Electron and positron fluxes: the role of anisotropies from known astrophysical sources

based on

S. Manconi, M. Di Mauro, F. Donato, *in preparation*

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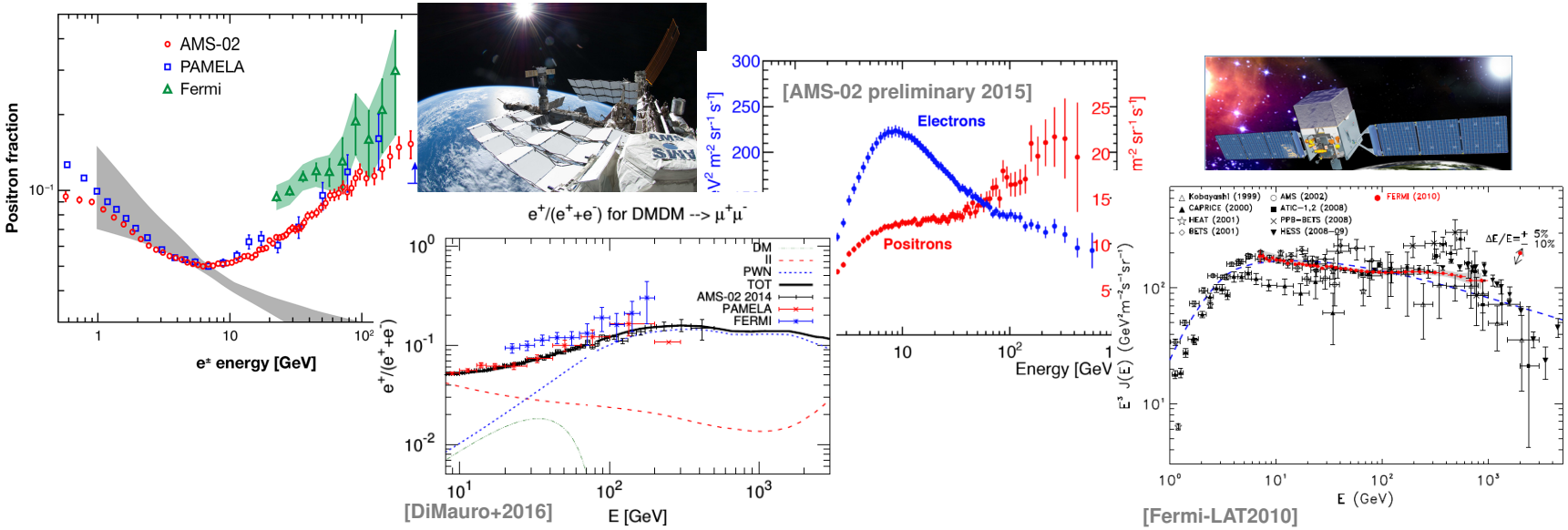
University of Torino and INFN

TeV Particle Astrophysics
CERN, 12-16 September, 2016

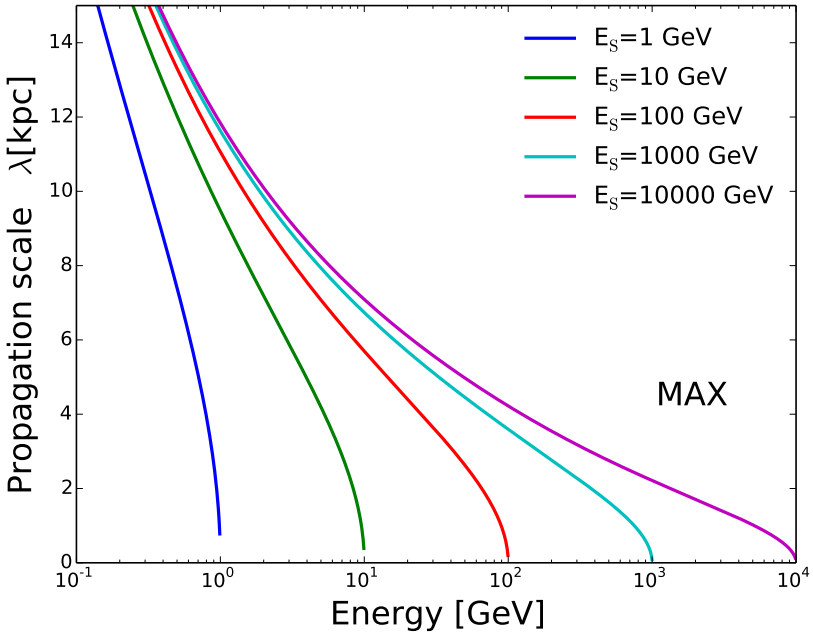
Introduction

- Precision measurements of GeV-TeV $e^{\pm}$ from PAMELA, AMS-02, Fermi-LAT
- Interpretation of fluxes: Uncertainty in theoretical models
  - from propagation
  - from modeling of sources
    - ⋆ Dark Matter annihilations [Cirelli+2009; Grasso+2009; Di Mauro+2016; ...]
    - ⋆ SNR,PWNe [Malyshev+2009; Di Mauro+2014; ...]



Motivation

- EM energy losses: GeV-TeV $e^{\pm}$ are local
- Typical propagation scale $<$ 5 kpc



$\Rightarrow$ Importance of local sources to constrain GeV-TeV flux

Focus on **Astrophysical known sources**

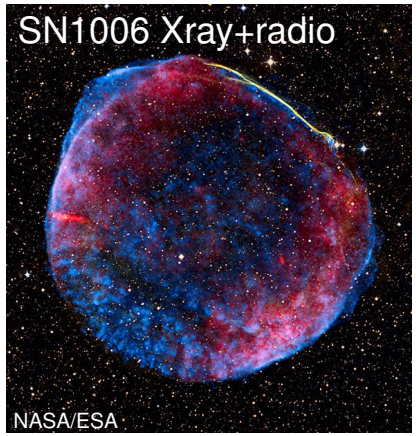
Role of anisotropies: *discerning the physical origin of the flux?*

Outline

See also M.Di Mauro talk in CR I, Monday 12/09

Supernova Remnants (SNRs) as e^- sources

Injection spectrum



- Acceleration mechanism: **Fermi non-relativistic shocks**
- Energy cutoff: TeV range [Acciari+2010 (VERITAS)]
- Injection spectrum:

$$Q(E) = Q_{0,\mathrm{SNR}} \left(\frac{E}{E_0}\right)^{-\gamma_{\mathrm{SNR}}} \exp\left(-\frac{E}{E_c}\right)$$

We fix $E_c = 5$ TeV, $E_0 = 1$ GeV

- Single SNR $Q_{0,\mathrm{SNR}}$ constrained with radio + catalog data [Delahaye+2010]

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

distance magnetic field radio flux

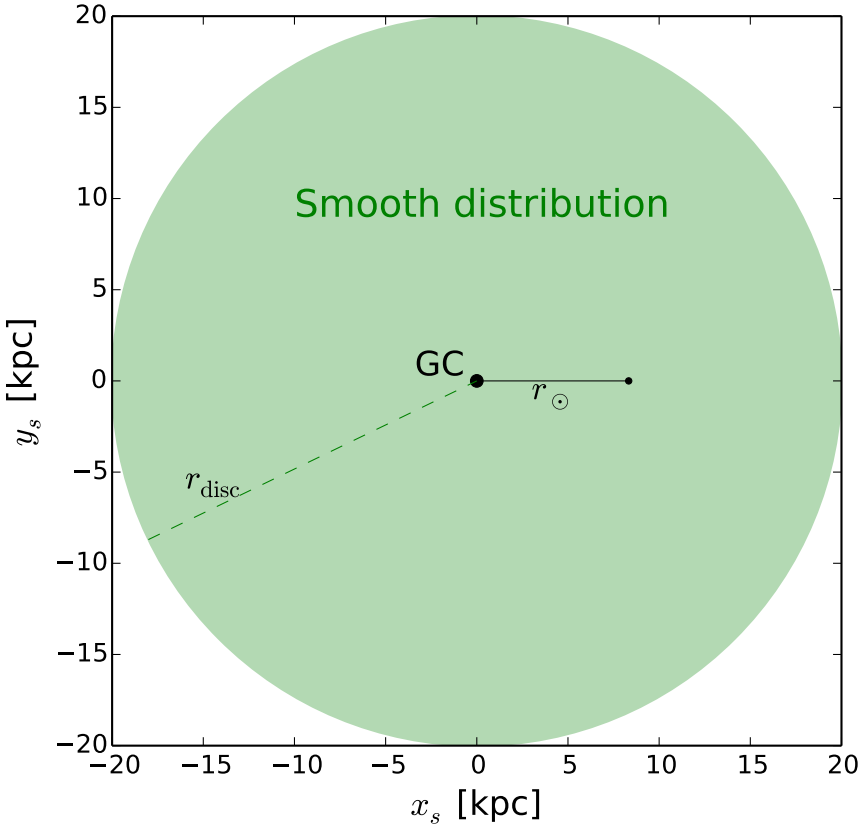
- Smooth SNR $Q_{0,\mathrm{SNR}}$ constraints from average characteristcs

[Delahaye+2010]

