(Towards) models of Galactic cosmic-ray electrons and positrons: Lessons from local measurements

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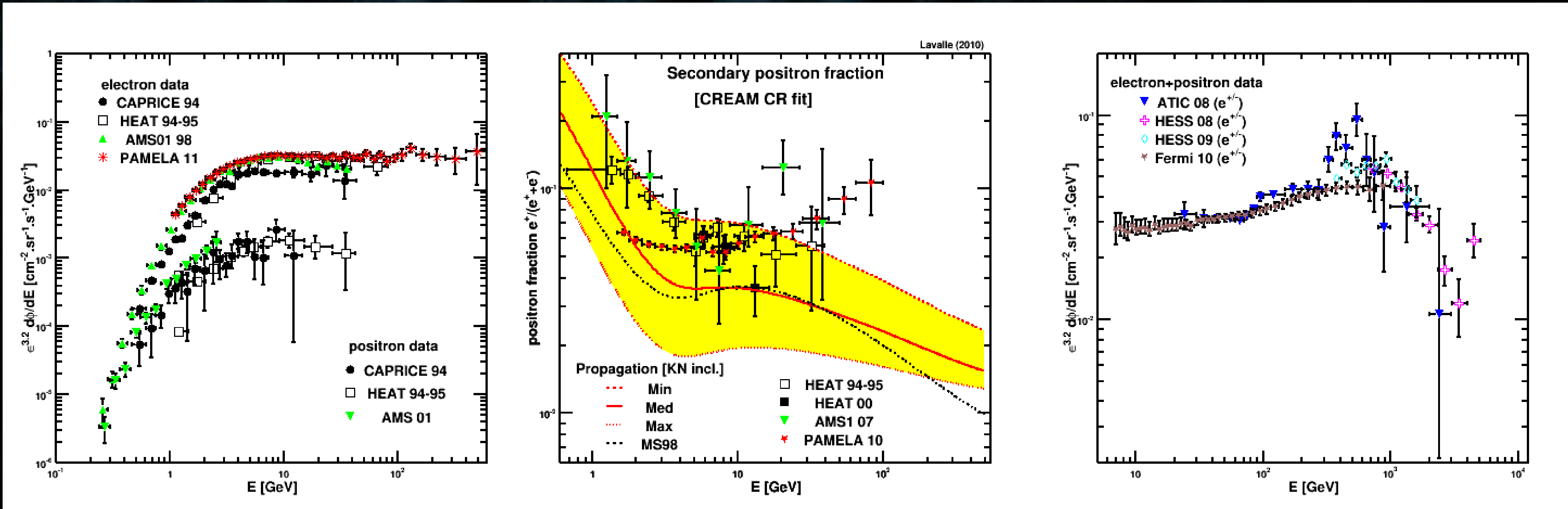
Refs: Delahaye, Lavalle, Lineros et al, A&A 524 A51 (2010)

++work in prep. with. T. Delahaye (IFT) & A. Marcowith (LUPM)

CRISM @ Montpellier, 27-VI-2011 – 1-VII-2011

A quick look at the $e^{+/-}$ data



e^+ and e^-:
CAPRICE 94, HEAT 94-95, AMS 98, PAMELA 11

$e^+/(e^+ + e^-)$:
HEAT 95, AMS 98, PAMELA 09-10
+++ Secondaries + unc.
Delahaye et al 09, Lavalle 11

$(e^+ + e^-)$:
ATIC 08, HESS 09, Fermi 09-10

- Primary Galactic positrons confirmed ! (see also Fermi Symposium 11)
- Need positron-only data (PAMELA release at fall 11)
- $e^{+/-}$ observed up to 3 TeV at Earth, source index ~ -2 OK

=> > 1 TeV $e^{+/-}$ DO ESCAPE from sources

A bit back in time (credit to old ideas!)

NATURE VOL. 227 AUGUST 1 1970

Pulsar Radiation Mechanisms

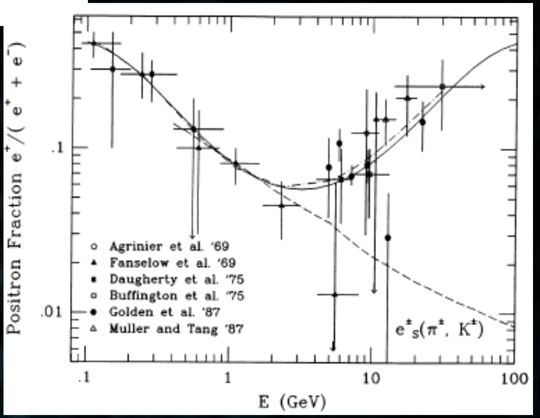
by
P. A. STURROCK*
Institute for Plasma Research,
Stanford University,
Stanford, California

Gamma rays produced by electrons accelerated in the strong magnetic fields of neutron stars annihilate to electron–positron pairs. This leads to a two-stream situation, which results in bunching and coherent radio emission.

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

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

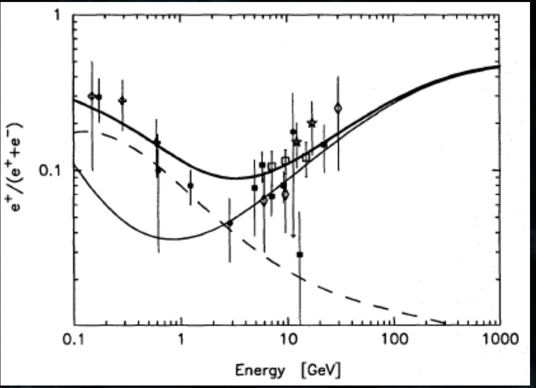
AHMED BOULARES
Physics Department, Space Physics Laboratory, University of Wisconsin–Madison



Astron. Astrophys. 294, L41–L44 (1995)

High energy electrons and positrons in cosmic rays as an indicator of the existence of a nearby cosmic tevatron

F.A. Aharonian[1], A.M. Atoyan[1,2], and H.J. Völk[1]
[1] Max-Planck-Institut für Kernphysik, Postfach 10 39 80, D-69029 Heidelberg, Germany
[2] Yerevan Physics Institute, Alikhanian Br.2, 375036 Yerevan, Armenia

