Is there any room left for an exotic contribution to cosmic rays ?

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Overview

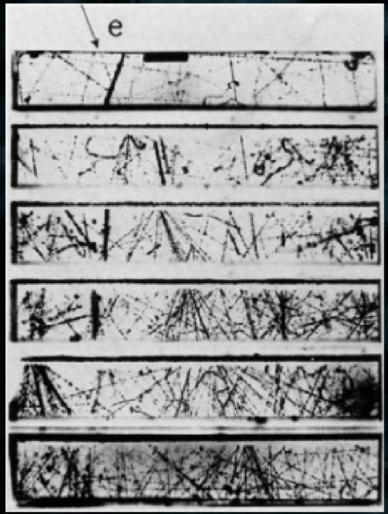
PART I: THE STANDARD LORE

- Short historical review
- Current observations of the Galactic electron and positron cosmic rays: the positron excess issue
- Review of the propagation modeling of electrons and positrons
- Secondary electrons and positrons
- Sources of primaries, basic predictions
- Discussion and perspectives

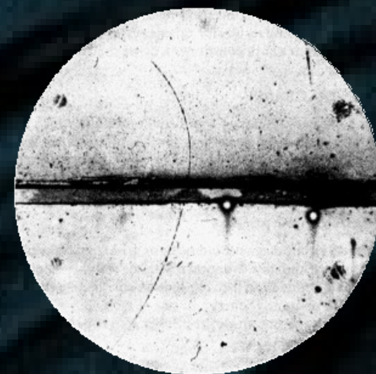
PART II: THE EXOTIC LORE

- Dark matter as potentially observable in antimatter cosmic rays
- Dark matter and positrons: standard predictions and the boost factor issue
- The role of cosmological substructures (clumpiness boost factor)
- Mixing the Sommerfeld effect with the clumpiness boost factor
- Latest news from latest N-body simulations
- Discussion and perspectives

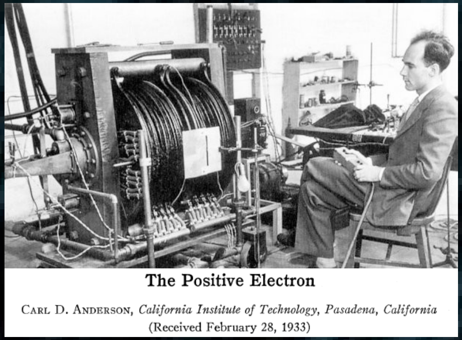
Brief historical review



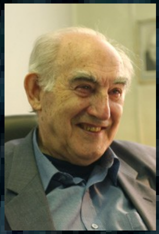
1[st] observation of cosmic ray electrons > 0.5 GeV
Earl (1961): e/p ~ 3%



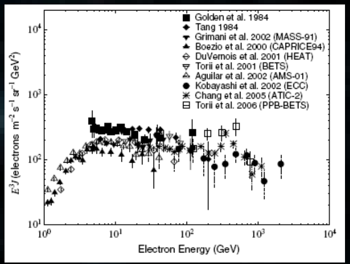
Discovery of the positron
Anderson, Phys. Rev. (1933)

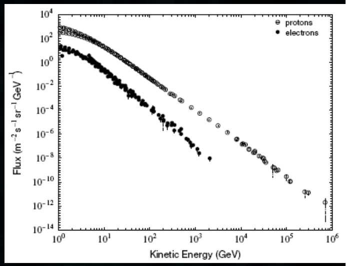


$$-D\Delta N + \frac{\partial}{\partial \varepsilon}[b(\varepsilon)N] = Q(\varepsilon, \mathbf{r}).$$



The origin of cosmic rays
Ginzburg & Sirovatsky (1964)

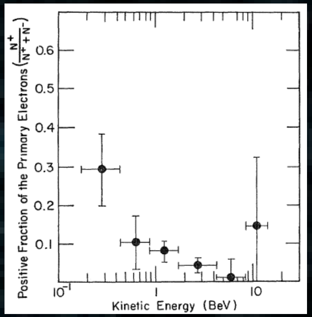


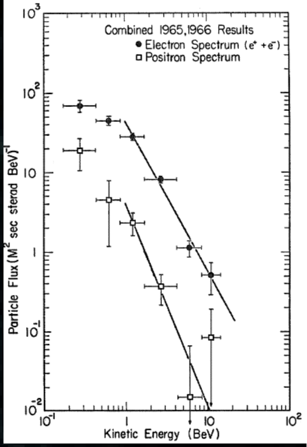


Review by Yoshida (2008)

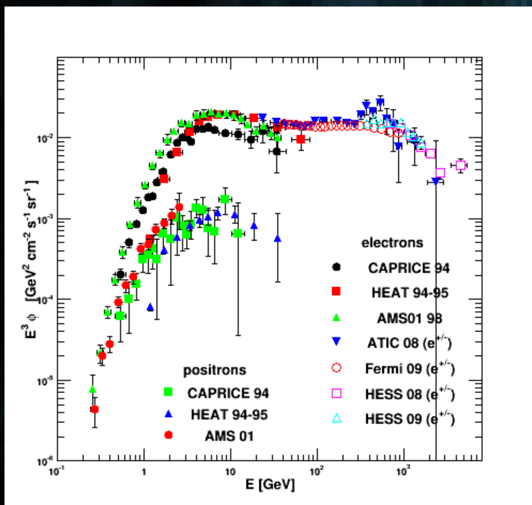
AMS-01 (1998)

Positron fraction
Fanselow et al (1969)

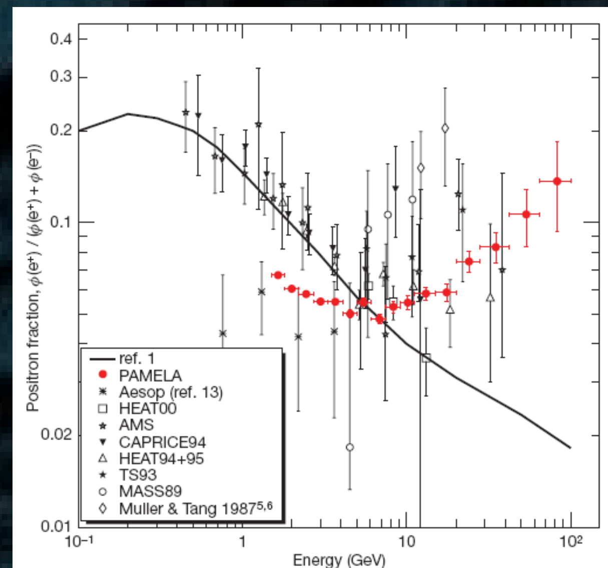




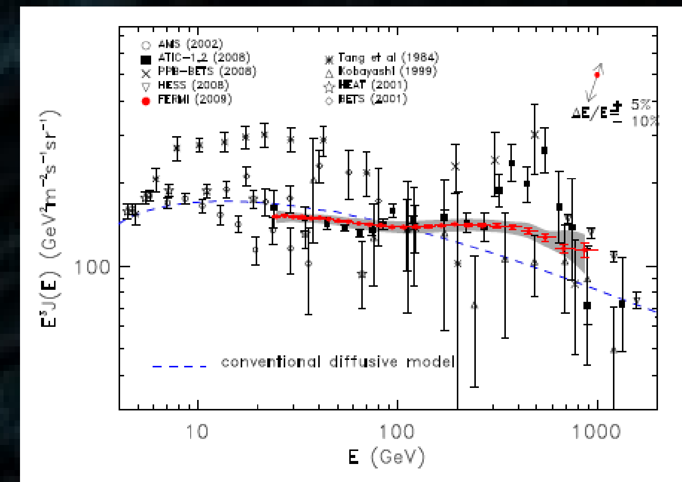
Current measurements of e^+'s and e^-'s



e+ and e-
data compilation



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

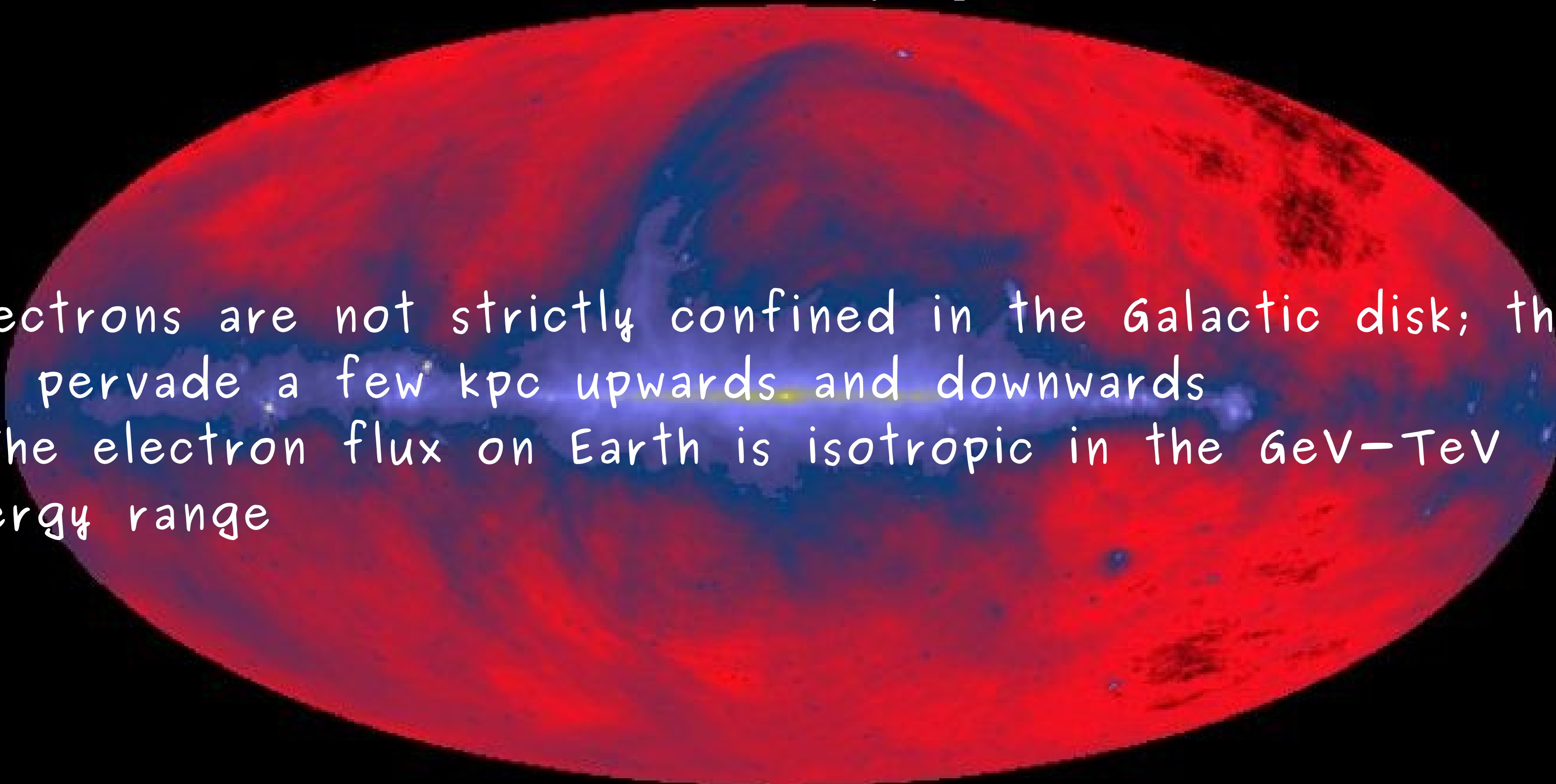


$(e^+ + e^-)$ HESS and Fermi
Aharonian et al (2009)
Abdo et al (2009)

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

Propagation of Galactic electrons
1. Observational facts

408 MHz all-sky map



- Electrons are not strictly confined in the Galactic disk; they can pervade a few kpc upwards and downwards
- The electron flux on Earth is isotropic in the GeV-TeV energy range

From Haslam et al data (1982)

Propagation of Galactic electrons
2. Phenomenology of transport

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

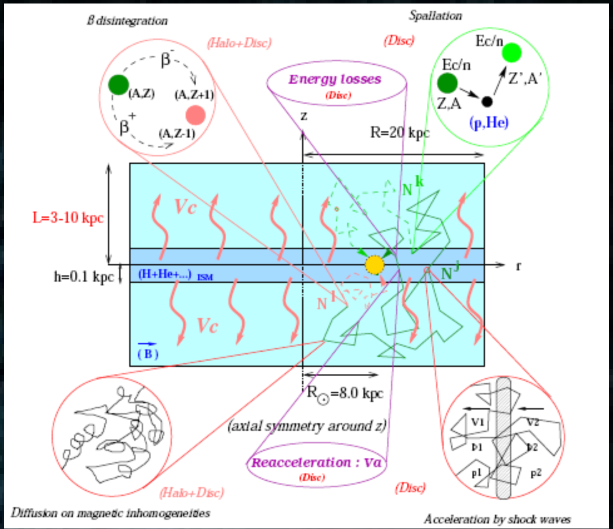
$$D_\mu \mathcal{J}^\mu + D_E \mathcal{J}^E = \mathcal{Q}$$

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

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

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

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

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

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

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)

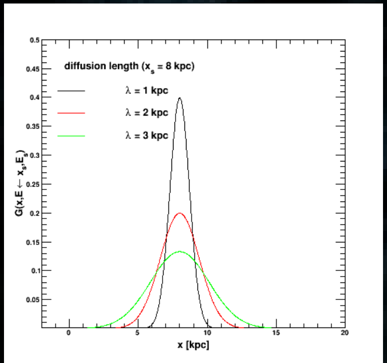
$$\frac{\partial \psi}{d\tilde{t}} - K_0 \Delta \psi = \tilde{Q}$$

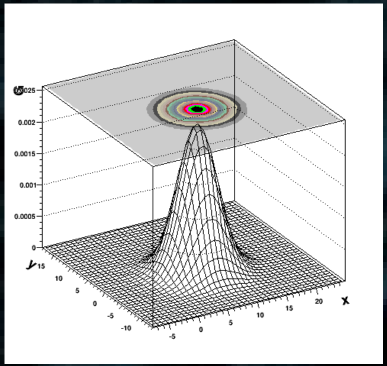
$$\tilde{\mathcal{G}}(\vec{x},\tilde{t} \leftarrow \vec{x}_s,\tilde{t}_s) = \frac{1}{\pi^{\frac{3}{2}}\lambda^3} \exp\left\{-\frac{|\vec{x}_s - \vec{x}|^2}{\lambda^2}\right\}$$

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

$$\begin{aligned}\psi(\vec{x},\tilde{t}) &= \int_{-\infty}^{t_0} d\tilde{t}_s \int d^3\vec{x}_s\,\tilde{\mathcal{G}}(\vec{x},\tilde{t} \leftarrow \vec{x}_s,\tilde{t}_s)\,\tilde{\mathcal{Q}}(\vec{x}_s,\tilde{t}_s)\\ \Leftrightarrow \mathcal{N}(\vec{x},E) &= \int_E^{\infty} dE_s \int d^3\vec{x}_s\,\mathcal{G}(\vec{x},E \leftarrow \vec{x}_s,E_s)\,\mathcal{Q}(\vec{x}_s,E_s)\end{aligned}$$

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

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

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.

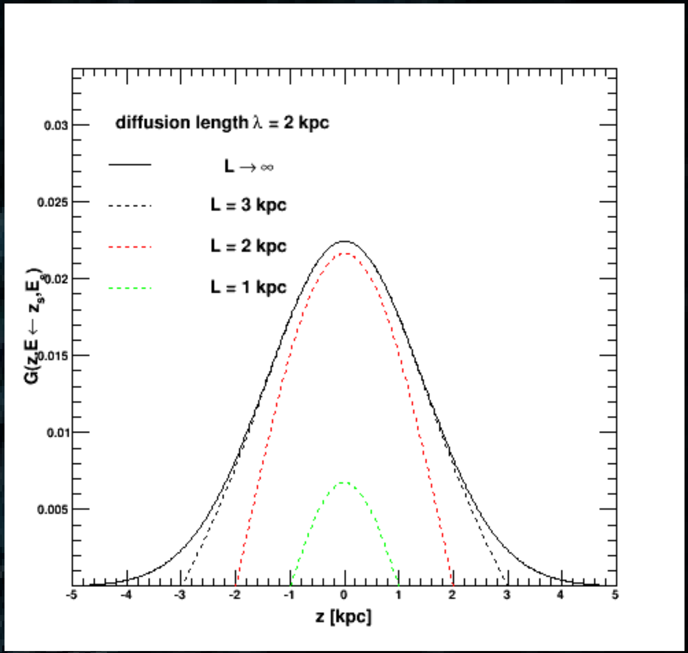
If **λ~L**, then one has to account for the **vertical boundary condition**: N(|z|=L) = 0.

