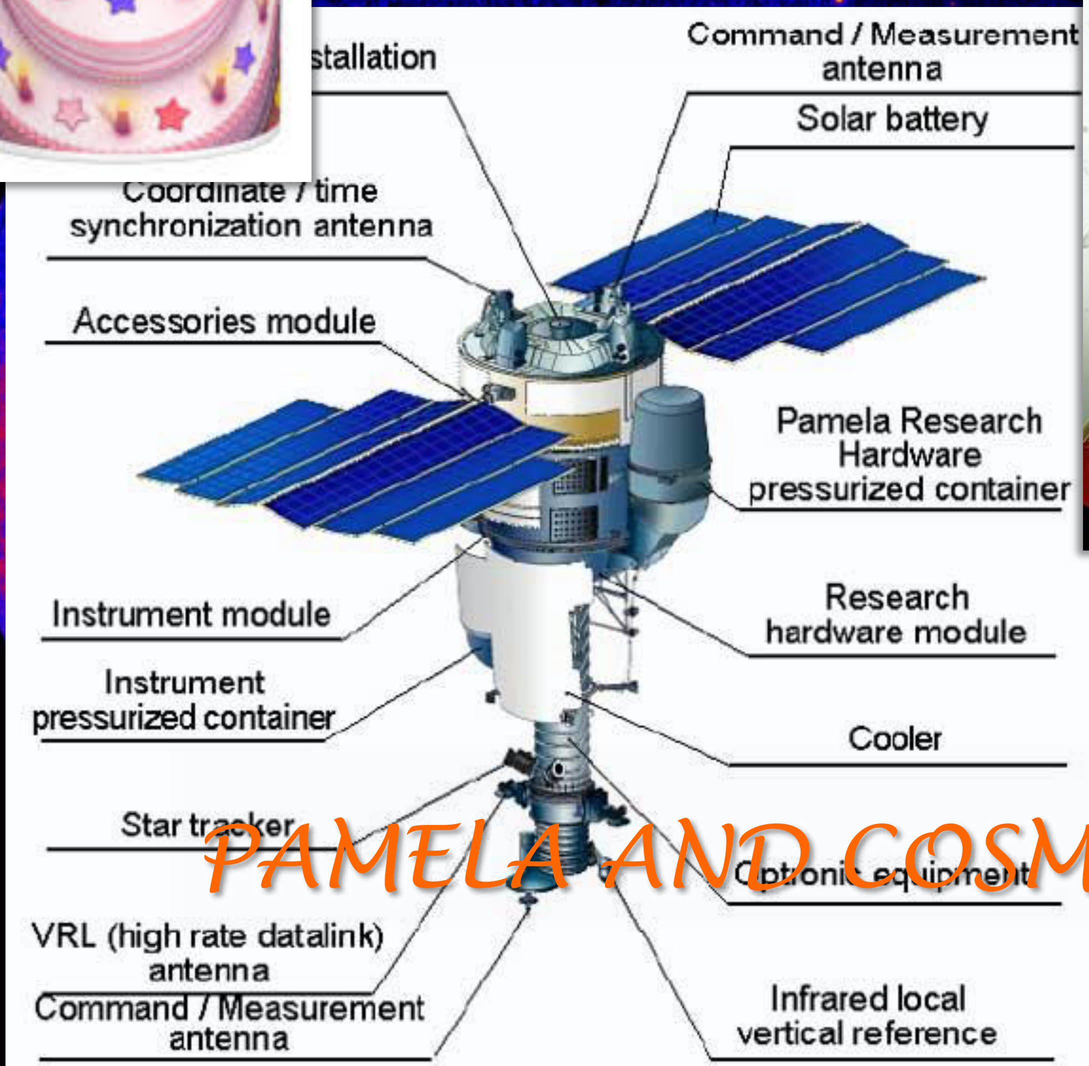
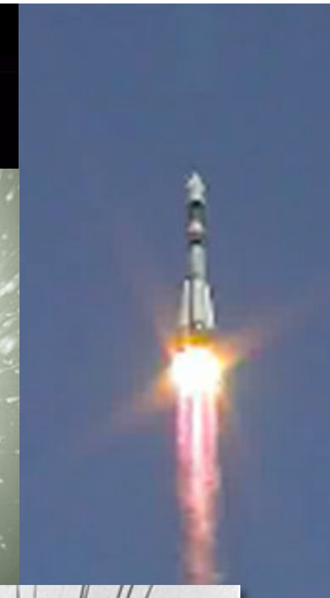
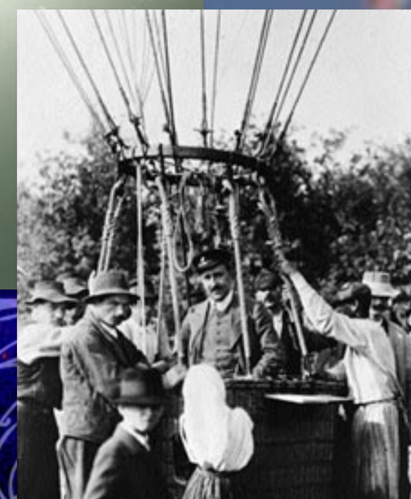
HAPPY BIRTHDAY!

PAMELA IS 10!







PAMELA AND COSMIC RAYS

IGOR V MOSKALENKO – STANFORD

The earliest evidence

24th International Cosmic Rays Conference (Rome), 1995, v. 3, p.591

$e^{\pm}/p^{\pm}$ separation and some li
PAMELA experiment will be
on board of the Earth-Observa
at the end of 1988.

The Magnetic Spectrometer PAMELA for the Study of Cosmic Antimatter in Space

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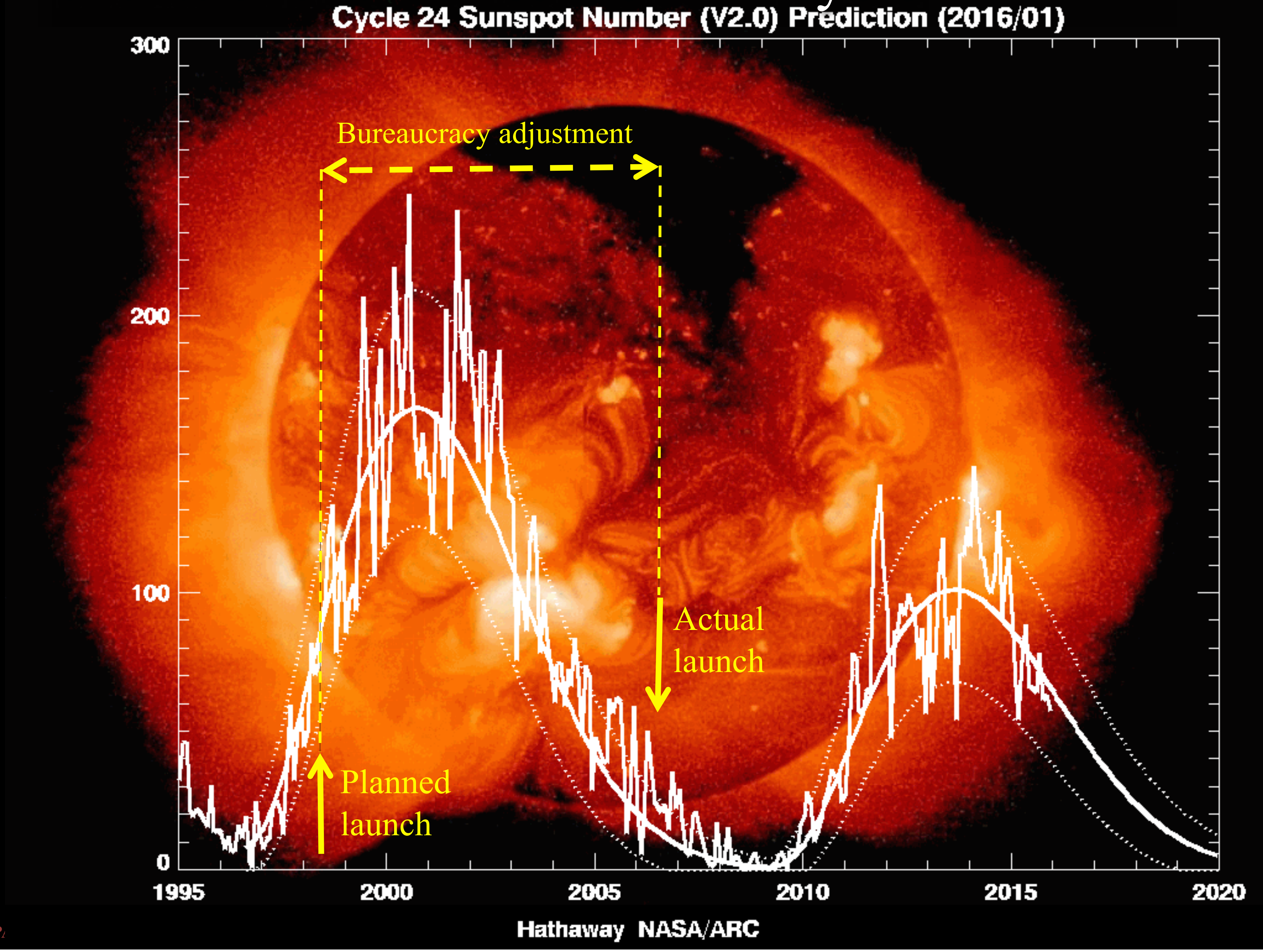
Abstract

In the framework of the Russian Italian Mission (RIM) program, PAMELA is the experiment devoted to the accurate measurement of the positron and antiproton spectra from the very low energy threshold of 100 MeV up to more than 50 GeV, and to hunt antinuclei with sensitivity better than 10^{-7} in the antihelium/helium ratio. A permanent magnet equipped by microstrip silicon sensors, measures the particle momentum with MDR=400 GV/c on GF=25 cm^2 sr. An accurate ToF system, a 19 X_0 deep imaging calorimeter, an aerogel Cherenkov counter and a TRD detector complement the spectrometer in order an efficient $e^{\pm}/p^{\pm}$ separation and some light isotope identification capability. The PAMELA experiment will be carried out on a 700 km high polar orbit, on board of the Earth-Observation Meteor-3A satellite, to be launched at the end of 1988.

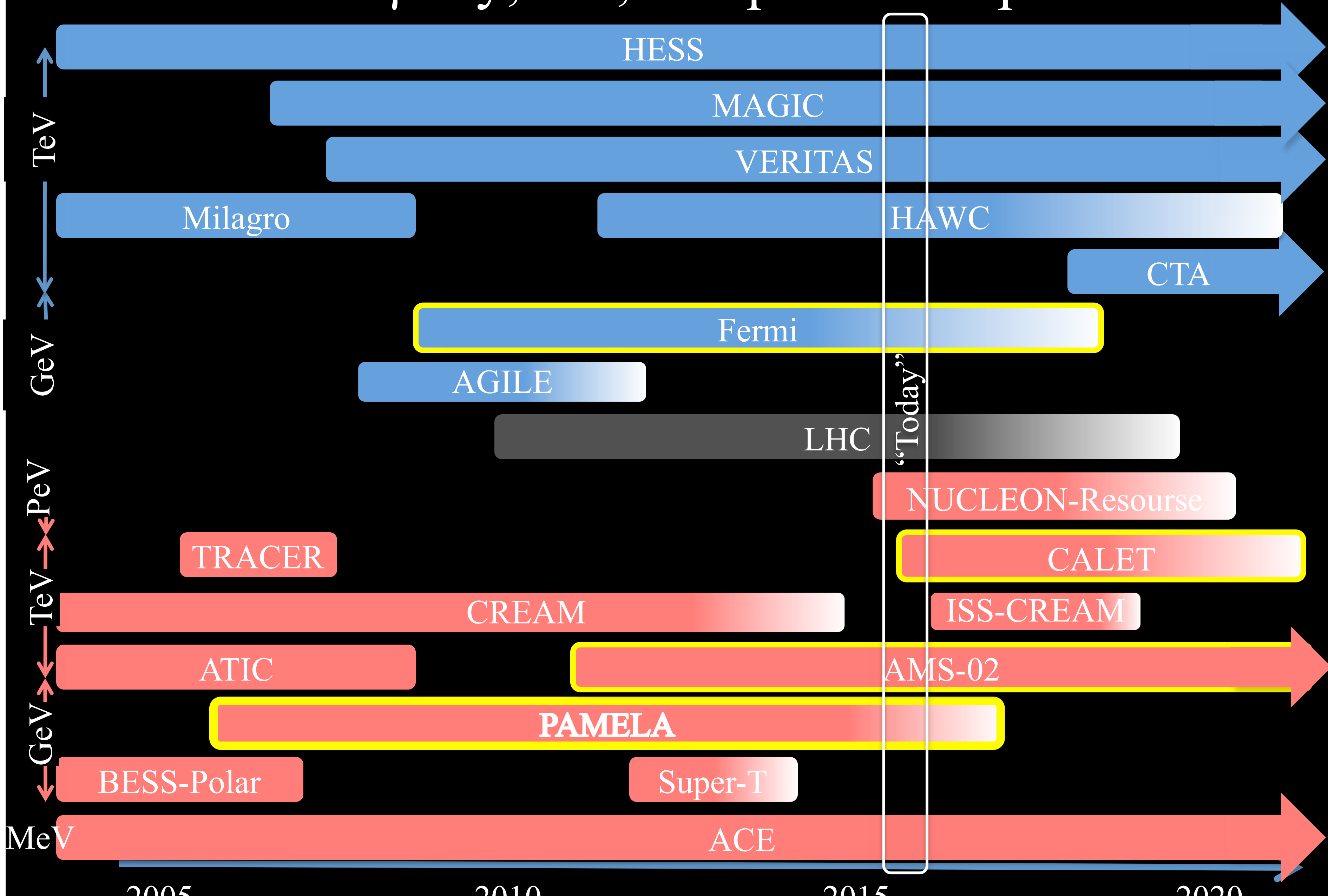
References

[1] "Objectives and feasibility of the Russian-Italian Mission program in Astroparticle Physics", November 1993.

PAMELA launch & the solar cycle

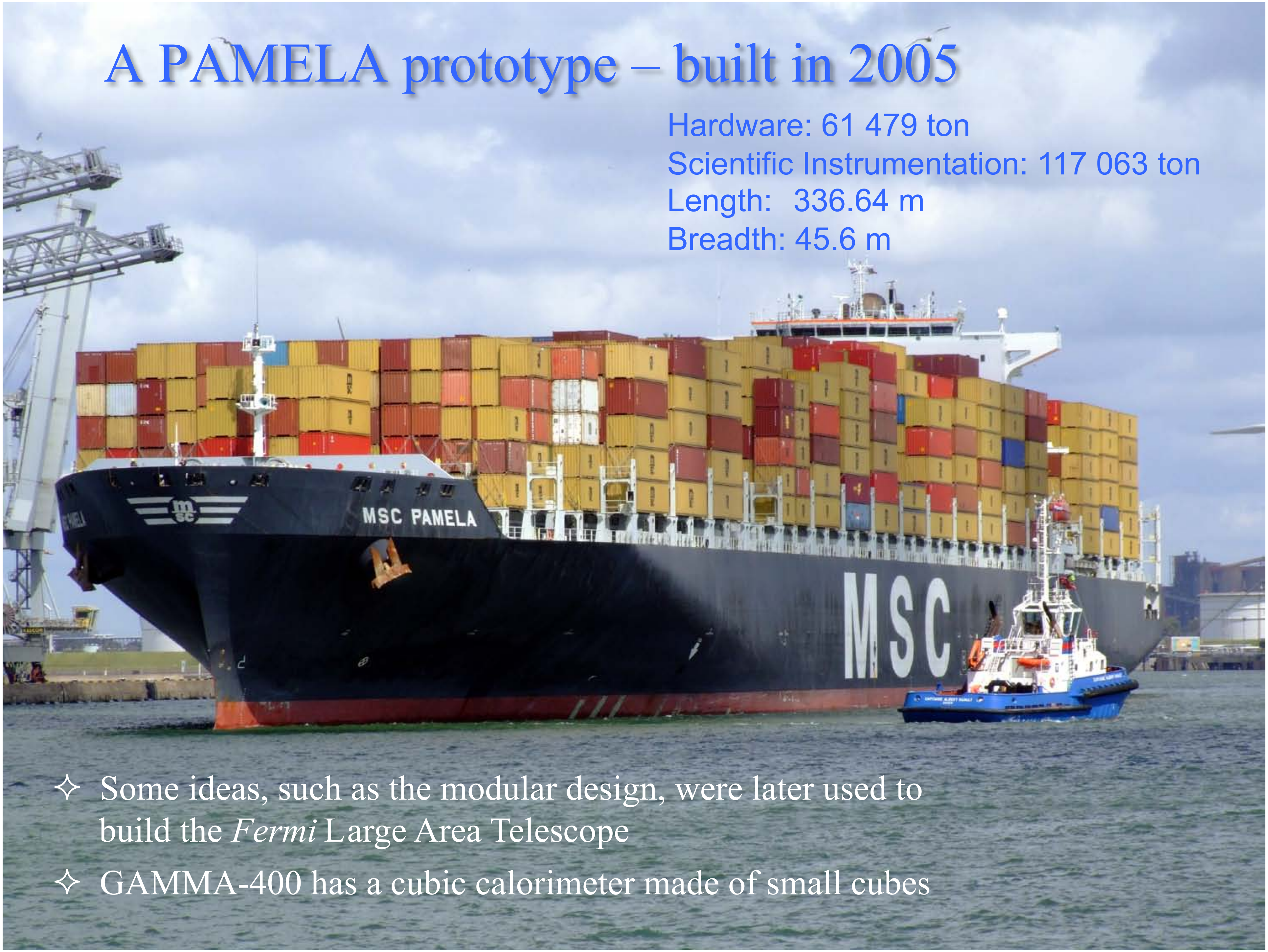


Timeline of γ-ray, CR, and particle experiments



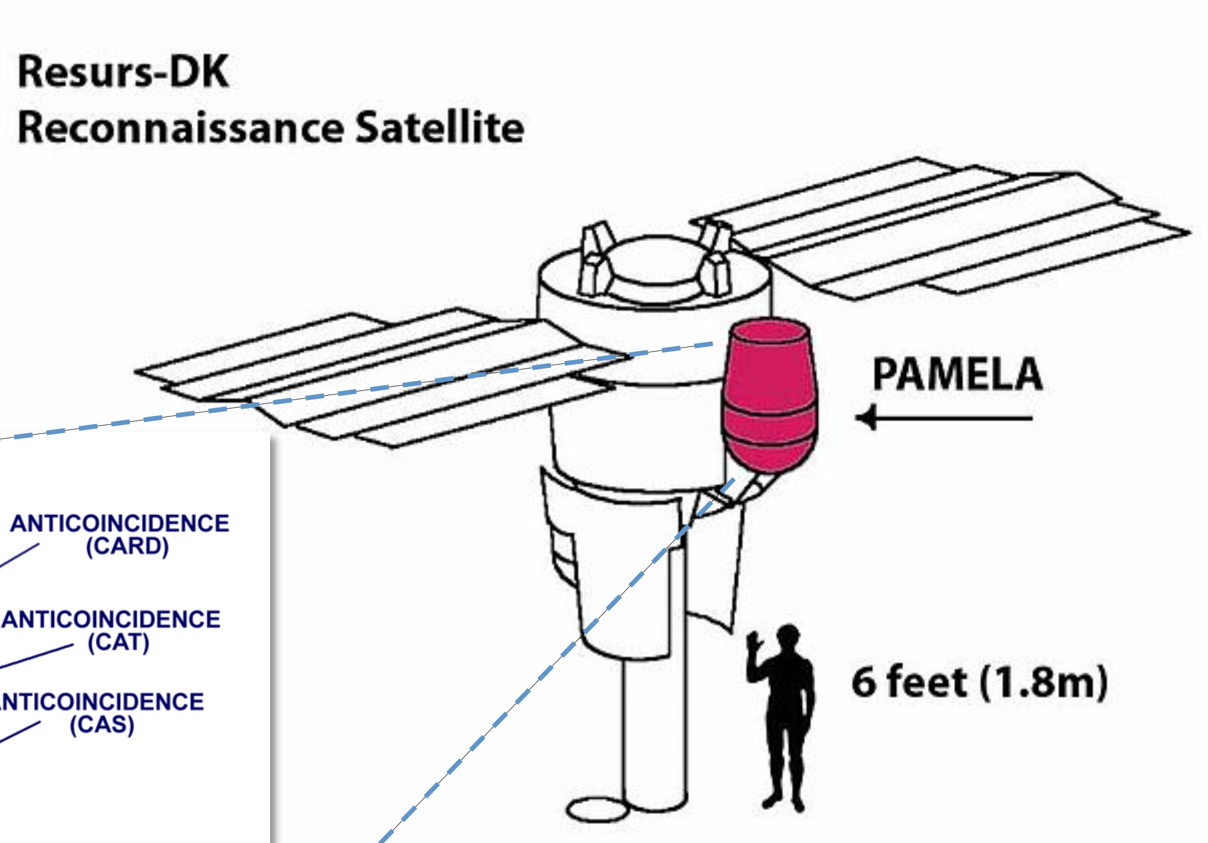
A PAMELA prototype – built in 2005

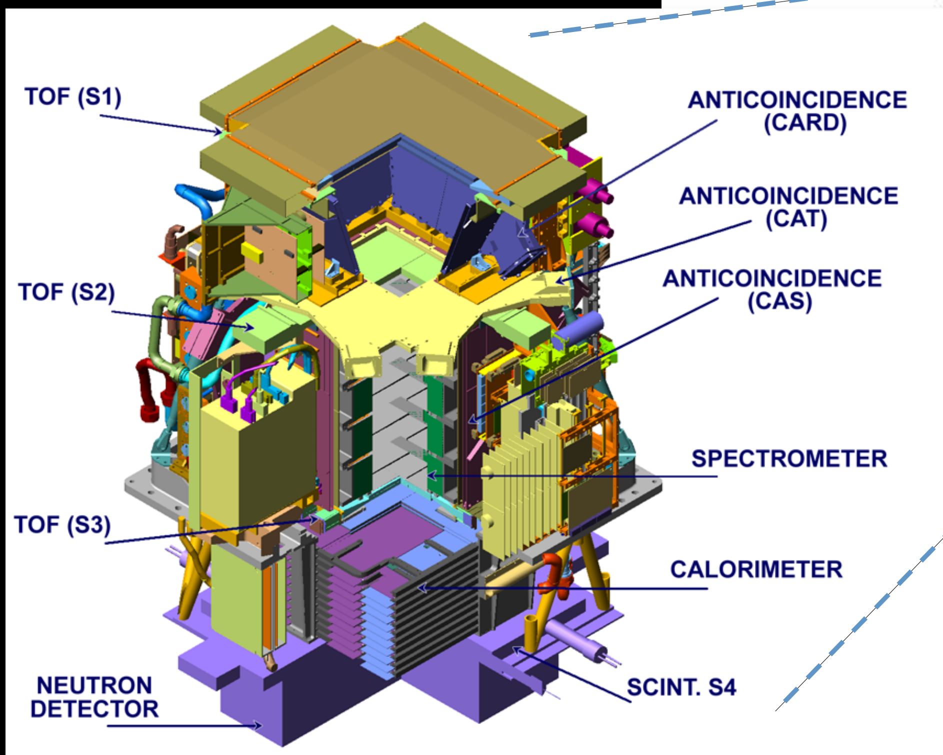
Hardware: 61 479 ton
Scientific Instrumentation: 117 063 ton
Length: 336.64 m
Breadth: 45.6 m



- ✧ Some ideas, such as the modular design, were later used to build the *Fermi* Large Area Telescope
- ✧ GAMMA-400 has a cubic calorimeter made of small cubes

After a series of modifications…





Series of tradeoffs that cost about €26M made is launchable by the Soyuz rocket in 2006 with

- Total mass – 470 kg
- Max length – 1.3 m
- Power consumption – 335 Watts

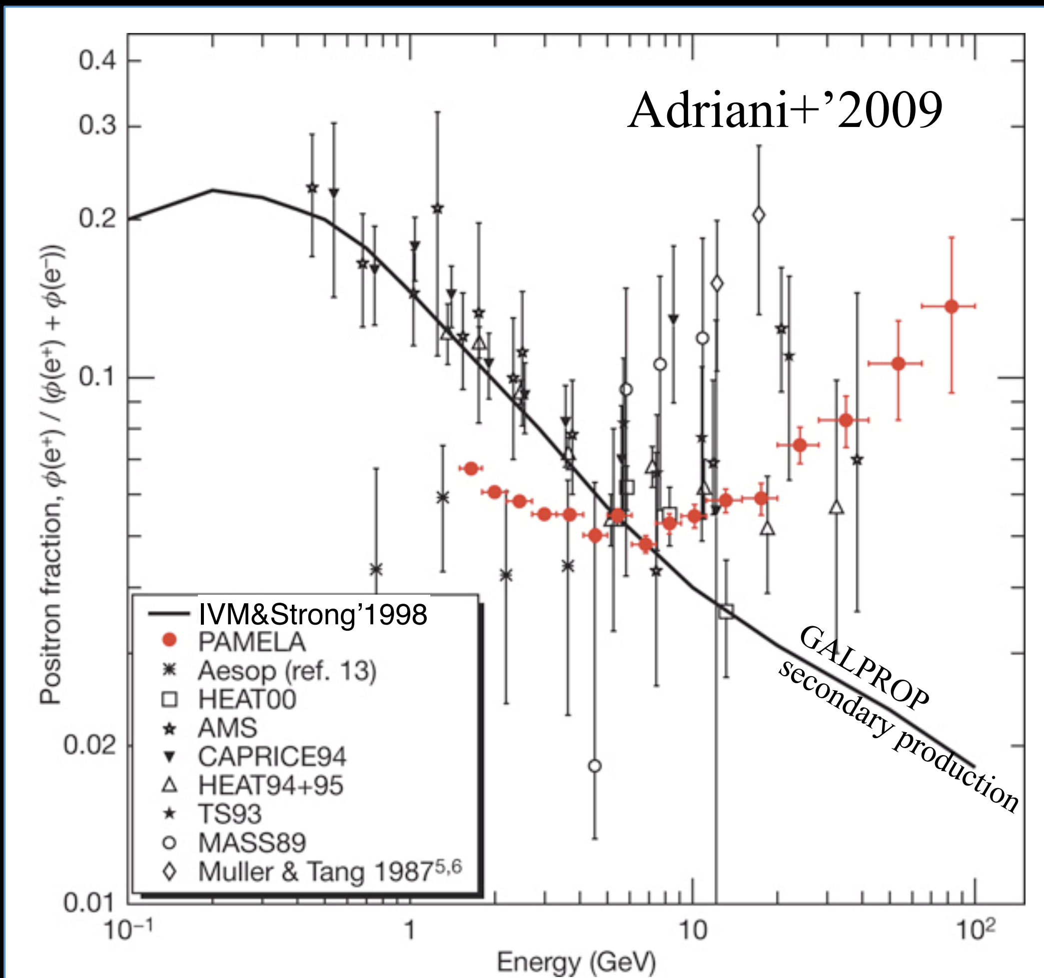
PAMELA and Churches of Rome

- Every single time I was in Rome in 2005-2006, Aldo Morselli went to show me some piece of the city. In every church that we visited we put a candle for success of PAMELA.
- In total, we have visited a couple of dozens of churches!
- So we were heard!

