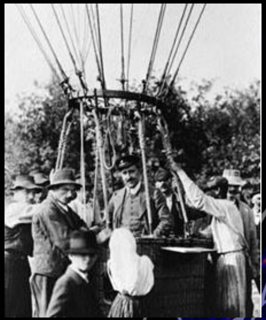
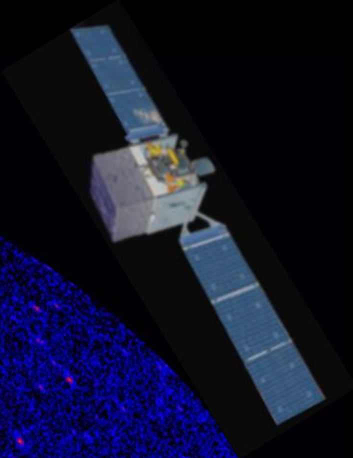




CURRENT STATUS OF ASTROPHYSICS OF COSMIC RAYS

IGOR V MOSKALENKO – STANFORD

One cannot embrace the
unembraceable – Kozma Prutkov

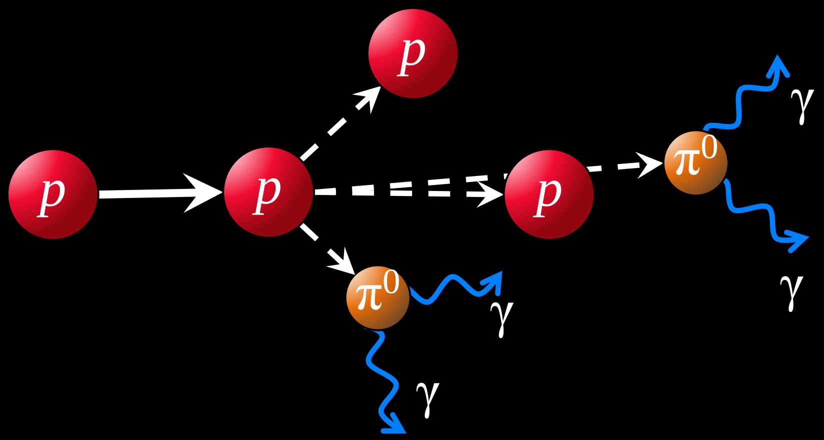
Subject of Astrophysics of Cosmic Rays

- Studies of the phenomenon of CRs, their sources and propagation in a broad sense, which includes:
  - Identification of the sources of the majority of CRs and of their particular species (minorities)
  - Identification and description of the mechanisms of acceleration of CRs in the sources and in the interstellar medium
  - Understanding the process of propagation of CRs from their sources to the observer and more generally in the Galaxy
  - Influence of CRs on the Galactic structure (star formation rate, halo size, Galactic wind driven by CRs)
  - Studies of the phenomenon of CRs in other normal galaxies
- Some of these studies are impossible without the γ-ray astronomy

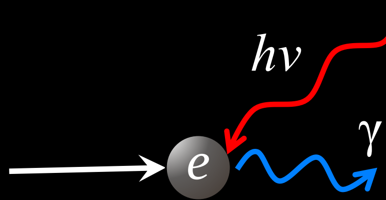
Our tools

- ✧ Direct measurements of CRs in space, inside of the heliosphere and in the interstellar medium
- ✧ Indirect measurements of CRs from the ground (extensive air showers)
- ✧ Indirect measurements of CRs through their emissions (synchrotron, γ-rays)
- ✧ Extensive modeling of CR acceleration and propagation (MHD codes, GALPROP, USINE)

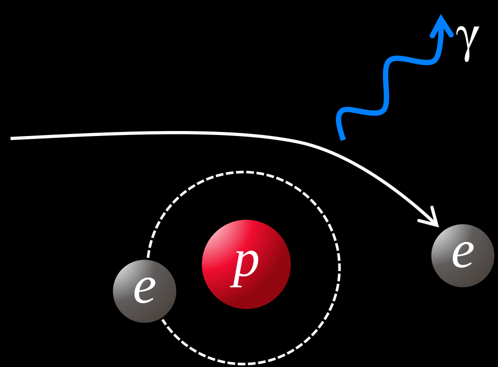
High energy gamma-ray emission processes



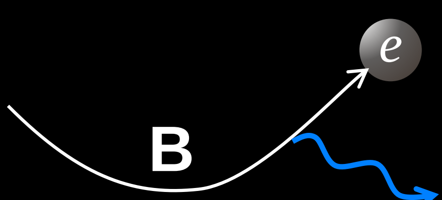
- ✧ $pp -> \pi^0(2\gamma)+X$ − neutral pion production and decay



- ✧ Inverse Compton scattering

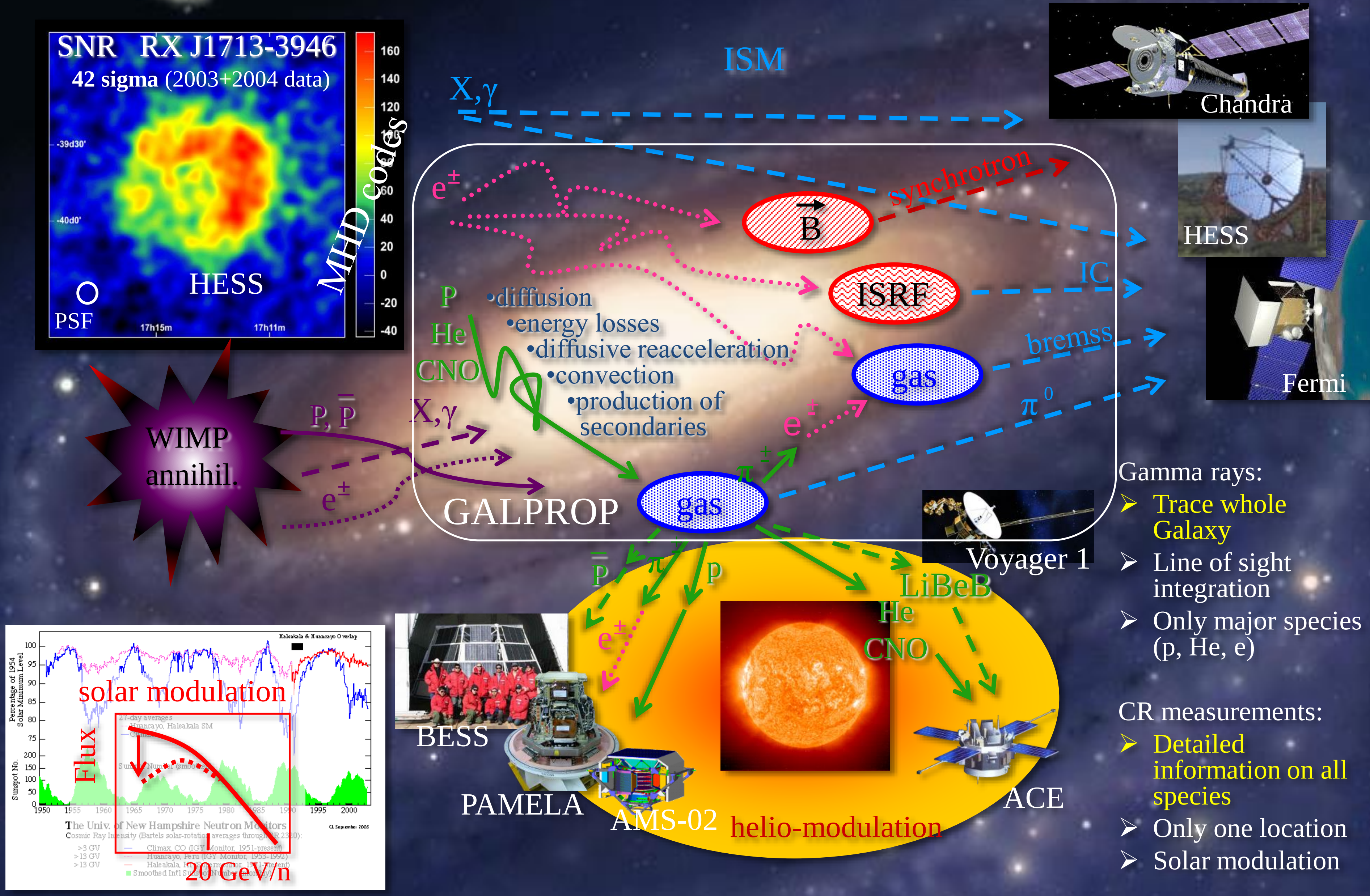


- ✧ Bremsstrahlung



- ✧ Curvature (or synchrotron) radiation

CRs in the interstellar medium



Gamma rays:

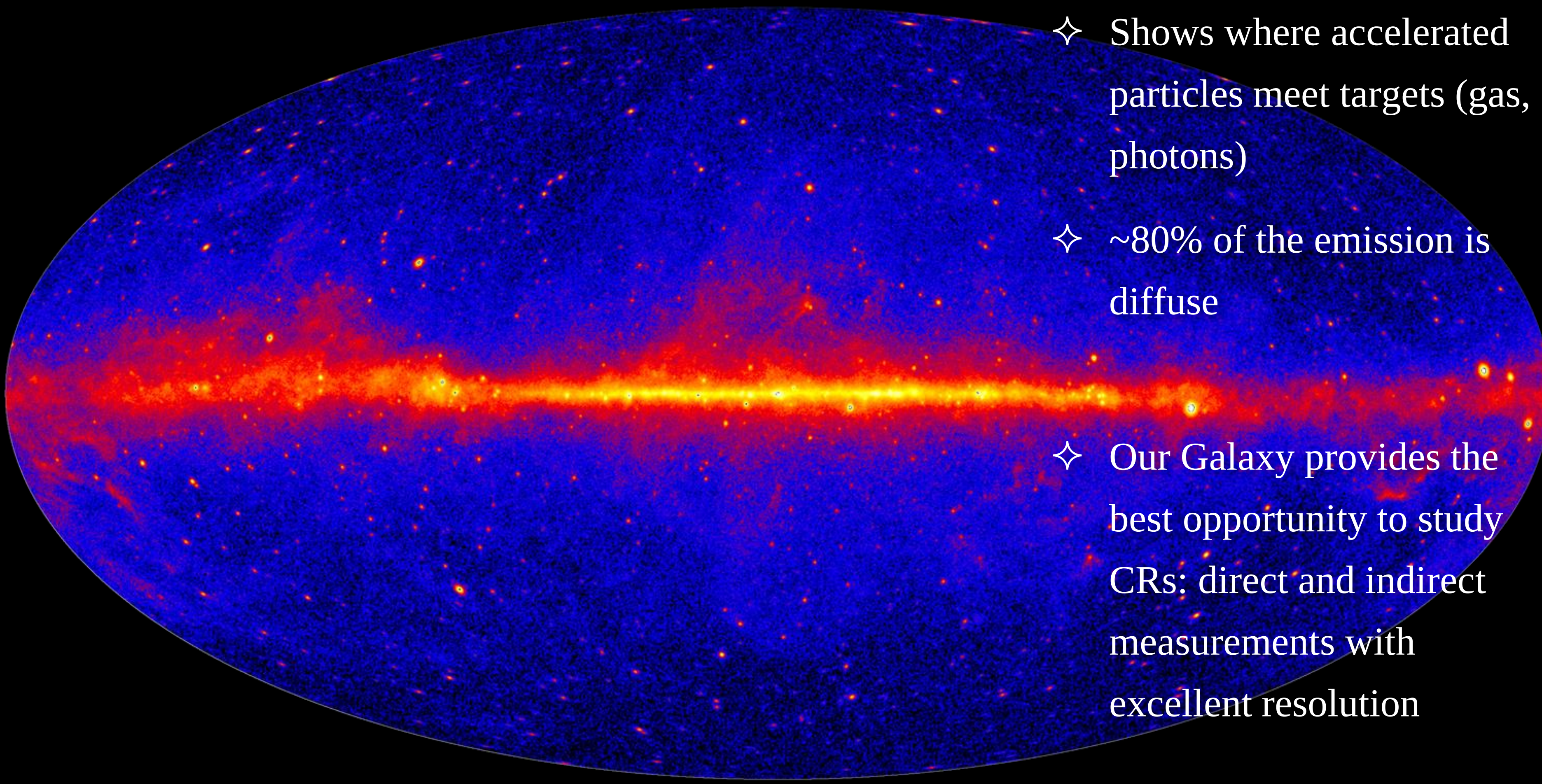
- Trace whole Galaxy
- Line of sight integration
- Only major species (p, He, e)

CR measurements:

- Detailed information on all species
- Only one location
- Solar modulation

Modeling is a must!

Fermi-LAT skymap >1 GeV, 48 months



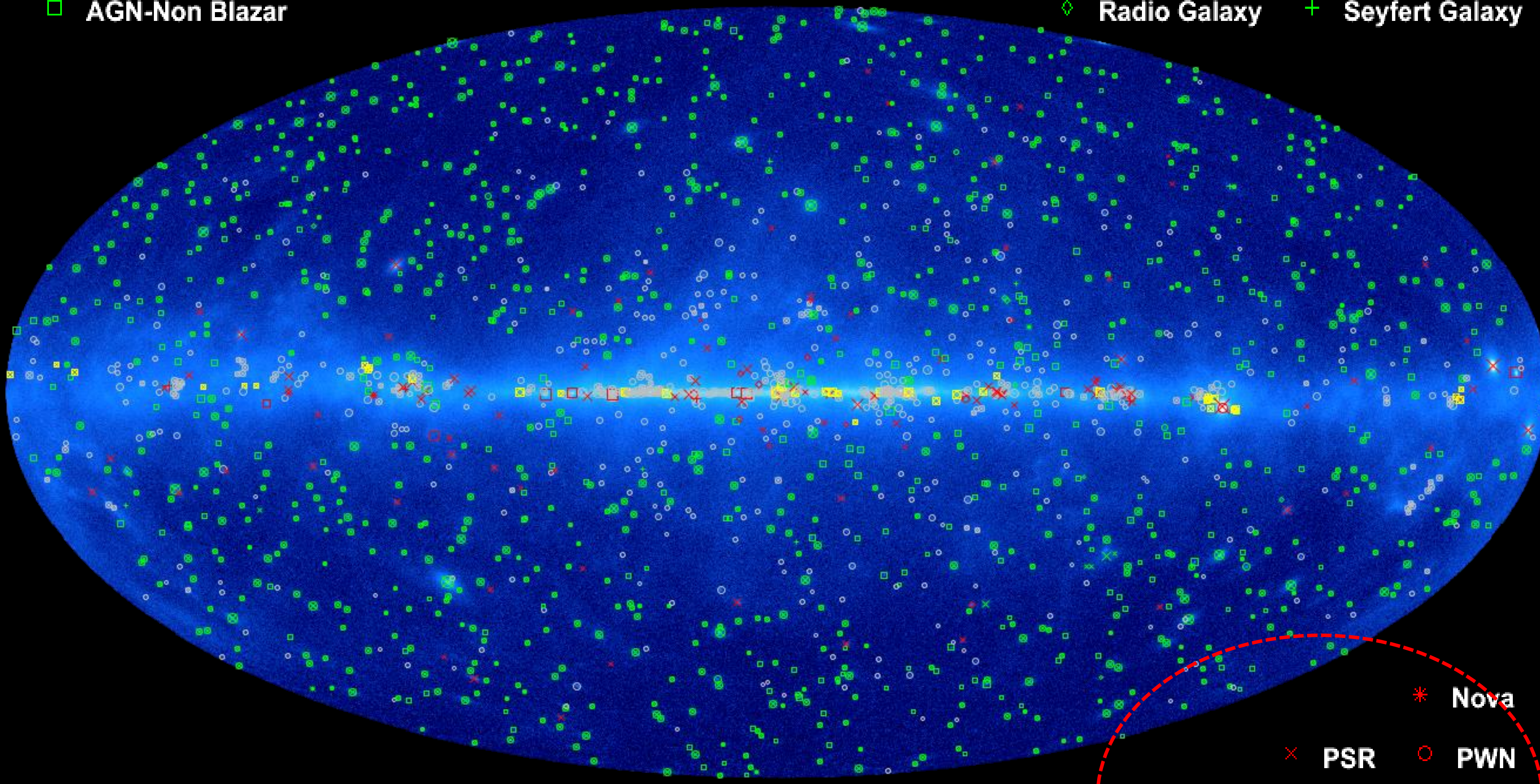
- ✧ Shows where accelerated particles meet targets (gas, photons)
- ✧ ~80% of the emission is diffuse
- ✧ Our Galaxy provides the best opportunity to study CRs: direct and indirect measurements with excellent resolution

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

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

2FGL Catalog – 1873 src

Based on integrated exposure (100 MeV to 100 GeV) from August 4, 2008, to July 31, 2010 (2 years), TS > 25



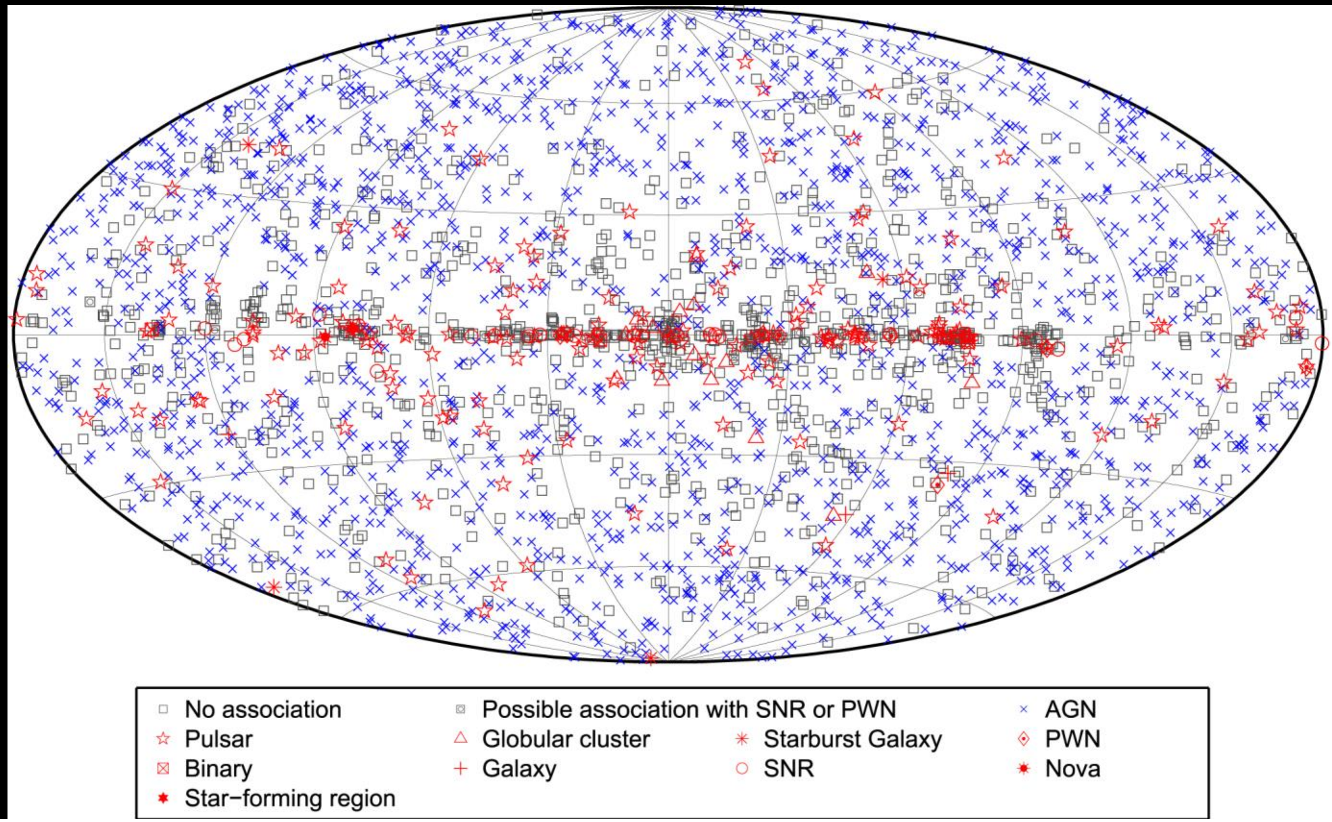
sources of CRs!

Credit: Fermi Large Area Telescope Collaboration

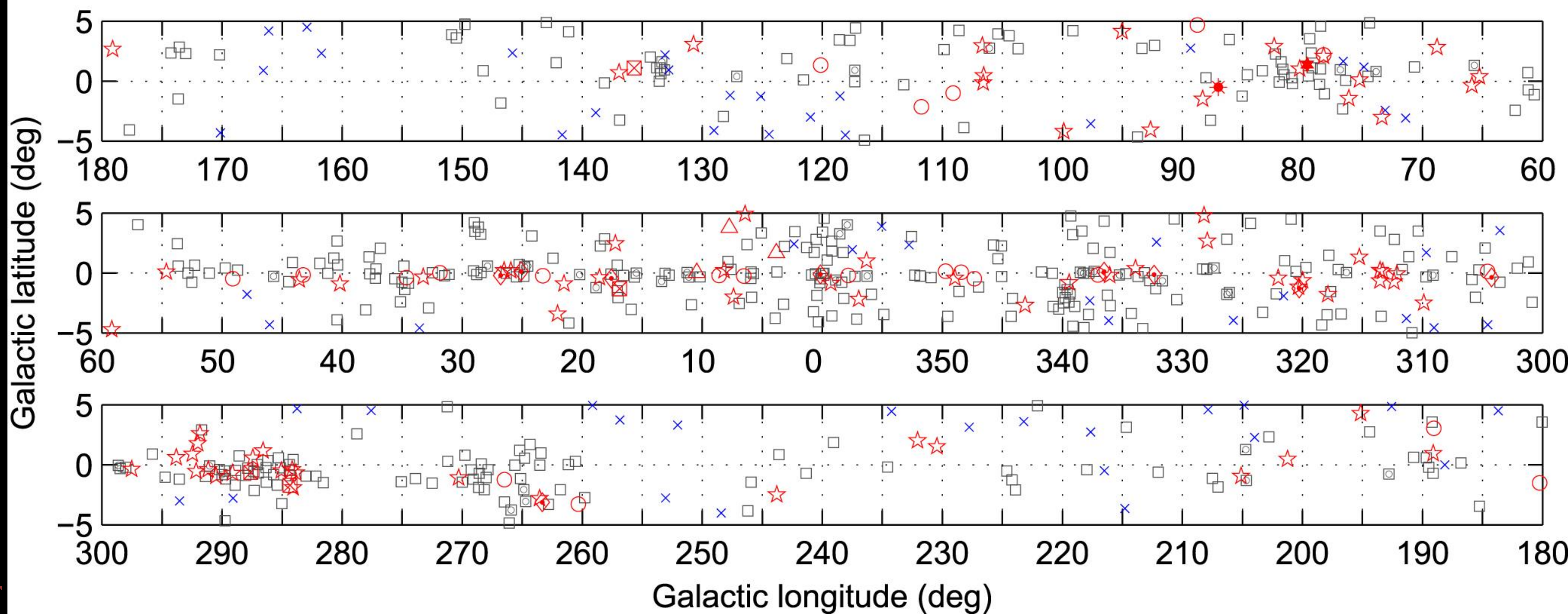
3FGL Catalog:

3033 sources

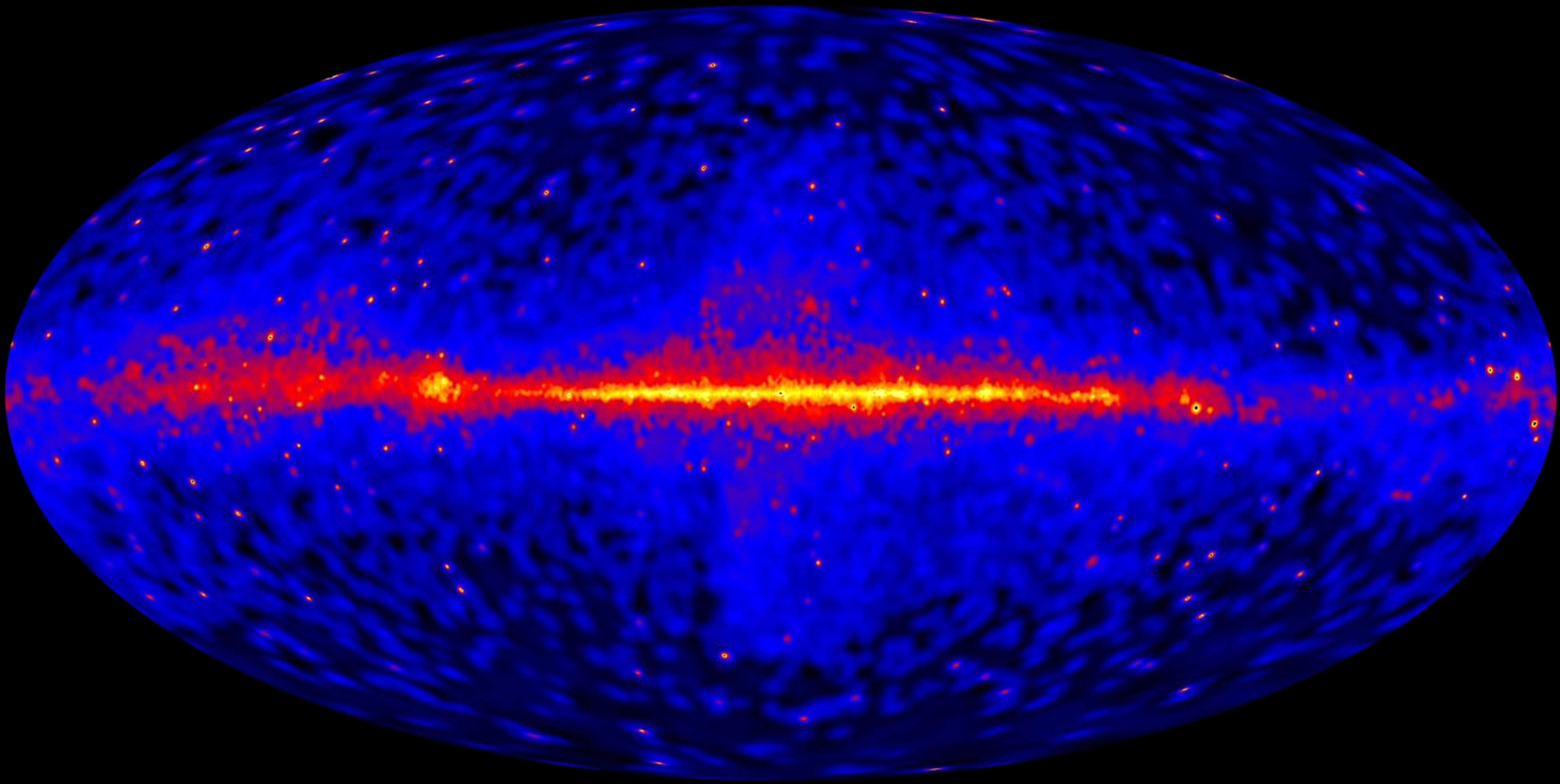
- ✧ 4 years (P7 reprocessed)
- ✧ 0.1 – 100 (300) GeV
- ✧ 5 (14) energy bins uniformly spaced in log E
- ✧ 20 extended sources
- ✧ Identified – 238
- ✧ Associated – 1745
- ✧ Unidentified ~1/3 of all sources



sources of CRs!