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

Example of the image method

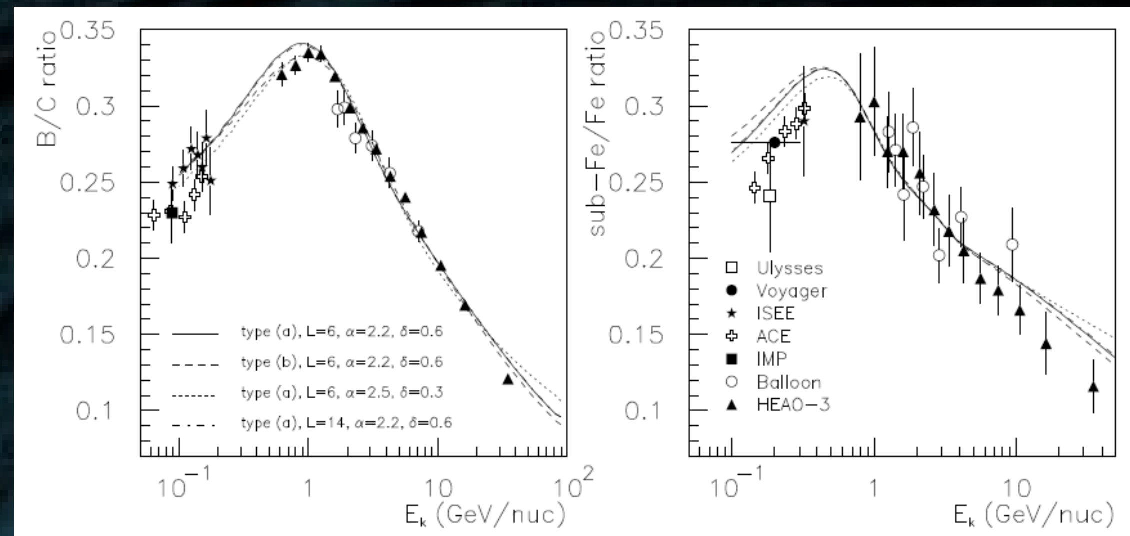
$$\tilde{V}(z, \tilde{t} \leftarrow z_S, \tilde{t}_S) = \sum_{n=-\infty}^{+\infty} (-1)^n \, \mathcal{V}_{1D}(z, \tilde{t} \leftarrow z_n, \tilde{t}_S)$$

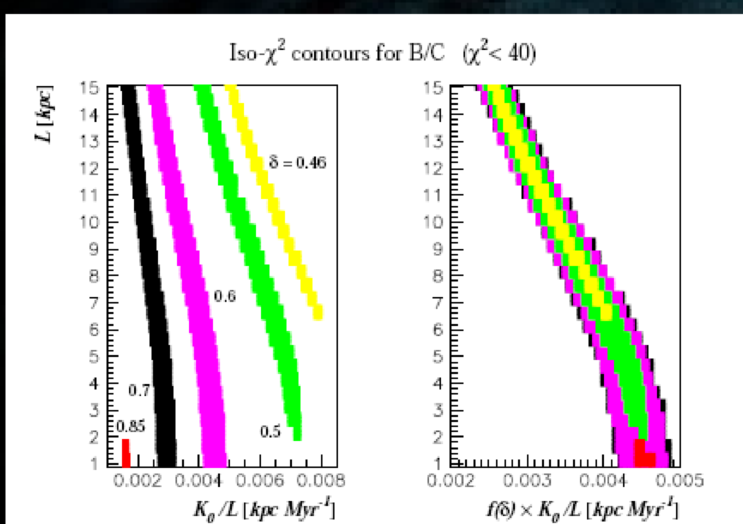
$$z_n = 2\,L\,n \; + \; (-1)^n \, z_S$$



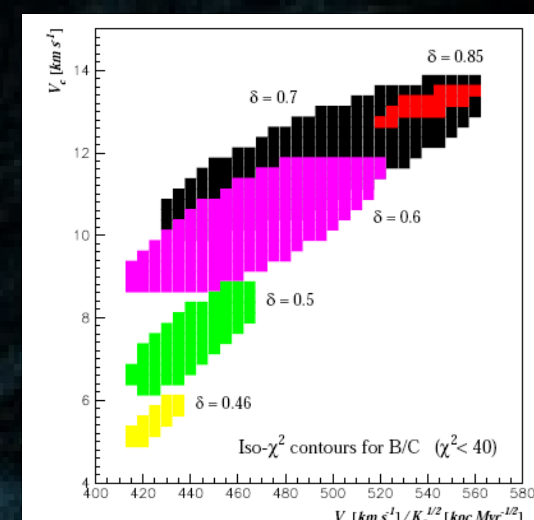
Propagation parameters

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)



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)

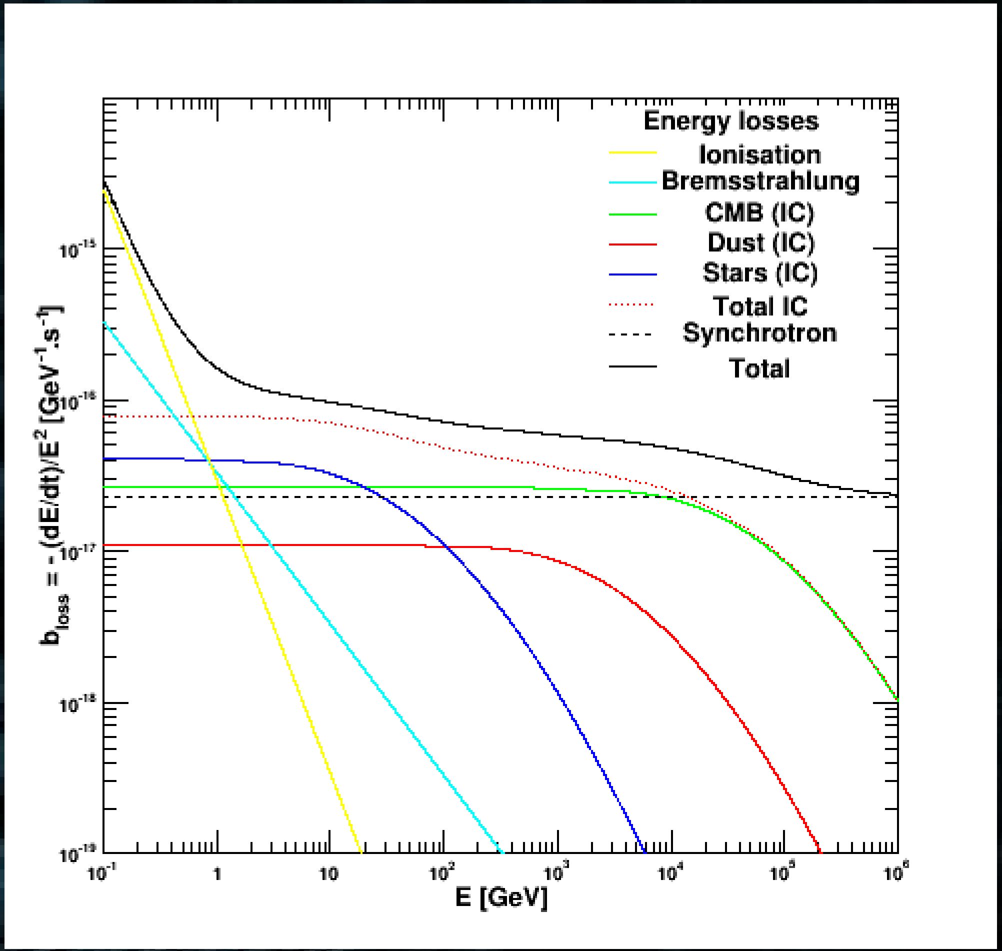
(i) Interactions with the ISM (in the disk): Bremsstrahlung (braking radiation), ionisation

$$\begin{aligned} b_{\rm ion}(E) &\propto n_{\rm gas}\ \ln(E) \\ b_{\rm brem}(E) &\propto n_{\rm gas}\ E\ \ln(E) \end{aligned}$$

(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 in propagation scale

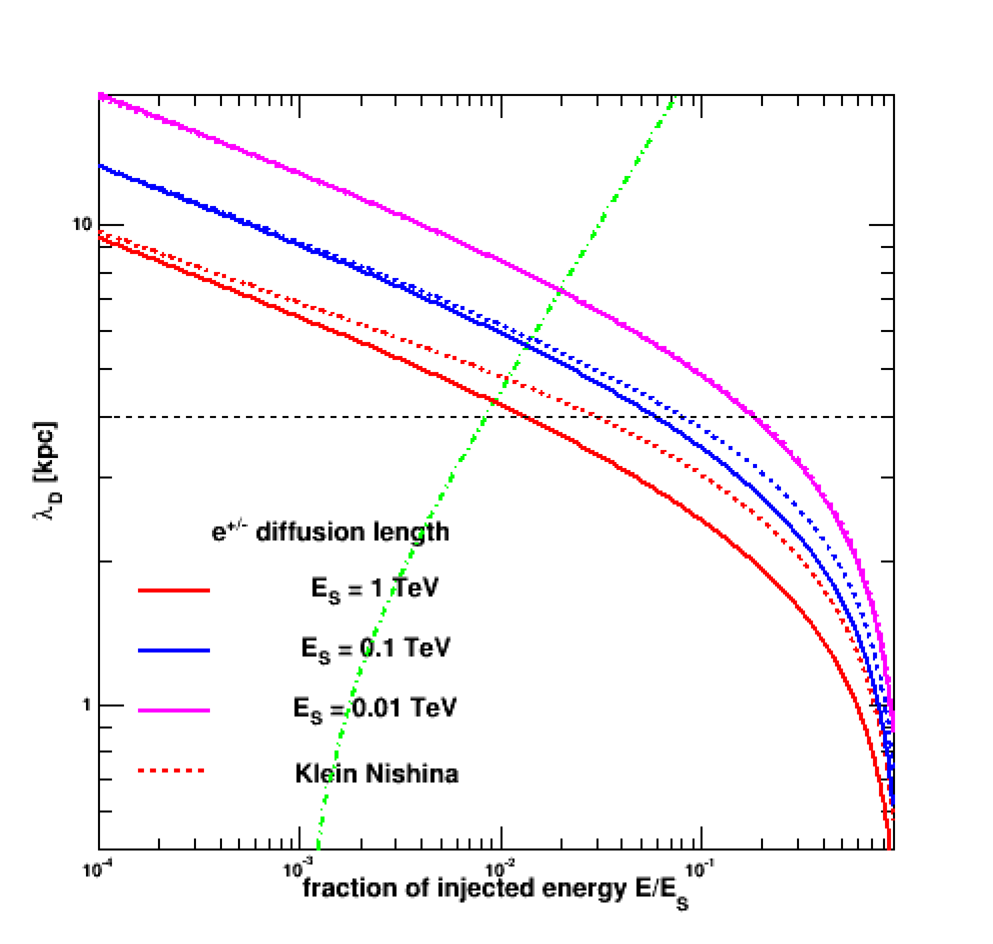
Transport mostly set by **spatial diffusion** and **energy losses**

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

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

Propagation scale: a very useful quantity

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

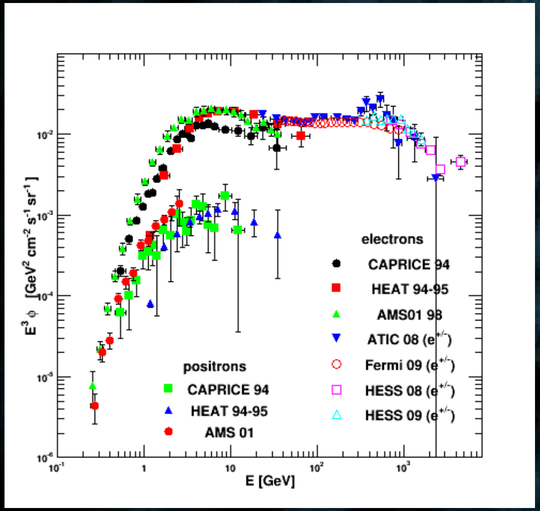


Electron horizon limited to a few kpc

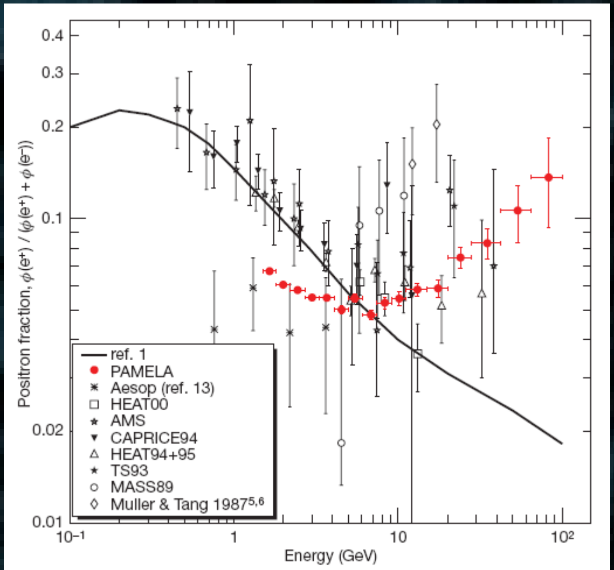
$$K_0 = 0.012\,\mathrm{kpc}^2/\mathrm{Myr};\ \tau = 10^{16}\mathrm{s};\ \delta = 0.7$$

$$\lambda(E = 1\,\mathrm{GeV} \leftarrow E_s \gg E) \approx 6\,\mathrm{kpc}$$

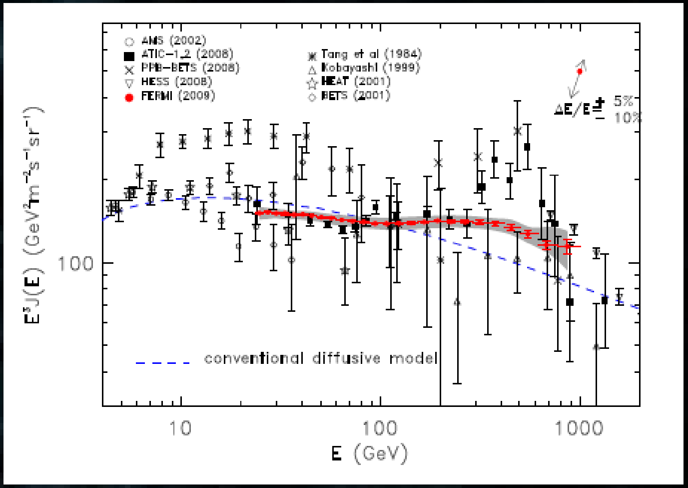
Current measurements of e^+'s and e^-'s



e+ and e-
data compilation



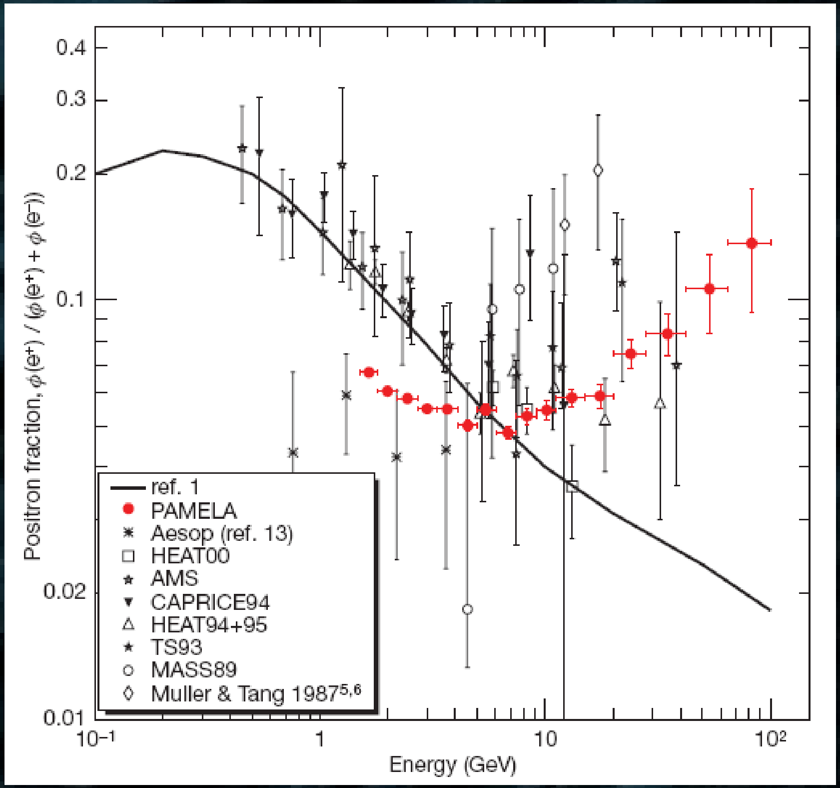
$e^+/(e^+ + e^-)$ PAMELA
Adriani et al (2009)



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

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

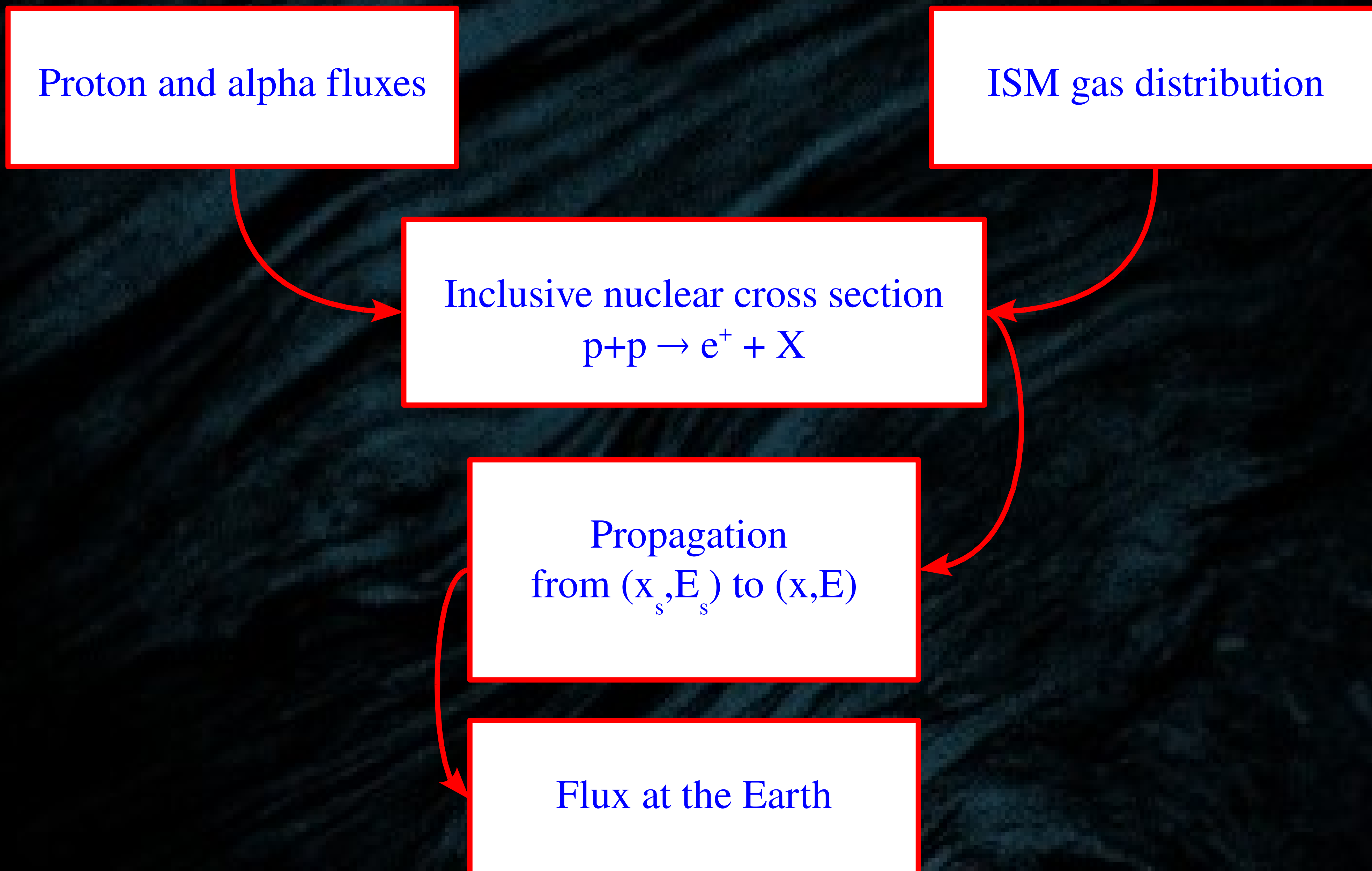
Can secondary e^+'s explain the PAMELA data ?



