Anisotropies in the flux of cosmic ray leptons

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Introduction

CR electrons and positrons detected at Earth at >10 GeV are the results local emission mechanisms, since cooling time is > than diffusion time

Data:

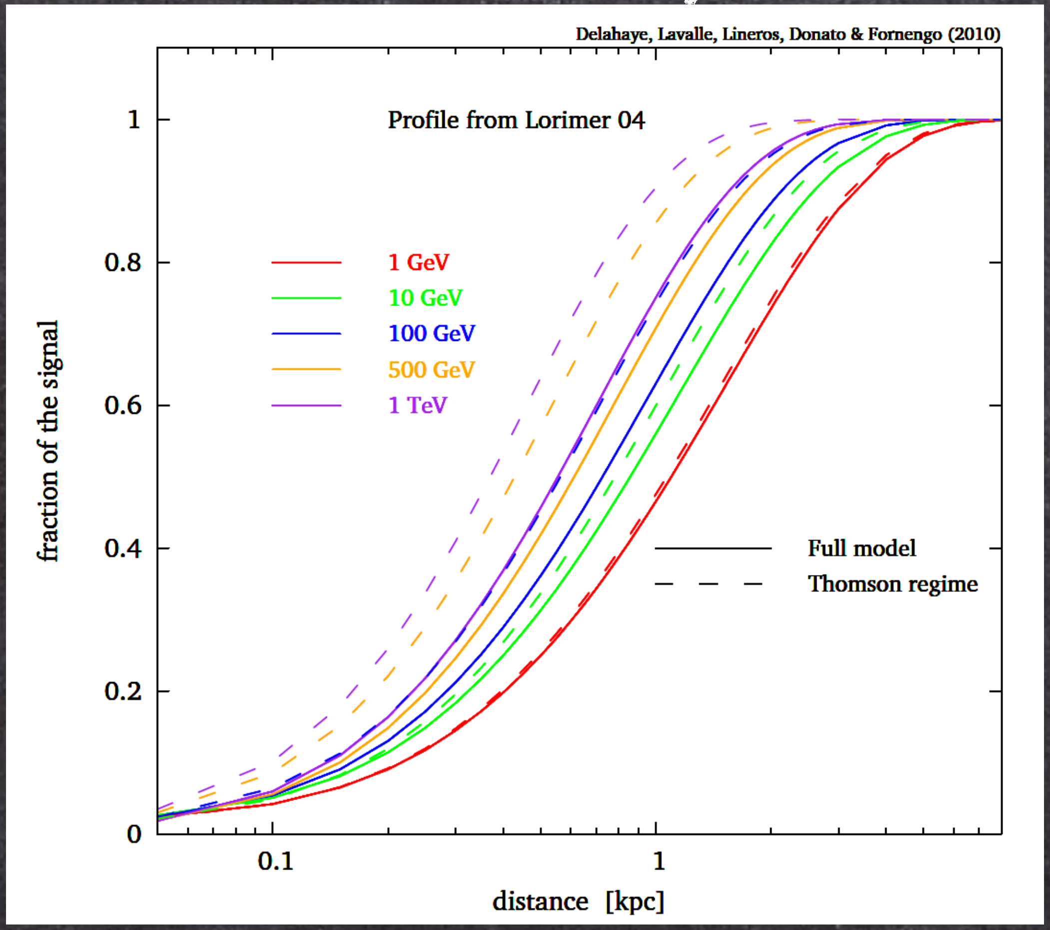
1) CR fluxes for e+, e-, e-+e+
2) radio fluxes from sources
3) upper bounds on dipole anisotropy

Inspection of local sources is crucial to interpret data

Can the dipole anisotropy from CR leptons be an additional (to CR and radio fluxes) tool to understand CR sources?

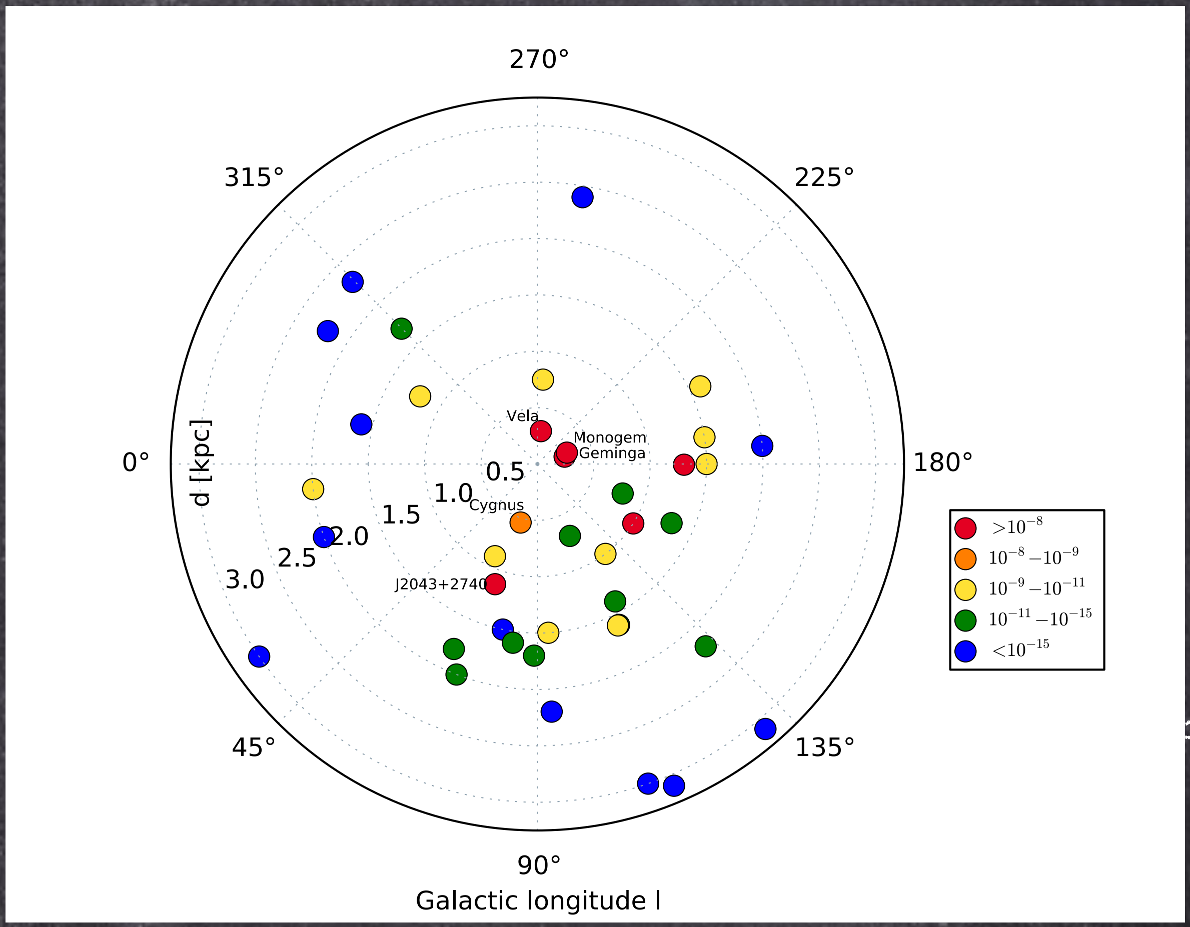
Electron sources are local

Delahaye+ A&A 2010



e-, e+ have strong radiative cooling and arrive at Earth if produced within few kpc around it

Manconi, Di Mauro, FD JCAP 2017

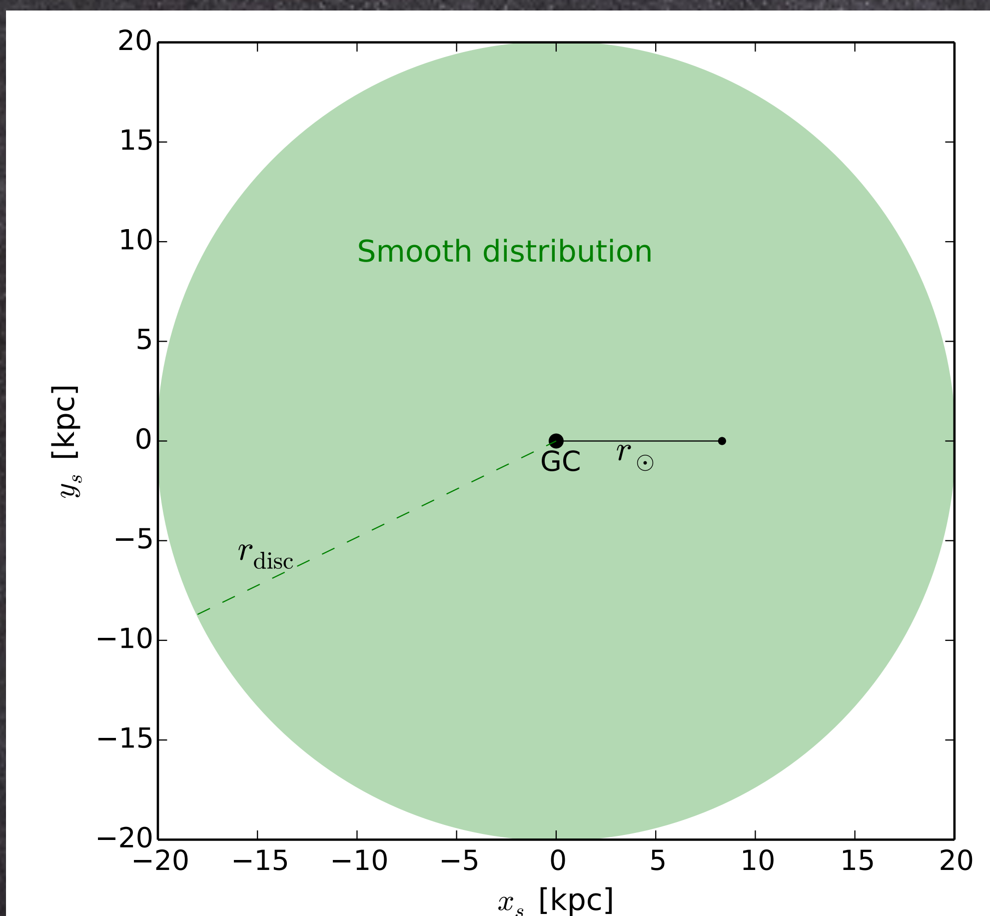


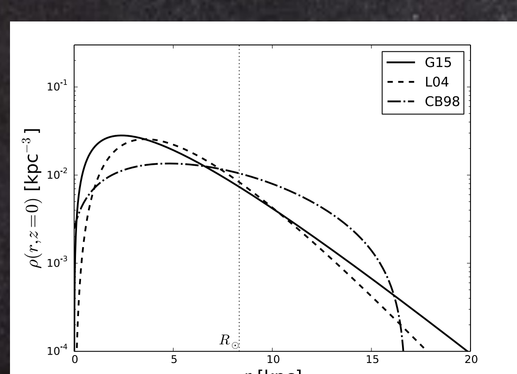
Most powerful sources within 3 kpc from the Sun.

SNRs (e-) and PWN (e+e-)

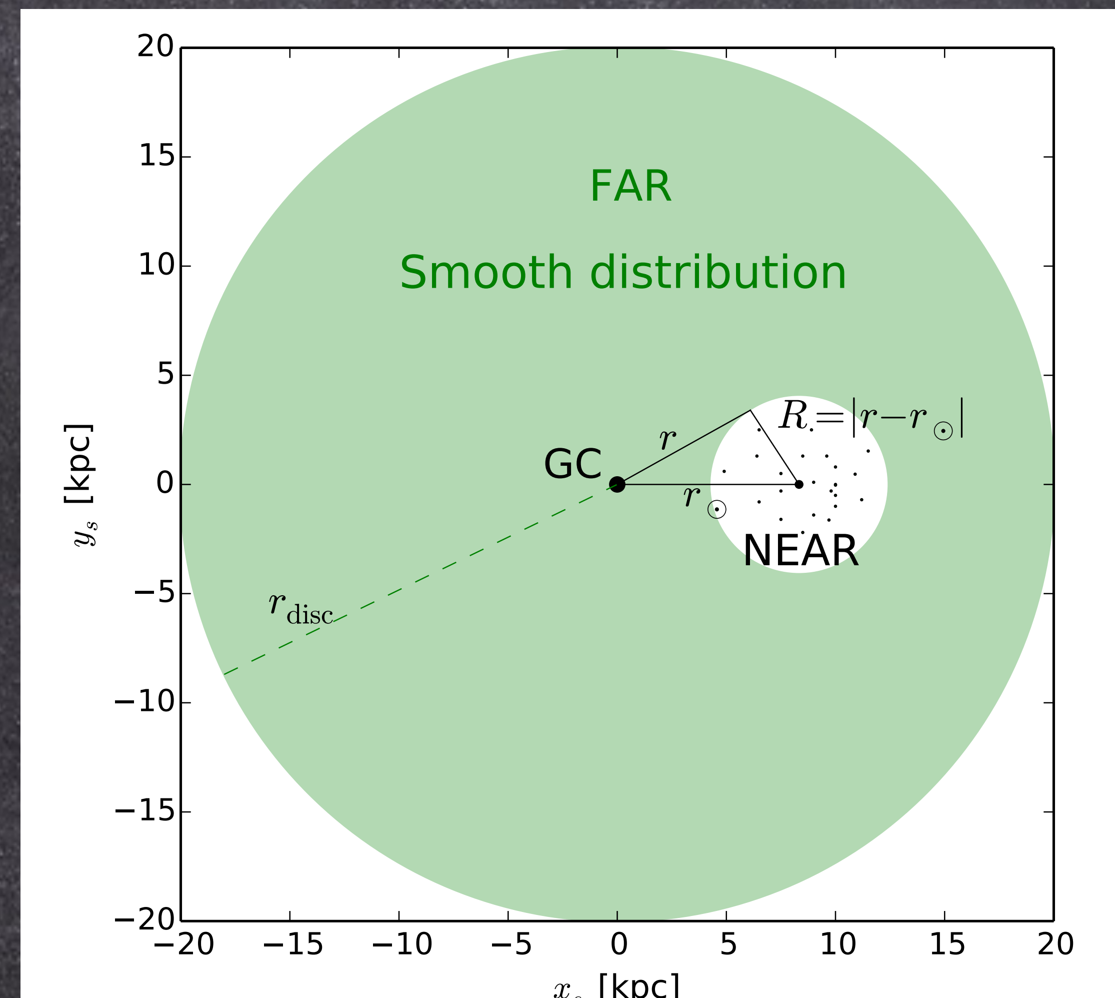
Far and near sources: geometry

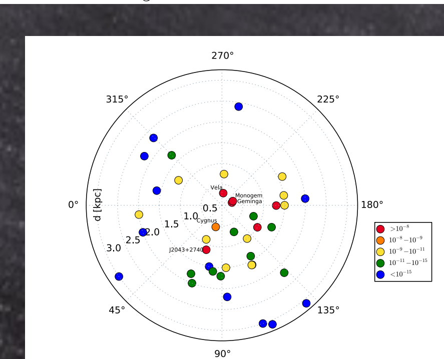
All the Galaxy is filled by a smooth SNR distribution





