Anisotropies in GeV-TeV cosmic ray electron and positron fluxes

based on
S. Manconi, M. Di Mauro, F. Donato, in preparation

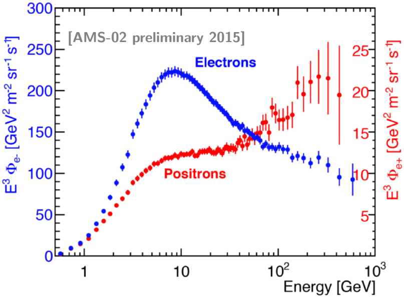
Silvia Manconi

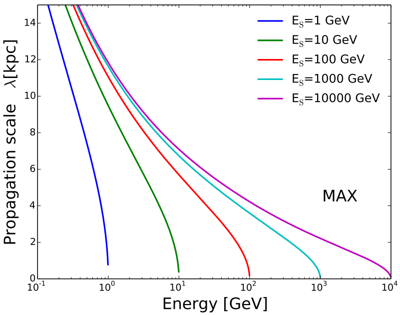
University of Torino and INFN

25th European Cosmic Ray Symposium
4-9 September, 2016

GeV-TeV $e^{\pm}$ are probes of the local Galaxy

AMS-02, *Fermi*-LAT, PAMELA: **high precision measurements** for GeV-TeV $e^{\pm}$ **fluxes** and **anisotropy** upper limits





⇒ Typical propagation scale for GeV-TeV $e^{\pm}$ is < 5 kpc

Flux interpretation:

- Astrophysical known sources? [Malyshev+2009; Di Mauro+2014; ...]
- Dark matter annihilations? [Cirelli+2009; Grasso+2009; Di Mauro+2016; ...]

Outline

Can local astrophysical sources produce anisotropies in GeV-TeV $e^{\pm}$?

1. Sources

2. Diffusion

3. Anisotropy

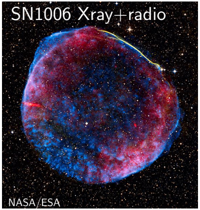
4. Analysis and methods

5. Results: Single sources

6. Results: Source collection

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

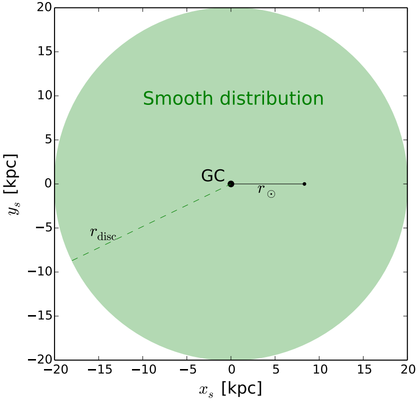
- Smooth SNR $Q_{0,\mathrm{SNR}}$ constraints from average characteristcs

[Delahaye+2010]

Supernova Remnants (SNRs) as e^- sources

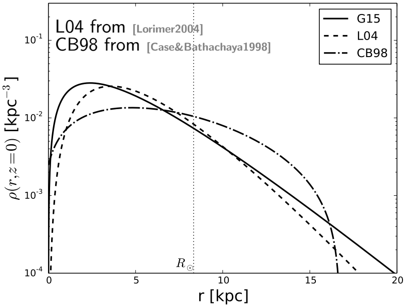
Spatial distribution

Smooth distribution of sources in the Galaxy:



Radial distribution from [Green2015] (G15)

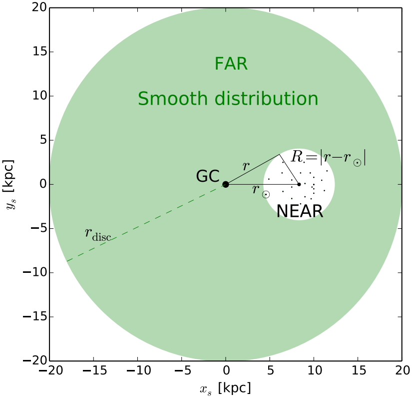
$$\rho(r) \propto \left(\frac{r}{r_\odot}\right)^\alpha \exp\left(-\beta\frac{(r-r_\odot)}{r_\odot}\right)$$



