The quest for indirect dark matter detection

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2nd OKC DIAS workshop: science with HESS II,
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Outline:

A review focussed on the weakly interacting massive particles (WIMPs) as dark matter candidates:

- Short introduction on the dark matter problem and the point of view of the cosmologist/astrophysicist on dark matter particles

- The WIMP paradigm facing the null detection so far of physics beyond the Standard Model at the LHC and the inconclusive picture from direct detection

- Recent experimental/theoretical highlights on WIMP indirect detection with γ-ray telescopes, focussing on channels with clean signatures

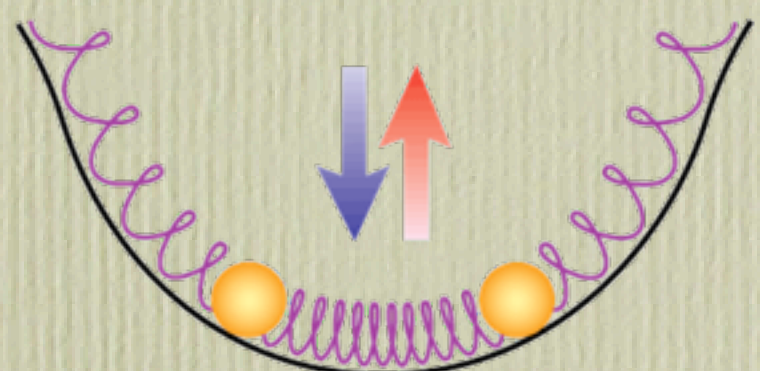
- In case clean signatures are not available, the complementarities among different messengers and targets may be the key to solve the dark matter puzzle; combining different information however is non-trivial: an exercise to illustrate this point

Disclaimer: a review making no attempt to produce an exhaustive list of references on all recent results

Dark matter (indirectly) detected!

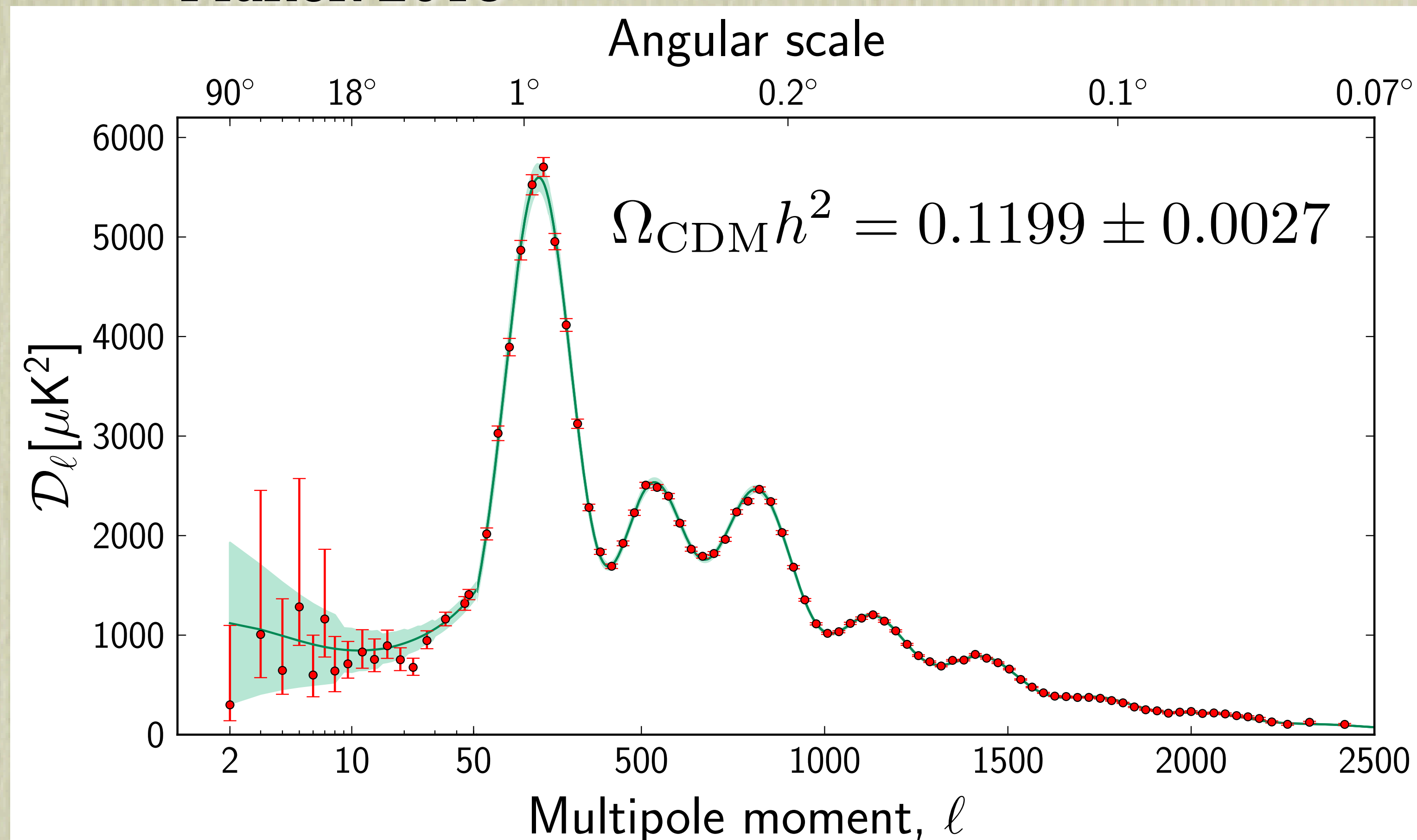
Plenty of (gravitational) evidence for non-baryonic cold (or coldish - as opposed to hot) DM being the building block of all structures in the Universe. E.g.:

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



Credit: W. Hu website

Planck 2013



Relying on the assumption that GR is the theory of gravity; still, it is very problematic to explain, e.g., the prominence of the third peak in an alternative theory of gravity and matter consisting of baryons only

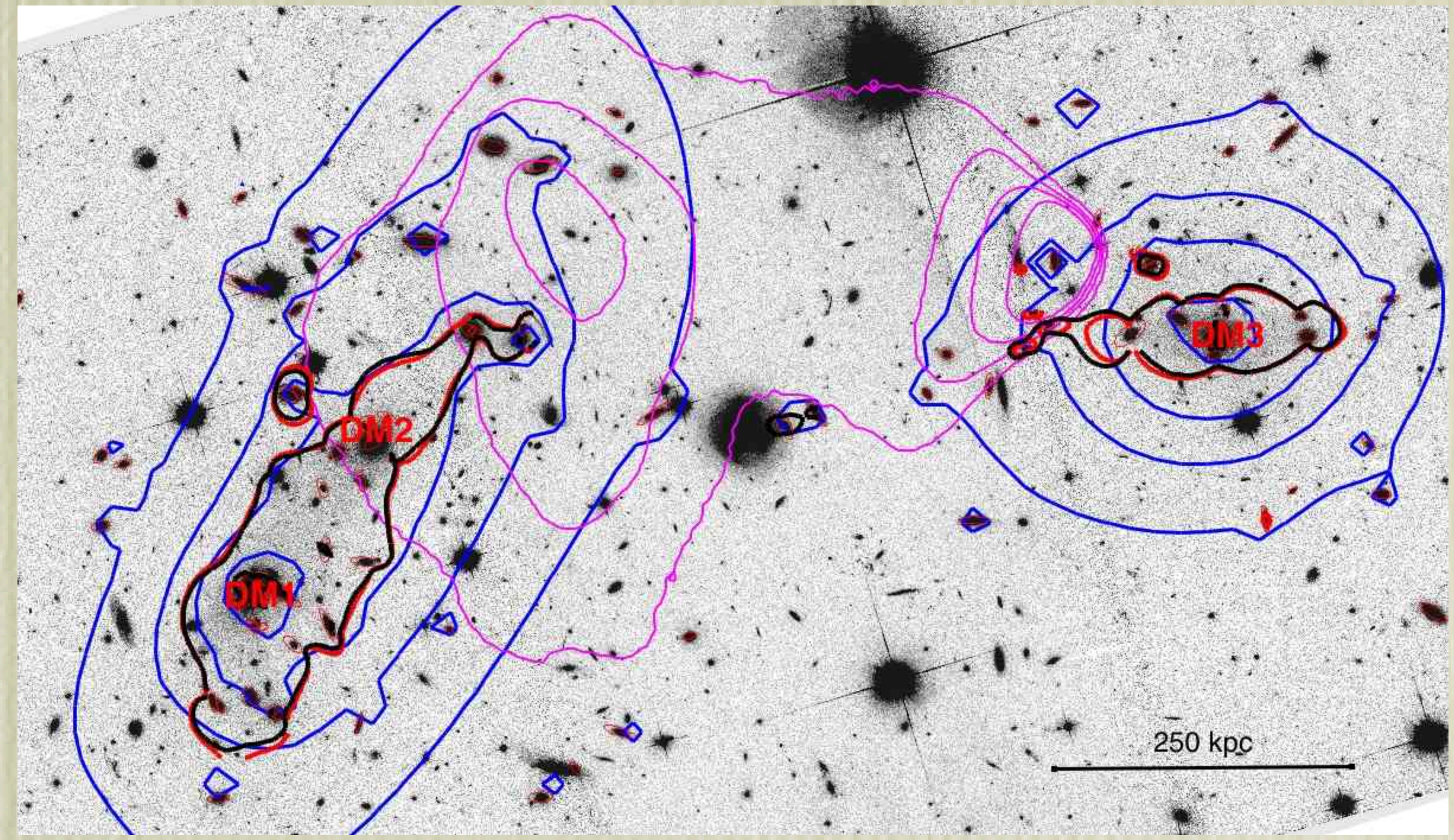
Dark matter (indirectly) detected!

Plenty of (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.:

Bullet cluster:

offset between DM, mapped via gravitational lensing, and hot gas - the bulk of the baryonic in the system, traced via its X-ray emissivity, in the 1E0657-558 cluster

Paraficz et al., arXiv: 1209.0384



magenta contours: Chandra X-ray image; blue contours: strong lensing map

Relying again on GR as a theory of gravity; again it is very problematic to introduce an alternative theory and explain the component segregation within a model without DM but having baryons only

(Indirect) detection of dark matter particles?

Jump from this indirect evidence to a specific particle DM candidate?

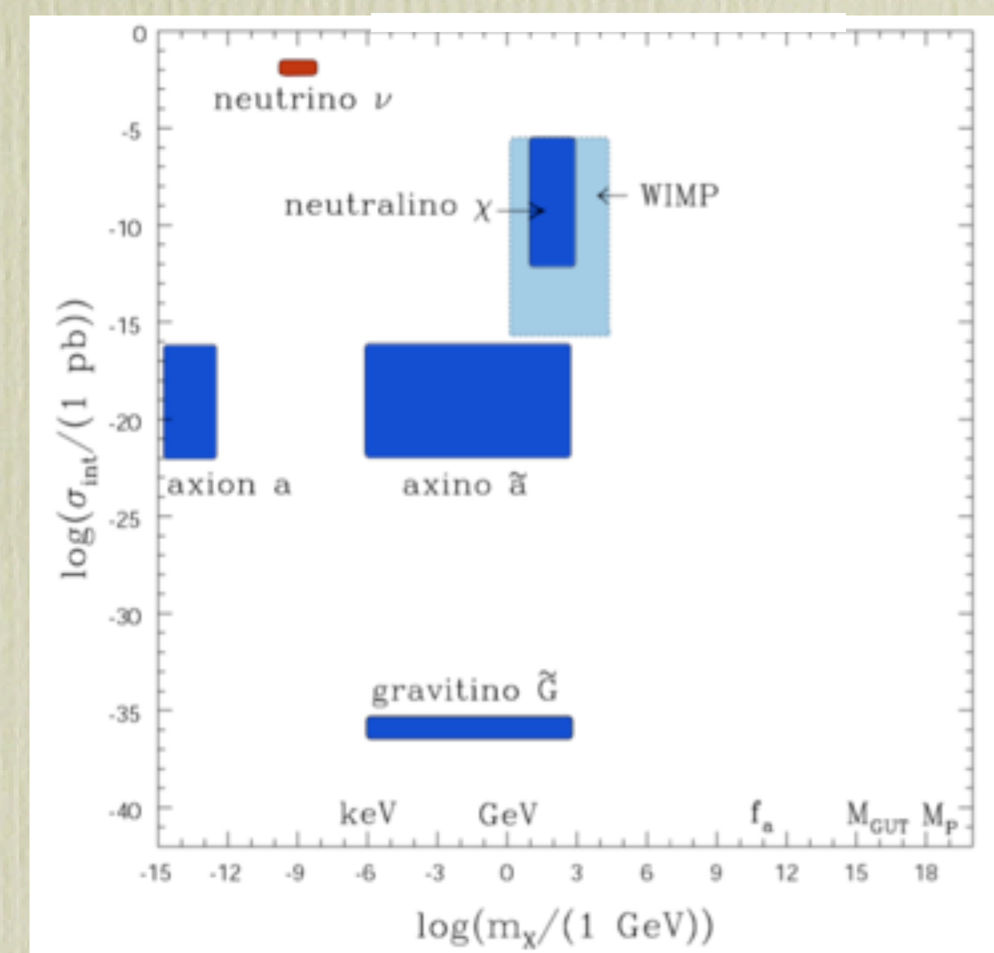
(review: Bertone, (ed.) e al., 2010)

On one hand: ΛCDM cosmology with extraordinarily accurate measurement of the mean density of DM particles:

$$\Omega_{\mathrm{CDM}} h^2 = 0.1199 \pm 0.0027$$

(Planck, 2013 + WMAP 7 yr pol.)

just a subset



Credit: L. Roszkowski

.. at the same time, very loose bounds on the properties which are crucial for devising a detection strategy for DM particles - the mass and coupling to ordinary matter.

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Jump from the indirect (gravitational) evidence to a particle DM candidate?

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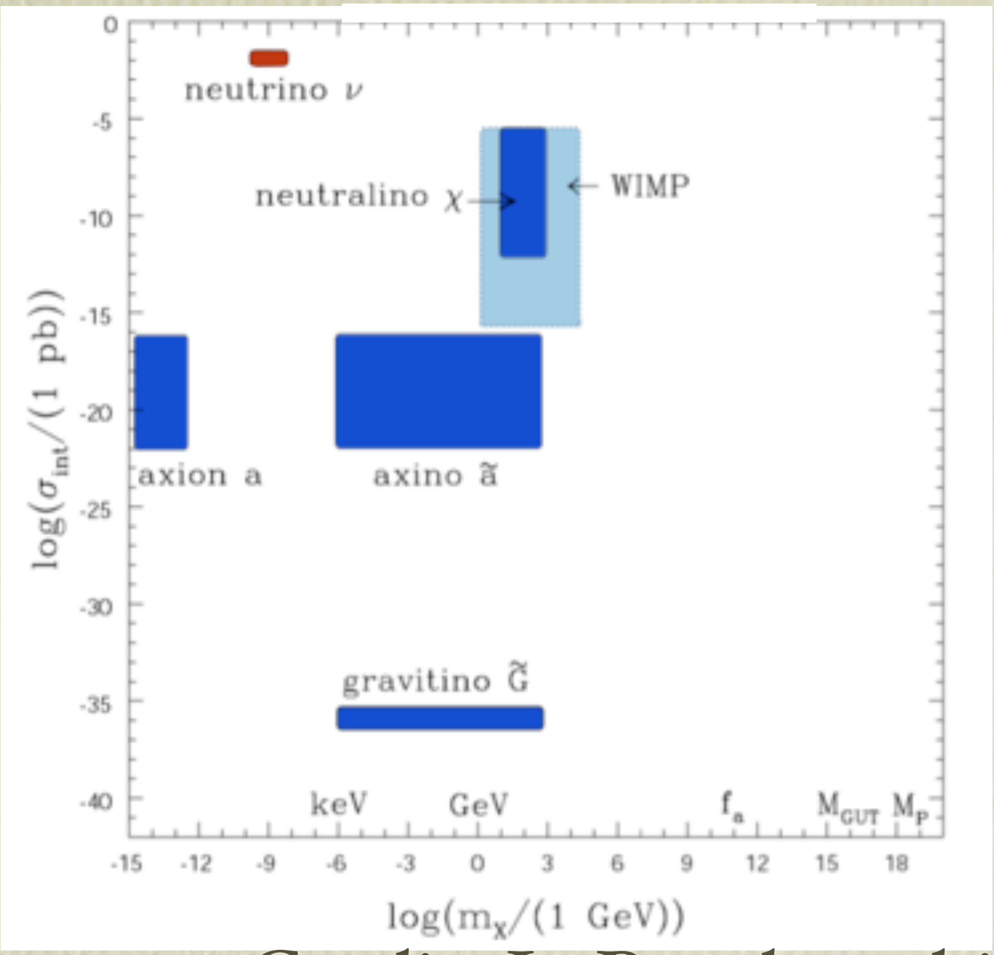
E.g.: from the CMB, limits on eventual DM electromagnetic couplings and on the DM heating of the plasma at (moderately) recent times, and, from the Bullet cluster, limits on the self-interaction of DM particles

just a subset



Credit: L. Roszkowski

Learning more on DM particles from cosmology?

In the SM for cosmology and structure formation, the ΛCDM model, DM is treated as a collisionless, cold fluid, coupled to ordinary (baryonic) matter only gravitationally: spectacular agreement between predictions from this model and data, especially on large scales!

Shortcomings of the model on small scales, in the (very) non-linear regime, usually addressed via numerical N-body simulations?

• the missing satellite "problem" (too few luminous satellites compared to the number of DM substructures in simulations), Moore et al., Klypin et al. 1999

• the too-big-to-fail Milky Way problem (normalizing the substructure mass function to the MW mass, too few massive satellites), Boylan-Kolchin et al. 2012

• the CDM profiles too cuspy (NFW: $\rho(r) \propto r^{-1}$, or Einasto) when looking at low mass objects, like dwarf or LSB galaxies, see, e.g., Salucci et al. 2011, Kuzio de Naray et al. 2008

• ...

All of these loosely targeted as an excess of power on small scales? Introduce a dissipation of power on small scales as an imprint from DM particles?

Learning more on DM particles from cosmology?

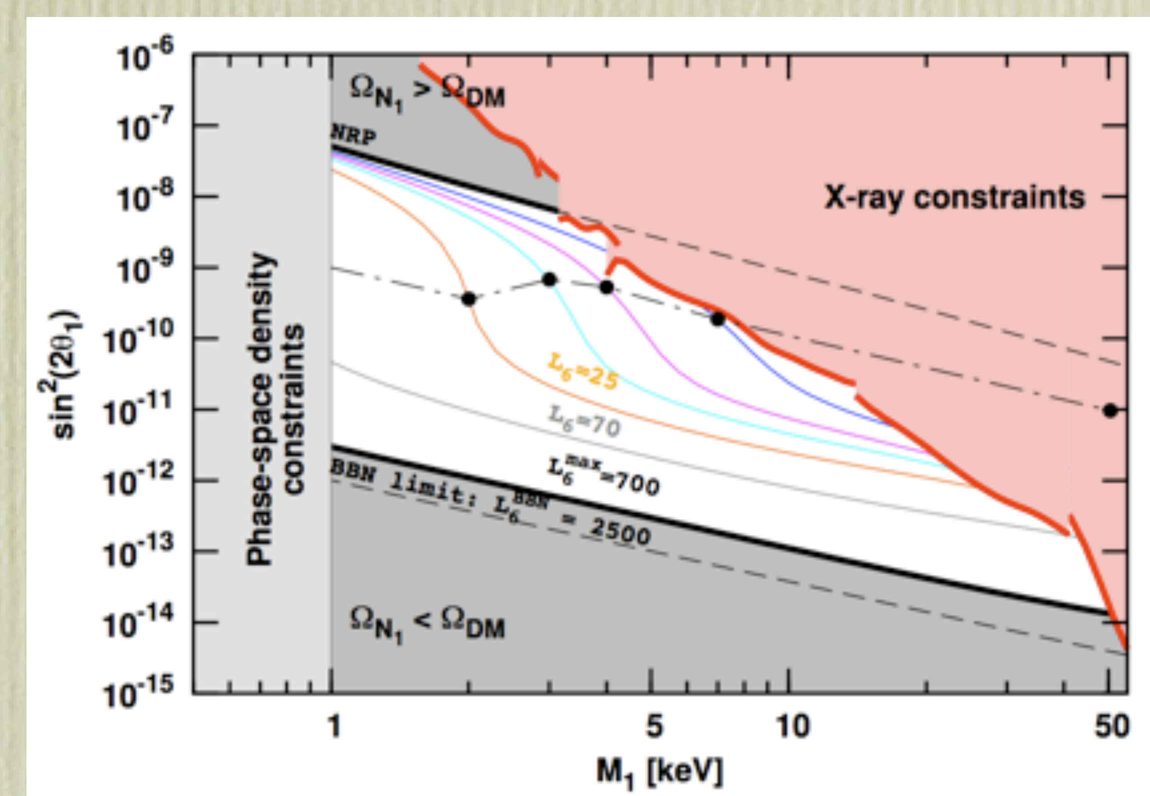
Improving on ΛCDM with some extra ingredient from particle physics:

Warm DM: imprint on the sky of the DM particle free streaming scale, approximately: $\lambda_{\rm FS} \simeq 0.4\ {\rm Mpc}\ (1\ {\rm keV}/m_p)\ (T_p/T)$

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

Learning more on DM particles from cosmology?

Improving on ΛCDM with some extra ingredient from particle physics:

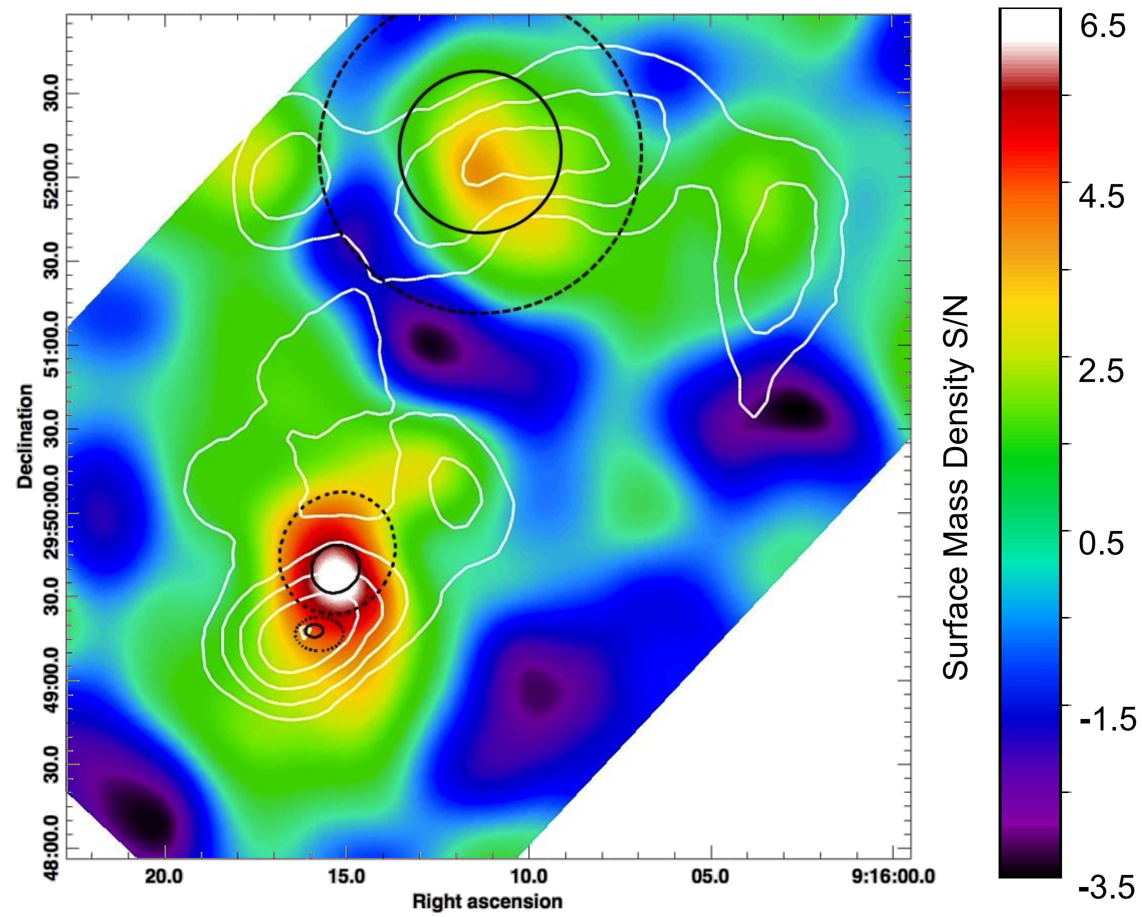
Self interacting DM: a "hint of detection" from the Musket Ball cluster?

Dawson et al. 2013

Surface mass density S/N map

Galaxy density (white contours)

Centroid errors; 68%, 95% Confidence (black contours)



another merging event, although at much smaller impact speed than for the Bullet cluster

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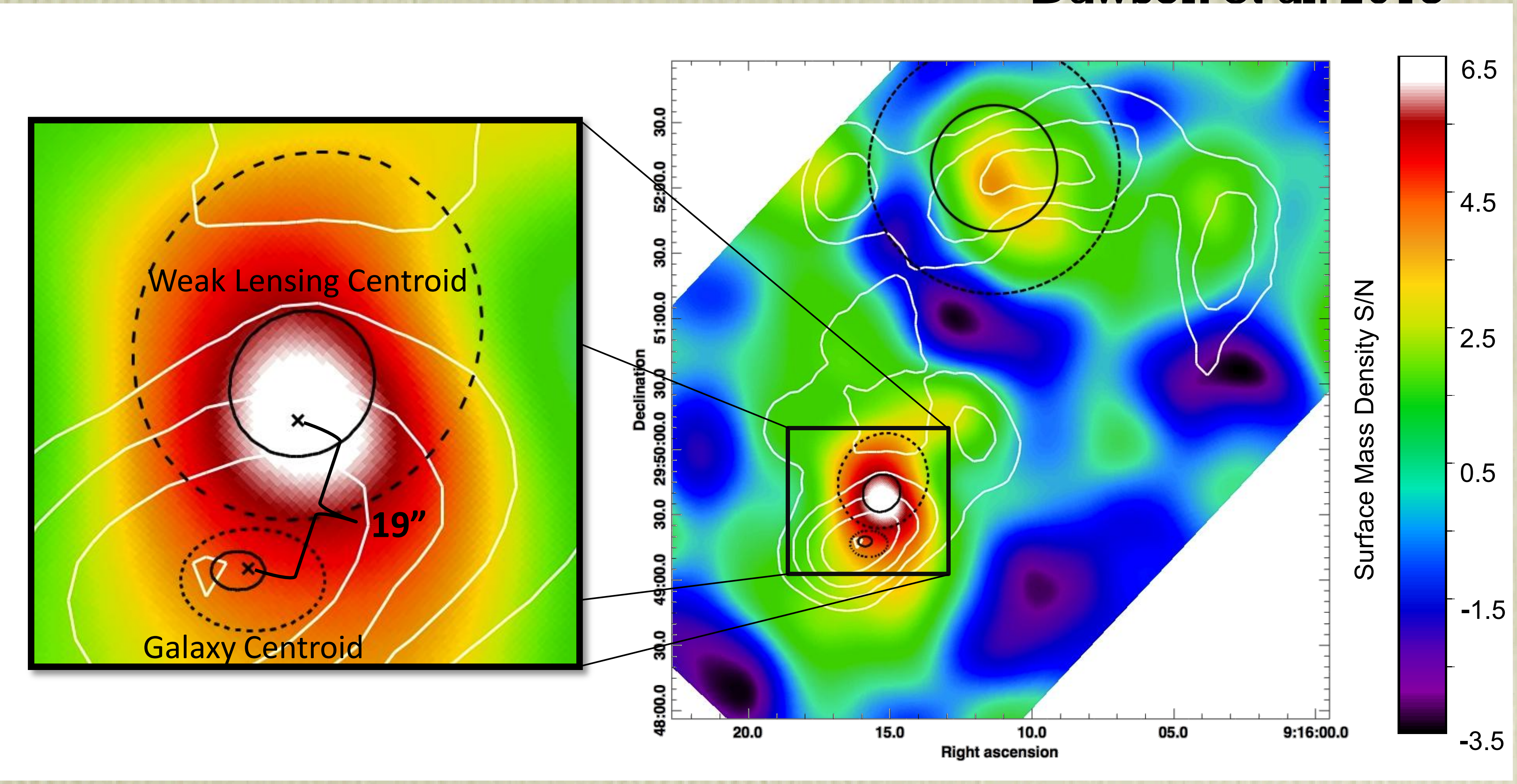


displacement consistent with: $\sigma_{DM}/M_{DM} \sim 0.8\,\mathrm{cm}^2\,\mathrm{g}^{-1}$, rather large effect!
Pointing towards, e.g., a dark sector with a light mediator generating a fifth force? Feng et al. 2009, Tulin et al. 2013

Learning more on DM particles from cosmology?

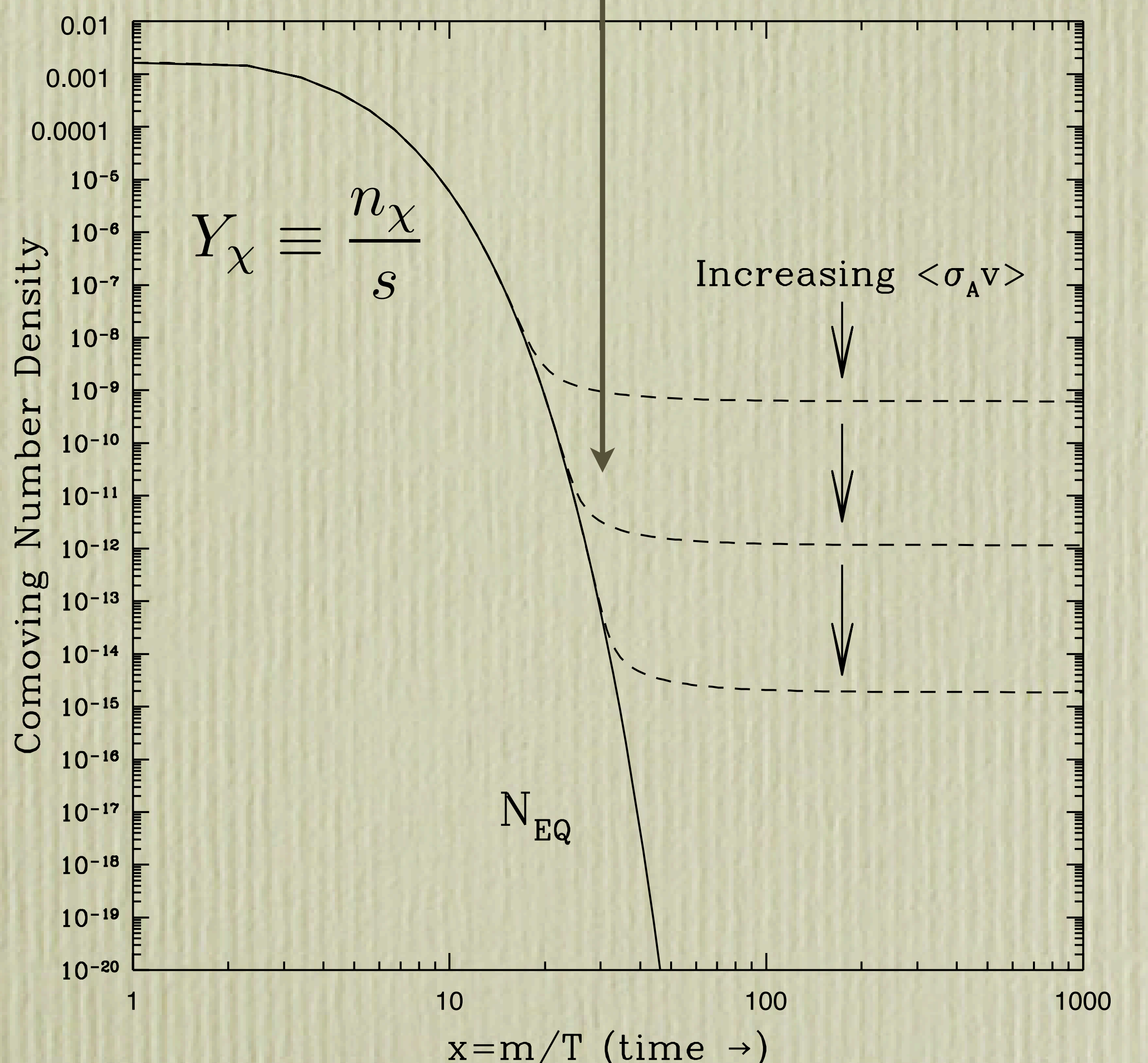
What about if the shortcomings of the ΛCDM model on small scales are just connected to the fact that it is really hard to include a realistic model for baryonic components in the DM numerical simulations?

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.

WIMPs as natural DM candidates (?)

Thermal generation of DM:

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



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

(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)

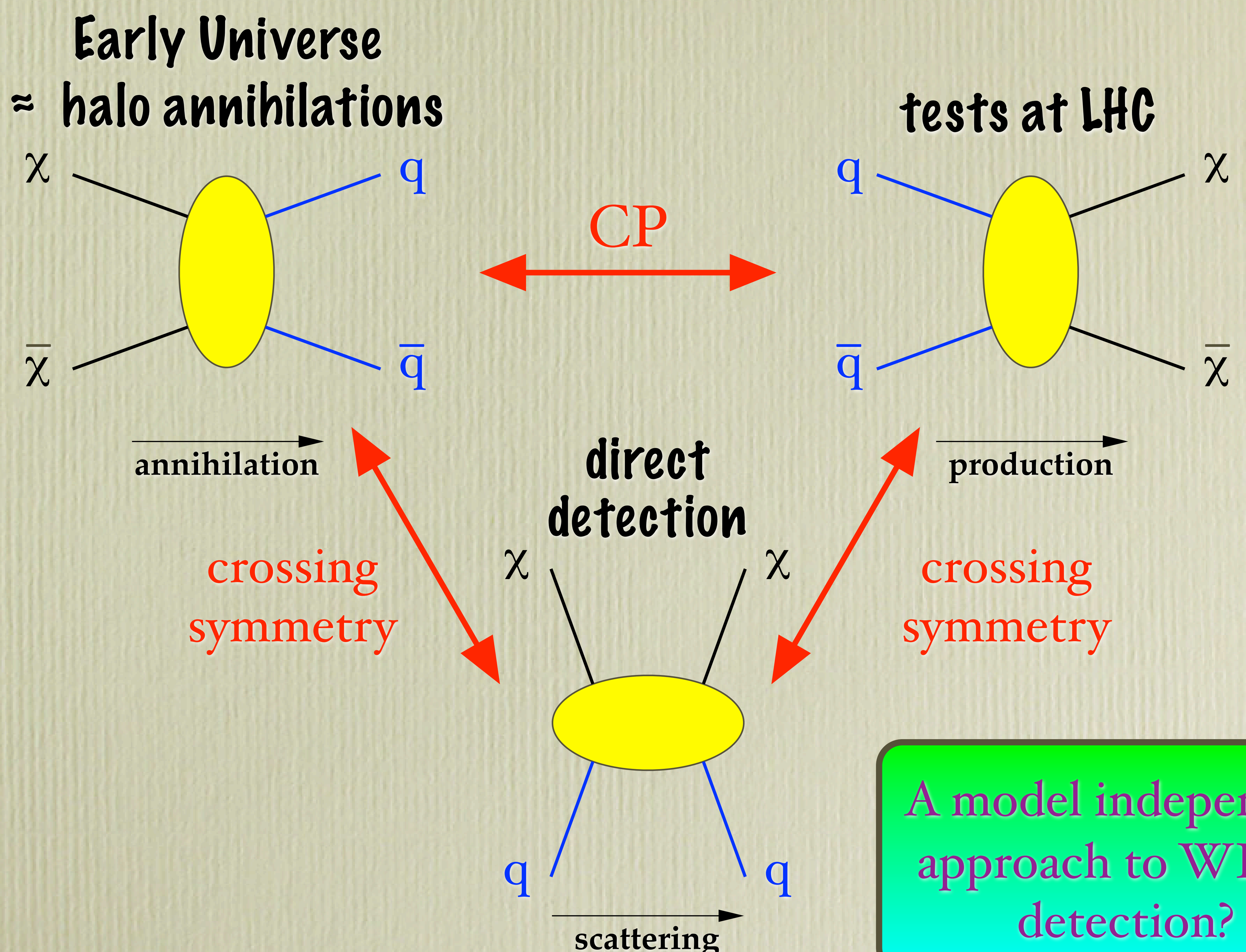
$$\simeq \frac{M_\chi}{T_f}\frac{g_\chi^\star}{g_{\rm eff}}\frac{1\cdot 10^{-27}{\rm cm}^{-3}{\rm s}^{-1}}{\langle\sigma_A v\rangle_{T=T_f}}$$

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

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

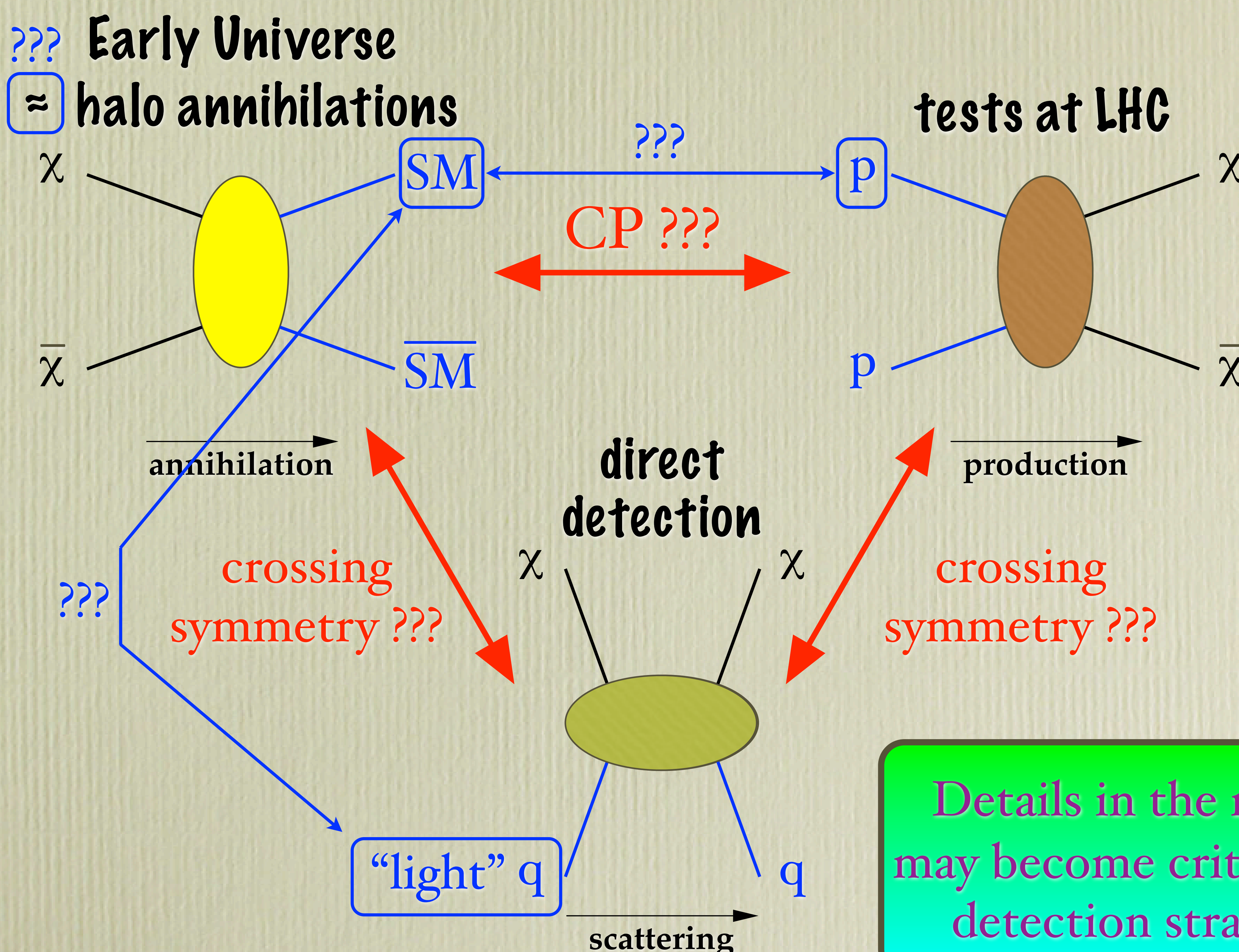
Plenty of WIMPs in BSM setups! DM as a byproduct of some other property of the theory which is calling for an extension of the SM (!/?)

WIMP coupling to ordinary matter:



A model independent approach to WIMP detection?