Smooth SNR distribution out of a ring filled with single sources

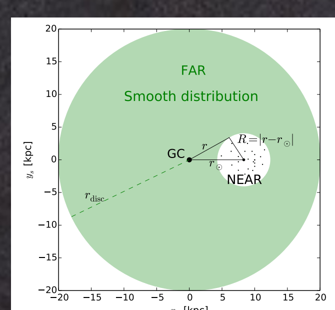


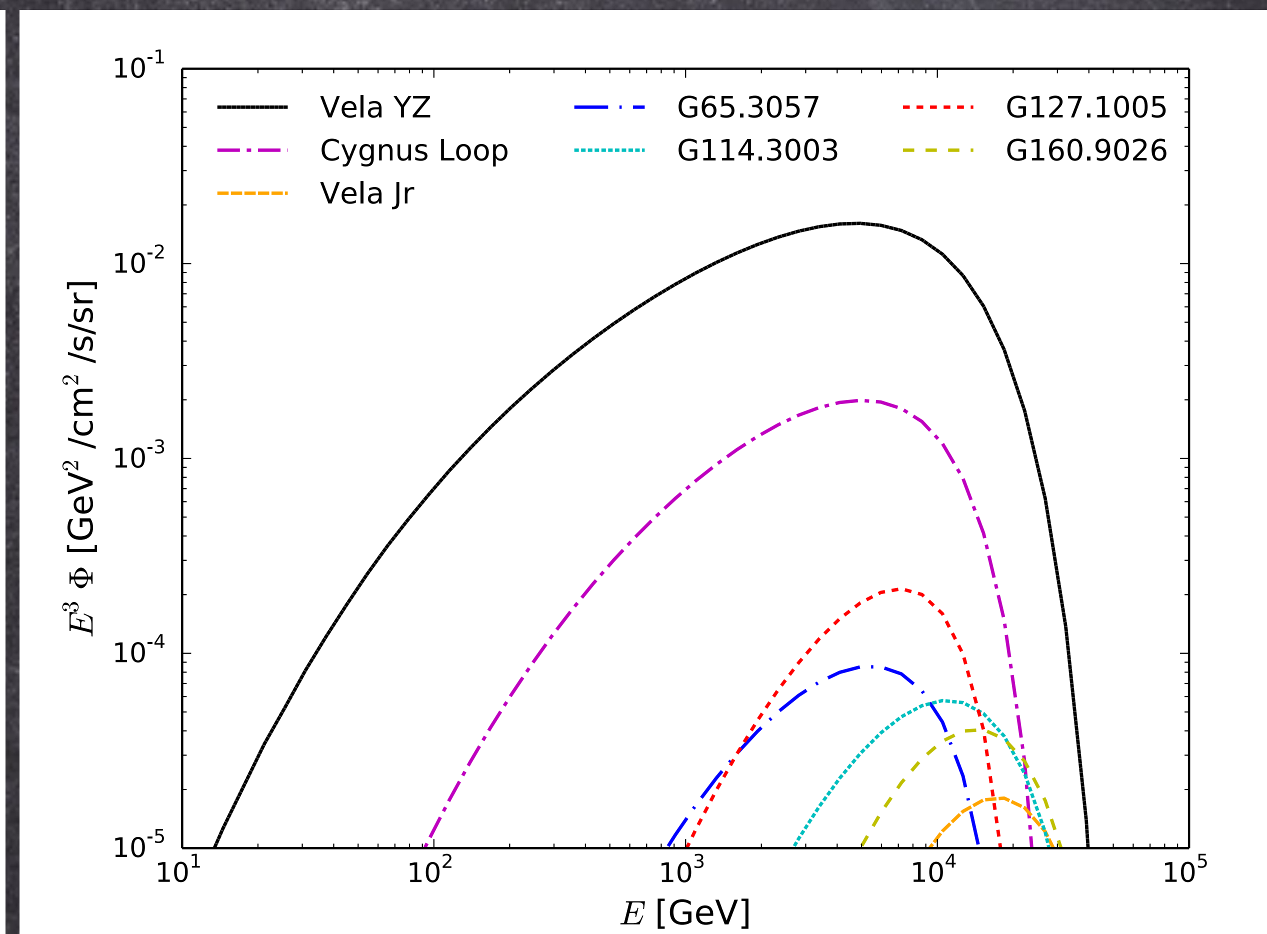


The population of near (<1kpc) SNRs

Selection of sources by catalog parameters

Source	other name	d [kpc]	t_{obs} [kyr]	α_r
G263.9-3.3	Vela YZ	0.295 $\pm$0.075	11.4	0.5
G74.0-8.5	Cygnus Loop	$0.54^{+0.10}_{-0.08}$	20	0.4
G266.2-1.2	Vela Jr	0.75	[2.7,4.3]	0.3
G65.3+5.7	-	1.0$\pm$0.4	26 $\pm$ 1	0.58
G114.4+03	-	0.7	7.7	-0.49
G127.1+05	R5	1.0 $\pm$0.1	25 $\pm$ 5	0.43
G160.9-2.6	HB9	0.8 $\pm$0.4	3	0.59





Vela YX and Cygnus Loop have highest flux

CR fluxes at Earth

e+e- are treated in a diffusion model with full (IC, sync.) and isotropic diffusion

$$\frac{\partial \psi}{\partial t} - \nabla \cdot \{K(E)\nabla\psi\} + \frac{\partial}{\partial E}\left\{\frac{dE}{dt}\psi\right\} = Q(E, \mathbf{x}, t)$$

Steady state for: secondary e+ and e-; the smooth SNR distribution (Green 2015)

Burst-like injection (Malyshev+ PRD 2016) for single sources (SNR, PWN):

$$Q(E, \mathbf{x}, t) = Q(E)\delta(t)\delta(\mathbf{x})$$

Inside R_{cut} sources are taken from catalog: Green catalog for SNR, ATNF catalog for PWNe.

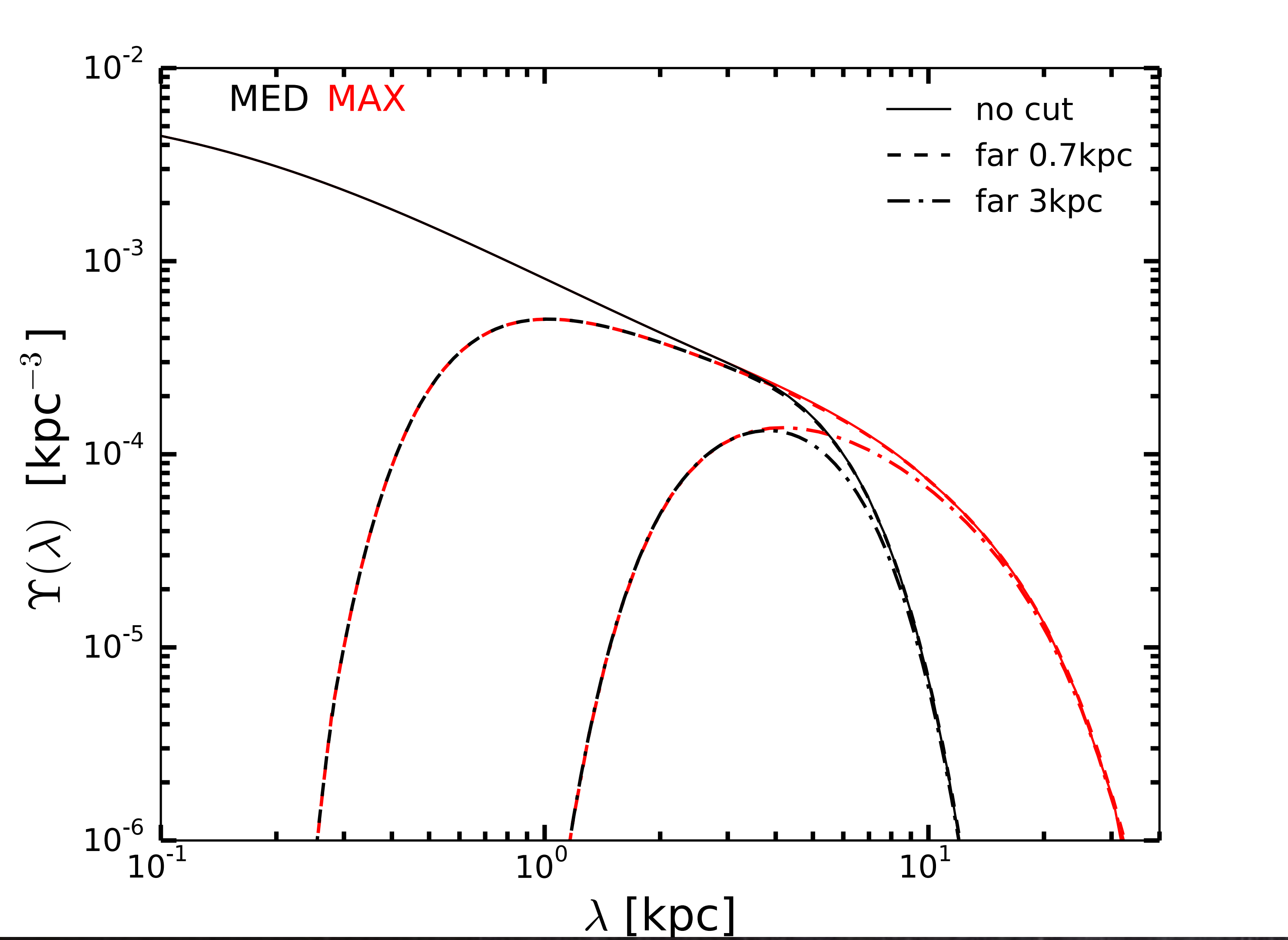
The energy spectrum: $$Q(E) = Q_0 \left(\frac{E}{E_0}\right)^{-\gamma} \exp\left(-\frac{E}{E_c}\right)$$

Treating the far, smooth sources

The halo function describes the probability for an e- to reach the Earth from the source position:

$$\Upsilon(\lambda) = \int d^3\mathbf{x_s}\rho(\mathbf{x_s})\mathcal{G}_\lambda(\lambda, x_\odot \leftarrow \mathbf{x_s})$$

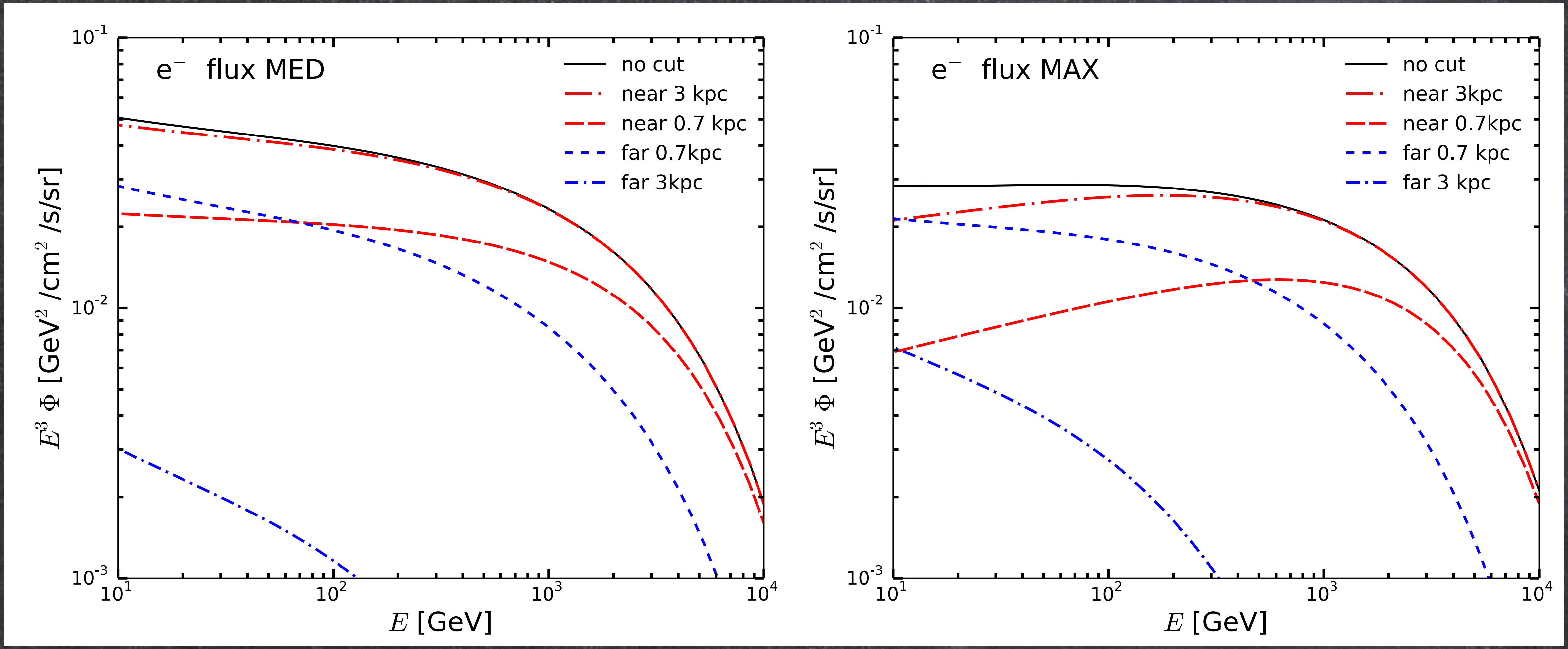
Diffusive length: $\lambda^2 = \lambda^2(E, E_s) \equiv 4\int_E^{E_s} dE' \frac{K(E')}{b(E')}$



Halo function drops to zero for:

- λ~ L (diffusive halo height)
- λ close to R_{cut}, below which e- injection is depleted

Far and near sources smooth contribution



Most of the electrons from a (Green 2015) smooth SNR distribution come from very few kpc from the Earth. Less than 10% of e- come from R>3kpc, even considering a large size L for the diffusive halo.

