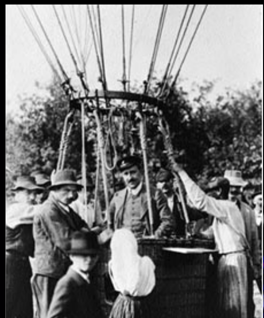
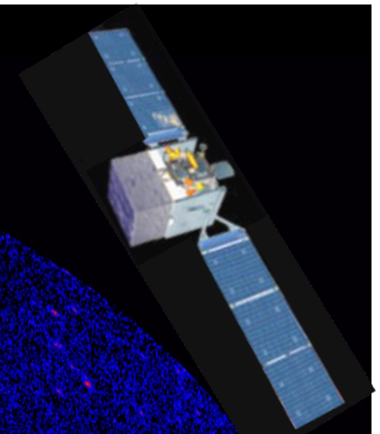




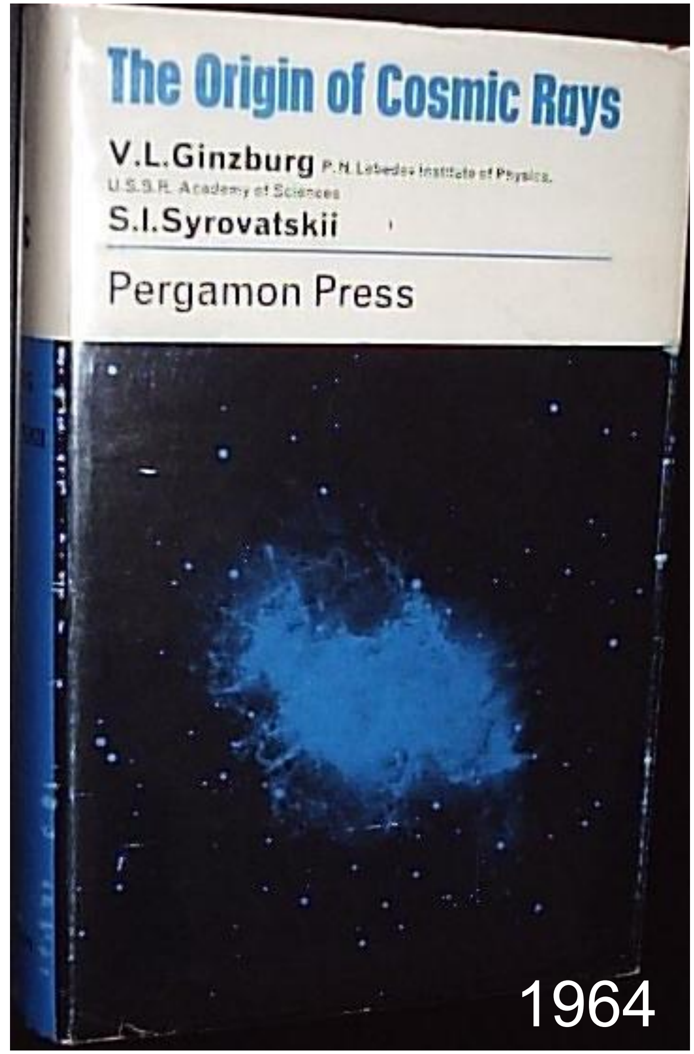
CURRENT STATUS OF ASTROPHYSICS OF COSMIC RAYS

(OR NIGHTMARE & PARADISE FOR A THEORETICIAN)

IGOR V MOSKALENKO – STANFORD

The Origin of Cosmic Rays

1963



1964

The main textbook in astrophysics of cosmic rays for many decades

Galactic vs. Metagalactic origin of CRs

LETTERS TO NATURE

Gamma Radiation of Magellanic Clouds and Metagalactic Origin of Cosmic Rays

IN metagalactic models for the origin of the primary component of cosmic rays (c.r.), observed near the Earth (energy density $\bar{\bar{\omega}}_G \sim 10^{-12}$ erg/cm^3), it is required that the c.r. energy density $\bar{\bar{\omega}}_{Mg}$ in some metagalactic region surrounding the Galaxy should be very close to $\bar{\bar{\omega}}_G$. In different metagalactic models the energy density in the source and

$$(\overline{\sigma I_G}) = \iint^{\infty} \sigma(E_\gamma, E) I_G(E) \mathrm{d}E \mathrm{d}E_\gamma \simeq 10^{-26} \ \mathrm{s}^{-1}$$

$$E_\gamma = 100 \ \mathrm{MeV} \quad \text{(see ref. 11, Figs. 5–11).}$$

According to Bok[12] the distances from the Sun and the neutral hydrogen mass for the Magellanic Clouds are respectively equal to

I discuss here the possibility of solving the problem convincingly by measuring the γ-ray flux from the Magellanic Clouds (LMC and SMC). In fact, in metagalactic models the c.r. intensity in LMC, SMC and in the Galaxy is expected to be the same:

$$\bar{\bar{\omega}}_{LMC} = \bar{\bar{\omega}}_{SMC} = \bar{\bar{\omega}}_G \sim 10^{-12} \ \mathrm{erg/cm^3} \qquad (1)$$

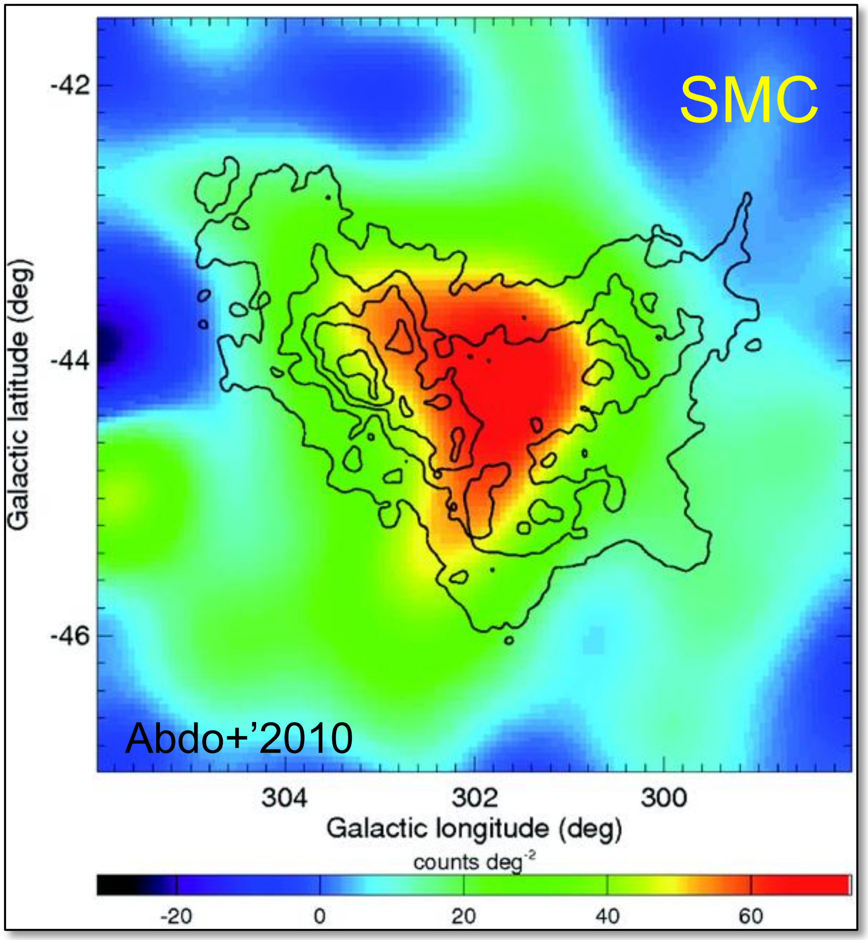
In more complicated models there may be powerful c.r. generation in the galaxies under consideration as well; but I consider that to confirm the inequalities

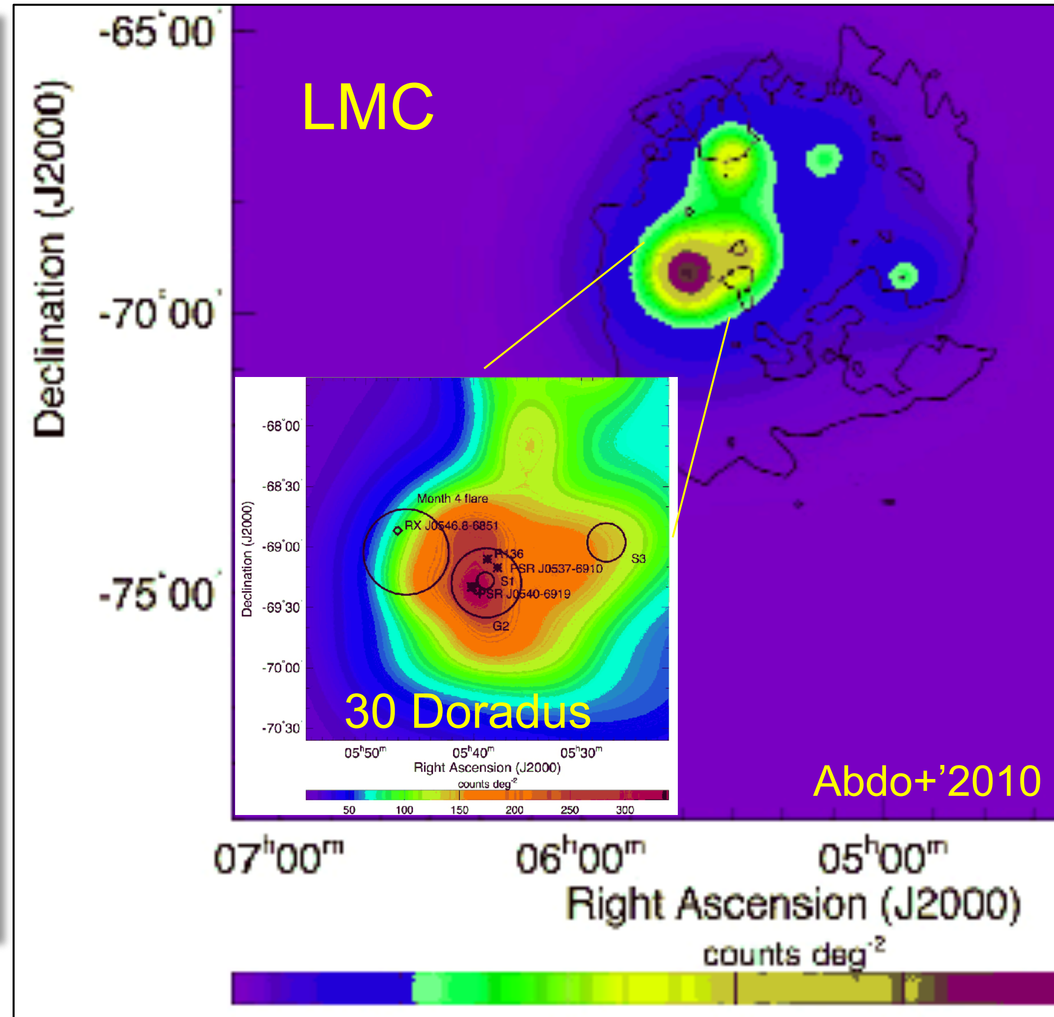
$$\bar{\bar{\omega}}_{LMC} \ll \bar{\bar{\omega}}_G, \ \bar{\bar{\omega}}_{SMC} \ll \bar{\bar{\omega}}_G \qquad (2)$$

would disprove the metagalactic hypothesis. In any case, in the

V. L. Ginzburg
Nature Physical Science
1972, vol. 239, page 8

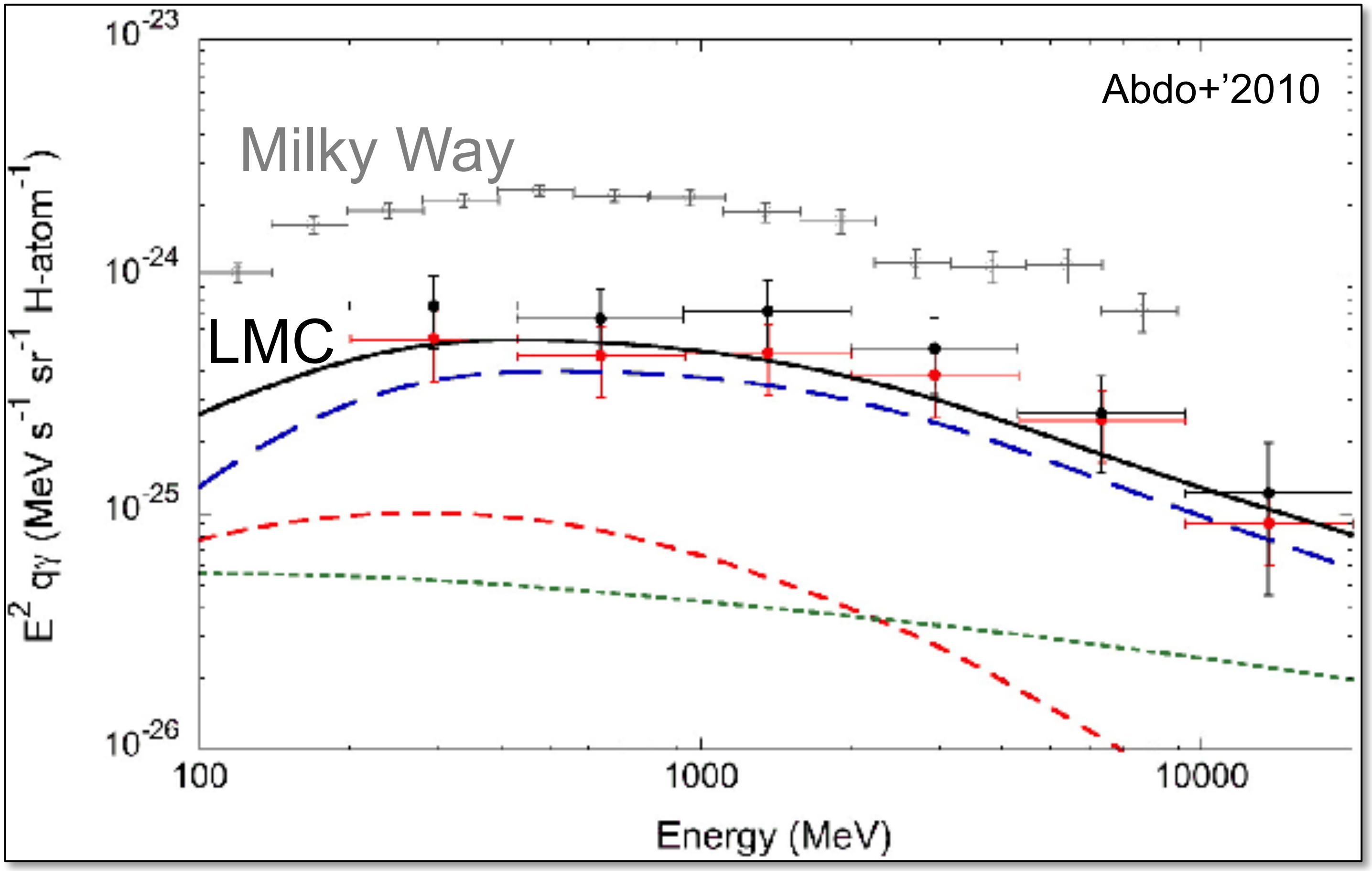
Fermi-LAT: Spatially resolved γ-ray emission from LMC & SMC





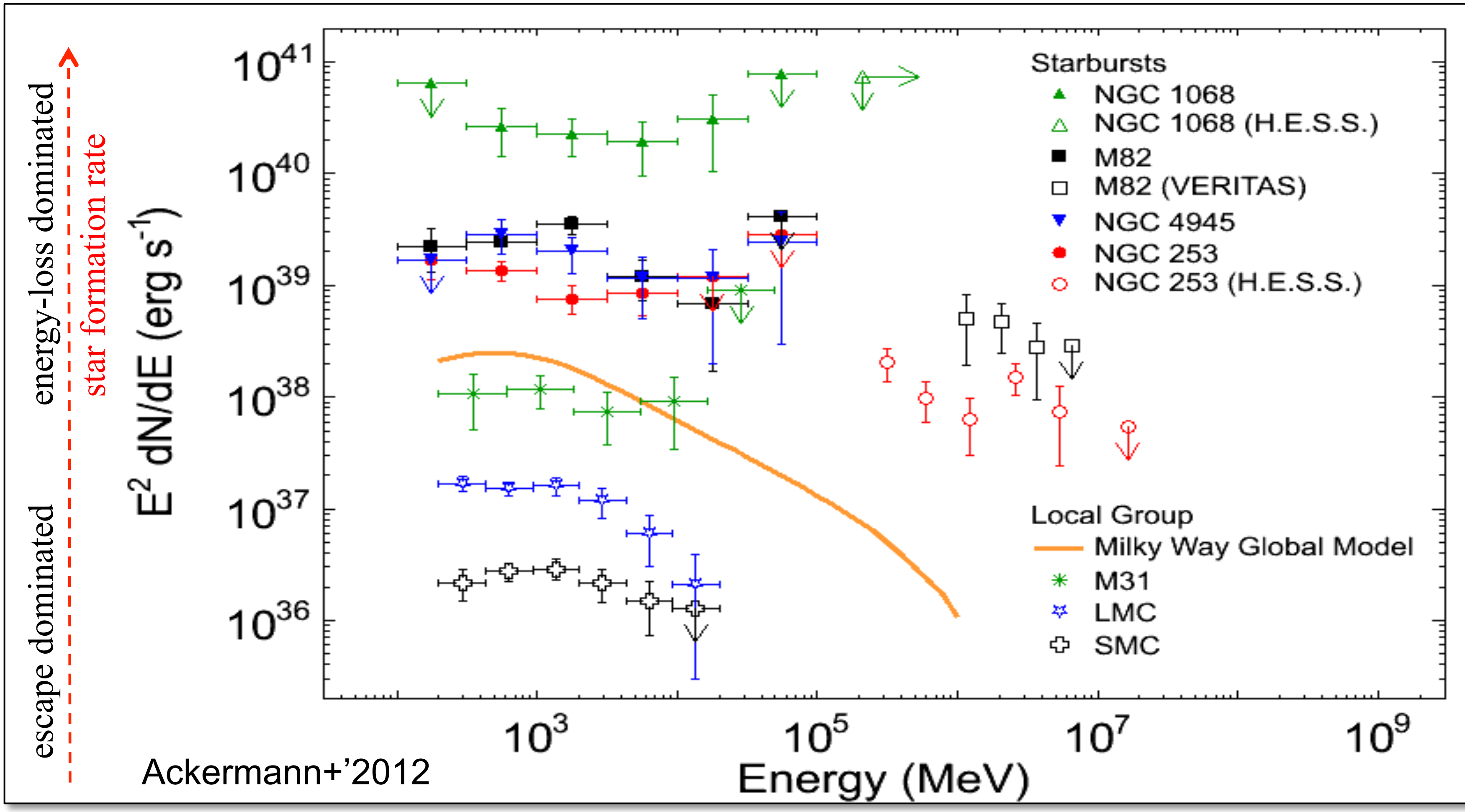
- ✧ SMC – first time detected in γ-rays
- ✧ Diffuse emission from LMC, SMC – first time spatially resolved in γ-rays
- ✧ The large variations in γ-ray emissivity confirms across the galaxies – the emission does not correlate well with gas column density in both LMC and SMC
- ✧ Diffuse emission is produced by local cosmic rays, not Metagalactic

Gamma-ray emissivity of LMC and SMC



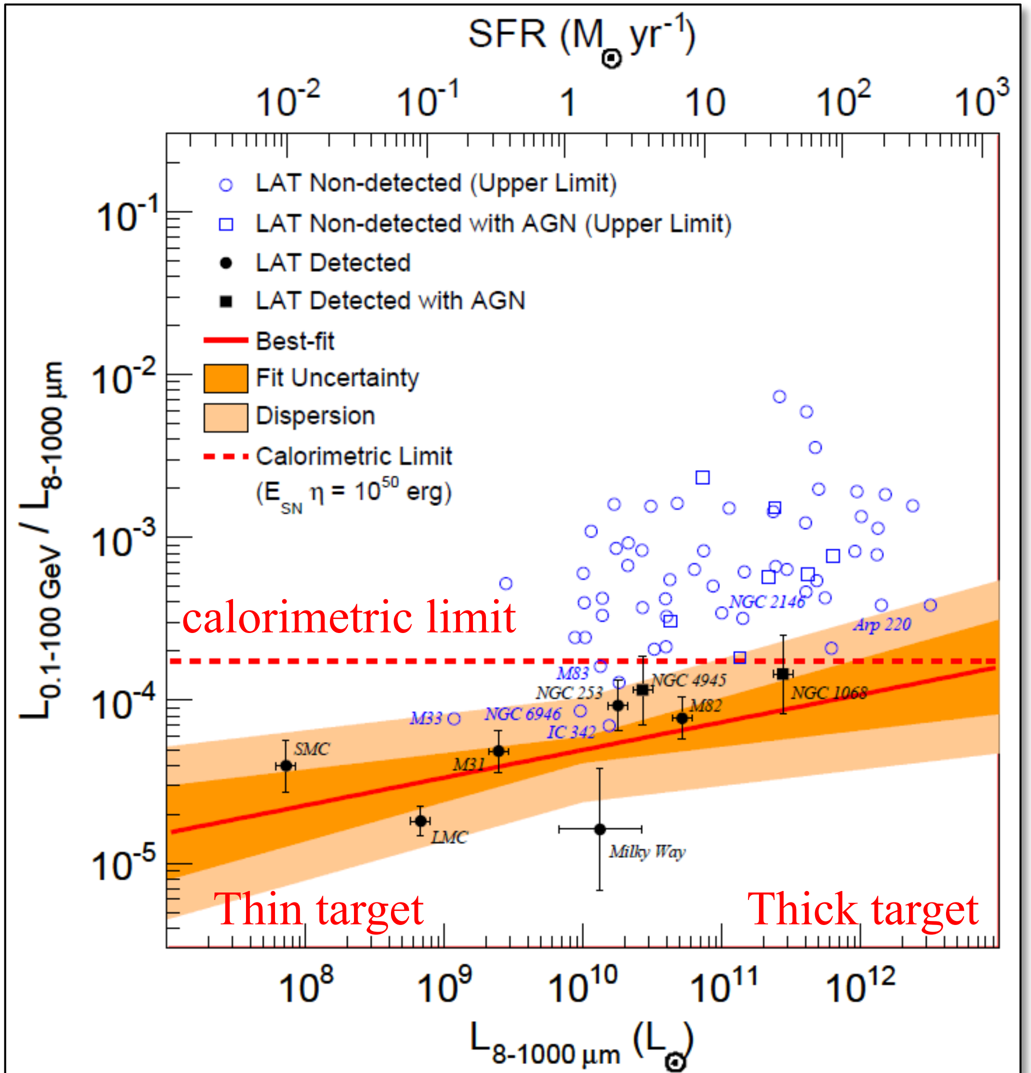
- ✧ The average γ-ray emissivity ratio is different for LMC and SMC:
  - ✦ q_{LMC}/q_{Milky_Way} (>100 MeV) ≈ 0.25-0.5
  - ✦ q_{SMC}/q_{Milky_Way} (>100 MeV) ≤ 0.14-0.17
- ✧ Far from unit – thus again rejecting the Matagalactic hypothesis

Diffuse emission from starforming Galaxies



From the bottom to top one can clearly see the transition from soft spectra for the escape-dominated galaxies to the hard spectra of the energy-loss-dominated galaxies, with inelastic scattering dominating the energy losses

