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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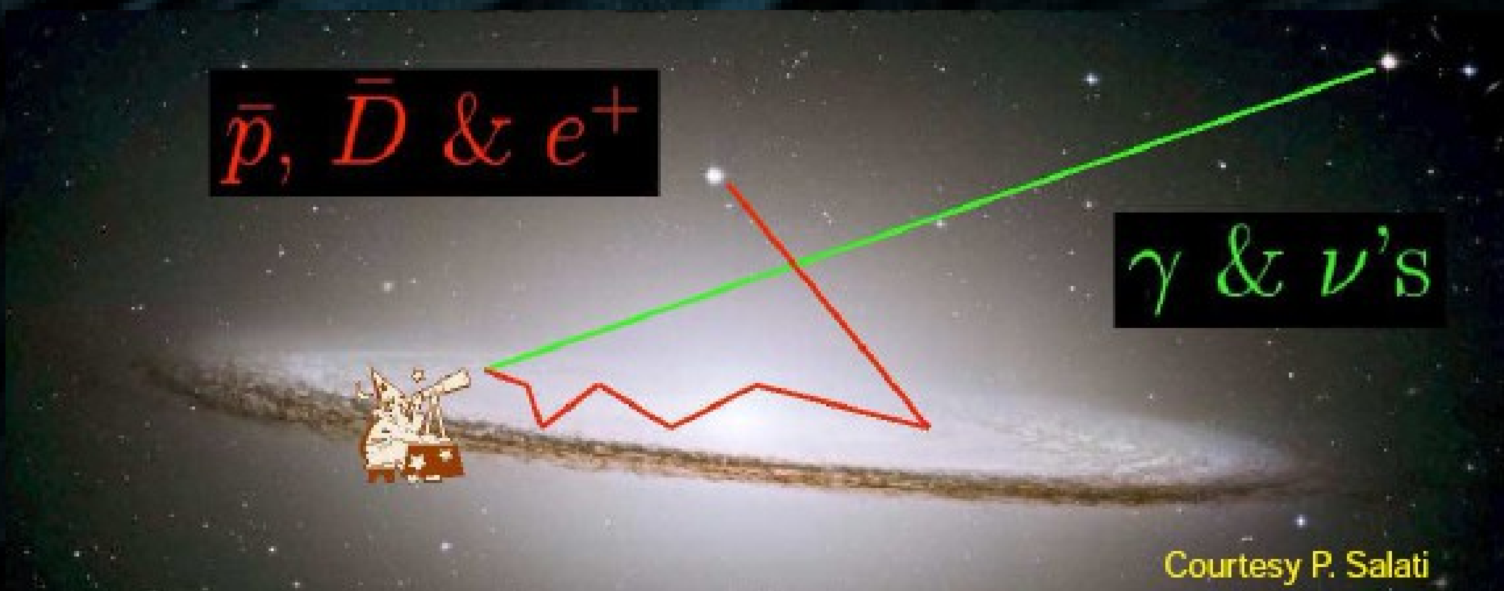
and
Mark Srednicki
Physics Department, University of California, Santa Barbara, California 93106
(Received 8 June 1984)



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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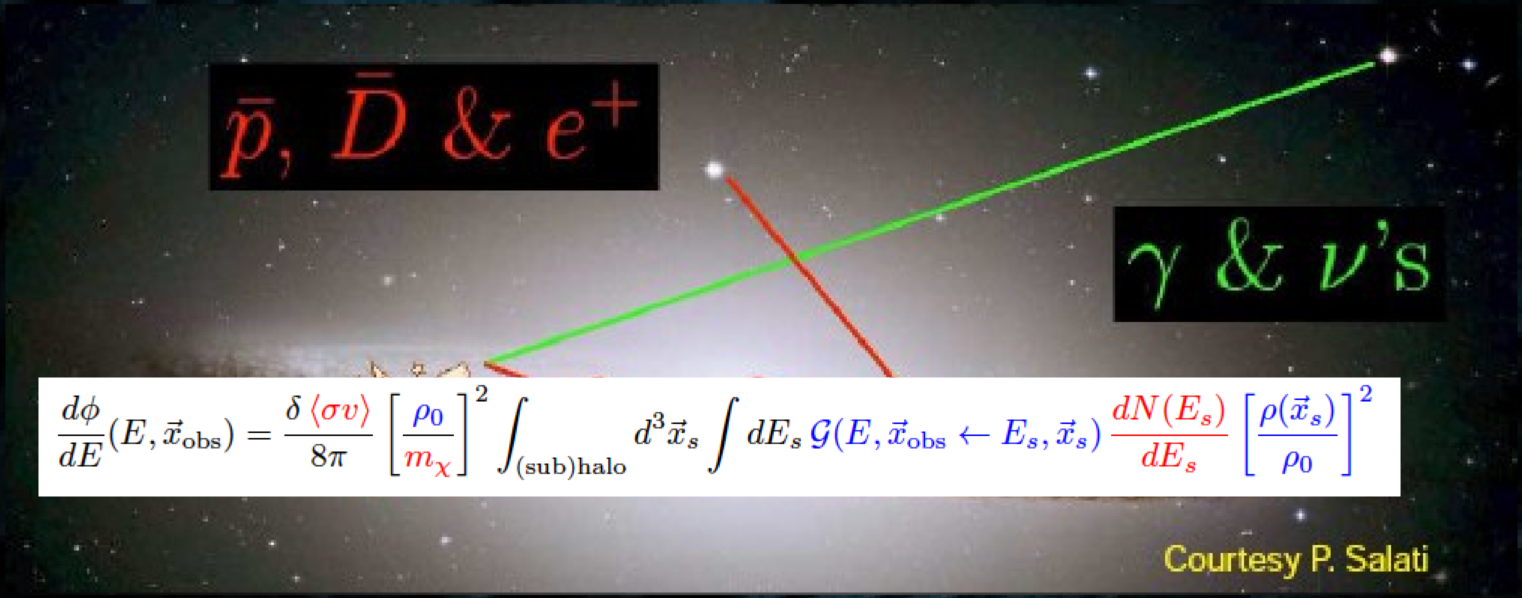

$$\frac{d\phi}{dE}(E,\vec{x}_{\rm obs}) = \frac{\delta\,\langle\sigma v\rangle}{8\pi}\left[\frac{\rho_0}{m_\chi}\right]^2 \int_{\rm (sub)halo} d^3\vec{x}_s \int dE_s\,\mathcal{G}(E,\vec{x}_{\rm obs}\leftarrow E_s,\vec{x}_s)\,\frac{dN(E_s)}{dE_s}\left[\frac{\rho(\vec{x}_s)}{\rho_0}\right]^2$$

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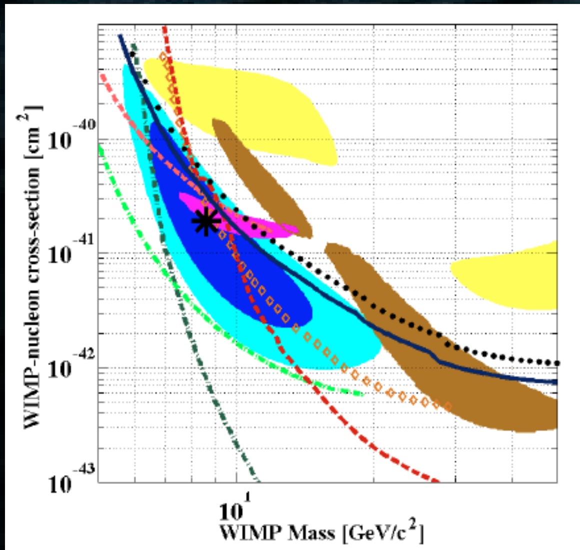
Transport of Galactic cosmic rays
The standard picture

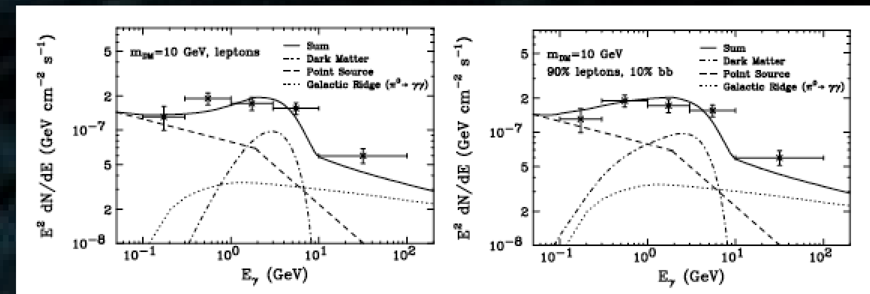
$$
\begin{aligned}
\partial_t \frac{dn}{dE} &= Q(E,\vec{x},t) \\
&+ \left\{ \vec{\nabla}\left(K(E,\vec{x})\vec{\nabla} - \vec{V}_{\mathrm{c}}\right) \right\} \frac{dn}{dE} \\
&- \left\{ \partial_E \left(\frac{dE}{dt} - \partial_E E^2 K_{\mathrm{pp}} \partial_p E^{-2} \right) \right\} \frac{dn}{dE} \\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

From Haslam et al data (1982)

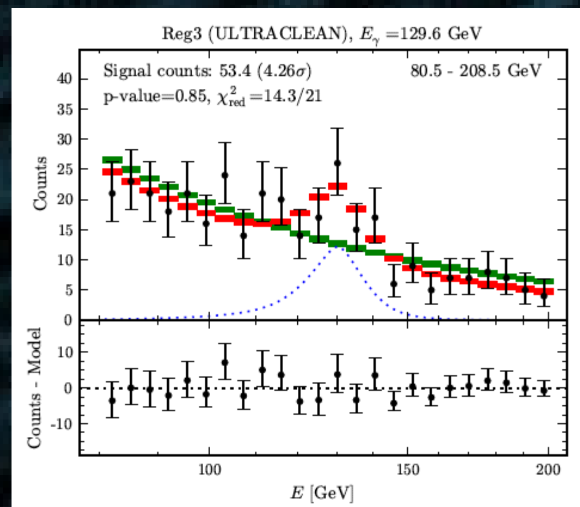
Dark matter has long been discovered !



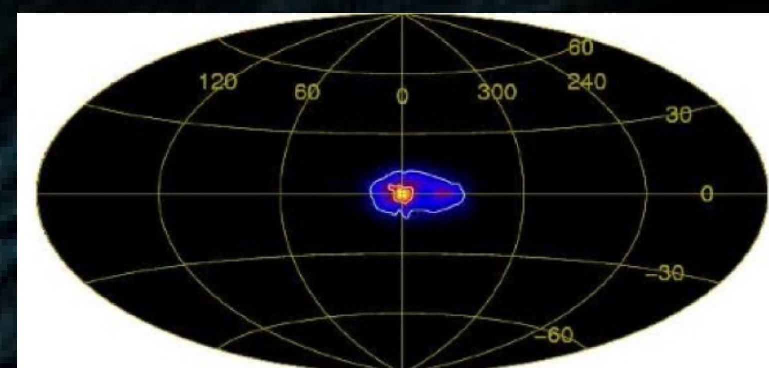
Agnese++ 13
DAMA, CoGenT, CRESST … + CDMSII(SI)
versus XENON-10, XENON-100
→ DM around 10 GeV



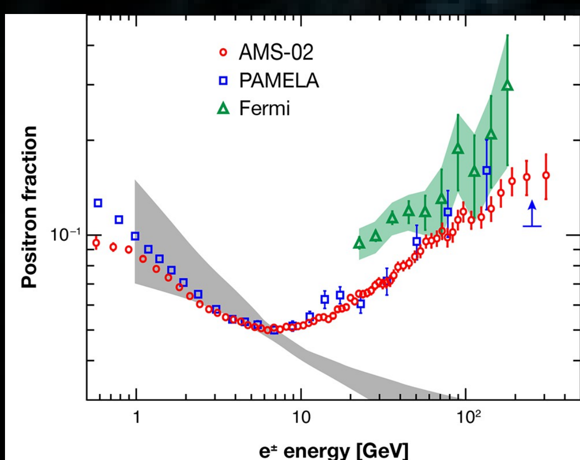
Hooper++ 12: gamma-rays + radio at GC
→ DM around 10 GeV



Around the GC
Weniger++, Su++ 12
→ DM around 130 GeV



511 keV, Knödlséder/Weidenspointner++ 05 - 08
Boehm, Hooper++ 04 → DM around 1 MeV



HEAT/PAMELA/AMS positron excess
Bergström++, Cirelli++ 08 → DM around 300-1000 GeV

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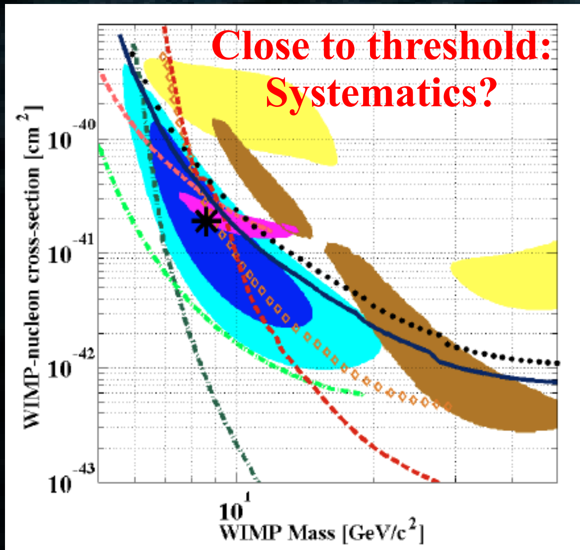

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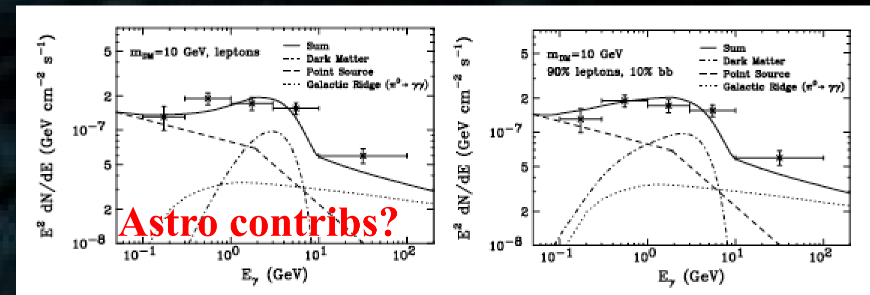

