Propagation of high-energy cosmic-ray electrons in the interstellar medium

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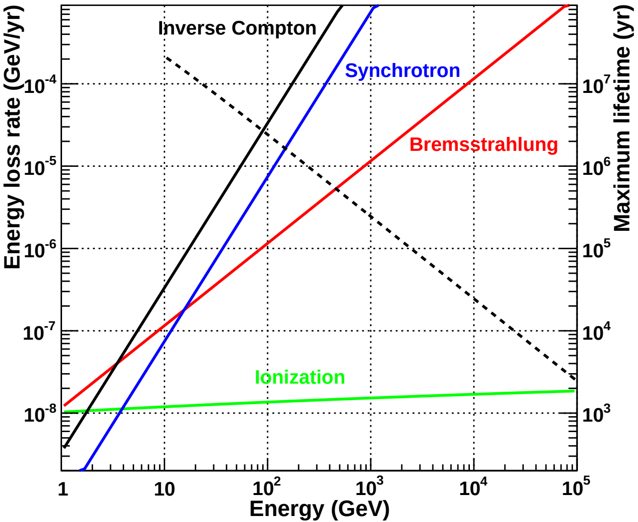
CRISM, June 24-27, 2014

Cosmic-ray electrons

- Strong energy loss at high energy
- Nearby sources
- Probe into local cosmic-ray accelerators
- X-ray and γ-ray astronomies, dark matter, ...

Electron energy loss processes



Distance of source(s)

- Random walk treatment of free diffusion

$$distance \approx \sqrt{2Dt}$$

- Diffusion coefficient

$$D = D_0 (E/\mathrm{GeV})^{\delta}$$

$$D_0 = 1\text{-}5 \times 10^{28}\ \mathrm{cm^2/s}\ ;\ \delta = 0.3\text{-}0.6$$

- For 10-1000 GeV, *distance* $\approx$ 1.8-0.4 kpc

$\Rightarrow$ The sources of high-energy cosmic-ray electrons are within a few kpc.

The conventional model

- $1^{\rm st}$ kind of sources: same as nuclei (SNR...)

  $\Longrightarrow$ Only negative electrons

- $2^{\rm nd}$ kind of sources: collision with the ISM

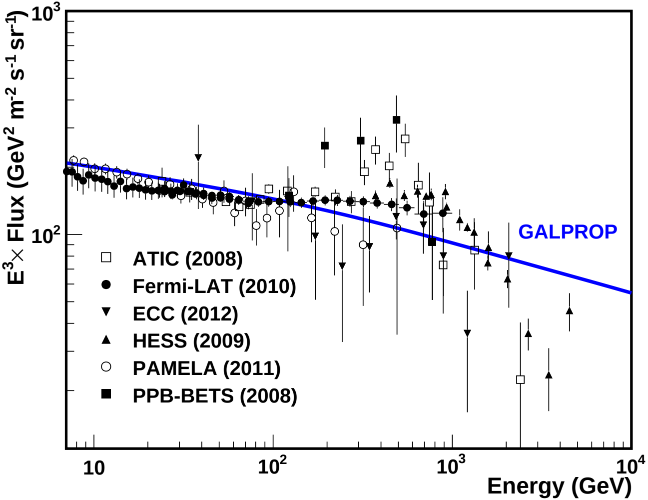
  $\Longrightarrow$ Equal amounts of negative electrons and positrons

- Predictions

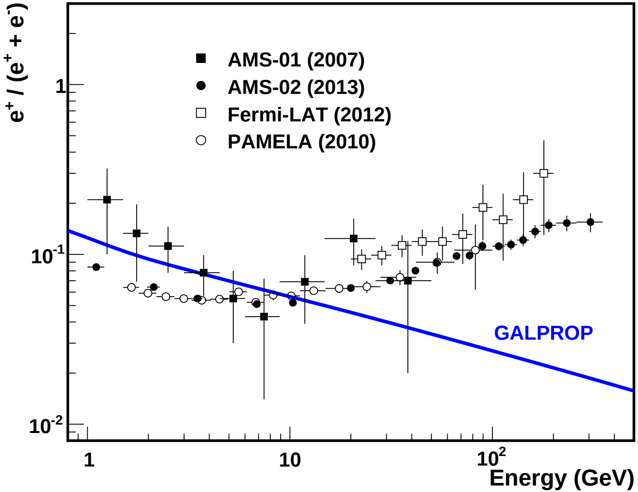
  1) The electron spectrum $\propto E^{-3}$ **with no features**

  2) The positron fraction **decreases** with energy

Electron energy spectrum



Positron fraction



Explaining anomalies

- Nearby astrophysical sources

  $\Longrightarrow$ Pulsars / SNRs / ...

