The quest for indirect dark matter detection: a critical outlook

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SISSA & INFN Trieste

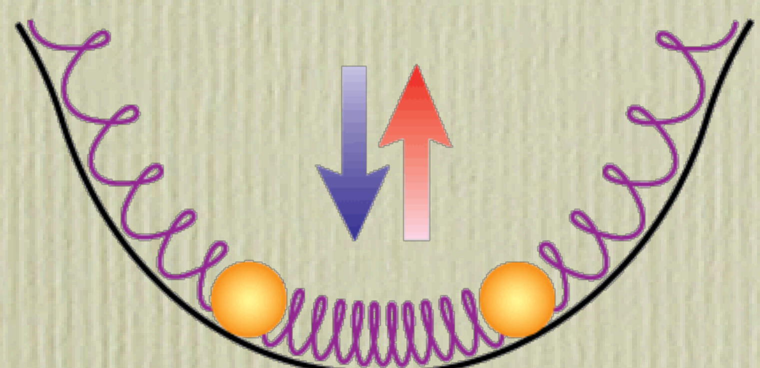
Oslo, November 25, 2015

Dark matter (indirectly) detected!

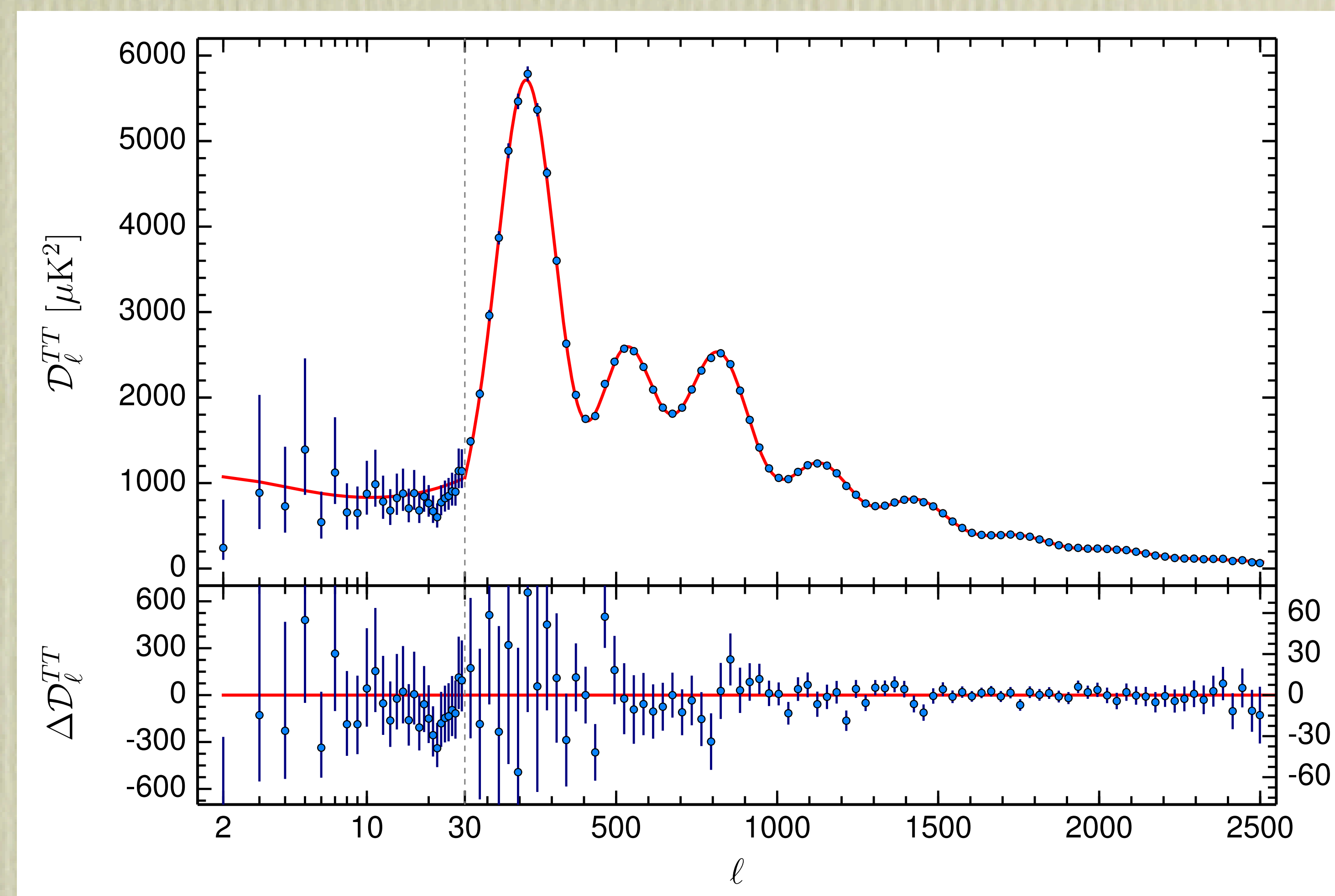
Plenty of (gravitational) evidence for non-baryonic cold (or coldish - as opposed to hot) DM being the building block of all structures in the Universe. E.g.:

Planck 2015: $\Omega_{\rm CDM}h^2 = 0.1198 \pm 0.0015$

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



Credit: W. Hu website



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!

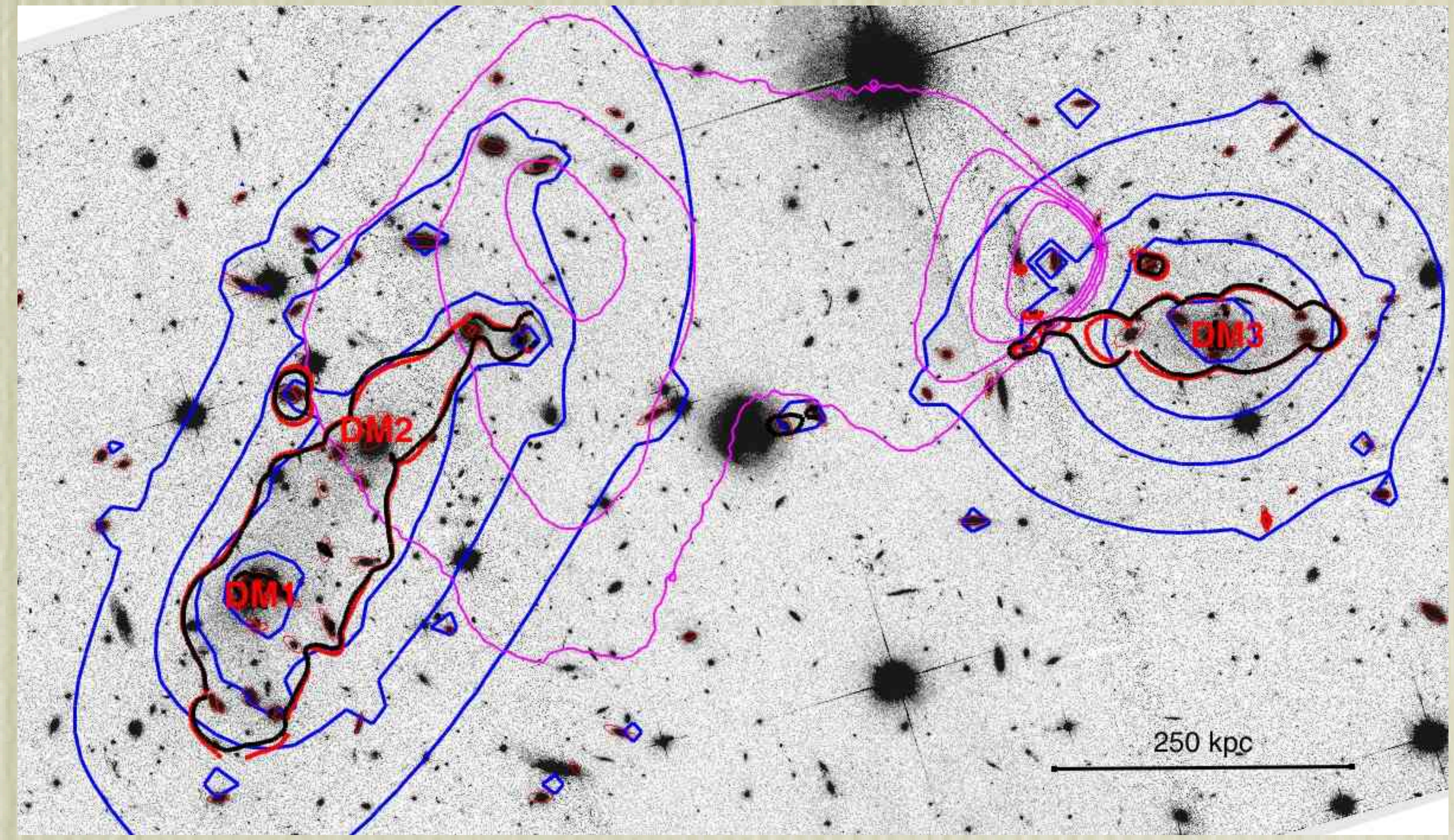
Plenty of (gravitational) evidence for non-baryonic cold (or coldish - as opposed to hot) DM being the building block of all structures in the Universe. E.g.:

Bullet cluster:

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

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

Paraficz et al, 2013



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?

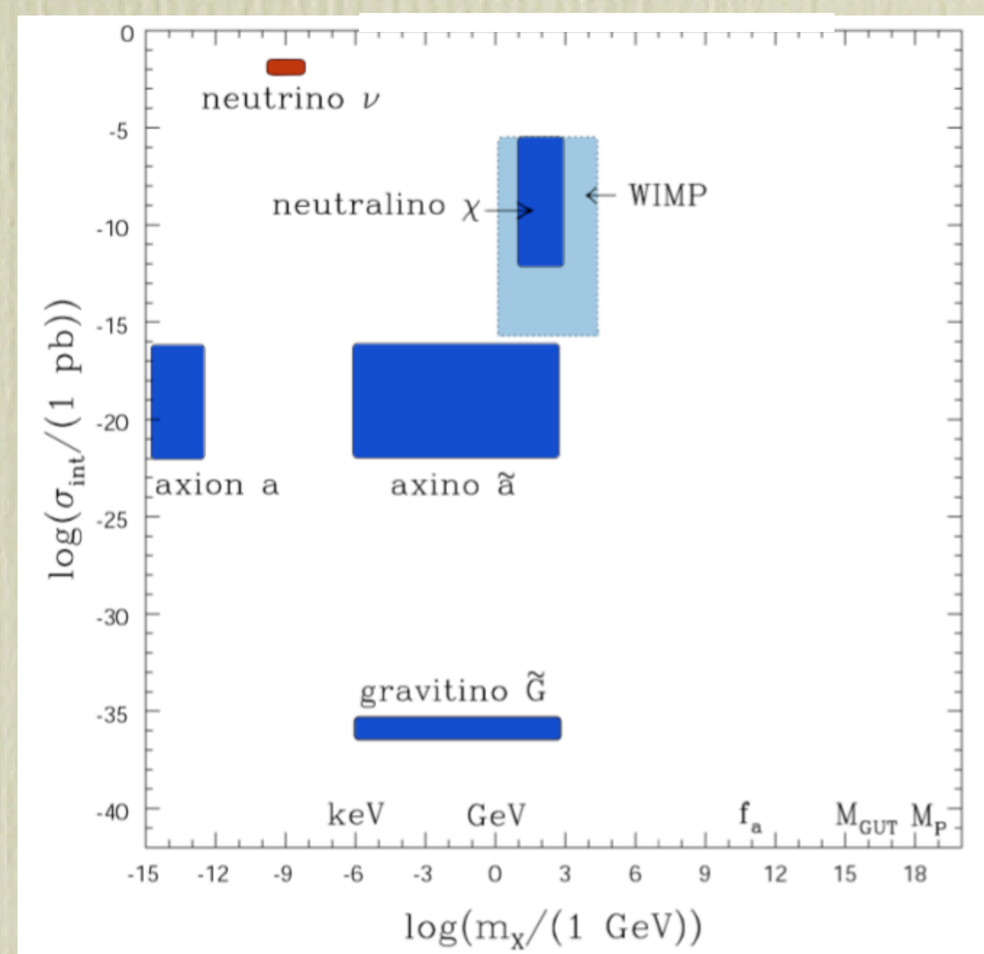
(review: Bertone, (ed.) e al., 2010)

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

$$\Omega_{\rm CDM} h^2 = 0.1188 \pm 0.0010$$

(Planck, 2015 + BAO, SNe Ia, ...)

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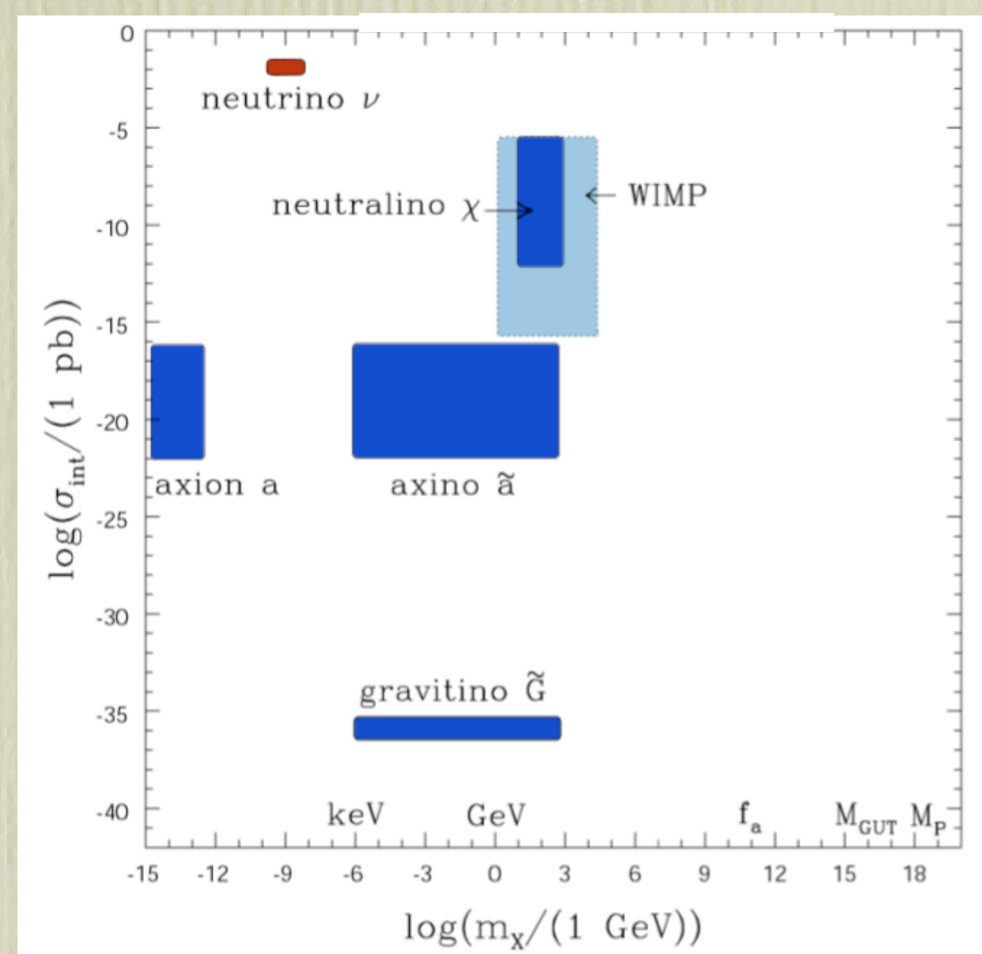
E.g.: from the CMB, limits on eventual DM electromagnetic couplings and on the DM heating of the plasma at (moderately) recent times, and, from the Bullet cluster, limits on the self-interaction of DM particles

just a subset



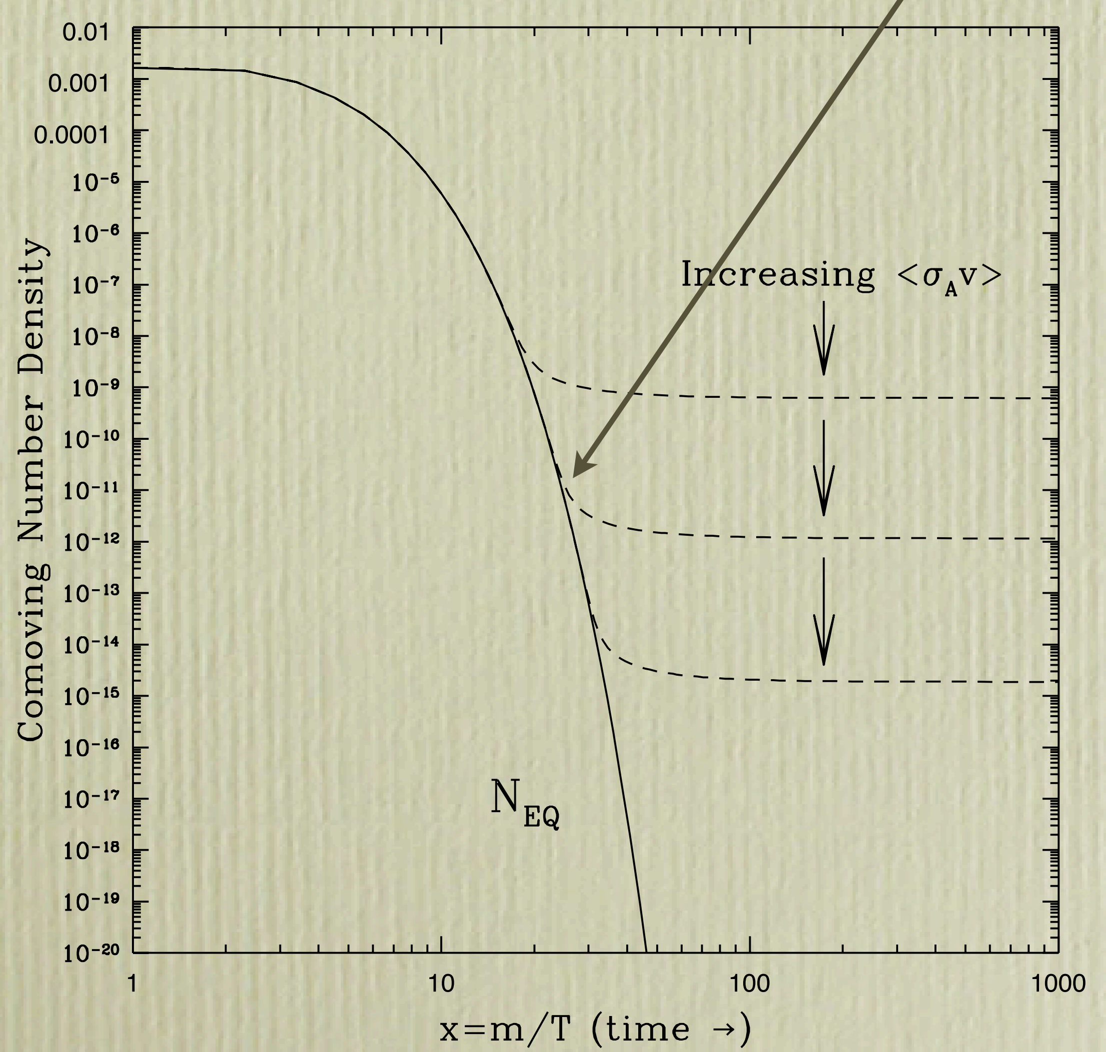
Credit: L. Roszkowski

Signals of DM particle annihilations or decay

In several frameworks for DM candidates and for early Universe DM production mechanisms, one predicts (in principle) detectable signals from the pair annihilation or the decay of particles in dark matter halos.

A very popular scenarios: Weakly Interacting Massive Particles (WIMPs) as early Universe thermal relics:

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



the WIMP "miracle":

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

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

Sizable couplings between DM and "visible" yields occurring also, e.g., in freeze-in or non-thermal production scenarios.

Signals of DM particle annihilations or decay

Look at those yields with clean spectral/angular signatures and/or low or well-understood backgrounds from standard astrophysical sources.

Proposed detection channels include: antimatter (antiproton, antideuteron and positron cosmic-ray fluxes at earth), neutrinos (annihilation/decays in DM halos, or at the center of the earth, the sun or other stars) and photons (prompt or radiative emission).

The most straightforward case is **GeV-TeV DM** particles inducing a **prompt γ-ray signal**: photons propagate on straight lines (geodesics) & absorption by the local environment is negligible in this band. For a given target, just sum all contributions along the line of sight!

Only one "astrophysical" uncertainty term, to be factorized with respect "particle physics" uncertainties (emissivity efficiency and spectrum of the γ-ray yield per annihilation/decay). In case of pair annihilations:

$$J \equiv \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_{l.o.s.} dl\ \rho^2_{DM}(l)$$

with the DM density in the target ρ_{DM} inferred from dynamical observations or numerical simulation of DM halos.