Back to WIMP coupling to ordinary matter:



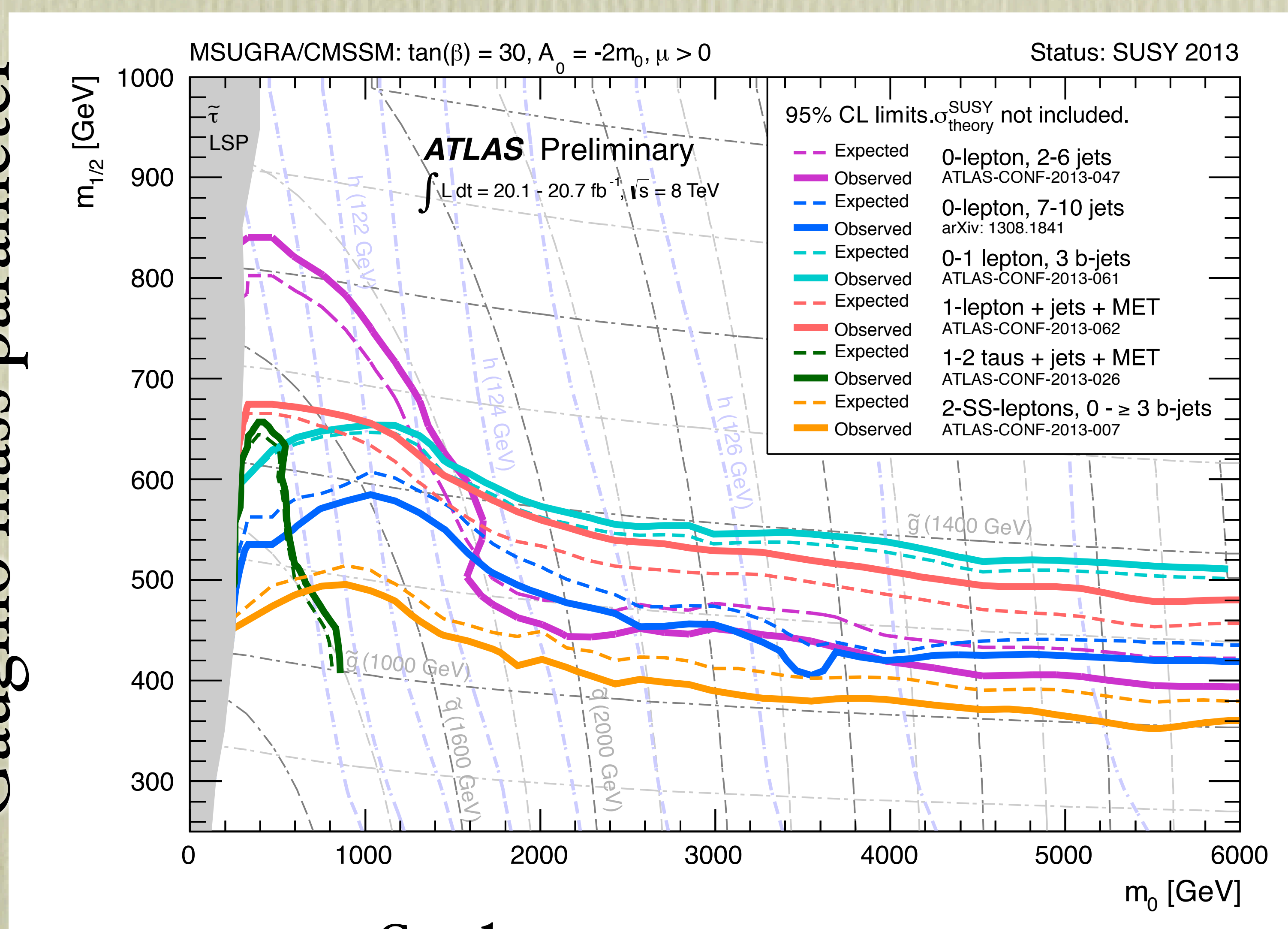
Details in the model may become critical for detection strategy

WIMPs and the LHC:

No evidence for BSM particles from the LHC so far!

E.g.: for SUSY setups, there are already very strong lower limits on the mass of strongly interacting states, namely gluinos have to be heavier than about 1.4 TeV, 1st & 2nd family squarks have to be heavier than about 1.7 TeV:

Gaugino mass parameter



Scalar mass parameter

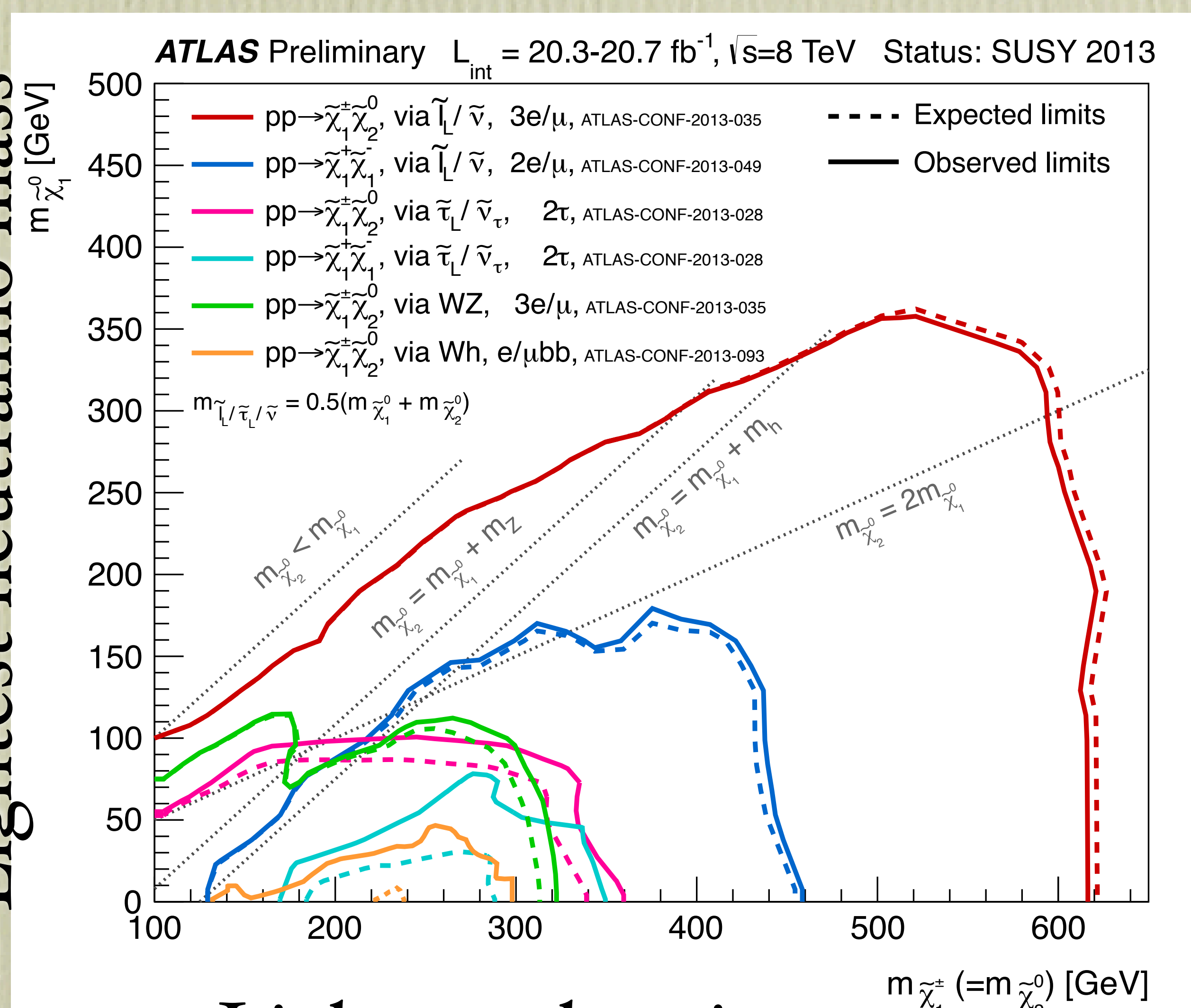
ATLAS,
August 3013

WIMPs and the LHC:

No evidence for BSM particles from the LHC so far!

Much less severe limits for electro-weakly interacting states, such as charginos and neutralinos (the lightest of the latter being, in R-parity conserving models, stable and, potentially, a WIMP dark matter candidate); limits depending critically on mass splittings between states:

Lightest neutralino mass



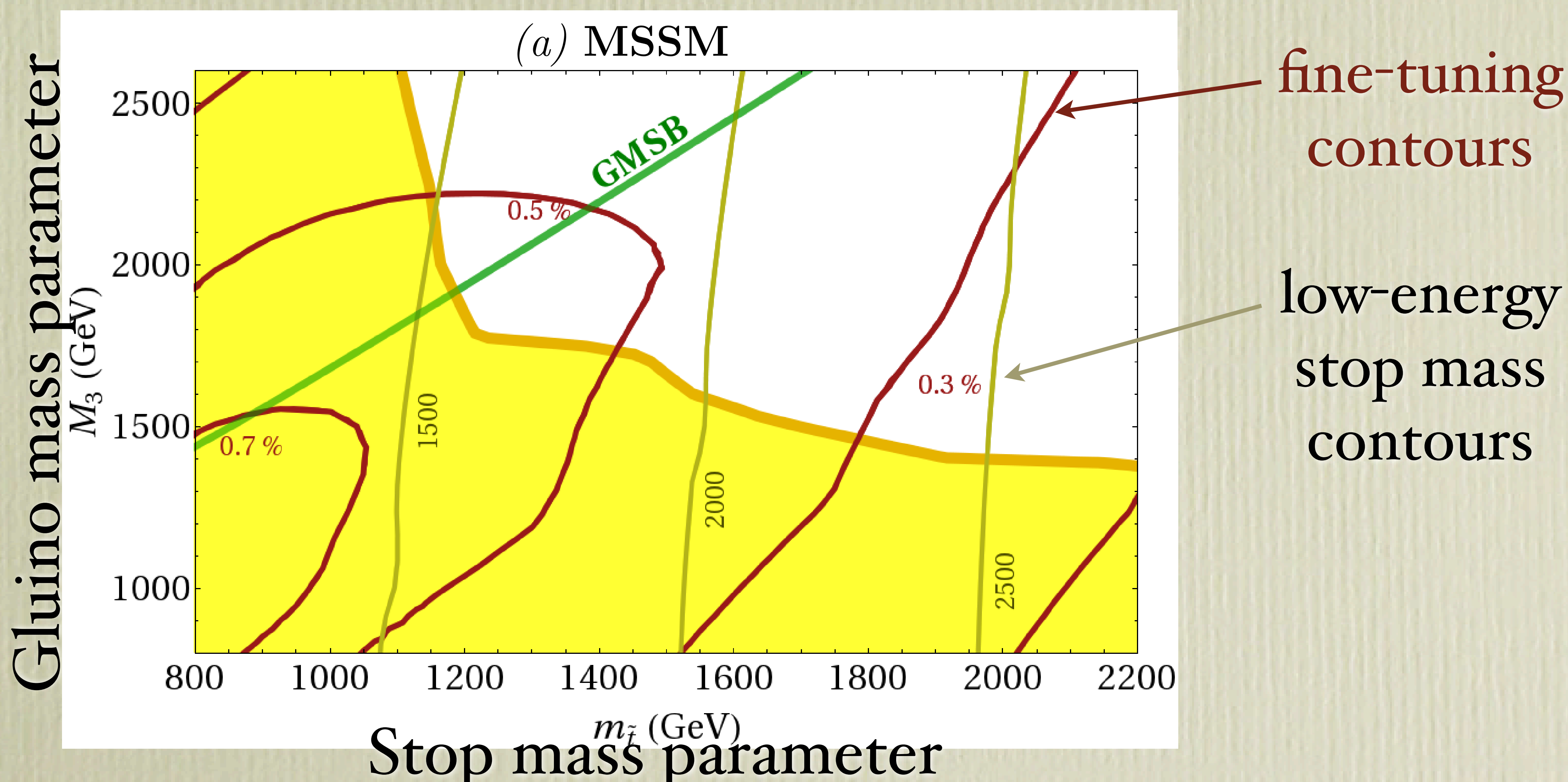
Lightest chargino mass

ATLAS,
August 3013

WIMPs and the LHC:

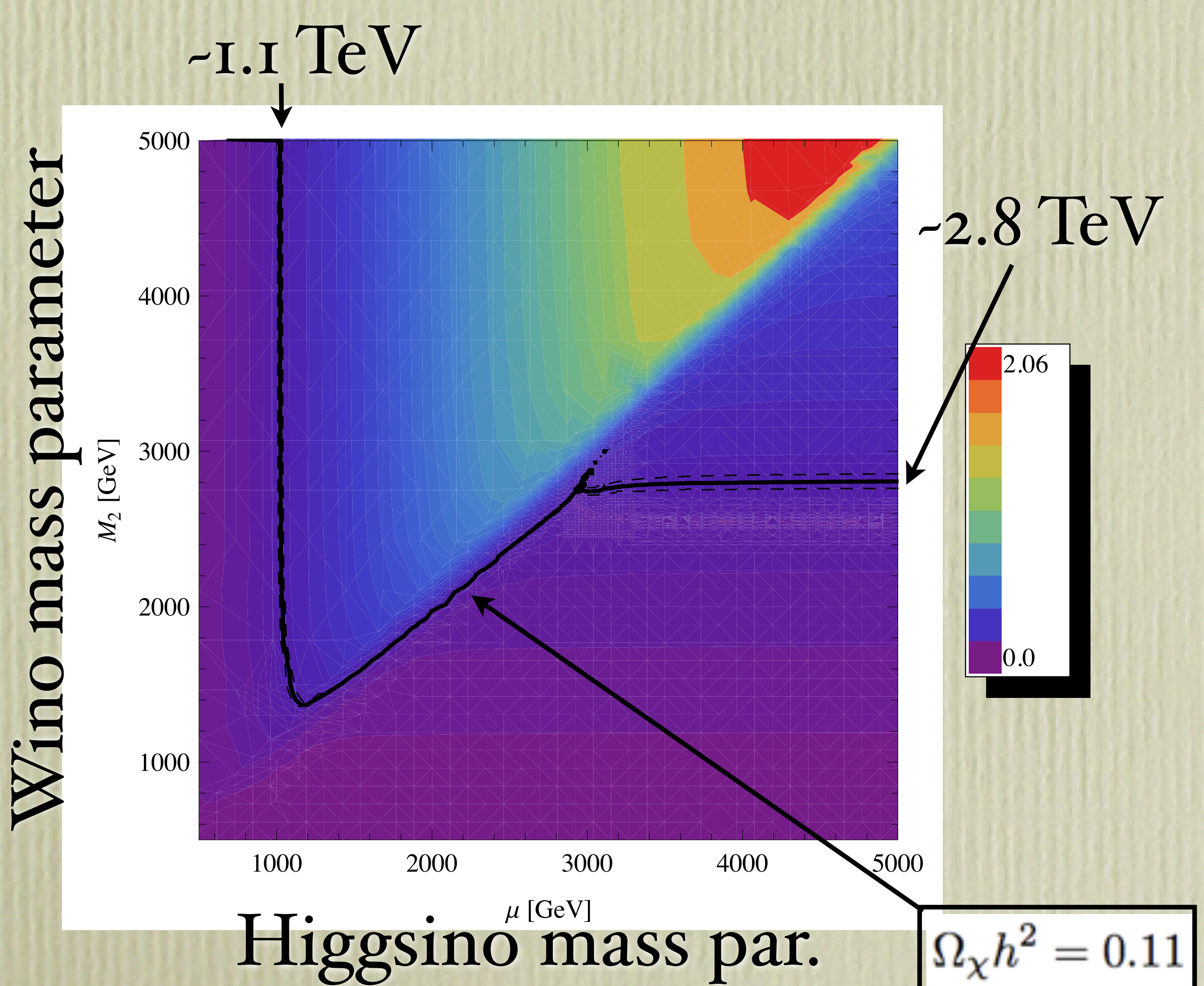
A 125 GeV Higgs is just ok with SUSY; an optimistic may even say that is an indication in favor of SUSY since a prediction of the MSSM was that it had to be lighter than about 135 GeV!

On the other hand naturalness arguments (i.e. addressing the question of why there are light elementary scalars) are fading away with tuning reaching worrisome levels, see, e.g., Arvanitaki et al., 1309.3568:



WIMPs and the LHC:

Naturalness used to be one of the main motivations for SUSY (or better for SUSY at the EW scale). Giving up on fine-tuning, but still insisting on SUSY since it drives gauge coupling unification or the flavor structure of the SM, having a WIMP DM candidates becomes the main motivation for requiring that some of the SUSY states are lighter than few TeV:



Hryczuk, Iengo & PU, arXiv:1010.2172

Split SUSY setup, i.e. all scalars are heavy. Actually this is just a model with a mixture of a triplet (Wino) and a doublet (Higgsino) of SU(2); if these states are heavy the EW interaction becomes a long range force and "explosives" annihilations take place (Sommerfeld enhancement).

Clearly DM is not a byproduct in this case!

WIMPs and direct detection:

Inconclusive picture, with some experiments finding null results and some a potential signal (as an excess over expected background or an annual modulation of the total event rate); taking all of them at face value and projecting on the plane WIMP-nucleon SI coupling versus WIMP mass there is tension among results:

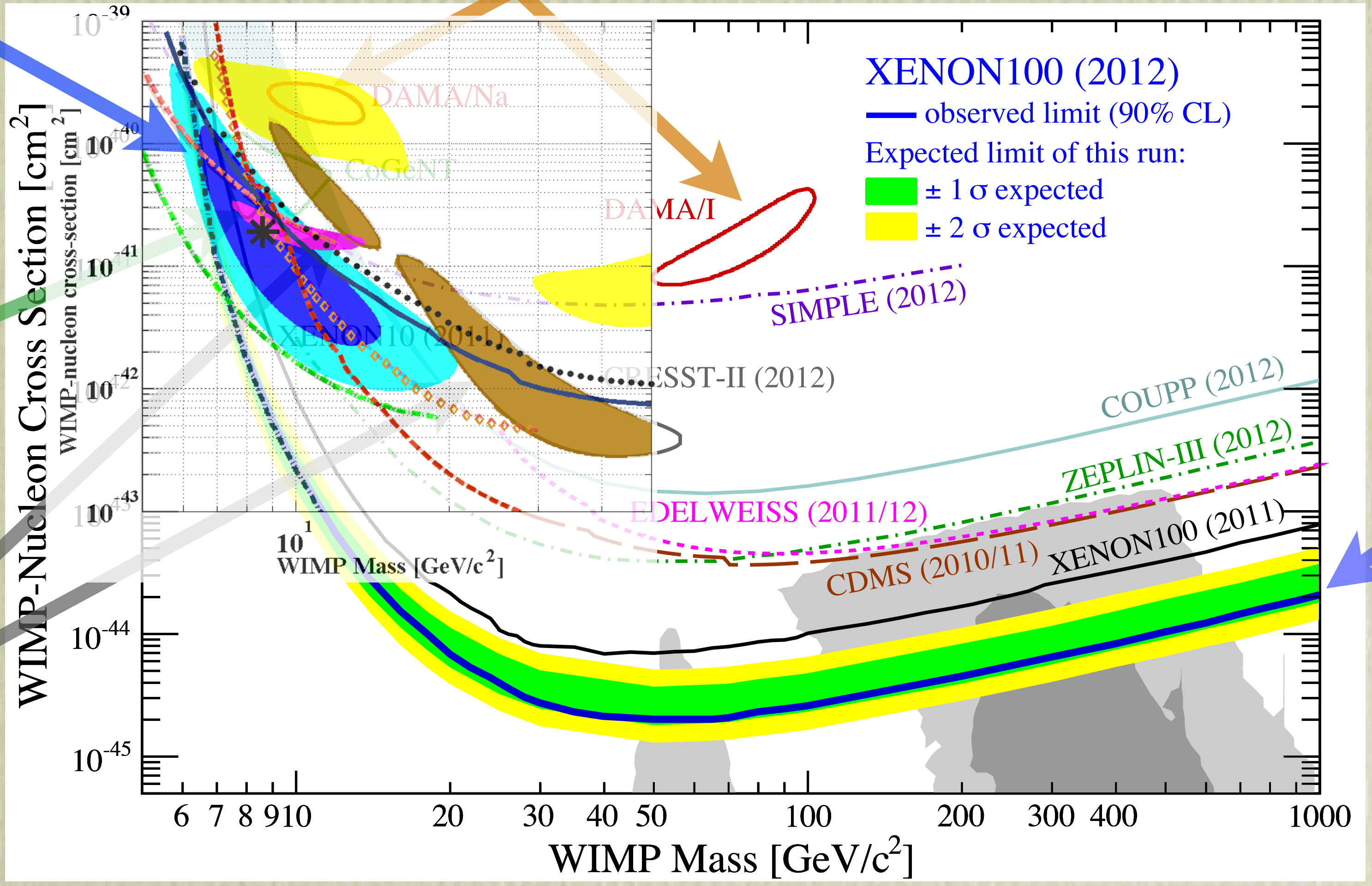
DAMA/LIBRA (annual modulation) Bernabei et al., arXiv:0804.2741

CDMSII Si (3 WIMP(?) events) Agnese et al., arXiv: 1304.4279

CoGeNT (excess + ann. mod.) Aalseth et al., arXiv:1106.0650

CRESST (excess) Angloher et al., arXiv:1109.0702

XENON100 (null result) Aprile et al., arXiv:1207.5988



Is the light mass window interesting?

Indirect detection of WIMP dark matter

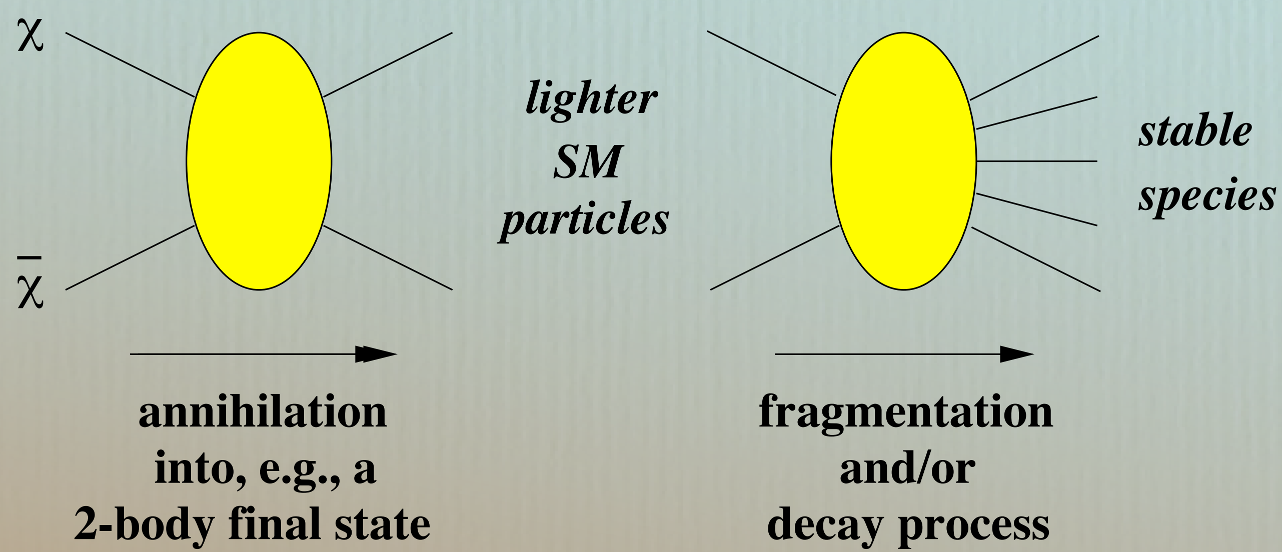
In principle the chance for detecting WIMPs is in the paradigm itself:

Pair annihilations of WIMPs in the early Universe (i.e. at $T = T_{f.o.}$)

Indirect detection of WIMP dark matter

A chance of detection stems from the WIMP paradigm itself:

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



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

WIMP DM source function (sum over all processes : $\chi\chi \to f\bar{f}$)

$$Q_i(\vec{r}, E) = \boxed{(\sigma_A v)_{T=0}} \sum_f \frac{dN_i^f}{dE}(E)\, B_f \mathcal{N}_{\text{pairs}}(\vec{r})$$

Is is fair to assume: $(\sigma_A v)_{T=0} \sim \langle \sigma_A v \rangle_{T=T_f}$?

Counterexamples: coannihilations, non-thermal WIMPs, ...

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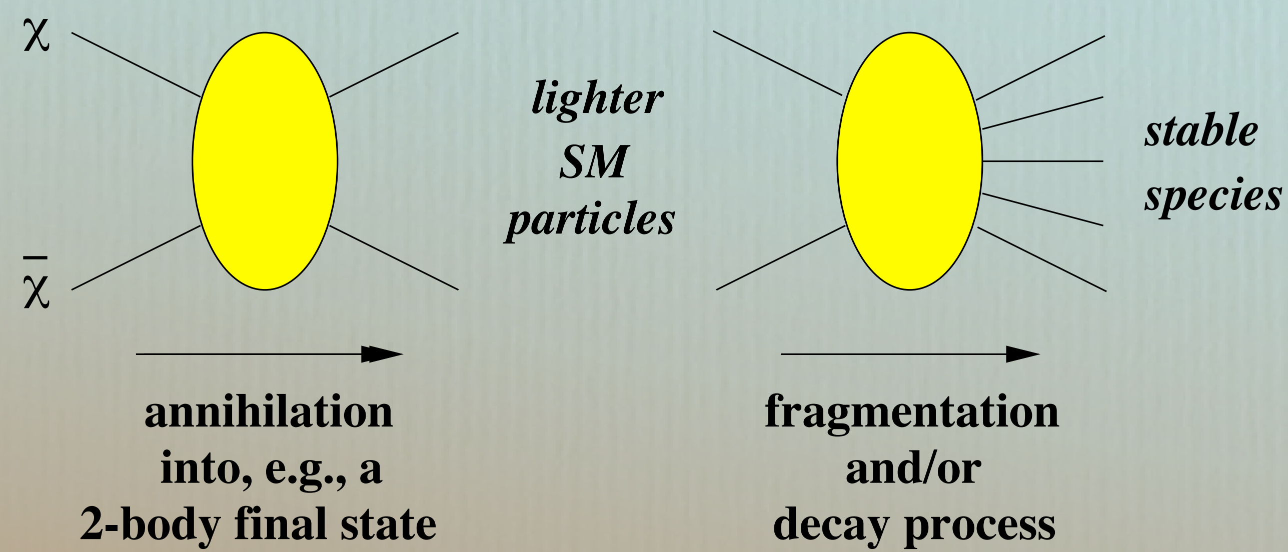

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$\mathcal{N}_{\rm pairs}(\vec{r}) \propto [\rho_\chi(\vec{r})]^2 \equiv [\rho_{\rm DM}(\vec{r})]^2$: learn it from dynamical observations (?) or numerical simulations (?); huge scale mismatch with respect to the DM clumping scale

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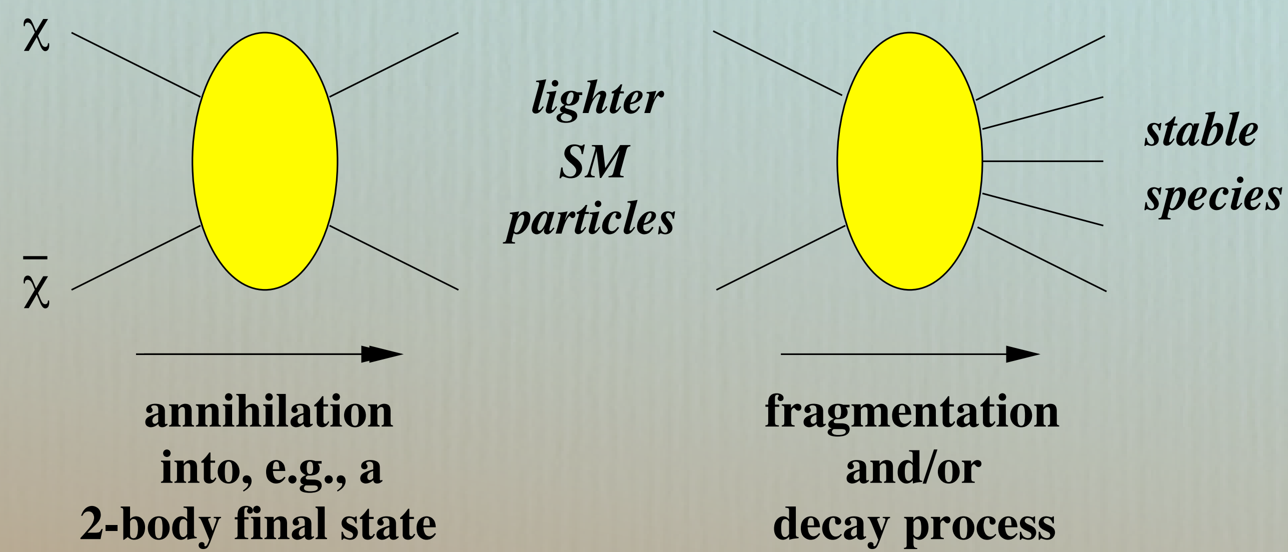

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What final state? Hard or soft yields? The WIMP paradigm relies on a generic coupling between WIMPs and thermal bath particles: it does not address in any way these issues!!!

Indirect detection of WIMP dark matter

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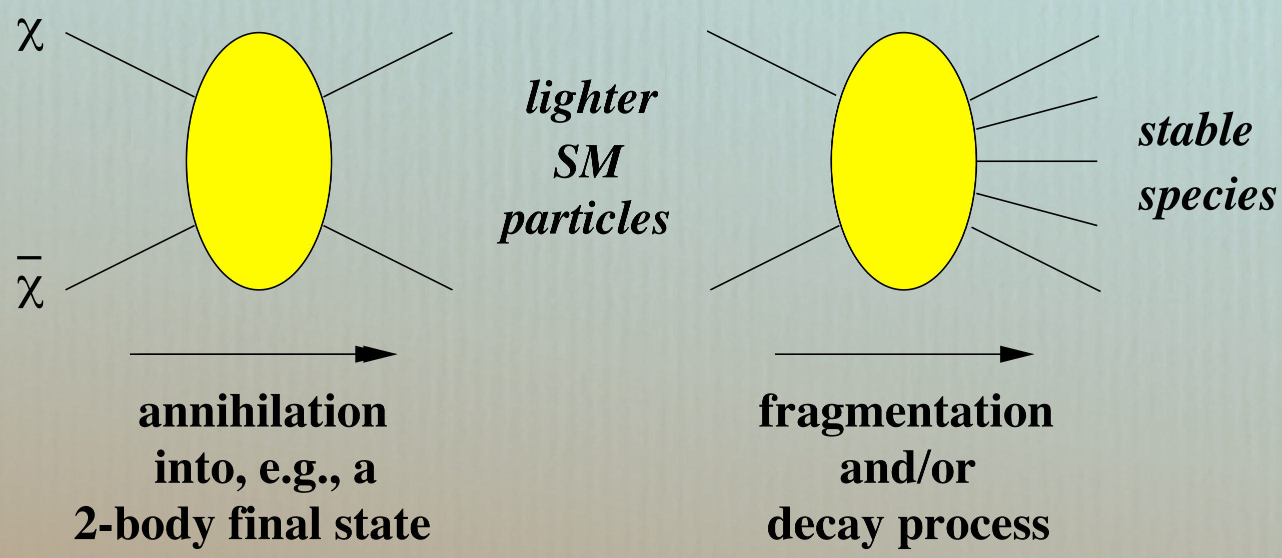


Focus on: antiprotons, positrons, antideuterons, gamma-rays, (neutrinos)

Can we target a clean signature? If such a signature is identified in the data, it gets obvious how to proceed!

Let's focus on γs, for which clean spectral signatures - such as the monochromatic γ-line - as well as clean morphological signatures exist.

DM annihilations and gamma-ray fluxes:

Prompt emission of γ-rays associated to three components:

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

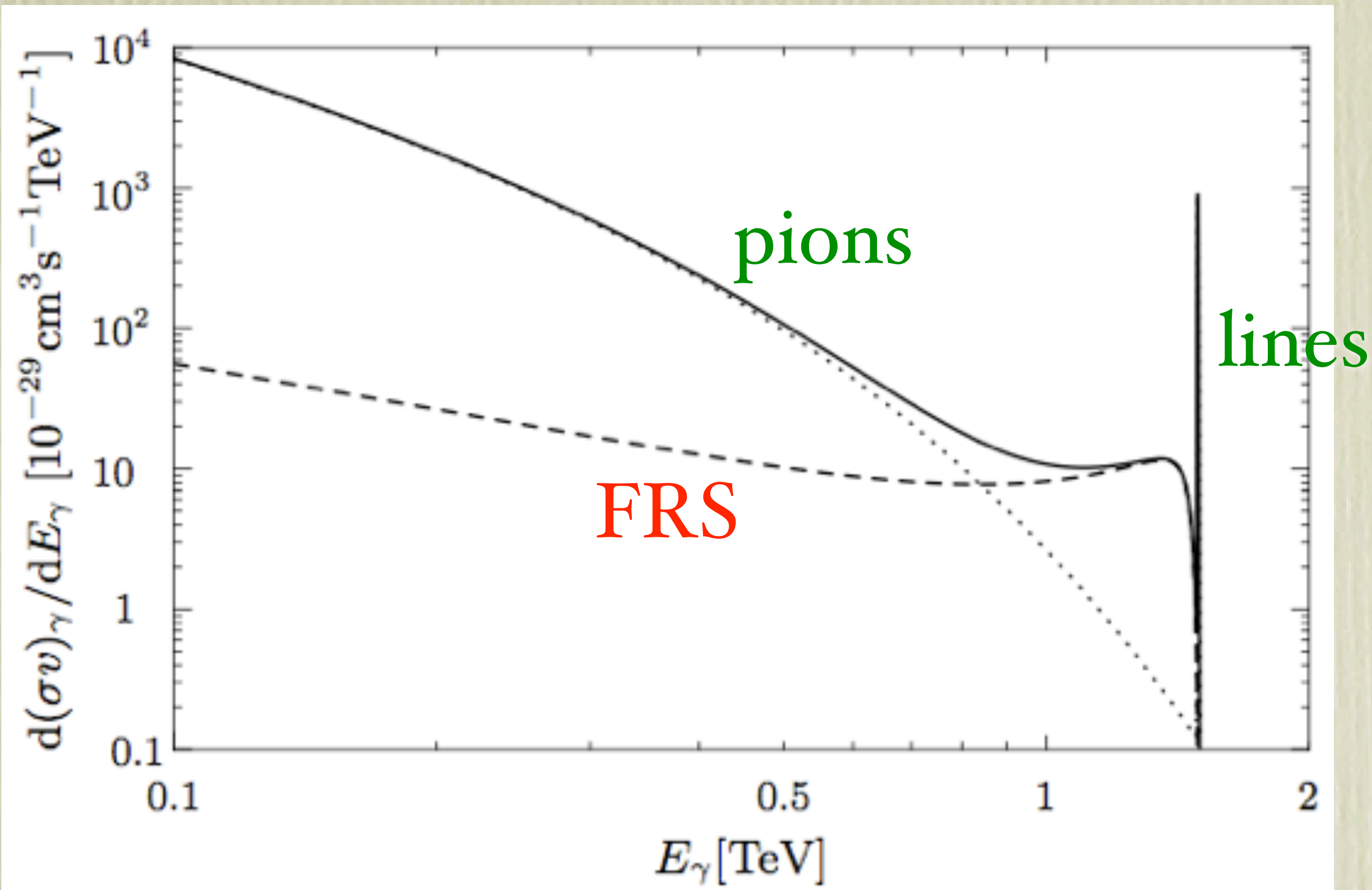
II) Monochromatic: i.e. the 1-loop induced $\chi\chi \to 2\gamma$ and $\chi\chi \to Z^0\gamma$ (in the MSSM, plus eventually others on other models)

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

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

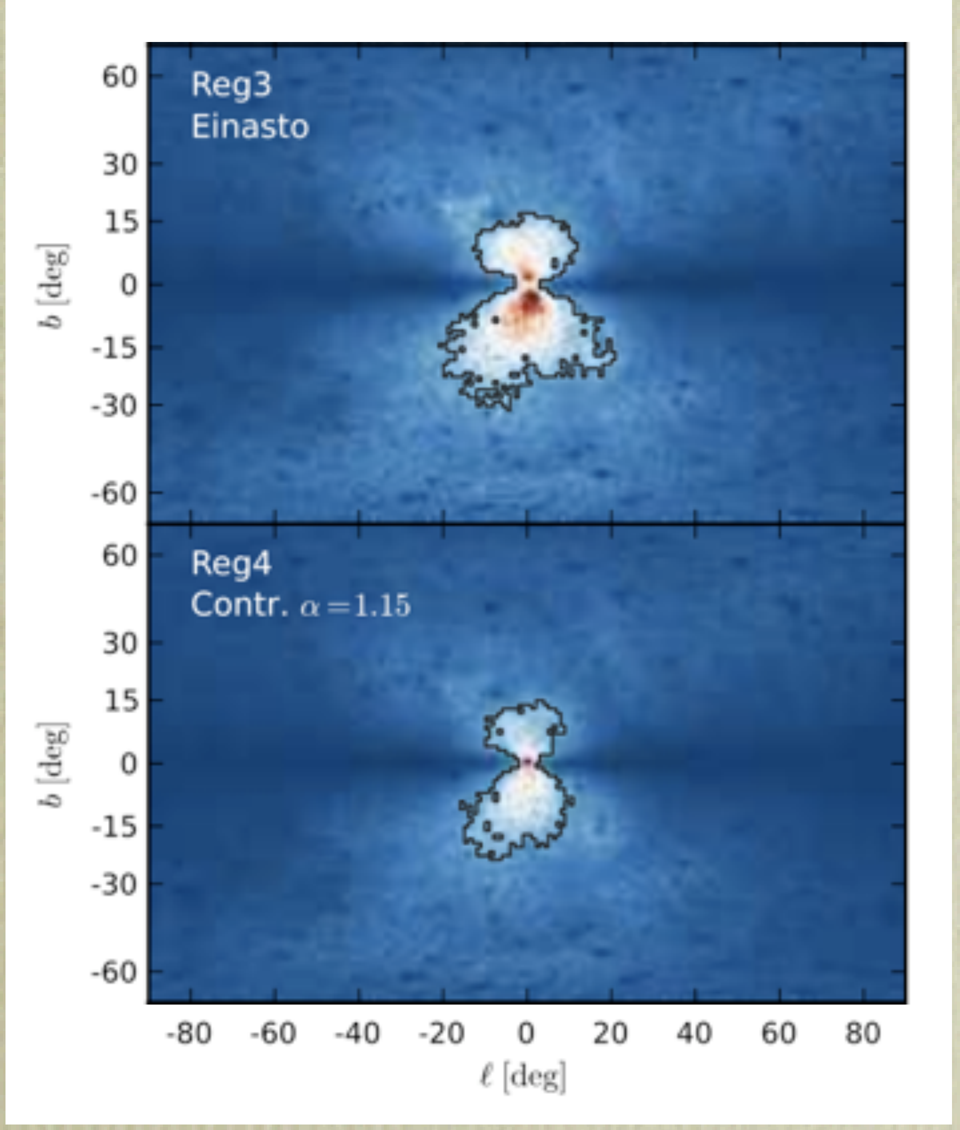
E.g. in a model for which all three terms are large (e.g. pure Higgsino):

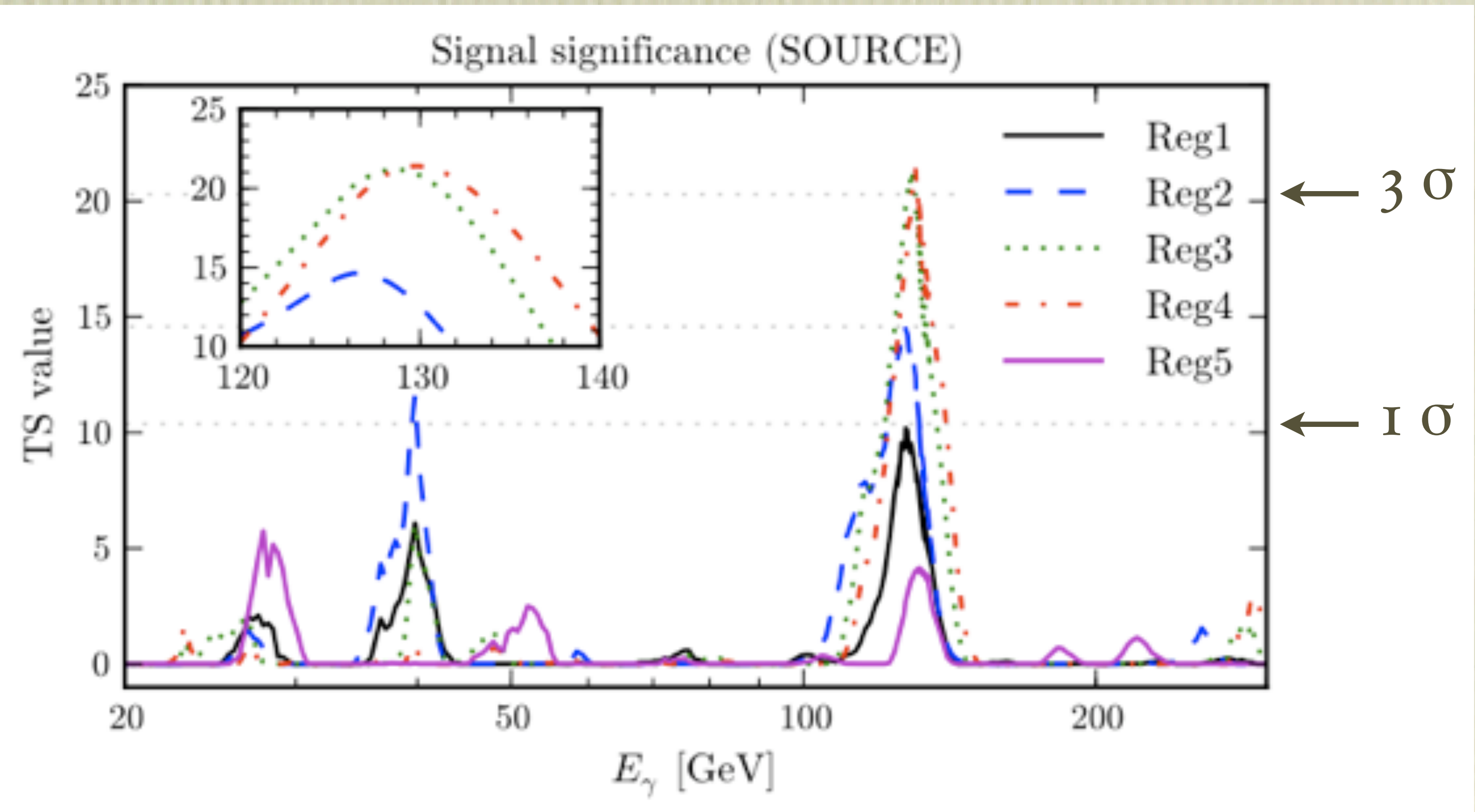
Bergström et al., astro-ph/0609510



A γ-ray line at 130 GeV in FERMI data ???

