

Probing the acceleration and propagation of Galactic cosmic rays with AMS-02 data

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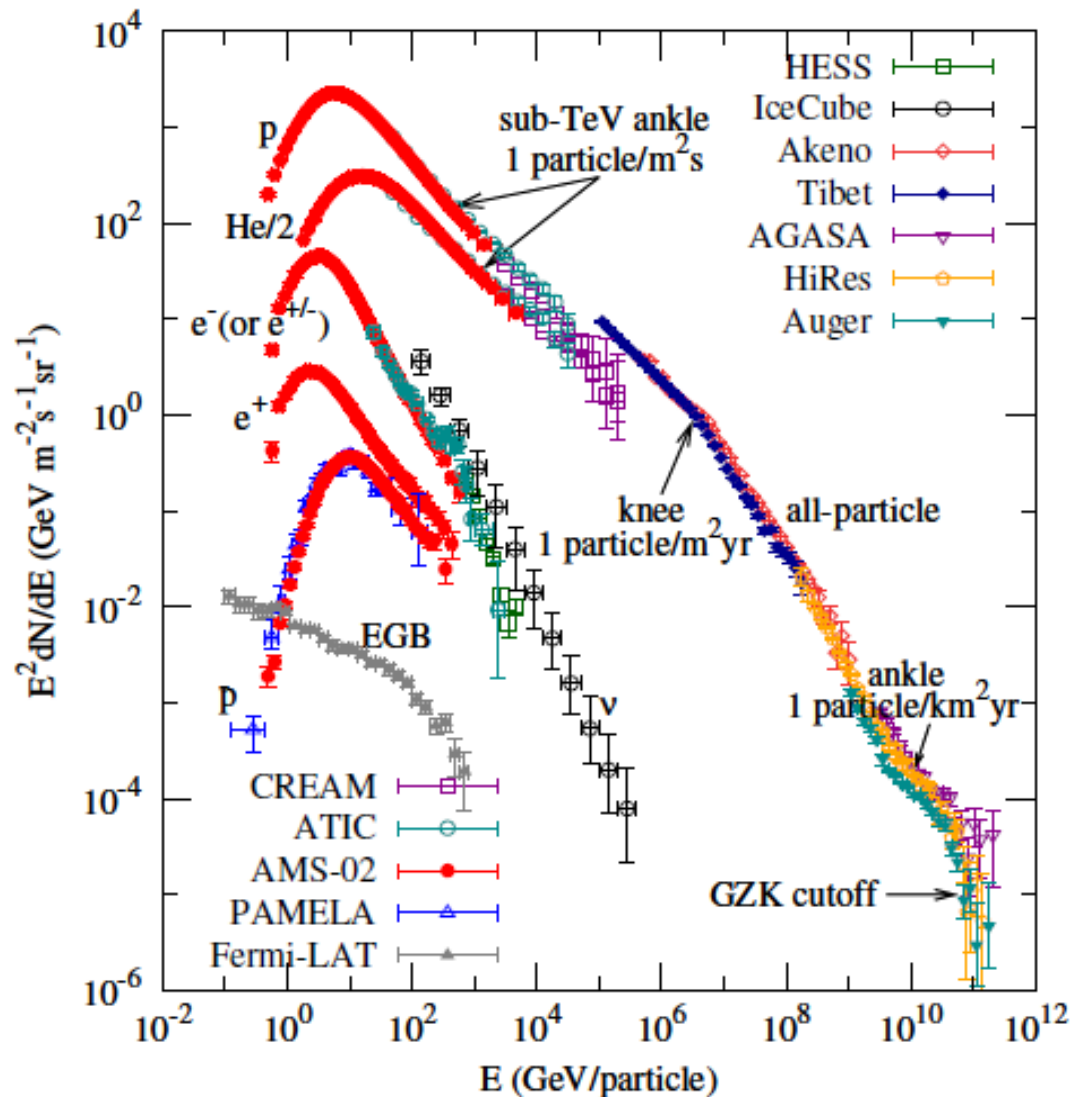
Purple Mountain Observatory, Chinese Academy
of Sciences

2017-08-17, KIAA-WAP II

Outline

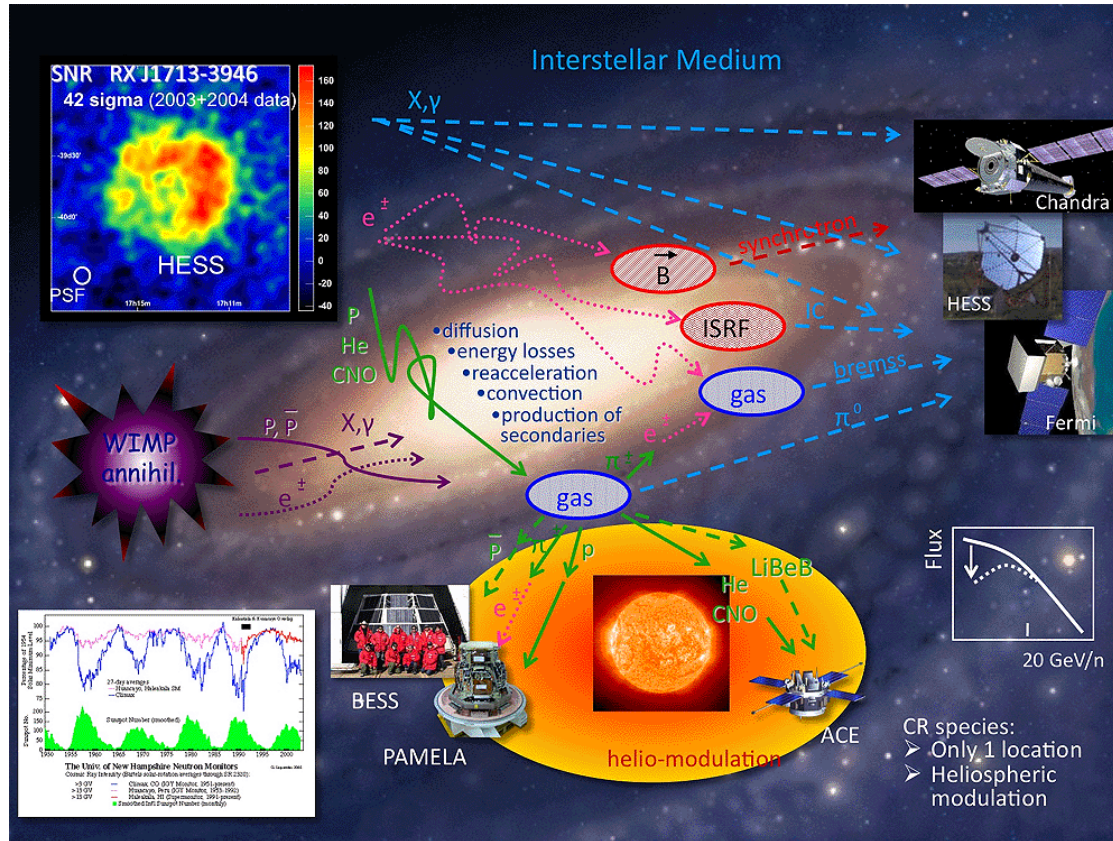
- Standard model of Galactic cosmic rays
- AMS-02 experiment and results
- Implications of AMS-02 data
- Conclusion

Summary of cosmic ray measurements



- Big power-law!
- Many structures (knee, ankle, GZK cutoff, sub-TeV ankle, e^+e^- excess) imply the origin, propagation, and interaction of cosmic rays
- Probe of dark matter particles (positron, antiproton, gamma-ray, neutrino)

Galactic cosmic rays: general picture



Acceleration at source

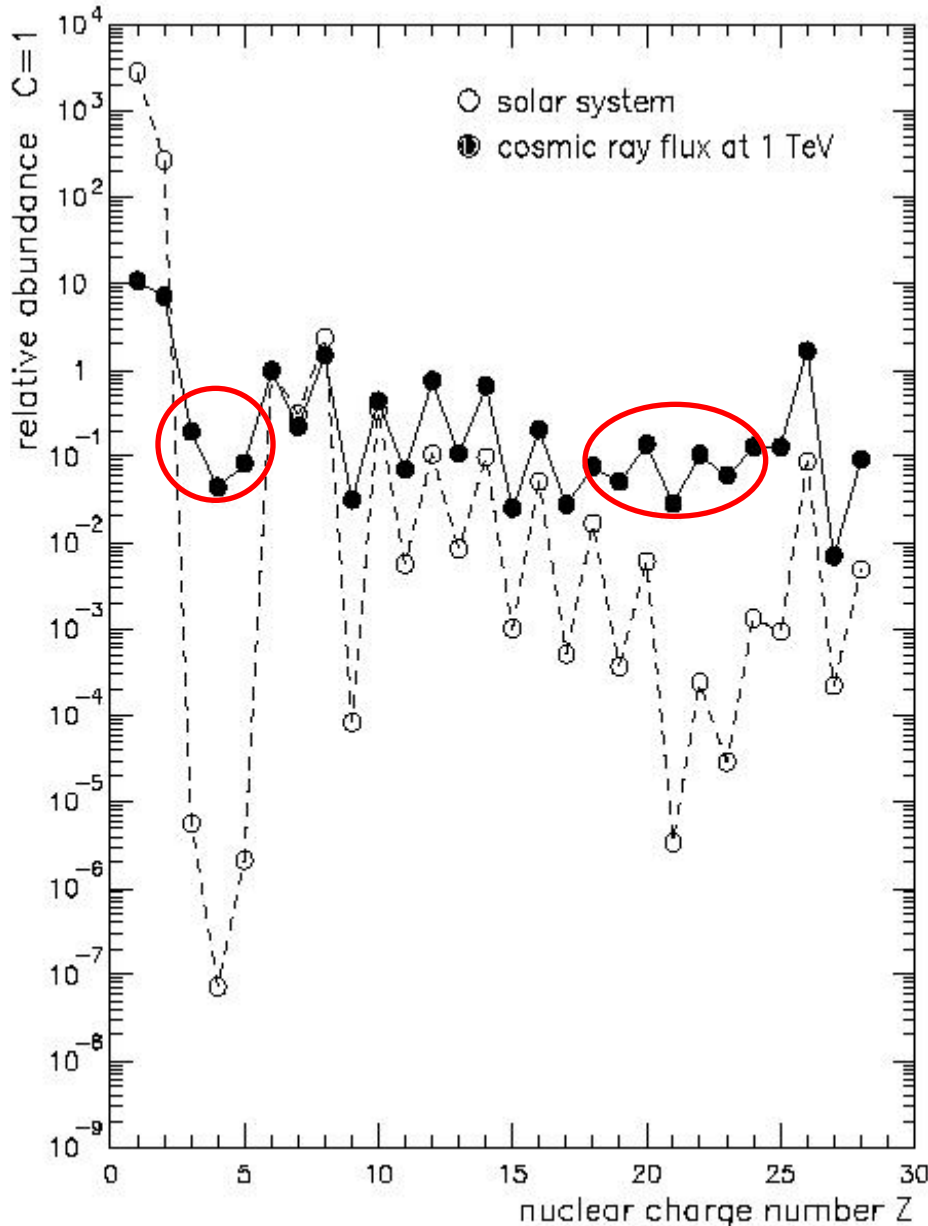
Diffusion and Interaction

Helio-sphere propagation

Detection at the Earth

Two unknowns: **source** and **propagation**

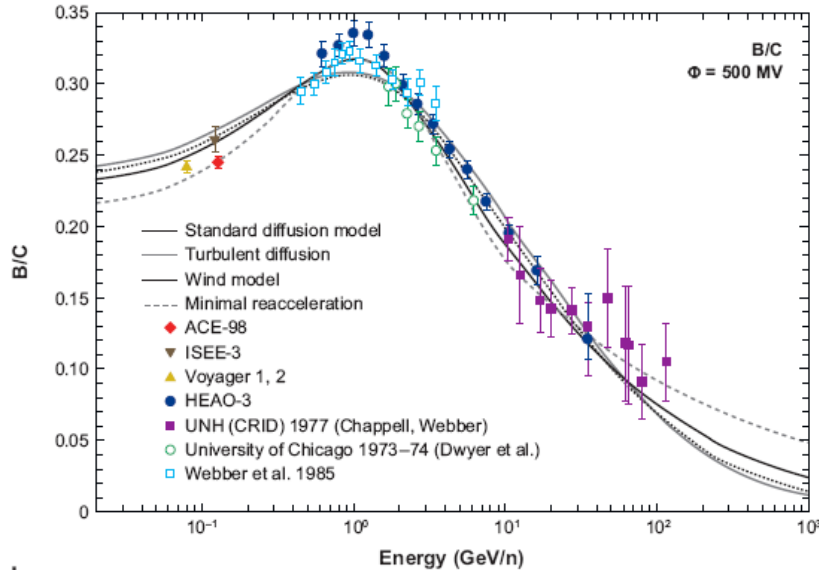
Chemical composition of cosmic rays



- Two groups of significantly over-abundant nuclei than that can be expected in stellar synthesis: Li, Be, B and sub-Iron (Sc, Ti, V, Cr, Mn)
- They are produced primarily by the fragmentation of C/O and Fe
- Their abundances trace the journey of cosmic rays

