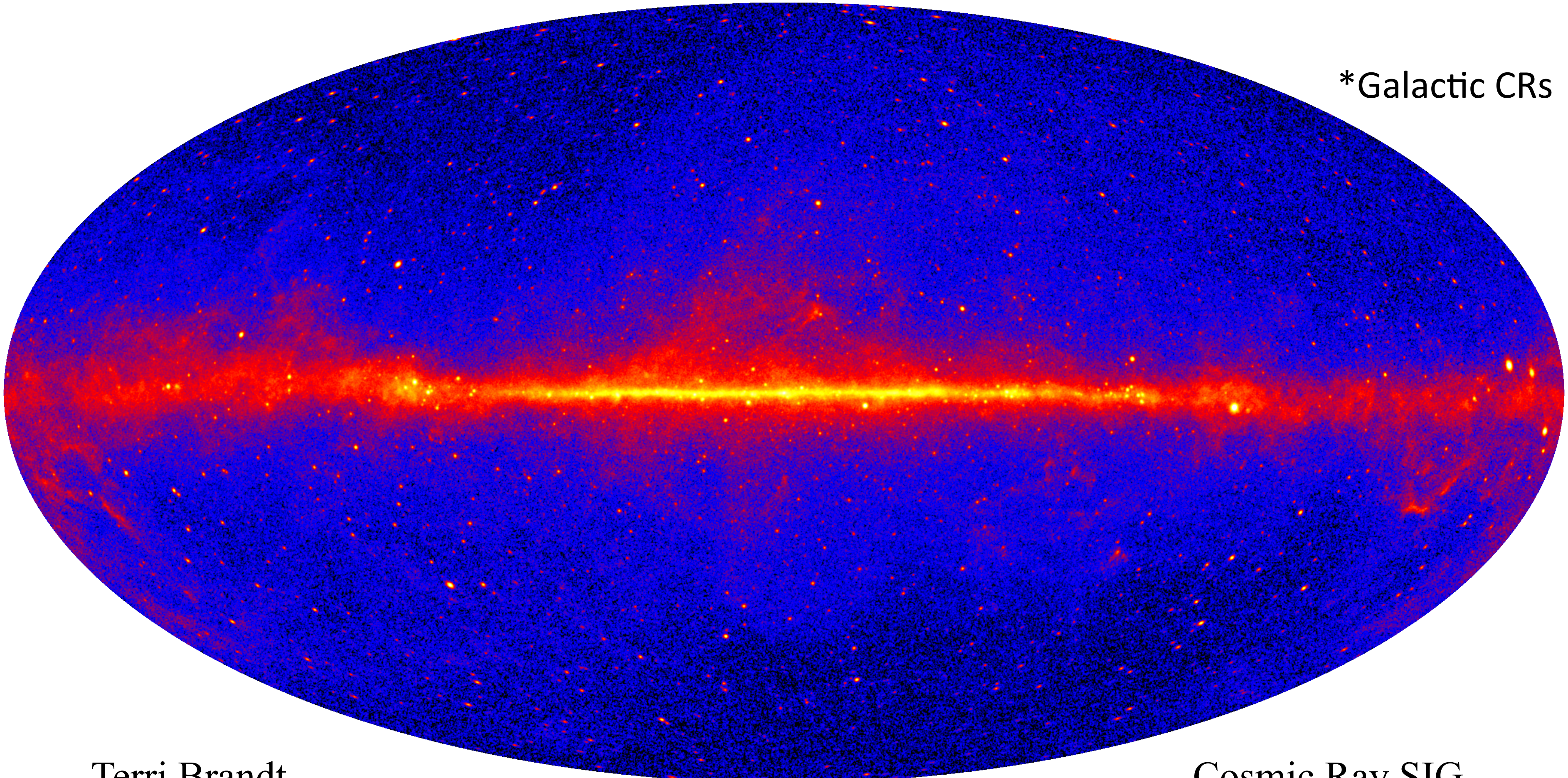
Cosmic Rays*
in the γ-ray Sky



*Galactic CRs

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Cosmic Ray SIG
APS
17 Apr 2016

Synergies:

γ-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 γ-rays give insight into CR propagation.

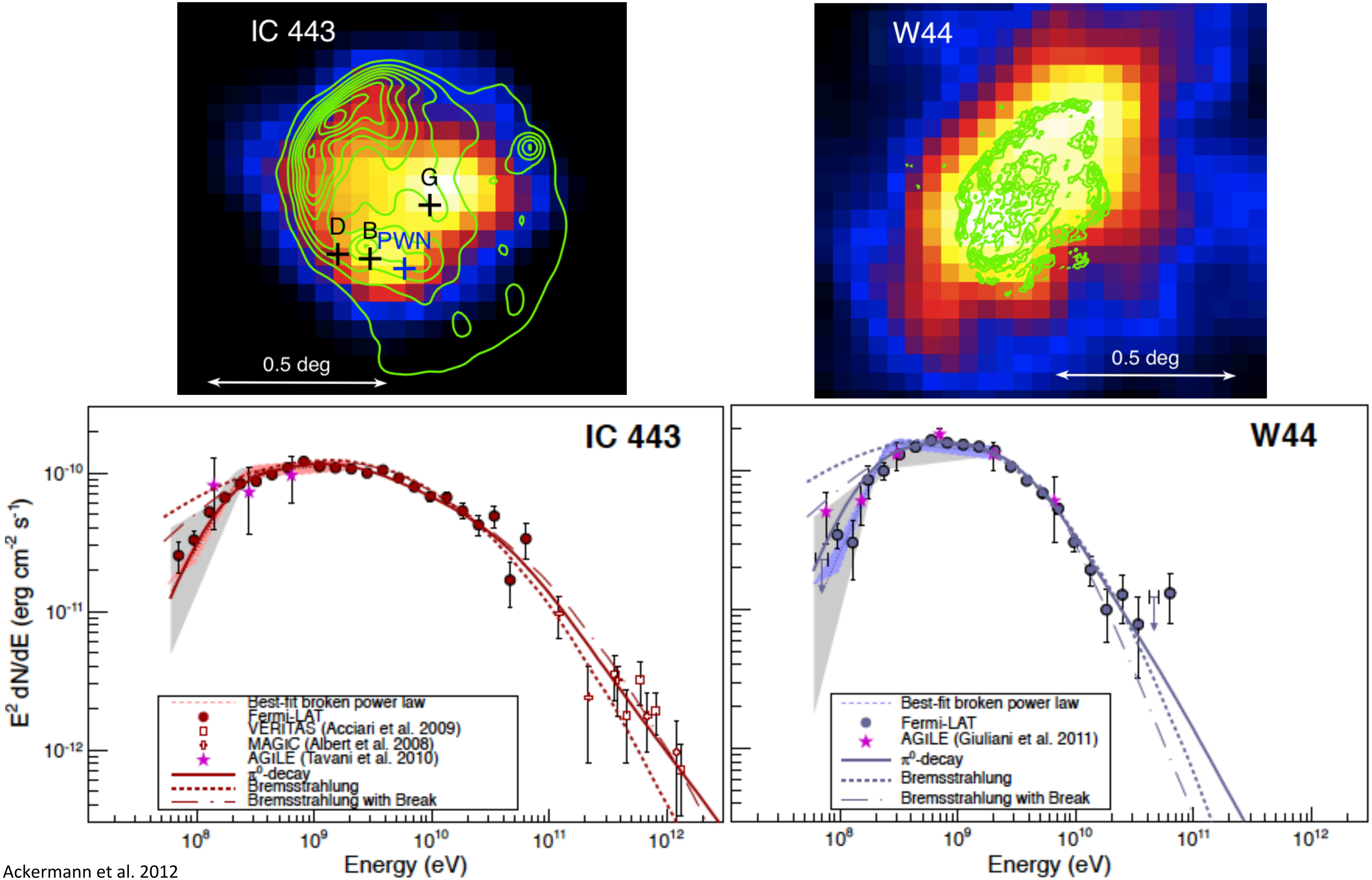
Direct CR detection:

- CRs are the background for all γ-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 γ-rays.