We can consider separately a smooth SNR distribution out of a R_{cut}, and single (catalog) SNR and PWN inside that circle.

Anisotropy in a diffusion model

Anisotropy should be computed by development on spherical harmonics.
For one or few sources,
we can expect only the dipole term to have some relevance (if any).
In diffusive propagation regime (Ginzburg & Syrovatskii 1964):

$$\Delta = \frac{3K}{c} \left| \frac{\nabla \psi}{\psi} \right|$$

For example, for a source at d_s:

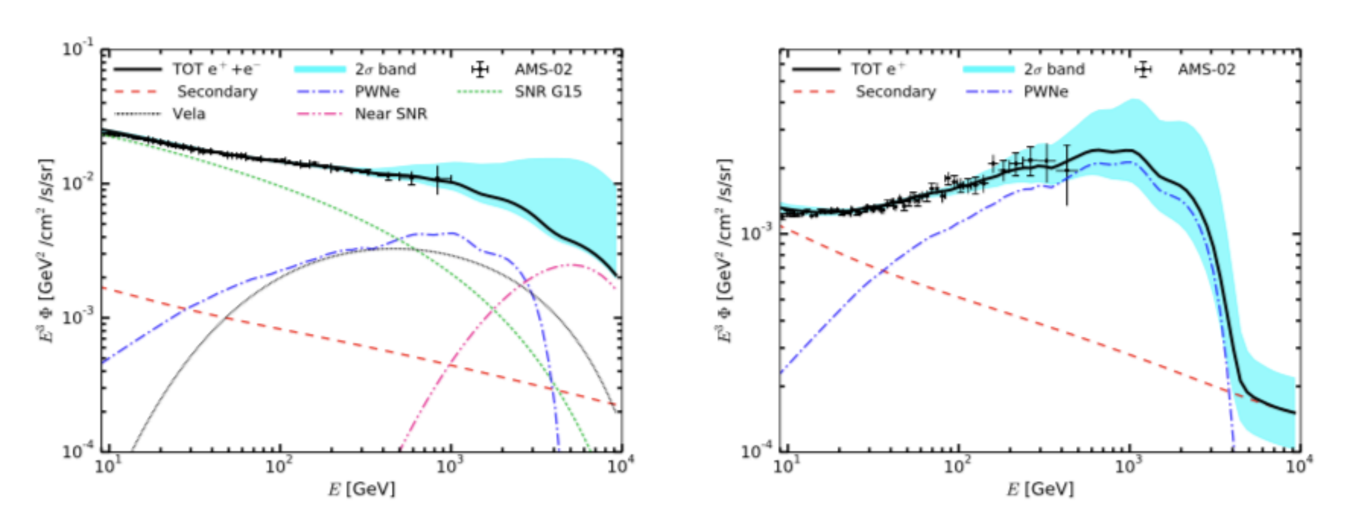
$$\Delta(E)_{e^+ + e^-} = \frac{3K(E)}{c} \frac{2 d_s}{\lambda^2(E, E_s)} \frac{\psi^s_{e^+ + e^-}(E)}{\psi^{\rm tot}_{e^+ + e^-}(E)}$$

More generally, for a collection of sources (Shen & Mao, ApJL 1971):

$$\Delta(n_{\rm max}, E) = \frac{1}{\psi^{\rm tot}(E)} \cdot \sum_i \frac{\mathbf{r}_i \cdot \mathbf{n}_{\rm max}}{||\mathbf{r}_i||} \cdot \psi_i(E)\, \Delta_i(E)$$

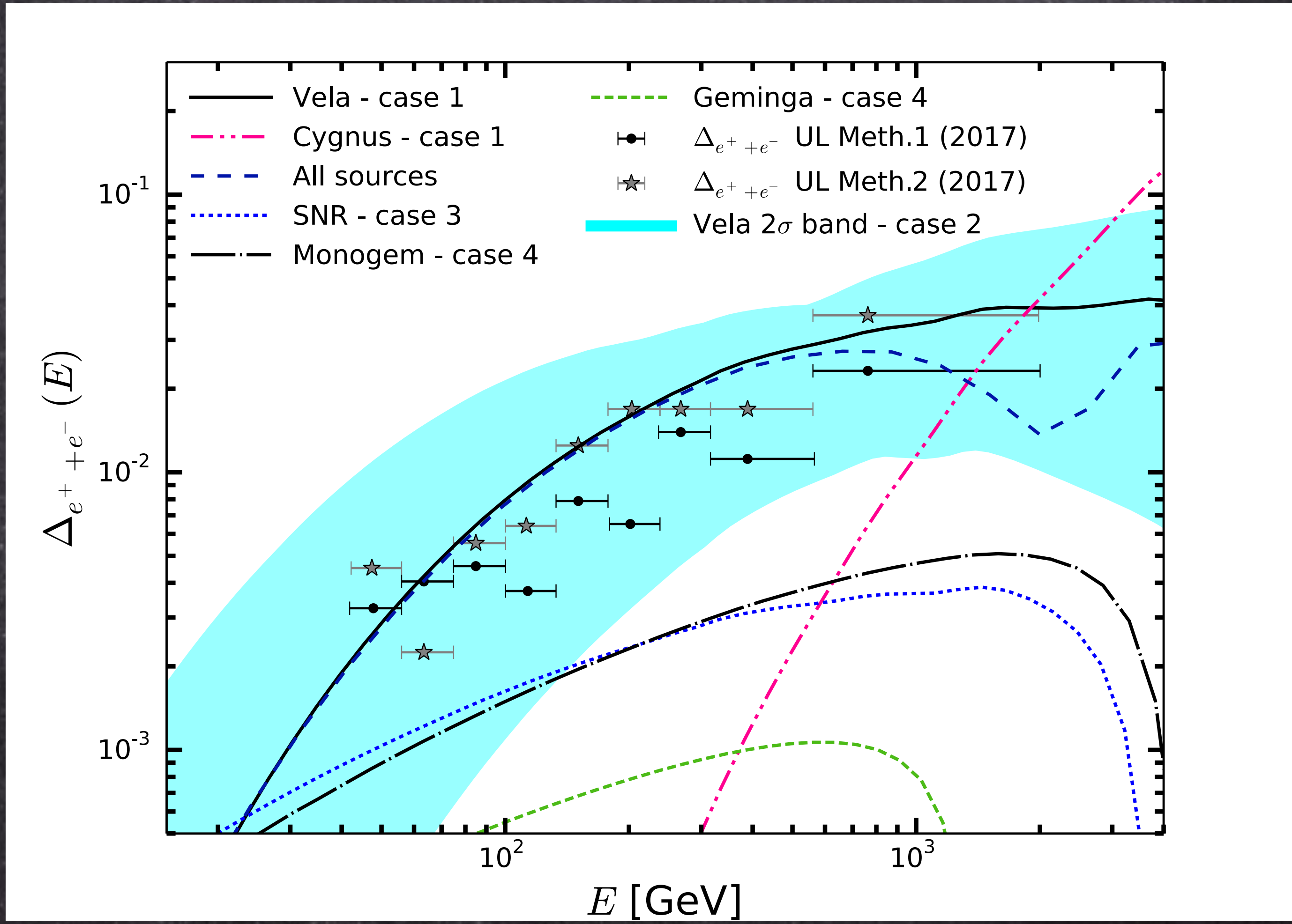
Dipole anisotropy in e+e-

Δ is derived after a fit to AMS-02 e+ AND e−+e+:
e+: sec & PWN
e+e−: sec (e+e−), PWN (e+e−), far SNR (e−), near cat. SNR (e−)



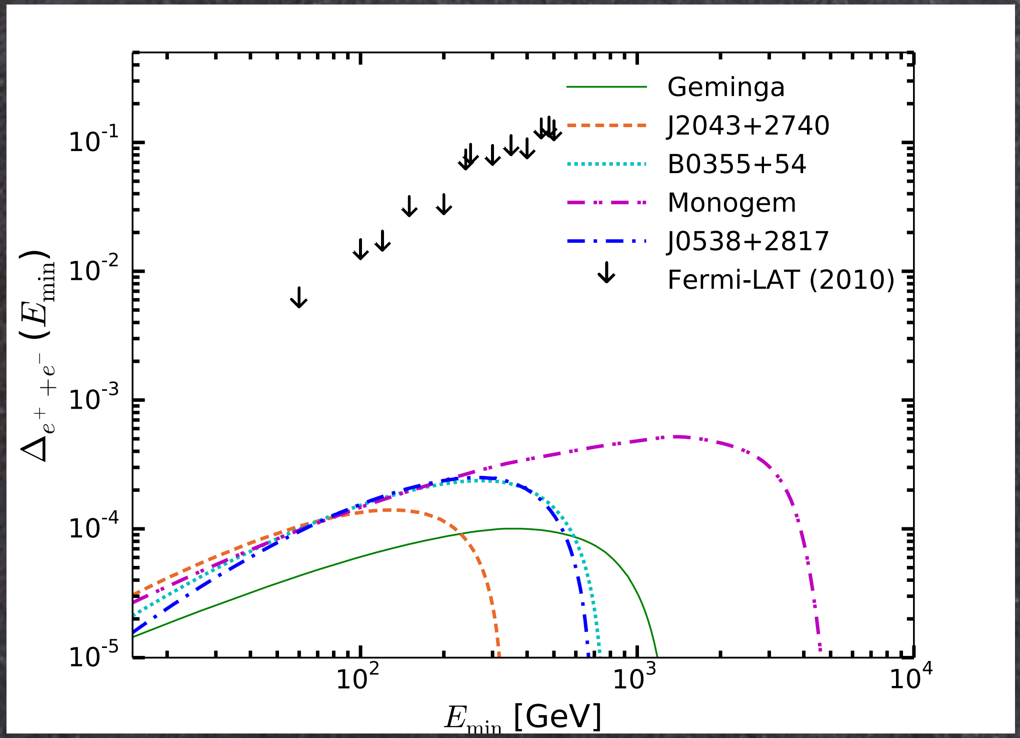
Case 1: Vela SNR is left free to fill the high energy flux (with uncertainty band).
Δ is at the level of present ULs, and is not compatible with zero.

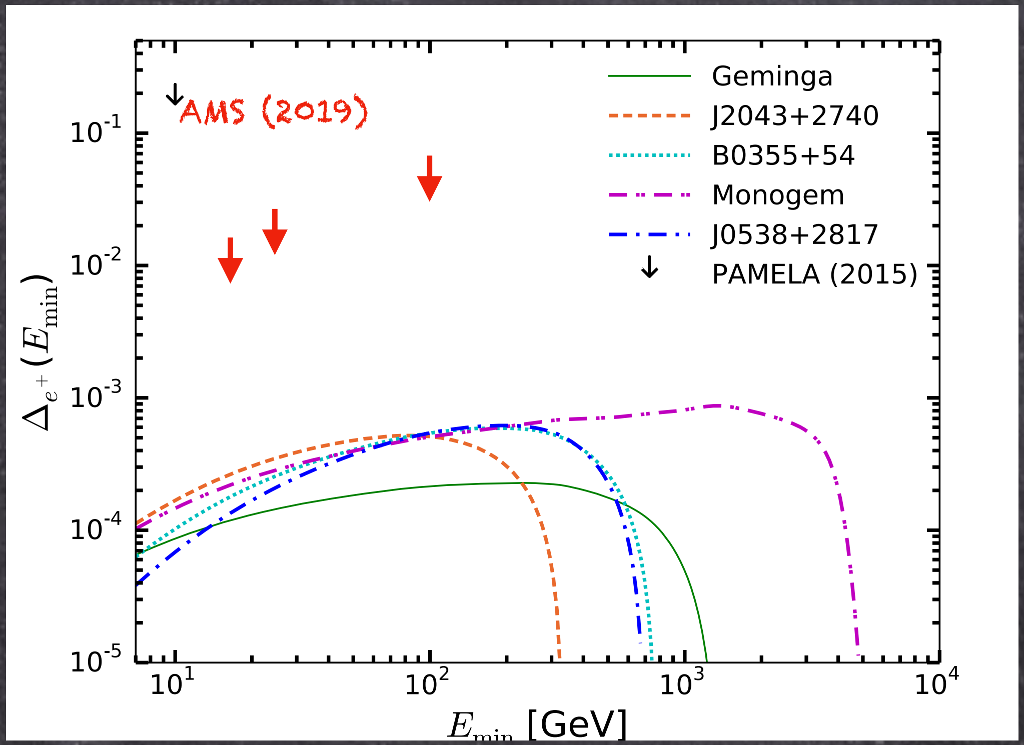
Case 4: Monogem OR Geminga PWNe are let as only PWN within 0.7 kpc



The anisotropy from nearby PWNe

We maximize the contribution of PWNe by setting R_{cut}=0 kpc (SNRs contribute only as a smooth population) to fit AMS-02 data





All the nearest PWNe have an extremely small dipole anisotropy, not testable by present or forthcoming experiments.
Main reason is the bound from e+ AMS-02 flux

Di Bernardo+ AP 2011, Grasso+ 2009,

A multi-wavelength, multi-messenger analysis

S. Manconi, M. Di Mauro, FD JCAP 2017, JCAP 2019

We build a model for the production and propagation of e- and e+ in the Galaxy and test it against 3 observables:

1. Radio brightness data from Vela YZ and Cygnus Loop SNRs at all frequencies.
   The radio emission is all synchrotron from e- accelerated by the source.