1FHL: Fermi-LAT skymap >10 GeV

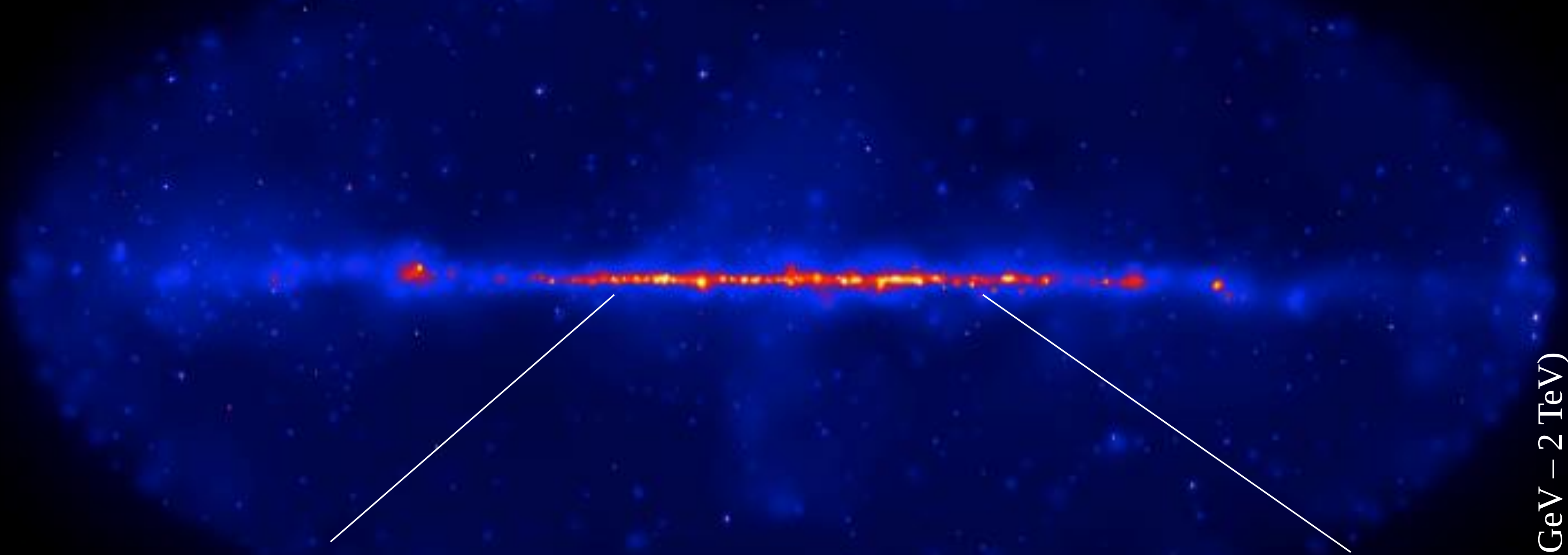


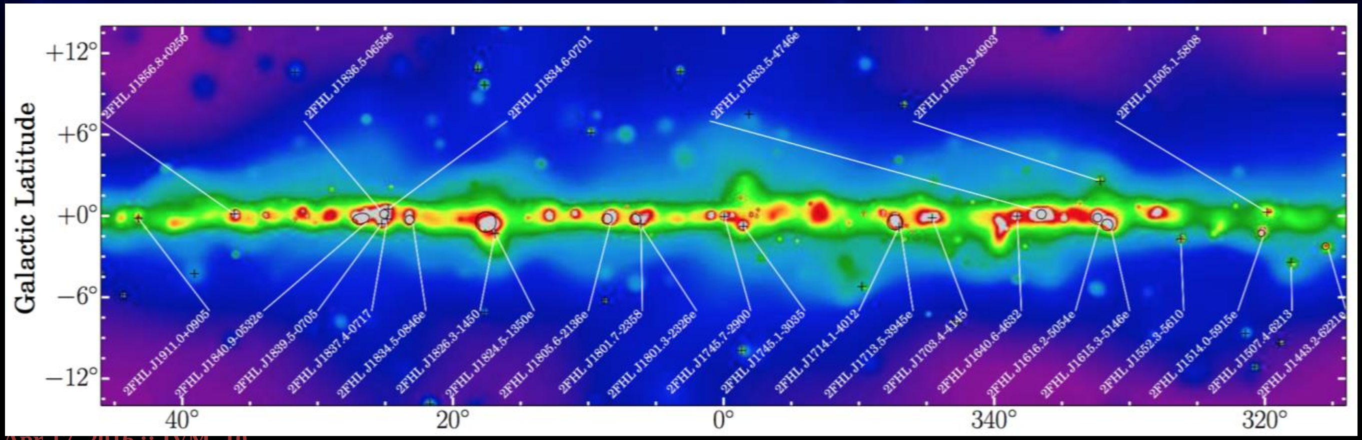
- ✧ Less diffuse emission
- ✧ Fewer but more powerful sources at high energies

2FHL: "TeVatron map" – Fermi Sky >50 GeV

61,000 photons E > 50 GeV
22,100 photons E > 100 GeV
2,000 photons E > 500 GeV

Compared with atmospheric Cherenkov telescopes (ACTs) which observed only a small fraction of the sky, Fermi-LAT observes the whole sky

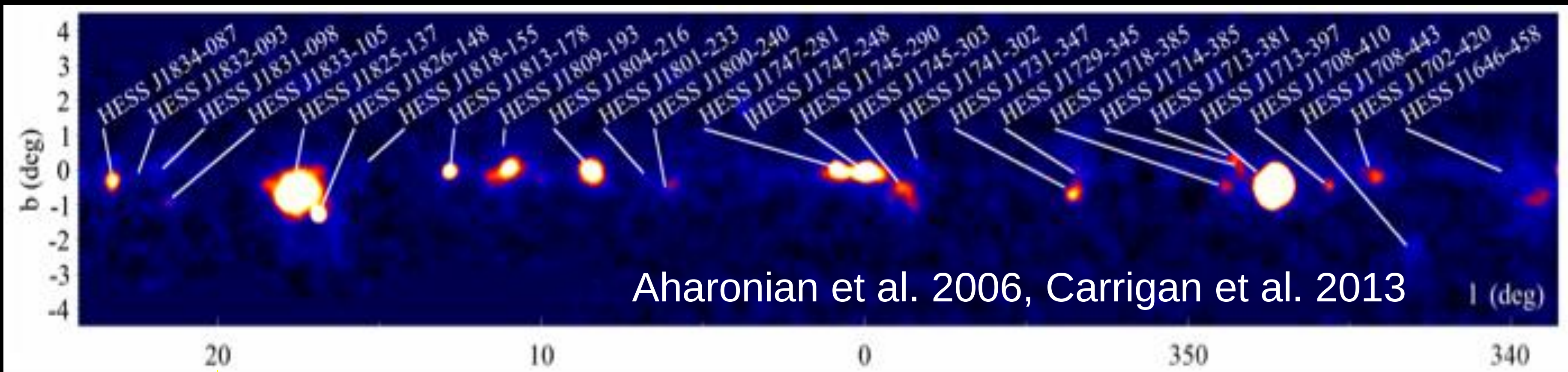




80 months of P8 data (50 GeV – 2 TeV)

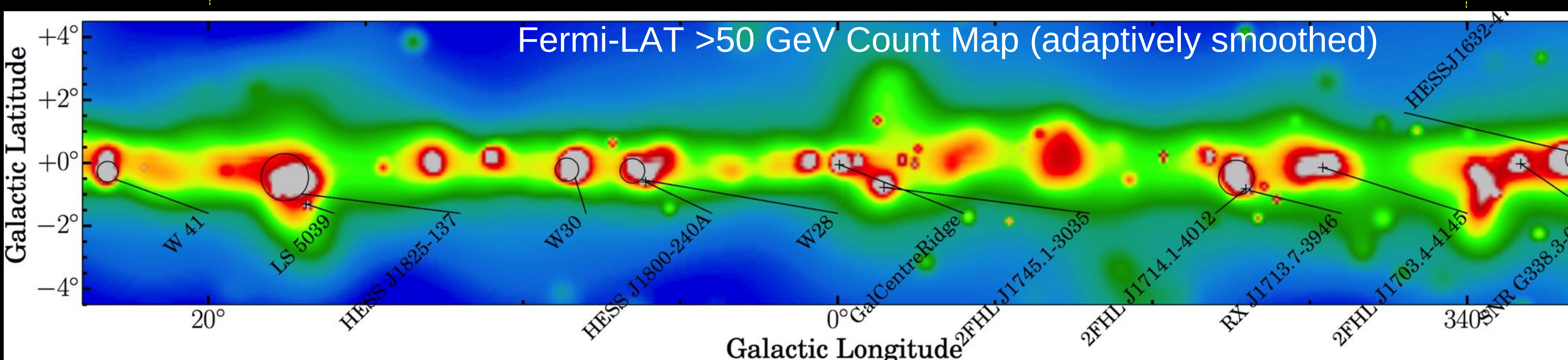
Comparison with HESS Galactic Plane survey

Significance Map



✧ H.E.S.S. detects 69 sources reaching a sensitivity of ~2% of the >1 TeV Crab Nebula flux

✧ LAT detects 36 sources (in 2FHL) in the same region reaching an average sensitivity of 3-4% of the Crab Nebula flux



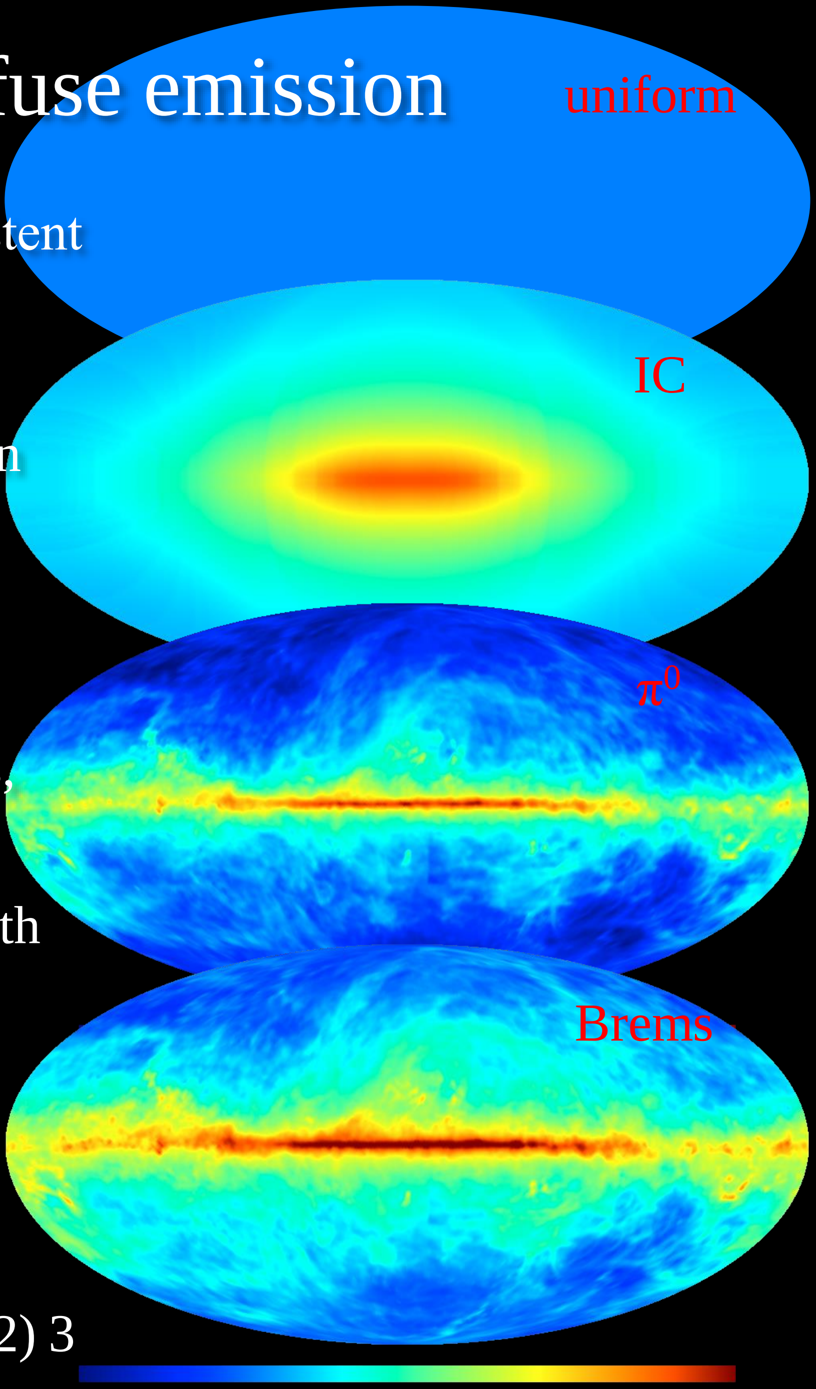
Total: 103 sources at |b|<10°

Take home message

- ✧ Most of these sources are too far and too young so that CRs did not come to us yet
- ✧ However, the same types of sources (SNRs, pulsars, PWNs,…) had produced the observed CRs. Therefore, we have to study them to understand the *past sources* that produced *observed* CRs
- ✧ And yet, some of these sources are close to us and thus influencing the observed fluxes of CR species
- ✧ Terry will talk more about the CR-gamma-ray connection

Large scale study of the diffuse emission

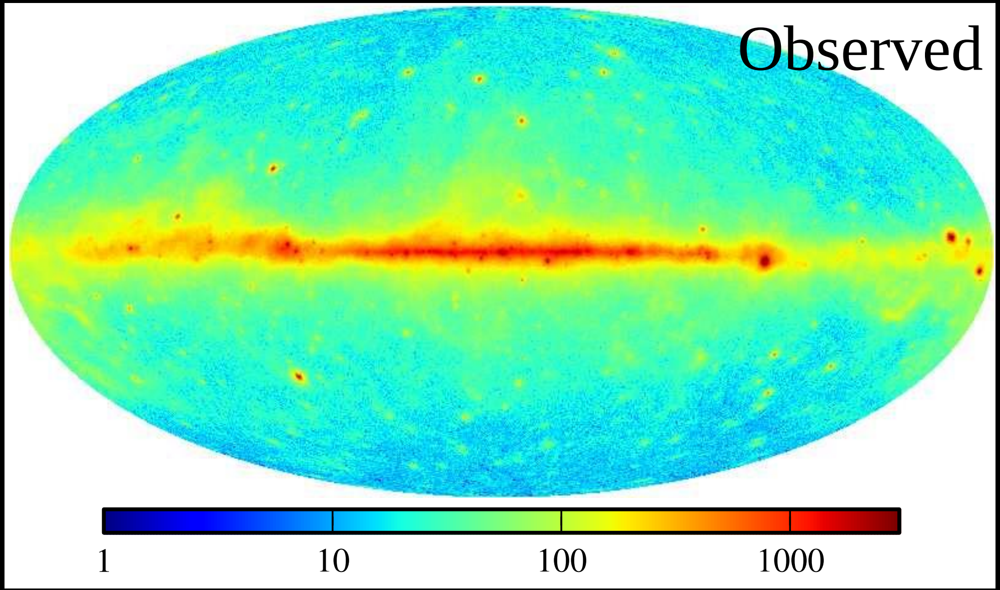
- ✧ "Conventional model": CR spectra are consistent with local measurements (CR nuclei, Fermi electrons)
- ✧ GALPROP code with diffusion-reacceleration model for CR propagation
- ✧ Propagation parameters - fixed from CR data
- ✧ Grid of 128 models covering plausible confinement volume, CR source distributions,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

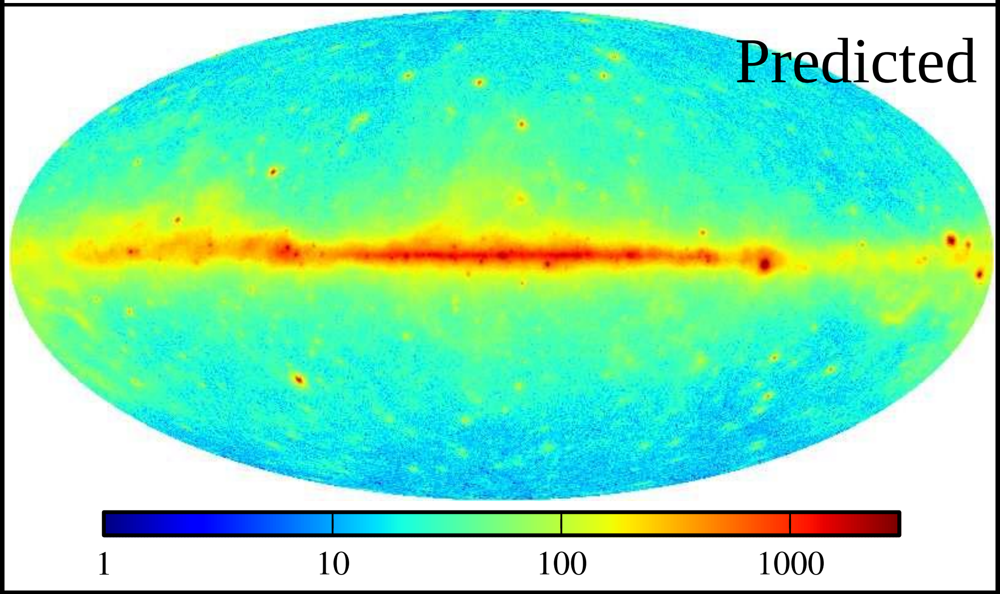


- ✧ A massive Fermi-LAT study – ApJ 750 (2012) 3

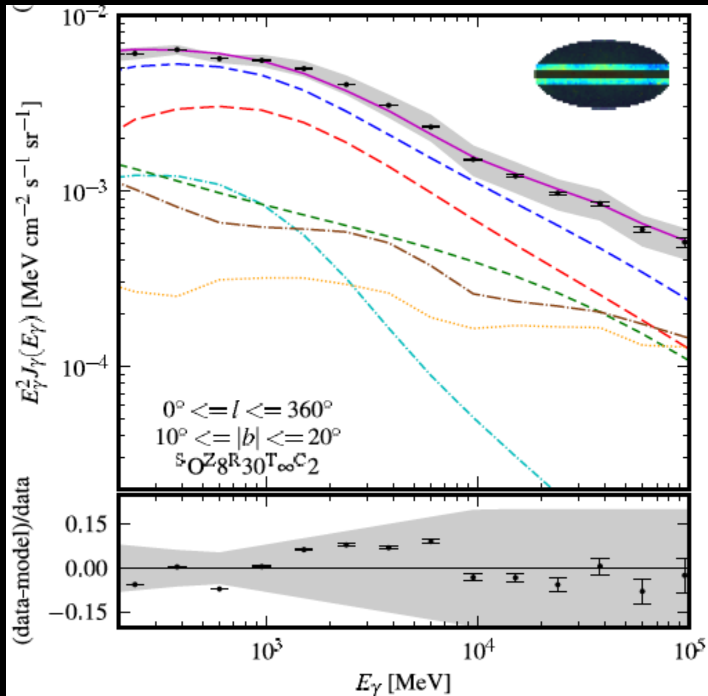
Diffuse emission skymap

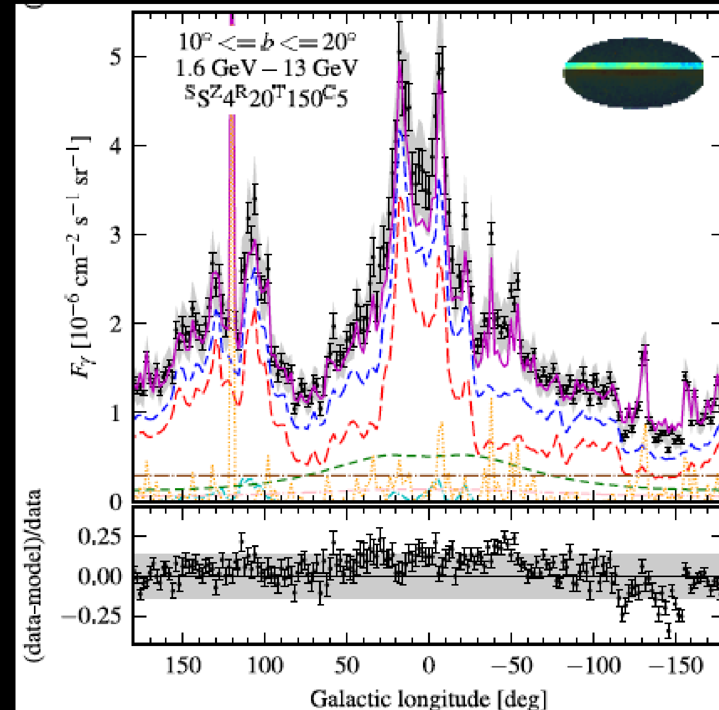
- ✧ Observed Fermi-LAT counts in the energy range 200 MeV to 100 GeV
- ✧ Predicted counts calculated using GALPROP reacceleration model tuned to CR data
- ✧ Residuals (Obs-Pred)/Obs ~ % level, ~10% in some places

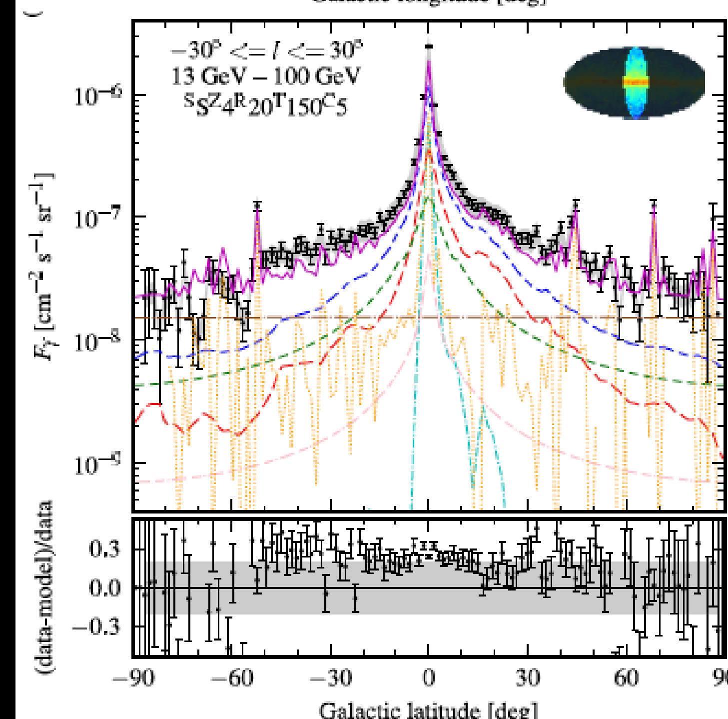




Spectrum and profiles

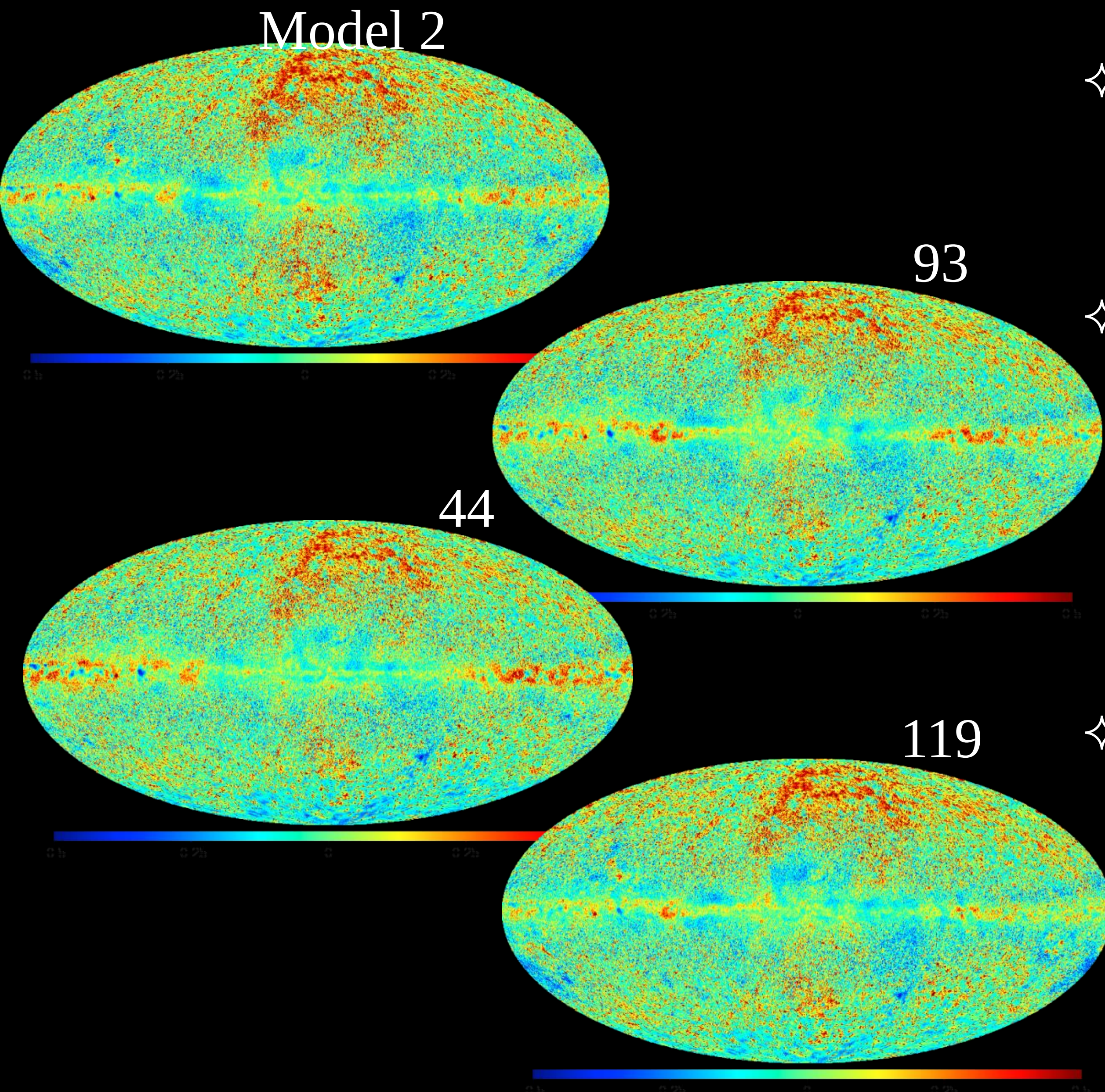






- Components of the model
  - Neutral pion emission from gas H_2, HI, HII
  - Inverse Compton
  - Bremsstrahlung
  - Detected sources
  - Isotropic emission

Large scale study: residuals



- Agreement for models is overall good, but features are visible in residuals at ~% level
- Difference between illustrative models shown in right maps : structure due to variations of model parameters

- Models details:

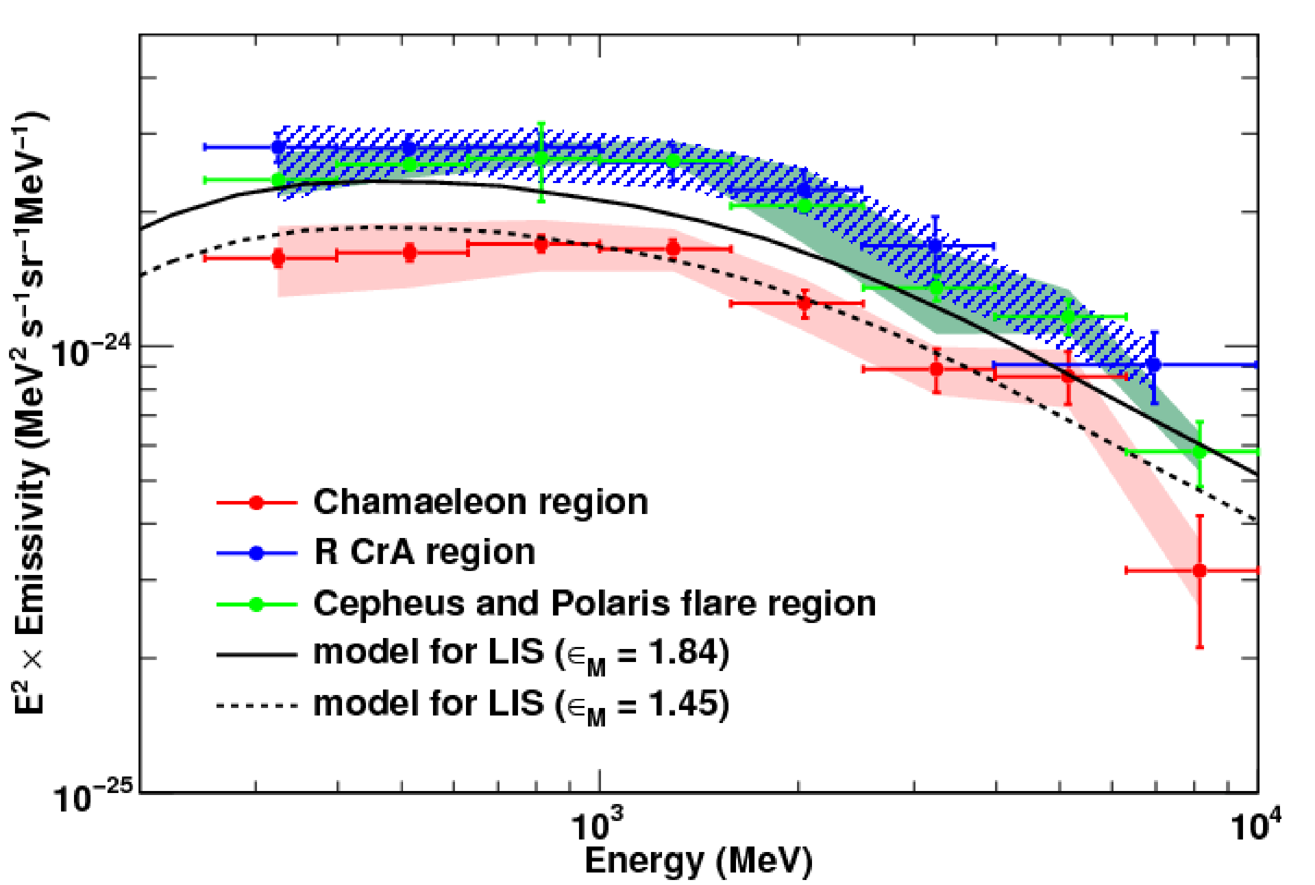
  2: $SNR^{Z}4^{R}20^{T}150^{C}5$

  44: $Lorimer^{Z}6^{R}20^{T}\infty^{C}5$

  93: $Yusifov^{Z}10^{R}30^{T}150^{C}2$

  119: $OB^{Z}8^{R}30^{T}\infty^{C}2$

Local γ-ray emissivities

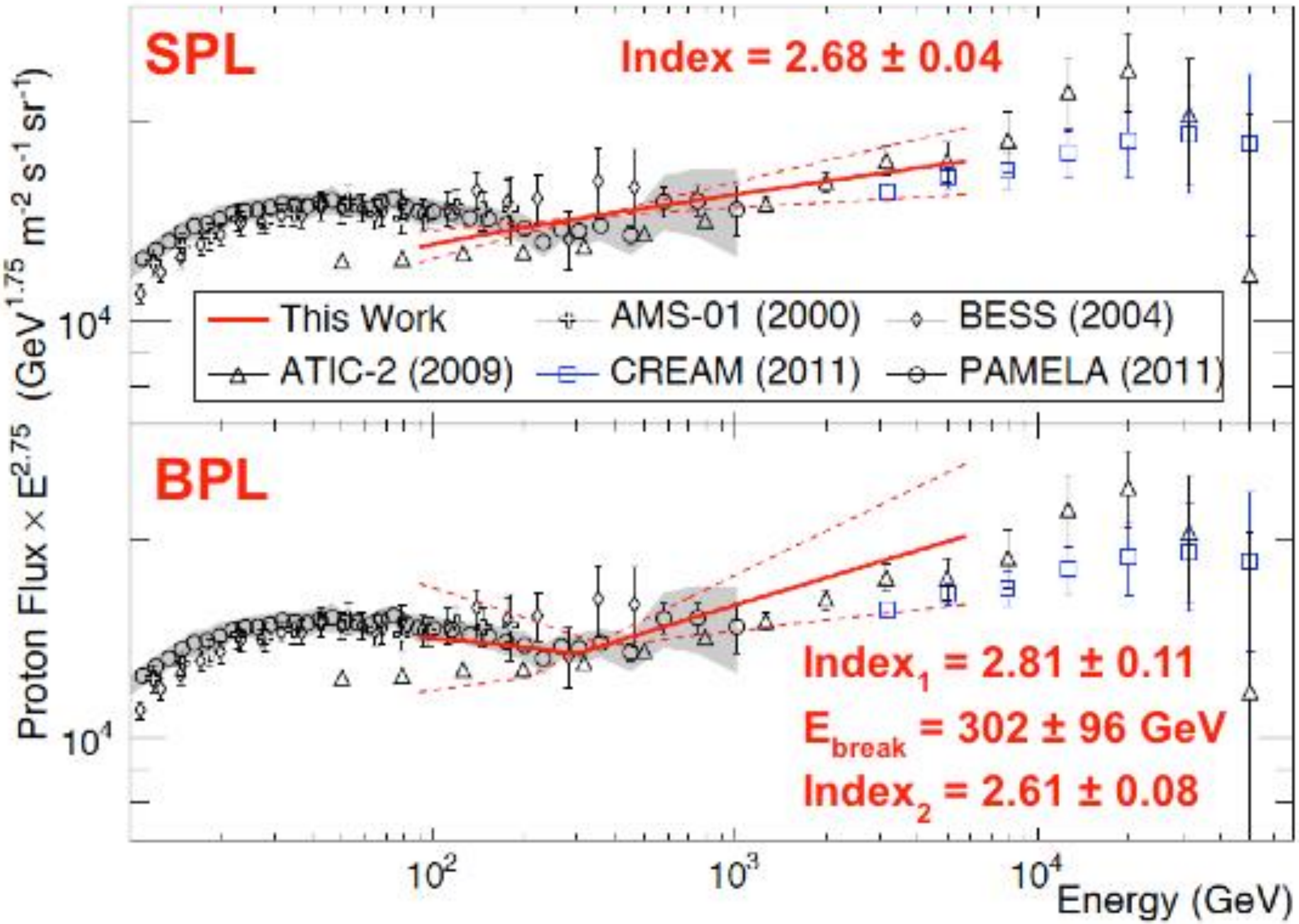


✧ Local gamma-ray emissivities derived from observations of the local gas clouds are consistent with the direct CR measurements

✧ Show intensity variations due to errors in gas mass estimates, gas composition, or true CR intensity variations

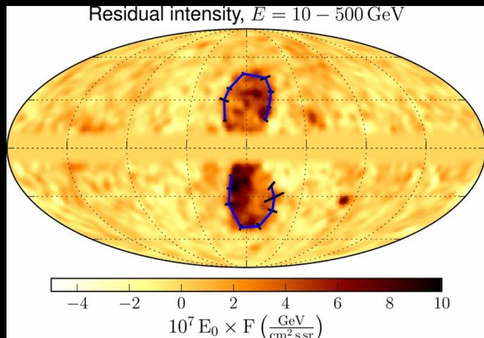
Inferred CR Proton Spectrum from *pp* Model by Kachelrieβ & Ostapchenko (2012)

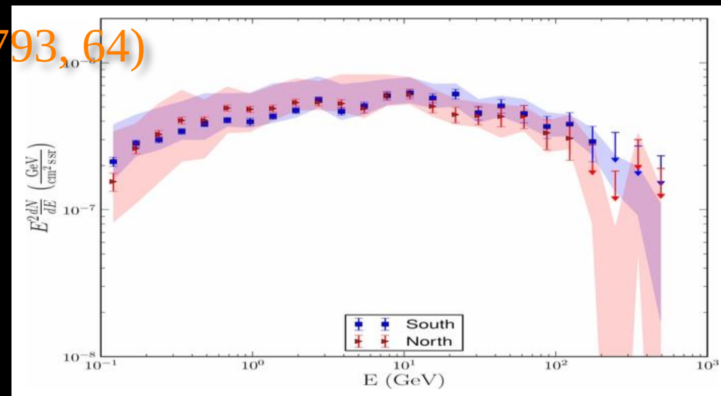
Fermi – Earth limb observations

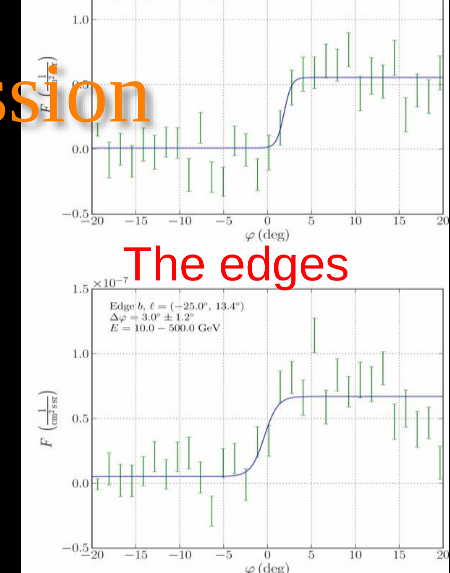


Fermi: recent studies of the diffuse emission

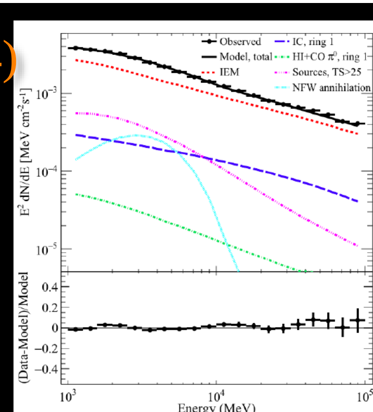
✧ Fermi Bubbles (ApJ 2014, 793, 64)

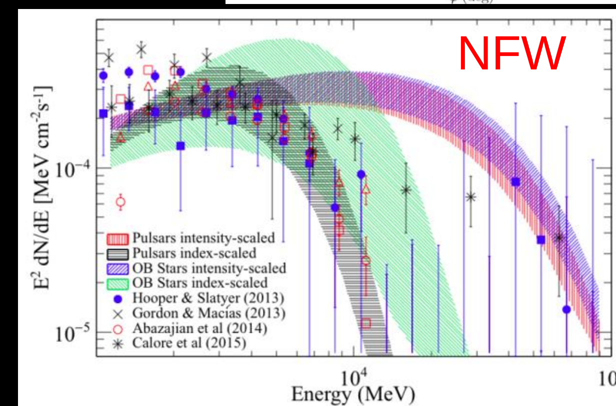




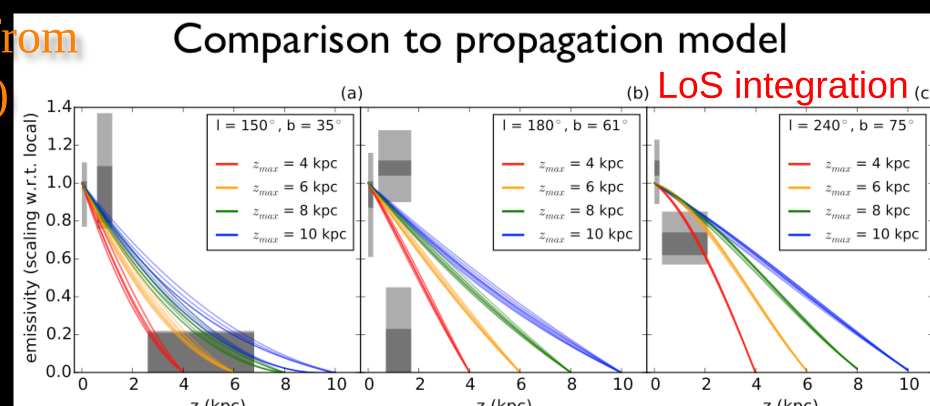


✧ Galactic Center (ApJ 2016, 819, 44)

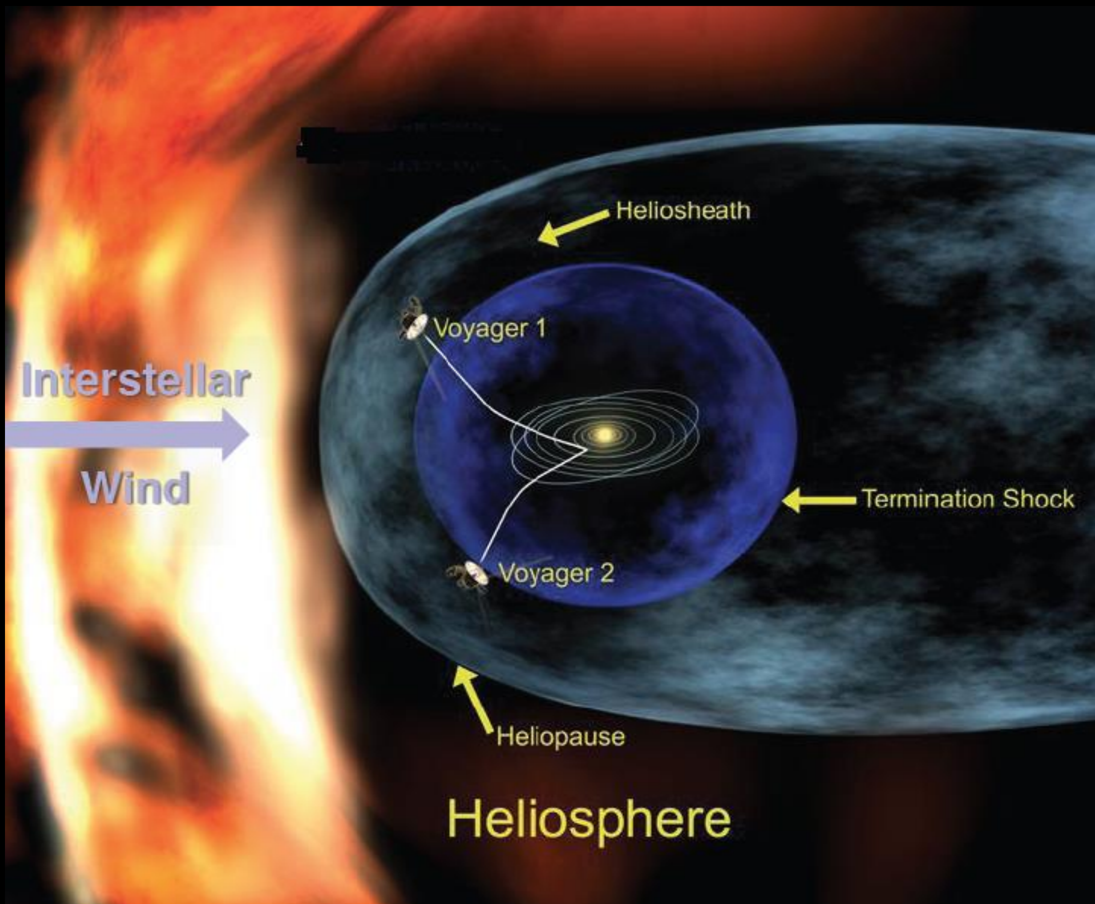




✧ High velocity clouds – large distances from the Galactic plane (ApJ 2015, 807, 161)



Voyager 1 in the interstellar space



Voyager 1 131.0 AU

19.7 billion km

Voyager 2 107.7 AU

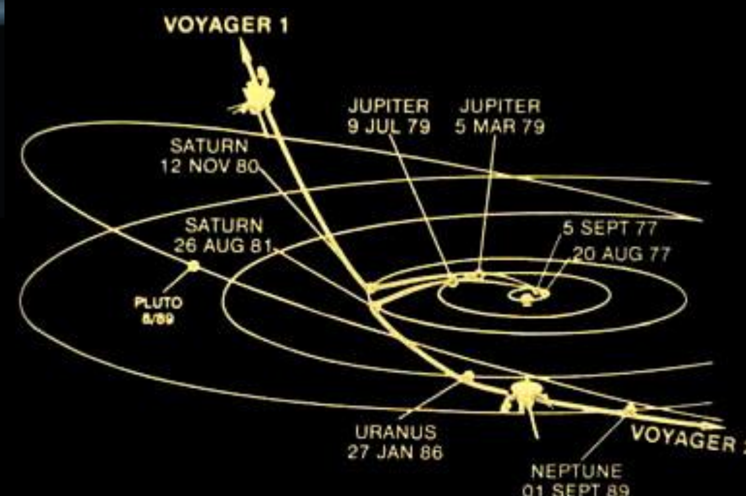
16.2 billion km

~2 years to interstellar space?

Launched in 1977!

First interstellar probe!

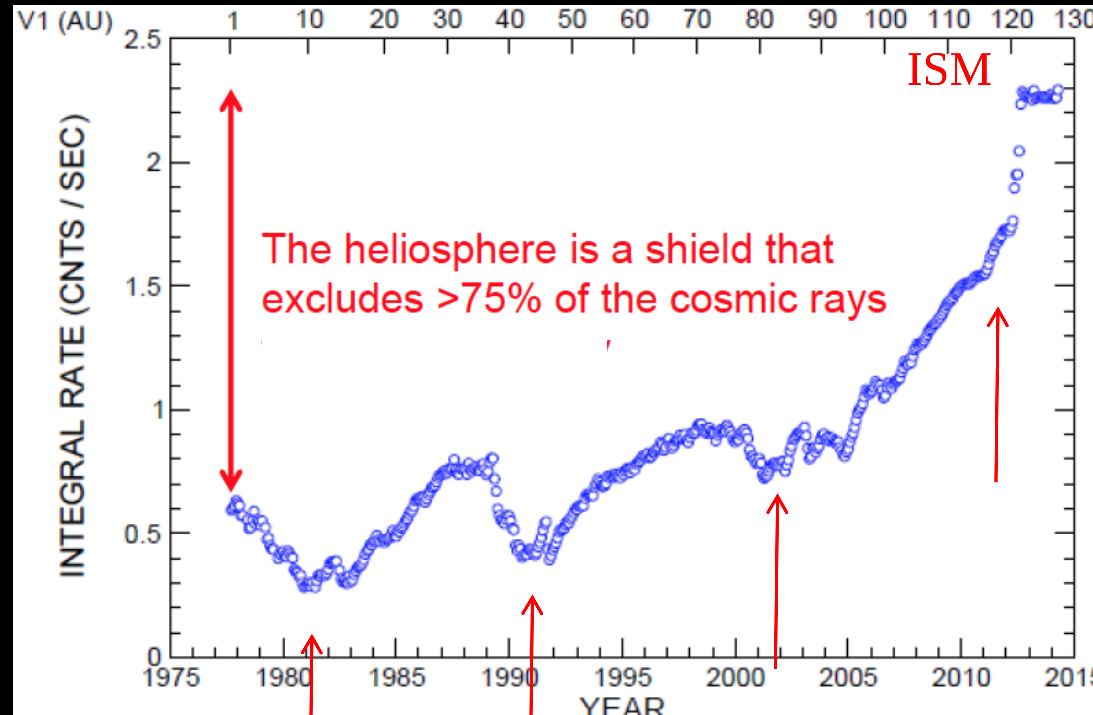
Will operate until 2026

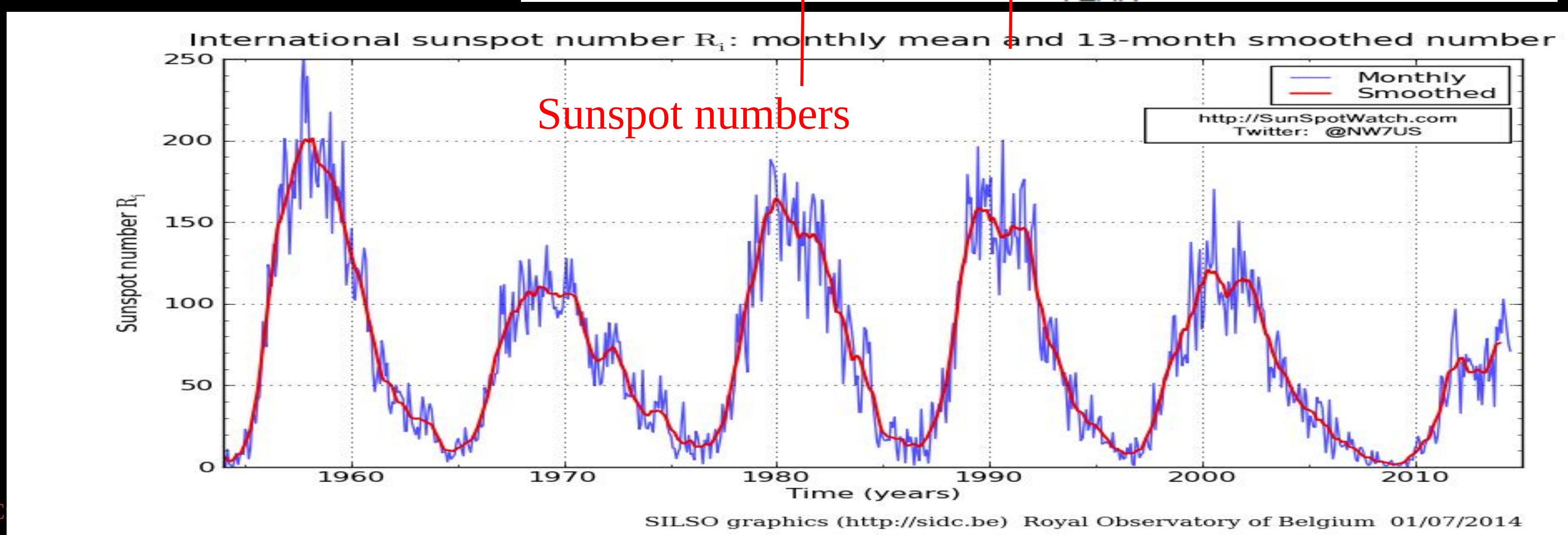


E. Stone 2015

Cosmic ray fluxes in the heliosphere

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





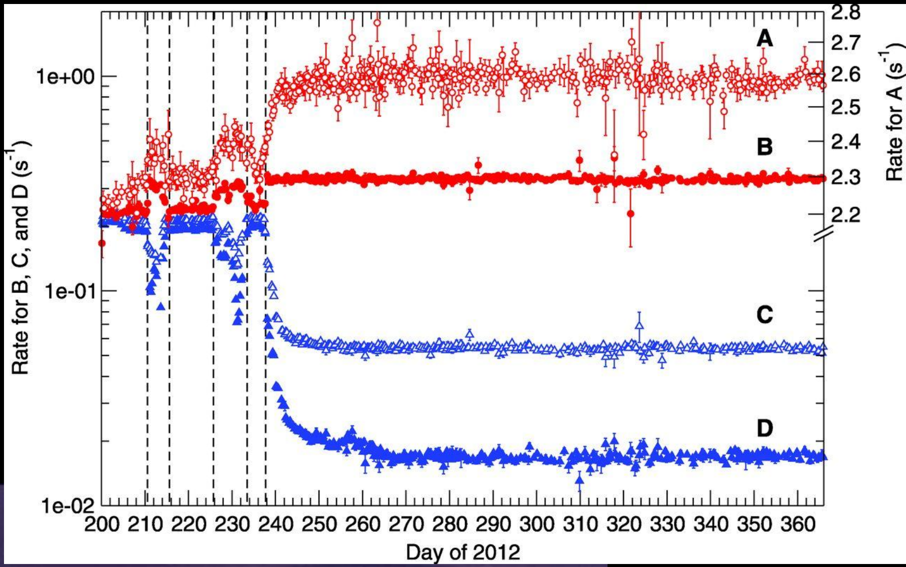
Interstellar probe – Voyager 1

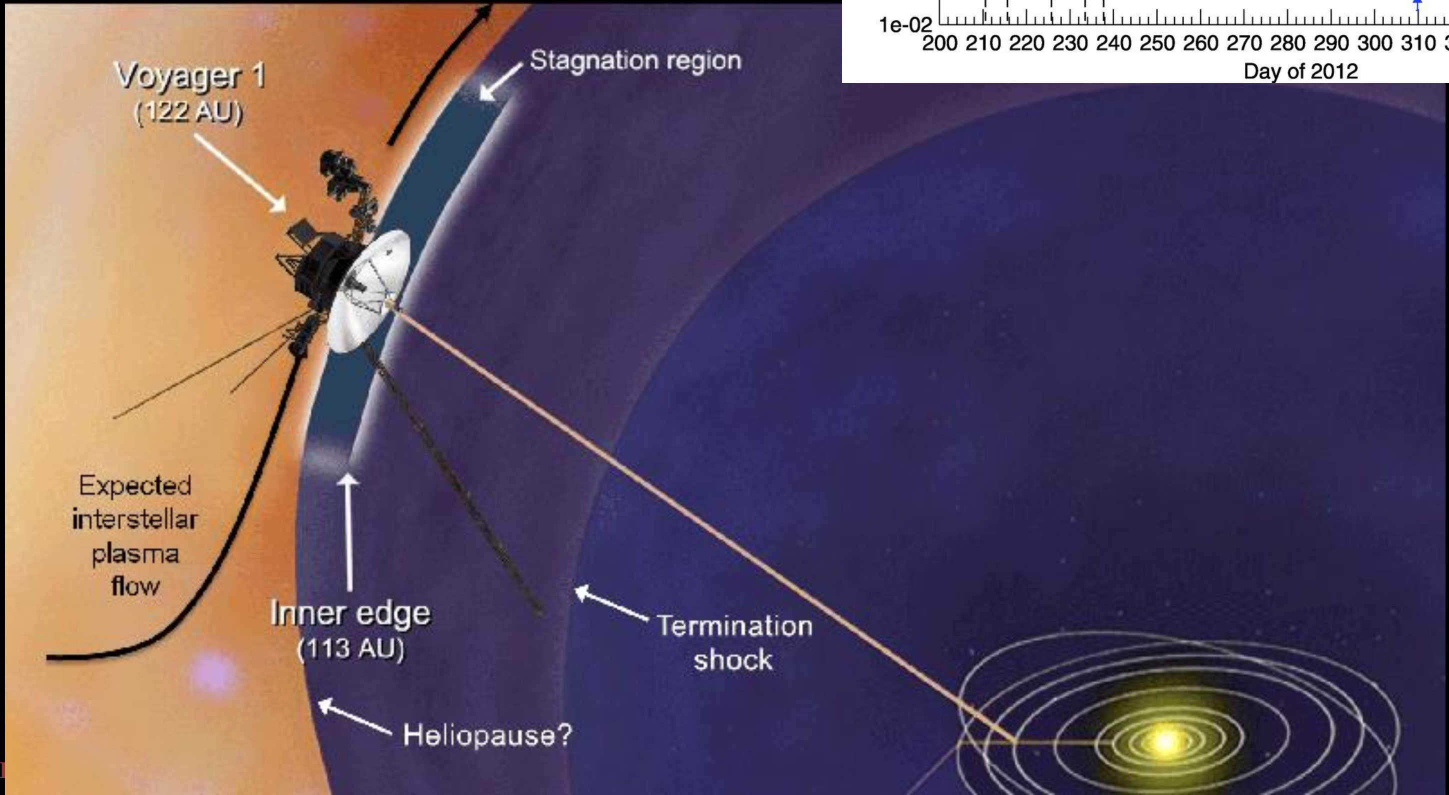
(A) (y axis on right) GCR nuclei (E > 70 MeV) at the High Energy Telescope 1

(B) (y axis on left) GCR electrons (6-100 MeV) observed by the Electron Telescope

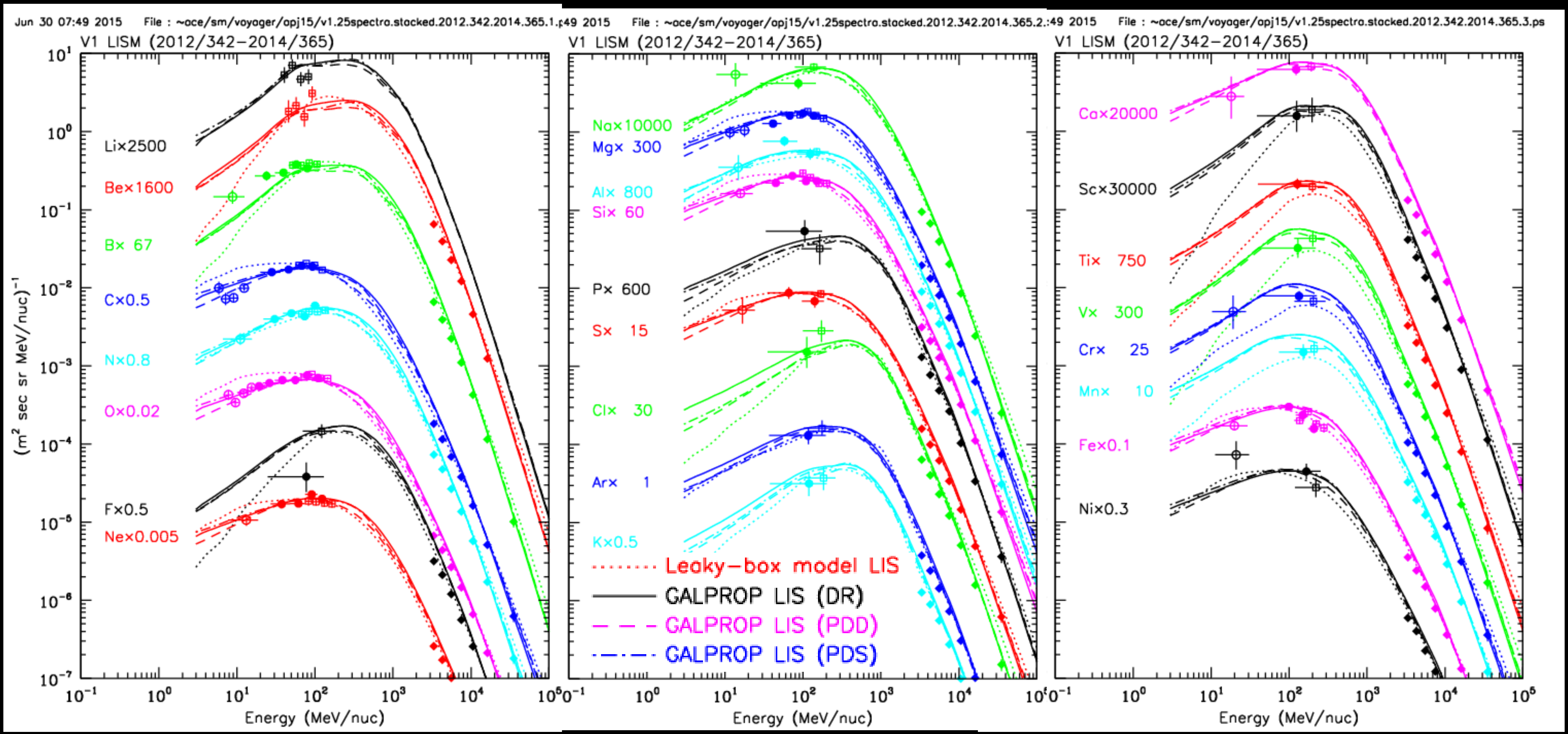
(C) (y axis on left) Protons with 7 to 60 MeV stopping in HET 1 are mainly anomalous cosmic rays before 2012/238 (25 August) and galactic cosmic rays after that

