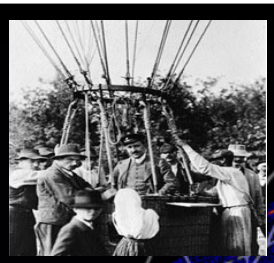
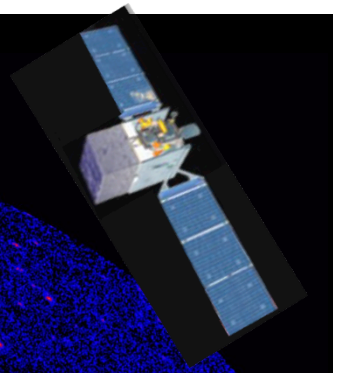


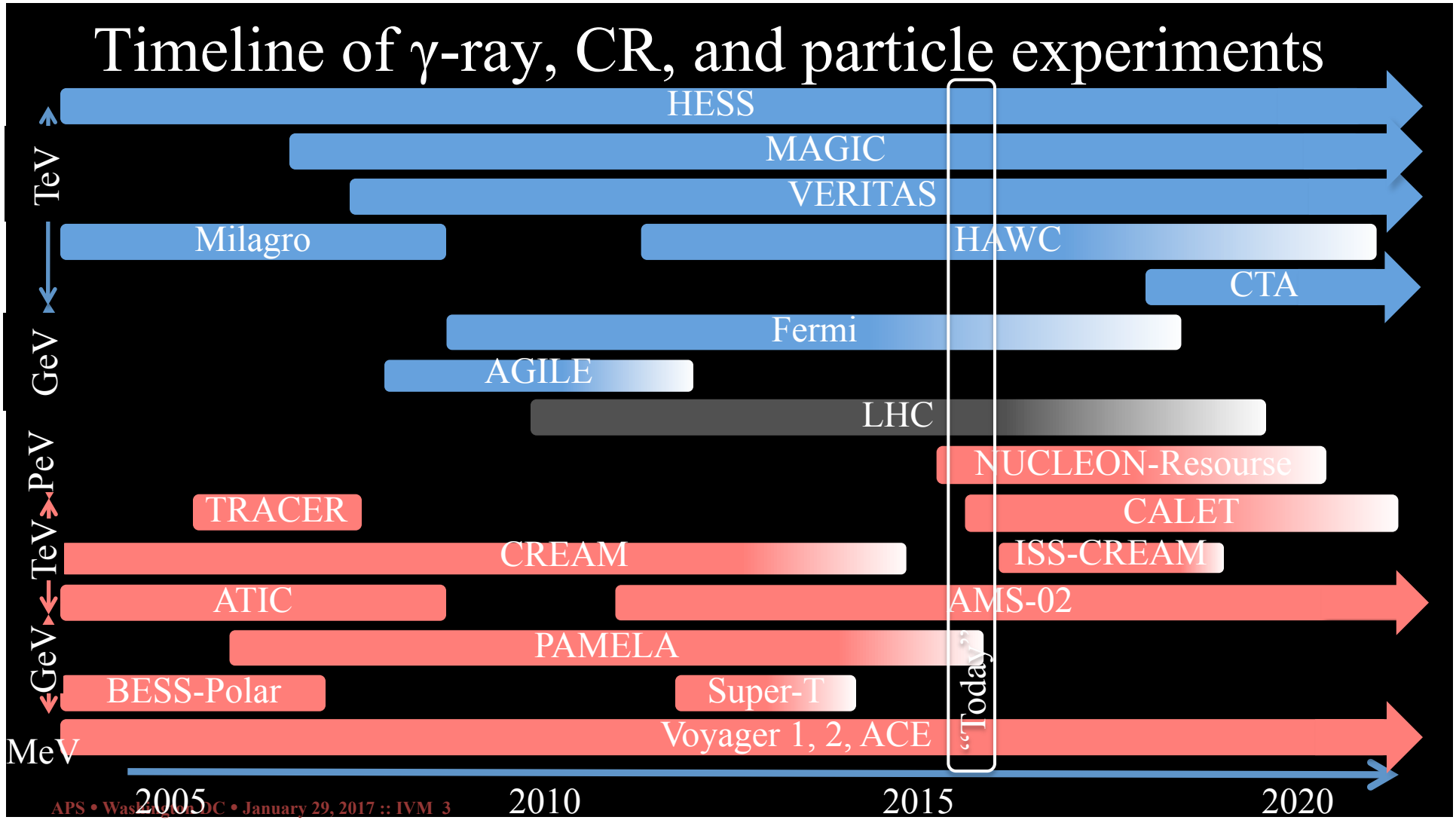


CURRENT STATUS OF ASTROPHYSICS OF COSMIC RAYS

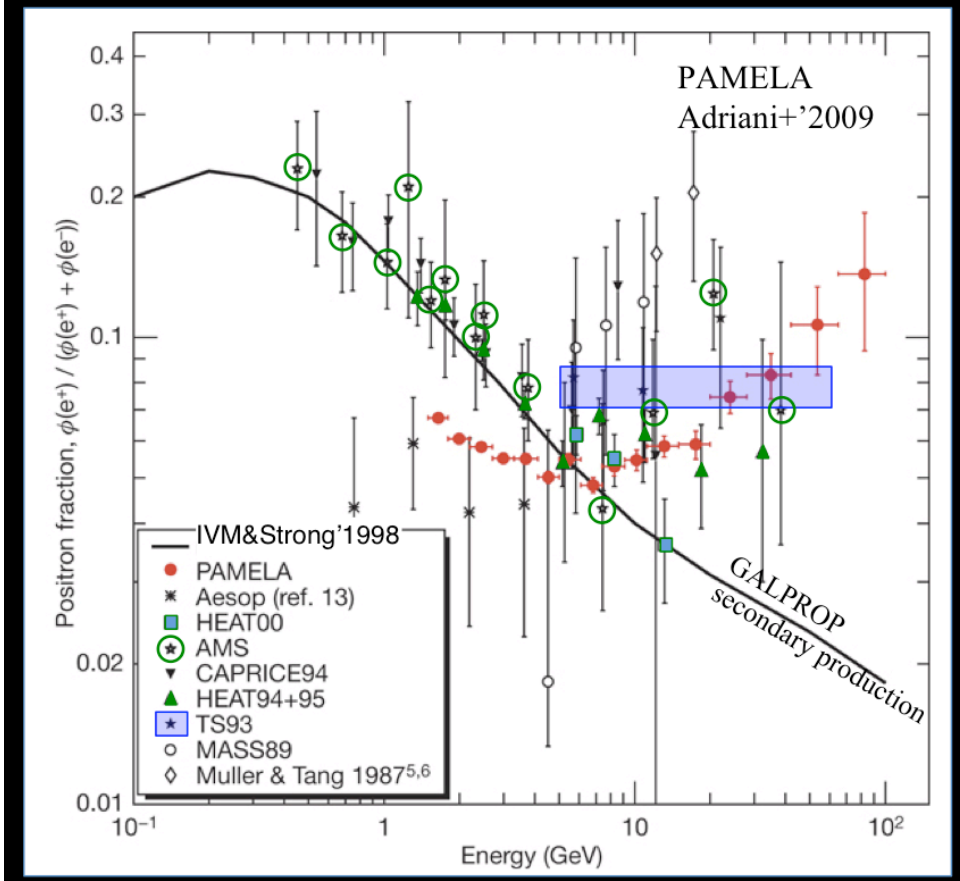
IGOR V MOSKALENKO – STANFORD

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

— Lord Kelvin, 1900

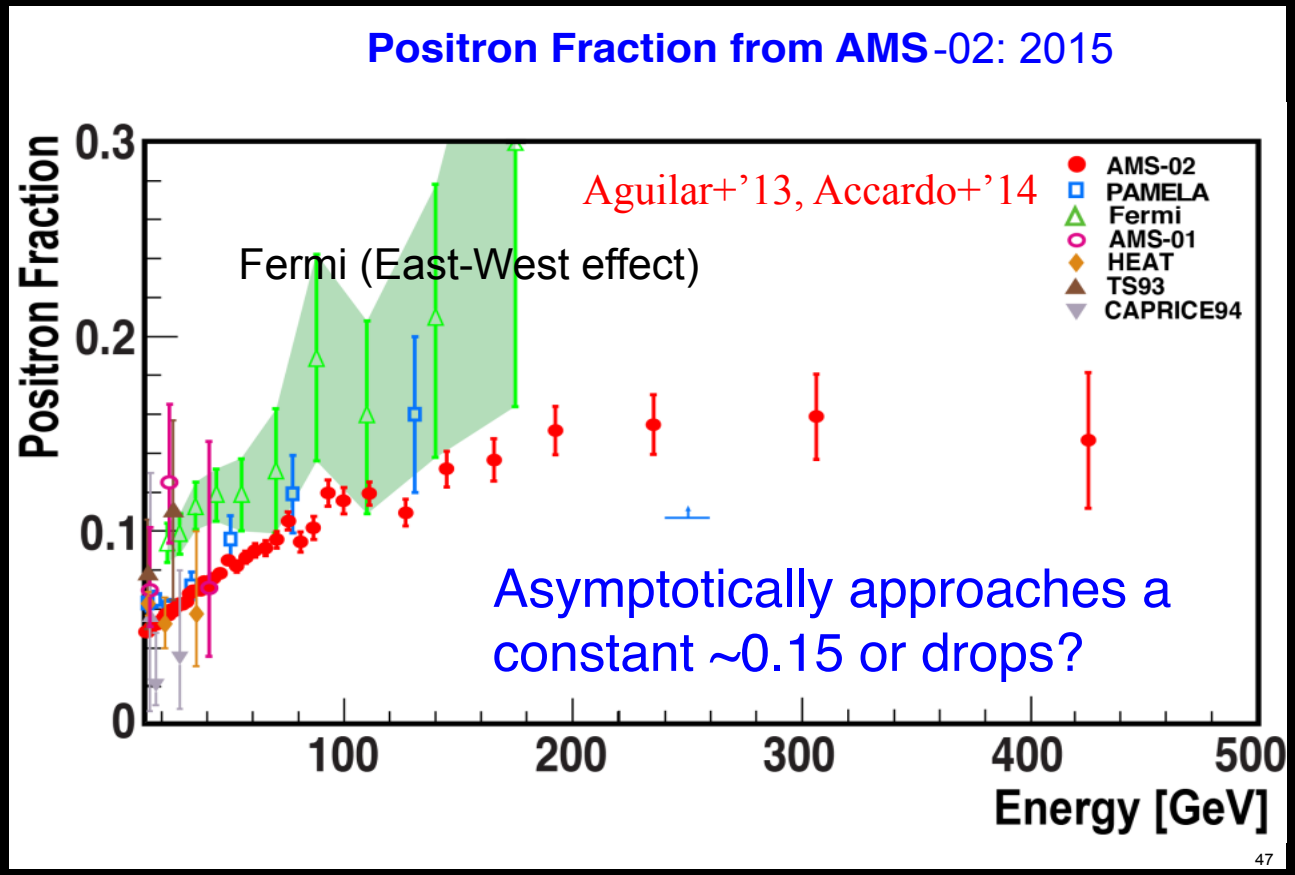

Timeline of γ-ray, CR, and particle experiments
HESS
MAGIC
VERITAS
Milagro
HAWC
CTA
Fermi
AGILE
LHC
NUCLEON-Resourse
TRACER
CALET
CREAM
ISS-CREAM
ATIC
AMS-02
PAMELA
BESS-Polar
Super-T
Voyager 1, 2, ACE
"Today"
TeV
GeV
PeV
TeV
GeV
MeV
2005
2010
2015
2020

PAMELA discovery: Rising positron fraction



- TS93 (Golden+'96): flat positron fraction 0.078±0.016 in the range 5-60 GeV (US)
- 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



- Confirmed and extended earlier PAMELA and Fermi-LAT measurements
- Keen to see the behavior >400 GeV!

The impact (NASA's ADS)

- *An anomalous positron abundance in cosmic rays with energies 1.5-100 GeV,* Nature 2009, 458, 607 (PAMELA) – 1600 citations
- *First Result from the Alpha Magnetic Spectrometer on the International Space Station: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5-350 GeV,* PRL 2013, 110, 141102 (AMS-02) – 470 citations
- *New Measurement of the Antiproton-to-Proton Flux Ratio up to 100 GeV in the Cosmic Radiation*, PRL 2009, 102, 051101 (PAMELA) – 470 citations
- *Measurement of the Cosmic Ray e^++e^- Spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope*, PRL 2009, 102, 18110 (Fermi-LAT) – 810 citations (cf. 1000 for 2FGL and 710 for 1FGL)
- *Measurement of Separate Cosmic-Ray Electron and Positron Spectra with the Fermi Large Area Telescope,* PRL 2012, 108, 011103 (Fermi-LAT) – 340 citations
- *PAMELA Results on the Cosmic-Ray Antiproton Flux from 60 MeV to 180 GeV in Kinetic Energy*, PRL 2010, 105, 121101 (PAMELA) – 380 citations
- *PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra,* Science 2011, 332, 69 (PAMELA) – 320 citations
- *Fermi-LAT Observations of the Diffuse γ-Ray Emission: Implications for Cosmic Rays and the Interstellar Medium*, ApJ 2012, 750, 3A (Fermi-LAT) – 270 citations