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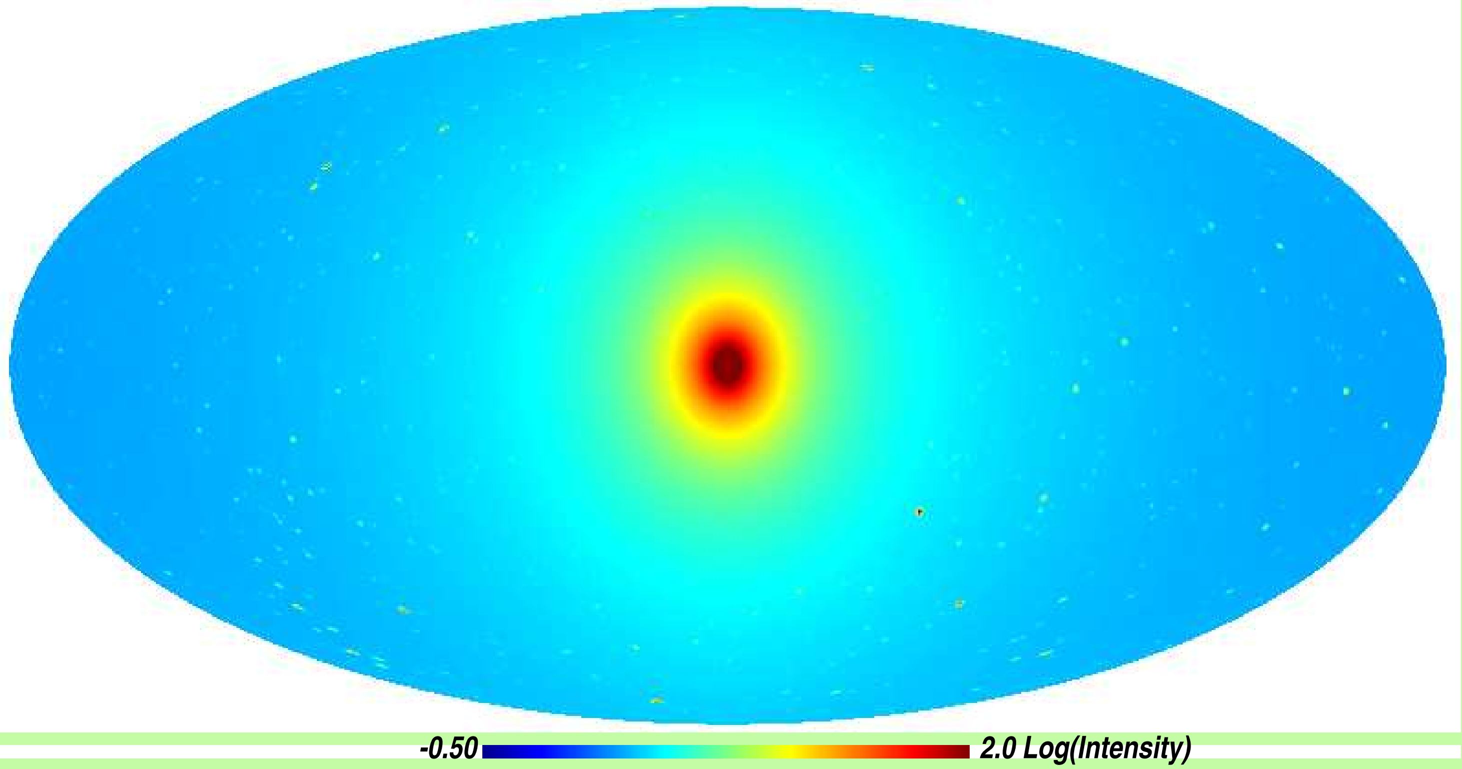
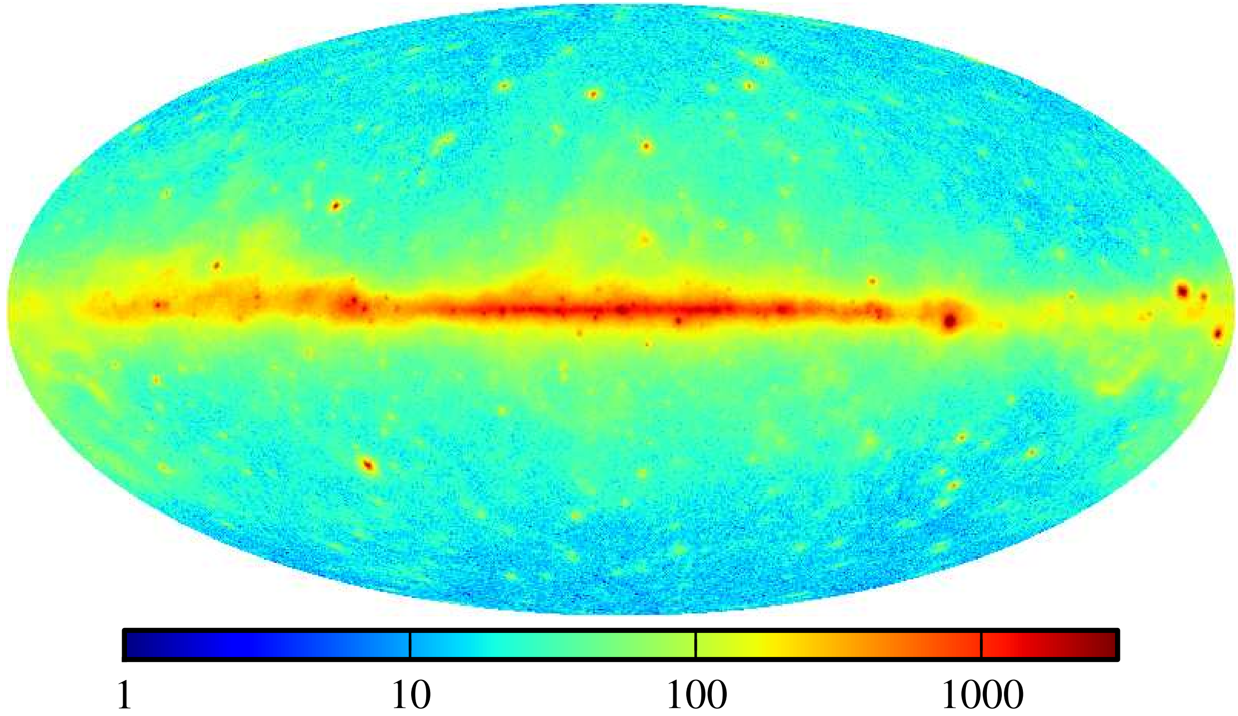
J-factor for the Milky Way (?):

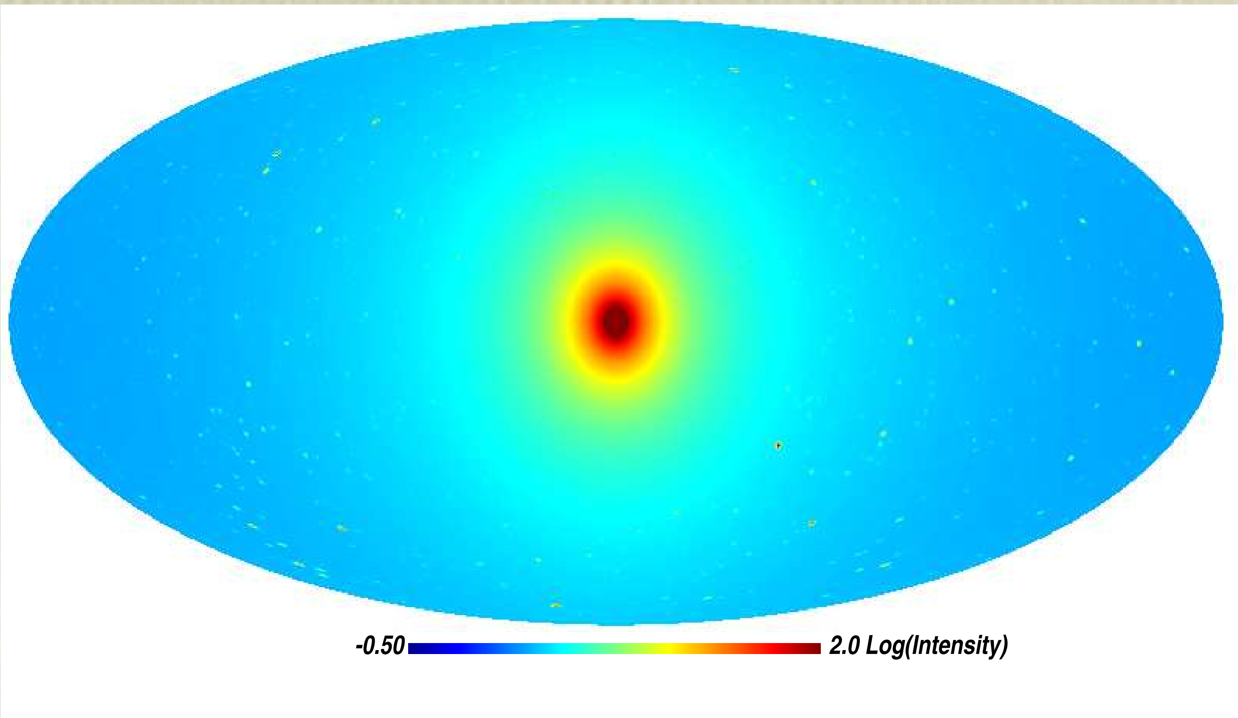


Springer et al., 2008: Acquarius simulation for a Milky-Way-type galaxy

DM γ-ray signals versus γ-ray data

A dramatic improvement in quality and energy coverage of γ-ray data in recent years, due to Air-Cherenkov telescopes and satellites detectors, most notably the Fermi Gamma-ray Space Telescope:





Fermi Coll., 2012: galactic diffuse emission: counts in 200 MeV-100 GeV, after subtracting point sources, isotropic extragalactic flux & instrumental background; it accounts for about 70% of total # of counts

clearly a very poor match with a DM annihilation template if assumed as dominant emission component

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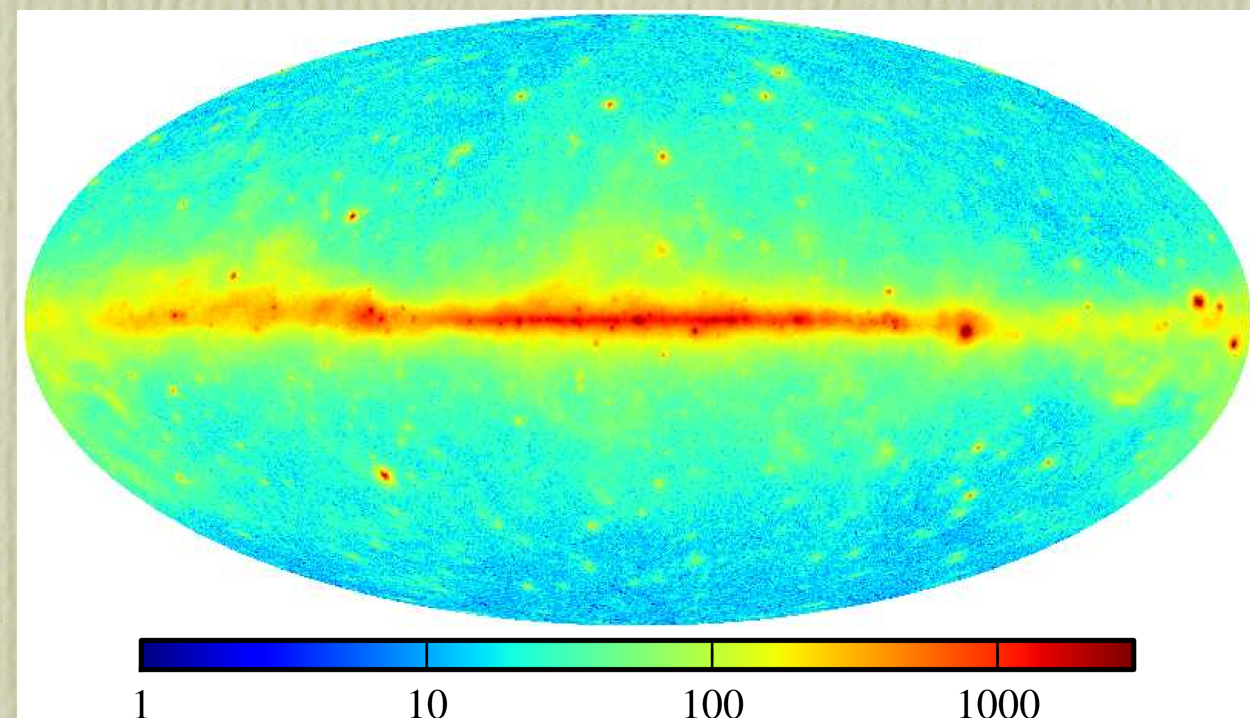

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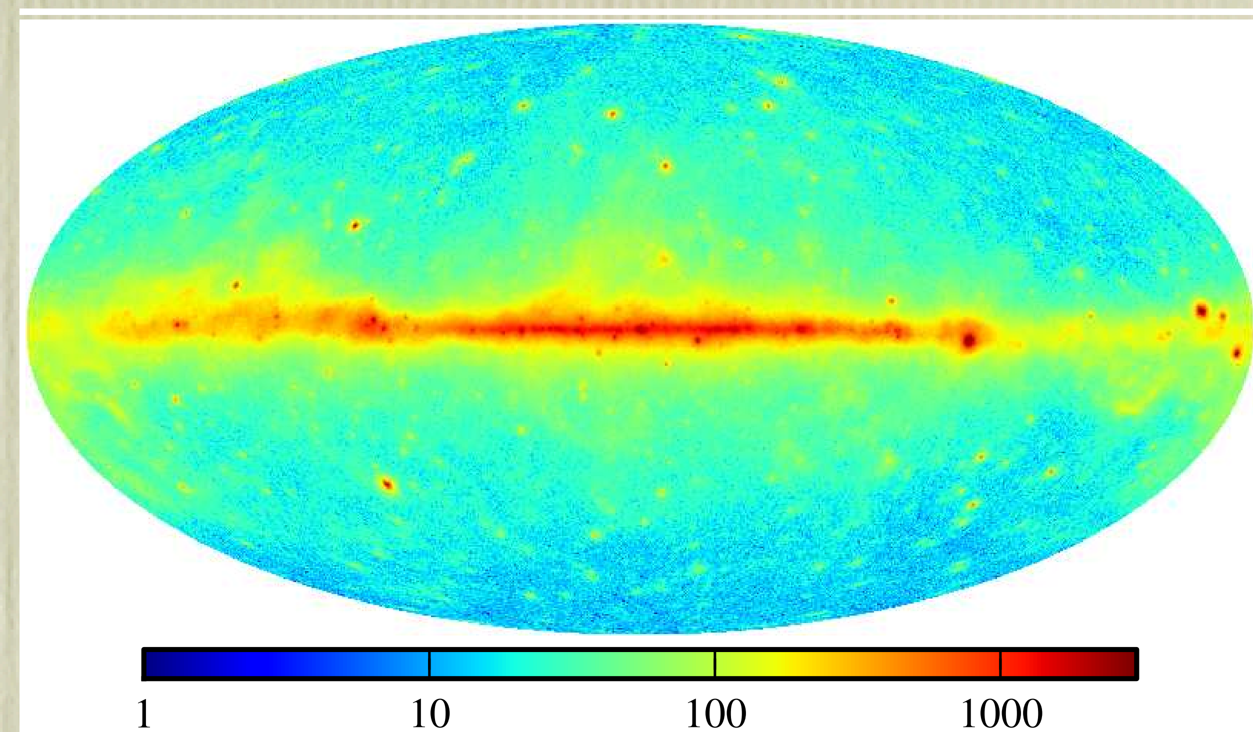

prediction (postdiction ?) of counts for the **Galactic cosmic-ray** emissivities in model ${}^{S}S^{Z}4^{R}20^{T}150^{C}5$ **Fermi Coll., 2012**

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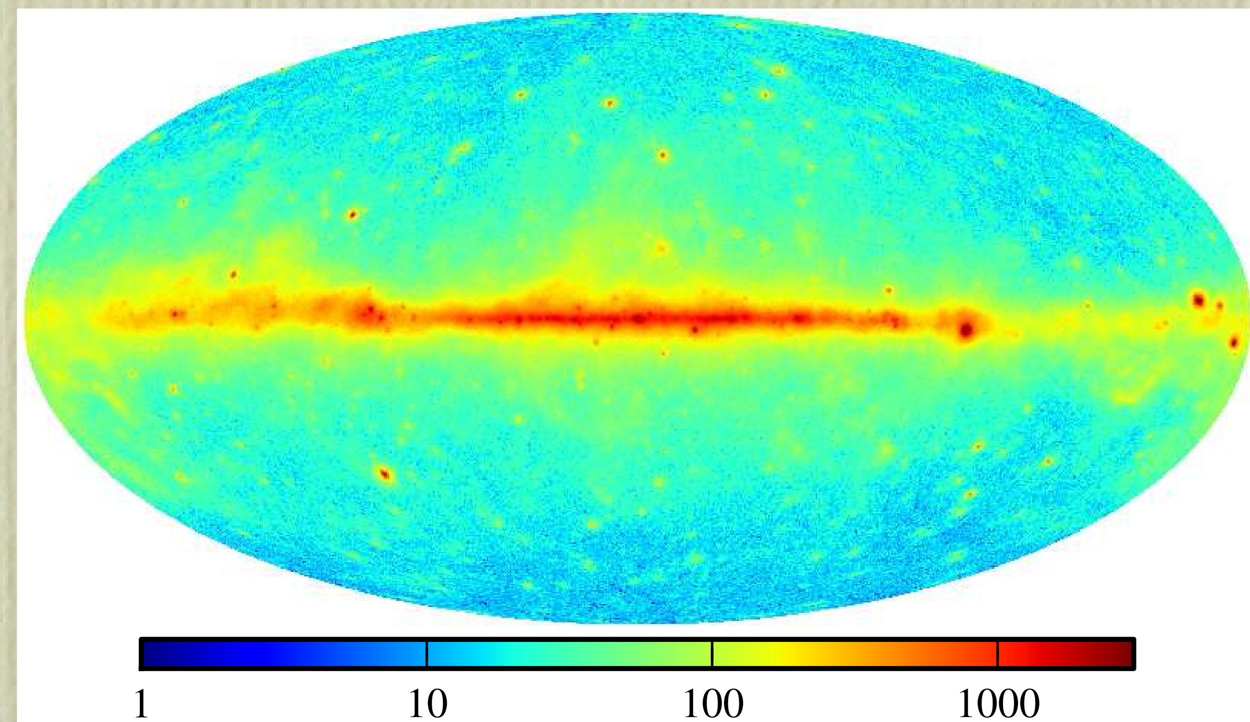

data

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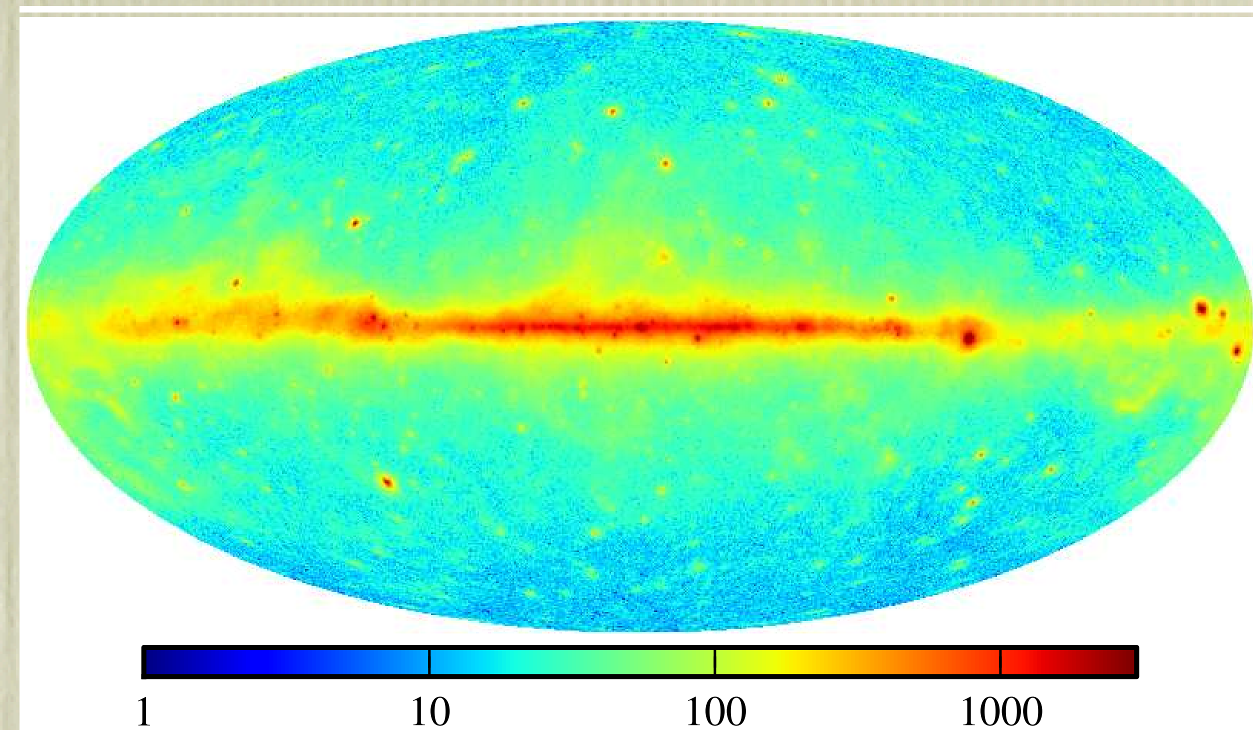
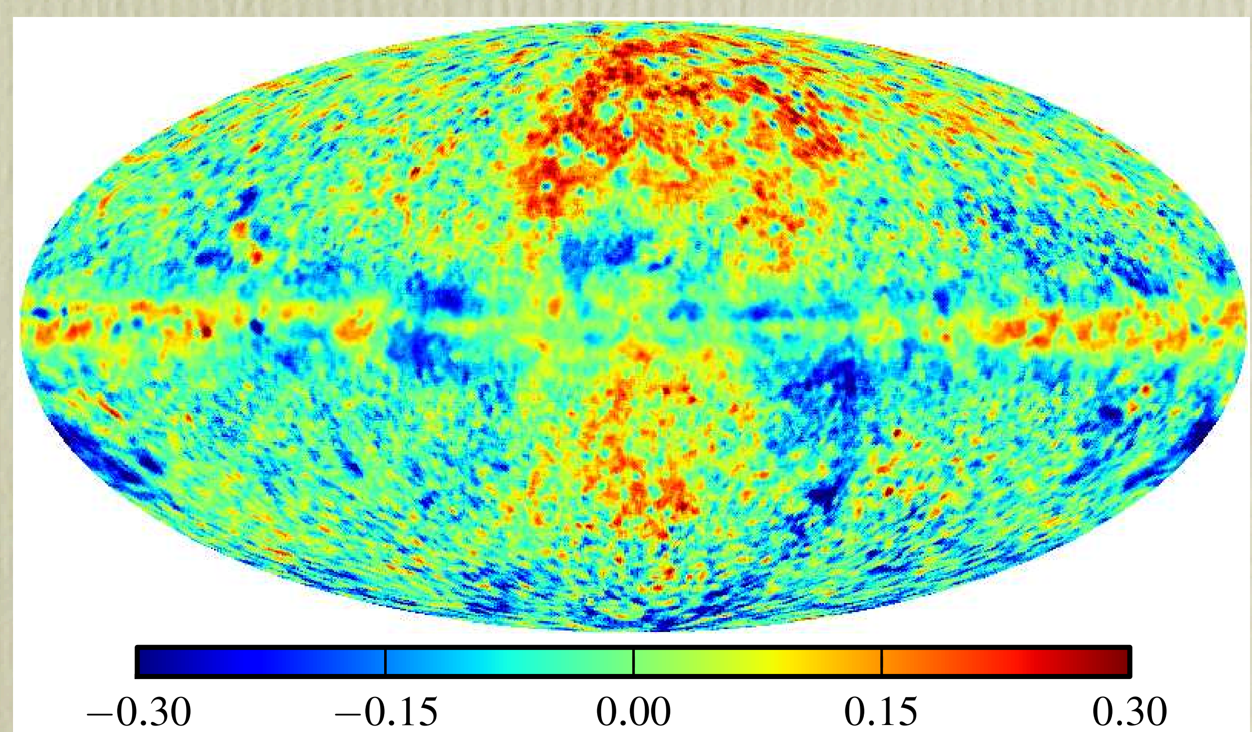


$^{S}S^{Z}4^{R}20^{T}150^{C}5$

=

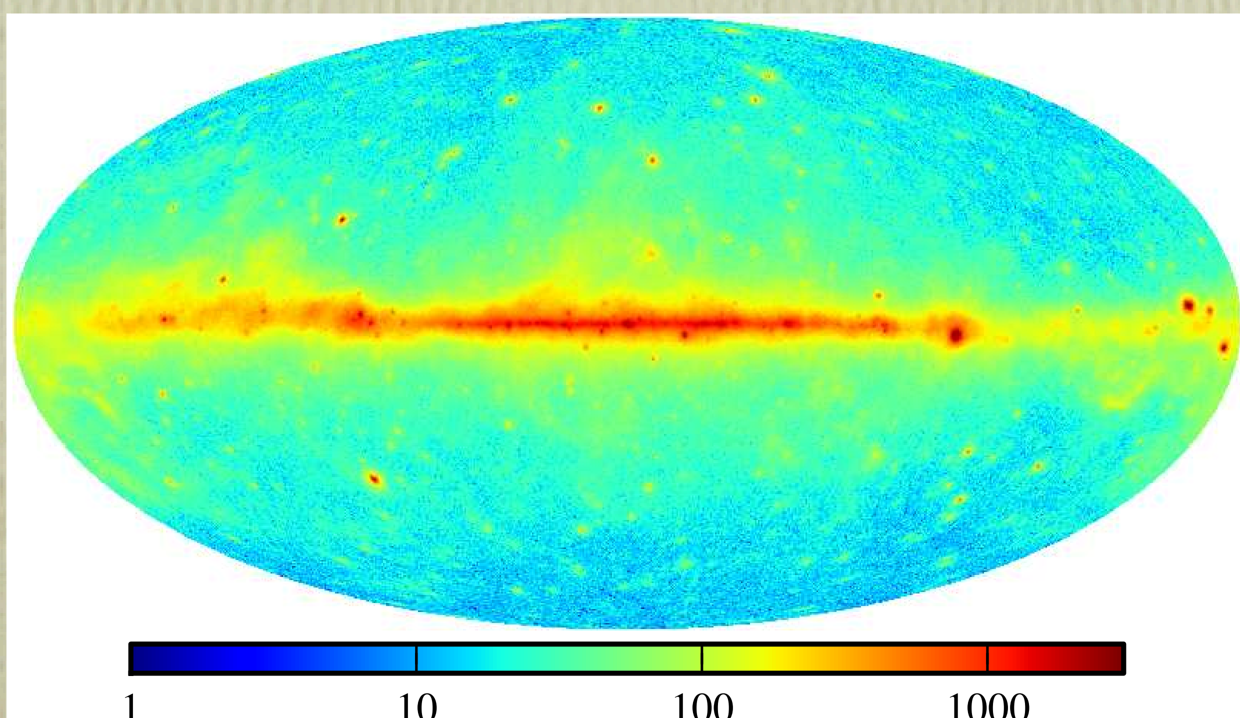
Fractional residuals



After including templates for local features and the so-called Fermi Bubbles + little extra tuning, residuals shrink to below about 10%

A subdominant DM term in γ-ray data?