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

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

Short recipe for secondaries



Short recipe for secondaries

Proton and alpha fluxes

ISM gas distribution

The source term

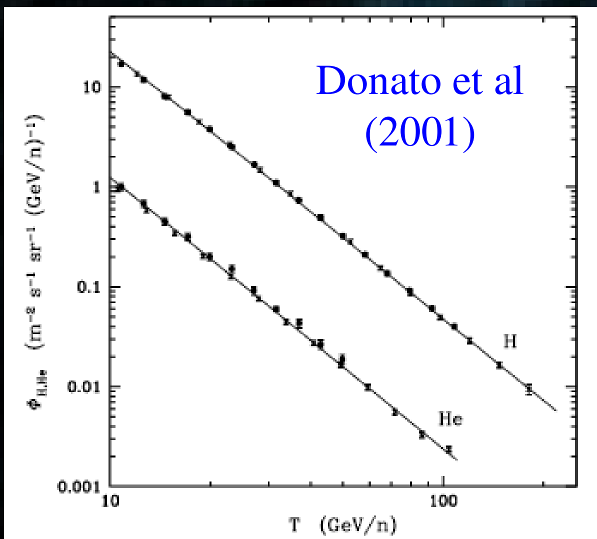
Inclusive nuclear cross section
$p+p \rightarrow e^{+} + X$

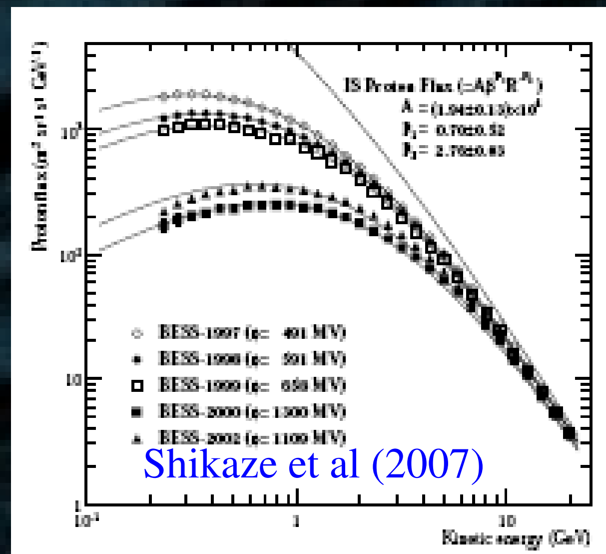
Propagation
from (x_s,E_s) to (x,E)

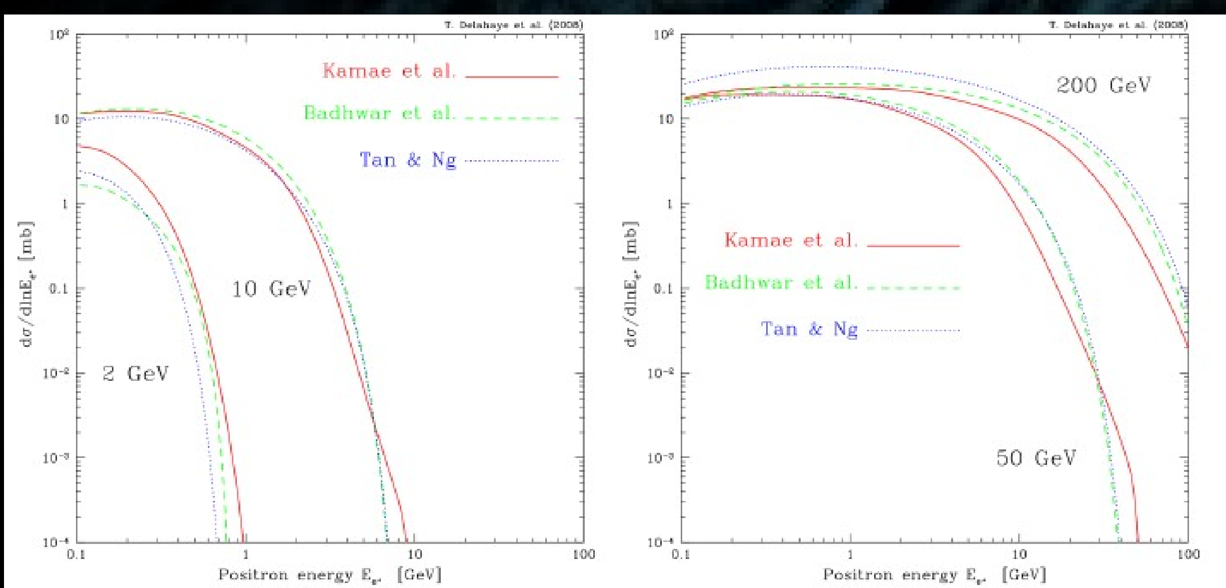
Flux at the Earth

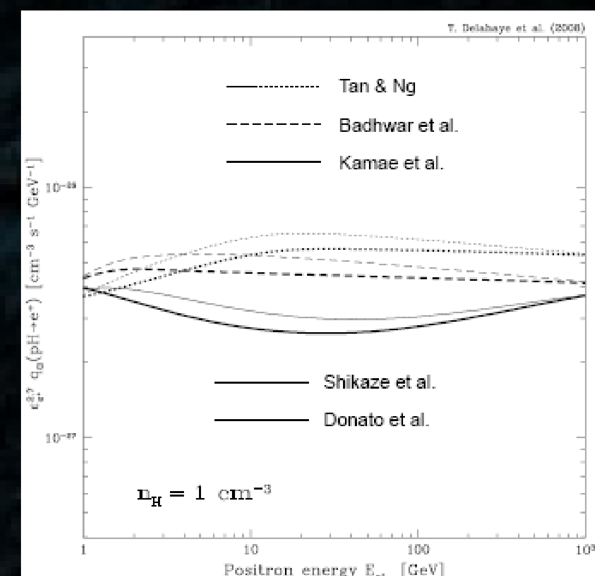
Each box contains uncertainties !!!

Uncertainties on the source term



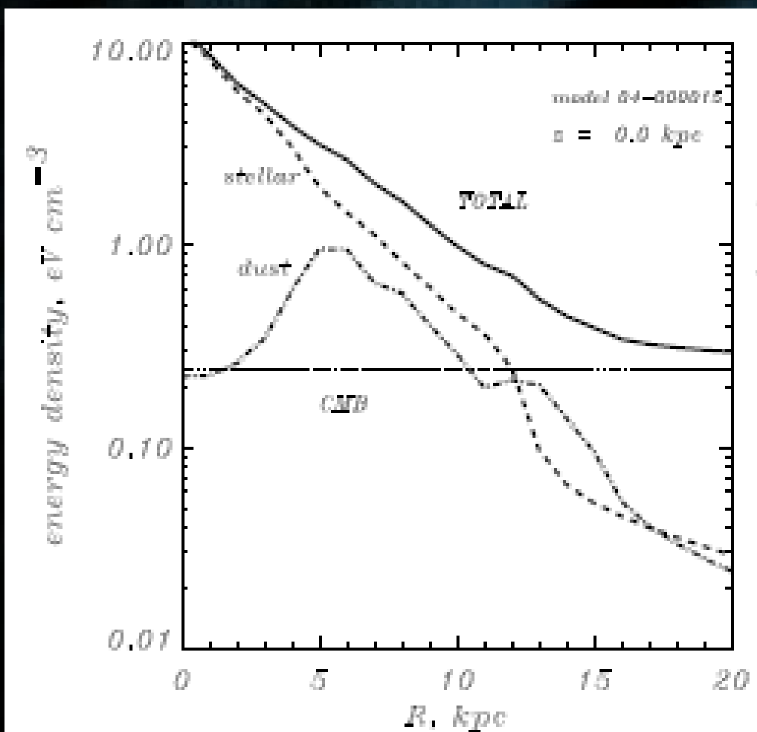




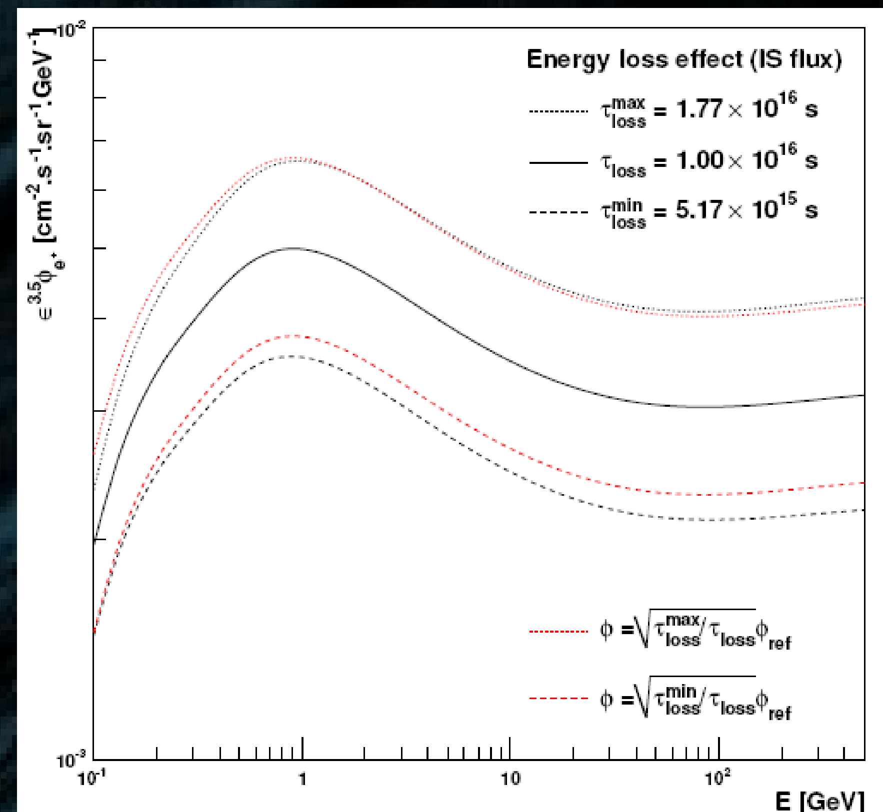


Delahaye et al (2009)

Uncertainties from energy losses



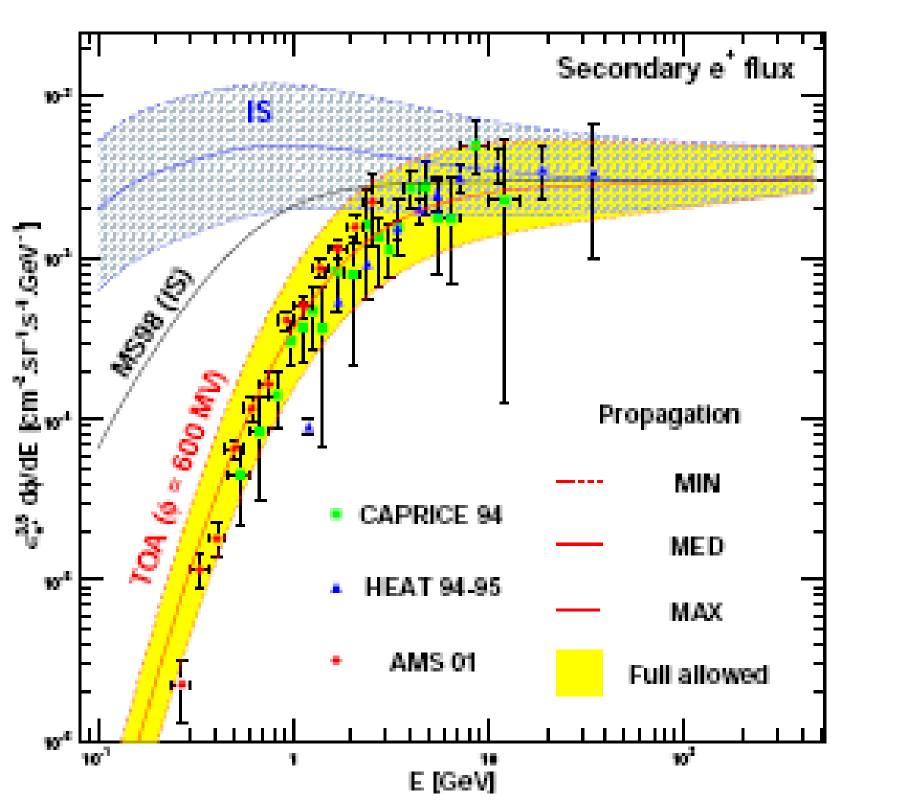
Strong et al (2000)



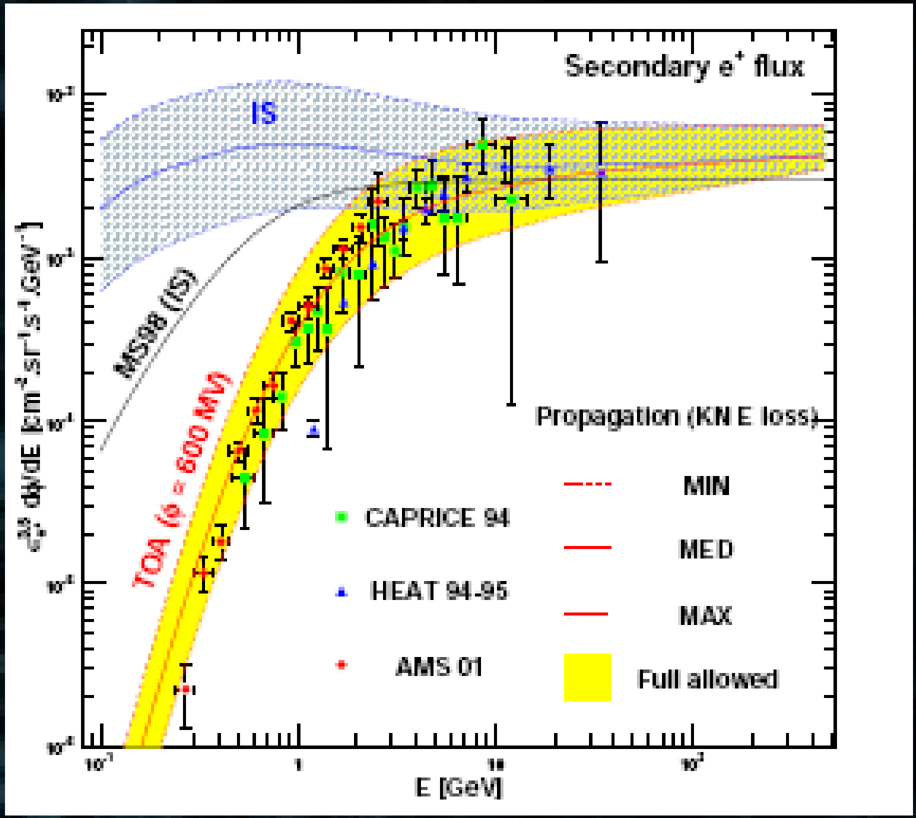
Delahaye et al (2009)

Uncertainties from propagation parameters

Delahaye et al (2009)

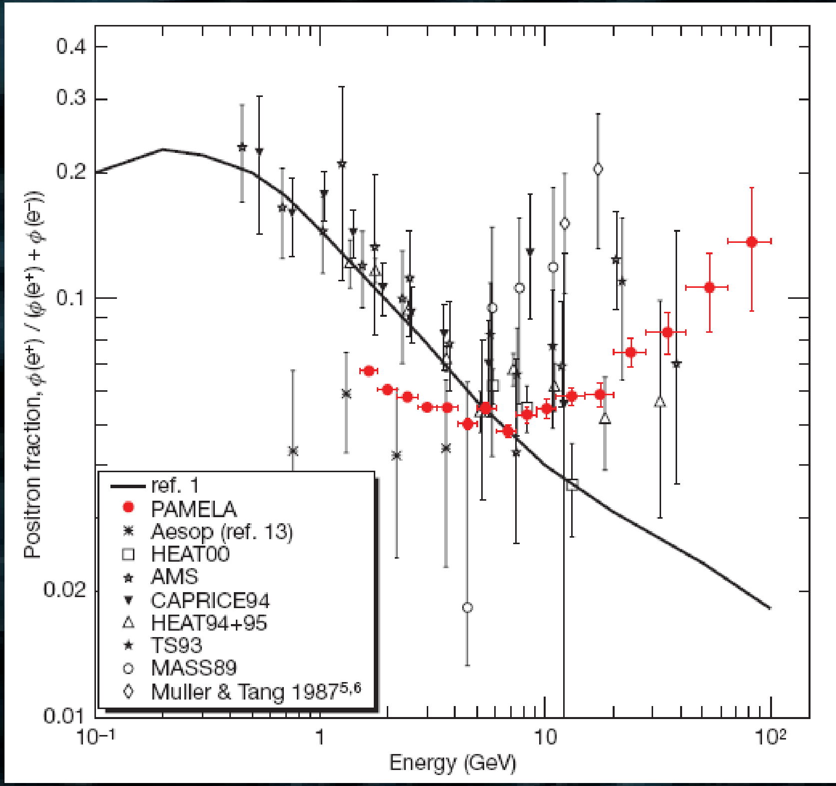


Same but with relativistic losses



Index close to 3.5. Time for a short blackboard explanation ?