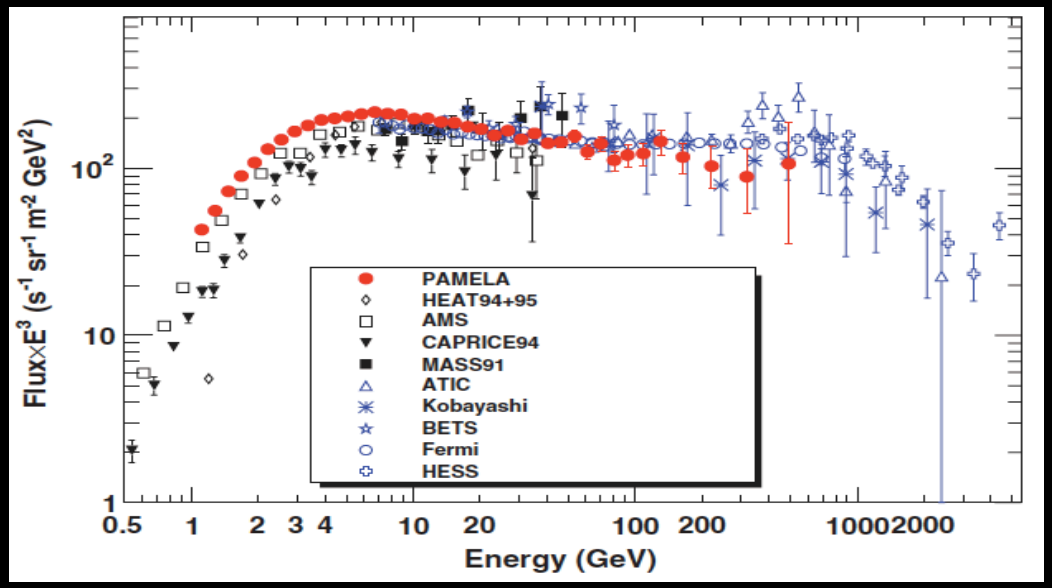
Other recent most remarkable results

- *Galactic Cosmic Rays in the Local Interstellar Medium: Voyager 1 Observations and Model Results*, ApJ 831 (2016) 18
- *Observation of the ^{60}Fe nucleosynthesis-clock isotope in galactic cosmic rays*, Science 352 (2016) 677
- *Precision Measurement of the Boron to Carbon Flux Ratio in Cosmic Rays from 1.9 GV to 2.6 TV with the Alpha Magnetic Spectrometer on the International Space Station*, PRL 2016, 117, 231102
- *Antiproton Flux, Antiproton-to-Proton Flux Ratio, and Properties of Elementary Particle Fluxes in Primary Cosmic Rays Measured with the Alpha Magnetic Spectrometer on the International Space Station,* PRL 2016, 117, 091103
- *Precision Measurement of the Helium Flux in Primary Cosmic Rays of Rigidities 1.9 GV to 3 TV with the Alpha Magnetic Spectrometer on the International Space Station,* PRL 2015, 115, 211101
- *Precision Measurement of the Proton Flux in Primary Cosmic Rays from Rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station,* PRL 2015, 114, 171103
- *Precision Measurement of the $(e^+ + e^-)$ Flux in Primary Cosmic Rays from 0.5 GeV to 1 TeV with the Alpha Magnetic Spectrometer on the International Space Station,* PRL 2014, 113, 221102
- *Electron and Positron Fluxes in Primary Cosmic Rays Measured with the Alpha Magnetic Spectrometer on the International Space Station,* PRL 2014, 113, 121102
- *High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5-500 GeV with the Alpha Magnetic Spectrometer on the International Space Station,* PRL 2013, 110, 141102

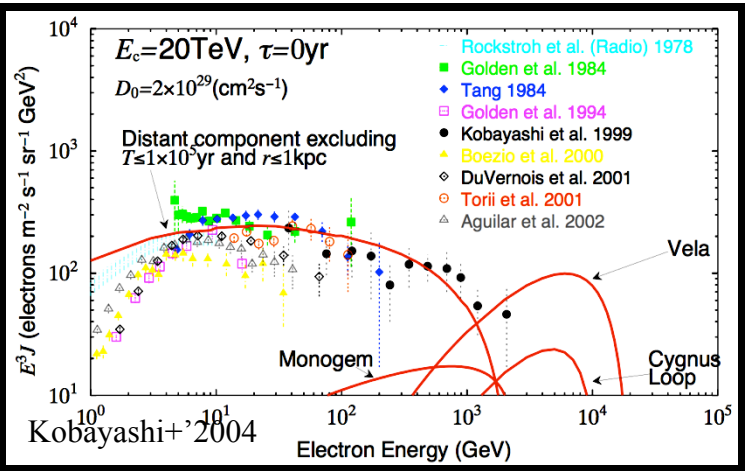
Positron anomaly: Astrophysical papers (~200)

- 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 papers >1300

All-electron spectrum

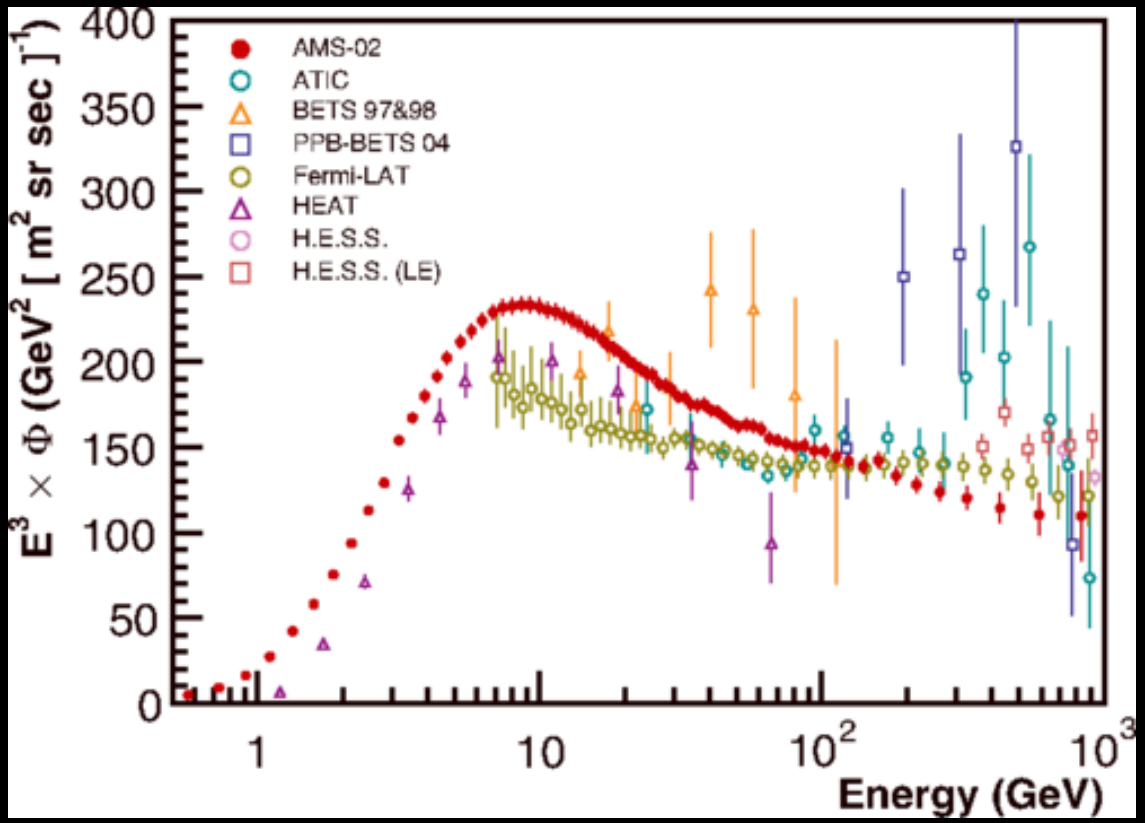


- Fermi-LAT and PAMELA data agree well
- Shows some structure
- Flatter than extrapolated from low energies
- Sharp cutoff at 1 TeV (HESS), as expected



- 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!