The DM signal does not stand clearly above the background from other standard astrophysical processes (unfortunately this is the case in any of the tested indirect DM detection channels). What about identifying anyway the DM source as a small contribution on top of the bulk of emissivity due to cosmic rays?



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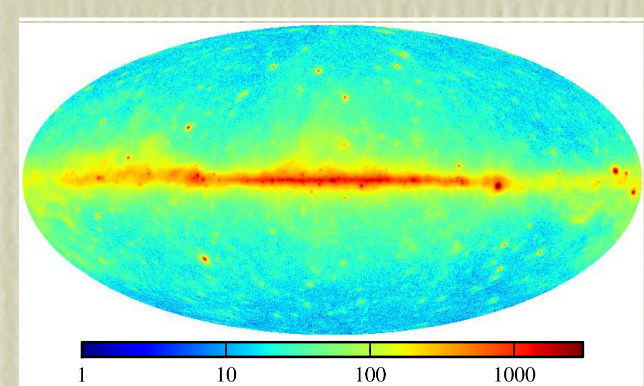
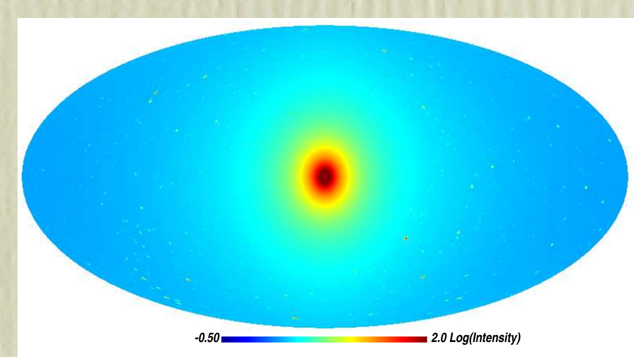


CRs

dominant

+



DM

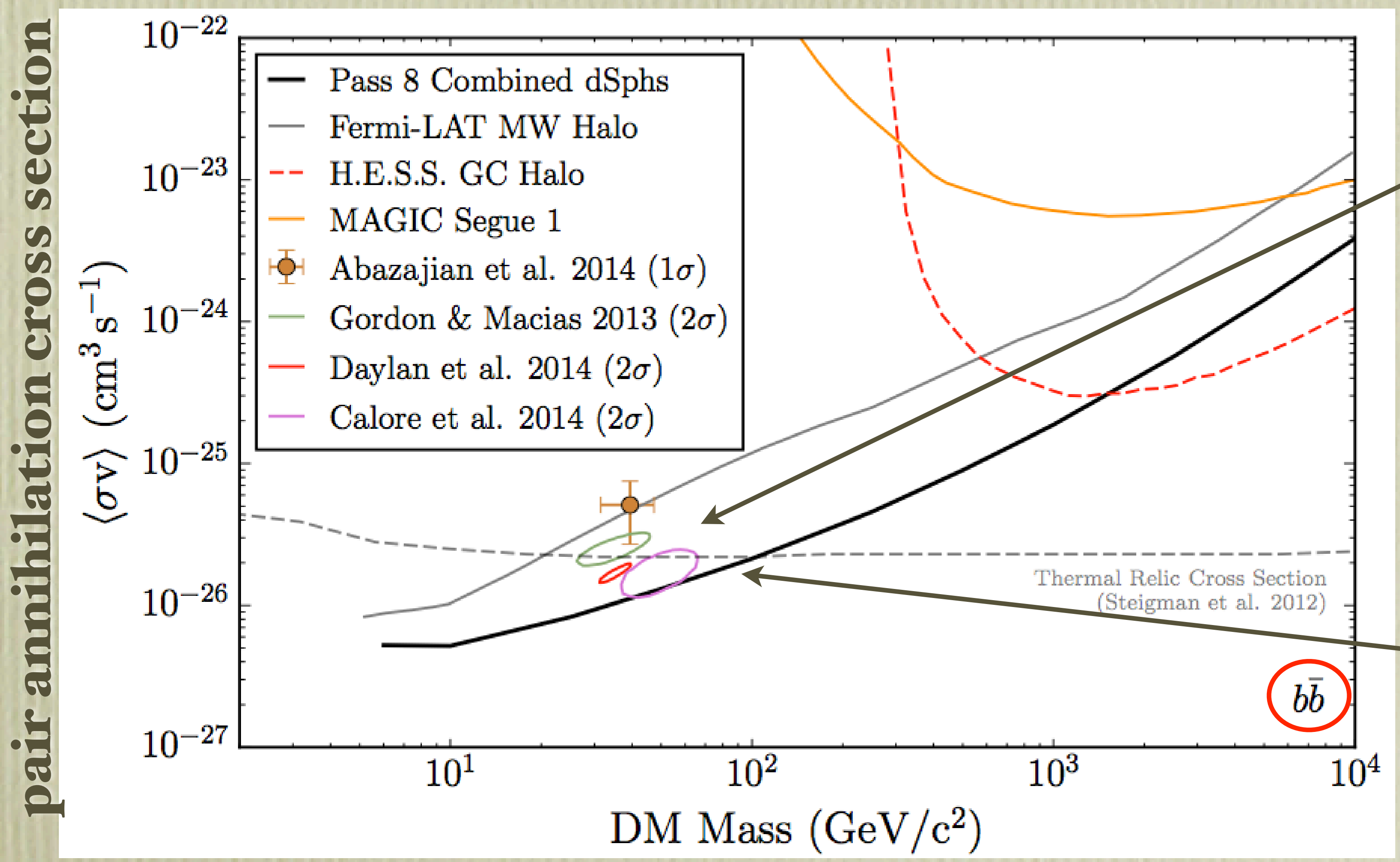
up to 10% contribution?

A route which may lead to unambiguous results only if both signals and backgrounds are well under control!

Two recent results in (apparent) contradiction

- A tentative indication of a DM signal in the inner region of the Galaxy;
- A null detection versus dwarf satellites of the Milky Way (DM matter dominated and cleanest targets from the background point of view), setting a very competitive flux limit.

"Detected" flux and upper limits projected on a plane parametrizing particle physics unknowns: in case of pair annihilations (at given final state)



Hooper et al. 2009-15 + several analyses by other authors: DM Galactic center excess

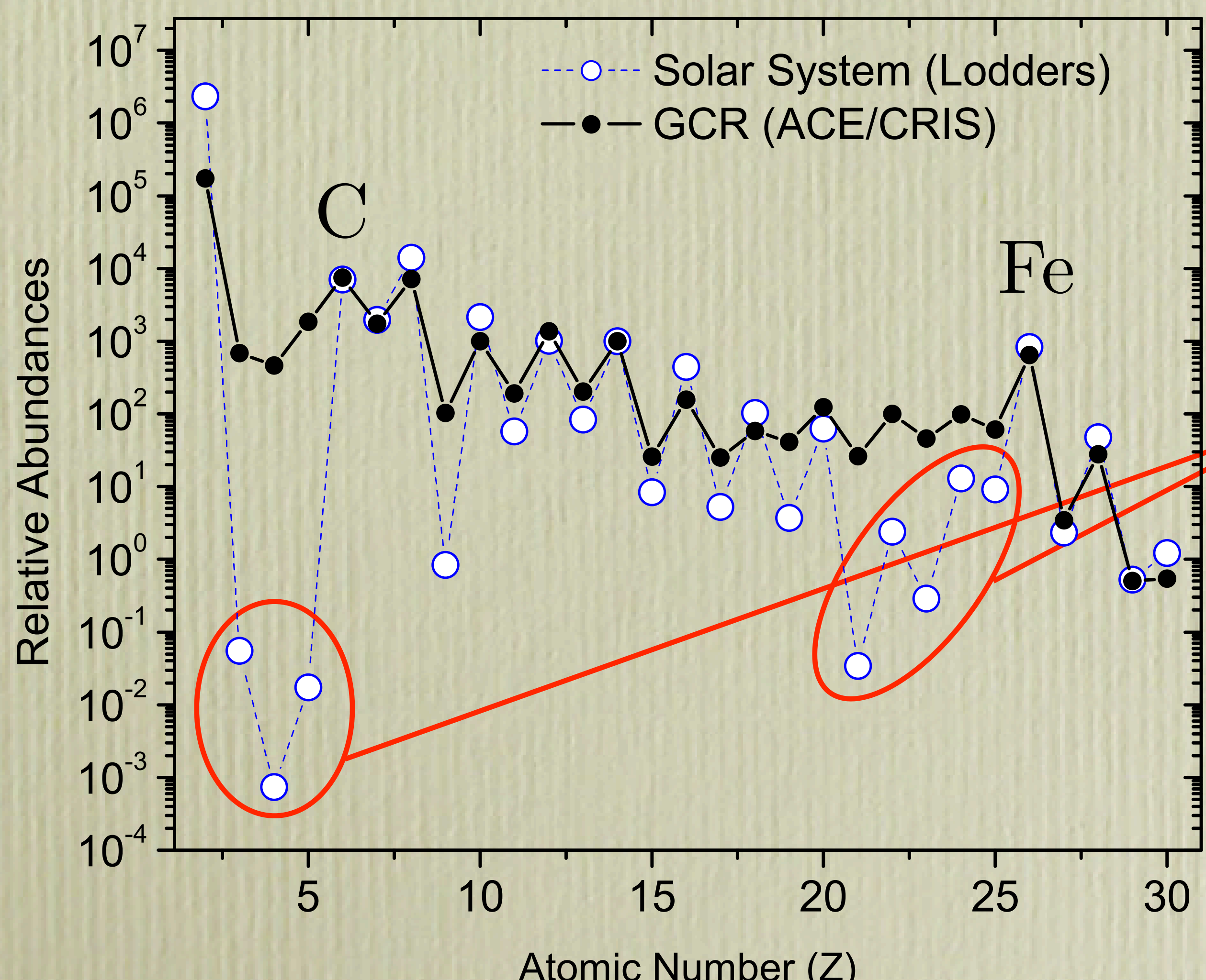
Fermi Coll. 2015: limits excluding thermal cross sections for WIMPs lighter than 100 GeV!

Are these signals and the relative backgrounds under control?

How much do we know about Galactic cosmic rays?

Galactic CRs: high energy (sub GeV to several tens of PeV) charged particles propagating in the magnetic fields of the Milky Way.

CR sources: Primary CRs most likely accelerated in supernova remnants (energetics ok; indirect detection of proton outflows from SNRs from γ-rays), details of the acceleration mechanism under study. Secondary CRs generated in the interaction of primary CRs with the interstellar medium along propagation.



Solar system: representative of nucleo-synthesis in stars, hence of what you can accelerate in SNRs

Deeps in solar system before C and Fe replenished in CRs: secondary elements sourced in spallation processes

$$p + \text{gas} \rightarrow s + X$$

(mainly Hydrogen & Helium)

How much do we know about Galactic cosmic rays?

For **s** and **p** coupled by spallation processes, the corresponding densities:

$$\frac{\mathrm{d}n_p}{\mathrm{d}X} = -\frac{n_p}{\lambda_p},$$

$$\frac{\mathrm{d}n_s}{\mathrm{d}X} = -\frac{n_s}{\lambda_s} + \frac{p_{\rm sp} n_p}{\lambda_p}$$

with: $X \equiv \int_{\rm prop.\ path} dl\,\rho_{\rm gas}$ grammage

$\lambda_i \equiv m/\sigma_i$ interaction length

$p_{\rm sp} \equiv \sigma_{\rm sp}/\sigma_{\rm tot}$ spallation probability

Solution:

$$\frac{n_s}{n_p} = \frac{p_{\rm sp}\lambda_s}{\lambda_s - \lambda_p}\left[\exp\left(\frac{X}{\lambda_p} - \frac{X}{\lambda_s}\right) - 1\right]$$

For **s=B** and **p=C**, being:

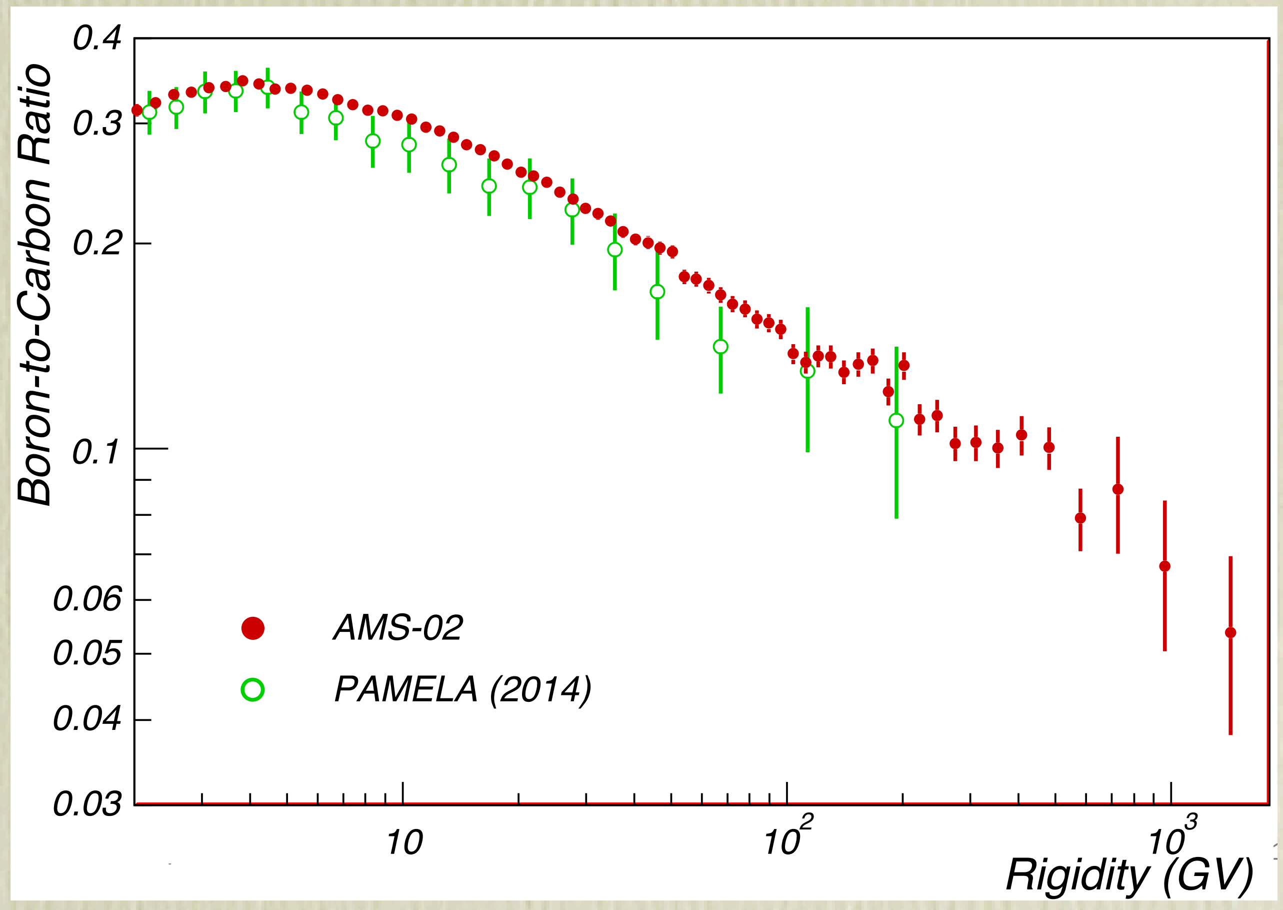
$\lambda_{\rm CNO} \approx 6.7\,{\rm g/cm^2}$ $\quad p_{\rm sp} \approx 0.35$

$\lambda_{\rm LiBeB} \approx 10\,{\rm g/cm^2}$

$\Longrightarrow X \approx 4.3\,{\rm g/cm^2}$ at 10 Gev

this is much larger than for a CR crossing on a straight line the gas disc of the Milky Way:

$$X = m_H n_H h \approx 10^{-3}{\rm g/cm^2}$$



Pamela 2014 + **AMS 2015** preliminary

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The measured B/C ratio shows that CRs of this energy do not propagate rectilinearly but with diffusive mode and residence time (at 10 GeV):

$$t \gtrsim (4.3/10^{-3})(h/c) \sim 1.4 \times 10^{14}\mathrm{s} \sim 5 \times 10^{6}\,\mathrm{yr}$$

most likely: random walk due to the small scale turbulent component of magnetic field, on top of a large scale regular component.

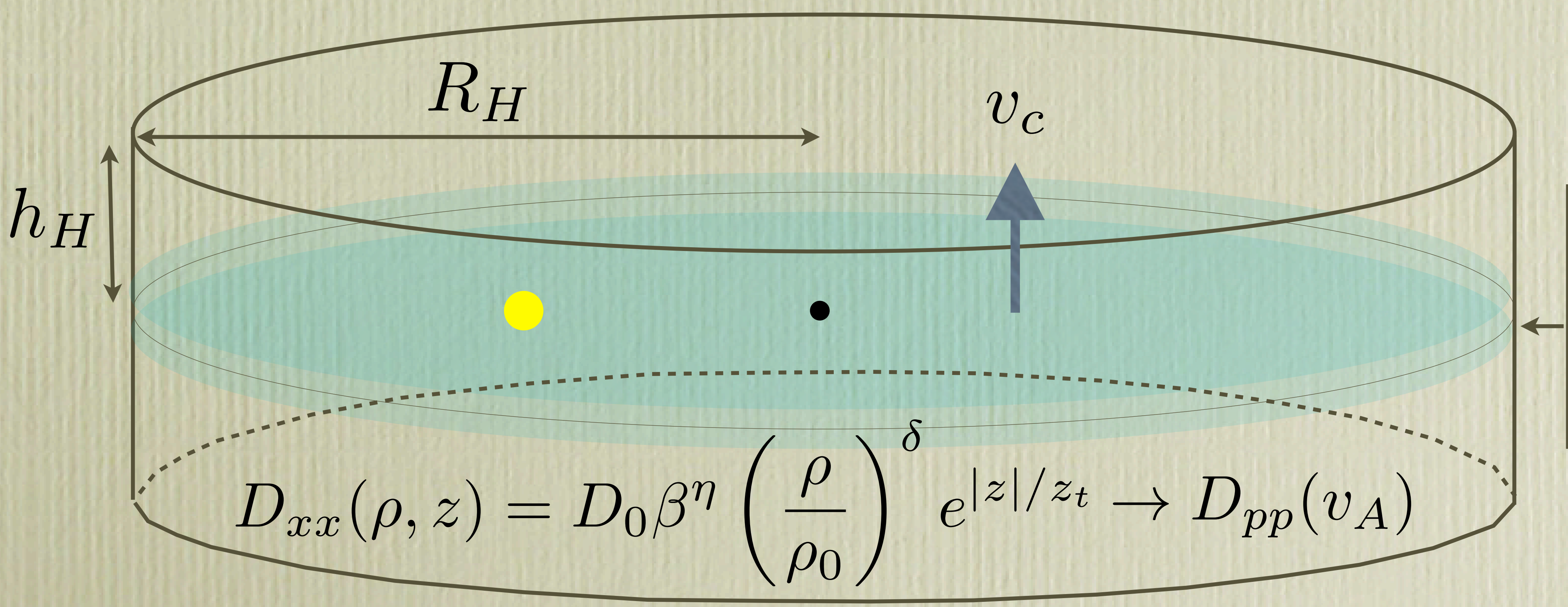
A propagation model for charged CRs

Assuming quasi-linear theory (magnetic field turbulent comp. small compared to regular comp.) the propagation equation takes the form:

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

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 $\rightarrow \gamma, e^-, e^+$

An effective approach, with no parameter derived from first principles!