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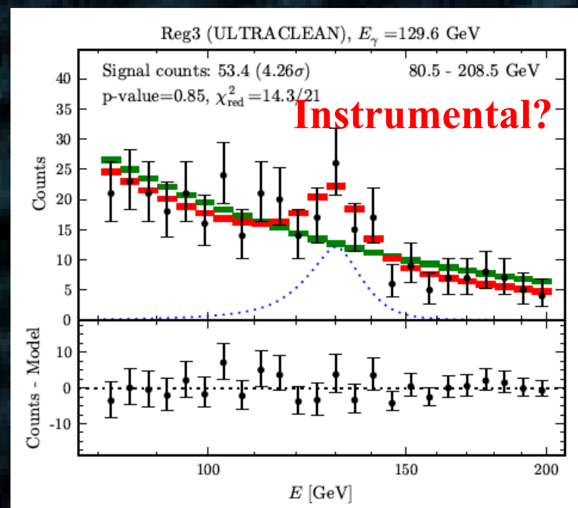
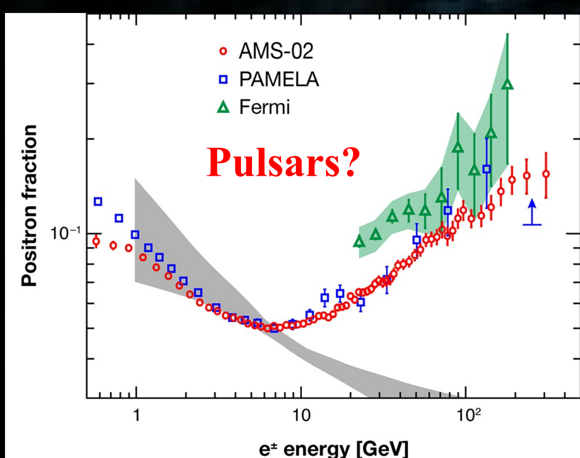
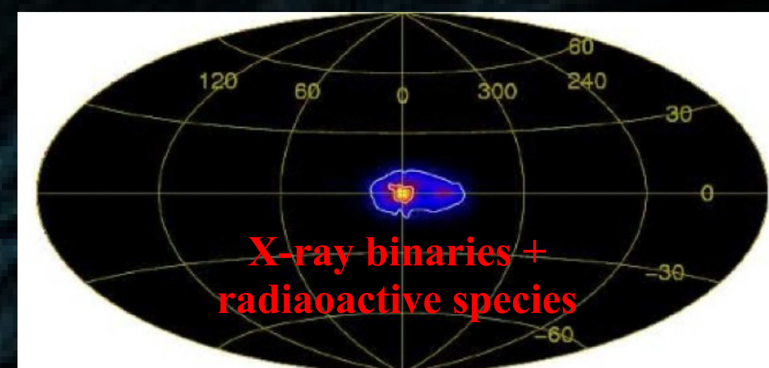


Around the GC
Weniger++, Su++ 12
→ DM around 130 GeV

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++ 04-12, Cline++, etc.)





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HEAT/PAMELA/AMS positron excess
Bergström++, Cirelli++ 08 → DM around 300-1000 GeV

Strategy?

* Instrumental effects (experimentalists' job)

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

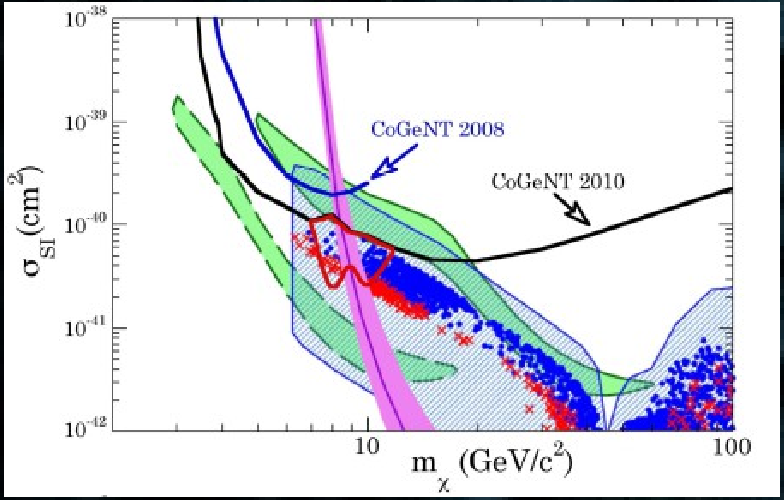
* Understand / quantify theoretical uncertainties (for discovery as well as constraints)
=> eg CR transport, DM distribution, Galactic components

* Understand / quantify backgrounds
=> astrophysical sources / mechanisms

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

Focus on antinuclei: antiproton constraints

CoGeNT Collab (2010), Bottino+ (2010)



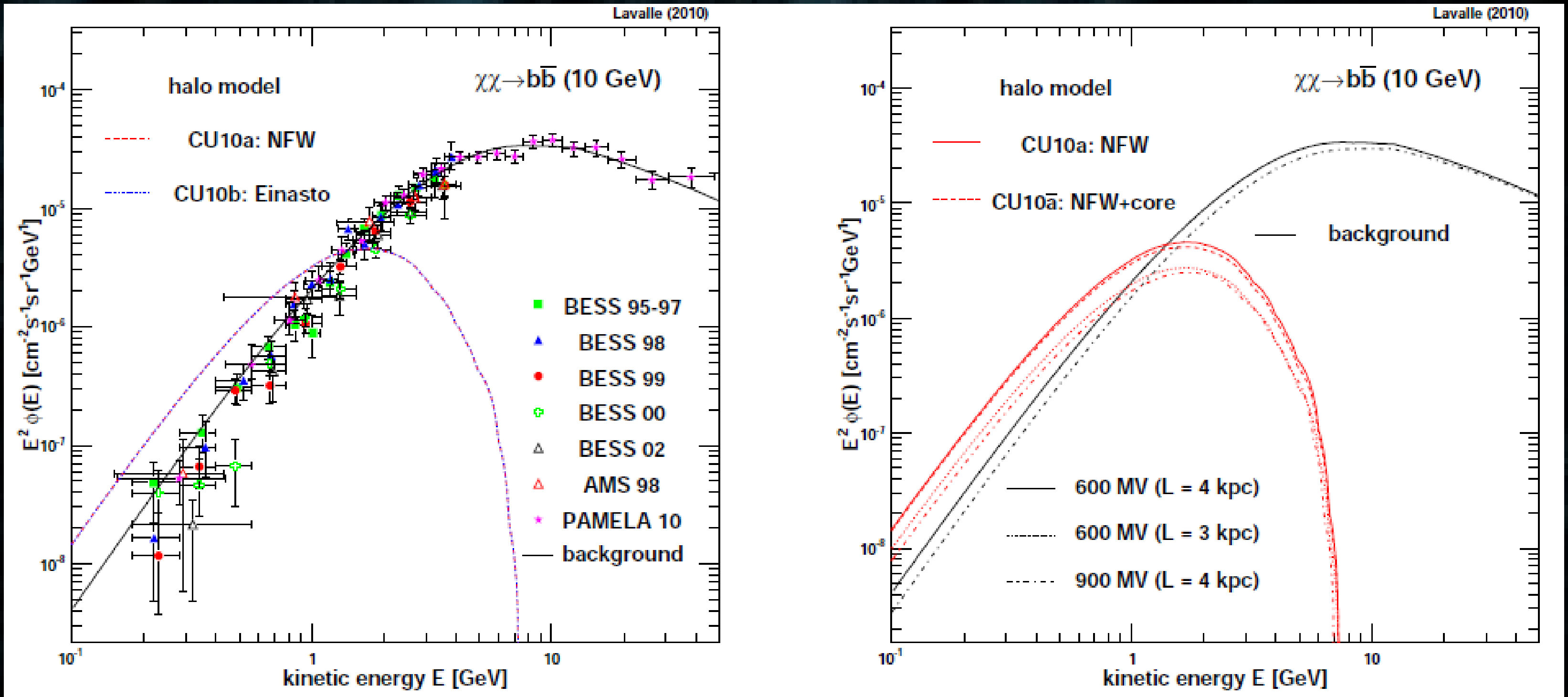
DAMA+CDMS+COGENT mass regions
(+ GC fit by Hooper++)
=> WIMP mass ~10 GeV

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

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

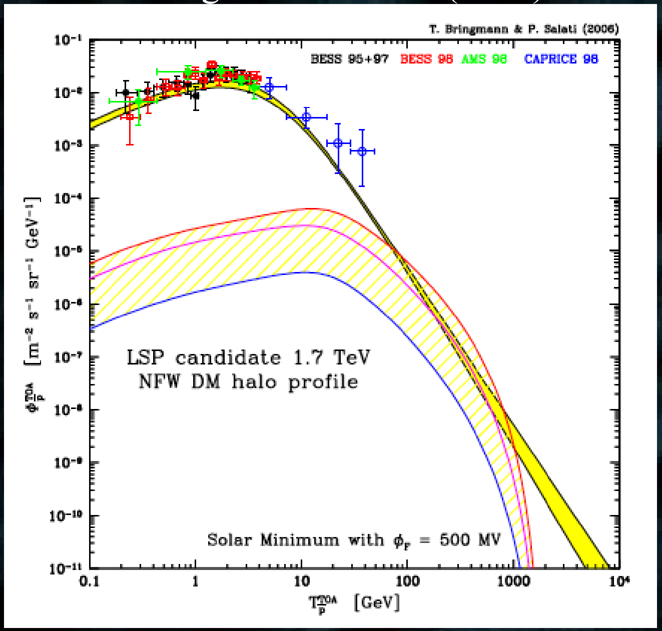
** Uncertainties due to the size of the diffusion zone?

Lavalle (2010)



Impact of the size of the diffusion zone

Bringmann & Salati (2007)



Maurin++ 01 & Donato++ 02
=> attempts to bracket theoretical uncertainties

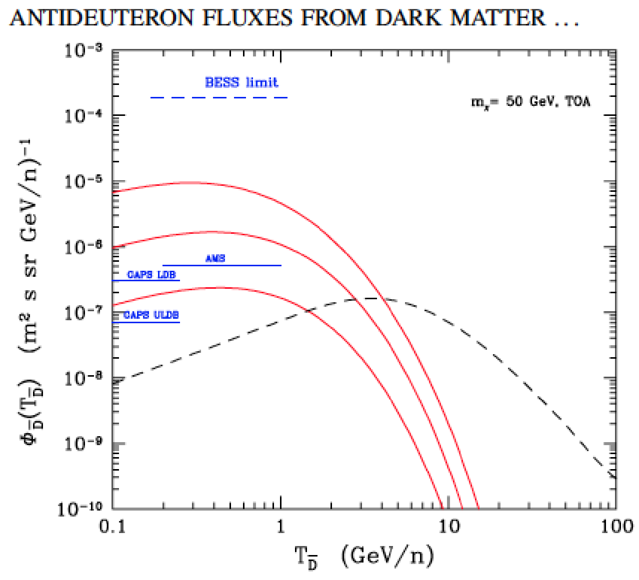
Besides best fit transport model (dubbed *med*), proposal for 2 extreme configurations:

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

minimizing and maximizing the DM-induced fluxes, respectively.

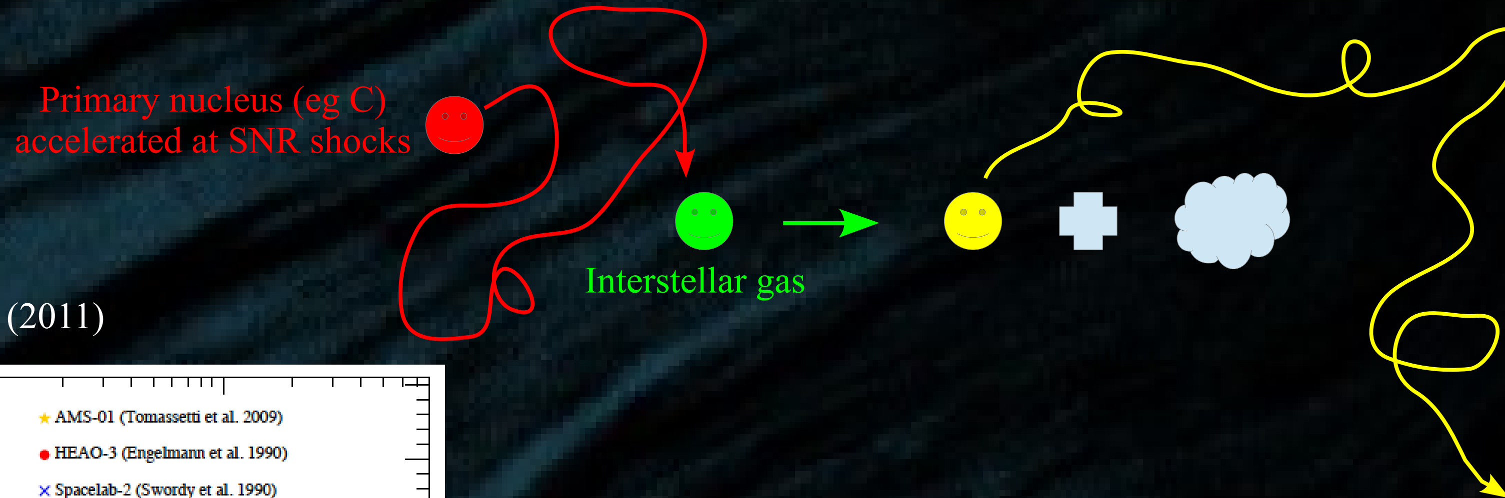
NB: much less effect on high-energy positrons (Lavalle++ 07, Delahaye++ 08) – short propagation scale.

Maurin, Donato, Fornengo (2008)

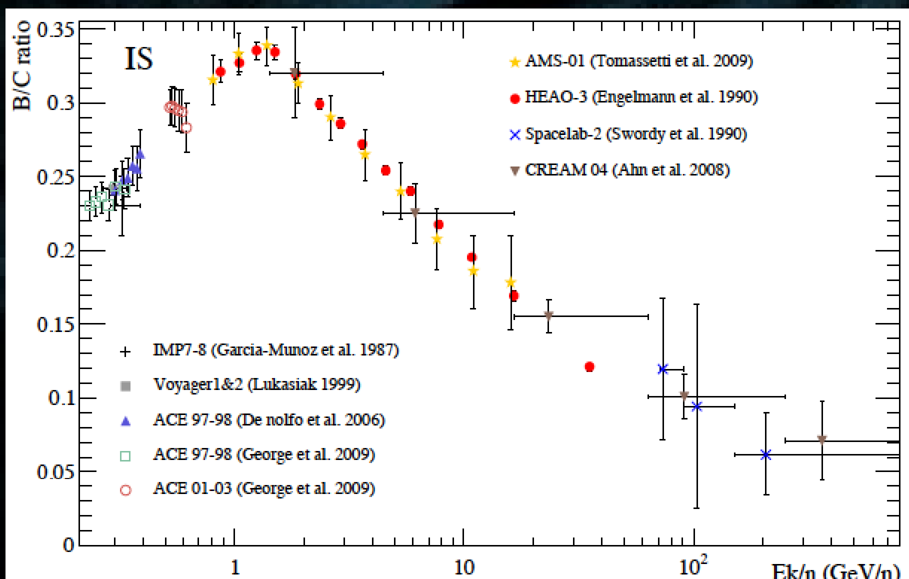


The game people usually play:
1) you want your model to survive antiproton constraints:
=> take a small L
2) you want to advertise your model for detection:
=> take L from med to max.