Cosmic Rays as a Universal Phenomenon

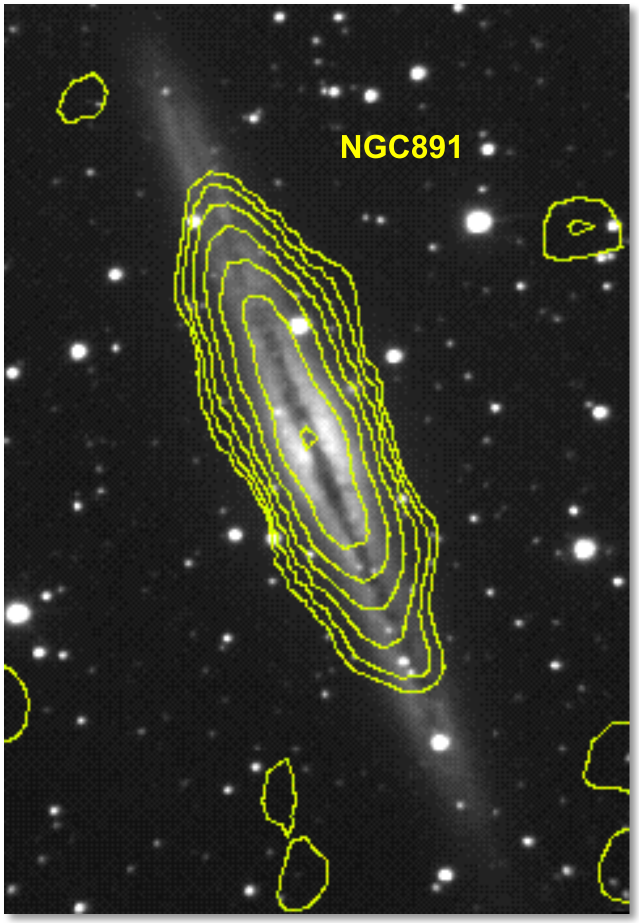


Ackermann+'2012

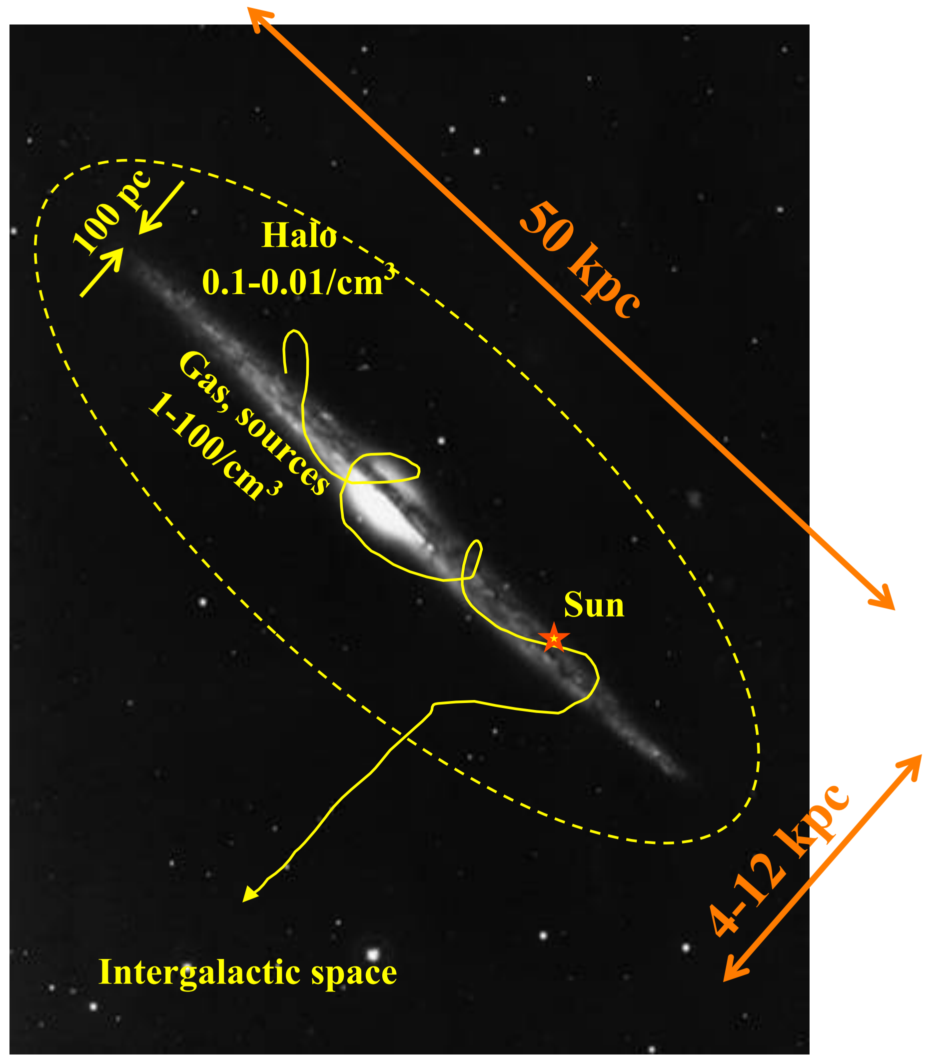
- γ-ray luminosity vs. IR luminosity for normal galaxies detected with Fermi-LAT
- The γ-ray luminosity scales linearly (index ~1.1) with the total emission of hot stars reprocessed by dust – a tracer of star formation
- The ratio approaches the calorimetric limit in star-burst galaxies
- An evidence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

Cosmic rays in the Galaxy

Optical image: Cheng et al. 1992, Brinkman et al. 1993
Radio contours: Condon et al. 1998 AJ 115, 1693

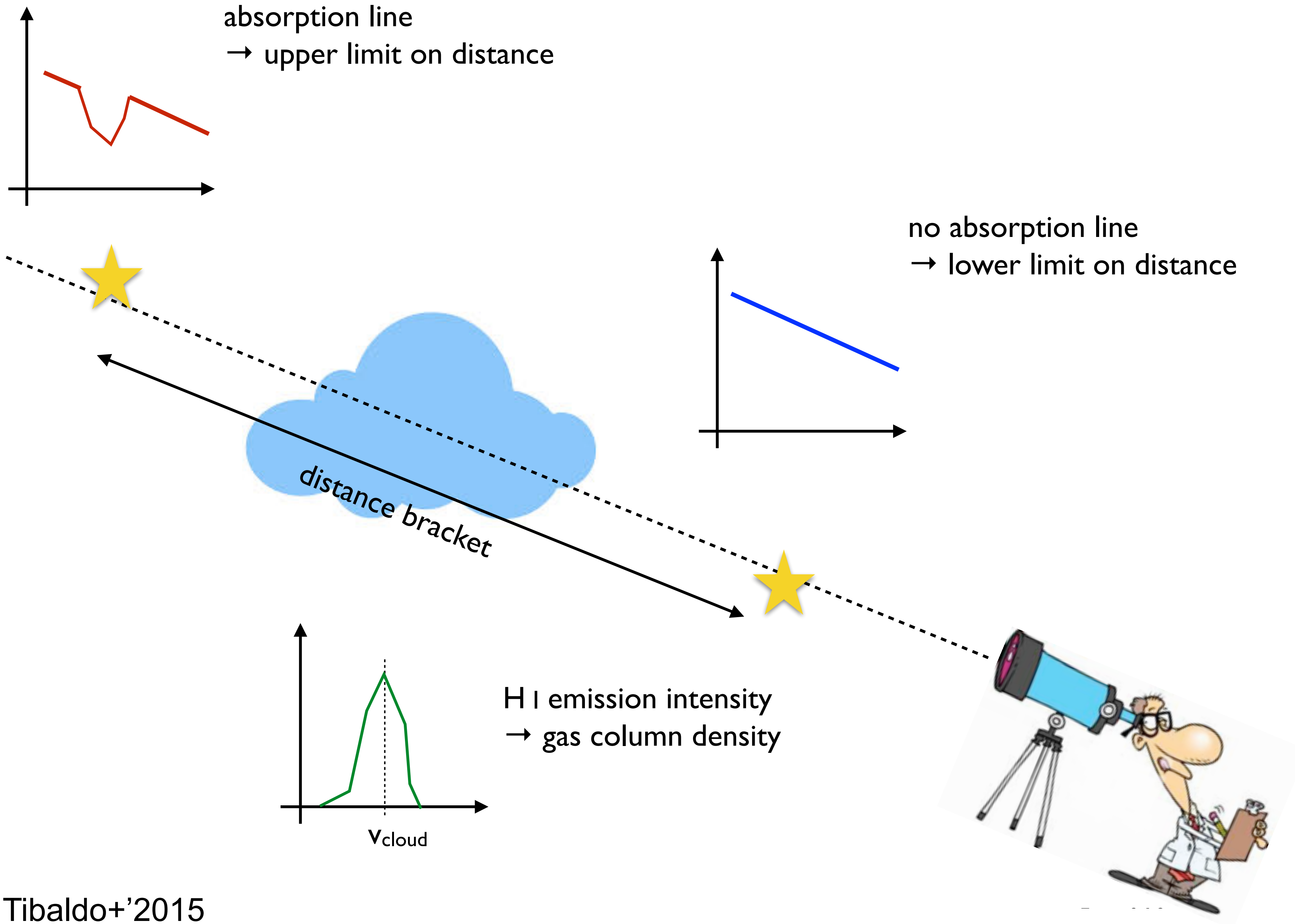


R Band image of NGC891
1.4 GHz continuum (NVSS), 1,2,…64 mJy/ beam



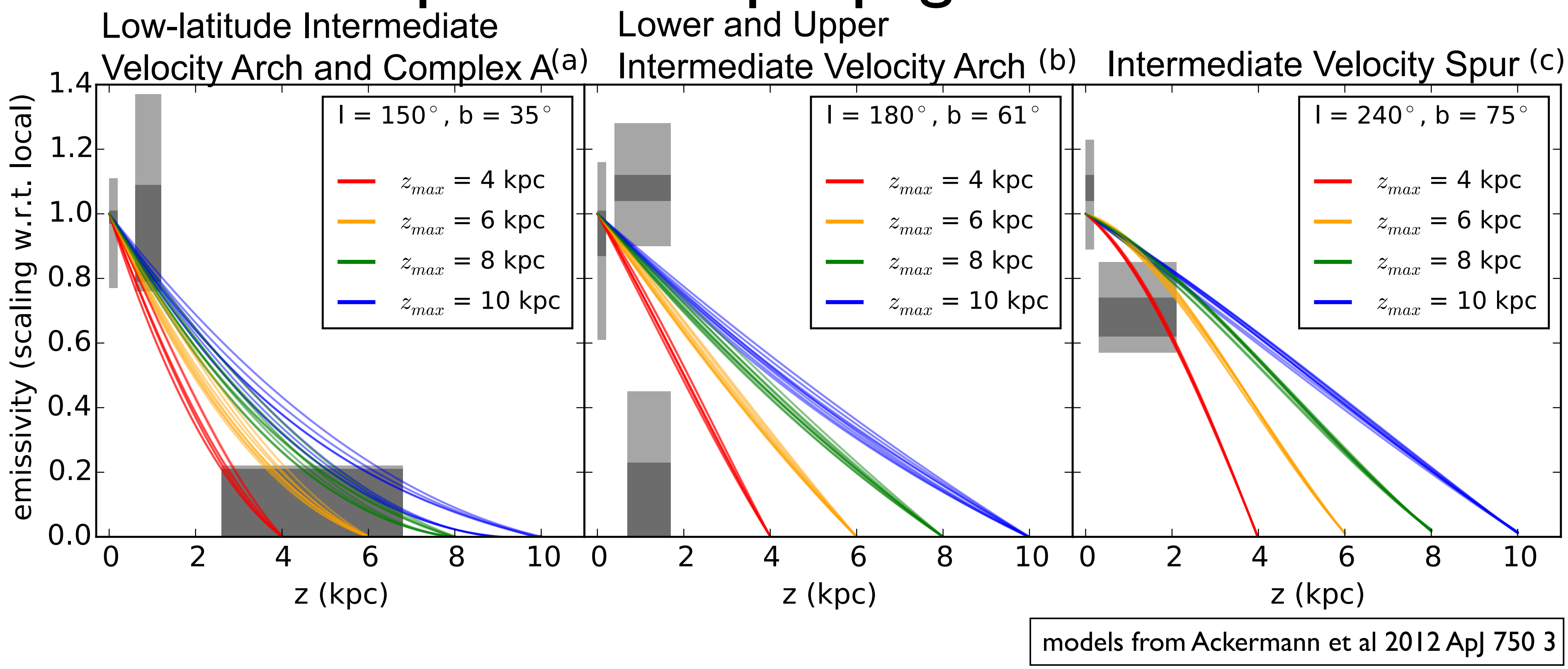
“Flat halo” model (Ginzburg & Ptuskin 1976)

Distances to HVCs/IVCs



Tibaldo+'2015

Comparison to propagation model



- broad agreement with propagation model
- hint at 50% decrease within 2 kpc from the disk $\not\leftrightarrow$ large halos

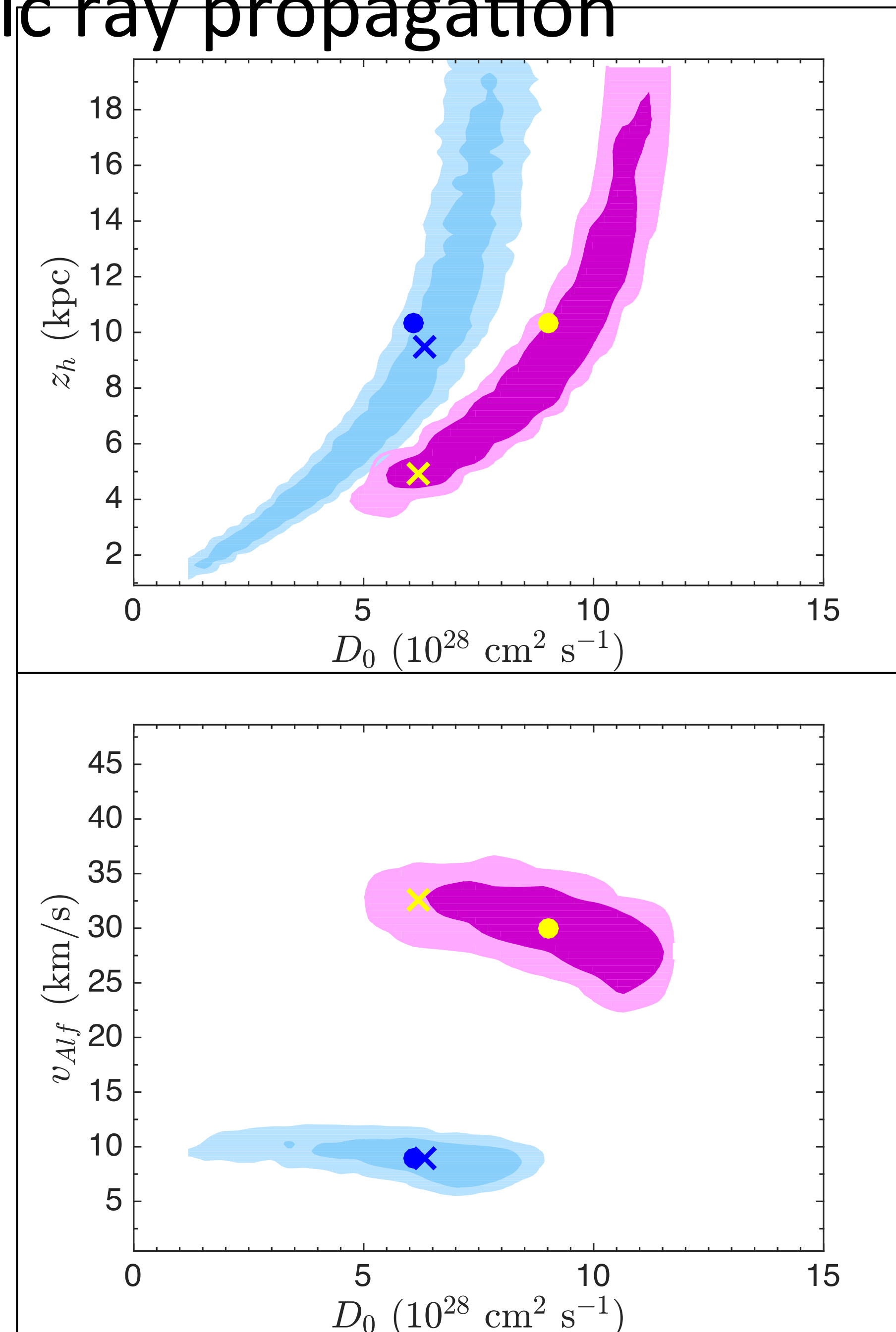
✧ First direct evidence of CR intensity in the Galactic halo

$\wedge$ first direct evidence of Galactic origin of CRs

Tibaldo+'2015

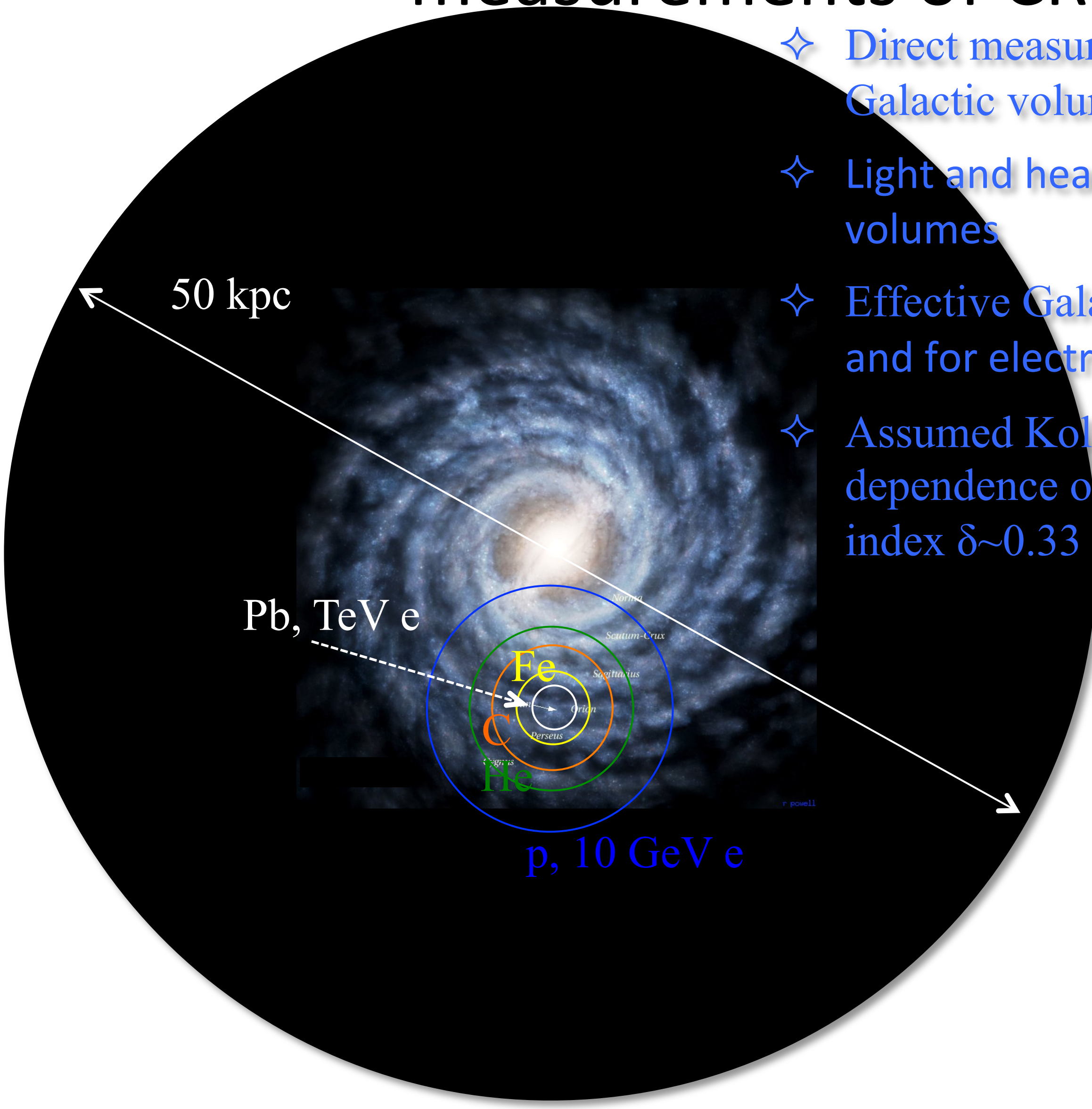
Bayesian analysis of cosmic ray propagation

- ✧ 2D posterior distributions:
  - ✦ halo size z_h vs. the diffusion coefficient D_0
  - ✦ Alfven velocity v_{Alf} vs. the diffusion coefficient D_0
- ✧ The distributions do not overlap
- ✧ Interpretation:
  - ✦ Non-uniform diffusion coefficient in the Galaxy
  - ✦ Local sources of primary nuclei (IVM+'03, Shaviv+'09)



Johannesson+'2016

Effective Galactic volume probed through direct measurements of CR species



- Direct measurements probe relatively small Galactic volume
- Light and heavy nuclei come from different volumes
- Effective Galactic volume is shown for ~1 GV, and for electrons for ~1 TeV
- Assumed Kolmogorov model with the rigidity dependence of the diffusion coefficient with index δ~0.33

Effective propagation distance:

$\langle X \rangle \sim \sqrt{6D\tau} \sim 2.7$ kpc $R^{\delta/2} (A/12)^{-1/3}$

Helium: ~ 3.6 kpc $R^{\delta/2}$

Carbon: ~ 2.7 kpc $R^{\delta/2}$

Iron: ~ 1.6 kpc $R^{\delta/2}$

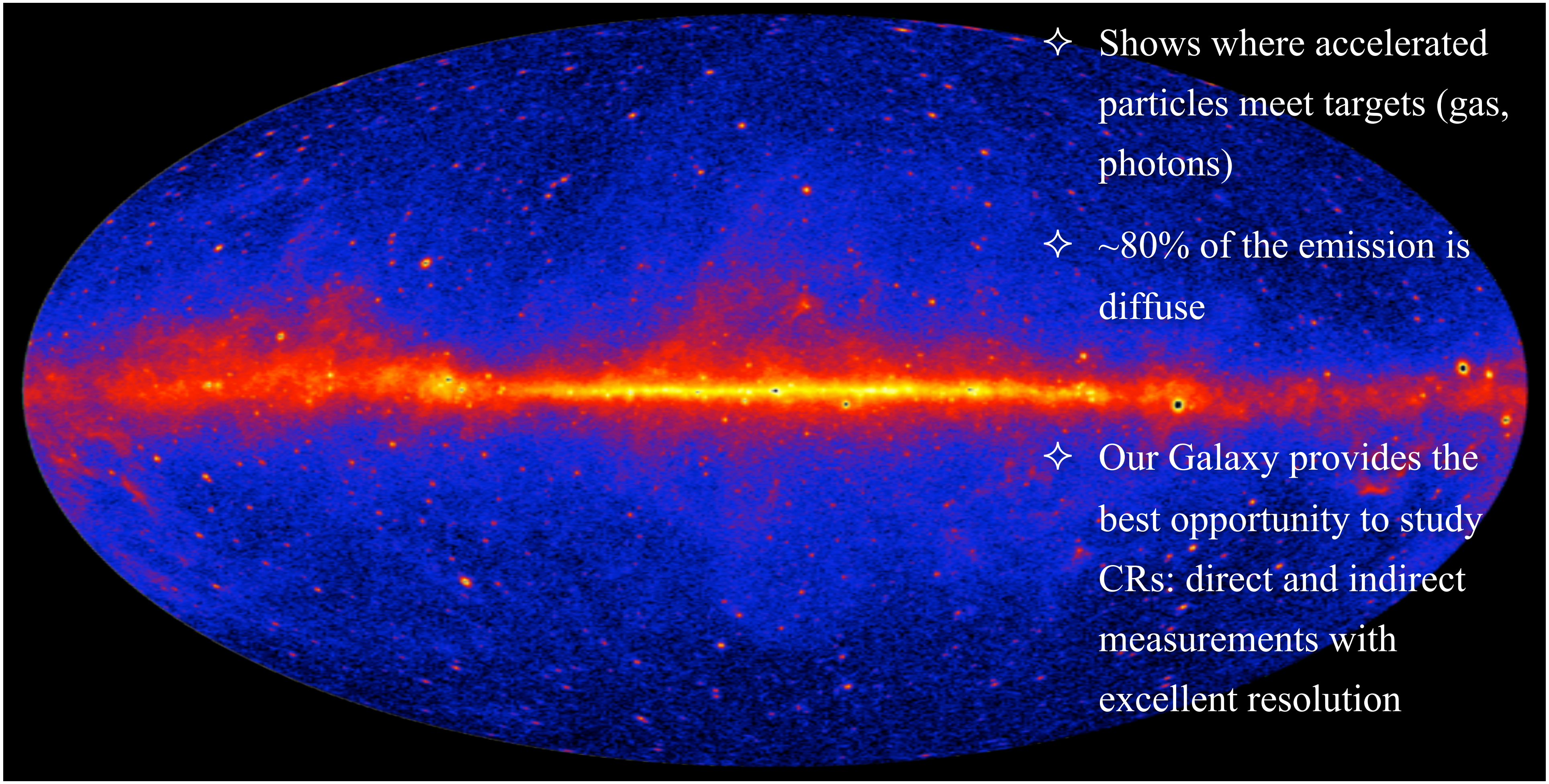
Lead: ~ 1.0 kpc $R^{\delta/2}$

(anti-) protons:~ 5.6 kpc $R^{\delta/2}$

electrons ~ 1 kpc $E_{12}^{-\delta/2}$

γ-rays: provide detailed information about *p*,*e* spectra in the whole Galaxy ~50 kpc

