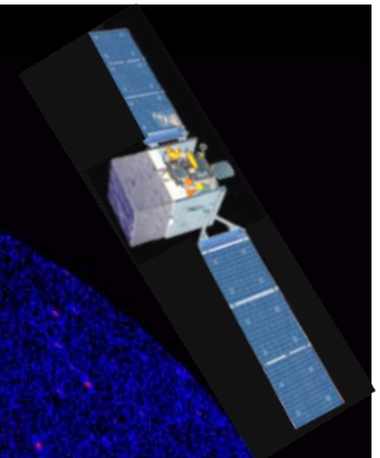


COSMIC RAYS IN THE MILKY WAY & OTHER GALAXIES – FERMI-LAT OBSERVATIONS

IGOR V MOSKALENKO – STANFORD

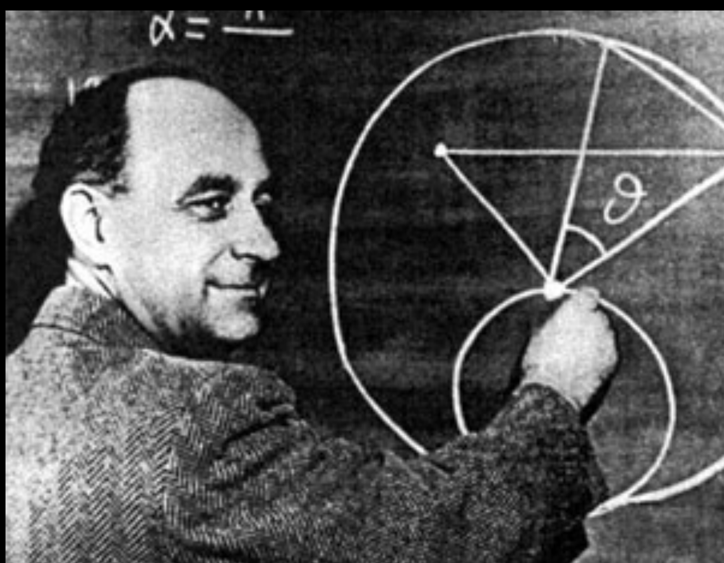

Fermi
Gamma-ray
Space Telescope
11 June 2008

PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

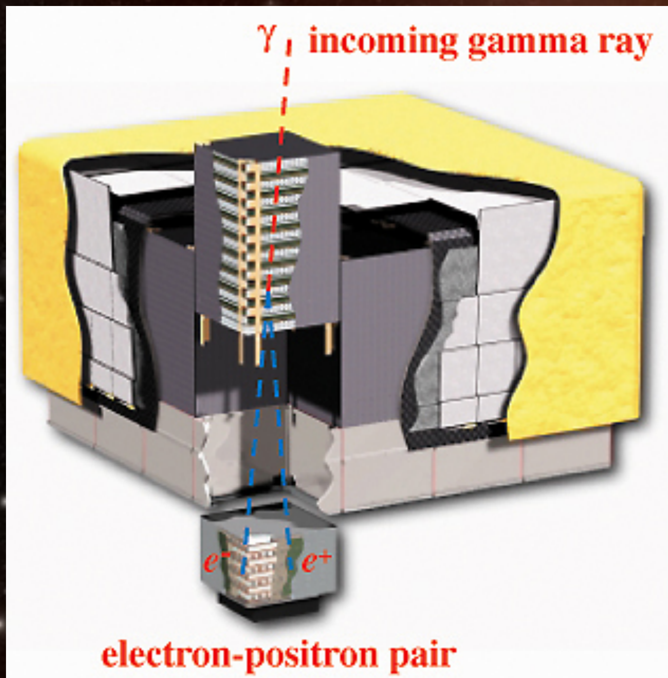
ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

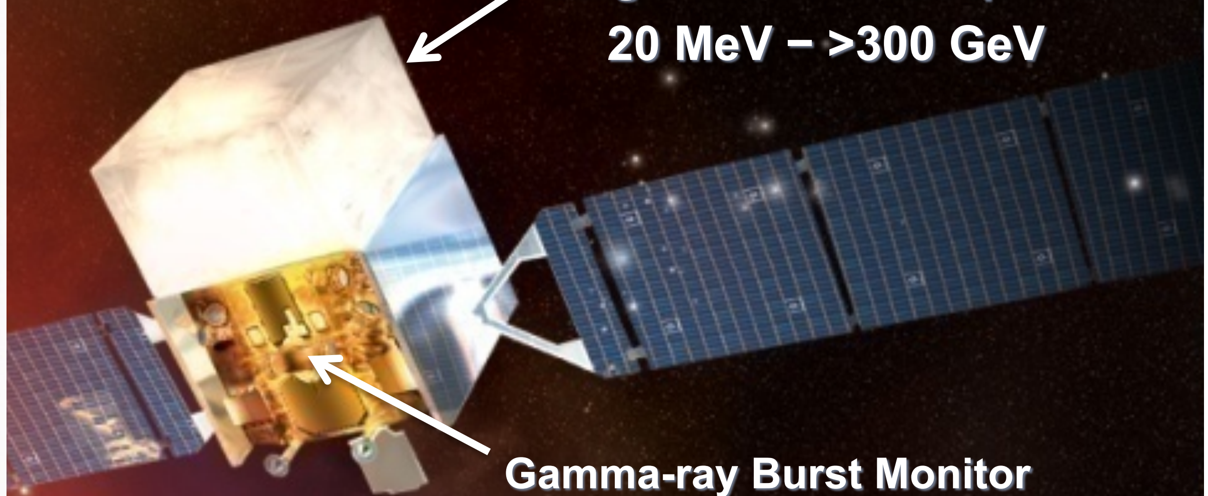
A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.



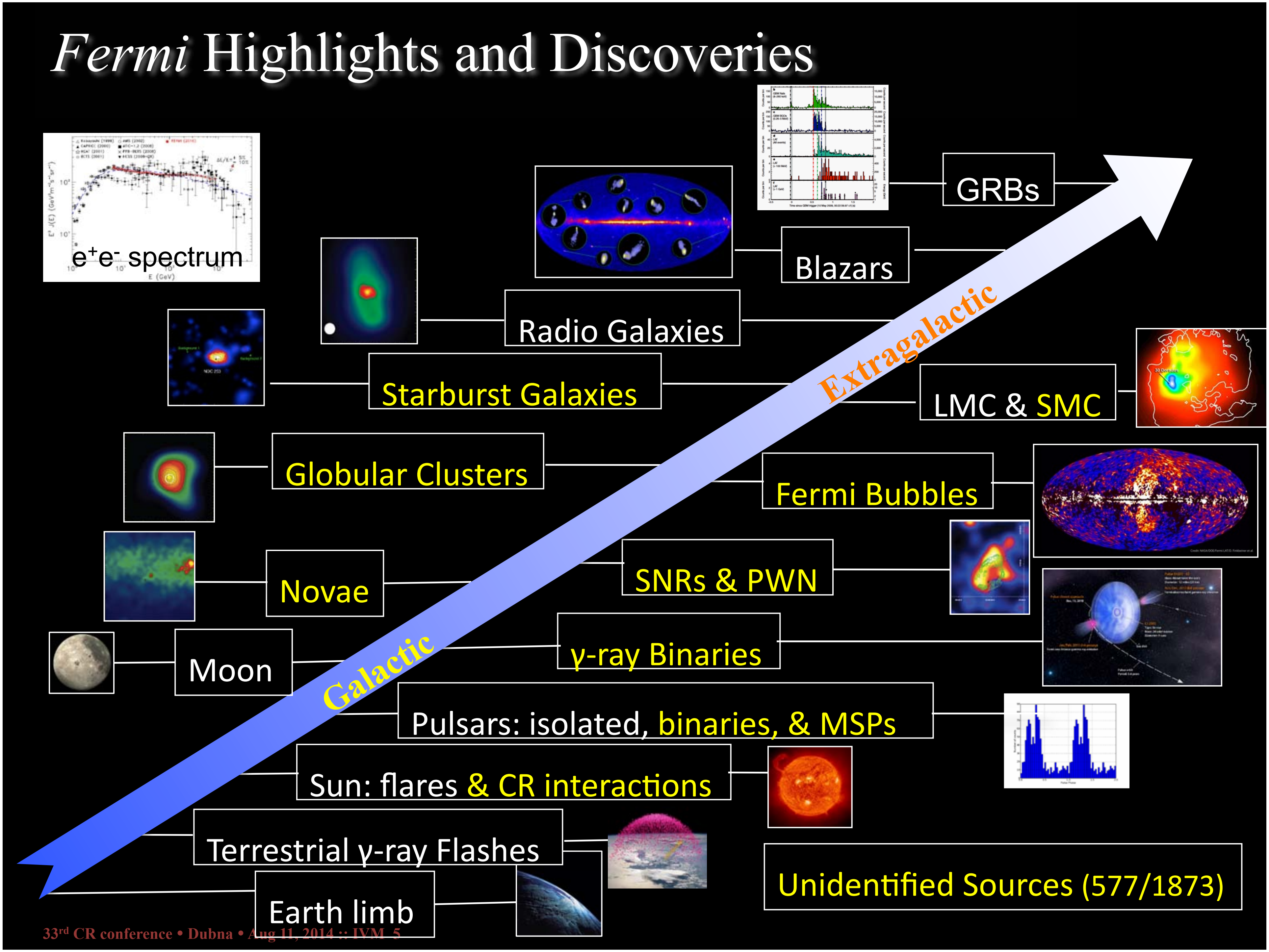
…if the mirror is moving towards the incident particle, the particle gains energy upon reflection, just as does a tennis ball pushed by a racket…

Fermi Gamma-ray Space Telescope

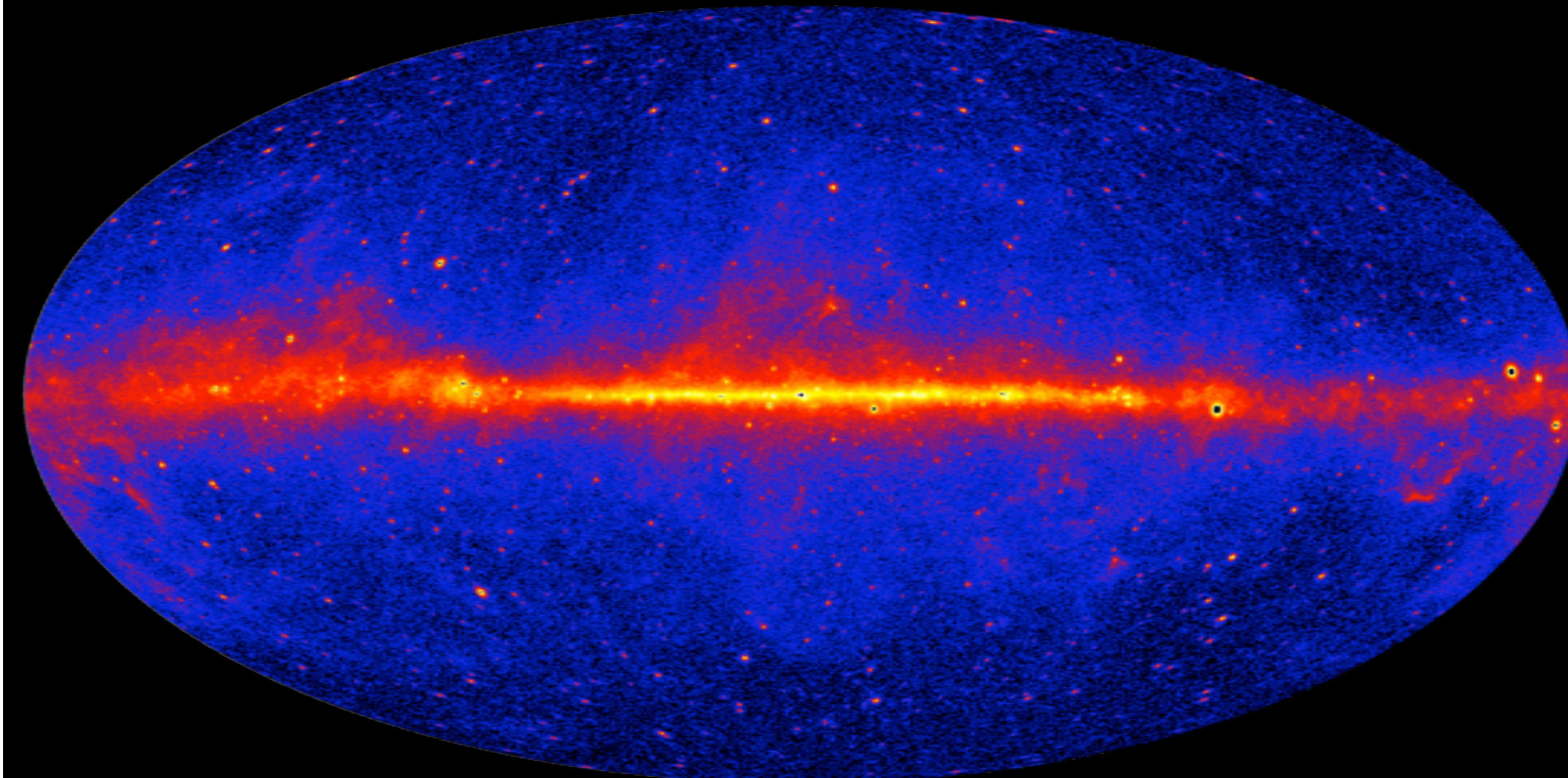




- The LAT is a unique resource providing
  - *Broad energy coverage, overlap with ACTs*
  - *Large FoV: all-sky coverage every 3 hours – transients*
- Observatory is operating smoothly
  - *Instruments and spacecraft operate as designed, no degradation in science performance since launch*

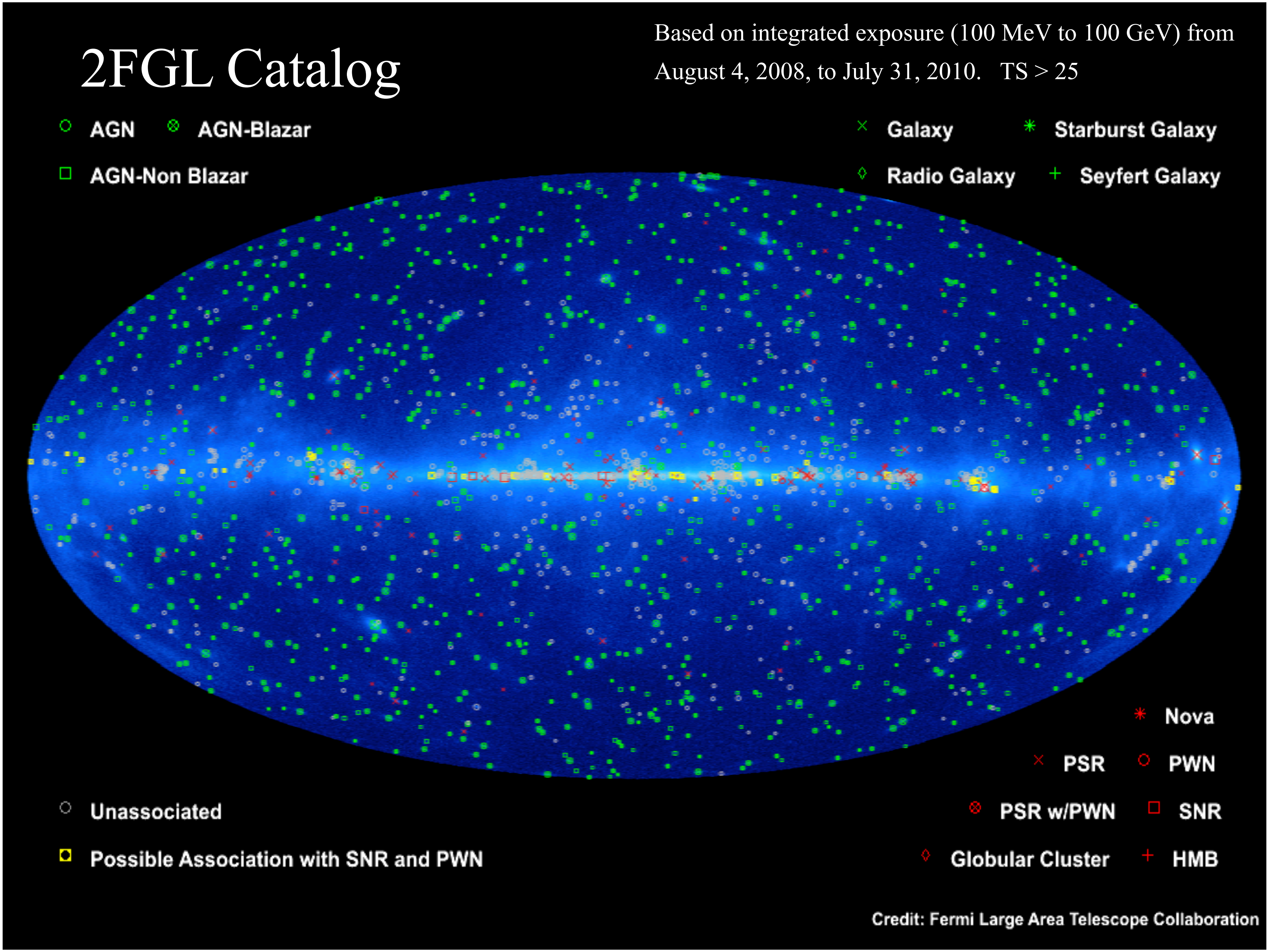

Fermi Highlights and Discoveries
e+e- spectrum
GRBs
Blazars
Radio Galaxies
Starburst Galaxies
LMC & SMC
Extragalactic
Globular Clusters
Fermi Bubbles
Novae
SNRs & PWN
Moon
γ-ray Binaries
Galactic
Pulsars: isolated, binaries, & MSPs
Sun: flares & CR interactions
Terrestrial γ-ray Flashes
Earth limb
Unidentified Sources (577/1873)

Fermi-LAT skymap >1 GeV, 48 months

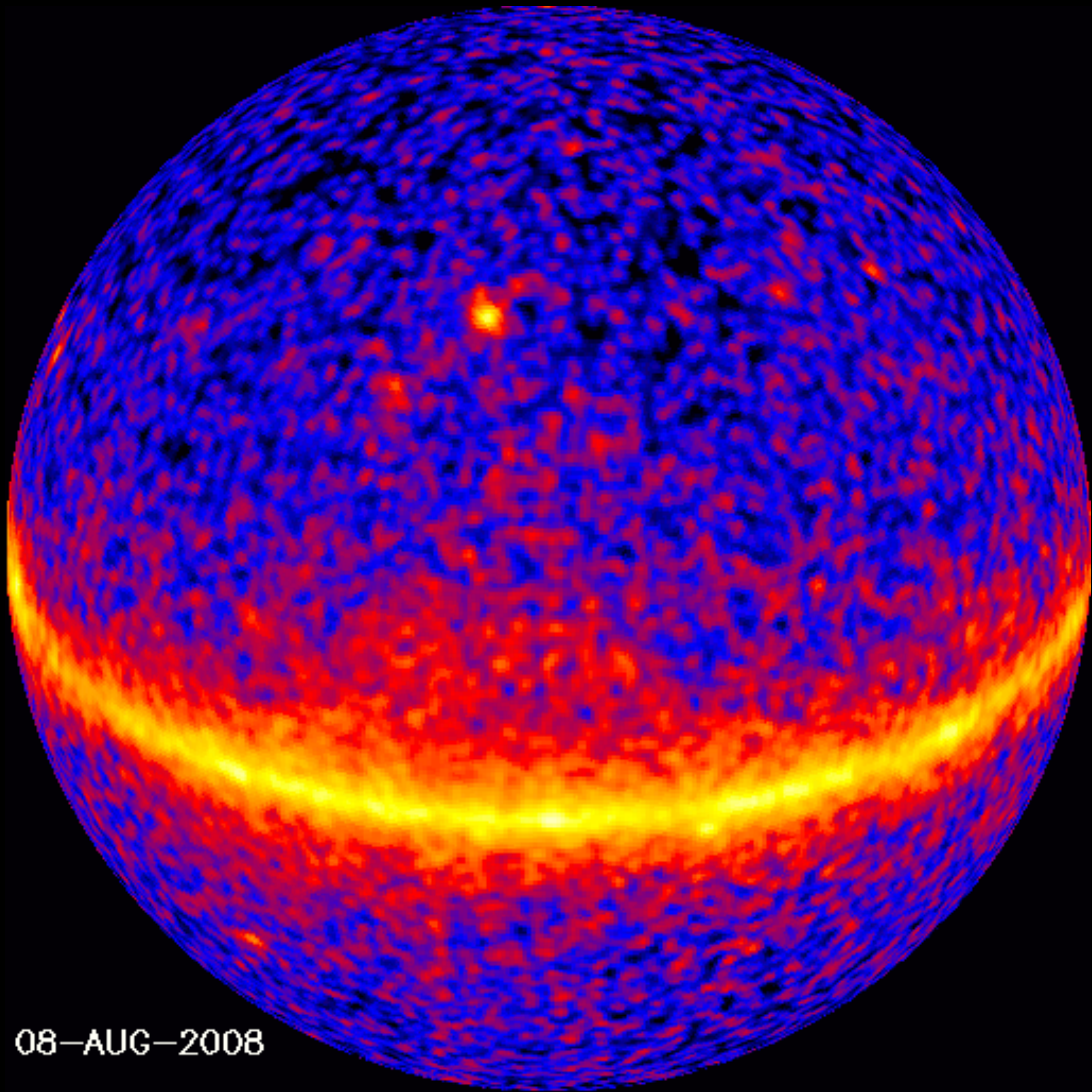


4-year sky map, >1 GeV, front converting (best psf) (4.52M events)

- ✧ LAT: ~275B triggers, 225M Source class events
- ✧ GBM: >1000 GRBs

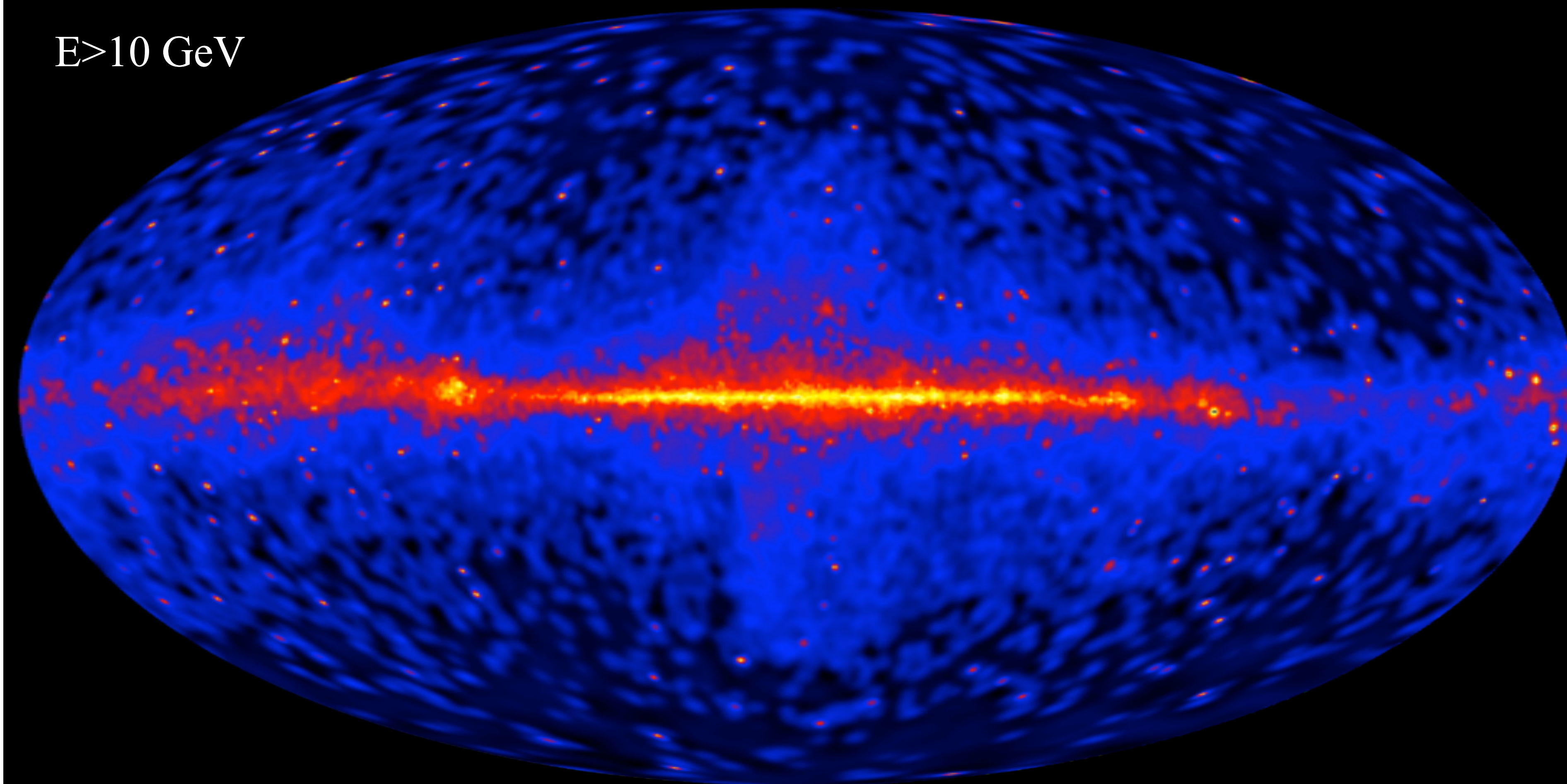

2FGL Catalog
Based on integrated exposure (100 MeV to 100 GeV) from August 4, 2008, to July 31, 2010. TS > 25
AGN
AGN-Blazar
AGN-Non Blazar
Galaxy
Starburst Galaxy
Radio Galaxy
Seyfert Galaxy
Nova
PSR
PWN
PSR w/PWN
SNR
Globular Cluster
HMB
Unassociated
Possible Association with SNR and PWN
Credit: Fermi Large Area Telescope Collaboration

