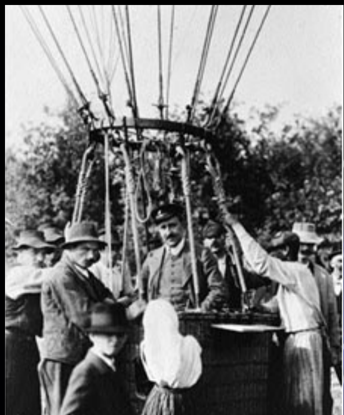
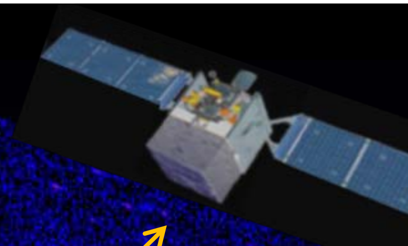




100 years

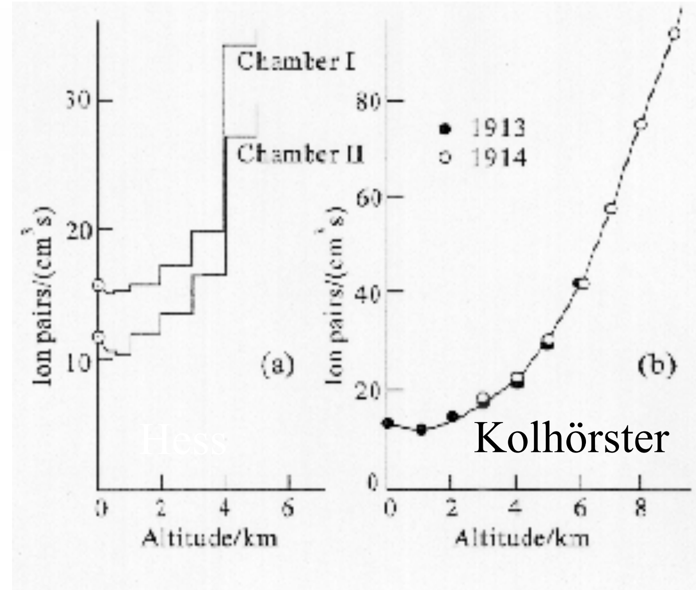
FROM GEV TO 100 TEV COSMIC RAYS

IGOR V MOSKALENKO – STANFORD

There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy.
– Hamlet (1.5.167-8)

*PIC*2019 • Taipei • Sep. 20, 2019

The discovery of cosmic rays

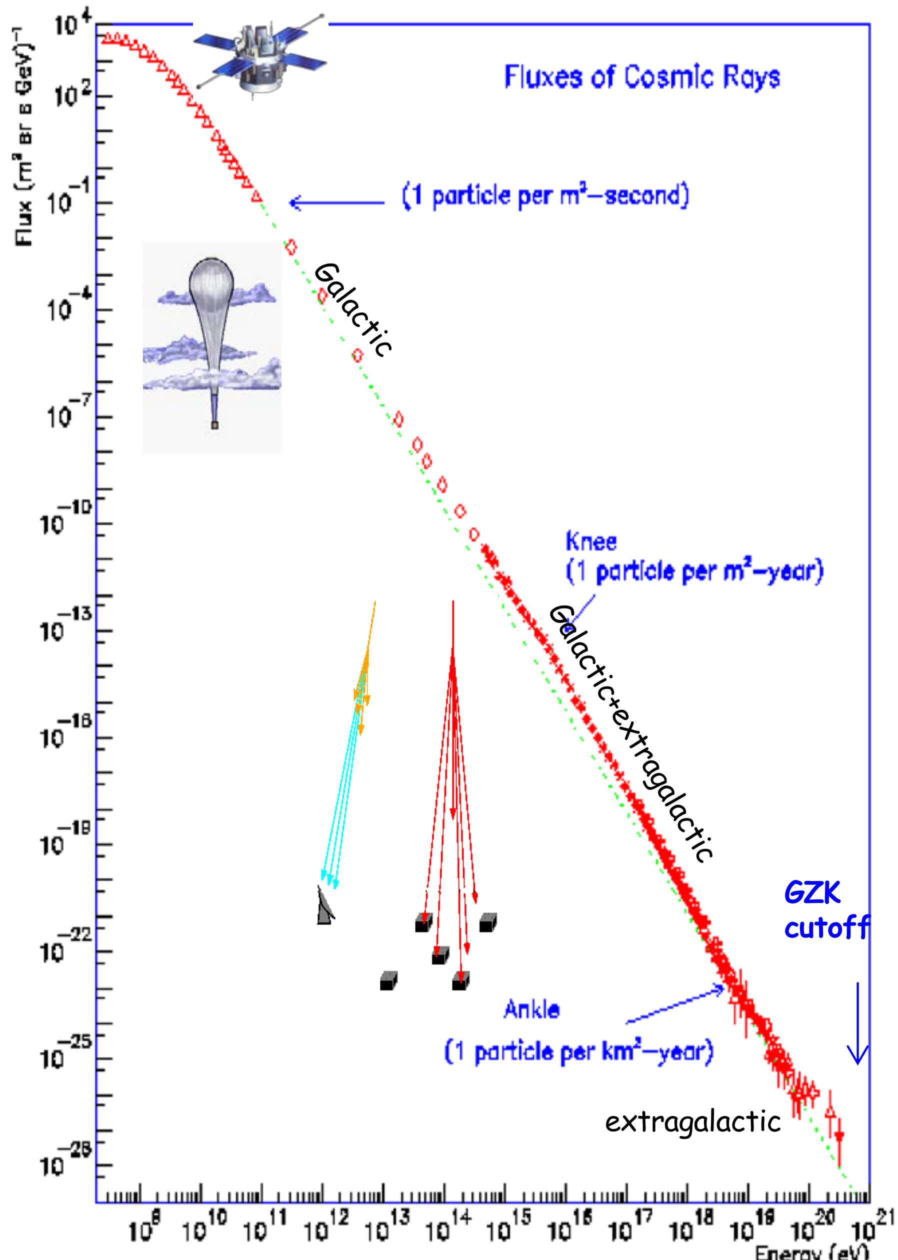


Victor Hess flight on August 7, 1912

Nobel Prize: 1936

- ✧ Victor Hess, an Austrian scientist, took a radiation counter (a simple electroscope) on a balloon flight
- ✧ He rose to 5200 m (without oxygen) and measured that the amount of radiation increases as the balloon climbed
- ✧ Hess correctly concluded that the ionization was caused by highly penetrating radiation coming from outside the atmosphere
- ✧ The results by Hess were later confirmed by the Kolhörster in a number of flights up to 9200 m

Spectrum of Cosmic Rays – 20th century

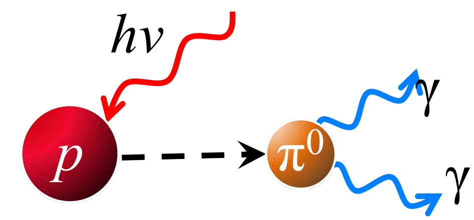


~32 orders of mag

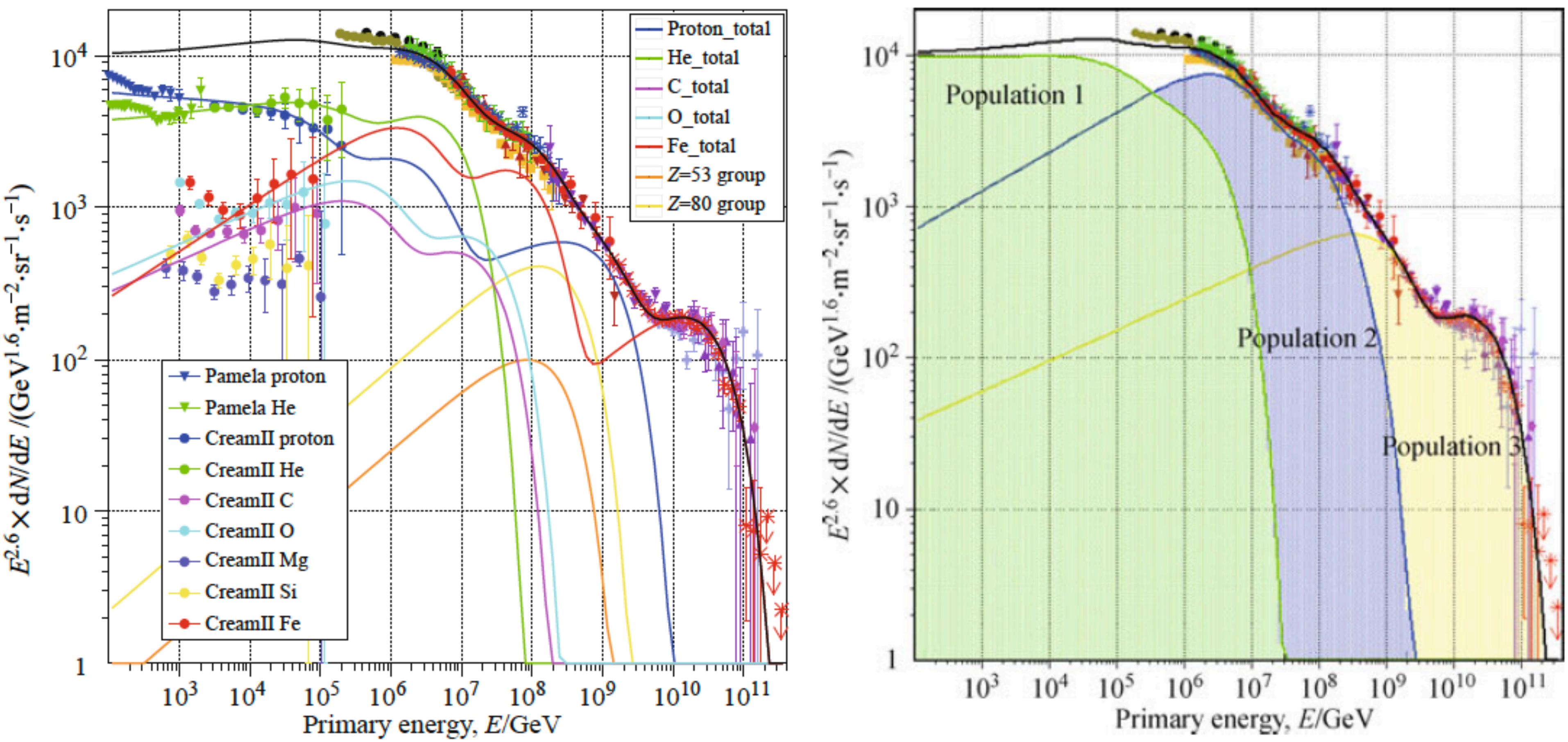
>12 orders of mag

- ✧ All particle CR spectrum:
  - ✦ the knee (Kulikov & Christiansen 1958)
  - ✦ the ankle (Linsley 1963, Fly's eye 1990s)
  - ✦ GZK cutoff (predicted Greisen-Zatsepin-Kuzmin 1966)

GZK cutoff:



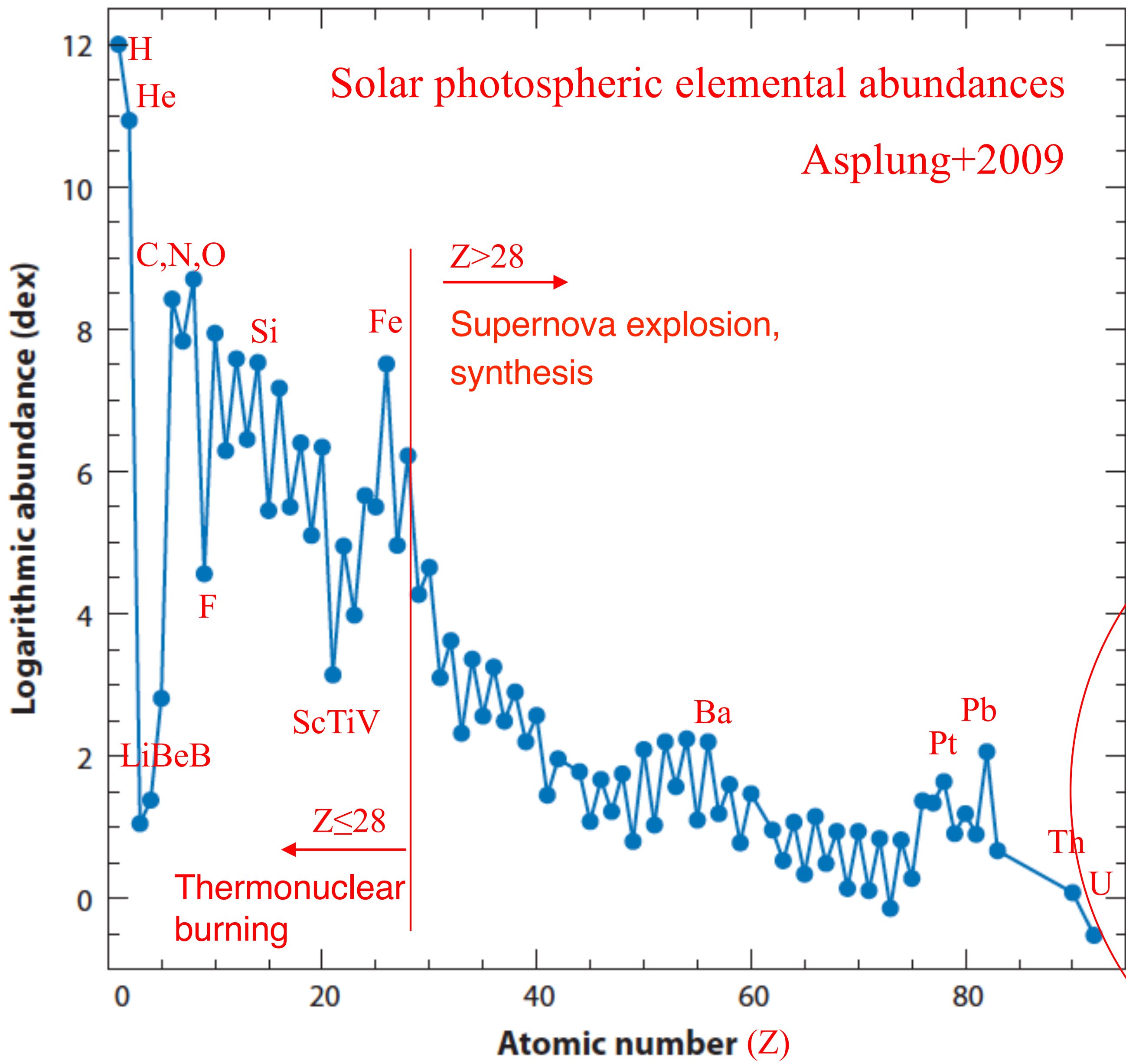
Spectrum of Cosmic Rays – about now



Gaisser, Stanev, Tilav 2013

- This is an illustration made in 2013. Now we see even more features and have more puzzles to solve. Each year brings several new breakthrough measurements

Comprise all known and yet unknown species



Solar photospheric abundances show interstellar abundances as they were ~4 Gyr ago

CRs are accelerated from this material + massive star ejecta

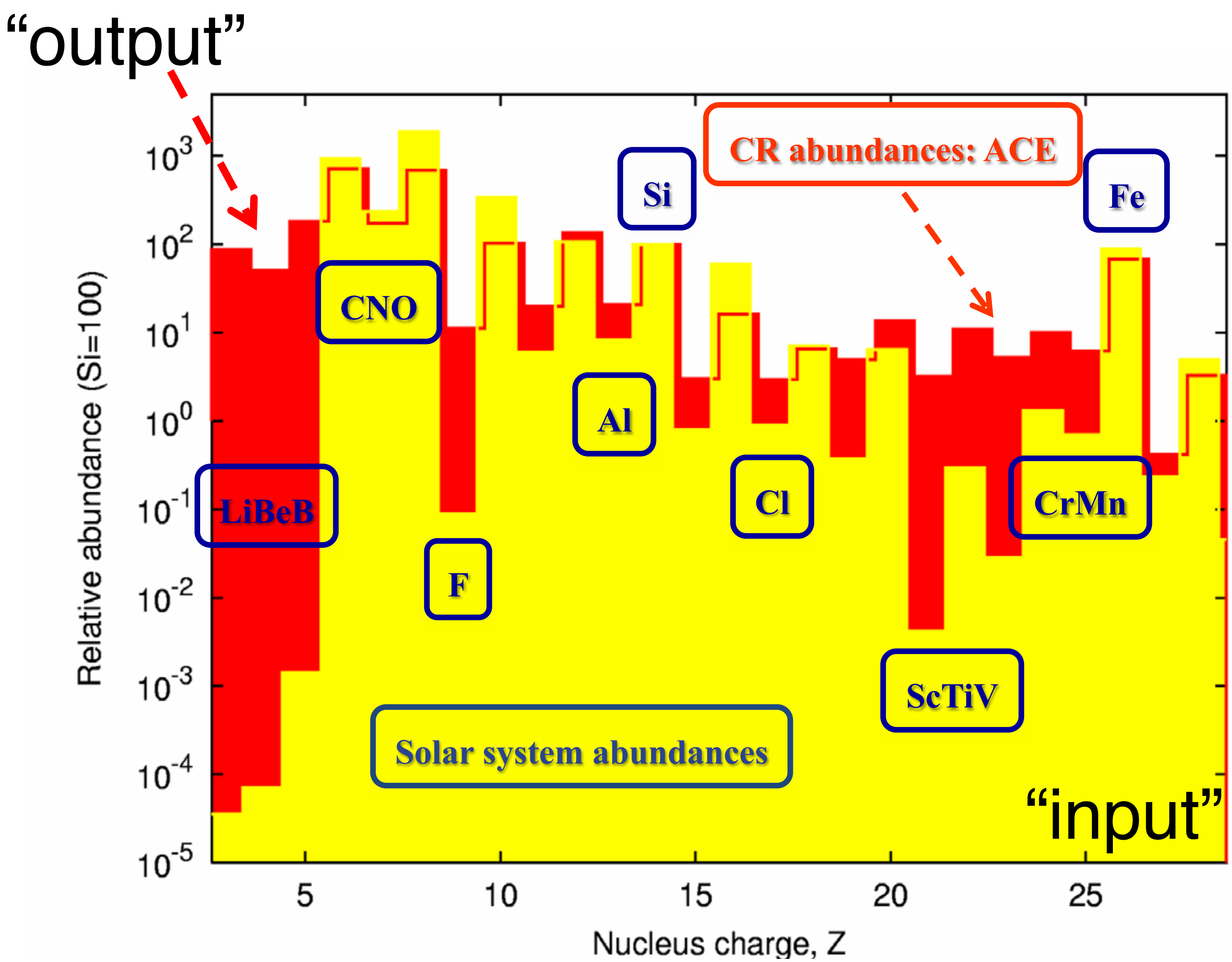
Known species:

- ✧ All stable and "long-lived-*f(E)*" isotopes ^{1}H-^{92}U (time dilation)
- ✧ n, $\bar{n}$, $e^{\pm}$, $\bar{p}$, $\bar{d}$, $\overline{He}$ (?)
- ✧ Decay products of exotic species

Unknown species:

- ✧ χ, WIMPs, DM, etc.

CR composition: propagation modifications



Secondary nuclei is an evidence of the long propagation history of CRs

Why do we know some elements are secondary?

