Astrophysical issues in indirect DM detection

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Outline

*** Introduction**

*** Practical examples of astrophysical issues (at the Galactic scale)**
=> size of the GCR diffusion zone: relevant to antiprotons, antideuterons, (diffuse gamma-rays)
=> positron fraction: clarifying the role of local astrophysical sources
=> impact of DM inhomogeneities: boost + reinterpreting current constraints
=> diffuse gamma-rays

*** Perspectives**

Indirect dark matter detection in the Milky Way

THE ASTROPHYSICAL JOURNAL, 223:1015–1031, 1978 August 1

SOME ASTROPHYSICAL CONSEQUENCES OF THE EXISTENCE OF A HEAVY STABLE NEUTRAL LEPTON

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Received 1977 December 1; accepted 1978 February 14

VOLUME 53, NUMBER 6 PHYSICAL REVIEW LETTERS 6 AUGUST 1984

Cosmic-Ray Antiprotons as a Probe of a Photino-Dominated Universe

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and
Mark Srednicki
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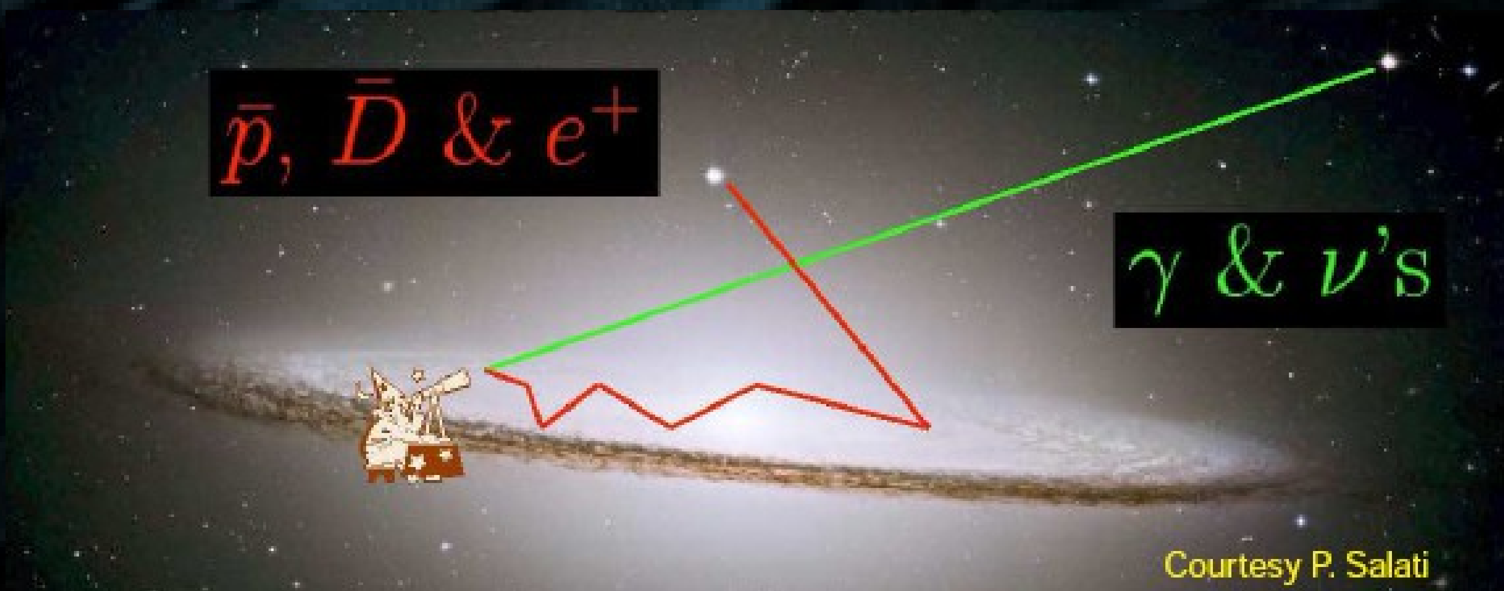
(Received 8 June 1984)



Main arguments:
- Annihilation final states lead to: gamma-rays + antimatter
- γ-rays : lines, spatial + spectral distribution of signals vs bg
- Antimatter cosmic rays: secondary, therefore low bg
- DM-induced antimatter has specific spectral properties

But:
- Do we control the backgrounds?
- Antiprotons are secondaries, not necessarily positrons
- Do the natural DM particle models provide clean signatures?

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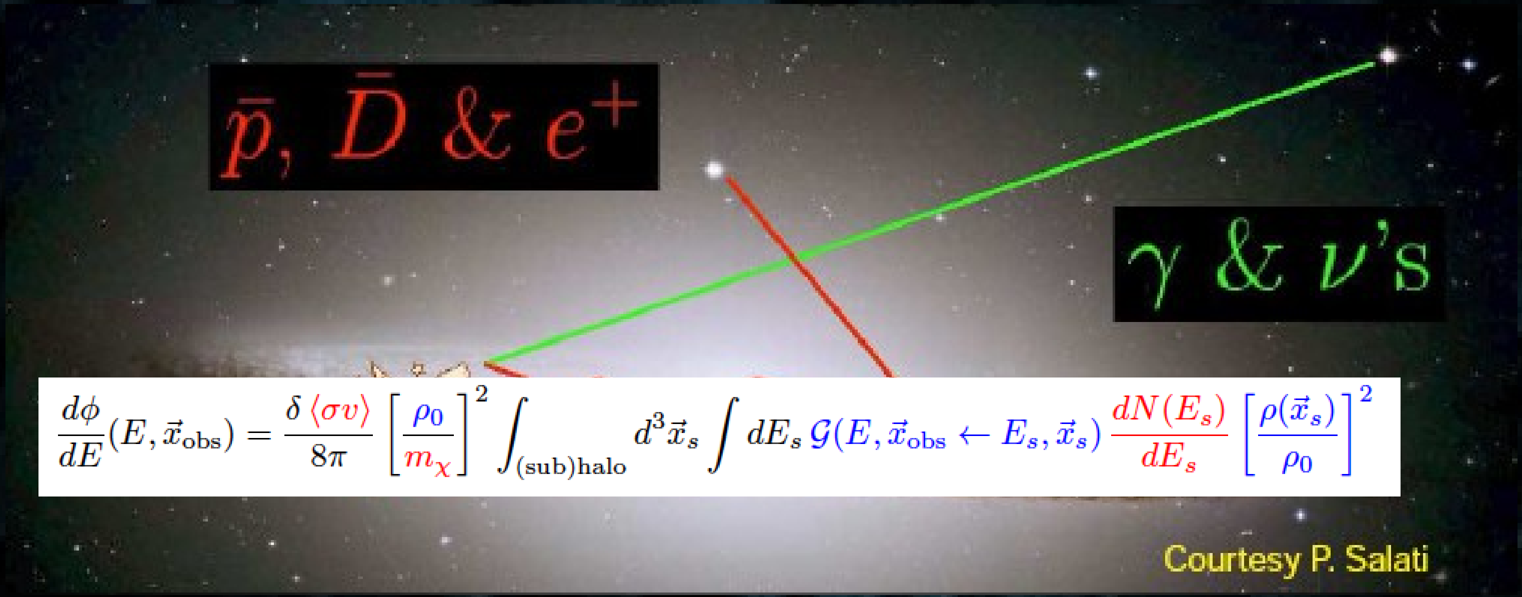

$$\frac{d\phi}{dE}(E,\vec{x}_{\rm obs}) = \frac{\delta\,\langle\sigma v\rangle}{8\pi}\left[\frac{\rho_0}{m_\chi}\right]^2 \int_{\rm (sub)halo} d^3\vec{x}_s \int dE_s\, \mathcal{G}(E,\vec{x}_{\rm obs}\leftarrow E_s,\vec{x}_s)\,\frac{dN(E_s)}{dE_s}\left[\frac{\rho(\vec{x}_s)}{\rho_0}\right]^2$$

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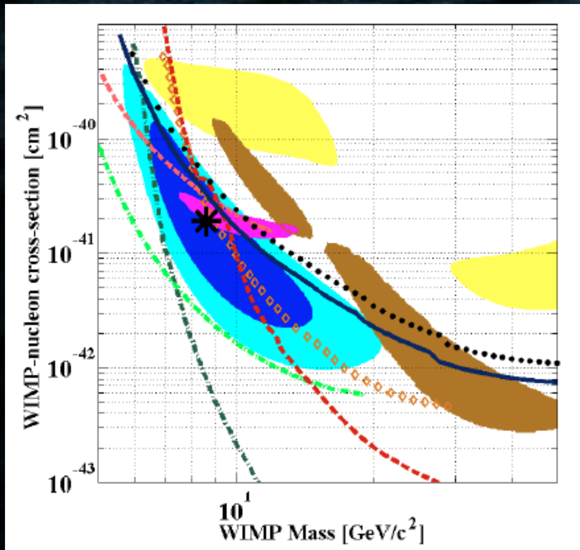
Transport of Galactic cosmic rays
The standard picture

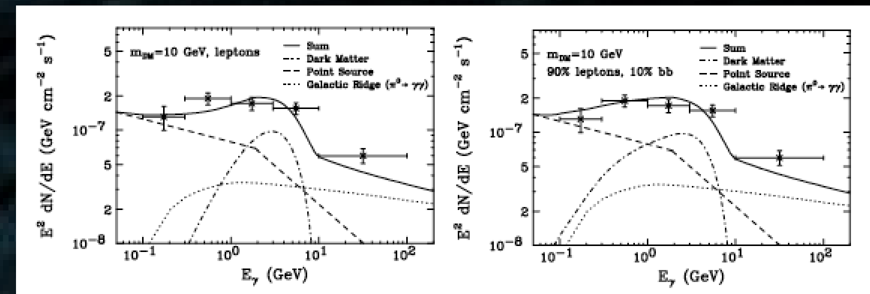
$$
\begin{aligned}
\partial_t \frac{dn}{dE} &= Q(E,\vec{x},t) \\
&+ \left\{\vec{\nabla}\left(K(E,\vec{x})\vec{\nabla} - \vec{V}_{\rm c}\right)\right\}\frac{dn}{dE} \\
&- \left\{\partial_E\left(\frac{dE}{dt} - \partial_E E^2 K_{\rm pp}\partial_p E^{-2}\right)\right\}\frac{dn}{dE} \\
&- \left\{\Gamma_{\rm spal}\right\}\frac{dn}{dE}
\end{aligned}
$$

From Haslam et al data (1982)

Dark matter has long been discovered !



Agnese + (2013)
DAMA, CoGenT, CRESST … + CDMSII(SI)
versus XENON-10, XENON-100
→ DM around 10 GeV



Hooper + (2012): gamma-rays + radio at GC
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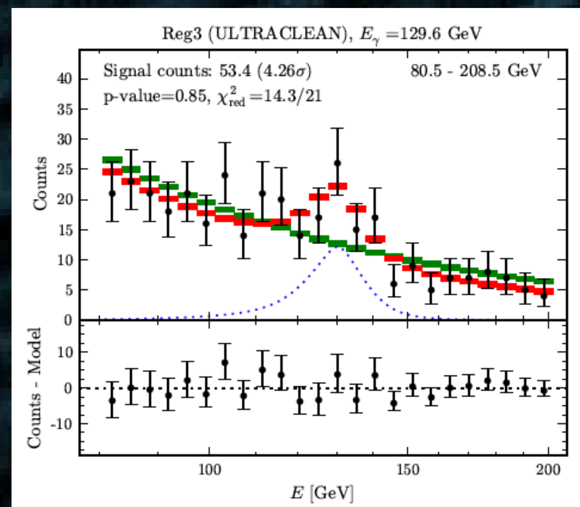
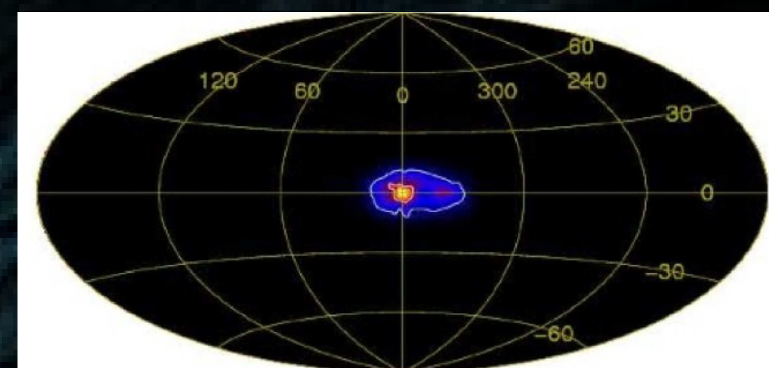
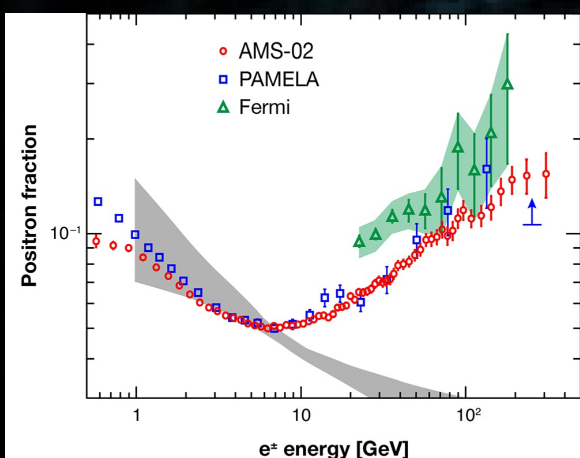


