Interpretation of recent measurements on CR electrons, positrons and light nuclei

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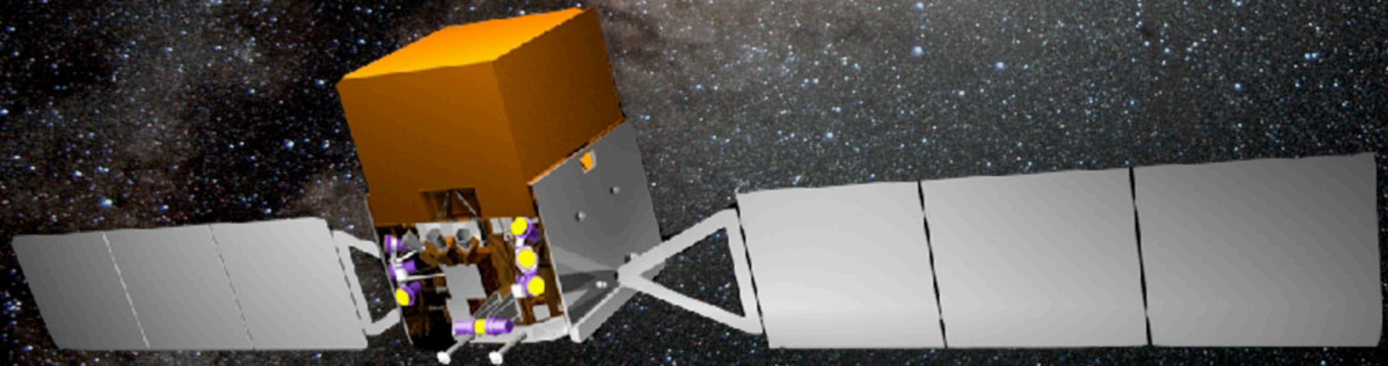
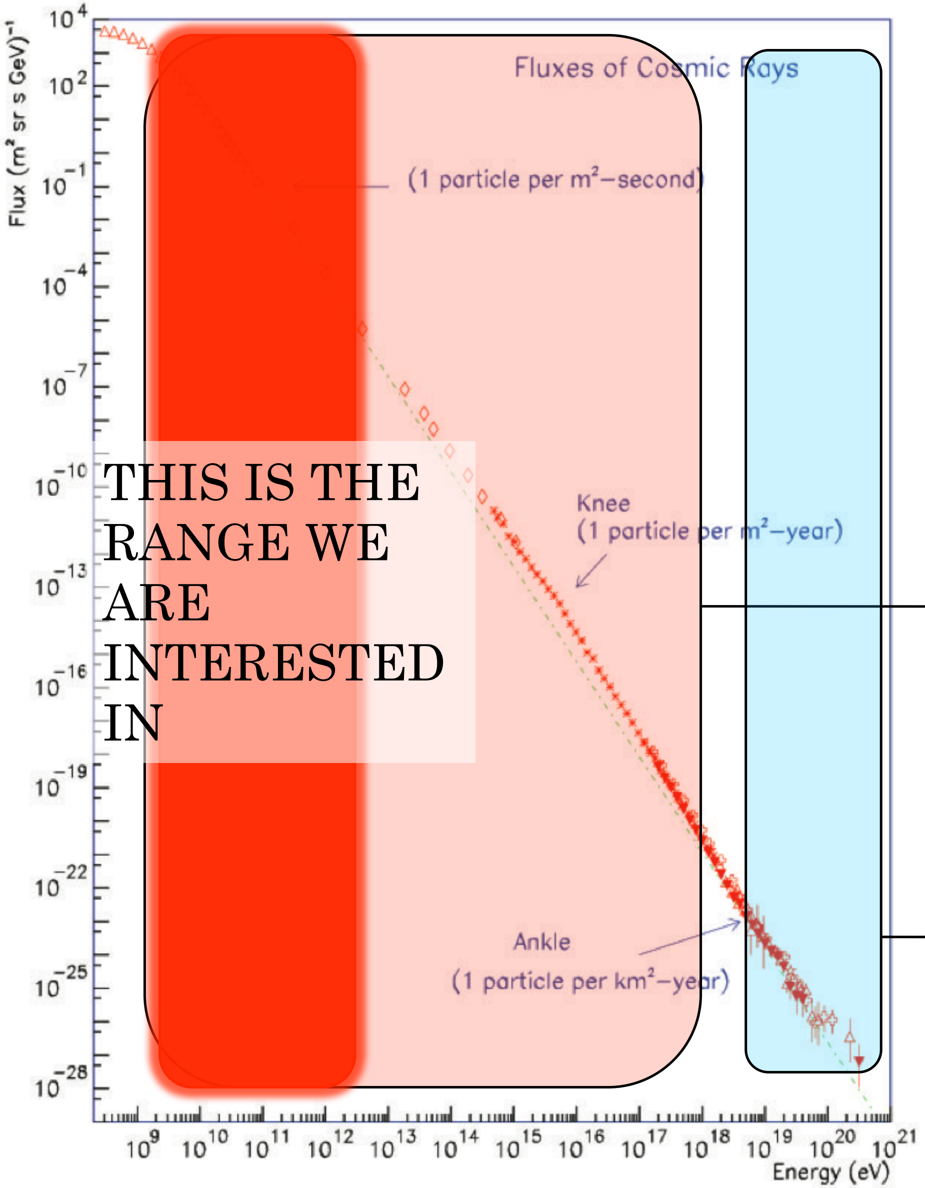


UniverseNet school, Lecce, September 13^{th}-18^{th}, 2010

Particles from outer space



Composition: protons, antiprotons, nuclei, electrons, positrons

Spectrum: non thermal, almost featureless

Rate: about 1000 per m^2 per second at Top of atmosphere

1 GeV to 1 EeV: **galactic origin**. CR in this energy range are believed to be accelerated in Supernova Remnants

Ultra high energy: **extragalactic origin**. Candidate accelerators: AGNs, …

Open problems in CR research

ORIGIN:
Details of acceleration mechanism?
Acceleration sites?

PROPAGATION:

- Modeling CRs diffusion in the galactic magnetic field: **determination of free parameters** (Diffusion coefficient, strength of reacceleration, …)
- Obtaining an unified interpretation of all measured fluxes within these models

Interaction with solar wind, i.e. modulation (for low-energy CRs)

Interaction with the Earth atmosphere: role in cloud formation, impact on Earth climate?

Open problems in CR research

NEW PHYSICS from Cosmic Rays?

Some "excesses" of CR fluxes (e.g. positron flux) may be interpreted as signals of new physics

- Signal from **particle Dark Matter annihilation or decay**?
- **New astrophysical sources** (e.g. pulsars)?

Multichannel analyses:

Computation of photon fluxes produced by CR interactions (via bremsstrahlung, syncrotron emission, decay of pions produced by interaction with IS gas) and **comparison of these fluxes with data** (old EGRET data and new Fermi-LAT data)

Propagation models for CRs

CR leptons and hadrons propagate in the turbulent galactic magnetic field and their motion is well described by a diffusion-loss equation of this kind:

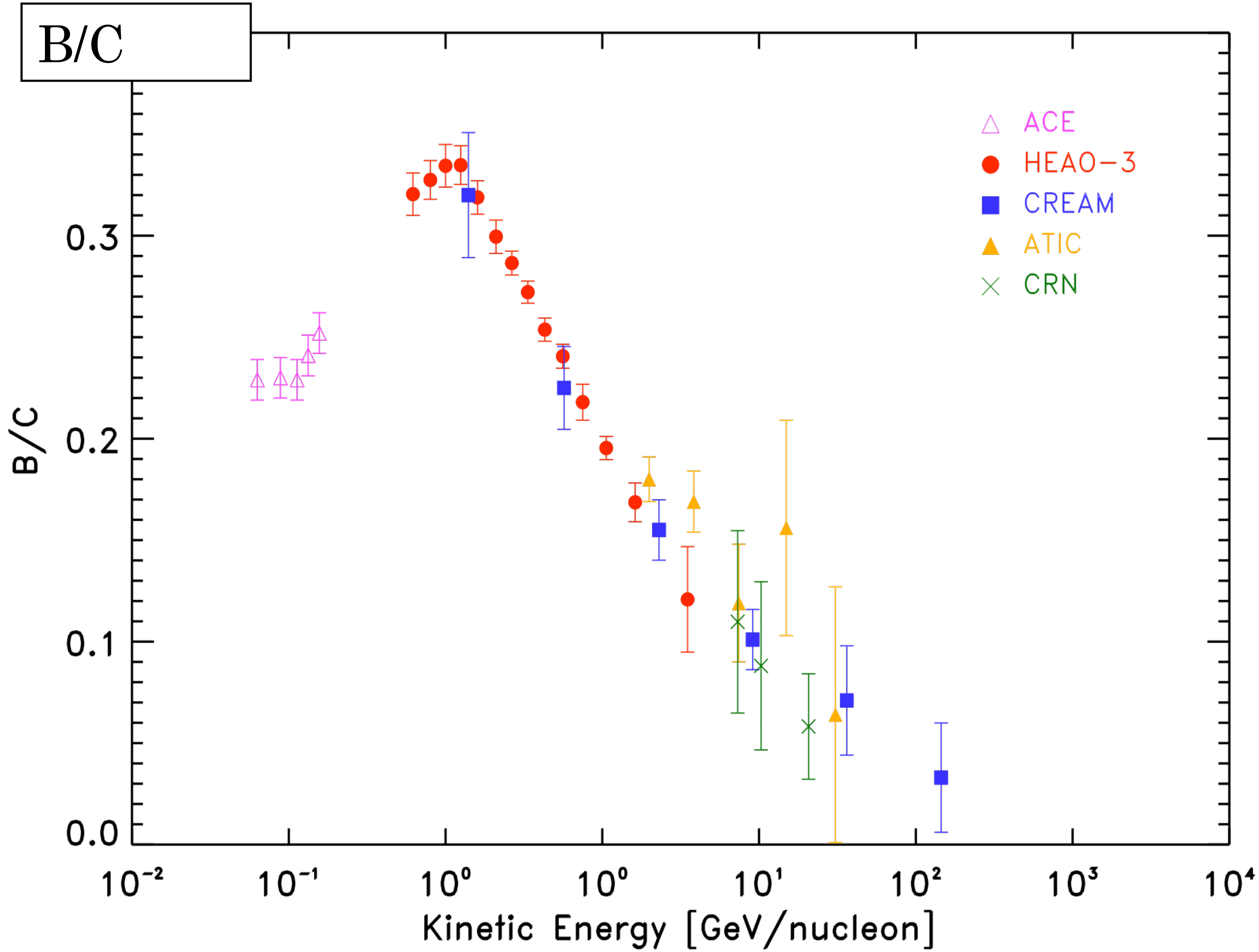
$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p,t) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$

This equation may be solved analitically (using simplified assumptions, i.e. on the spatial distribution of sources) or numerically (using numerical packages such as GALPROP or DRAGON)

FREE PARAMETERS:

- Injection spectrum (usually a power law, with one or more breaks if necessary)
- Alfven velocity (the higher it is, the more reacceleration is effective)
- Normalization and energy dependence of diffusion coefficient $D = D_0 R^{\delta}$

The data on Cosmic Ray spectra that we have to interpret

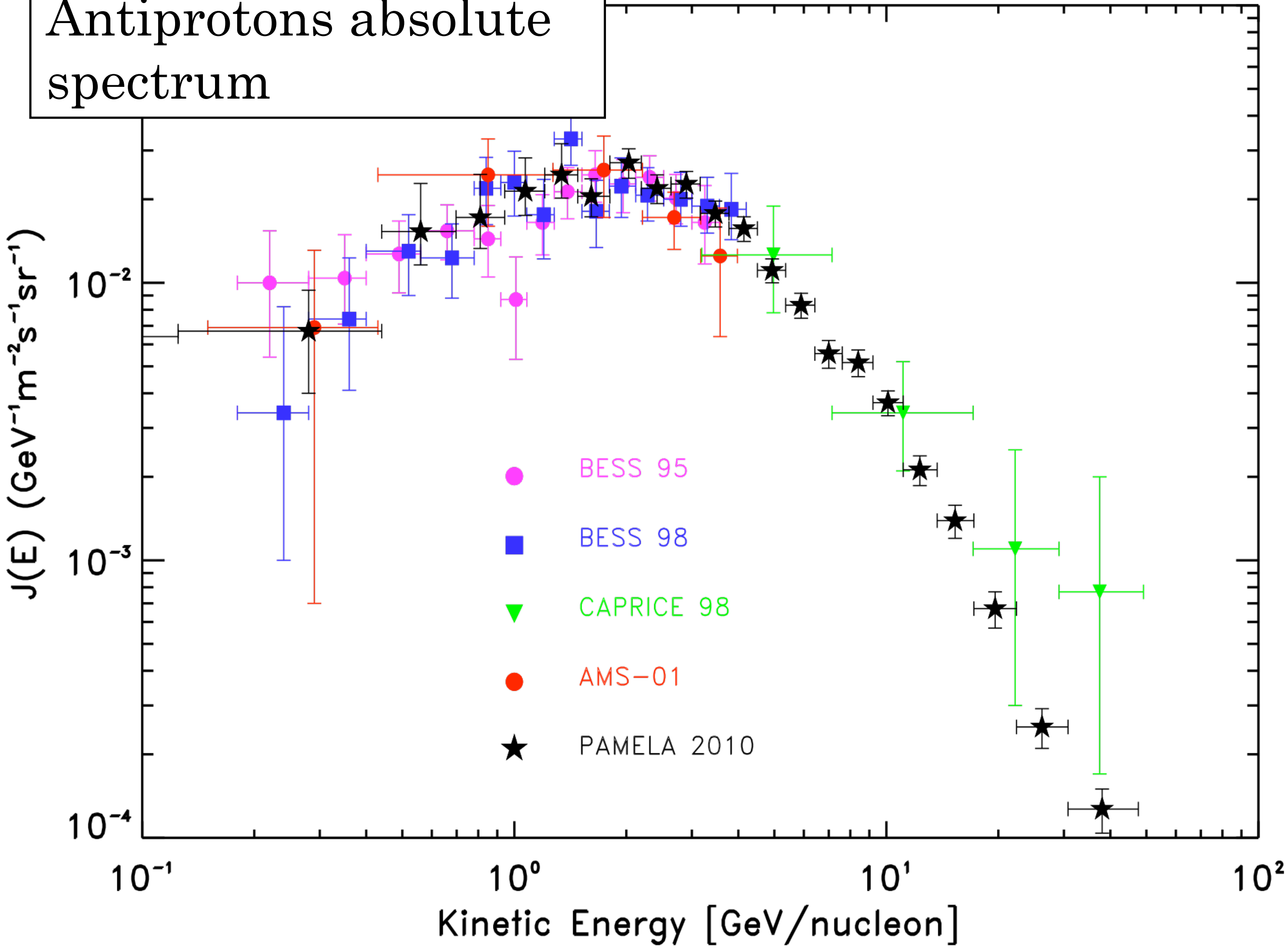


Boron to Carbon ratio

Since it is a secondary/ primary ratio, it gives constraints on the normalization and energy dependence of diffusion coefficient

The data on Cosmic Ray spectra that we have to interpret

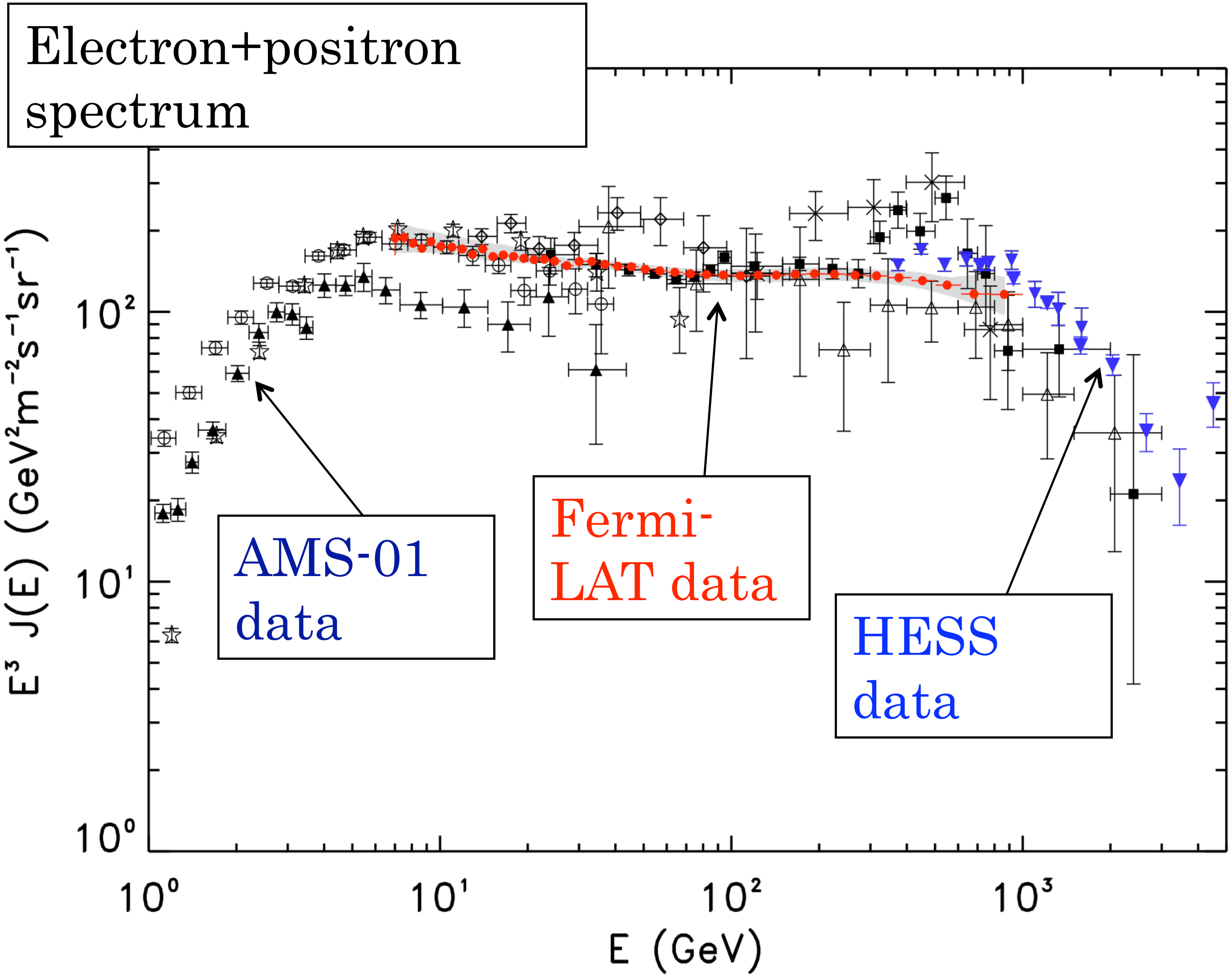
Antiprotons absolute spectrum



Absolute flux of antiprotons

It helps giving constraints on the normalization and energy dependence of diffusion coefficient, as well as on the level of Reacceleration