Fermi's skymap of particle interactions

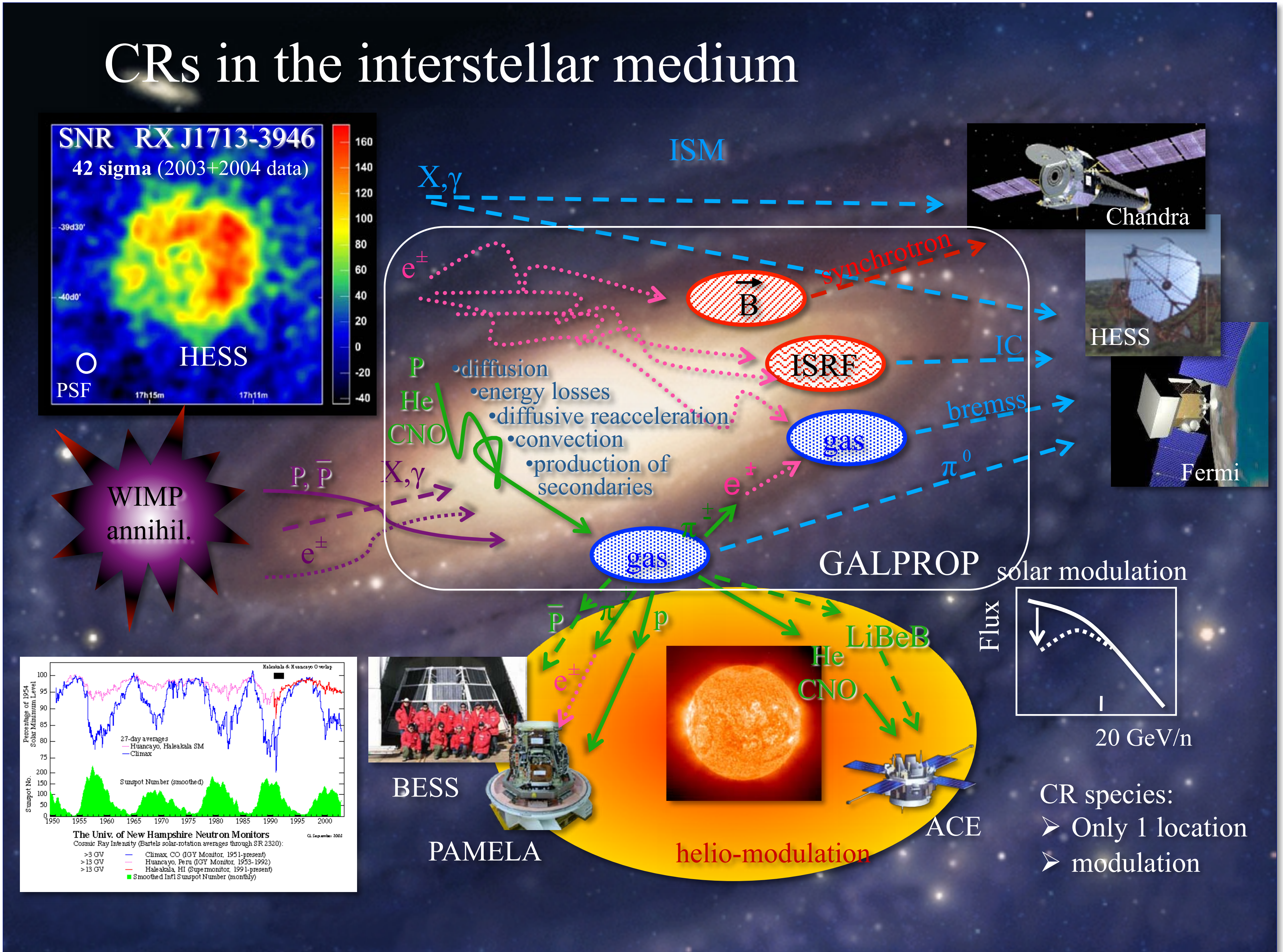


- >100 MeV, 36 months
- shows where accelerated particles meet targets (gas, photons)
- ~80% of the emission is diffuse
- A lot of transients
- our Galaxy provides the best opportunity to study CRs: direct and indirect measurements with excellent resolution

Fermi-LAT skymaps, 48 months

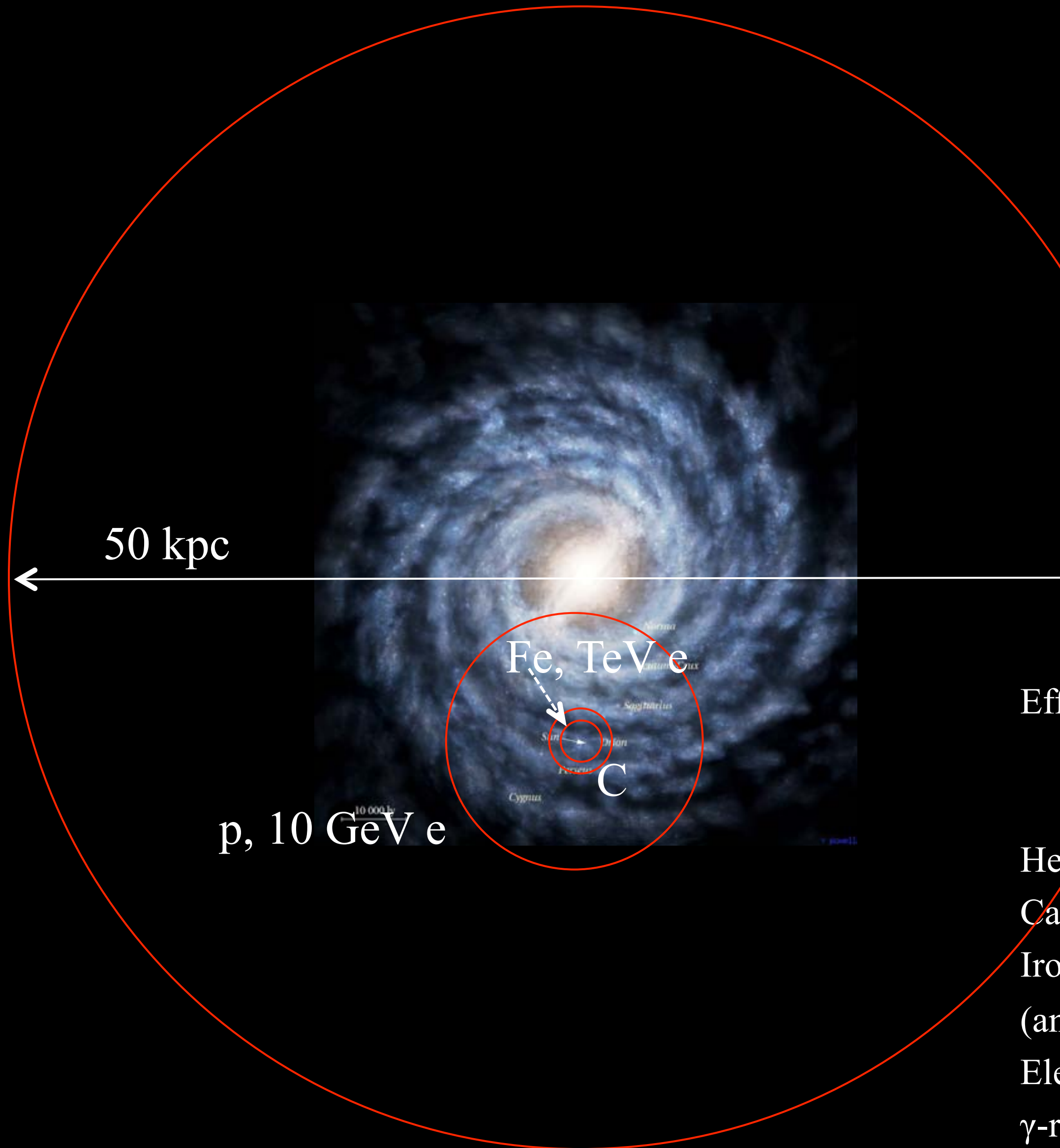


- Fewer sources at high energies
- Less diffuse emission
- Interesting physics



CRs in the interstellar medium
SNR RX J1713-3946
42 sigma (2003+2004 data)
HESS
PSF
ISM
X,γ
Chandra
HESS
Fermi
e±
B
synchrotron
ISRF
IC
gas
bremss
π0
P
He
CNO
•diffusion
•energy losses
•diffusive reacceleration
•convection
•production of secondaries
WIMP annihil.
P, P̄
X,γ
e±
π±
gas
GALPROP
solar modulation
Flux
20 GeV/n
P̄
π
p
e±
LiBeB
He
CNO
BESS
PAMELA
ACE
helio-modulation
CR species:
➢ Only 1 location
➢ modulation
The Univ. of New Hampshire Neutron Monitors
Sunspot Number (smoothed)

Direct probes of CR propagation



- Direct measurements probe a very small volume of the Galaxy
- Light & heavy nuclei probe different propagation volume
- The propagation distances are shown for nuclei for rigidity ~1 GV, and for electrons ~1 TeV

Effective propagation distance:

$\langle X \rangle \sim \sqrt{6D\tau} \sim 4.5\times10^{21}\ R^{1/4}\,(A/12)^{-1/3}$ cm

~ 1.5 kpc $R^{1/4}\,(A/12)^{-1/3}$

Helium: ~ 2.1 kpc $R^{1/4}$

Carbon: ~ 1.5 kpc $R^{1/4}$ - 0.36% of the surface area

Iron: ~ 0.9 kpc $R^{1/4}$ - 0.16%

(anti-) protons: ~ 6 kpc $R^{1/4}$ - 5.76%

Electrons ~ 1 kpc $E_{12}^{-1/4}$

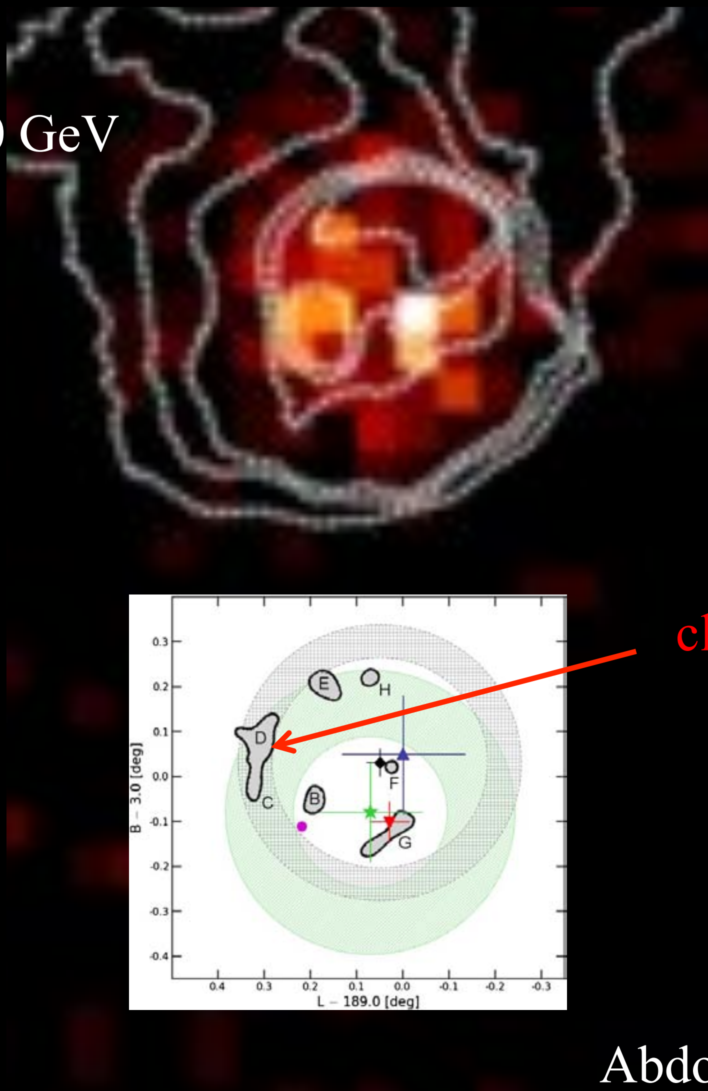
γ-rays: probe CR p (pbar) and e± spectra in the whole Galaxy ~50 kpc across

Fermi-LAT observations of SNRs IC443 & W44

✧ Morphology of γ-ray emission coincides well with shocked H_2

IC443

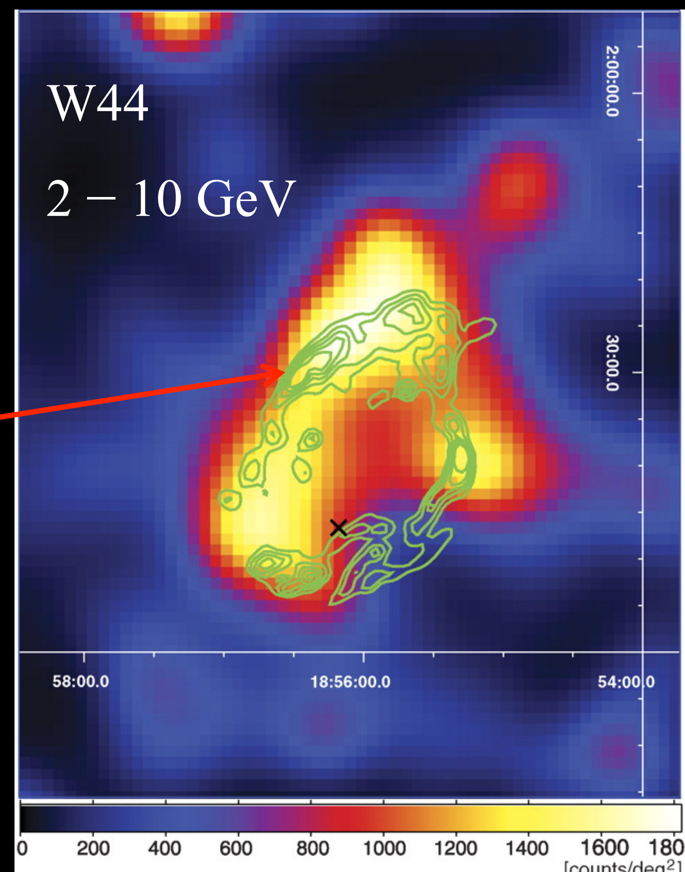
5 − 50 GeV



clouds

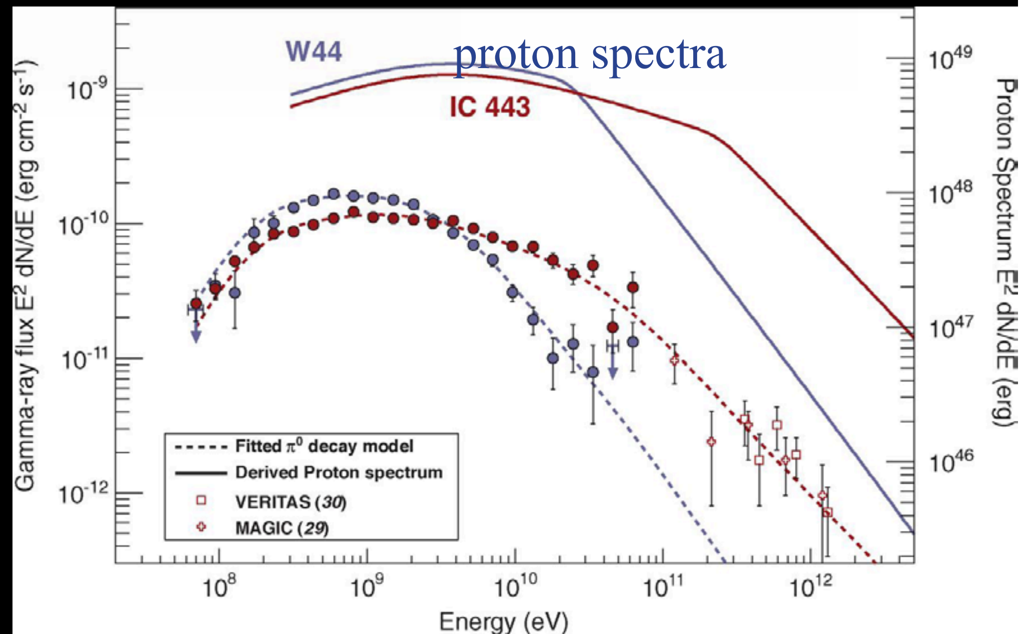
W44

2 − 10 GeV

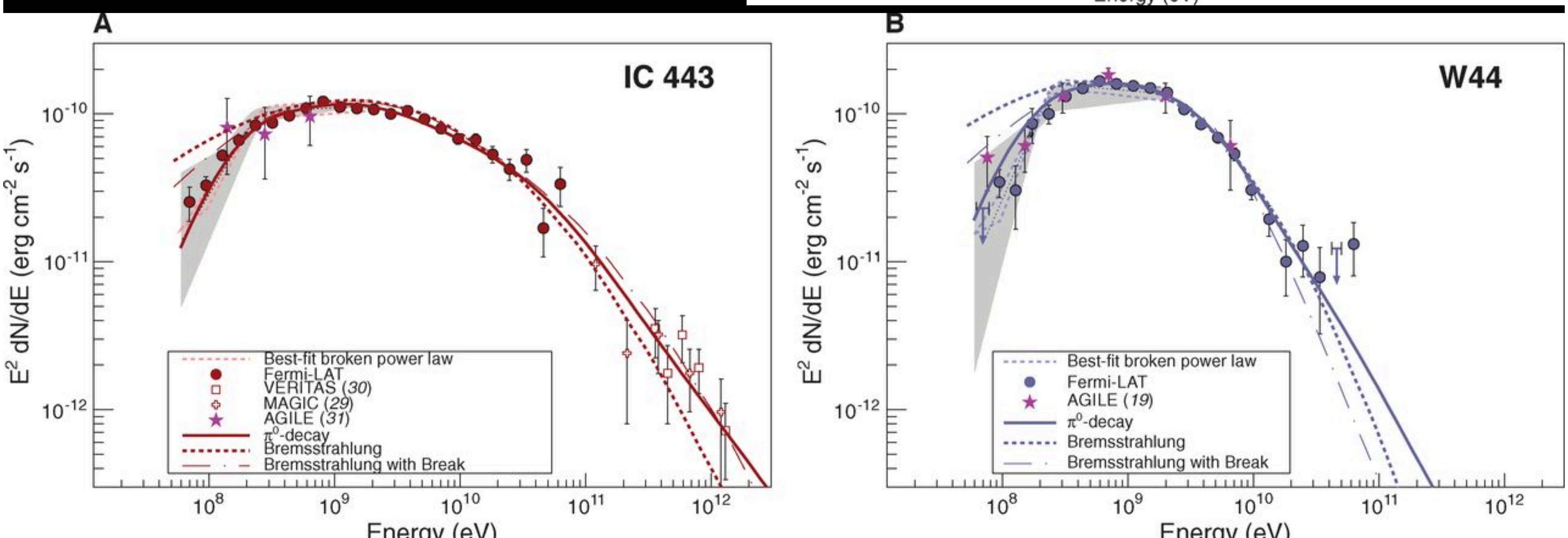


Abdo+2010

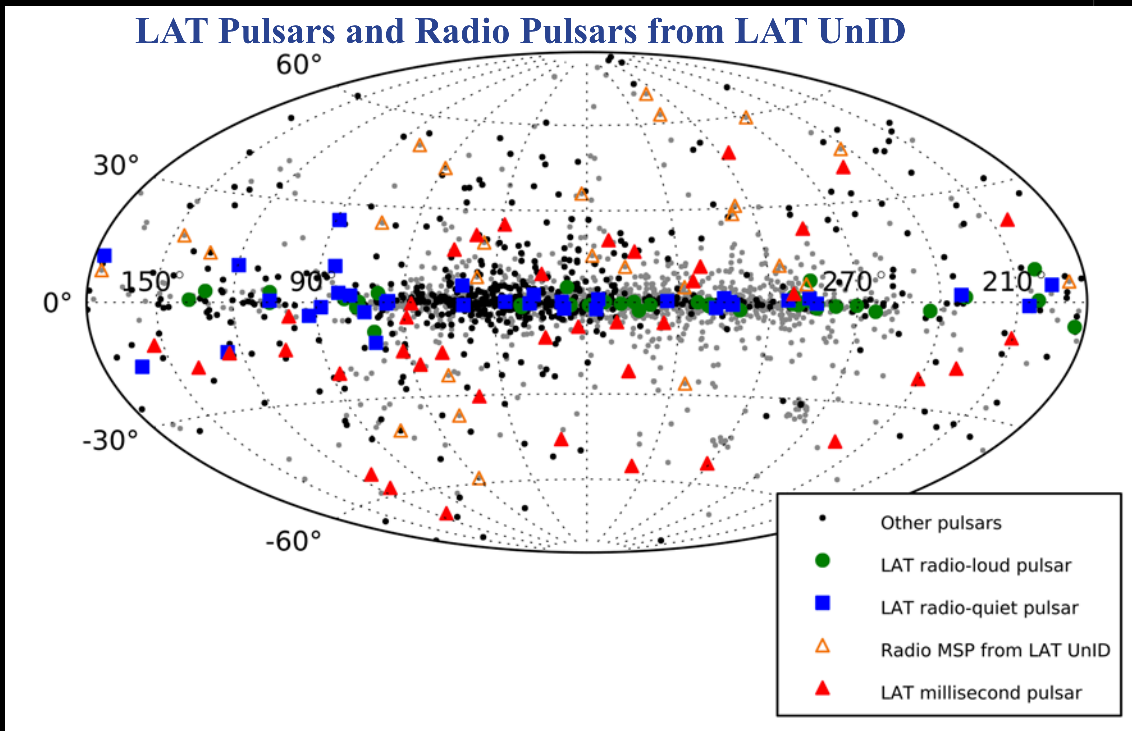
Fermi-LAT spectra of IC443 & W44: π^0 decay γ-rays

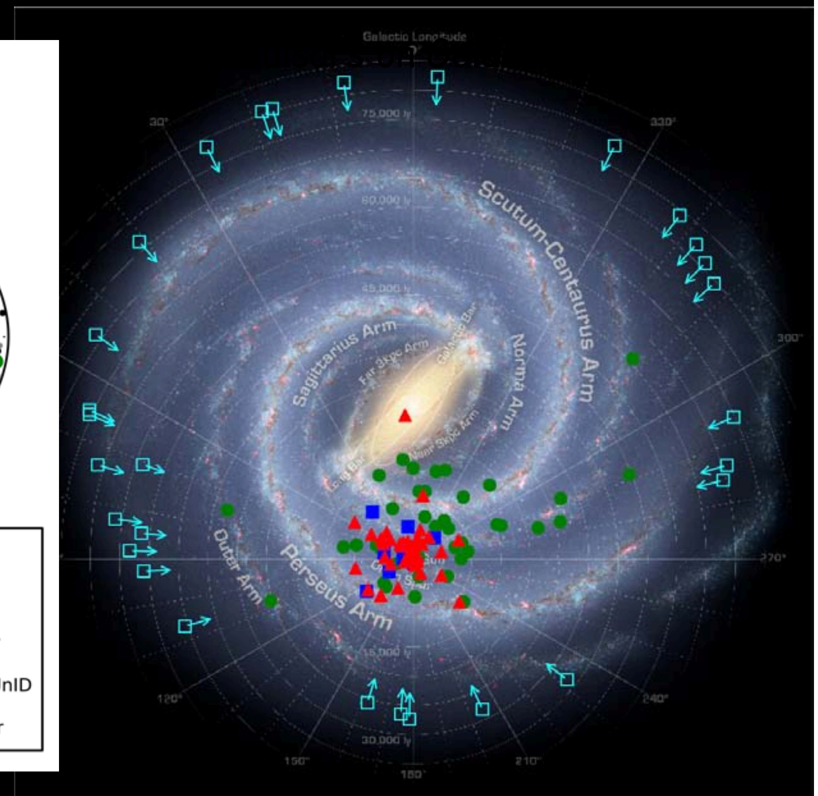


- Low-energy cut off at half the π^0 mass
- Clear evidence for SNR as hadronic acceleration sites