Weniger, arXiv:1204.2797 look at the Galactic center, optimizing the search region with respect to the assumption on the DM density profile (assuming a simple power-law background) and find a 3.2σ statistical significance (if "look elsewhere" effect included) for a **monochromatic signal** at about 130 GeV:

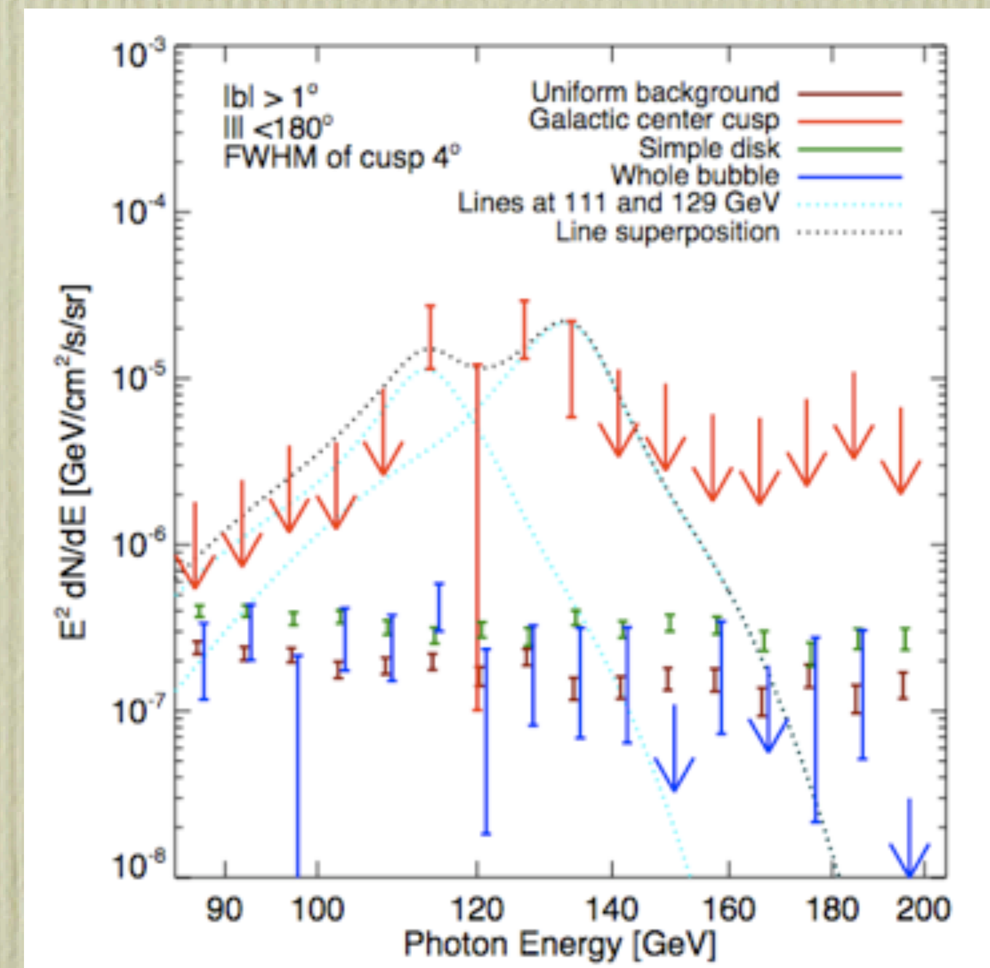


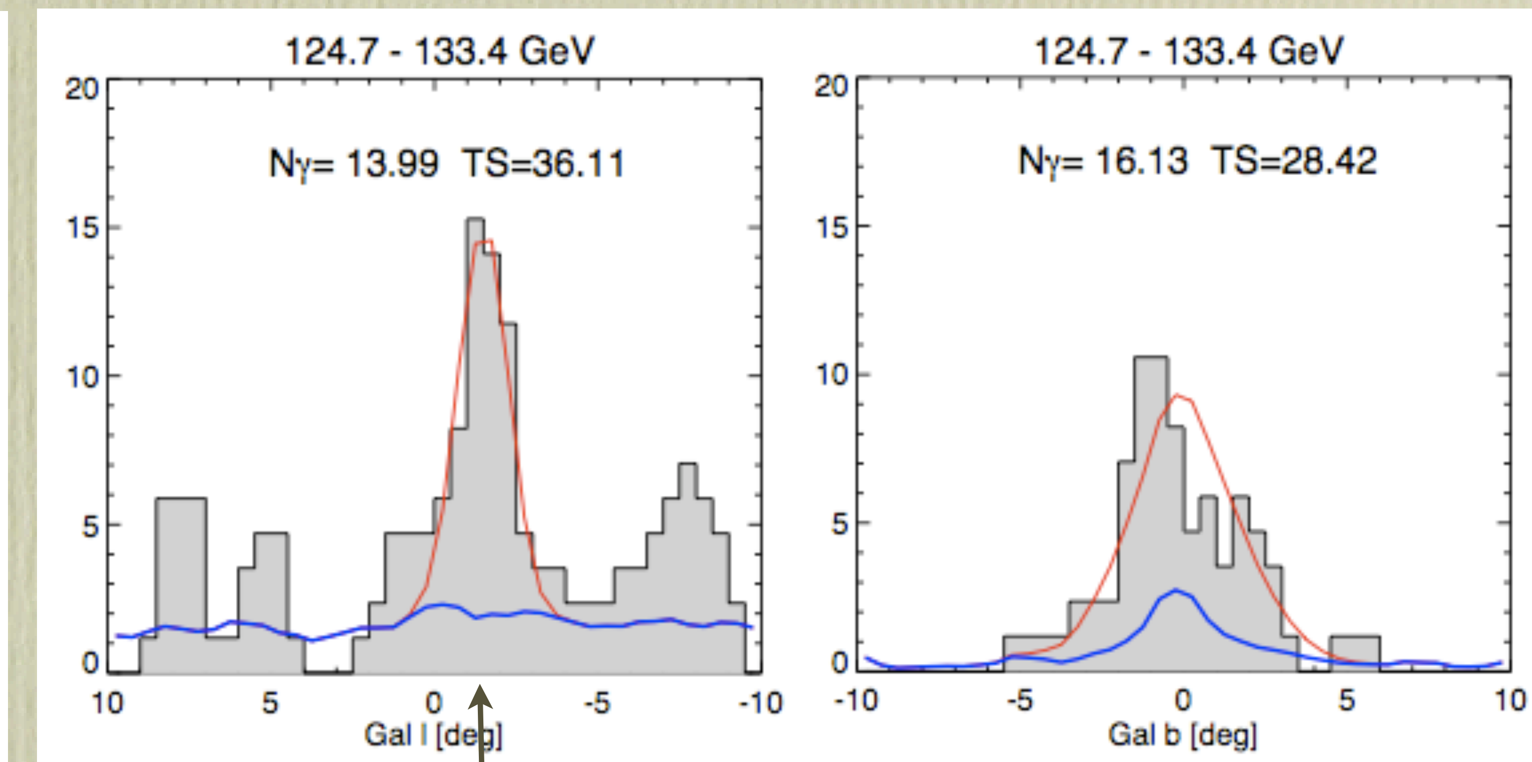


Compatible with line limits from the whole sky: Fermi-LAT coll., arXiv:1205.2739, as well as from dwarfs: Geringer-Sameth & Koushiappas, arXiv:1206.0796

A γ-ray line at 130 GeV in FERMI data ???

Su & Finkbeiner, arXiv:1206.1616 use a template fitting method and claim "strong evidence", with *local significance* of 5 o 6 σ for **2 lines** at 111 & 129 GeV!





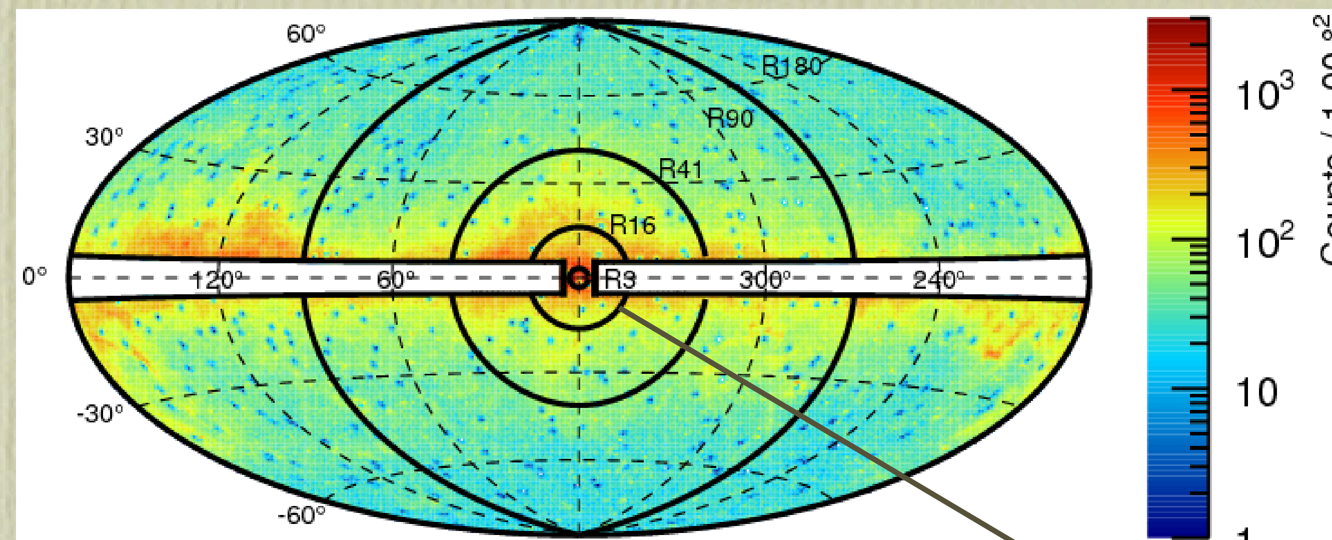
Template for the DM cusp off-centered by 1.5° (200 pc)

Off-center due to a density wave excitation by the stellar components? Matching a hydrodynamical N-body result Kuhlen et al., arXiv:1208.4844

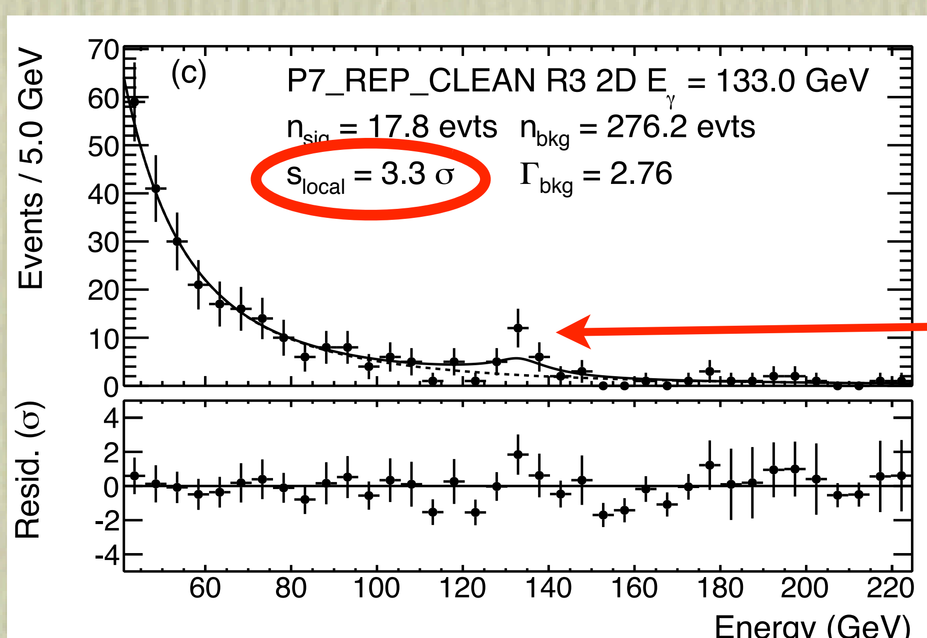
Hektor et al., 2012 find evidence for 2 lines at 3.6σ from stacked analysis of 18 galaxy clusters; Su & Finkbeiner, 2012 at 3.3σ from unassociated LAT sources

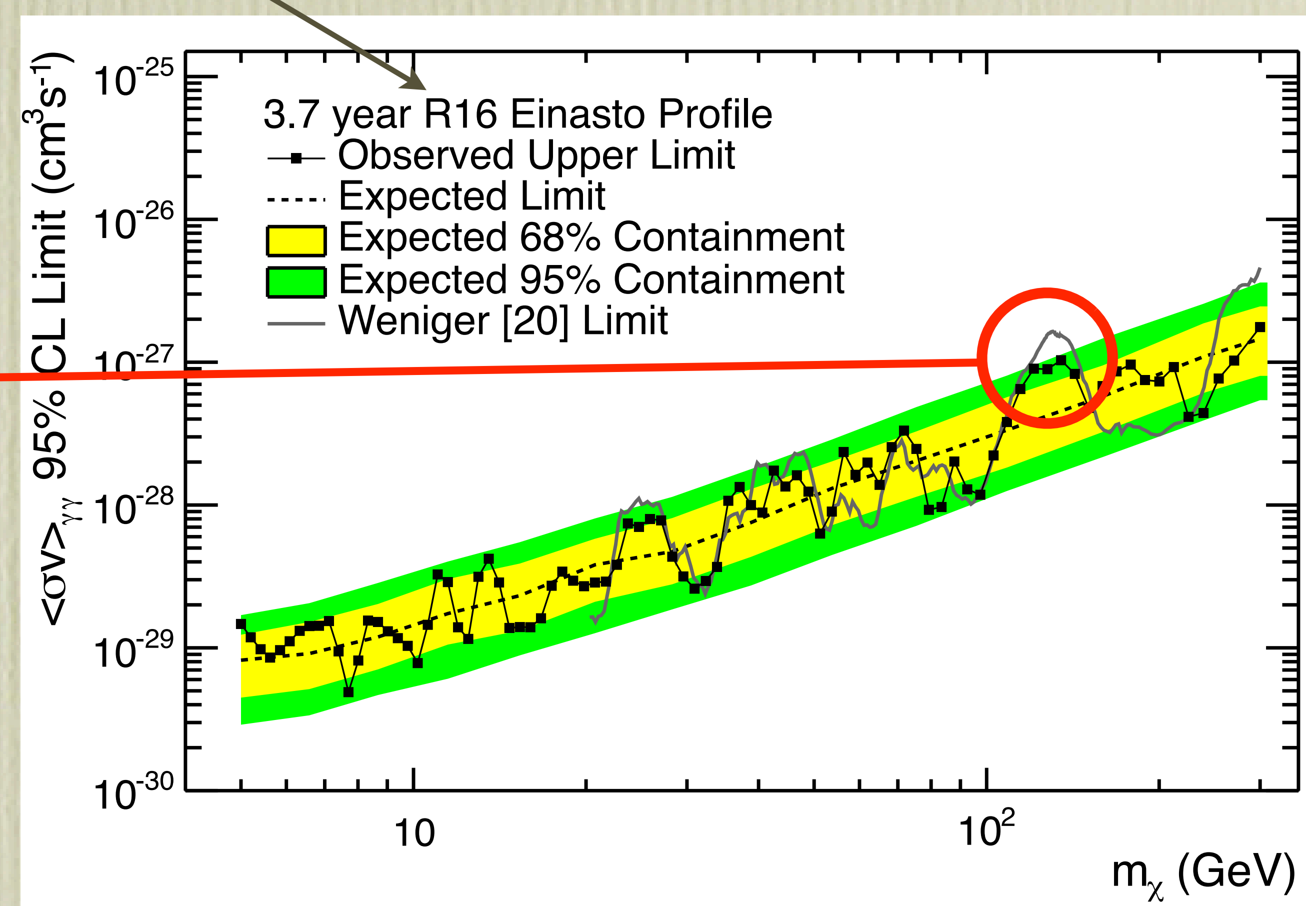
A γ-ray line at 130 GeV in FERMI data ???

Fermi Coll., arXiv:1305.5597 addressed the issue with reprocessed data, updated 2D energy reconstruction and more data, as well as optimized regions:



Limits falling within the expected bands



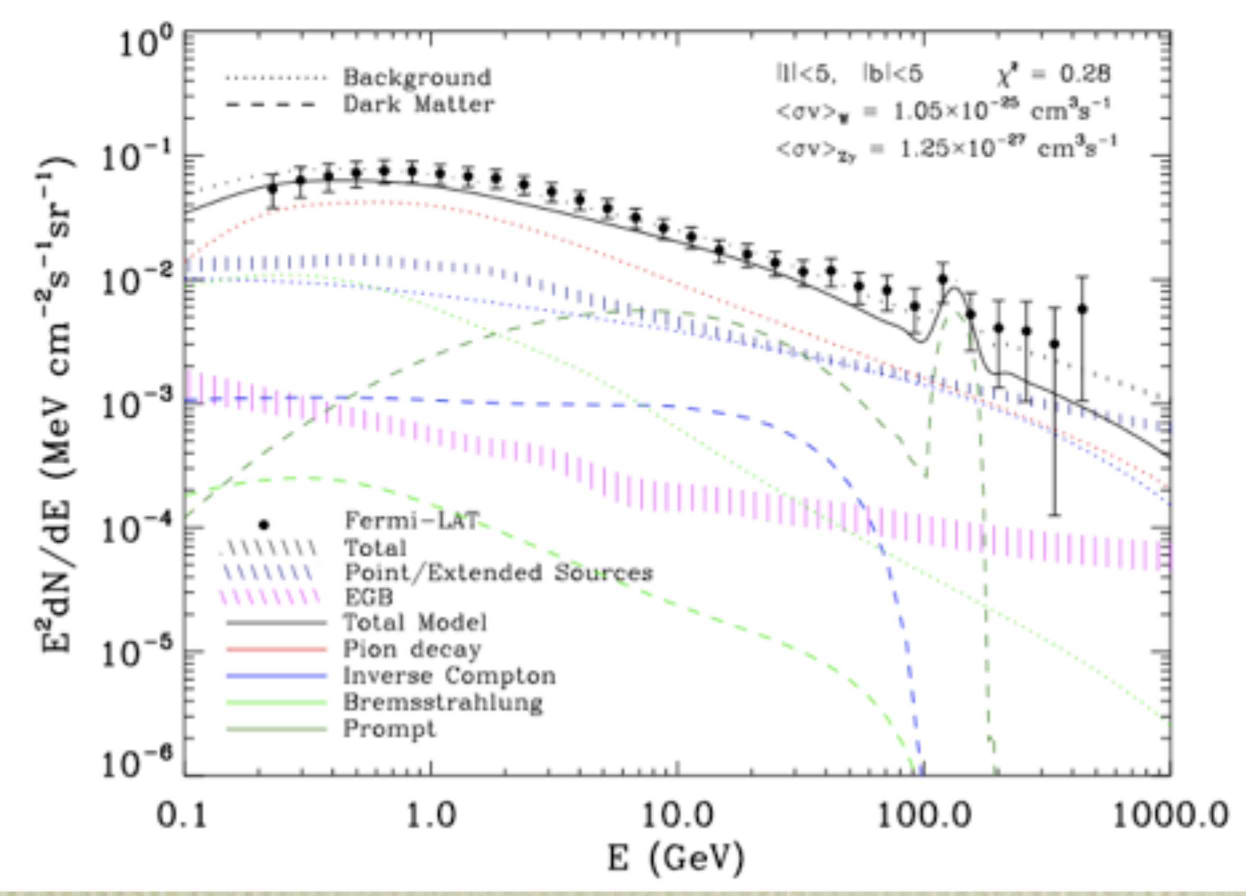


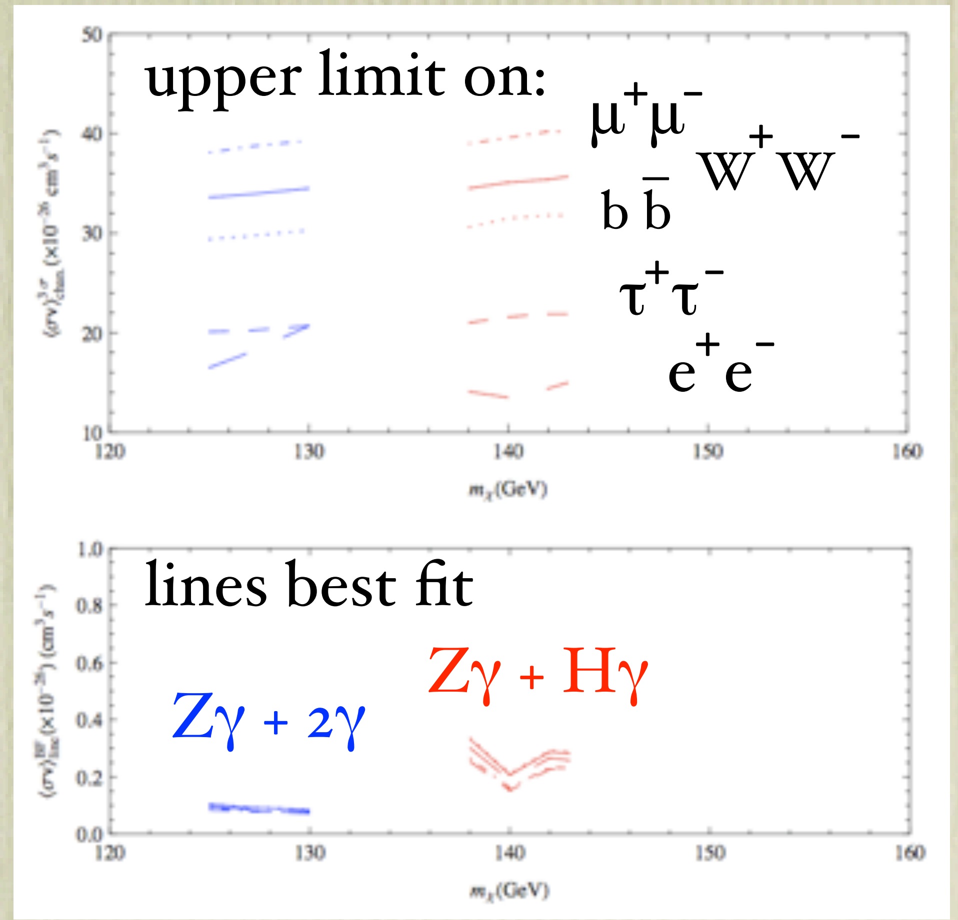
Local 3.3σ corresponding to only a global 1.5σ

Excesses in FERMI γ-ray data ???

A **monochromatic signal** + **continuum counterpart** in a model with physical background: Cholis, Tavakoli & P.U., arXiv:1207.1468

Sample model fitting the data:





A fit with several degeneracies, given the many components in the fit: Diffuse emission + point sources + DM component

Significantly away from the typical 1-loop over tree-level ratio: definite guideline for the DM model?

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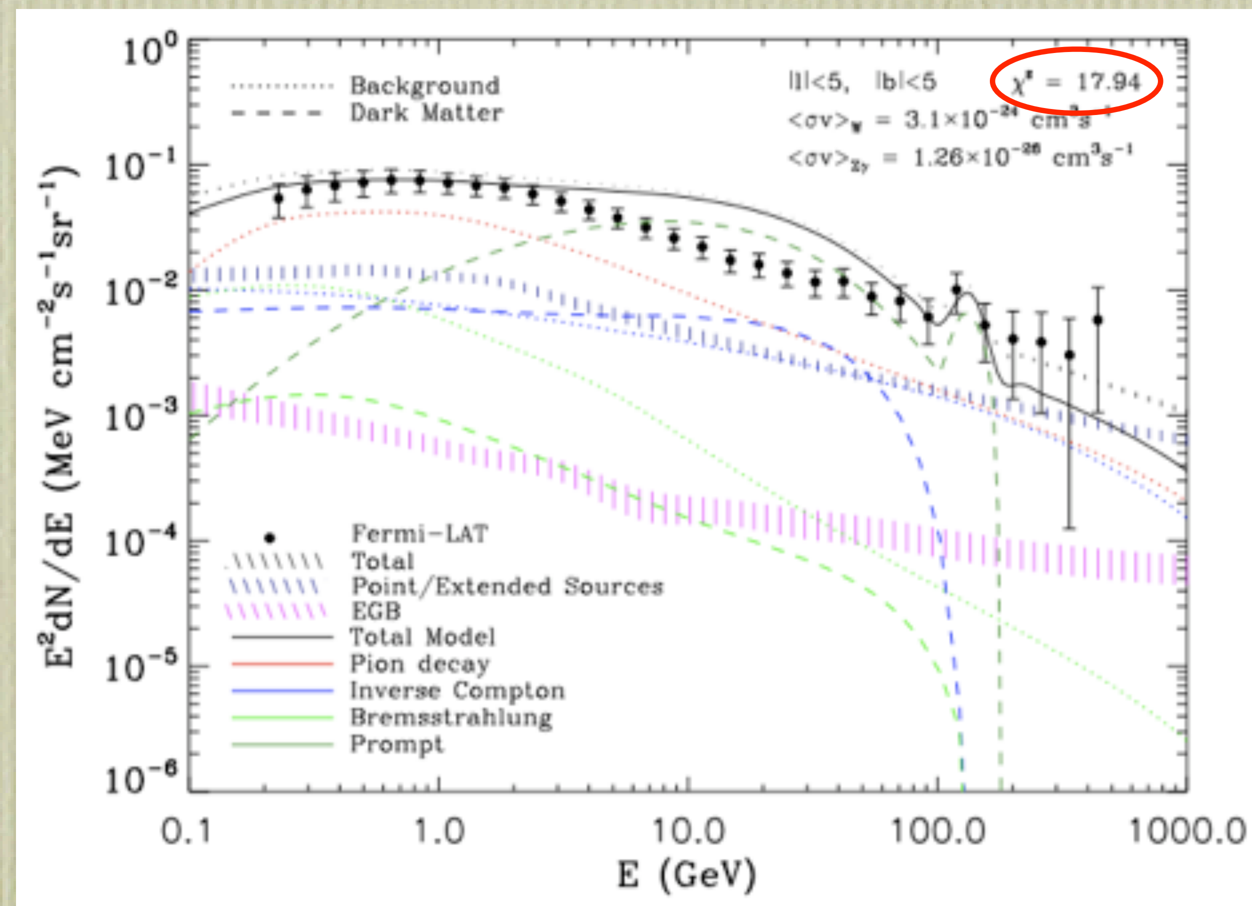

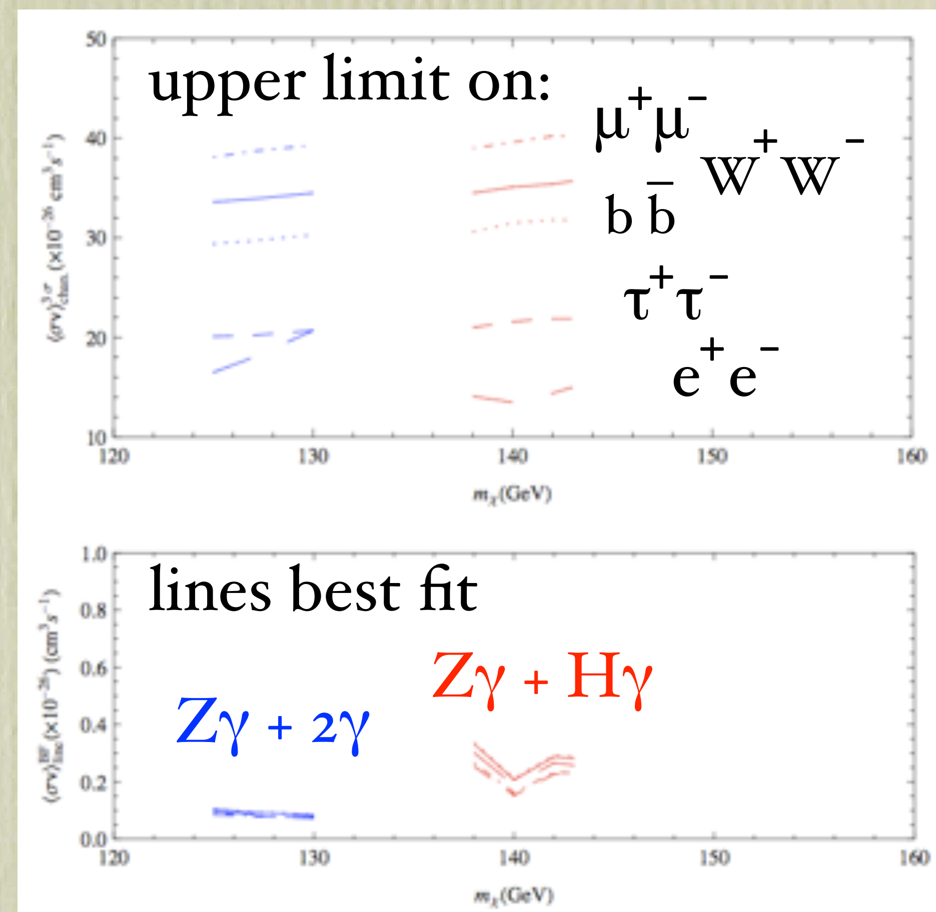

Wino model (with given correlation between Zγ & WW) excluded, as for most MSSM setups

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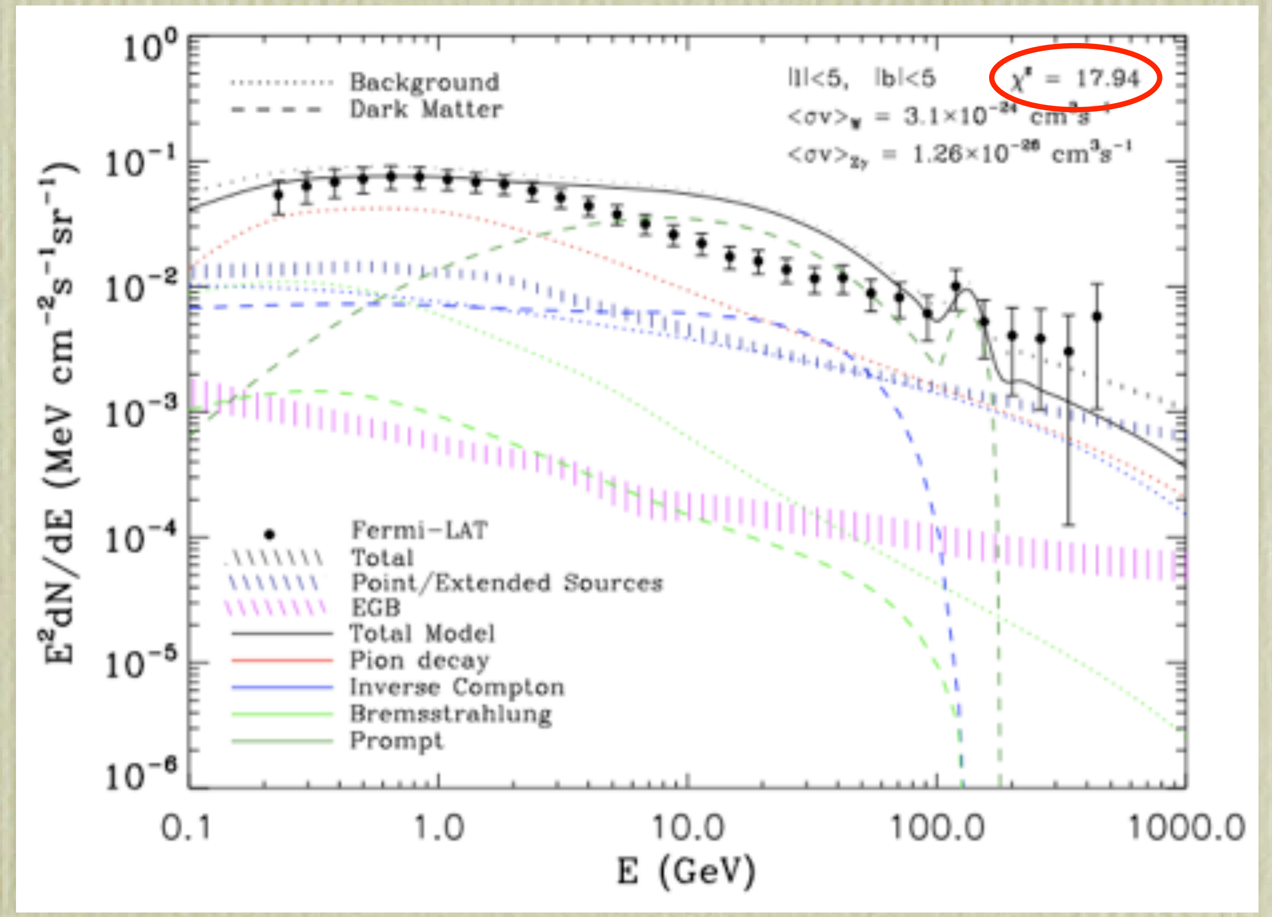

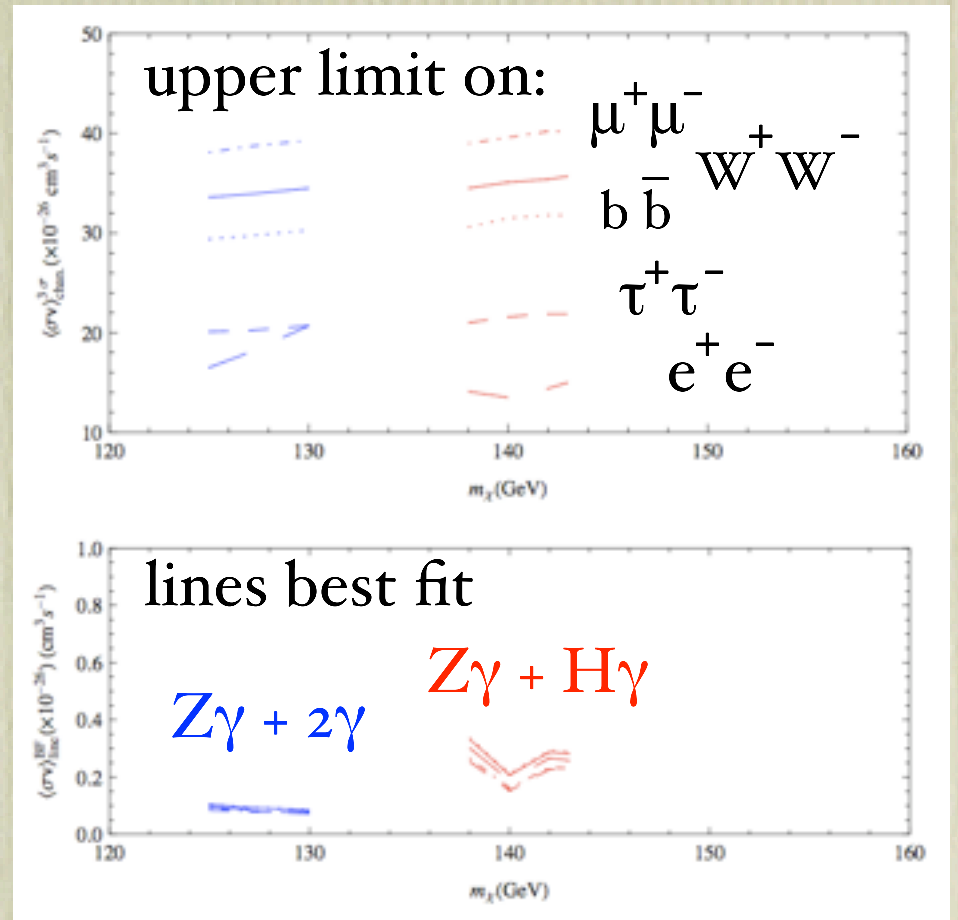

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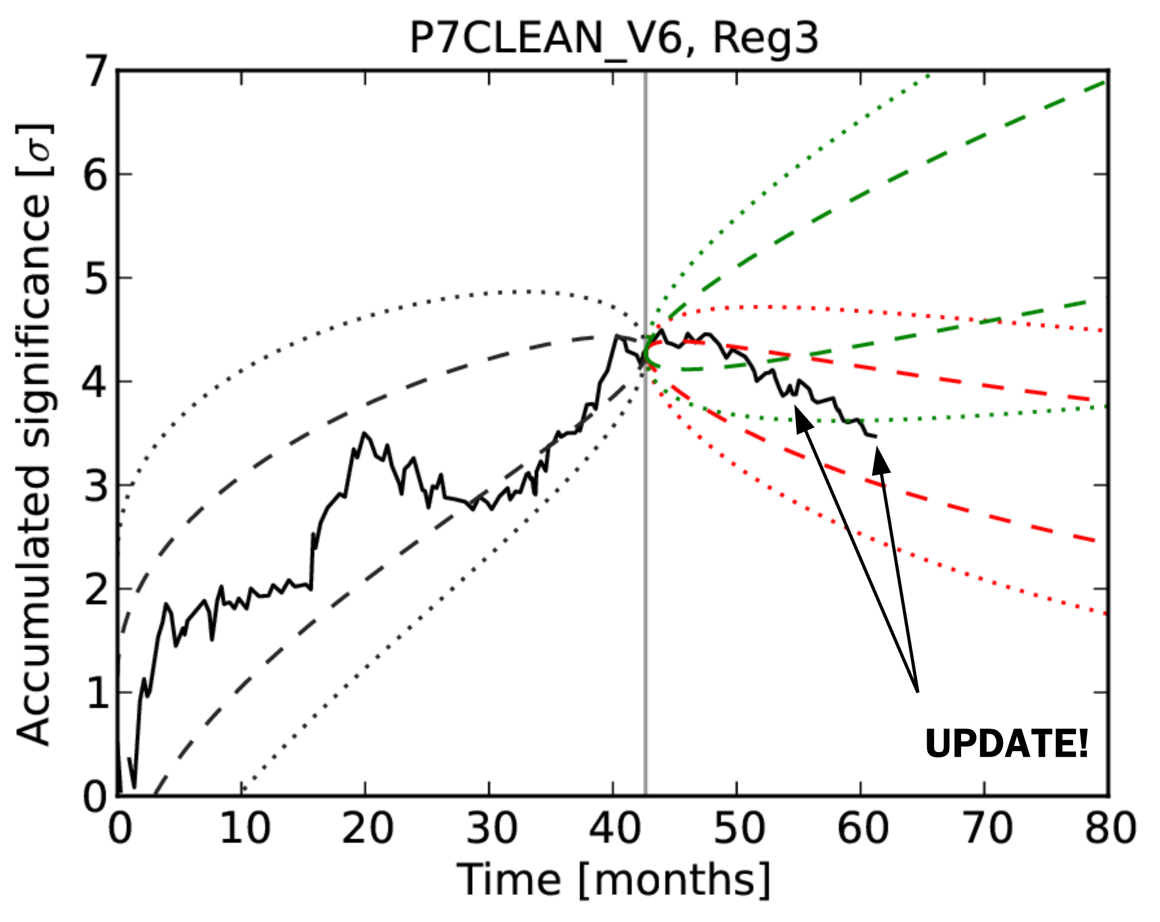
There are models for which it was predicted that the 1-loop should dominate, see, e.g. the LIMP model, Bergström, 2012

A γ-ray line at 130 GeV in FERMI data ???

Other puzzles: about a 3σ evidence for a 130 GeV line in low-incidence-angle Earth limb data (Finkbeiner et al. & Hektor et al., 2012; Fermi Coll., arXiv: 1305.5597) and within 5° from the position of the Sun (Whiteson 2013)!

Evolution of the effect in time (Weniger 2013):

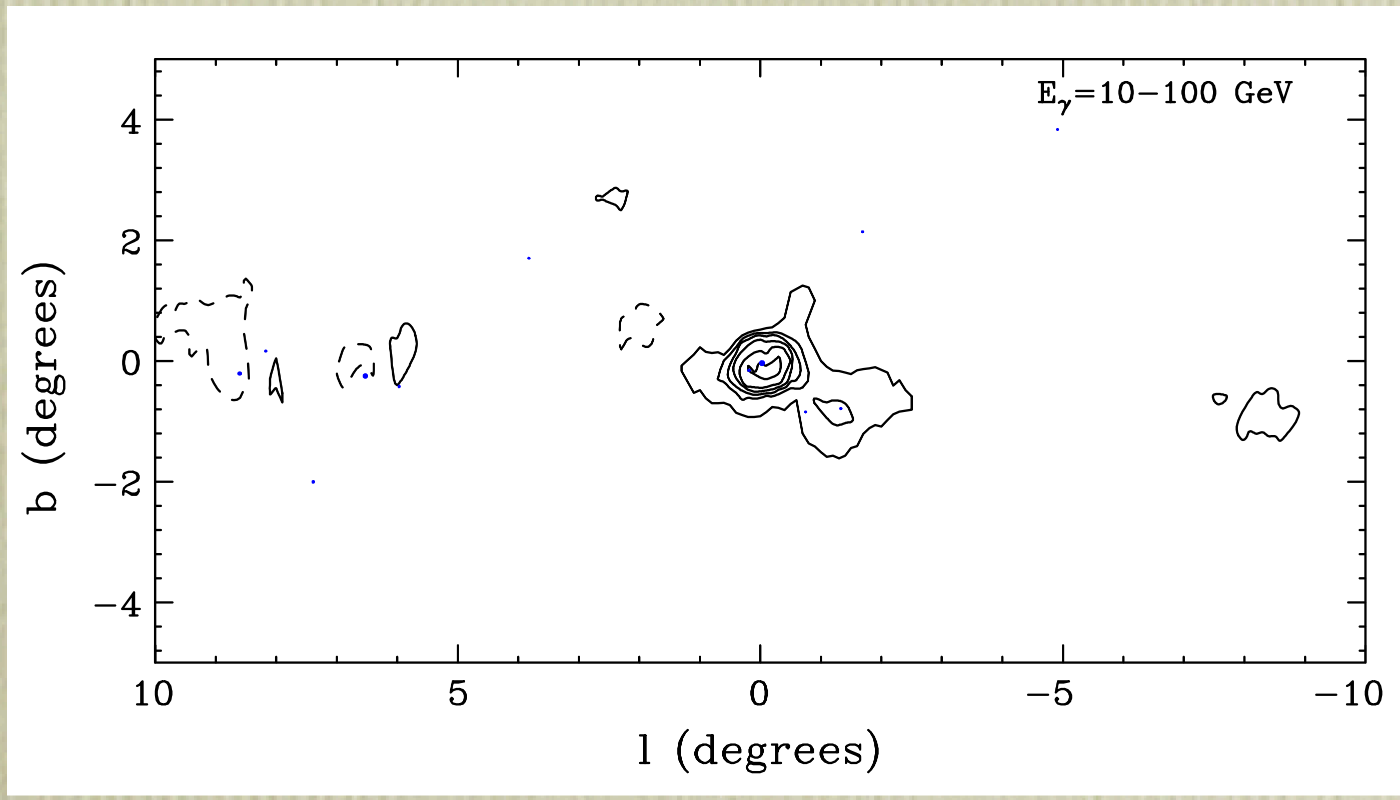


Dashed/dotted lines:
68% and 95% CL containment regions for **real signal** and **statistical fluke**.