The data on Cosmic Ray spectra that we have to interpret

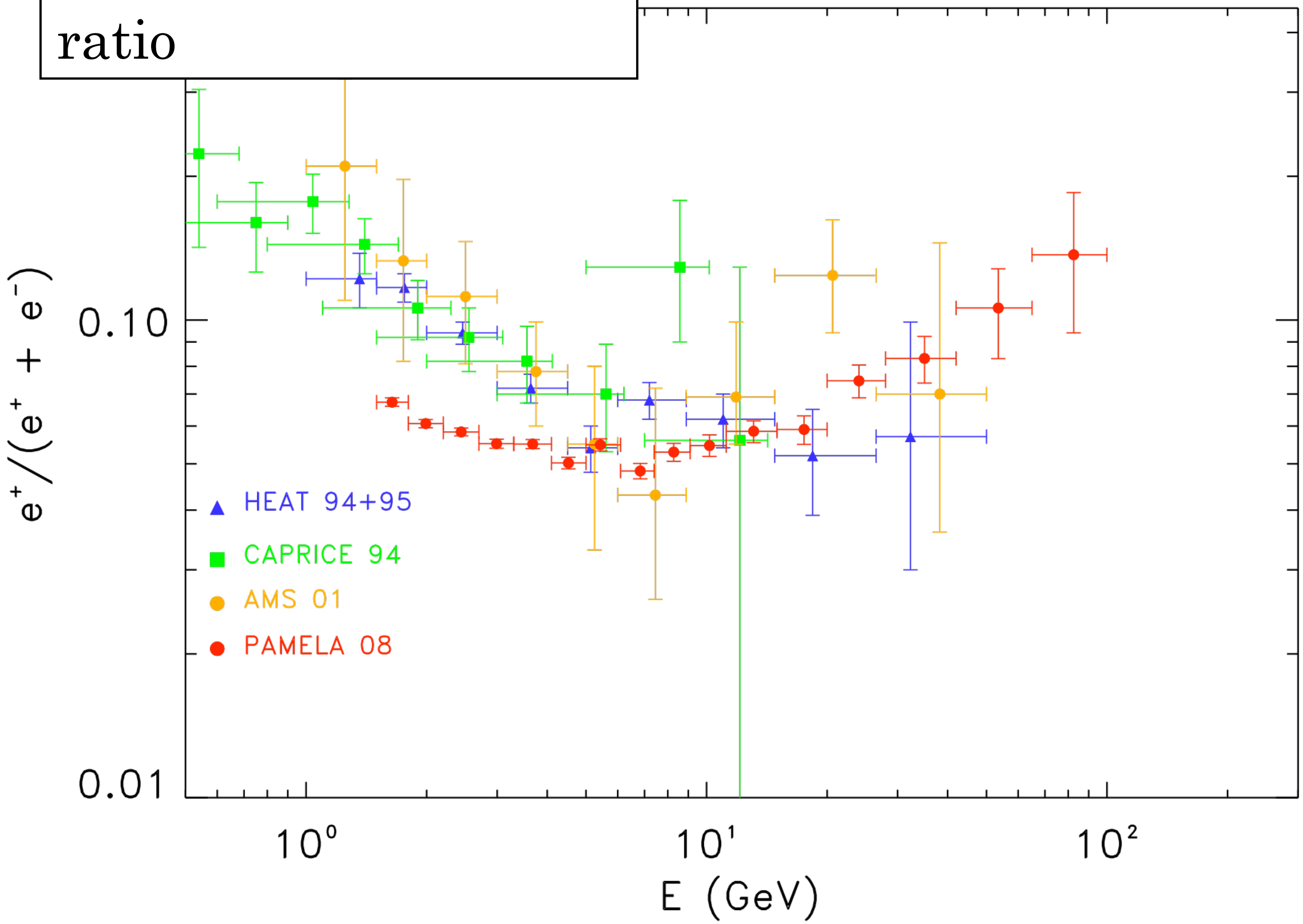


Electron + positron spectrum.

Since electrons are primary product, the slope depends both on the injection spectrum and on diffusion setup.

The data on Cosmic Ray spectra that we have to interpret

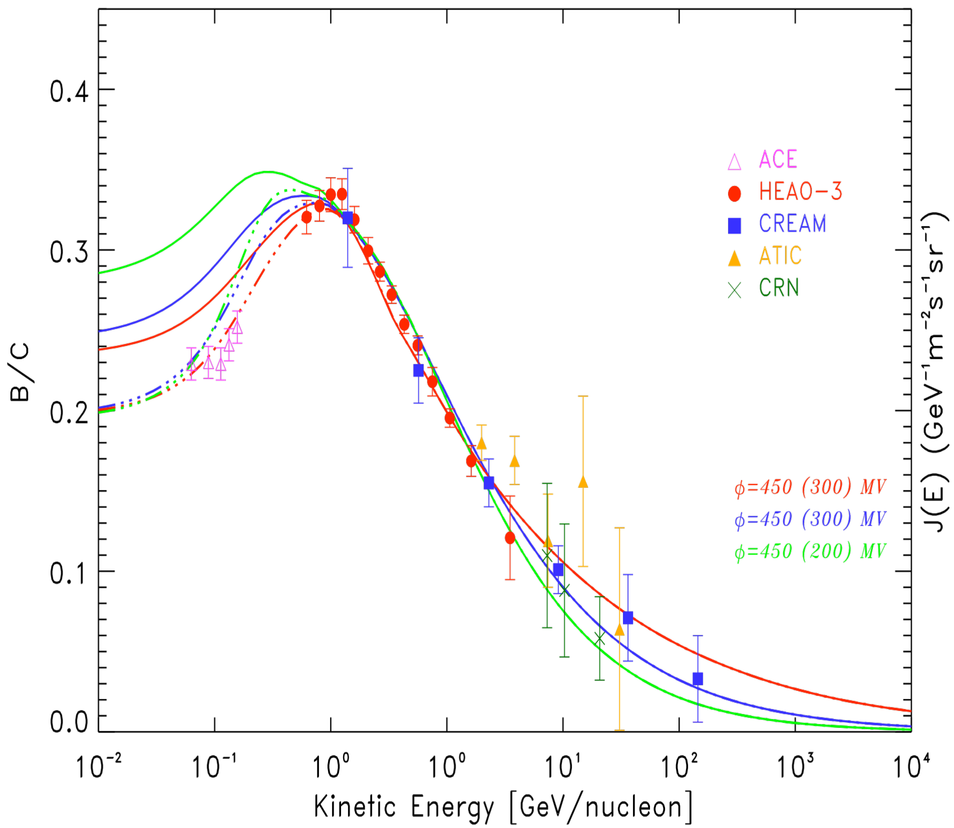
Positron-to-electron ratio

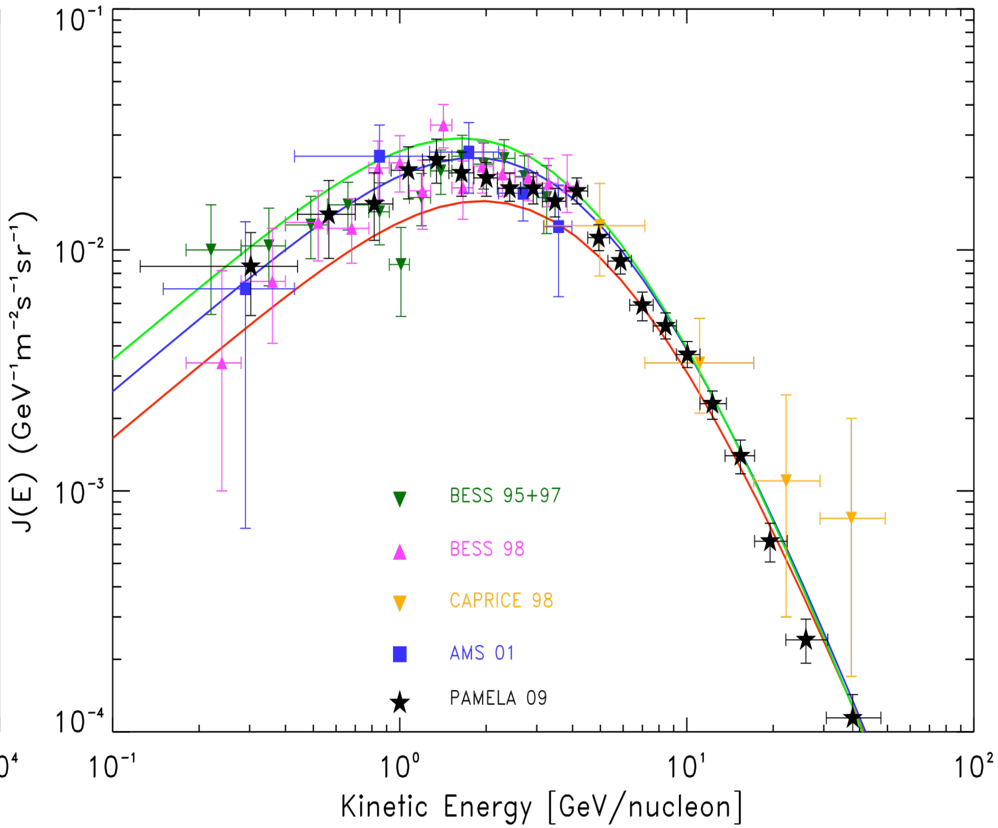


Positron to electron ratio

The anomalous rising behavior of PAMELA data may be the sign of a primary extra source of positrons!

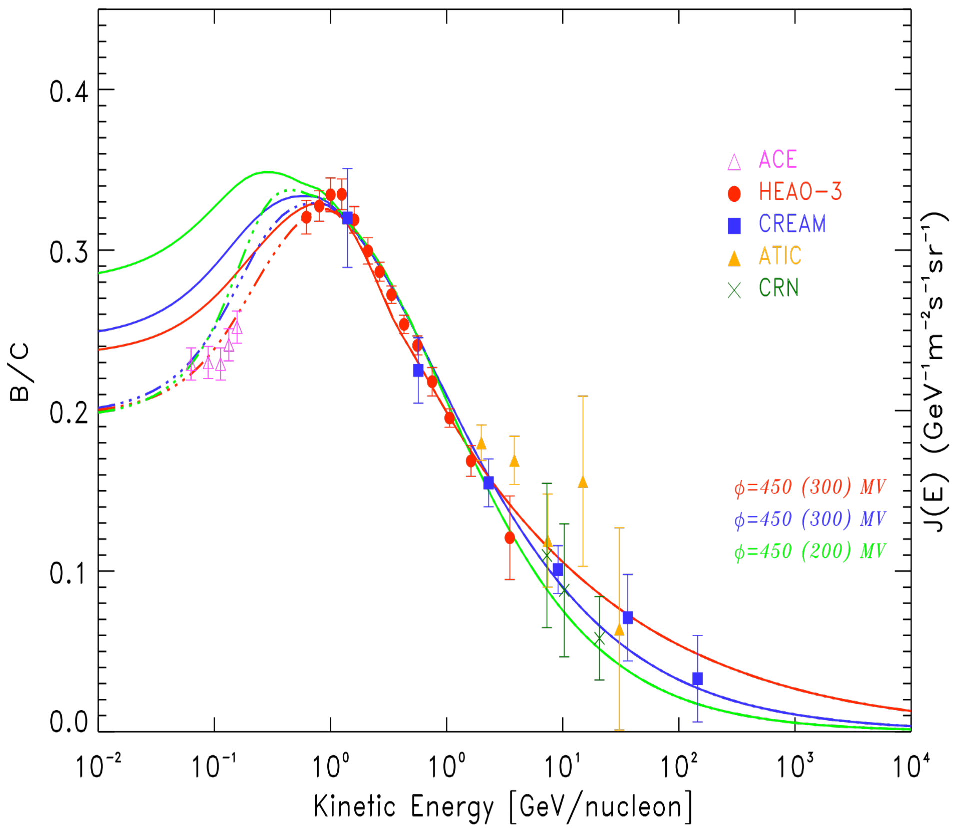
The diffusion setups we are considering

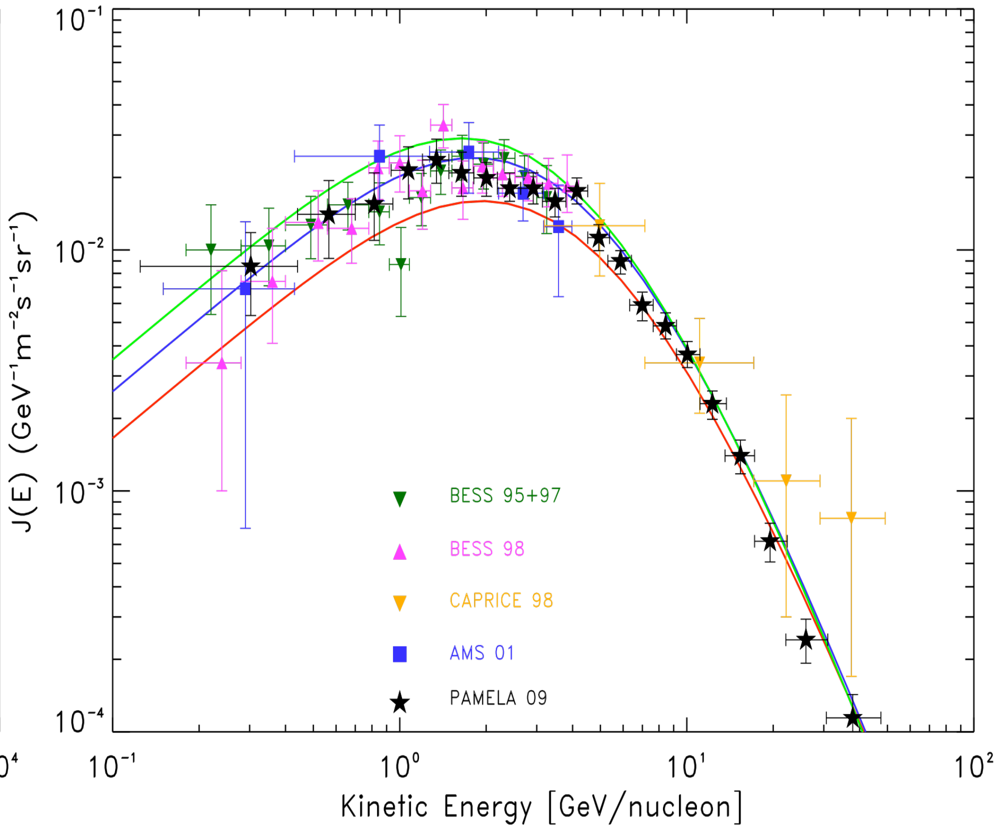




Red line → "Conventional" diffusion setup: $\delta = 0.33$; v_Alfvén = 30 km/s

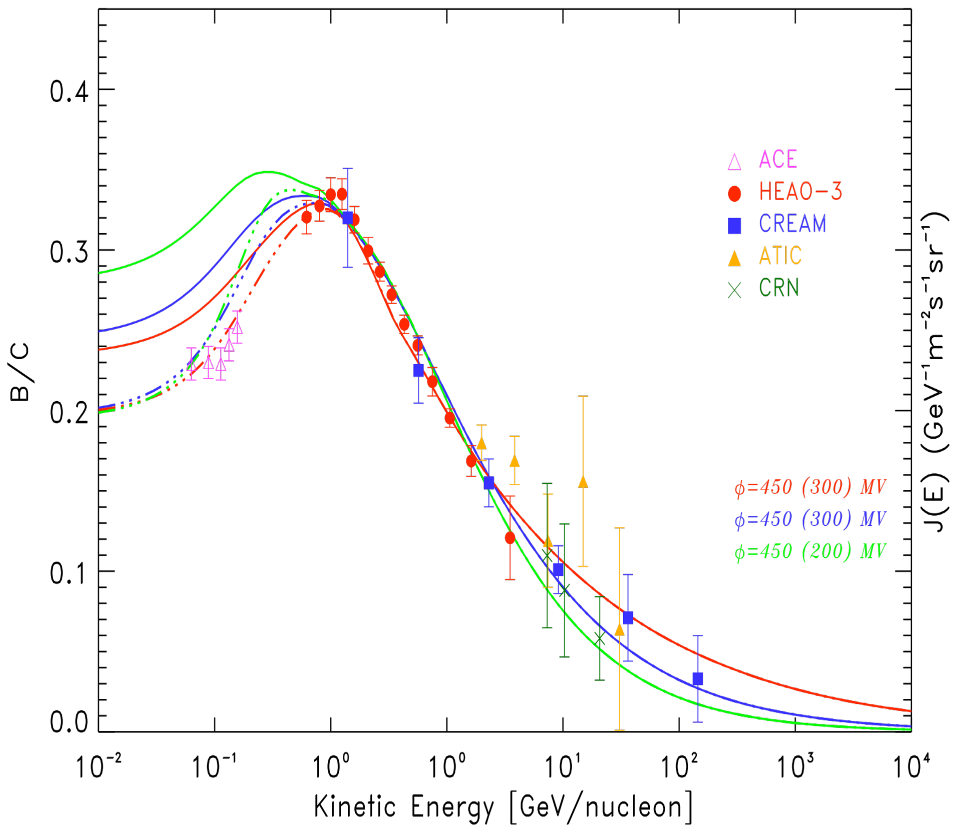
The diffusion setups we are considering

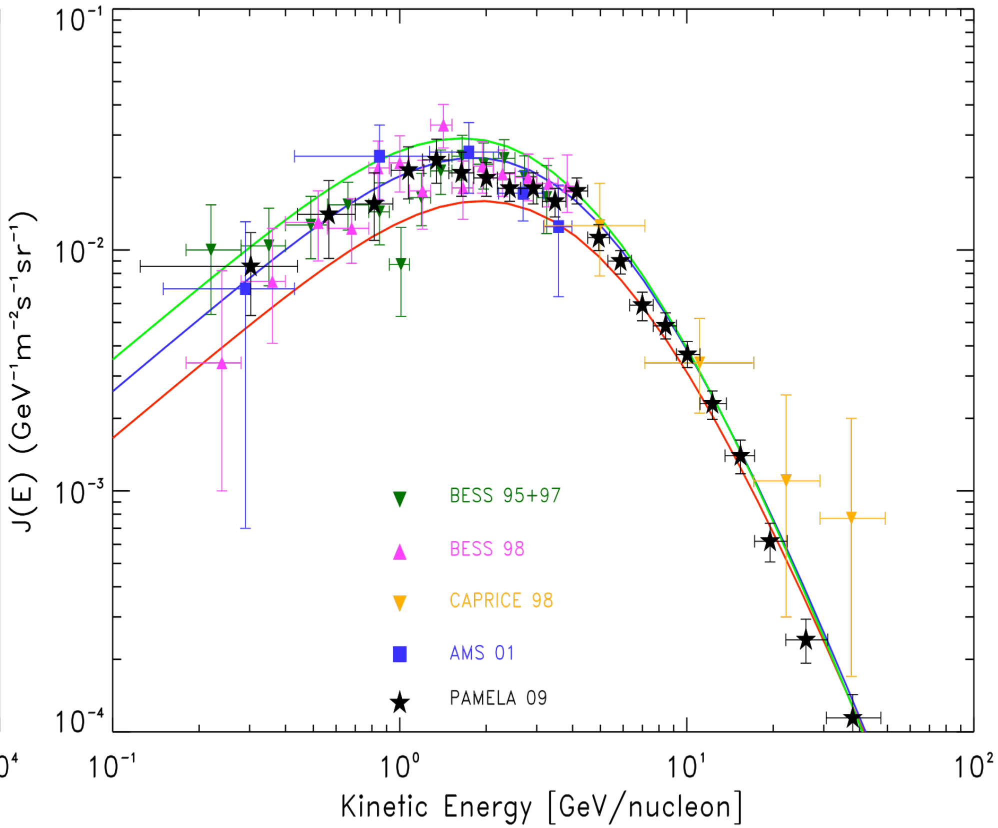




Blue line → "Kraichnan" setup: $\delta = 0.5$, v_Alfvén = 15 km/s. **A maximum likelihood analysis performed with our code (`DRAGON`) suggested this model as the preferred one (see `arXiv:0909.4548`)**