Where do constraints on L come from?



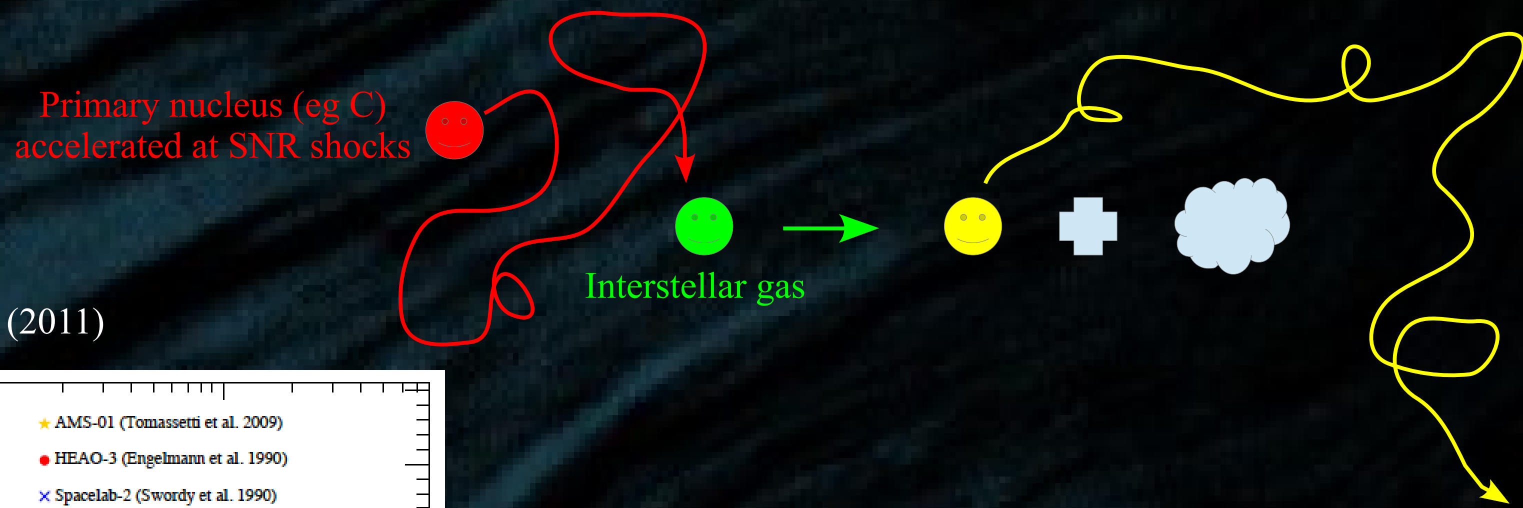
Putze+ (2011)



Secondary/primary ratios constrain
transport history
=> most used is B/C
** provides constraints on K/L
(K and L degenerate!)

On the blackboard

Where do constraints on L come from?



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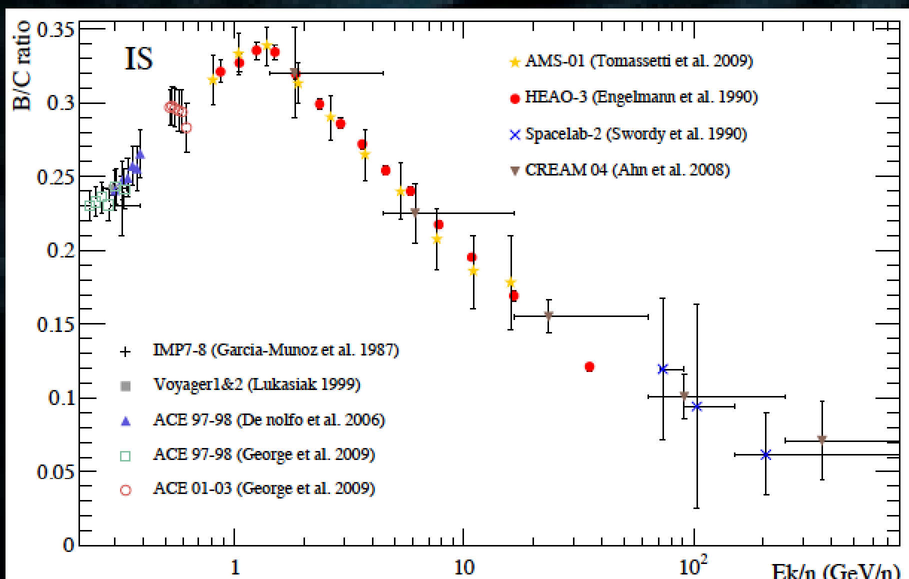
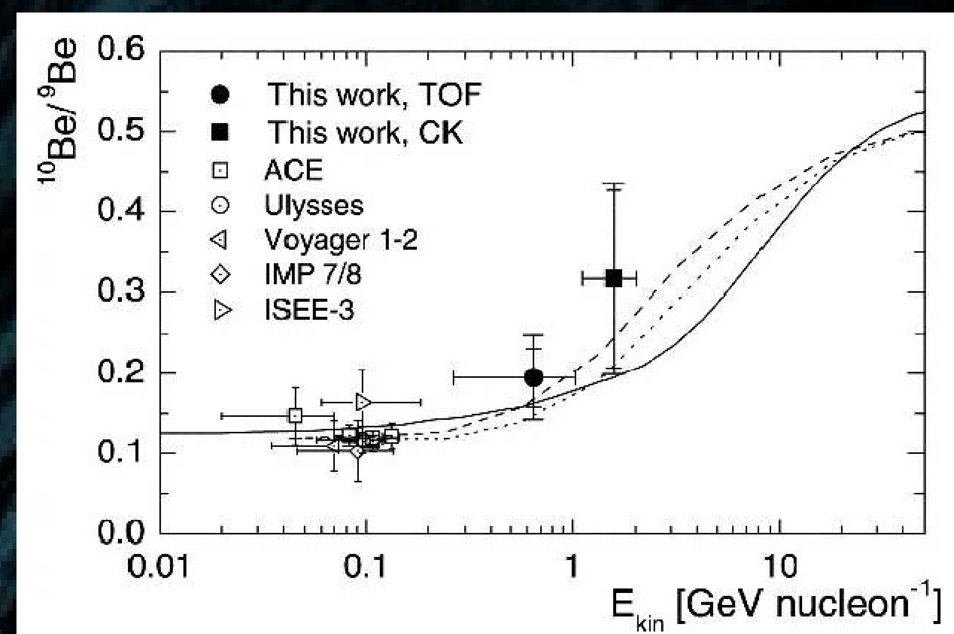


Breaking degeneracy with
radioactive secondaries
=> lifetime too short to reach L

Strong+ (2004)

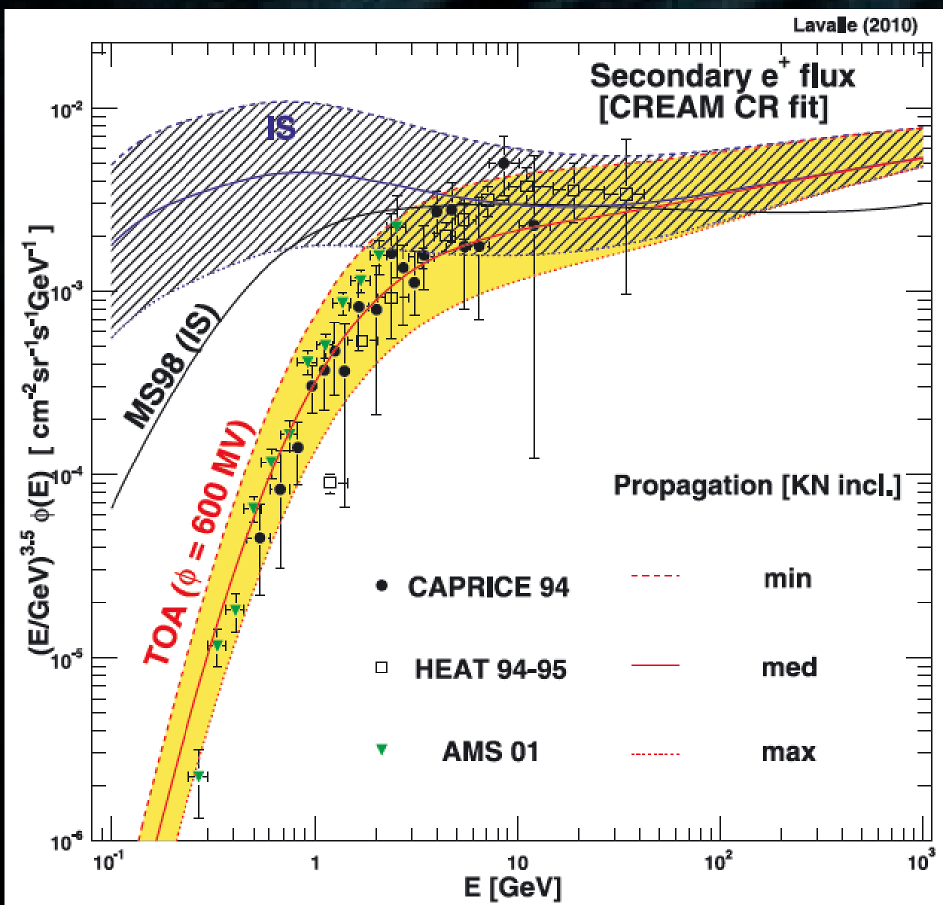


AMS02 should significantly improve
measurements of radioactive species

Uncertainties in the diffusion halo size? (digression to 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:

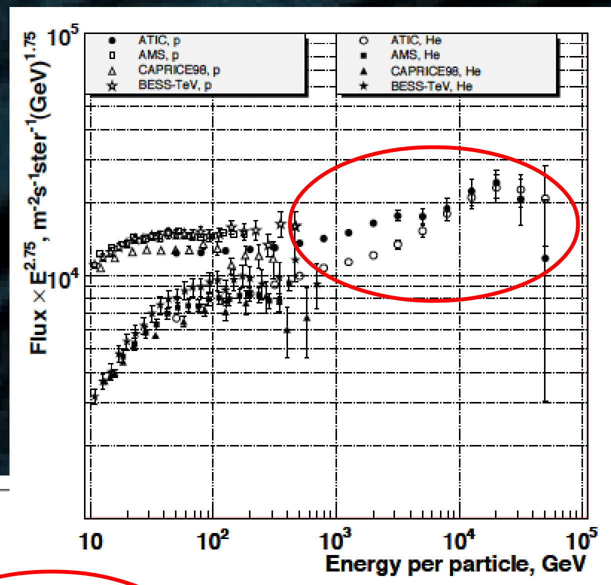
- PAMELA/AMS data still to come

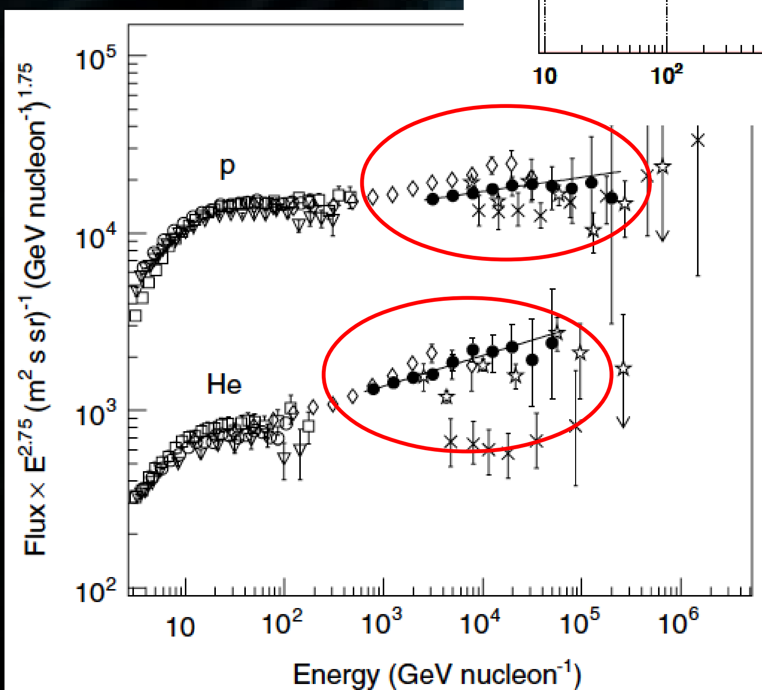
=> Ongoing work with Maurin and Putze

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

ATIC Collab (2006-2012)

Cream Collab (2010-2011)



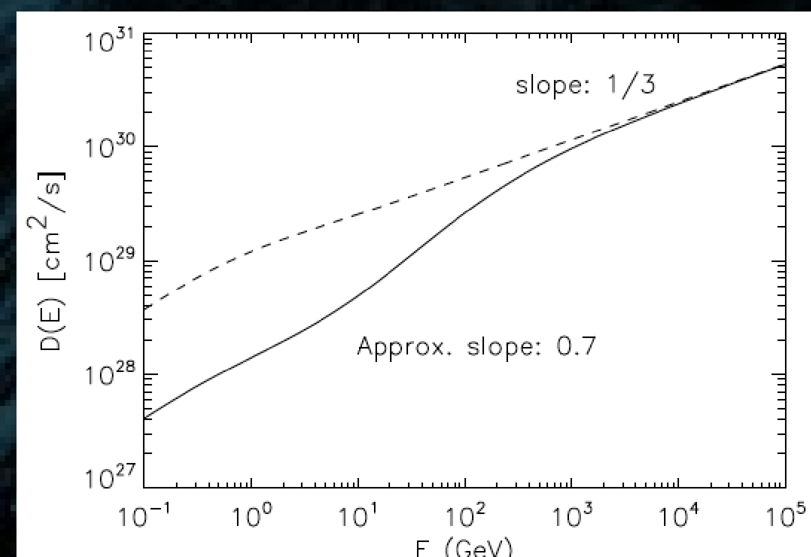


Could be due to a change in diffusion properties (eg Blasi++ 12)