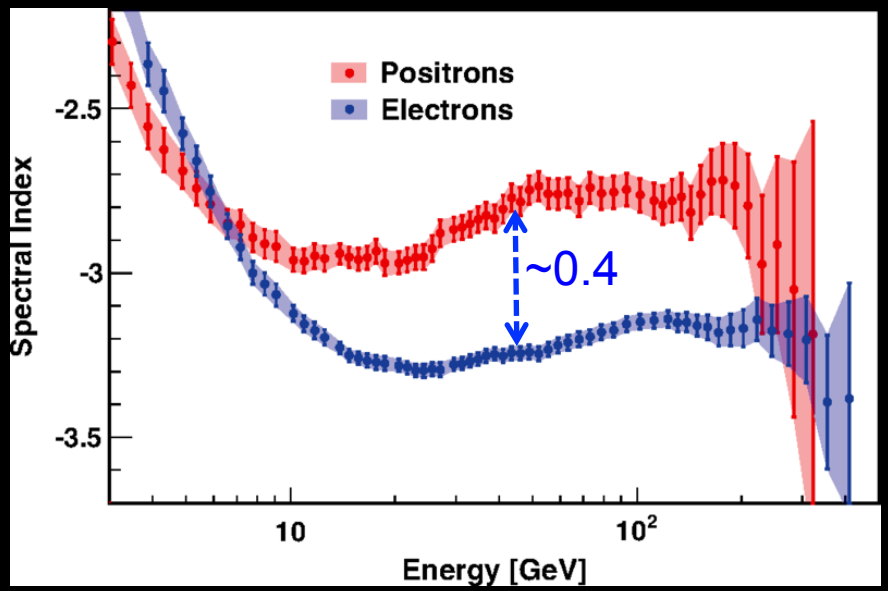
AMS-02 All Electron Spectrum

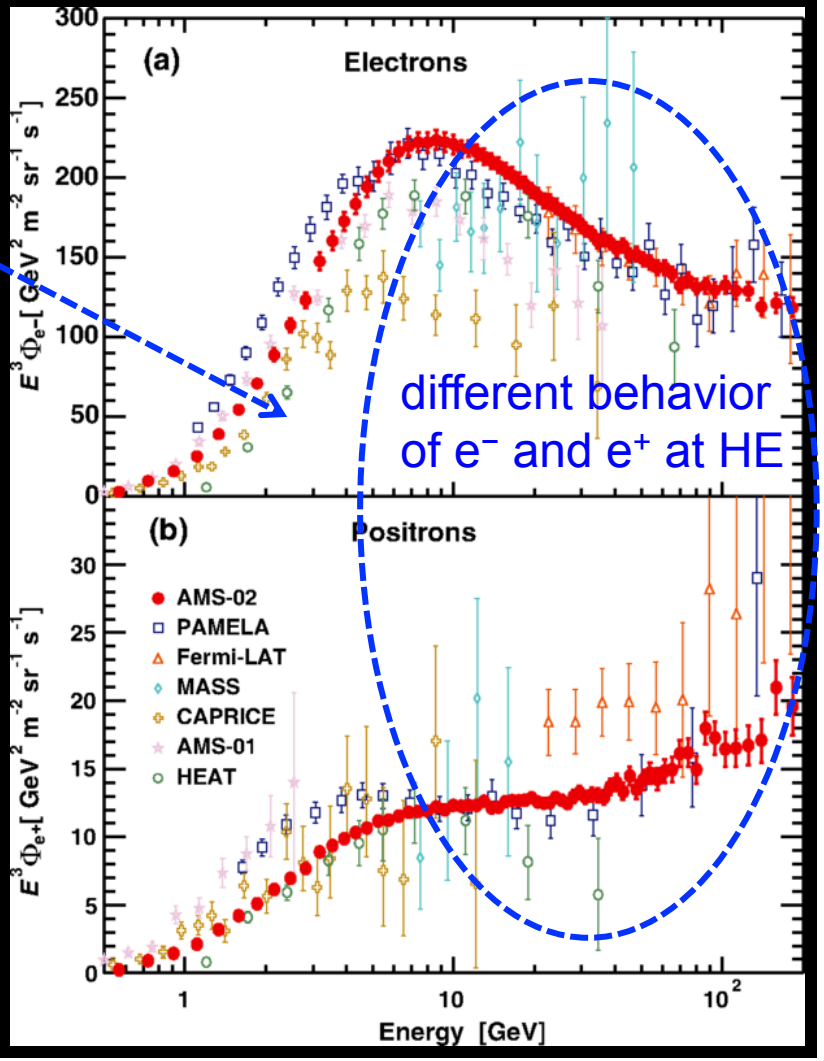


- A dedicated experiment AMS-02 has improved a measurement of the all-electron spectrum
- Still show a puzzlingly flat spectrum with no breaks from 10 GeV to ~1 TeV
- Note the linear scale in intensity!
- No effect of energy losses at HE or an additional (local) component?
- Local source of HE electrons?

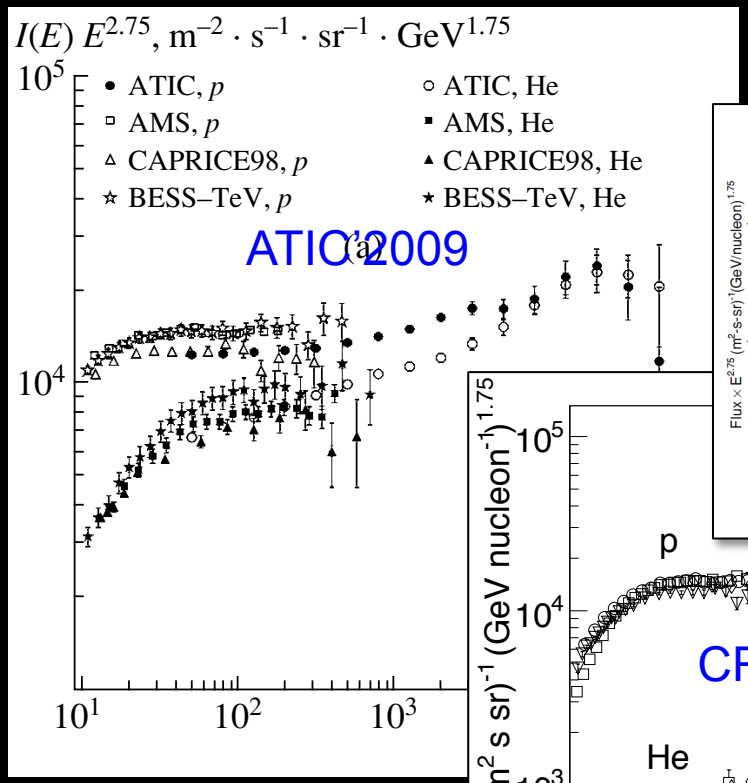
More on electrons and positrons

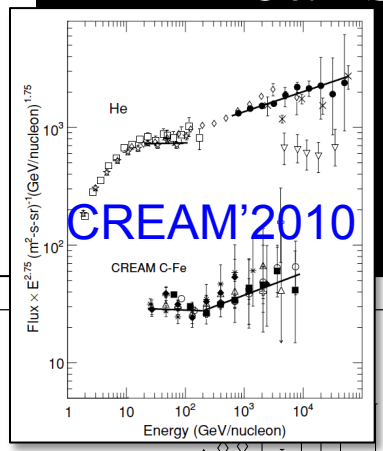
- Looks like the individual spectra of e^- and e^+ are disconnected
- But indices (different in absolute value!) behave similarly. Why?