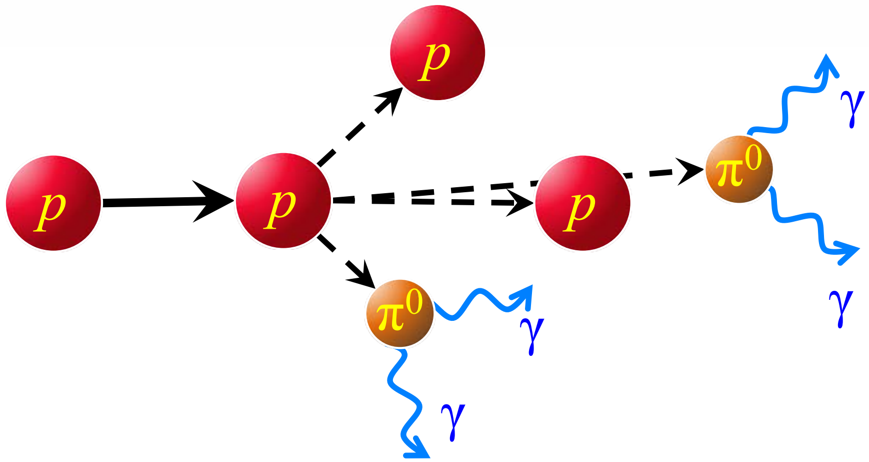
- ✧ A comparison with solar system abundances (interstellar medium ~4 Gyr ago)
- ✧ Models of nucleosynthesis
- ✧ CR propagation models

Cosmic ray vs. solar system abundances, normalized to Si=100

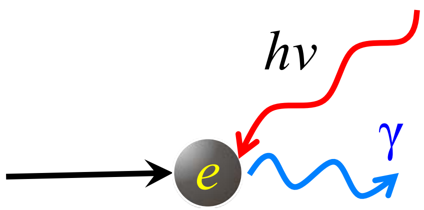
Experiments in astrophysics…

…are pretty much like traveling in a train. They are very different from experiments in all other areas of science where experimentalists can actually touch the studied object. In a train we can only observe the images or silhouettes of the passing landscapes and sometimes feel the smell and get a pinch of dust, but cannot touch, turn, or look from the other side…

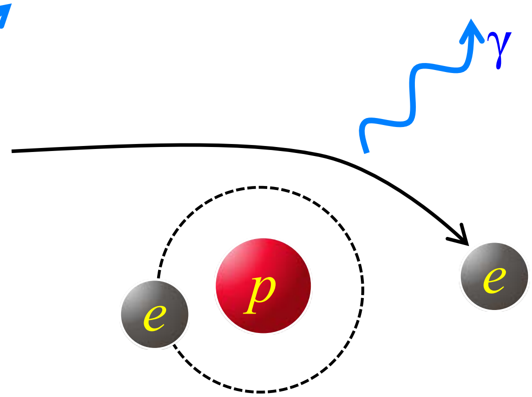
Production of high energy γ-rays



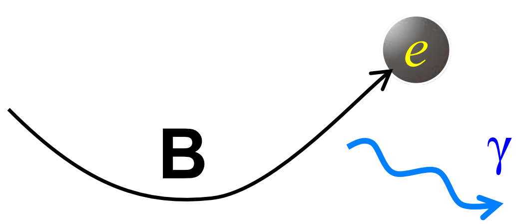
- ✧ $pp \rightarrow \pi^0(2\gamma)+X$ – production and decay of neutral pions π^0 and Kaons K^0



- ✧ Inverse Compton Scattering

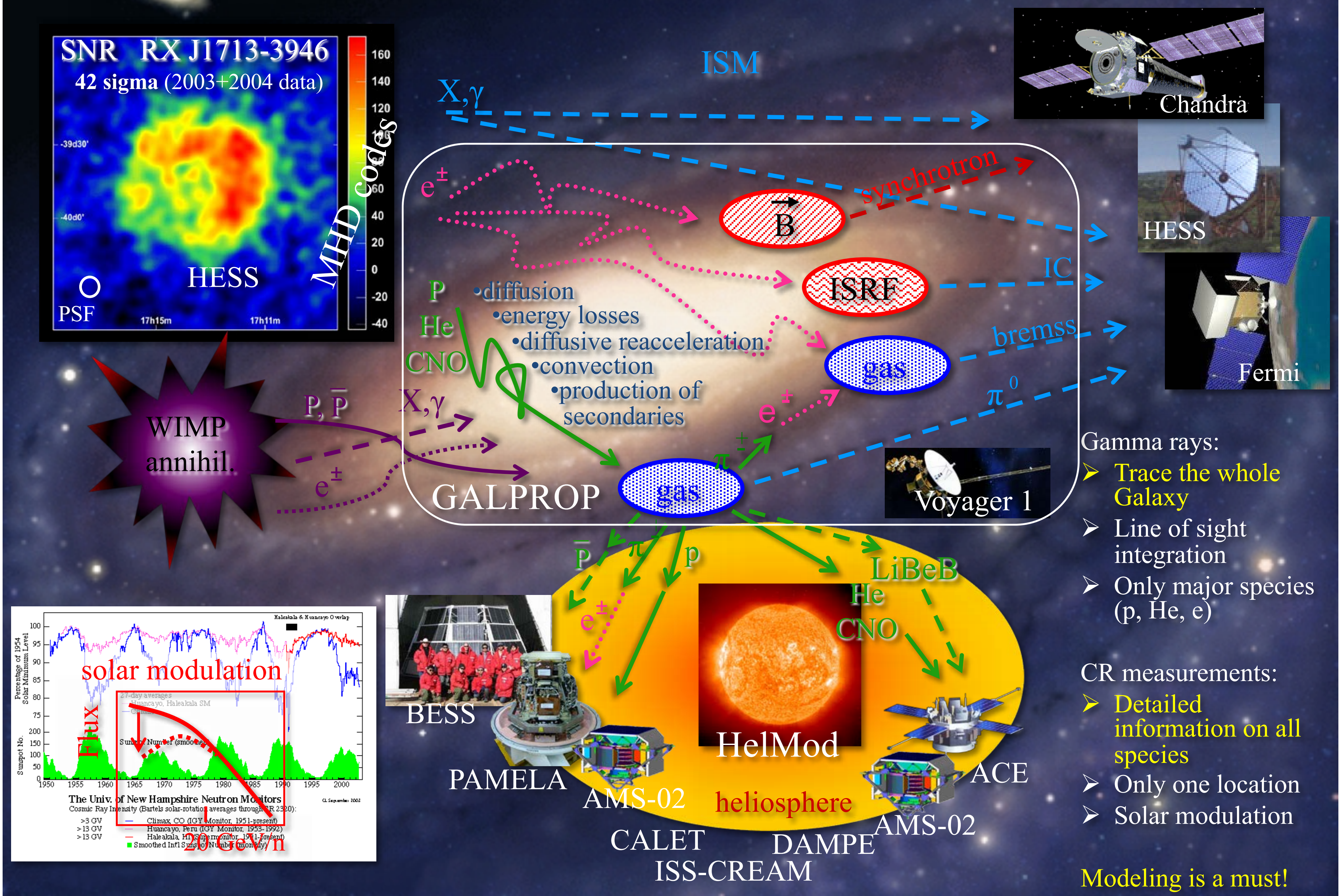


- ✧ Bremsstrahlung

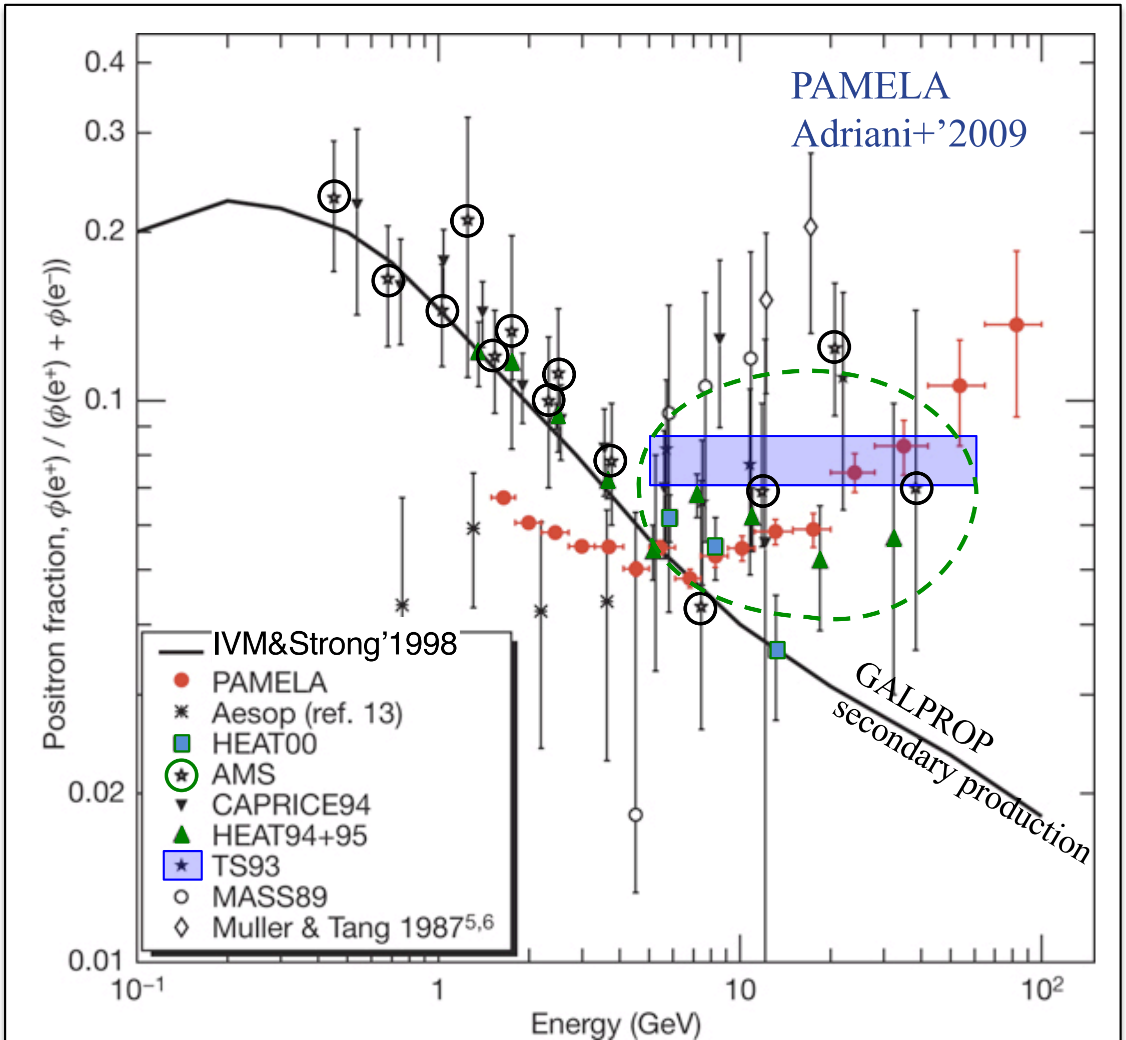


- ✧ Synchrotron emission

CRs in the interstellar medium



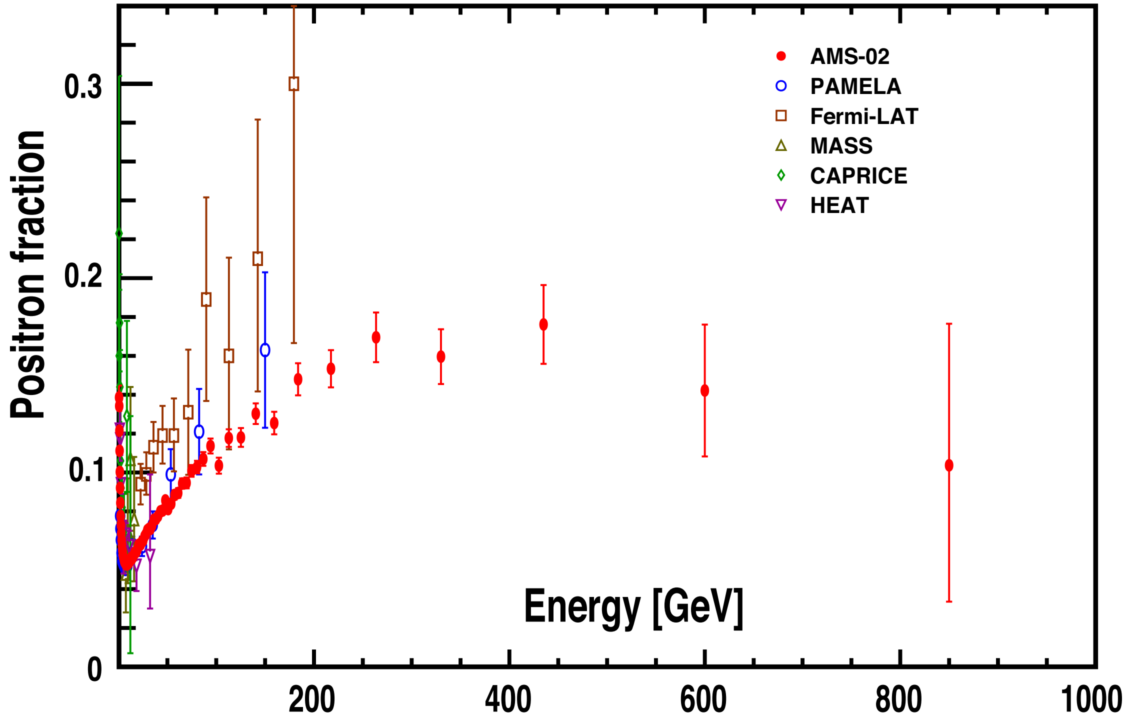
PAMELA discovery: Rising positron fraction

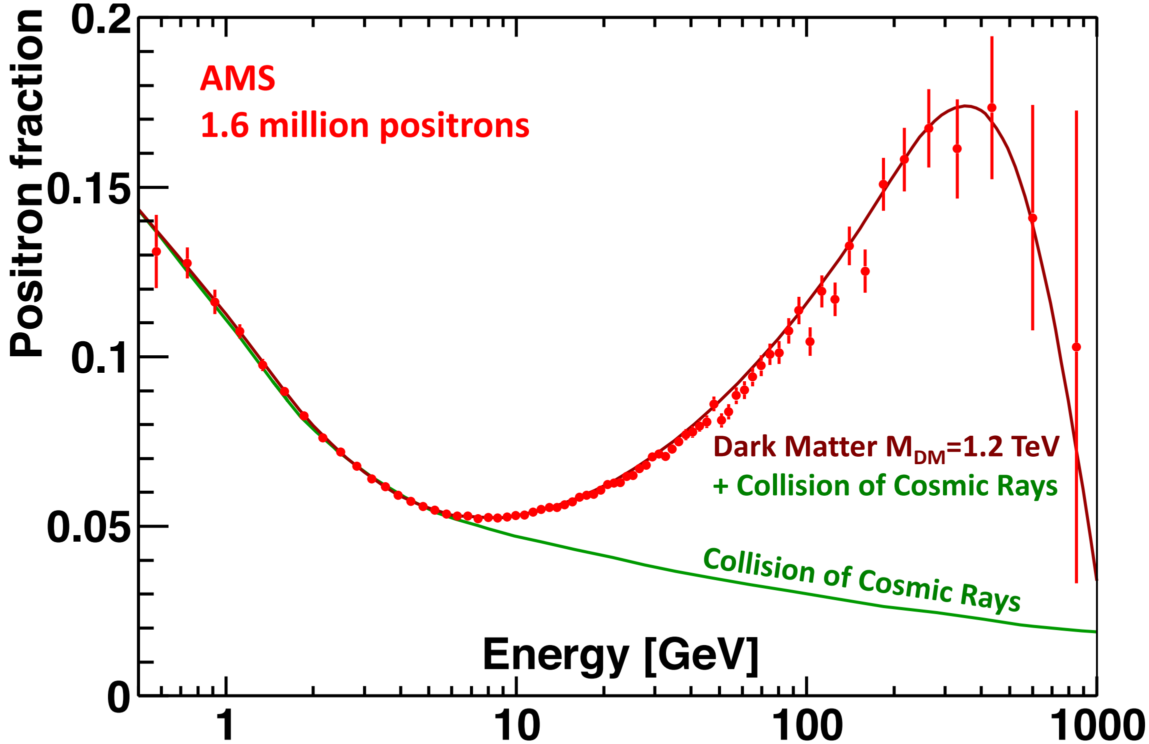


- TS93 (Golden+'96): flat positron fraction 0.078±0.016 in the range 5-60 GeV
- HEAT-94,95,00 (Beatty+'04): "a small positron flux of nonstandard origin"
- PAMELA team reported a clear and very significant rise in the positron fraction compared to the "standard" model predictions
- "Standard" model: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

AMS-02 data on positron fraction

- ✧ The raise of the positron fraction over the expectations of the secondary production model was confirmed by Fermi-LAT and AMS-02
- ✧ AMS-02 extended the measurements up to ~900 GeV
- ✧ It looks like the fraction is declining above ~500 GeV, but the error bars are too large yet

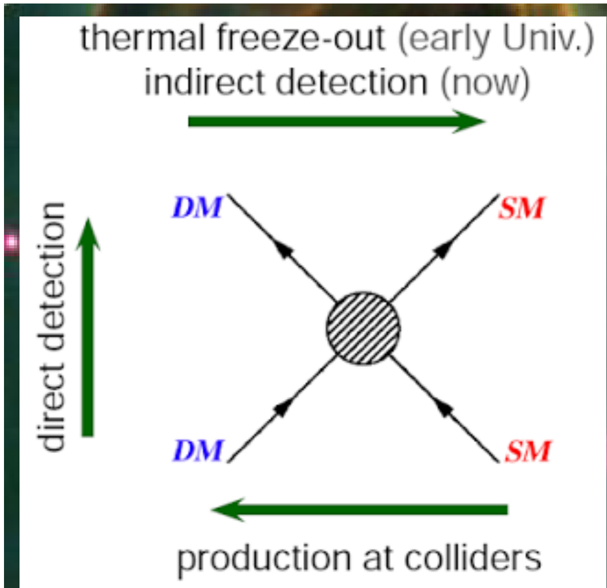




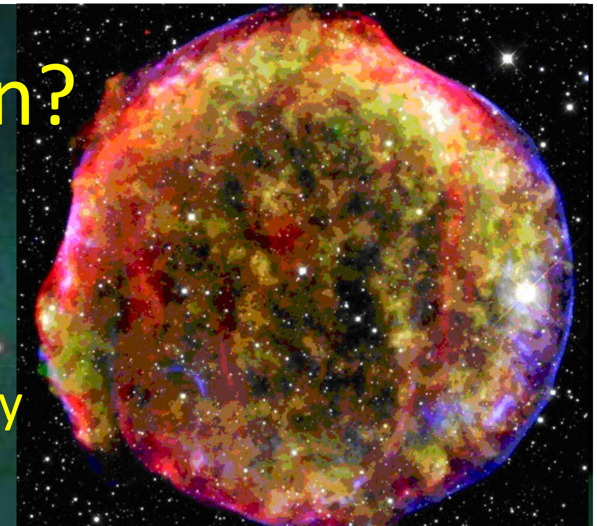
Dark Matter model is based on J. Kopp, Phys. Rev. D 88, 076013 (2013).

Professor Ting's question

This is a good question, but the answer in not straightforward



What does this mean?