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

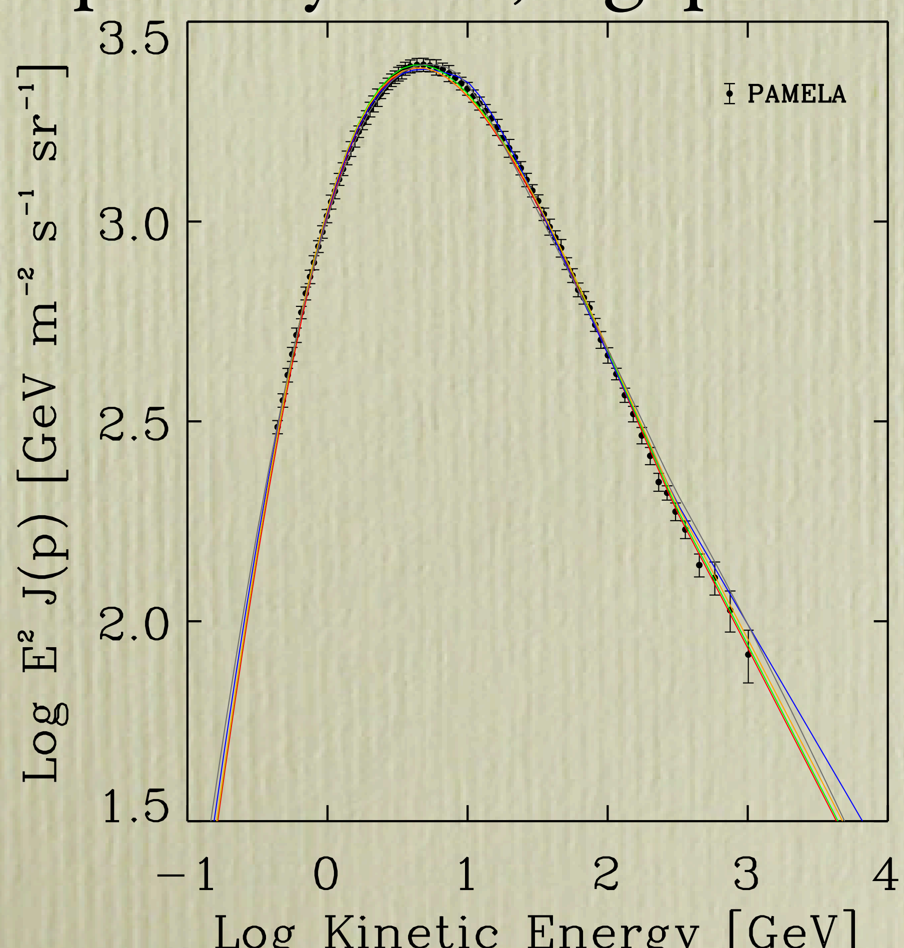
"thick" model

Kolmogorov model

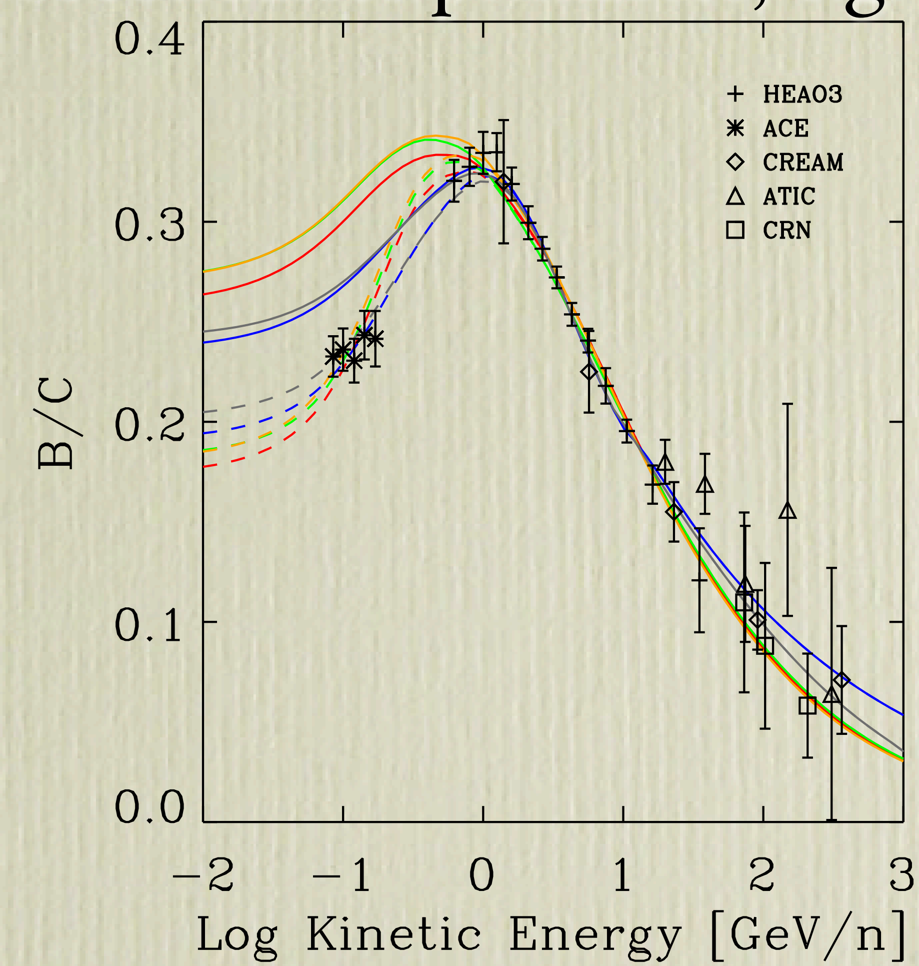
"convective" model

any of these is tuned to reproduce the local:

primary CRs, e.g. protons



secondaries/primaries, e.g. B/C



Evoli, Cholis, Grasso, Maccione & PU, 2012

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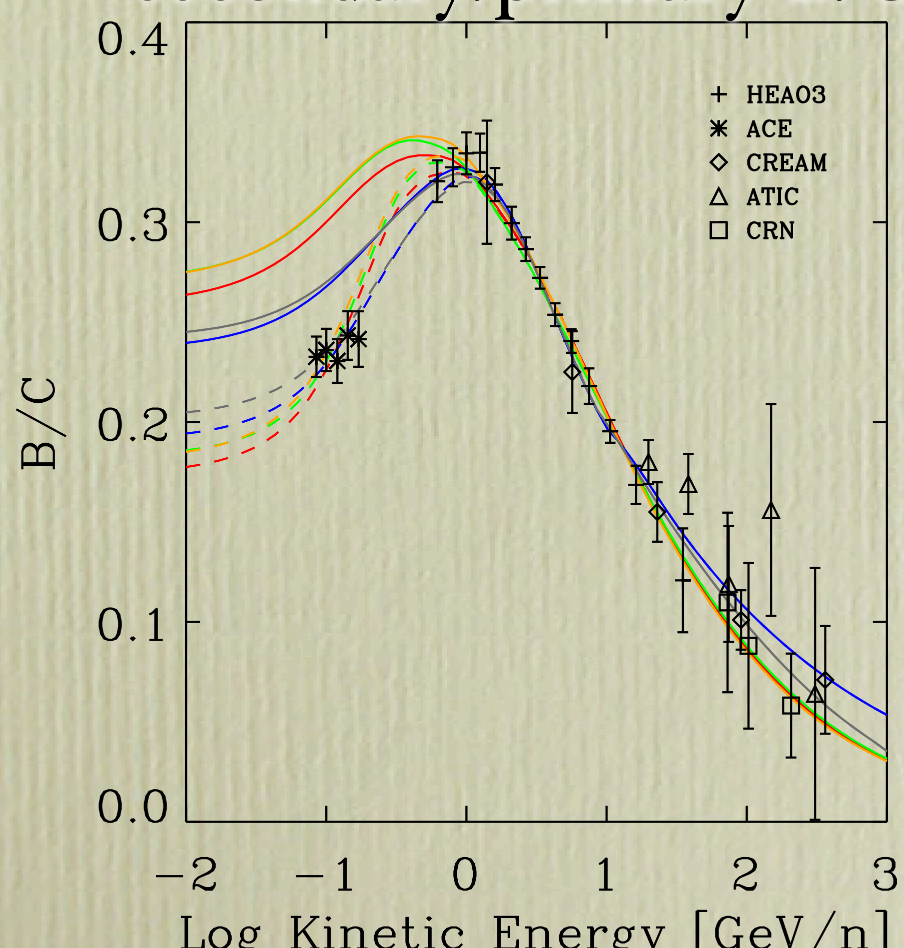
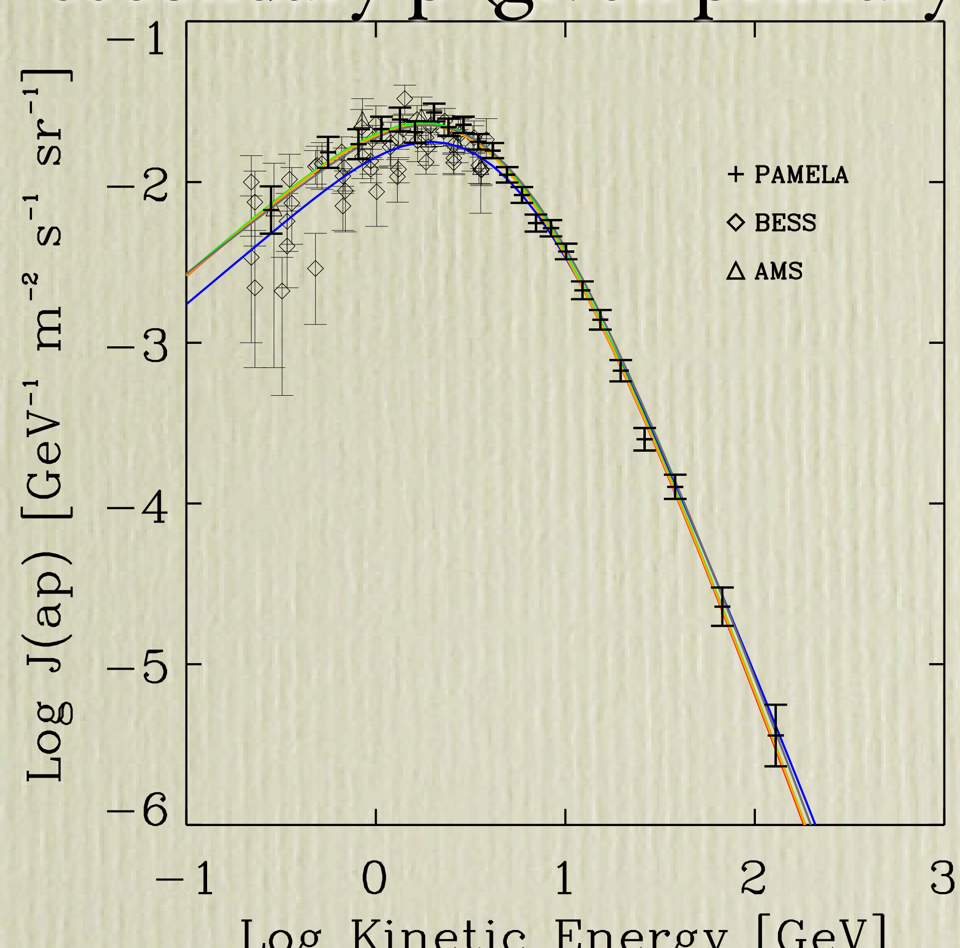
... and can be used to make a prediction for specular processes:

secondary/primary B/C



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



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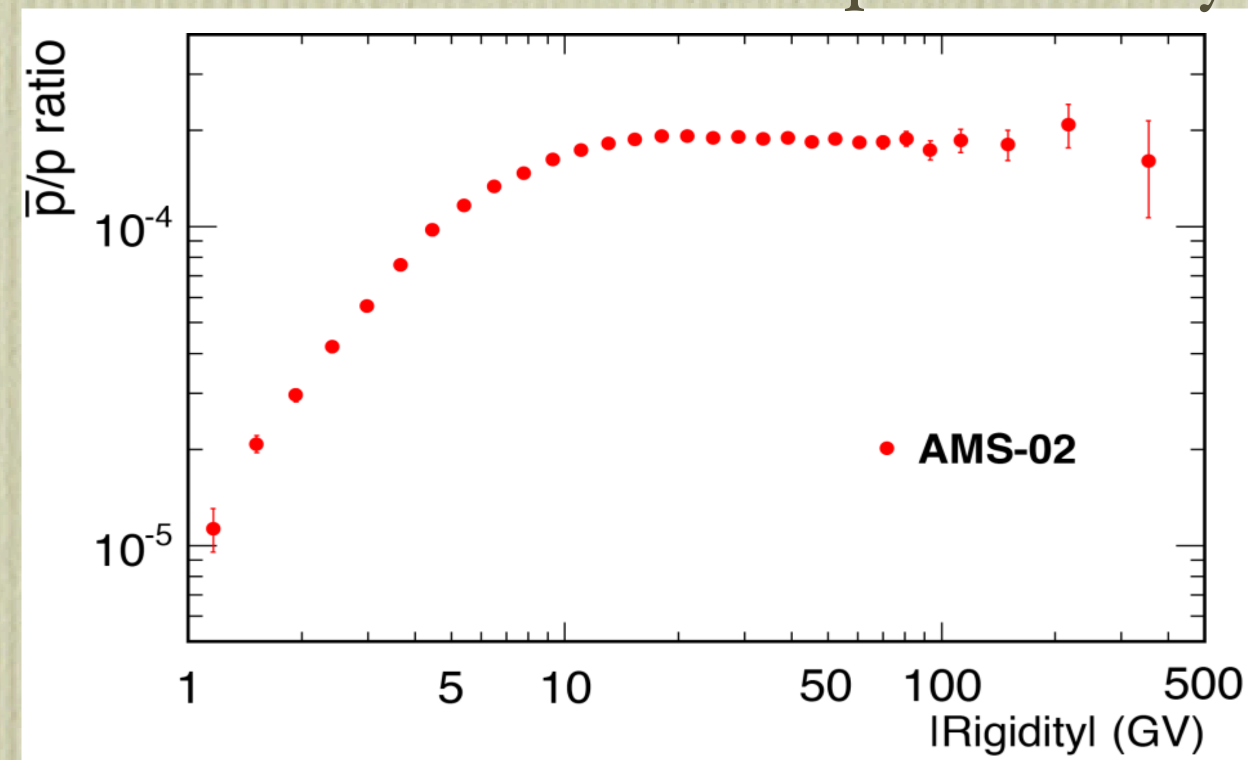
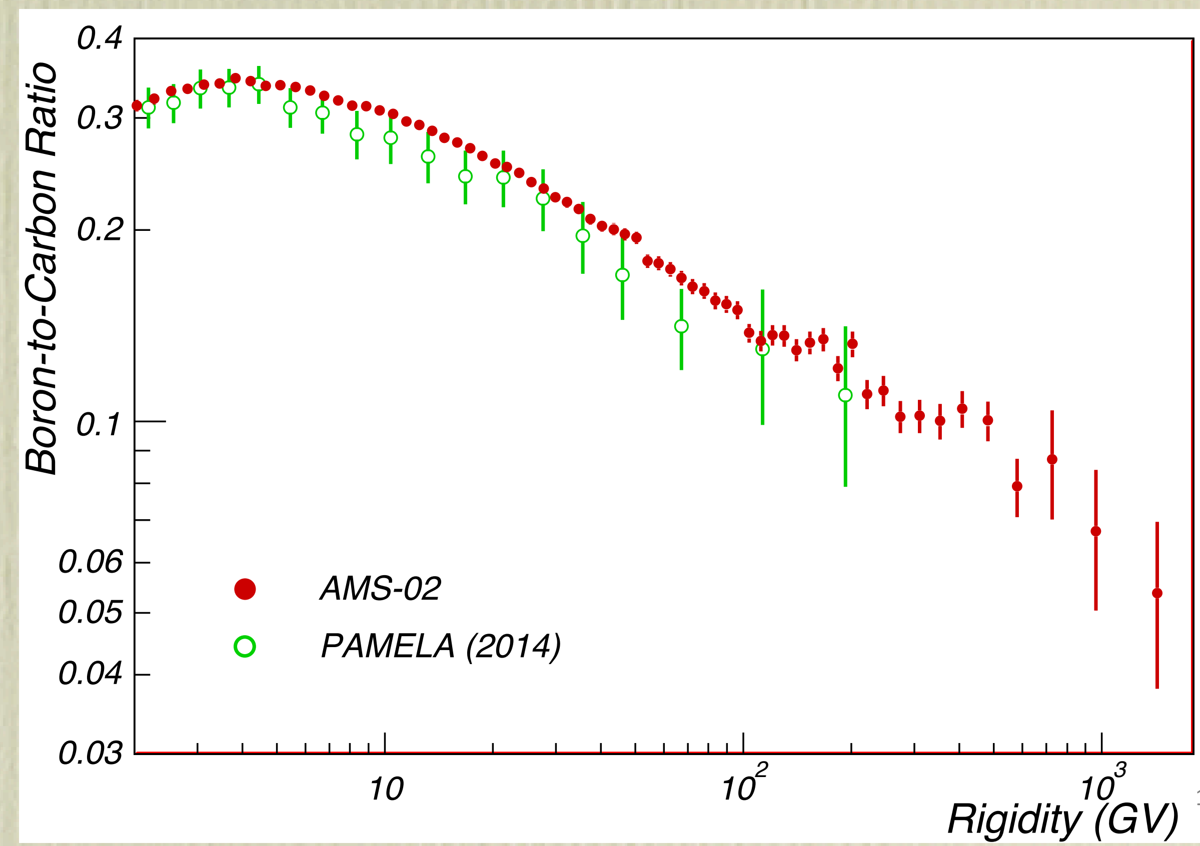
Some excitement with AMS (preliminary) $\bar{p}$ data:

AMS has reported preliminary data on the antiproton to proton data at largest energies accessed so far, with a visual mismatch with respect to B/C:

AMS 2015 preliminary





$\bar{p}$/p ratio flat at high energy as opposed to a declining B/C ratio! Room (evidence) for a DM component?

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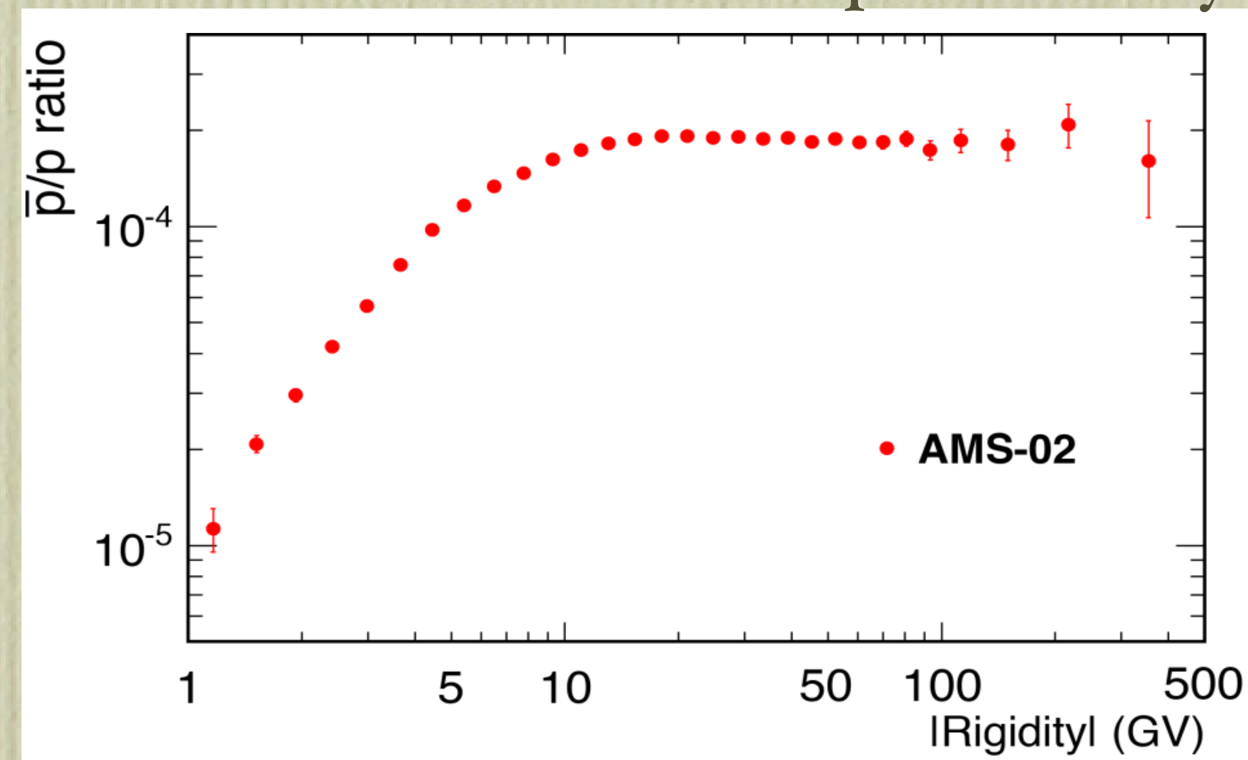
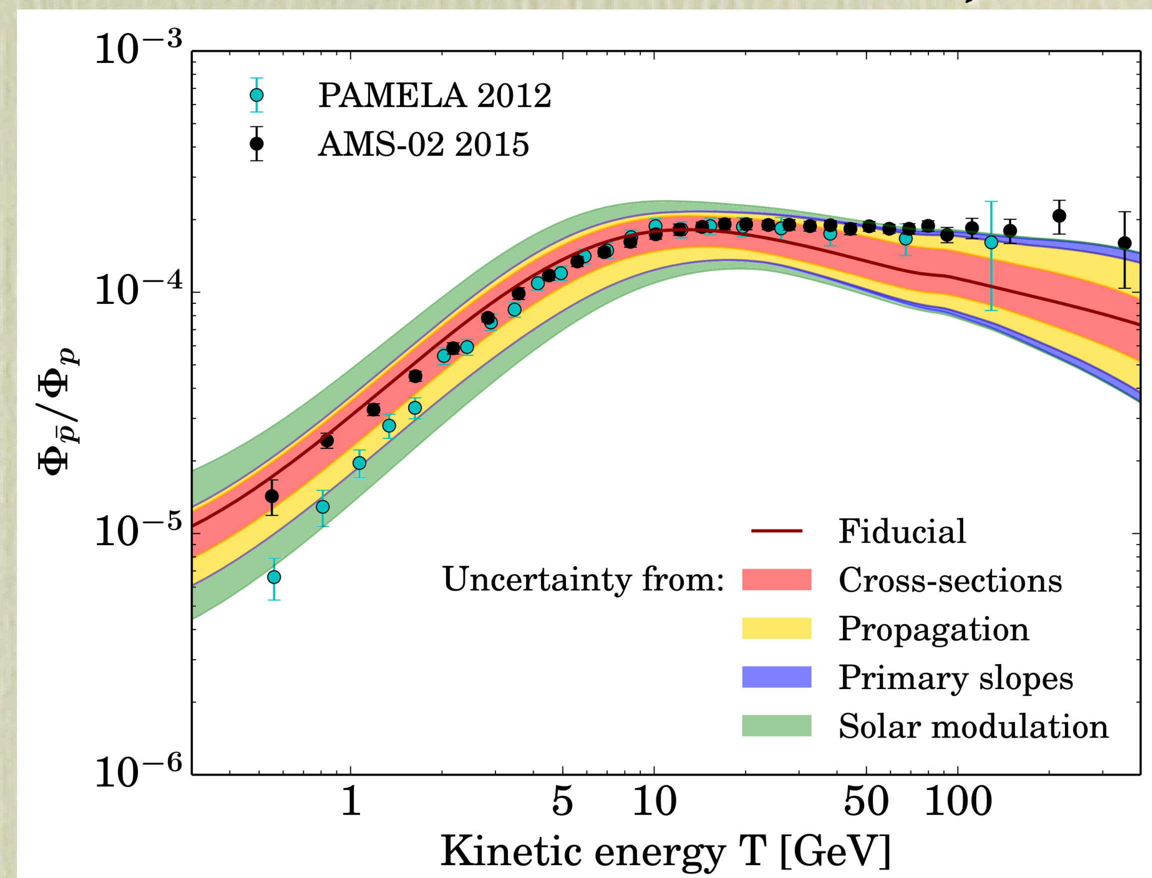