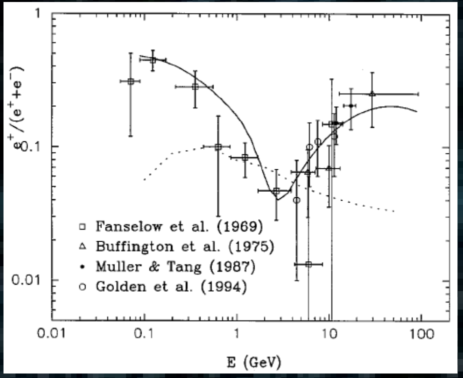


THE ASTROPHYSICAL JOURNAL, 459:L83–L86, 1996 March 10

PULSAR-WIND ORIGIN OF COSMIC-RAY POSITRONS

X. CHI,[1] K. S. CHENG,[2] AND E. C. M. YOUNG[1]

Received 1995 April 10; accepted 1995 December 28

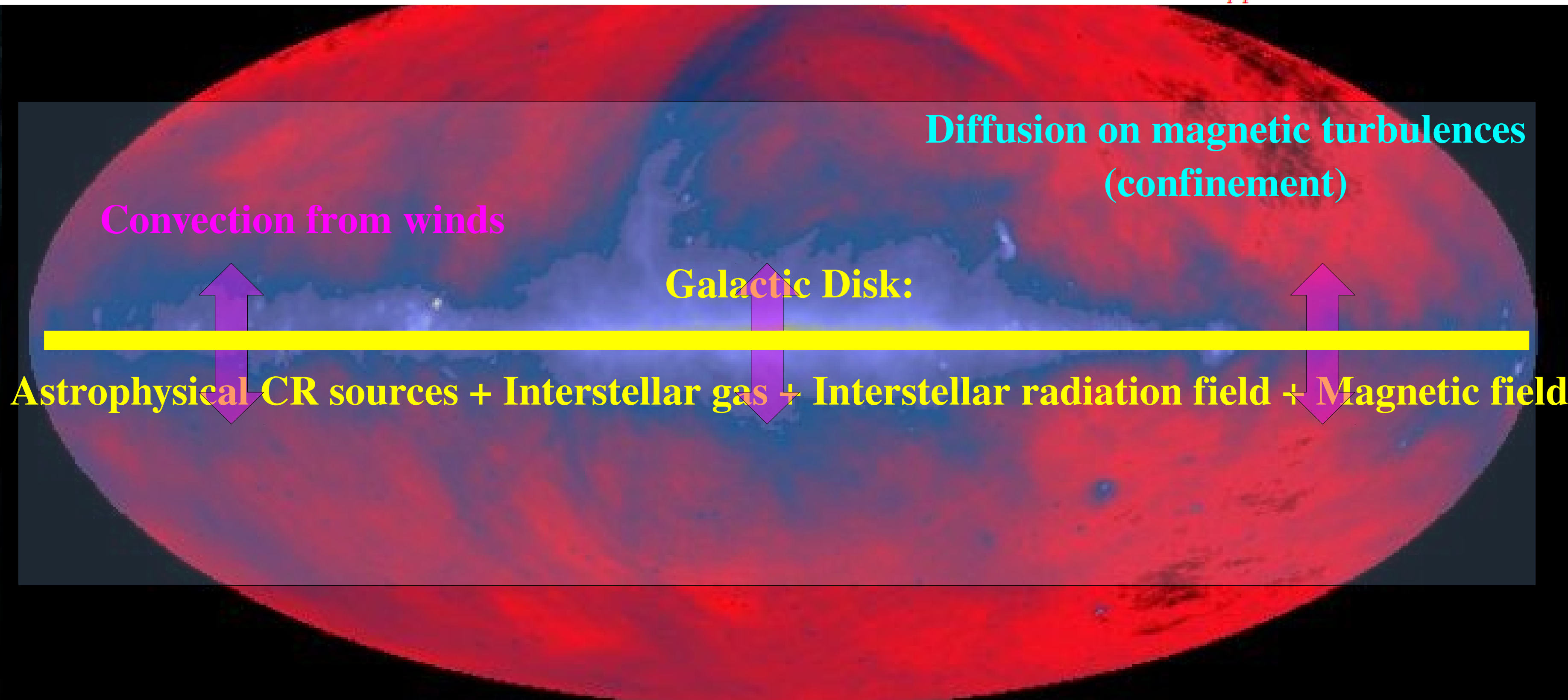


Pulsars have long been predicted to be sources of high-energy positrons

Propagation of Galactic cosmic rays: The standard picture

e.g. Berezinsky et al 90, Ptuskin's talk, Putze's talk

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



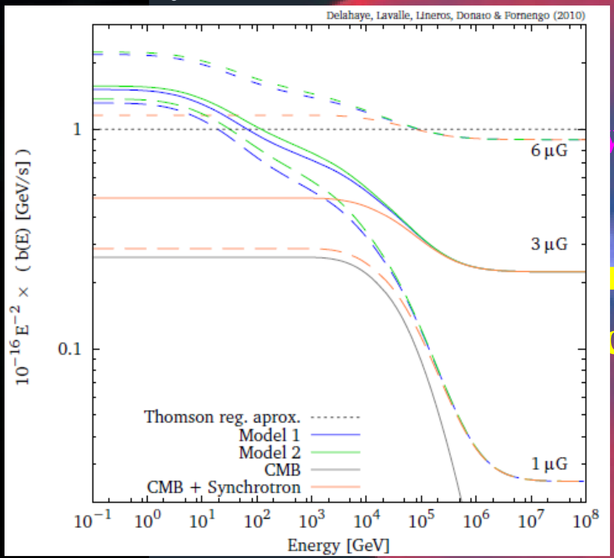
408 MHz synchrotron, Haslam et al (1982)

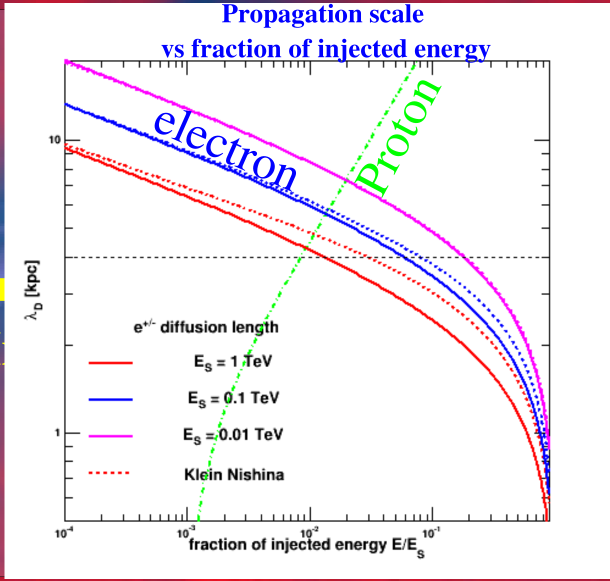
In the GeV-TeV energy range, electrons lose energy quickly as they propagate, protons do not

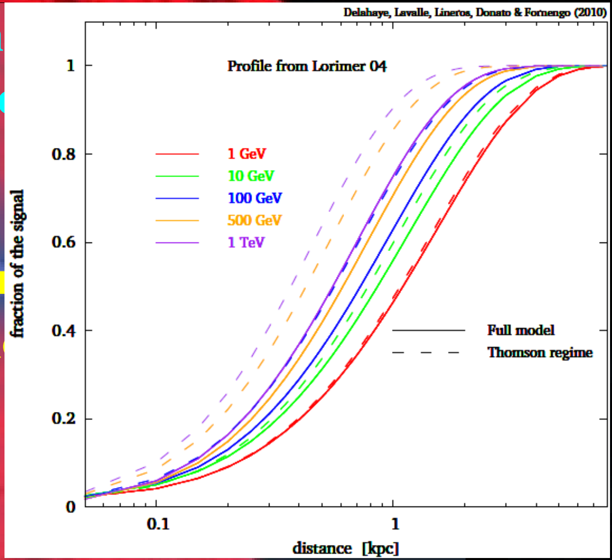
Propagation of Galactic cosmic rays: The standard picture

$e^{+/-}$ > 5 GeV: neglect convection, reacceleration, interaction with gas
=> Transport driven by spatial diffusion and IC/synchrotron energy losses

ISRF by Porter et al 06







From Haslam et al data (1982)

In the GeV-TeV energy range, electrons lose energy quickly as they propagate, protons do not

Electron energy loss rate $\propto E^2$ (Compton, synchrotron processes)

Short range propagation: local fluctuations dominate in the range 0.1-1 TeV

THE ASTROPHYSICAL JOURNAL, 162:L181–L186, December 1970

PULSARS AND VERY HIGH-ENERGY COSMIC-RAY ELECTRONS

C. S. SHEN*
Department of Physics, Purdue University, Lafayette, Indiana 47907

In the study of the propagation of cosmic-ray electrons, the use of a continuous source distribution is not valid in the range of very high energies. The electron spectrum in that energy range depends on the age and distance of a few local sources. It is shown that if the far-infrared background discovered recently exists in the Galaxy, the very high-energy electrons observed at Earth probably all come from the source Vela X, and a cutoff energy at about 2 × 10³ BeV is predicted. Implications on the propagation of cosmic rays in the Galaxy are discussed.

