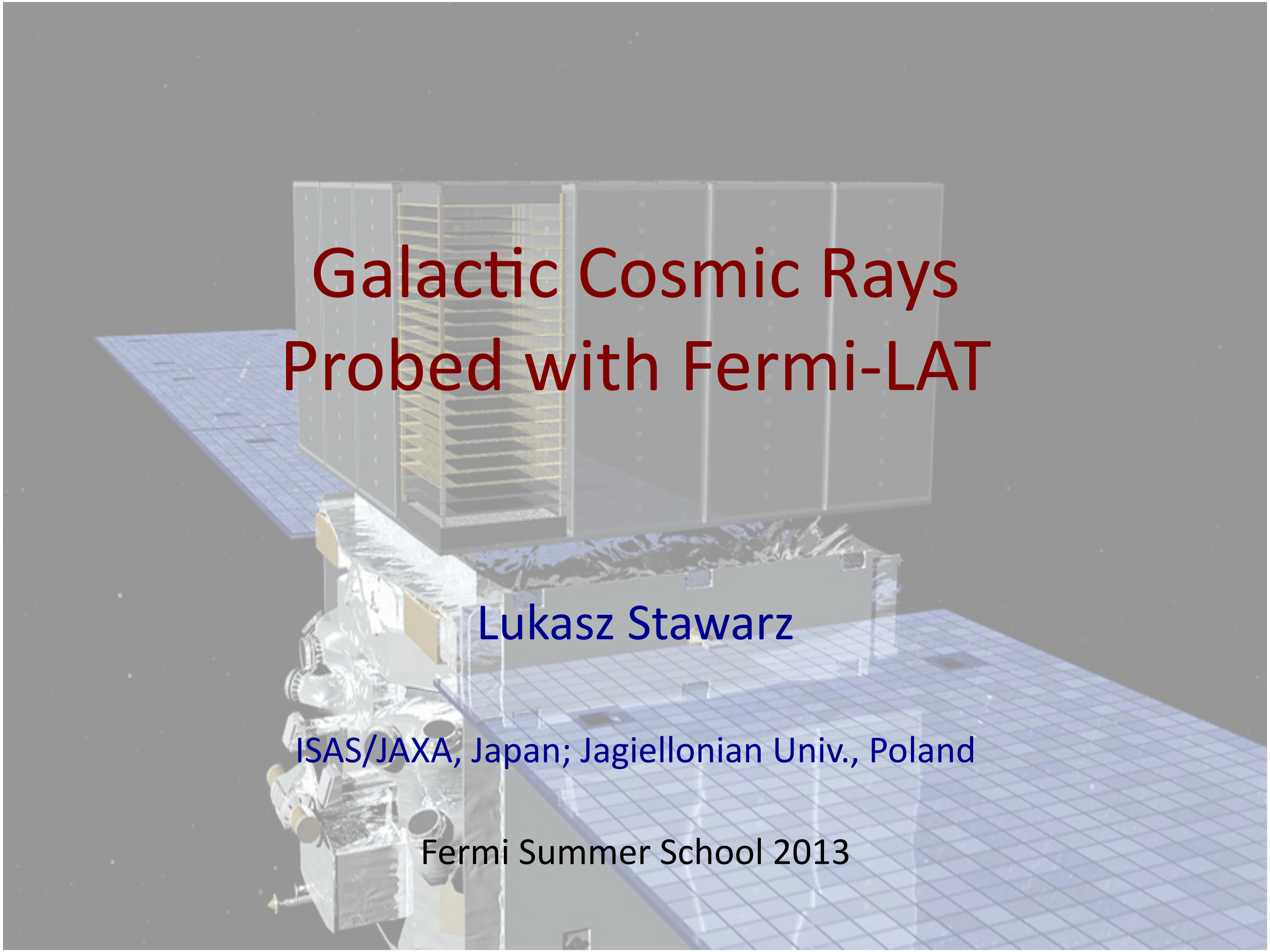

Galactic Cosmic Rays Probed with Fermi-LAT

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ISAS/JAXA, Japan; Jagiellonian Univ., Poland

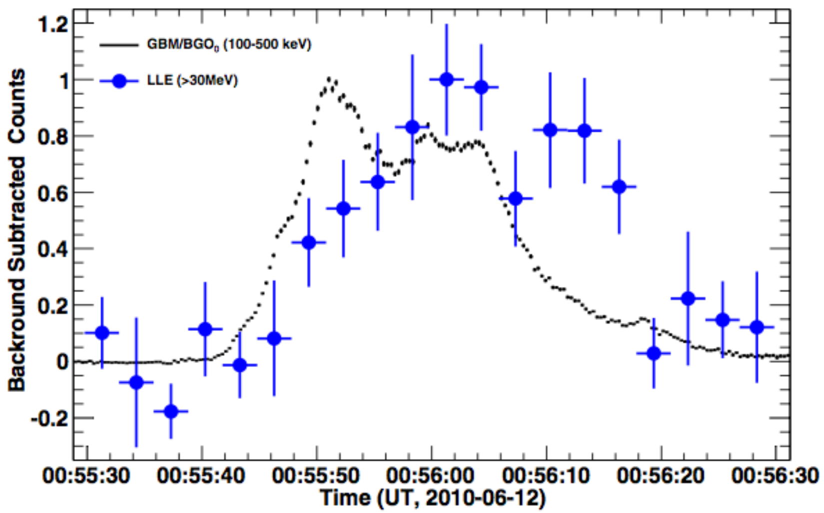
Fermi Summer School 2013

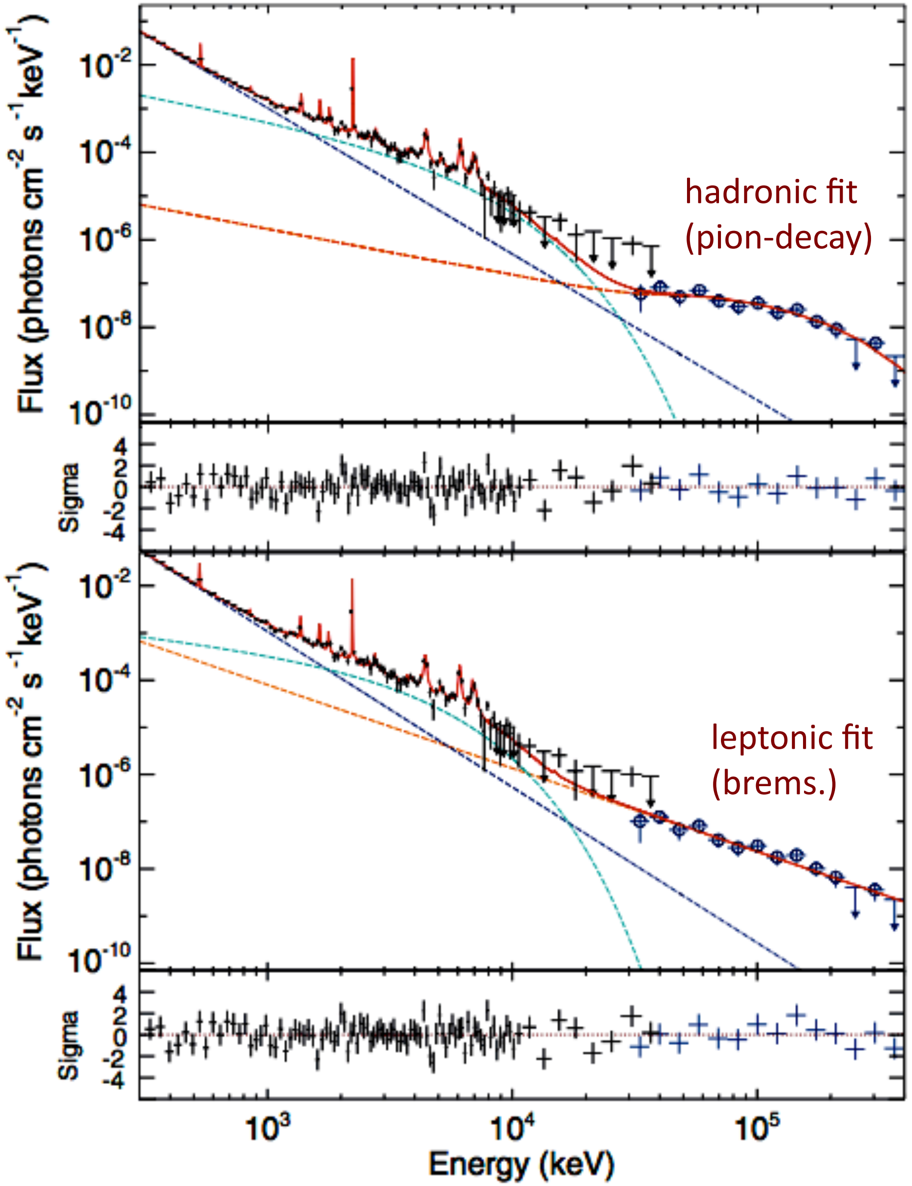
Outline

- Solar Flares
- Gamma-Ray Binaries
- Supernova Remnants
- Galactic ISM

Solar Flares

Ackermann et al. 2012, ApJ 745:
M2-class flare **SOL2010-06-12T00:57.**
The flare produced an ~50s impulsive burst of hard X- and gamma-ray emission up to at least 400 MeV observed by the Fermi GBM and LAT. The acceleration of hundreds of keV electrons and hundreds of MeV electrons and/or protons in the chromosphere took place with 10s lag.

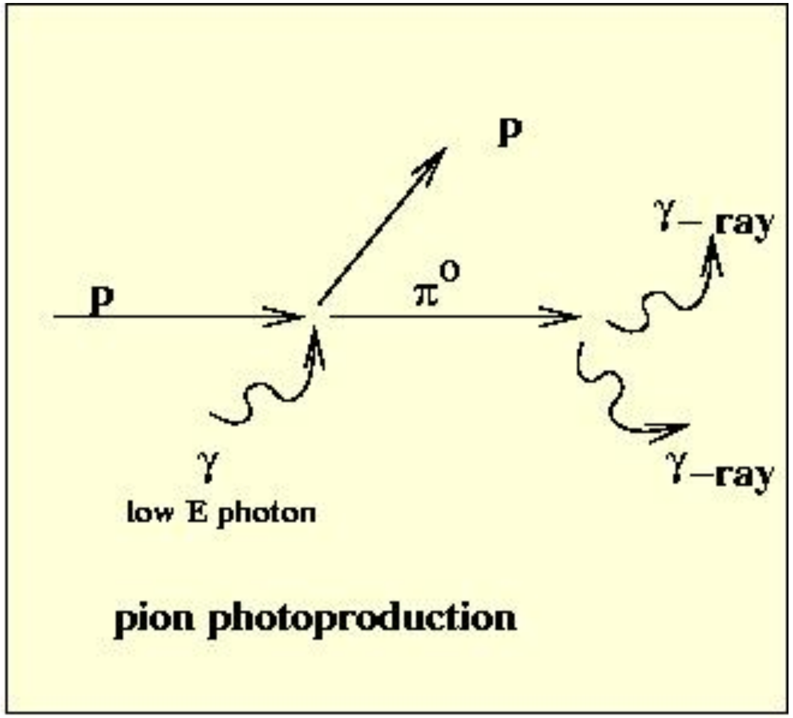


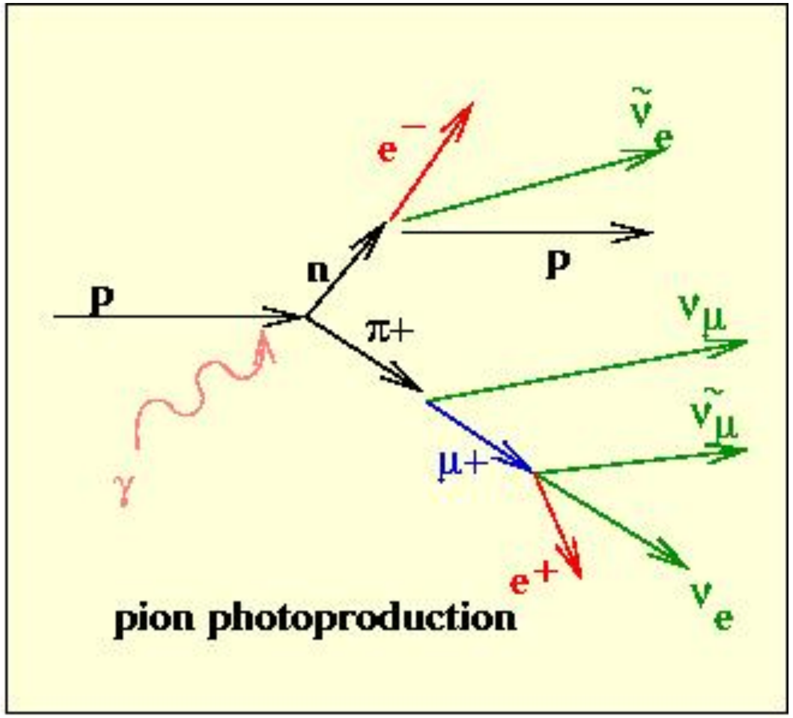


High-Energy Astrophysics

• acceleration of protons and electrons;
• "leptonic/hadronic" modeling degeneracy;
• hadronic emission accompanied by the production of neutrinos and secondary electrons;

• *hadronic emission: inelastic proton-proton interactions*
• *hadronic emission: photo-mezon production*

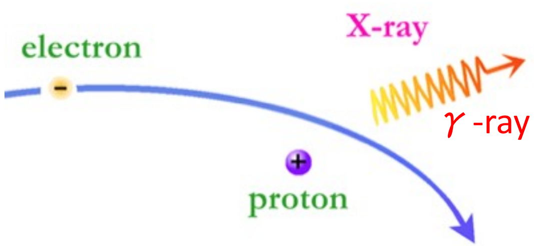


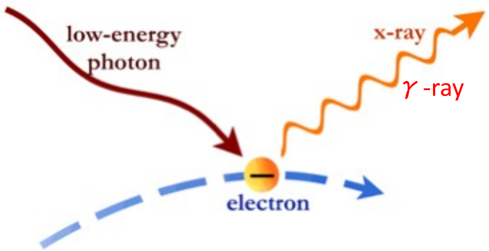


High-Energy Astrophysics

• ultrarelativistic electrons are very efficient emitters!