Supernova Remnants (SNRs) as e^- sources

Spatial distribution

Cutted smooth distribution +
single sources in the Galaxy:



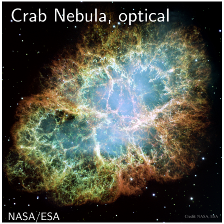
FAR component (R>$R_{\rm cut}$)
Radial distribution from [Green2015]

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

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

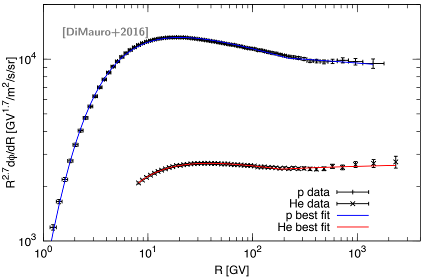
1. **Spatial distribution**: single PSR from ATNF catalog [Manchester+2005] (distance d, age T, W_0)
2. Pair release in the ISM for **T $\gtrsim$ 50 kyr** [Blasi&Amato2011]

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

Fit to AMS-02 p and He data



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

interstellar gas density   primary CR flux   inclusive cross section [Kamae+2006]

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

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, ...]

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

only for burst-like sources

diffusion

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

energy losses: synchrotron,IC

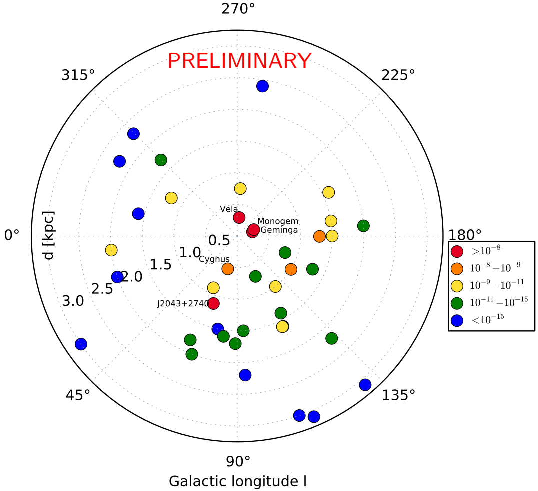
source term

- Propagation parameters constrained by B/C data[Donato2004]
- Solar modulation negligible for $E > 10$ GeV[Strauss&Potgieter2014]

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

Local known sources may contribute to anisotropy

Near SNRs from the **Green catalog** [Green2014]
Powerful PSRs from the **ATNF catalog** [Manchester+2005]



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

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

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

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

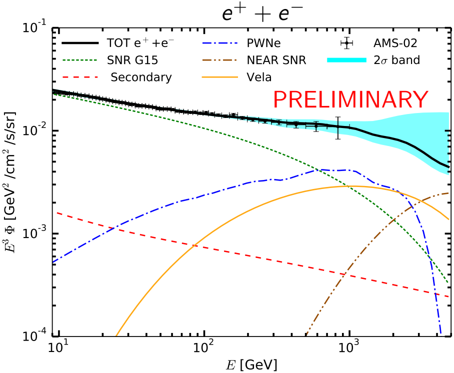
where ψ is the CR number density per unit volume and energy.

