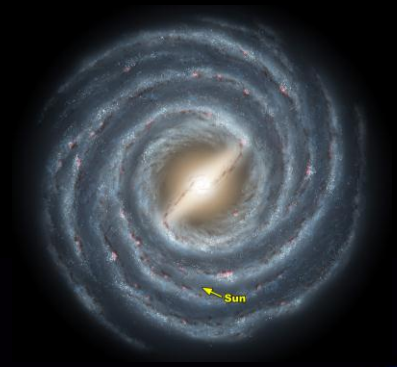


IGOR V MOSKALENKO – STANFORD

COSMIC RAYS IN THE MILKY WAY AND BEYOND

SpacePart2012

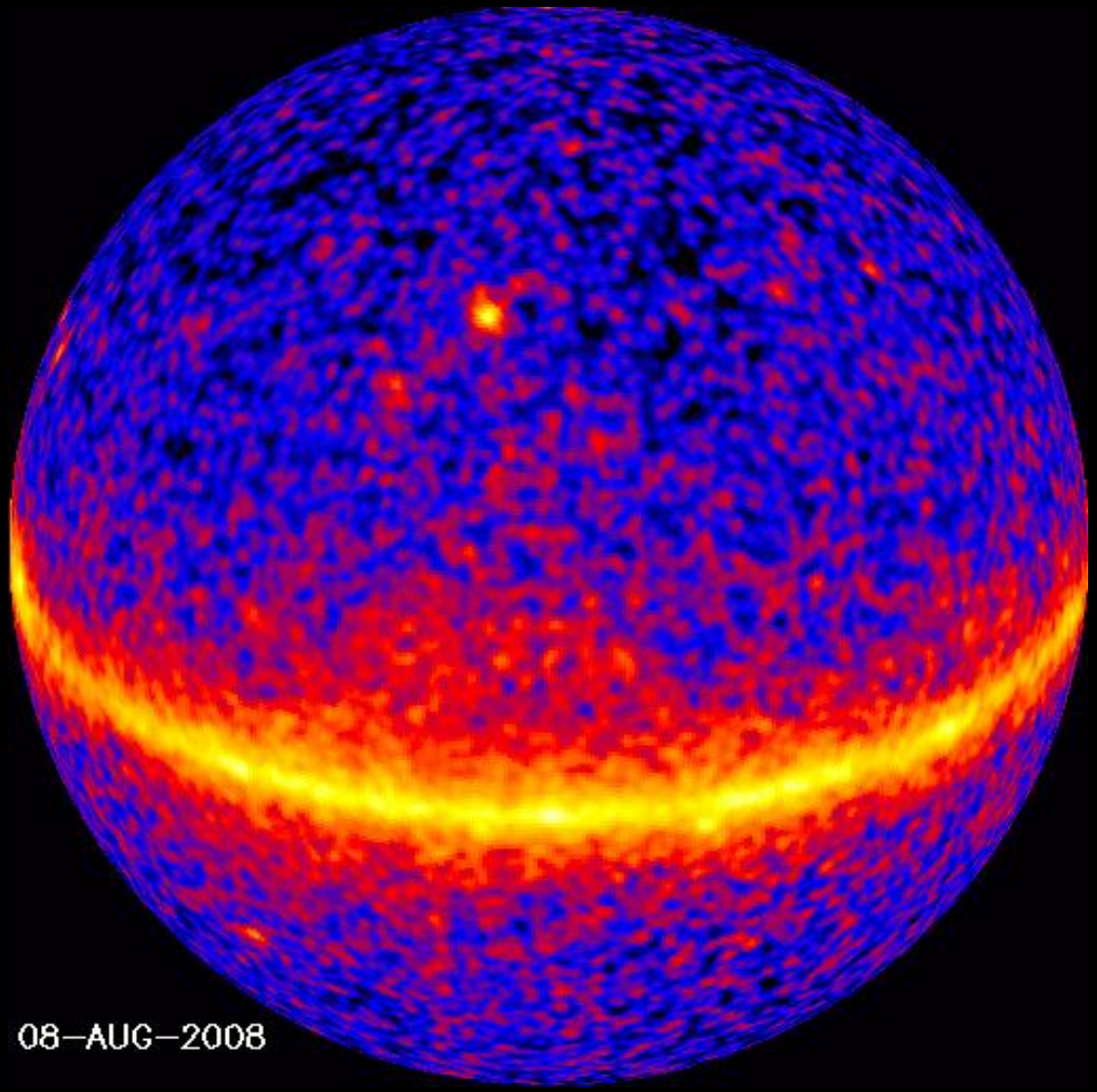
4th International Conference on Particle and Fundamental Physics in Space

November 5-8, 2012 • CERN

Hundred years of research

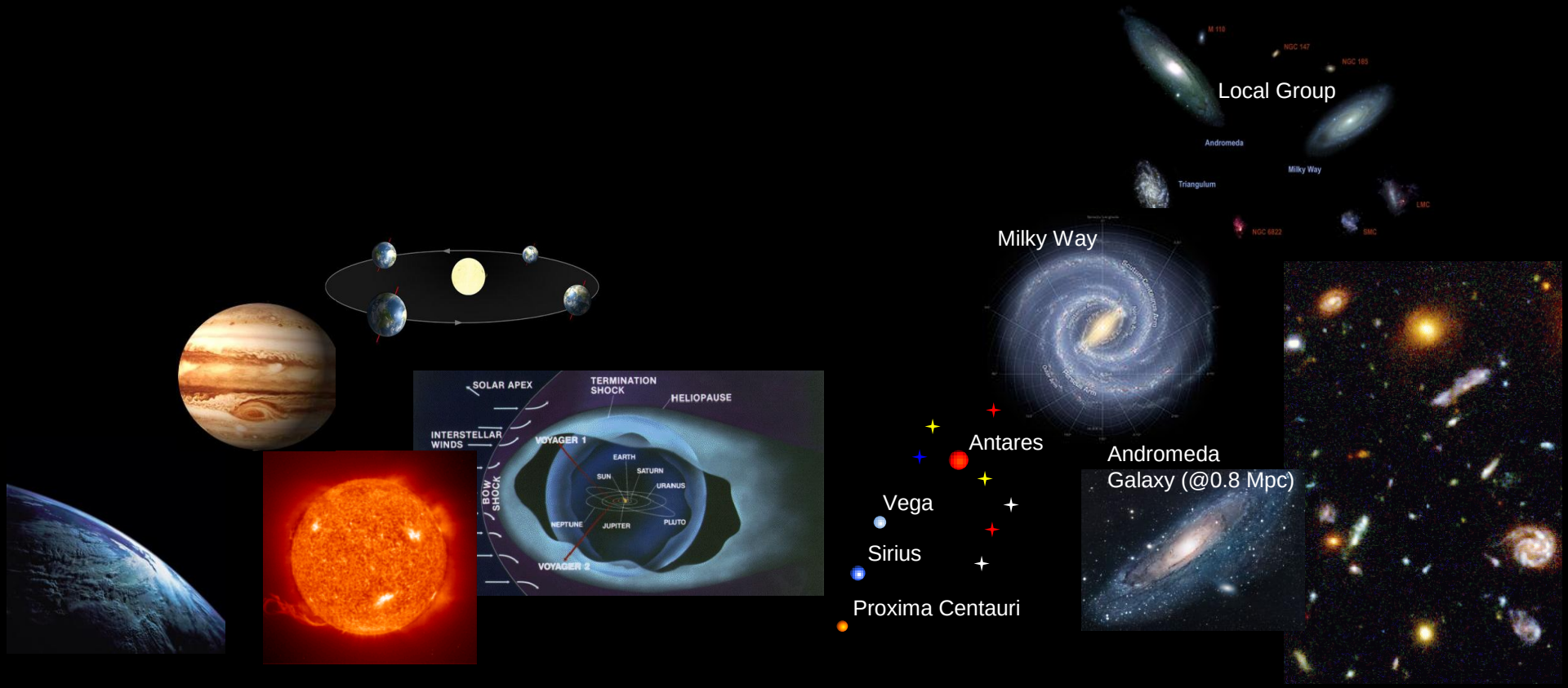
- Galactic and extragalactic cosmic rays (universal phenomenon!)
- Energy range: 10^6 eV – 10^{21} eV
- Galactic sources: SNRs, pulsars, star flares, stochastic acceleration in the ISM
- Extragalactic sources: AGN, gamma-ray bursts, intergalactic shocks
- Propagation: diffusion, convection
- Interactions with gas (p, e), radiation and magnetic fields (e)
- Emission: radio (synchrotron), X-rays (IC, bremsstrahlung), gamma rays (neutral pion decay, IC, bremsstrahlung)
- Detection: direct (satellites, balloons), indirect (EAS – Cherenkov light, cascade particles), even more indirect (via electromagnetic emissions)
- Composition: all stable and long-lived particles and isotopes
- Possible new physics: products of WIMP annihilations/decay, exotic particles

Fermi's skymap of particle interactions



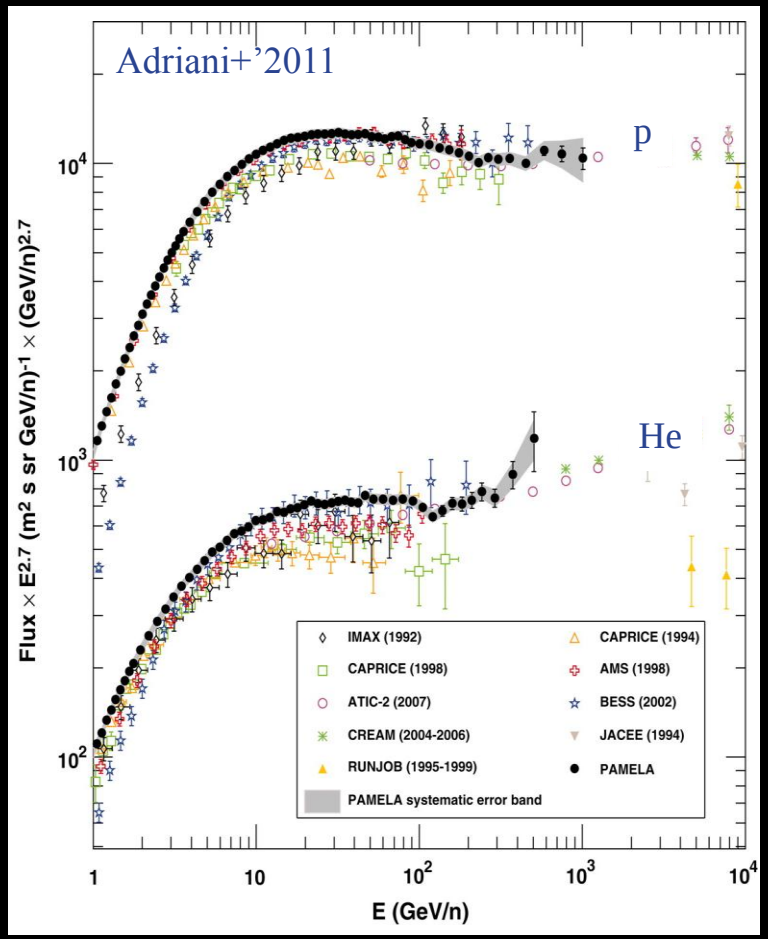
- >100 MeV, 36 months
- shows where accelerated particles meet target (gas, photons)
- ~80% of the emission is diffuse
- many transients in the ©-ray sky

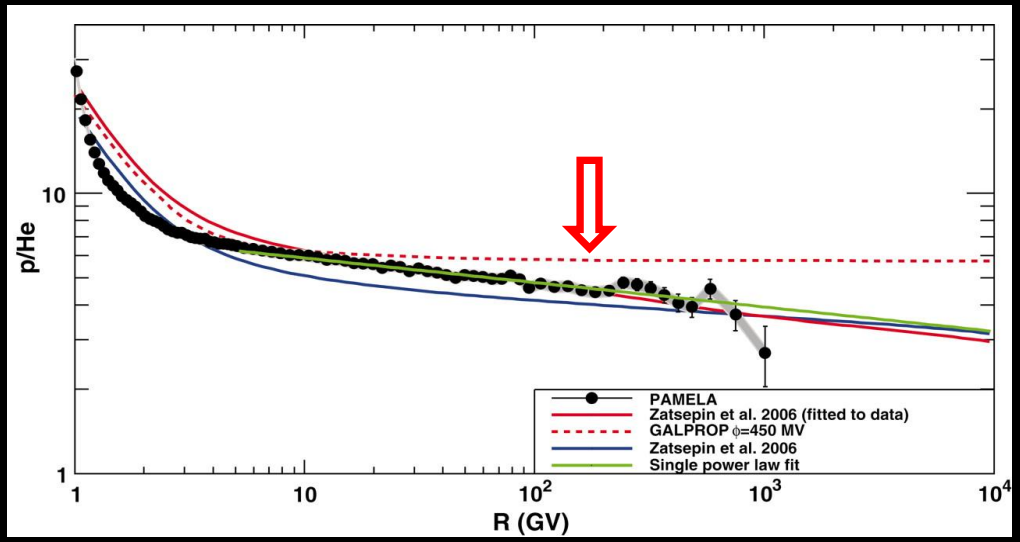
Cosmic Scales



parsec	10^{-10}	10^{-9}	10^{-8}	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	10^{0}	10^{1}	10^{2}	10^{3}	10^{4}	10^{5}	10^{6}	10^{7}	10^{8}	10^{9}	10^{10}
	3 000 km	30 000 km	300 000 km	3×10^{6} km	3×10^{7} km	2 AU	20 AU	200 AU	2 000 AU	0.1 pc	1 pc	10 pc	100 pc	1 kpc	10 kpc	100 kpc	1 Mpc	10 Mpc	100 Mpc	1 Gpc	10 Gpc

Break in the CR p and He absolute fluxes



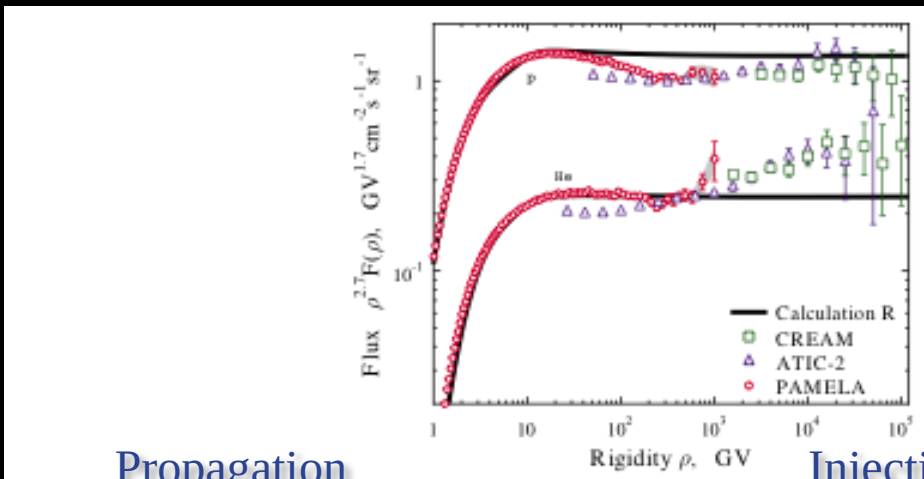


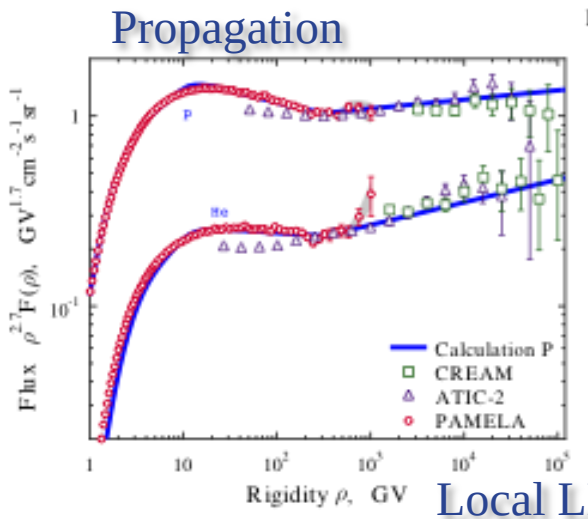
- Data from several experiments (BESS, AMS-01, ATIC'2009, CREAM'2010, PAMELA'2011) are all consistent and indicate spectral hardening above ~100 GeV/nucleon
- p/He ratio vs. rigidity R is smooth
- He spectrum is flatter than proton spectrum
- Heavier nuclei seem to share the same trend
- New data may provide us with a hint to the origin of high energy CRs

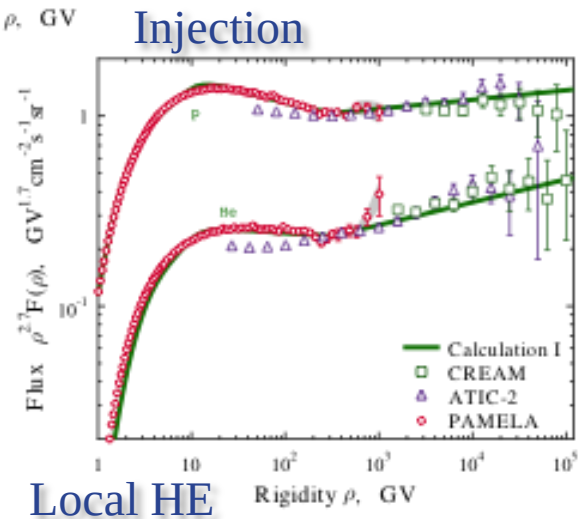
P and He spectra

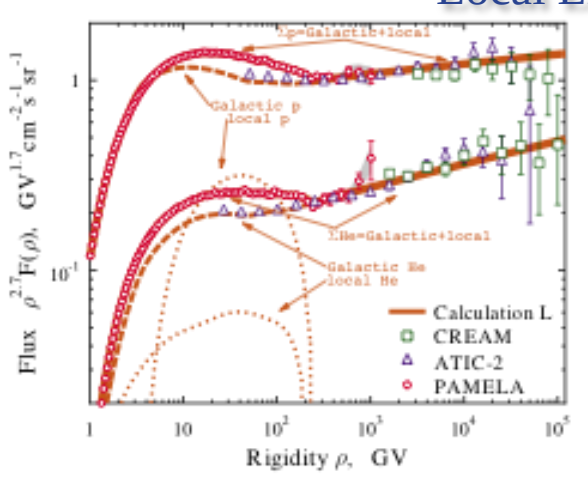
- ✧ All scenarios are tuned to the data, except the Reference scenario
- ✧ Scenarios L and H: the local source component is calculated by the subtraction of the propagated Galactic spectrum from the data
- ✧ The local source is assumed to be close to us, so no propagation; only primary CR species