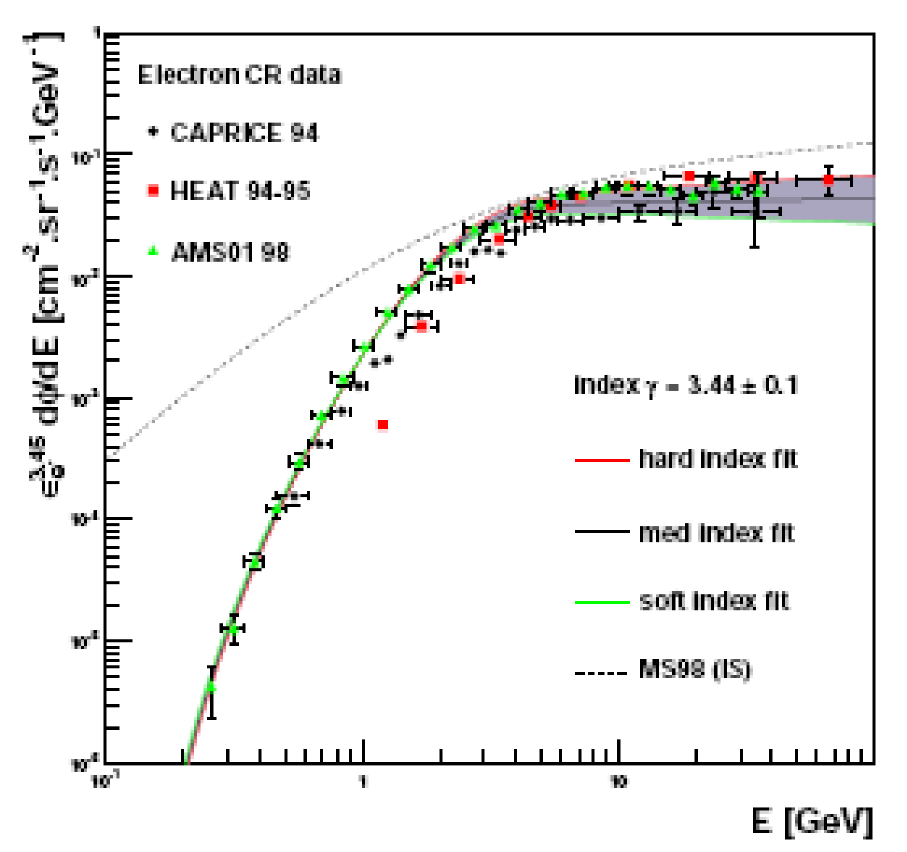
Positron fraction !



$$f_{e^+} \equiv \frac{\phi_{e^+}}{\phi_{e^+} + \phi_{e^-}}$$

Well, we also need the electrons ...
but no need for predictions if data ...

Electrons ...



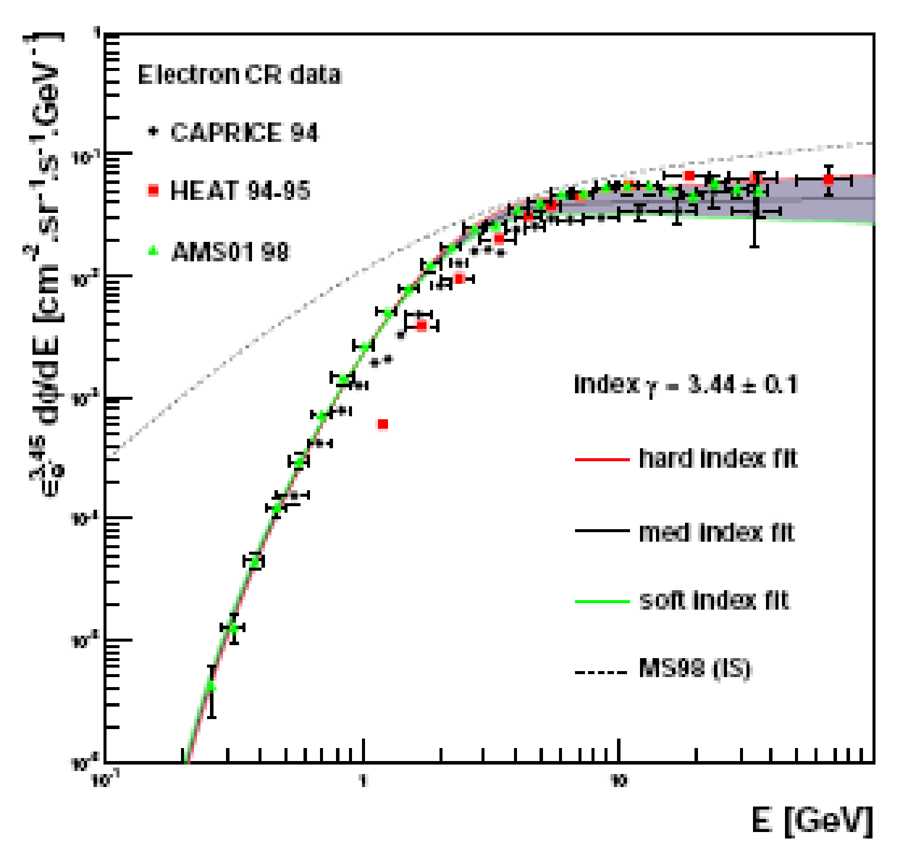
Why using the data instead of predictions ?

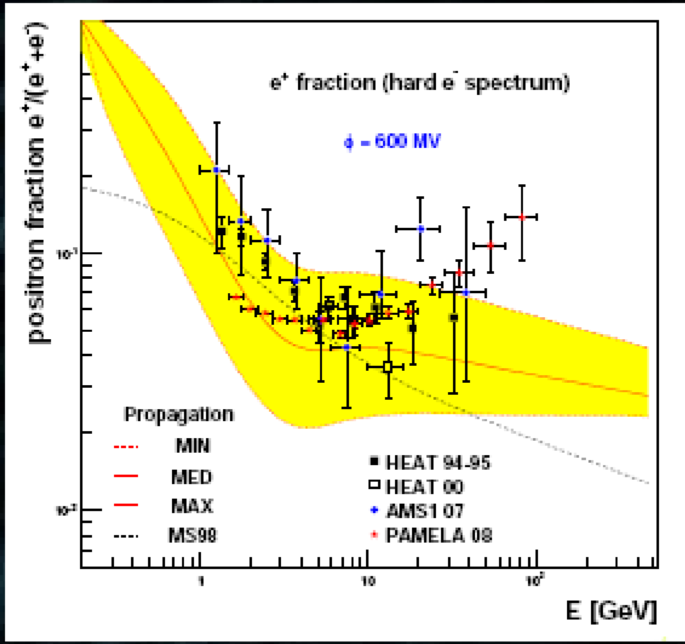
- There are data !
- There are primary sources of electrons: no theoretical uncertainties when using data.

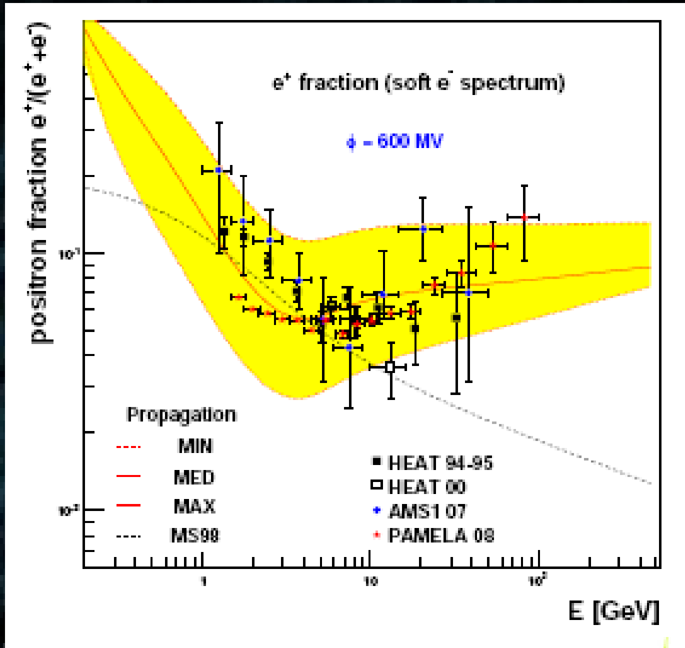
But ....

- Limited energy range ~ 1-50 GeV (pre-Fermi data).
- Scatter from an experiment to another ~ factor of 2 in flux, but larger when using different fits.

From electrons to positron fraction

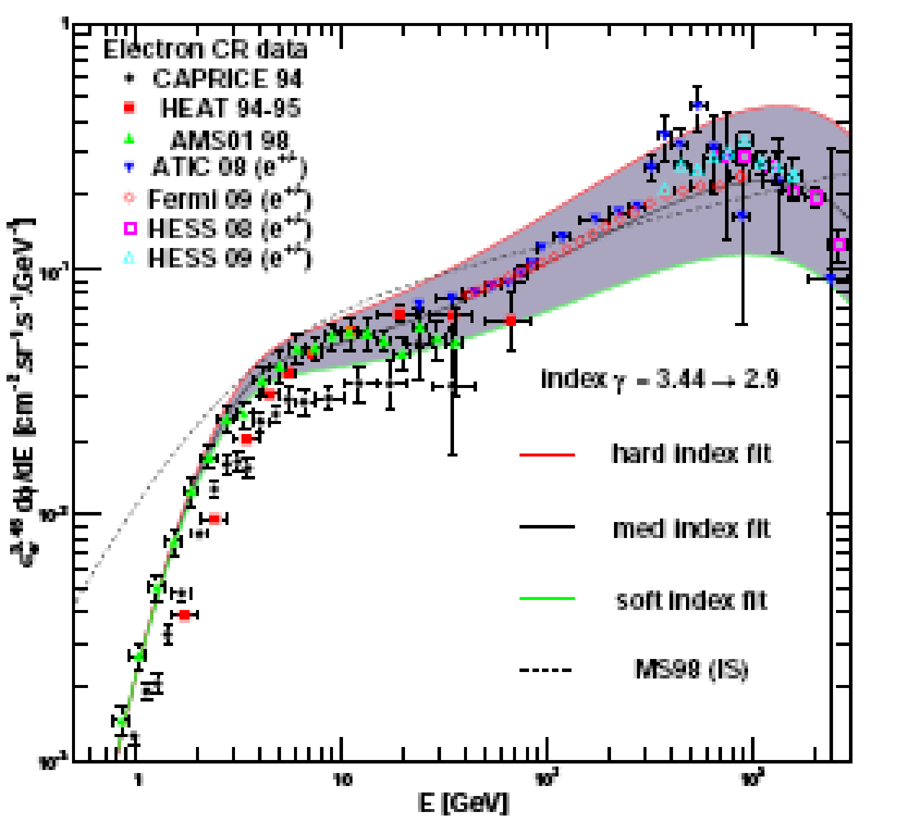


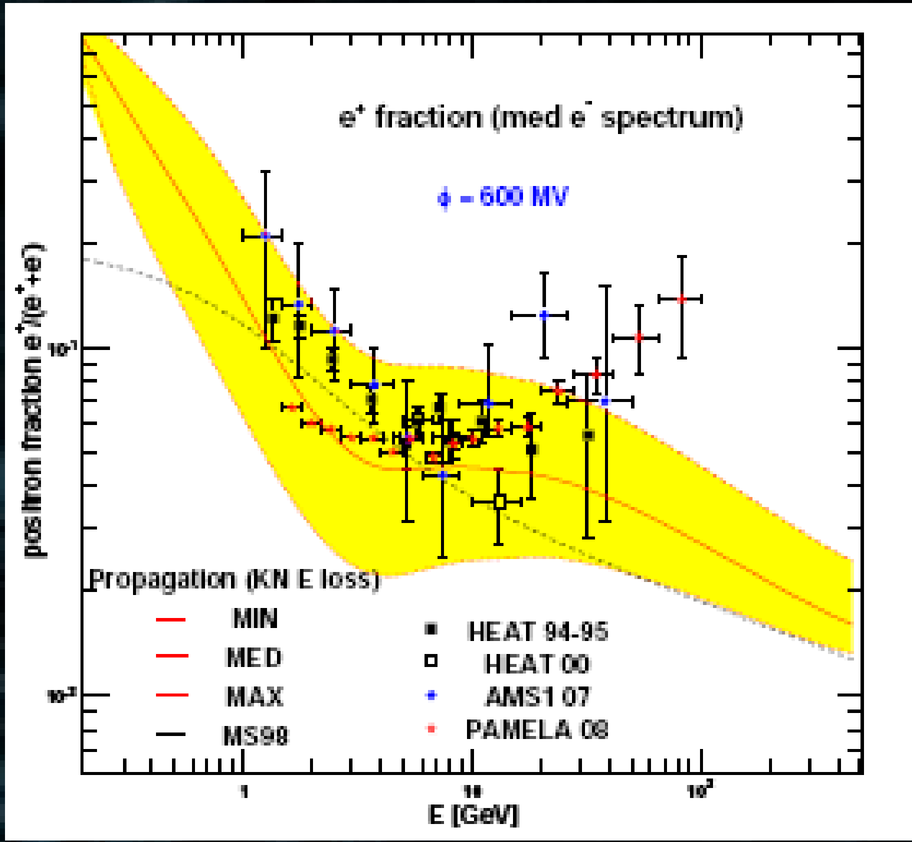




Let us play the devil's advocate ...
Hard versus soft electron spectrum
(Delahaye et al, 2009)

Fermi has just released the denominator



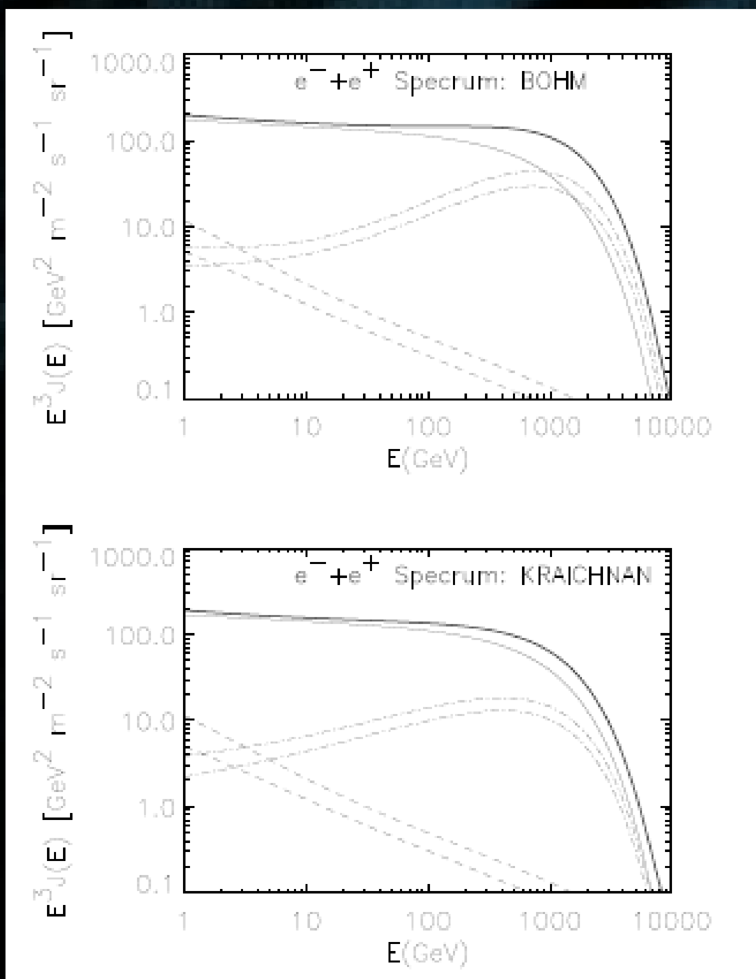


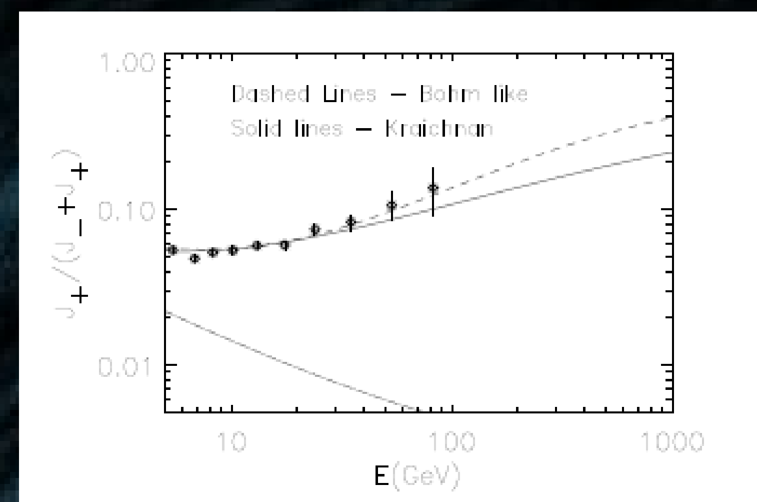
Uncertainties are still large ... (relevance of analysis for additional primaries ?)
Yet, a conventional secondary origin seems unlikely ...