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

— Lord Kelvin, 1900

PAMELA discovery: Rising positron fraction



It is the opinion of the investigators that the e^+ observation is a substantially more difficult task than the antiproton observation. […] For negatively charged particles, one has to distinguish antiprotons from a 20 times higher flux of e^- and from atmospheric mesons. In the case of e^+, however, one must separate the desired particles from protons, which have the same charge and a flux nearly 1000 times as great…
– R.L. Golden et al. A&A 1987, 188, 145

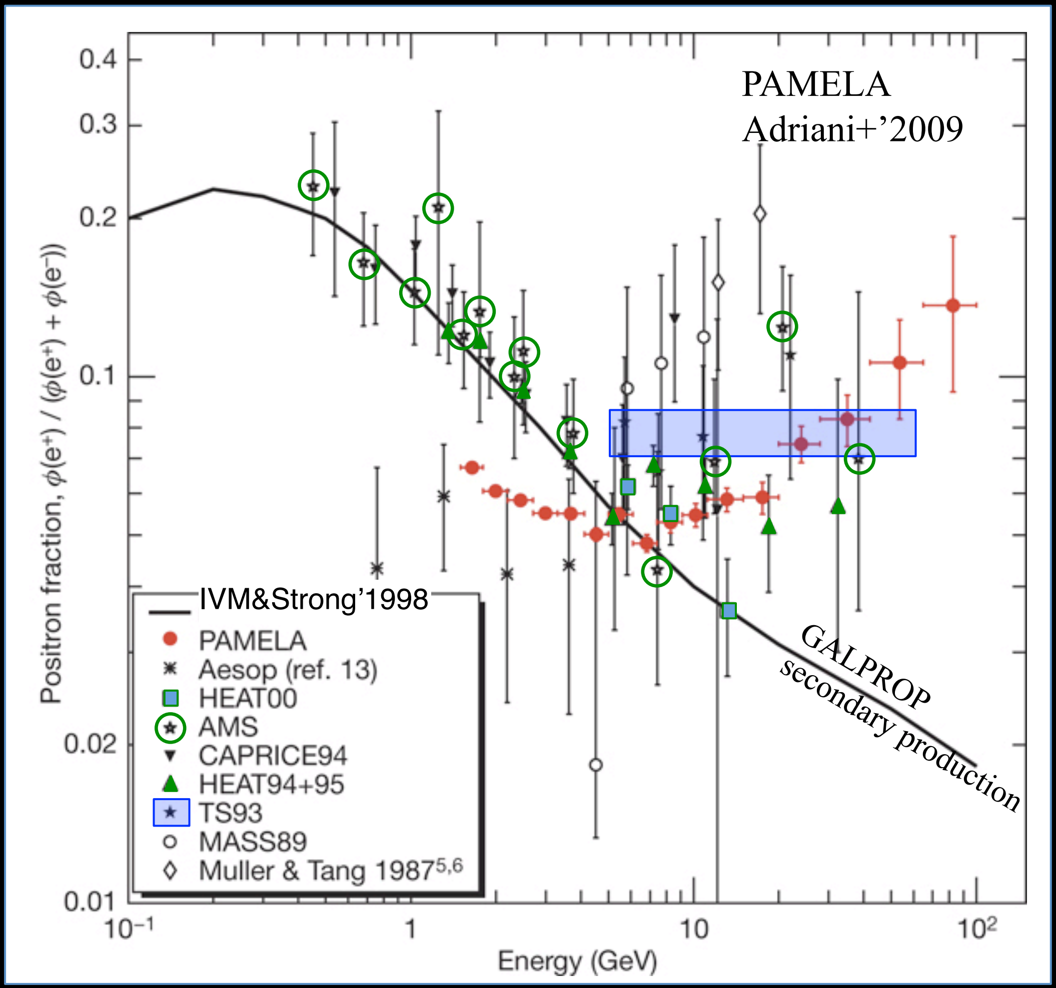
Some statistics (NASA's ADS)

- Total: about 116 (140) journal + proceedings papers, 4000 citations
- *An anomalous positron abundance in cosmic rays with energies 1.5-100 GeV,* Nature 2009, 458, 607 – 1500 hits
- *New Measurement of the Antiproton-to-Proton Flux Ratio up to 100 GeV in the Cosmic Radiation*, PRL 2009, 102, 051101 – 470 hits
- *PAMELA Results on the Cosmic-Ray Antiproton Flux from 60 MeV to 180 GeV in Kinetic Energy*, PRL 2010, 105, 121101 – 360 hits
- *PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra,* Science 2011, 332, 69 – 300 hits
- *PAMELA – A payload for antimatter matter exploration and light-nuclei astrophysics*, Astroparticle Physics, 2007, 27, 296 – 230 hits
- *Cosmic-Ray Electron Flux Measured by the PAMELA Experiment between 1 and 625 GeV*, PRL 2011, 106, 201101 – 170 hits
- *Cosmic-Ray Positron Energy Spectrum Measured by PAMELA*, PRL 2013, 111, 081102 – 110 hits
- *Time Dependence of the Proton Flux Measured by PAMELA during the 2006 July-2009 December Solar Minimum*, ApJ 2013, 765, 91

Other most remarkable results

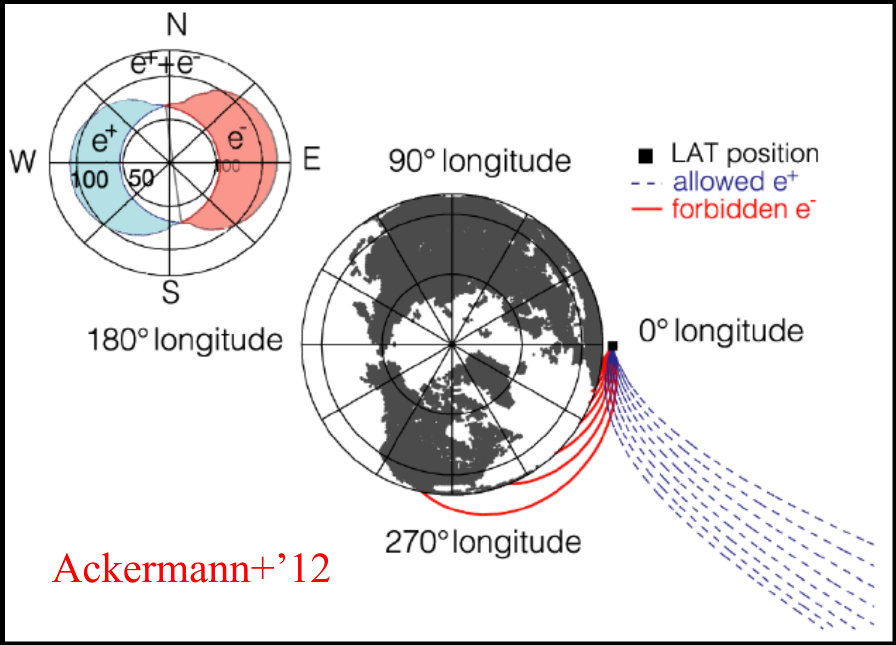
- *Measurement of the flux of primary cosmic ray antiprotons with energies of 60 MeV to 350 GeV in the PAMELA experiment*, JETPL 2013, 96, 621
- *The PAMELA Mission: Heralding a new era in precision cosmic ray physics,* Physics Reports 2014, 544, 323
- *Measurement of Boron and Carbon Fluxes in Cosmic Rays with the PAMELA Experiment*, ApJ 2014, 791, 93
- *Measurement of the Isotopic Composition of Hydrogen and Helium Nuclei in Cosmic Rays with the PAMELA Experiment*, ApJ 2013, 770, 2
- *The Discovery of Geomagnetically Trapped Cosmic-ray Antiprotons,* ApJL 2011, 737, 29
- *Time Dependence of the e^- Flux Measured by PAMELA during the July 2006-December 2009 Solar Minimum,* ApJ 2015, ApJ 810, 142
- *Trapped positrons observed by PAMELA experiment*, J. of Physics: Conf. Ser., 2016, 675, 032003
- *H, He, Li and Be Isotopes in the PAMELA-Experiment*, J. of Physics: Conf. Ser., 2016, 675, 032001

PAMELA discovery: Rising positron fraction

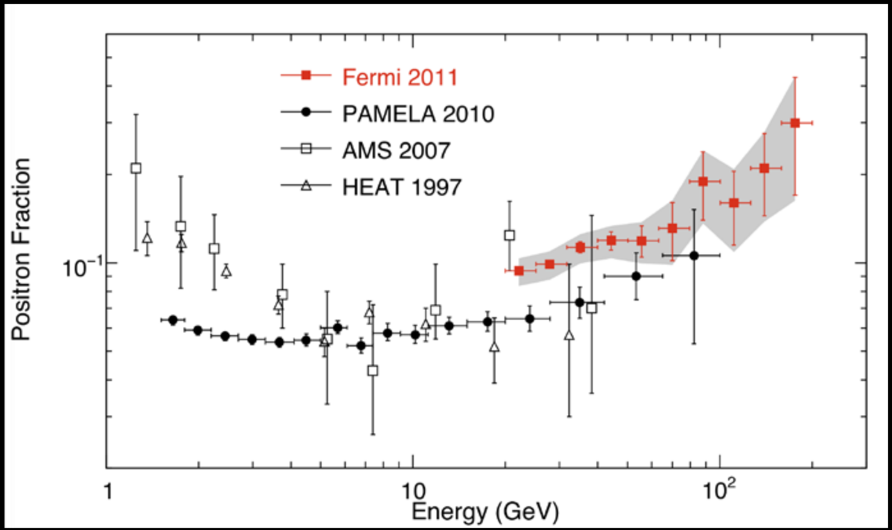


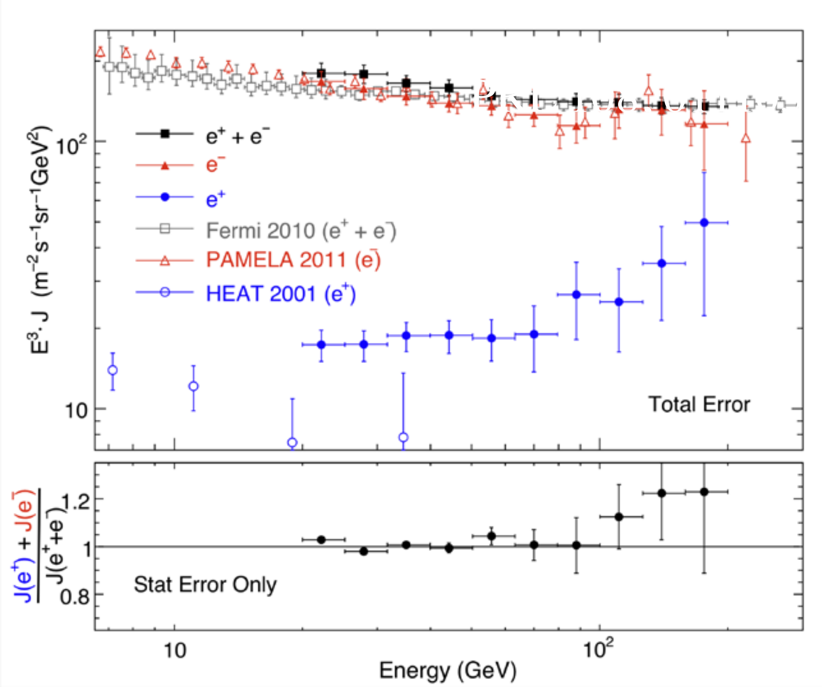
- TS93 (Golden+'96): flat positron fraction 0.078±0.016 in the range 5-60 GeV
- HEAT-94,95,00 (Beatty+'04): "a small positron flux of nonstandard origin"
- PAMELA team reported a clear and very significant rise in the positron fraction compared to the "standard" model predictions
- "Standard" model: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

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

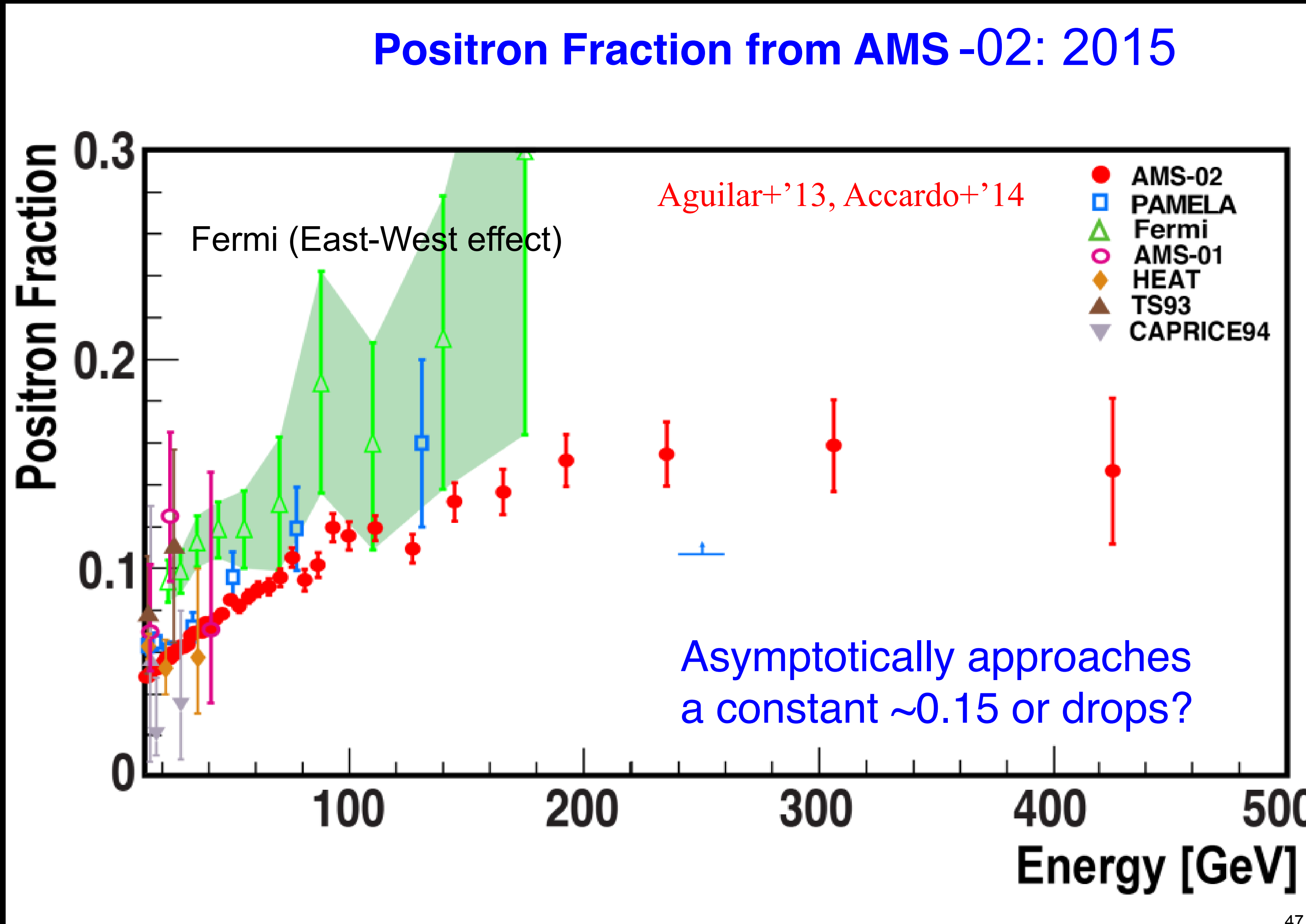


- Fermi-LAT does not have a magnet, but used geomagnetic field (East-West effect)
- Confirmed rise in the positron fraction
- Extended measurements up to 200 GeV
- Clearly seen is a flat component in the e^+ flux

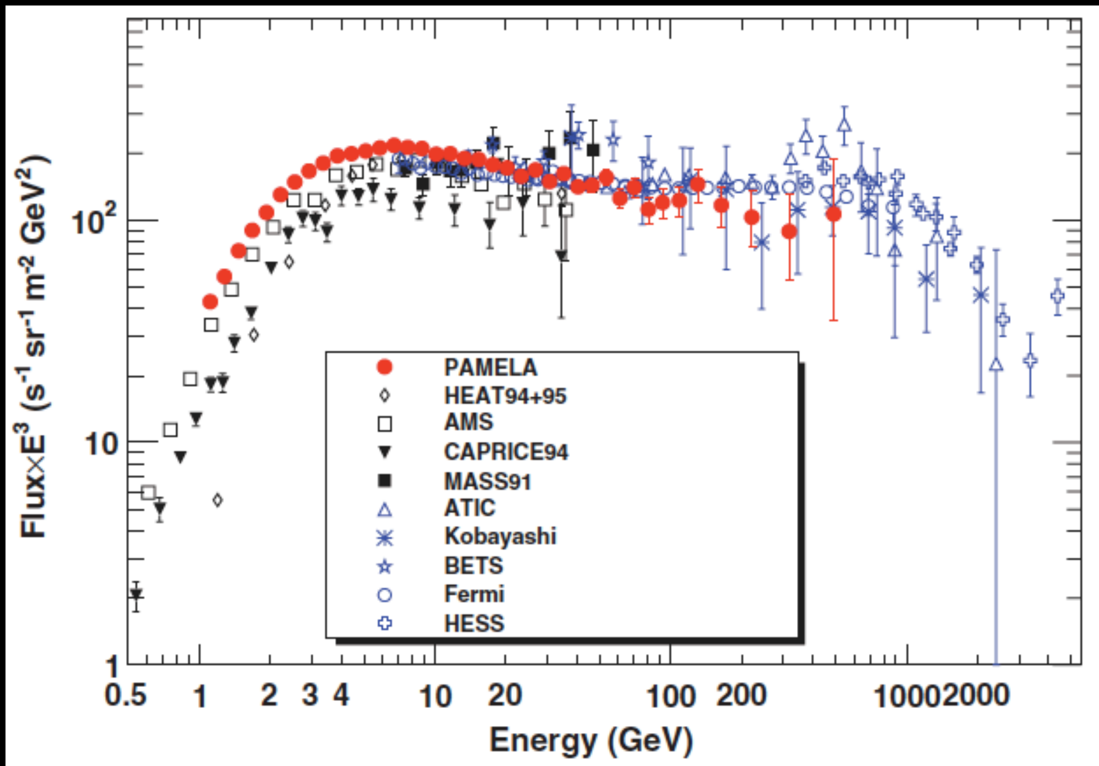


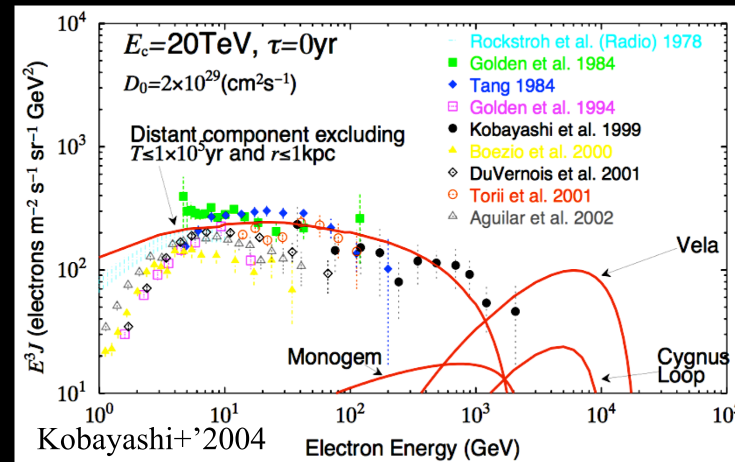


AMS-02: measurement of the positron fraction



All-electron spectrum





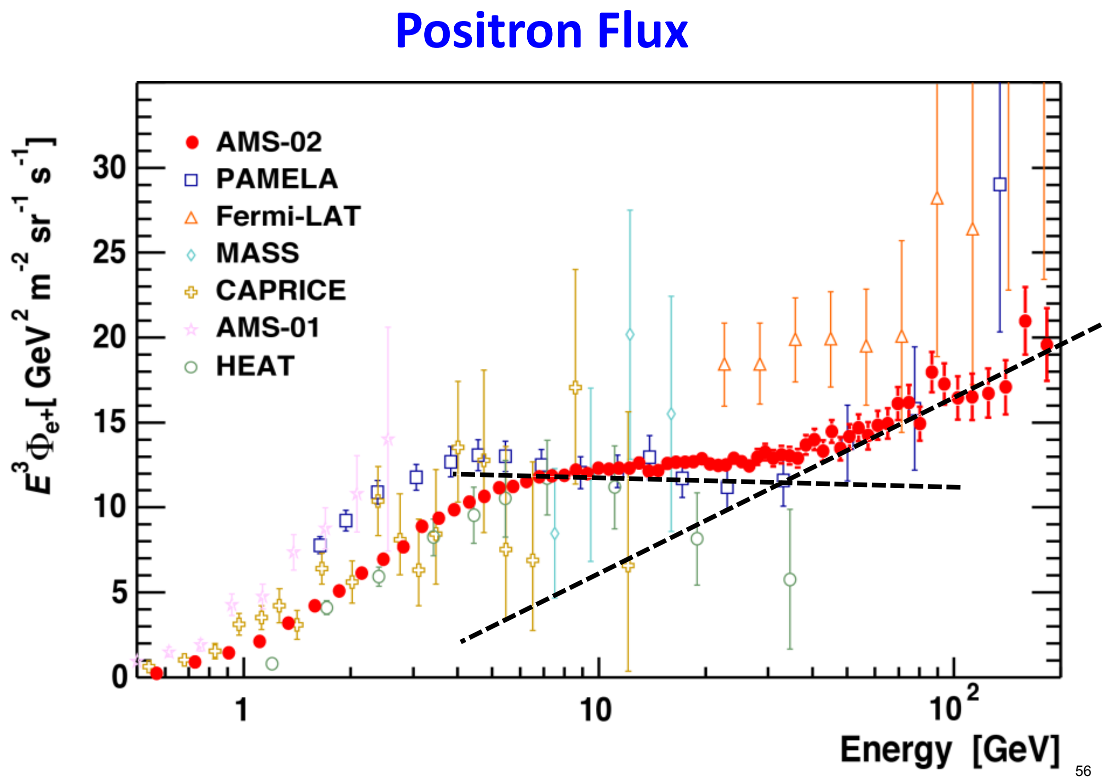
- Fermi-LAT and PAMELA data agree well
- Shows some structure (breaks and bumps)
- Flatter than extrapolated from low energies
- Sharp cutoff at 1 TeV (HESS), as expected

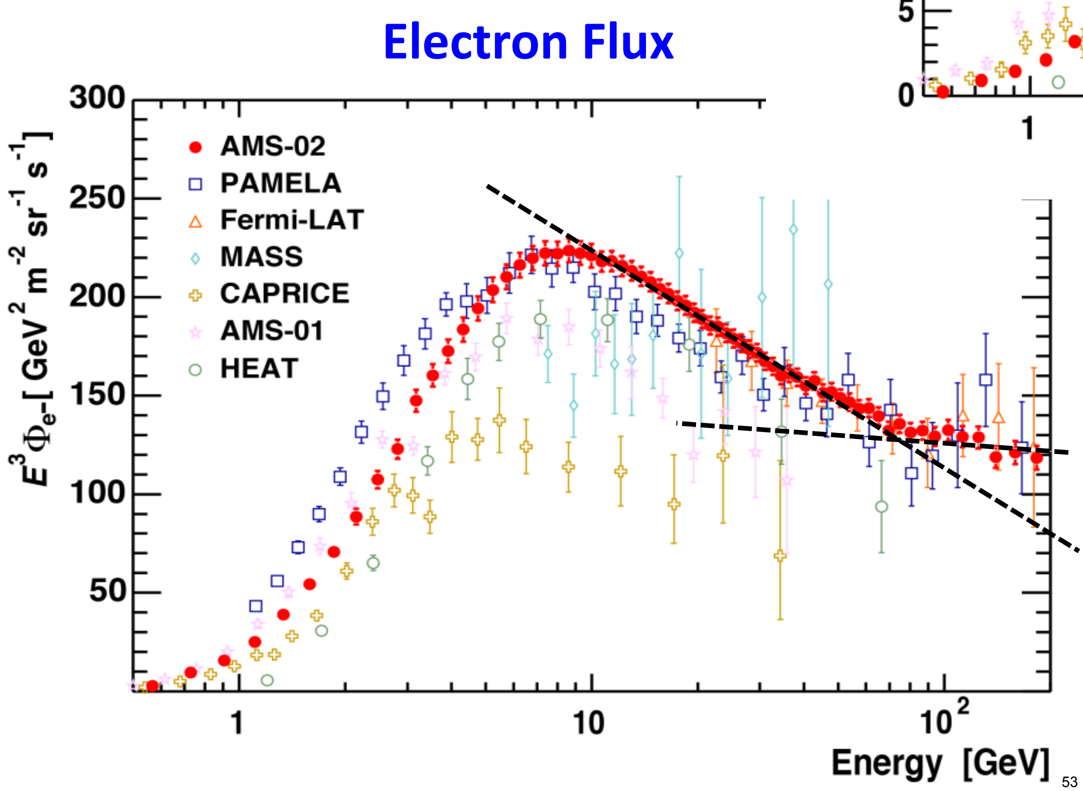
- Cannot be reproduced with a single power-law injection spectrum
- Origin
  - Local sources?
  - needs a component with hard spectrum (positrons?)

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

e^+ & e^- spectra

✧ The fluxes of e^+ & e^- can tell more



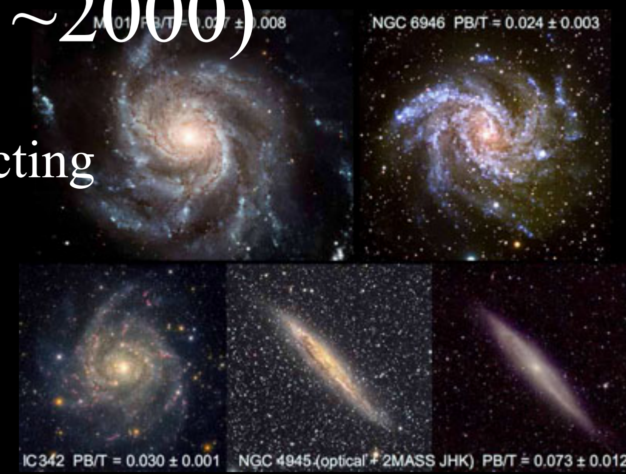


✧ Noticeable is a concave shape in both cases, a clear indication of an additional component (>20 GeV for e^+, >100 GeV for e^-)

Positron anomaly: Astrophysical papers (~200)

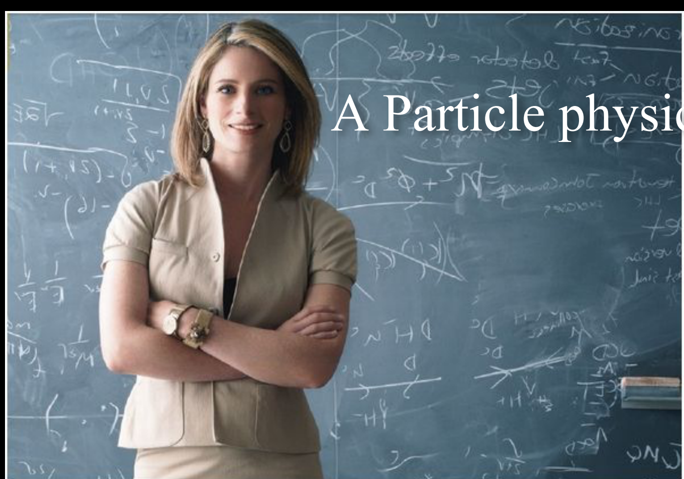
- Blasi 2009 “Origin of the positron excess in cosmic rays”
- Blasi & Serpico 2009 “High-energy antiprotons from old supernova remnants”
- Mertsch & Sarkar 2009 “Testing astrophysical models for the PAMELA positron excess with cosmic ray nuclei”
- Shaviv+ 2009 “Inhomogeneity in cosmic ray sources as the origin of the electron spectrum and the PAMELA anomaly”
- Delahaye+2010 “Galactic electrons and positrons at the Earth: new estimate of the proimary and secondary fluxes”
- Stawarz+2010 “on the energy spectra of GeV/TeV cosmic ray leptons”
- Lee+ 2011 “Explaining the cosmic ray $e^+/(e^-+e^+)$ and pbar/p ratios using a steady-state injection model”
- Kachelriess+2011 “Antimatter production in supernova remnants”
- Kachelriess & Ostapchenko 2013 “B/C ratio and the PAMELA positron excess”
- Blum+ 2013 “AMS-02 results support the secondary origin of cosmic ray positrons”
- Cholis & Hooper 2013 “Dark matter and pulsar origin of the rising cosmic ray positron fraction in light of new data from the AMS”
- Erlykin & Wolfendale 2013 “Cosmic ray positrons from a local, middle-aged supernova remnant”
- Berezhko & Ksenofontov 2013 “Energy spectra of electrons and positrons produced in supernova remnants”
- Berezhko & Ksenofontov 2013 “Antiprotons produced in supernova remnants”
- Cholis & Hooper 2014 “Constraining the origin of the rising cosmic ray positron fraction with the boron-to-carbon ratio”
- Di Mauro+2014 “Interpretation of AMS-02 electrons and positrons data”
- Mertsch & Sarkar 2014 “AMS-02 data confronts acceleration of cosmic ray secondaries in nearby sources”
- Cowsik+2014 “The origin of the spectral intensities of cosmic ray positrons”
- …
- + Dark Matter paper >1300 (see talks by Tim Tait & Fiorenza Donato)

A Particle Physicist's View (pre ~2000)



An Astronomer does stamp collecting

An Astrophysicist does engineering



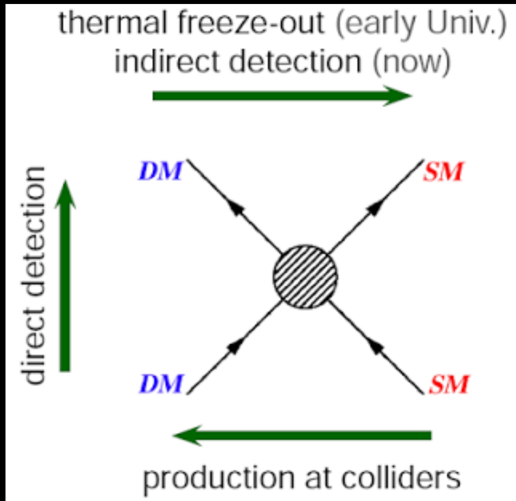
A Particle physicist does fundamental science

...we have been humbled!

Astrophysics is an essential part of Particle Physics!!

