Towards Fermi-LAT Detected Supernova Remnants as Cosmic Ray Accelerators

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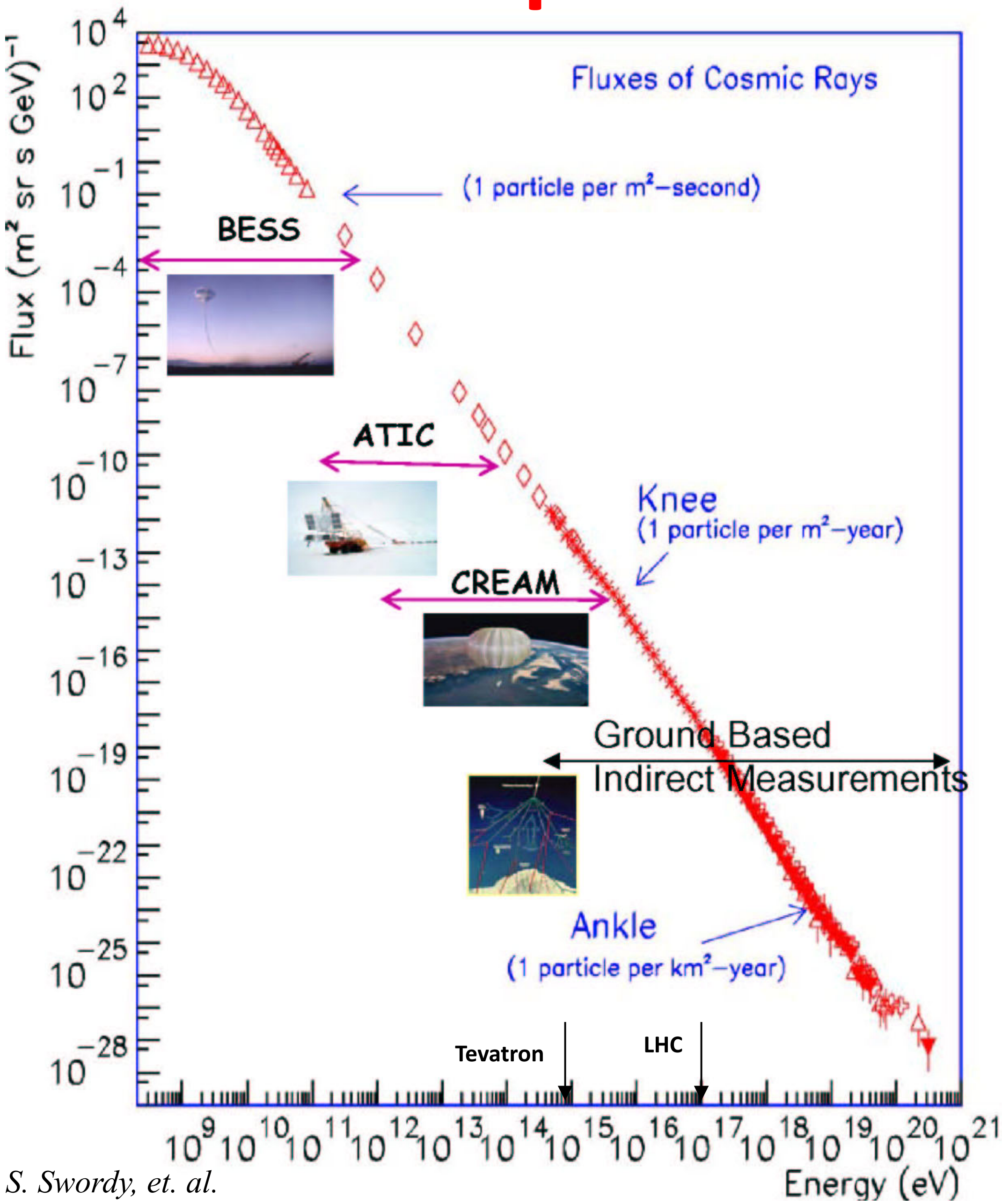
CRISM: 27 Jun 2011

All-particle CR Spectrum



S. Swordy, et. al.

Cosmic rays are:

- charged particles from outer space (V. Hess, 1912)
- ~90% Hydrogen
  ~9% Helium
  ~1% Z > 2

Spectrum falls as:

- **$dF/dE \propto E^{-\alpha}$**
- $\alpha \approx 2.7$
  for ~ 10^9 eV < E < 10^{15} eV
- $\alpha \approx 3.3$
  for ~ 10^{15} eV < E < $10^{18.6}$ eV
- $\alpha \approx 2.6$
  for ~ E > $10^{18.6}$ eV

+ propagation =>

- γ ~2.1
- for galactic CRs (E<~ 10^{15} eV)

Understanding CRs: Methods

Direct (galactic) CR measurements:

- CREAM, ATIC, BESS, PAMELA, ACE, CRIS, AMS, …
- measure incident particle energy and charge and/or mass
- at the top of Earth's atmosphere or in space
- to infer propagation and source/acceleration properties.

Indirect CR detection

- Use photons to trace CR interactions:
- image potential sources in gamma-rays
  - … and other wavelengths!
- measure the CR propagation component of the diffuse galactic (gamma-ray) emission
- and more!