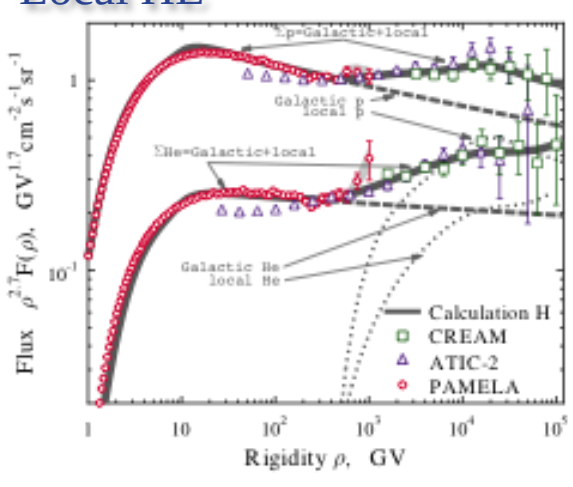
Vladimirov+'2012, ApJ 752, 68





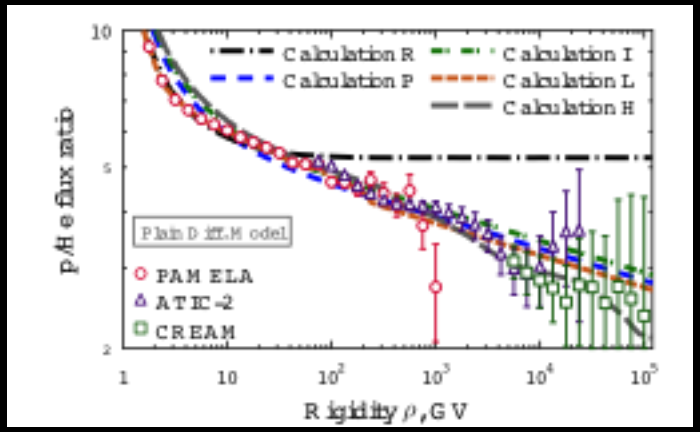


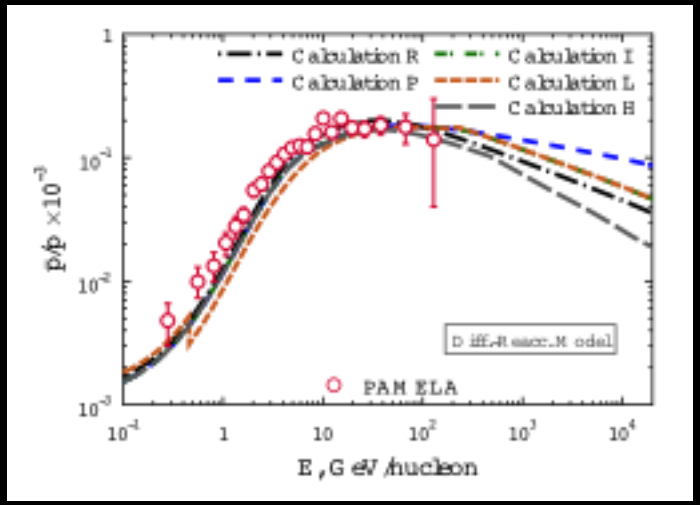


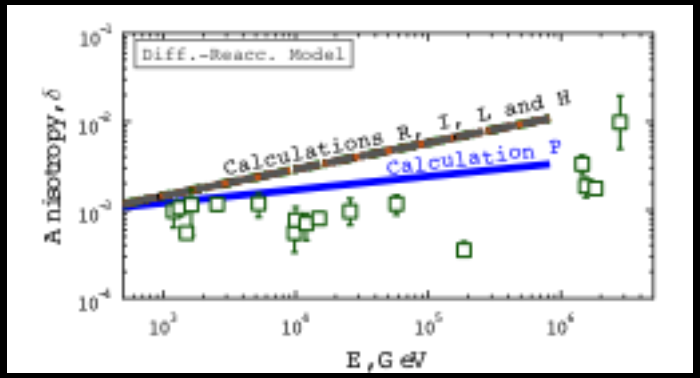


Model predictions

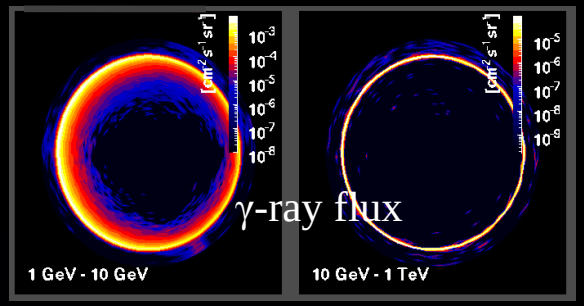
- P/He ratio is tuned in all scenarios except Reference scenario
- Predicted antiproton/proton ratio agrees with the existing data, but exhibits different behavior at >100 GeV
- Only scenario P agrees with the data on CR anisotropy
- Only scenario L can explain the sharp break in the p, He spectra
- Awaits for a confirmation of the break from an independent experiment and more accurate data

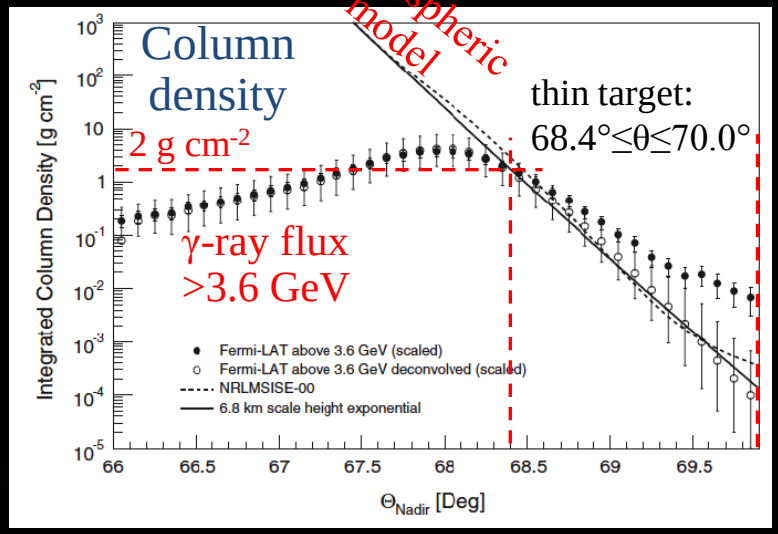


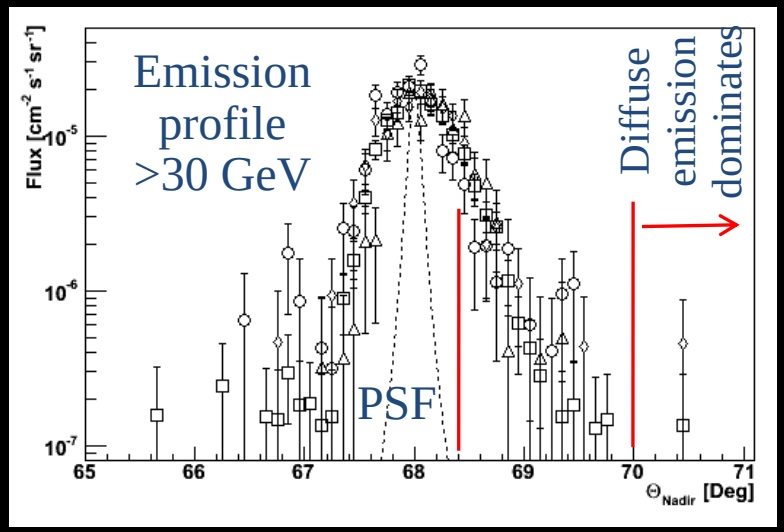




Fermi-LAT observations of the Earth's limb

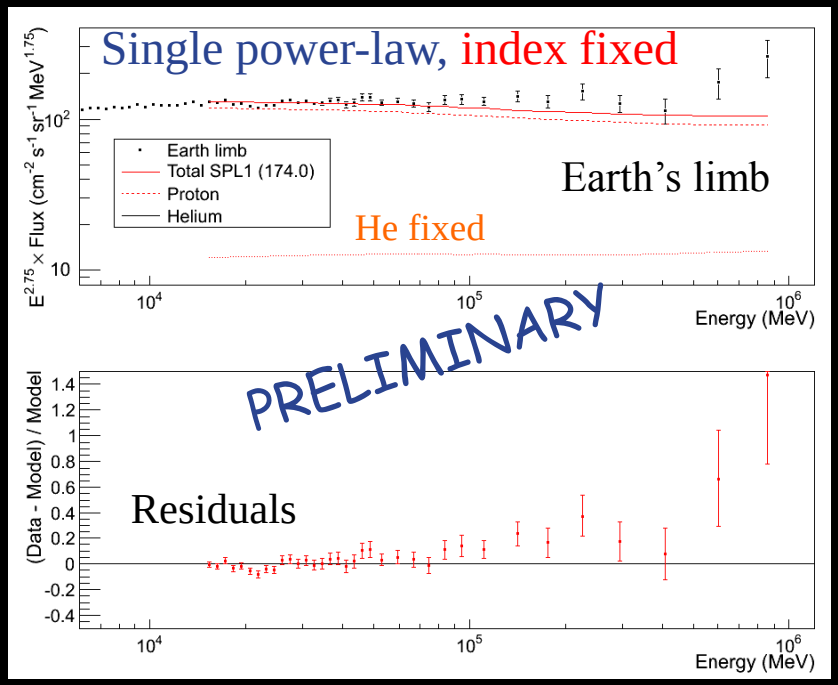


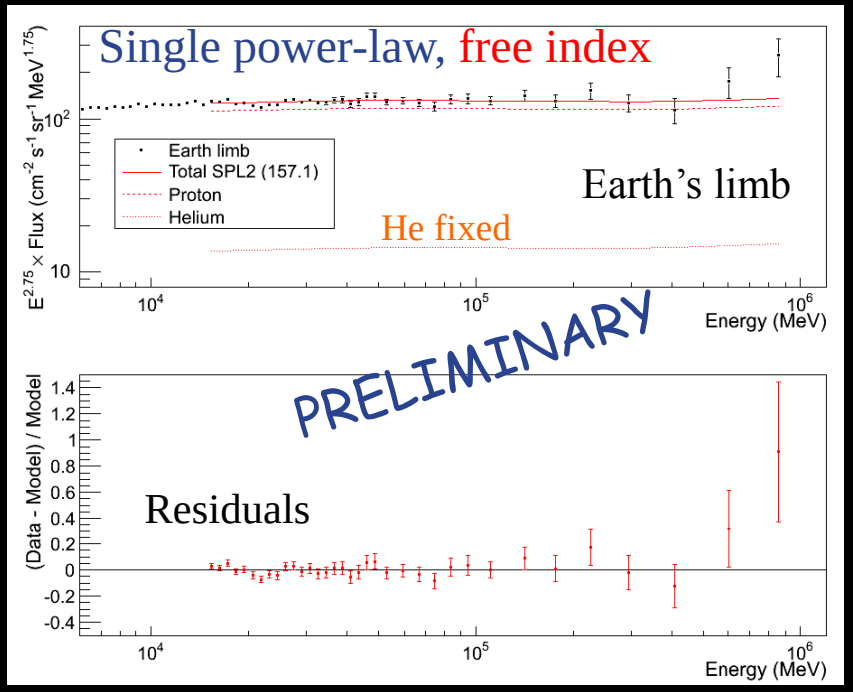


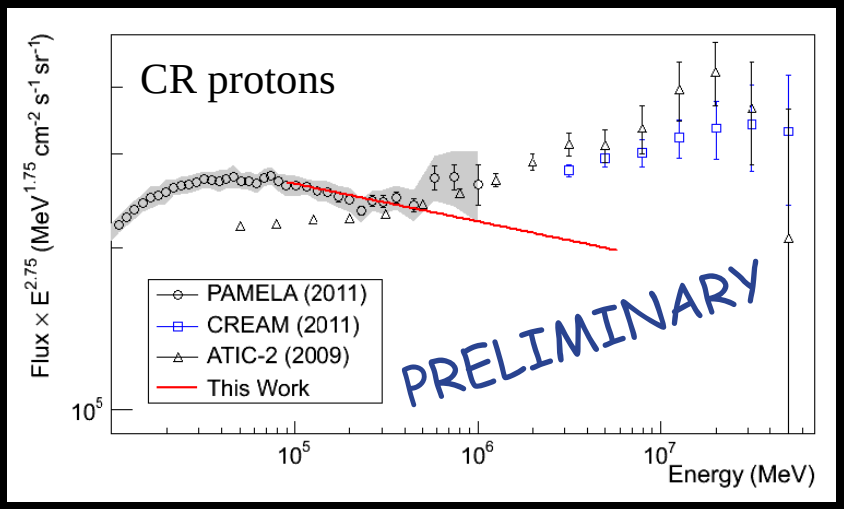


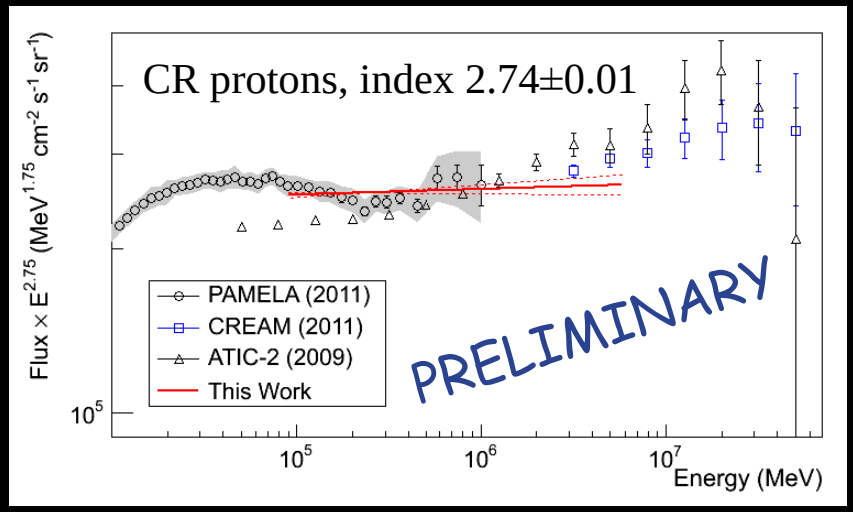
- Due to its proximity, the Earth is the brightest γ-ray source on the sky
- The emission is produced by the CR cascades in the atmosphere
- Most energetic γ-rays are produced by CRs hitting the top of the atmosphere at tangential directions (thin target)