• *leptonic emission: bremsstrahlung*
• *leptonic emission: synchrotron*
• *leptonic emission: inverse-Compton*





$$\tau_{e,\,syn} \simeq 10^4 \left(\frac{E_e}{\mathrm{GeV}}\right)^{-1} \left(\frac{B}{\mu\mathrm{G}}\right)^{-2} \ \mathrm{Myr}$$

$$\tau_{e,\,coul} \simeq 50 \left(\frac{E_e}{\mathrm{GeV}}\right) \left(\frac{n_g}{\mathrm{cm}^{-3}}\right)^{-1} \ \mathrm{Myr}$$

$$\tau_{brem} \simeq 50 \left(\frac{\chi(E_e)}{10}\right)^{-1} \left(\frac{n_g}{\mathrm{cm}^{-3}}\right)^{-1} \ \mathrm{Myr}$$

$$\tau_{ic/T} \simeq 3 \times 10^2 \left(\frac{E_e}{\mathrm{GeV}}\right)^{-1} \left(\frac{u_{rad}}{\mathrm{eV/cm^3}}\right)^{-1} \ \mathrm{Myr}$$

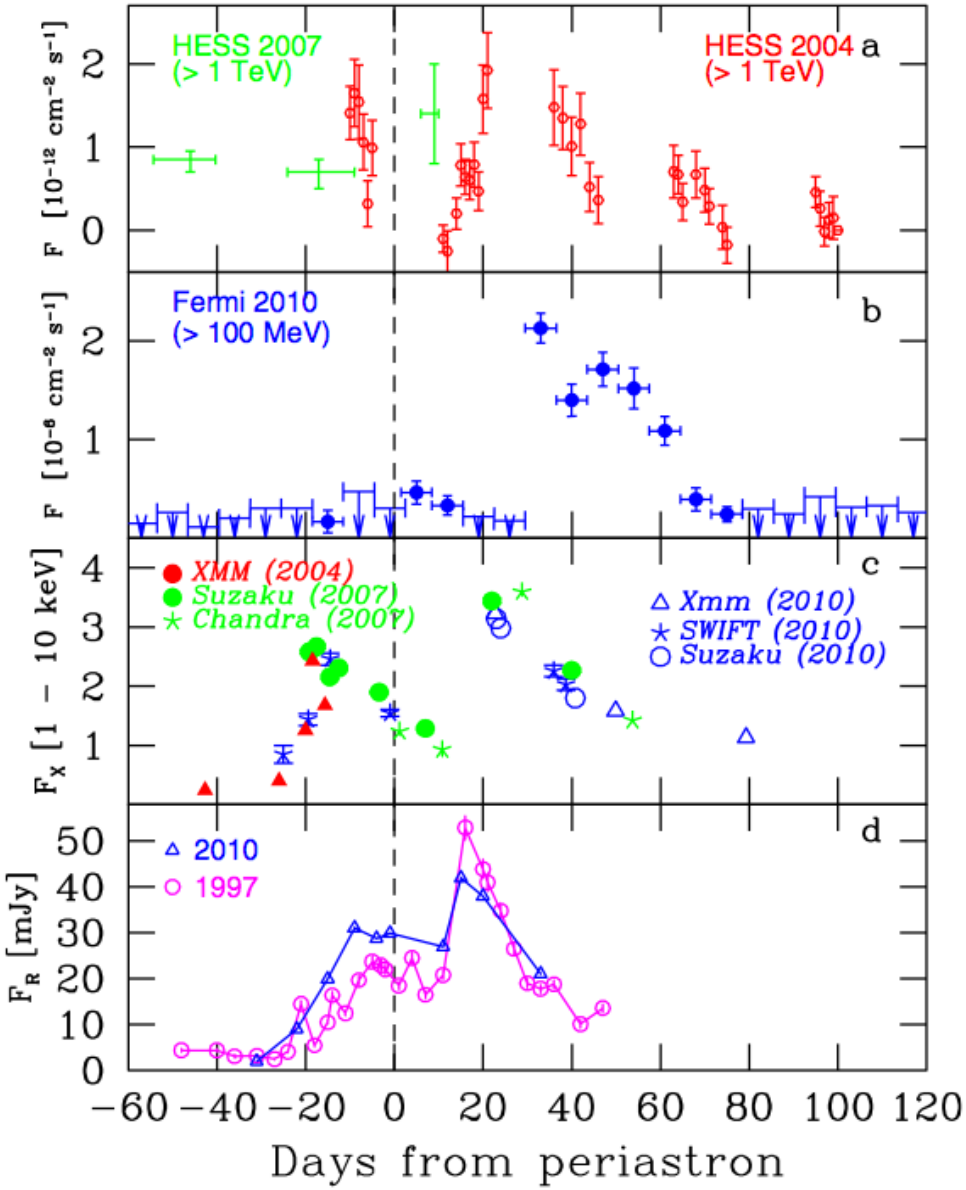
$$\tau_{p,\,syn} \simeq 10^{17} \left(\frac{E_p}{\mathrm{GeV}}\right)^{-1} \left(\frac{B}{\mu\mathrm{G}}\right)^{-2} \ \mathrm{Myr}$$

$$\tau_{p,\,coul} \simeq 10^2 \left(\frac{E_p}{\mathrm{GeV}}\right) \left(\frac{n_g}{\mathrm{cm}^{-3}}\right)^{-1} \ \mathrm{Myr}$$

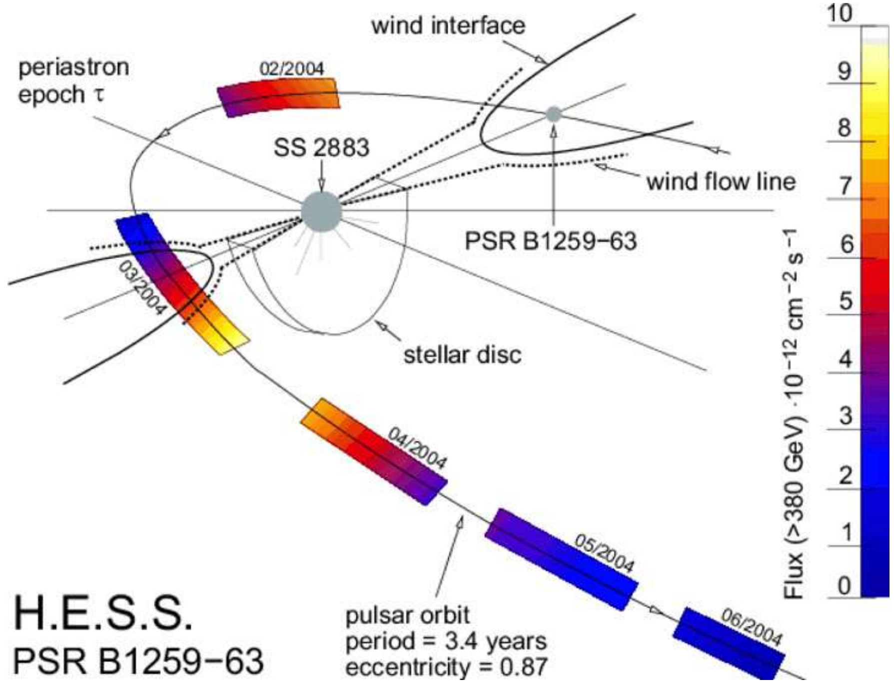
$$\tau_{pp} \simeq 3 \times 10^{-2} \left(\frac{n_g}{\mathrm{cm}^{-3}}\right)^{-1} \ \mathrm{Myr}$$

$$\tau_{p\gamma} \simeq 2 \times 10^{17} \left(\frac{E_p}{\mathrm{GeV}}\right)^{-1} \left(\frac{u_\gamma}{10^{-5}\,\mathrm{eV/cm^3}}\right)^{-1} \ \mathrm{Myr}$$

Gamma-Ray Binaries



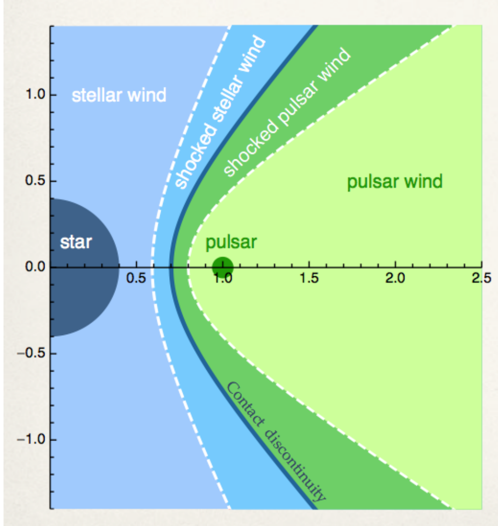
Abdo et al. 2011, ApJL 736:
LAT detection of the binary system **PSR B1259−63** (radio pulsar!) around periastron.

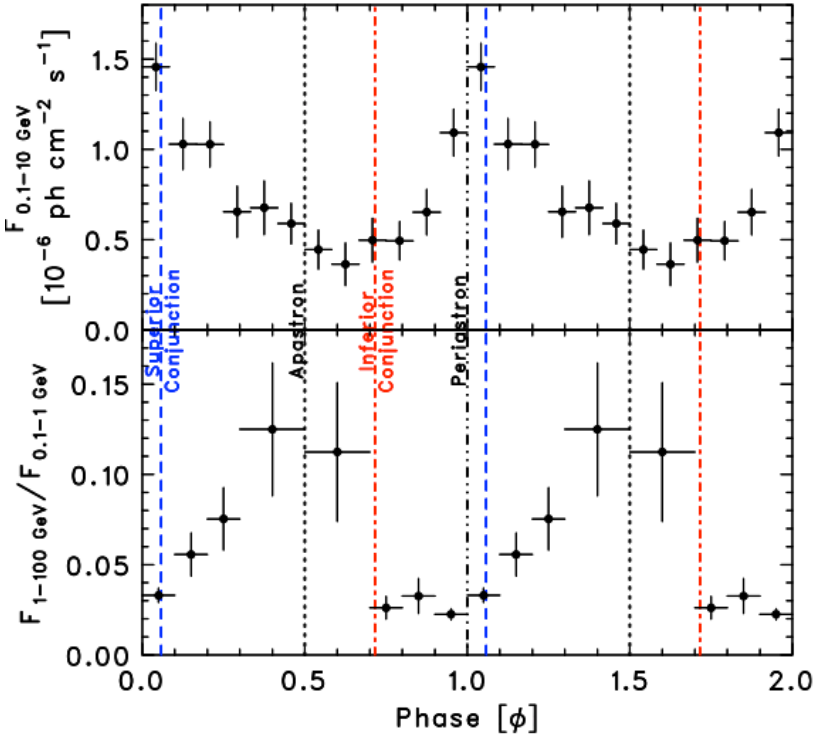


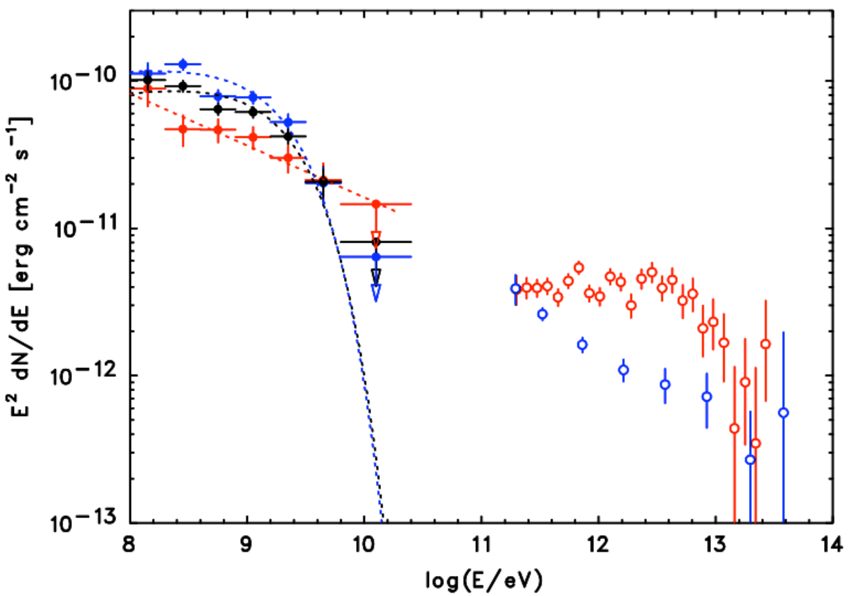
Gamma-Ray Binaries

Abdo et al. 2009, ApJ 706:

Detection of the orbital modulation in the gamma-ray lightcurve and spectrum of high-mass X-ray binary **LS 5039** (neutron star candidate); exponential cutoff around 2 GeV; the phase difference can be explained mostly as a result of the competition between IC scattering on high-energy electrons and TeV pair production.

