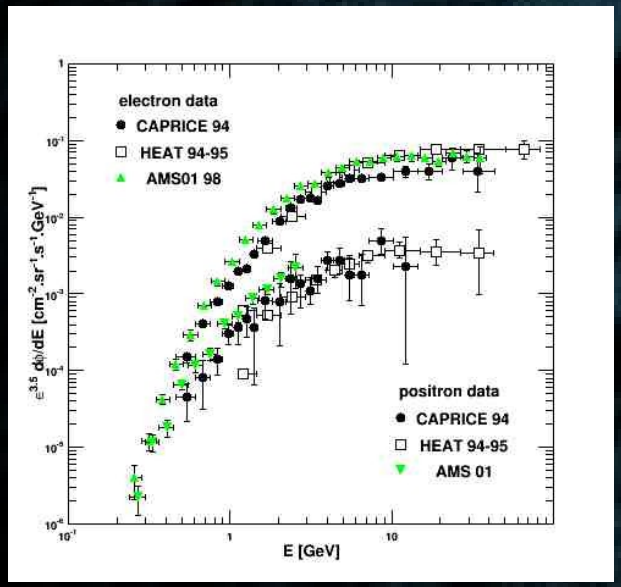
Astrophysical issues in the cosmic ray $e^{+/-}$ spectra: Have we seen dark matter annihilation?

Julien Lavalle
Department of Theoretical Physics
University of Torino and INFN

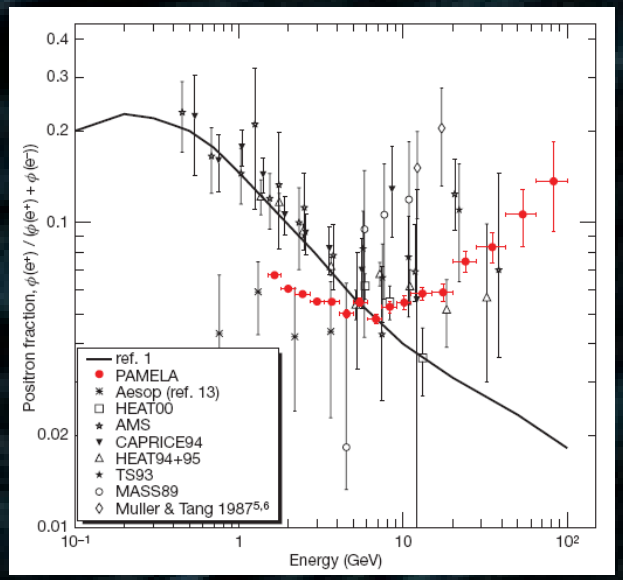
Collab:
Torino: R. Lineros, F. Donato, N. Fornengo
Annecy: T. Delahaye, P. Salati, R. Taillet
+++: T. Bringmann, D. Maurin, E. Nezri, L. Pieri, G. Bertone, E. Branchini, etc.

PPC 2010 @ Torino - 12-16/VII/2010

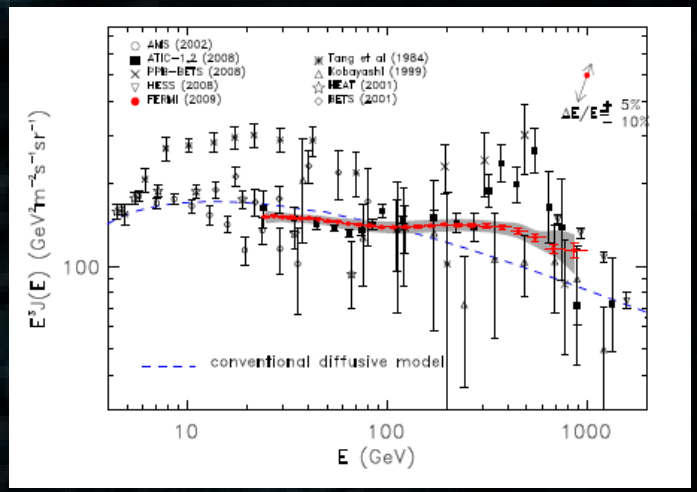
The data:
Current local measurements of cosmic-ray $e^{+/-}$



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 these measurements ?
(e+ excess, spectral features in e+e−)

Propagation of Galactic cosmic rays (electrons): The standard picture

408 MHz all-sky map

From Haslam et al data (1982)

Propagation of Galactic cosmic rays (electrons): The standard picture

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

From Haslam et al data (1982)

The case for electrons: 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)

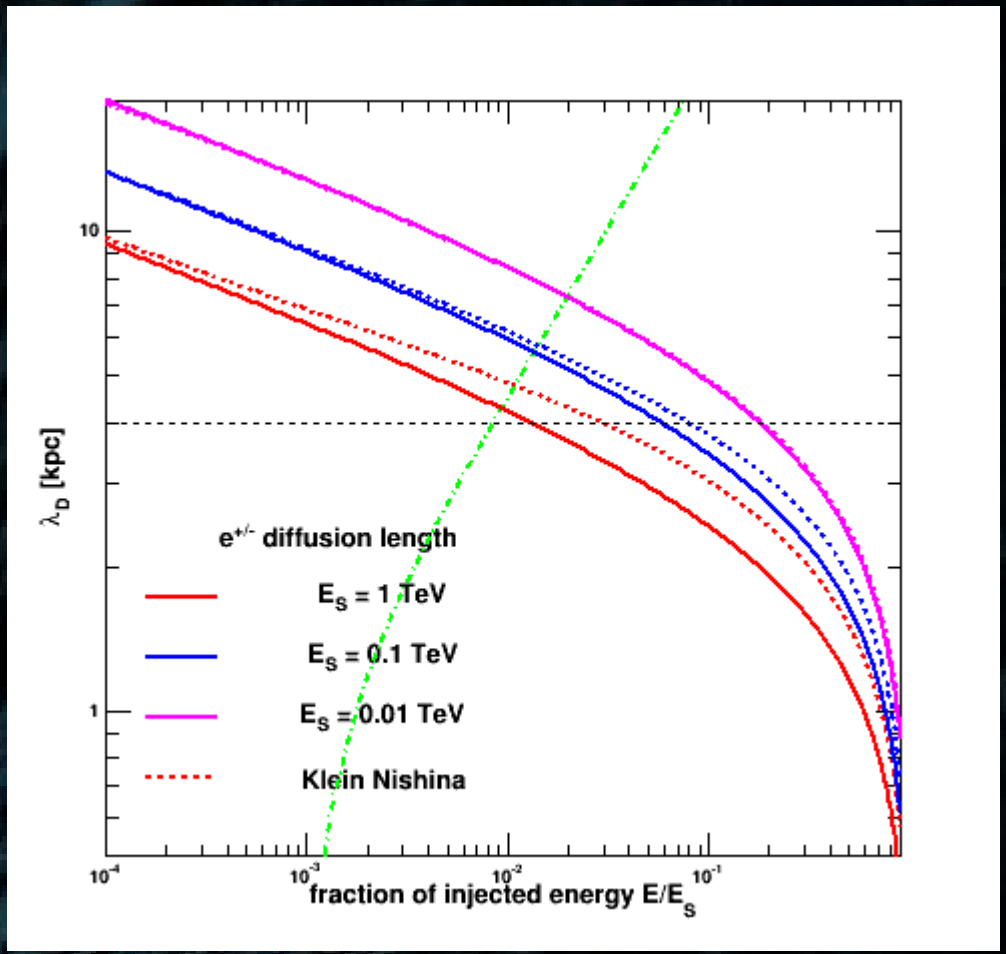
(i) **Interactions with the ISM** :
Bremsstrahlung (braking radiation), ionisation – for E < few GeV

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

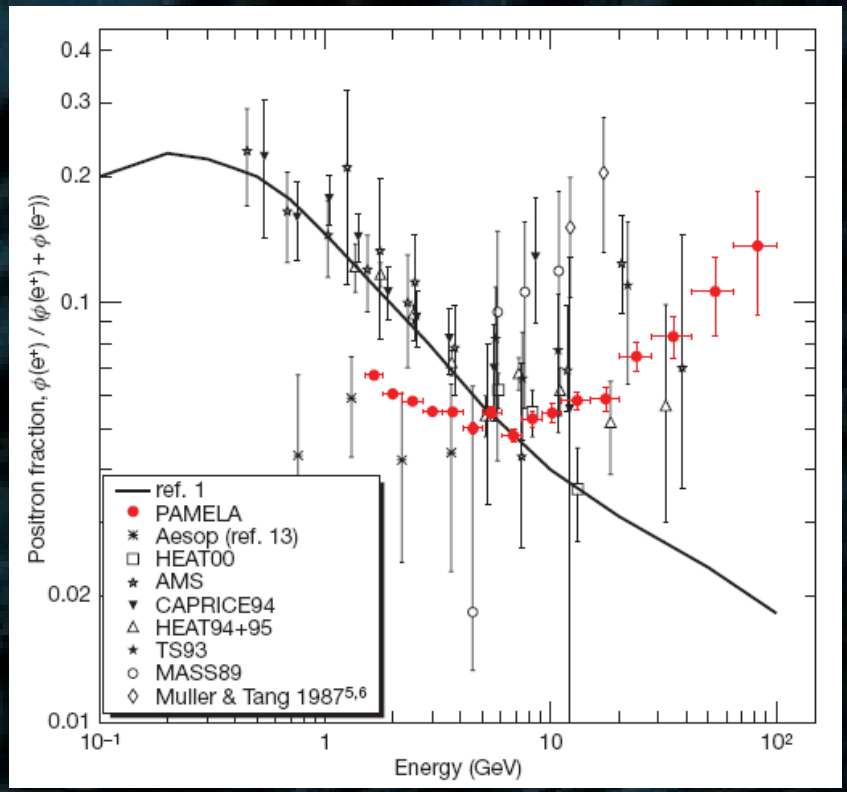
(ii) **Interactions with the ISRF** (including CMB) and **magnetic fields**: (inverse) Compton processes