Inferring the CR spectrum - I

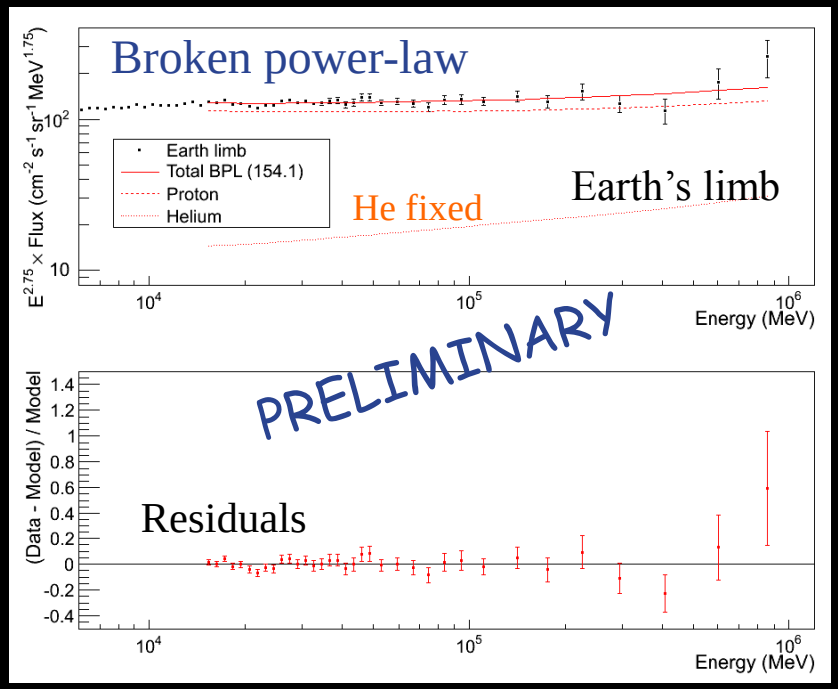


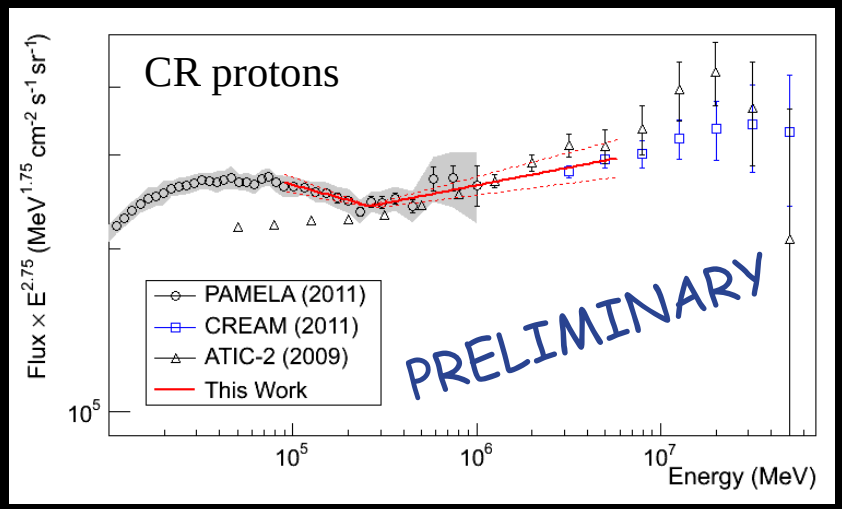






Inferring the CR spectrum - II

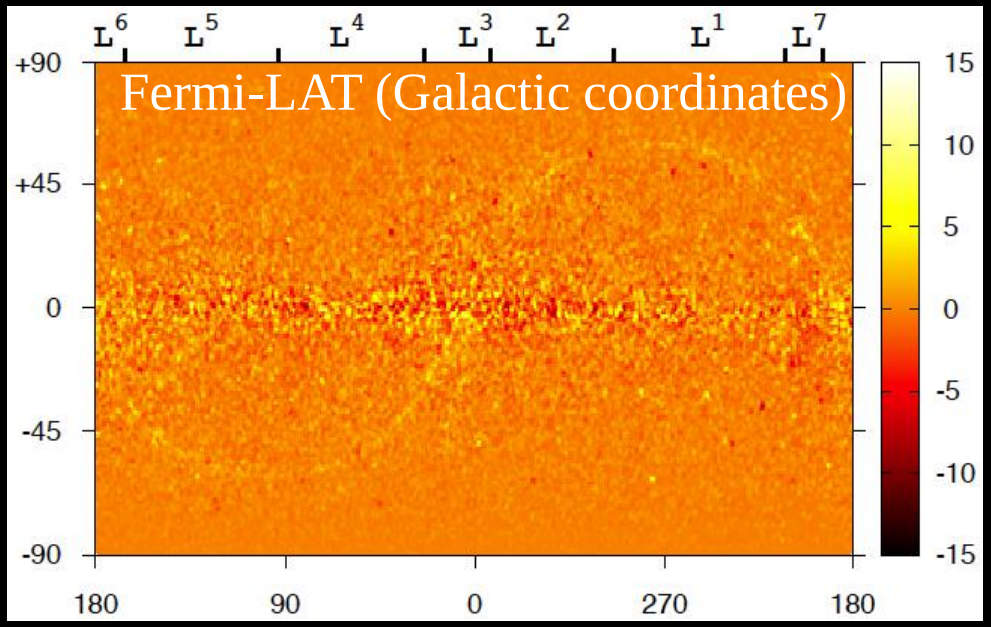


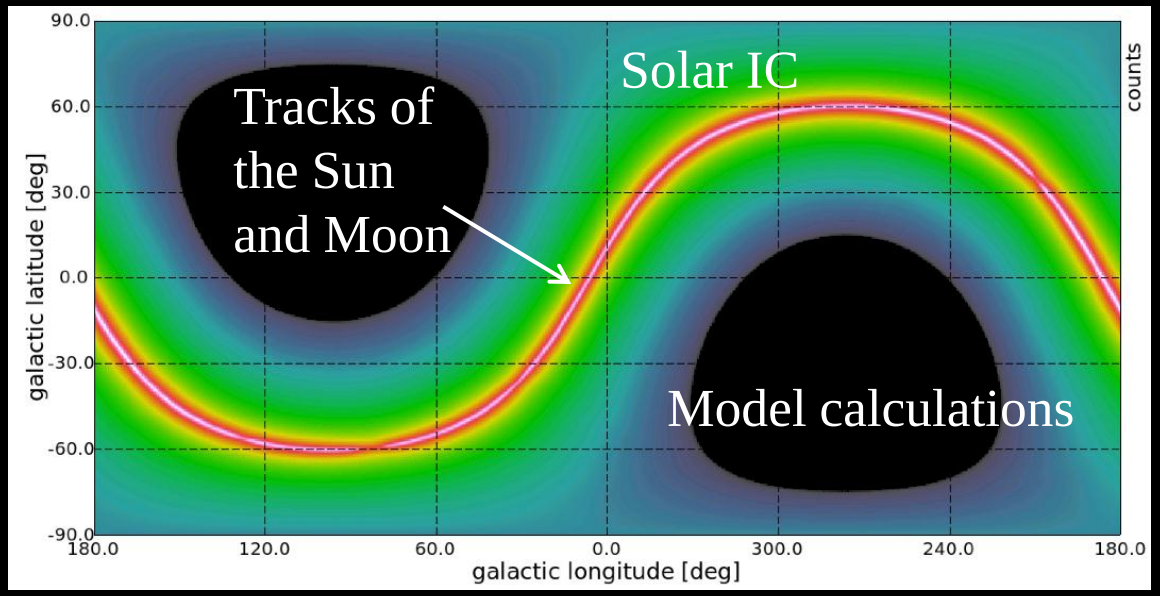


- Broken power-law provides the best fit with indices 2.84±0.03 / 2.68±0.02 below/above the break at 264±19 GeV
- In perfect agreement with direct CR measurements! cf. PAMELA: 2.85±0.015±0.004 / 2.67±0.03±0.05, break at 232+35-30 GV
- A single power-law with index 2.74±0.01 can't be ruled out yet
- Fermi-LAT continues to collect data: more statistics, and extension to higher energies
- Can be used for instrument calibration

Solar system

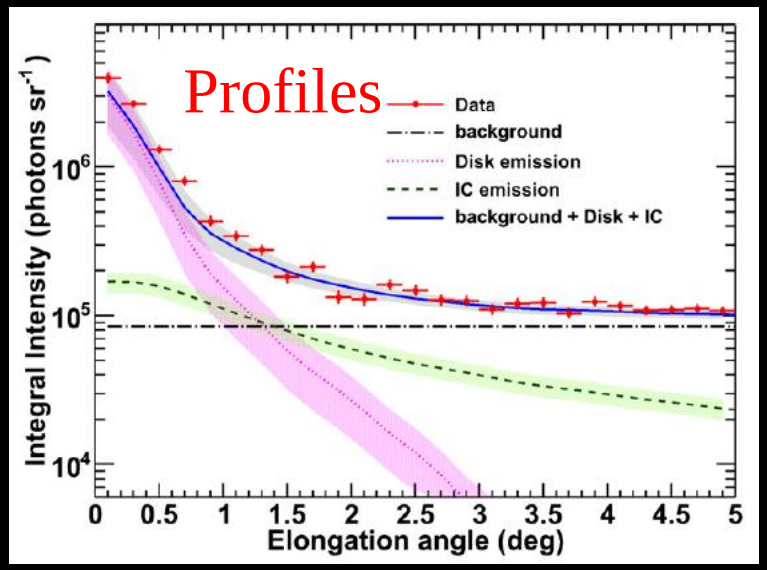
- Raw data sliced by 2 months interval, background removed; ➔ the solar track is clearly visible

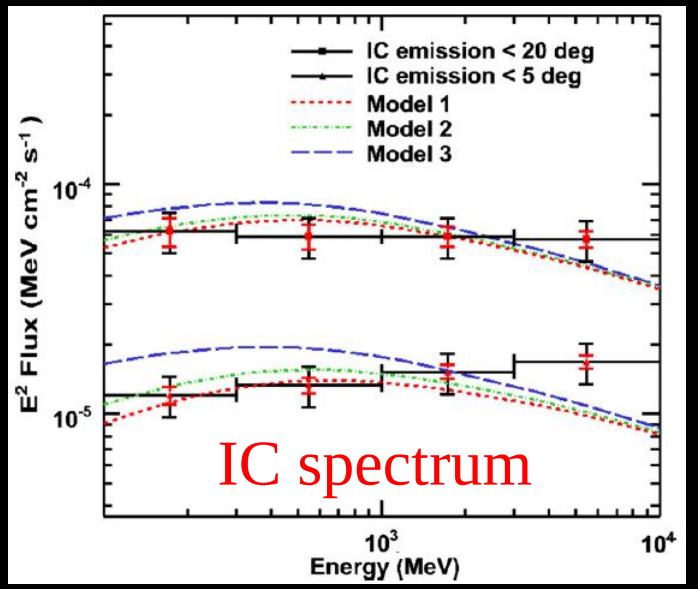


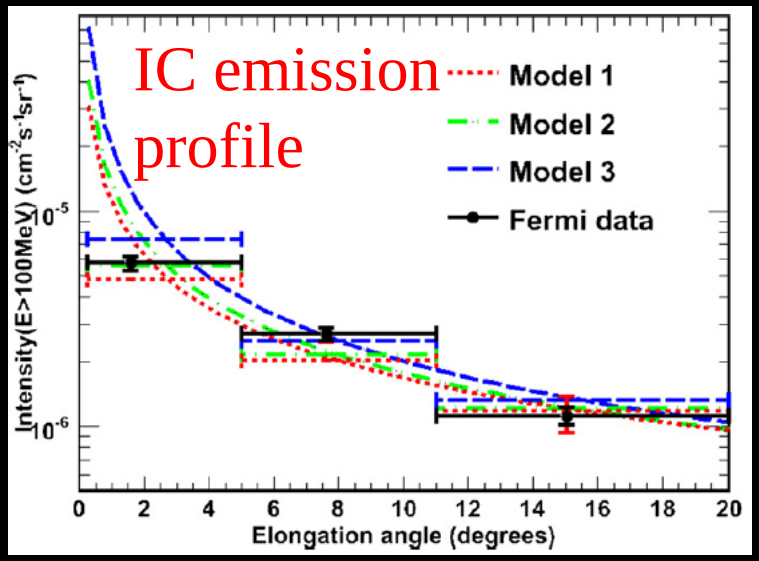


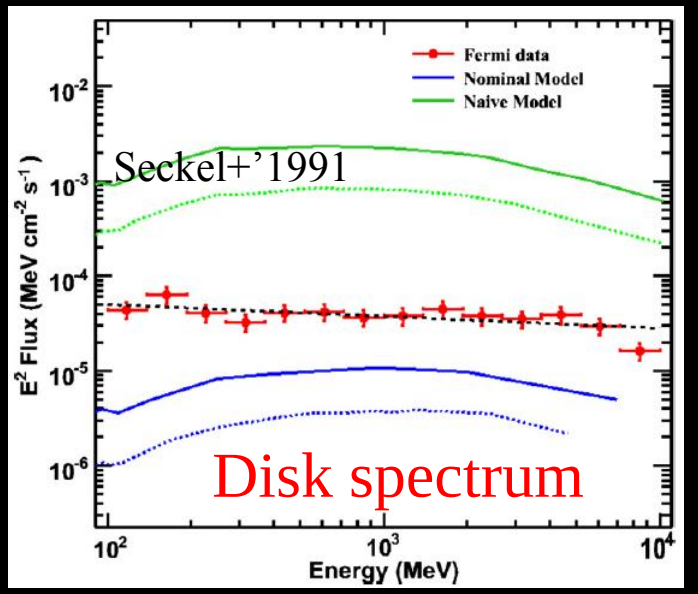
- Averaged over one year, the ecliptic is seen as a bright stripe on the sky, but the emission comes from all directions