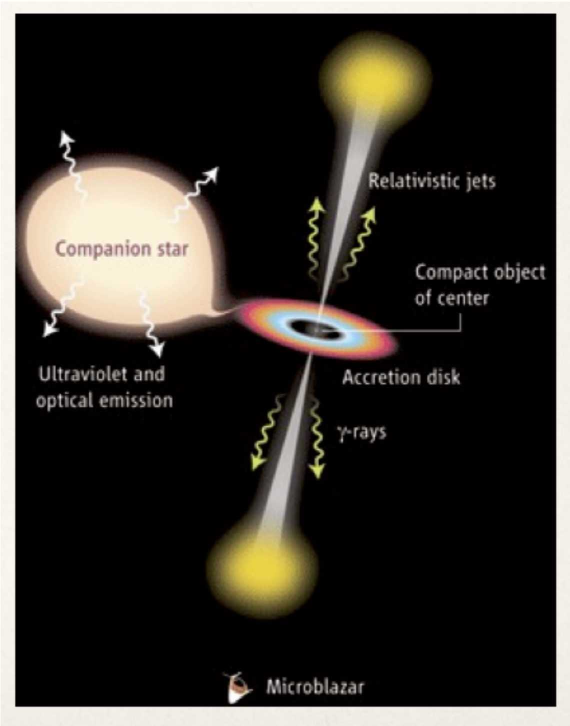




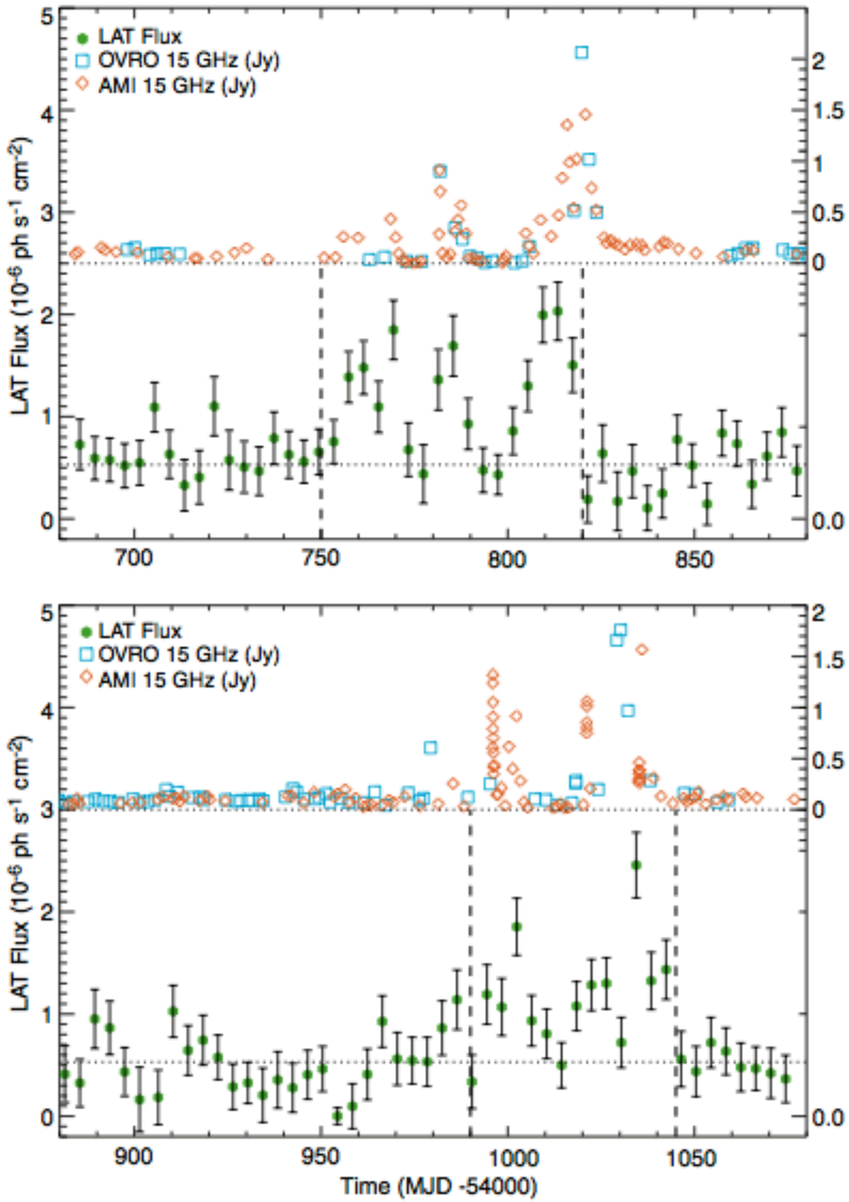


Gamma-Ray Binaries

Abdo et al. 2009, Science 326:
a variable source coinciding with the position of the high-mass x-ray binary system **Cygnus X-3** (black hole candidate); identification secured by the detection of the orbital period in gamma rays, and a correlation of the LAT flux with radio emission from the relativistic jets.



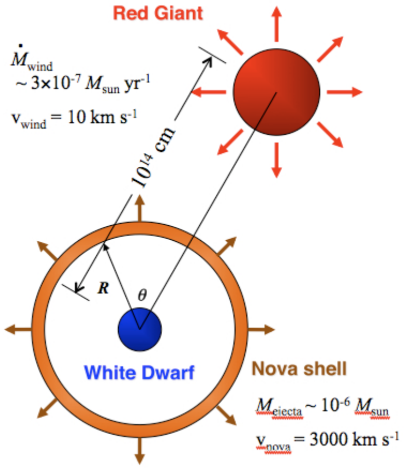
Credit: Mirabel Science, 2012, 335, 175

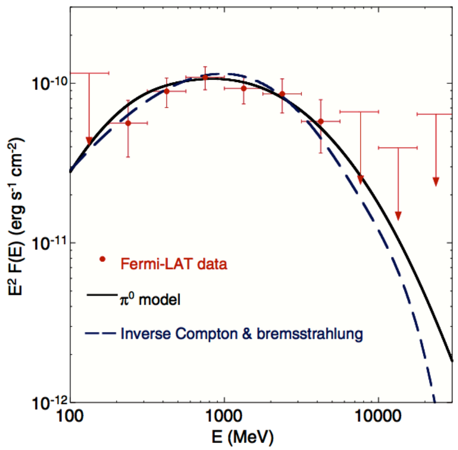


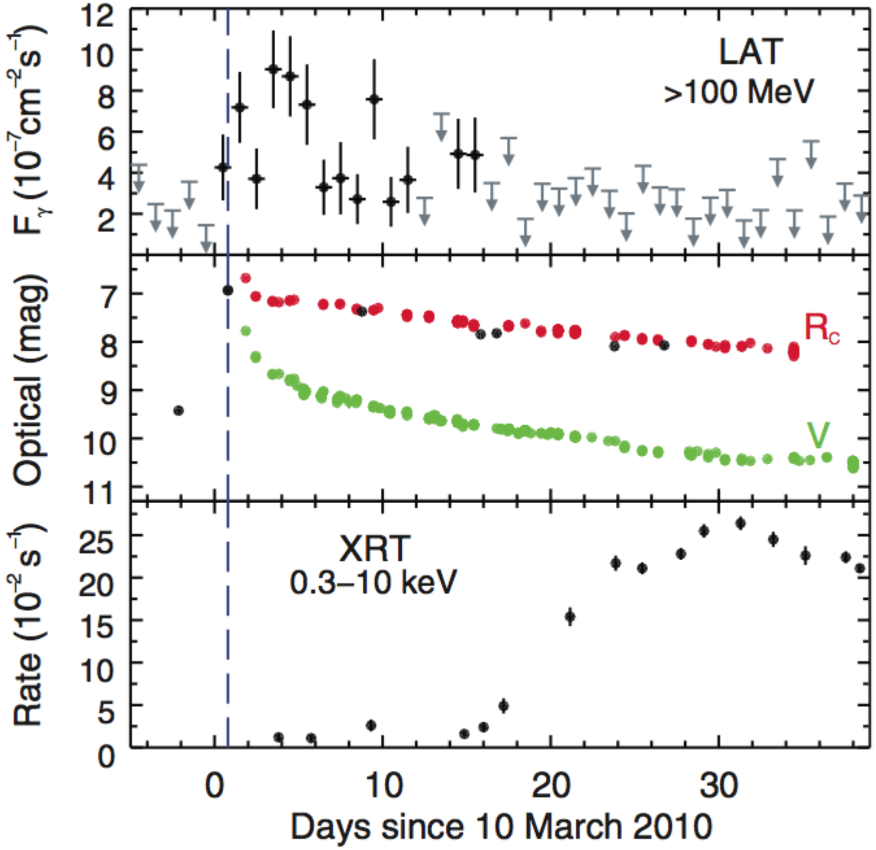
Gamma-Ray Binaries

Abdo et al. 2010, Science 329:

Symbiotic binary **V407 Cyg** - small white dwarf and large red giant orbiting each other closely. Nova thermonuclear runaway on WD surface. Nova shell initially freely expands into asymmetric dense medium. Shell toward RG slows down quickly. Hence gamma rays peak early when efficiency for pion and inverse-Compton processes is favorable. Shell decelerates slowly away from RG. Hence X rays peak later, flux increasing with volume of shock-heated gas.