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

→ Need for accurate description of ISRF and magnetic fields:
high energy => local fields



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



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

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

Short recipe for secondaries

Proton and alpha fluxes

ISM gas distribution

The source term

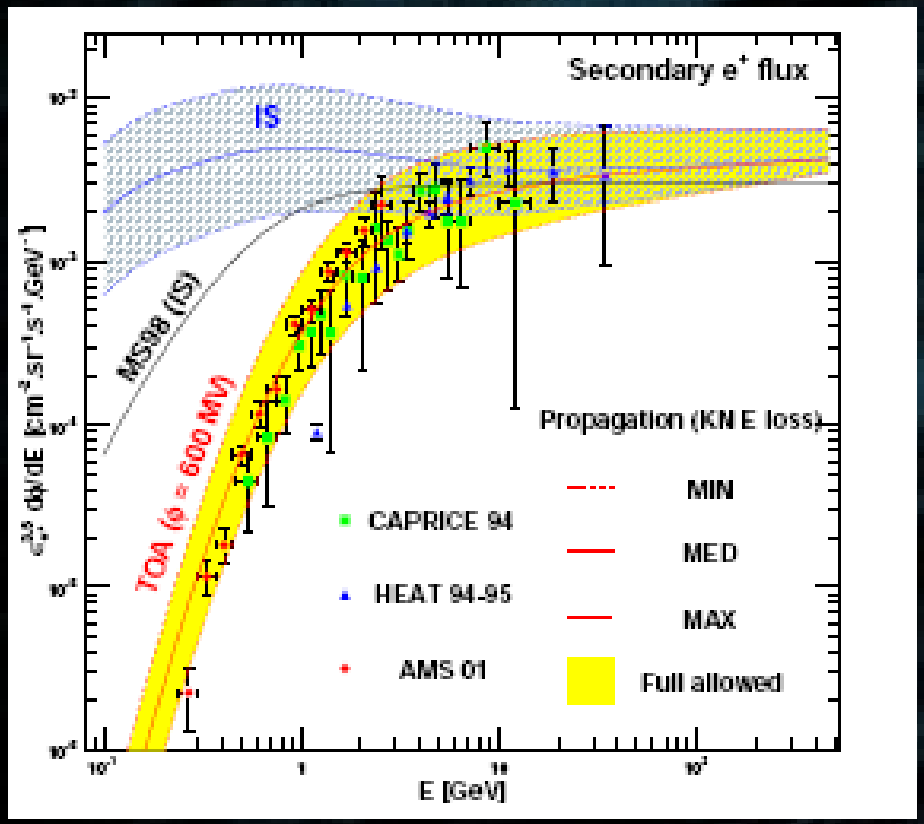
Inclusive nuclear cross section
$p+p \rightarrow e^{+} + X$

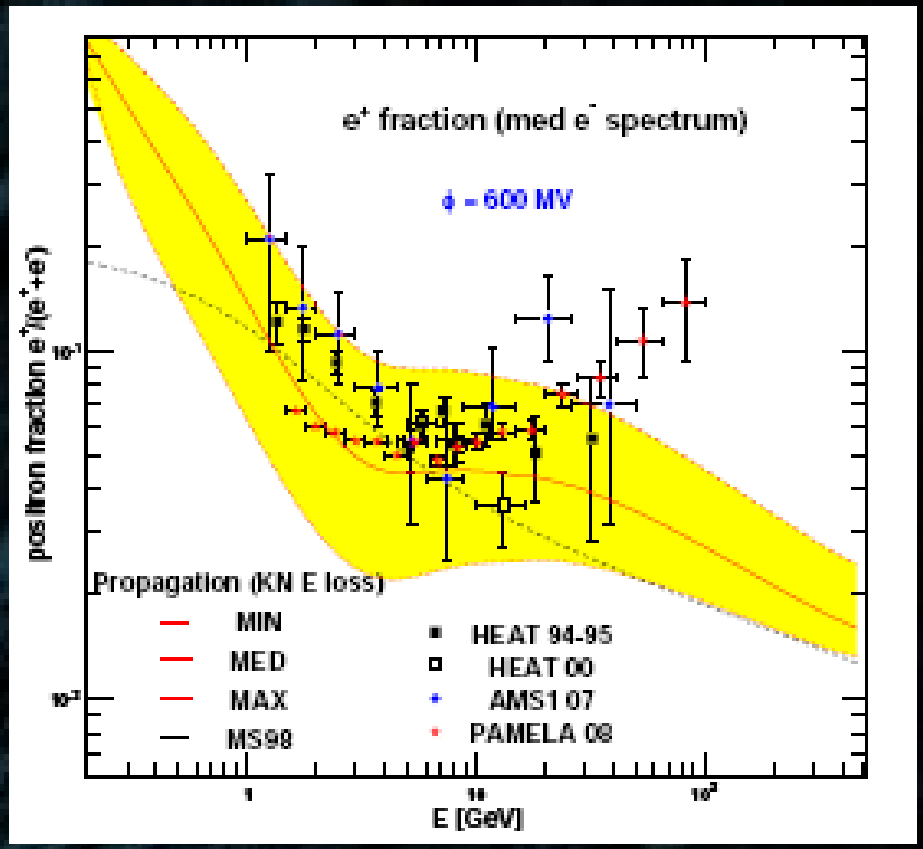
Propagation
from (x_s, E_s) to (x, E)

Each box contains uncertainties !!!

Flux at the Earth

Can secondary positrons account for PAMELA data?





Uncertainties are still large ...

Yet, a conventional secondary origin seems unlikely ...

Need of a primary contribution 5–10 times the secondary one at ~100 GeV

The Dark Matter interpretation

(about 250 papers on the arXiv)

Dark matter annihilation as antimatter factory (aside from gamma rays)

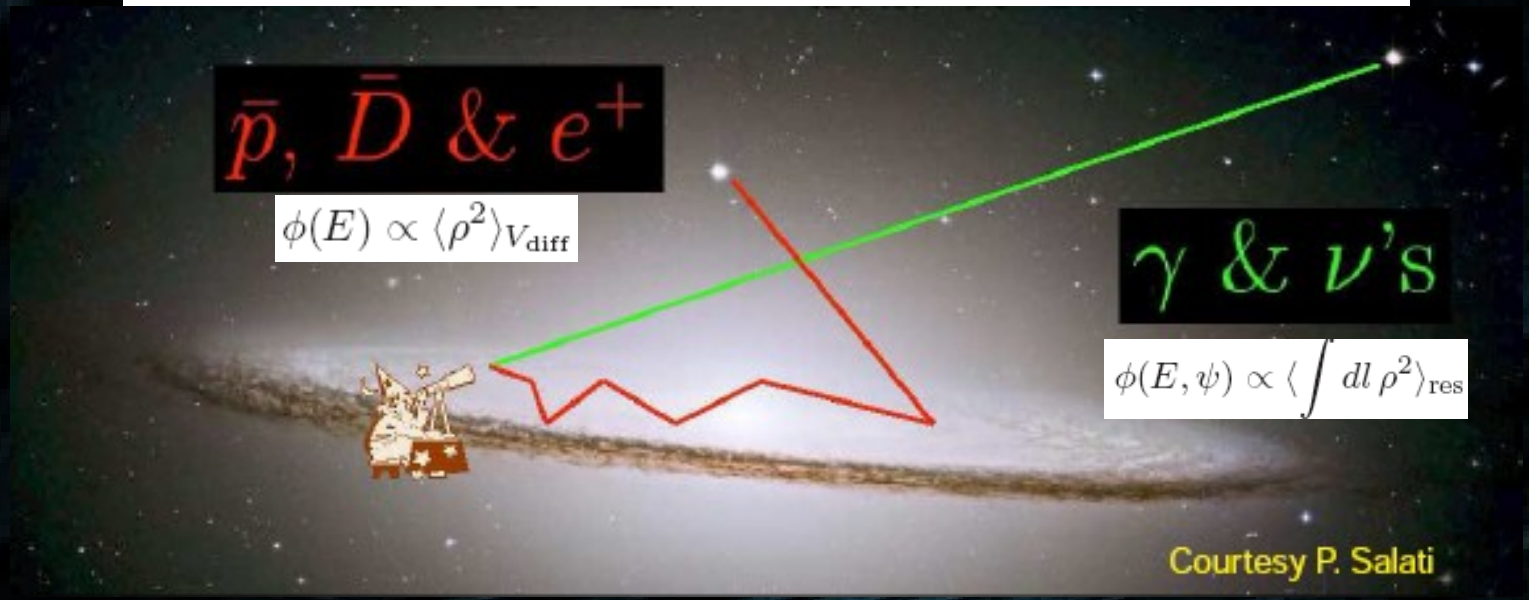
VOLUME 53, NUMBER 6 PHYSICAL REVIEW LETTERS 6 AUGUST 1984