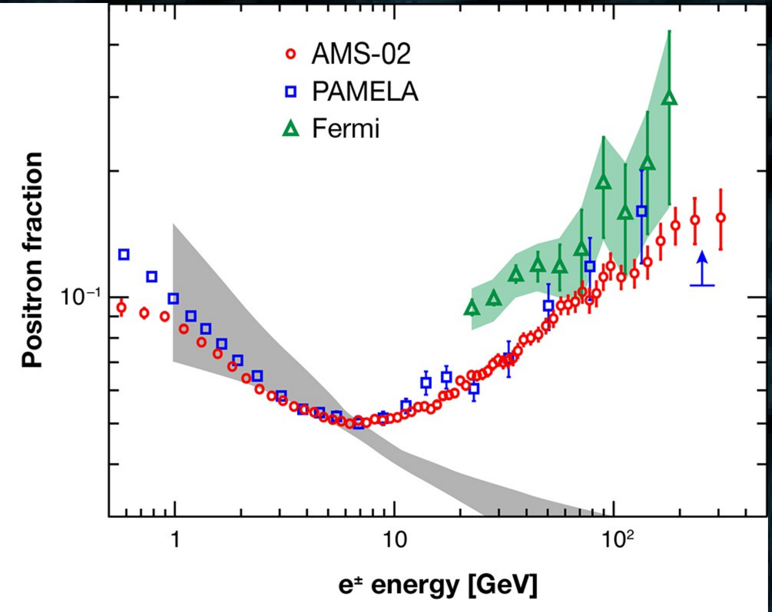
=> K has different slope > 100 GeV (from 0.7 to 0.3)

=> impact on secondary CR production

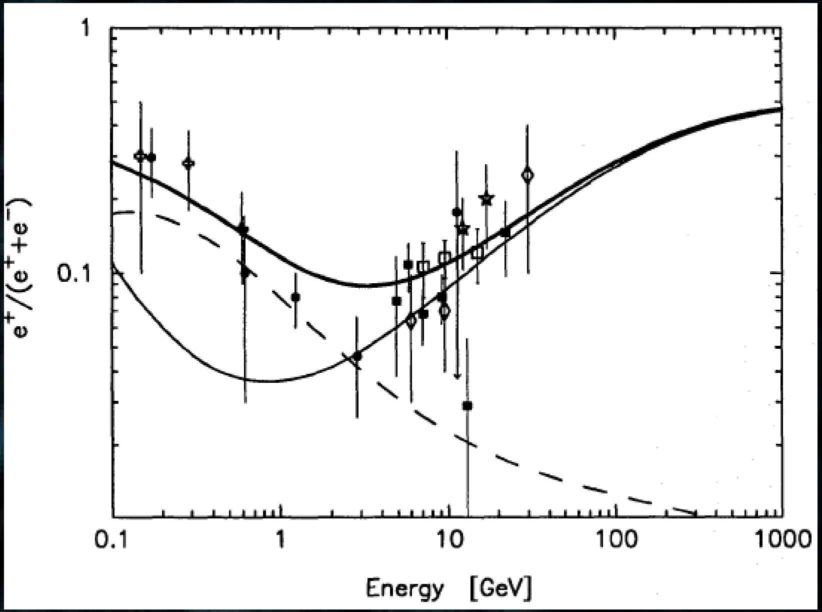
Blasi++ 12



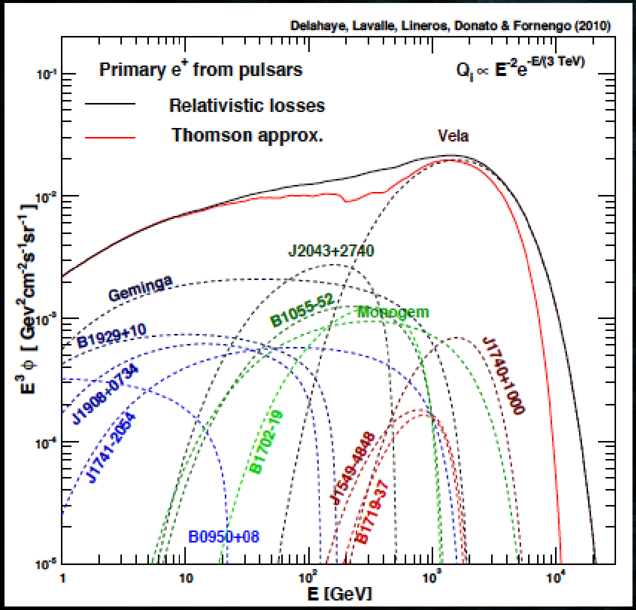
Short comments on the positron fraction



AMS Collab (2013)



Aharonian++ 95



We know pulsars can make it in principle.
Going to realistic modeling is complicated (eg Delahaye++ 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)

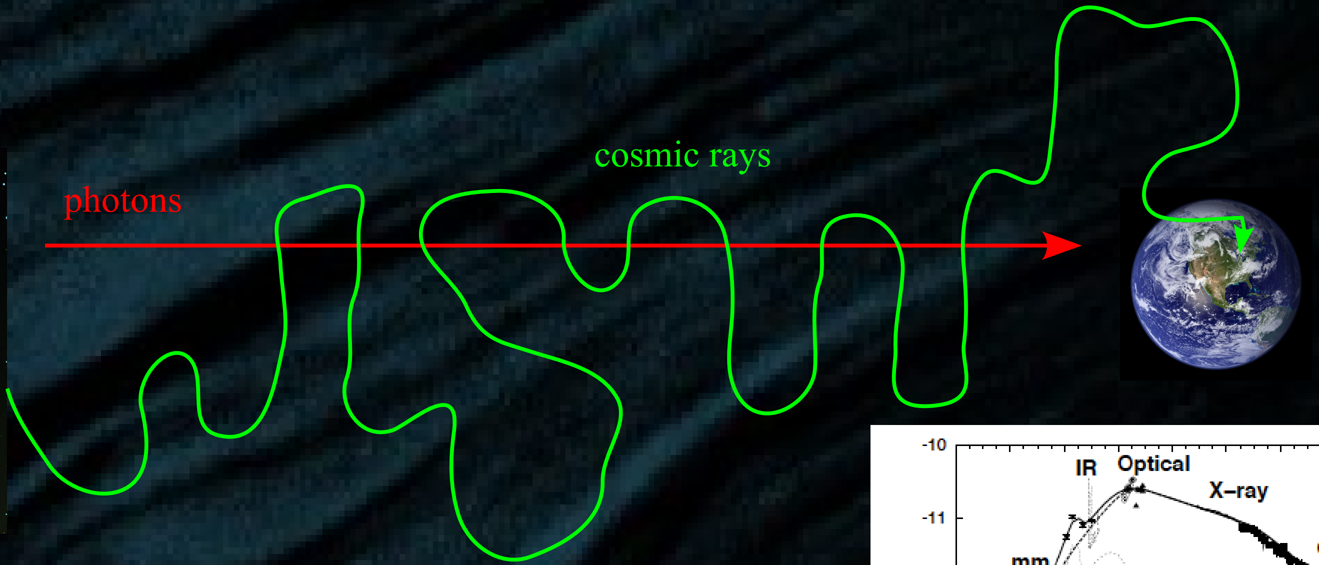
=> you may fit amplitudes / spectral indices … then what?

** Observational constraints!

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

Modeling the electron/positron sources?

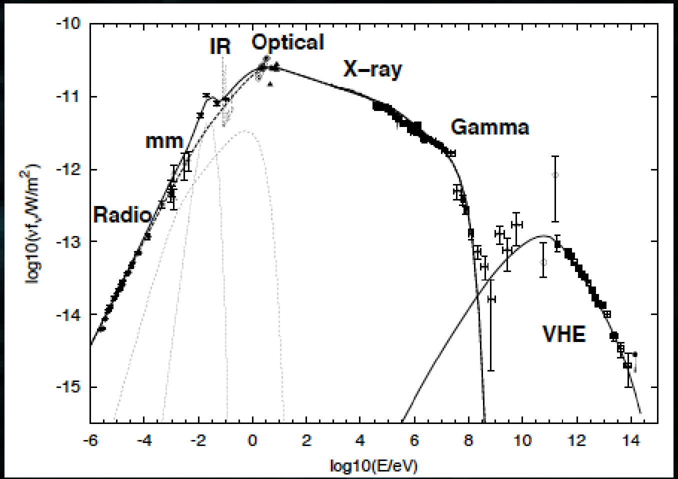
Crab nebula (ESA)
(just for illustration,
not relevant for e+/e-)



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

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

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



Horns & Aharonian 04
Crab SED

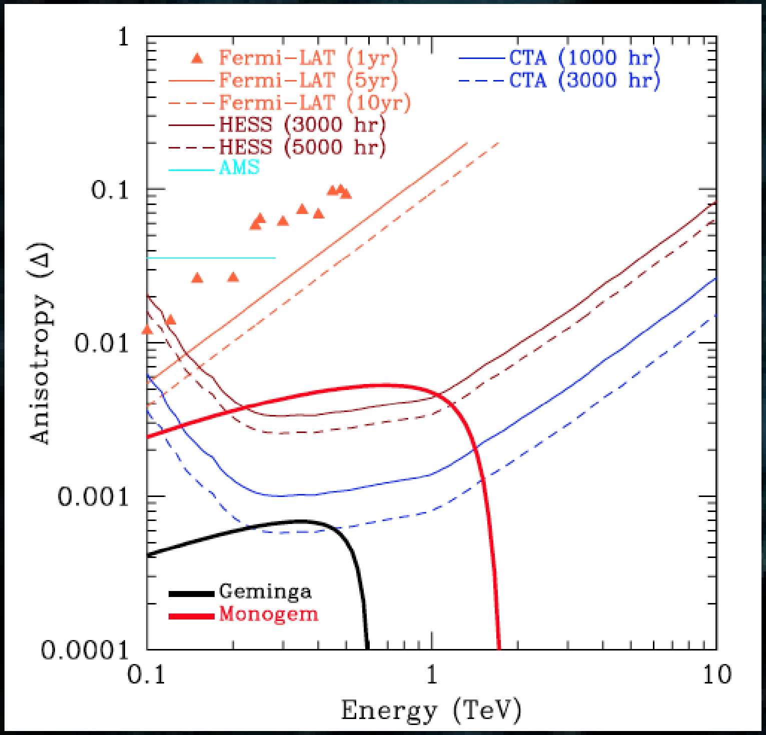
Different timescales:
1) E-loss time > source age > transport time
2) transport time >> photon time
=> cannot directly use photon data
=> requires dynamical models for sources (time evolution)

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 13

Caveats:

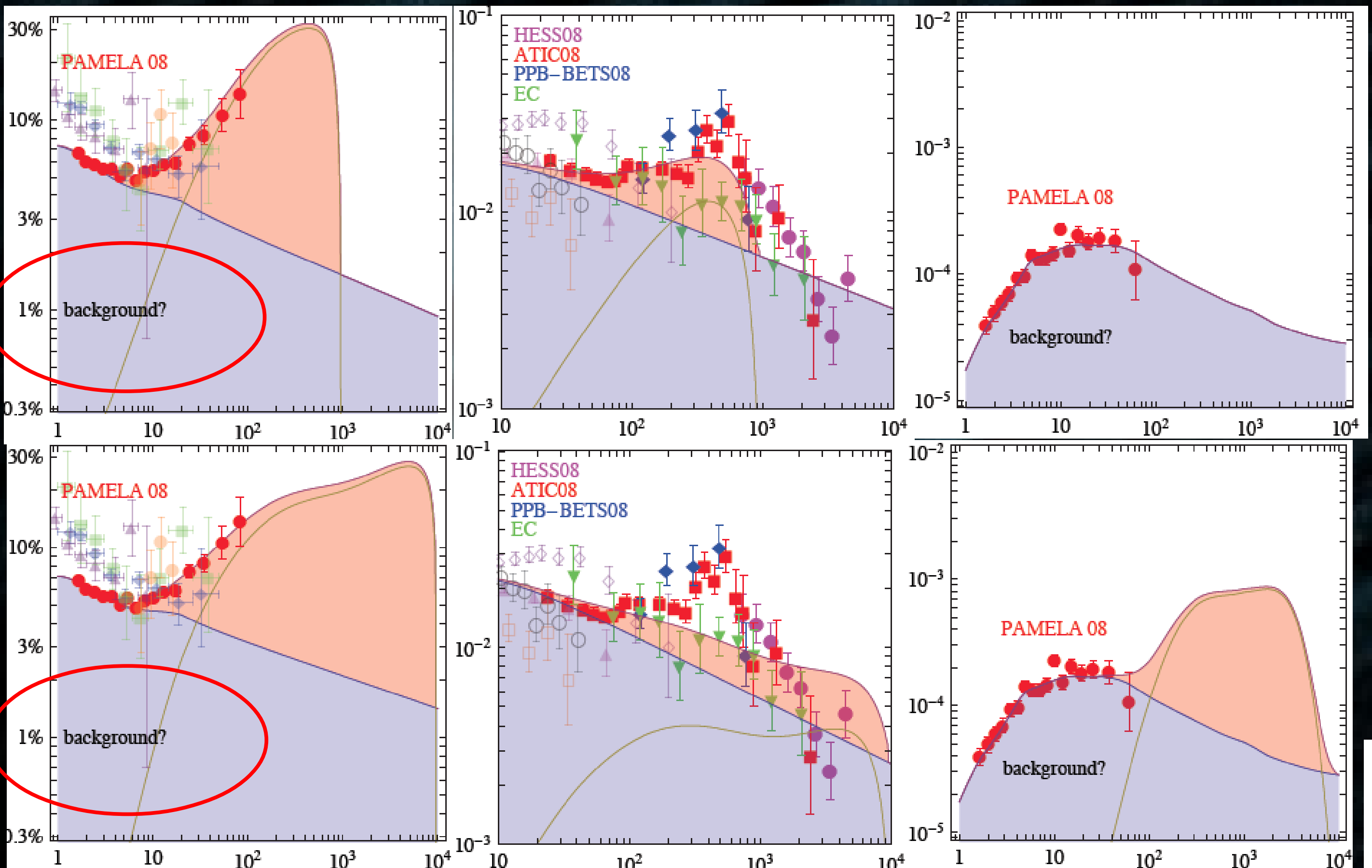
* model-dependent (diffusion halo size again!)
* contributions of other sources (eg dipole from GC/antiGC asymmetry in the source distribution)
* cancellations might occur in the dipole

Still:

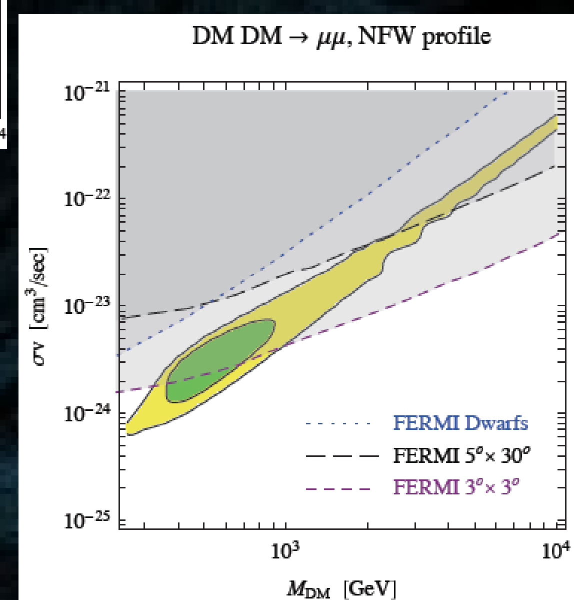
* physically meaningful information
* should be provided for all CR species separately (eg positrons, antiprotons, etc.)
* will provide constraints to the full transport model
* AMS may reach the necessary sensitivity

DM interpretation of the positron excess?