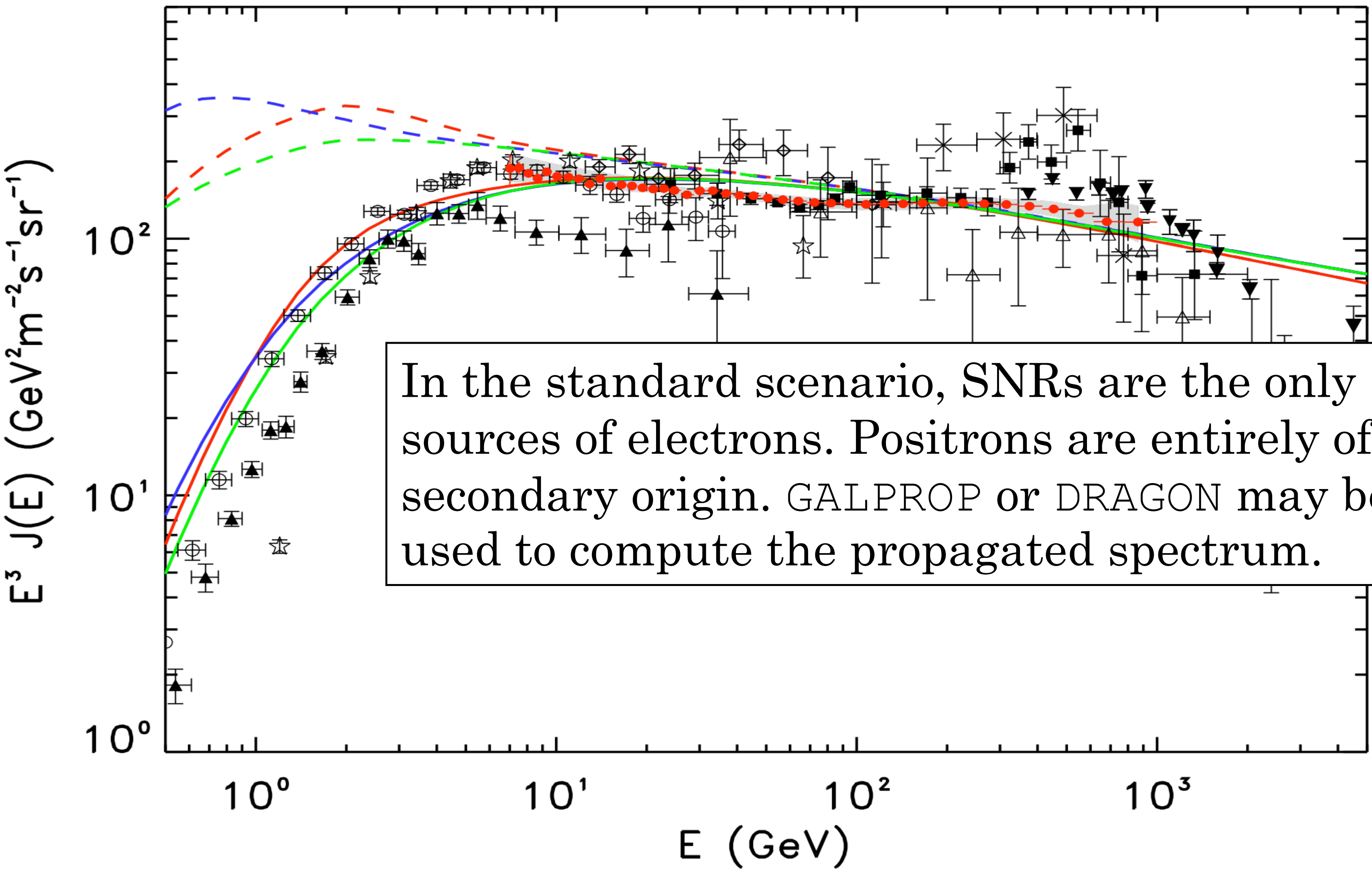
The diffusion setups we are considering





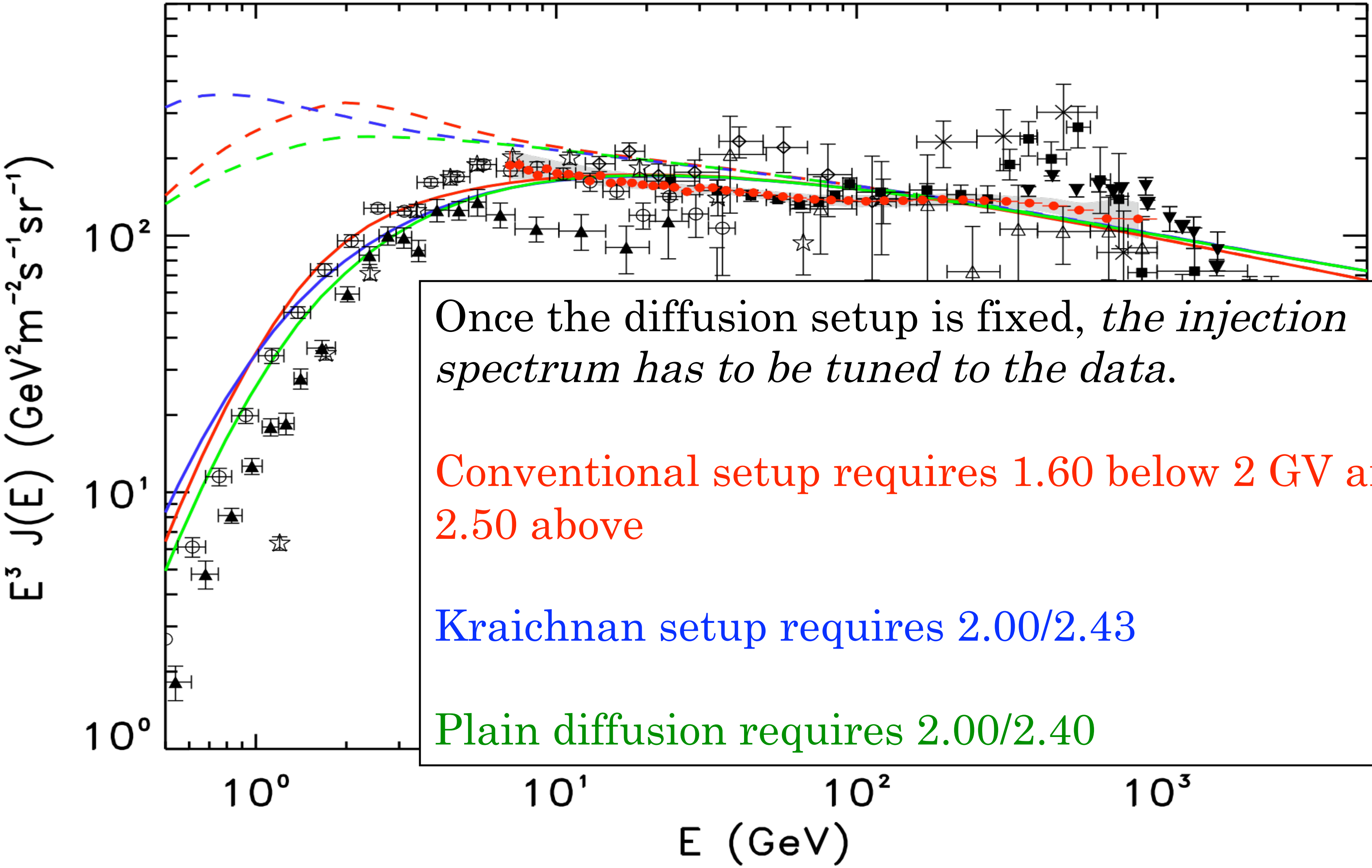
Green line → "Plain diffusion" setup: δ = 0.6, v_Alfvén = 0 km/s (no reacceleration at all)

Interpreting the electron+positron spectrum in a "standard" scenario



In the standard scenario, SNRs are the only sources of electrons. Positrons are entirely of secondary origin. `GALPROP` or `DRAGON` may be used to compute the propagated spectrum.

Interpreting the electron+positron spectrum in a "standard" scenario



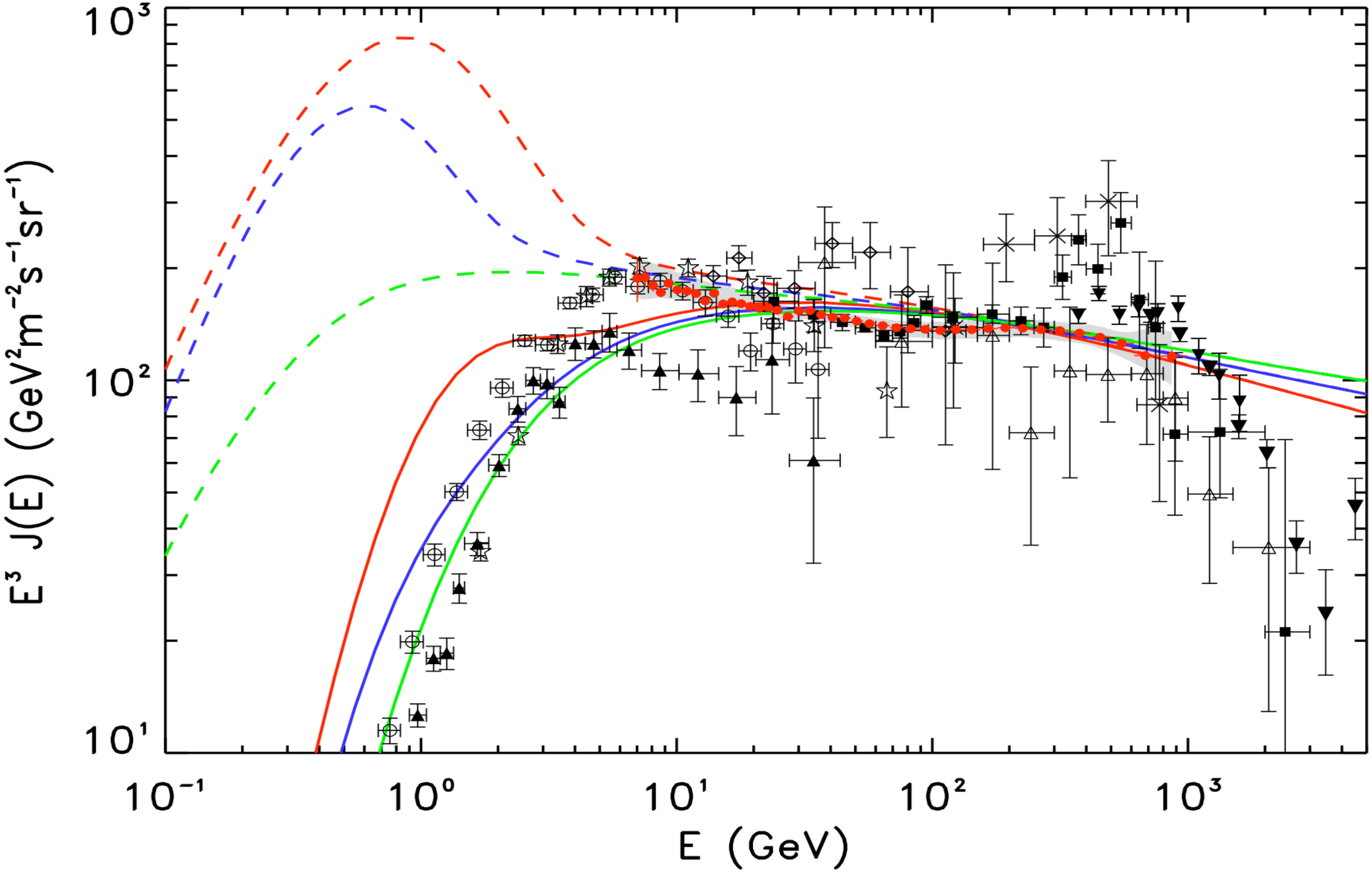
Once the diffusion setup is fixed, *the injection spectrum has to be tuned to the data.*