Ginzburg & Syrovastki 65-70, Shen 70:

Energy-loss timescale
~ 1/[E b(E)]
TeV => t ~ 300 kyr

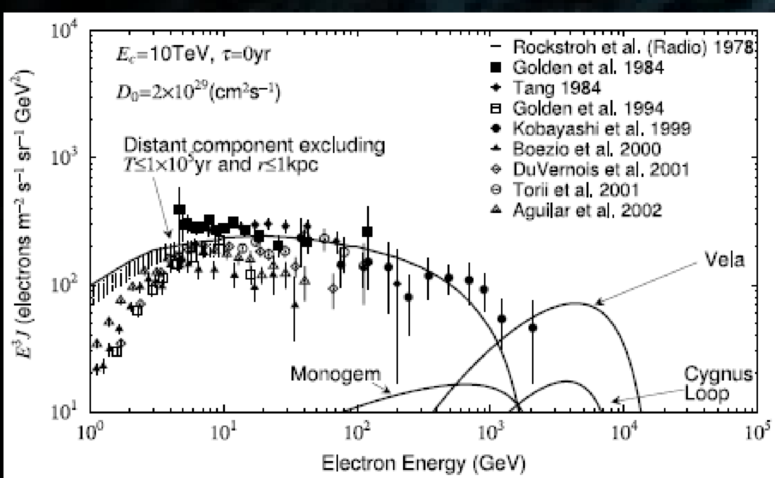
Corresponding spatial scale
l ~ $(D/bE)^{1/2}$ ~ 1 kpc

Corresponding source stat.
N ~ *O*(1-10)
(assuming 3 SNe/100 yr)

THE ASTROPHYSICAL JOURNAL, 601:340–351, 2004 January 20

THE MOST LIKELY SOURCES OF HIGH-ENERGY COSMIC-RAY ELECTRONS IN SUPERNOVA REMNANTS

Kobayashi et al 04: smooth + single sources

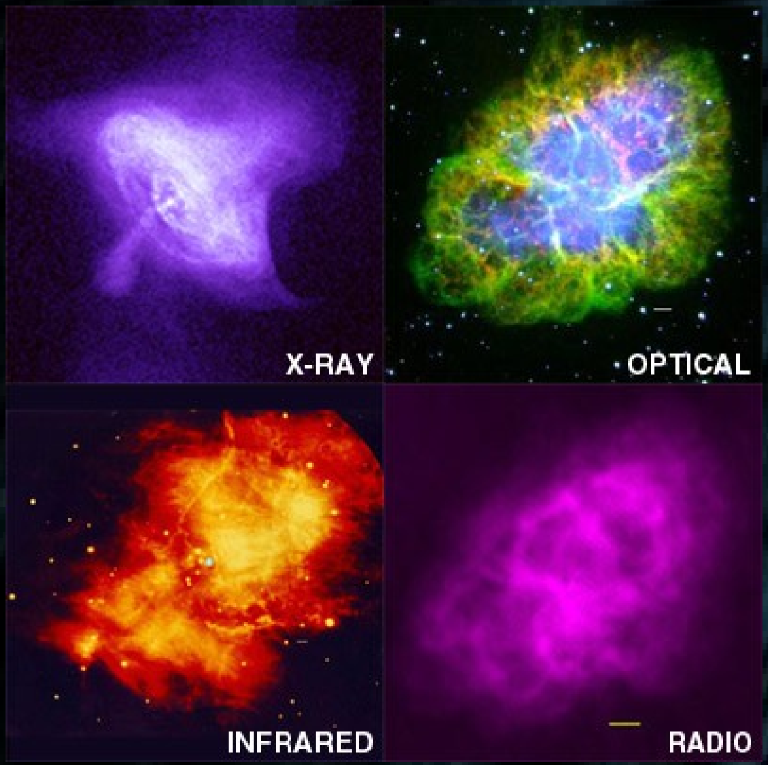


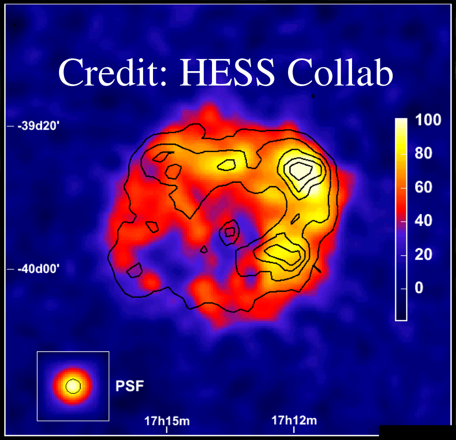
Kobayashi et al 04:

- Distant sources modeled with a smooth spatial distribution
- Local sources < 1 kpc from observations
- Self-consistency => radial cut-off to the smooth distrib

=> Beware: merely adding single sources to any smooth prediction suffers inconsistency.

Towards a consistent picture and modeling





Include all primaries (after secondaries):

- SNRs accelerate electrons mostly
- Pulsar winds 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 source properties (smooth distrib.)