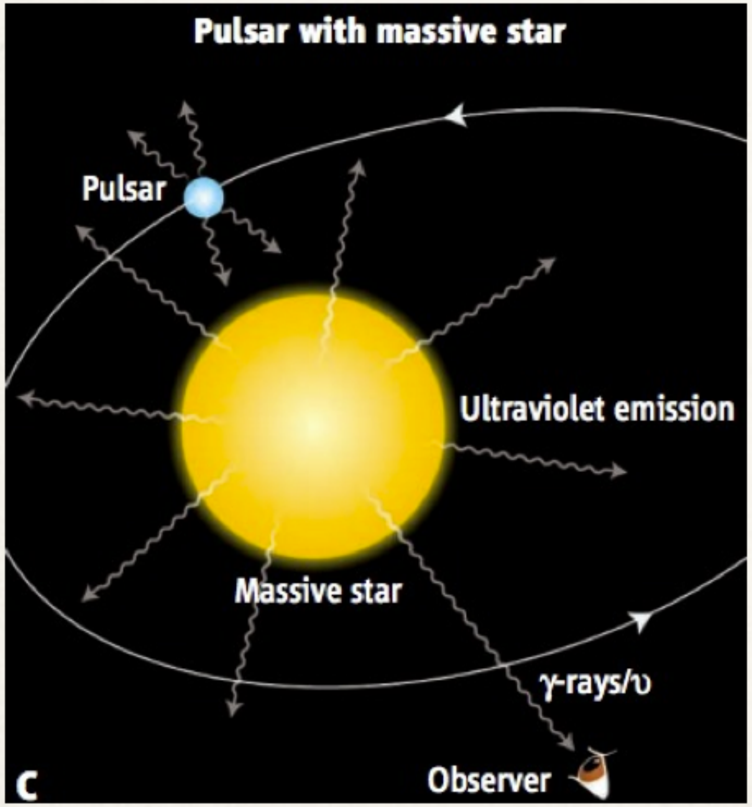




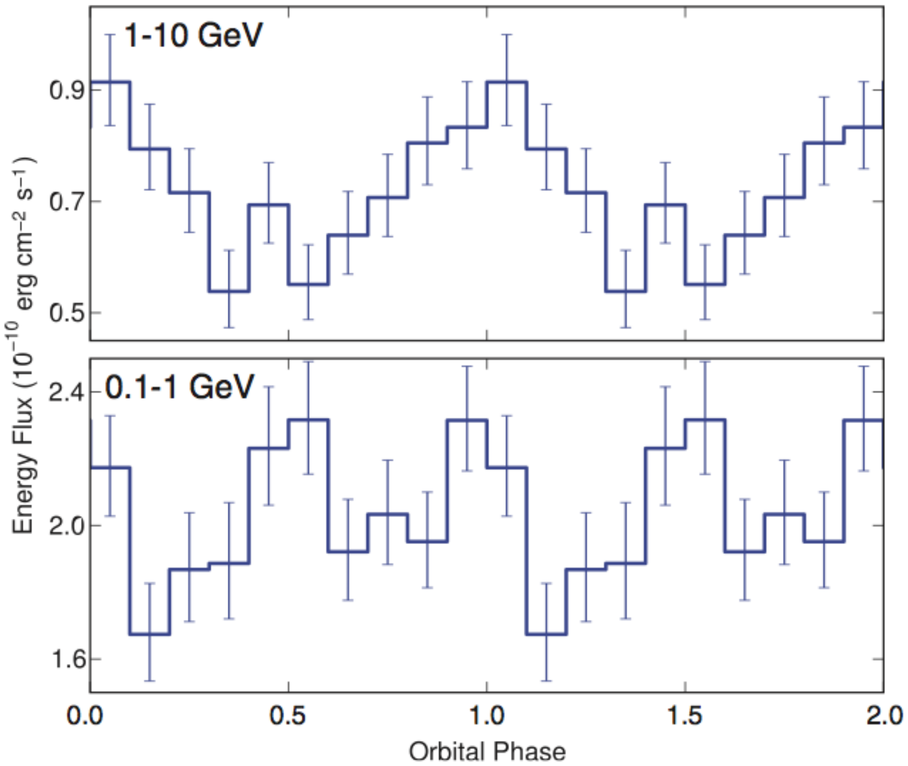
Gamma-Ray Binaries

Ackermann et al. 2012, Science 335:

intensity and spectral modulation of **1FGL J1018.6–5856** discovered with Fermi-LAT implies a binary nature of the system (similar to LS 5039).



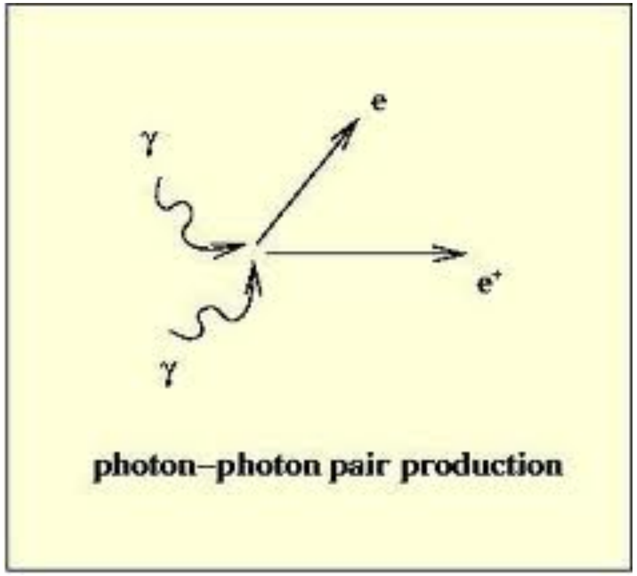
Credit: Mirabel Science, 2012, 335, 175



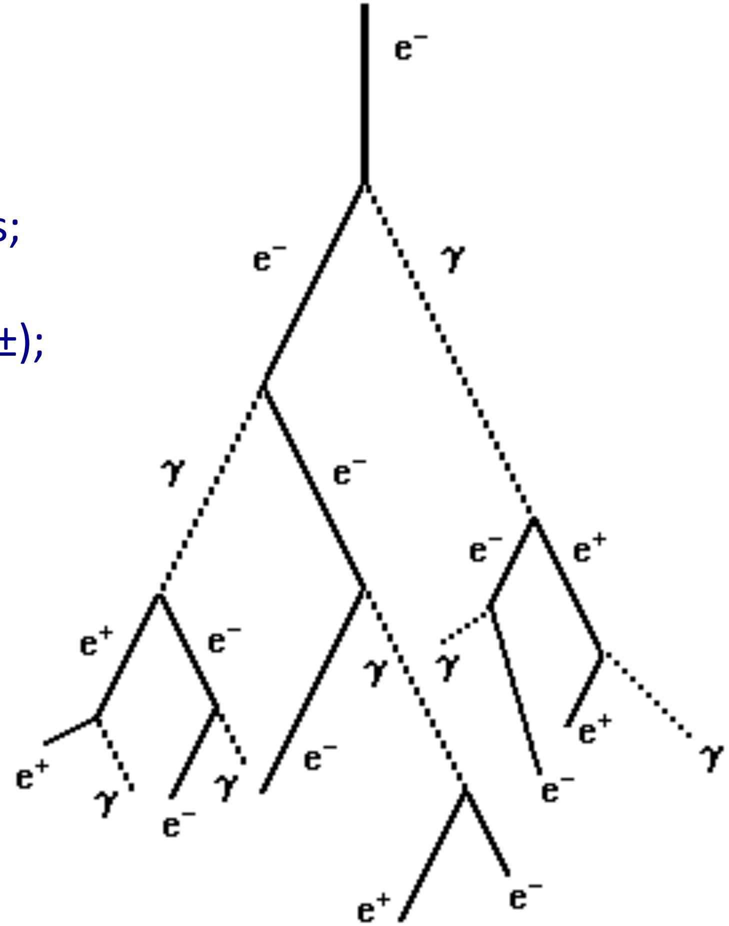
Gamma-Ray Binaries

• Radio pulsars;
• Neutron star candidates;
• Black hole candidates;
• Accreting white dwarfs.

• Orbital modulation, nova explosions, relativistic jets;
• Variety of radiative processes involved;
• Unknown acceleration sites and γ-ray emitters (p+/e±);
• Photon-photon annihilation, KN effects, cascades.



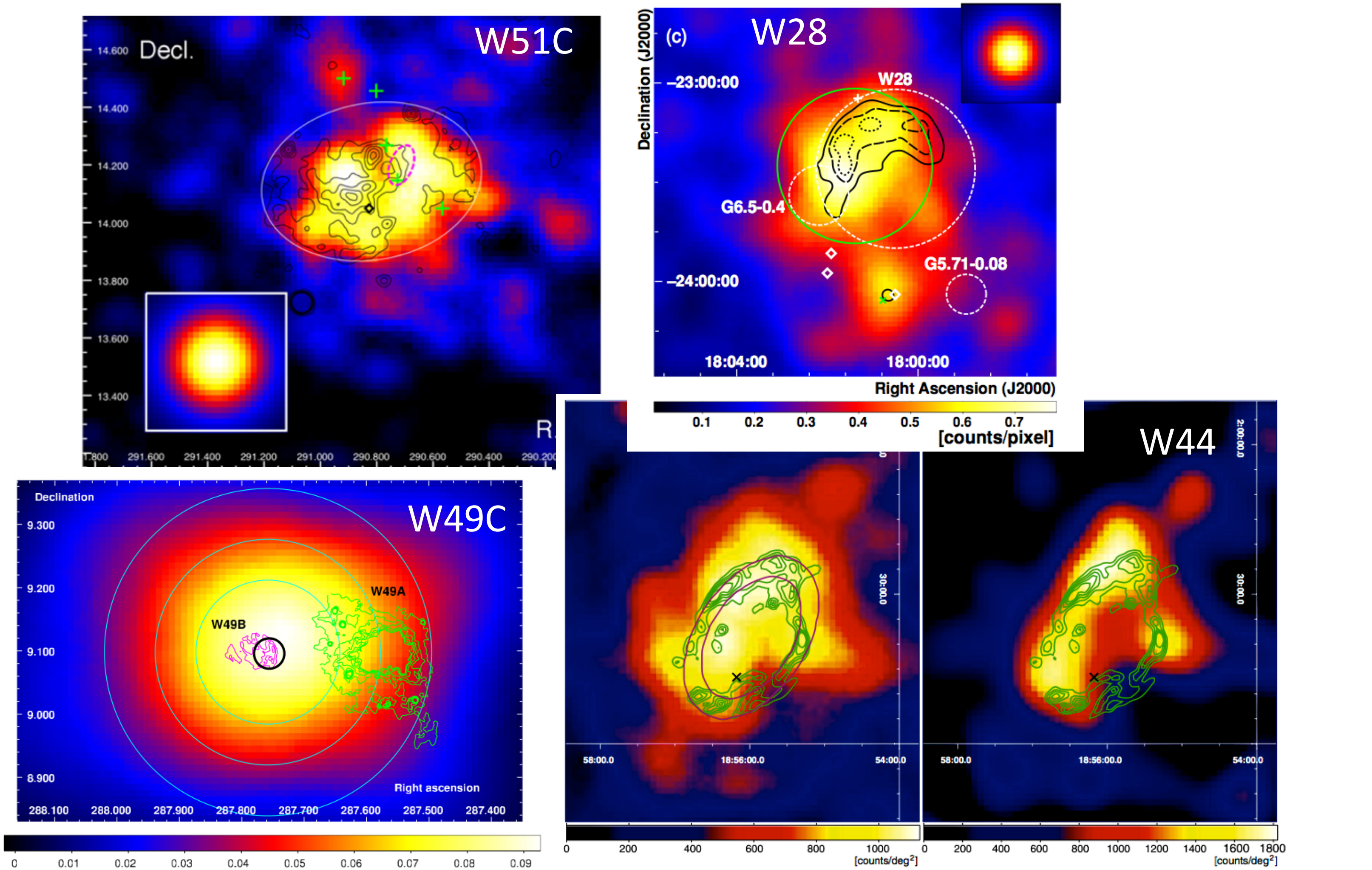
photon–photon pair production



Supernova Remnants

Abdo et al. 2009, ApJ 706, Abdo et al. 2010, Science 327, ApJL 712, ApJ 718, 722:

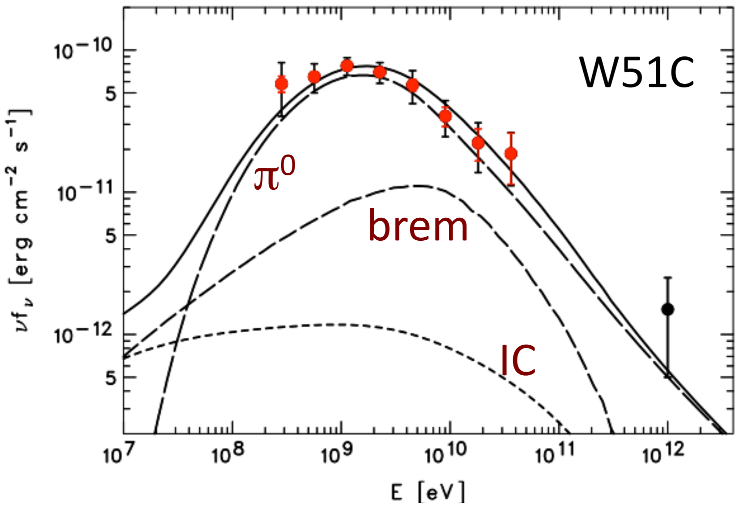
Middle-aged (~10^4 yr) SNRs with intense radio synchrotron emission in shells, often mixed morphologies, and interacting with molecular clouds **W51C, W44, IC 443, W28, W49B**.