Conventional setup requires 1.60 below 2 GV and 2.50 above

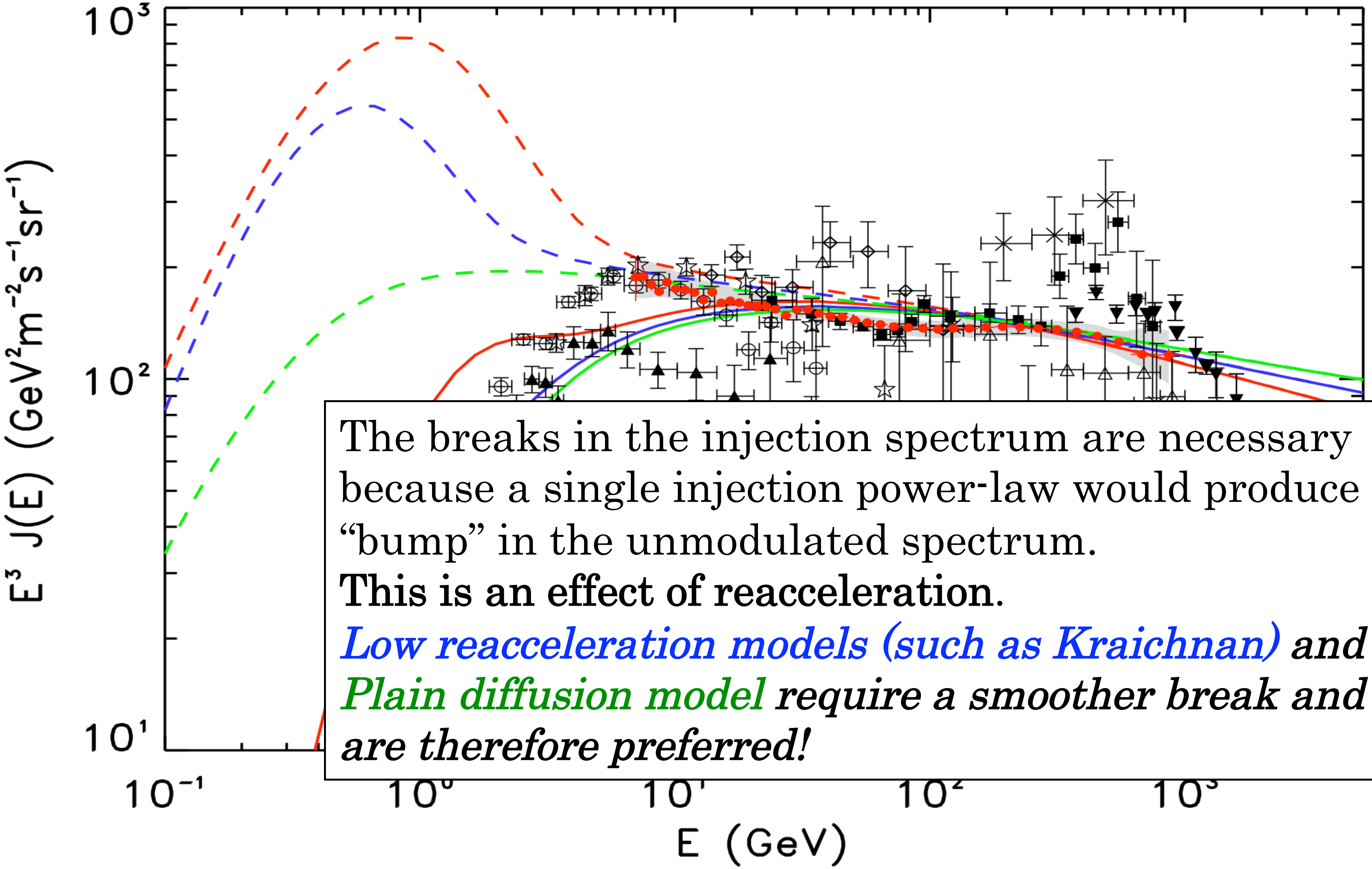
Kraichnan setup requires 2.00/2.43

Plain diffusion requires 2.00/2.40

The "bump" problem



The “bump” problem

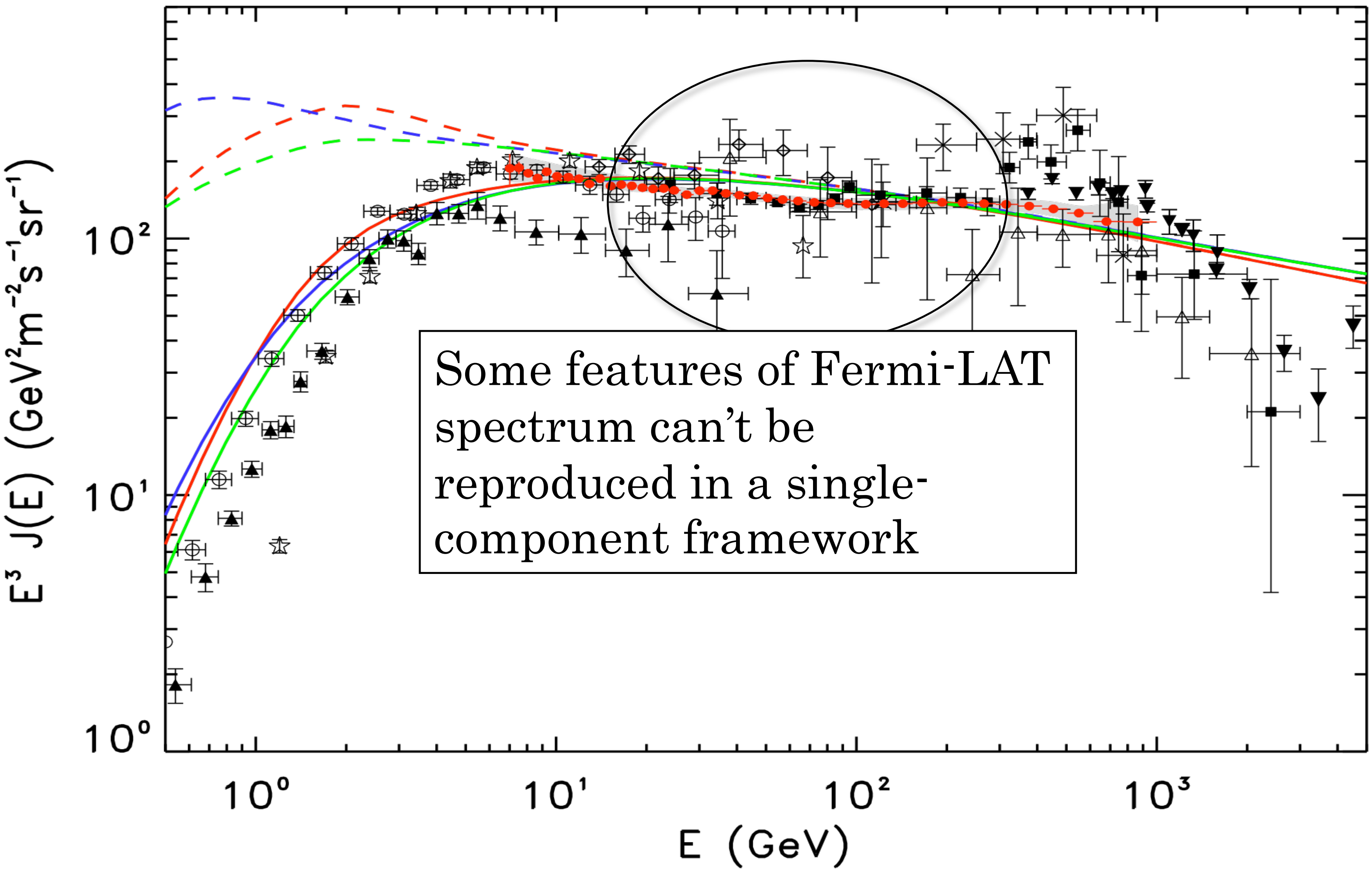


The breaks in the injection spectrum are necessary because a single injection power-law would produce a “bump” in the unmodulated spectrum.

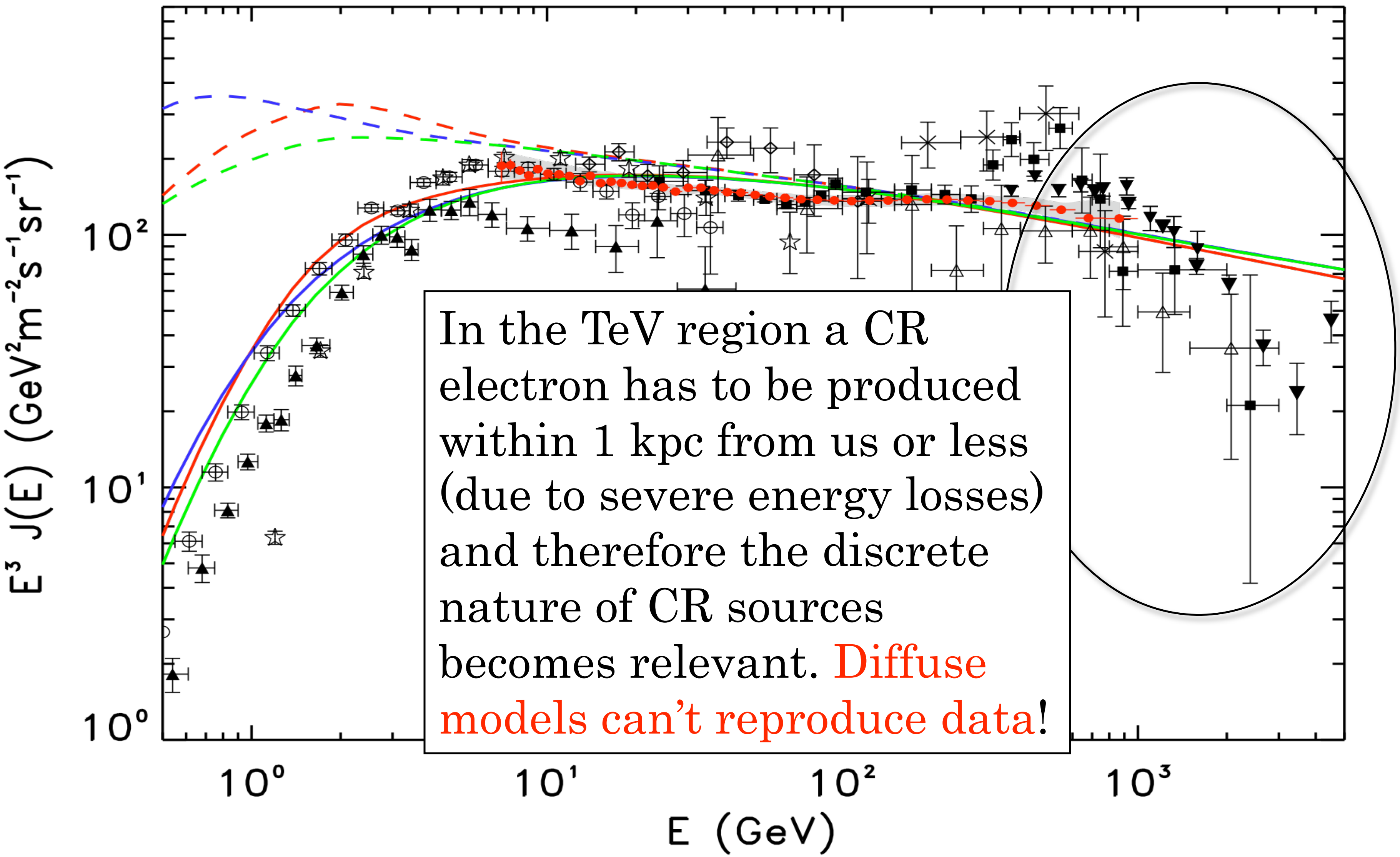
This is an effect of reacceleration.

Low reacceleration models (such as Kraichnan) and Plain diffusion model require a smoother break and are therefore preferred!

PROBLEMS of single component scenarios

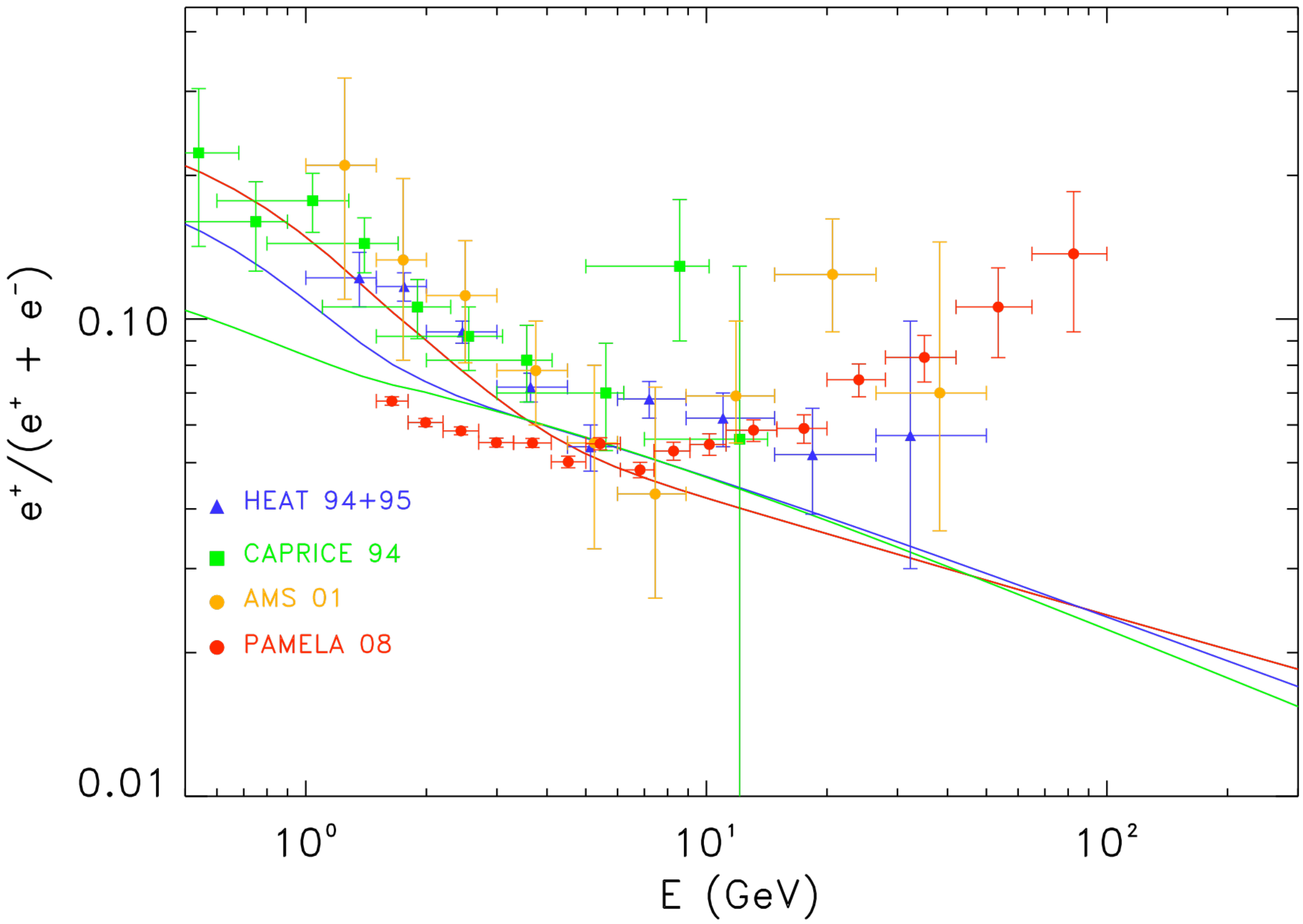


PROBLEMS of single component scenarios

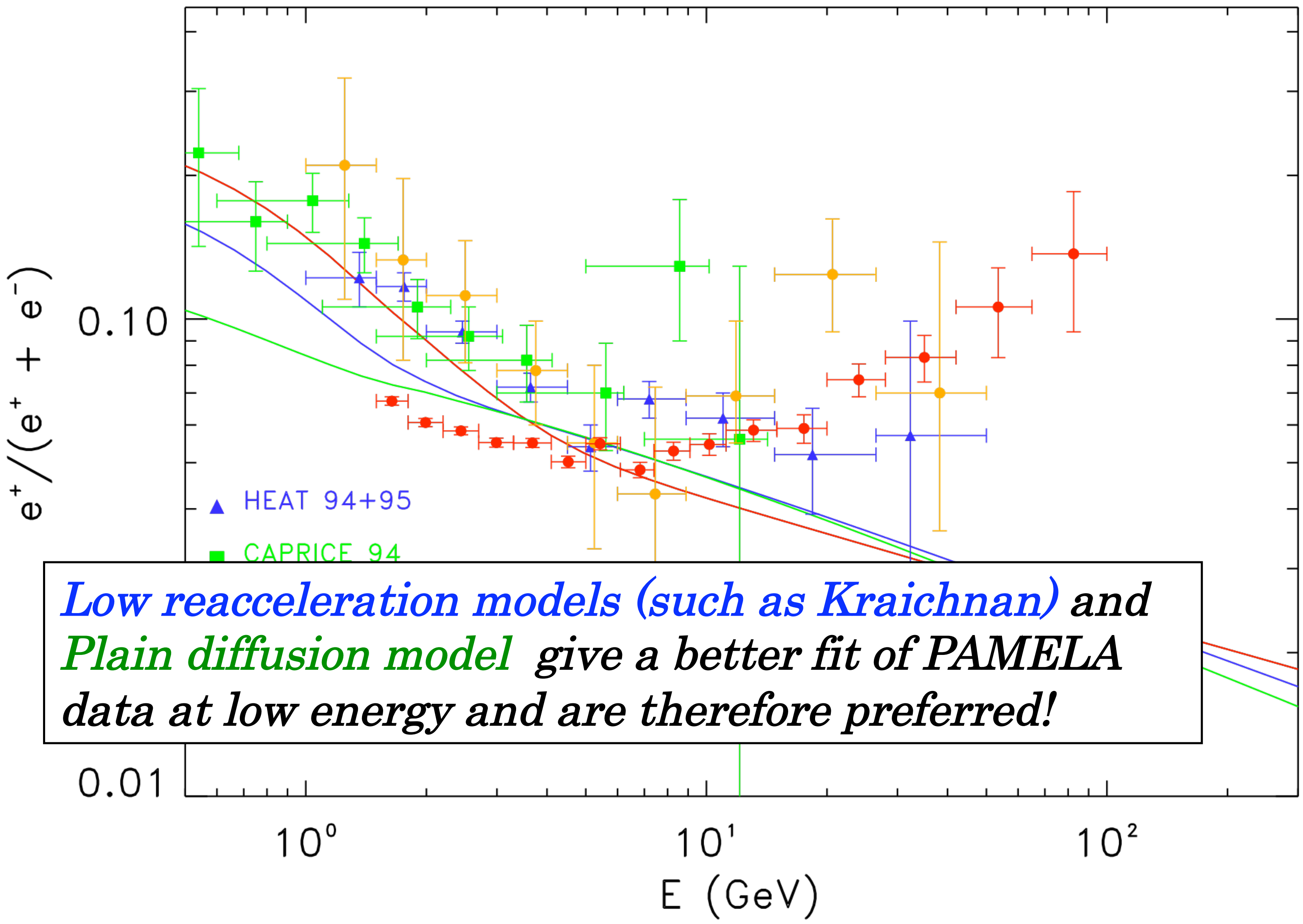


In the TeV region a CR electron has to be produced within 1 kpc from us or less (due to severe energy losses) and therefore the discrete nature of CR sources becomes relevant. Diffuse models can't reproduce data!