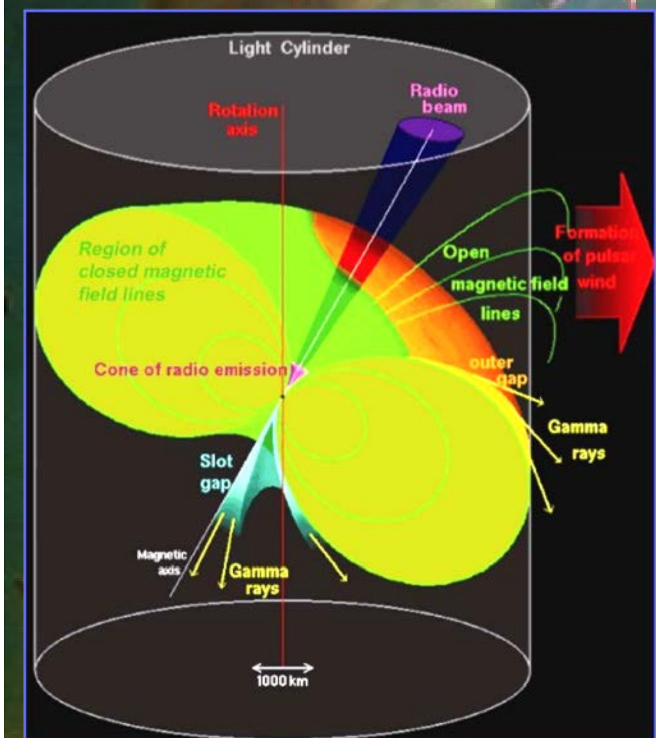
There are ~1750 answers!

- ✧ Dark matter annihilation/decay (>1500 papers)

Astrophysical origin (~250 papers):

- ✧ SNR shocks:
  - ✦ Galactic SNRs
  - ✦ Local SNR(s)
  - ✦ SNR shocks interacting with clouds
  - ✦ "Nested Leaky-Box" (SNRs)
- ✧ Pulsars & Pulsar Wind Nebulae
  - ✦ Pulsar bow shocks
- ✧ "Model-independent estimates"
- ✧ Inhomogeneity of CR sources (SNRs, pulsars)
- ✧ Time-dependent effects

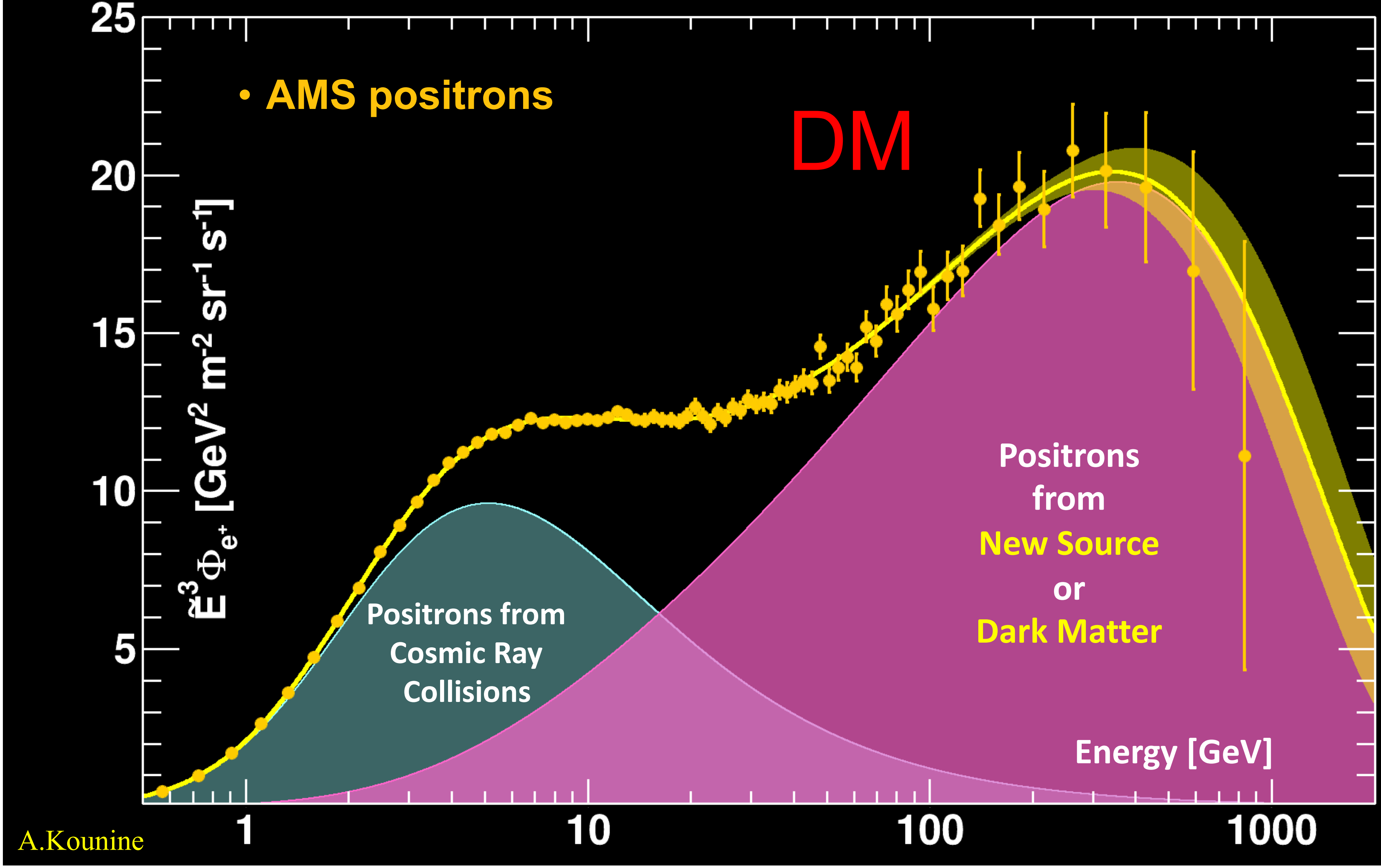
ISM



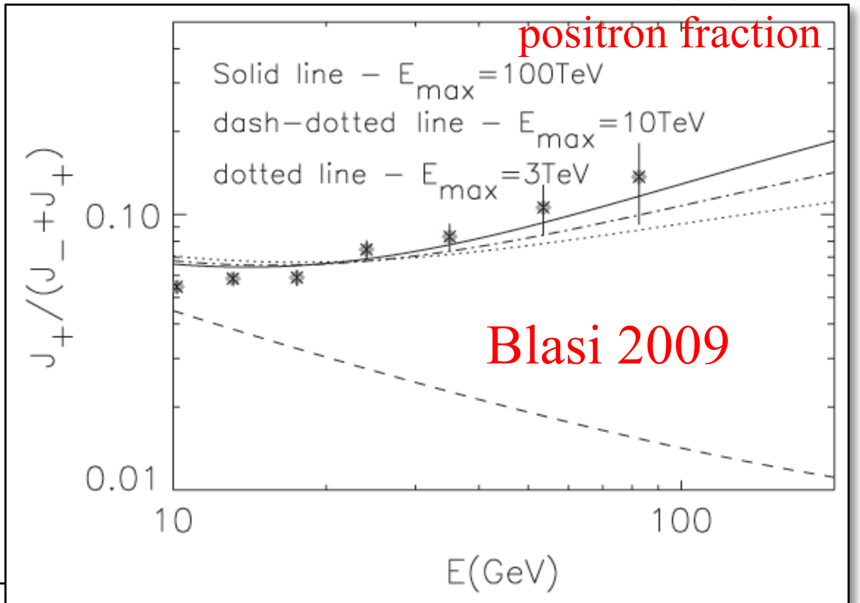
The positron flux is the sum of low-energy part from cosmic ray collisions plus a high-energy part from a new source or dark matter both with a cutoff energy E_s.

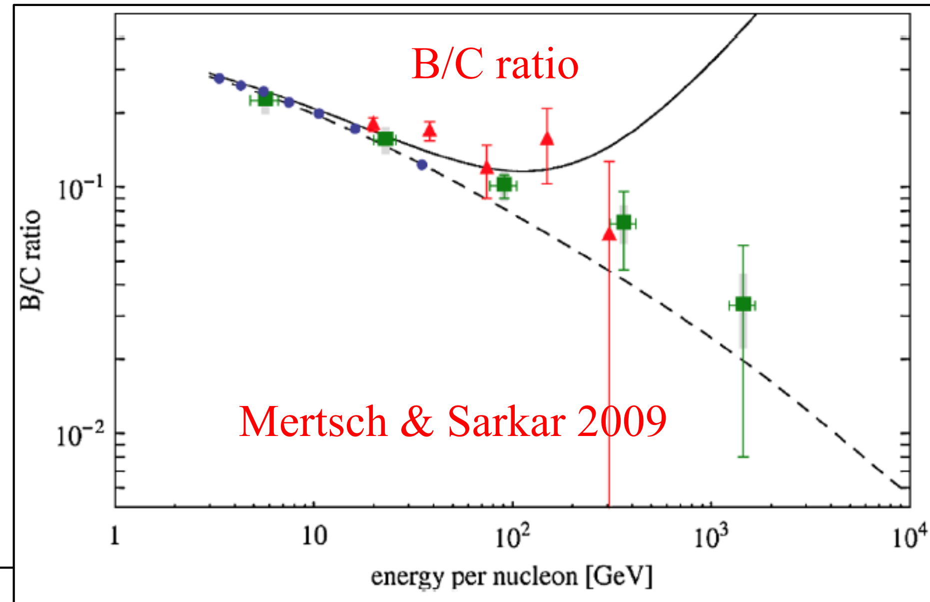
Collisions — New Source or Dark Matter

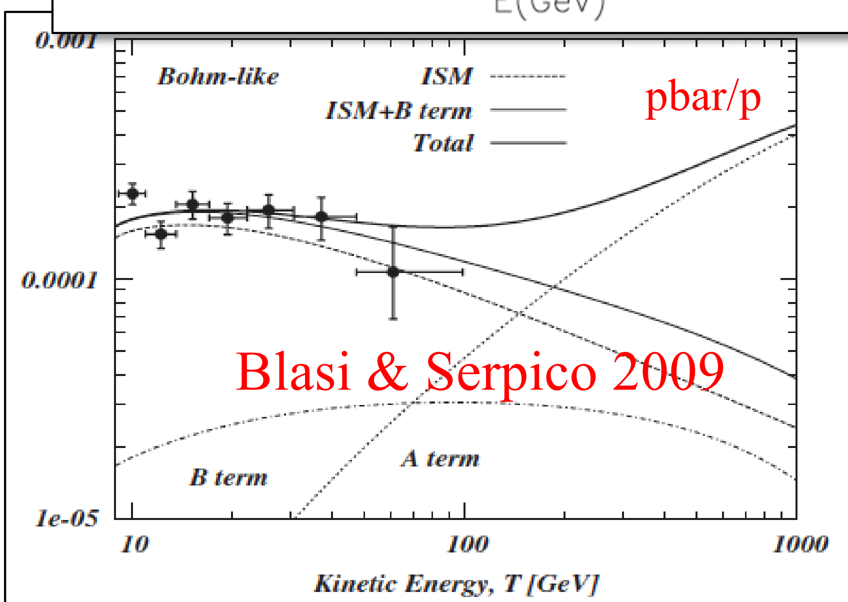
$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$

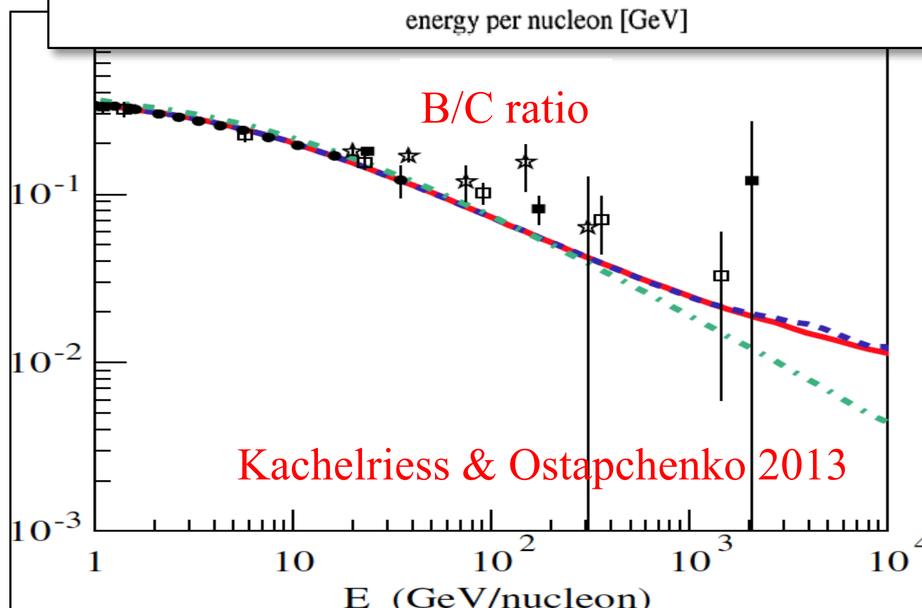


Astro: Secondary production in a SNR shock



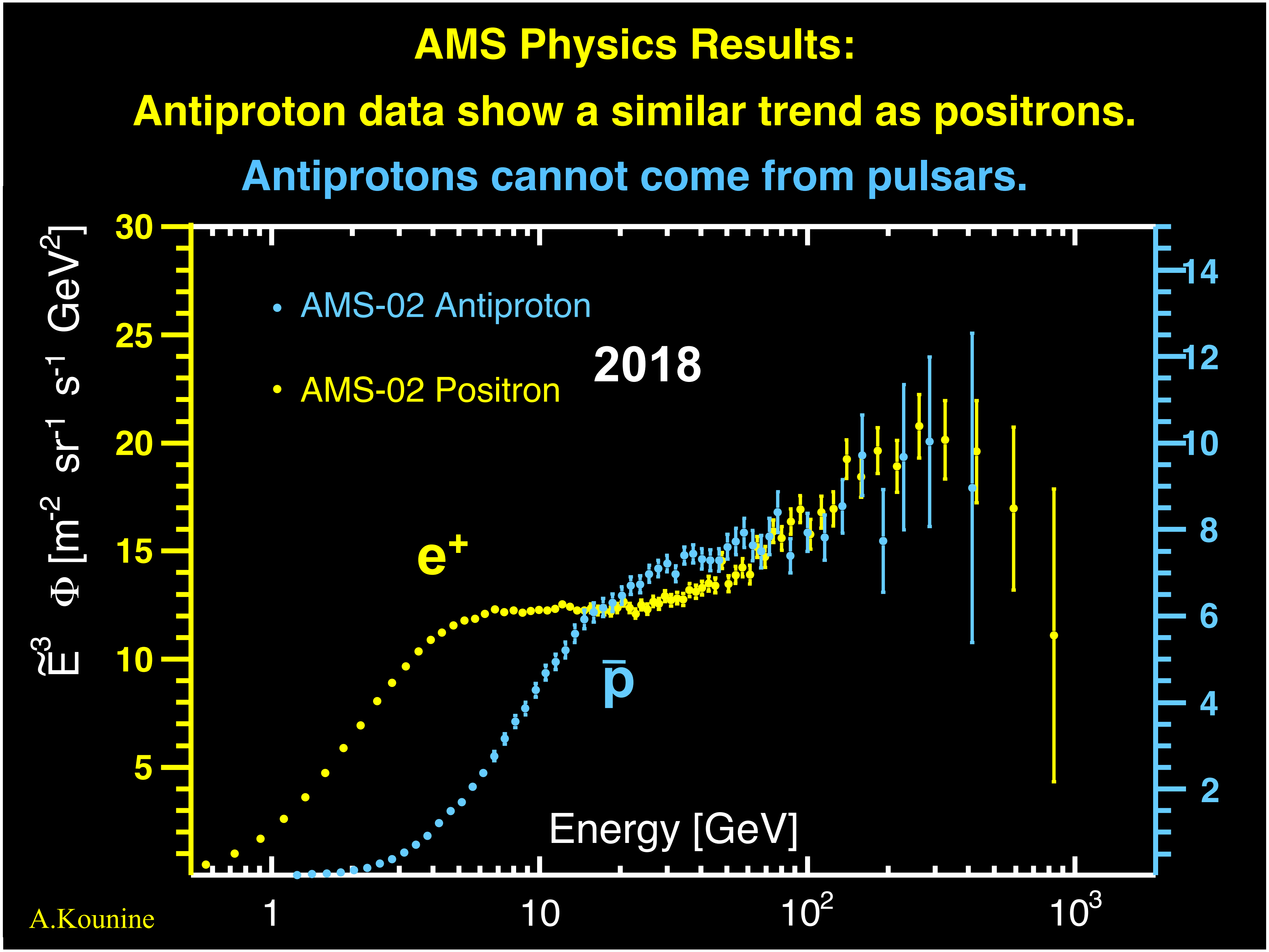




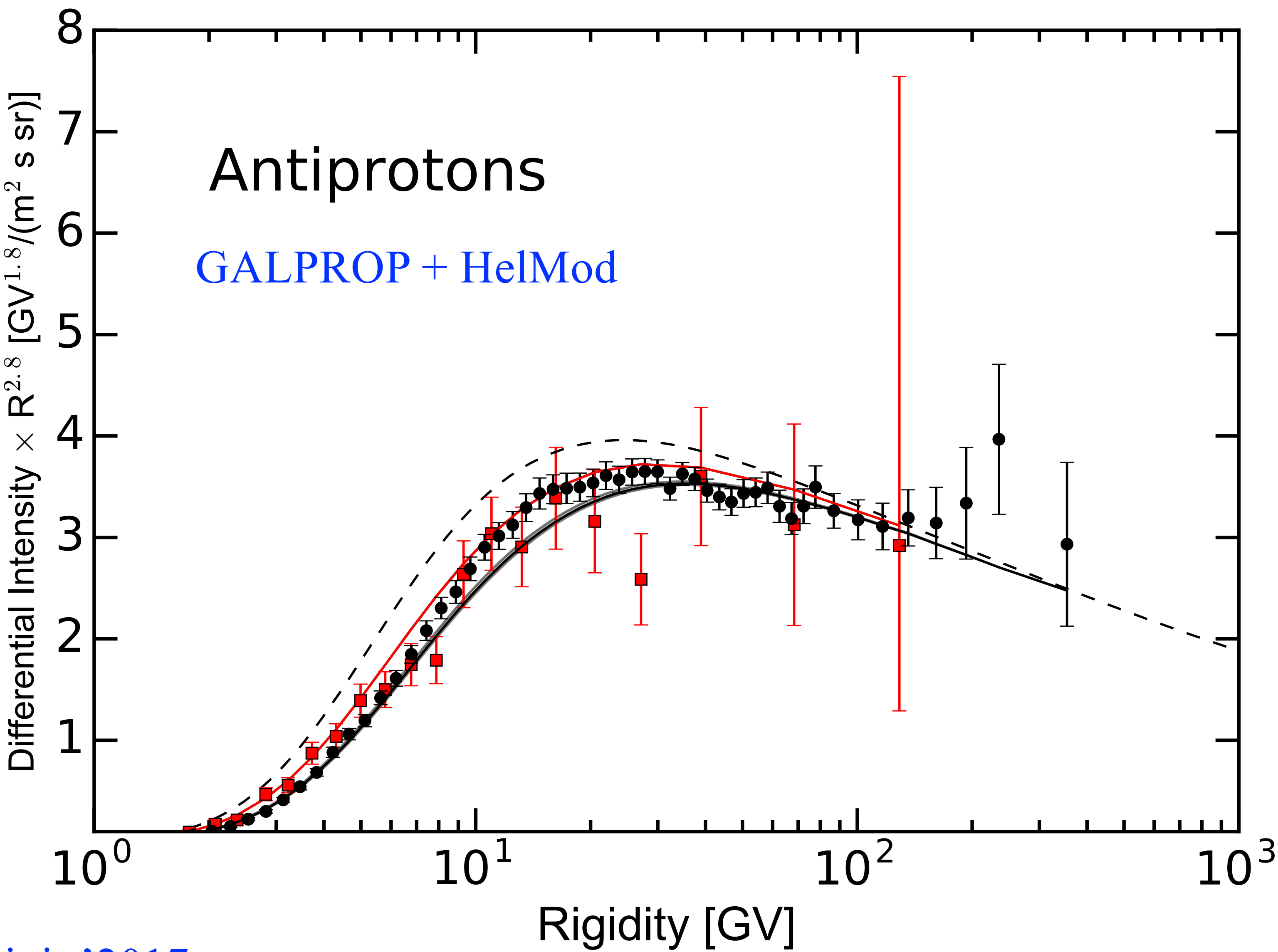


✧ The model assumptions are somewhat different, but all models predict a rise in the secondary products

