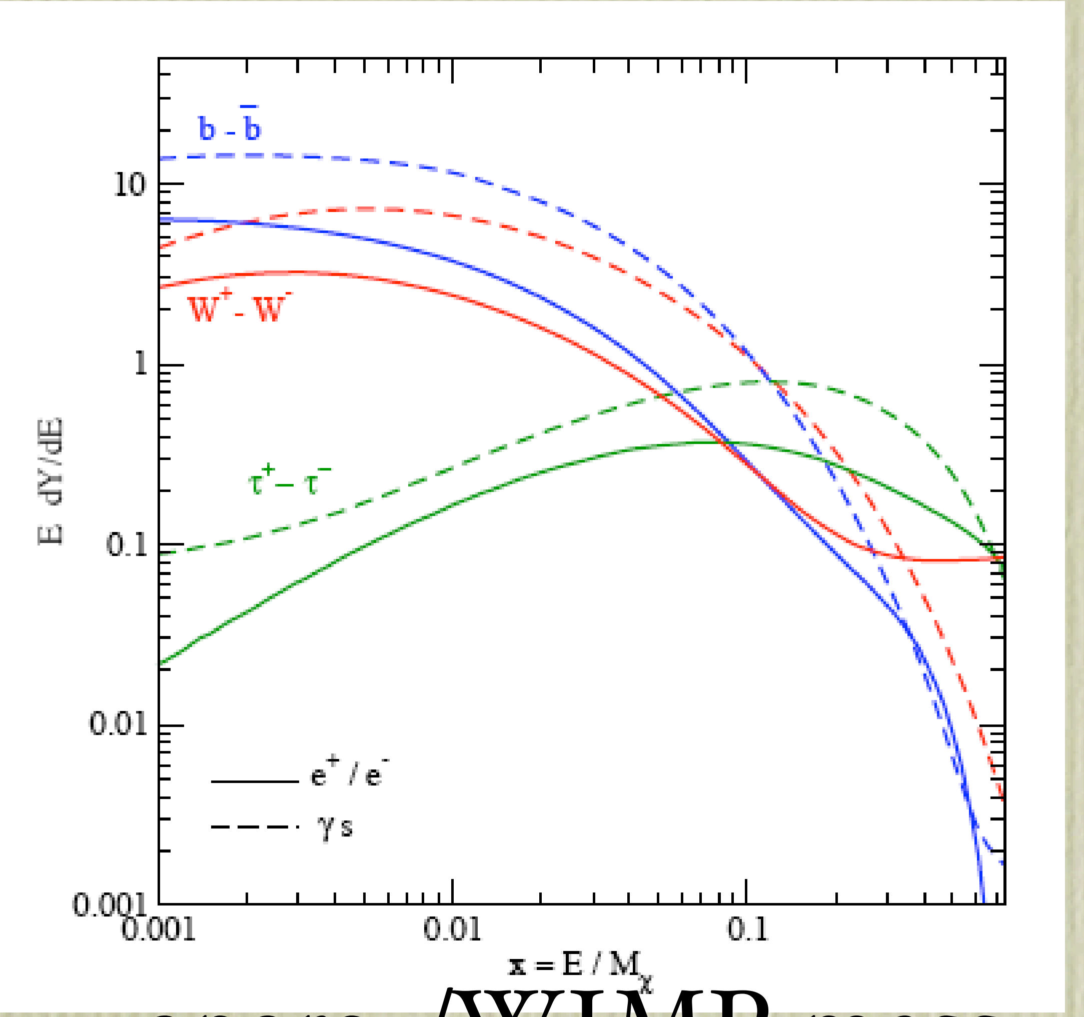
WIMP DM source function:

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

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

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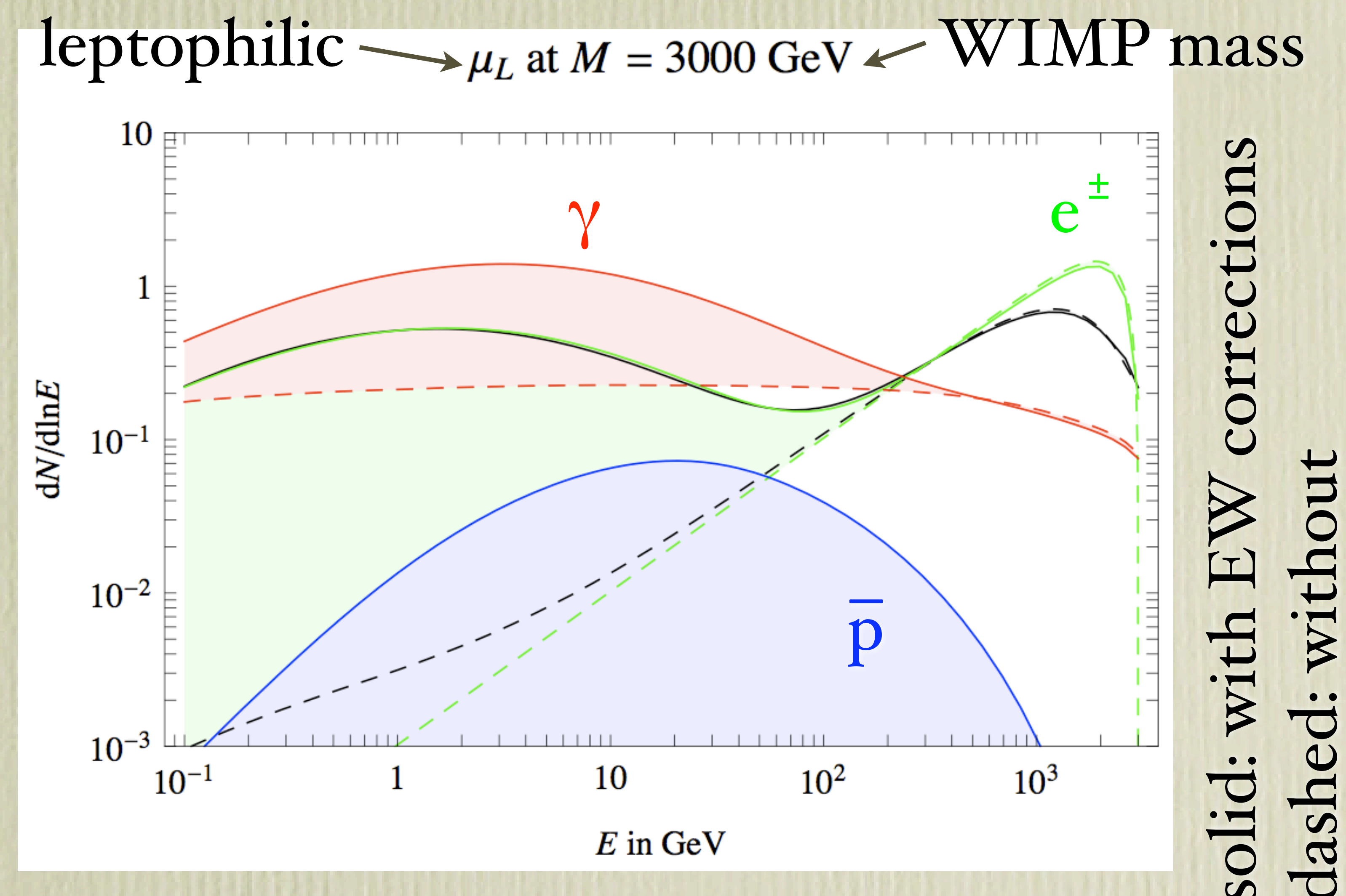
Even for leptophilic models, designed to prevent large $\bar{p}$ yields, in case of heavy WIMPS, there is a non-negligible $\bar{p}$ component due to radiative emission of EW gauge bosons.



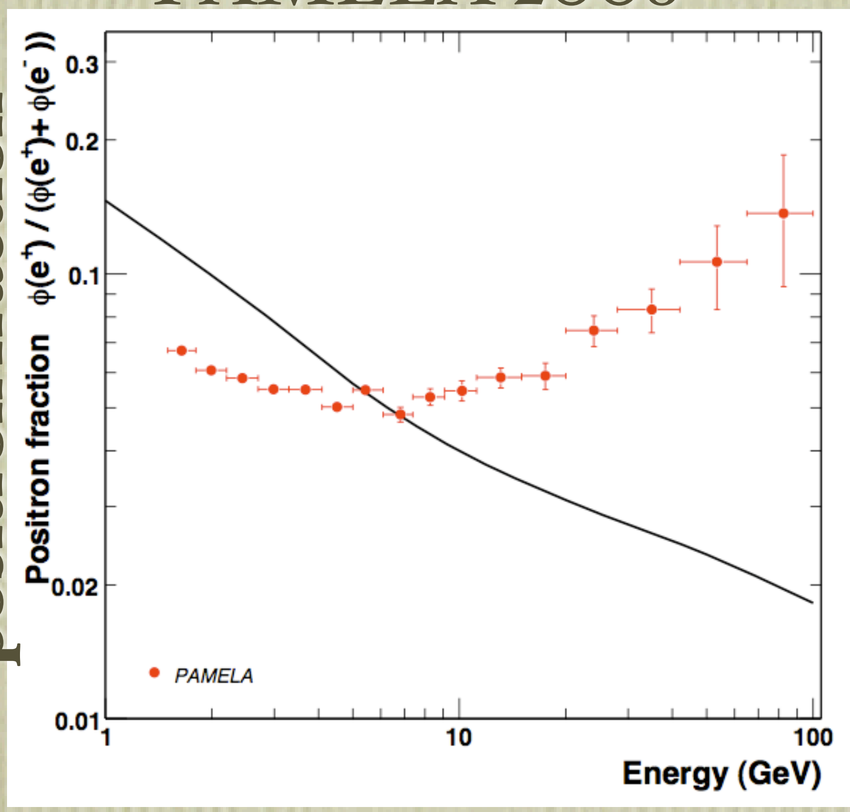
Ciafaloni et al., arXiv: 1009.0224

To be or not to be … leptophilic

The focus on leptophilic models driven the CR lepton puzzle:

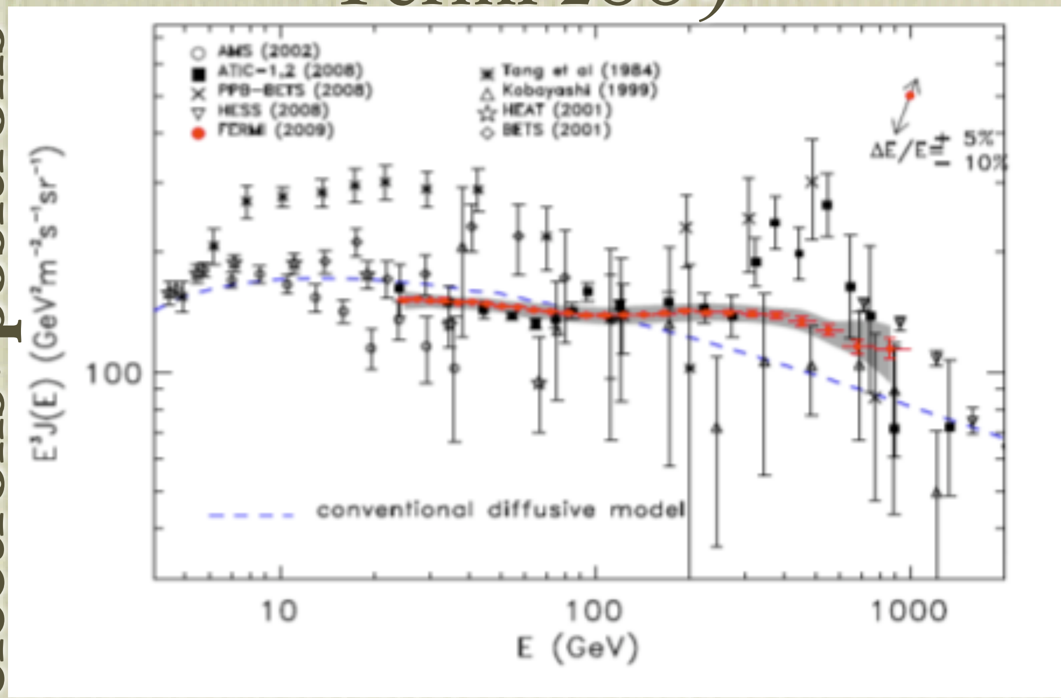
PAMELA 2008

positron fraction



Fermi 2009

electrons+ positrons



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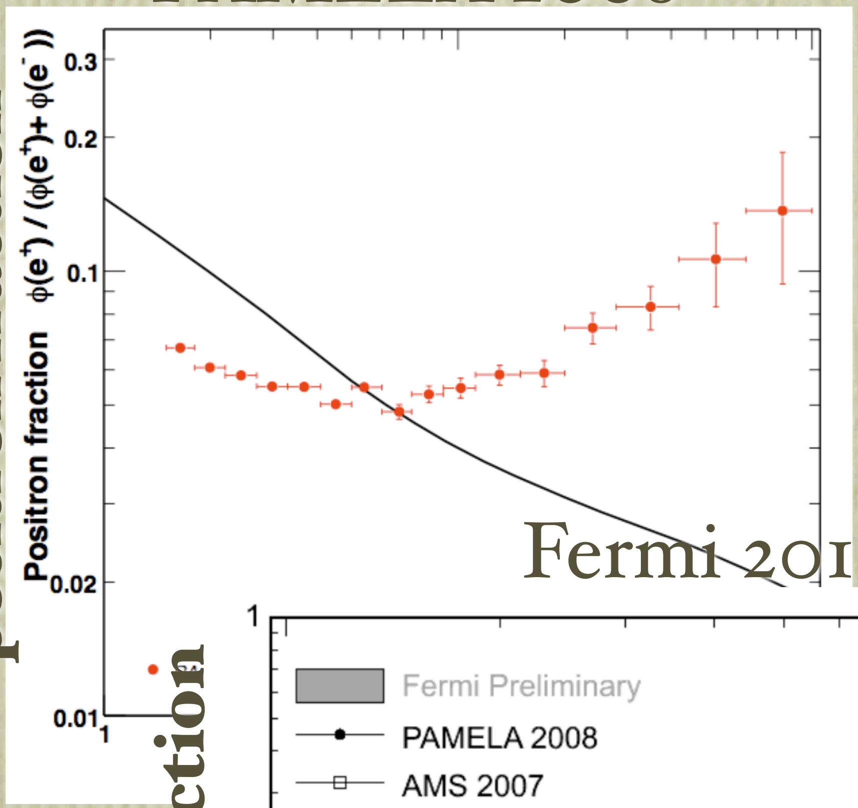

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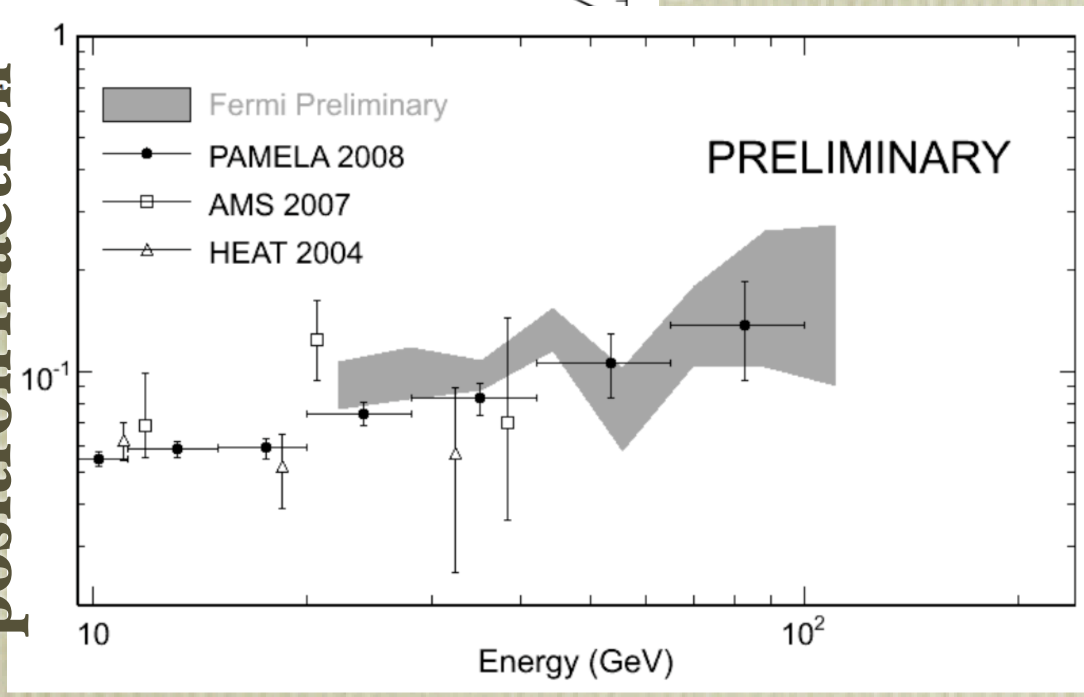

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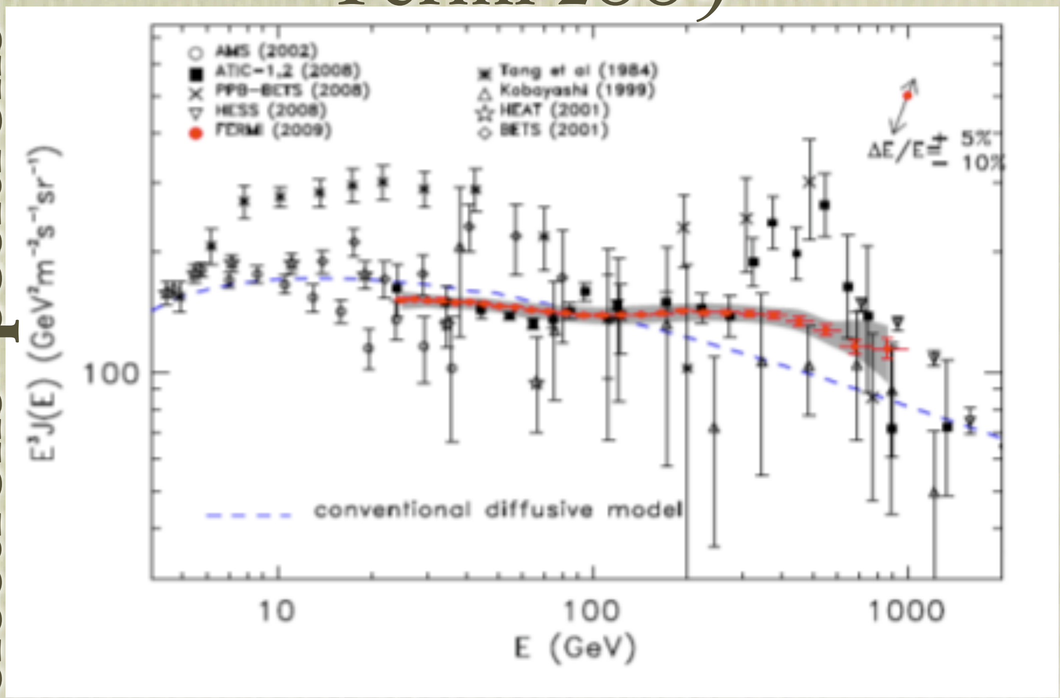

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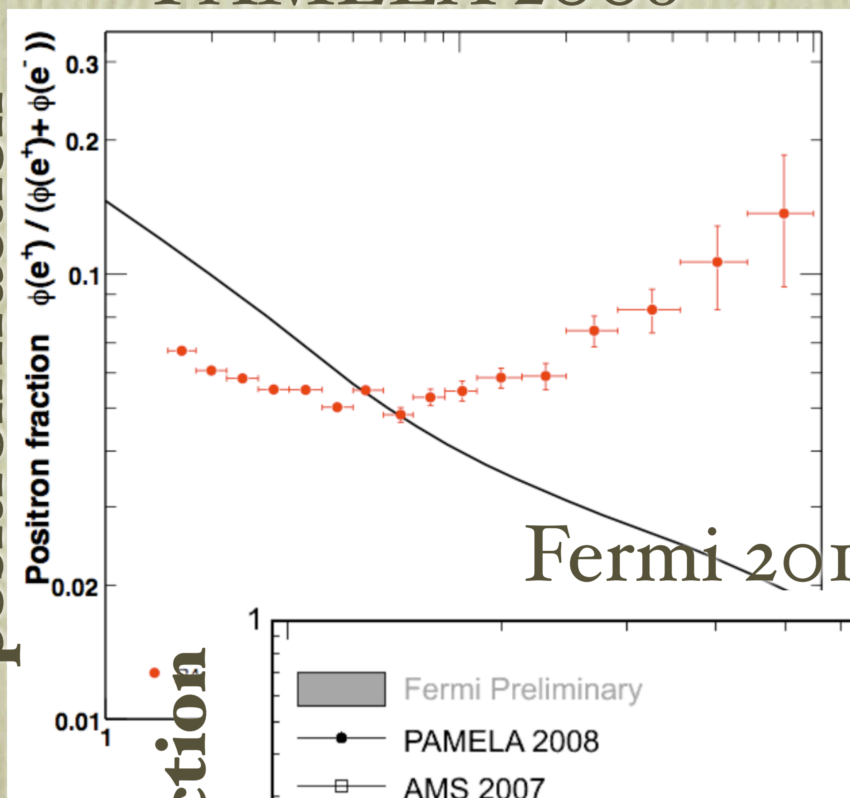

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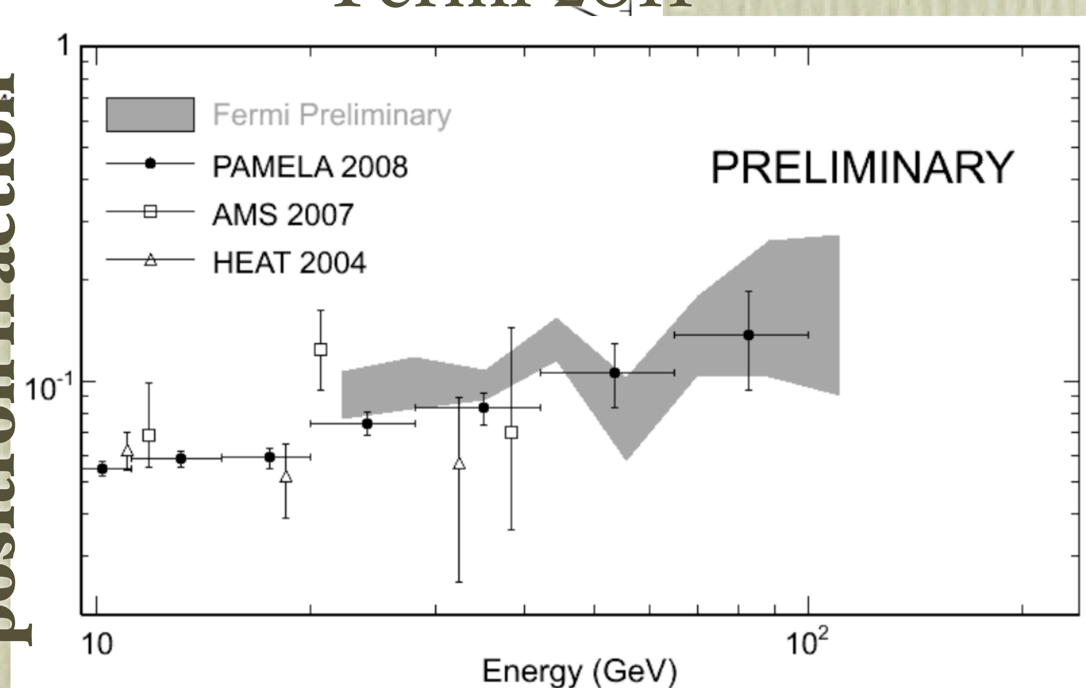

