Galactic cosmic rays
+ *e^+/e^- asymmetry* +
++ *dark matter signals* ++

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Outline

***Part I:* Cosmic-ray nuclei, propagation models**

- Generalities
- From a leaky box to slab models
- Secondary-to-primary ratios and constraints
- State-of-the-art; current predictions/issues

***Part II:* Cosmic-ray electrons and positrons**

- Energy-loss dominated propagation
- Interpretation of current data: the importance of local sources

***Part III:* Searches for dark matter annihilation signals**

- Gamma-rays and antimatter cosmic rays
- Constraints vs discovery potentials

Bibliography

Part I: ***Cosmic-ray nuclei, propagation models***

- Longair, *High-energy astrophysics* vol.2, Cambridge University press (2nd ed. 1994).
- Berezinsky et al, *Astrophysics of cosmic rays*, Amsterdam:North-Holland, ed. Ginzburg (1990) – sold out.
- Ginzburg & Syrovastkii, *The origin of cosmic rays*, New-York:Macmillan (1964).
- Strong et al, *Cosmic-ray propagation and interactions in the Galaxy*, ARNPS 57 (2007) – astro-ph/0701517
- Maurin et al, *Galactic cosmic-ray nuclei as tools for astroparticle physics*, astro-ph/0212111

Part II: ***Cosmic-ray electrons and positrons***

- Delahaye et al, *Galactic electrons and positrons at the Earth*, A&A 524, A51 (2010), arXiv:

Part III: ***Searches for dark matter annihilation signals***

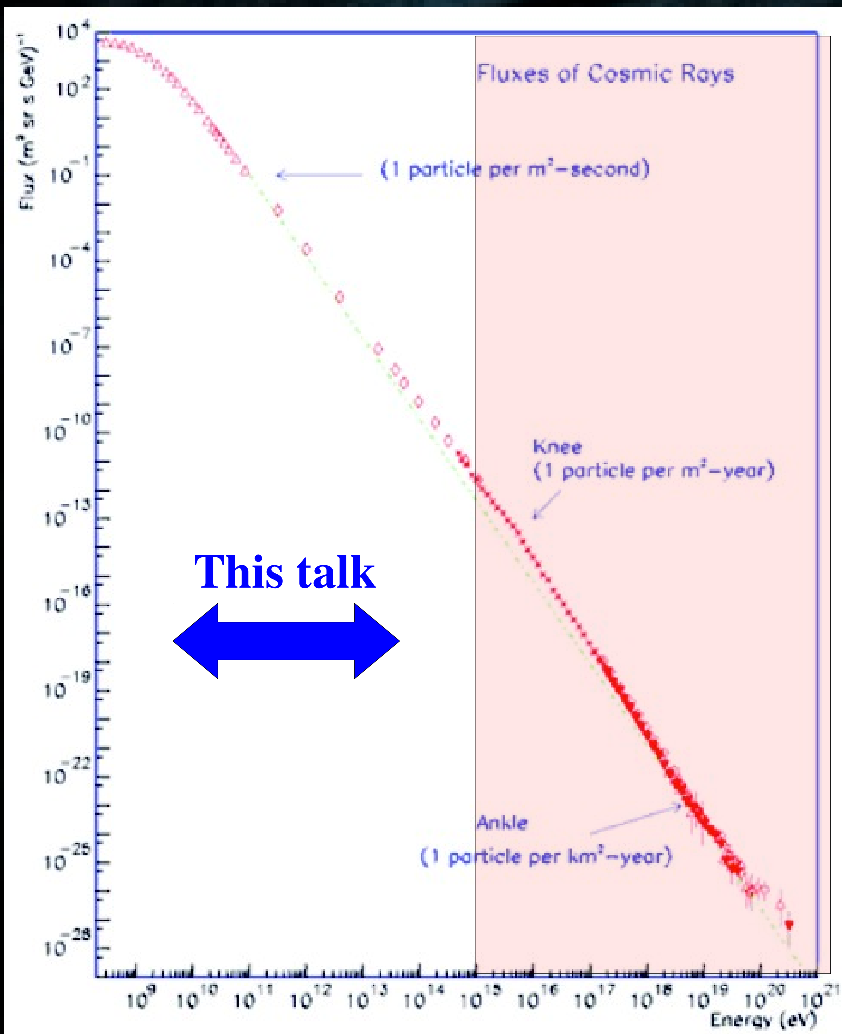
- Salati's lectures:

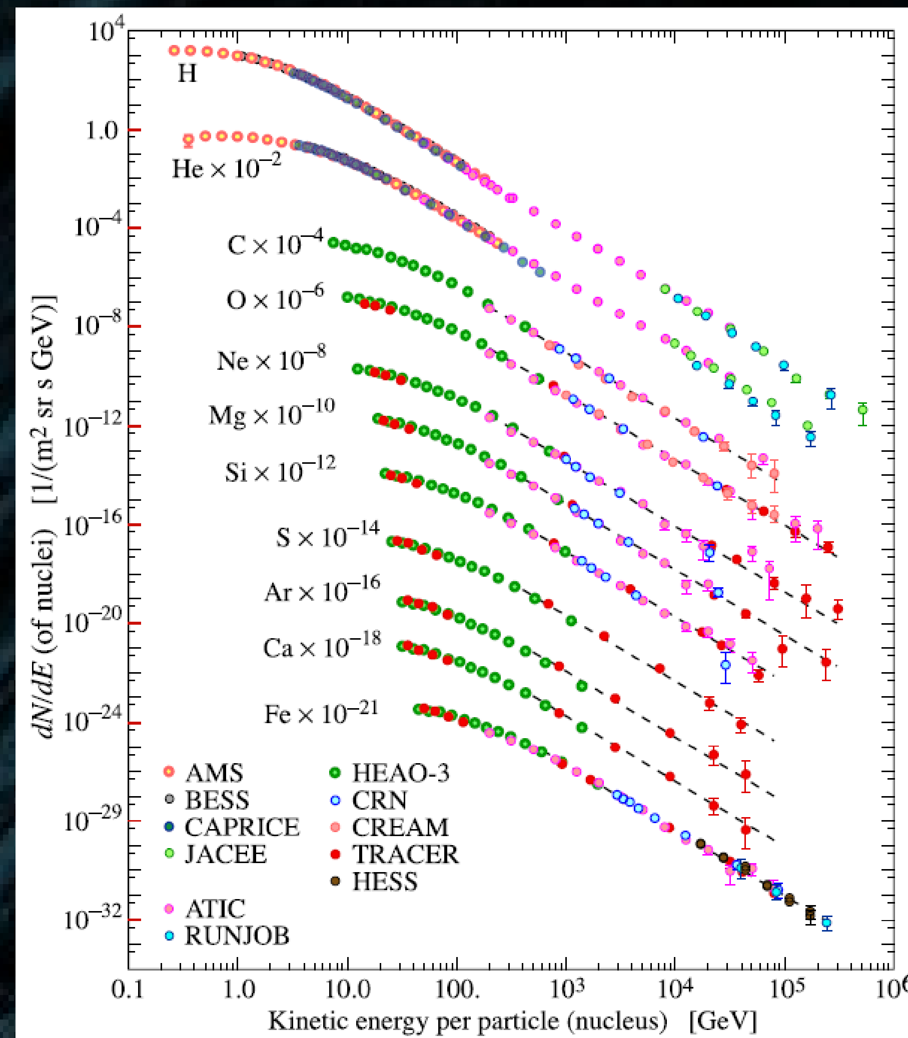
http://www.lapth.in2p3.fr/~salati/APP_ENS_11.pdf (in French, M2 lectures ENS-Lyon)
http://pos.sissa.it/archive//conference/049/009/cargese_009.pdf (in English, Cargese 07)

Generalities

Cosmic rays (CRs) as tools for fundamental physics:

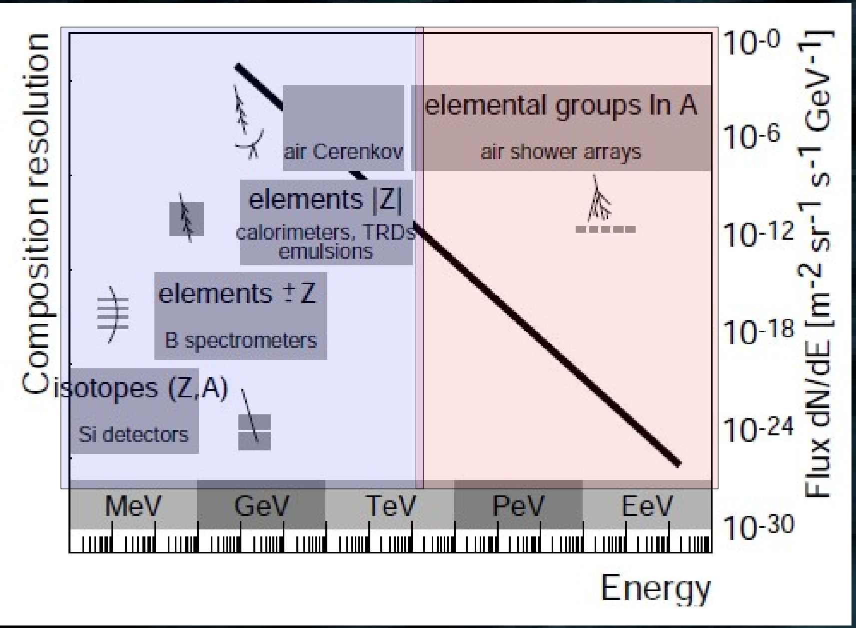
- 1900-1913: Victor Hess, Theodor Wulf and Domenico Pacini pioneer the discovery of CRs
- 1932: Anderson discovers the positron by chance in a bubble chamber (CR-induced shower) – positrons were predicted by Dirac in 1928.
- 1930-1953: discovery of muons, pions and kaons
- 1950's: beginning of the accelerators' era (> 1 GeV)





Detection techniques: from balloons to space

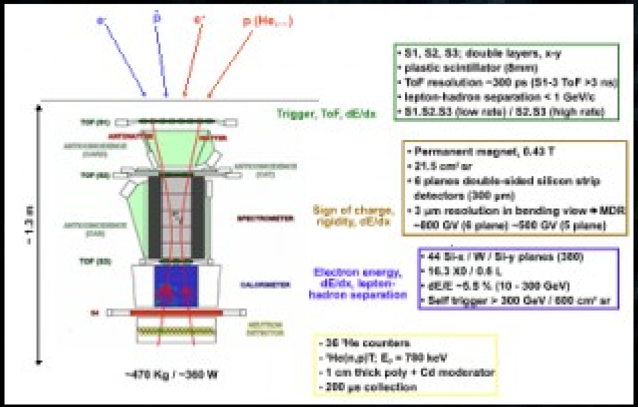
Hörandel (2007)



CREAM IV flight

Endeavour (AMS onboard)

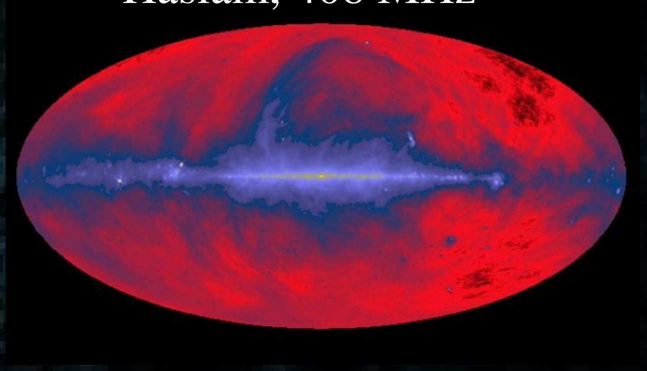
PAMELA design



Cosmic-ray transport throughout the Galaxy

$$\underbrace{\partial_t \mathcal{N}}_{\text{time evolution}} = \underbrace{\mathcal{Q}(\vec{x},E,t)}_{\text{source}} + \vec{\nabla} \underbrace{\left\{\left(K_{xx}(E)\vec{\nabla} - \vec{V}_c\right)\mathcal{N}\right\}}_{\text{spatial current } \vec{\mathcal{J}}_{xx}} - \partial_p \underbrace{\left\{\left(\dot{p} - \frac{p}{3}\vec{\nabla}\cdot\vec{V}_c - p^2 K_{pp}(E)\partial_p \frac{1}{p^2}\right)\mathcal{N}\right\}}_{\text{momentum current } \mathcal{J}_{pp}} - \underbrace{\frac{\tau_s+\tau_r}{\tau_s\,\tau_r}\mathcal{N}}_{\text{spallation, decay}}$$

Haslam, 408 MHz



The level of assumptions/simplifications should be defined for each specific problem under study

Link between diffusion and turbulence (Martin Lemoine's lecture)

$$\frac{d\vec{p}}{dt} = q\left(\vec{E} + \vec{\beta} \times \vec{B}\right)$$

$$\vec{B} = \vec{B}_0 + \delta\vec{B}$$

$$\vec{E} = \vec{E}_0 + \delta\vec{E}$$

$$\langle(\Delta x)^2\rangle = \langle(x(t) - x(0))^2\rangle \propto t^\gamma$$

$$K_{xx} = \lim_{t\to\infty} \frac{\langle(\Delta x)^2\rangle}{2\,t}$$

$$K_{xx} = K_{xx}(\mathcal{R}) \approx \beta\, K_0 \left[\frac{\mathcal{R}}{\mathcal{R}_0}\right]^{2-a}$$

Galactic B-field difficult to model: δB~B_0, spiral structure for the regular field, etc.

=> Diffusion is treated semi-empirically in CR transport models

(usually homogeneous, with free K0 and δ)

A simplistic but pedagogical approach: the Leaky Box model

$$\partial_t \mathcal{N}_i = 0$$

$$\frac{\mathcal{N}_i}{\tau_{\rm esc}} + \Gamma_i \mathcal{N}_i = \mathcal{Q}_i + \sum_j \Gamma_{j\to i} \mathcal{N}_j$$

Leaky Box: escape time from secondary-to-primary ratios

$$\frac{\mathcal{N}_p}{\tau_{\rm esc}} + \Gamma_p \mathcal{N}_p = \mathcal{Q}_p$$

Pure primary species: escape time degenerate with source

$$\frac{\mathcal{N}_s}{\tau_{\rm esc}} + \Gamma_s \mathcal{N}_s = \Gamma_p \mathcal{N}_p$$

Pure secondary species: escape time degenerate with primary density

$$\frac{\mathcal{N}_s}{\mathcal{N}_p} = \frac{\Gamma_p}{\Gamma_s + 1/\tau_{\rm esc}} \overset{\sim}{\propto} \tau_{\rm esc}(E)$$

Ratio: degeneracy broken!

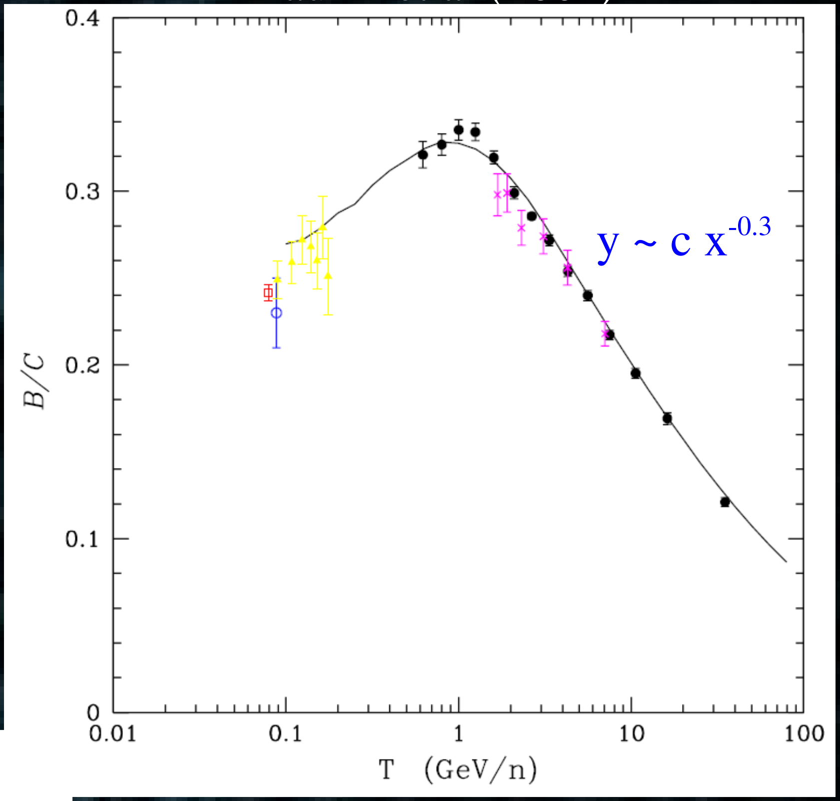
Leaky Box: escape time from secondary-to-primary ratios

$$\frac{\mathcal{N}_p}{\tau_{\rm esc}} + \Gamma_p \mathcal{N}_p = \mathcal{Q}_p$$

$$\frac{\mathcal{N}_s}{\tau_{\rm esc}} + \Gamma_s \mathcal{N}_s = \Gamma_p \mathcal{N}_p$$

$$\frac{\mathcal{N}_s}{\mathcal{N}_p} = \frac{\Gamma_p}{\Gamma_s + 1/\tau_{\rm esc}} \mathrel{\tilde{\propto}} \tau_{\rm esc}(E)$$

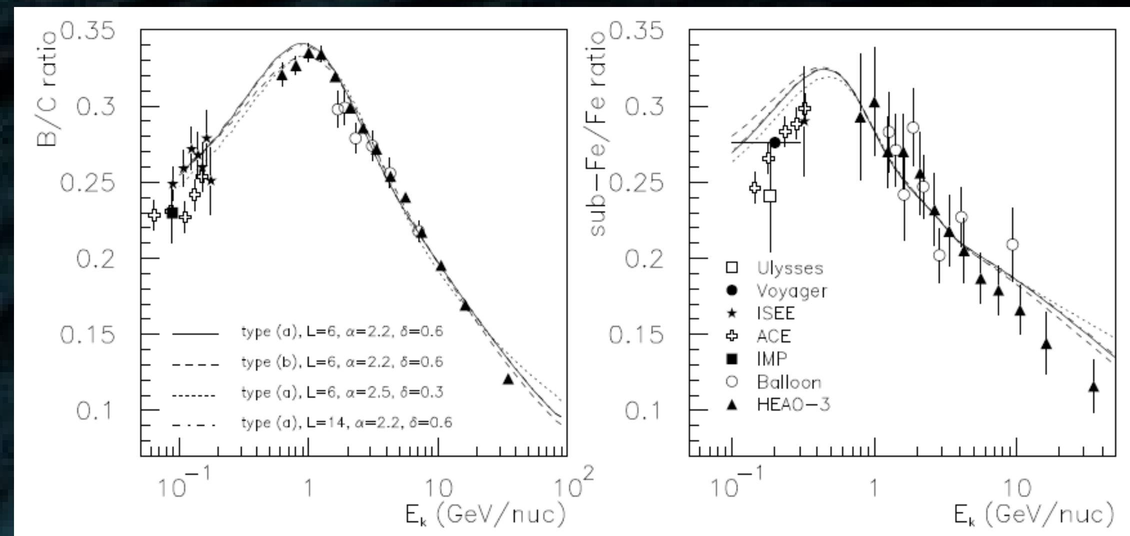
Maurin et al (2001)



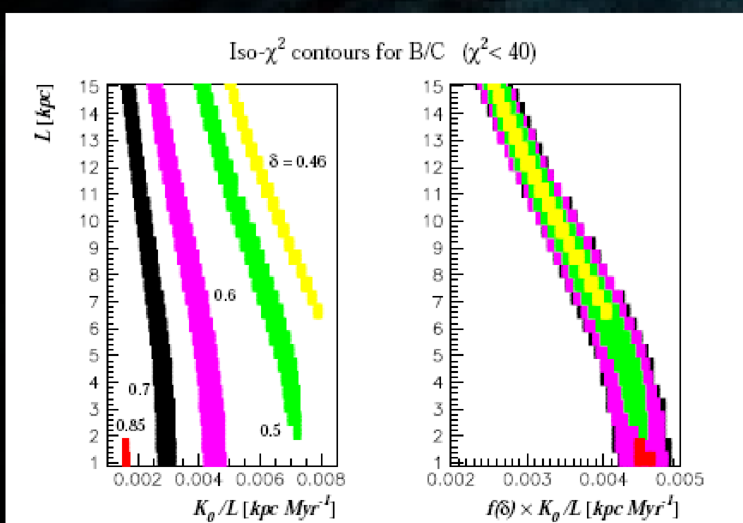
Ratio: degeneracy broken!

Escape time ~ 10-100 Myr

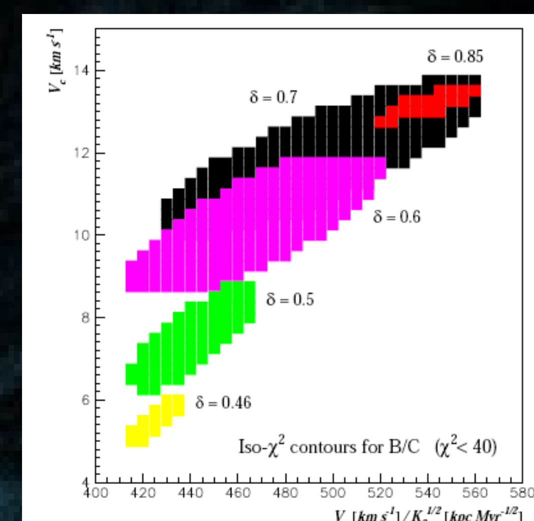
Transport parameter degeneracy



Propagation parameters constrained with data on **secondaries/primaries** (e.g. B/C): **degeneracies !!!!**

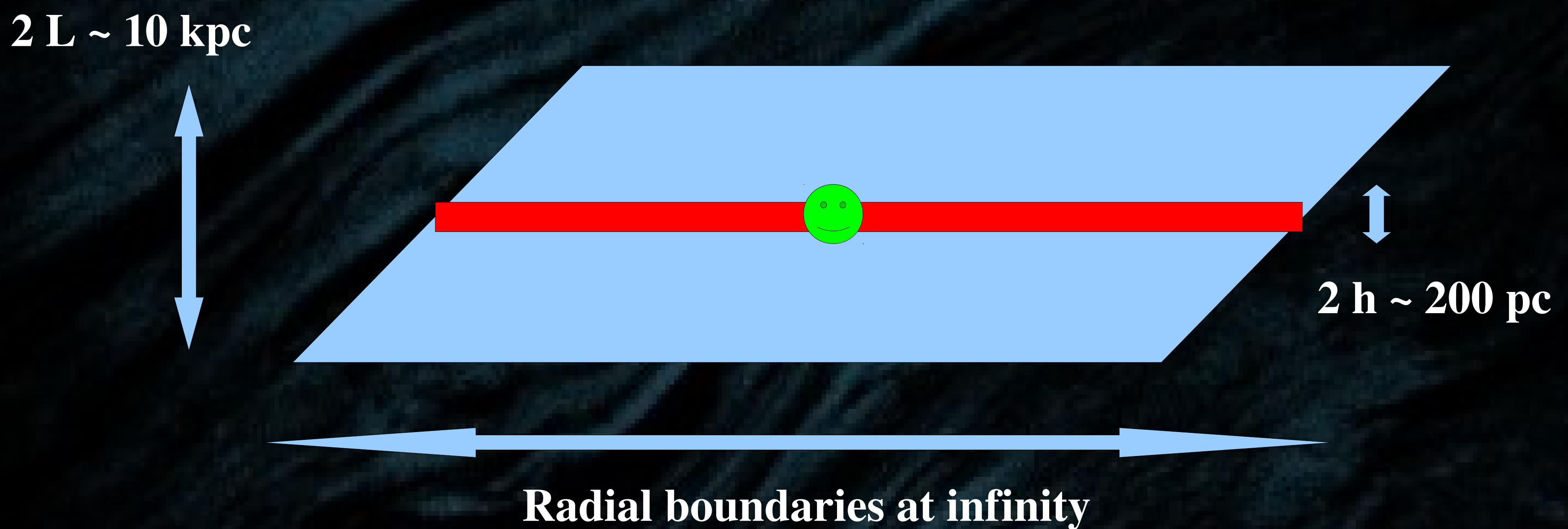


e.g.:
Maurin's PhD thesis (2001)
also Maurin et al (2001)



A more physical model: the infinite slab

$$-K_{xx}\frac{d^2\mathcal{N}}{dz^2} + 2\,h\,\delta(z)\,n_{\rm ism}\,v\,\sigma\,\mathcal{N} = 2\,h\,\delta(z)\,q$$



$$\mathcal{N}(|z| = L) = 0$$

$$\begin{cases} \mathcal{N}(z) = \mathcal{N}(0)\,\frac{L-|z|}{L} \\ \frac{K_{xx}}{h\,L}\mathcal{N}(0) + n_{\rm ism}\,v\,\sigma\,\mathcal{N}(0) = q \end{cases}$$

Link with the Leaky Box approximation: Key tool to understand degeneracies

$$\begin{cases} \mathcal{N}(z) = \mathcal{N}(0)\frac{L-|z|}{L} \\ \frac{K_{xx}}{h\,L}\mathcal{N}(0) + n_{\rm ism}\,v\,\sigma\,\mathcal{N}(0) = q \end{cases}$$

$$\frac{\mathcal{N}_p}{\tau_{\rm esc}} + \Gamma_p \mathcal{N}_p = \mathcal{Q}_p$$

$$\tau_{\rm esc} = \frac{h\,L}{K_{xx}}$$

Secondary-to-primary ratios provide constraints on K/L, not K!
<=> K and L degenerate

Radioactive species: a way to break K-L degeneracy

$$-K_{xx}\frac{d^2\mathcal{N}_r}{dz^2}+\frac{\mathcal{N}_r}{\tau_r}=2\,h\,\delta(z)\,n_{\rm ism}\,v\,\sigma\,\mathcal{N}$$

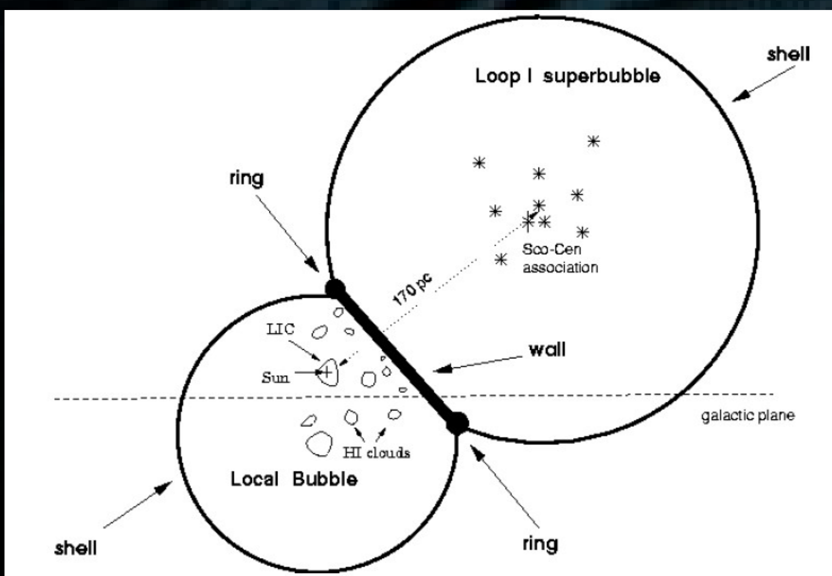
Make sure that $K\tau_r << L^2$

$$\begin{cases}\mathcal{N}_r(z)=\mathcal{N}_r(0)\,\exp\left\{-\frac{|z|}{\sqrt{K_{xx}\tau_r}}\right\}\\ \frac{\mathcal{N}_r(0)}{\mathcal{N}(0)}=\frac{h\,n_{\rm ism}\,\sigma\,v}{\sqrt{K_{xx}\tau_r}}\end{cases}$$

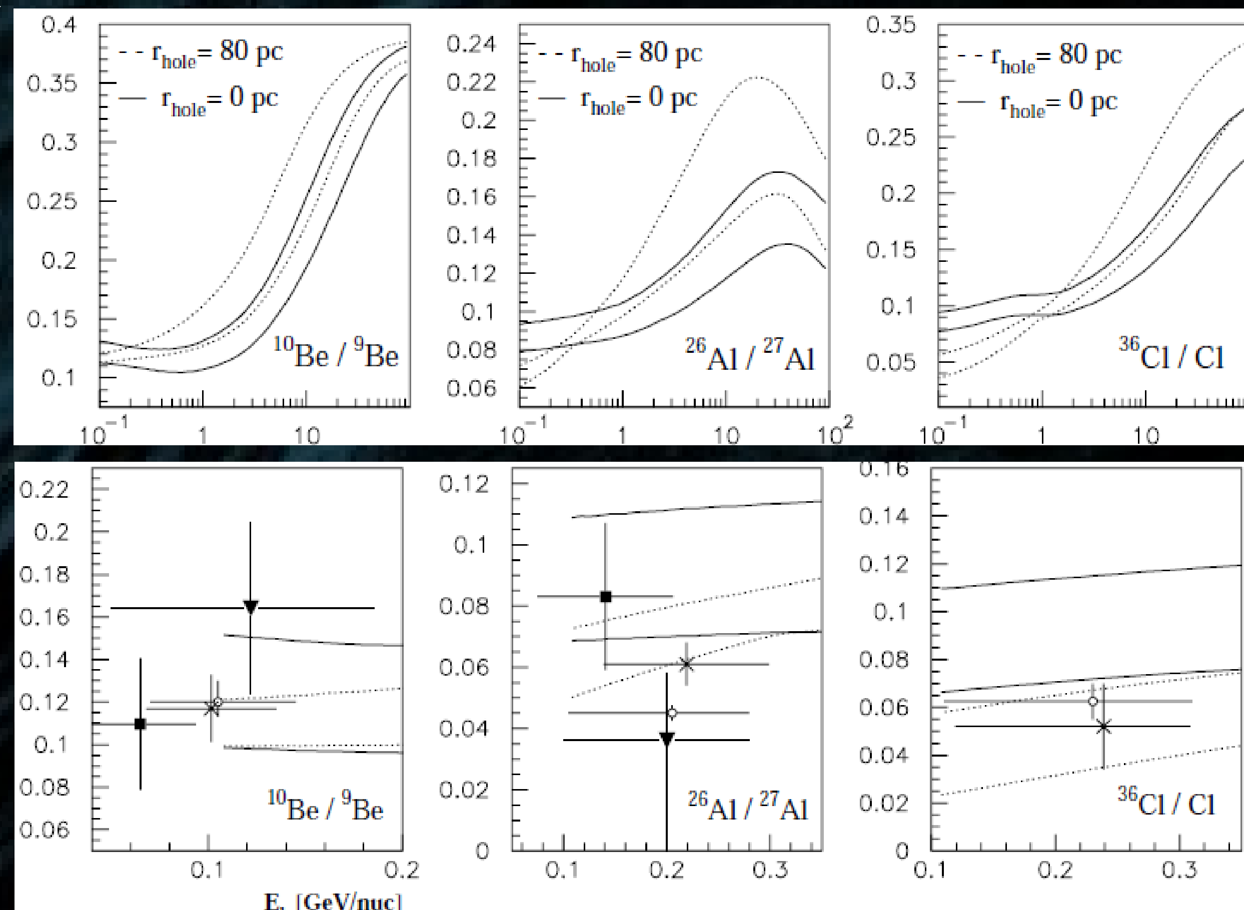
=> direct measure of K !!!!