Fermi Gamma-ray Space Telescope

Photon Detector

Launched: 11 June 2008 on a Delta II rocket

Photon Energy and Direction

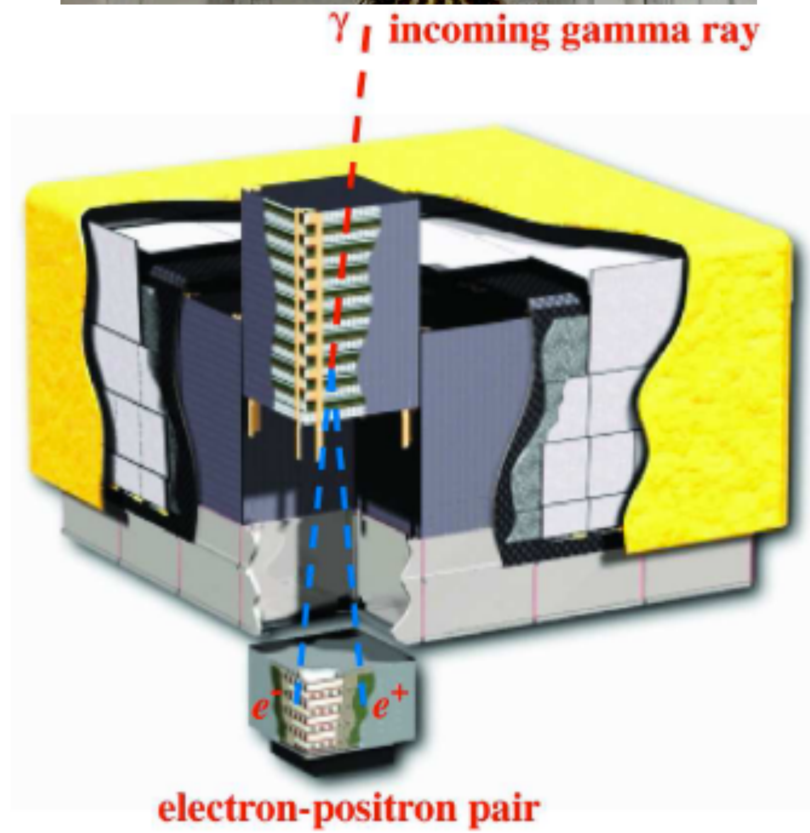
from 2 main (science) subsystems:

- GBM: GLAST Burst Monitor
  - 12 NaI detectors: 8 keV – 1 MeV
  - 2 BGO detectors: 0.15 – 30 MeV
  - nearly full sky coverage at all times
- LAT: Large Area Telescope
  - Tracker: 4x4 array of towers, each with 18 planes of Si-strip detectors interleaved with W converting foils
  - Calorimeter - E: 8 layers of 12 CsI(Tl) crystals oriented orthogonally
  - ACD - CR veto: tiled plastic scintillator

Fermi Collaboration

Fermi Gamma-ray Space Telescope

Photon Detector



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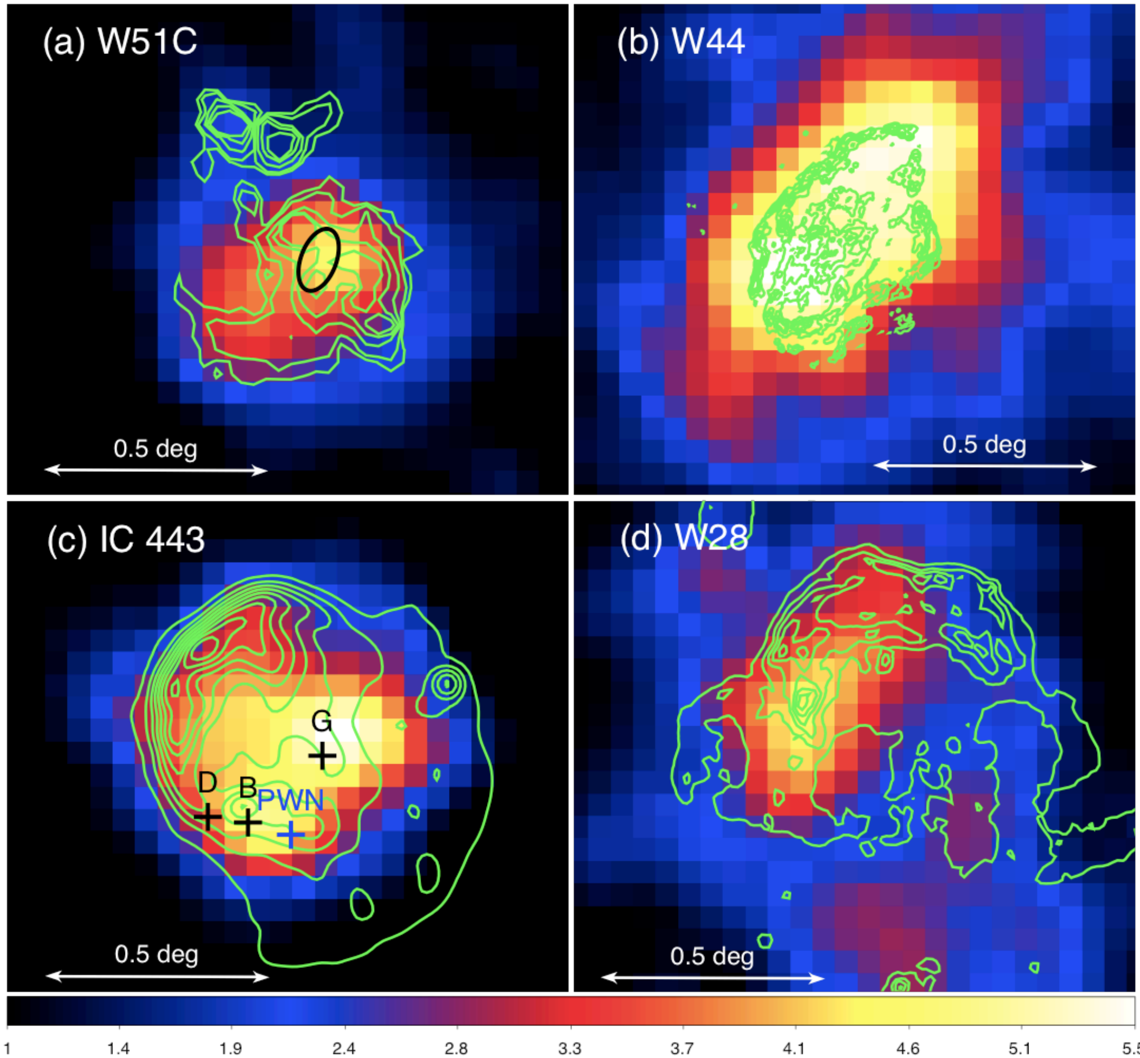
Fermi-Detected Sources