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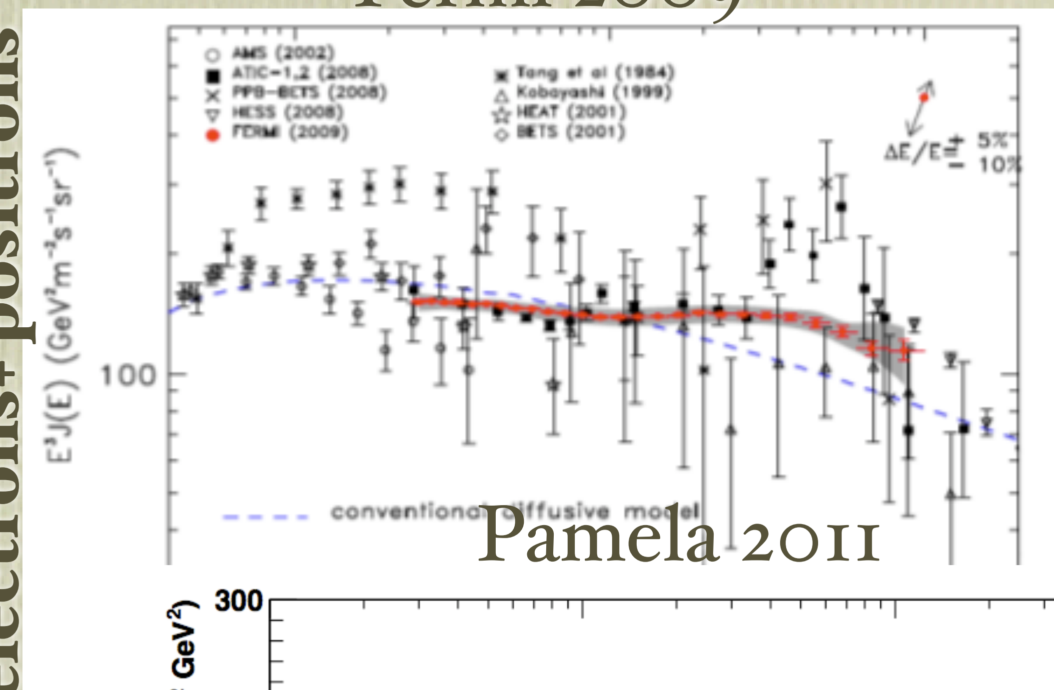
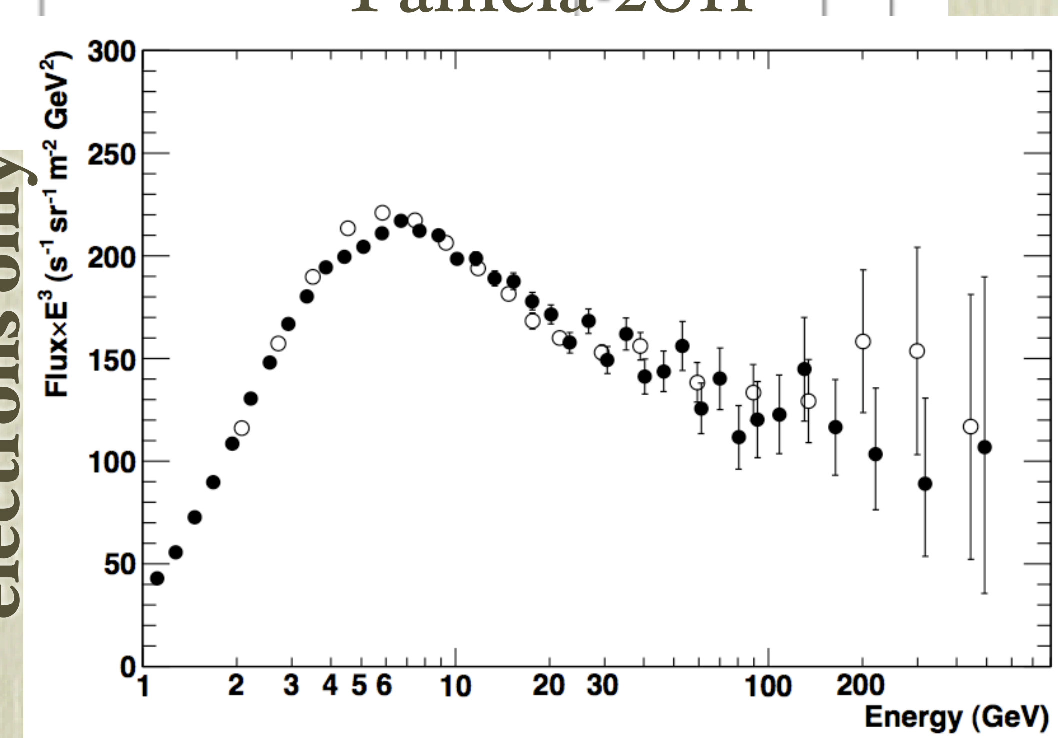


Pamela 2011

electrons only



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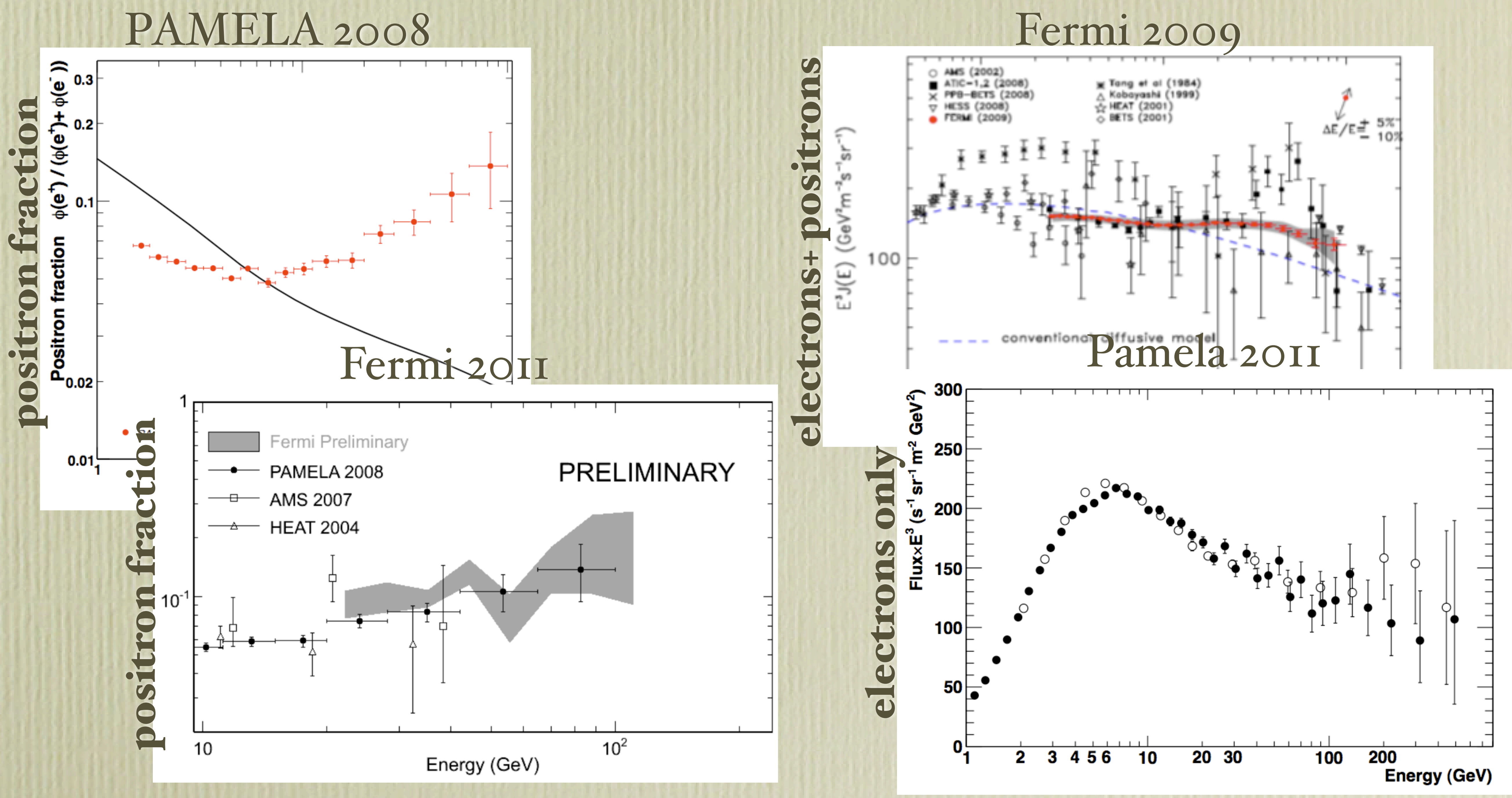


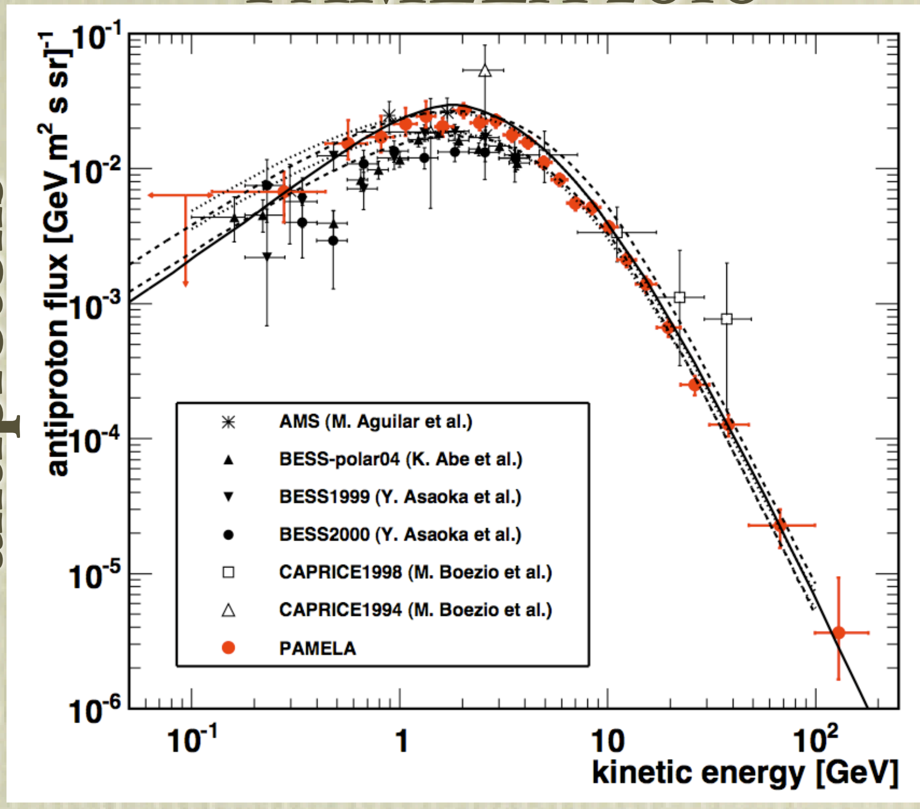
these data (most probably) cannot be fitted assuming positrons are secondary CRs generated by primary CRs during propagation.

To be or not to be … leptophilic

An exotic source of primary positrons, such as a few TeV DM WIMP, should be introduced without producing a sizable antiproton term (leptophilic DM?), since antiproton measurements match the standard background.

PAMELA 2010

antiprotons



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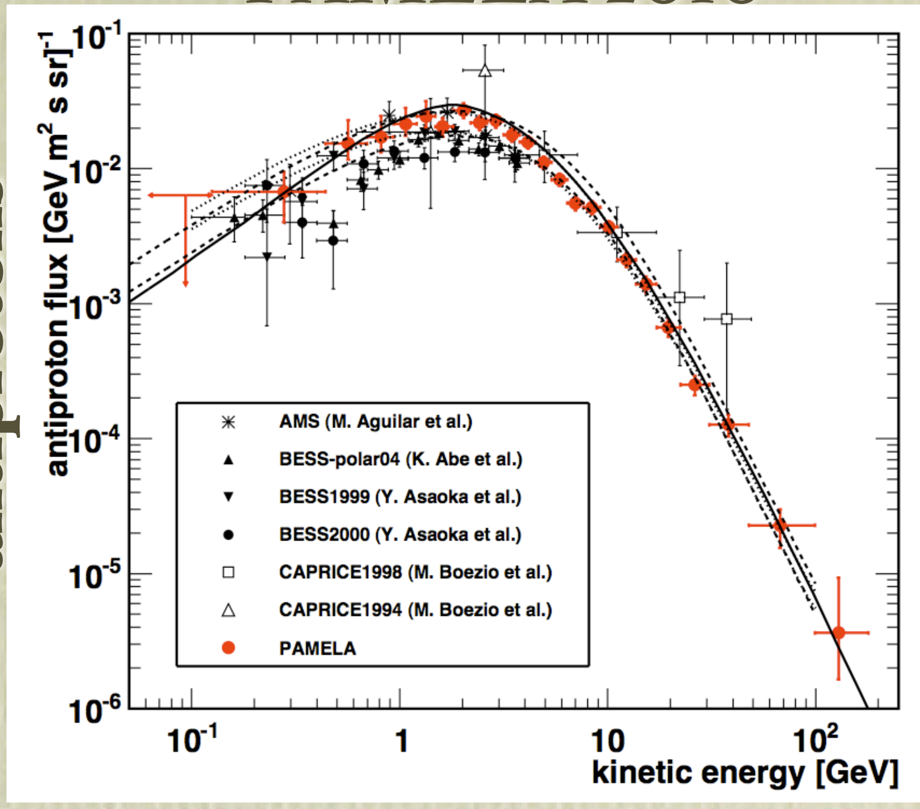

However: there are viable astrophysical sources of primary positrons (e.g. pulsars), as well as the production of secondary species may take place within the CR sources (SNRs).

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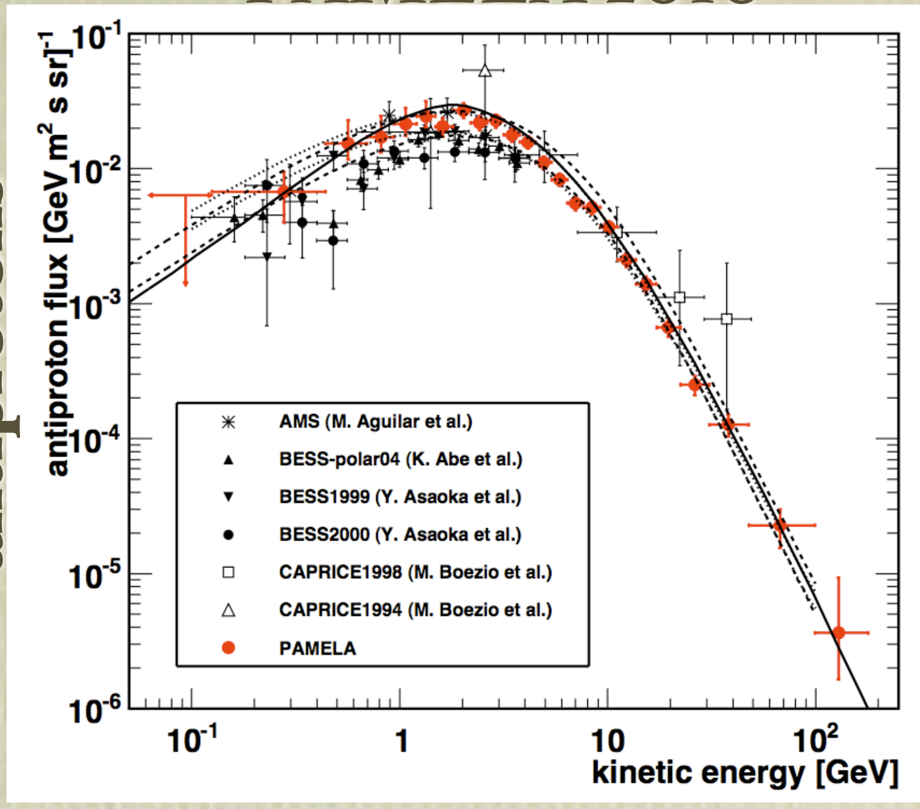

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Also: in the CR leptons we may have seen a DM signal, but definitely have not identified a DM signature. The DM interpretation might be disproved by finding a spatial anisotropy or spectral features connected to individual sources (in case they are not DM clumps): possible with CALET or PEBS?

Multi-wavelength signals from WIMP DM

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

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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

Multi-wavelength DM targets

It looks feasible to correlate the DM emissivities in e.g.:

- objects with large DM densities and well-measured SEDs, e.g.: the **Galactic center** & **galaxy clusters**; e.g.: Gondolo, 2000; Bertone, Sigl & Silk, 2001; Aloisio, Blasi & Olinto, 2004; Bergstrom et al, 2006; Colafrancesco & Mele, 2000; Totani, 2004;

- objects with well-understood standard astrophysical backgrounds, e.g.: the **Galactic emission** at intermediate and high galactic latitudes (???); e.g.: Borriello, Cuoco & Miele, 2008 & 2009; Hooper et al., 2008; Cirelli, Panci & Serpico, 2009;

- objects with very suppressed backgrounds from standard astrophysical sources, e.g.: **dwarf galaxies**, the LMC (?); e.g.: Colafrancesco, Profumo & P.U., 2007; Jeltema & Profumo, 2008; Siffert et al., 2010.

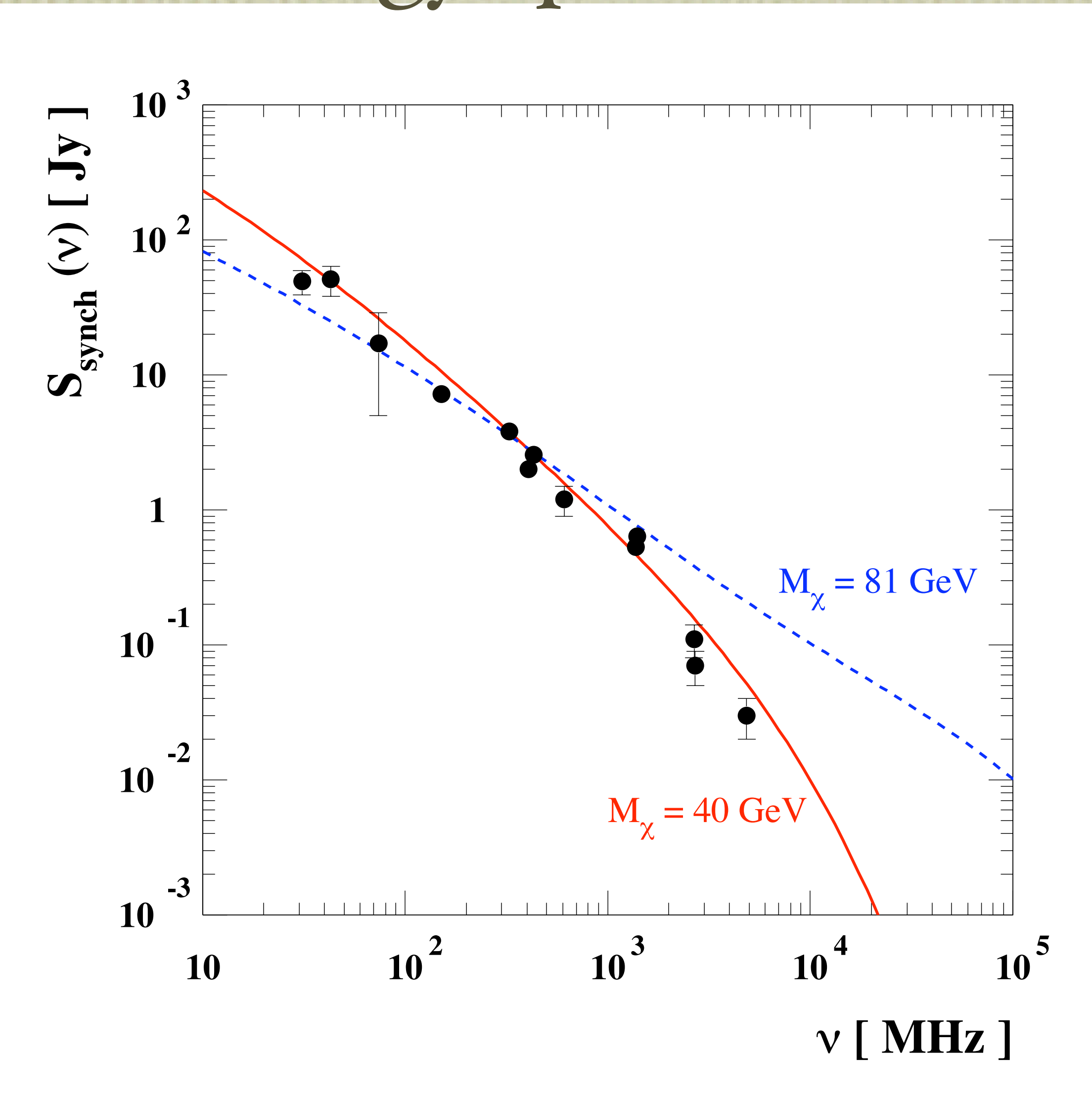
Other studies are more subtle, such as for the **WMAP** and **Fermi haze/bubbles**, e.g.: Finkbeiner, 2004; Hooper, Finkbeiner & Dobler, 2007; Cholis, Goodenough & Weiner, 2009; Goodenough & Hooper, 2009; Su, Slayter & Finkbeiner, 2010.