More on Dark Matter scenario

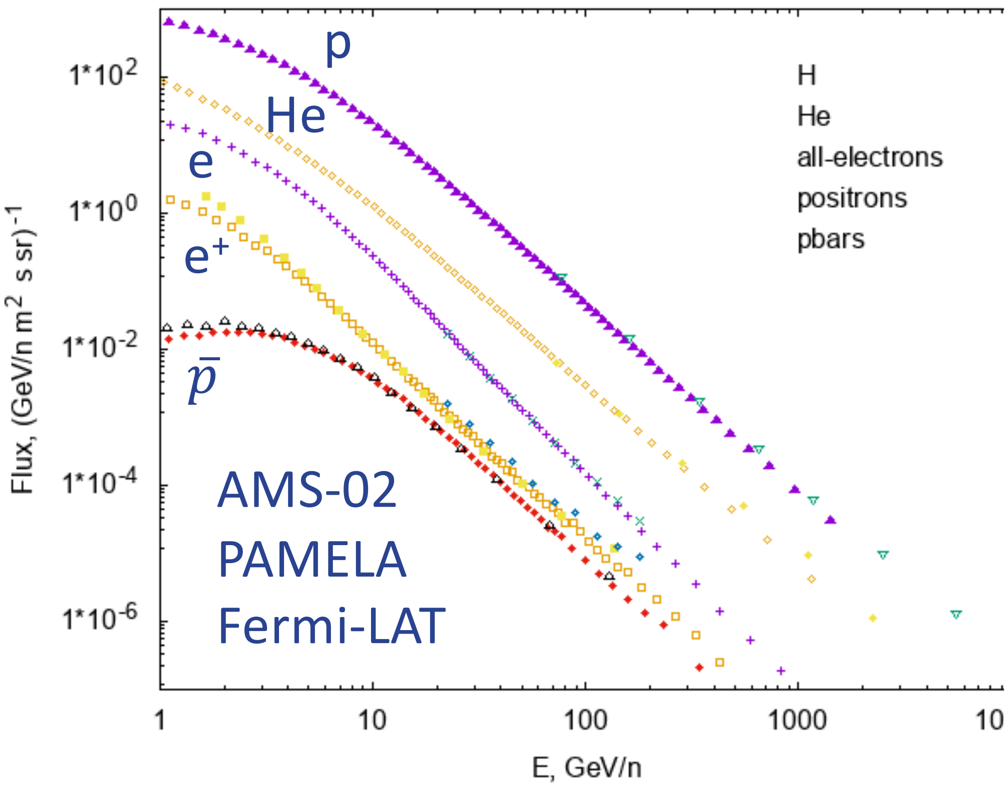


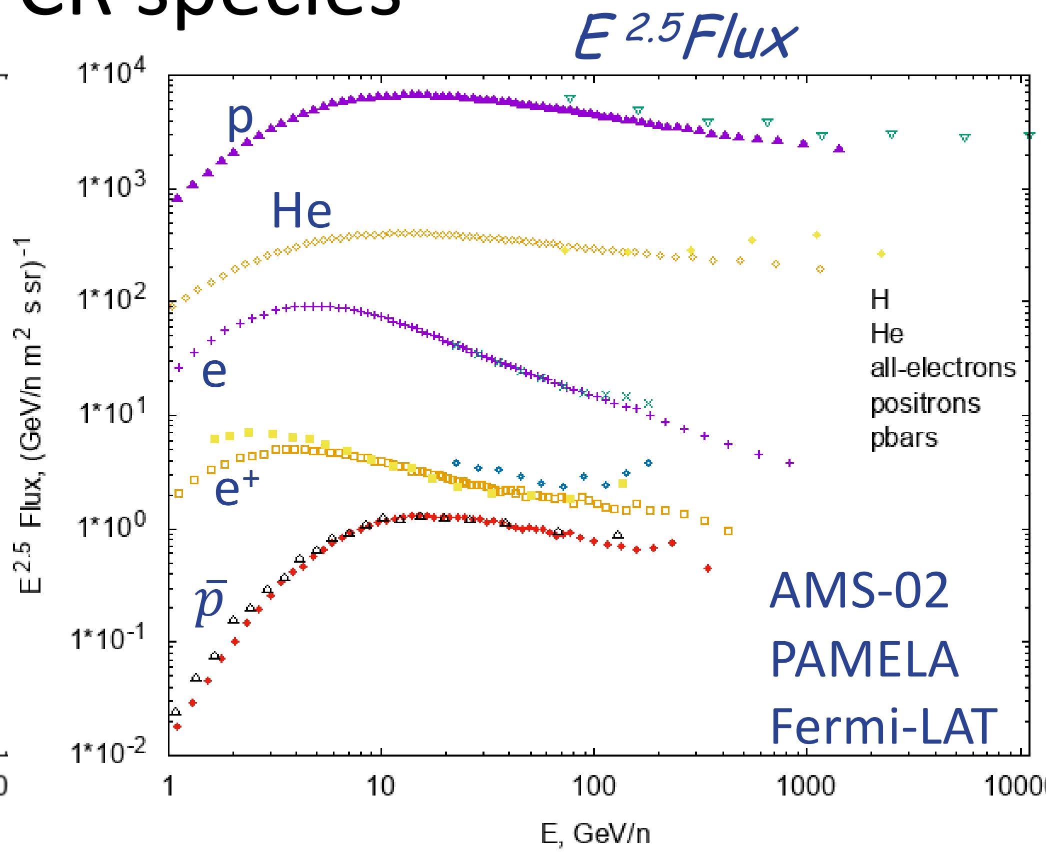
The reality: Secondary antiprotons



Boschini+'2017

Fluxes of CR species

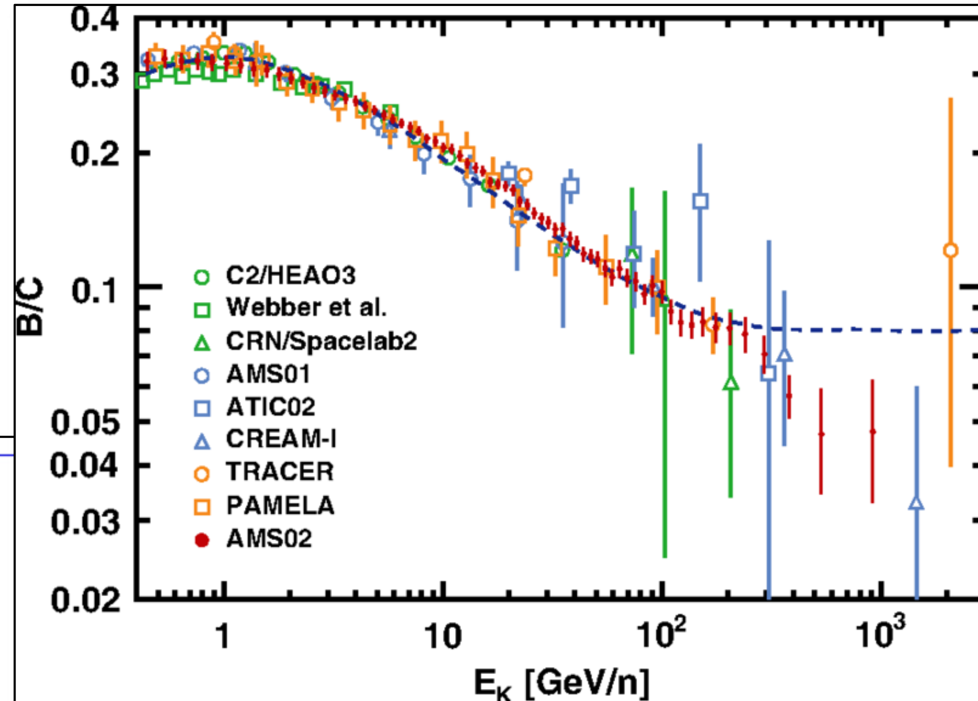


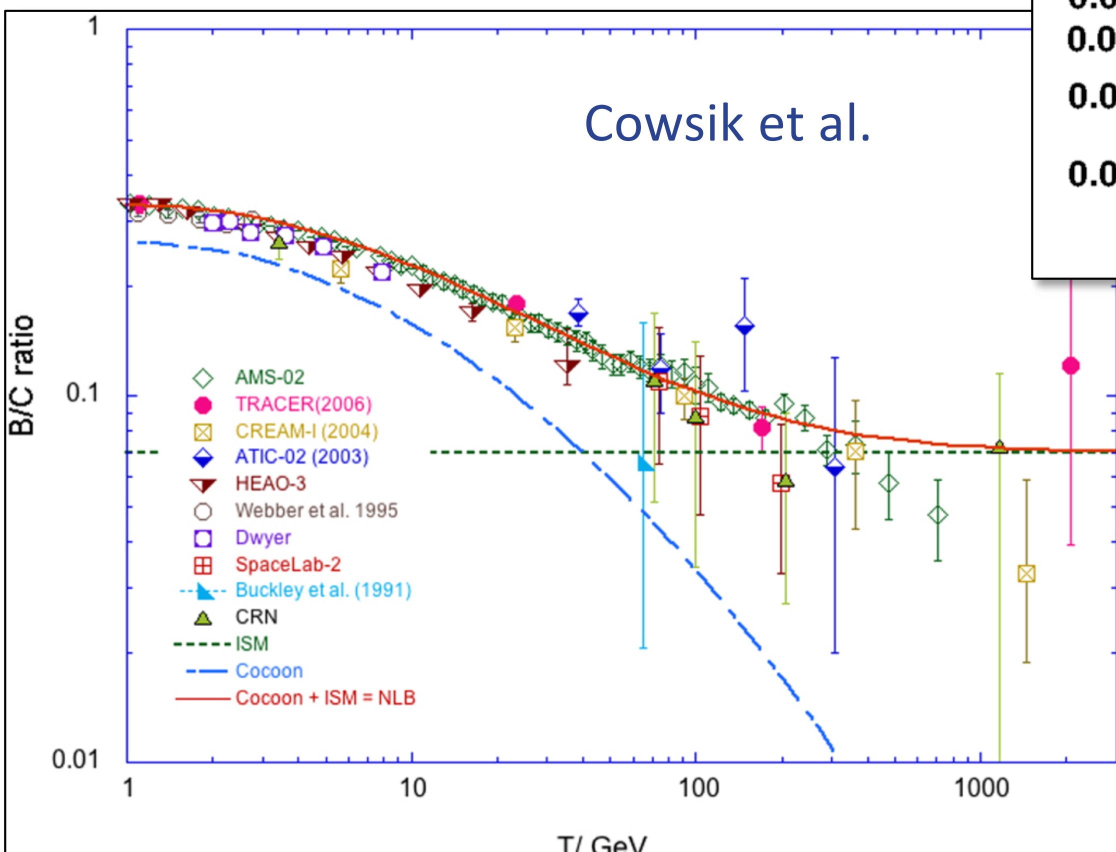


- Changing the scale from *Flux* to $E^{2.5}$*Flux* makes a big difference too!
- However, both are important:
  - see the ratio of fluxes of different species
  - see the real drop of the flux with energy
  - see the systematics

Astro: Nested Leaky-Box – cocoon model

- The model includes a cocoon around SNR with most of the grammage
- Secondaries are produced in cocoons
- ISM - small energy independent grammage

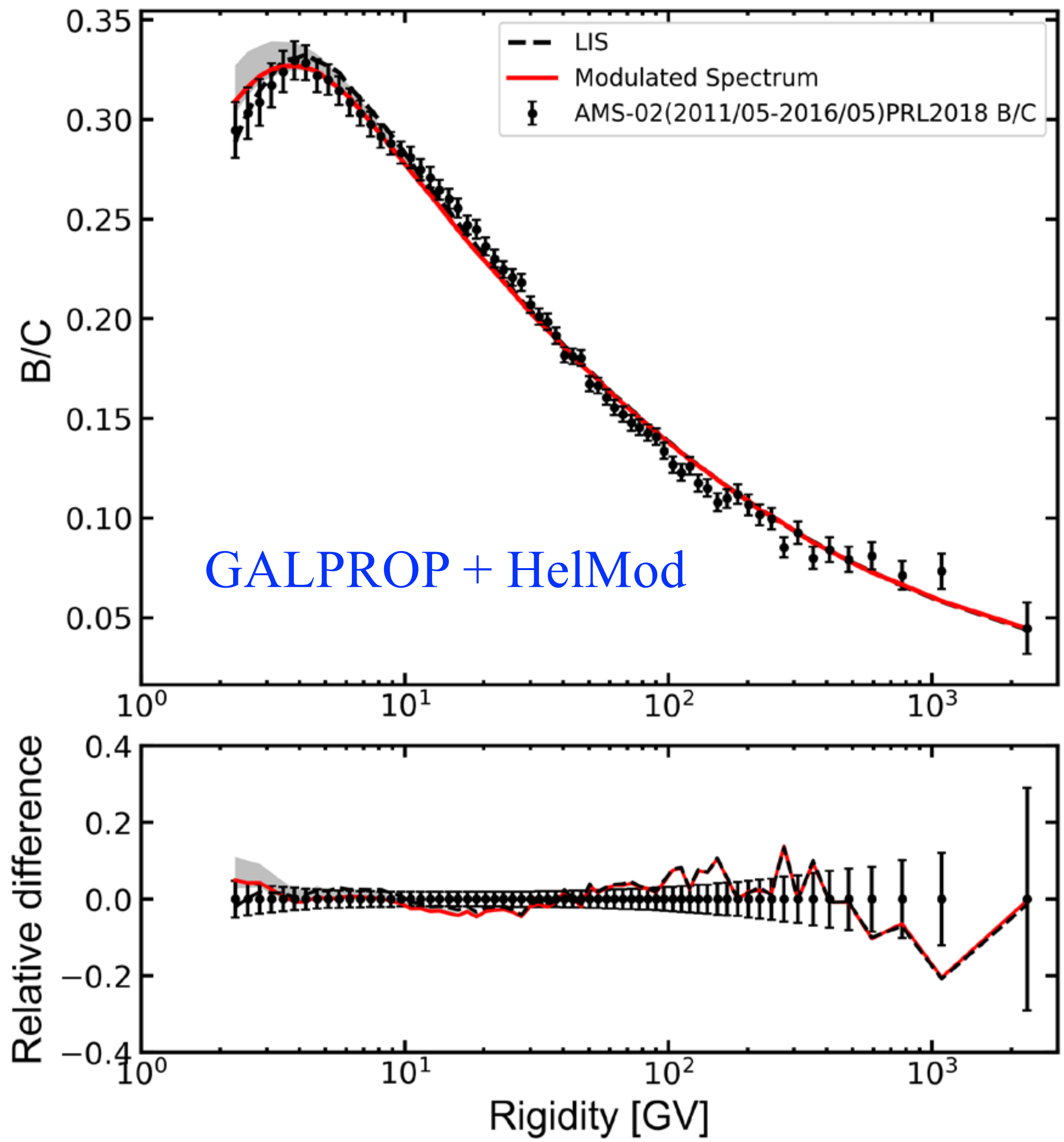




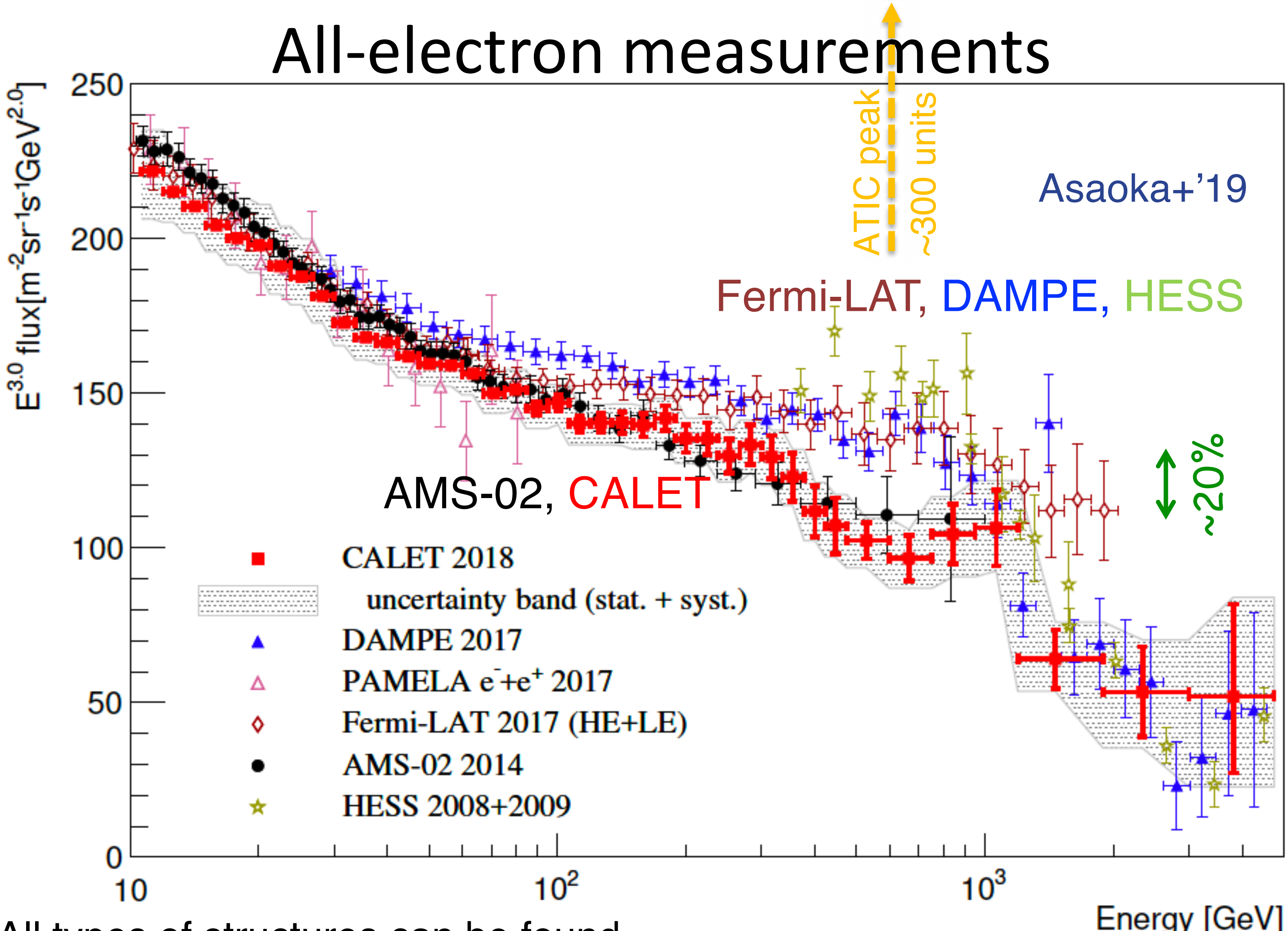
- ✧ The diffuse gamma-ray emission predicted by the model would be very faint
- ✧ The model also contradicts to the most recent B/C data
- ✧ Hypothesis rejected ?