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

Joseph Silk
Astronomy Department, University of California, Berkeley, California 94720, and Institute for Theoretical Physics, University of California, Santa Barbara, California 93106

and

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

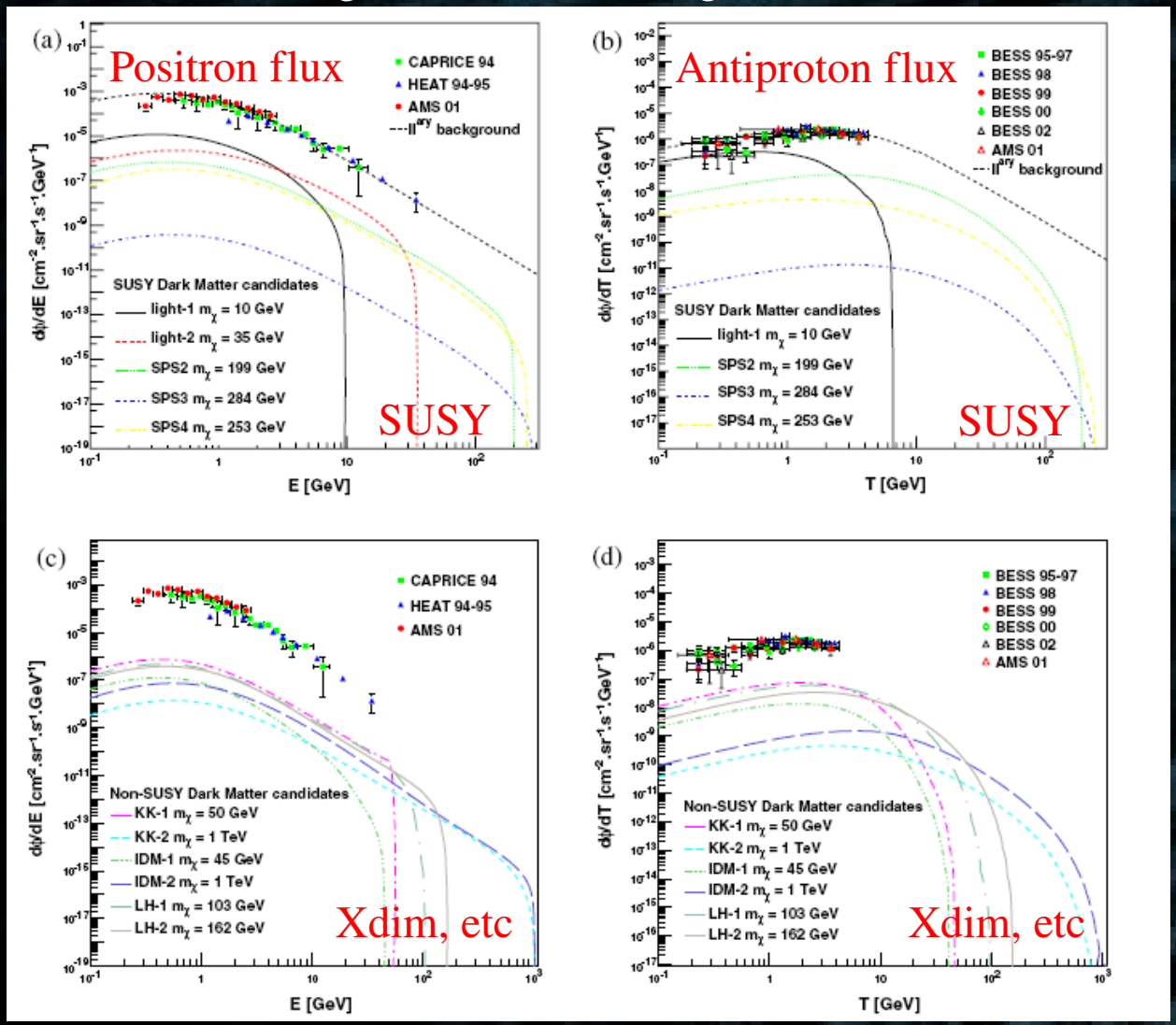


Main arguments:
- DM annihilation provides as many particles as antiparticles
- Antimatter cosmic rays are rare because secondary products
- DM-induced antimatter CRs may have specific spectral properties

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

Dark Matter annihilation: generic predictions for positrons

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



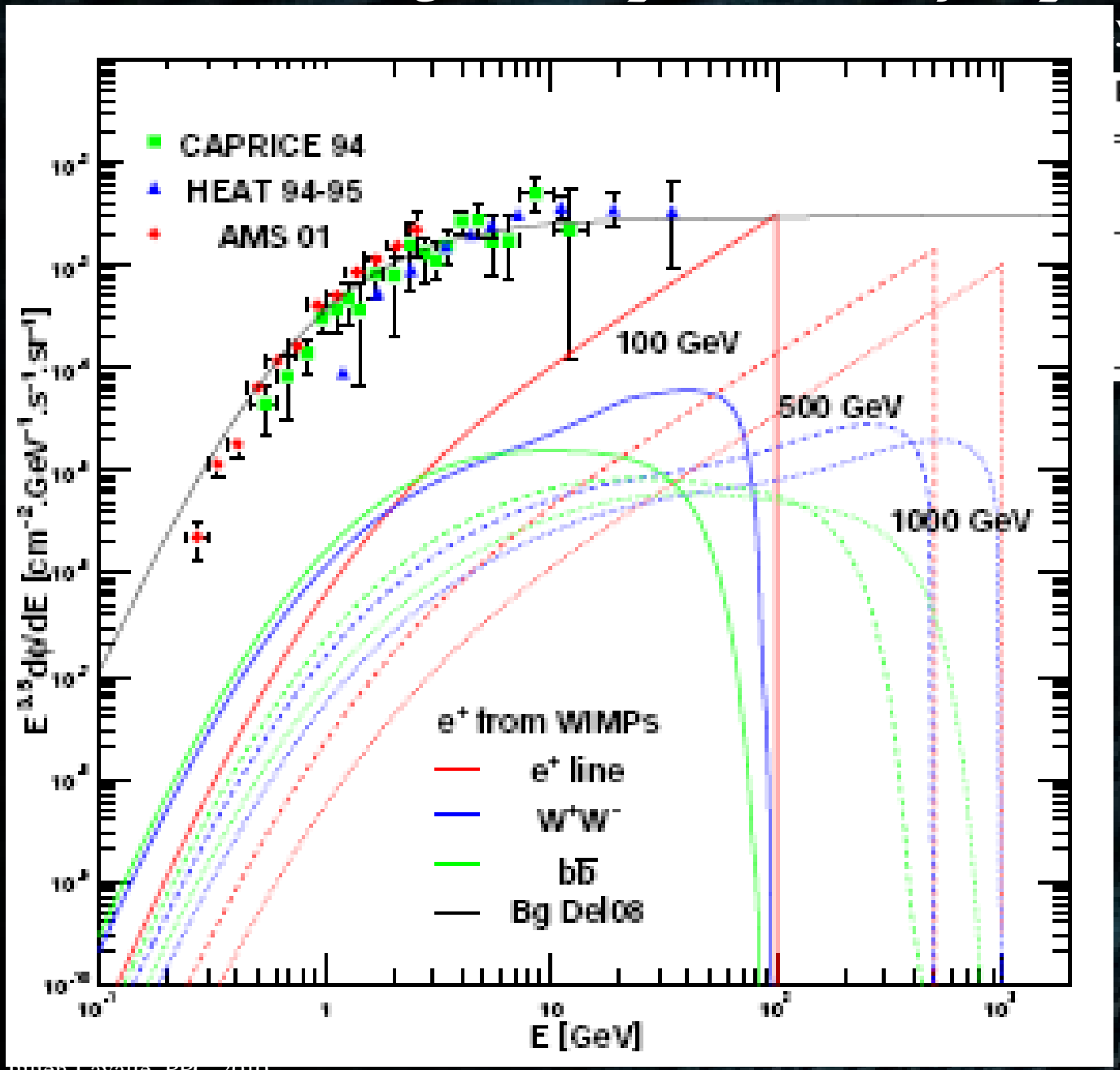
Susy candidates:
positron (left) – antiproton (right)

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

Dark Matter annihilation: generic predictions for positrons



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:

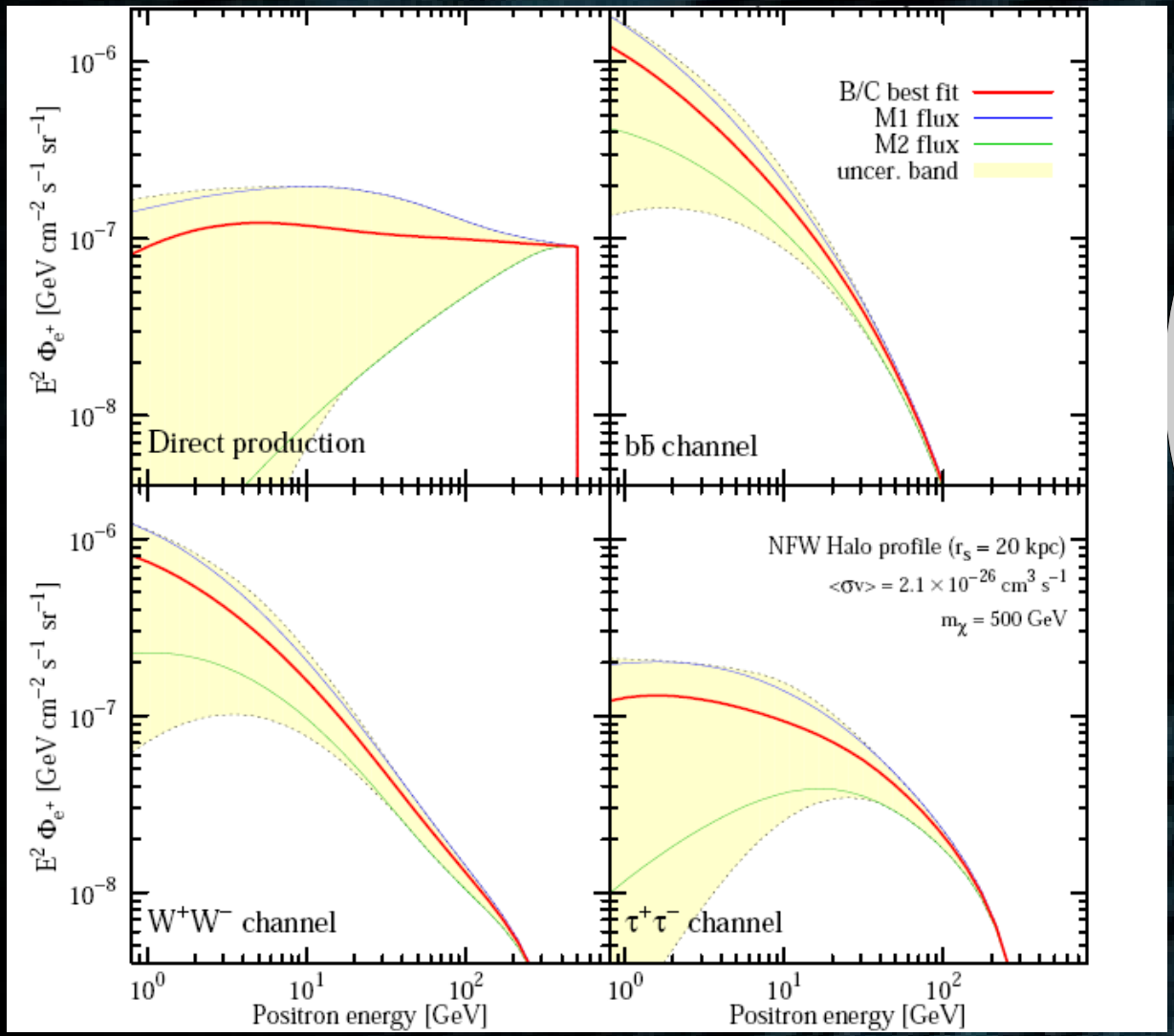
(i) boost the cross section → contrived scenarios (¾ of published papers) ~ excluded (see e.g. Cirelli et al)

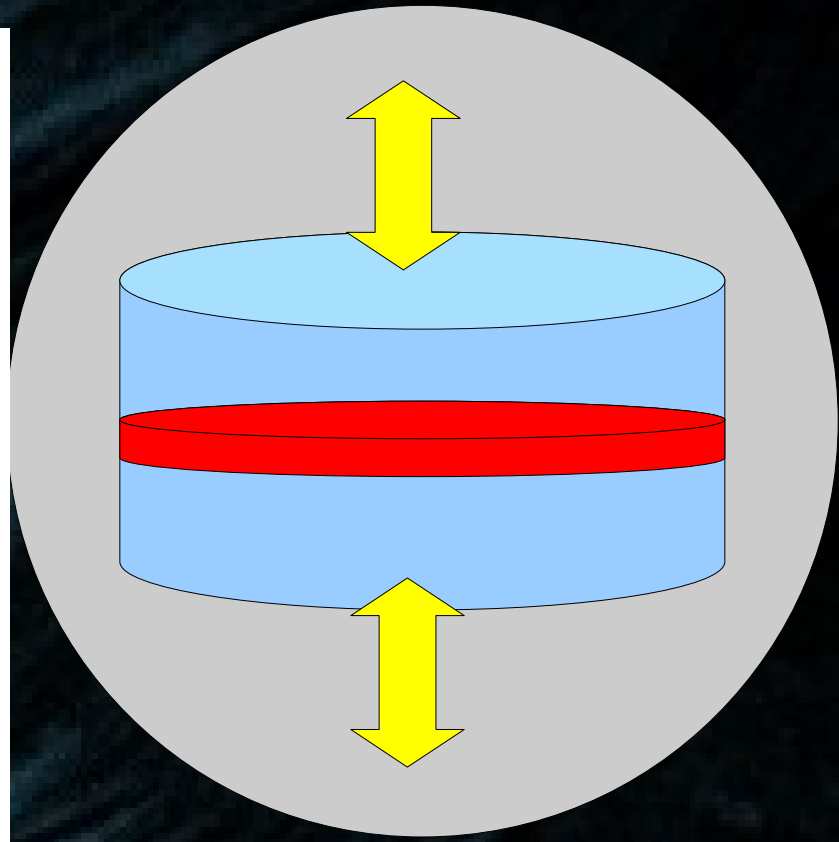
(ii) play with the propagation parameters

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

Play with propagation

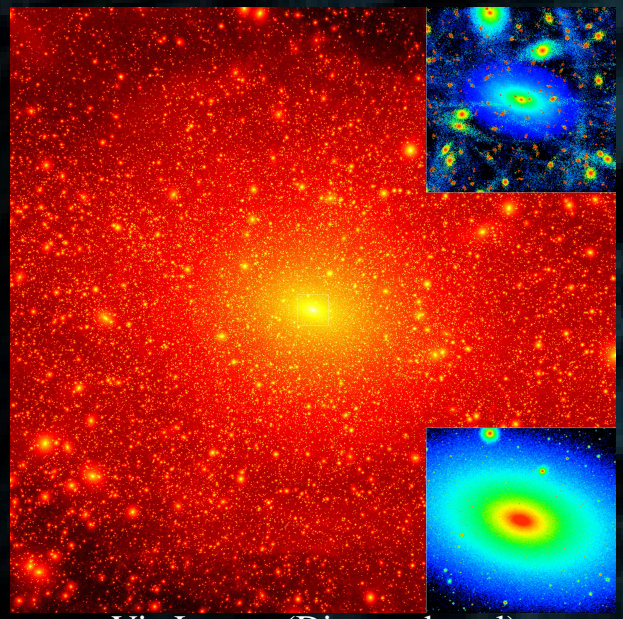
Delahaye et al (2008)





Increasing L implies more DM in the diffusion zone.
Translation into 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

JOSEPH SILK
Departments of Astronomy and Physics, and Center for Particle Astrophysics, University of California, Berkeley, CA 94720
AND
ALBERT STEBBINS
NASA/FermiLab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, IL 60510
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.

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

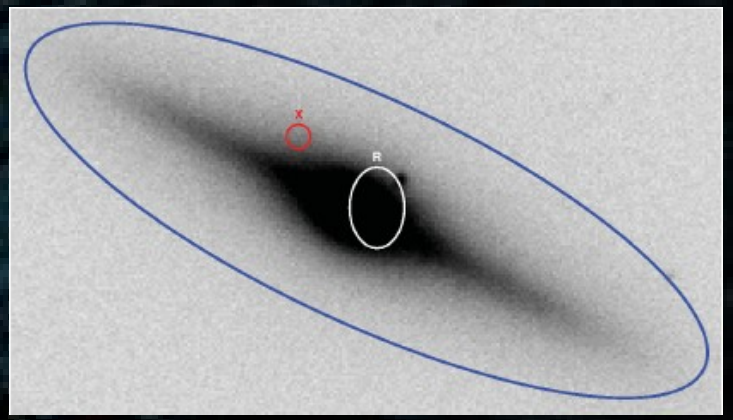
An intermediate-mass black hole of over 500 solar masses in the galaxy ESO 243-49

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:

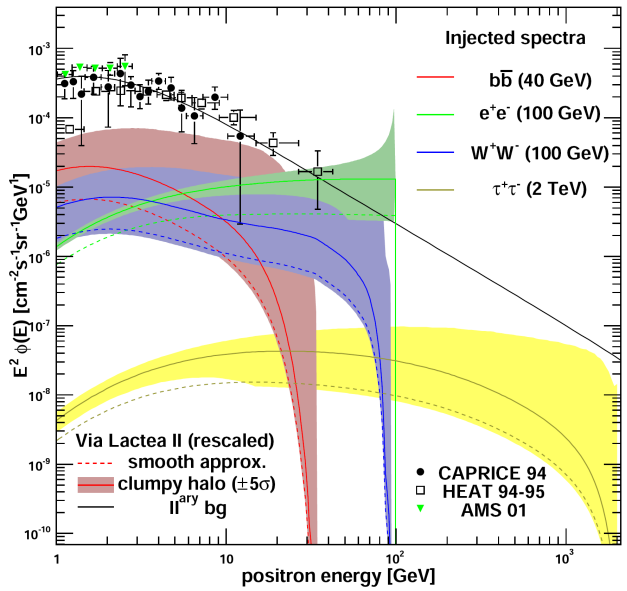
- Collective effect.
- A very "bright" single object ?

