Cosmic ray electrons from here and there (the Galactic scale)

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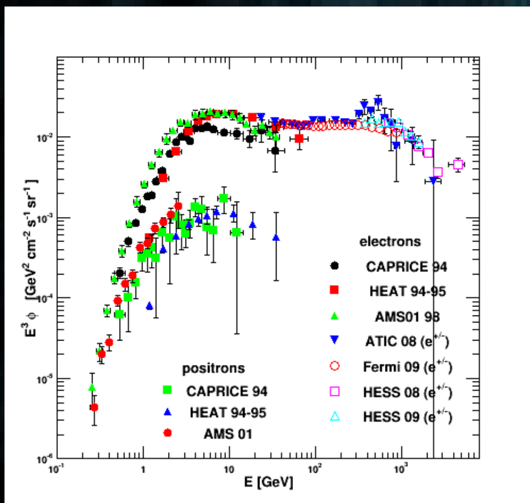
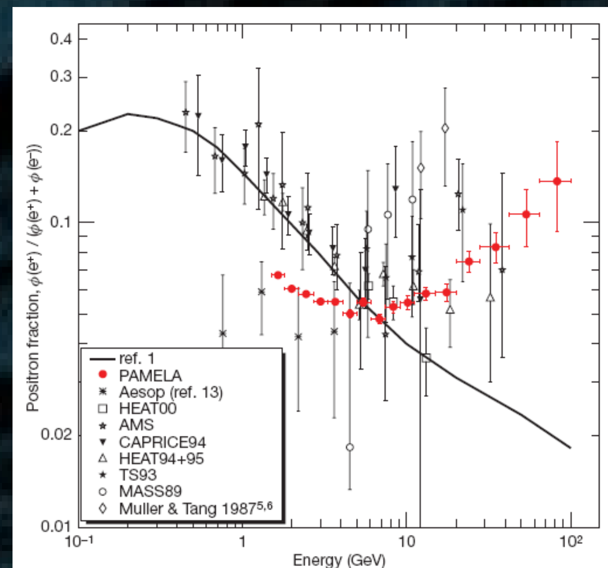
Outline: (i) local electrons (ii) comments on synchrotron
[based on works with Timur Delahaye, Roberto Lineros and Pierre Salati]

Diffuse emissions – GDR PCHE @ IAS, Orsay
9/VI/2010

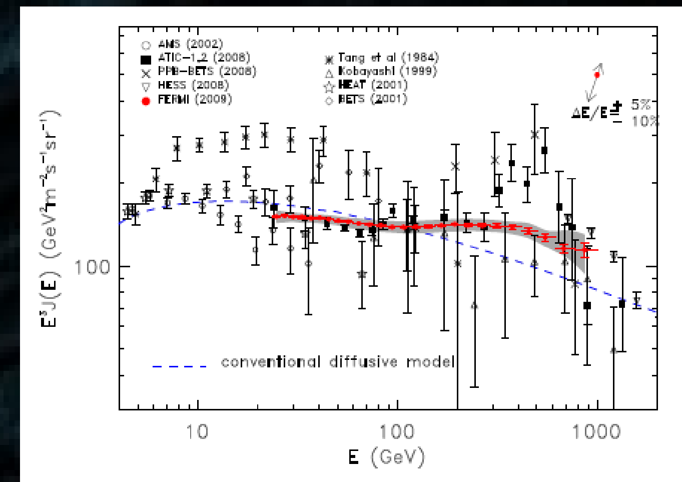
Current local measurements of e^+'s and e^-'s



e+ and e-
data compilation



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

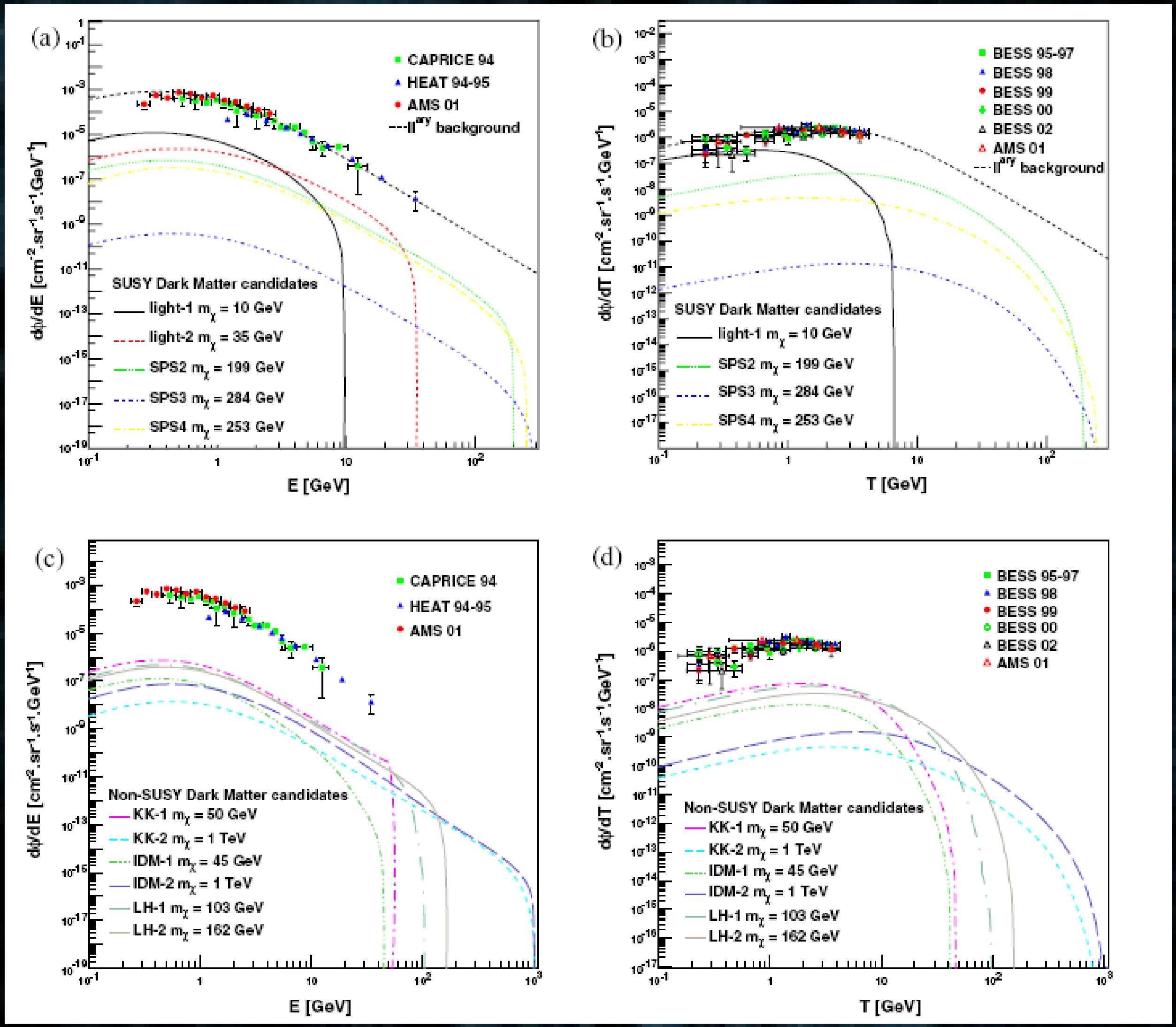


$(e^+ + e^-)$ HESS and Fermi
Aharonian et al (2009)
Abdo et al (2009)

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

Closing the case for Dark Matter: generic predictions

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



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

Propagation of Galactic electrons
Phenomenology of transport (GeV-TeV)

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

Current conservation
(continuity equation)

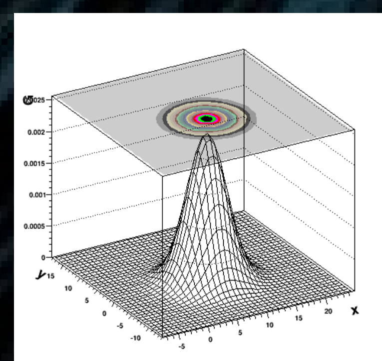
$$\begin{aligned}\partial_t \mathcal{N} &= Q(\vec{x}, E, t) \\ &+\vec{\nabla}\left\{\left(K_x(E)\vec{\nabla} + \vec{V}_c\right)\mathcal{N}\right\} \\ &+\partial_E\left\{\left(\frac{dE}{dt} + K_E(E)\partial_E\right)\mathcal{N}\right\}\end{aligned}$$

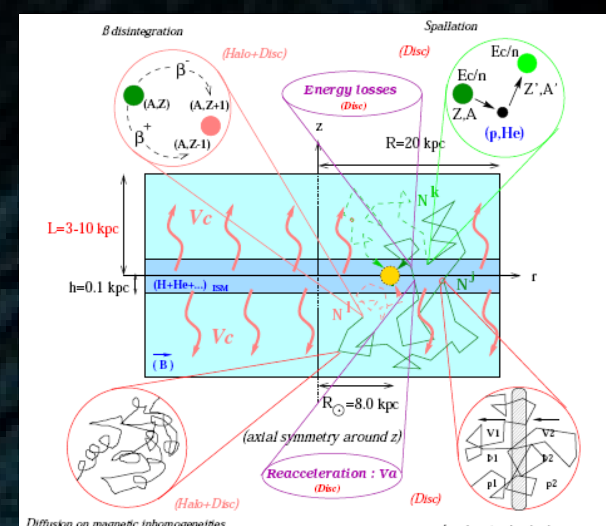
Spatial current (diffusion + convection)
Momentum current (losses + reacceleration)