B/C ratio in reality

- The B/C ratio as measured by AMS-02 (2018) agrees pretty well with the model calculations
- Does not exhibit any significant excess

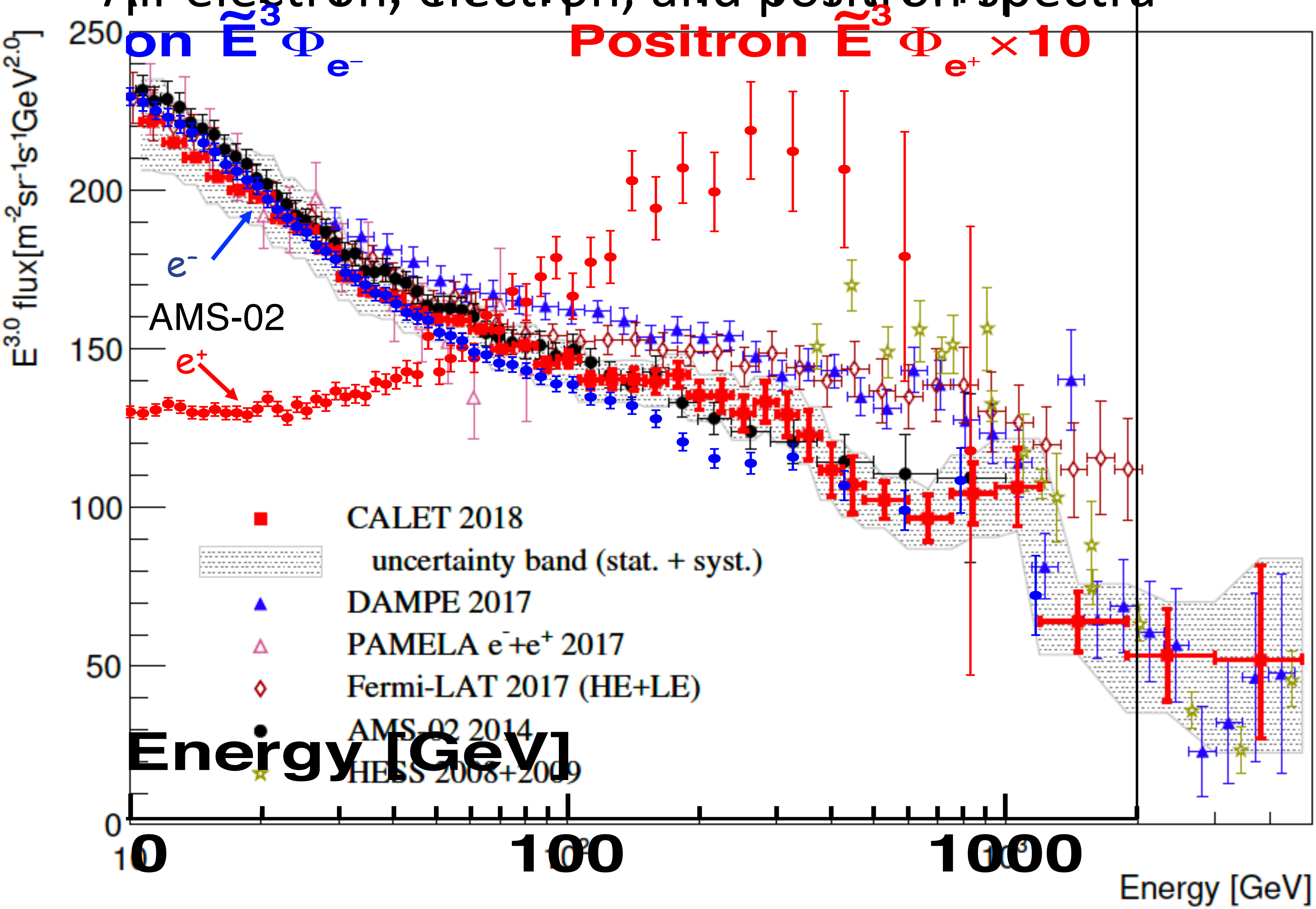


All-electron measurements

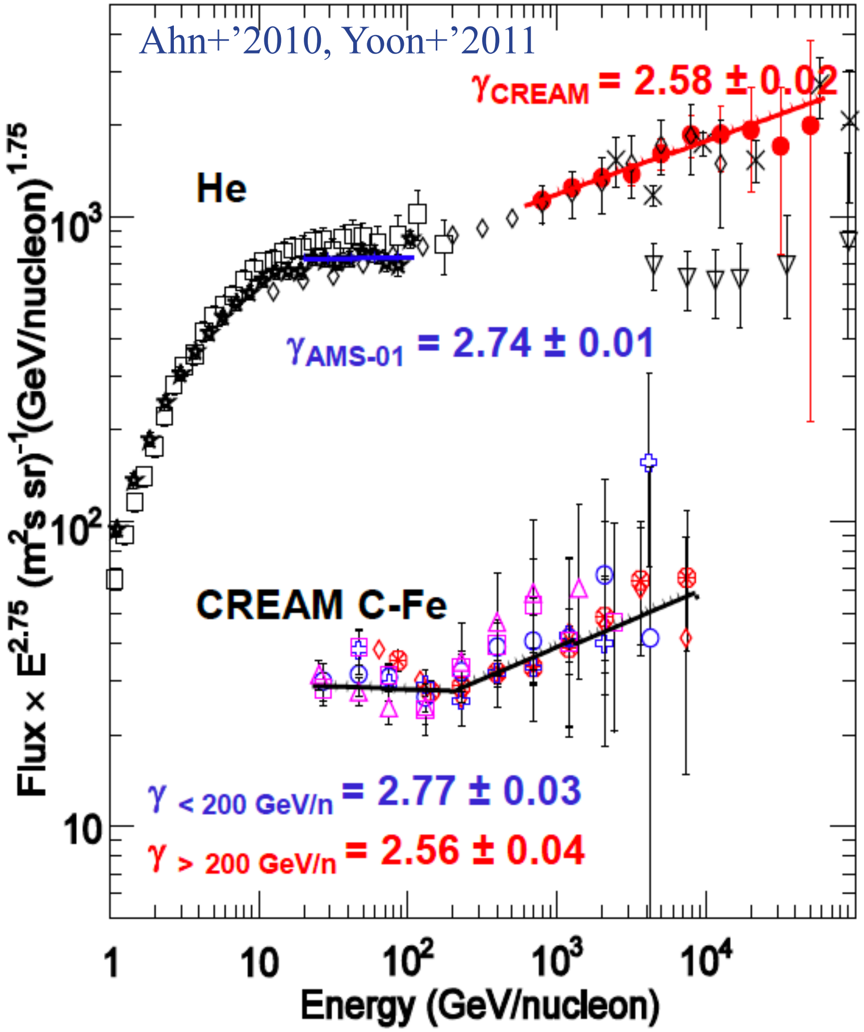


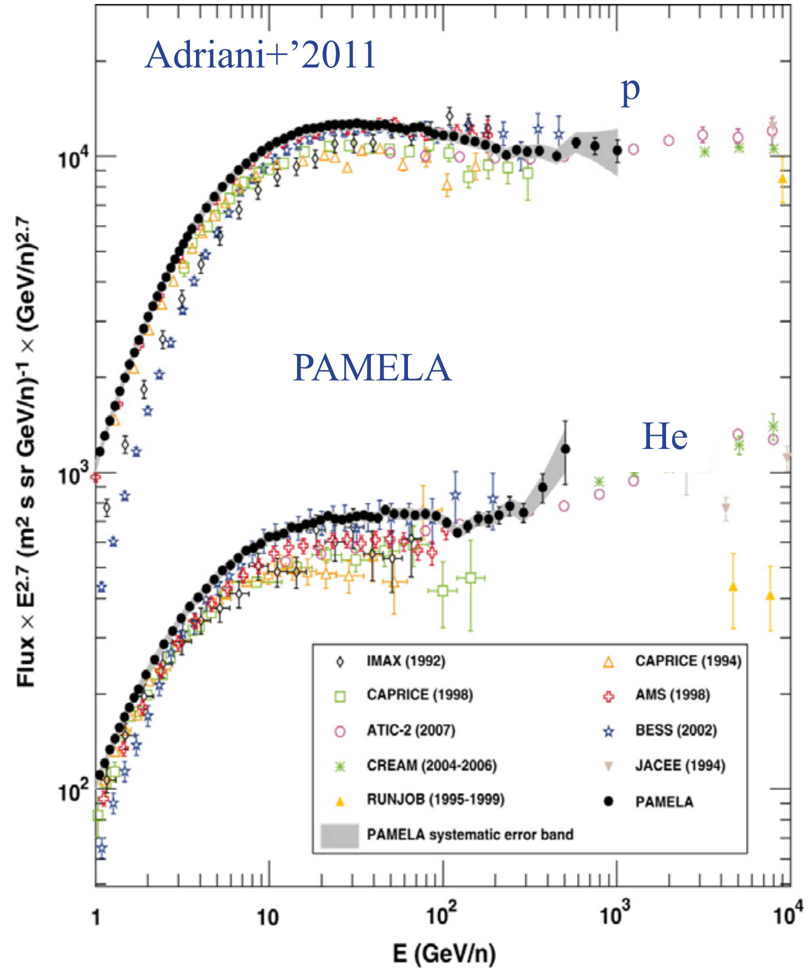
- All types of structures can be found
- Results by pairs of instruments (AMS-02 & CALET) and (Fermi-LAT & DAMPE) confirm each other, but look quite different from another pair with high significance!

All-electron, electron, and positron spectra



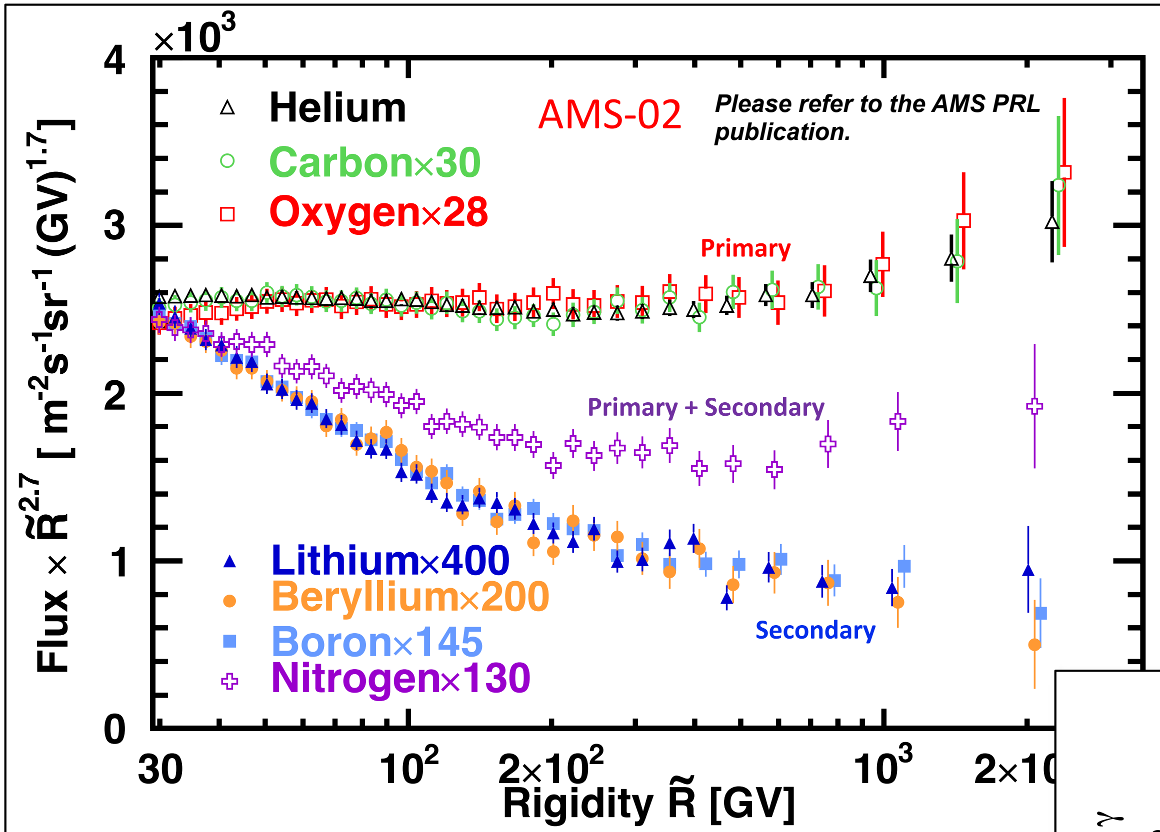
Break in the spectra of CR nucleons





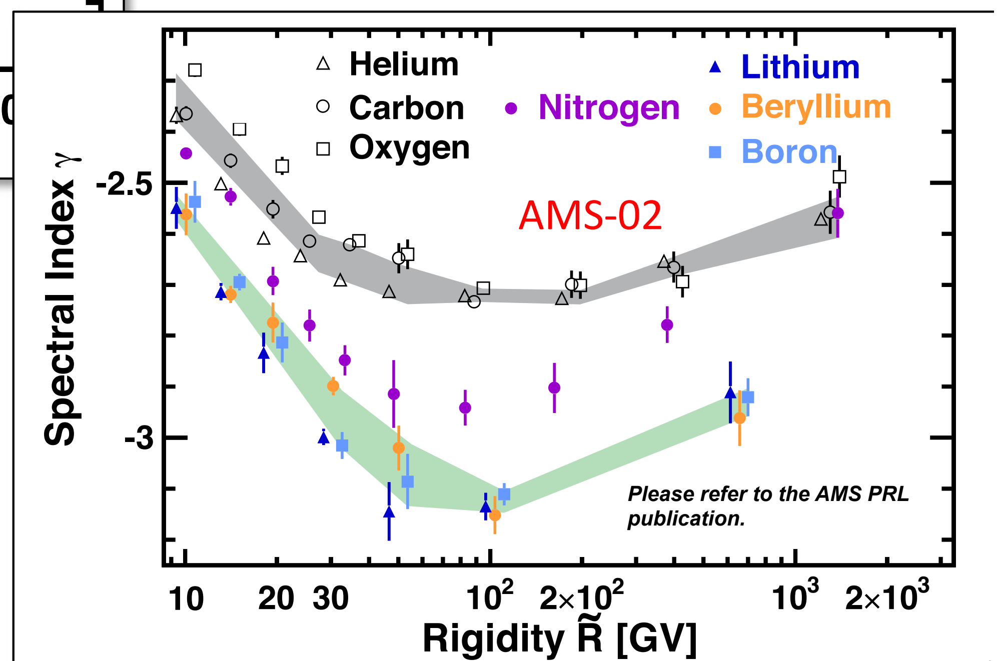
- ✧ First noticed in the data by CREAM and ATIC
- ✧ Looked like an energy calibration issue…
- ✧ until it was confirmed by PAMELA and with more statistics by AMS-02

AMS-02: Breaks in the spectra of CR species



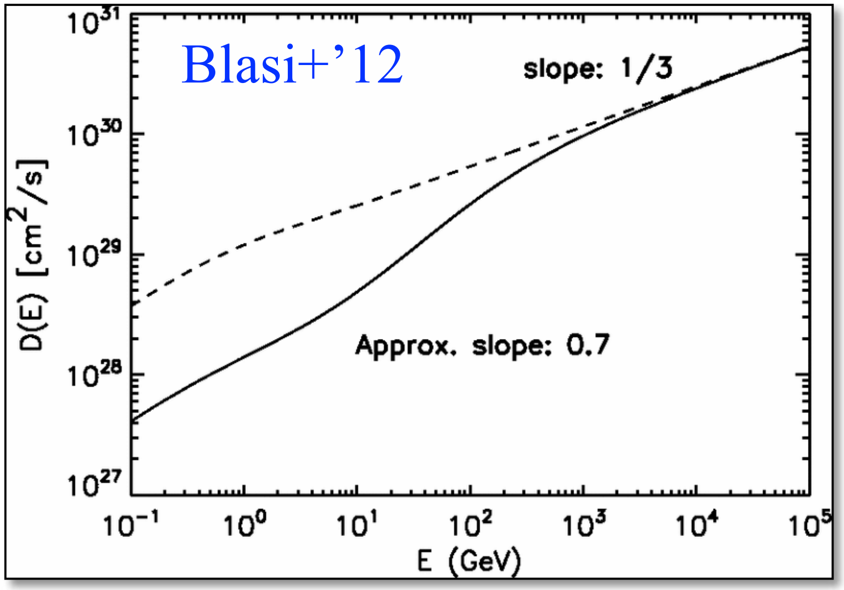
- ◇ Spectra of secondaries are steeper than primaries in the whole energy range – contradictory to the hypothesis of secondary production in SNR shocks
- ◇ Difficult is to have so well correlated behavior (vs rigidity) of all primary and all secondary species because of very much different fragmentation and production cross sections

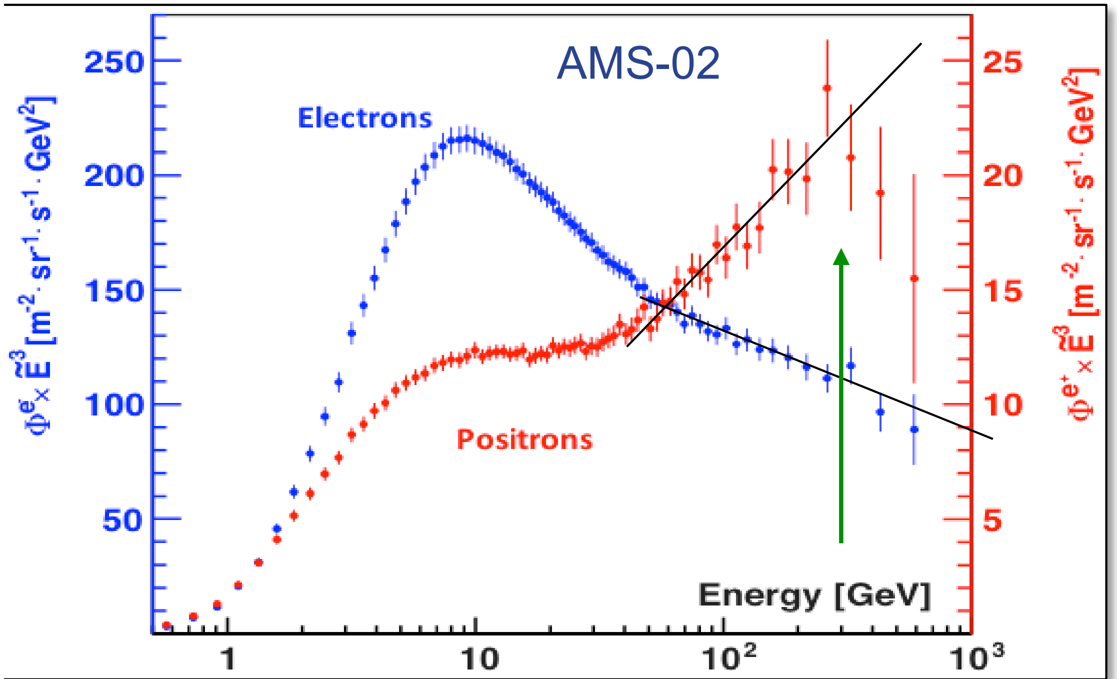
- ◇ More likely and consistent with change in the propagation properties of the interstellar medium, in the diffusion coefficient (Vladimirov+'12)
- ◇ The magnitude of the break in the spectra of secondaries should be twice as much as that in the spectra of primaries

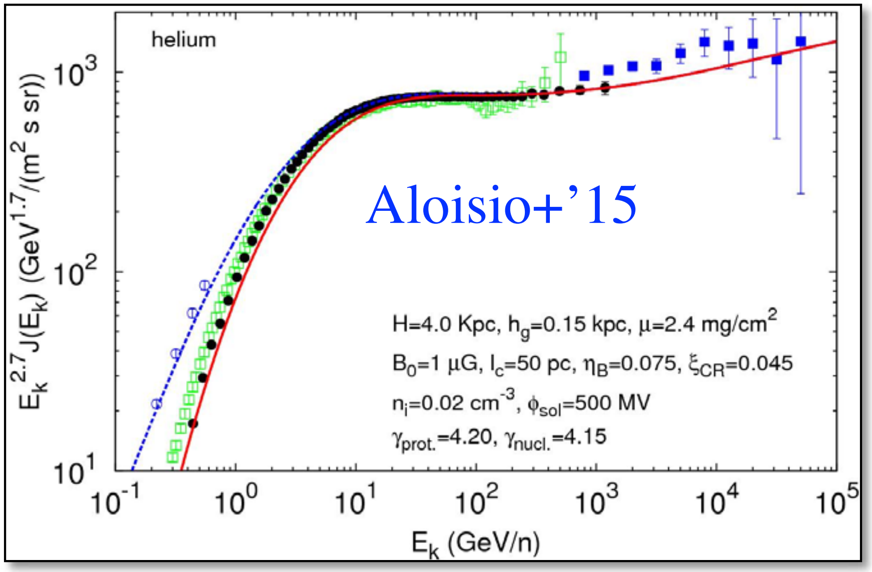


Interstellar turbulence and the diffusion coeff.