Interpreting the positron-to-electron ratio in a "standard" scenario

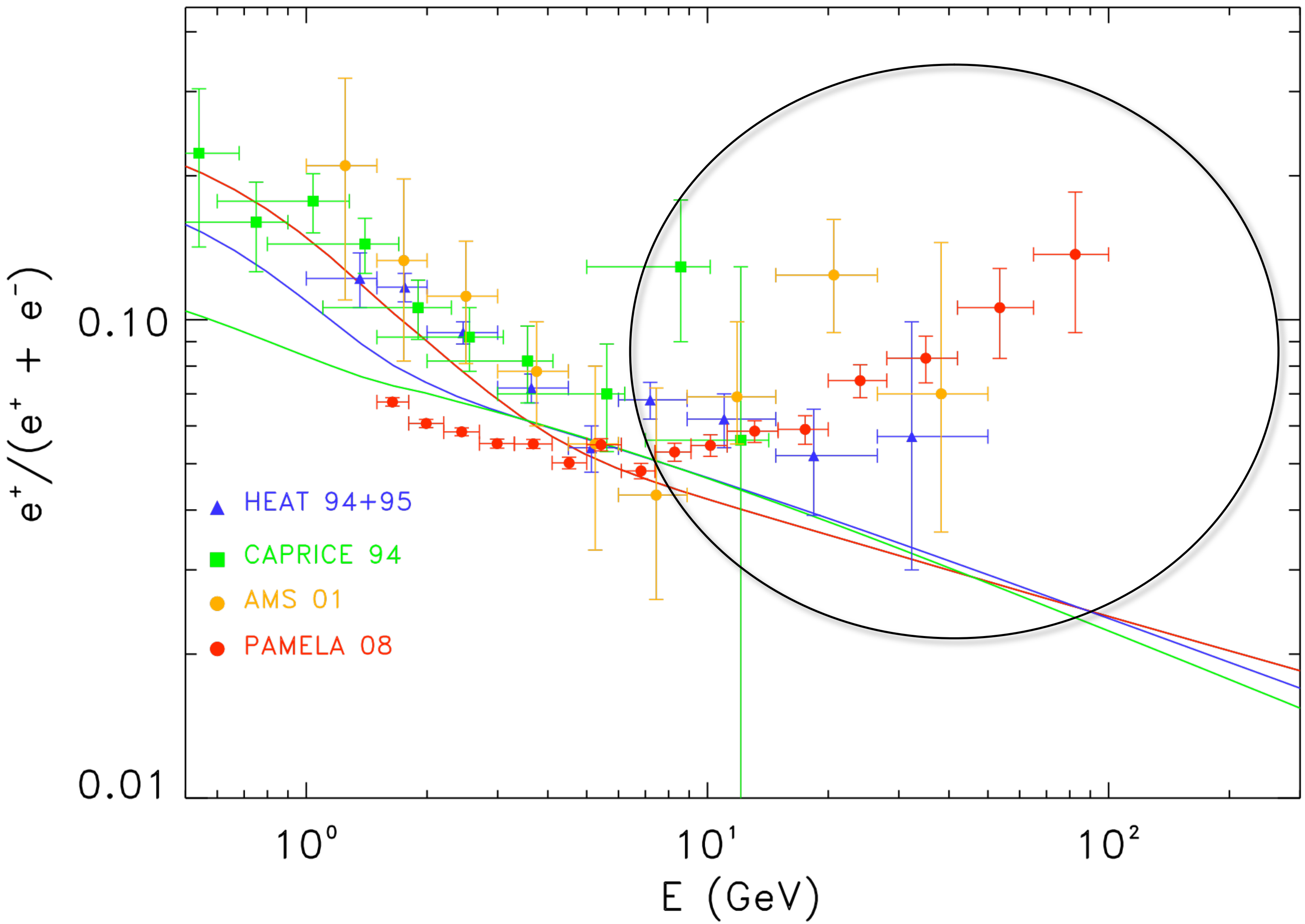


Interpreting the positron-to-electron ratio in a "standard" scenario

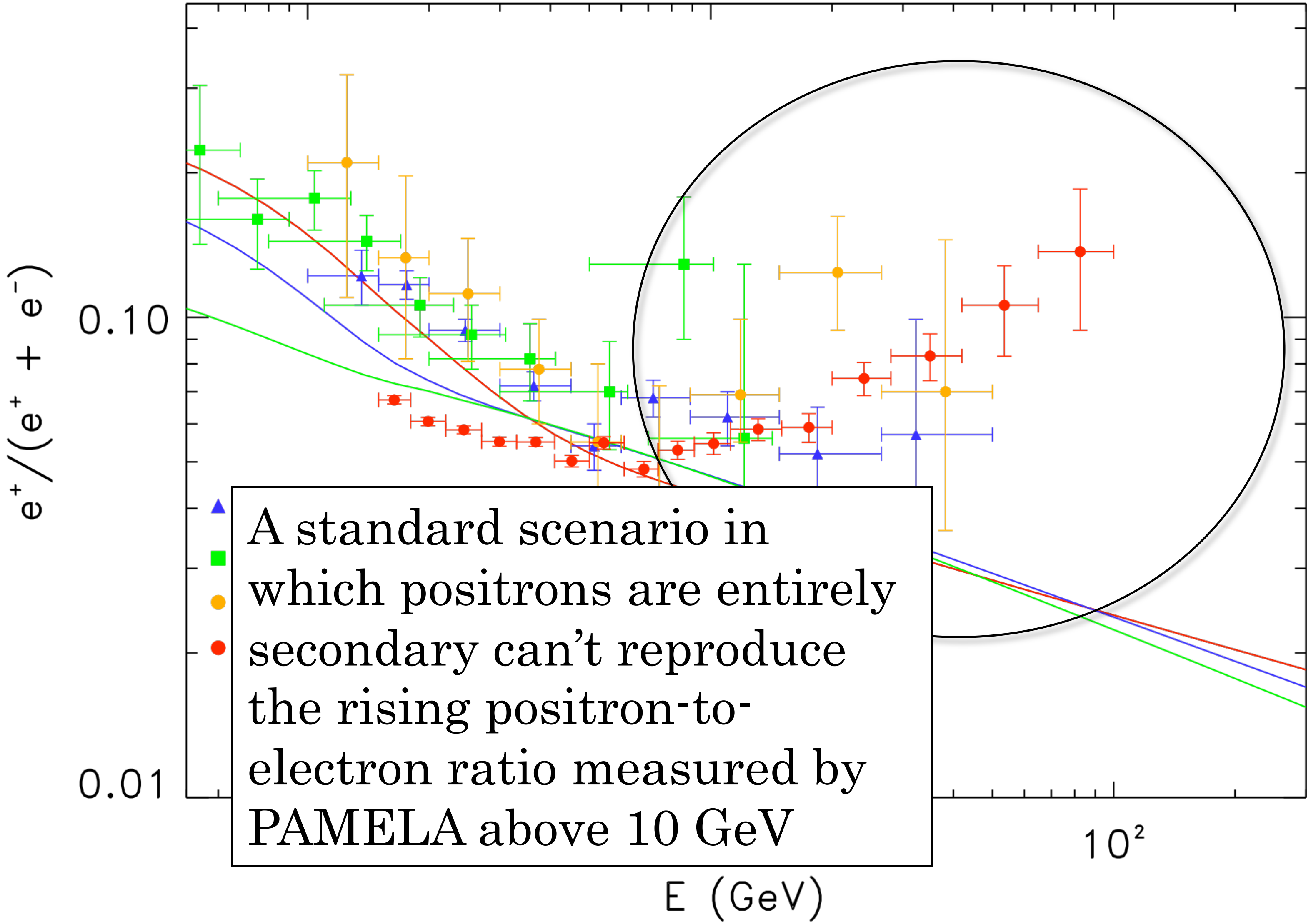


Low reacceleration models (such as Kraichnan) and *Plain diffusion model* *give a better fit of PAMELA data at low energy and are therefore preferred!*

PROBLEMS of single component scenarios



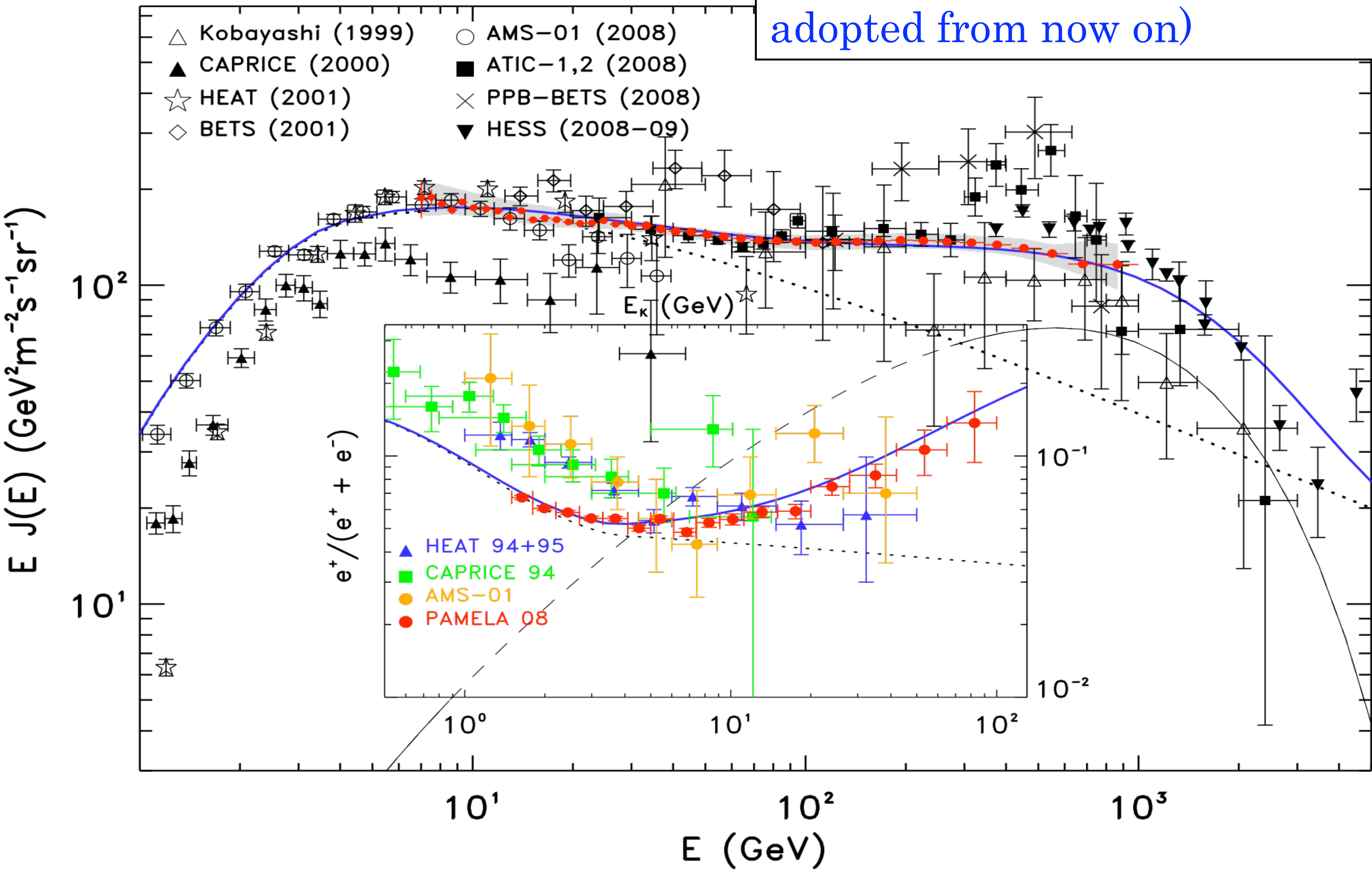
PROBLEMS of single component scenarios



A standard scenario in which positrons are entirely secondary can't reproduce the rising positron-to-electron ratio measured by PAMELA above 10 GeV

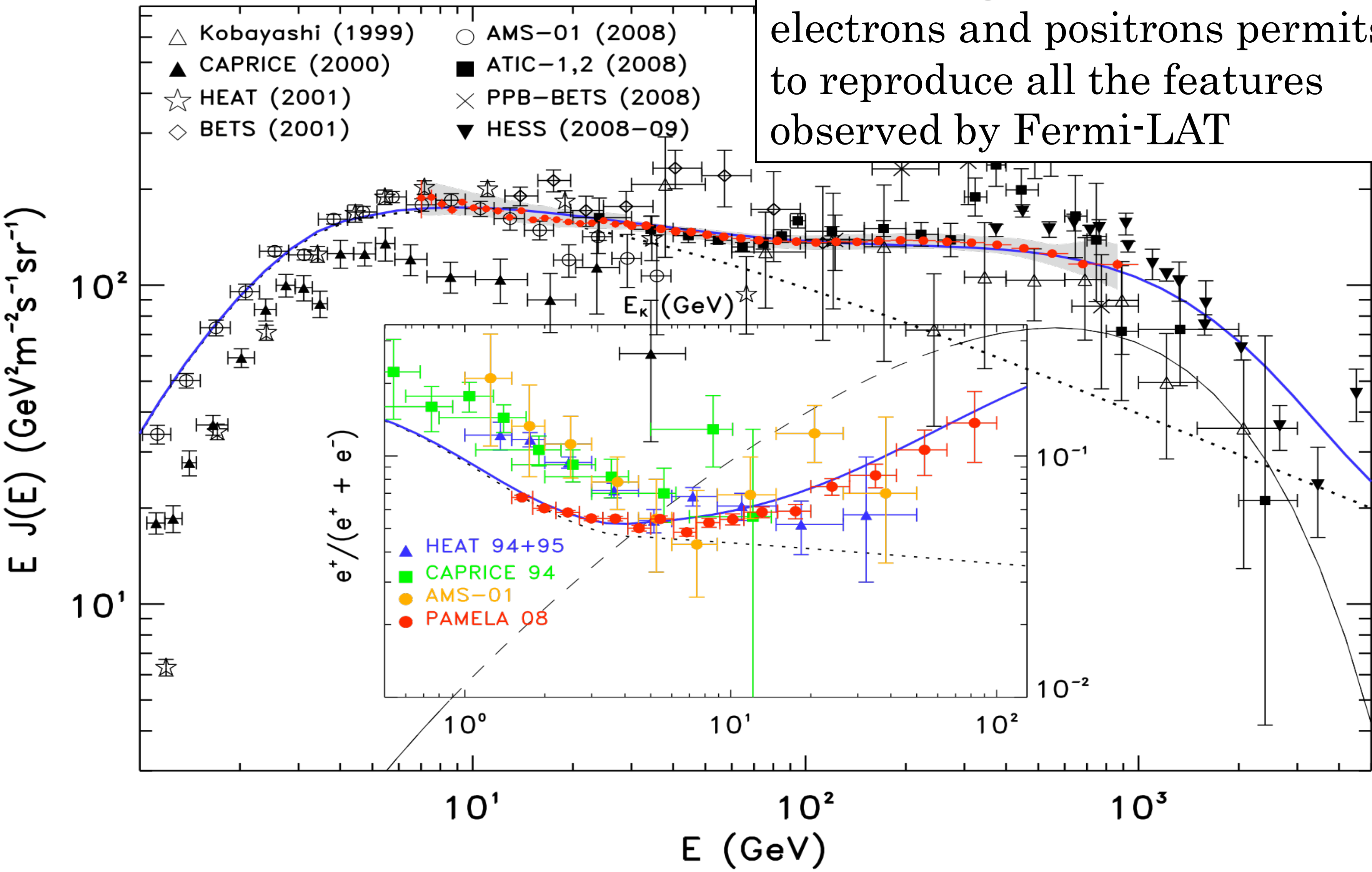
Introducing a primary extra-component of electrons and positrons

(Kraichnan diffusion setup is adopted from now on)

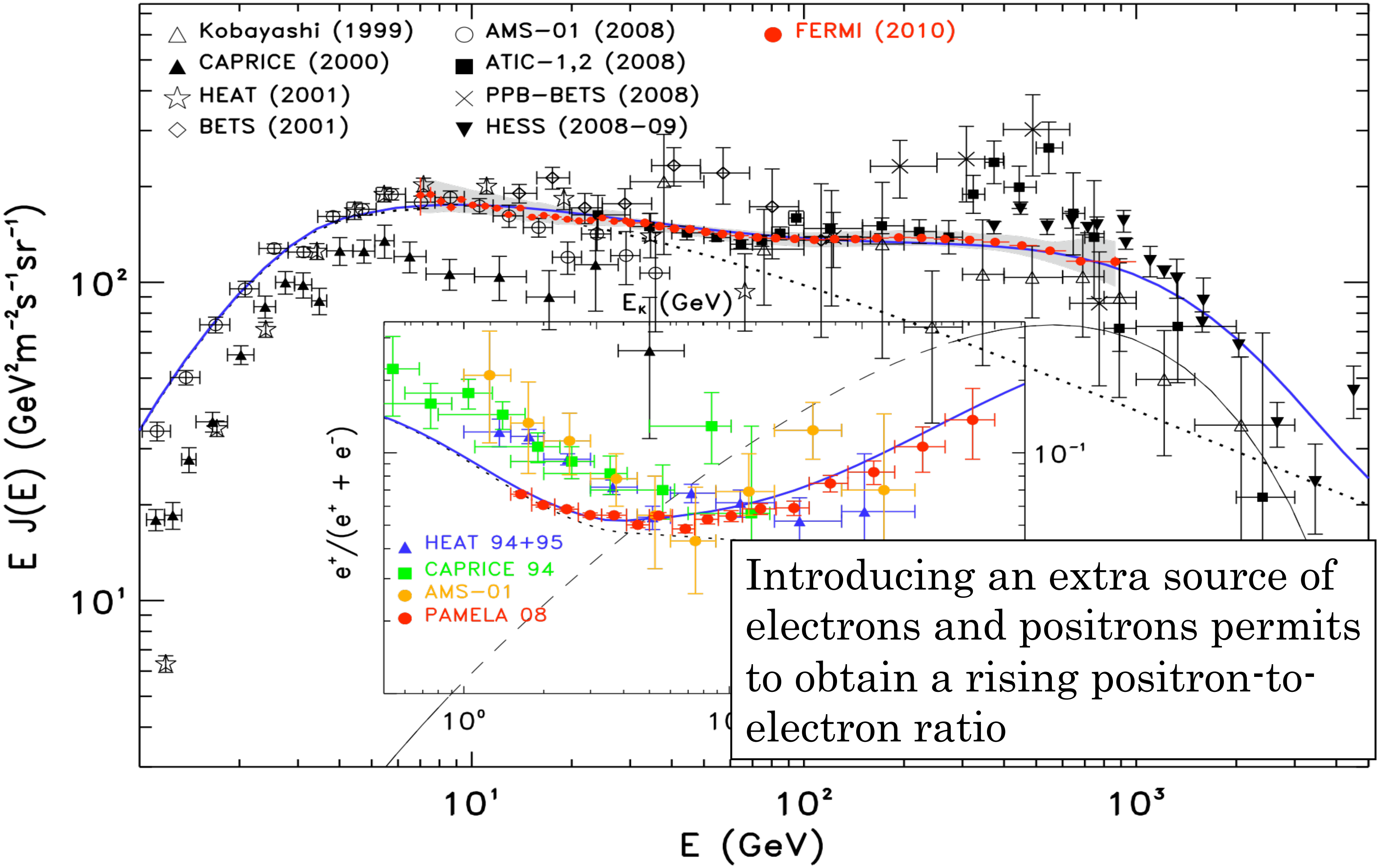


Introducing a primary extra-component of electrons and positrons

Introducing an extra source of electrons and positrons permits to reproduce all the features observed by Fermi-LAT

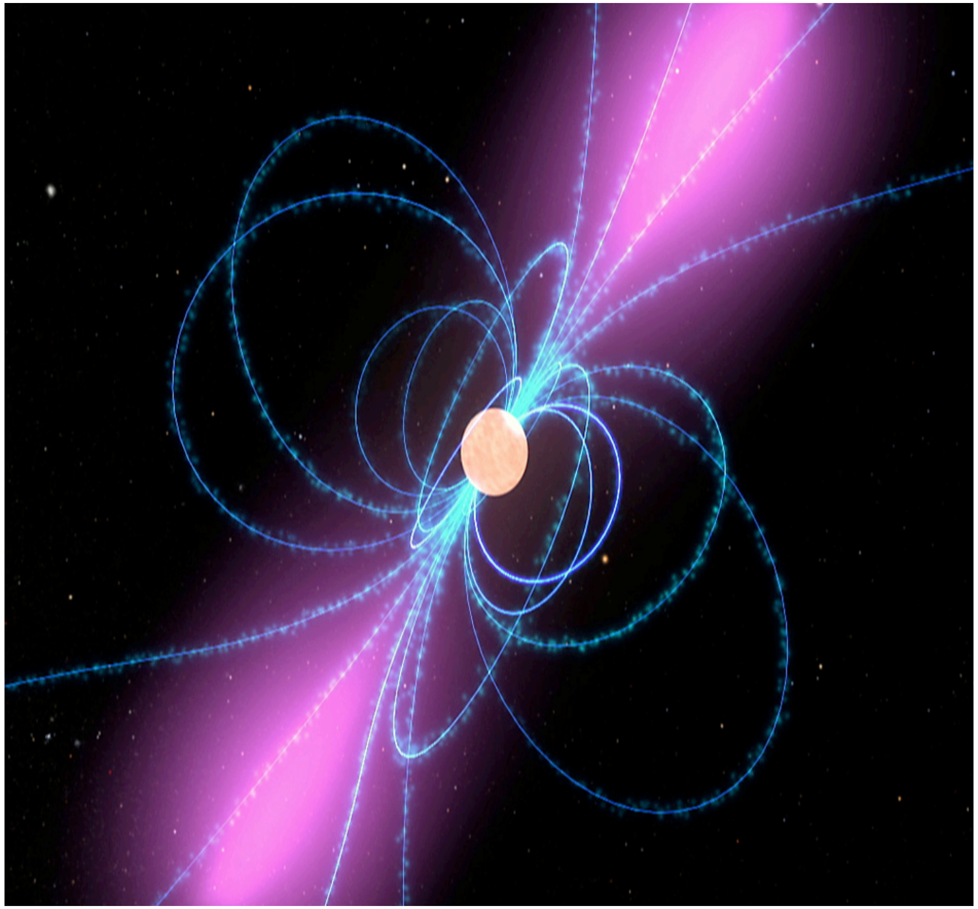


Introducing a primary extra-component of electrons and positrons



Introducing an extra source of electrons and positrons permits to obtain a rising positron-to-electron ratio