Around the GC
Weniger +, Finkbeiner + (2012)
→ DM around 130 GeV



511 keV, Knödlsëder/Weidenspointner + (2005 - 2008)
Boehm, Hooper + (2004) → DM around 1 MeV



HEAT/PAMELA/AMS positron excess
Bergström +, Cirelli + (2008) → DM around 300-1000 GeV

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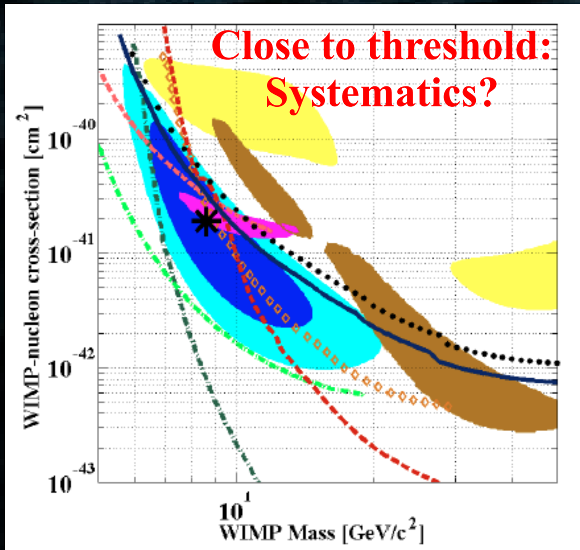

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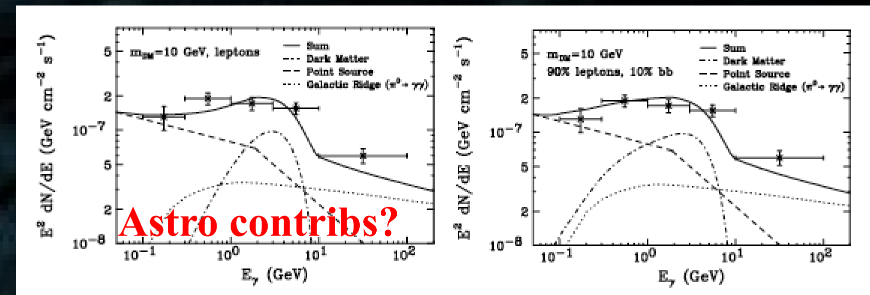

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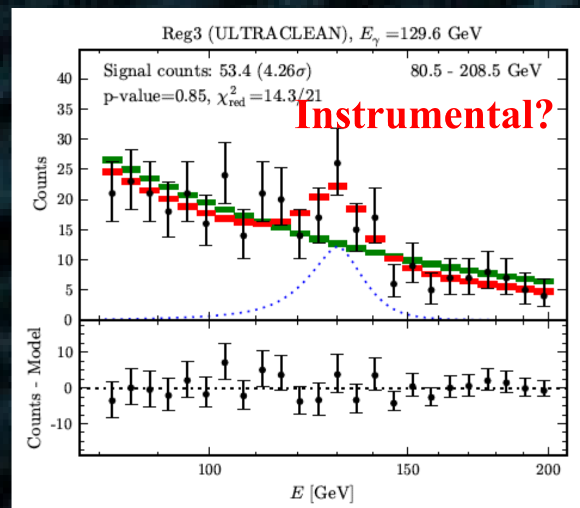
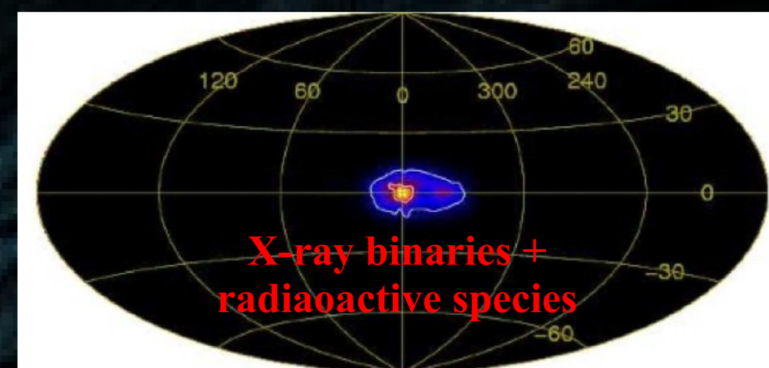


Around the GC
Weniger +, Finkbeiner + (2012)
→ DM around 130 GeV

All point toward different mass scales :
1 MeV / 10 GeV / 130 GeV / 500 GeV

Hard to explain with a single DM candidate
(except maybe for XDM,
Weiner ++ 2004-2012, Cline +, etc.)



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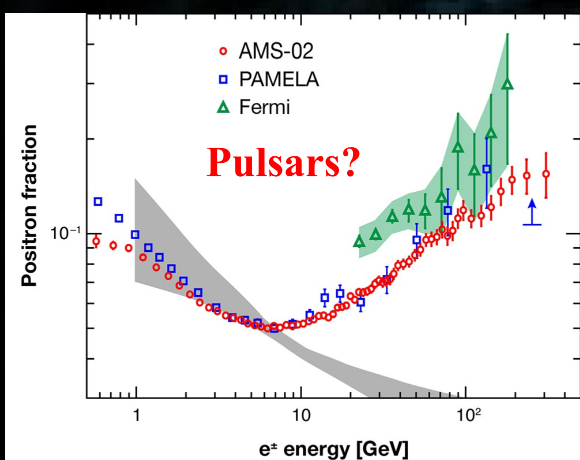

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Strategy?

*** Instrumental effects (not our job)**

*** Check consistency with complementary signals**
=> multi-messenger analyses (multiwavelength photons, antimatter CRs, neutrinos)
=> multi-source analyses (MW, Dwarf galaxies,)
=> (other detection methods: LHC+direct+indirect+early universe+etc.)

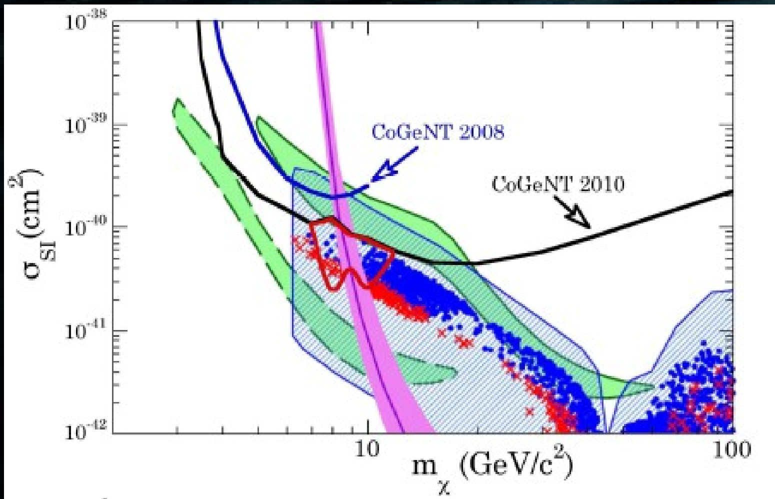
*** Understand / quantify theoretical uncertainties (for discovery as well as constraints)**
=> eg CR transport, DM distribution, Galactic components

*** Understand / quantify backgrounds**
=> astrophysical sources / mechanisms

NB: Fermi + HESS2 + AMS02 + CTA => beginning of precision era in GeV-TeV astrophysics

Focus on antinuclei: antiproton constraints

CoGeNT Collab (2010), Bottino+ (2010)



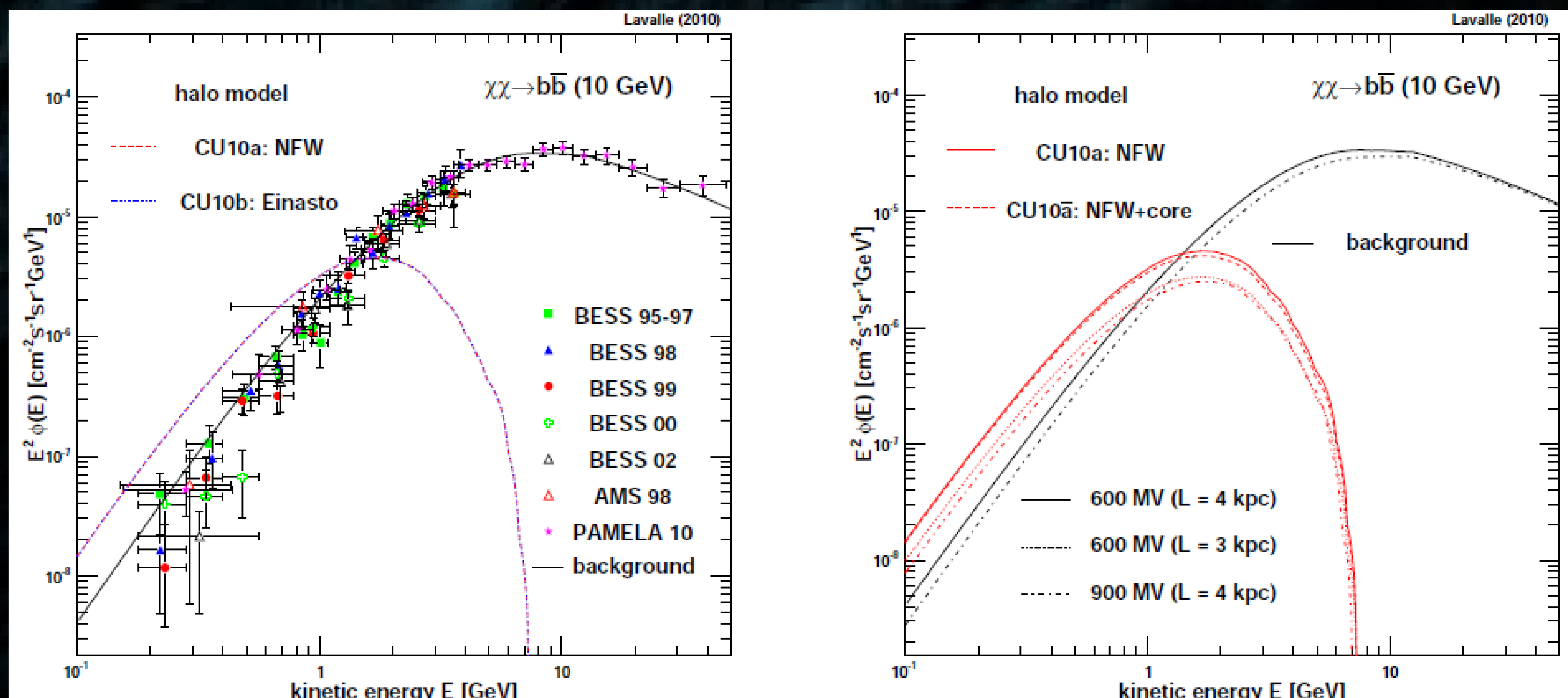
DAMA+CDMS+COGENT mass regions
(+ GC fit by Hooper+)
=> WIMP mass ~10 GeV

Couplings to quarks => annihilation may produce antiprotons (not generic for Majorana fermions, only s-wave contributions)

Large antiproton flux expected (scales like $1/m^2$)

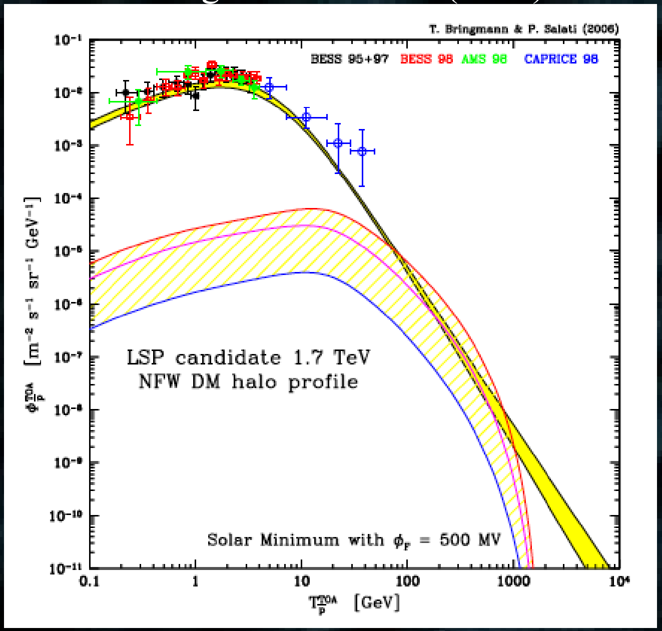
** Uncertainties due to the size of the diffusion zone?