Not that easy … short propagation scale requires accurate description of LISM …

We are located in a low ISM density bubble (eg Breitshwerdt 2000)



Donato et al (2002)

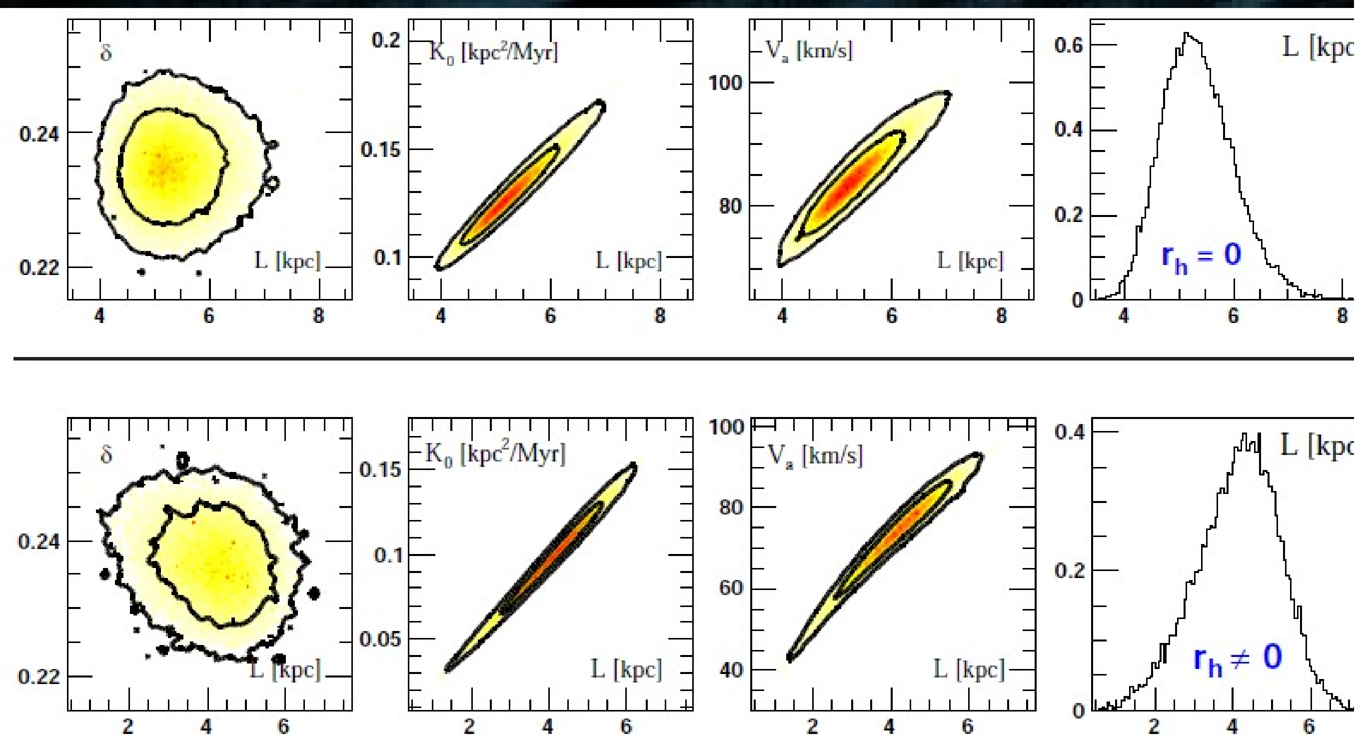


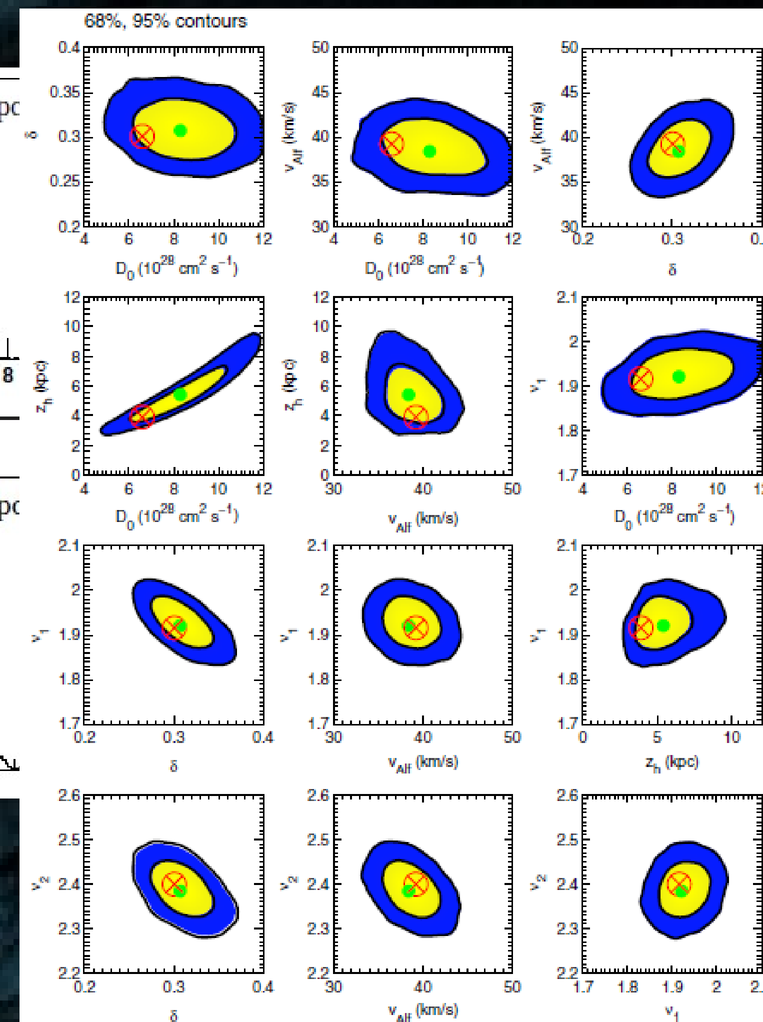
=> Predictions very sensitive to LISM modeling; data not accurate enough (waiting for AMS02)

Current state of the art:
Statistical analysis and constraints

Putze, Maurin et al (2010-xxxx)
MCMC analysis, semi-analytical models

Trotta et al (2010) – Galprop





=> Phenomenological analyses providing sets of parameters associated with statistical significances.

=> Do not forget initial assumptions!

Transport of CR nuclei: summary

- Diffusion equation hard to solve in a general context: approximations needed.

- Different complementary approaches: full numerical / semi-analytical.

- Transport parameters are somewhat degenerate (eg K and L).

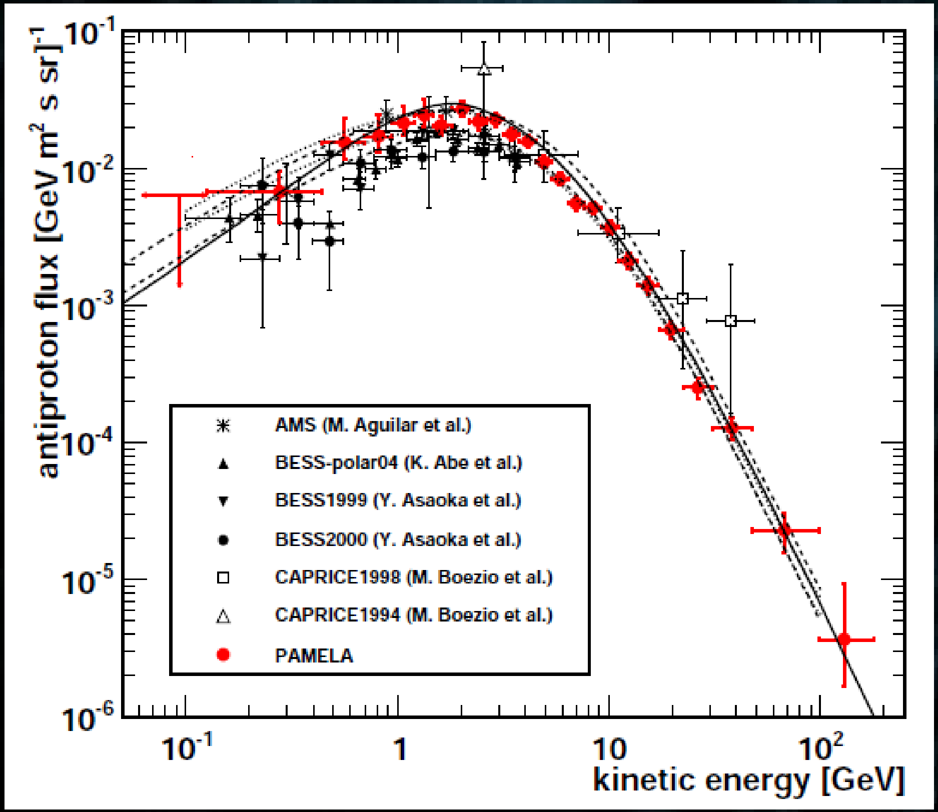
- Modelings of sources (spatial distribution) and ISM have some impact.

- Still some uncertainties in the nuclear cross sections.

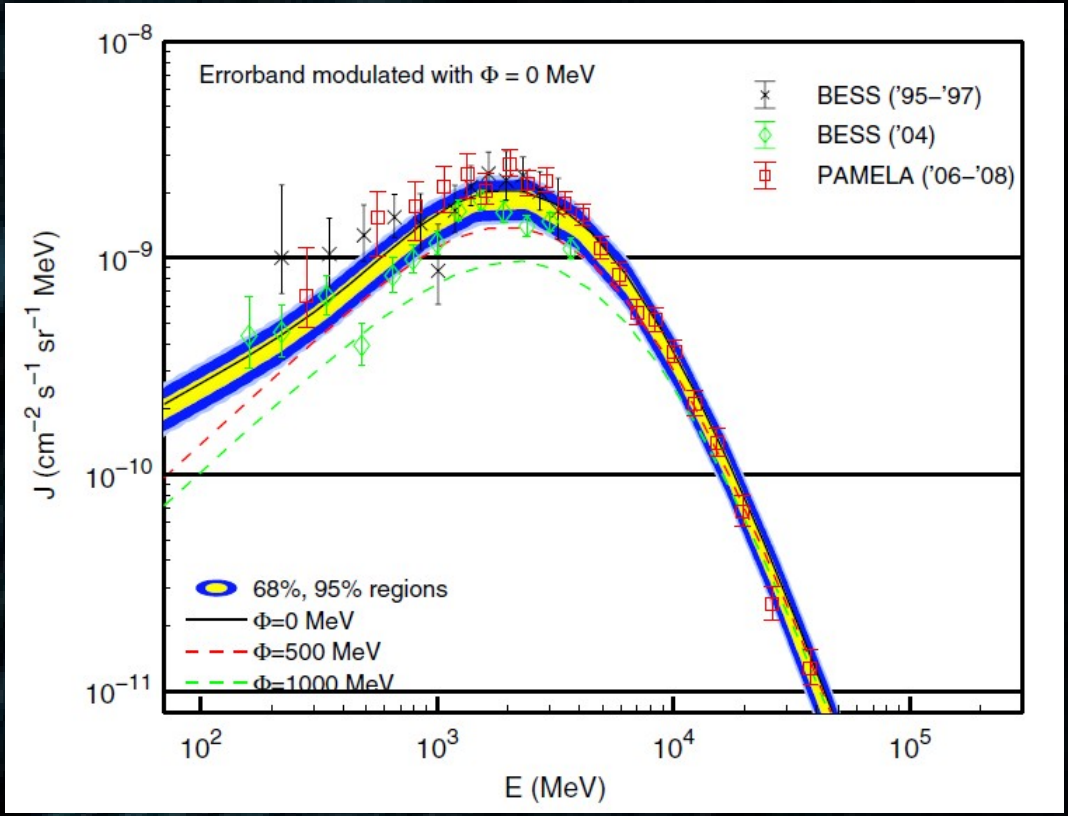
- Current state-of-the-art: Full statistical analyses of Sub-C/C, sub-Fe/Fe and isotopic ratios => AMS-02 will improve error bars!

CR nuclei transport models: applications
1) Antiprotons

PAMELA antiproton data (Adriani et al 10) vs predictions by Donato et al 01, Ptuskin et al 06



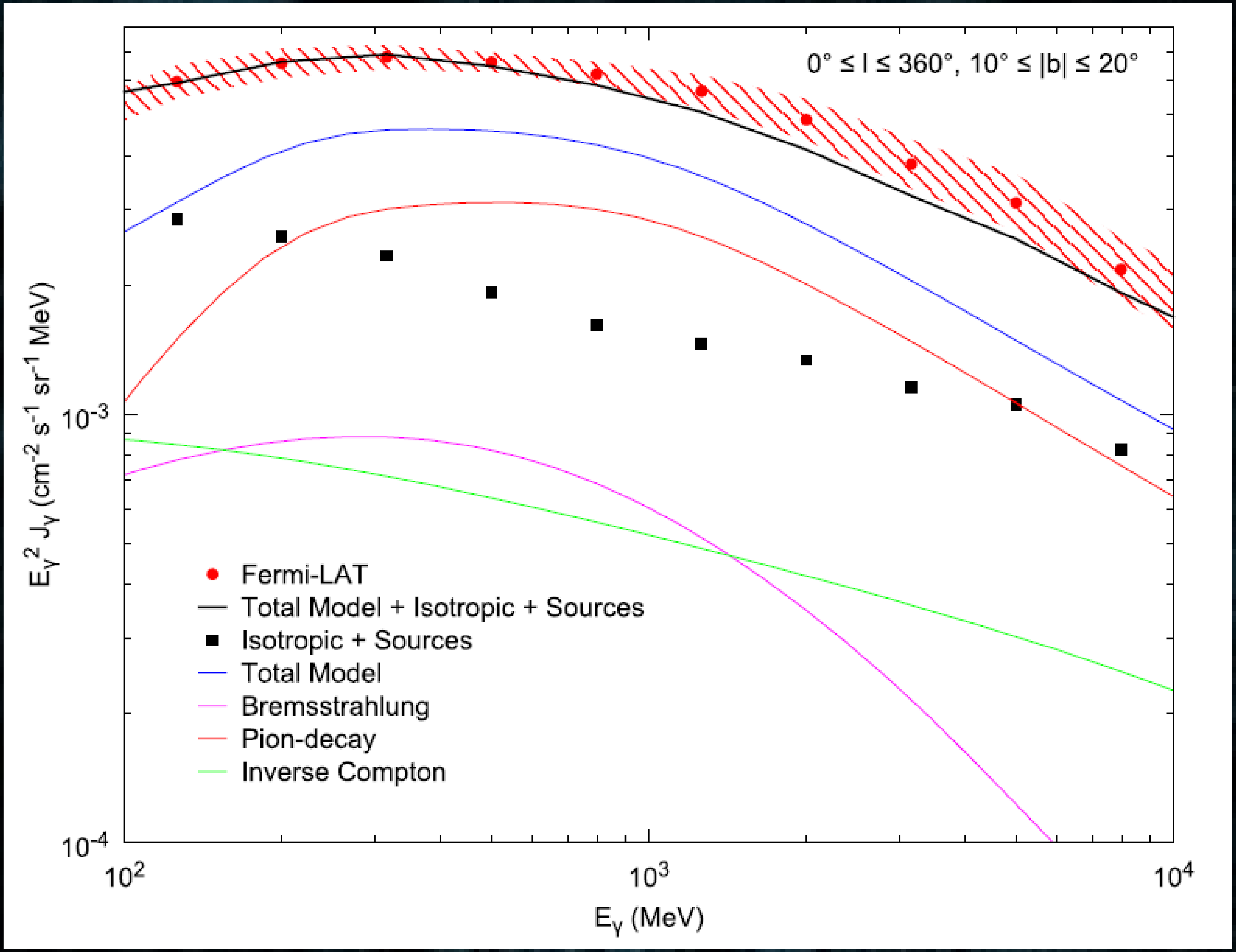
Galprop predictions (Trotta et al 10)



Semi-analytical models provide good fit to the antiproton data.
Galprop finds the data in excess wrt predictions
(but fails to fit a reacceleration+convection model to B/C)

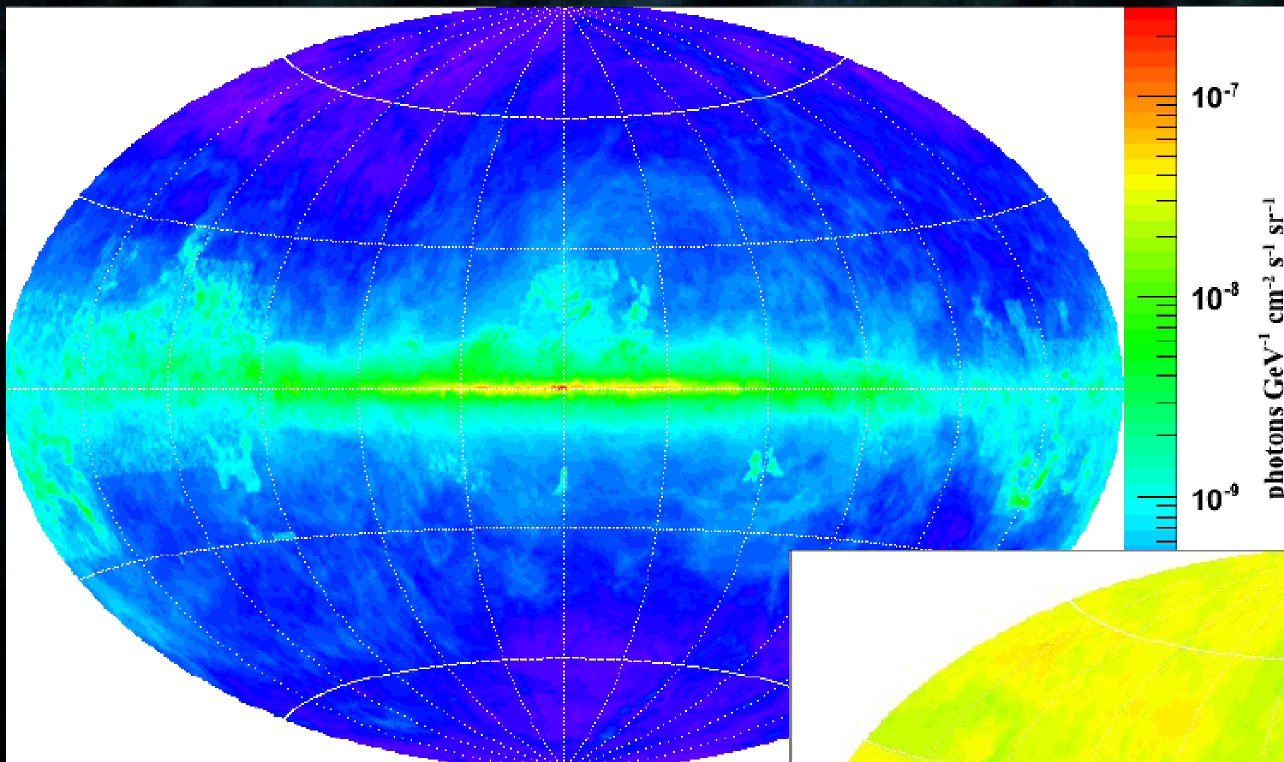
CR nuclei transport models: applications
2) Diffuse gamma-rays

Galprop predictions (Trotta et al 10)

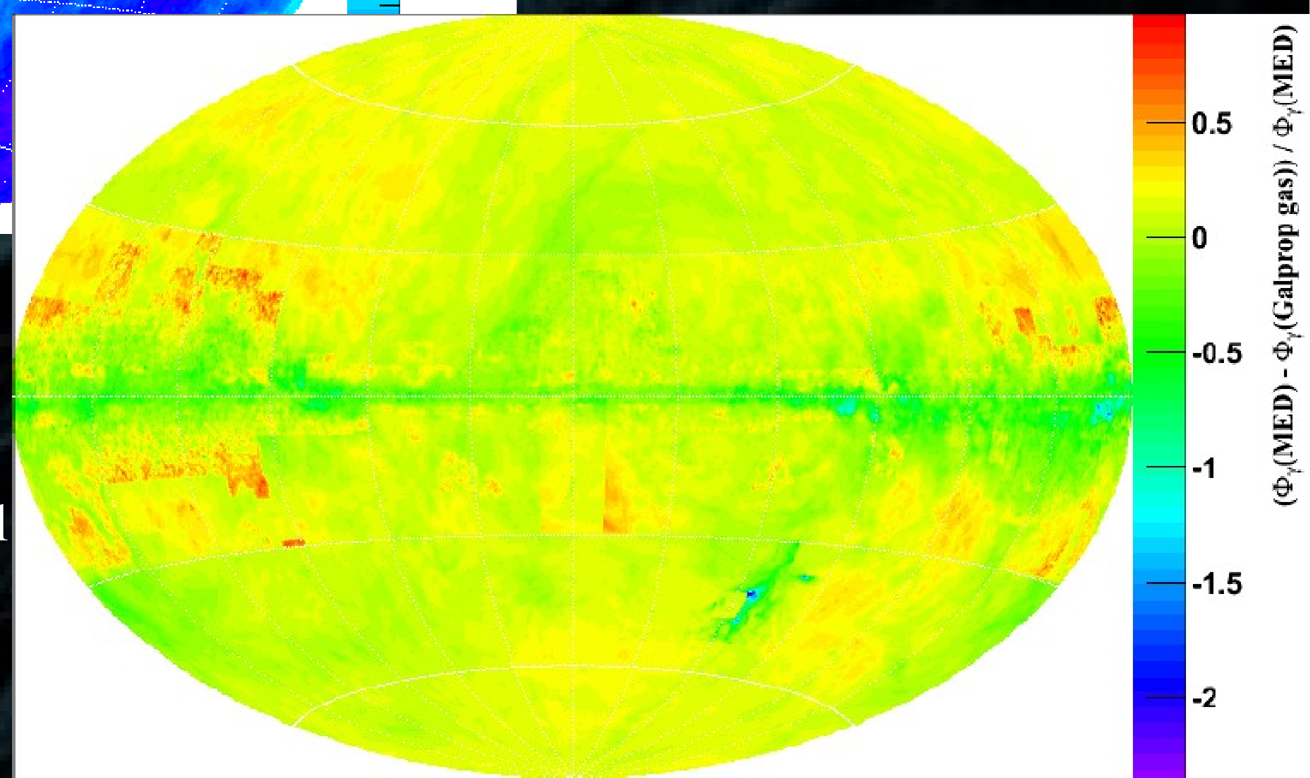


CR nuclei transport models: applications

2) Diffuse gamma-rays



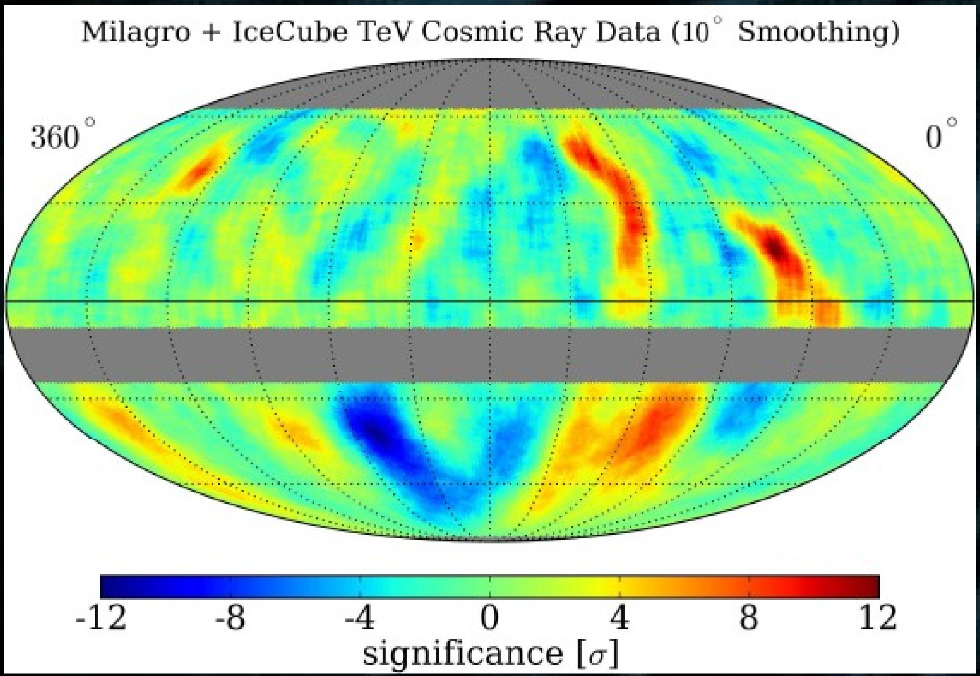
Hadronic component only
from Delahaye et al (2011)



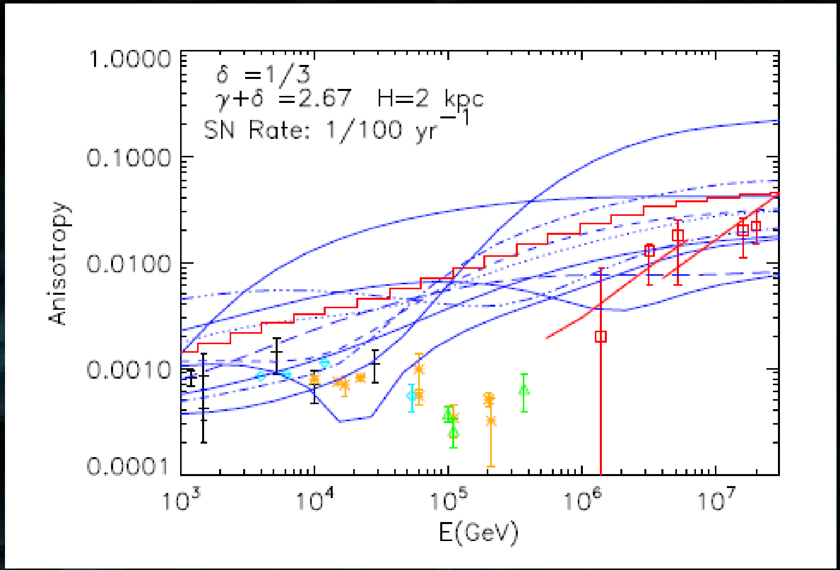
Hydrogen 3D map from
Pohl et a (2008).
HI and CO surveys deconvolved with
an SPH gas-flow model (Bissantz et al
03)
=> **large discrepancies wrt Galprop**

CR nuclei transport models: applications
3) Anisotropies

Icecube: arXiv:1105.2326



MC trials by Blasi & Amato
arXiv:1105.4529



$$\delta(\theta) = \frac{I_{\max}(\theta) - I_{\min}(\theta)}{I_{\max}(\theta) + I_{\min}(\theta)}$$

$$I(\theta,\phi) = \sum A_{l,m} Y_l^m(\theta,\phi)$$

$$I_i(\theta) = A_{0,0} + A_{1,0}\cos(\theta) = \bar{I}_i + \delta\,\bar{I}_i\cos(\theta)$$

$$\phi_i(0) - \phi_i(\pi) = -|\mathcal{J}| = \int d\Omega\,\cos(\theta)\,I_i(\theta) = \frac{4\pi}{3}\delta\,\bar{I}_i$$

$$\delta_i = \frac{3\,K_{xx}\,|\vec{\nabla}\mathcal{N}_i|}{4\,\pi\,\bar{I}_i} = \frac{3\,K_{xx}}{c}\frac{|\vec{\nabla}\mathcal{N}_i|}{\mathcal{N}_i}$$

Phd Thesis Guilhem Bernard
(LAPTh-Annecy)

Predictions involving CR nuclei: summary

- Rough agreement for predictions relying on large scale averages (eg antiprotons).

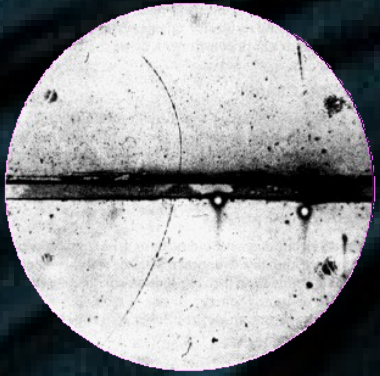
- Incredibly successful for diffuse gamma-rays !

- Strongly model-dependent for finer effects (eg gas modeling for diffuse gamma-rays); more reliable but less constrained at high energy (no convection nor reacceleration effects).

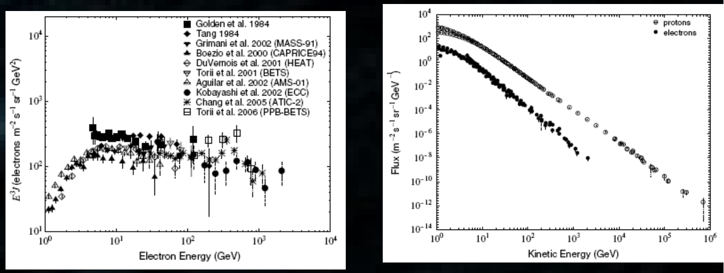
- No standard model so far (Galprop is not a “standard model”).