Astrophysical objects that may contribute to the primary extra-component

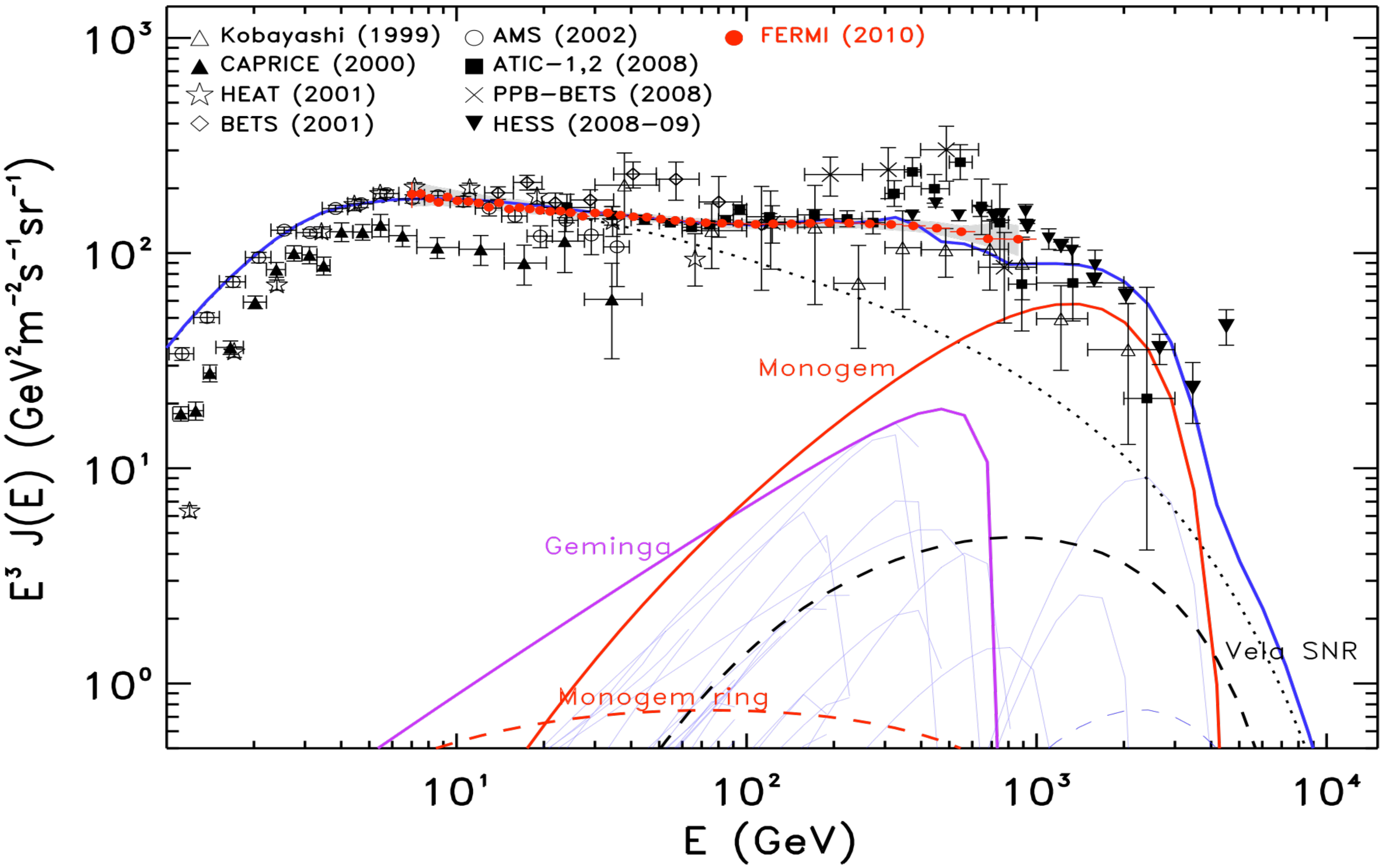


Pulsars are candidate sources of relativistic electrons and positrons.

Electrons-positrons pairs are believed to be produced in the magnetosphere and re-accelerated in the wind.

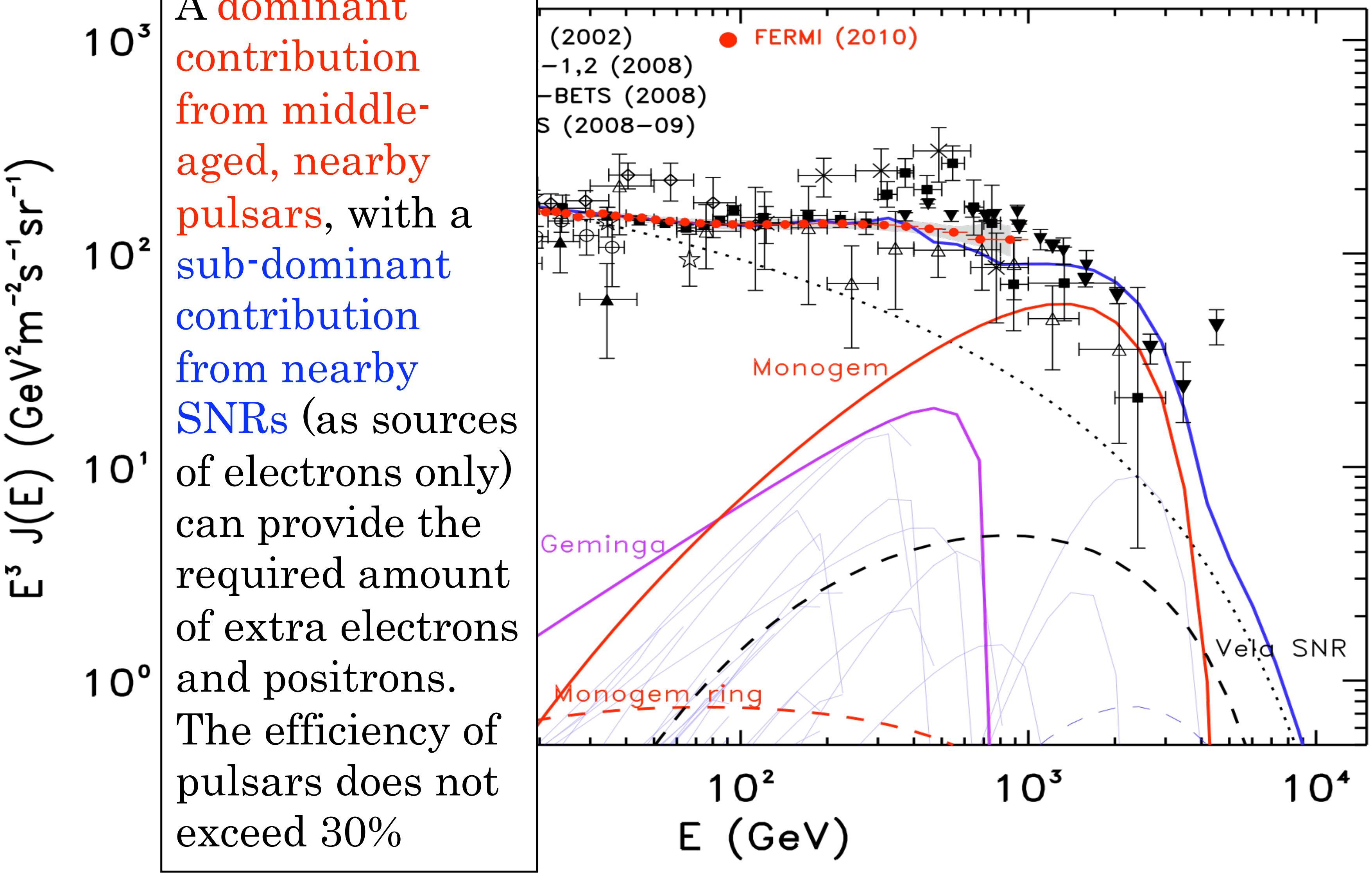
To explain Fermi/Pamela excesses with respect to conventional model, the pulsar we are interested in are nearby (because of heavy energy losses) and mature (because electrons remain confined in the Pulsar Wind Nebula until it merges with the ISM.

Astrophysical objects that may contribute to the primary extra-component

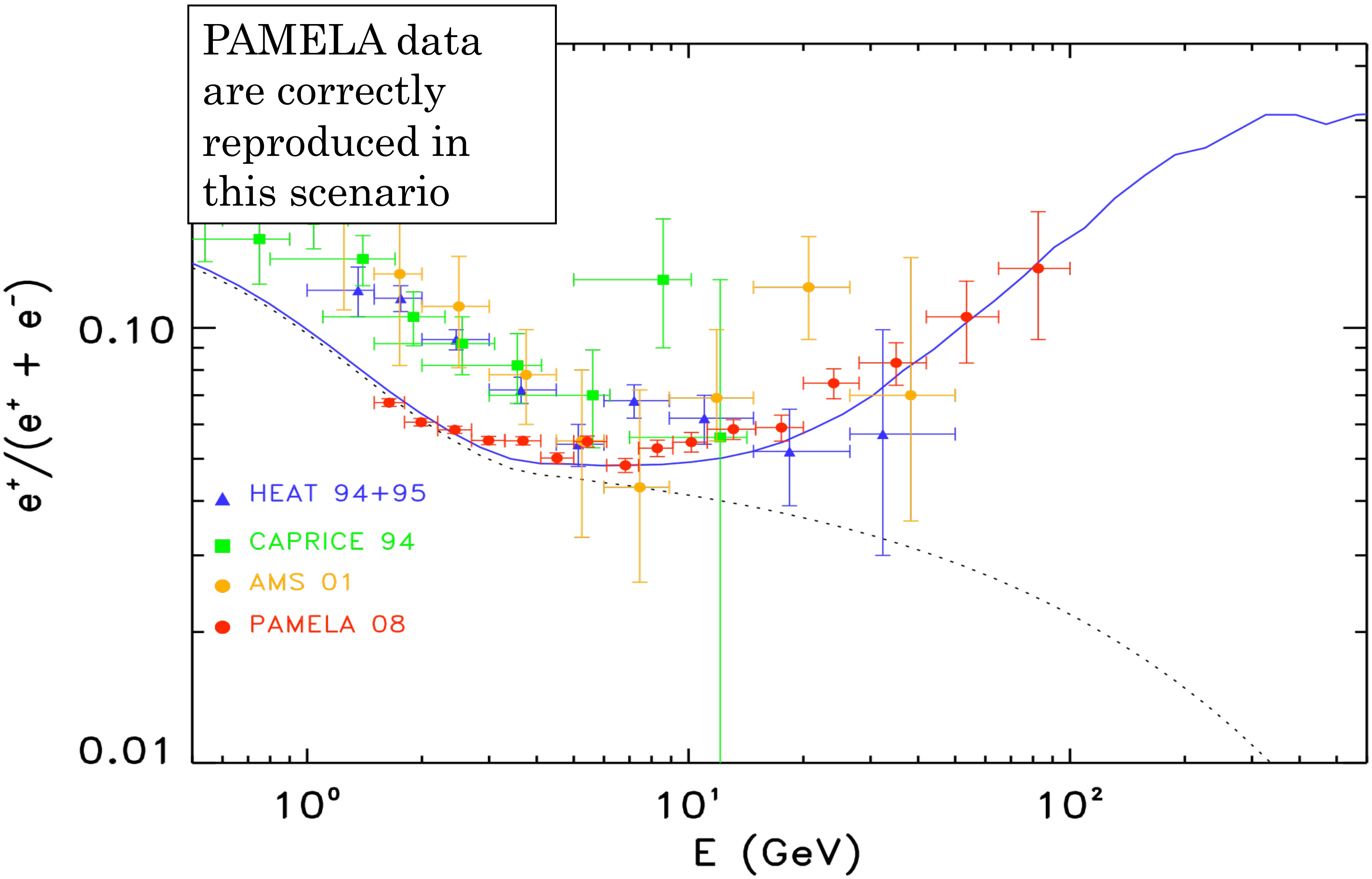


Astrophysical objects that may contribute to the primary extra-component

A dominant contribution from middle-aged, nearby pulsars, with a sub-dominant contribution from nearby SNRs (as sources of electrons only) can provide the required amount of extra electrons and positrons. The efficiency of pulsars does not exceed 30%

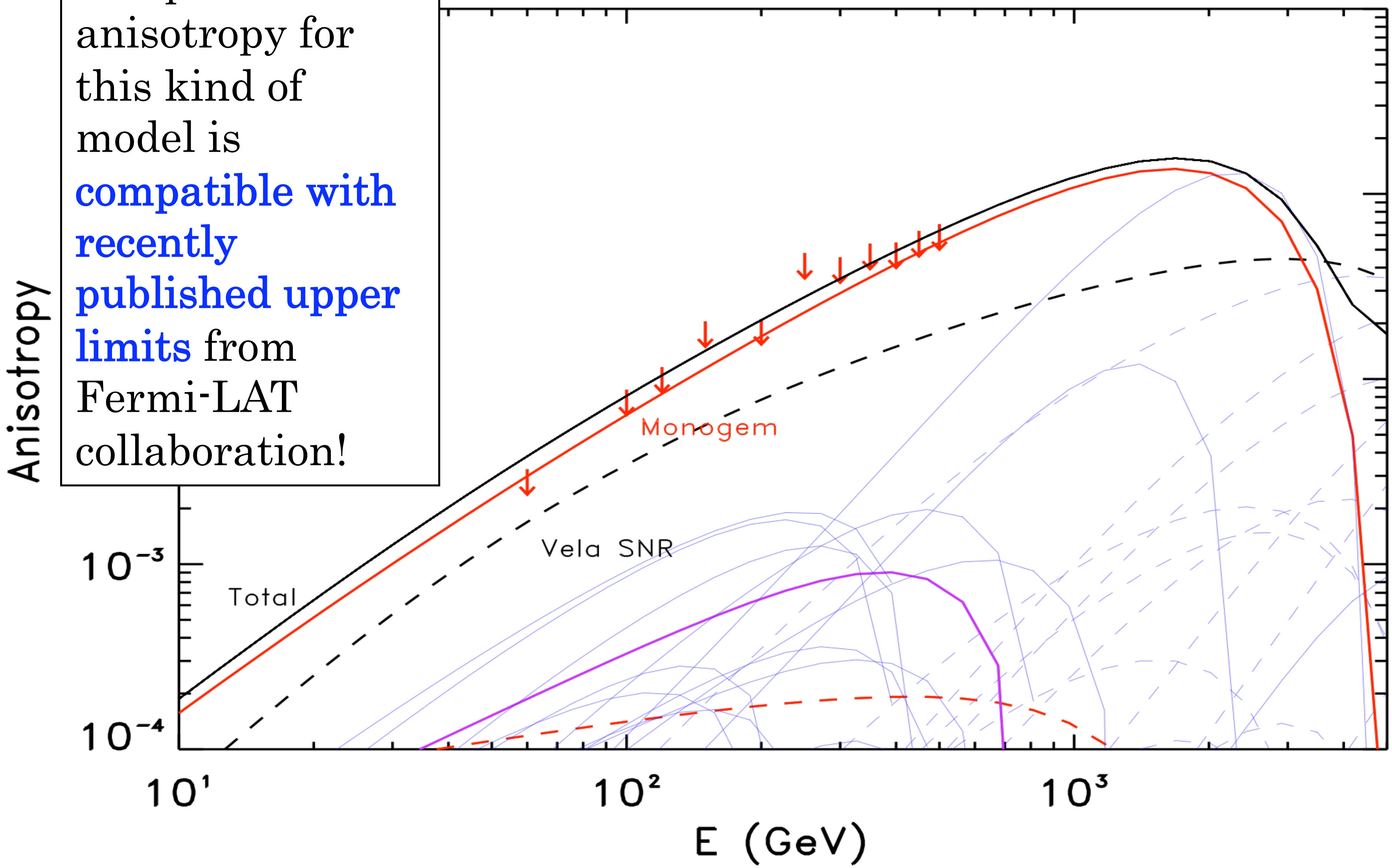


Astrophysical objects that may contribute to the primary extra-component



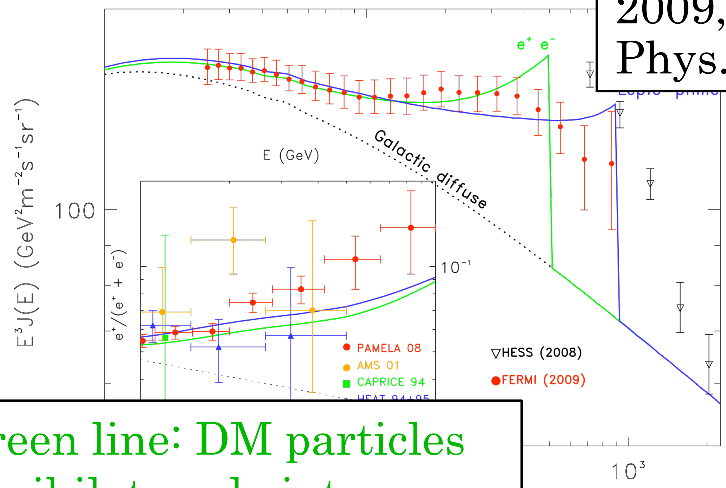
Astrophysical objects that may contribute to the primary extra-component

The predicted anisotropy for this kind of model is **compatible with recently published upper limits** from Fermi-LAT collaboration!