Supernova Remnants (SNRs) as e^- sources

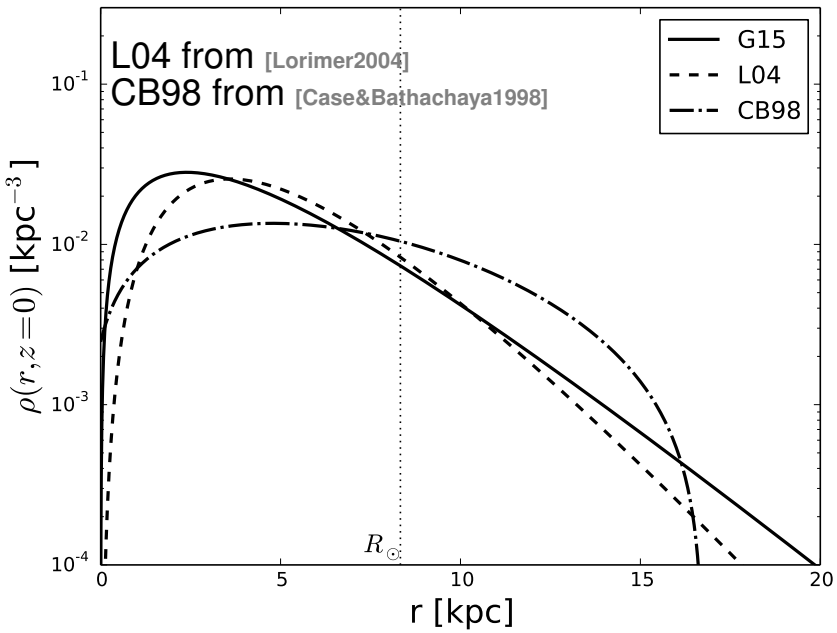
Spatial distribution

Smooth distribution of sources in the Galaxy:



Radial distribution from [Green2015] (G15)

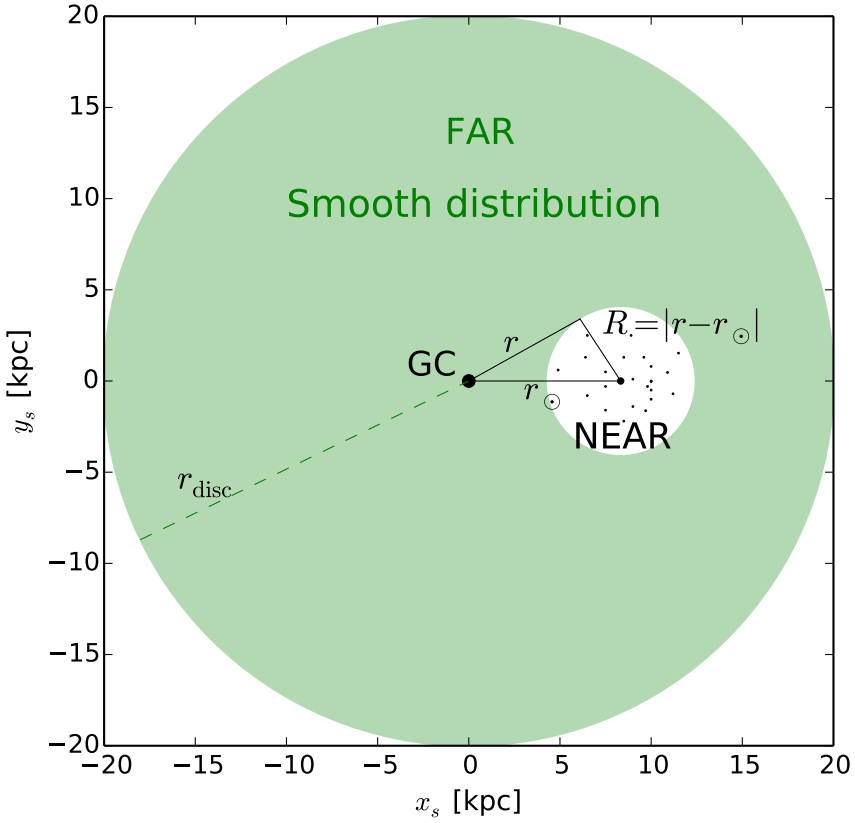
$$\rho(r) \propto \left(\frac{r}{r_\odot}\right)^\alpha \exp\left(-\beta\frac{(r-r_\odot)}{r_\odot}\right)$$



Supernova Remnants (SNRs) as e^- sources

Spatial distribution

Cutted smooth distribution +
single sources in the Galaxy:



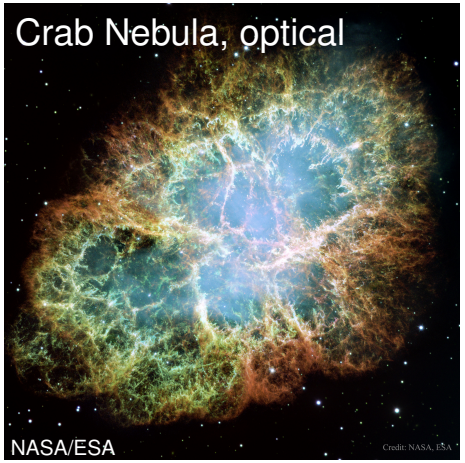
FAR component ($R > R_{\rm cut}$)
Radial distribution from [Green2015]

$$\rho(r) \propto \left(\frac{r}{r_\odot}\right)^\alpha \exp\left(-\beta \frac{(r - r_\odot)}{r_\odot}\right)$$

NEAR component ($R < R_{\rm cut}$)
Single sources from SNR Green catalog
[Green2014]

$R_{\rm cut}$ = 0.7, 3 kpc

Pulsar wind nebulae (PWNe) as $e^{\pm}$ sources



- Acceleration mechanism: **relativistic shocks**
- Injection spectrum:

$$Q(E) = Q_{0,\mathrm{PWN}} \left(\frac{E}{E_0}\right)^{-\gamma_{\mathrm{PWN}}} \exp\left(-\frac{E}{E_c}\right)$$

Single $Q_{0,\mathrm{PWN}}$ from

$$E_{e^{\pm}} = \int dE\, E\, Q(E) = \eta W_0$$

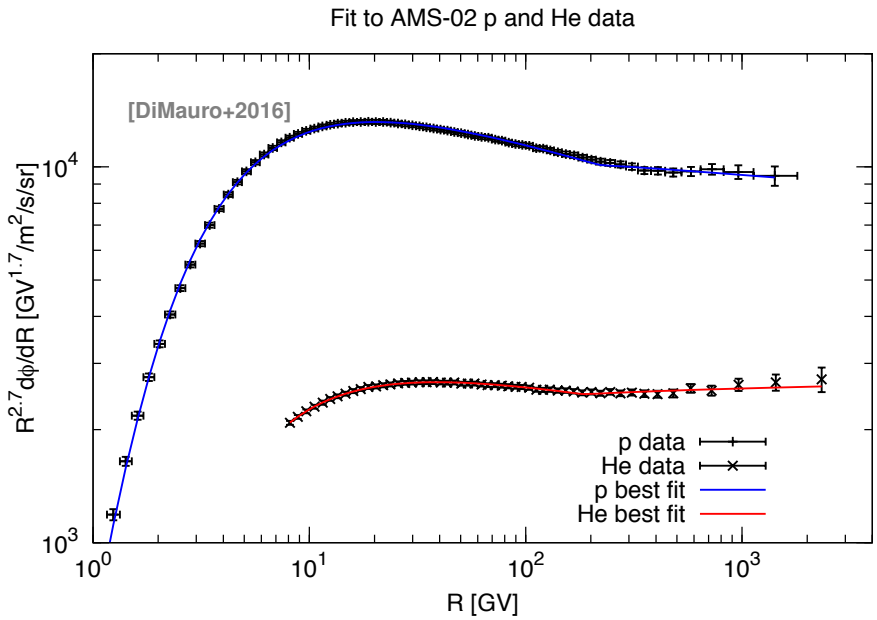
η= conversion efficiency $\sim 10\%$ [Gelfand+2009], W_0= spin-down energy

1. **Spatial distribution**: single PSR from ATNF catalog [Manchester+2005] (distance d, age T, W_0)
2. Pair release in the ISM for **T $\gtrsim$ 50 kyr** [Blasi&Amato2011]

NB: η and γ_{PWN} are the same for all PWNe

Secondary $e^{\pm}$ are produced by CR nuclei fragmentation on the ISM

- Dominant mechanism: $p_{\rm CR} + H_{\rm ISM} \to X + \pi^{\pm} \to ...$
- **Primary $\Phi_{\rm CR}$ (p, He)** from a **fit to AMS-02 data** $\Rightarrow$
- Source term: [Delahaye+2009]



$$Q_{\rm sec}(\mathbf{x}, E_e) = 4\pi\, n_{\rm ISM}(\mathbf{x}) \int dE_{\rm CR}\, \Phi_{\rm CR}(\mathbf{x}, E_{\rm CR}) \frac{d\sigma}{dE_e}(E_{\rm CR}, E_e)$$

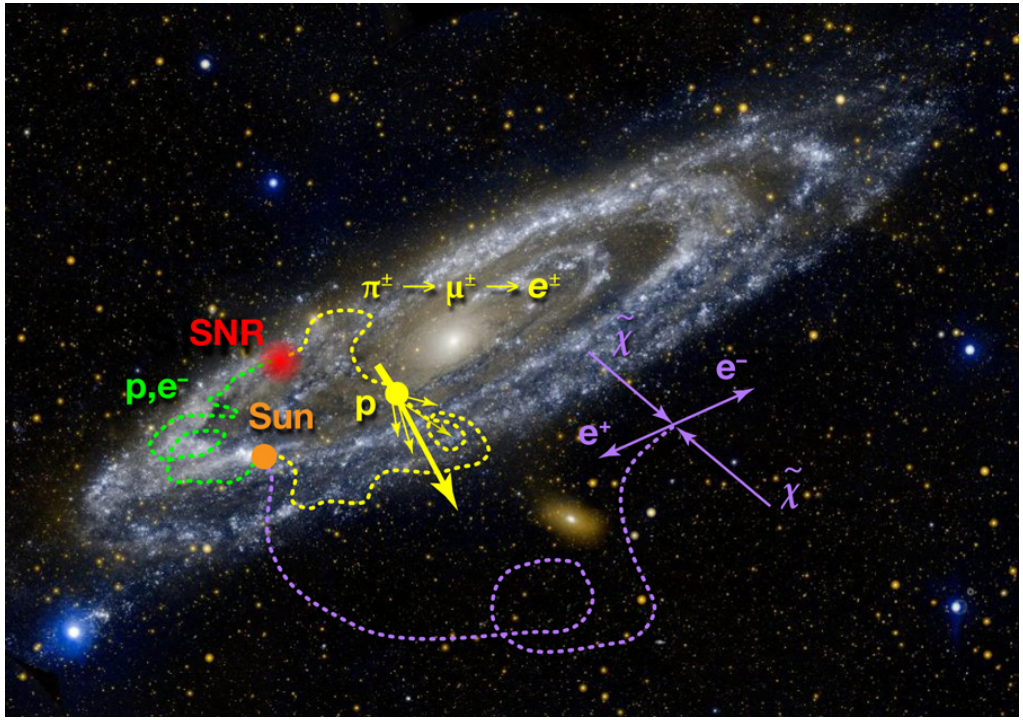
interstellar gas density

primary CR flux

inclusive cross section [Kamae+2006]

$\Rightarrow$ Results from [DiMauro+2016] with **additional free normalization** $q_{\rm sec}$.