Giesel et al., 2015



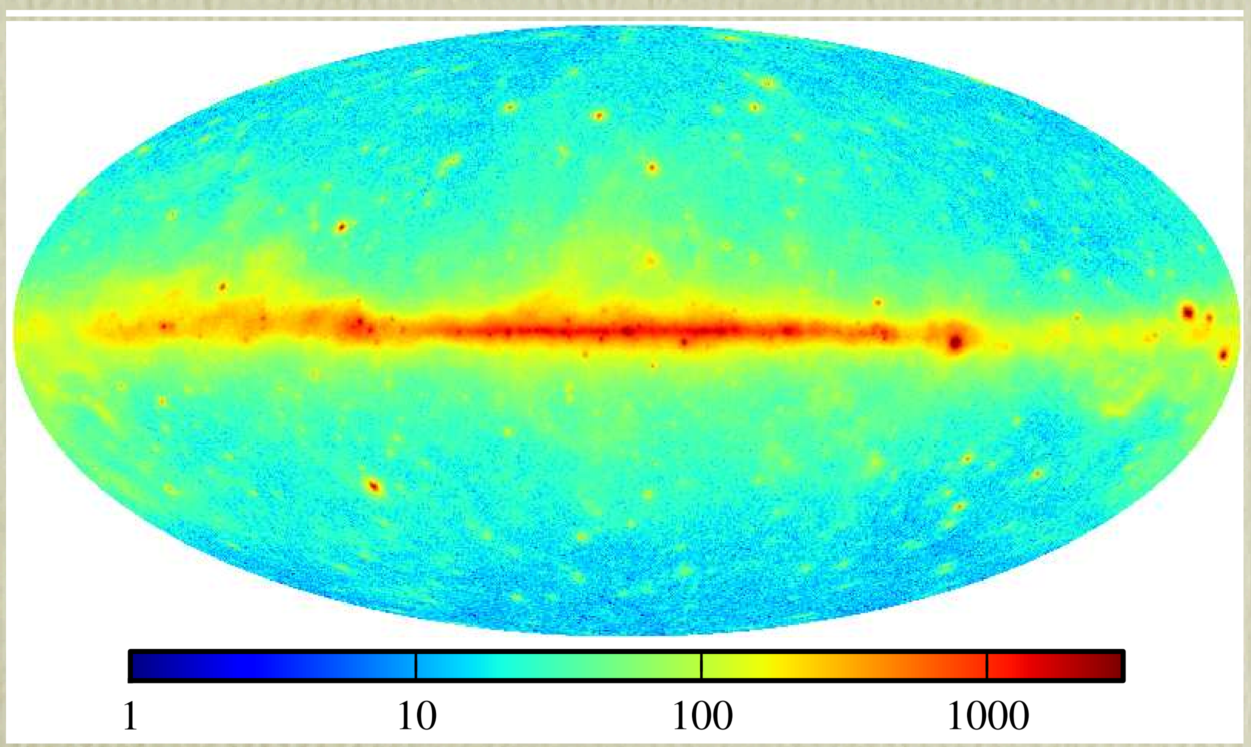
Unfortunately this dataset is still compatible, within uncertainties, with a secondary antiproton component only.

Galactic CRs and the γ-ray emissivity

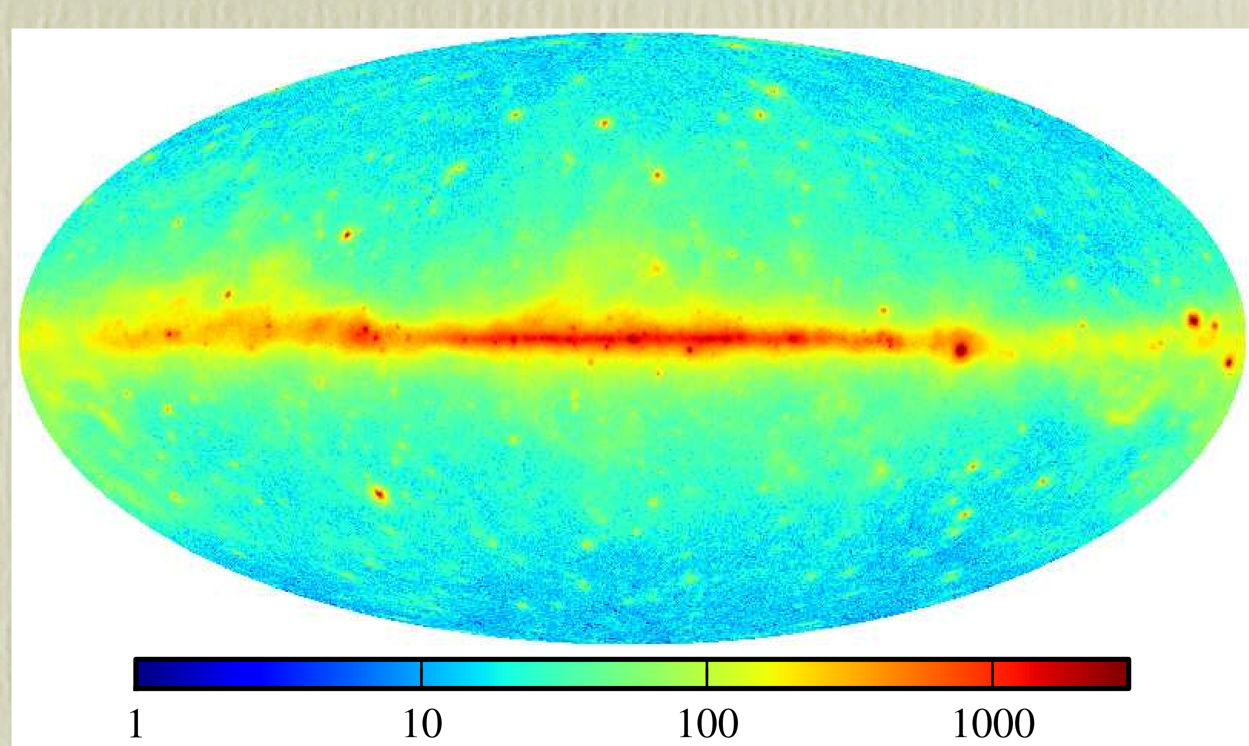
Along propagation the Galactic CRs interact with the interstellar medium (ISM) giving rise to a γ-ray flux (as well as radiation at other wavelengths). Three main components:

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

Prediction: loop over models to find the one best matching data, e.g.:



$^{S}S^{Z}4^{R}20^{T}150^{C}5$



data

Postdiction: beside a tuning on local CR measurements, there is a tuning on the CR source distribution and over all ISM targets (nearly pixel by pixel)

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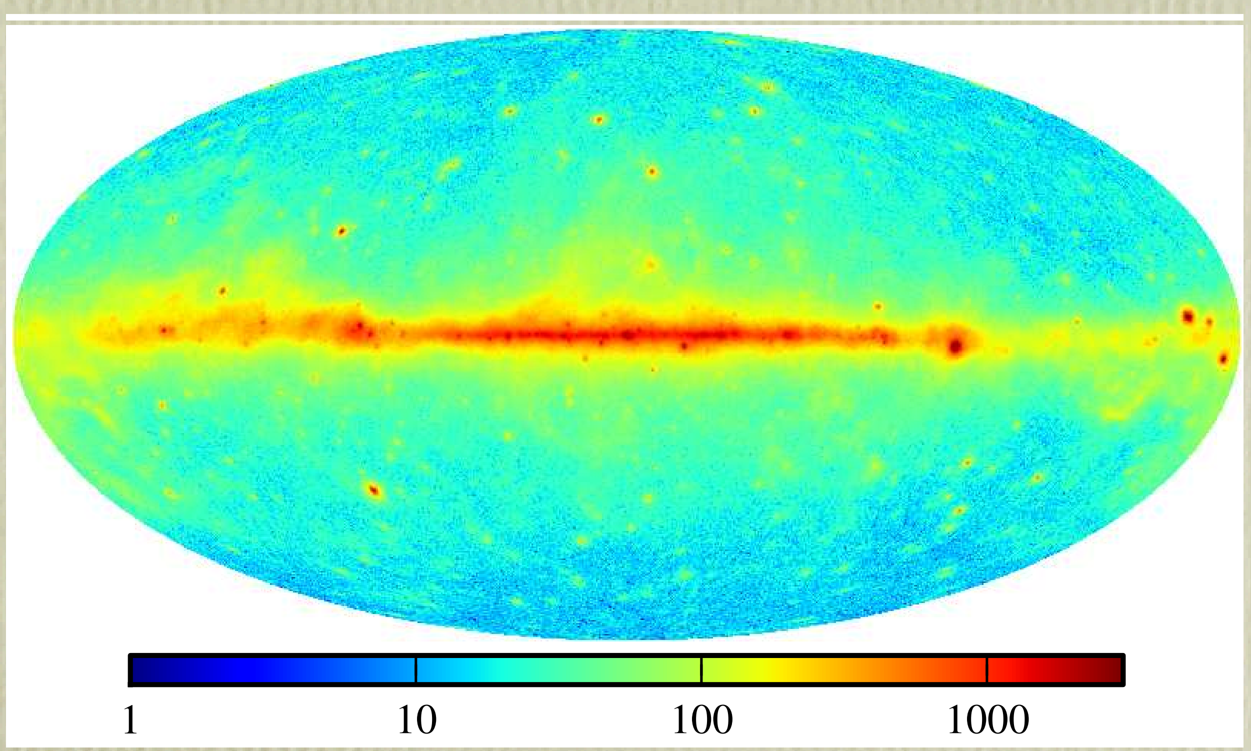


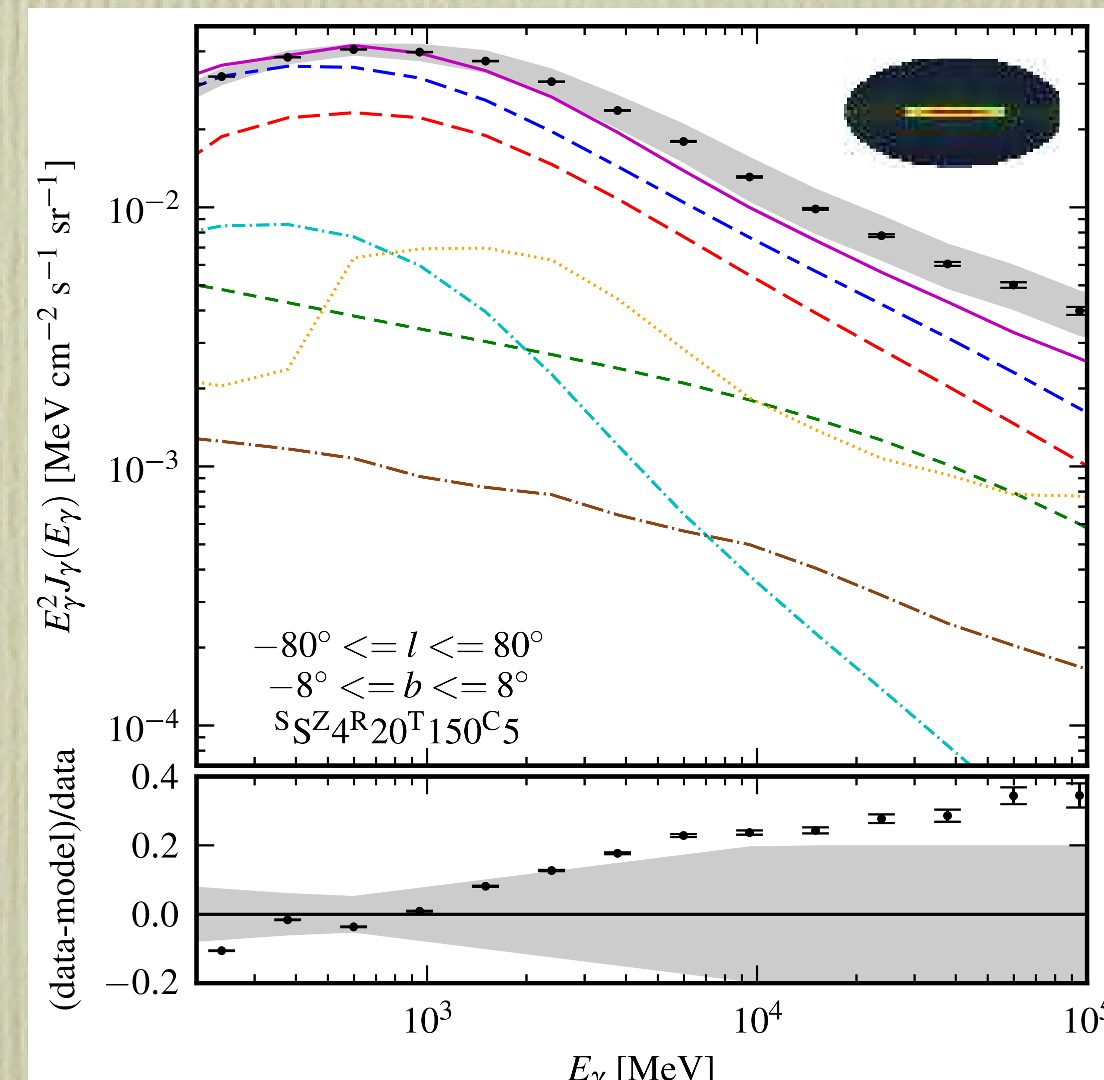
$^{S}S^{Z}4^{R}20^{T}150^{C}5$

A drastic choice in this prediction/postdiction scheme:
it is assumed that the mean local properties of CR propagation are universal, with a rigid extrapolation to the whole Galaxy what you learn from locally measured grammage!
No environmental dependencies?

Postdiction: beside a tuning on local CR measurements, there is a tuning on the CR source distribution and over all ISM targets (nearly pixel by pixel)

Slight discrepancies: γ-rays in inner Galactic plane

A systematic underestimate of the measured flux above few GeV in any model in the loop of **Fermi Coll., 2012**:



there seems to be the problem of having the wrong spectral index, reflecting an angular gradient of the spectral index in the γ-ray flux:

sky window ($\lvert b\rvert < 5°$)	α ($\Phi \sim E_\gamma^{-\alpha}$)	sky window ($\lvert b\rvert < 5°$)	α ($\Phi \sim E_\gamma^{-\alpha}$)
$0° < \lvert l\rvert < 10°$	2.55 ± 0.09	$40° < \lvert l\rvert < 50°$	2.57 ± 0.09
$10° < \lvert l\rvert < 20°$	2.49 ± 0.09	$50° < \lvert l\rvert < 60°$	2.56 ± 0.09
$20° < \lvert l\rvert < 30°$	2.47 ± 0.08	$60° < \lvert l\rvert < 70°$	2.60 ± 0.09
$30° < \lvert l\rvert < 40°$	2.57 ± 0.08	$70° < \lvert l\rvert < 80°$	2.52 ± 0.09

no way to fix such problem by scaling the ISM or SNRs

Gaggero, Urbano, Valli & PU, 2015

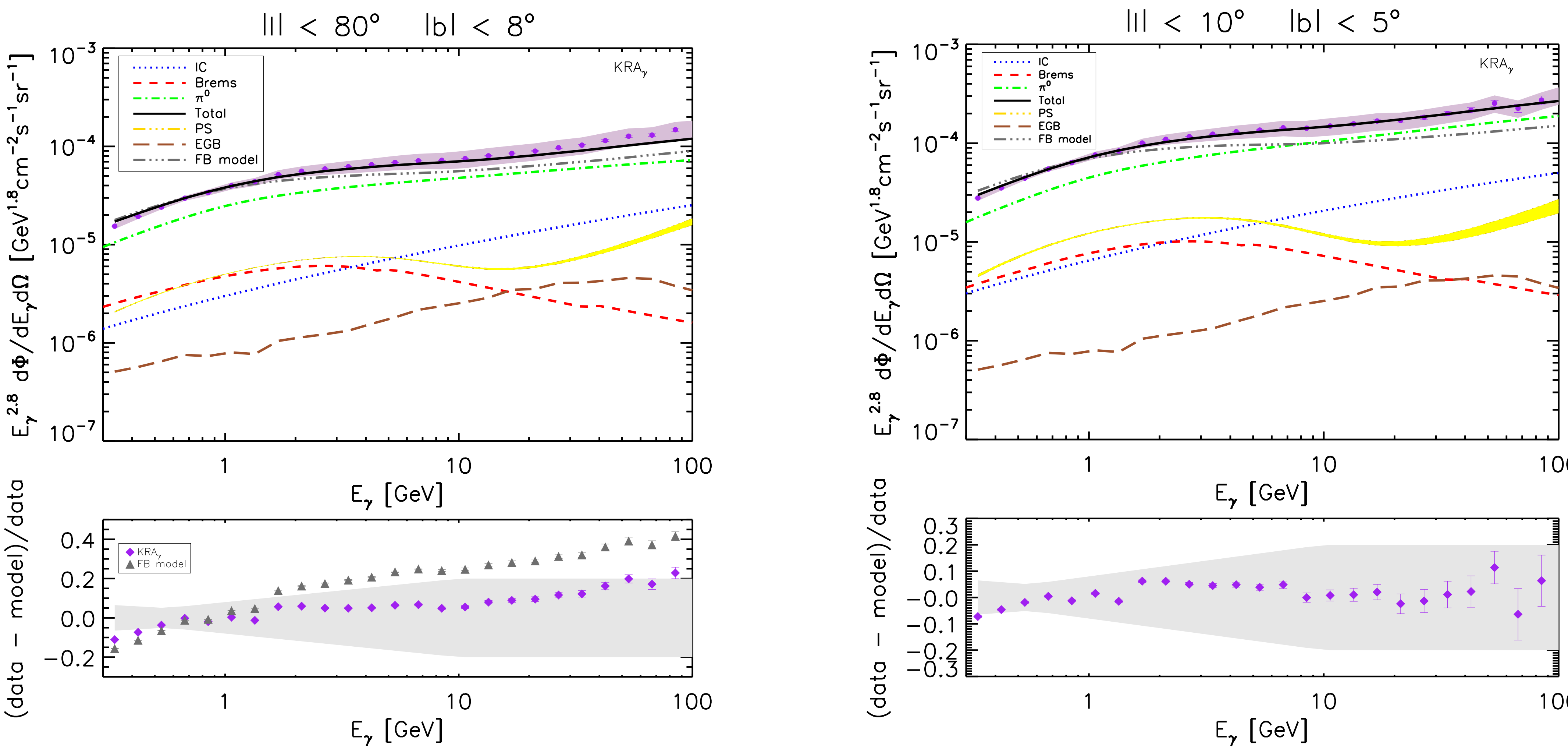
Since in this region the diffuse Galactic flux is dominated by the meson component, the spectral index reflects the spectral index of the CR proton density at the emission spot. In **Fermi Coll., 2012** this is assumed to be the same as the local by construction of the model. What about changing this?

Slight discrepancies: γ-rays in inner Galactic plane

Introduce a radial gradient in the spectral index of the diffusion coefficient:

$$D = D(\rho, R) \propto \rho^{\delta} \quad \text{with:} \quad \delta = \delta(R)$$

Simplest toy-model to be fitted to the data: take a linear dependence.
Sharp increase in the match with data:



Gaggero, Urbano, Valli & PU, 2015

Of course we could have also advocated an exotic inner-disc DM component doing the job ... (of course not!)

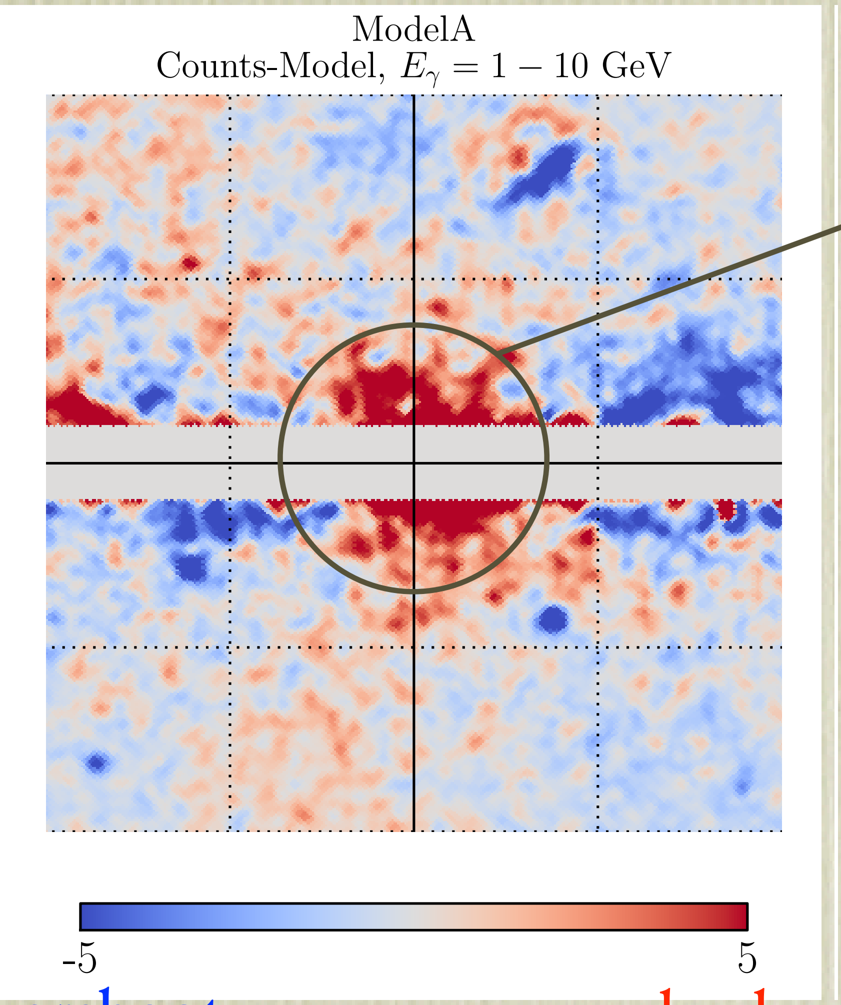
Slight discrepancies: γ-rays in Galactic center region

Morphological and spectral mismatches when looking at the central region of the Galaxy - say, the inner 10 to 20 degrees - even when cutting out the Galactic plane component (**Hooper et al., 2009-15** + several analyses by other authors, see in particular **Calore, Cholis & Weniger, 2014**).