Cosmic-ray electrons and positrons

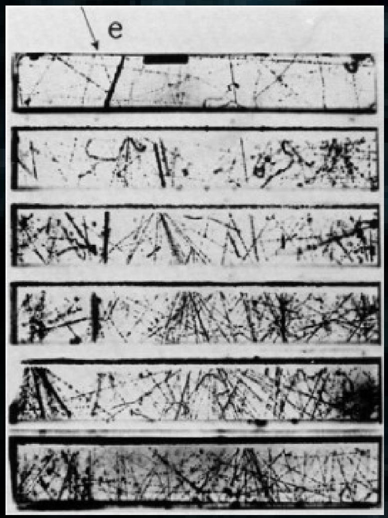
Brief historical review



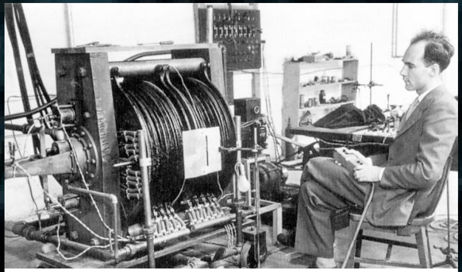
Discovery of the positron
Anderson, Phys. Rev. (1933)



Review by Yoshida (2008)



1st observation of cosmic ray
electrons > 0.5 GeV
Earl (1961): e/p ~ 3%

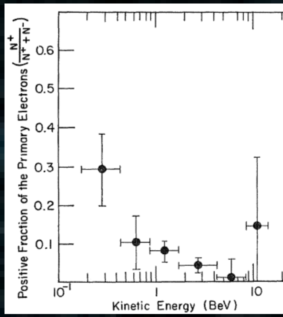


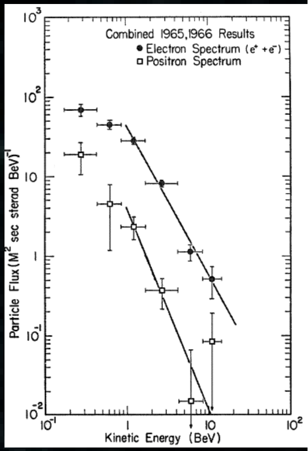
The Positive Electron

Carl D. Anderson, *California Institute of Technology, Pasadena, California*
(Received February 28, 1933)

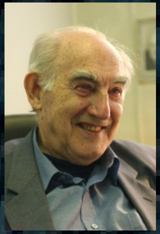
AMS-01 (1998)

Positron fraction
Fanselow et al (1969)



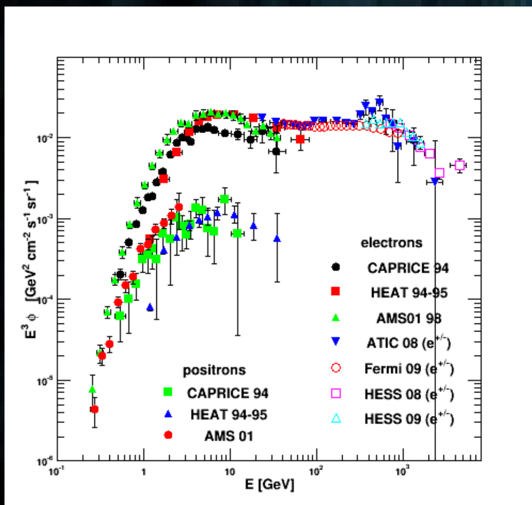


$$-D\Delta N + \frac{\partial}{\partial \varepsilon}[b(\varepsilon)N] = Q(\varepsilon, \mathbf{r}).$$

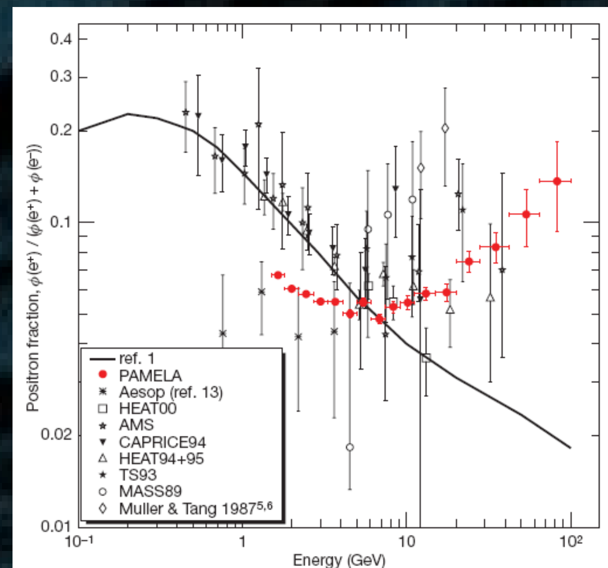


The origin of cosmic rays
Ginzburg & Sirovatsky (1964)

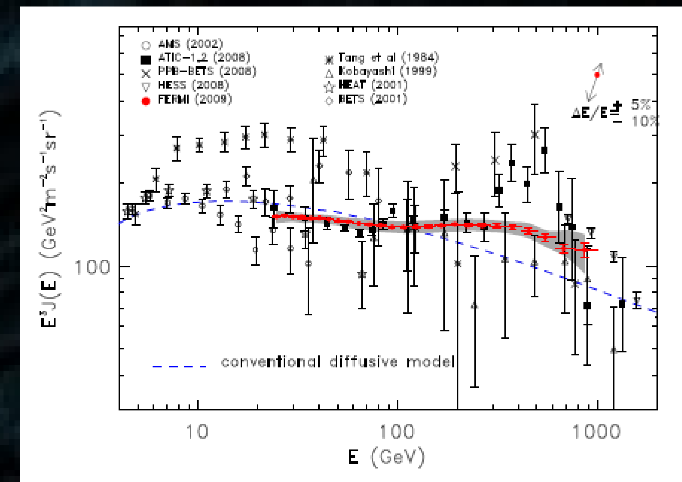
Current measurements of e^+'s and e^-'s



e+ and e-
data compilation



$e^+/(e^+ + e^-)$ PAMELA
Adriani et al (2009)



$(e^+ + e^-)$ HESS and Fermi
Aharonian et al (2009)
Abdo et al (2009)

Do we understand all of these measurements ?
(positron excess, spectral features)

Propagation of Galactic electrons

$$\hat{D}\mathcal{J} = \mathcal{Q}$$

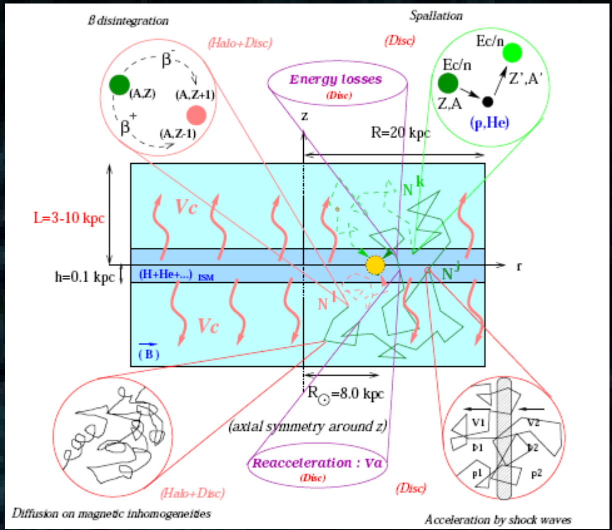
$$D_\mu \mathcal{J}^\mu + D_E \mathcal{J}^E = \mathcal{Q}$$

$$\begin{aligned} \partial_t \mathcal{N} &= \mathcal{Q}(\vec{x}, E, t) \\ &+\vec{\nabla}\left\{\left(K_x(E)\vec{\nabla} - \vec{V}_c\right)\mathcal{N}\right\} \\ &-\partial_E\left\{\left(\frac{dE}{dt} - K_E(E)\partial_E\right)\mathcal{N}\right\} \end{aligned}$$

Current conservation
(continuity equation)

Spatial current (diffusion + convection)
Momentum current (losses + reacceleration)

See formalism in:
Ginzburg & Sirovatskii (1964)
Berezinskii et al (1990)



Credit: Maurin et al (2002)

Program:
- Solve the equation given boundary conditions
- Constrain the different parameters
- Make predictions, compare with data

The Green function method

$$\hat{D}\mathcal{J} = \mathcal{Q}$$

$$D_\mu \mathcal{J}^\mu + D_E \mathcal{J}^E = \mathcal{Q}$$

$$\hat{D}\mathcal{G} = \delta^3(\vec{x} - \vec{x}_s)\delta(E - E_s)\delta(t - t_s)$$

$$\mathcal{J}(\vec{x}, E, t) = \int d^3\vec{x}_s dE_s dt_s\, \mathcal{G}(\vec{x}, E, t \leftarrow \vec{x}_s, E_s, t_s)\, \mathcal{Q}(\vec{x}_s, E_s, t_s)$$

Analytical solutions in the following cases for electrons:

- Isotropic diffusion + homogeneous losses + no convection + no reacceleration
- Radial diffusion + convection + homogeneous losses + no reacceleration

Solution in an infinite 3D halo (1)

$$\partial_t \mathcal{N} - K(E)\Delta\mathcal{N} + \partial_E \left\{ \frac{dE}{dt} \mathcal{N} \right\} = Q$$

Assumptions: diffusion + energy losses homogeneous and isotropic

$$\mathcal{N} \equiv dn/dE$$

We are looking for the **particle density** per unit energy at **any place, any energy, any time**.

$$\partial_t \mathcal{N} = 0$$

Assume **steady state** (time fluctuations negligible when averaged over diffusion/energy loss timescales) – reasonable for energies ~ 1-100 GeV, not for >100 GeV.

$$\begin{aligned} K(E) &= K_0 k(E) \\ b(E) &\equiv -dE/dt \\ \psi &\equiv b(E)\mathcal{N} \\ d\tilde{t} &\equiv -\frac{k(E)}{b(E)} dE \end{aligned}$$

$$\frac{\partial \psi}{d\tilde{t}} - K_0 \Delta\psi = \tilde{Q}$$

Heat equation !!!!

Solution in an infinite 3D halo (2)

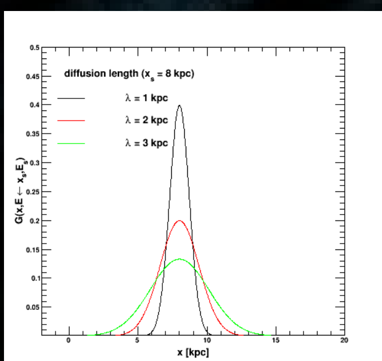
$$\frac{\partial \psi}{d\tilde{t}} - K_0 \Delta \psi = \tilde{Q}$$

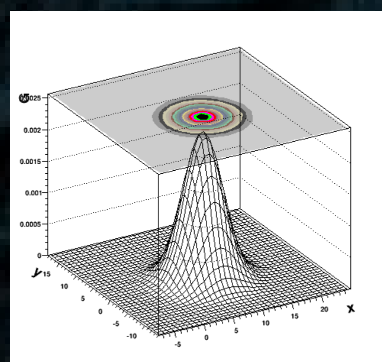
$$\tilde{\mathcal{G}}(\vec{x}, \tilde{t} \leftarrow \vec{x}_s, \tilde{t}_s) = \frac{1}{\pi^{\frac{3}{2}} \lambda^3} \exp\left\{ -\frac{|\vec{x}_s - \vec{x}|^2}{\lambda^2} \right\}$$

Green function characterized by a propagation scale

$$\lambda^2 \equiv 4 K_0 (\tilde{t} - \tilde{t}_s) = 4 \int_E^{E_s} dE' \frac{K(E')}{b(E')}$$

Propagation scale set by pseudo-time (energy)





The electron propagator is a Gaussian in space

$$\psi(\vec{x}, \tilde{t}) = \int_{-\infty}^{t_0} d\tilde{t}_s \int d^3\vec{x}_s \, \tilde{\mathcal{G}}(\vec{x}, \tilde{t} \leftarrow \vec{x}_s, \tilde{t}_s) \, \tilde{Q}(\vec{x}_s, \tilde{t}_s)$$

$$\Leftrightarrow \mathcal{N}(\vec{x}, E) = \int_E^{\infty} dE_s \int d^3\vec{x}_s \, \mathcal{G}(\vec{x}, E \leftarrow \vec{x}_s, E_s) \, Q(\vec{x}_s, E_s)$$

$$\mathcal{G}(\vec{x}, E \leftarrow \vec{x}_s, E_s) = \frac{1}{\pi^{\frac{3}{2}} \lambda^3 \, b(E)} \exp\left\{ -\frac{|\vec{x}_s - \vec{x}|^2}{\lambda^2} \right\}$$

$$\frac{d\phi}{dE}(\vec{x}, E) = \frac{\beta c}{4\pi} \mathcal{N}(\vec{x}, E)$$

The flux is the quantity to be compared with the data

Boundary conditions

The diffusion zone has a finite size flat cylinder of radius R~20 kpc and half-height L ~ 1-10 kpc.

Let us assume that **the observer is on Earth**, and that **R-r < L**

If **λ<< L**, the **3D** solution is valid.

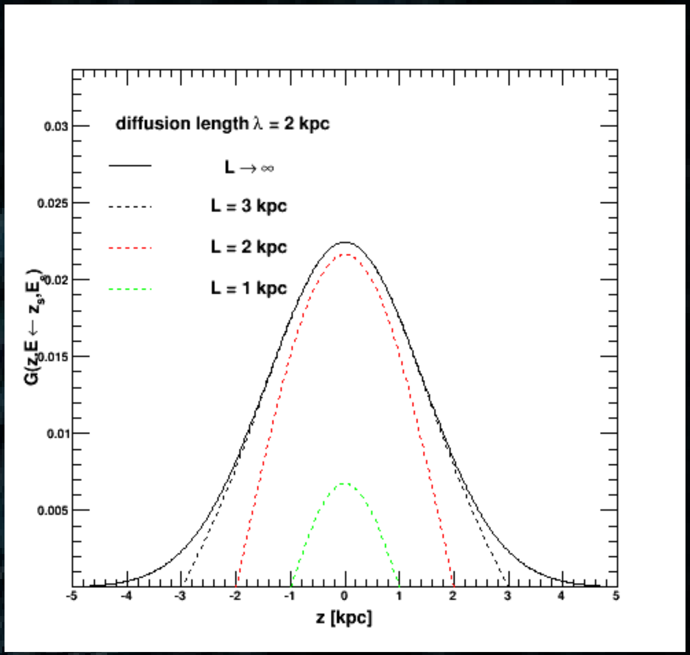
If **λ~L**, then one has to account for the **vertical boundary condition**: N(|z|=L) = 0.

Different methods exist: image method, expansion in terms of Helmholtz eigen-functions, etc.

Example of the image method

$$\tilde{V}\left(z, \tilde{t} \leftarrow z_S, \tilde{t}_S\right) = \sum_{n=-\infty}^{+\infty} (-1)^n \, \mathcal{V}_{1D}\left(z, \tilde{t} \leftarrow z_n, \tilde{t}_S\right)$$

$$z_n = 2\,L\,n \; + \; (-1)^n \, z_S$$



Energy losses

Electrons lose their energy through electromagnetic interactions
(I) with the interstellar medium (ISM)
(ii) with the interstellar radiation fields (ISRF) and the magnetic fields
(see Blumenthal & Gould, 1970)

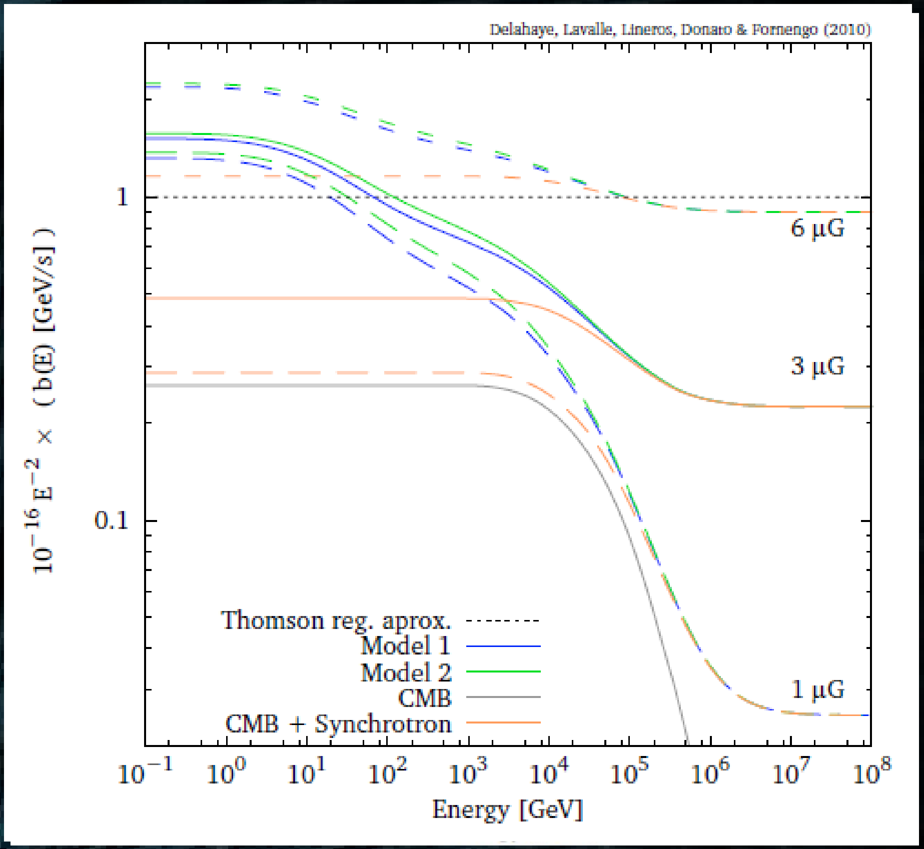
(i) Interactions with the ISM (in the disk): Bremsstrahlung (braking radiation), ionization

$$b_{\rm ion}(E) \propto n_{\rm gas} \ln(E)$$
$$b_{\rm brem}(E) \propto n_{\rm gas}\, E \ln(E)$$

(ii) Interactions with the ISRF (including CMB) and magnetic fields: (inverse) Compton processes

$$b_{\rm sync/ic} \propto U_{mag/rad} E^2$$

Caveats: .... CMB anywhere, but ISRF concentrated in the disk ... Thomson regime only valid for $\gamma_e E_{ph}$ < m ...



Translate losses into propagation scale

Transport mostly set by **spatial diffusion** and **energy losses**

$$K(E) = K_0 k(E) = K_0 \beta \left(\frac{\mathcal{R}}{1\,\mathrm{GV}}\right)^{\delta}$$

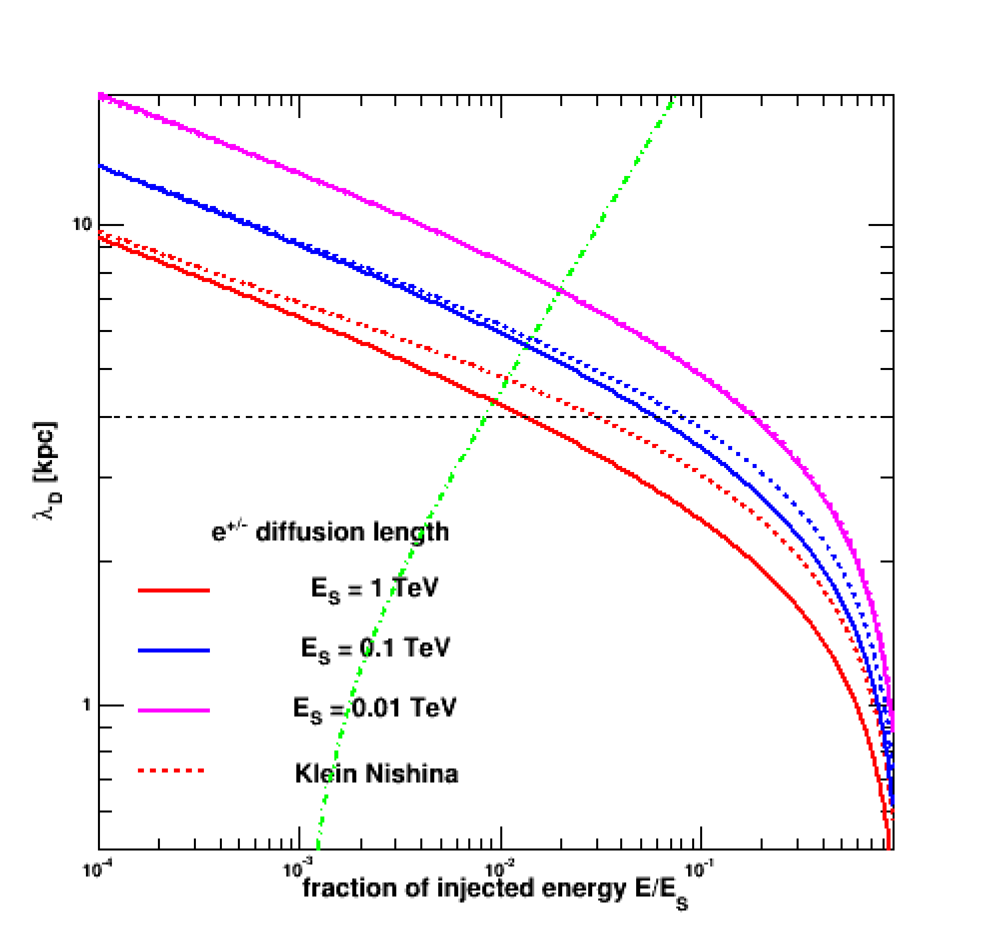
$$b(E) \equiv -dE/dt \approx \frac{E_0}{\tau_0}\left(\frac{E}{E_0}\right)^{\alpha}$$

Propagation scale: a very useful quantity

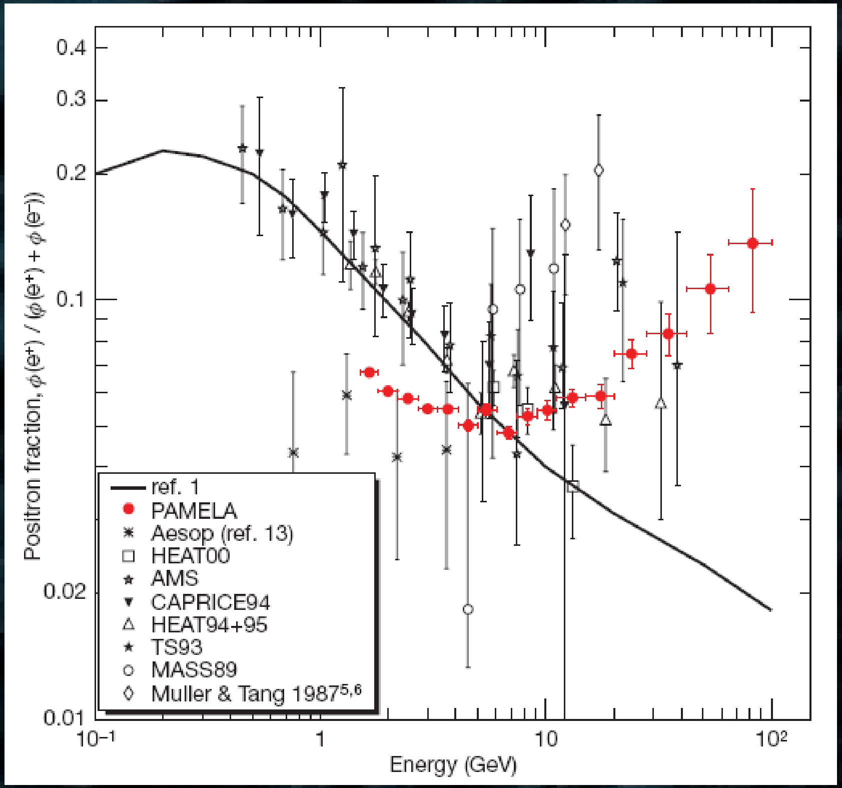
$$\lambda^2 \equiv 4\int_E^{E_s} dE' \, \frac{K(E')}{b(E')} = \frac{4\,K_0\,\tau_0}{1+\delta-\alpha}\left(\frac{\epsilon}{1\,\mathrm{GeV}}\right)^{1+\delta-\alpha}\Bigg|_E^{E_s}$$

Electron horizon limited to a few kpc

$$K_0 = 0.012\,\mathrm{kpc}^2/\mathrm{Myr};\ \tau = 10^{16}\mathrm{s};\ \delta = 0.7$$
$$\lambda(E = 1\,\mathrm{GeV} \leftarrow E_s \gg E) \approx 6\,\mathrm{kpc}$$



Can secondary e^+'s explain the PAMELA data ?



$e^+/(e^+ + e^-)$ PAMELA
Adriani et al (2009)

Is there a standard model for secondary e^+'s ?

Short recipe for secondaries

Proton and alpha fluxes

ISM gas distribution

The source term

Inclusive nuclear cross section
$p+p \rightarrow e^{+} + X$

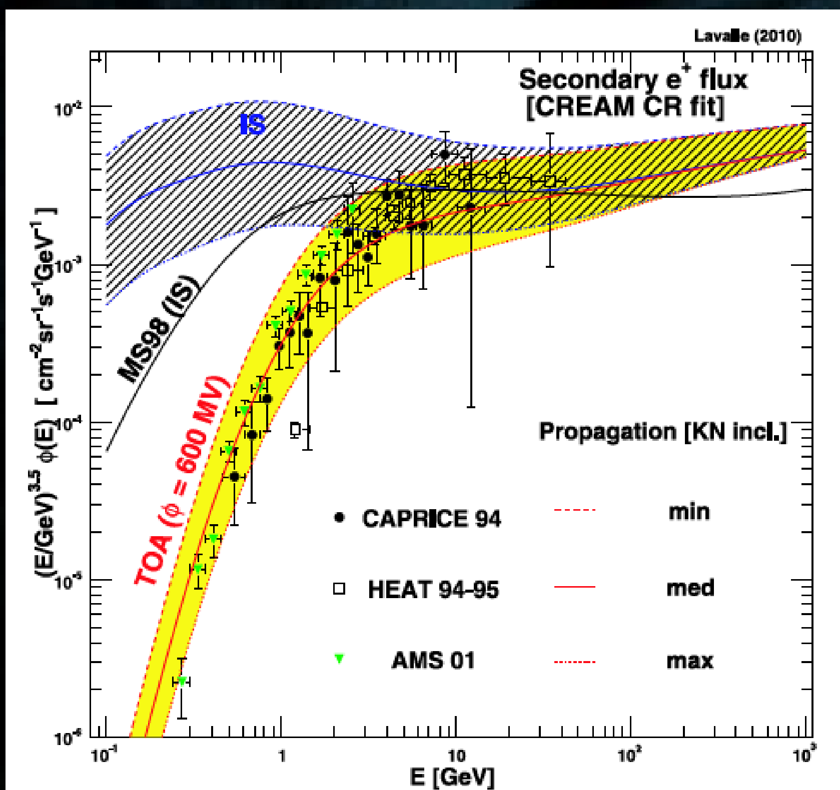
Propagation
from (x_s,E_s) to (x,E)

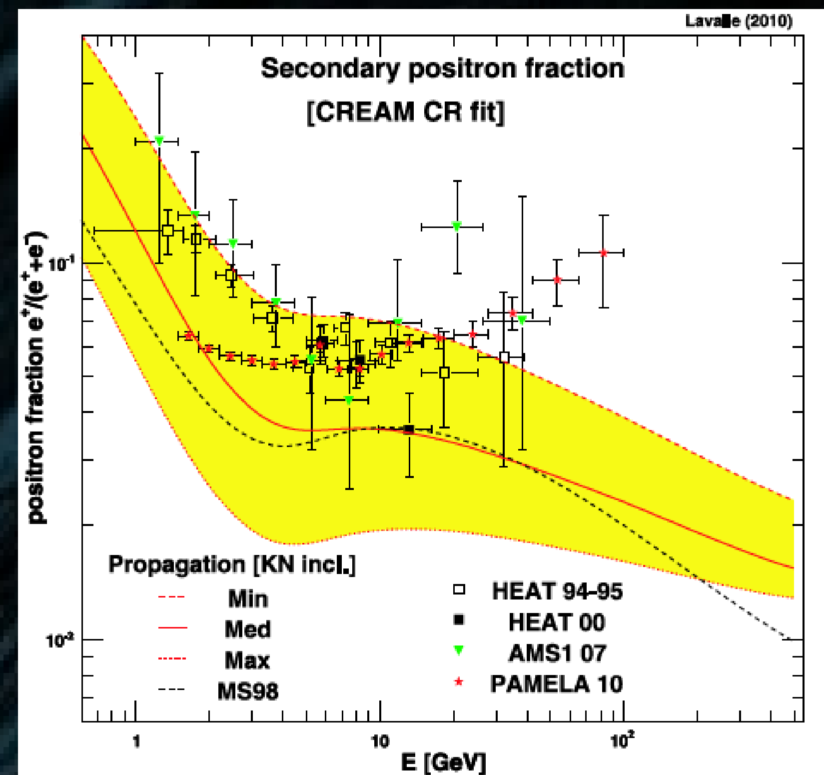
Flux at the Earth

Each box contains uncertainties !!!

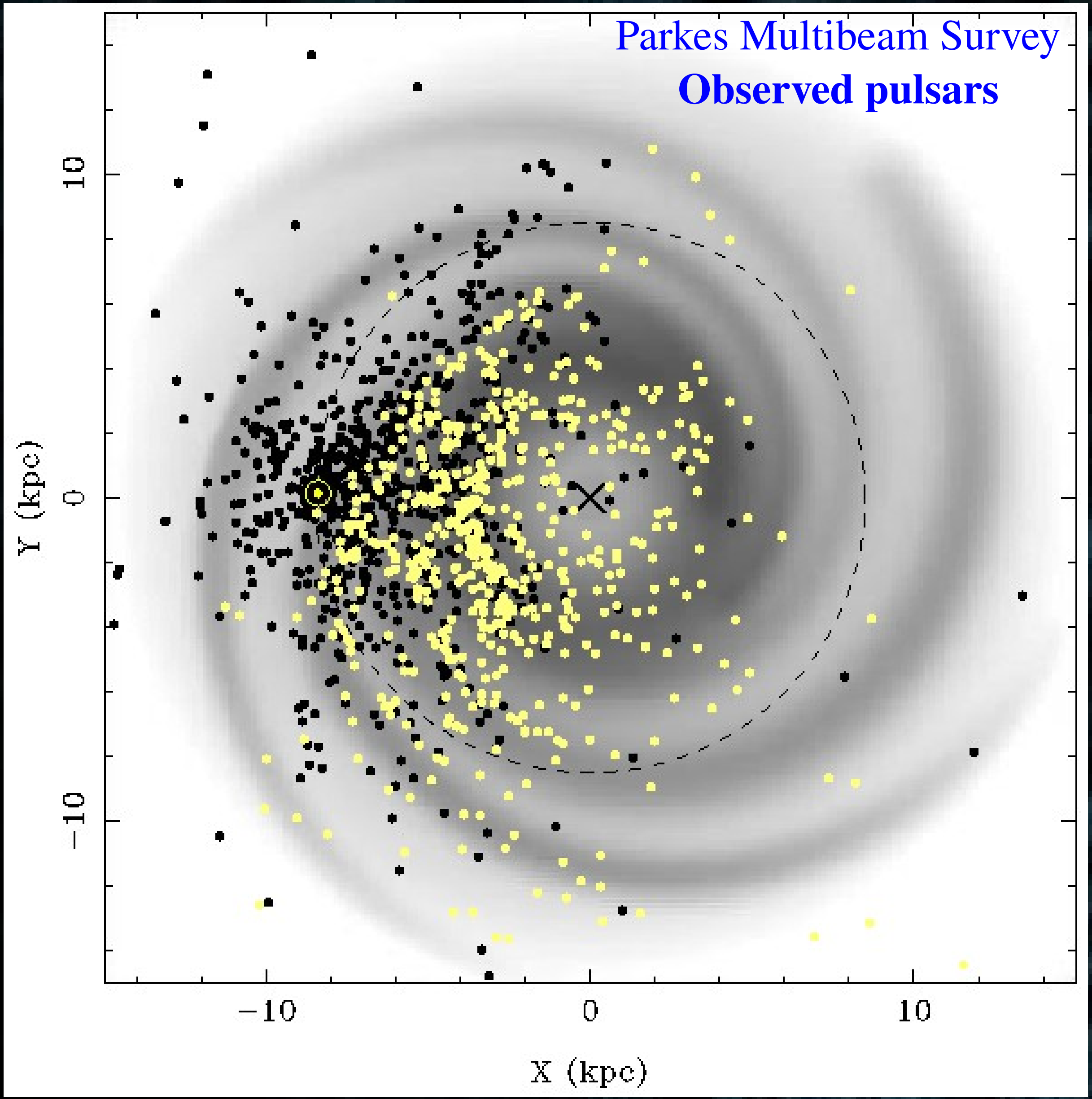
Short recipe for secondaries

Secondaries with theoretical uncertainties
Delahaye et al 09, Lavalle 11





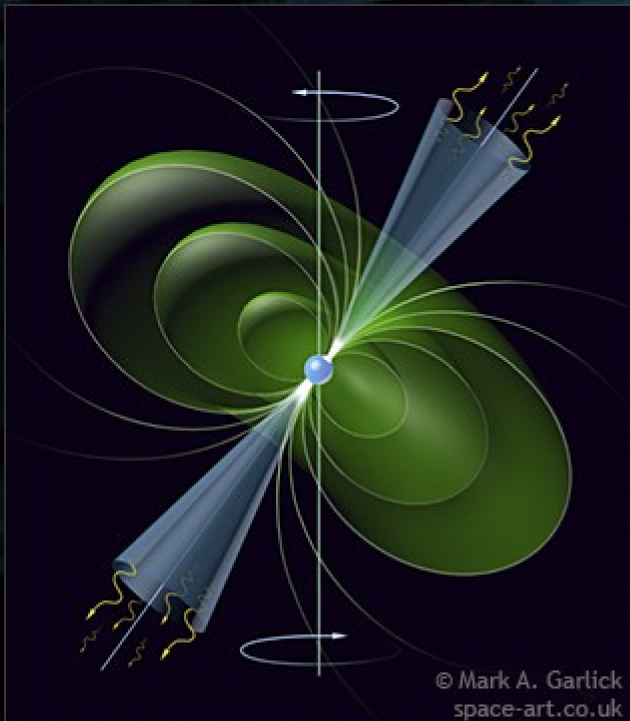
Galactic sources of cosmic rays: supernova outcomes

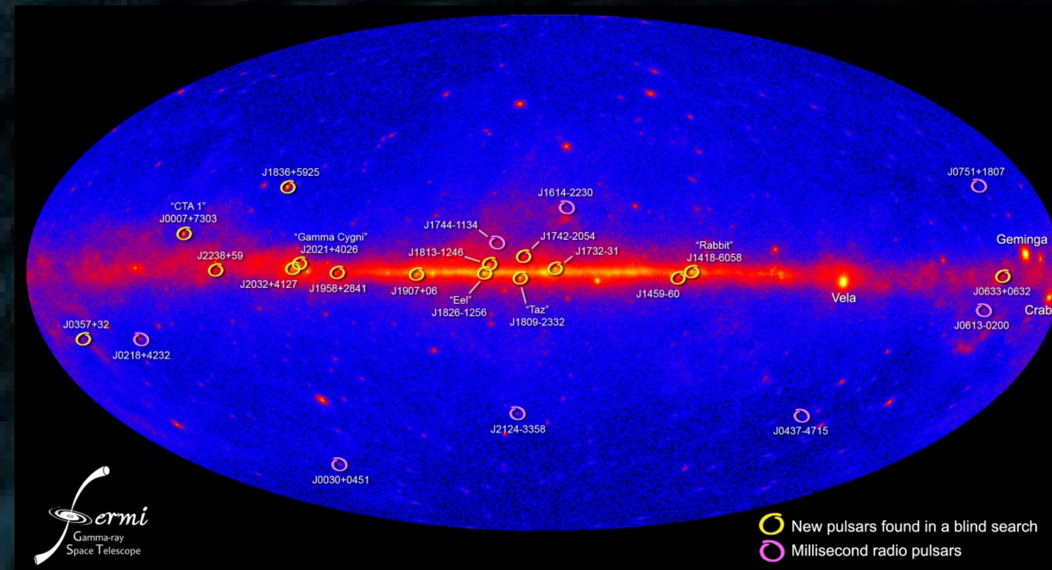


- CRs accelerated by SNR and pulsar shocks (observation + theory)
- SN explosion rate ~ 1/century
- ~1900 pulsars and ~280 SNRs observed (ATNF and Green catalogs)

Sources of positrons ?