2. e+e- flux. Data from 5 experiments, e+ flux from AMS-02
   Contributors: Far and near SNRs, near SNRs and PWNe, secondaries for e+e-.
   The e+ flux constrains the PWN emission.
   e+e- data taken with their uncertainty on the energy scale.

3. e+e- dipole anisotropy upper bounds from Fermi-LAT
   Test on the power of this observable on the closest SNRs.

Injection of e+e- from SNR into the ISM

Burst like model: all the e- are injected at $t=T_{SNR}$ (T_{Vela} = 11.3 kyr, T_{Cygnus} = 20 kyr)

$$Q(E) = Q_0 \left(\frac{E}{E_0}\right)^{-\gamma} \exp\left(-\frac{E}{E_c}\right)$$

$$E_{\rm tot} = \int_{E_1}^{\infty} dE\, E\, Q(E)$$

Evolutionary model (Ohira+ MNRAS 2012): of the SNR radius and velocity.
The maximum E of accelerated e- is limited by SNR age, cooling by synchrotron emission or escape (Bohm-like).

$$E_{\rm m,esc}(t) = E_{\rm knee} \left(\frac{T}{t_{\rm Sedov}}\right)^{-\alpha}$$

$E_{m,esc,Vela}$ = 88 GeV

$E_{m,esc,Cygnus}$ = 17 GeV

below which e- are still trapped in the SNR:

$$Q_{\rm trap}(E,T) = Q_{0,\rm trap}(T) \left(\frac{E}{E_0}\right)^{-\gamma} \exp\left(-\frac{E}{E_c}\right)$$

while the runaway e- follow:

$$Q_{\rm esc}(E) = A \left(\frac{E}{E_0}\right)^{-(\gamma+\beta/\alpha)} \exp\left(-\frac{E}{E_c}\right)$$

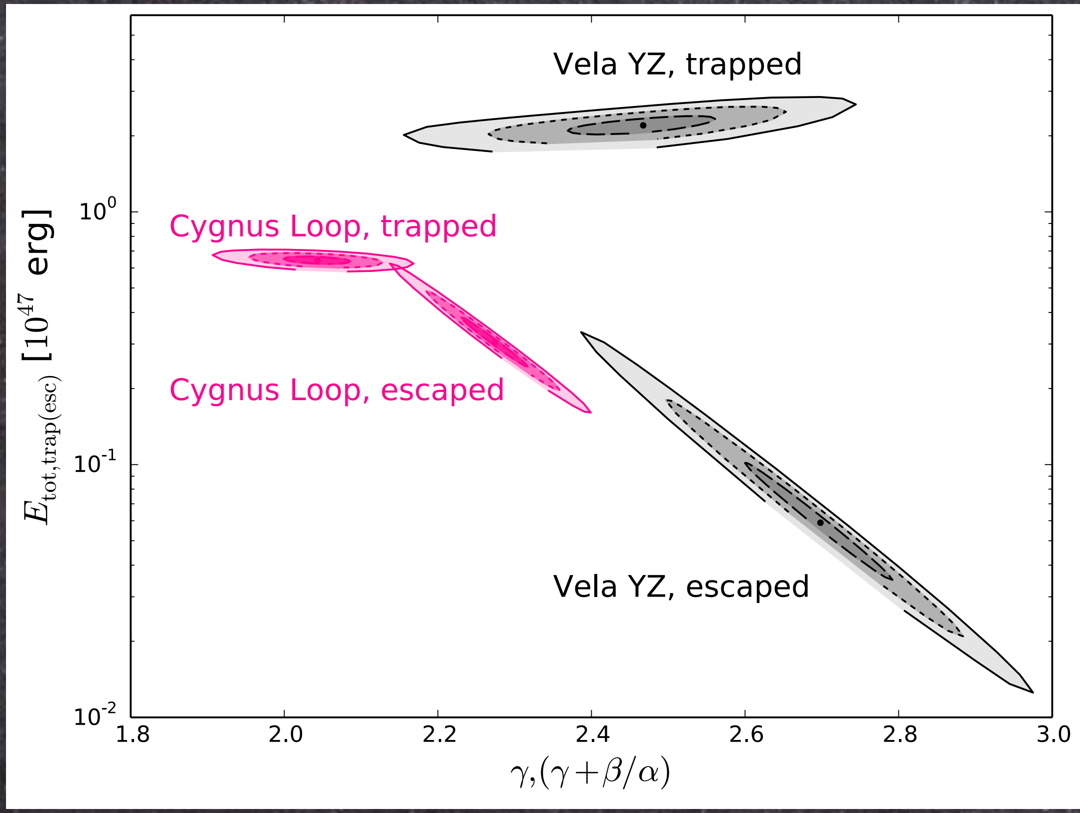
Ohira+MNRAS 2012

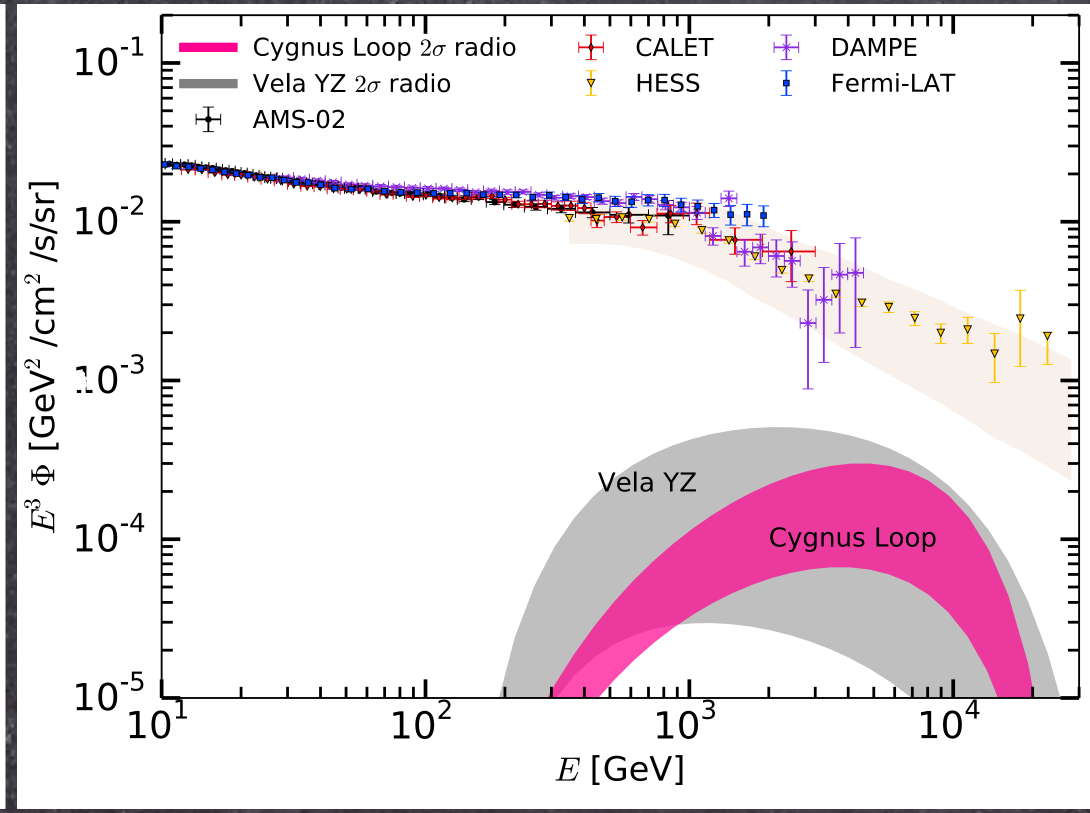
I - Bounds from radio emission

Hyp.: Radio flux is due to synchrotron emission from accelerated e- in the SNR

$$Q_{0,\mathrm{SNR}} = 1.2 \cdot 10^{47}\mathrm{GeV}^{-1}(0.79)^{\gamma}\frac{B_r^{\nu}(\nu)}{\mathrm{Jy}}\left[\frac{d}{\mathrm{kpc}}\right]^2\left[\frac{\nu}{\mathrm{GHz}}\right]^{\frac{\gamma-1}{2}}\left[\frac{B}{100\mu\mathrm{G}}\right]^{-\frac{\gamma+1}{2}}$$

Evolutionary model





We fit all the available radio data fixing B_{Vela} =36 μG and C_{ygnus} = 60 μG.

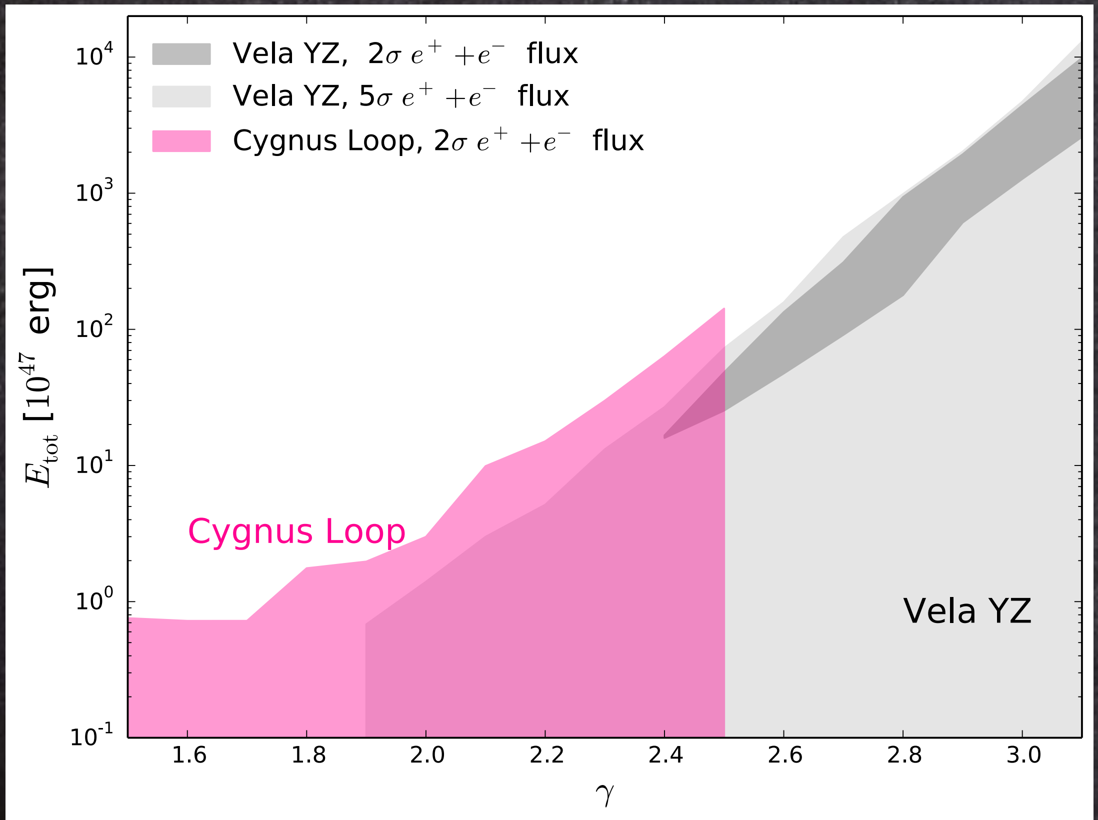
Vela has more energetic trapped e-, and only E>88 GeV have escaped (17 GeV for Cygnus).