(D) (y axis on left) Low-energy particles mainly protons with 0.5 to ~30 MeV accelerated at the termination shock and in the heliosheath





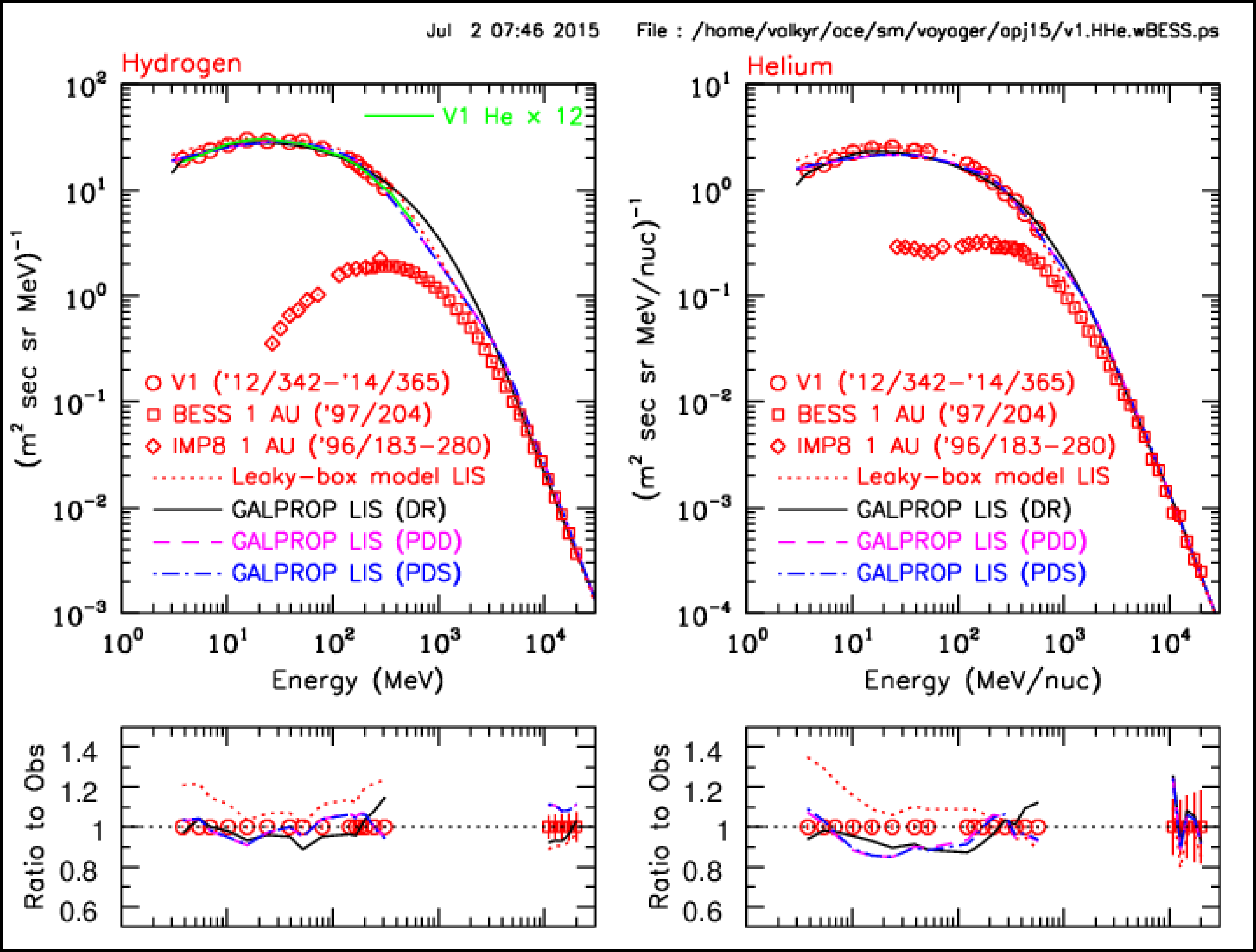
Voyager 1 spectra for 2012/342-2014/365



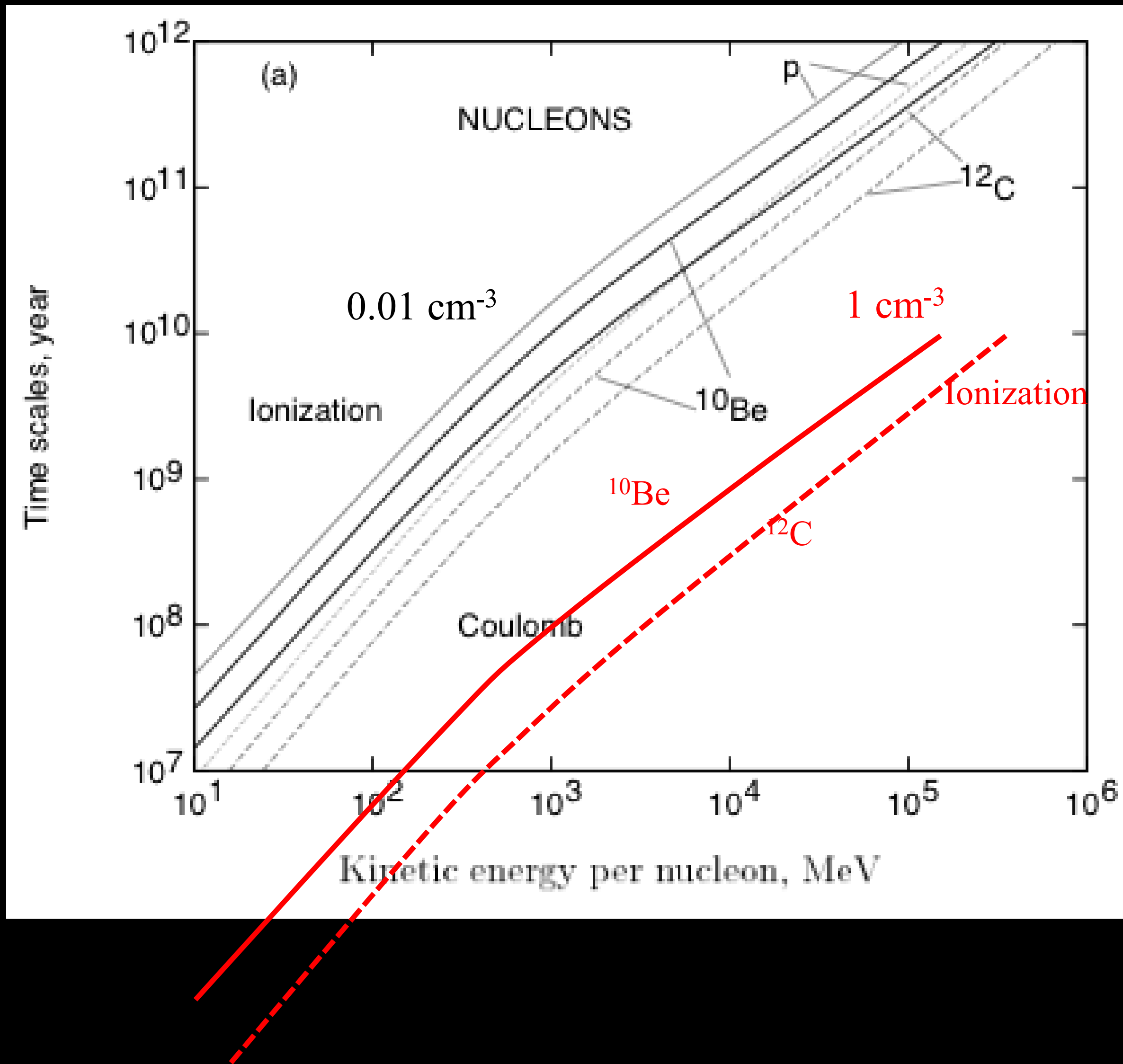
Li – Ni : V1 spectra together with HEAO-3-C2 data (≥3.35 GeV/nuc)

ApJ paper – submitted

Voyager 1 – H and He spectra



Energy losses of nucleons



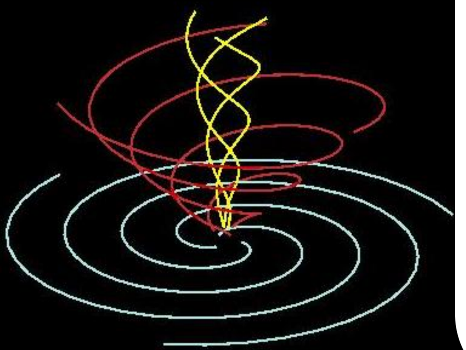
- ✧ The ionization and Coulomb losses are calculated for the gas number density 0.01 cm^{-3} & 1 cm^{-3}

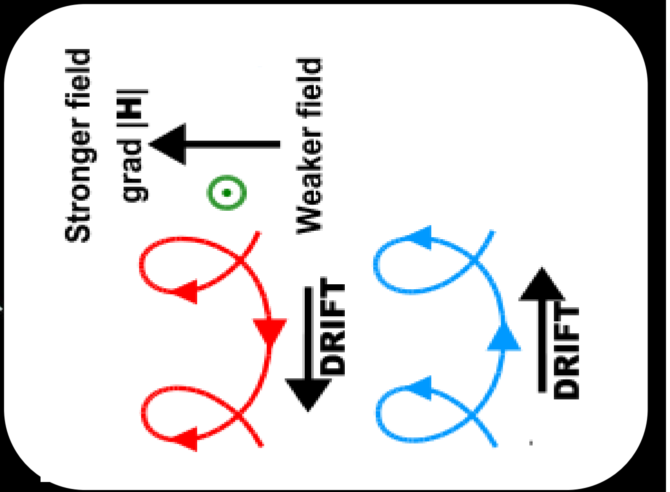
  Carbon at 10 MeV/n ($nH \sim 1\ cm^{-3}$):

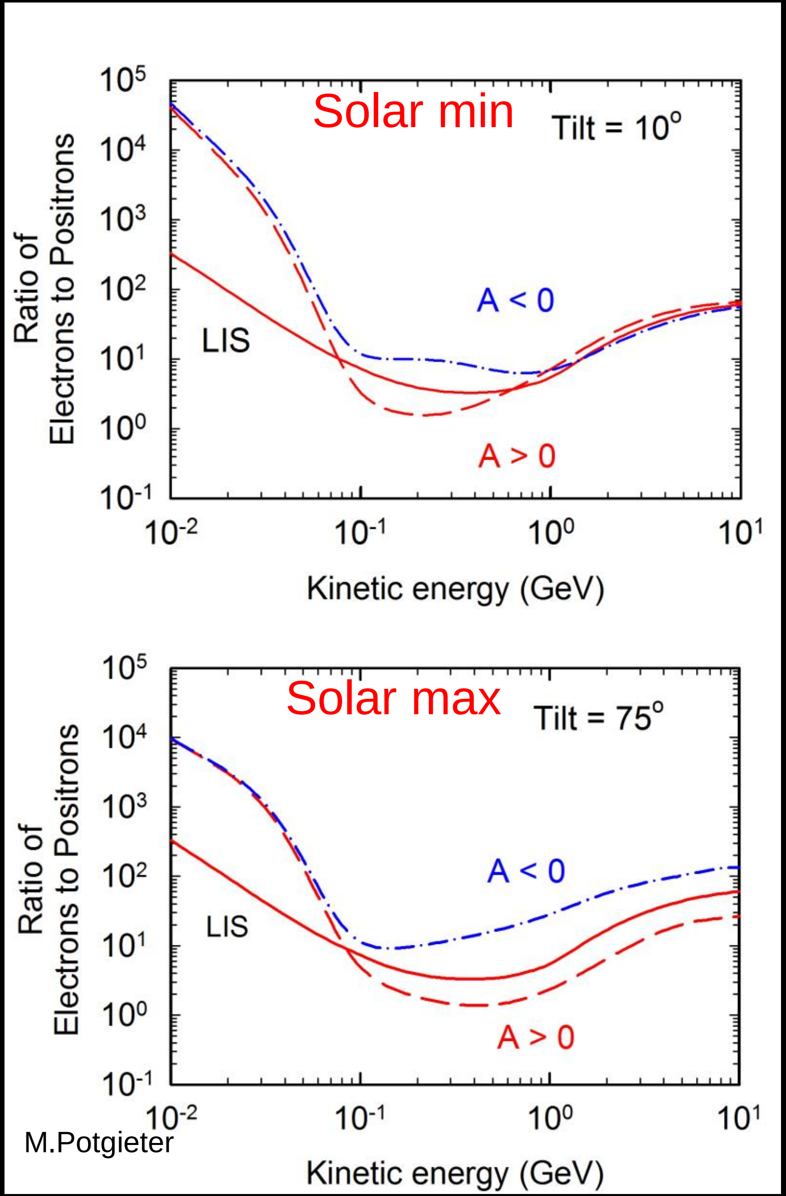
  $\tau \sim 30$ kyr
- ✧ The energy losses by nucleons can be neglected above ~1 GeV
- ✧ Nuclear interactions are more important

Heliospheric modulation: Charge-sign effect I

The Parker magnetic field has opposite magnetic polarity above and below the helio-equator, but the spiral field lines are mirror images of each other.

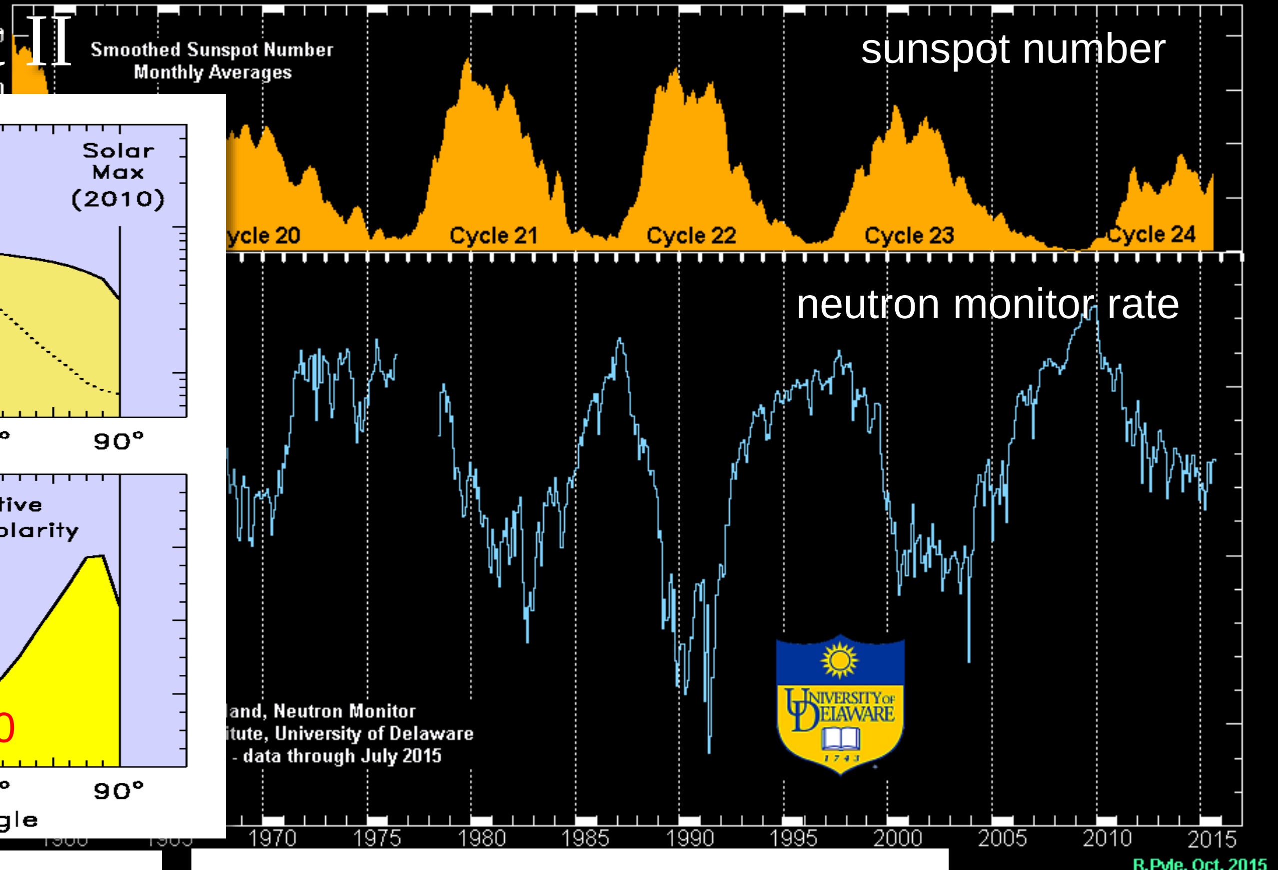


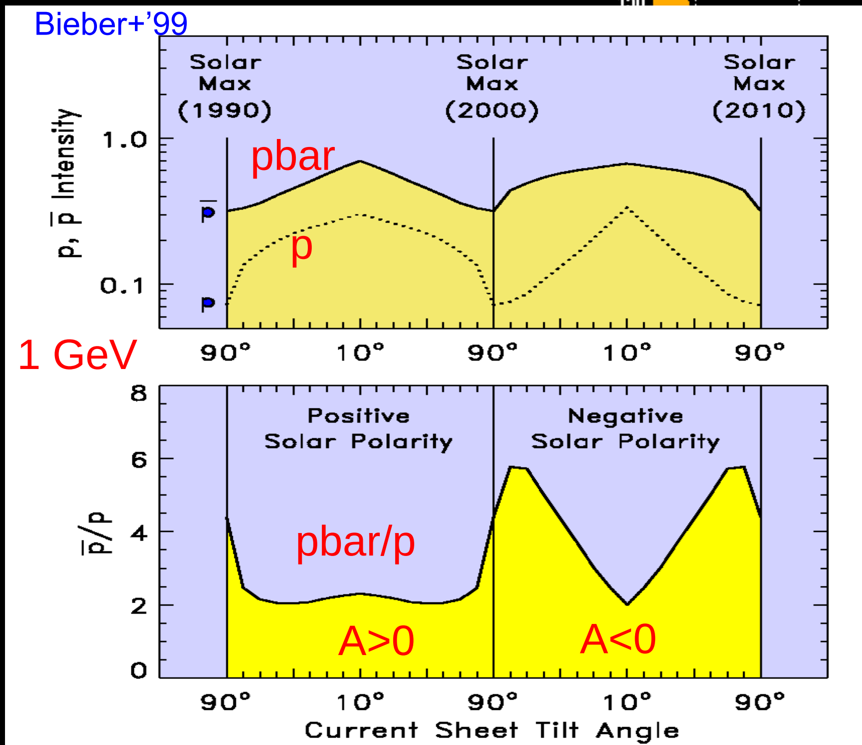


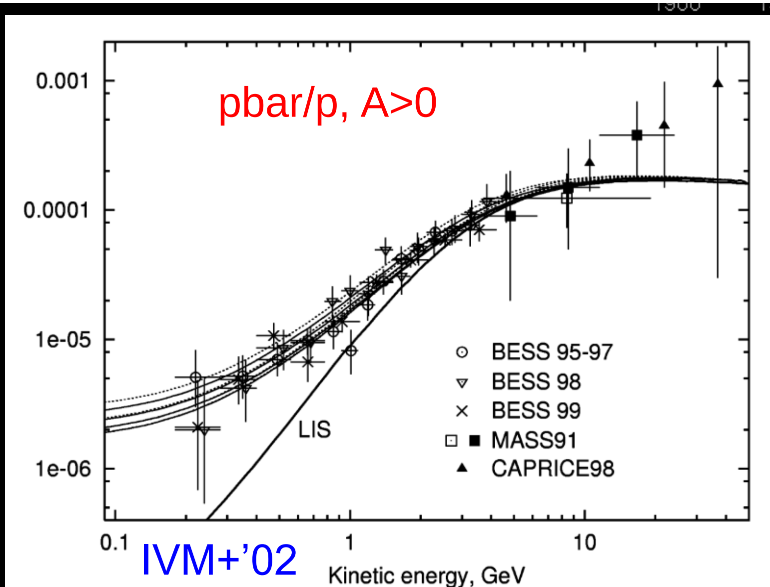


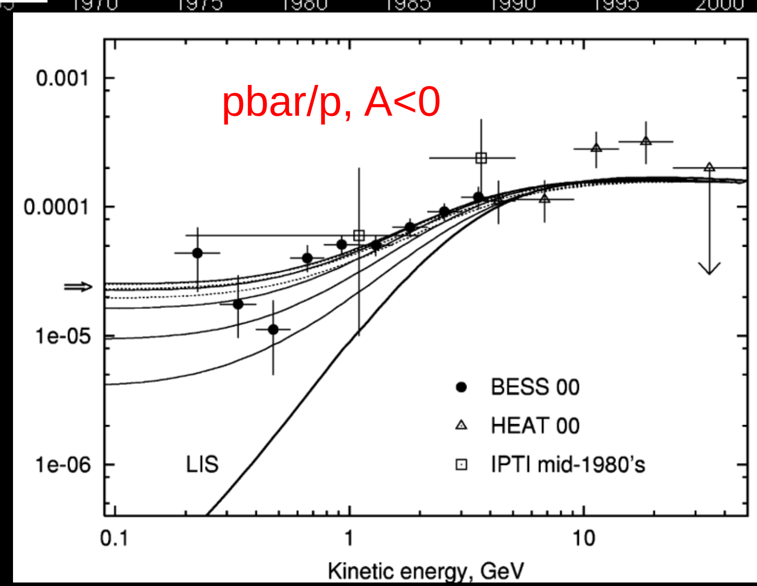
This antisymmetry produces the drift velocity fields that affect the particles of opposite charge in different ways (converge on heliospheric equator or diverge from it).

Charge Sign Effect II









HELMOD

- Working with HELMOD people to provide reliable spectra of CR species in the interstellar medium
- Fully compatible with GALPROP

HOME NEWS PUBLICATIONS MODEL DESCRIPTION HELMOD AUTHORS

web version of HelMod

HelMod online - Beta version : Registration : Login

EXAMPLE

Catalog

HelMod Web model : cosmic rays differential intensity at 1AU calculator

Year / month 2007 1

Send Cancel

Evaluation of proton differential intensity at 1AU

HelMod Web model : cosmic rays intensity evolution at 1AU calculator

Energy [GeV] 6.59

Send Cancel

Evaluation of proton intensities evolution in time for different energetic bins from 0.5 GeV to 177 GeV at 1AU

Notes:
- version HelMod 1.5
- spectra evaluated for heliospheric ecliptic plane
- energies are centers of AMS experiment energetic/registration bins

HOME NEWS PUBLICATIONS MODEL DESCRIPTION HELMOD AUTHORS

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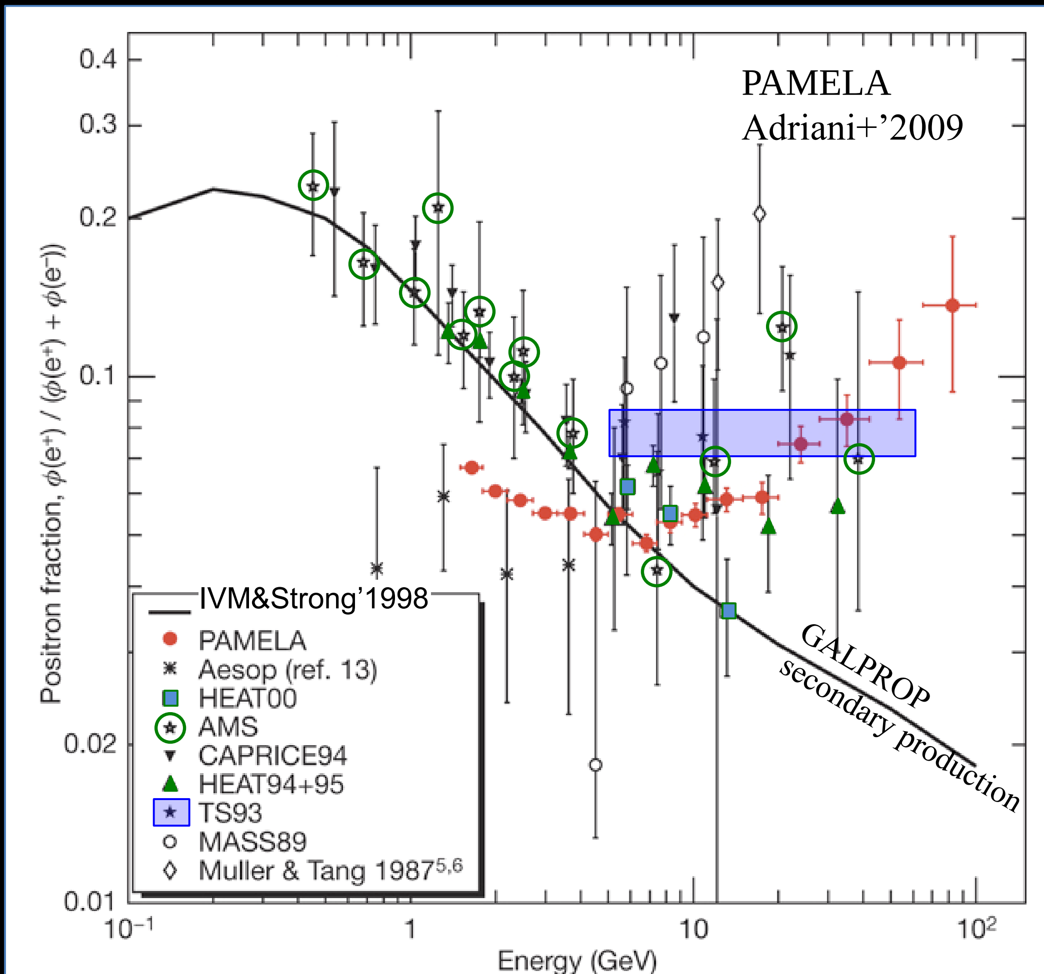
IEP SAS SPACE PHYSICS

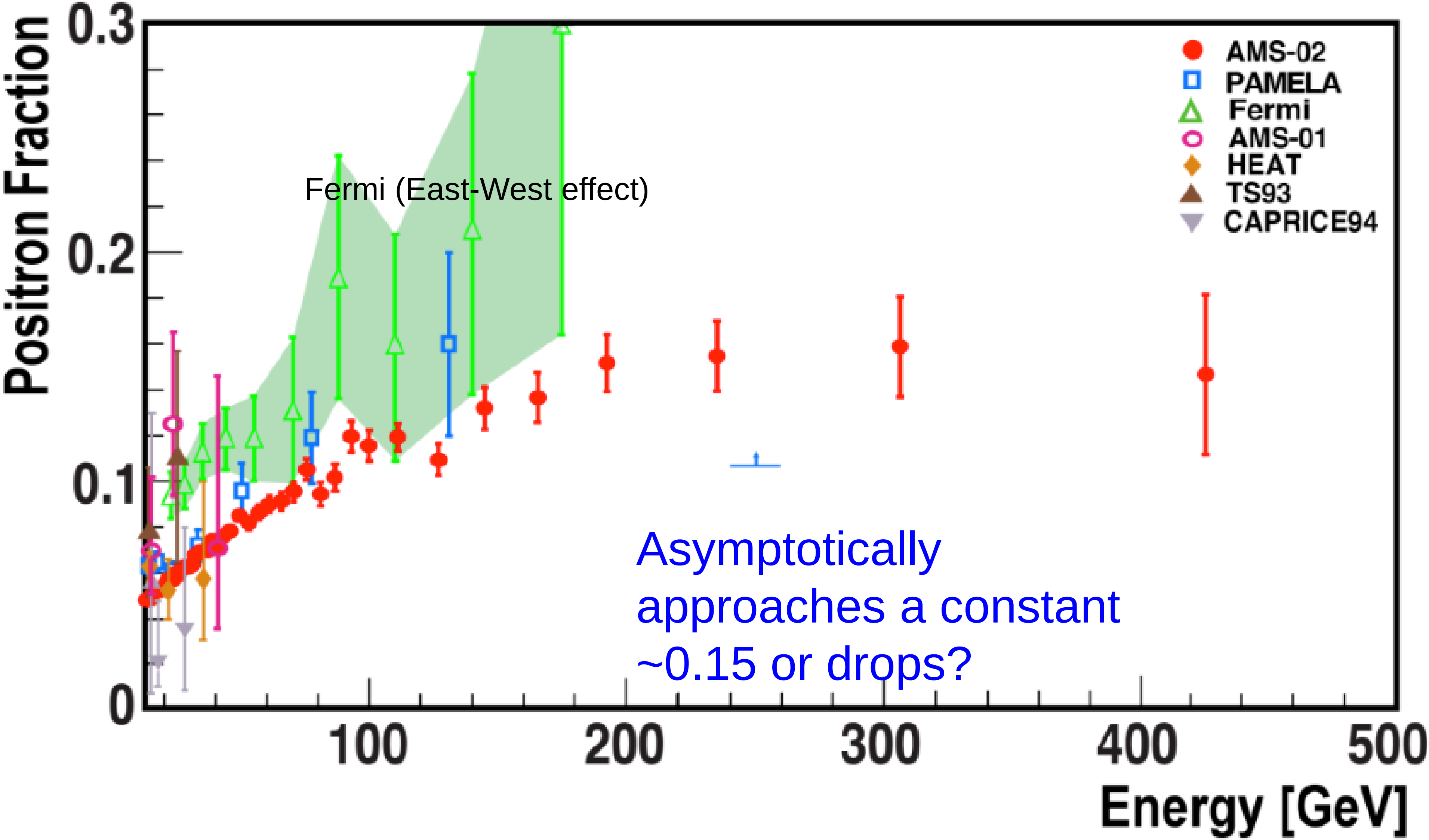
- Goal: Modulation of arbitrary spectrum (provided by a user) at the arbitrary epoch
- ApJ paper on the interstellar spectra of CR species is in progress

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

Positron Fraction from AMS-02: 2015

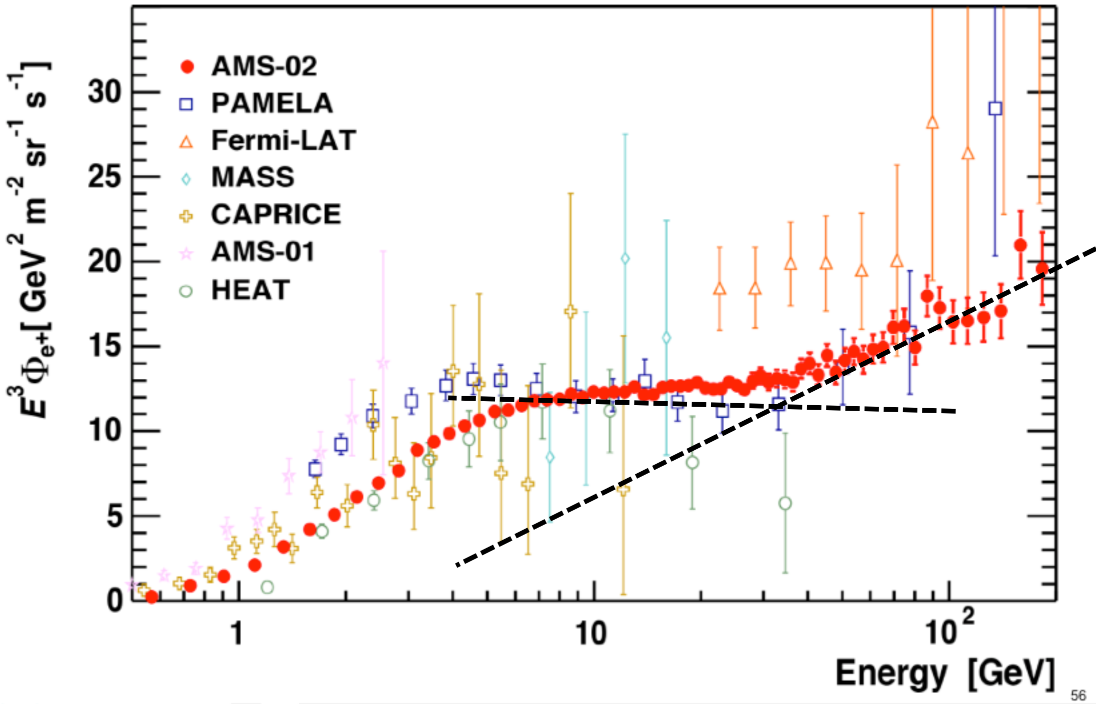


Asymptotically approaches a constant ~0.15 or drops?