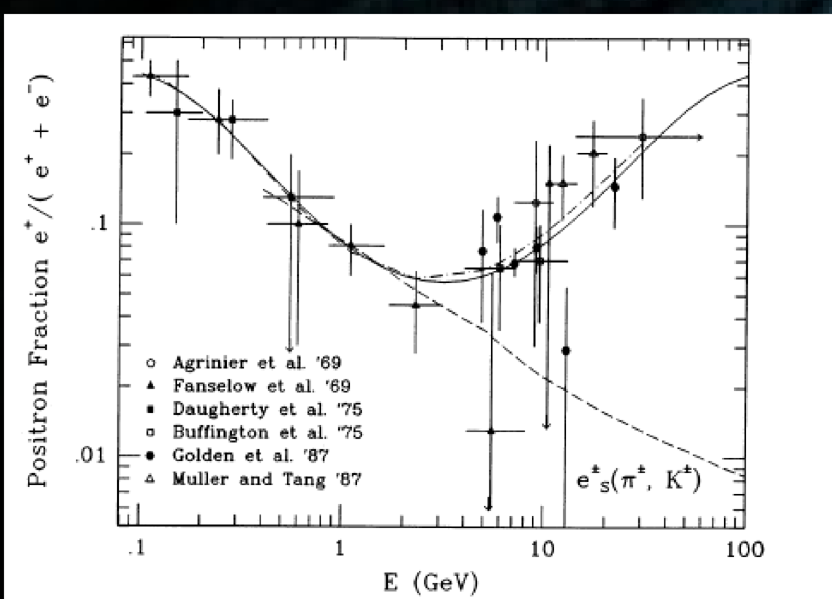
"Standard" positron sources ? ... Pulsars !





Science AAAS

A Population of Gamma-Ray Millisecond Pulsars Seen with the Fermi Large Area Telescope
A. A. Abdo, *et al.*
Science **325**, 848 (2009);
DOI: 10.1126/science.1176113



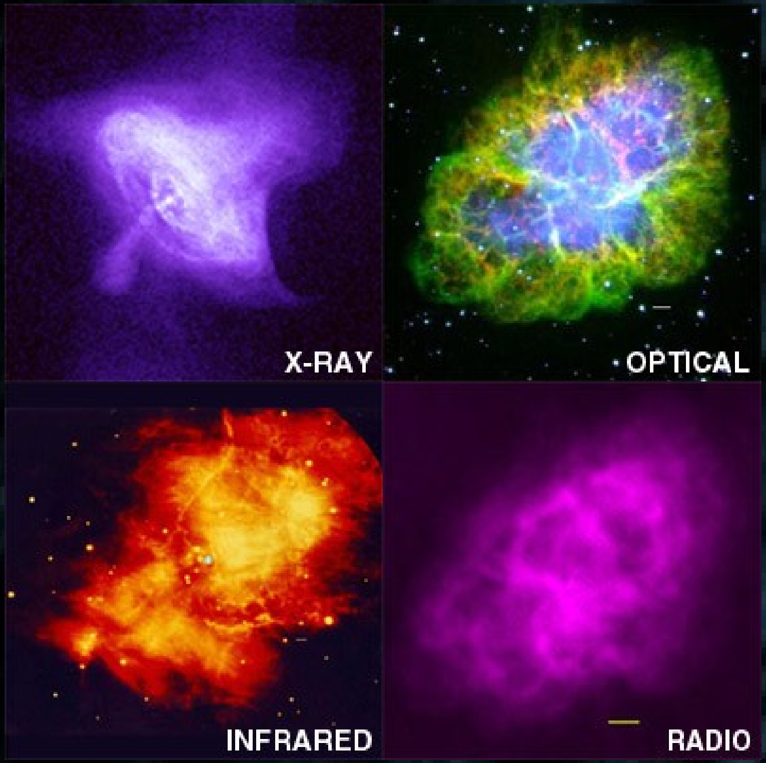
THE ASTROPHYSICAL JOURNAL, 342:807–813, 1989 July 15

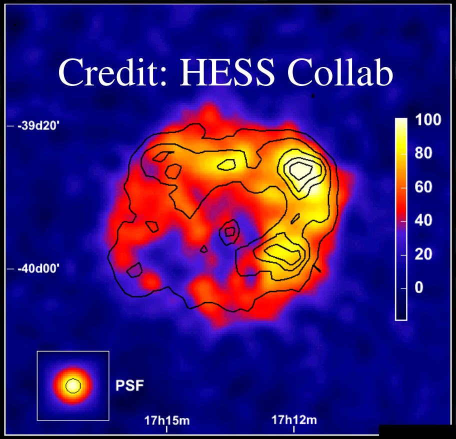
THE NATURE OF THE COSMIC-RAY ELECTRON SPECTRUM, AND SUPERNOVA REMNANT CONTRIBUTIONS

AHMED BOULARES
Physics Department, Space Physics Laboratory, University of Wisconsin–Madison
Received 1988 October 24; accepted 1988 December 29

radio, γ-rays) suggest this possibility. In fact, if the recent $e^+/(e^+ + e^-)$ measurements are reliable, this will definitely require a pulsar source, because no other nearby conventional astrophysical sources (within 100–500 pc) can generate both e^- and e^+ at high energies (of course, dark matter annihilation may be important if it exists).

Towards a consistent picture





Include all primaries:
- SNRs accelerate electrons mostly
- Pulsars accelerate electrons + positrons
- Each pulsar must be paired with a SNR
- Many pulsars are not observable

Low energy electrons (< 20 GeV):
- Contribution of distant sources (collective effects) : average properties

High energy electrons (> 20 GeV)
- Consider local sources: large fluctuations expected
- Use multi-wavelength observational constraints

(see Shen 70, Kobayashi et al 04)

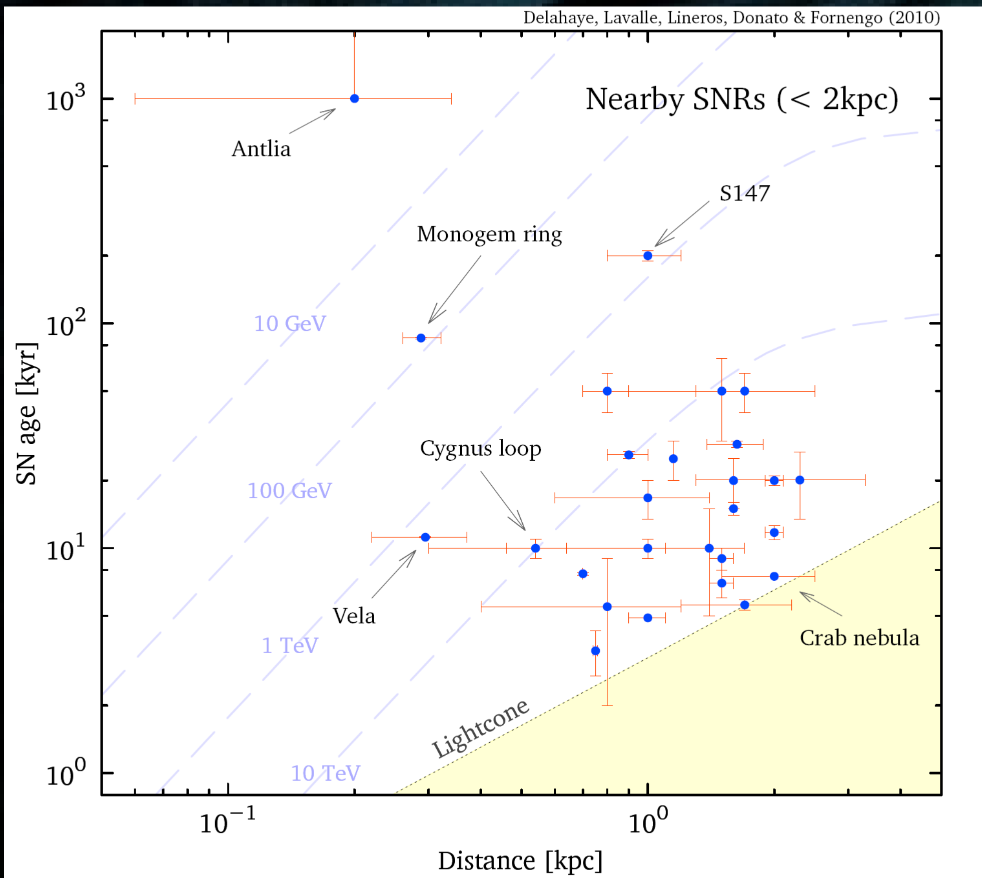
Issues
- Modeling of local sources (many degeneracies)
- More general: release of CRs in the ISM

Standard paradigm, but not standard model!

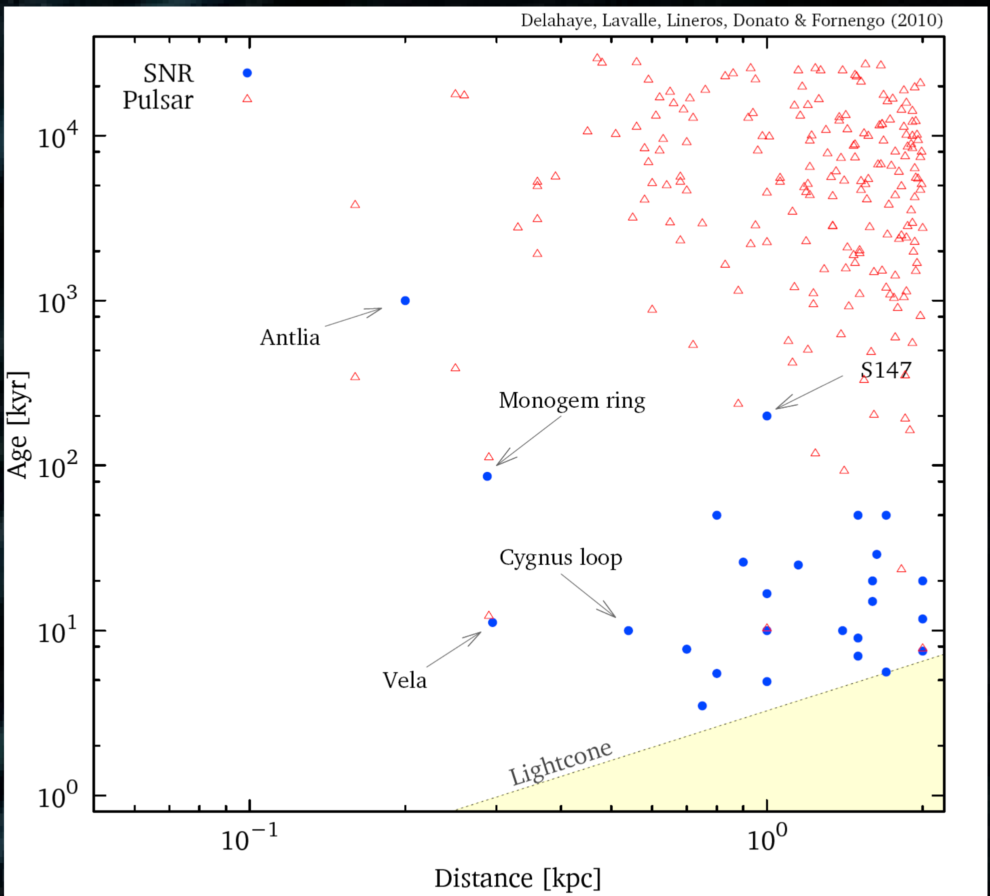
Deal with the complexity of Nature: Include all known local sources self-consistently

Delahaye et al 10
arXiv:1002.1910

27 obs SNRs within 2 kpc



~200 obs pulsars within 2 kpc



SNRs contribute to e^-, pulsars inject e^+e^- pairs ...

... but each pulsar should be associated with a SNR => Add missing SNRs !

Deal with the complexity of Nature: Include all known local sources self-consistently

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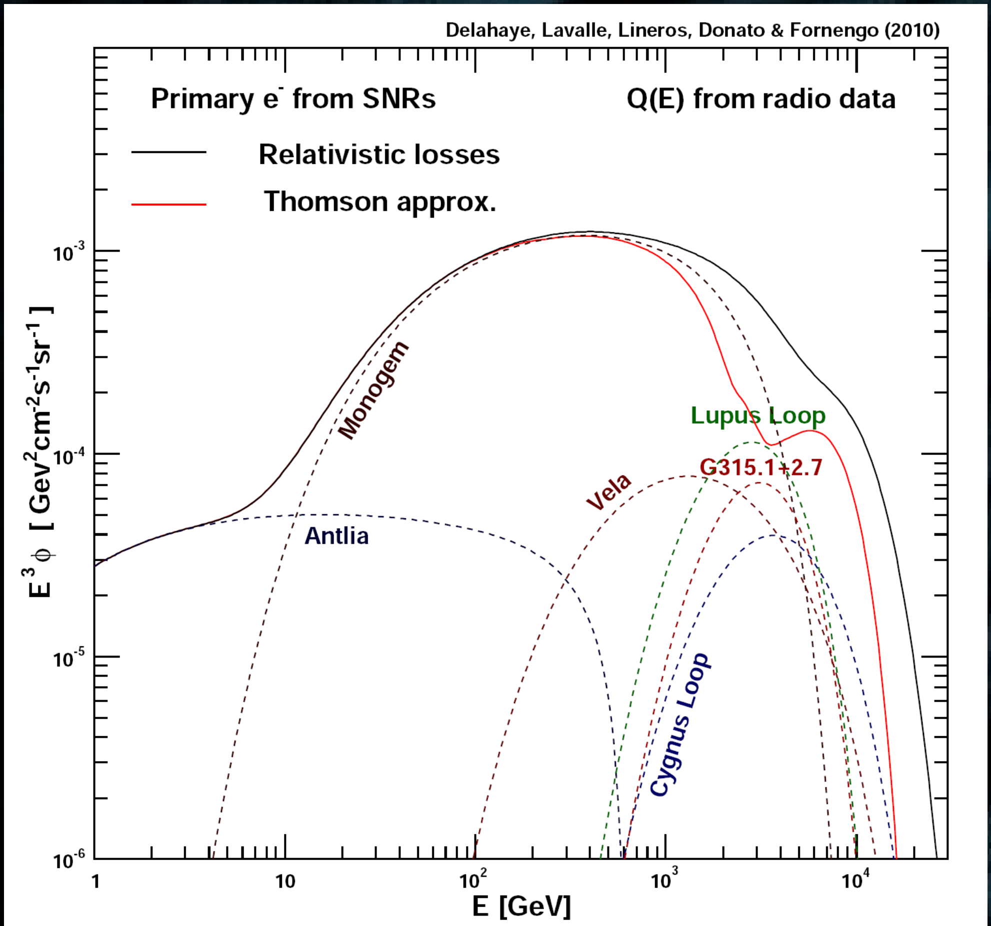

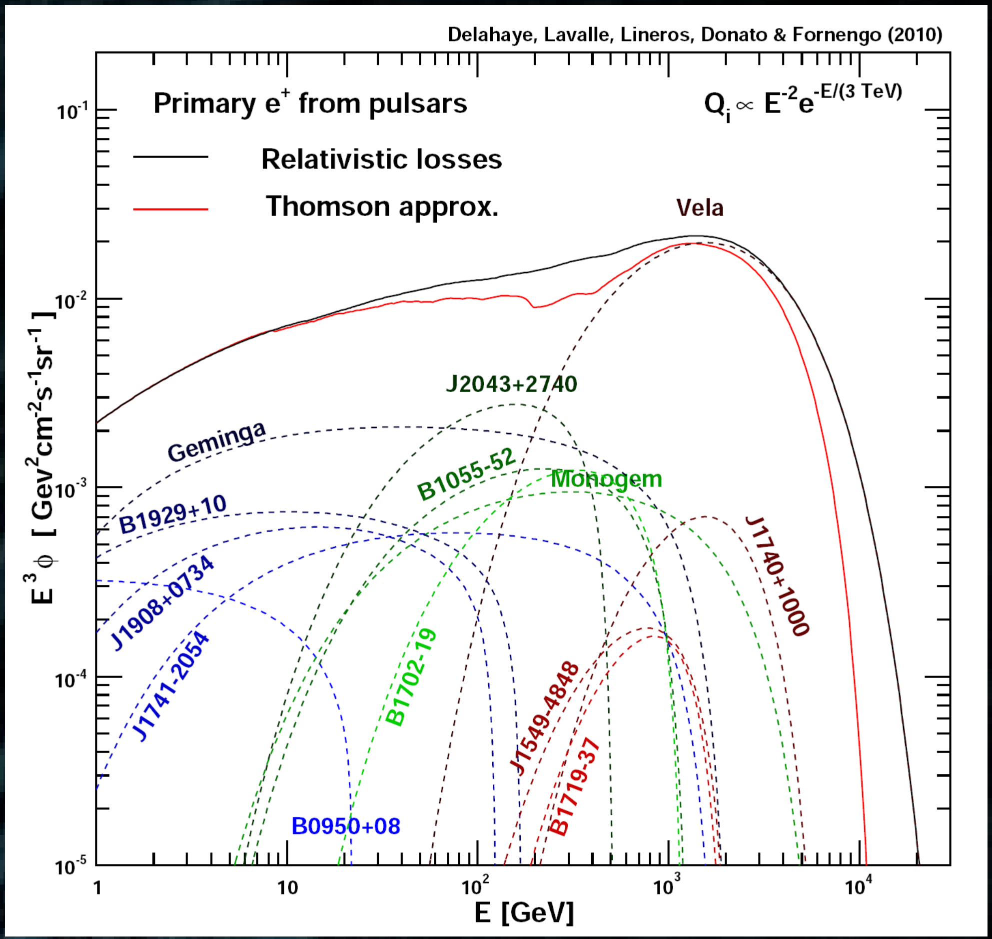

SNRs contribute to e^-, pulsars inject e^+e^- pairs ...

... but each pulsar should be associated with a SNR => Add missing SNRs !

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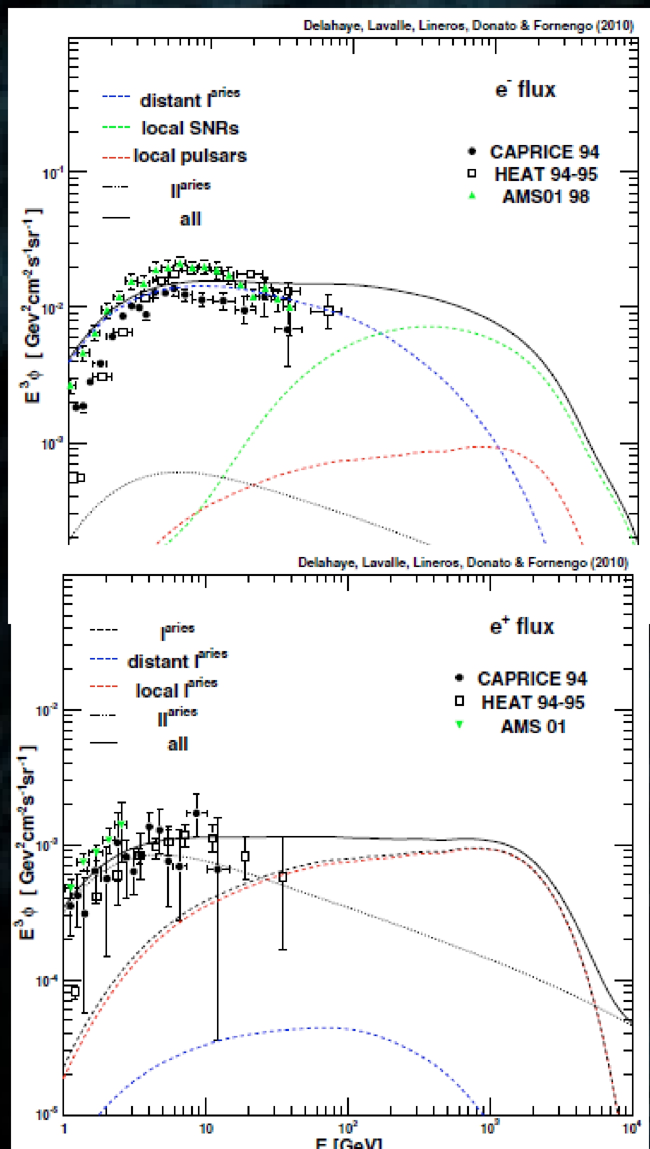
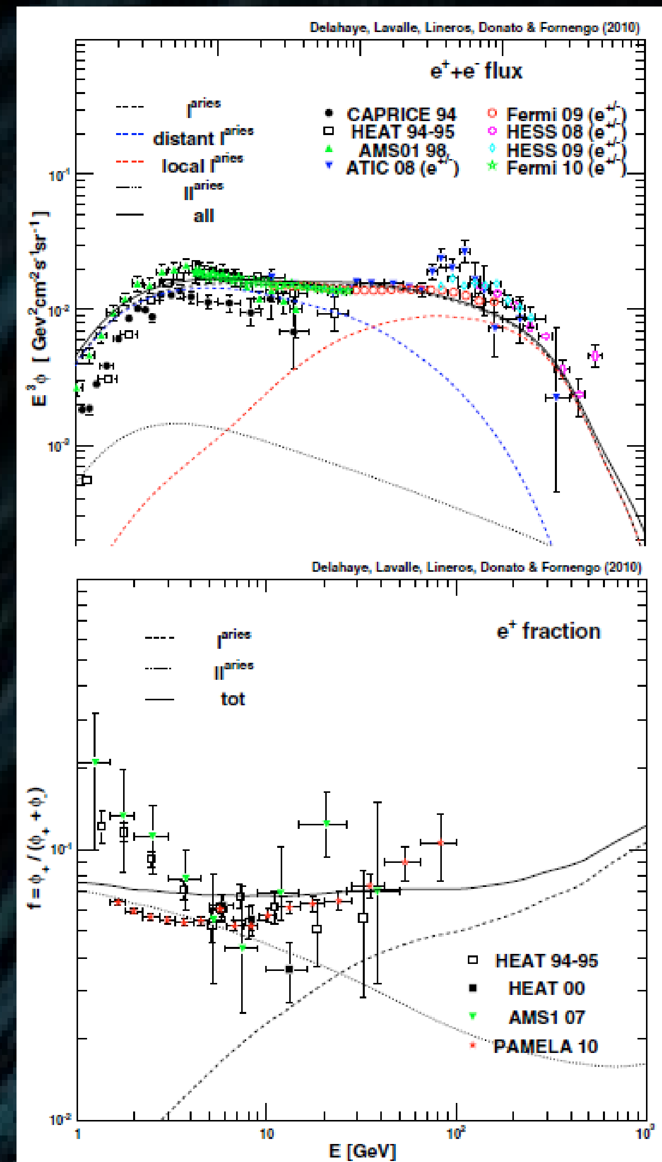
No choice, Nature is observed to be complex: Include all known local sources self-consistently

electrons



positrons

Delahaye et al 2010



electrons + positrons

positron fraction

Standard astrophysical sources make it!

Cosmic-ray electrons and positrons: summary

- **Electron transport very sensitive to ISRF and magnetic field.**

- **High-energy predictions require the accurate modeling of local sources, both SNRs and pulsars: some hope to test diffusion locally?**

- **Large uncertainties for local predictions, but standard astrophysics makes it (no exotic physics needed).**

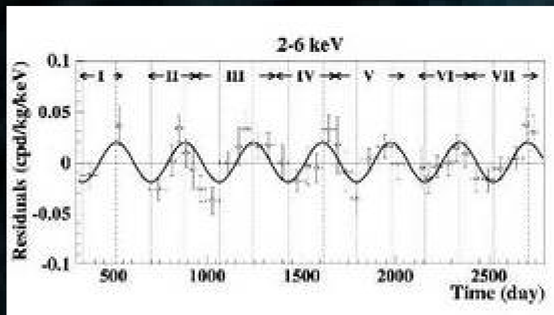
- **Much larger uncertainties expected for eg the Galactic center.**

- **No standard model so far (Galprop is not a “standard model”).**

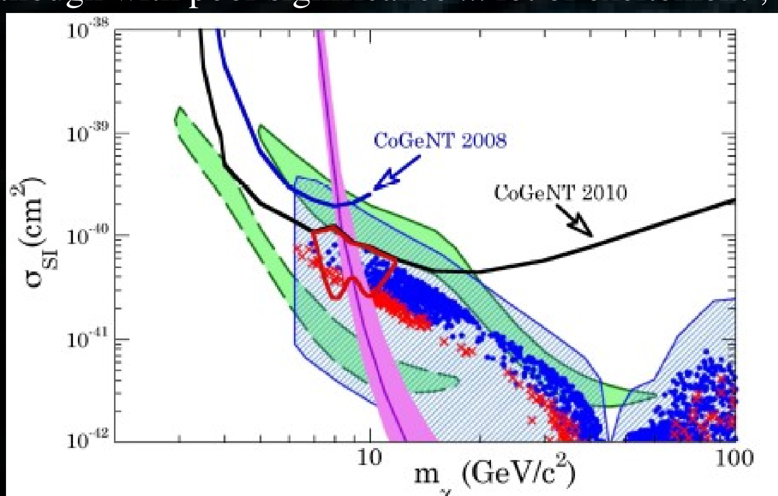
- **Multiwavelength analyses useful, though complex (magnetic field, ISRF, source distribution): from Planck to Fermi.**

Dark Matter searches in the sky

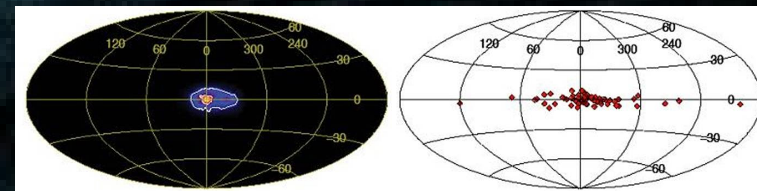
Hints ?



Direct detection:
DAMA oscillation (Bernabei et al), large significance.
Oscillation not yet detected by others.
Few events in other experiments (CDMS and Cogent),
though with poor significance ... lot of excitement ;-)



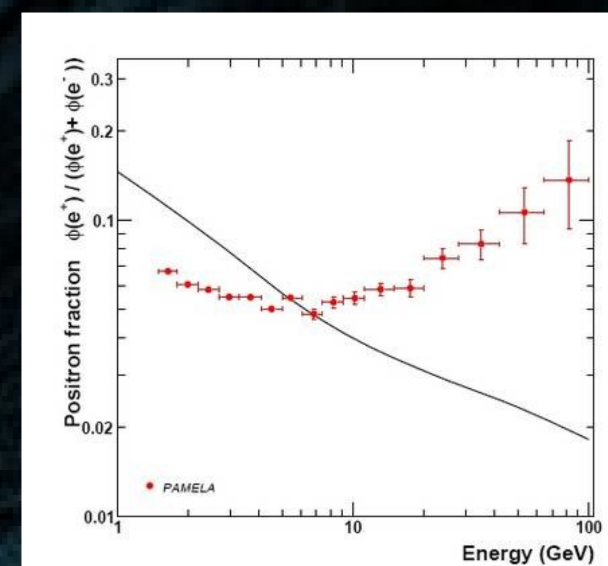
Aaltest et al 10 (Cogent)
see also Ahmed et al 09 (CDMS)
Theoretical prediction: eg Bottino et al 10, Ling et al 10
Interpretation issues: Kopp et al 10
[~10 GeV mass]



511 keV emission from the GC
Knodlseder et al 05, Weidenspointner et al 08

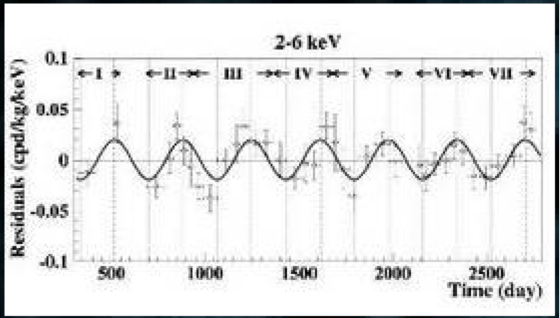
Spatial association with X-binaries, but
positron production rate and transport issues.

MeV dark matter ? Boehm et al 04
[~1 MeV mass]



Local positron excess measured by PAMELA
(Adriani et al 08)
Astrophysical sources or dark matter ???
[> 100 GeV mass]

Hints ?



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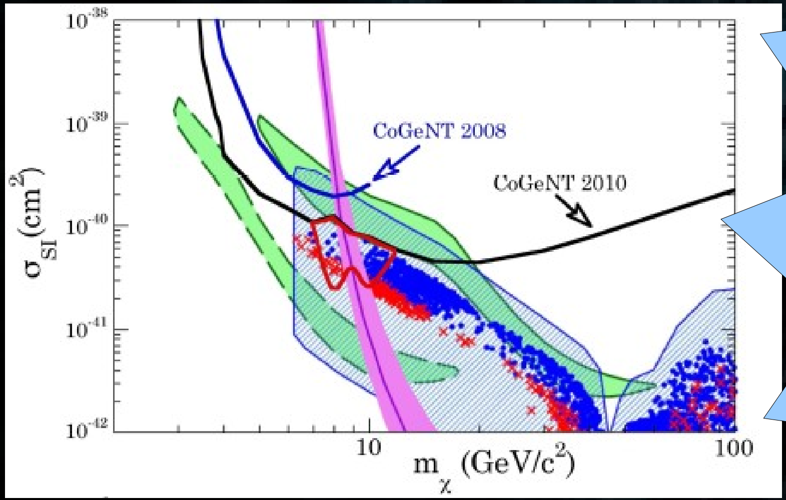

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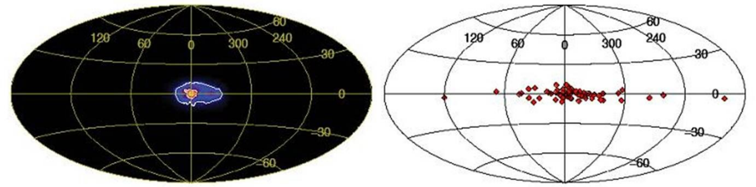

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Knodlseder et al 05, Weidenspointner et al 08

Spatial association with X-binaries, but
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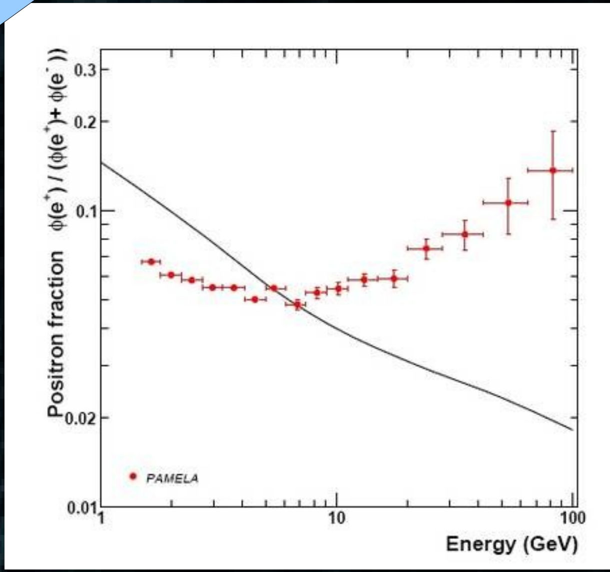
eV dark matter ? Boehm et al 04
[~1 MeV mass]

If interpreted as hints, none points towards the same dark matter particle



Local positron excess measured by PAMELA
(Adriani et al 08)
Astrophysical sources or dark matter ???
[> 100 GeV mass]

Antimatter signals

VOLUME 53, NUMBER 6 PHYSICAL REVIEW LETTERS 6 AUGUST 1984

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

Joseph Silk
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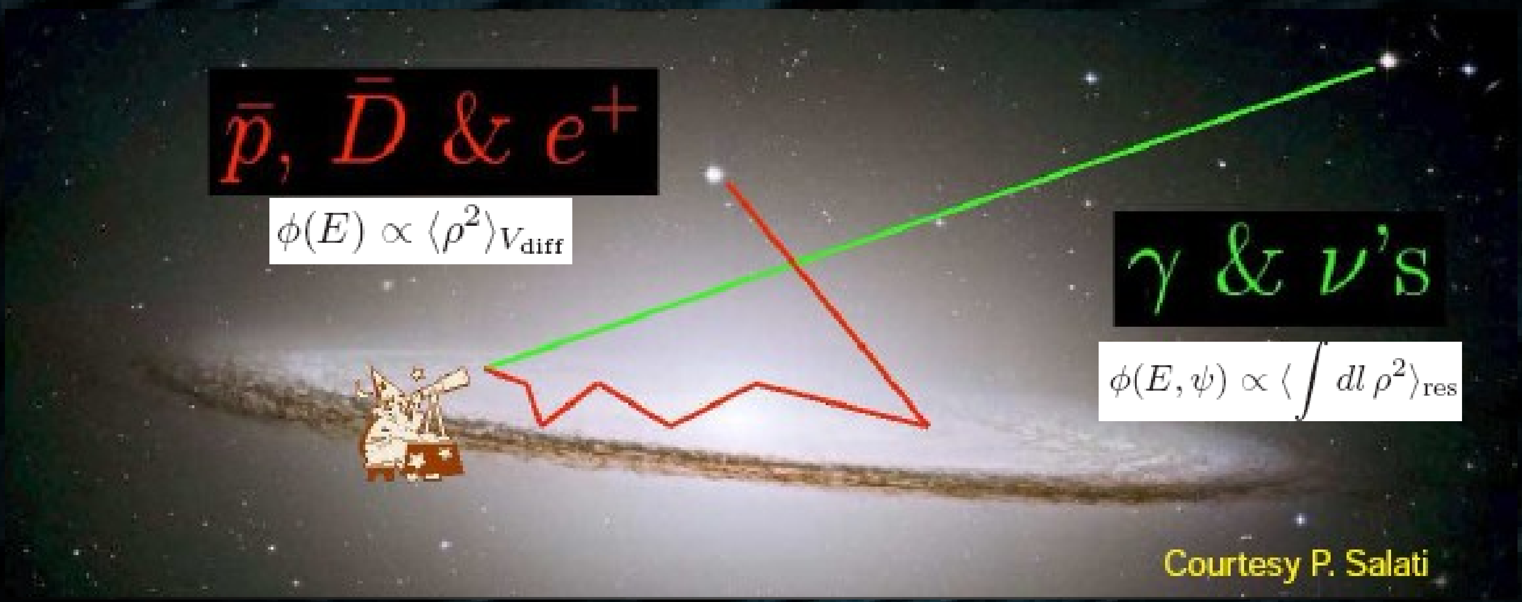
and

Mark Srednicki
Physics Department, University of California, Santa Barbara, California 93106

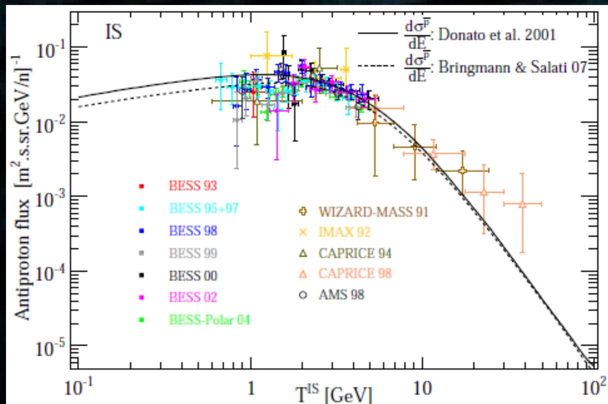
(Received 8 June 1984)



Main arguments:
- DM annihilation provides as many particles as antiparticles
- Antimatter cosmic rays are rare because secondary products
- DM-induced antimatter CRs may have specific spectral properties

But:
- We must control the backgrounds
- Antiprotons are secondaries, what about positrons ?
- Do the natural DM particle models provide clean signatures?