Apologies for the very incomplete list of references

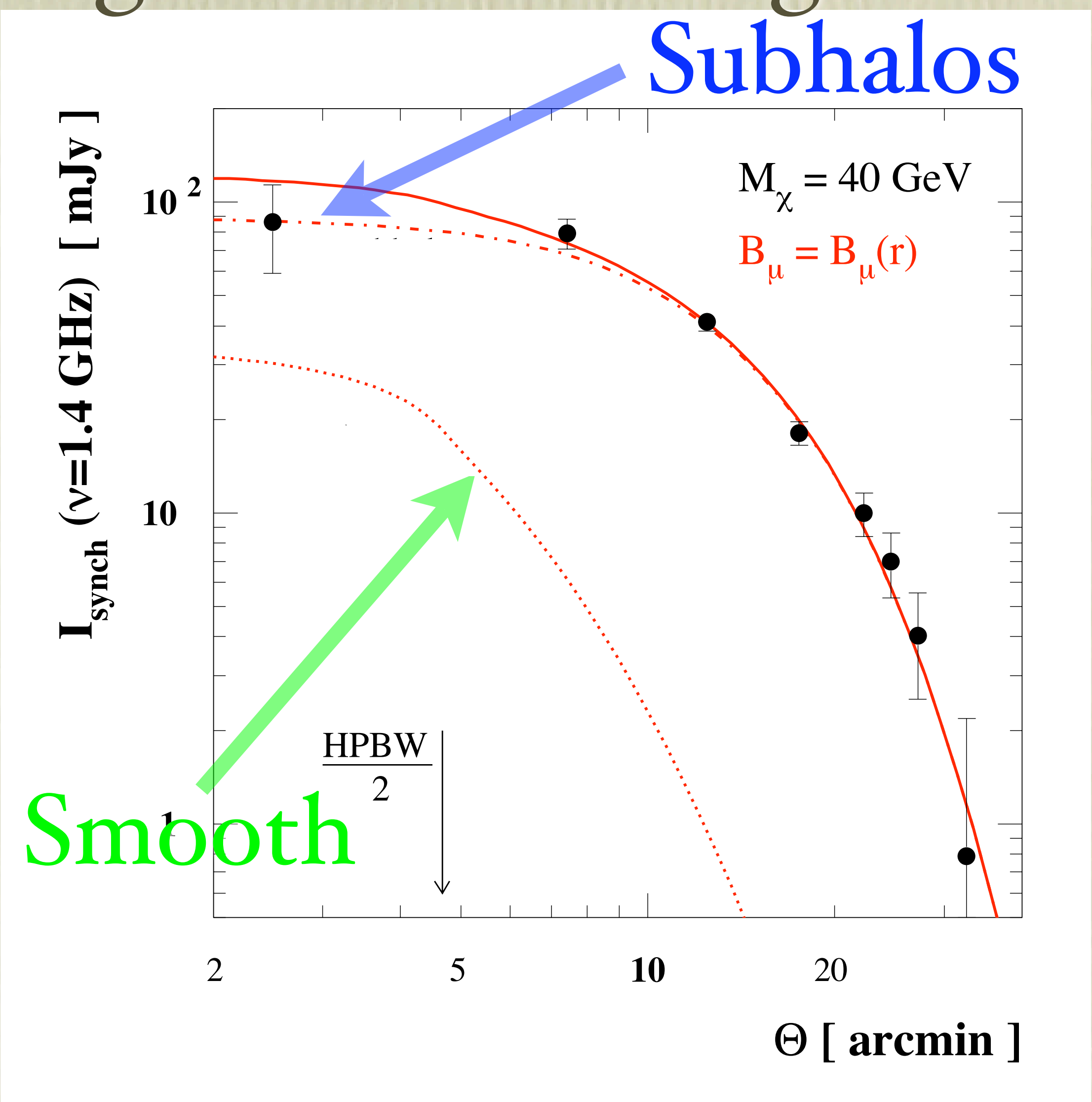
A sample "easy" target: the Coma cluster

Good fits of the **radio halo** can be obtained with a WIMP annihilating into a soft channel, adjusting the WIMP mass and the annihilation rates (generally larger than for thermal relics)

energy spectrum



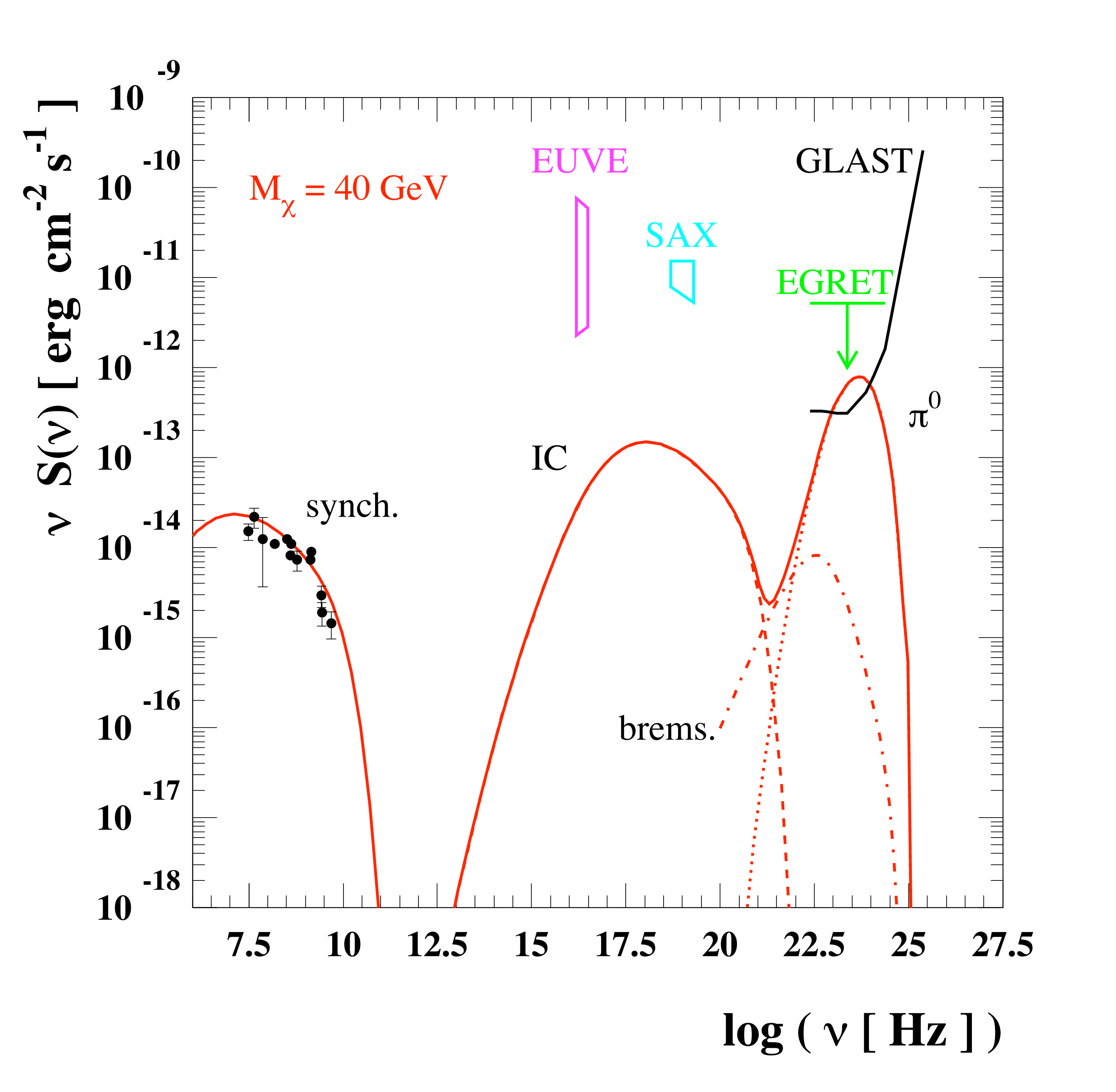
angular surface brightness



radial dependence of B from Faraday RM fits

Colafrancesco, Profumo & P.U.,2006

For such DM model, the multi-wavelength SED corresponding to the sample model (NOTE: it is just a sample case) fitting the radio halo has an inverse Compton component (on the CMB) undershooting the UV ad X-ray emission in Coma,

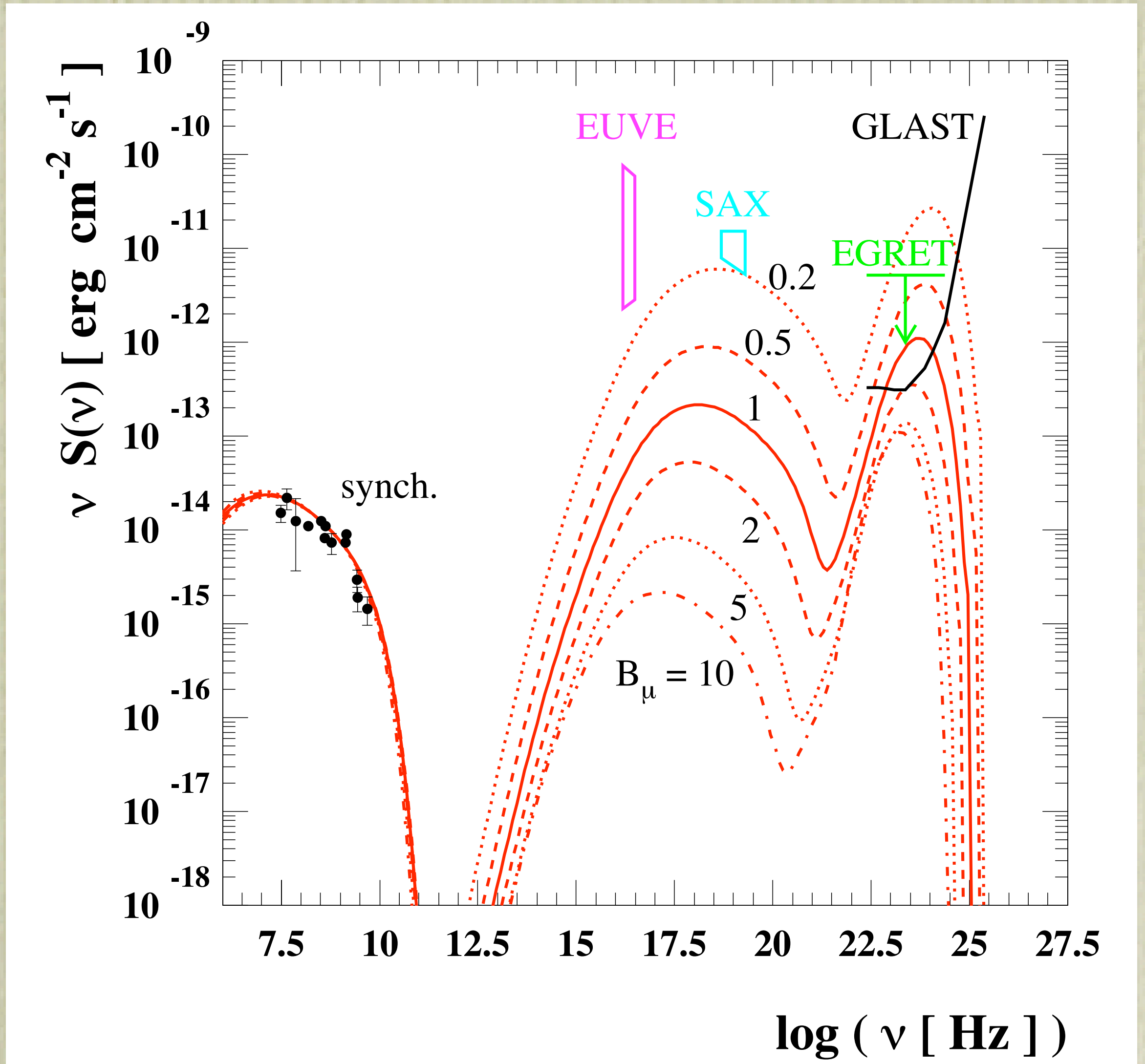


while the associated γ-ray component might be within the sensitivity of Fermi.

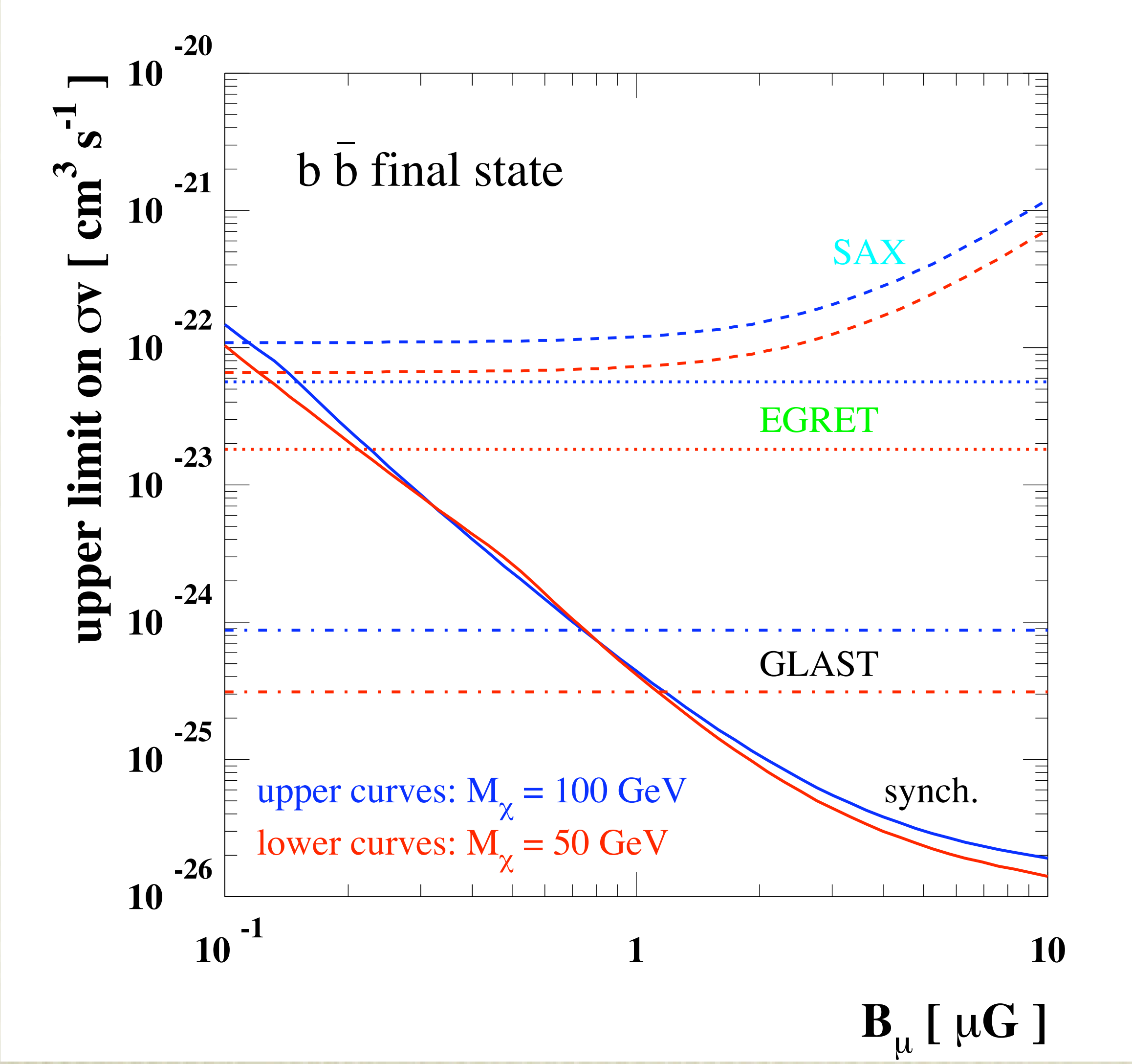
Colafrancesco, Profumo & P.U.,2006

The assumption on the magnetic field is the most critical in this analysis: the inferred properties of the WIMP change accordingly!

Assume a few sample value for the mean B and adjust mass and σv to the radio halo:



Upper limits on σv for two sample values of the mass, varying the mean B:



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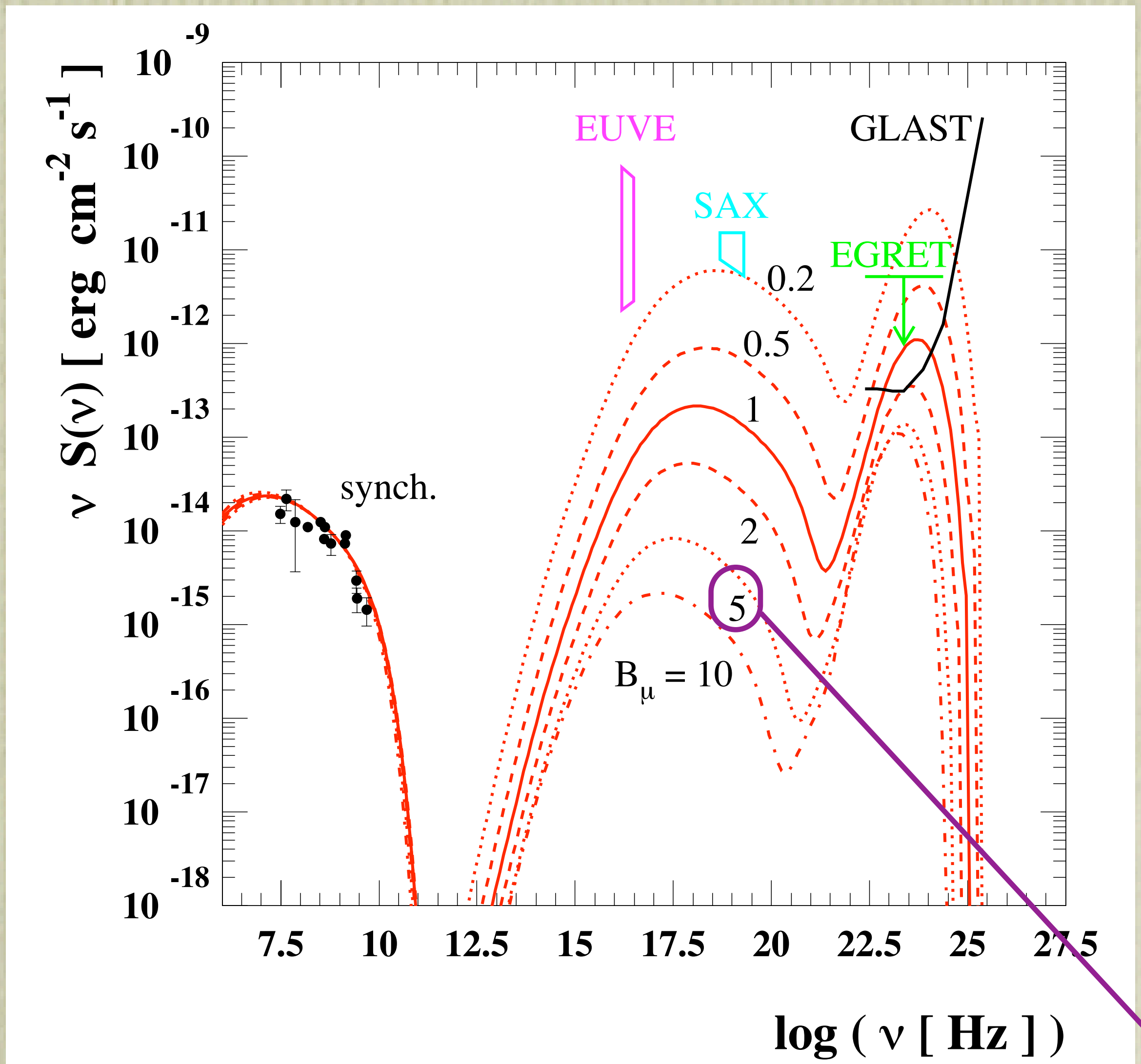

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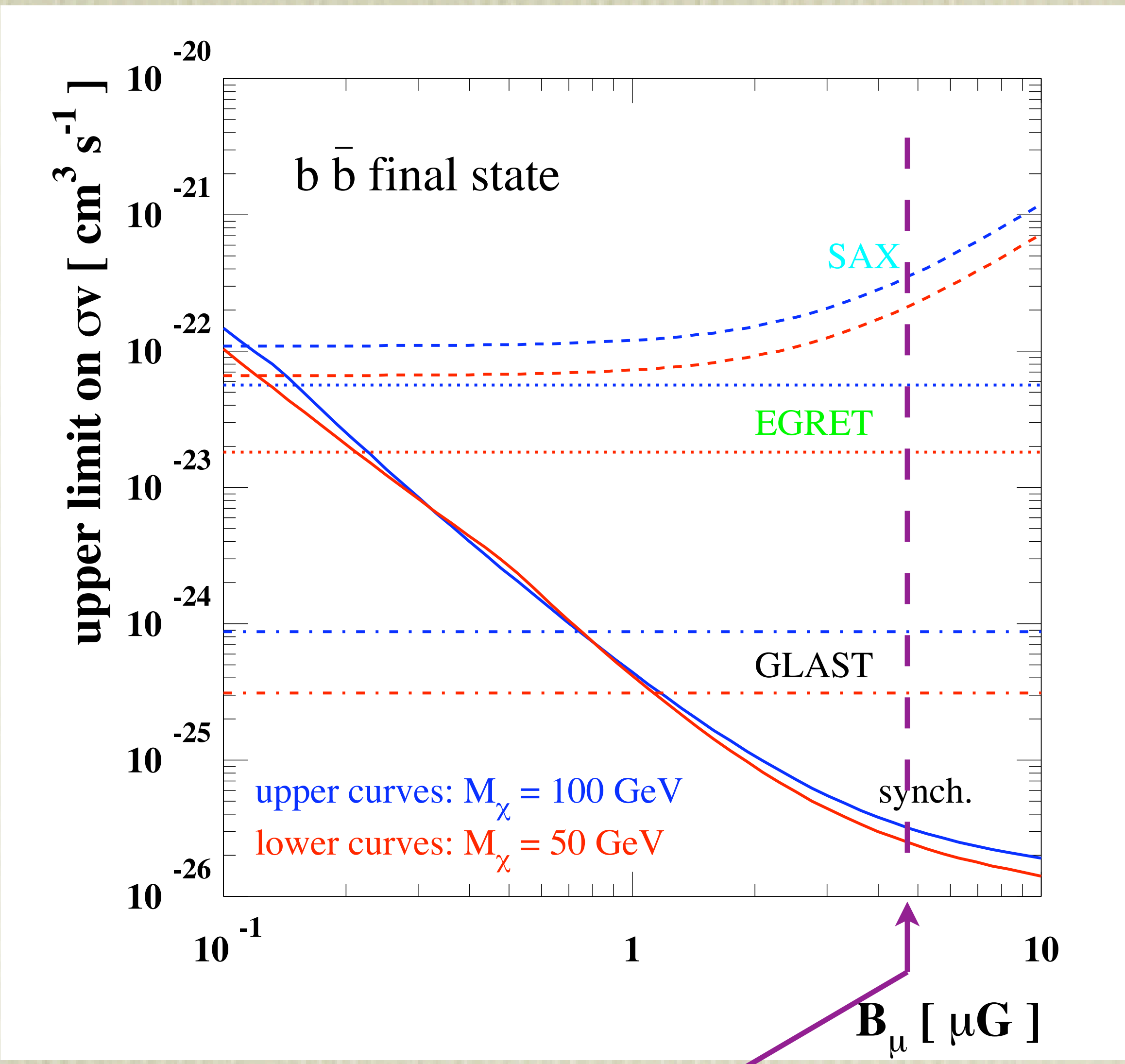
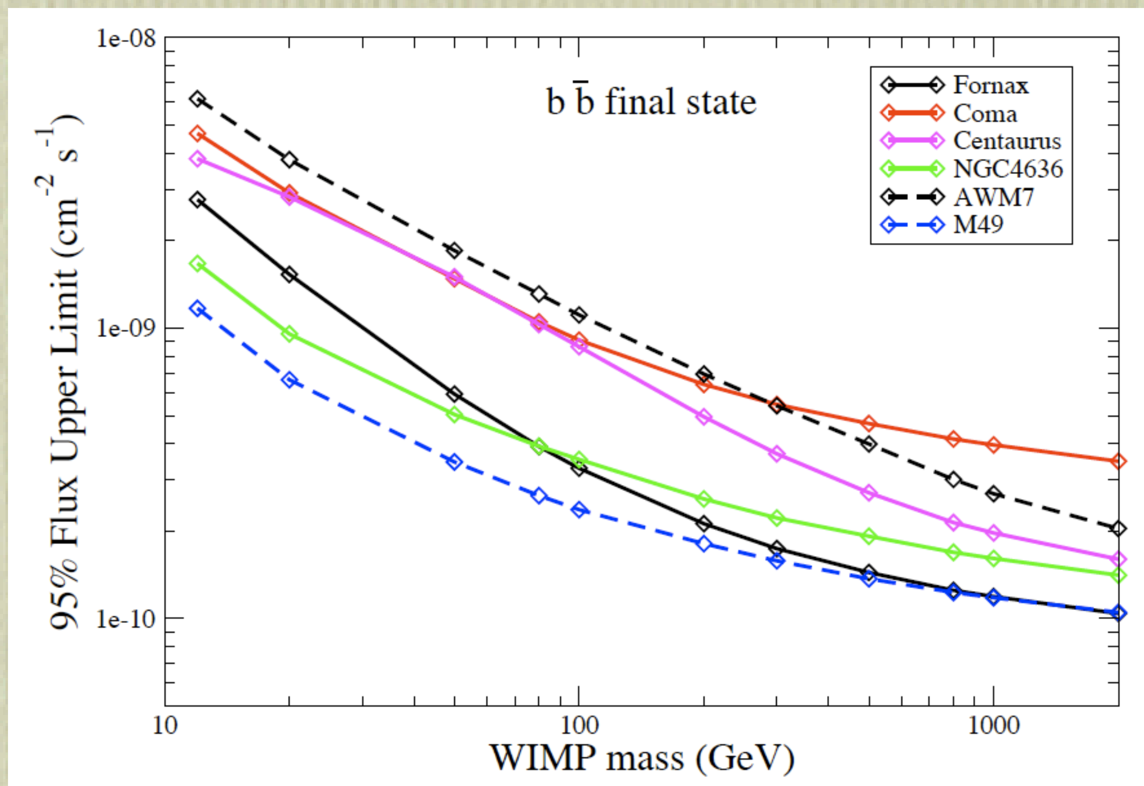