Indirect: Potential Sources

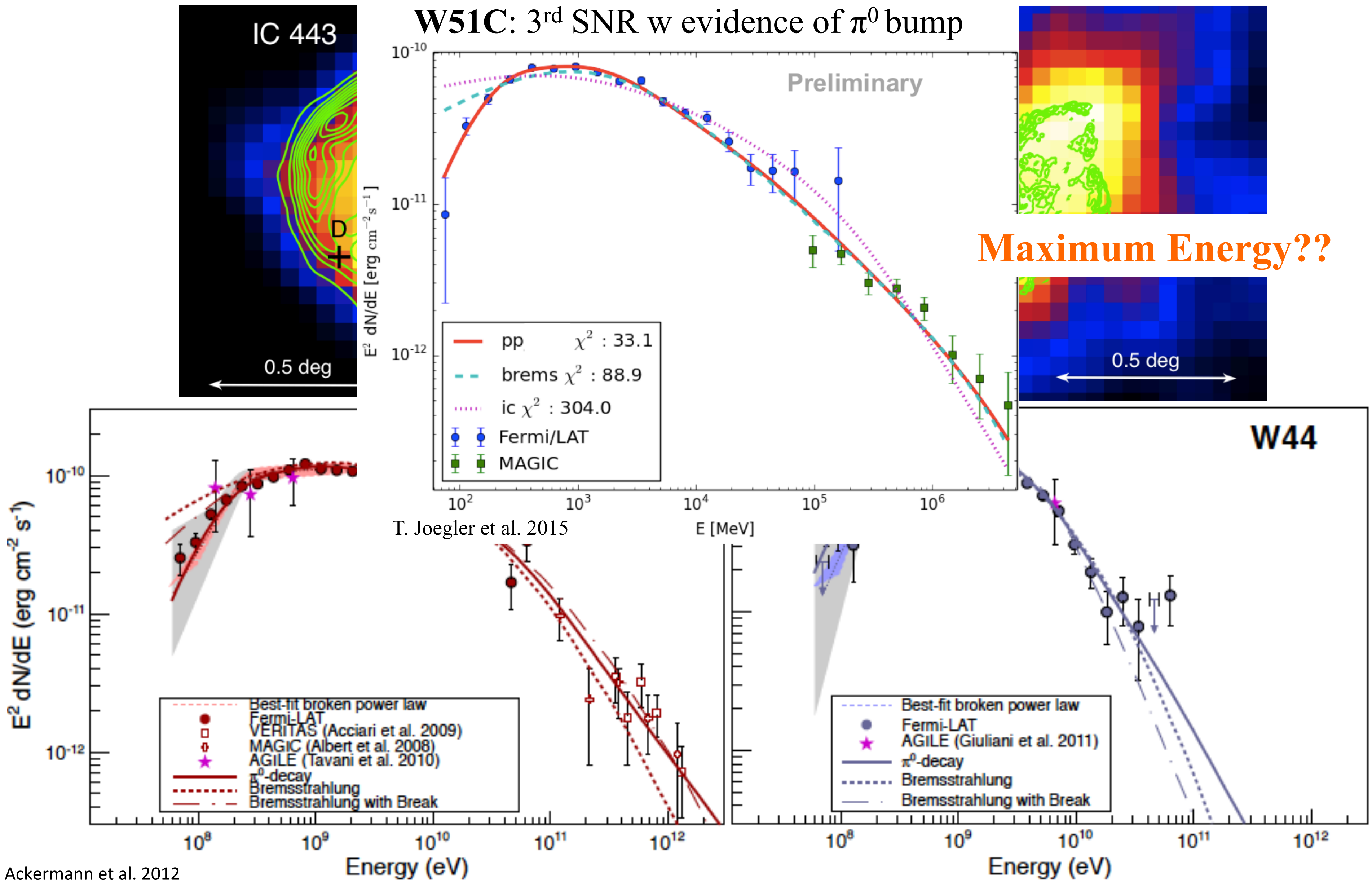
Detection of low energy pion-decay cutoff in 3 SNRs' spectra suggests proton acceleration:



Ackermann et al. 2012

Indirect: Potential Sources

Detection of low energy π^0-decay cutoff in 3 SNRs' spectra suggests proton acceleration:



Constraining SNRs' CR Acceleration

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

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

ε_{CR} => energy content in particles accelerated up to the observation time relative to the SN explosion energy. If energy losses & escape negligible, ε_{CR} = hadron efficiency.

Acero et al. 2015

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where we take:

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

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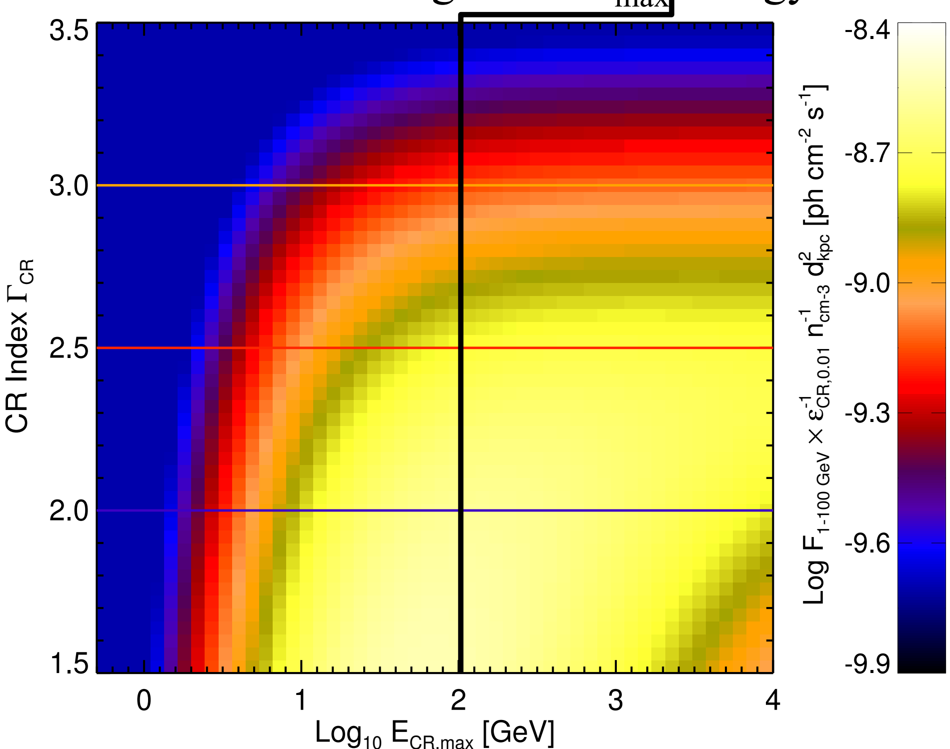
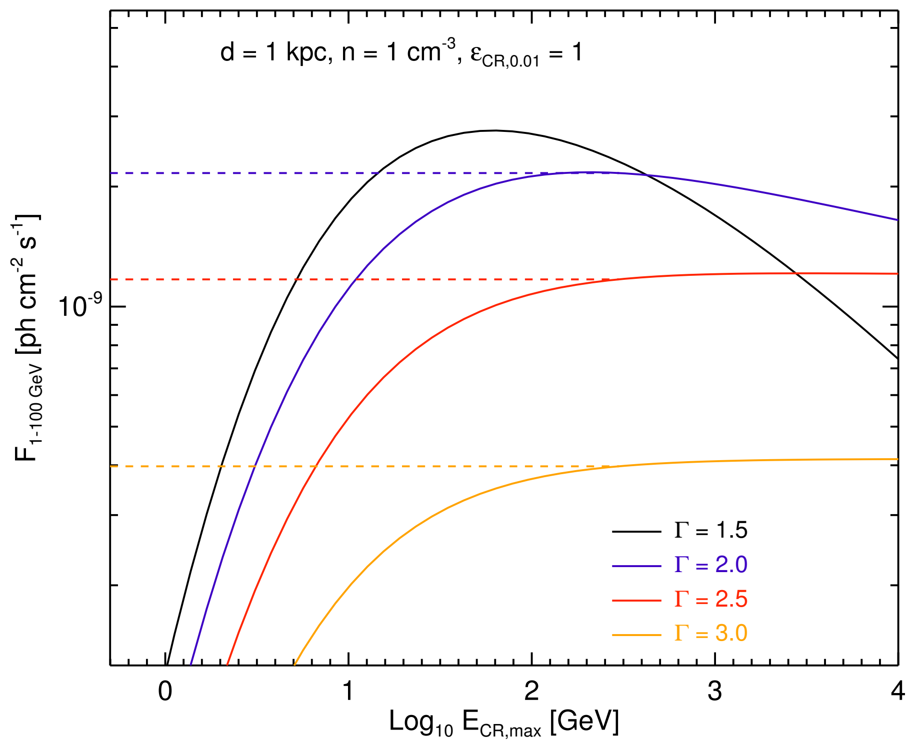
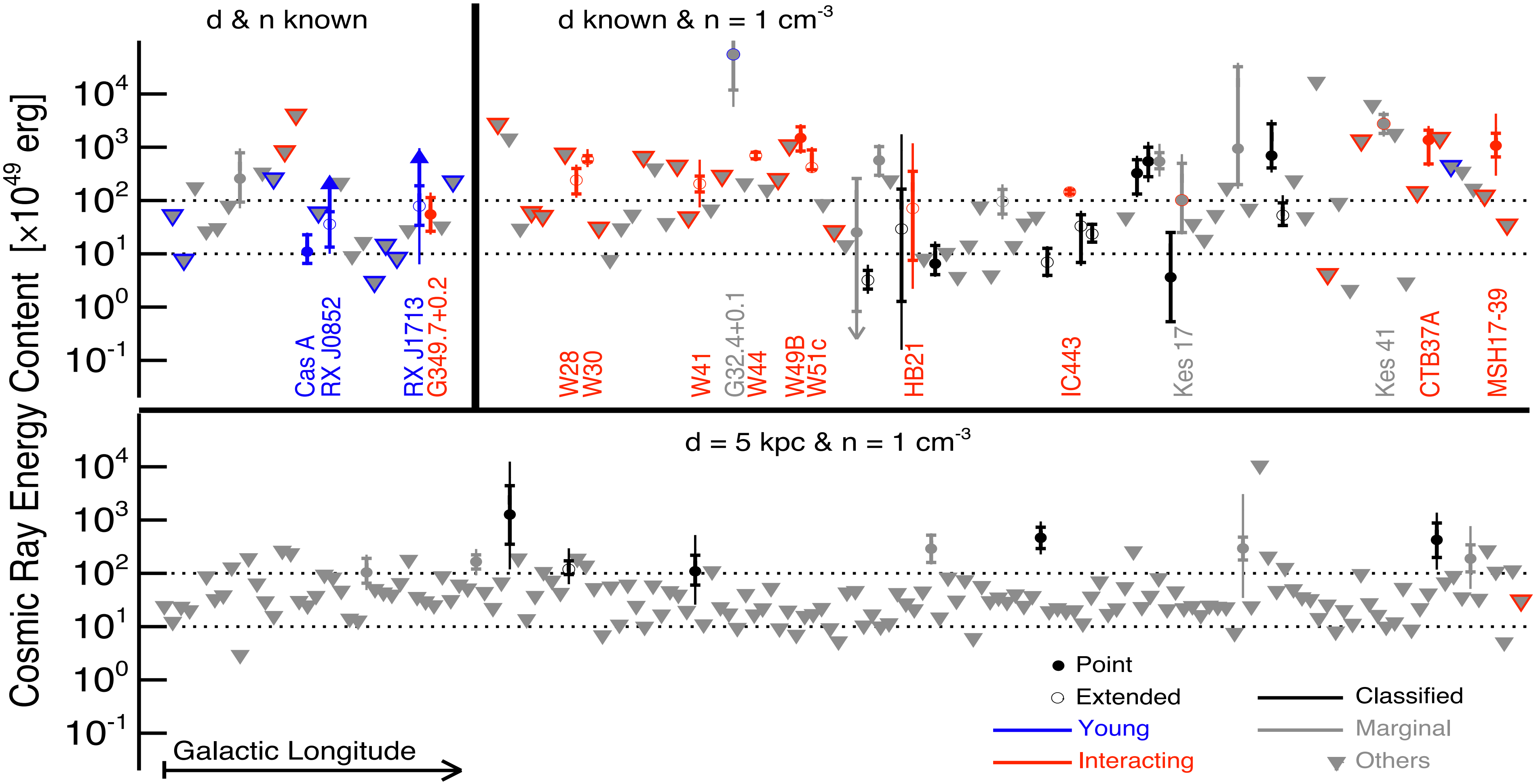
1-100 GeV flux for a given CR_{max} energy:





Constraining SNRs' CR Acceleration

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



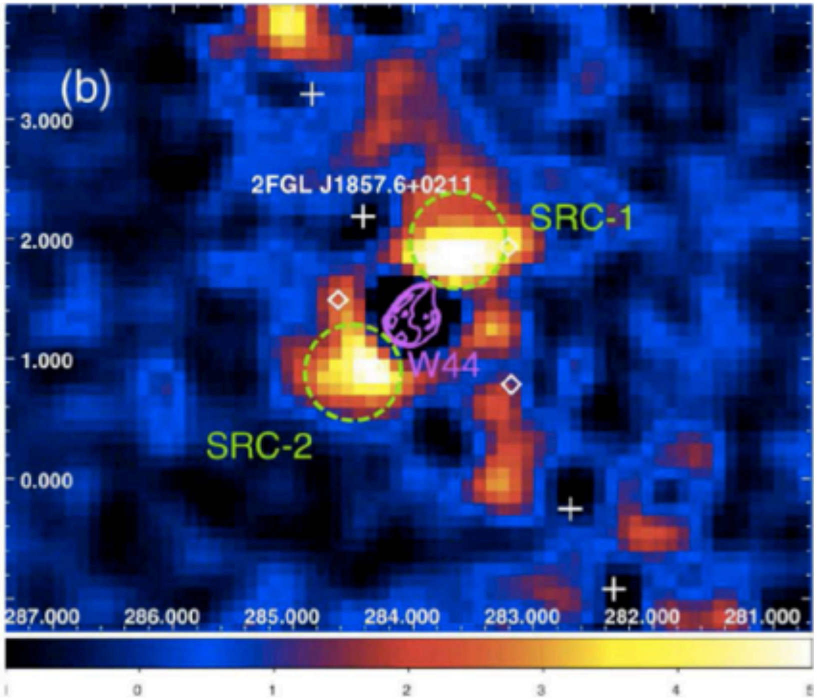
- SNRs w > $\varepsilon_{CR} = 1$ ($E_{CR} \equiv E_{SN} \equiv 10^{51}$ erg) => higher density than derived from X-ray or assumed => interacting SNRs are in a dense environment.
- Young SNRs ε_{CR} ~ 0.1 - 1.0 => IC processes may contribute to their measured luminosity