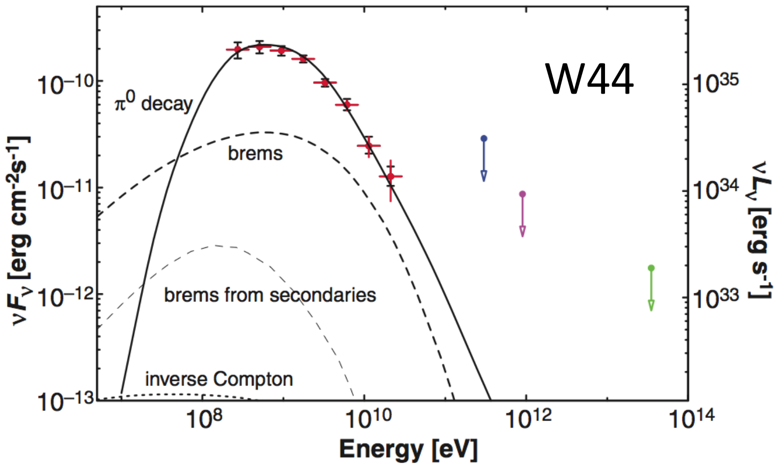


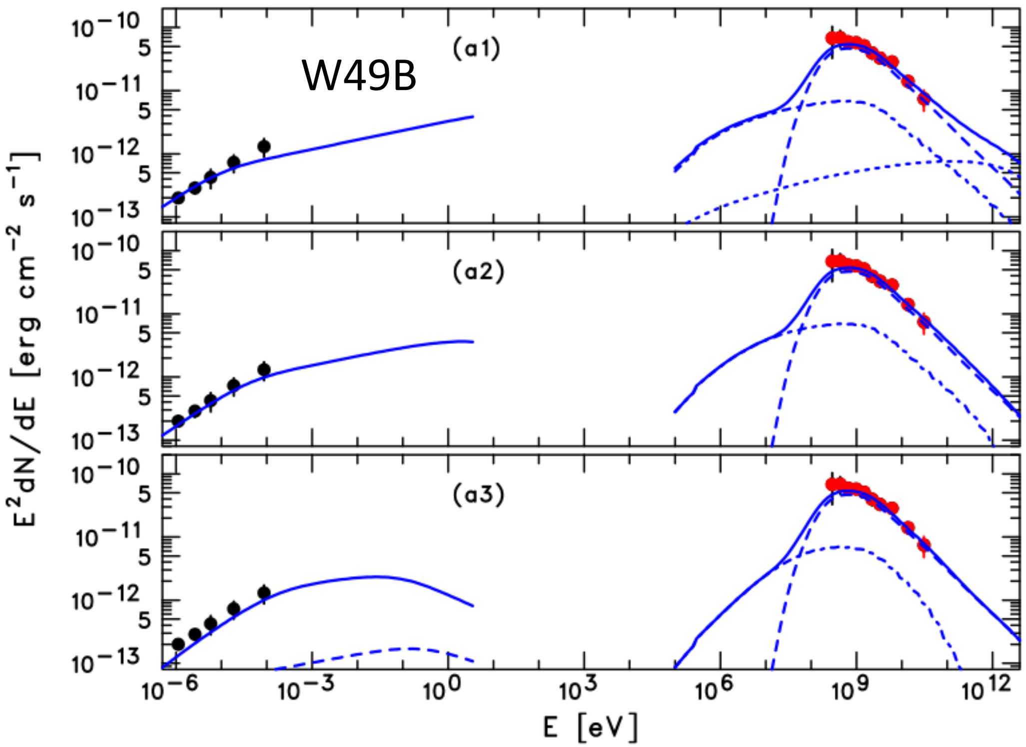
Supernova Remnants

Abdo et al. 2009, ApJ 706, Abdo et al. 2010, Science 327, ApJL 712, ApJ 718, 722:

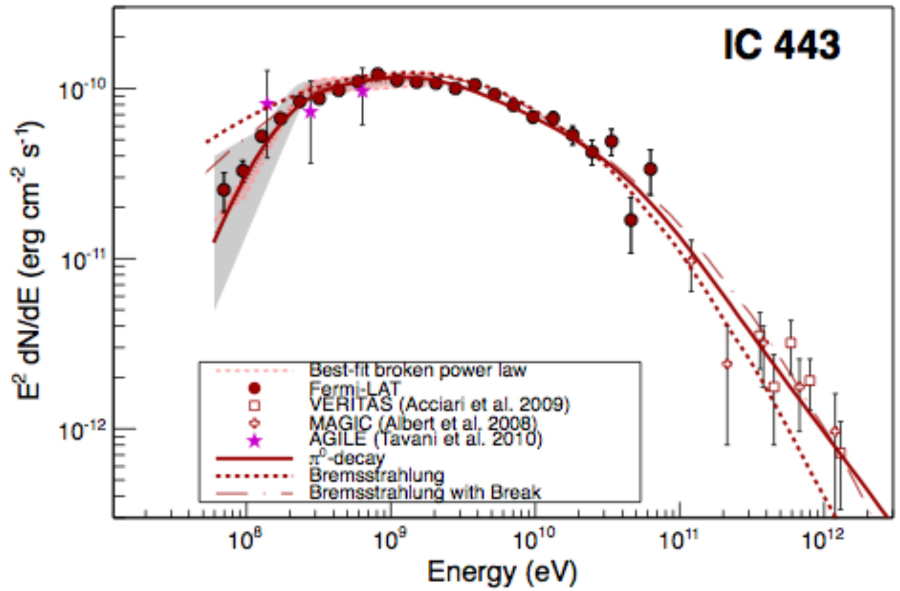
Gamma-ray spectra of middle-aged SNRs, which are relatively steep, are better fitted with the hadronic (π^0-decay) models, although bremsstrahlung model cannot be excluded.

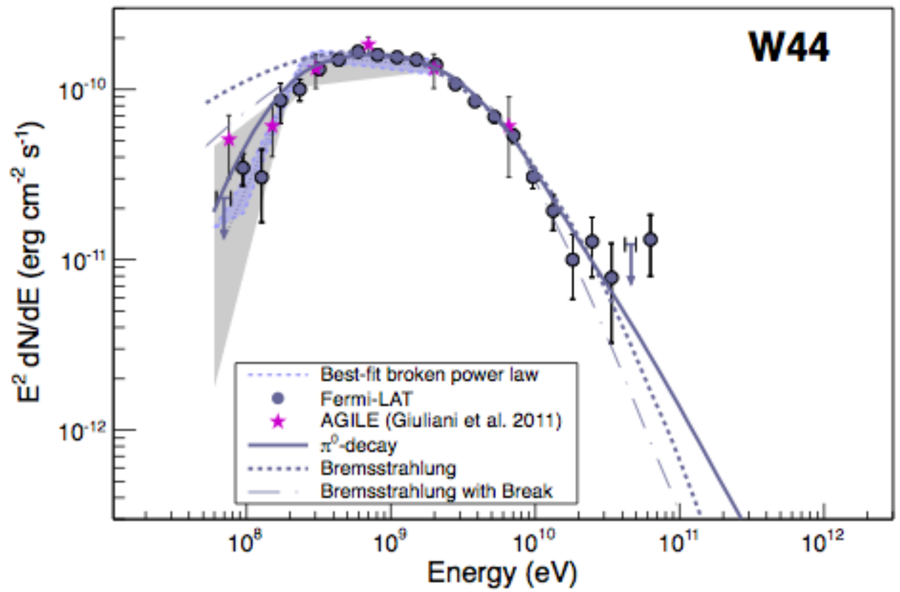






Supernova Remnants





Ackermann et al. 2013, Science 339:

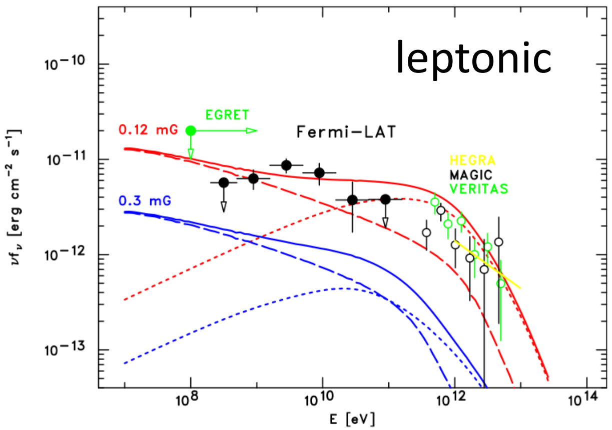
Improved analysis of the LAT data ≤200 MeV enabled the detection of pion-decay spectral signatures: low-energy cutoffs!

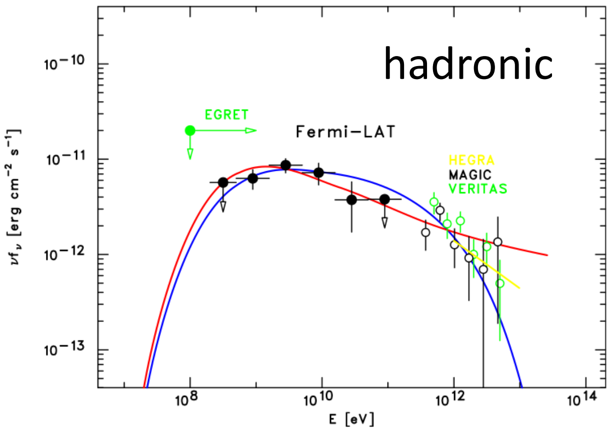
$$\pi^0 \rightarrow e^- + e^+ + \gamma \qquad mass = 264 m_e = 135.0 MeV / c^2$$

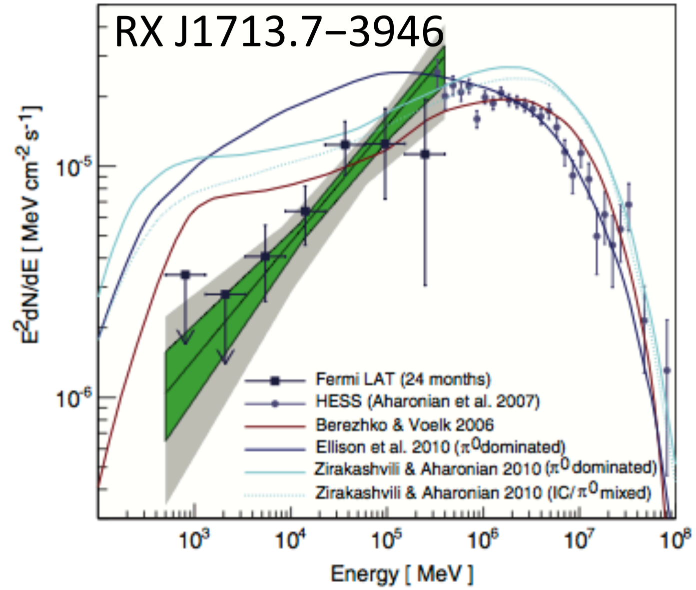
$$\pi^{+/-} \rightarrow \mu^{+/-} + \nu \qquad mass = 273 m_e = 139.6 MeV / c^2$$

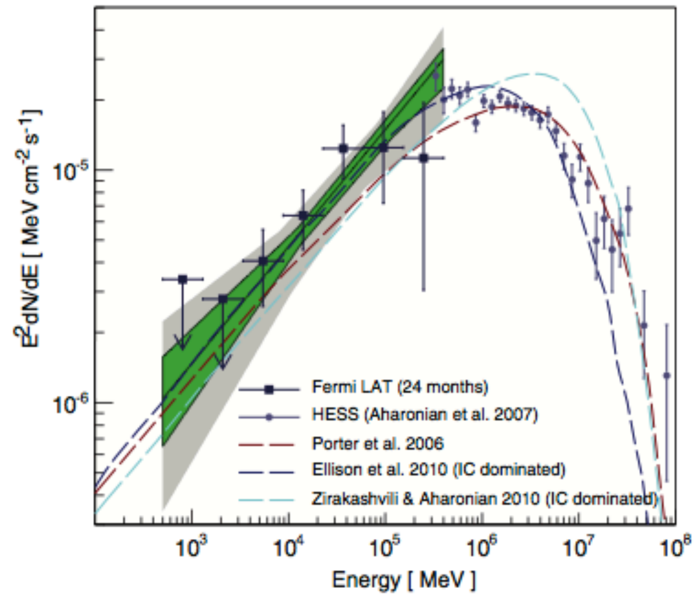
Supernova Remnants

Abdo et al. 2010, ApJL 710; 2011, ApJ 734:
young SNRs **Cassiopeia A** and **RX J1713.7–3946**
mixed hadronic/leptonic models or leptonic models
(very hard GeV continuum of RX J1713.7–3946!)