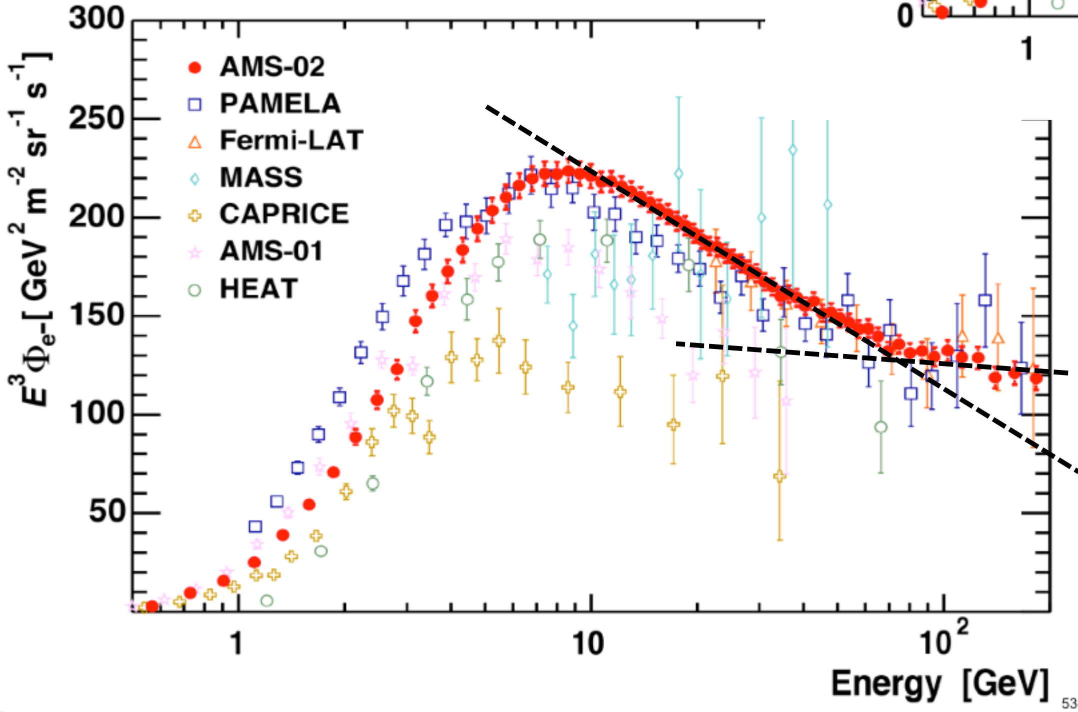
AMS-02 e^+ & e^-

- ✧ One should look at the fluxes of e^+ & e^-, not the positron fraction

Positron Flux

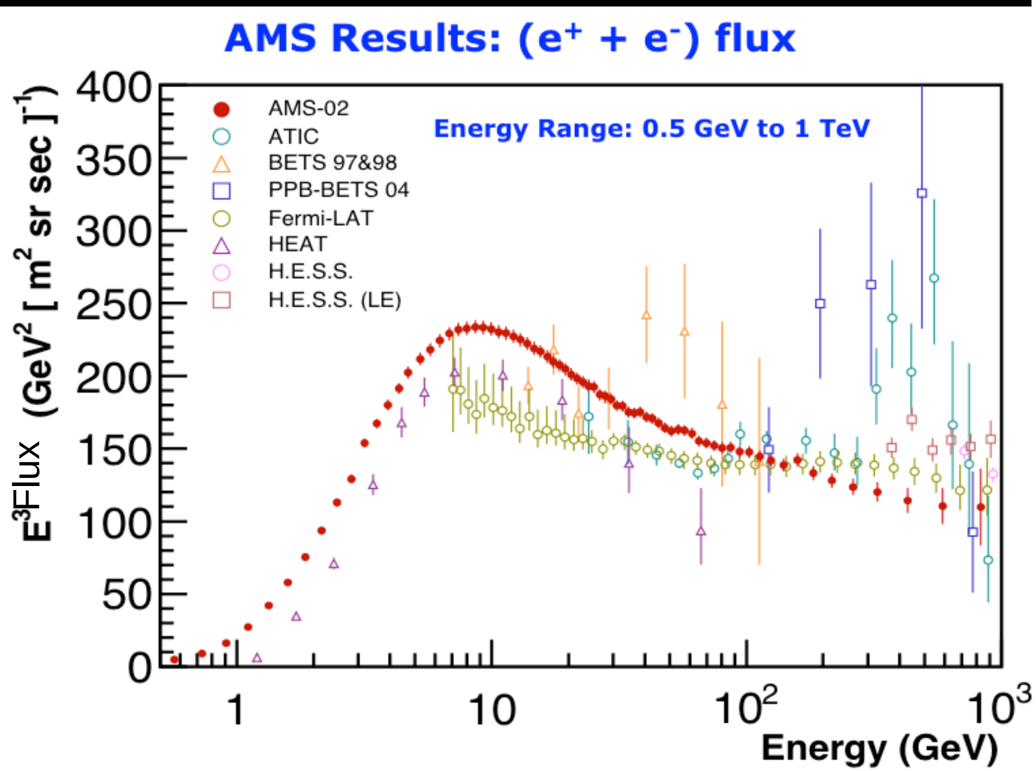


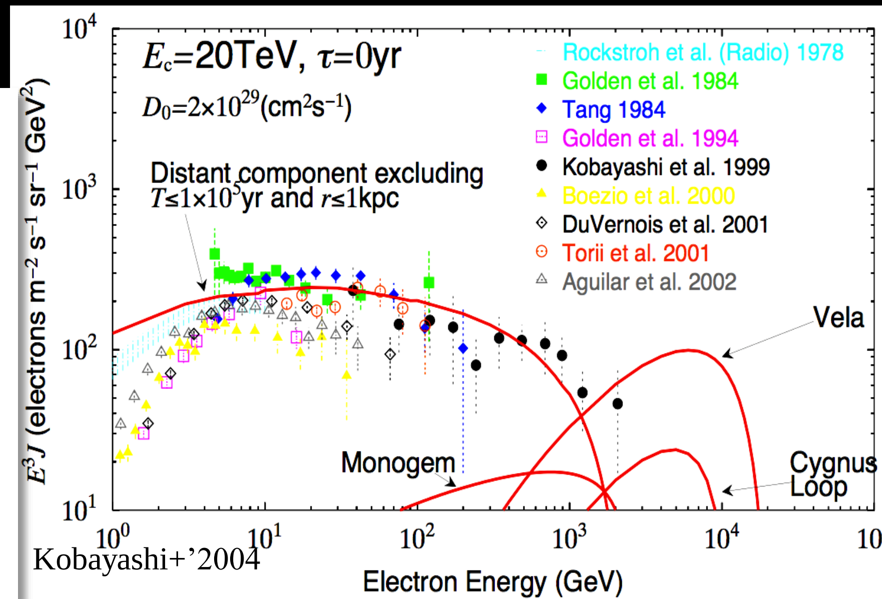
Electron Flux

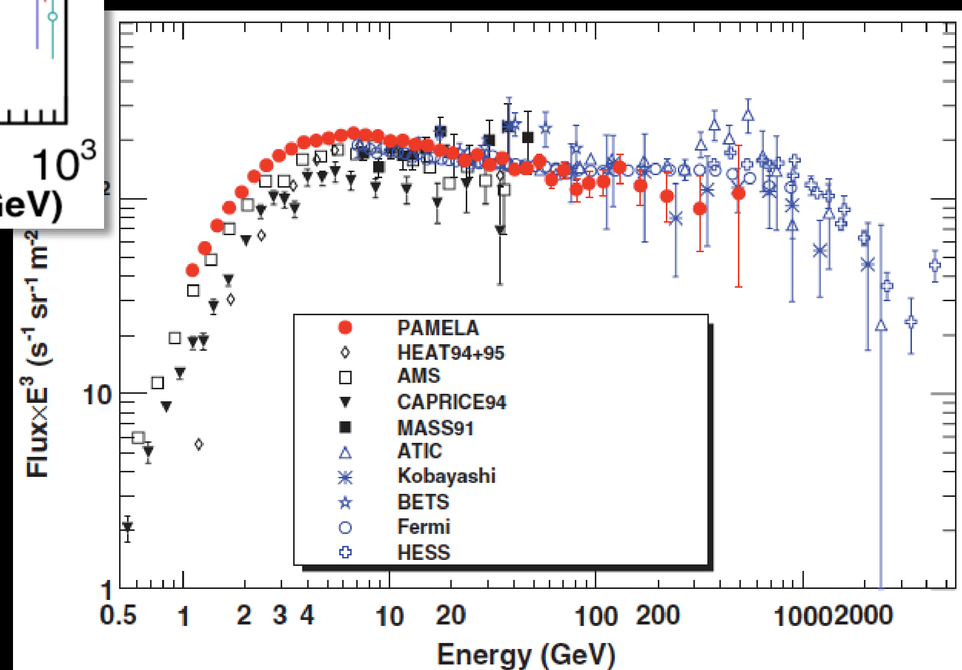


- ✧ Noticeable is a concave shape in both cases, a clear indication of an additional component (>20 GeV for e^+, >100 GeV for e^-)

All-electron spectrum





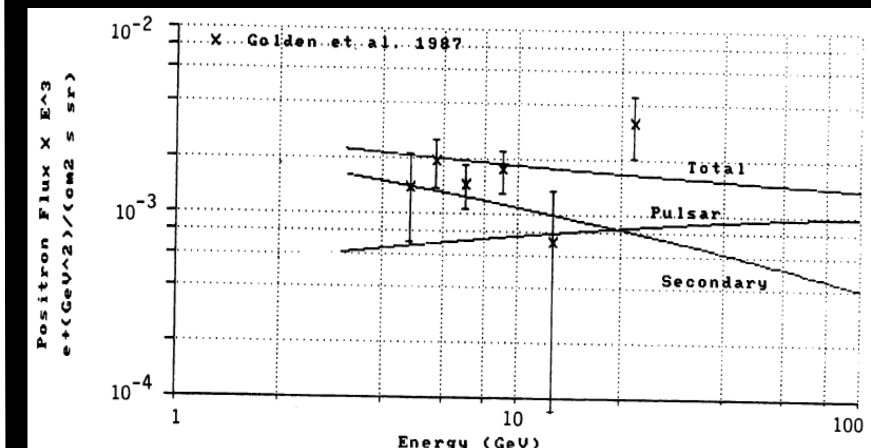


- ✧ Flatter than extrapolated from low energies
- ✧ Sharp cutoff at 1 TeV (HESS)
- ✧ Cannot be reproduced with a single power-law injection spectrum
- ✧ Monogem SNR: 86 kyr-old, at ~300 pc
- ✧ Need precise measurement and extension beyond TeV energies

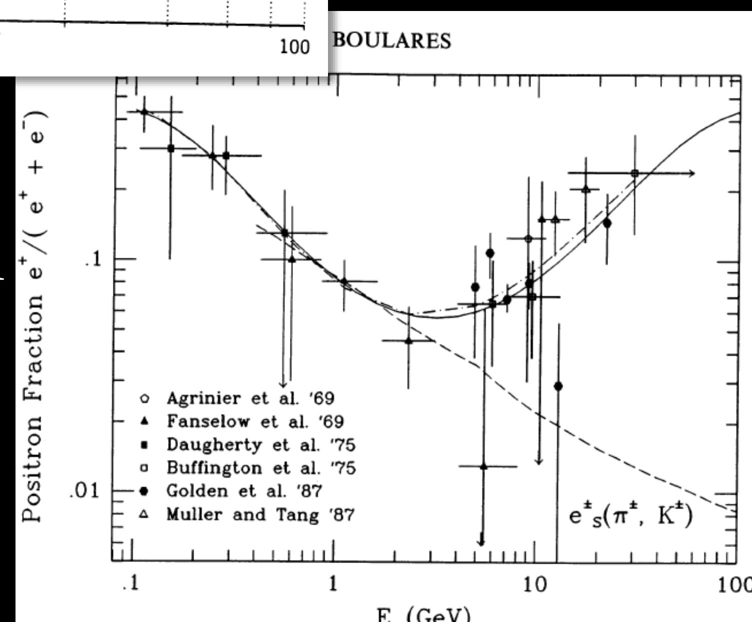
Old friends – pulsars

- ✧ 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

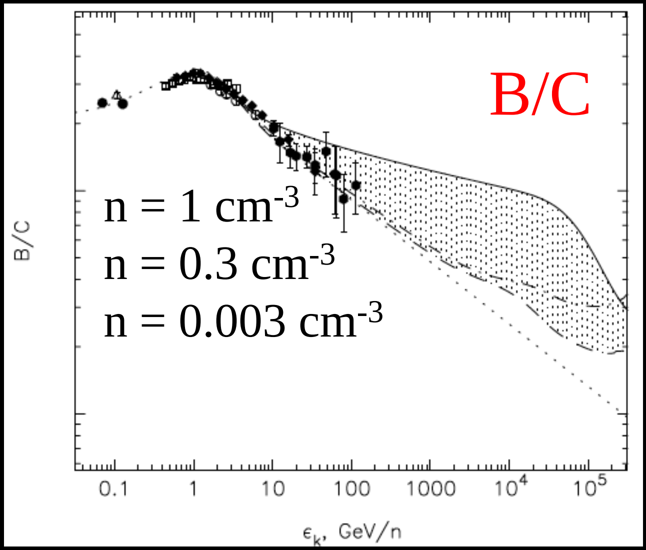


Reinvention of the Nested Leaky-Box – SNRs

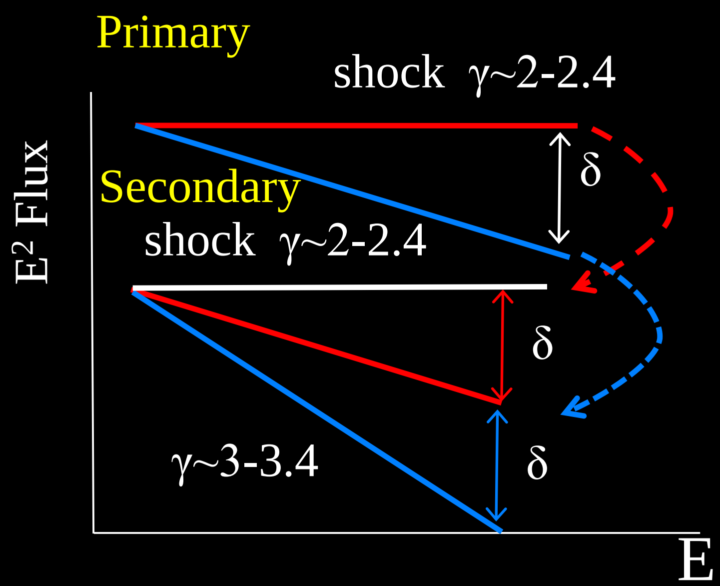
- Cowsik & Wilson 1974 "The nested Leaky-Box model for Galactic cosmic rays"
- Berezkho+2003 "Cosmic ray production in supernova remnants including reacceleration: The secondary to primary ratio"

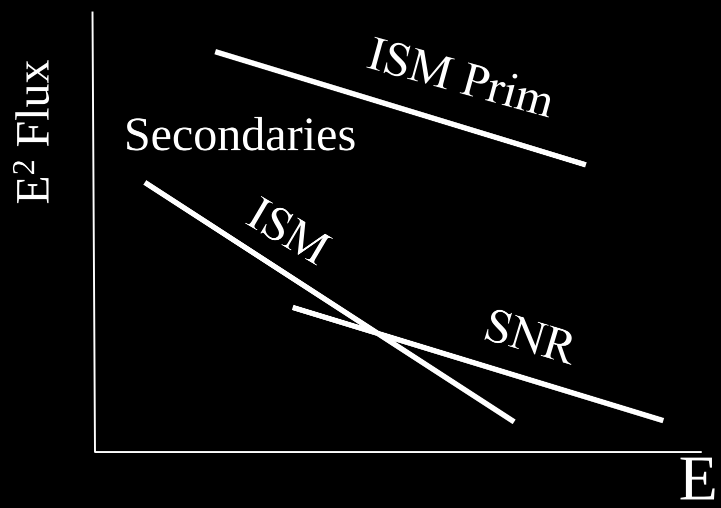
"The 'inner box' of cosmic ray confinement, corresponding to the region immediately surrounding the source, is assumed to have energy-dependent life time..."

"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..."



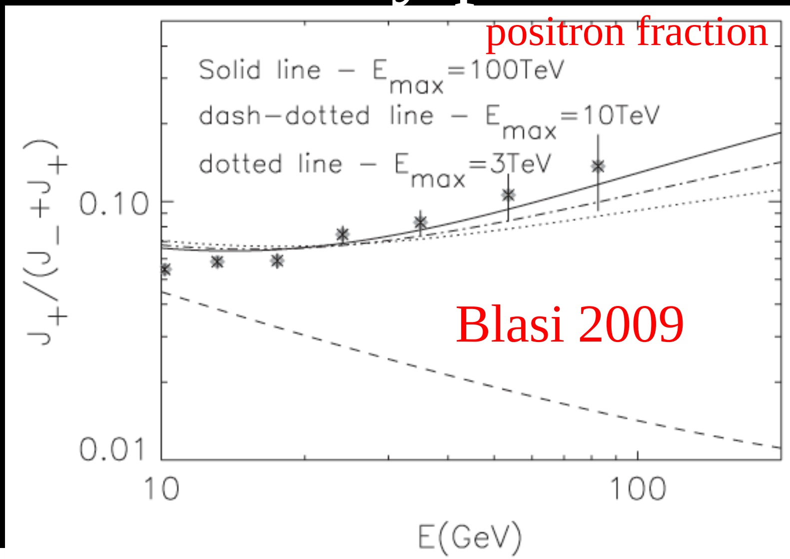
Secondary production in SNR shock

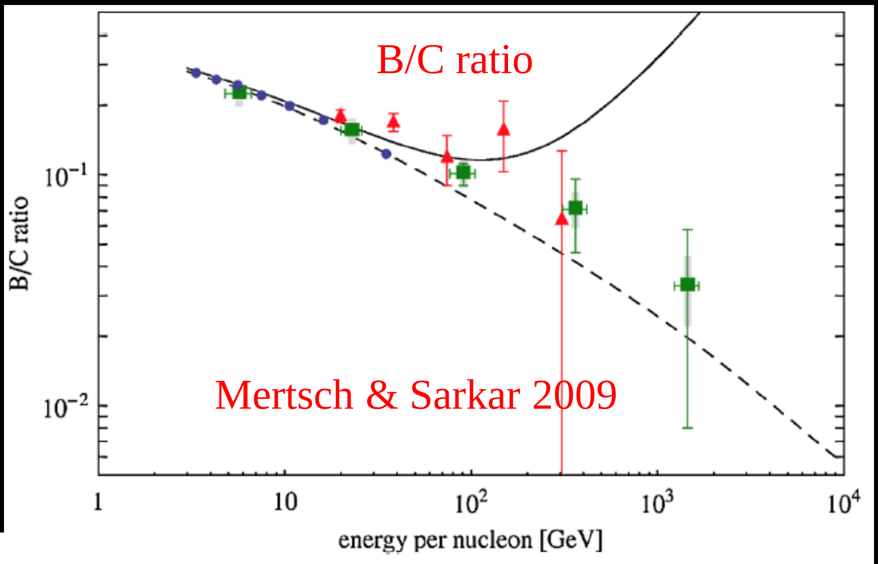


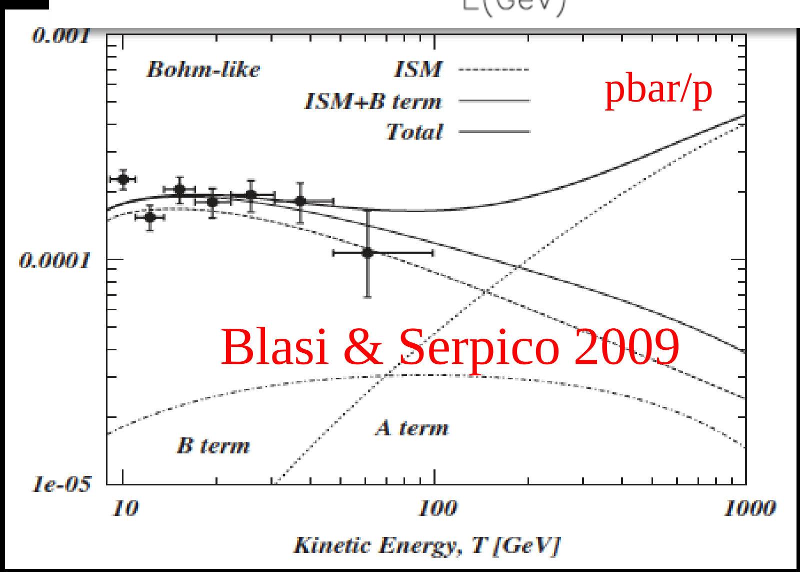


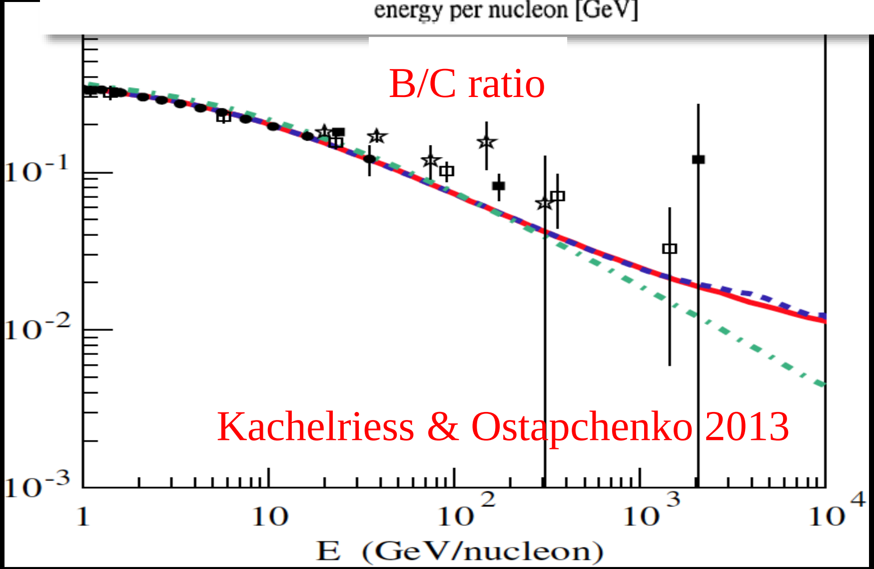
- ✧ Gas in the shock – target for p, A
- ✧ Flatter spectrum of p, A – flatter spectrum of secondaries
- ✧ Assume no energy losses
- ✧ δ~0.3-0.7 – effect of IS propagation (no losses)
- ✧ Same effect should be observed for ***any*** secondaries (pbars, B, $e^{+/-}$)
- ✧ Energy losses will modify the spectra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