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

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

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





Program:
• Used constrained propagation parameters (diffusion zone extent, diffusion coefficient, etc)
• Make predictions, compare with data

Maurin et al (2002)

CR Electron Propagation: 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)

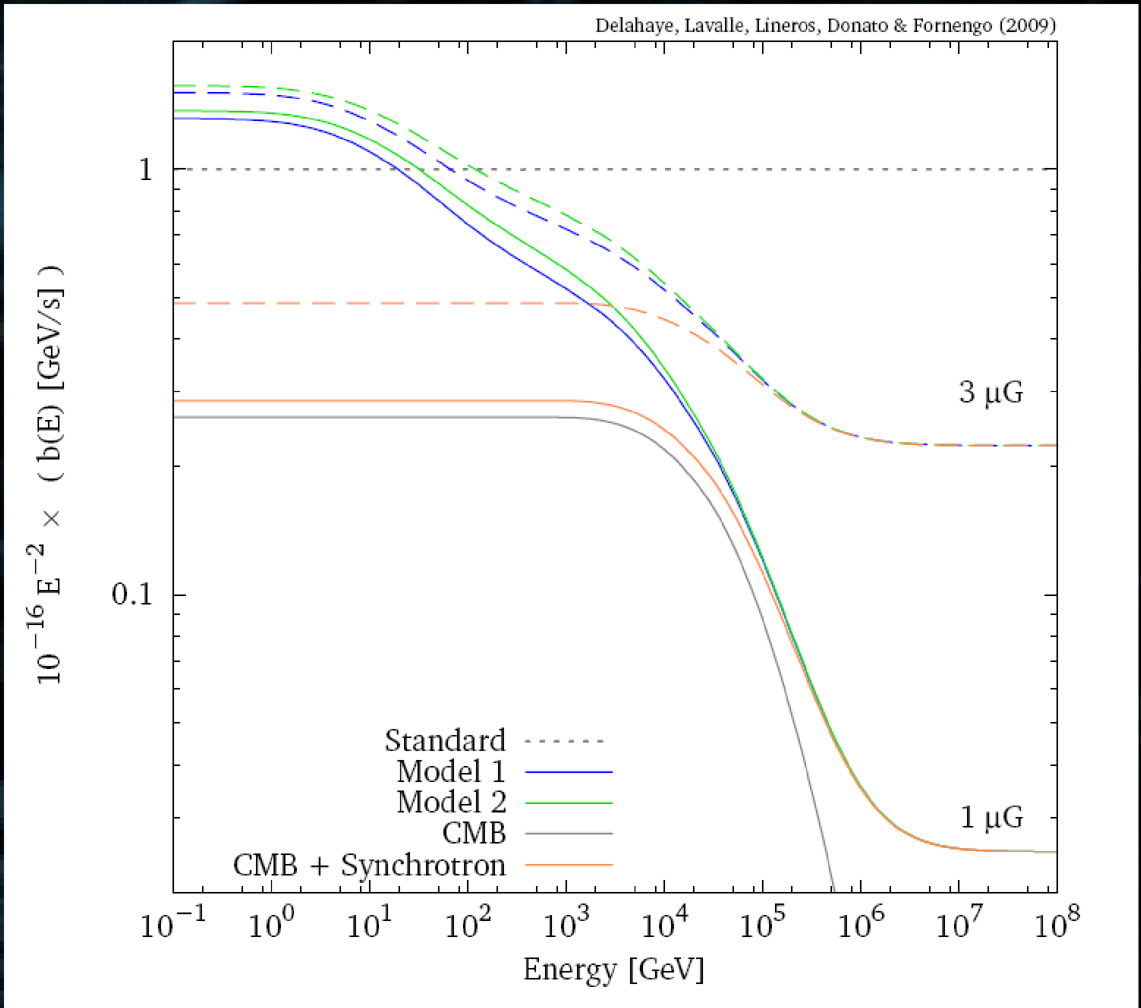
(i) Interactions with the ISM (in the disk): Bremsstrahlung (braking radiation), ionisation – for E < 5 GeV

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

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

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

Caveats: .... CMB everywhere, 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

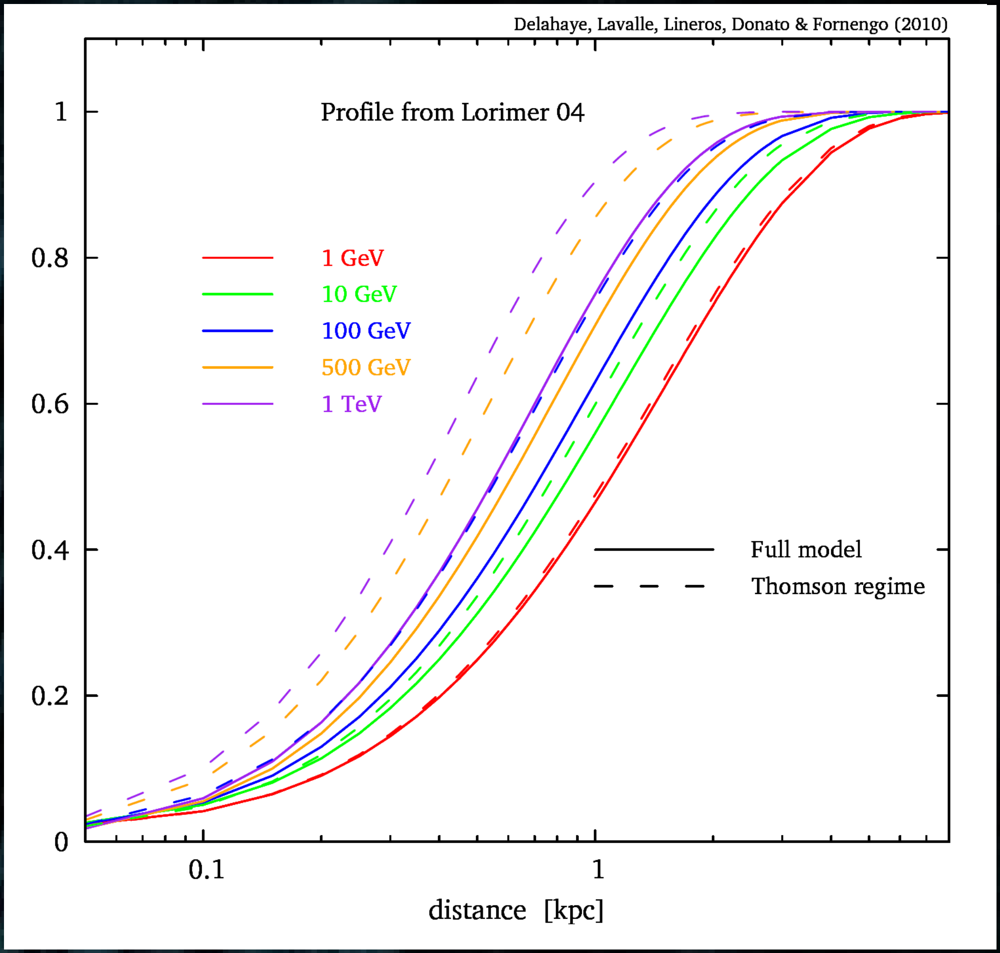
$$\lambda^2 \equiv 4\int_E^{E_s} dE' \frac{K(E')}{b(E')}$$

$$= \frac{4\,K_0\,\tau_0}{1+\delta-\alpha}\left(\frac{\epsilon}{1\,\mathrm{GeV}}\right)^{1+\delta-\alpha}\Bigg|_E^{E_s}$$

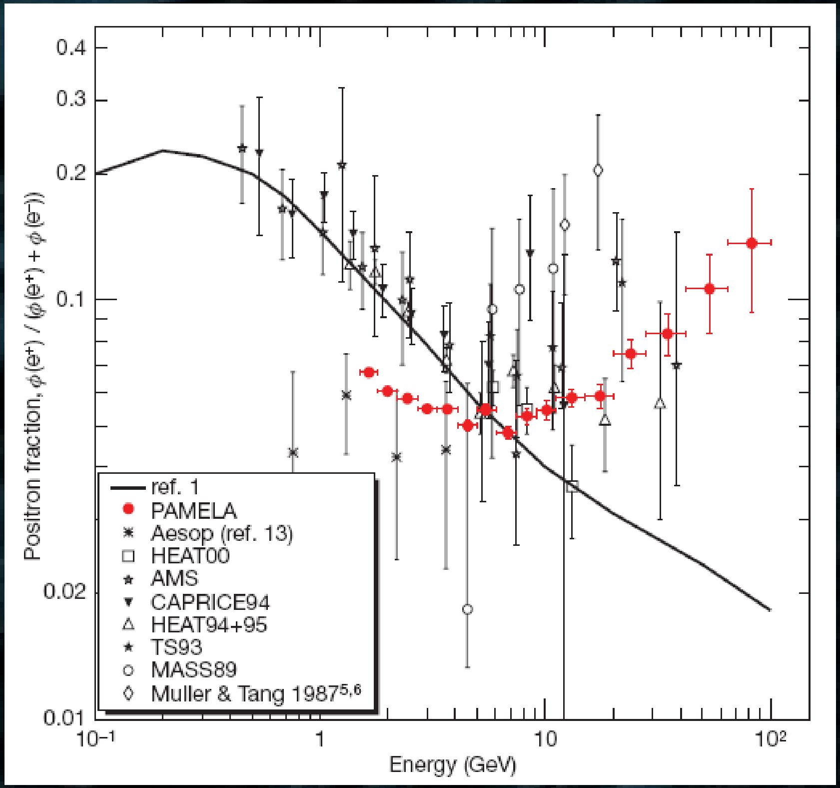
Electron horizon limited to a few kpc

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

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



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
$p+p \rightarrow e^{+} + X$