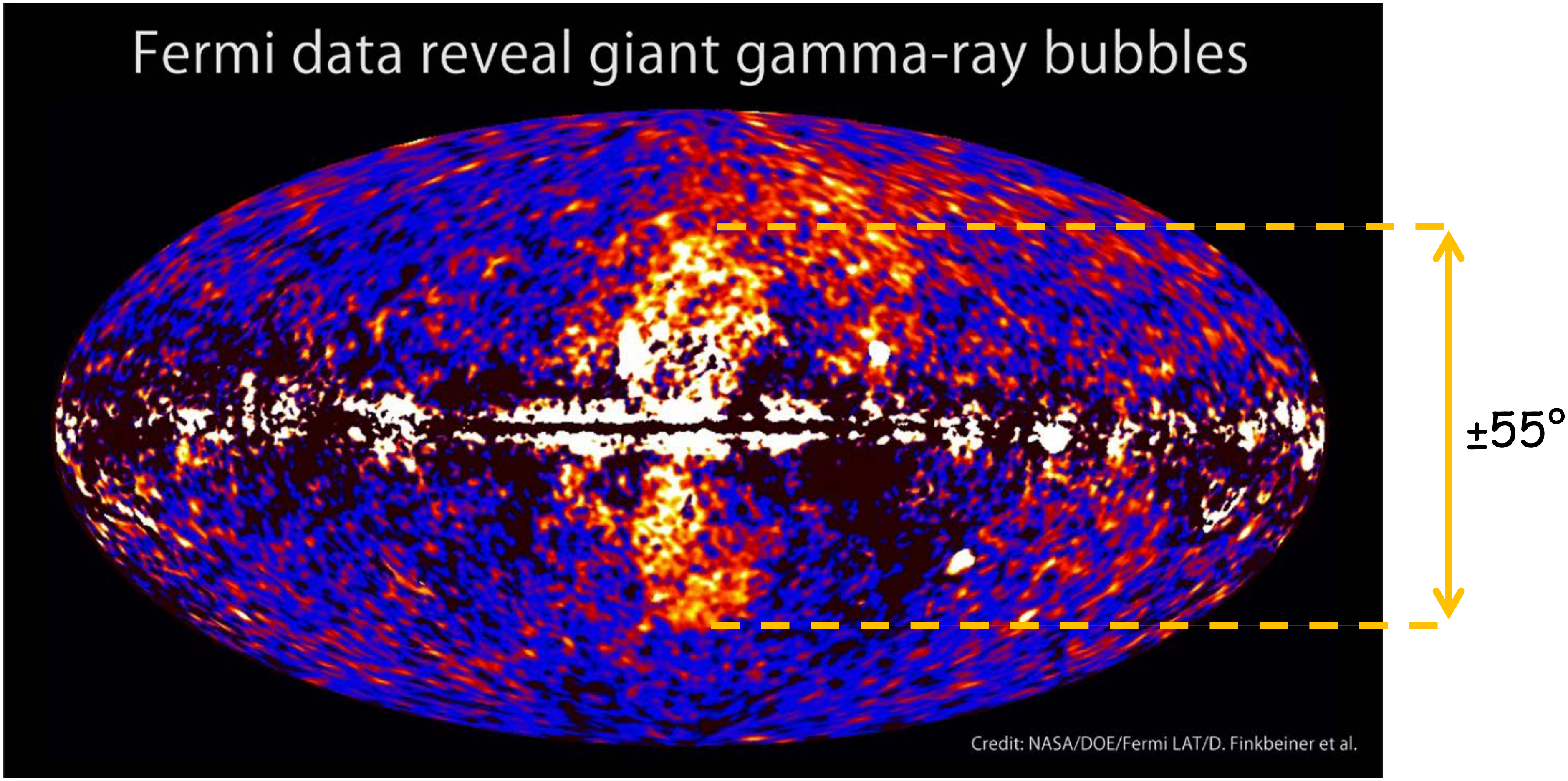
- ✧ 300 GV break: A transition from the self-generated turbulence to the cascading of externally generated turbulence (for instance due to supernova bubbles) from large spatial scales to smaller scales
- ✧ The agreement with AMS-02 data is pretty good, but does not explain the difference between the spectra of *p* and heavier species (He-O)
- ✧ No break in e^- and a cutoff in e^+





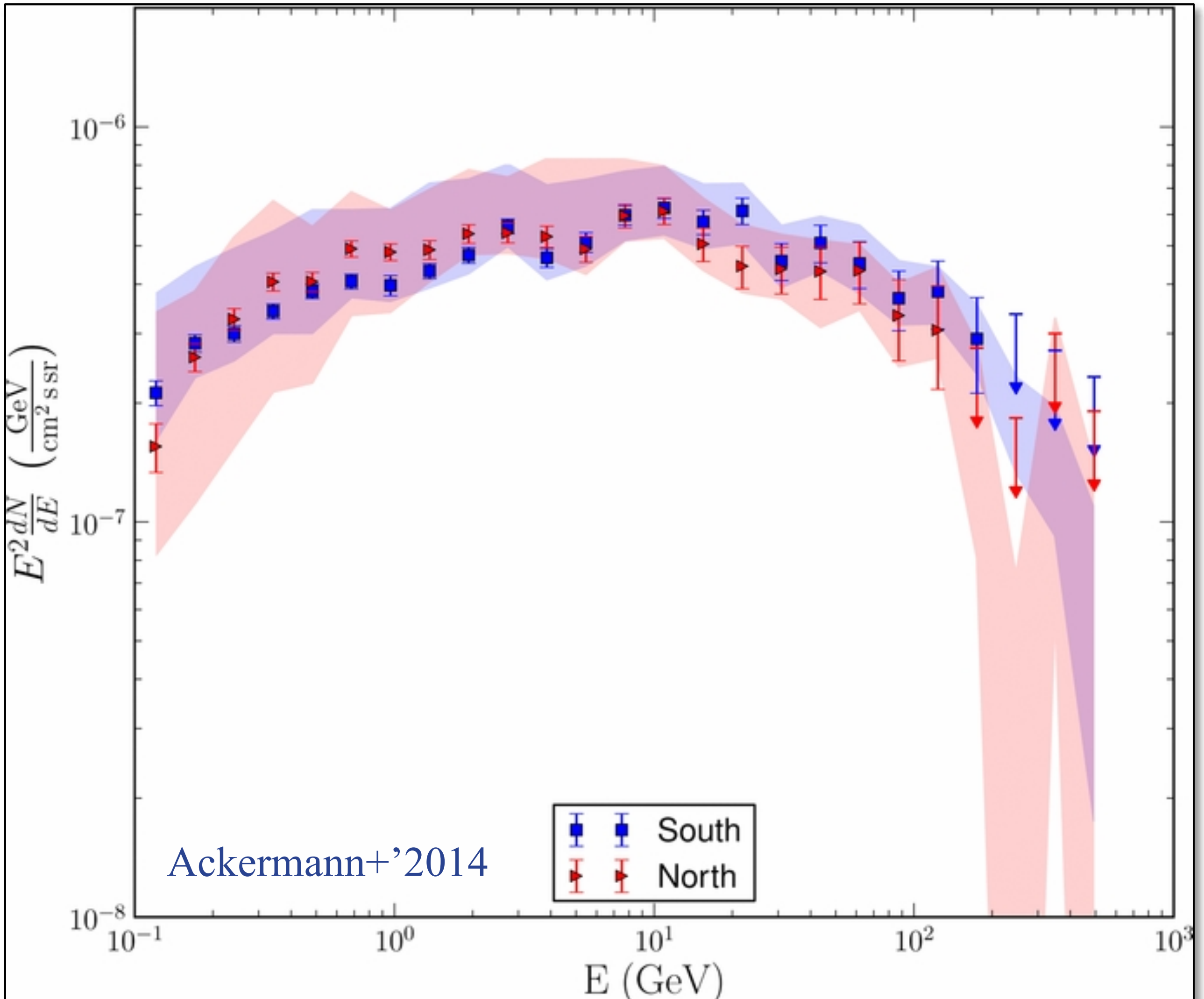


NASA press release



- 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

Spectrum of the Fermi 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

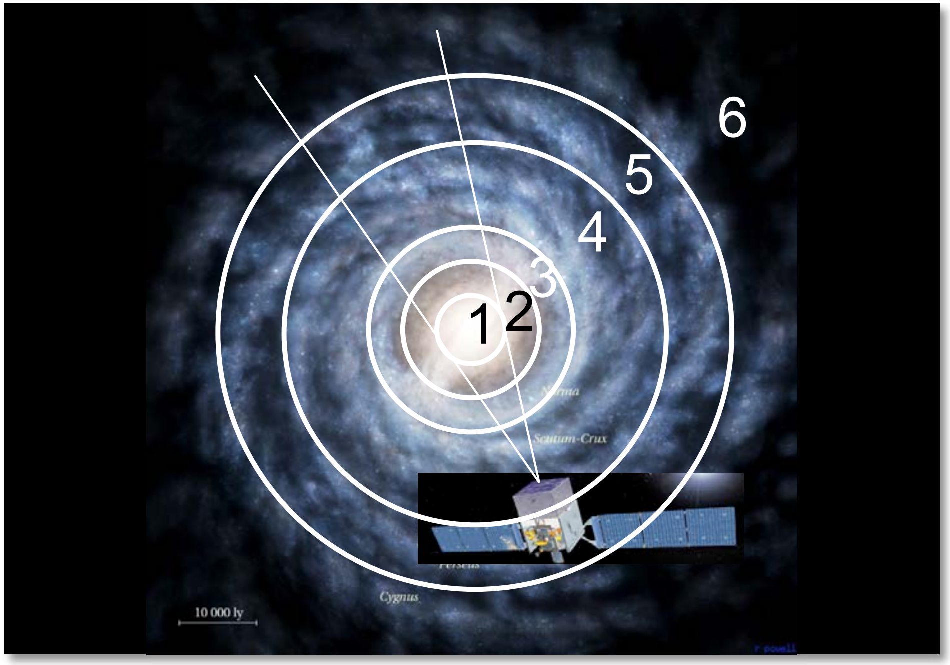
Fermi-LAT: Observations of the Inner Galaxy

- Cylindrically symmetrical model – GALPROP
- Gas-related (H_2, HI, HII) and inverse Compton emission components are divided into 6 Galactocentric rings and fitted to the observations
- Point sources, initially from 3FGL, isotropic emission, and Loop I are fitted to data in iterations
- Fit starts from the outer Galaxy
- Emission from the outer Galaxy is subtracted: inner Galaxy and projected sources remain

Ajello+, ApJ 819 [2016] 44A

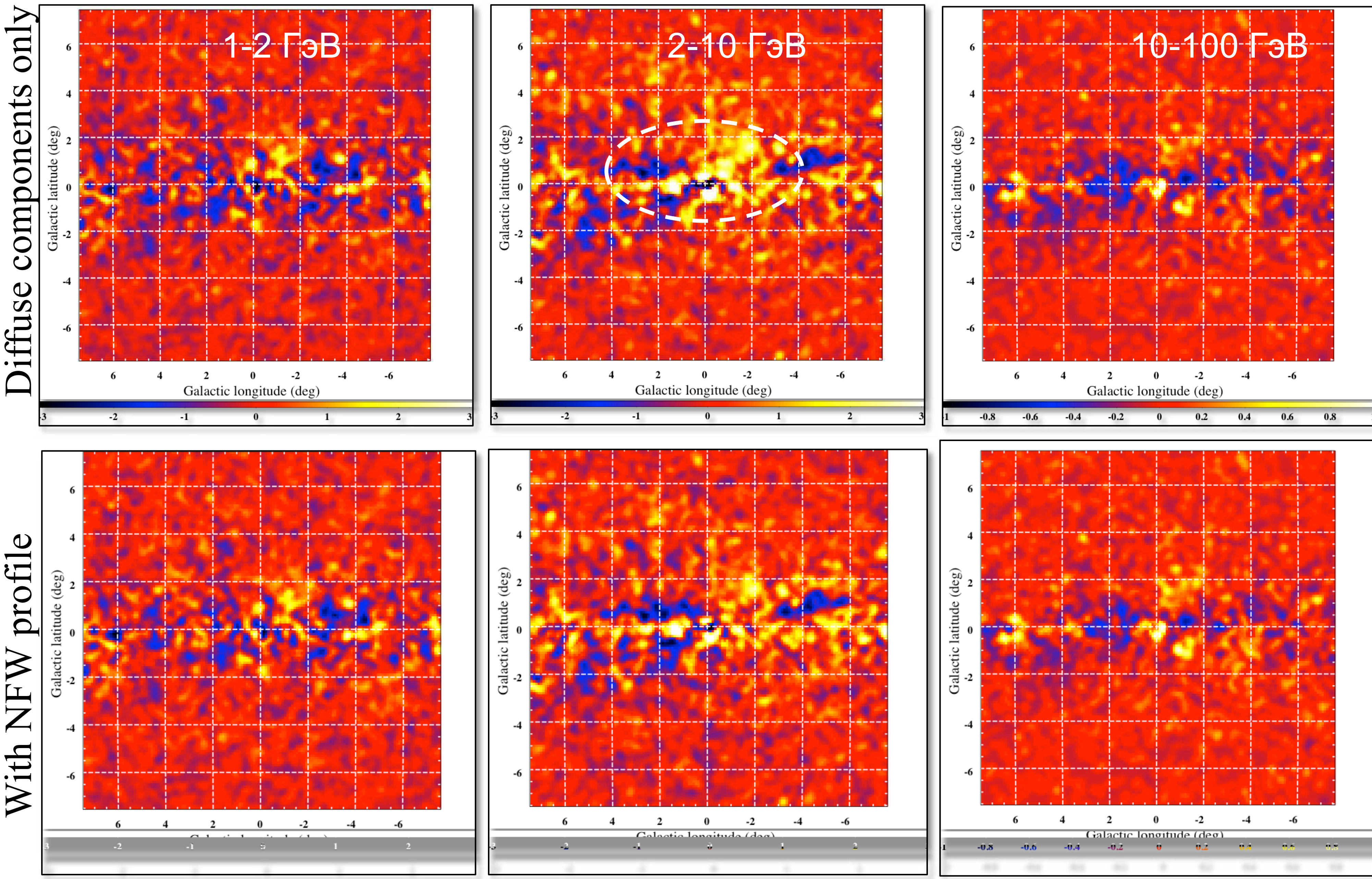
Table 1
Galactocentric Annular Boundaries

Annulus #	R_{min} (kpc)	R_{max} (kpc)	Longitude Range (Full)	Longitude Range (Tangent)
1	0	1.5	$-10° \leqslant l \leqslant 10°$	...
2	1.5	2.5	$-17° \leqslant l \leqslant 17°$	$10° \leqslant \lvert l \rvert \leqslant 17°$
3	2.5	3.5	$-24° \leqslant l \leqslant 24°$	$17° \leqslant \lvert l \rvert \leqslant 24°$
4	3.5	8.0	$-70° \leqslant l \leqslant 70°$	$24° \leqslant \lvert l \rvert \leqslant 70°$
5	8.0	10.0	$-180 \leqslant l \leqslant 180°$	...
6	10.0	50.0	$-180 \leqslant l \leqslant 180°$	...