2nd Fermi-LAT pulsar catalog





- 117 pulsars at >100 MeV: MSP, young radio-loud, young radio-quiet
- Millisecond pulsars are very stable and can be used as clocks
- Some MSP are being tracked by NANOGRAV gravity wave search team

Pulsars Populations: 2PC Catalog

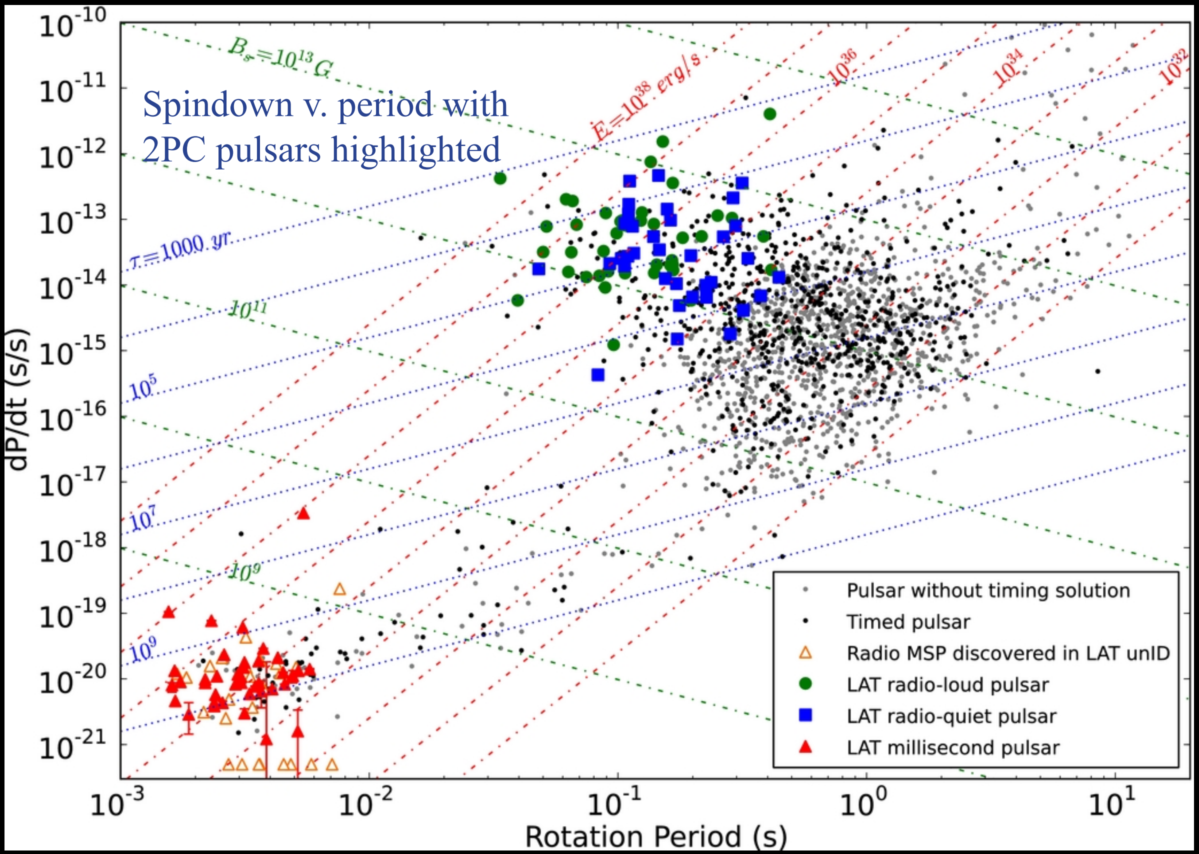
Only 7 γ-ray pulsars known pre-Fermi, now we have >117

77 young pulsars:

- ~50% are radio quiet

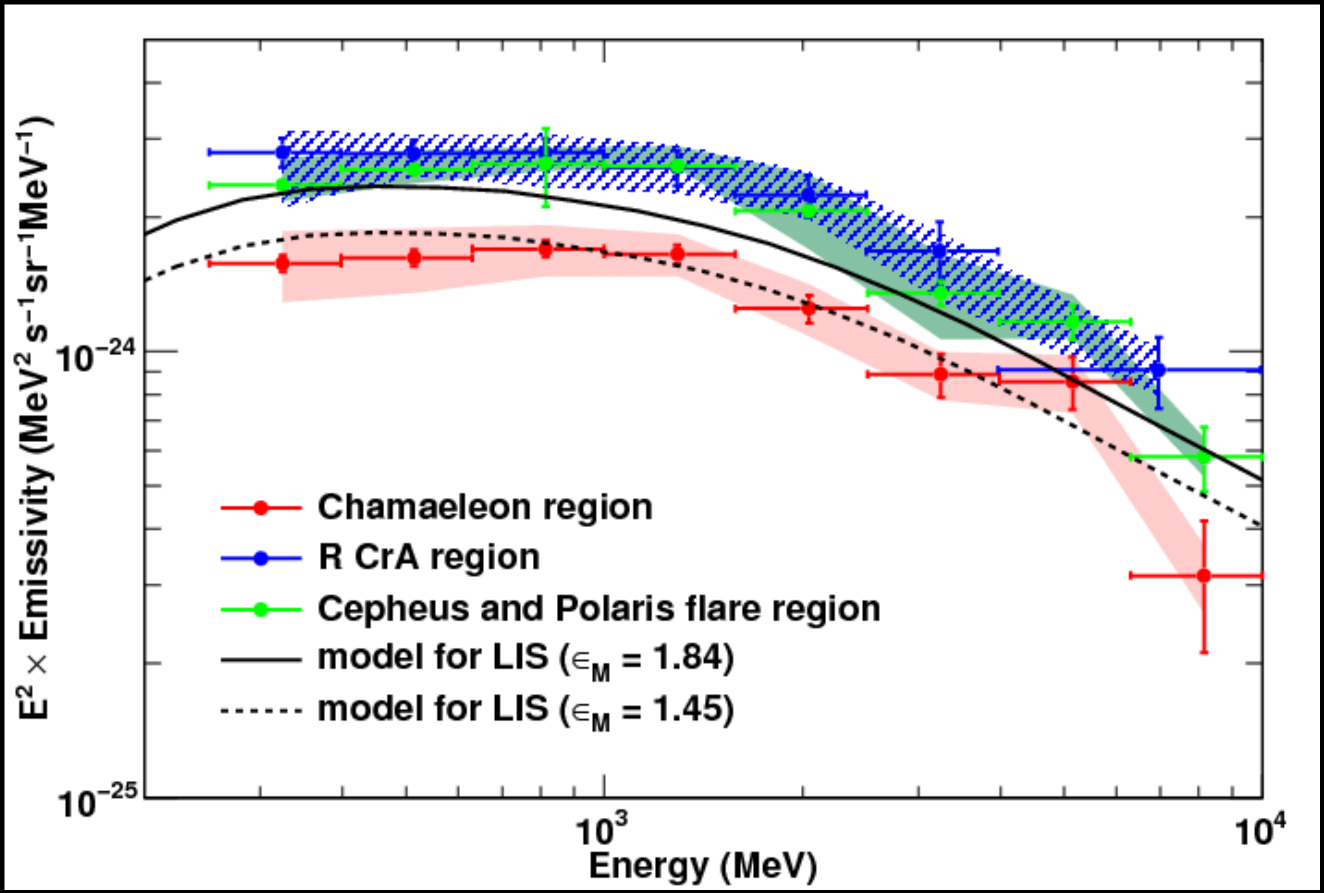
40 millisecond pulsars:

- 1 radio faint first seen in γ-rays
- 2 MSP in globular clusters



- Radio and γ ray fluxes are largely uncorrelated
  - Fermi UNID sources are excellent targets for radio pulsation searches
  - Many MSPs are found this way

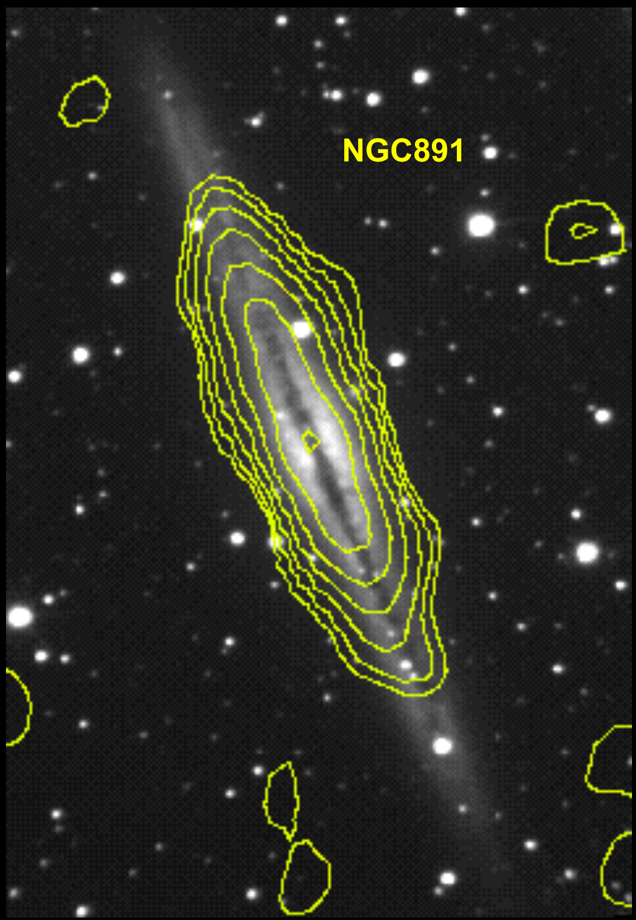
Local emissivities



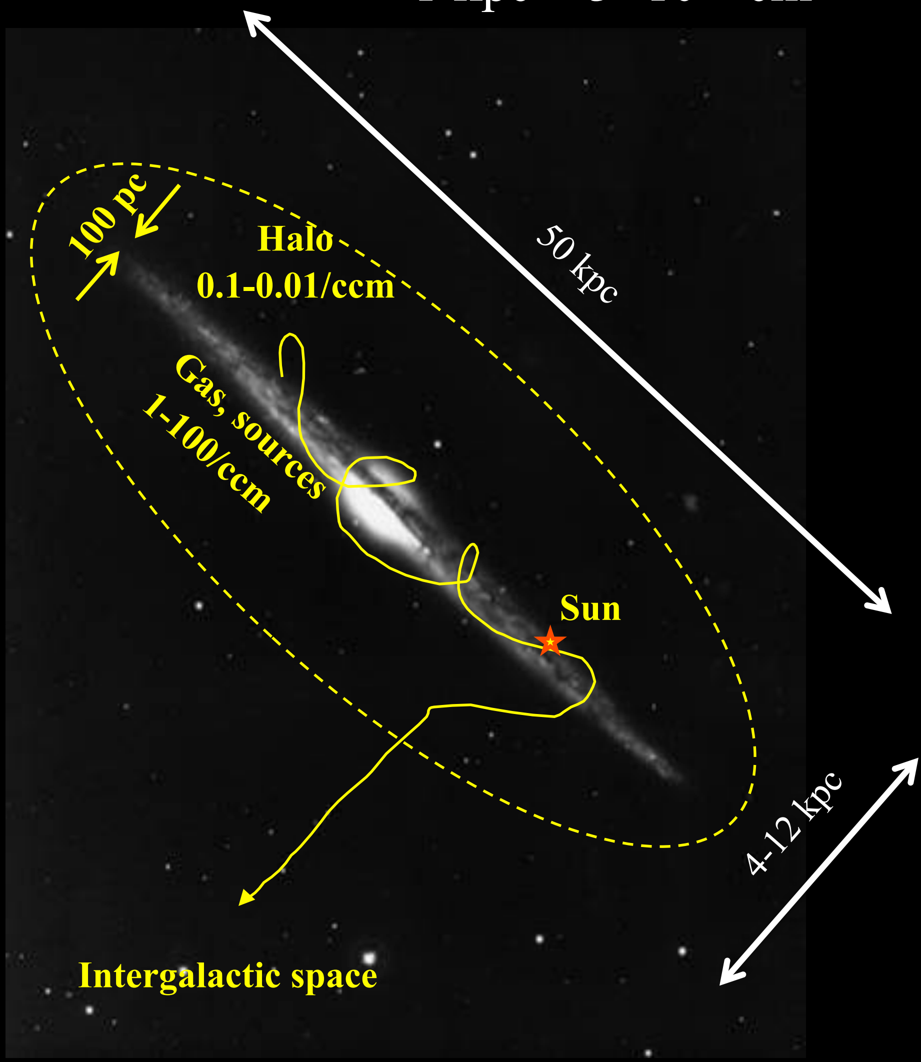
- ✧ Local gamma-ray emissivities derived from observations of the local gas clouds are consistent with the direct CR measurements
- ✧ Show intensity variations due to errors in gas mass estimates, gas composition, or true CR intensity variations

CR Propagation: Milky Way Galaxy

1 **k**pc ~ 3×10^{21} cm



R Band image of NGC891
1.4 GHz continuum (NVSS), 1,2,…64 mJy/ beam



"Flat halo" model (Ginzburg & Ptuskin 1976)

Transport Equations ~90 (no. of CR species)

$$\frac{\partial\psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p)$$ sources (SNR, nuclear reactions…)

diffusion $$+\vec{\nabla}\cdot[D_{xx}\vec{\nabla}\psi - \vec{V}\psi]$$

diffusive reacceleration
(diffusion in the momentum space) $$+\frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\frac{\psi}{p^2}\right]$$

convection
(Galactic wind)

E-loss $$-\frac{\partial}{\partial p}\left[\frac{dp}{dt}\psi - \frac{1}{3}p\vec{\nabla}\cdot\vec{V}\psi\right]$$

fragmentation $$-\frac{\psi}{\tau_f} - \frac{\psi}{\tau_d}$$ radioactive decay

+ boundary conditions

ψ(r,p,t) *– density per total momentum*

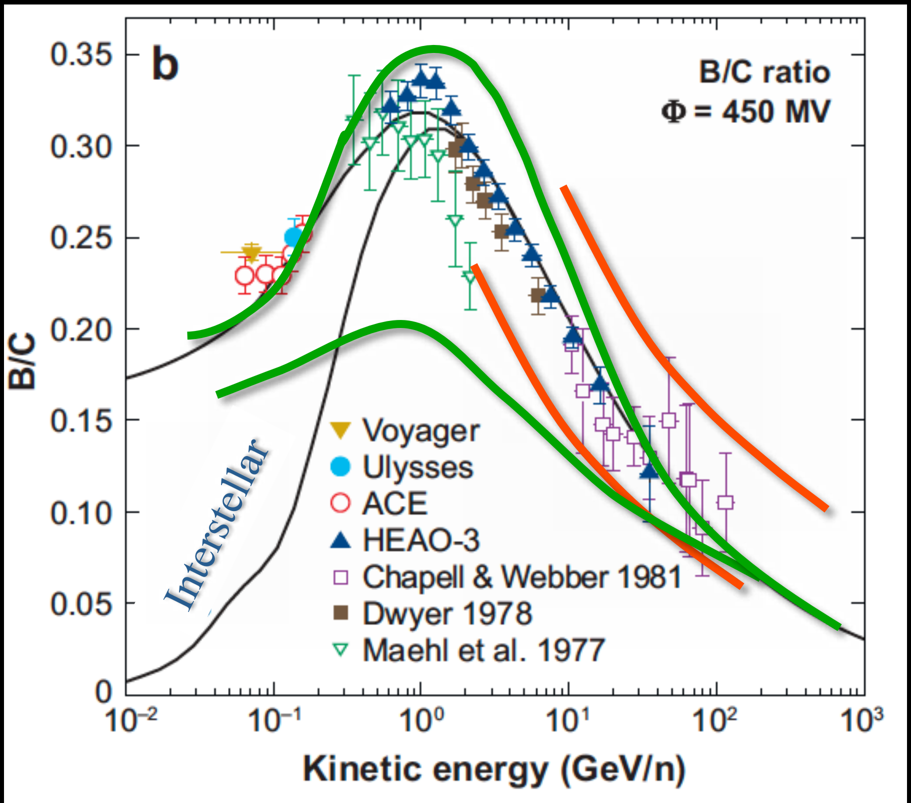
Secondary/primary nuclei ratio & CR propagation

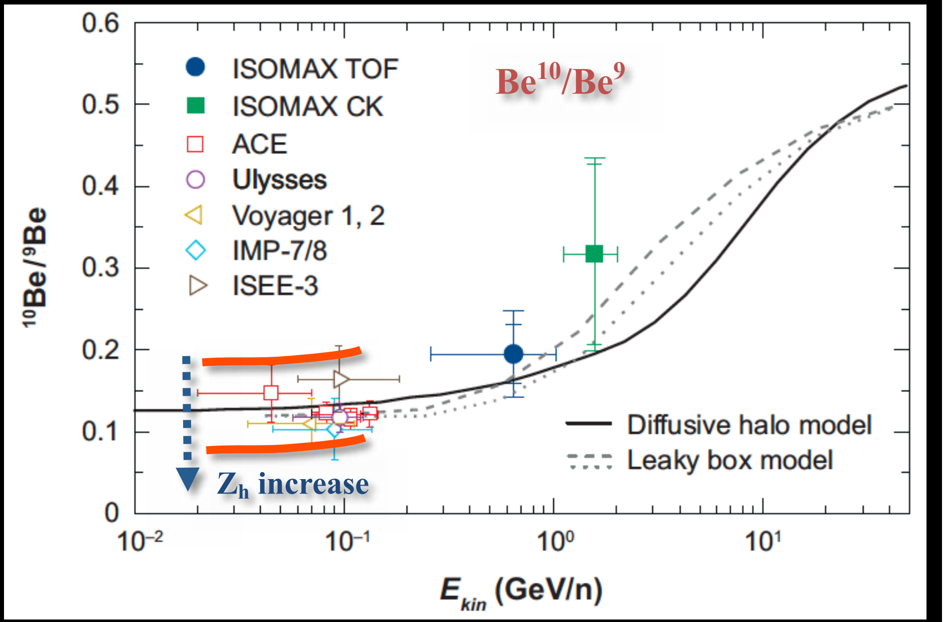
Typical parameters (model-dependent):

$D \sim 10^{28} (\rho/1\ GV)^{\alpha}\ cm^2/s$

$\alpha \approx 0.3\text{-}0.6$

$Z_h \sim 4\text{-}6$ kpc; $V_A \sim 30$ km/s

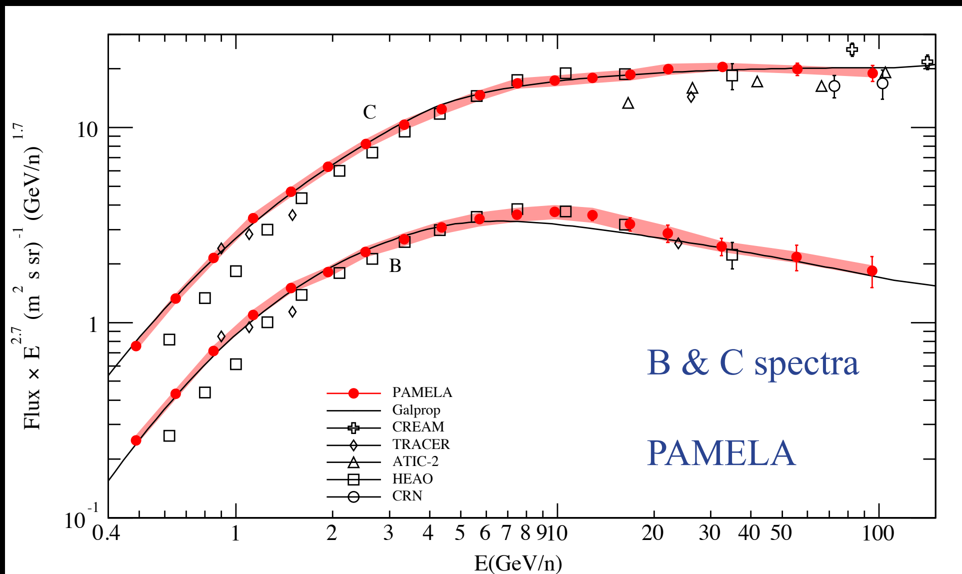


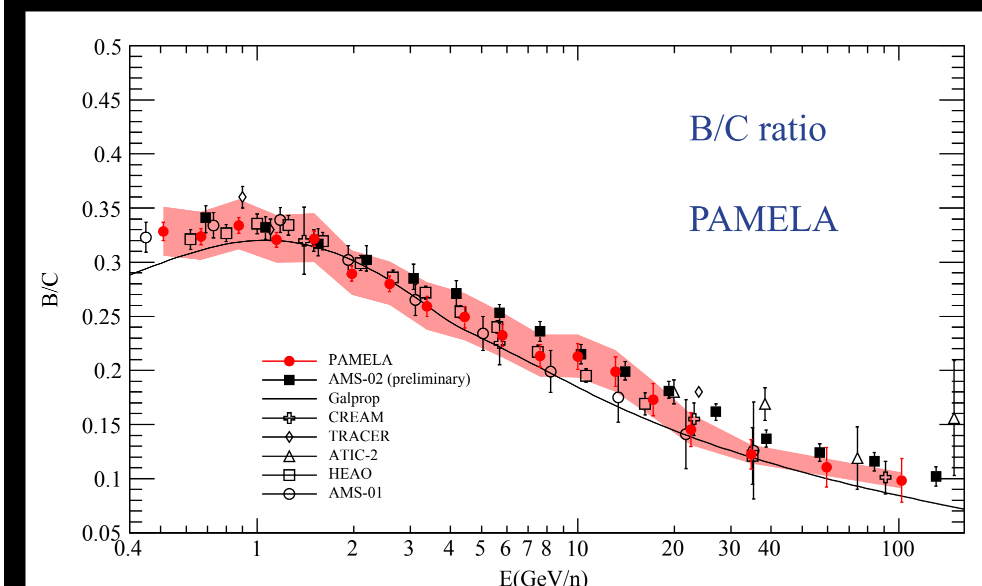


Using secondary/primary nuclei ratio (B/C) & radioactive isotopes (e.g. Be^{10}):

- ✧ Diffusion coefficient and its index
- ✧ Galactic halo size Z_h
- ✧ Propagation mode and its parameters (e.g., reacceleration V_A, convection V_z)
- ✧ Propagation parameters are model-dependent

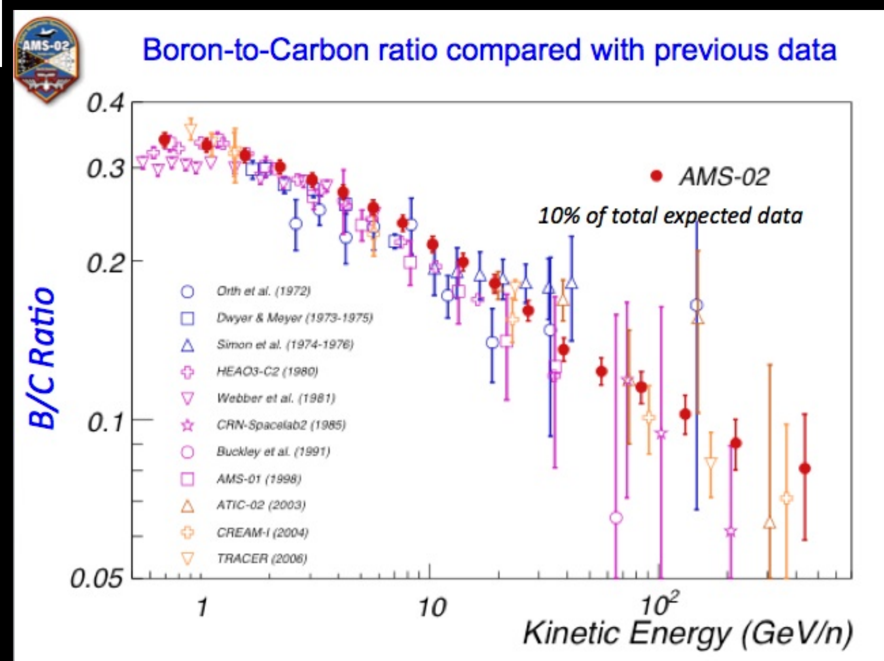
New measurements of B/C ratio





PAMELA fit to the B/C ratio

- ✧ Used GALPROP
- ✧ Parameters from Vladimirov+'2012
- ✧ Best fit index of the diffusion coefficient: $\delta = 0.4$
- ✧ No significant spectral features <400 GeV/n (AMS-02)