Propagation of $e^{\pm}$ is dominated by diffusion and energy losses



- Propagation parameters constrained by B/C data
- Solar modulation negligible for $E > 10$ GeV [Strauss&Potgieter2014]

[Donato2004]

Model	δ	K_0[kpc^2/Myr]	L[kpc]
MED	0.70	0.0112	4
MAX	0.46	0.0765	15

Results from [Kappl+2015, Genolini+2015] included in MED-MAX uncertainties

Propagation of $e^{\pm}$ is dominated by diffusion and energy losses

Semi analytical diffusion model succesfully used to interpret CR leptons, protons [Maurin+2001, Donato+2004, DiMauro+2014, ...]

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

diffusion

$$K(E) = K_0 E^{\delta}$$

only for burst-like sources

energy losses: syn-chrotron,IC

source term

- Propagation parameters constrained by B/C data
- Solar modulation negligible for $E > 10$ GeV [Strauss&Potgieter2014]

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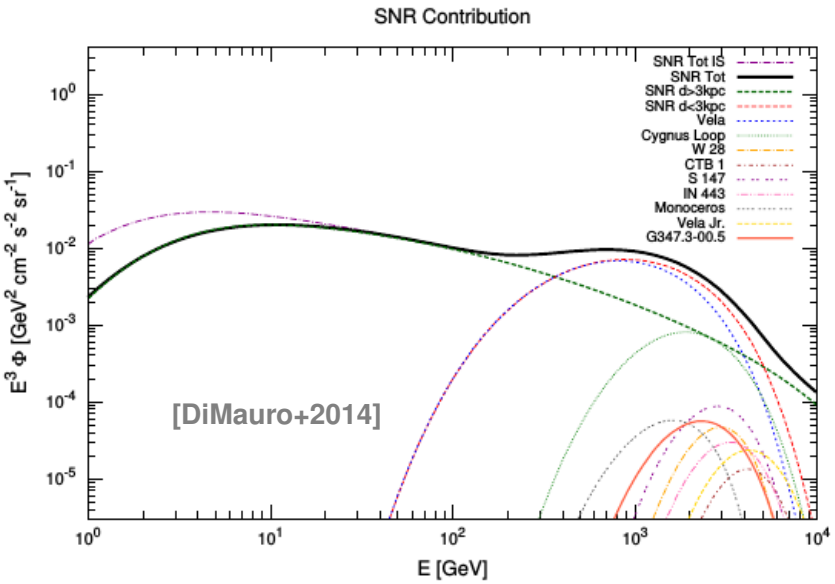
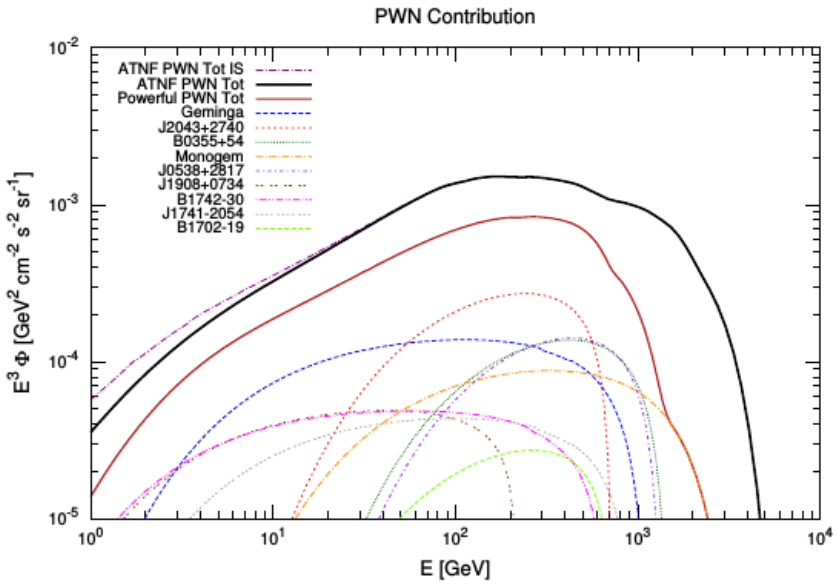
Local known sources may contribute to anisotropy

Near SNRs from the **Green catalog** [Green2014]

Powerful PSRs from the **ATNF catalog** [Manchester+2005]





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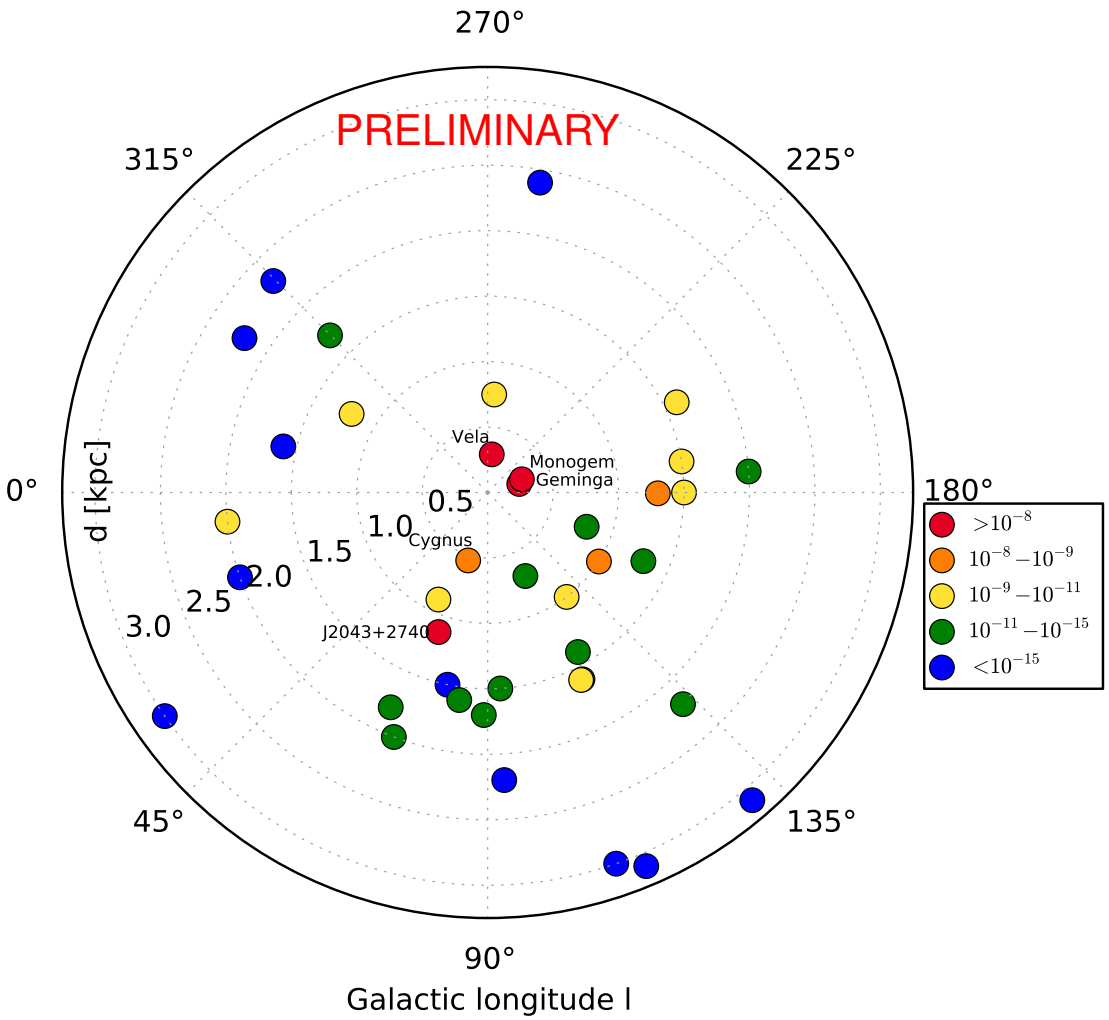


Dot color: integrated e^- flux at Earth from 50 GeV to 5 TeV in $[\mathrm{cm}^2\mathrm{s\ sr}]^{-1}$

Anisotropy from one dominant sources? From a collection of sources?