Lavalle (2010)



Impact of the size of the diffusion zone

Bringmann & Salati (2007)



Maurin+ (2001) & Donato+ (2002)
=> attempts to bracket theoretical uncertainties

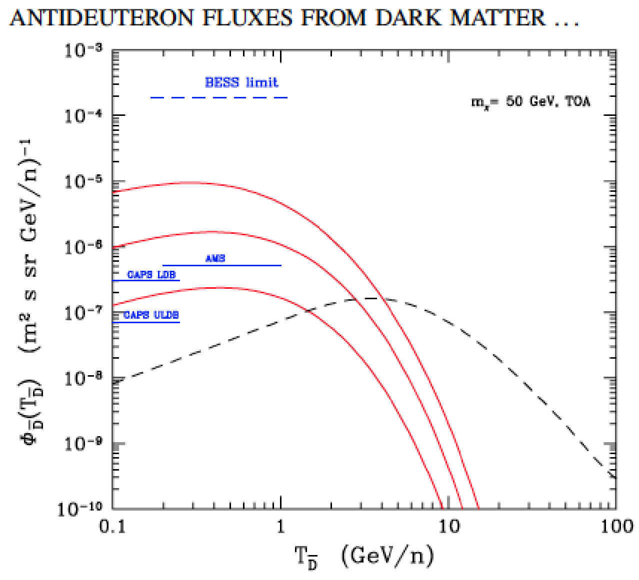
Besides best fit transport model (dubbed *med*), proposal for 2 extreme configurations:

min: L = 1 kpc
max: L = 15 kpc

minimizing and maximizing the DM-induced fluxes, respectively.

NB: much less effect on high-energy positrons (Lavalle+ 07, Delahaye+ 08) – short propagation scale.

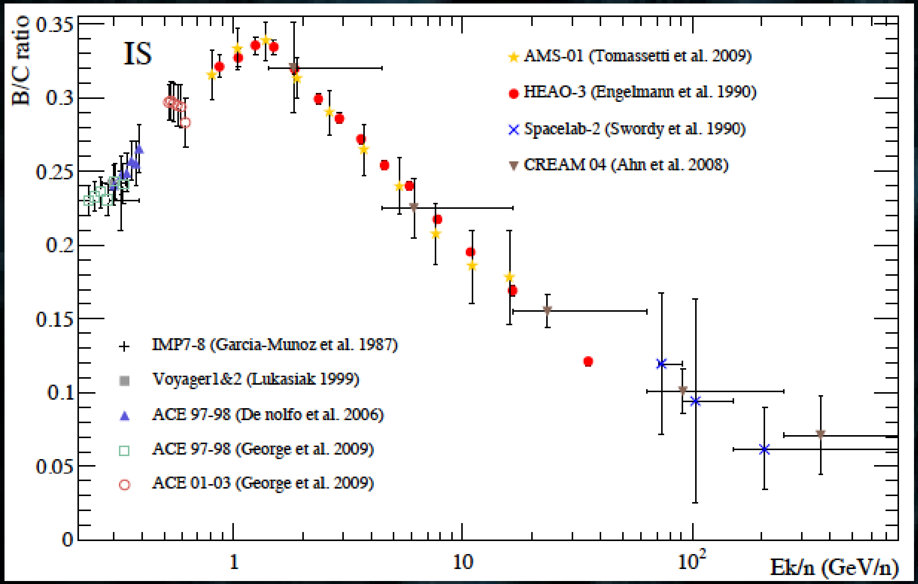
Maurin, Donato, Fornengo (2008)



The game people usually play:
1) you want your model to survive antiproton constraints:
=> take a small L
2) you want to advertise your model for detection:
=> take L from med to max.

Where do constraints on L come from?

Putze+ (2011)



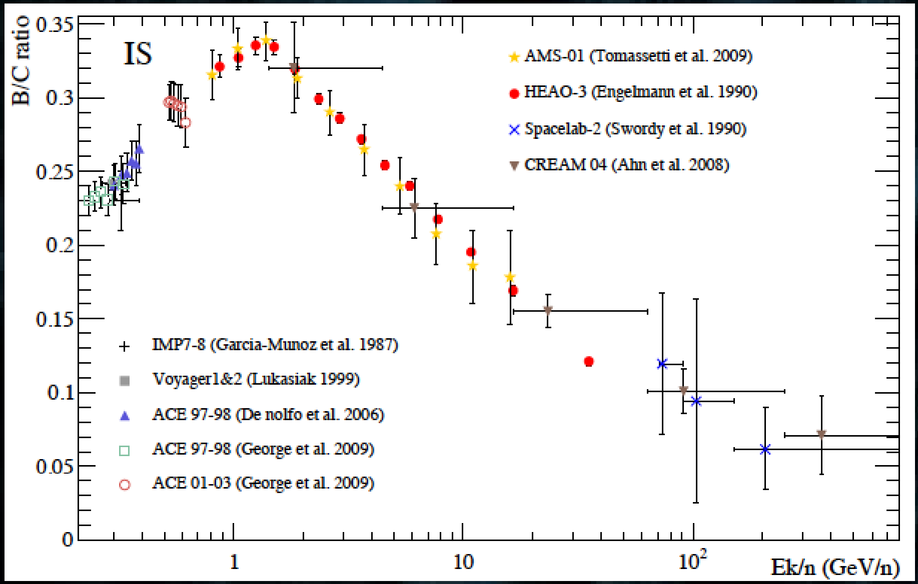
Secondary/Primary ratios:

Degeneracy between K and L!

On the blackboard

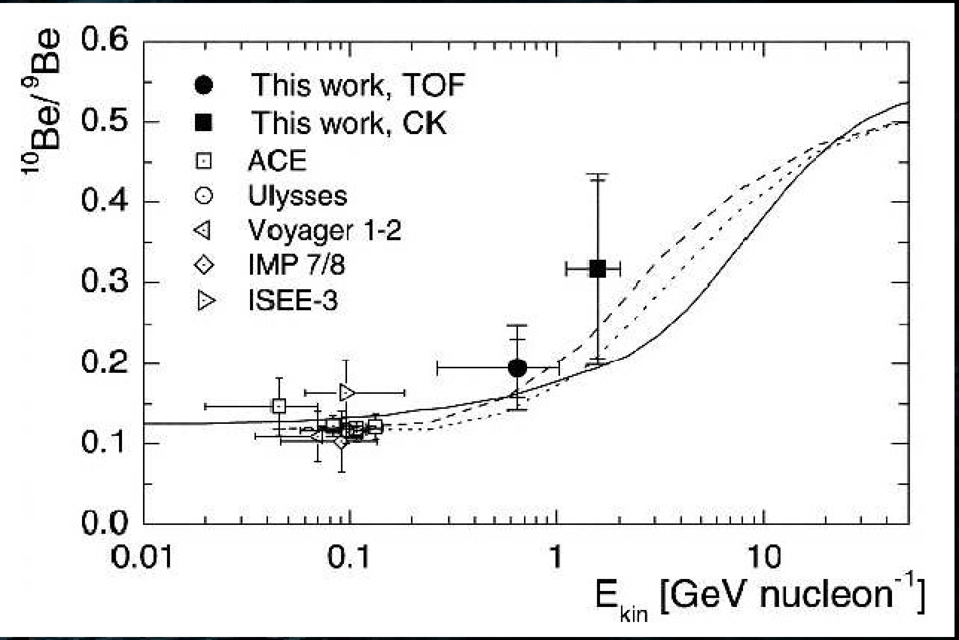
Where do constraints on L come from?

Putze+ (2011)



Breaking degeneracy with radioactive secondaries
=> lifetime too short to reach L

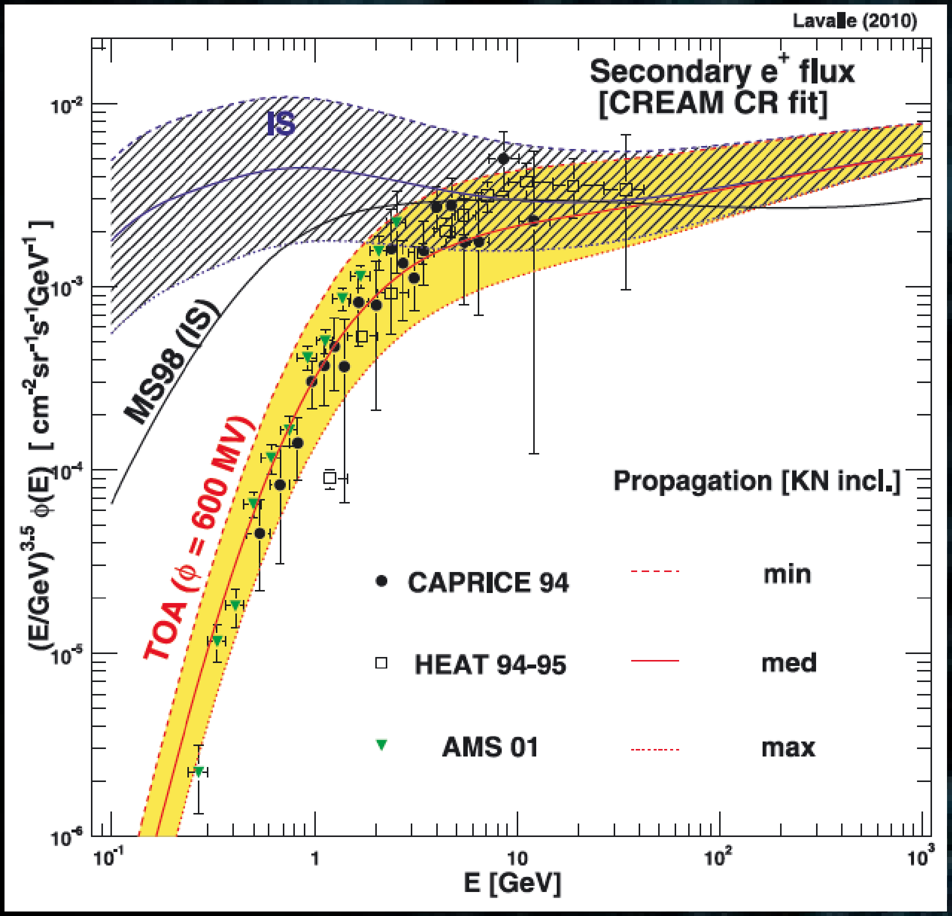
Strong+ (2004)



Uncertainties in the diffusion halo size? Quick digression towards positrons

Secondary positrons
(eg. Delahaye+09, Lavalle 11)

$$\phi_{e^+} \propto 1/\sqrt{K_0}$$



$$\frac{K_0}{L} \approx \mathrm{Cst}$$

Small L models in tension with positron data

=> L > 1 kpc => Very conservative statement!