Fermi-LAT skymap >1 GeV, 48 months



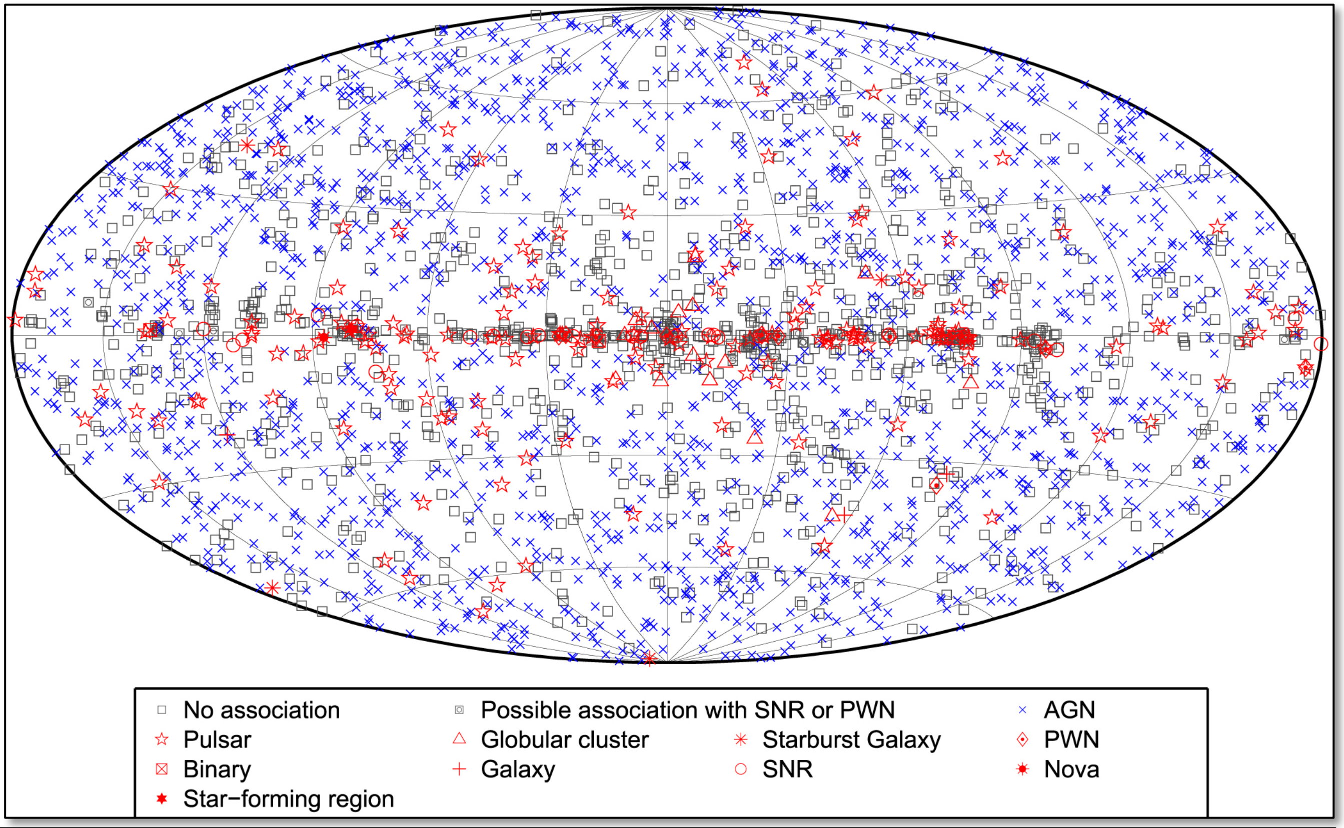
- Shows where accelerated particles meet targets (gas, photons)
- ~80% of the emission is diffuse
- Our Galaxy provides the best opportunity to study CRs: direct and indirect measurements with excellent resolution

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

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

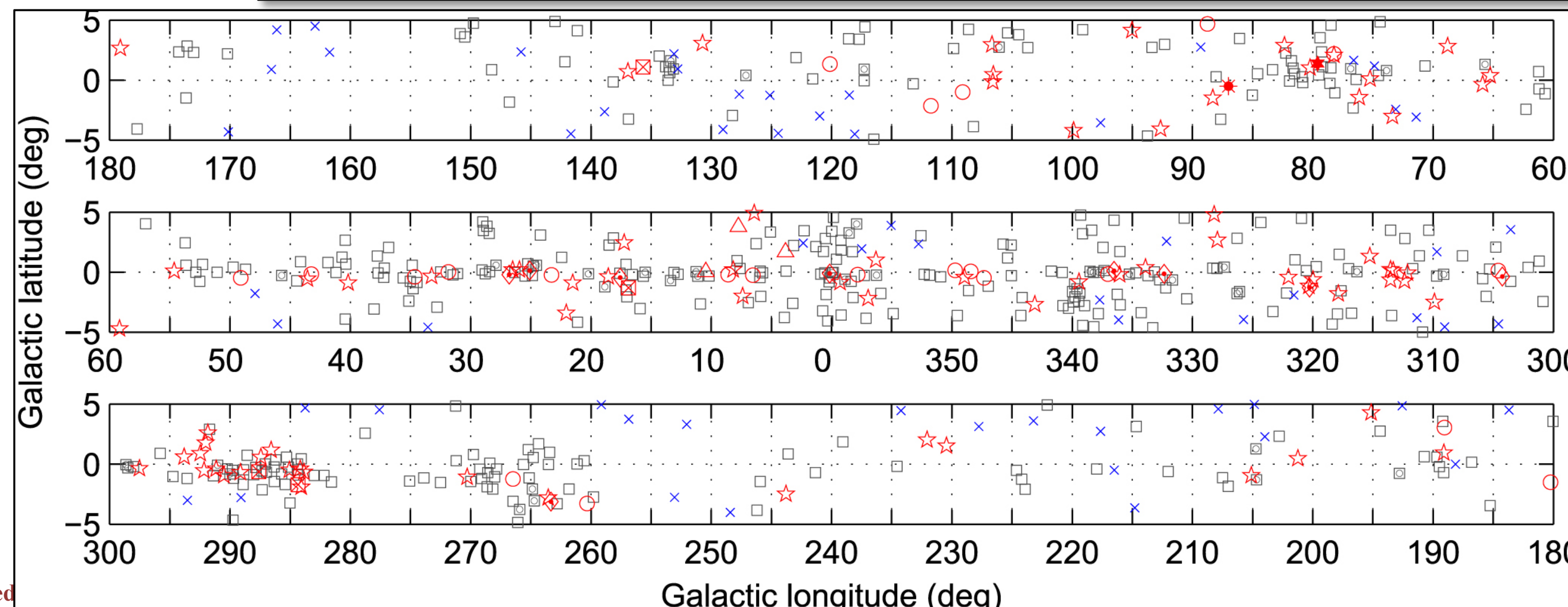
3FGL Catalog:

3033 sources



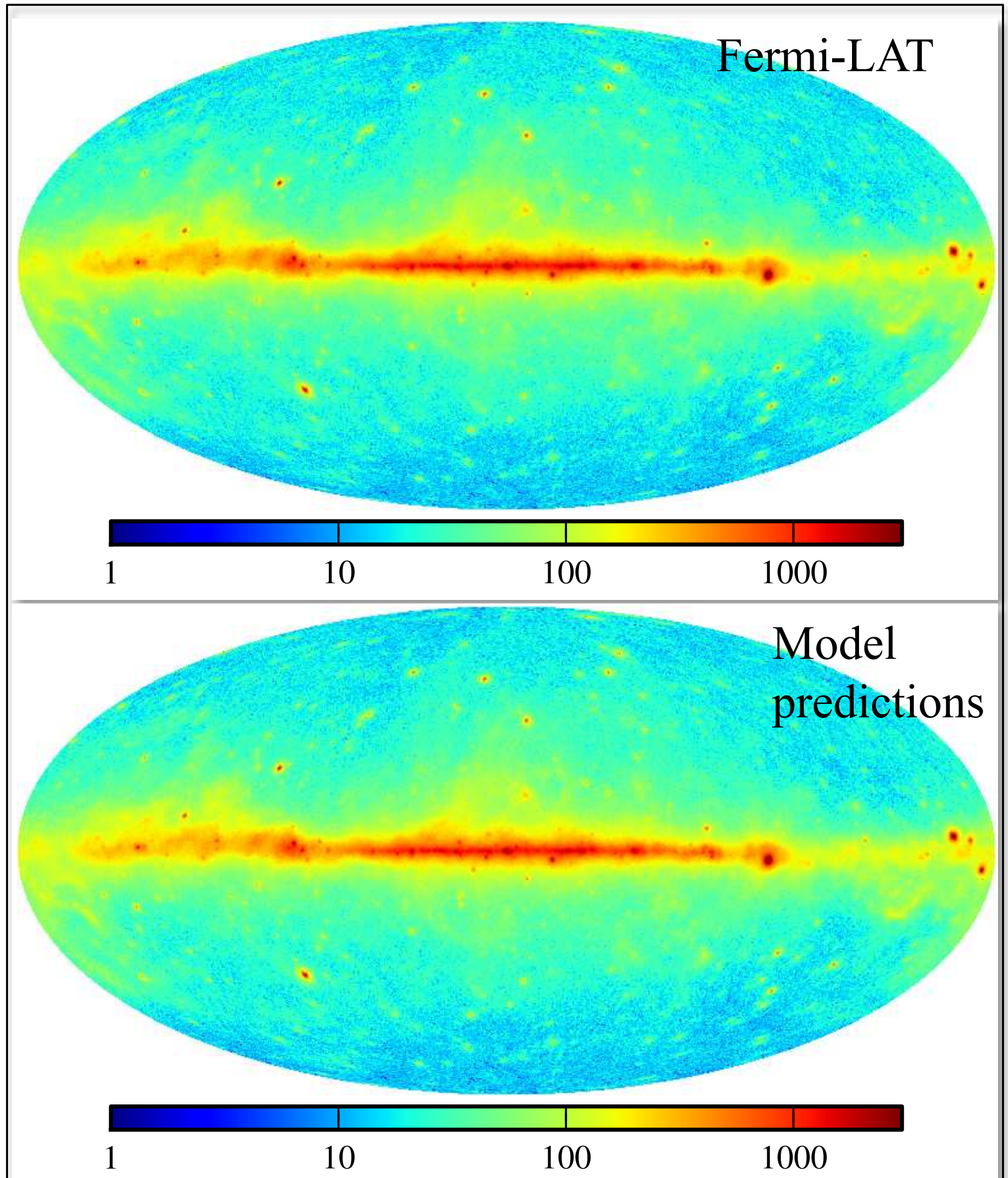
- ✧ 4 years (P7 reprocessed)
- ✧ 0.1 – 100 (300) GeV
- ✧ 5 (14) energy bins uniformly spaced in log E
- ✧ 20 extended sources
- ✧ Identified – 238
- ✧ Associated – 1745
- ✧ Unidentified ~1/3 of all sources

- ✧ More than tenfold increase vs. EGRET3 catalog!



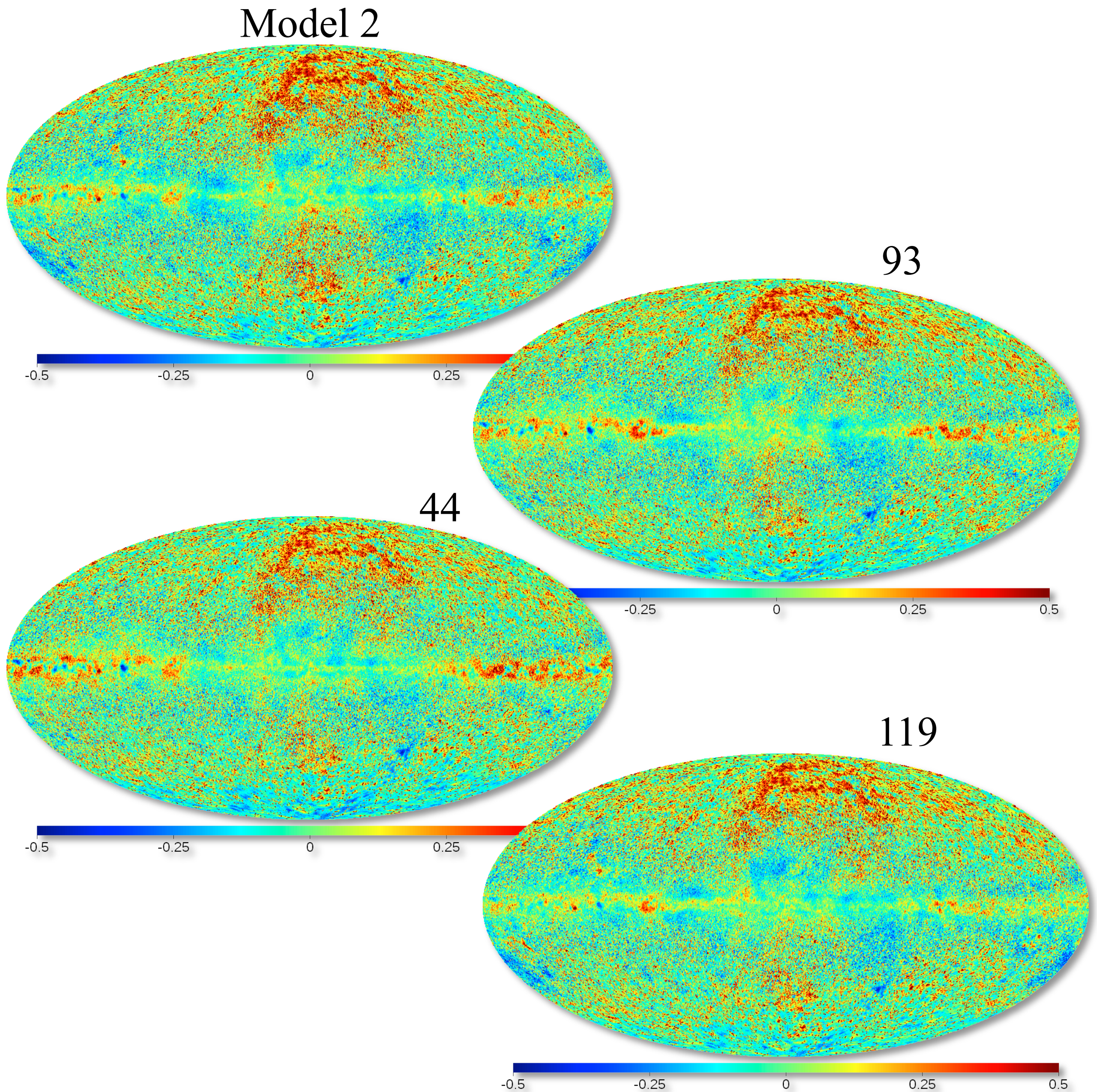
Diffuse γ-ray emission

- Fermi-LAT photon count in the range 200 MeV – 100 GeV
- Model calculations are made with GALPROP tuned to the local CR data
- Residual emission (obs.-model)/obs. is at the level %, up to ~10% in some places
- Excellent agreement between model predictions and observations



Ackermann+'2012

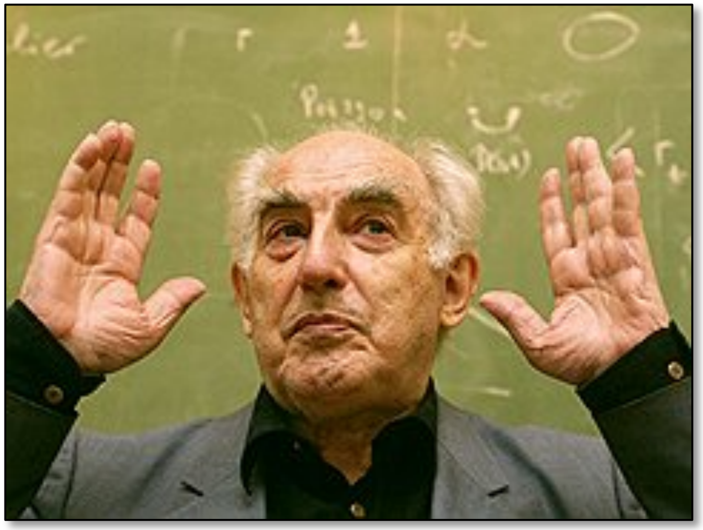
Distribution of the residual emission



- General agreement with models is good, but there are excesses at the level of a few %
- General features of CR propagation are reproduced well
- Indicate location of new sources/phenomena
- Differences in the distributions of the residual emission are due to the differences in the model parameters

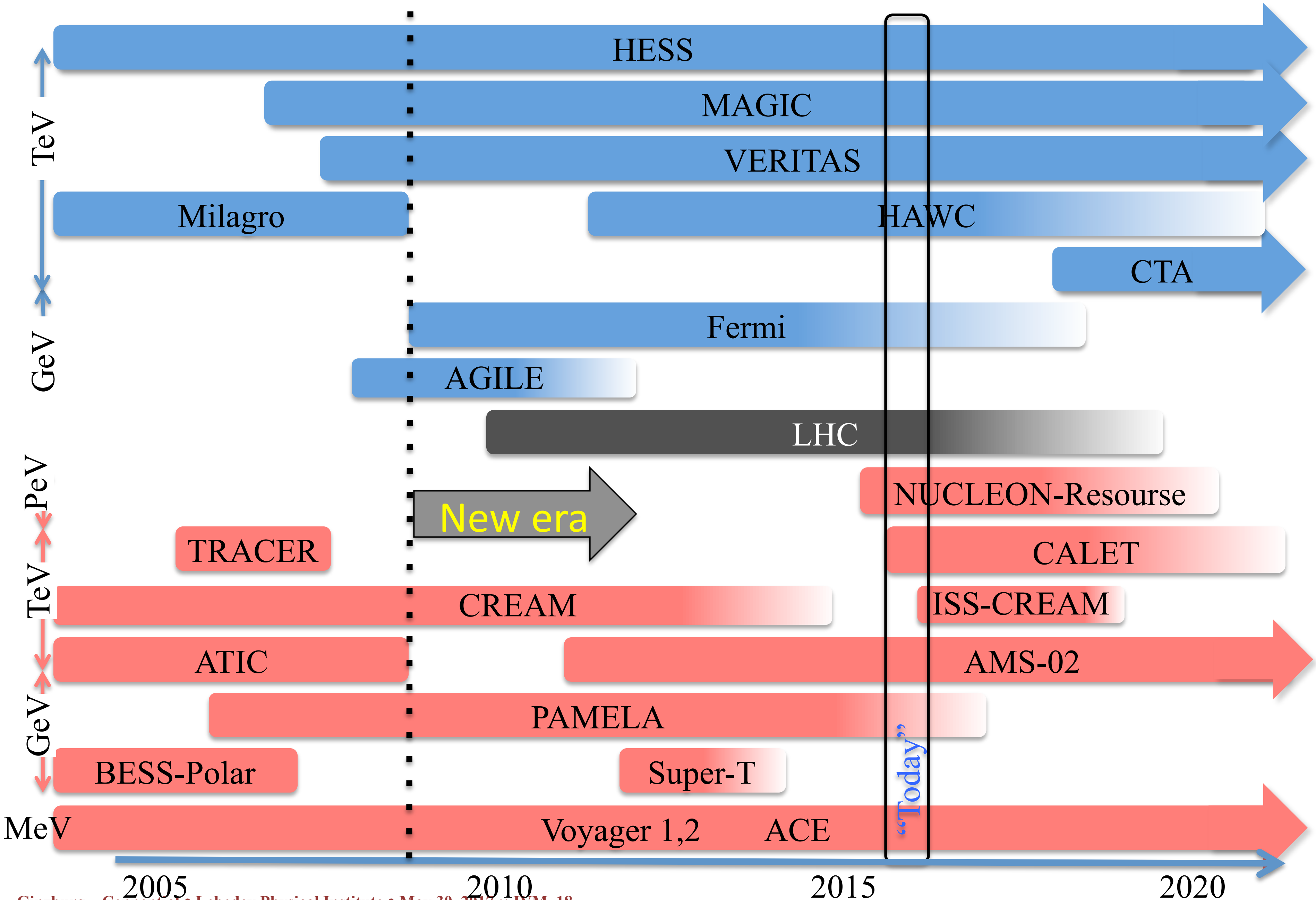
- Детали моделей:
  2: $\mathrm{SNR}^{Z}4^{R}20^{T}150^{C}5$
  44: $\mathrm{Lorimer}^{Z}6^{R}20^{T}\infty^{C}5$
  93: $\mathrm{Yusifov}^{Z}10^{R}30^{T}150^{C}2$
  119: $\mathrm{OB}^{Z}8^{R}30^{T}\infty^{C}2$

- It looks like we have a pretty good understanding of basic features of cosmic ray propagation in the Galaxy.
- Meanwhile, some of new cosmic ray data look contradictory in the existing framework, therefore, we are on the verge of a significant change in our understanding of the processes of acceleration and propagation of cosmic rays, i.e. of their origin.