– Persis Drell @ TeVPA 2009

Positron Anomaly Interpretations



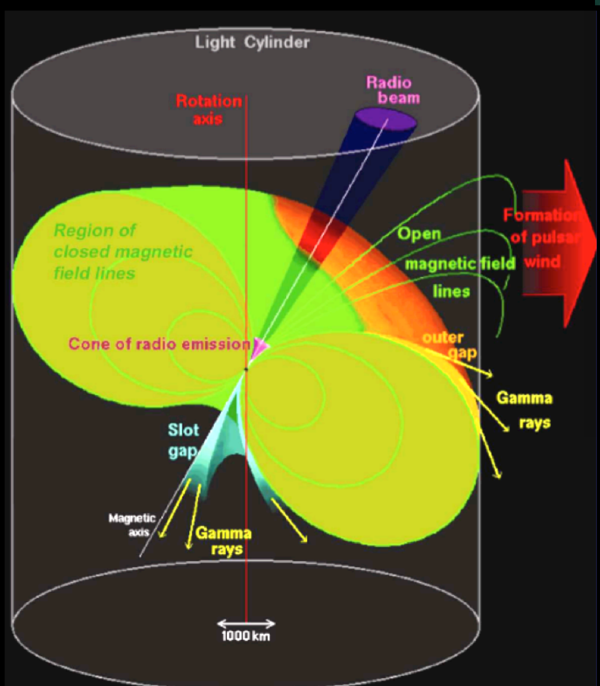
- Dark matter annihilation/decay (>1300 papers)

Astrophysical origin :

- SNR shocks:
  - Galactic SNRs
  - Local SNR(s)
- "Nested Leaky-Box" (SNRs)
- Inhomogeneity of CR sources (SNRs)
- Small halo/fast propagation
- "Model-independent estimates" (too many tradeoffs)
- Photoproduction (requires a specific environment)
- Pulsars & Pulsar Wind Nebulae

"fresh" e^+

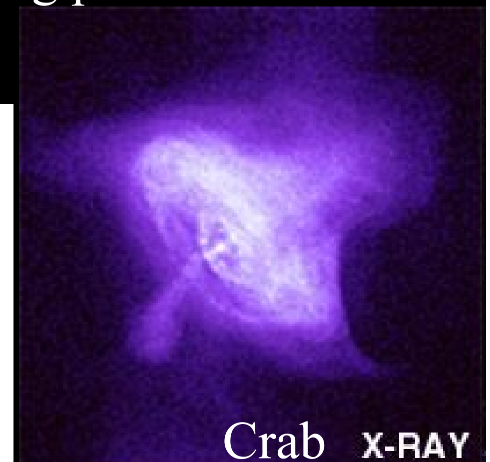
ISM

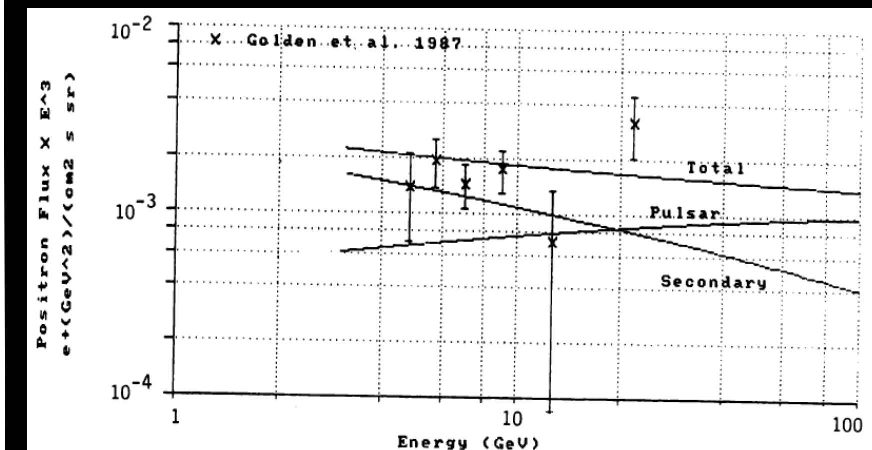


Old friends – pulsars

- Arons 1981 "Particle acceleration by pulsars"
- Harding & Ramaty 1987 "The pulsar contribution to Galactic cosmic ray positrons"
- Boulares 1989 "The nature of the cosmic-ray electron spectrum, and supernova remnant contributions"

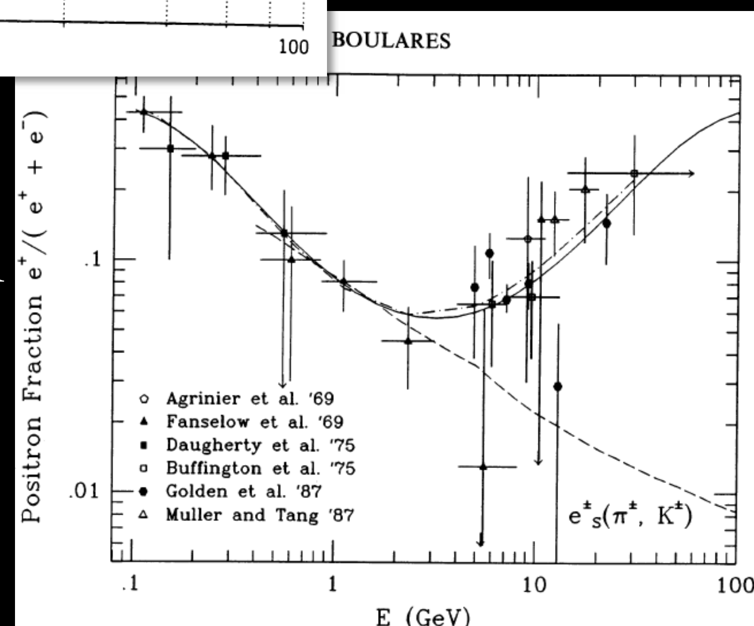
"Therefore, the only role observed pulsars might play as direct cosmic ray sources is in providing positrons and electrons…"





3 components:

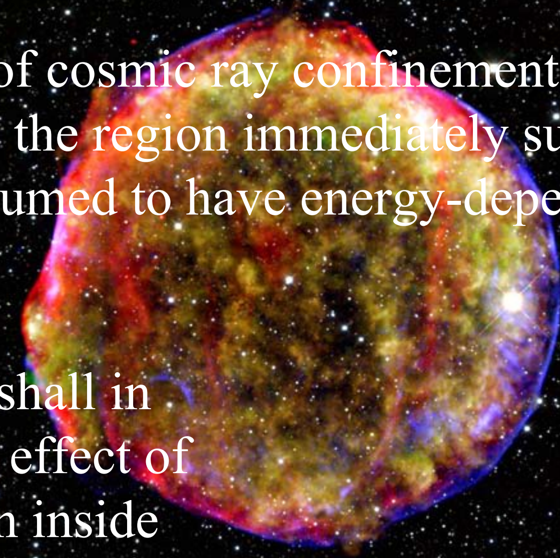
- Secondary $e^{+/-}$
- Primary e^- from SNR
- Primary $e^{+/-}$ from pulsars



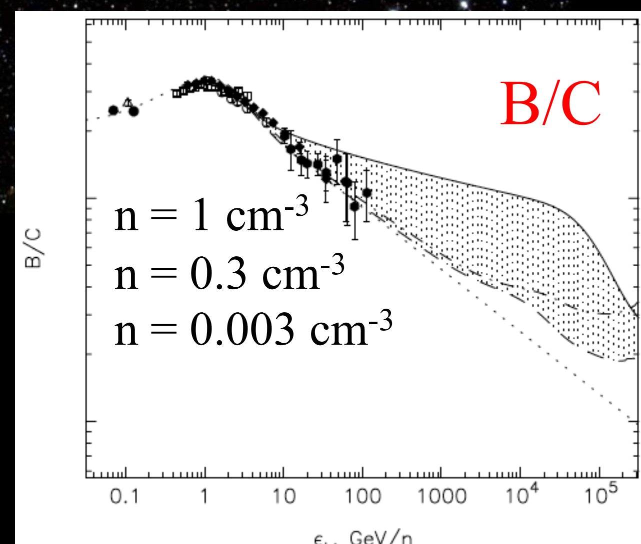
Reinvention of the Nested Leaky-Box – SNRs

- Cowsik & Wilson 1974 "The nested Leaky-Box model for Galactic cosmic rays"
- Berezkho+2003 "Cosmic ray production in supernova remnants including reacceleration: The secondary to primary ratio"

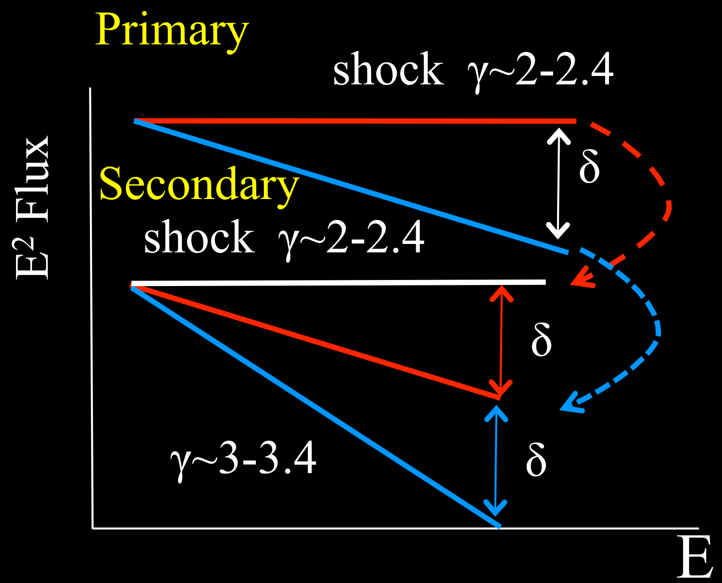
"The 'inner box' of cosmic ray confinement, corresponding to the region immediately surrounding the source, is assumed to have energy-dependent life time..."

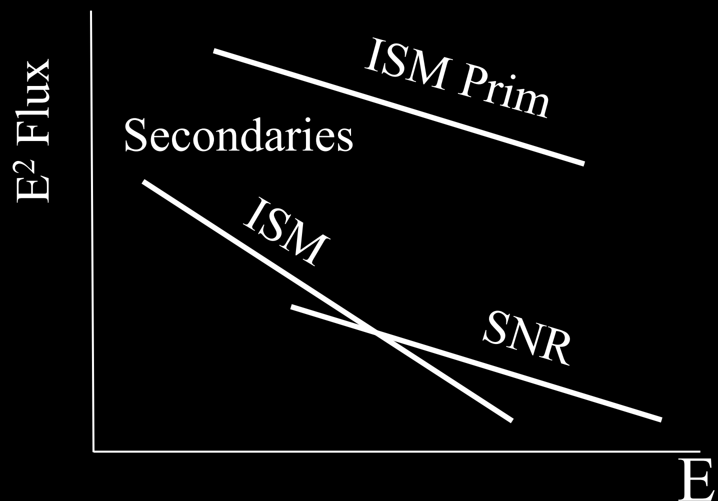

Tycho SN 1572

"In this paper we shall in addition take the effect of nuclear spallation inside the sources into account. The energy spectrum of these source secondaries is harder than that of reaccelerated secondaries. Therefore it plays a dominant role at high energies for a high-density ISM..."



Secondary production in SNR shock

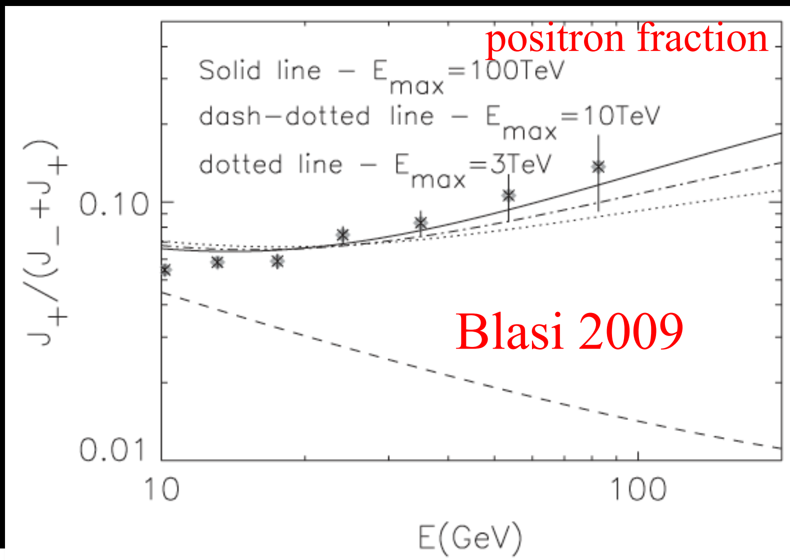


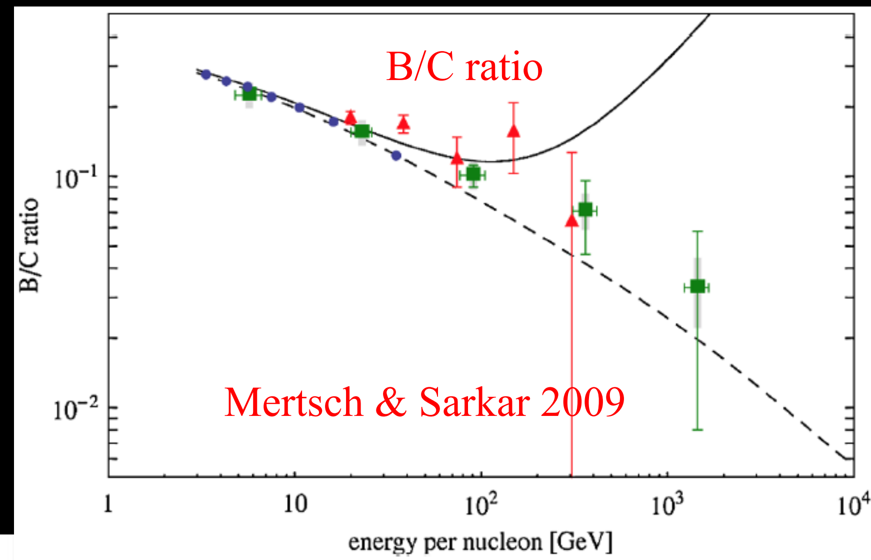


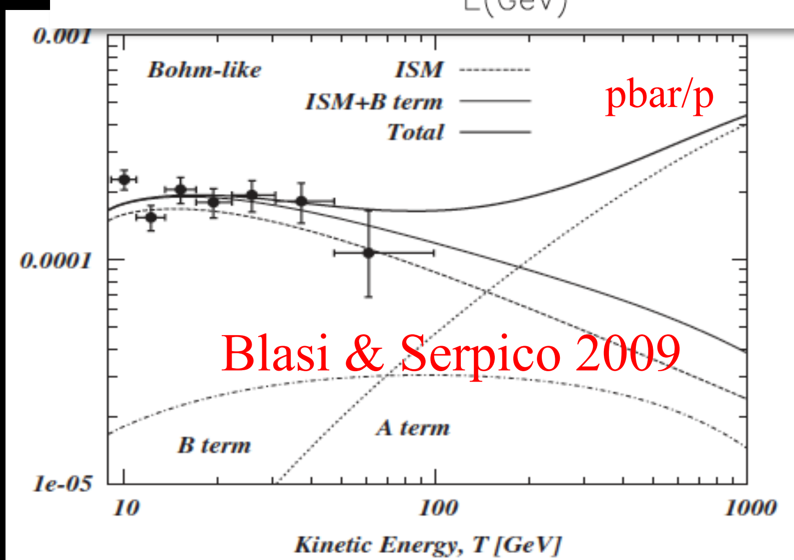
- ✧ Gas in the shock – target for p, A
- ✧ Flatter spectrum of p, A – flatter spectrum of secondaries
- ✧ Assume no energy losses
- ✧ δ~0.3-0.7 – effect of IS propagation (no losses)
- ✧ Same effect should be observed for *__any__* secondaries (pbars, B, $e^{+/-}$)
- ✧ Energy losses will modify the spectra of $e^{+/-}$ at low and high energies - depend on the environment

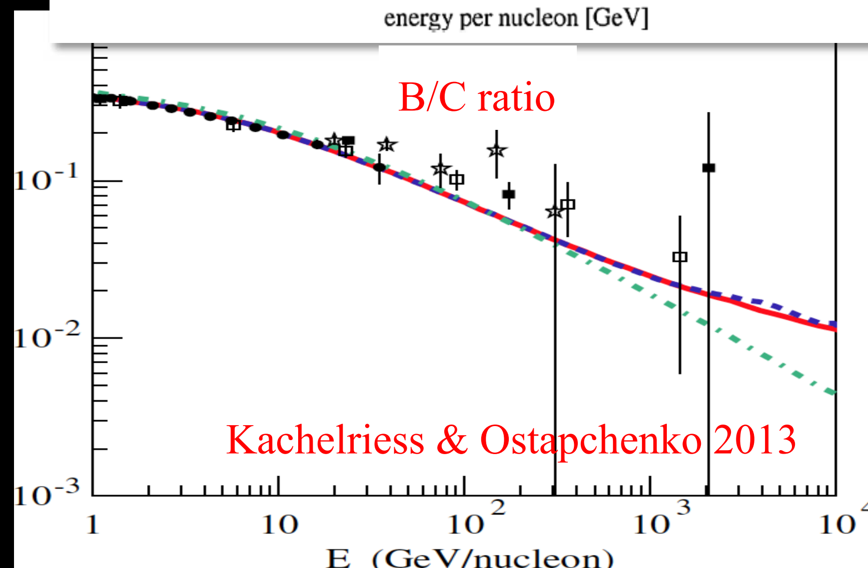
Secondary production in a SNR shock

- ✧ 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

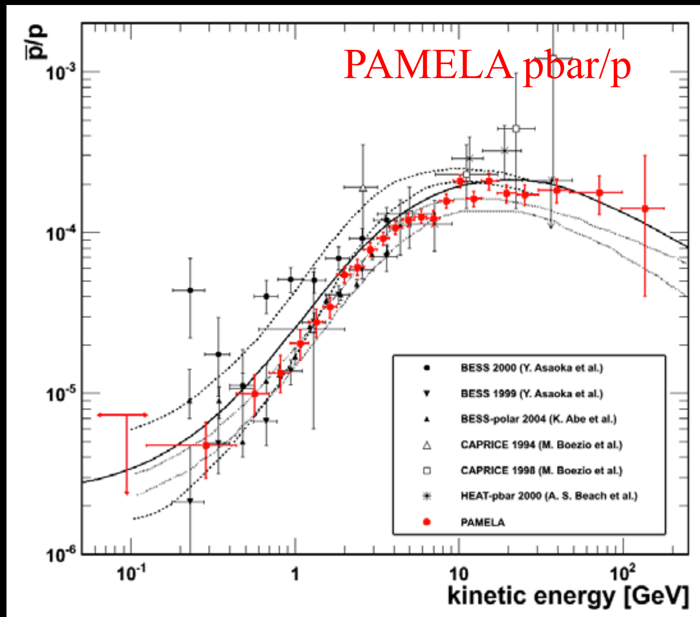


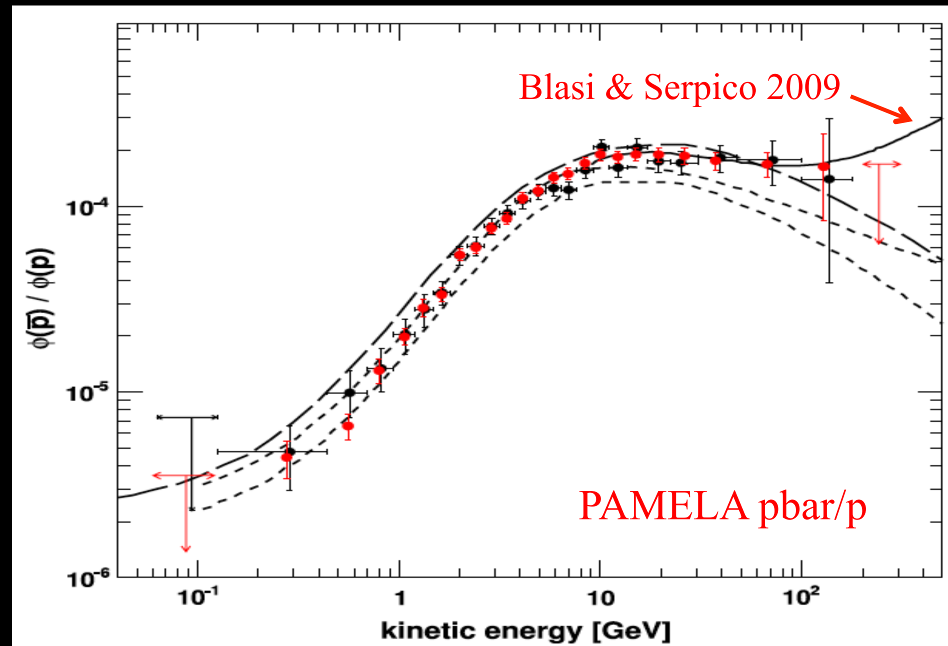


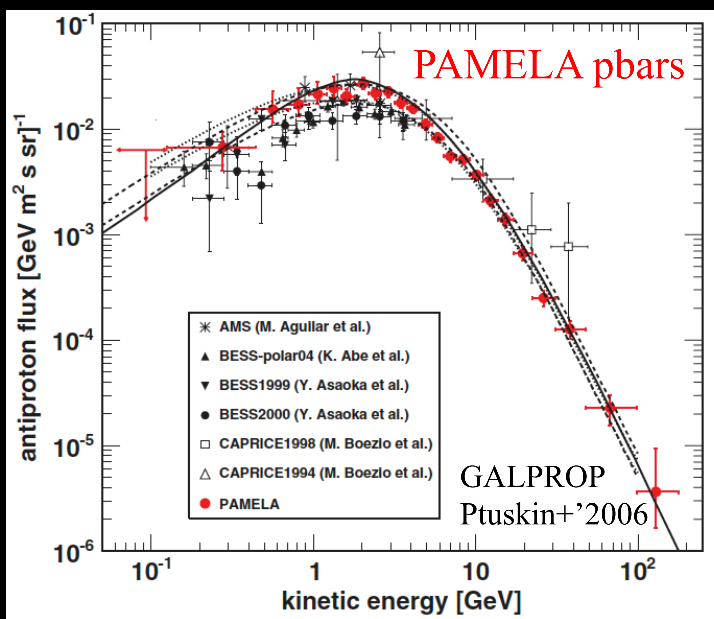




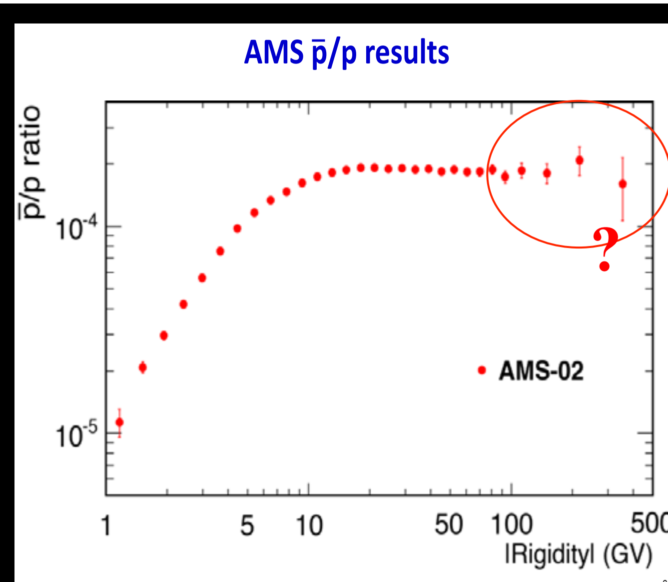
pbar/p ratio







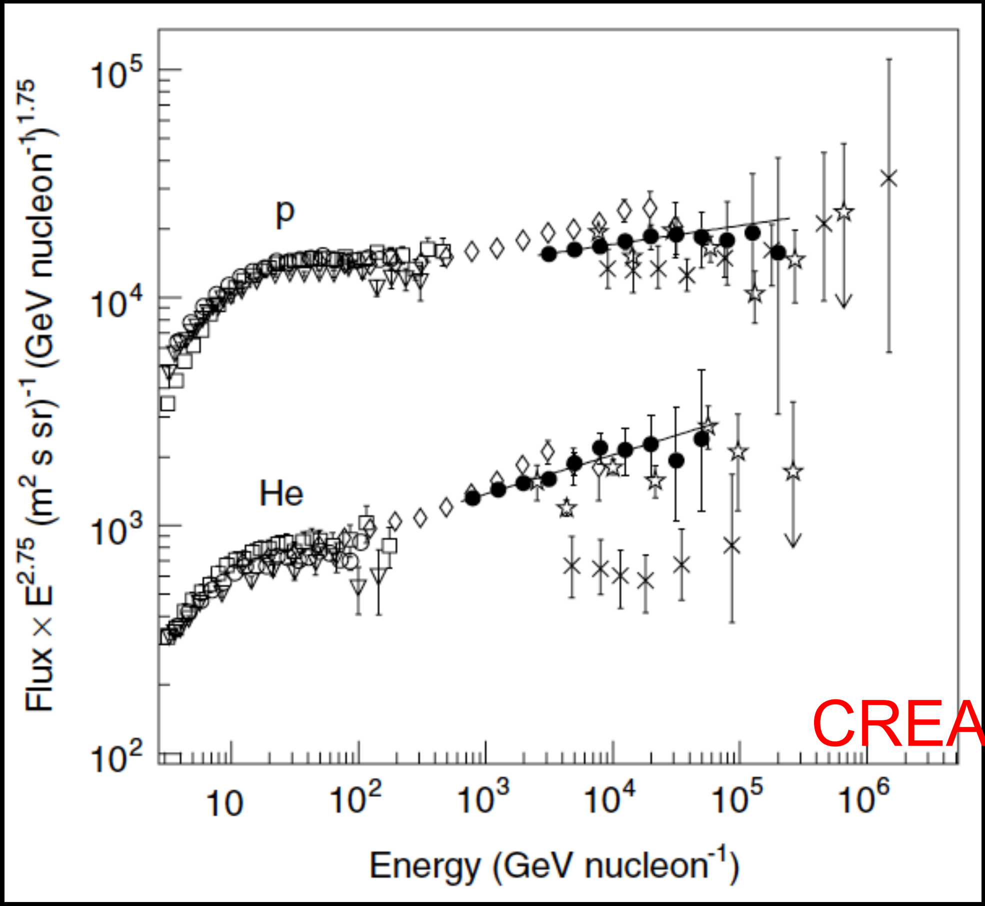
✧ pbar/p ratio is consistent with secondary production, but one point at 400 GeV

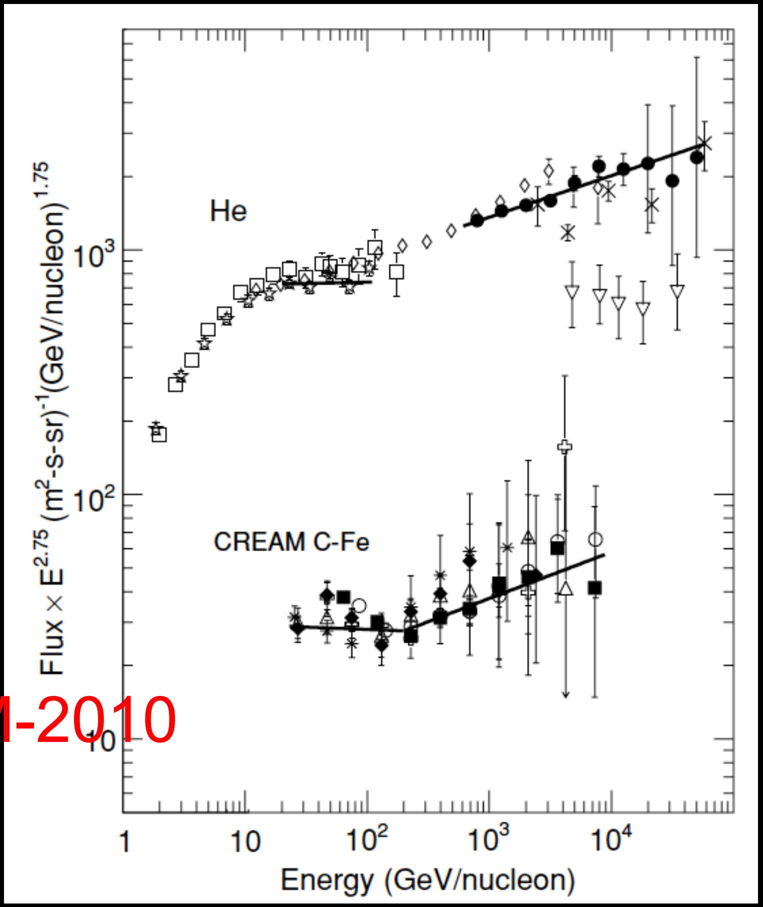


Same scale

Breaks or a calibration problem?