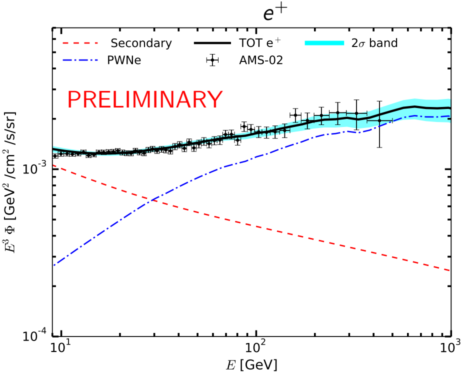
- Heliosphere effects for E<TeV
- **Integrated anisotropy** computed for $E_{\mathrm{max}} = 5$ TeV

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

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

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





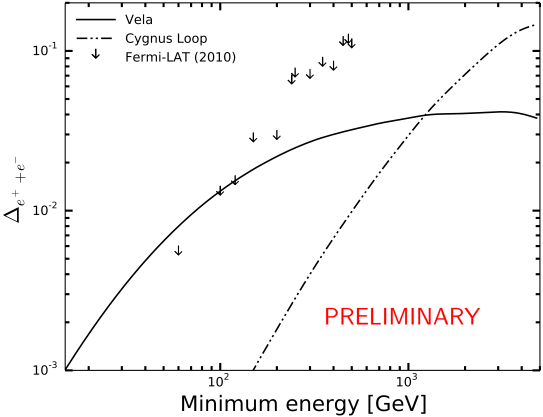
Preliminary results for $R_{\rm cut} = 0.7$ kpc, MAX

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:

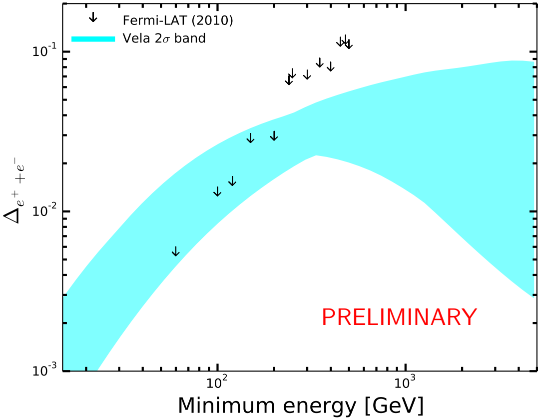
- Magnetic field $[1, 100]\mu$G
- Spectral index γ $[2.2, 2.8]$

[Alvarez+2001]

- Distance $[0.22, 0.32]$ kpc

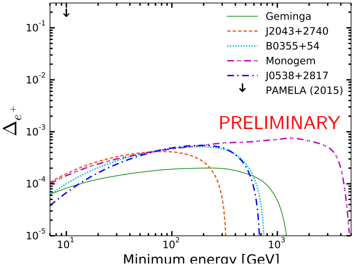
[Dodson+2003,Cha+1999]

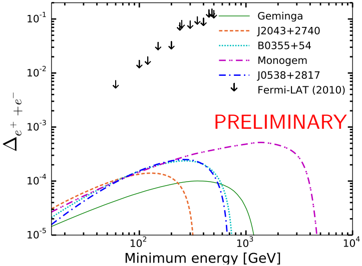
Uncertainties in source parameters are reflected in uncertainties for the predicted anisotropy