A detailed model in this region is very problematic (while for standard CR models is just a nearly empty spot 8 kpc away from us).

Most analyses consider the template fitting technique:
I) fix the morphology of each component of the CR diffuse emission (plus sources, plus bubbles) from some theory/ data-driven prior;
II) scale freely the templates in each energy bin to minimize the residuals.

Residuals:



overshoot

undershoot

A blob-like excess seems to emerge

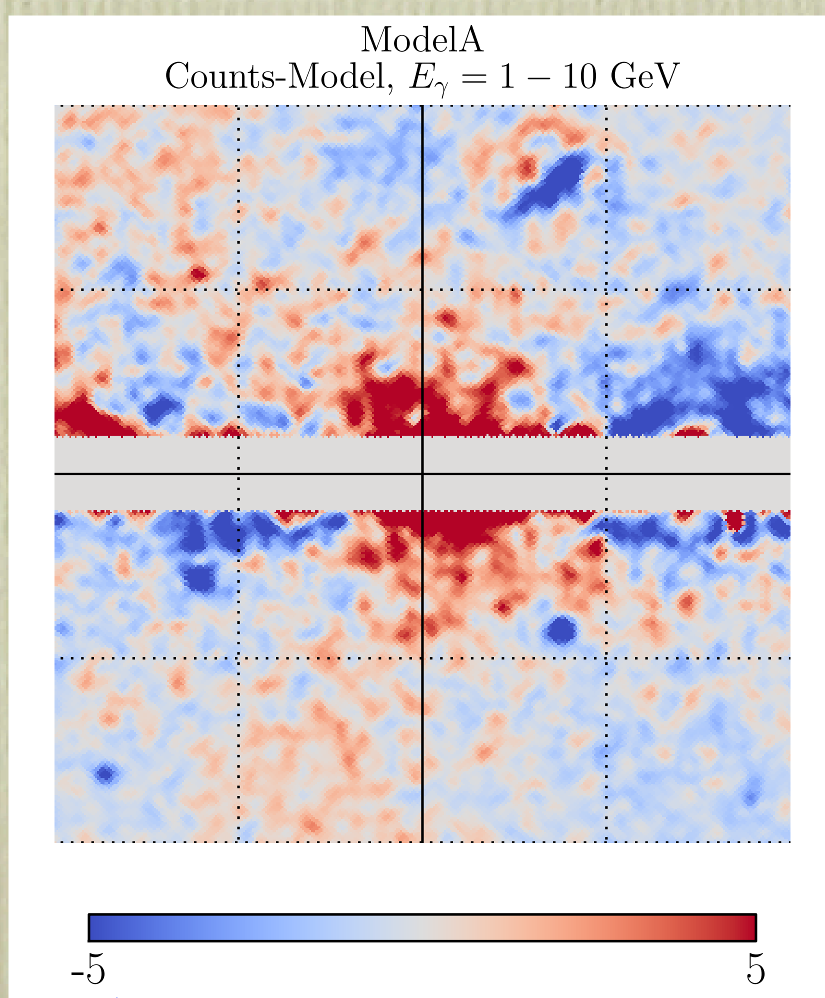
Slight discrepancies: γ-rays in Galactic center region

A component from DM pair annihilations is expected to be centrally concentrated: try to wipe out the blob adding an extra template scaling like

$$J \equiv \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega \int_{l.o.s.} dl \; \rho_{DM}^2(l) \quad \text{with} \quad \rho_{DM}(r) = \rho_0 \left(\frac{r}{r_s}\right)^{-\gamma} \left(1 + \frac{r}{r_s}\right)^{3-\gamma}$$

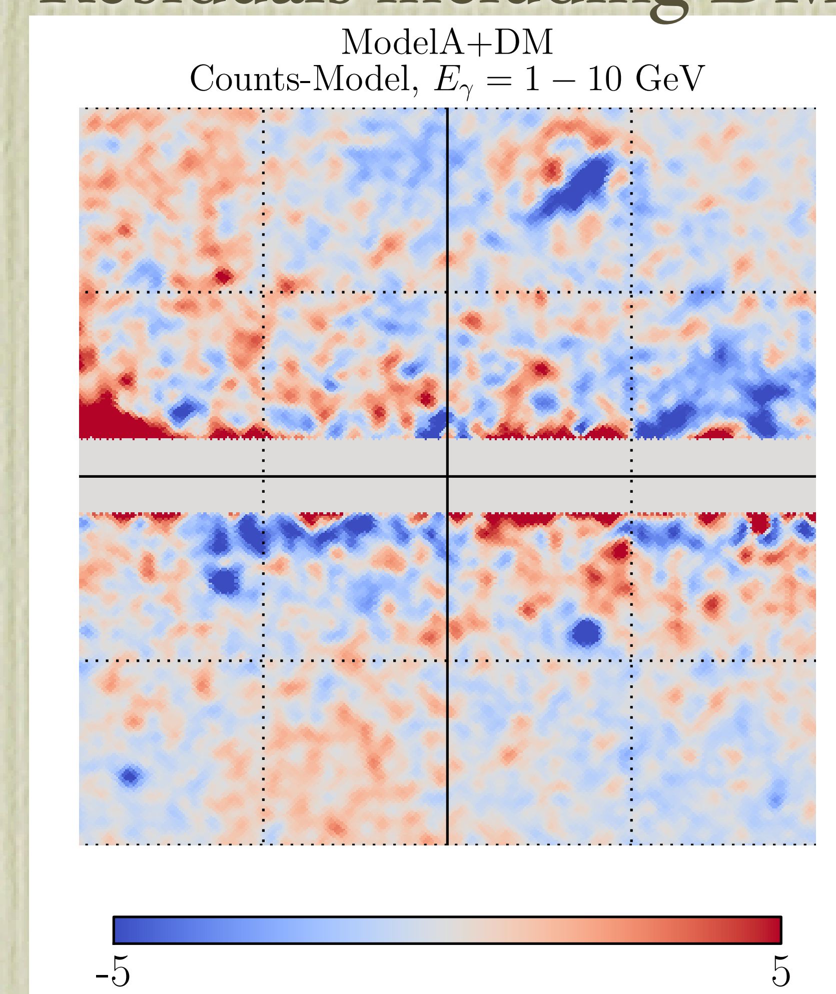
and $\gamma = 1.26$, analogously to numerical simulation results.

Residuals without DM



overshoot undershoot

Residuals including DM



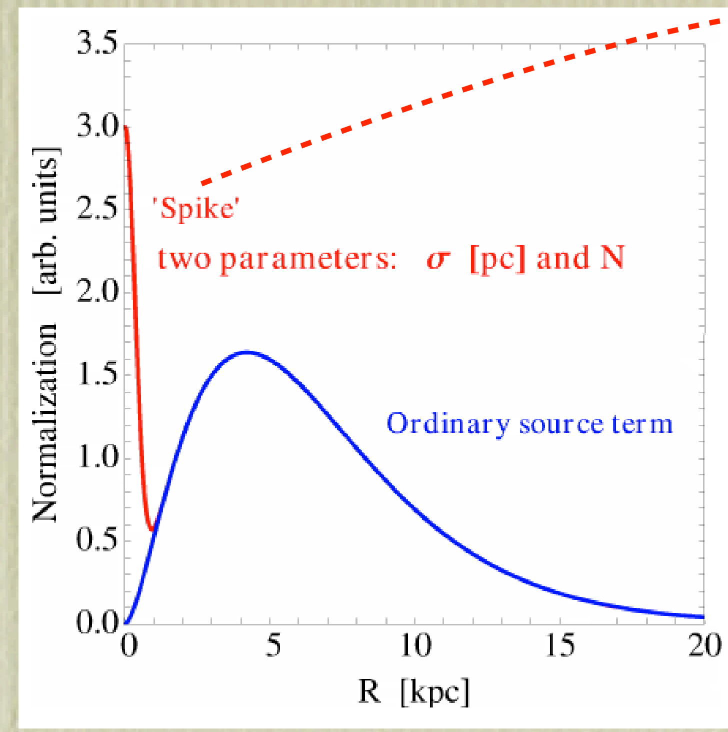
overshoot undershoot

The fit has clearly improved!

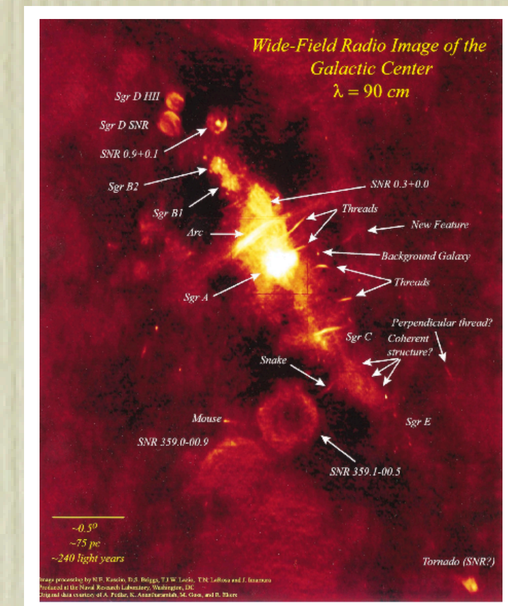
Slight discrepancies: γ-rays in Galactic center region

What about including an extra SNR source, connected to the "Central Molecular Zone", usually neglected in standard CR models?

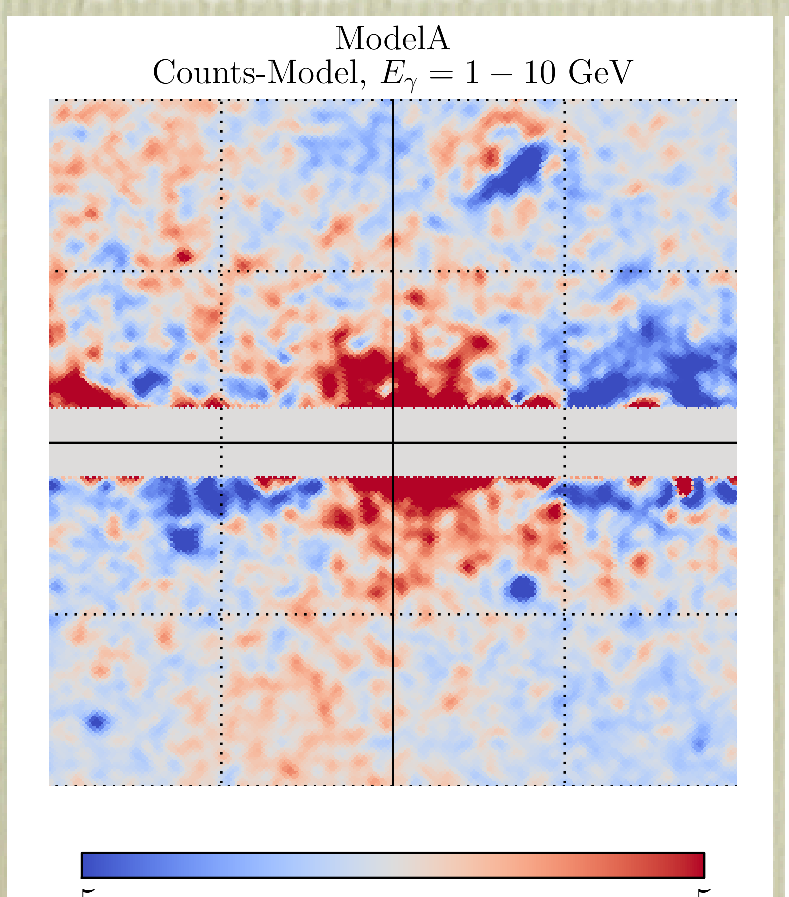
Toy model: a gaussian term with tunable width.



CMZ

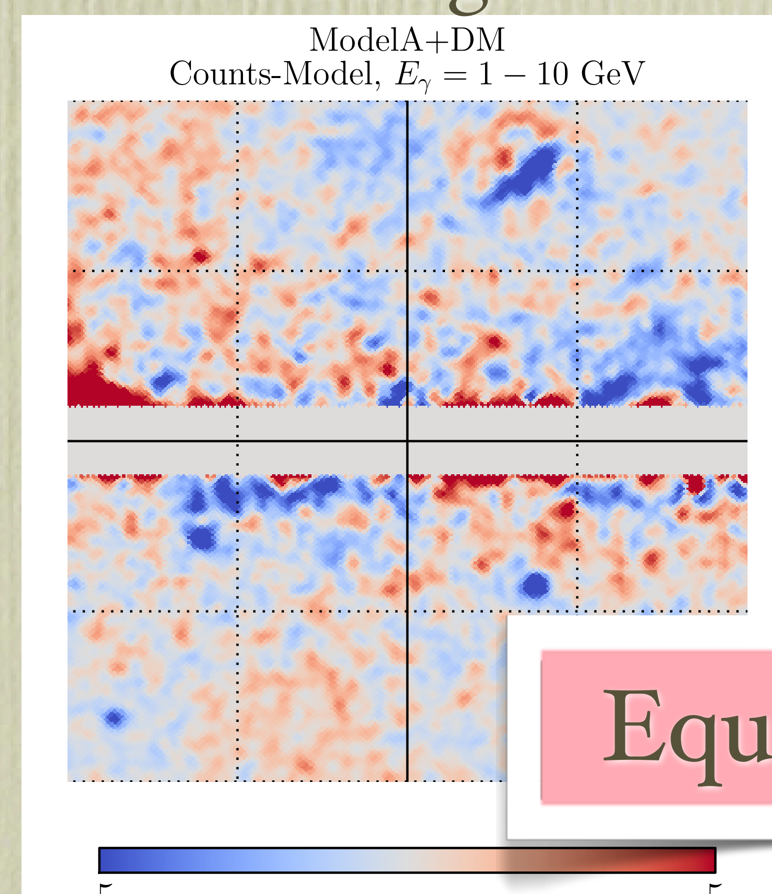


Fiducial CR model



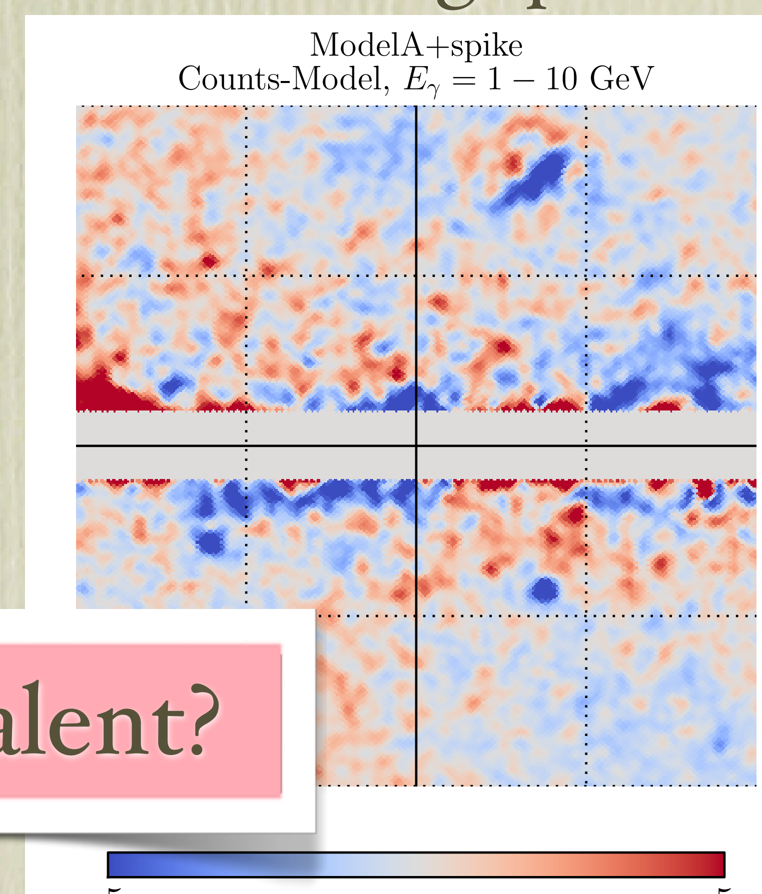
overshoot undershoot

Including DM



overshoot undershoot

Including spike



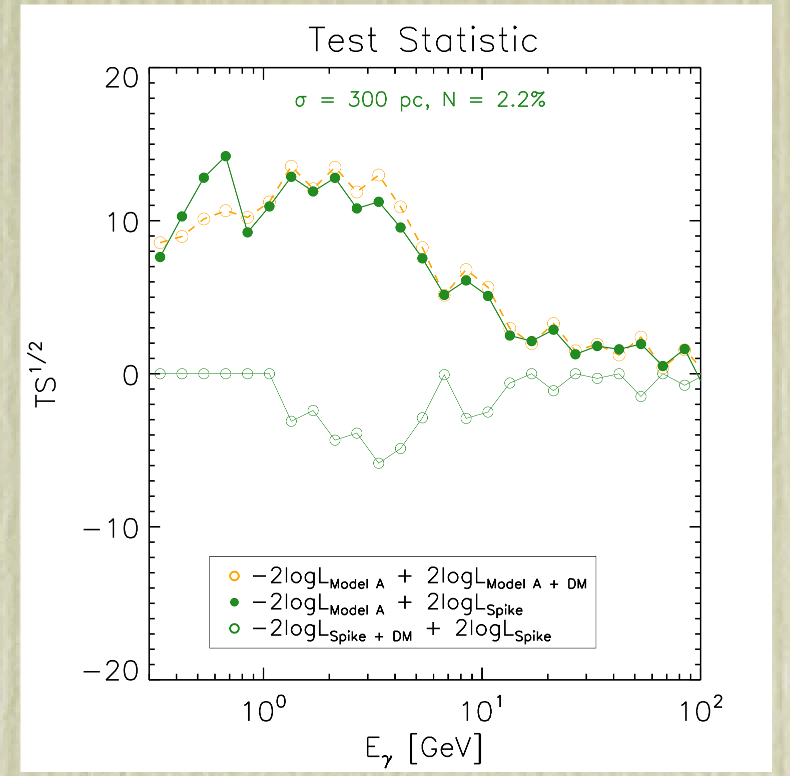
overshoot undershoot

Equivalent?

Gaggero, Taoso,Urbano, Valli & PU, 2015

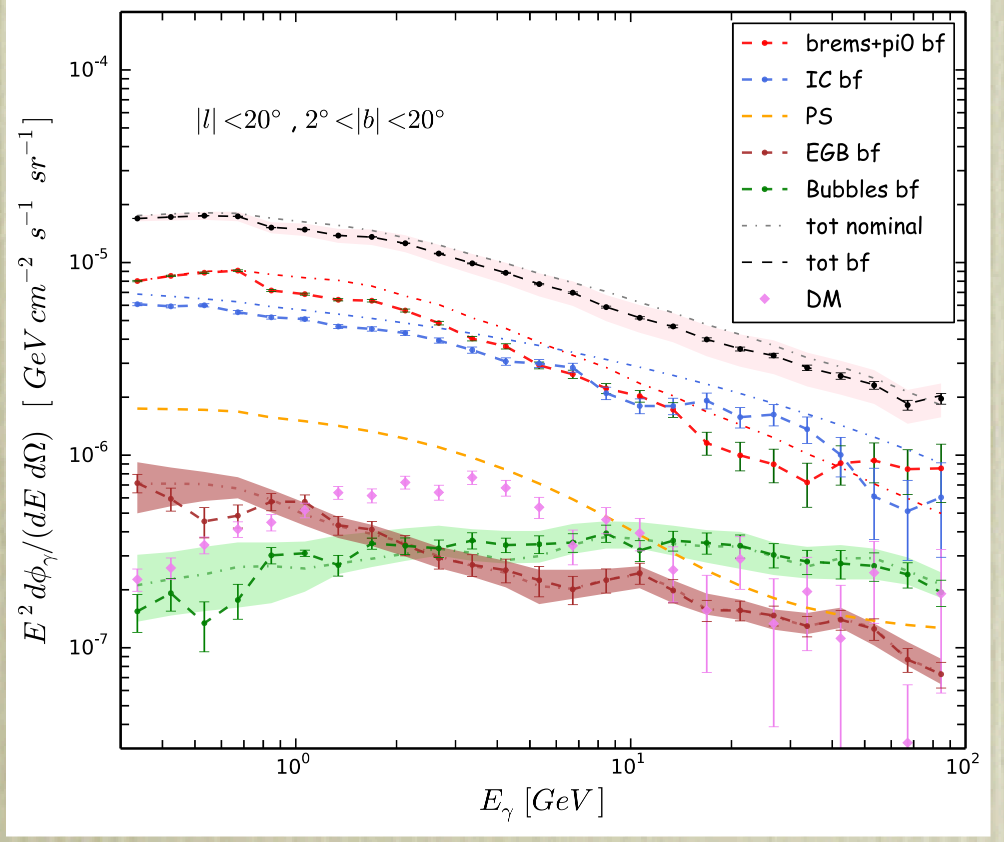
Slight discrepancies: γ-rays in Galactic center region

At the test statistic level, DM and spike do perform analogously, with the DM case being marginally better only on longitude profile tests.