Anisotropies can be computed starting from the $e^{\pm}$ number density

- Multipole expansion: if one (few) dominant nearby sources exist, **the dipole term dominates**:

$$\Delta = \frac{I_{max} - I_{min}}{I_{max} + I_{min}},$$

where $I_{\max(\min)}$ are the max (min) values of CR intensity

$\Rightarrow$ In the diffusion propagation regime: [Ginzburg&Syrovatskii1964]:

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

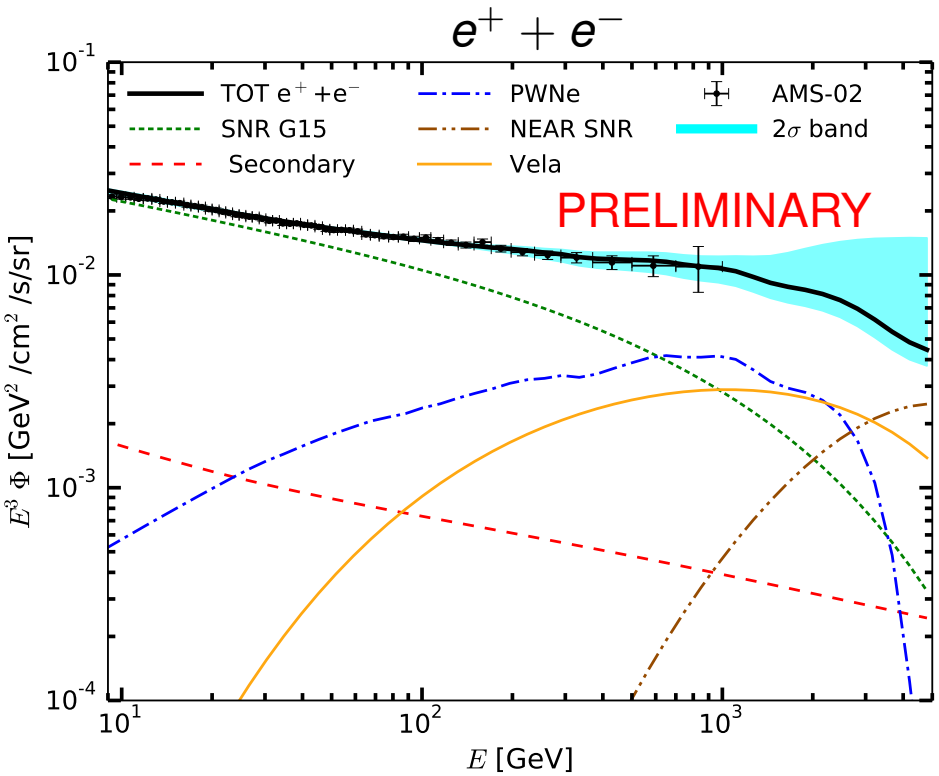
where ψ is the CR number density per unit volume and energy.

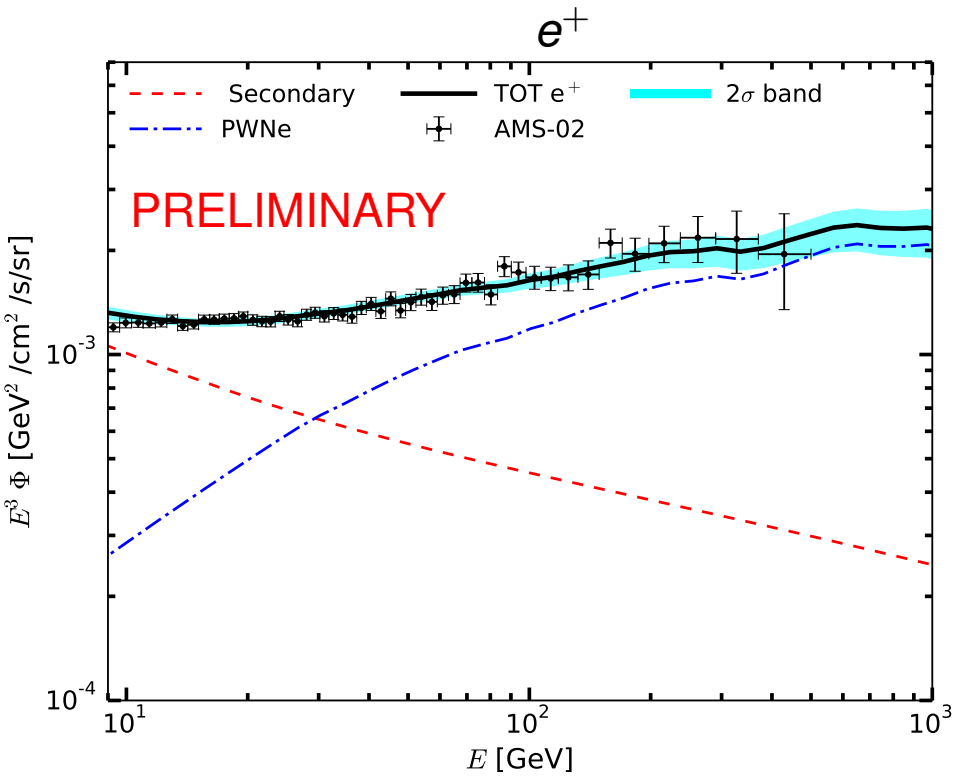
- Heliosphere effects for E$<$TeV
- **Integrated anisotropy** computed for $E_{\max} = 5$ TeV

Anisotropy predictions are obtained consistently with AMS-02 $e^{\pm}$ fluxes

Data from [Aguilar+2014]. Free parameters see [DiMauro+2014, DiMauro+2016]:

$$\gamma_{\rm SNR} \;\Big|\; Q_{0,\rm SNR} \;\Big|\; B_{\rm Vela} \;\Big|\; B_{\rm near} \;\Big|\; \gamma_{\rm PWN} \;\Big|\; \eta_{\rm PWN} \;\Big|\; q_{\rm sec}$$





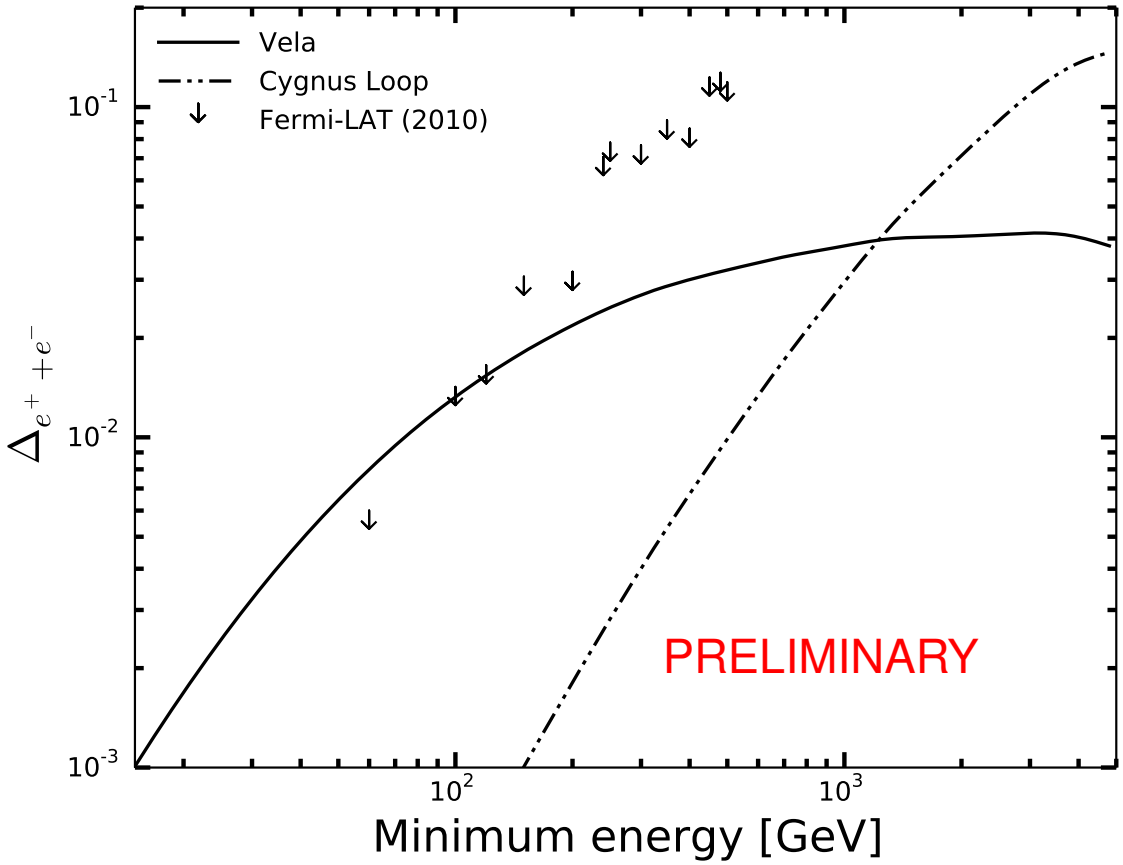
Preliminary results for $R_{\rm cut} = 0.7$ kpc, MAX

Anisotropies from single near SNRs

$R_{\rm cut} = 0.7$ kpc: Vela and Cygnus Loop

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

- Vela and Cygnus parameters are fixed except $B \propto Q_0$
- Upper limits from [Ackerman+2010]
- $\Delta_{e^+ + e^-} > 10^{-2}$ in TeV range



An uncertainty band for Vela SNR parameters

Single source parameters are uncertain:

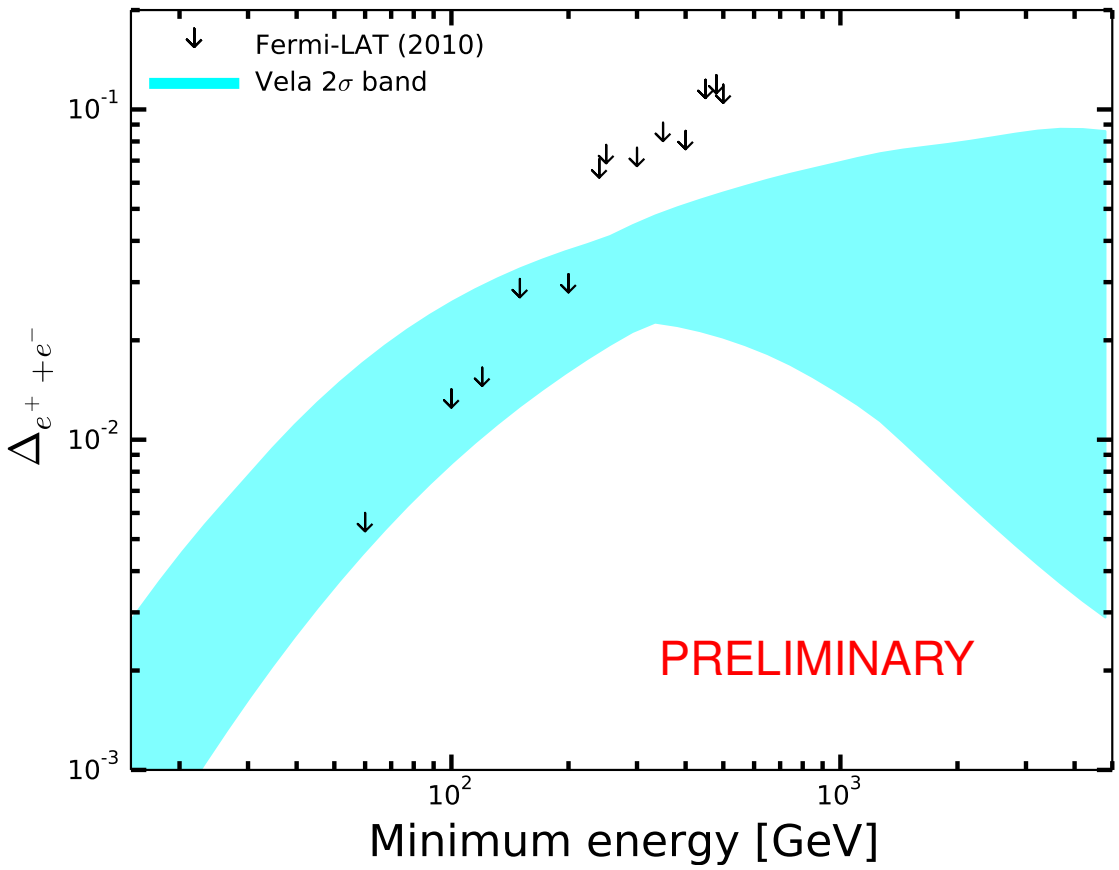
- Magnetic field $[1, 100]\mu$G
- Spectral index γ $[2.2, 2.8]$

