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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TeV Particle Astrophysics

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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

⇒ 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

1. Sources
2. Diffusion
3. Anisotropy
4. Analysis and methods
5. Results: Single sources
6. Results: Source collection

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:

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

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

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

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

- Smooth SNR $Q_{0,\text{SNR}}$ constraints from average characteristics [Delahaye+2010]
Supernova Remnants (SNRs) as $e^-$ sources

Spatial distribution

Smooth distribution of sources in the Galaxy:

Radial distribution from [Green2015] (G15)

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

$L04$ from [Lorimer2004]
$CB98$ from [Case&Bathachaya1998]
Supernova Remnants (SNRs) as $e^-$ sources

Spatial distribution

Cutted smooth distribution + single sources in the Galaxy:

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

$R_{\text{cut}} = 0.7, 3$ kpc
Pulsar wind nebulae (PWNe) as $e^\pm$ sources

- Acceleration mechanism: **relativistic shocks**
- Injection spectrum:
  
  $$Q(E) = Q_{0,\text{PWN}} \left( \frac{E}{E_0} \right)^{-\gamma_{\text{PWN}}} \exp \left( -\frac{E}{E_c} \right)$$

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

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

  $\eta =$ 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: $\eta$ and $\gamma_{\text{PWN}}$ are the same for all PWNe
Secondary $e^\pm$ are produced by CR nuclei fragmentation on the ISM

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

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

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

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

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<tr>
<th>Model</th>
<th>$\delta$</th>
<th>$K_0$ [kpc$^2$/Myr]</th>
<th>$L$ [kpc]</th>
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<td>MED</td>
<td>0.70</td>
<td>0.0112</td>
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<td>MAX</td>
<td>0.46</td>
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Results from [Kappl+2015, Genolini+2015] included in MED-MAX uncertainties

[Donato2004] [Strauss&Potgieter2014]
Propagation of $e^\pm$ is dominated by diffusion and energy losses

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

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

only for burst-like sources

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

energy losses: synchrotron, IC

source term

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

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Results from [Kappl+2015, Genolini+2015] included in MED-MAX uncertainties
Local known sources may contribute to anisotropy

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

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

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

⇒ In the diffusion propagation regime: [Ginzburg&Syrovatskii1964]:

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

where $\psi$ is the CR number density per unit volume and energy.

- Heliosphere effects for $E < \text{TeV}$
- **Integrated anisotropy** computed for $E_{\text{max}} = 5 \text{ TeV}$
Anisotropy predictions are obtained consistently with AMS-02 $e^{\pm}$ fluxes

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

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

Preliminary results for $R_{cut} = 0.7$ kpc, MAX
Anisotropies from single near SNRs

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

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

- 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 $\gamma [2.2, 2.8]$
  
  [Alvarez+2001]

- Distance $[0.22, 0.32] \text{kpc}$
  
  [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
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 \cite{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 $\eta \gtrsim 40\%$

PRELIMINARY
Anisotropy from a collection of sources

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

\[ [\text{Shen\&Mao1971}] \]
Anisotropy from a collection of sources

\[ \Delta = \frac{l_{\text{max}} - l_{\text{min}}}{l_{\text{max}} + l_{\text{min}}} \]

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[Shen&Mao1971]
Anisotropy from a collection of sources

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

[Shen&Mao1971]
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[Shen&Mao1971]

Work in progress

S. Manconi (University of Torino & INFN) Anisotropies in CR leptons
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.
  - $I_{\text{max}}$ 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 $\sim 5$ 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 $B = 3.6 \mu \text{G}$ [Sun+2007]
Heliosphere effects on lepton anisotropy

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

Effects for $E < \text{TeV}$ 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 $> \text{TeV}$ energies
Fit to AMS-02 fluxes

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

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

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<tr>
<th>$\gamma_{\text{SNR}}$</th>
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<tr>
<td>2.25</td>
<td>$2.25 \cdot 10^{49}$ erg/100yr</td>
<td>9$\mu$G</td>
<td>0.35</td>
<td>1.9</td>
<td>0.07</td>
<td>1.74</td>
</tr>
</tbody>
</table>

- 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.