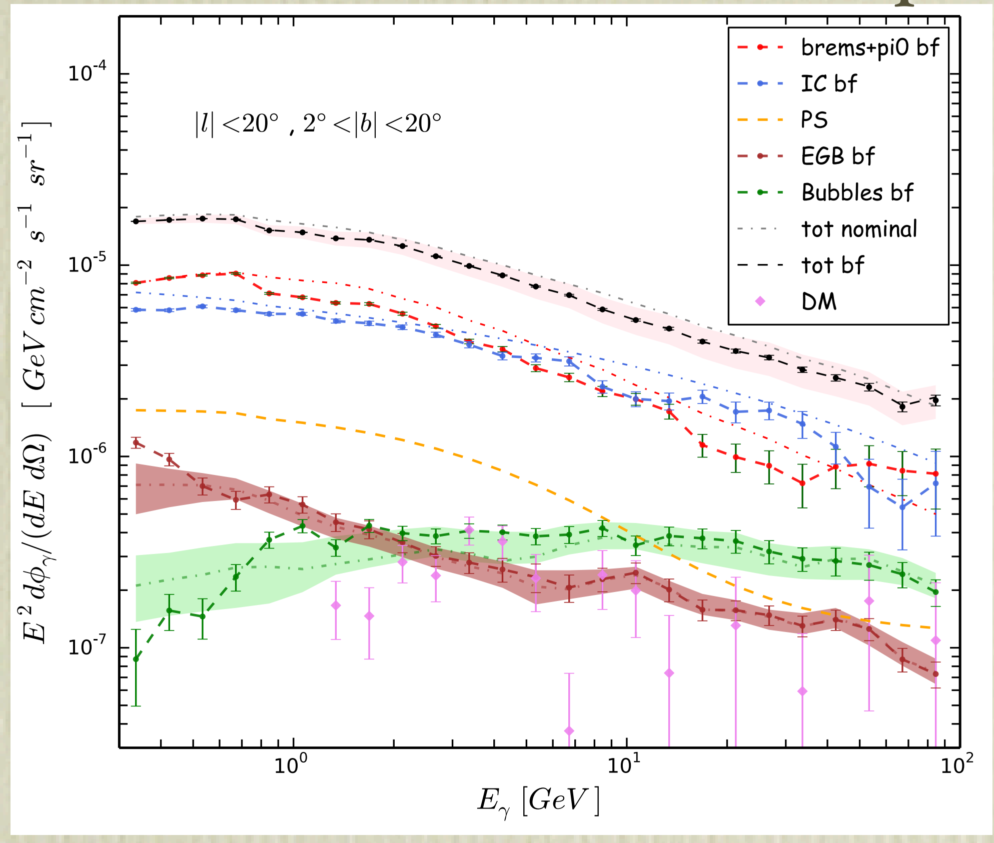


Spectral results:

Fiducial CR model + DM



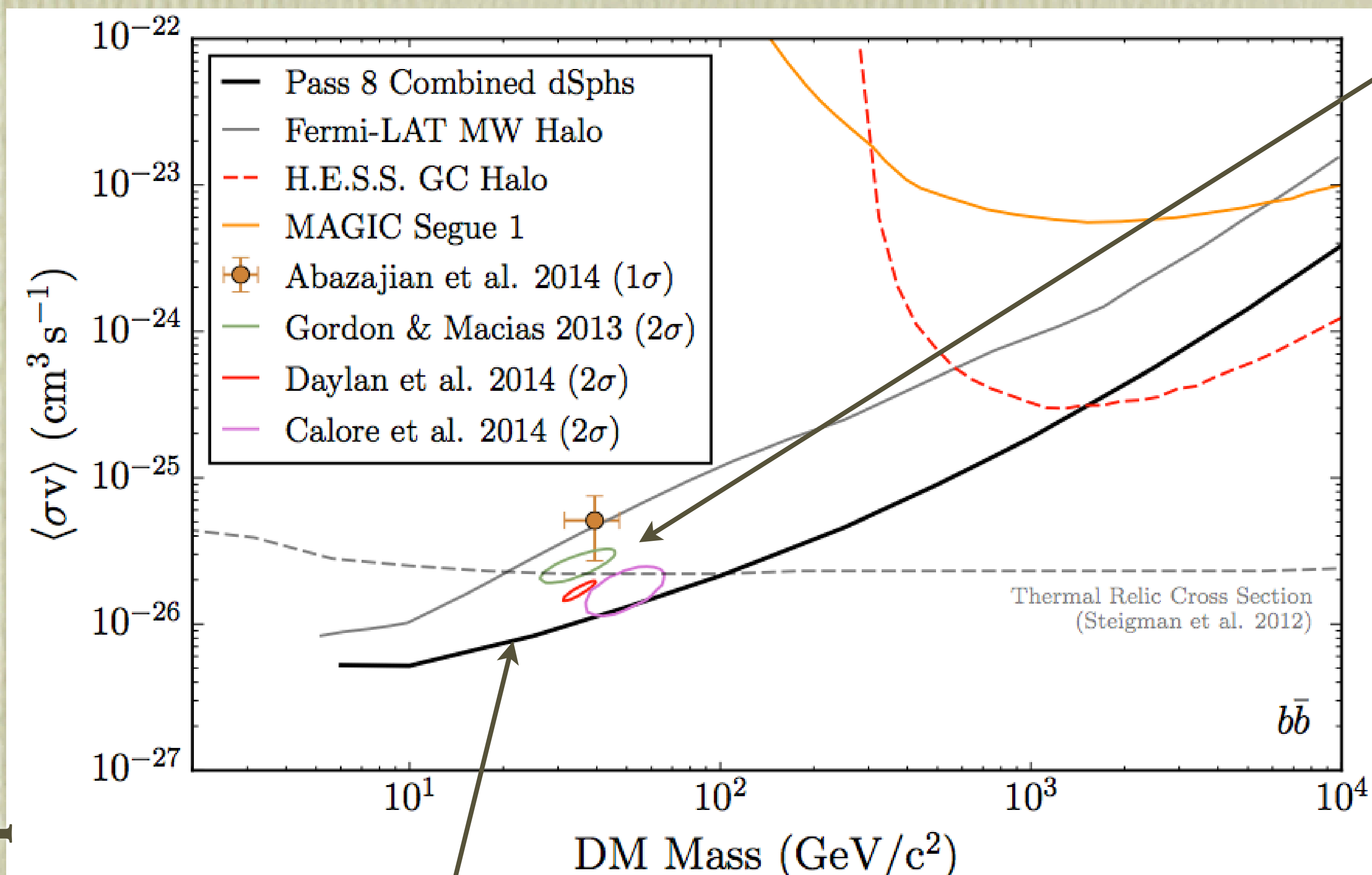
Fiducial CR model + DM + spike



Slight discrepancies: γ-rays in Galactic center region

Back to the plot with tentative indication of a DM signal in the inner region of the Galaxy:

pair annihilation cross section



level at which you may have a DM signal, but it is not excluded that the GC excess corresponds to something else:

see also the vast recent literature on explaining the excess in terms of a population of unresolved point sources (pulsars?)

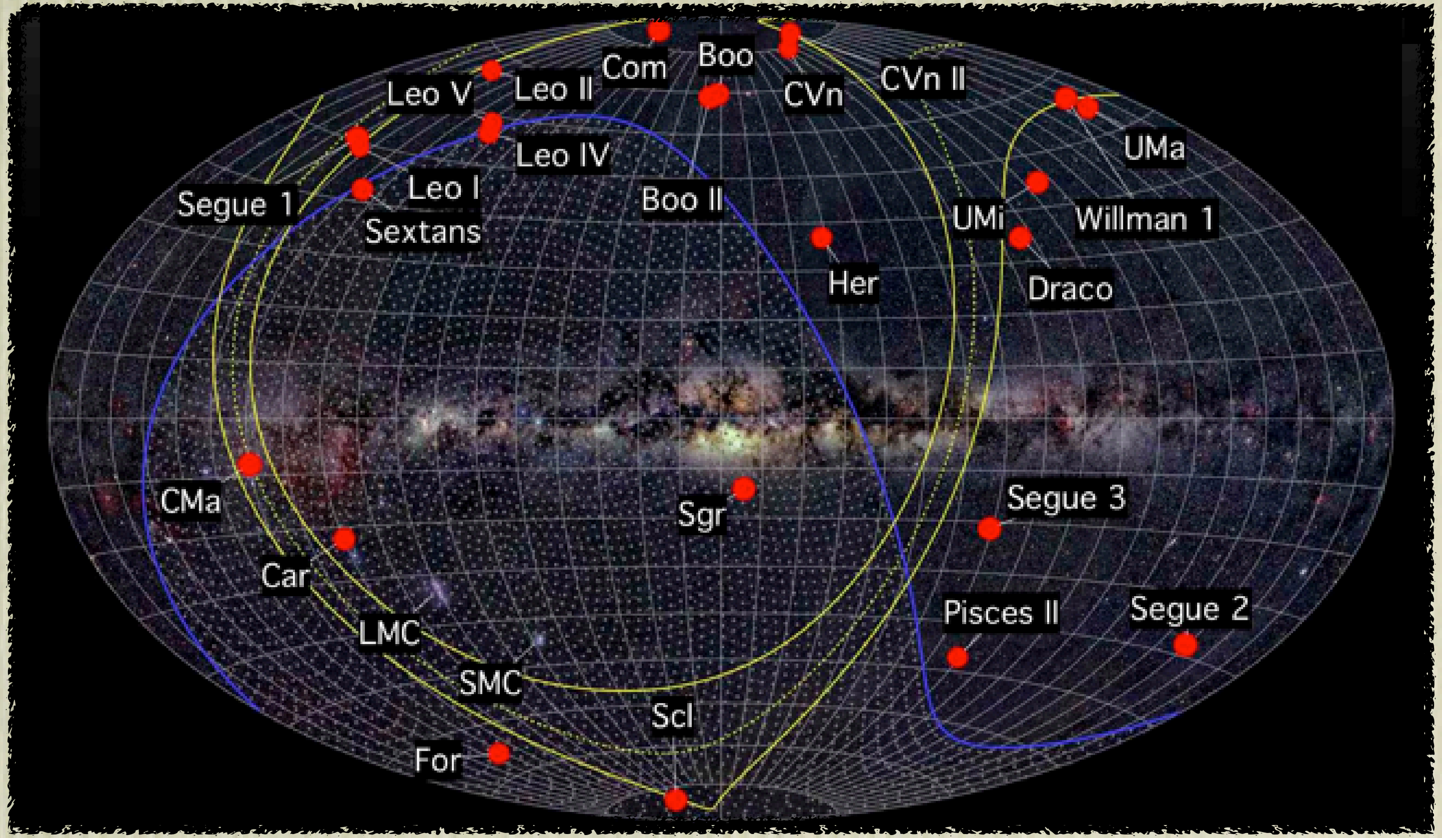
Is the DM signal excluded by the **Fermi Coll. 2015** limit from dwarf satellites?

Milky Way dwarfs as Dark Matter detection Labs

Ideal targets for **detecting** a DM signal (prompt or radiative emission from DM particle pair annihilations or decays):

- objects with fairly large DM densities, located fairly close to the Sun (about 10 to 200 kpc);

- intrinsic backgrounds from "standard" astrophysical sources below detection sensitivities (?)
+ low Milky Way foregrounds (intermediate to high latitude locations).



About 35 (tentatively) identified;
8 with adequate kinematic data samples, the so-called "classical" dwarfs.

Are they ideal targets for **setting limits** as well? For the classical dwarfs 1-σ uncertainties on J-factors often assumed within factors of 1.5 ≪ the "astro" uncertainty in any other indirect detection tool! Where does it come from?

Mass models for dwarf galaxies

A stellar population as tracer of the gravitational potential (i.e. the DM distribution) assuming dynamical equilibrium. Velocity moments of the collision-less Boltzmann equation. Spherical symmetry for all components:

$\Rightarrow$ a single Jeans equation

$$\frac{d}{dr}(\nu\sigma_r^2) + \frac{2\,\beta(r)}{r}\nu\sigma_r^2 = -\nu\frac{M(r)}{r^2}$$

Usually solved for the radial pressure: $p(r) \equiv \nu(r)\sigma_r^2(r)$ in terms of the 3 unknown functions:

the star density profile	the star anisotropy profile	the DM mass profile
$\nu(r)$	$\beta(r) \equiv 1 - \dfrac{\sigma_\theta^2 + \sigma_\phi^2}{2\,\sigma_r^2}$	$M(r)$

$$-\infty \;\leq\; \beta(r) \;\leq\; 1$$

circular orbits ($-\infty$) — radial orbits (1)

isotropy: $\beta(r) = 0$

Mass models for dwarf galaxies (ii)

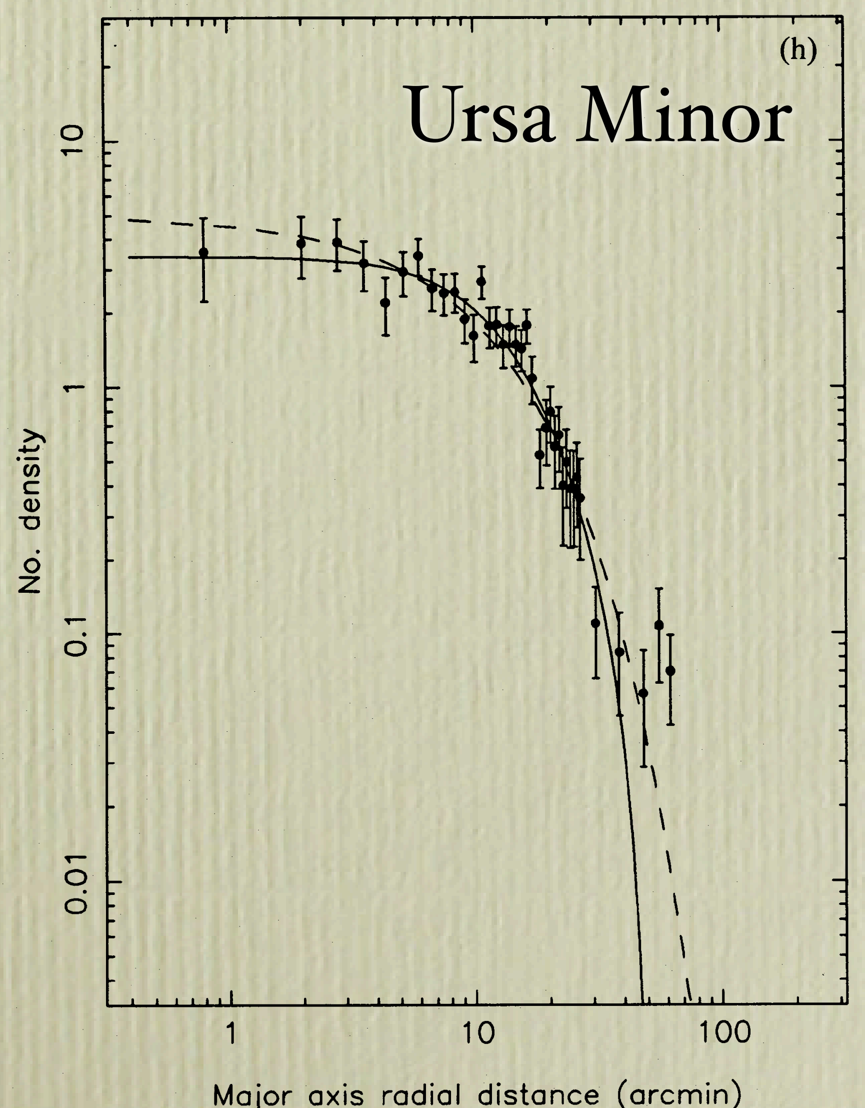
The 3 unknowns: $\nu(r)$, $\beta(r)$ and $M(r)$ can be mapped into 2 observables:

the star surface brightness

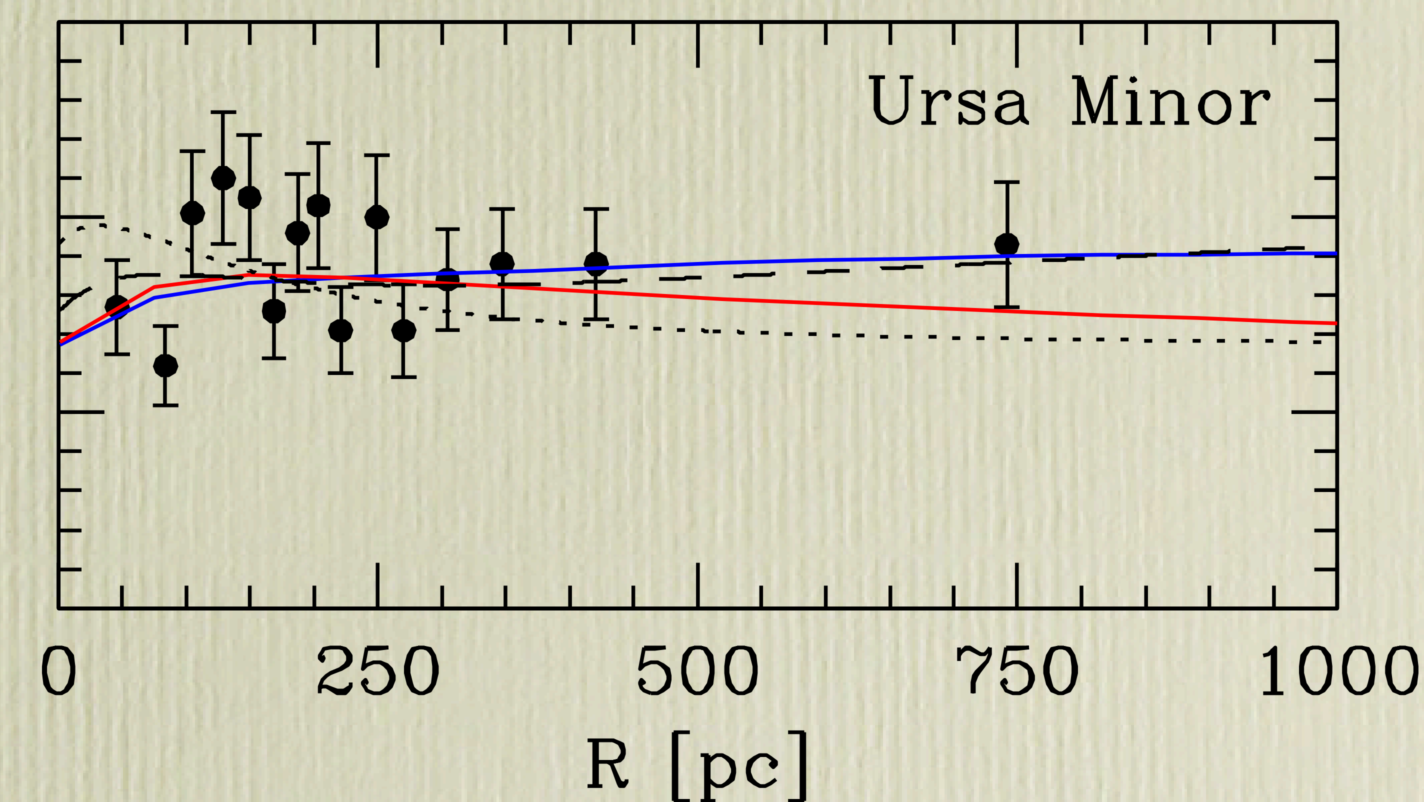
$$I(R) = 2\int_R^\infty \frac{dr\,r}{\sqrt{r^2 - R^2}}\nu(r)$$

the l.o.s. velocity dispersion

$$\sigma^2_{l.o.s.}(R) = \frac{2}{I(R)}\int_R^\infty \frac{dr\,r}{\sqrt{r^2 - R^2}}\left(1 - \beta(r)\frac{R^2}{r^2}\right)p(r)$$



Irwin + Hatzidimitriuo 1995



e.g.: **Walker et al. 2009**

Mass models for dwarf galaxies (iii)

The mapping is usually done introducing parametric forms for:

$\nu(r)$ - Plummer, King, Sersic ... profile as supported from star profiles in other observed systems;

$M(r)$ [or DM $\rho(r)$] - from N-body simulations or DM phenomenology;

$\beta(r)$ - as an arbitrary choice, since there is no real observational handle.

and performing:

- a frequentist fit of $\nu(r)$ to data on $I(R)$;

- a Markov-Chain Monte Carlo sampling of a likelihood defined from data on $\sigma^2_{l.o.s.}(R)$: posteriors on $M(r)$ [or $\rho(r)$] parameters after marginalization over $\beta(r)$ parameters [prior choice for the latter again arbitrary]. The derived posterior for J (and its small error bar) is what will enter as an input for particle physics limits.

How much should we trust this procedure?

Mass models: our approach **PU & Valli, 2015 to appear**

the star surface brightness the l.o.s. velocity dispersion

$$I(R) = 2\int_R^\infty \frac{dr\, r}{\sqrt{r^2 - R^2}} \nu(r) \qquad \sigma^2_{l.o.s.}(R) = \frac{2}{I(R)} \int_R^\infty \frac{dr\, r}{\sqrt{r^2 - R^2}} \left(1 - \beta(r)\frac{R^2}{r^2}\right) p(r)$$

are in a form which resembles the Abel integral transform for the pair $f \leftrightarrow \widehat{f}$:

$$f(x) = \mathbf{A}[\widehat{f}(y)] = \int_x^\infty \frac{dy}{\sqrt{y-x}} \widehat{f}(y) \quad \longleftrightarrow \quad \widehat{f}(y) = \mathbf{A}^{-1}[f(x)] = -\frac{1}{\pi}\int_y^\infty \frac{dx}{\sqrt{x-y}} \frac{df}{dx}$$

Actually $I(R^2) \leftrightarrow \widehat{I}(r^2) = \nu(r)$. Analogously you can invert also the projected dynamical pressure $P(R^2) \equiv I(R)\, \sigma^2_{l.o.s.}(R)$ and find:

$$M(r) = \frac{r^2}{G_N\, \widehat{I}(r)} \left\{ -\frac{d\widehat{P}}{dr}[1 - a_\beta(r)] + \frac{a_\beta(r)}{r} \cdot b_\beta(r) \left[\widehat{P}(r) + \int_r^\infty d\tilde{r} \frac{a_\beta(\tilde{r})}{\tilde{r}} \mathcal{H}_\beta(r, \tilde{r})\, \widehat{P}(\tilde{r}) \right] \right\}$$

having defined: $a_\beta(r) \equiv -\dfrac{\beta}{1-\beta}$ $\qquad b_\beta(r) = 3 - a_\beta(r) - \dfrac{d\log a_\beta}{d\log r}$

$$\mathcal{H}_\beta(r, \tilde{r}) \equiv \exp\left(\int_r^{\tilde{r}} dr' \frac{a_\beta(r')}{r'} \right)$$

see also: **Wolf et al. 2010** + **Mamon & Boué 2009**.

