Cosmic Rays* in the $\gamma$-ray Sky

*Galactic CRs

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Cosmic Ray SIG
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**Synergies:**

\(\gamma\)-rays provide a unique perspective on cosmic ray astrophysics:

- via direct and indirect detection techniques
- to address CR origins, acceleration, and propagation

Indirect CR evidence:

- potential sources: MW studies using spatial and spectral information give insight into particle populations and acceleration processes
- can depend on environment…
- Use environment as CR “calorimeter” to infer CR distributions beyond Earth. Studies of diffuse \(\gamma\)-rays give insight into CR propagation.

Direct CR detection:

- CRs are the background for all \(\gamma\)-ray experiments: collect and analyze data!
- Use particle shower techniques, Earth’s B-field, etc for charge separation.

CR measurements provide insight into the sources best investigated in \(\gamma\)-rays.
Indirect: Potential Sources

Detection of low energy pion-decay cutoff in 3 SNRs’ spectra suggests proton acceleration:

Ackermann et al. 2012
Detection of low energy $\pi^0$-decay cutoff in 3 SNRs’ spectra suggests proton acceleration:

W51C: 3rd SNR w evidence of $\pi^0$ bump

Maximum Energy??
Fermi-LAT SNR Catalog: relate flux measurements to the energy imparted to CRs:

\[ F(1-100\,\text{GeV}) \approx f(\Gamma_{CR}) \times \frac{\epsilon_{CR}}{0.01} \times \frac{E_{SN}}{10^{51}\,\text{ergs}} \times \frac{n}{1\,\text{cm}^{-3}} \times \left(\frac{d}{1\,\text{kpc}}\right)^{-2} \times 10^{-9}\,\text{cm}^{-2}\text{s}^{-1} \]

\( \epsilon_{CR} \) => energy content in particles accelerated up to the observation time relative to the SN explosion energy. If energy losses & escape negligible, \( \epsilon_{CR} = \) hadron efficiency.
Constraining SNRs’ CR Acceleration

Fermi-LAT SNR Catalog: relate flux measurements to the energy imparted to CRs:

\[
F(1 - 100 \text{ GeV}) \approx f(\Gamma_{CR}) \times \frac{\varepsilon_{CR}}{0.01} \times \frac{E_{\text{SN}}}{10^{51} \text{ ergs}} \times \frac{n}{1 \text{ cm}^{-3}} \times \left(\frac{d}{1 \text{ kpc}}\right)^{-2} 10^{-9} \text{ cm}^{-2} \text{s}^{-1}
\]

where we take:

- photon index $\Gamma_{\text{GeV}}$ as a proxy for CR index $\Gamma_{\text{CR}}$
- $f(\Gamma_{\text{CR}}) \sim \text{constant for } E_{\text{CR,max}} > \sim 200 \text{ GeV}$

1-100 GeV flux for a given CR$_{\text{max}}$ energy:

$\varepsilon_{\text{CR}} \Rightarrow$ energy content in particles accelerated up to the observation time relative to the SN explosion energy.

If energy losses & escape negligible,

$\varepsilon_{\text{CR}} = \text{hadron efficiency.}$

[Diagram showing the relationship between CR$_{\text{max}}$ energy and 1-100 GeV flux with color-coded regions and line graphs for different values of $\Gamma$.]
Constraining SNRs’ CR Acceleration

Estimates of and upper limits on the CR energy content span more than 3 orders of magnitude:

- SNRs with $\varepsilon_{CR} = 1$ ($E_{CR} = E_{SN} \equiv 10^{51}$ erg) => higher density than derived from X-ray or assumed
  => interacting SNRs are in a dense environment.
- Young SNRs $\varepsilon_{CR} \sim 0.1 - 1.0$ => IC processes may contribute to their measured luminosity.
Indirect: Diffuse Studies

Study propagation around sources:

**W44:**
Particle escape? Shocked cloud?

Use MW observations to find new sources!

Cocoon of 10-100 GeV γ-ray emission
IR emission from Cygnus Superbubble

Fermi-LAT SNR Catalog has >100 GeV sources detected within 3° of a known SNR…

Credit: I. A. Grenier (Fermi LAT/AIM/U. Paris Diderot/CEA) and L. Tibaldo (Fermi LAT/SLAC).

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Indirect: Diffuse Studies

Infer CR propagation using High and Medium Velocity Clouds:

- Emissivity = $\gamma$-ray emission rate / H atom
- $z =$ height above Galactic plane

- $\gamma$-ray emissivity decreases as a function of distance from Galactic disk
- First direct corroboration of CR acceleration in disk and propagation into halo
- Complex A upper limit: currently most stringent constraint on CR flux at $z \sim$ few kpc.

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Direct: Leptons

$\gamma$-ray instruments such as Fermi and Imaging Air Cherenkov Telescopes measure lepton showers: $e^+ + e^-$

LAT/Bonino, et al. 2015

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Direct: Leptons

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LAT/Bonino, et al. 2015

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LAT/DiMauro, et al. 2015
Direct: Positron Fraction

Fermi measurement uses Earth’s magnetic field to separate $e^+$ from $e^-$:

Direct: Positron Fraction

Fermi measurement uses Earth’s magnetic field to separate $e^+$ from $e^−$:

![Graph showing positron fraction measurements across different energies and longitudes.](image)

Direct: Positron Fraction

Fermi measurement uses Earth’s magnetic field to separate $e^+$ from $e^-$:

Direct: Positron Fraction

Fermi measurement uses Earth’s magnetic field to separate $e^+$ from $e^-$:

Direct: Hadrons

Fermi-LAT proton measurement:

- $E > 20\text{GeV}$
- 3 month’s data
- Above atmosphere…

LAT/Green, et al. 2015
We can use $\gamma$-rays to gain insight:
- into CR origins, acceleration, and propagation
- via direct and indirect detection techniques

Potential sources: SNRs, PWNe, PSRs, Massive star associations, …
- Combine spatial and spectral $\gamma$-rays information with MW observations to infer the underlying particle populations, acceleration mechanisms, and emission processes.
- Study shock dynamics/escape via nearby sources.
- Use MW data to find/identify new sources!

Propagation:
- Use clouds as CR “calorimeter” to infer CR distributions beyond Earth.
- H&IVCs and also see Chamaeleon complex, local HI emissivities, L & SMC, …

Direct CR measurements:
- constrain sources, locations, and propagation.
- Measurement with different techniques helps reduce impact of systematic error!

By diversifying and expanding our multimessenger CR studies, we will obtain the most profound insights in CR astrophysics.

PaMELA + AMS + ISS-CREAM + SuperTIGER + CALET + ACE + HELIX + HNX + HAWC + Fermi + VERITAS + MAGIC + HESS + CTA + NuSTAR + Chandra + XMM + IR + $\mu$wave + radio + IceCube + distances + … => CR origins, propagation!