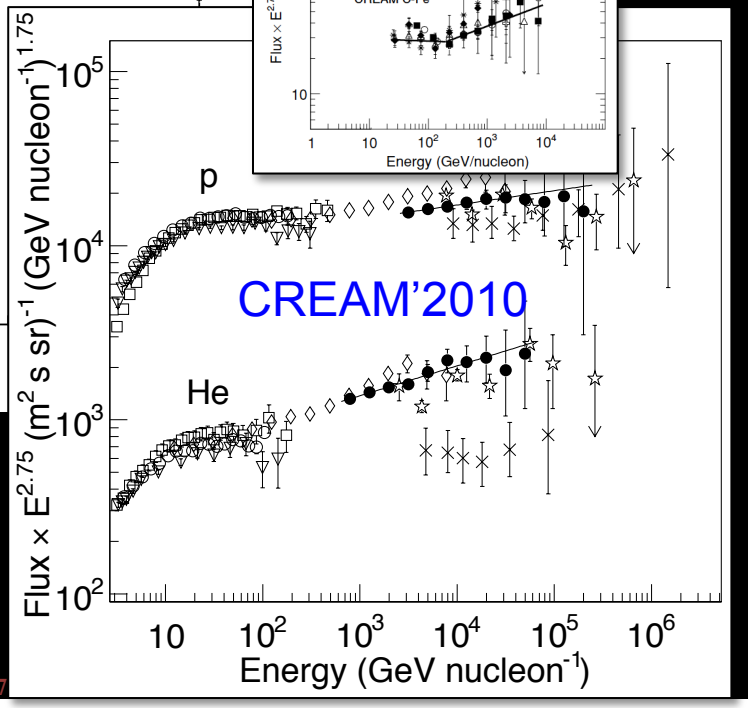




Breaks in p and He spectra

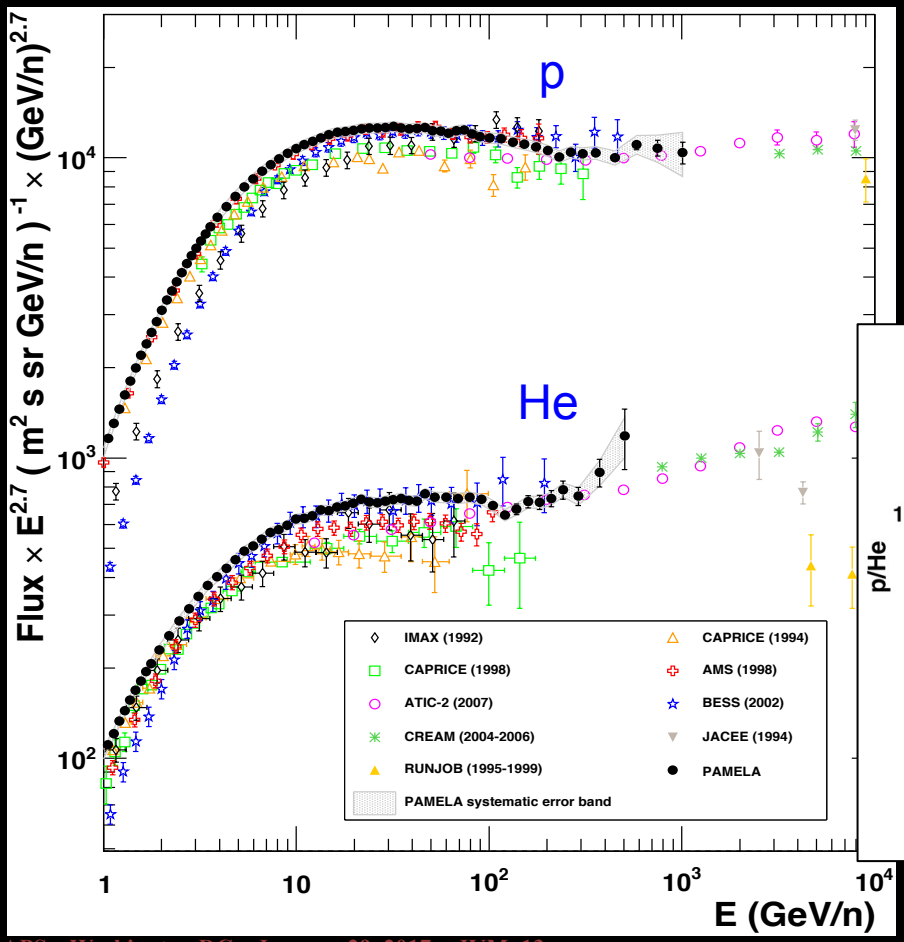




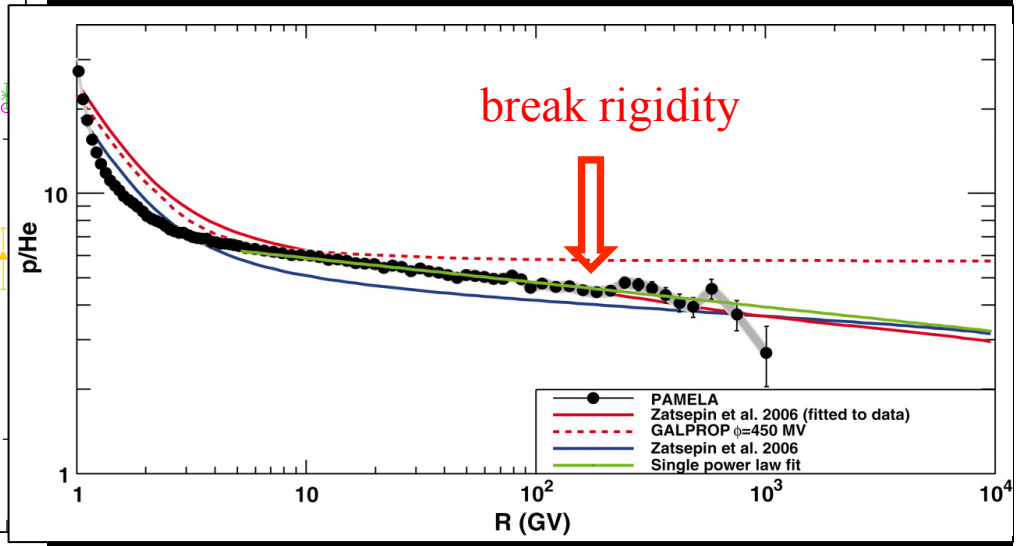


- First noticed in ATIC and CREAM data, hints were present in earlier data
- Spectrum of He is flatter than spectrum of protons
- Perhaps similar breaks exist in spectra of heavier nuclei

PAMELA: first definitive evidence of the breaks

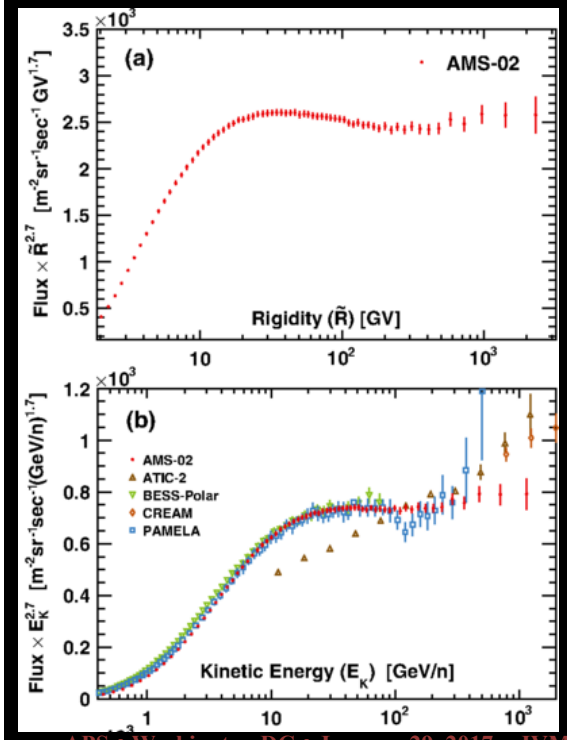


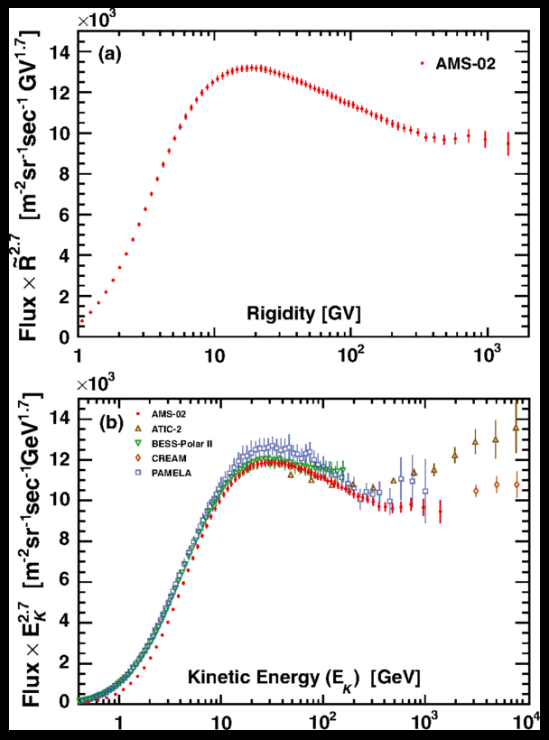
- Breaks are at the same rigidity pointing to the same origin of the breaks