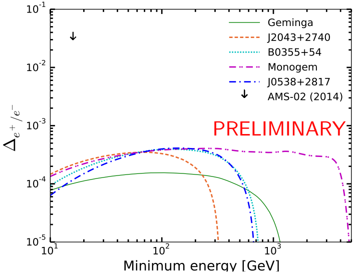


Anisotropies from single powerful PWNe

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





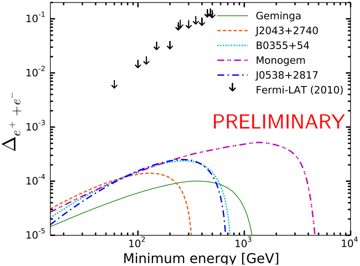


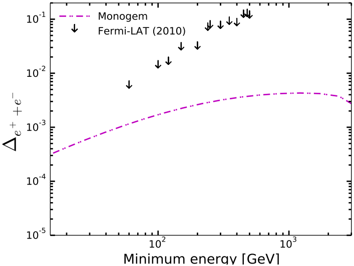
Anisotropies from single powerful PWNe

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

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

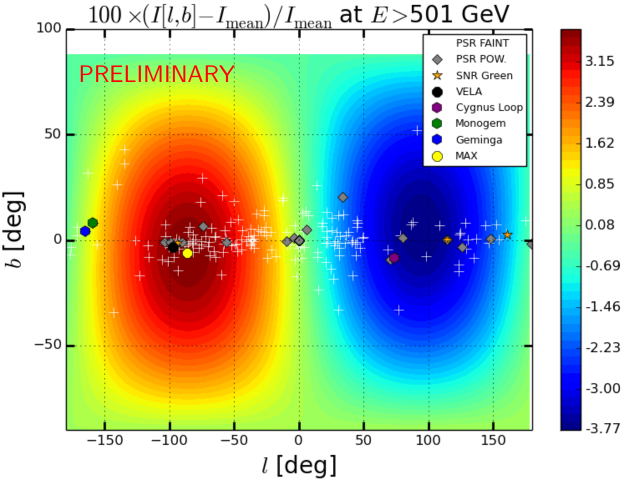
$\Downarrow$





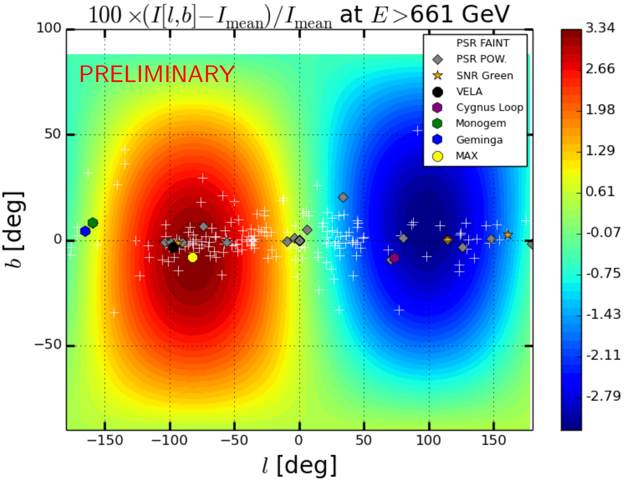
Anisotropy from a collection of sources

$$\Delta = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}; \quad I(E, \mathbf{n}) = \frac{c}{4\pi} \sum_i \psi_i(E, \mathbf{r}_i, t_i) \left(1 + \frac{3\mathbf{n} \cdot \mathbf{r}_i}{2ct_i}\right)$$ [Shen&Mao1971]



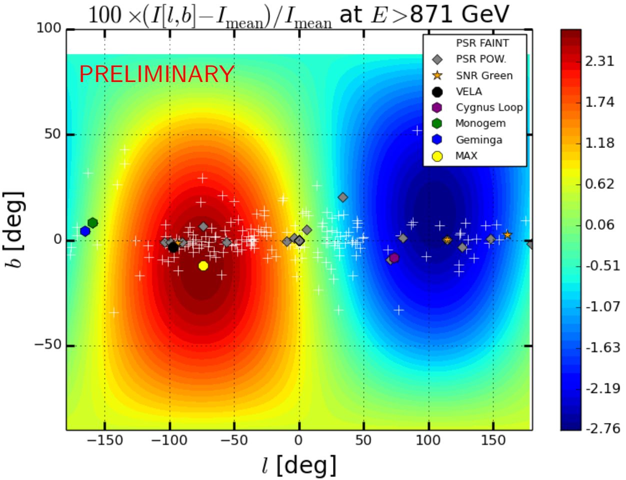
Anisotropy from a collection of sources

$$\Delta = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}; \quad I(E, \mathbf{n}) = \frac{c}{4\pi} \sum_i \psi_i(E, \mathbf{r}_i, t_i) \left(1 + \frac{3\mathbf{n} \cdot \mathbf{r}_i}{2ct_i}\right)$$ [Shen&Mao1971]