"Primary" secondaries ?

Blasi (2009)

Secondaries created in sources are accelerated like primaries



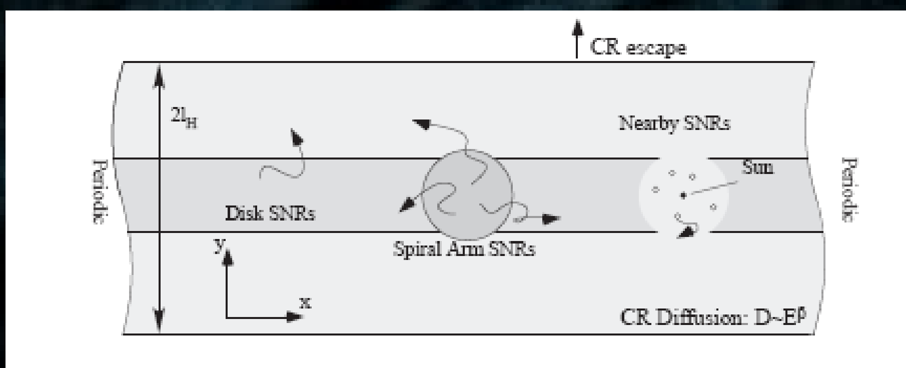


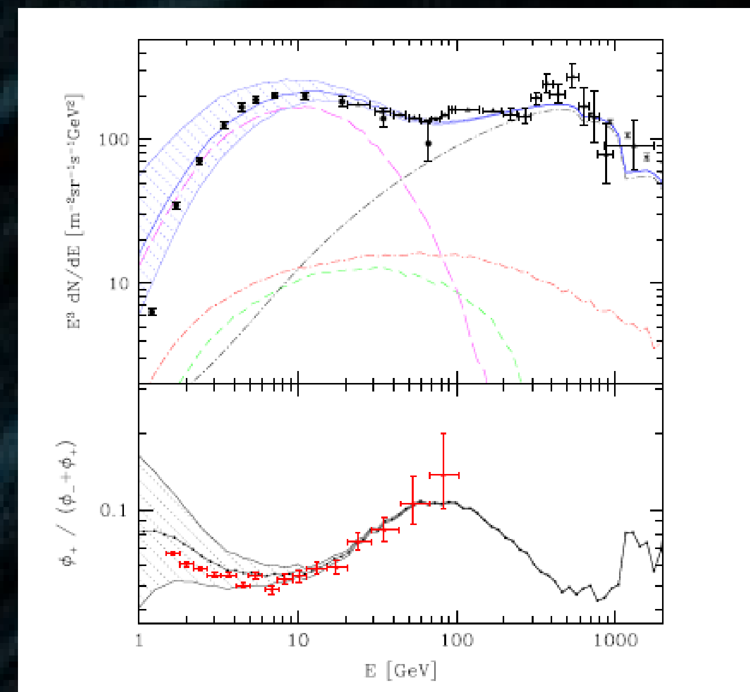
But ...

- Calculation "à la louche"
- Time effects important at high energy
- Antiprotons should also be produced ...

Spatial effects ?

Shaviv et al (2009)

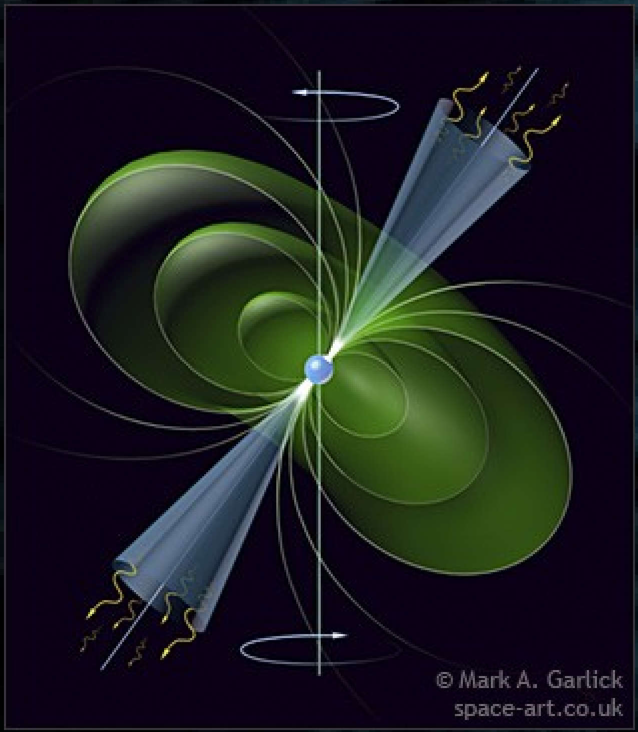


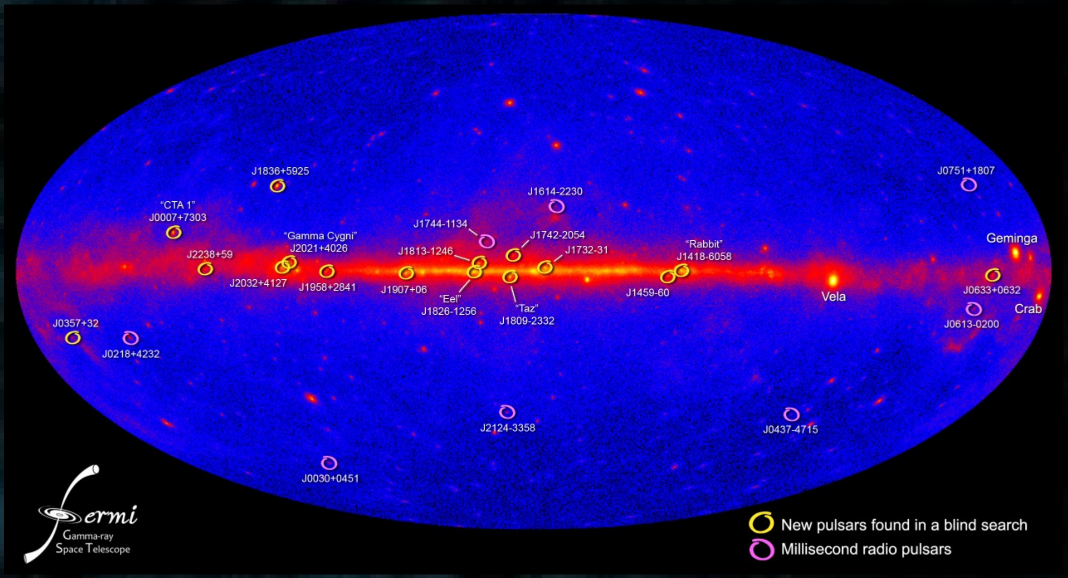


3 populations of electrons:
- From sources in the nearest arm
- From the disk
- From nearby SNRs

+ secondary positrons ... this might make it.

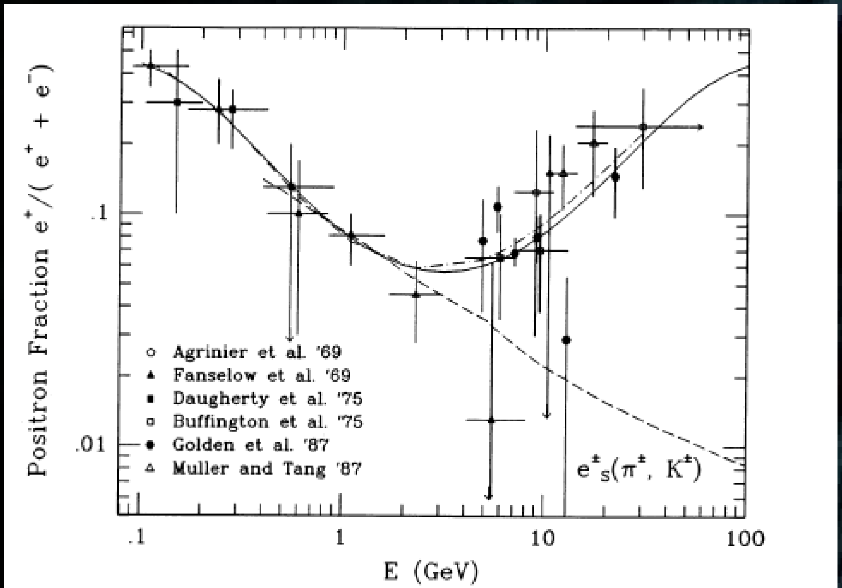
"Standard" positron sources ? ... Pulsars !





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

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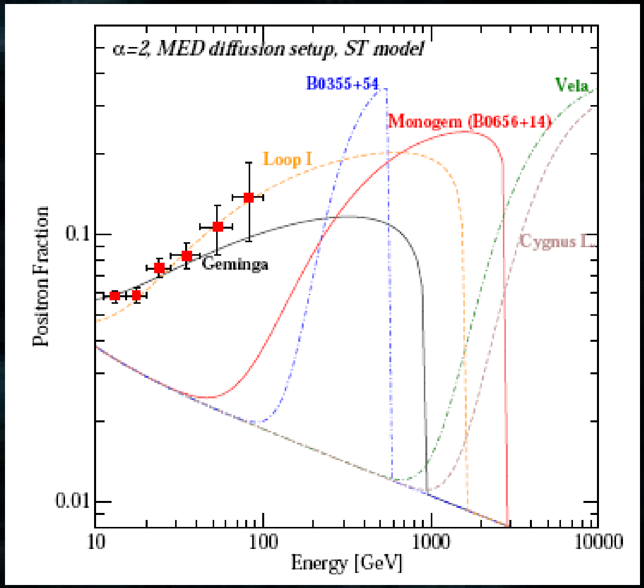
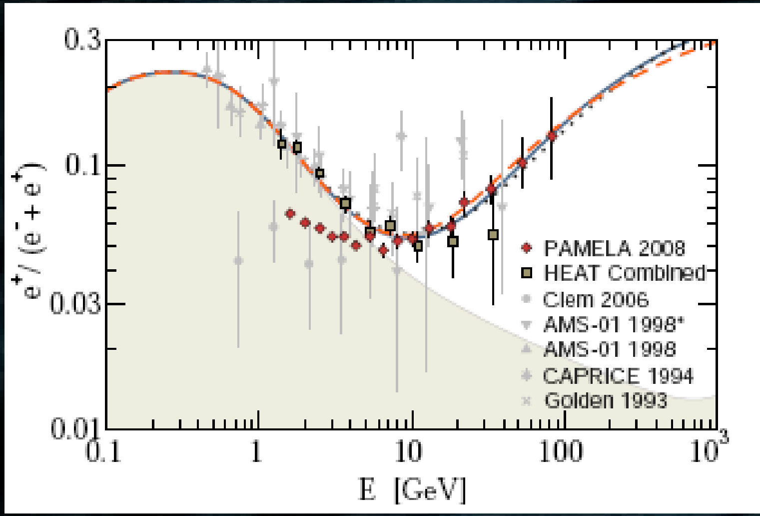
Received 1988 October 24; accepted 1988 December 29

nate. There are many suggested sources of electrons and positrons at high energy: Type I SN explosions (Colgate and Johnson 1960; Colgate 1983); pulsar magnetospheres (Gunn and Ostriker 1969; Arons 1983); dark matter annihilation (Rudaz and Stecker 1988). Most of the positrons are produced by pair production in these sources.

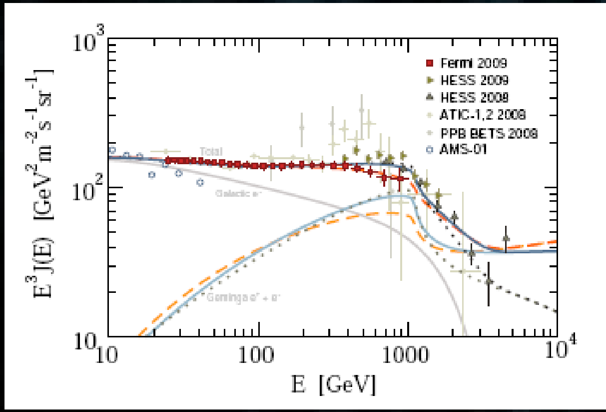
"Standard" positron sources ? ... Pulsars !

Profumo (2009)





Yuksel et al (2009)

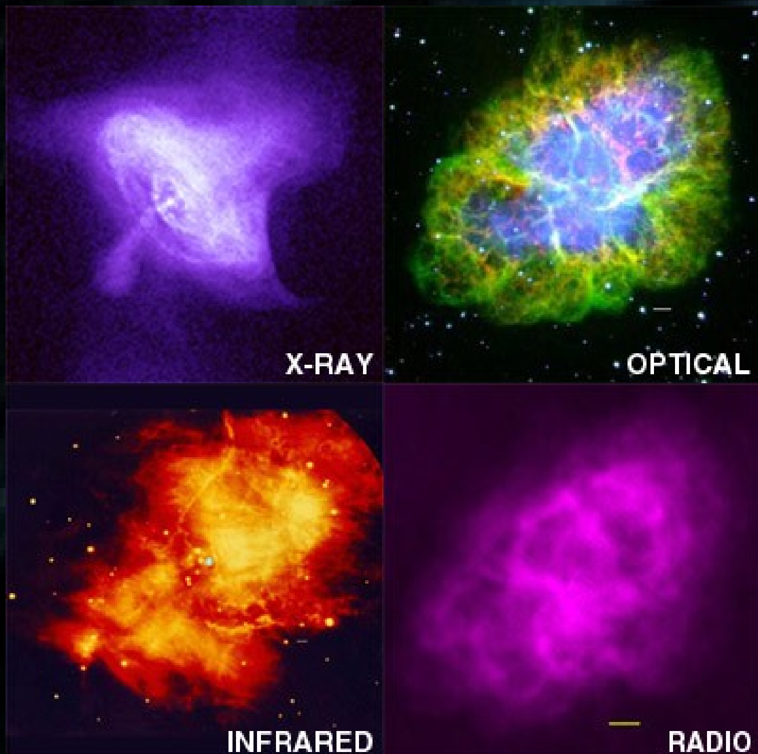


Caveats:

- Inconsistencies in the propagation setup
- Theoretical uncertainties ?

Yet, pulsars are indeed very good candidates (not a scoop !)

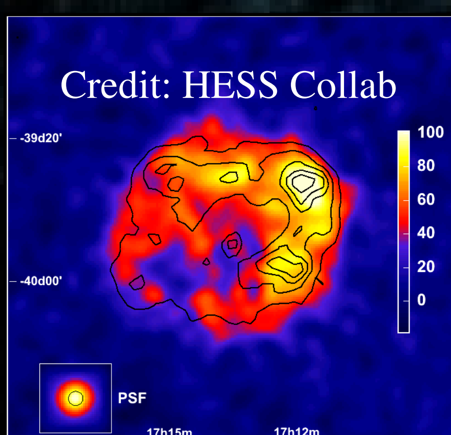
"Standard" primaries: the big mess



Standard paradigm:

• Cosmic rays in the GeV-TeV diffuse on magnetic inhomogeneities (Ginzburg & Sirovatskii, 1964)

• They originate from the vicinity of supernova remnants (SNRs) or pulsars where they are accelerated by shock waves (Drury, 1983).



But many many many many uncertainties!

• Spectral features of cosmic rays released in the ISM: spectral index ~2, energy range ? max energy ? Environment effects ? Species effects ?

• Relative fraction of e/p in sources ?

• Copious sources of positrons ?

• Time effects at the kpc scale (relevant for electrons)

standard paradigm, but not standard model!

Conclusions of Part I

General statements:

• The principles underlying the physics of cosmic ray transport have been understood for a long time (Ginzburg & Sirovatskii, 1964).