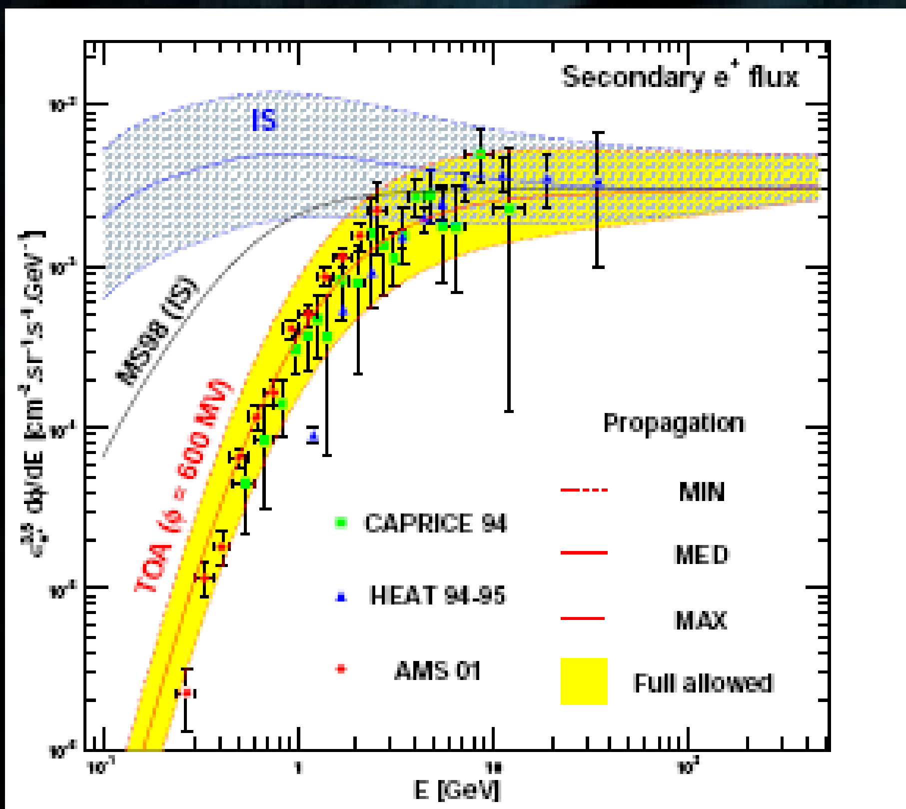
Propagation
from (x_s,E_s) to (x,E)

Flux at the Earth

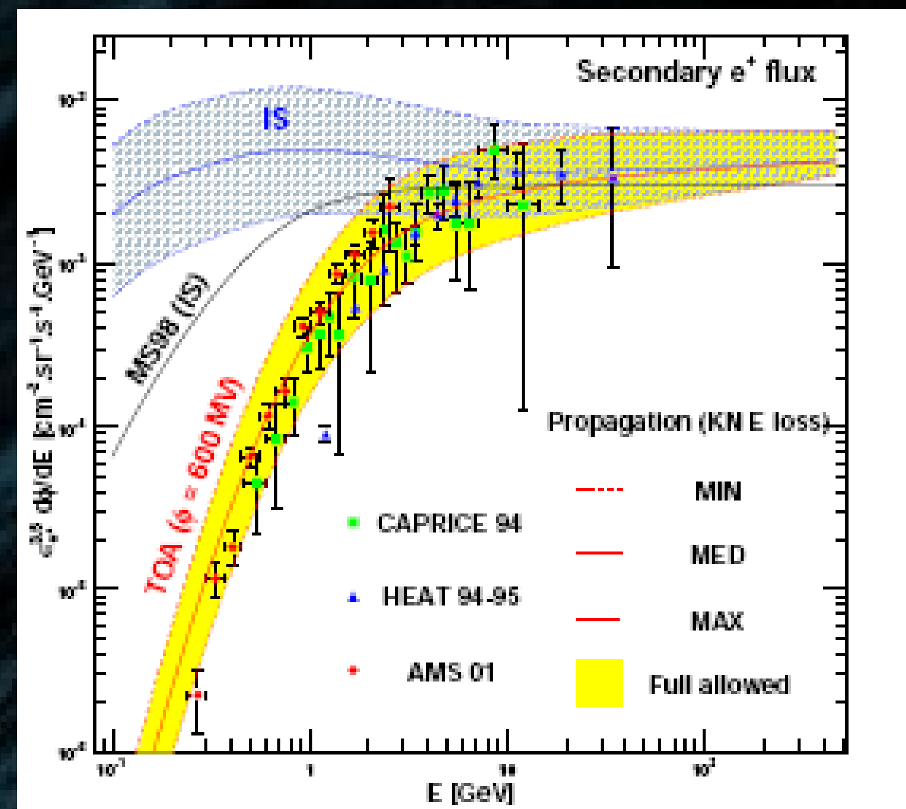
Each box contains uncertainties !!!

Uncertainties from propagation parameters

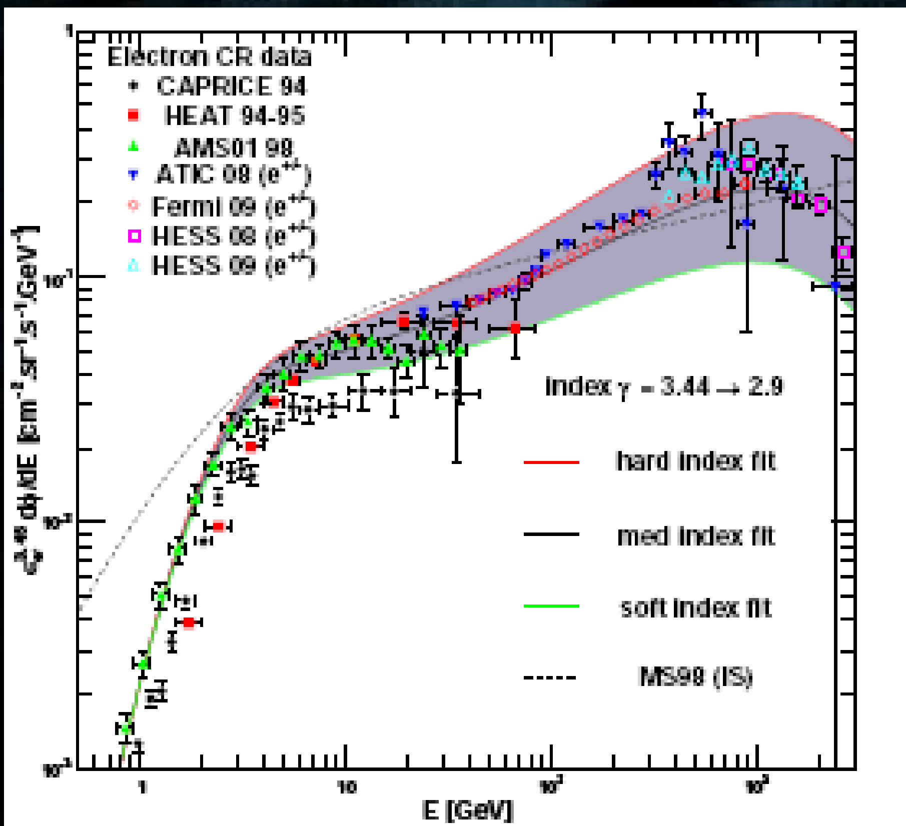
Delahaye et al (2009)