  [Alvarez+2001]

- Distance $[0.22, 0.32]$ kpc

  [Dodson+2003,Cha+1999]

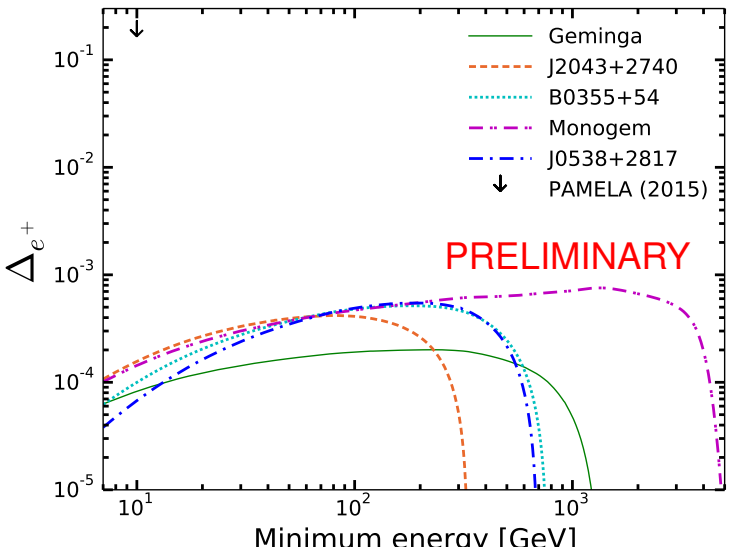
Uncertainties in source parameters are reflected in uncertainties for the predicted anisotropy

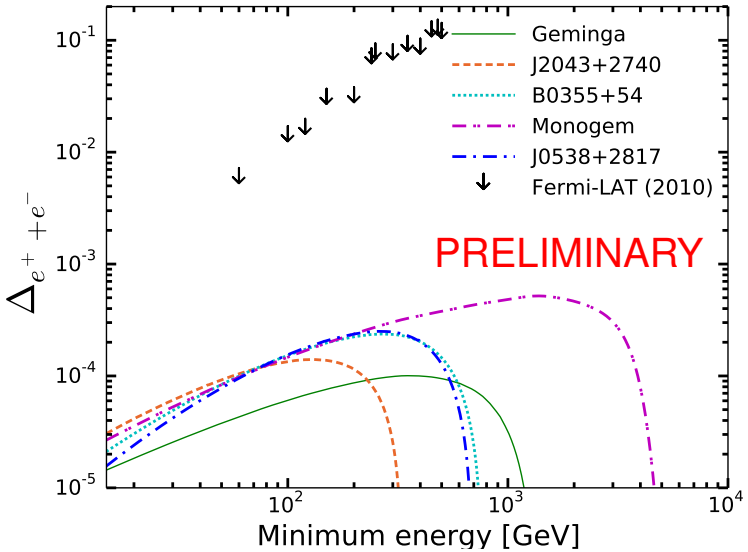


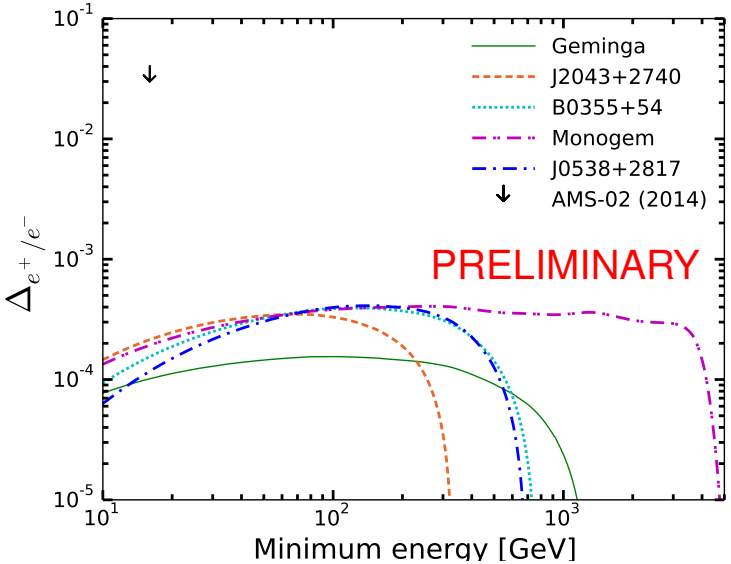
Anisotropies from single powerful PWNe

1. All ATNF pulsars contribution considered
2. At least **2 order of magnitude lower wrt upper limits** from

   [Ackerman+2010, Accardo+2014, Adriani+2015]
3. No significant dominating source







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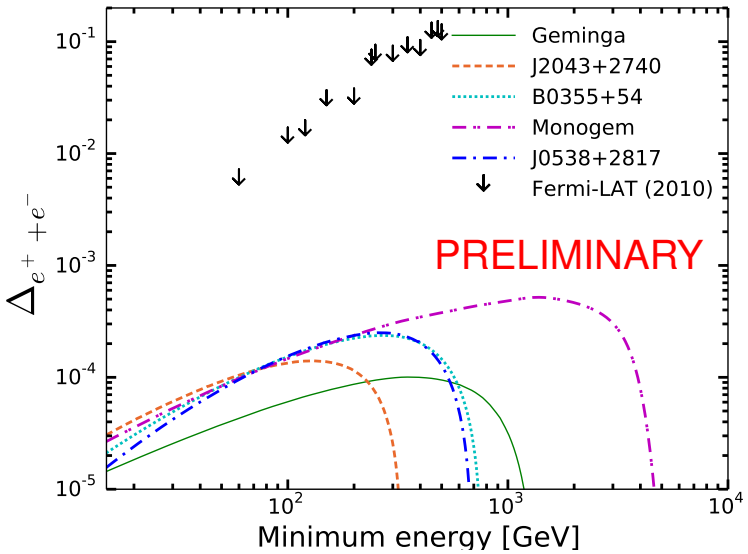
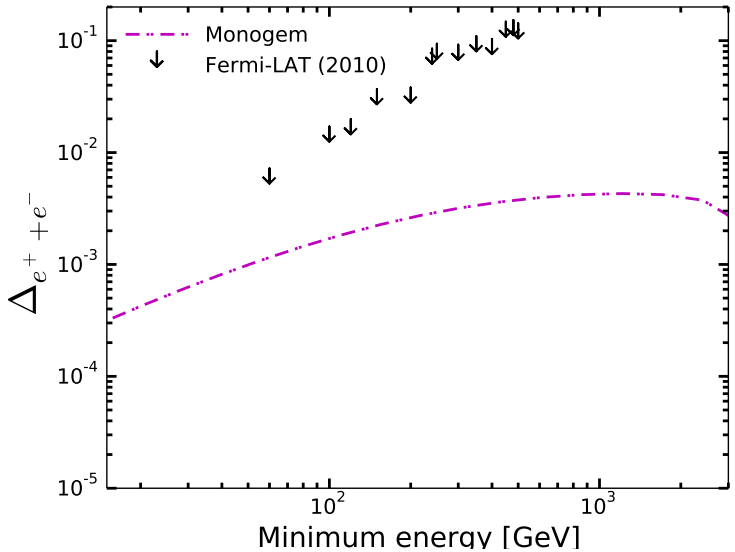
If only one PWN provides the $e^{\pm}$ fluxes the anisotropy is higher, **but $\eta \gtrsim$ 40%**