Secondary production in a SNR shock



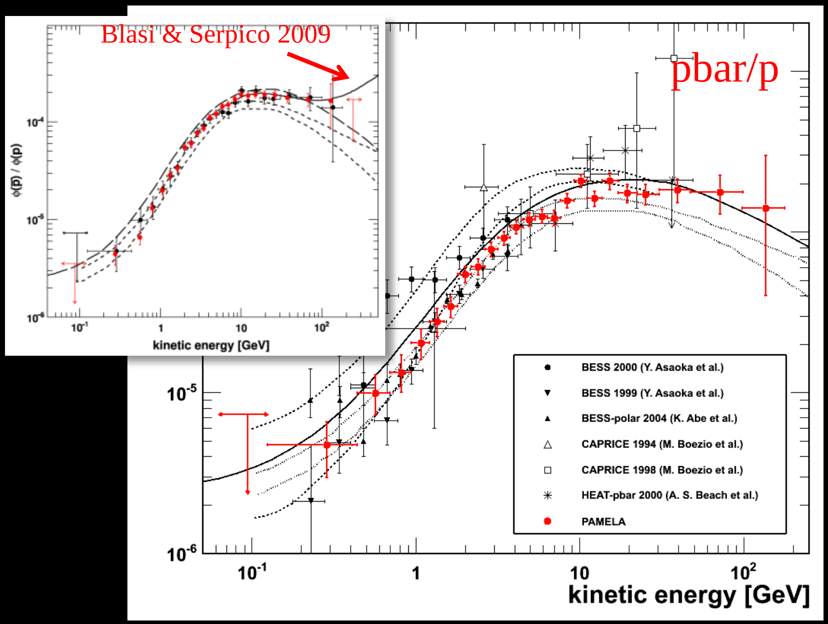


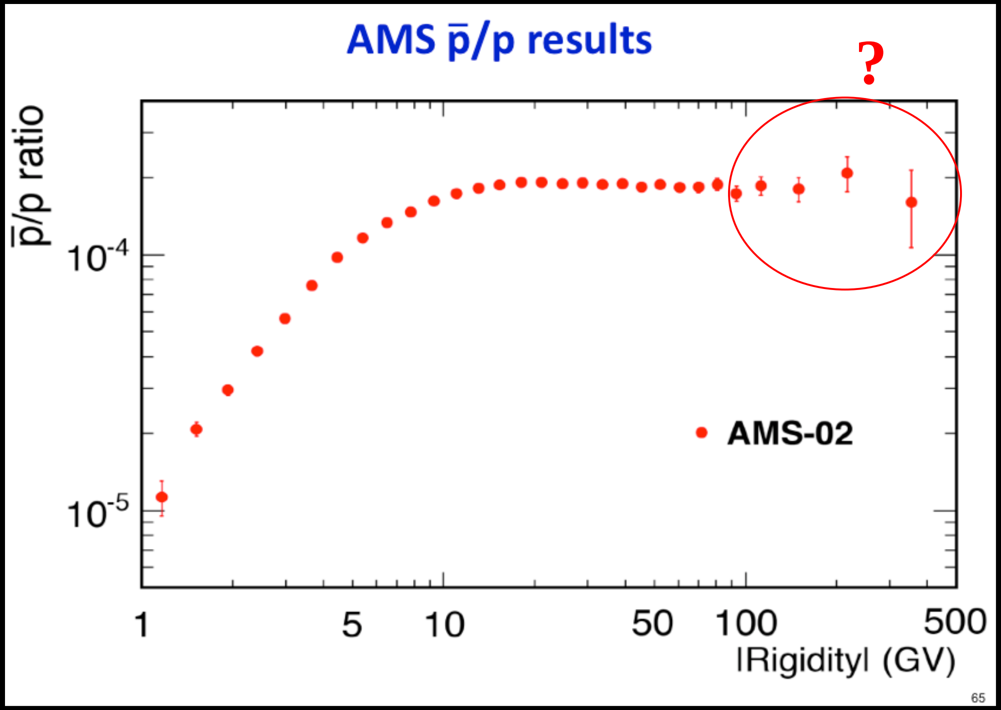


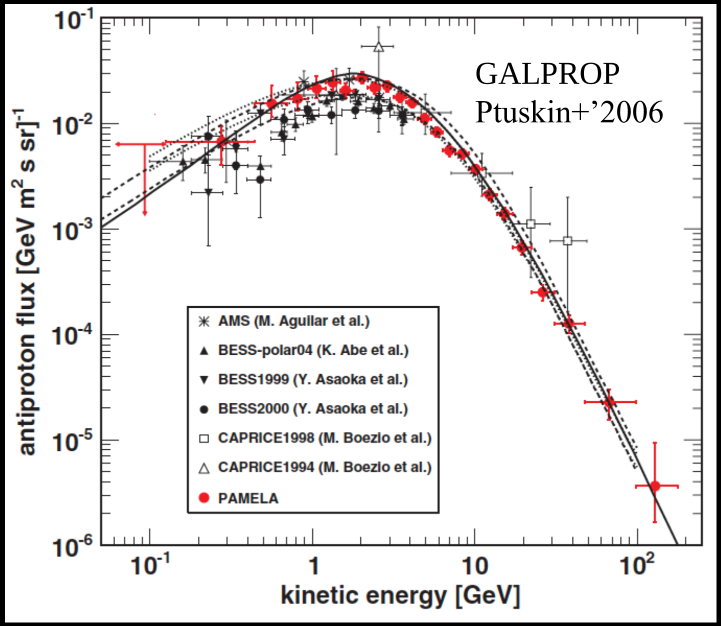


- ✧ The model assumptions are somewhat different, but all models predict a rise in the secondary products

pbar/p ratio

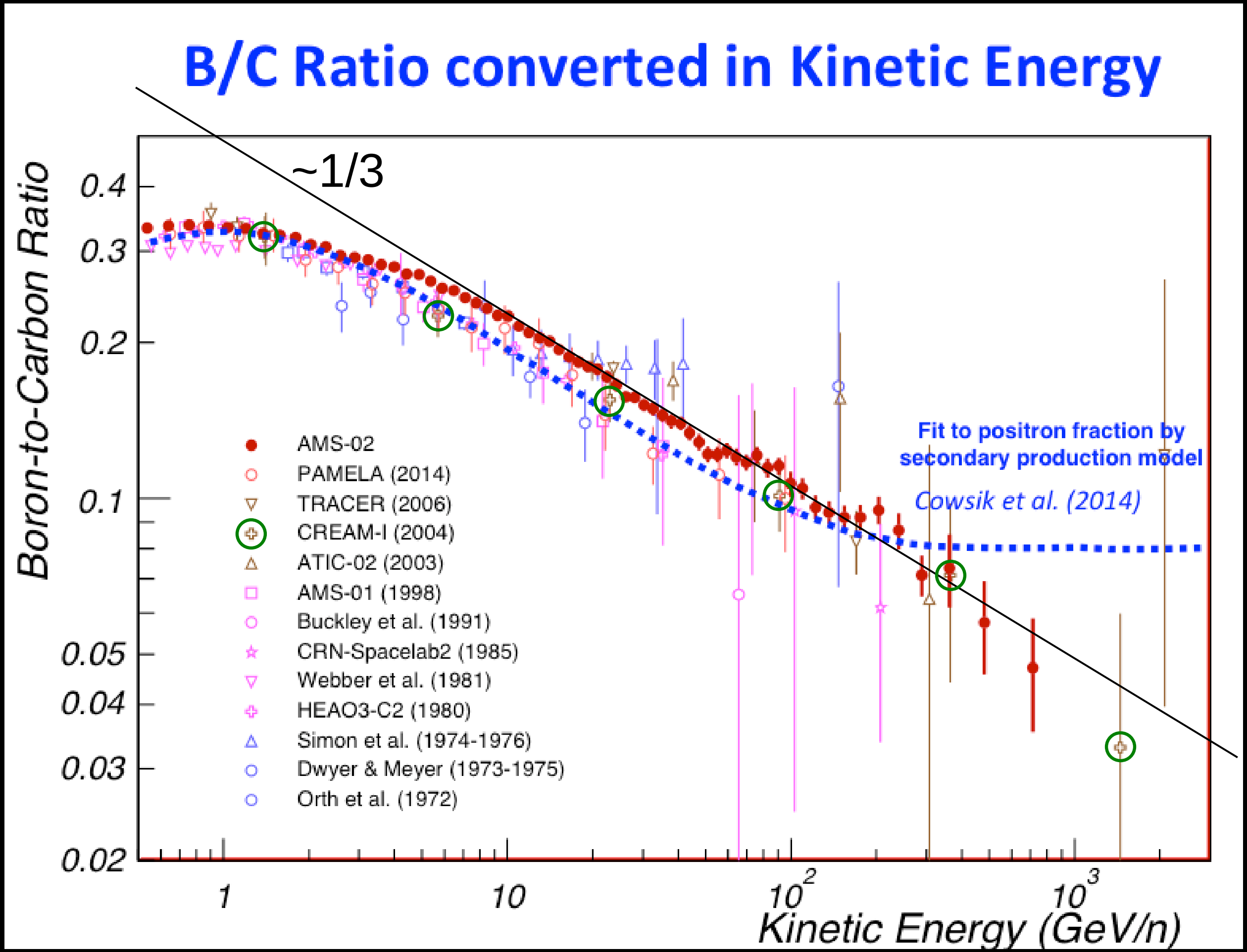






- ✧ The calculations were done in Ptuskin+'2006 with the CR p and He spectra without breaks and flattening above ~200 GV, so expect a bit of flattening in pbars >50 GeV
- ✧ New pbar production cross section is implemented in GALPROP (Kachelriess, IM, Ostapchenko'2015), which provides more pbars at HE, so stay tuned

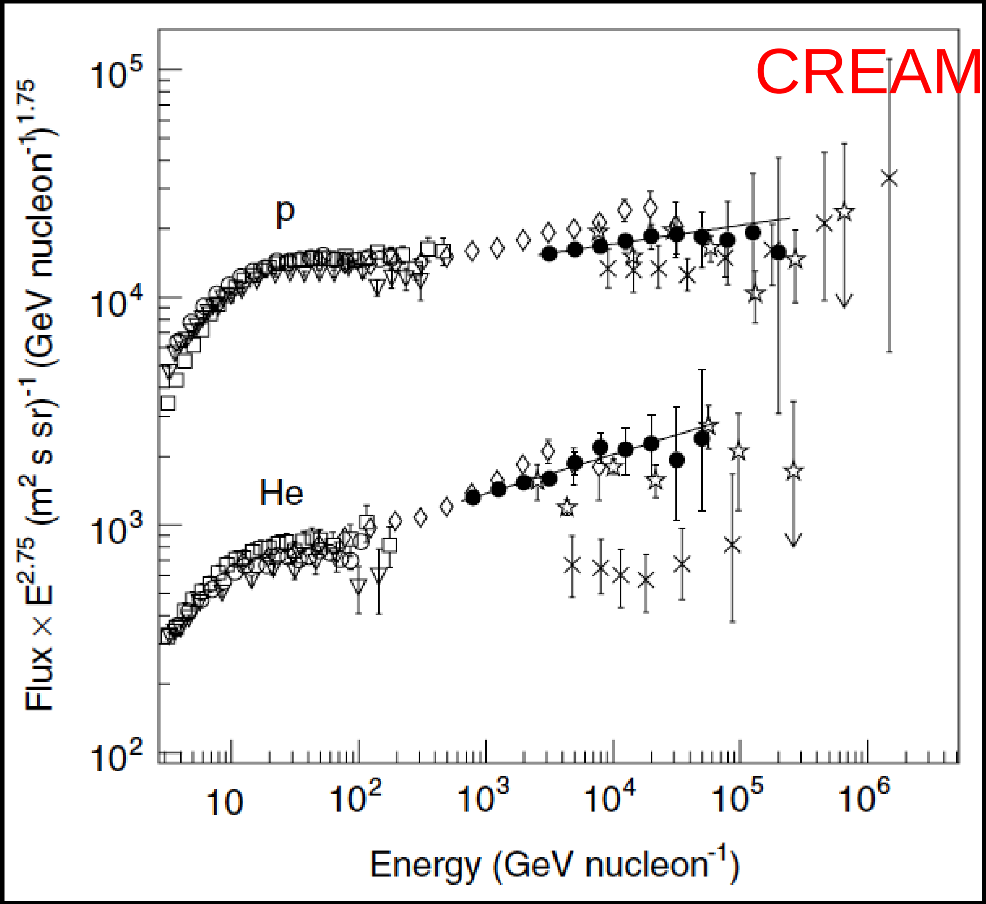
B/C ratio

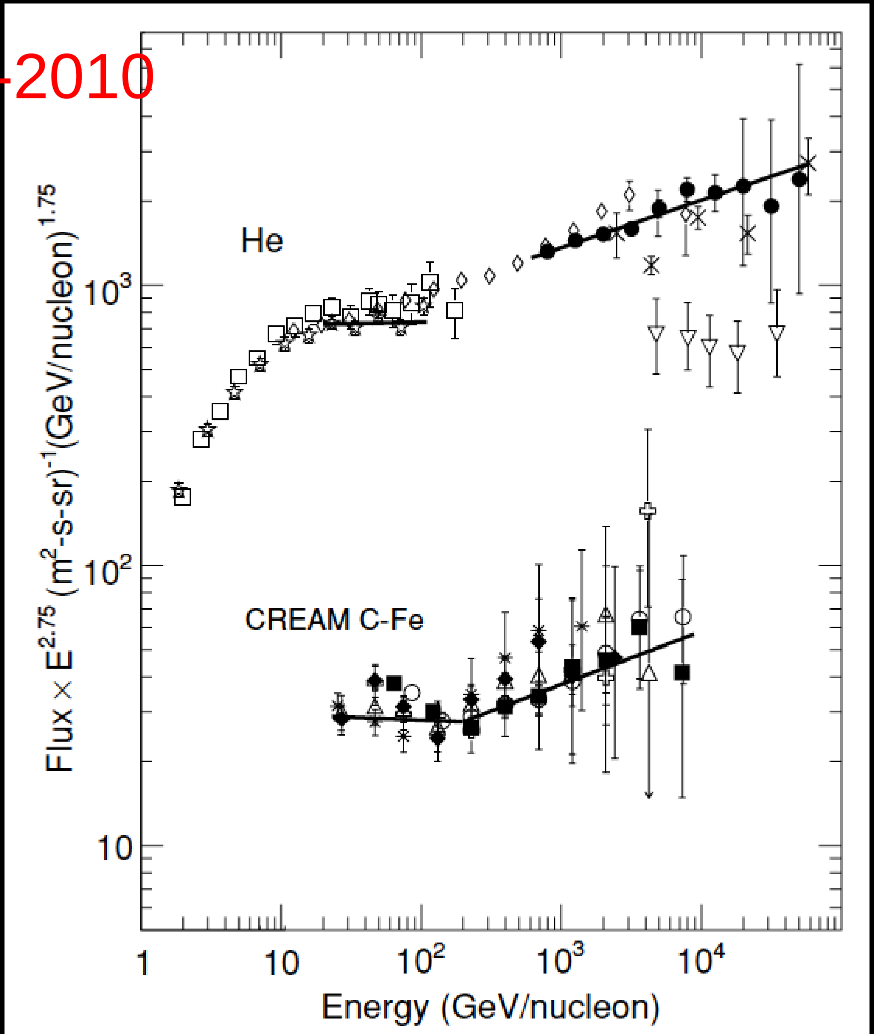


- ✧ Continues to fall up to ~2 TeV/nucleon (CREAM)
- ✧ No significant change in the slope of the B/C ratio
- ✧ The slope >7 GeV/n is ~1/3 – clearly supports Kolmogorov reacceleration model
- ✧ Rules out Cowsik+ model

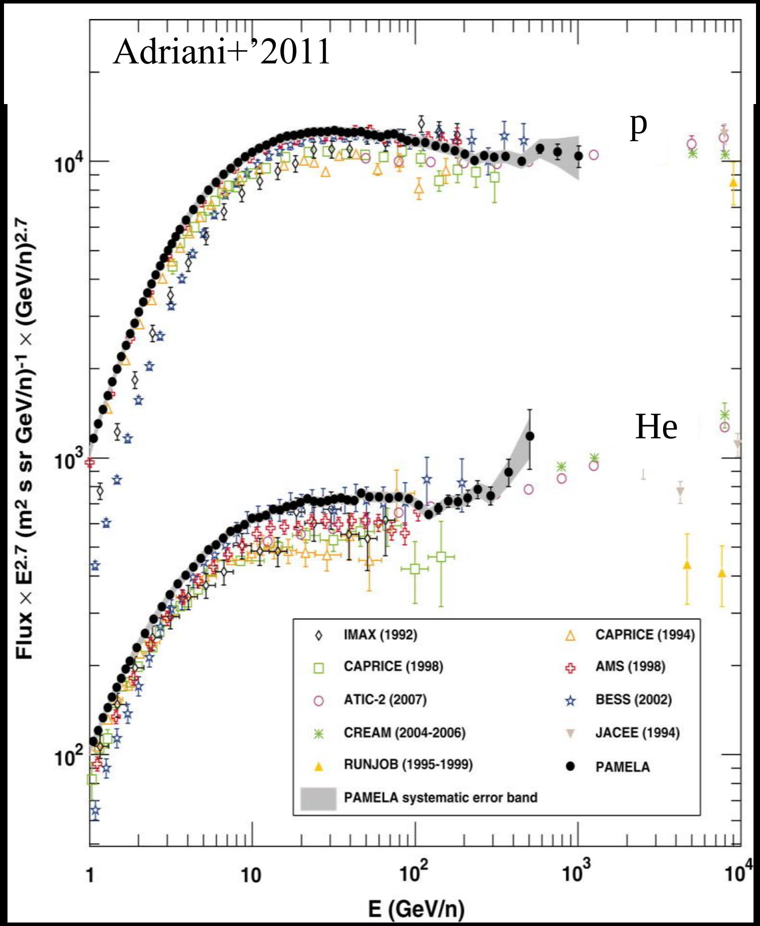
Breaks, breaks, breaks…

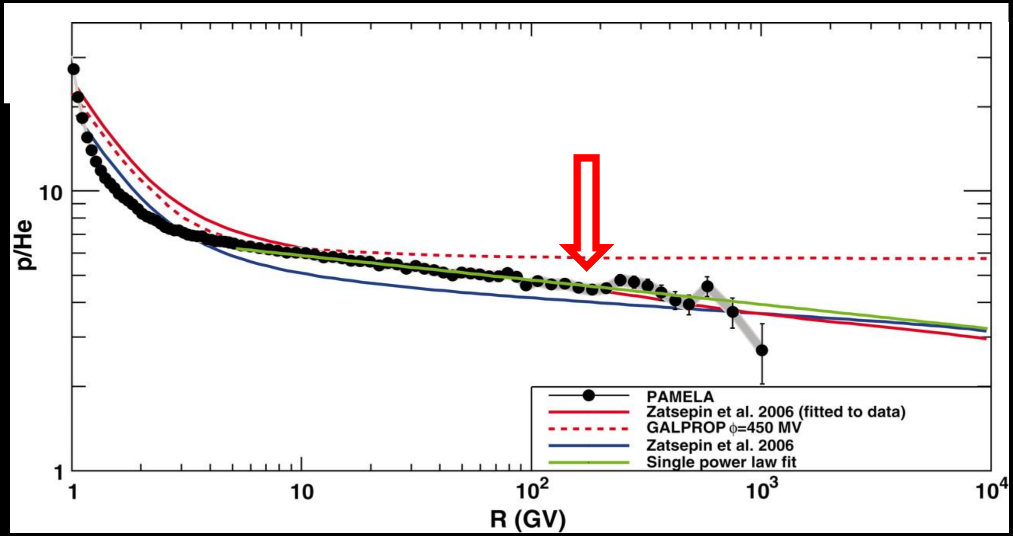
- CREAM papers of 2010 definitively indicate He spectrum is flatter than p at HE
- Hint on breaks in p and He spectra
- Break in C, O, Ne, Mg, Si, Fe spectra at the same E/nucleon, i.e. at the same rigidity
- He and heavier nuclei possibly have the same spectral index at HE





Break in the CR p and He absolute fluxes

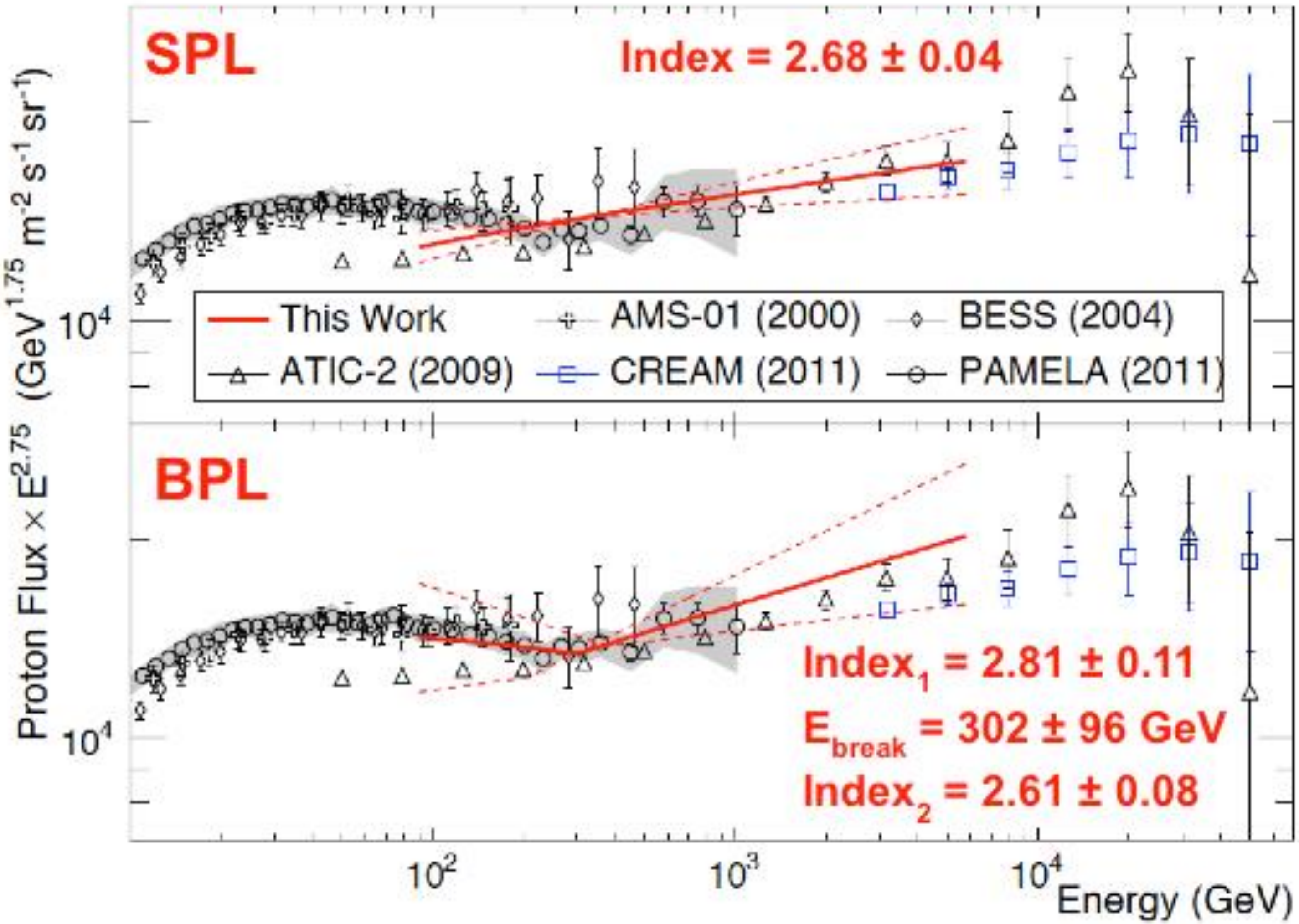




- ✧ Data from several experiments (BESS, AMS-01, ATIC'2009, CREAM'2010, PAMELA'2011) are all consistent and indicate spectral hardening above ~100 GeV/nucleon
- ✧ p/He ratio vs. rigidity R is smooth
- ✧ He spectrum is flatter than proton spectrum
- ✧ Heavier nuclei seem to share the same trend
- ✧ New data may provide us with a hint to the origin of high energy CRs

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

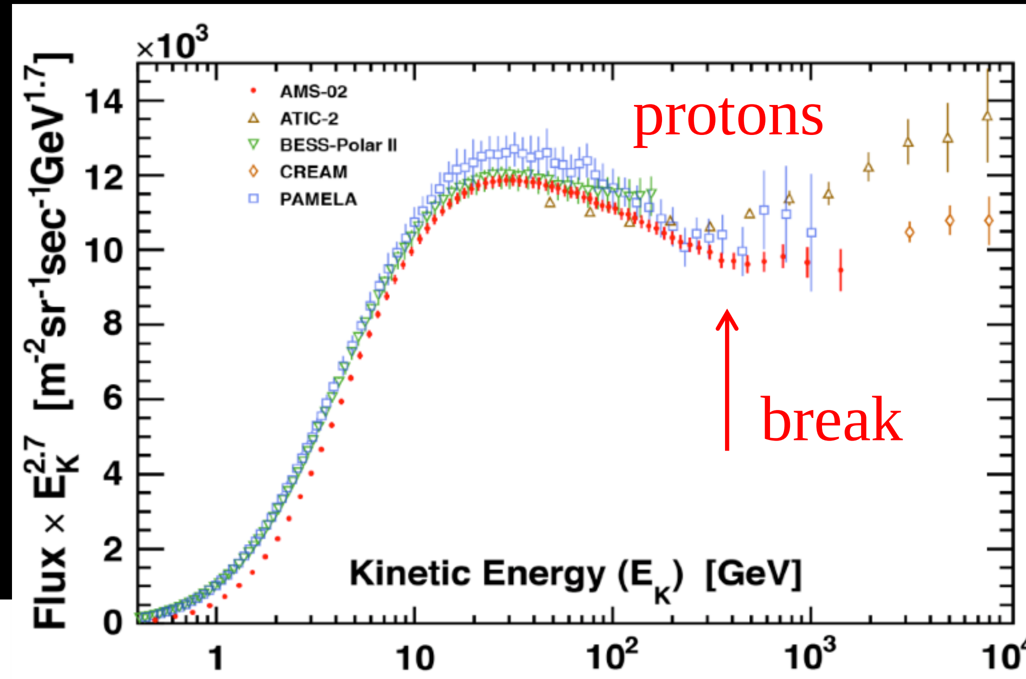
Fermi – Earth limb observations

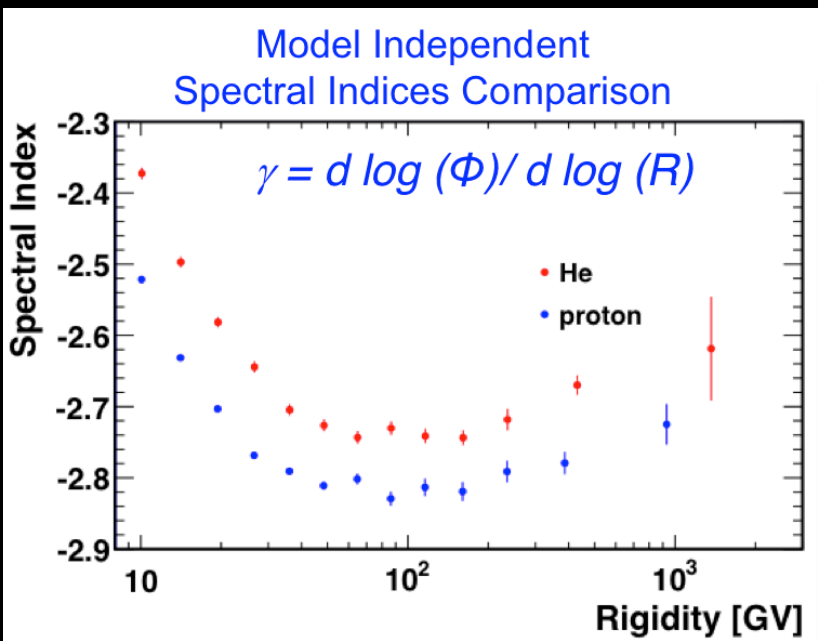


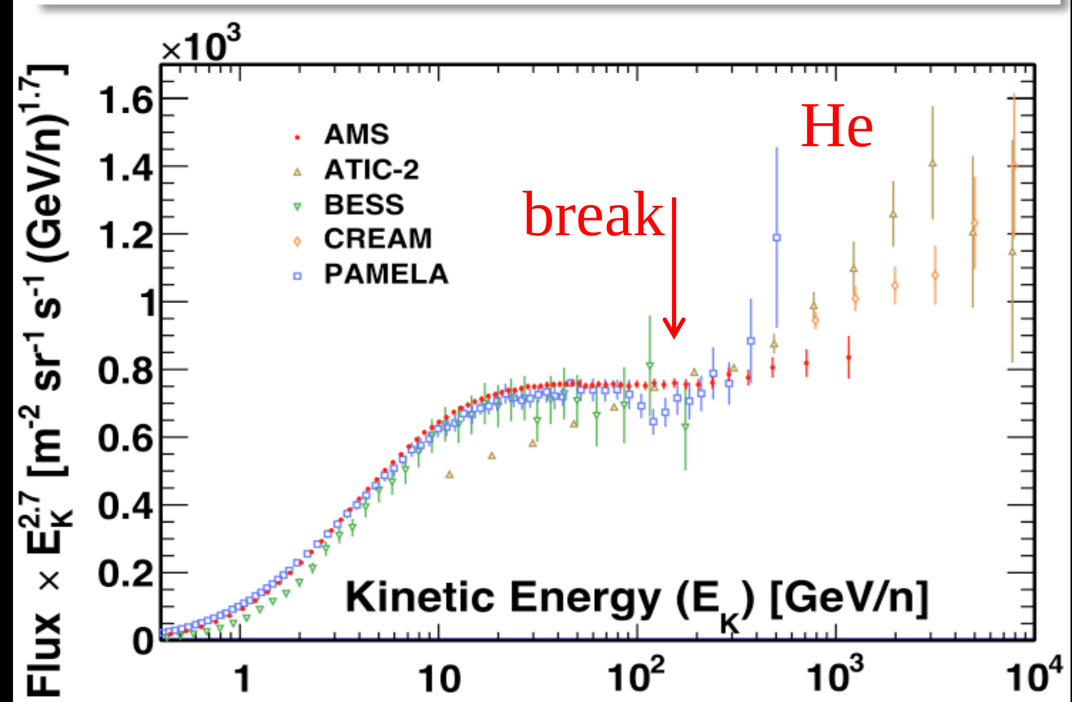
March 28, 2014 W. Mitthumsiri Page 10 / 12

AMS-02 p & He

- ✧ The indices of p and He spectra differ by ~0.1 in a wide energy range
- ✧ Expansion of the SNR into the stellar wind enriched with heavy elements?