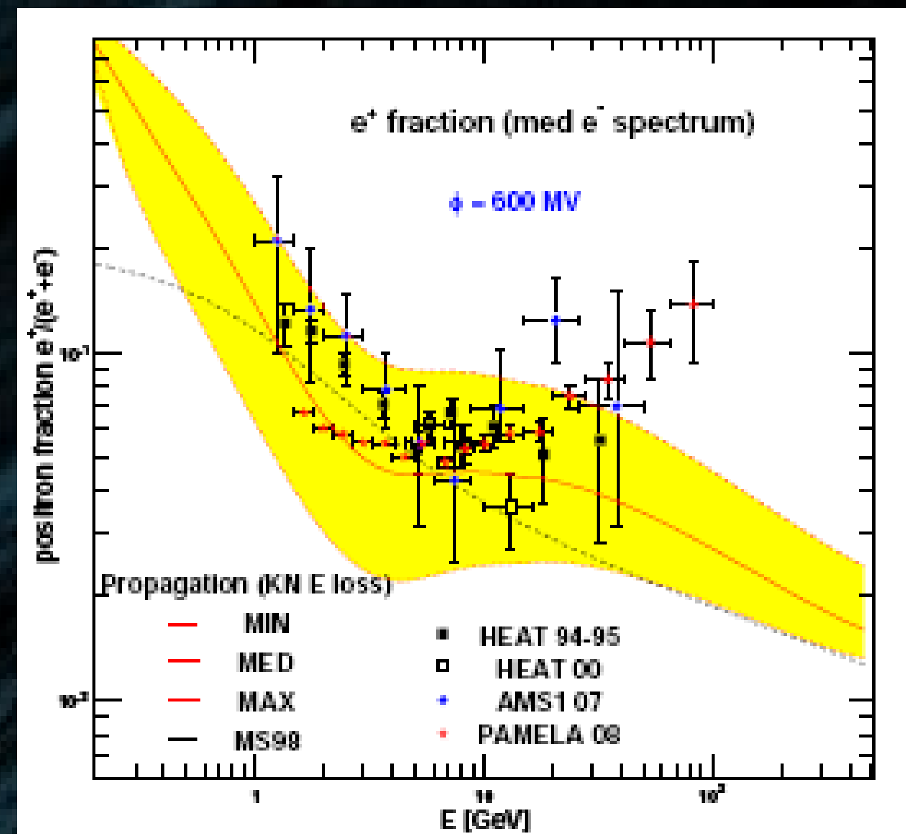


Same but with relativistic losses



Fermi has just released the denominator

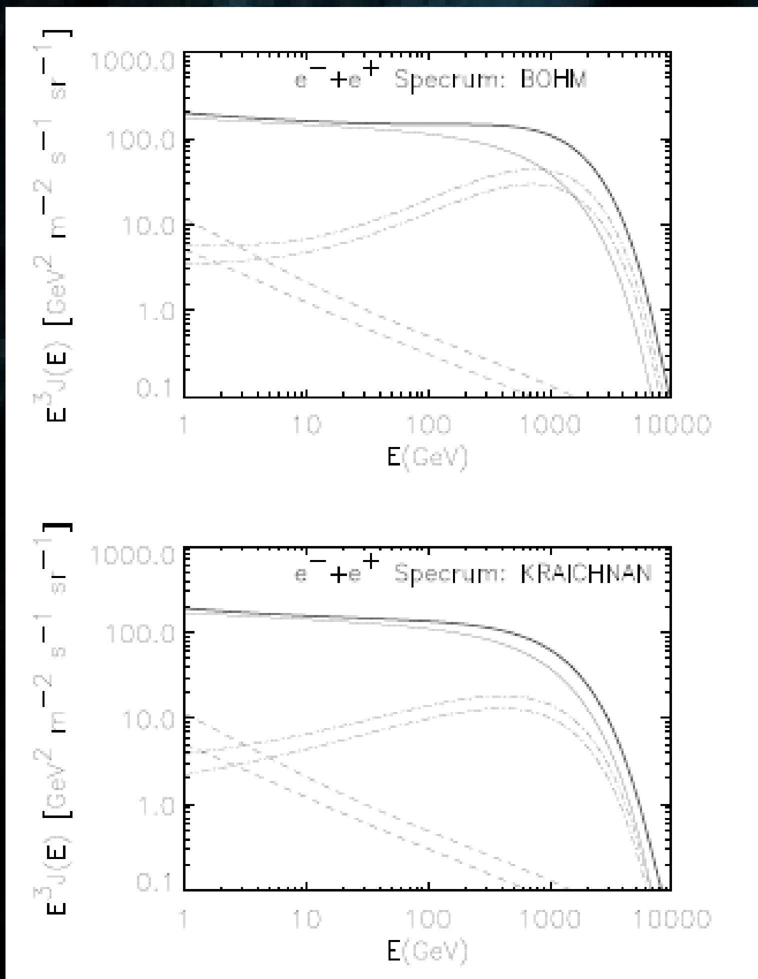


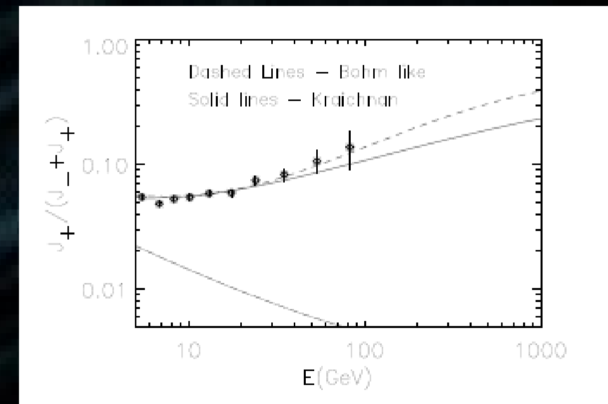


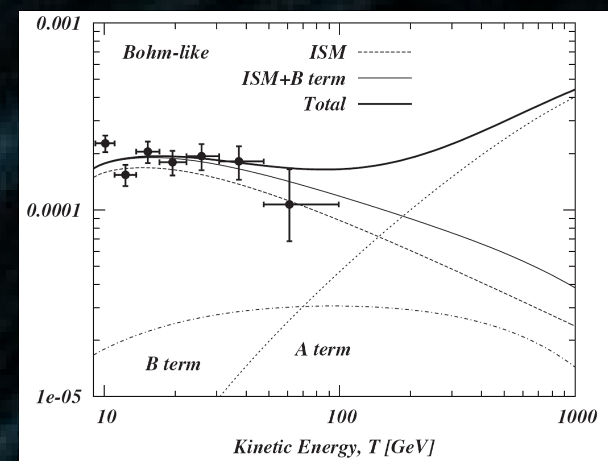
Uncertainties are still large ... (relevance of analysis for additional primaries ?)
Yet, a conventional secondary origin seems unlikely ...

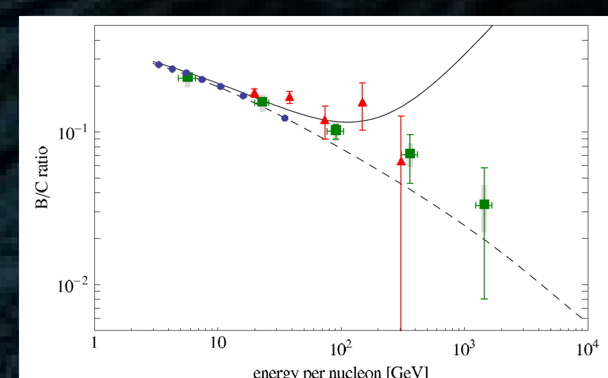
"Primary" secondaries ?