(excluded from gamma-ray data, Bringmann, Lavalle & Salati 09)

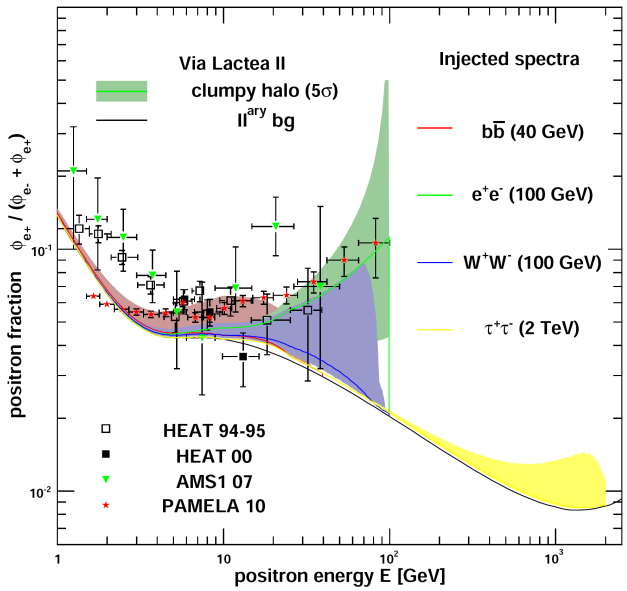


Dark Matter subhalos: boost factor < 10 for positrons (modulo variance)

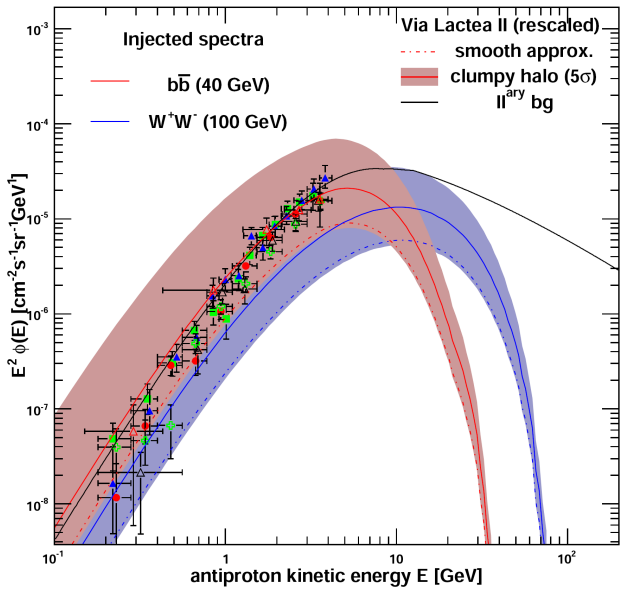
Positron flux



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) --

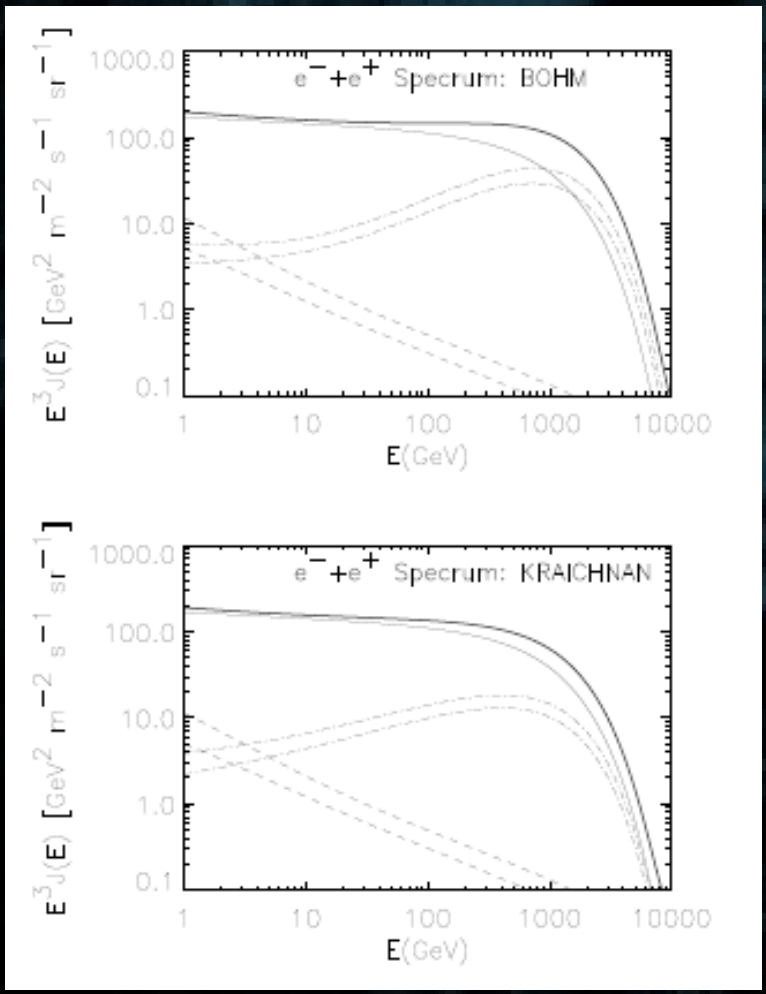
Need >5 sigma boost from subhalos for all generic WIMPs ...
Yet, a 100 GeV one annihilating in e^+e^- could make it ...

Astrophysical explanations

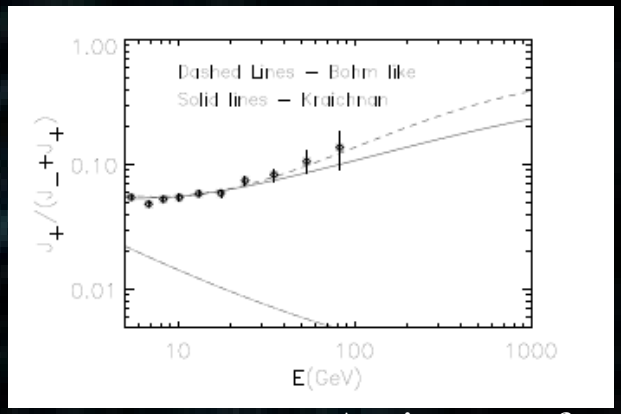
... the nose on one's face ...
(a few tens of papers on the arXiv)

"Primary" secondaries ?

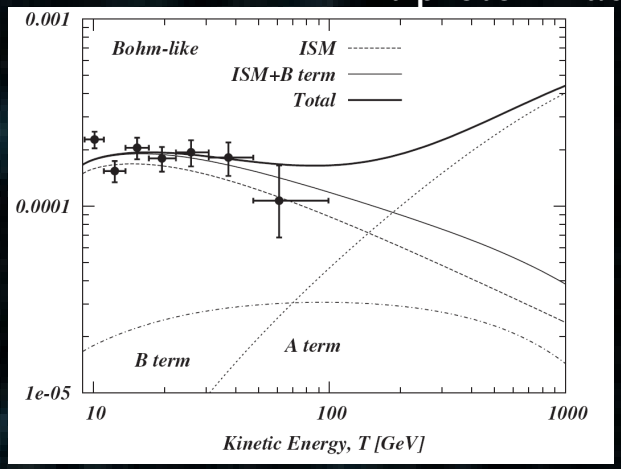
Berezhko et al (2003), Blasi (2009), Blasi & Serpico (2009),
Mertch & Sarkar (2009), Ahler et al (2009)
Secondaries created in SNRs are accelerated like primaries