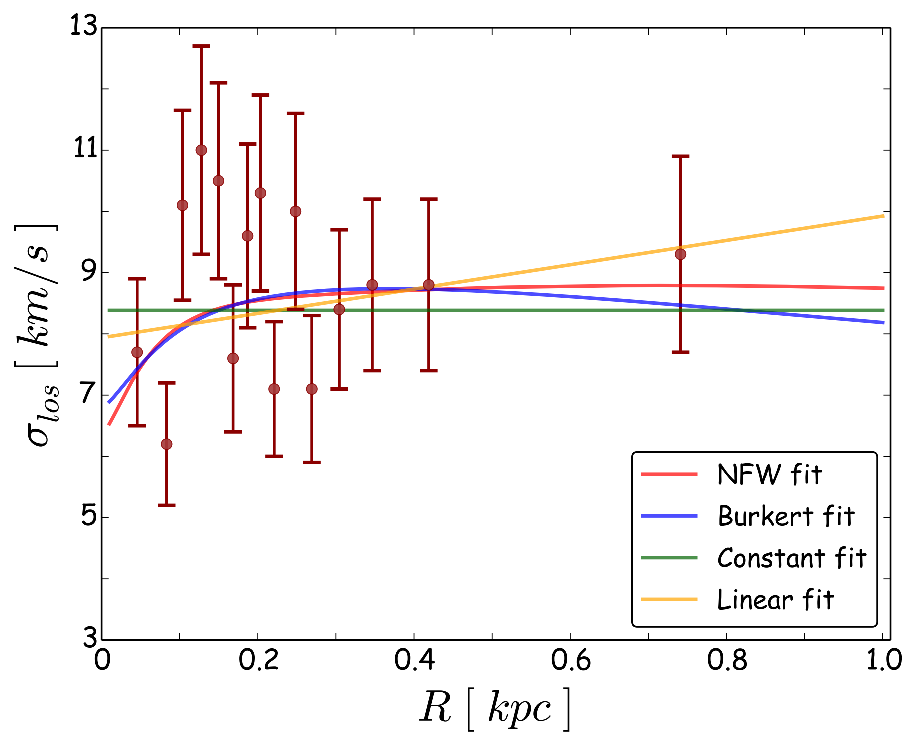
Mass models: our approach (ii)

Now: model $I(R)$ and $\sigma_{l.o.s.}(R)$ with a direct parametric fit on data for these observables. E.g.: assume for the surface brightness a Plummer model:

$$I(R) = \frac{L_0}{\pi R_{1/2}^2} \frac{1}{(1 + R^2/R_{1/2}^2)^2}$$

and fit the half-light radius $R_{1/2}$, i.e. in Ursa Minor: $R_{1/2} \simeq 0.3$ kpc .

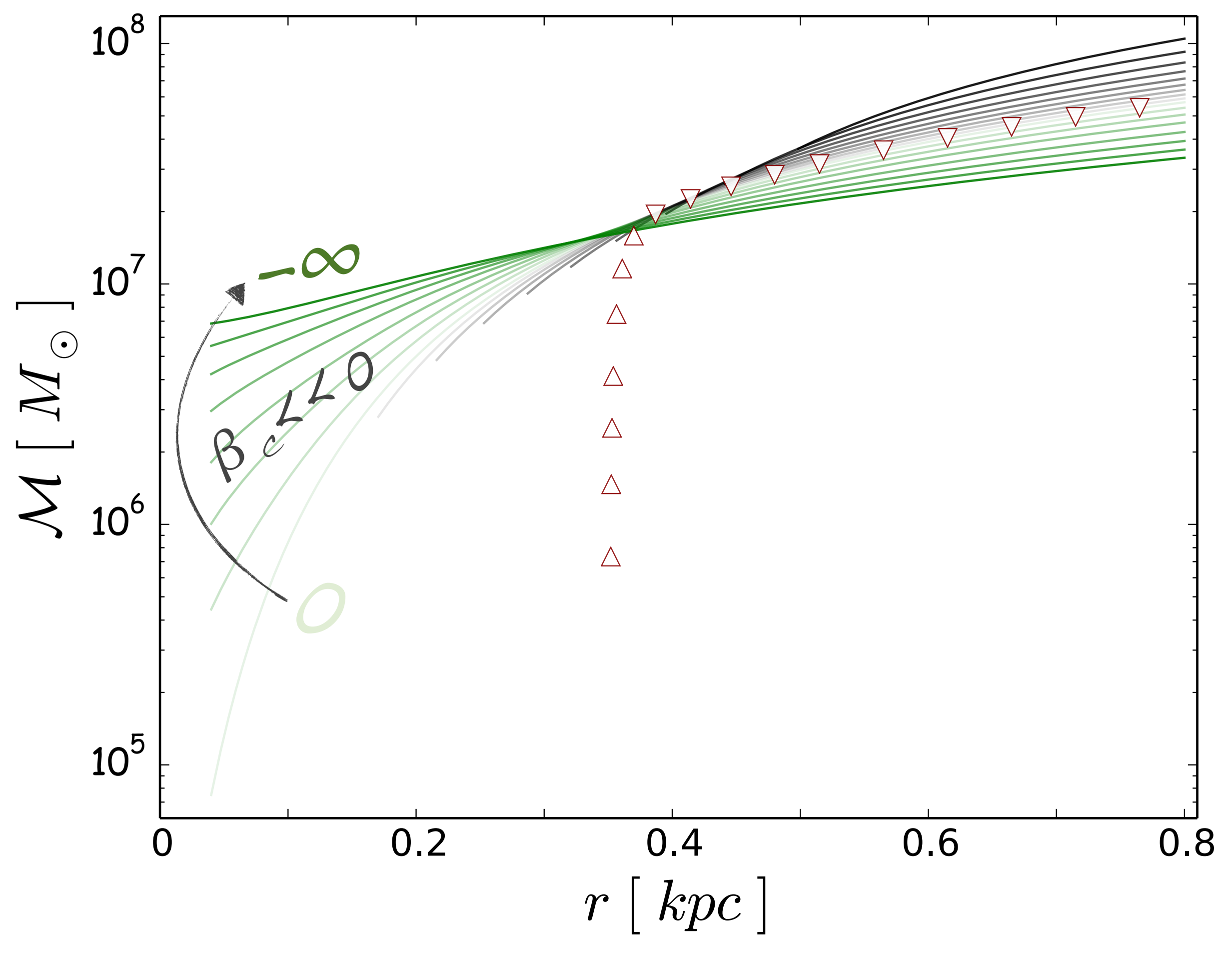
For the line-of-sight projected velocity dispersion in general data are less constraining and one can consider different possibilities, e.g.:



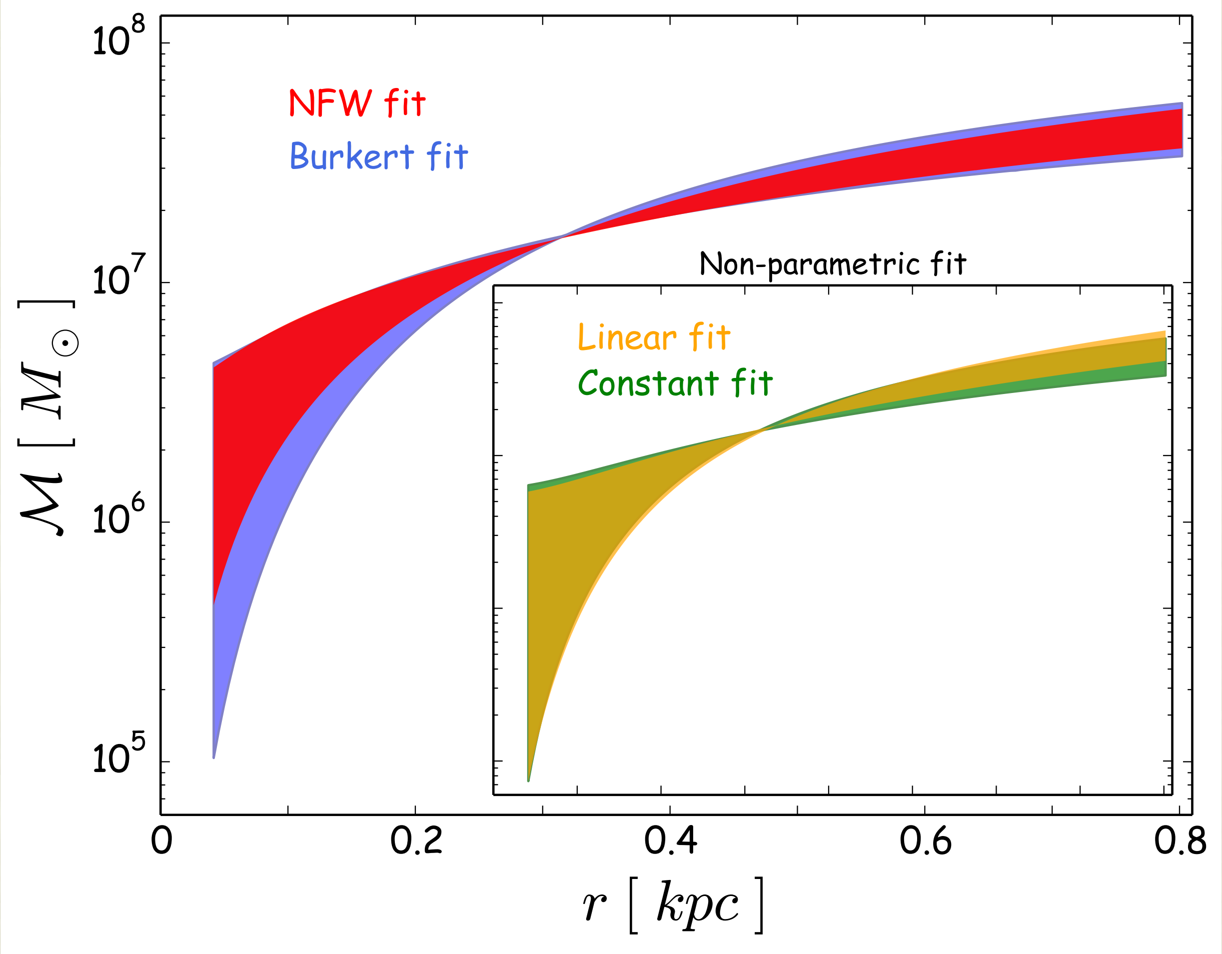
The Abel transforms $\widehat{P}(r)$ and $\widehat{I}(r)$ are computed numerically, and then one can perform a direct projection of what you do (not) know about $\beta(r)$ into a prediction for $M(r)$, $\rho(r)$ and J , and hence have a more direct assessment of uncertainties in the predictions for dark matter signals.

Mass profiles in Ursa Minor as a function of constant β:

In practice, agnostic mass reconstruction with our inversion formula not always give physical results. In a concrete example we need to restrain (a posteriori) to cases in which we get $M(r) > 0$, $dM/dr > 0$ and $d\rho/dr \leq 0$:



Burkert profile: imposing radial orbits gives unphysical results at low radii



Span of results for 4 different possible fits of the line-of-sight projected velocity dispersion

Mass profiles in Ursa Minor as a function of constant β:

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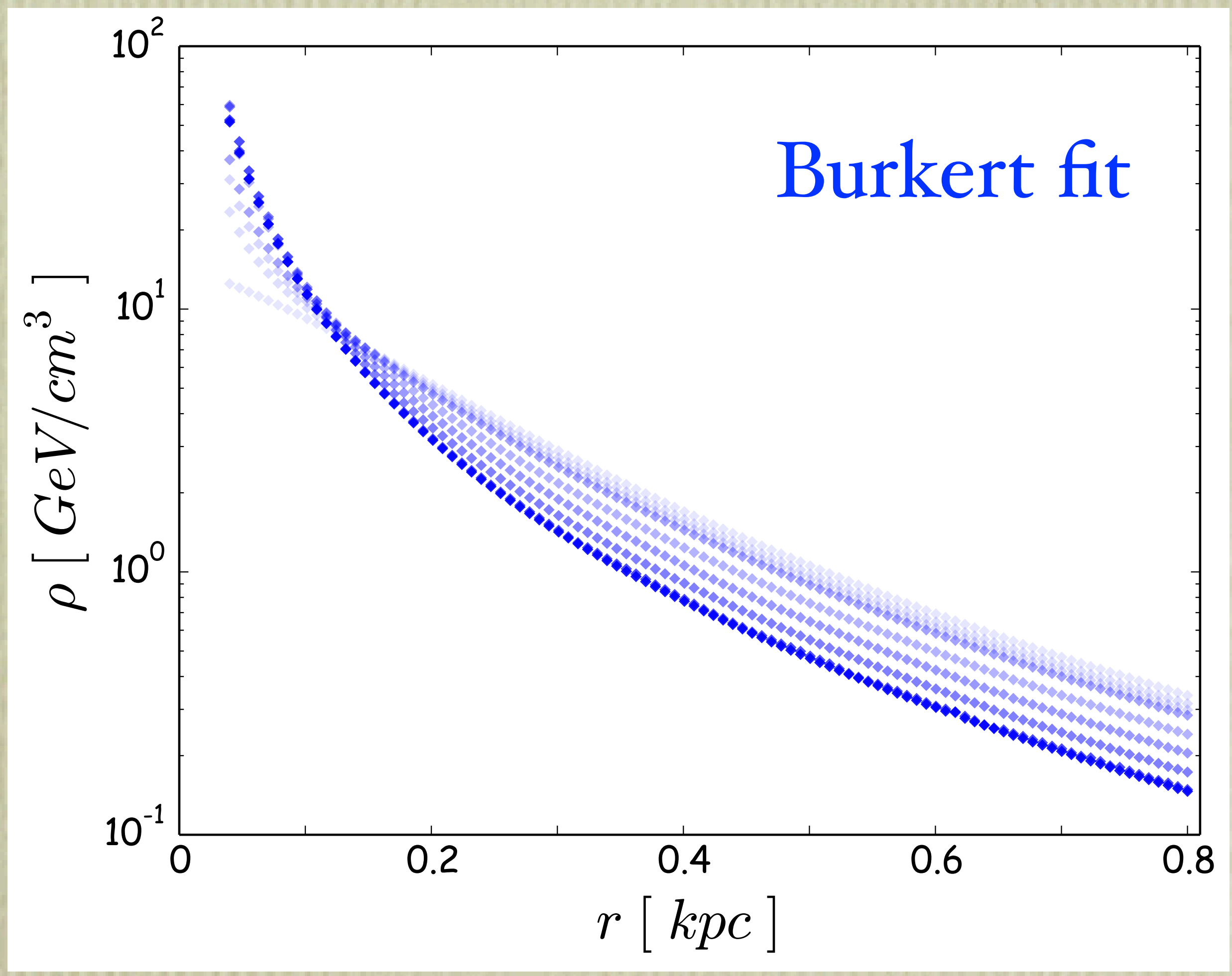
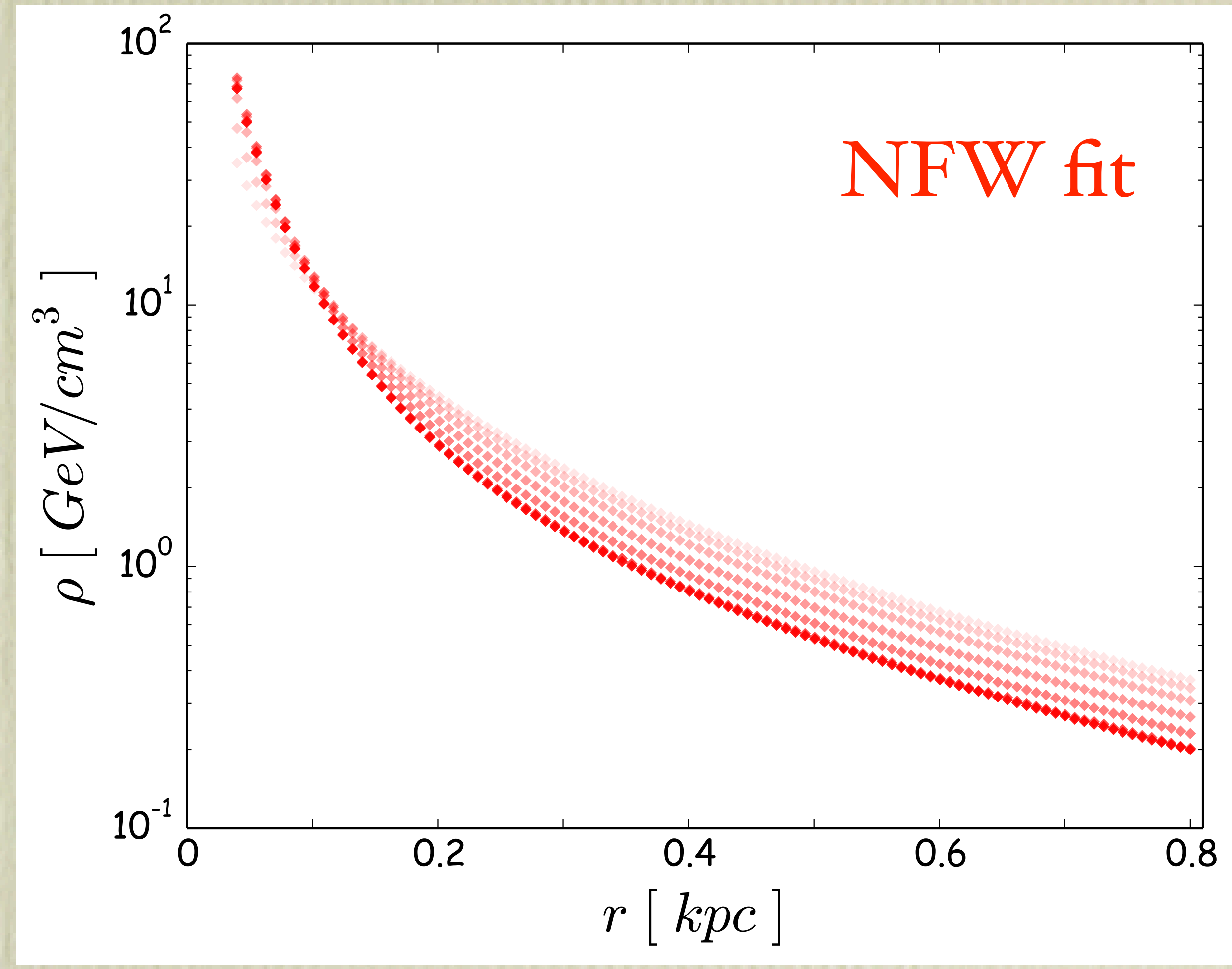




Sample limits:

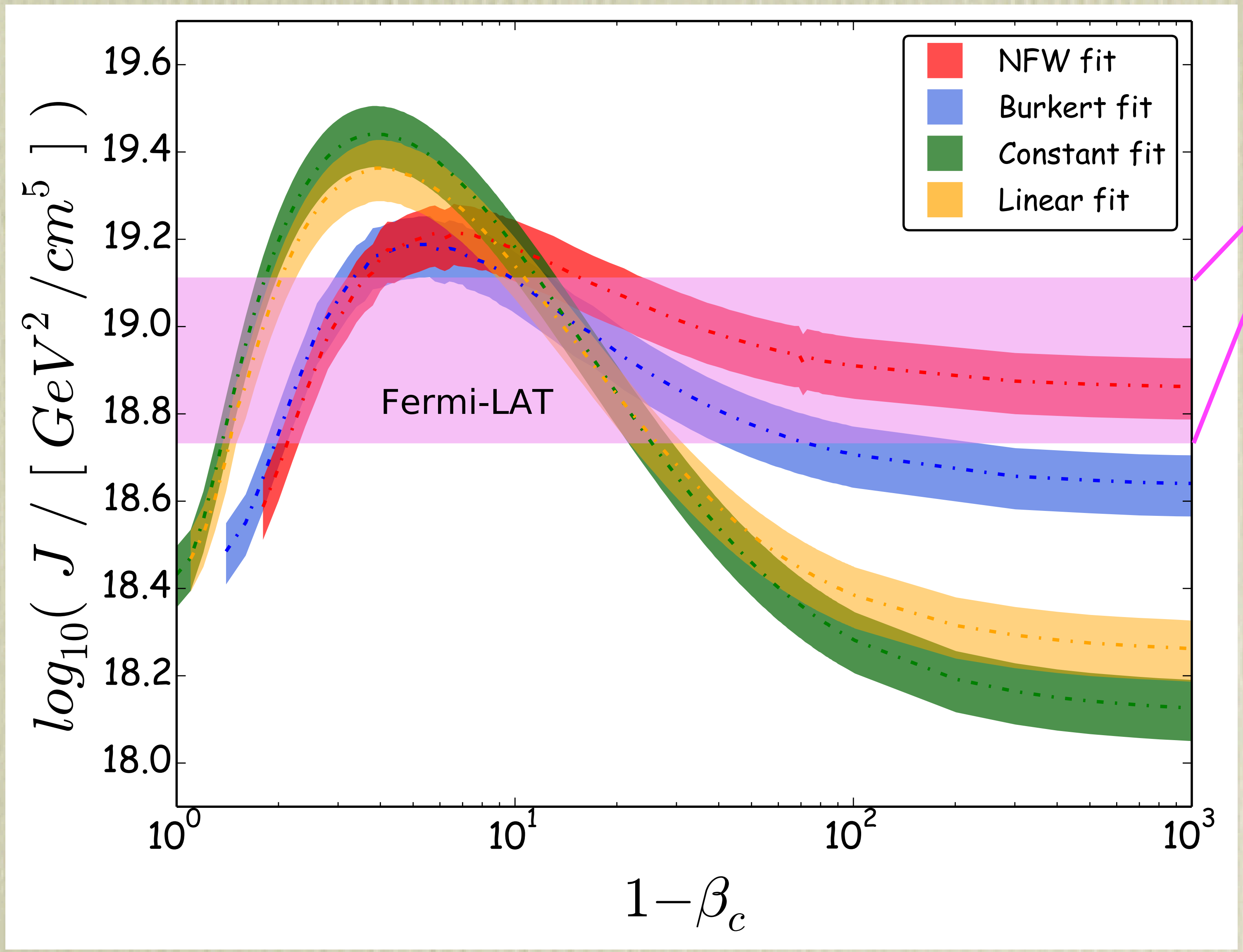
- for $\sigma_{l.o.s.}(R) = \text{const.}$, Plummer $I(R)$ + $\beta(r) = 0$ $\Rightarrow$ $\rho(r) \overset{r \to 0}{\simeq} \text{const}$
- for $\sigma_{l.o.s.}(R) = \text{const.}$, Plummer $I(R)$ + $\beta(r) = -\infty$ $\Rightarrow$ $\rho(r) \overset{r \to 0}{\propto} r^{-2}$ + black hole

J-factors in Ursa Minor as a function of constant β:

In line-of-sight integrals: $J \equiv \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega \int_{l.o.s.} dl \; \rho^2_{DM}(l)$

we conservative set $\rho(r)$ to a constant at radii smaller than the radius at which $\sigma_{l.o.s.}(R)$ can be measured (smallest radius in our data binning):

Span of predictions for the 4 sample fits of $\sigma_{l.o.s.}(R)$



1-σ band for Ursa Minor in **Fermi Coll. 2015** apparently not fully catching the β uncertainty

Take home message: current and projected limits from dwarfs need caution!

Conclusions:

Dark matter has been indirectly detected (via its gravitational effects).

Dark matter particles may still be indirectly detected (as well as directly detected in underground labs or produced at accelerators), but the playground for almost all detection channels proposed so far is that a small signal is expected on top of a large background.

Particular caution is then needed in this playground, examining critically what are the assumptions involved in both background estimates and signal predictions.

The point has been illustrated here via two examples which received particular attention recently: a tentative DM γ-ray signal from the central region of the Galaxy and DM γ-ray limits from dwarf satellites.