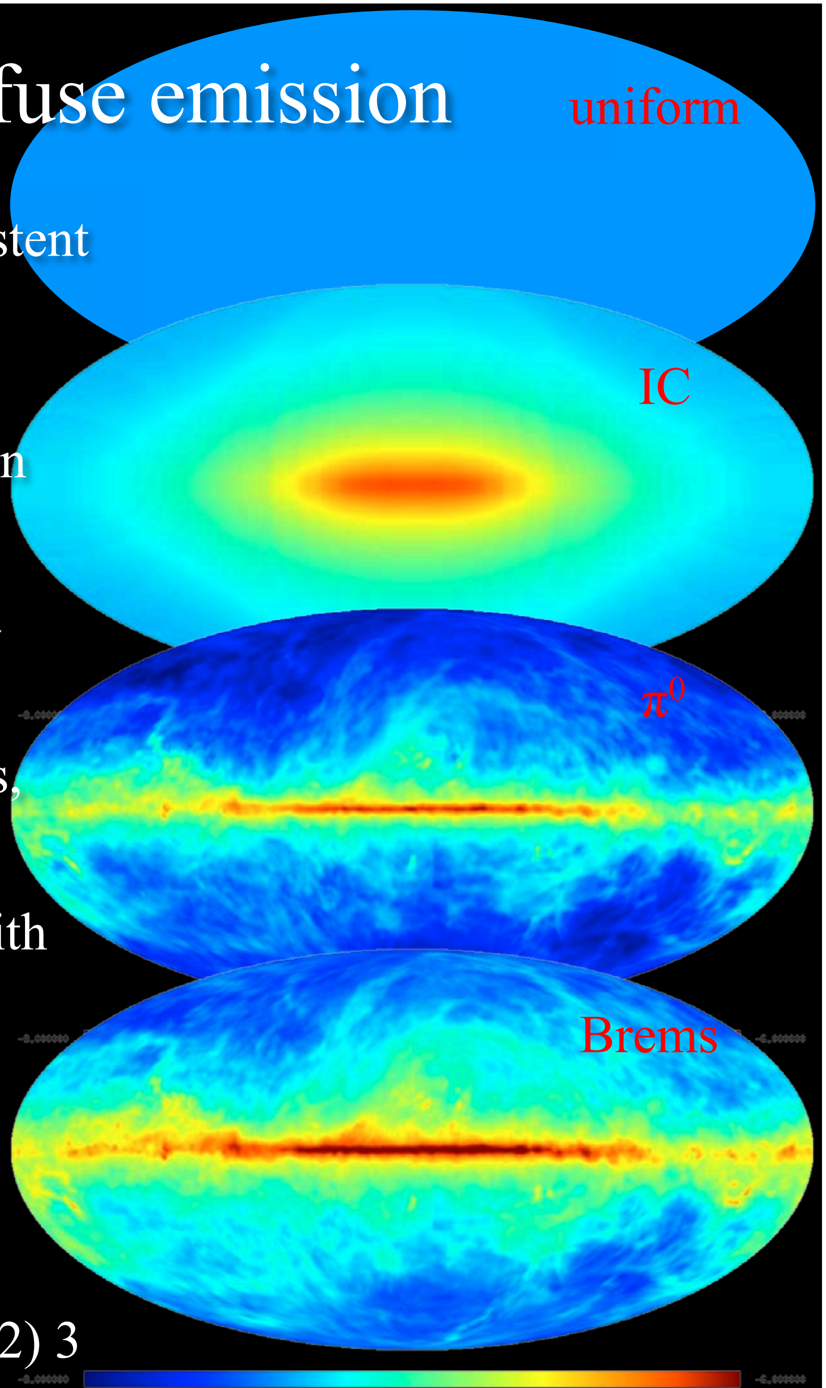


Components of GALPROP

- Detailed gas distribution from HI and CO gas surveys (energy losses from ionization, bremsstrahlung; secondary production; γ-rays from π^0-decay, bremsstrahlung)
- Interstellar radiation field (inverse Compton losses/γ-rays for $e^{\pm}$)
- B-field model
- Nuclear & particle production cross sections + the reaction network (cross section database + LANL nuclear codes + phenomenological codes)
- Cosmic ray source distribution(s)
- Propagation, diffusive acceleration, convection
- Numerically solve transport equations for all cosmic ray species (stable + long-lived isotopes + pbars + leptons ~90) in 2D or 3D
- Derive the propagation parameters corresponding to the assumed transport phenomenology and source distribution

Large scale study of the diffuse emission

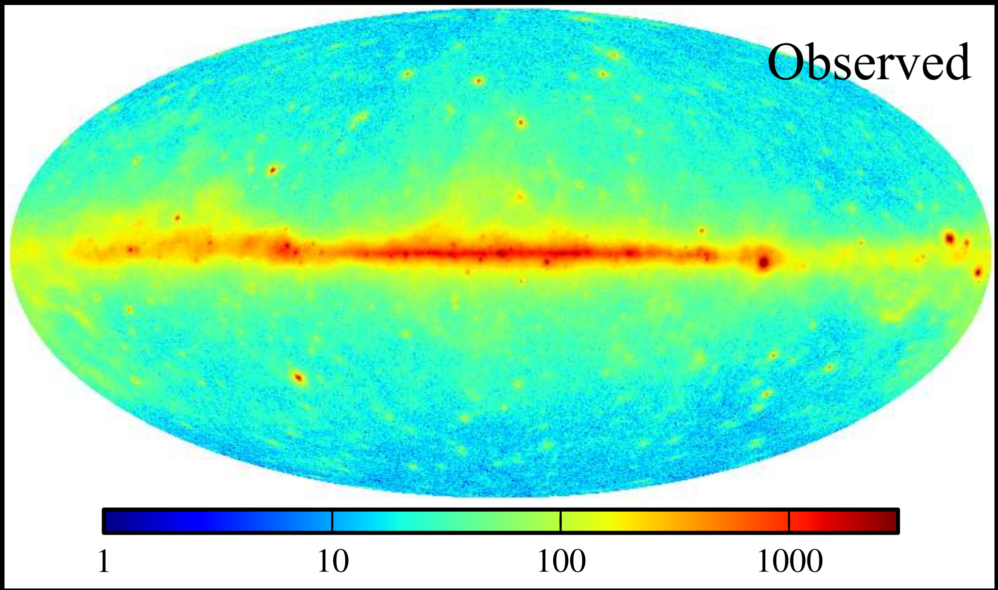
- ✧ "Conventional model": CR spectra are consistent with local measurements (CR nuclei, Fermi electrons)
- ✧ GALPROP code with diffusion-reacceleration model for CR propagation
- ✧ Propagation parameters - fixed from CR data
- ✧ Grid of 128 models covering plausible confinement volume, CR source distributions,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

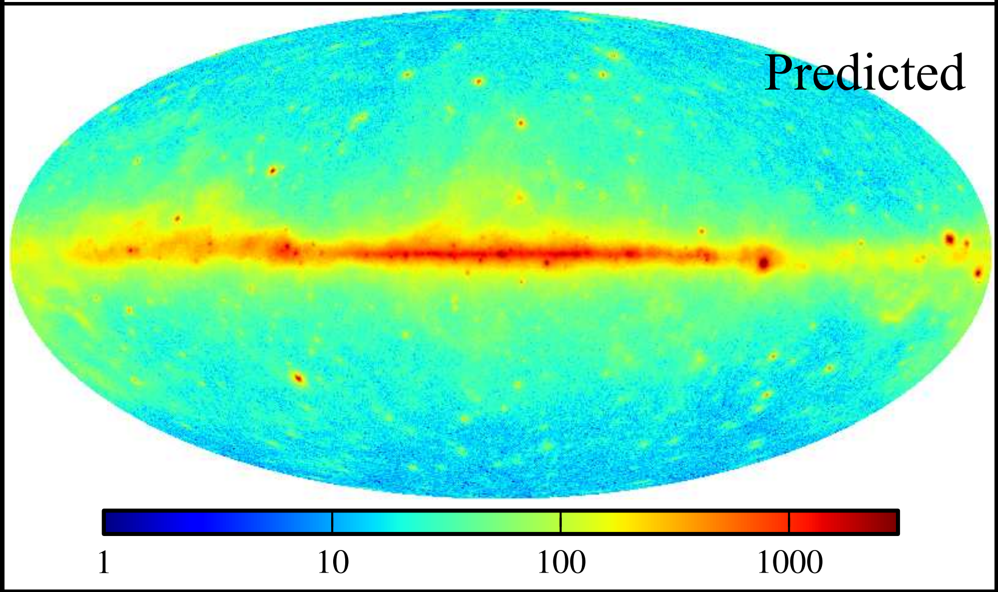


- ✧ A massive Fermi-LAT study – ApJ 750 (2012) 3

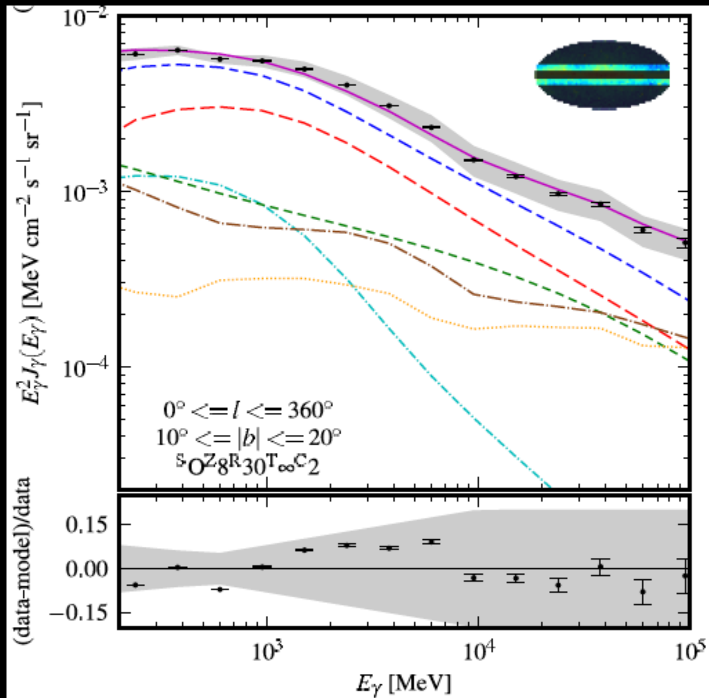
Diffuse emission skymap

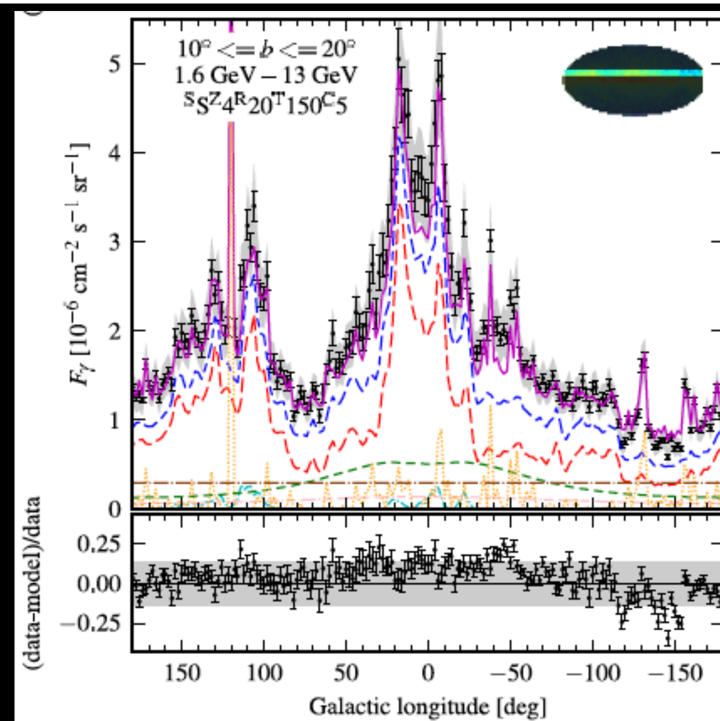
- ✧ Observed Fermi-LAT counts in the energy range 200 MeV to 100 GeV
- ✧ Predicted counts calculated using GALPROP reacceleration model tuned to CR data
- ✧ Residuals (Obs-Pred)/Obs ~ % level, ~10% in some places

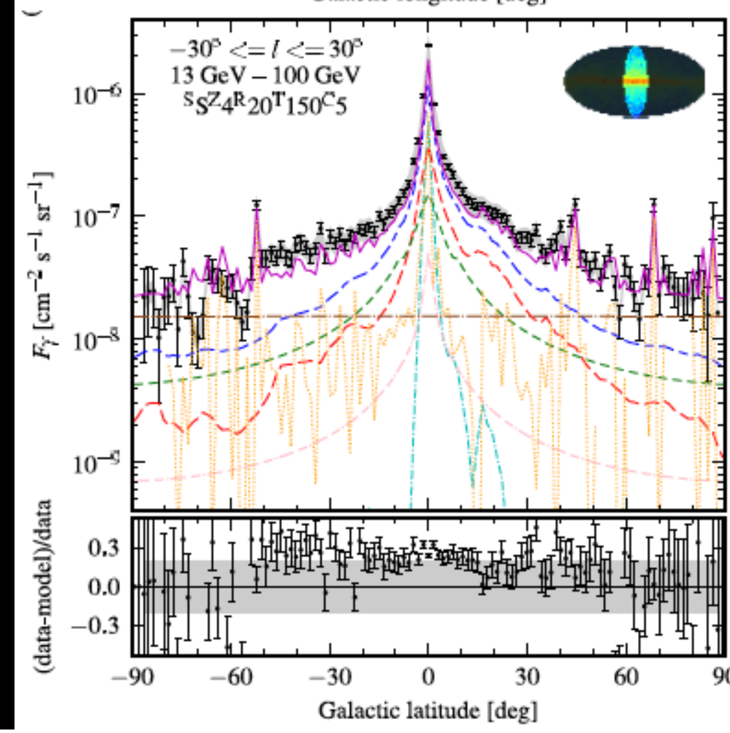




Spectrum and profiles

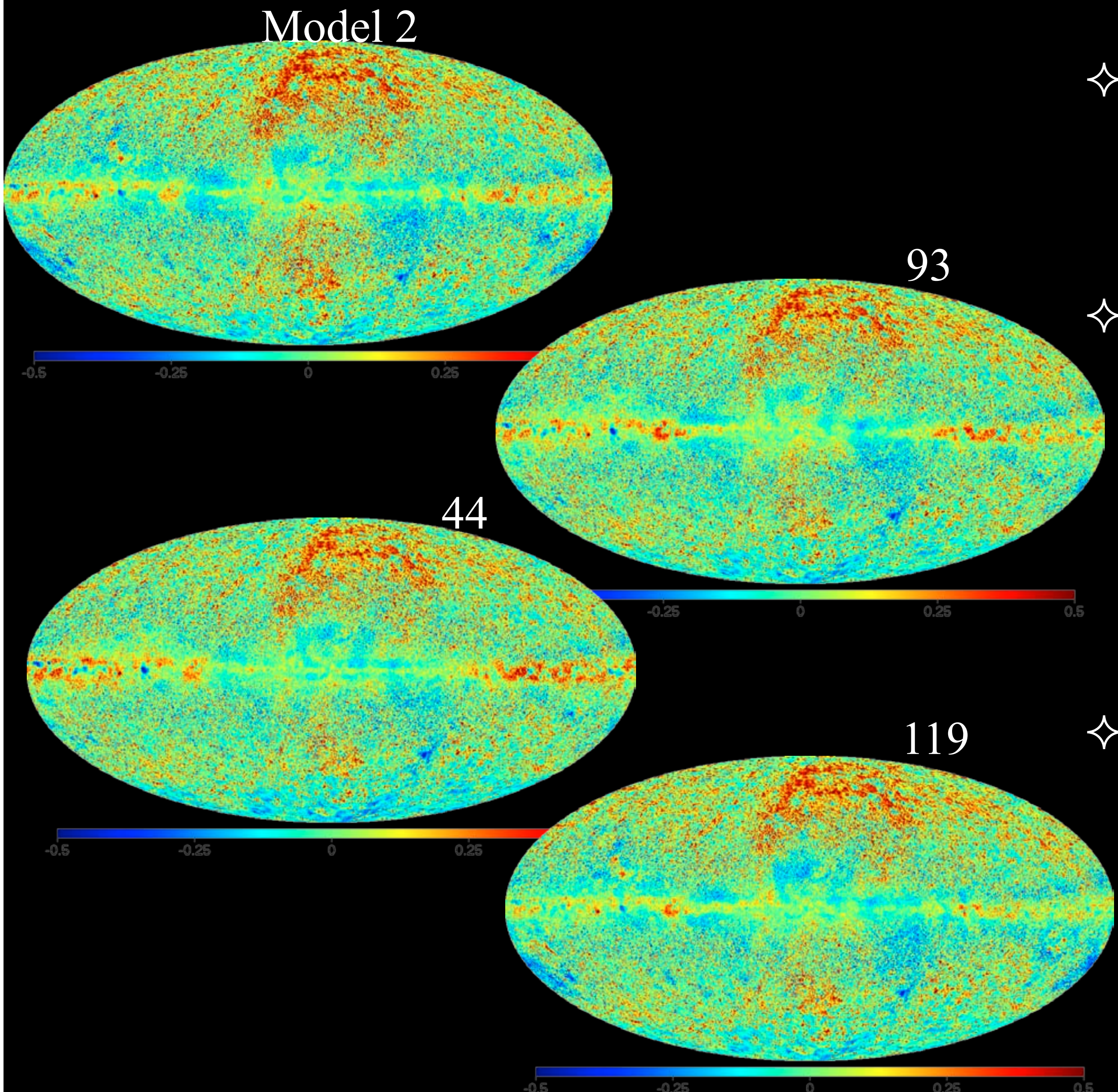






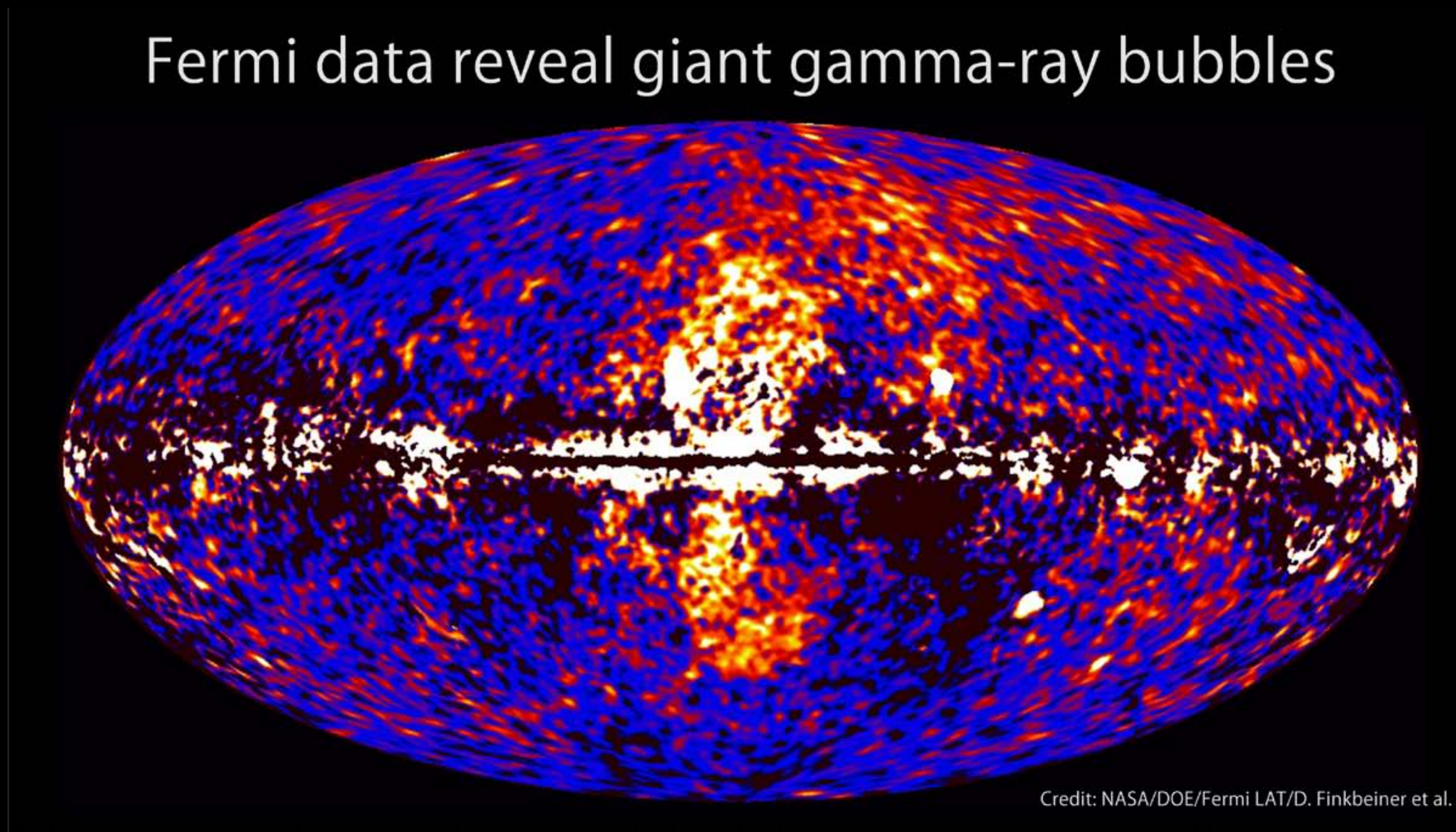
- ✧ Components of the model
  - ✦ Neutral pion emission from gas H_2, HI, HII
  - ✦ Inverse Compton
  - ✦ Bremsstrahlung
  - ✦ Detected sources
  - ✦ Isotropic emission

Large scale study: residuals



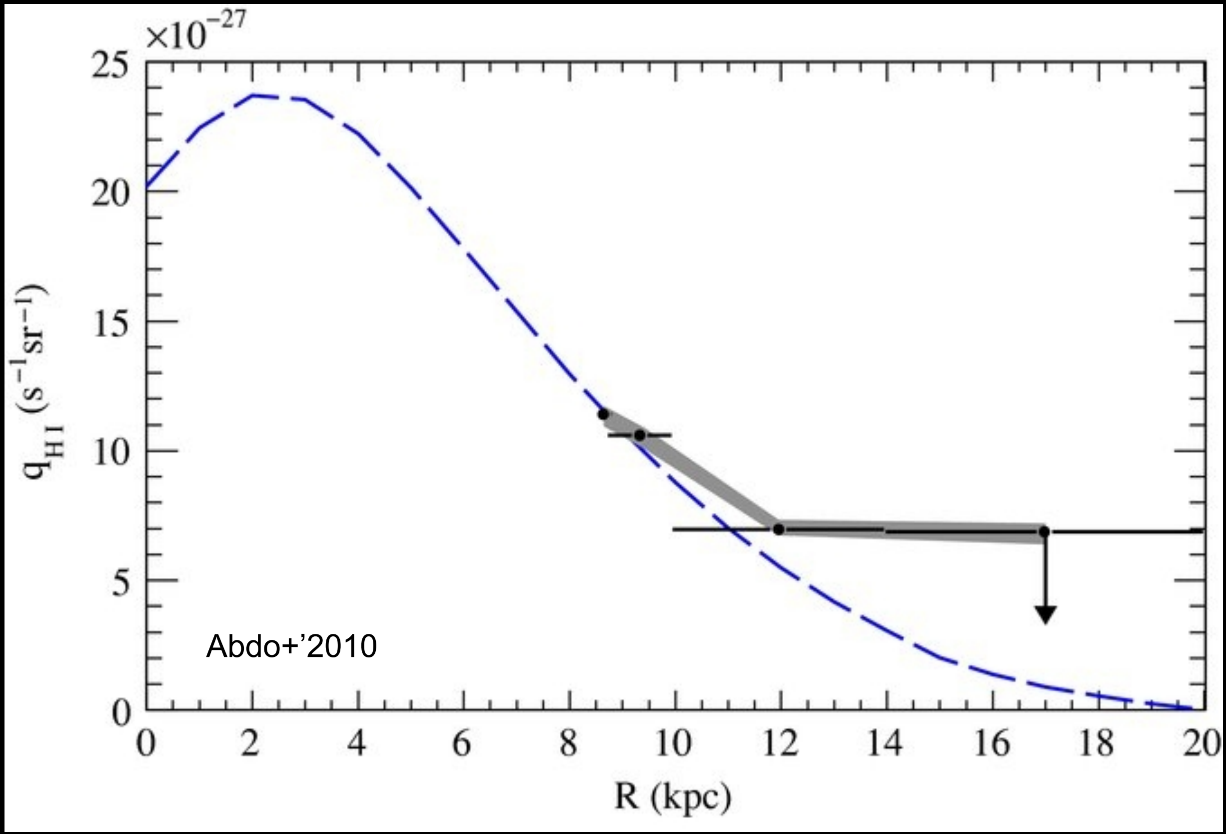
- ✧ Agreement for models is overall good, but features are visible in residuals at ~% level
- ✧ Difference between illustrative models shown in right maps : structure due to variations of model parameters
- ✧ Models details:
  2: $\mathrm{SNR}^{Z}4^{R}20^{T}150^{C}5$
  44: $\mathrm{Lorimer}^{Z}6^{R}20^{T}\infty^{C}5$
  93: $\mathrm{Yusifov}^{Z}10^{R}30^{T}150^{C}2$
  119: $\mathrm{OB}^{Z}8^{R}30^{T}\infty^{C}2$