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





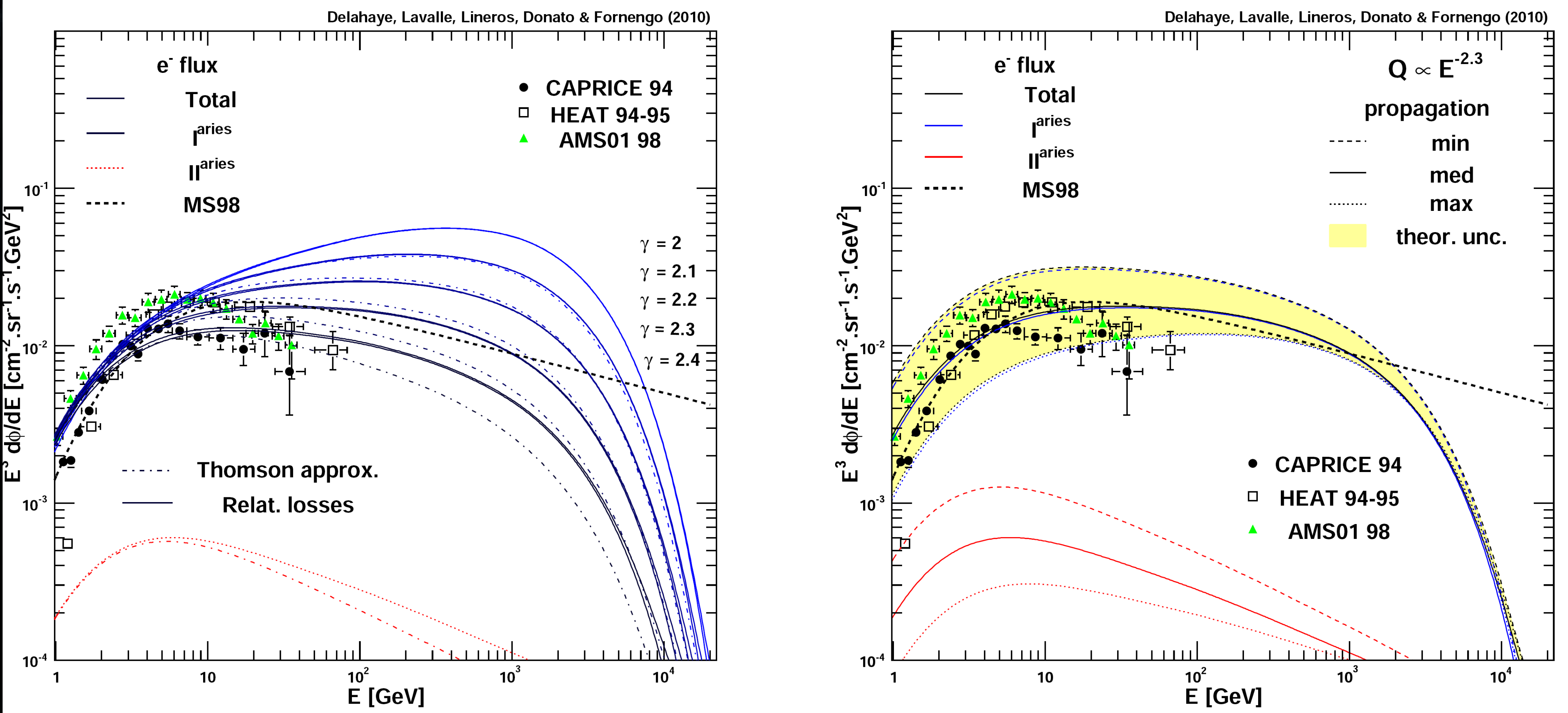




Observational signatures: rising antiproton fraction (like DM) and B/C ratio

Focus on primaries

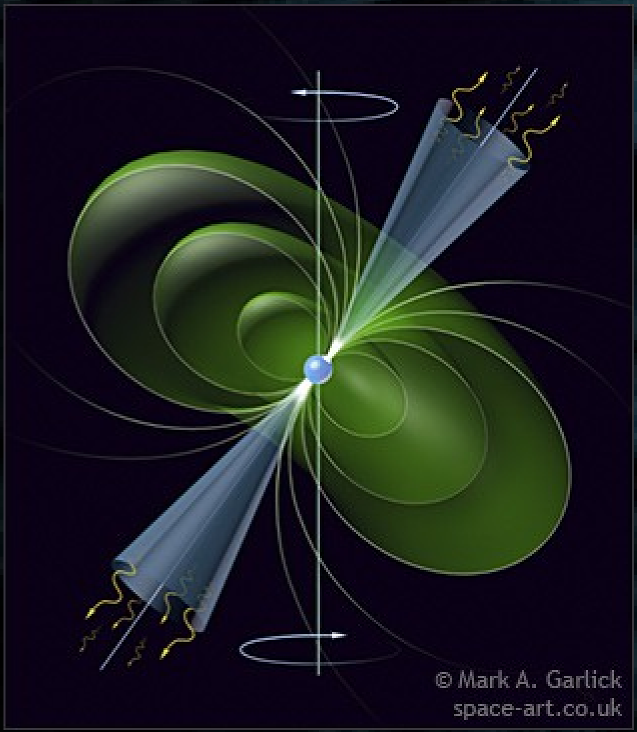
arXiv:1002.1910

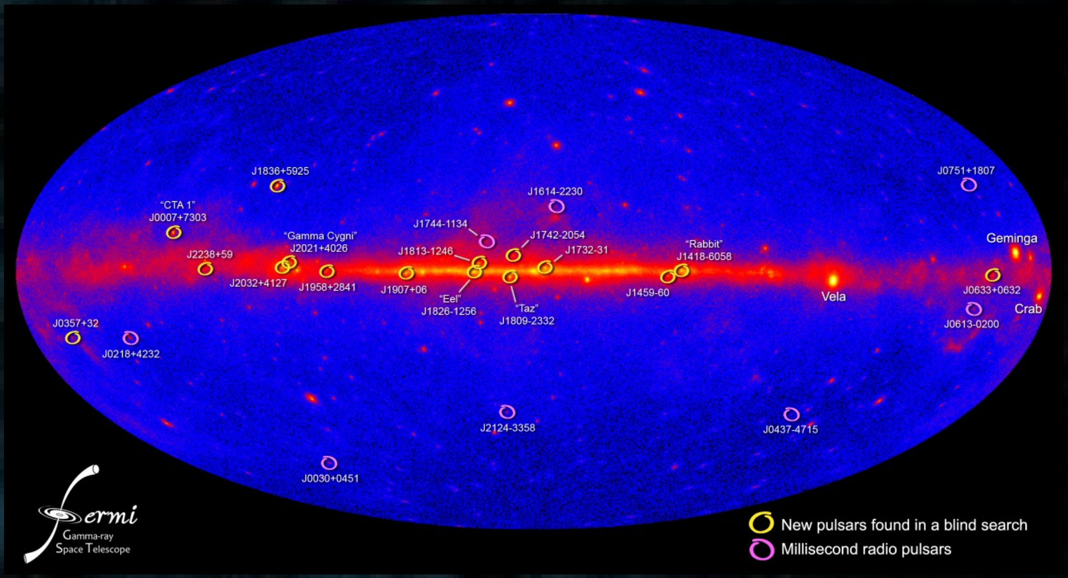


Can predict electron flux from a single injected source spectrum (smooth distribution of sources)

Caveats: local effects important above 50 GeV; smooth representation likely fails (Shen 70)

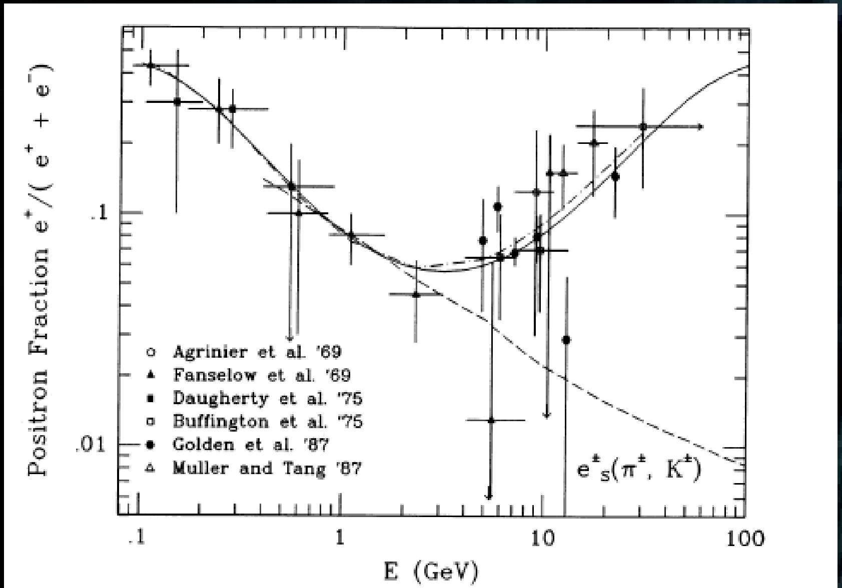
"Standard" positron sources ? ... Pulsars !





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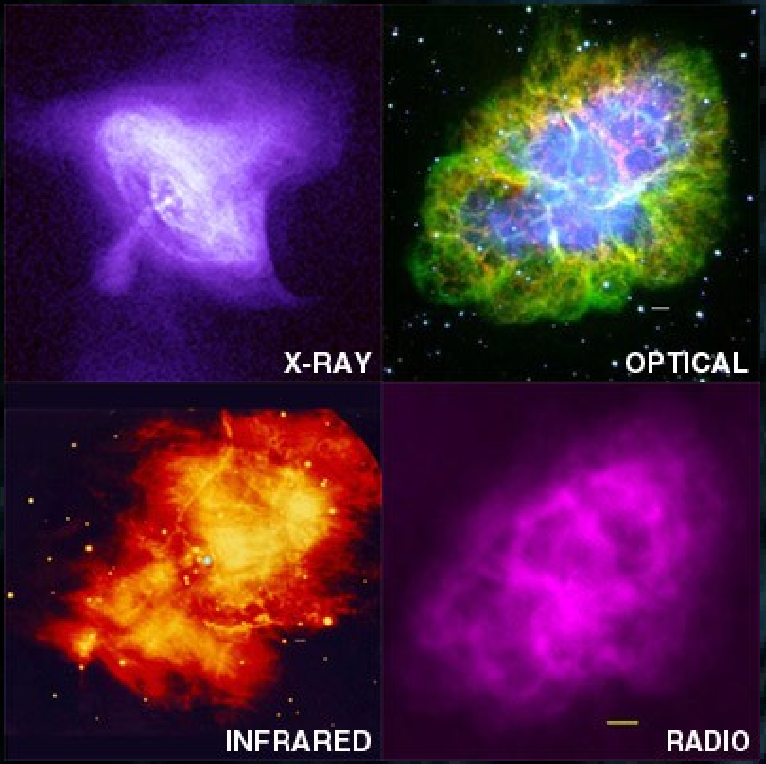
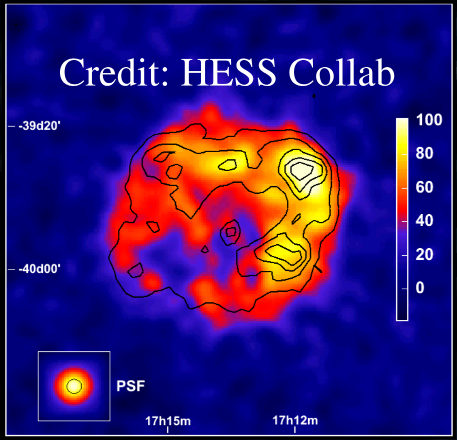
radio, γ-rays) suggest this possibility. In fact, if the recent $e^+/(e^+ + e^-)$ measurements are reliable, this will definitely require a pulsar source, because no other nearby conventional astrophysical sources (within 100–500 pc) can generate both e^- and e^+ at high energies (of course, dark matter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

“Standard” primaries: the big mess





Standard paradigm:

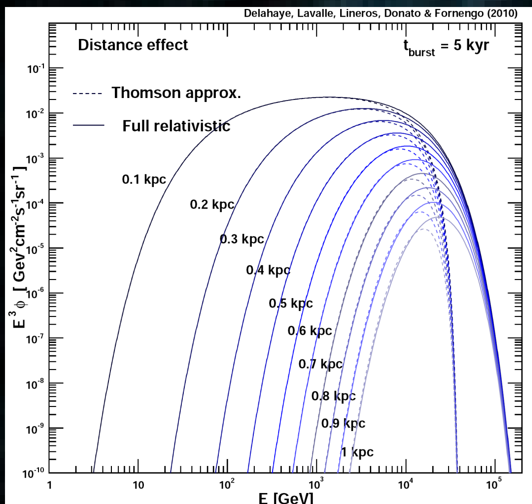
- Cosmic rays in the GeV-TeV diffuse on magnetic inhomogeneities (Ginzburg & Sirovatskii, 1964)
- They originate from the vicinity of supernova remnants (SNRs) or pulsars where they are accelerated by shock waves (Drury, 1983).

But many many many uncertainties!