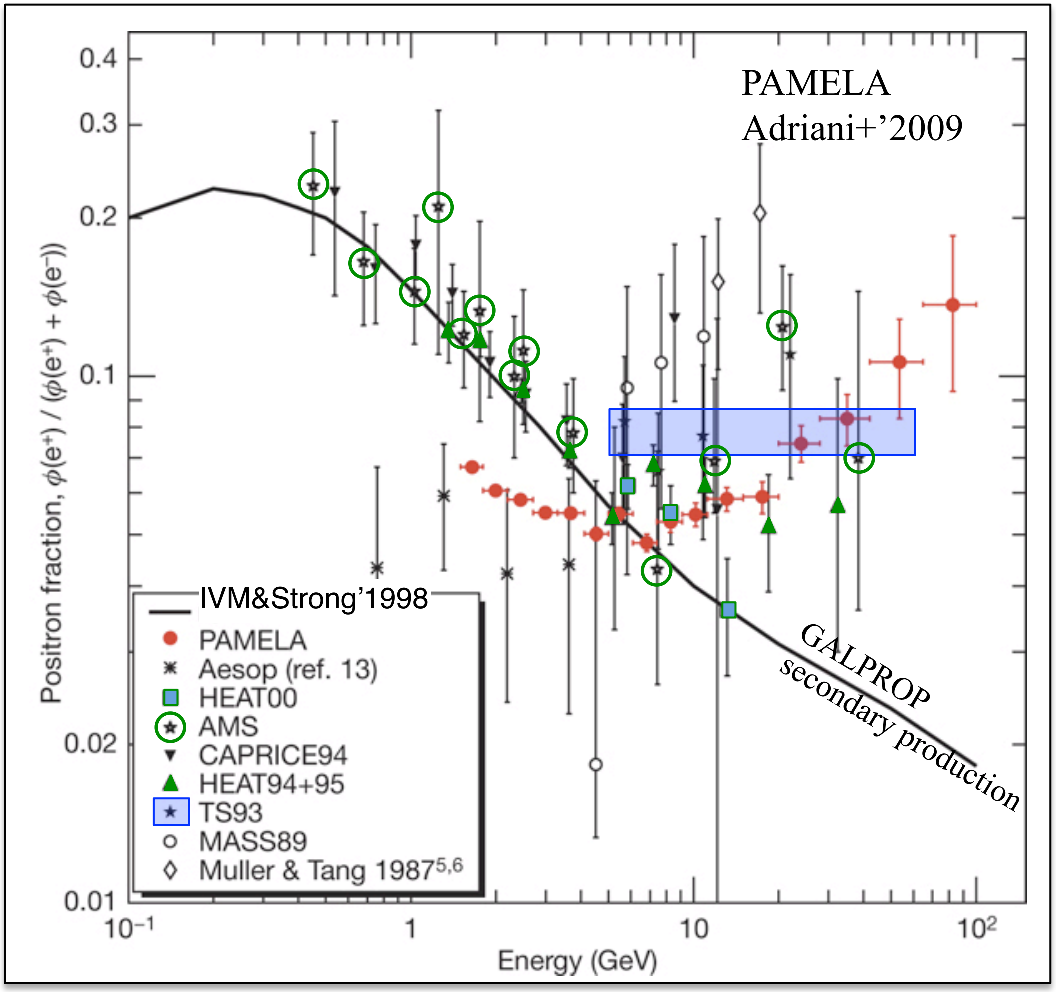


- It can be called a nightmare or a paradise for a theoretician – dependently on how you look at it. In any case, it is interesting.

Timeline of γ-ray, CR, and particle experiments

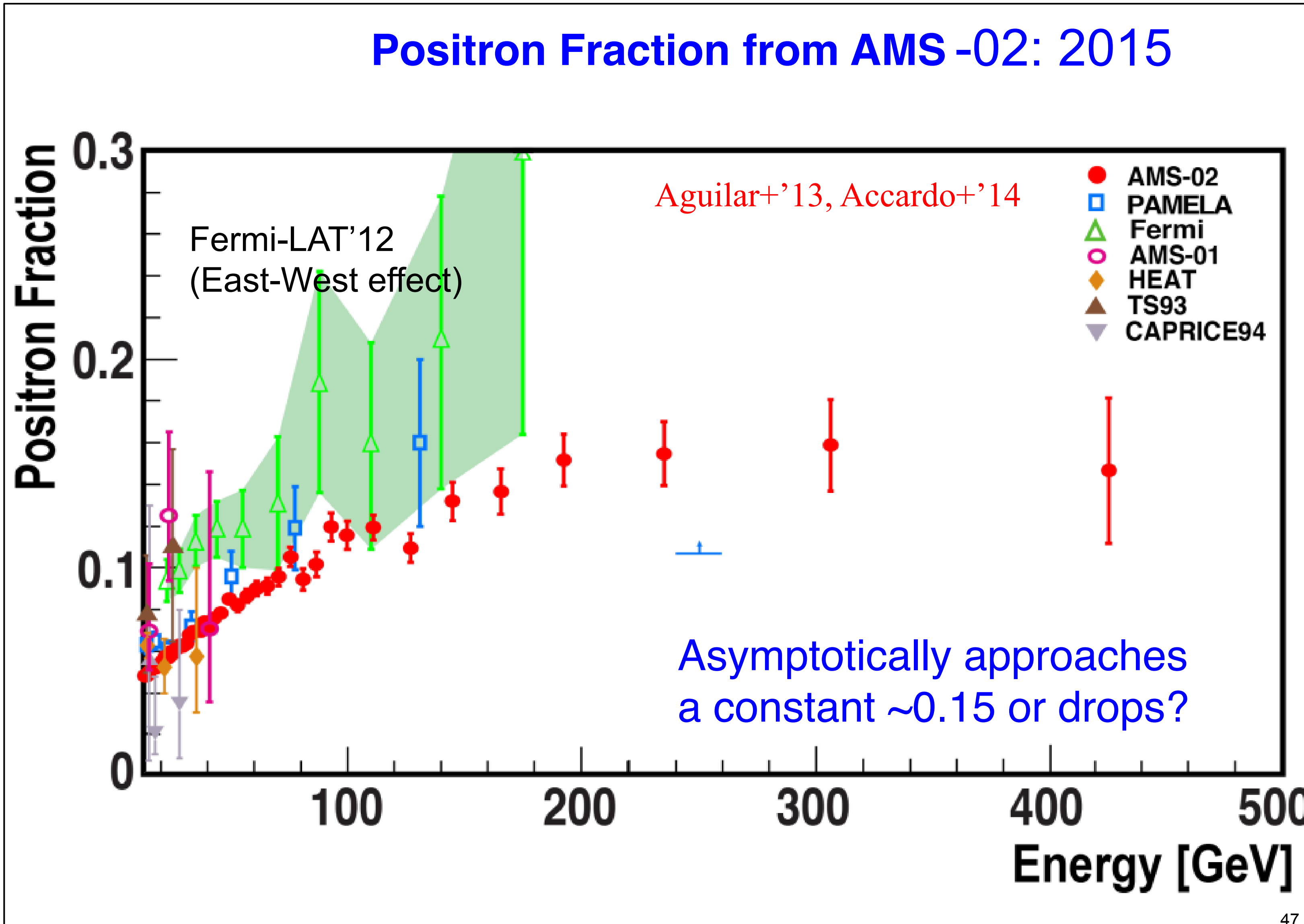


PAMELA discovery: Rising positron fraction

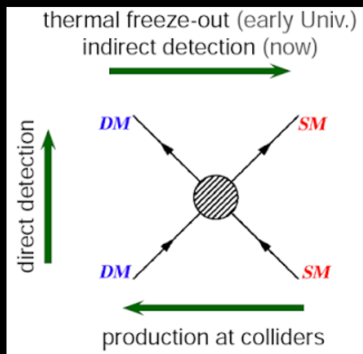


- ✧ TS93 (Golden+'96): flat positron fraction 0.078±0.016 in the range 5-60 GeV
- ✧ HEAT-94,95,00 (Beatty+'04): "a small positron flux of nonstandard origin"
- ✧ PAMELA team reported a clear and very significant rise in the positron fraction compared to the "standard" model predictions
- ✧ "Standard" model:
  - ✦ Secondary production in the ISM
  - ✦ Steady state
  - ✦ Smooth CR source distribution

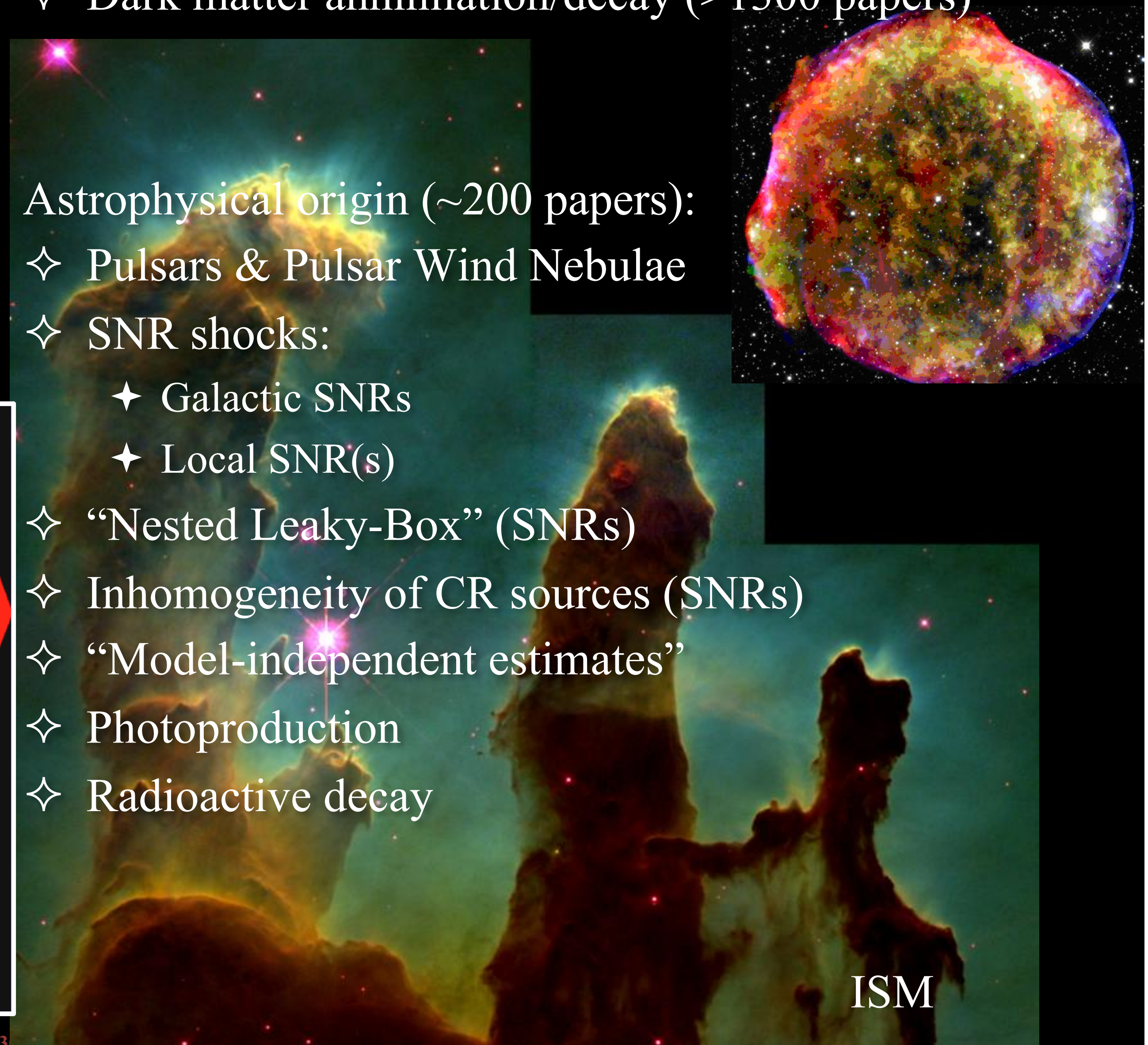
AMS-02: measurement of the positron fraction



Interpretations



✧ Dark matter annihilation/decay (>1300 papers)



Astrophysical origin (~200 papers):

✧ Pulsars & Pulsar Wind Nebulae

✧ SNR shocks:

  ✦ Galactic SNRs

  ✦ Local SNR(s)

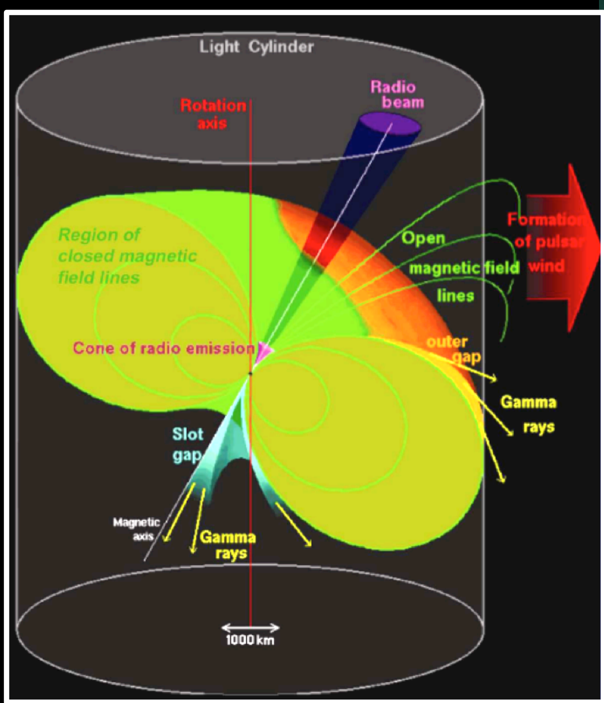
✧ "Nested Leaky-Box" (SNRs)

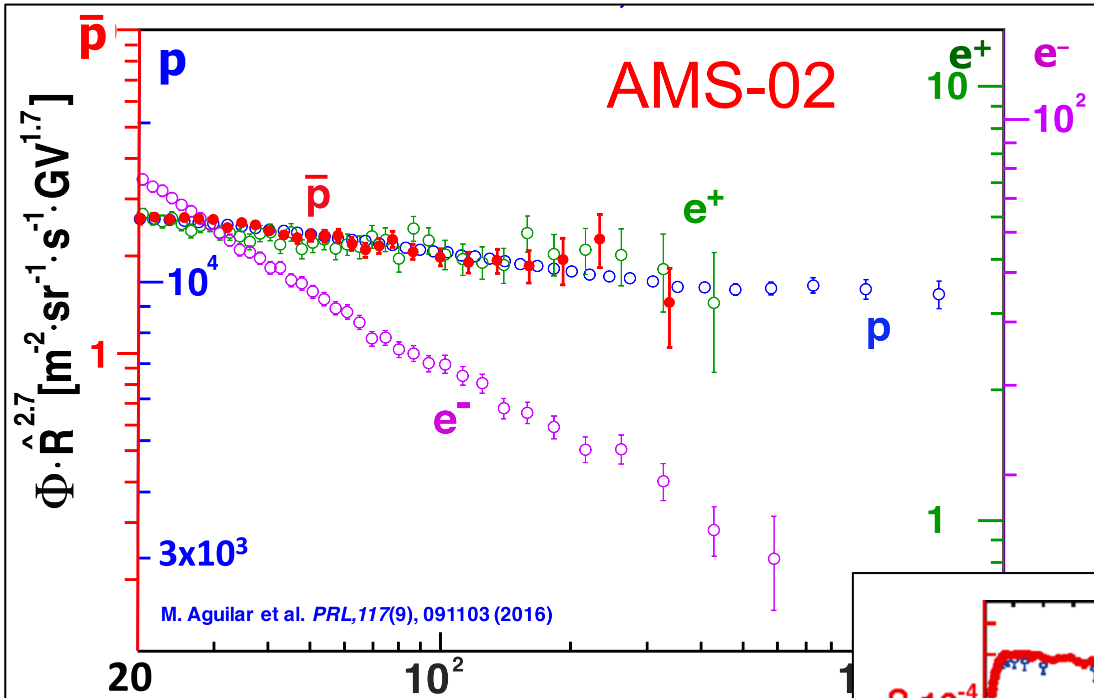
✧ Inhomogeneity of CR sources (SNRs)

✧ "Model-independent estimates"

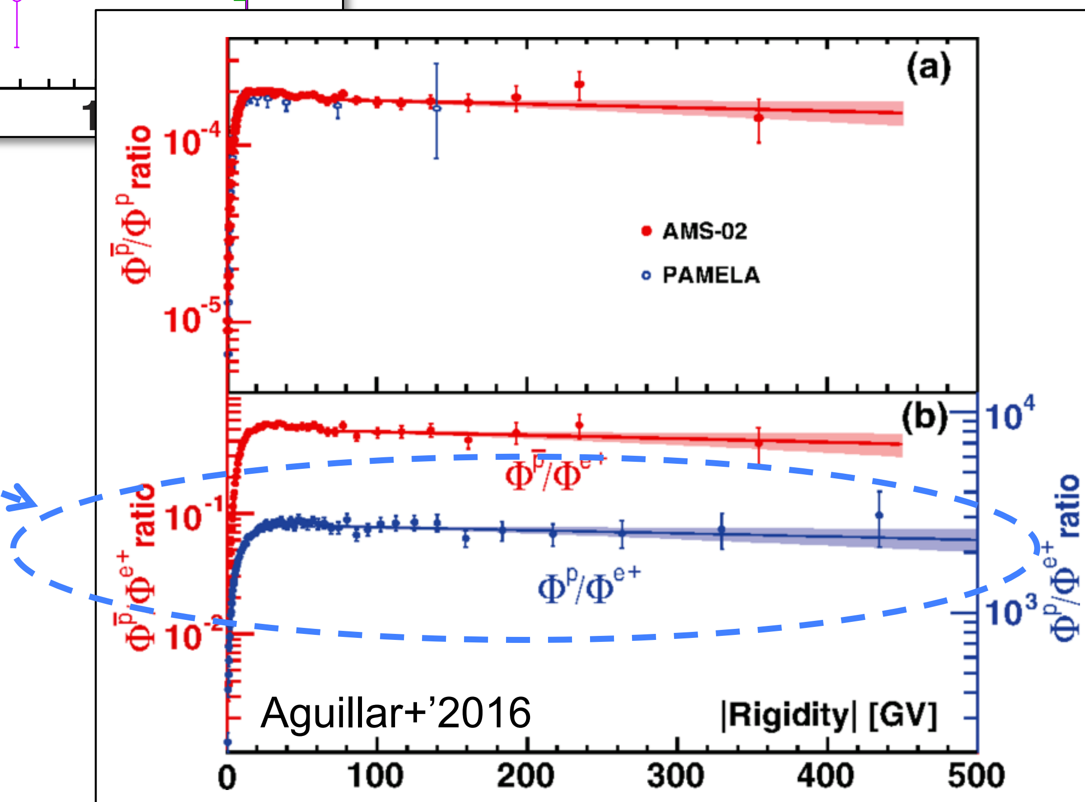
✧ Photoproduction

✧ Radioactive decay



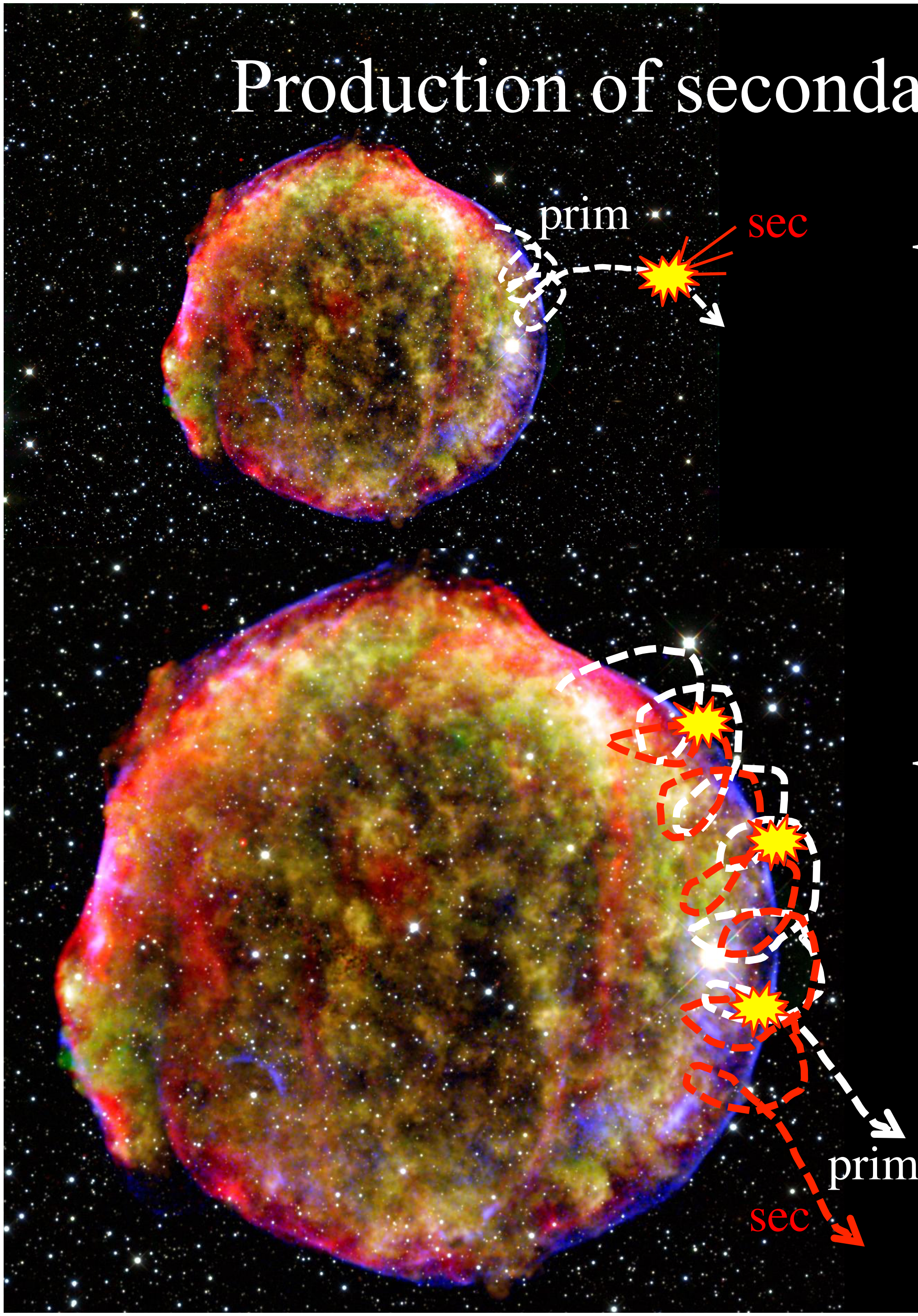


Unexpected!



- ✧ If excess positrons are produced in pulsars or DM decays why the p/e^+ ratio is flat?
- ✧ The flat p/e^+ ratio perhaps indicates a common origin of p and e^+!