NASA press release



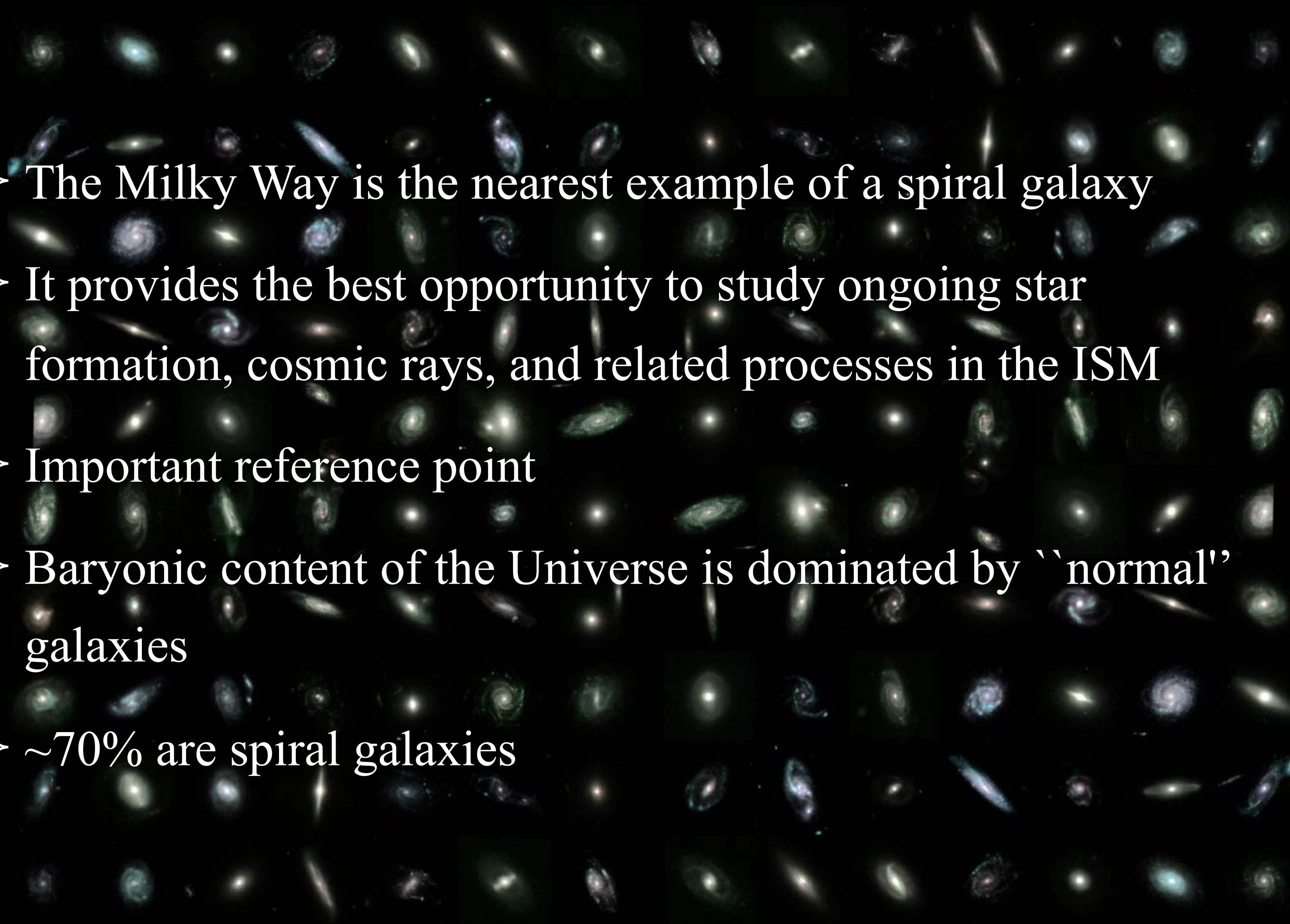
- ✧ Discrepancies between the physical model and high-resolution data (residuals) are the gold mines of new phenomena!
- ✧ Every extended source and/or process that is not included into the model pops up and exposes itself as a residual

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.

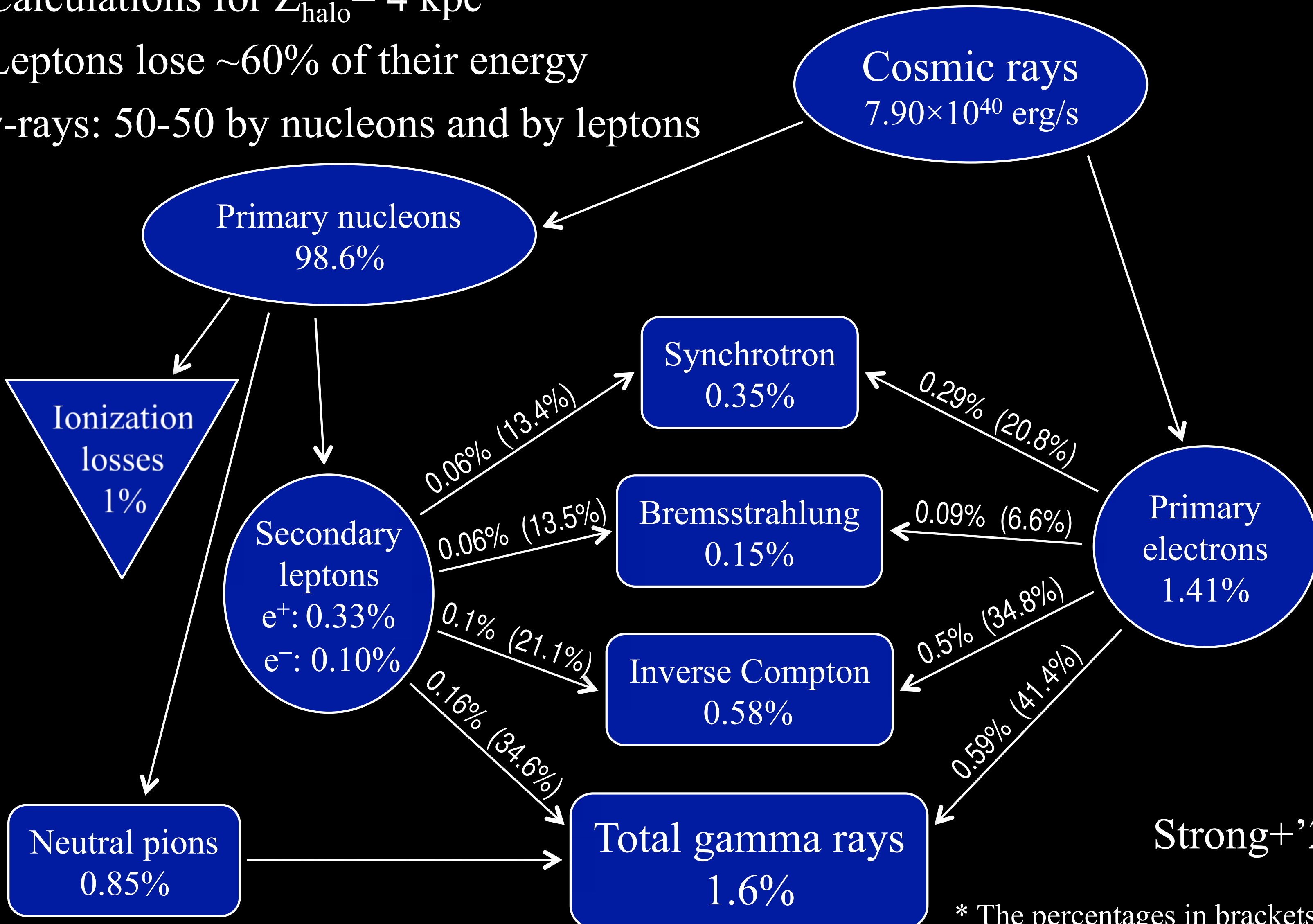
Milky Way in the global picture



- ✧ 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

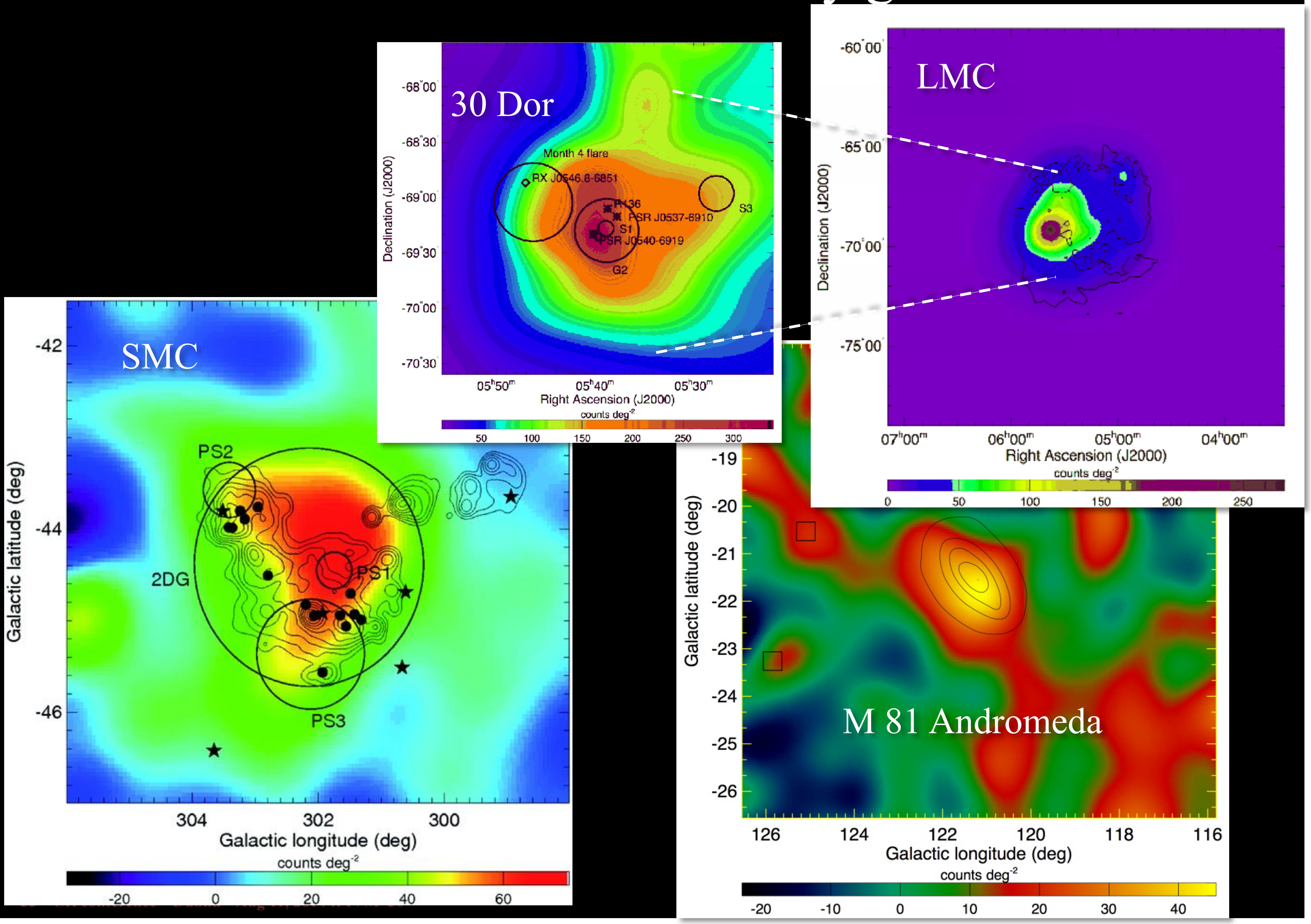
- Calculations for Z_{halo}= 4 kpc
- Leptons lose ~60% of their energy
- γ-rays: 50-50 by nucleons and by leptons



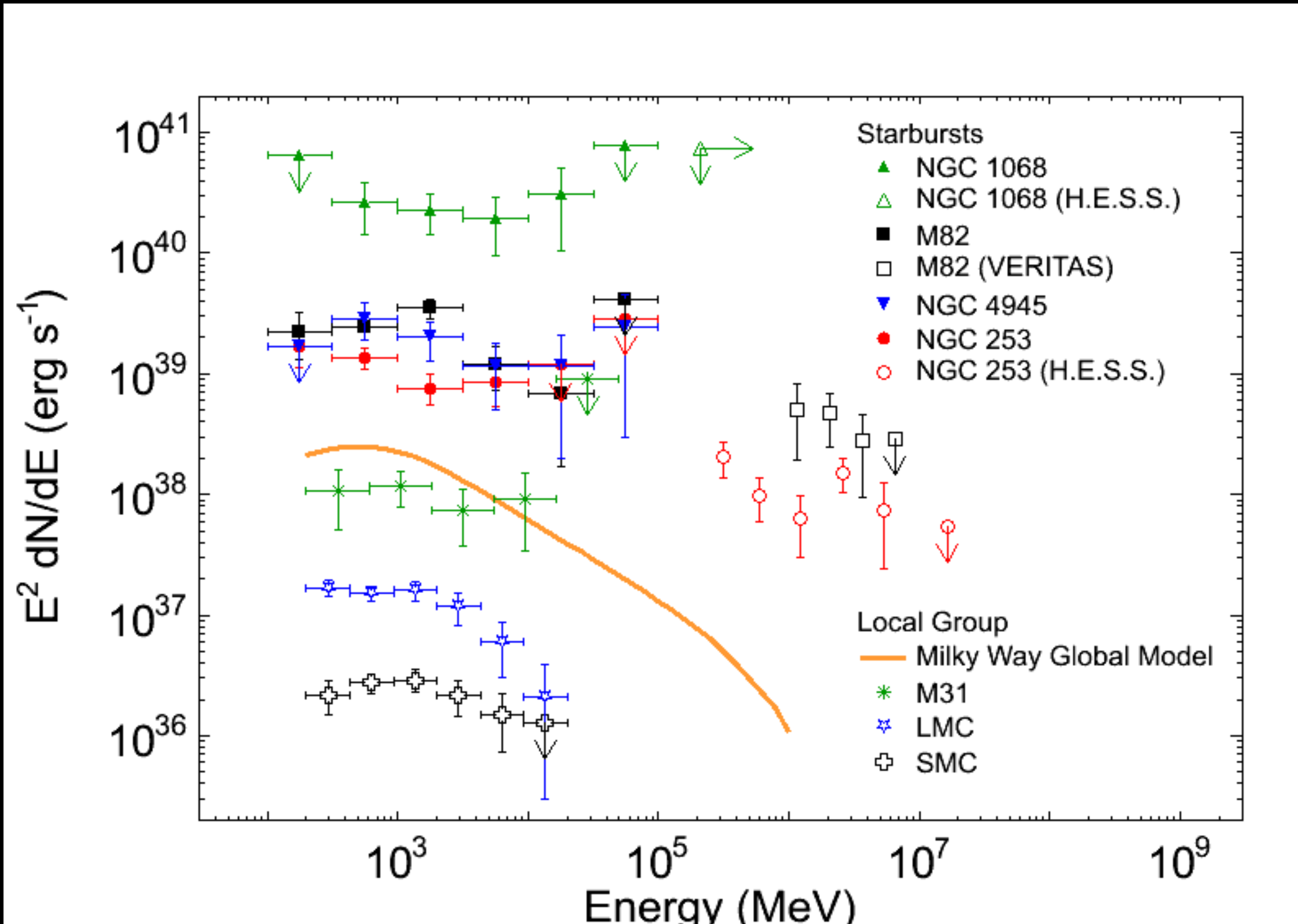
Strong+'2011

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

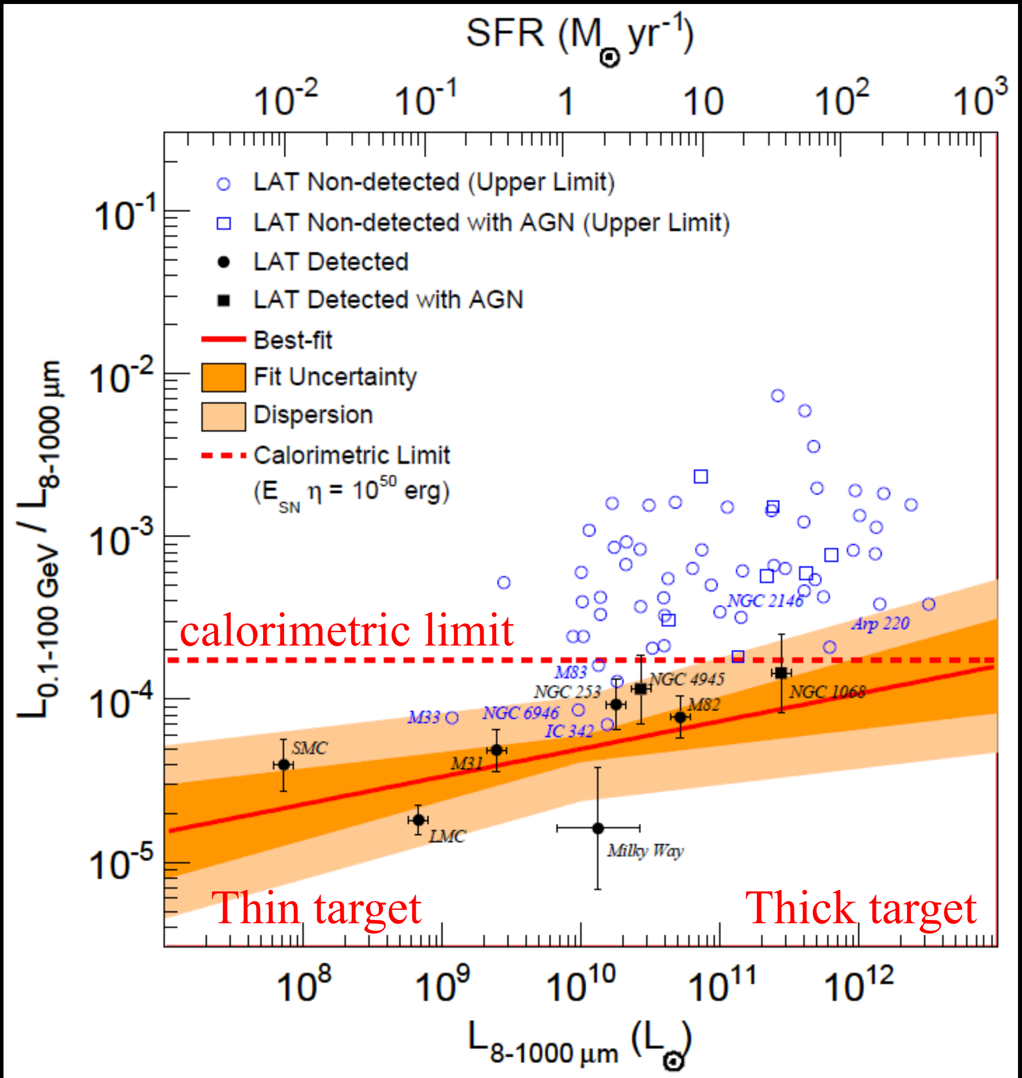
Fermi-LAT observations of nearby galaxies



Starforming Galaxies

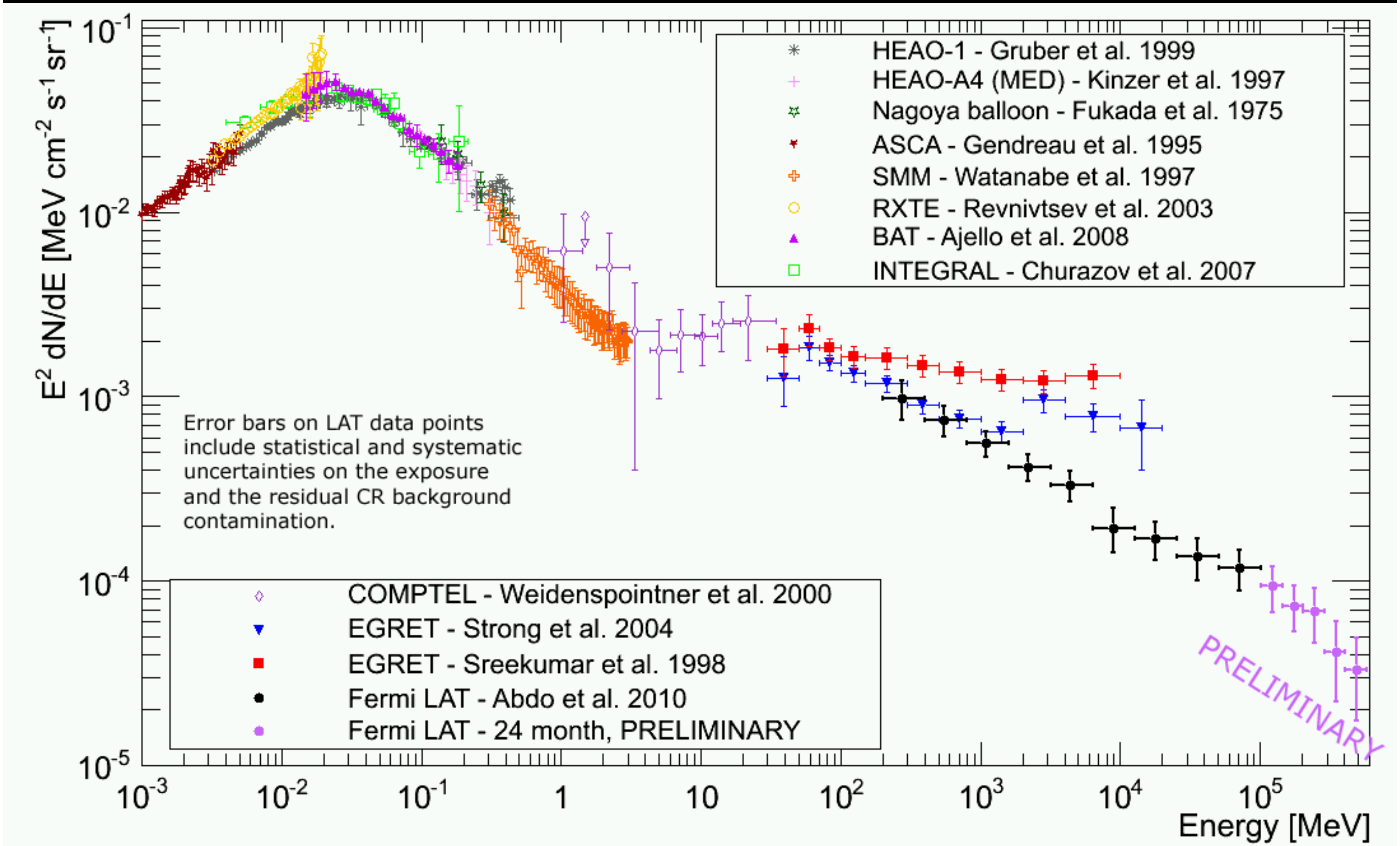


Cosmic Rays as a Universal Phenomenon

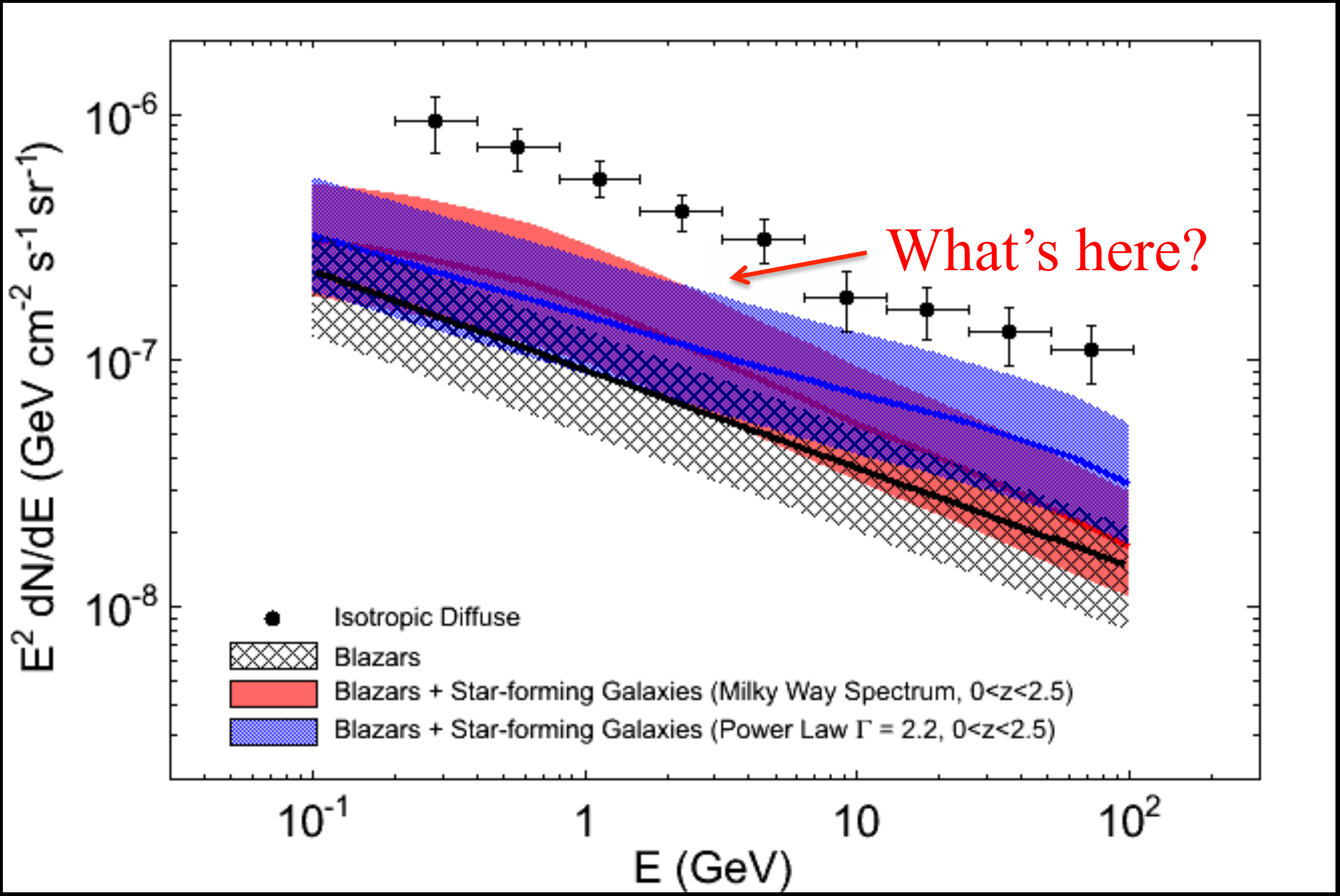


- γ-ray luminosity vs. IR luminosity for normal galaxies detected with Fermi-LAT
- The γ-ray luminosity scales linearly (index ~1.1) with the total emission of hot stars reprocessed by dust – a tracer of star formation
- The ratio approaches the calorimetric limit in star-burst galaxies
- An evidence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