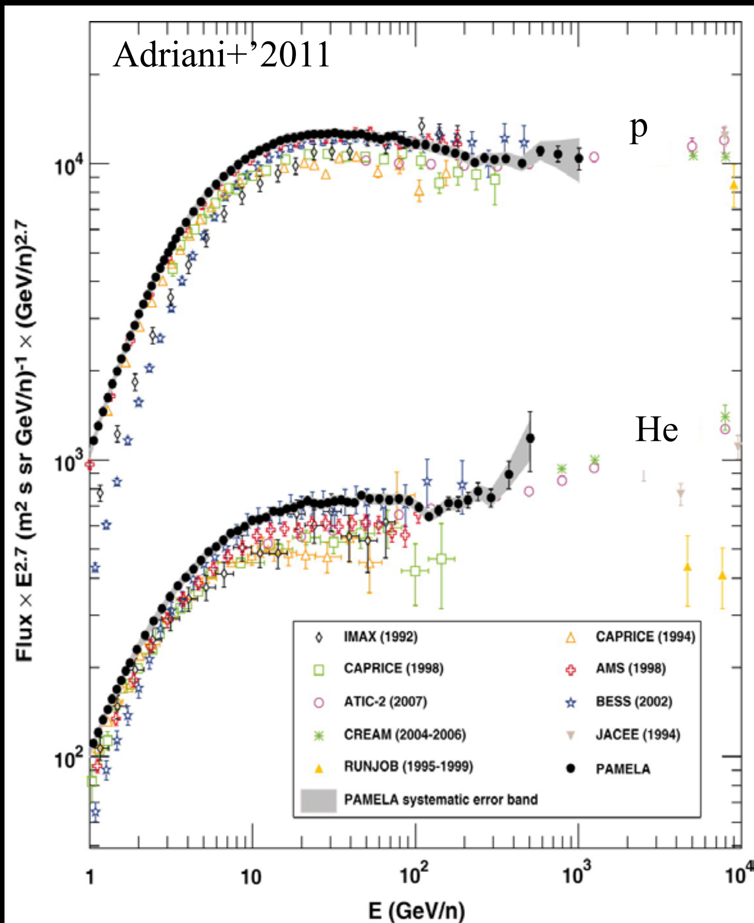
- CREAM & earlier experiments hint at He spectrum to be flatter than p at HE, but scattering of data points was pretty large to make it certain
- Hint on breaks in p and He spectra, but different techniques were used below/above ~200 GeV/n
- Overall it looked as a cross calibration problem between different instruments
- Break in C, O, Ne, Mg, Si, Fe spectra at the same E/nucleon, but the error bars are large

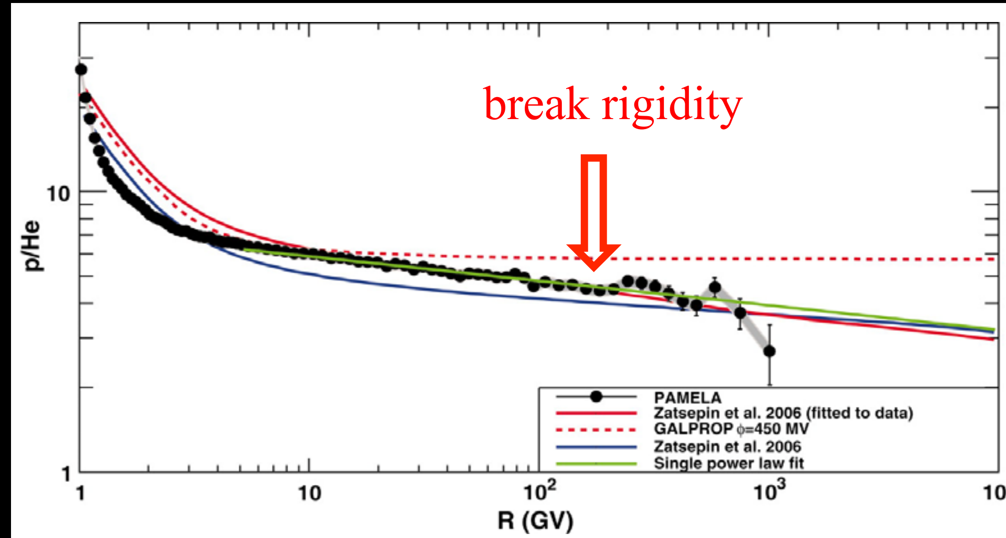




CREAM-2010

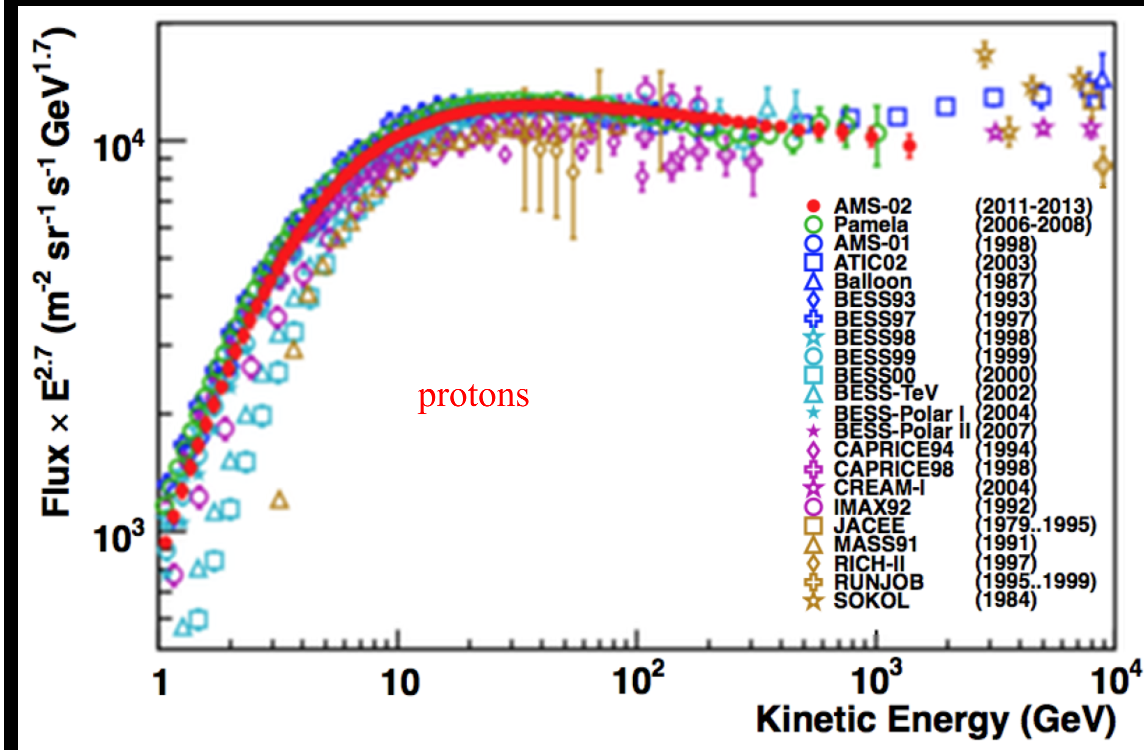
PAMELA discovery: Breaks in p and He spectra



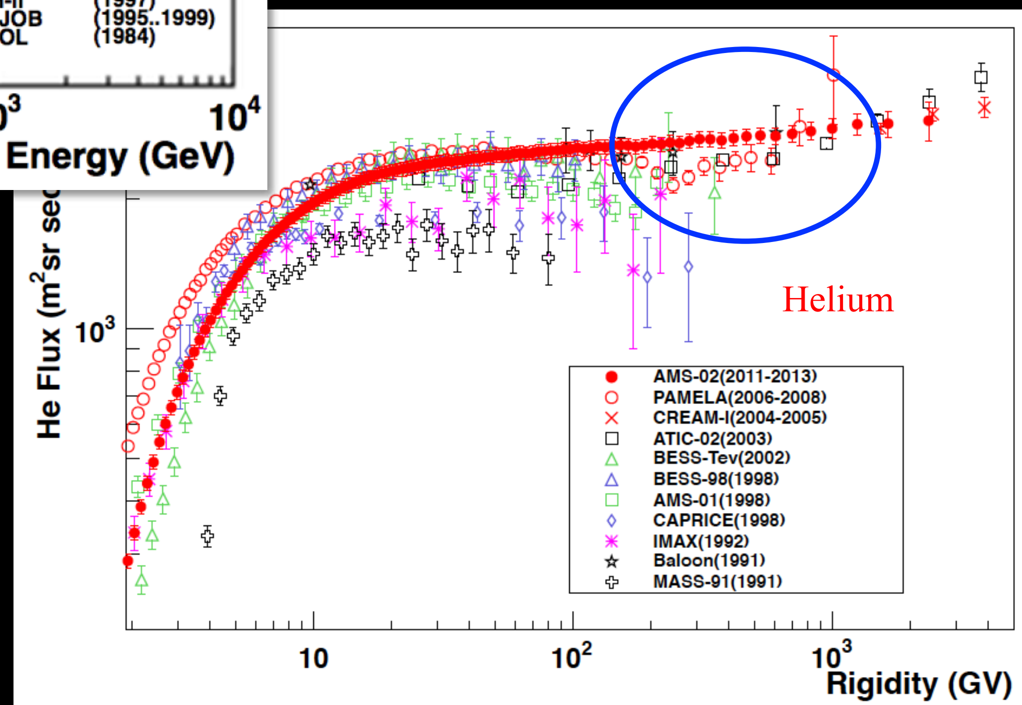


- ✧ PAMELA extension of the energy range up to ~1 TeV solved the puzzle!
- ✧ Suddenly: Data from several experiments (BESS, AMS-01, ATIC'2009, CREAM'2010, PAMELA'2011) become all consistent and indicate hardening above ~100-200 GeV/nucleon
- ✧ Astonishing: p/He ratio vs. rigidity R is smooth
- ✧ He spectrum is flatter than proton spectrum
- ✧ Heavier nuclei seem to share the same trend
- ✧ A hint on the origin of high energy CRs?

33rd ICRC (Rio de Janeiro): AMS-02 session

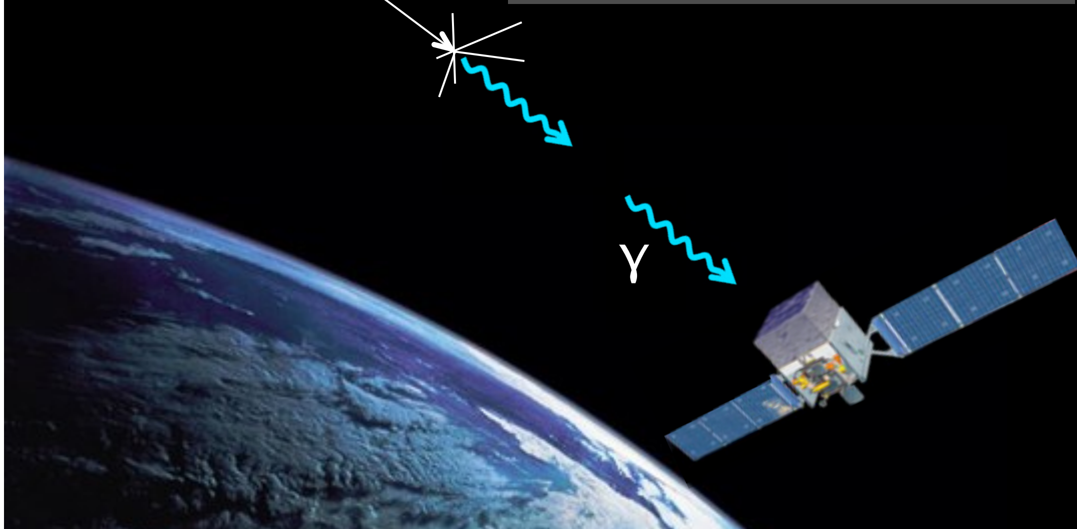


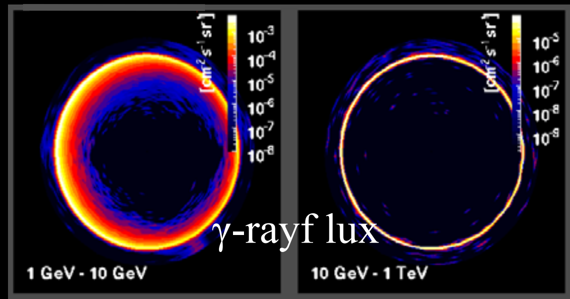
- ✧ At the ICRC-2013, AMS-02 reported no breaks in proton nor Helium spectra
- ✧ Question of the validity of PAMELA results raised…

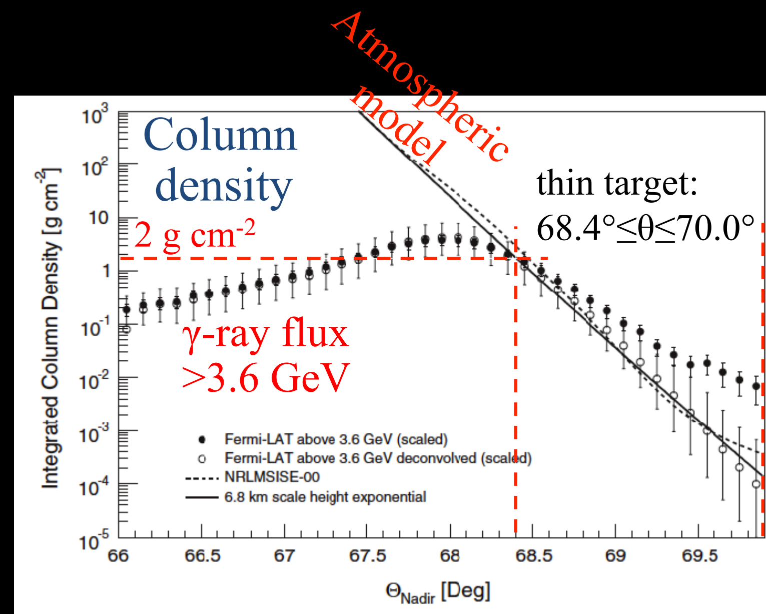


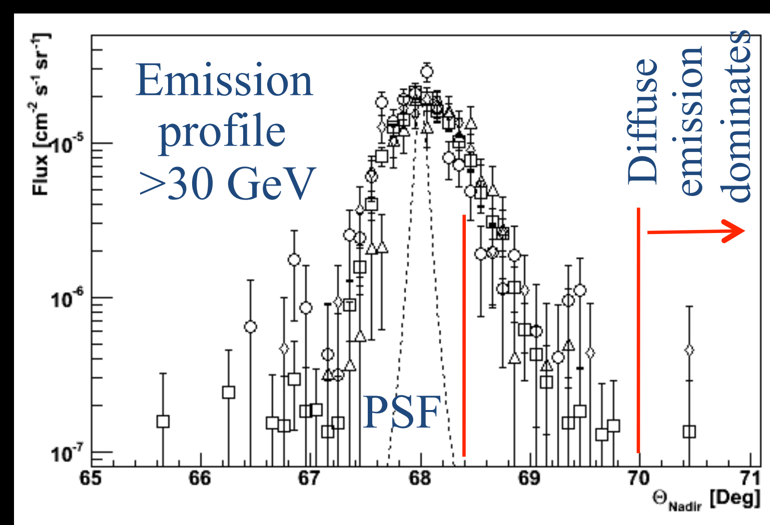
- ✧ PAMELA scientists turned to *Fermi*-LAT to back the PAMELA discovery

Fermi-LAT observations of the Earth's limb





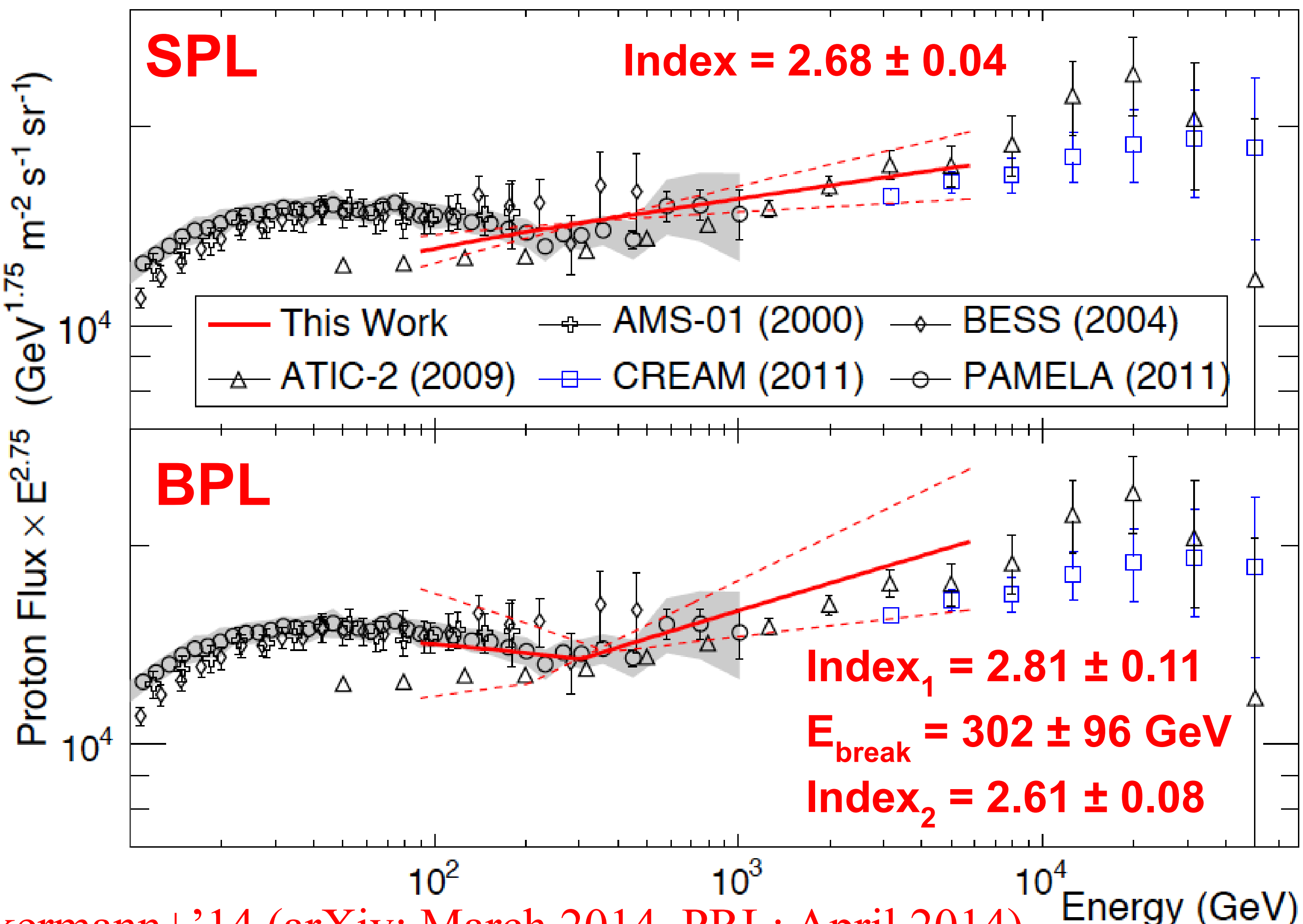




- ✧ Due to its proximity, the Earth is the brightest γ-ray source on the sky
- ✧ The emission is produced by the CR cascades in the atmosphere
- ✧ Most energetic γ-rays are produced by CRs hitting the top of the atmosphere at tangential directions (thin target)

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

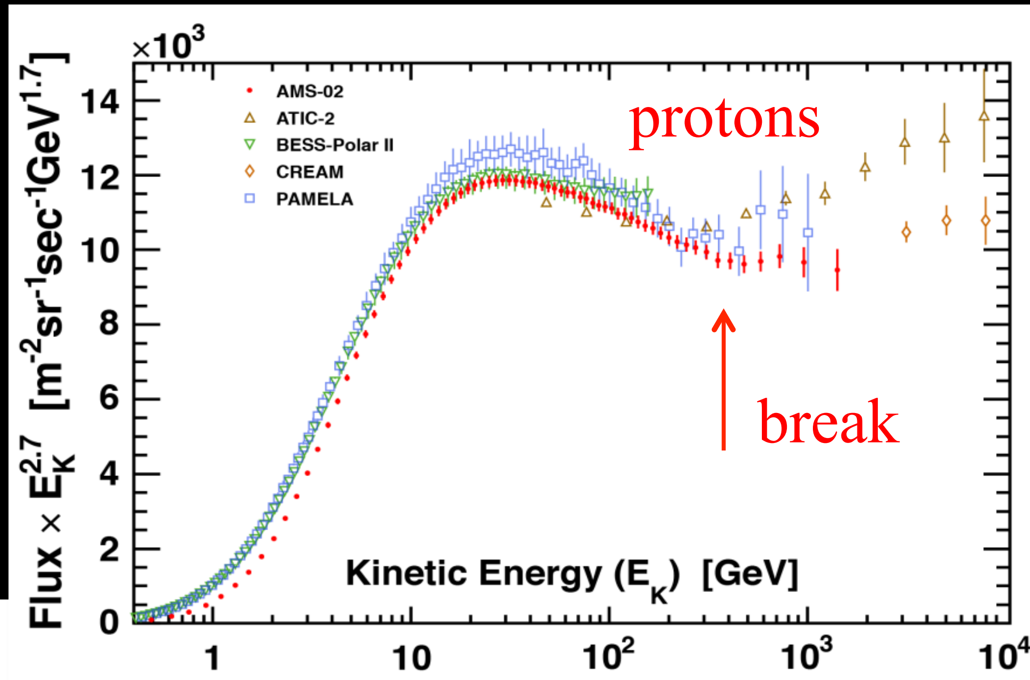
Fermi – Earth limb observations

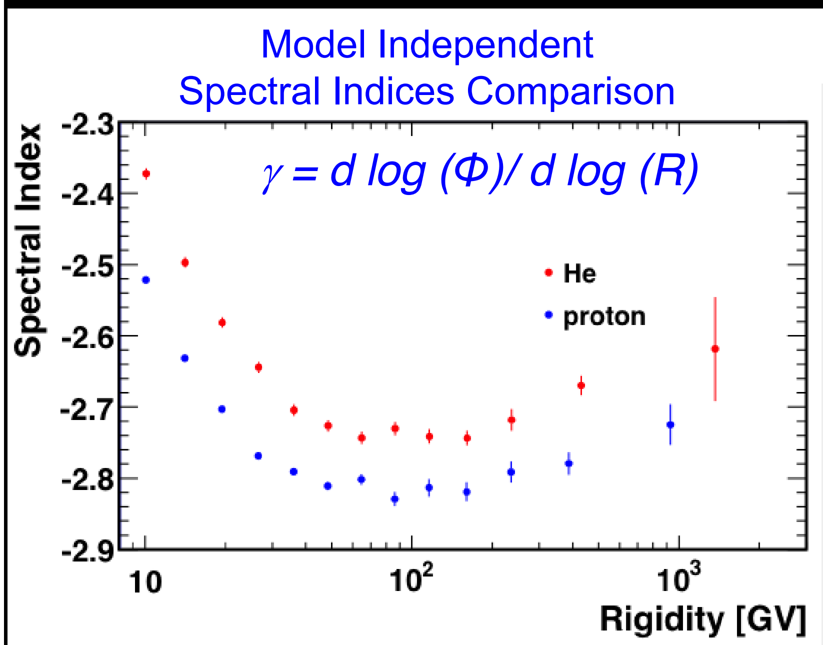


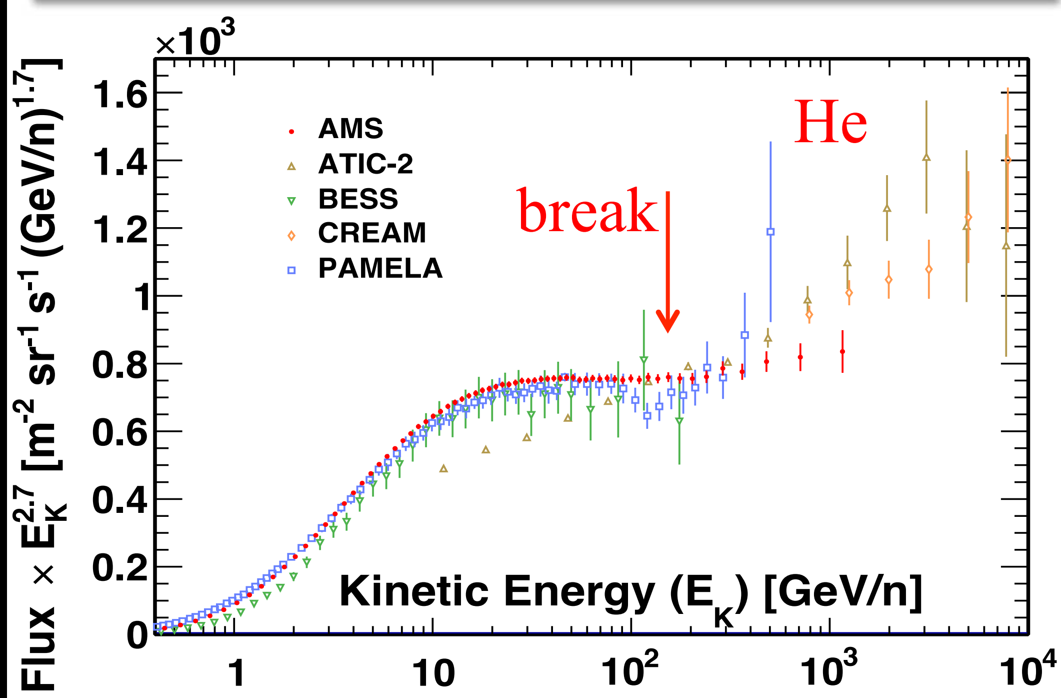
Ackermann+’14 (arXiv: March 2014, PRL: April 2014)

AMS-02 confirmation!

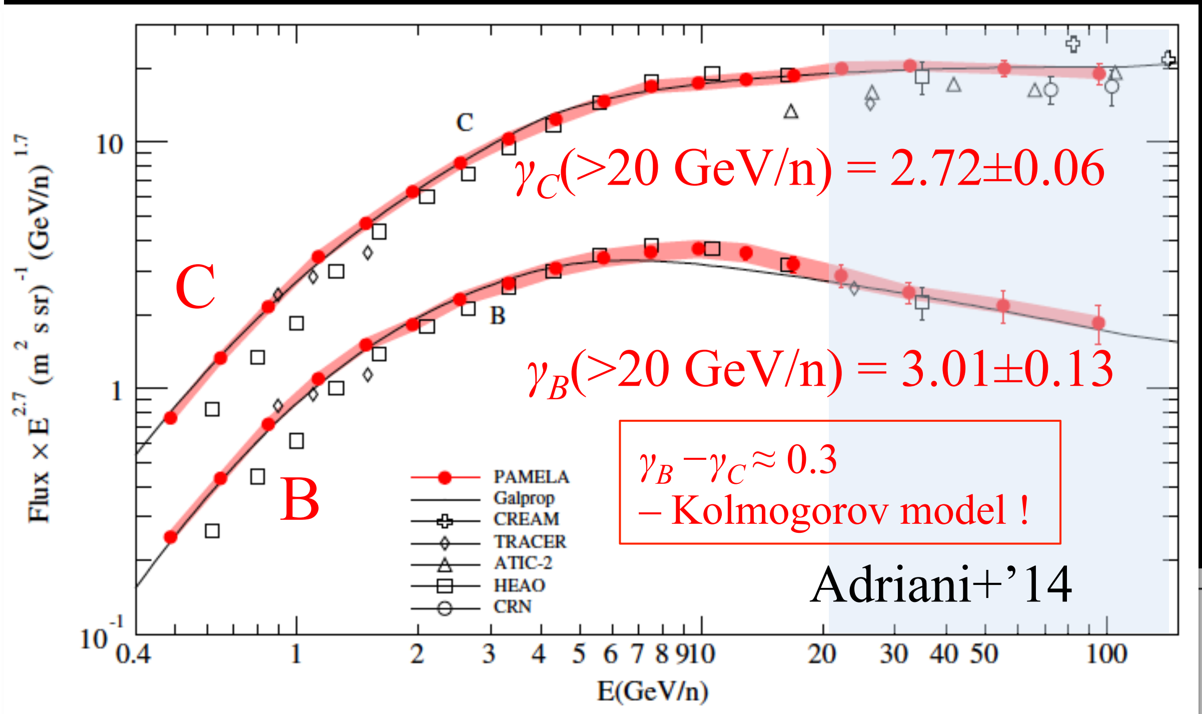
- ✧ In 2015 AMS-02 collaboration reported the flattening in p and He spectra confirming PAMELA's discovery
- ✧ The indices of p and He spectra differ by ~0.1 in a wide energy range, why?