Acero et al. 2015

Indirect: Diffuse Studies

Study propagation around sources:

W44:
Particle escape? Shocked cloud?

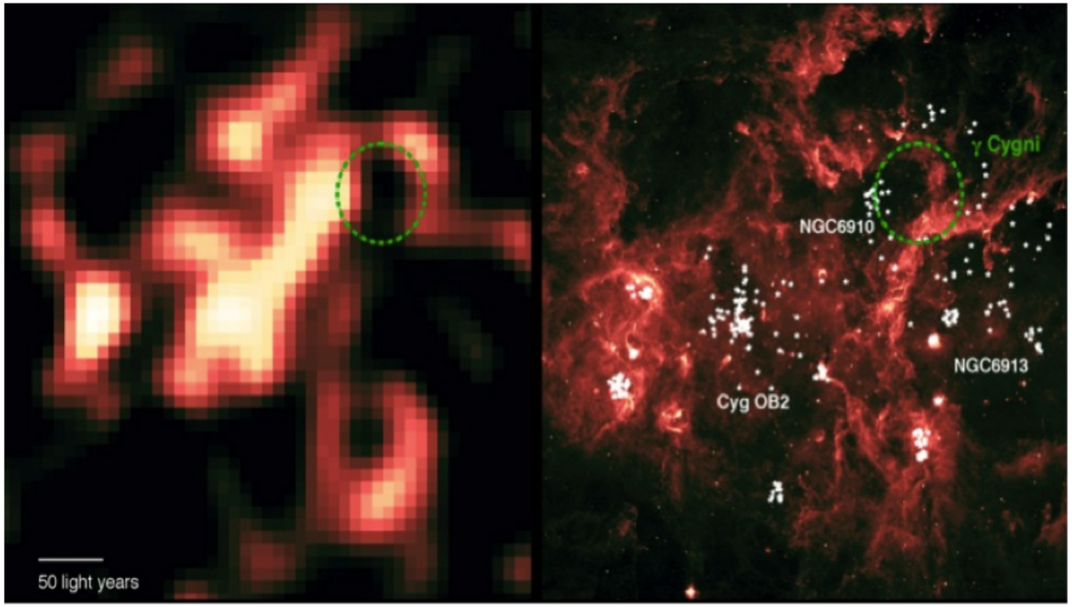


Uchiyama, et al. 2012

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

Use MW observations to find **new** sources!

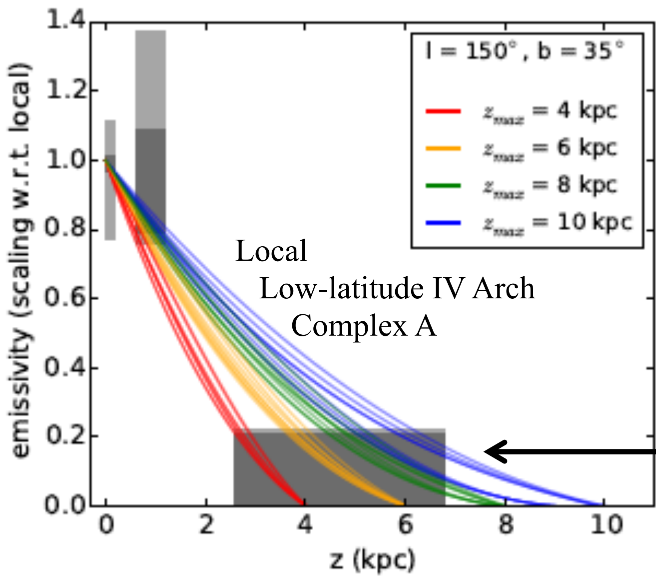
Cocoon of 10-100 GeV γ-ray emission **IR emission from Cygnus Superbubble**



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

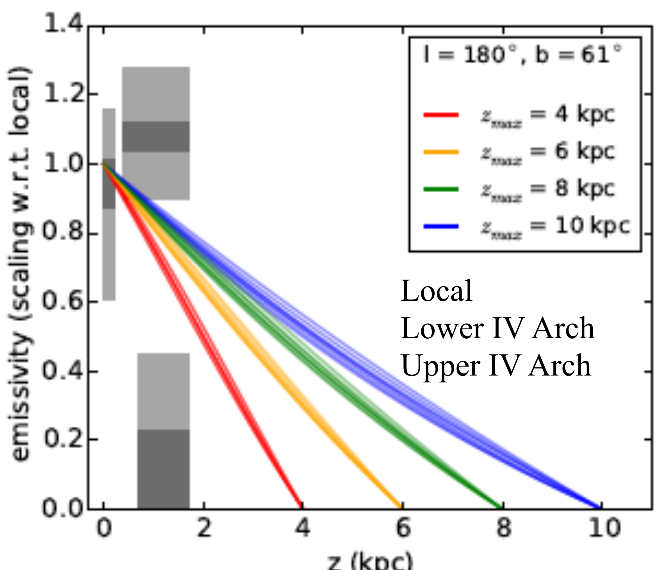
Indirect: Diffuse Studies

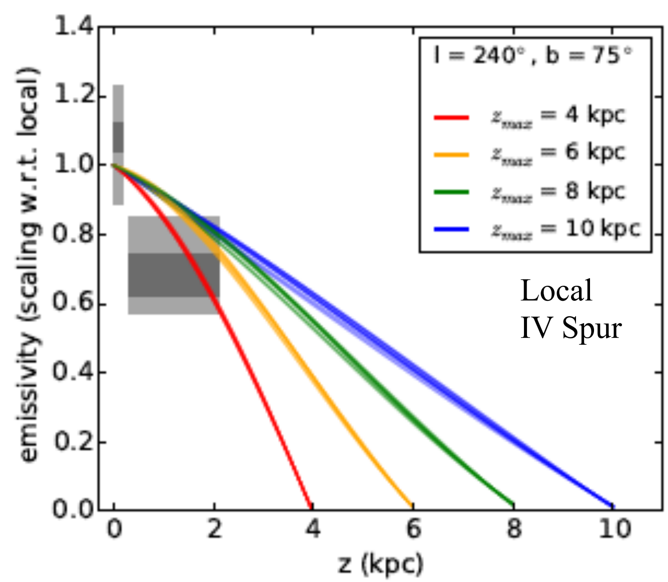
Infer CR propagation using High and Medium Velocity Clouds:



Emissivity = γ-ray emission rate / H atom
z = height above Galactic plane

- γ-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 ~ few kpc.