Fermi-LAT observations of the Sun



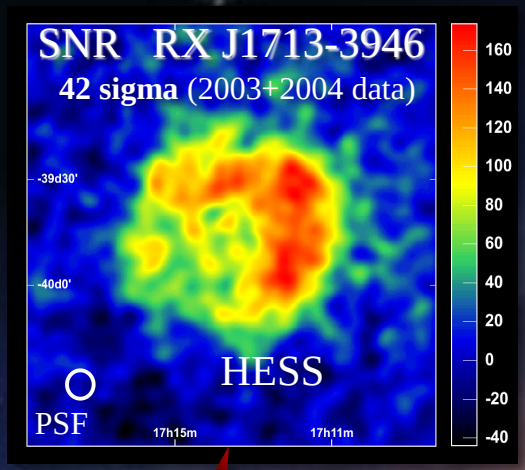


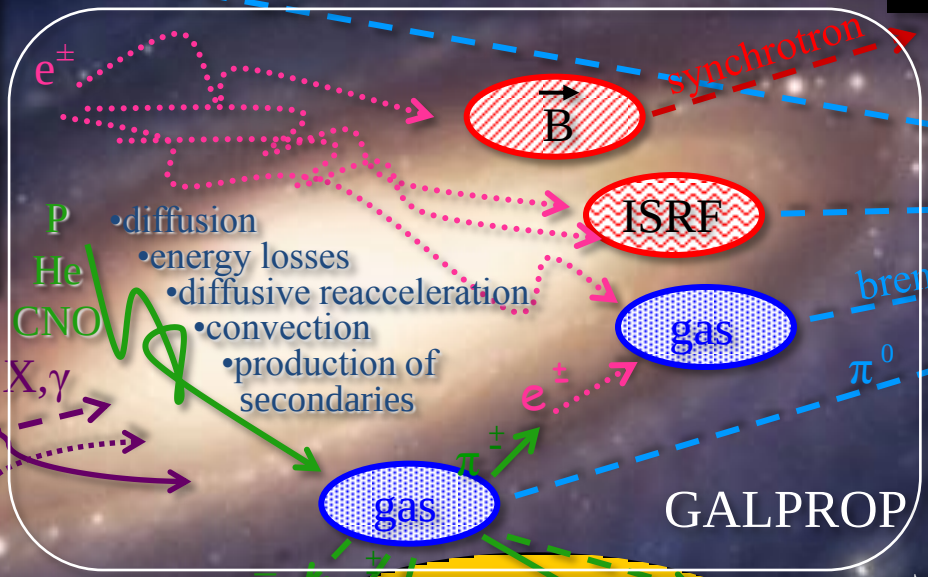


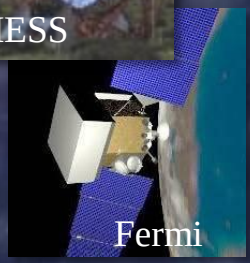


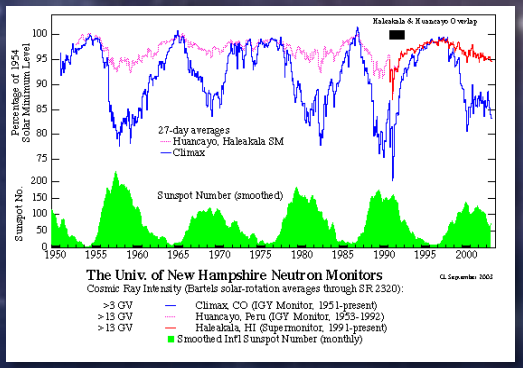
Abdo+'2011

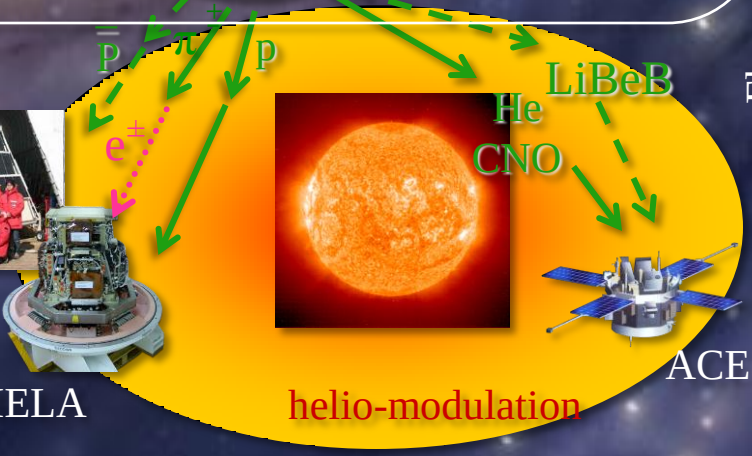
CRs in the interstellar medium

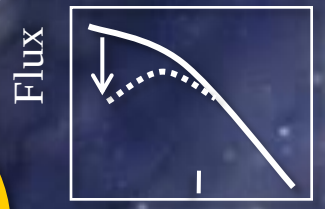






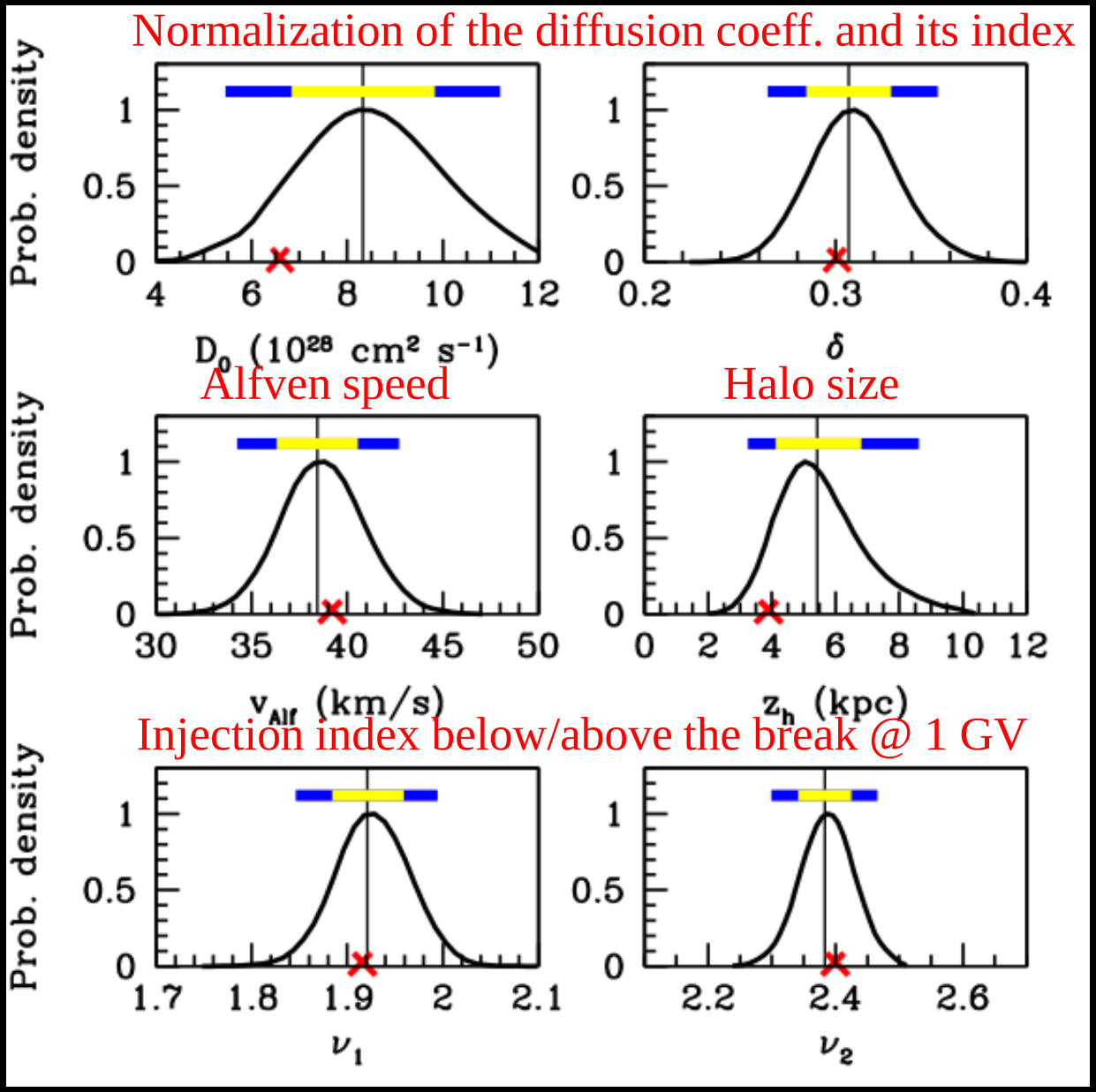






CR species:
- Only 1 location
- modulation

Constrains on CR propagation from global scans

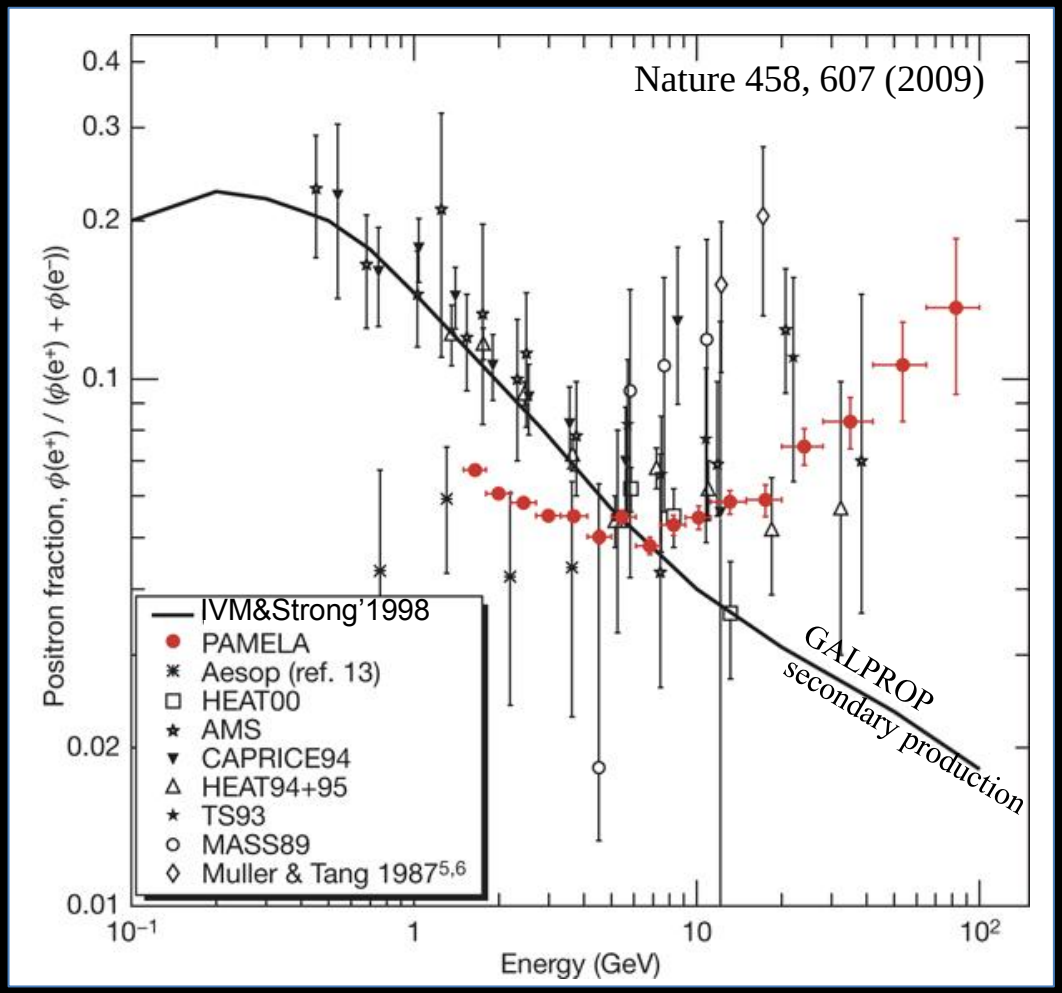


Posterior probability distributions

- color bar – 68%, 95% error ranges
- vertical line – posterior mean
- ✗ - the best fit
- Reacceleration model
  - δ = 0.3 – very close to classical value 1/3 for Kolmogorov diffusion
- All parameters are very close to those derived by the "eye-fitting" method

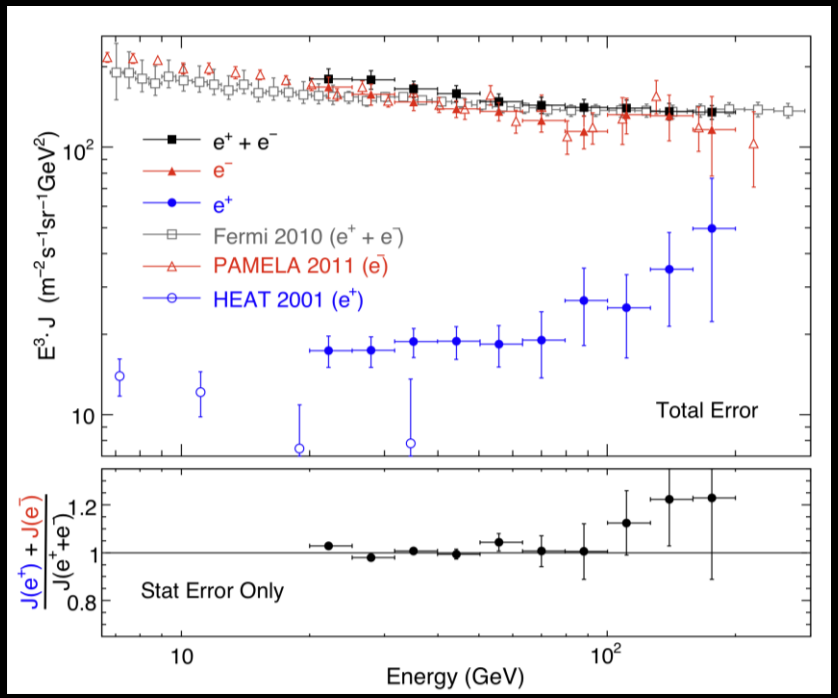
Trotta+'2011

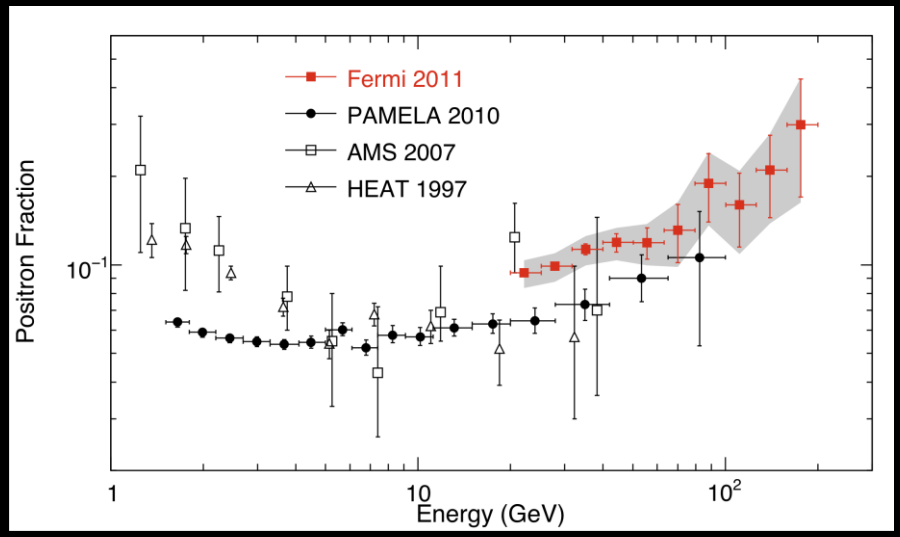
PAMELA data show rise in the positron fraction



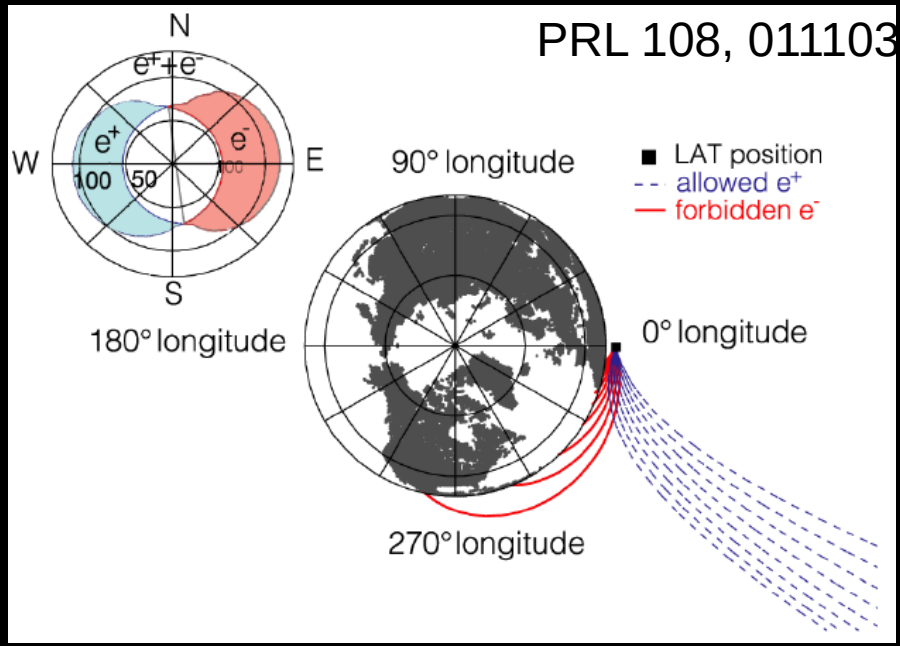
- PAMELA team reported a rise in the positron fraction perhaps due to "primary" positrons
- So unexpected, it can't be true!
- Possible explanations:
  - primary astrophysical sources (e.g., pulsars)
  - dark matter
  - nonstandard secondary production (e.g., in the SNR shock)

Fermi-LAT: e^+ & e^- fluxes and positron fraction

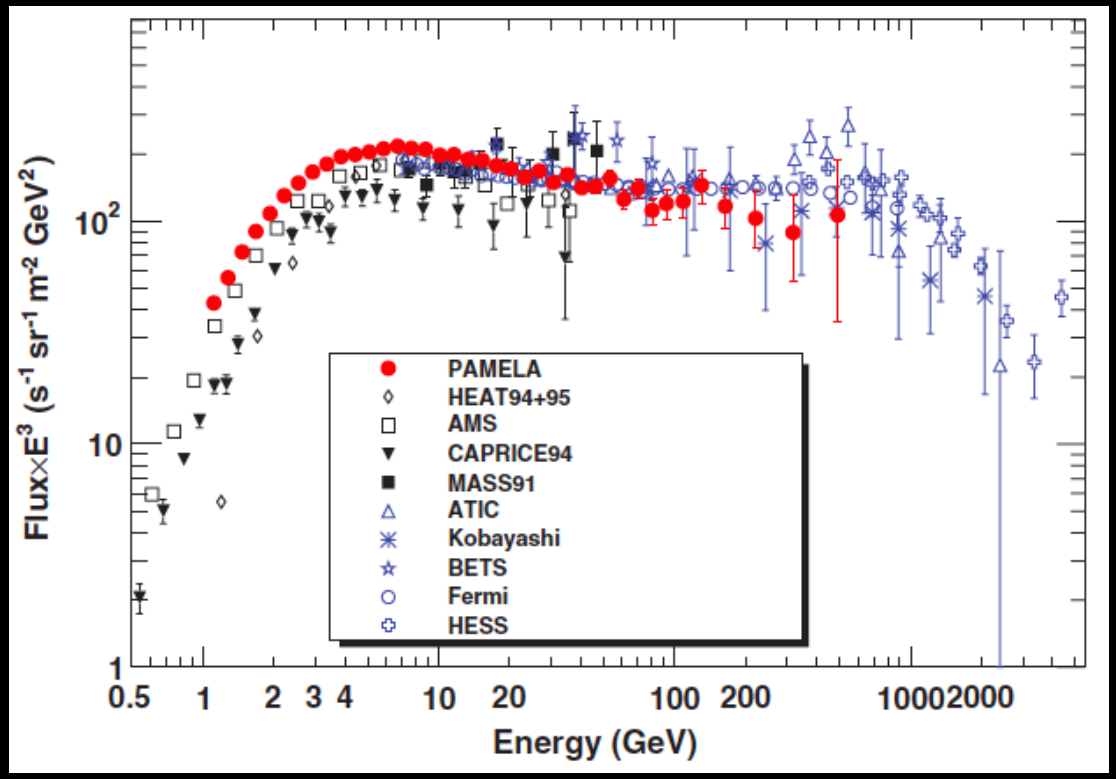


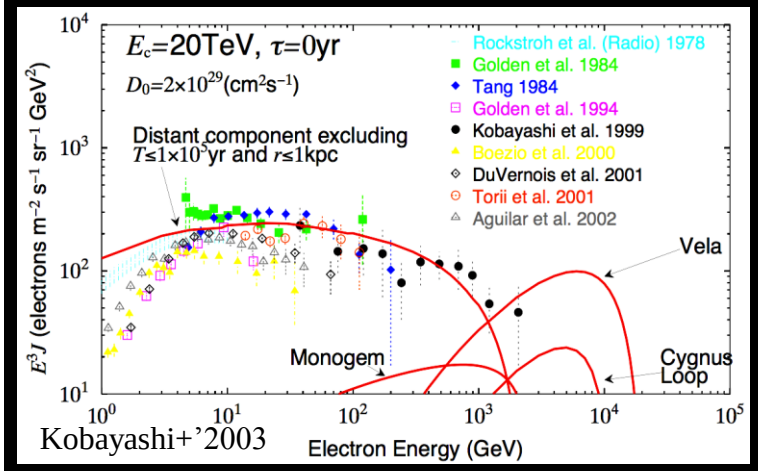


- State-of-the-art: Fermi-LAT does not have a magnet, but used geomagnetic field
- Measured absolute fluxes of e^+ & e^-
- Fraction = $\phi(e^+) / [\phi(e^+) + \phi(e^-)]$
- Confirmed rise in the positron fraction
- Extended measurements up to 200 GeV



All-electron spectrum

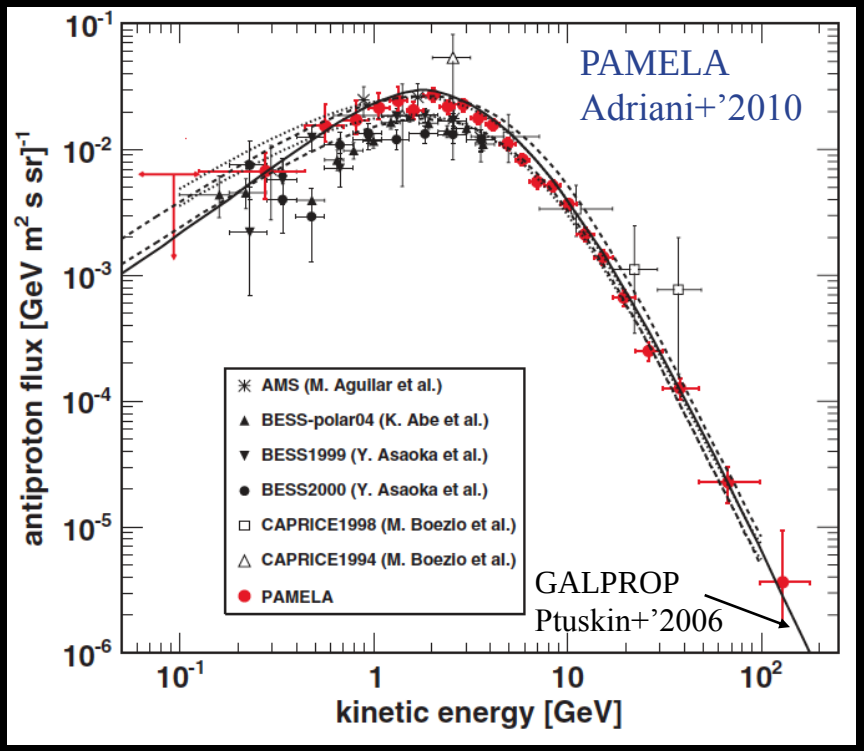


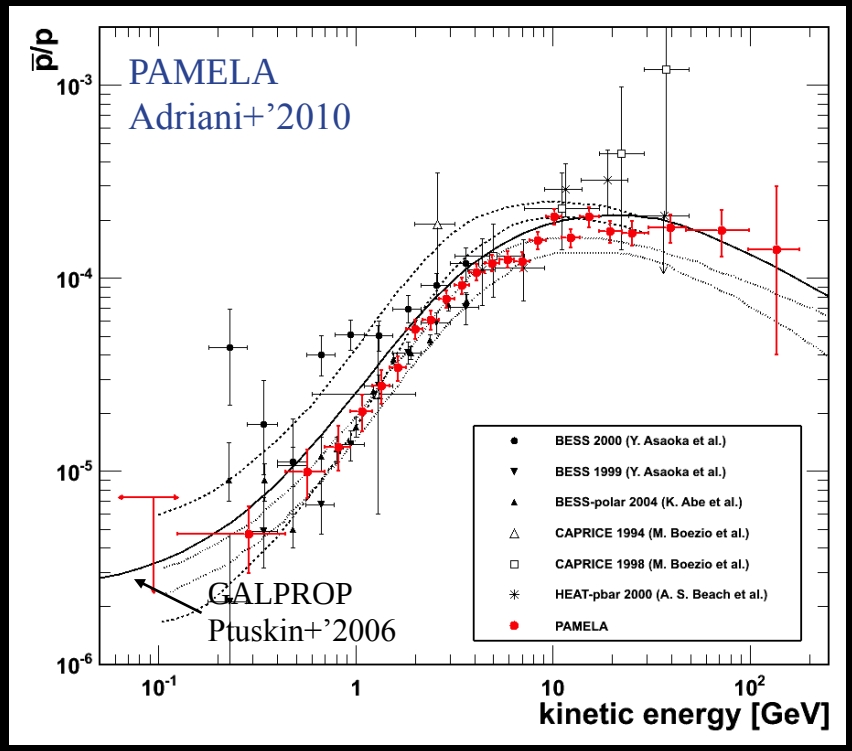


- ✧ Fermi-LAT and PAMELA data agree well
- ✧ Shows some structure (breaks and bumps)
- ✧ Flatter than extrapolated from low energies
- ✧ Sharp cutoff at 1 TeV (HESS), as expected

- ✧ Cannot be reproduced with a single power-law injection spectrum
- ✧ Origin
  - ✦ Local sources?
  - ✦ perhaps needs a second component with hard spectrum (positrons?)