(if you still want to believe ...)



Cirelli, Strumia++ 08-13



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

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

But …

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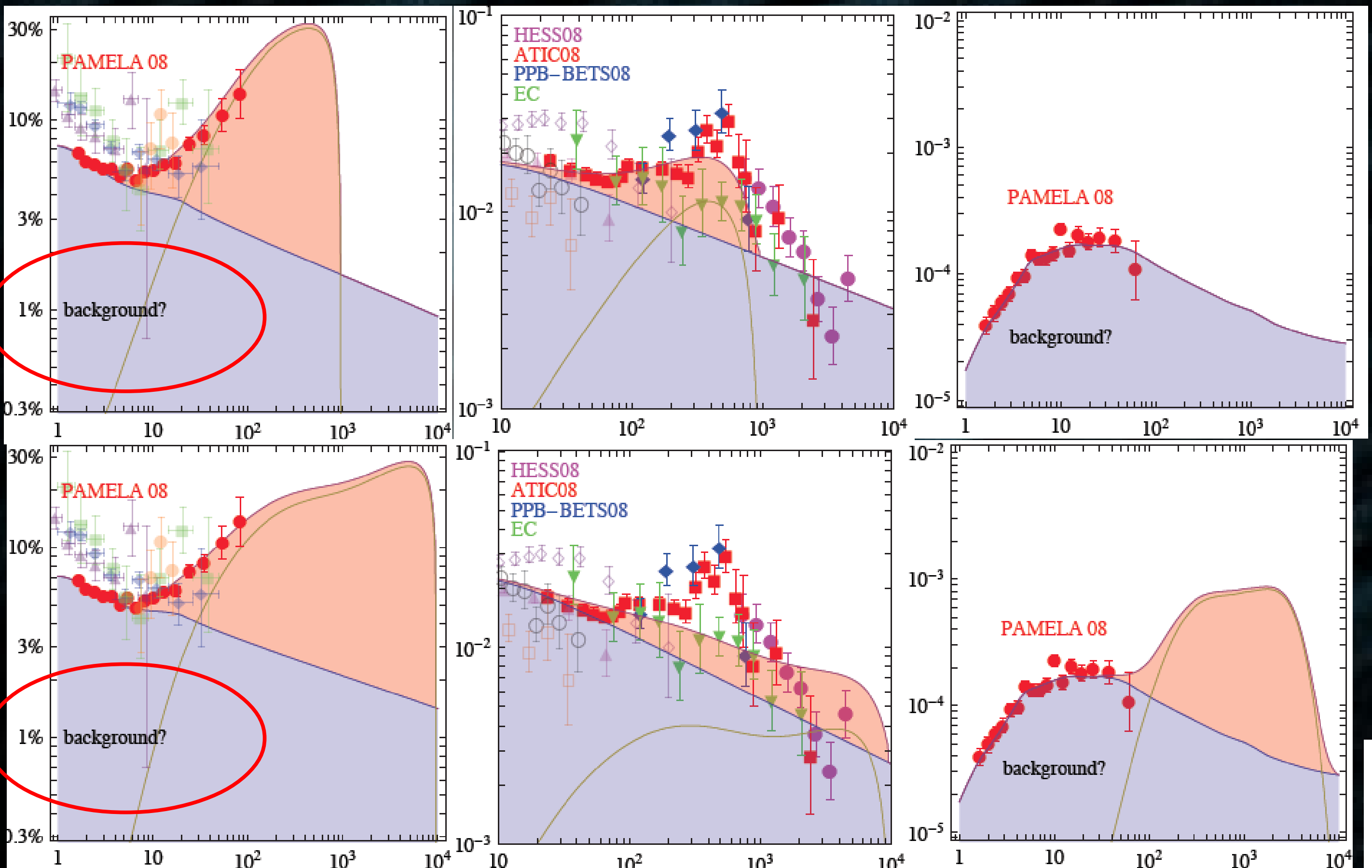

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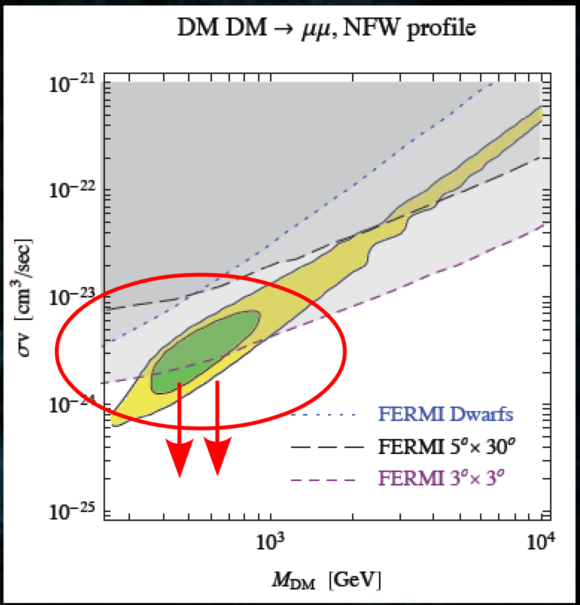

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Conclusions:

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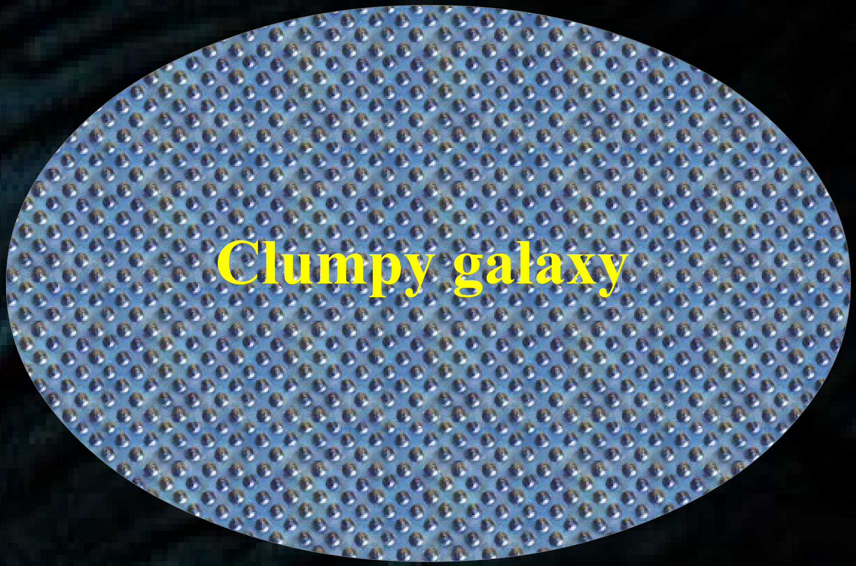
But … local DM: 0.3 → 0.4 GeV/cm3, DM subhalos => BF ~ 2-3

=> factor of 4-5 possible

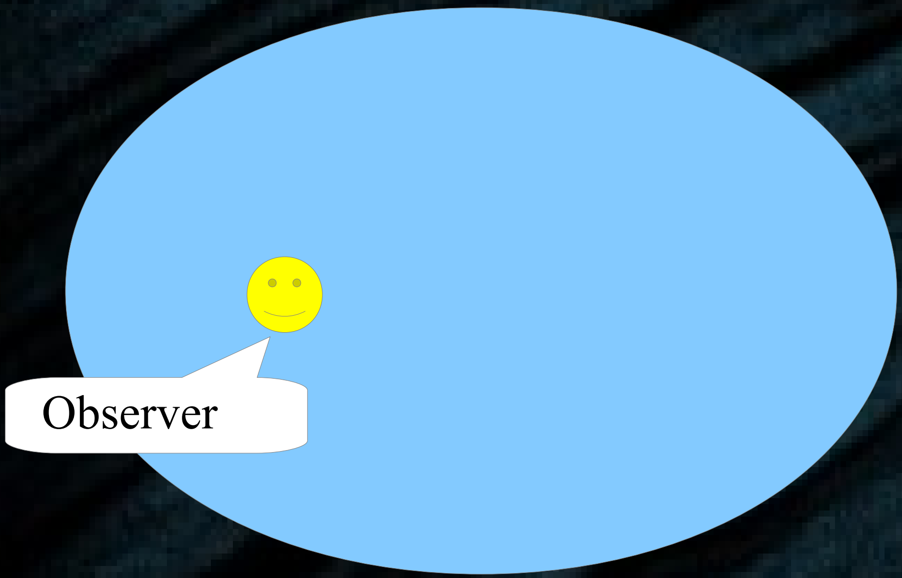
Boost factor ? ... well, in fact, boost factors

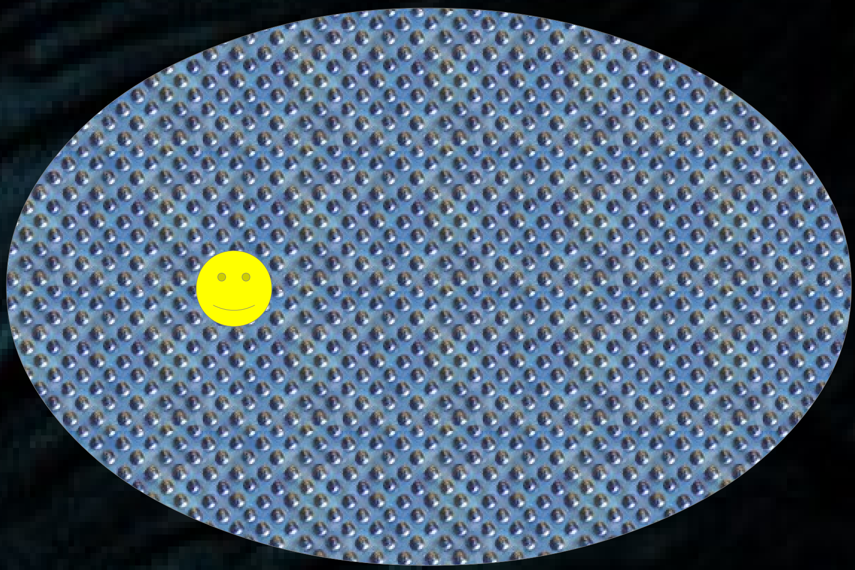


$$\mathcal{B} = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} \geq 1$$

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

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





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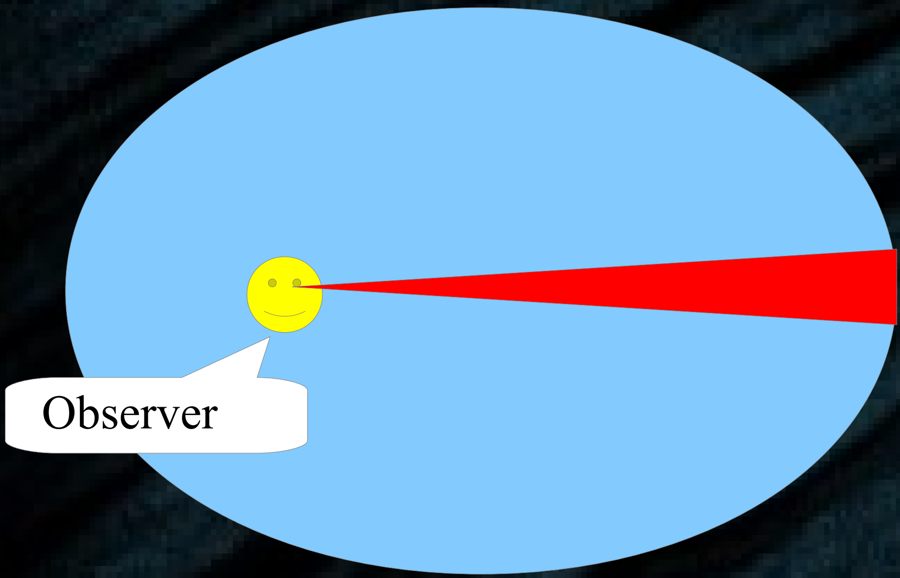
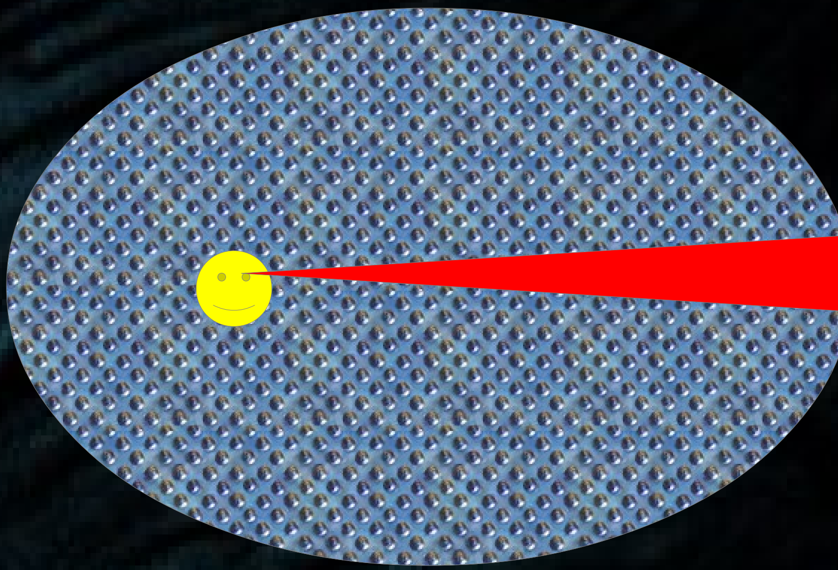
The volume over which the average is performed depends on the cosmic messenger!