The flux of electrons as constrained by radio data contribute few % to the (e+e-) data

II - Bounds from e+e- flux

Hyp: e+e- data are explained by:

- emission from smooth far SNR (e-)
- emission from catalog near SNR (e-)
- secondary production from spallation of CRs on the ISM (asymmetric e+e-)
- emission from ATNF catalog PWN (symmetric e+e-)



Fit to data:

- e+e- CALET, HESS, AMS-02, Fermi-LAT, DAMPE
- e+ AMS-02

At 2sigma, Vela parameters selected by a fit to flux data do not overlap radio fit.
Full agreement at 2 sigma is reached for a fit t DAMPE data alone, or to AMS-02, HESS and CALET.

p.s.: Galactic propagation treated and in Manconi, Di Mauro, FD JCAP 2017

III - Bounds from dipole anisotropy

Data from e+e- dipole anisotropy are upper bounds vs E - Fermi-LAT (Abdollahi+ PRL 2017)

$$\Delta(E)_{e^++e^-} = \frac{3K(E)}{c}\frac{2d}{\lambda^2(E,E_s)}\frac{\psi^s_{e^++e^-}(E)}{\psi^{tot}_{e^++e^-}(E)}$$

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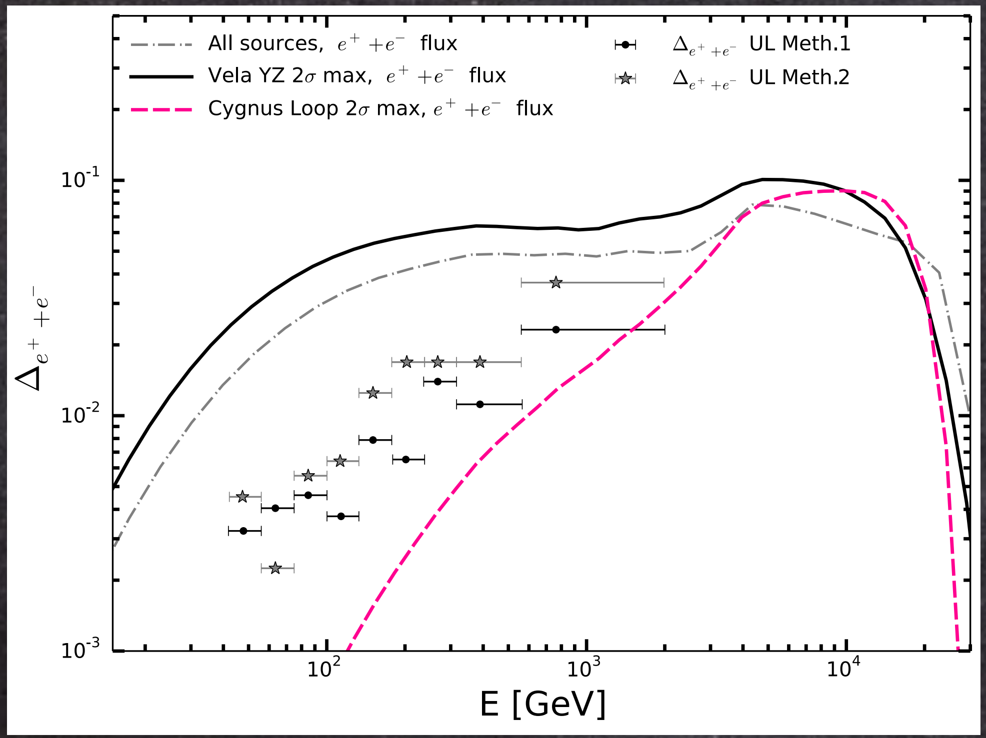
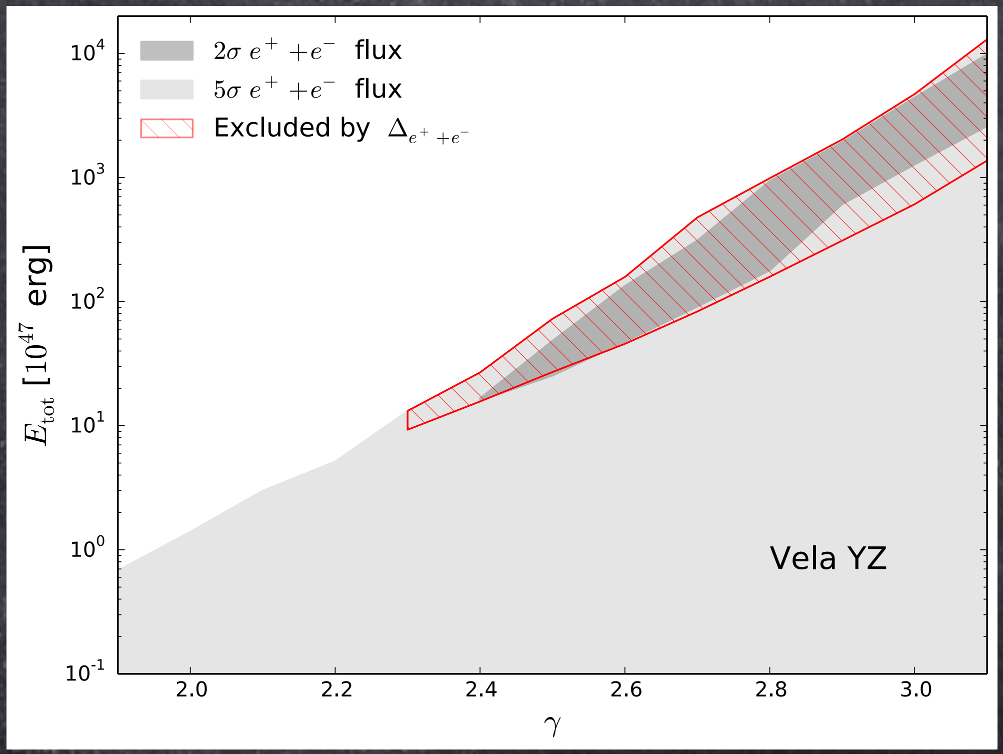


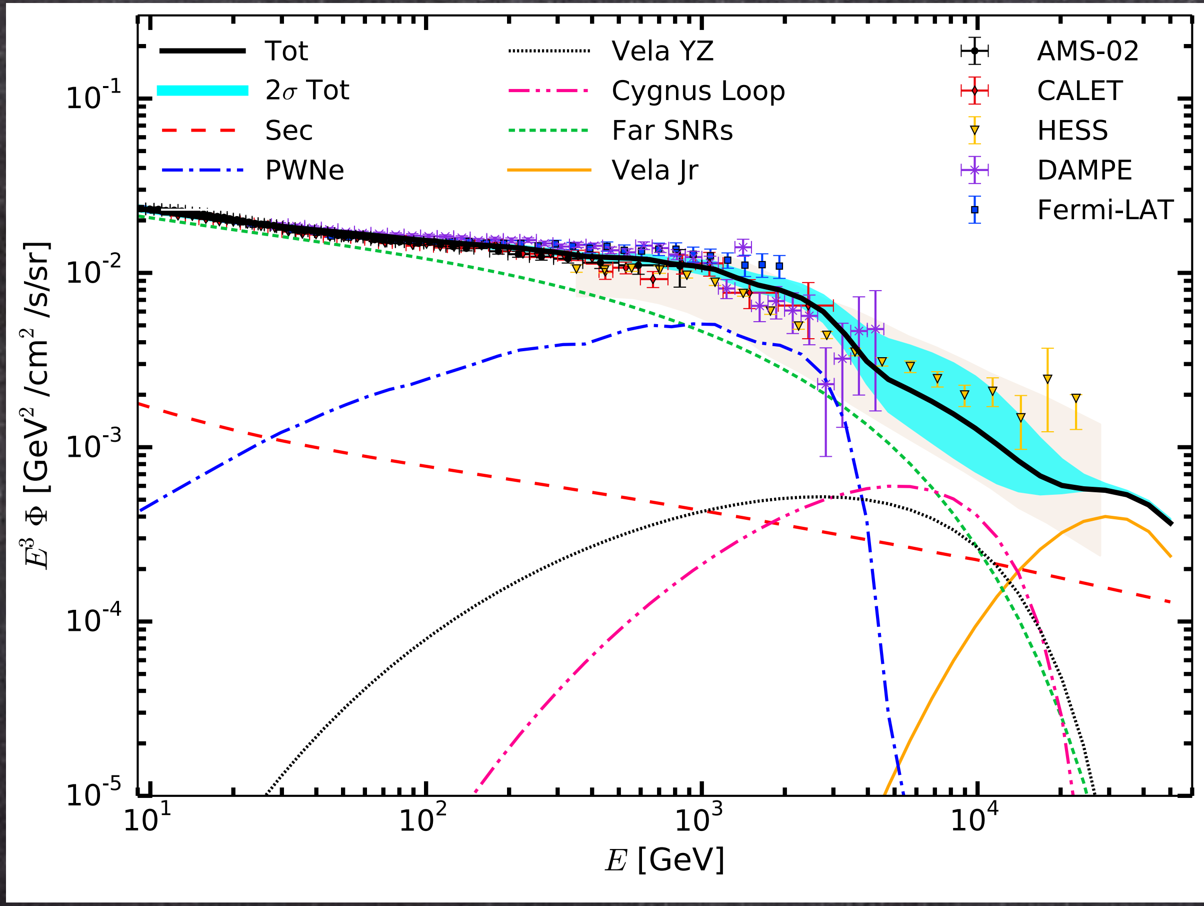
Maximal anisotropy from e+e- flux selected configurations

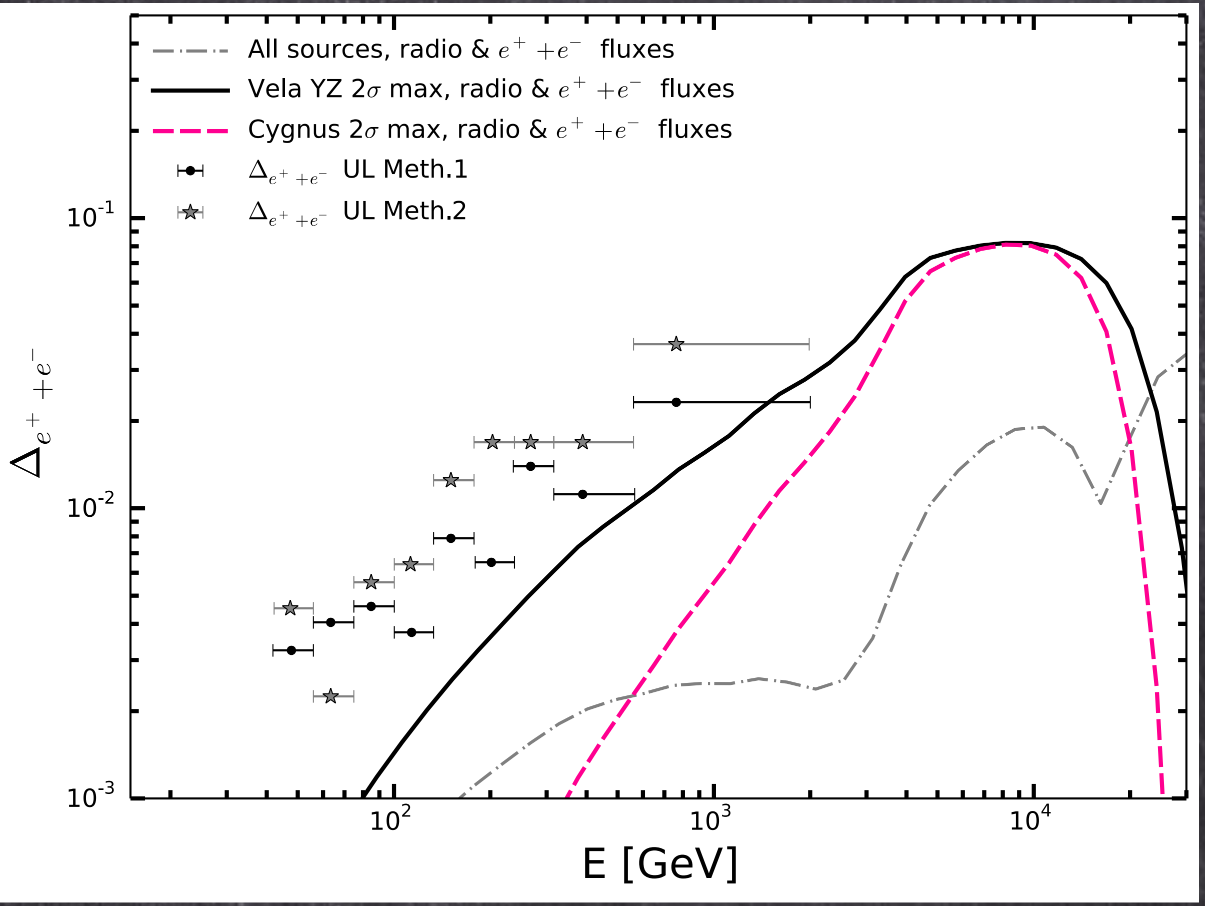


Anisotropy excludes configurations selected by e+e- flux

A multi-wavelength / multi-messenger analysis

We now fit the parameters selected by radio and e+e- flux data and check against dipole anisotropy data