Include many SNRs:

- many middle-aged SNRs
- consistent with radio,
- apparently interacting with molecular clouds
- likely pion decay…



LAT count maps in 2-10 GeV of the Molecular Cloud-interacting SNRs with extended gamma-ray emission for front-converting events.

Contours: VLA radio maps.
(a) Black ellipse: shocked CO
(c) Black crosses: OH maser emission => shocked molecular clumps

Uchiyama, Texas Symp 2010

Indirect Detection:

Image potential sources of galactic CRs to determine:

- their acceleration processes
- the composition of accelerated particles and thus,
- their ability to produce high energy particles with the observed galactic CR properties
- using Fermi GST.

Gamma-rays (and Fermi in particular)

- Good image resolution ⇒ spatial separation of the components
- Sensitivity to pion decay products ($\pi^0 \to \gamma\, \gamma$)
  - and bremsstrahlung & inverse Compton processes
- ⇒ spectral separation of acceleration processes
- Survey mode gives high statistics.
- In combination with full EM spectrum and spectroscopy, can begin to resolve potential sources' ability to accelerate CRs.

One source → a catalog → a possible statistical correlation

- SNR CTB 37A is one such potential source resolved by Fermi and H.E.S.S. with corresponding radio, IR, and X-ray data.
- By combining many such sources into a catalog, we can make statistically significant observations about the class's ability to produce CRs.

Analysis

Using standard Fermi science tools:

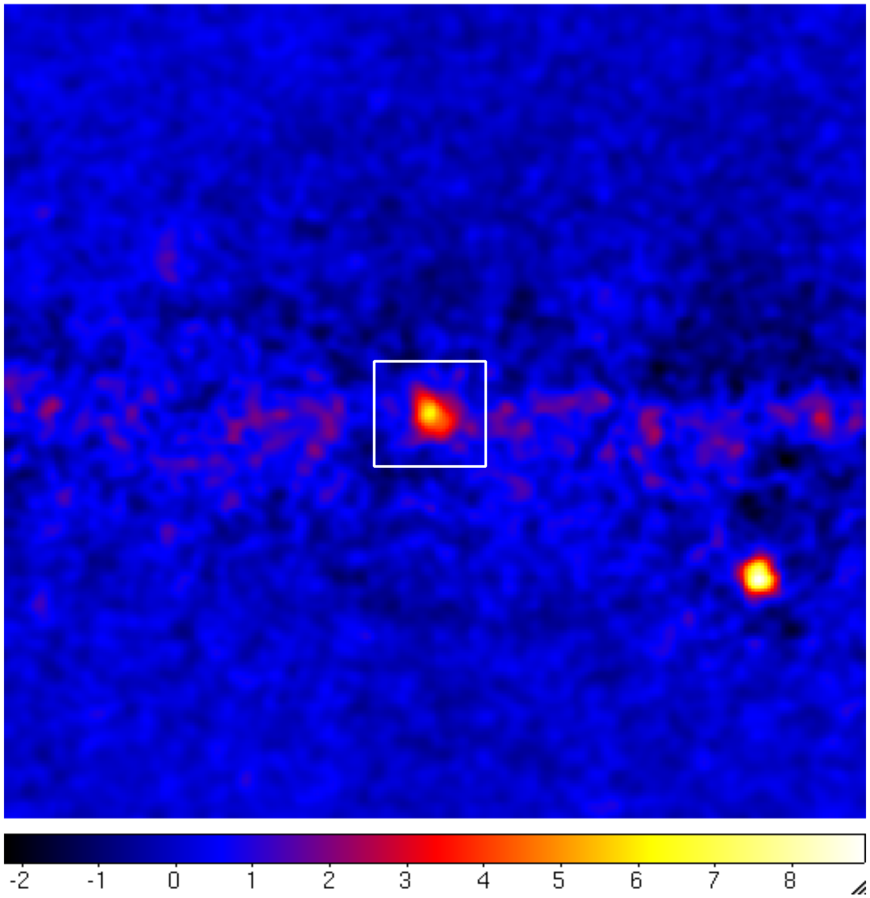
- Binned likelihood analysis (gtlike)
- MET: 239903654 – 287682854 = 18 month's data
- E: 0.2 – 50 GeV
- 4.5° ROI
- Event Class: Diffuse