Production of secondaries



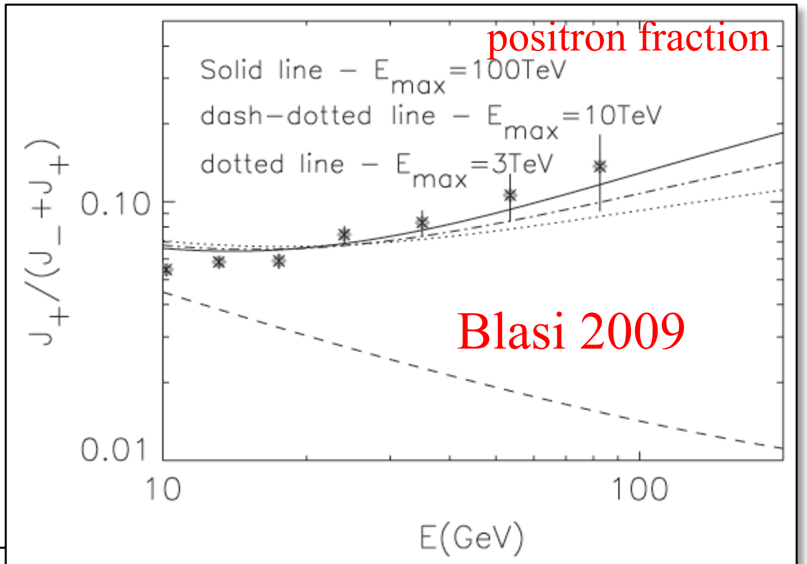
✧ In the "standard" scenario, secondary species are produced in the interstellar medium – softer spectrum at all energies

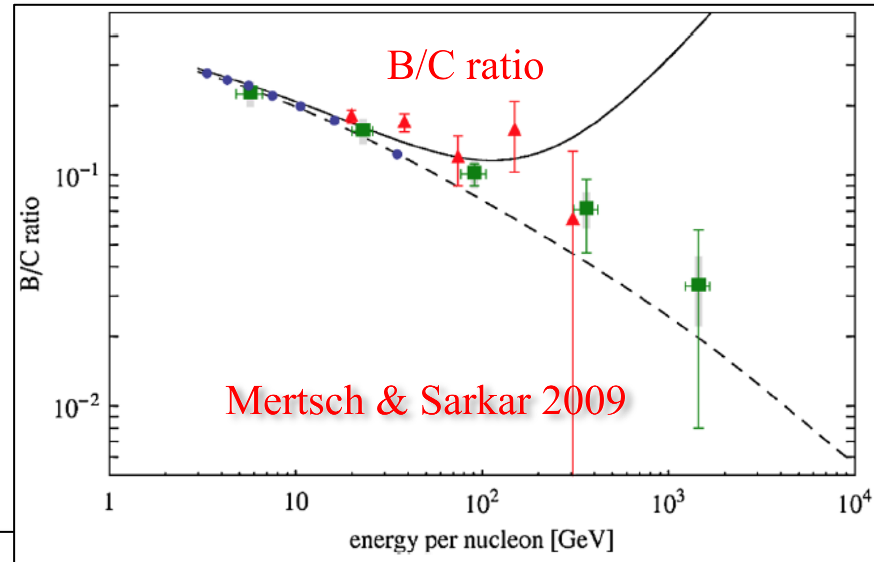
✧ In the SNR scenario, some proportion of secondary species is produced in the shock and then accelerated together with primary species – harder spectrum at <u>high energies</u>

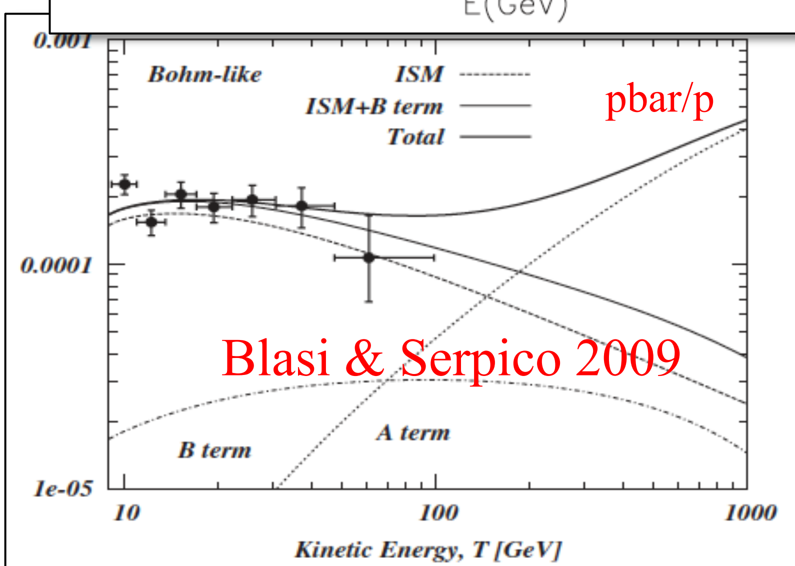
Berezkho+'2003

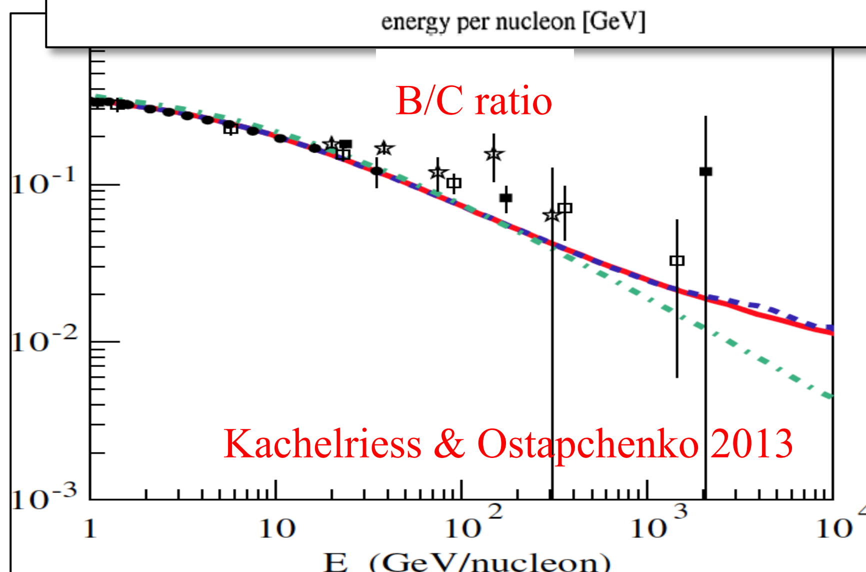
Secondary production in a SNR shock

- The model assumptions are somewhat different, but all models predict a rise in the secondary products
- The rise in pbar/p and B/C ratios become more subtle as the higher energy data become available



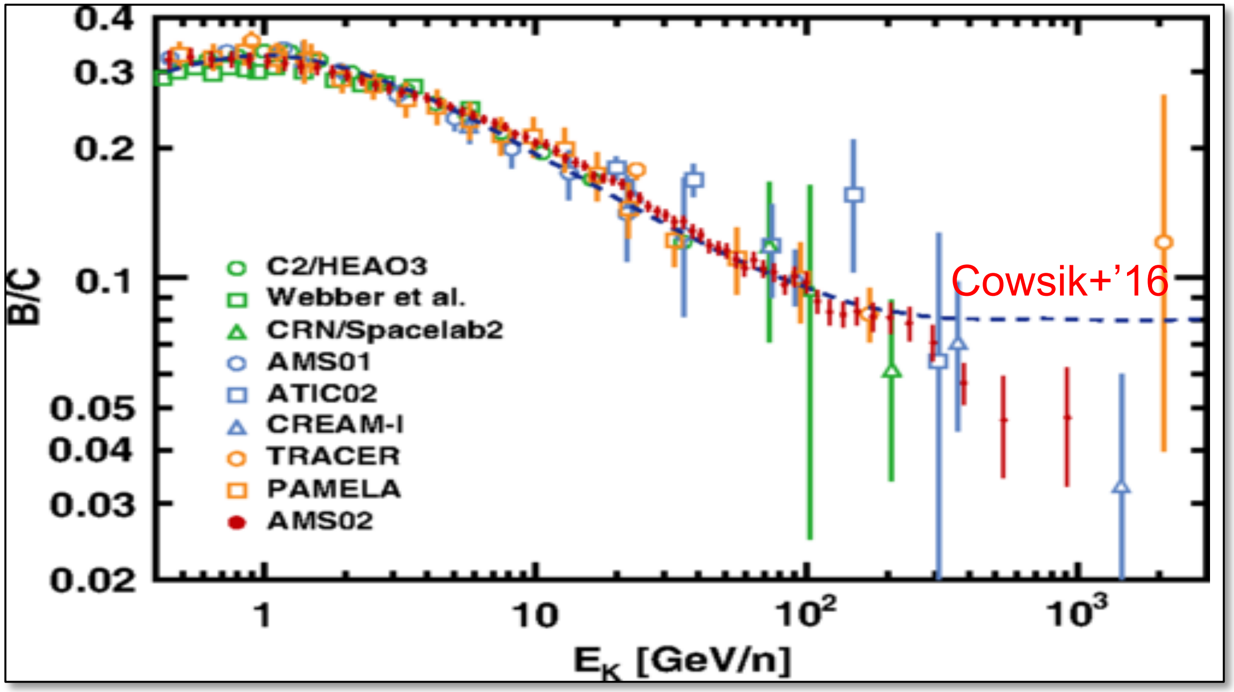


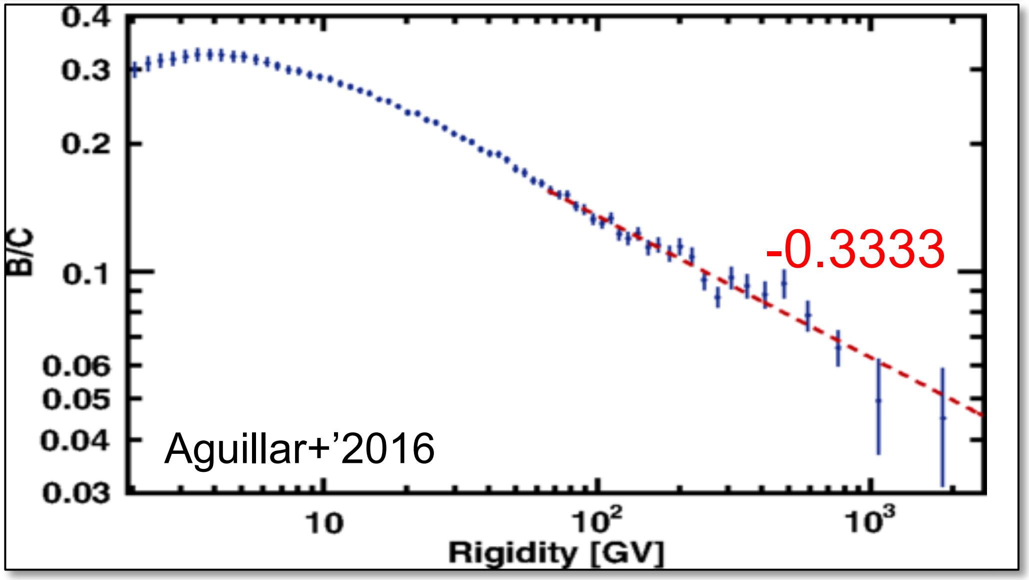




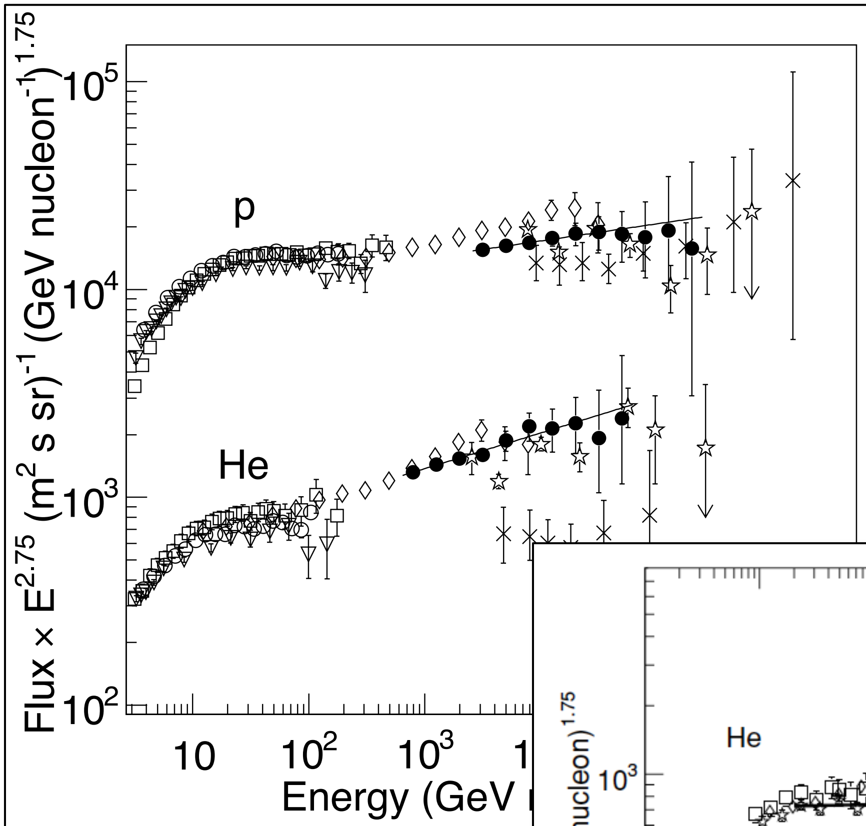
AMS-02: B/C ratio

- ✧ Contrary to expectations, the B/C ratio is monotonically falling up to 2 TV
- ✧ The “structure” is limited-statistics related and is not significant
- ✧ The dashed red line is a plain fit to the data that yields an index 0.3333

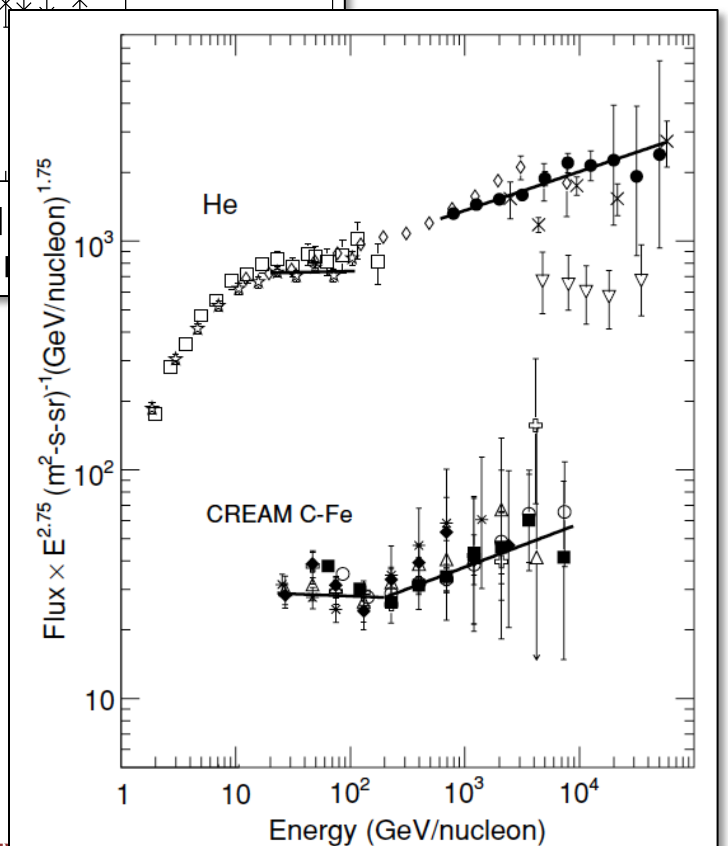




“Discrepant hardening” breaks in p and He spectra

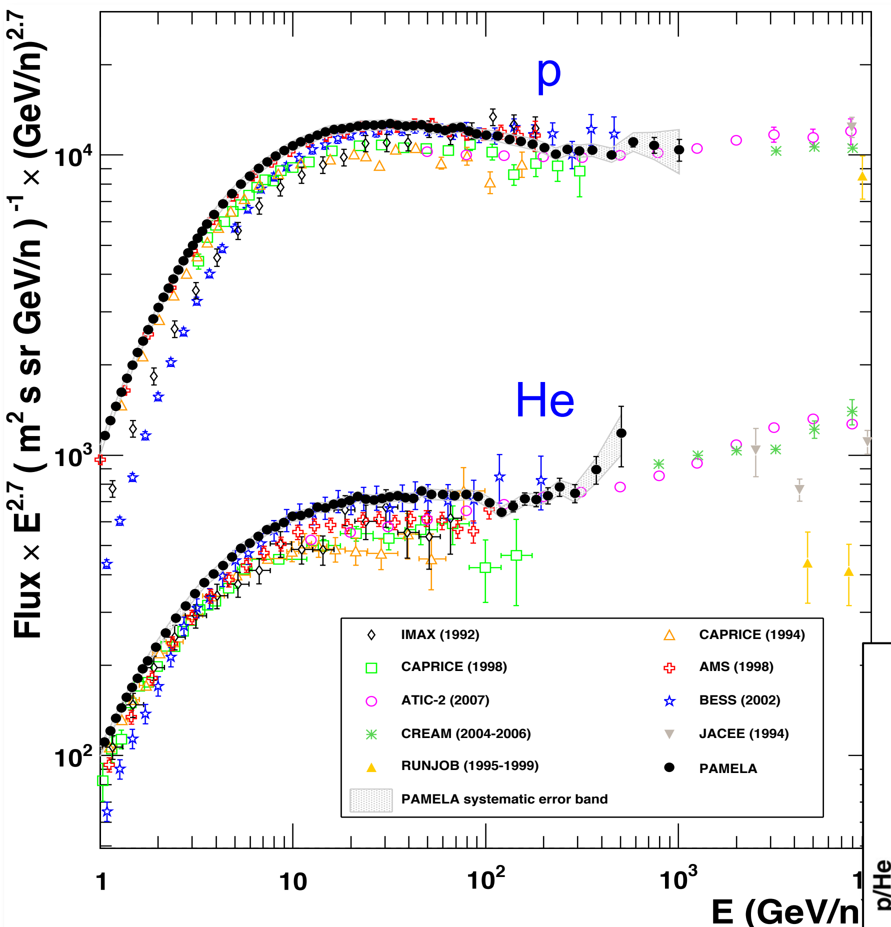


CREAM’2010

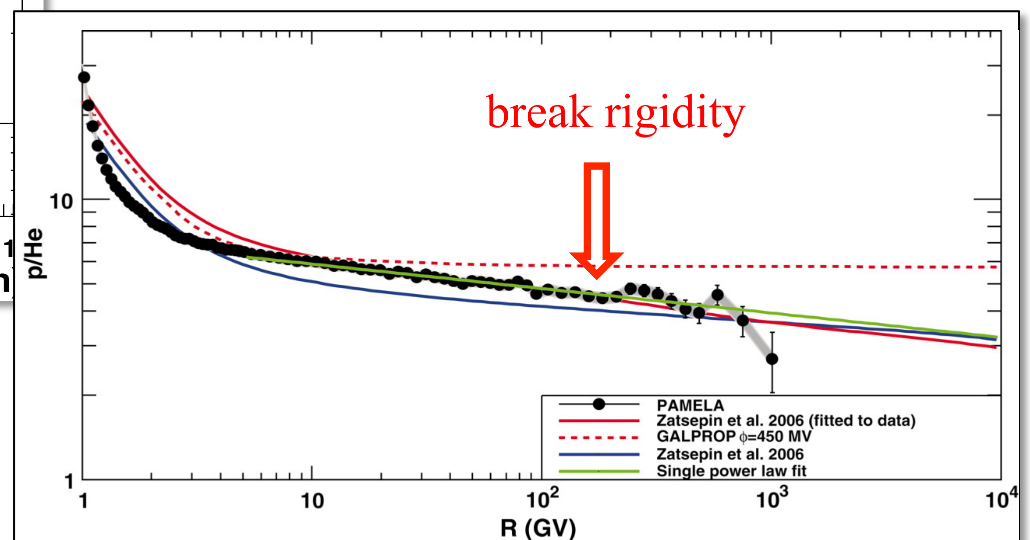


- ✧ First noticed in CREAM data, hints were present in earlier data
- ✧ Spectrum of He is flatter than spectrum of protons
- ✧ Perhaps similar breaks exist in spectra of heavier nuclei