$\Downarrow$

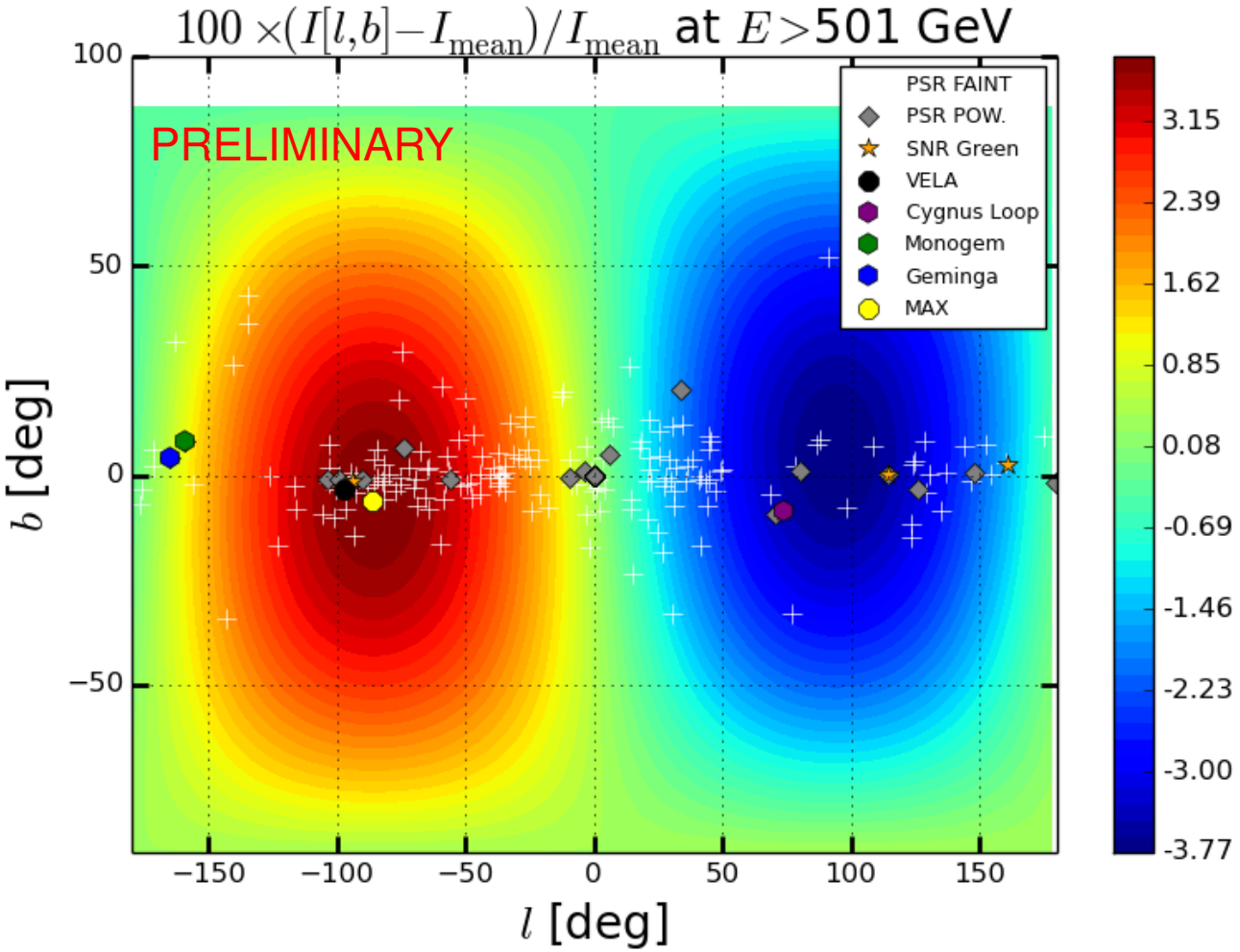




Anisotropy from a collection of sources

$$\Delta = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}; \quad I(E, \mathbf{n}) = \frac{c}{4\pi} \sum_i \psi_i(E, \mathbf{r}_i, t_i) \left(1 + \frac{3\mathbf{n} \cdot \mathbf{r}_i}{2ct_i}\right)$$

[Shen&Mao1971]



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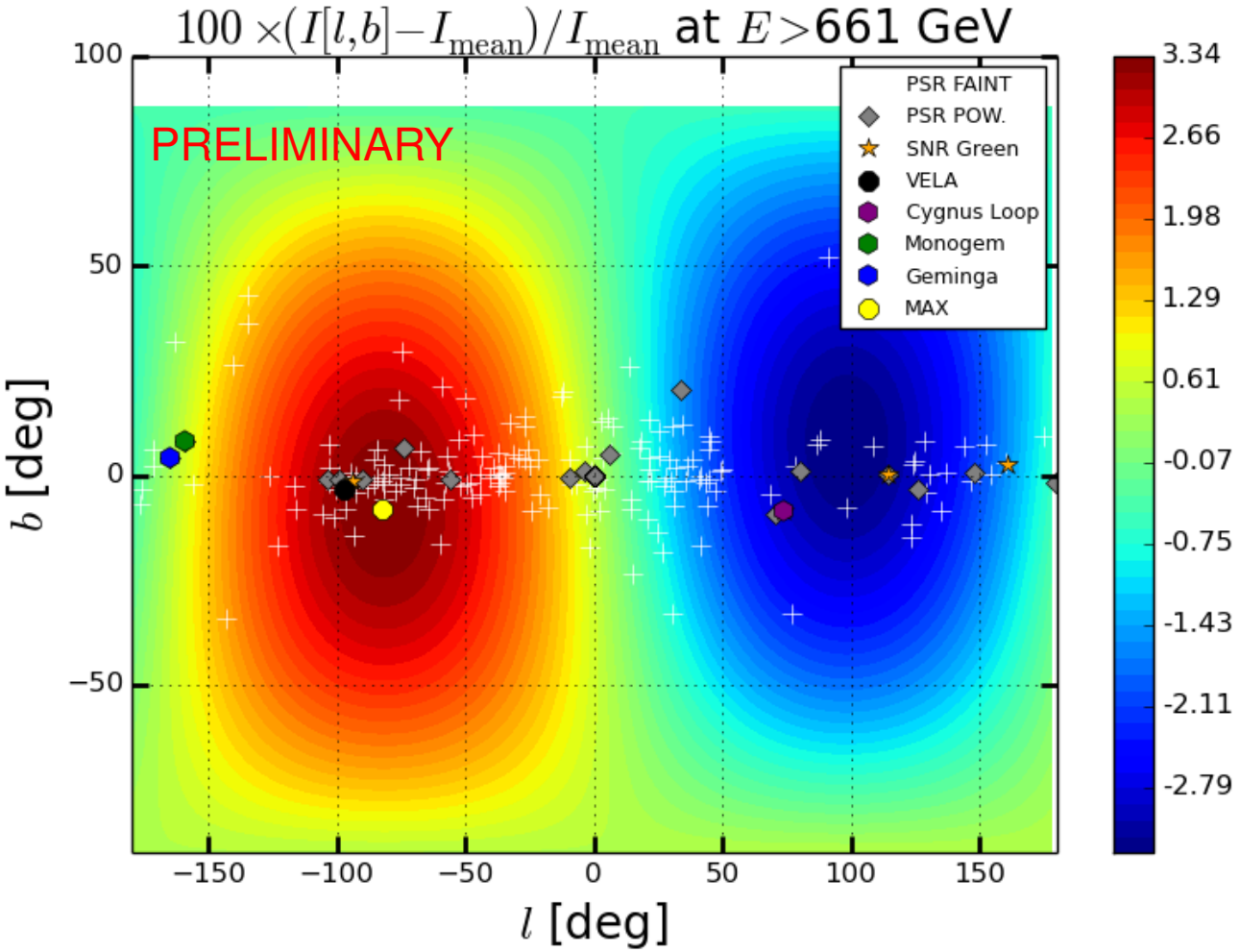

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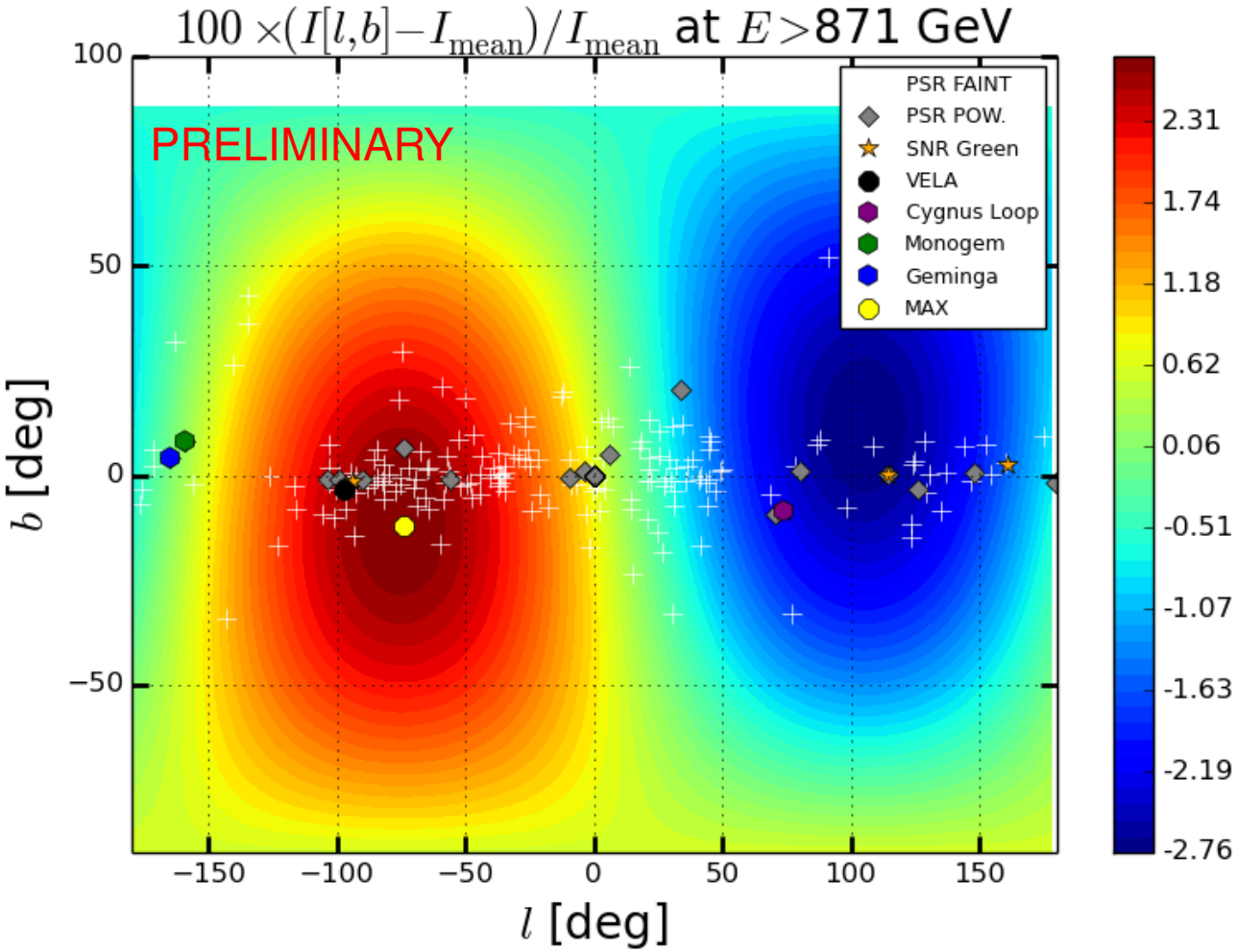