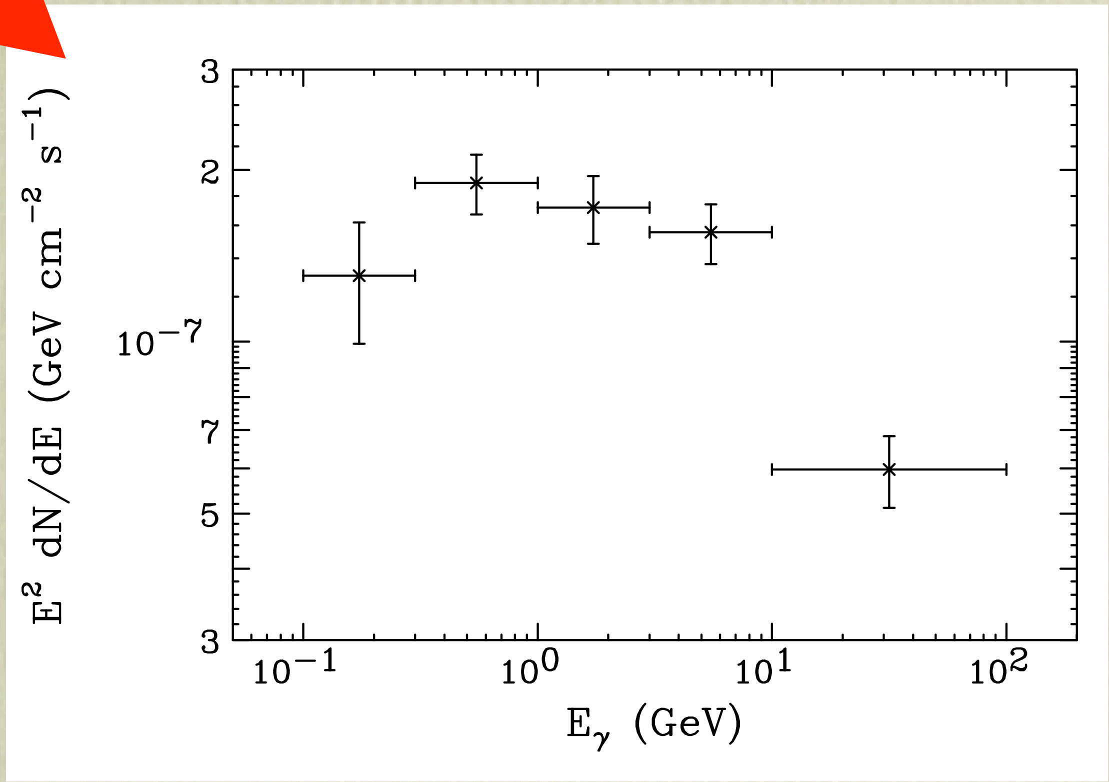
Fermi modified survey strategy to address the issue on a shorter timescale. The effect as initially claimed possibly confirmed by HESS II at 5σ for systematics under control (Bergström et al. 2012) and detected at 5σ in 10 months by the proposed Gamma-400 (launch in 2018?)

A γ-ray excess at ~ GeV energies towards the GC ???

Morphology signature, connected to the enhancement in DM density towards the Galactic center to trace the presence of a DM γ-ray term with continuum energy spectrum: Hooper & Linden, 1110.0006 (building up from 0910.2998 and 1010.2752) take the diffuse emission map from **Fermi** (pass 7, ultraclean), subtract point sources (2-yr Fermi catalogue) and a model for diffuse emission, finding a residual at the level of 10% of the intensity:



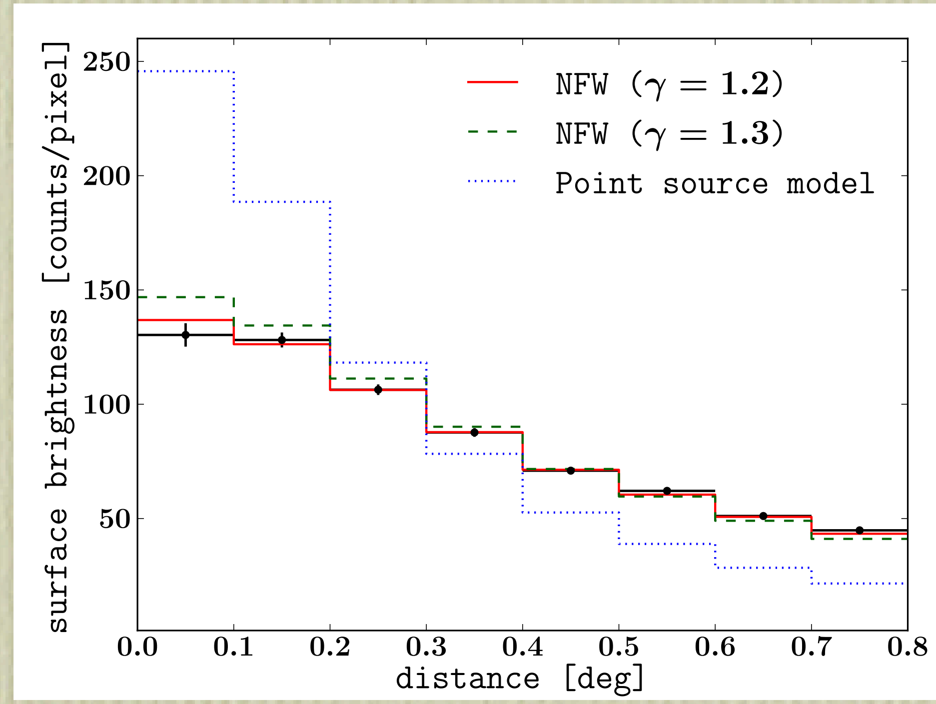
consistent with $\rho_{DM} \propto r^{-1.3}$, e.g. from N-body result $\rho_{NFW} \propto r^{-1}$ + mild adiabatic contraction from baryon infall



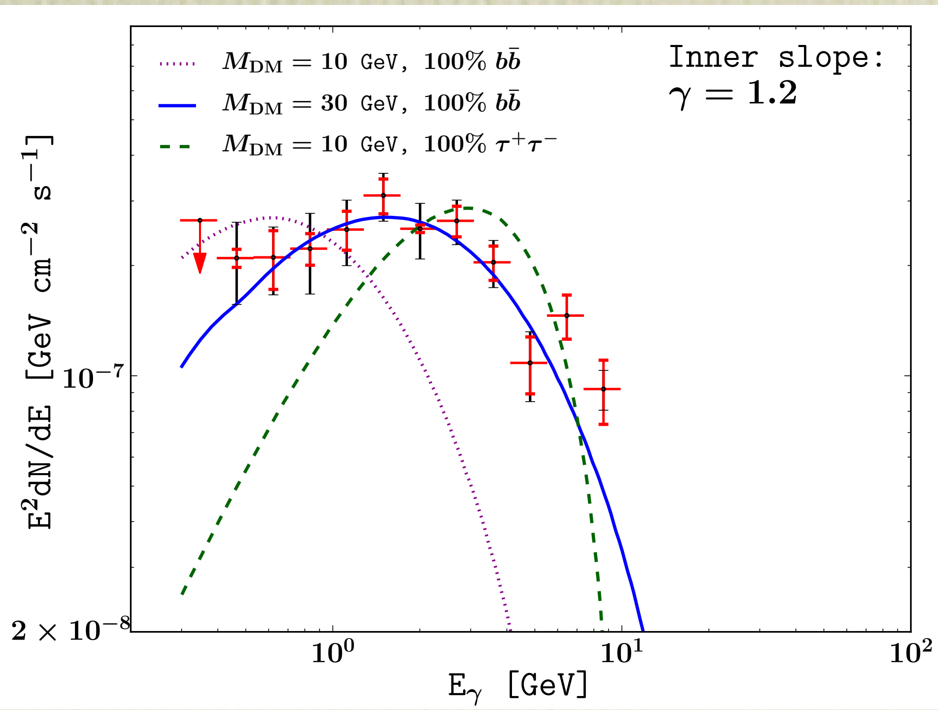
Spectrum with ~ 10 GeV cutoff

A γ-ray excess at ~ GeV energies towards the GC ???

Result confirmed in other independent recent works, considering slightly different approaches to model the background, see Abazajian & Kaplinghat, 1207.6047 and Gordon & Macias, 1306.5725:

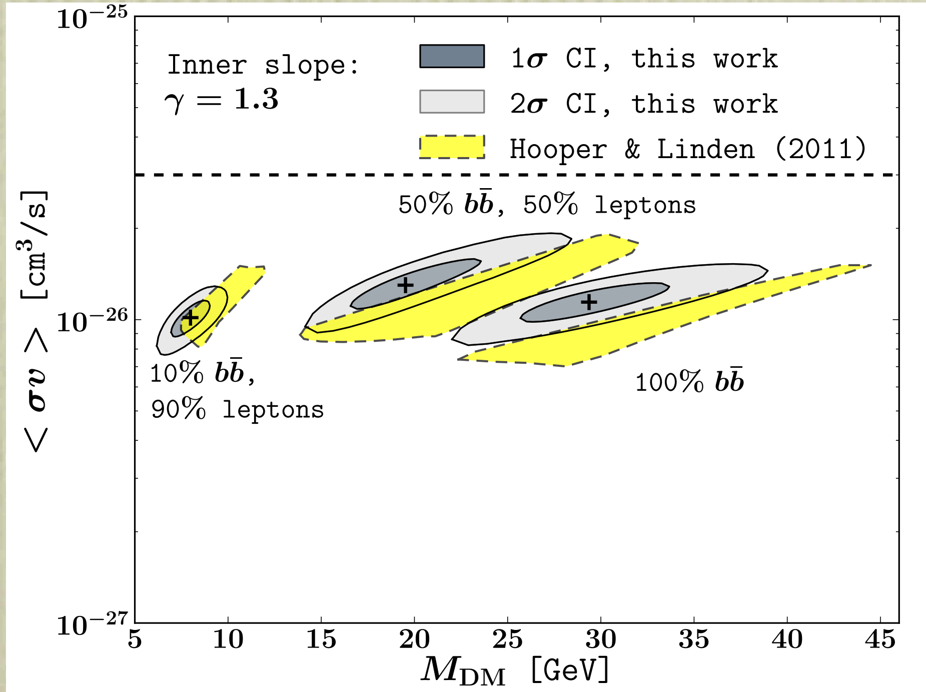


again cuspy profile, not point source



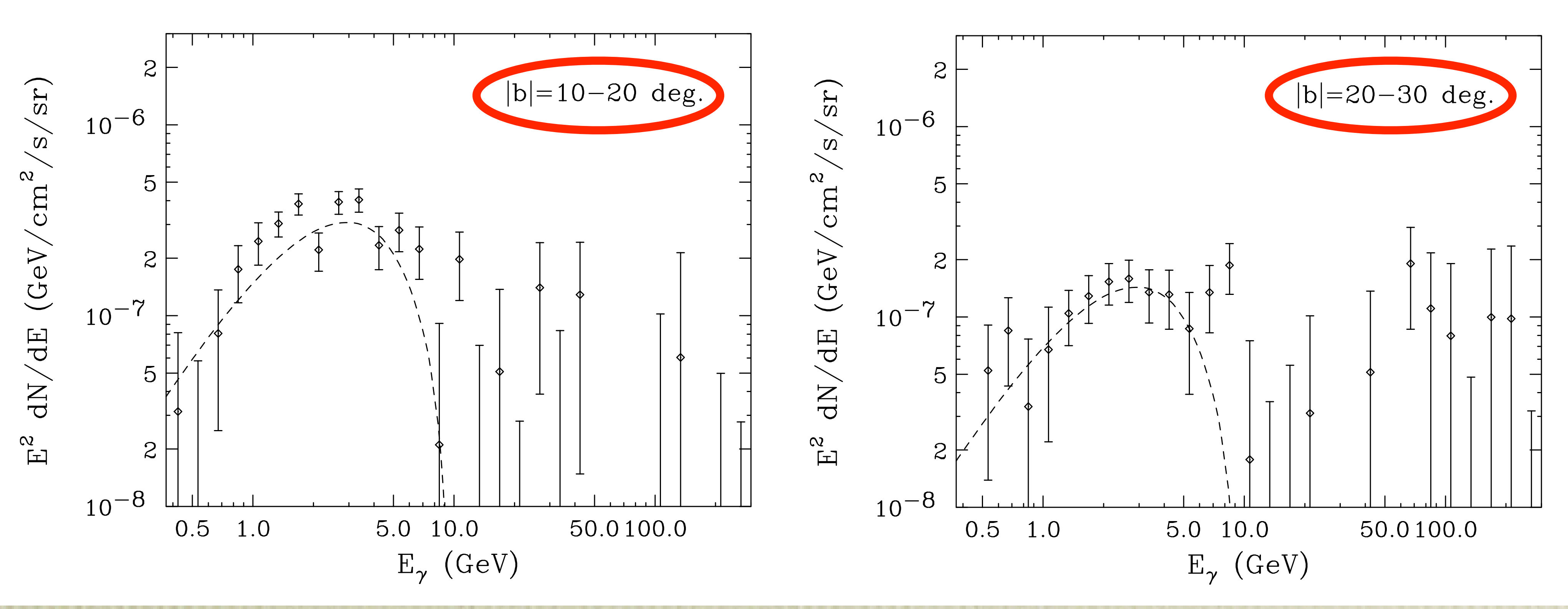
again a sharp cut-off

best fit with WIMP annihilations into b-quarks or leptons or a combination



A γ-ray excess at ~ GeV energies towards the GC ???

Residuals searched for and found also in different parts of the sky; in particular Hooper & Slatyer, 1302.6589 find consistent energy spectrum and morphology at slightly higher latitudes, in the Fermi bubbles region, where assumptions on the background needs to be different, but still very uncertain (see also results from Huang et al., 1307.6862):



$\rho_{\rm DM} \propto r^{-1.2}$

$M_\chi = 10$ GeV

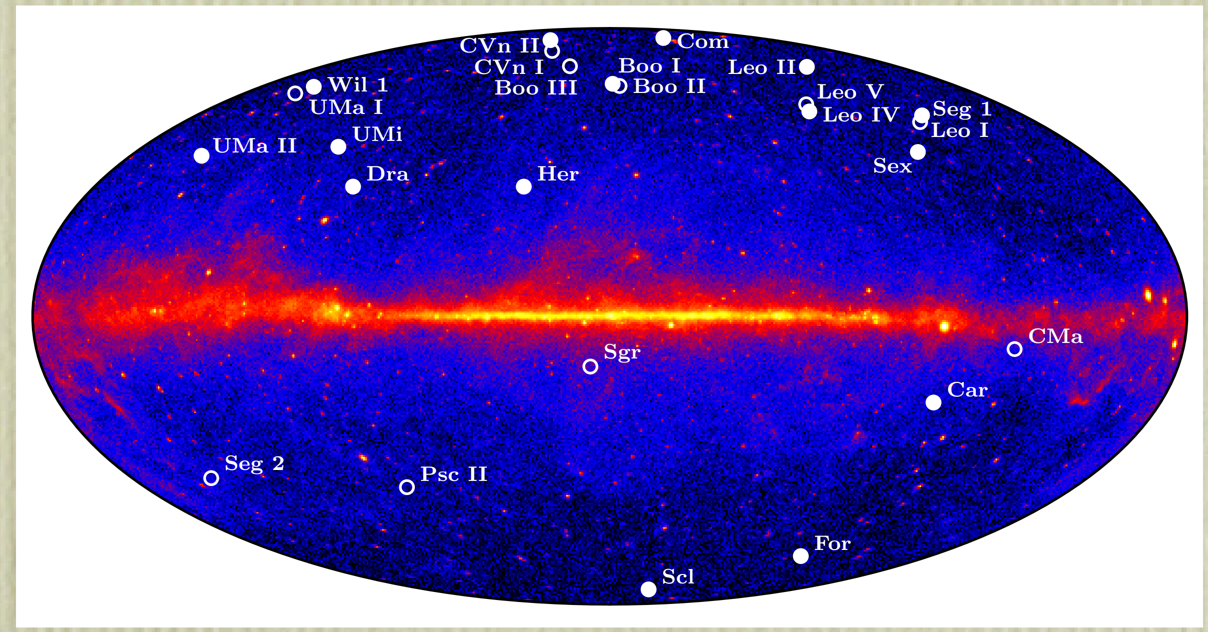
$\tau^+\tau^-$

final state

Hooper, Cholis et al., 1302.6589 show that this is inconsistent with an unresolved population of millisecond pulsars (MSPs) with the same spectral features as those measured by Fermi for MSPs in the sun neighborhood. The Fermi coll. has not produced an official statement so far (preliminary results with an indication of an excess where given in 0912.3828).

Searches for a γ-ray flux from MW dwarf satellites

Signature: identify a γ-ray signal from objects which are DM dominated, have gas and plasma components below detectable levels and hence a very low internal contamination from standard astrophysical backgrounds. Unfortunately there no dwarf is "bright" in γ-rays: upper limits from null detections, from, e.g., Hess (1012.5602), and most recently Fermi (1310.0828):



the 25 dwarfs discovered so far

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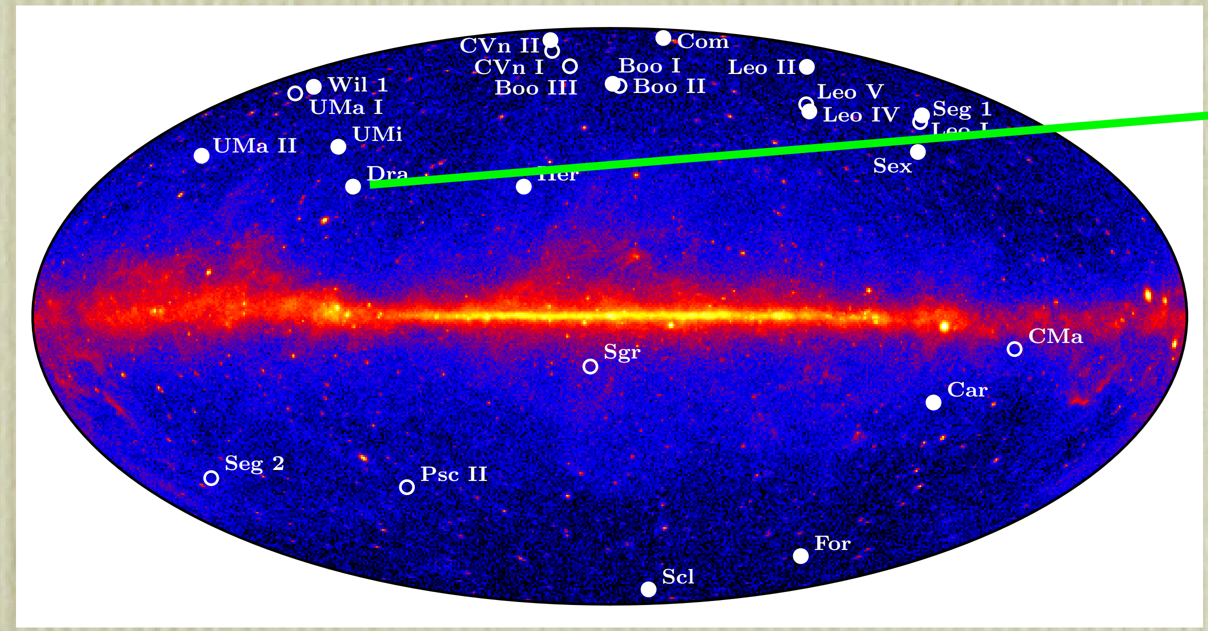
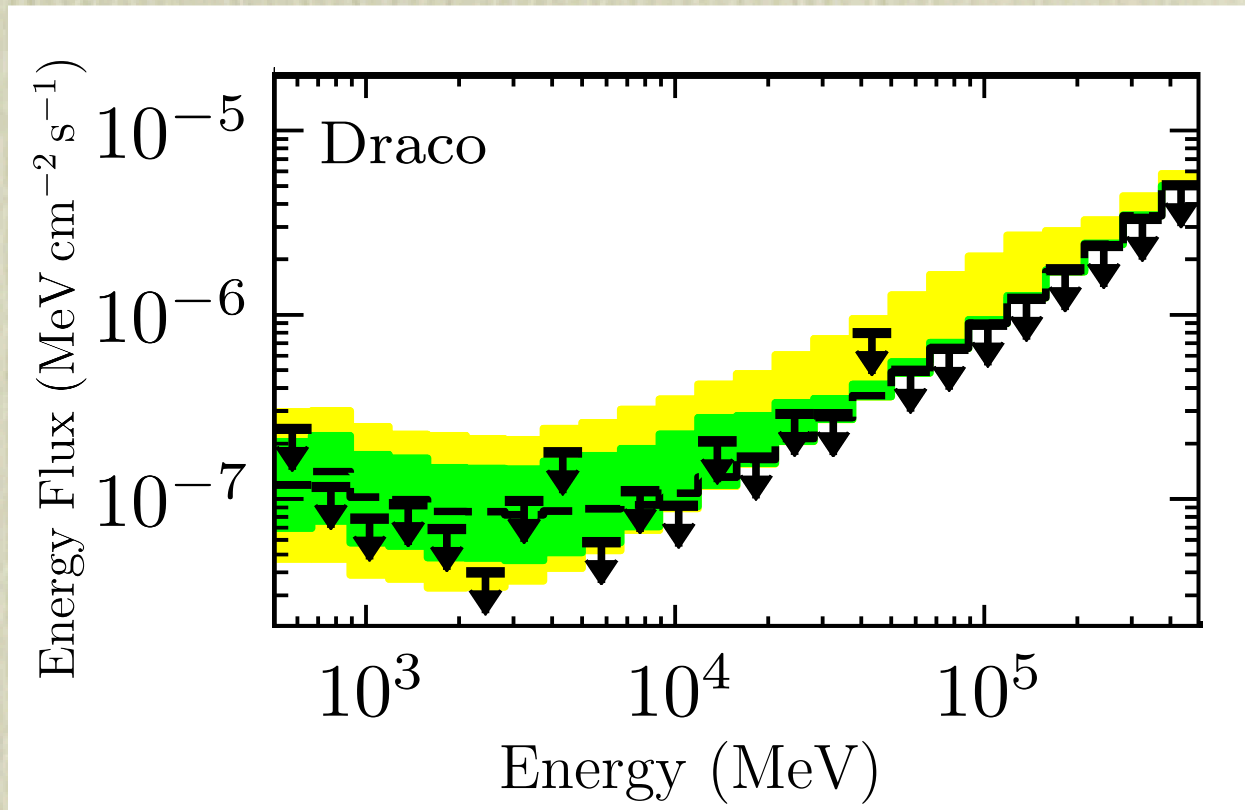


the 25 dwarfs discovered so far



bin-by-bin energy flux limits and expected sensitivities from 500 MeV to 500 GeV & 4 yrs of LAT data

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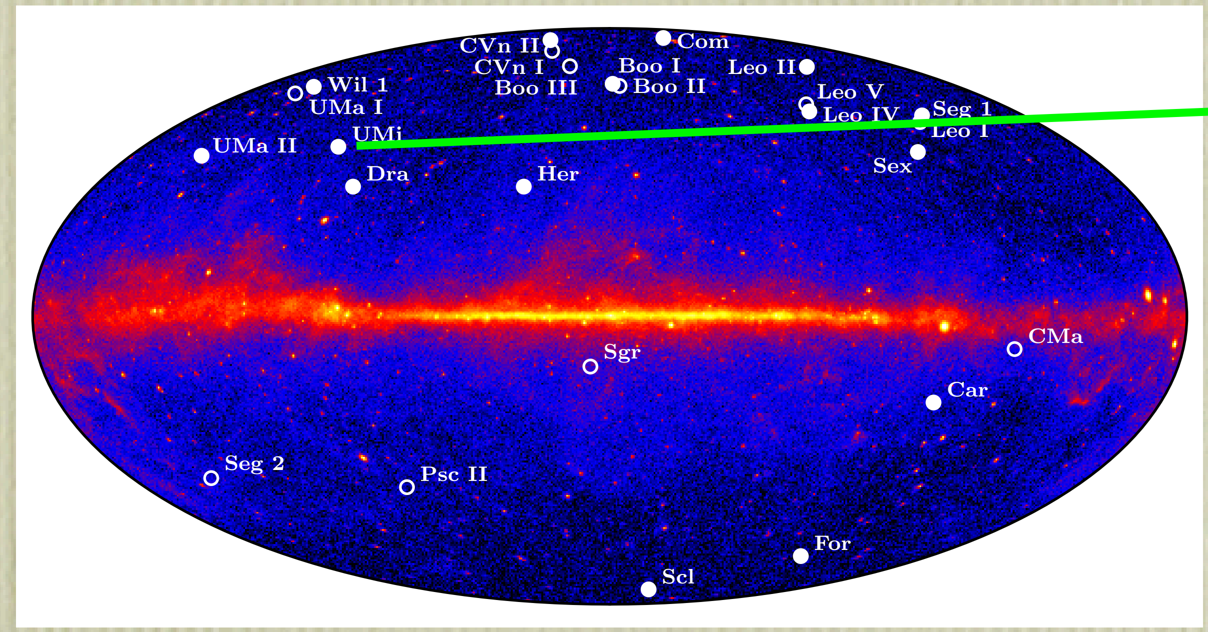

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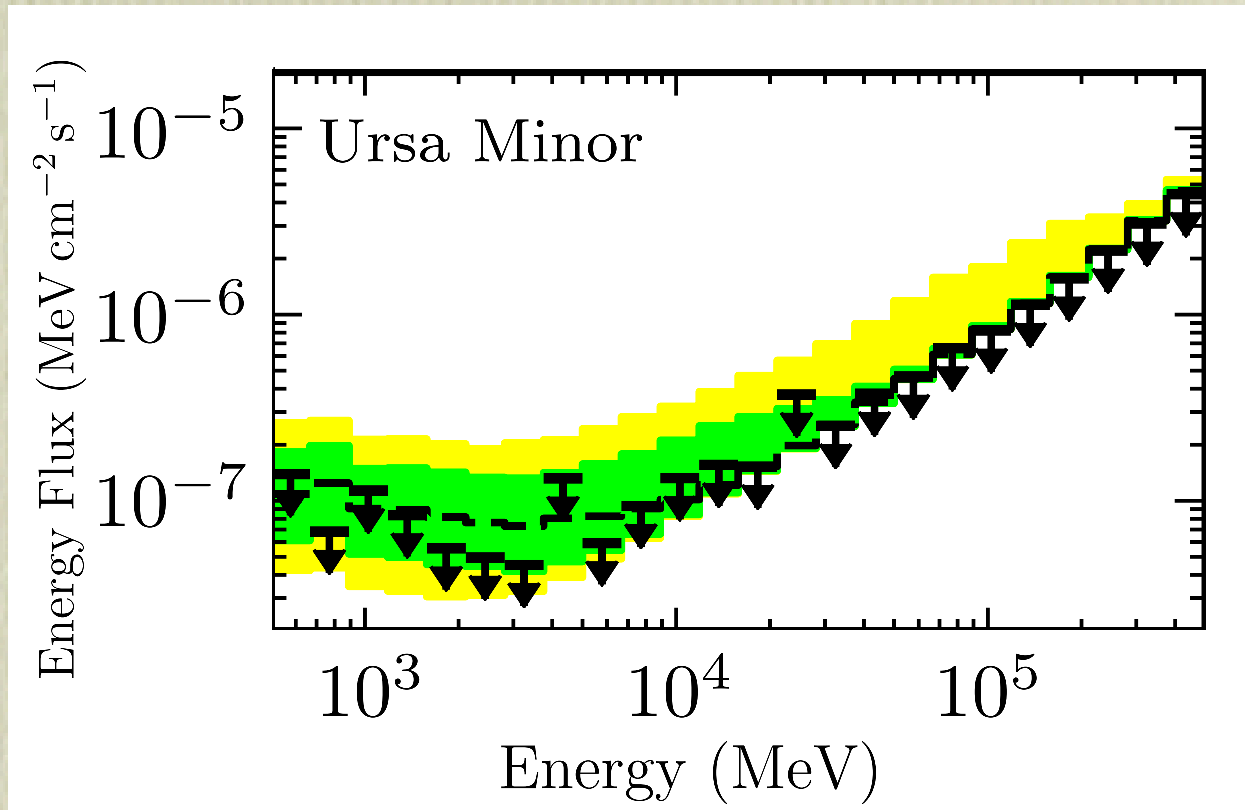

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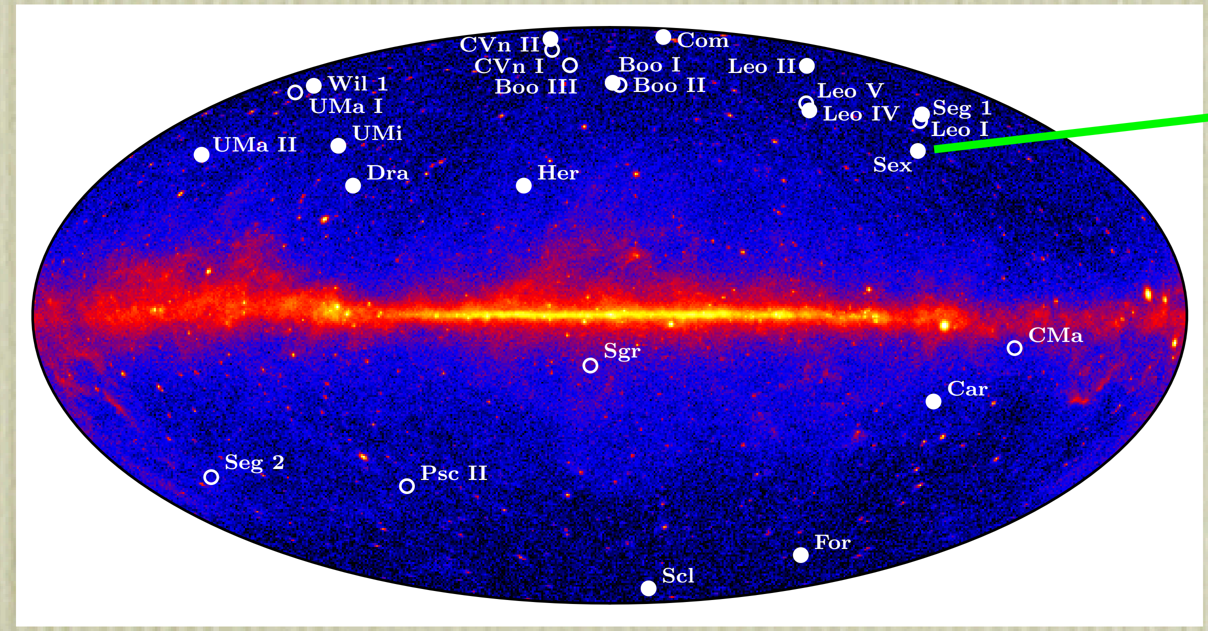

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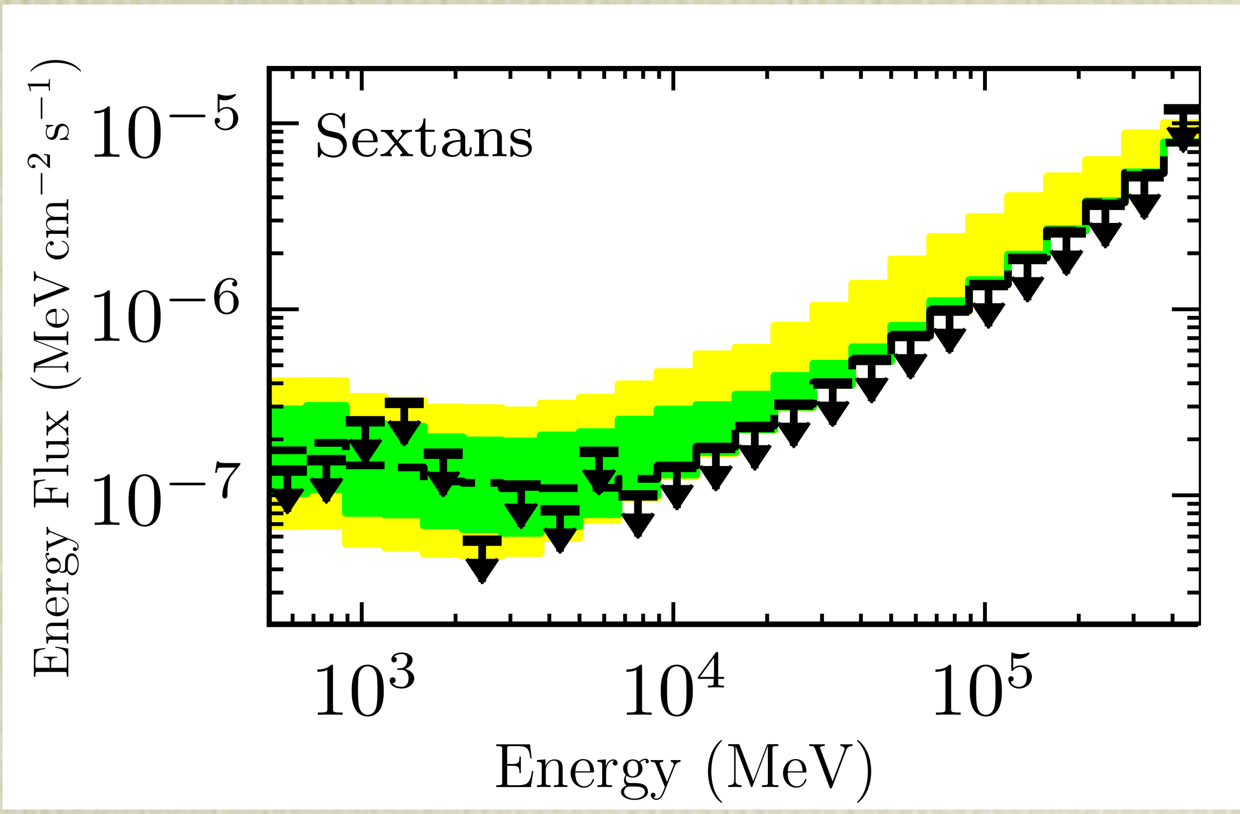

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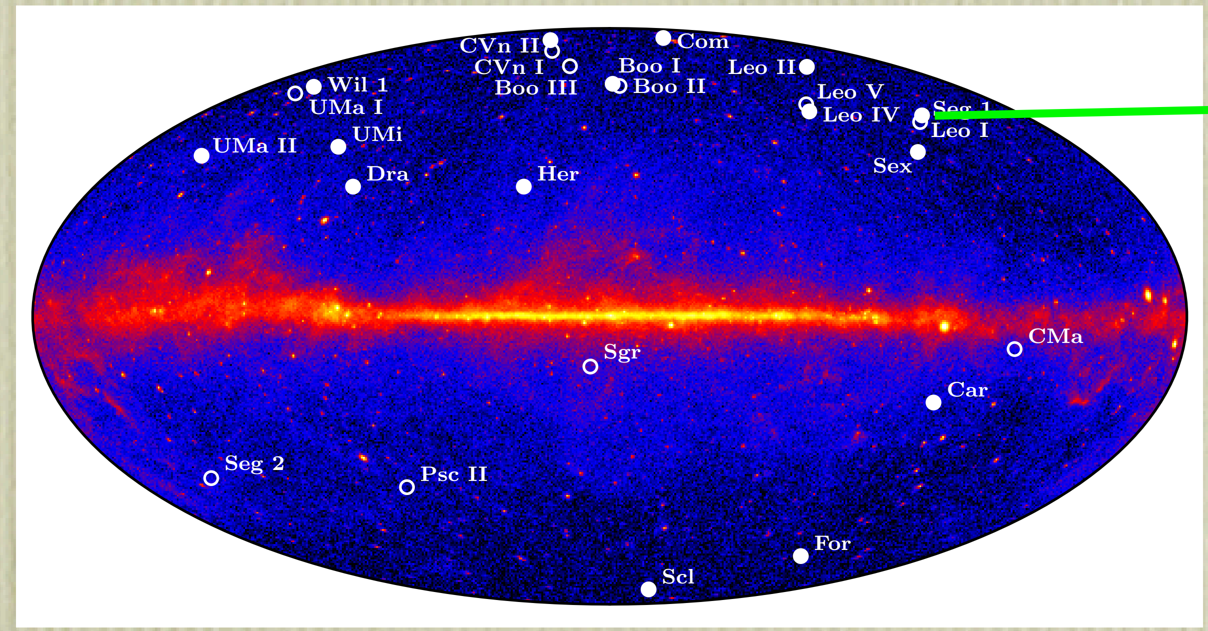

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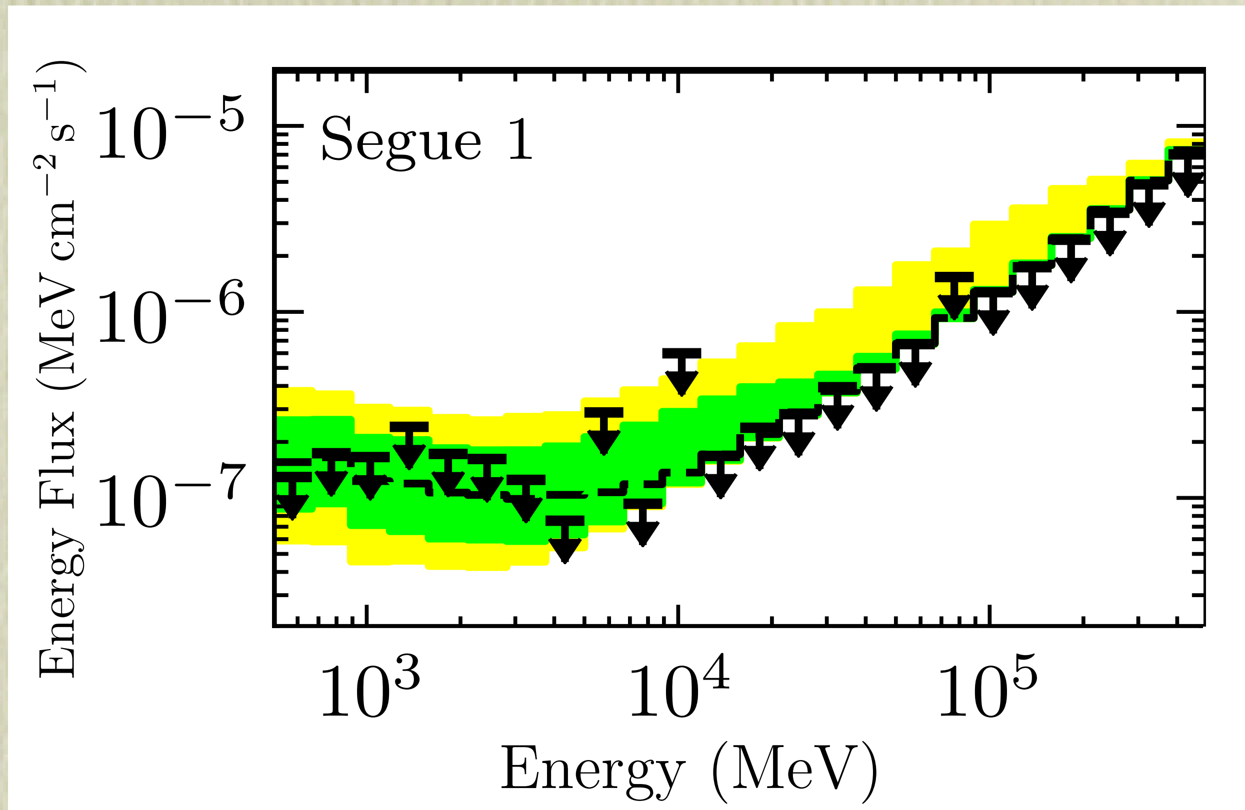

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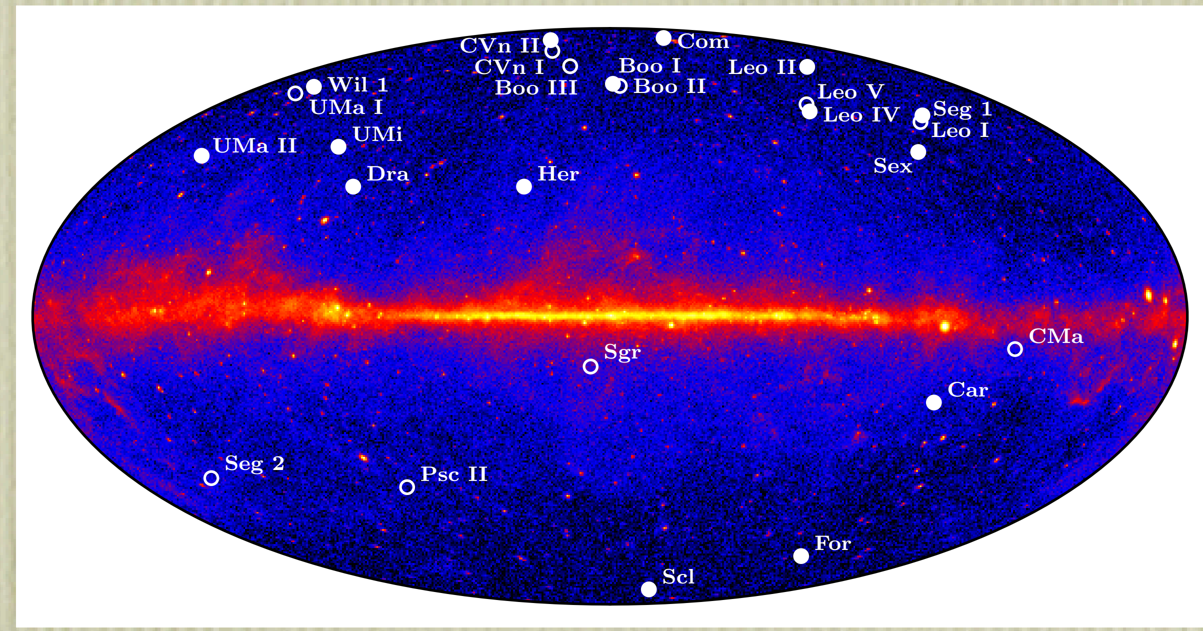