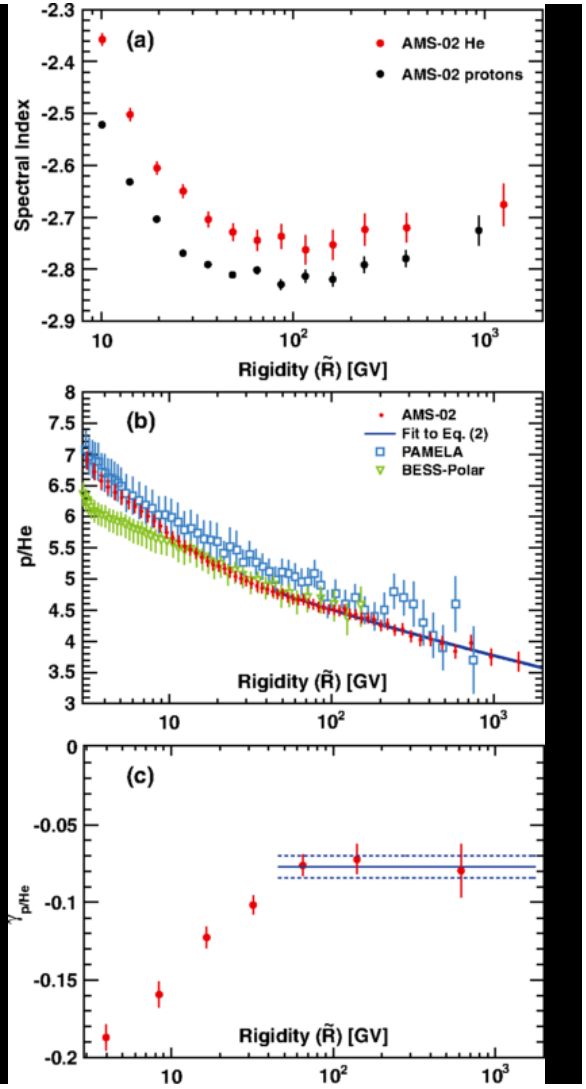


AMS-02 study of the break structure

- ✧ Breaks are smooth at the same rigidity
- ✧ p/He ratio shows no structure, why?
- ✧ Diff. in indices p, He: $\Delta\delta \sim 0.1$, why?

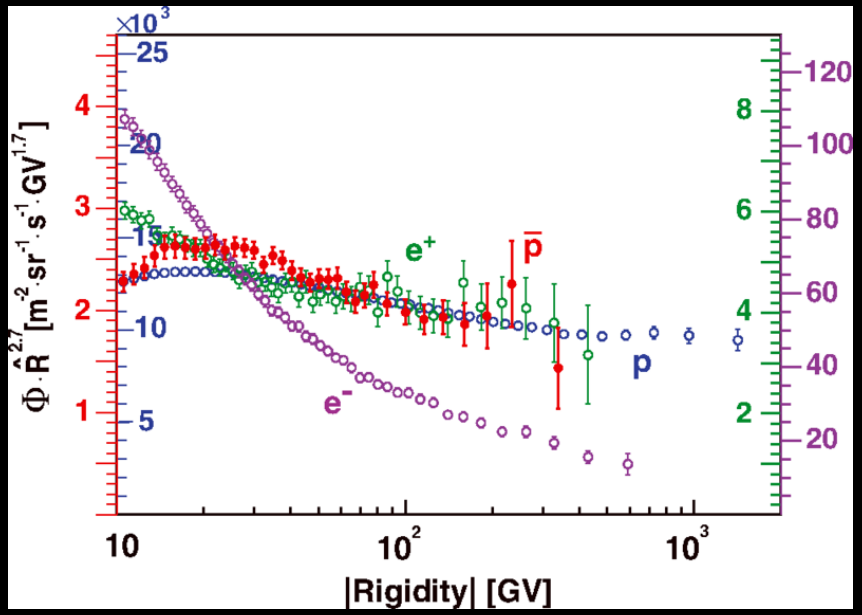




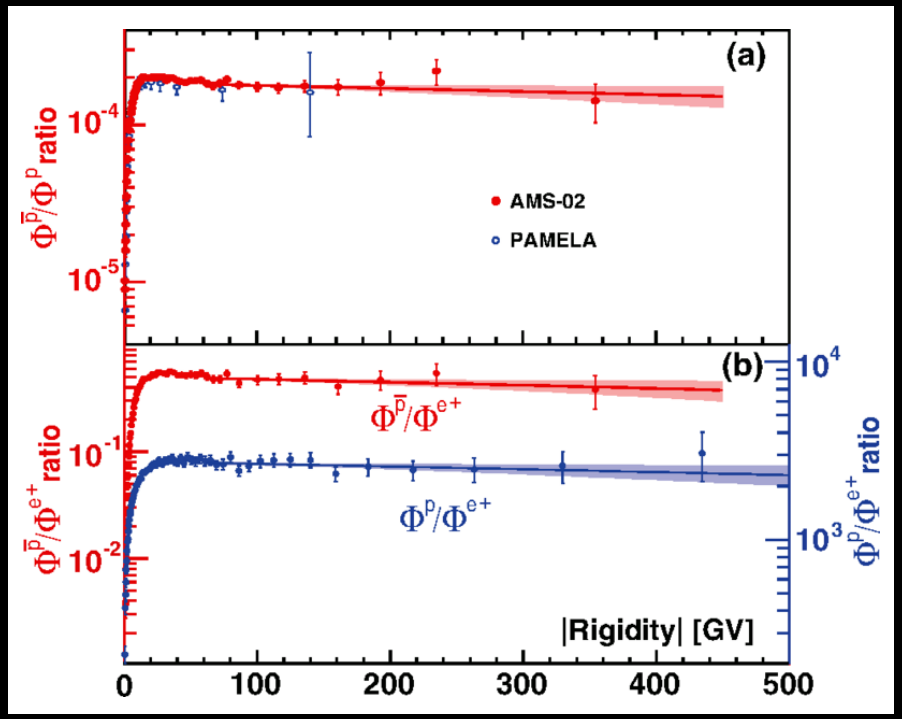


Most puzzling!

- If excess positrons are produced in pulsars or DM why the p/e$^+$ ratio is flat?
- Is there a break in the p/e$^+$ ratio (and e$^+$)?