to perform analysis:

- Removed all other identified Fermi (1FGL) catalog sources within 4.5° ROI

and find:

- Galactic plane is relatively flat; source apparent and coincident with CTB 37A and radio contours.



Fermi Detection of CTB 37A:

Location & extension consistent with radio & H.E.S.S. data as well as nominal CTB 37A position.

- Detected with 18.6σ

- Radio contours
- H.E.S.S. detection
- Fermi detection
- XMM contours (MOS1: 0.2-10keV)

Location:

- RA = 258.68°± 0.05 ± 0.004
- Dec = -38.54°± 0.04° ± 0.02

Extension:

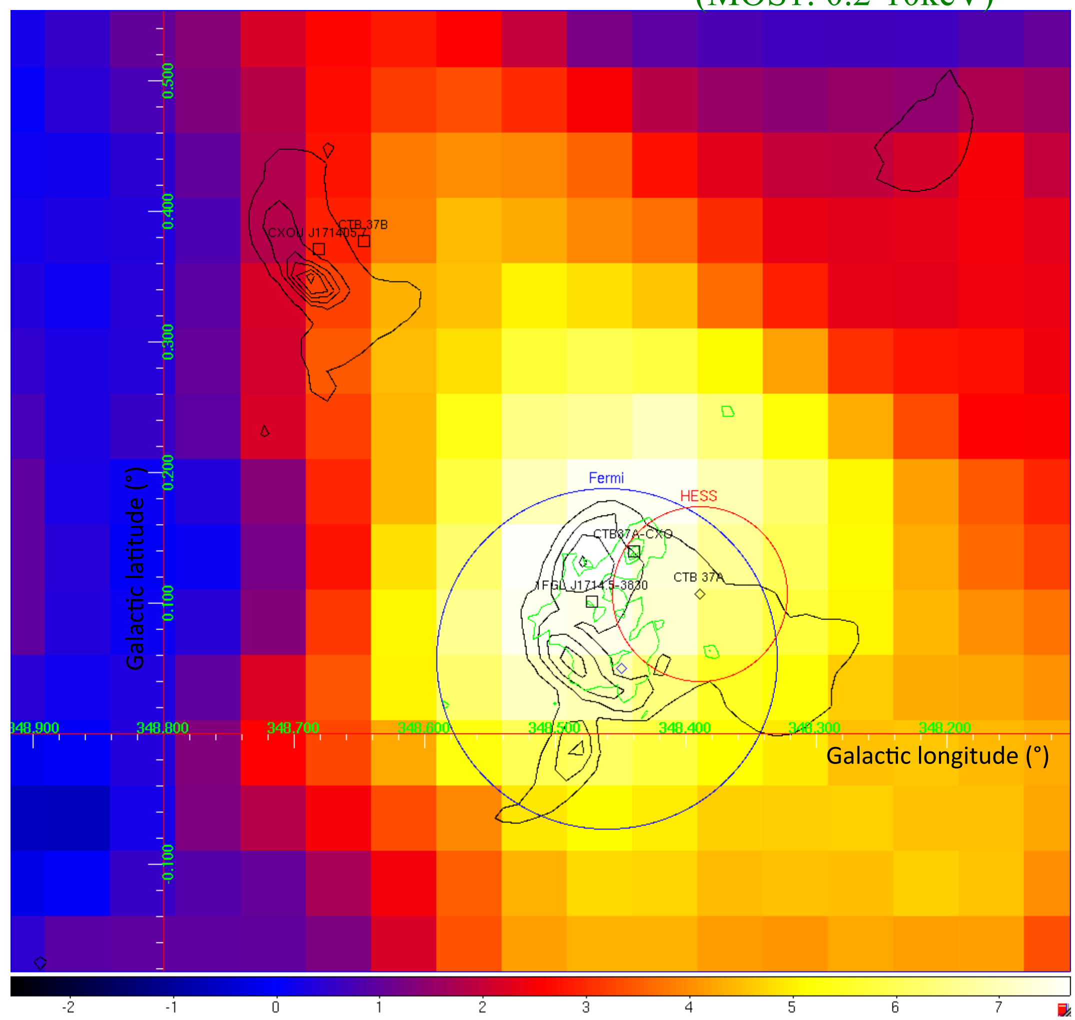
- 0.13° ± 0.02° ± 0.04°
- Significance: ~4.5σ