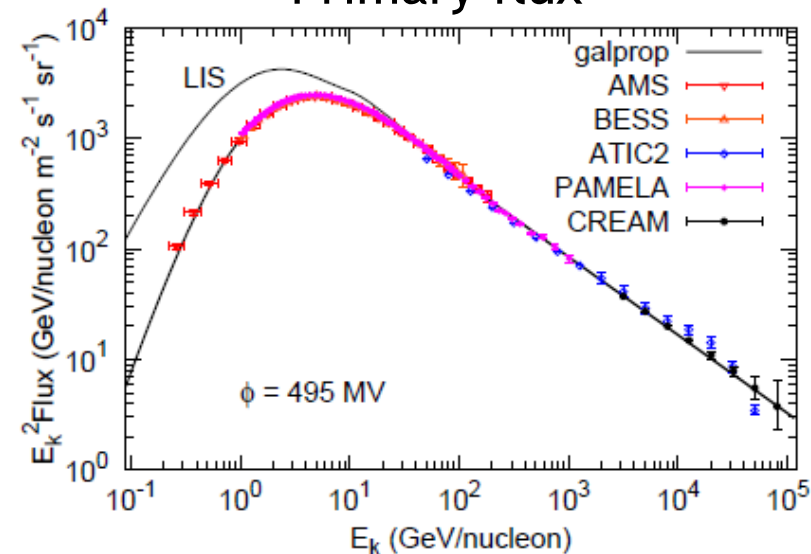
Disentangle the source and propagation

Secondary-to-primary ratio



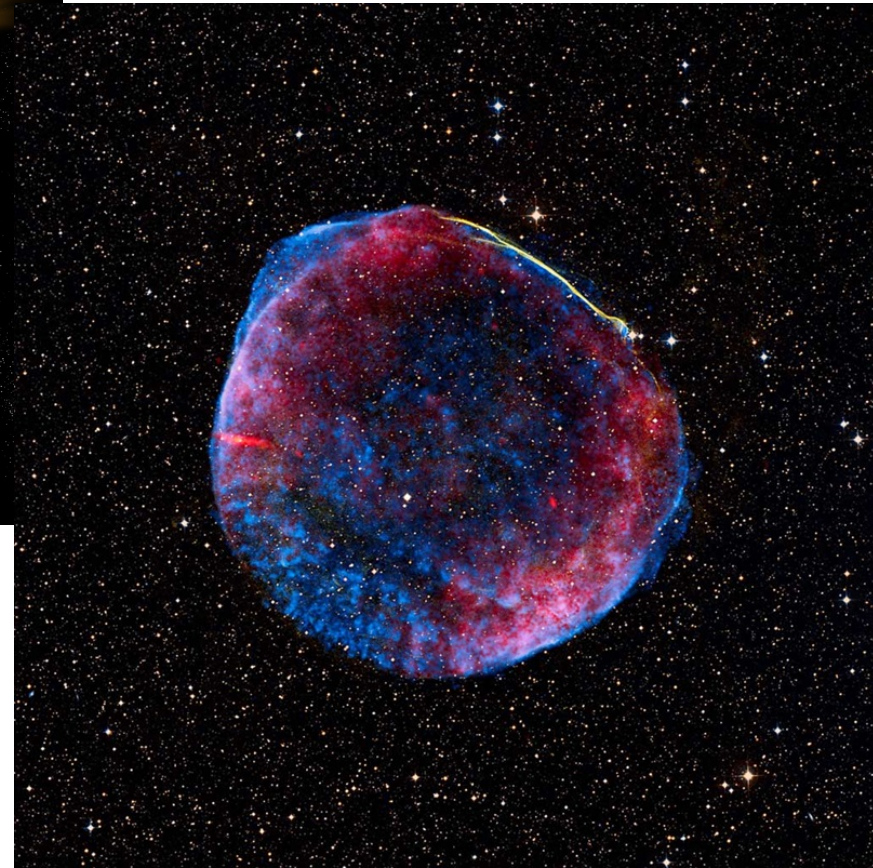
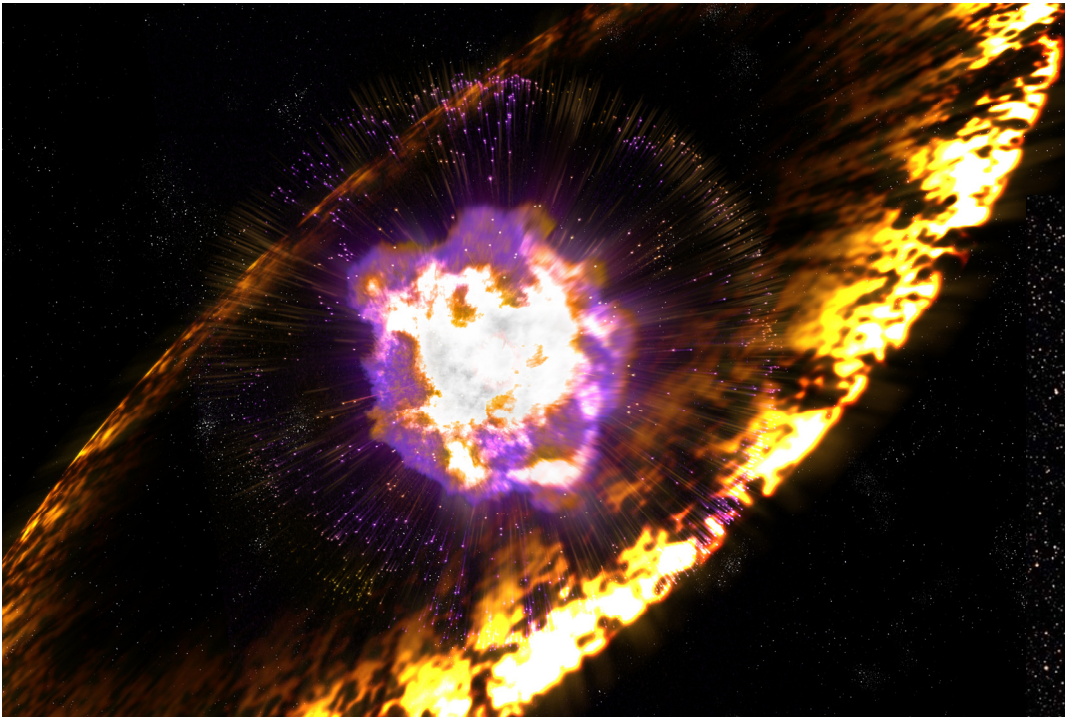
Propagation parameters

Primary flux



Source parameters

Cosmic accelerators: supernova shocks



Supernovae as cosmic ray sources

Badde & Zwicky (1934)

Ginzburg & Syrovatskii (1964)

➤ Total power of Galactic cosmic rays

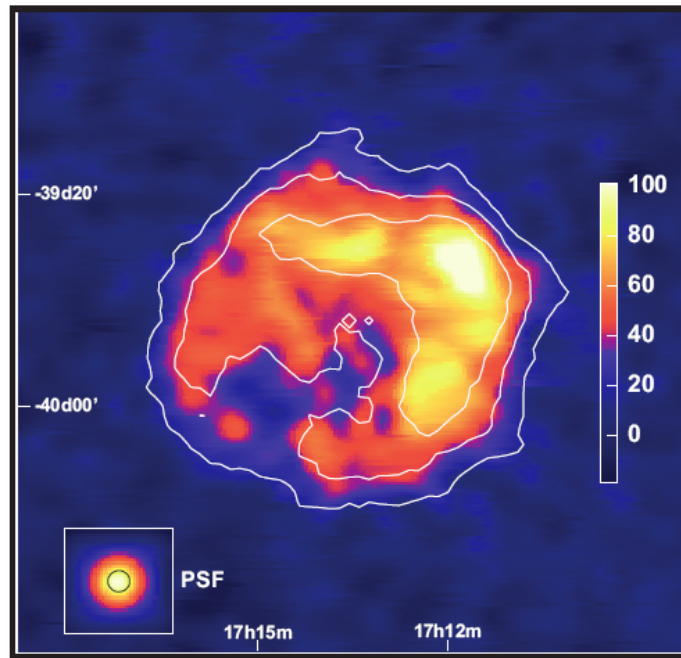
$$L_{\text{CR}} = \frac{V_D \rho_E}{\tau_R} \sim 5 \times 10^{40} \frac{\text{erg}}{\text{sec}},$$

➤ For a SN rate of one per century, and an average energy release of 10^{51} erg per SN

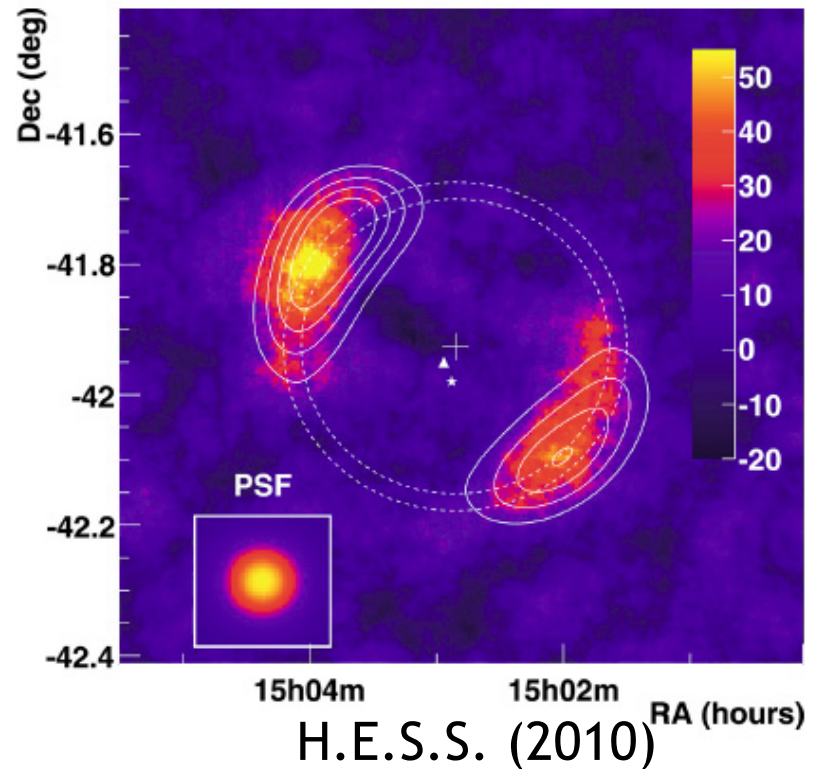
$$L_{\text{SN}} \sim 10^{42} \text{ erg/s.}$$

➤ A few percent energy from all SNe can sustain the Galactic cosmic rays

Observational evidence: very high energy gamma-rays from shells of SNRs



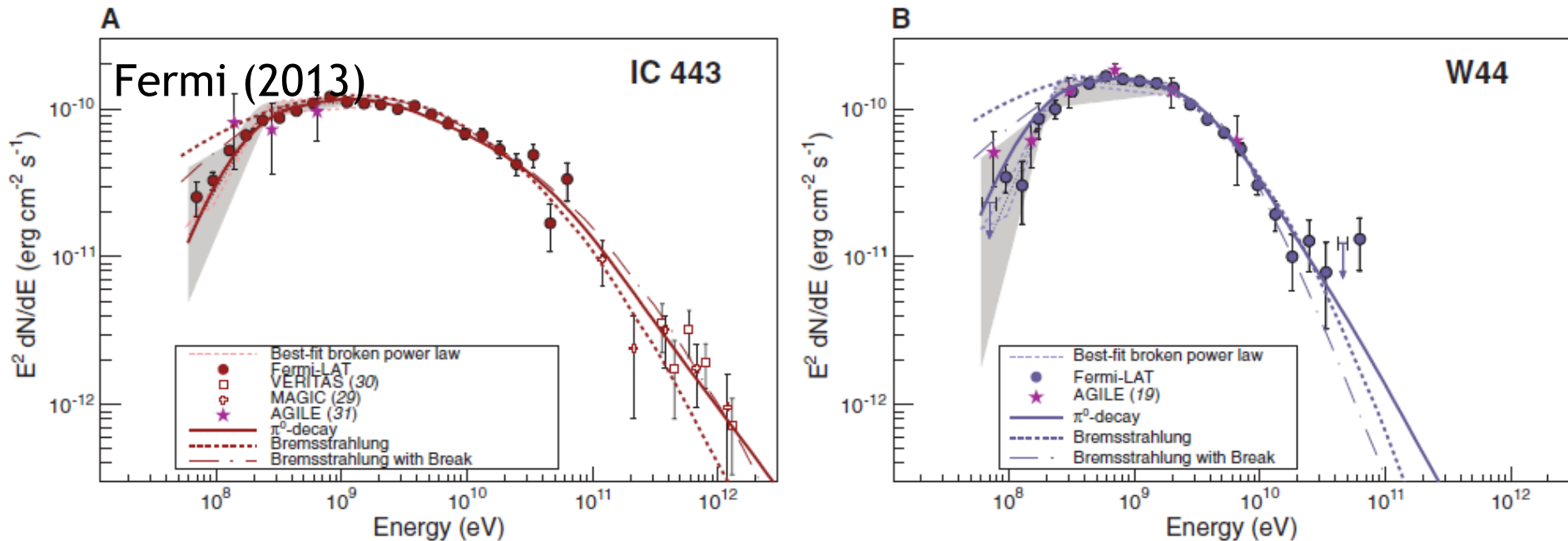
H.E.S.S. (2006)