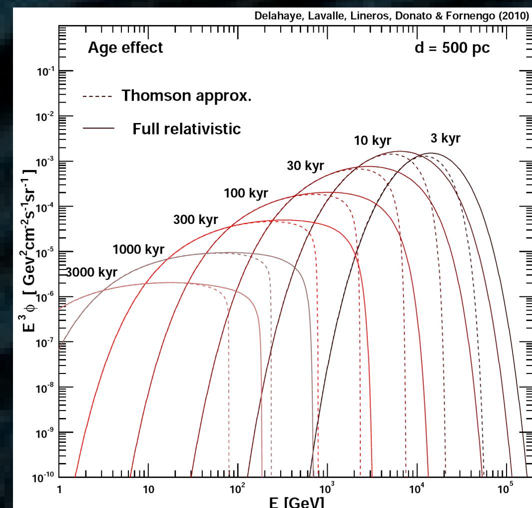
- Spectral features of cosmic rays released in the ISM: spectral index ~2, energy range ? max energy ? Environment effects ? Species effects ?
- Relative fraction of e/p in sources ?
- Copious sources of positrons ?
- Time effects at the kpc scale (relevant for electrons)

Standard paradigm, but not standard model!

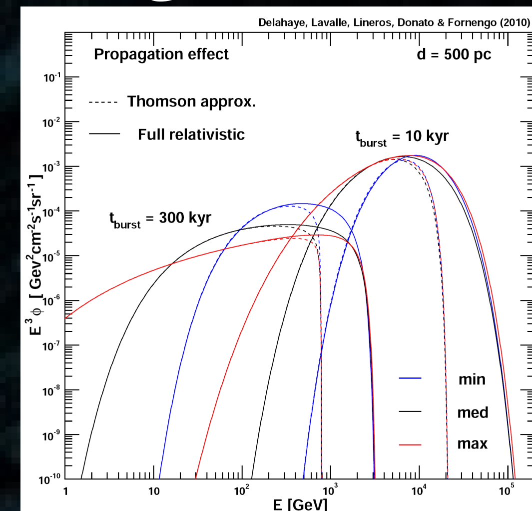
Time, spatial and spectral fluctuations at HE: Origin of uncertainties for local bursting sources



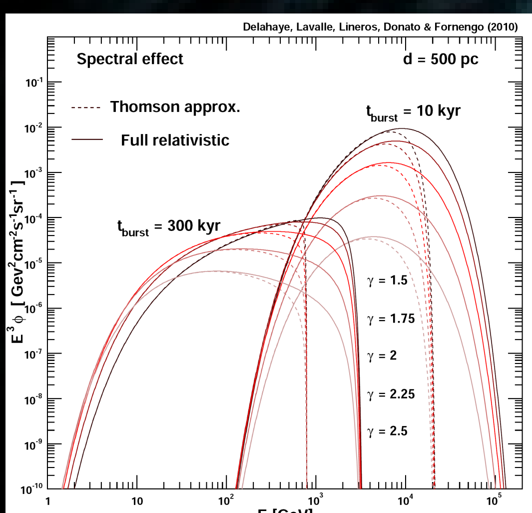
Distance effect



Age effect



Propagation effect



Spectral effect

arXiv:1002.1910

Time-dependent propagator

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

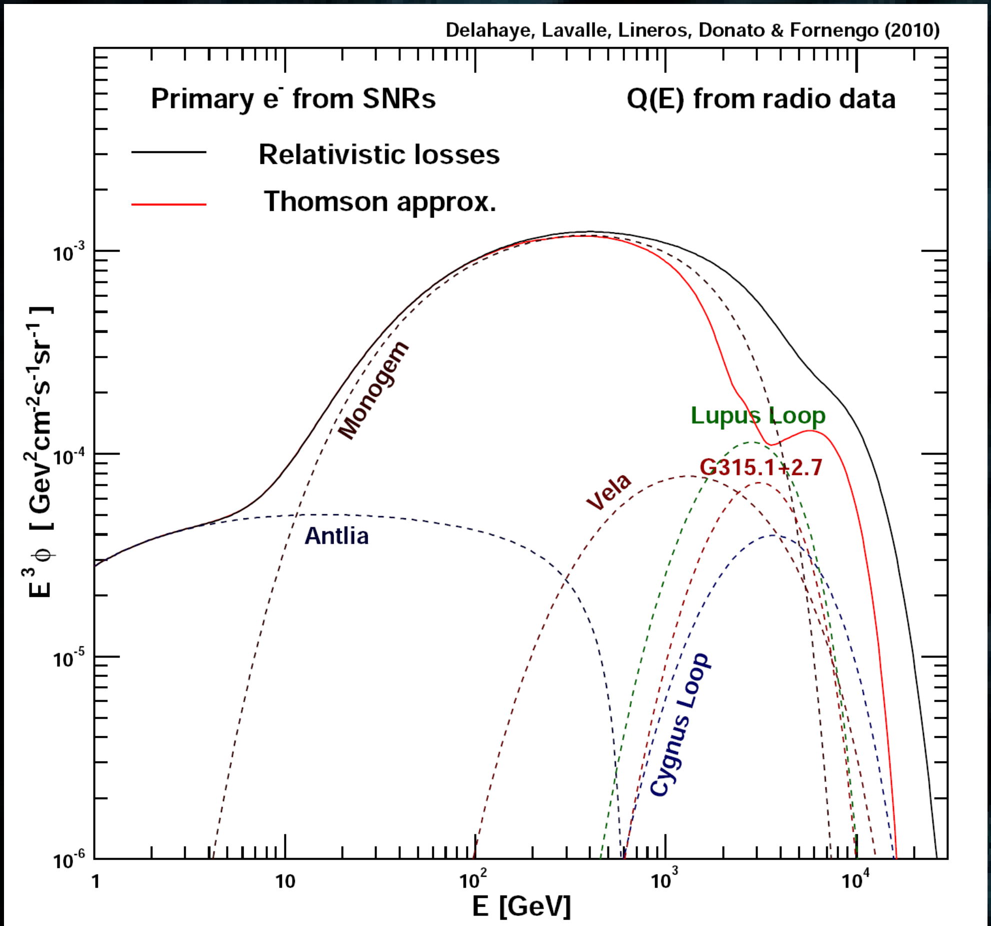
Although observational constraints exist, uncertainties are very large

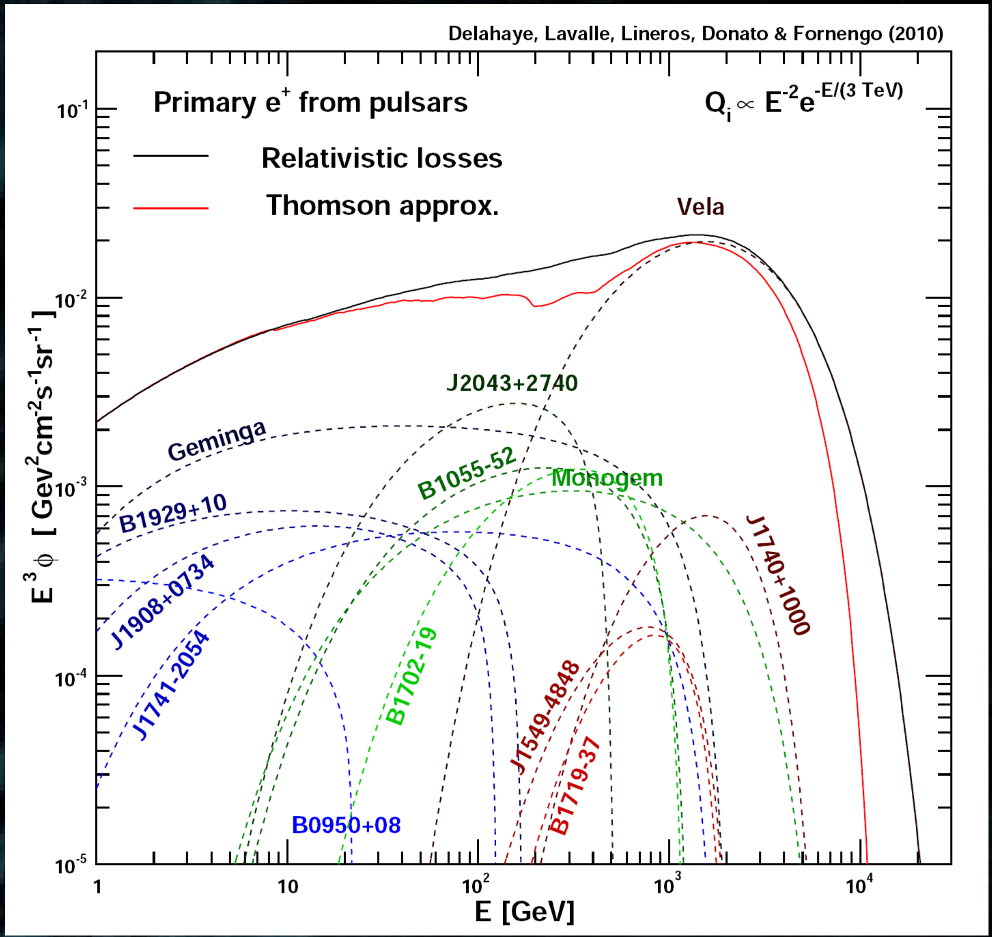
Deal with the complexity of Nature: Include all known local sources self-consistently