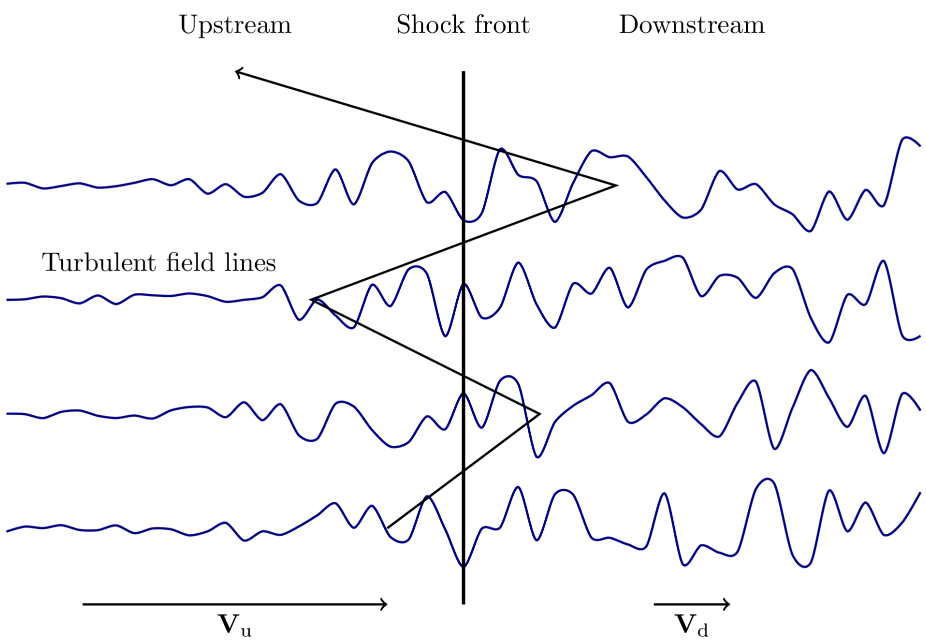


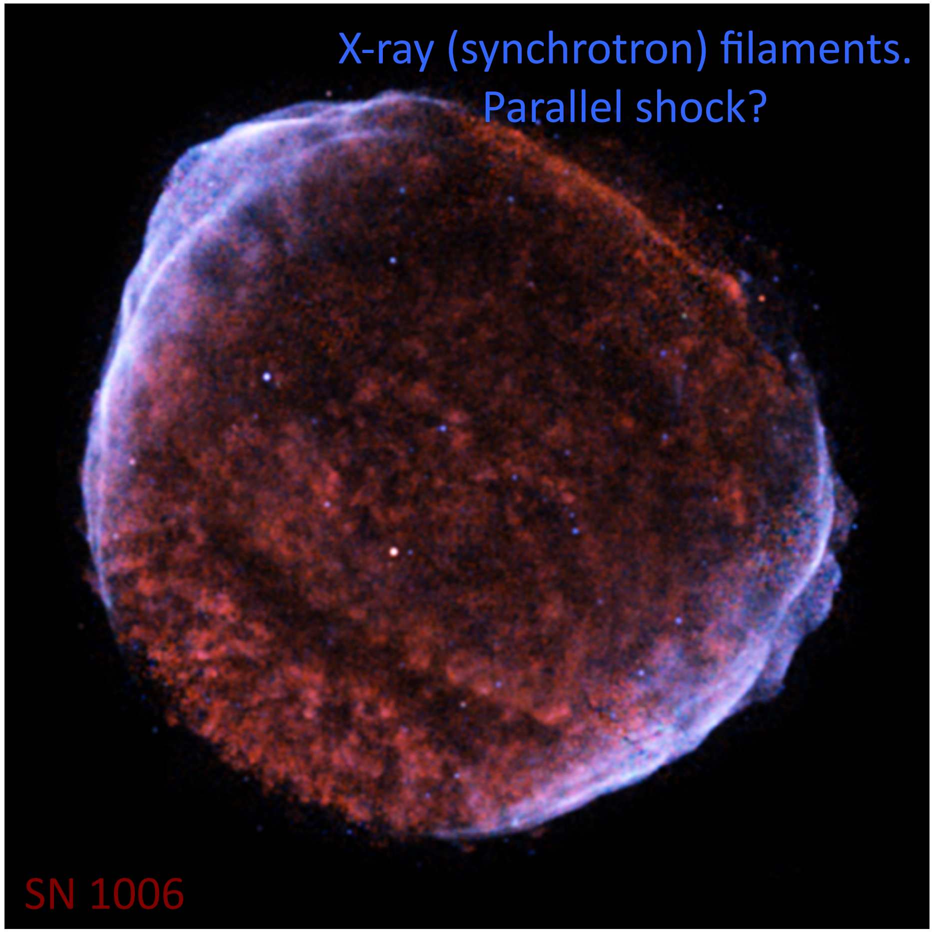


Supernova Remnants

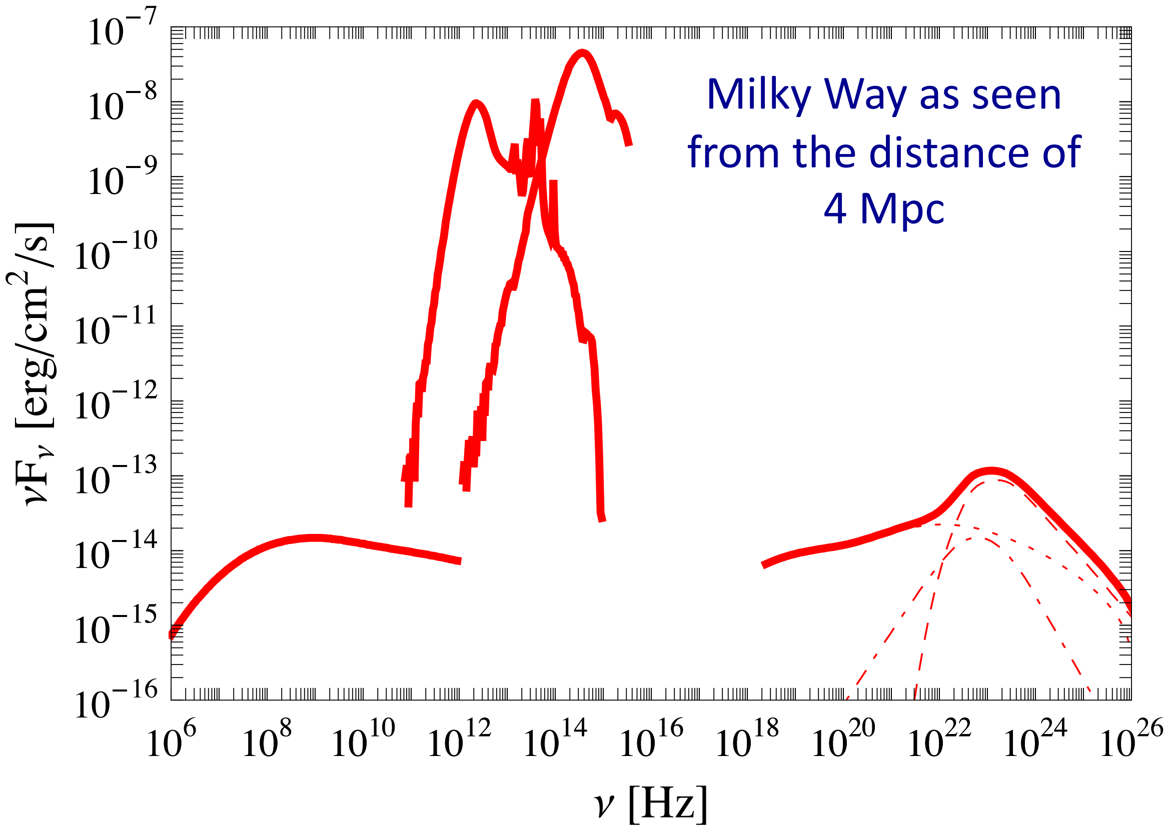
- Strong shock driven in the ISM;
- Sources of Galactic cosmic rays;
- "Diffusive shock acceleration" model;

- Need for the magnetic field amplification;
- CR-modified (non-linear) shocks;
- "Leptonic vs hadronic" controversy;





Galactic ISM

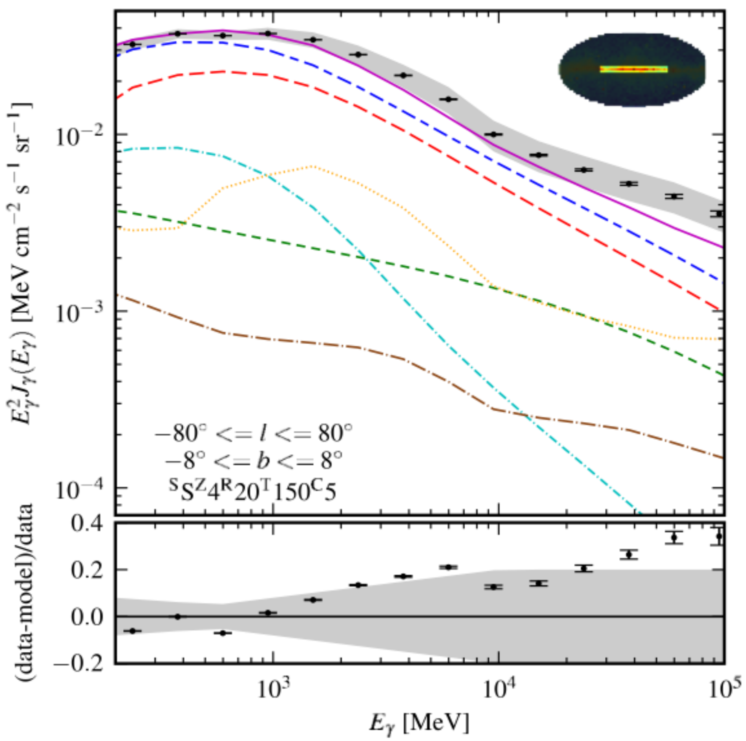


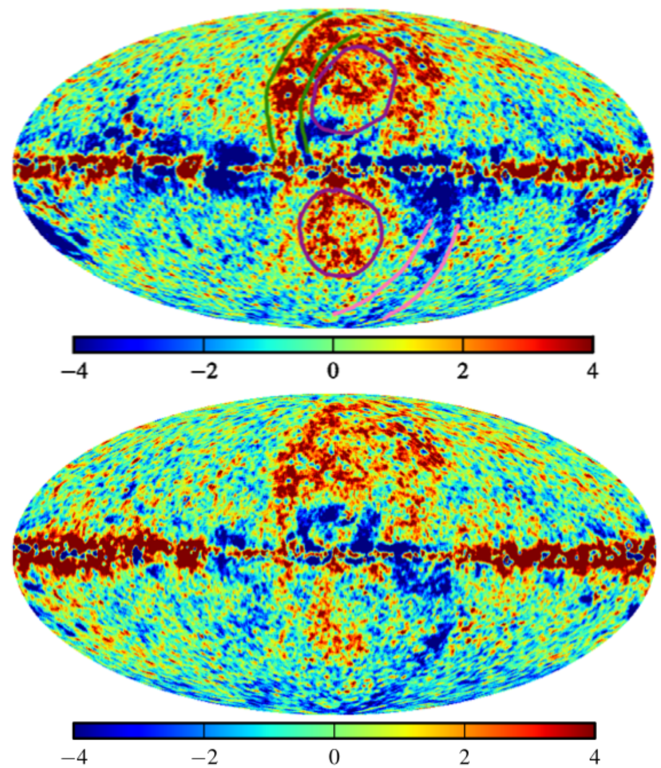
GLAPROP model developed by Moskalenko & Strong (1998) and Strong & Moskalenko (1998). This model assumes injection of a power-law electrons and nuclei by SNRs, and follows their spatial and energy evolution under the influence of different losses processes (Coulomb losses, synchrotron and IC cooling, proton-proton collisions, etc.), taking also into account the relevant interactions of charged particles with the interstellar turbulent magnetic field (with the assumed Kolmogorov spectrum) in a quasi-linear approximation regime.