H.E.S.S. (2010)

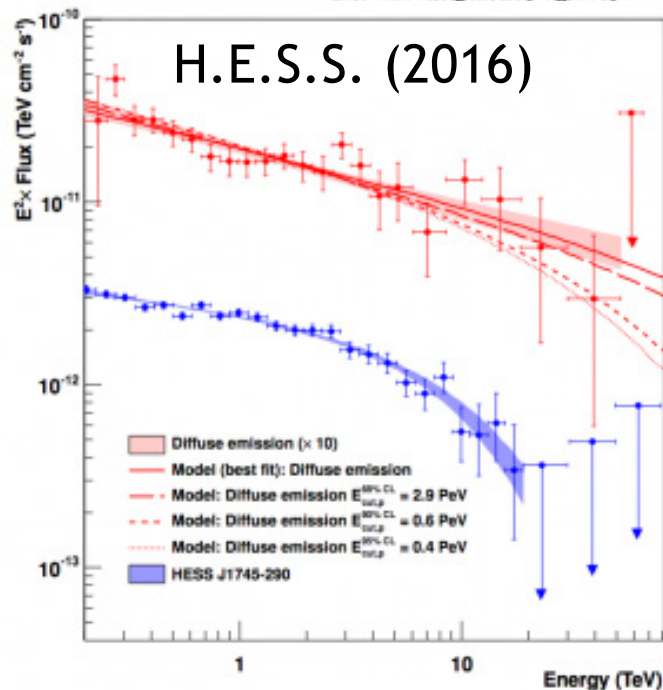
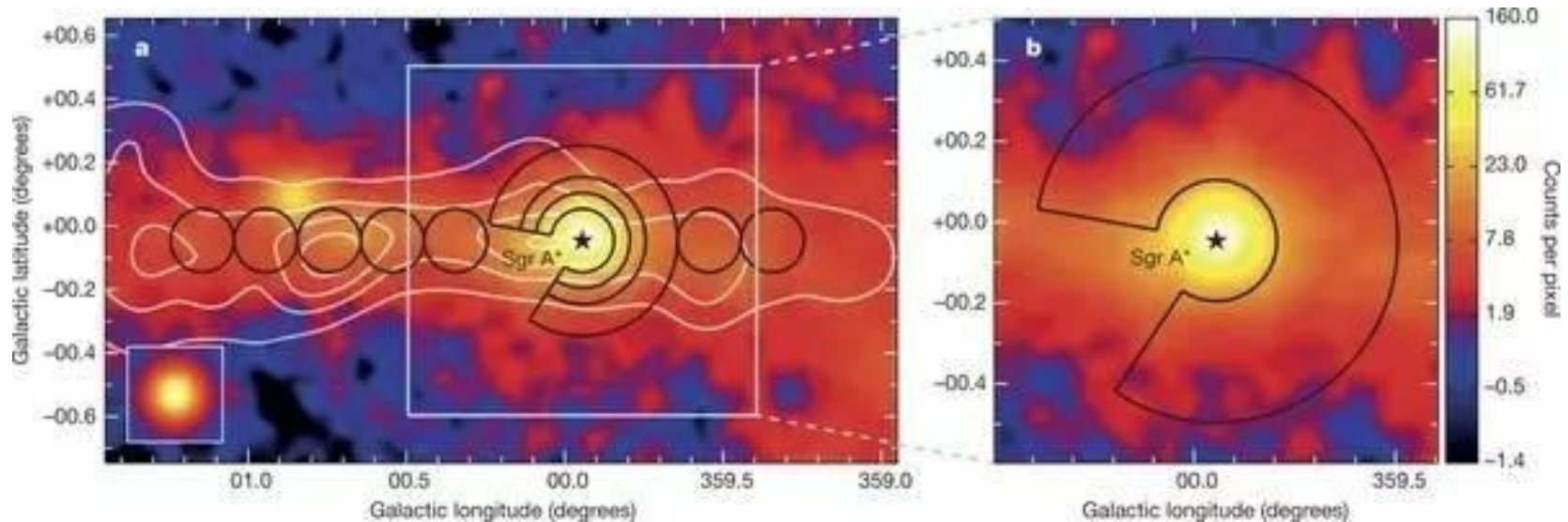
SNRs are high energy (>100 TeV) particle (either electrons or protons) accelerators

Observational evidence: π^0 -decay bump of gamma-ray emission



Fermi observations further revealed π^0 -decay bump of gamma-ray emission from SNRs, supporting SNRs being hadronic cosmic ray accelerators.

Supermassive black hole at Galactic center

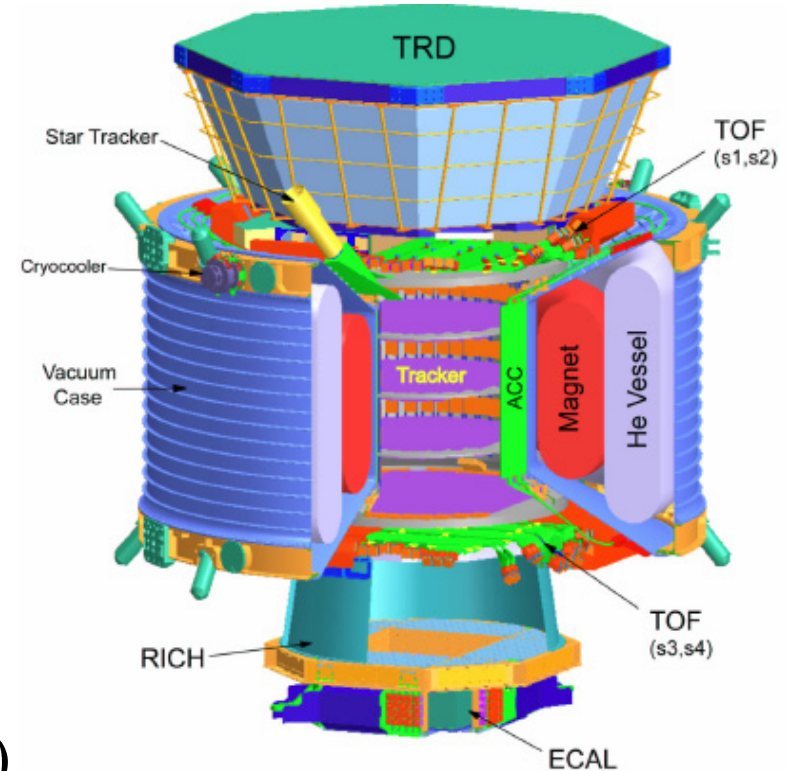
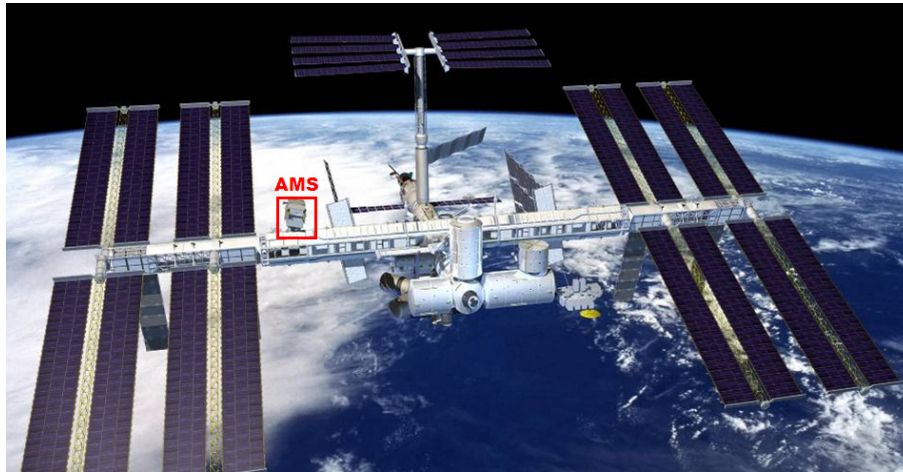


- HESS observations of Galactic center gamma-ray emission shows a single power-law up to 50 TeV, suggesting SMBH at GC being a Pevatron!
- See Liu et al. (2016) for a TDE model of SMBH accelerating particles

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Alpha Magnetic Spectrometer on International Space Station

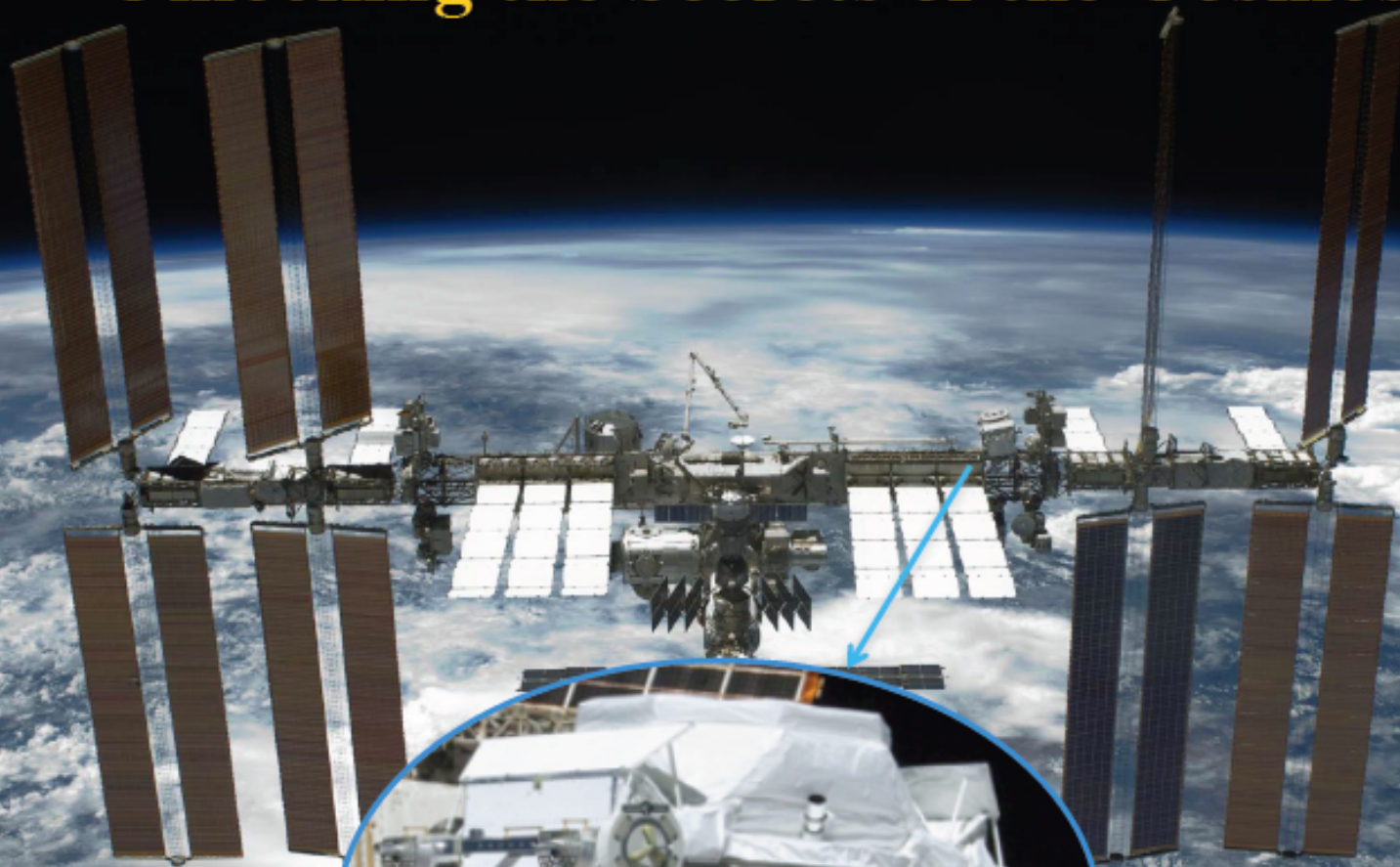


Prof. Samuel C.
C. Ting (丁肇中)

- Weight 6.7 ton
- Cost 2 billion USD
- Launched 2011/5
- Expected to run till 2024