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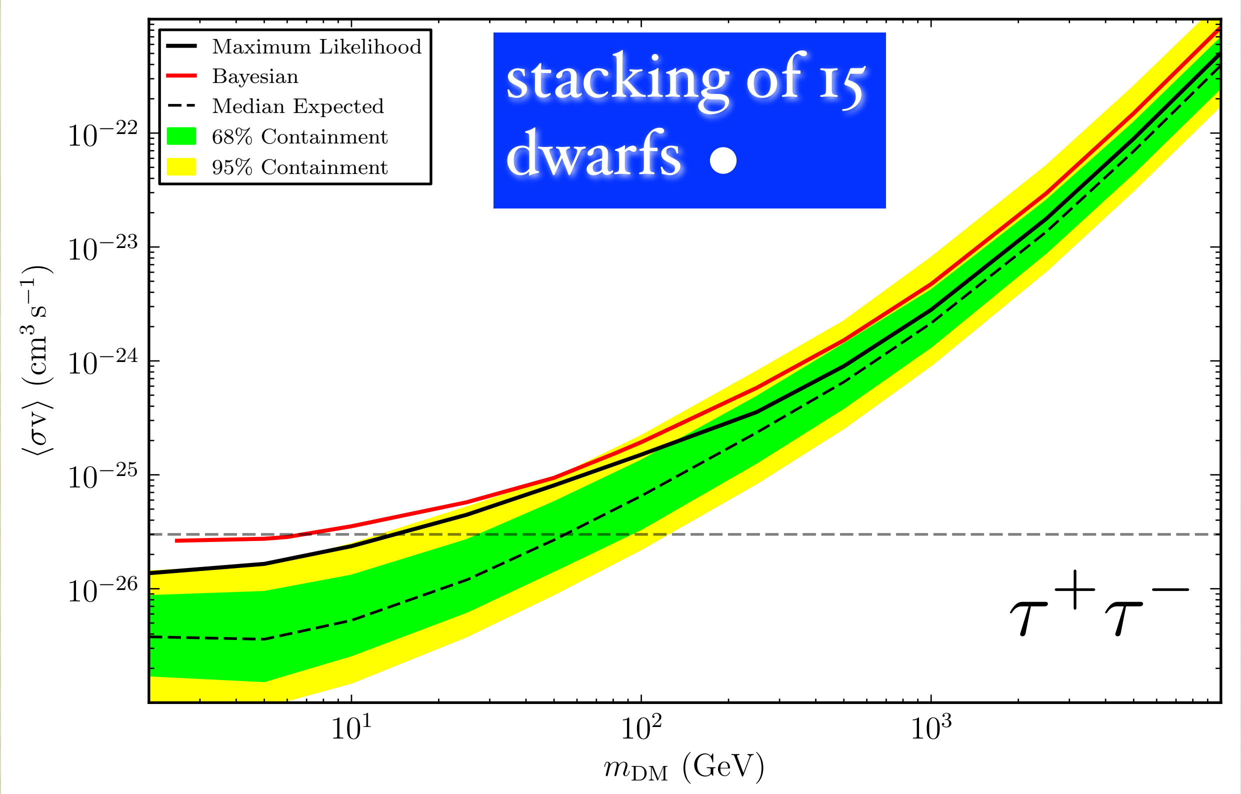
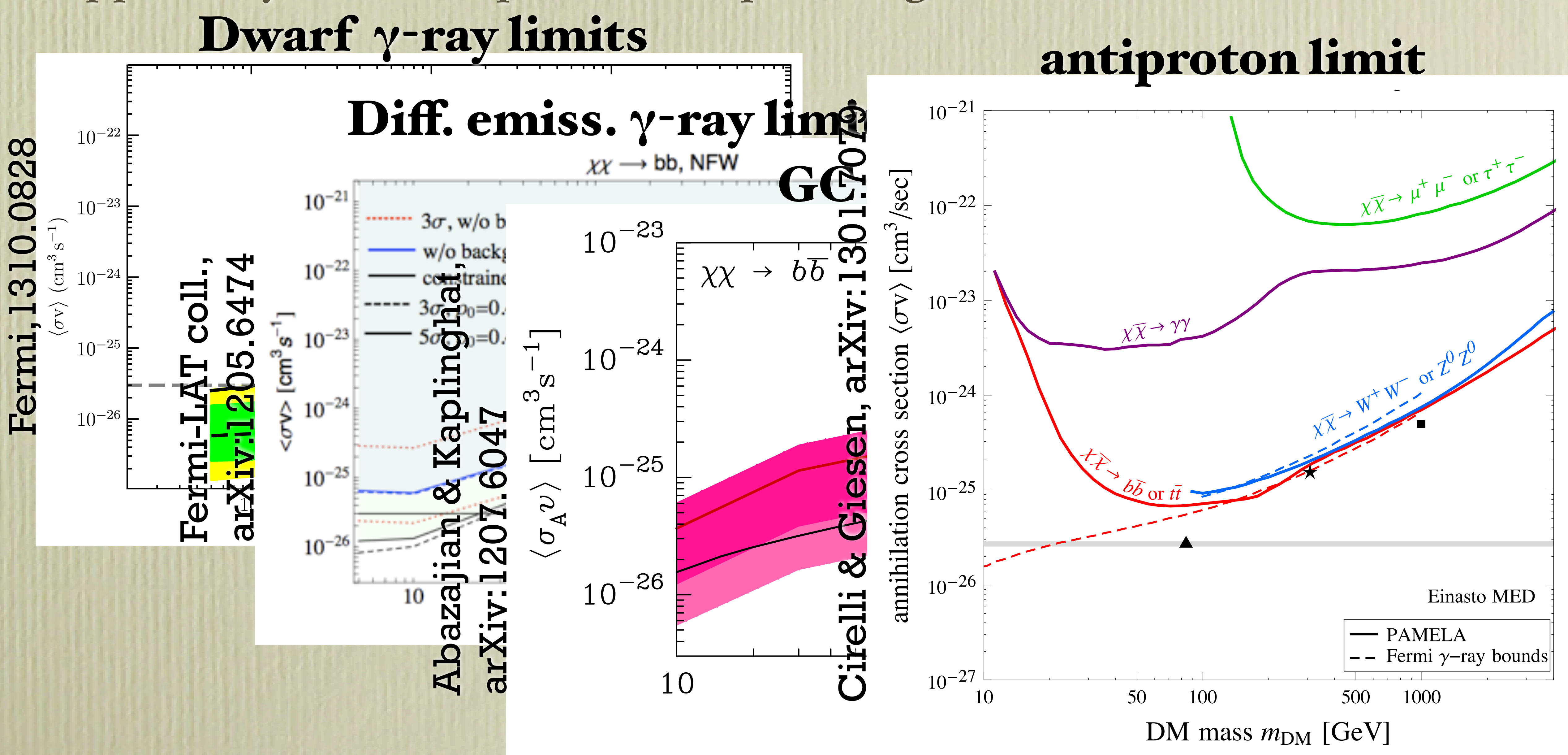


For this limit you need to assume a dynamical model for the tracer stellar population and a density profile for the DM; a number of simplifying assumptions implemented. Slightly weaker limits than in the previous analysis (1108.3546) on 10 dwarfs; still touching thermal DM candidates.

Multi-messenger & -source indirect detection

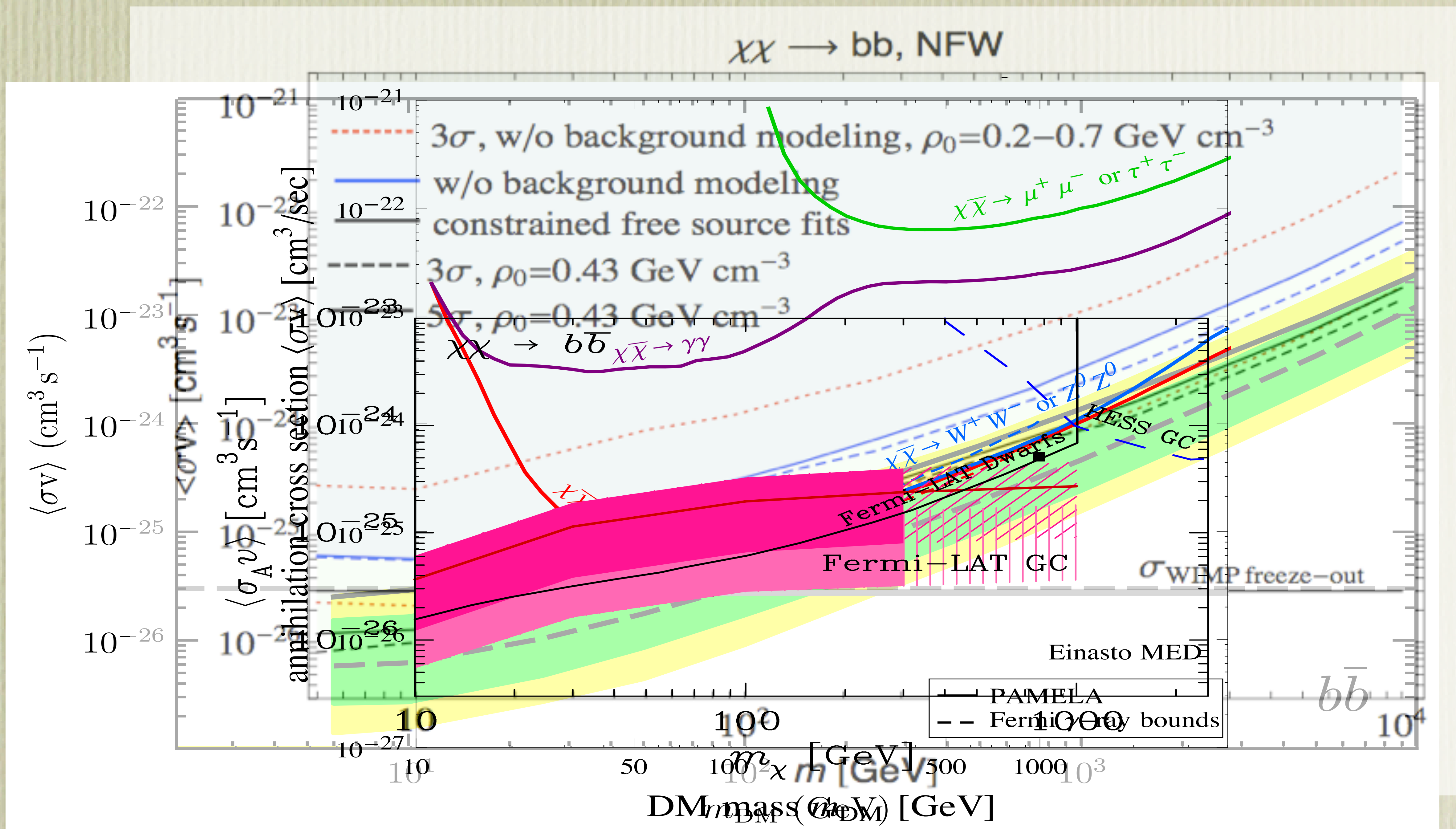
If Nature has not been kind enough to provide a smoking-gun signature, one is forced to play the delicate game of combining informations from different messengers and different targets. We are in a sort of golden age in this respect, given the wealth of techniques and the wealth of data!

Outcome so far: a wealth of null (or ambiguous) results to be projected in an apparently the same parameter space. E.g.:



Multi-messenger & -source indirect detection

How to compare and/or combine? It's tempting just to put one on top of the other:



Tempting, but probably of vey little use...

Multi-messenger & -source indirect detection

Most often results are presented in a format which does not even try to address the impact of underlying assumptions and/or uncertainties - in many examples it is just not possible to do it!

Face value comparisons may be then rather obscure to address and in some cases are even deceiving. A situation which is much worse than for face value comparisons among results from different direct detection experiments, which - given the apparent incompatibility between DAMA, CoGeNT, CDMS, ... signal "detections" & Xenon 100, ... null results - are always a source of vehement discussions.

In the final part of the talk some of these issues will be discussed, taking however a more modest view on this problem, namely considering one single physical process - DM WIMP annihilations in the halo of the Milky Way - and deriving the predictions for the different messengers in such process - antiprotons, leptons, γ-rays - in a single, coherent framework, to try to address how to make a direct comparison among them.

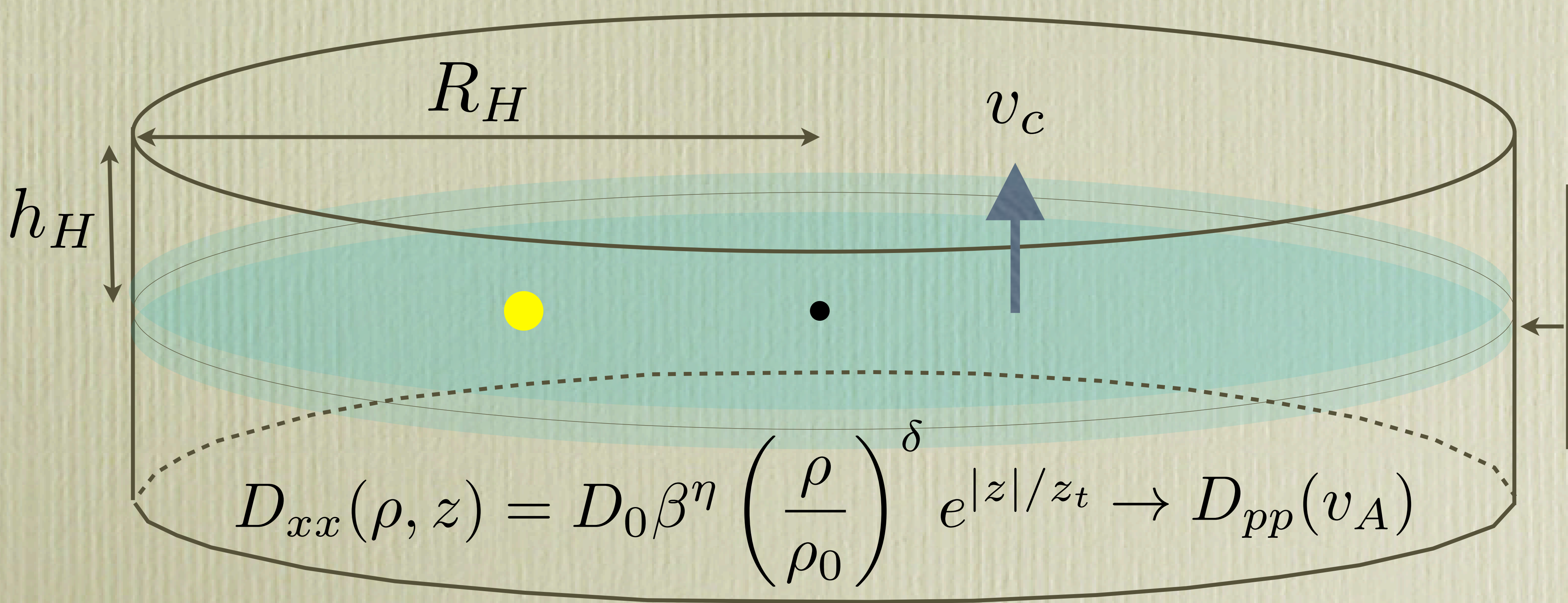
Charged particles in the Galaxy

A random walk (maybe with a preferred drift direction) 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 — convection — source — decay, fragmentation

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



primary CR sources [q(R) poorly known] & gas sourcing, via scattering with primaries, stable secondaries + e.g. pions $\rightarrow \gamma, e^-, e^+$

… disclaimer:

An effective approach, with no parameter derived from first principles, successful (flexible enough) in reproducing secondary to primary ratios (not the rise in positron fraction measured by Pamela/Fermi/AMS02: you need a primary positron component, or secondary positrons produced at sources).

Since it can works with secondary to primary ratios, use that to fix the effective parameters: great! … except that in this way you are arbitrarily imposing that global properties for diffusion in the Galaxy must reflect local measurements of secondary to primary ratios, mostly a probe of how the random walk on average works in a nearby region of the Galaxy, for fairly local sources sitting in a thin disk and as seen by an observer located within the disc itself (statement depending on species and energy).

There are well-known correlations patterns in the parameter space: e.g., you are not sensitive to the normalization of the diffusion coefficient D_0 and the scale height z_t (roughly speaking the scale height of the turbulent component of the magnetic field in the Galaxy) but only to $D_0 \,/\, z_t$

Even within this narrow alley, no way you can select the model univocally.

For example:

"reference" Krainchnan model

Model	z_t(kpc)	δ	$D_0(10^{28}\mathrm{cm}^2/\mathrm{s})$	η	v_A(km/s)	γ	dv_c/dz(km/s/kpc)	Color in Fig.s
KRA	4	0.50	2.64	−0.39	14.2	2.35	0	Red
KOL	4	0.33	4.46	1.	36.	1.78/2.45	0	Blue
THN	0.5	0.50	0.31	−0.27	11.6	2.35	0	Green
THK	10	0.50	4.75	−0.15	14.1	2.35	0	Orange
CON	4	0.6	0.97	1.	38.1	1.62/2.35	50	Gray

"thin" model

"thick" model

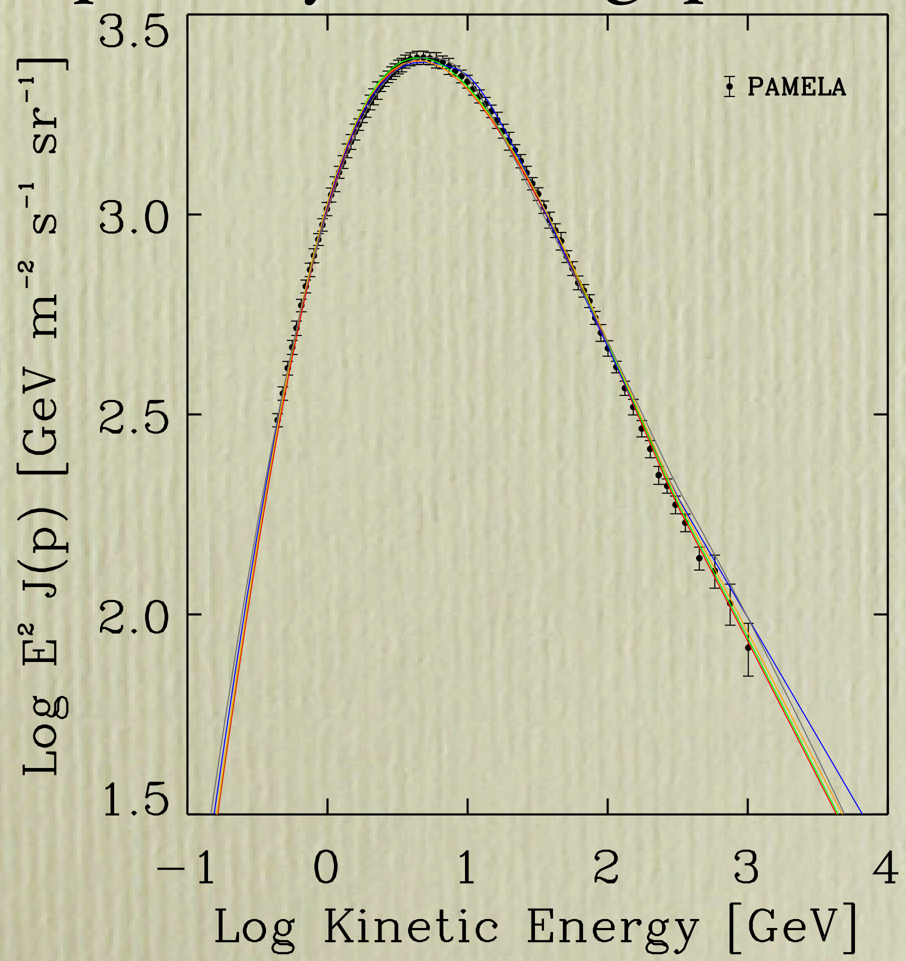
Kolmogorov model

"convective" model

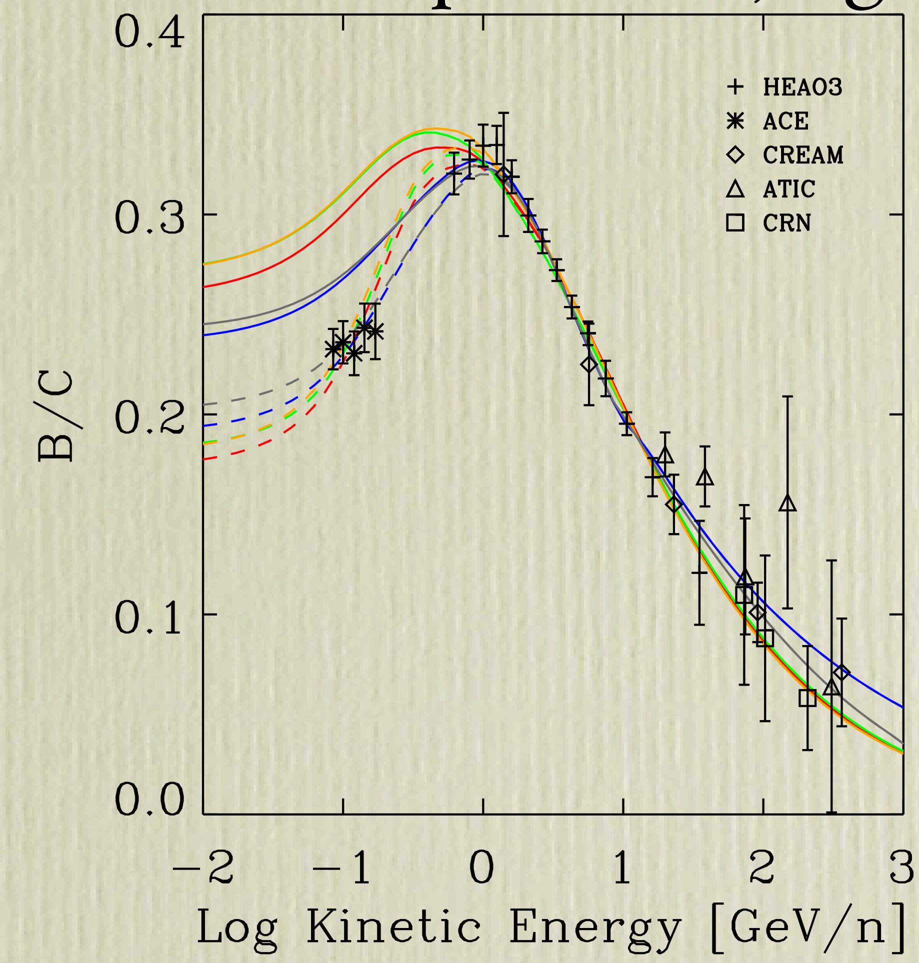
Evoli, Cholis, Grasso, Maccione & PU, arXiv:1108.0664

any of these is tuned to reproduce the local:

primary CRs, e.g. protons



secondaries/primaries, e.g. B/C



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"reference" Krainchan model

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"thin" model

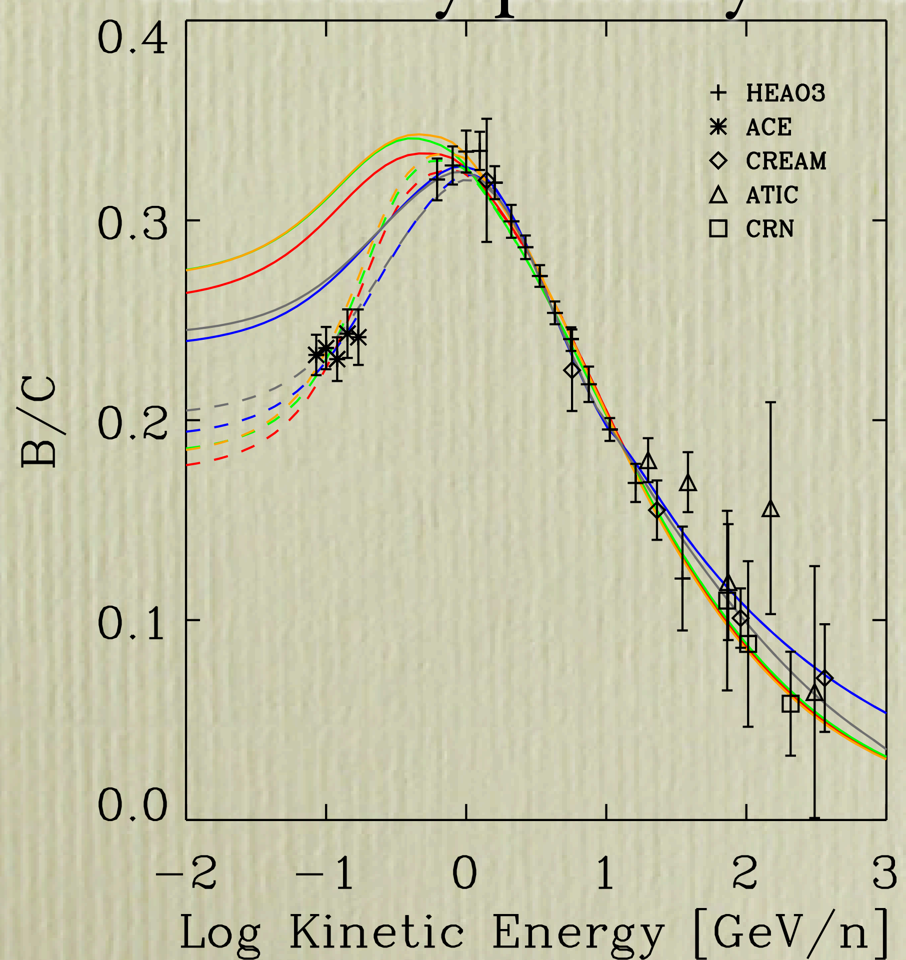
"thick" model

Kolmogorov model

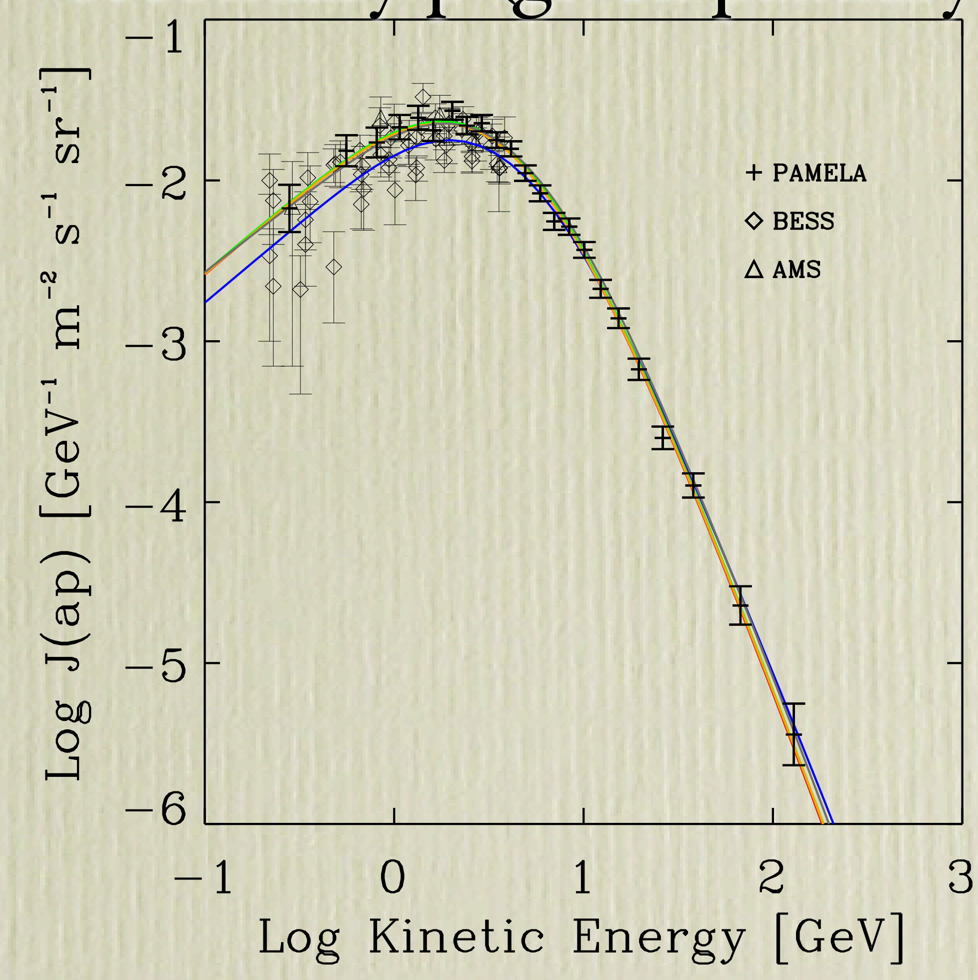
"convective" model

... and can be used to make a prediction for specular processes:

secondary/primary B/C



secondary $\bar{p}$ (given primary p)



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"reference" Krainchan model

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game with larger uncertainties... Am I stalled?

"thin" model

"thick" model

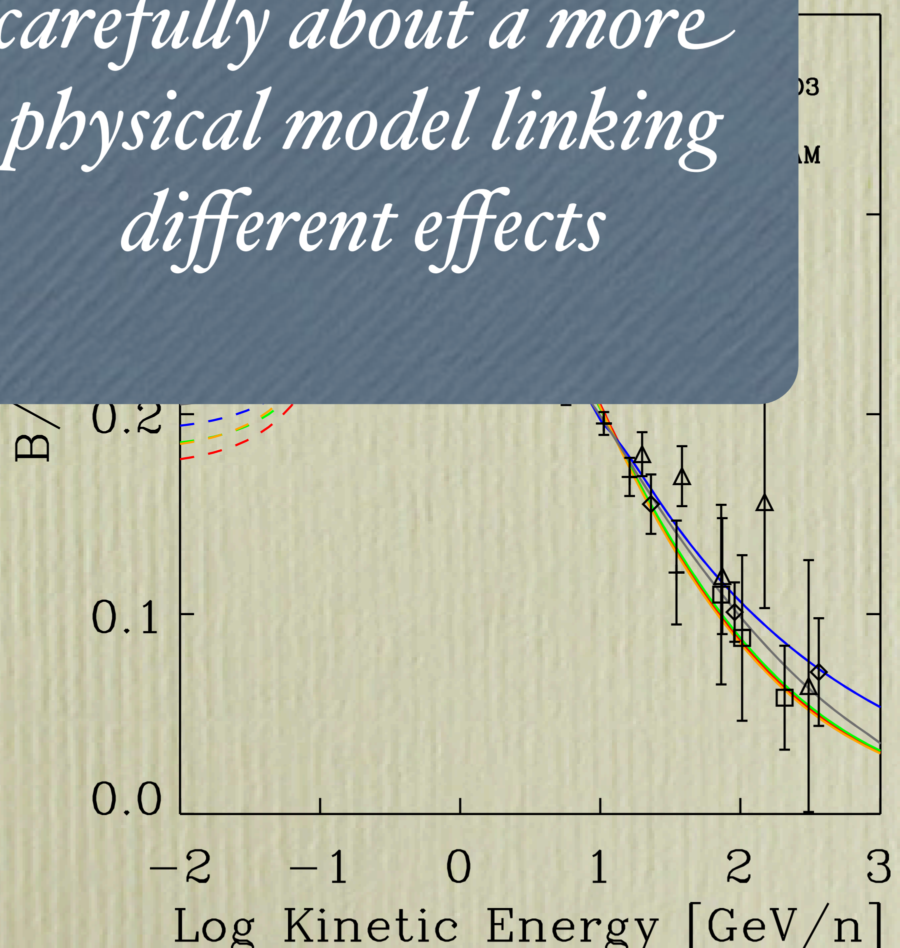
Kolmogorov model

"convective" model

… a prediction for specular processes:

stop and think more carefully about a more physical model linking different effects

B/C



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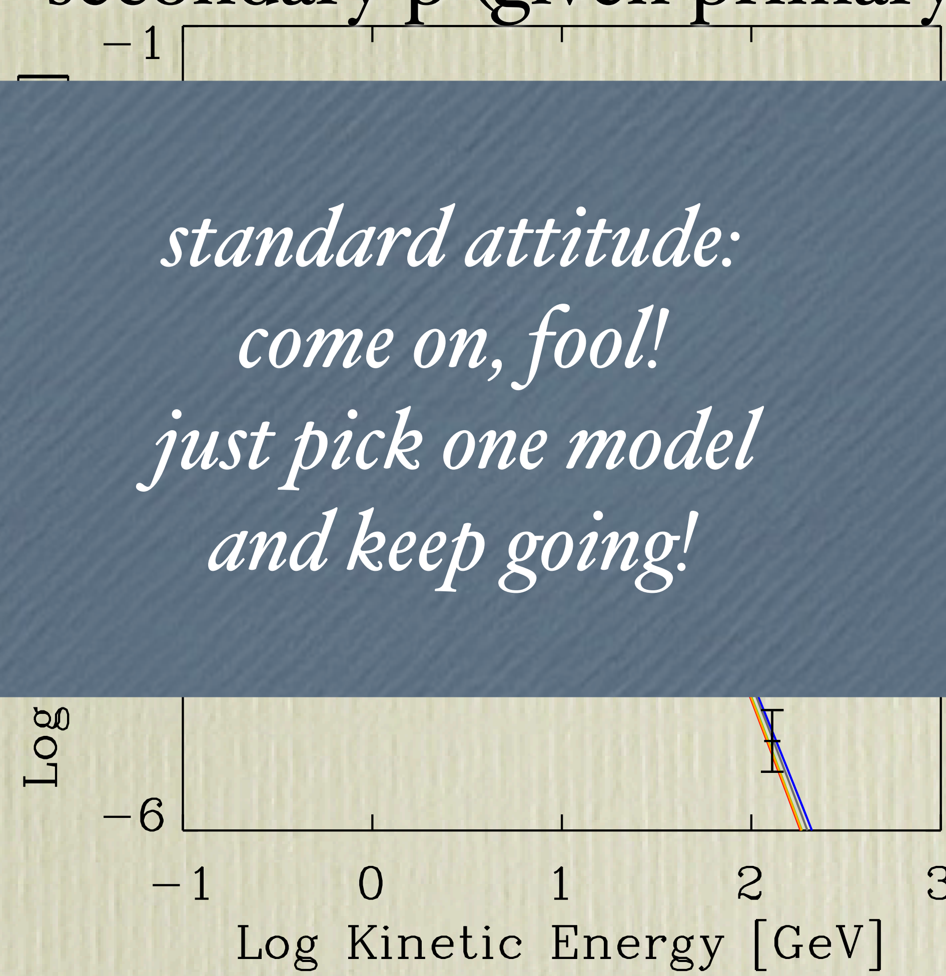


standard attitude:
come on, fool!
just pick one model
and keep going!

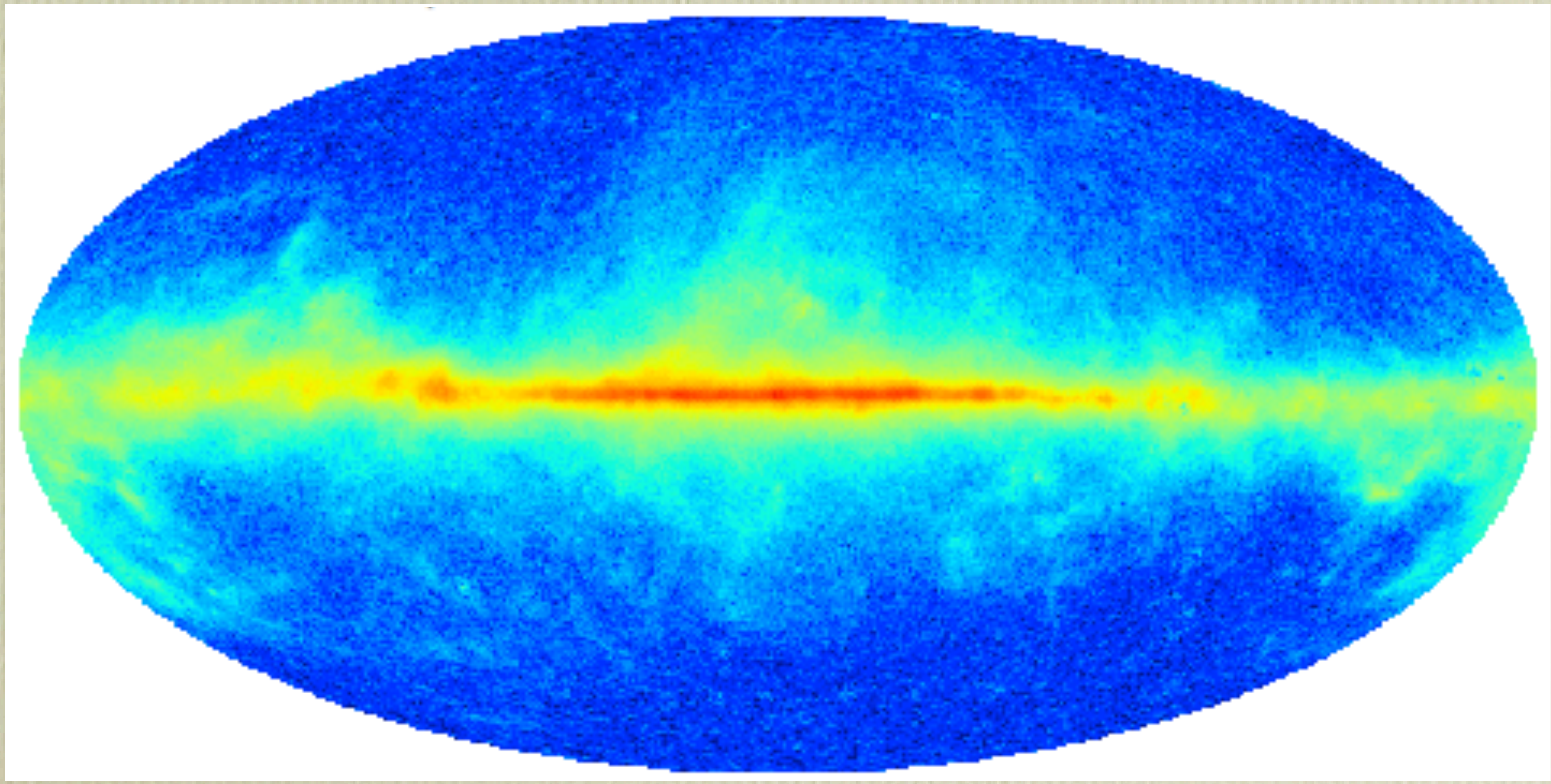
Gamma-ray emissivity in the Galaxy

Fold the previous picture for charged CRs to compute γ-ray emissivities:

- decay of mesons produced in the interaction of CRs with the ISM gas;
- CR lepton inverse Compton scattering of CMB, IR and optical γs;
- bremsstrahlung radiation off CR leptons ;

and obtain a prediction for the diffuse γ-ray flux from the Galaxy.

This should match the picture of the sky from Fermi, after subtracting point sources, isotropic extragalactic, instrumental background:



Modeling the MW diffuse γ-ray flux

Cholis, Tavakoli, Evoli, Maccione & PU, arXiv:1106.5073
Tavakoli, Cholis, Evoli & PU, arXiv:1308.4135

- Implement, **self-consistently in CR propagation and γ emissivity**, an as-accurate-as possible model for the gas distribution in the Galaxy: column densities of HI from 21 cm surveys, corrected for opacity through an estimate of the spin temperature; column densities of H_2 via conversion of 2.6 mm CO surveys; conversion of column densities to 3D models via gas flow kinematics (rotation curve or more refined models)

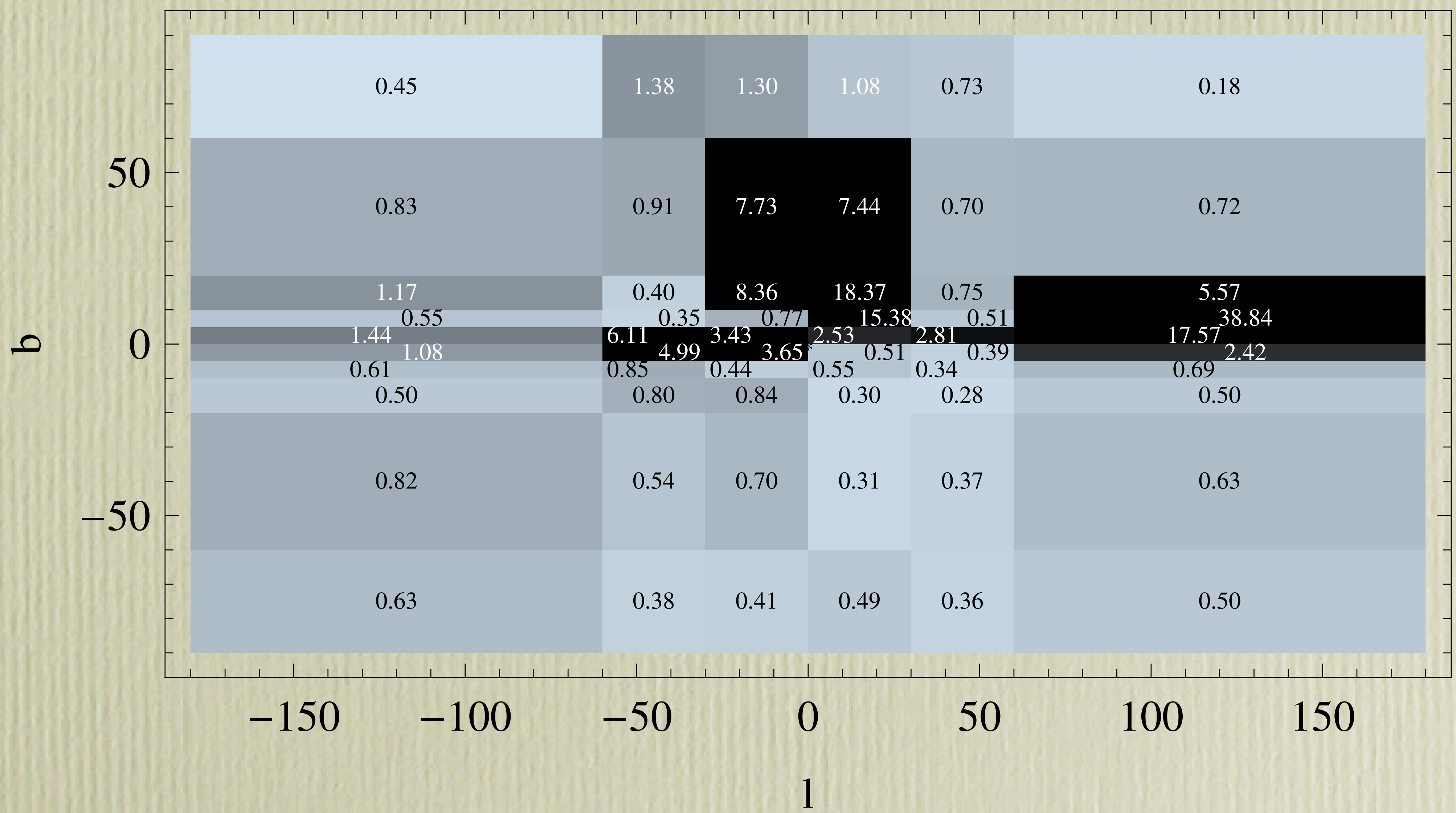
- Guess a functional form for the distribution of CR sources (marginally probed by local measurements) - usually a steady state axially symmetric smoothing inferred from the spatial distribution of SNRs or pulsars.