Galactic ISM

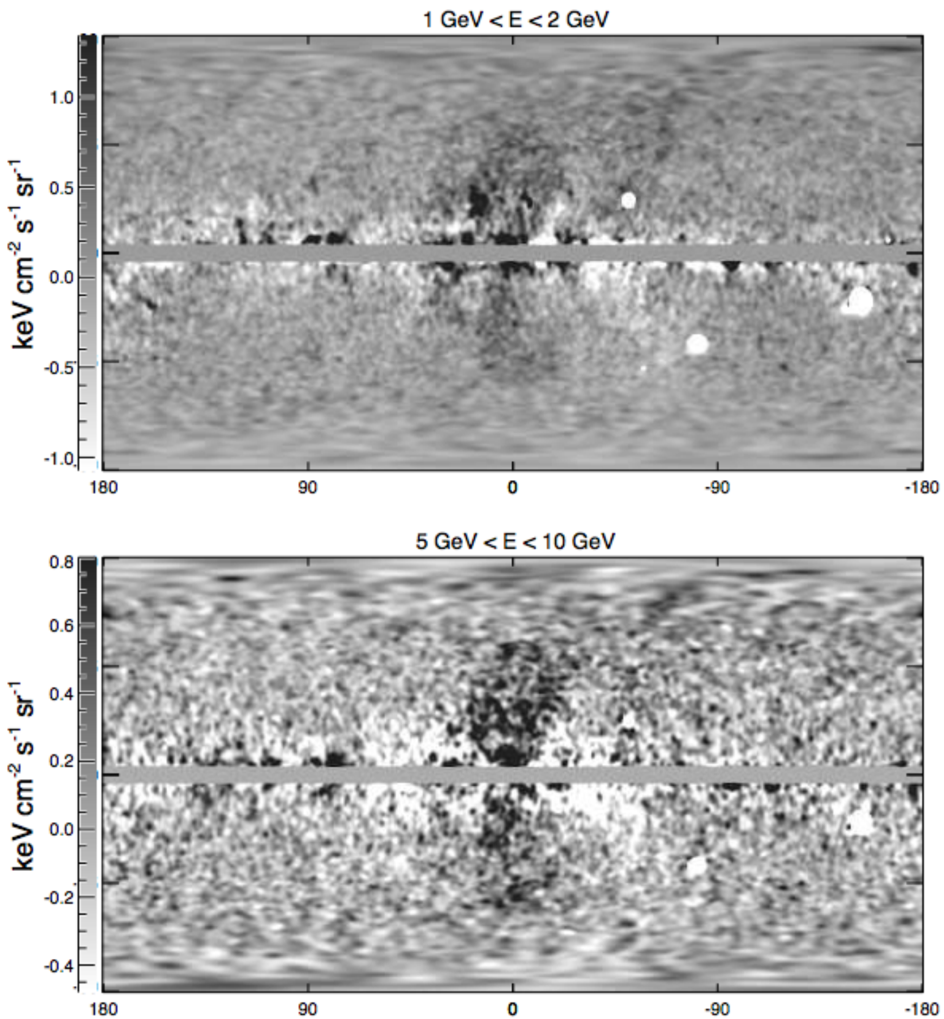
Ackermann et al. 2012, ApJ 750:

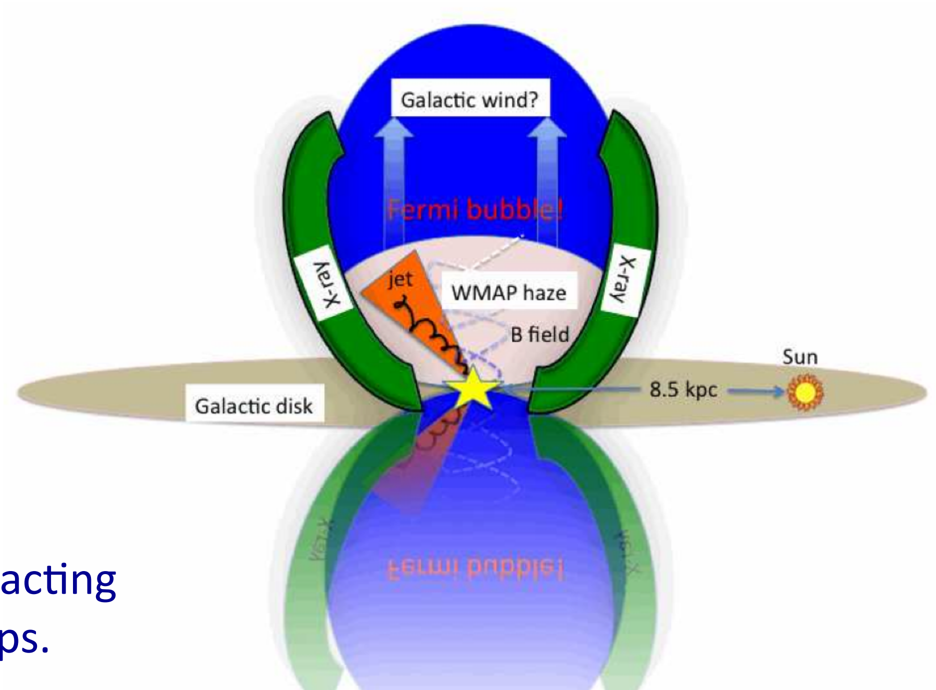
Analysis of the **diffuse Galactic emission**: the GALPROP modeling is consistent with the data at high and intermediate latitudes but under-predicts the data in the inner Galaxy for energies above a few GeV (meaning either contribution from the undetected source population or variations in the CR spectra). In the outer Galaxy, the data prefer models with a flatter distribution of CR sources (CR sources other than SNRs?), a larger CR halo, or greater gas density than assumed; large-scale structures seen in the residual map ("**Fermi Bubbles**").





Galactic ISM

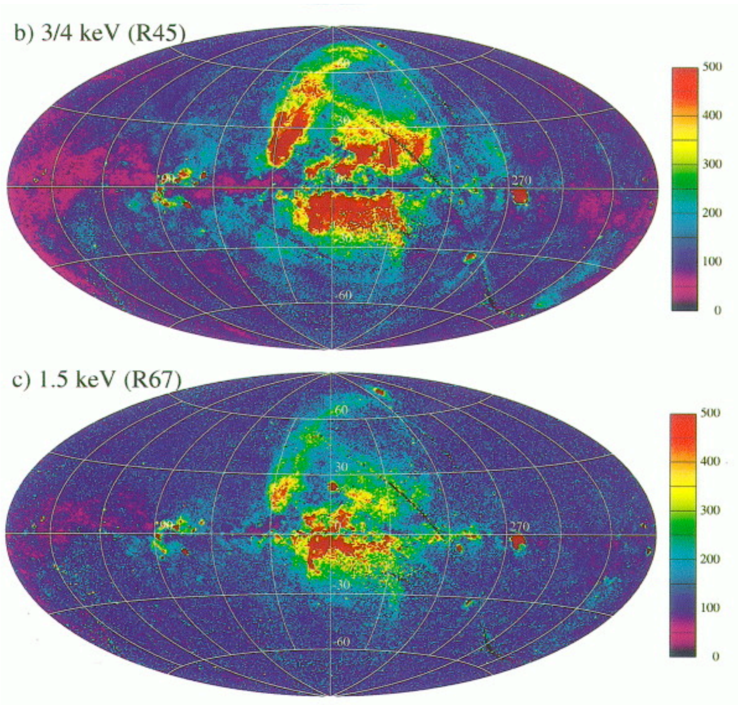


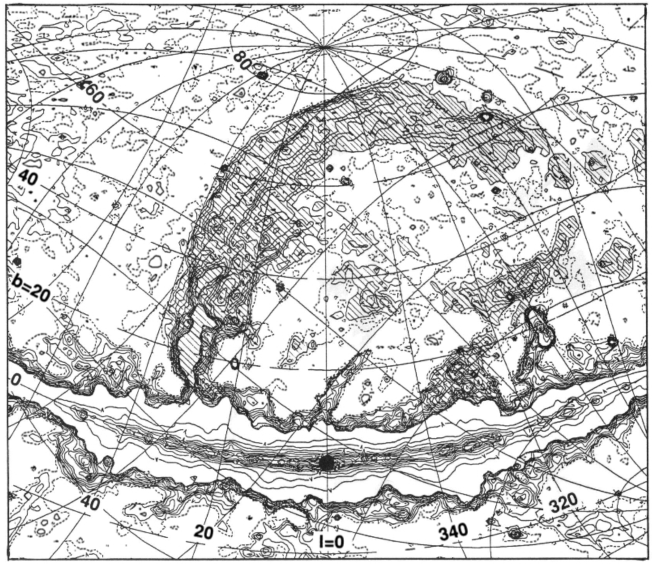


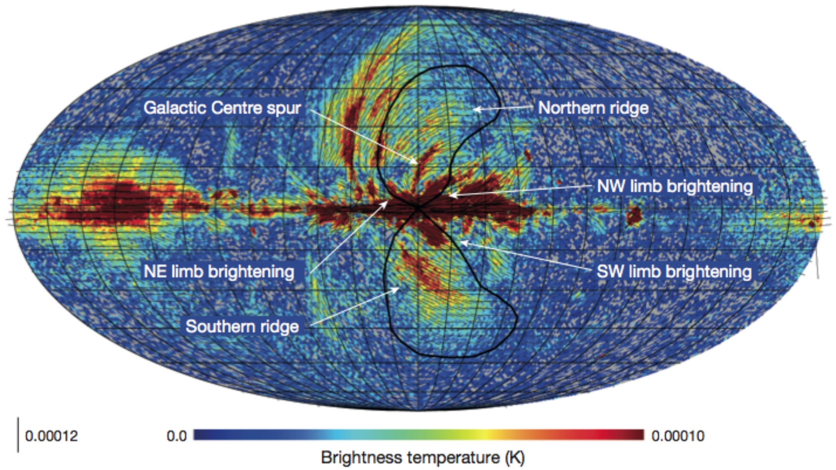
Su et al. 2010: All-sky residual maps after subtracting the diffuse Galactic model from the LAT maps.

Galactic ISM

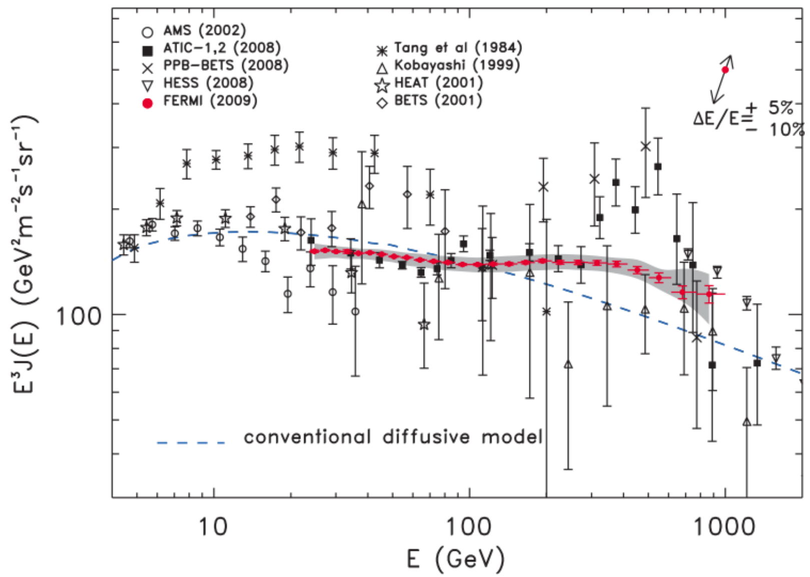
Large-scale structures extending above the Galactic disk were known before at radio and X-ray frequencies (Sofue 1994, Snowden et al. 1997). Recently seen also with WMAP (Carretti et al. 2013).