Fermi-LAT observations of the inner Galaxy: residuals

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

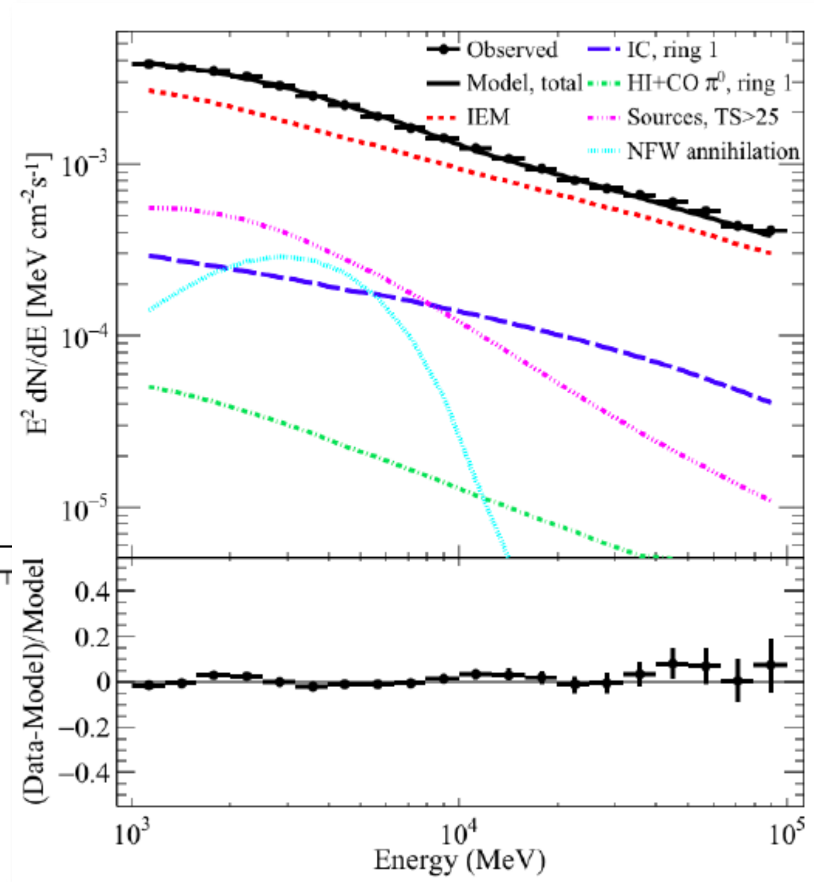


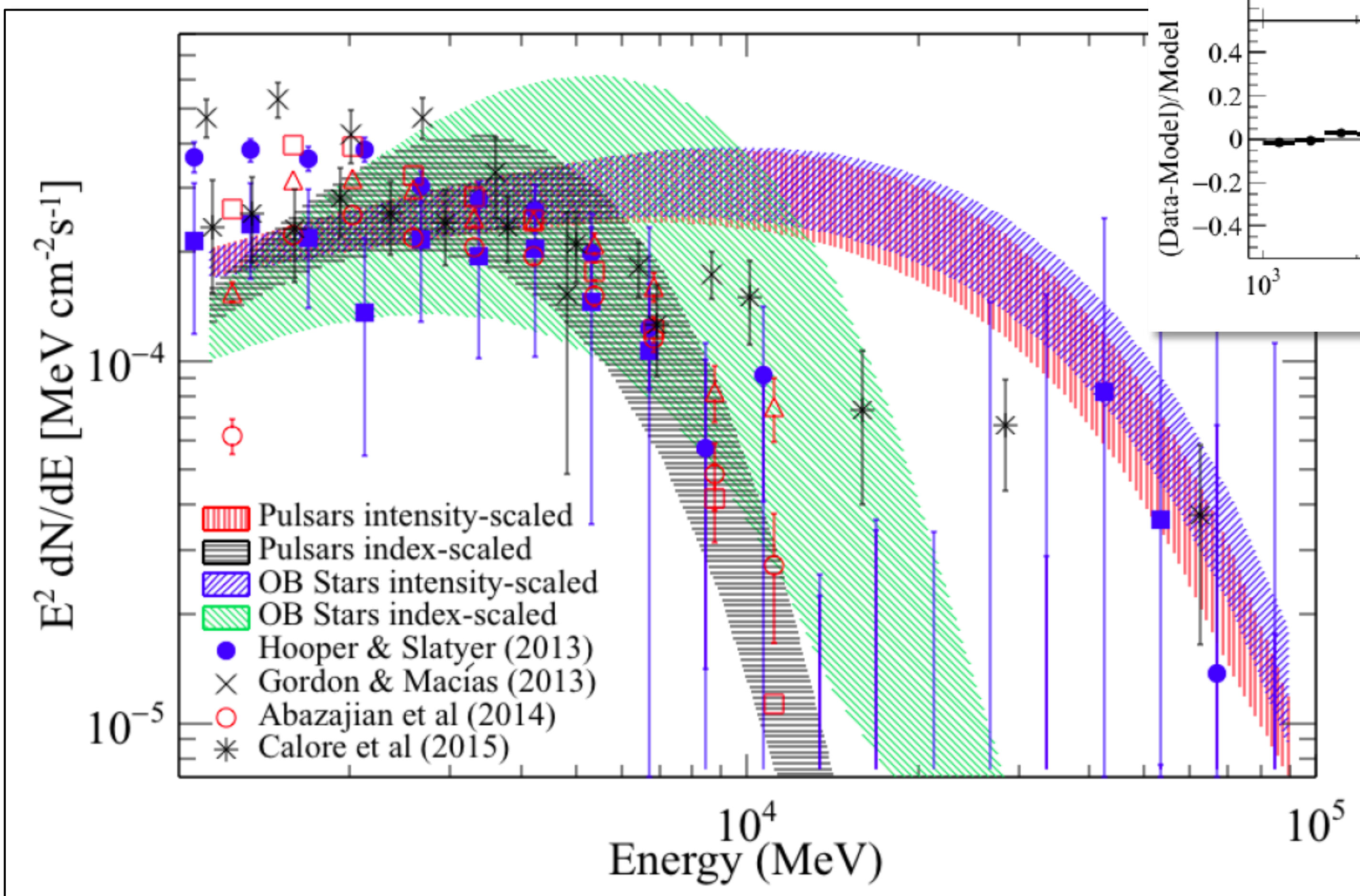
Events per pixel 0.1° × 0.1°

Spectrum of NFW component

✧ NFW profile:

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

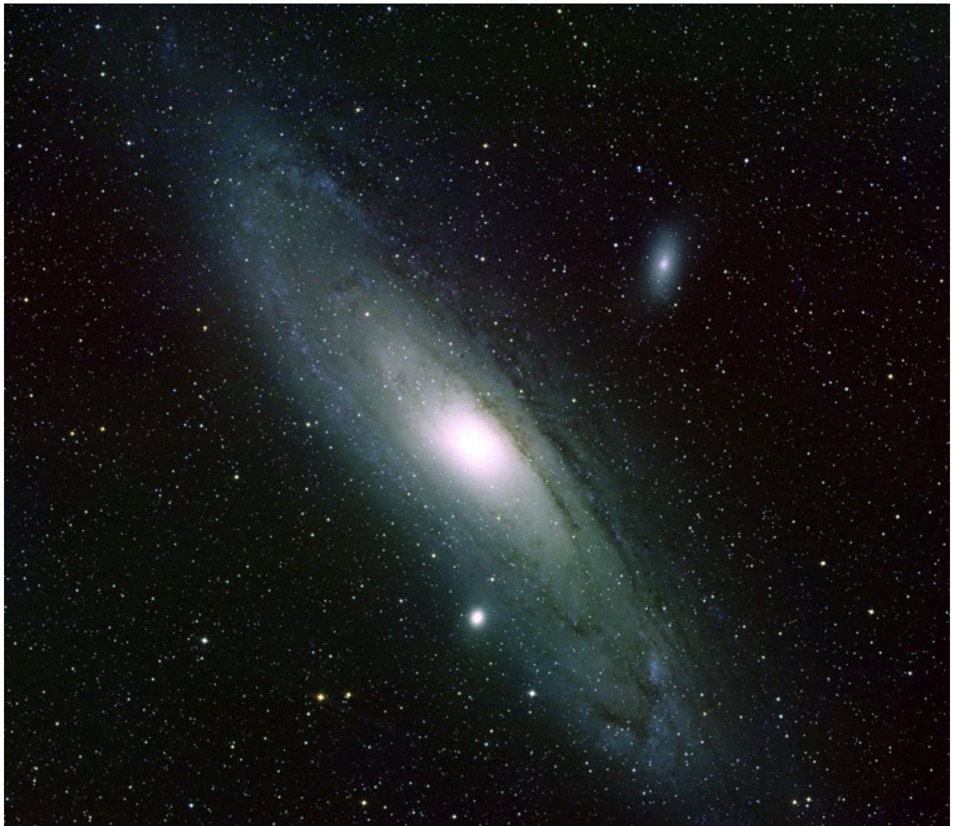




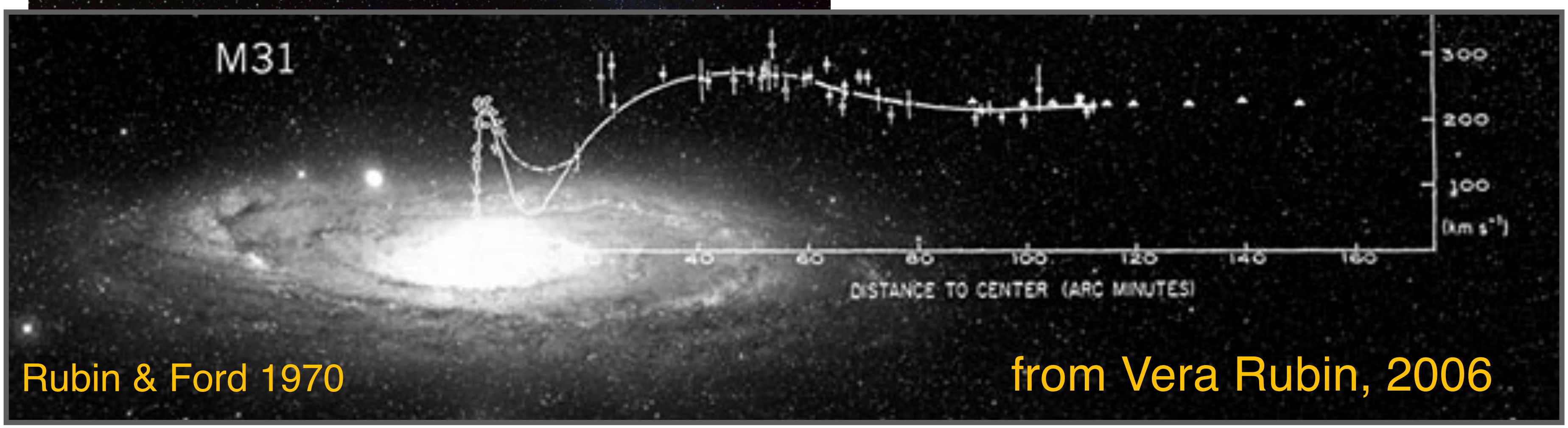
✧ Components of the emission from ROI 15° × 15° at the Galactic center

✧ Spectrum of NFW component for different CR source distributions

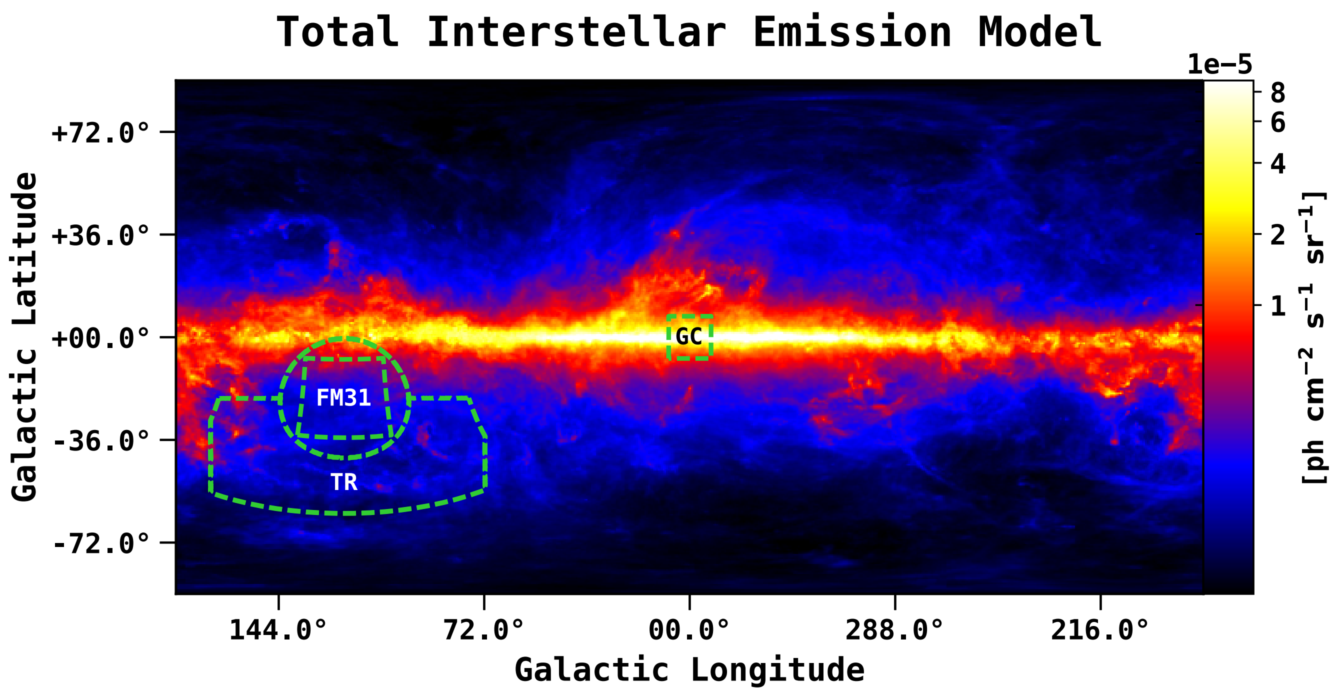
Andromeda galaxy M31 – a closest spiral

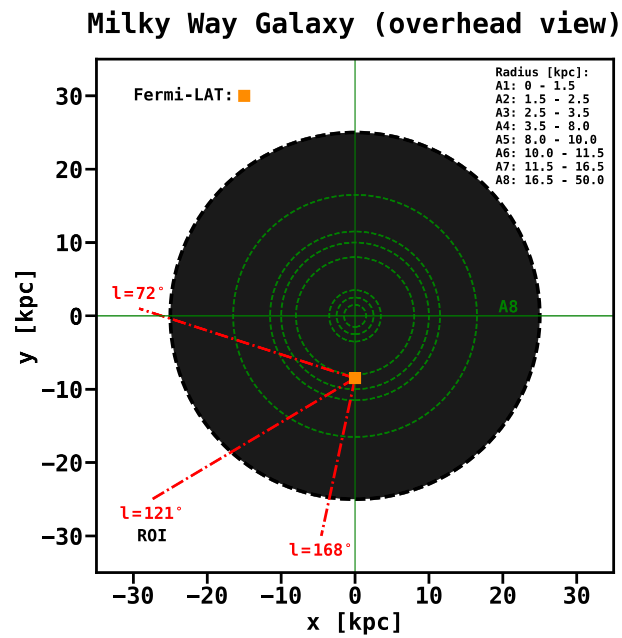


- ✧ Similar to the Milky Way at 778 kpc
- ✧ Provides an external view on our own Galaxy
- ✧ Large size on the sky 3°×1° – easy to resolve
- ✧ The rotation curve remains constant over large distances – large content of DM
- ✧ Virial radius ~300 kpc



Test region and M31 field

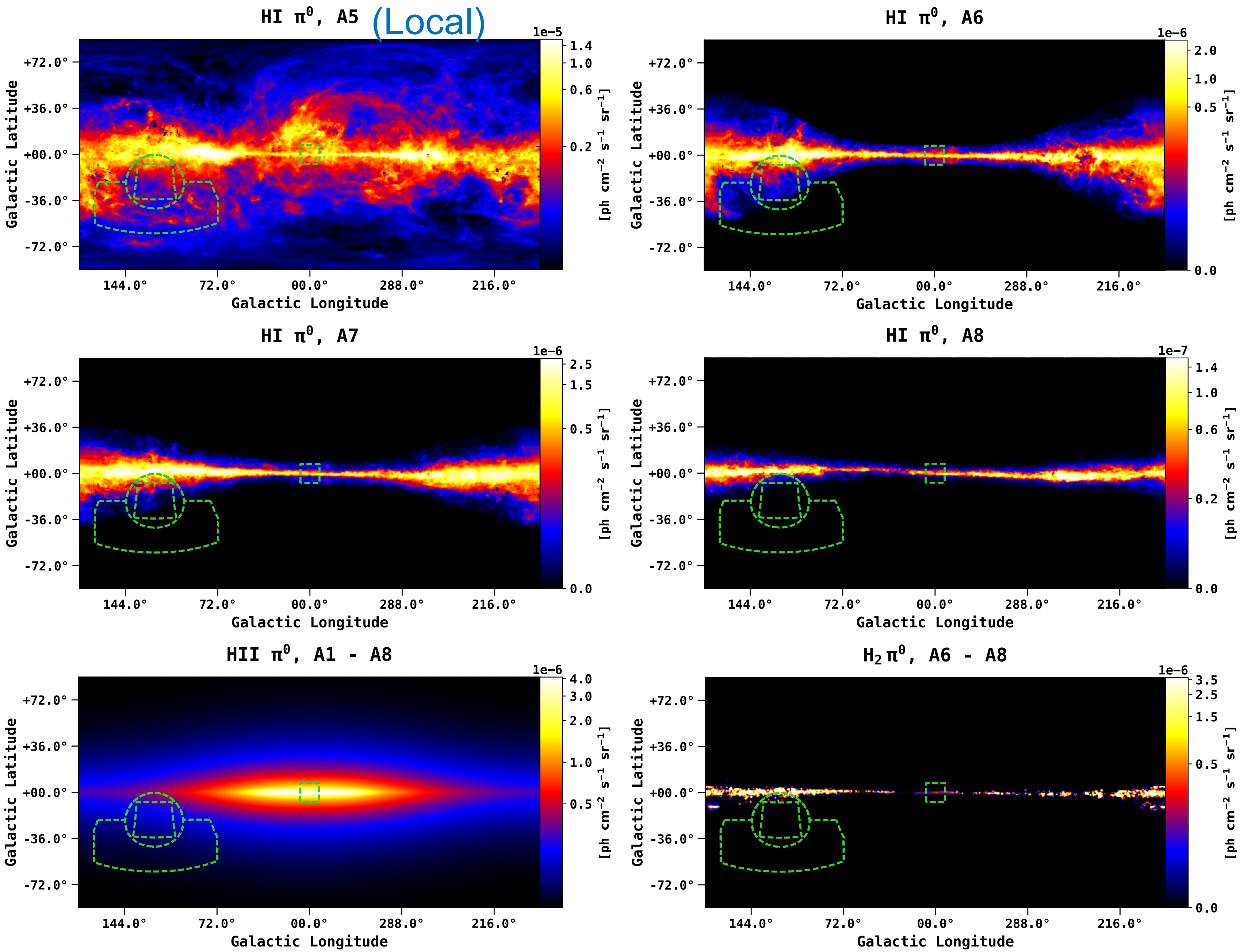




- ✧ The interstellar emission model for the MW (1-100 GeV):
  π^0-decay + (anisotropic) inverse Compton + Bremsstrahlung
- ✧ "Square" region is M31 field (28°×28°)
- ✧ "TR" labels the test region
- ✧ Schematic of the eight concentric circles which define the annuli (A1-A8) in the MW foreground model. Only A5-A8 contribute to the Galactic foreground emission for the field used in this analysis.