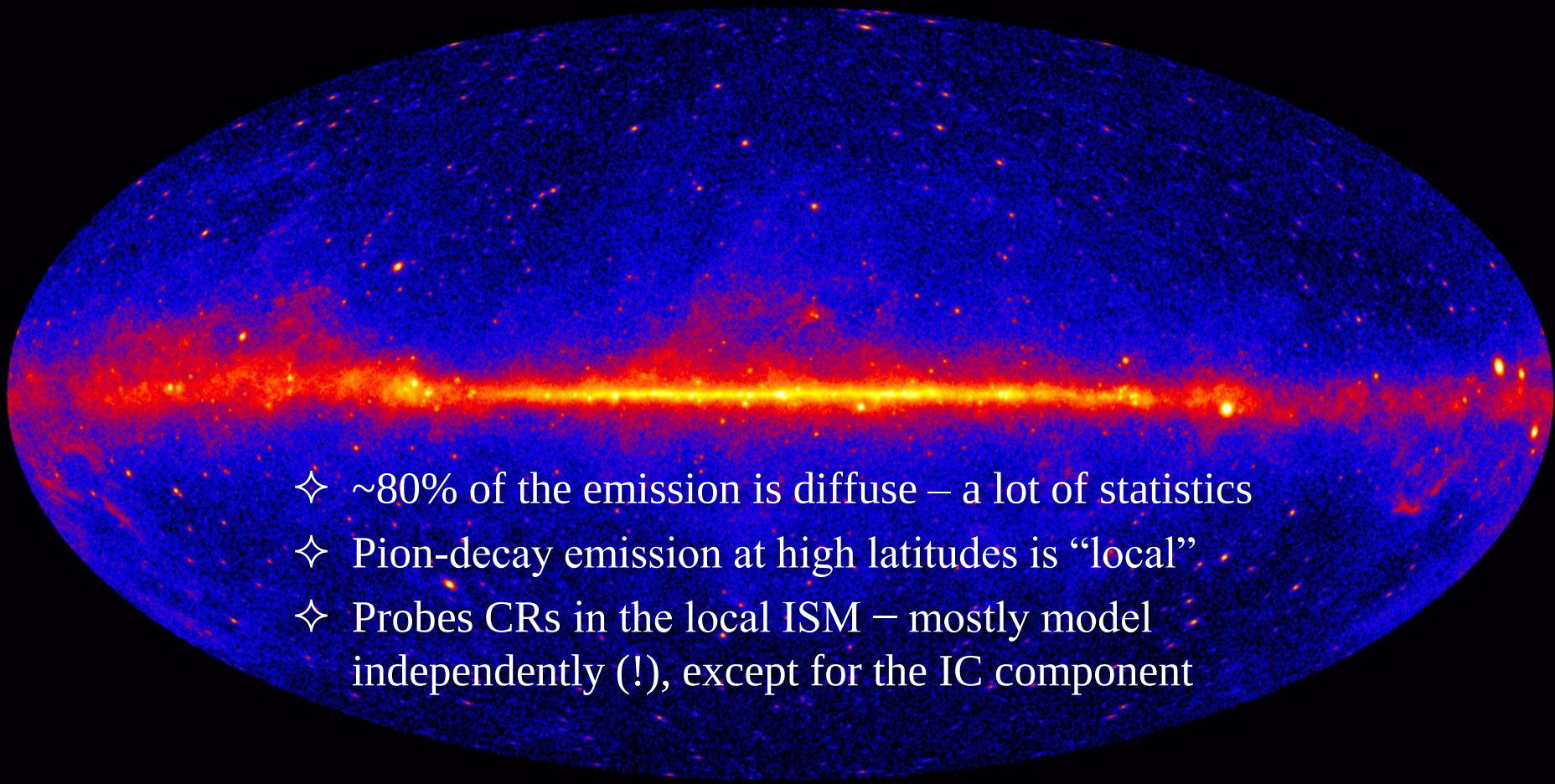
Antiprotons





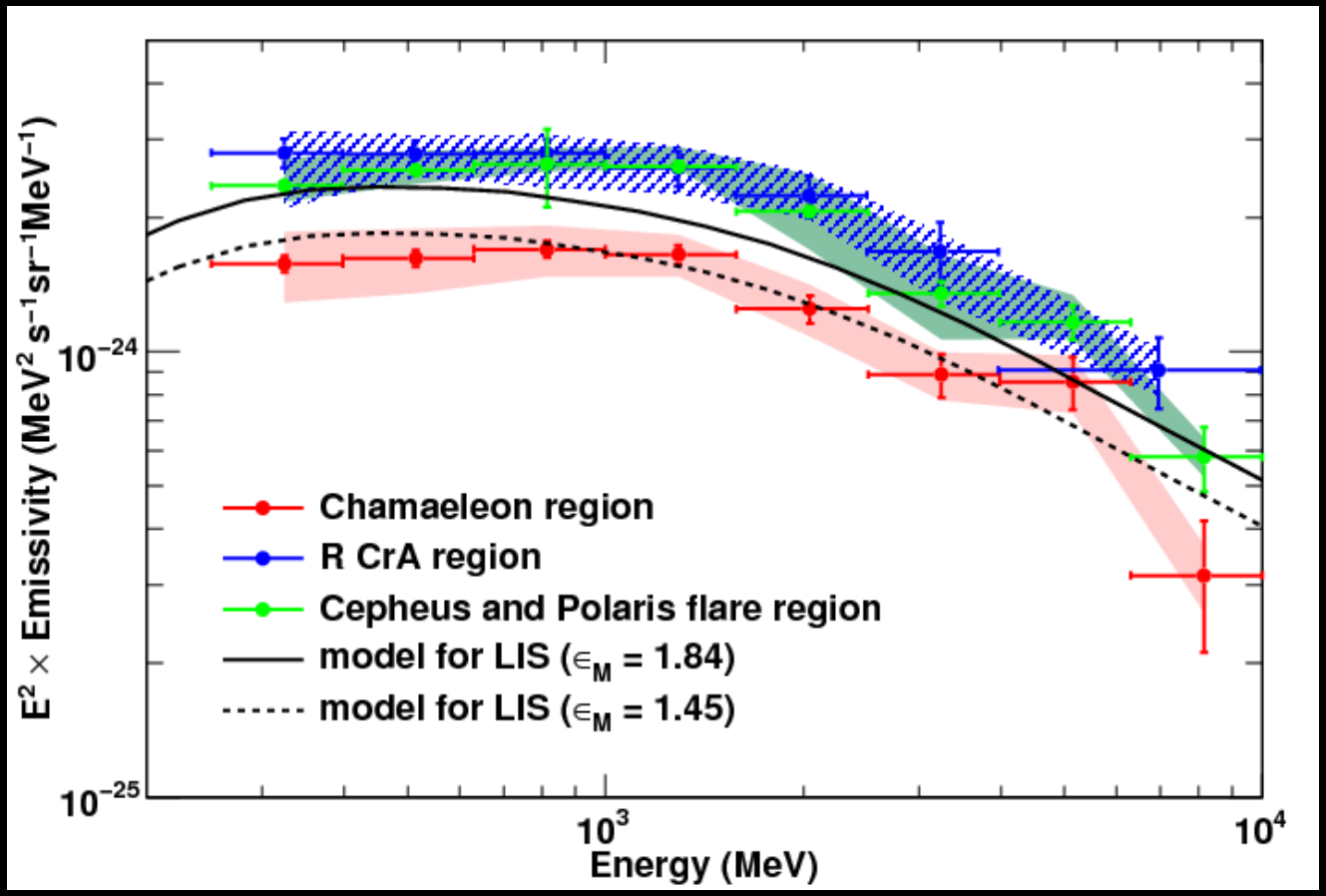
- Surprisingly, antiproton data perfectly agree with predictions of the propagation models (e.g., GALPROP: Ptuskin'2006)
- Something interesting is going on!
  - Antiprotons are secondary produced in the same process of pp-interactions as positrons (and gammas)– so rule out anomalous secondary production and diffusion

Fermi-LAT skymap (>100 MeV, 36 months)



- ~80% of the emission is diffuse – a lot of statistics
- Pion-decay emission at high latitudes is “local”
- Probes CRs in the local ISM − mostly model independently (!), except for the IC component

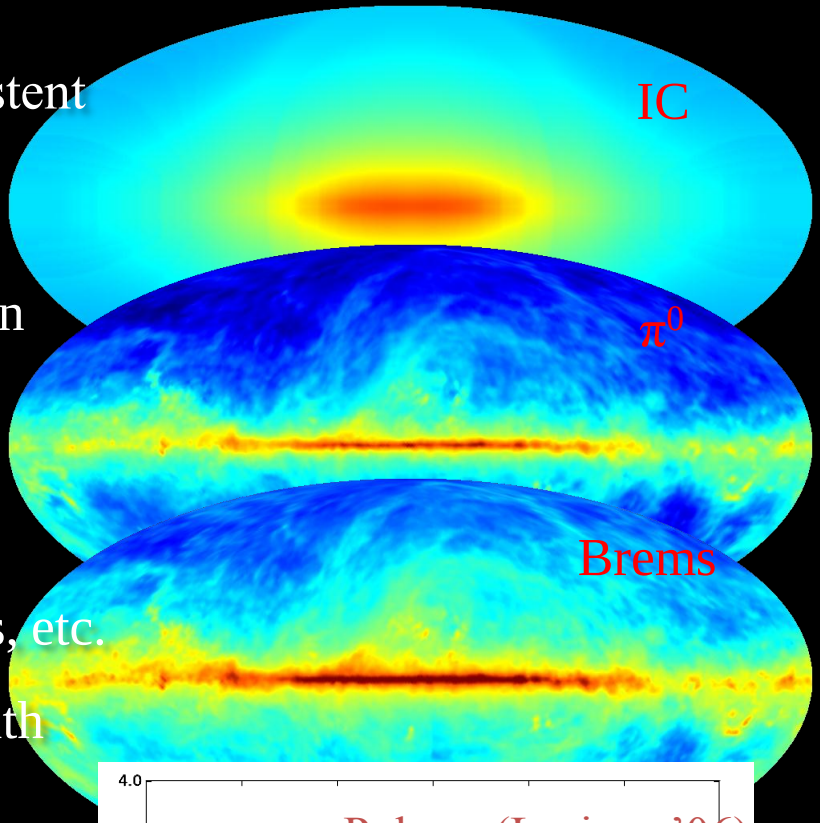
Local emissivities

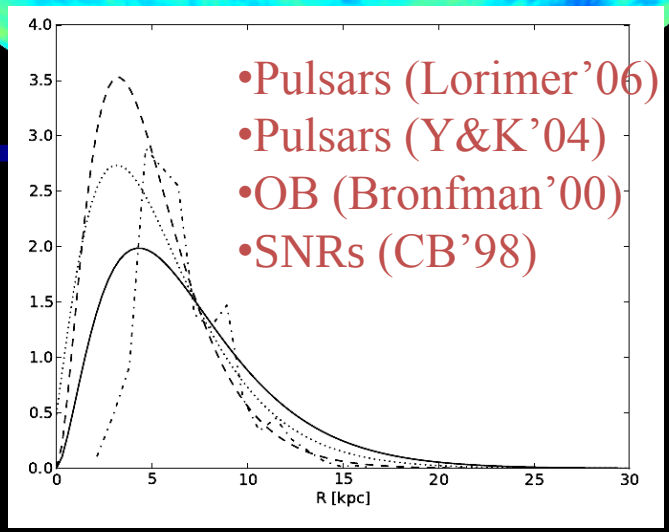


- Local gamma-ray emissivities derived from observations of the local gas clouds are consistent with the direct CR measurements
- Show intensity variations due to errors in gas mass estimates, gas composition, or true CR intensity variations

Large scale study of the diffuse emission

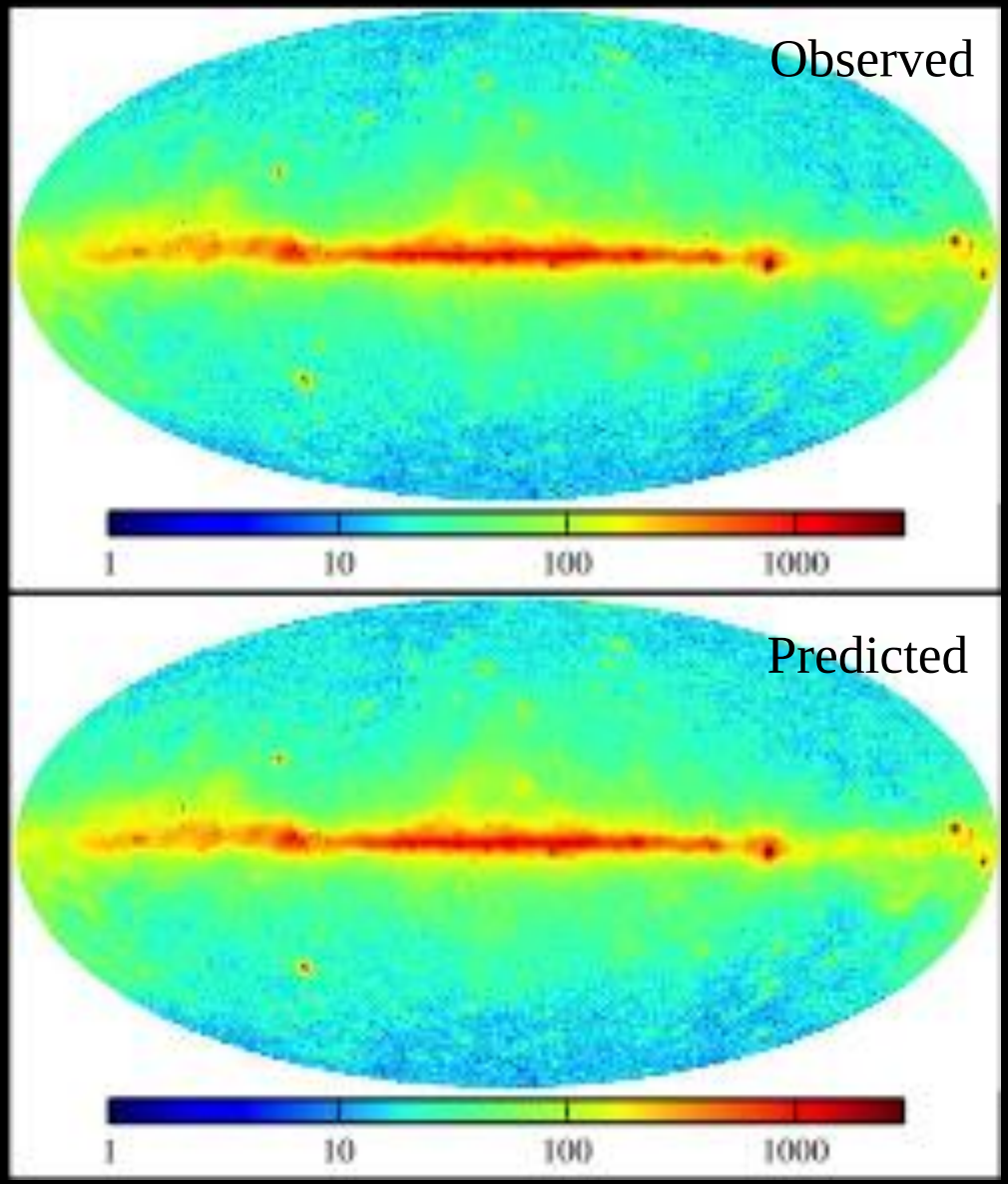
- "Conventional model": CR spectra are consistent with local measurements (CR nuclei, Fermi electrons)
- GALPROP code with diffusion-reacceleration model for CR propagation
- Propagation parameters - fixed from CR data
- Grid of 128 models covering plausible confinement volume, CR source distributions, etc.
- Corresponding model sky maps compared with data using maximum likelihood
- Iterative process since the model parameters depend on outcome of the fit
- A massive Fermi-LAT study – ApJ 750 (2012) 3