Position and extension stable for

- 4 of the reasonable diffuse models ~ spanning the parameter space
- high energy events (2-50 GeV)
- "Front" events (inherently better PSF)

Variability: None yet observed

- Light curve: no long-term variability
- Pulsations: none seen in
  - Blind search: < ~3x10^{-7} ph/cm^2/s (pulsed)
  - of possible counterparts (□)

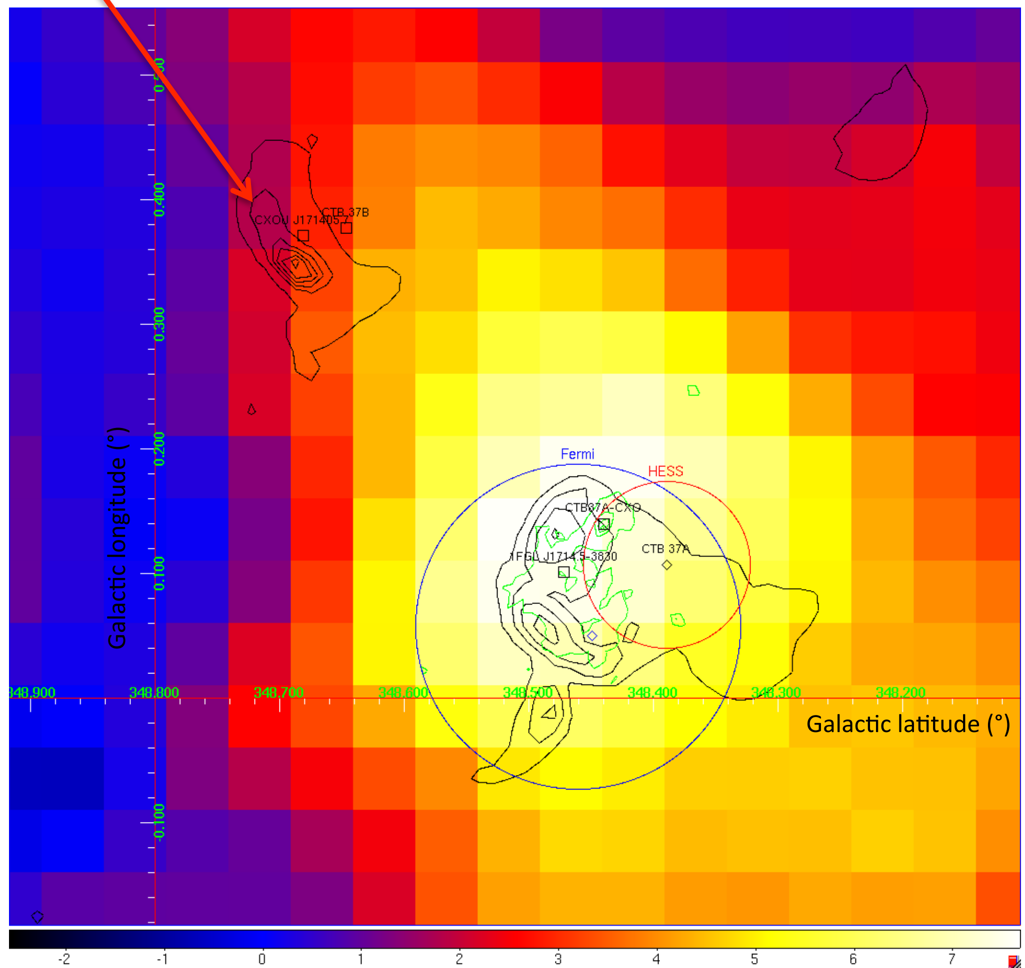


CTB 37B: Upper Limit

Used gtlike to determine upper limits at the HESS position.

- Tested:
  - HESS position
  - Power law (PL) and exponentially cutoff PL (ECPL)
  - Spectral index: i = 2.1, 2.3, 2.5
  - Minimum γ energy: E_{min} = 200 MeV, 5 GeV
  - Fixed E_{max} = 50 GeV

- Flux limits are consistent for all spectral forms and indices
- $F_{2\sigma} < 8\times10^{-8}$ ph/cm^2/s for E = 200 MeV – 50 GeV



Fermi Residual map with:

- Radio contours [2]
- H.E.S.S. detection [1]
- XMM contours (MOS1: 0.2-10 keV)
- Fermi detection

Multiwavelength Spectrum: Data

- Synchrotron emission:
  - **Radio** (Kassim et al., 1991)
  - IR: Spitzer (Reach et al., 1991)
    - (unconstraining) upper limit
  - X-ray:
    - XMM-Newton spectrum consistent with absorbed thermal emission
    - in agreement with XMM & Chandra analysis performed by HESS team
    - upper limit
- Gamma-ray:
  - **Fermi**
  - **HESS** (Aharonian et al., 2008)

Multiwavelength Spectrum: Model

Simultaneously fit both lepton and hadron populations:

- Lepton population:
  - Assume: exponentially cutoff power law:
    - $N_e(E) = N_{0,e}\, E^{\gamma e} \exp(-E/E_{cut,e})$
  - Fit: $N_{0,e}$, γ_e, $E_{cut,e}$
- Hadron population:
  - Assume: simple power law:
    - $N_p(E) = N_{0,p}\, E^{\gamma p}$
  - Fit: $N_{0,p}$, γ_p
- Magnetic field:
  - Constrained <1.5mG from OH maser Zeeman splitting observations
  - Fit: magnetic field intensity (B)
- Gas mass:
  - Assume: reasonable $M_H = 6.5 \times 10^4\, M_\odot$
  - Consistent with CO measurements
  - Determine: parameters' scaling relations with M_H
- Model emission processes:
  - Synchrotron
  - Bremsstrahlung*
  - inverse Compton
  - Pion decay*
  - *Scaled to solar metallicity
- Minimized χ^2
  - using Powell method, results consistent with other methods
  - $\chi^2 = 16.4$ for 17 dof
- 1σ errors:
  - searched extreme values for which $\Delta\chi^2 = 1$

Multiwavelength Spectrum: Results

- Lepton population:
  - $N_{0,e} = 3.79^{+3.99}_{-1.70}$ e/s/cm^2/GeV/sr
  - $\gamma_e = -1.35^{+0.32}_{-0.23}$
  - $E_{cut,e} = 4.1^{+3.4}_{-1.7}$ GeV
- Hadron population:
  - $N_{0,p} = 163.5^{+60.5}_{-137.7}$ p/s/cm^2/GeV/sr
  - $\gamma_p = -2.5^{+0.04}_{-0.19}$
- Magnetic field:
  - $B = 109^{+56}_{-49}$ μG
  - 1st lower limit
  - Constraining upper limit
- Gas mass:
  - Parameters' scaling relations with M_H
  - $N_{0,p}$ has slope ~1, as expected for π^0 emissivity scaling with gas mass
  - All other parameters showed no significant variation with gas mass beyond the errors.
- Particle type:
  - ✓ Hadrons
- Spectral index
  - ✓ 1σ, consistent with γ ~ 2.1 from direct detection
- Proton Cutoff Energy
  - $E_{p,max} \sim 10^{14}$eV
  - ✓ consistent with direct detection $E_{max} \sim 10^{15}$eV for all CR accelerators

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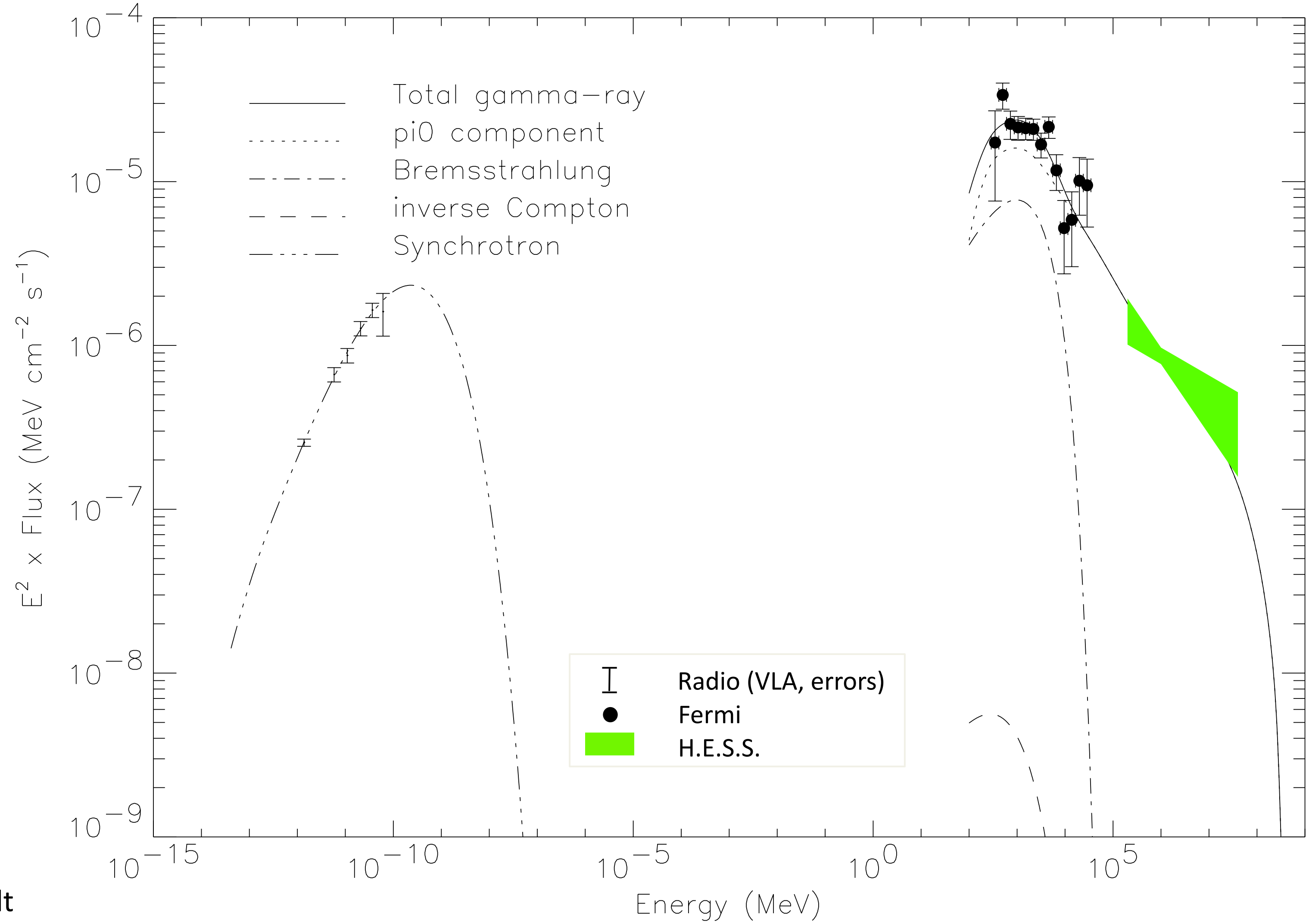
- Energetics:
  - Total, steady-state energy:
  - hadrons = $5.1^{+1.3}_{-3.6} \times 10^{49}$ ergs
  - leptons = $2.7^{+4.0}_{-1.4} \times 10^{48}$ ergs
  - $E_{cut,e} = 4.1^{+3.4}_{-1.7}$ GeV
- Find typical conversion efficiency: ~5%
  - $\eta \sim (1.5\text{-}6.4) \mathrm{x} (M/M_H)^{-1} \mathrm{x} (d/10.3\mathrm{kpc})^5 \mathrm{x} (E_{SN}/10^{51}\mathrm{erg})$ %
  - Consistent with HESS result when scaled to their mass and distance