**The First Five Years of the Alpha Magnetic Spectrometer
on the International Space Station:**

Unlocking the Secrets of the Cosmos

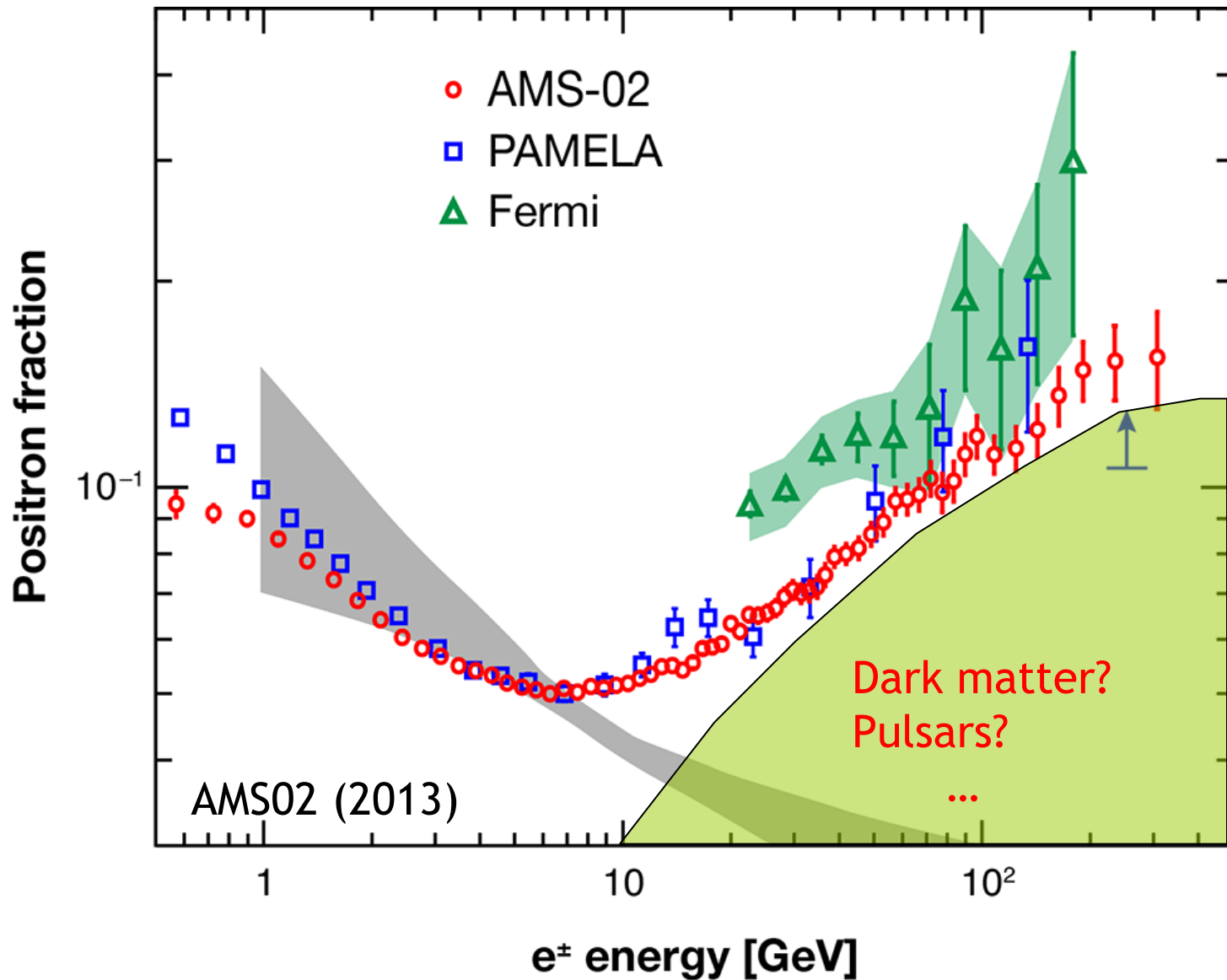


See also ICRC2017

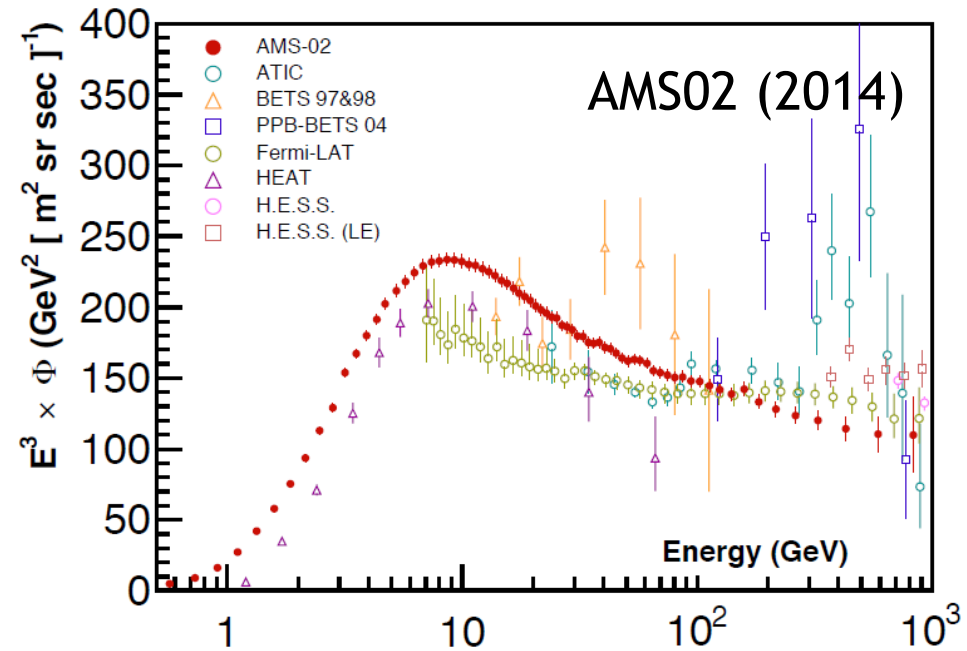
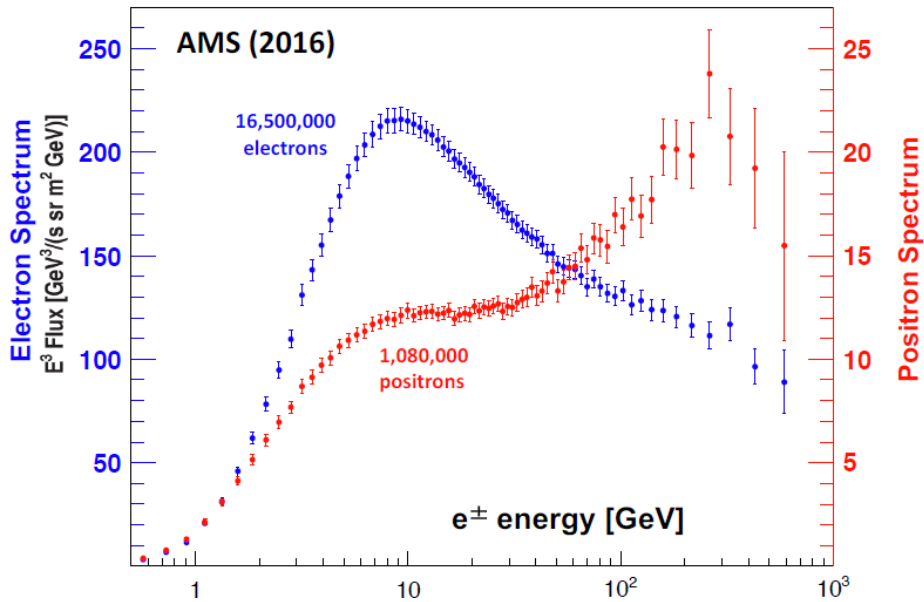
December 8, 2016

S. Ting

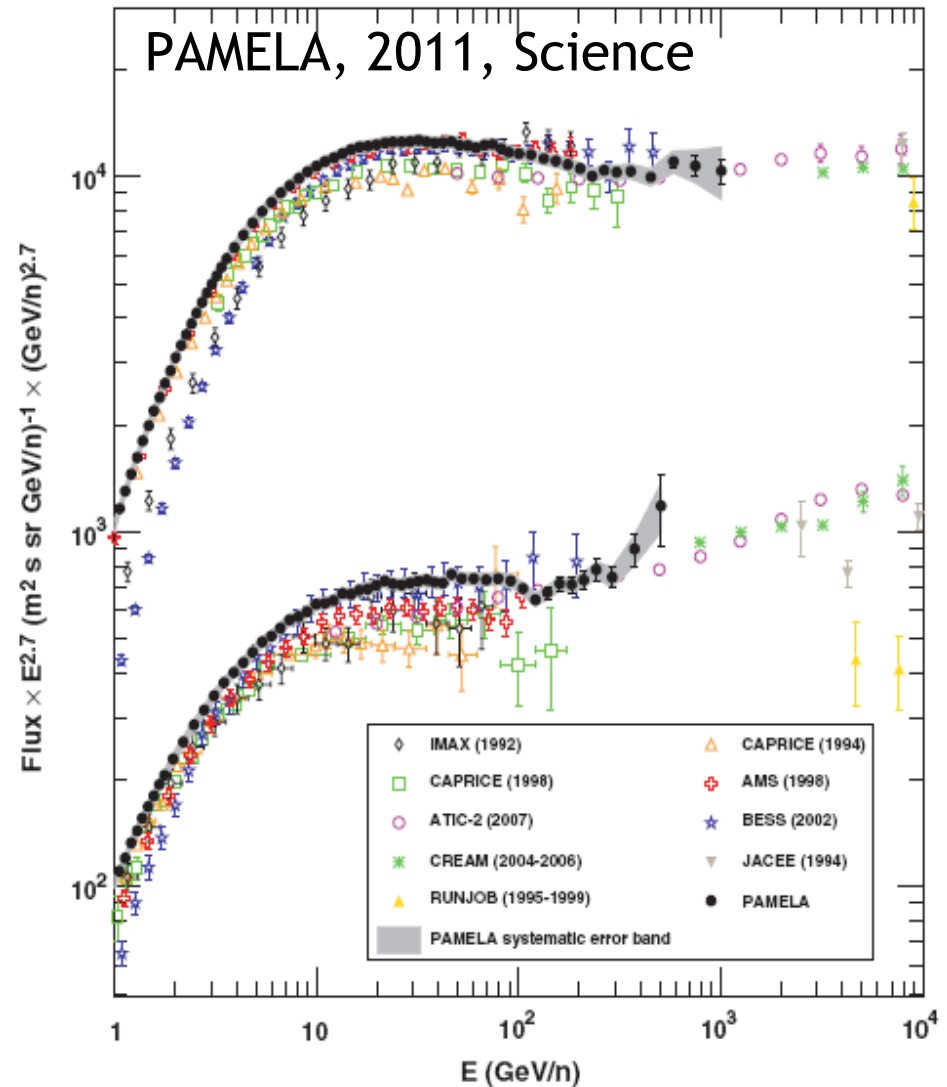
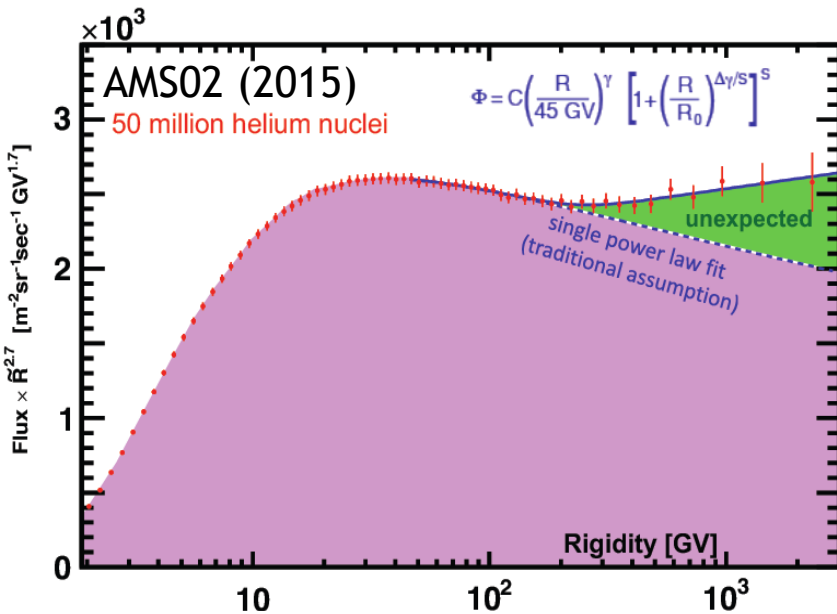
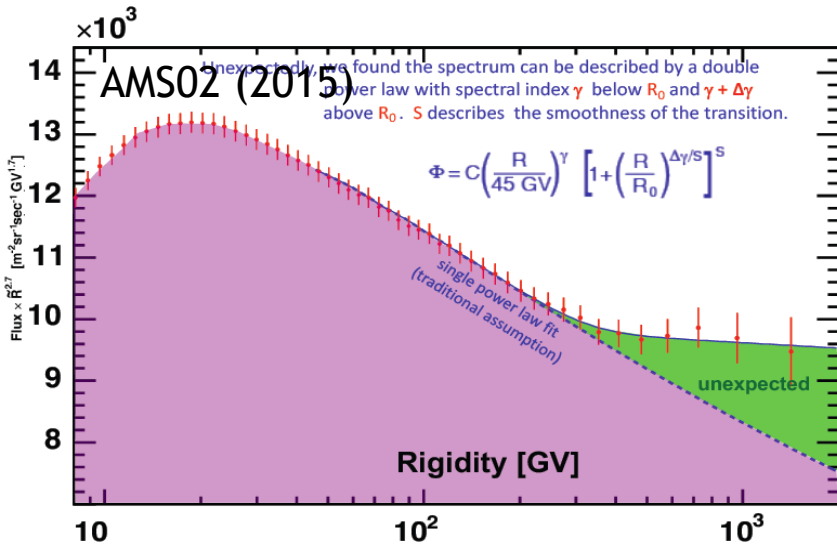
Excess of high energy positron fraction