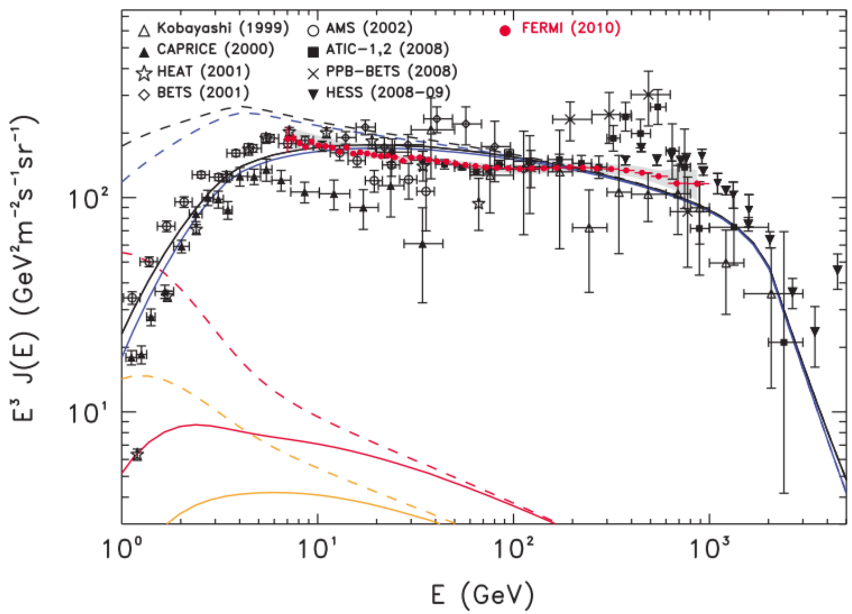






Galactic ISM

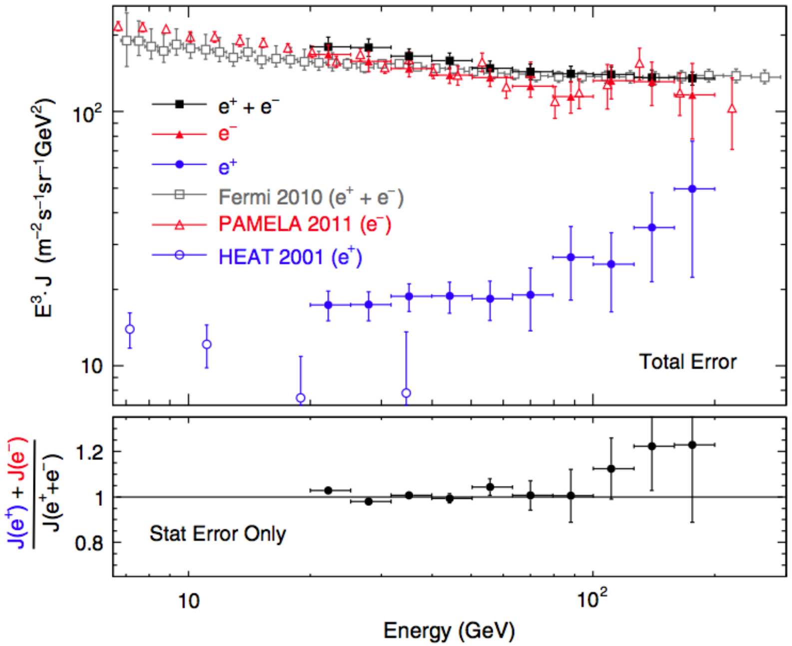


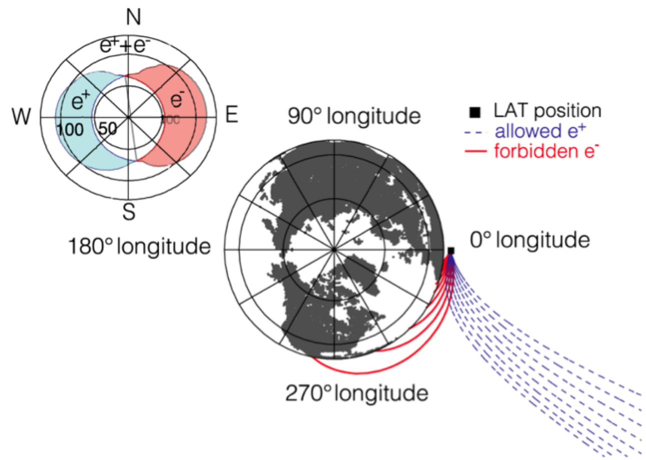


Abdo et al. 2009, PRL 102
Ackermann et al. 2010a, PRD 82

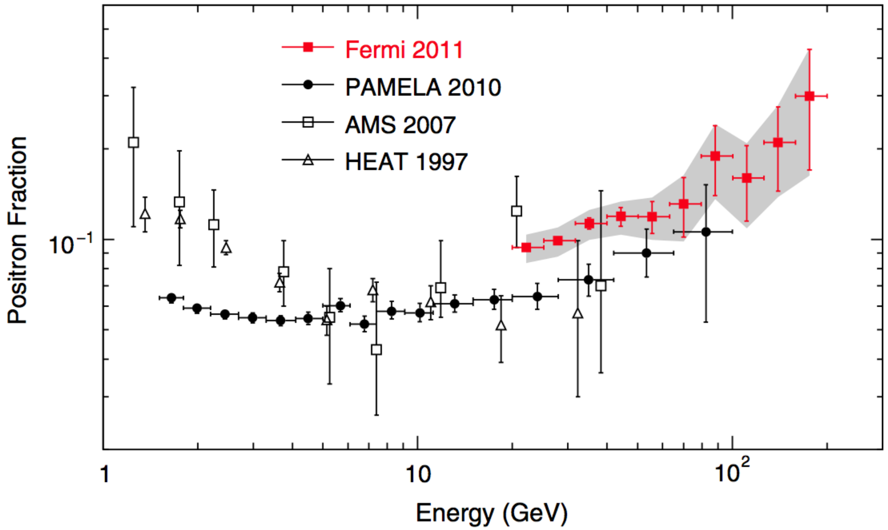
Fermi-LAT data revealed a mild excess in the spectrum of CR leptons around the energy range $E_e \sim 0.1 - 1$ TeV over the E_e^{-3} power-law expected from the GALPROP modeling (Moskalenko & Strong 1998). The sharp pile-up feature as reported by the ATIC Collaboration (Chang et al. 2008), is however not confirmed.

Galactic ISM





Ackermann et al. 2012, PRL 108:

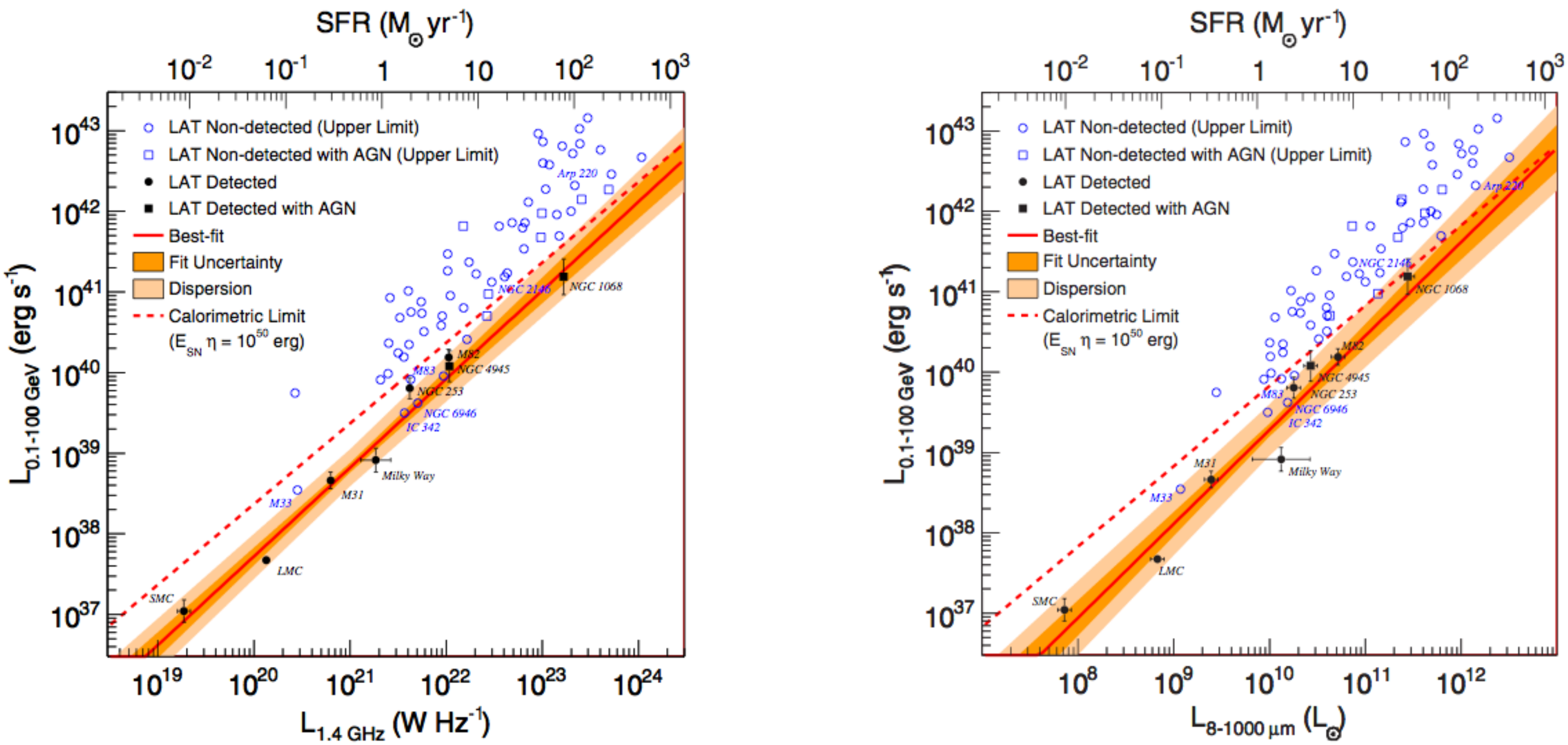


Measured separate CR electron and positron spectra by exploiting Earth's shadow, which is offset in opposite directions for opposite charges due to Earth's magnetic field.

Positron fraction rises with energy in the range 20–100 GeV, contrary to the predictions of the GALPROP model, but in agreement with the PAMELA results.

Galactic ISM

Abdo et al. 2010, ApJL 709, Ackermann et al. 2012, ApJ, 755:
detections of nearby starbursts galaxies with LAT, together the observations of Local Group galaxies, suggest a scaling between different tracers of the starformation rate and the L_γ .



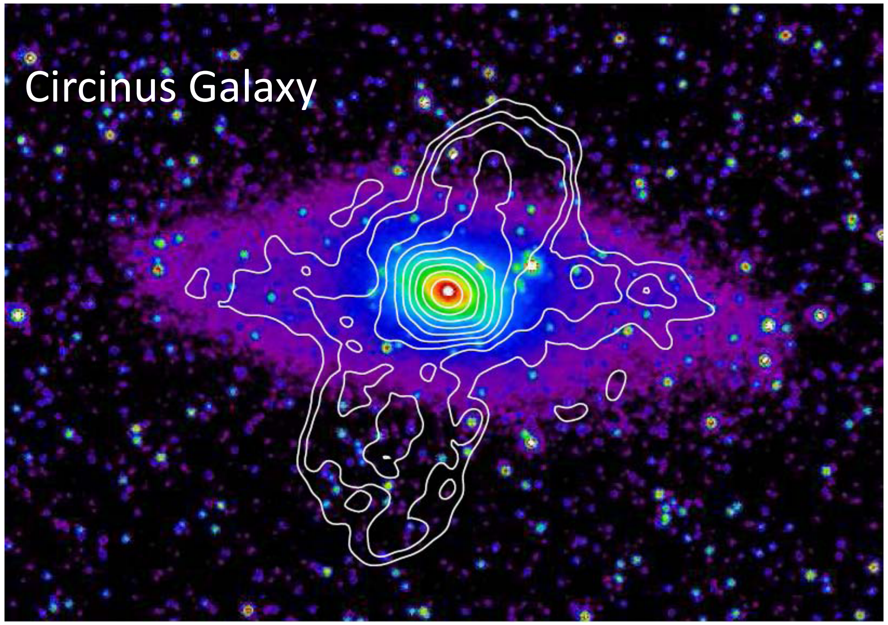
Galactic ISM

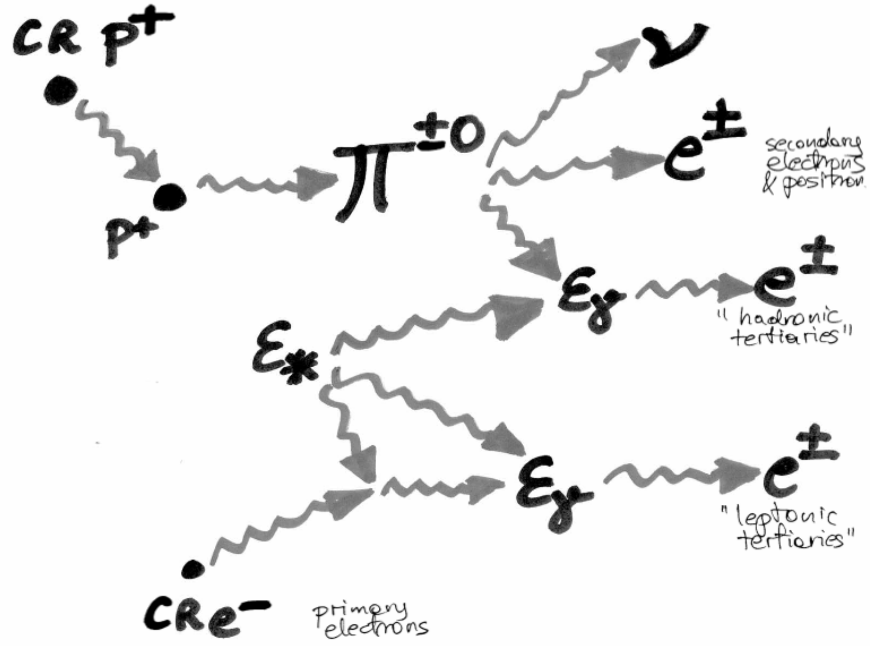
Fermi Bubbles:

- Previous jet or starburst activity?
- Hadronic or leptonic?
- How common are such structures?

Electron/positron excess:

- DM decay/annihilation?
- Local anomaly due to a nearby source (pulsar)?
- “Non-standard” energy evolution of CR electrons?





SNRs may not be the only relevant sources of Galactic CRs!

Conclusions

• Excellent gamma-ray data provided by Fermi-LAT and ground-based Cherenkov Telescopes (H.E.S.S., MAGIC, VERITAS).
• Good multiwavelength coverage enabled by the modern X-ray satellites, optical telescopes, and radio interferometers.

• Variety of astrophysical sources of high-energy emission and particles, from stellar binary systems and SNRs to Mpc-scale structures (lobes, clusters of galaxies).
• Variety of emission and particle acceleration processes involved (not only DSA!).

• A need for a cross-disciplinary, MWL approach.
• Progress driven by the data, many previously developed models to be abandoned.