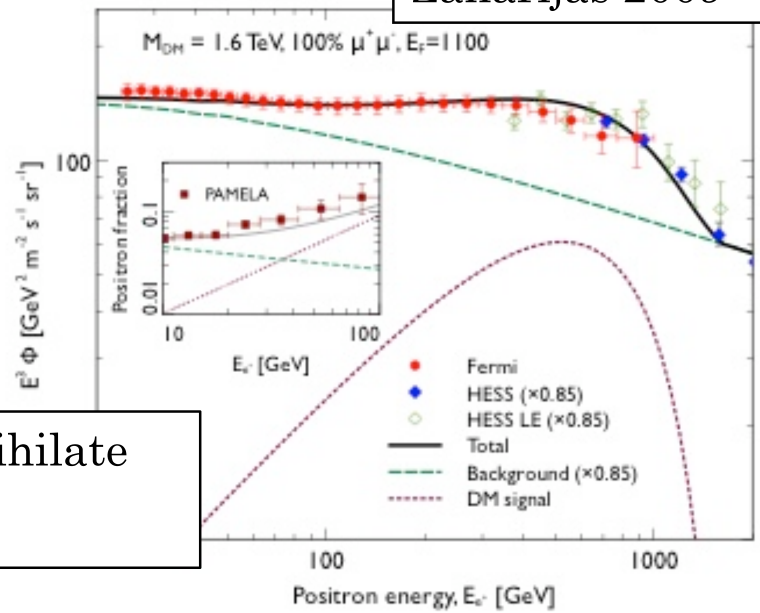
The extra-component may also be originated by annihilation or decay of Dark Matter particles

D.Grasso et al. 2009, Astrop. Phys.



Green line: DM particles annihilate only into electrons and positrons
Blue line: DM particles annihilate into e^+/e^- μ^+/μ^- τ^+/τ^-

Bergström, Edsjö & Zaharijas 2009



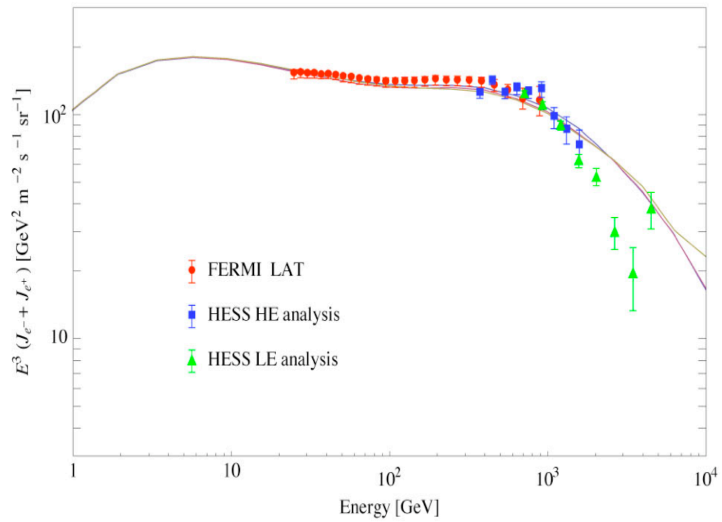
DM particles annihilate into μ^+/μ^-

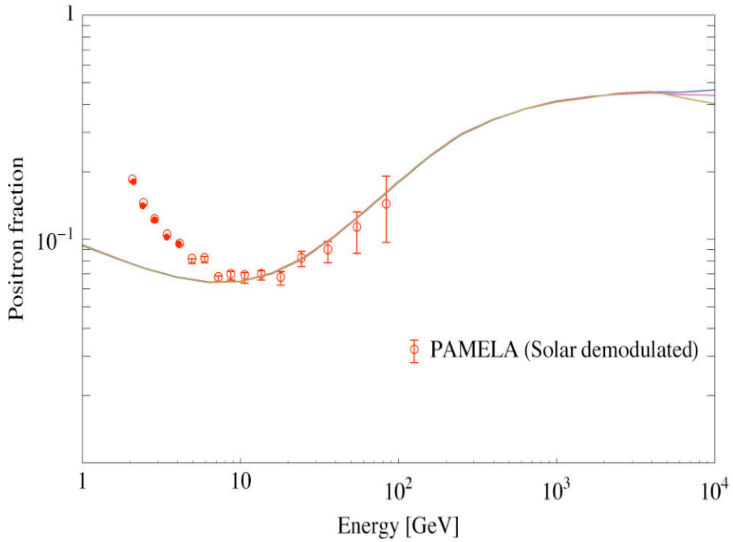
An interpretation based on dark matter annihilation is still an open possibility

However DM interpretation seems disfavoured because:

- Antiproton measurements rule out most annihilation modes, only "leptonic" models are allowed
- Large "boost factors" are needed (from 20 to 100) compared with expected annihilation rates

Another possible scenario: secondary production in the accelerator





It has been proposed that the observed rise in the positron fraction could be due to acceleration of secondary positrons in the same spatial region where primary species are accelerated (SNR shocks) [P.Blasi, 2009]

This scenario can account for Fermi and PAMELA datasets [P.Mertsch et al. 2009]

Conclusions

Recently released Fermi-LAT electron+positron spectrum can be reproduced tuning "conventional" diffusive models, but this interpretation isn't in accord with PAMELA positron data

In order to simultaneously fit Fermi, HESS and PAMELA datasets, an extra-component is needed

Nearby mature pulsars are natural candidates for this purpose

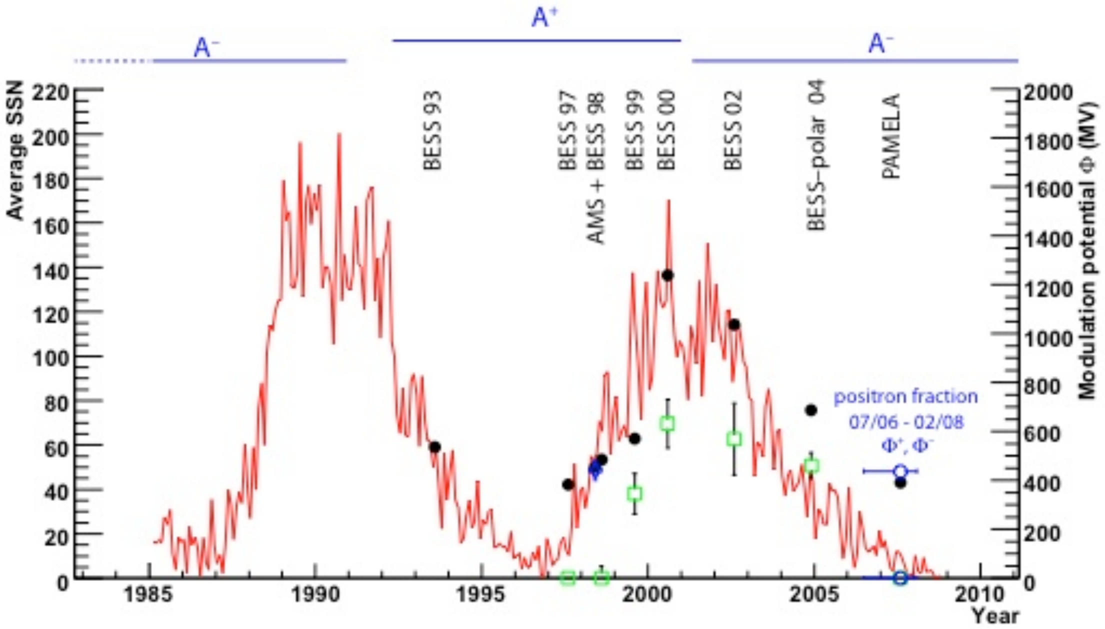
The contribution of pulsars within few kpc, summed to a conventional "background", with a subdominant contribution from SNRs, can nicely reproduce all data mentioned above; a scenario of this kind is compatible with published upper limits on anisotropy

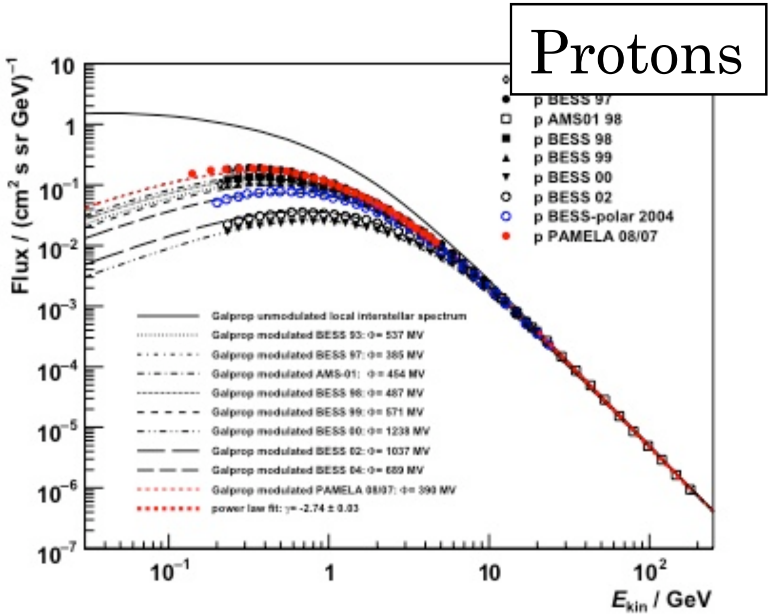
Other interpretations, such as Dark Matter annihilation or decay, or secondary positron production in the accelerator, cannot be excluded and give reasonably good fits to Fermi and PAMELA data sets

Backup slides

A low electron modulation potential is possible in the context of ***charge-sign-dependent solar modulation***

(see Gast and Schael 2009)

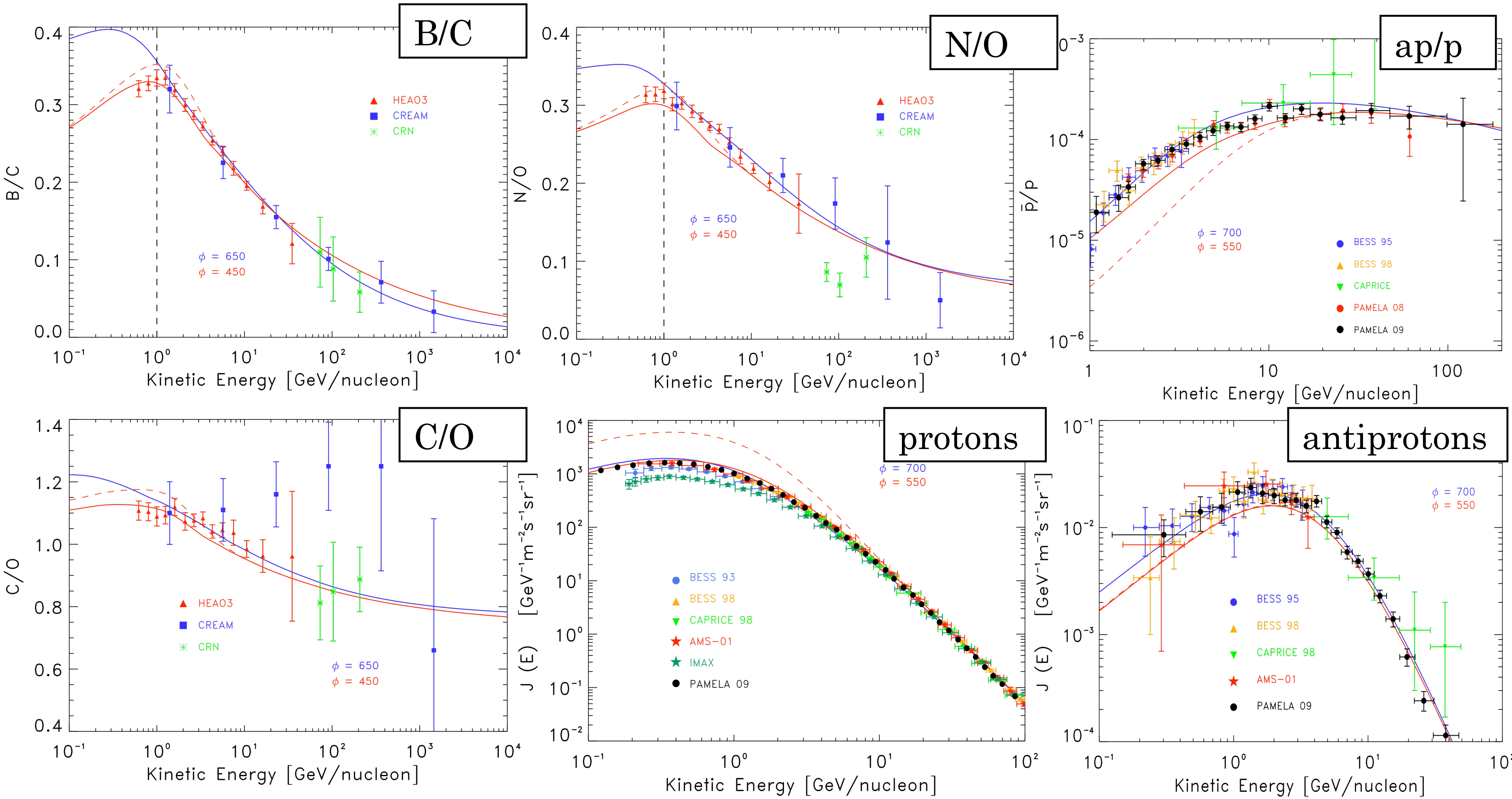




Experiment	Year	ϕ_p^+ (MV)	$\phi_{\bar{p}}^-$ (MV)	$\phi_{e^-}^-$ (MV)
BESS	1993	537		
BESS	1997	385	0	
AMS1	1998	454		442
BESS	1998	487	0	
BESS	1999	571	345	
BESS	2000	1238	632	
BESS	2002	1037	568	
BESS	2004	689	461	
PAMELA	2007	390	0	

In this scheme there are two free parameters because we allow negatively-charged particles (electrons, antiprotons) and positively-charged particles (protons, positrons) to be modulated by different potentials

Conventional model VS Kraichnan model: all observables



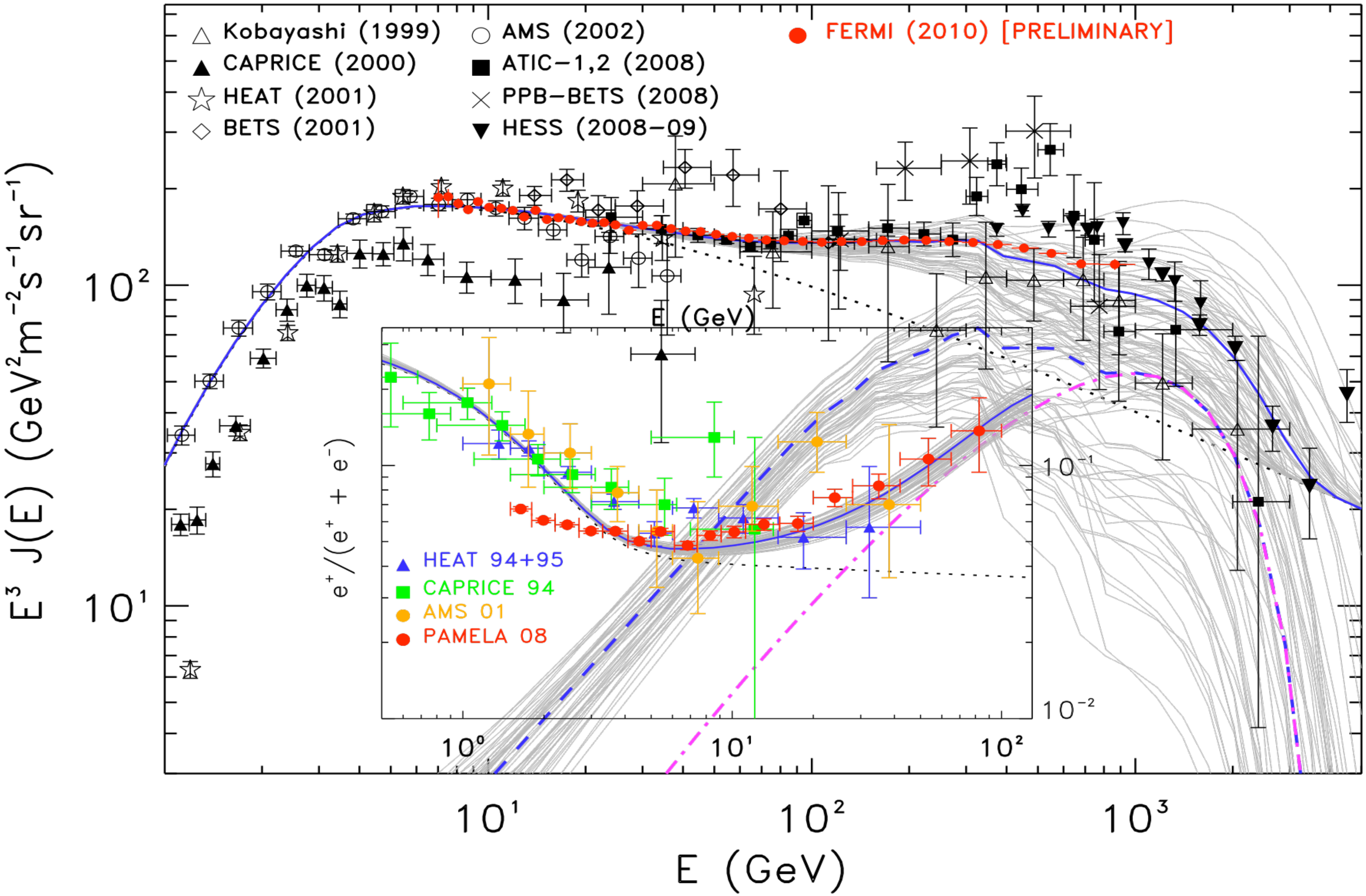
Blue line: new model. Red line: conventional model