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

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





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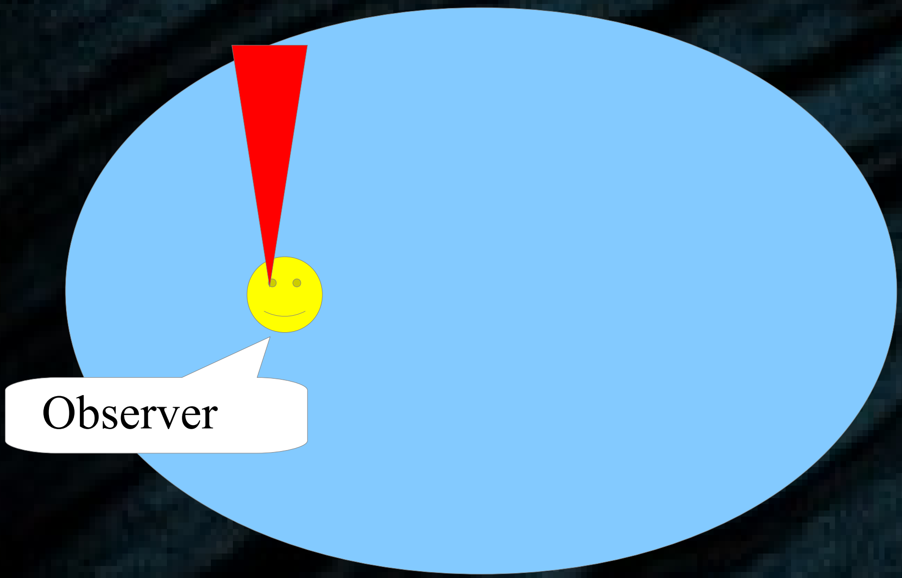
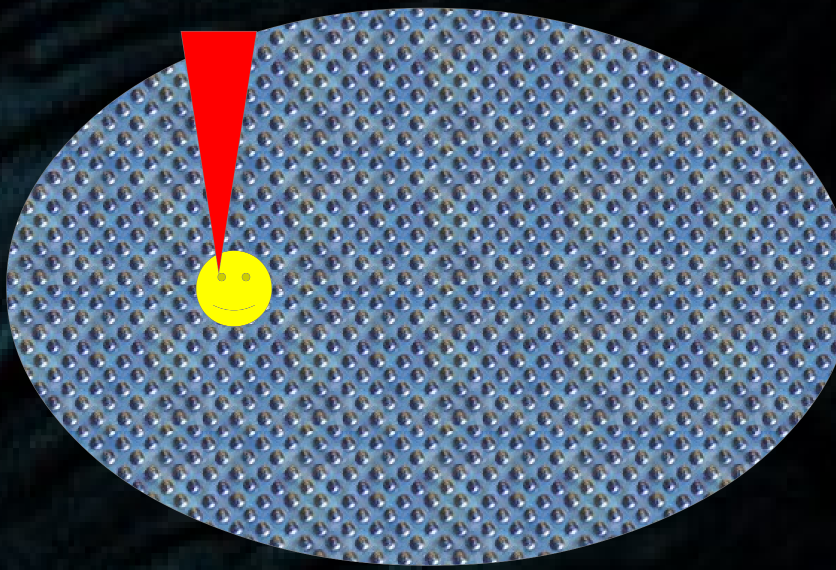
1) **Prompt gamma-rays:** point a telescope to a certain direction, and average over a volume set by the angular resolution

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

Boost factor ? … well, in fact, boost factors





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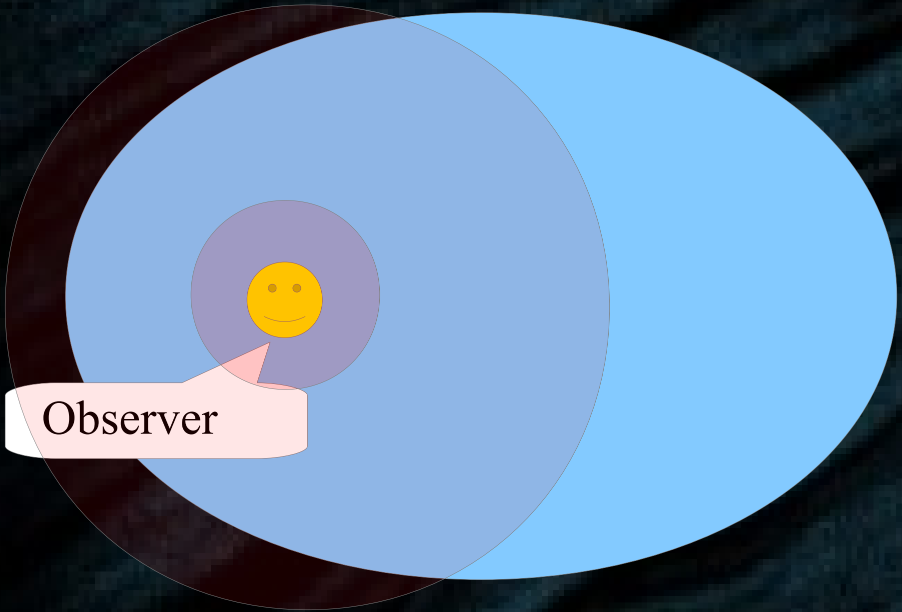
The volume over which the average is performed depends on the cosmic messenger!

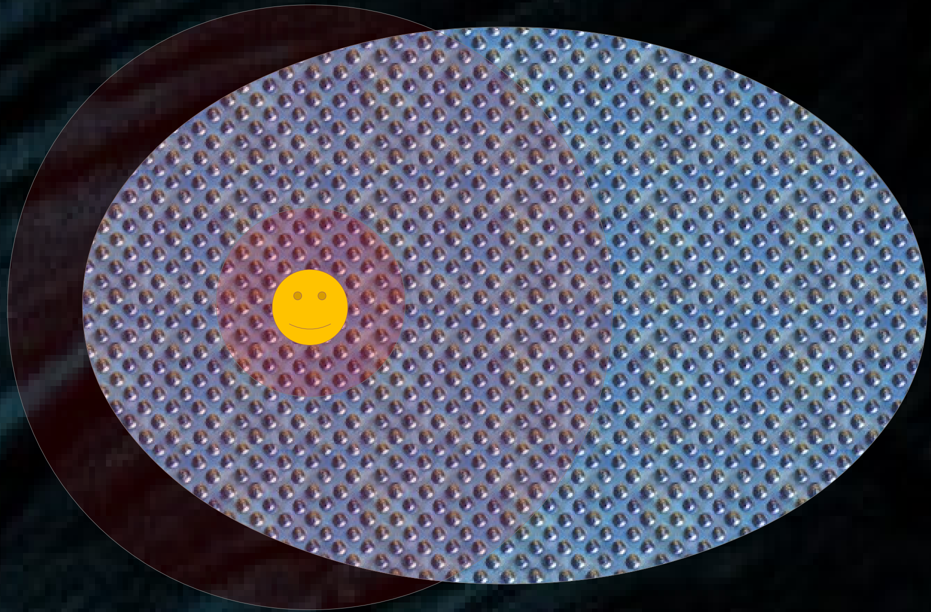
1) **Prompt gamma-rays:** point a telescope to a certain direction, and average over a volume set by the angular resolution

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**

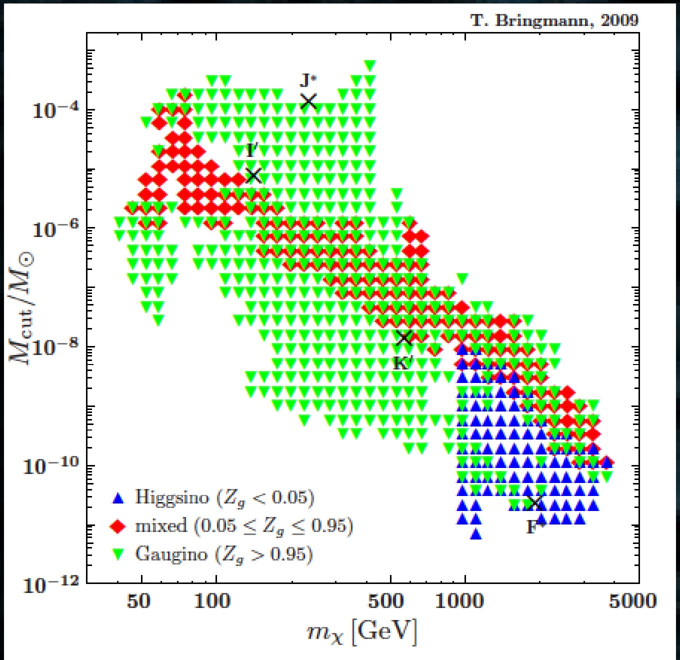
b) To high latitudes/longitudes: the smooth halo contributes much less, **B>>1**

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 09

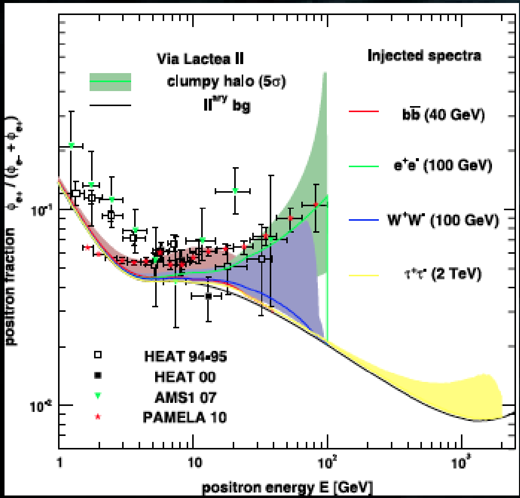
If DM is cold, subhalos must exist and survive tidal stripping (eg Berezinsky++ 05).

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

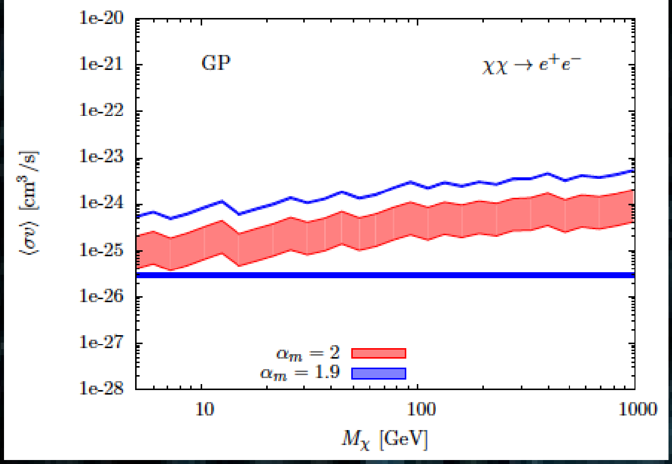
Properties studied in cosmological simulations, but limited by resolution => M > 10^4 Msun only.

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

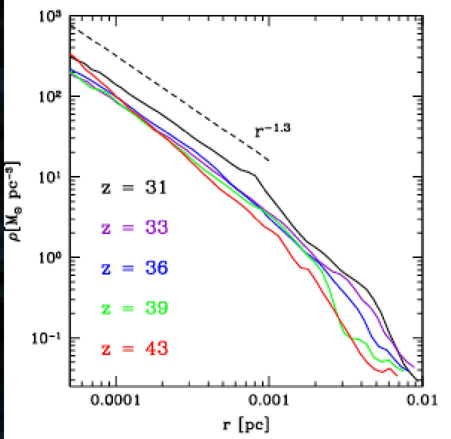
=> PAMELA could be explained by 100 GeV WIMPs (not AMS)



Positron fraction
Lavalle++ 07, Pieri, Lavalle++ 10



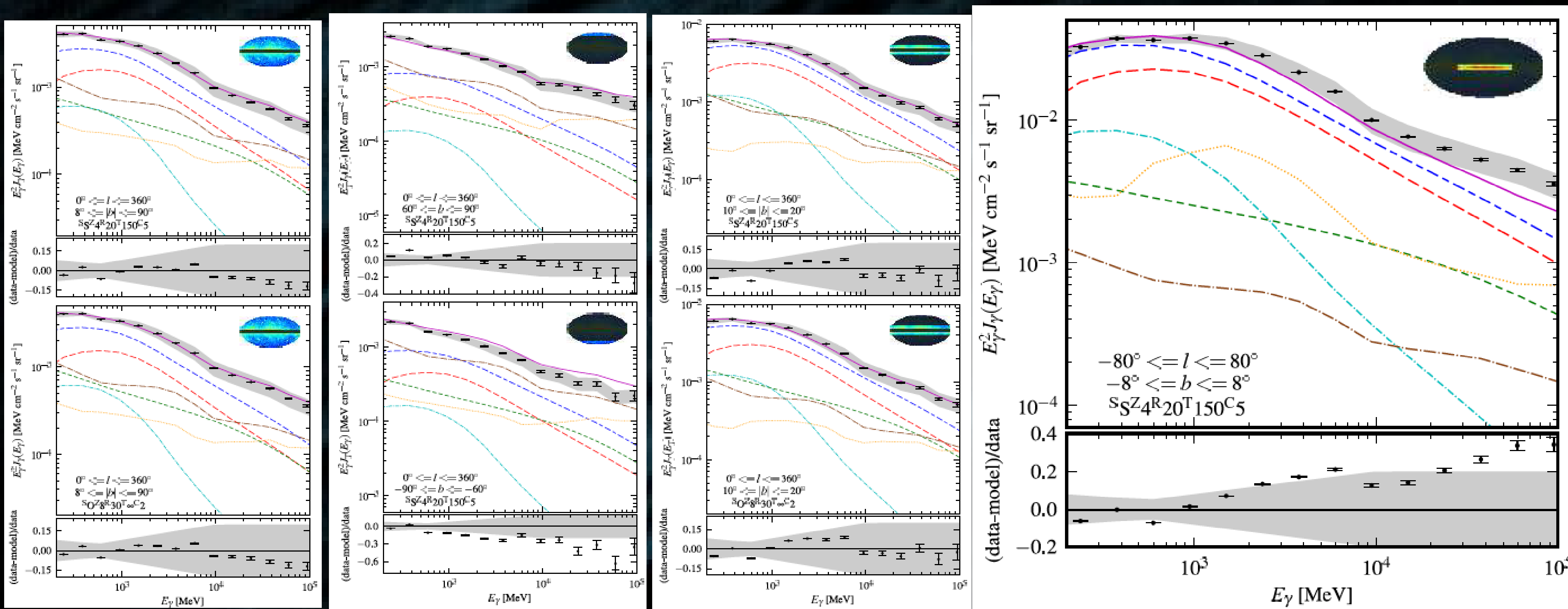
Diffuse gamma-rays
Blanchet & Lavalle 12