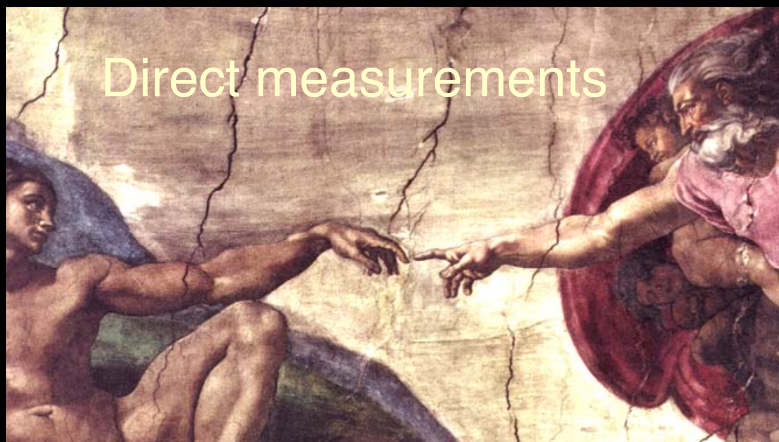
Spectrum and Origin of the Isotropic Background



Origin of the Isotropic Background

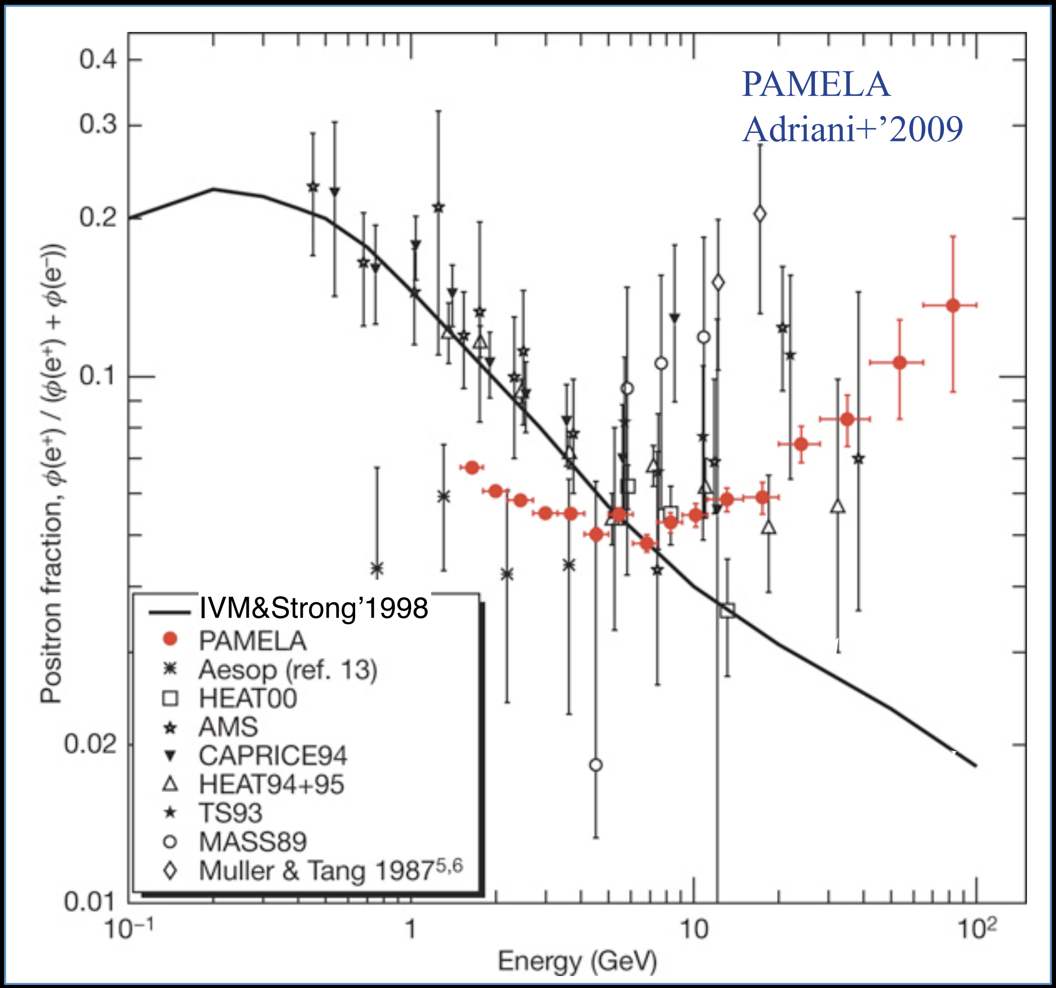


Galactic cosmic rays in the solar system



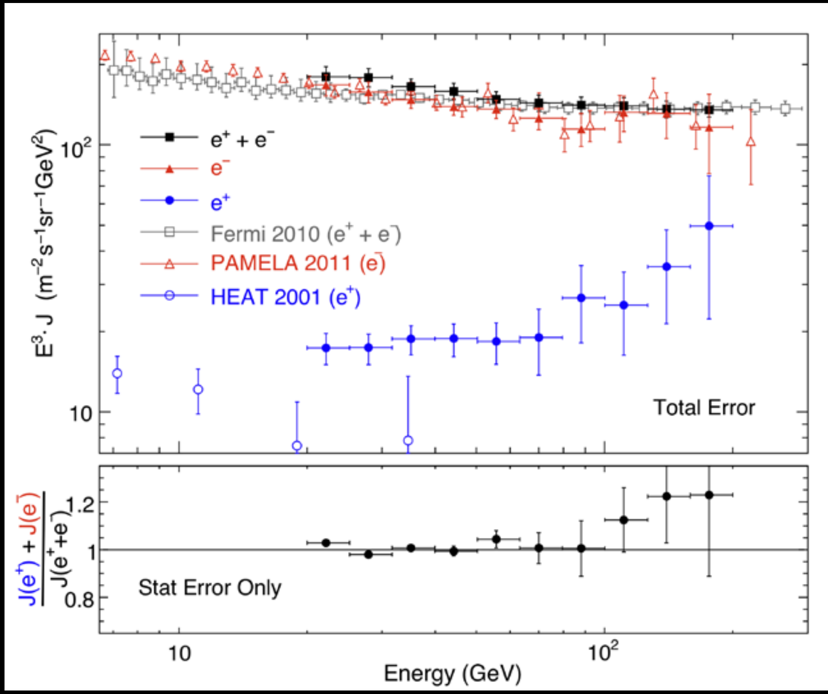
- Allows to reconcile direct & indirect observations
  - Test models of interactions
  - Calibration of the instrument
- Detected sources:
  - The Earth (PRD 80, 122004, 2009)
    - The limb
    - Terrestrial γ-ray flashes
  - The Moon (ApJ 758, 140, 2012)
  - The steady Sun (ApJ 734, 116, 2011)
  - Solar flares
- Potential sources (in progress):
  - Main Belt rocks & dust
  - Jovian & Neptunian Trojans
  - Kuiper Belt rocks & dust
  - Oort Cloud

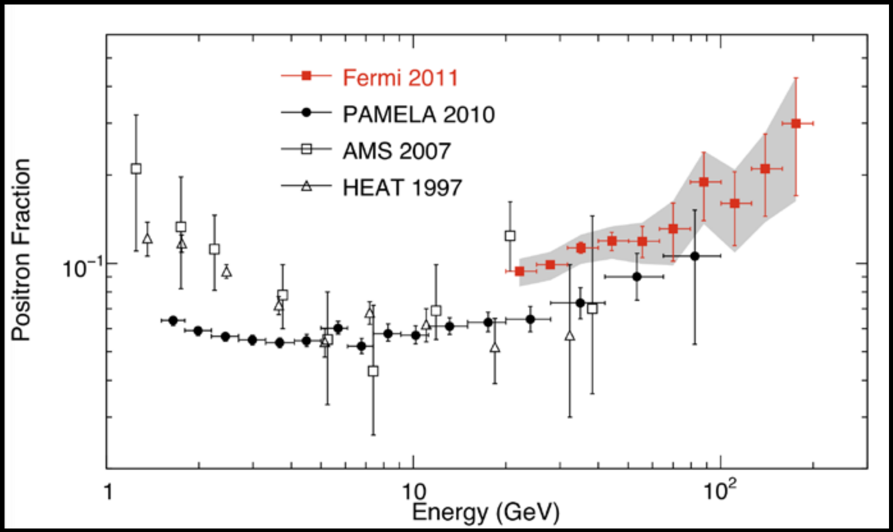
PAMELA data: rising positron fraction

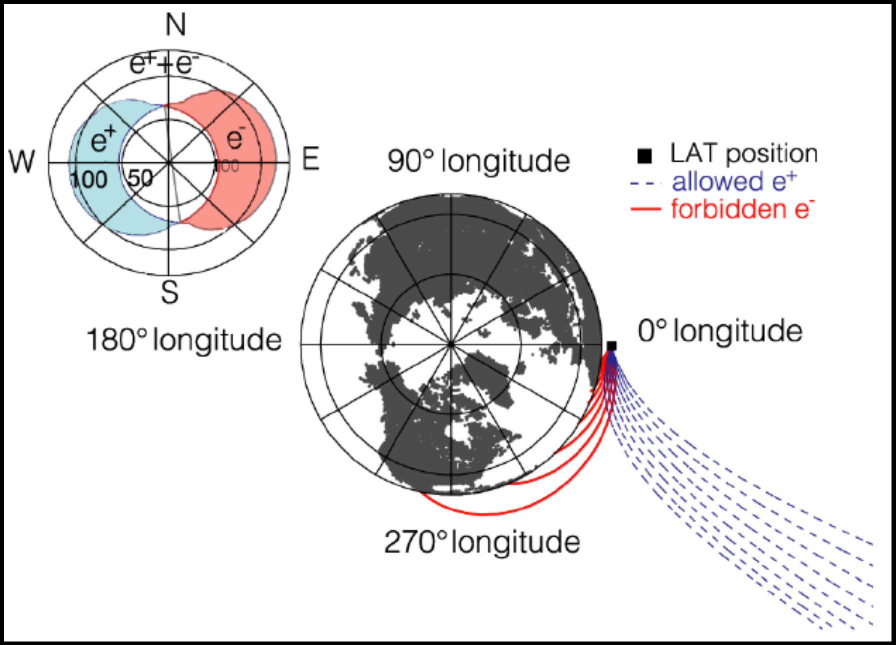


- ✧ PAMELA team reported a rise in the positron fraction compared to the "standard" model predictions
- ✧ "Standard" model:
  - ✦ Secondary production
  - ✦ Steady state
  - ✦ Smooth CR source distribution

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

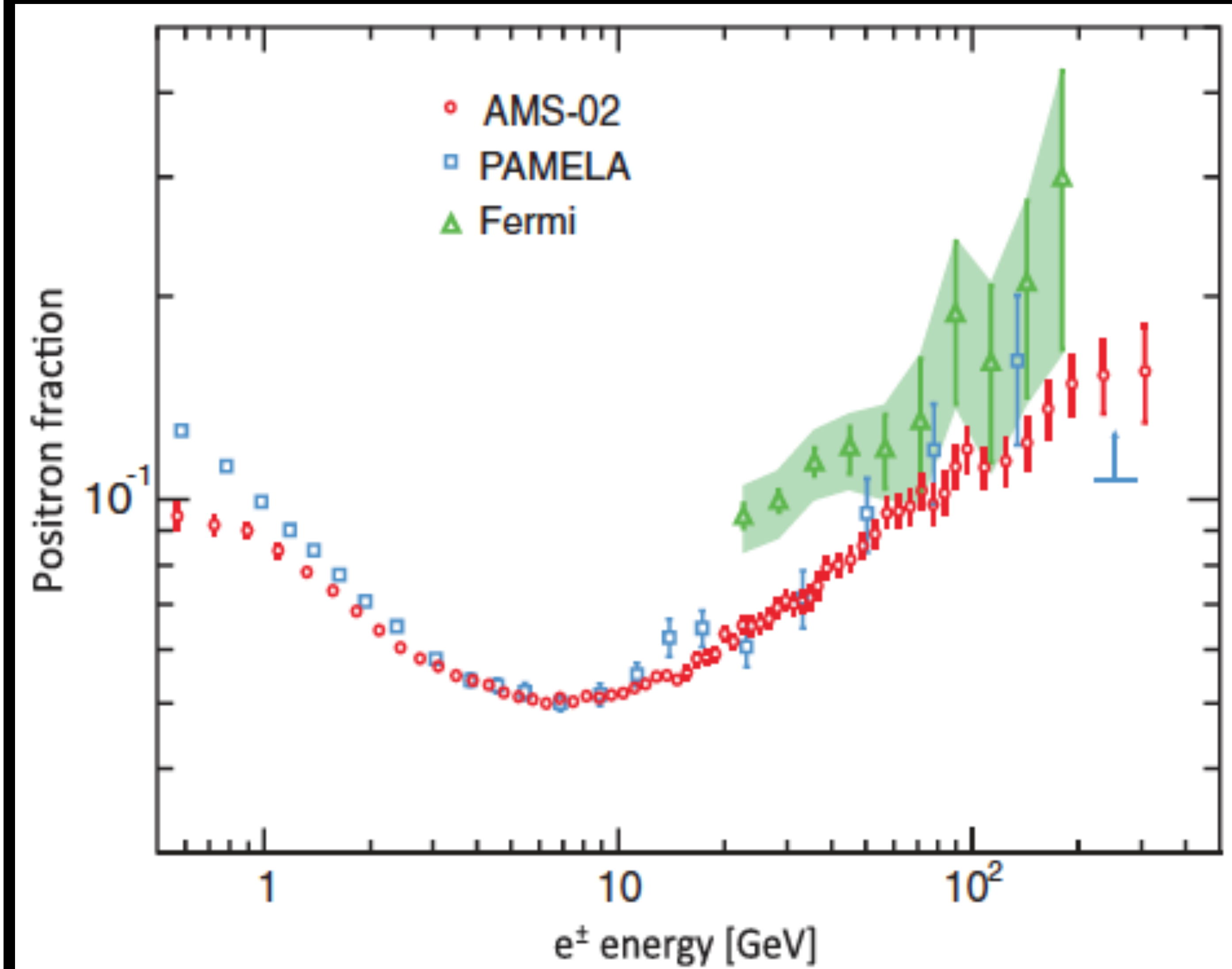






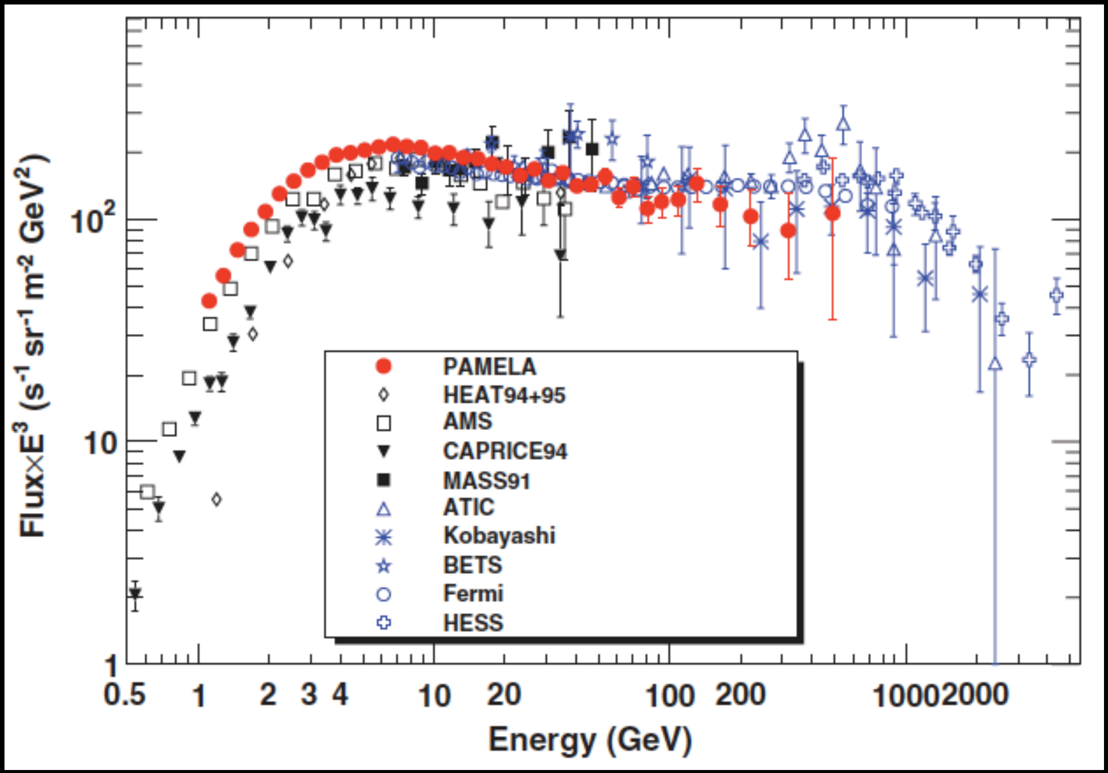
- ✧ Fermi-LAT does not have a magnet, but used geomagnetic field
- ✧ Confirmed rise in the positron fraction
- ✧ Extended measurements up to 200 GeV

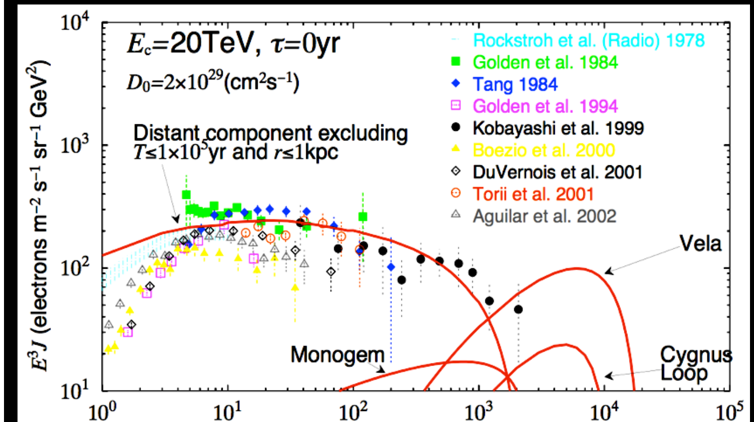
AMS-02: Rise in the positron fraction



- ✧ Asymptotically approaches a const ~0.15-0.2 ?
- ✧ A cut off at HE ?

All-electron spectrum



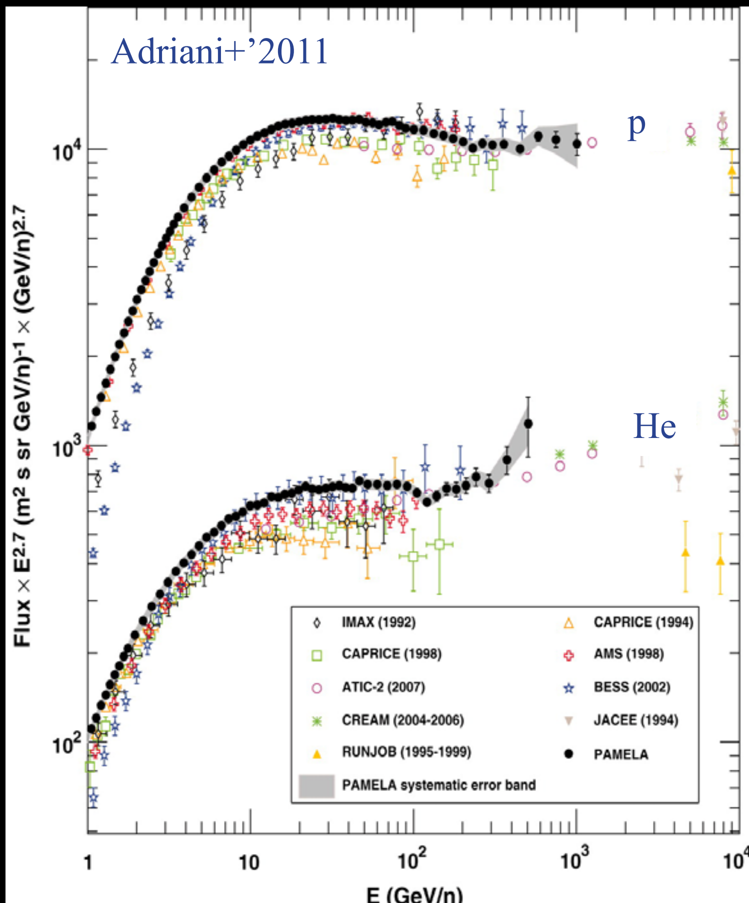


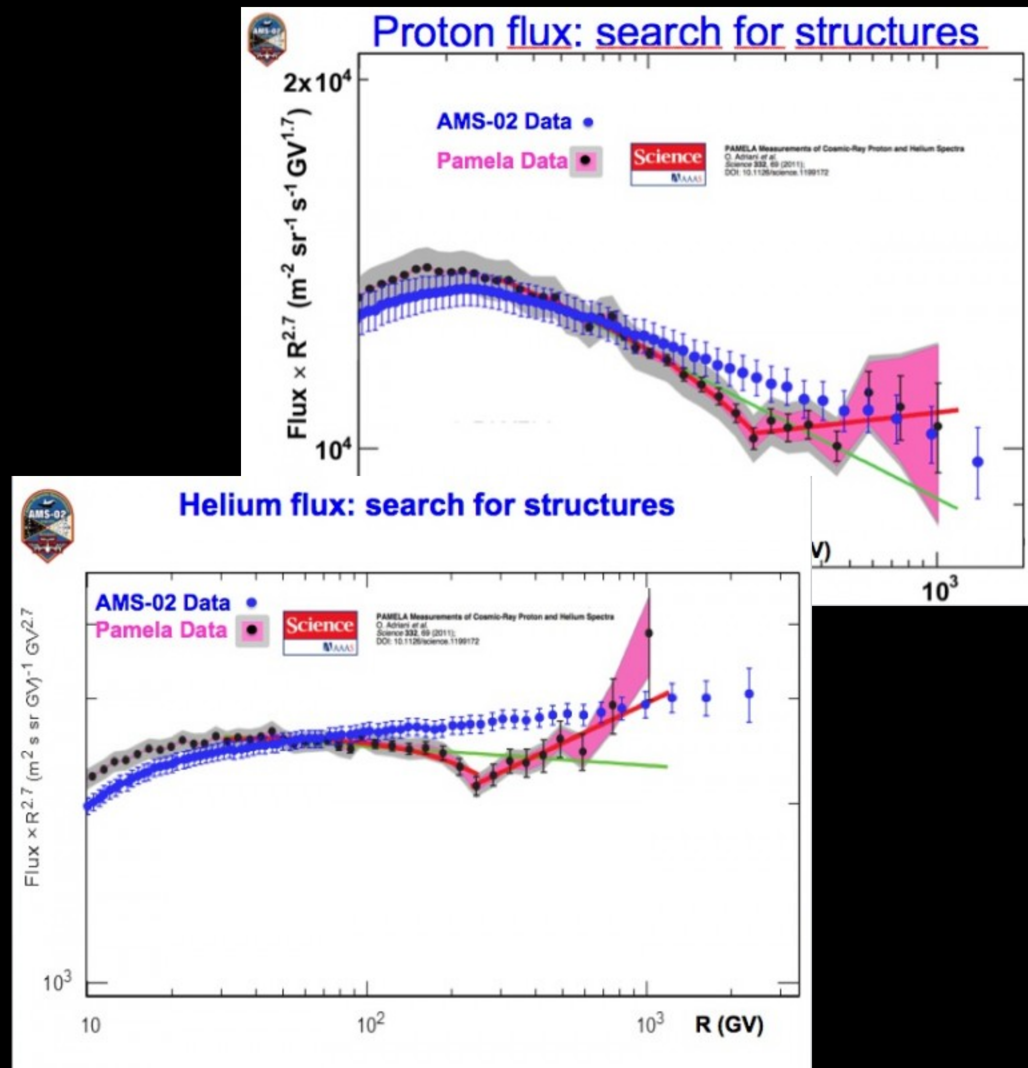
Kobayashi+'2004

- 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?)