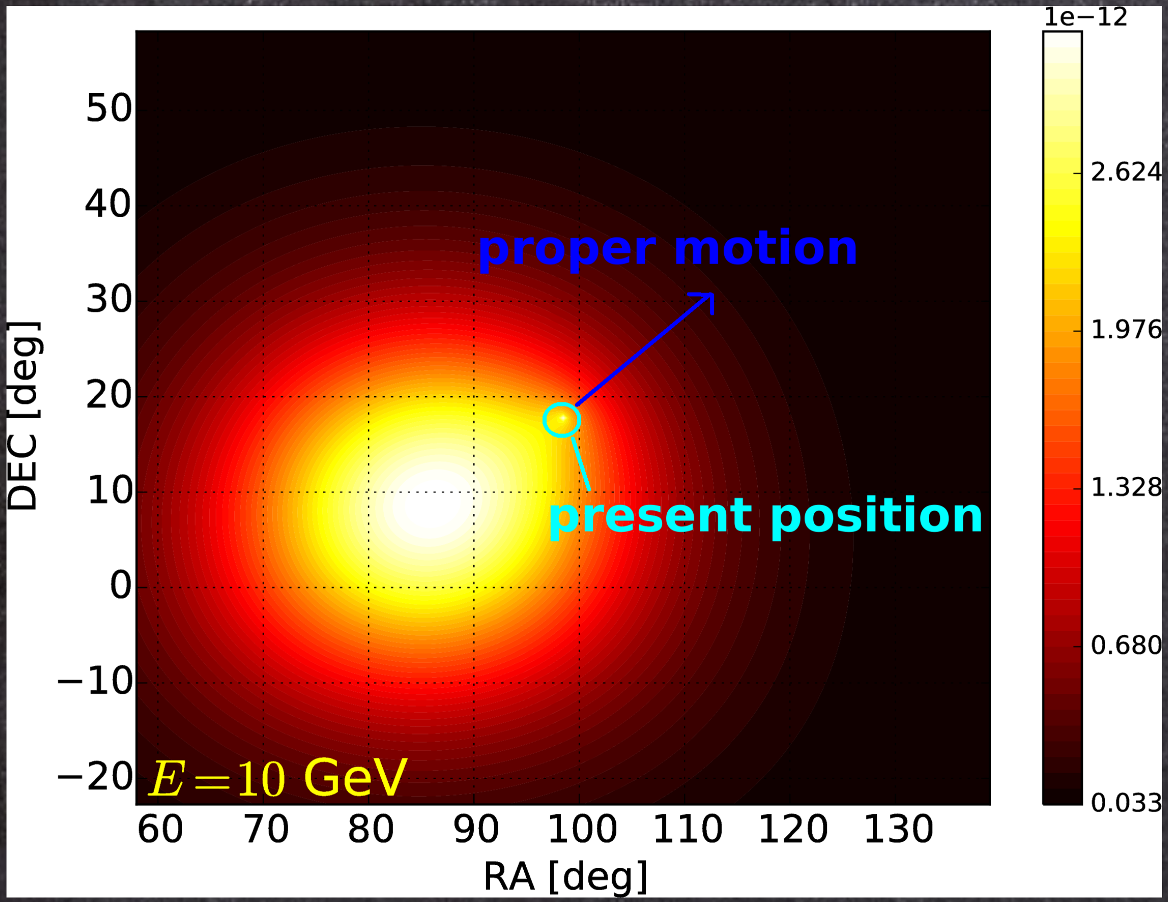


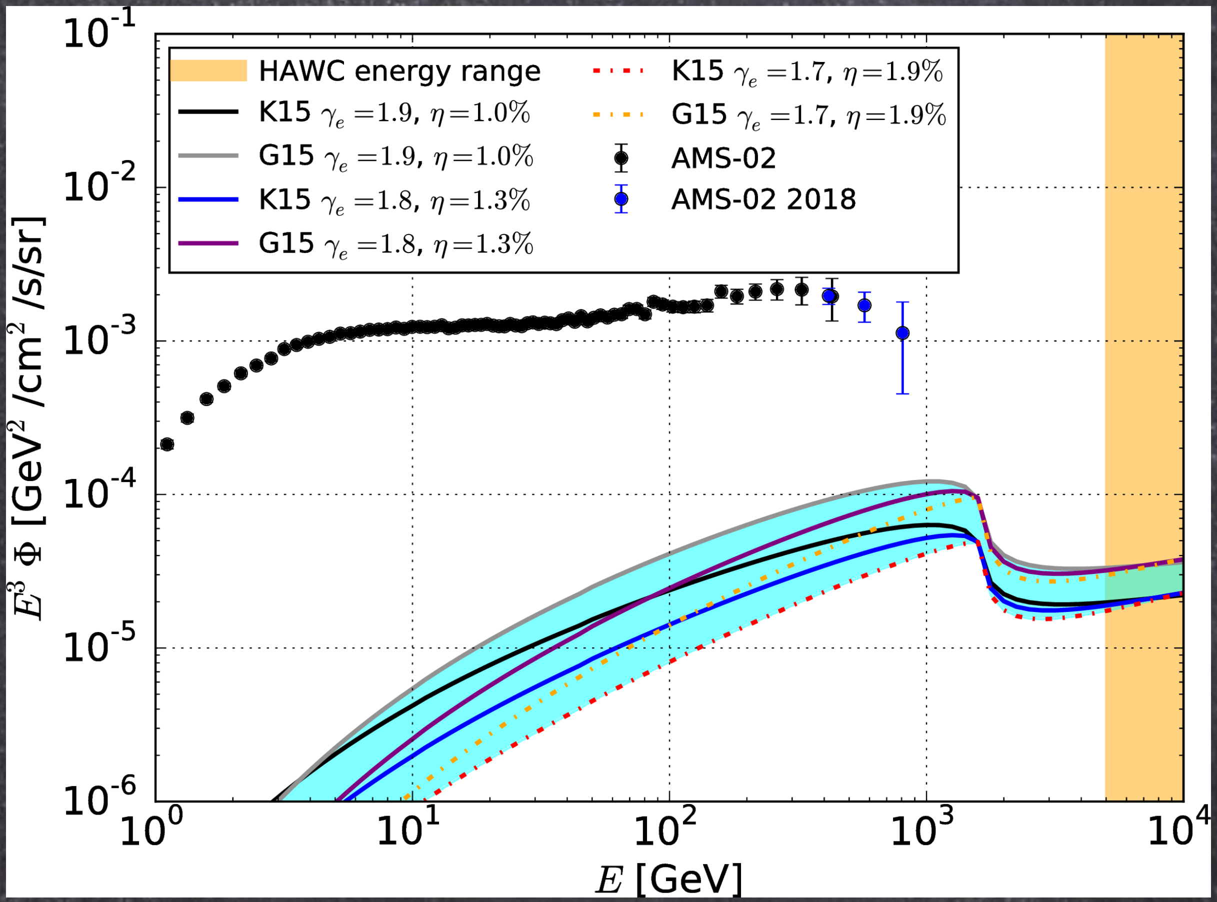


We find models compatible with the three independent observables (here burst model - similarly for evolutionary model)

Contributions to e+e- from Geminga PWN

Di Mauro, Manconi, FD 1903.05647, sub PRD





Discovery of a gamma-ray Inverse Compton halo around Geminga in Hawc data (Abeysekara, Science 2017) and in Fermi-LAT data (Di Mauro, Manconi, FD 1903.05647)

The contribution of Geminga to the e+ is 20% at most of AMS-02 data

See talk by S. Manconi GAD4b, July 31st

Conclusions

Leptons at Earth have a composite origin: e- from far smooth and near catalog SNR, e+e- from PWN, e+e- as secondaries in the ISM

We compare our model with three observables:
1. The radio flux from Vela YZ and Cygnus Loop
2. The CR e+e-, e+ flux
3. The e+e- dipole anisotropy upper bounds

- Radio data are strong constraints
- Dipole anisotropy is bounding when no other priors are set
- A multi-wavelength and multi-messenger combined analysis finds models compatible with data from all observables
- IC gamma rays around PWN can size the e+ flux at Earth

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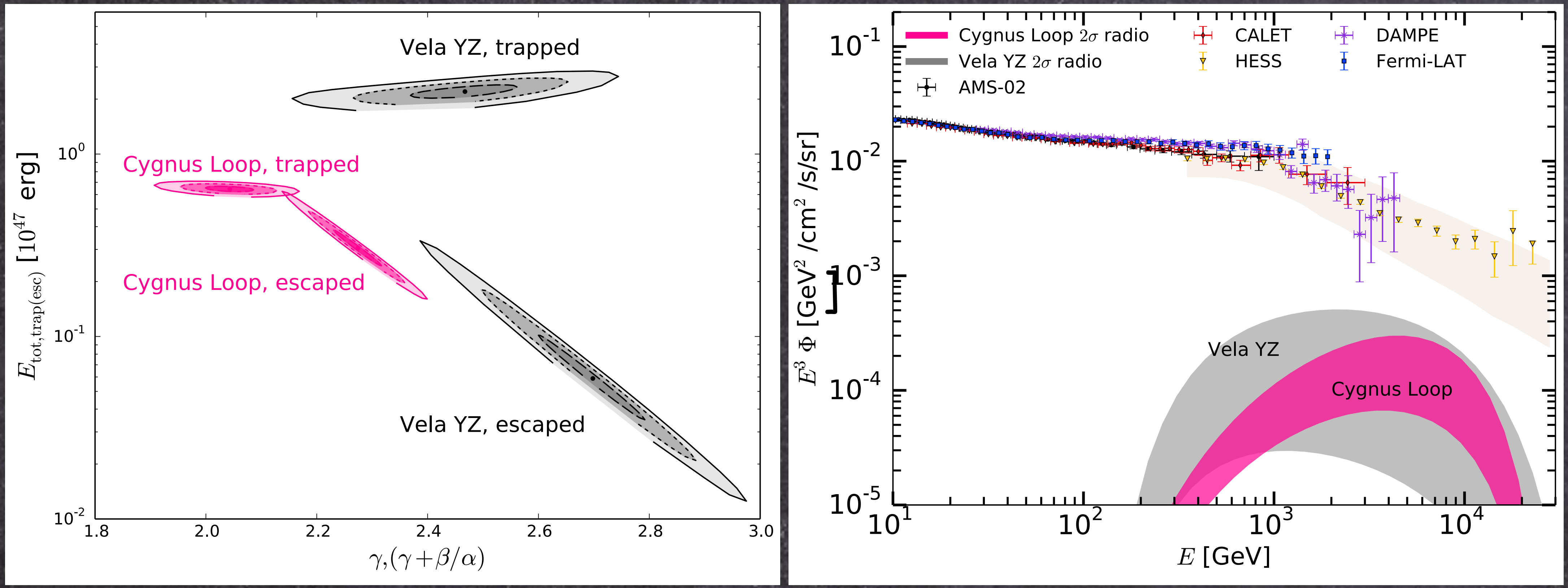

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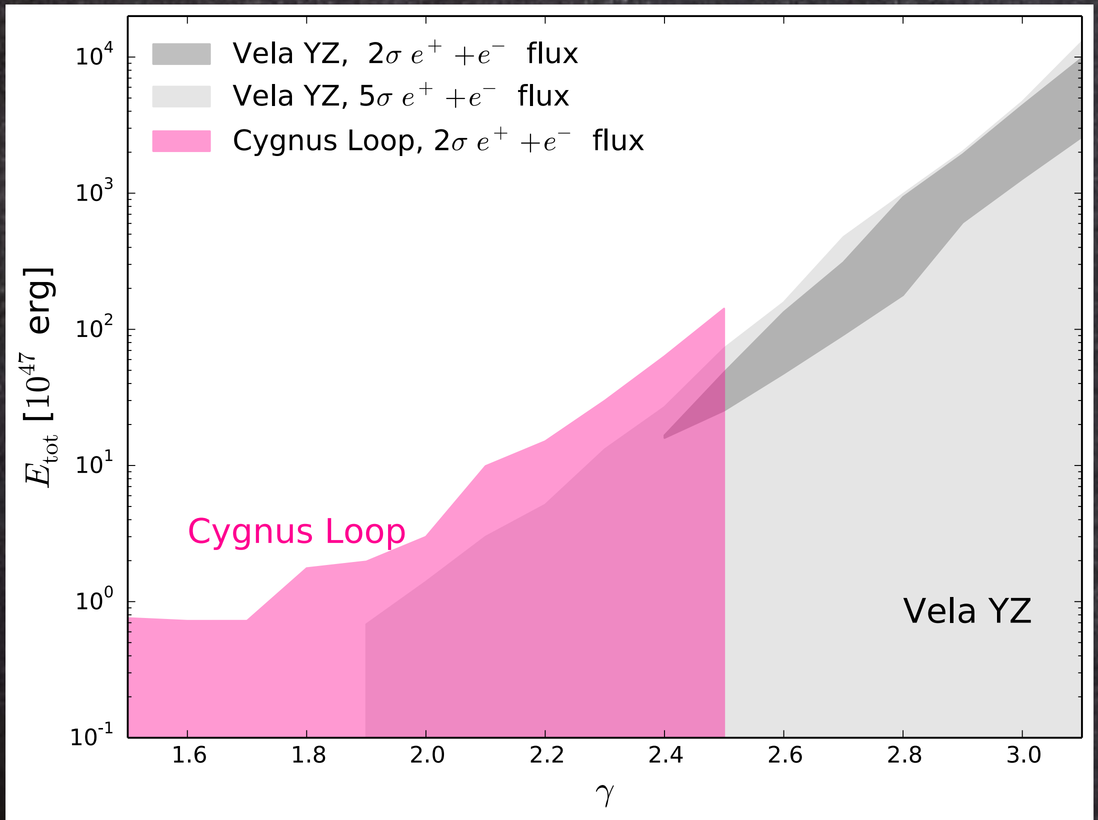

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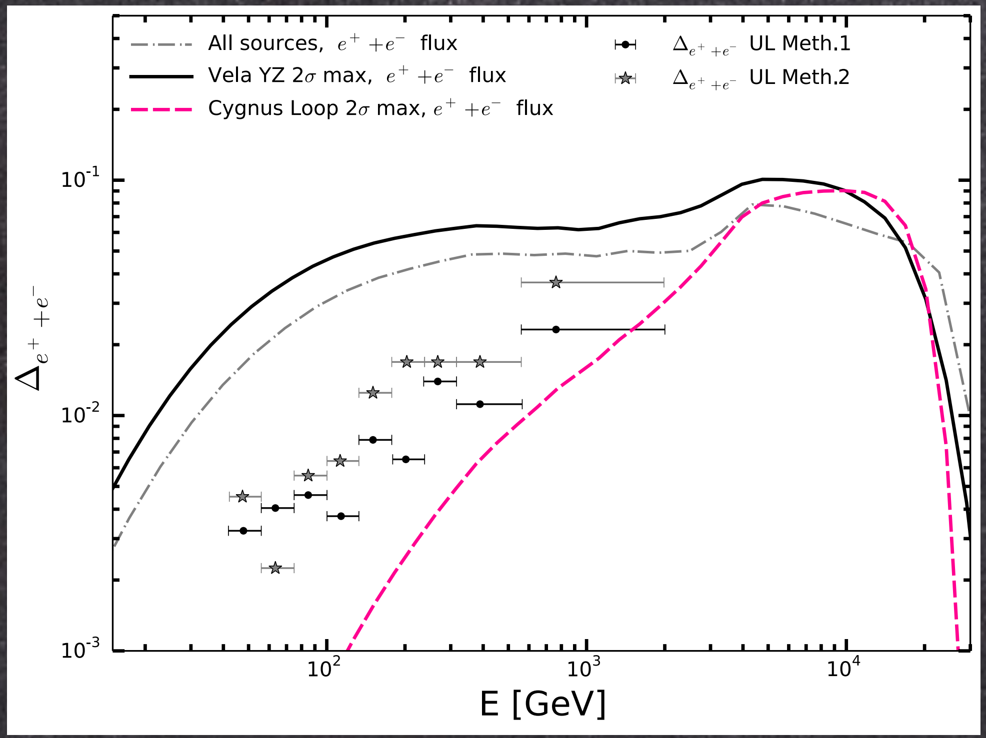
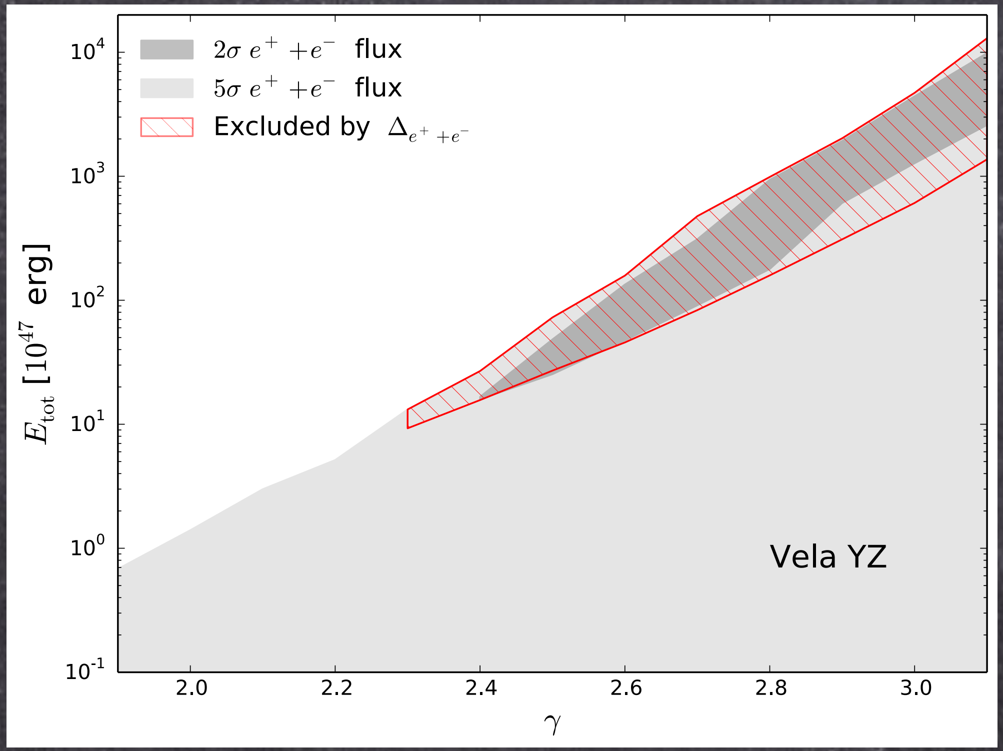