Perspectives:

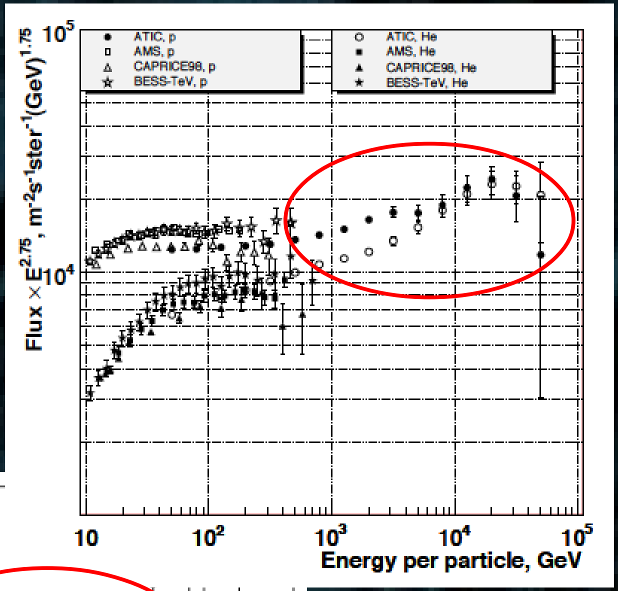
- PAMELA/AMS data still to come

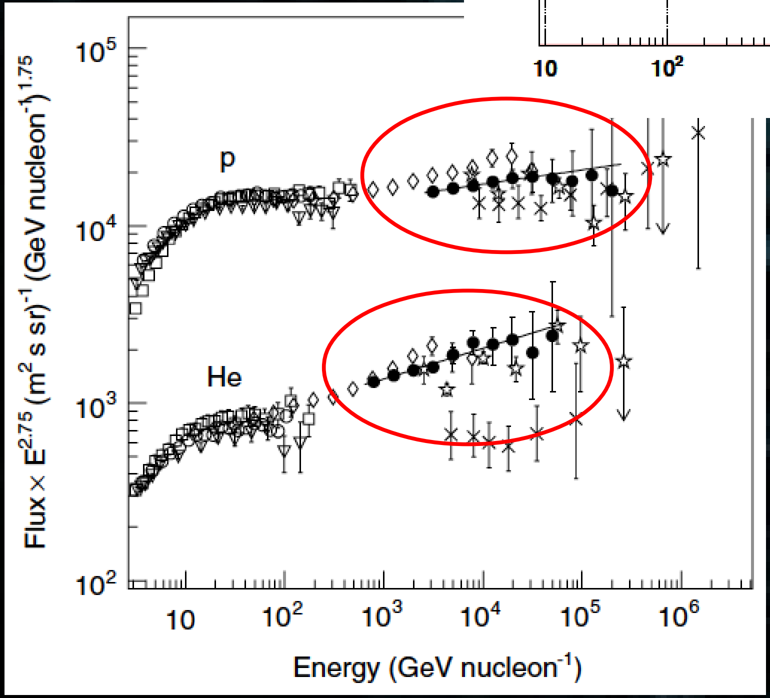
=> Ongoing work with Maurin and Putze

What else on K and L?
(on the spectral hardening)

ATIC Collab (2006-2012)

Cream Collab (2010-2011)



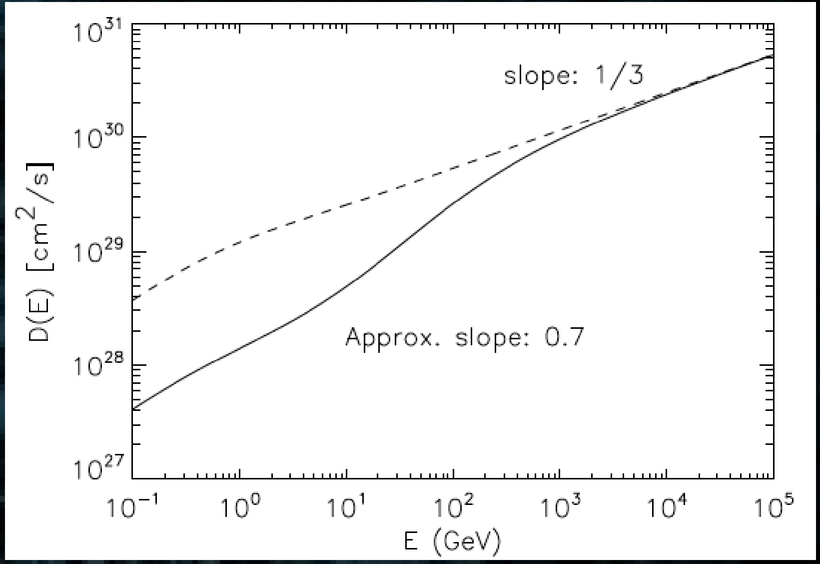


Could be due to a change in diffusion properties (eg Blasi+ 12)

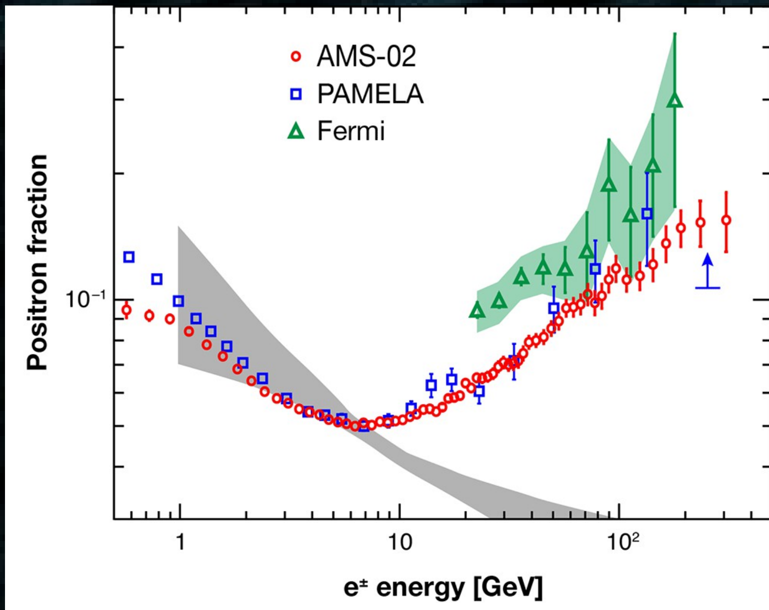
=> K has different slope > 100 GeV (from 0.7 to 0.3)

=> impact on secondary CR production

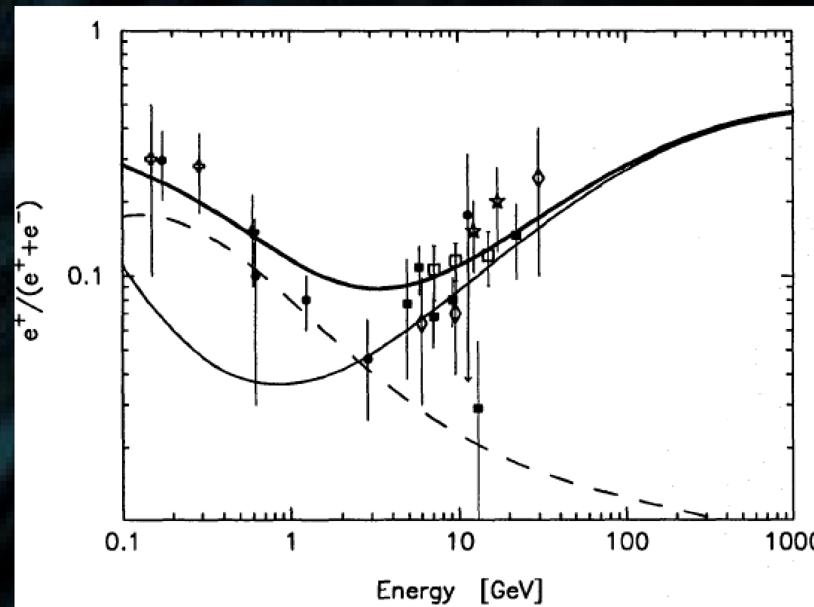
Blasi+ (2012)



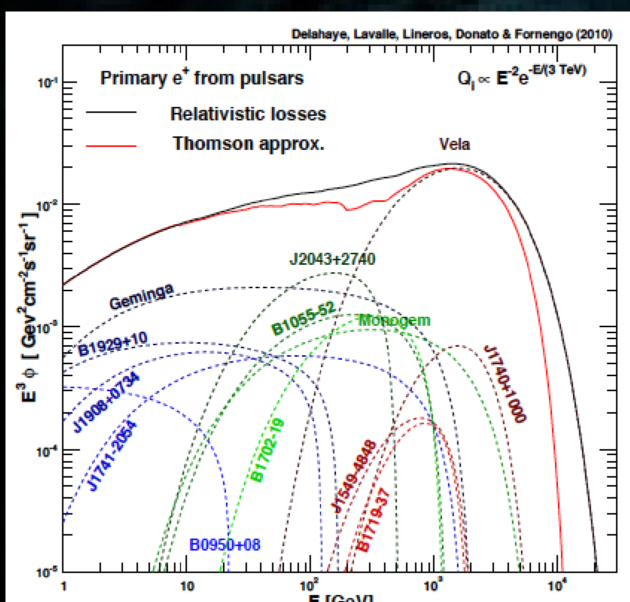
Short comments on the positron fraction



AMS Collab (2013)



Aharonian+ (1995)



We know pulsars can make it in principle.
Going to realistic modeling is complicated (eg Delahaye et al 10).
=> separate distant/local sources, and accommodate the full data (e-, e+, e+e-, e+/e+e-) …

=> Pulsar wind nebulae (PWNe) as positron/electron sources
=> SNRs as electron sources (each PWN must be paired with an SNR)

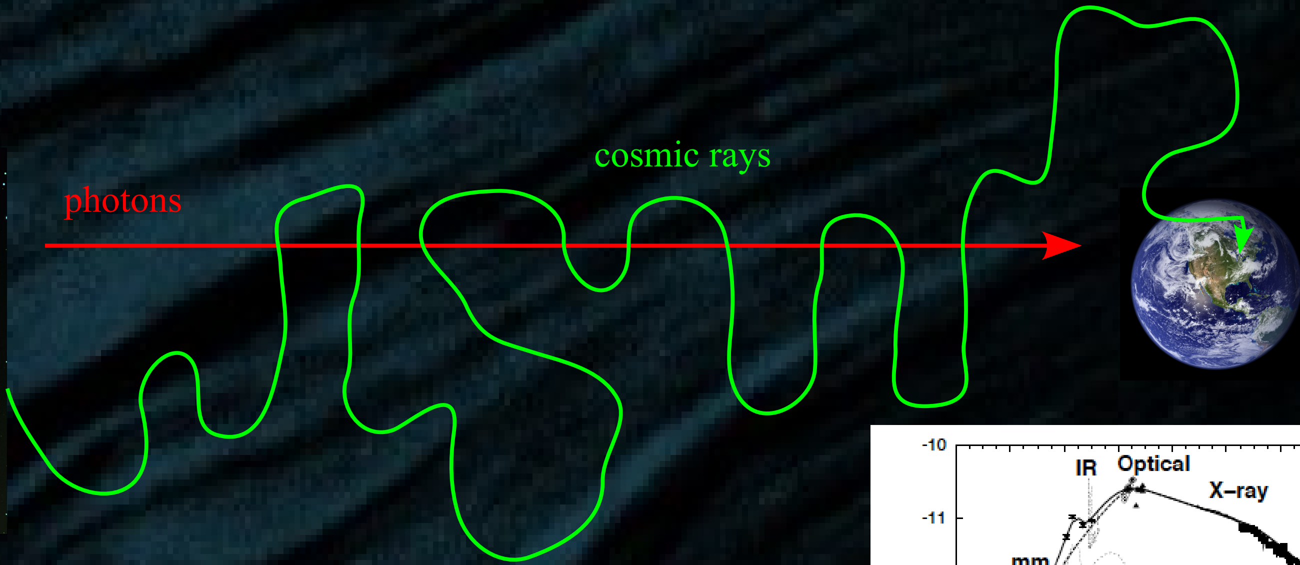
=> you may fit amplitudes / spectral indices … then what?

** Observational constraints!

=> use pulsar period, multiwavelength data for all observed sources … but … not that simple.

Modeling the electron/positron sources?