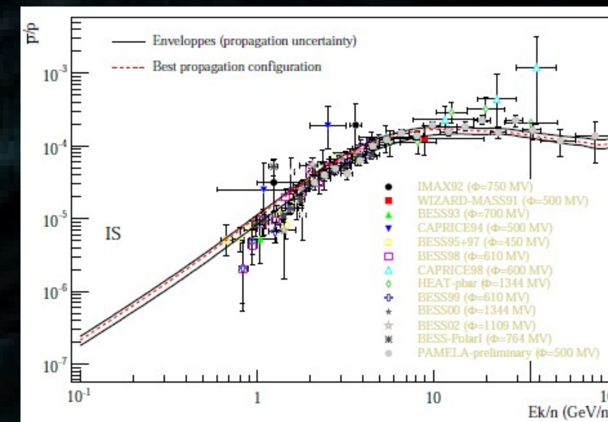
Secondary backgrounds: CRs interaction with ISM
→ Don't forget theoretical uncertainties!



<u>Antiprotons</u>

Donato et al 01, 09

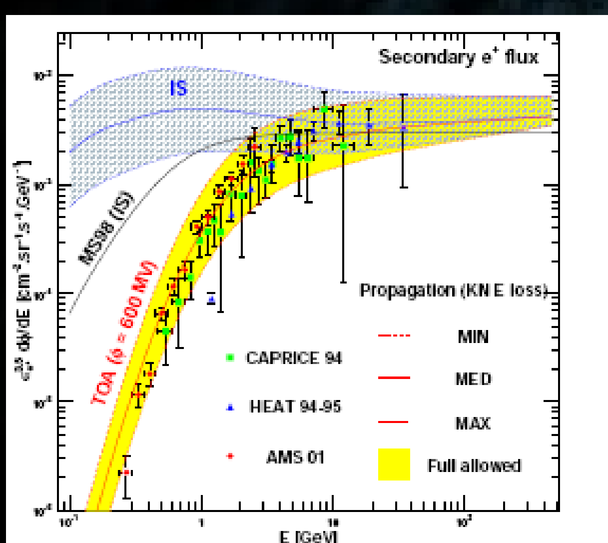
Bringmann & Salati 07



Flux at the Earth

Secondary bg: antiprotons fit, positrons do not

Fraction at the Earth

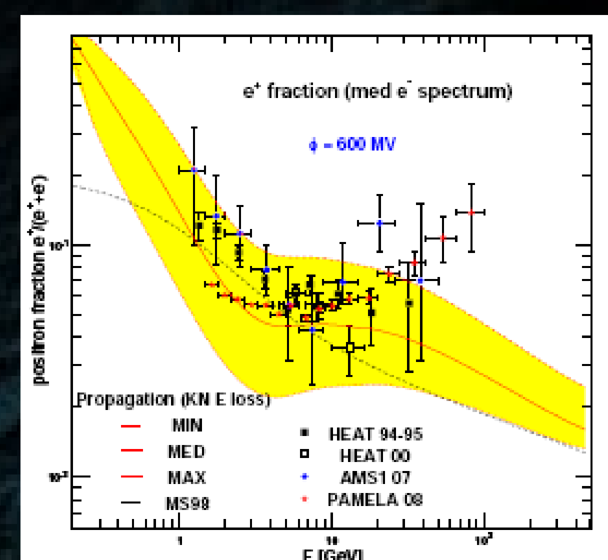


<u>Positrons</u>

Moskalenko & Strong 98

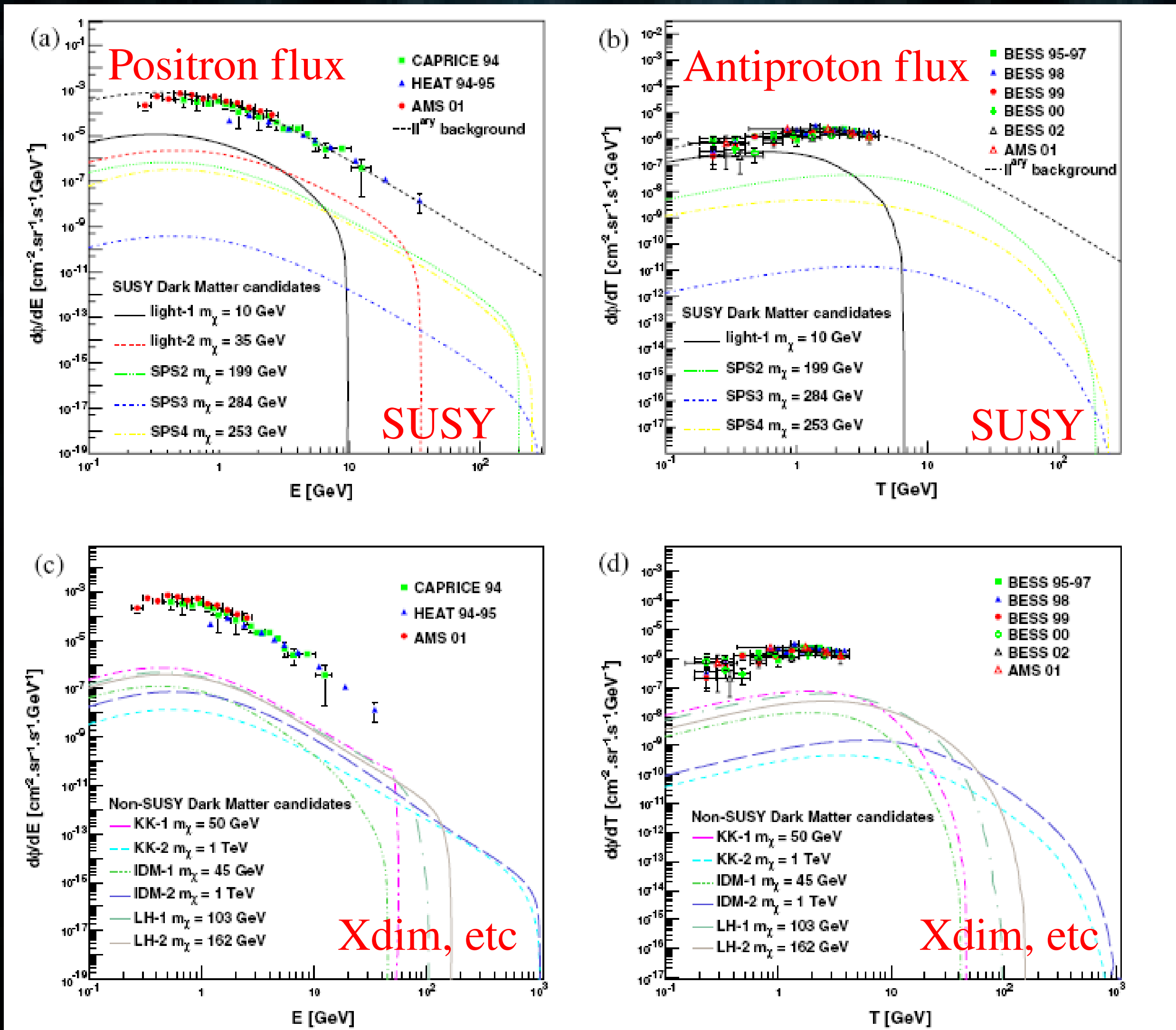
Delahaye et al 09

Lavalle 10



Dark Matter annihilation: generic predictions for positrons

Lavalle, Nezri, Ling et al (2008) – using a Horizon MW-like Galaxy



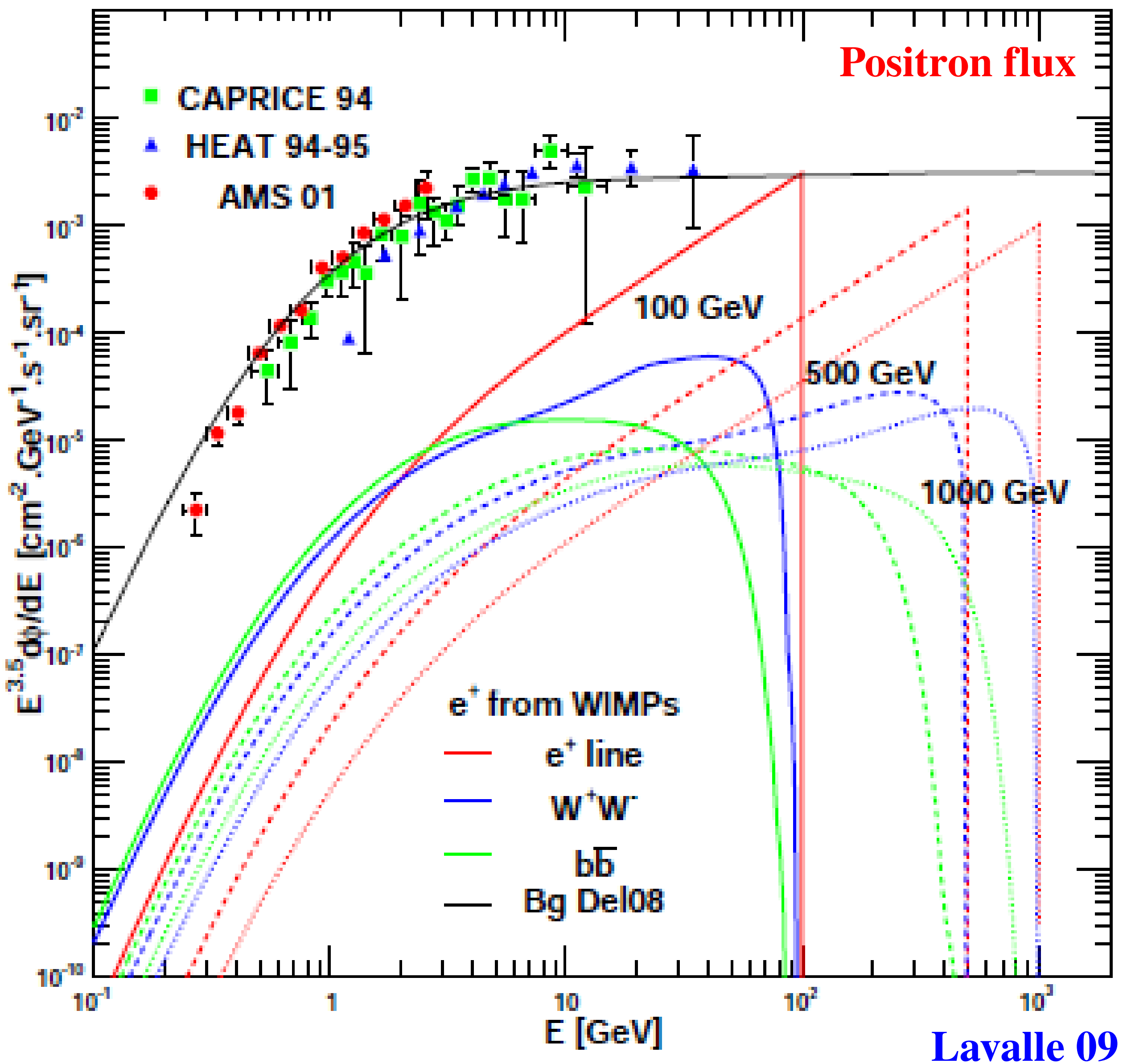
Susy candidates: positron (left) – antiproton (right)

(see e^+ study in eg Baltz & Edsjo 98)
(pbars in eg Chardonnet et al 96, Bottino et al 98)

Non-Susy candidates (KK, etc): positron (left) – antiproton (right)

Most motivated thermal models (SUSY, X-dim, LH, IDM) are **usually not predicted observable** in the antimatter spectrum.

Dark Matter annihilation: generic predictions for positrons



Lavalle 09

Boost to get $\sim 5 \times \phi_{bg}$ at ~100 GeV:

WIMP mass final state	100 GeV	500 GeV	1 TeV
e^+e^-	10	100	350
W^+W^-	80	500	1000
$b\bar{b}$	250	500	1000

The signal must be boosted:

(i) boost the cross section

→ contrived scenarios (¾ of published papers) ~ excluded by antiprotons

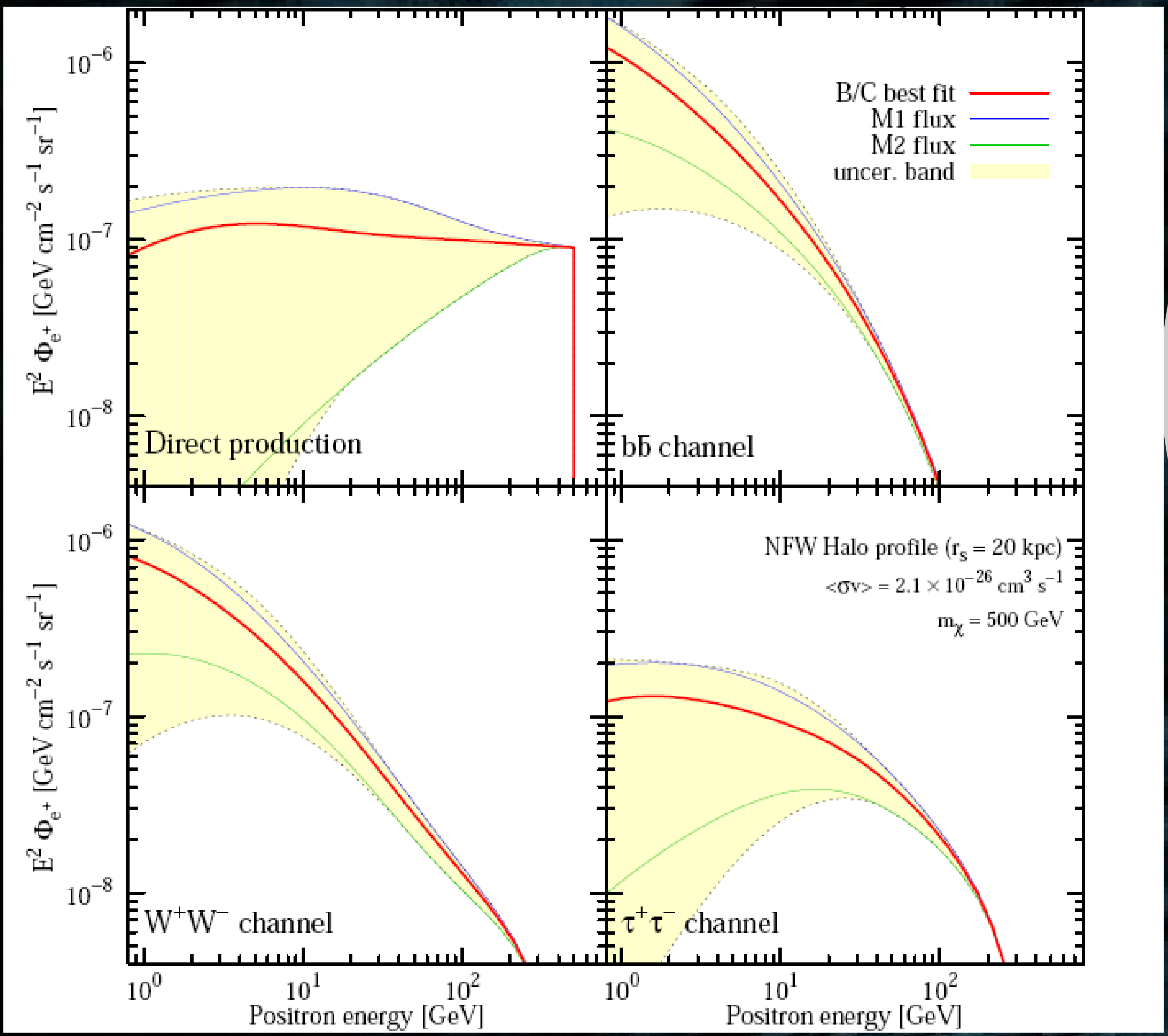
(see e.g. Cirelli et al 08, Donato et al 09)

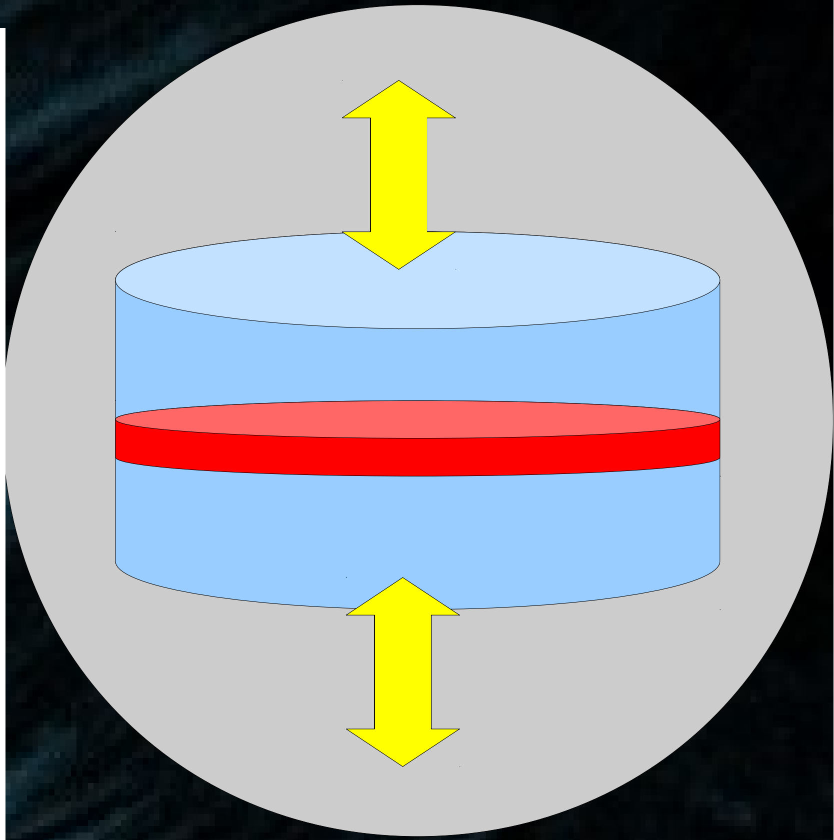
(ii) play with the propagation parameters

(iii) consider extra-sources (subhalos, IMBHs)

Boost: Play with propagation

Delahaye et al (2008)

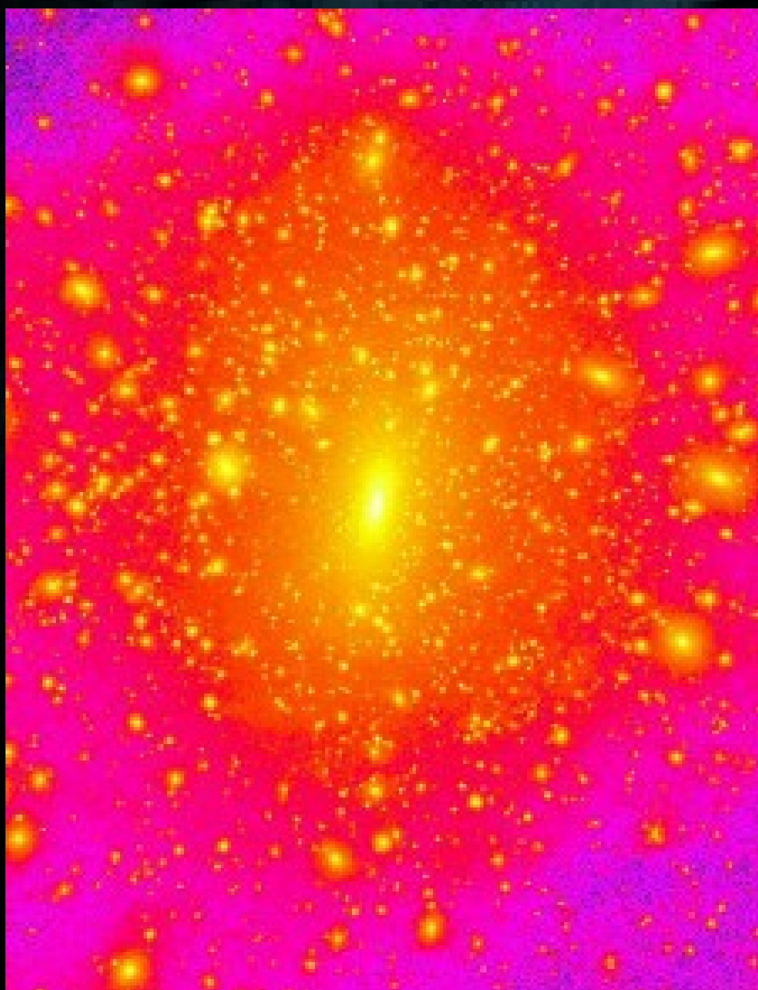




Increasing L implies more DM in the diffusion zone.

Very large effect on antiproton, but not on positrons since energy losses dominate at high energy (short range).

Collective effect: clumpiness boost factor



Diemand et al 04

- Clumps are predicted by the current theory of structure formation (Peebles and others)
- They are observed in N-body simulations at all resolved scales, as predicted.
- The minimal mass scale is set by the WIMP properties (free streaming) ~ Earth mass.
- Smallest objects collapse first: they are more DM concentrated !

$$< n_{\rm dm}^2 > \geq < n_{\rm dm} >^2 \quad \Rightarrow \quad B_{\rm ann} \sim \frac{< n_{\rm dm}^2 >}{< n_{\rm dm} >^2}$$

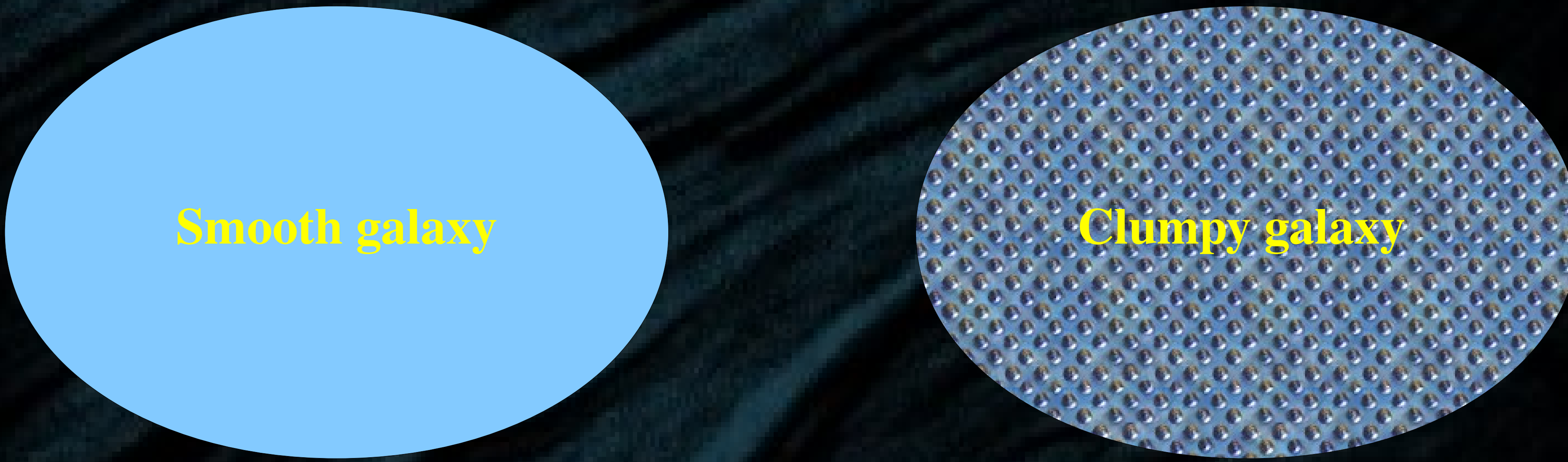
Clumps are numerous: statistical properties

The flux from an object is a stochastic variable

$$\phi_i(E,\vec{x}_\odot) = S \times \xi_i \times \tilde{\mathcal{G}}_i(E,\vec{x}_\odot \leftarrow \vec{x}_i, E_S)$$

$$\frac{dn_{\rm cl}}{d\mathcal{L}}(\mathcal{L},\vec{x}) = \frac{dN_{\rm cl}}{dV\, d\mathcal{L}}(\mathcal{L},\vec{x}) = N_0 \times \frac{d\mathcal{P}}{dV}(\vec{x}) \times \frac{d\mathcal{P}}{d\mathcal{L}}(\mathcal{L},\vec{x})$$

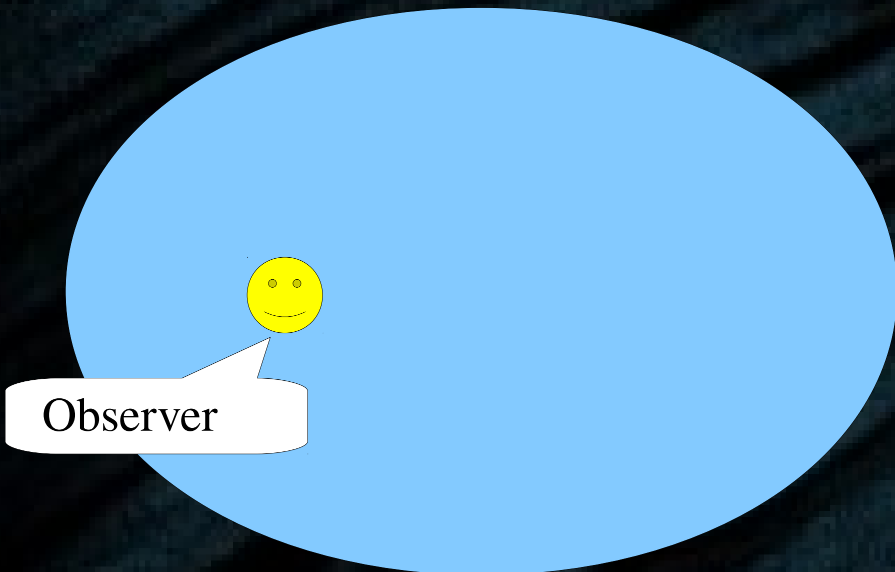
Boost factor ? … well, in fact, boost factors

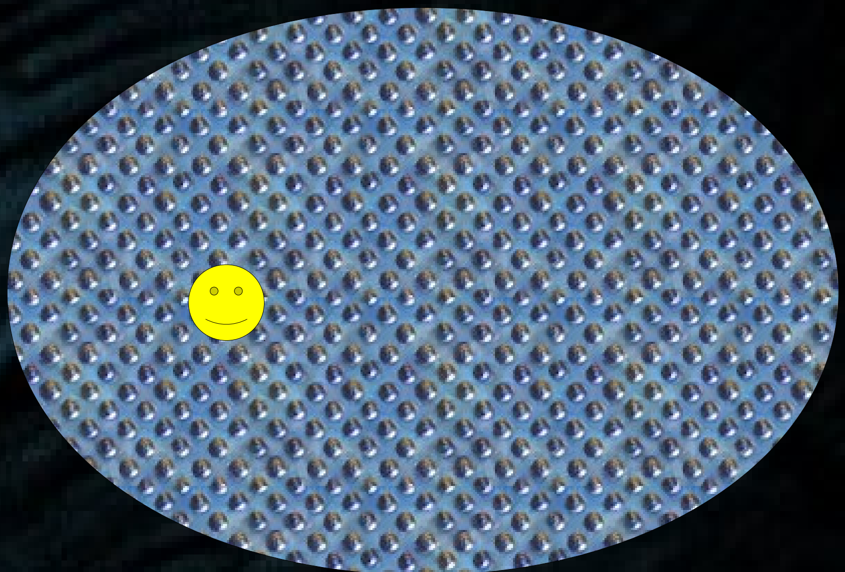


$$\mathcal{B} = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} \geq 1$$

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

Boost factor ? … well, in fact, boost factors





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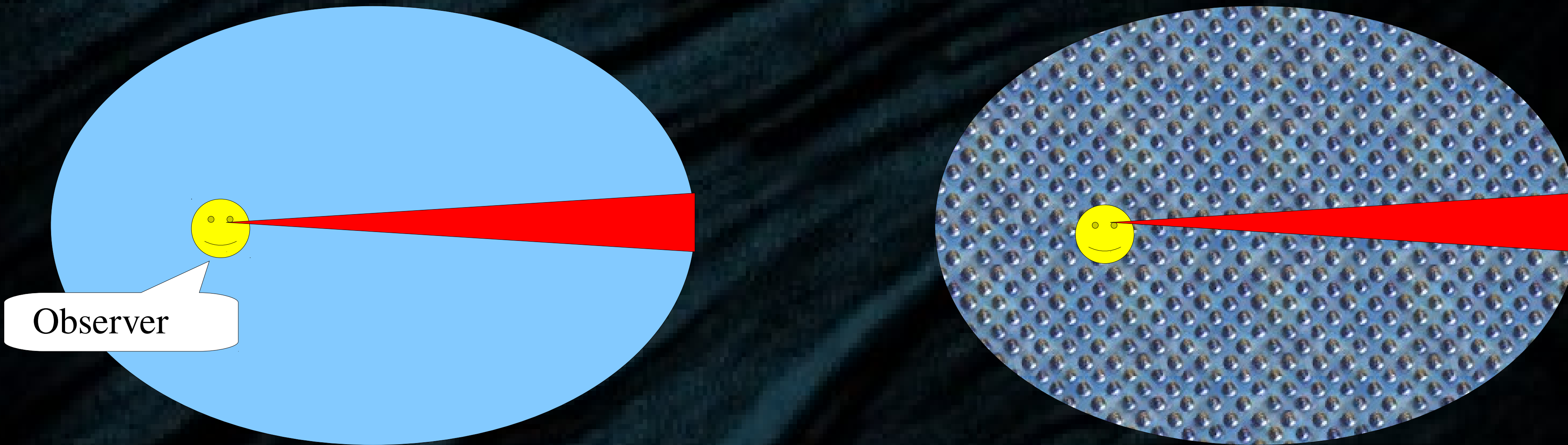
1) **Prompt gamma-rays:** point a telescope to a certain direction, and average over a volume set by the angular resolution

Boost factor ? … well, in fact, boost factors



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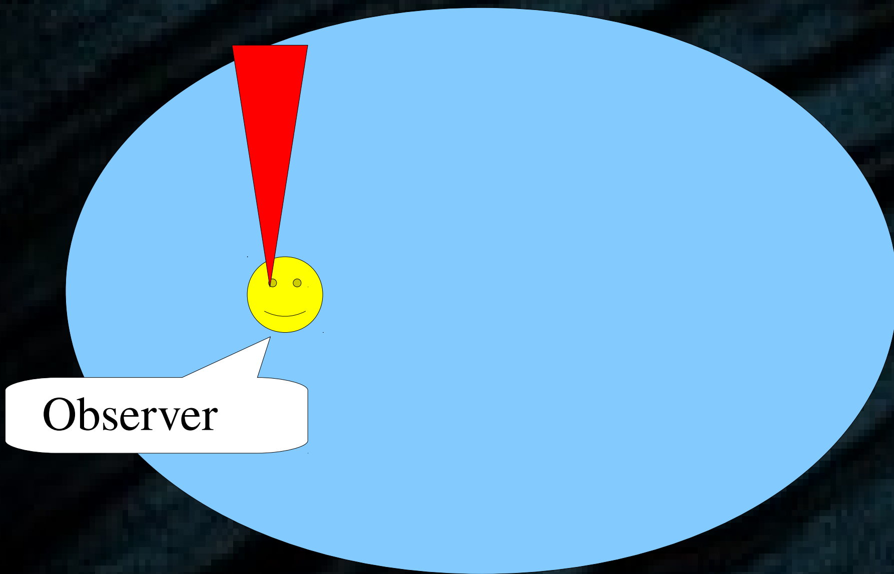
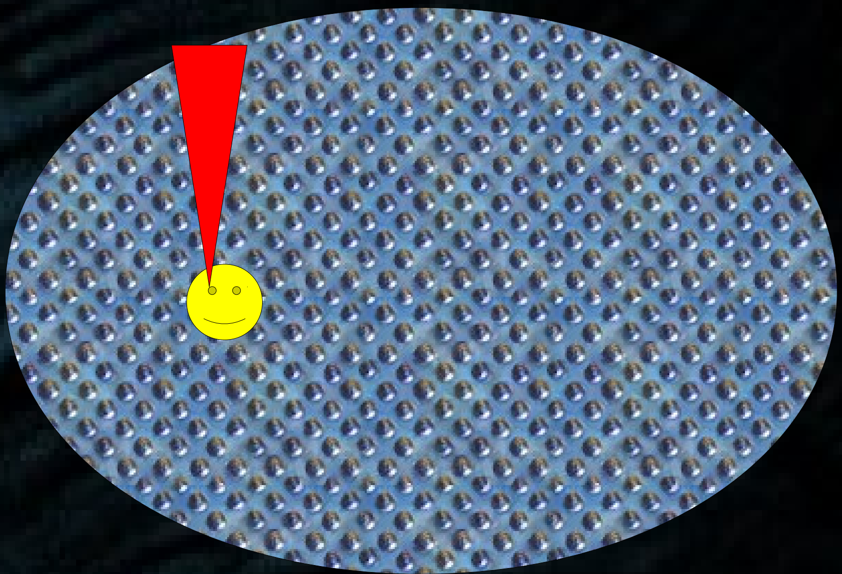
The volume over which the average is performed depends on the cosmic messenger!