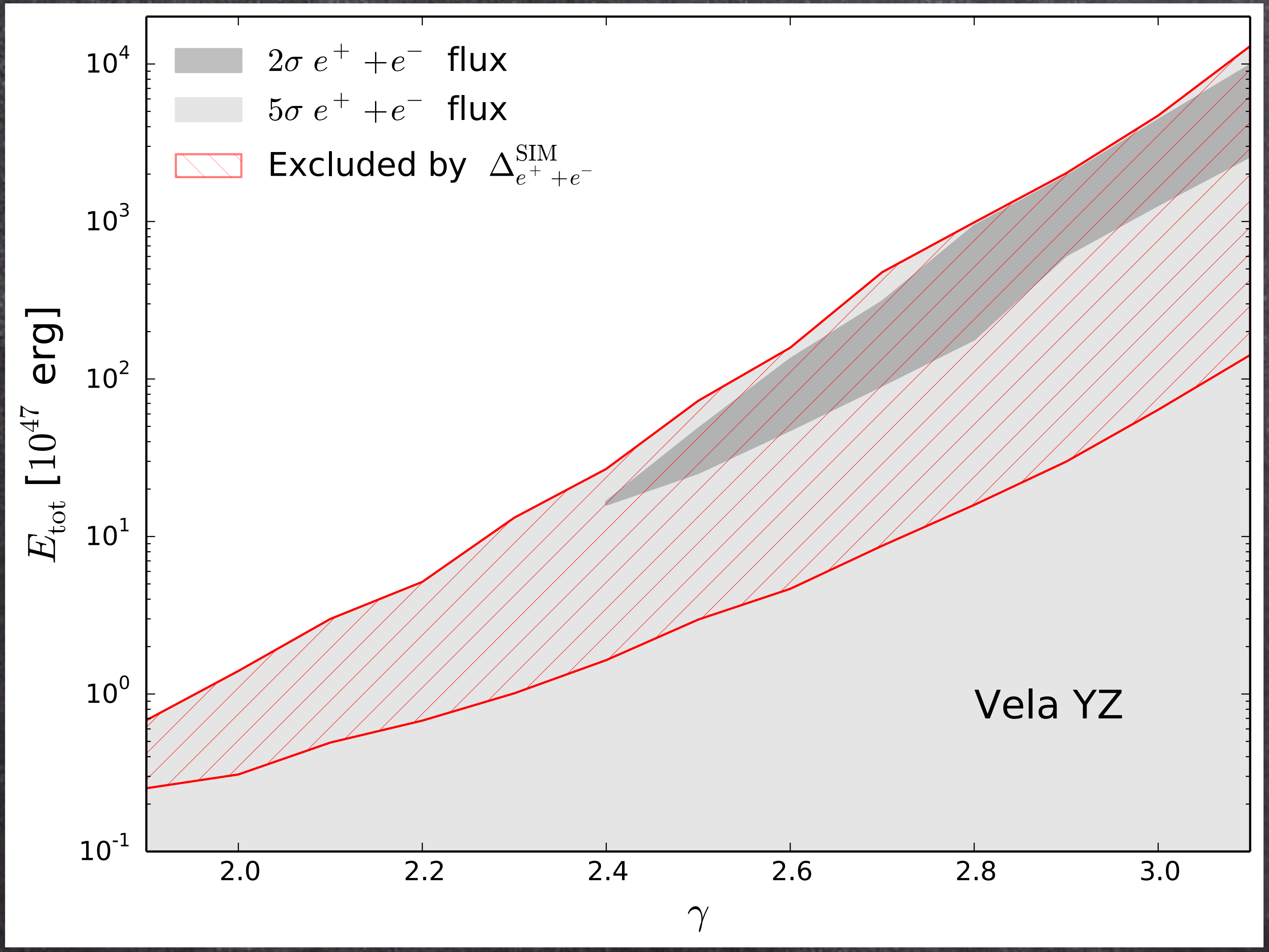


Maximal anisotropy from e+e- flux selected configurations

Anisotropy excludes configurations selected by e+e- flux

Perspectives with anisotropy

Hyp: UL on dipole e+e- are 10 times lower than Fermi-LAT 2017



The Vela parameter space would be widely tested bu Δ_{e+e-}

A multi-wavelength / multi-messenger analysis

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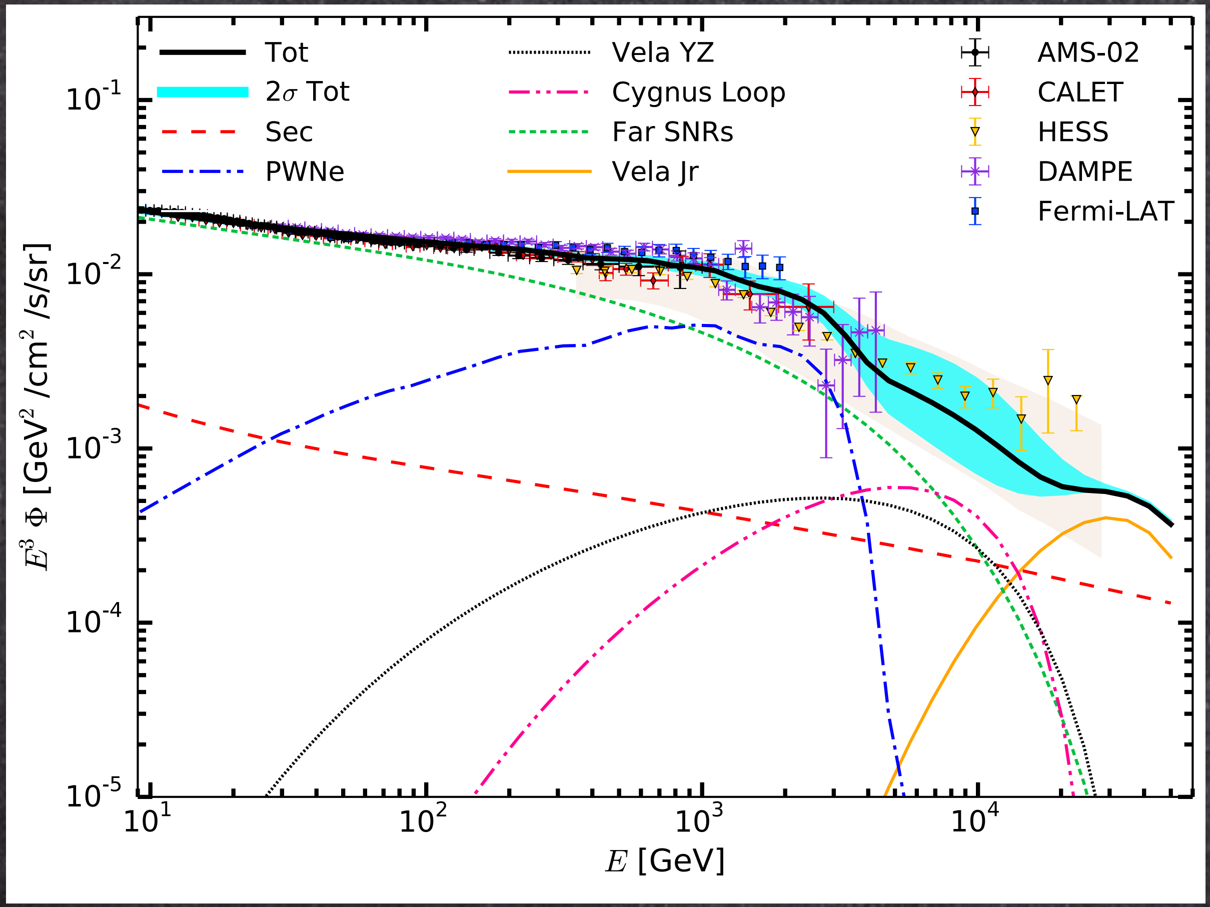