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

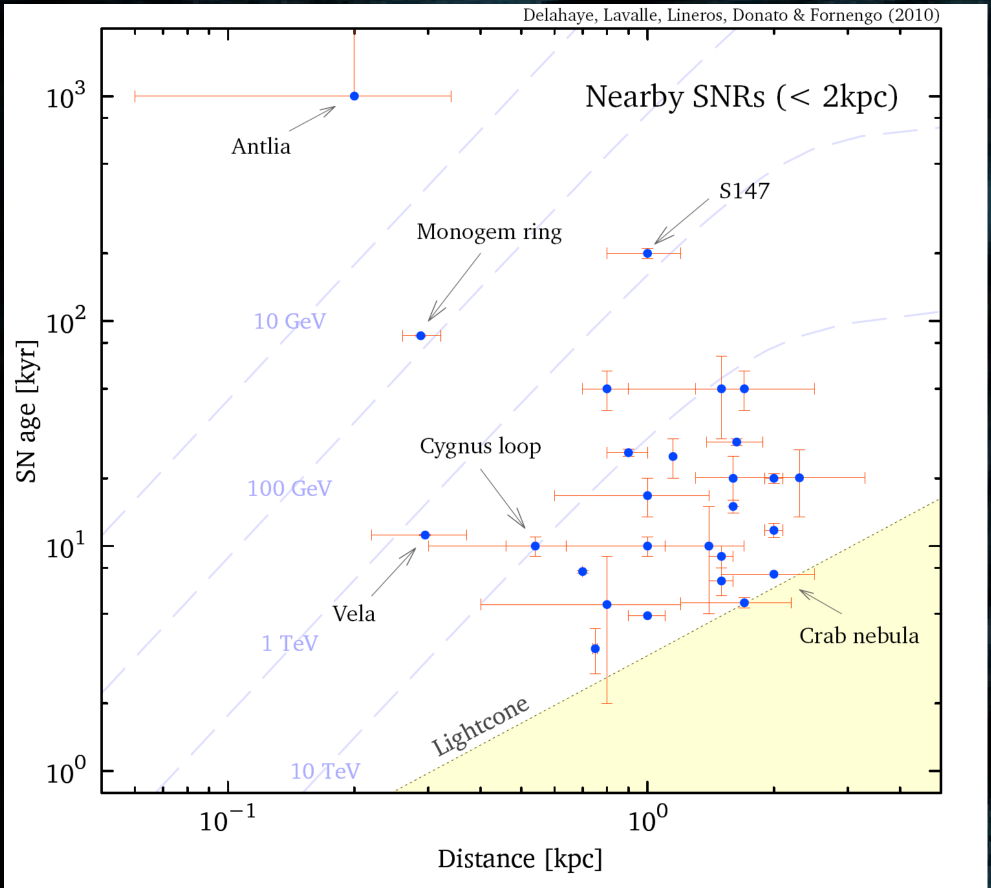
Standard paradigm, but not standard model!

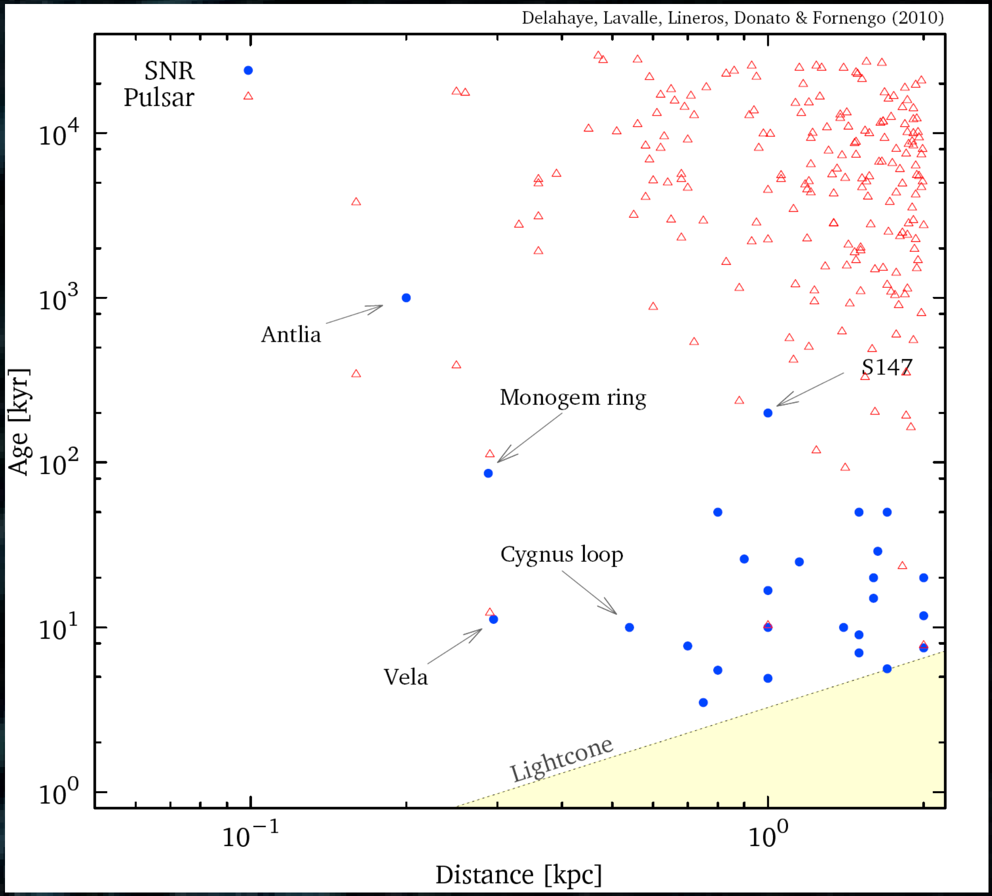
Deal with the complexity of Nature: Include all known local sources self-consistently

27 obs SNRs within 2 kpc (Green catalog)

Delahaye et al 10 arXiv:1002.1910

~200 obs pulsars within 2 kpc (ATNF catalog)





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

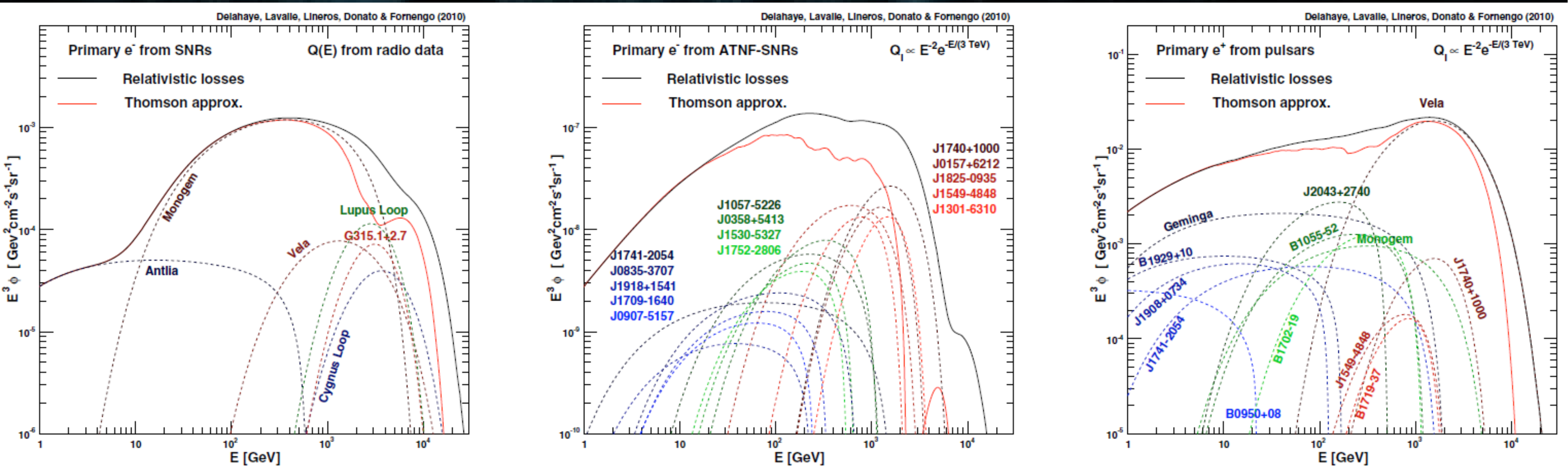
... but each pulsar should be associated with a SNR => Add missing SNRs !

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

27 obs SNRs within 2 kpc

Delahaye et al 10
arXiv:1002.1910

~200 obs pulsars within 2 kpc
=> many unobs SNR counterparts



SNRs contribute to e^-, pulsar winds inject e^+e^- pairs ...