arXiv:1002.1910

27 obs SNRs within 2 kpc

~200 obs pulsars within 2



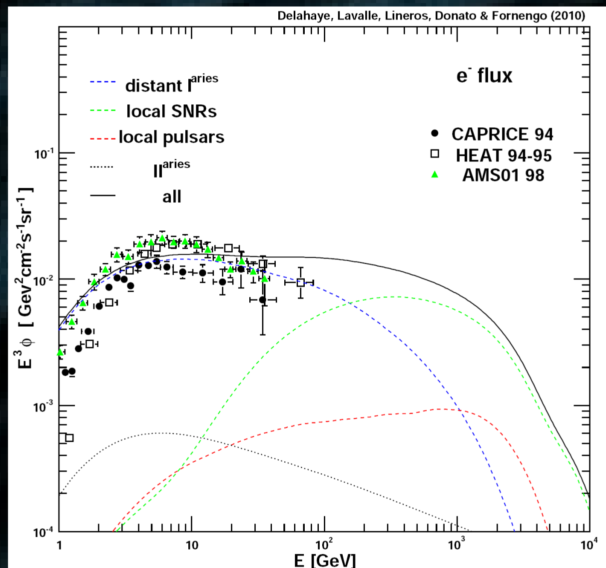


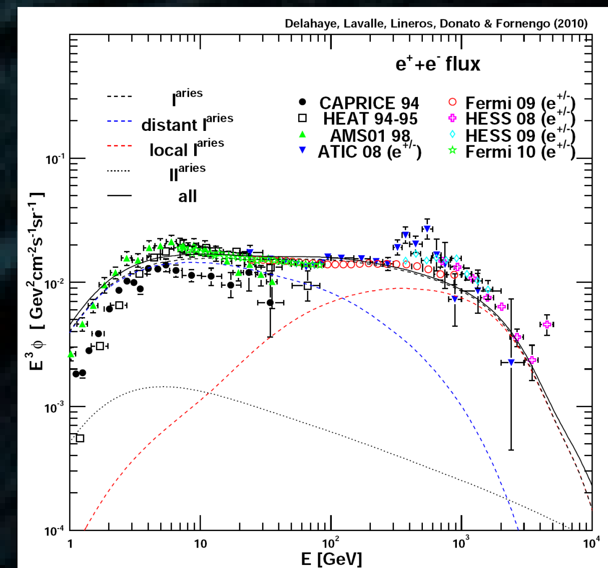
SNRs contribute to e^-, pulsars inject e^+e^- pairs ...

... 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

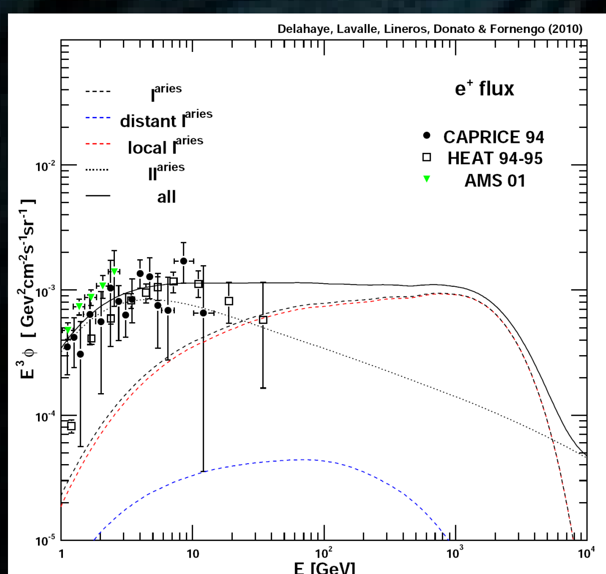


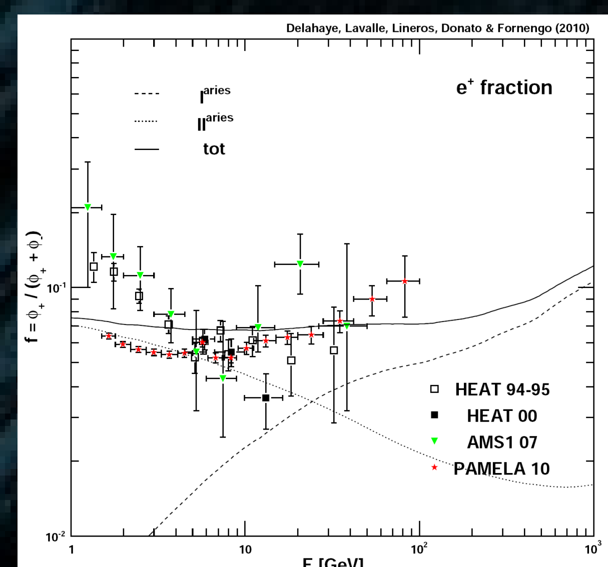


electrons + positrons

arXiv:1002.1910

positrons





positron fraction

standard astrophysical sources make it!

Distant electrons : diffuse emissions

Observables:

- **Diffuse gamma-rays :** Bremsstrahlung (< 5 GeV) and inverse Compton (GeV-TeV)

⇒ **Subdominant contribution (proton-ISM dominated)**

- **Synchrotron emission:** frequency > 20 GHz implies E > 35 GeV for B = 1 μG

General problematic:

- **Distribution of sources** (e.g. in the GC) – remember that propagation is short range
- **Diffusion coefficient elsewhere in the MW ?**
- **Losses: ISRF + magnetic field ???**

Synchrotron problematic:

- **Degeneracy between magnetic field and electron distribution !!!**

The synchrotron degeneracies

Magnetic field models:

- **Zeeman splitting of 21 cm (HI regions: cold neutral clouds)**
- **Faraday rotation measures : needs thermal e- density + pulsar distances**
- **Many pulsar distances from dispersion measures : needs thermal e- density**

- **From synchrotron : needs non-thermal e- density**

Caveats: usual assumption is equipartition, i.e. e- density = f(B)

Synchrotron studies:

- **Take magnetic field models + constrain electrons: beware of consistency !**

$$\begin{aligned} B &= \bar{B} + b \\ \text{total Sync.} &\propto \int dl\, B_\perp^2\, n_e^{\rm non-th} \\ \text{pol. Sync.} &\propto \int dl\, \bar{B}_\perp^2\, n_e^{\rm non-th} \\ \text{RM}(\lambda) &\propto \lambda^2 \int dl\, B_\parallel^2\, n_e^{\rm th} \end{aligned}$$

$$\nu_{\rm sync}(\text{peak}) \simeq 1.6\,\text{GHz} \left[\frac{E}{10\,\text{GeV}}\right]^2 \left[\frac{B}{1\,\mu\text{G}}\right]$$

10 GeV e- travel a few kpc only: distribution of sources + propagation fundamental

potentially large uncertainties

Propagation issues

• Local propagation parameter likely not constant throughout the Galaxy (clearly true for ISRF and magnetic field)

• Diffusion coefficient: should increase with z above the Galactic disk ! The vertical extent of the diffusion zone has in fact weak physical meaning. (+Variation wrt arm-interarm and wrt coherence scale of the B-field ?)

• Convection : quite low velocities (~ 10 km/s) while much larger values observed in star forming regions (cf T. Montmerle's talk) ; convection should spatially correlate with density of sources.

• This definitely needs to be investigated (some attempts in Gebauer & de Boer 10)

Conclusions

Local electrons

• Local electrons well understood from standard astrophysics, but still no clean prediction above 50-100 GeV (local sources)

• Source modeling is the main source of uncertainties: focus on local objects to learn more

Distant electrons (inverse Compton, synchrotron)

• Inverse Compton sub-dominant in general, could be sizable > 100 GeV: large uncertainties due to source distributions

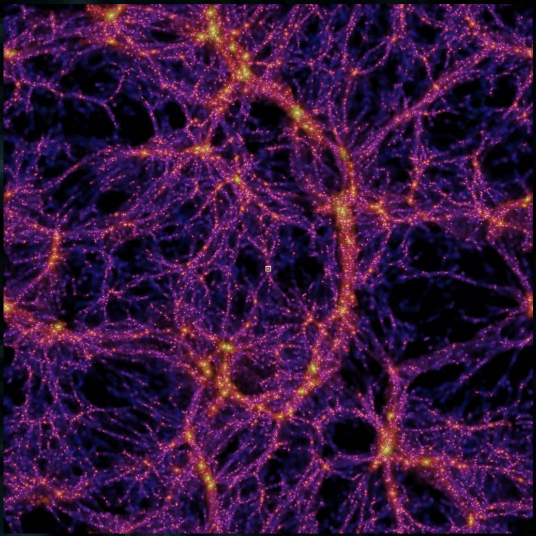
• Synchrotron: beware of degeneracies between B-field models and e- density

• General: source distribution, source modeling, Ginzburg et al propagation model (1964) reaches its limits, need to go farther to understand details (e.g. GC).

Backup slides

Via Lactea II versus Aquarius

Via Lactea II: Diemand et al (2008)
Aquarius: Springel et al (2008)



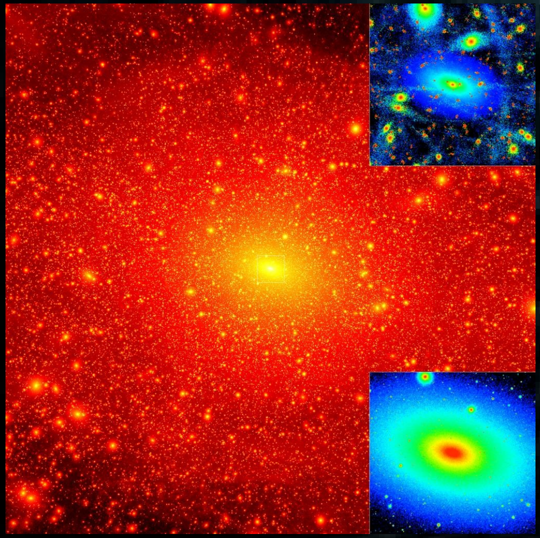
MW-like halo with ~ 1 billion particles of $\sim 10^3\ M_\odot$
~ 10,000-20,000 subhalos with masses $> 10^{4.5}\ M_\odot$

Slightly different initial conditions.