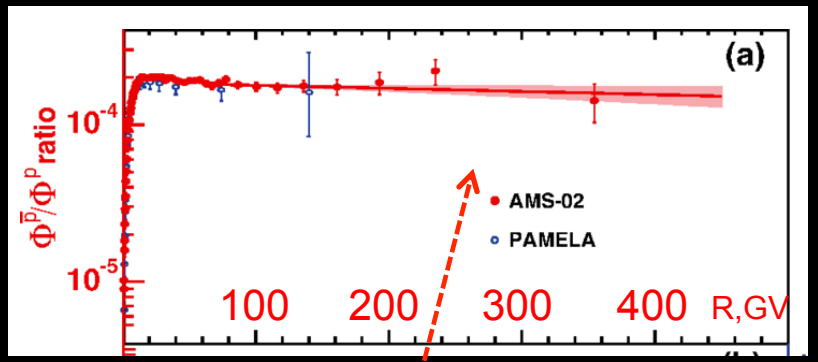


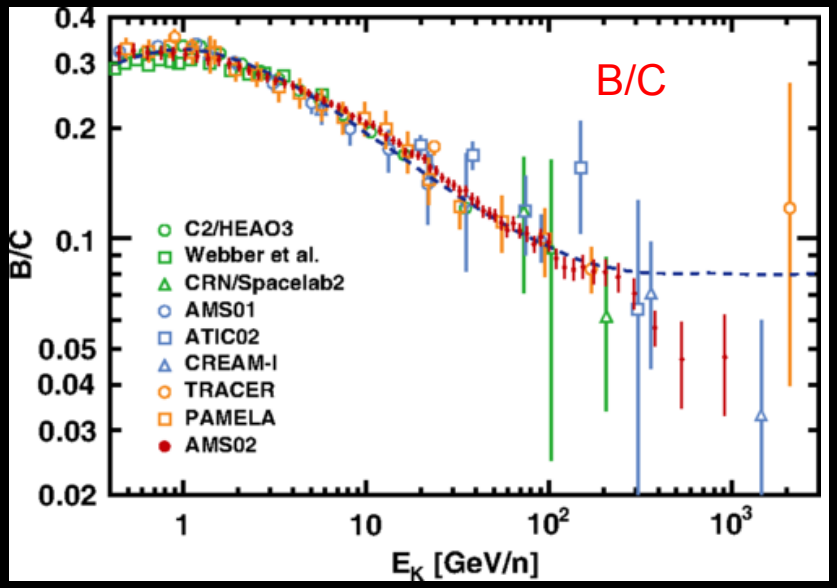
- The flat ratios of pbar/p, p/e$^+$, and pbar/e$^+$ indicate a common origin of p, pbar, e$^+$!

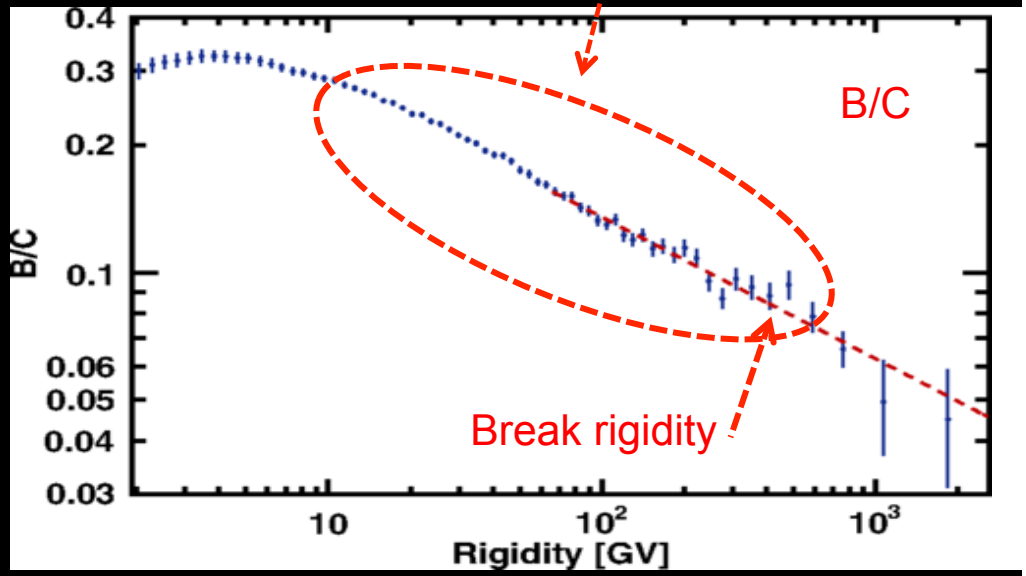


Yet more puzzling!

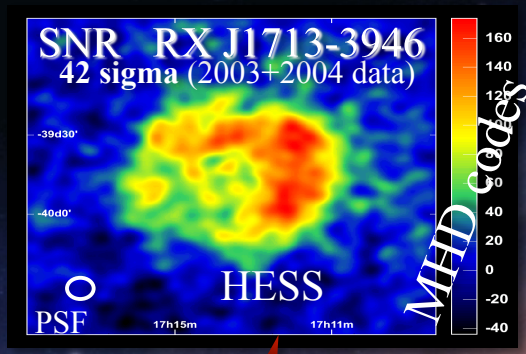
- Boron and pbars both are secondary, but why pbar/p is flat when B/C ratio is falling?
- Same break in Carbon and Boron spectra?
- "Standard picture" is wrong?