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

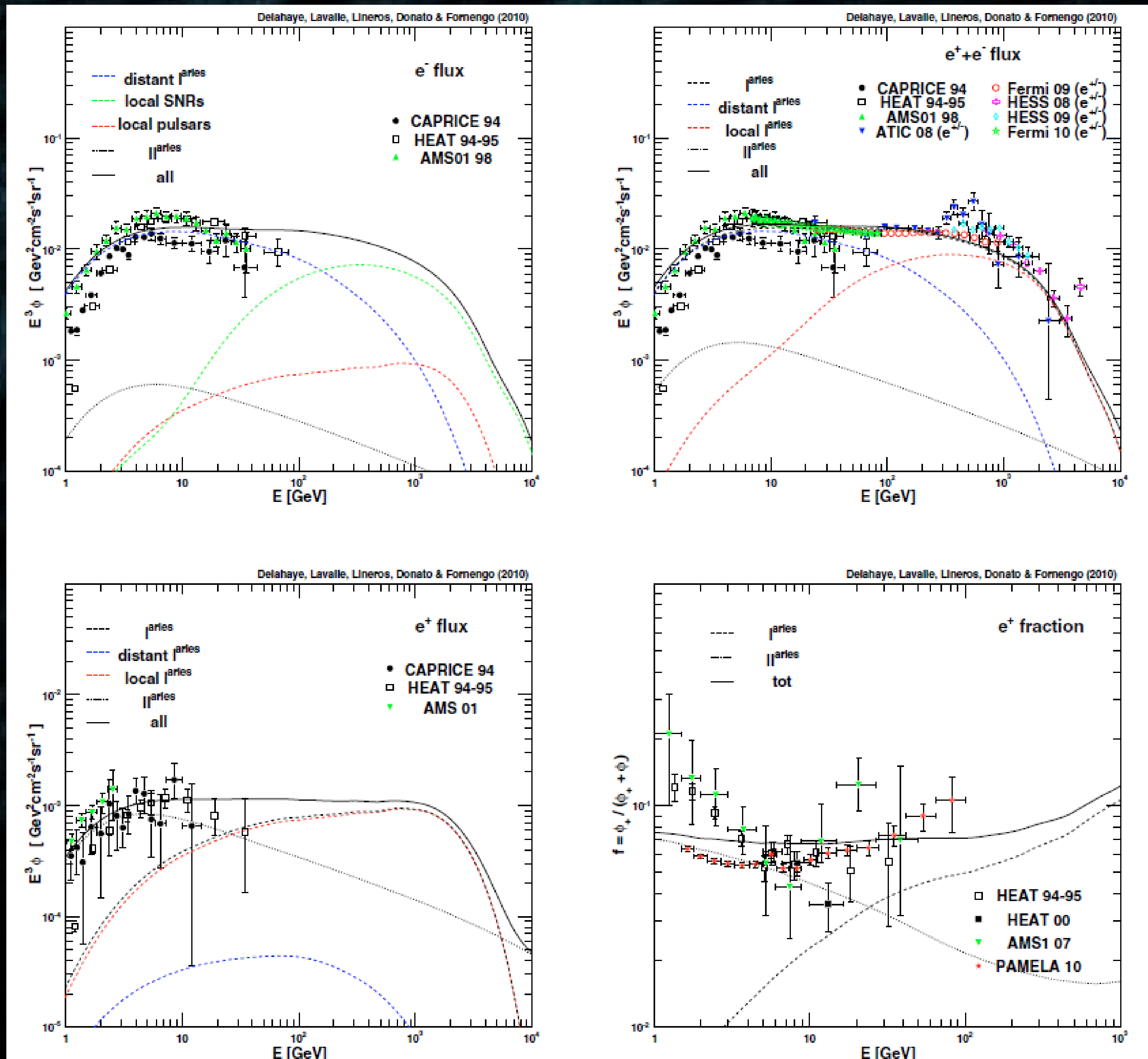
Applying sensitivity constraints to unobs. SNRs make them quite subdominant wrt to obs. SNRs

=> Monte-Carlo methods irrelevant for local $e^{+/-}$ budget

Include all known local sources self-consistently

electrons

electrons + positrons



positrons

positron fraction

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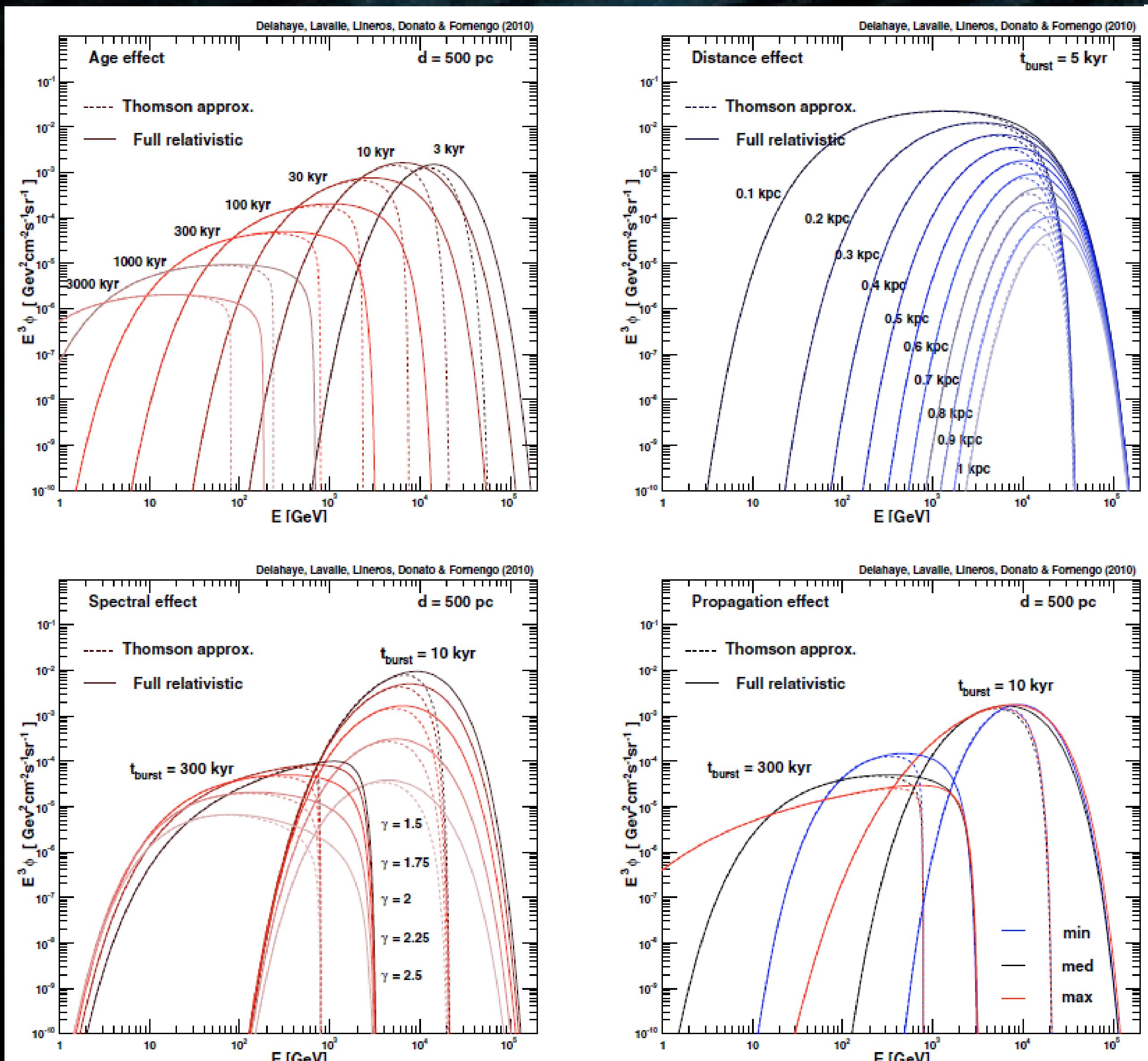
No fine tuning: local sources qualitatively make it!