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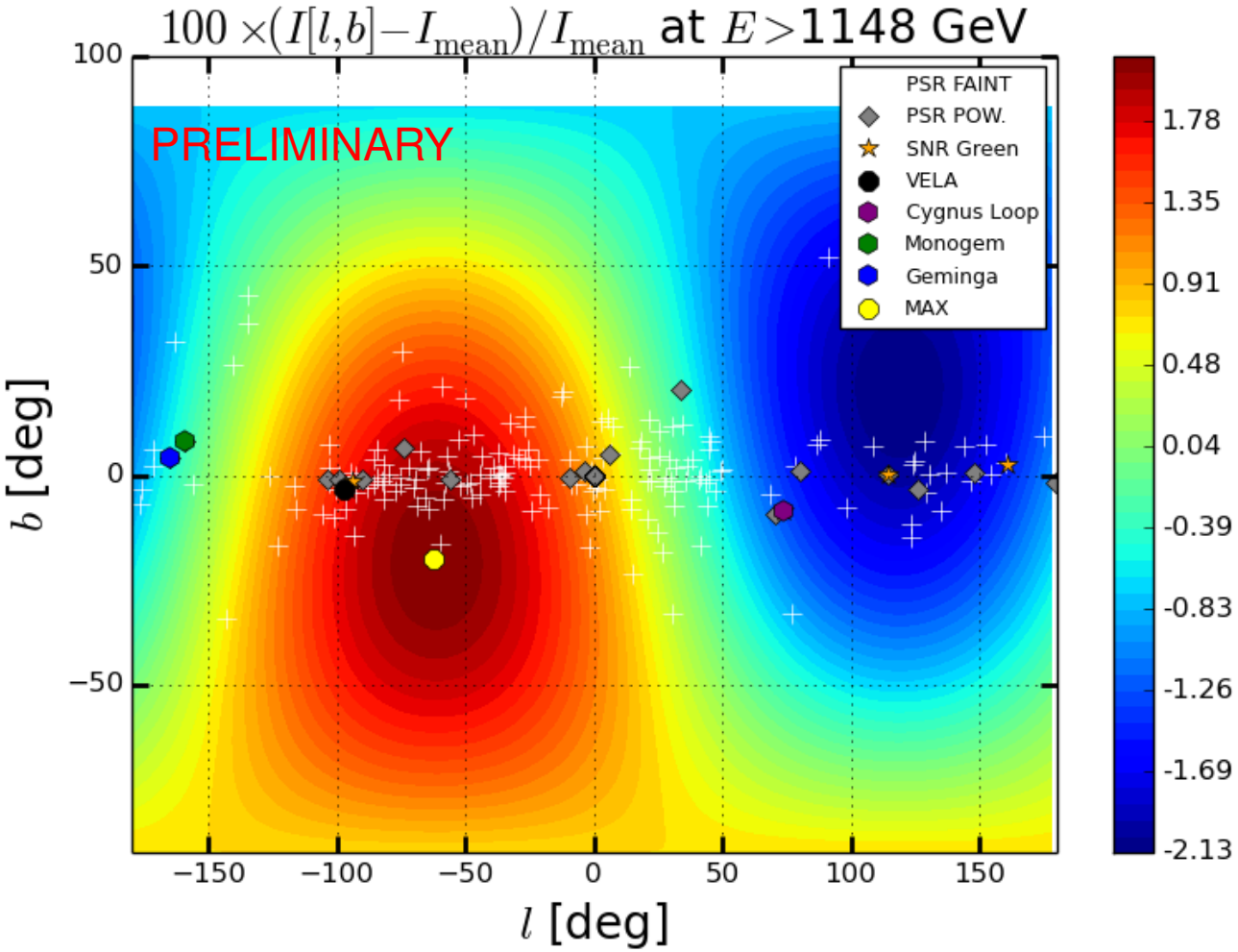

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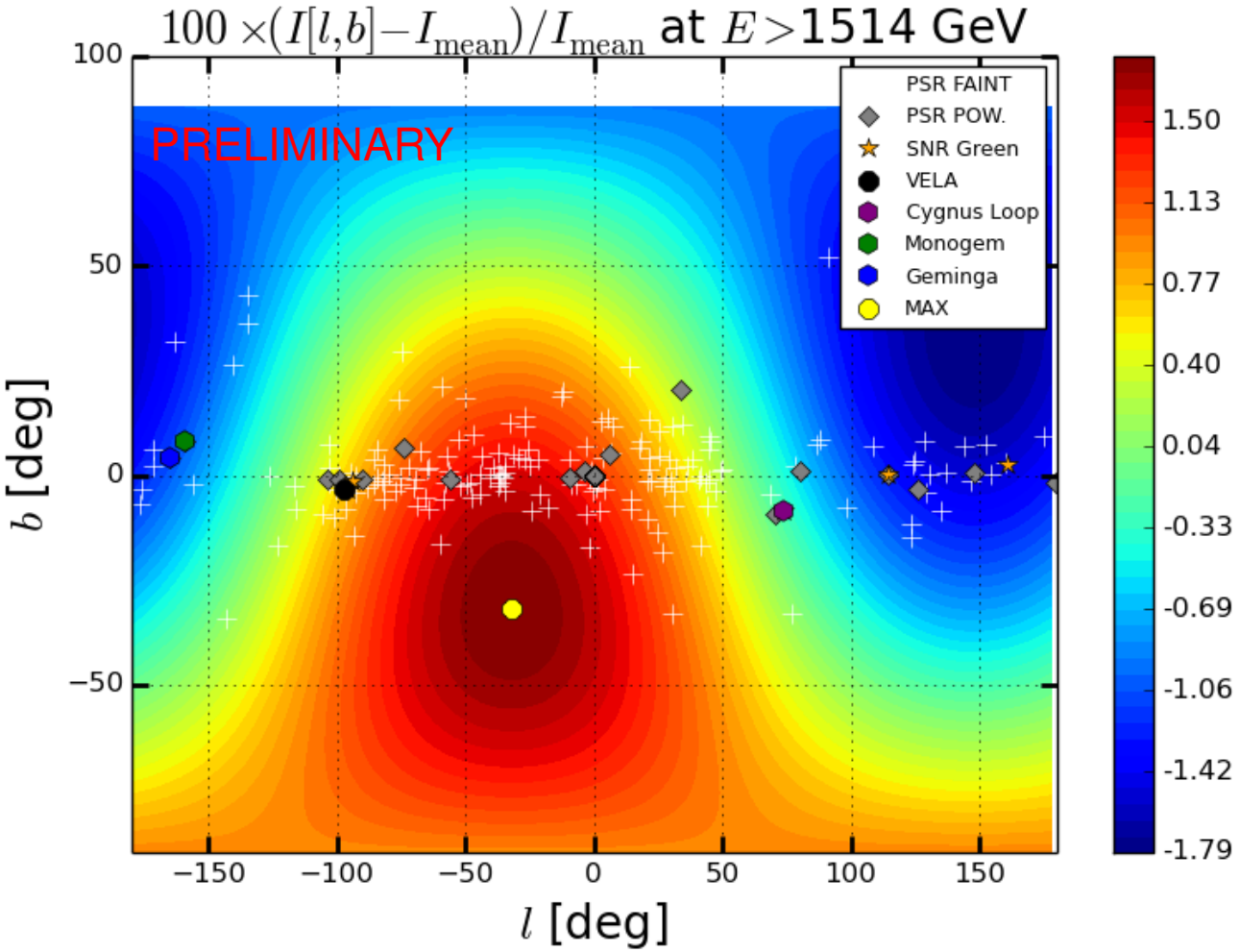