- Dark matter origin

  $\Longrightarrow$ WIMPs ...

- Propagation effects

  $\Longrightarrow$ Special distribution of sources

Monte Carlo feasibility

- Proximity of sources

  $\Longrightarrow$ Limited lifetime of electrons

- Simplicity of interactions

  $\Longrightarrow$ No hadronic interaction

- Availability of computing resources

  $\Longrightarrow$ Clusters, grids, ...

Comparison

Transport equation	Monte Carlo simulation
macroscopic	microscopic
source term	
diffusion coefficient (D)	mean free path (λ)
$D = \frac{1}{3} v \lambda$	
average values	average values + fluctuations

Monte Carlo procedure

- Select the source
- Inject an electron with an energy E
- Generate the free path l ($\propto e^{-l/\lambda}$)
- Adjust energy (energy loss rate: $aE + bE^2$)
- Calculate diffusion time and position
- Iterate the process until

    1) Position goes beyond Galaxy boundaries

    2) Diffusion time exceeds maximum lifetime

    3) Electron crosses solar system
- Calculate the energy spectrum

Basic hypotheses

- Pulsars/SNRs as sources of electrons

  $\Longrightarrow$ Equal parts of e^- and e^+

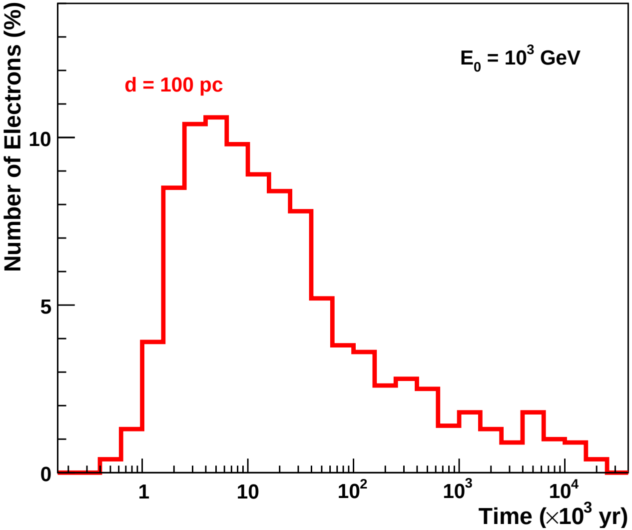
- 2-component model

  $\Longrightarrow$ Distant sources + Nearby sources

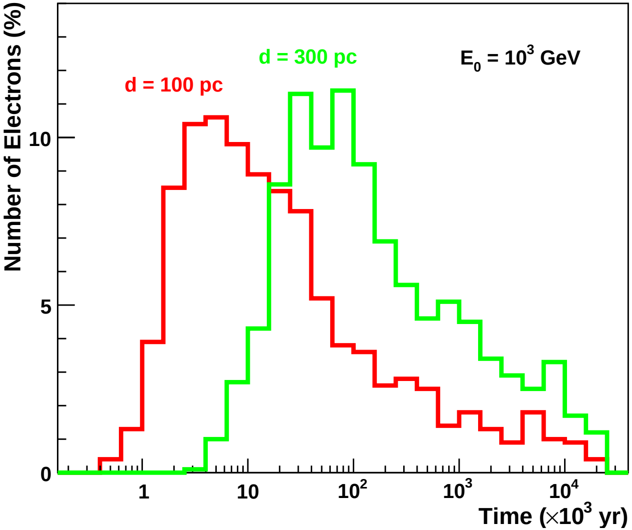
- Burst like approximation

  $\Longrightarrow$ Point-like and instantaneous sources

Electron lifetime distribution



Electron lifetime distribution



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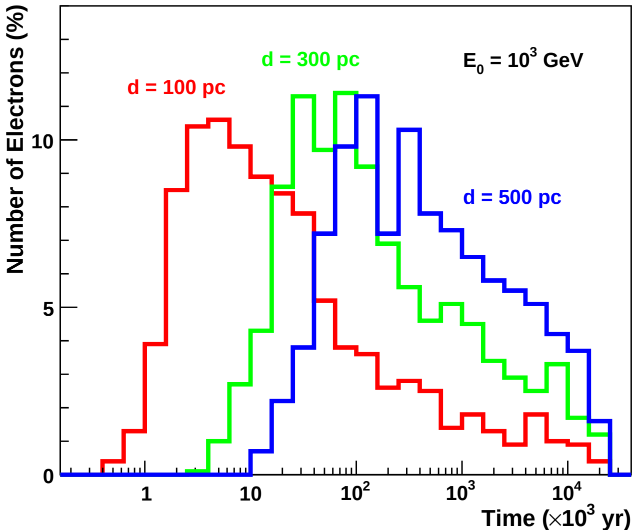