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**

Boost factor ? … well, in fact, boost factors





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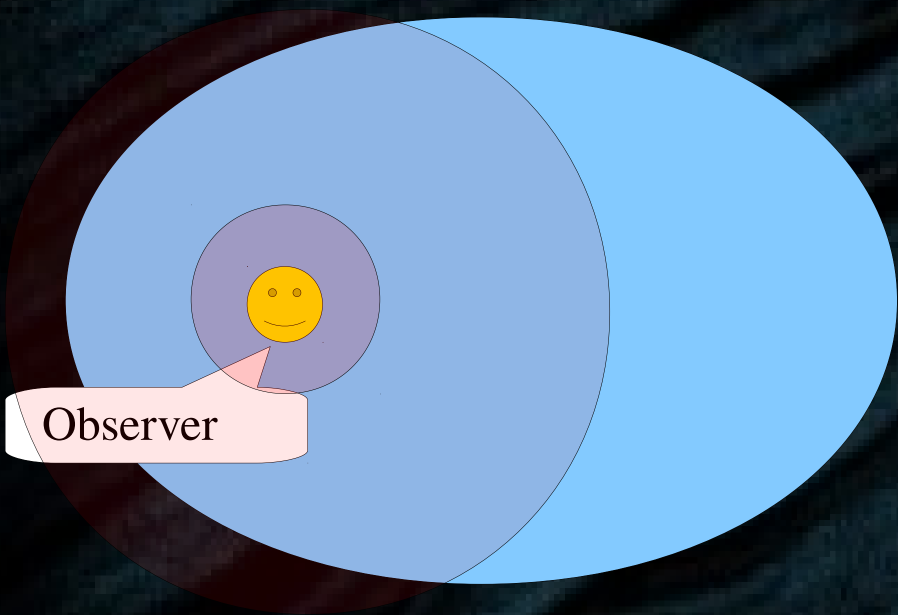
The volume over which the average is performed depends on the cosmic messenger!

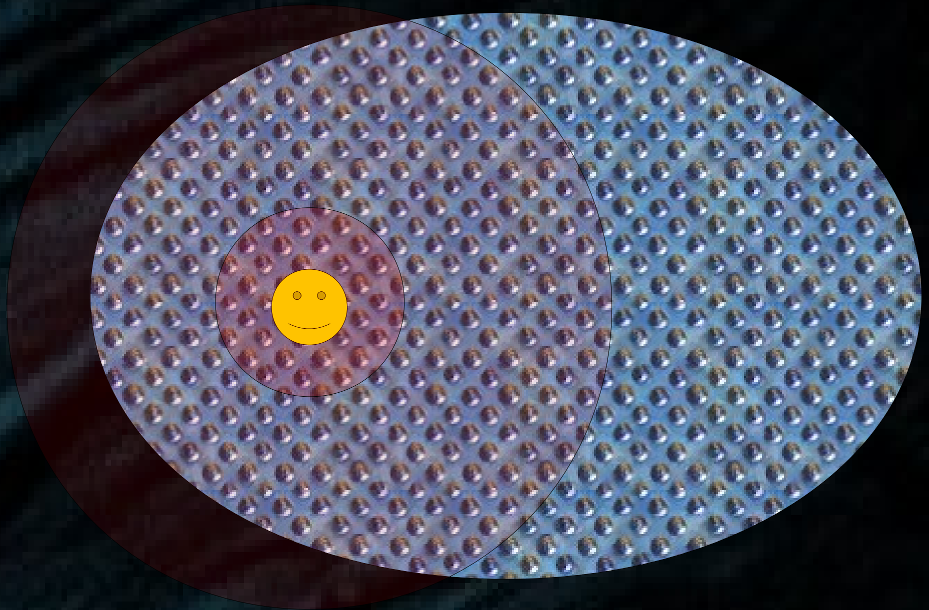
1) **Prompt gamma-rays:** point a telescope to a certain direction, and average over a volume set by the angular resolution

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





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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.

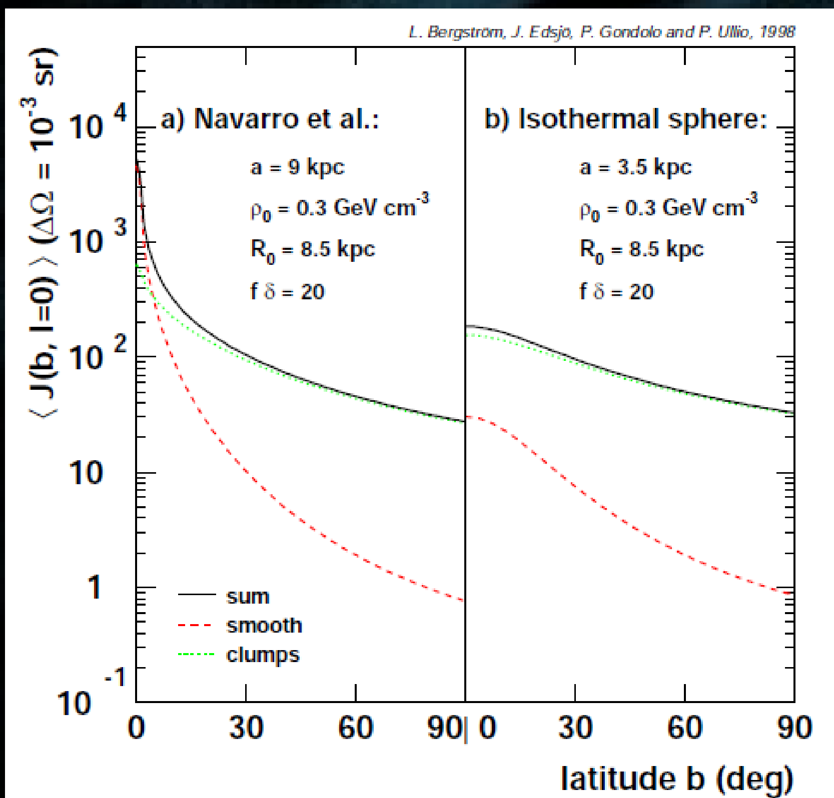
a) Large propagation scale: if enough to feel regions close to GC, then **B ~ 1**

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

Summary pictures

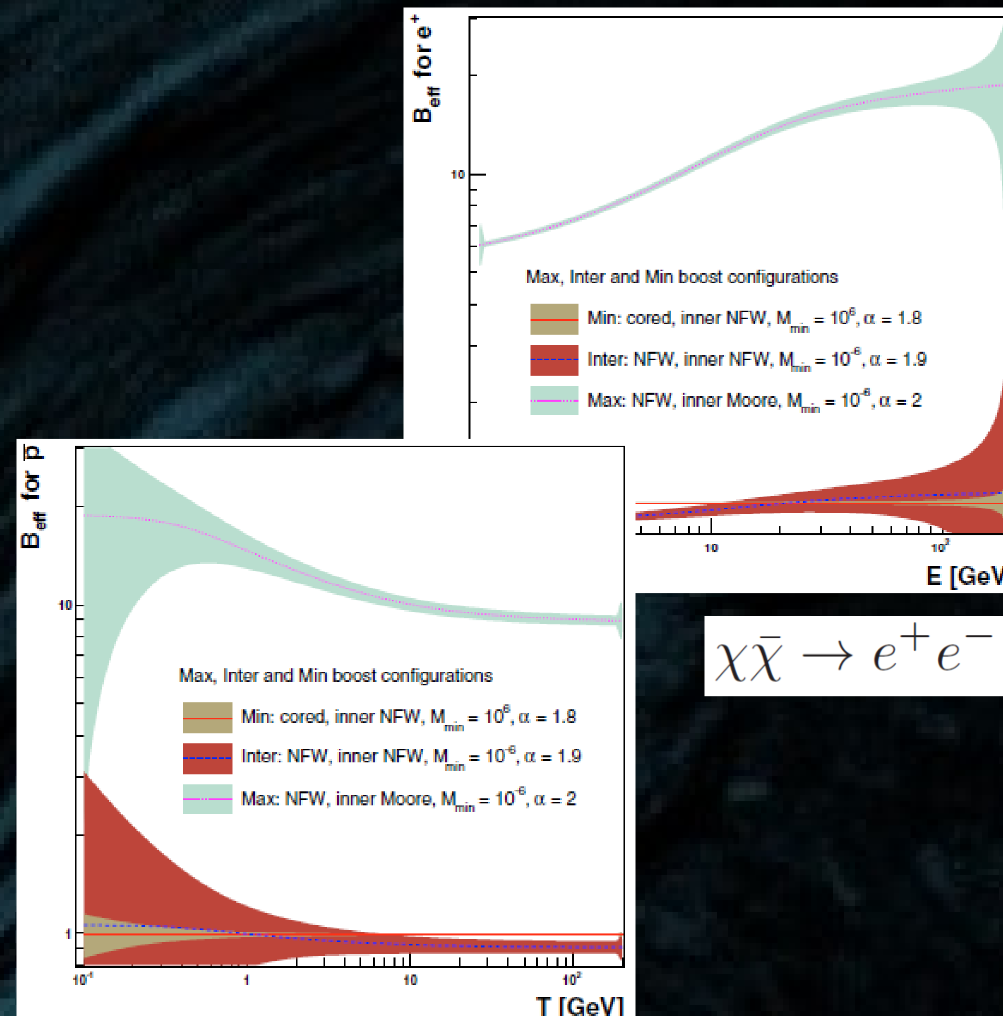
Gamma rays:

Bergström et al (1999), assuming that clumps spatially track the smooth halo



Antimatter cosmic rays:

Lavalle et al (2007,2008)



$$\chi\bar{\chi} \rightarrow e^+e^-$$

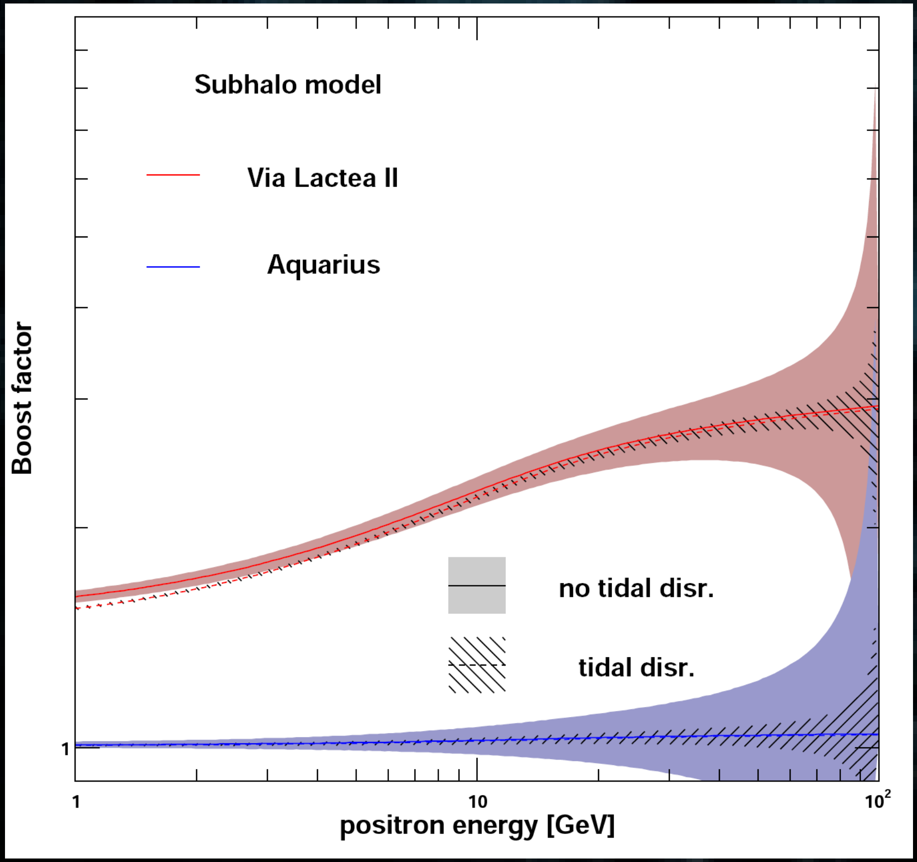
$$\chi\bar{\chi} \rightarrow \ldots \rightarrow X + \bar{p}$$

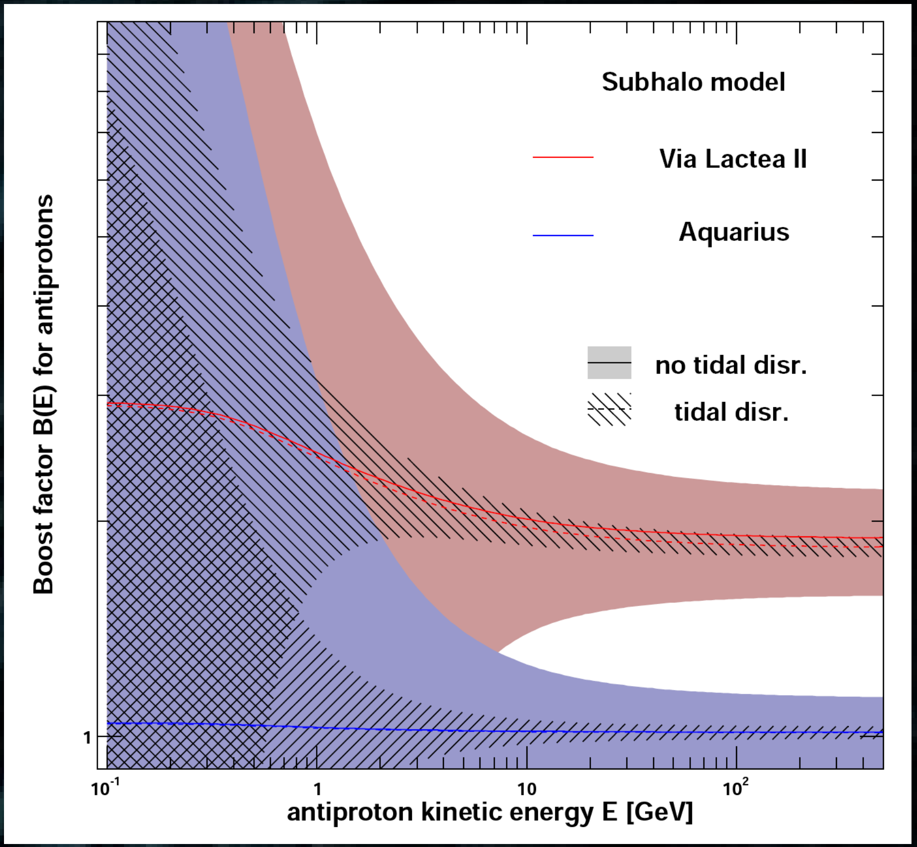
Caution:

- Statistical meaning only
- Energy dependence of propagation depends on the species (nuclei/electrons)

Boost factors for positrons and antiprotons

Pieri, JL, Bertone & Branchini (2009)

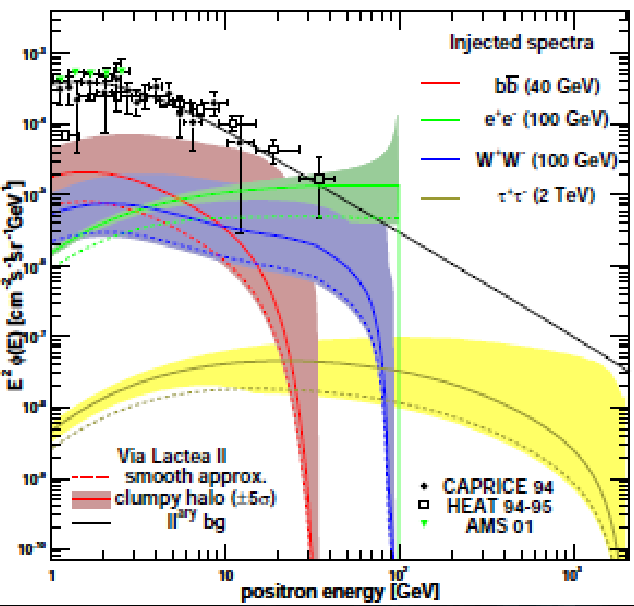




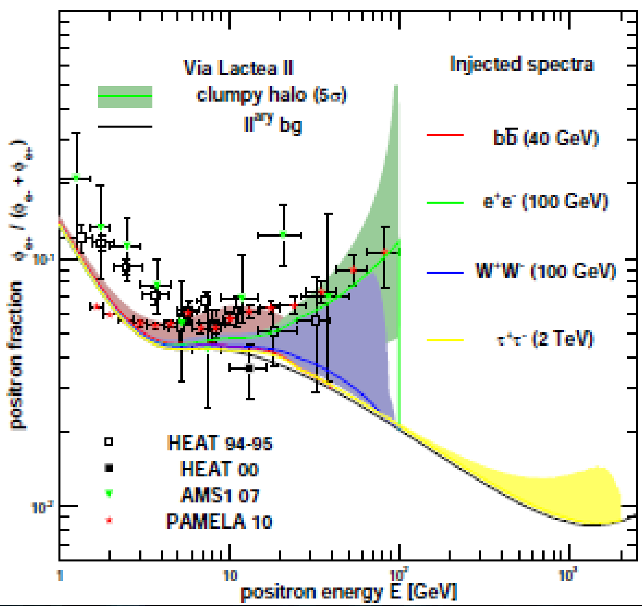
See also Lavalle et al (2007,2008)

Clumpiness summary: Predictions with VL2 configuration

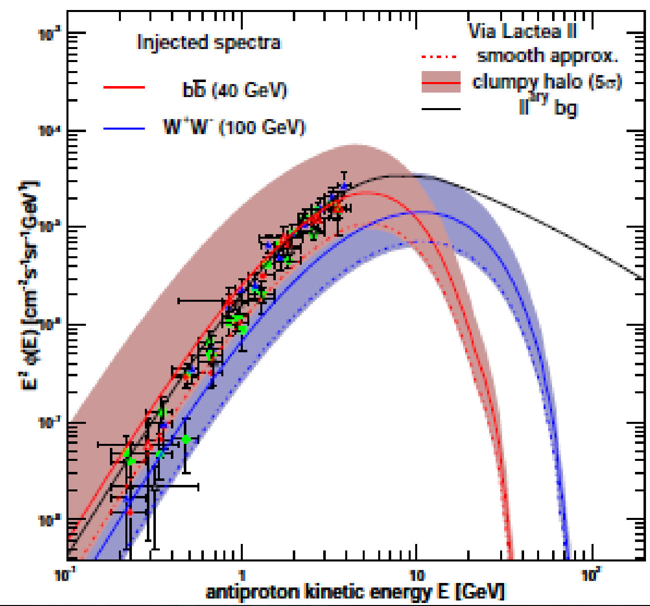
Positron flux



Positron fraction



Antiproton flux



Pieri, JL, Bertone & Branchini (2009)
using results from Via Lactea II (Diemand et al) and Aquarius (Springel et al)
-- see early calculations in Lavalle et al (2007-2008) --

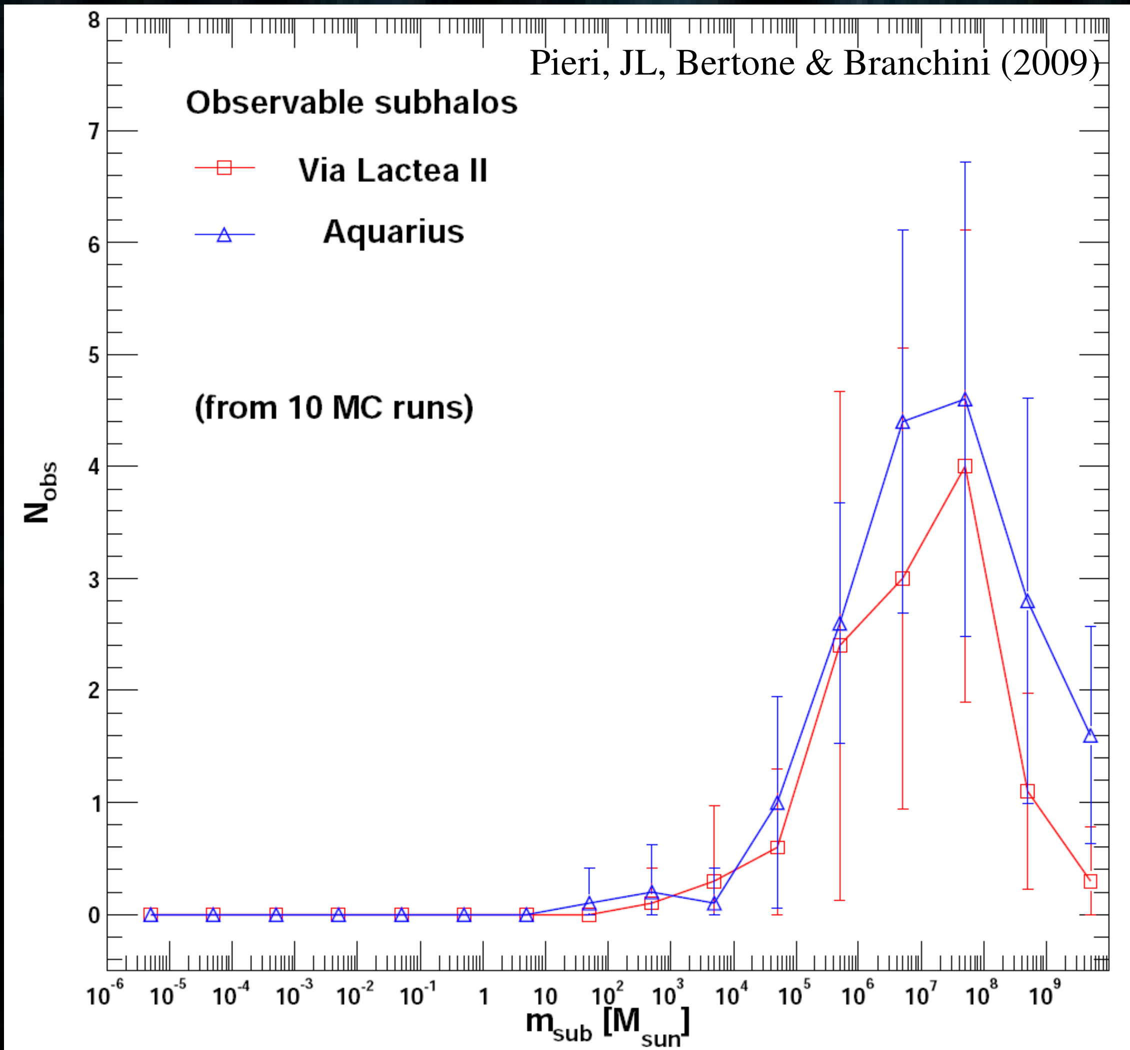
$\langle \sigma v \rangle = 3\,10^{-26}\ \mathrm{cm}^3/\mathrm{s}$

model	m_χ [GeV]	final state
A	40	bb
B	100	W^+W^-
C	100	e^+e^-
D	2000	$\tau^+\tau^-$

Important features:

- 40 GeV WIMP (b-bbar) excluded by antiproton constraints
- 100 GeV WIMP (WW) at the edge of tension with the antiproton data
- 100 GeV WIMP going to e^+e^- can fit the PAMELA data; but pulsars not included => background must be known before any claim.

Sensitivity to individual subhalos



Galactic center:
astrophysical contributions not under control, notably cosmic ray electrons.

Subhalos:
clean signal if located at high latitude, no counterpart at lower energies ... but have to be very massive and nearby to be observable.

N <10 objects detectable with Fermi in 5 years.

Model A: 40 GeV WIMP going to b-bbar
Model B: 100 GeV WIMP going to WW

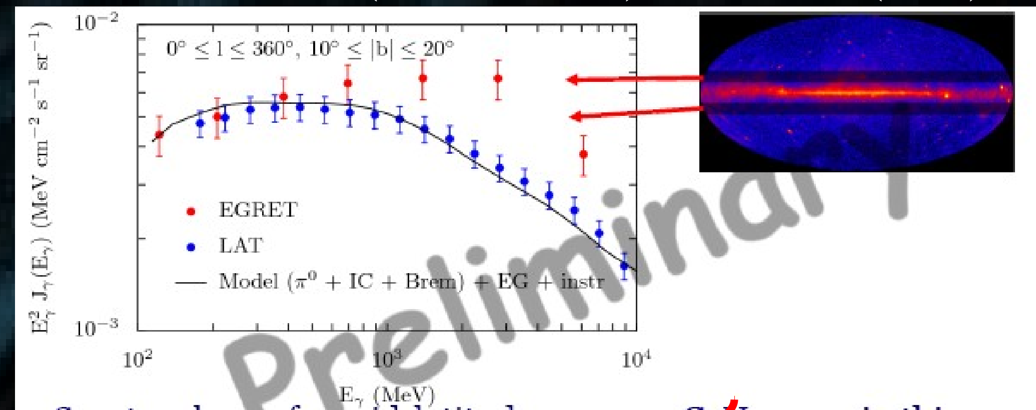
model	$VLII\ 3\ \sigma$	$VLII\ 5\ \sigma$	$Aq\ 3\ \sigma$	$Aq\ 5\ \sigma$
A	9.2 ± 2.6	4.1 ± 1.3	13.5 ± 2.5	7.3 ± 2.4
B	3.1 ± 1.1	1.4 ± 0.8	6.2 ± 2.1	2.9 ± 1.4

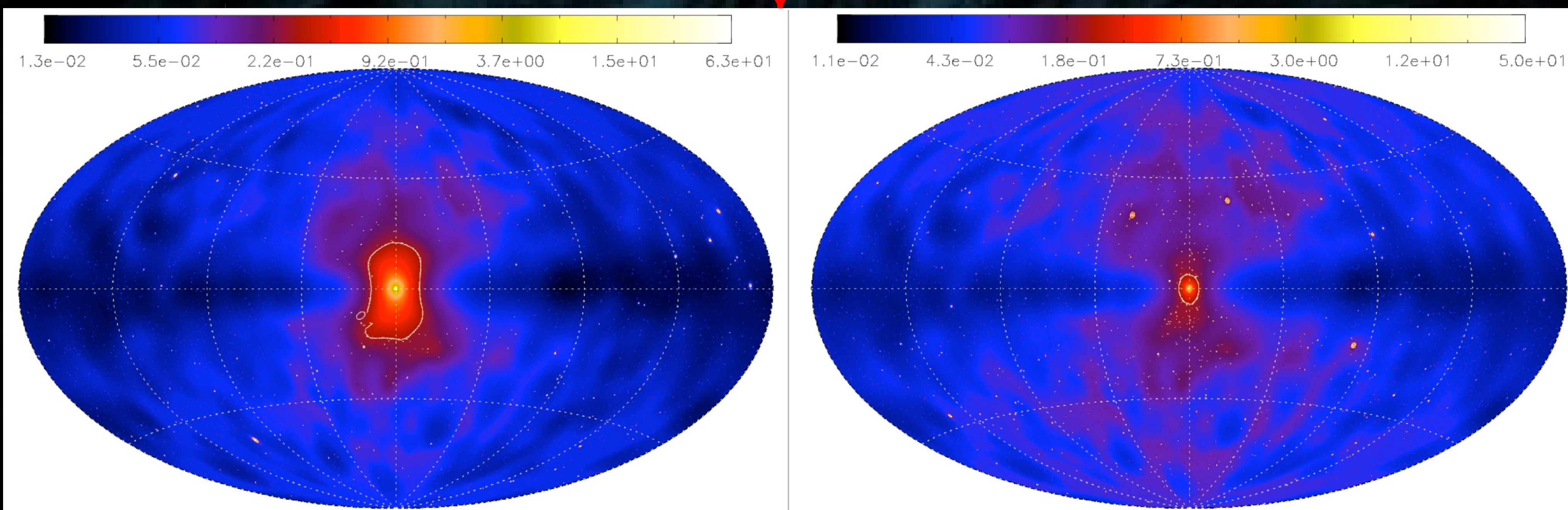
Gamma-ray skymaps

Empirical diffuse emission model:
template maps from EGRET
(Cillis & Hartman 05)