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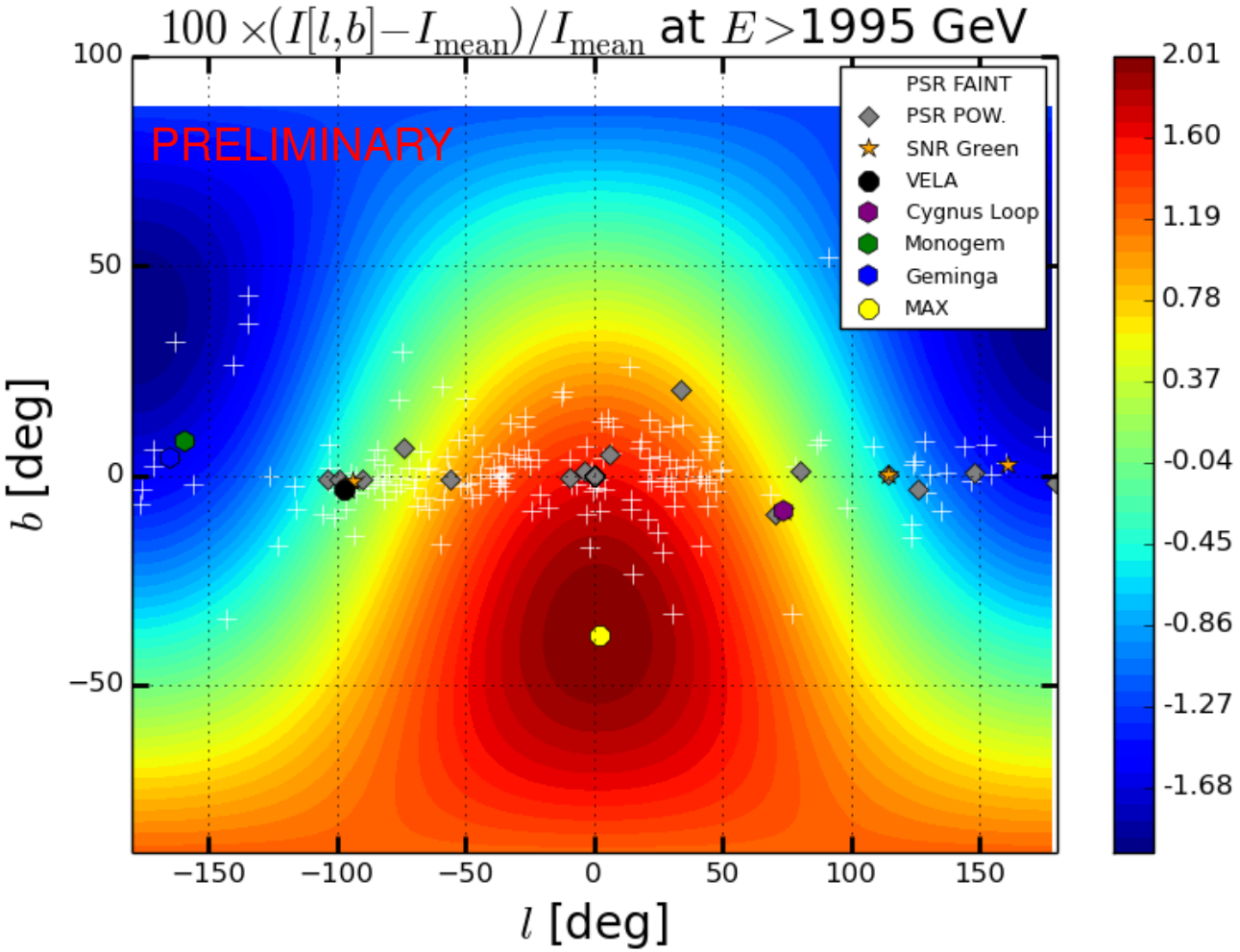

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[Shen&Mao1971]

Summary and outlook

Anisotropy from local sources may play a role in the interpretation of GeV-TeV $e^{\pm}$.

- We compute anisotropies from single near sources consistenly with AMS-02 $e^{\pm}$ fluxes.
- Vela ans Cygnus SNR can give $\Delta_{e^+ + e^-} > 10^{-2}$ in TeV range
- Source parameters uncertainties affect the anisotropy prediction

- We compute the CR $e^+ + e^-$ intensity as a function of direction.
- $I_{\max}$ is dominated by Vela SNR
- Interplay with Cygnus at TeV energies

⋆ AMS-02, Fermi-LAT: forthcoming results with more statistics
⋆ CALET-DAMPE: scheduled analysis in ∼5 years

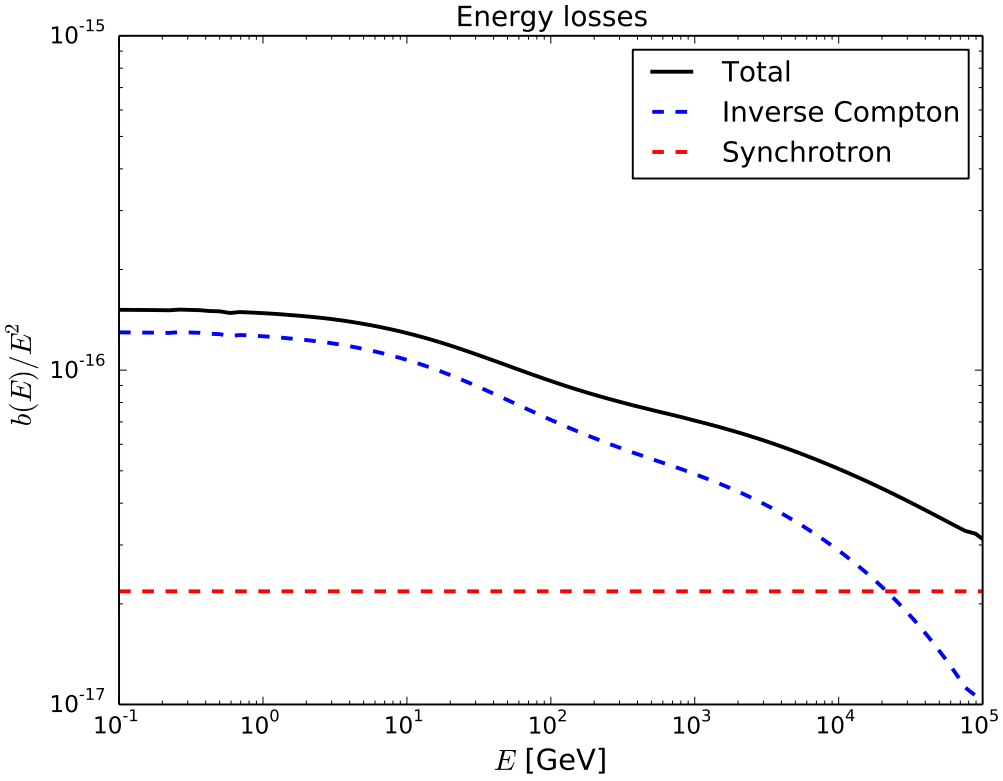
Thank you for the attention!

Backup

Energy losses

Above a few GeV Synchrotron + Inverse Compton dominate over ionization, adiabatic and bremsstrahlung. [Delahaye+2008]

- Full relativistic treatment from [Delahaye+2010]
- IC scattering off the interstellar radiation field (ISR)
- ISR from [Delahaye+2010] M2
- Synchrotron emission on galactic magnetic field $B = 3.6\mu$G [Sun+2007]



Heliosphere effects on lepton anisotropy

Heliosphere or local galaxy effects on anisotropy are beyond of the scope of this work.

Effects for E$<$TeV may be important, but

1. Same effect on proton and leptons
2. Solar time variations [Busching+2008]
3. Energy dependency connected to flux and cutoff of sources
4. Propagation in HMF is dominated by diffusion [Strauss&Potgieter2014]

- Anisotropic diffusion: small scale features, hotspots or streams [Drury+2008; Kister+2012]
- DAMPE-CALET: predictions for $>$ TeV energies

Fit to AMS-02 fluxes

Fit parameters results consistent with [DiMauro+2014, DiMauro+2016]

Table: Fit results for $R_{\rm cut} = 0.7$ kpc, MAX, $\gamma_{\rm Vela} = 2.5$

$\gamma_{\rm SNR}$	$Q_{0,\rm SNR}$	$B_{\rm Vela}$	$B_{\rm near}$	$\gamma_{\rm PWN}$	$\eta_{\rm PWN}$	$q_{\rm sec}$
2.25	$2.25 \cdot 10^{49} erg/100$yr	9μG	0.35	1.9	0.07	1.74

- SNR spectral index $\gamma \sim 2$: Fermi mechanism+ mean radio index from Green catalog
- PWN spectral index: from observed PWN radio index of synch emission: $\gamma < 2$

Age effect on local sources

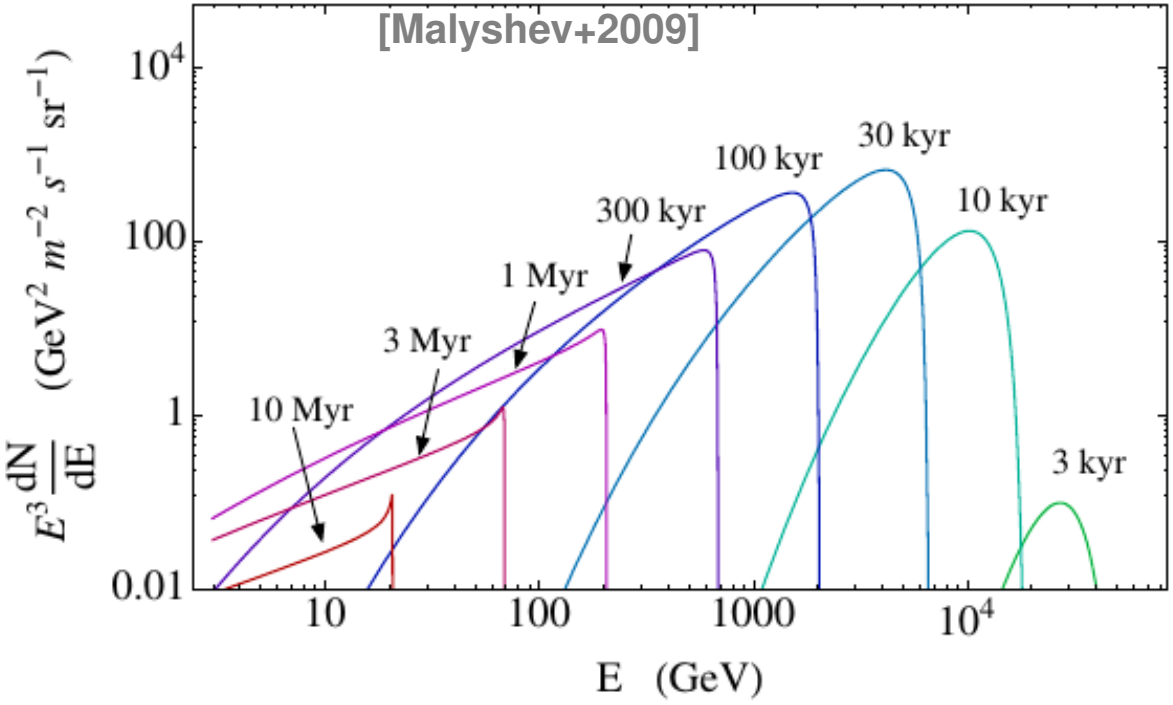


FIG. 1: Time evolution of e^+e^- flux on the Earth from a pulsar at a distance of 1 kpc with $\eta W_0 = 3 \times 10^{49}$ erg, an injection index $n = 1.6$, and an injection cutoff $M = 10$ TeV.