Colafrancesco, Profumo & P.U., 2006

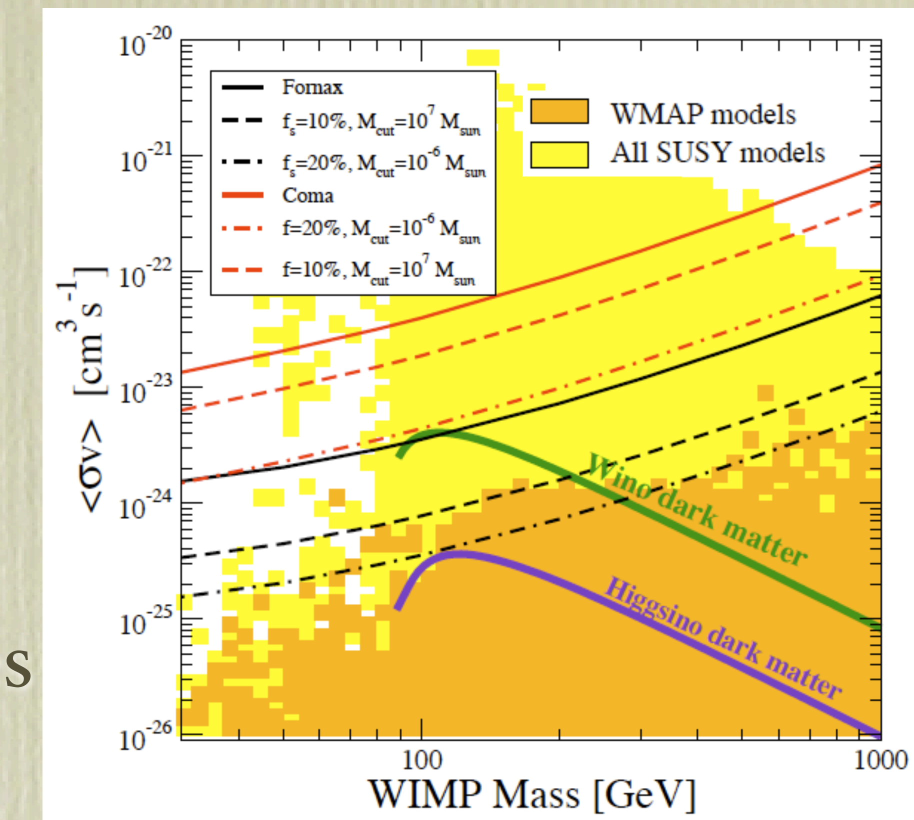
Latest value from FR: $B \approx 4.7\ \mu G$

Bonafede et al., 2010

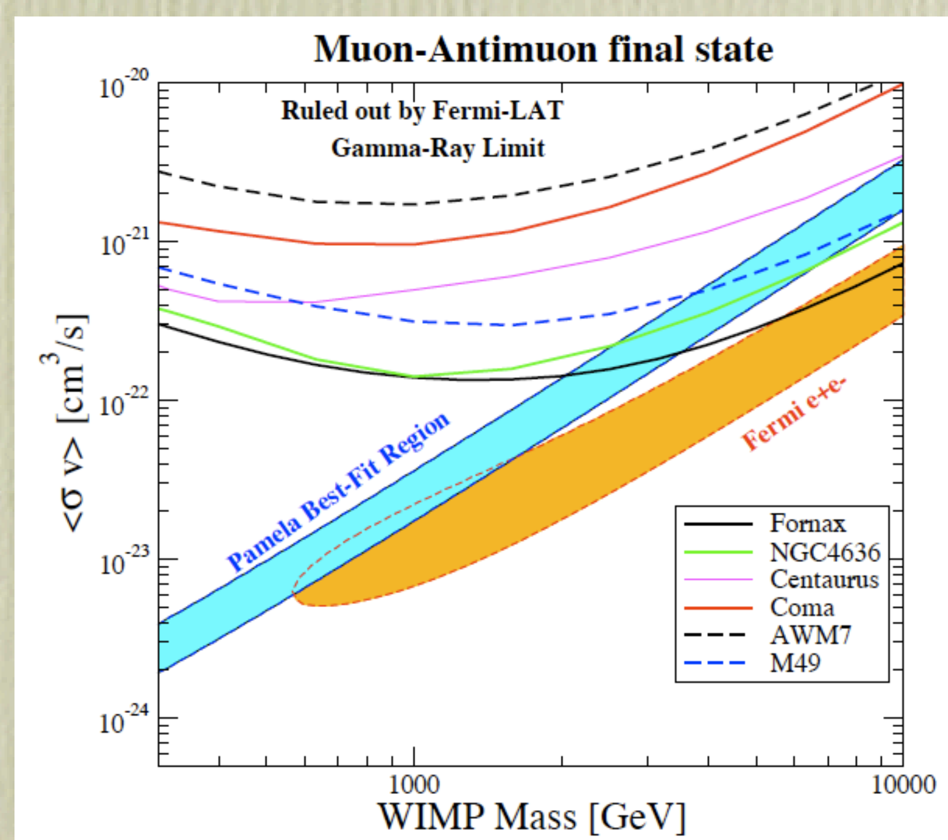
Fermi has searched for the γ-ray emission from nearby clusters and set upper limits: **The Fermi LAT collaboration, arXiv:1002.2239**



Depending on density profile/ substructures

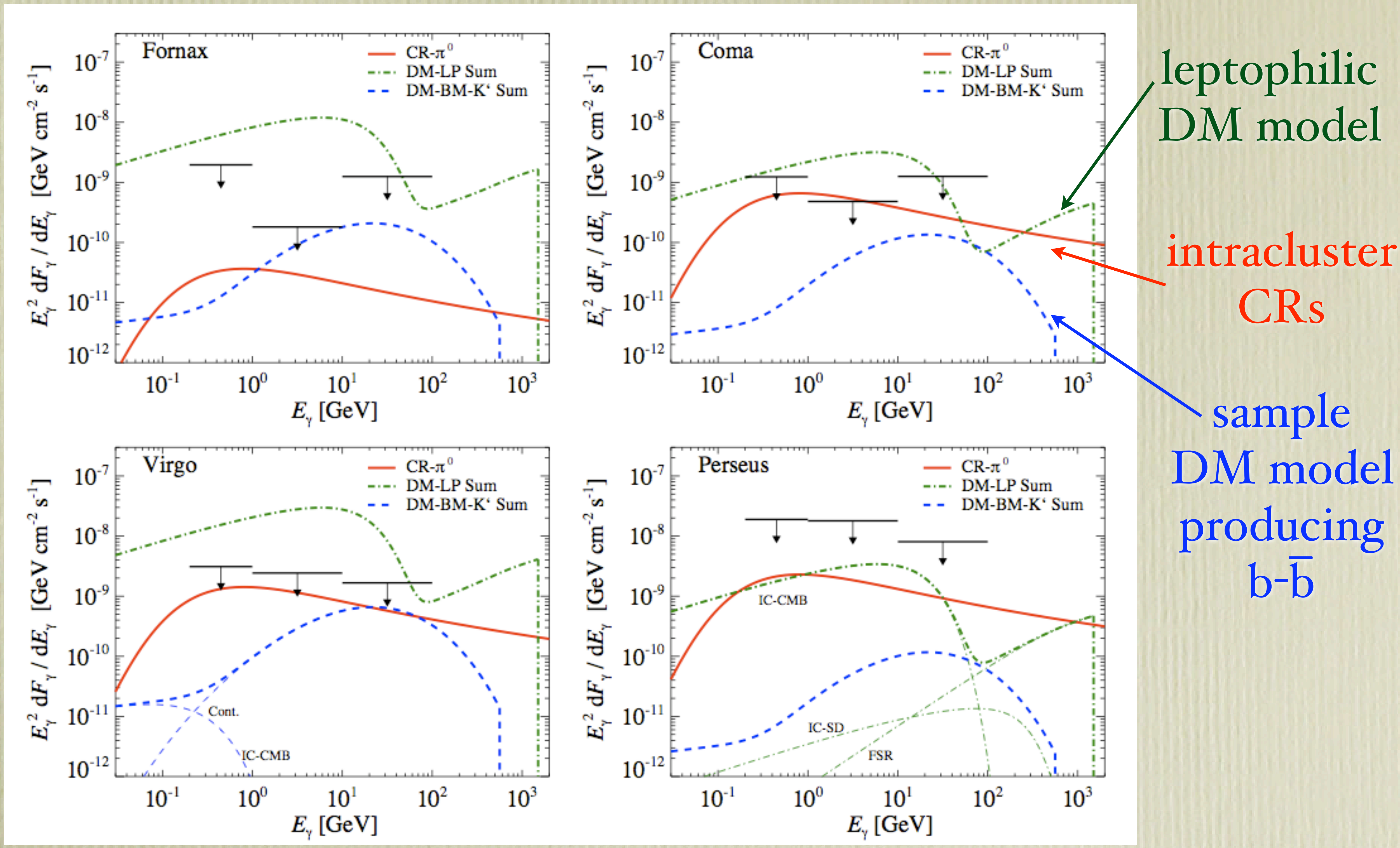


For leptophilic channels γs from FSR + IC on the CMB: more critical dependence on the magnetic fields



Depending on B, radio constraints can be more competitive.

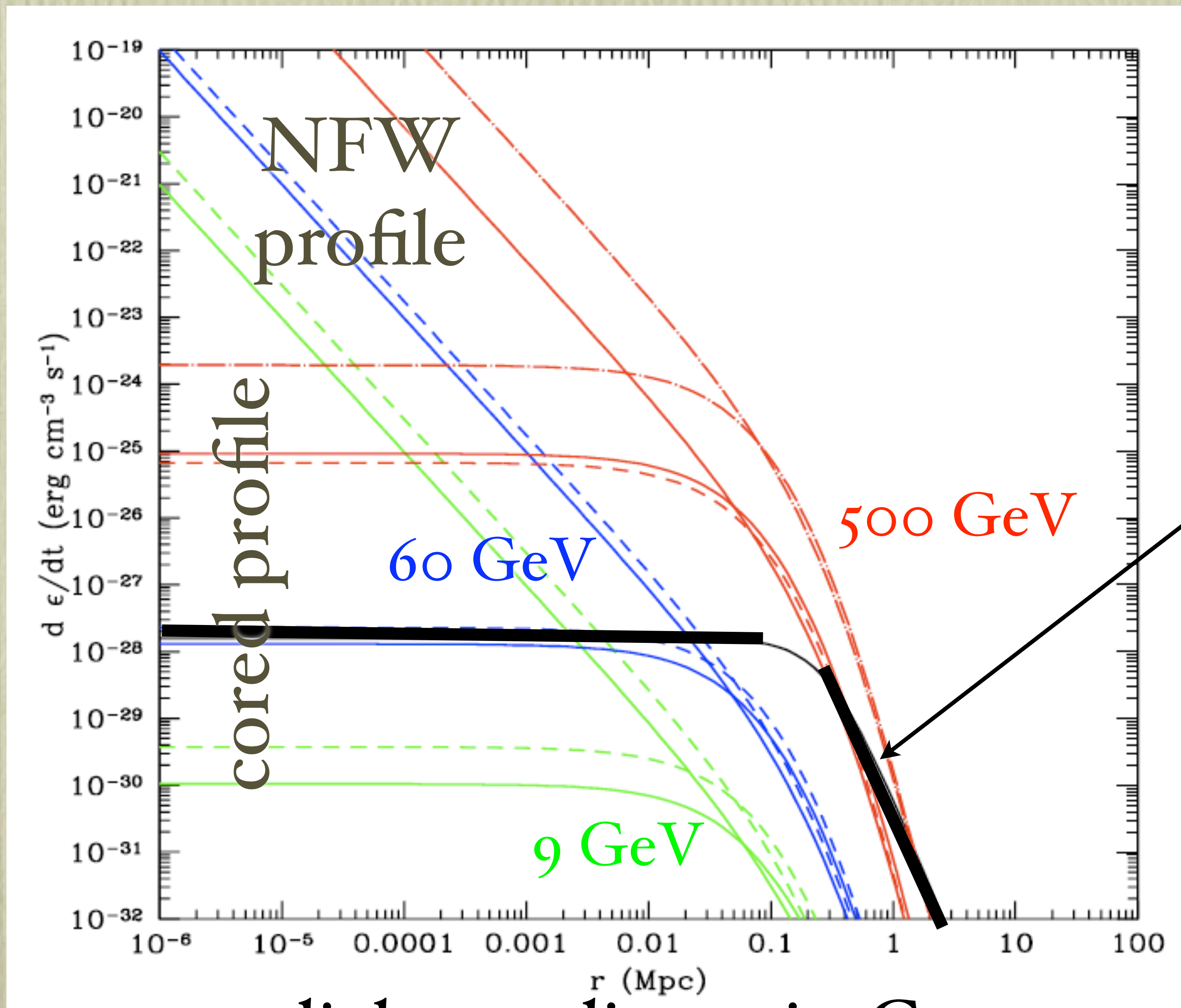
Recent reanalysis including also the IC γ-ray emissivity of electrons from dust and starlight:



Pinzke, Pfrommer & Bergström, arXiv:1105.3240

Another effect one should consider: the heating produced by the DM annihilation yields can be larger than the intracluster gas cooling rate. Back to the case of Coma and assuming again the synchrotron component at the radio halo level, adjusting B:

Colafrancesco et al., arXiv: 1004.1286



radial coordinate in Coma

bremsstrahlung cooling rate

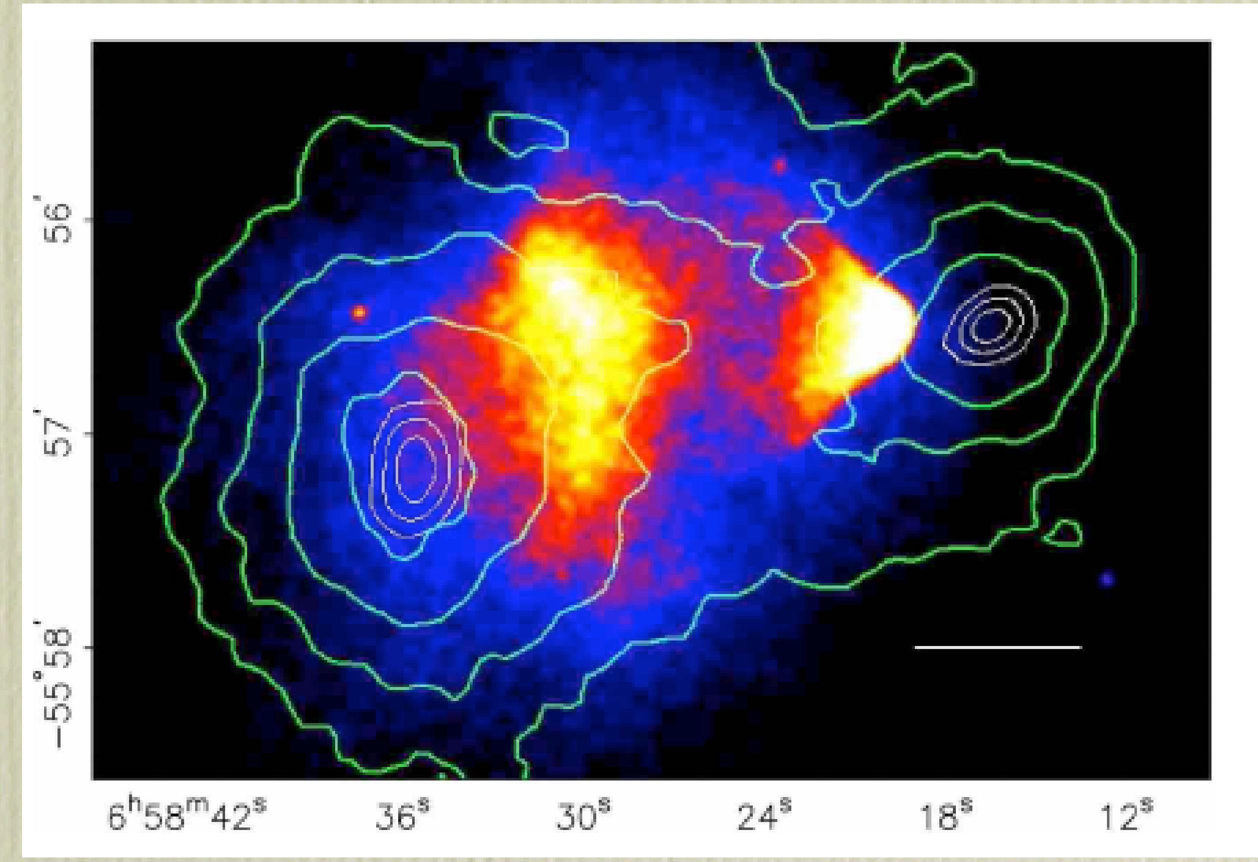
Cuspy profiles excluded?

What about tracing WIMPs in clusters through the Sunyaev-Zel'dovich effect?

Colafrancesco 2004

SZ: Compton scattering of CMB photons on the electron/positron populations in clusters. Net effect: low energy photons are "heated up", hence there is a low frequency decrement and high frequency increment in the CMB spectrum. A large SZ effect is expected (and detected) in connection to the thermal gas in clusters, it may be hard to fight against this "background" in standard systems.

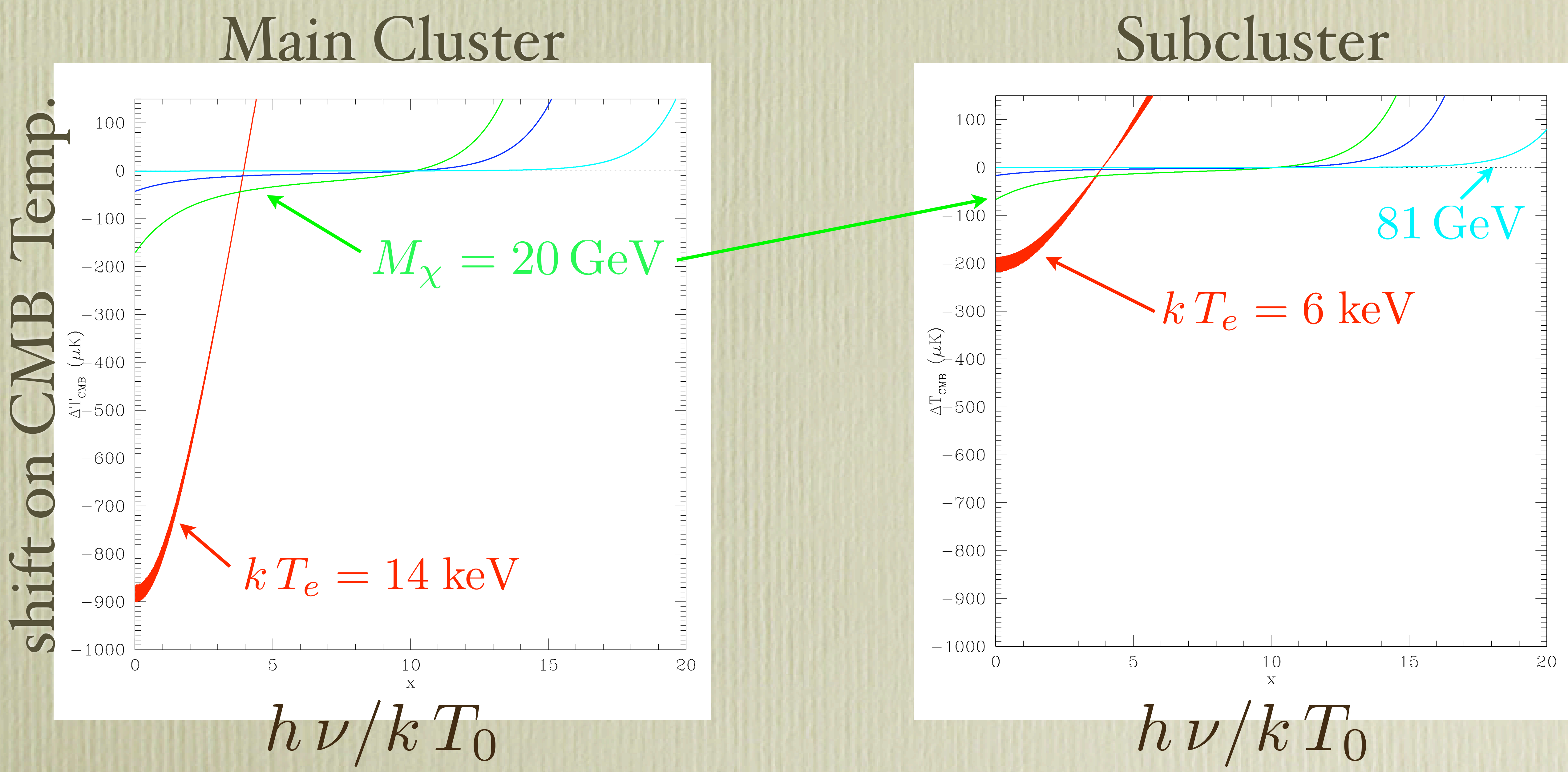
What about in a system like the Bullet cluster, with recent merging and thermal components displaced from the DM potential wells?



Lensing map superimposed on Chandra X-ray image

Clove et al., 2006

SZ effect in the simplified picture with two spherical DM halos (NFW profile) plus two isothermal gas components of given temperature (shock front neglected):



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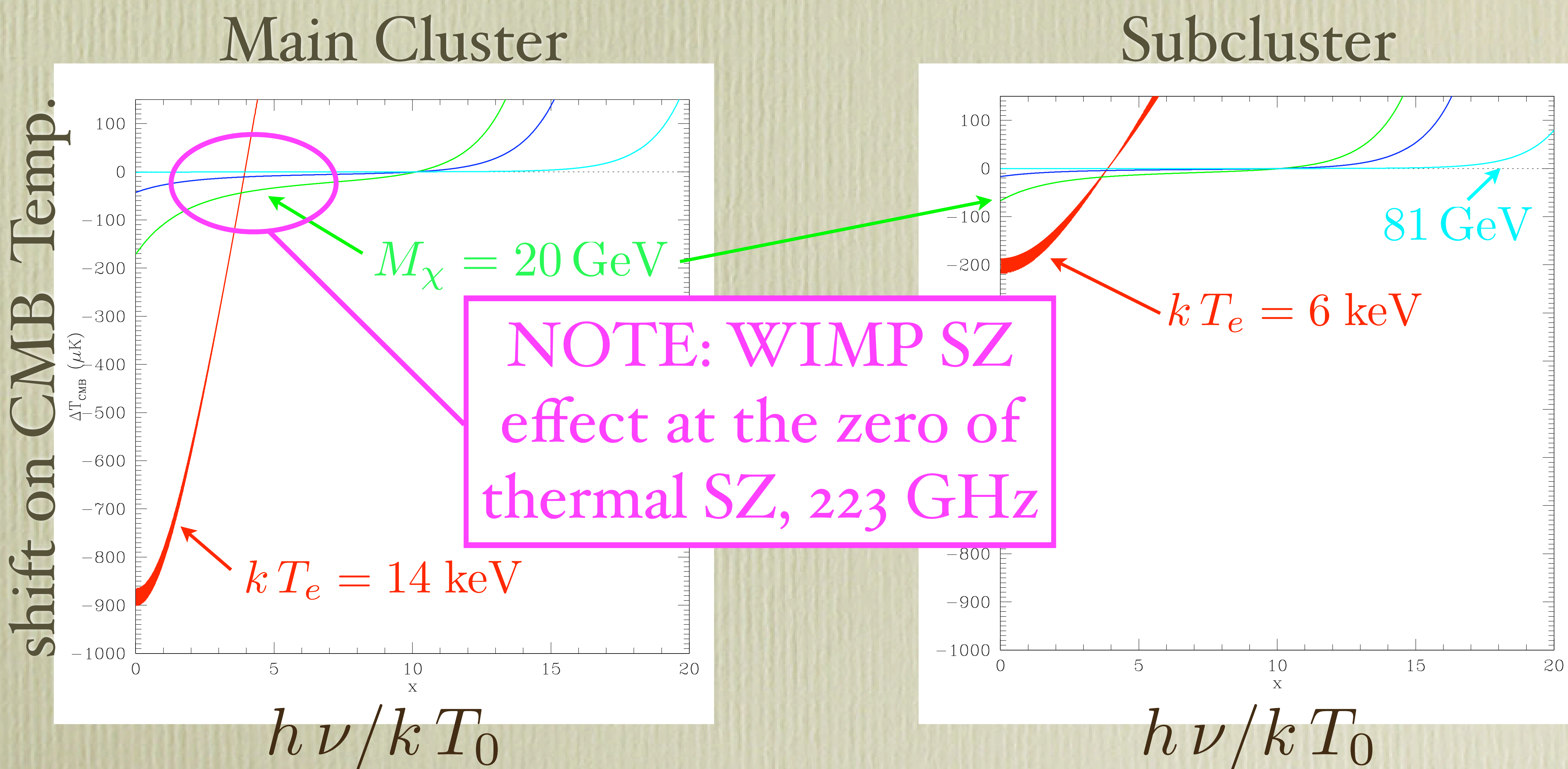