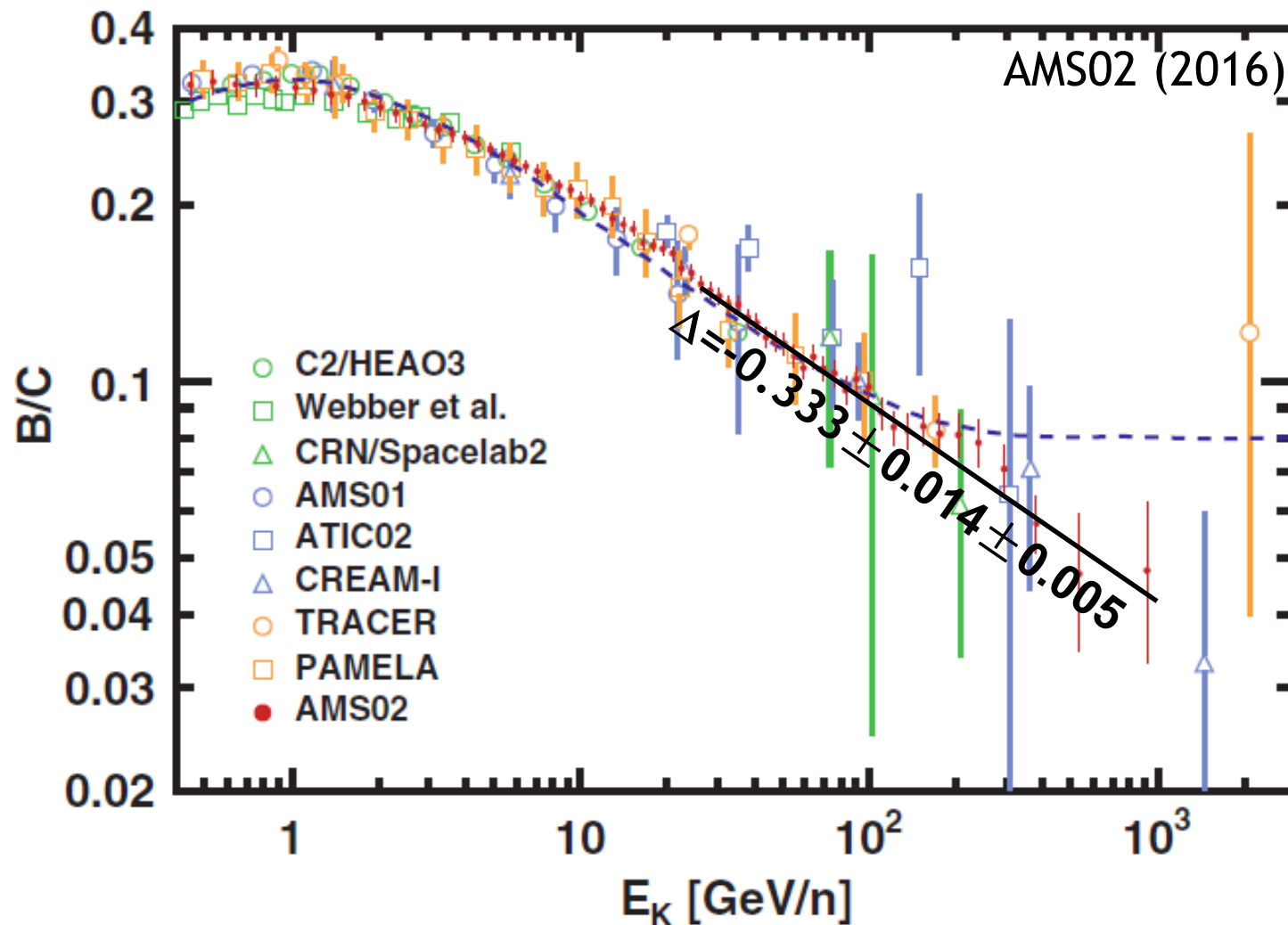
High precision measurements of electron, positron, and (e^+e^-) fluxes



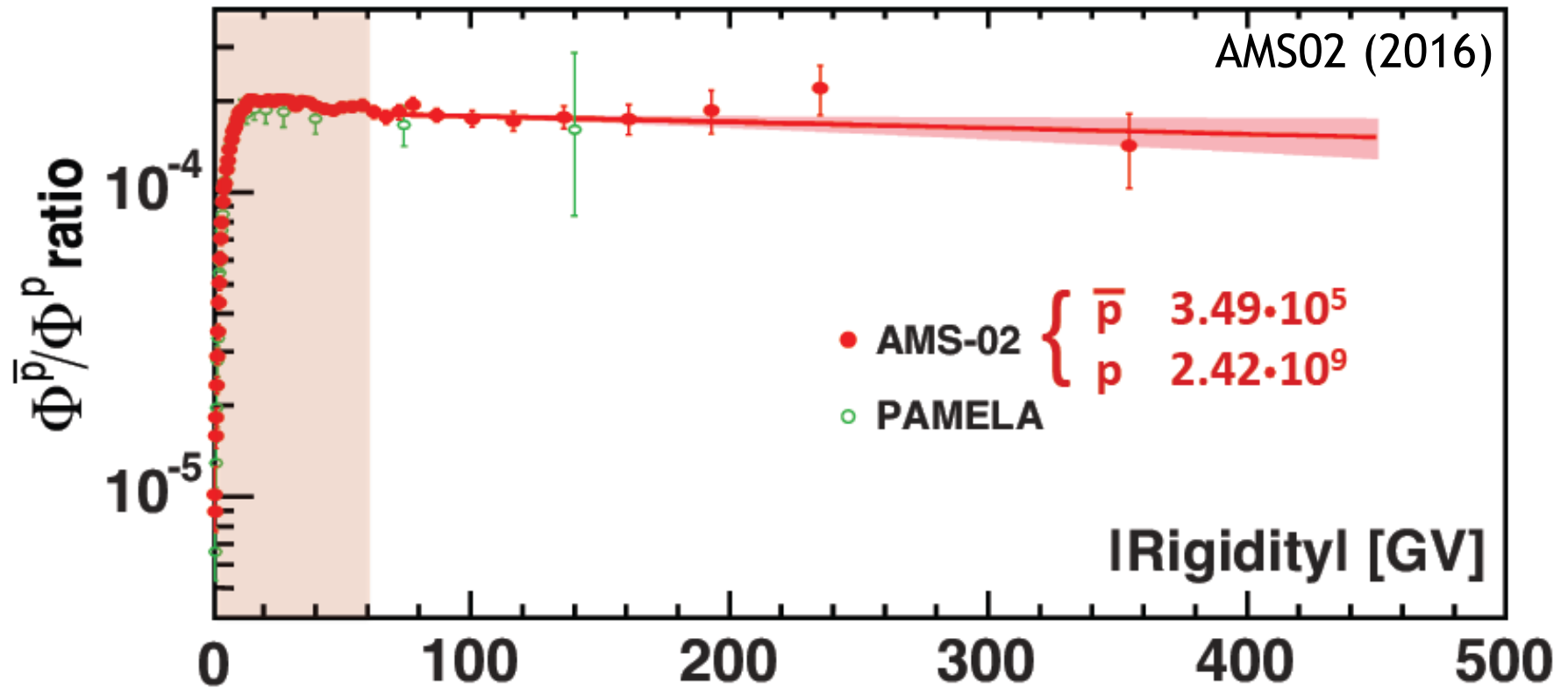
High precision measurements of proton and helium fluxes



High precision measurements of B/C ratio



High precision measurements of pbar/p ratio



Personal point of view

AMS's biggest achievement is to improve the precision of cosmic ray measurements from a factor of a few to **a few percents**, which reveals new phenomena hiding behind large error bars before (not only astrophysical problems, but also nuclear and particle physics ones).

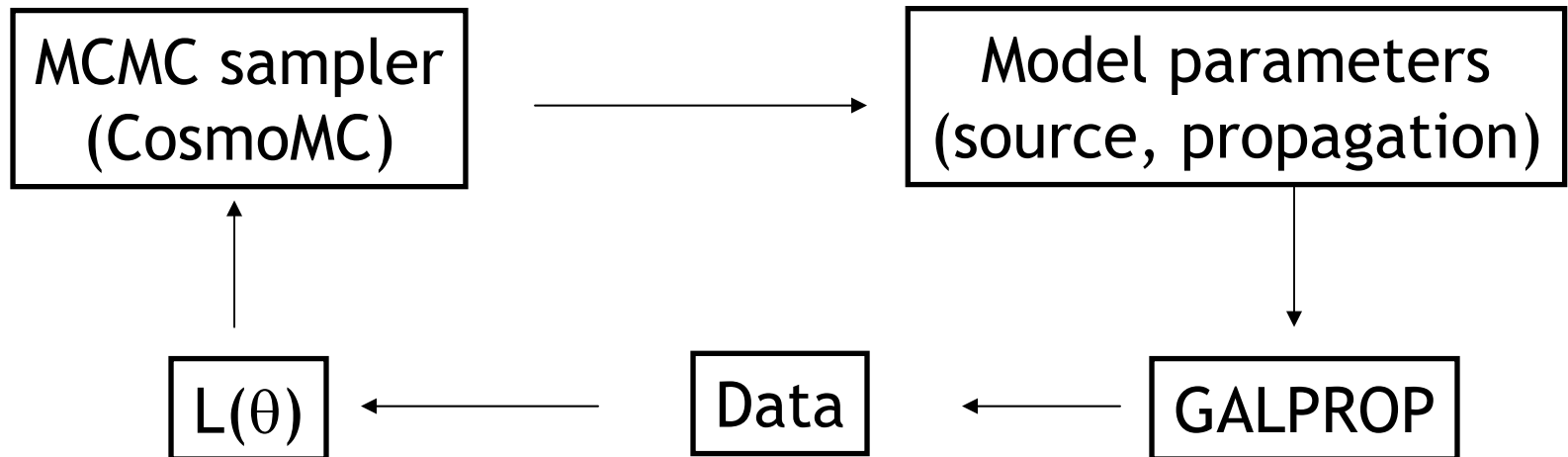
We have entered a **precise** cosmic ray era!

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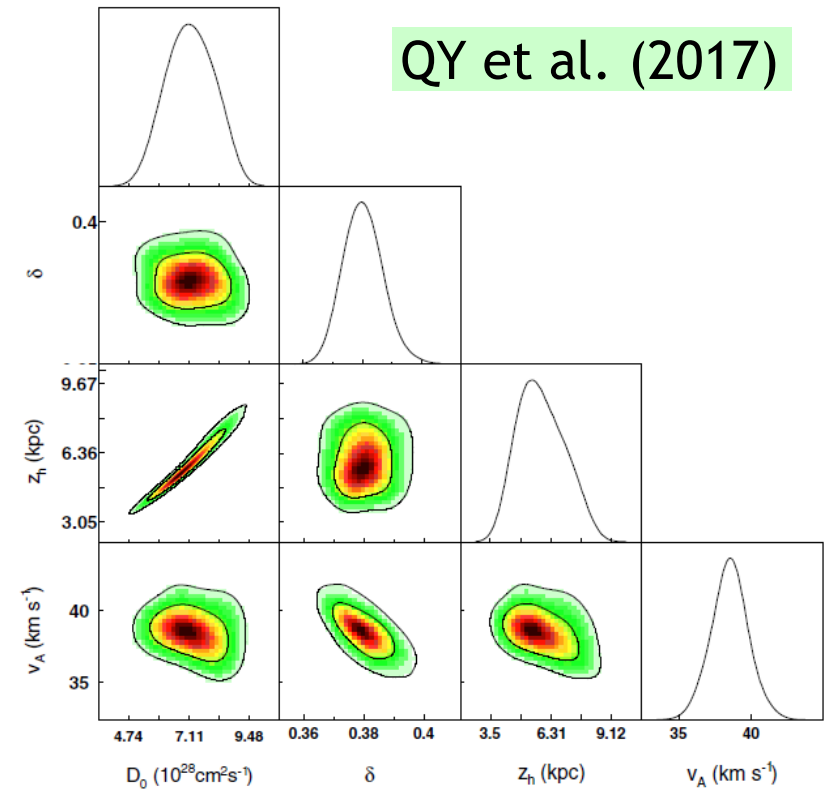
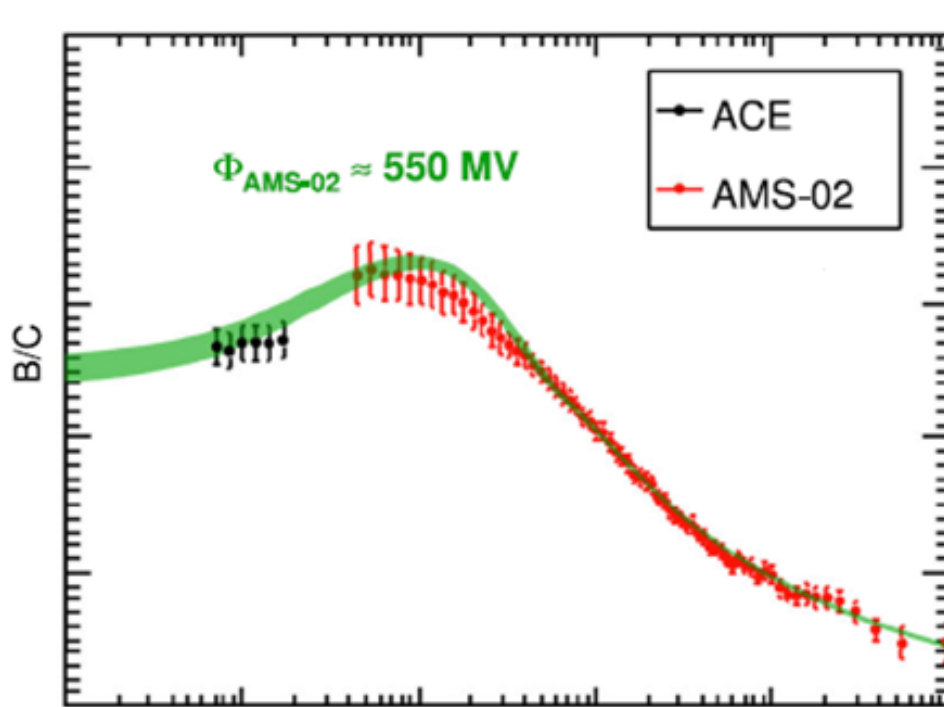
CosRayMC: Markov Chain Monte Carlo (MCMC) tool for cosmic ray propagation