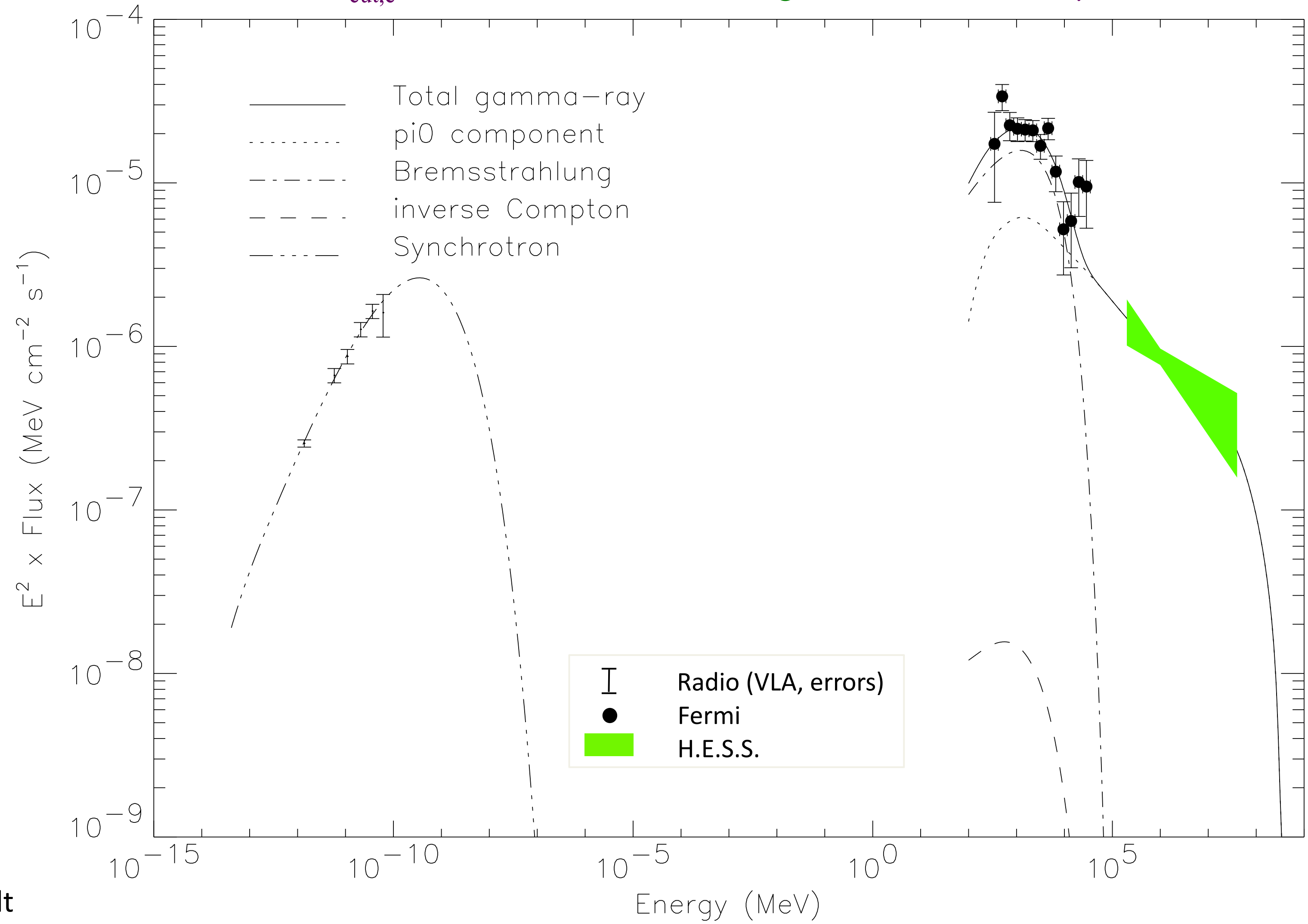
Dominant Emission Mechanism

We find within the constraints of our model, the most likely gamma-ray emission scenario to be hadron-dominated, with a non-negligible contribution from bremsstrahlung emission.