Slightly different results.

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

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

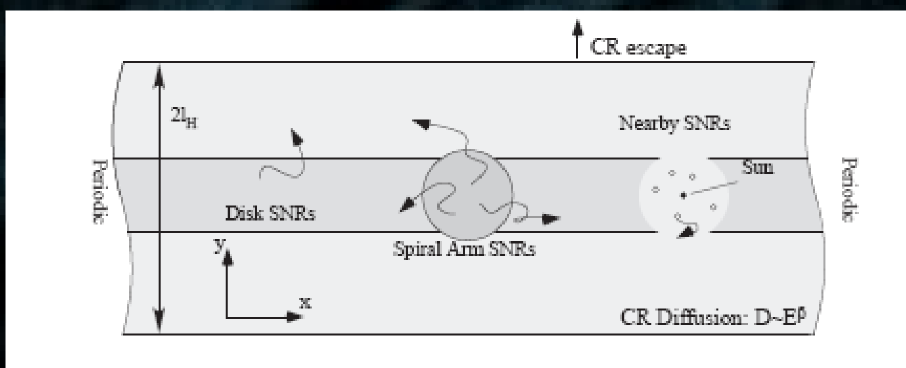


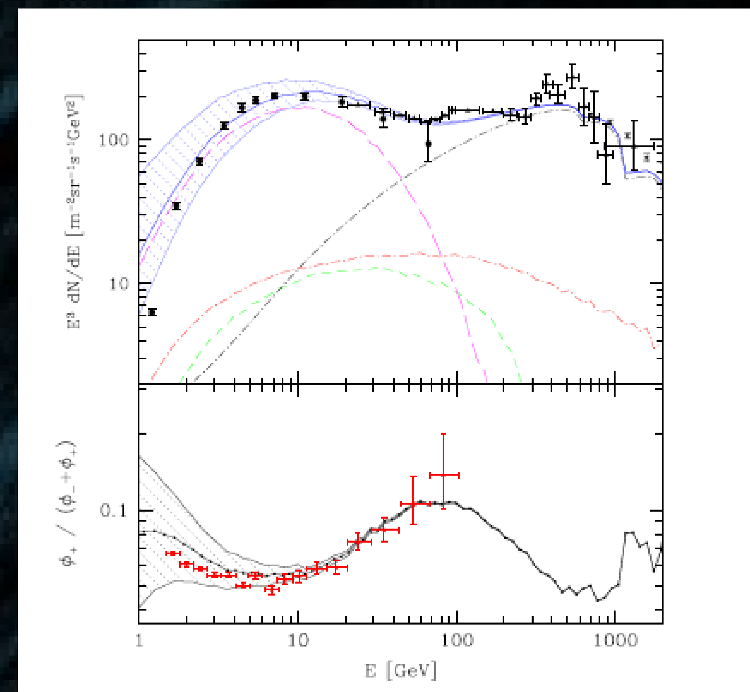
Extrapolate properties and check detection prospects:
- Gamma rays: Fermi
- Antimatter: PAMELA

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

Spatial effects ?

Shaviv et al (2009)





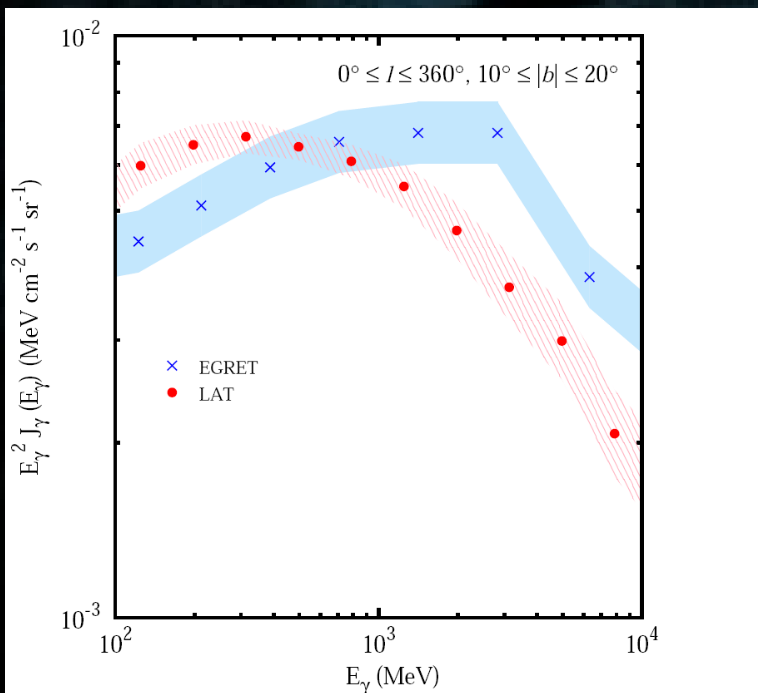
3 populations of electrons:

- From sources in the nearest arm
- From the disk
- From nearby SNRs

+ secondary positrons ... this might make it.

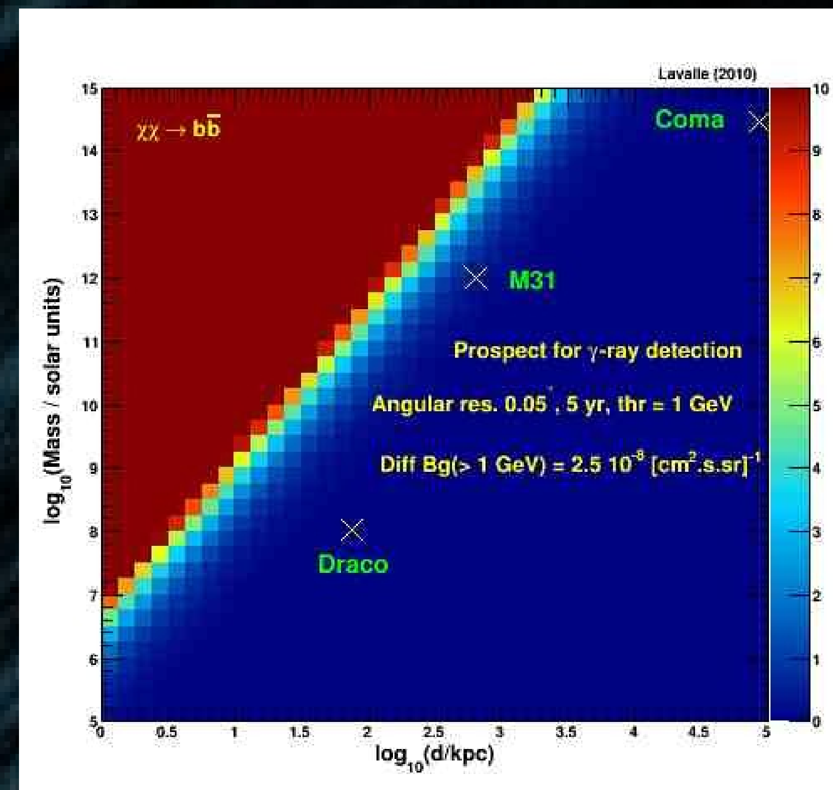
Detection prospects with gamma rays ?

Assume a diffuse Galactic foreground



Tibaldo (Fermi-LAT)
arXiv:1002.1576
$10° < | b | < 20°$

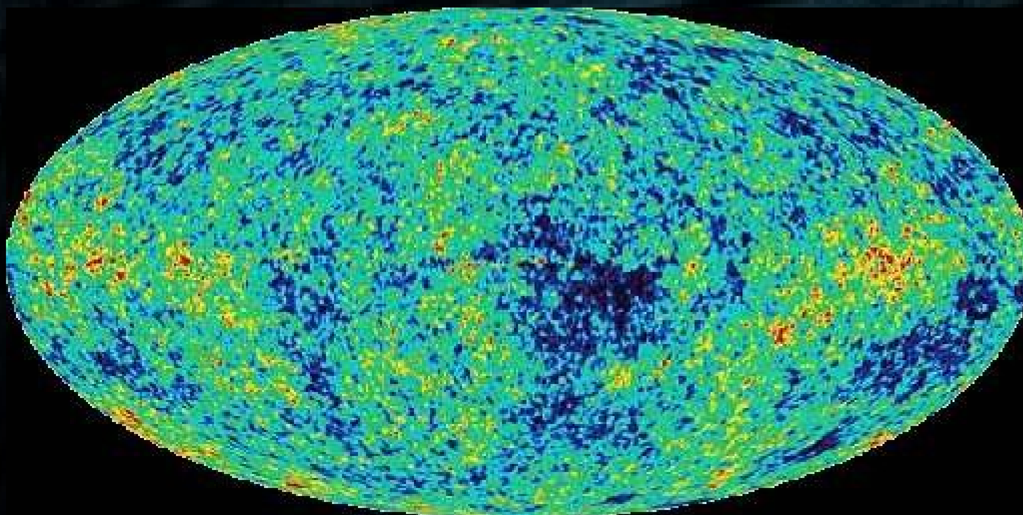
Assume angular resolution 0.05°
+ 5 yr exposure + infinite sensitivity
+ threshold 10 GeV
+ $\chi\chi \rightarrow$ b bbar (m = 0.1 TeV)



$$N_\sigma = \Phi_{dm}\, \tau\ \delta\Omega\ /\ (\Phi_{bg}\, \tau\ \delta\Omega)^{1/2}$$

Photon counting is not enough:
spectral analysis (energy resolution) better for hard spectra or heavy WIMPs

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.