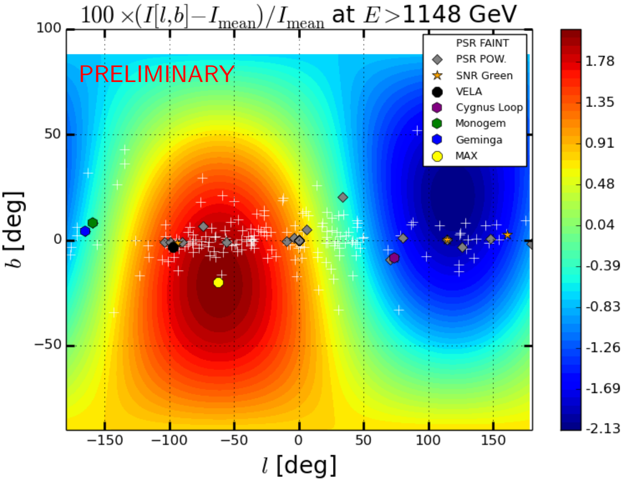
Anisotropy from a collection of sources

$$\Delta = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}; \quad I(E, \mathbf{n}) = \frac{c}{4\pi} \sum_i \psi_i(E, \mathbf{r}_i, t_i) \left(1 + \frac{3\mathbf{n} \cdot \mathbf{r}_i}{2ct_i}\right)$$ [Shen&Mao1971]



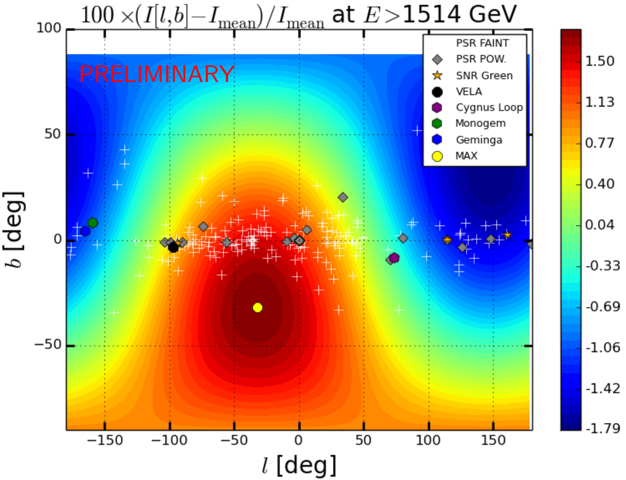
Anisotropy from a collection of sources

$$\Delta = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}; \quad I(E, \mathbf{n}) = \frac{c}{4\pi} \sum_i \psi_i(E, \mathbf{r}_i, t_i) \left(1 + \frac{3\mathbf{n} \cdot \mathbf{r}_i}{2ct_i}\right)$$ [Shen&Mao1971]



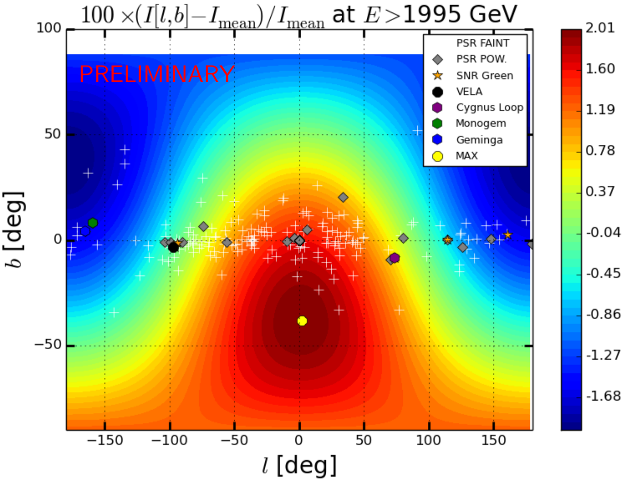
Anisotropy from a collection of sources

$$\Delta = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}; \quad I(E, \mathbf{n}) = \frac{c}{4\pi} \sum_i \psi_i(E, \mathbf{r}_i, t_i) \left(1 + \frac{3\mathbf{n} \cdot \mathbf{r}_i}{2ct_i}\right)$$ [Shen&Mao1971]