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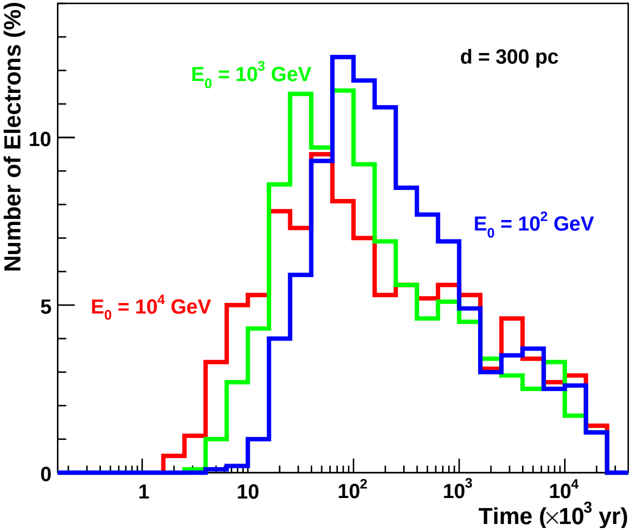

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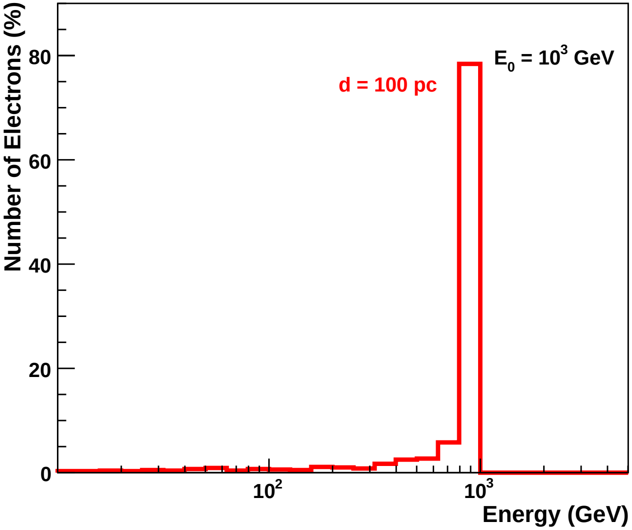

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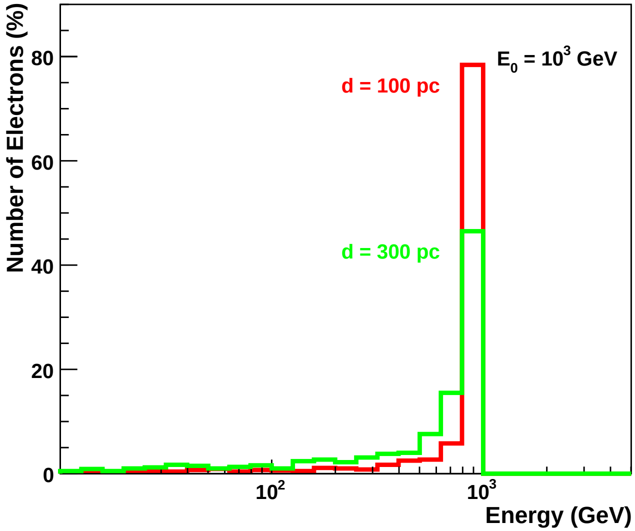

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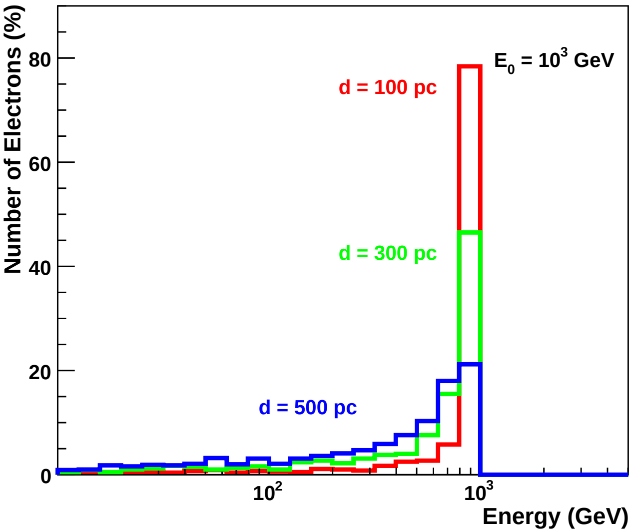