PAMELA: definitive evidence of the breaks

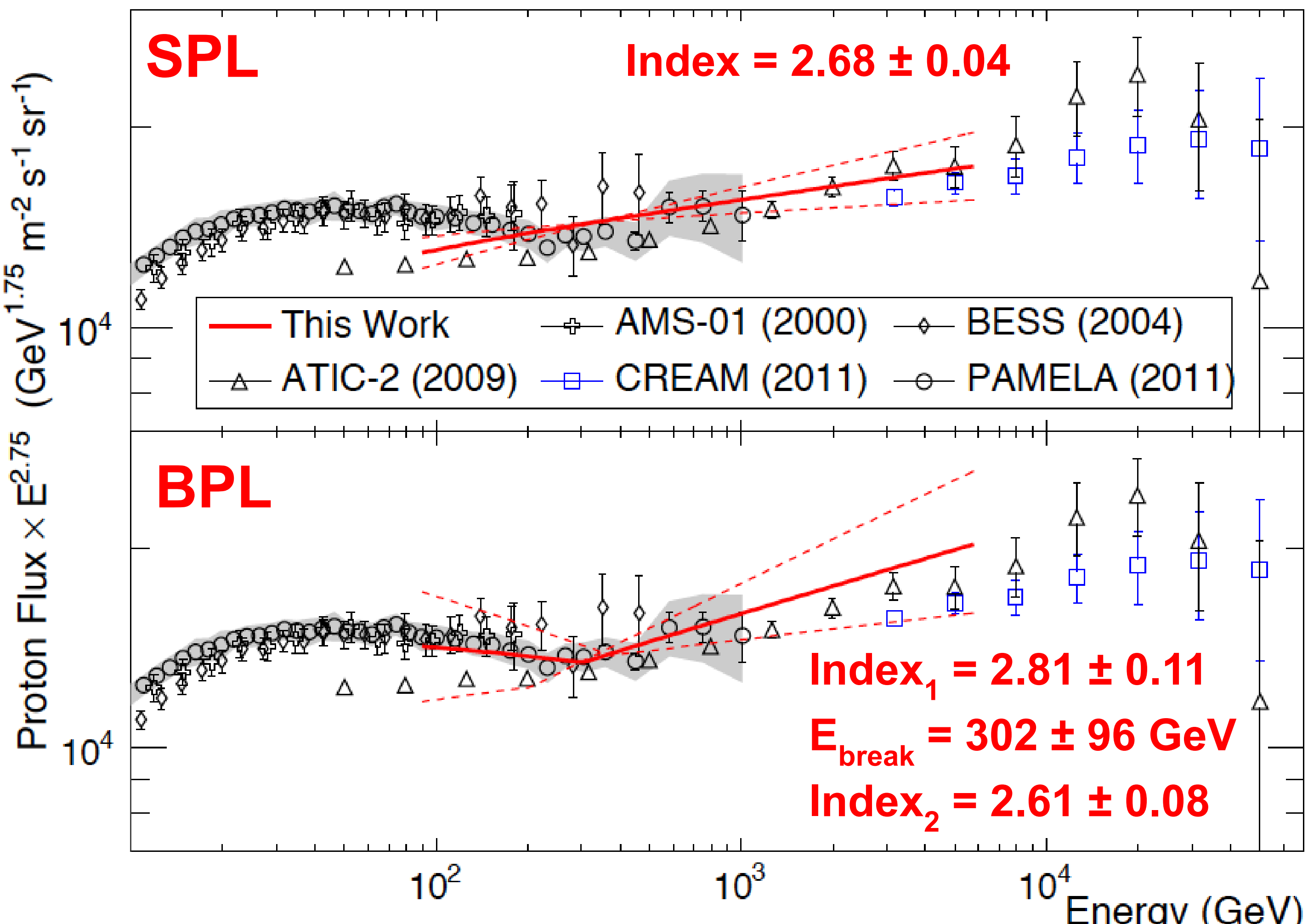


✧ Breaks are at the same rigidity pointing to the same origin of the breaks



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

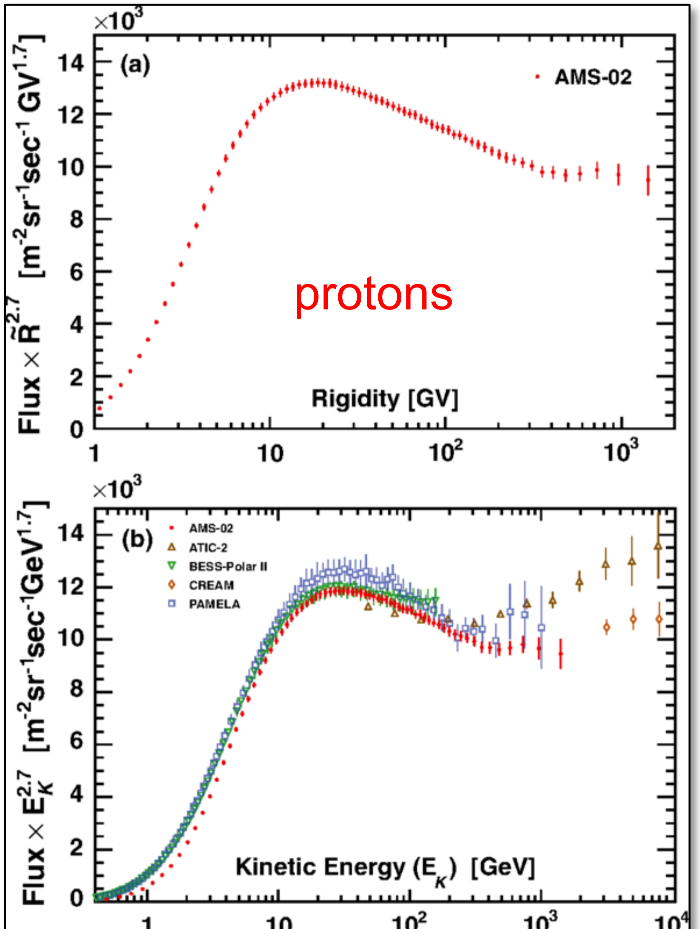
Fermi – Earth limb observations

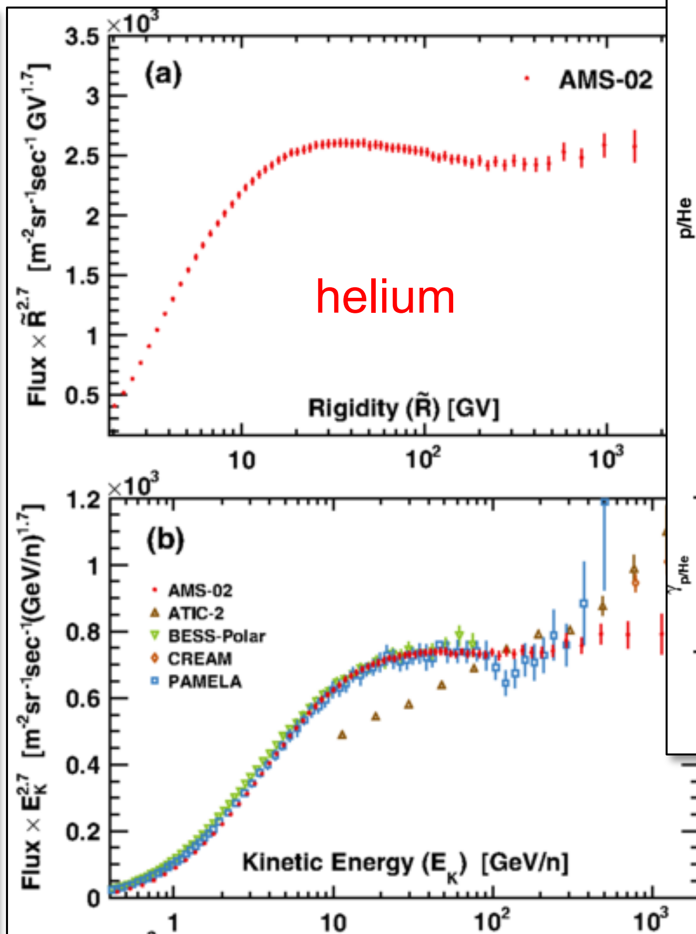


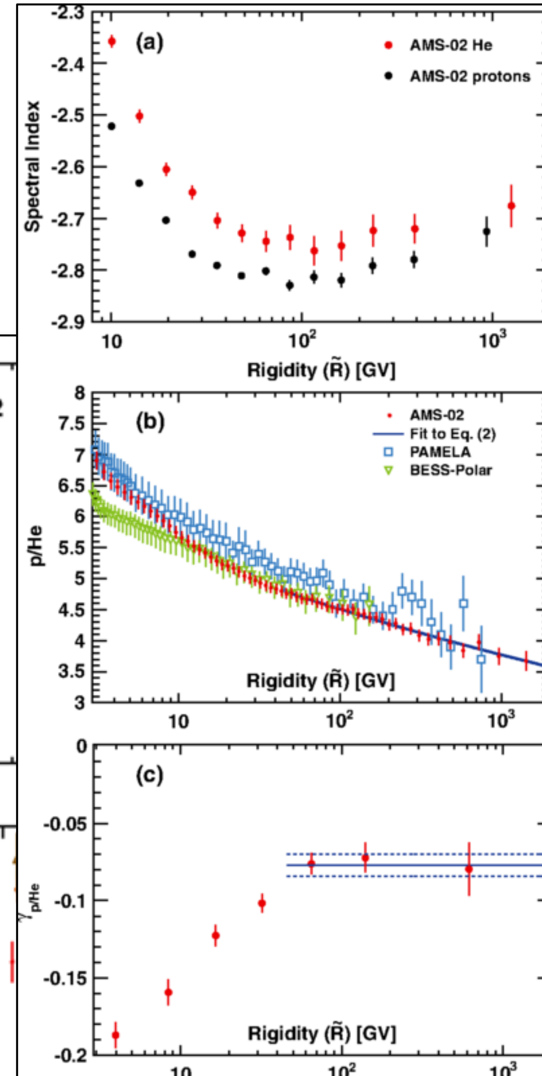
Ackermann+'14 (PRL: 112, 151103)

AMS-02 study of the break structure

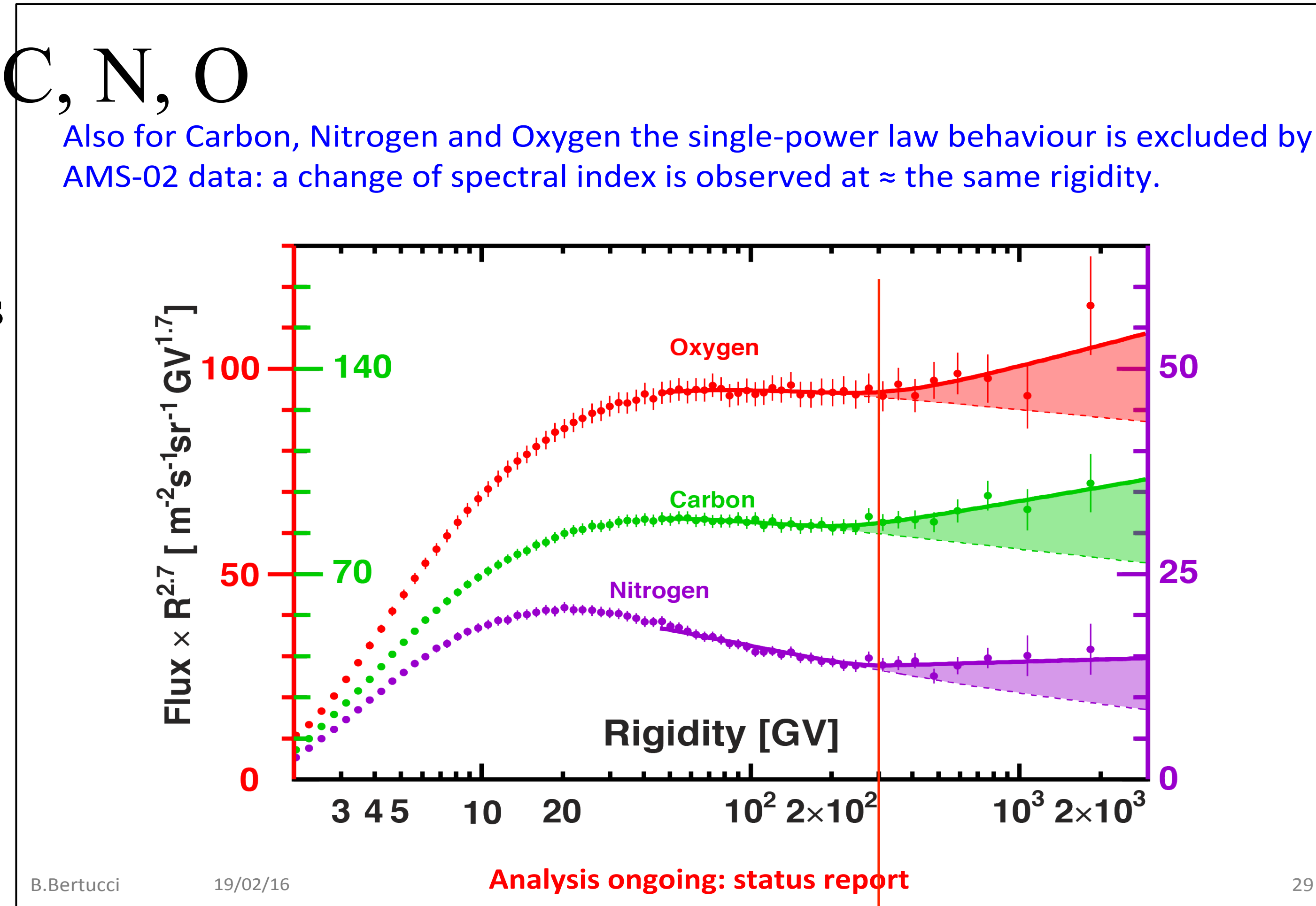
- ✧ Breaks are smooth at the same rigidity
- ✧ p/He ratio shows no structure
- ✧ Difference in indices of p, He: $\Delta\delta \sim 0.1$ over large energy range
- ✧ Why?



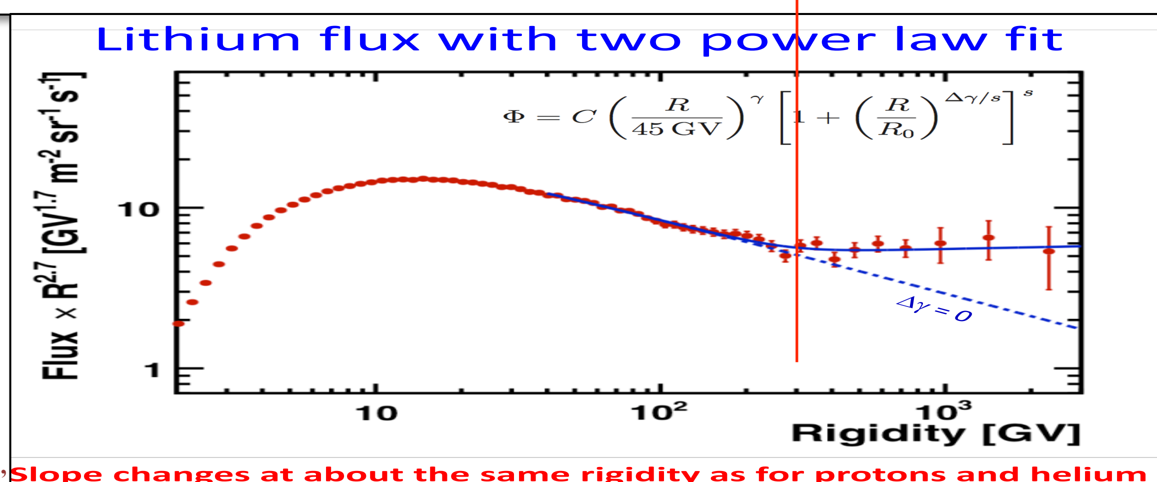




Breaks in Li, C, N, O

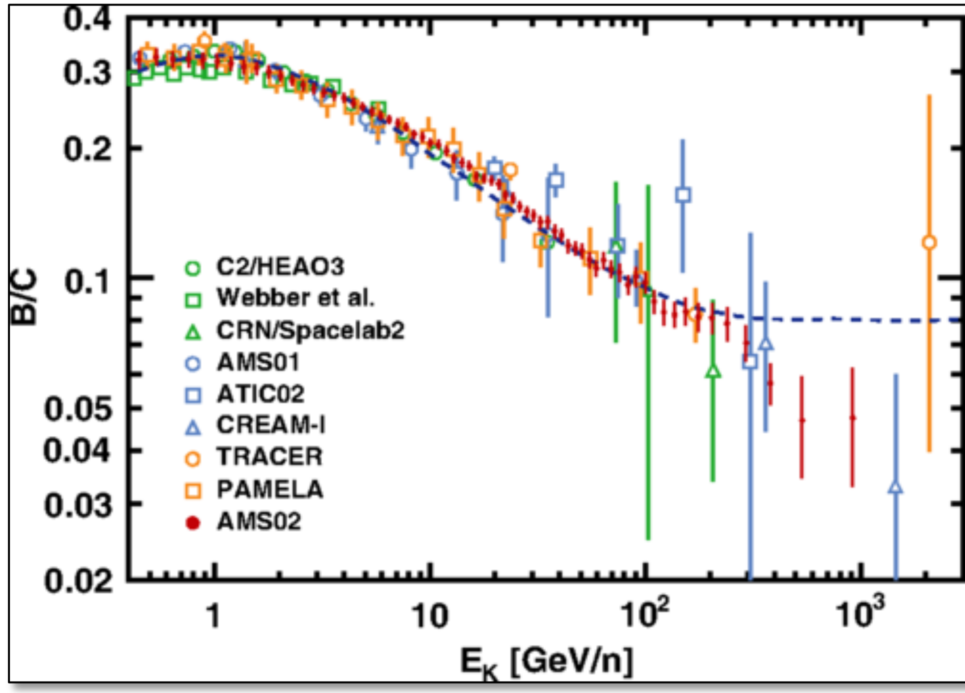


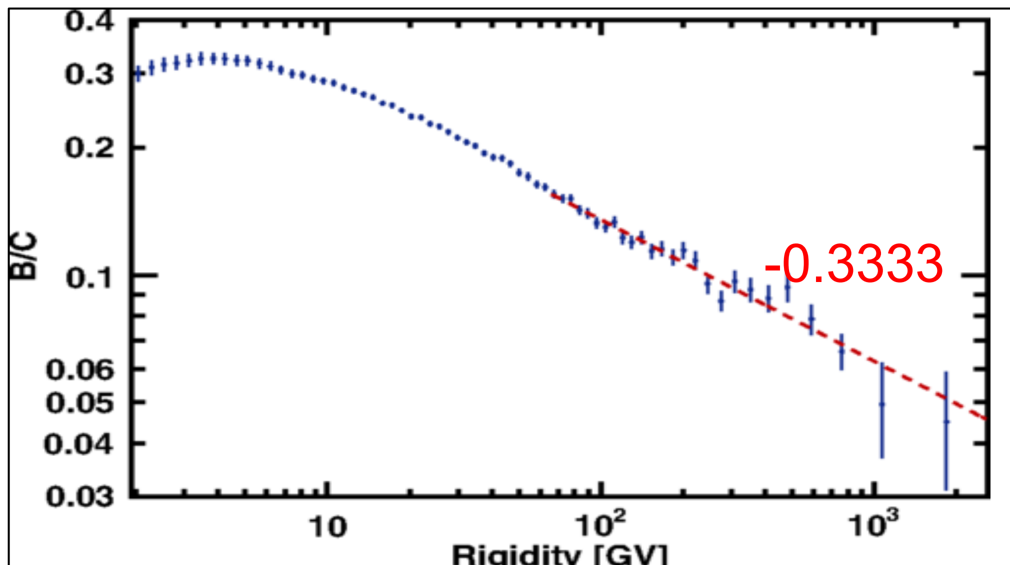
- ✧ Finally breaks in CNO are found at the same rigidity as earlier in p, He, Li
- ✧ A significant proportion of Nitrogen is secondary – so steeper spectrum
- ✧ The break in N is less pronounced than in C & O
- ✧ Li is 100% secondary and has a stronger break, but shown on a logarithmic Flux-scale



AMS-02: B/C ratio

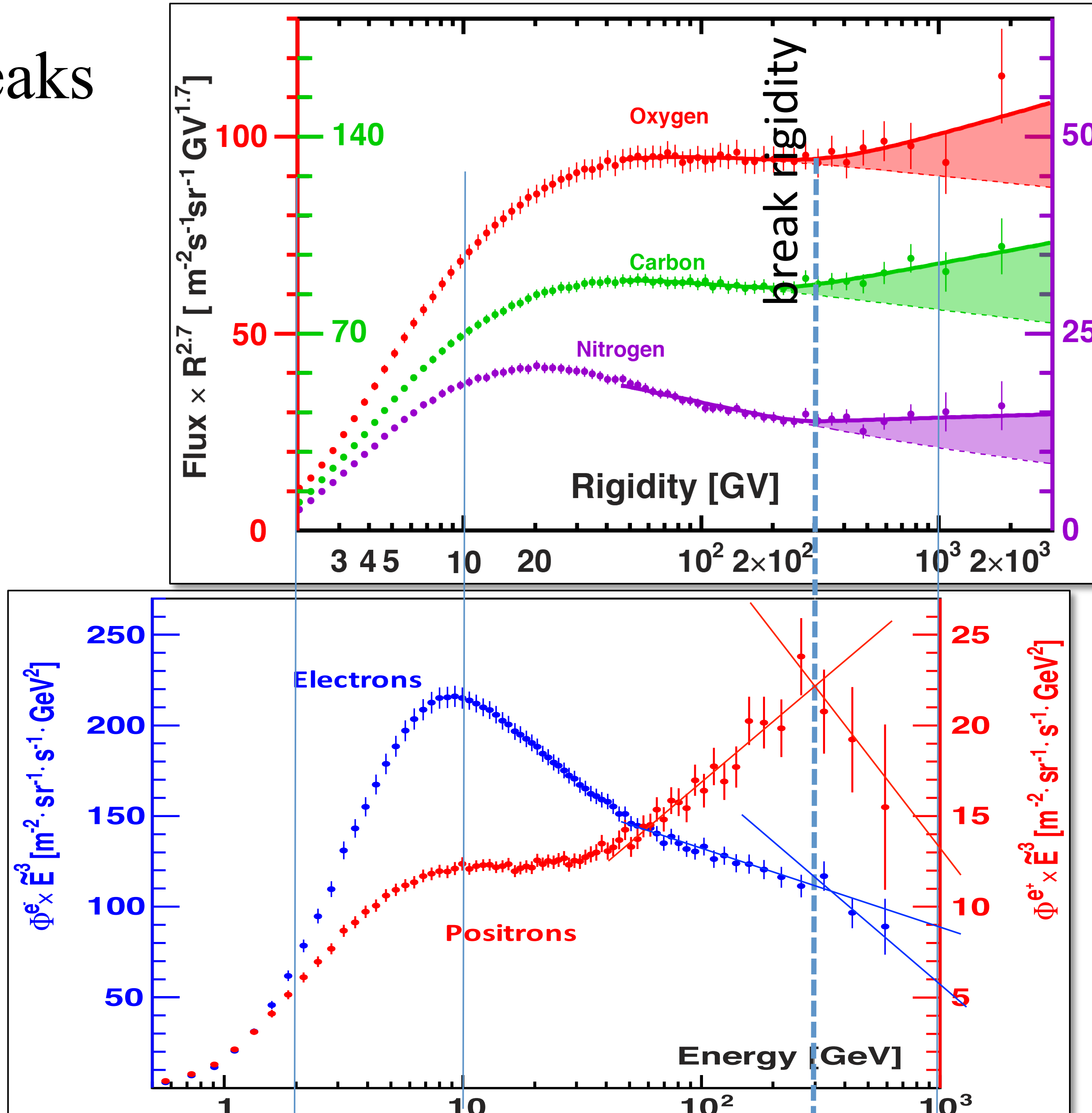
- Contrary to expectations, the B/C ratio is monotonically falling up to 2 TV
- The "structure" is not significant
- The dashed red line is a fit that yields an index 0.3333
- If C has the "break", B should also have it!
- and the breaks in C and B must be the same!
- but B is 100% secondary…





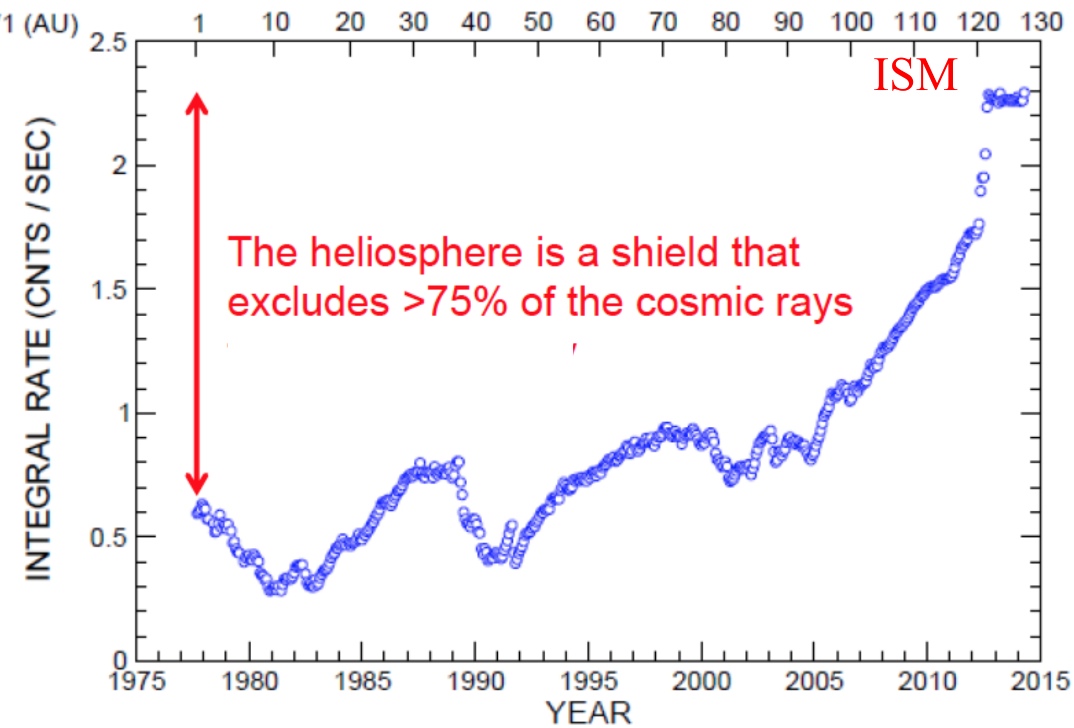
More on breaks

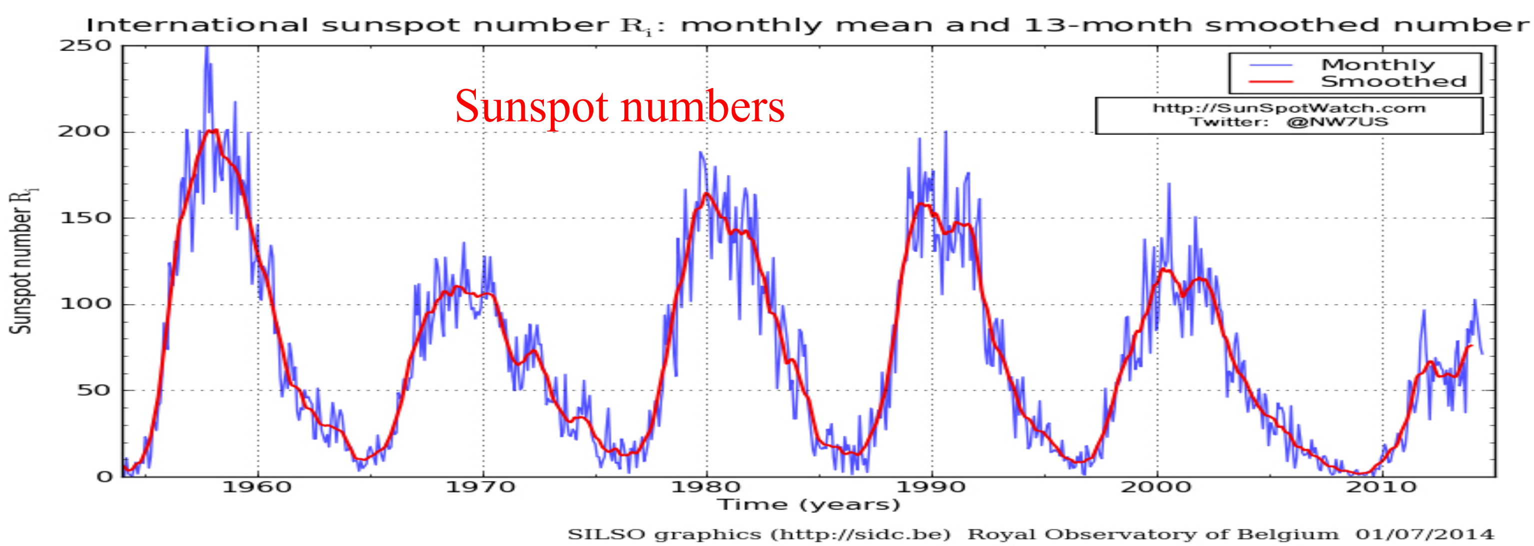
- The breaks are at the same rigidity – indicates that the same (unknown) mechanism works for p, He, and heavier elements
- What's about electrons and/or positrons?
- The breaks are rather opposite – spectral steepening (I am not saying that they are significant)
- Why?