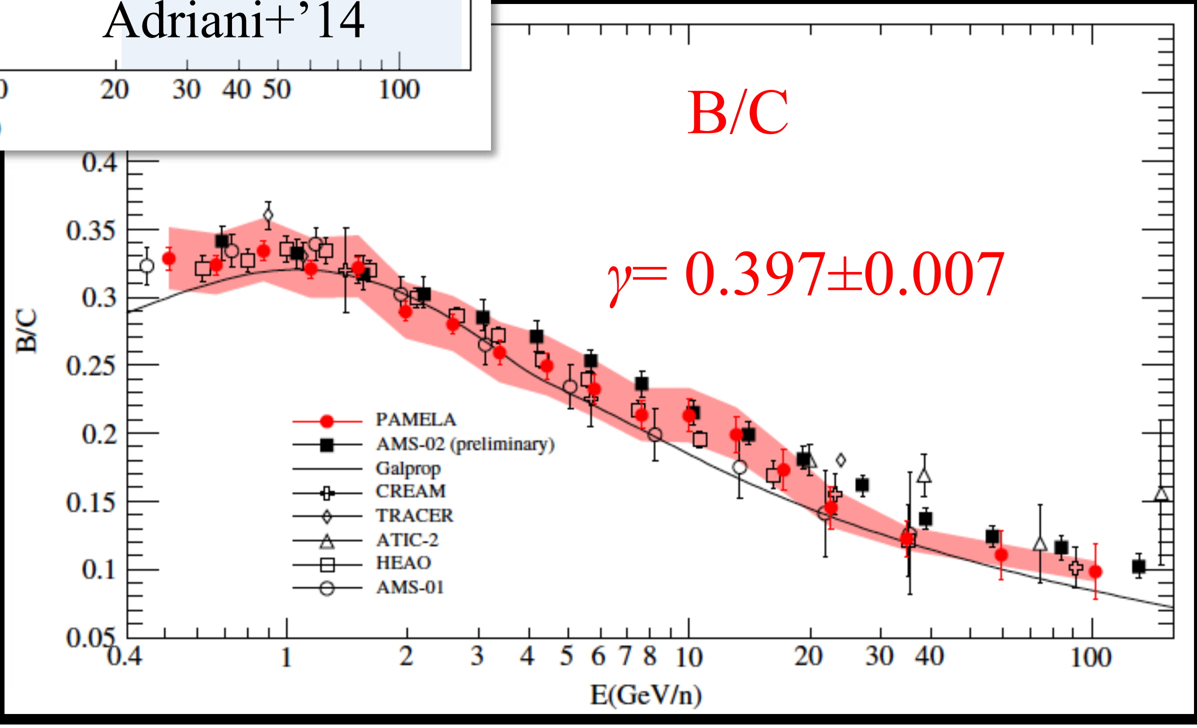




PAMELA breakthrough: B/C ratio



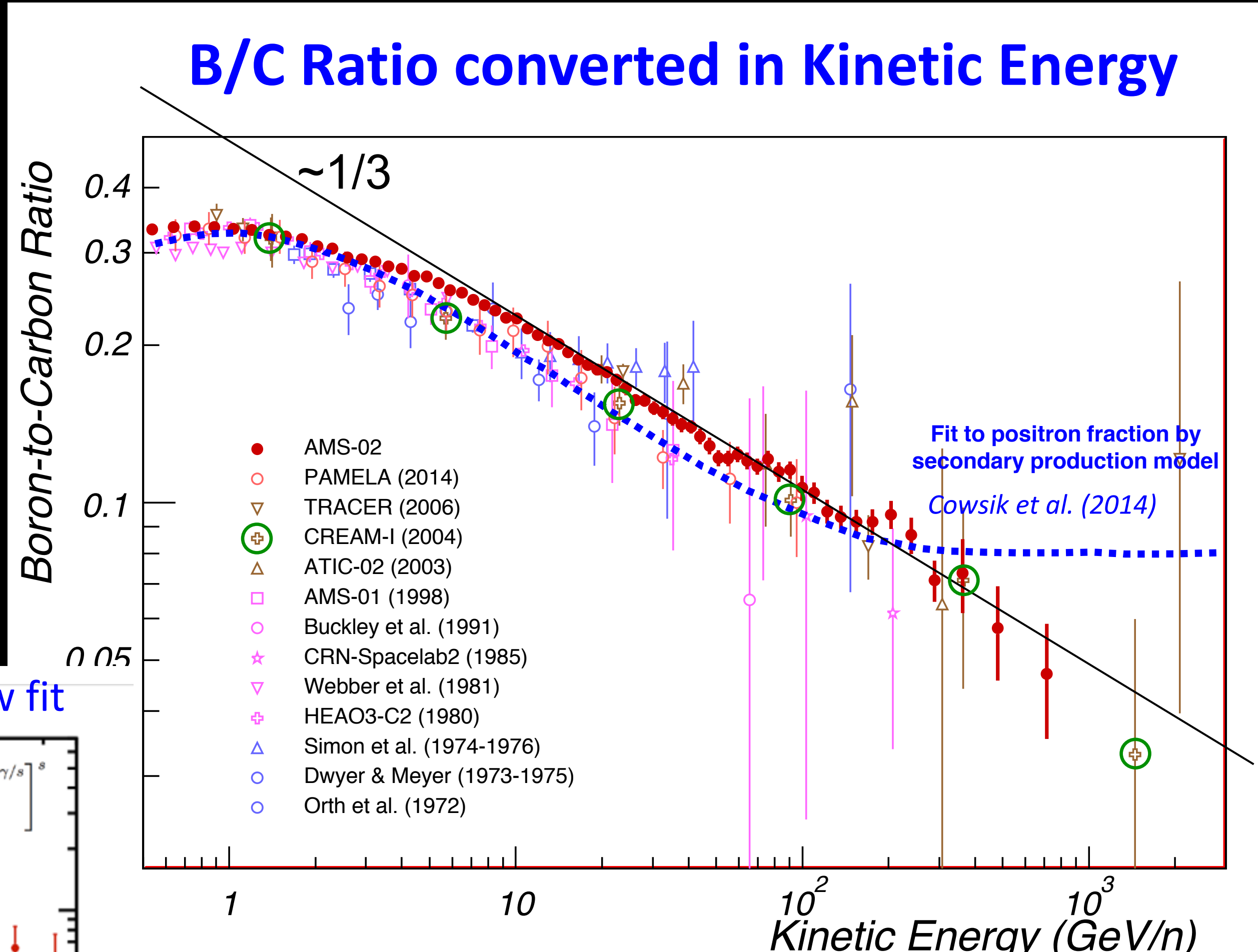
- For decades HEAO-3 (1979-1980) data were the best at 0.6 – 35 GeV/n
- It was not clear if the sharp peak at ~1 GeV/n is real or is an artifact
- The HE dependence is vital for propagation models



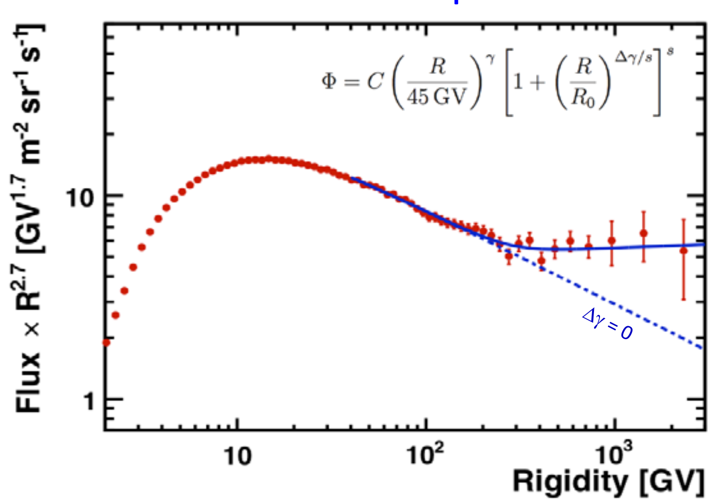
- PAMELA: 0.44-129 GeV/n
- δ = 0.397±0.007 – closest to 1/3 (Kolmogorov) or 1/2 (Iroshnikov-Kraichnan)
- Rejects δ>0.5 plain diffusion used for decades!

AMS-02: preliminary B/C ratio

- ✧ Agrees with PAMELA
- ✧ The ratio continues to fall up to ~2 TeV/nucleon (CREAM)
- ✧ No significant change in the slope of the B/C ratio
- ✧ Break in C, B spectra?
- ✧ The slope >10 GeV/n is ~1/3 – clearly supports Kolmogorov reacceleration model
- ✧ Rules out Nested Leaky-Box model



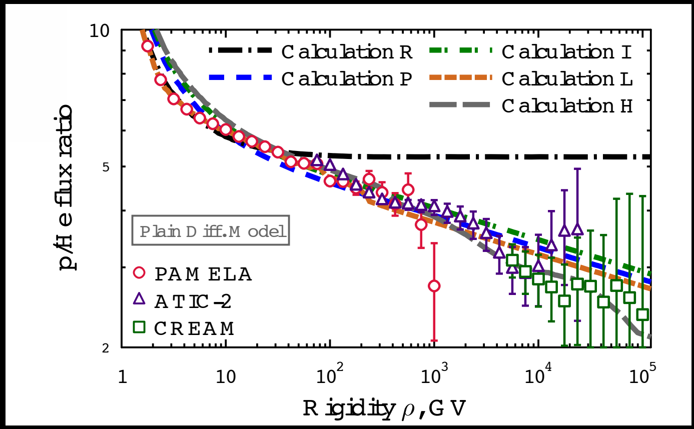
Lithium flux with two power law fit



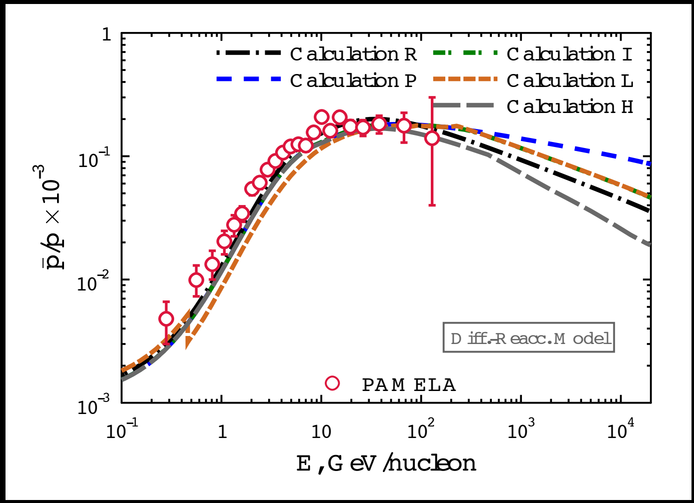
Slope changes at about the same rigidity as for protons and helium

Possible scenarios of the breaks (based on PAMELA data)

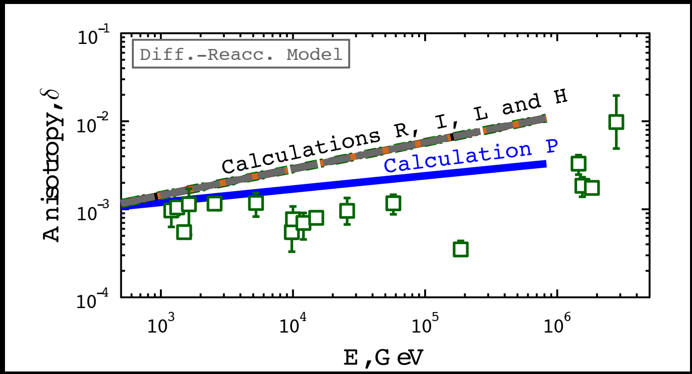
- ✧ Reference (R) scenario – standard model
- ✧ Propagation (P)
- ✧ Injection spectrum (I) or two types of sources
- ✧ Local source at LE (L) or at HE (H)



- ✧ P/He ratio is tuned in all scenarios except Reference scenario



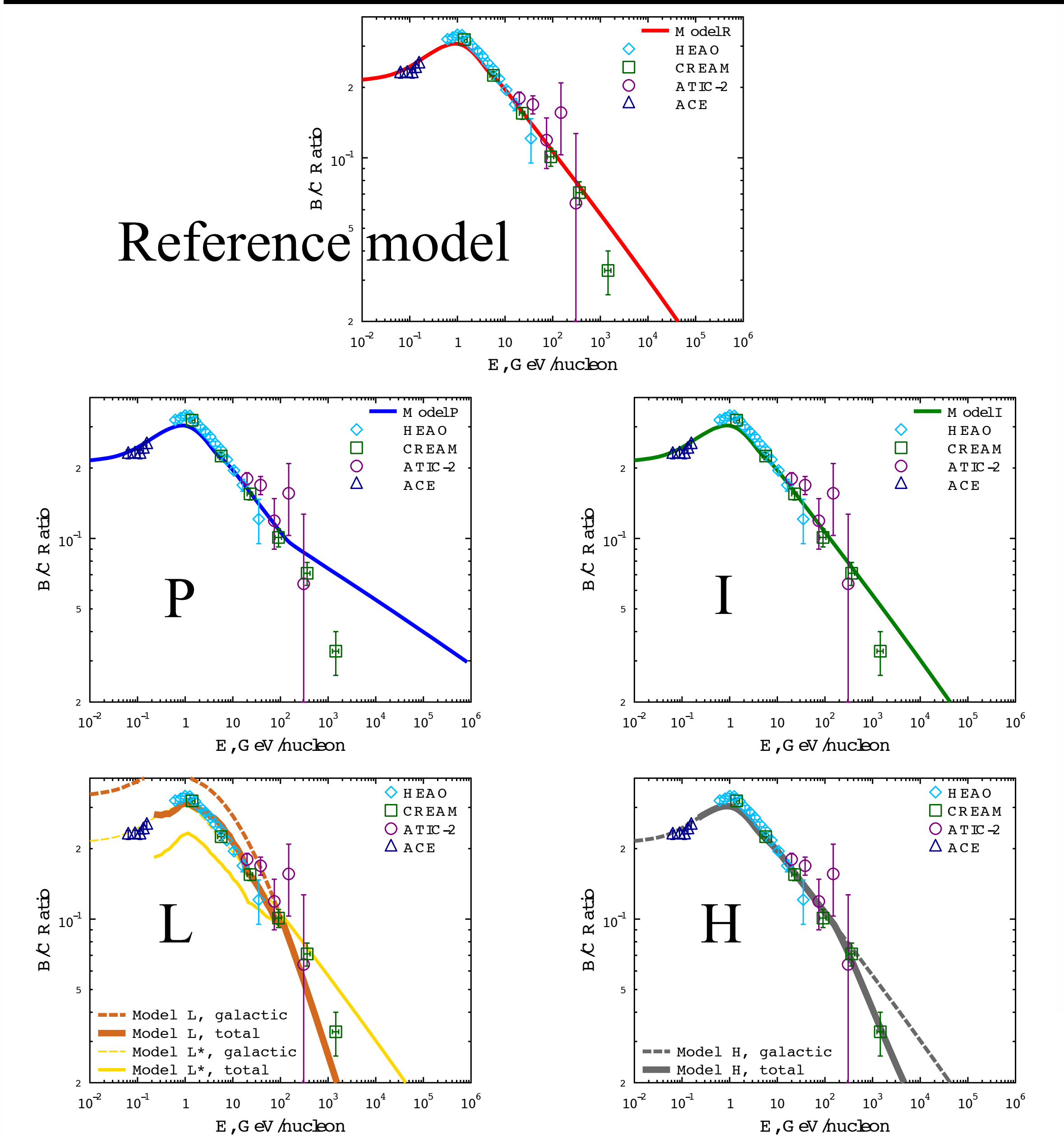
- ✧ Predicted antiproton/proton ratio agrees with the existing data, but exhibits different behavior at >100 GeV



- ✧ Only scenario P agrees with the data on CR anisotropy and with AMS-02 pbar/p ratio

Vladimirov+'2012, ApJ 752, 68

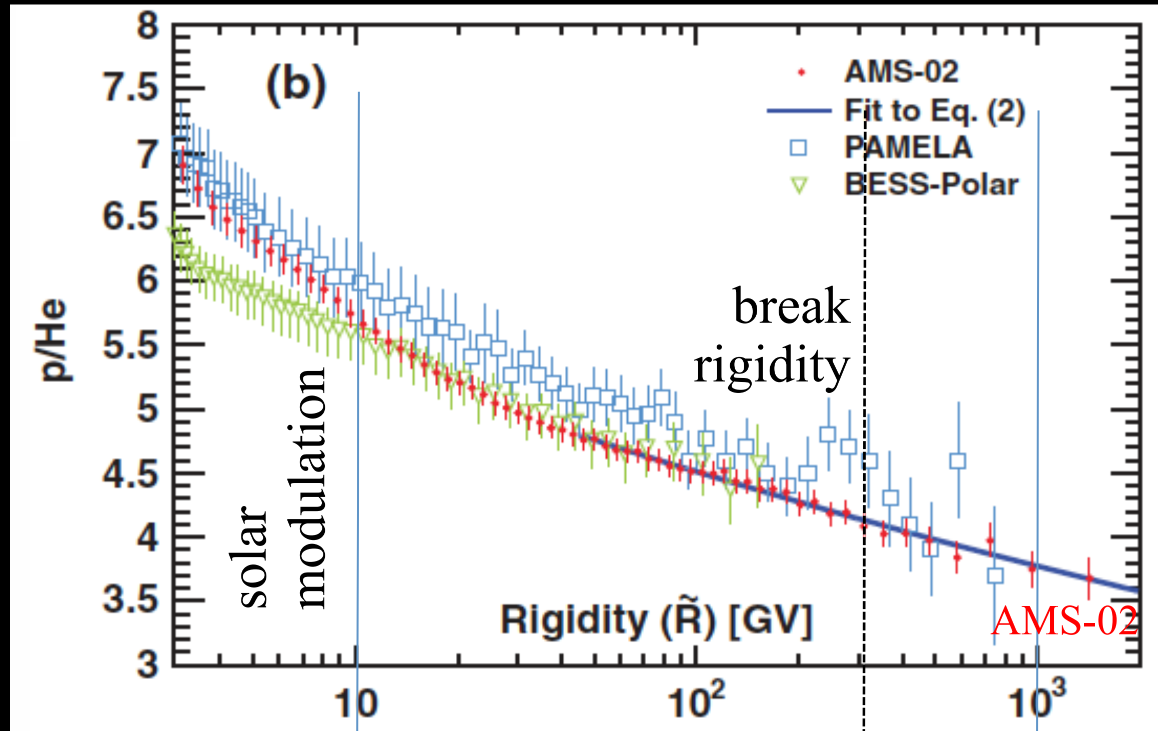
B/C ratio in different scenarios

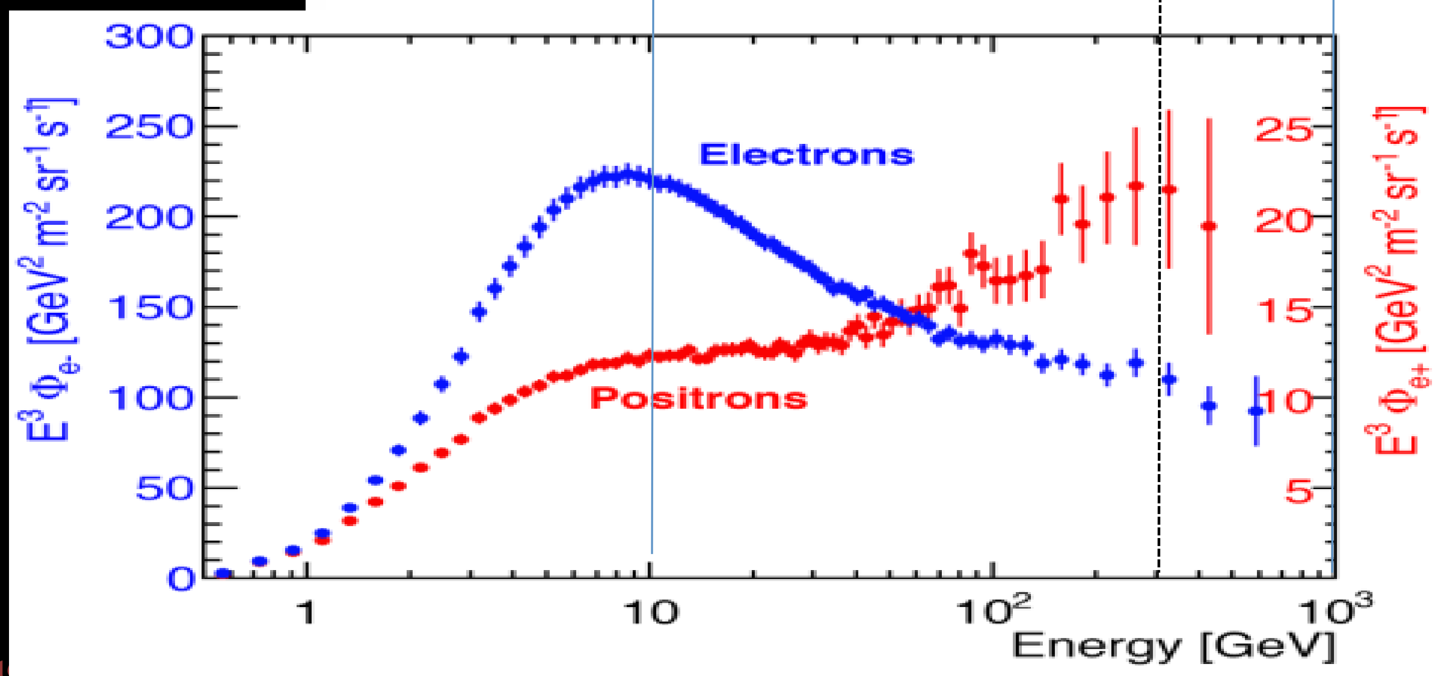


- ✧ B/C is flatter in Scenario P
- ✧ Breaks in B & C spectra (?) and accurate measurement of the B/C ratio are critical
- ✧ Local sources are assumed to produce only primary isotopes
- ✧ B/C is steeper in scenario L and H, but due to the different reasons
  - Scenario L: P-L index of the diffusion coefficient steepens to 0.67
  - Scenario H: there is no Boron in the local source, but there is Carbon

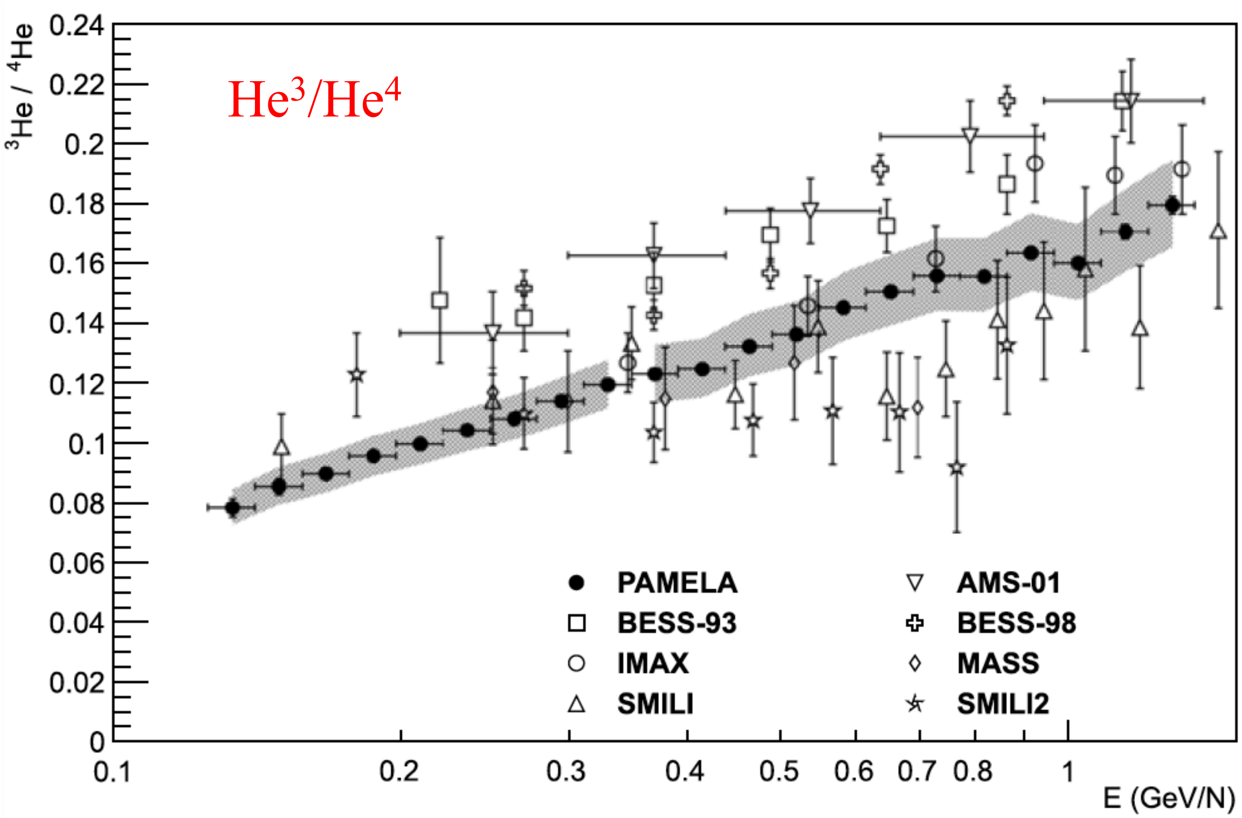
p/He ratio, e^+, e^-

- The ratio is featureless
- Indicates that the same (unknown) mechanism works for p, He, and possibly heavier elements
- What's about electrons and/ or positrons?
- More statistics is necessary



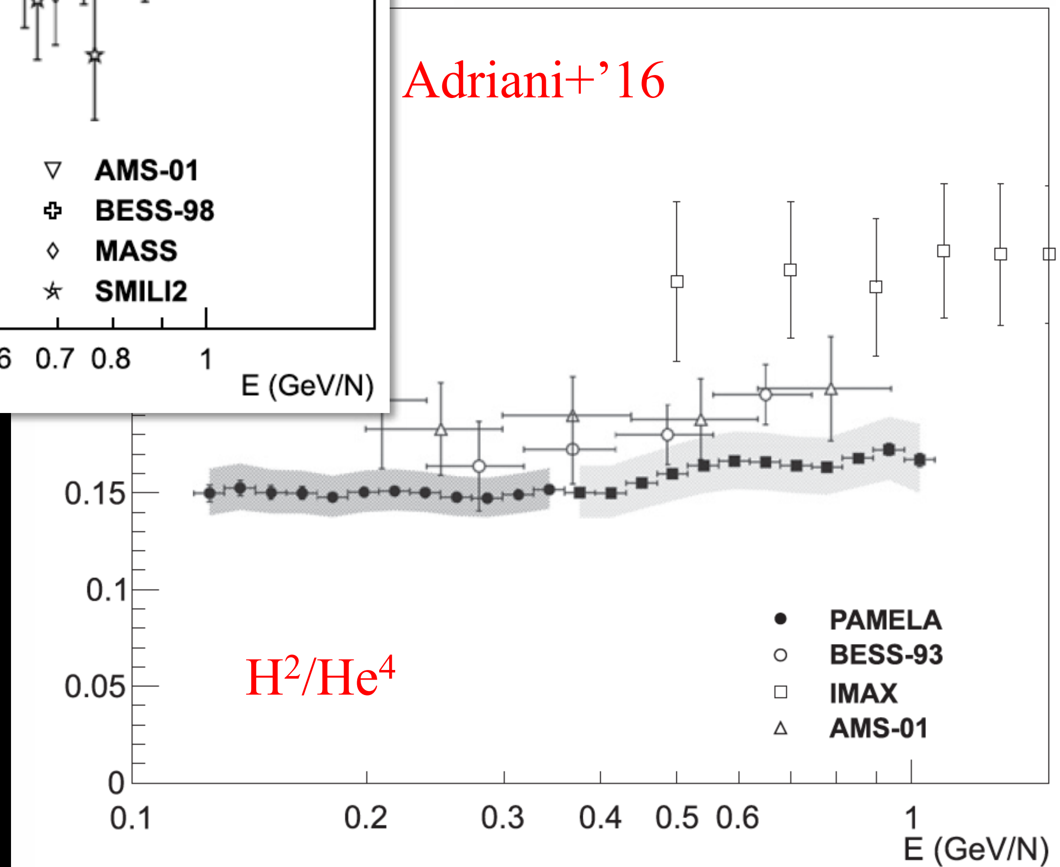


PAMELA @ solar minimum: H^2 and He^3



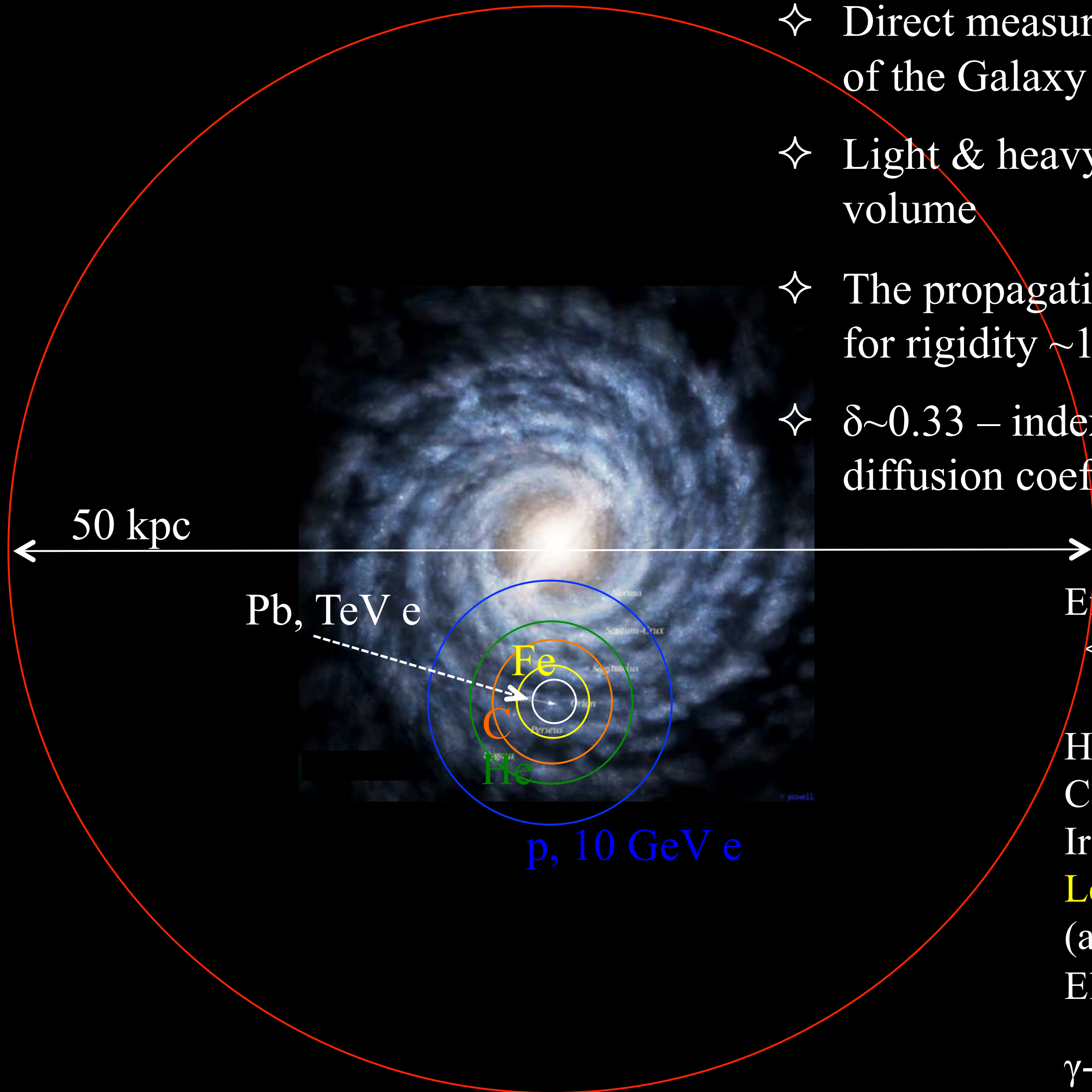
- Most accurate measurement of d, He^3 isotopes up to ~2 GeV/n @ the solar minimum