Break in the CR p and He absolute fluxes

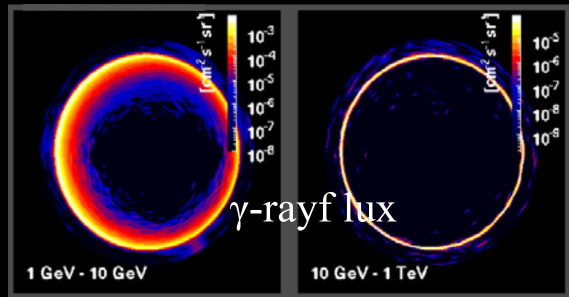


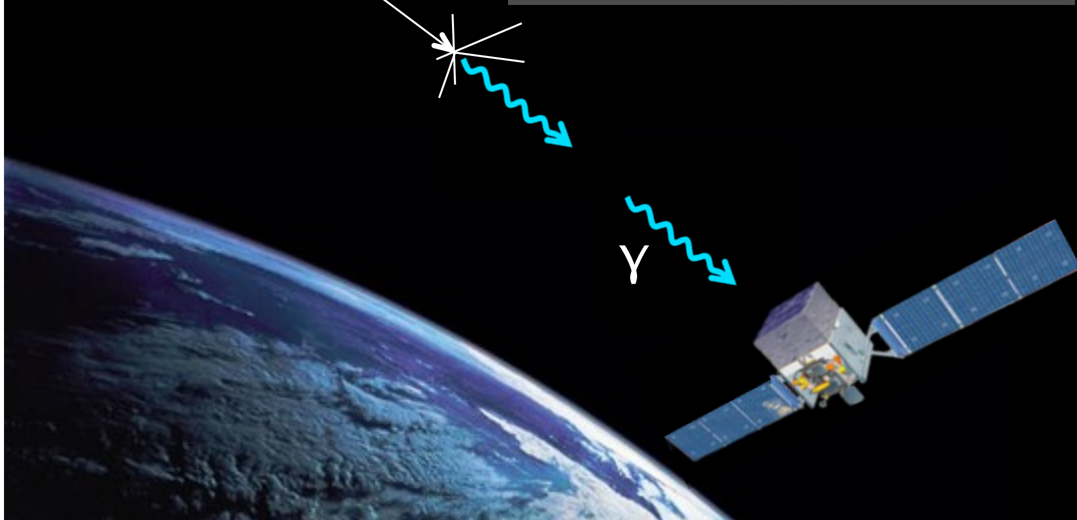


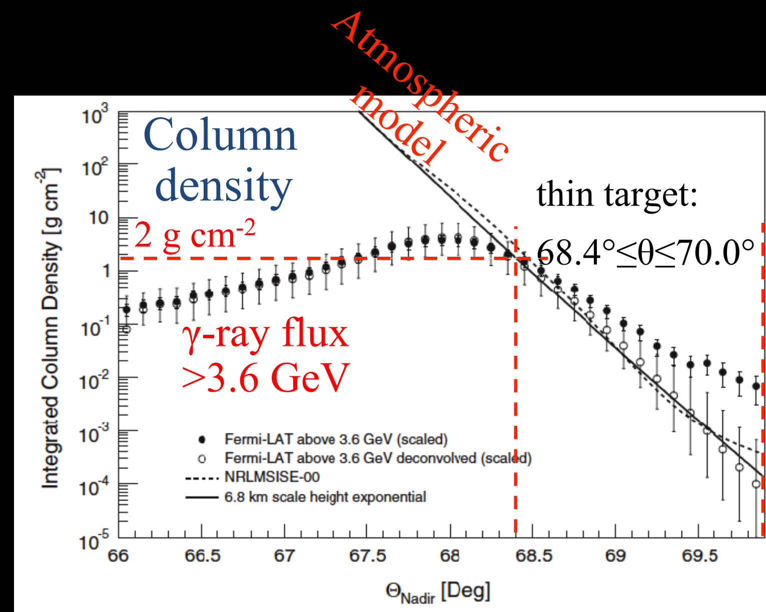
Data from several experiments (BESS, AMS-01, ATIC'2009, CREAM'2010, PAMELA'2011) are all consistent and indicate spectral hardening above ~100 GeV/nucleon

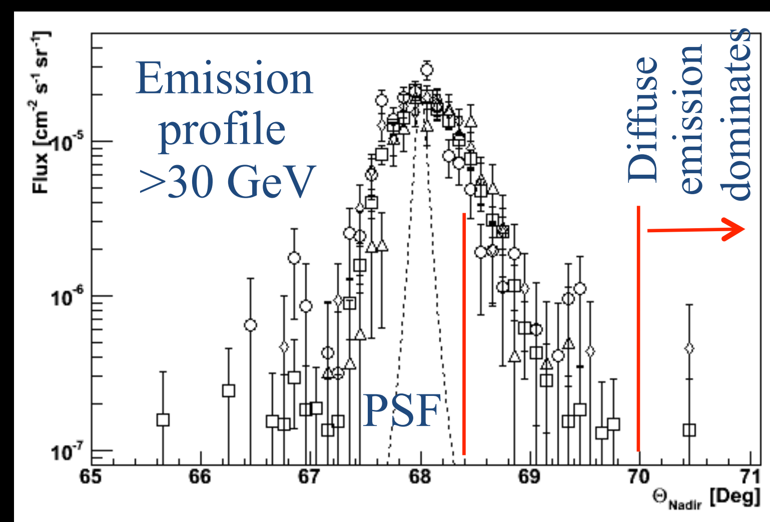
Preliminary AMS-02 data do nor show any spectral feature

Fermi-LAT observations of the Earth's limb



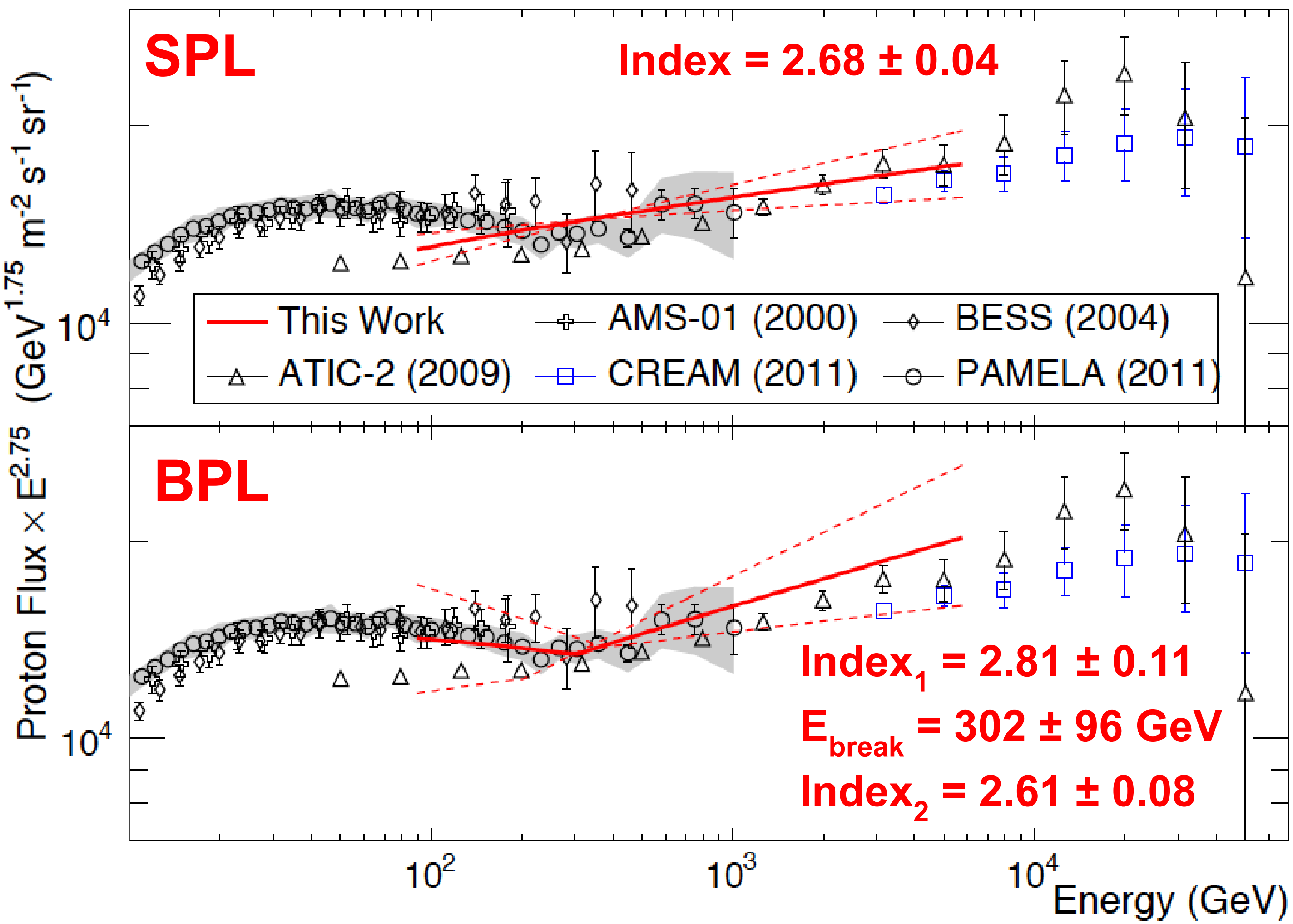






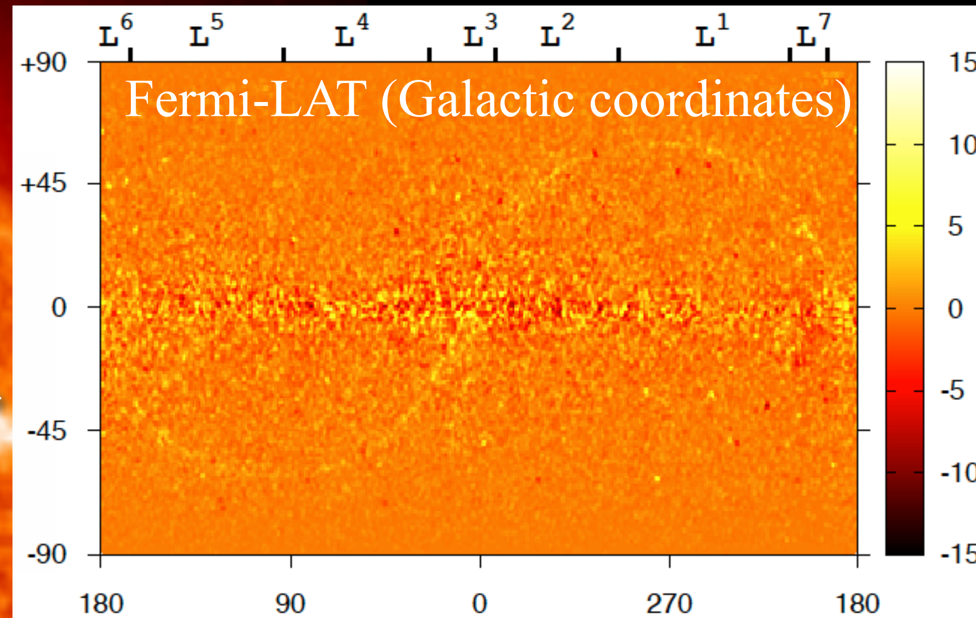
- ✧ Due to its proximity, the Earth is the brightest γ-ray source on the sky
- ✧ The emission is produced by the CR cascades in the atmosphere
- ✧ Most energetic γ-rays are produced by CRs hitting the top of the atmosphere at tangential directions (thin target)

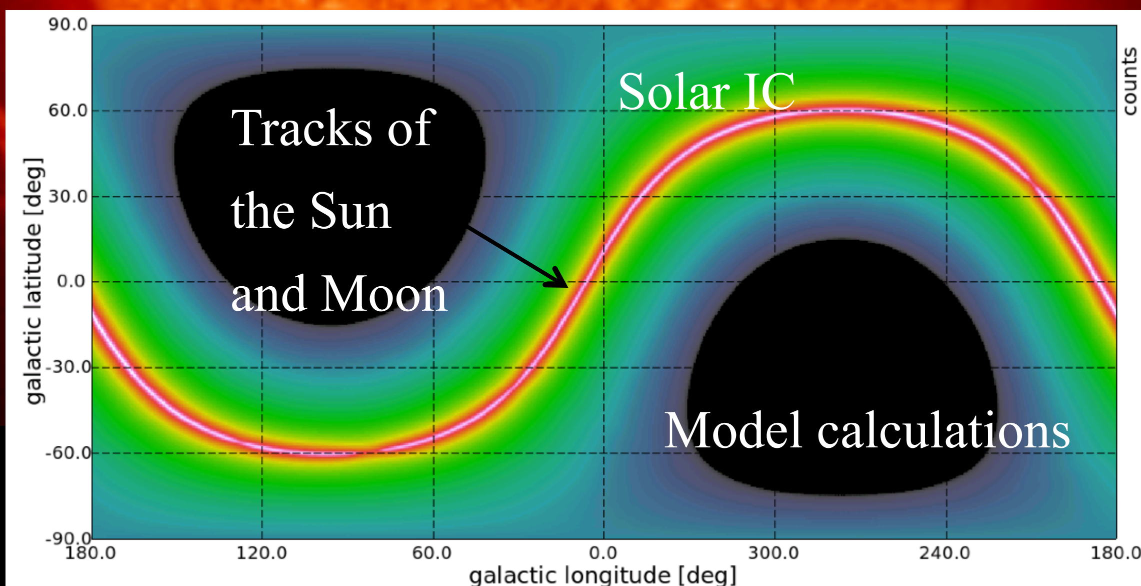
Inferred CR Proton Spectrum from *pp* Model by Kachelrieβ & Ostapchenko (2012)



Solar system

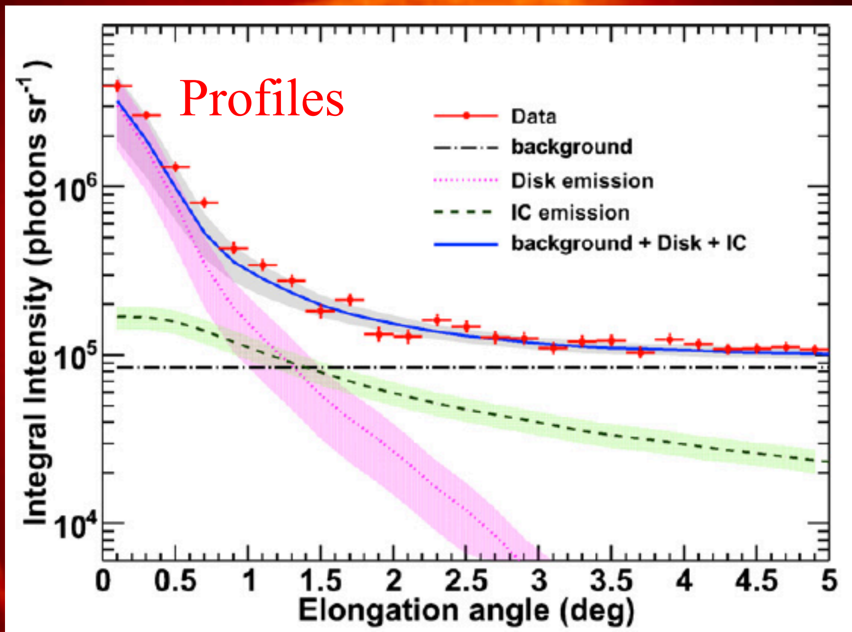
- ✧ Raw data sliced by 2 months interval, background removed; → the solar track is clearly visible

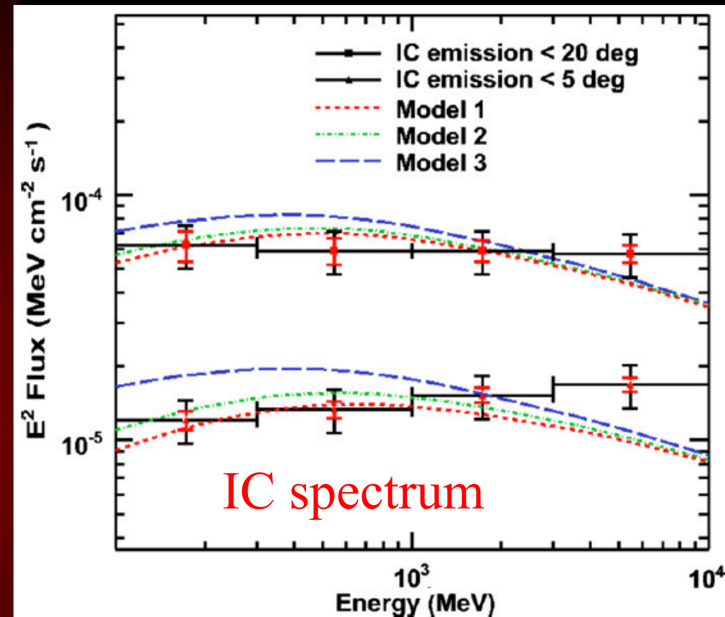


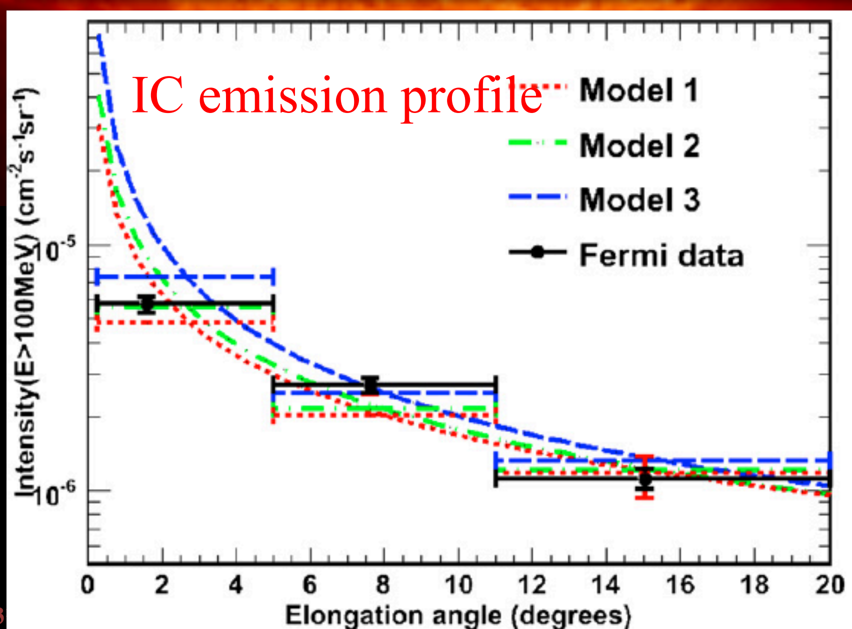


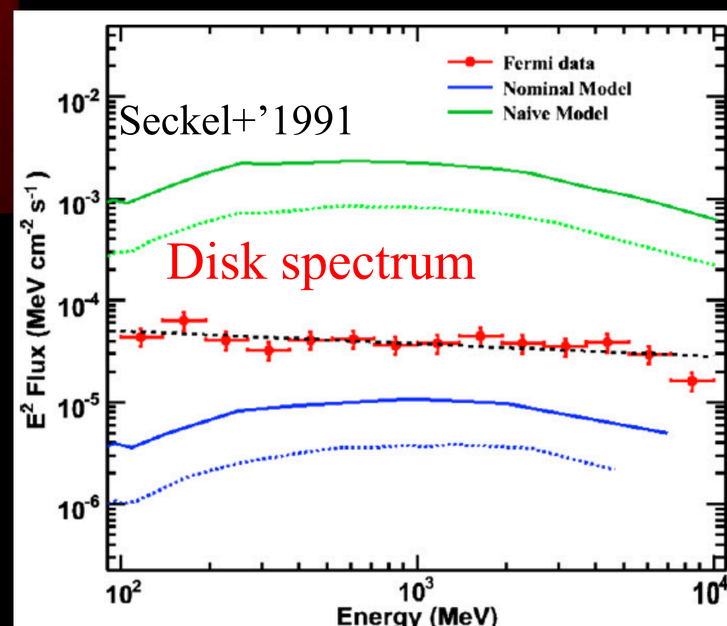
- ✧ Averaged over one year, the ecliptic is seen as a bright stripe on the sky, but the emission comes from all directions

Fermi-LAT observations of the Sun



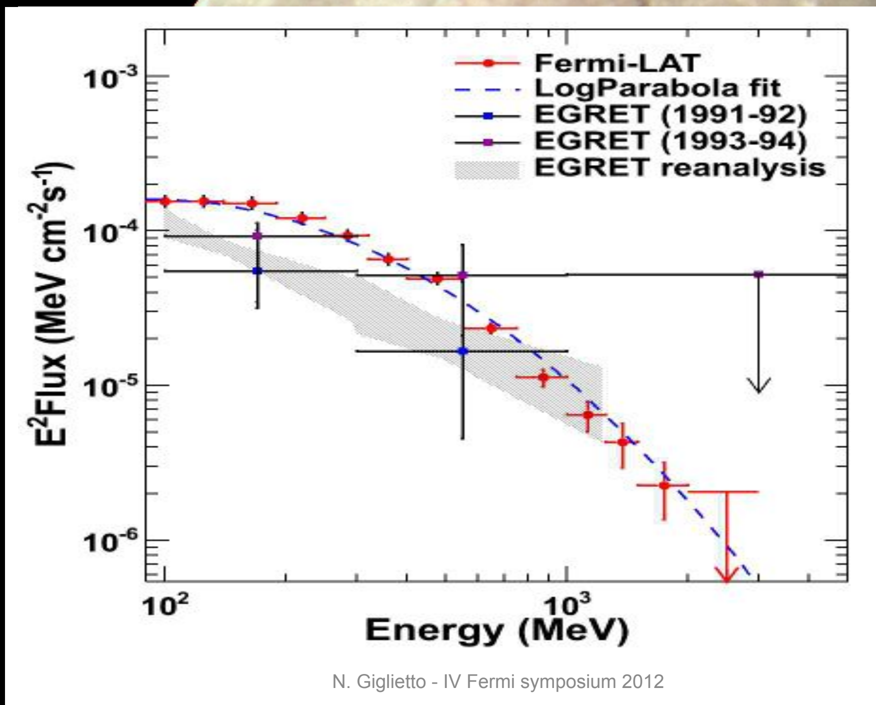


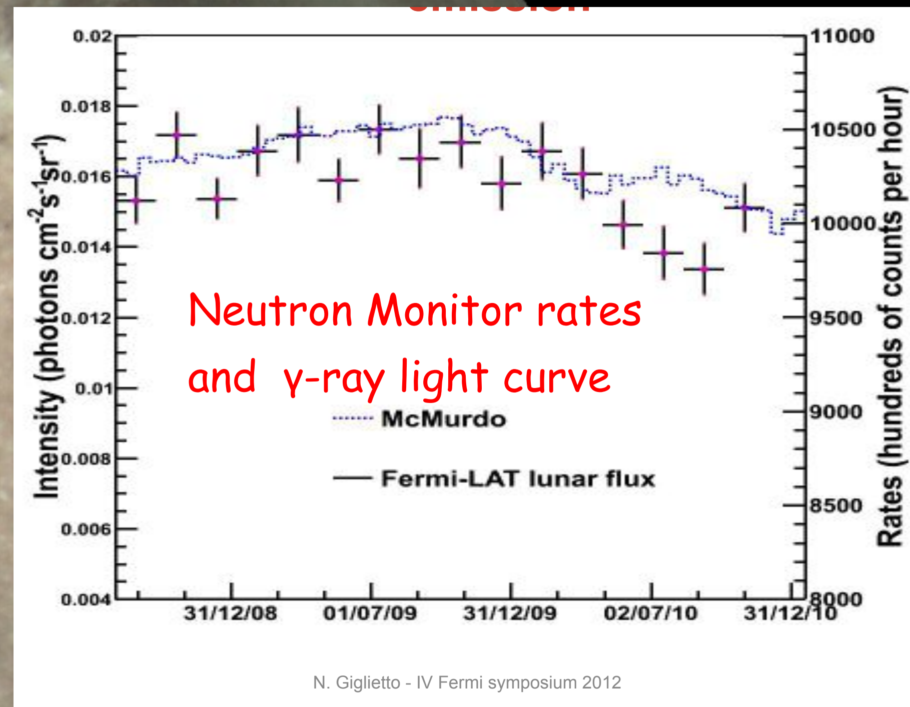




Abdo+'2011

Fermi LAT observation of the Moon (3 years)