Large theoretical uncertainties: impact of parameters

$$Q_s(x,E,t) = Q_0\,(E/E_0)^{-\gamma}\,\exp(-E/E_c)\,\delta(x-x_s)\,\delta(t-t_s)$$



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

- Time kills high energies
- Distance kills low energies
- Spectral index: changes the amplitude (cst normalization effect)
- Diffusion coef. K
  +++ charaterizes the Gaussian width
  +++ flux propto 1/K^3/2

Klein-Nishina effects must be included: potentially strong impact on the amplitude, spectrum and max energy! (depends on <B-field>)

=> Source modeling is a key point

Local source modeling: issues

Relevant timescales at the source

$$\text{actual source age} = \text{obs. source age} + \left\{ \frac{d}{c} \approx 3\,\text{kyr}\,\left[\frac{d}{1\,\text{kpc}}\right] \right\}$$

CR $e^{+/-}$ must escape! ... SNRs versus PWNe

SNRs – gross phenomenological aspects (eg Drury 10, Ohira et al 10-11):

- CR e- are fully confined up to Sedov phase
- Max energy when Sedov phase starts, then decreases
- Can escape during Sedov phase provided tesc(E) < tloss(E)
- Much less synchrotron emission for runaway e- (B~B(ism))

PWNe – see eg Blasi & Amato 10

- Pulsars inside SNR shell at first
- Ballistic reasoning: 500 km/s kick => 40-50 kyr to cross SNR shell
- Much smaller magnetic fields than in SNRs => B-losses less efficient, escape efficient after crossing the SNR shell.

=> Still very difficult to deal with escape

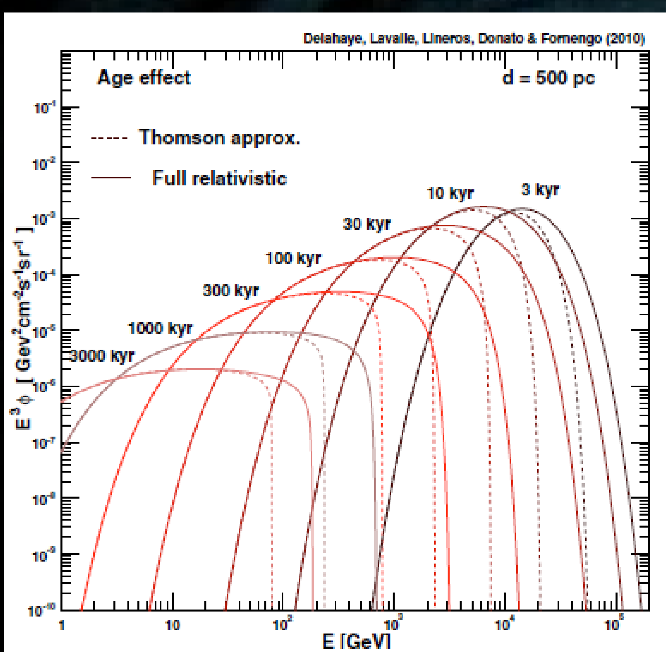
=> use phenomenological arguments and multiwavelength constraints

Local transport timescale constraints

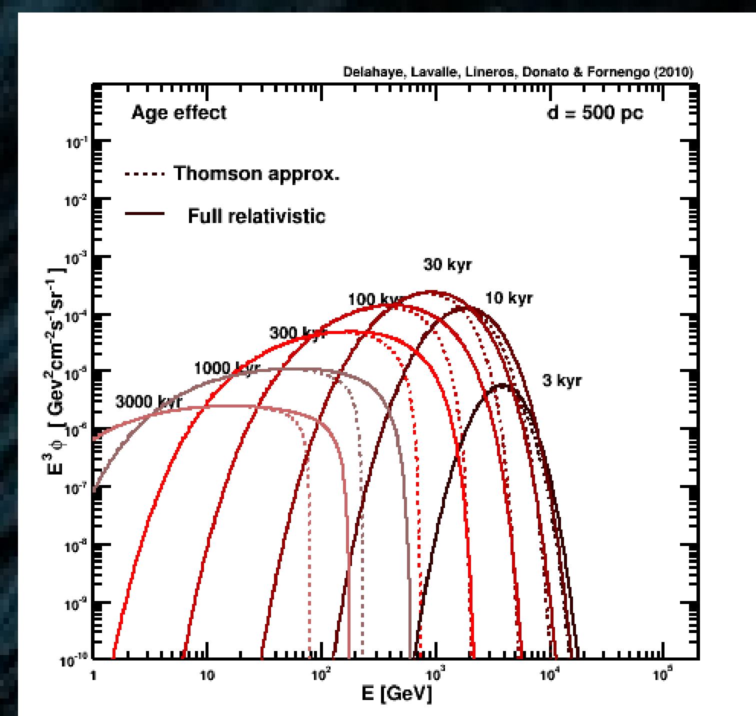
$$\text{transport time} \approx \frac{d^2}{K(E)} \approx 89\,\text{Myr}\left[\frac{K_0}{0.01\,\text{kpc}^2/\text{Myr}}\right]^{-1}\left[\frac{E}{1\,\text{GeV}}\right]^{-\delta}\left[\frac{d}{1\,\text{kpc}}\right]^{2}$$
$$\approx 150(700)\,\text{kyr @ } 10(1)\,\text{TeV}$$

$$\text{E-loss time} = \int_E^{E_s} dE'\, b(E') \approx 30(300)\,\text{kyr @ } 10(1)\,\text{TeV}$$

=> Ages < 30 kyr likely dismissed (Vela and Cygnus Loop out of the race: t ~ 10 kyr)
=> Most probable contributors: Geminga-PWN (300 kyr), Monogem-SNR/PWN (100 kyr)
Analytical solutions to transport do not ensure causality; by-hand method not necessarily correct.