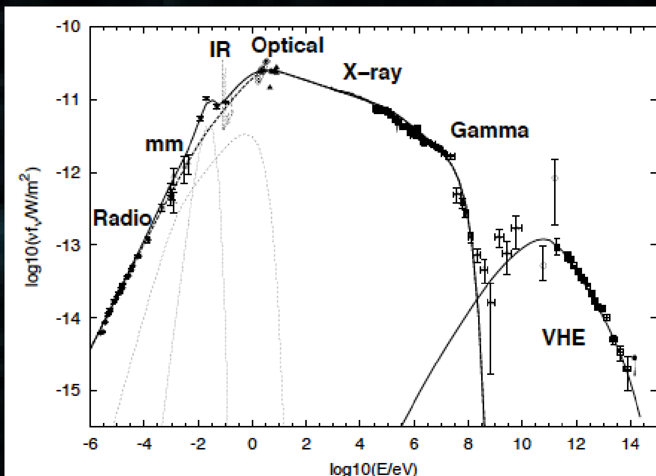
Crab nebula (ESA)
(just for illustration,
not relevant for e+/e-)



$$\text{photon obs. time} = \frac{d}{c} \approx 300\,\text{yr} \left[\frac{d}{100\,\text{pc}}\right]$$

$$\text{transport time} \approx \frac{d^2}{K(E)} \approx 30\,\text{kyr} \left[\frac{E}{1\,\text{TeV}}\right]^{-1/2} \left[\frac{d}{100\,\text{pc}}\right]^2$$

$$\text{E-loss time} = \int_E^{E_s} dE'\, b(E') \approx 300\,\text{kyr @ 1 TeV}$$



Horns & Aharonian (04)
Crab SED

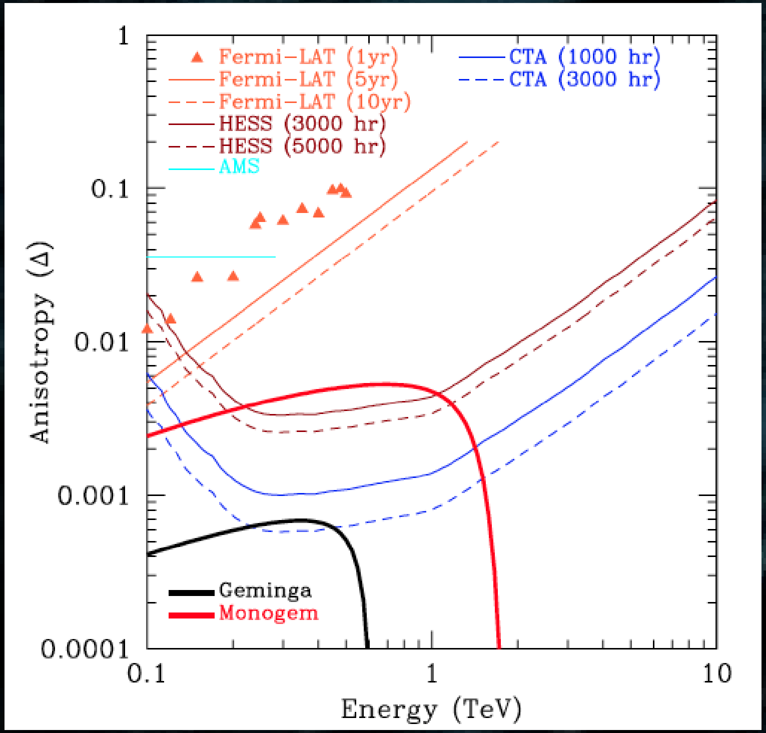
Different timescales:
1) E-loss time > source age > transport time
2) transport time >> photon time
=> cannot directly use photon data
=> requires dynamical models for sources (time evolution)

Very complicated problem:
1) photon data: CRs which are mostly still confined in sources (escape issue)
2) coupled evolution of magnetic fields and CR density

Some attempts at the source level (eg Ohira+ 10-11), but much more work necessary.

Work in prep. with Y. Gallant and A. Marcowith (LUPM).

Anisotropy as a test?



Linden & Profumo (2013)

Caveats:

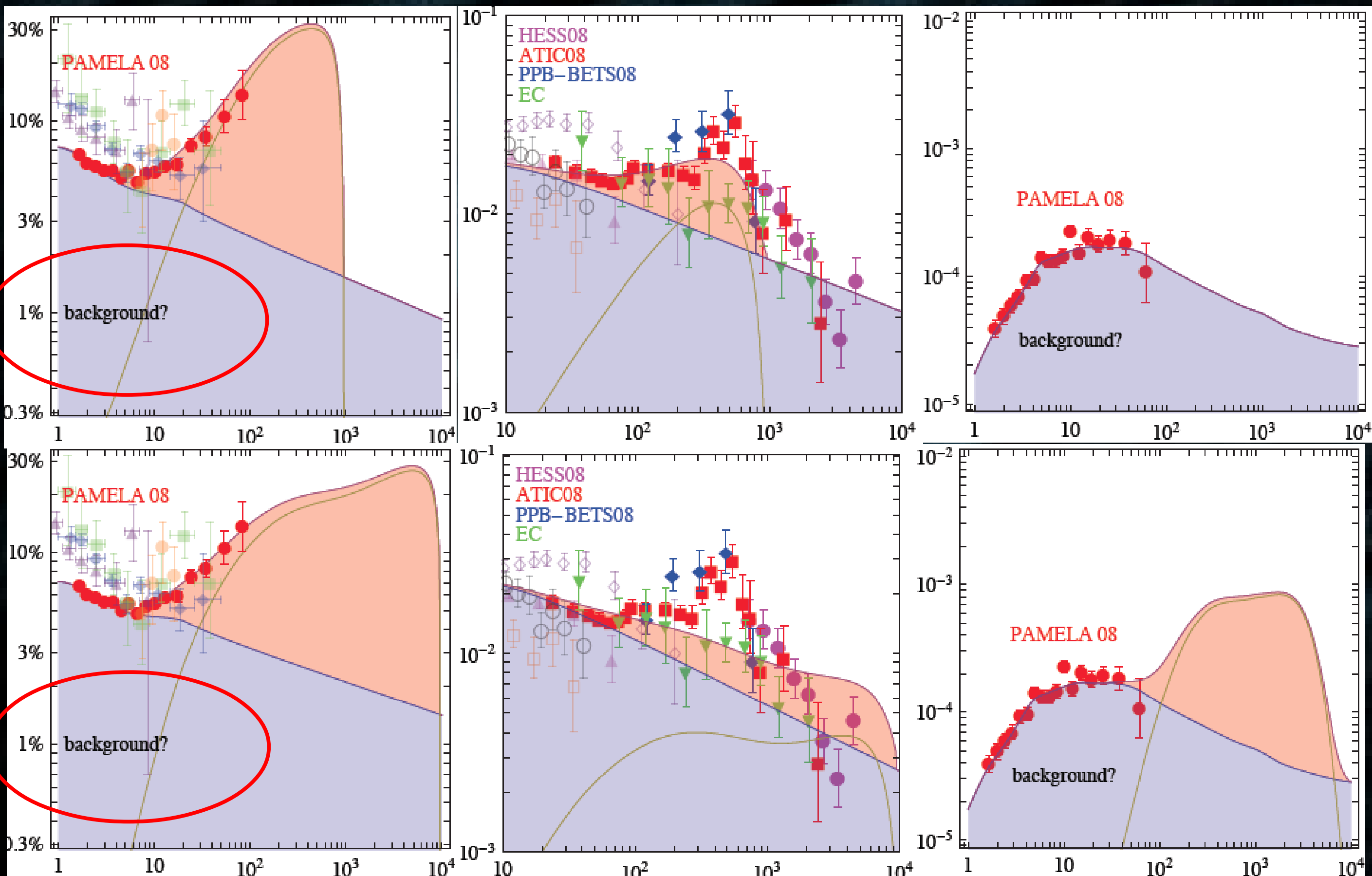
* model-dependent (diffusion halo size again!)
* contributions of other sources (eg dipole from GC/antiGC asymmetry in the source distribution)
* cancellations might occur in the dipole

Still:

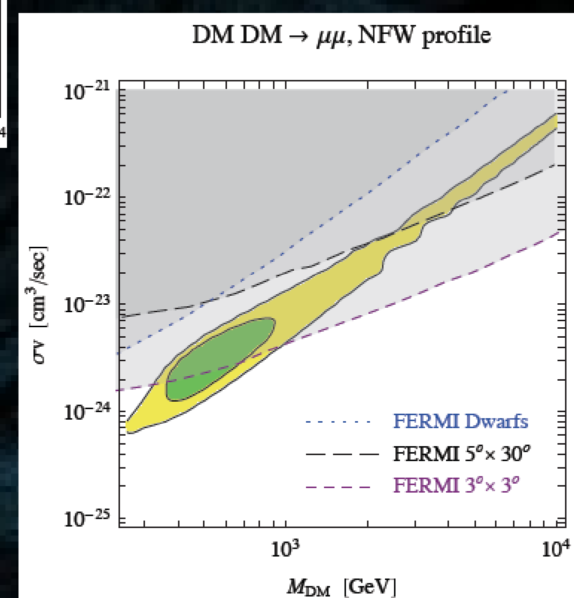
* physically meaningful information
* should be provided for all CR species separately (eg positrons, antiprotons, etc.)
* will provide constraints to the full transport model
* AMS may reach the necessary sensitivity

DM interpretation of the positron excess?

(if you still want to believe …)



Cirelli, Strumia+ (2008-2013)



Method:

* background (!!!) + annihilation cross-section as free params.

Conclusions:

* severe antiproton constraints => multi-TeV or leptophilic models

But …

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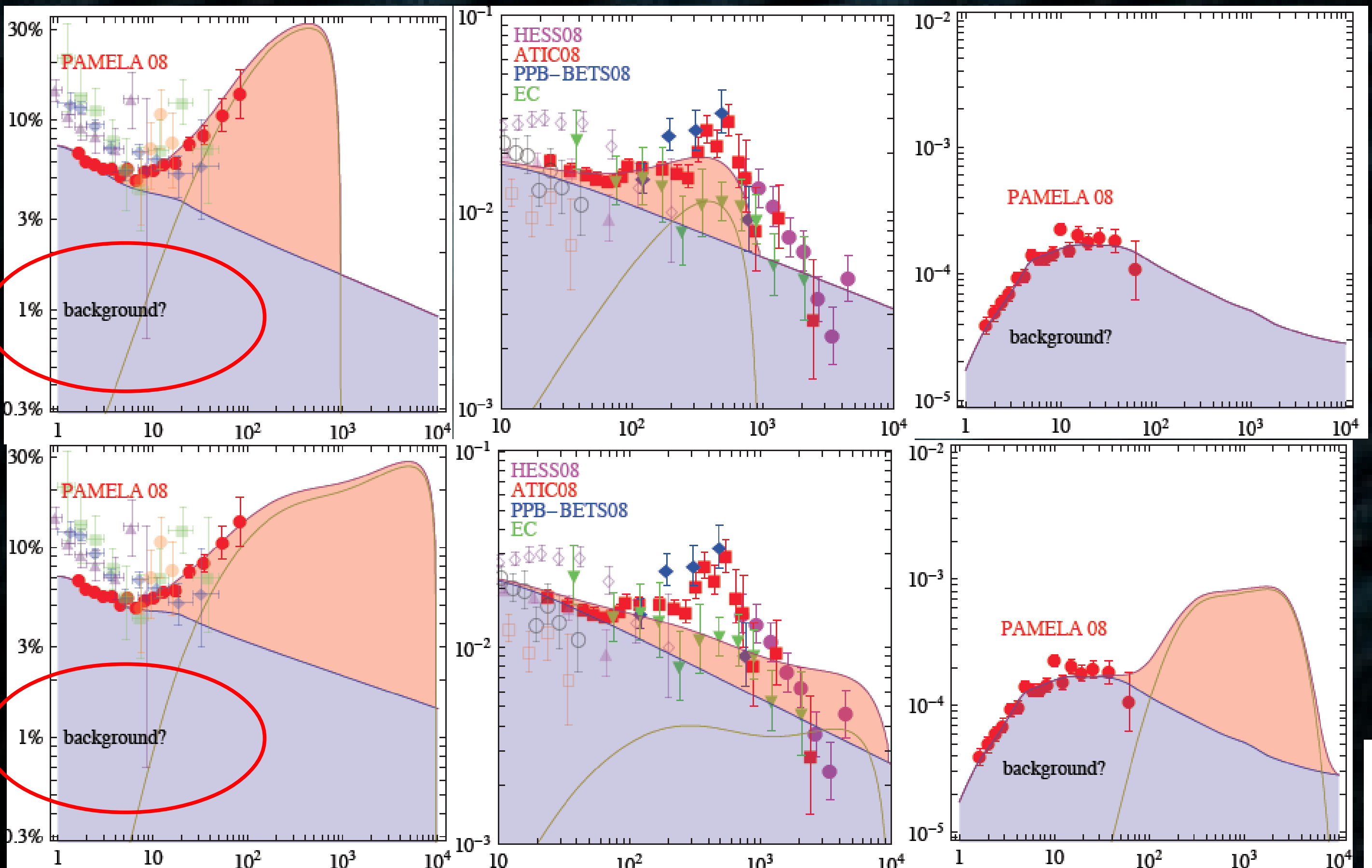