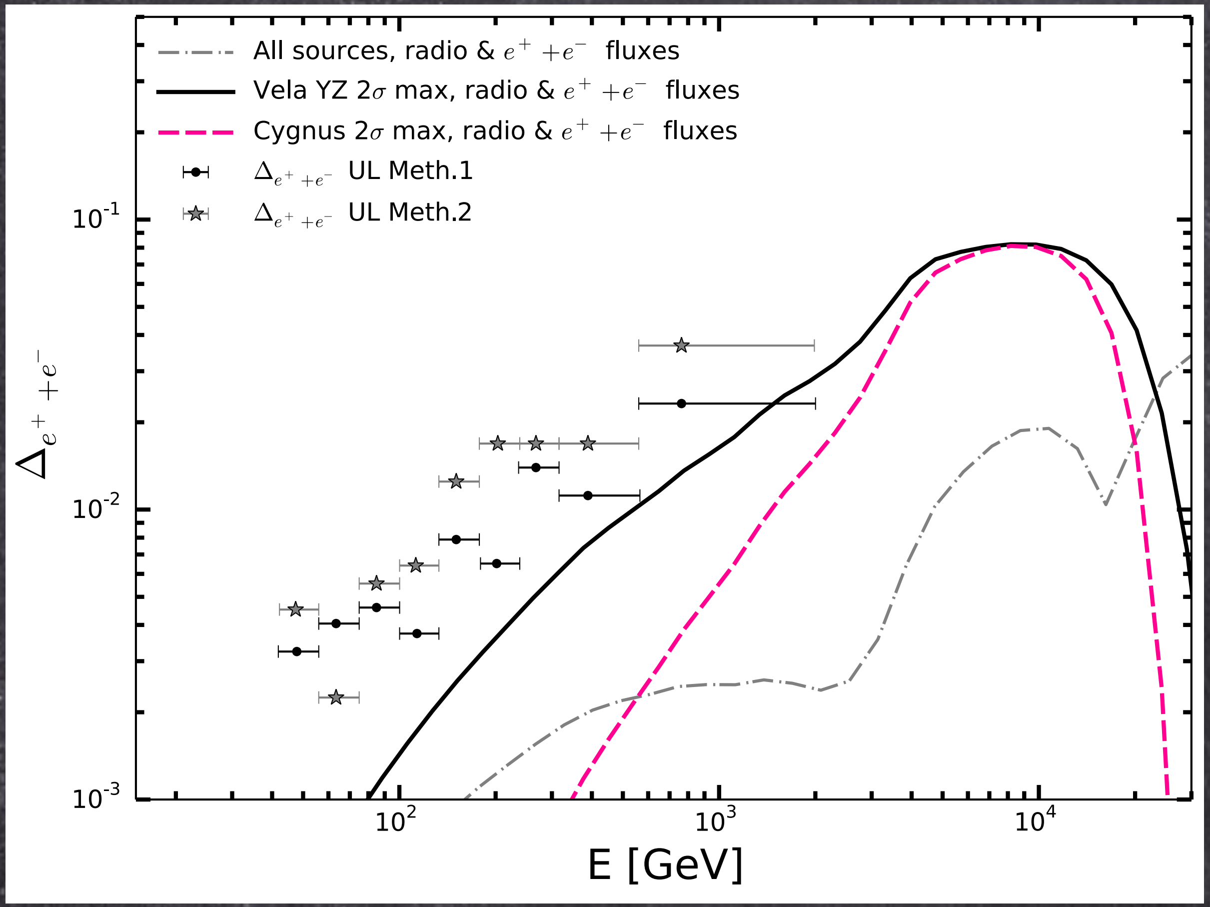

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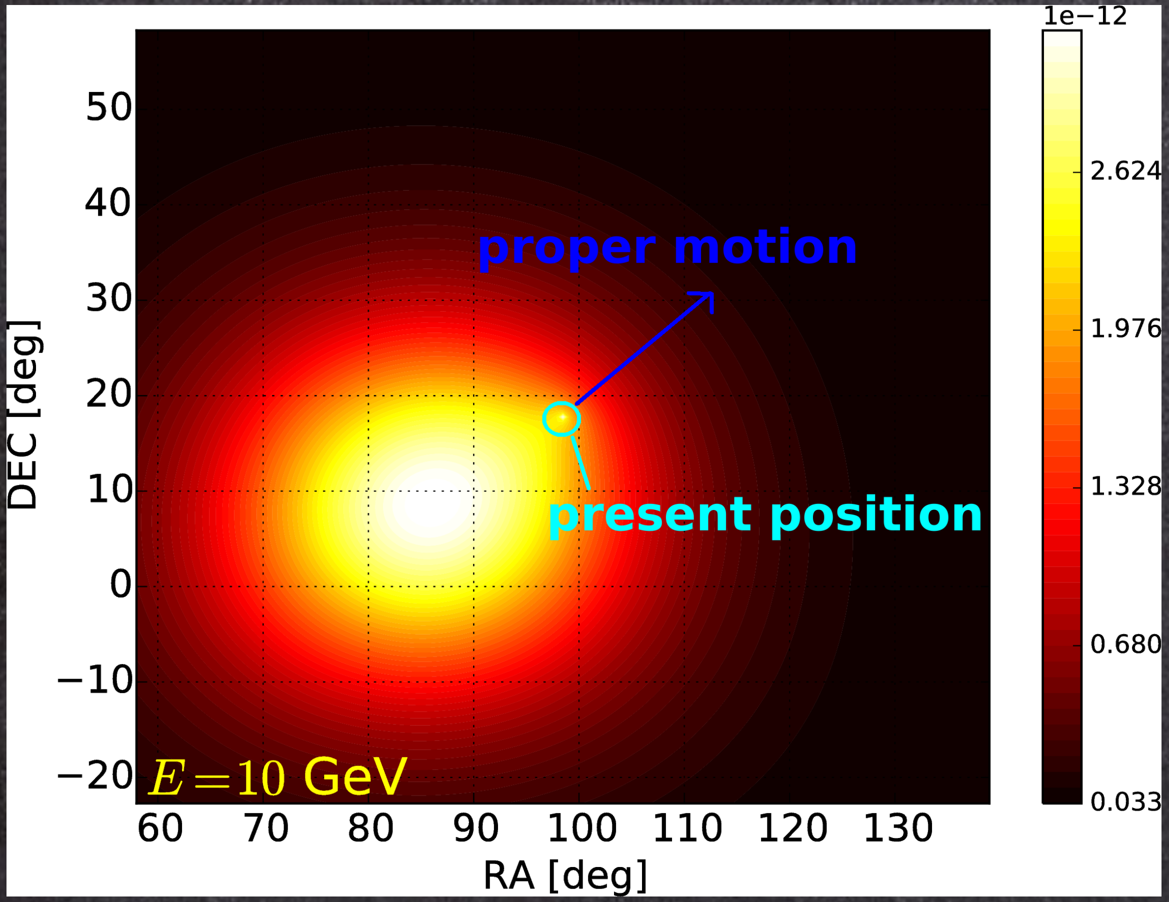

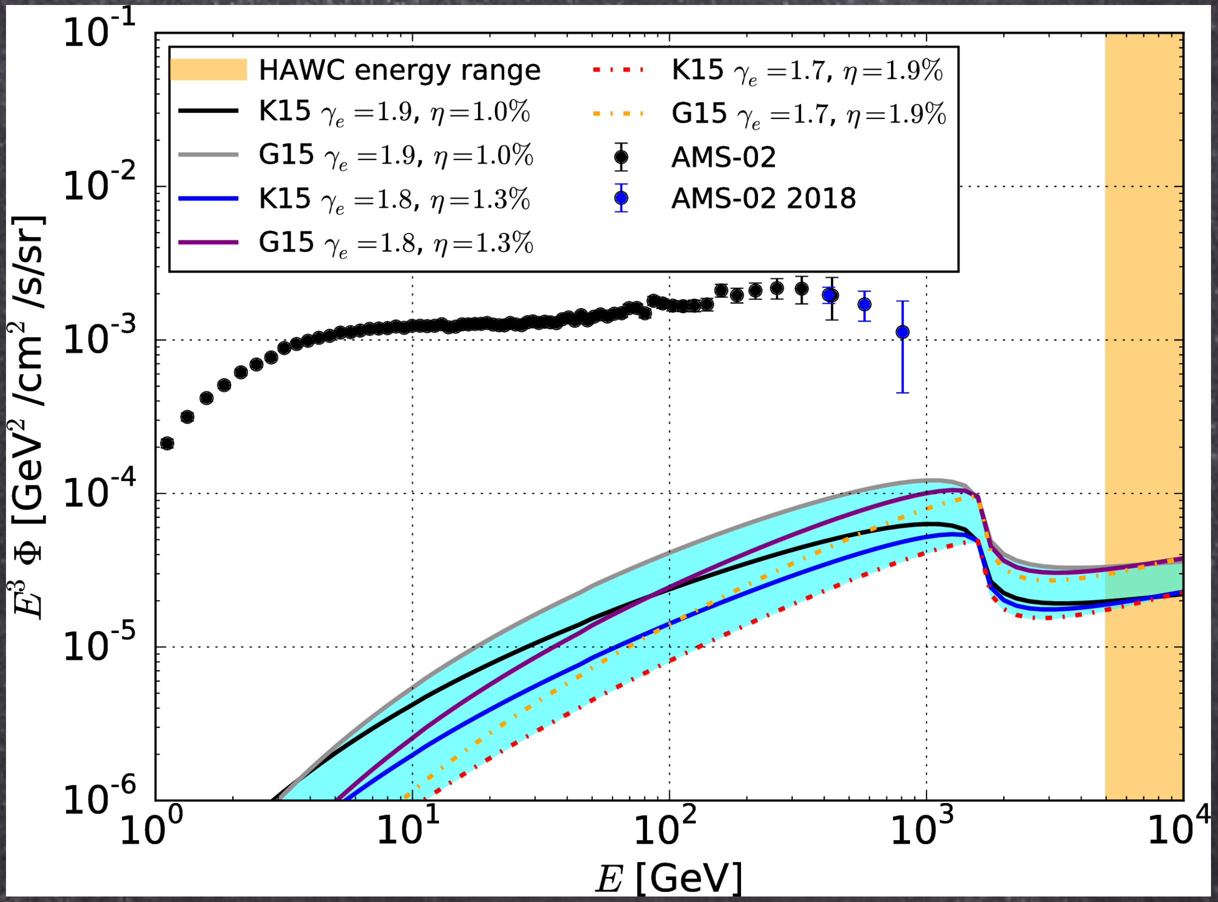

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See talk by S. Manconi

Conclusions

Extended study on the opportunity
of learning about nearby sources also from anisotropy

Single source / dominant source is chosen here for maximizing the dipole -

AMS-02 e+ flux strongly bounds the role of PWNe.
Geminga and Monogem are the most optimistic case:
near, even bright in gamma-rays.

Dipole anisotropy is more informative for SNR than for PWN

For SNR as Vela an improvement of 10 in dipole anisotropy
would have an impact - together with radio data - for the
understanding of SNR physics

Dipole anisotropy in CR leptons is a valuable observable to study the properties of local sources - SNRs

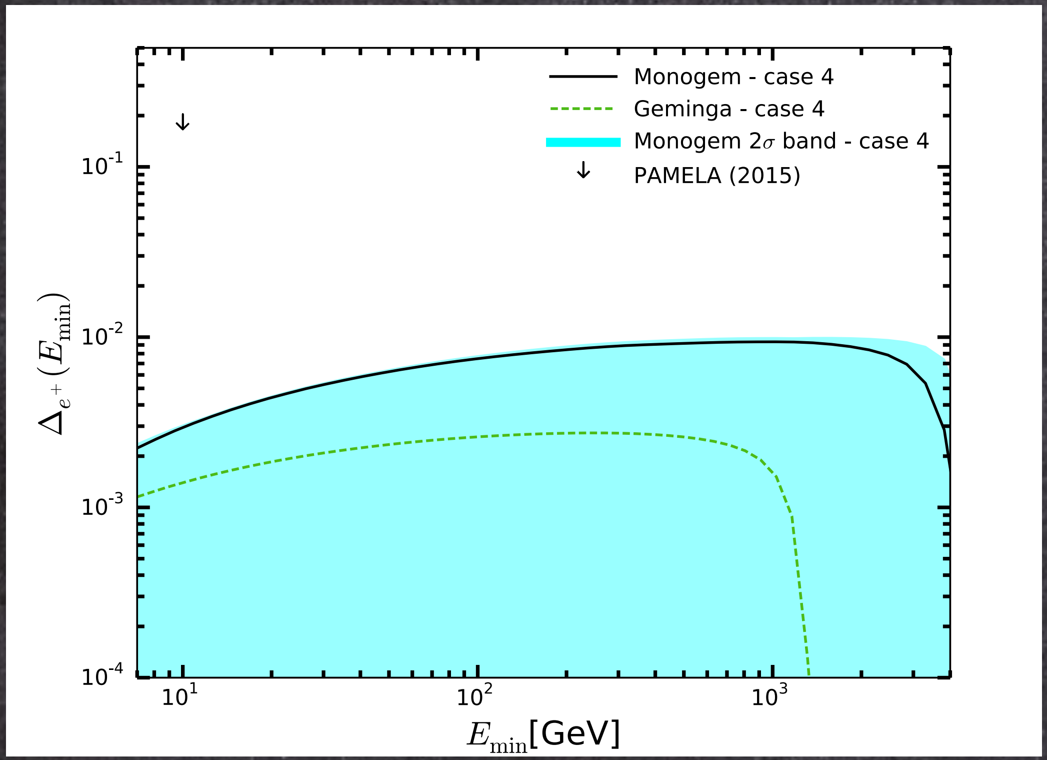
XSCRC2019

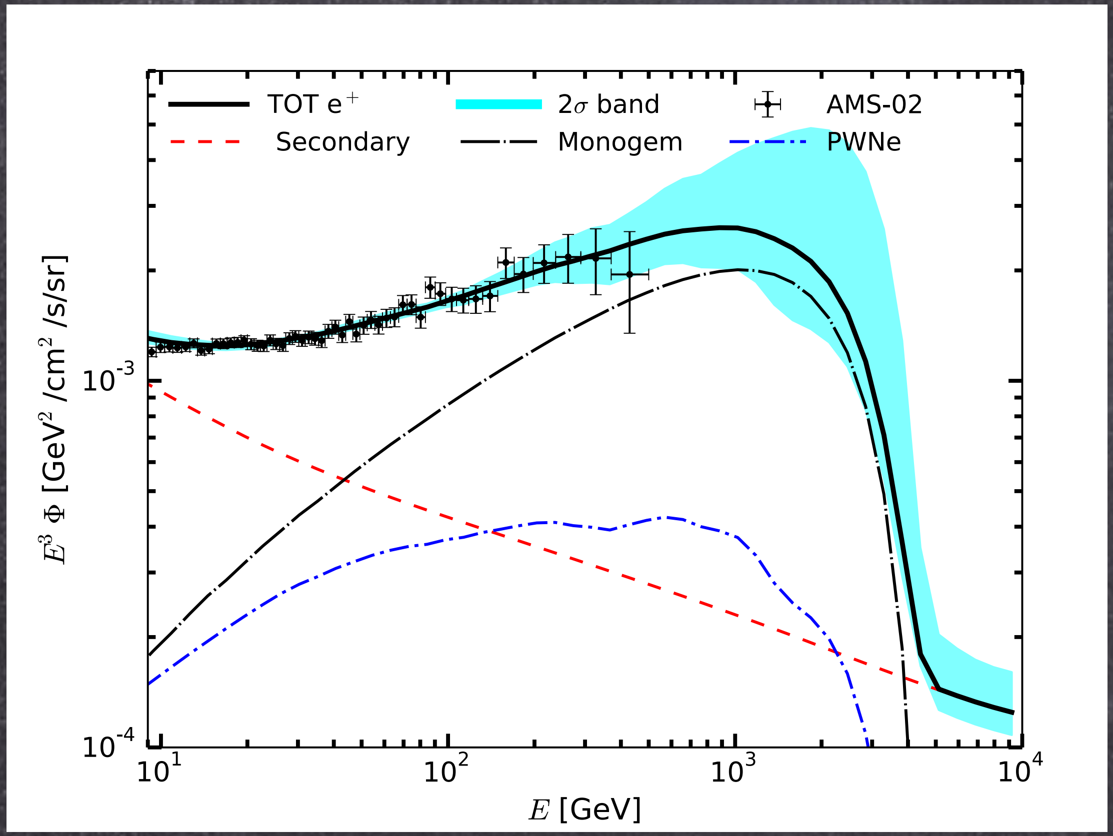
The second workshop dedicated to the cross sections for cosmic rays, XSCRC2019, will take place at Cern Nov. 13-15, 2019 (2 full days)

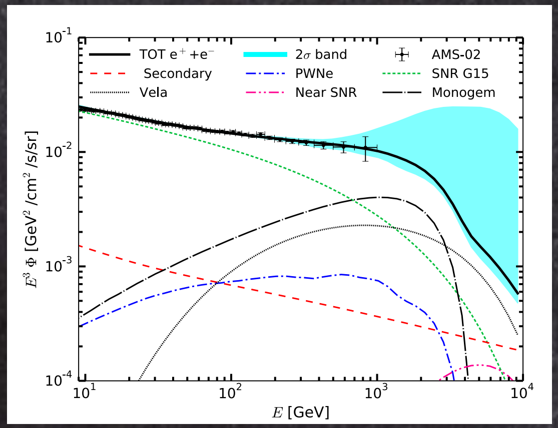
https://indico.cern.ch/event/820869/

Participation is free (no fee). Still very few slots for contributed talks.

One dominant PWN, and Vela SNR







The magnitude of Δ is strongly bound by the e+ data,
that with fit contemporary
to e+e-