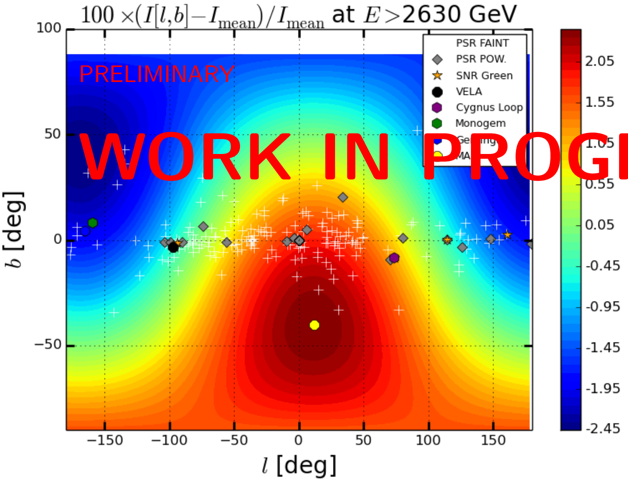
Anisotropy from a collection of sources

$$\Delta = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}; \quad I(E, \mathbf{n}) = \frac{c}{4\pi} \sum_i \psi_i(E, \mathbf{r}_i, t_i) \left(1 + \frac{3\mathbf{n} \cdot \mathbf{r}_i}{2ct_i}\right)$$ [Shen&Mao1971]



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]



Conclusions

Start: GeV-TeV $e^{\pm}$ are messengers of the local Galaxy

Goal: To study the anisotropy in GeV-TeV $e^{\pm}$ from near SNRs and PWNe

Done We compute anisotropies from single near sources consistenly with AMS-02 $e^{\pm}$ fluxes.

Result Vela ans Cygnus SNR can give $\Delta_{e^{+}+e^{-}} > 10^{-2}$ in TeV range

Result Source parameters uncertainties affect the anisotropy prediction

Done We compute the CR $e^{+}+e^{-}$ intensity as a function of direction.

Result $I_{\rm max}$ is dominated by Vela SNR

Result Interplay with Cygnus at TeV energies

Anisotropies can contribute to the CR $e^{\pm}$ flux interpretation.

Conclusions

Start: GeV-TeV $e^{\pm}$ are messengers of the local Galaxy

Goal: To study the anisotropy in GeV-TeV $e^{\pm}$ from near SNRs and PWNe

Done We compute anisotropies from single near sources consistenly with AMS-02 $e^{\pm}$ fluxes.

Result Vela ans Cygnus SNR can give $\Delta_{e^{+}+e^{-}} > 10^{-2}$ in TeV range

Result Source parameters uncertainties affect the anisotropy prediction

Done We compute the CR $e^{+} + e^{-}$ intensity as a function of direction.

Result $I_{\max}$ is dominated by Vela SNR

Result Interplay with Cygnus at TeV energies

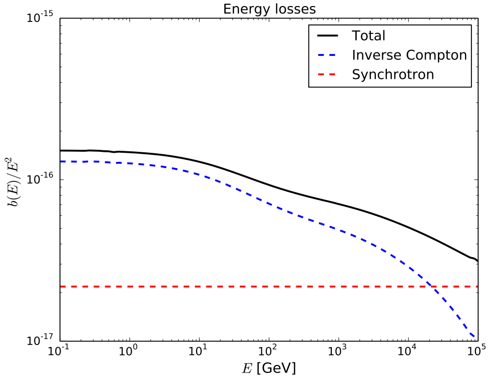
Anisotropies can contribute to the CR $e^{\pm}$ flux interpretation.

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: $\gamma < 2$