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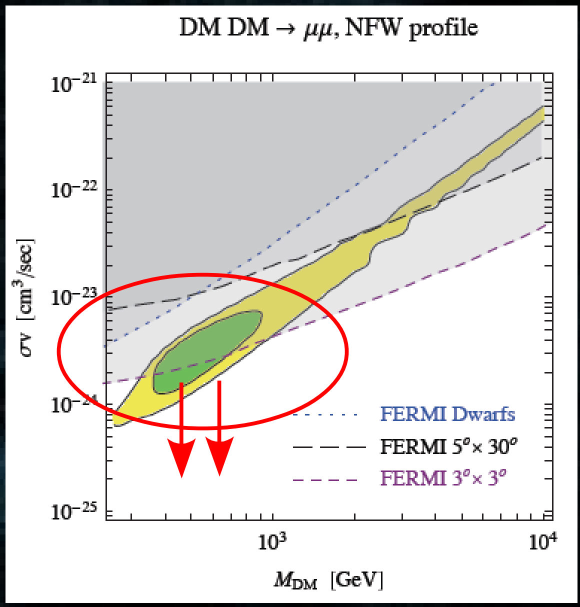

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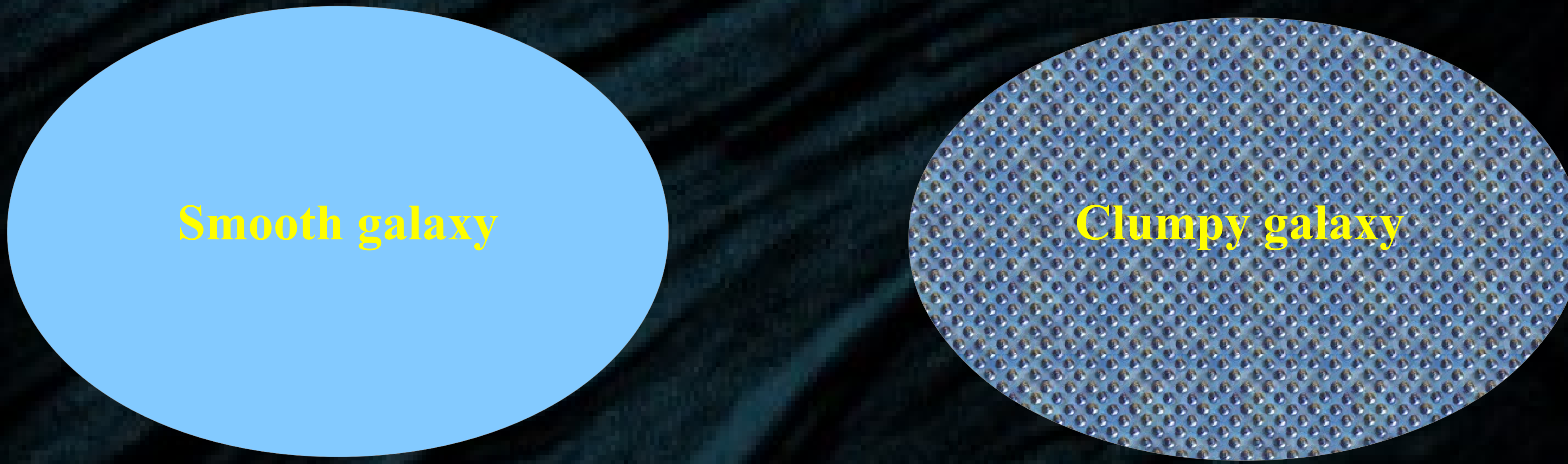
But … local DM: 0.3 → 0.4 GeV/cm3, DM subhalos => BF ~ 2-3
=> factor of 4-5 possible

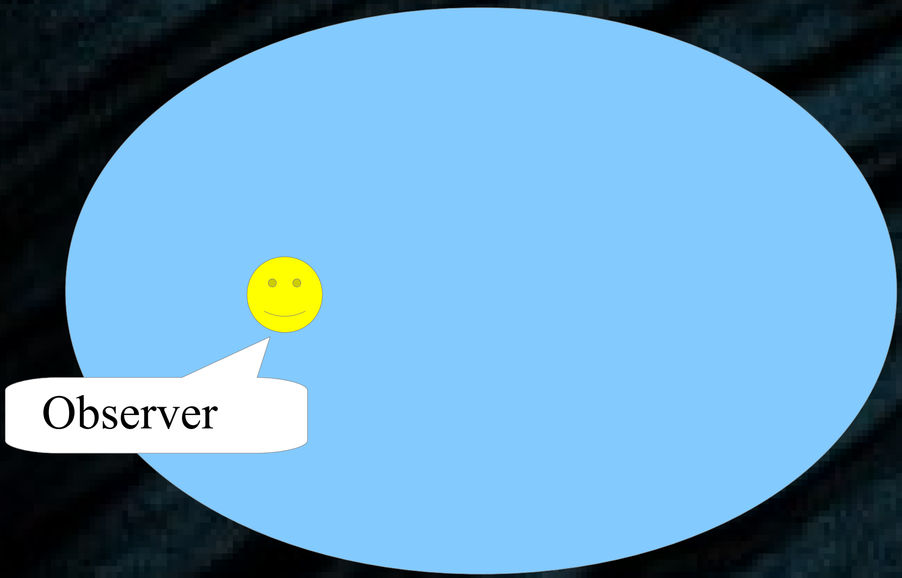
*Boost factor ? ... well, in fact, boost factor**s***

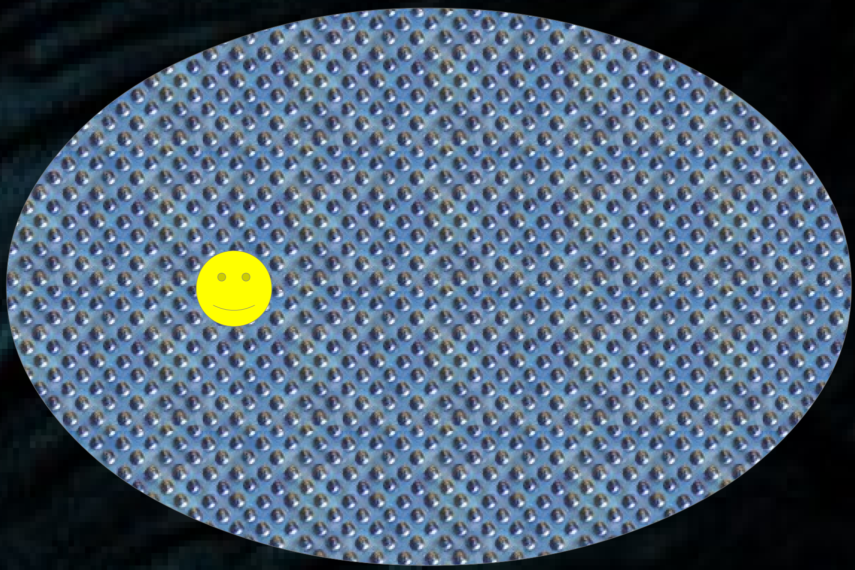


$$\mathcal{B} = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} \geq 1$$

The volume over which the average is performed depends on the cosmic messenger!

Boost factor ? ... well, in fact, boost factors





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The volume over which the average is performed depends on the cosmic messenger!

1) **Prompt gamma-rays:** point a telescope to a certain direction, and average over a volume set by the angular resolution

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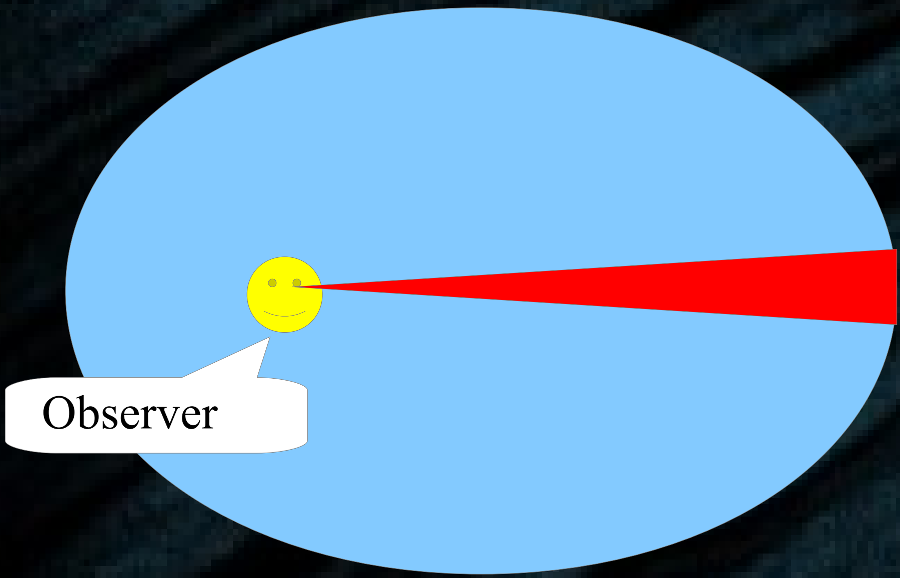

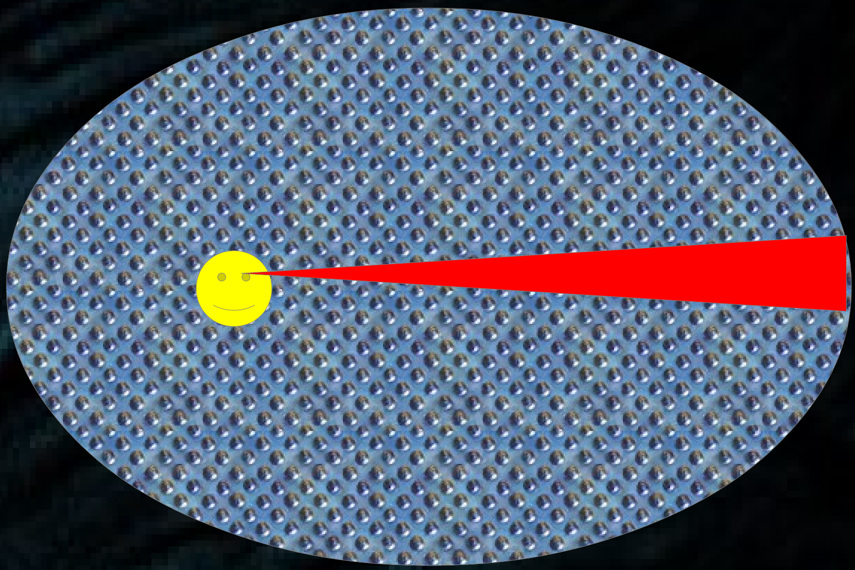

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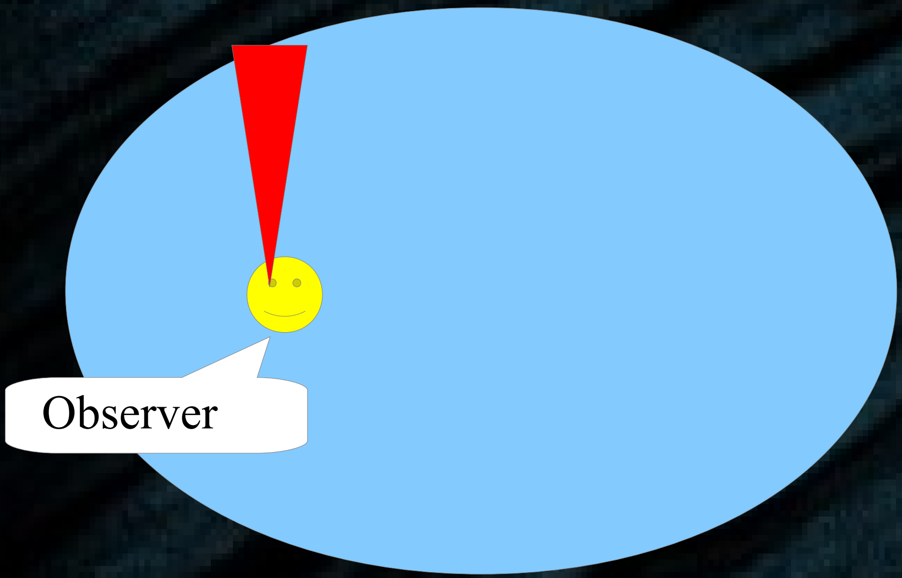
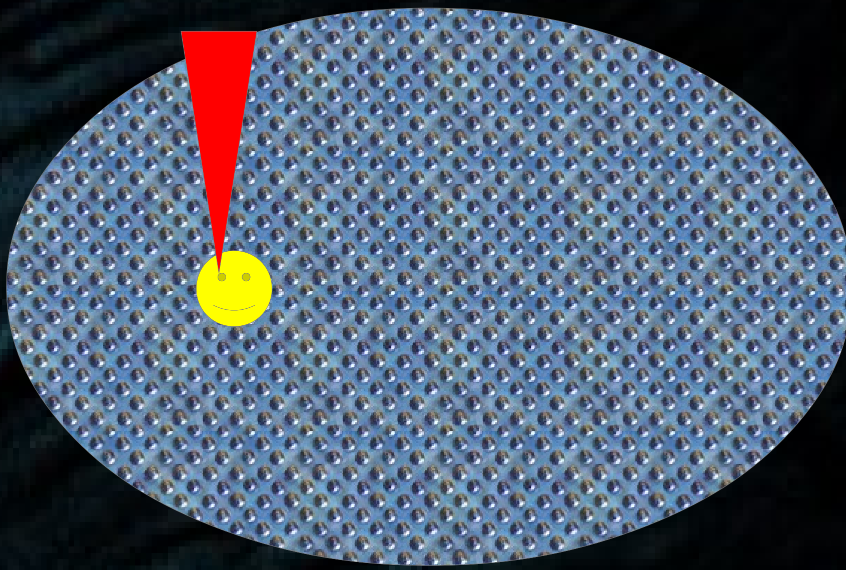
1) **Prompt gamma-rays:** point a telescope to a certain direction, and average over a volume set by the angular resolution

a) To the Galactic center: the smooth halo is singular, clumps have no effect, **B ~ 1**