But EGRET is no longer a reference:
our Bg = EGRET – 50%

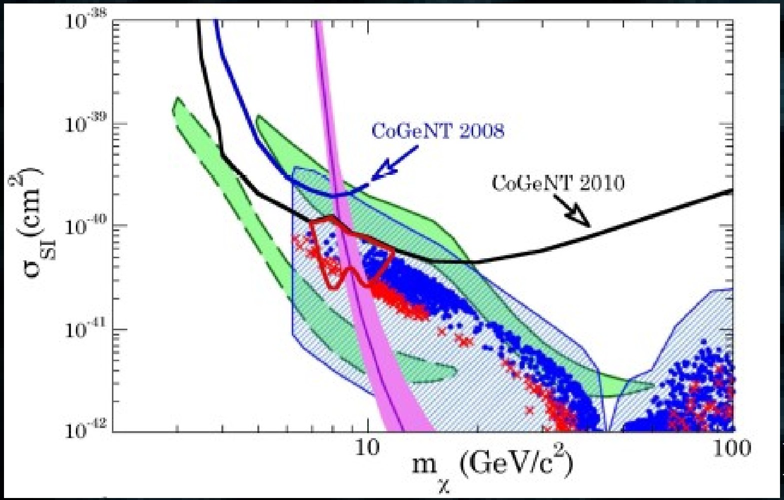
Johannesson (Moriond 2009) – Abdo et al (2009)





Pieri, JL, Bertone & Branchini (2011)

(Parenthesis: antiprotons versus small WIMP masses)

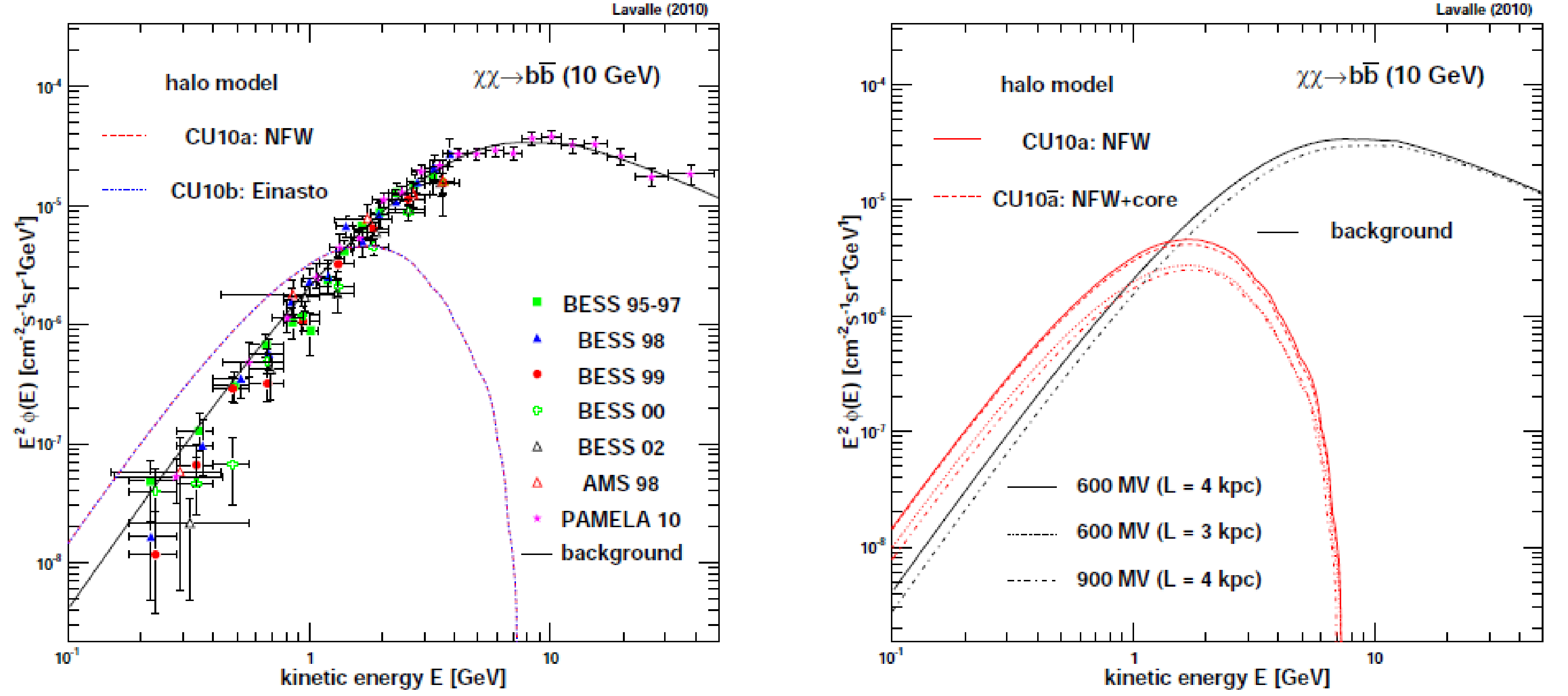


DAMA+CDMS+COGENT mass regions
=> WIMP mass ~10 GeV

If WIMPs couple to quarks, annihilation can produce antiprotons if $m_{wimp} > m_p$

Large antiproton flux expected (it scales like 1/m2)
New constraints on propagation (Putze et al 10) => excess wrt data

Lavalle (2010)



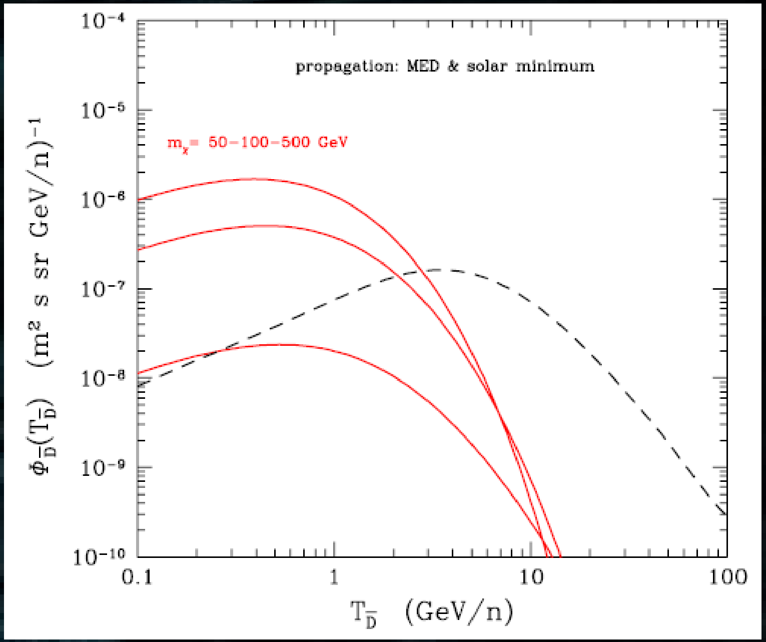
An optimistic view about non-discovery (yet): WIMP candidates are not excluded !

Status of WIMP searches:

- WIMPs are fairly well motivated from particle physics beyond the Standard Model.
- From generic predictions, they are not expected to show up in current data.
- Interesting constraints from antiprotons: complementarity required! (multiwavelength, multimessenger)
- Most promising sources in the future: dwarf spheroidal galaxies and subhalos (gamma-rays).
- Cosmic-ray antideuterons below 1 GeV ? (Salati et al, 00)

Astrophysical issues:

- Backgrounds !
- The impact of baryons on dark matter distribution:
    - Adiabatic contraction in galaxy centers ? Or cores ? (see Governato et al 10)
    - Local dark matter density and velocity distribution ? (Catena & Ullio 10, Salucci et al 10)
    - Subhalo survival ? Power in small scales vs reionization ? (Klypin et al 10)



Donato, Fornengo & Salati 00
Donato, Fornengo & Maurin 08

Conclusions & perspectives

Part I: ***Cosmic-ray nuclei, propagation models***

- Models incredibly successful despite the very crude assumptions.
- Limits are reached for very accurate predictions.
- Improve Galaxy modeling (ISM, ISRF, magnetic field, convection, etc.).
- More fundamental understanding required: link between turbulence and transport => try top-down approaches.

Part II: ***Cosmic-ray electrons and positrons***

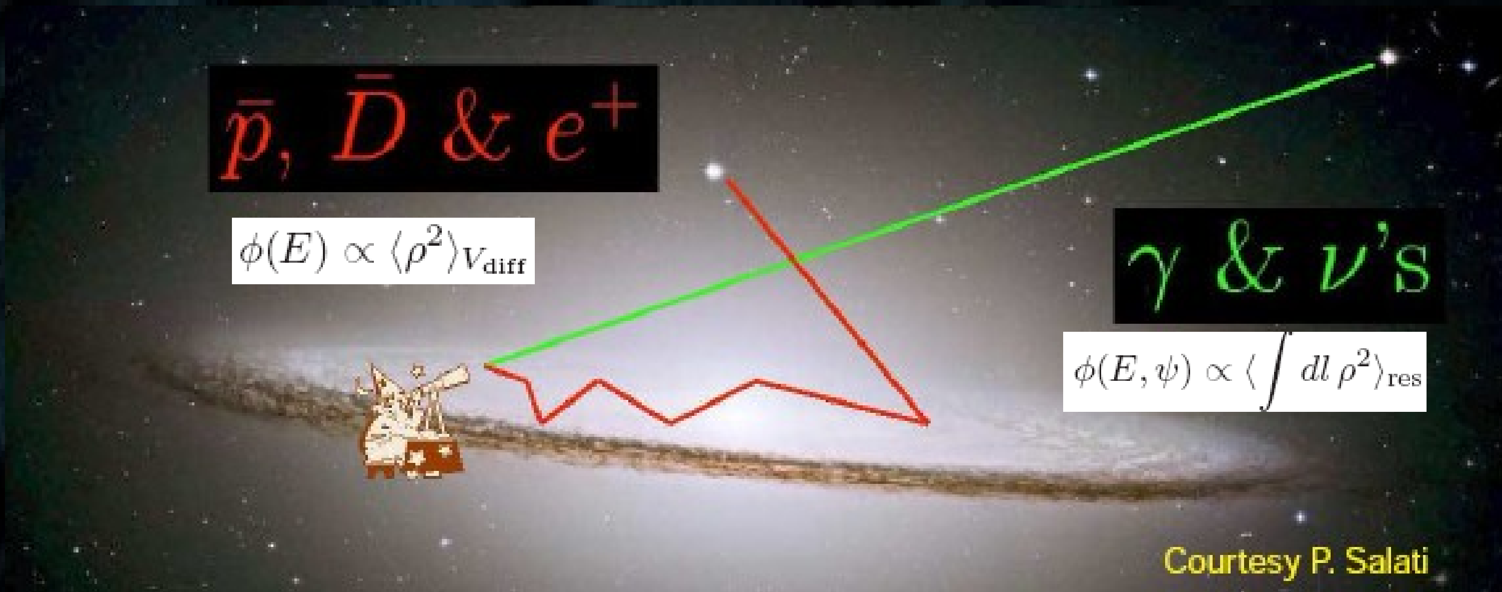
- Local sources give hopes to improve our modeling/understanding.
- Large uncertainties above 50 GeV.
- On going improvements (source modeling, diffuse emissions).

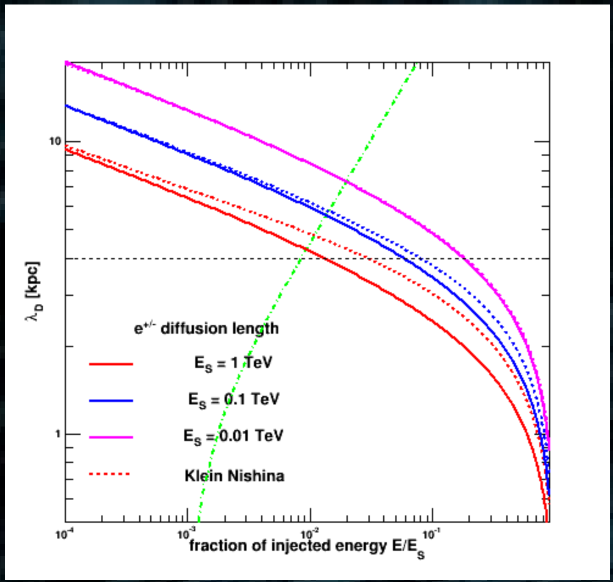
Part III: ***Searches for dark matter annihilation signals***

- Difficult searches: signals are weak and does not show up easily. Interesting constraints (antiprotons, diffuse emissions).
- Targets: DSph, Galactic Center, antideuterons ++ complementarity

Backup

Cosmic messengers: boost related to their spatial origin





Why should we take subhalos into account?

• They are **predicted** by the theory of structure formation, while their features (minimal scale, number density, inner profile) depend on dark matter properties: eg CDM versus WDM.

• They are "**observed**" in N-body simulations of structures on different scales (from the galaxy cluster scale down to the dwarf galaxy scale); but current resolution limit => Mres ~ 10^4 Msun.

• They might be observed in Nature above scales able to accrete the baryons efficiently enough (dwarf galaxies).

• The small-scale clustering of dark matter can **increase the annihilation rate** quite significantly.

=> **Self-consistency +++ increase discovery / exclusion potential**.

Credit to the original idea

THE ASTROPHYSICAL JOURNAL, 411:439–449, 1993 July 10

CLUMPY COLD DARK MATTER

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Received 1992 March 25; accepted 1992 December 16

- WIMPs freeze out (chemically and kinematically) in a radiation-dominated universe before BBN. They feed gravitational perturbations down to their free-streaming scale.

- Perturbations start to grow efficiently after radiation-matter equivalence (z ~ 3500): DM seeds have very large densities at that time. 10^{-6} Msun objects enter the non-linear regime around z ~ 100.

- Galaxies form at z~6 in a much less dense universe, and should contain many of these very dense cores of dark matter, called clumps.

- Some of these clumps may survive tidal disruption and increase the annihilation rate.

The small scale issue

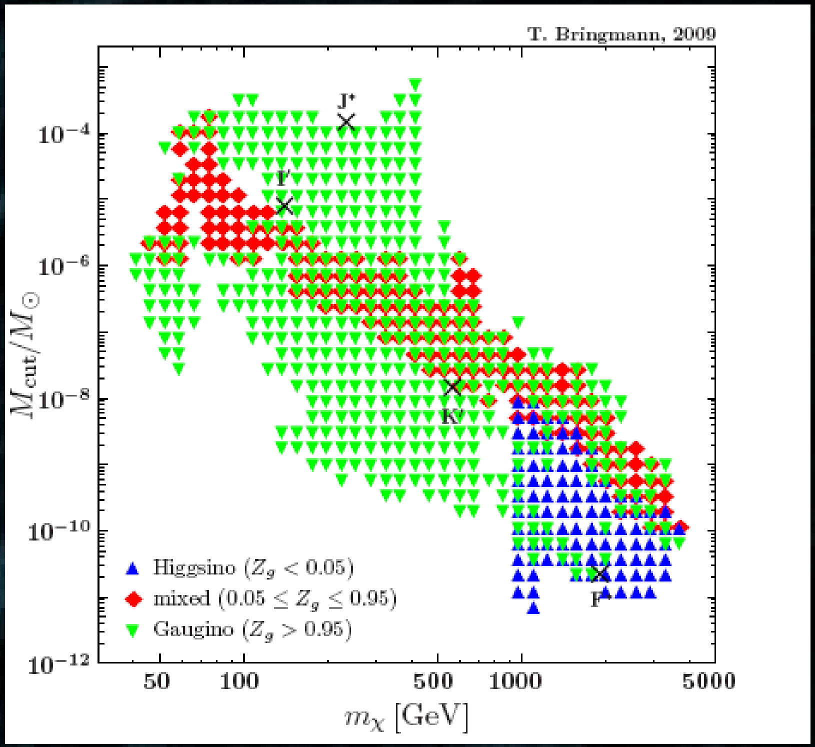
(see review by T. Bringmann (2009))

The free streaming scale depends on the time of kinetic ($\neq$ chemical) decoupling of WIMPs from the primordial soup.

The weaker the collision rate, the smaller the free streaming scale and the cut-off mass.

Subhalo mass down to 10^{-11}-10^{-3} $M_\odot$ (SUSY). The lighter the denser.

Tidal effects ? Large survival fraction (Berezinsky et al, 2008)



T. Bringmann arXiv:0903.0189

	M_{sub}^{res} $[10^4 M_\odot]$	N_{sub}^{res} $[10^4]$	Mass slope	f_{sub}^{res} [%]
VL2	$\sim 10^2$	5.3	2	10
AQ	3.24	30	1.9	13.2

Extrapolation

down to 10^{-6} Msun

	M_{sub}^{min} $[10^{-6} M_\odot]$	N_{sub}^{tot} $[10^{15}]$	Mass slope	f_{sub}^{tot} [%]
VL2	1	28	2	54.2
AQ	1	1.1	1.9	17.1

Going into more details: a statistical approach (1)

General expression for the flux measured on Earth

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

The Green function encodes the propagation properties

=> trivial for gamma-rays

$$\int_{\rm (sub)halo} d^3\vec{x}_s\int dE_s\,G(E,\vec{x}_{\rm obs}\leftarrow E_s,\vec{x}_s) \stackrel{\gamma-\rm rays}{\longrightarrow} \int_{\rm l.o.s.} d\Omega_{\rm res}\,dl\int dE_s\,\delta(E-E_s)$$

Subhalos: point-like sources provided *G* does not vary too much over the object

$$\text{if }\lambda_{\rm prop}\gg r_s \Longrightarrow \int_{\rm sub} d^3\vec{x}_s\,\tilde{\mathcal{G}}(\vec{x}_{\rm obs}\leftarrow\vec{x}_s)\left[\frac{\rho_i(\vec{x}_s)}{\rho_0}\right]^2 \longrightarrow \tilde{\mathcal{G}}(\vec{x}_{\rm obs}\leftarrow\vec{x}_i)\underbrace{4\pi\int dr\,r^2\left[\frac{\rho_i(r)}{\rho_0}\right]^2}_{\xi_i}$$

$$\phi_i = \mathcal{S}\times\tilde{\mathcal{G}}(\vec{x}_{\rm obs}\leftarrow\vec{x}_i)\times\xi_i$$

$$\phi_{\rm tot} = \phi_{\rm sm} + \sum_{i\in\rm sub}\phi_i = \phi_{\rm sm} + N_{\rm tot}\langle\phi_{\rm sub}\rangle$$

$$\mathcal{B} = \frac{\phi_{\rm tot}}{\phi_{\rm smooth}} = \left\{\frac{\phi_{\rm sm}}{\phi_{\rm smooth}}\approx 1\right\} + N_{\rm tot}\frac{\langle\phi_{\rm sub}\rangle}{\phi_{\rm smooth}}$$

Going into more details: a statistical approach (2)

Define the flux pdf for subhalos

$$\langle \phi_{\rm sub} \rangle = \int d\phi \, \phi \, \frac{d\mathcal{P}_\phi(\phi)}{d\phi}$$

The flux pdf is completely set by:

$$\frac{d\mathcal{P}_\phi(\phi)}{d\phi} \propto \underbrace{\frac{d\mathcal{P}_V(\vec{x})}{dV}}_{\text{spatial distrib.}} \times \underbrace{\frac{d\mathcal{P}_M(M,\vec{x})}{dM}}_{\text{mass distrib.}} \times \underbrace{\frac{d\mathcal{P}_c(c,M,\vec{x})}{dc}}_{\text{concentration distrib.}}$$

The average subhalo flux is entirely defined (same way for variance)

$$\begin{aligned}\langle \phi_{\rm sub} \rangle &= \mathcal{S} \int d^3\vec{x}_s \, \tilde{\mathcal{G}}(\vec{x}_{\rm obs} \leftarrow \vec{x}_s) \frac{d\mathcal{P}_V(\vec{x}_s)}{dV} \int dM \, \frac{d\mathcal{P}_M(M,\vec{x}_s)}{dM} \int dc \, \frac{d\mathcal{P}_c(c,M,\vec{x})}{dc} \, \xi(\vec{x}_s, M, c) \\ &= \mathcal{S} \times \langle \tilde{\mathcal{G}} \, \langle \xi \rangle_{c,M} \rangle_V \approx \mathcal{S} \times \langle \tilde{\mathcal{G}} \rangle_V \times \langle \xi \rangle_{c,M}\end{aligned}$$

Remind: the subhalo properties are fully set by its mass and its concentration (and position in the Galaxy)

$$M_{\rm vir} = \frac{4\pi}{3} \, (\delta \, \rho_c) \, r_{\rm vir}^3$$

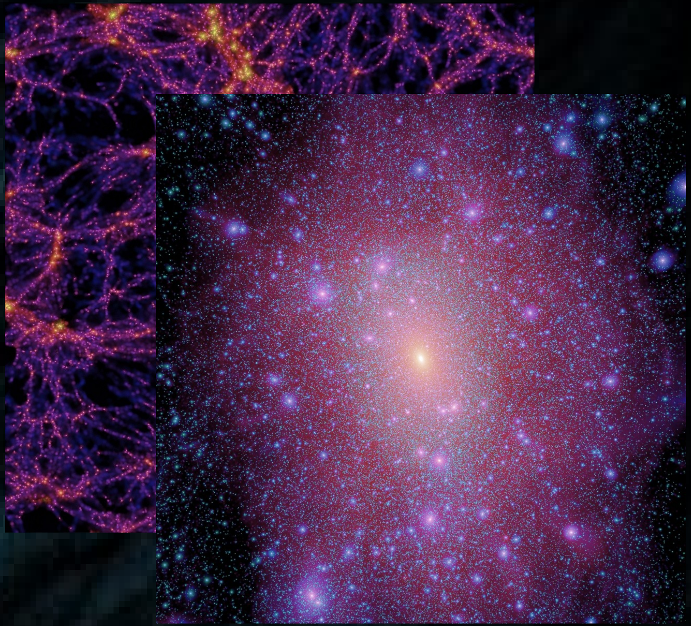
$$\begin{aligned}M_{200} &= M_{\rm vir}(\delta = 200) \\ M_{vir} &= M_{\rm vir}(\delta = \Delta(z) \, \Omega_m(z))\end{aligned}$$

$$\begin{aligned}c_{200} &= \frac{r_{200}}{r_{-2}} \\ c_{\rm vir} &= \frac{r_{\rm vir}}{r_{-2}}\end{aligned}$$

Use N-body info: Via Lactea II versus Aquarius

<u>Via Lactea II:</u> Diemand et al (2008)
<u>Aquarius:</u> Springel et al (2008)

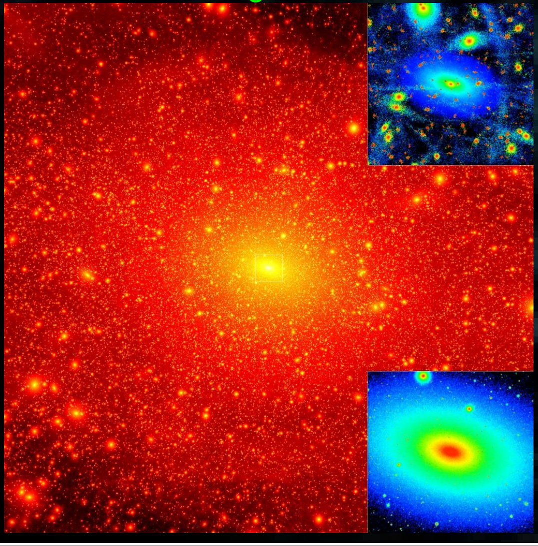
http://www.mpa-garching.mpg.de/aquarius/



MW-like halos with ~ 1 billion particles of ~10^3 $M_\odot$
> 50,000-300,000 subhalos with masses > 10^6 -$10^{4.5}$ $M_\odot$

Slightly different cosmologies: WMAP3 vs WMAP5
(σ_8 = 0.74 vs 0.9)

http://www.ucolick.org/~diemand/vl/index.html



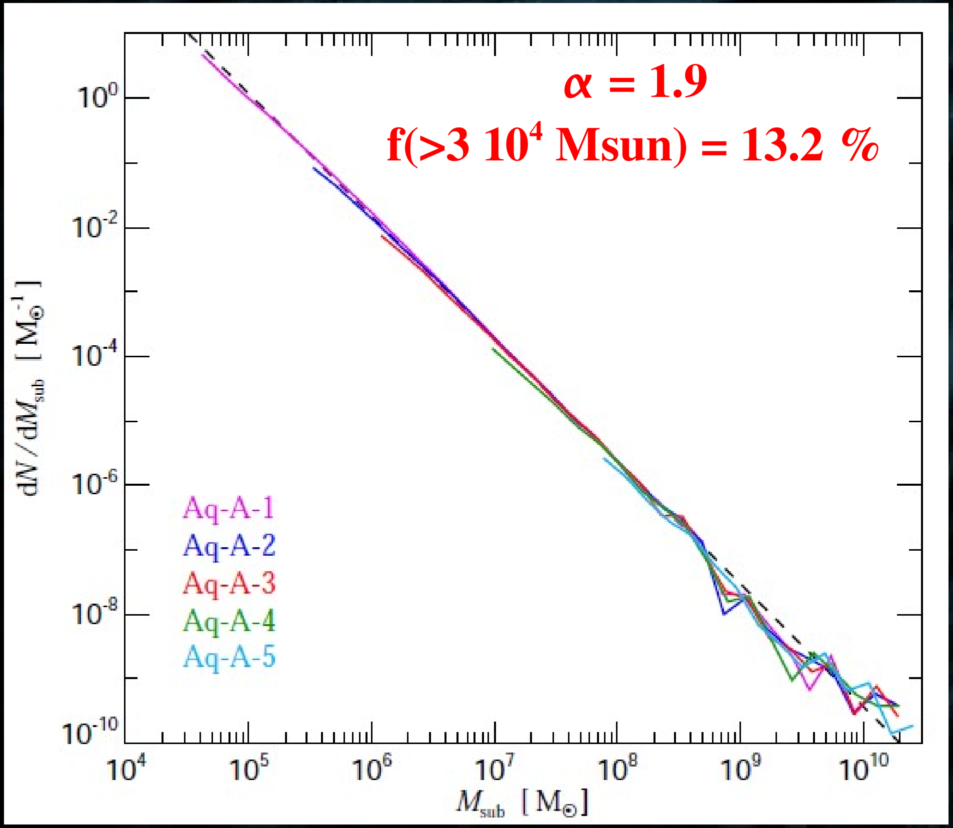
Gamma-ray studies in:

Kuhlen et al (2008) – VL2
Springel et al (2008) – AQ

					Overall DM		Subhalos			
	$M_{\rm part}$ $[10^3 M_\odot]$	$N_{\rm part}$ $[10^8]$	M_{50} $[10^{12} M_\odot]$	R_{50} [kpc]	Density profile	$\rho_\odot$ [GeV/cm^3]	$M_{\rm sub}^{\rm res}$ $[10^4 M_\odot]$	$N_{\rm sub}^{\rm res}$ $[10^4]$	Mass slope	$f_{\rm sub}^{\rm res}$ [%]
VL2	4.1	4.7	1.9	402	NFW	0.42	$\sim 10^2$	5.3	2	10
AQ	1.7	14.7	2.52	433	Einasto	0.57	3.24	30	1.9	13.2

Mass function

Subhalo mass function from Aquarius
(Springel et al, 2008)



Power law mass function

$$\frac{d\mathcal{P}_M(M)}{dM} = K_M \left[\frac{M}{M_\odot}\right]^{-\alpha}$$

Press & Schechter (1974): $\alpha = 2$ (theory)
Aquarius (Springel et al): $\alpha \sim 1.9$
Via Lactea (Diemand et al): $\alpha \sim 2.0$

NB: resolution limit => **assume scale invariance**

Calibrate subhalo mass content from simulations:

$$f_{\rm tot} = f_{\rm res} \times \frac{(M_{\rm max}^{2-\alpha} - M_{\rm min}^{2-\alpha})}{(M_{\rm max}^{2-\alpha} - M_{\rm res}^{2-\alpha})}$$

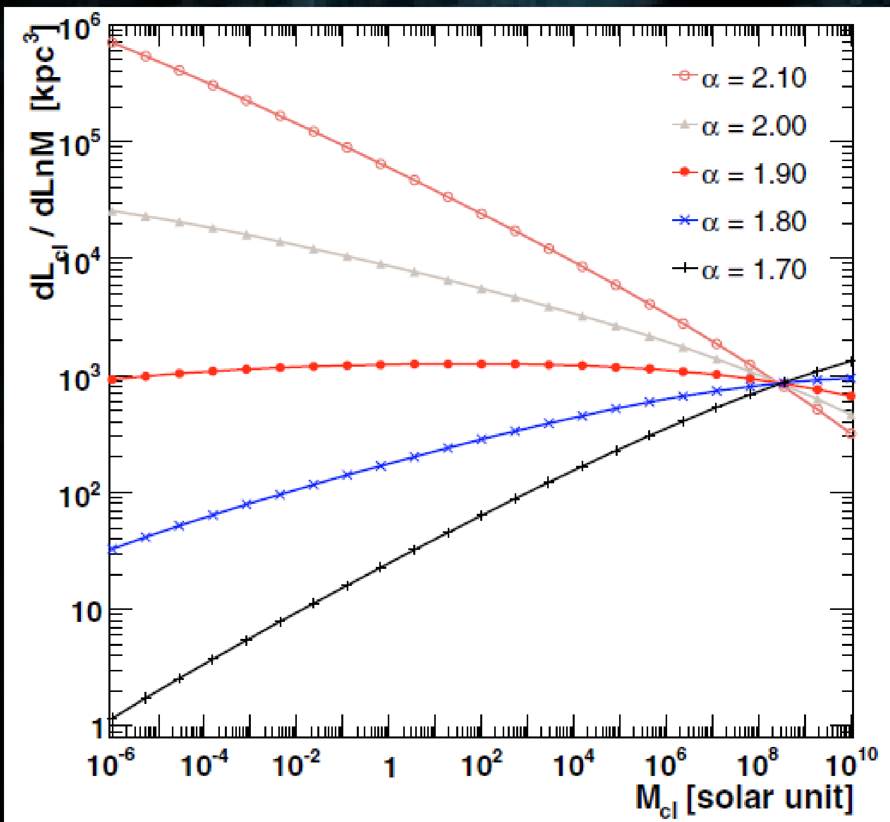
=> Get total number of subhalos:

$$N_{\rm tot} = \frac{f_{\rm tot} M_{MW}}{\langle M \rangle} \tilde{\propto} M_{\rm min}^{1-\alpha}$$

The subhalo mass content is determined by the minimal mass Mmin and the slope α, and is calibrated from the mass fraction resolved in N-body simulations => **Extrapolation down over > 10 OM !!!**

Luminosity function

Analytical luminosity function
(NFW, concentration from Bullock et al 2001)
(Lavalle et al, 2008)



Luminosity per mass decade

$$\frac{d\mathcal{L}}{d\ln M} \propto N_{\rm tot} \times M \times \frac{d\mathcal{P}_M(M)}{dM} \times \xi(M)$$

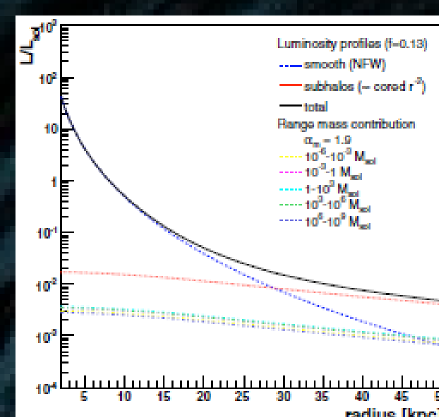
<= Impact of Mmin depends on α :

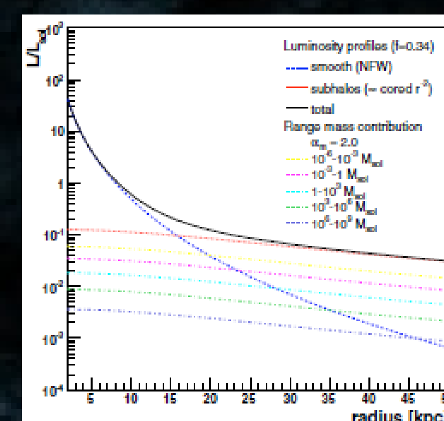
α ~ 1.9: constant luminosity per mass decade

α ~ 2.0: luminosity dominated by small objects

Similar dependence

$$\xi_{\rm NFW}(M) \overset{\sim}{\propto} M^{0.9} \Longrightarrow \langle \xi_{\rm NFW} \rangle \overset{\sim}{\propto} M_{\rm min}^{1.9-\alpha}$$





Spatial distribution: a self-consistent method

Trivial cases:

1) given from N-body analysis (still to check consistency)
2) subhalos track the host halo: dP/dV = rho(r)/M_{MW}

(i) Global fit to the N-body simulation (eg NFW)

$$\rho_{\rm MW}(r) \text{ such that } 4\pi \int dr\, r^2 \rho_{\rm MW}(r) \quad = \quad M_{\rm MW}$$