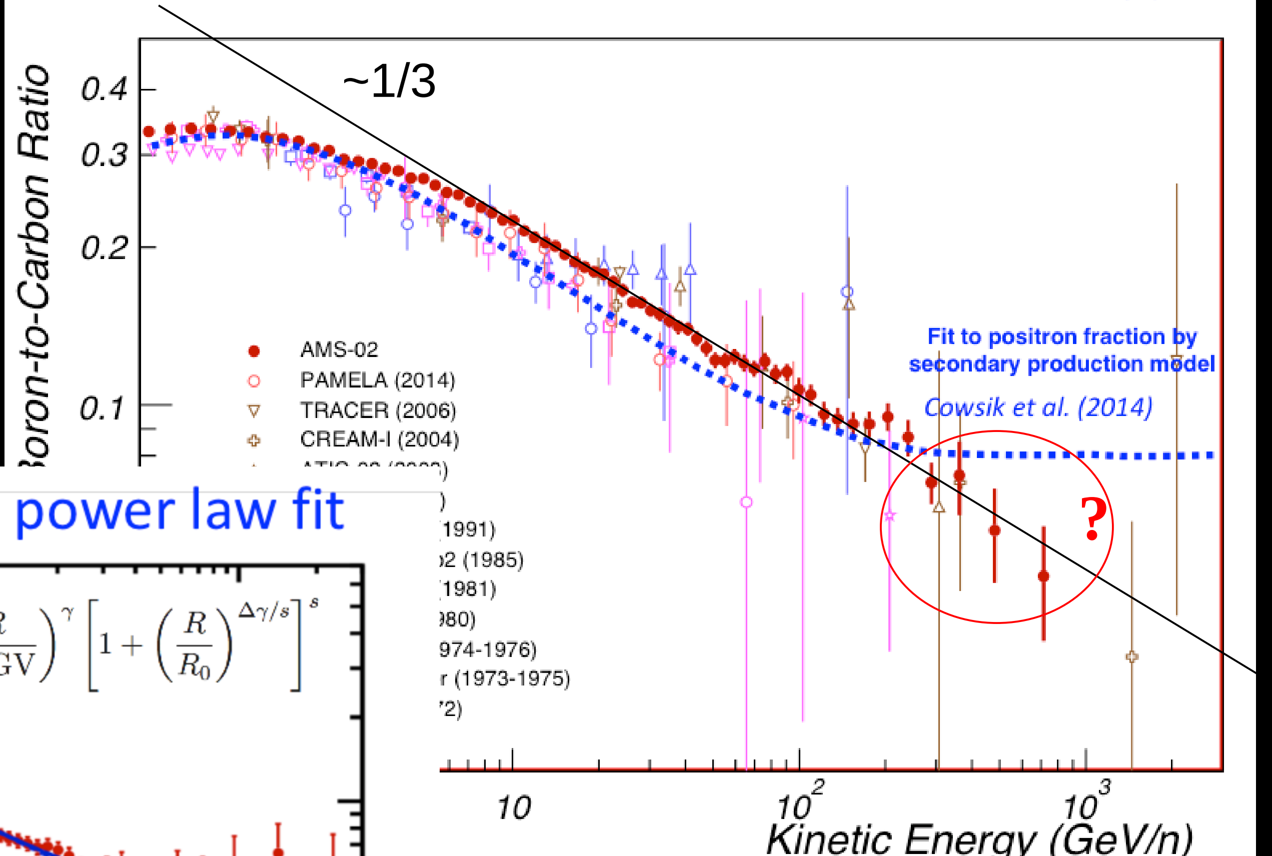




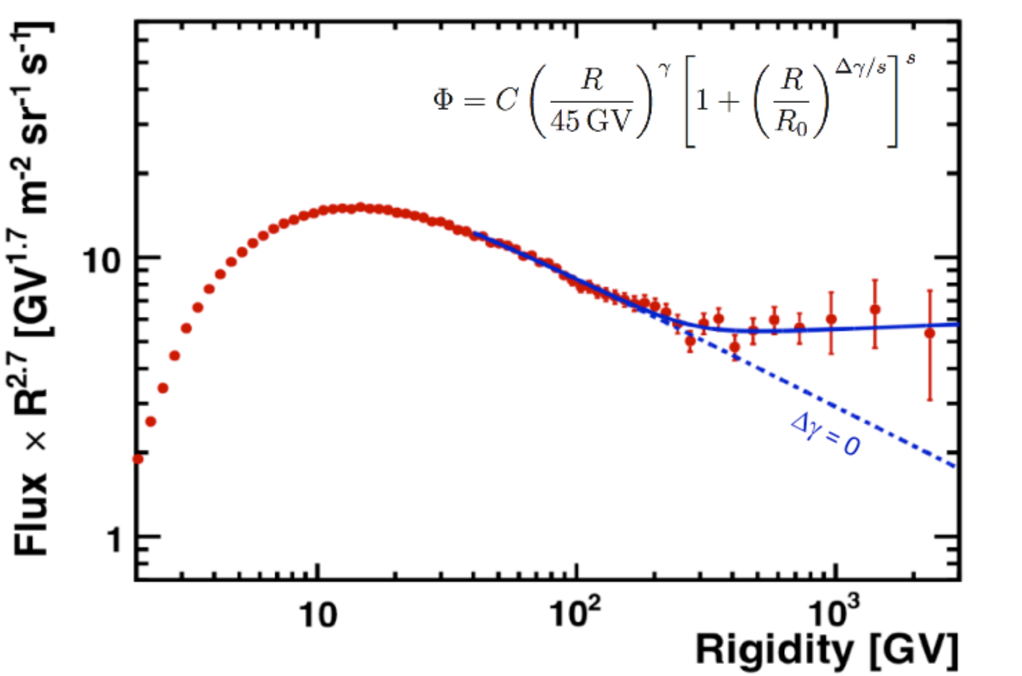
AMS B/C ratio

- ✧ No significant change in the slope of the B/C ratio
- ✧ A break in Li spectrum at approx the same rigidity as for p and He!

B/C Ratio converted in Kinetic Energy



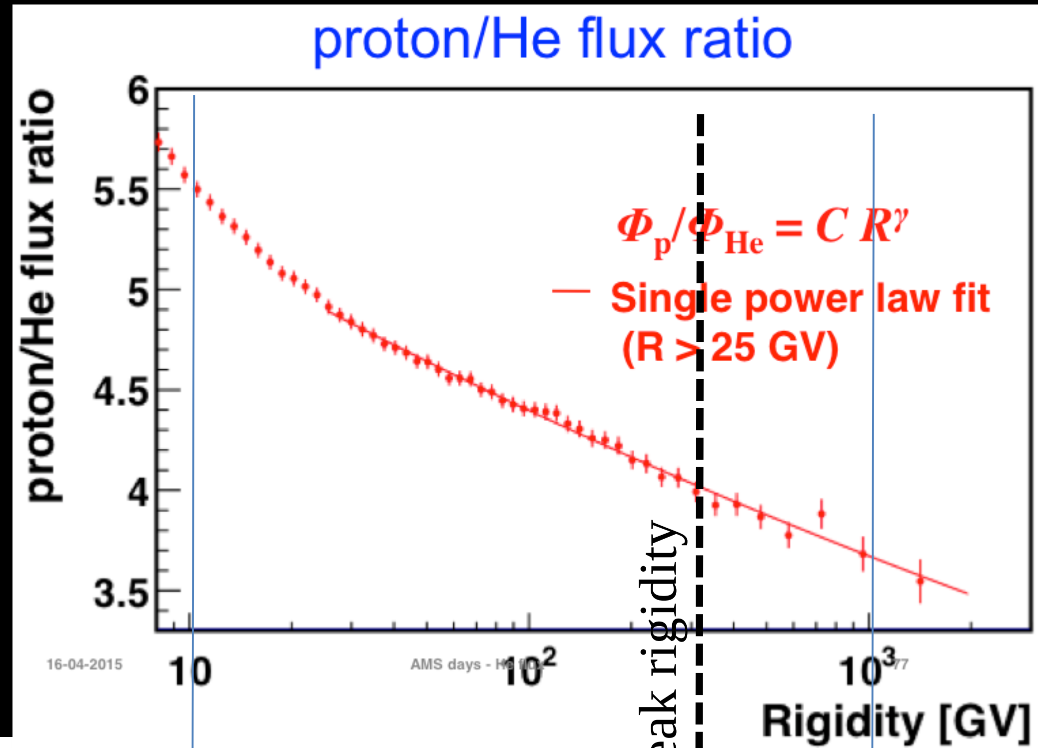
Lithium flux with two power law fit

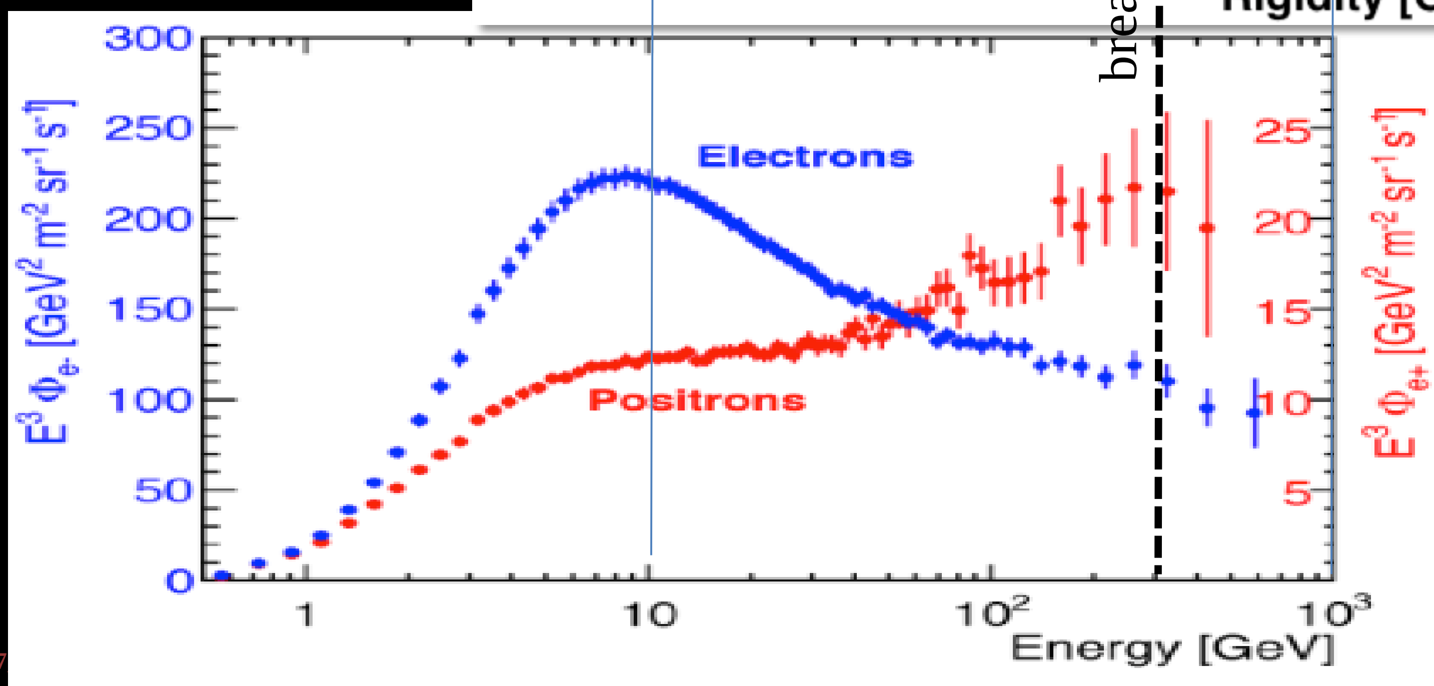


Slope changes at about the same rigidity as for protons and helium

AMS p/He ratio

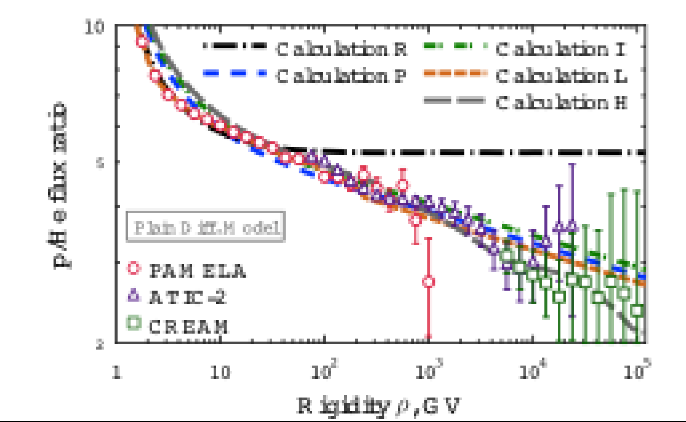
- ✧ The ratio is featureless
- ✧ Indicates that the same (unknown) mechanism works for p, He, and possibly heavier elements
- ✧ What's about electrons and/or positrons
- ✧ More statistics is necessary

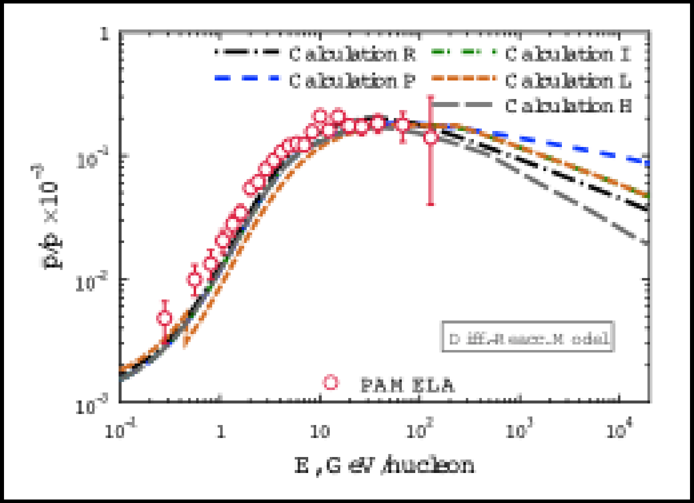


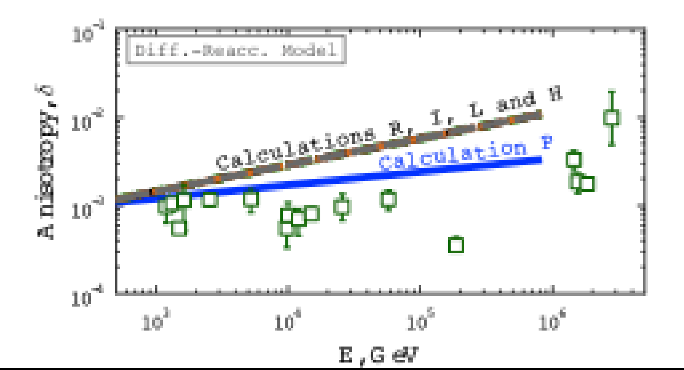


Possible scenarios

- P/He ratio is tuned in all scenarios except Reference scenario
  - Propagation (P)
  - Injection spectrum (I)
  - Local source at LE or HE
- 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
- Only scenario L can explain the sharp break in the p, He spectra
- Await for more accurate data

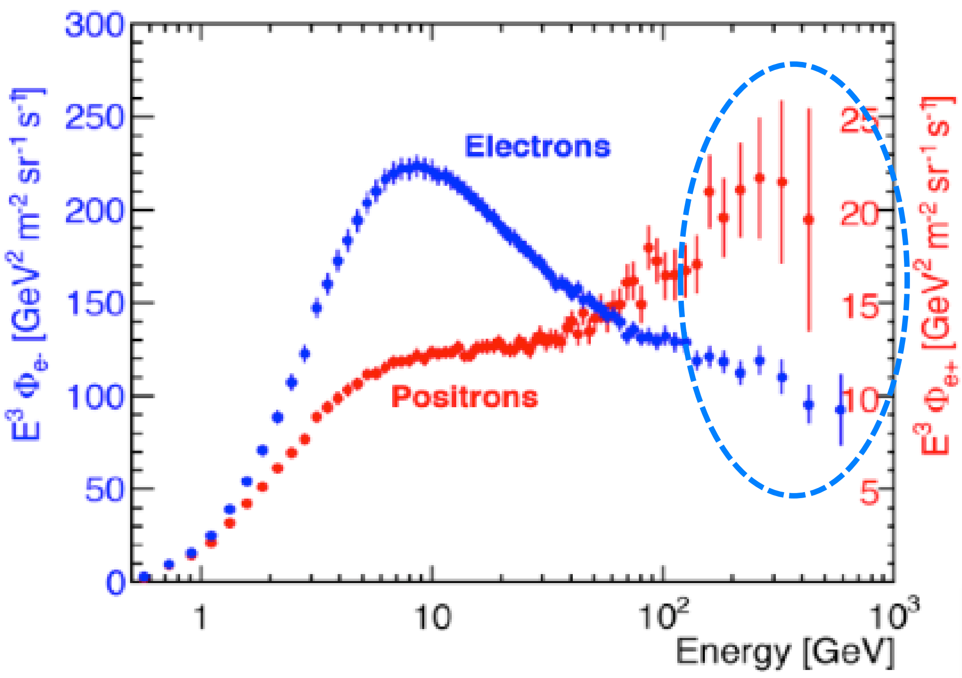


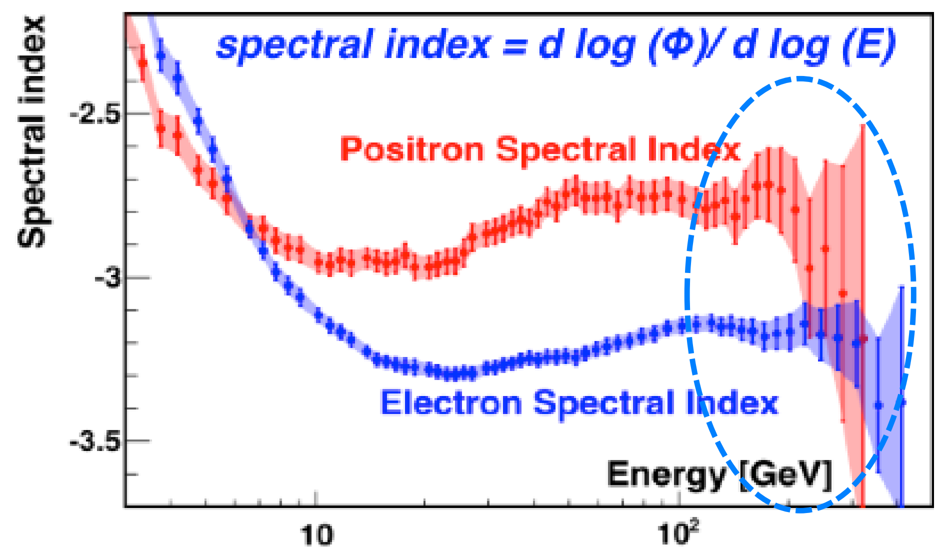




Vladimirov+'2012, ApJ 752, 68

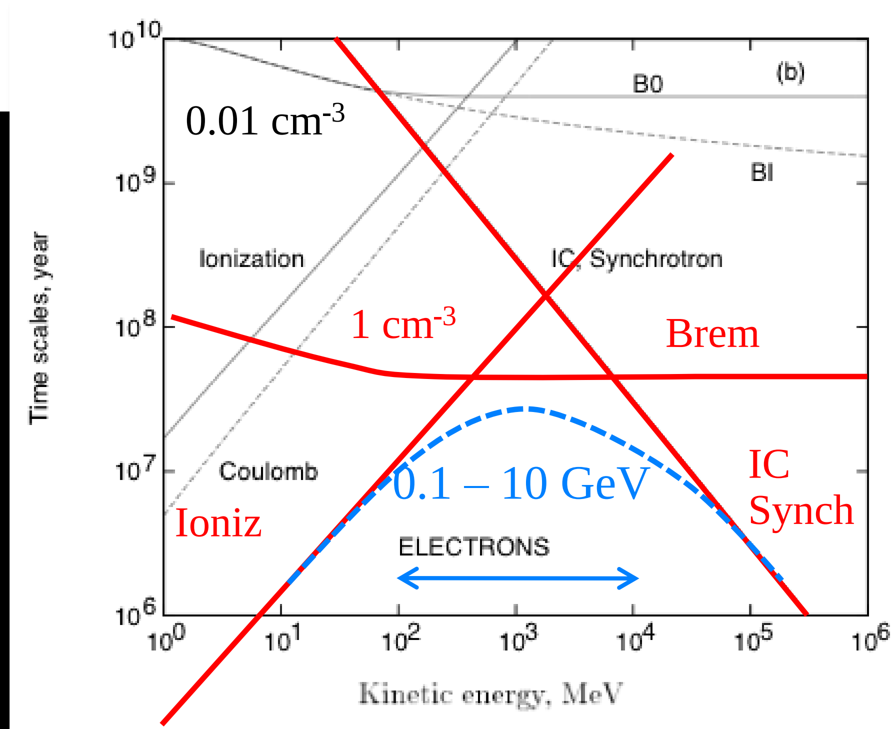
The Electron Flux and the Positron Flux



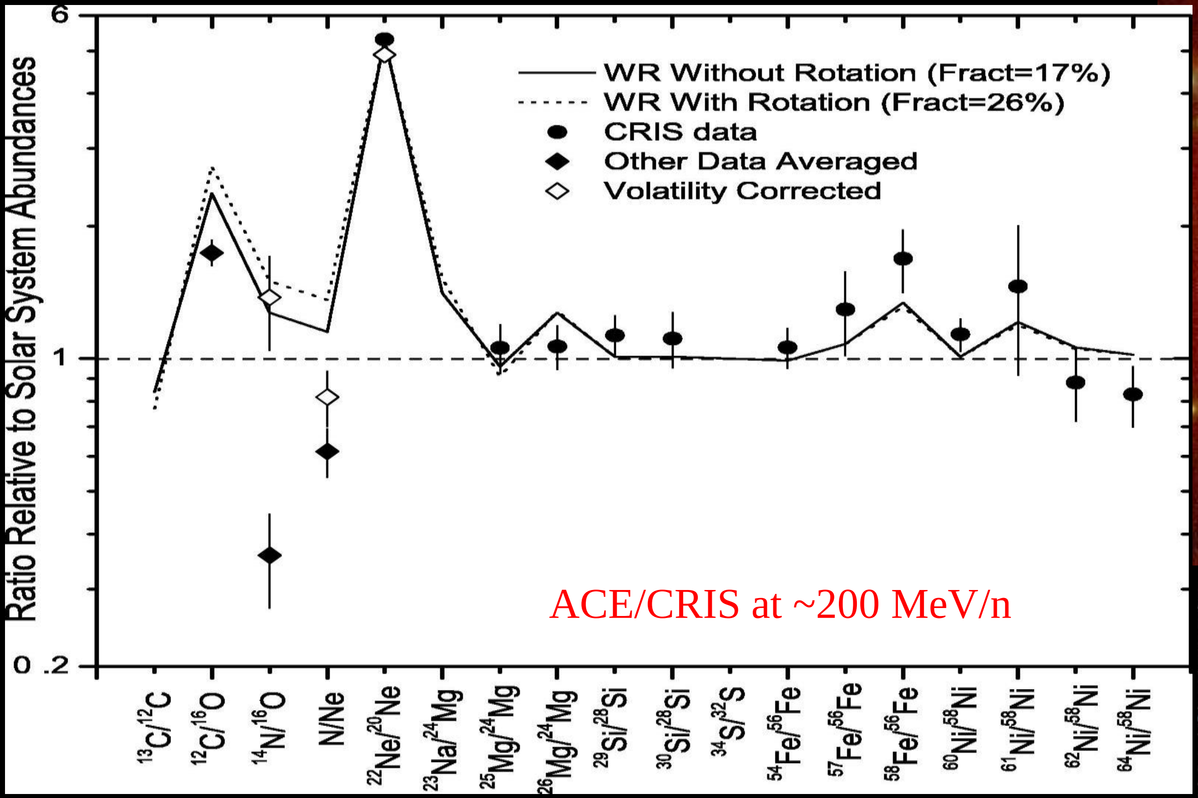


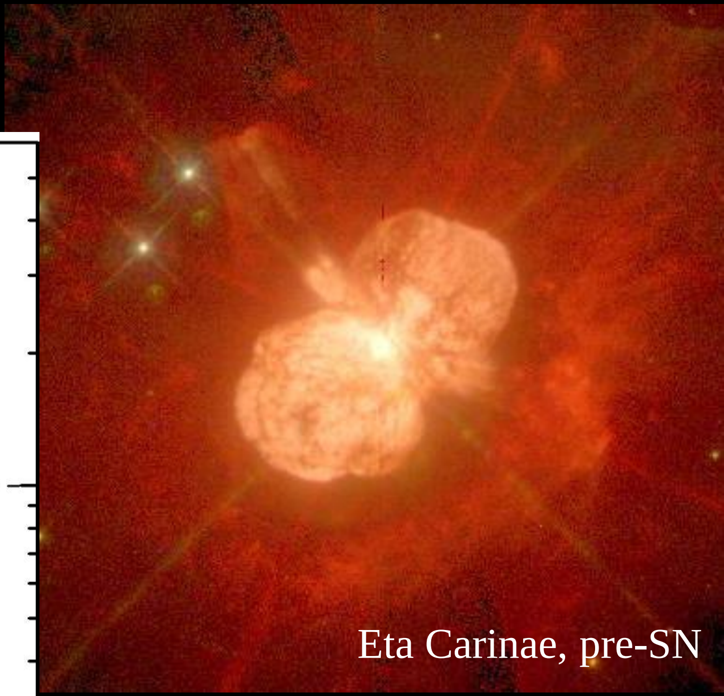
Energy losses of electrons

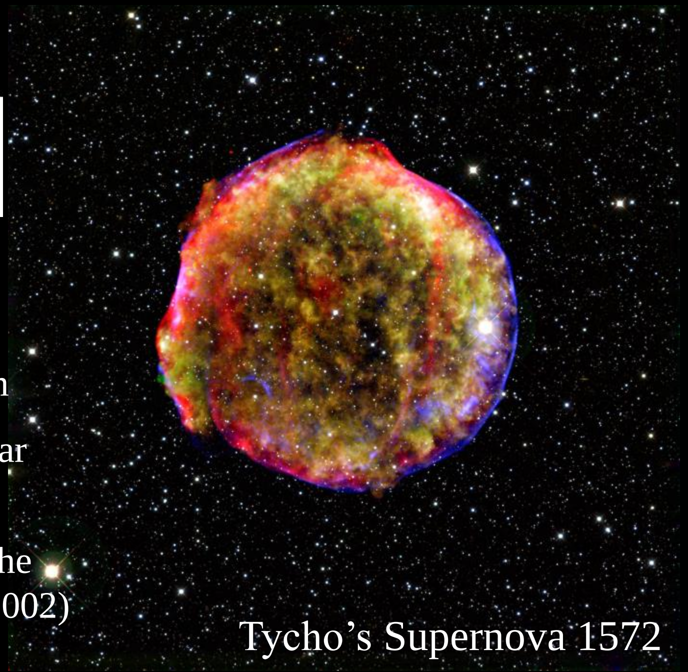
- ✧ The ionization and Coulomb losses are calculated for the gas number density 0.01 cm^{-3} & 1 cm^{-3}
- ✧ Min losses are between 0.1 – 10 GeV (τ ~ 10 Myr) and increase fast toward LE and HE
- ✧ Cutoff shape in *e*− and *e*+ spectra at HE will tell about the distance to the sources