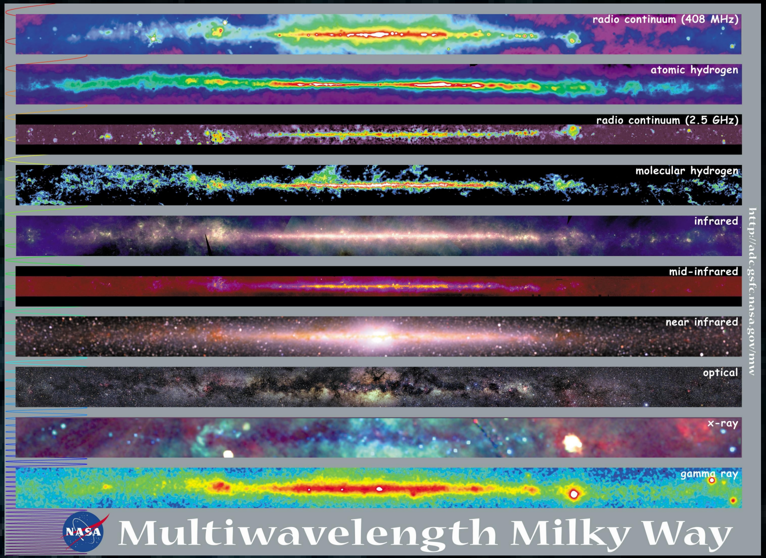
• Yet, the unprecedented precision and amount of data allow and require to go farther: better constraints on parameters + refinements in the models themselves. (more fundamental links between turbulence and transport, etc.).

• Semi-analytical studies help in selecting the relevant information and parameters: complementary to full numerical tools (e.g. GALPROP – Strong, Moskalenko et al).

• Although there is a standard framework, it is fair to say that there is no standard model of cosmic rays at the moment.

On the positron excess and electron cosmic rays:

• A secondary origin seems unlikely, but ...
• Nearby pulsars could provide enough primaries
• Important to understand electrons
• High energy means short scale: spatial+time fluctuations!
• Theoretical uncertainties still very large (sources + ISM + propagation), more data!



Strategy:

• Multimessenger + multiwavelength
• Connect people (ISM+turbulence+sources+transport)

Overview

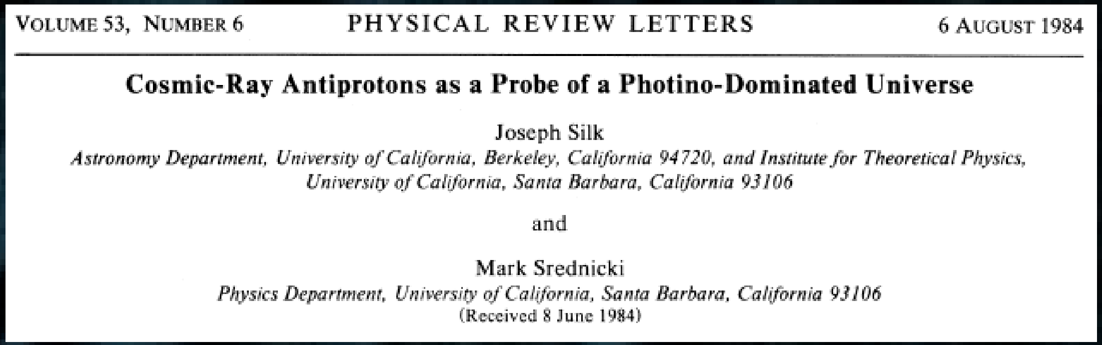
PART I: THE STANDARD LORE

- Short historical review
- Current observations of the Galactic electron and positron cosmic rays: the positron excess issue
- Review of the propagation modeling of electrons and positrons
- Secondary positrons
- Sources of primaries, basic predictions
- Discussion and perspectives

PART II: THE EXOTIC LORE

- Dark matter as potentially observable in antimatter cosmic rays
- Dark matter and positrons: standard predictions and the boost factor issue
- The role of cosmological substructures (clumpiness boost factor)
- Latest news from latest N-body simulations
- Mixing the Sommerfeld effect with the clumpiness boost factor
- Discussion and perspectives

Dark matter annihilation as Galactic antimatter factory



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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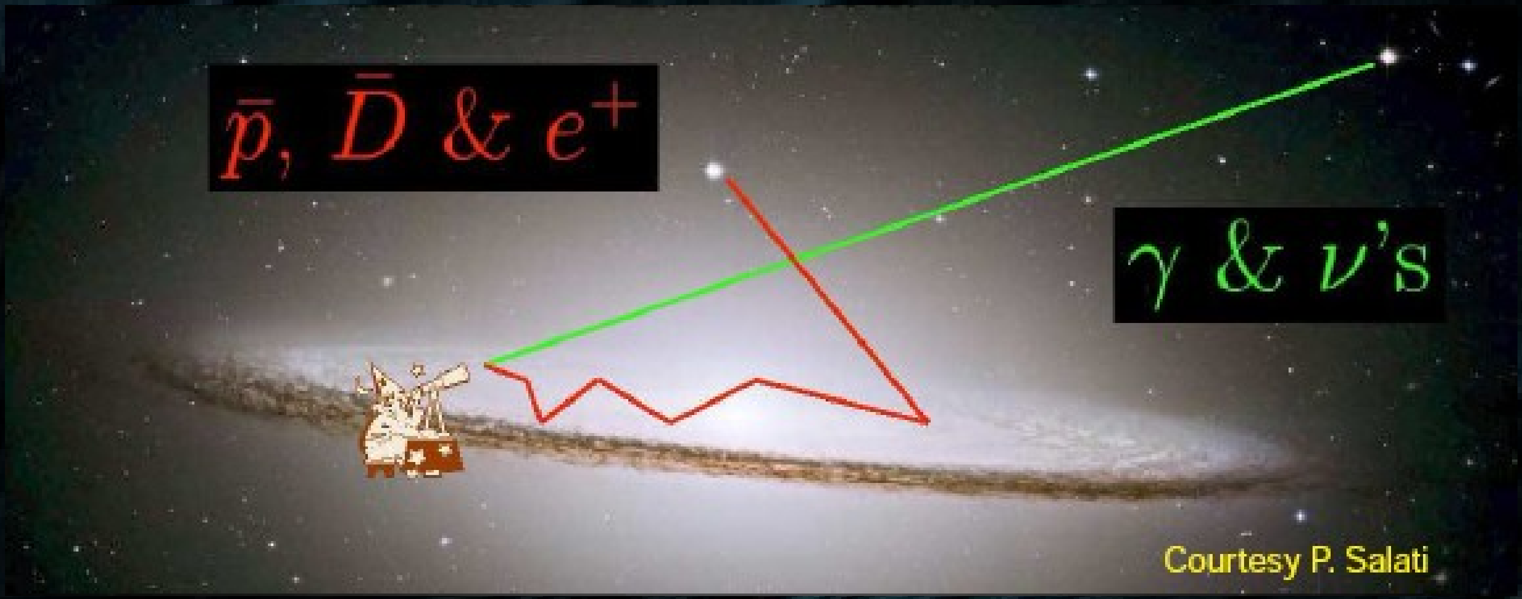
and

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

(Received 8 June 1984)



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

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

Origin of theoretical uncertainties

WIMP model (SUSY, KK, etc.):
mass & annihilation final states?
<σ v> constrained by Ω_m

Propagation:
parameters?
depends on the species

The primary flux reads:

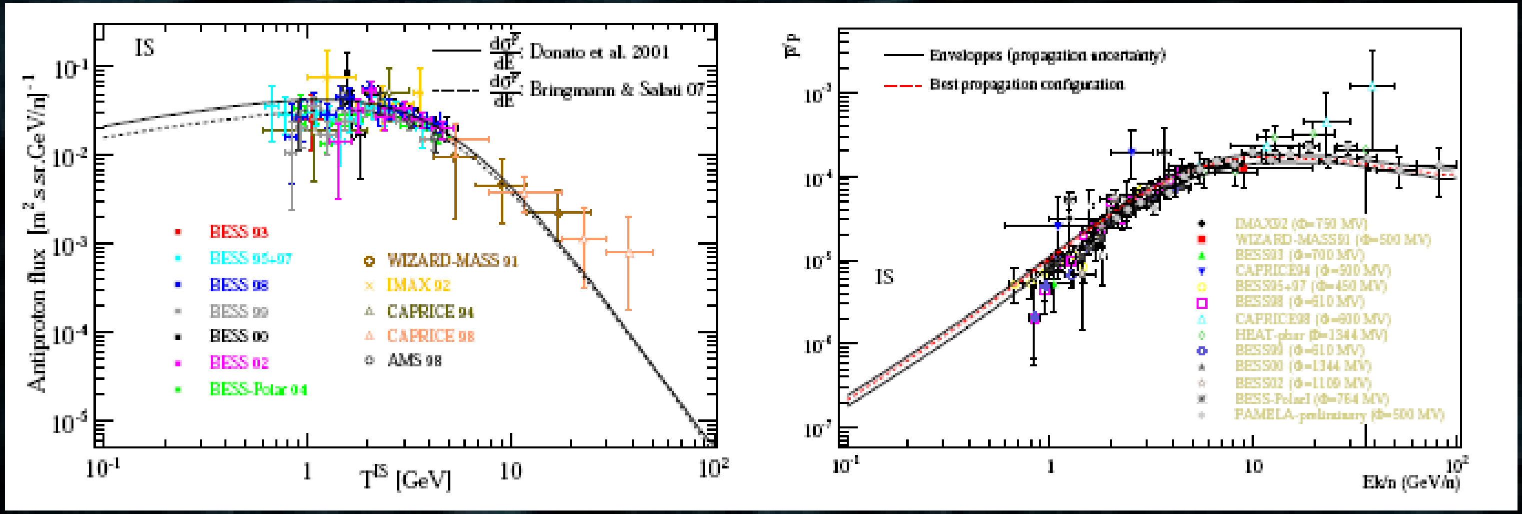
$$\frac{d\phi_{\rm prim}}{dE} = \delta \frac{B_{\rm prim} \times <\sigma v>}{8\pi m_\chi^2} \times \int dE_S \int d^3\vec{x}_S \mathcal{G}(\vec{x}_\odot, E \leftarrow \vec{x}_S, E_S) \times \rho^2_{\rm nn}(\vec{x}_S) \times \frac{dN_{\rm prim}}{dE_S}$$

Differential flux:
Experimental data (statistics)
e.g. EGRET vs Fermi

Dark matter distribution:
N-body simulations
spherical symmetry?
cusps vs observations?
substructures or fluctuations?

Closing the case for antiprotons

Donato et al (2009)



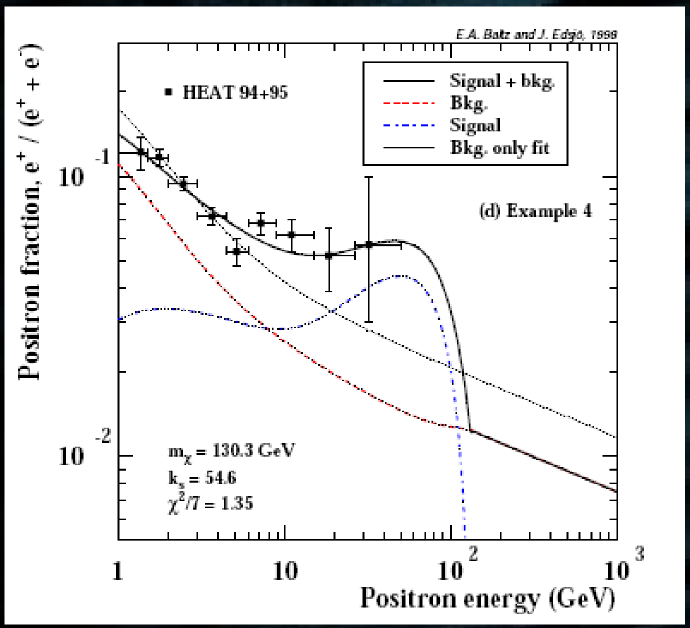
Data are perfectly consistent with predictions for secondaries.

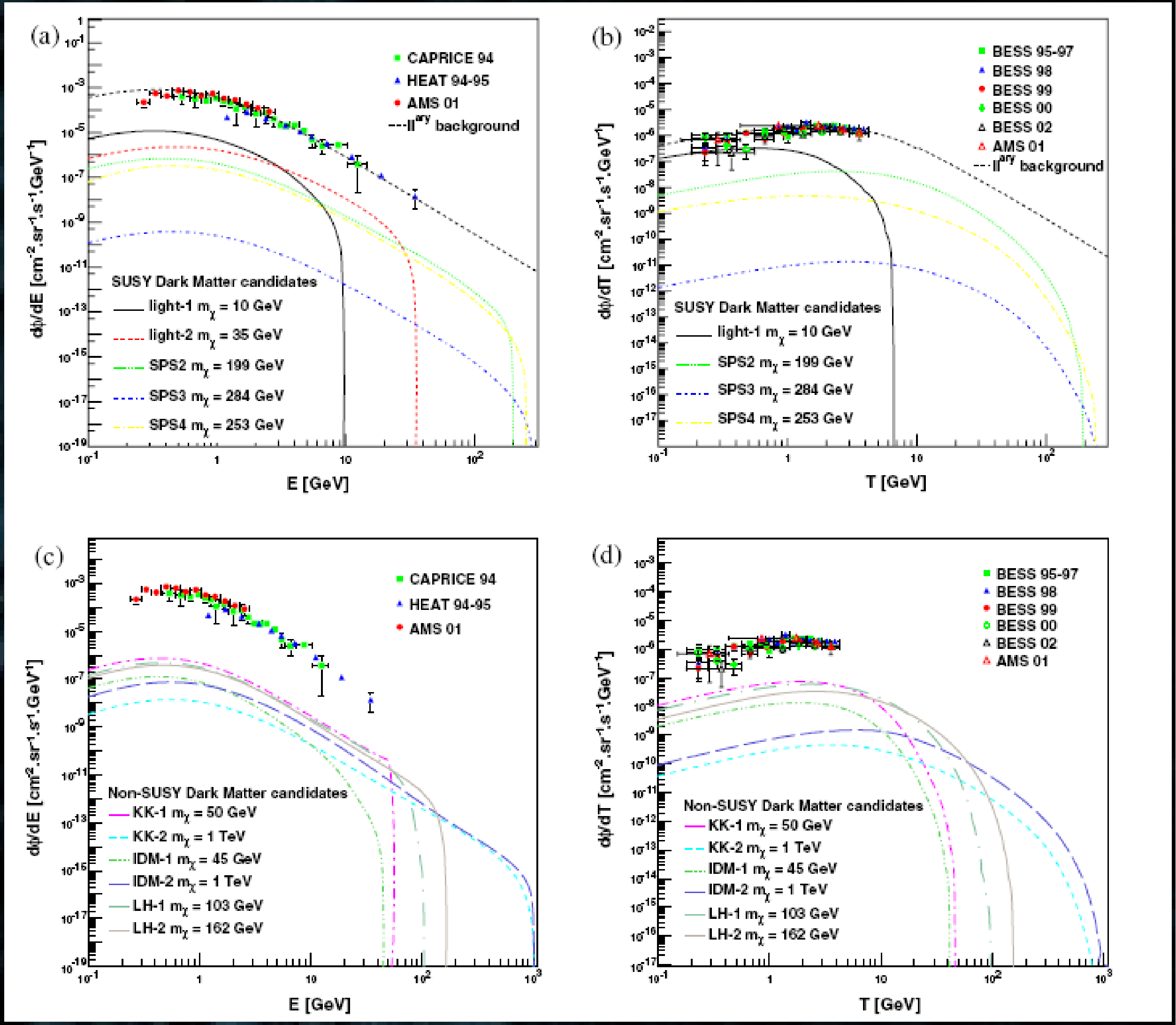
Antiproton data can be used as constraints for DM
(e.g. in a multimessenger analysis)

The positron issue

Lavalle, Nezri, Ling et al (2008)

Baltz & Edsjo (1998)

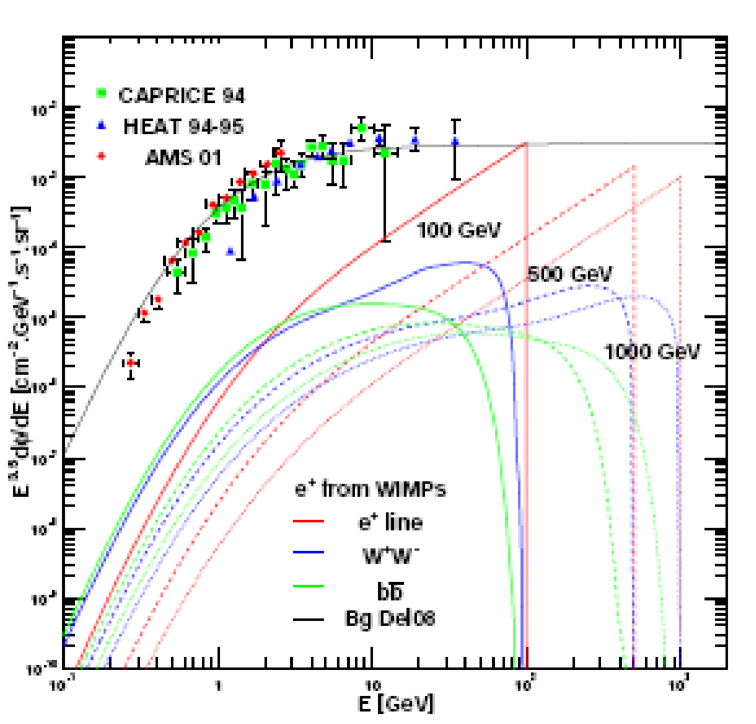




SUSY: higgsino-like neutralino
Need to boost the signal!
(invoke clumpiness)

Particle physics motivated models are not generically observable in the antimatter spectrum.