- Cosmic ray propagation is a multiple parameter problem
- Strong degeneracy among model parameters
- MCMC enables an efficient, unbiased survey of the high-dimensional parameter space



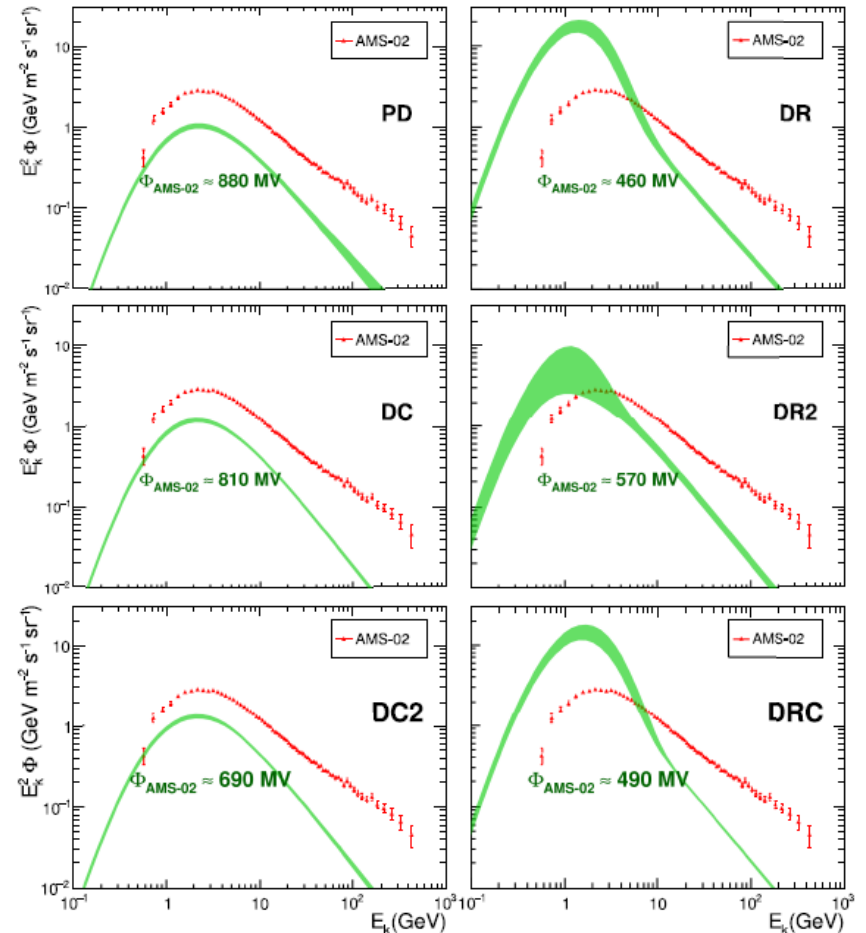
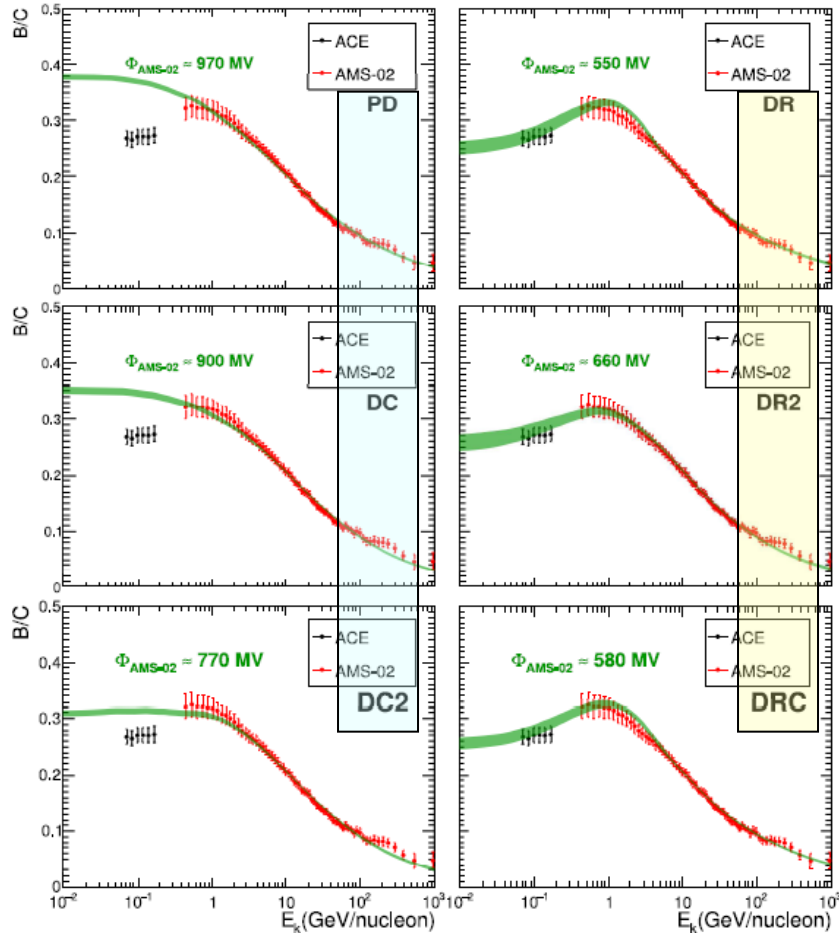
Liu, QY et al. (2010; 2012)

Constraining CR propagation with B/C



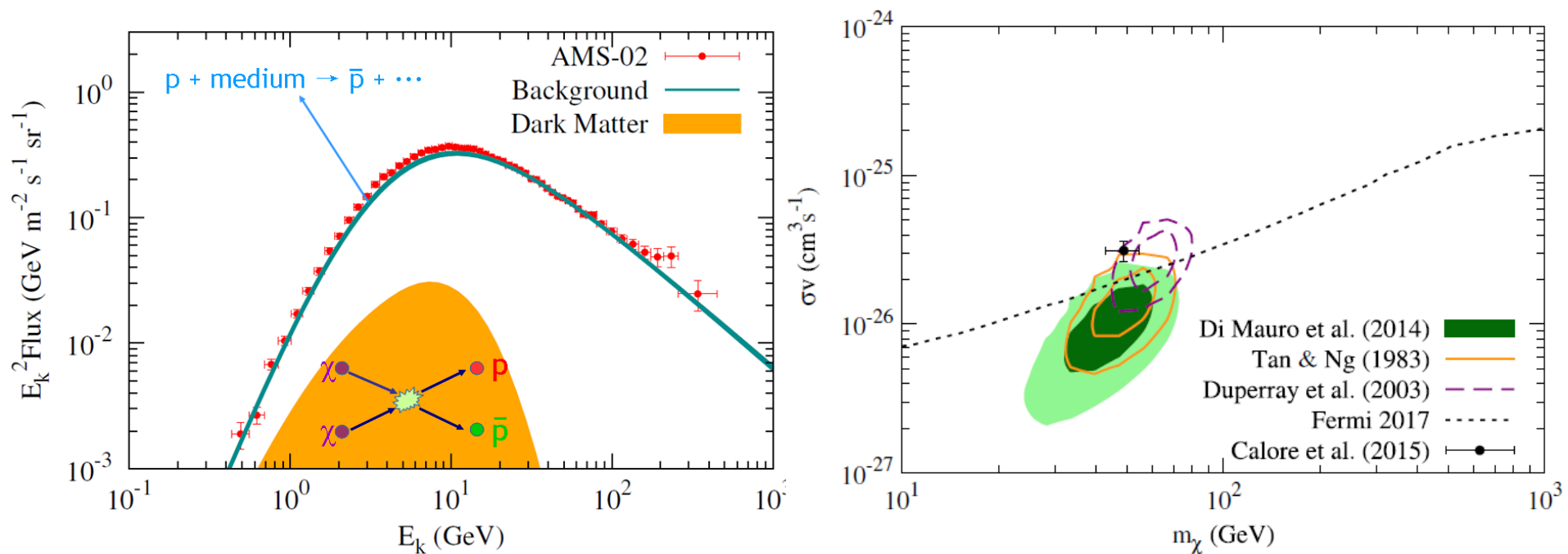
- Much improved constraints on the model parameters
- Favor a class of models with reacceleration by MHD waves

Comparison of B/C and positrons



- Reacceleration models fit the B/C well, but over-produce low energy positrons
- There could be difference of propagation of nuclei and positrons (besides cooling) in either the Galaxy or the heliosphere

Possible dark matter signal in antiprotons?



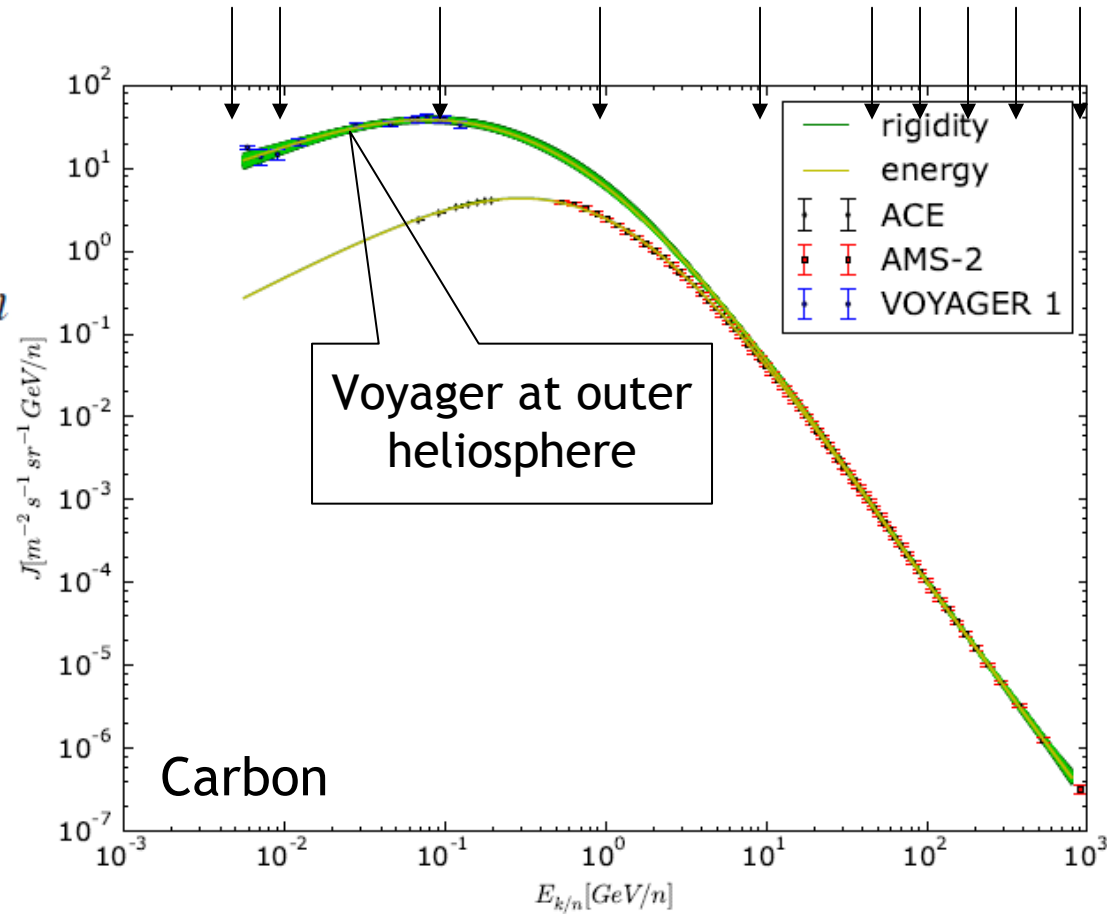
- Antiprotons share the same journey as Boron, so precise B/C predicts precise antiproton/proton ratio
- We find an “excess” of the data at 1-10 GeV, can be well fitted with a dark matter component
- Caveat: uncertainties from hadronic interaction models and/or charge-sign dependent solar modulation