Adriani+'16



- pbar, p, d, He^3, He^4 are the lightest CR hadron species
- pbar, d, He^3 are secondaries – can be used to derive propagation parameters (in place of boron)
- Probe the Galaxy on a large scale

Direct probes of CR propagation



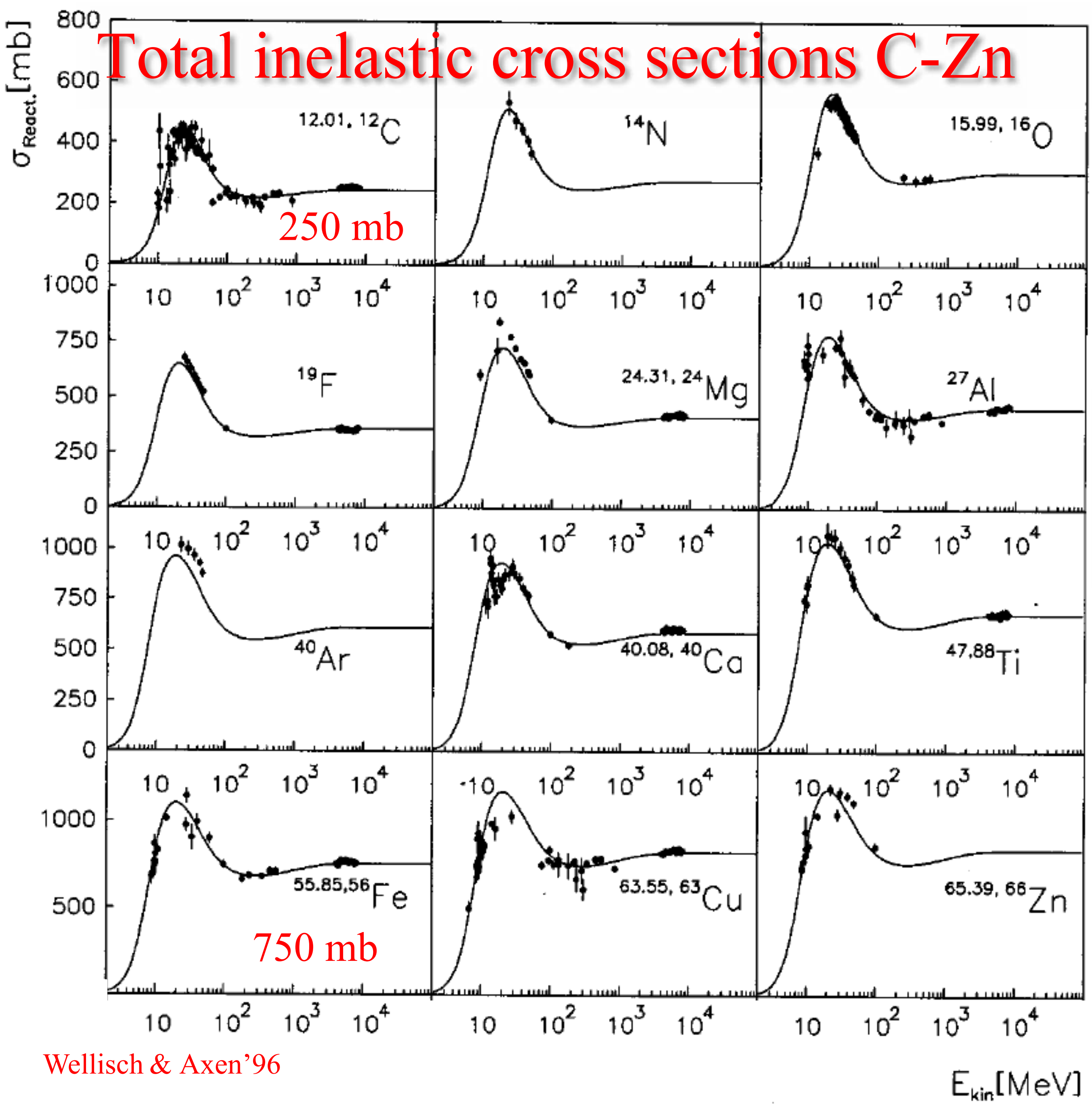
- Direct measurements probe a very small volume of the Galaxy
- Light & heavy nuclei probe different propagation volume
- The propagation distances are shown for nuclei for rigidity ~1 GV, and for electrons ~1 TeV
- $\delta \sim 0.33$ – index of the rigidity dependence of the diffusion coefficient

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

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

Total inelastic cross sections C-Zn



Wellisch & Axen'96

pbar, p ~ 40 mb

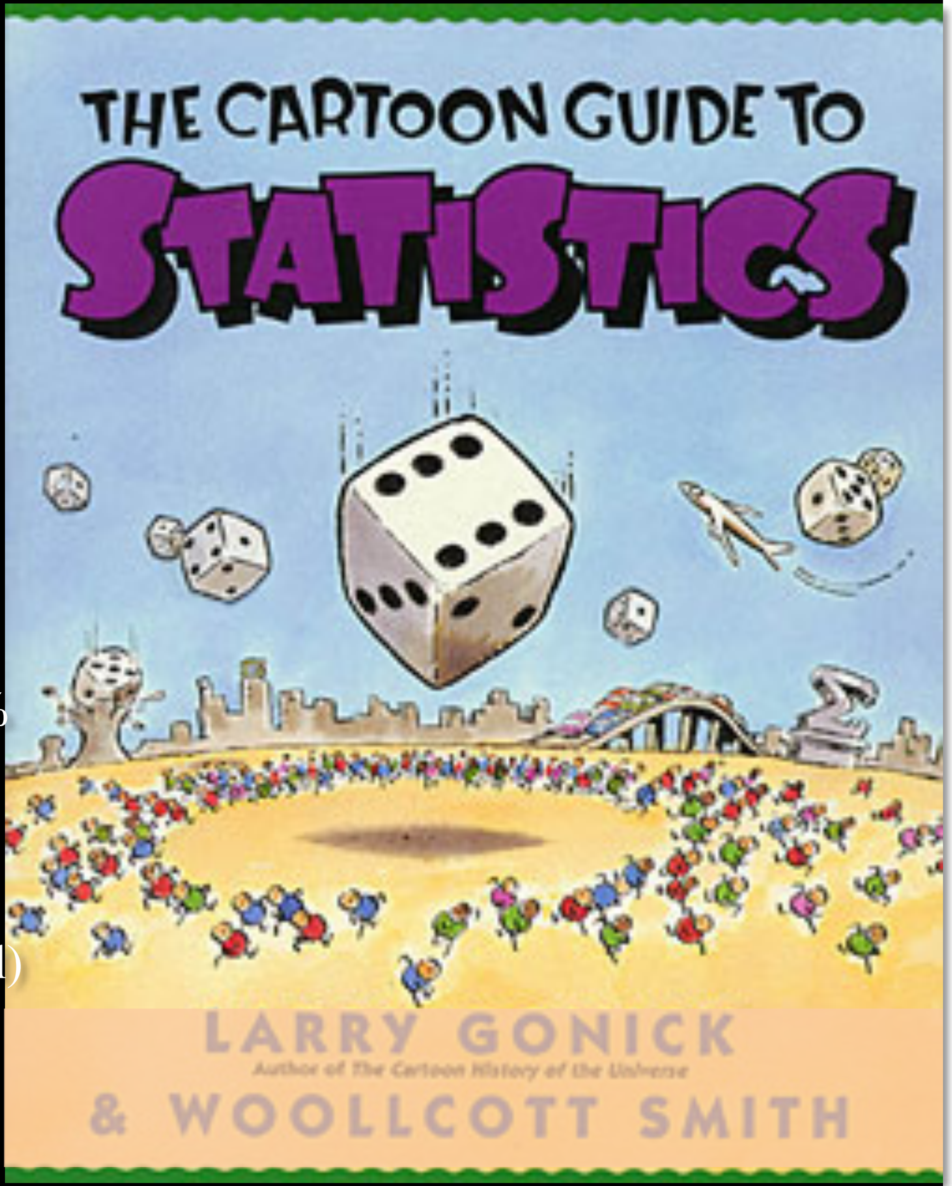
Nuclei: above ~1 GeV/n:

$\sigma \sim 250$ mb $(A/12)^{2/3}$

Bayesian Analysis of CR propagation

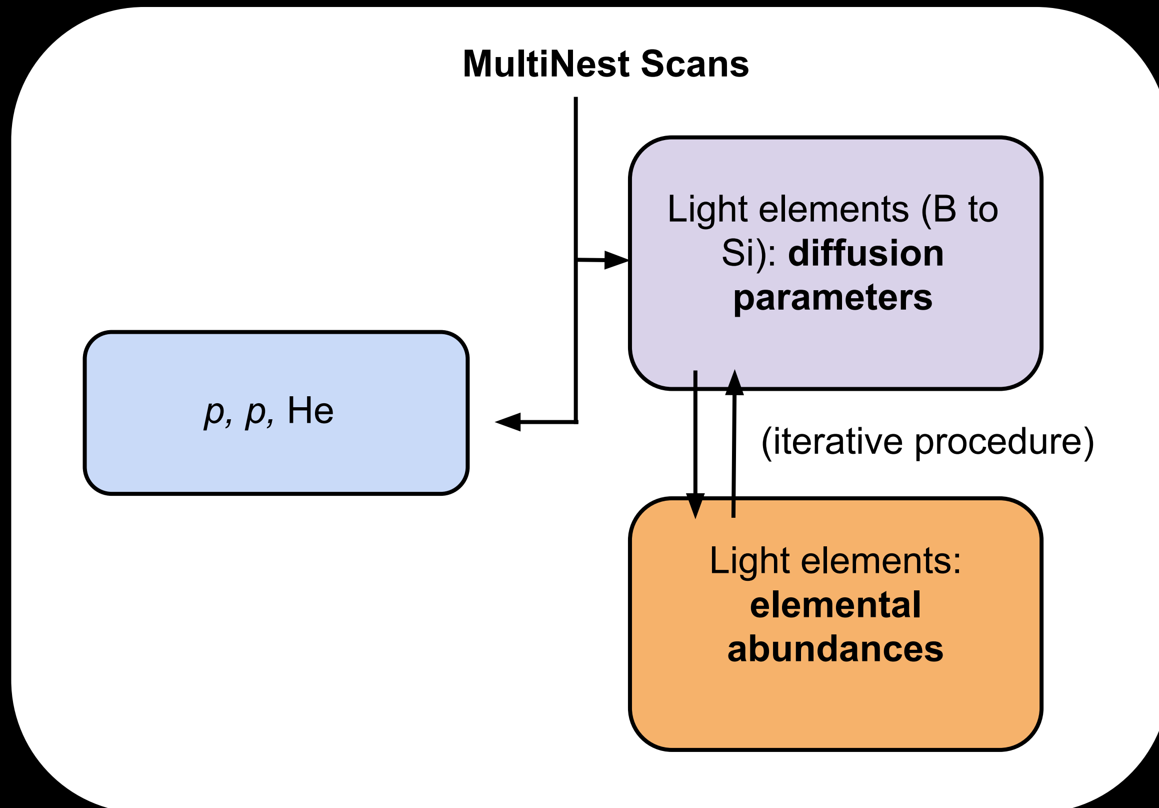
- First successful attempt – Trotta'11
- SuperBayeS with optimized GALPROP
- Statistical analysis of the entire parameter space
- Returns global best fit points and confidence limits
- Includes "nuisance" parameters

- New analysis (Johannesson+'16) employs machine-learning techniques (BAMBI algorithm), reduces computing time by ~20%
- BAMBI = MultiNest sampling + SkyNet neural network training
- Constrains both CR propagation parameters and source abundances (reacceleration model)
- Split data sets: (i) pbar, p, He and (ii) light nuclei: Be-Si
- Finer grid provides better accuracy



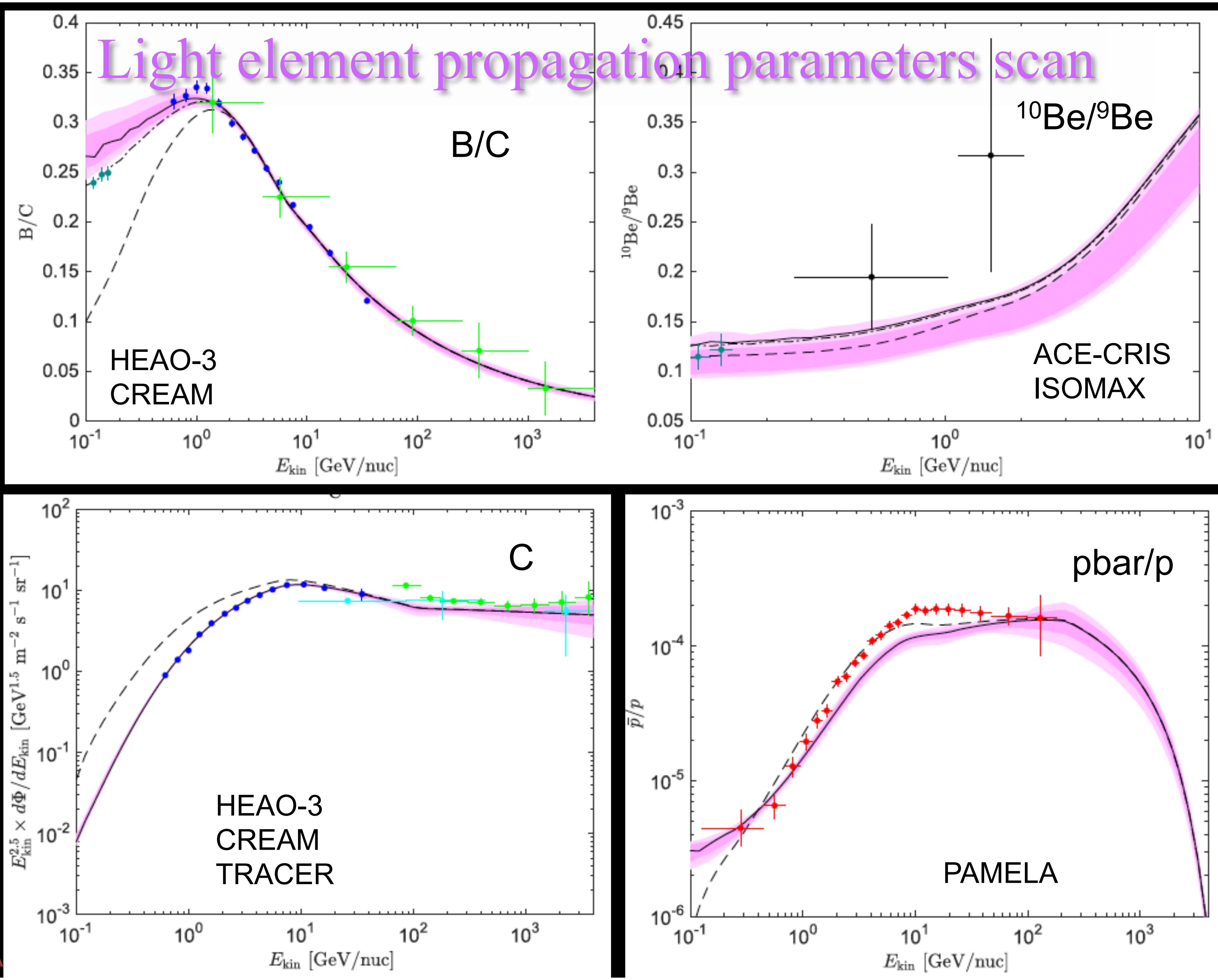
Computational effort – just to get you impressed!

- pbar, p, He scan
  - 144 CPUs
  - 2M GALPROP calls
  - 5.5 CPU years

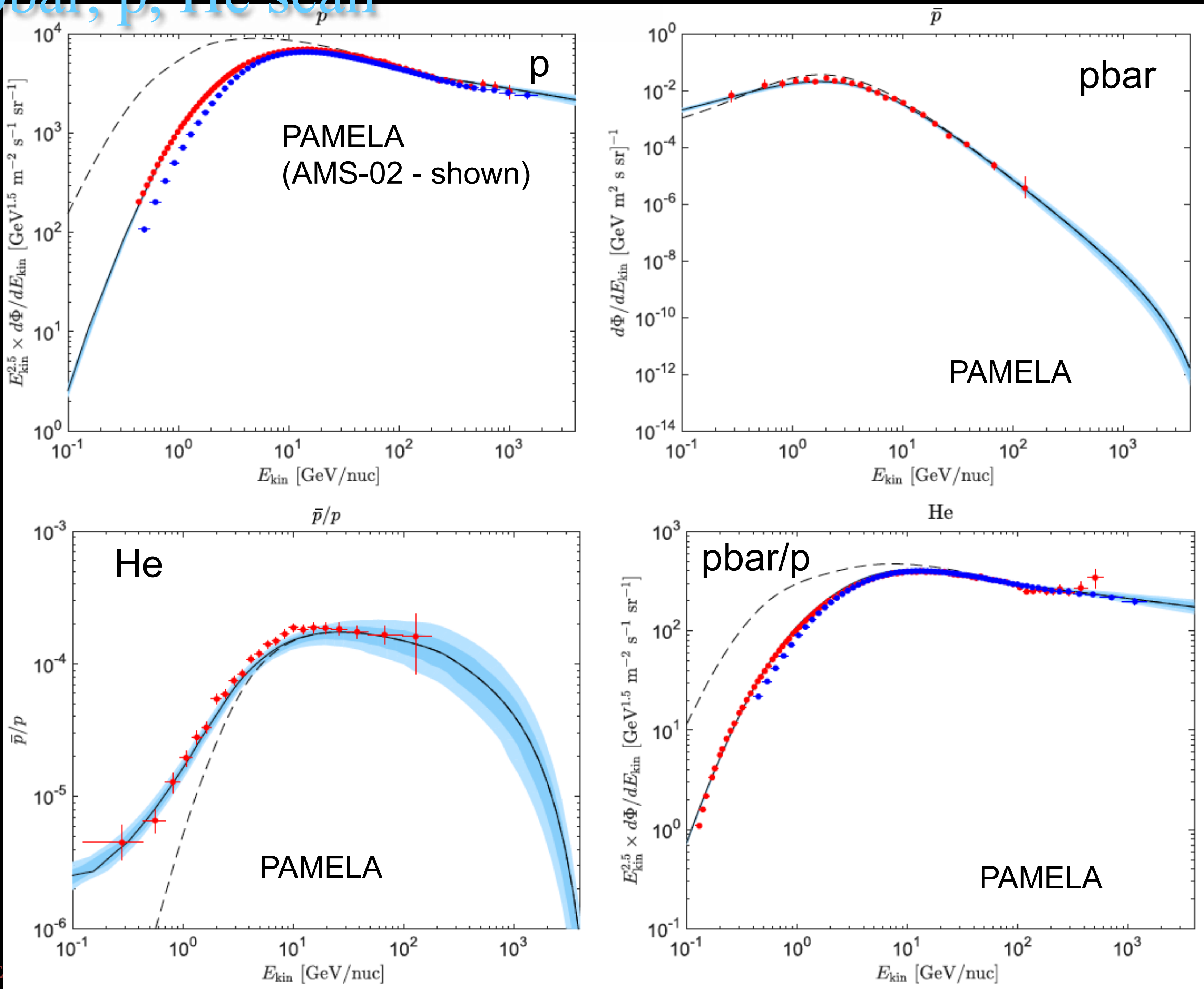


- Be-Si scan
  - Iterative procedure
  - 96 CPUs
  - 2M GALPROP calls
  - 35 CPU years
- BAMBI efficiency
  - 1% effort spent on training
  - saved 20%: ~10 CPU years or 4.5 months of real time
- FULL run time – 2 years of real time!

Light element propagation parameters scan



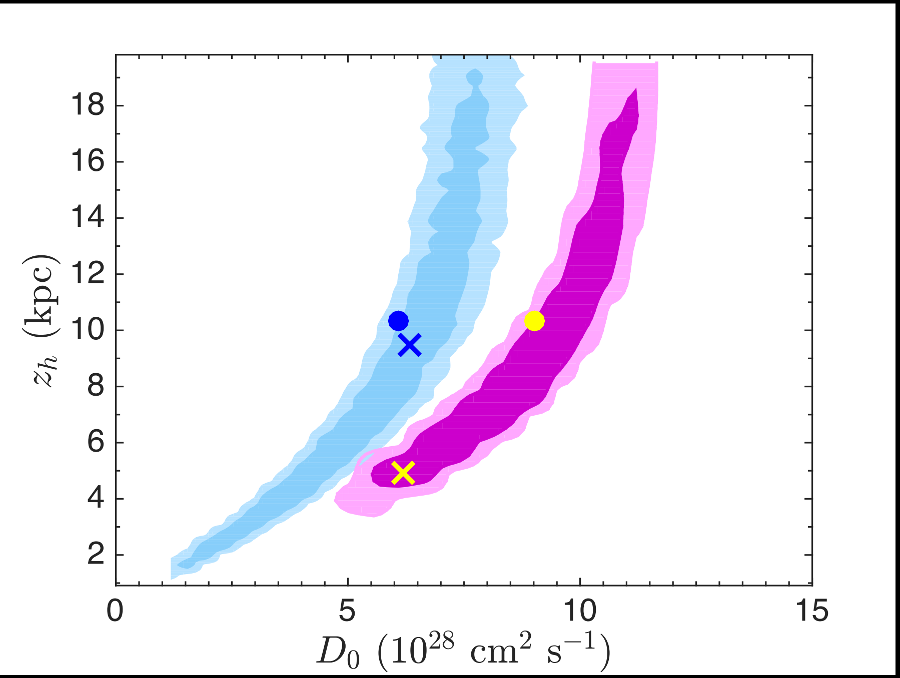
pbar, p, He scan

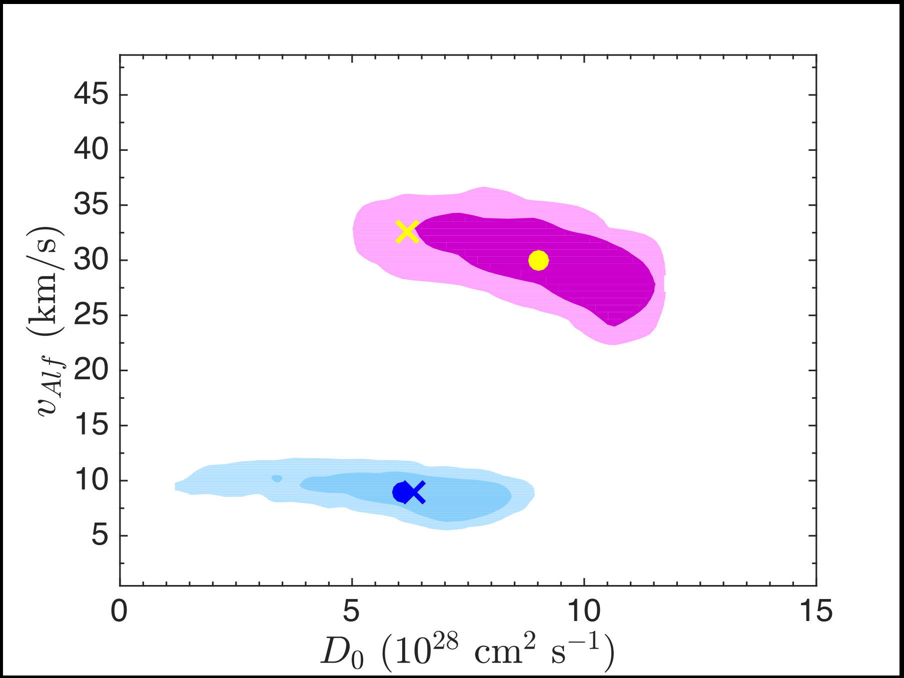


PAME

2D posterior distributions

- 2D posterior distributions:
  - halo size z_h vs diffusion coefficient D_0
  - Alfven velocity v_{Alf} vs diffusion coefficient D_0
- Clearly demonstrate the distributions do not overlap
- Interpretations:
  - Non-uniform diffusion coefficient in the Galaxy
  - Local sources (~1 kpc) of primary nuclei (IVM+'03, Shaviv+'09)





Non-uniform diffusion

- Interaction time scale

$$\tau \sim [\sigma_r n c]^{-1}$$

- Diffusion coefficient

$$D_{xx} = \beta D_0 \left(\frac{\rho}{\rho_0}\right)^{\delta}$$

- Effective propagation distance

$$\langle x \rangle \sim \sqrt{6D\tau} \sim \left(\frac{6D_0}{\sigma_r n c}\right)^{1/2} \left(\frac{\rho}{\rho_0}\right)^{\delta/2}$$