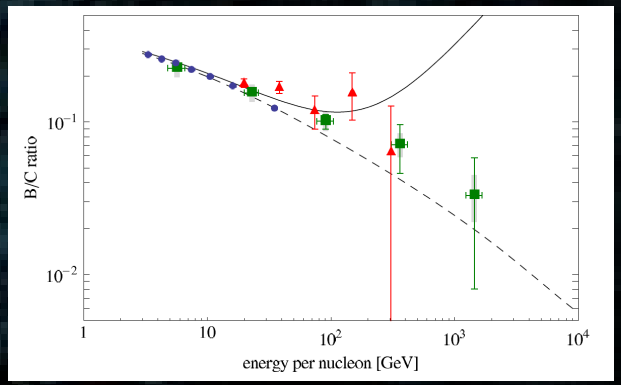
Positron fraction



Antiproton fraction

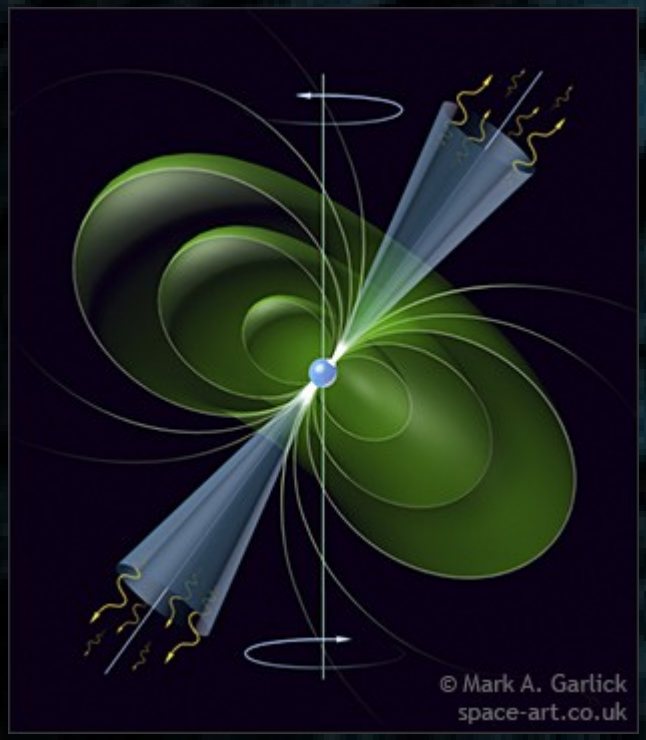


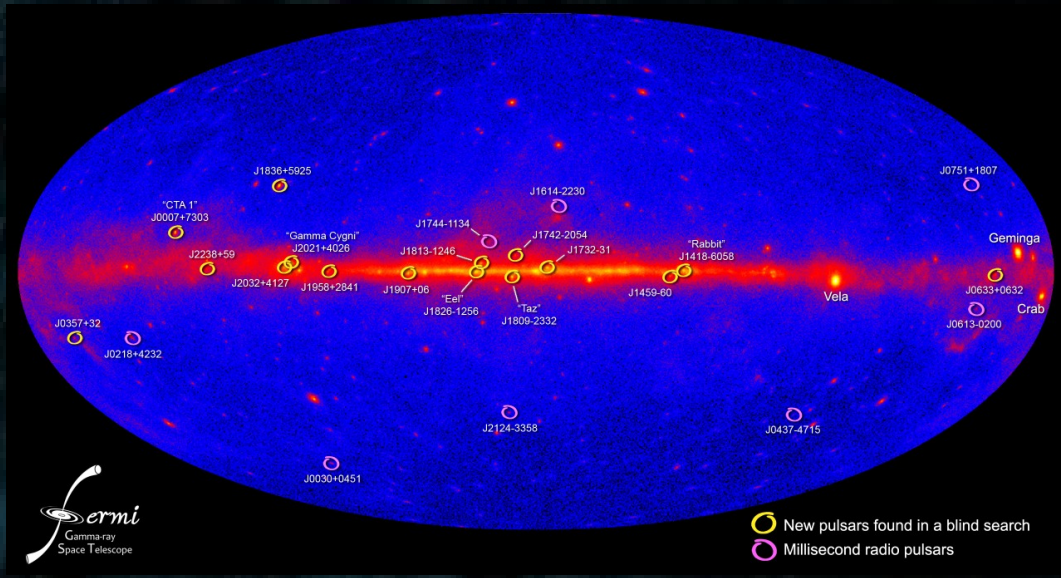
B/C measurements



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

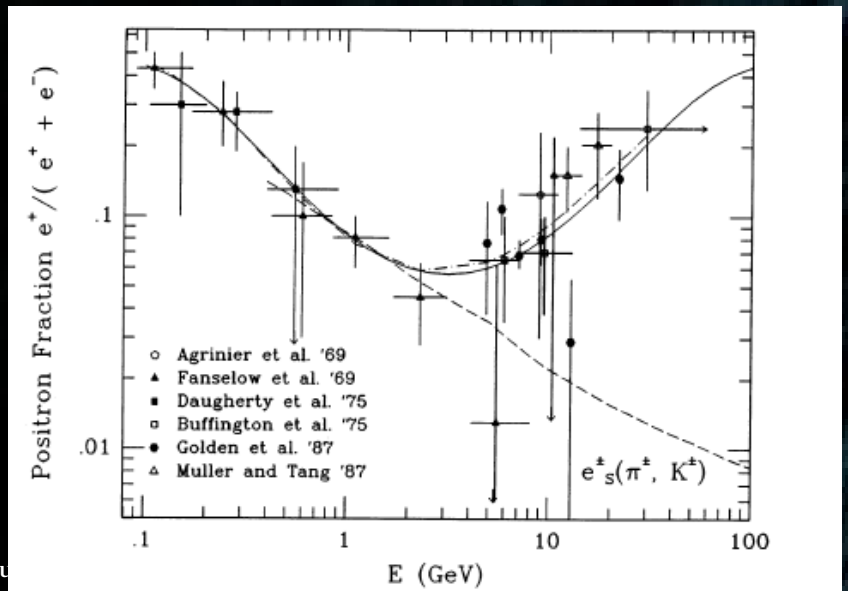
"Standard" positron sources ? ... Pulsars !





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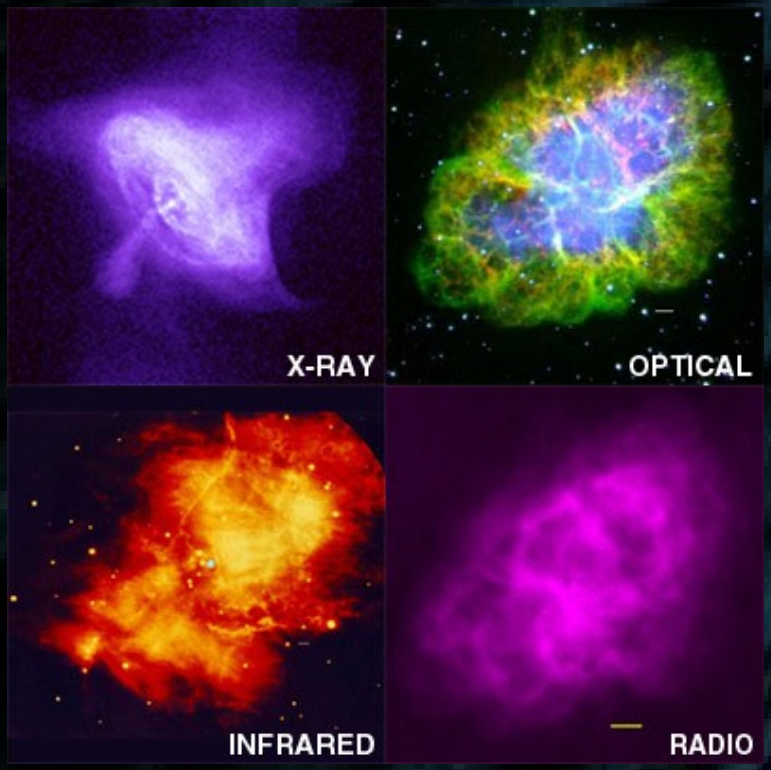
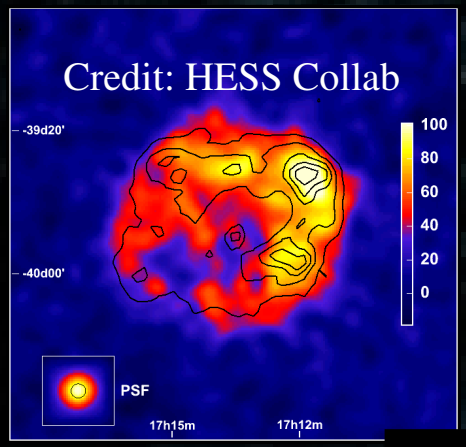
THE NATURE OF THE COSMIC-RAY ELECTRON SPECTRUM, AND SUPERNOVA REMNANT CONTRIBUTIONS

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

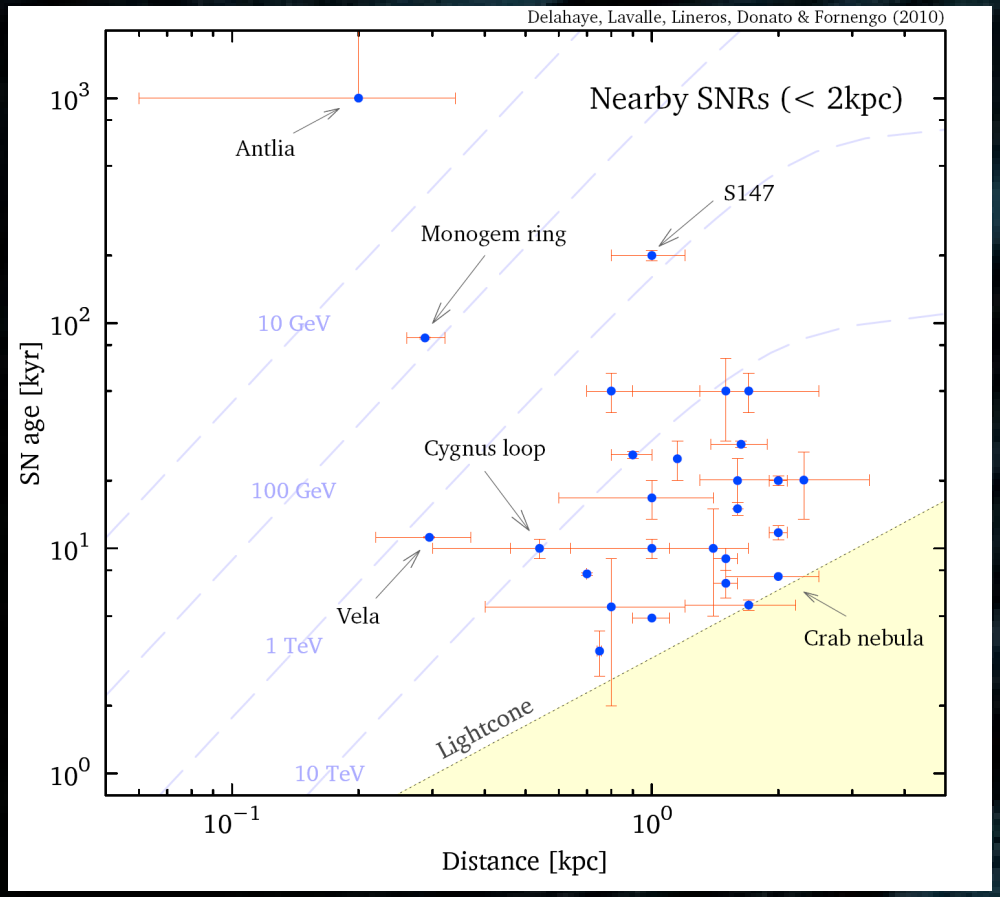
Standard paradigm, but not standard model!