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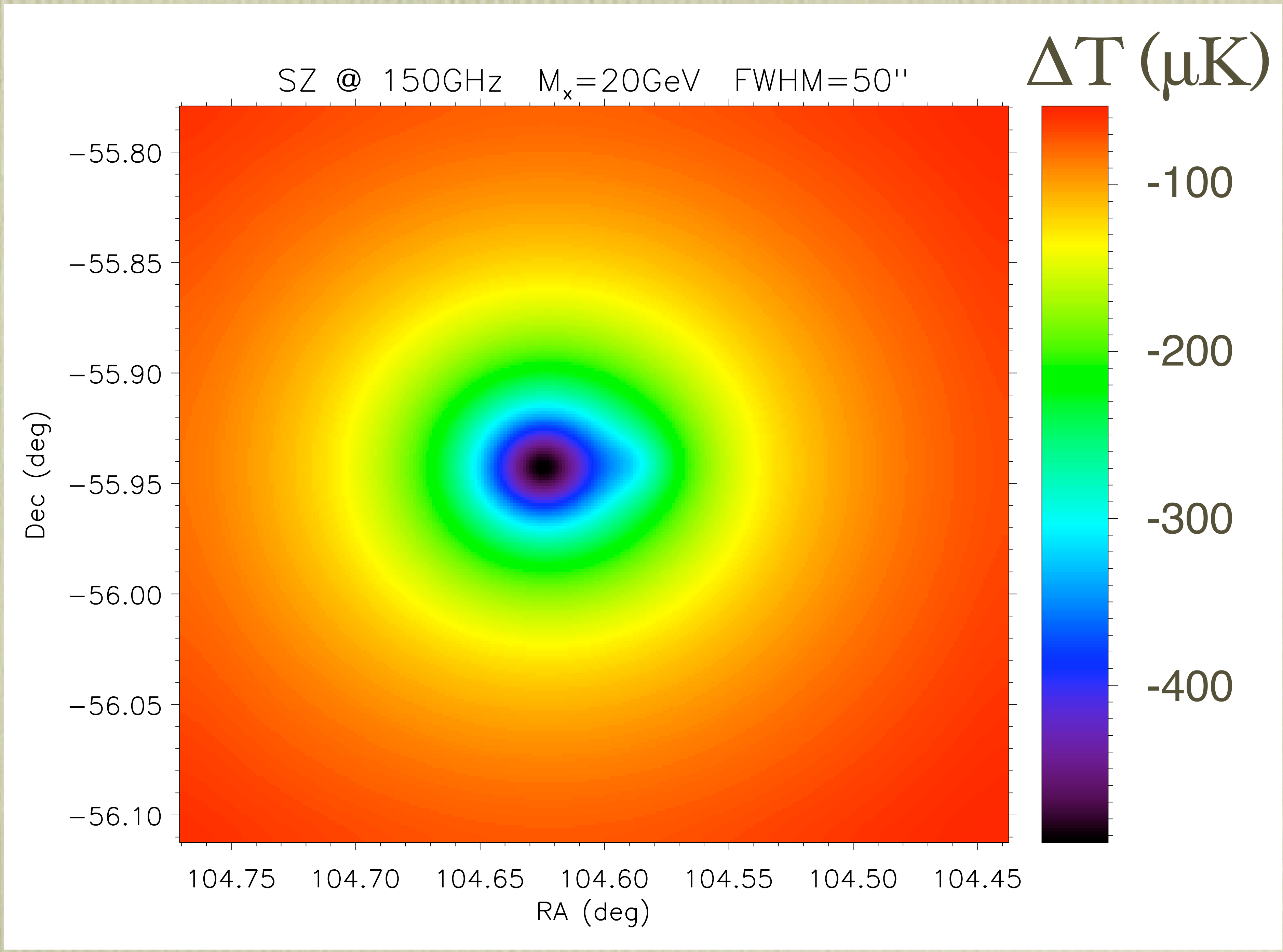
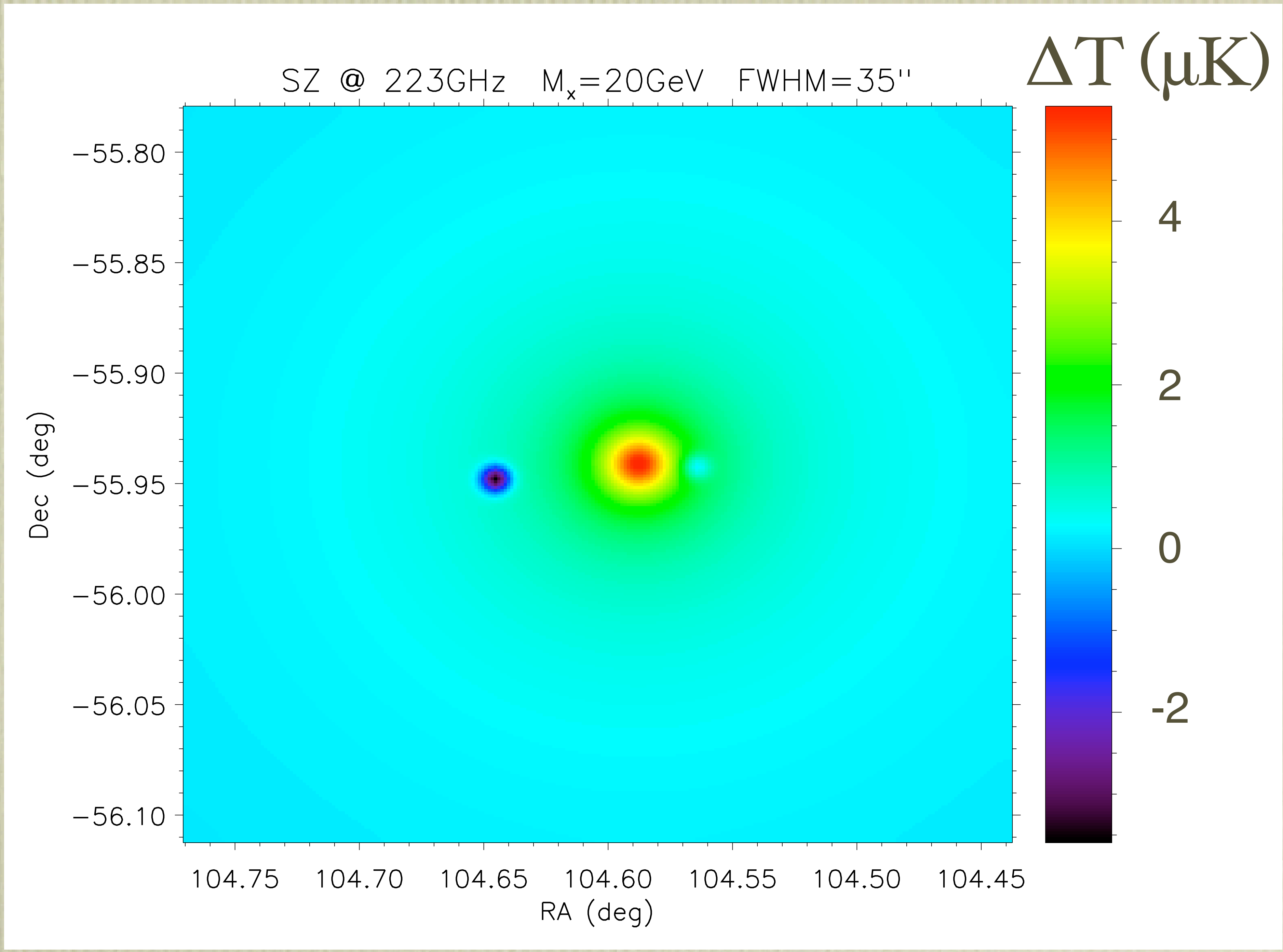
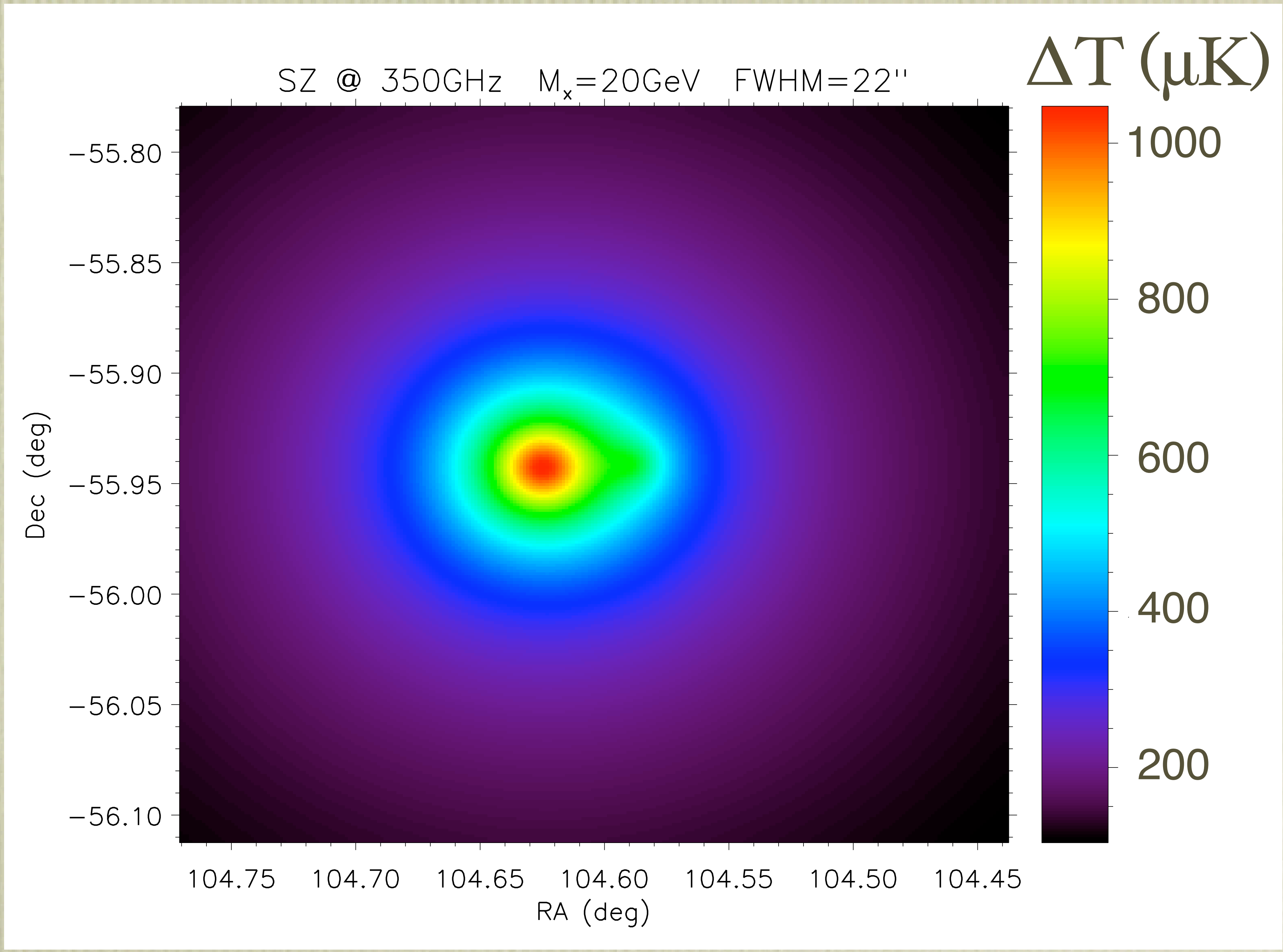
SZ map at 150 GHz:



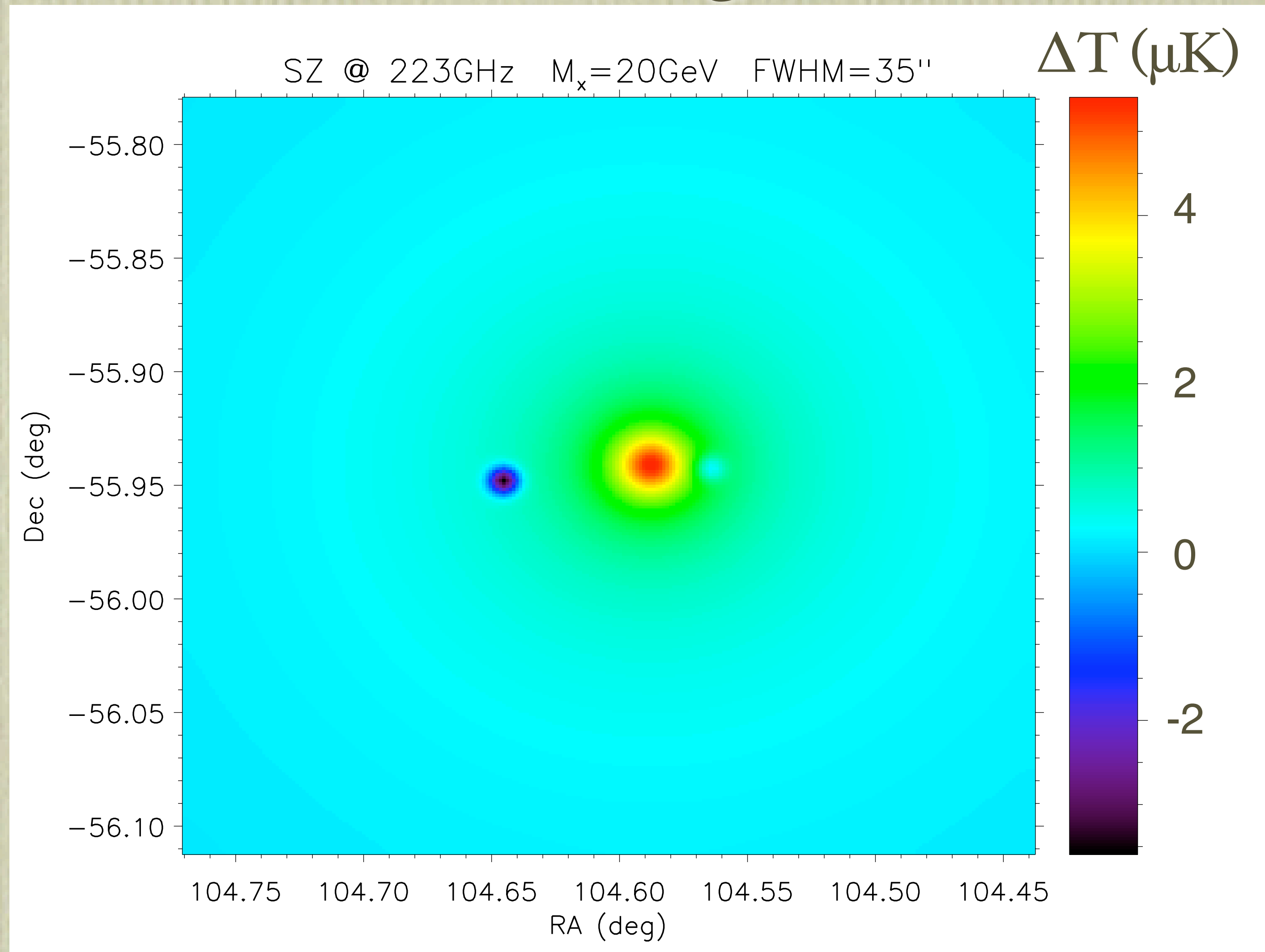
SZ map at 233 GHz:



SZ map at 350 GHz:



A light WIMP, say 20 GeV, gives a detectable (though small) effect:



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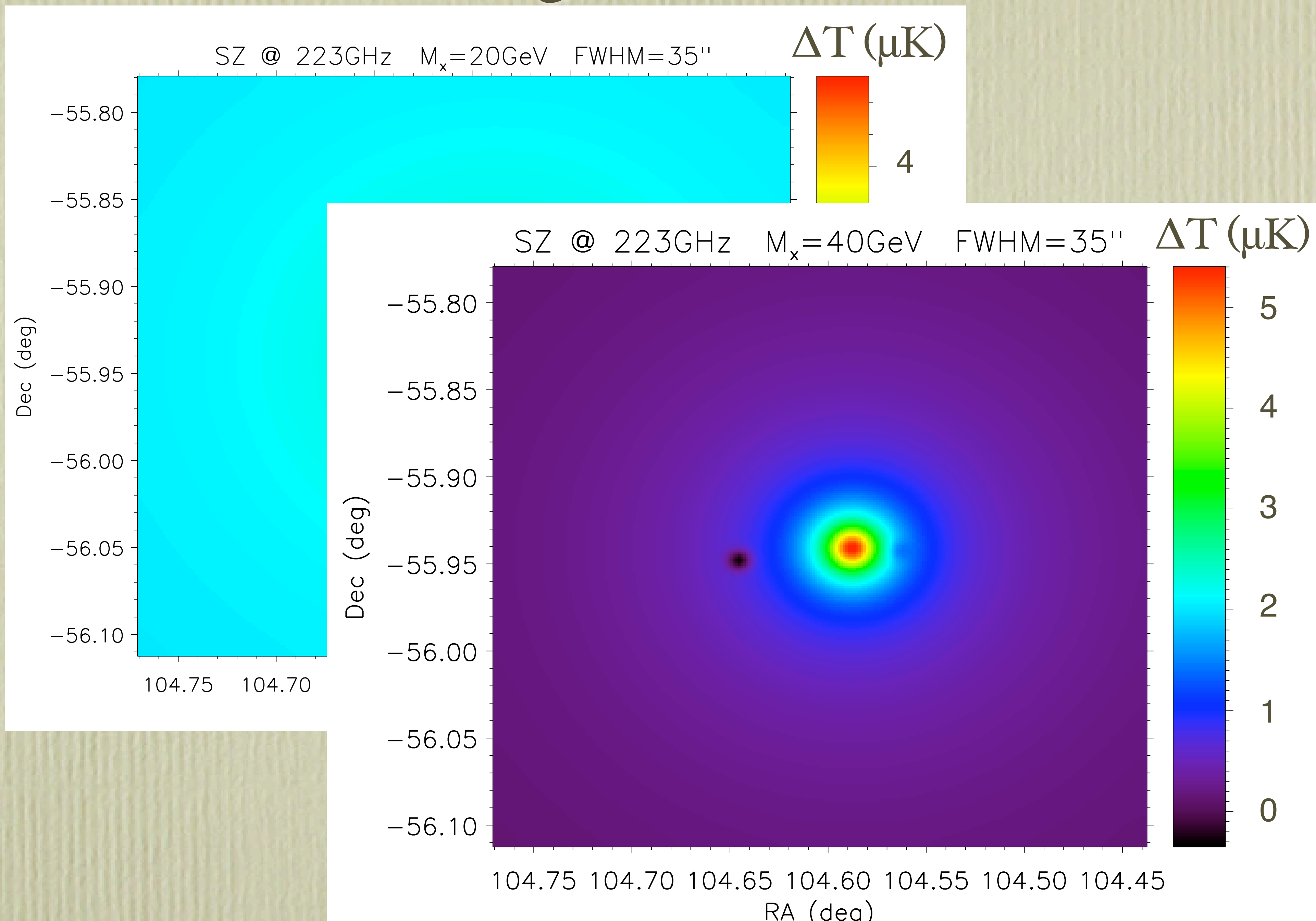