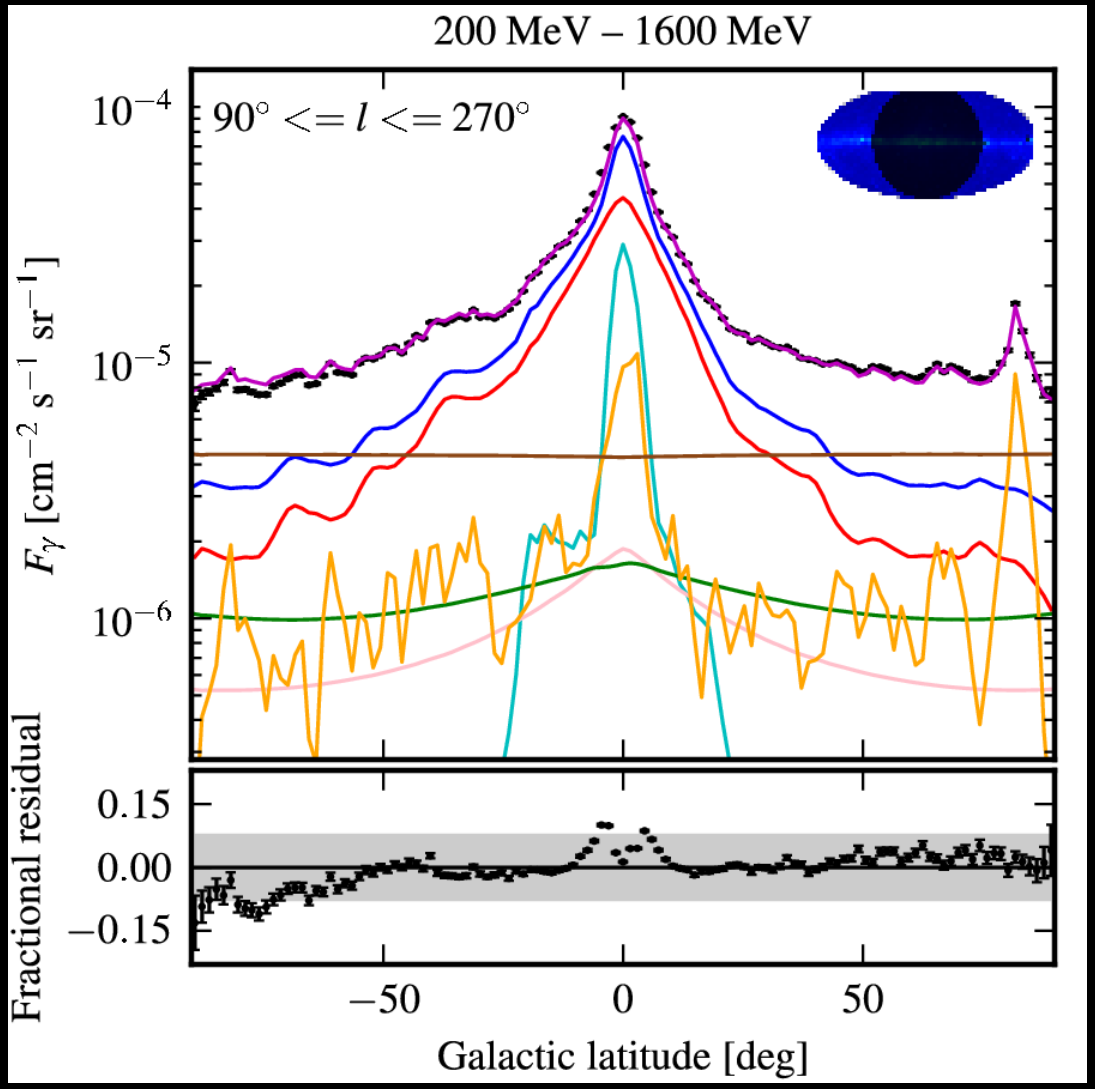


Diffuse emission skymap

- Observed Fermi-LAT counts in the energy range 200 MeV to 100 GeV
- Predicted counts calculated using GALPROP model tuned to CR data

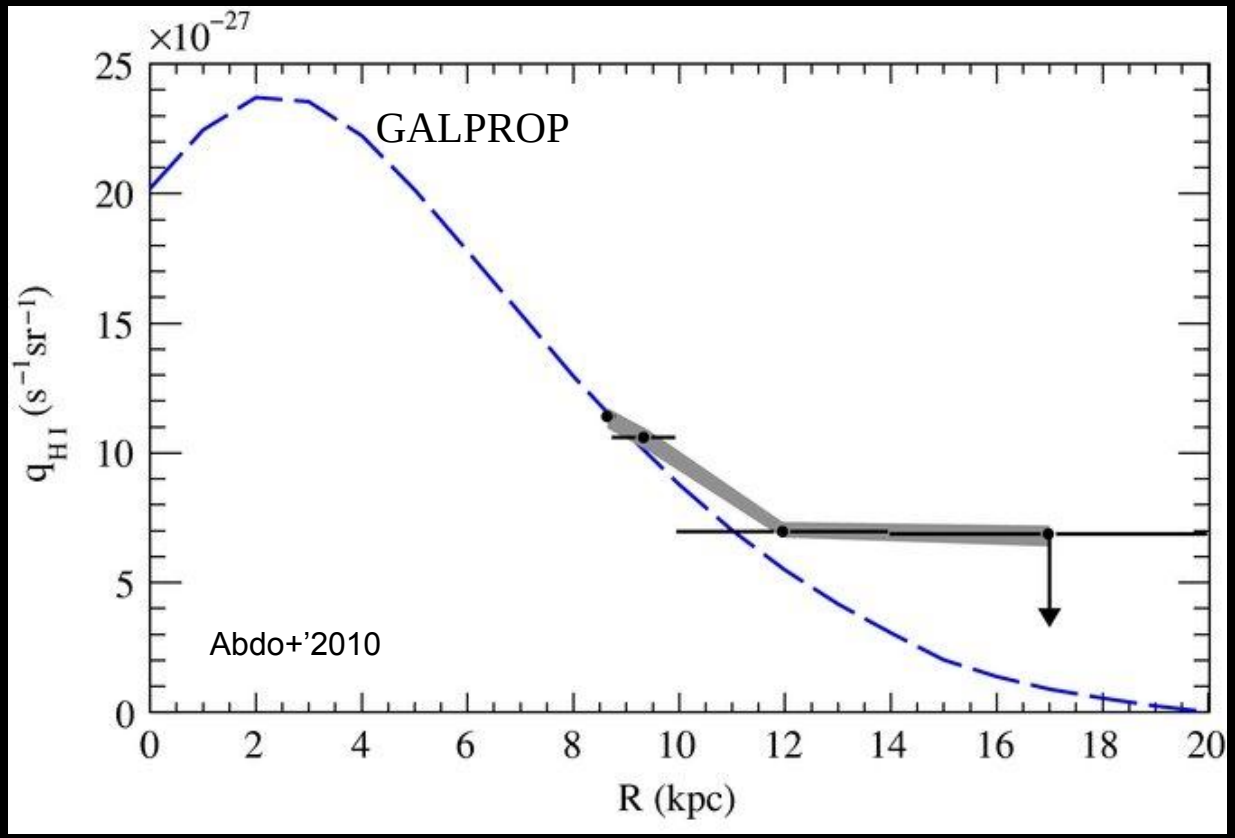


Diffuse emission model(s)



- Models agree with data spanning more than an order of magnitude in intensity!
- Components: gas (H_2, HI, HII), IC, sources, isotropic
- Theoretical challenge, but we can learn a lot!

Fermi-LAT: emissivity gradient in the Galaxy



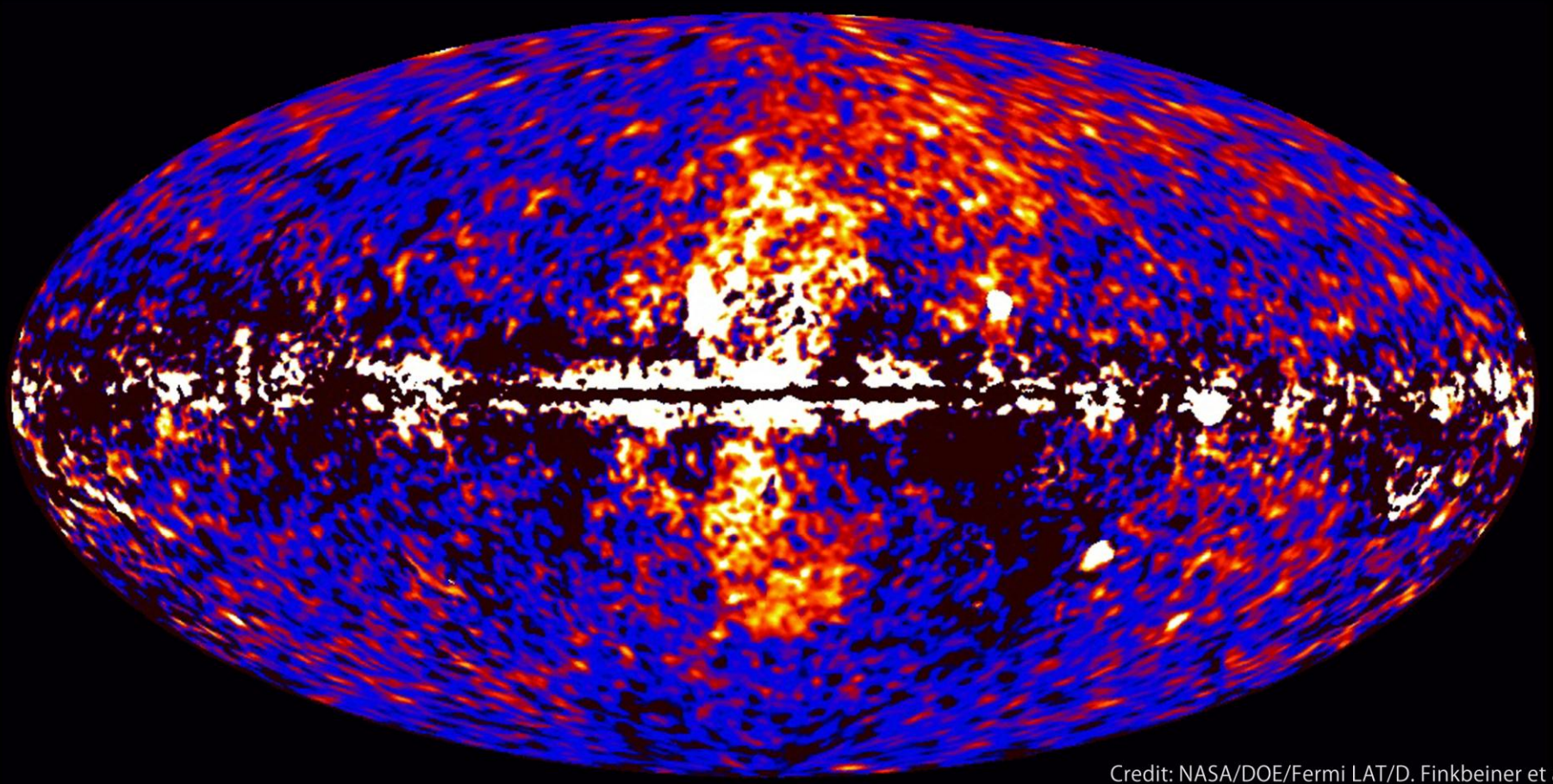
- Radial profile with Galactocentric radius of the emissivity integrated between 200 MeV and 10 GeV. Black dots/horizontal bars mark the ranges in kinematic distance encompassing the Gould Belt, the main part of the local arm, the Perseus and outer arms.

What could be learned from “residuals”?

- Diffuse emissions (radio to gamma rays) arise from various kids of interactions of CRs with interstellar matter, interstellar radiation field, B-field
- Diffuse emissions probe CR intensities and spectra in distant locations
- Models reproduce the main features of the diffuse emission quite well
- Discrepancies between the physical model and high-resolution data (residuals) are the gold mines of new phenomena!
- Every extended source and/or process that is not included into the model pops up and exposes itself as a residual
- Example: “Fermi Bubbles”
- The negative residuals are equally interesting!

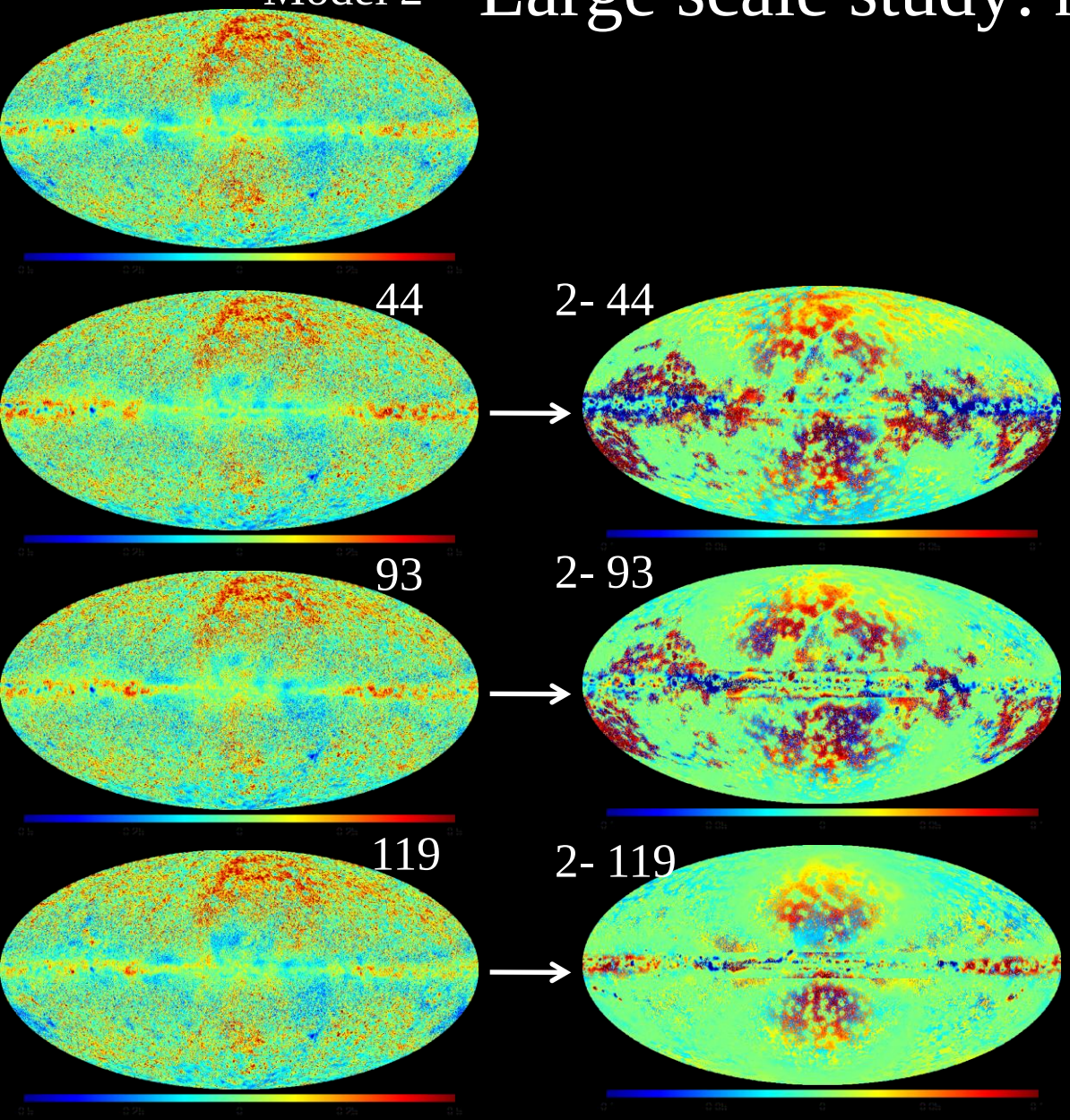
NASA press release

Fermi data reveal giant gamma-ray bubbles



Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

Large scale study: residuals



- Agreement for models is overall good, but features are visible in residuals at ~% level
- Difference between illustrative models shown in right maps : structure due to variations of model parameters

- Models details:

  2: $SNR^{Z}4^{R}20^{T}150^{C}5$

  44: $Lorimer^{Z}6^{R}20^{T}\infty^{C}5$

  93: $Yusifov^{Z}10^{R}30^{T}150^{C}2$

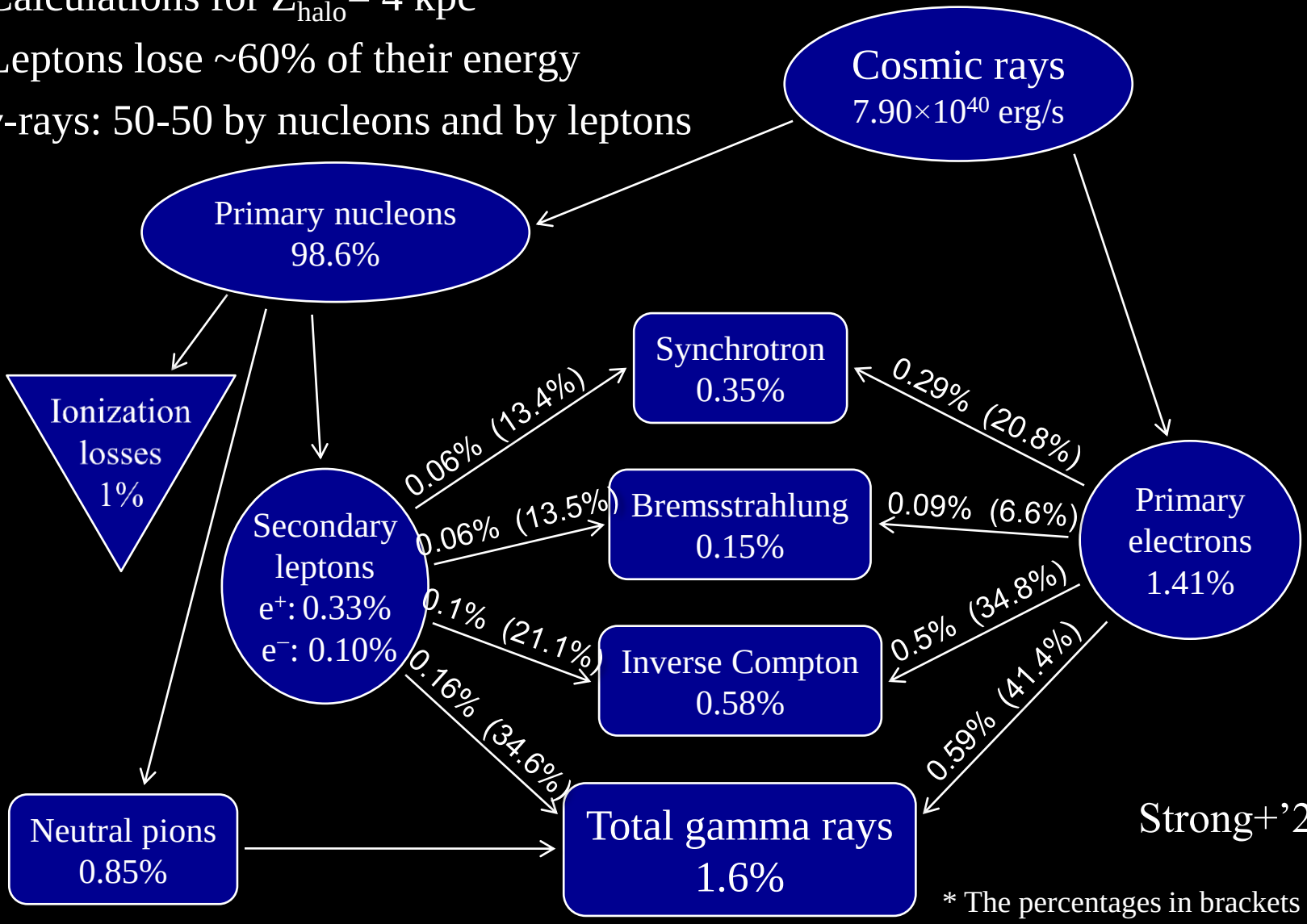
  119: $OB^{Z}8^{R}30^{T}\infty^{C}2$

Milky Way in the global picture

- The Milky Way is the nearest example of a spiral galaxy
- It provides the best opportunity to study ongoing star formation, cosmic rays, and related processes in the ISM
- Important reference point
- Baryonic content of the Universe is dominated by ``normal'' galaxies
- ~70% are spiral galaxies

Milky Way as an electron calorimeter

- Calculations for Z_{halo}= 4 kpc
- Leptons lose ~60% of their energy
- γ-rays: 50-50 by nucleons and by leptons



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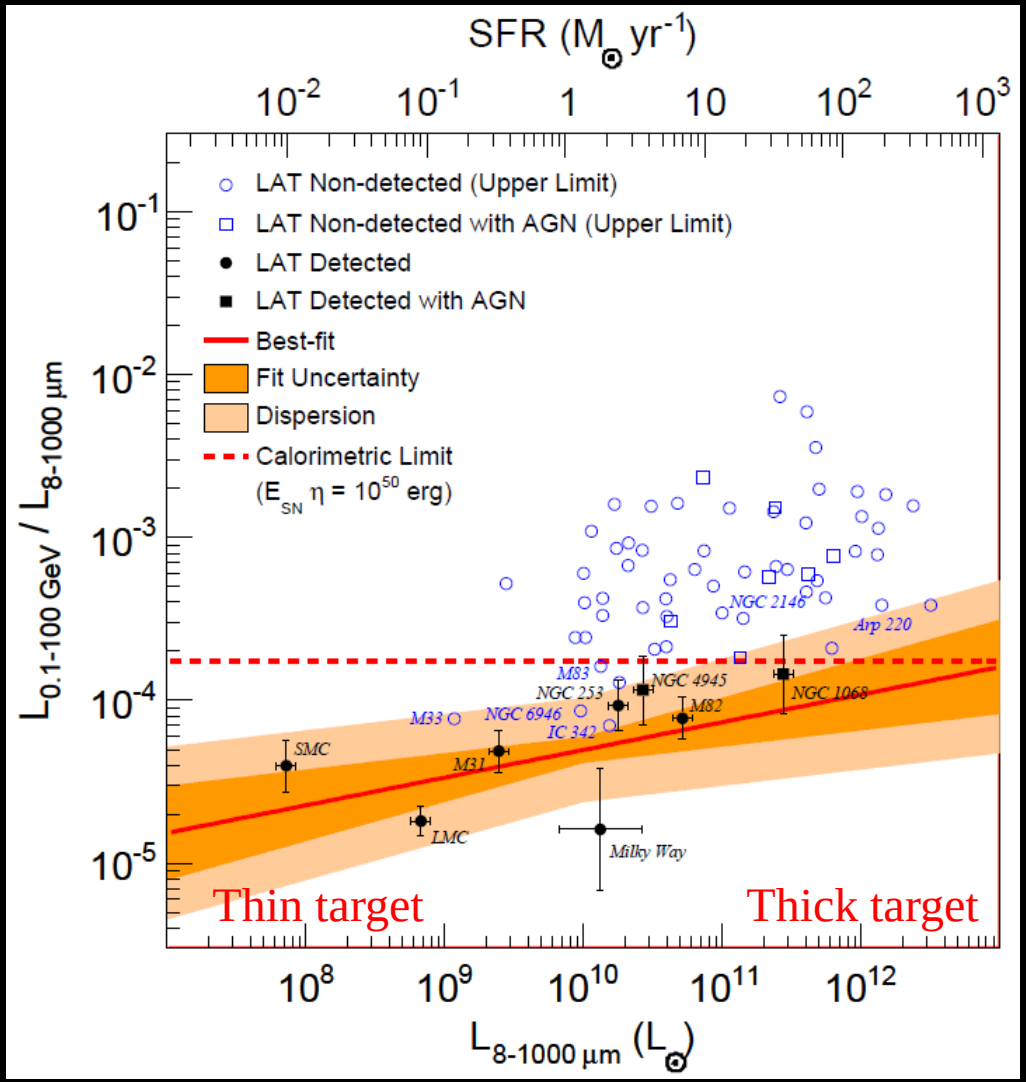
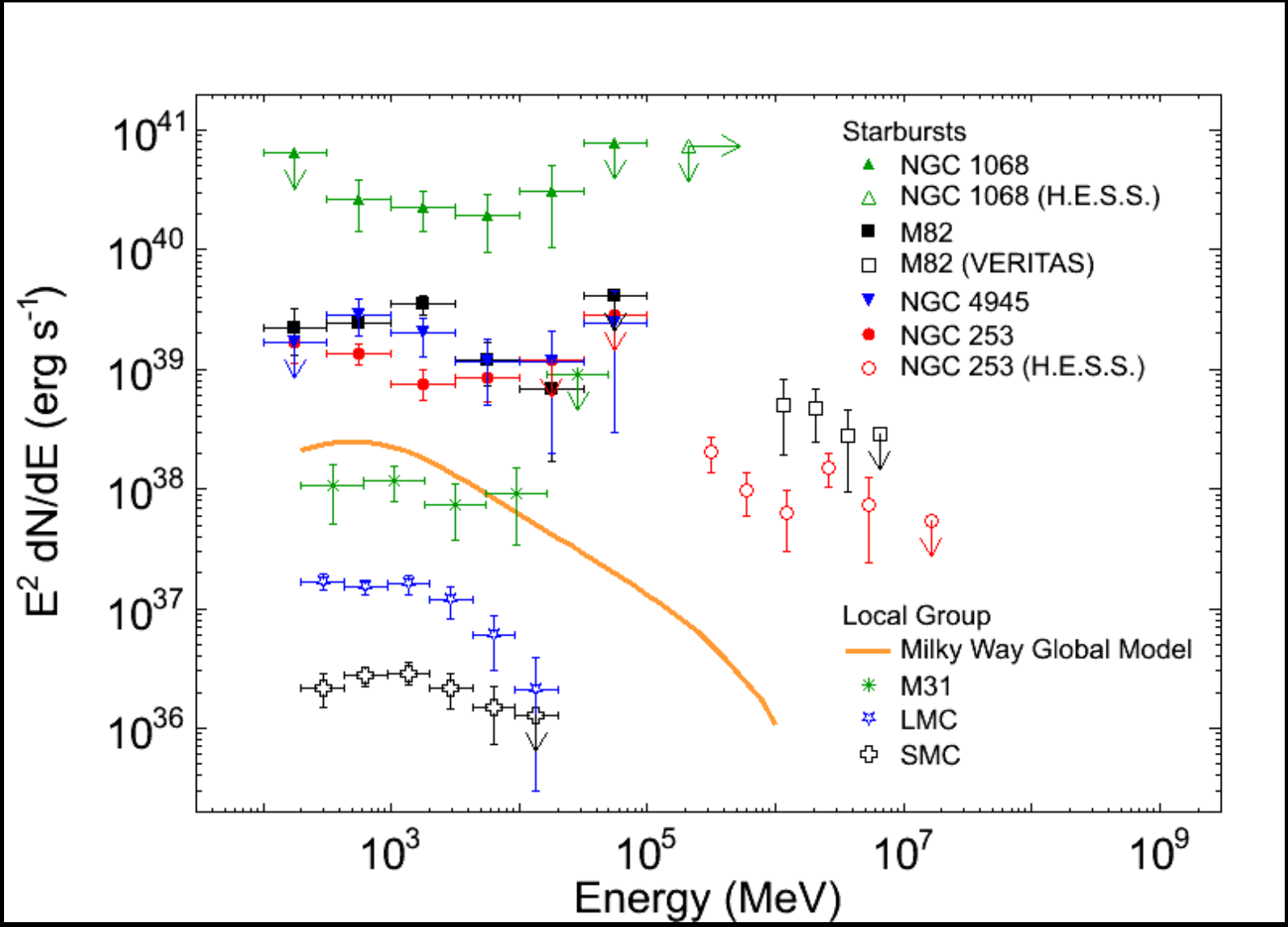
* The percentages in brackets show the values relative to the luminosity of their respective lepton populations

Cosmic ray is a universal phenomenon

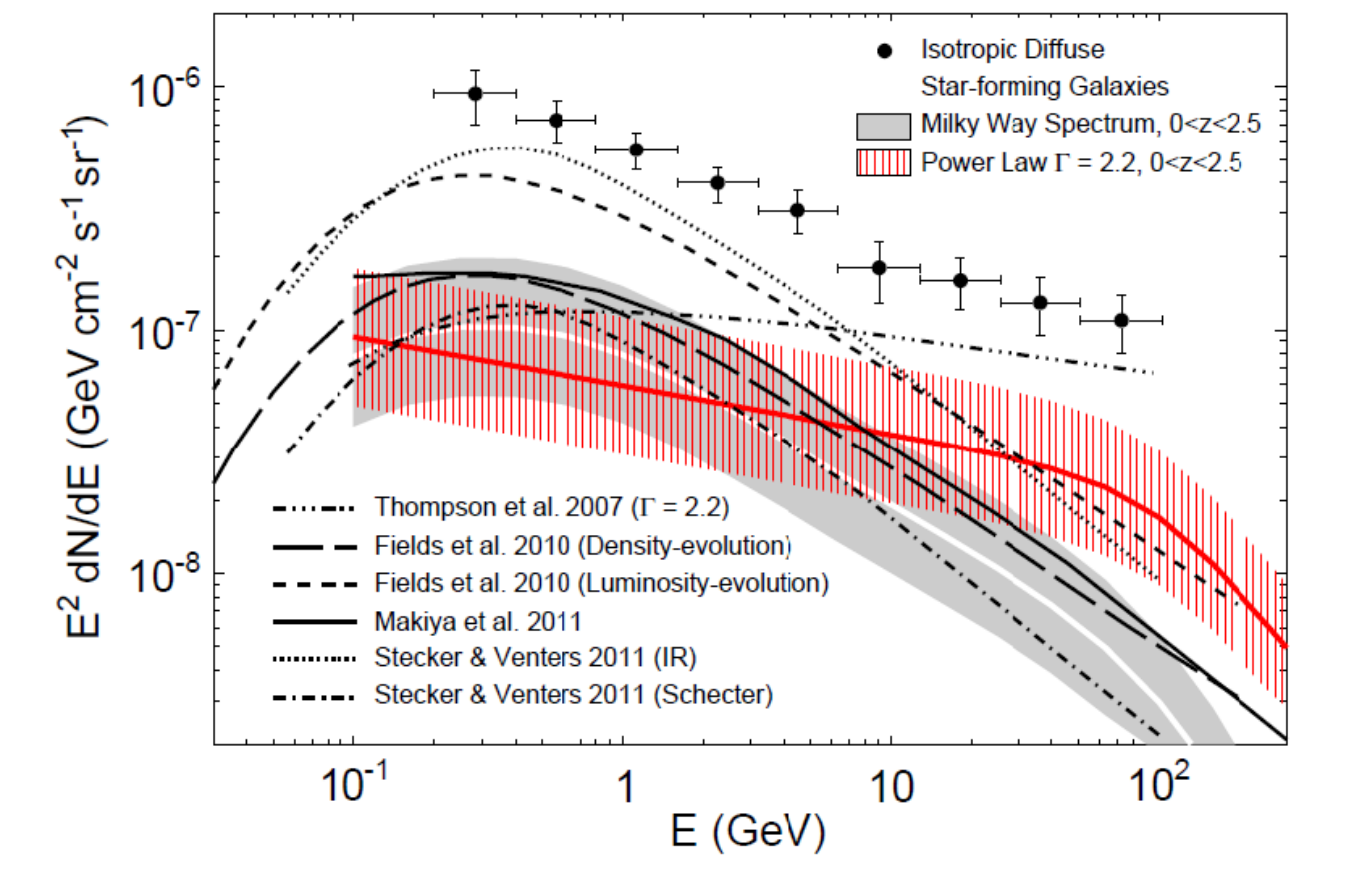


- γ-ray luminosity vs. IR luminosity for normal galaxies detected with Fermi-LAT
- The γ-ray luminosity scales linearly (index ~1.1) with the total emission of hot stars reprocessed by dust – a tracer of star formation
- The ratio approaches the calorimetric limit in star-burst galaxies
- An evidence of the SNR-CR connection in normal star-forming galaxies

Milky Way as a reference point

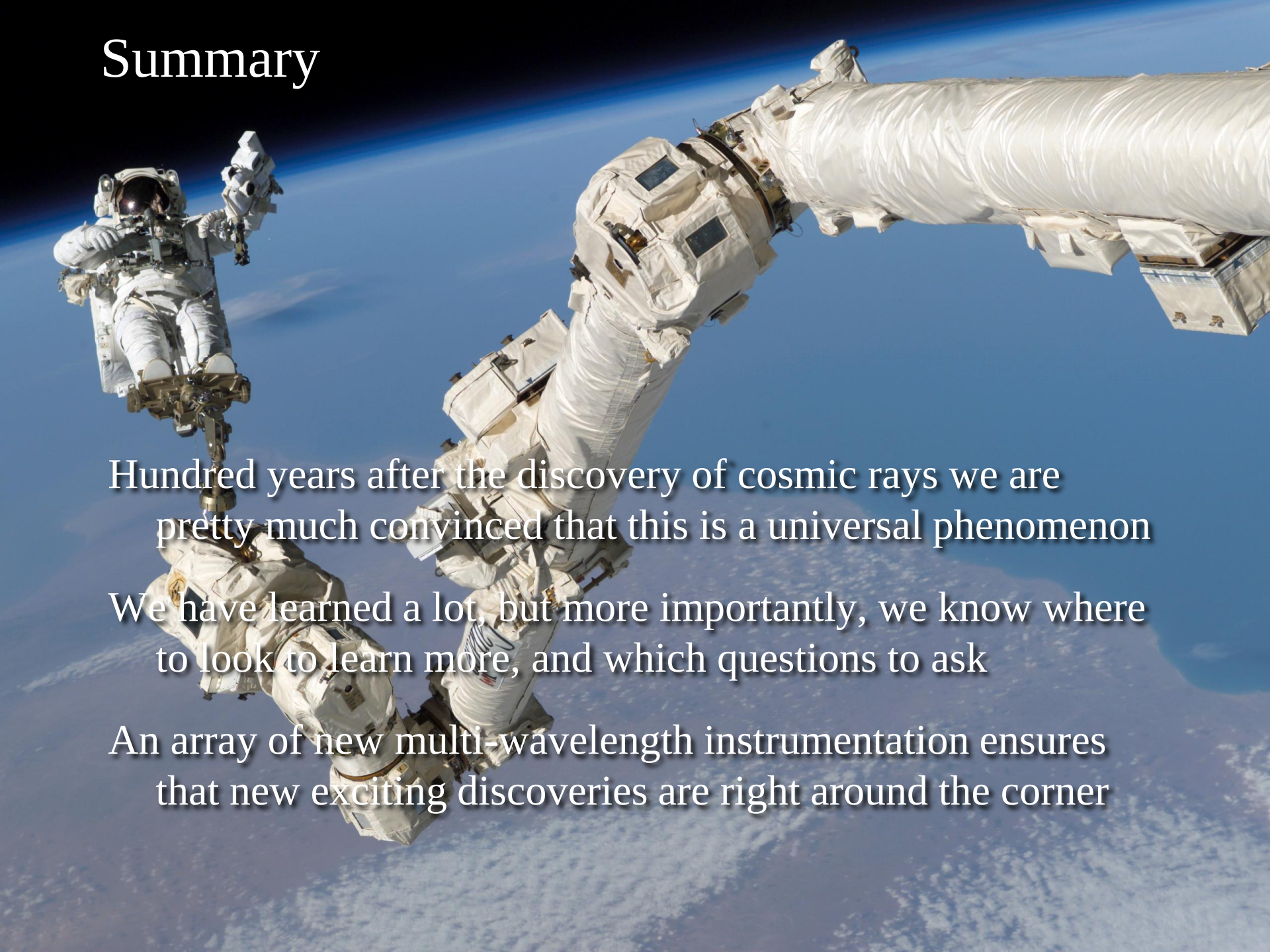


Contribution to extragalactic background



Comparable to that of blazars: 4-23% of Fermi-LAT measured isotropic diffuse intensity >0.1 GeV