Cosmic ray sources

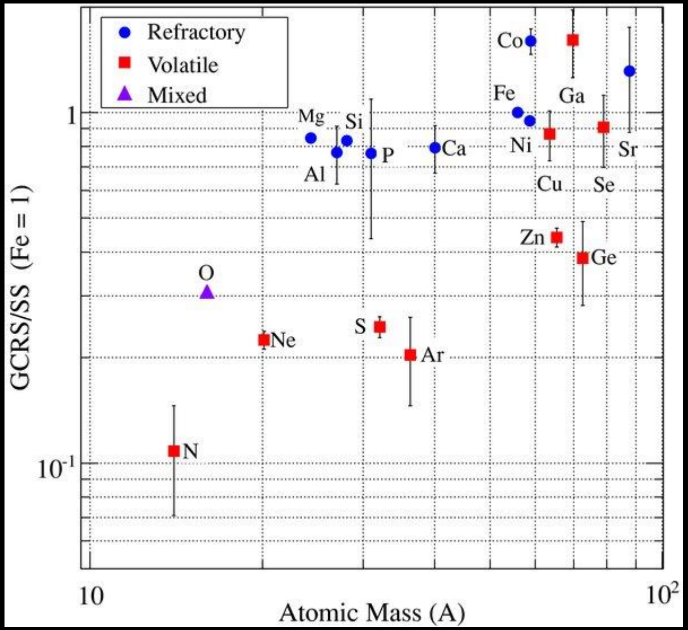



Eta Carinae, pre-SN

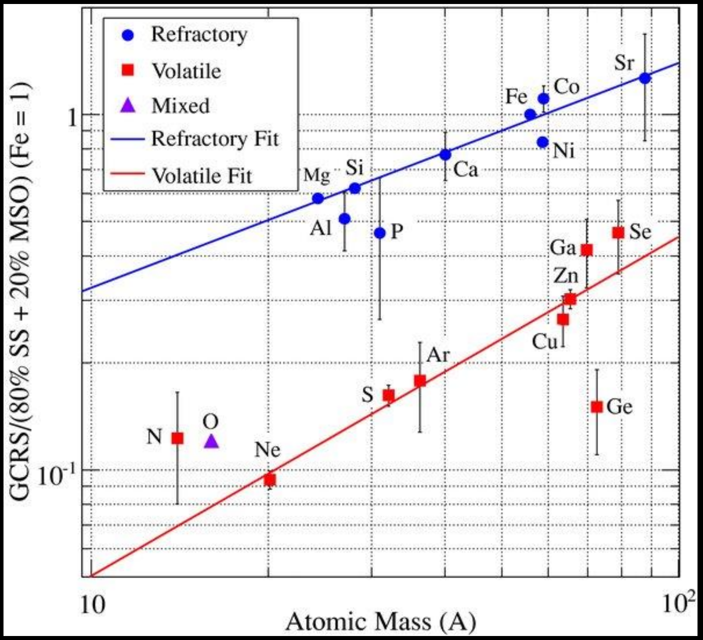

Tycho's Supernova 1572

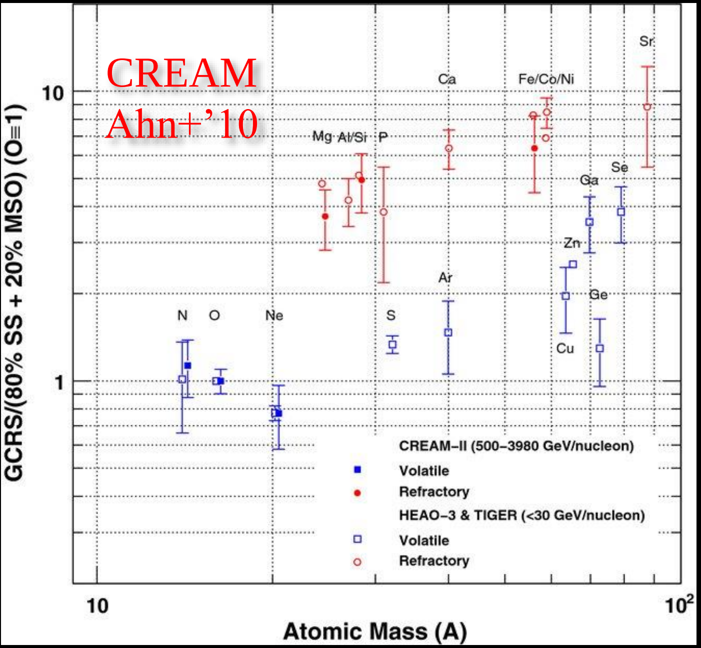
- Anomalous isotopic ratios are known since 1970s (Fisher+'75, Garsia-Munoz+'79 – Chicago CR Telescope/IMP-7)
- Some isotopes in CR sources are more abundant than in the solar system
- May indicate that ~20% of CR particles are coming from Wolf-Rayet star winds
- Note recent papers on overabundance of Fe^{60} on the ocean floor and in the lunar soil hinting at a close SN ~2.2 Myr ago (see also ACE talk S13.00002)

The origin of cosmic rays



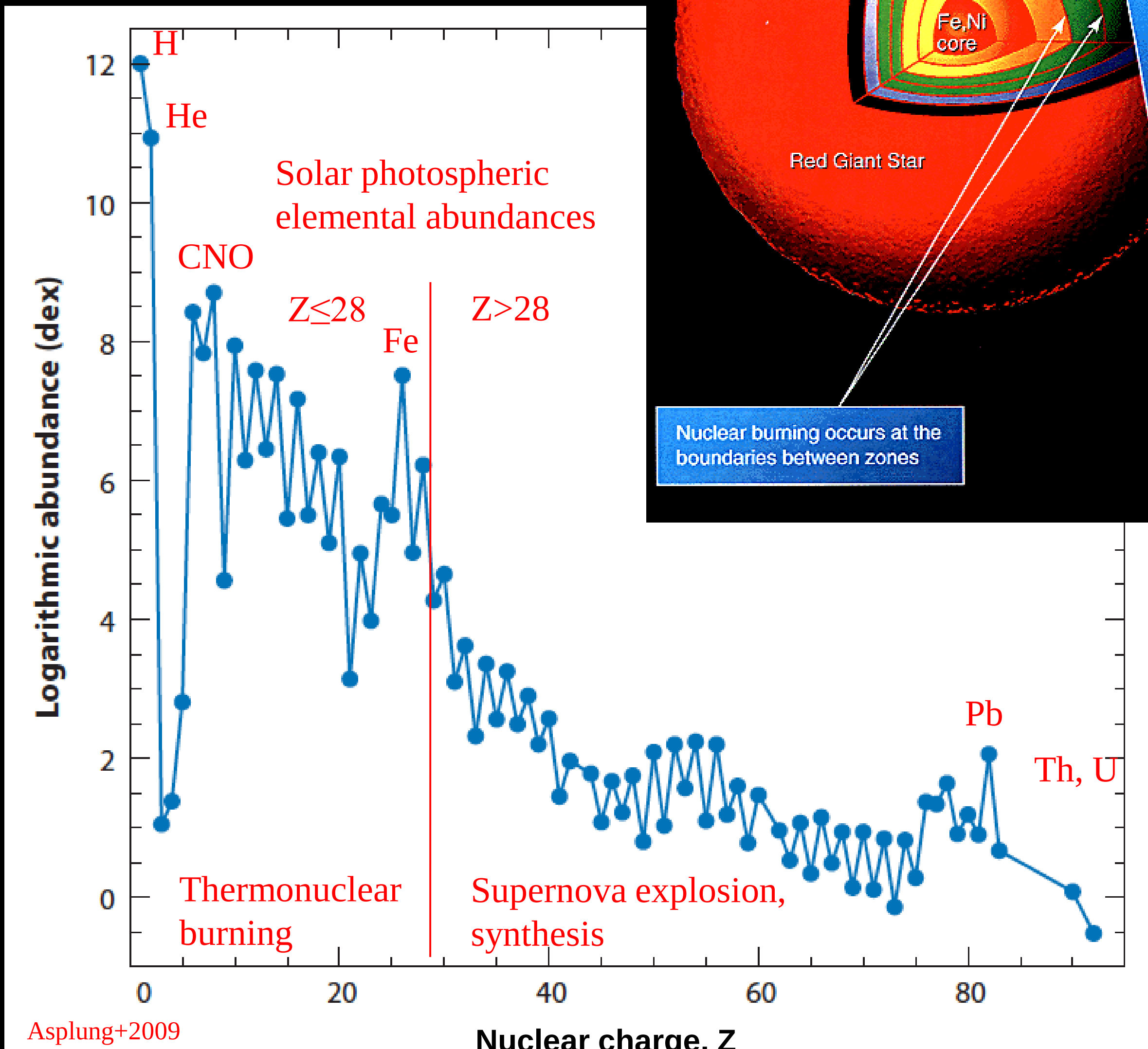
TIGER
Rauch+'09



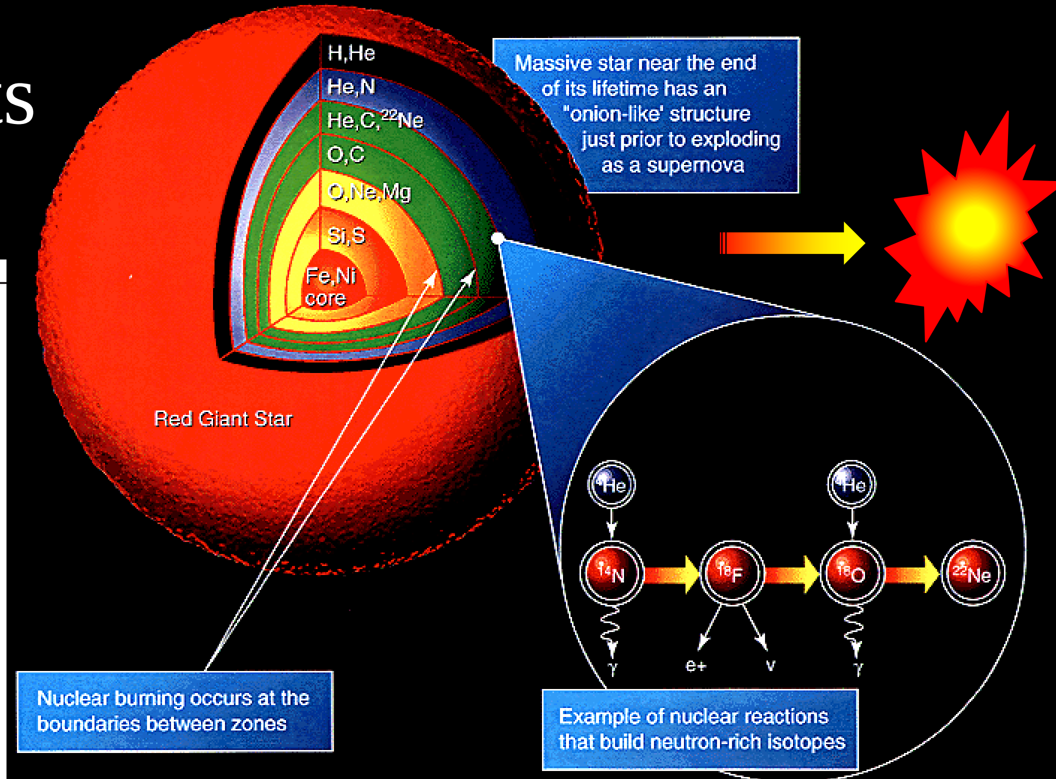


- ✧ Mixed with 20% of the WR wind outflow, the CR source composition/Solar system ratio shows a clear trend: $\sim A^{2/3}$ for refractory and $\sim A$ for volatile elements
- ✧ A similar trend is observed at VHE
- ✧ This dependence is yet to be understood

Origin of elements



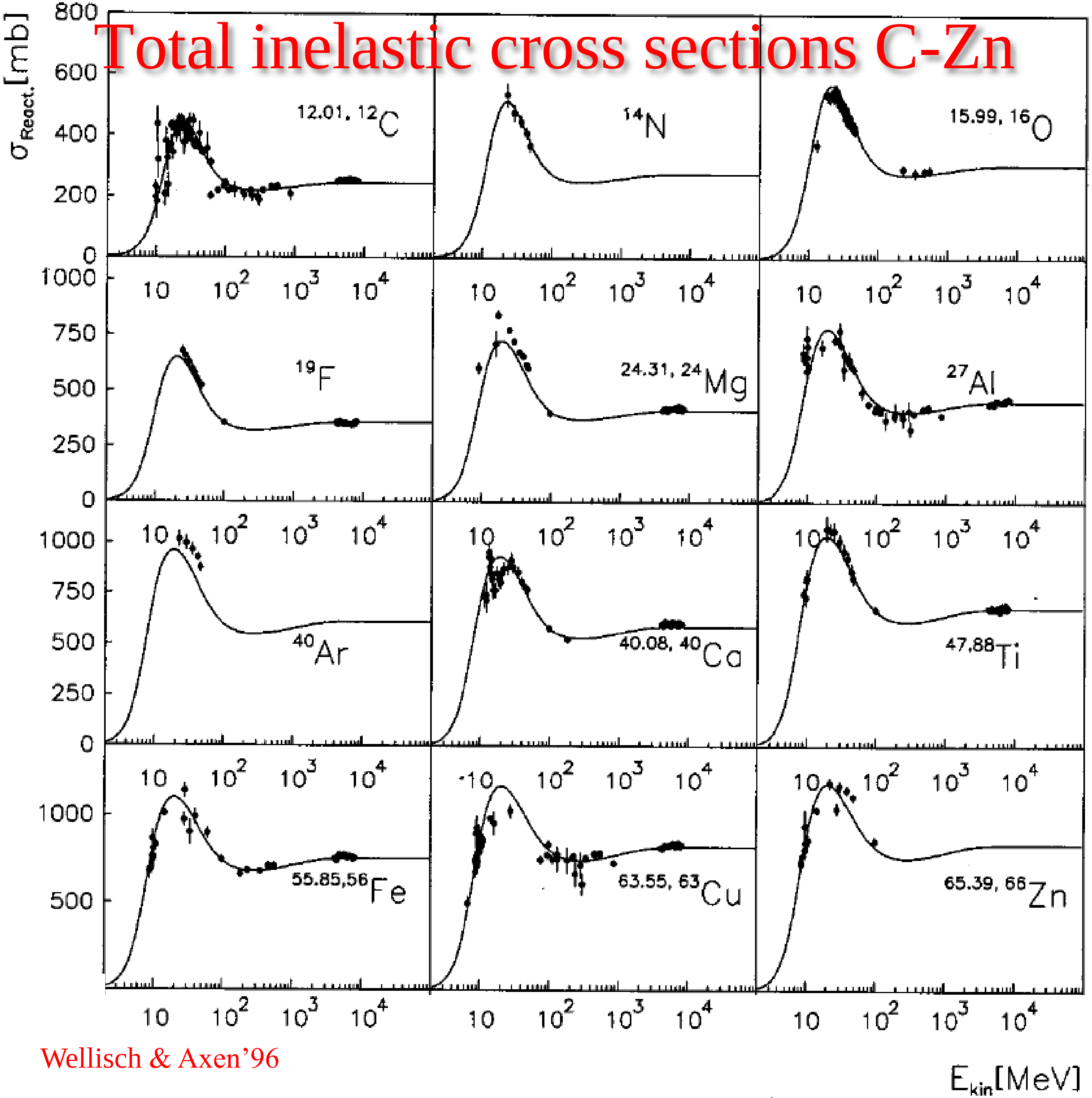
Asplung+2009



Heavy nuclei in CRs:

- ✧ Probe explosive nucleosynthesis
- ✧ Properties of the local interstellar medium
- ✧ Acceleration timescale
- ✧ Acceleration mechanisms
- ✧ History of our local Galaxy

Total inelastic cross sections C-Zn

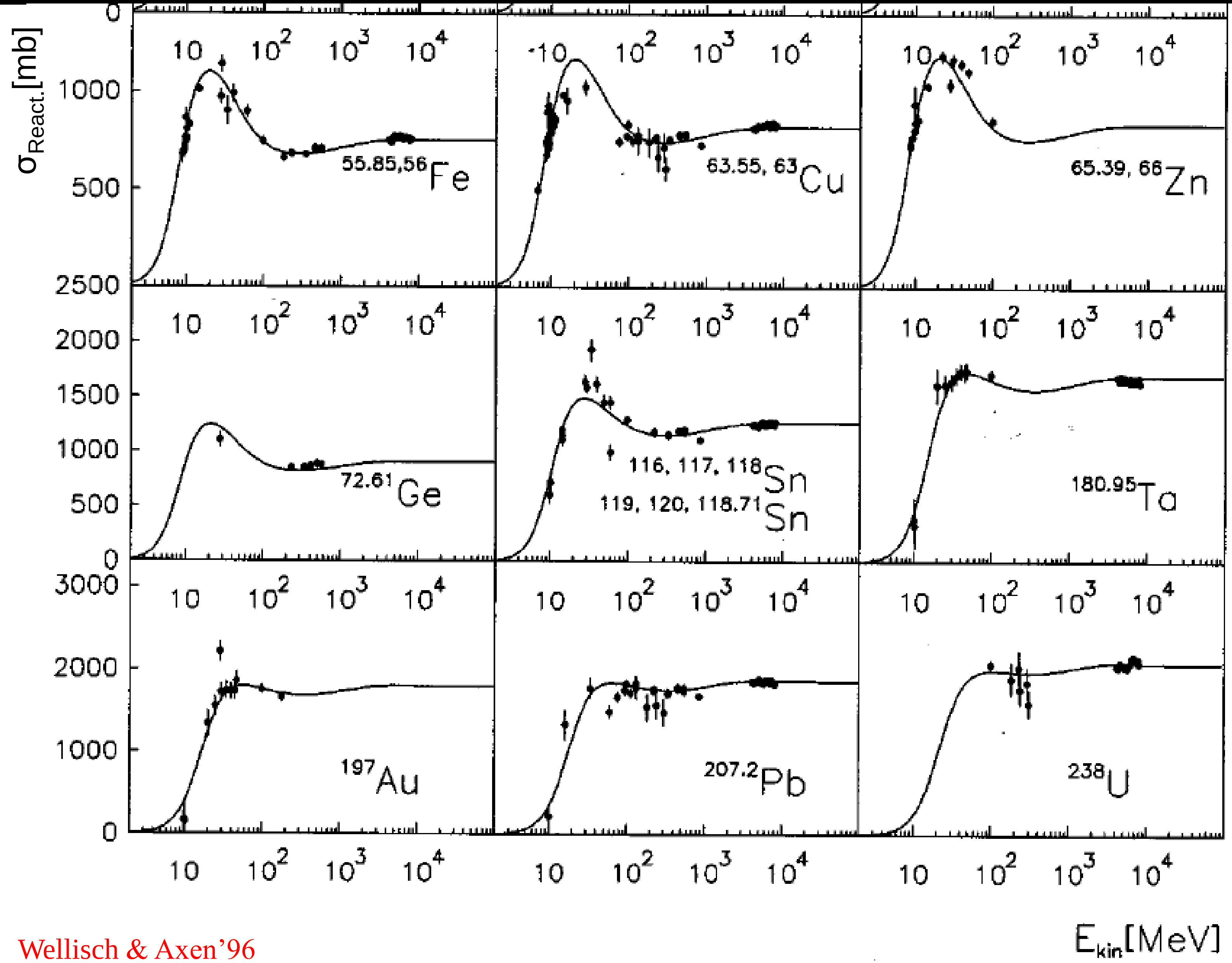


Above ~1 GeV/n:

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

Wellisch & Axen'96

Total inelastic cross sections Fe-U



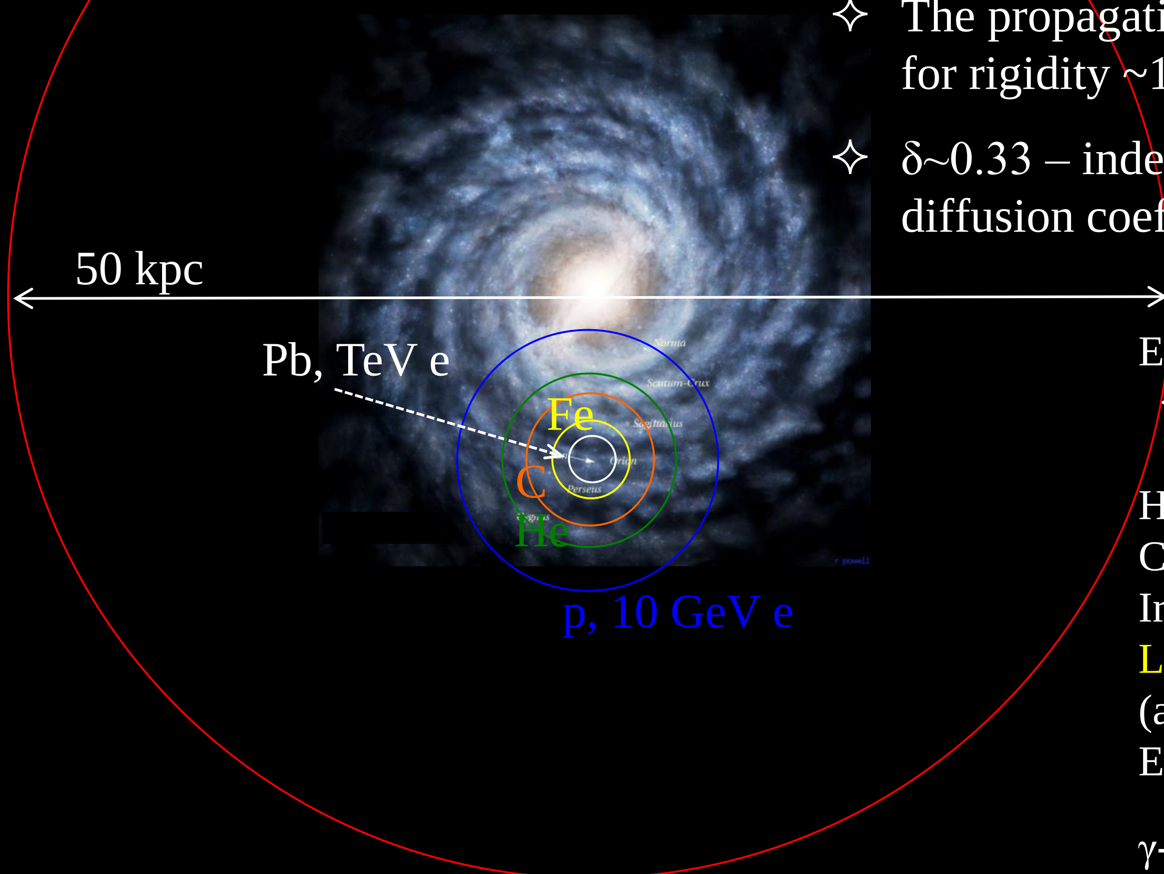
Wellisch & Axen'96

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 $$\sigma_r(A) \approx 250\ \mathrm{mb}\ (A/12)^{2/3}$$
- p, pbar inelastic cross section ~40 mb
- Effective propagation distance of carbon nuclei and protons (antiprotons)
$$\langle x \rangle_A \sim 2.7\ \mathrm{kpc} \left(\frac{A}{12}\right)^{-1/3} \left(\frac{\rho}{\rho_0}\right)^{\delta/2}$$
$$\langle x \rangle_p \sim 5.6\ \mathrm{kpc} \left(\frac{\rho}{\rho_0}\right)^{\delta/2}.$$
- Probes the area ~ $< x >^2$: p probes 4 times the area that is probed by C

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
- δ~0.33 – index of the rigidity dependence of the diffusion coefficient



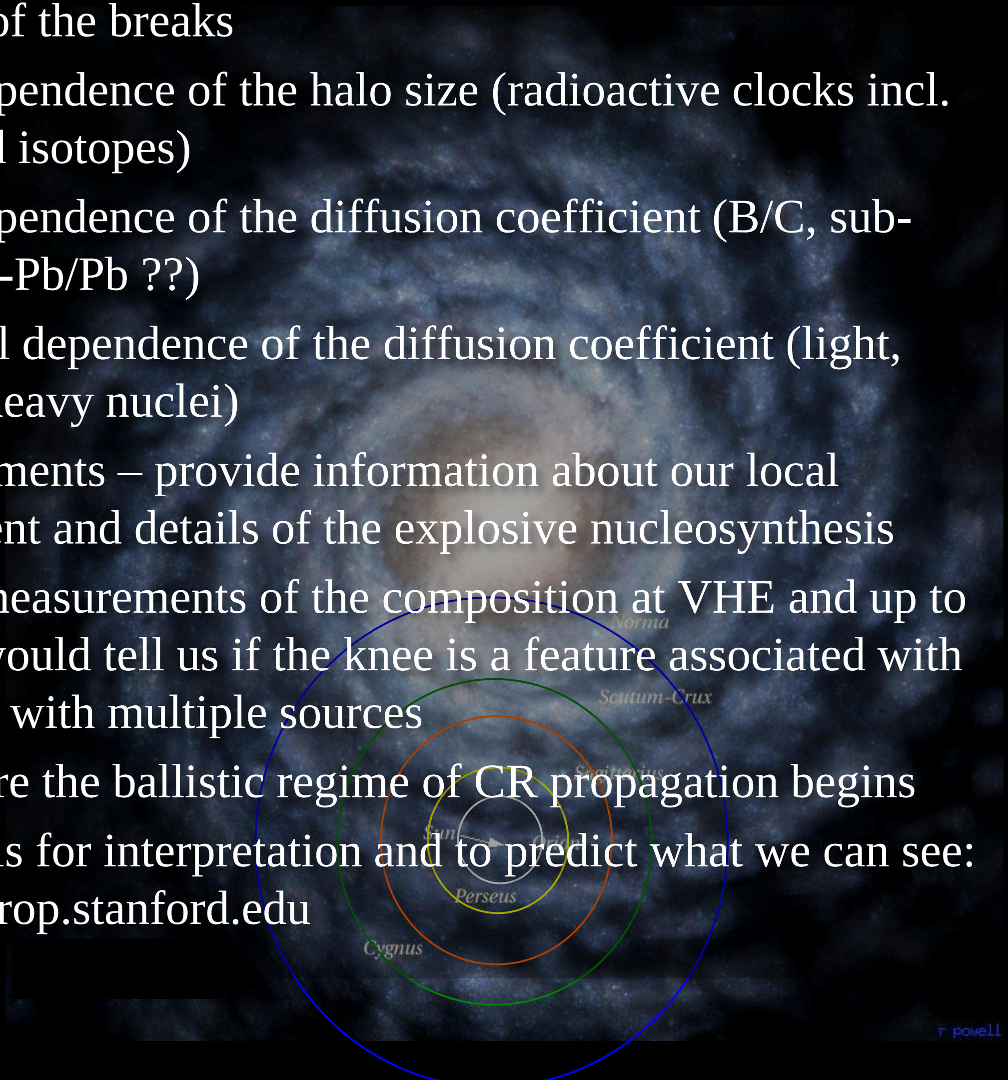
Effective propagation distance:
$\langle X\rangle \sim \sqrt{6D\tau} \sim 2.7 \text{ kpc } R^{\delta/2} (A/12)^{-1/3}$

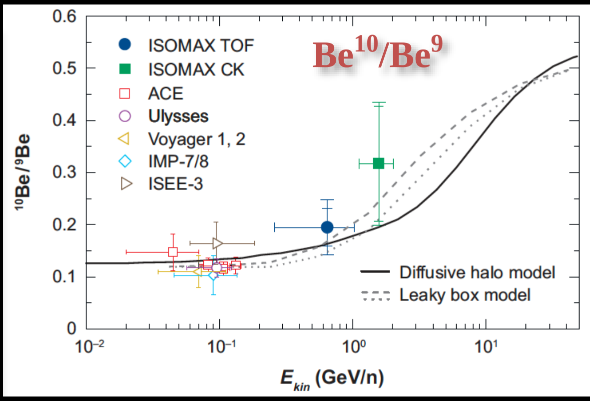
Helium: ~ 3.6 kpc $R^{\delta/2}$
Carbon: ~ 2.7 kpc $R^{\delta/2}$
Iron: ~ 1.6 kpc $R^{\delta/2}$
Lead ~ 1.0 kpc $R^{\delta/2}$
(anti-) protons: ~ 5.6 kpc $R^{\delta/2}$
Electrons ~ 1 kpc $E_{12}^{-\delta/2}$

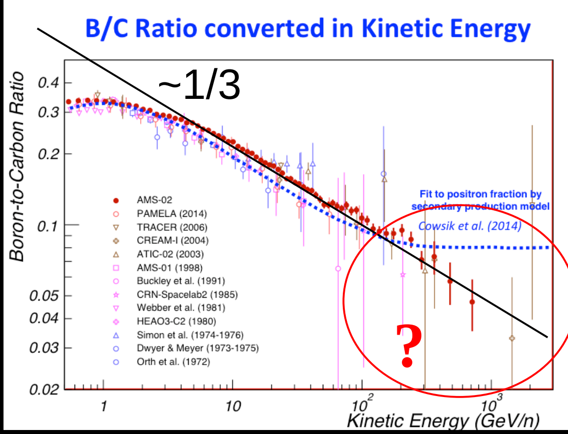
γ-rays: probe CR p (pbar) and e± spectra in the whole Galaxy ~50 kpc across

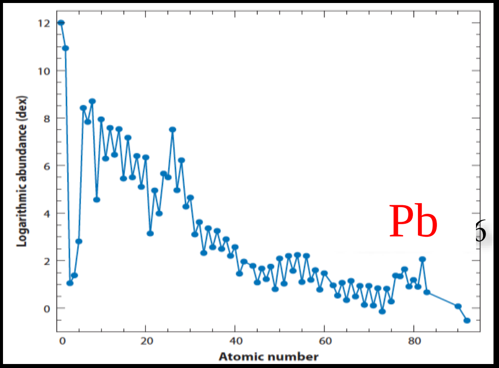
Some questions to address with future instruments

- ✧ Origin of excess positrons and spectra of secondaries at VHE
- ✧ Spectrum of electrons
- ✧ Origin(s) of the breaks
- ✧ Energy dependence of the halo size (radioactive clocks incl. short-lived isotopes)
- ✧ Energy dependence of the diffusion coefficient (B/C, sub-Fe/Fe, sub-Pb/Pb ??)
- ✧ The spatial dependence of the diffusion coefficient (light, medium, heavy nuclei)
- ✧ Heavy elements – provide information about our local environment and details of the explosive nucleosynthesis
- ✧ Detailed measurements of the composition at VHE and up to the knee would tell us if the knee is a feature associated with a single or with multiple sources
- ✧ Also, where the ballistic regime of CR propagation begins
- ✧ Use models for interpretation and to predict what we can see: http://galprop.stanford.edu









Thank you