Cui, QY et al. (2017)

Non-parameterized method to derive the local interstellar spectra with Voyager, ACE and AMS-02

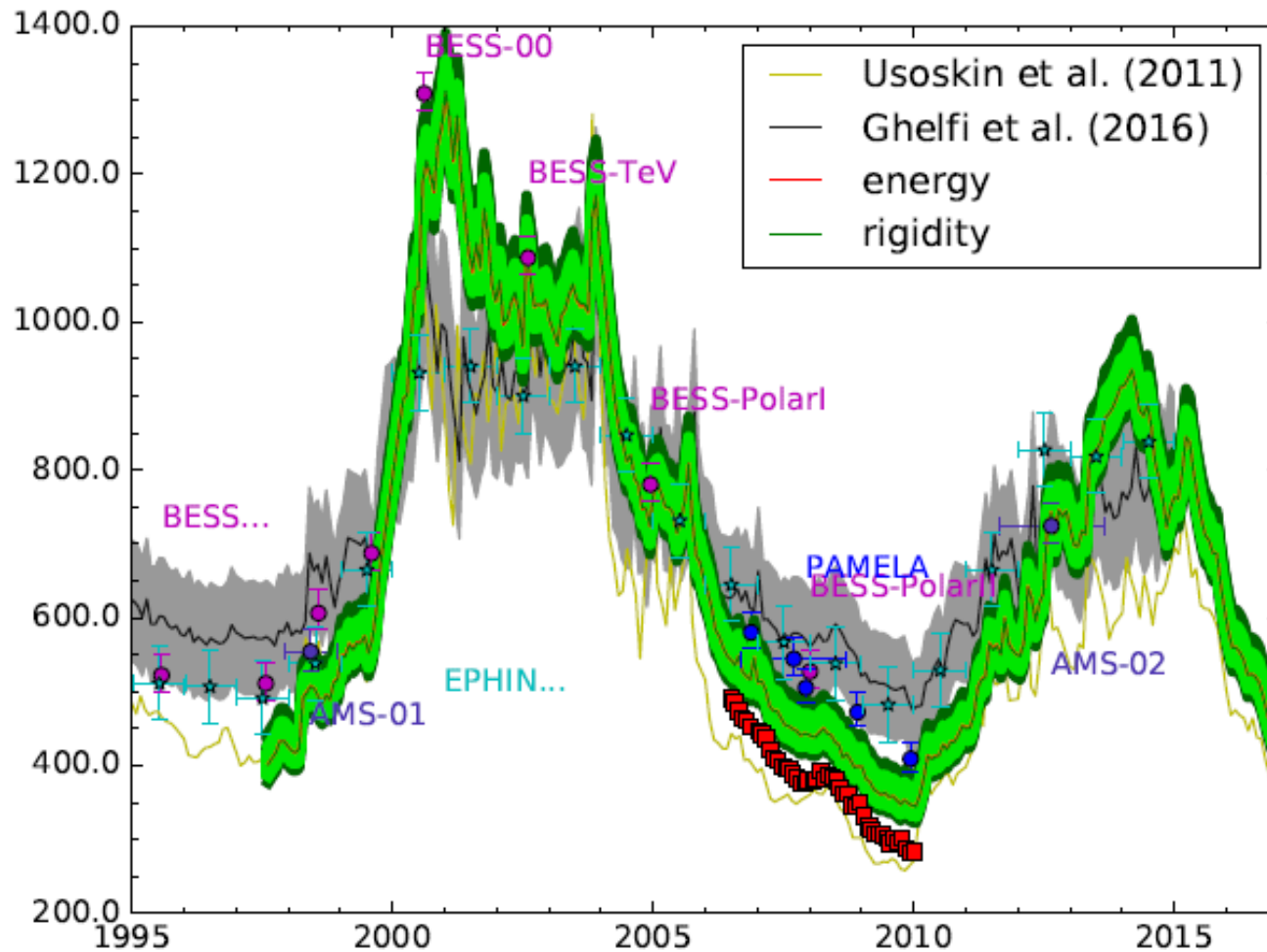
$[E_1, E_2, E_3, E_4, E_5,$
 $E_6, E_7, E_8, E_9, E_{10}]$
 $= [0.005, 0.01, 0.1, 1, 10,$
 $50, 100, 200, 400, 1000] \text{ GeV}/n$

- Spline interpolation between energy grids (Ghelfi et al. 2015)
- Force-field approximation of solar modulation
- The LIS spectra can be used to study CR prop.



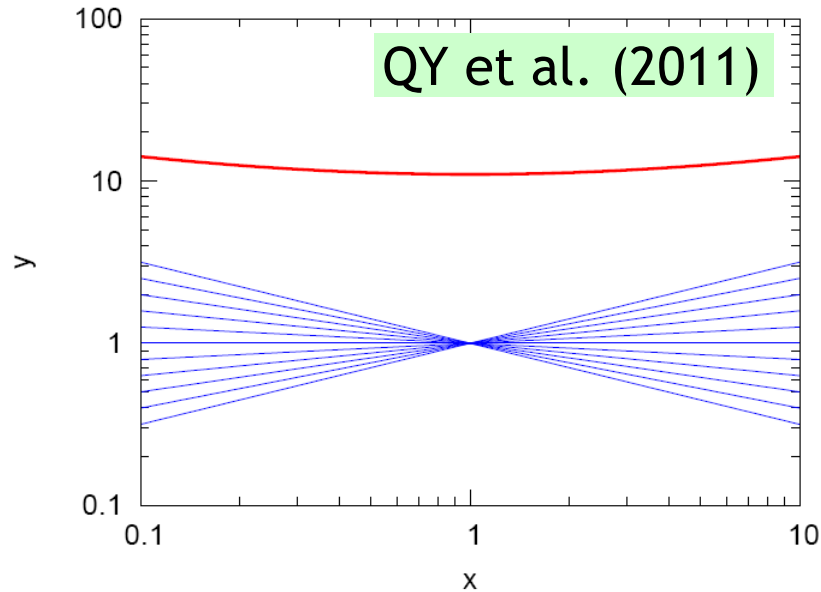
Zhu, QY et al. in prep.

Long-term solar modulation evolution with ACE data

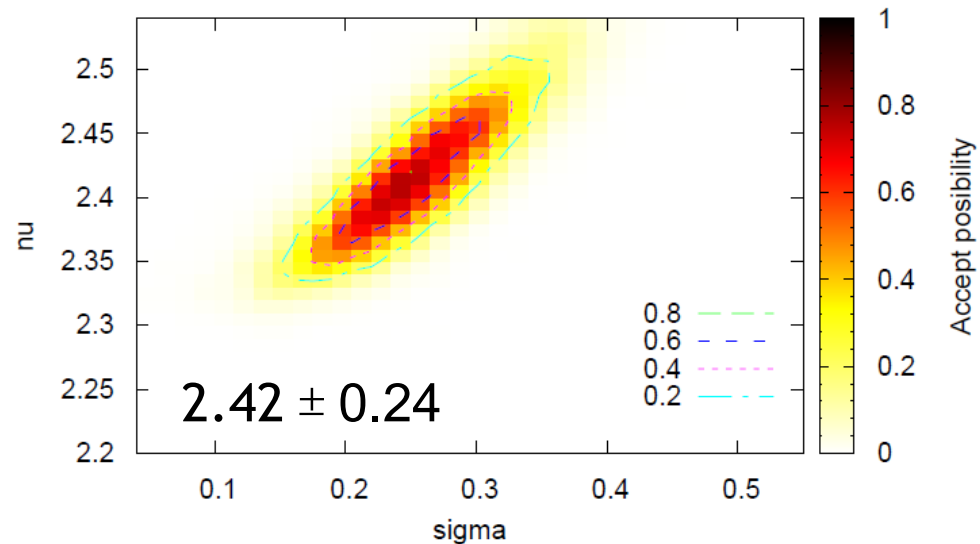
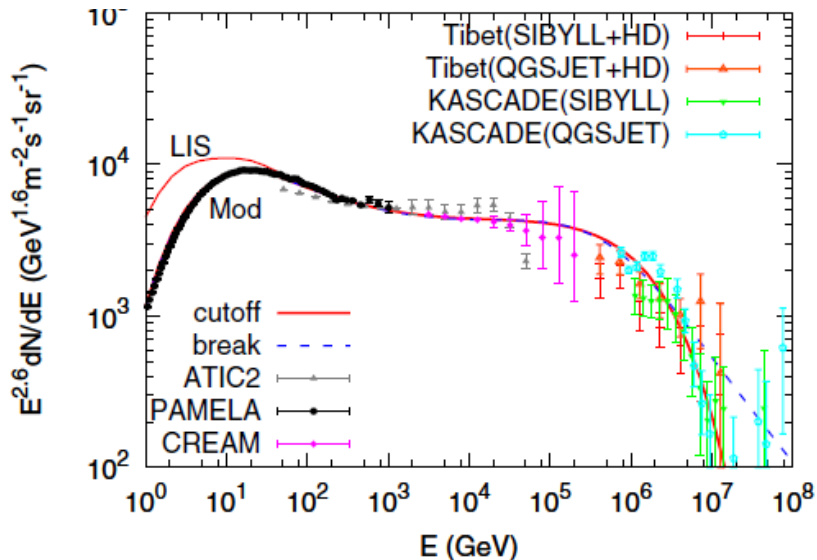


Zhu, QY et al. in prep.

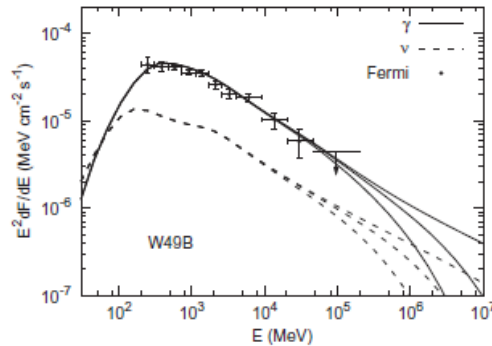
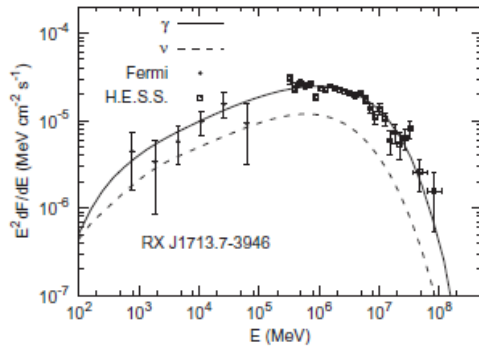
Spectral breaks of proton and helium: implications on CR sources



$$f(v) = \frac{N}{\sigma_v * \sqrt{2\pi}} e^{-\frac{(v-v_0)^2}{2\sigma_v^2}}$$

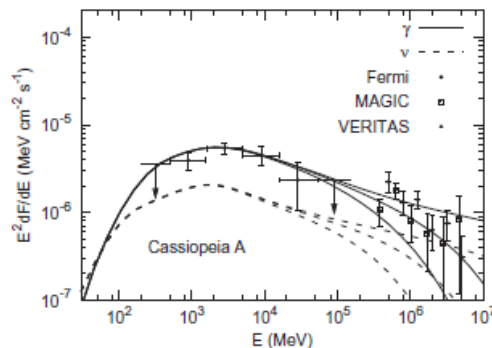
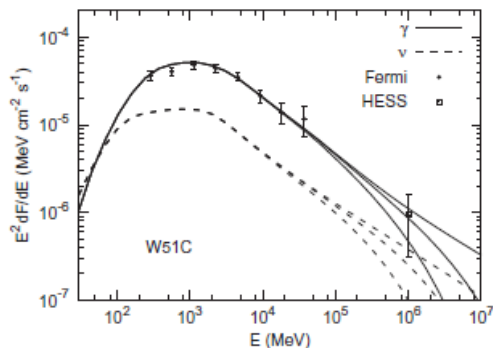
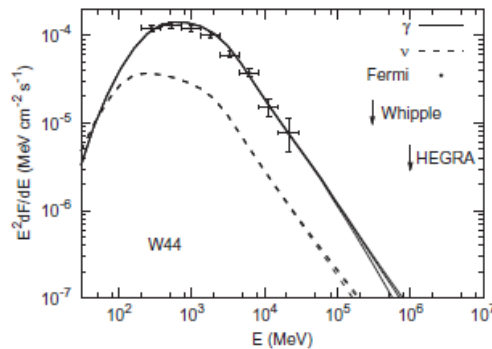
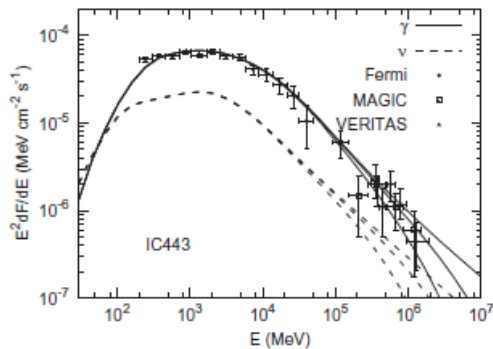