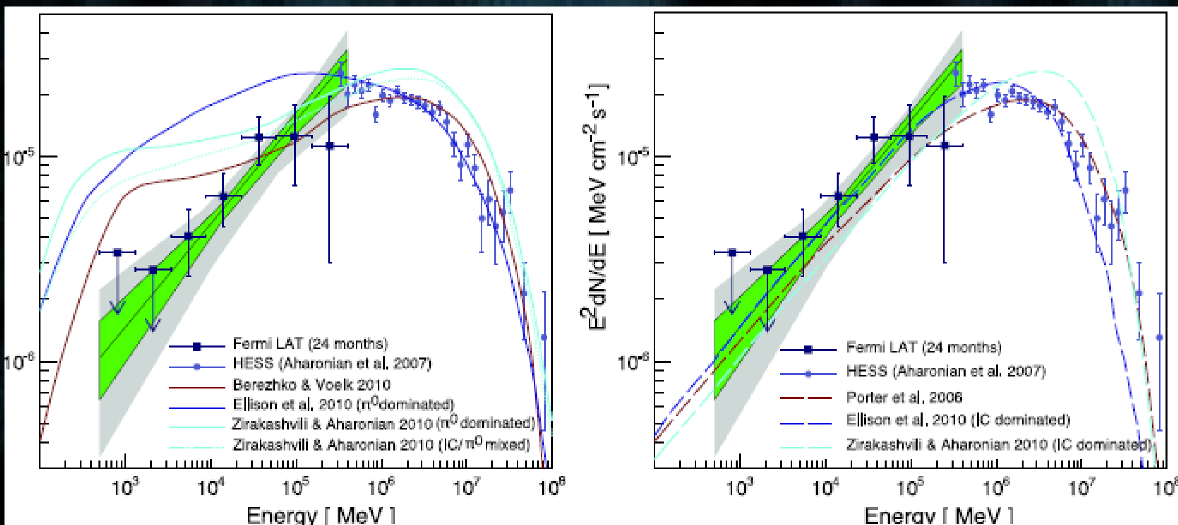


10 TeV to 1 TeV
=> 1 TeV cut-off OK

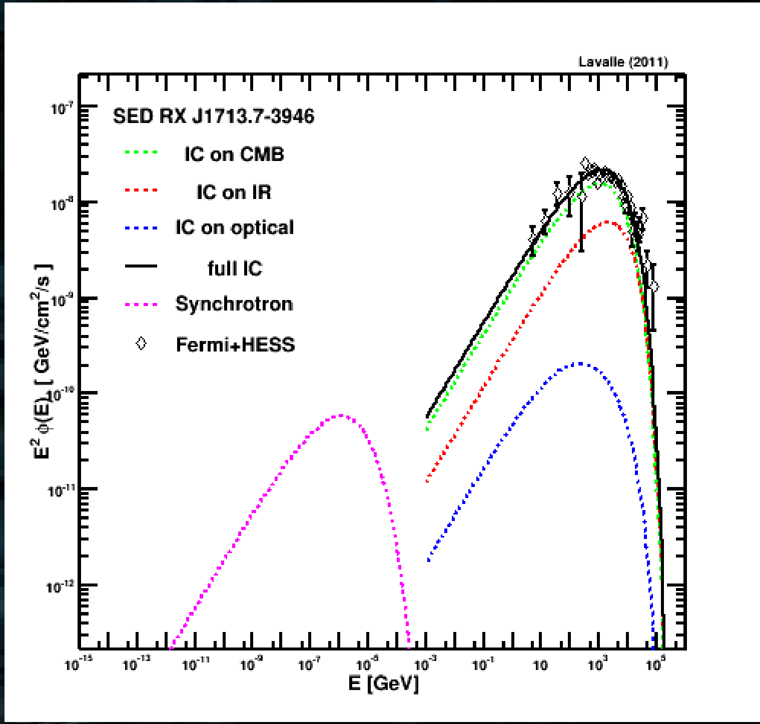


How to improve? Multi-lambda + source model

Fermi Collab. arXiv:1103.5727
SNR RX J1713.7-3946



Example of RX J1713, GeV-TeV emission



~2 * source term used in Delahaye et al 10 =>

Issue:

- are the electrons responsible for the emission the same as the escaped electrons?
- What we observed occurred a time $t = d/c$ ago.

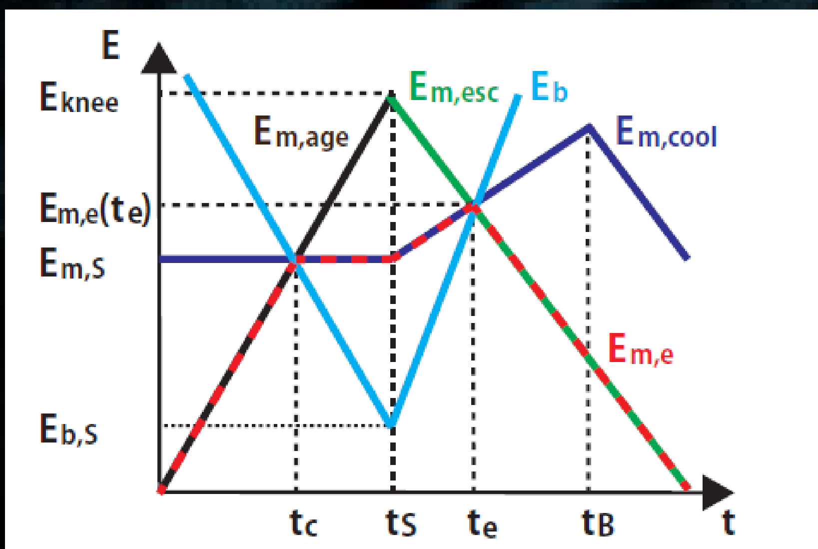
=> transport timescale quite different, need time correction: full time evolution is required.

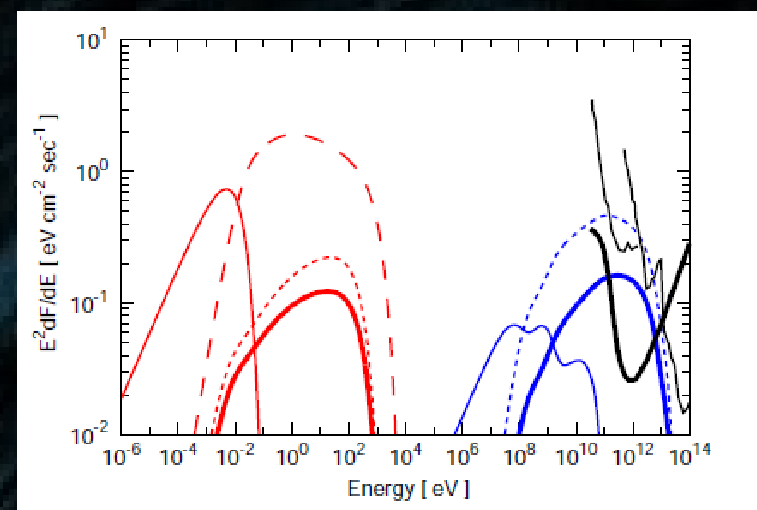
Source models for escaped/trapped electrons + time evolution

ESCAPE OF COSMIC-RAY ELECTRONS FROM SUPERNOVA REMNANTS

Yutaka Ohira[1], Ryo Yamazaki[2], Norita Kawanaka[1], and Kunihito Ioka[1]

Submitted: June 9, 2011





What we observe now did occur 3 kyr (d/kpc) ago.
=> need to "evolve" observations backwards in time to constrain the CR source term.
[Ongoing work with T. Delahaye & A. Marcowith]

Conclusions and perspectives

Standard sources (SNRs and pulsars) provide a natural and phenomenological explanation to the data. Standard paradigm, but not yet a standard model!