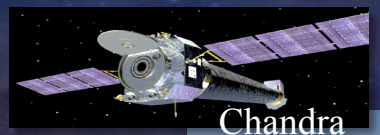


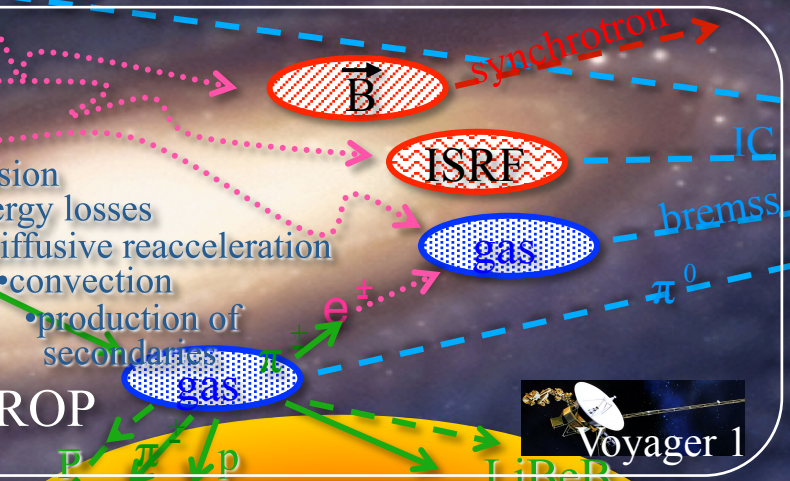


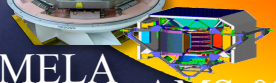


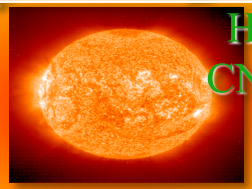
CRs in the interstellar medium

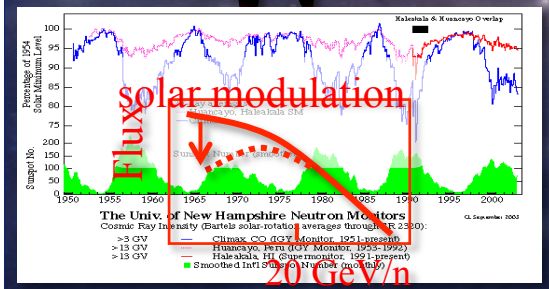












helio-modulation

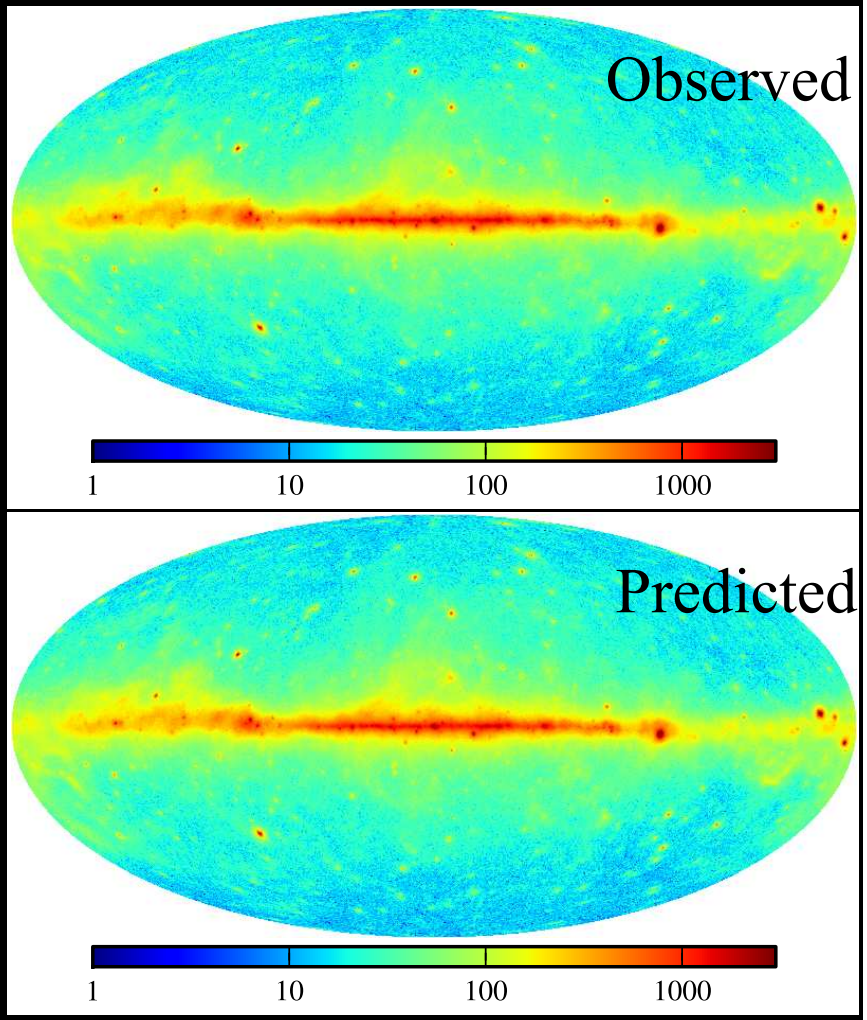
Gamma rays:
- Trace whole Galaxy
- Line of sight integration
- Only major species (p, He, e)

CR measurements:
- Detailed information on all species
- Only one location
- Solar modulation

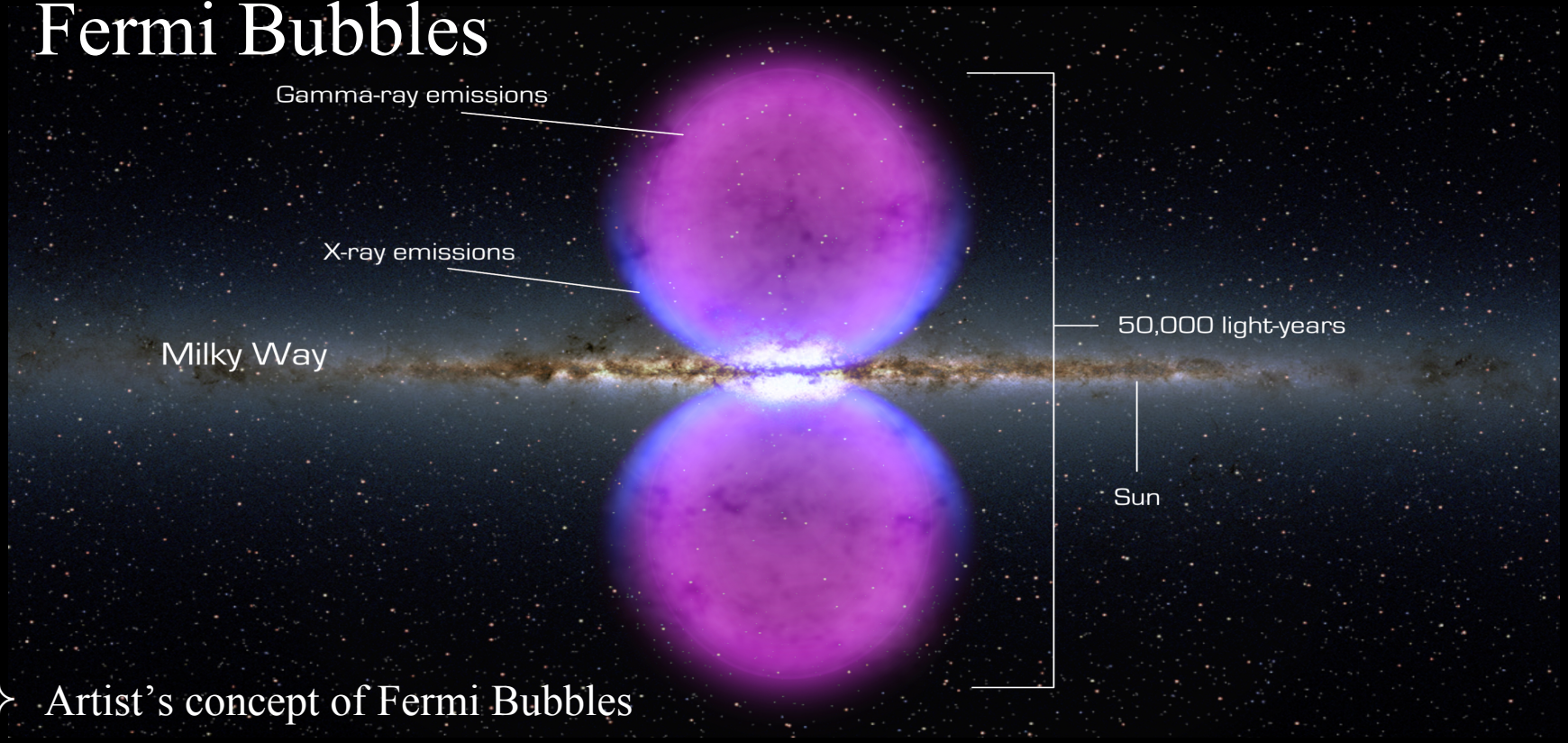
Modeling is a must!

And yet even more puzzling!

- ✧ Observed Fermi-LAT counts in the energy range 200 MeV to 100 GeV
- ✧ Gamma rays are tracing the whole Galaxy!
- ✧ Predictions are made on the basis of conventional propagation model (GALPROP reacceleration model tuned to local CR observations)
- ✧ Remarkable agreement: residuals (Obs-Pred)/Obs ~ % level, ~10% in some places
- ✧ So, the "standard picture" is correct?



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?)

What the heck does this all mean?

— An anonymous astrophysicist, ca. 2017

ACCURACY is now the next frontier!

- Last decade has clearly demonstrated that the ACCURACY is the key in discovering new phenomena in CR
- To understand what is going on, we have to extend the coverage of CR measurements beyond the current limits
- Increase statistics and energy resolution
- Some directions to extend:
  - P, He, Z>2 spectra >0.5 TeV/n
  - Isotopic spectra/abundances >0.5 GeV/n & esp. redioactives
  - Heavy nuclei Z>28 - all energies
  - Search for fine structure in $e^{\pm}$ spectra at all energies, and esp. >1 TeV
  - Antiproton measurements

Next steps?

- However, we do not have any new NASA's major mission
  - PAMELA was an Italian-Russian mission
  - AMS-02 is a DoE mission which primary goal is the dark matter
  - CALET is a Japanese mission
  - Voyager 1,2 were launched in 1977
  - ACE was launched in 1990's with a 5-year goal
  - FERMI is a gamma-ray mission (not cosmic ray)
  - ISS-CREAM is sitting on the ground since 2015
- The US cosmic ray community has a number of bright and crazy ideas on what to do and which missions to launch to address the current challenges
- Bright and crazy enough to make them successful!

Without a clear path to the next NASA mission the US cosmic ray community is losing a life-time opportunity to lead the discovery crew!