*Boost factor ? ... well, in fact, boost factor**s***





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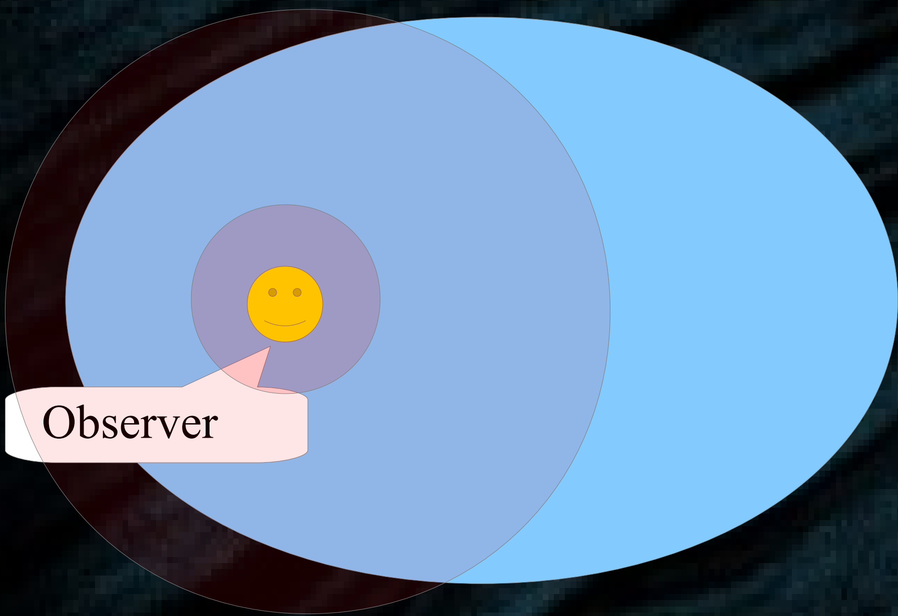
The volume over which the average is performed depends on the cosmic messenger!

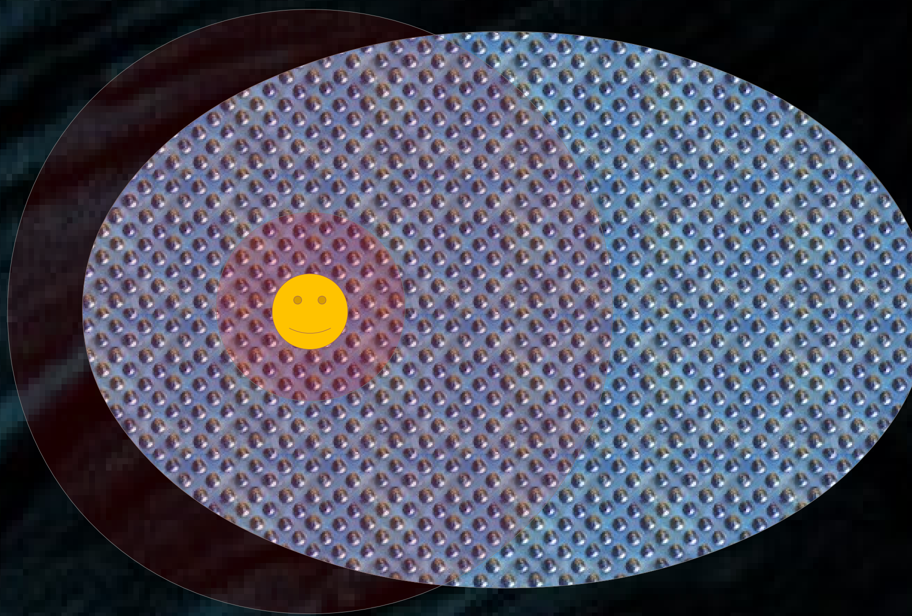
1) **Prompt gamma-rays:** point a telescope to a certain direction, and average over a volume set by the angular resolution

a) To the Galactic center: the smooth halo is singular, clumps have no effect, **B ~ 1**

b) To high latitudes/longitudes: the smooth halo contributes much less, **B>>1**

Boost factor ? ... well, in fact, boost factors





$$\mathcal{B} = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} \geq 1$$

The volume over which the average is performed depends on the cosmic messenger!

1) **Prompt gamma-rays:** point a telescope to a certain direction, and average over a volume set by the angular resolution

a) To the Galactic center: the smooth halo is singular, clumps have no effect, **B ~ 1**

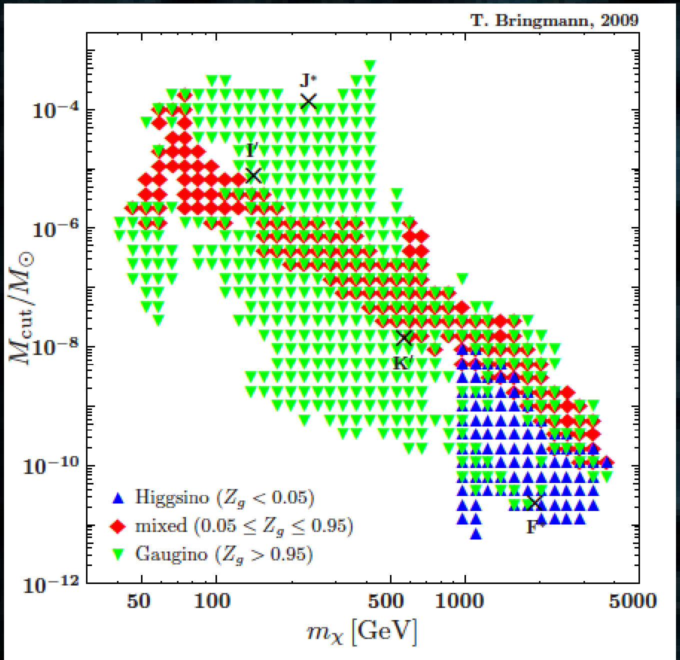
b) To high latitudes/longitudes: the smooth halo contributes much less, **B>>1**

2) **Cosmic rays:** stochastic motion, define energy-dependent propagation scale.

a) Large propagation scale: if enough to feel regions close to GC, then **B ~ 1**

b) Small propagation scale: if we are sitting on a clump, then **B>>1**, otherwise **B moderate**

Impact of subhalos on the positron flux



Bringmann (2009)

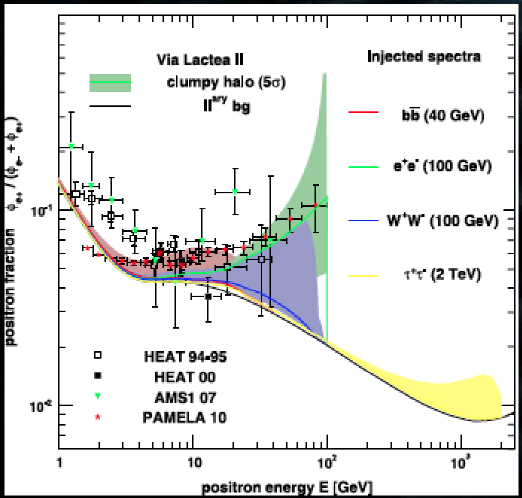
If DM is cold, subhalos must exist and survive tidal stripping (eg Berezinsky+ 05).

Very small masses can be achieved, fixed by the WIMP free streaming scale (eg Bringmann 09).

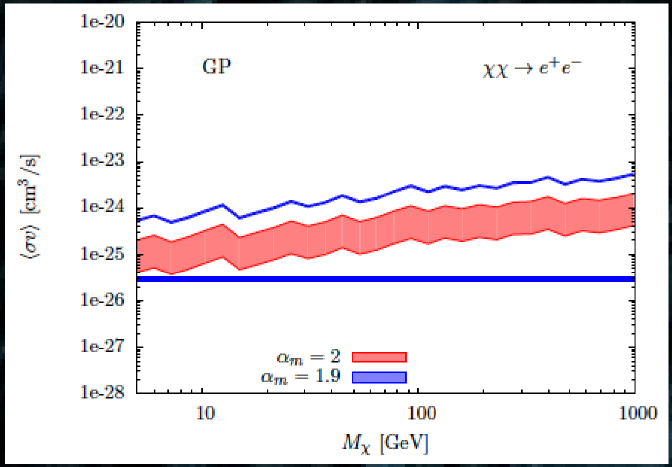
Properties studied in cosmological simulations, but limited by resolution => M > 104 Msun only.

Latest dedicated studies show profiles more cuspy than NFW at cut-off mass (eg Ishiyama+ 10, Anderhalden+ 13).

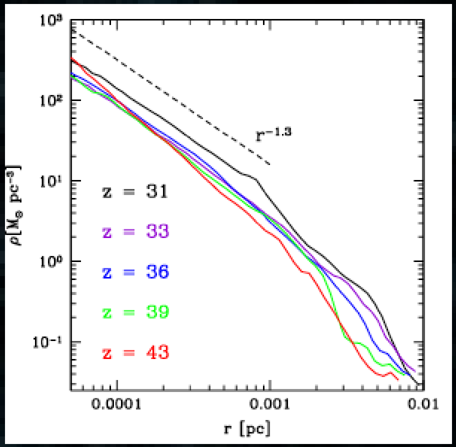
=> PAMELA could be explained by 100 GeV WIMPs (not AMS)



Positron fraction
Lavalle+ (2007), Pieri, Lavalle+ (2010)



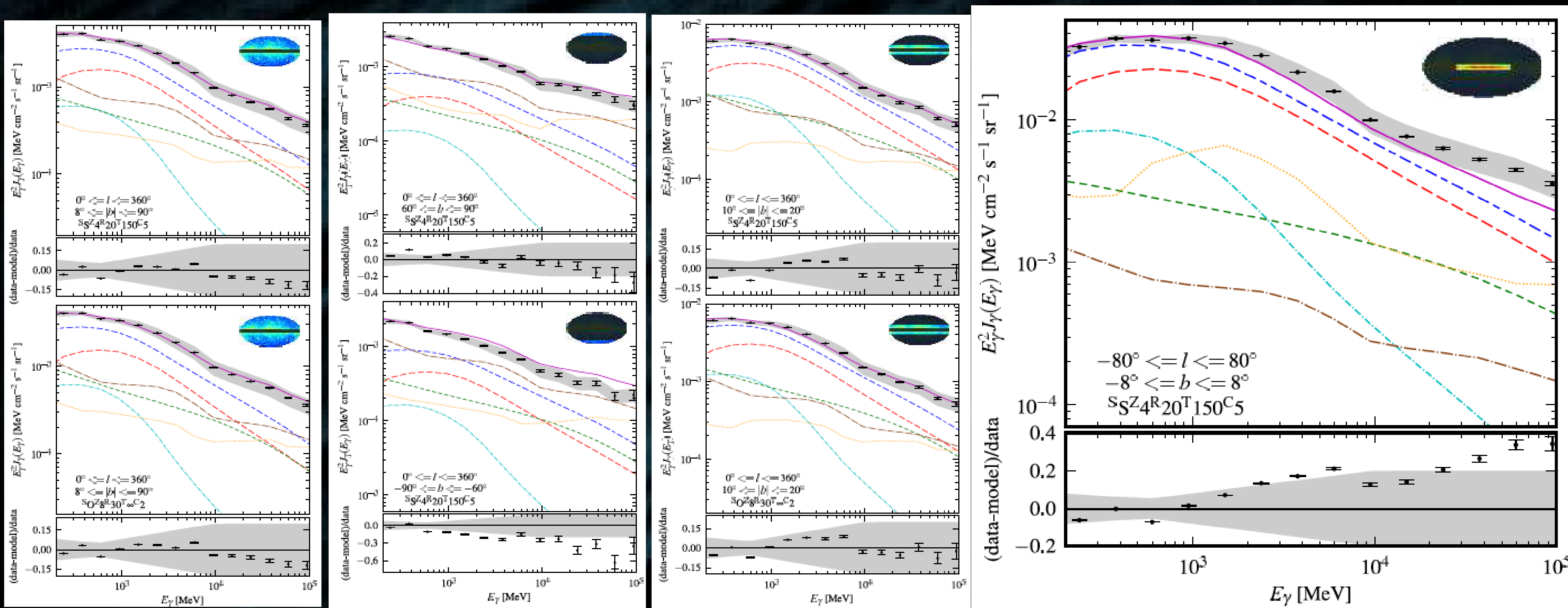
Diffuse gamma-rays
Blanchet & Lavalle (2012)