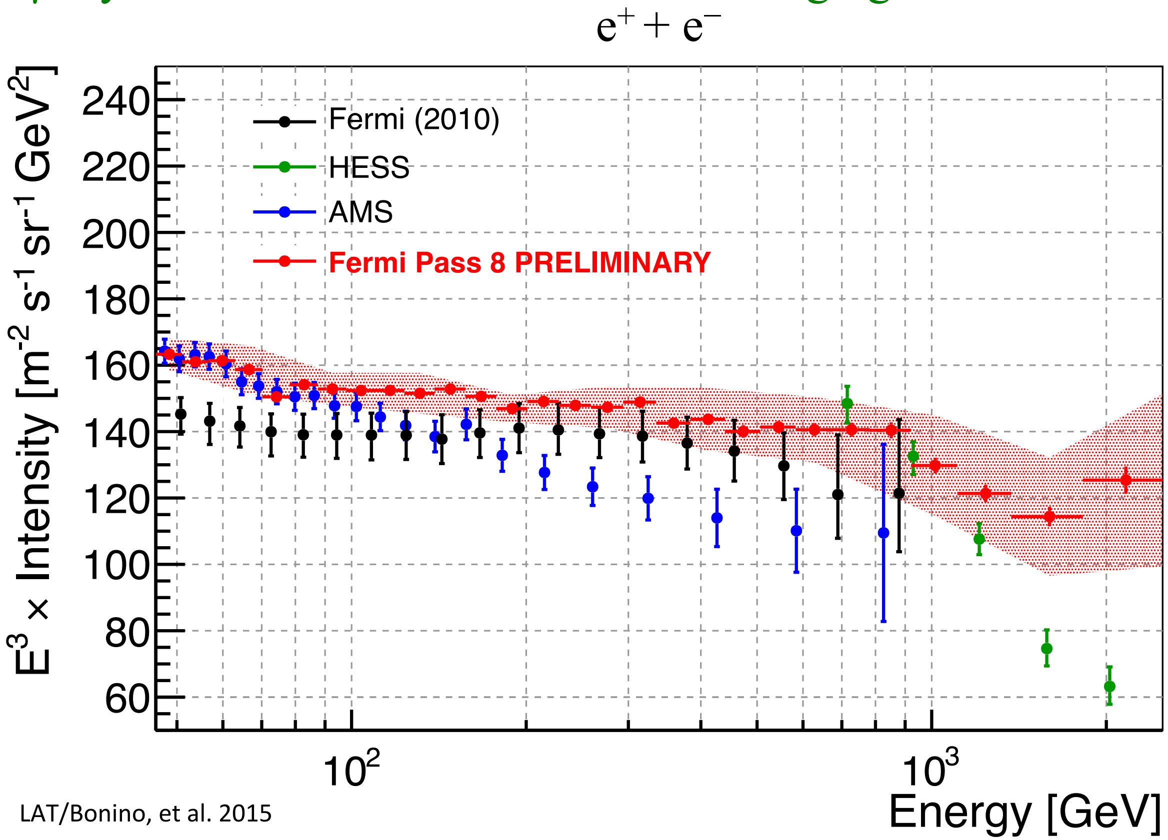




Tibaldo, et al. 2015

Direct: Leptons

γ-ray instruments such as Fermi and Imaging Air Cherenkov Telescopes measure lepton showers:

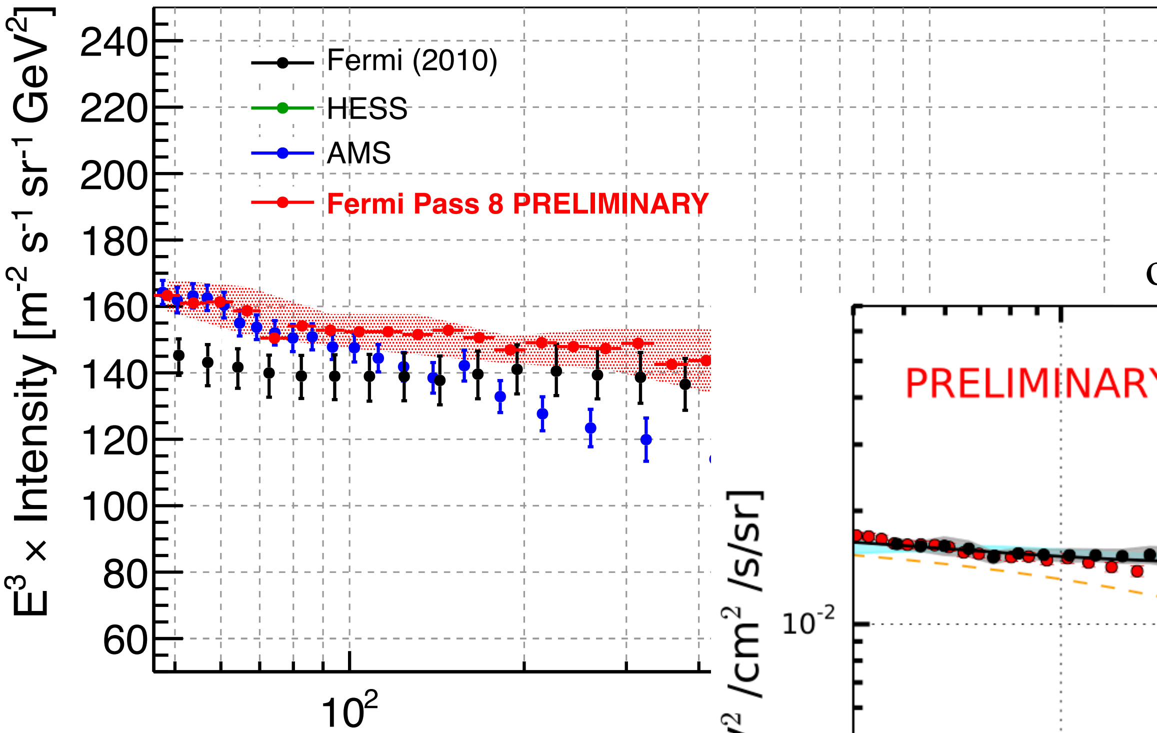


LAT/Bonino, et al. 2015

Direct: Leptons

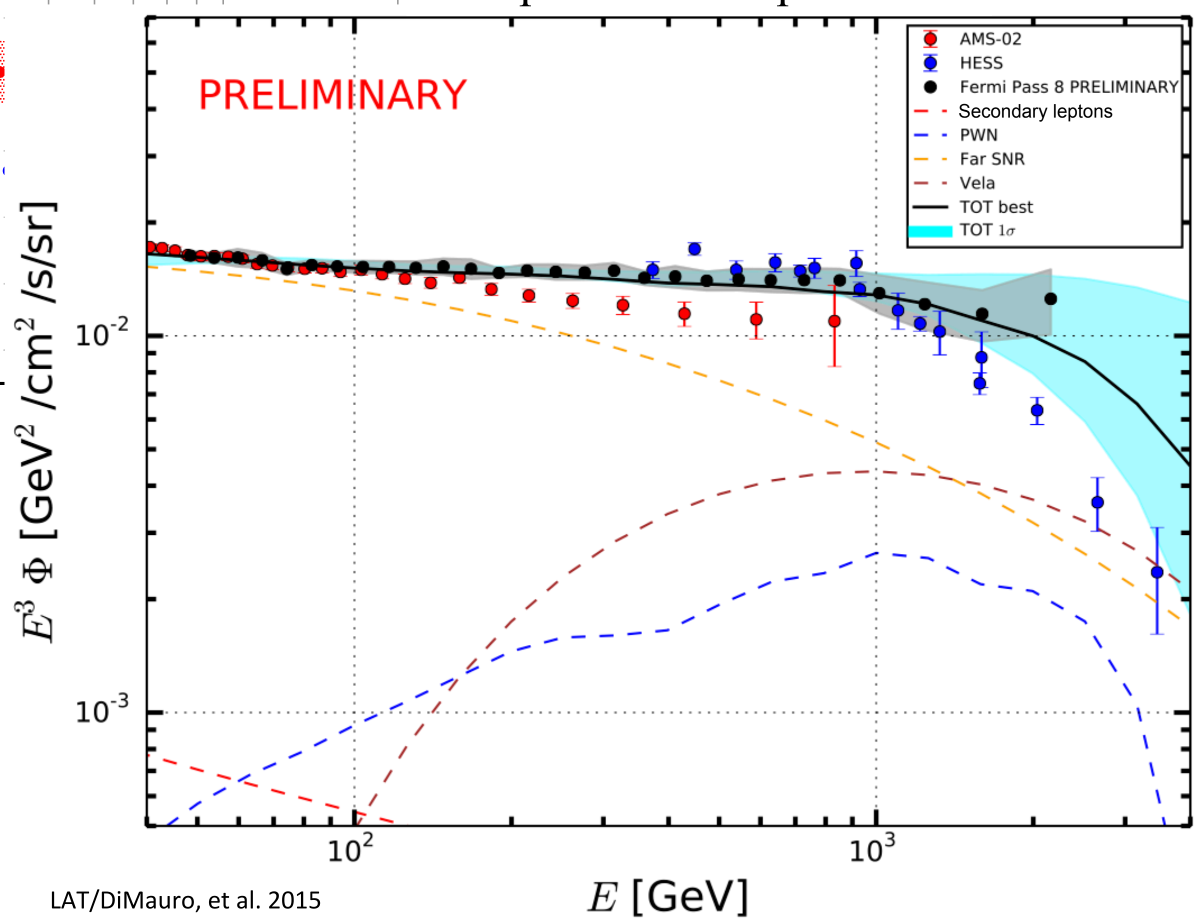
γ-ray instruments such as Fermi and Imaging Air Cherenkov Telescopes measure lepton showers:

$e^+ + e^-$



LAT/Bonino, et al. 2015

one possible interpretation:

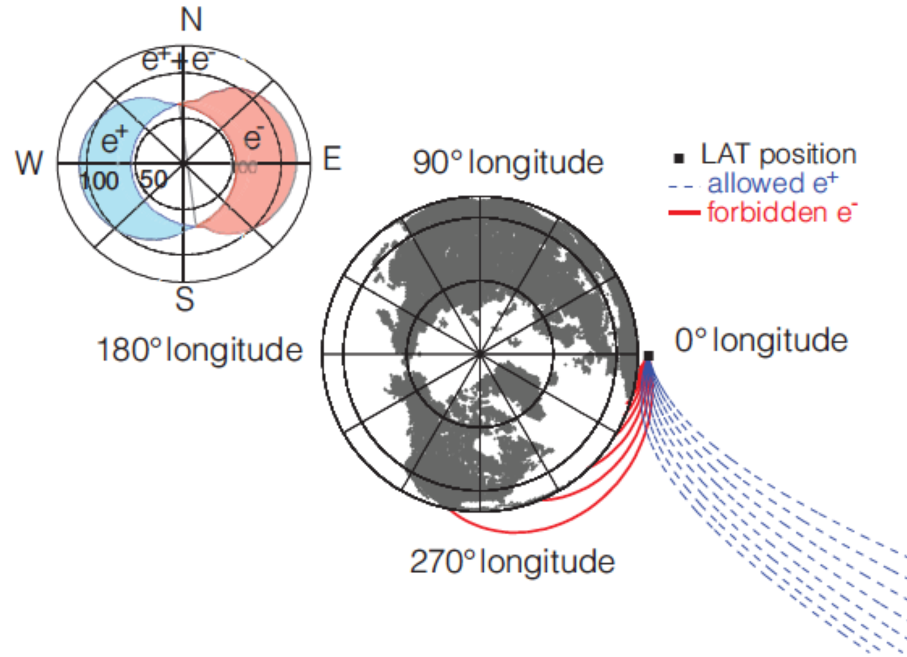


LAT/DiMauro, et al. 2015

T. J. Brandt

Direct: Positron Fraction

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



Ackermann, et al. 2012

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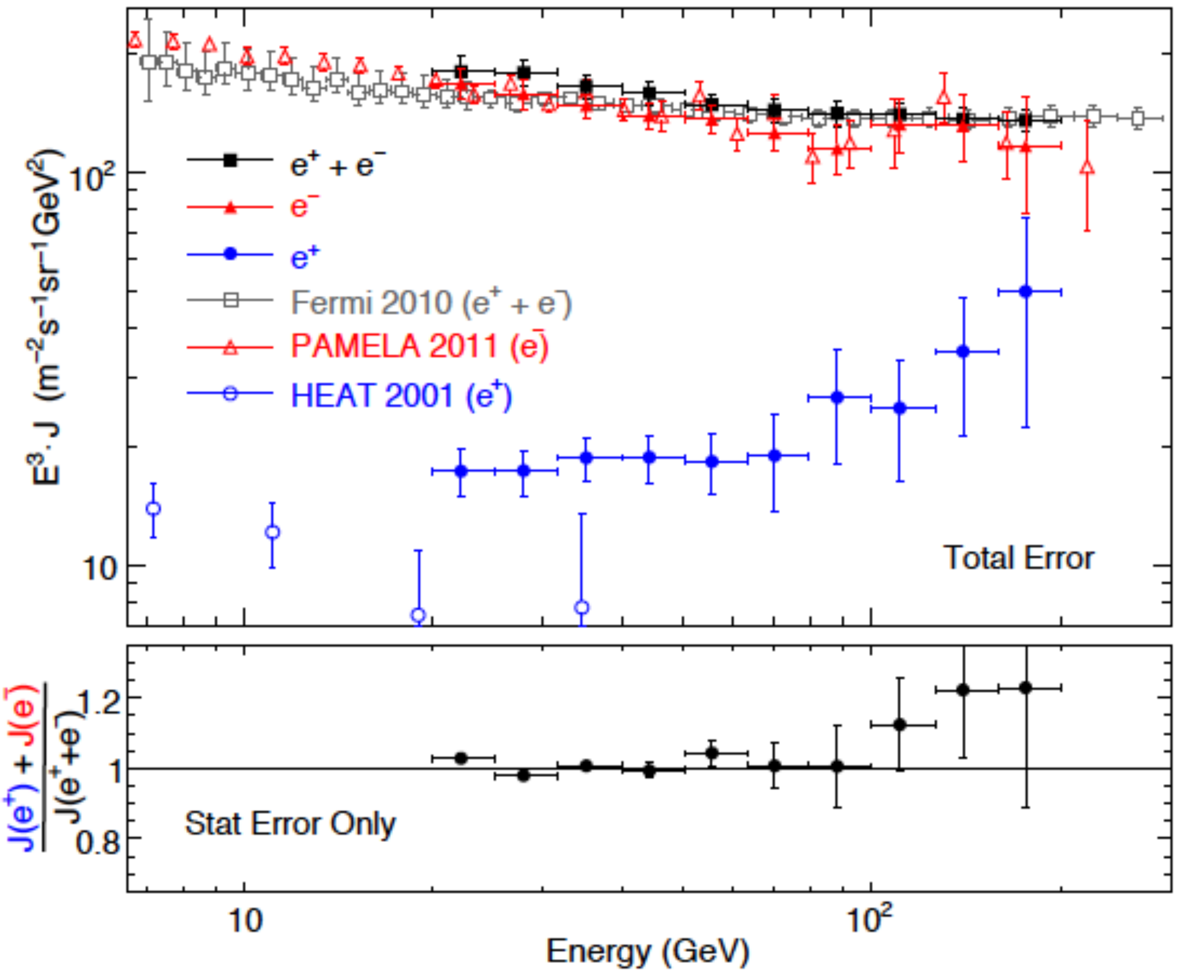