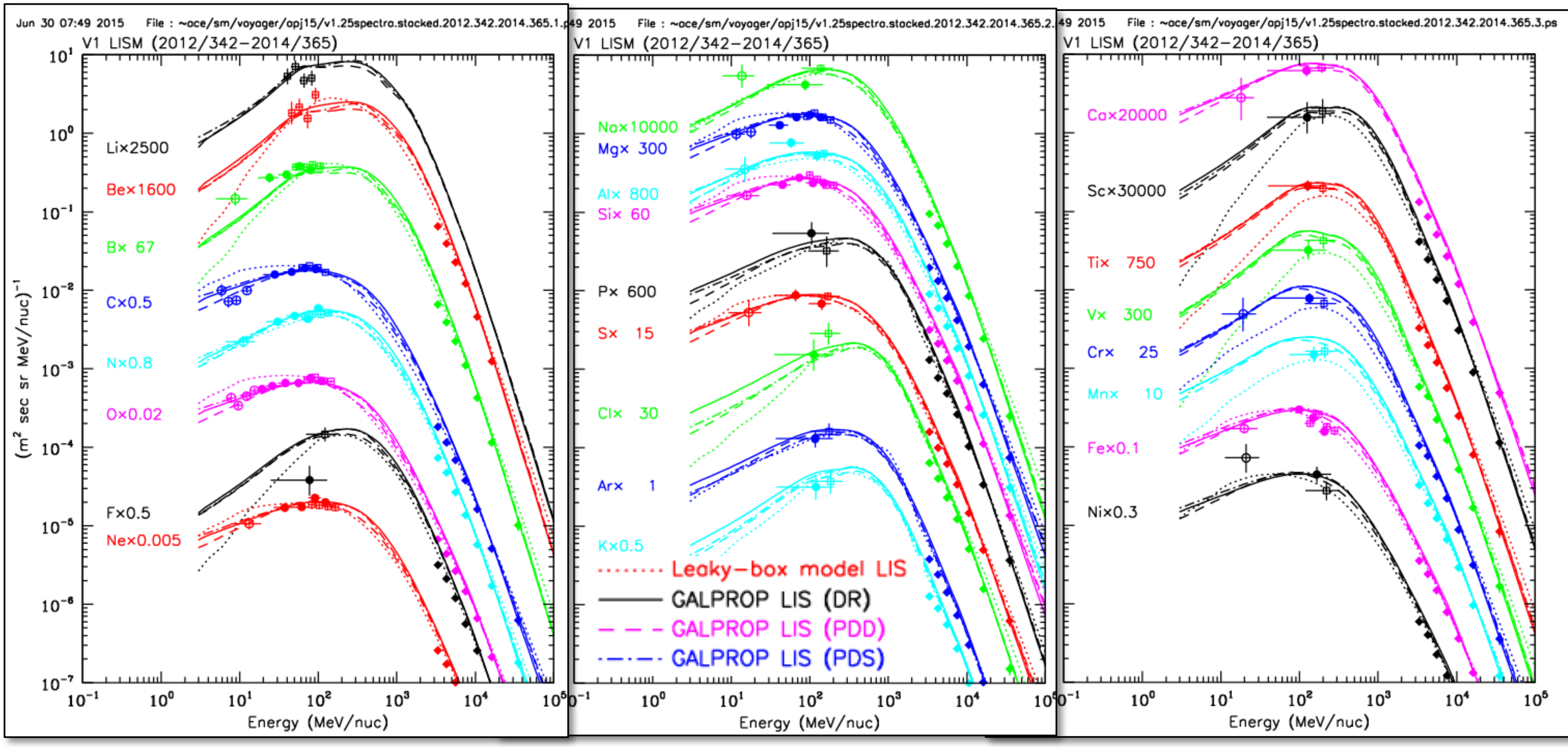
Voyager 1 counting rate in the heliosphere and beyond

- CR flux along the Voyager 1 path
- Note some delay relative to the sunspot maxima
- Weak last solar max helped to reach the ISM faster – smaller size of the heliosphere





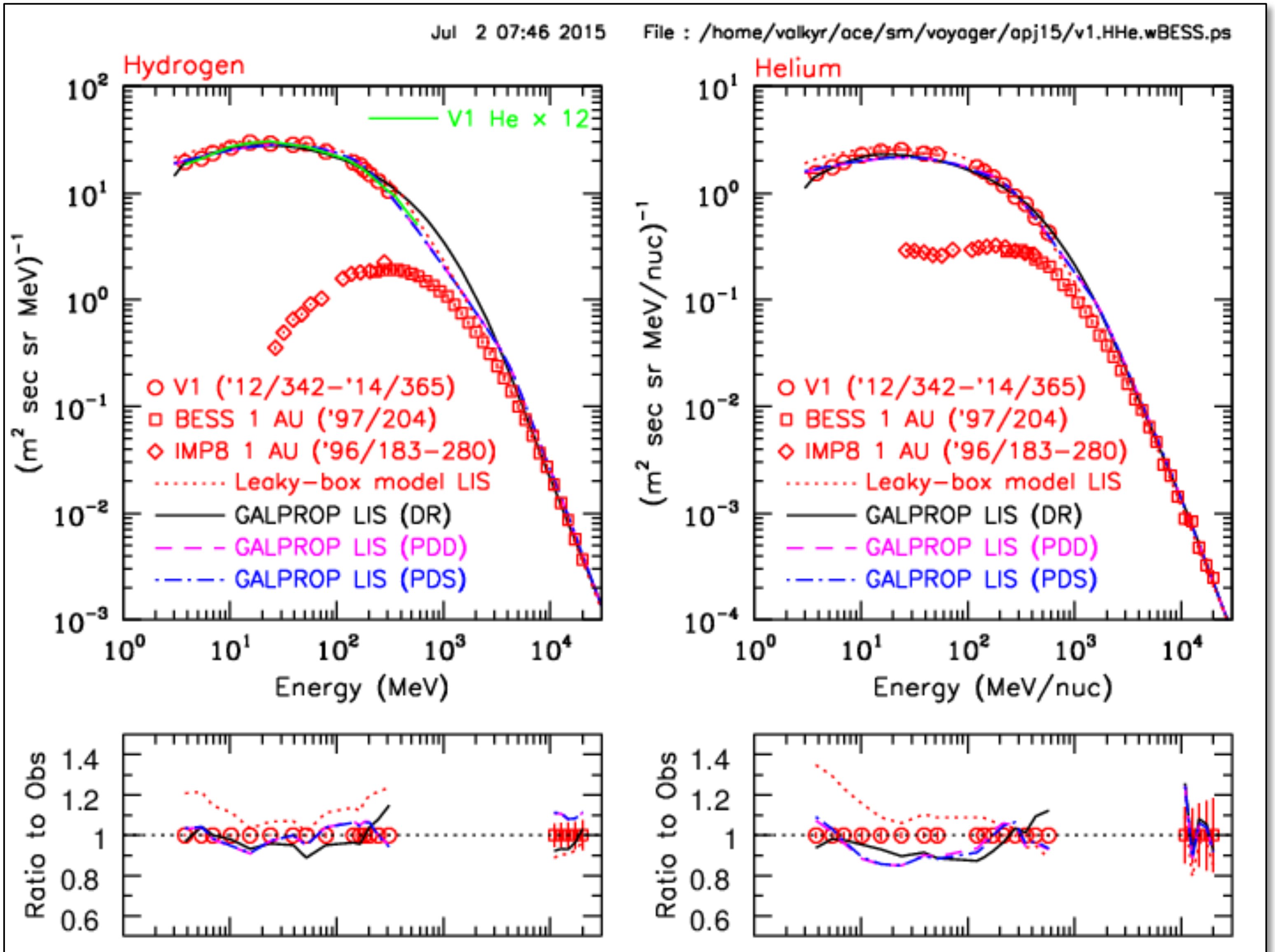
Voyager 1 spectra for 2012/342-2014/365



Li – Ni : V1 spectra together with HEAO-3-C2 data (≥3.35 GeV/nuc)

Cummings+'2016

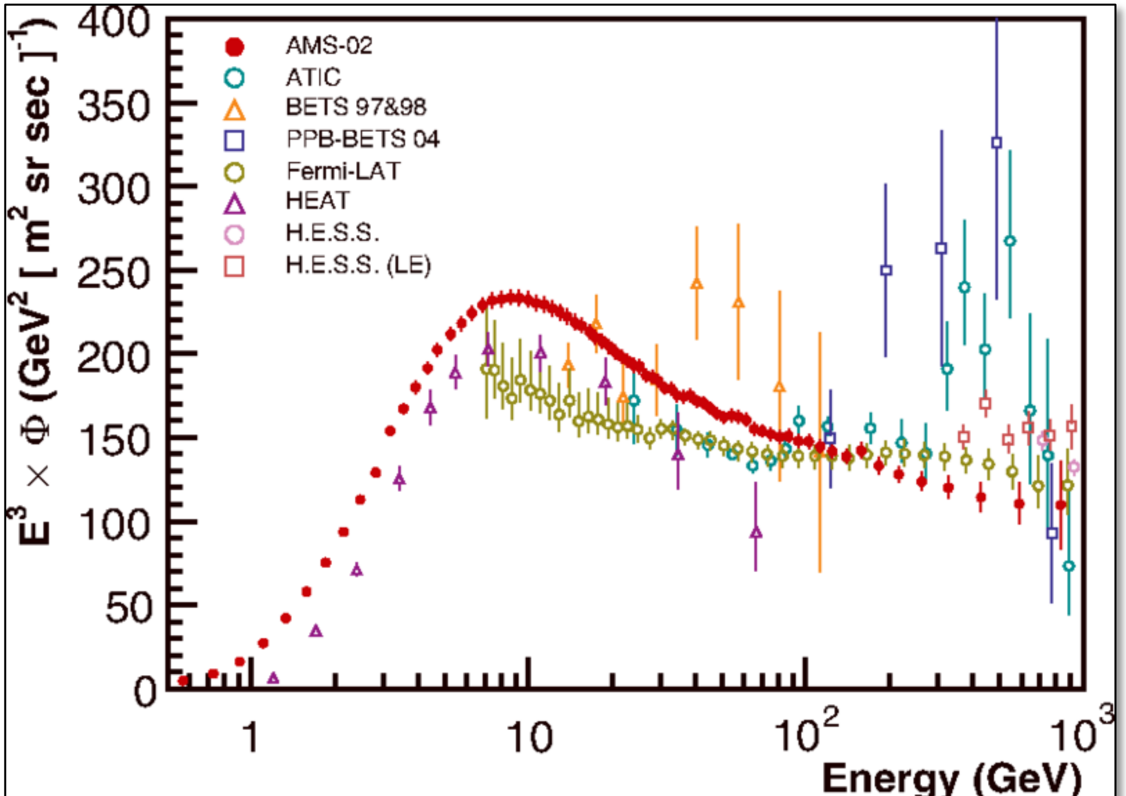
Voyager 1 – H and He spectra

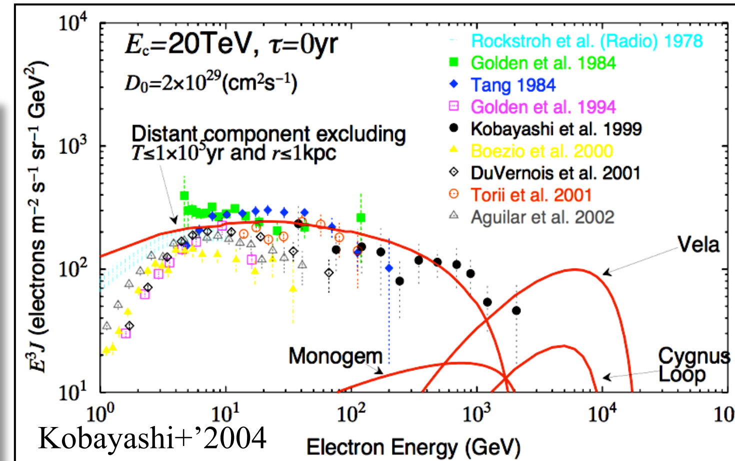


Flattening at LE is understood:

- ✧Injection: power-law in rigidity
- ✧Energy losses (ionization & Coulomb)
- ✧Jacobian for a transformation from rigidity to Ekin variable
- ✧Rigidity dependence of the diffusion coefficient at LE

All-electron spectrum





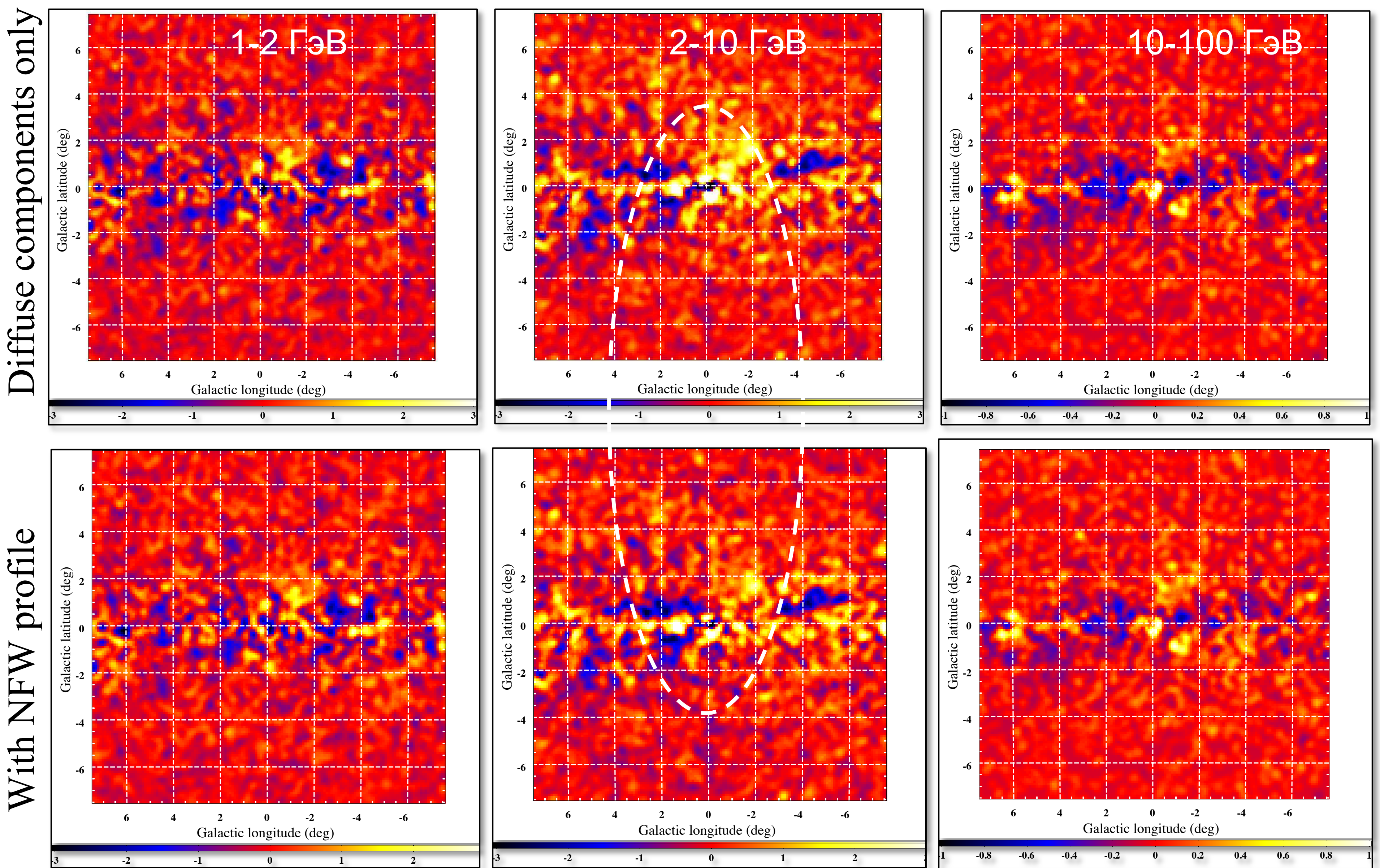
- ✧ Fermi-LAT and PAMELA data agree well
- ✧ Shows some structure
- ✧ Flatter than extrapolated from low energies
- ✧ Sharp cutoff at 1 TeV (HESS), as expected

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

- ✧ CALET was launched to the ISS in 2015 to find out!

Fermi-LAT observations of the inner Galaxy: residuals

(Data–Model): CR sources – pulsar distribution, point sources removed

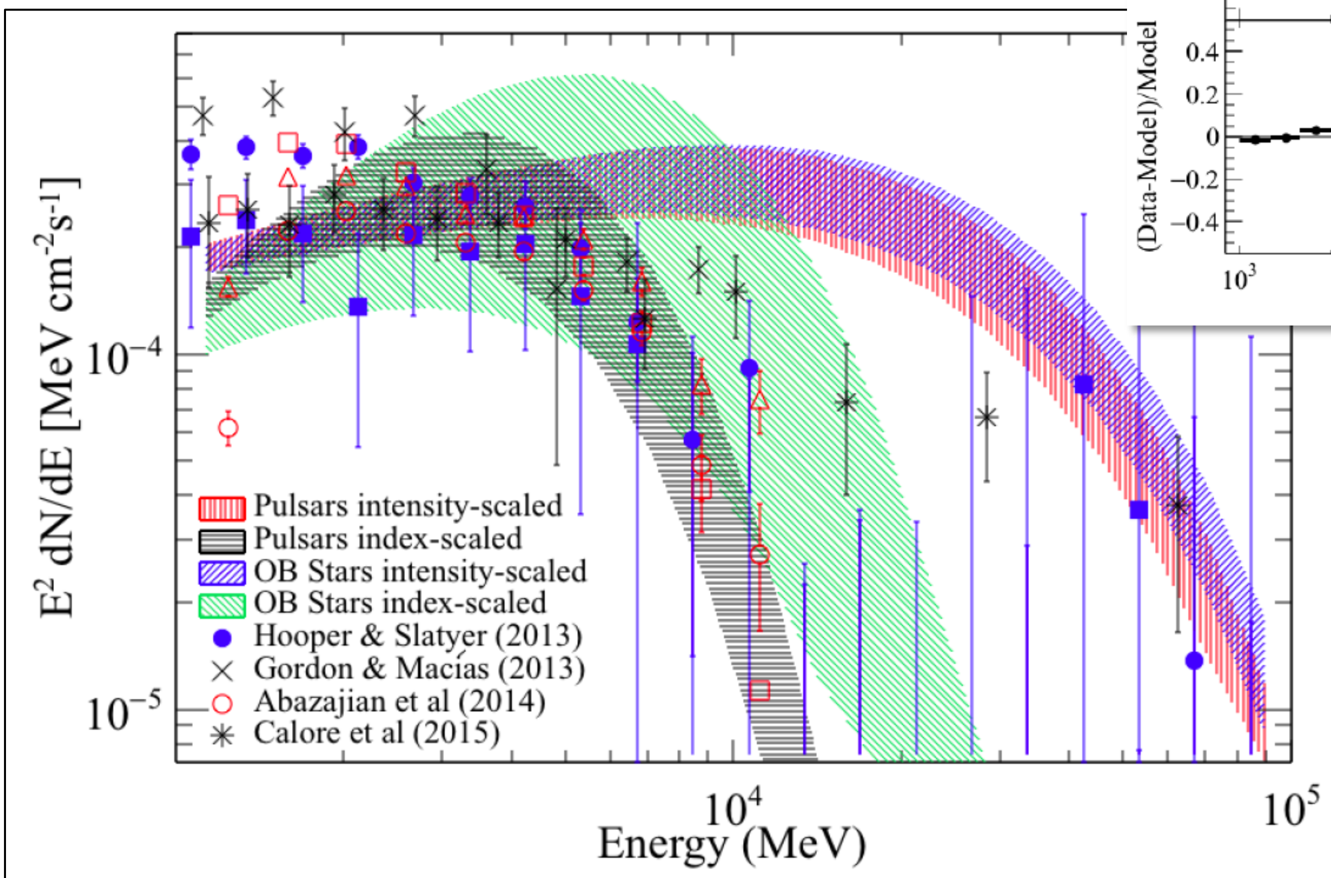


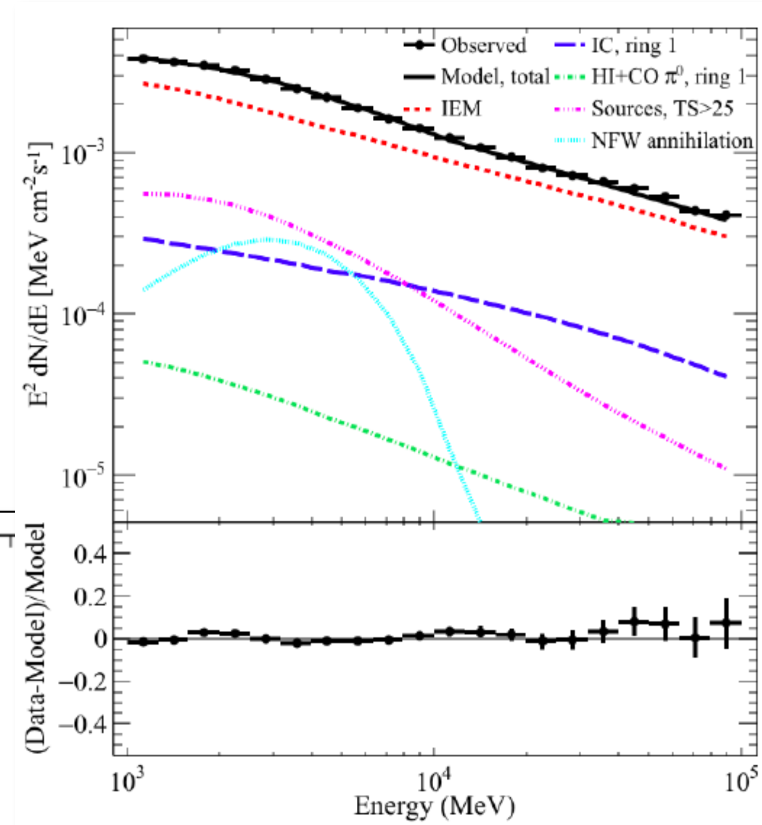
Events per pixel 0.1°×0.1°

Spectrum of NFW component

✧ NFW profile:

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$

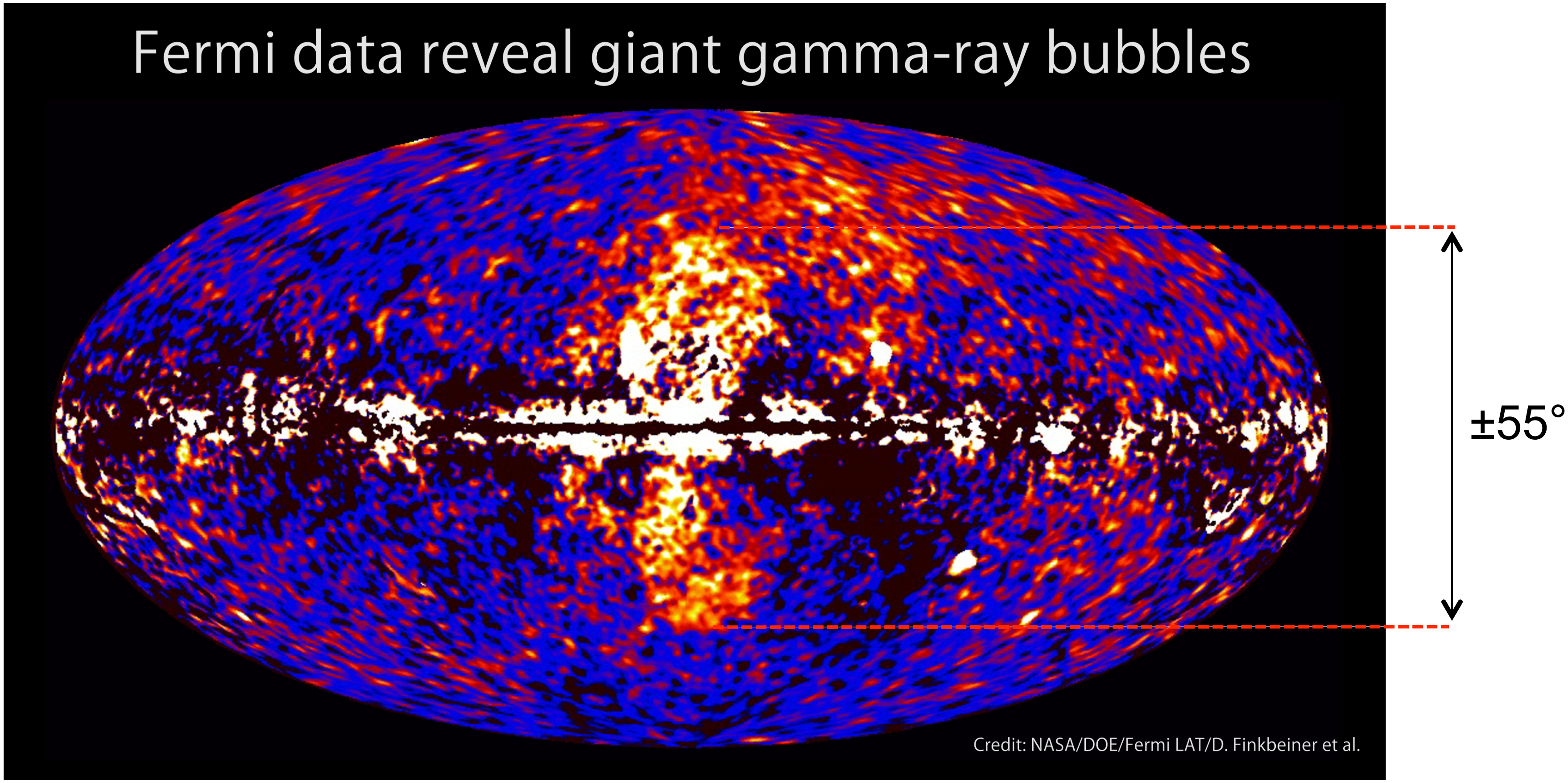




✧ Components of the emission from ROI 15°×15° at the Galactic center

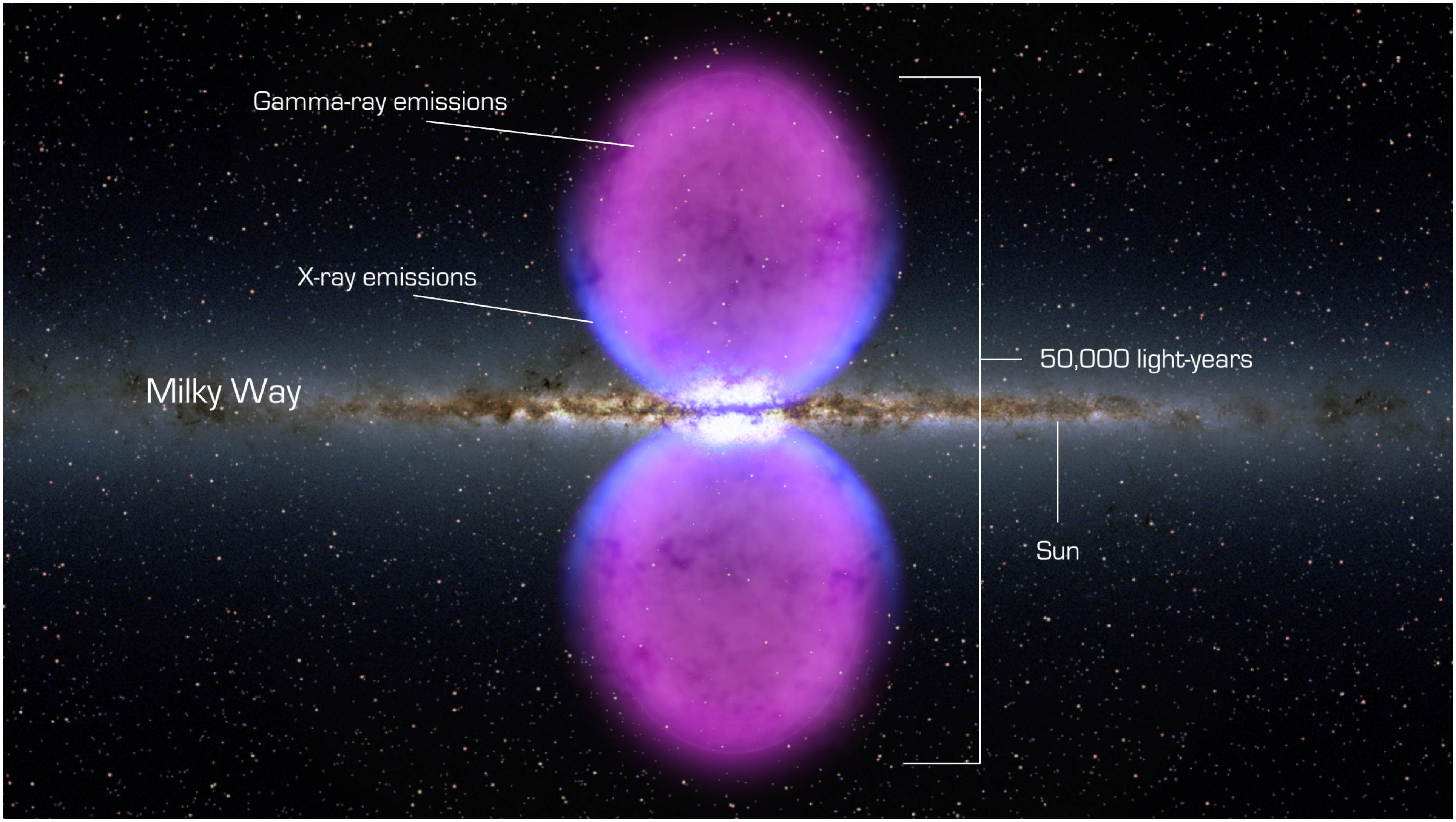
✧ Spectrum of NFW component for different CR source distributions

NASA press release



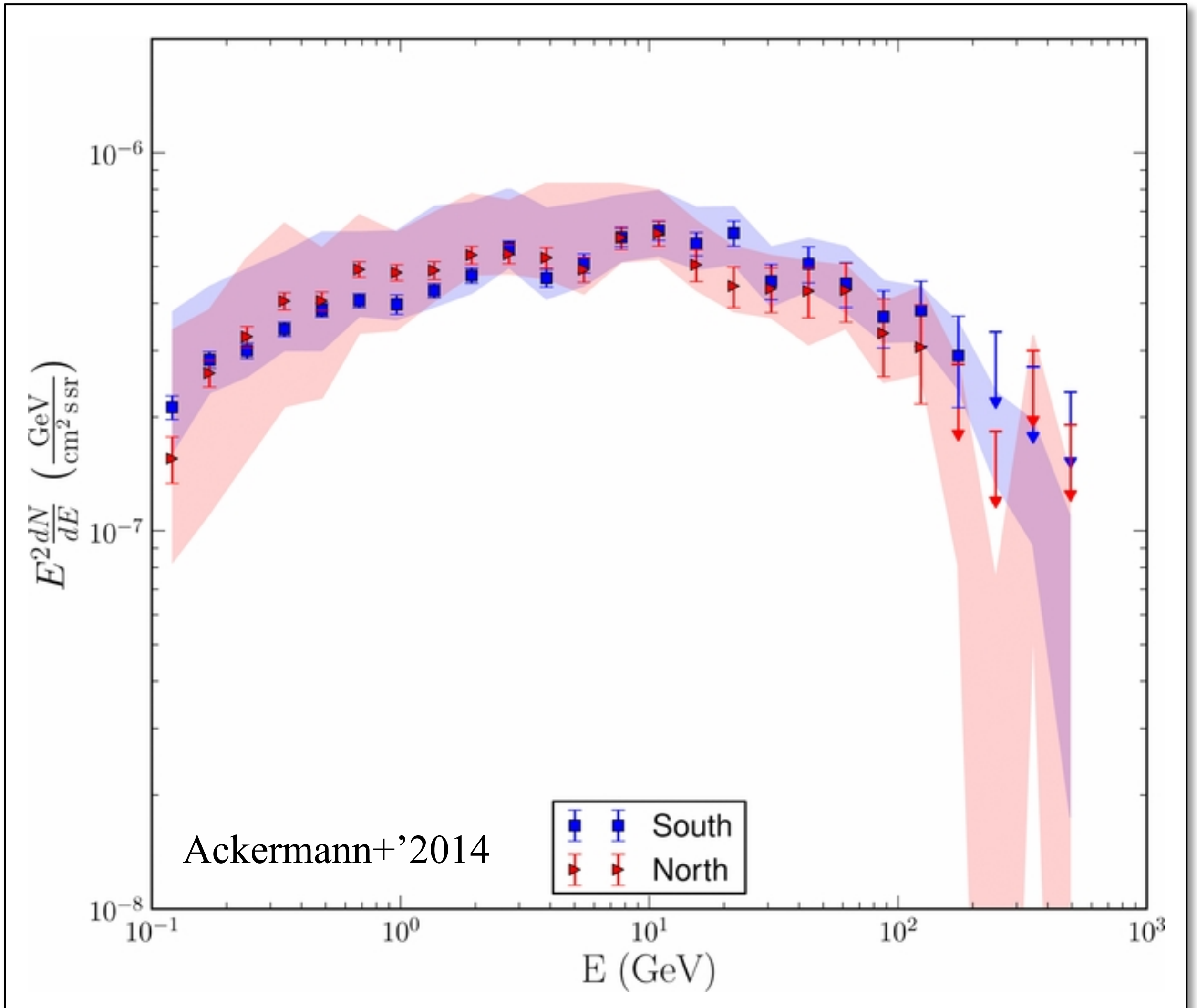
- Models reproduce the main features of the diffuse emission quite well
- Discrepancies between the physical model and high-resolution data (residuals) are the gold mines of new phenomena!
- Every extended source and/or process that is not included into the model pops up and exposes itself as a residual

Artist's concept of Fermi Bubbles



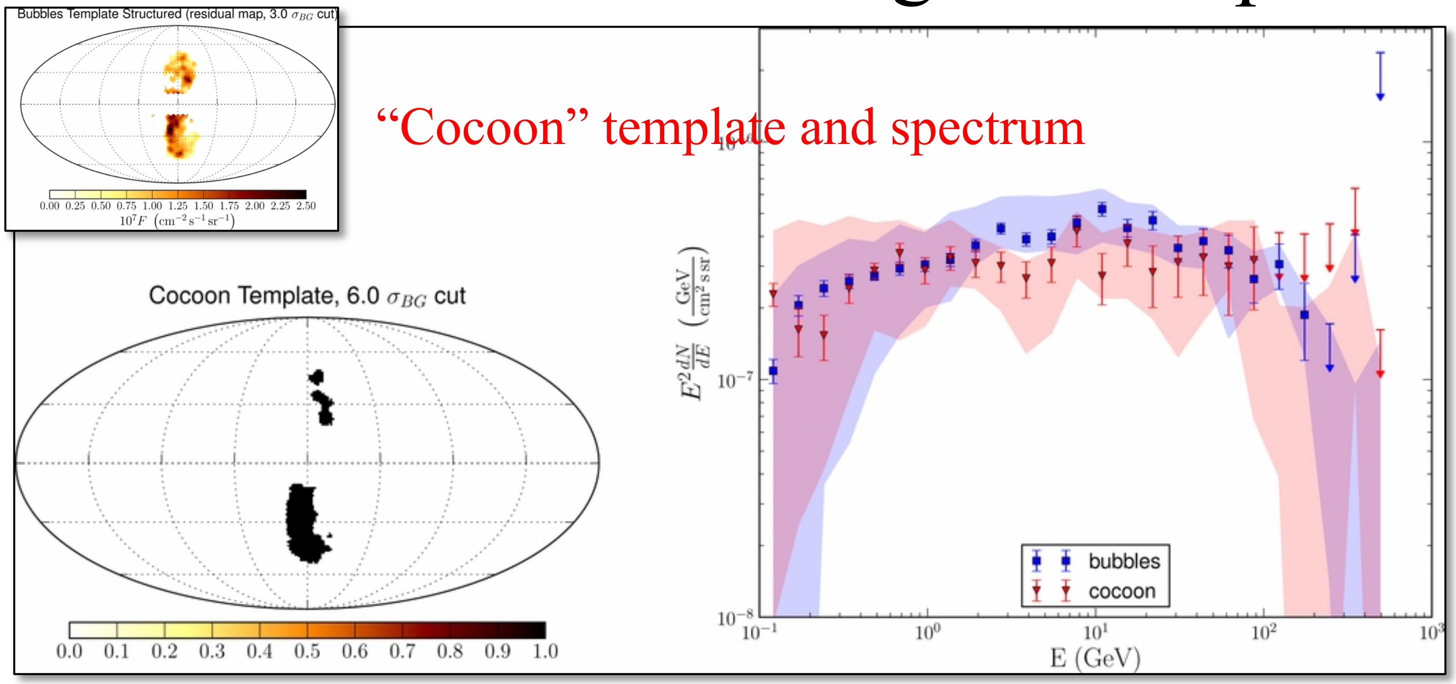
- The spectrum is "flat" (ongoing acceleration!)
- The spectrum is uniform across these huge structures! (what is the mechanism?)

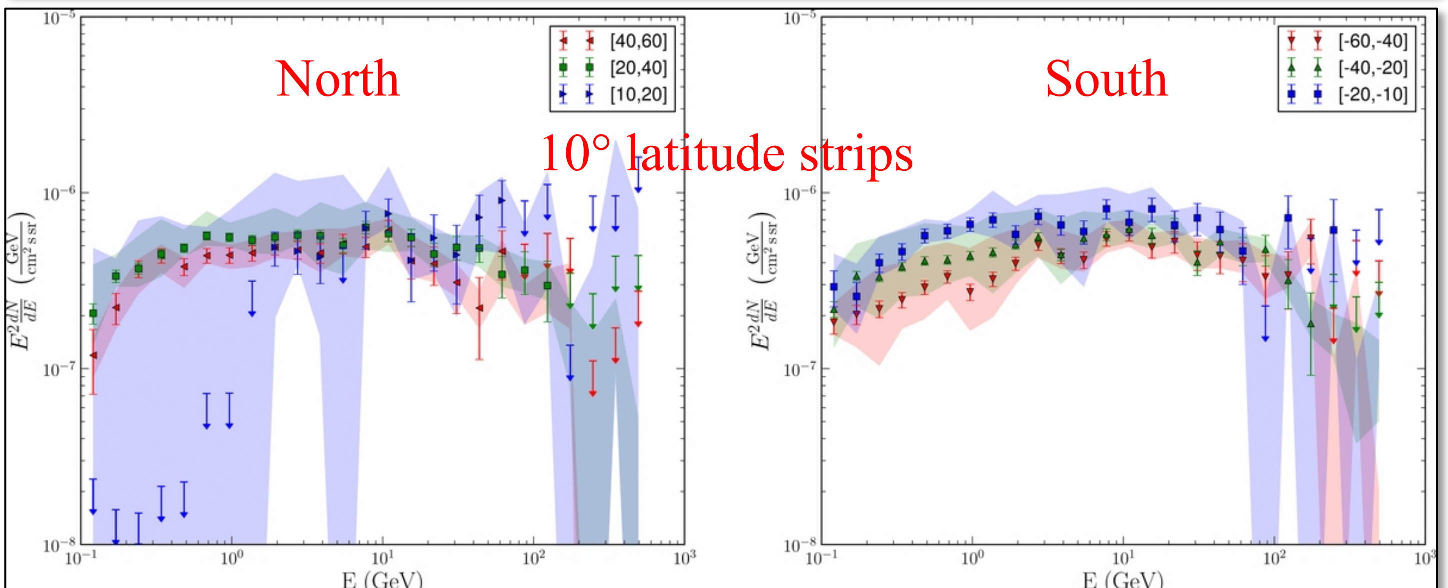
Spectrum of the Bubbles



- ✧ The North and South lobes have very similar spectra
- ✧ The spectrum is very flat which testifies that the particle acceleration is ongoing
- ✧ Power-law with an exponential cutoff: index 1.9±0.2, cutoff energy 110±50 GeV

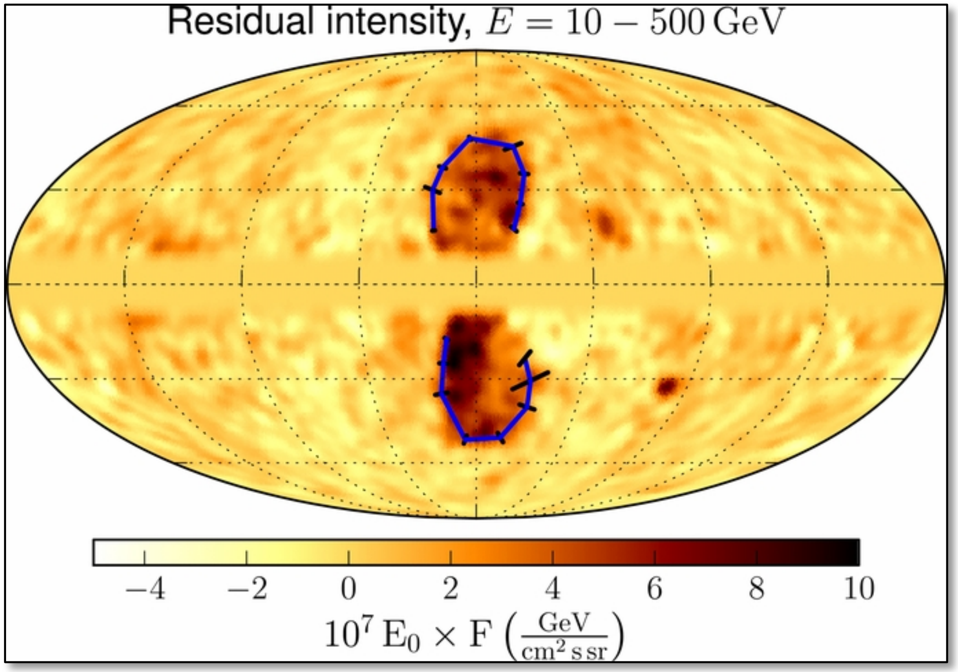
Substructures and longitude strips

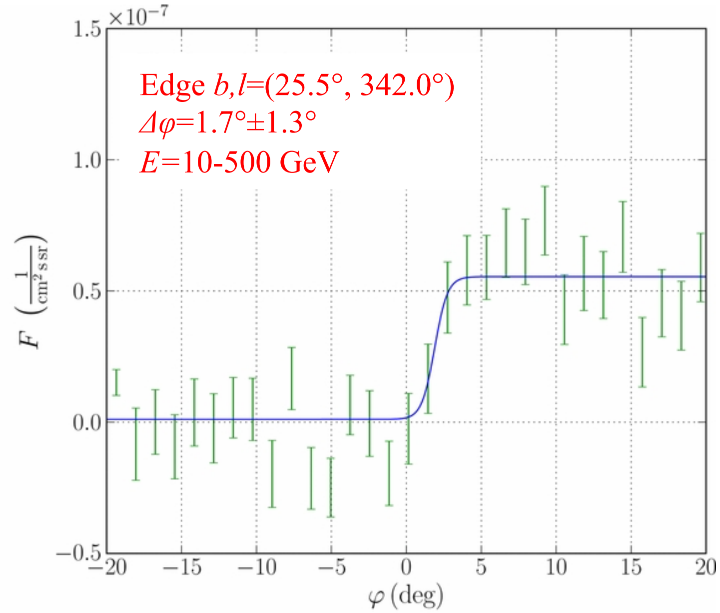


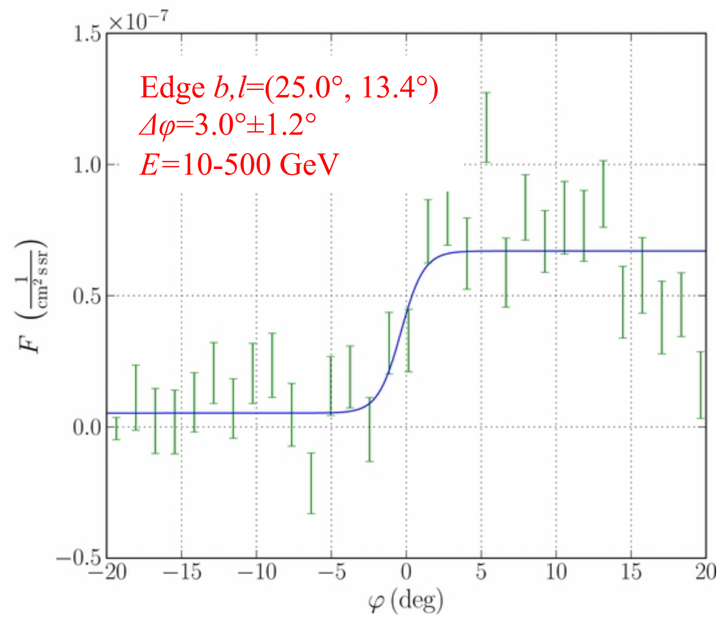


- ✧ The lobes are uniform
- ✧ The spectrum of the "cocoon" is pretty much the same as the spectrum of the whole lobes
- ✧ No spectral variations with the Galactic longitude

Edges: the width of the boundary

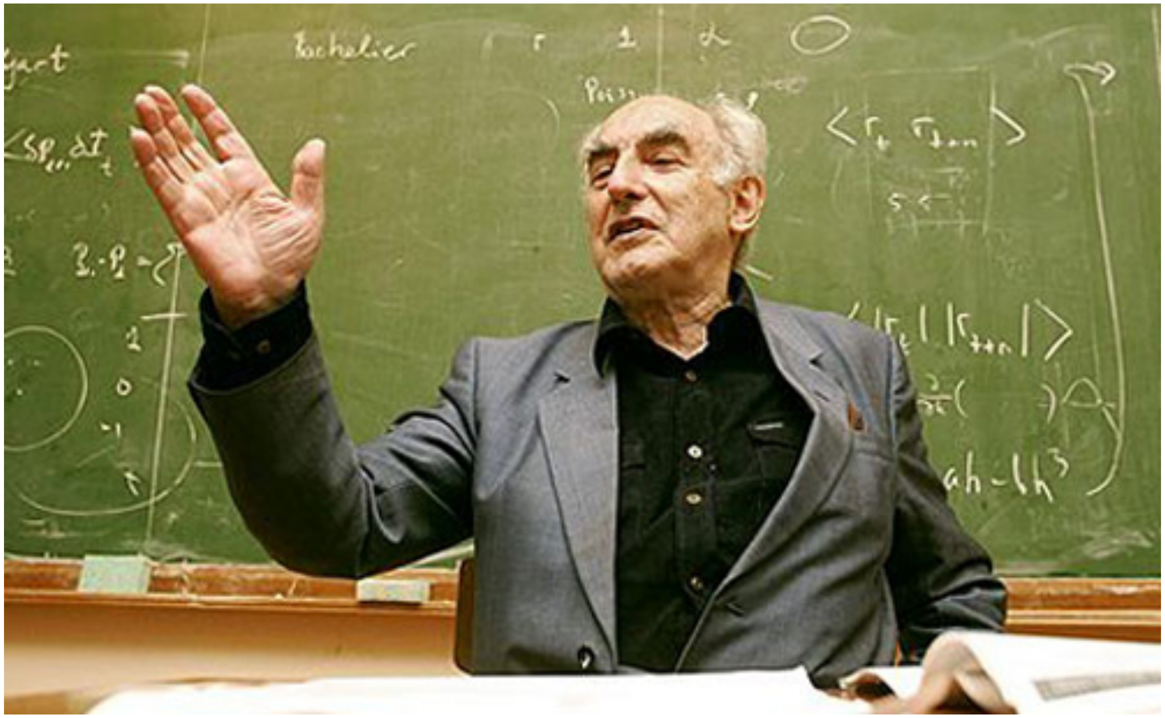






- ✧ Three energy ranges (68% PSF):
  - ✦ 1–3 GeV (0.5°)
  - ✦ 3–10 GeV (0.25°)
  - ✦ 10–500 GeV (0.12°)

- ✧ The edges of the Bubbles are well defined
- ✧ The width is <6°, about $3.4°_{-2.6}^{+3.7}$ in average



V.L. would likely have an explanation ready by the end of the talk!

Thanks!