Karwin+, 2019 ApJ 880, 95

γ-ray maps for π^0-decay for different rings (GALPROP) – 1

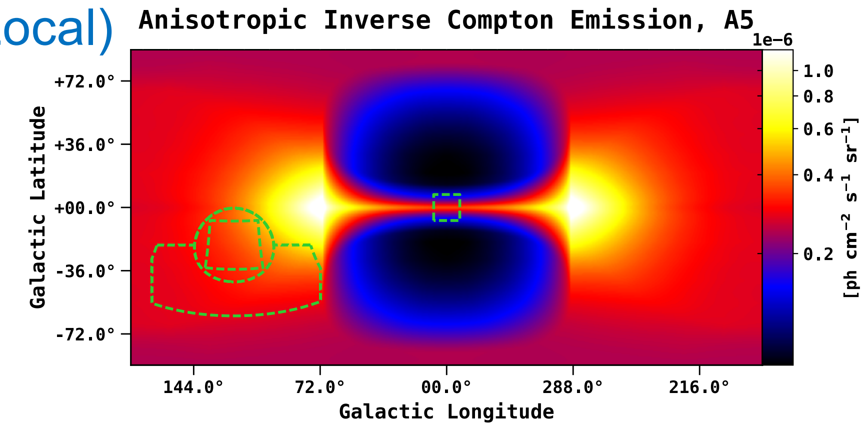


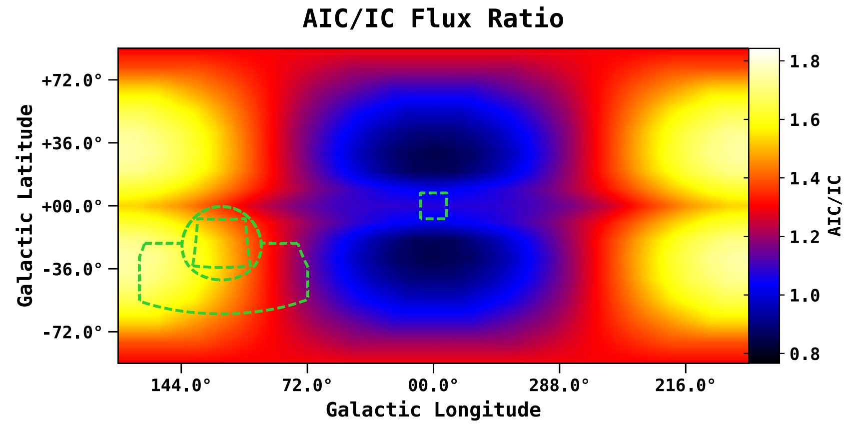
H I gas

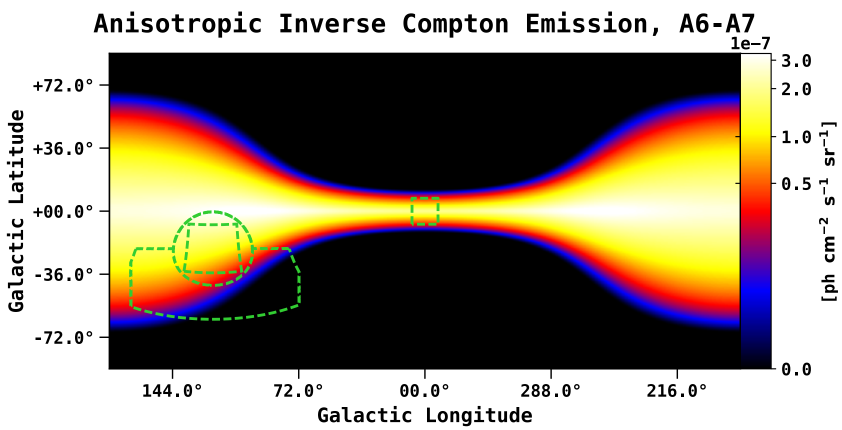
H II, H_2 gas

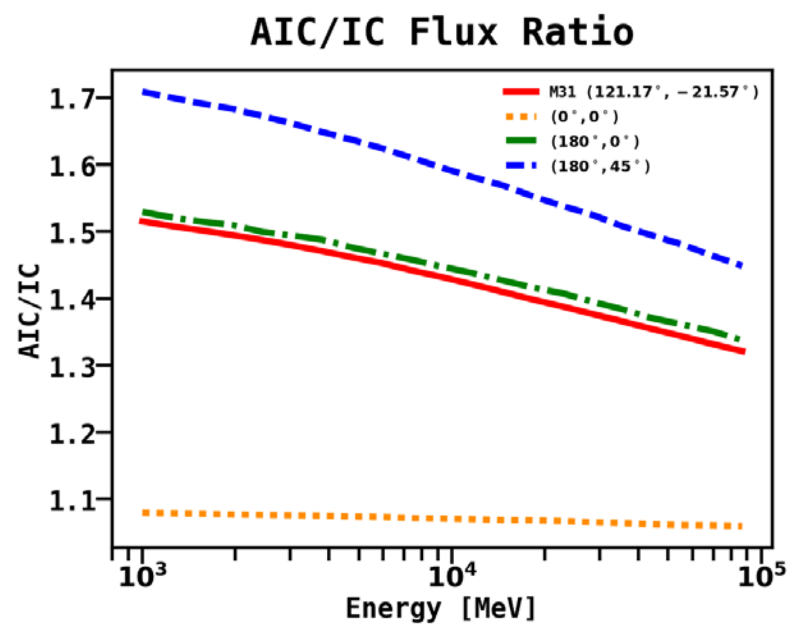
γ-ray maps for anisotropic IC for different rings (GALPROP) –2

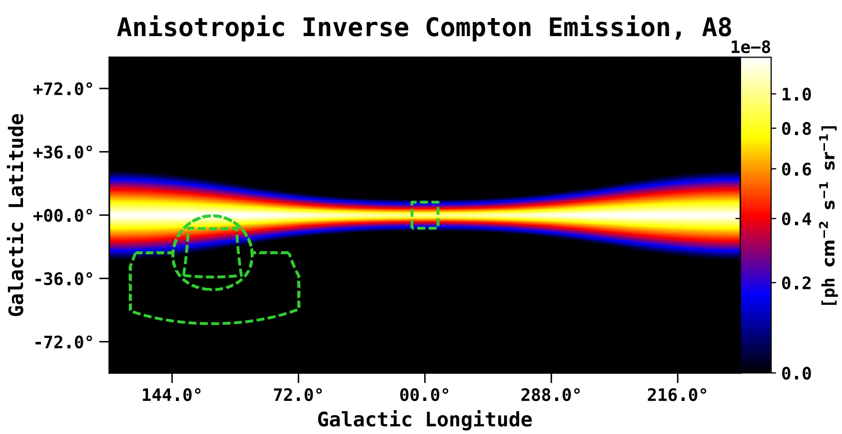
(Local)





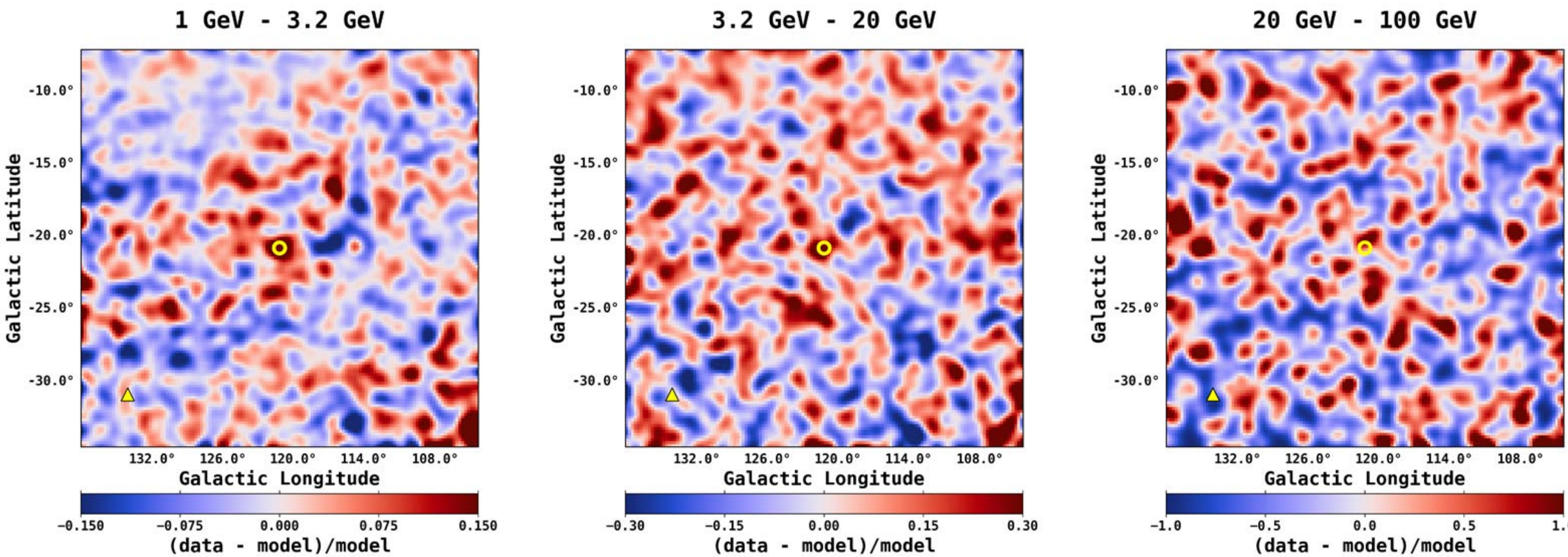






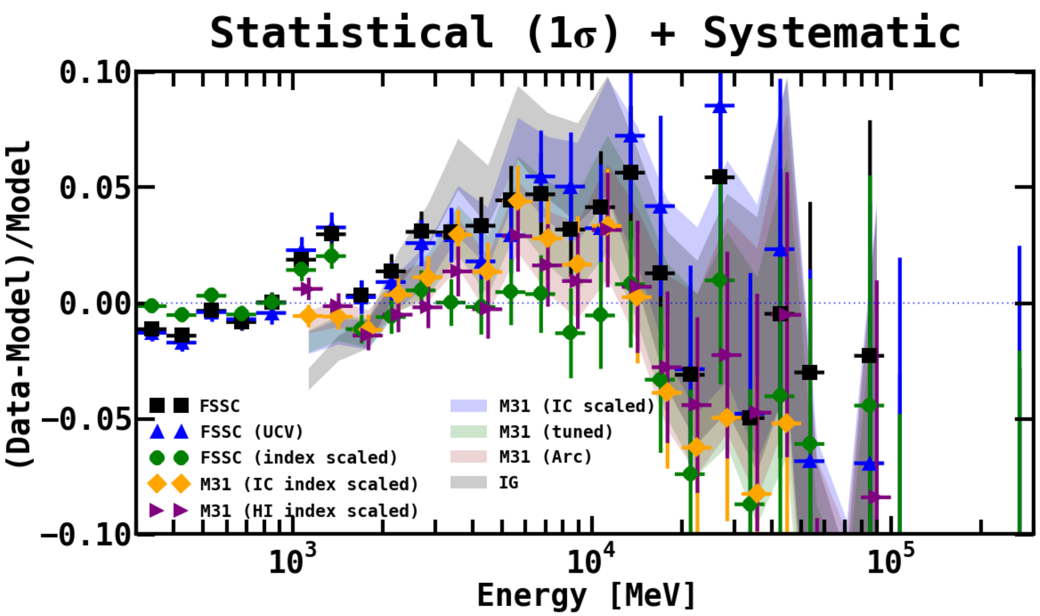
- ✧ Anisotropic/isotropic ratio illustrates the importance of the effect that reaches a factor of 1.7 for certain directions and is non-uniform on the sky

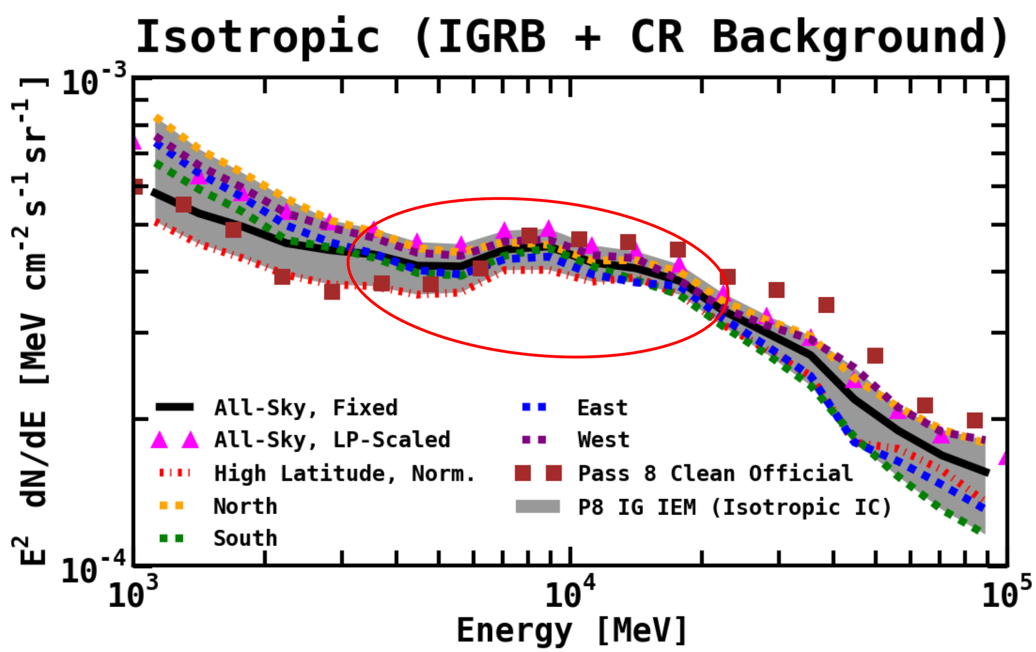
2D residuals after the Arc fit



- ✧ Subtraction of the Arc template flattens the 2D residuals, which show no obvious residual structure

Excess in different foreground models

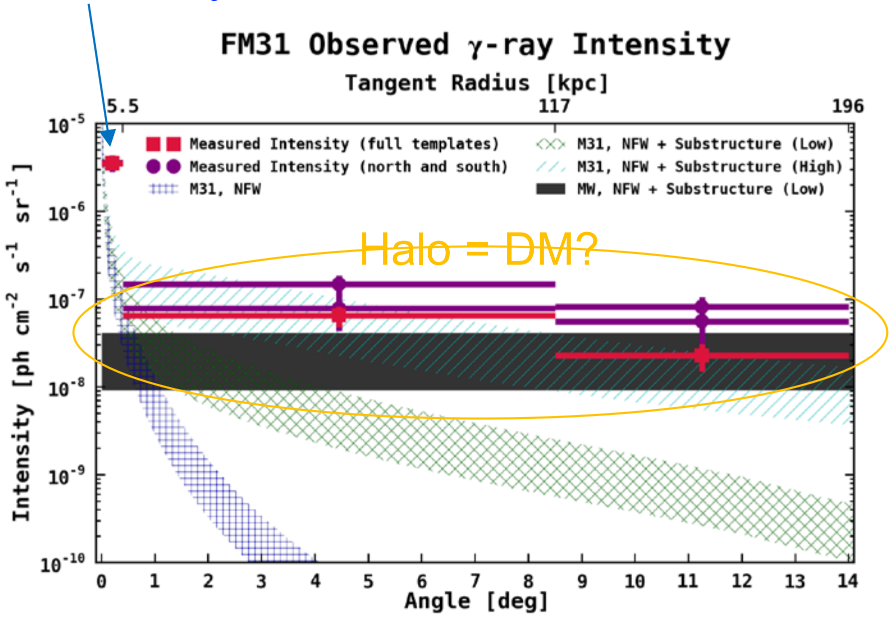


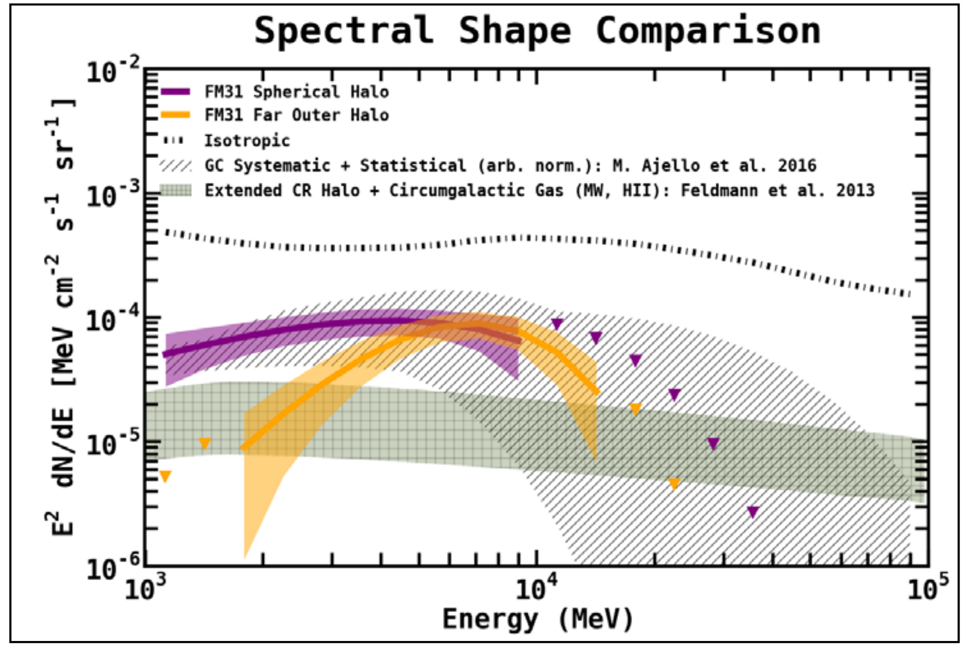


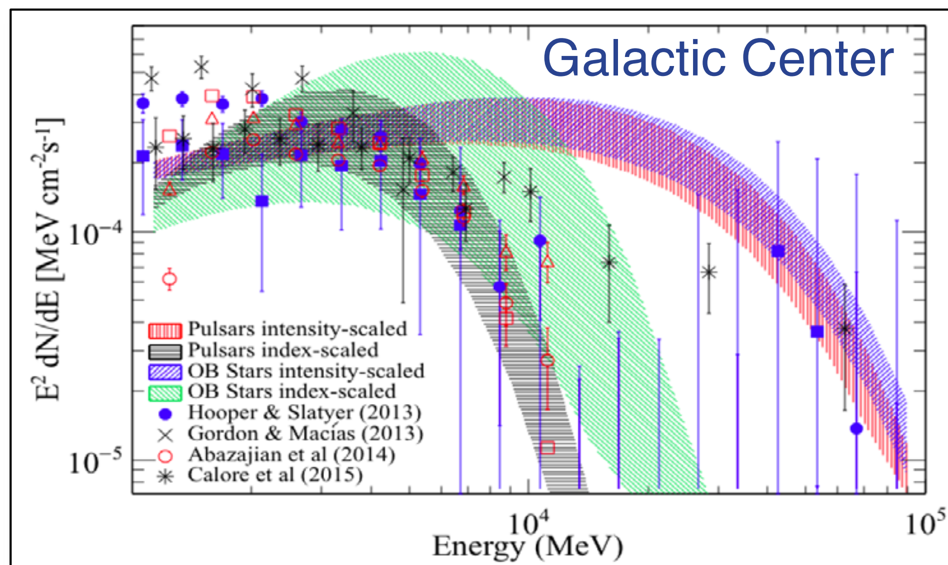
- ✧ A systematic excess is observed between 3–20 GeV at the level of 3–5% independently on the background (foreground) model used
- ✧ Absent only in case of the foreground model that is built using the LAT data itself, yet with free index (FSSC index scaled)
- ✧ Interestingly, isotropic component has a “bump” in the same energy range as the observed excess
- ✧ Dark Matter halo around the Milky Way?

Spectrum of the excess and interpretation

Inner Galaxy = sources + diffuse + DM







- ✧ Spectral shape is not resembling other CR-related components
- ✧ FM31: properties of the extended (DM?) halo remain highly uncertain
- ✧ Consistent with DM interpretation of the Galactic center excess (requires a large boost factor)
- ✧ Decaying DM looks more natural

In place of a conclusion

In respect of CR with $E_{CR}<10^{15}\div10^{16}$ eV there generally remain some vague points, but on the whole the picture is clear enough…

— V.L. Ginzburg, 1999

There is nothing new to be discovered in physics now. All that remains is more and more precise measurement

— Lord Kelvin, 1900