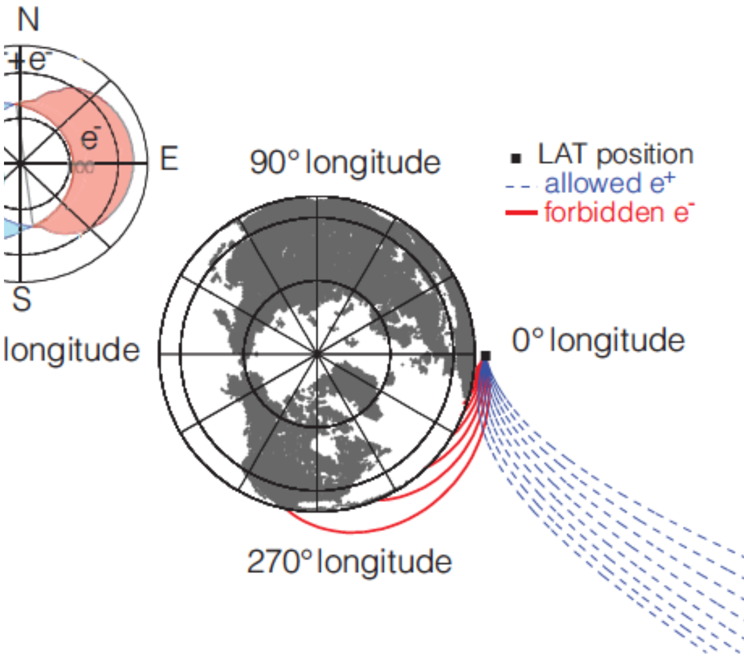

Ackermann, et al. 2012

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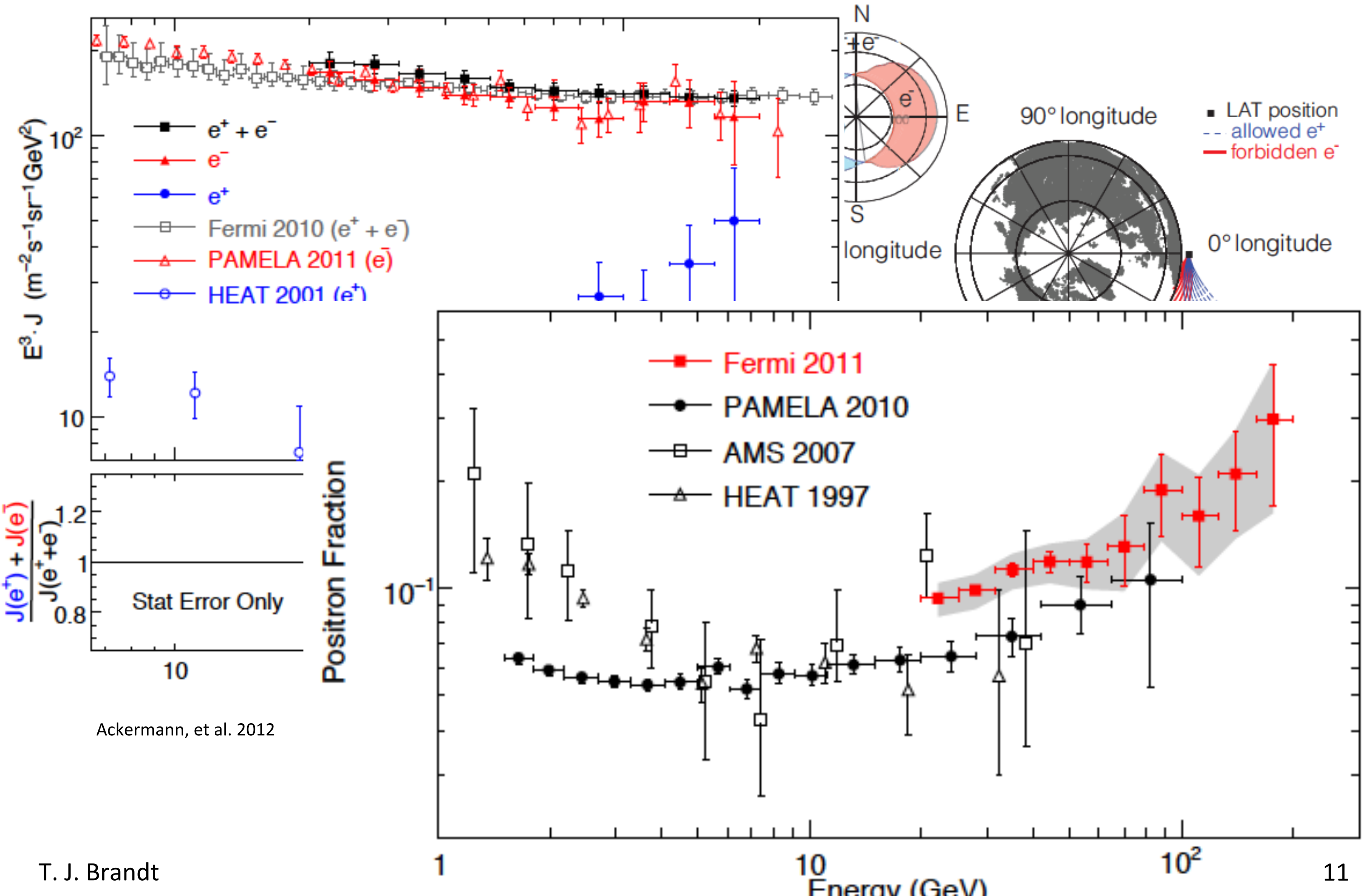