Pulsar parameters

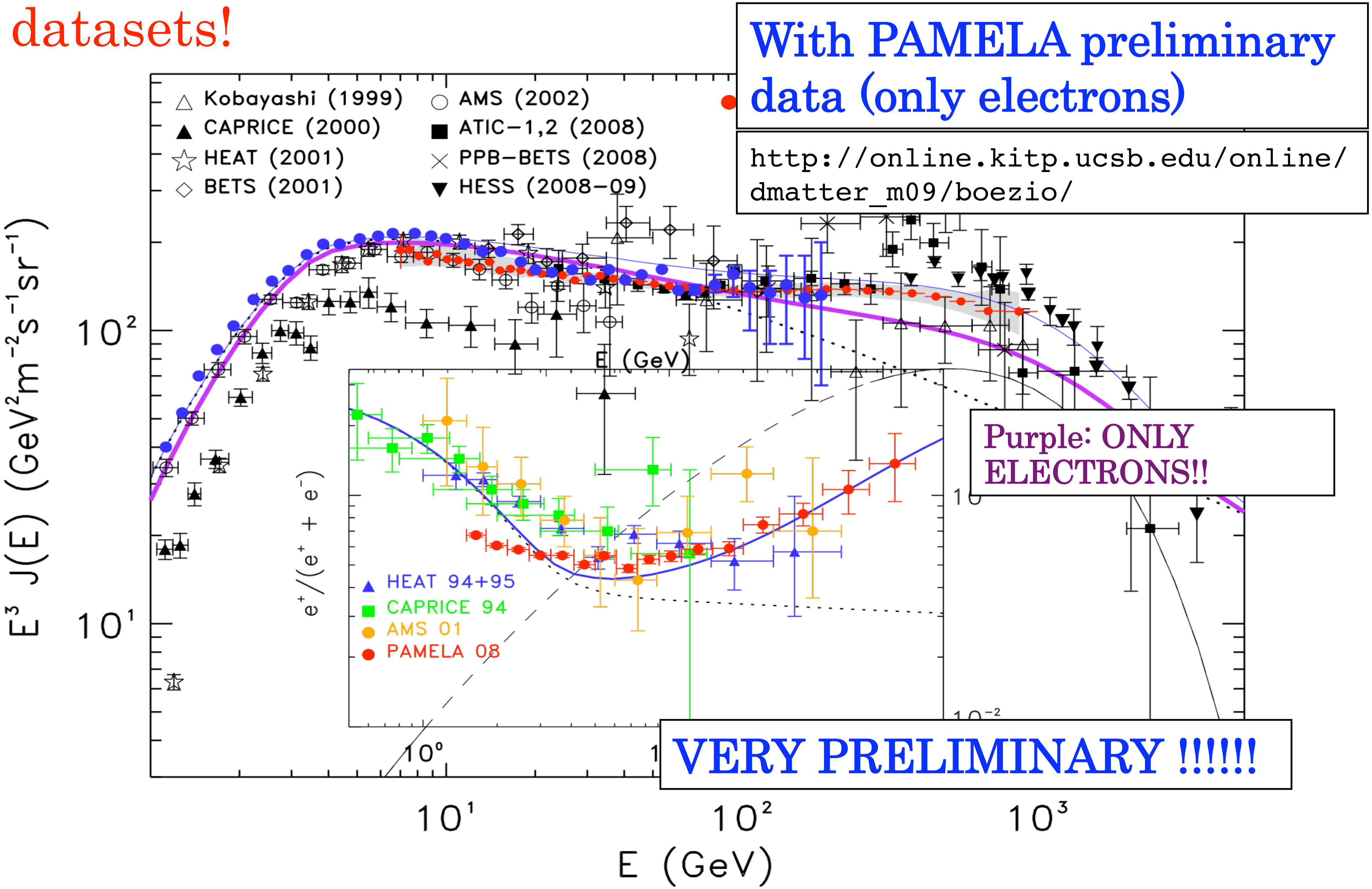
#	NAME		DIST kpc)	AGE (Yr)	EDOT (ergs/s)	
1	J0633+1746	hh92	0.16	3.42e+05	3.2e+34	← Geminga
2	J1856-3754	tm07	0.16	3.76e+06	3.3e+30	
3	B0656+14	mlt+78	0.29	1.11e+05	3.8e+34	← Monogem
4	J0720-3125	hmb+97	0.36	1.9e+06	4.7e+30	
5	B0823+26	cls68	0.36	4.92e+06	4.5e+32	
6	B1133+16	phbc68	0.36	5.04e+06	8.8e+31	
7	B1929+10	lvw68	0.36	3.1e+06	3.9e+33	
8	B2327-20	ll76	0.49	5.62e+06	4.1e+31	
9	J1908+0734	nft95	0.58	4.08e+06	3.4e+33	
10	B0906-17	mlt+78	0.63	9.5e+06	4.1e+32	
11	B2045-16	tv68	0.64	2.84e+06	5.7e+31	
12	J1918+1541	nft95	0.68	2.31e+06	2.0e+33	
13	J0006+1834	cnt96	0.70	5.24e+06	2.5e+32	
14	B0834+06	phbc68	0.72	2.97e+06	1.3e+32	
15	B0450+55	dth78	0.79	2.28e+06	2.4e+33	
16	B0917+63	dtws85	0.79	6.89e+06	3.7e+31	
17	B2151-56	mlt+78	0.86	5.15e+06	6.4e+31	
18	B0203-40	mlt+78	0.88	8.33e+06	1.9e+32	
19	B1845-19	mlt+78	0.95	2.93e+06	1.1e+31	
20	J0636-4549	bjd+06	0.98	9.91e+06	1.6e+31	
21	B0943+10	vazs69	0.98	4.98e+06	1.0e+32	

$$E_{e^\pm} \simeq \eta_{e^\pm} \, \dot{E}_{\rm PSD} \, \frac{T^2}{\tau_0} \, ,$$

Nearby, observed middle aged pulsars are good candidates as extra-sources of electrons and positrons



An extra-component with injection index = 1.5 and an exponential cutoff at 1 TeV gives a good fit of all datasets!



Dark Matter models in Fermi interpretation paper

$$\rho_{\mathrm{DM}}(r) = \rho_{\odot} \left(\frac{r}{R_{\odot}} \right)^{-1.24} \left(\frac{R_{\odot} + R_s}{r + R_s} \right)^{1.76}$$

DM profile, from Via Lactea II N-body simulation (Diemand et al. 2008); The simulation follows the growth of a Milky Way-size system from redshift 104.3 to the present

DM models parameters

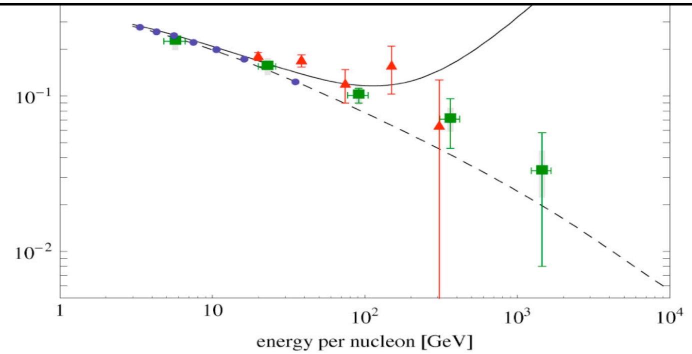
Model	Ann. Final State	Mass (GeV)	$\langle \sigma v \rangle$ (cm^3/s)
e^+e^-	e^+e^-	500	9×10^{-25}
Leptophilic	$33\%(e^+e^-)+33\%(\mu^+\mu^-)+33\%(\tau^+\tau^-)$	900	4.3×10^{-24}

Summary of possible extra-components and their implications

PULSAR SCENARIO → Implies a 1% anisotropy at about 1 TeV in CR electron flux towards the nearest mature pulsars (in particular Monogem). Testable with Fermi-LAT with some years of data taking.

DM scenario → May imply an anisotropy in CR flux towards central region of Galaxy. May imply observable features in gamma-ray map of the Galaxy, different from those produced by pulsars. Testable with Fermi-LAT.

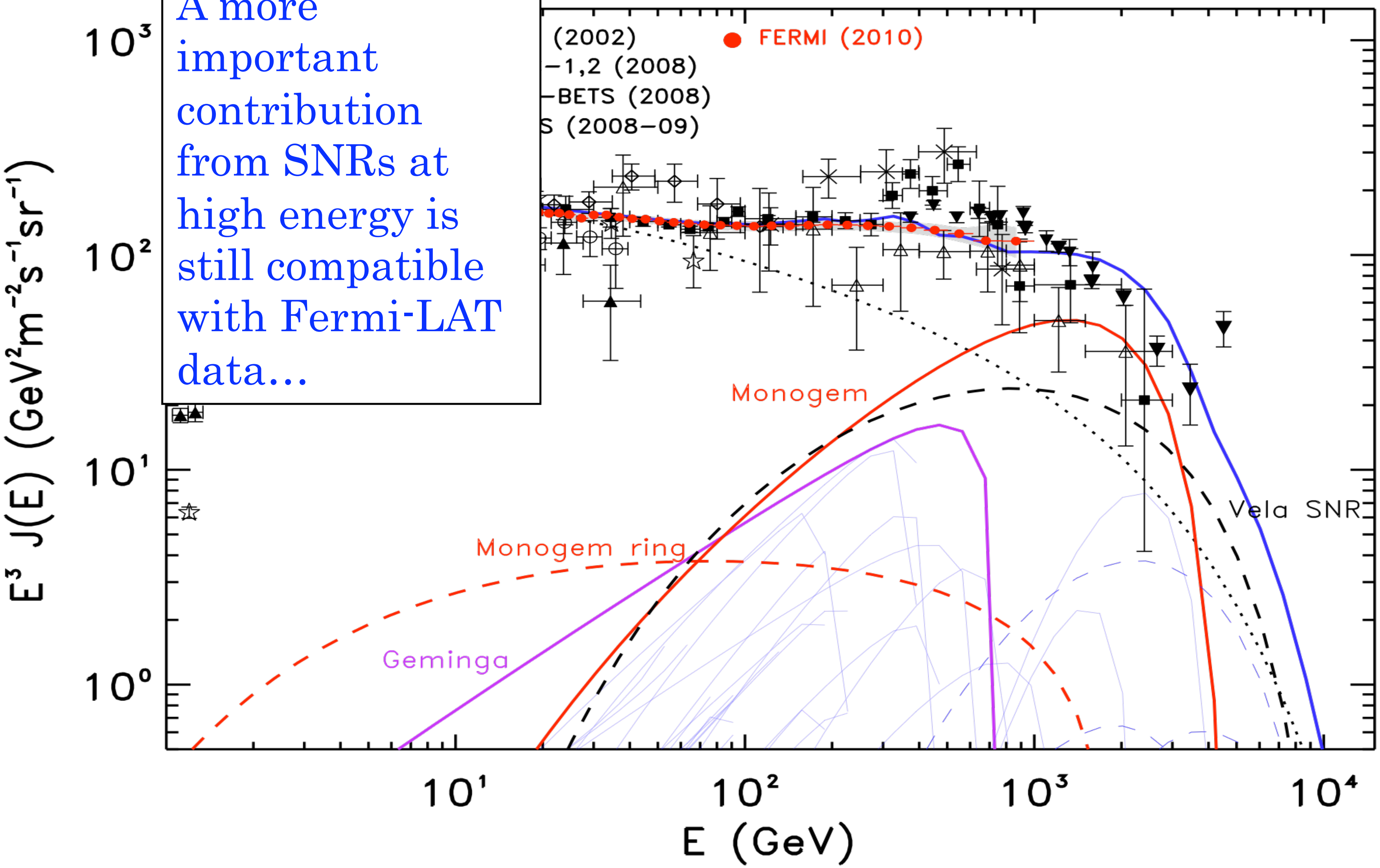
Secondary production in the accelerator → Predicts a boron-to-carbon ratio which starts to increase at high energy [Mertsch and Sarkar 2009]. This feature is compatible with ATIC data but in tension with CREAM data.



NEW DATA ARE NEEDED IN ORDER TO UNDERSTAND WHICH IS THE CORRECT INTERPRETATION!

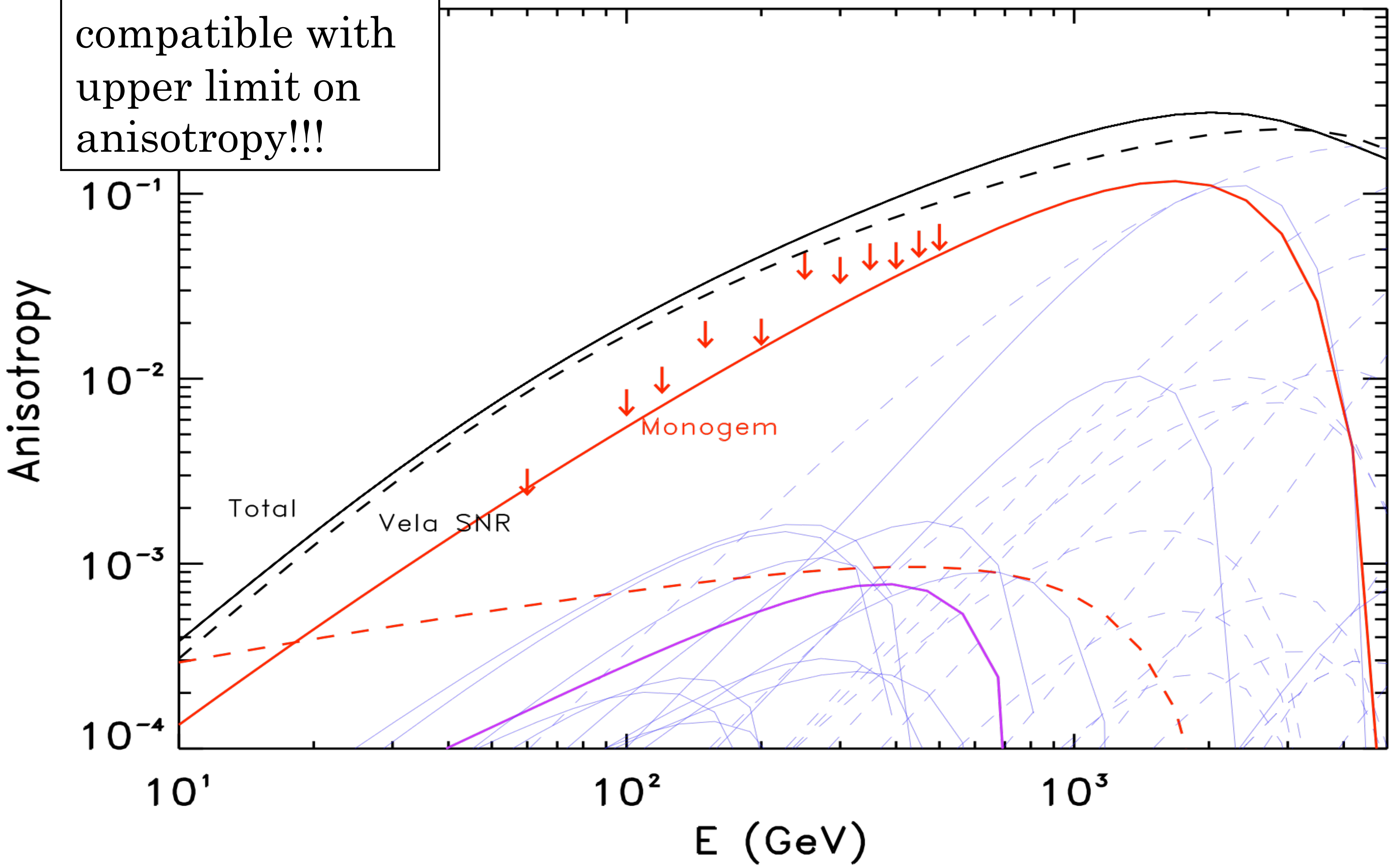
Astrophysical objects that may contribute to the primary extra-component

A more important contribution from SNRs at high energy is still compatible with Fermi-LAT data…



Astrophysical objects that may contribute to the primary extra-component

…but is not compatible with upper limit on anisotropy!!!

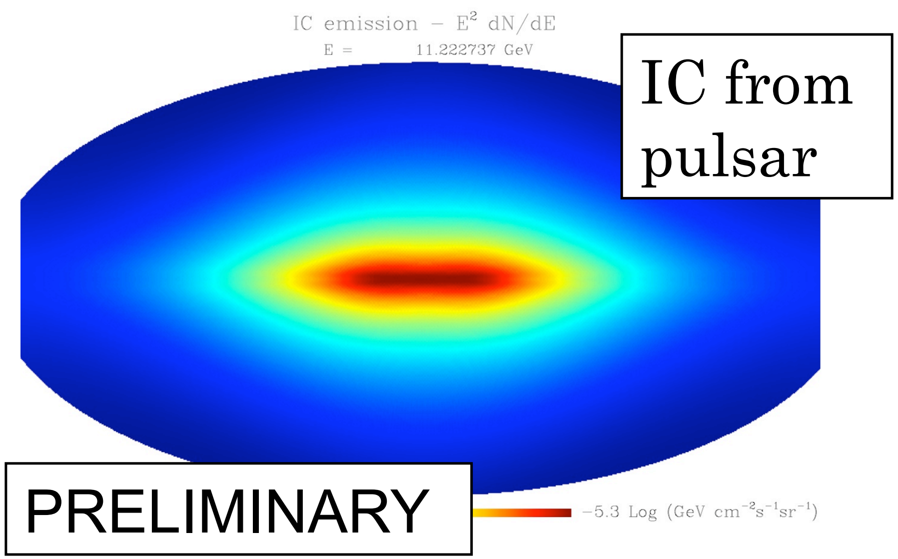


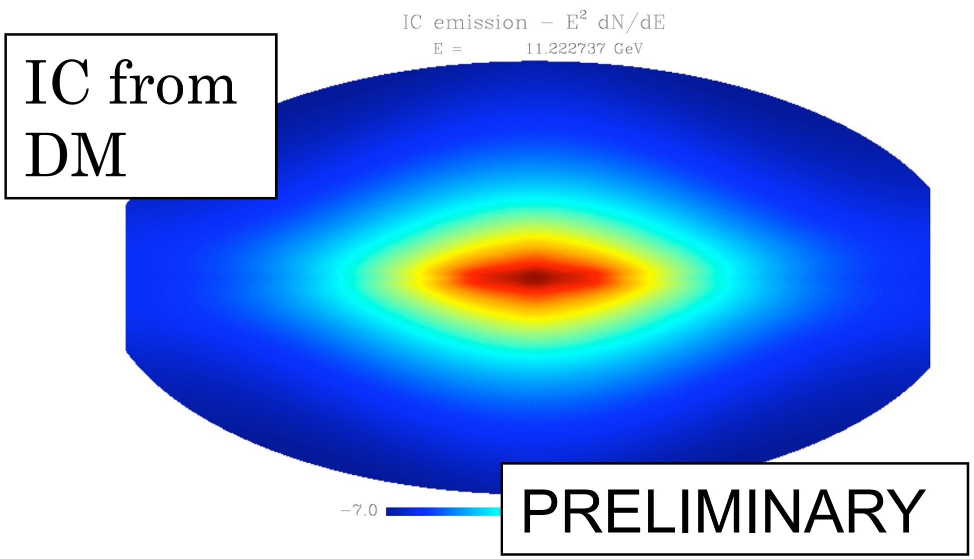
The extra-component may also be originated by annihilation or decay of Dark Matter particles

How do we distinguish between the two possibilities?

1) Study of ANISOTROPIES: pulsar model implies an anisotropy of order of 1 % in the direction of the closest middle-aged pulsar (Monogem)

2) Study of DIFFUSE GAMMA RAY sky. Both the DM extra-component and the pulsar component are expected to produce gamma rays via Inverse Compton. The γ ray map is expected to be different in the two cases





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-10° < b < 10°