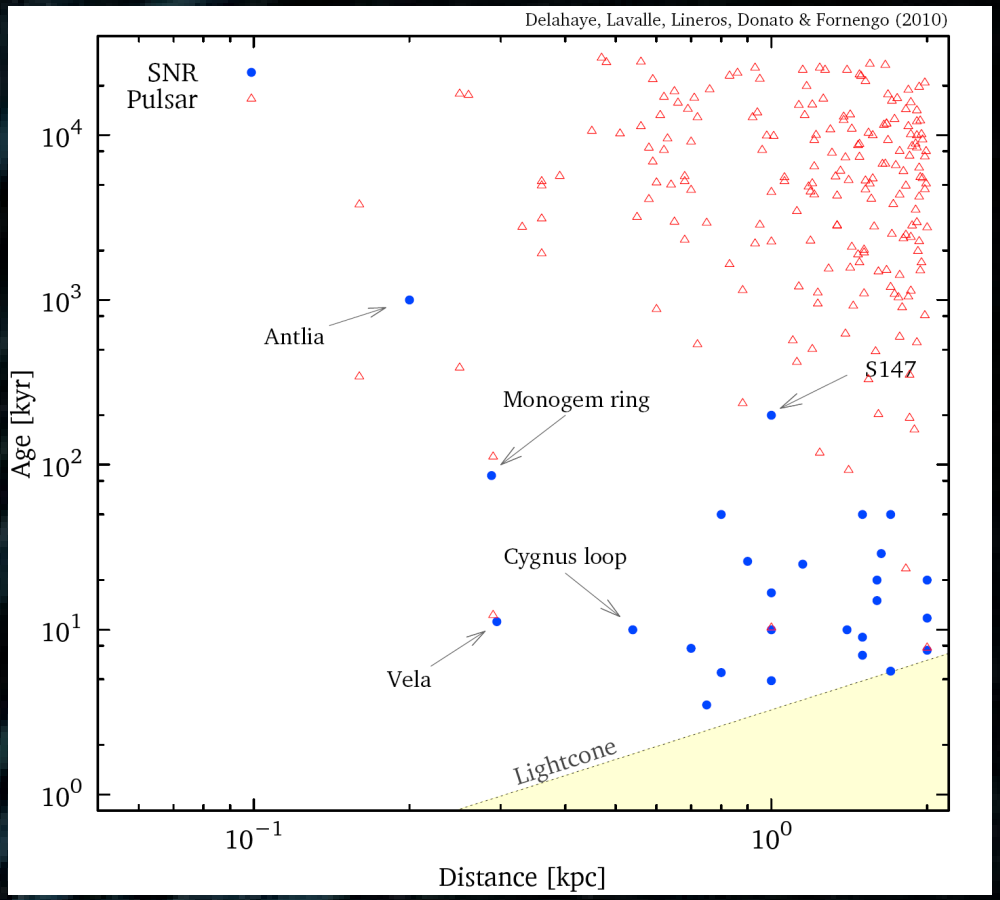
Deal with the complexity of Nature: Include all known local sources self-consistently

27 obs SNRs within 2 kpc

Delahaye et al 10
arXiv:1002.1910

~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

Delahaye et al 10
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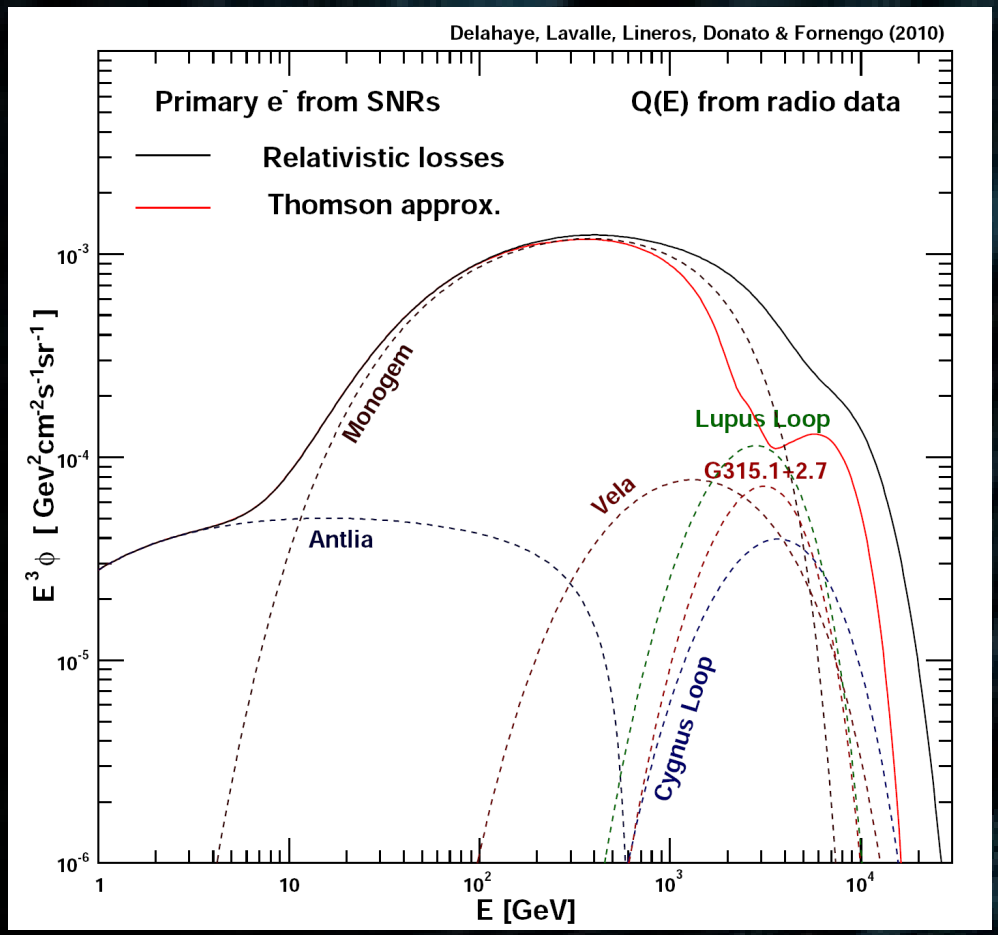
27 obs SNRs within 2 kpc



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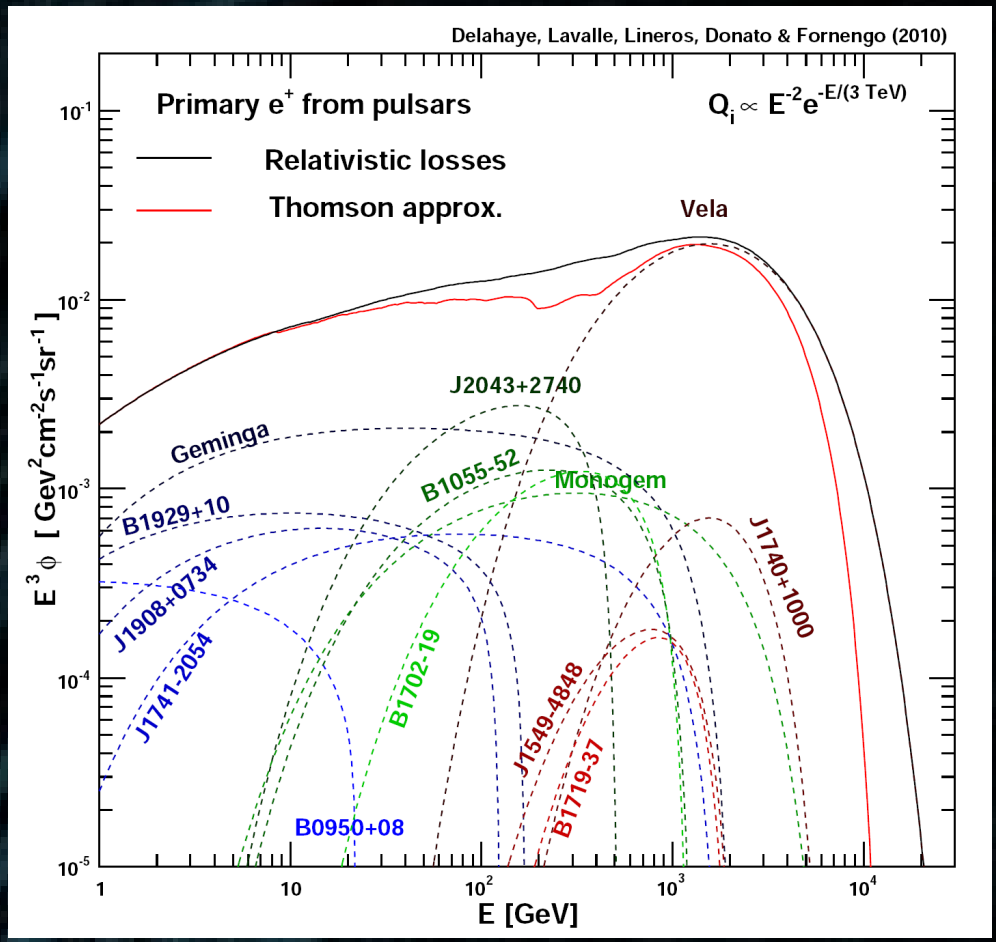
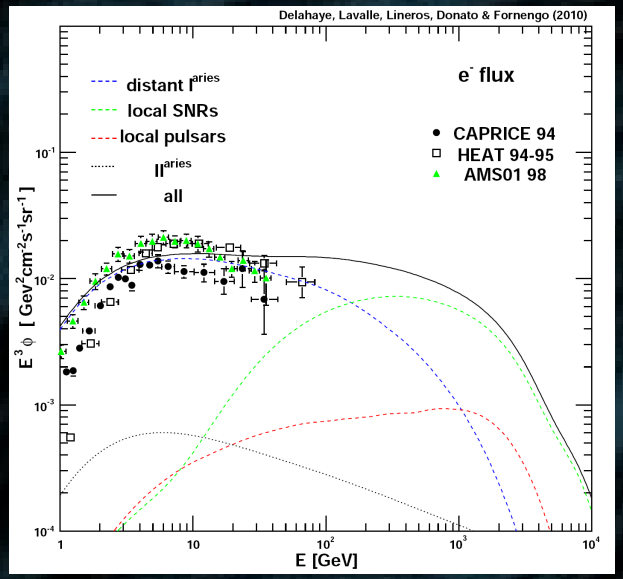