Ackermann, et al. 2012

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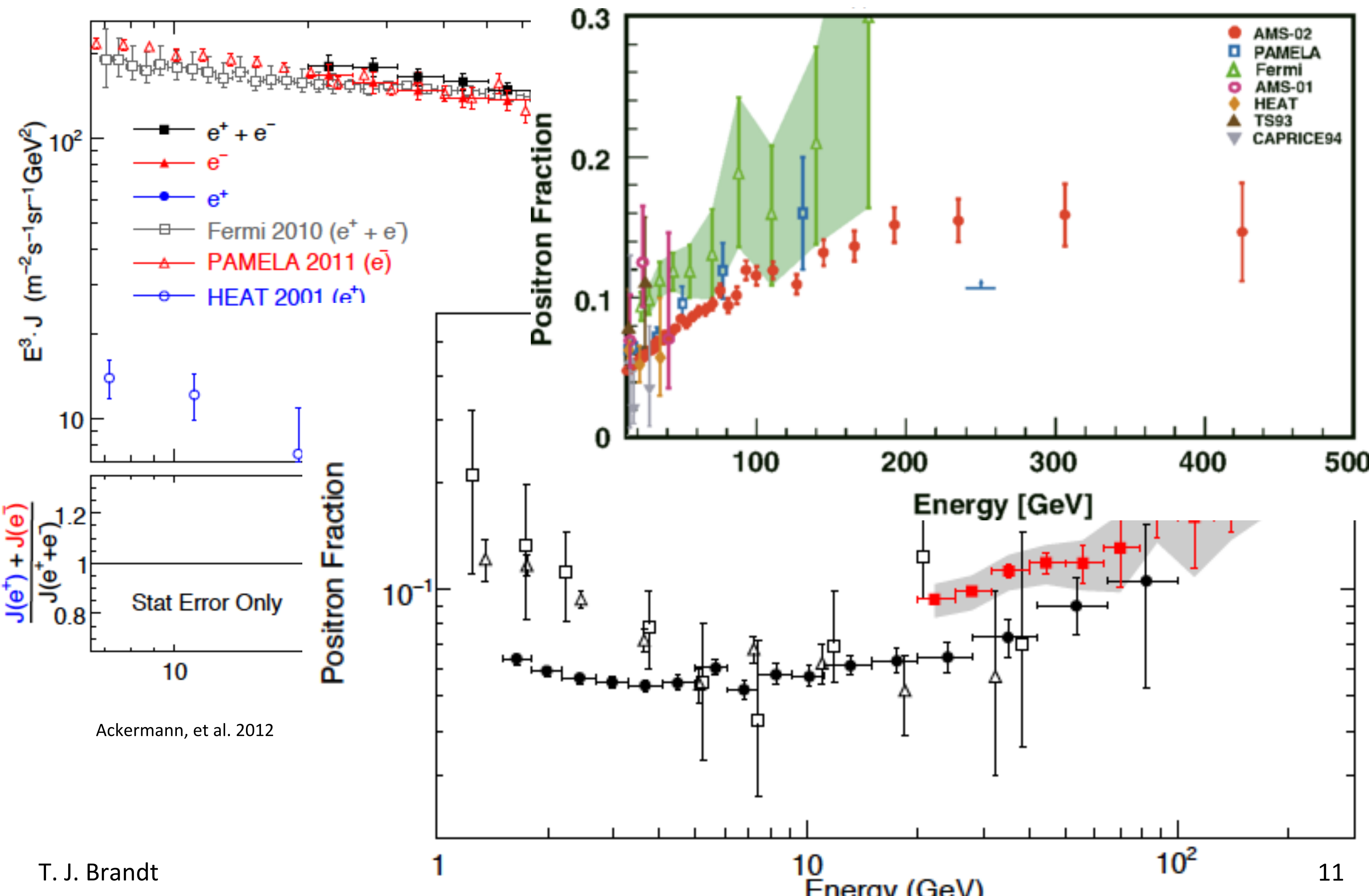
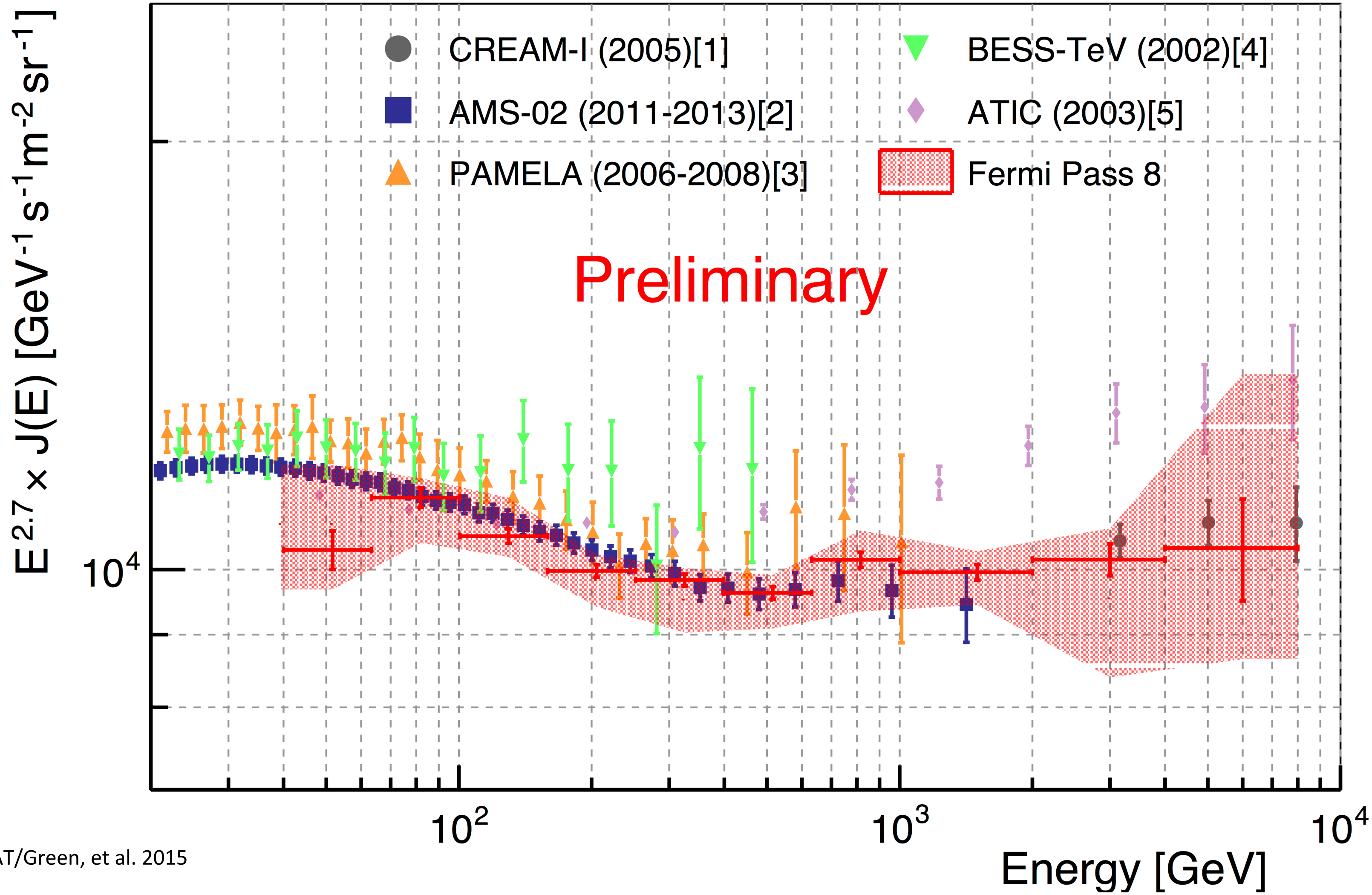


Direct: Hadrons

Fermi-LAT proton measurement:

- E > 20GeV
- 3 month's data
- Above atmosphere…



LAT/Green, et al. 2015

Conclusions

We can use γ-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 γ-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** + **μwave** + **radio** + **IceCube** + **distances** + … => **CR origins, propagation!**