... fading away for heavier WIMPs, say 40 GeV,

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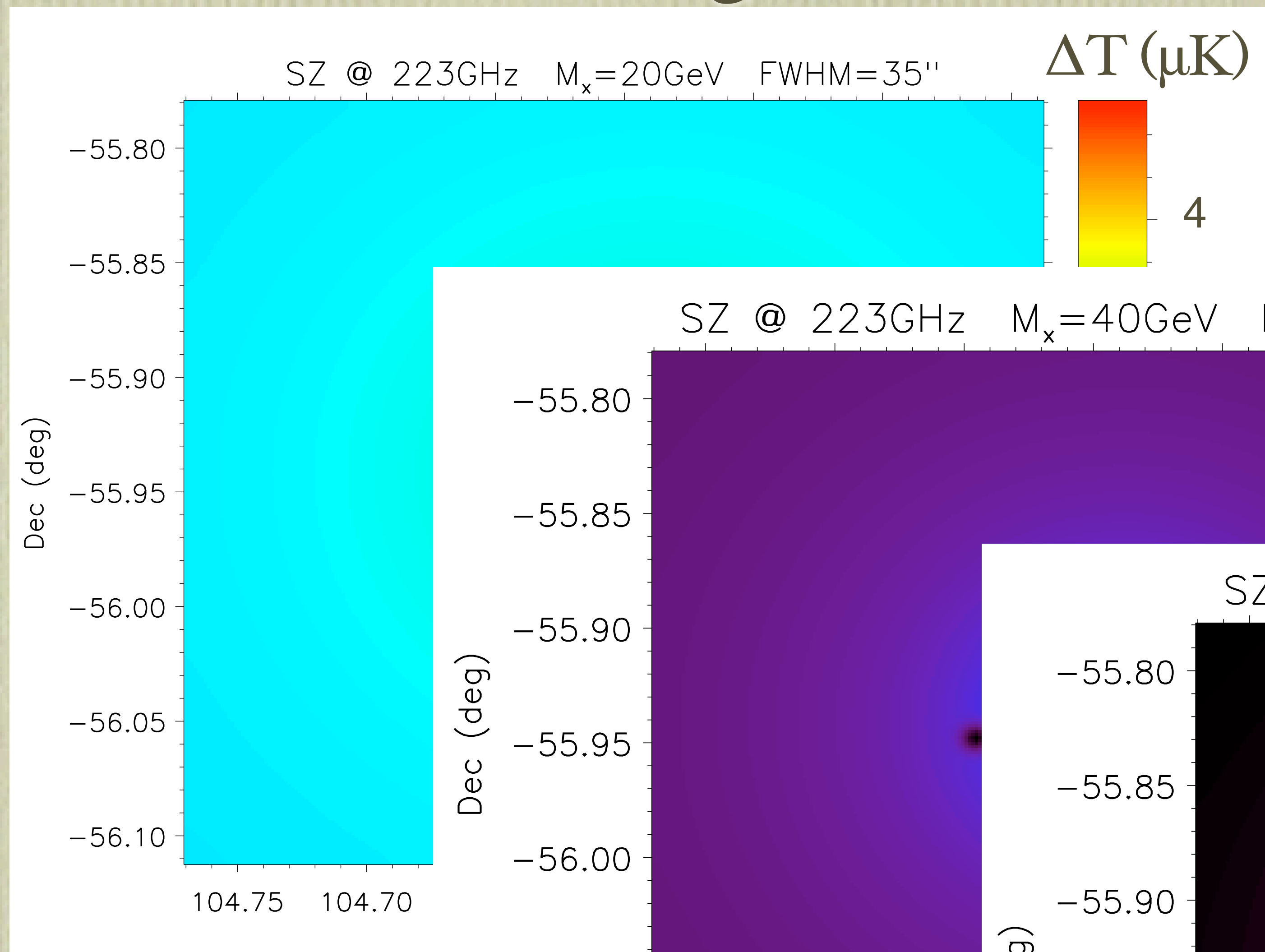
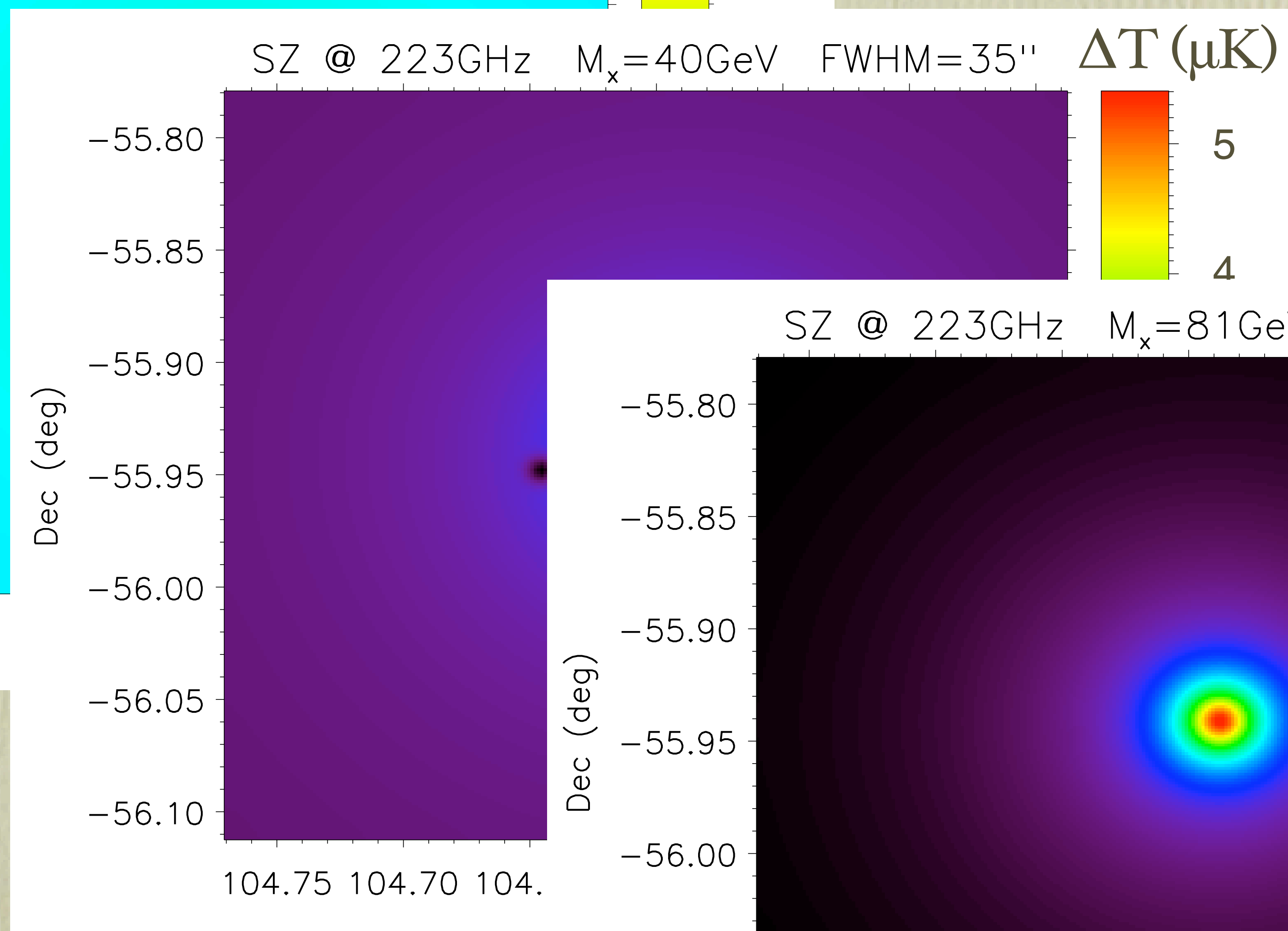
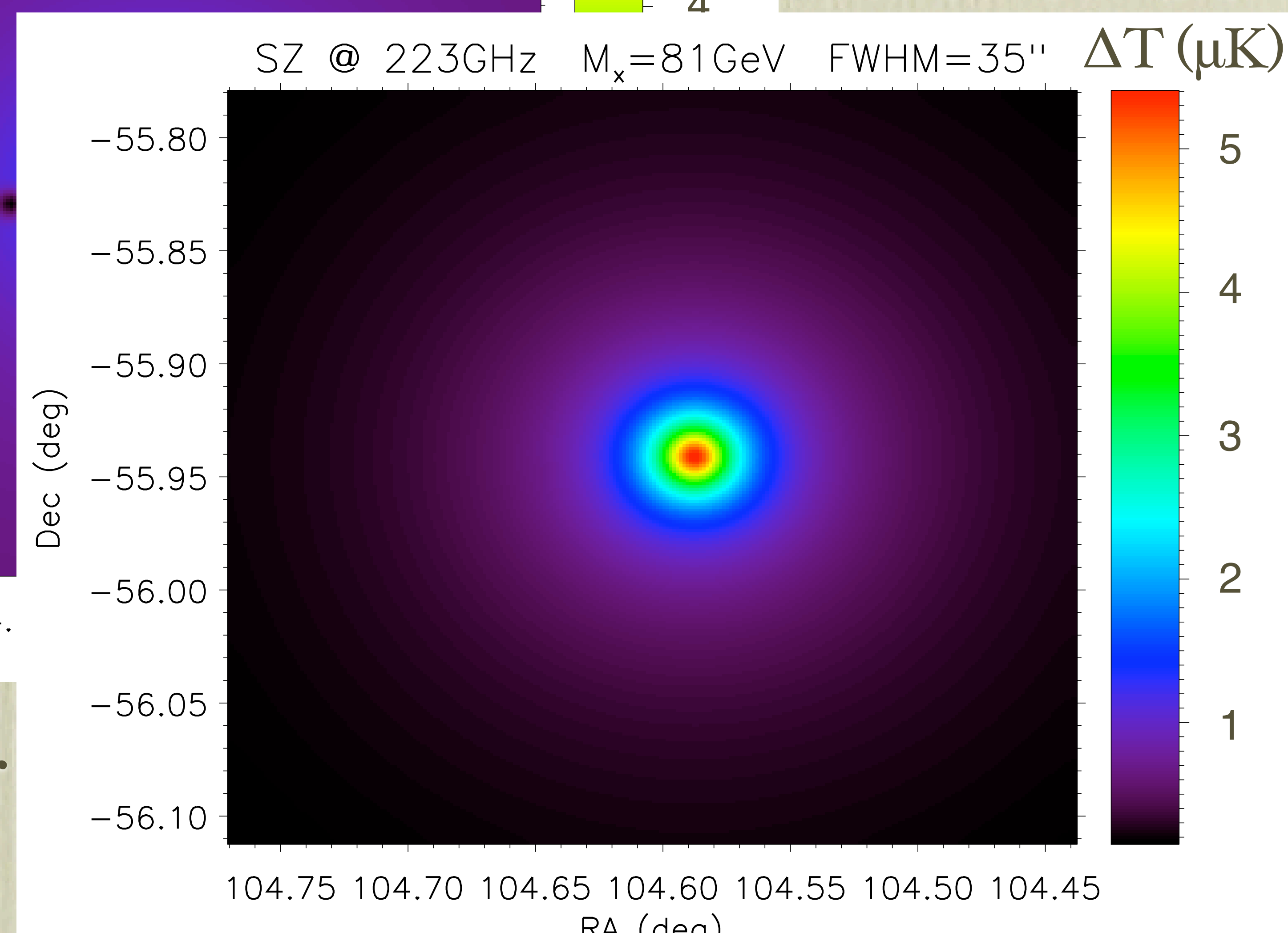


... fading away for heavier WIMPs, say 40 GeV,



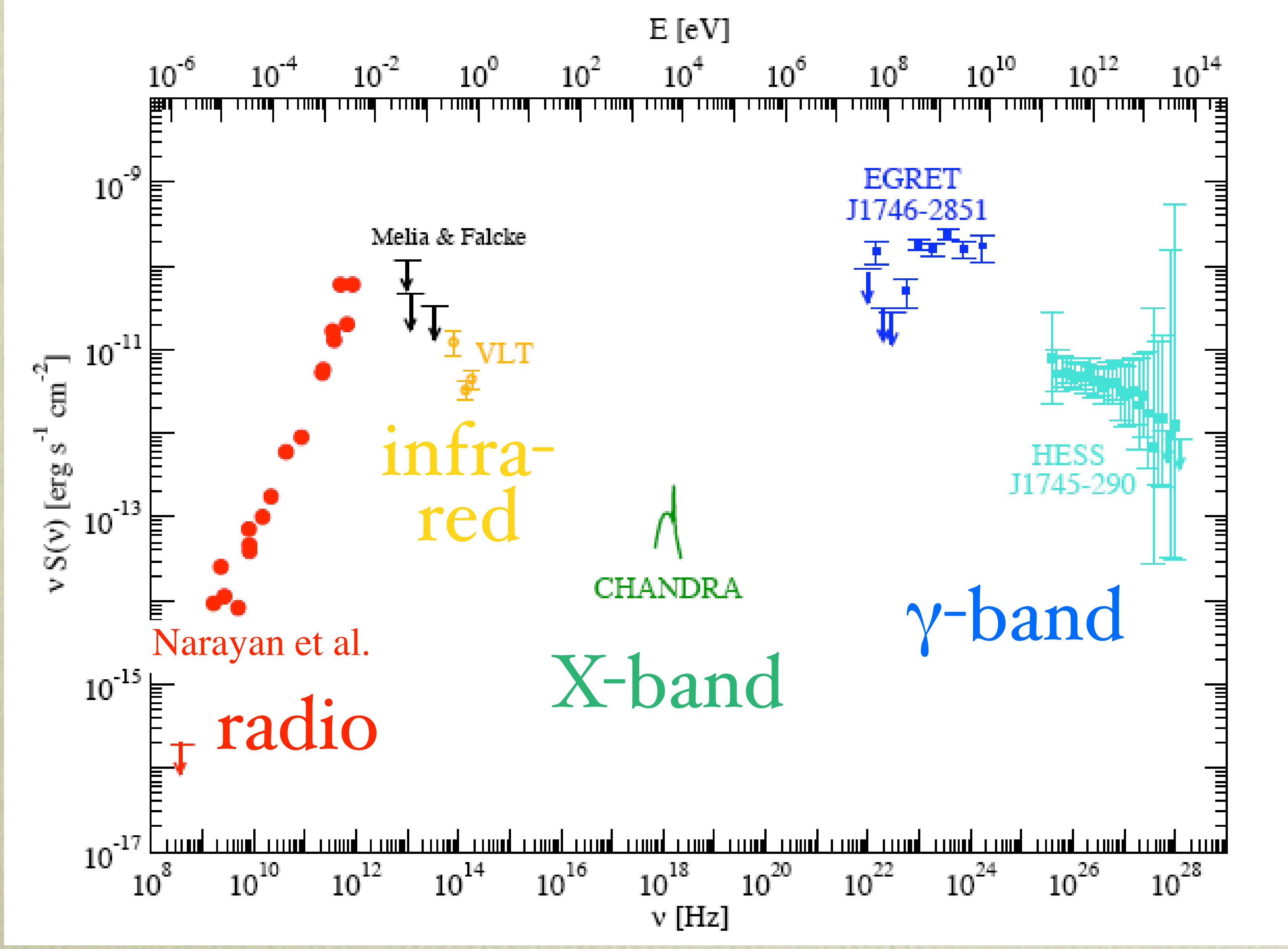
... or 81 GeV



A sample "tough" multifrequency target: the GC

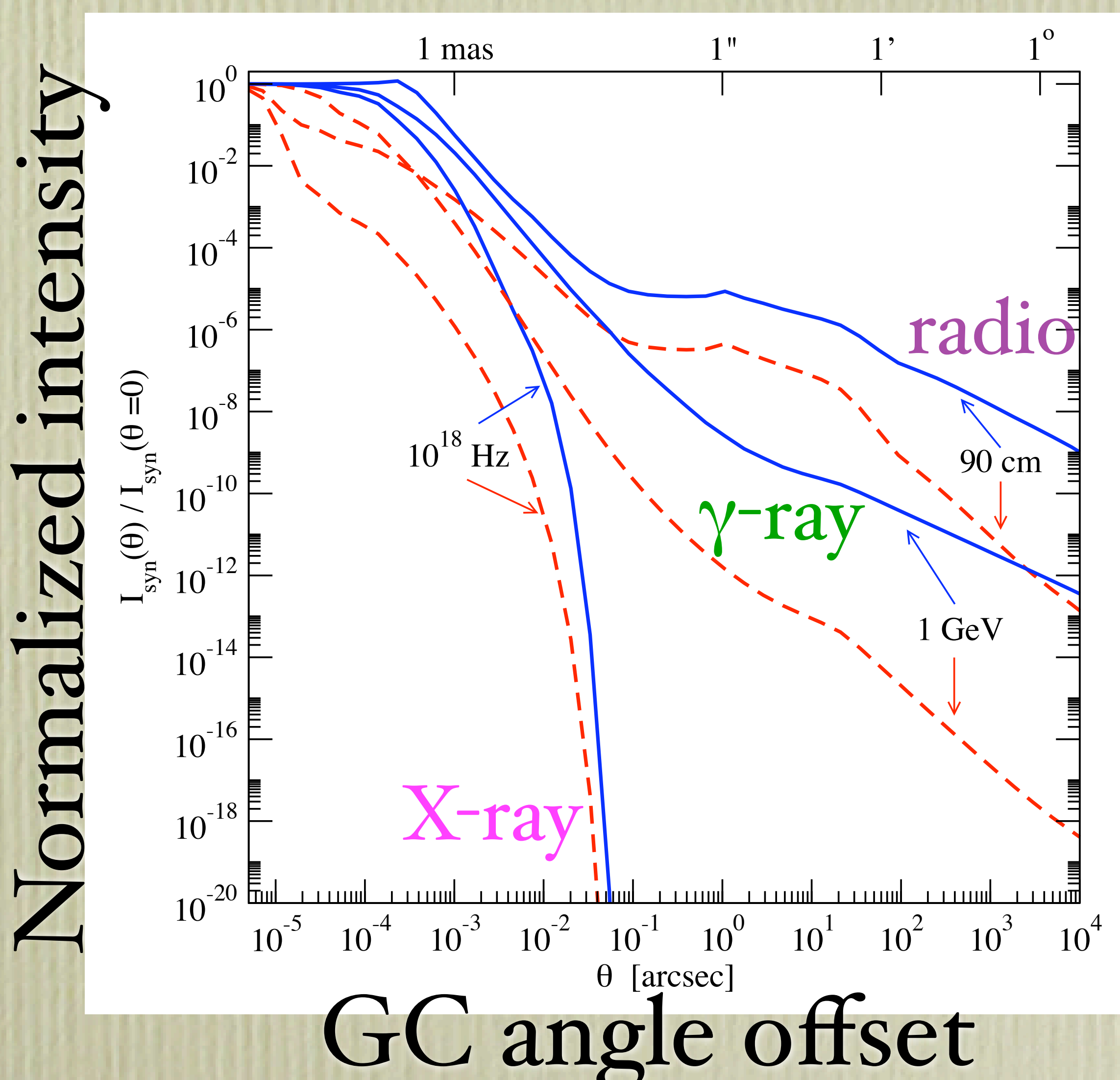
A BH source with unusually low luminosity over the whole spectrum, at such a level that it is plausible for an exotic component, e.g. WIMP component, may be relevant!

Multi-wavelength SED of Sgr A* in quiescent stage:

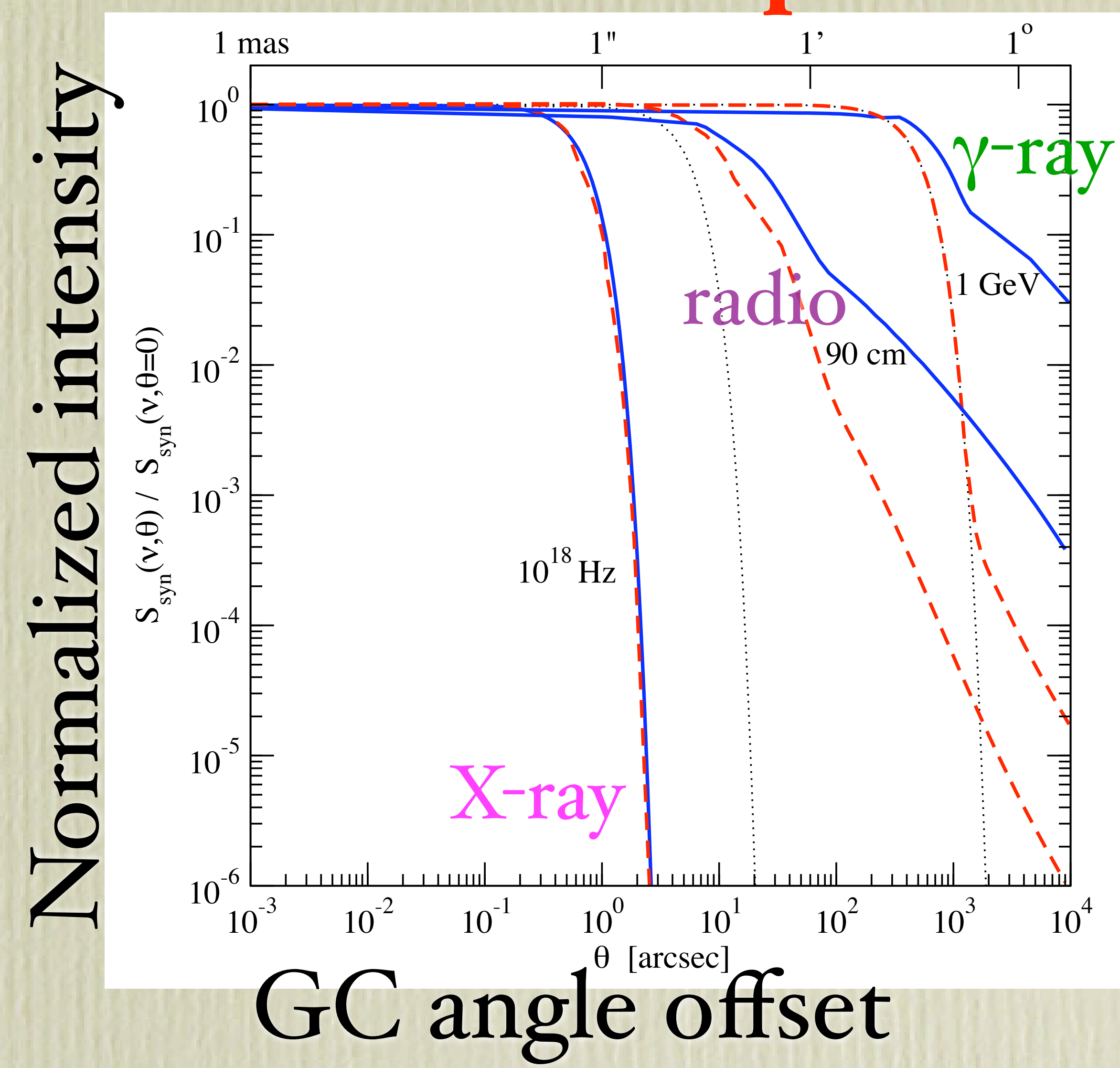


WIMP annihilations are expected to give a radio signal which is wider than the width of the source (and hence of the γ-ray flux), while the X-ray signal (synchrotron on the very large B in the most inner region) is much smaller:

intrinsic



smoothed by gaussian detector response



Regis & P.U., 2008

——— NFW + “Bertone & Merritt”

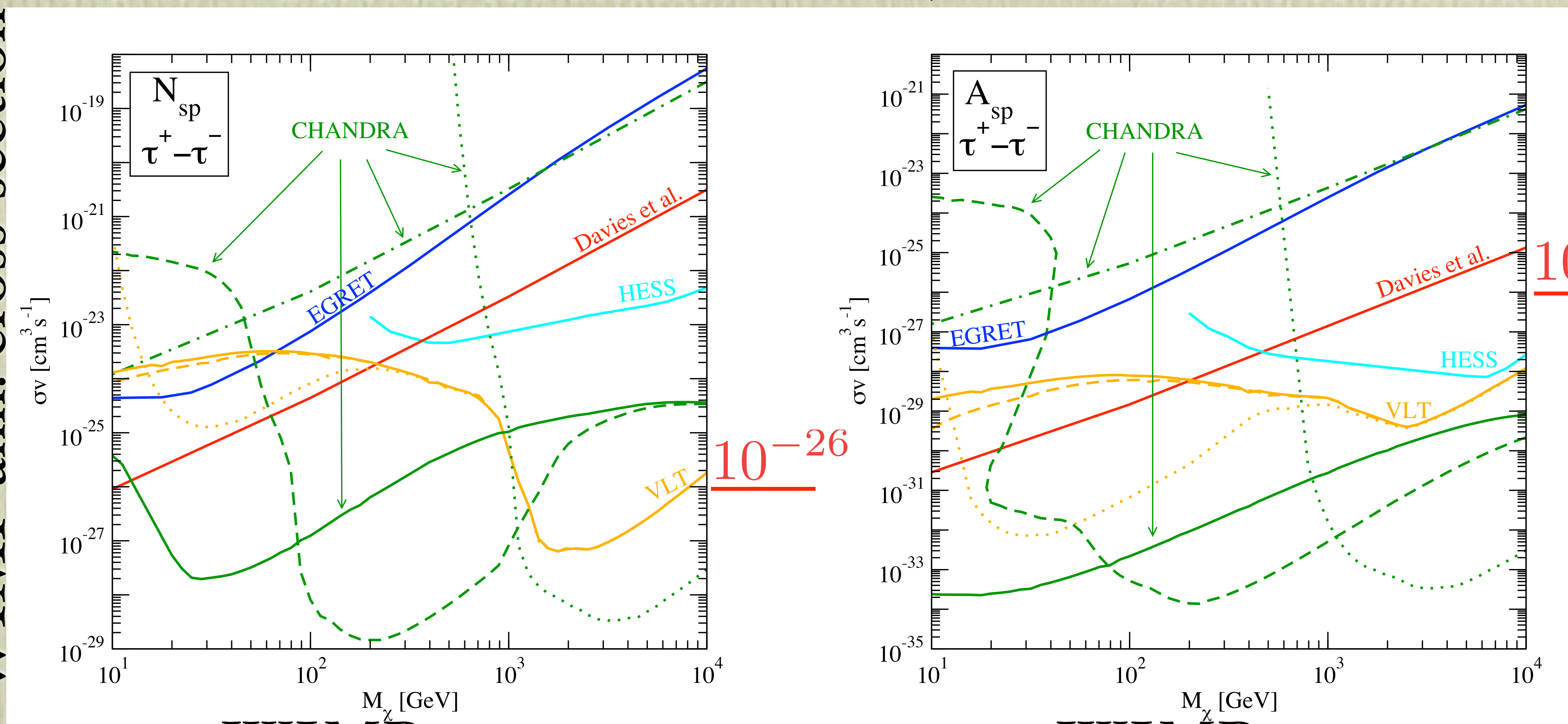
– – – – – $1/r^{1.5}$ + “Bertone & Merritt”

Multi-wavelength limits in the plane WIMP mass - annihilation cross-section

NFW + “Bertone & Merritt”

$1/r^{1.5}$ + “Bertone & Merritt”