- ✧ Emits γ-rays due to the cosmic ray interactions with the surface material
- ✧ The spectrum is softer than predicted – effect of the surface roughness?
- ✧ Independent method to monitor cosmic ray flux outside of the geomagnetic field

A Zoo of Solar System Bodies

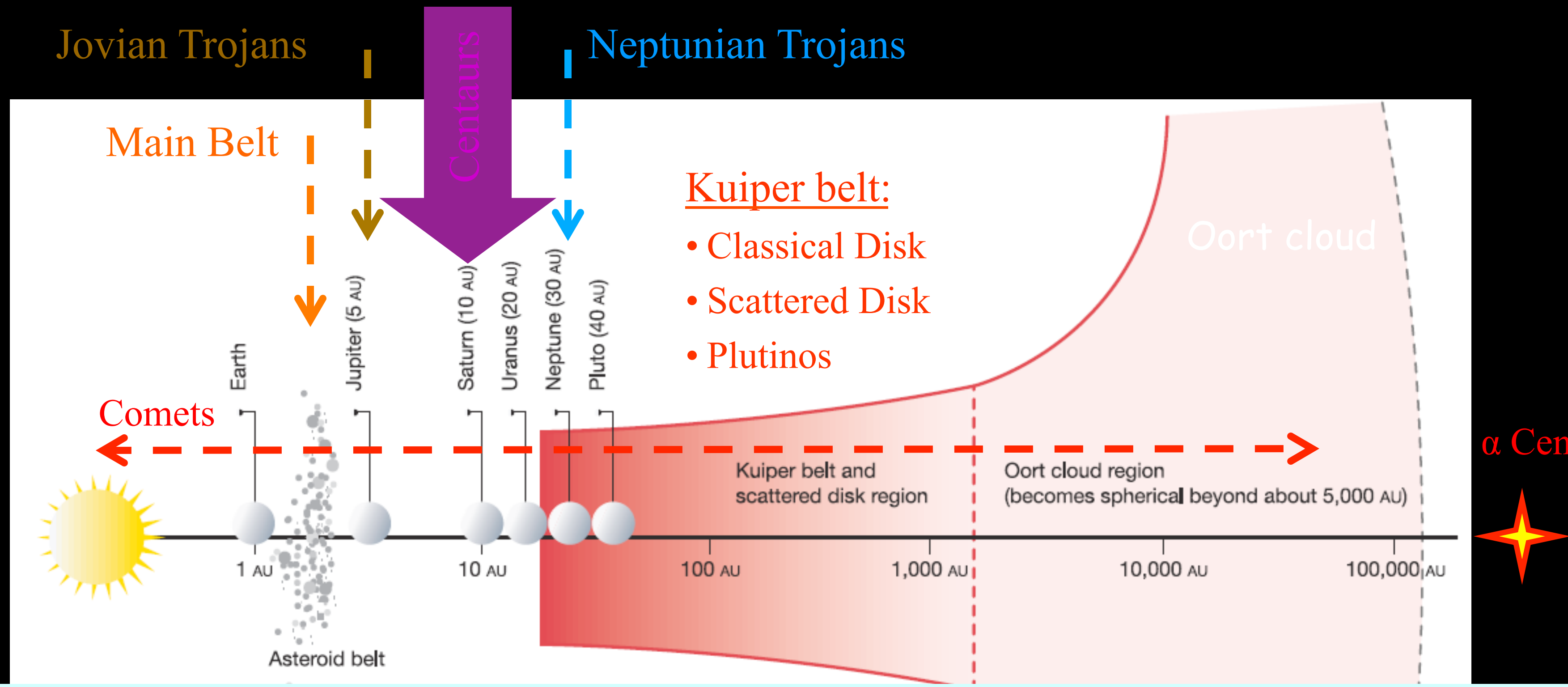


Table 1 **The primary cometary reservoirs of the Solar System**

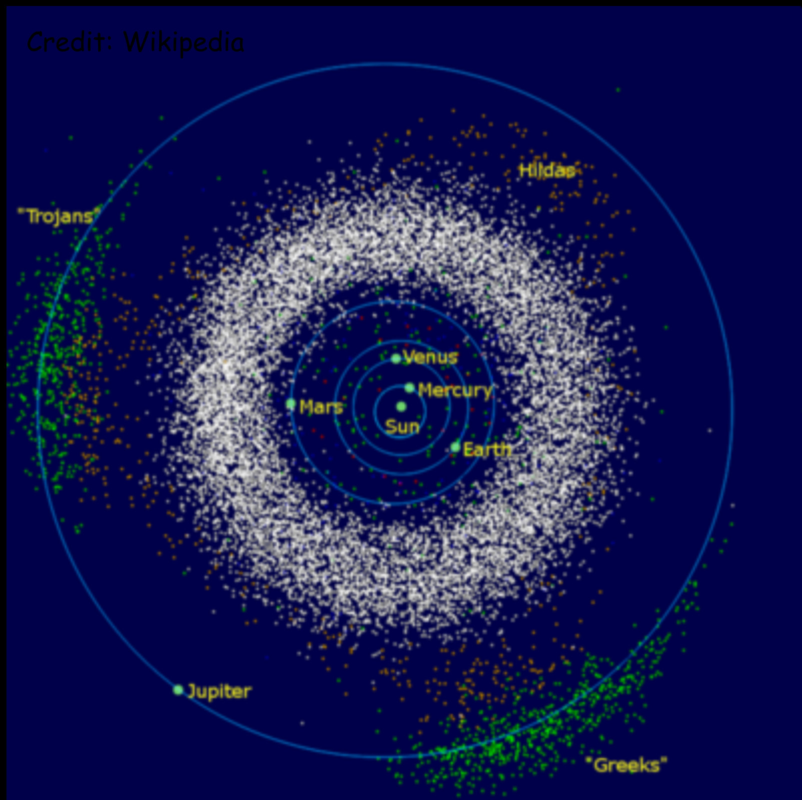
	Kuiper belt	Oort cloud
Shape	Disk-like	Spheroidal
Distance range	30–1,000 AU	1×10^3–1×10^5 AU
Comet population	~5–10 × 10^9	1×10^{11}–5×10^{12}
Estimated mass (including smaller debris)	~0.1 $M_\oplus$	1–50 $M_\oplus$
Ambient surface temperatures	30–60 K	5–6 K
Origin	Largely *in situ*	Ejected material from the Kuiper belt and outer-planets zone
Return mechanism from the reservoir	Dynamical chaos due to planetary perturbations and collisions	Perturbations due to passing stars, galactic tides and molecular clouds

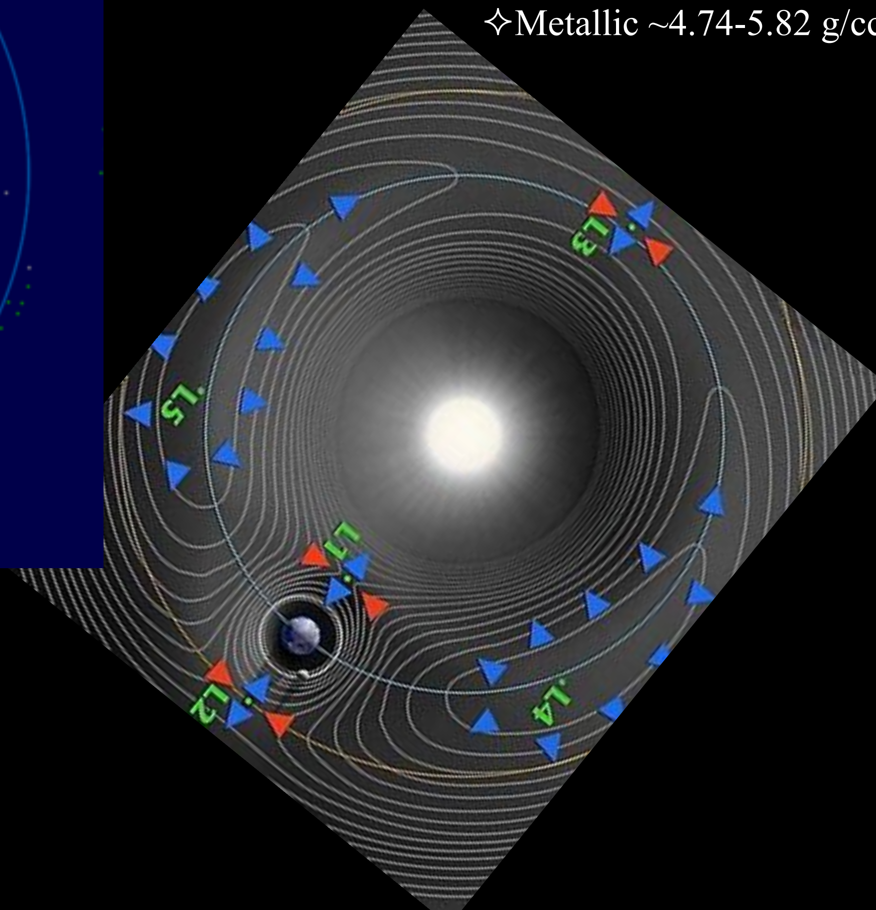
Stern'03

Trojans: Lagrangian Points

<u>Main Belt</u>

- ✧Total mass ~0.05 M_{moon}
- ✧N(>1 km) ~(1.2-1.9)x10^6
- ✧Densities 1.0-3.5 g/cc ~2 g/cc
  - ✧Carbonaceous ~1.23-1.40 g/cc
  - ✧Silicate ~2.65-2.75 g/cc
  - ✧Metallic ~4.74-5.82 g/cc





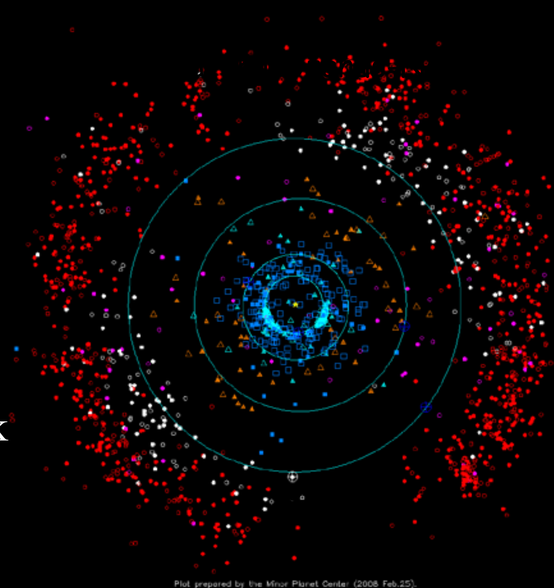
<u>Trojans</u>

- ✧Total mass ~0.08 M_{moon}
- ✧N(>1 km) ~1.3x10^6
- ✧Densities ~1 g/cc
- ✧"Freeze-in" capture

Pretty much similar to MBAs, but move in 2 bunches (L4 & L5)

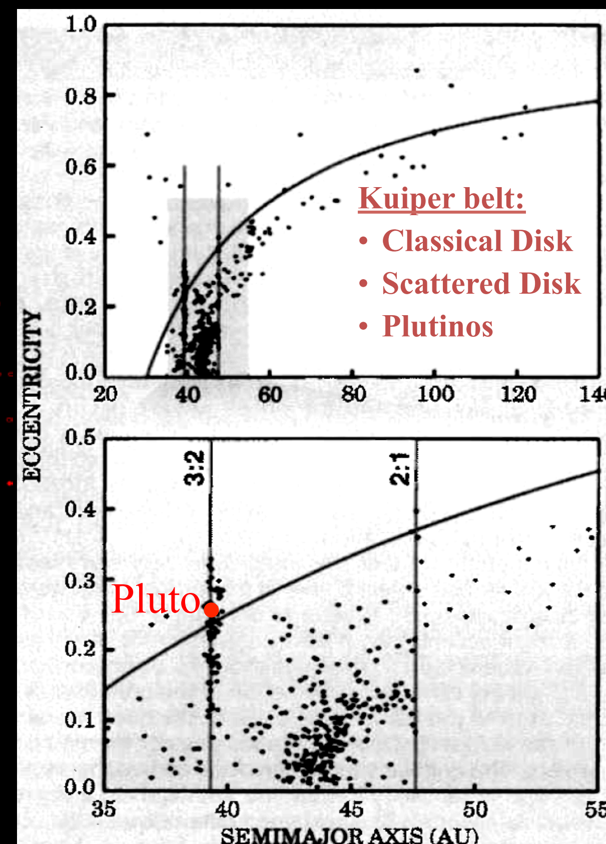
Kuiper Belt Objects

Figure 1. Gerard Kuiper (1905–73) argued in 1950 that the Solar System shouldn't end abruptly beyond Pluto, and proposed the existence of a belt of small unseen bodies beyond Pluto's orbit. (Photo courtesy of AIP Emilio Segrè Visual Archives, PHYSICS TODAY Collection.)

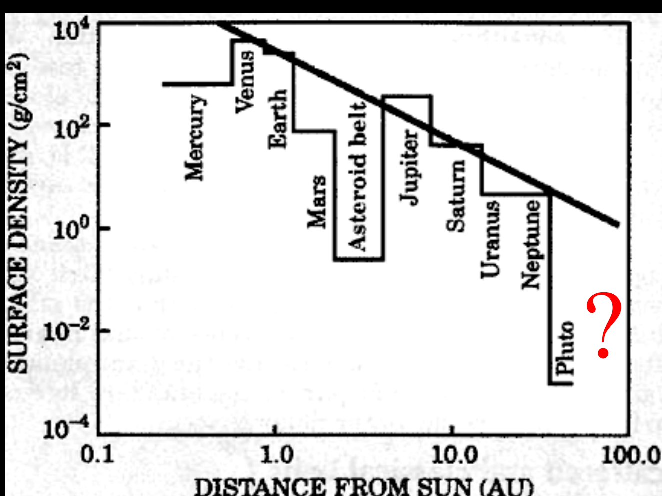


Credit: MPC

KBO resonances with Neptune



Surface density of proto-planetary disk



Brown'04

✧N(>1 km) ~(5-10)x10^9

✧Densities ~0.5 g/cc (ice)

✧Surface density ~ r^{-2}

✧Total mass ~0.1 M_{earth} ~8.13 M_{moon}

✧Distribution in the ecliptic latitude FWHM~12.5º±3.5º

SSSB Size Distributions

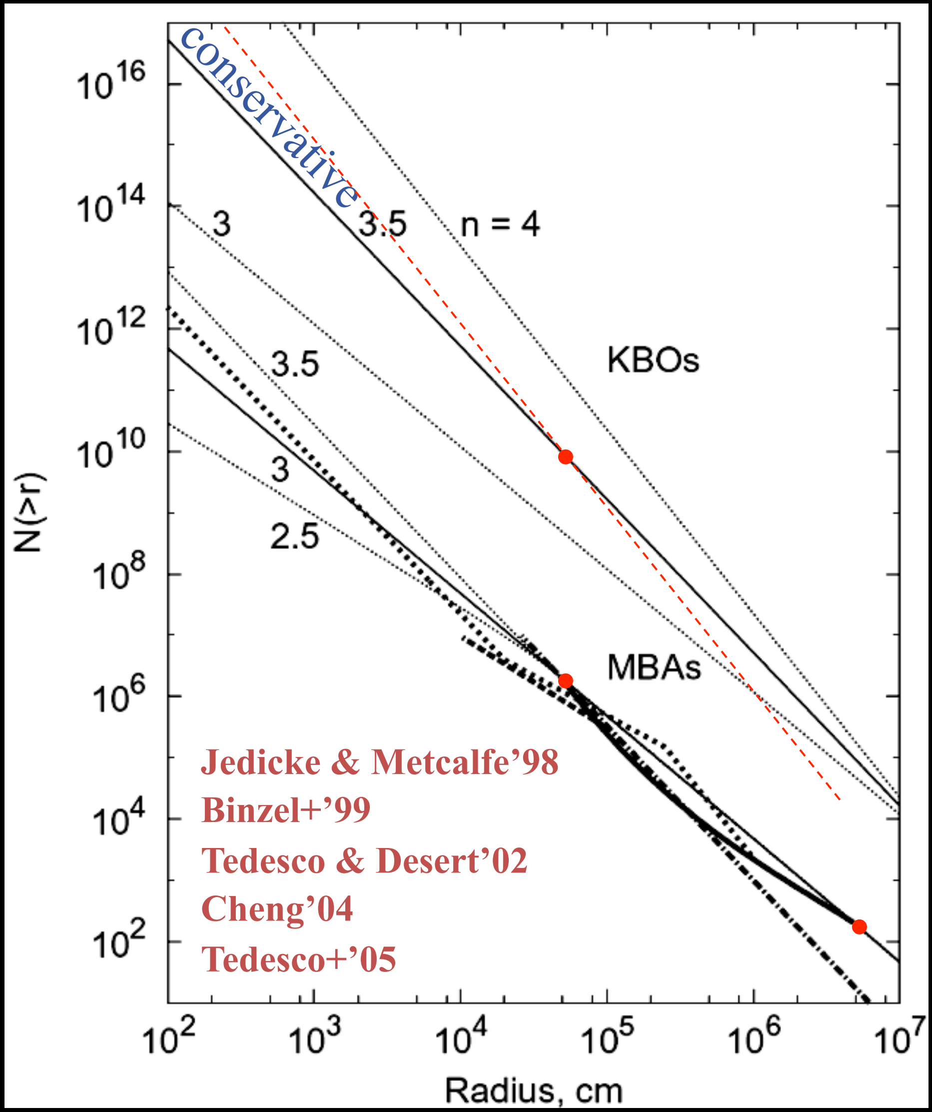
2. SMALL SOLAR SYSTEM BODIES

The asteroid mass and size distributions are thought to be governed by collisional evolution and accretion. Collisions between asteroids give rise to a cascade of fragments, shifting mass toward smaller sizes, while a small body impact with a much larger asteroid leads to the growth of the latter. The first comprehensive analytical description of such a collisional cascade is given by Dohnanyi (1969). Under the assumptions of scaling of the collisional response parameters and an upper cutoff in mass, the relaxed size and mass distributions approach power-laws:

$$dN = am^{-k}dm \quad (1)$$

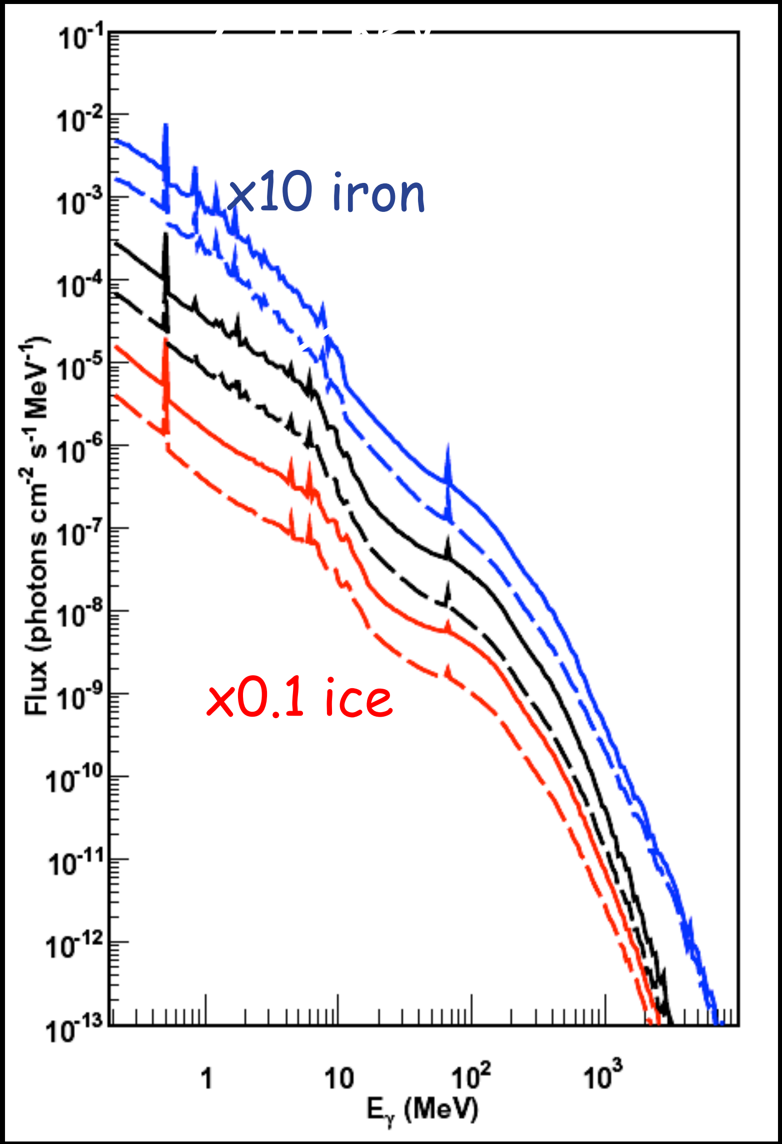
$$dN = br^{-n}dr, \quad (2)$$

where m is the asteroid mass, r is the asteroid radius, and a, b, k, n are constants. These equilibrium distributions extend over all size and mass ranges of the population except near its high-mass end. The constants in eqs. (1),



- ✧Collisional evolution & accretion
- ✧Relaxed size distribution n=3.5 (assuming scaling of collisional response parameters)
- ✧Scaling breaks…

Iron, Regolith, and Water Ice



- ✧The albedo of the Moon size body made of Iron, regolith, and water ice
- ✧Upper: interstellar CR flux

  Lower: modulated 1500 MV
- ✧Albedo water ice/iron ~ 2
- ✧Regolith and water ice produce similar spectrum above ~100 MeV
- ✧Low-energy parts show larger difference (+lines)

Gamma-Ray Albedo Flux Estimates

- MBAs (sum over ecliptic latitude and longitude)

  F_{tot}/F_{moon} ~ 0.06, 0.67, 10 (n = 2.5, 3.0, 3.5)

  Changes by x5 with solar elongation angle (from 1.7 AU to 3.7 AU)

- Jovian Trojans (assuming the same size distr. as MBAs)

  F_{tot}/F_{moon} ~ 0.009, 0.07, 0.77 (n = 2.5, 3.0, 3.5) –average

  F_{tot}/F_{moon} ~ 0.01, 0.1, 1.1 (n = 2.5, 3.0, 3.5) -max

  F_{tot}/F_{moon} ~ 0.006, 0.05, 0.5 (n = 2.5, 3.0, 3.5) –min

  Concentrated in small bunches, positions are well known – relative to Jupiter

- KBOs (probe of the local interstellar CR spectrum!)

  F_{tot}/F_{moon} ~ 0.2, 34, 1168 (n = 3.0, 3.5, 3.9)

  Does not vary with solar elongation angle

5TH FERMI SYMPOSIUM

October 20-24 2014, Nagoya, Japan

The 5th International Fermi Symposium will focus on new results and prospects for the Fermi Gamma-ray Space Telescope and related multi-wavelength and multi-messenger studies.

Topics include:

- Blazars and Other Active Galaxies
- Cosmic Rays
- Dark Matter
- Diffuse γ-ray Emission
- Gamma-ray Bursts
- Galactic Sources and Transients
- Pulsars
- Solar System γ-ray Sources
- Supernova Remnants and Pulsar Wind Nebulae

http://fermi.gsfc.nasa.gov/science/mtgs/symposia/2014

Fermi Gamma-ray Space Telescope