(ii) Adding subhalos means splitting the global fit into a smooth + clumpy components

$$\text{Adding subhalos } \Rightarrow \rho_{\rm MW}(r) = \rho_{\rm sm}(r) + \rho_{\rm sub}(r)$$

$$\rho_{\rm sm}(r) \text{ such that } 4\pi \int dr\, r^2 \rho_{\rm sm}(r) \quad = \quad (1 - f_{\rm sub})\, M_{\rm MW}$$

$$\rho_{\rm sub}(r) \text{ such that } 4\pi \int dr\, r^2 \rho_{\rm sub}(r) \quad = \quad f_{\rm sub}\, M_{\rm MW}$$

Warning !!!

$$\rho_{\rm sm}(r) \neq (1 - f_{\rm sub})\rho_{\rm MW}(r)$$

often assumed = in the past

(iii) Use N-body prescriptions: subhalo distribution cored in the center.

in Via Lactea, **antibiased** relation: subhalo distrib $\propto$ r $\times$ global **smooth** distrib

$$\rho_{\rm sm}(r) = \frac{\rho_{\rm MW}(r)}{(1 - r/r_b)} \propto \begin{cases} r^{-1} & \text{for } r \lesssim r_b \sim r_s \\ r^{-4} & \text{for } r \gtrsim r_b \sim r_s \end{cases}$$

$$\rho_{\rm sub}(r) = \frac{\rho_{\rm MW}(r)(r/r_b)}{(1 - r/r_b)} \propto \begin{cases} \text{cst} & \text{for } r \lesssim r_b \sim r_s \\ r^{-3} & \text{for } r \gtrsim r_b \sim r_s \end{cases}$$

Spatial distribution: a self-consistent method

Trivial cases:

1) given from N-body analysis (still to check consistency)

2) subhalos track the host halo: dP/dV = rho(r)/M_{MW}

(i) Global fit to the N

$\rho_{\rm MW}(r)$ such that 4π

(ii) Adding subhalos means splitting the glob
fit into a smooth + clumpy components

Adding subhalos $\Rightarrow \rho_{\rm MW}(r) = \rho_{\rm sm}(r) +$

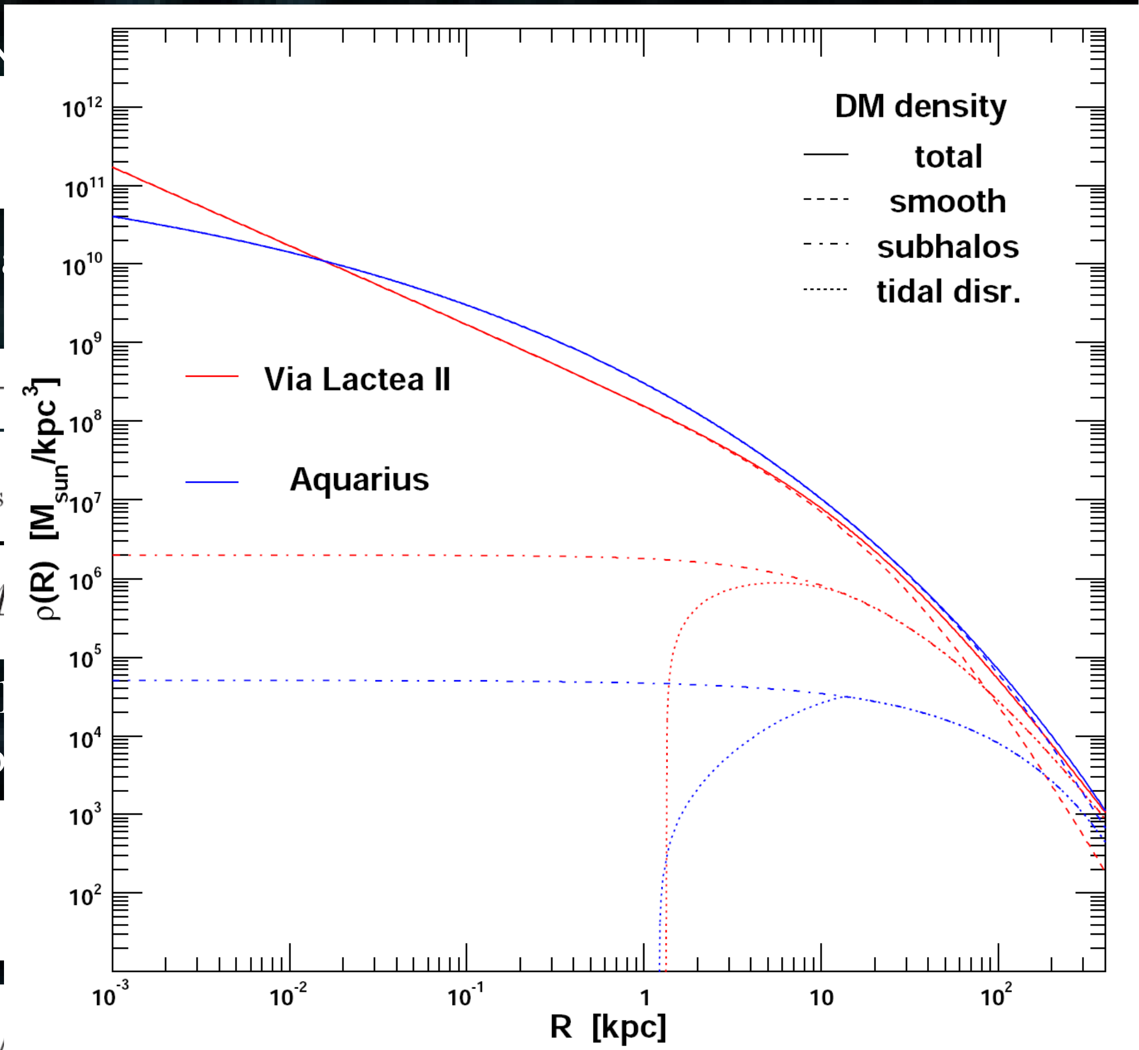
$\rho_{\rm sm}(r)$ such that $4\pi \int dr\, r^2 \rho_{\rm sm}(r) \;=\; (1 - f_{\rm s}$

$\rho_{\rm sub}(r)$ such that $4\pi \int dr\, r^2 \rho_{\rm sub}(r) \;=\; f_{\rm sub}\, M$

(iii) Use N-body prescriptions: subhal
in Via Lactea, **antibiased** relatio

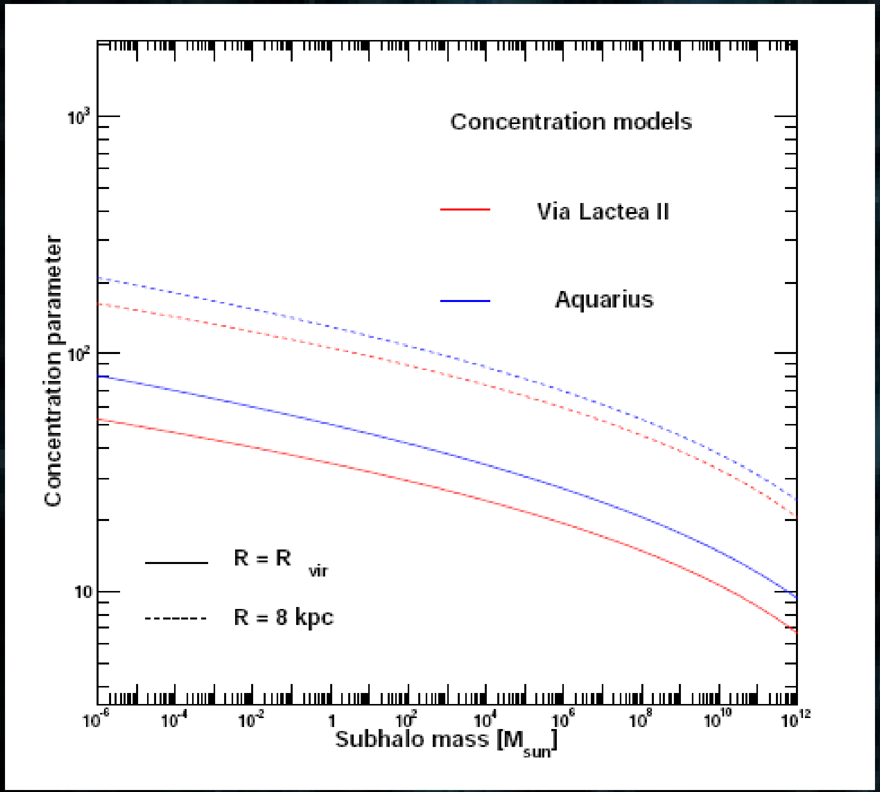
$$\rho_{\rm sm}(r) = \frac{\rho_{\rm MW}(r)}{(1 - r/r_b)}$$

$$\rho_{\rm sub}(r) = \frac{\rho_{\rm MW}(r)(r,}{(1 - r/r_b)} \propto \Big\{ r^{-3} \quad \text{for } r \gtrsim r_b \sim r_s$$

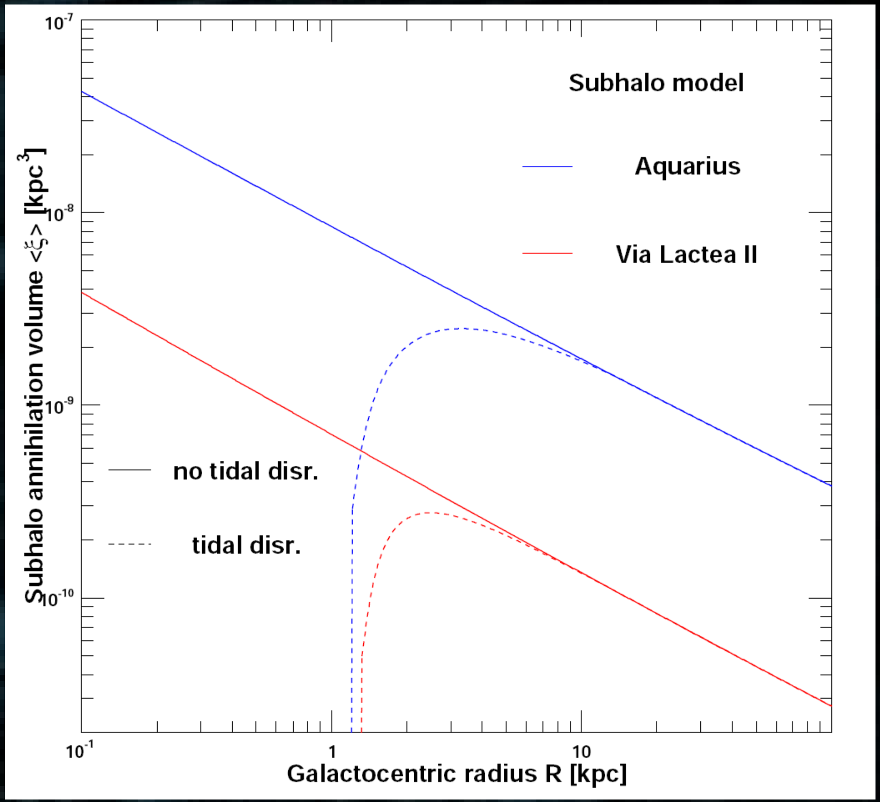


Concentration function

Concentration vs mass and location in the MW



Average subhalo luminosity vs distance to GC



Concentrations:

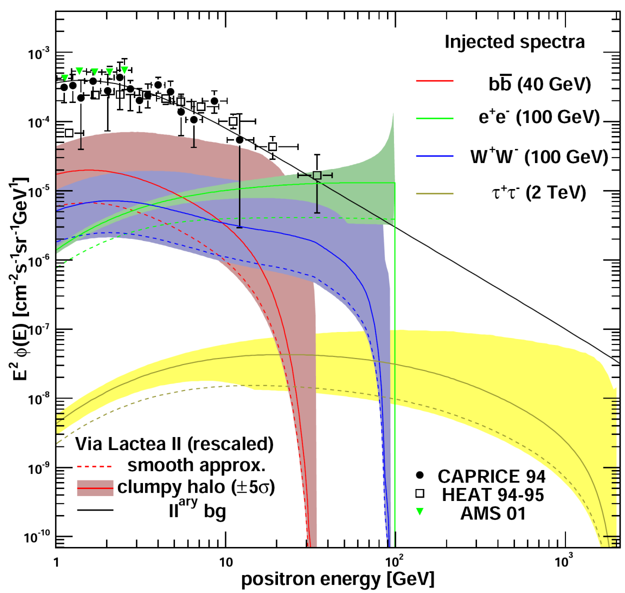
1) Large theoretical uncertainties (impact of cosmological inputs).
2) Tidal effects: concentrations get larger when closer to the GC (demonstrated in VL2 and Aquarius).

$$\xi \overset{\sim}{\propto} c_{\rm vir}^{3}$$

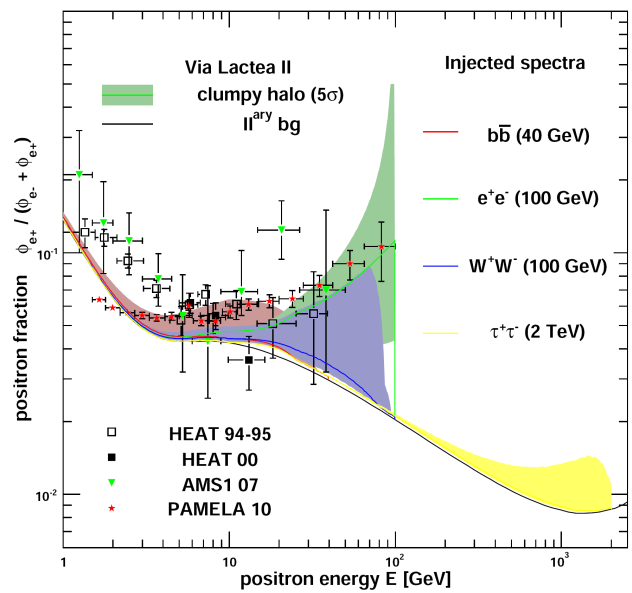
Average luminosity strongly affected!

Dark Matter subhalos: energy-dependent boost factor < 5 (modulo variance)

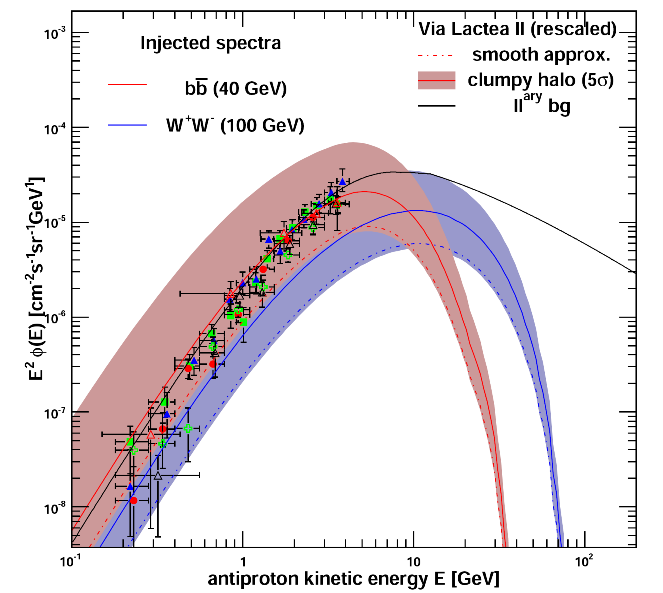
Positron flux



Positron fraction



Antiproton flux



Pieri, JL, Bertone & Branchini (2009)
using results from Via Lactea II (Diemand et al) and Aquarius (Springel et al)
-- see early calculations in Lavalle et al (2007-2008) --

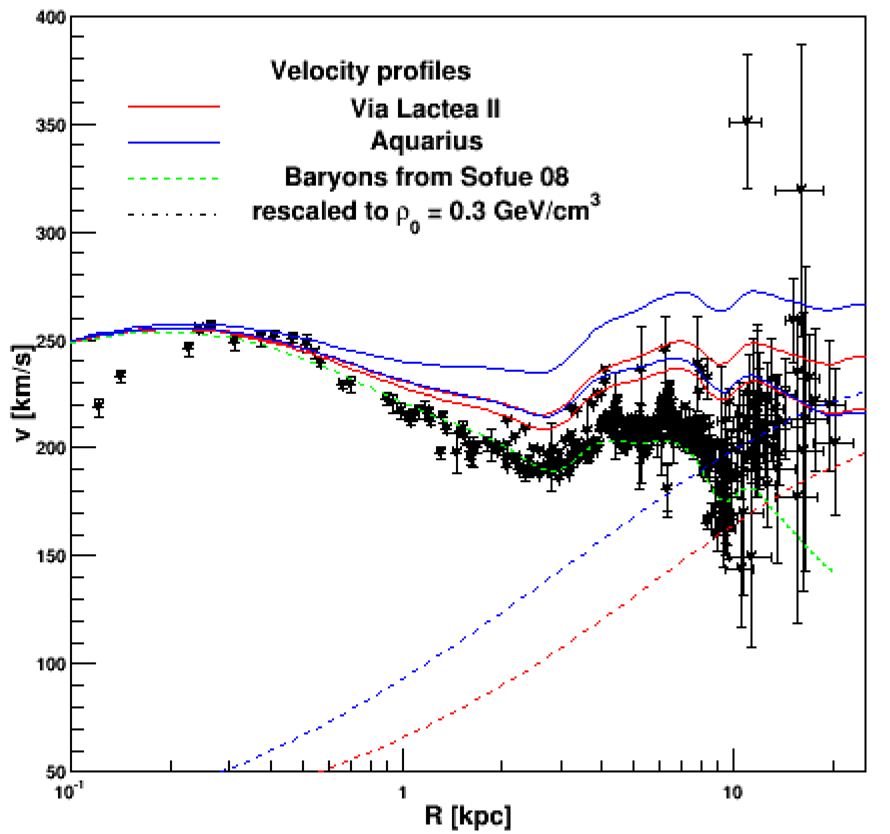
model	m_χ [GeV]	final state
A	40	bb
B	100	W^+W^-
C	100	e^+e^-
D	2000	$\tau^+\tau^-$

Important features:

- 40 GeV WIMP (b-bbar) excluded by antiproton constraints
- 100 GeV WIMP (WW) at the edge of tension with the antiproton data
- 100 GeV WIMP going t o e+e- can fit the PAMELA data; but pulsars not included => background must be known before any claim.

High-resolution is not the end of the story: what about baryons?

VL2/Aquarius + baryons from Sofue et al 09



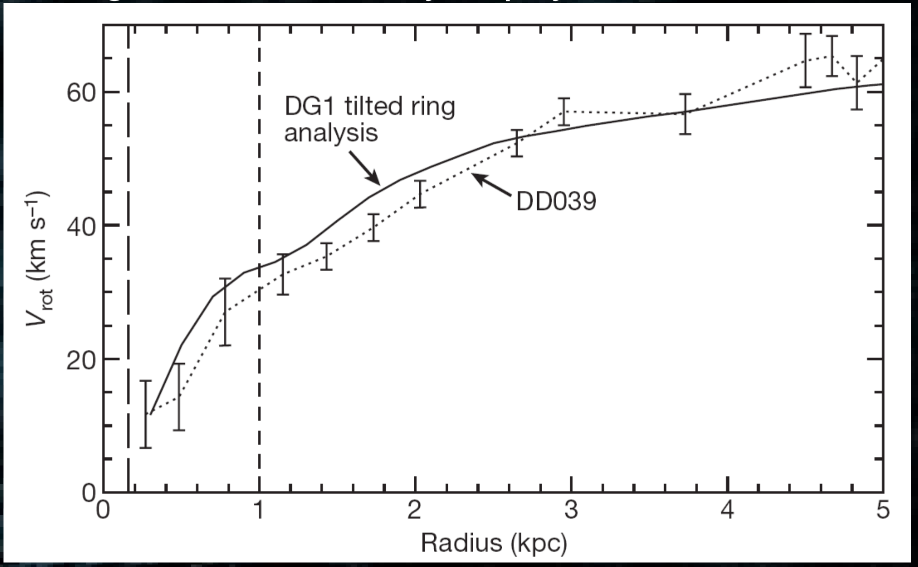
Kinematics data are available for the MW:
→ try to use them to improve predictions

Subhalos:
Small sclae issue + more efficient tidal stripping in the disk and the bulge leading to a dark disk (cf Read et al)

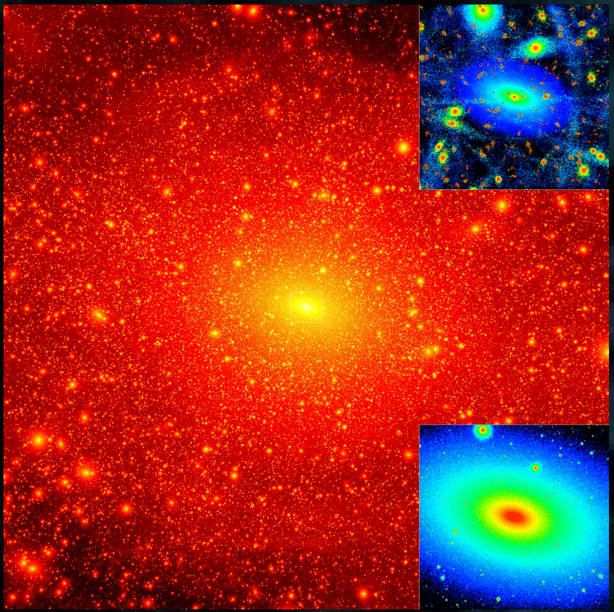
Galactic center:
Adiabatic compression might increase the DM density, but competition with dynamical friction from SF feedback re-heating the gas.

=> Still large uncertainties

Governato et al 10:
CDM + high-resolution baryon physics can lead to cores



Dark matter inhomogeneities wandering around ?



Via Lactea (Diemand et al)

CLUMPY COLD DARK MATTER

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cores in globular clusters, and in galactic nuclei. The enhanced annihilation rate in clumps can lead to a significant contribution to the diffuse γ-ray background, as well as emission from the Galactic center. Results from terrestrial dark matter detection experiments might be significantly affected by clumpiness in the Galactic halo.

Mini-dark halos with intermediate mass black holes

HongSheng Zhao and Joseph Silk

(Dated: 1 June 2005 on Phys. Rev. Letters 95, 011301)

Further developed by Bertone et al

Vol 460 | 2 July 2009 | **doi:10.1038/nature08083**

An intermediate-mass black hole of over 500 solar masses in the galaxy ESO 243-49

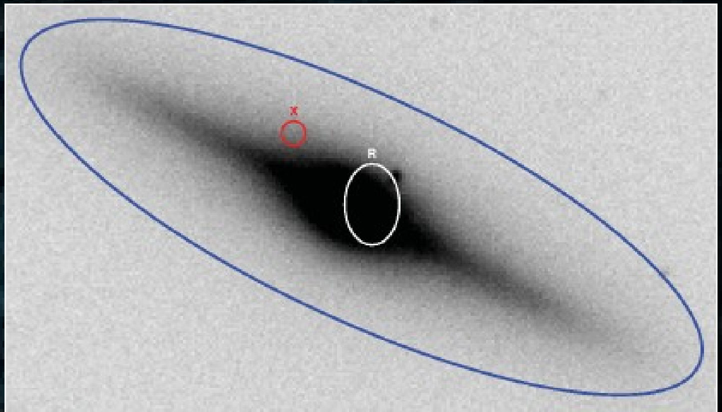
Sean A. Farrell[1,2]†, Natalie A. Webb[1,2], Didier Barret[1,2], Olivier Godet[3] & Joana M. Rodrigues[1,2]

Two main cases:

- Collective effect.
- A very bright single objects

(excluded from gamma-ray data,

Bringmann, Lavalle & Salati 09)

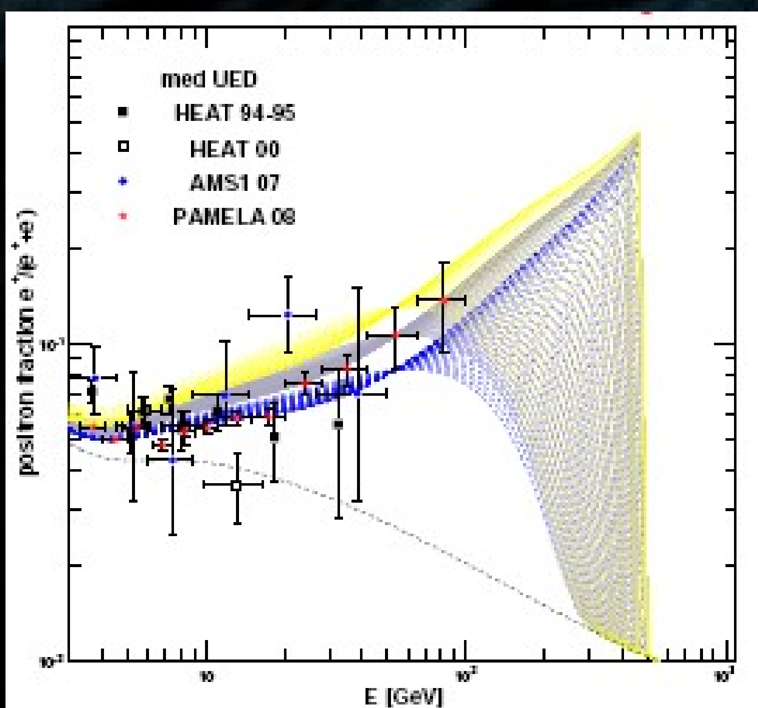


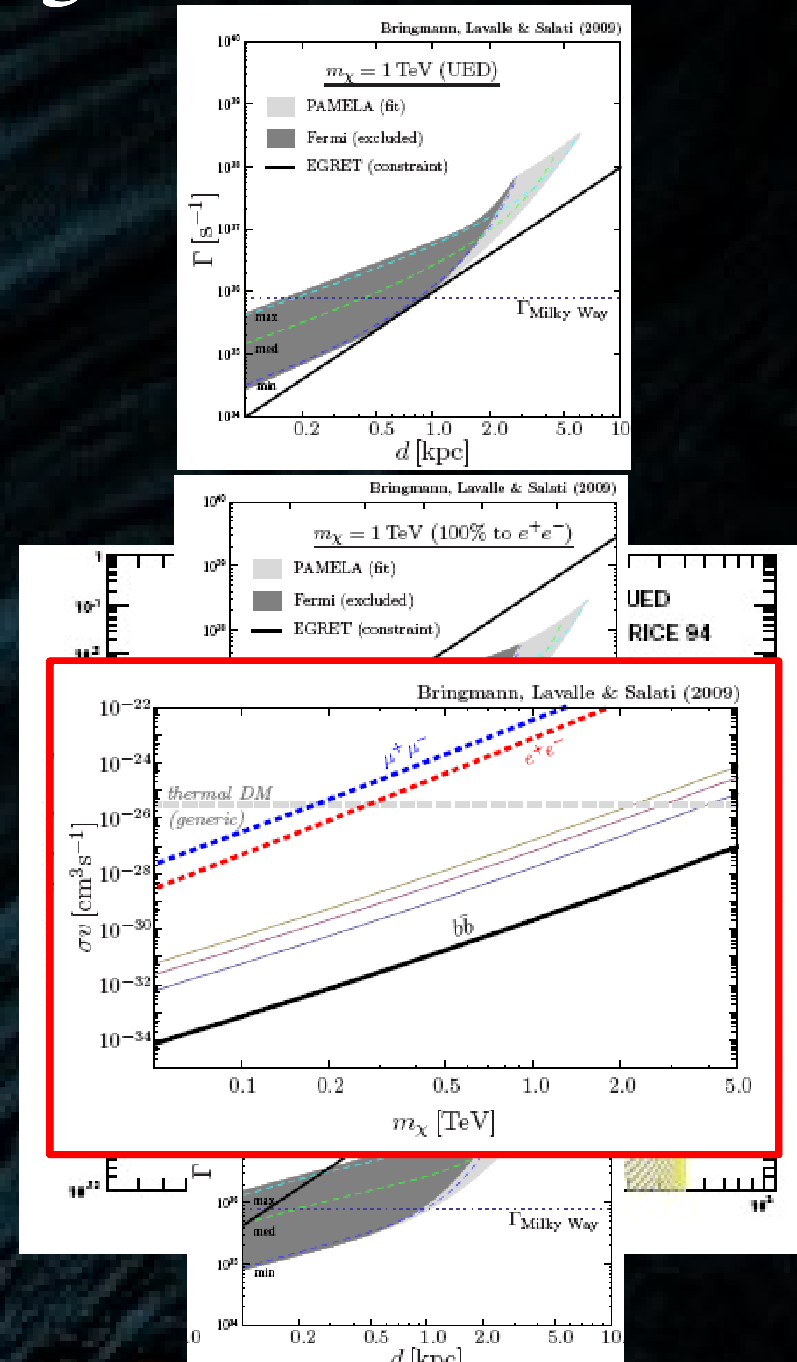
Single object wandering around

The game one can play:

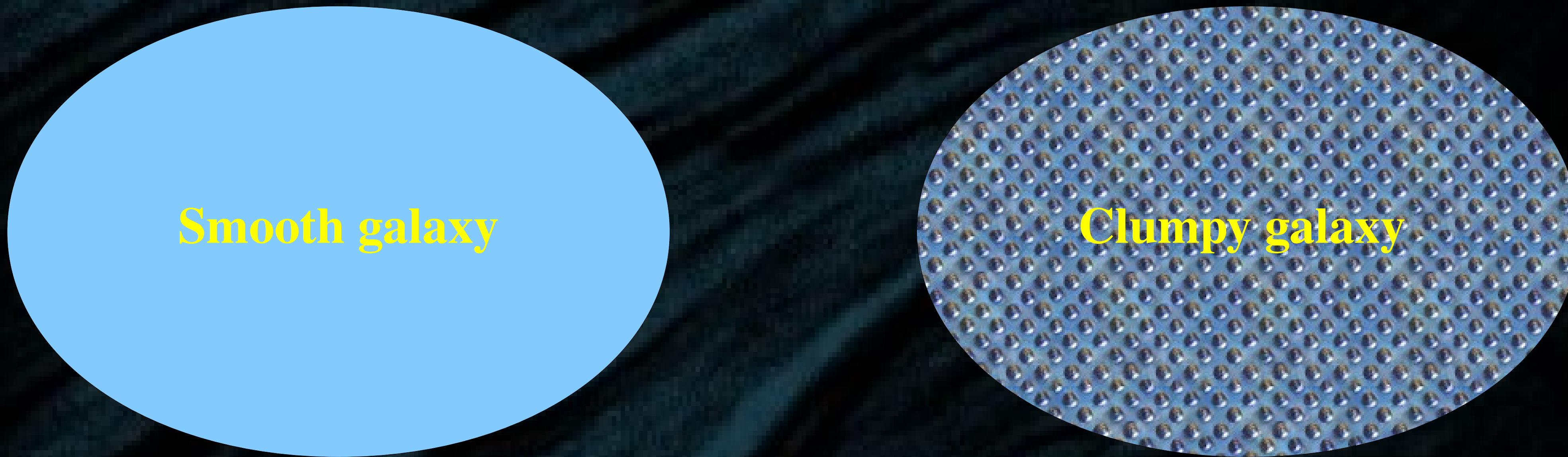
- Assume a single DM source at any distance d to the Earth.
- Assume a WIMP mass and its annihilation final states.
- Search for the brightness necessary to fit PAMELA.
- Check against other data (gamma, antiprotons, etc.)

Bringmann, Lavalle & Salati (2009)





Boost factor: a simplistic view



$$\langle \rho(\vec{x}) \rangle \stackrel{\text{assumption}}{=} \rho(\vec{x})$$

Usual assumption: simulations provide us with the net density profile function ρ(r)

=> keep in mind that it comes from a fit of <ρ>

$$\Gamma_{\text{ann}}^{\text{smooth}}(\vec{x}) \propto \langle \sigma v \rangle \rho^2(\vec{x}) = \langle \sigma v \rangle \langle \rho(\vec{x}) \rangle^2$$

If clumps are considered:

$$\Gamma_{\text{ann}}^{\text{clumpy}}(\vec{x}) \propto \langle \sigma v \rangle \rho^2(\vec{x}) = \langle \sigma v \rangle \langle \rho^2(\vec{x}) \rangle$$

This allows to define the so-called boost factor:

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