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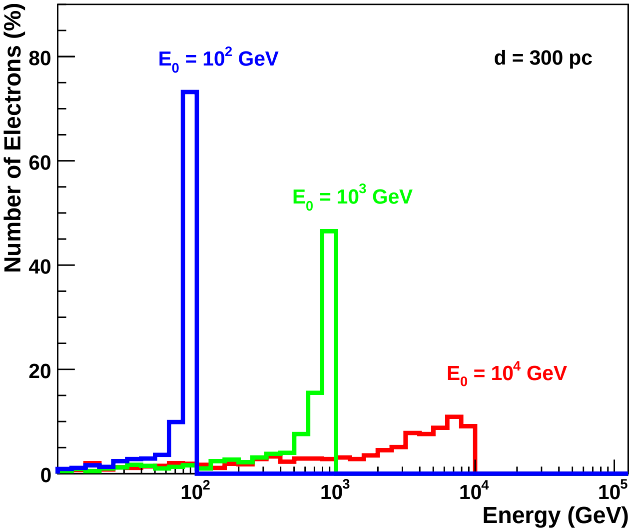
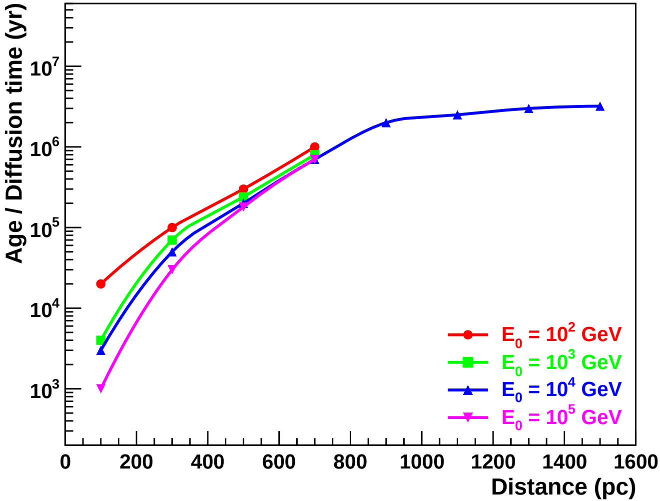


First deductions

- The lifetime distribution depends more on the source distance than the initial energy.
- There exist a "right timing" of electron emission for each position of the source.
- More effective contribution of a source if its age is around the diffusion time at maximum.

Potential candidates



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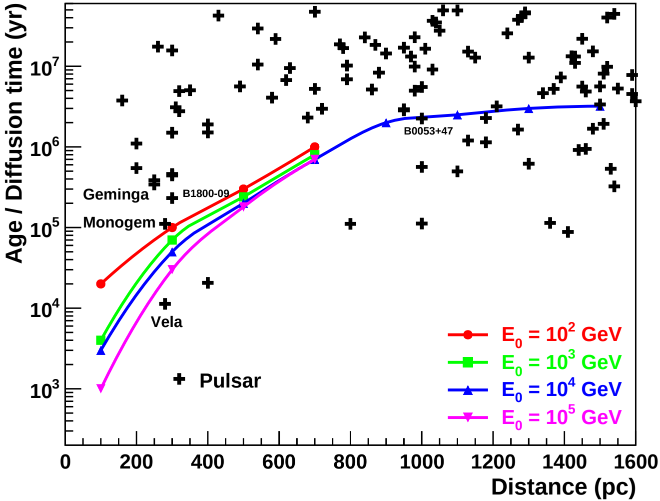