Need to treat distant and local sources differently and self-consistently (smooth distrib. + radial cut-off vs local point sources + obs. Constr.). MC irrelevant locally (observed sources' yield dominates).

Source modeling very complicated from first principles, escape issue: obs. constrained empirical/phenomenological models as a first step. Still promising, potential test of CR transport.

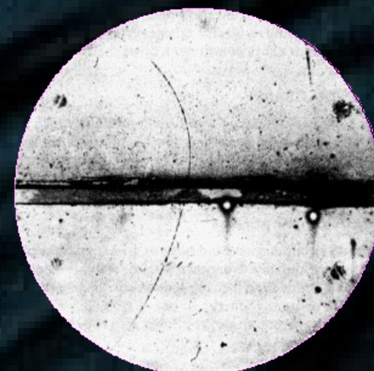
Need more data: e^+ and e^- SEPARATELY > 100 GeV (PAMELA + AMS02)

Understanding local features important for multiwavelength analyses:
Diffuse radio and gamma-rays, Galactic center, Galactic magnetic field.

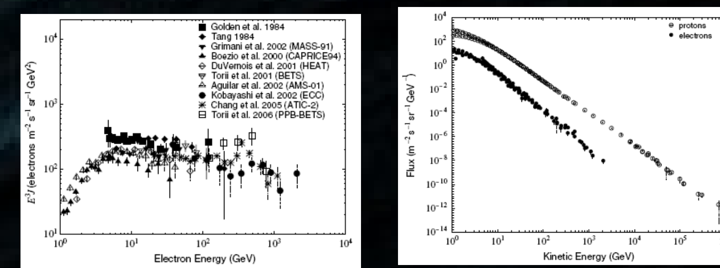
Warning: Smooth and average treatment of > 100 GeV e+/- hardly reliable away from Earth for the moment (eg Galactic center)

Backup slides

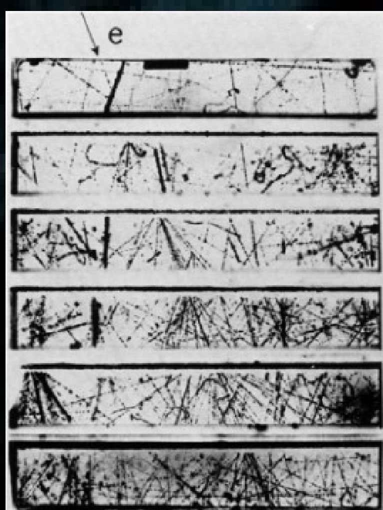
Cosmic e^-s and e^+s: Before PAMELA



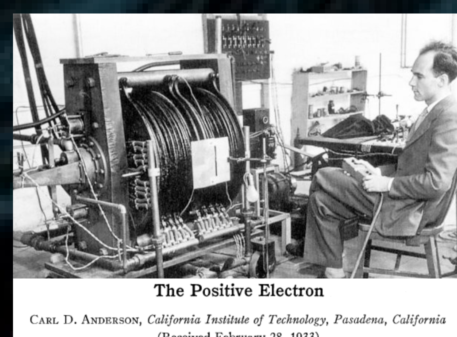
Discovery of the positron
Anderson, Phys. Rev. (1933)



Review by Yoshida (2008)



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

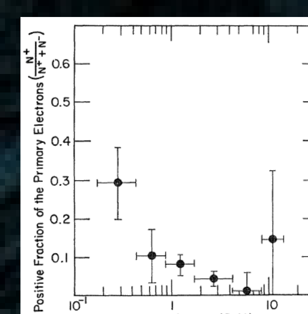


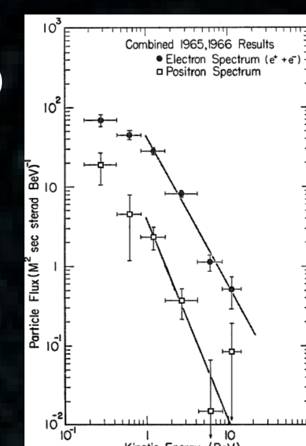
AMS-01 (1998)

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

The origin of cosmic rays
Ginzburg & Sirovatsky (1964)

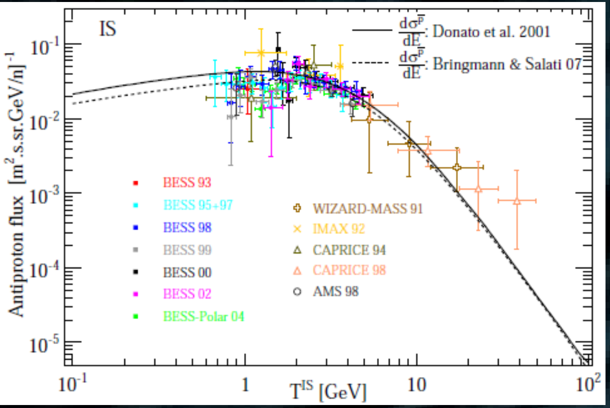
Positron fraction
Fanselow et al (1969)





Secondaries: CRs interaction with ISM

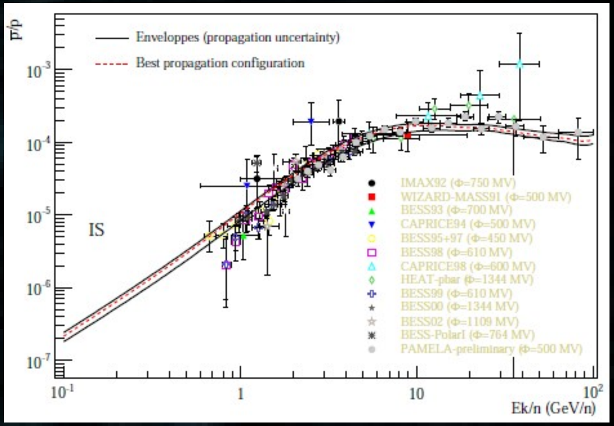
→ Don't forget theoretical uncertainties!



Antiprotons

Donato et al 01, 09

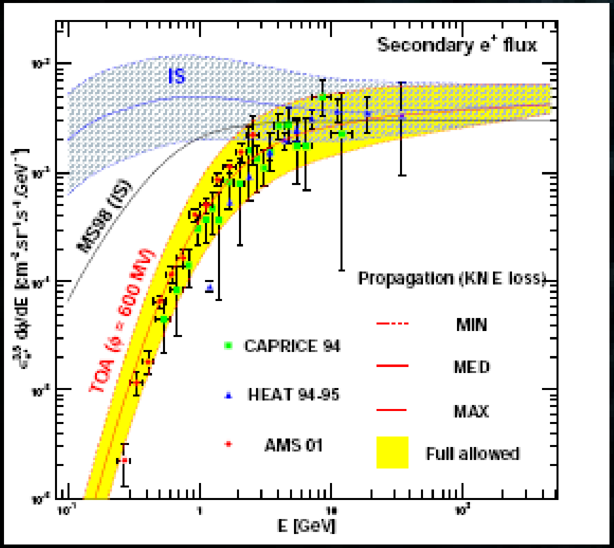
Bringmann & Salati 07



Flux at the Earth

Antiprotons fit, positrons don't

Fraction at the Earth



Positrons

Moskalenko & Strong 98

Delahaye et al 09