Anderhalden, Diemand (2013)

Diffuse gamma-rays (Fermi) and GCR models

Ackermann et al (2012) – 1202.4039

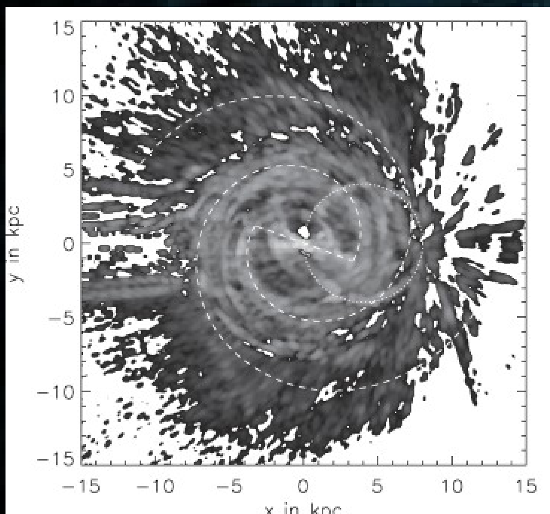


Assumptions:
- homogeneous/isotropic diffusion coefficient
- continuous distribution of sources; CRs escape sources with ad-hoc broken power laws (indices are free parameters)
- ISM from HI, H2 (CO), HII (Lazio & Cordes), dust correlations … maps

Results:
- global fit to the data not too bad (10-20% residuals), except GC and G-edges (30-40%)
- large magnetic halo preferred, L ~ 10 kpc
- Caveats: potentially large (and degenerate) systematic errors, but physical interpretation meaningful => encouraging

Diffuse emission and CRs: theoretical uncertainties (T. Delahaye, IFT-LAPTh)

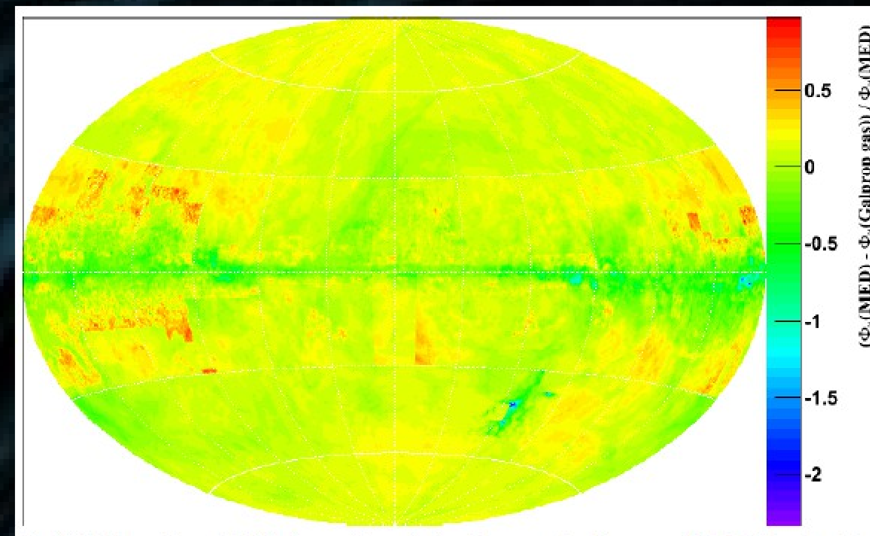
Pohl et al (2008)
3D model of H2



Impact of ISM modeling

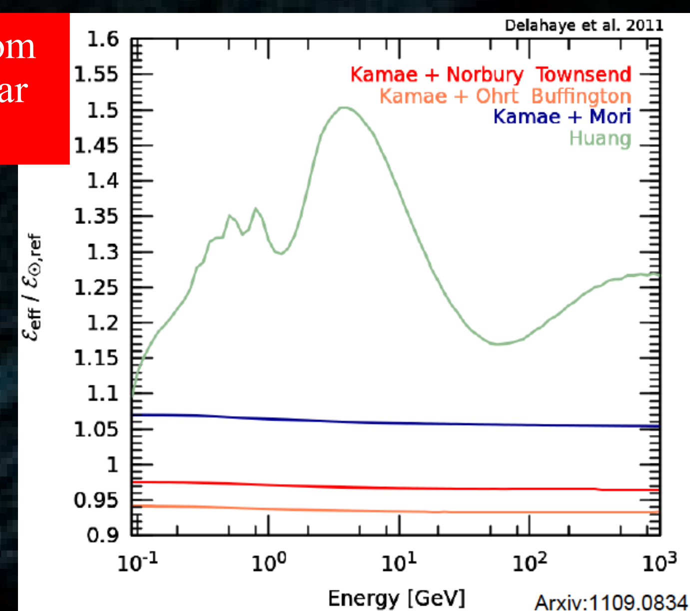
1102.0744

Diff with Galprop (hadronic contribution)
~ 50% in the disk!



- Advantages
  - ∗ Good sensitivity, sampling & uniformity of CO survey
  - ∗ Kinematic resolution toward GC
- Limitations
  - ∗ Limited resolution of SPH simulations (problem near GC)
  - ∗ Single value of X_{CO}
- Comments
  - ∗ Very thorough & lucid analysis
  - ∗ Globally reliable, except within $\sim$ 1 kpc from GC
  - ∗ Model available online

Other potential th. errors from ISM composition and nuclear cross sections:



Diffuse emission: a top bottom approach

Cosmological simulation:
self-consistent modeling of a galaxy (DM, gas, stars)

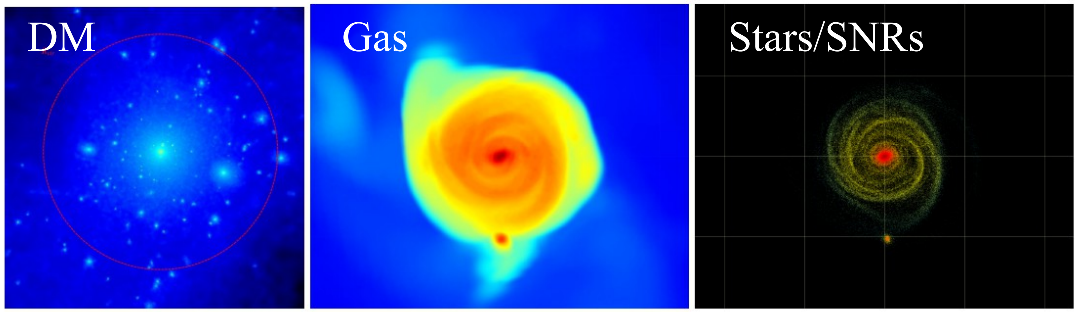
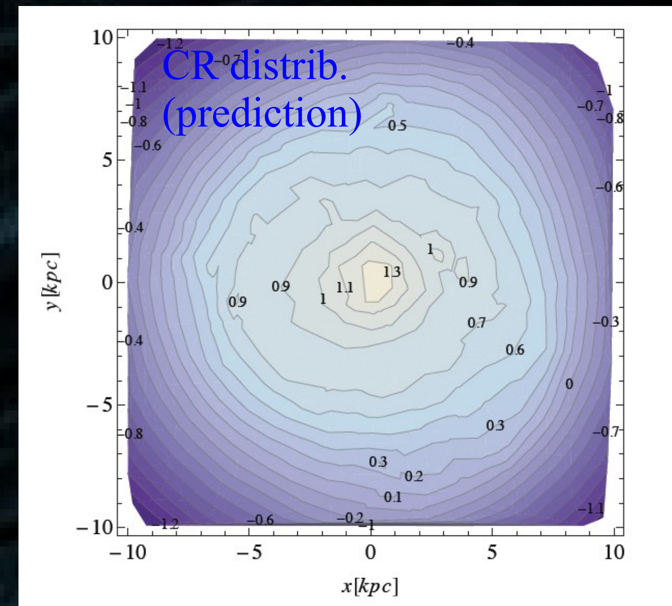
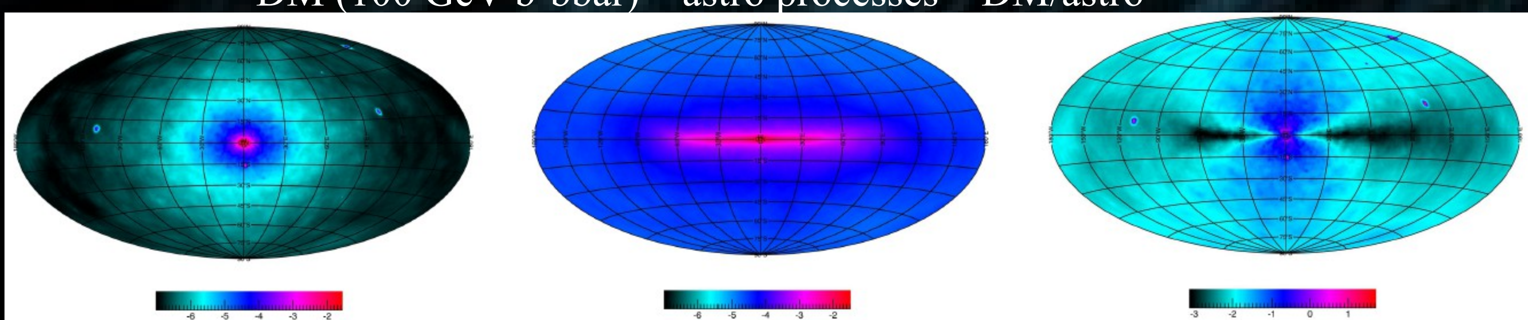


FIG. 1. Left: DM halo and subhalos; the virial radius (264 kpc) appears as a red circle. Middle: top view of the gas content (scaled as in right panel). Right: SN events in the last 500 Myr (10 kpc grid).

1204.4121

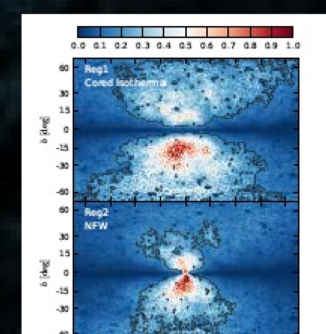


Skymaps:
DM (100 GeV b-bbar) – astro processes – DM/astro



Advantages:
* all ingredients are identified and localized (sources and gas)
* check the relevance of current assumptions
Limits: spatial resolution

=> preliminary results encouraging, work in progress



Compare e.g. with Weniger 12
(optimized region for 130 GeV line)

Conclusions

- Current GCR models allow for a reasonable understanding of (i) the local CR budget and (ii) the Galactic diffuse emission(s)
- Nota: there is no “standard model” for GCRs! (many inputs, lucidity is required)
- Not accurate enough for specific regions (e.g. GC), but still very useful
- Current models have reached their limits
=> prediction power saturates, need to put more physics in ... at the price of increasing theoretical uncertainties (though expected to decrease in the future)

For DM:
- Best targets remain:
1) DSPhs as observed in gamma-rays + gamma-ray lines
2) neutrinos from the Sun
- Antimatter CRs + diffuse emissions more relevant to constraints: astrophysics pollutes a lot, and is not completely controlled yet
***** Complementarity with other detection methods (direct/LHC) is definitely the best strategy.**

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