Summary



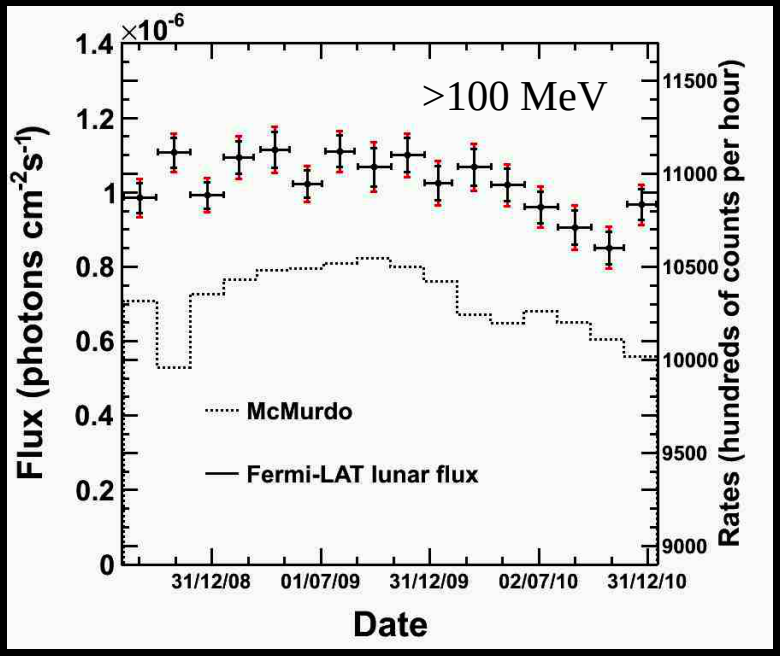
Hundred years after the discovery of cosmic rays we are pretty much convinced that this is a universal phenomenon

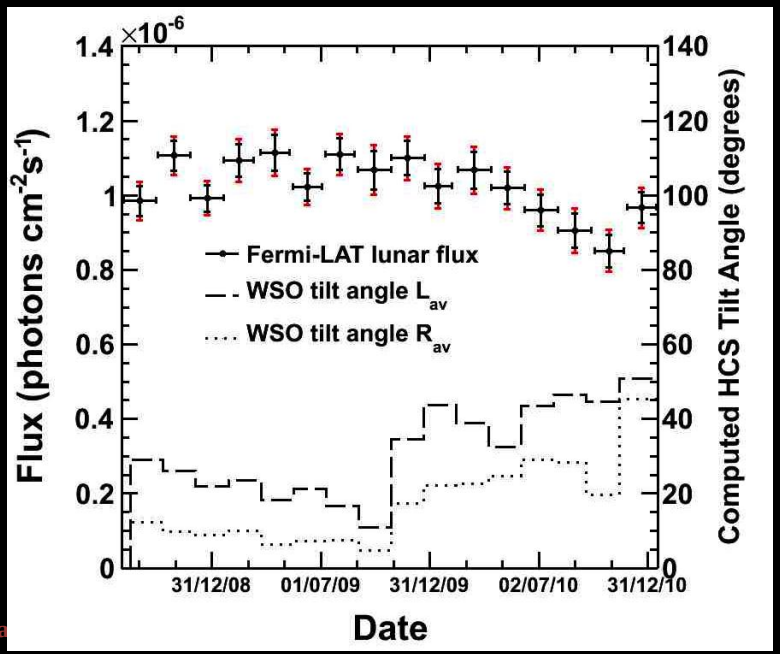
We have learned a lot, but more importantly, we know where to look to learn more, and which questions to ask

An array of new multi-wavelength instrumentation ensures that new exciting discoveries are right around the corner

Backup slides

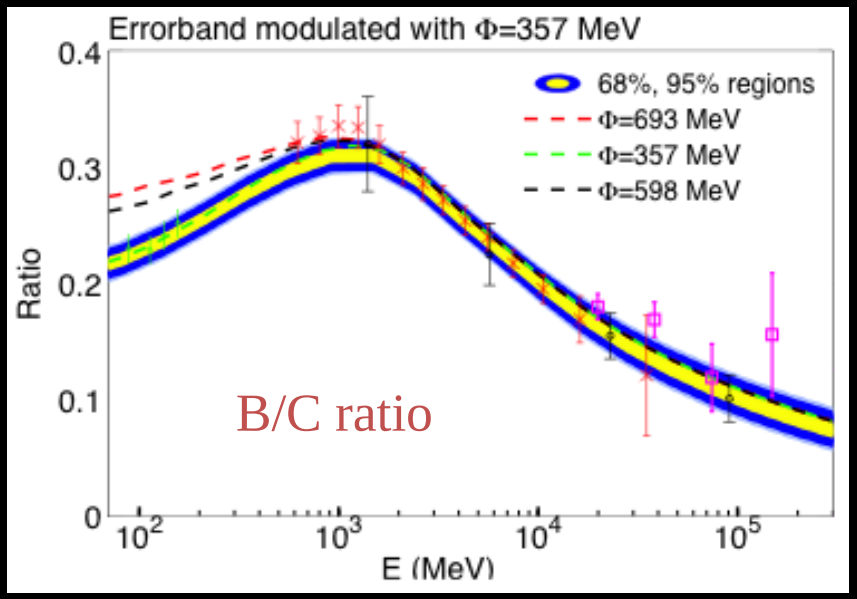
Fermi-LAT observations of the Moon

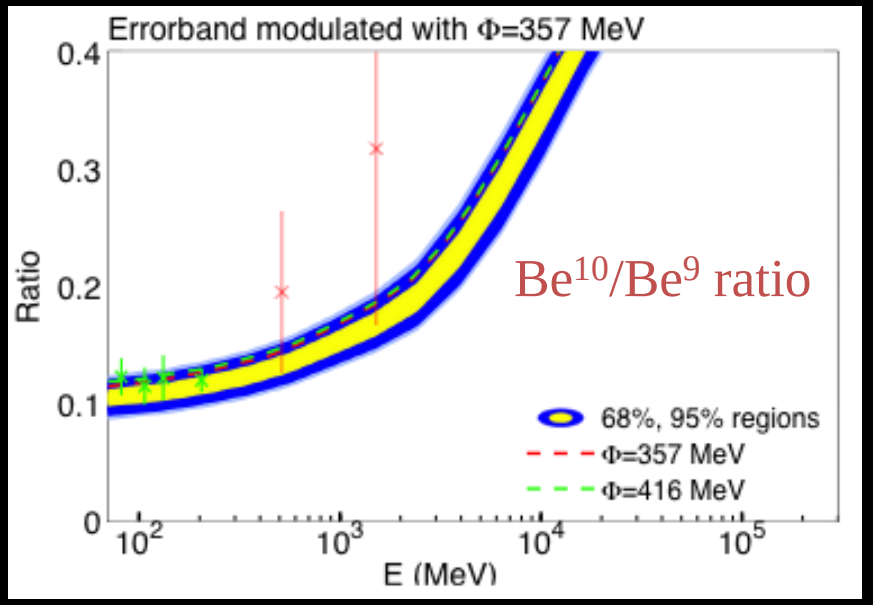


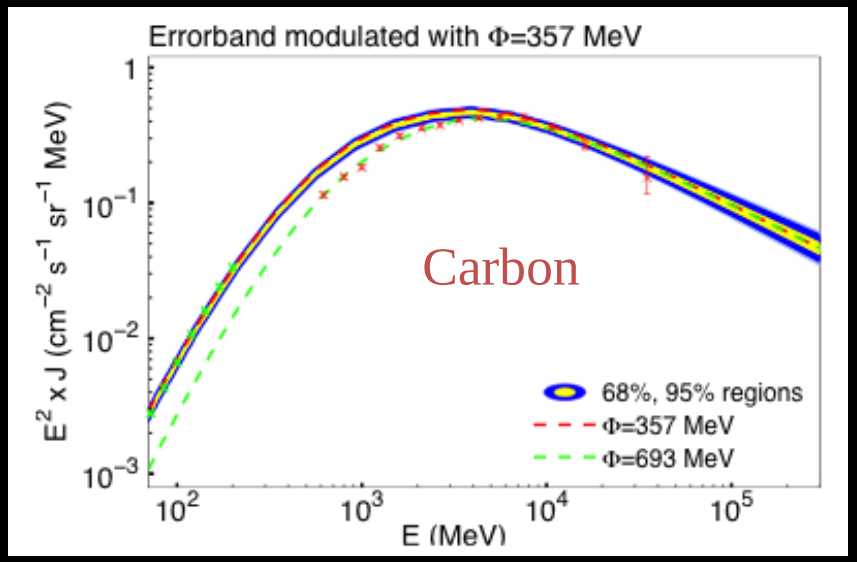


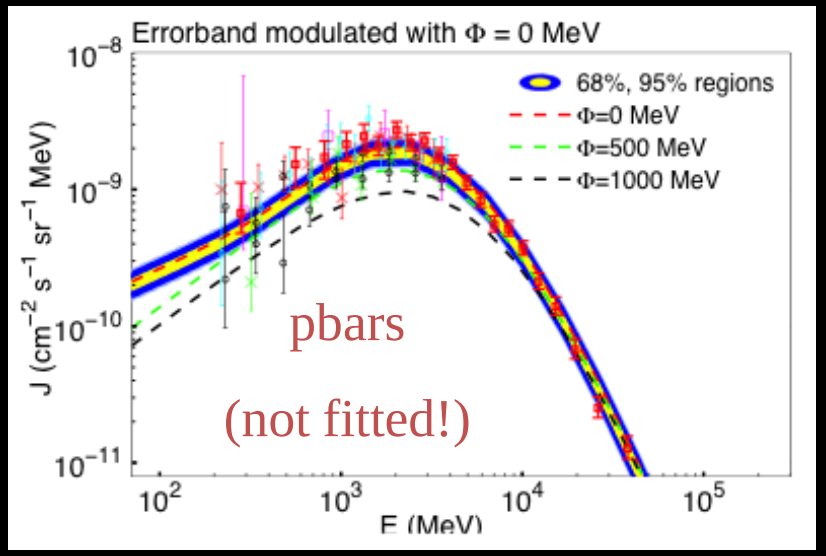
- The spectrum is steep – cuts off at ~2 GeV – due to the CR cascades in the lunar rock (regolith)
- Correlates with the Neutron Monitor rate (McMurdo)
- Anticorrelates with the tilt angle of the heliospheric current sheet
- Allows the low energy CR flux to be monitored – outside of the Earth's magnetosphere
- Complementary to the Neutron Monitors, but not the same

Examples: B/C and Be ratios, C and pbars

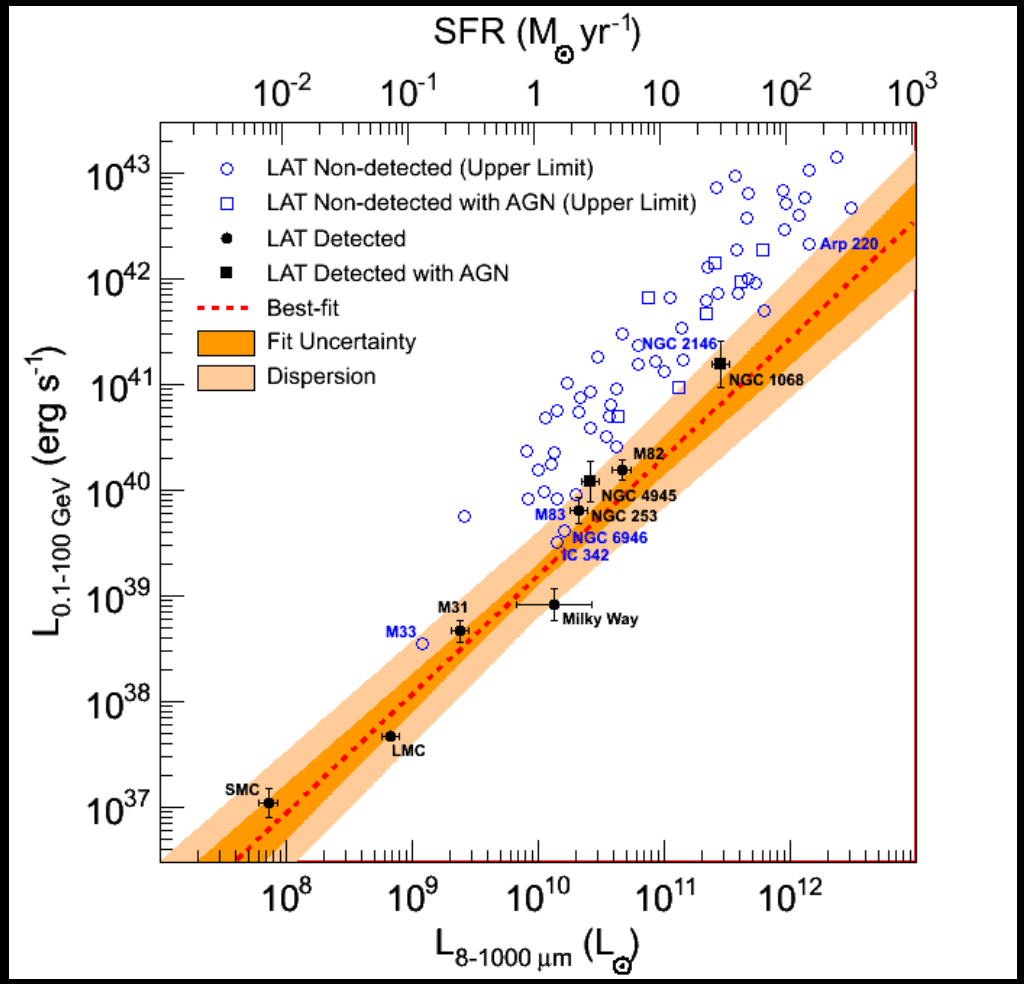








Cosmic ray is a universal phenomenon



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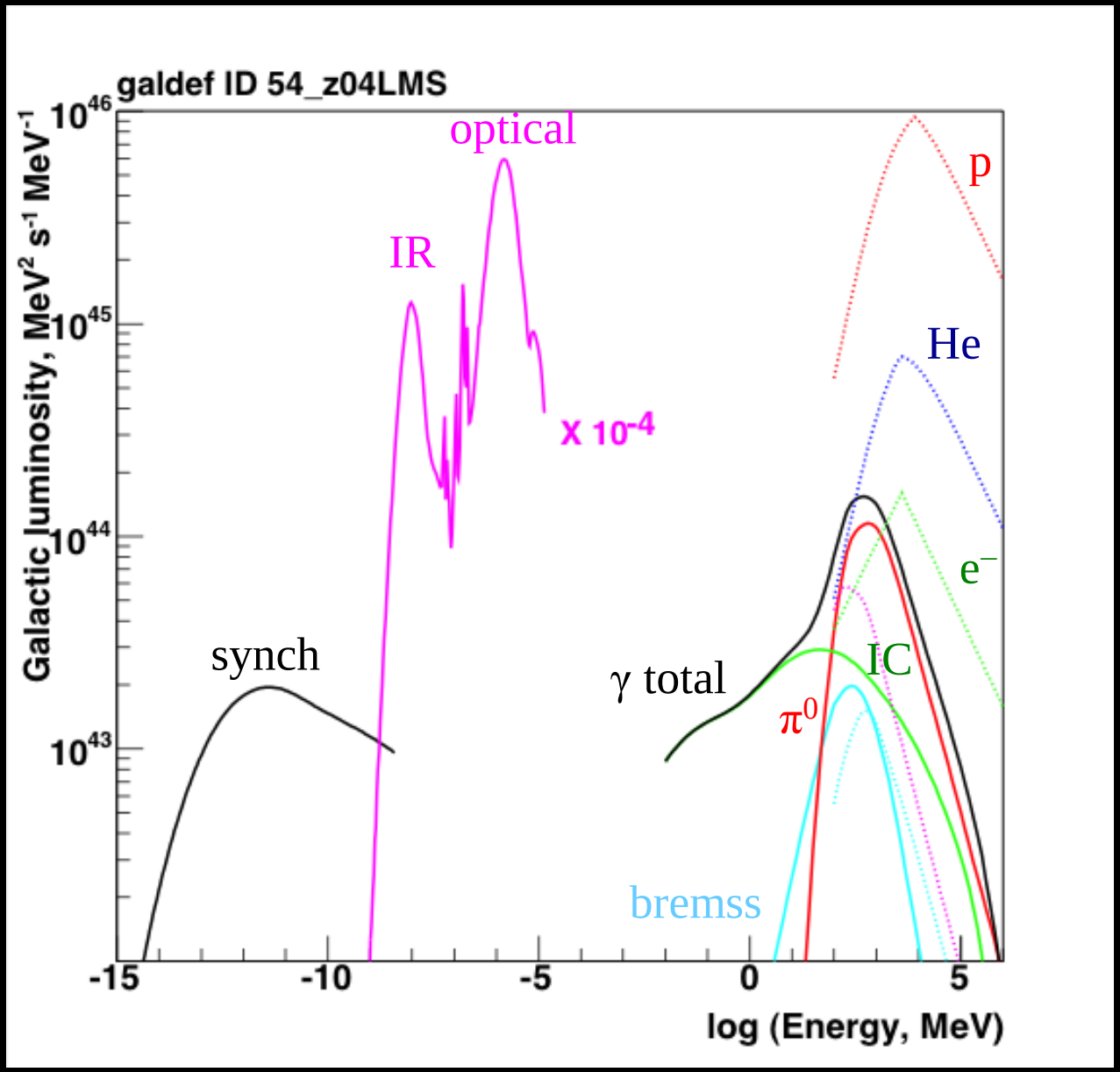
- An evidence of the SNR-CR connection in normal starforming galaxies

Multi-λ luminosity of the Milky Way galaxy



- "Proximity" of the MW plus direct measurements provide an opportunity to construct its detailed "microscopic" model (GALPROP)
- Integral properties of the MW – a useful template for studies of other normal galaxies

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