- Implement a model for the ISRF from stellar pop.s (Porter et al. 2005)

- Address the CR lepton puzzle emerged from the measurements of Pamela, Fermi, AMs02, ... adding (by hand at this level) an extra-component of electrons and positrons, a local term you need somehow to extrapolate everywhere else in the Galaxy: take the same as for other CRs?

Consistency with Fermi data

Comparing against the 4-yr-data “ultraclean” sample by splitting the sky into 60 angular windows, the one-model I picked, the “reference” Krainchnan model (+ all other assumptions) works fairly well:

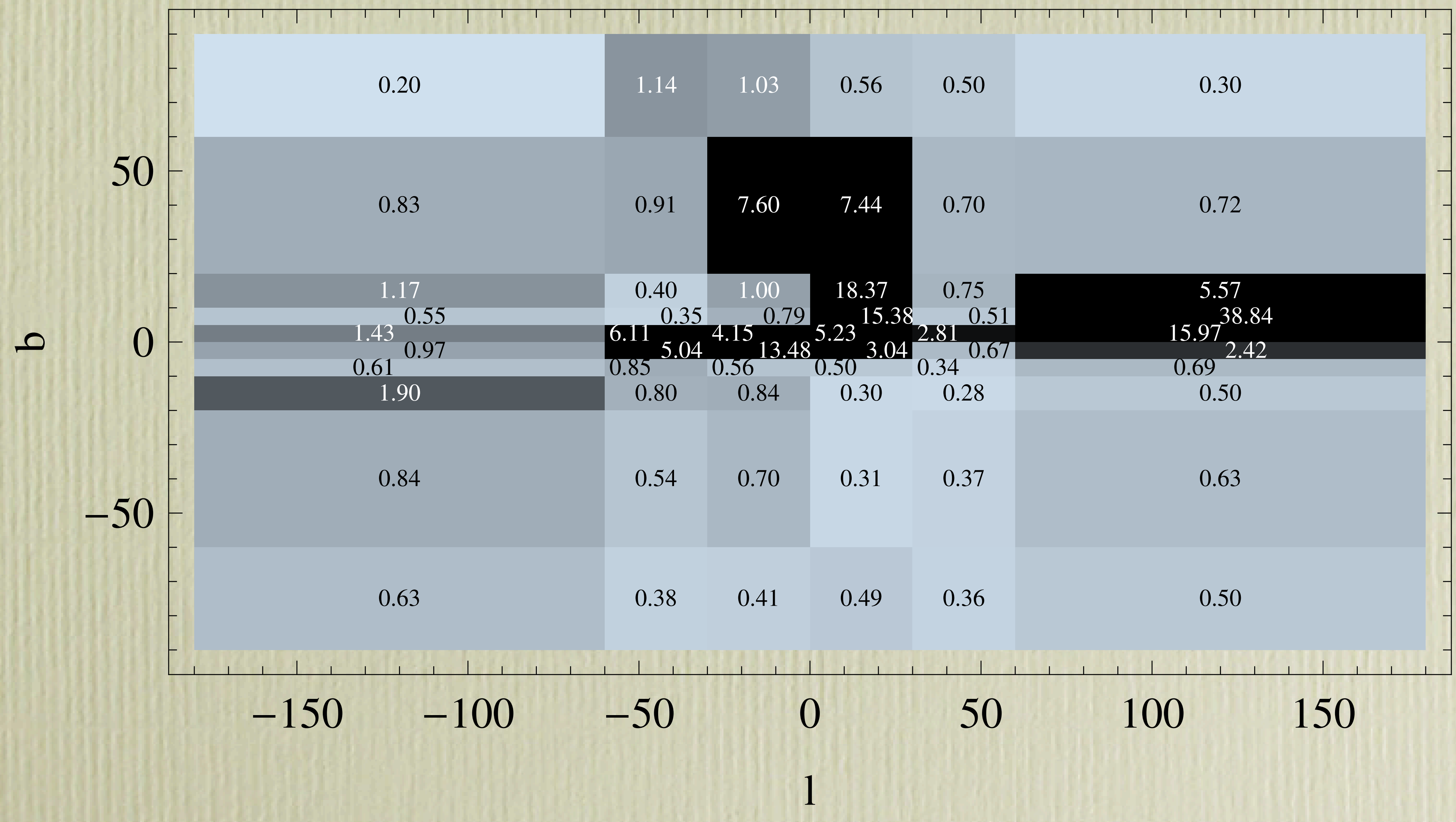


The darker the region, the poorer the fit.

Goodness of the fit shown in terms of reduced χ^2, computed including systematic errors associated to exposure and energy resolution adding them via nuisance parameters.

Consistency with Fermi data

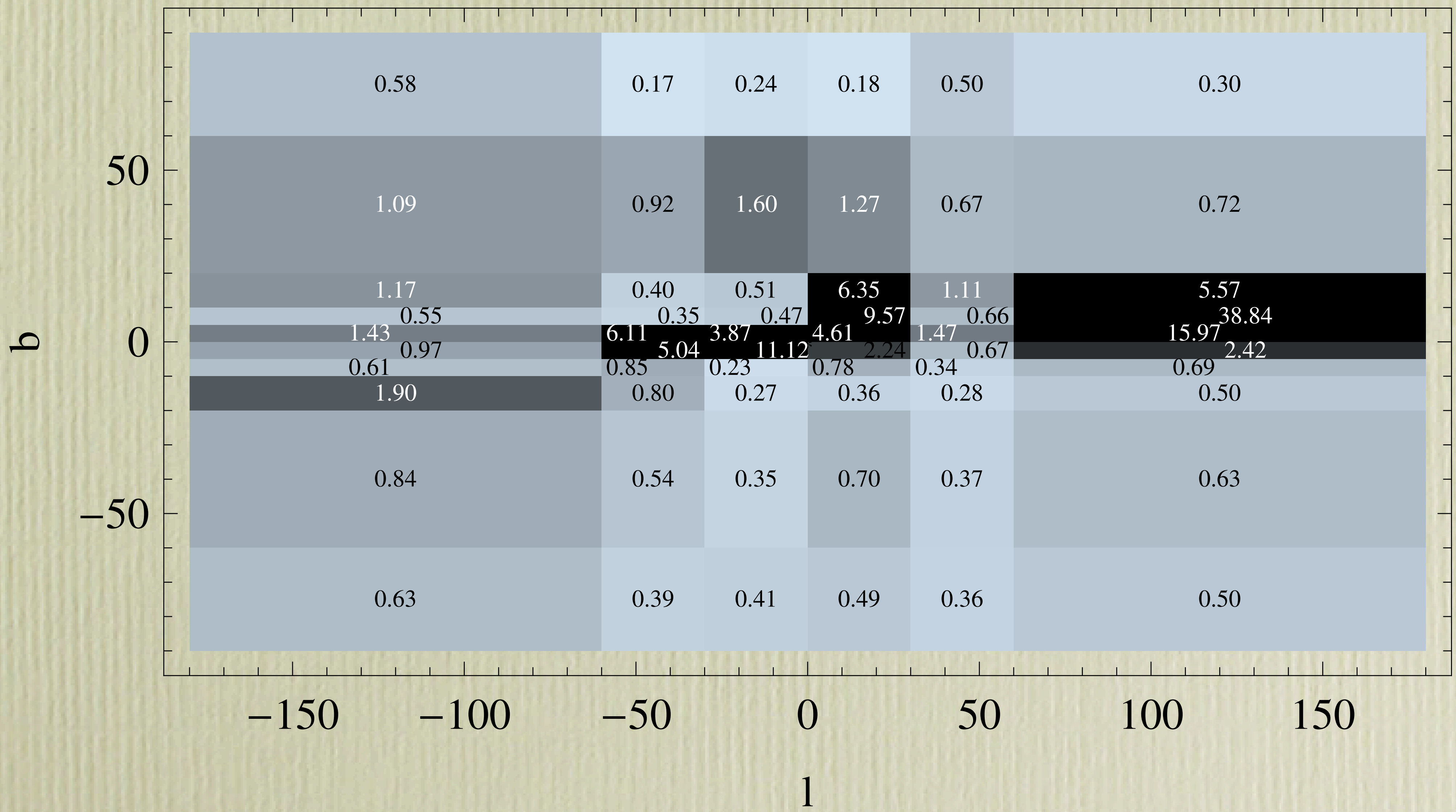
The fit improves if I accept that 21 cm HI and 2.6 mm CO lines do not trace all neutral hydrogen, suffering from absorption. Include a “dark gas” component (Grenier et al. 2005) correlating HI and CO column densities to dust maps via maximum likelihood fits (Dobler et al. 2010):



The darker the region, the poorer the fit.

Consistency with Fermi data

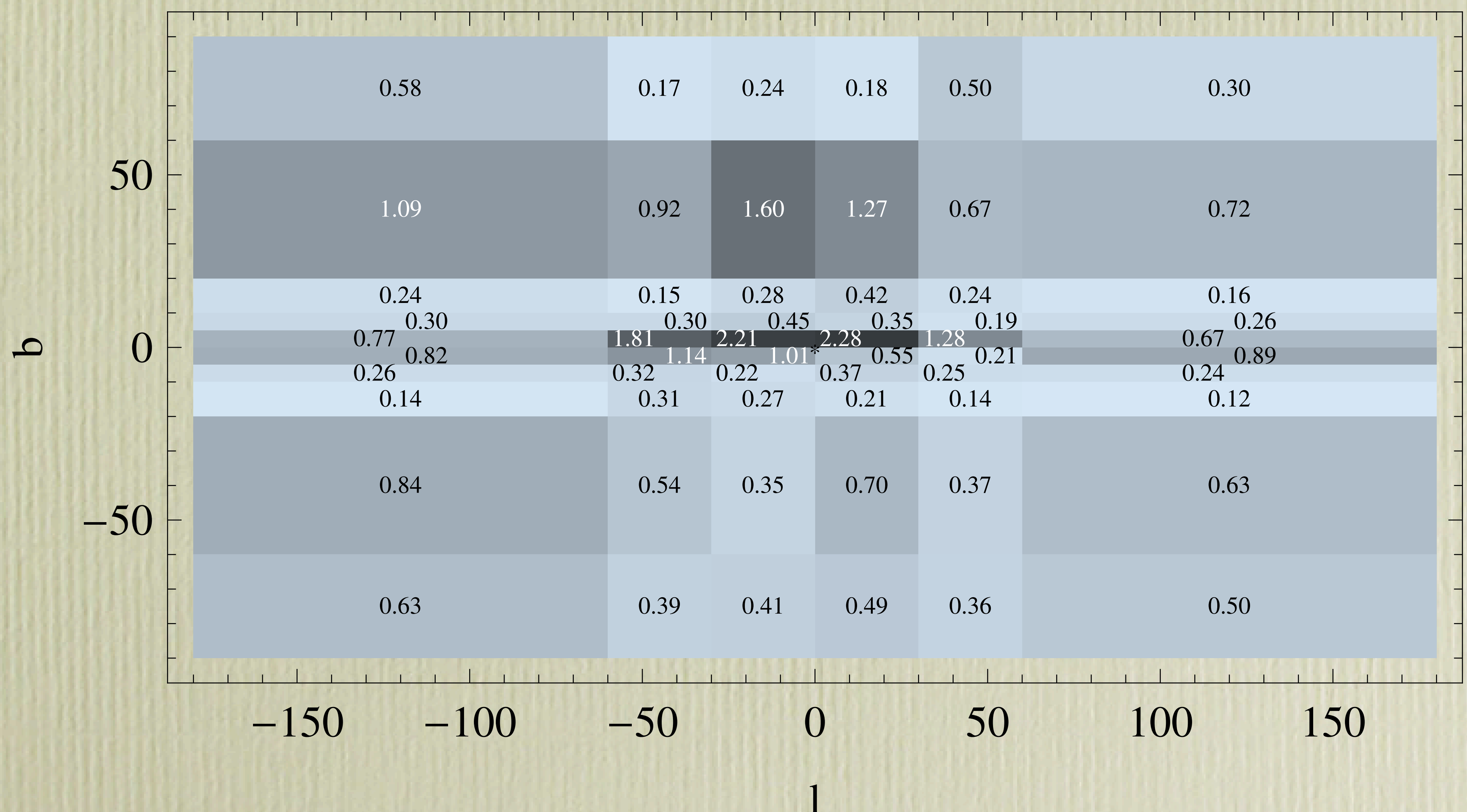
Even better if you play a little bit with template fitting including by hand features there was no attempt to model, such as Loop I and the northern arm - most probably local terms - and the Fermi bubbles/haze (Su et al. 2010):



The darker the region, the poorer the fit.

Consistency with Fermi data

... and even further if we admit that the 3D gas models inverted from column densities and used in propagation is not accurate enough to reproduce small-scale pion emissivity features. If we allow for up to a factor of 2 rescaling in the gas density in each angular window:



The darker the region, the poorer the fit.

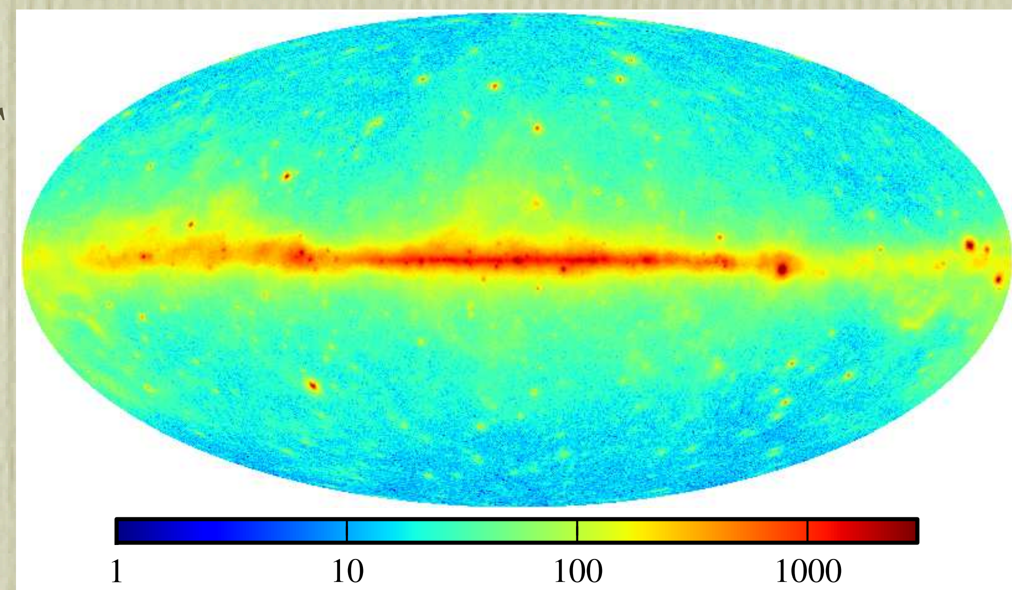
+ eventually further correction in the ISRF, CO conversion factor, ...

Fermi collaboration fits of diffuse emission

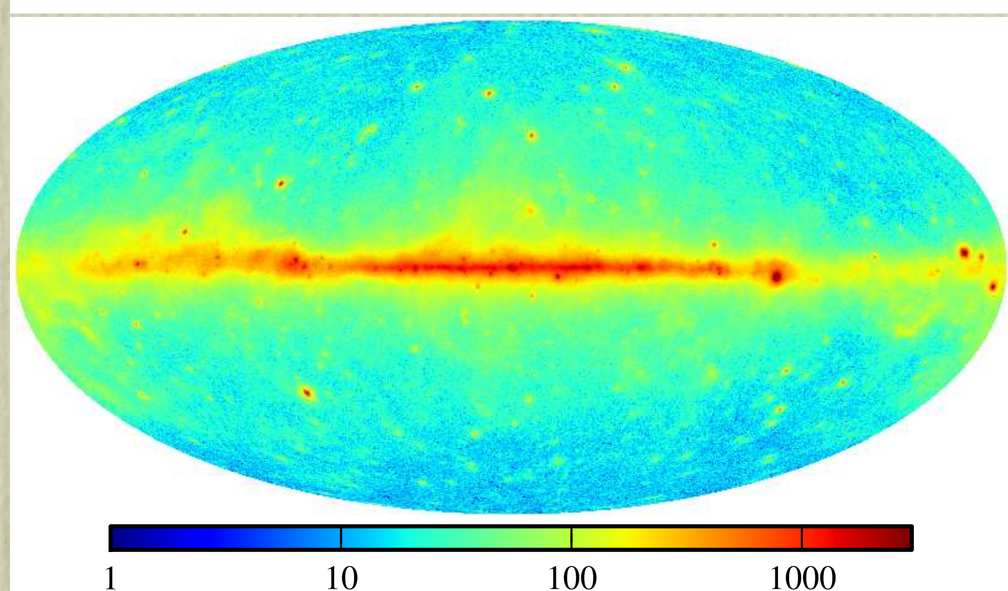
Fermi Collaboration, arXiv: 1202.4039

Detailed study - allowing more fitting freedom - finding an exquisite agreement with the data:

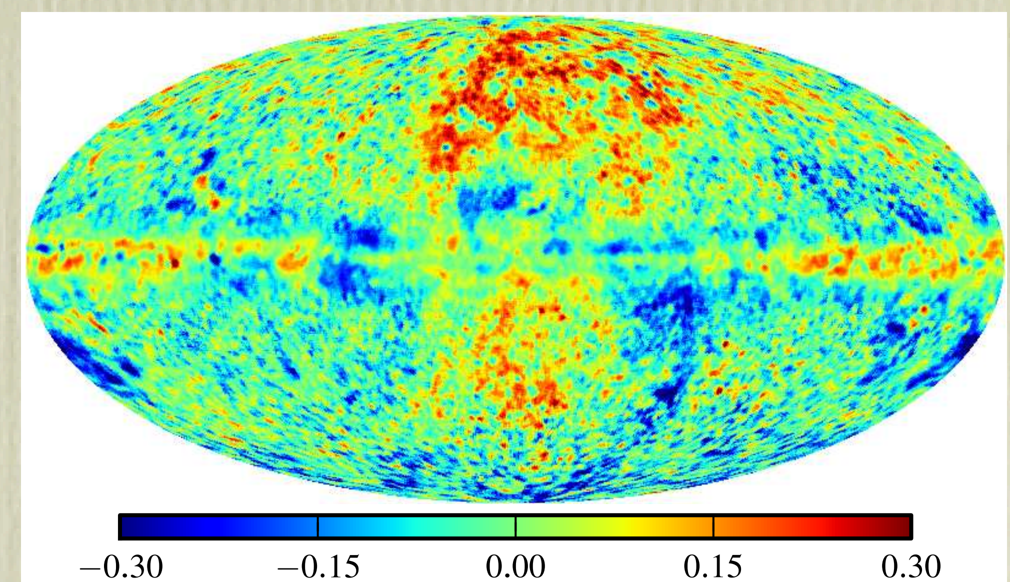
Fermi-LAT counts, 200 MeV-100 GeV



Predicted counts in model: ${}^{S}S^{Z}4^{R}20^{T}150^{C}5$



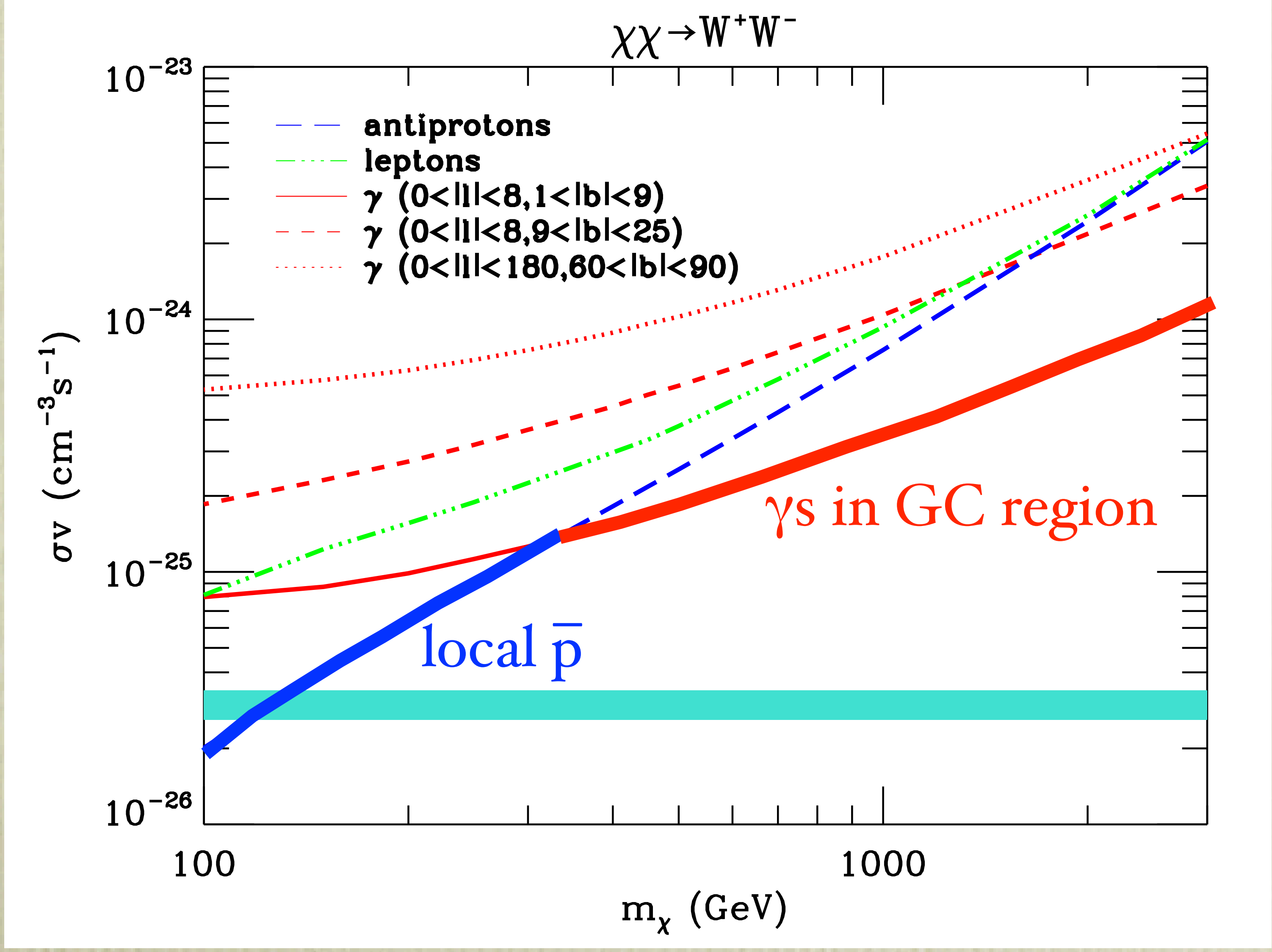
Fractional residuals



After including templates for local features and bubbles + little extra tuning, residuals shrink to below about 10%

Add a WIMP term, ... in the one-model attitude:

A WIMP defined by with one single annihilation state and a sample Einasto profile (+ my "reference" Krainchnan model + reference choices for the γ-ray computation); scan over DM mass and annihilation cross section parameter space and find the limits:

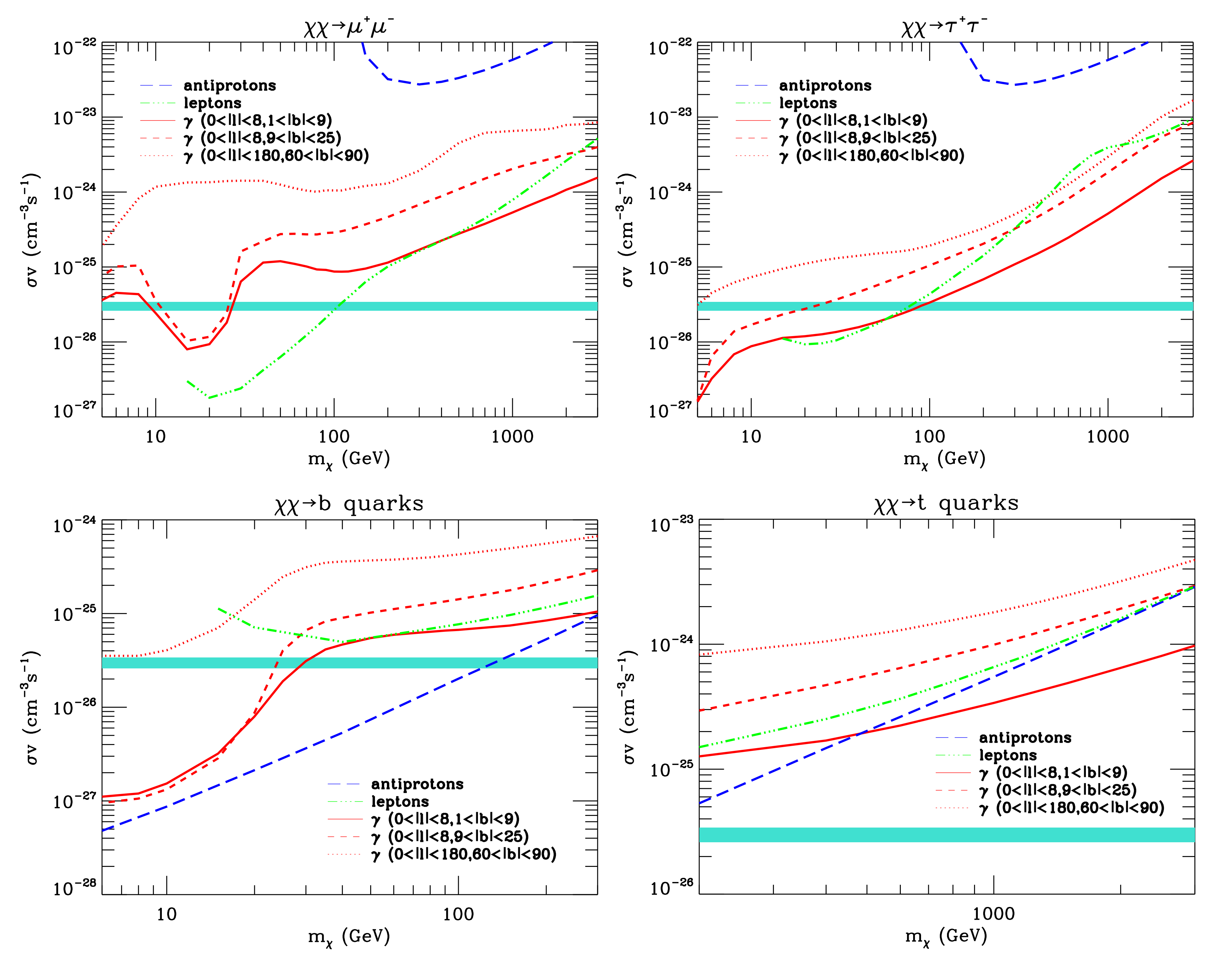


Comparing, **within the same model** against:

- measurements of the local antiproton flux;
- measurements of the local lepton fluxes;
- γ-rays at low, intermediate and high latitudes.

Add a WIMP term, ... in the one-model attitude:

A WIMP defined by with one single annihilation state and a sample Einasto profile (+ my "reference" Krainchnan model + reference choices for the γ-ray computation); scan over DM mass and annihilation cross section parameter space and find the limits:



Comparing, **within the same model** against:

- measurements of the local antiproton flux;
- measurements of the local lepton fluxes;
- γ-rays at low, intermediate and high latitudes.

Add a WIMP term, ... in the one-model attitude:

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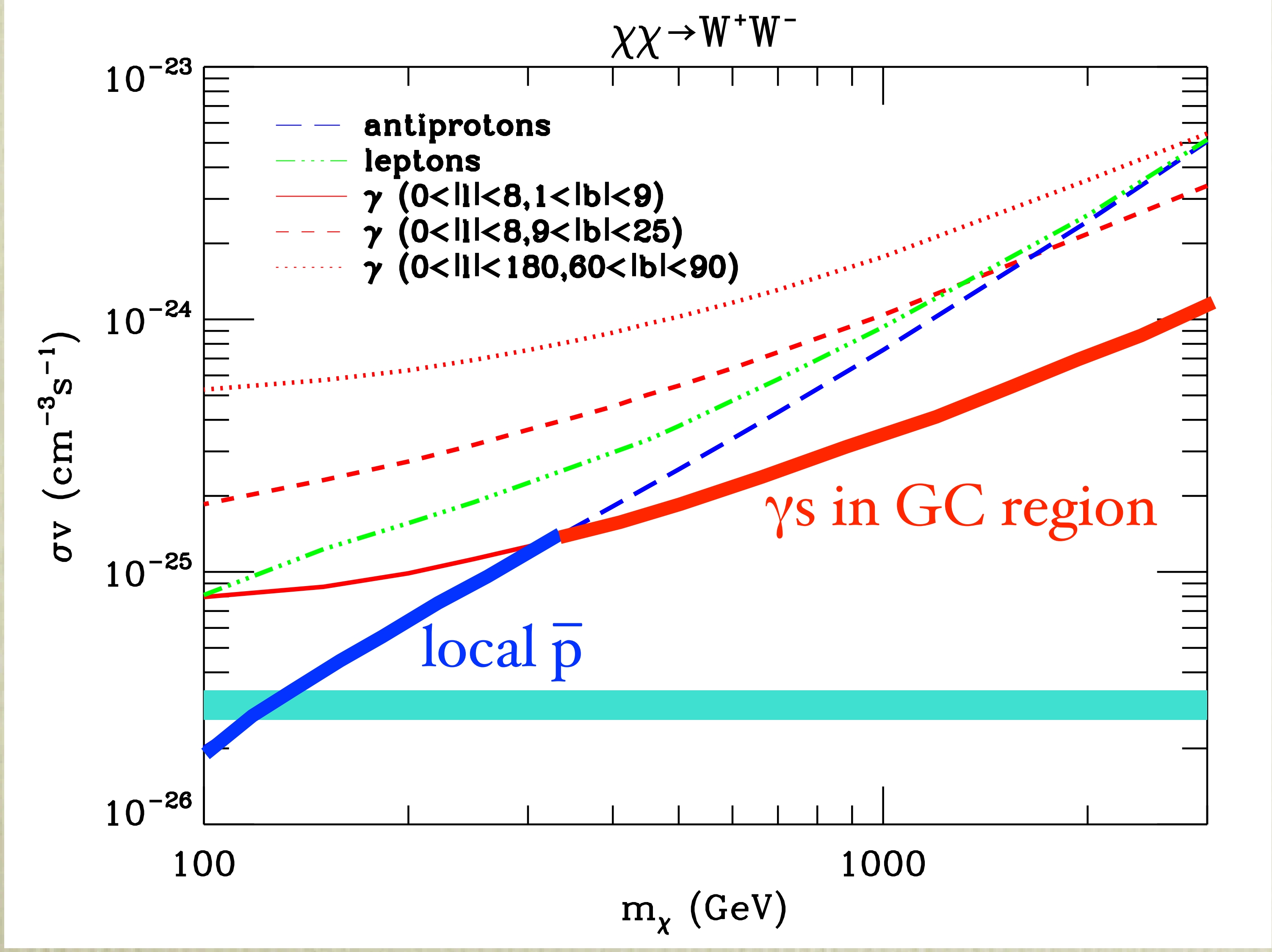


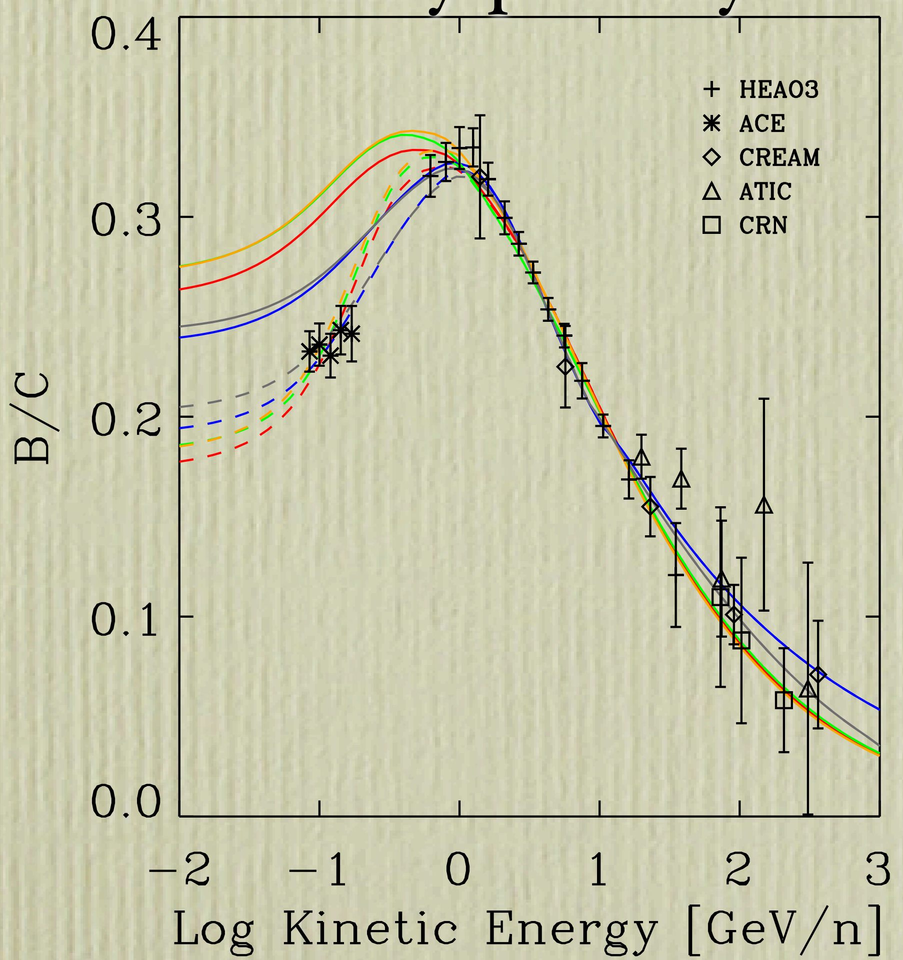
Pay closer attention: since there is no limit several orders of magnitudes more constraining than the others, the one-model attitude might be potentially very deceiving!

To answer the question of whether one method is better than another, we need to go back and reconsider the framework more carefully.

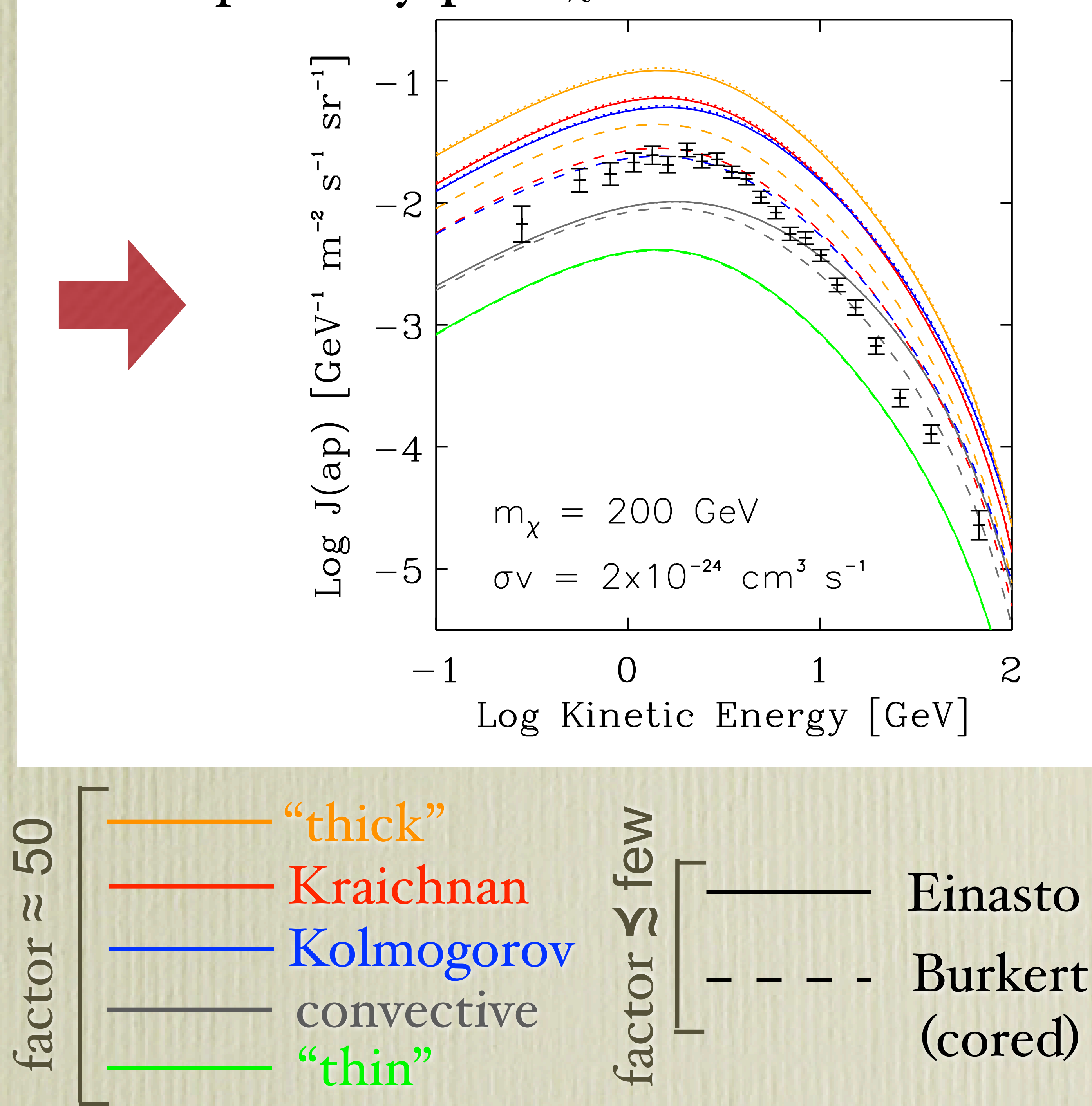
Back on CRs and antiprotons predictions

We stressed that predictions for secondaries are fairly robust; the same is unfortunately not true for primaries from DM annihilations:

secondary/primary B/C



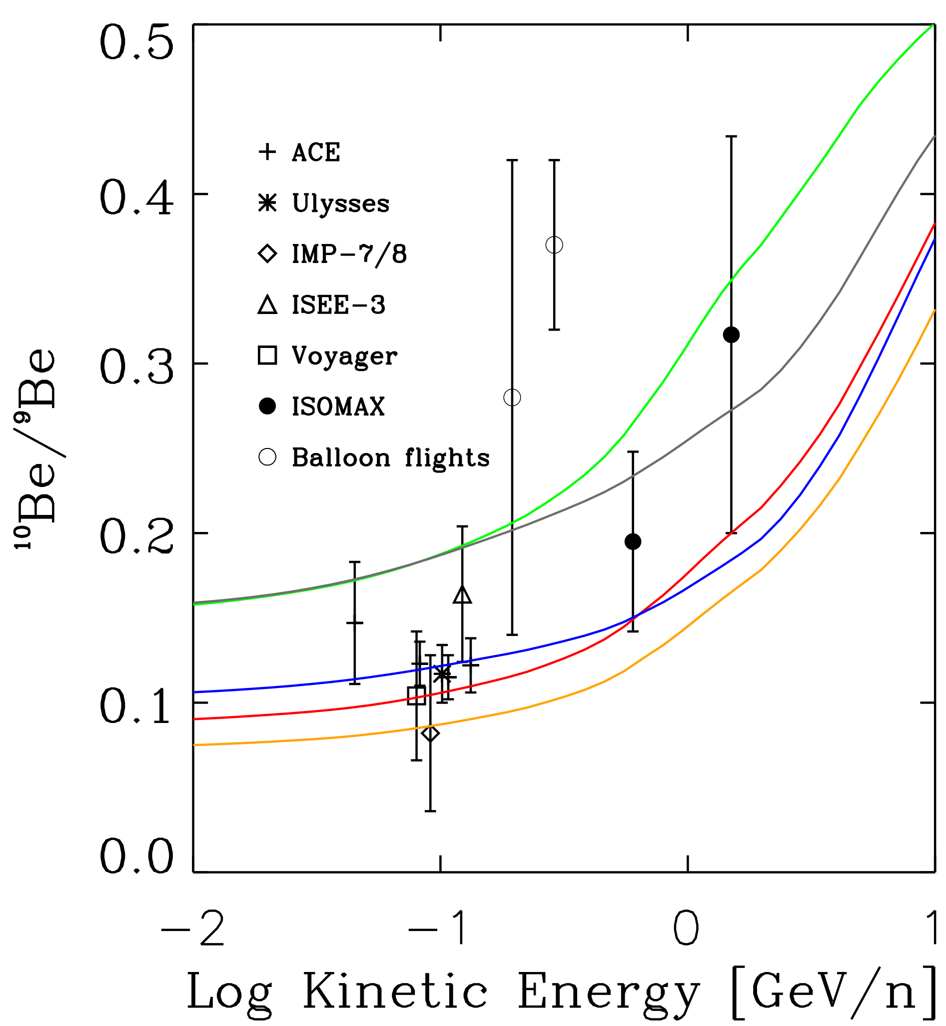
primary $\bar{p}$ $(M_\chi = 200\,\text{GeV}, W^+W^-)$



Back on CRs and antiprotons predictions

The most severe scaling with the **scale height for the turbulent magnetic field component**: B/C hardly sensitive to that;

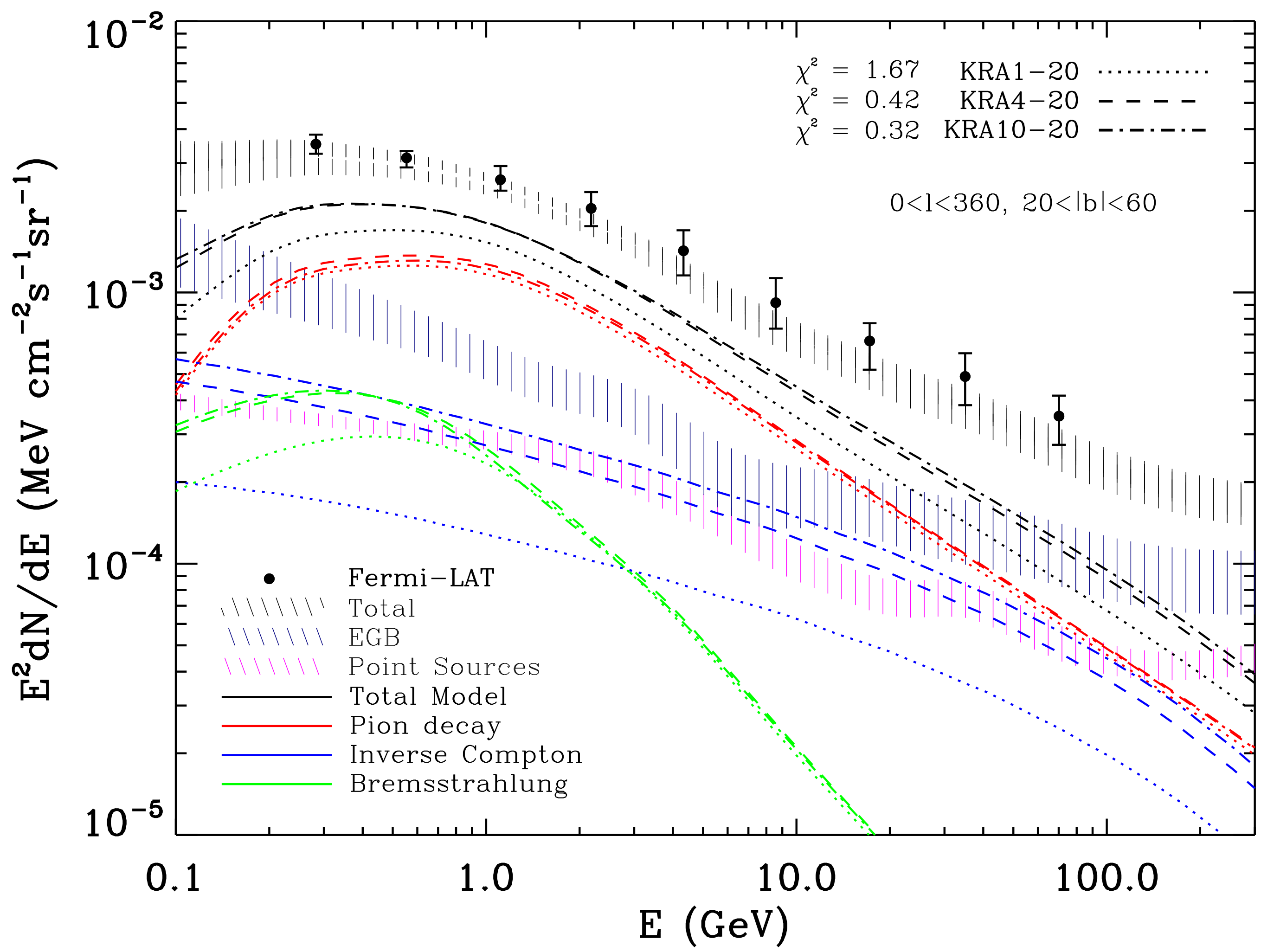
The abundance of long-lived **radioactive nuclei** is in principle very sensitive to the scale height (as well as other parameters). A novel neat measurement with AMS nailing down this feature? Yes, except that to model these data understanding propagation in the very local environment is crucial.