WIMP ann. cross-section



WIMP mass

WIMP mass

HARD SPECTRA

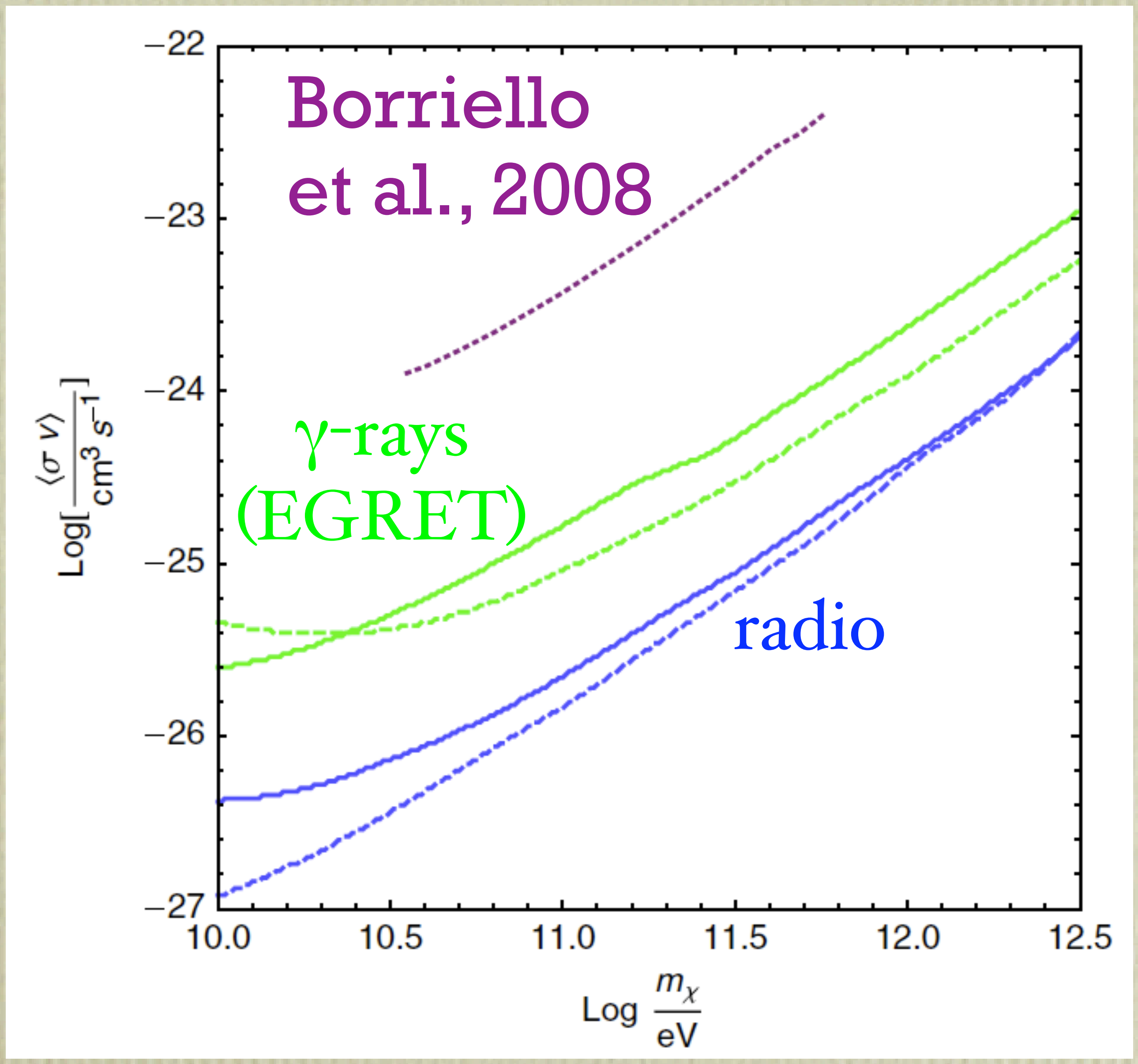
equipartition B

reconnection B

constant B

NOTE MISMATCH ON VERT. SCALE

Analogously, looking at a slightly larger angular region, allowing for larger magnetic fields + assuming a bare NFW, one can extrapolate the limits: Crocker et al., 2010



solid and dashed curves represent a loop over viable magnetic fields

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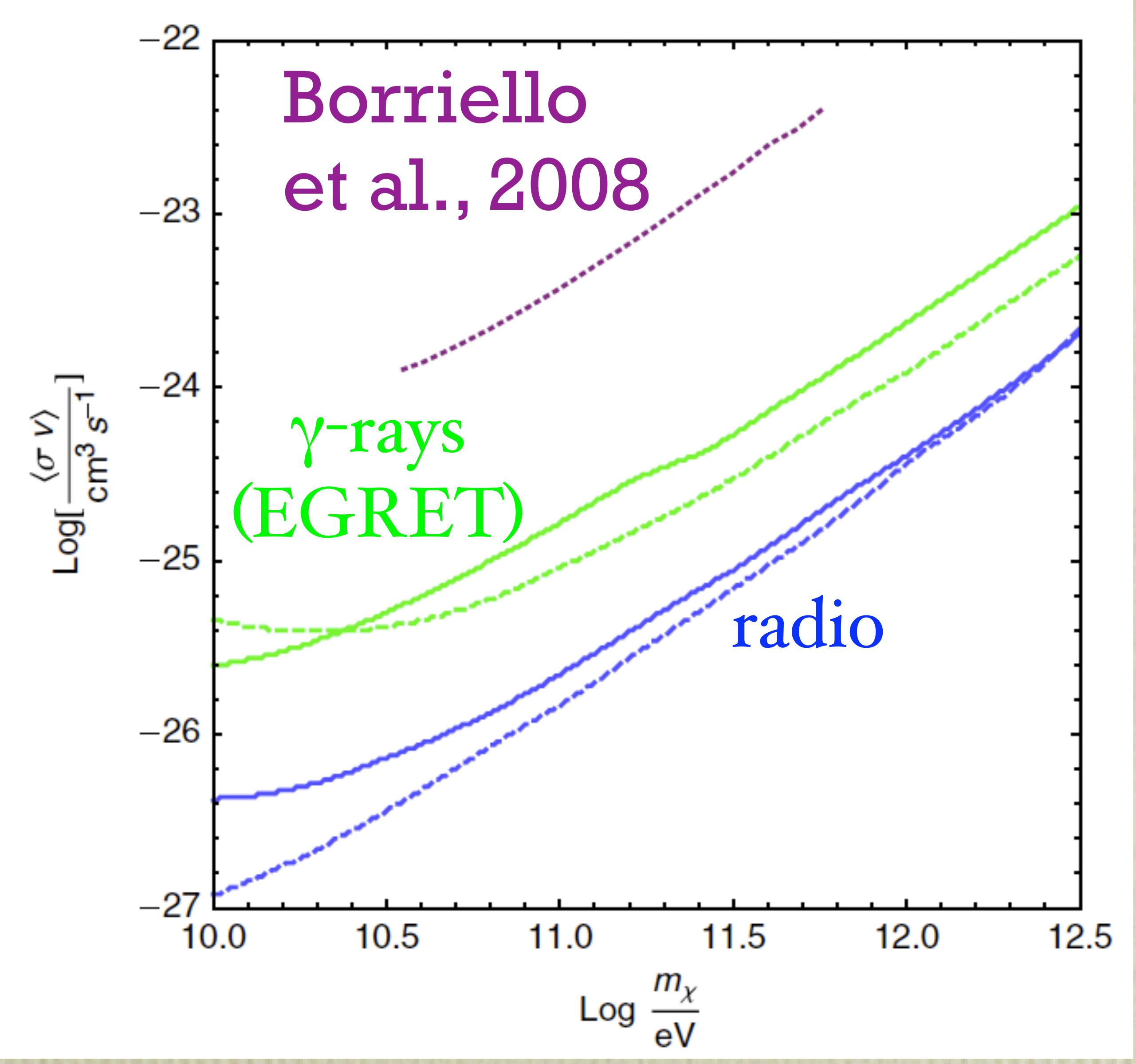
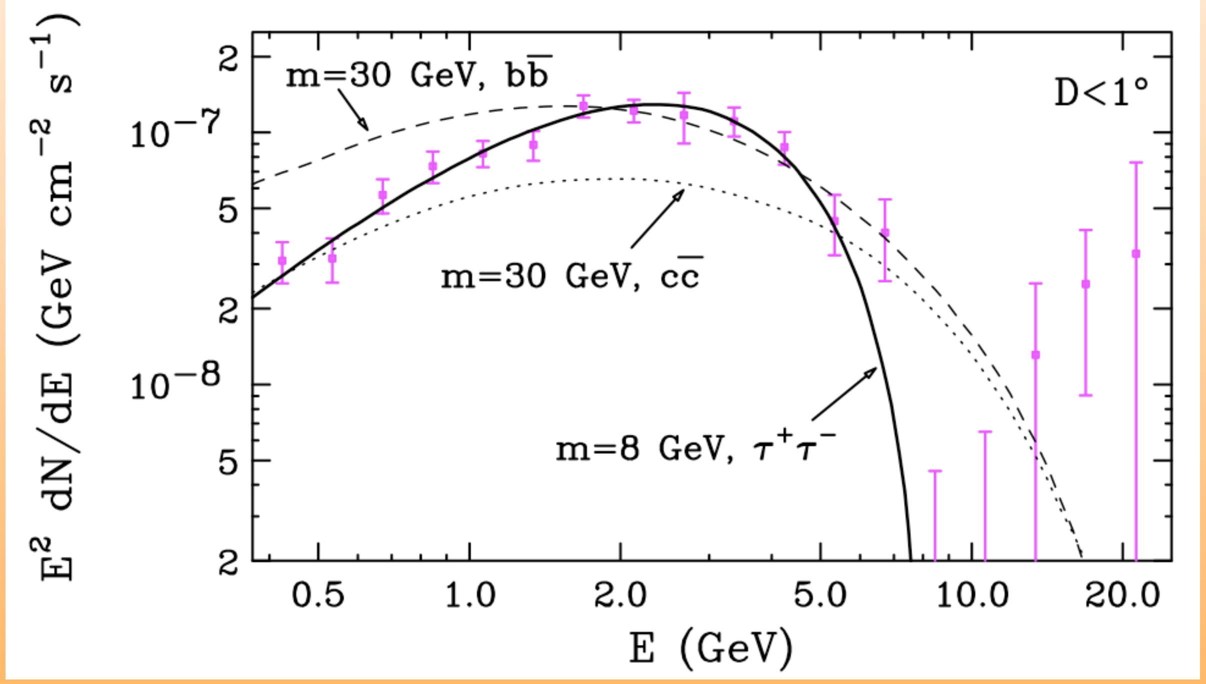


solid and dashed curves represent a loop over viable magnetic fields

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

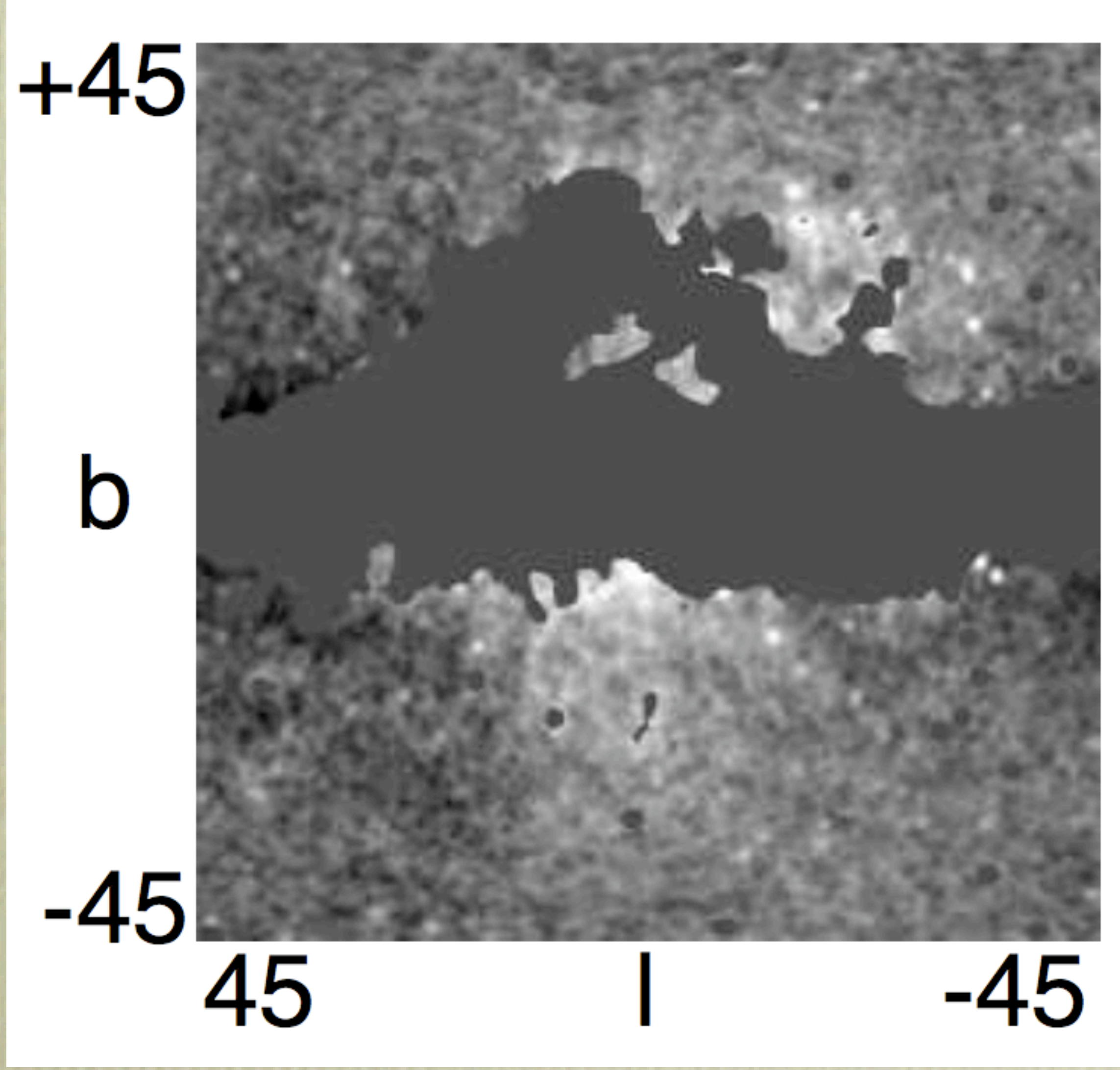


Hooper & Goodenough, arXiv: 1010.2752

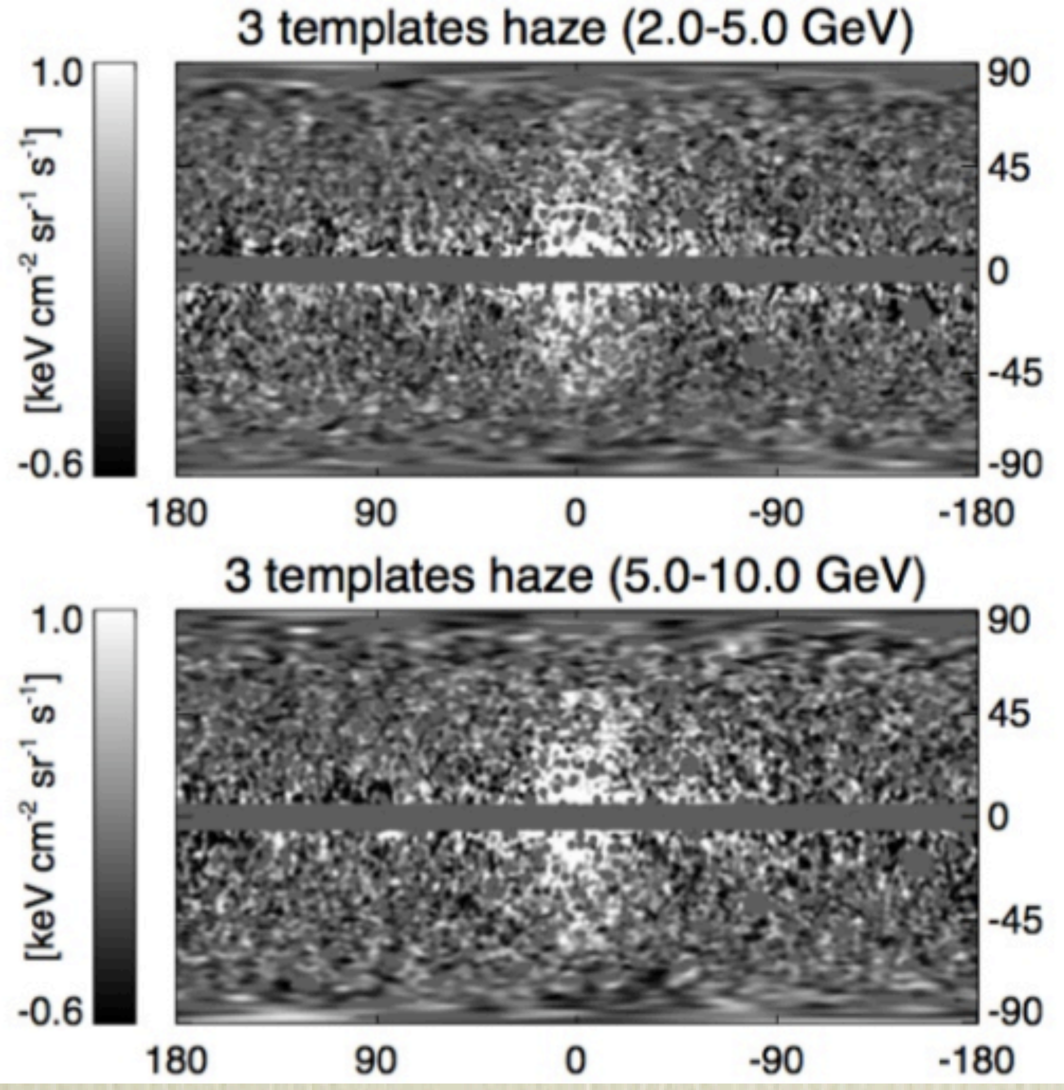
Multi-wavelength tests of an eventual DM component should be rather powerful.

WMAP haze & FERMI haze/bubbles

An extra component of CR leptons seems also needed to account for the emissivity in the central region of the Galaxy on a much larger angular scale. This extra component was claimed to be identified in WMAP data and later confirmed in Fermi:



Finkbeiner, 2004

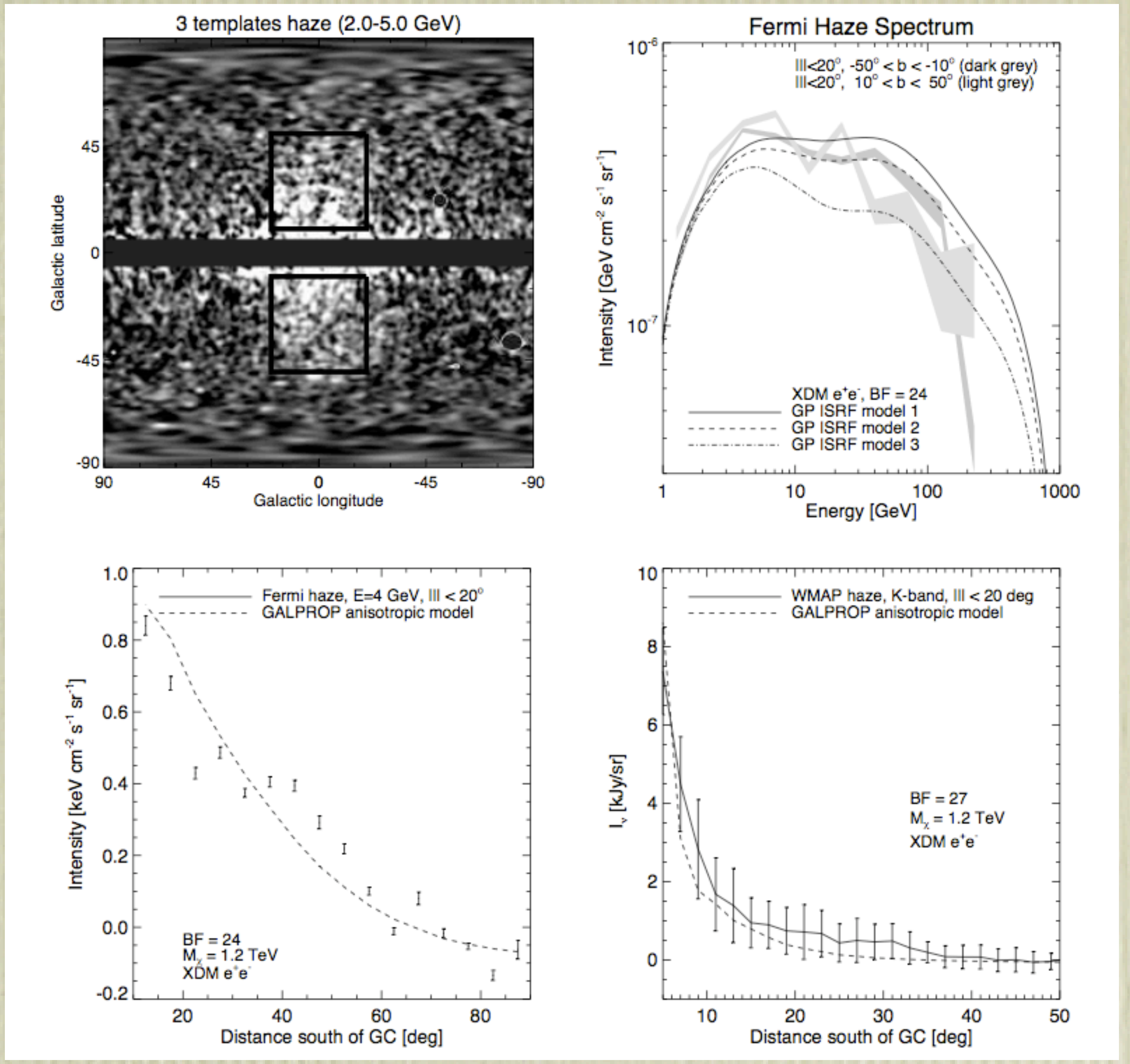


Dobler, Cholis & Weiner, 2011

WMAP haze & FERMI haze/bubbles

Assuming a prolate halo & anisotropic diffusion, the FERMI & WMAP hazes can be fitted within a leptophilic model with mass of 1.2 TeV and BF of 30:

Dobler, Cholis & Weiner, 2011



Caveats: different templates give different morphologies (haze or bubbles?), the edges are rather sharp for a DM component. Also: there are several contenders to this explanation, both in terms of additional astrophysical sources and of variants to the electron propagation or acceleration model.

Singling out DM in the central region of the Galaxy (low up to, maybe, intermediate latitudes) may remain problematic even in the future. Predictions for the background rely on severe extrapolations, such as on :

- the radial (vertical ?) distribution of sources (the same as the local sources?) which is very poorly known towards the GC;
- the diffusion and reacceleration terms (in most cases assumed spatially constant, ignoring the observed pattern of magnetic fields on large scales, and probably some structure in the turbulent component as well);
- the interstellar medium, again poorly determined in the central region of the Galaxy;
- ...

Even the DM source function is rather uncertain since we do not know (after the baryon infall) whether the density of WIMP DM is Einasto-like (NFW-like) or cored. It will be vital to identify a clean DM spectral and/or morphological signature.