Anderhalden, Diemand 13

Diffuse gamma-rays (Fermi) and GCR models

Ackermann++ 12 – 1202.4039



Assumptions: (Galprop code – Strong & Moskalenko)

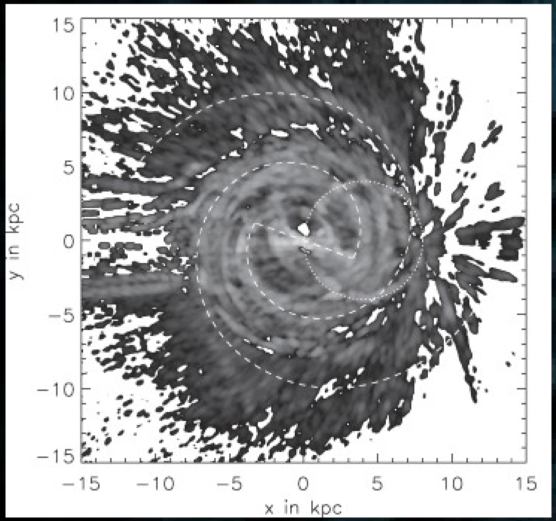
- homogeneous/isotropic diffusion coefficient
- continuous distribution of sources; CRs escape sources with ad-hoc broken power laws (indices are free parameters)
- ISM from HI, H2 (CO), HII (Lazio & Cordes), dust correlations … maps

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 (e.g. Delahaye++ 10)

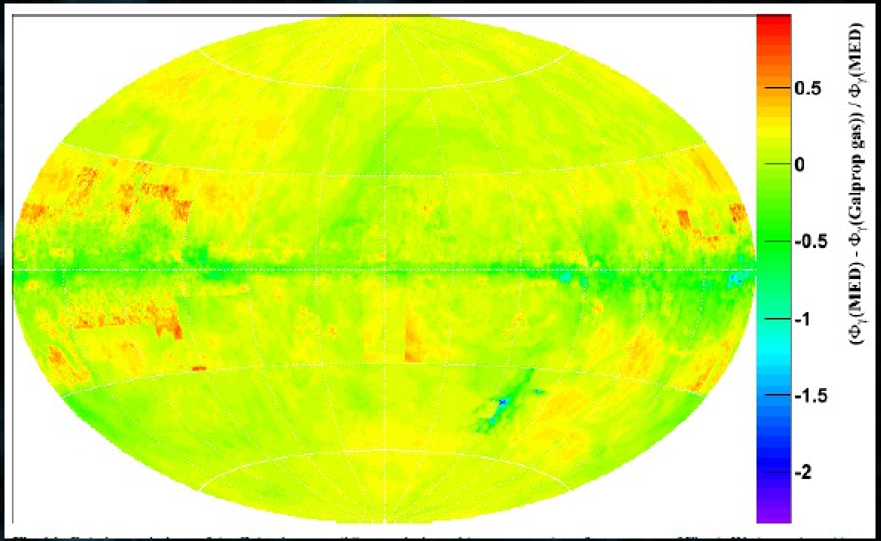
Pohl++ 08
3D model of H2



Impact of ISM modeling

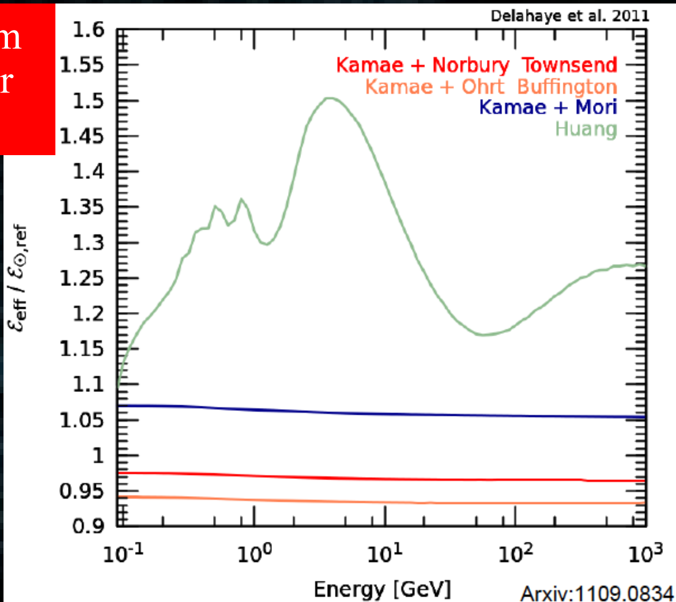
1102.0744

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 ~ 1 kpc from GC
  - ∗ Model available online

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



Arxiv:1109.0834

Diffuse emission: a top bottom approach

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

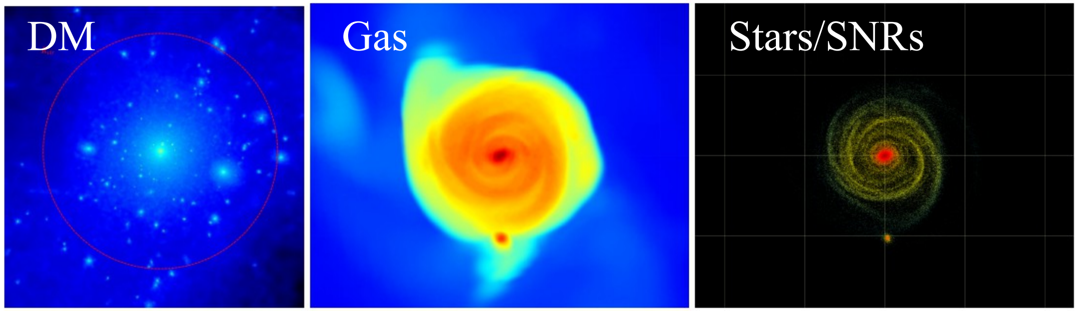
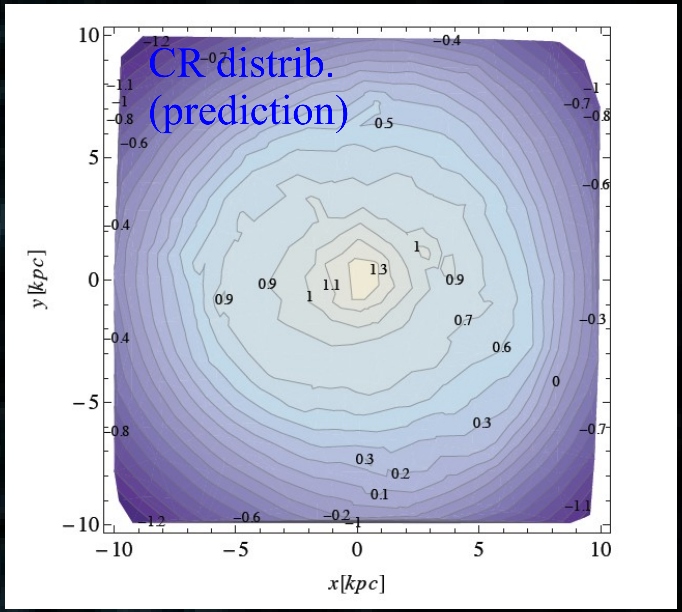
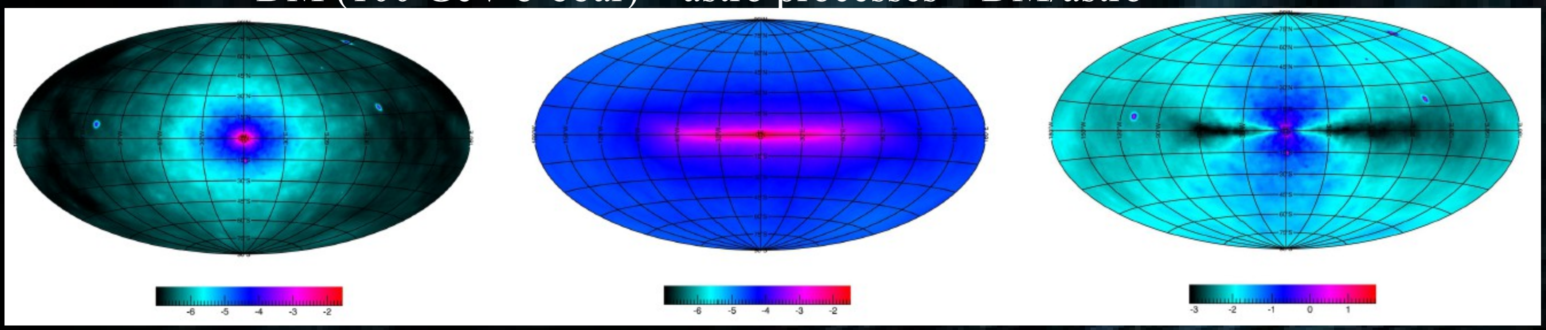


FIG. 1. Left: DM halo and subhalos; the virial radius (264 kpc) appears as a red circle. Middle: top view of the gas content (scaled as in right panel). Right: SN events in the last 500 Myr (10 kpc grid).

1204.4121



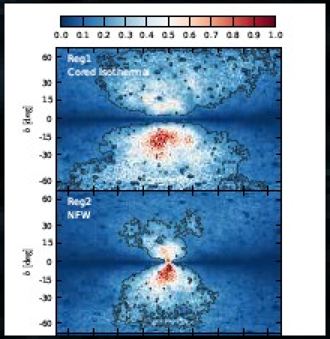
Skymaps:
DM (100 GeV b-bbar) – astro processes – DM/astro



<u>Advantages:</u>
* all ingredients are identified and localized (sources and gas)
* check the relevance of current assumptions

<u>Limits:</u> 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

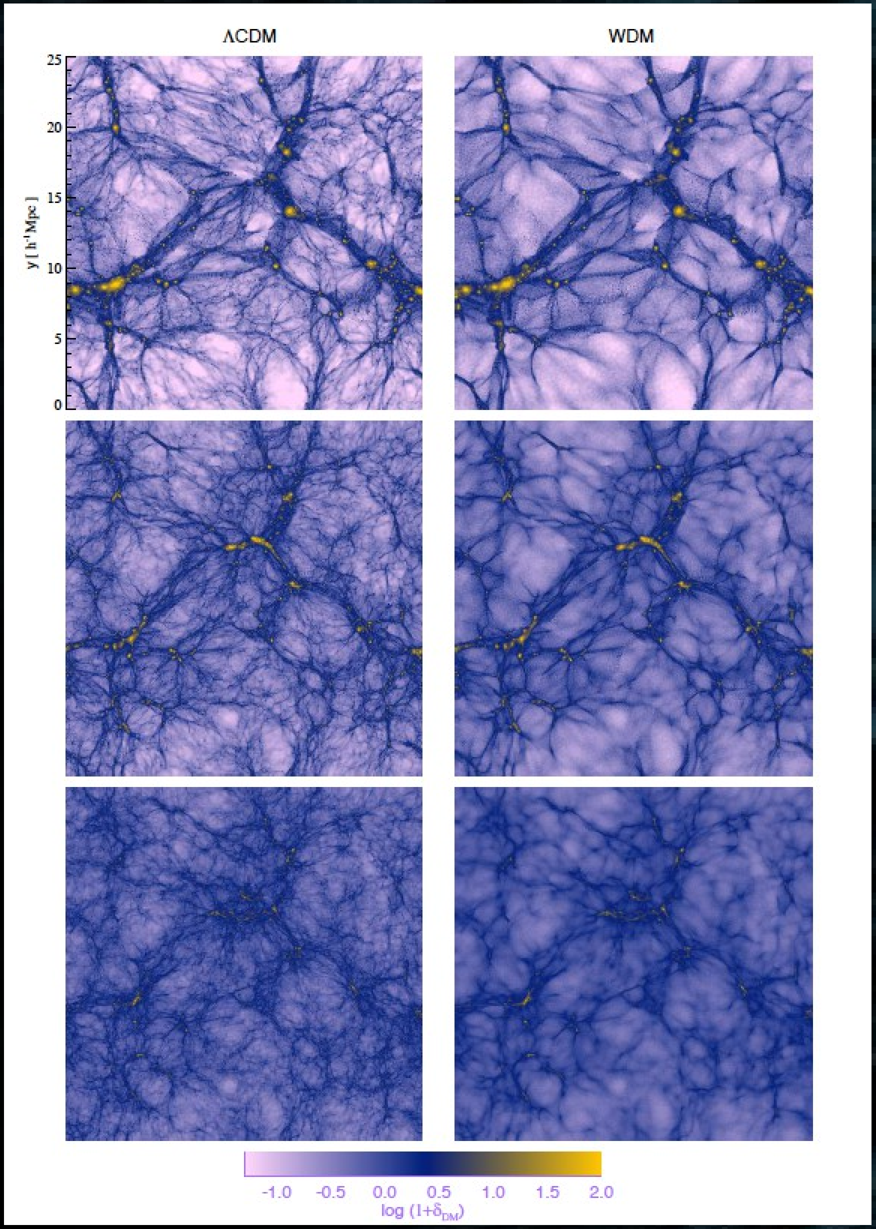
- Antimatter CRs + diffuse emissions more relevant to constraints: astrophysics pollutes a lot, and is not completely controlled yet

***** Complementarity with other detection methods (direct/LHC) is definitely the best strategy.**

Backup

CDM: successes and issues

Viel++ (11)



Indirect proofs for DM:

Observed (gravitational effects) from sub-galactic to cosmological scales

CDM successes:

- Leads to successful theory of structure formation

=> CDM seeds galaxies, galaxies embedded in DM halos

- Non-linear collapse probed with cosmological N-body simulations
- Including baryons is an ongoing (difficult) task but seems promising
- Most of observed properties (CMB / clusters / galaxies) reproduced from theory

Alternatives to DM: Modified gravity ????

- Interesting and difficult theoretical direction
- Fails in forming galaxies without DM (eg large CMB multipoles)

=> DM required even in modified gravity models!!!!