Back on CRs and antiprotons predictions

The most severe scaling with the **scale height for the turbulent magnetic field component**: B/C hardly sensitive to that;

γ-rays seem to disfavor thin models, since, while leaving pion decay and bremsstrahlung components unchanged, the IC component is suppressed by confining leptons into a thinner vertical region. Compensate for that with a drastic change in the ISRF model?



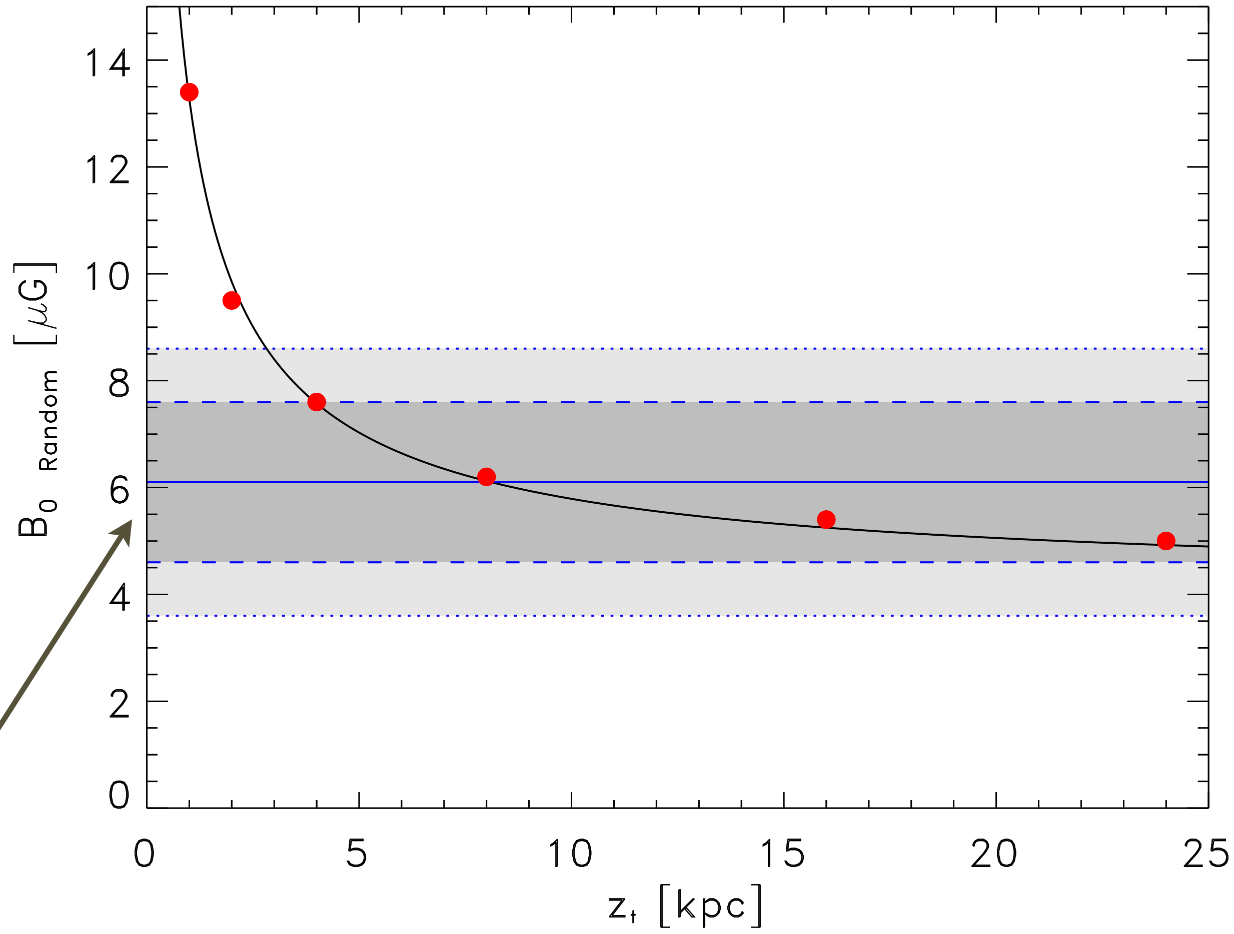
Back on CRs and antiprotons predictions

The most severe scaling with the **scale height for the turbulent magnetic field component**: B/C hardly sensitive to that;

the same lepton populations are probed in the radio via **synchrotron** emission; this however depends in turn on what is assumed for the magnetic field strength. Again thin models looks disfavored (excluded ???)

range from Faraday RMs

Di Bernardo et al., arXiv:1210.4546



Back on γ-ray predictions

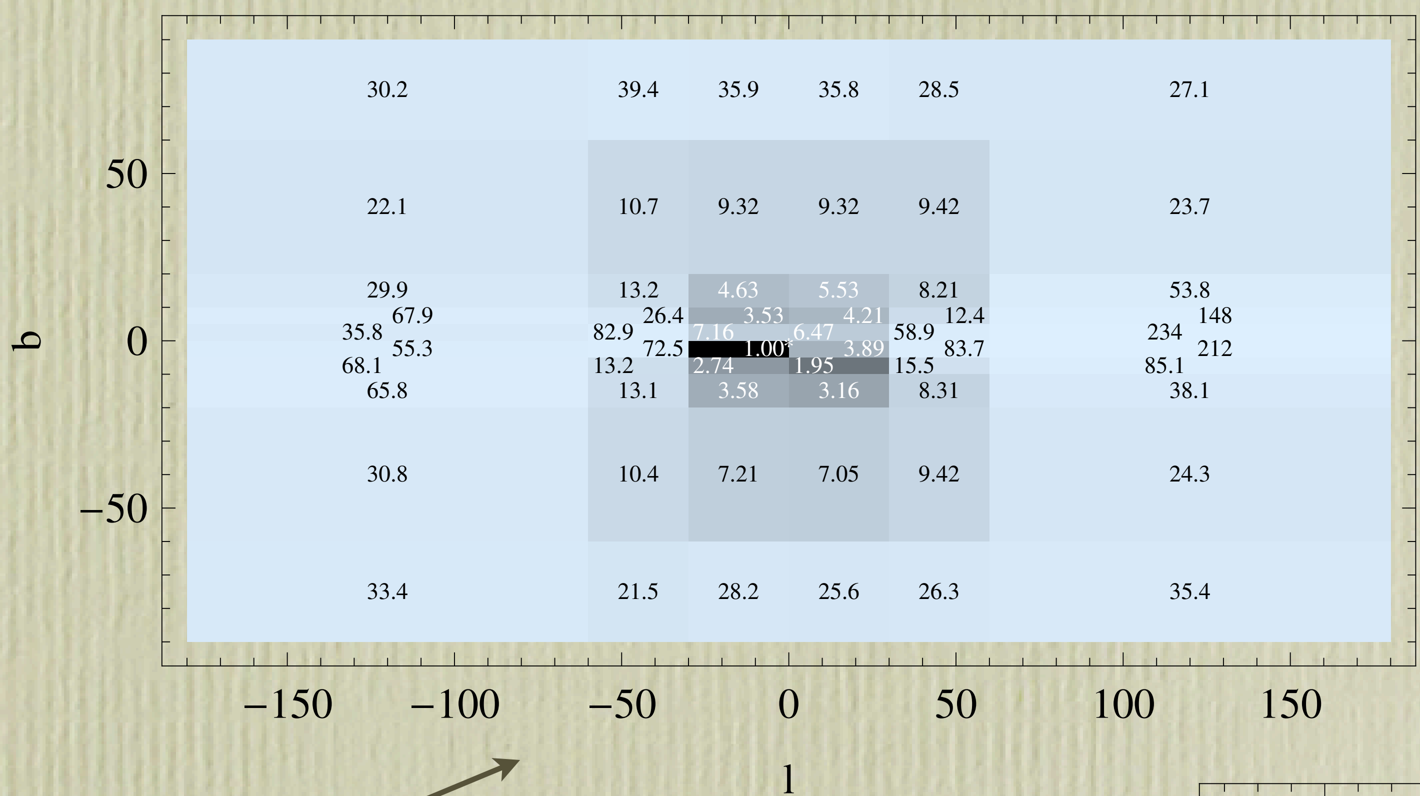
Rather than low, intermediate & high latitude, follow the strength of the limit on the whole sky:

$M_\chi = 100\,\mathrm{GeV},\ W^+W^-$

plotting: $(\sigma v)^{3\sigma}/(\sigma v)^{3\sigma}_{\mathrm{min}}$

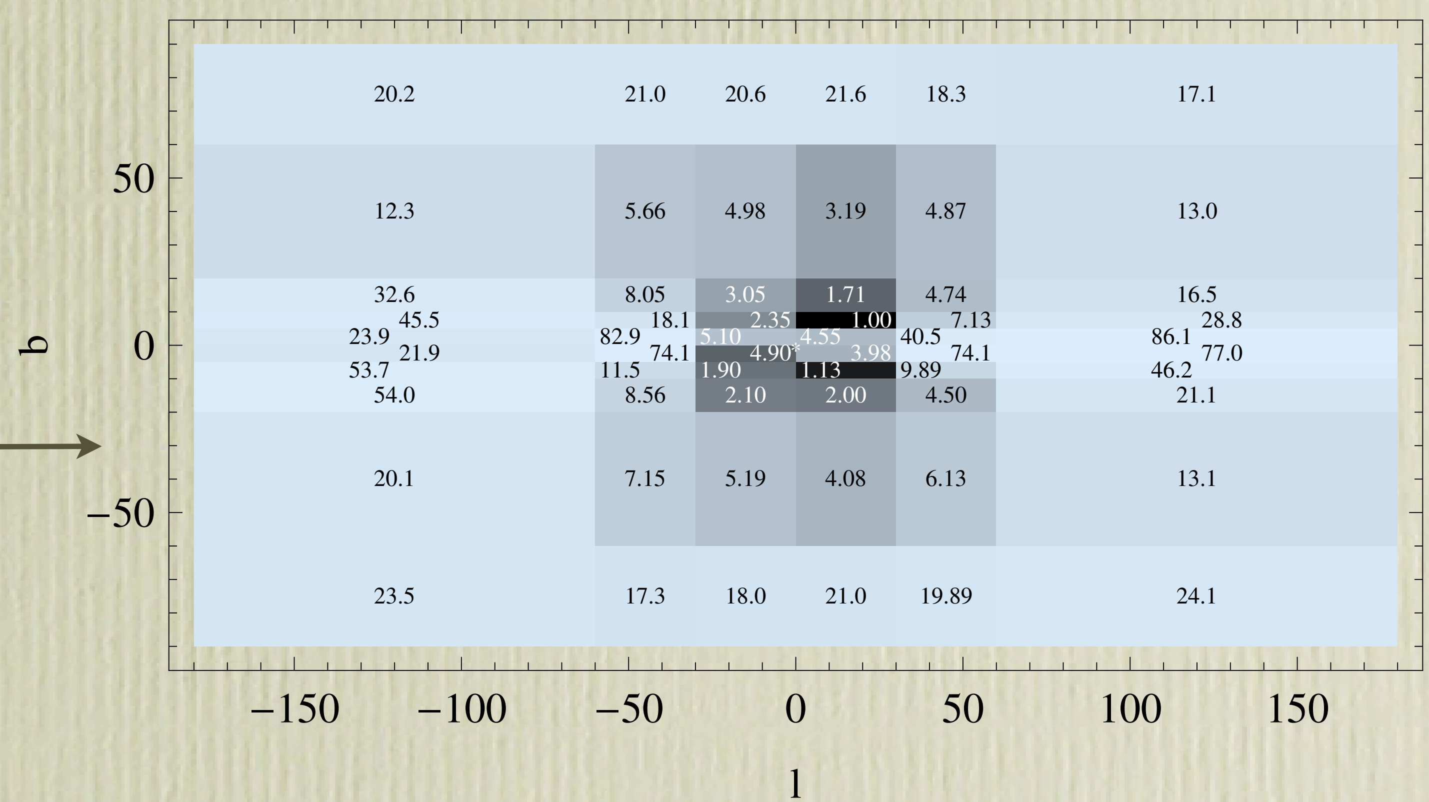
with: $(\sigma v)^{3\sigma}_{\mathrm{min}} = 9.3\cdot 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$

The darker the region, the tighter the constraint



reference model with "fixed" gas

gas density scaled up to a factor of 2



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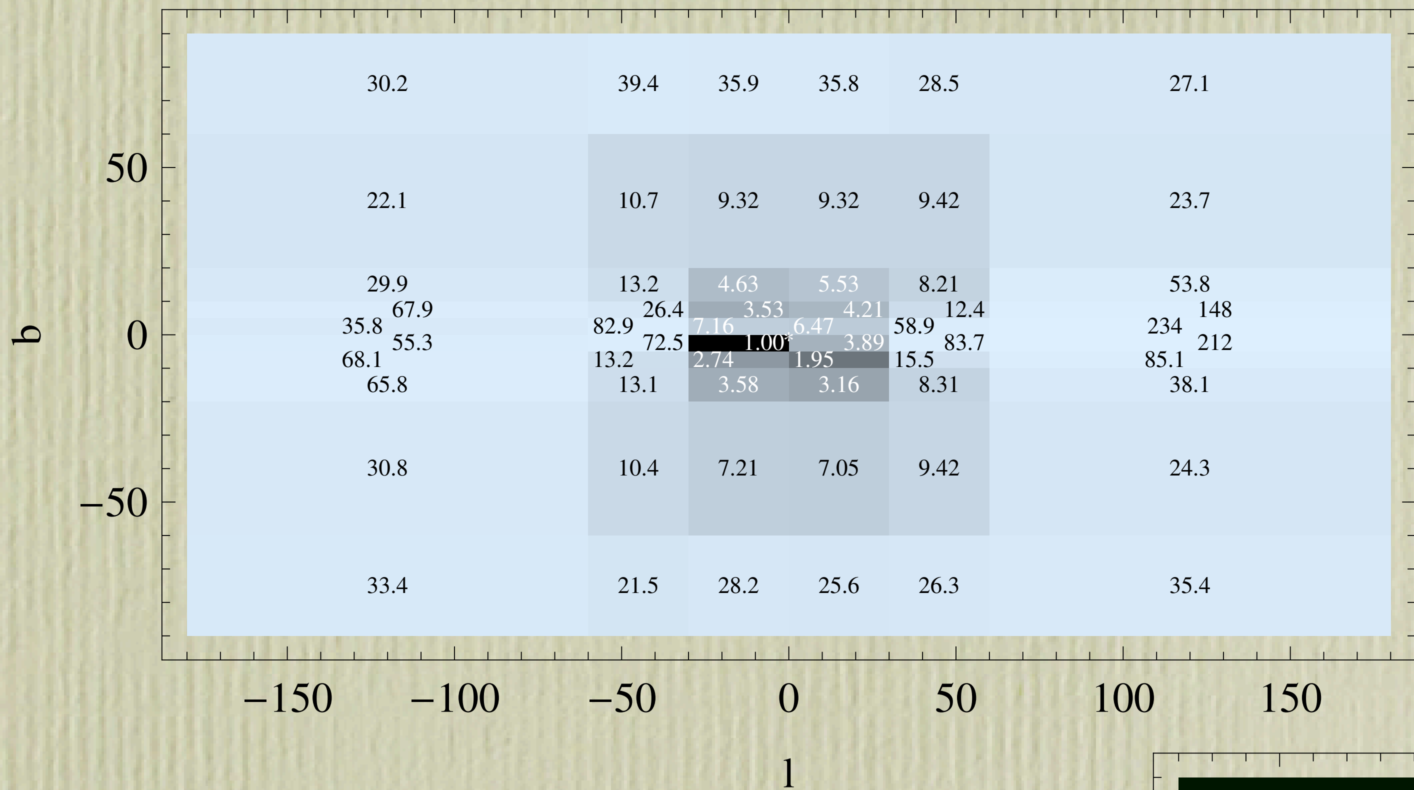

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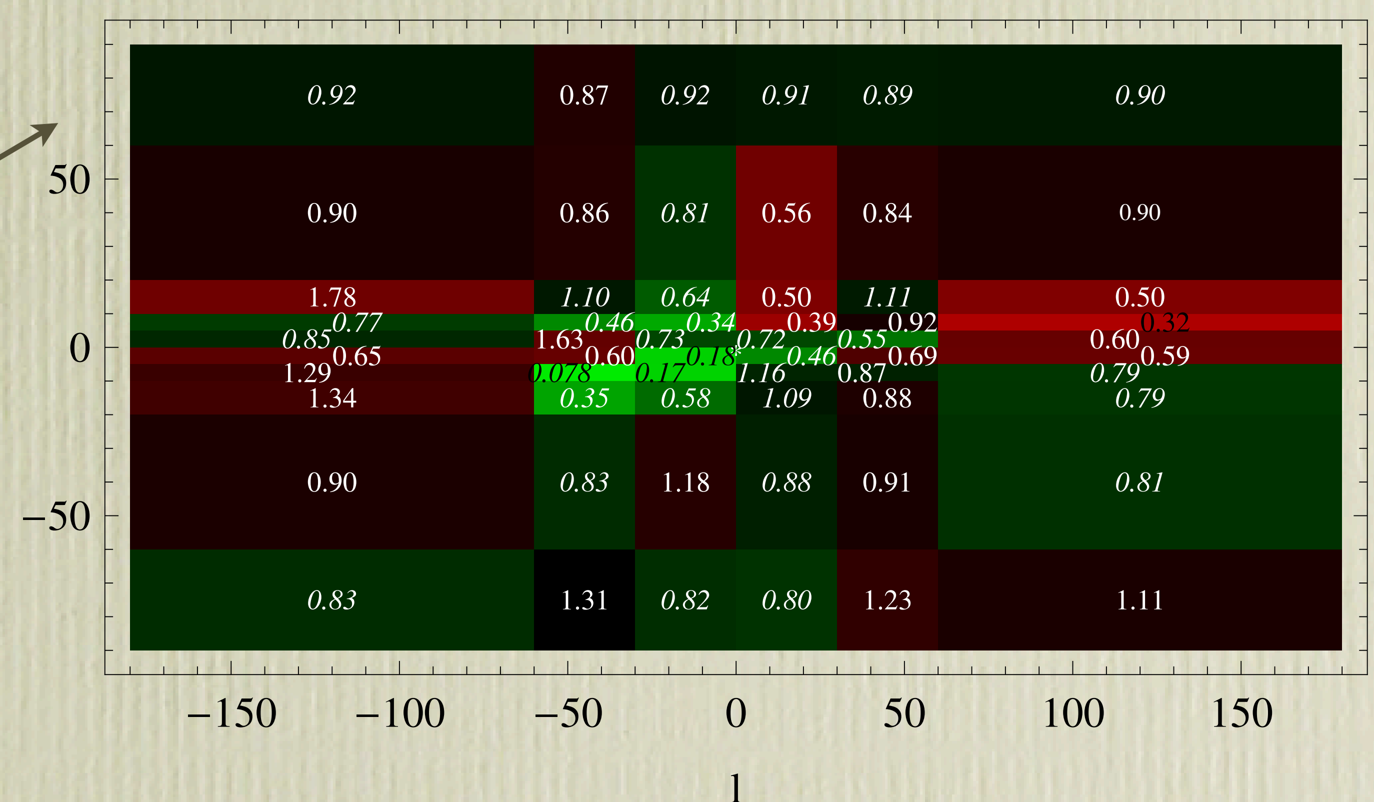
in the “reference” case.

The brightest the color, the less robust the limit:

plotting the largest departure from 1 of: $(\sigma v)^{3\sigma}_{\rm i}/(\sigma v)^{3\sigma}_{\rm ref}$

where “i” labels a set of models with different assumptions on the gas (reddish regions) or on the ISRF (greenish regions).



Back on γ-ray predictions

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$M_\chi = 10\,\mathrm{GeV},\ b\bar{b}$

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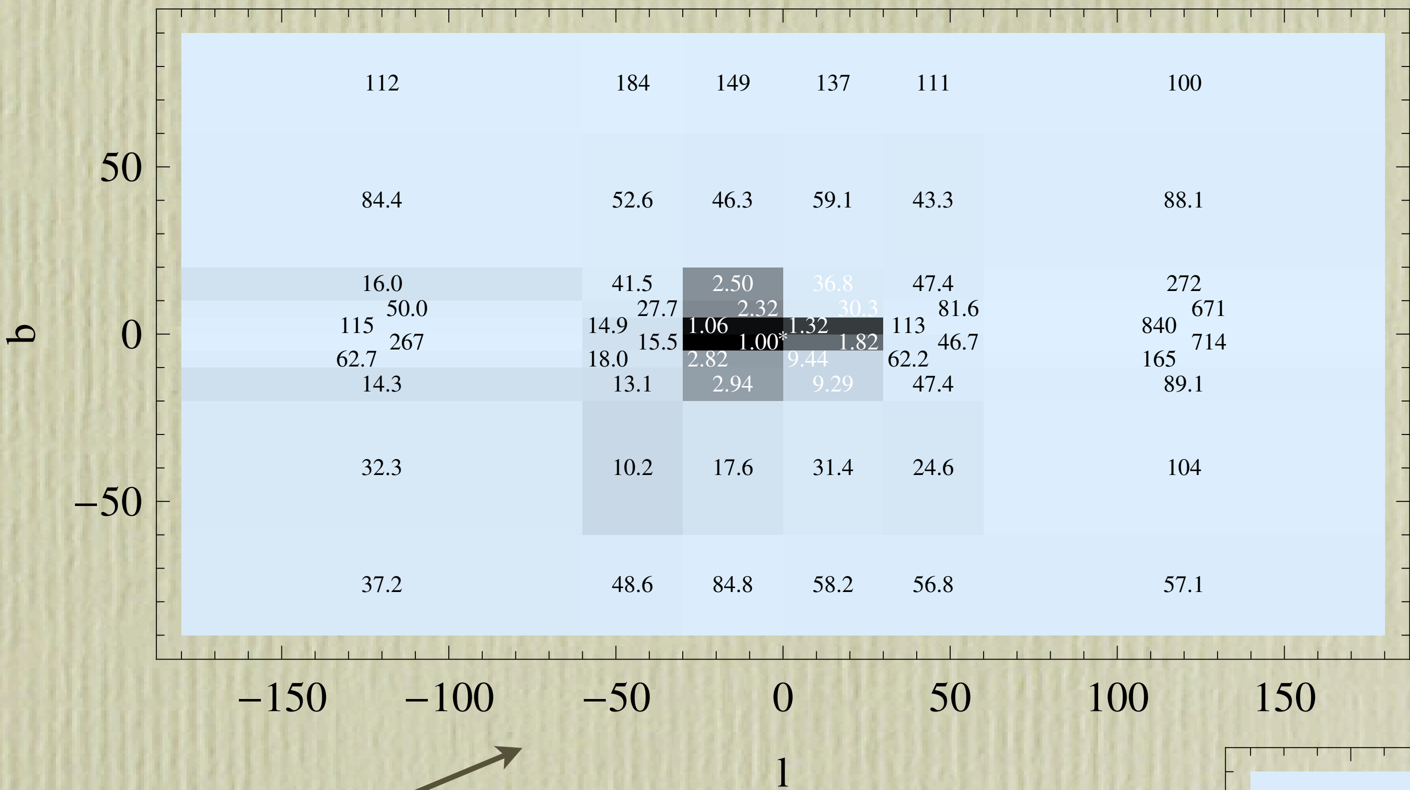
with: $(\sigma v)^{3\sigma}_{\rm min} = 2.5 \cdot 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}$

The darker the region, the tighter the constraint



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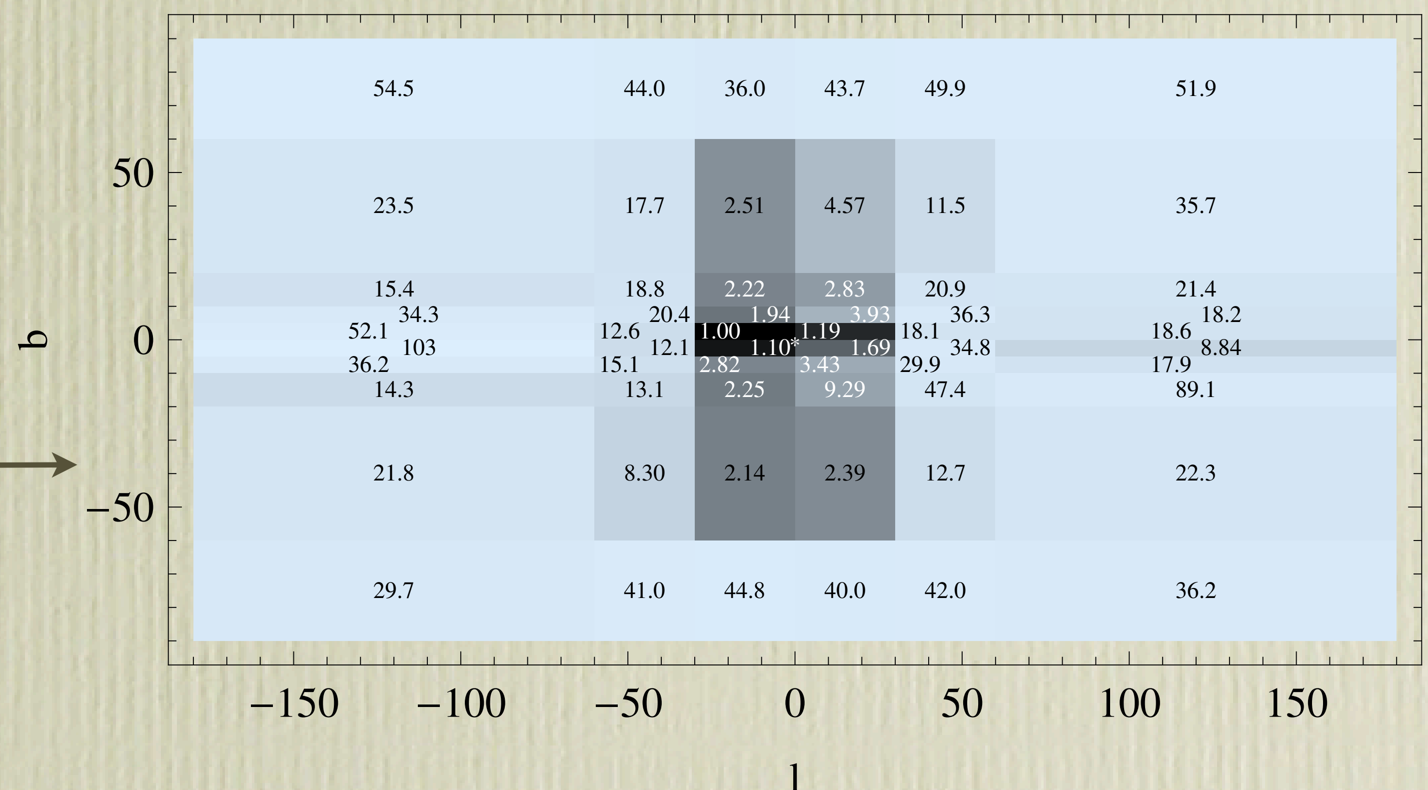

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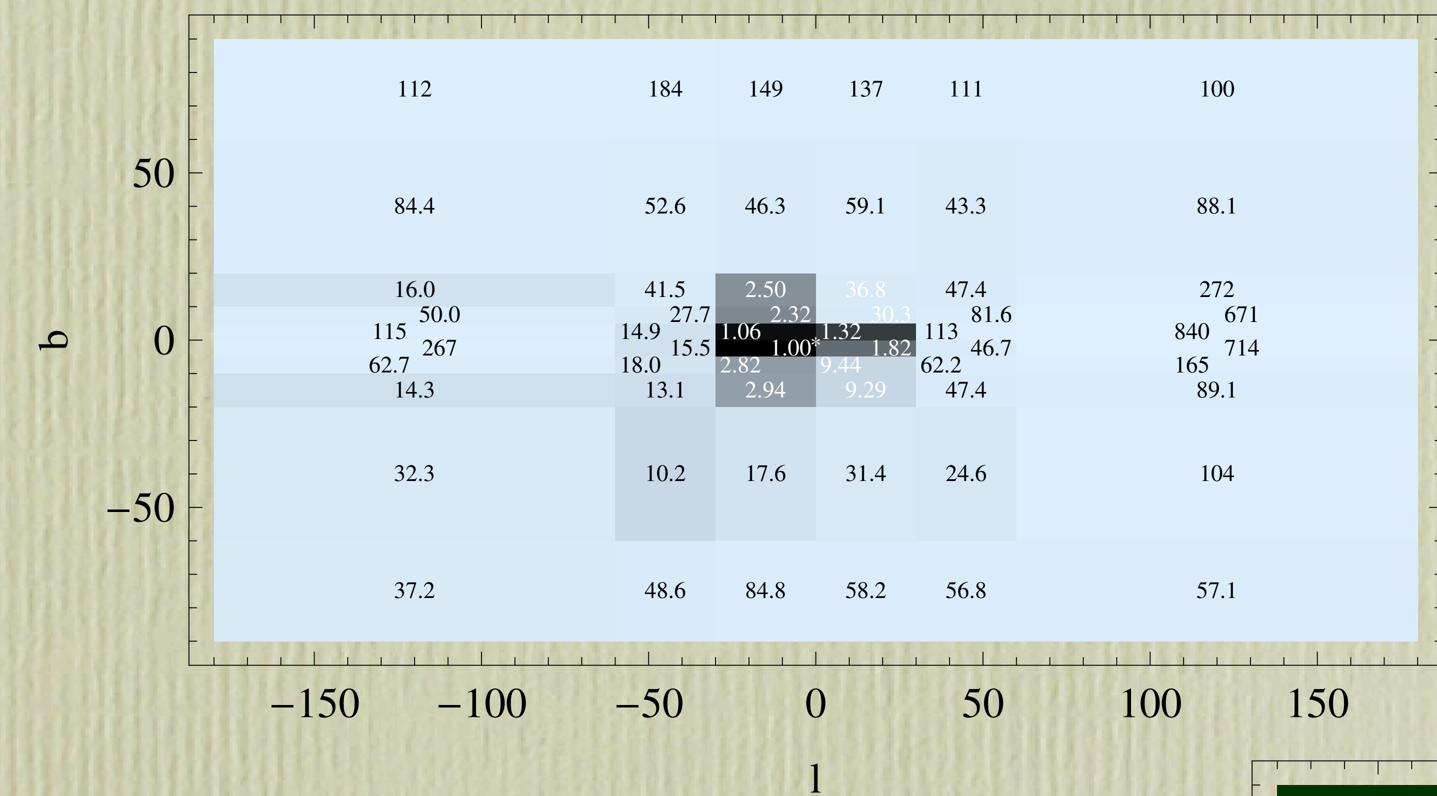

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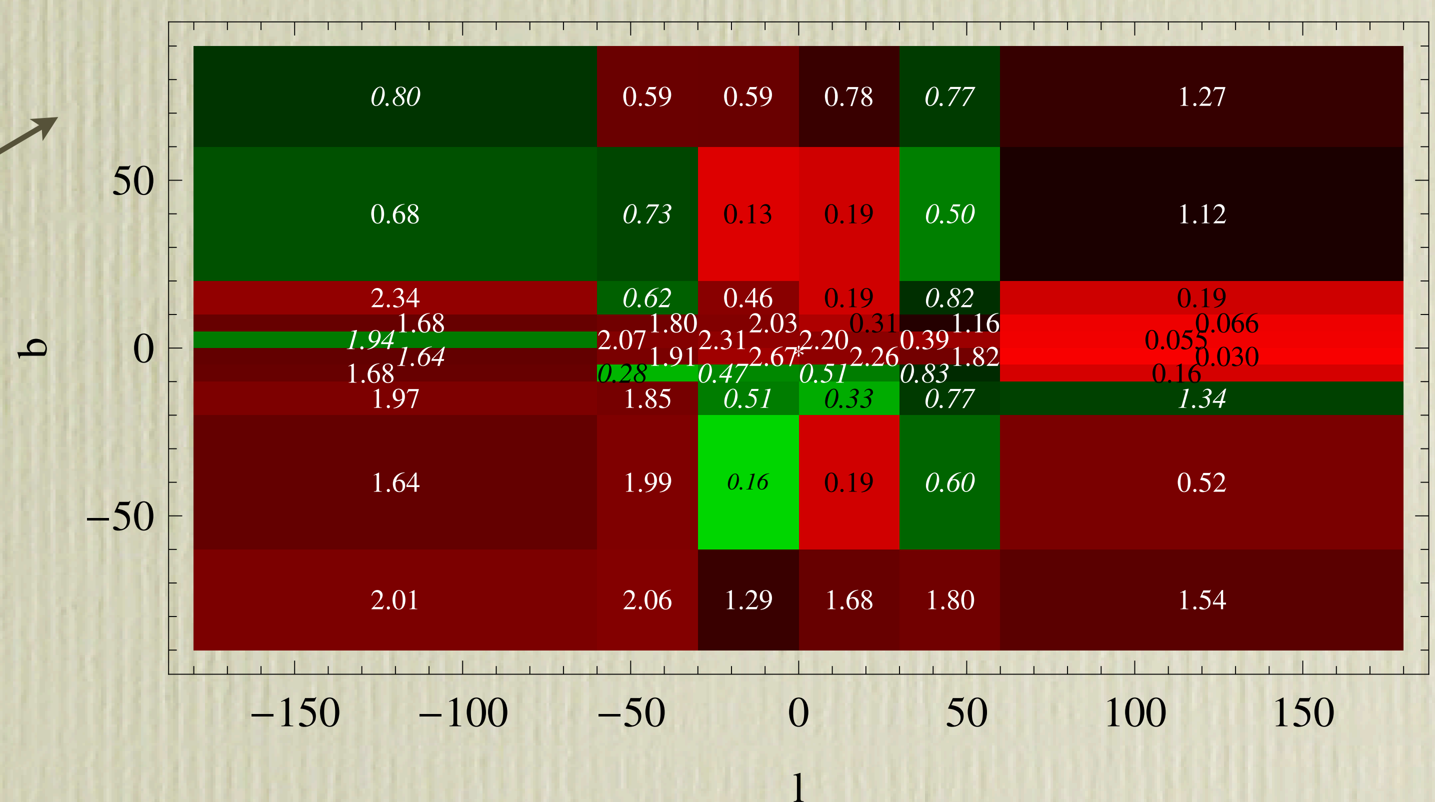
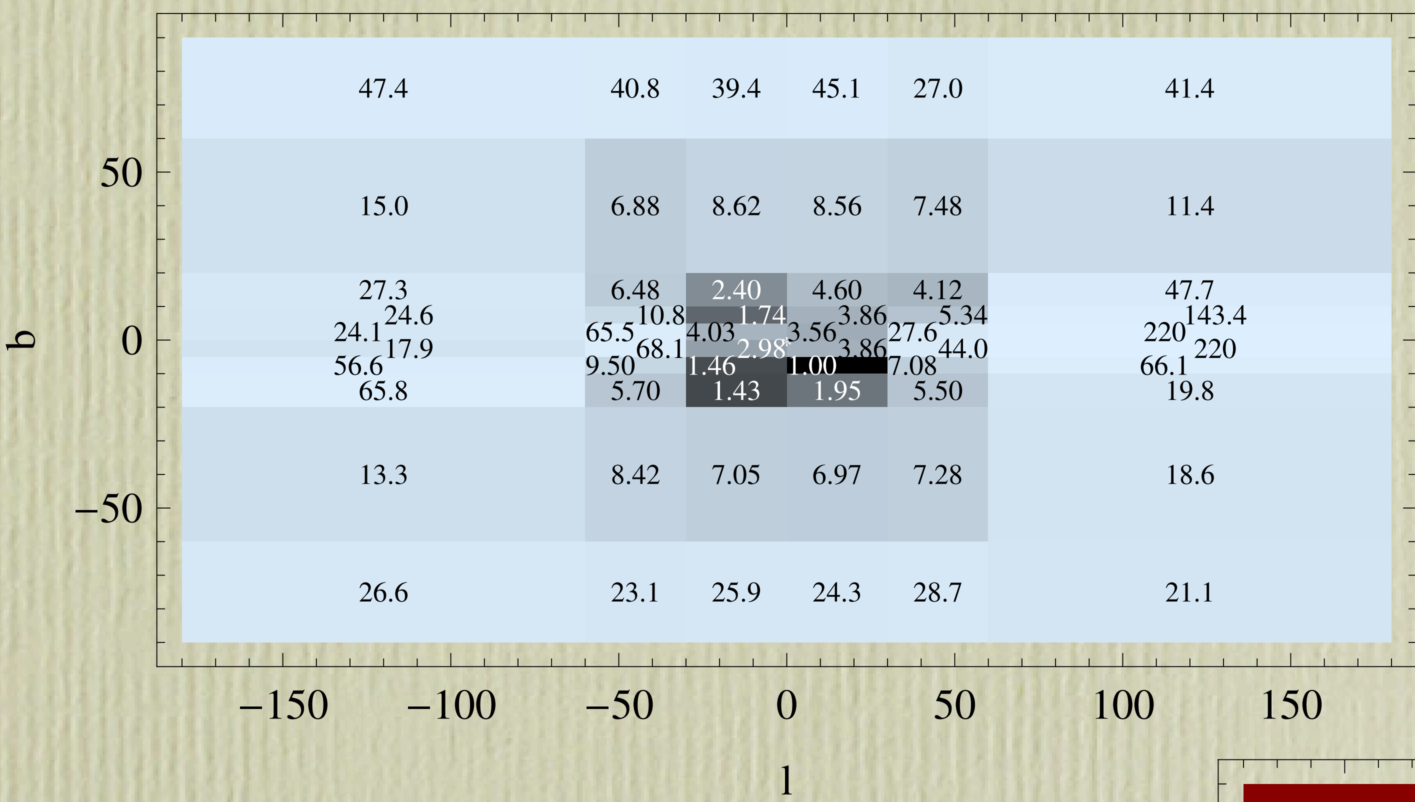


Back on γ-ray predictions

Rather than low, intermediate & high latitude, follow the strength of the limit on the whole sky:

$M_\chi = 1.6\,\mathrm{TeV}, \phi\,\phi$



plotting: $(\sigma v)^{3\sigma}/(\sigma v)^{3\sigma}_{\mathrm{min}}$

with: $(\sigma v)^{3\sigma}_{\mathrm{min}} = 8.9 \cdot 10^{-25}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$

in the "reference" case.