Allowed Lepton Scenario

- at 1σ:
  - Lepton population:
    - $N_{0,e}$ = 6.39 e/s/cm²/GeV/sr
    - γ_e= -1.49
    - $E_{cut,e}$ = 7.0 GeV
  - Hadron population:
    - $N_{0,p}$ = 42.6 p/s/cm²/GeV/sr
    - γ_p = -2.35
  - Magnetic field: B = 67 μG



Emission Mechanism: Similarities

- inverse Compton emission essentially non-existent
  - as ambient photon field (1.25 eV/cm^3; Porter, et. al., 2008) and CMB (0.26 eV/cm^3) are too low relative to other environmental conditions
- Bremsstrahlung mainly occurs at Fermi energies
  - as π^0 + brem cannot reproduce both the Fermi and HESS data and
  - we have allowed the leptons to have a cutoff above the maximum HESS energy
- Both π^0 and bremsstrahlung are necessary to reproduce the data

- Differentiate scenarios?
  - Lepton-dominated model predicts somewhat more radio emission in the Planck regime (30-857 GHz)
  - Not in the Early Release Compact Source Catalog, but probably has the sensitivity
  - would better constrain leptonic population and, thereby, the maximum hadronic contribution

Fermi-Detected SNRs:

Young [2]

Middle-aged

Likely hadronic processes

Fermi-detected SNRs	Index [1]	Index 2	E_{Break} (GeV)	Age (yrs)	Notes
Casssiopeia A	−2.1 ±0.1	-2.4**	>100	330	[1]
Tycho	−2.3 ± 0.1			438	[2]
Vela Jr.	-1.87 ± 0.2	-2.1**		680	[3]
RX J1713	-1.5 ± 0.1	-2.2**		1600	[4] Lepton-dominated
CTB 37A	−2.28 ± 0.1	-2.3 ± 0.3**		1500?	[5]
W49B	−2.18 ± 0.04 −2.29 ± 0.02	−2.9 ± 0.2	4.8 ± 1.6	1k-4k	[6] PL disfavored at 4.4σ
Cygnus Loop	-1.83 ± 0.06	-3.23 ± 0.19	-2.39 ± 0.26	20k	[7] No clear MC interaction
IC 443	−1.93 ± 0.03	−2.56 ± 0.11	3.25 ± 0.6	3-4k or 20-30k	[8]
W44	−2.06 ± 0.1	−3.02 ± 0.22	1.9 ± 0.5	~20k	[9]
W51C	−1.97 ± 0.08	-2.44 ± 0.09	1.9 ± 0.2	~30k	[10]
W28 (N) (and G6.5-0.4)	−2.09 ± 0.36	−2.74 ± 0.15	1.0 ± 0.2	35-150k (40k)	[11]

[1] for Power Law or I1 for Broken Power Law

[2] See Giordano, this conference.

**from VHE measurement

... 11 and counting!

including W30, G349.7+0.2, 3C391, W41, …

[1] Abdo et al. 2010 (ApJL 720)
[2] Neumann-Godo 2011, Fermi Symp.
[3] Taka 2011, Fermi Symposium
[4] 2011arXiv1103.5727A
[5] Brandt 2011, Fermi Symposium
[6] Kadagiri H. et al., Submitted to ApJ
[7] Abdo et al., 2010 ApJ 718
[8] Abdo et al., 2010 (ApJ 722)
[9] Abdo, et al. 2010 (AJ 712, 459)
[10] Abdo et al., 2009 (ApJ 706L)
[11] Abdo, et al. 2010 (Sci. 327, 1103)

Conclusions:

- Fermi-LAT is detecting an increasing number of SNRs
  - allows us to access a unique window in emission associated with hadronic processes
  - with multiwavelength data, we better constrain particle acceleration and environmental conditions.
- One example: SNR CTB 37A
  - detected at 18.6σ, slightly extended, stable for diffuse models & data subsets
  - emission consistent with H.E.S.S., X-ray, IR, and radio data
  - no long-term (blazar) or short-term (pulsation) variability
- SNR CTB 37A: Multiwavelength model
  - Simultaneously fit lepton & hadron populations + B-field to data
    - both π^0 and bremsstrahlung are required to reproduce the data
    - => CTB 37A is accelerating hadrons
    - B-field: $B = 109^{+56}_{-49}$ μG: 1st lower limit, constraining upper limit.
  - Conversion efficiency: η~5%
- Fermi-LAT SNRs: so far most middle-aged SNRs detected to date…
  - are interacting with Molecular Clouds
  - likely hadronic-dominant emission mechanism
- A statistically significant catalog of such objects will permit us to more precisely compare SNR acceleration properties to the directly measured CRs themselves, allowing us to illuminate the 100-year mystery of CR origin.

End of slide show