The boost factor issue



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

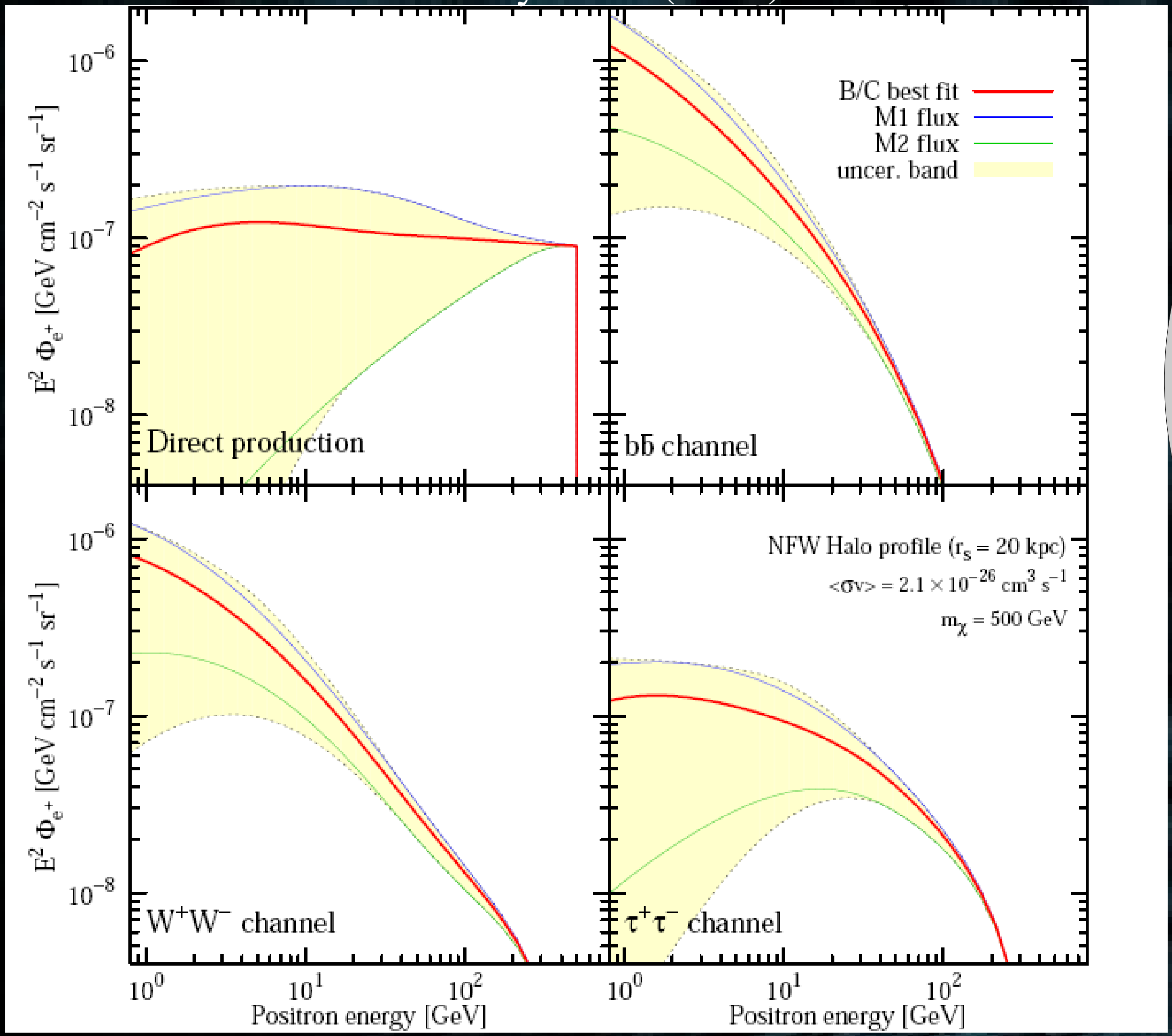
WIMP mass / final state	100 GeV	500 GeV	1 TeV
e^+e^-	10	100	350
W^+W^-	80	500	1000
$b\bar{b}$	250	500	1000

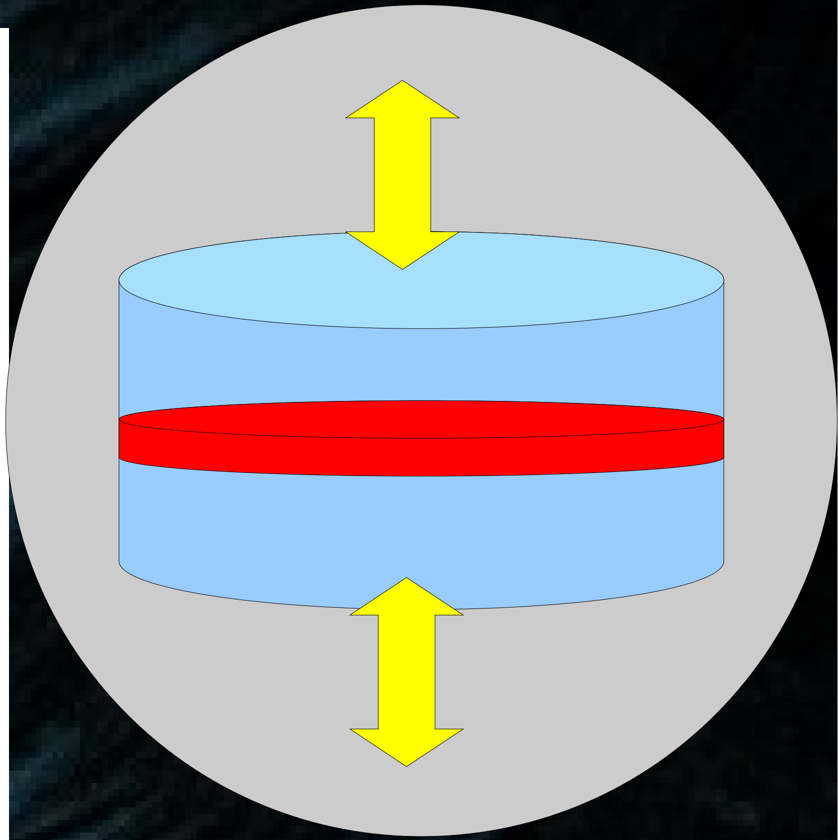
Basically, 3 possibilities to boost the signal:

- Play with the propagation parameters
- Increase the local DM density, add other DM sources (e.g. inhomogeneities)
- Enhance the annihilation cross section

Play with propagation

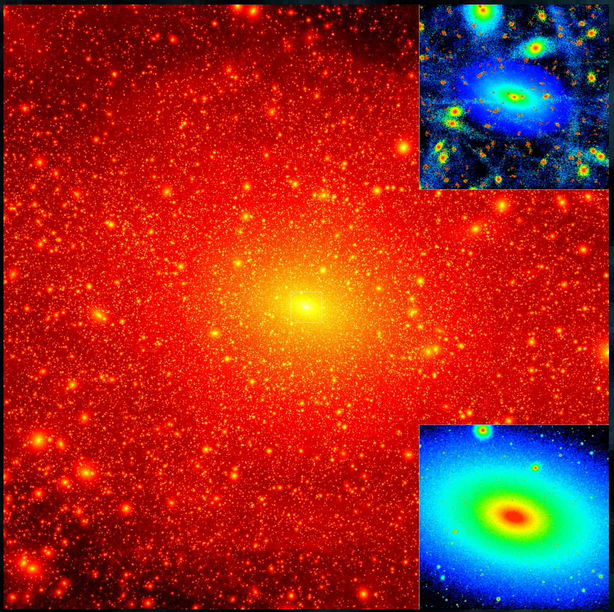
Delahaye et al (2008)





Increasing L implies more DM in the diffusion zone.
Translation in flux not that simple, since B/C imposes K/L ~ cst.
Low energy effect for positrons (large propagation scale), but small.

Dark matter inhomogeneities wandering around ?



Via Lactea (Diemand et al)

CLUMPY COLD DARK MATTER

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Received 1992 March 25; accepted 1992 December 16

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.

Two main cases:

- A very "bright" single object ?
- Collective effect.

Mini-dark halos with intermediate mass black holes

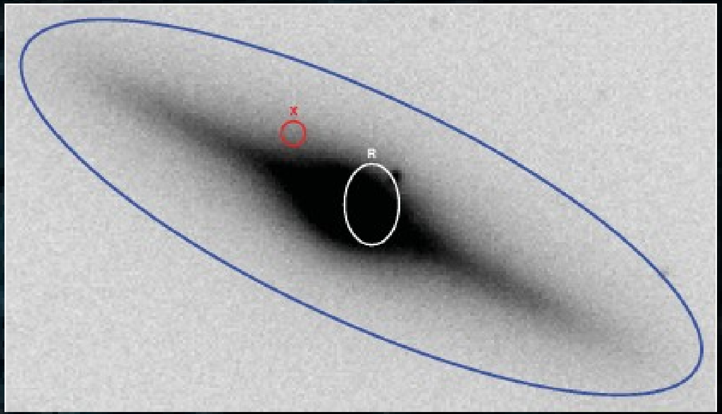
HongSheng Zhao and Joseph Silk
(Dated: 1 June 2005 on Phys. Rev. Letters 95, 011301)

Further developed by Bertone et al

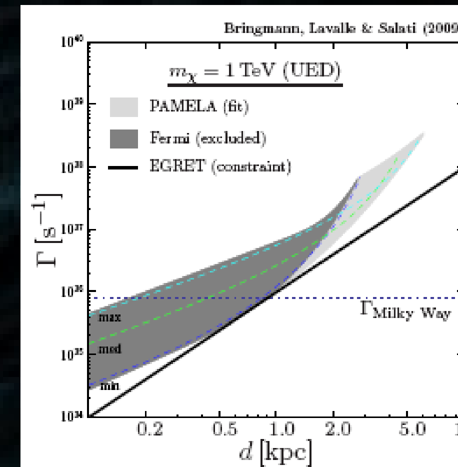
Vol 460 | 2 July 2009 | **doi:10.1038/nature08083**

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]



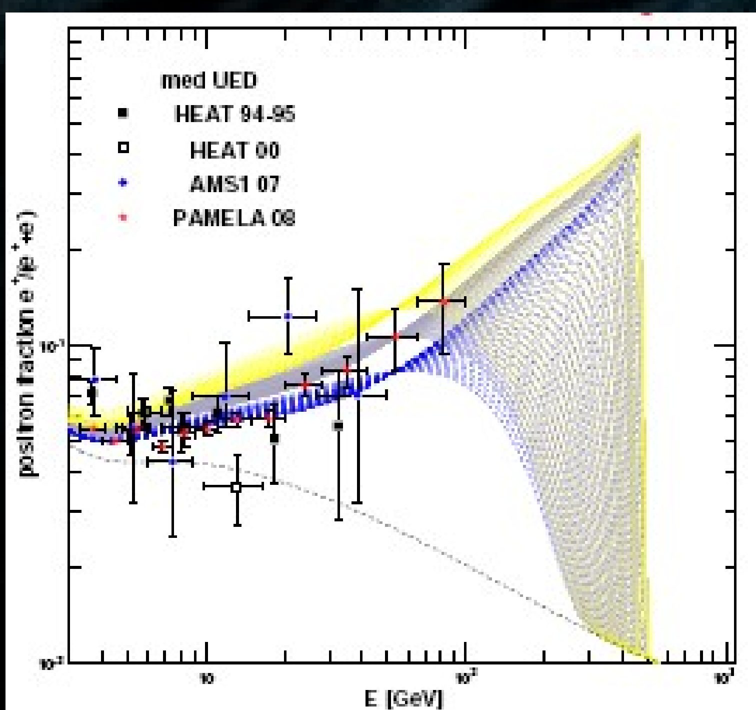
Single object wandering around

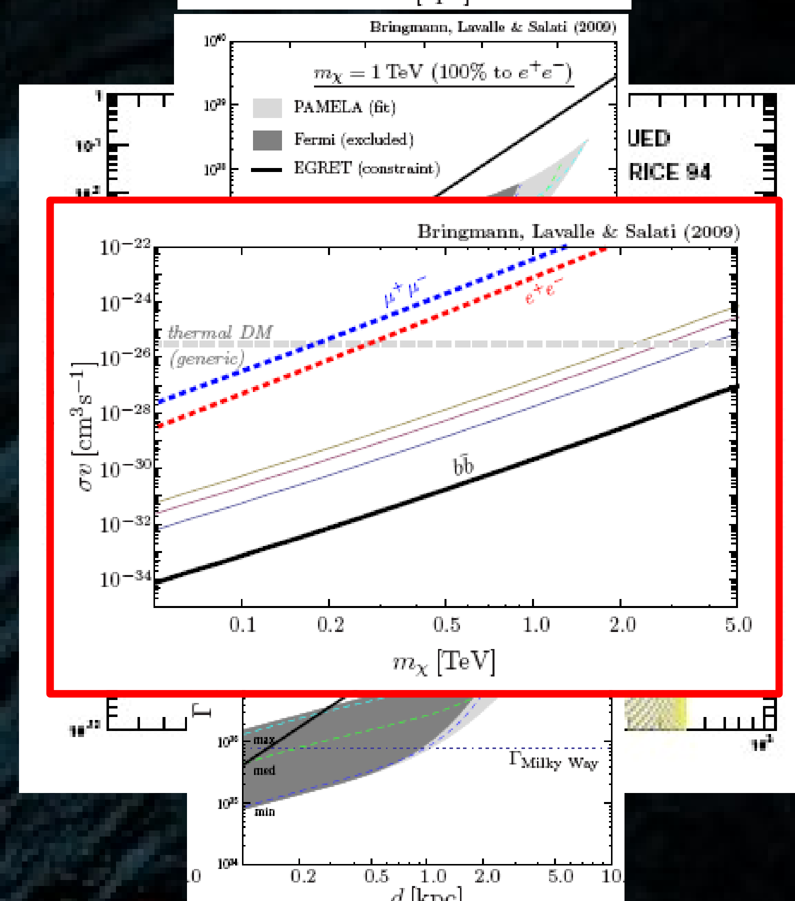


The game one can play:

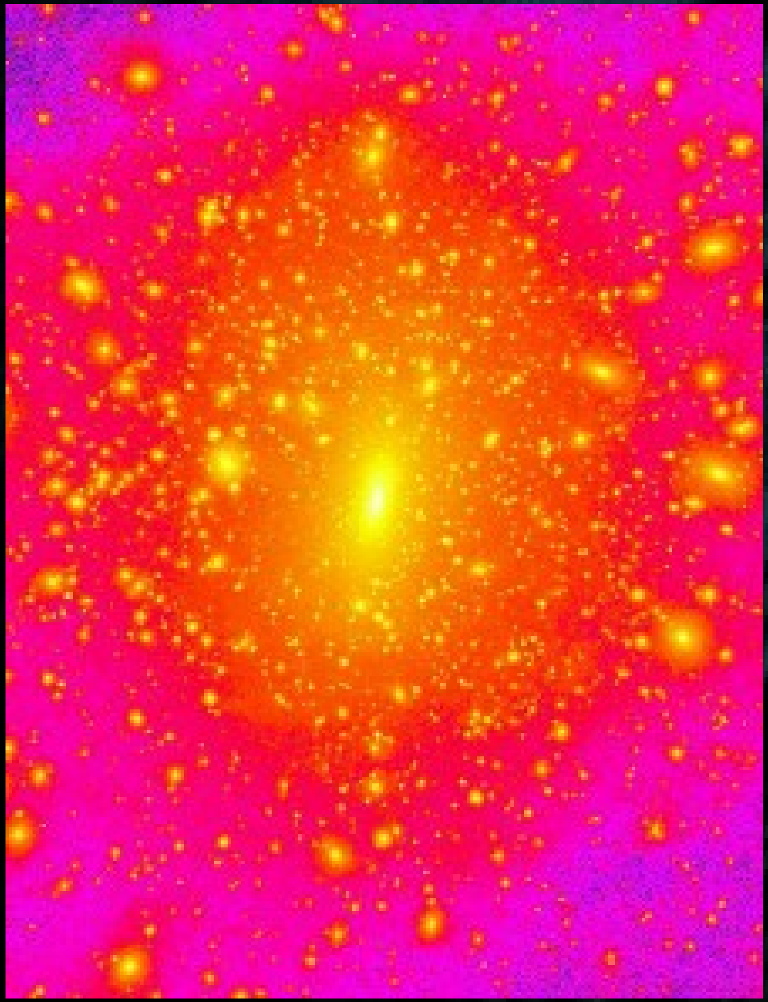
- Assume a single DM source at any distance d to the Earth.
- Assume a WIMP mass and its annihilation final states.
- Search for the brightness necessary to fit PAMELA.
- Check against other data (gamma, antiprotons, etc.)