The brightest the color, the less robust the limit:

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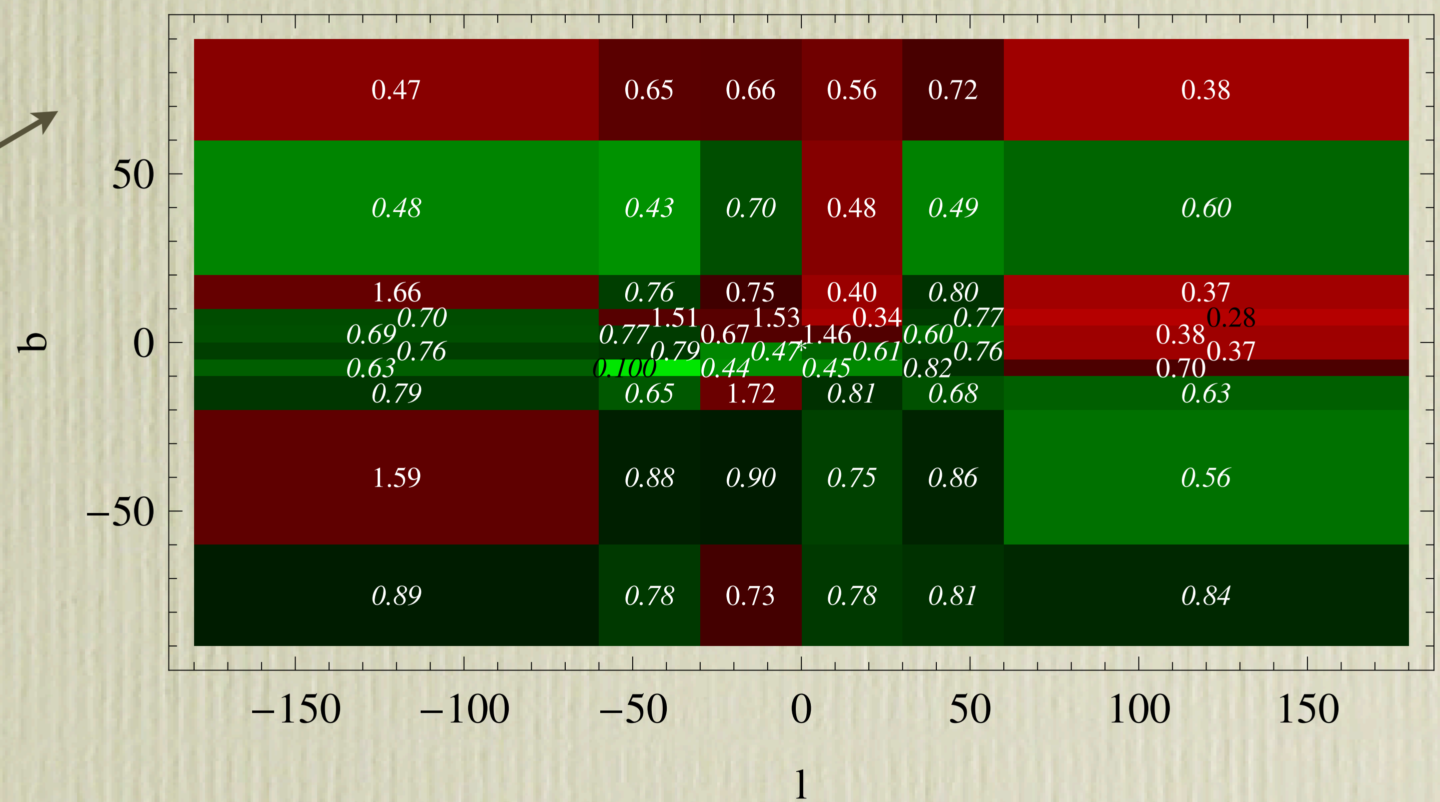
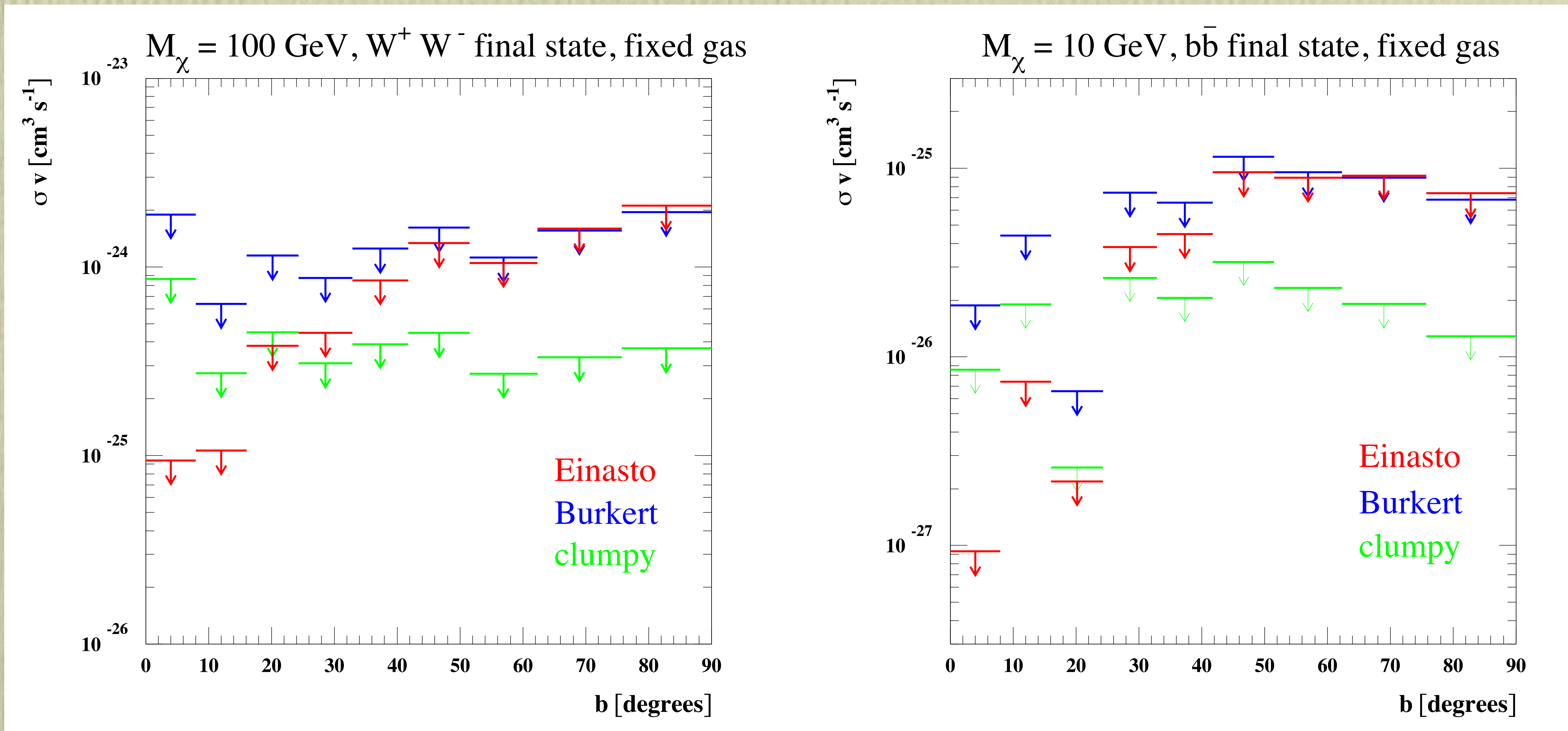


Back on γ-ray predictions

Project the limit into latitude bins and translate them from the sample Einasto halo profile into other possibilities:



$\rho_{\rm Ein} \propto \exp\left[-\frac{2}{\alpha}\left(x^{\alpha}-1\right)\right]$ $\quad \rho_{\rm Bur} \propto \frac{1}{(1+x)(1+x^2)}$ $\quad$ clumpy: $\mathcal{N}_{\rm pairs} \propto \rho$

All normalized to a local halo density: $\rho(R_{\odot}) = 0.4\,{\rm GeV\,cm^{-3}}$

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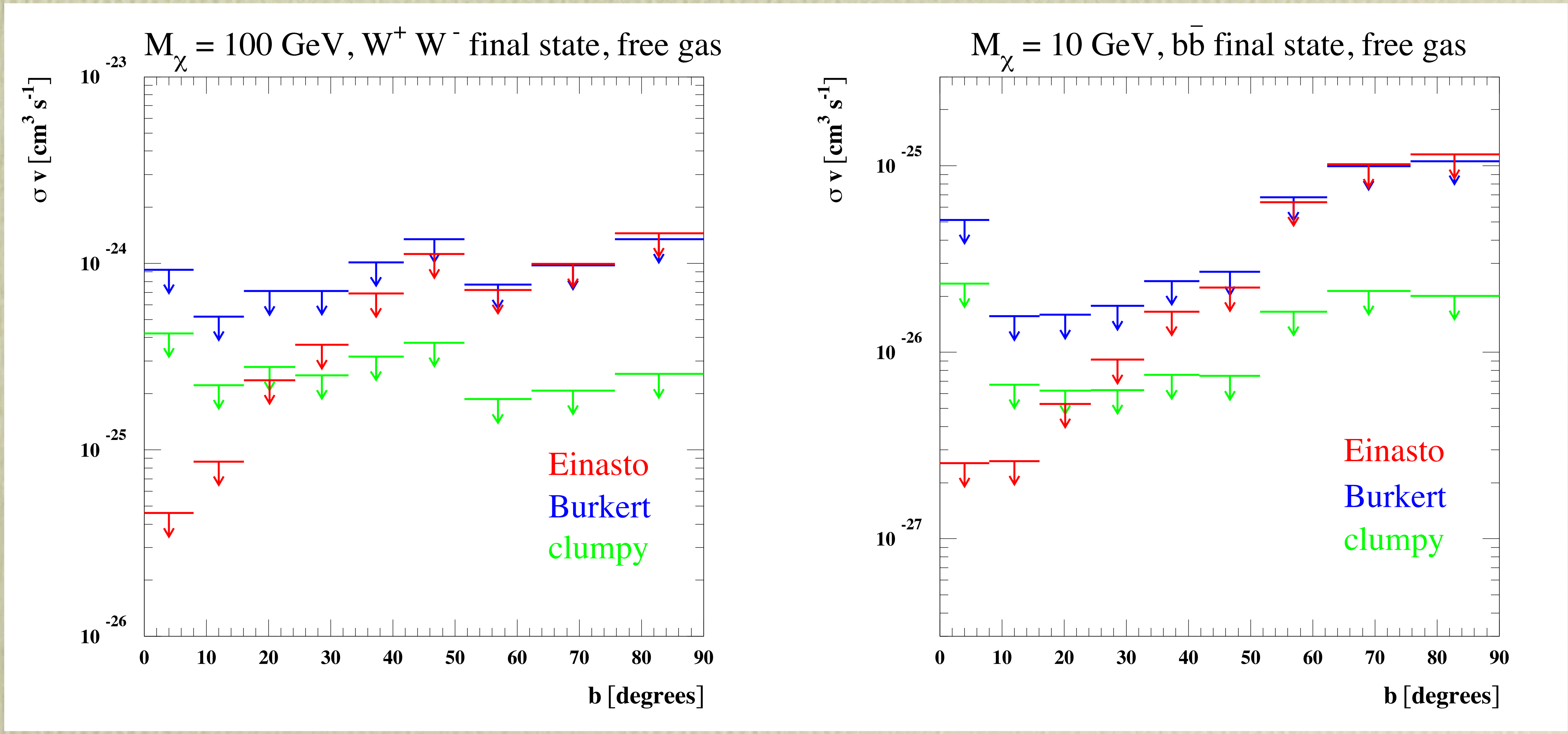

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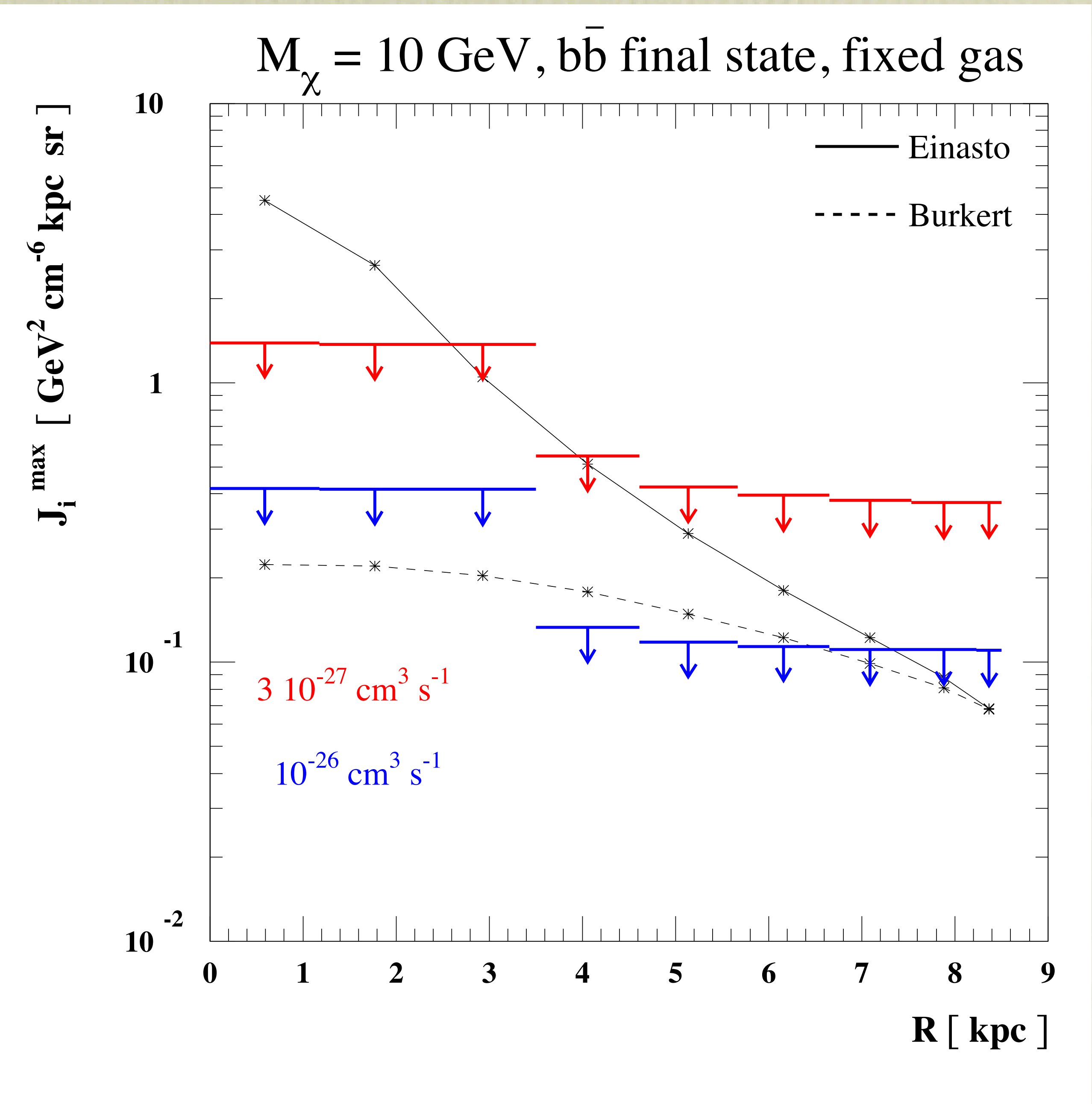
Back on γ-ray predictions

Play it even harder and define the density profile as log-log interpolation of a set of discrete values ρ_i at the galactocentric distances r_i corresponding to the radii at the tangential points in the latitude bins. Assume also that the profile is monotonic and that:

$$\rho(r) = \rho_{\mathrm{Ein}}(r) \quad \text{for} \quad r > R_\odot$$

Fix the annihilation rate, and generate a random sample of ρ_i, testing whether each configuration is excluded by the flux limits in all latitude bins. For all surviving models, consider the bin encompassing the GC and compute the line of sight integration factors J_i obtained by imposing that the density profile is constant below r_i. Plot the maximum of J_i in the sample and compare it to the analogous quantity for the preferred parametric profile:



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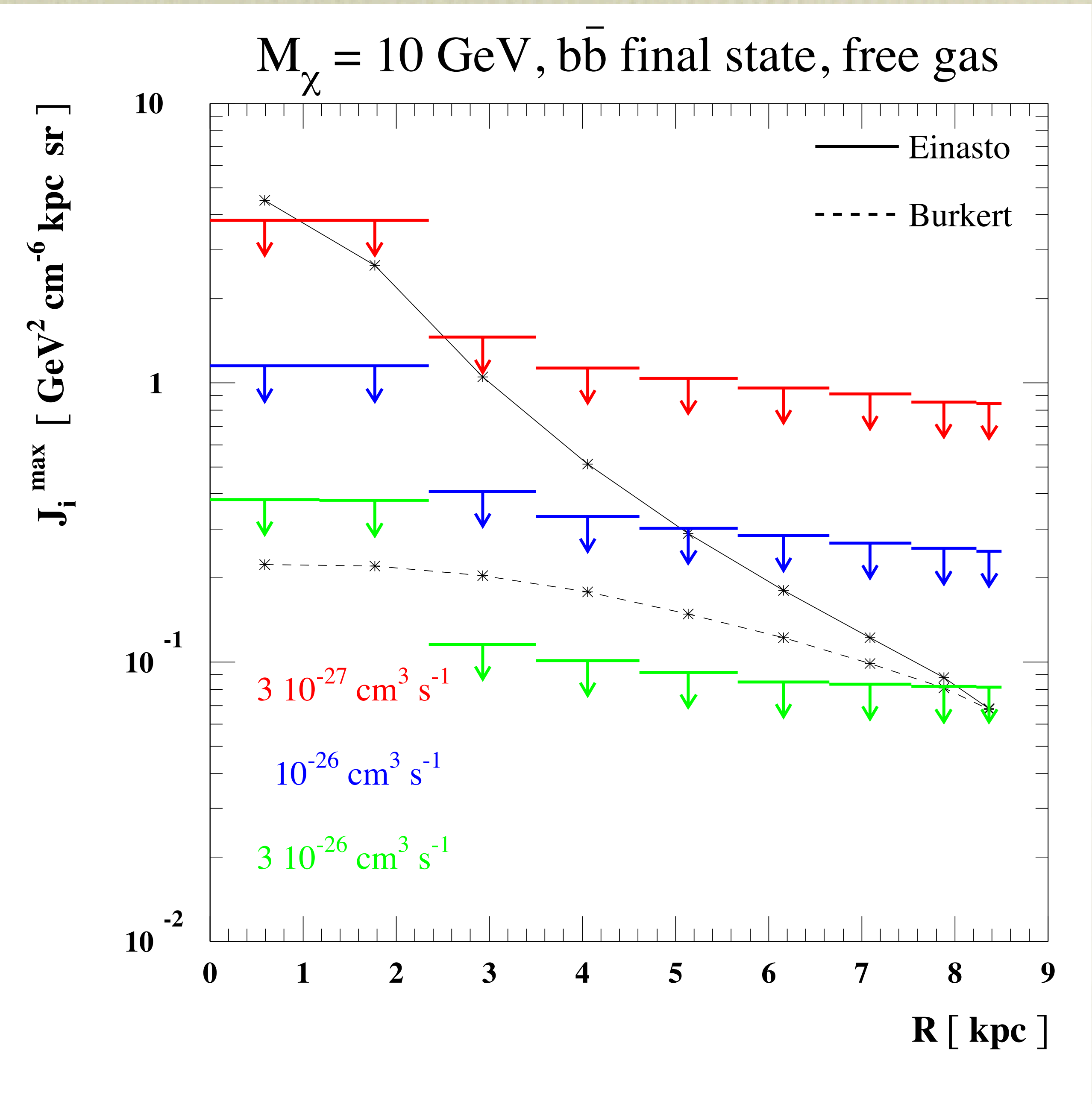
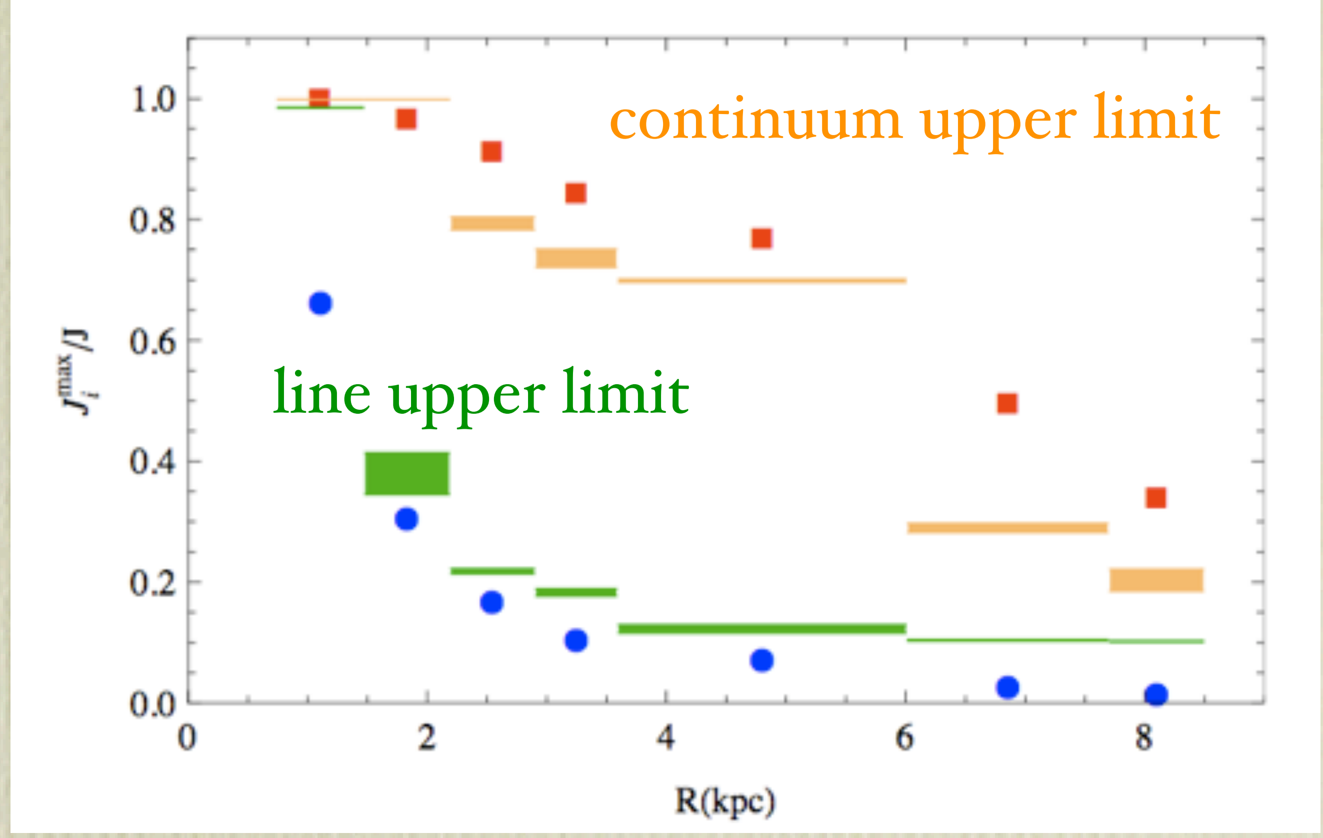


Back on γ-ray predictions

A rather powerful visual method to understand how deep towards the Galactic center you need to trust the extrapolation of a given density profile for your limit to hold. If you are addressing a GC excess you want to explain in terms of dark matter annihilations, the method allows to discriminate among different density profiles.

E.g.: in case of the γ-line signal:

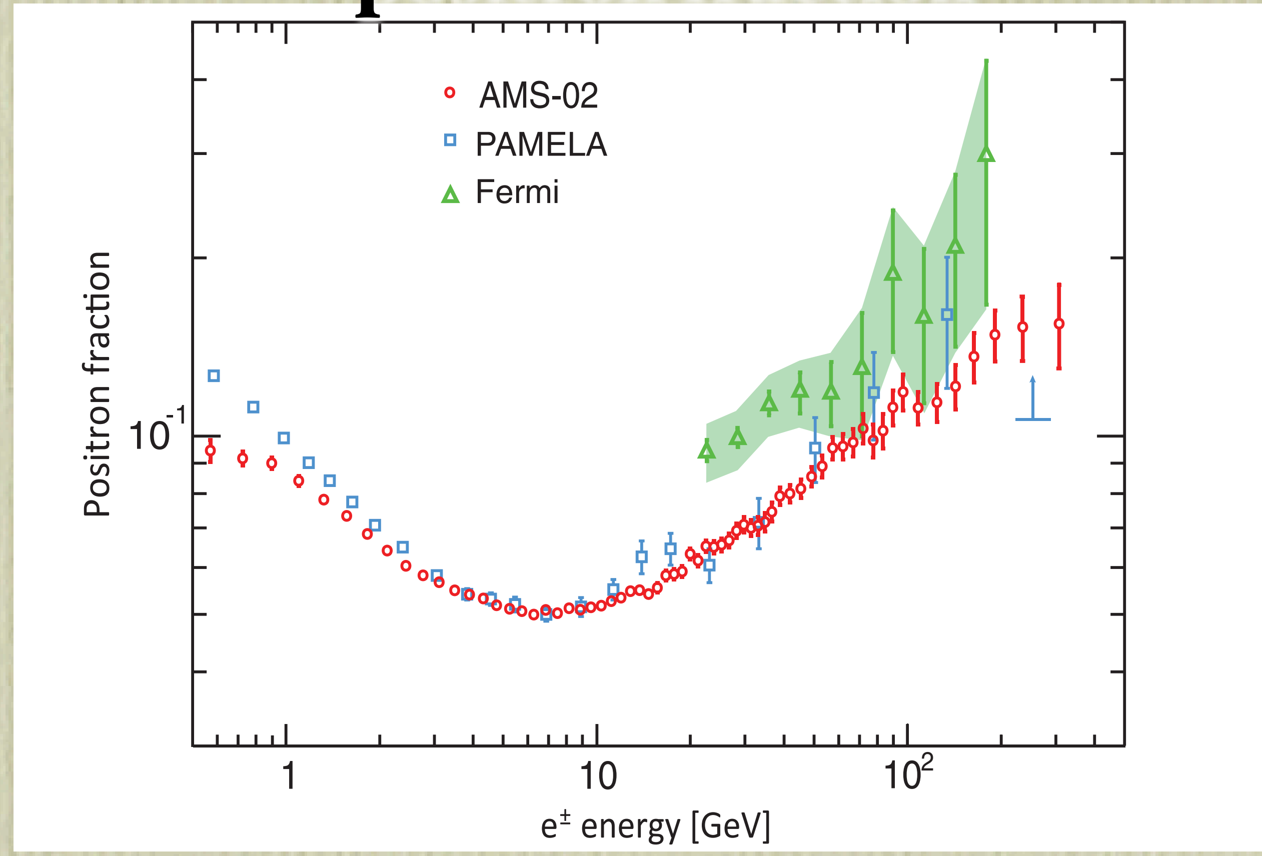
Maximum partial contribution to the l.o.s.i. factor towards the GC due to DM annihilations at radii larger than R (red: partial contributions for a Burkert profile; blue: for an Einasto profile)



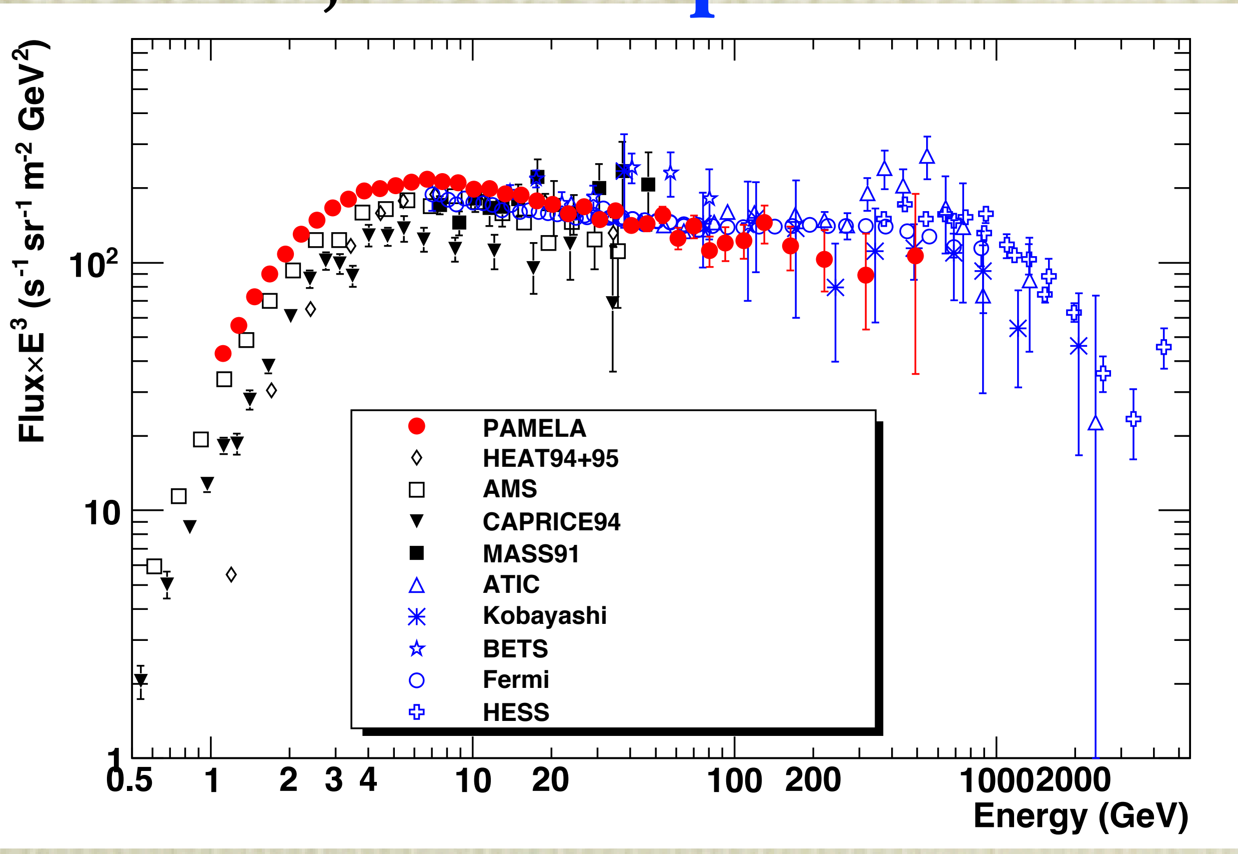
Cholis, Tavakoli & P.U., arXiv:1207.1468

What about the lepton puzzle?

positron fraction



electron, electron+positron fluxes

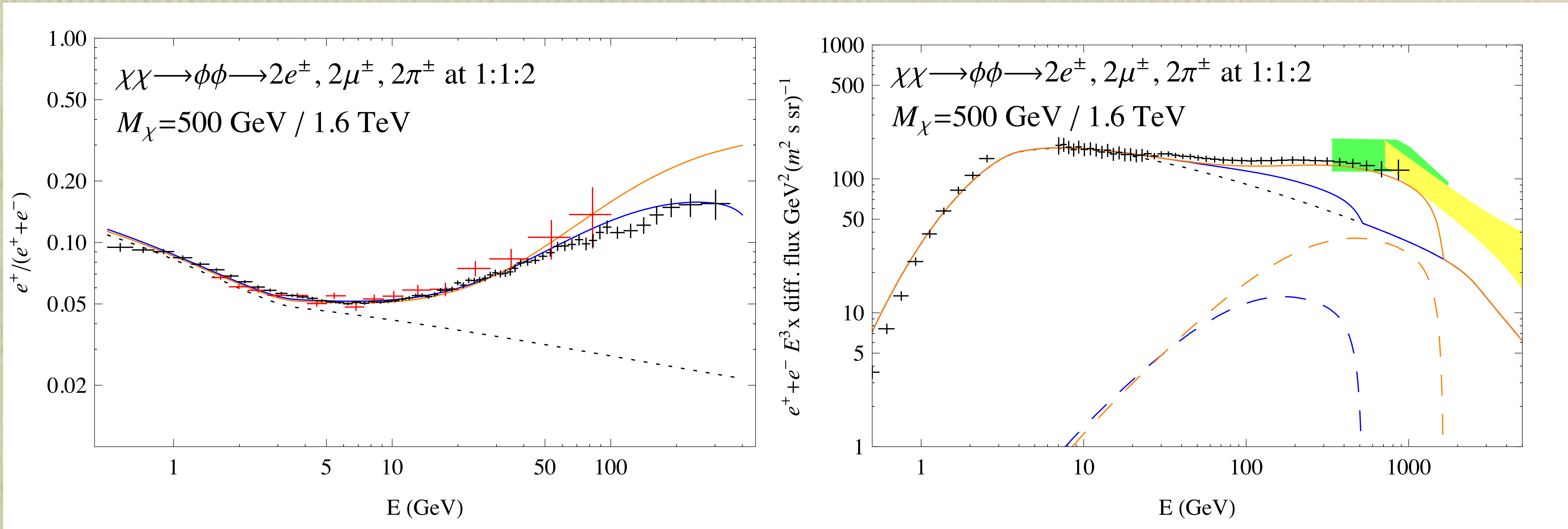


From the spectacularly precise recent measurements of the leptonic components in cosmic ray, by AMS02, Pamela, Fermi, ..., we learned that the picture with electrons as primaries from SNRs and positrons as secondaries from the interaction of CRs on the ISM is wrong!

You need extra (hard) positron sources and they need to be close to us (because 100 GeV - few TeV leptons lose energy on short timescale). In most cases WIMP DM does not have the correct spectrum; you saturate the observed spectra, e.g., with pulsar sources and get a competitive WIMP limit.

What about saturating the extra component with DM only?

A hard component (from AMS data possibly slightly softer than from Pamela data) in fair agreement with measurements, can still be obtained from toy models of annihilating WIMPs, e.g.: **Cholis & Hooper, arXiv:1304.1840**



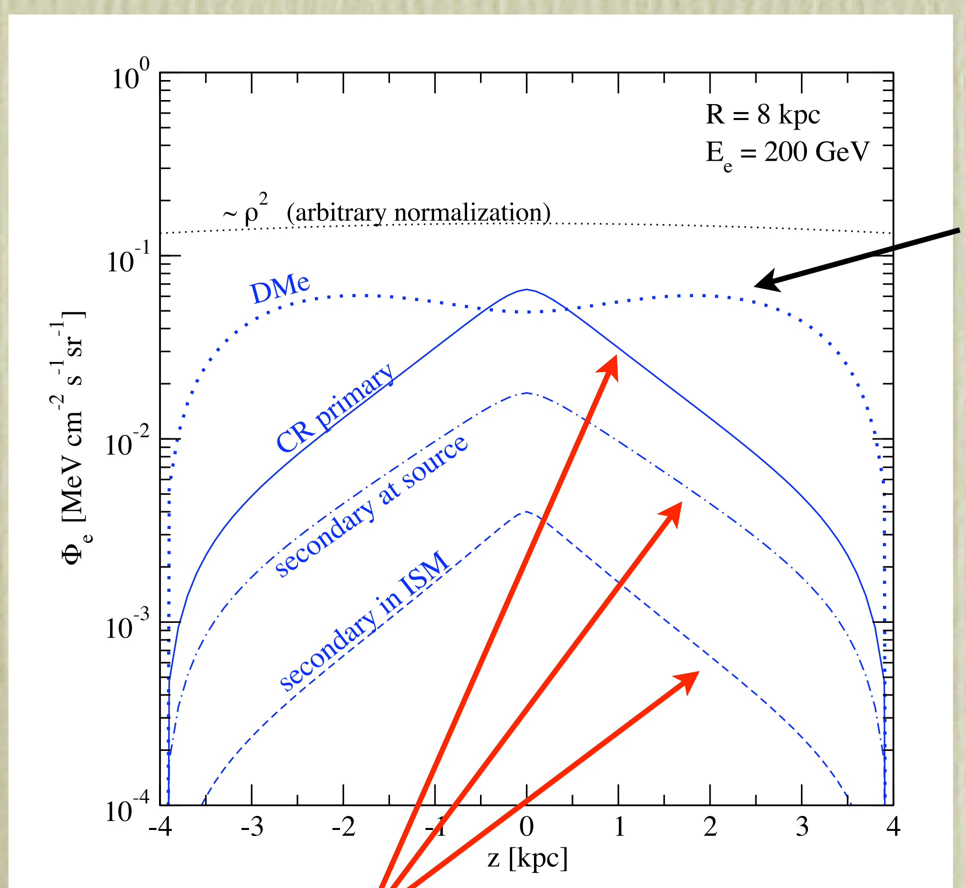
Not really a "vanilla" WIMP. You need: i) a large boost factor in the cross section compared the level at thermal freeze out ($1.5 \cdot 10^{-24}/1.3 \cdot 10^{-23}\mathrm{cm}^3\mathrm{s}^{-1}$ in the example above) or in local density of WIMP pairs (substructures???); ii) a (combination of) leptophilic annihilation channel (hard from the model building point of view, possibly enforced via kinematics, see e.g.: **Arkani-Hamed et al., arXiv:0810.0713; Nomura & Thaler, arXiv:0810.5397**)

Testing the DM hypothesis against other possibilities?

• Very hard from CR lepton data alone; possible falsification of the DM hypothesis from the detection of angular anisotropies in the flux (still one should be confident about modeling propagation in the local environment).

• In principle possible by looking at the radiative emissions associated to the extra lepton components. Sources confined to the disc (as in case of pulsars) or spread out in the whole diffusive halo (as for DM annihilations) produce very different vertical lepton density profiles:

Regis & P.U., arXiv: 0904.4645



versus a DM term extending to much larger z

Primary/secondary astrophysical components mostly localized at z≅0

High-latitude inverse Compton and synchrotron profiles are sensibly different in the two case and should be distinguishable in the future.

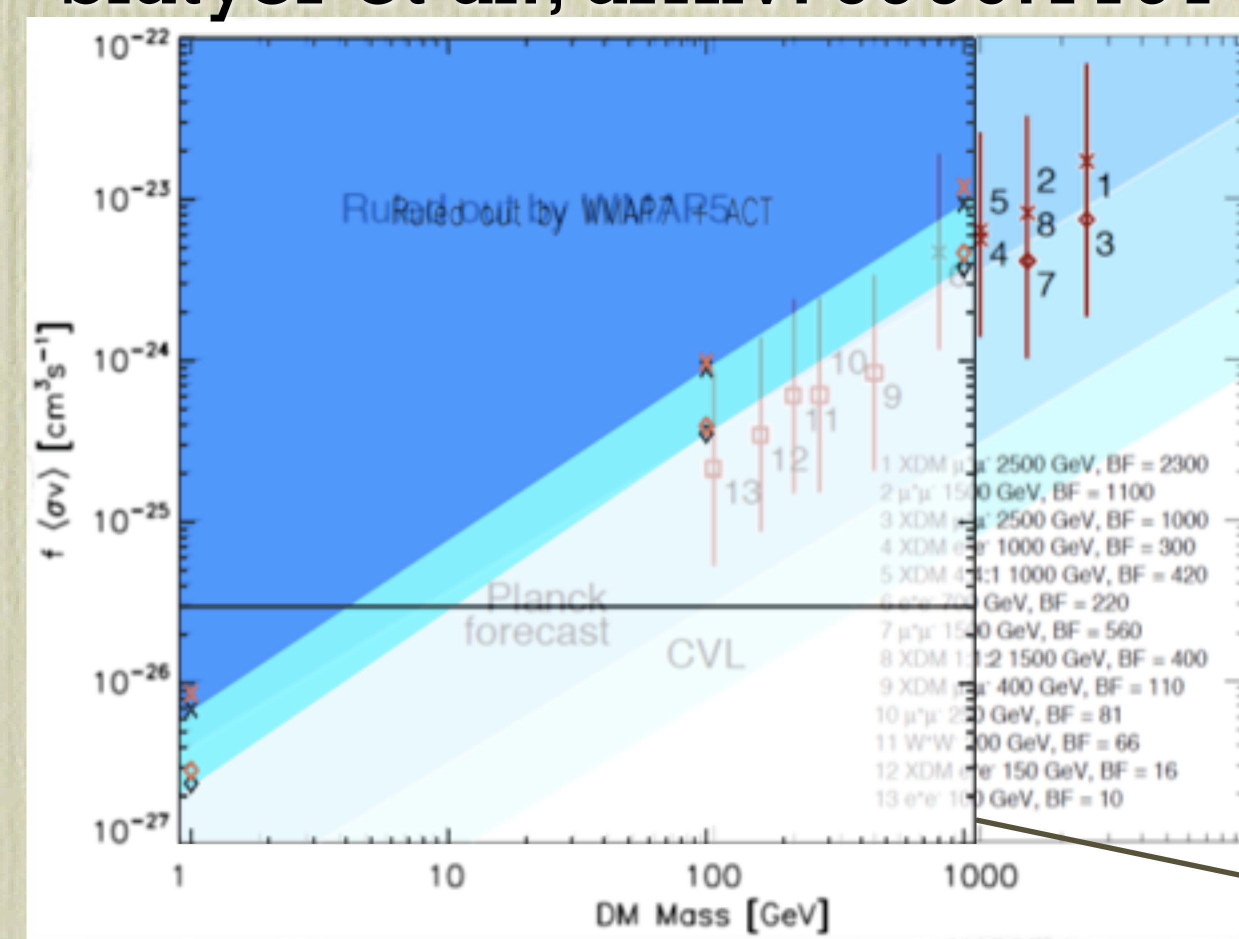
Testing the DM hypothesis against other possibilities?

• Consistency checks are also possible looking at radiative emissions from the central region of the Galaxy, however these are much more model dependent. In particular they heavily rely on what extrapolation one takes for the dark matter distribution from the local neighborhood to the the Galactic center and on magnetic fields + energy losses models; in case of Einasto profile, the tension with currently available radio data is very severe (e.g. Bertone et al. 2009).

• Limits from "polluting" the early Universe with DM yields:

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

Slatyer et al., arXiv: 0906.1197



Galli et al., arXiv:1106.1528

Summary and conclusions

• There is limited information on dark matter particles one can extract from cosmological astrophysical observations, still it is not excluded that on top of the indirect evidence for dark matter, they may give indirect evidence for dark matter particles

• The WIMP paradigm is still relatively healthy after the first rounds at the LHC, however one may have to abandon some of the cornerstones such as naturalness

• Clean signatures for WIMP indirect detection with γ-ray telescopes are being tested or will be tested in the near future

• Would clean WIMP signature unavailable, the key would be to efficiently combine multi-messenger and multi-targets signals; such synthesis however may be particularly delicate.