Free-streaming scale must at least allow for Dwarf Galaxies:

Fermionic DM => Tremaine & Gunn 79, Boyarsky+ 06: m > 1 keV

=> WDM and/or CDM allowed

Small scale issues for CDM (too much power on small scales):

So-called "Cusp-core problem"

=> CDM predicts cusps + concentrated centers, observations cores

(e.g. Navarro-Frenk-White profile)

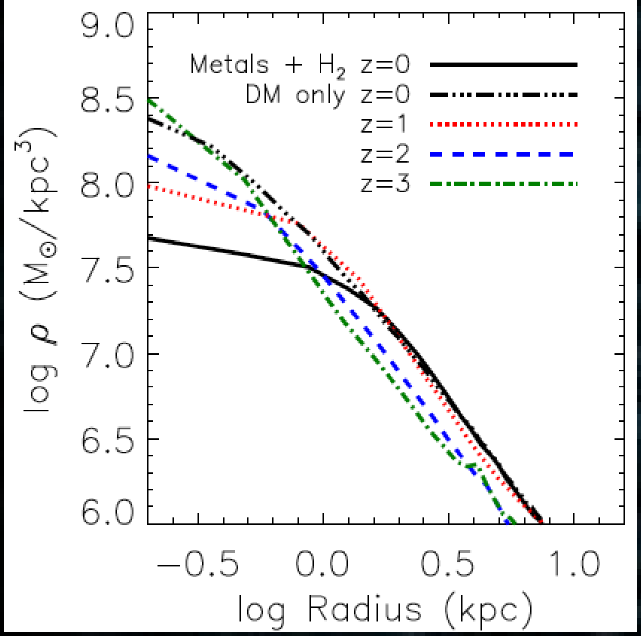
More subhalos than observed ($\lesssim$ dwarf galaxy mass)

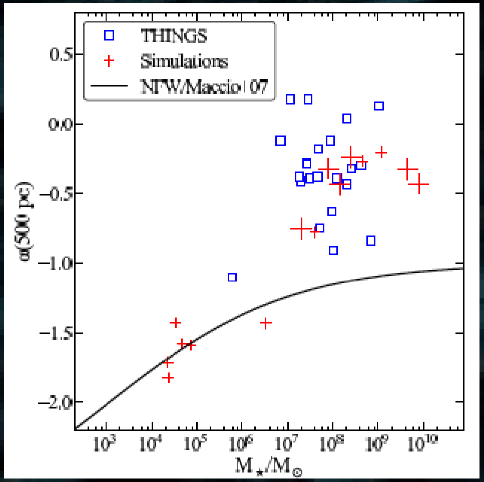
*** more have been detected recently (SDSS)

*** inefficient star formation, feedback effects (UV pressure, SN)

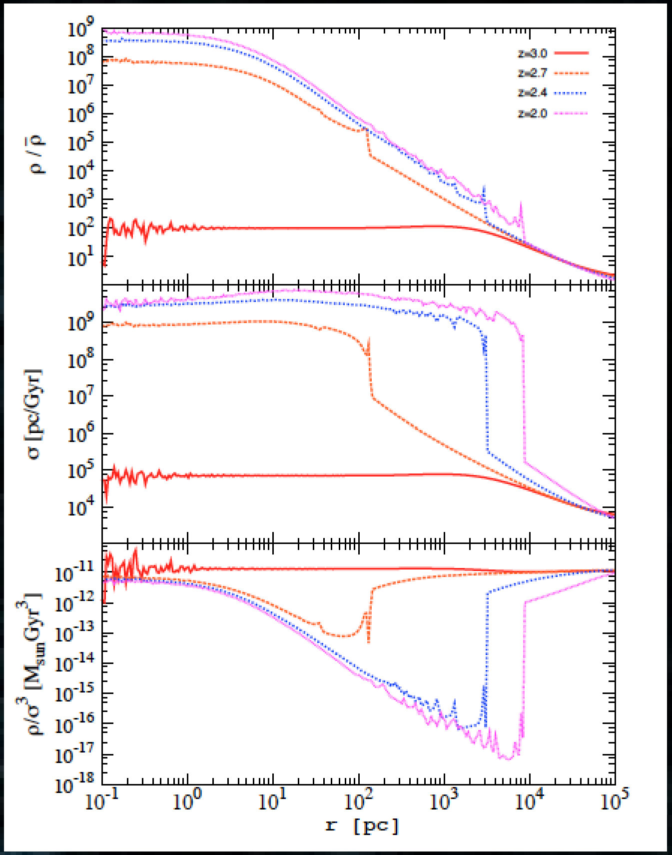
The core-cusp problem
(mostly in late-type LSB galaxies, e.g. de Blok 10)

Governato++ (12)
CDM + more realistic physics for baryons => cusps are flattened
(star formation: radiative feedback from massive star + SN feedback)





Villaescuela-Navarro & Dalal (10)
WDM does not prevent cusp formation
(Core radius / virial radius < 0.001)

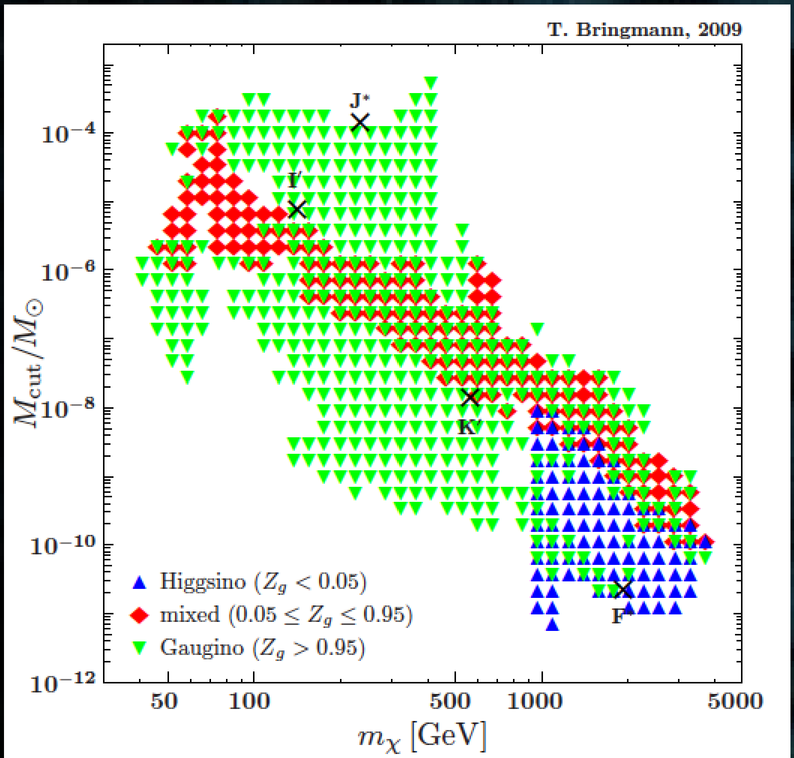


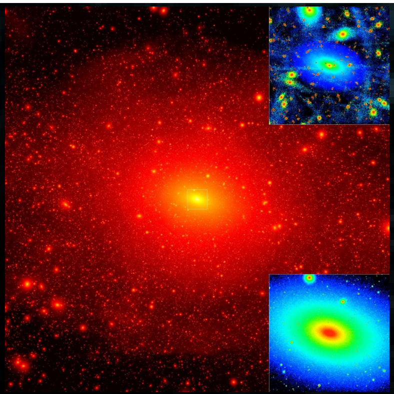
Conclusions:
→ WDM alone does not solve the issue:
* must be close to CDM to form DSphs (> 1-10 keV)
* then core radii are way too small wrt observations

→ CDM in better shape when baryons are included
(still some debate)

The subhalo problem: too many, too concentrated

Bringmann (09):
The minimal proto-halo scales for SUSY WIMPs





Via Lactea II simulation (MW-like galaxy)
Diemand++ (08) – CDM only
=> > 20,000 subhalos with $M > 10^{6-7}$ Msun

Too big to fail? The puzzling darkness of massive Milky Way subhaloes

Michael Boylan-Kolchin*†, James S. Bullock, and Manoj Kaplinghat
Center for Cosmology, Department of Physics and Astronomy, 4129 Reines Hall, University of California, Irvine, CA 92697, USA

“Too big to fail”:
* CDM => massive, concentrated subhalos => should form stars, but not observed (ultra-faint SDSS DSphs not enough)

Potential solutions come from baryonic effects:
* feedback (Governato ++12)
* H2-regulated star formation (Kuhlen++ 12-13)

Other solutions from particle physics:
* Self-interacting DM (Spergel & Steinhard 00)

=> Biggest challenge for CDM
=> Investigate baryonic effects in detail

DARK MATTER SUB-HALO COUNTS VIA STAR STREAM CROSSINGS

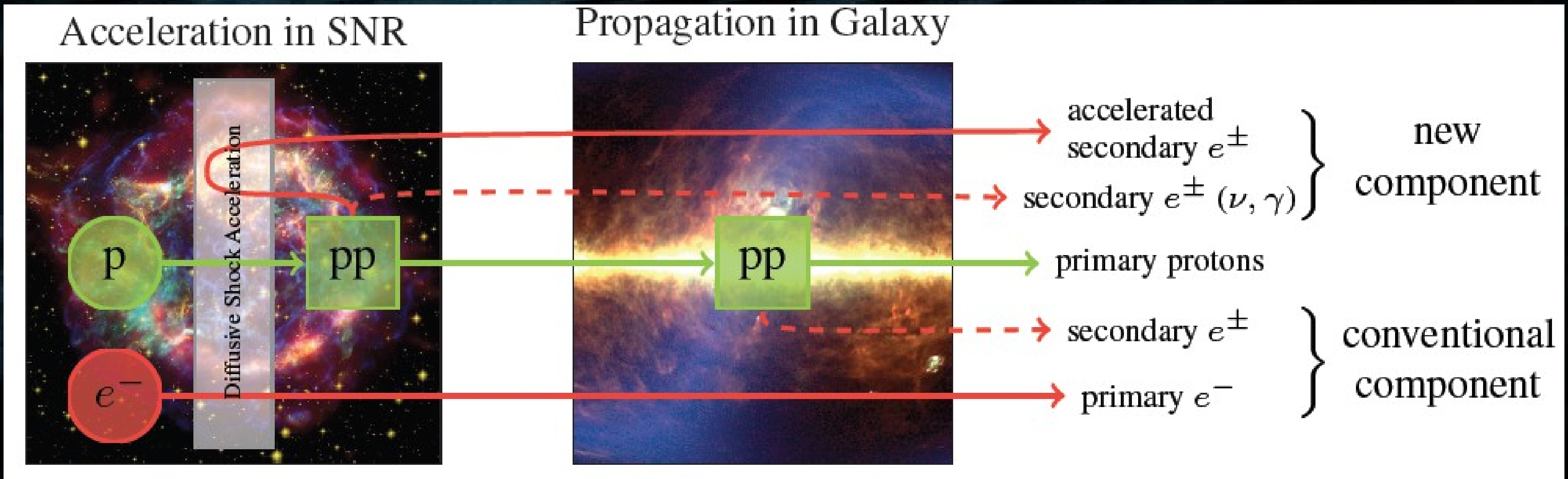
R. G. Carlberg[1]

Carlberg (arXiv:1109.6022):
Gaps in star streams: NW (M31), Pal 5, Orphan, EBS (MW)
=> ~ 10^5 subhalos with M > 10^5 Msun
(potentially large systematic errors)

See also Ly-alpha studies.

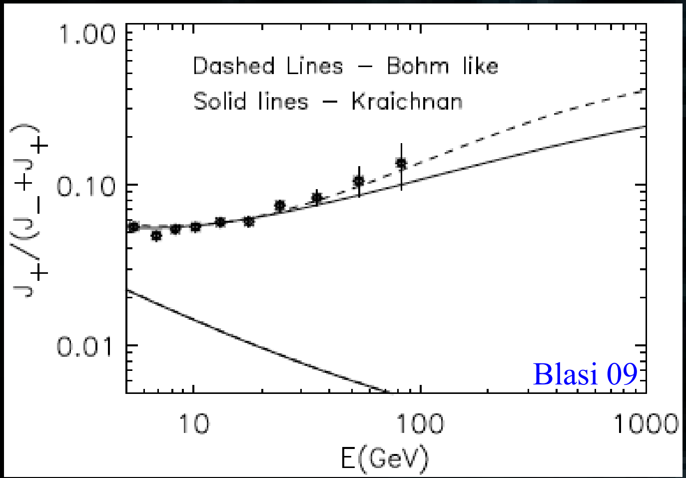
Other astrophysical solution(s)

Secondaries generated in SNRs are accelerated like primaries:
Berezhko++ 03, Blasi 09, Blasi & Serpico 09,
Mertch & Sarkar 09, Ahler++ 09

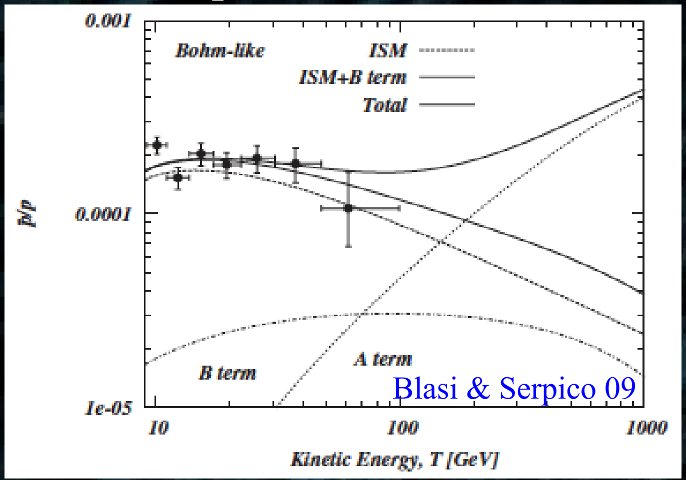


(from Ahler++ 09)

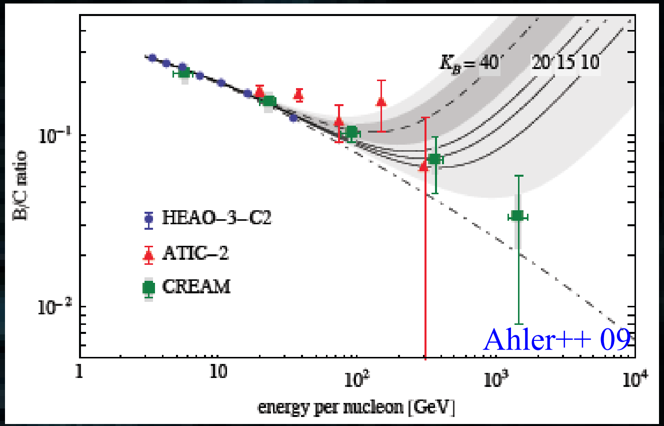
Positron fraction



Antiproton fraction



B/C ratio



Associated signatures: rising antiproton fraction (like DM) and B/C ratio