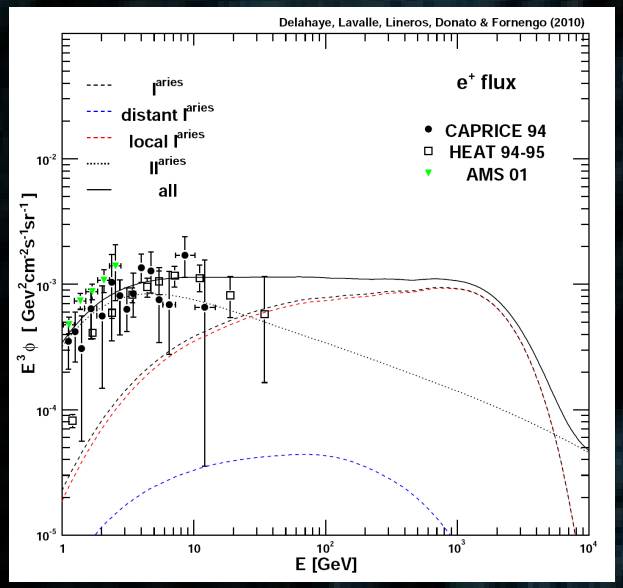
SNRs contribute to e^-, pulsars inject e^+e^- pairs ...
... but each pulsar should be associated with a SNR => Add missing SNRs !

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

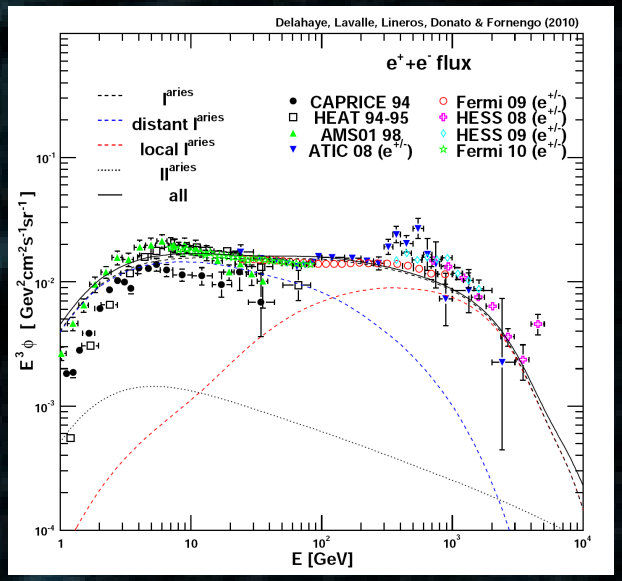
electrons



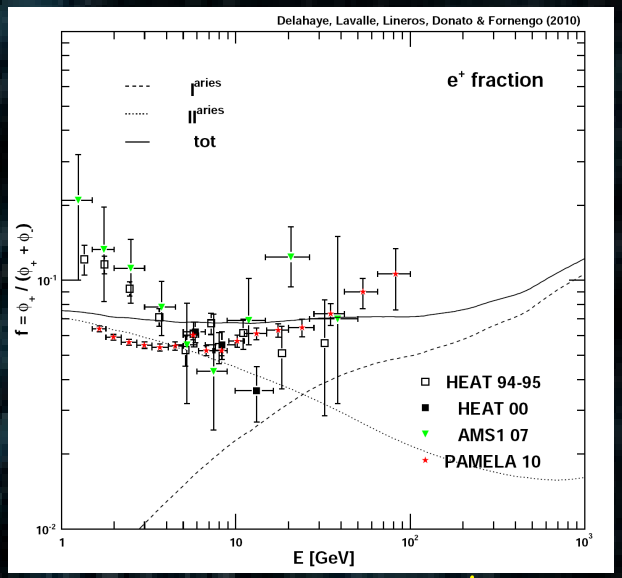
positrons



Delahaye et al 10 (arXiv:1002.1910 a



electrons + positrons



positron fraction

Standard astrophysical sources make it!

The local $e^{+/-}$ anomalies: Summary and conclusions

Dark matter interpretation

- Unnatural for most of DM candidates in particle physics: fluxes far too low
- Other contrived models likely excluded (gamma-ray data, synchrotron, early universe)
- Caveats: background not under control ! Use the data as constraints only.

Perspectives: combine LHC + astrophysics (multi-messenger, multi-λ) + direct detection ... some smoking guns soon hopefully

Astrophysical explanations

- High energy e^+e^- pairs naturally created from strong magnetic fields around pulsars
- Minimal assumptions lead to the correct amount of positrons
- A consistent model of >20 GeV CR electrons must include local sources (SNRs & pulsars)
- A complete model, though still too simplistic, can explain the data all together

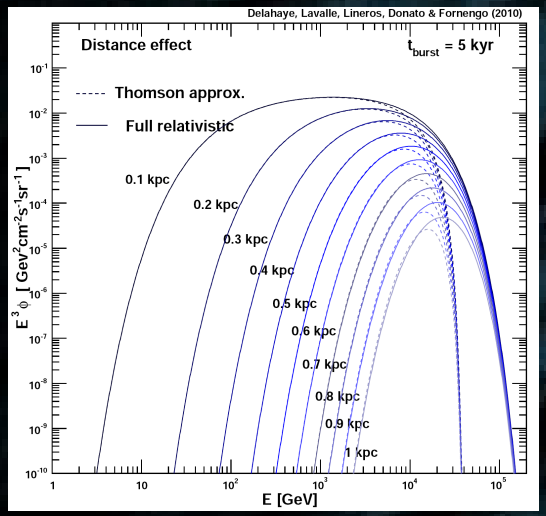
Perspectives: (local) source modeling, propagation to refine

General

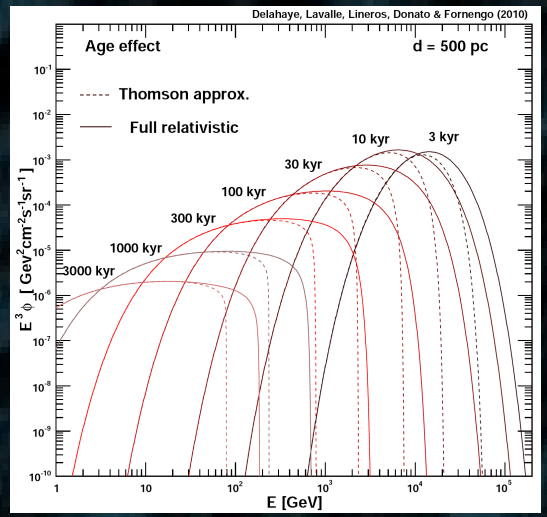
- Improving our understanding of high energy CR electrons will provide new insights on: magnetic fields (synchrotron), diffuse emissions (**Galactic center**), etc.

Backup slides

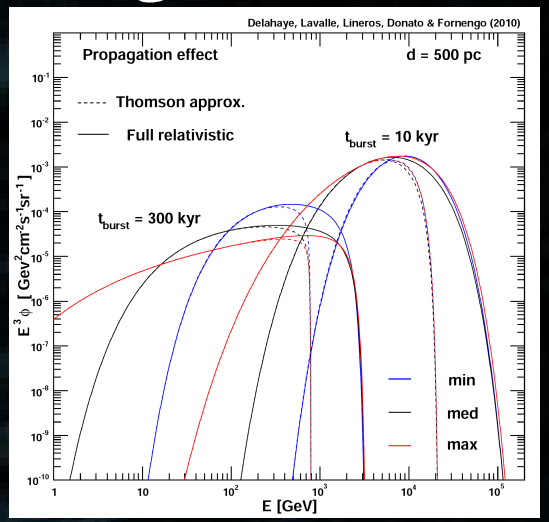
Time, spatial and spectral fluctuations at HE: Origin of uncertainties for local bursting sources



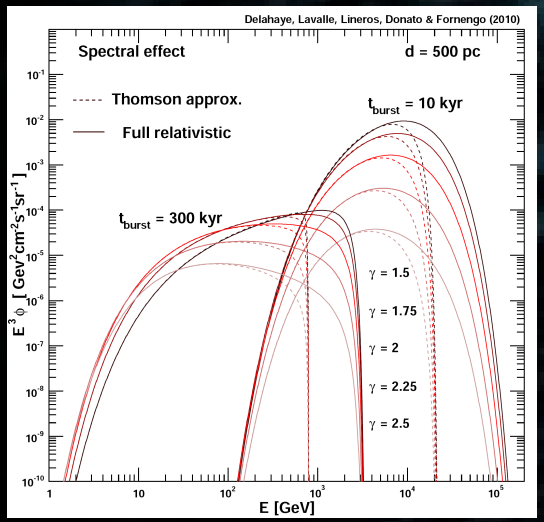
Distance effect



Age effect



Propagation effect



Spectral effect

arXiv:1002.1910

Time-dependent propagator

$$\mathcal{G}_t(t, E, \boldsymbol{x} \leftarrow t_s, E_s, \boldsymbol{x}_s) = \frac{\delta(\Delta t - \Delta\tau)}{b(E)} \frac{\exp\left\{-\frac{(\boldsymbol{x}-\boldsymbol{x}_s)^2}{\lambda^2}\right\}}{(\pi\lambda^2)^{3/2}}$$

Although observational constraints exist, uncertainties are very large