Bringmann, Lavalle & Salati (2009)





Collective effect: clumpiness boost factor



Diemand et al (2004)

• Clumps are predicted by the current theory of structure formation.
• They are observed in N-body simulations at all resolved scales, as predicted.
• The minimal mass scale if ixed 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

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

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

A taste of the final result

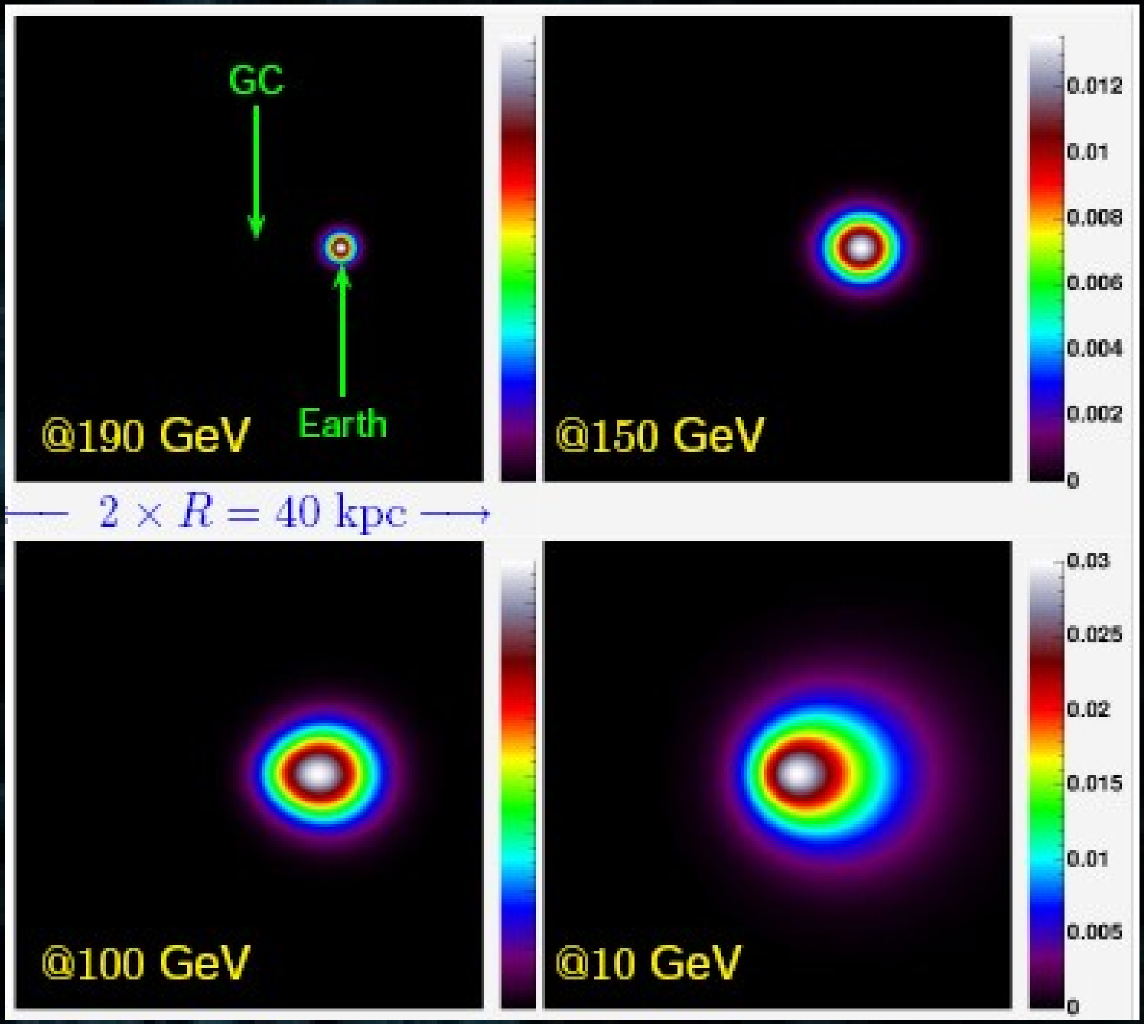
Inject a 200 GeV positron according to an NFW profile.

Short propagation scale (high energy):

- The detected positron comes from close around (small volume).
- The local DM density is small, a clump there will be an efficient booster.
- The probability is small: large statistical variance.

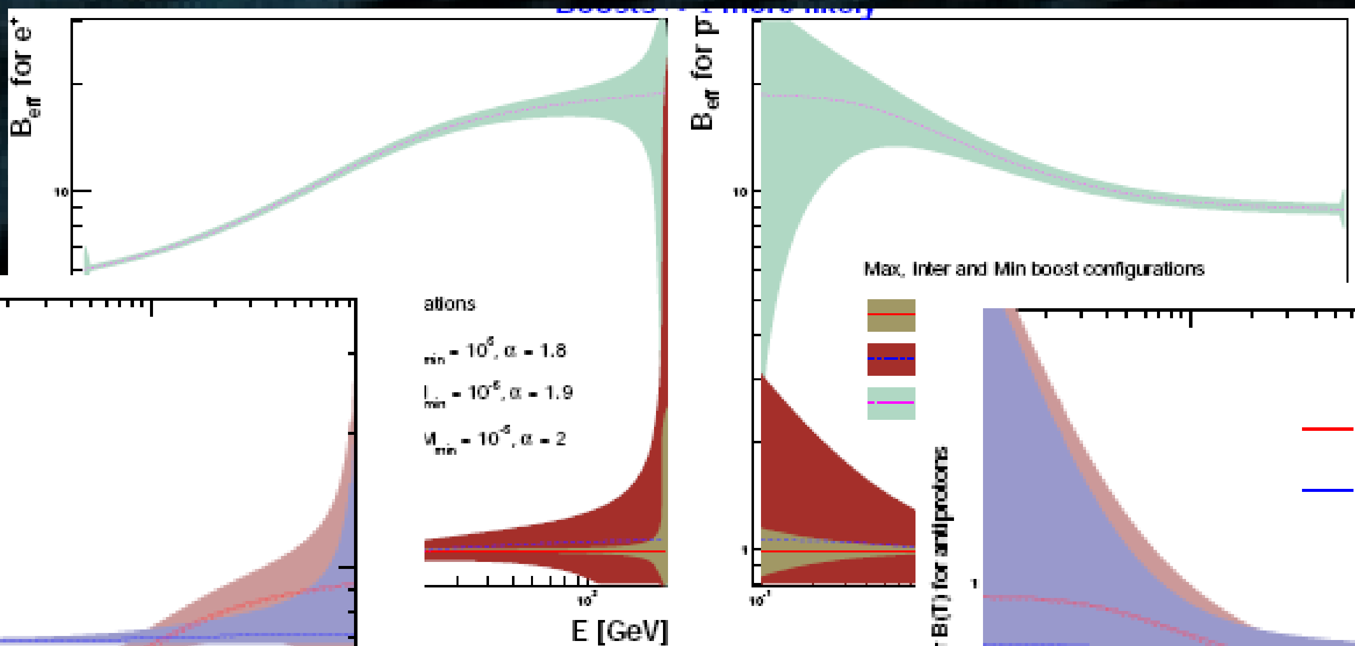
Large propagation scale (low energy):

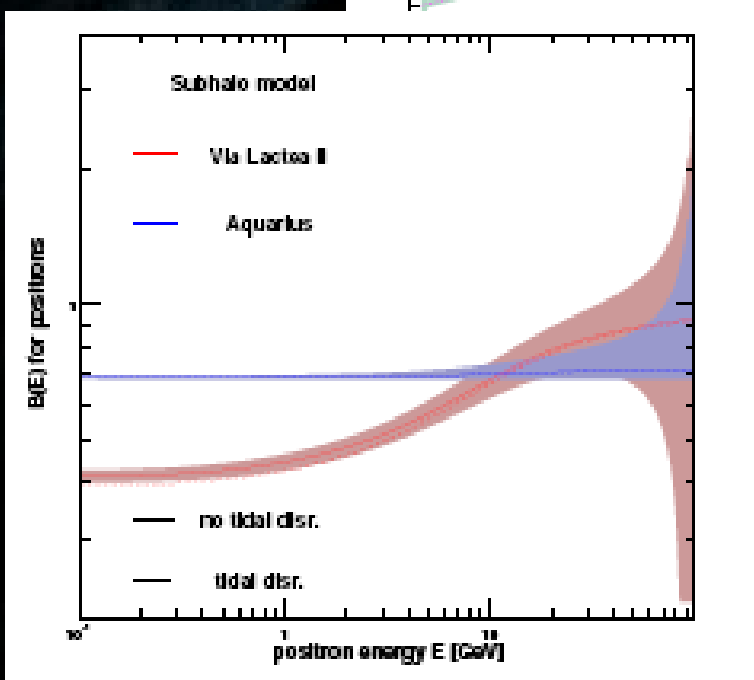
- Large volume, can feel the Galactic center
- Many clumps, but signal likely dominated by GC.
- Small statistical variance.



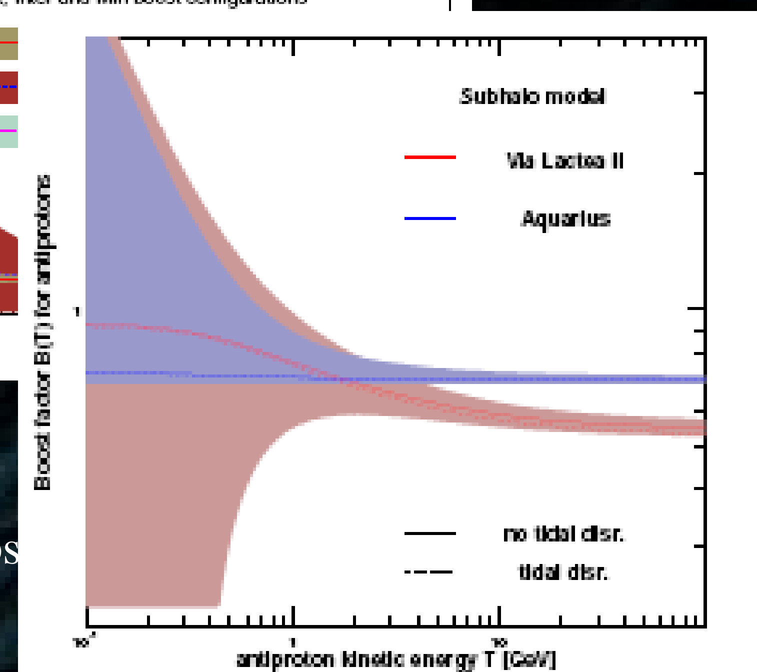
Span over extreme cosmological configurations

Lavalle et al (2007)

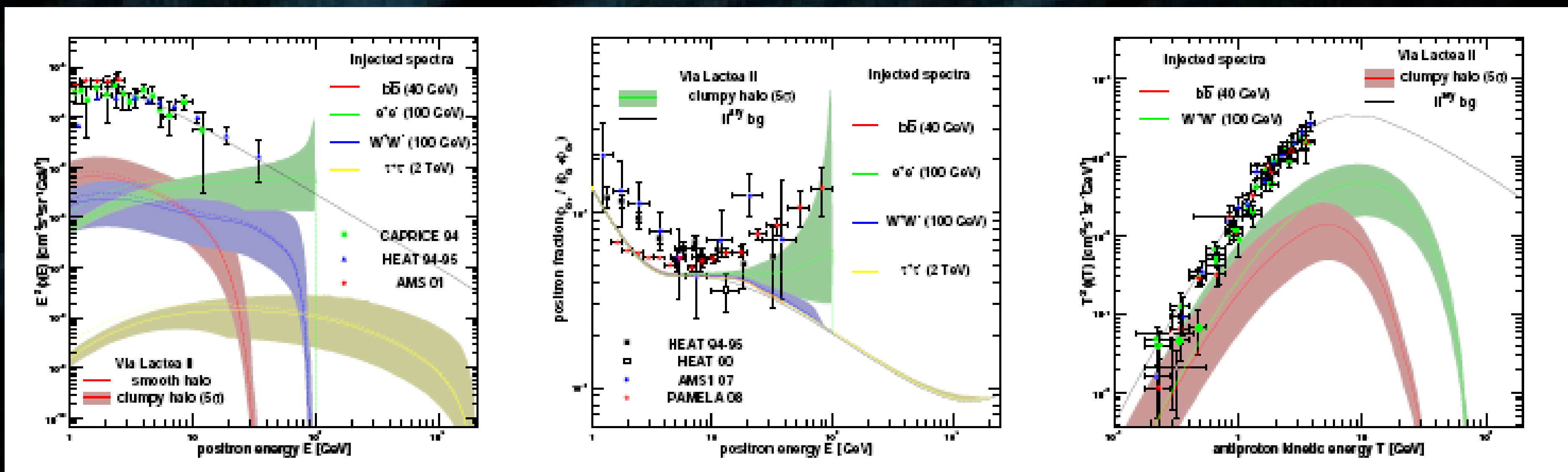




VLII and Aquarius setups
Pieri et al (2009)



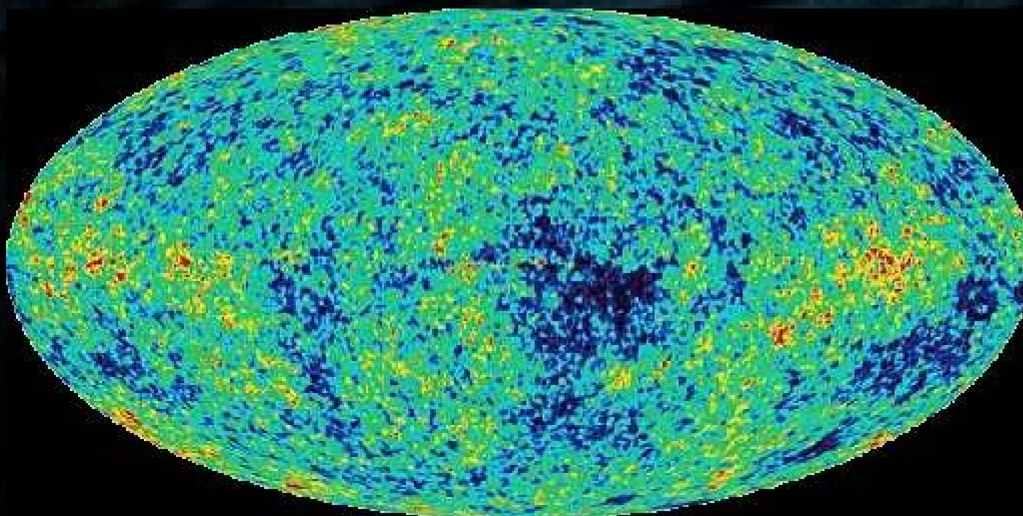
Clumpiness summary:
Use the current state of the art in N-body cosmology



Pieri et al (2009)
using results from Via Lactea II (Diemand et al) and Aquarius (Springel et al)

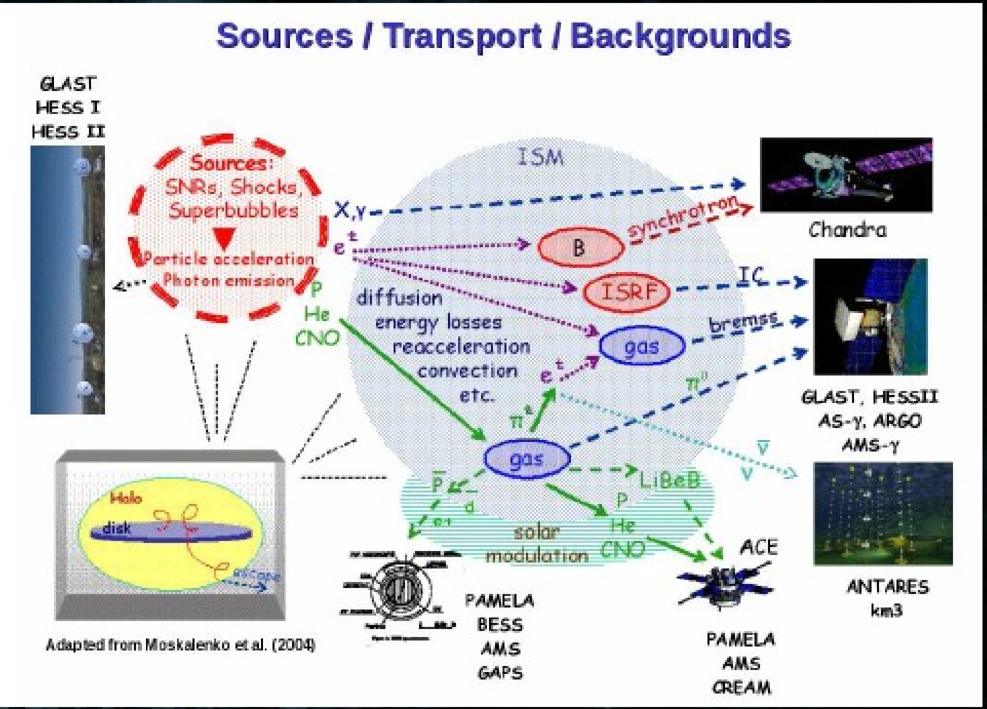
Marginal enhancement from subhalos for all generic WIMPs ...
Yet, a 100 GeV one annihilating in e^+e^- does not require a large boost ...

Multimessenger, multiwavelength, multiscale



DM phenomenology may manifest itself from the early times of the Universe (e.g. BBN), and on the largest scales (CMB, clusters, etc.).

DM could still be detected at the Galactic scale, provided standard astrophysical processes are under control: self-consistent analyses necessary.



Conclusions on Part II

Dark matter in the cosmic ray spectra:

• Identifying DM in current cosmic ray measurements is unlikely, even if it were there.
• Higher energy measurements of antimatter cosmic rays necessary (PAMELA, AMS).
• Multimessenger, multiwavelength, multiscale !!!!!
• Full electromagnetic spectrum more promising (information not limited to local regions).

Some criticism about the community:

• The hunt for scoops and citations pollutes the hunt for DM (more DM models in 1 year than in the last 2 decades).
• People should not hide (even to themselves) the theoretical uncertainties: strong statements should be weighted accordingly.

Some facts and hopes:

• DM remains a big mystery, but is still one the main building block of structure formation: strong independent motivations for its existence.
• LHC is about to run and might provide interesting results: easier when WIMP properties are known.
• Interdisciplinary field ! Complementarity of detection methods !
• Looking for the unknown imposes on improving our understanding of the known (backgrounds !)

Many thanks !