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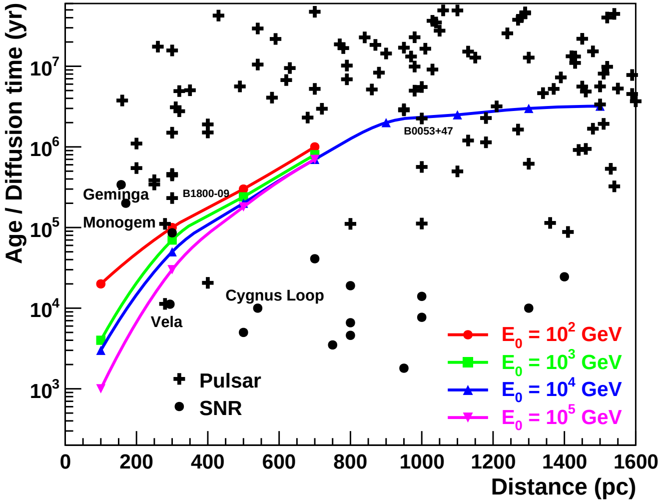


Injection energy spectrum

- Exponentially-truncated power-law spectrum

$$Q(E) = Q_0 E^{-\gamma} \exp(-E/E_{cut})$$

- Source spectral index γ

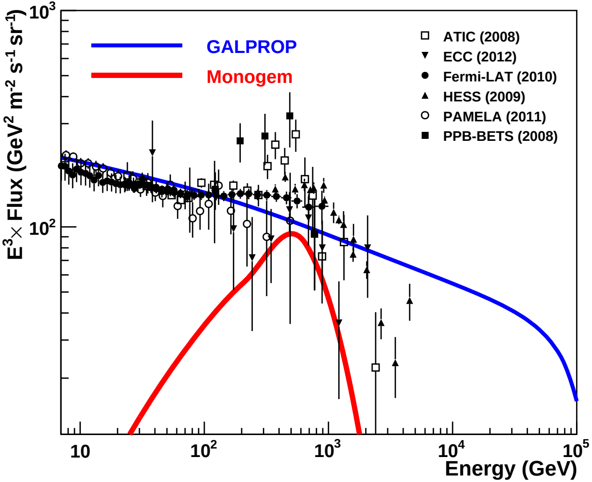
$$\gamma_{\rm PWN} \lesssim 2 \; ; \qquad \gamma_{\rm SNR} \gtrsim 2.0$$

- Energy cutoff $E_{\rm cut}$: 100 GeV - 100 TeV
- Parameter Q_0

$$\int_0^\infty Q(E)\, E\, \mathrm{d}E = \eta W \approx 10^{48}\ \mathrm{erg}$$

Monogem pulsar

$\gamma = 2.0$; $E_{\rm cut} = 1\,$TeV; $\eta W = 10^{45}$ erg



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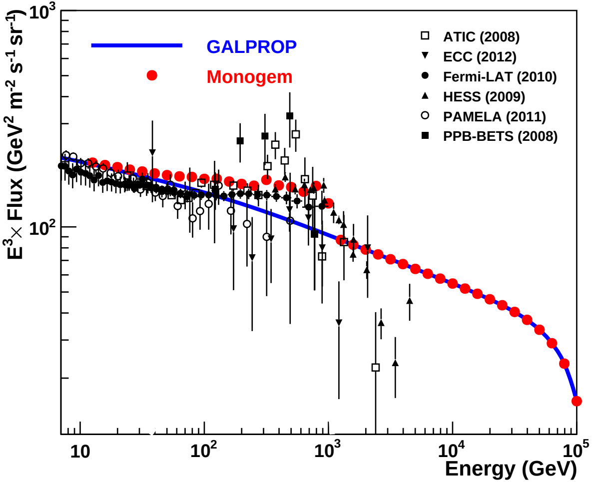

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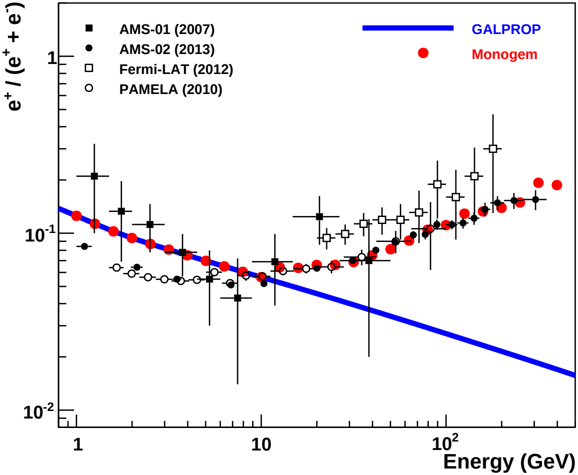

Conclusion

- The high-energy cosmic-ray electrons should originate from nearby sources
- The exact nature of these sources is still very controversial
- Monte Carlo simulation may help in our quest for the origin of these particles

Thank you!

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CRISM-2014, Montpellier