Multi-messenger approach to local DM signals

Local observations compared to backgrounds as estimated from local observables are probably much safer. At the same time:

The local DM density is determined with good accuracy by dynamical constraints. Assuming a spherical halo, one finds:

Catena & P.U., arXiv:0907.0018

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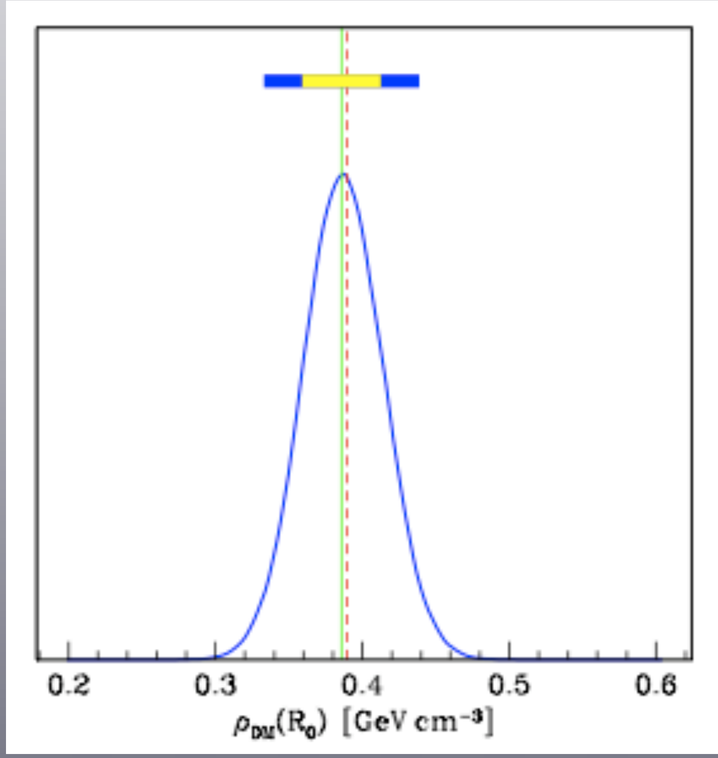
Einasto profile: $f_E(x) = \exp\left[-\frac{2}{\alpha_E}\left(x^{\alpha_E} - 1\right)\right]$



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

Catena & P.U., arXiv:0907.0018

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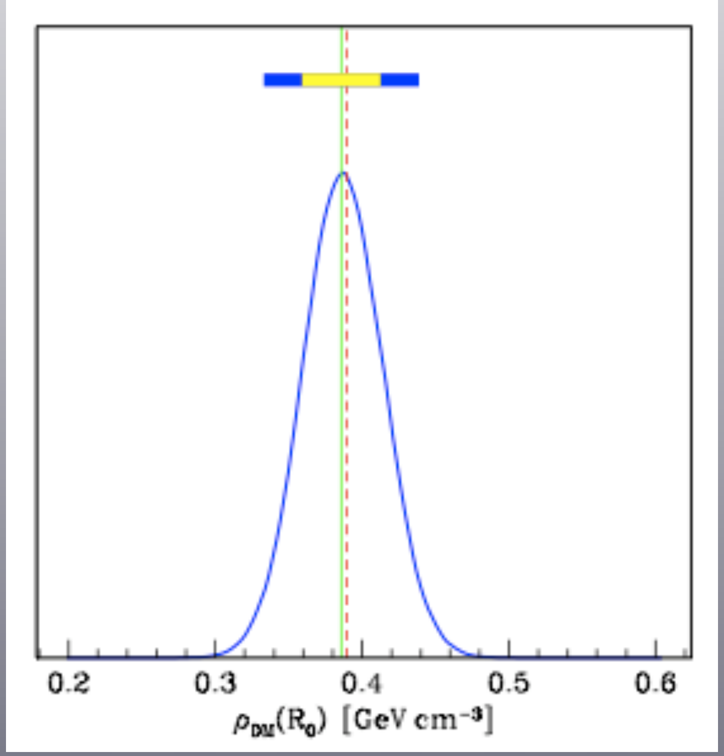
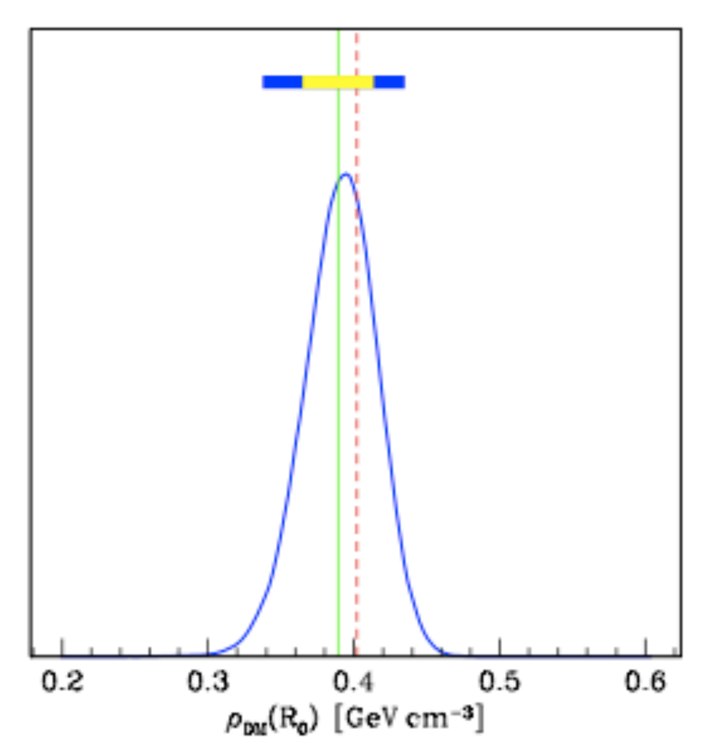


$$\rho_{DM}(R_0) = 0.385 \pm 0.027\,\mathrm{GeV\,cm^{-3}}$$

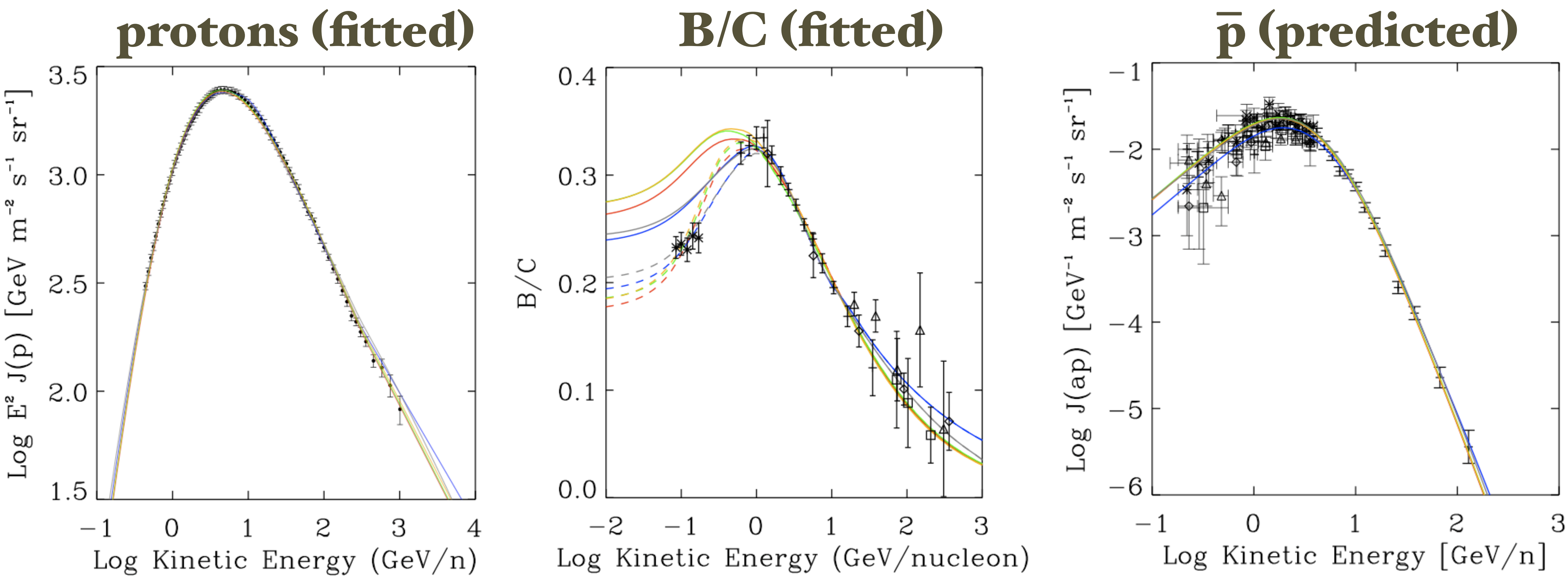
NFW profile: $f_{NFW}(x) = \frac{1}{x(1+x)^2}$



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

Catena & P.U., arXiv:0907.0018

The input from the locally measured proton and helium spectra and the ratio of secondary to primary nuclei is sufficient for a fairly accurate prediction of the antiproton background:



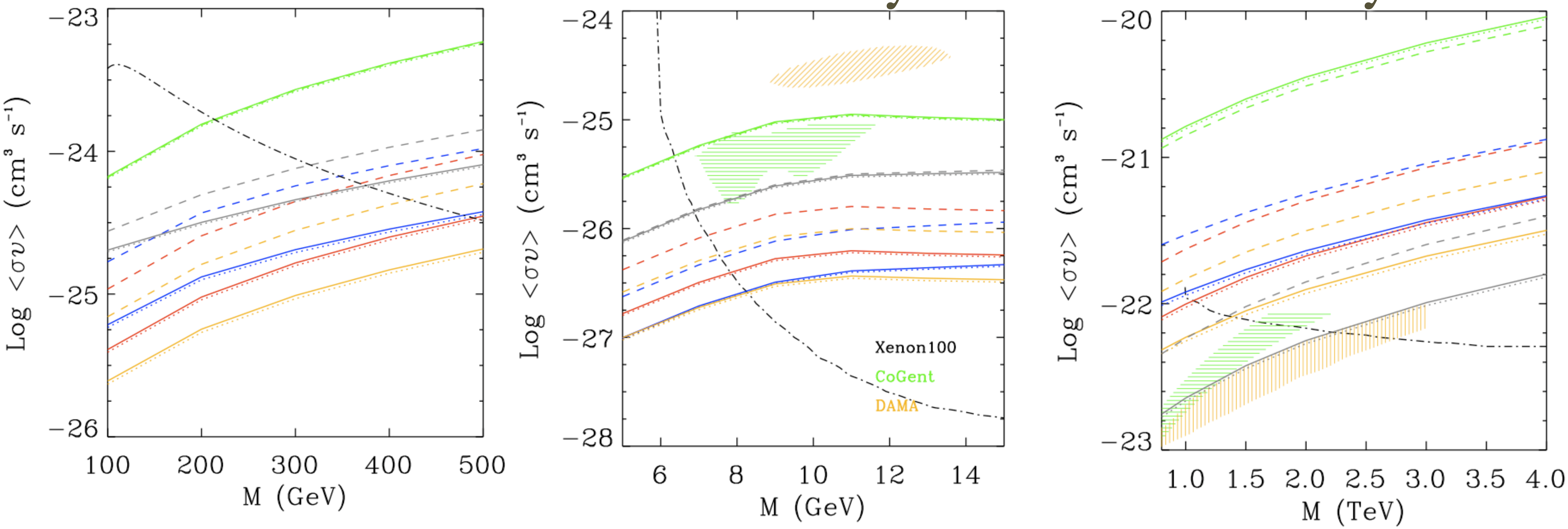
Set of sample propagation models simulated with Dragon:
Evoli, Cholis, Grasso, Maccione & P.U., to appear

Kraichnan
Kolmogorov
thick (z_t= 10 kpc)
thin (z_t= 0.5 kpc)
convective (dv_c/dz = 50 km/s/kpc)

Analogous to what shown yesterday with Galprop or Usine.

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

non-thermal WINO | **light DM motivated by DD** | **leptophilic heavy DM**



Limits depending o propagation model as well as (mildly) on the density profile:

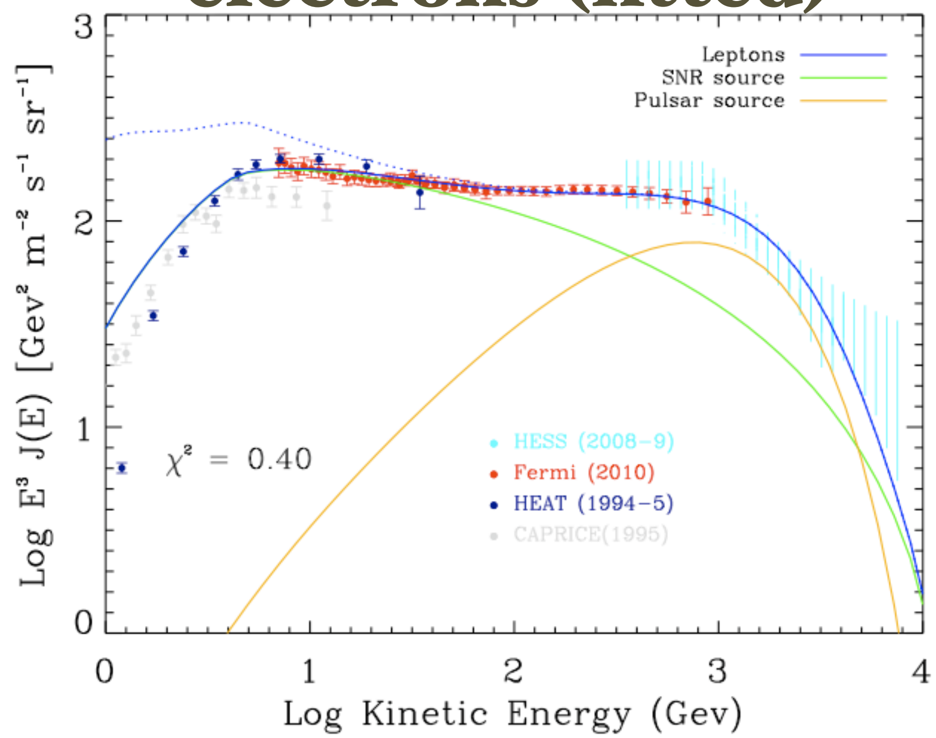
Einasto
NFW
Burkert

Kraichnan
Kolmogorov
thick (z_t= 10 kpc)
thin (z_t= 0.5 kpc)
convective (dv_c/dz = 50 km/s/kpc)

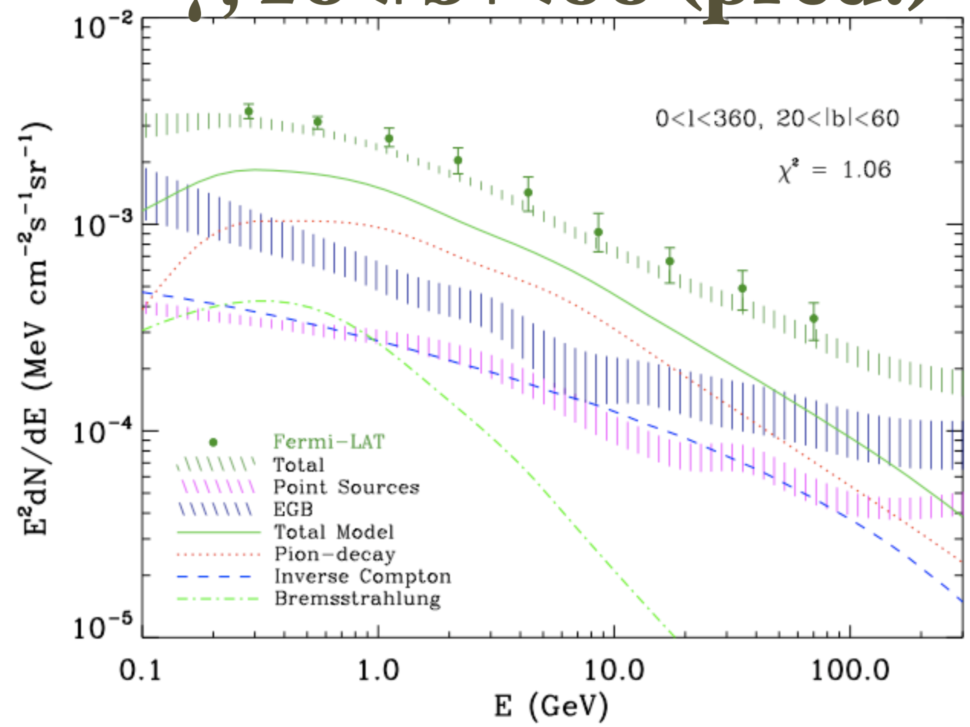
Evoli, Cholis, Grasso, Maccione & P.U., to appear

Extra input from the locally measured electron and positron spectra (plus some assumptions on gas and IRF) and prediction of the high-latitude gamma-ray background:

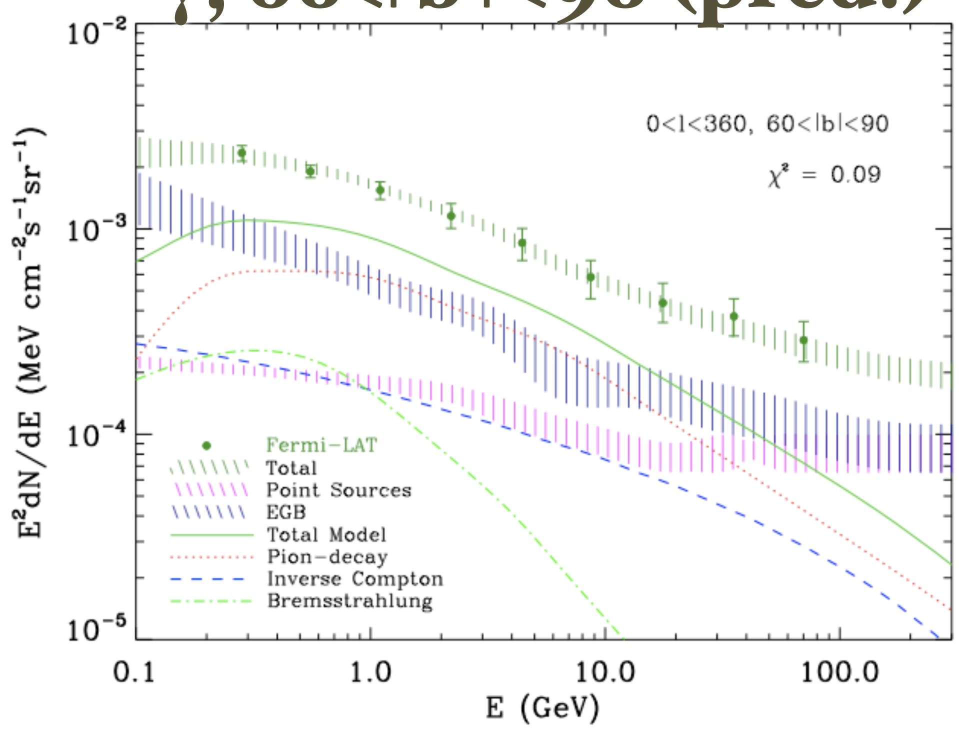
electrons (fitted)



γ, 20<|b|<60 (pred.)



γ, 60<|b|<90 (pred.)



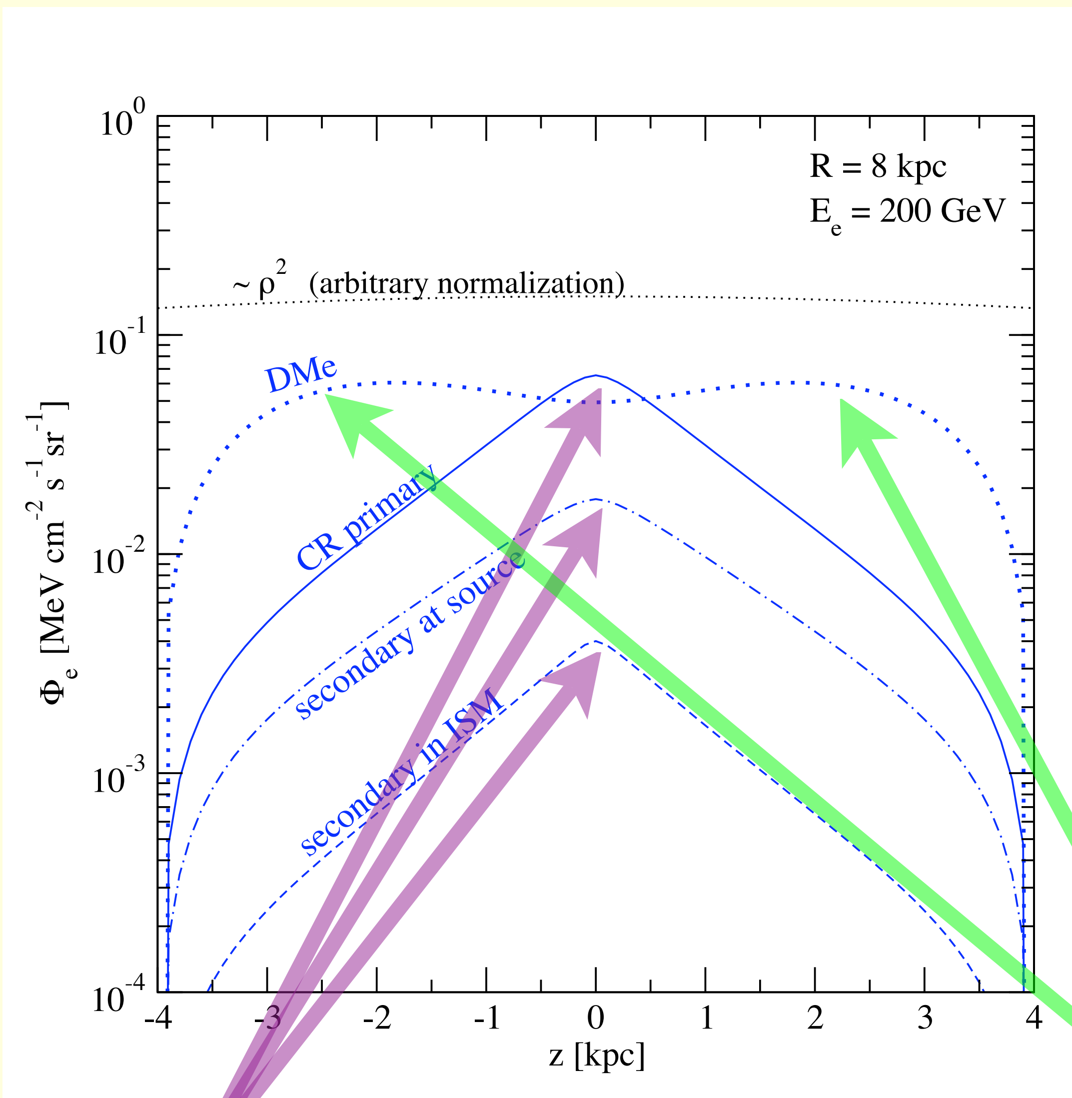
Again very good agreement with data. Results for the reference Kraichnan model, the other cases are analogous, still with fairly good fits.

Cholis, Evoli, Tavakoli & P.U., to appear

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

Fermi should contribute to address the issue of whether the local positron excess is due to primary sources located in the disc or to a leptophilic DM component distributed in a much thicker halo:

Regis & P.U., 2009



Equilibrium number density profile of "all-electrons", at the local Galacto-centric distance and as a function of height over the disc - plot obtained with Galprop within a (older) reference propagation model; the sketch for other models is perfectly analogous.

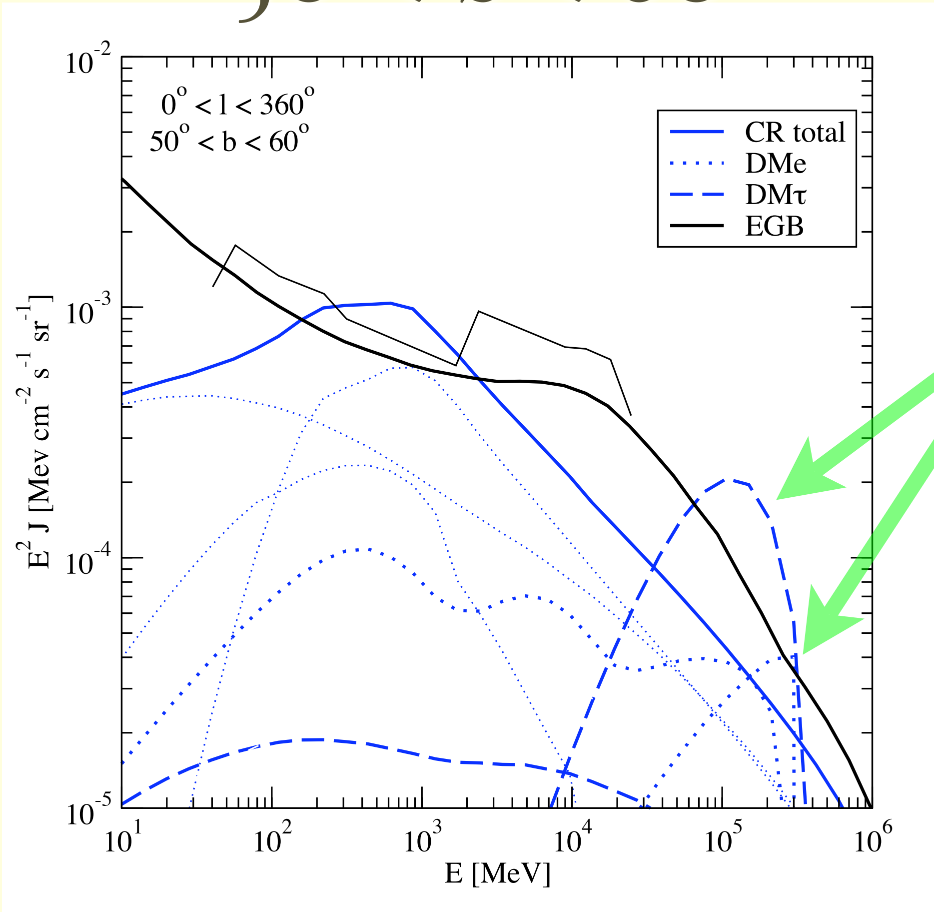
Primary/secondary sources located in the disc

DM sources extending in the halo

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

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

Regis & P.U., 2009



DM spectral feature at E≥ 100 GeV (?)

a prediction independent on propagation at high latitudes

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

Conclusions

There are definite patterns in the source functions for the different species generated in WIMP DM annihilations; hence, correlations among the different indirect detection signals are expected.

Several examples for which the multi-wavelength / multi-messenger approach to DM detection is at hand and very powerful.

The issue of discriminating the signal from background contaminations is a delicate one, however the approach combining different detection techniques looks promising. Given the wealth of data experiments are delivering, surprises may be around the corner!