- Total inelastic cross section (fragmentation) at a few GeV/nuc

$$\sigma_r(A) \approx 250 \text{ mb } (A/12)^{2/3}$$

- p, pbar inelastic cross section ~40 mb

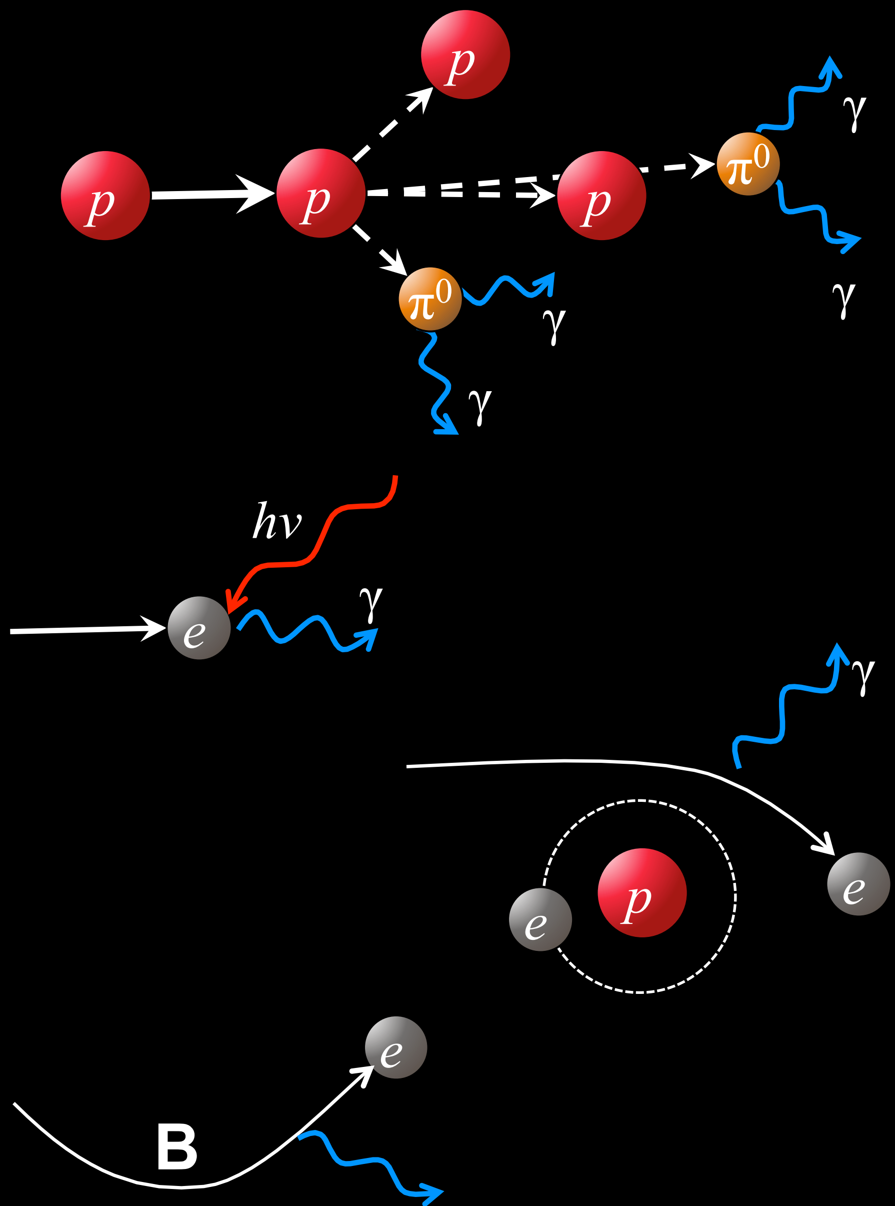
- Effective propagation distance of carbon nuclei and protons (antiprotons)

$$\langle x \rangle_A \sim 2.7 \text{ kpc } \left(\frac{A}{12}\right)^{-1/3} \left(\frac{\rho}{\rho_0}\right)^{\delta/2}$$

$$\langle x \rangle_p \sim 5.6 \text{ kpc } \left(\frac{\rho}{\rho_0}\right)^{\delta/2}.$$

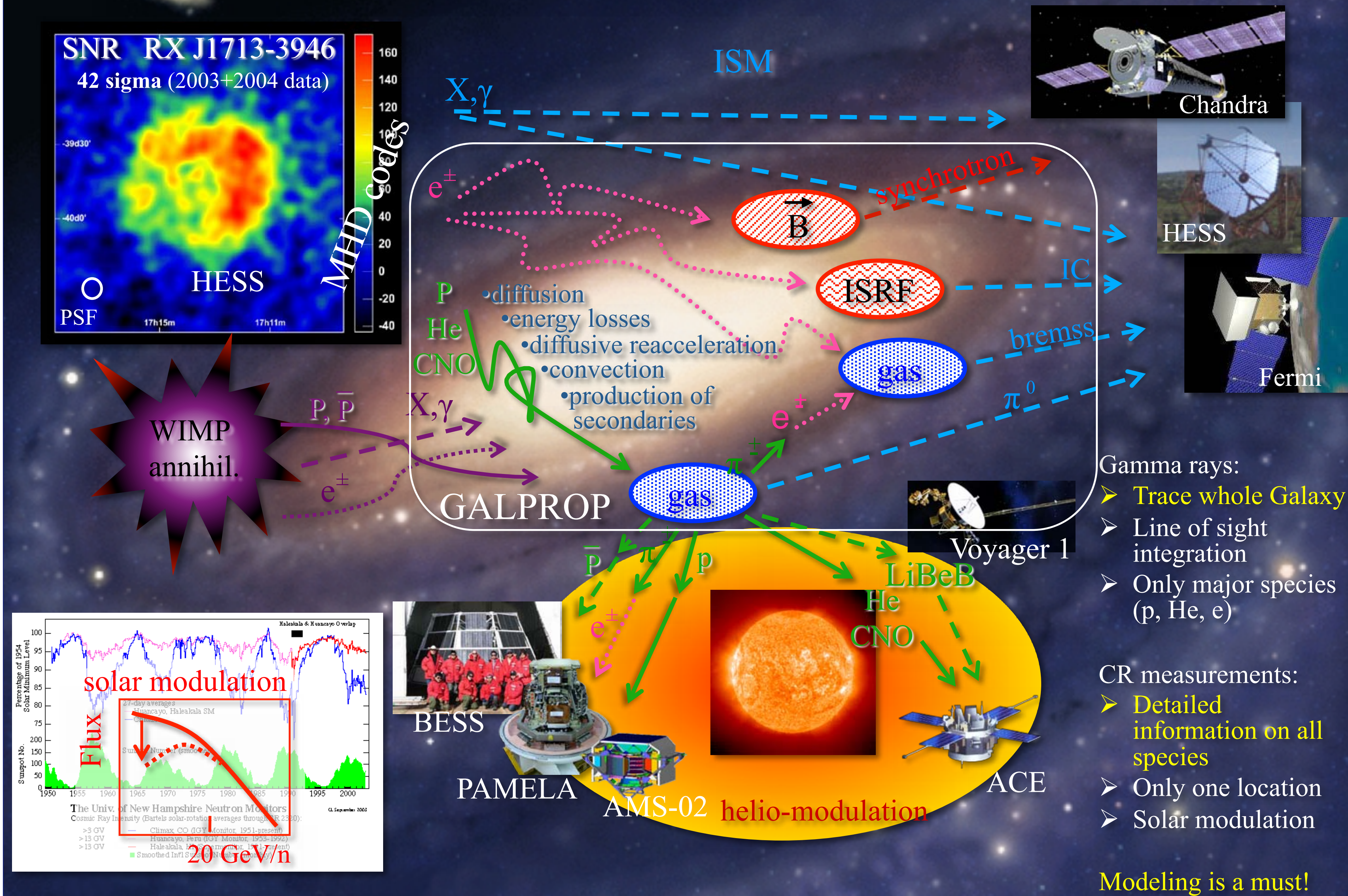
- Probes the area $\sim < x >^2$: p probes 4 times the area that is probed by C

High energy gamma-ray emission processes

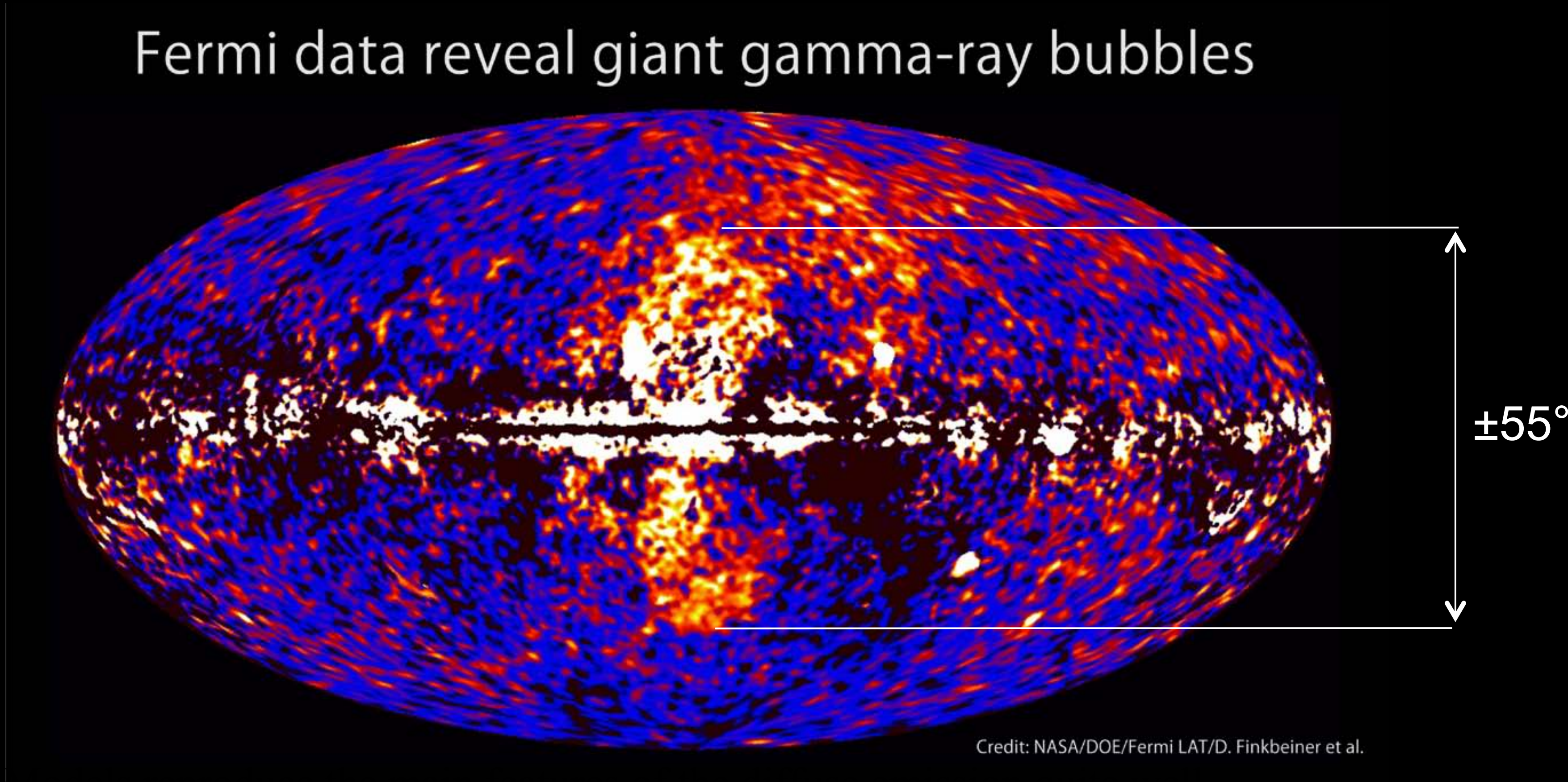


- ✧ *pp −> π⁰(2γ)+X* − neutral pion production and decay
- ✧ Inverse Compton scattering
- ✧ Bremsstrahlung
- ✧ Curvature (or synchrotron) radiation

CRs in the interstellar medium

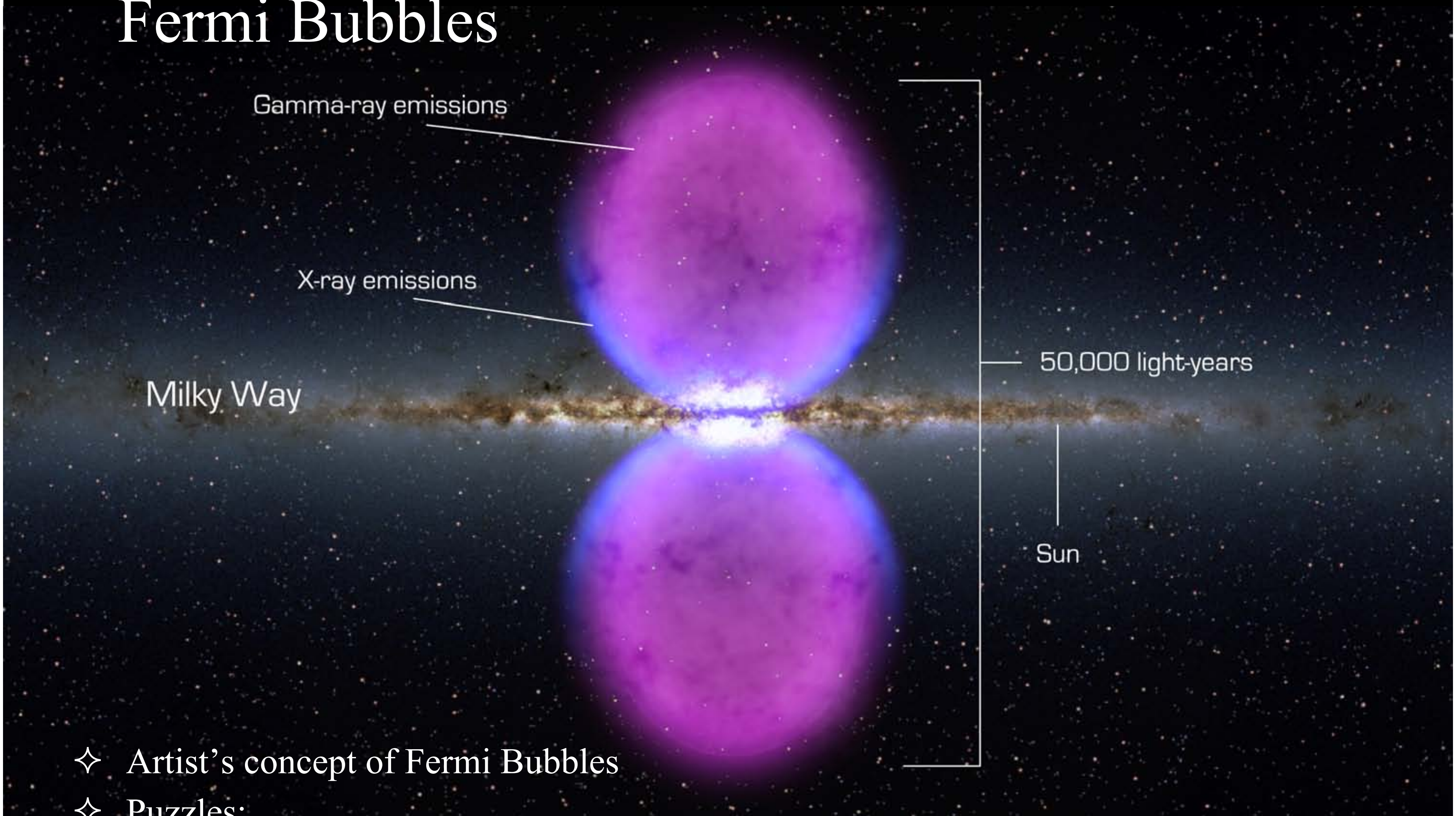


NASA press release



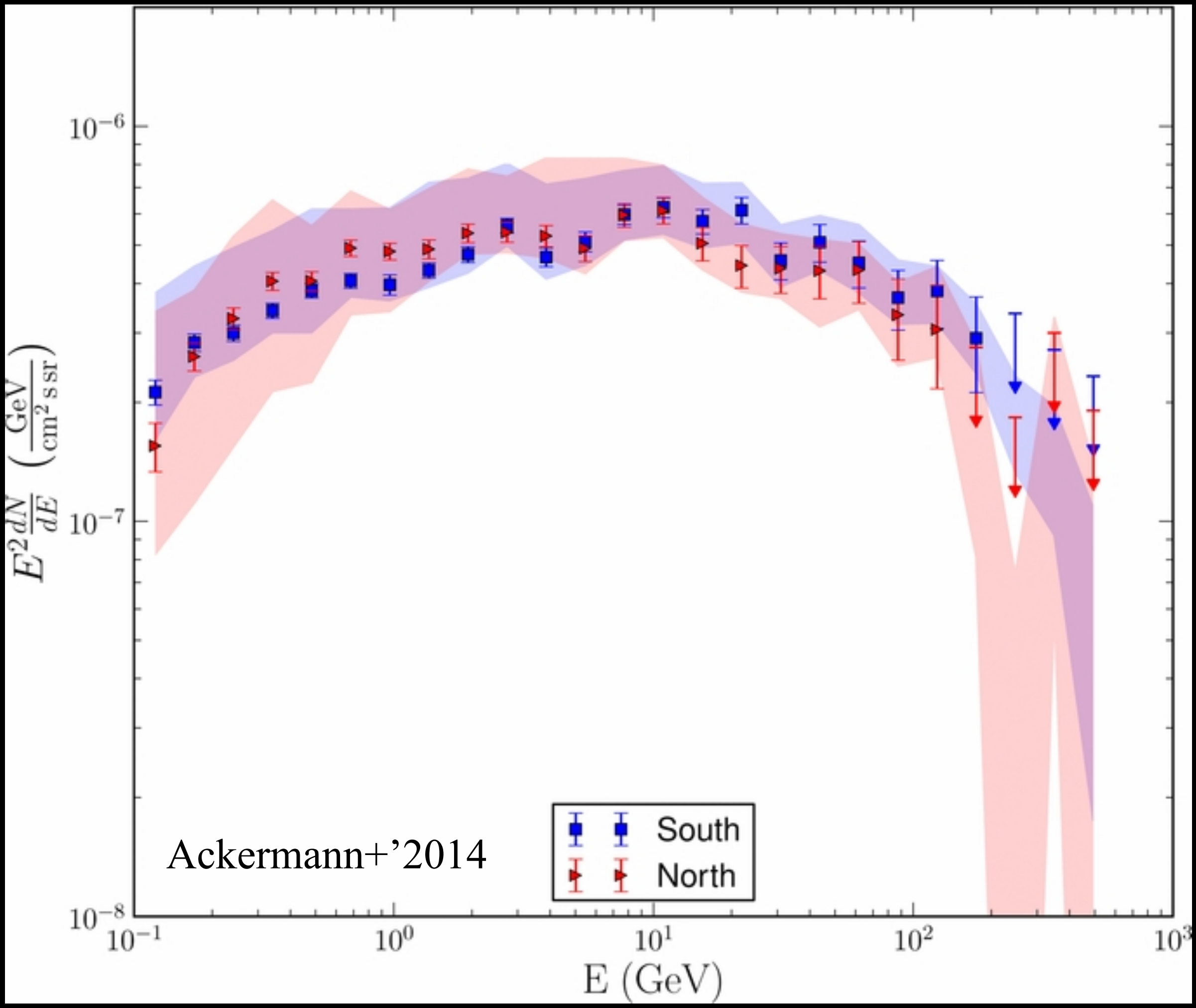
- Discrepancies between the physical model and high-resolution data (residuals) are the gold mines of new phenomena!

Fermi Bubbles



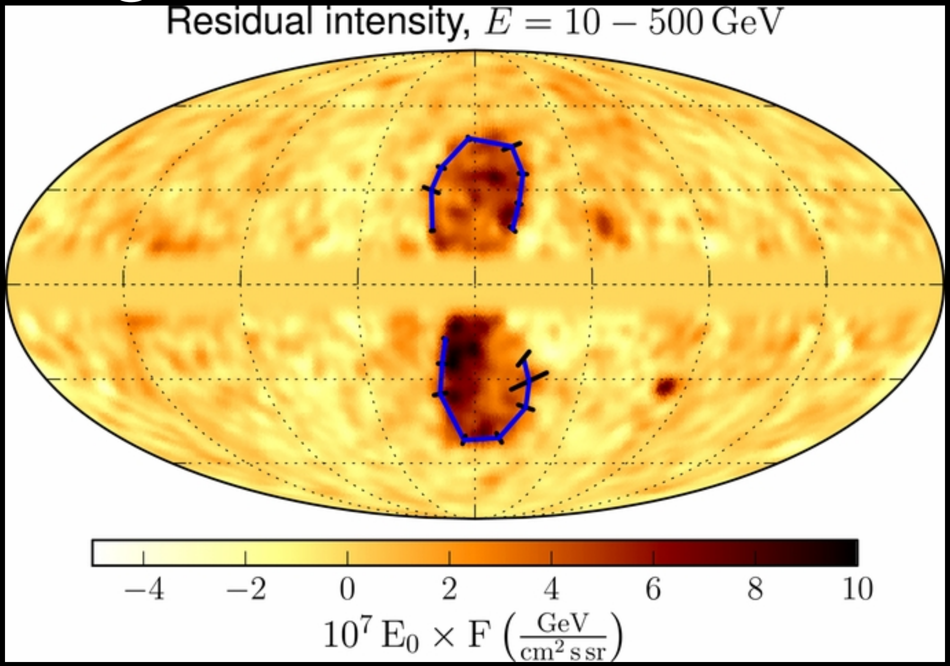
- ✧ Artist's concept of Fermi Bubbles
- ✧ Puzzles:
  - ✧ The spectrum is "flat" (ongoing acceleration!)
  - ✧ The spectrum is uniform over these huge structures! (what is the mechanism?)

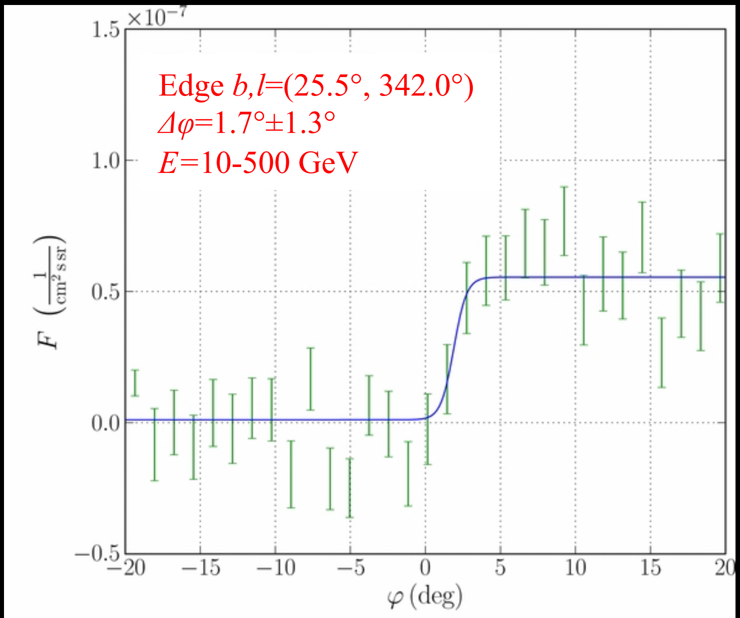
Spectrum of the Bubbles

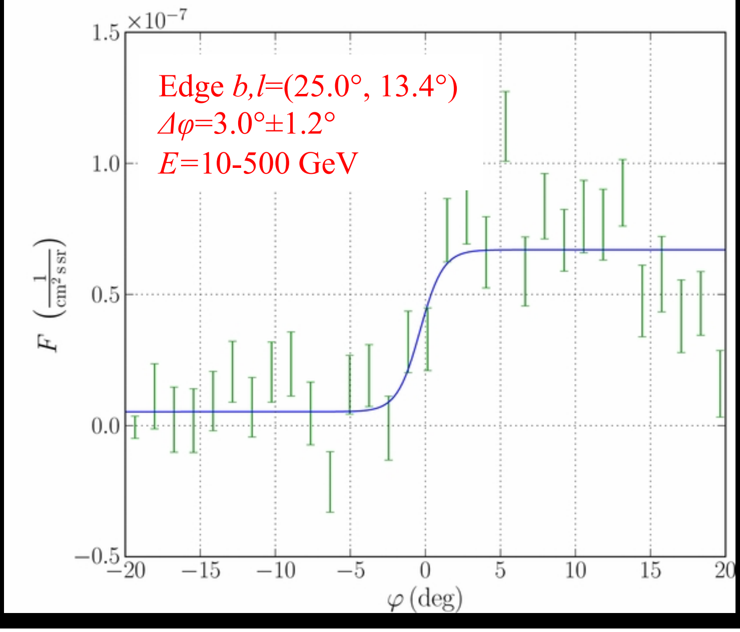


- The North and South lobes have very similar spectra
- The spectrum is very flat which testifies that the particle acceleration is ongoing
- Power-law with an exponential cutoff: index 1.9±0.2, cutoff energy 110±50 GeV

Edges: the width of the boundary

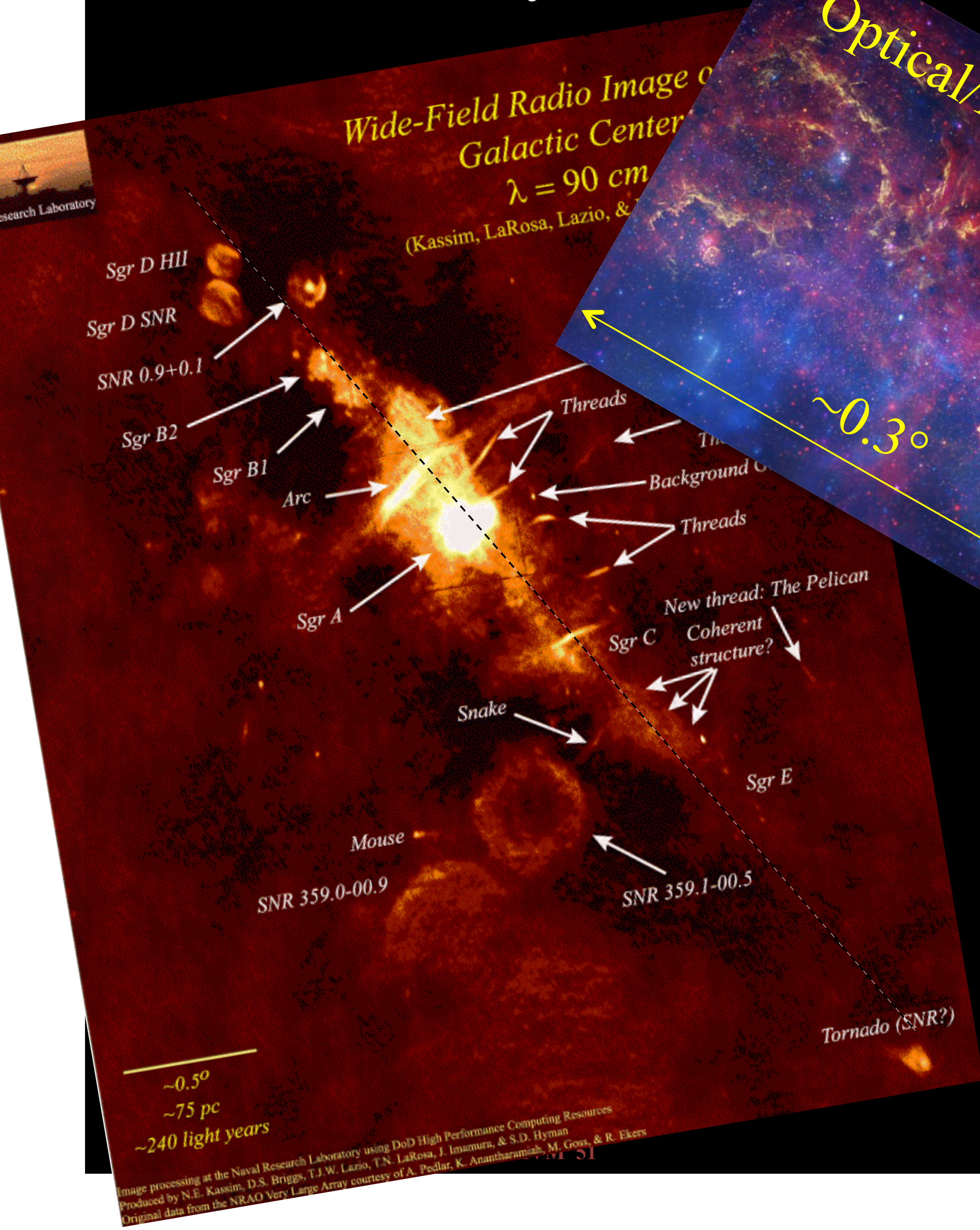


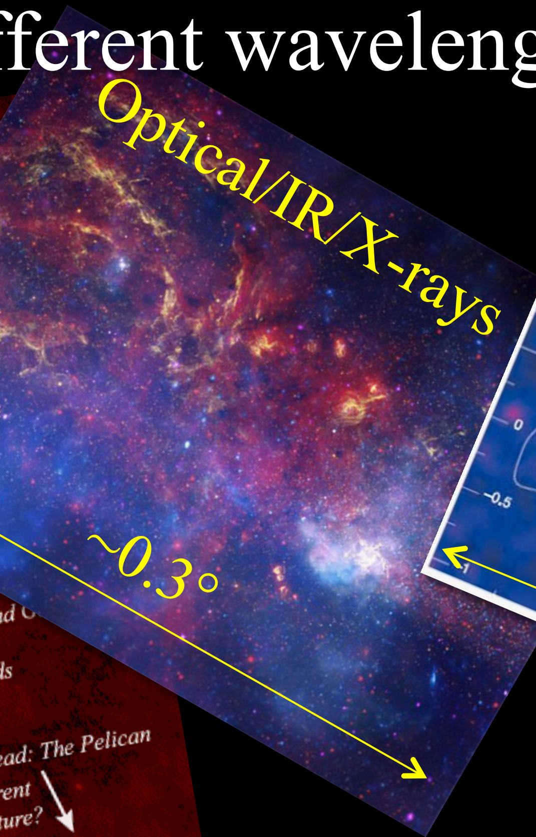


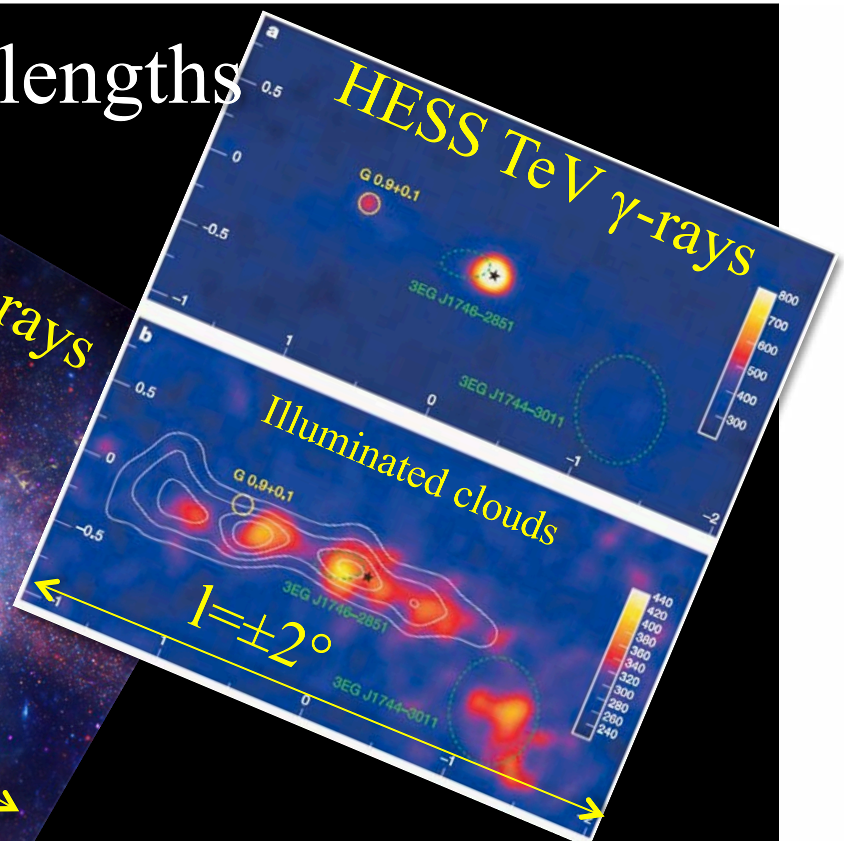


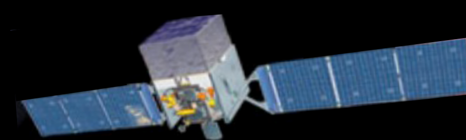
- Three energy ranges:
  - 1–3 GeV
  - 3–10 GeV
  - 10–500 GeV
- 68% PSF:
  - 0.5° at 1 GeV
  - 0.25° at 3 GeV
  - 0.12° at 10 GeV
- The edges of the Bubbles are well defined
- The width is <6°, about $3.4°_{-2.6}^{+3.7}$ in average

Inner Galaxy at different wavelengths









✧ Continuous collection of data by the Fermi-LAT significantly adds to the available multi-λ data

S. Murgia ICRC 2015 (LAT paper, 2016)

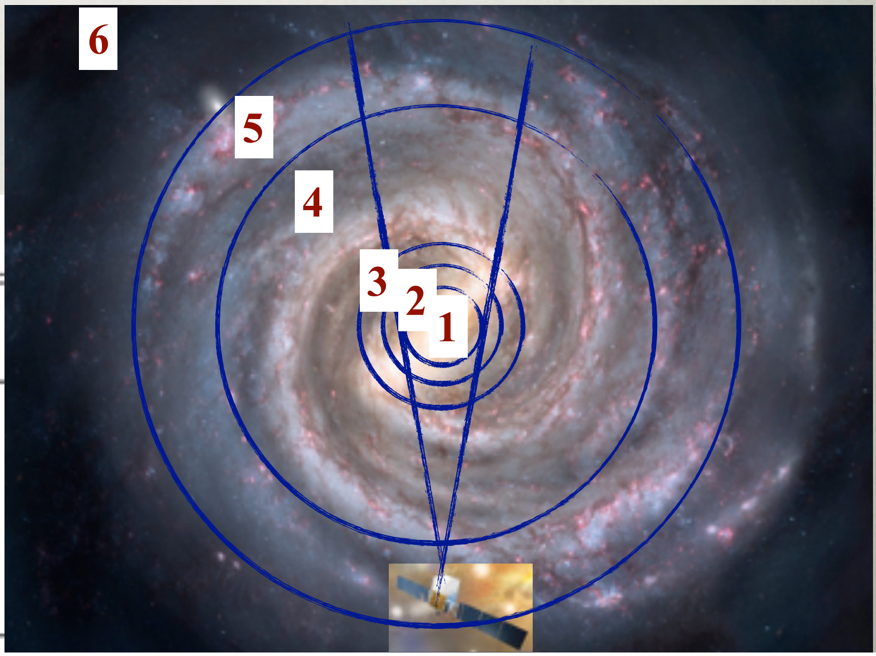
Fermi-LAT Study of the Inner Galaxy

Scaling Procedure

- Determine intensity for π^0 (from HI and H_2 gas) and IC contributions in galactocentric rings,
  - IC component divided in rings (dev. version of GALPROP), same boundaries as the gas: these additional degrees of freedom can compensate for uncertainties in the GALPROP model of the electron spectrum or ISRF used to calculate the IC templates
- Isotropic and Loop I (*Wolleben, 2007, ApJ 664*) emissions also fitted to the data
- Different sky regions are employed based on where the components that are fitted dominate. Point source locations and spectra taken from the preliminary 3FGL.

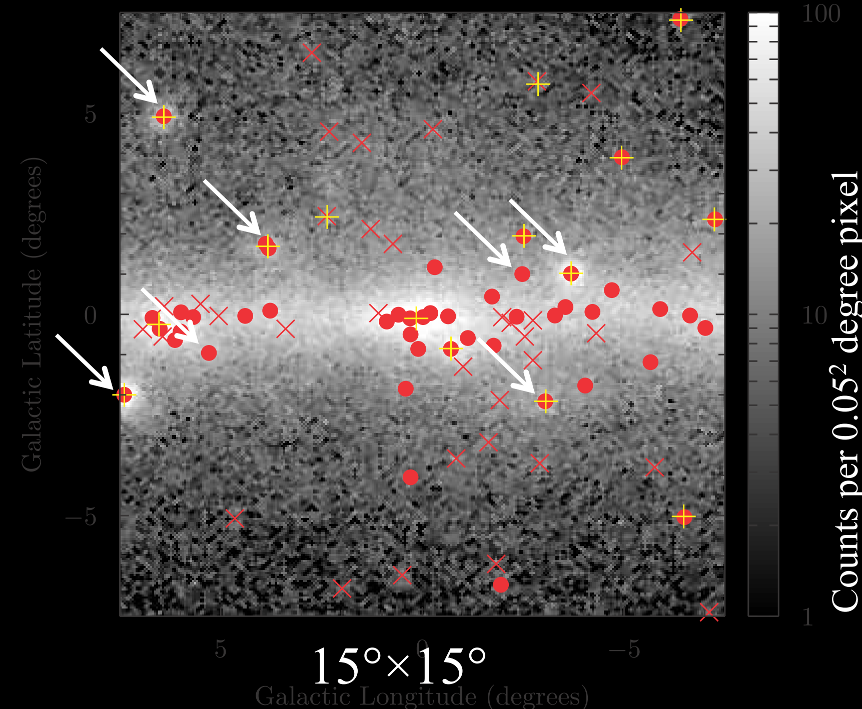
Galactocentric ring boundaries.

Ring #	$R_{\rm min}$ [kpc]	$R_{\rm max}$ [kpc]	Longitude Range (Full)
1	0	1.5	$-10° \leq l \leq 10°$
2	1.5	2.5	$-17° \leq l \leq 17°$
3	2.5	3.5	$-24° \leq l \leq 24°$
4	3.5	8.0	$-70° \leq l \leq 70°$
5	8.0	10.0	$-180 \leq l \leq 180°$
6	10.0	50.0	$-180 \leq l \leq 180°$

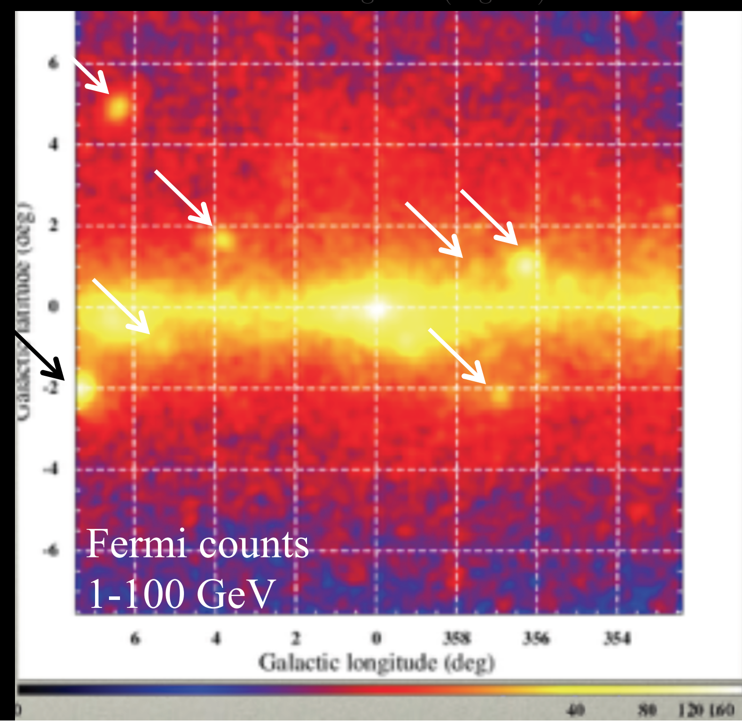


Sources in the inner Galaxy

- ✧ Fixing the background model allows the sources to be detected
- ✧ The sources' position and spectra depend on the background model
- ✧ Once the sources are detected, the background model is tuned again; the sources are readjusted with the new background model etc. in the loop
- ✧ The brightest sources (TS≥25) are not very much model-dependent



15°×15°



● – 1FIG sources TS≥25

× – 1FIG source candidates TS≤25

+ – 3FGL sources with multi-wavelengths associations

(1FIG = 1st Fermi Inner Galaxy Catalog)

ApJ 2016, in press

S. Murgia ICRC 2015

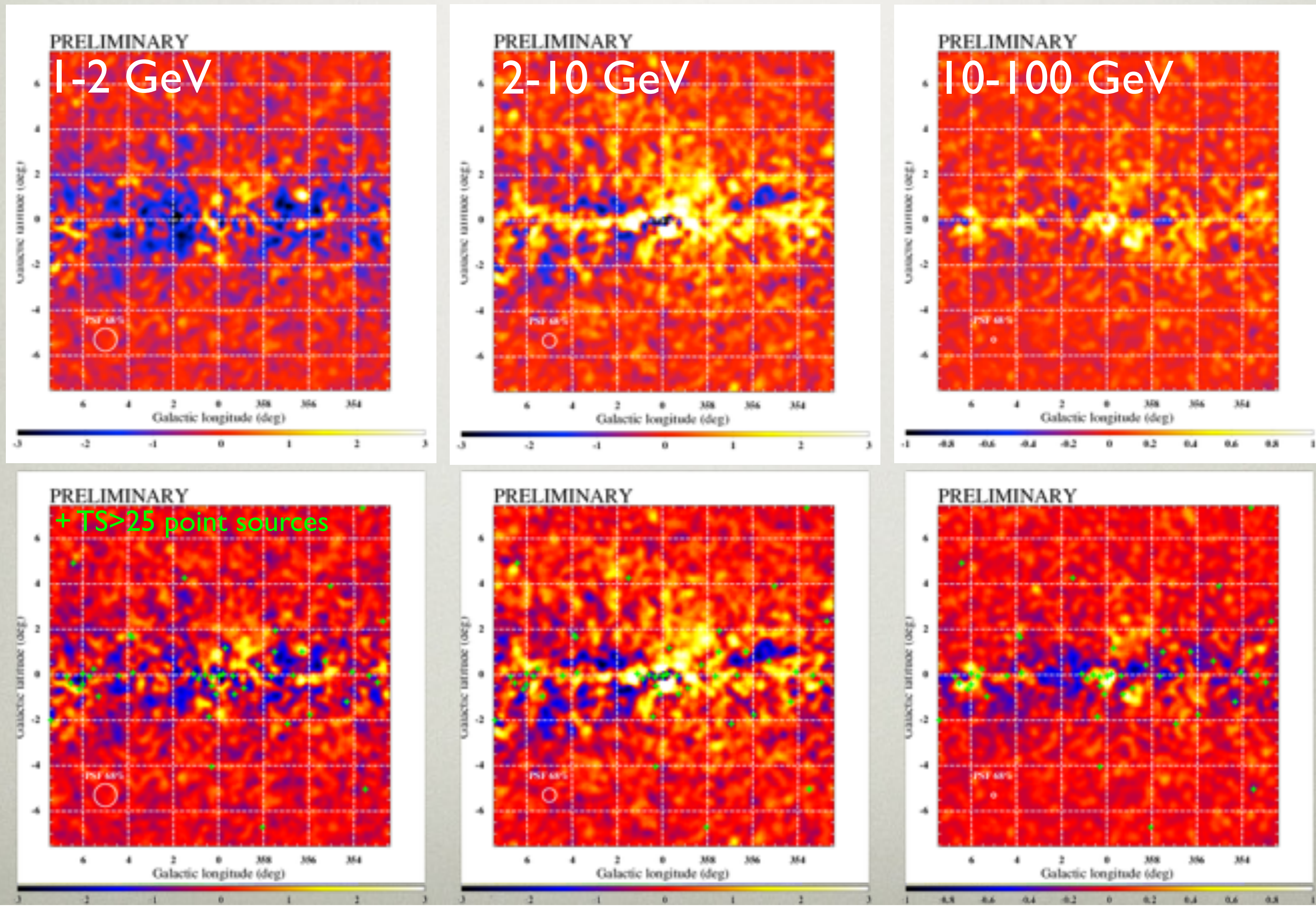
Point sources removed

RESULTS - RESIDUAL MAPS

DATA-MODEL

Pulsars, tuned-intensity

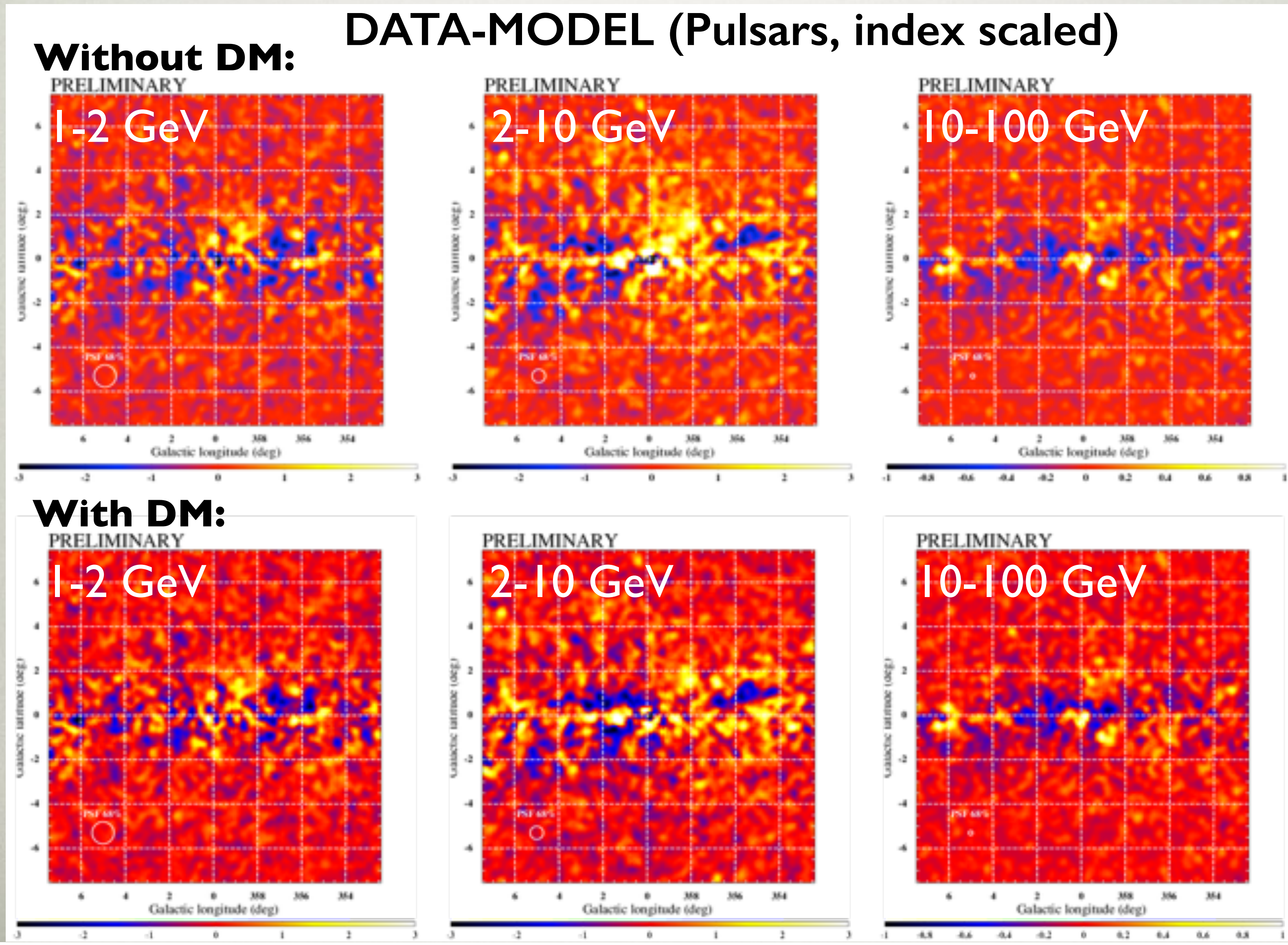
Pulsars, tuned-index



Counts in 0.1°x0.1° pixels, 0.3° radius gaussian smoothing

S. Murgia ICRC 2015

RESULTS - DARK MATTER

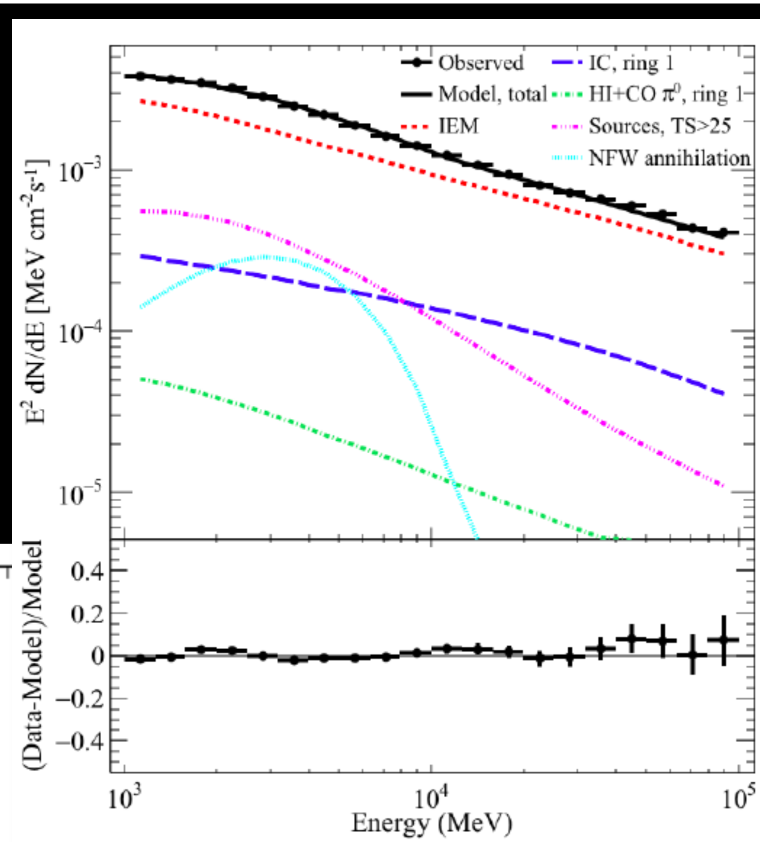


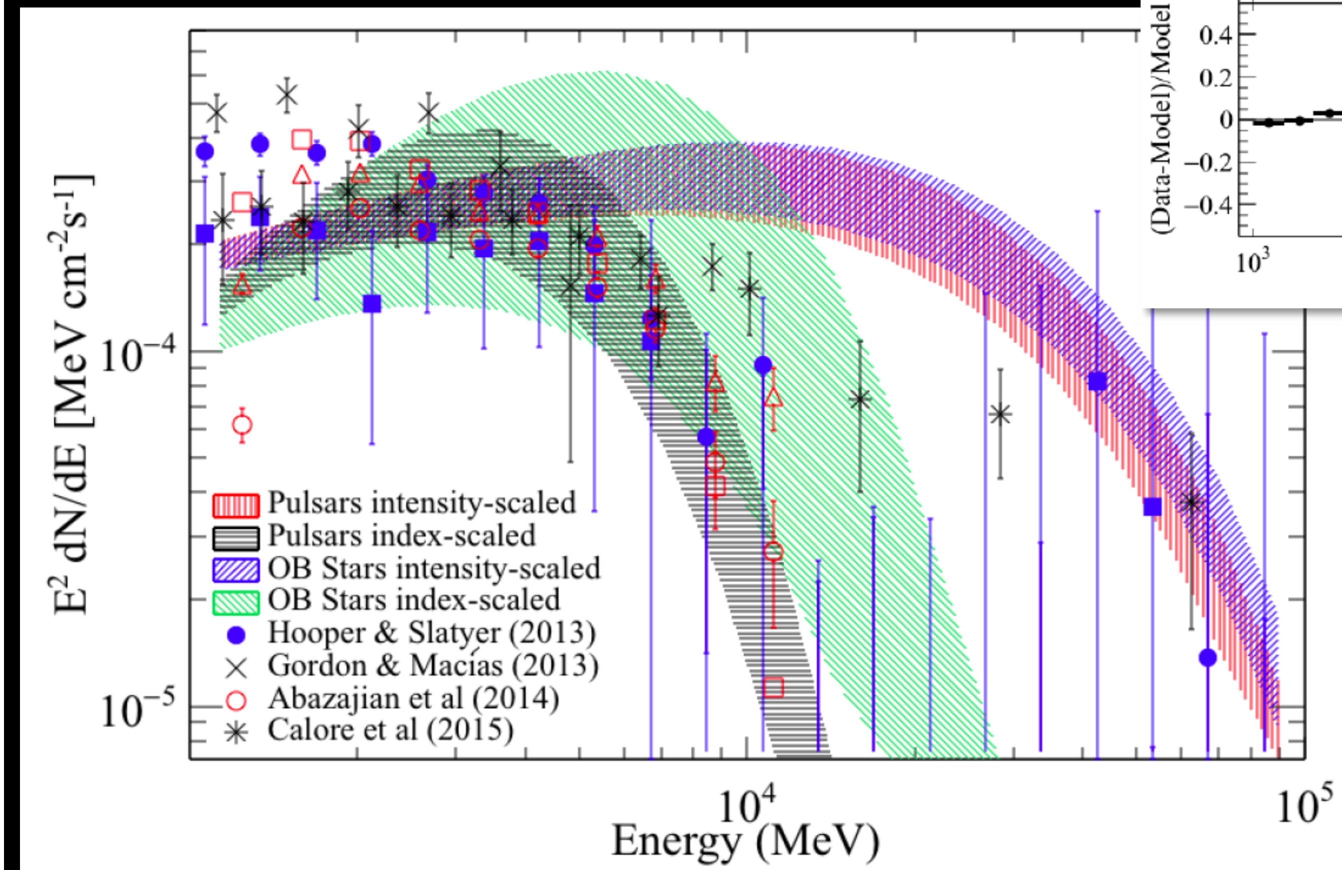
Counts in 0.1°x0.1° pixels, 0.3° radius gaussian smoothing

NFW component in different background models

✧ A peaked NFW profile

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

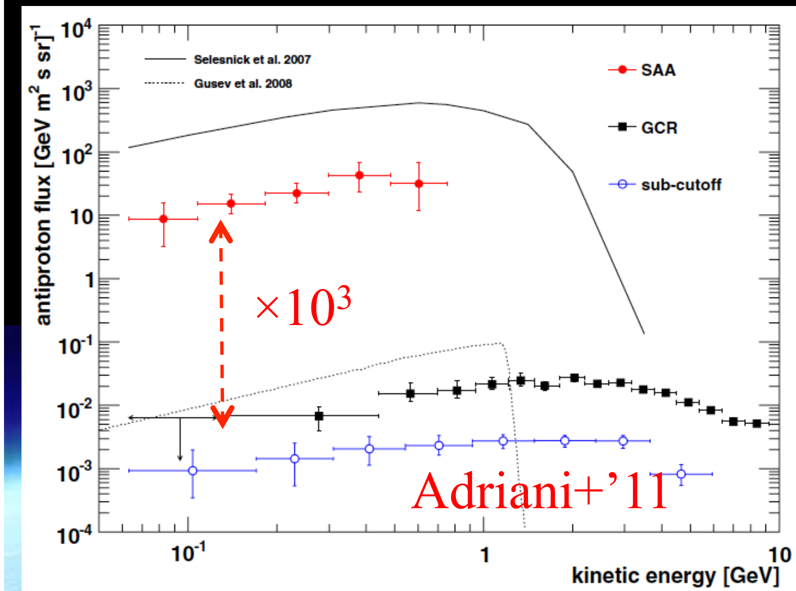




✧ Components of the emission observed in the inner 15°×15° (one of the models)

✧ Spectrum of the NFW component in different models

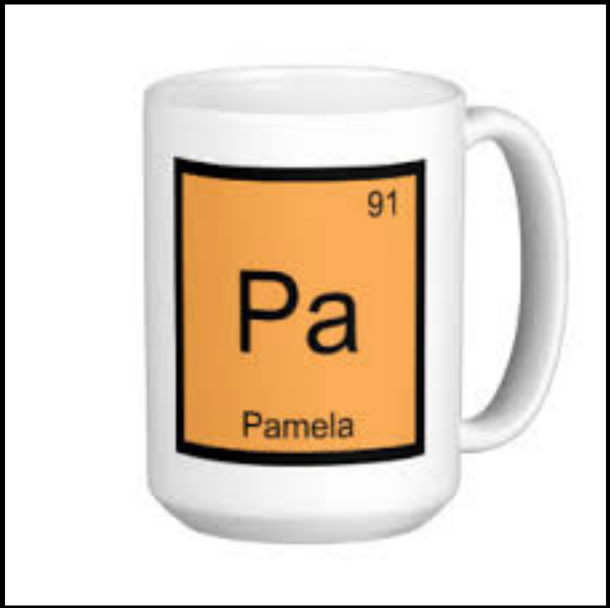
Near future: Antiproton fuel at the Earth orbit



The discovery of the huge number of pbars trapped in the geomagnetic field presents a unique opportunity for future space travel!

PAMELA's success is celebrated widely

- A widespread butterfly found in all Latin America countries was called "*Perrhybris PAMELA*" after PAMELA
- Renaming 91st element!



Perrhybris pamela

From Wikipedia, the free encyclopedia

PAMELA a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

The **Pamela**[1] (*Perrhybris pamela*) is a butterfly of the Pieridae family. It is found from Mexico, Honduras, Costa Rica and Panama, south to Colombia, Venezuela, Suriname, French Guiana, Brazil, Ecuador, Peru, and Bolivia. This species breeds in lowland rainforest at altitudes between sea level and about 900 metres.

Pieris malenka. Figs. 5 (male), 6 (female). Accepted as Perrhybris pamela (Stoll, 1780).

The wingspan is 66–70 mm (2.6–2.8 in). It is strongly sexually dichromatic, with the female resembling some species of Heliconiini.

Larvae have been recorded on *Capparis isthmensis* and *Capparis pittieri*.

Subspecies

- *Perrhybris pamela pamela* (Suriname)
- *Perrhybris pamela eleidias* (Brazil (Espírito Santo, São Paulo))
- *Perrhybris pamela malenka* (Venezuela)
- *Perrhybris pamela alethina* (Costa Rica, Panama)
- *Perrhybris pamela flava*
- *Perrhybris pamela bogotana* (Colombia)
- *Perrhybris pamela amazonica* (Peru)
- *Perrhybris pamela glessaria* (Ecuador)
- *Perrhybris pamela carmenta* (Peru, Bolivia)
- *Perrhybris pamela incisa* (Brazil (Bahia))
- *Perrhybris pamela lucasi* (French Guiana)
- *Perrhybris pamela fruhstorferi* (Panama)
- *Perrhybris pamela boyi* (Brazil (Amazonas))
- *Perrhybris pamela chajulensis* (Mexico, Honduras)
- *Perrhybris pamela mapa* (Mexico)
- *Perrhybris pamela bertha* (Peru)
- *Perrhybris pamela mazuka* (Peru)

There is also an undescribed subspecies from Costa Rica.

References

Pamela

Upperside of male

Underside of male

Scientific classification

Kingdom:	Animalia
Phylum:	Arthropoda
Class:	Insecta
Order:	Lepidoptera
Family:	Pieridae
Genus:	*Perrhybris*
Species:	***P. pamela***

Binomial name

Perrhybris pamela

In Place of a Conclusion

✧ Last decade the Cosmic Ray and Astrophysical communities were exposed to the overwhelming amount of new and accurate data and are expecting more to come!

✧ It will probably take some time to fully appreciate the significance of new information, but it is absolutely clear that we are currently witnessing dramatic breakthroughs in Astrophysics, Particle Physics, and Cosmology

✧Brilliant job! Congratulations, PAMELA!