Gamma-ray spectra of SNRs do show diversity



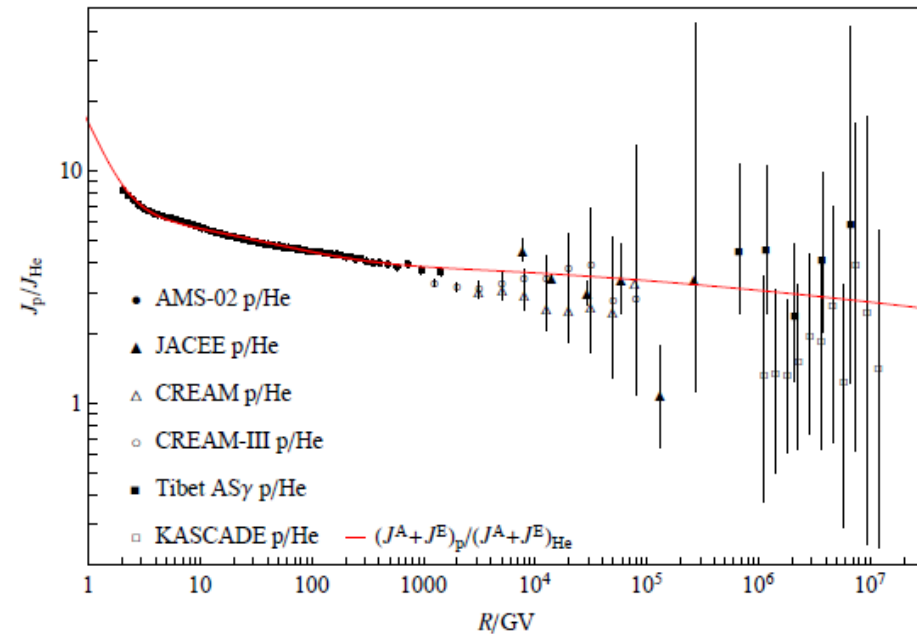
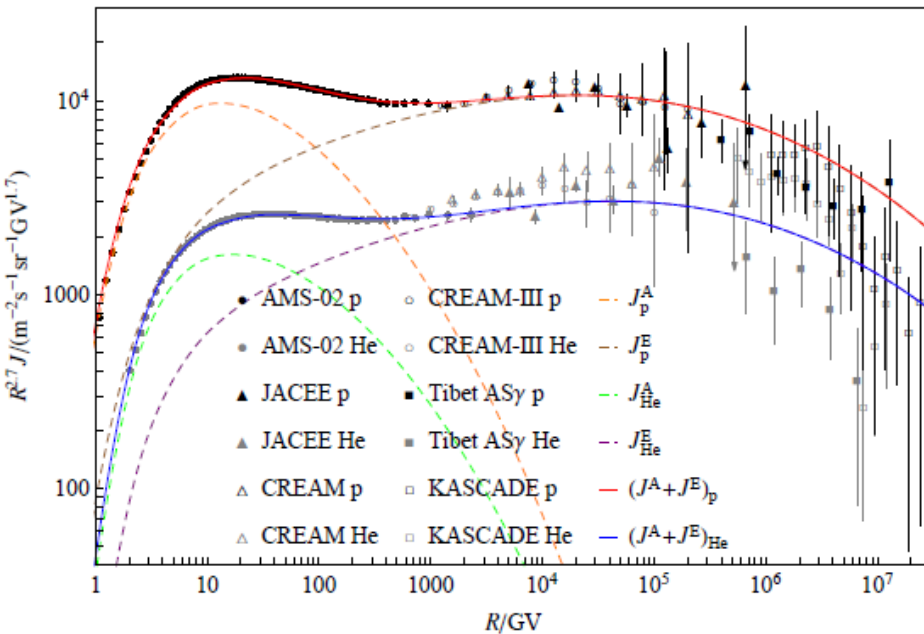
$$\gamma_1 \approx 2.15 \pm 0.33$$

$$\gamma_2 \approx 2.54 \pm 0.44$$



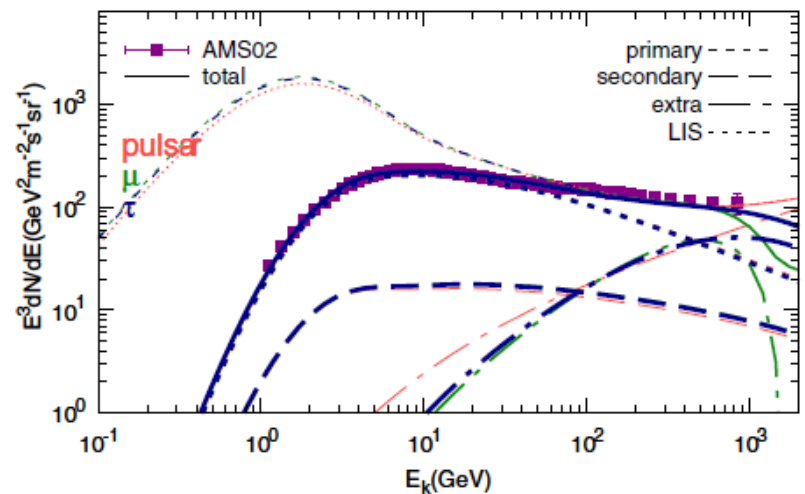
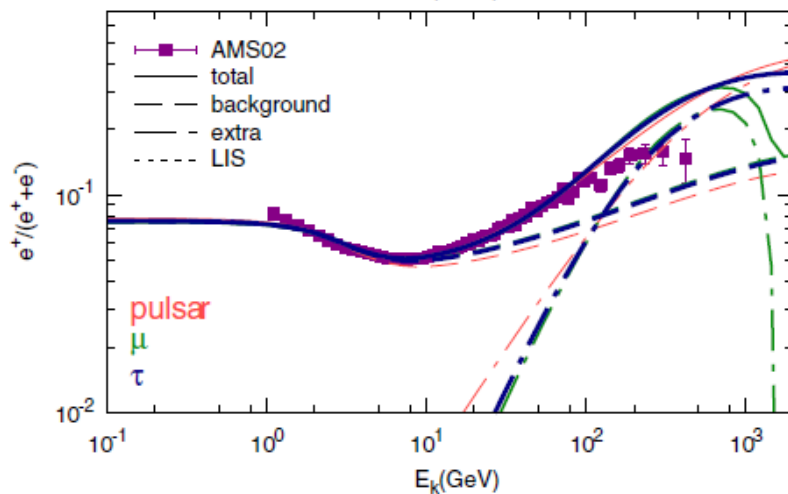
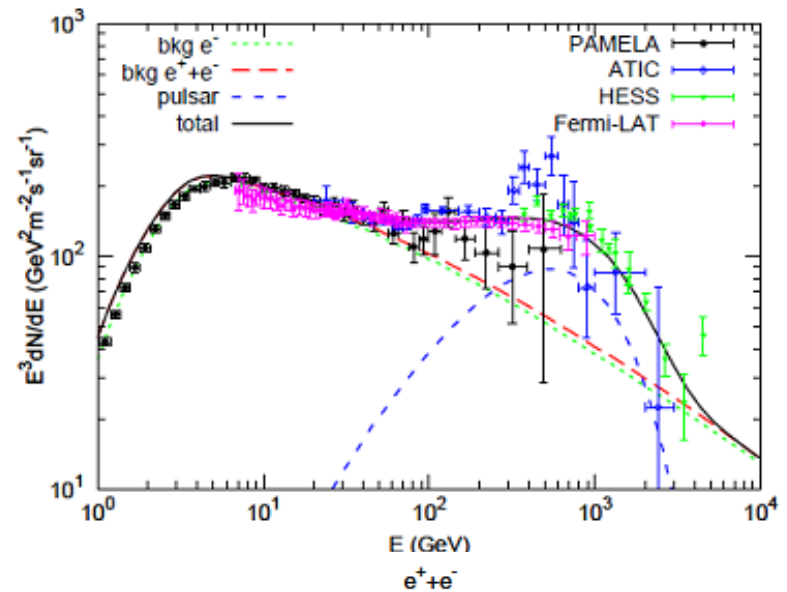
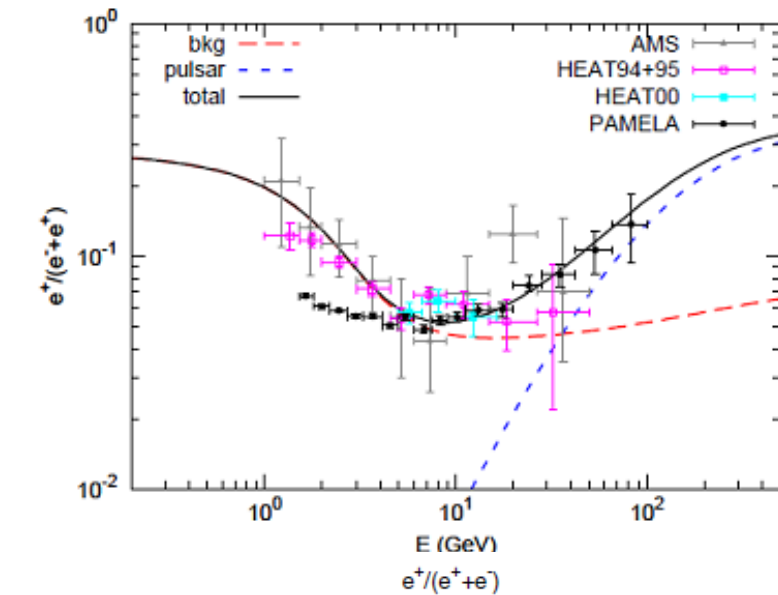
QY et al. (2011)

Spectral hardenings: an alternative scenario — time dependent particle acceleration



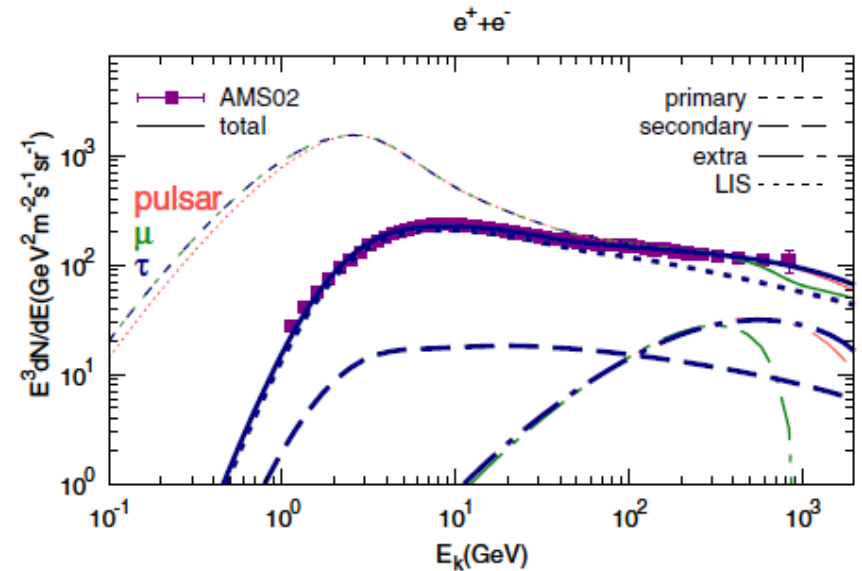
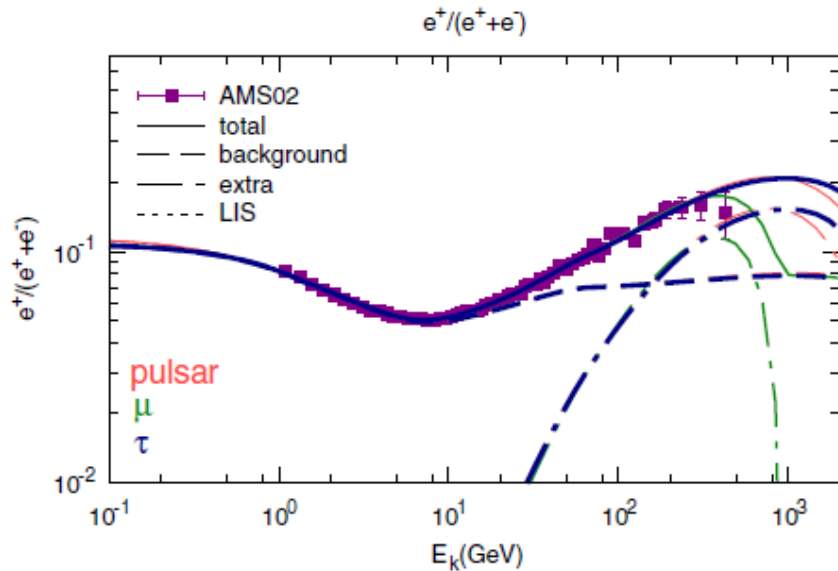
- Steady-state DSA predicts power-laws of accelerated particles
- Time-dependent solution gives gradually softening spectra
- The p/He ratio can be attributed to different injection rigidities (the same velocity)
- A two-phase SNR is assumed to explain the spectral hardenings: fast (e.g., free expansion) and slow (e.g., radiative) phases

Electrons/positrons before and after AMS-02



AMS-02 data make the simple bkg model not work any more!

Solution: an additional spectral break (hardening) of high energy bkg electron spectrum

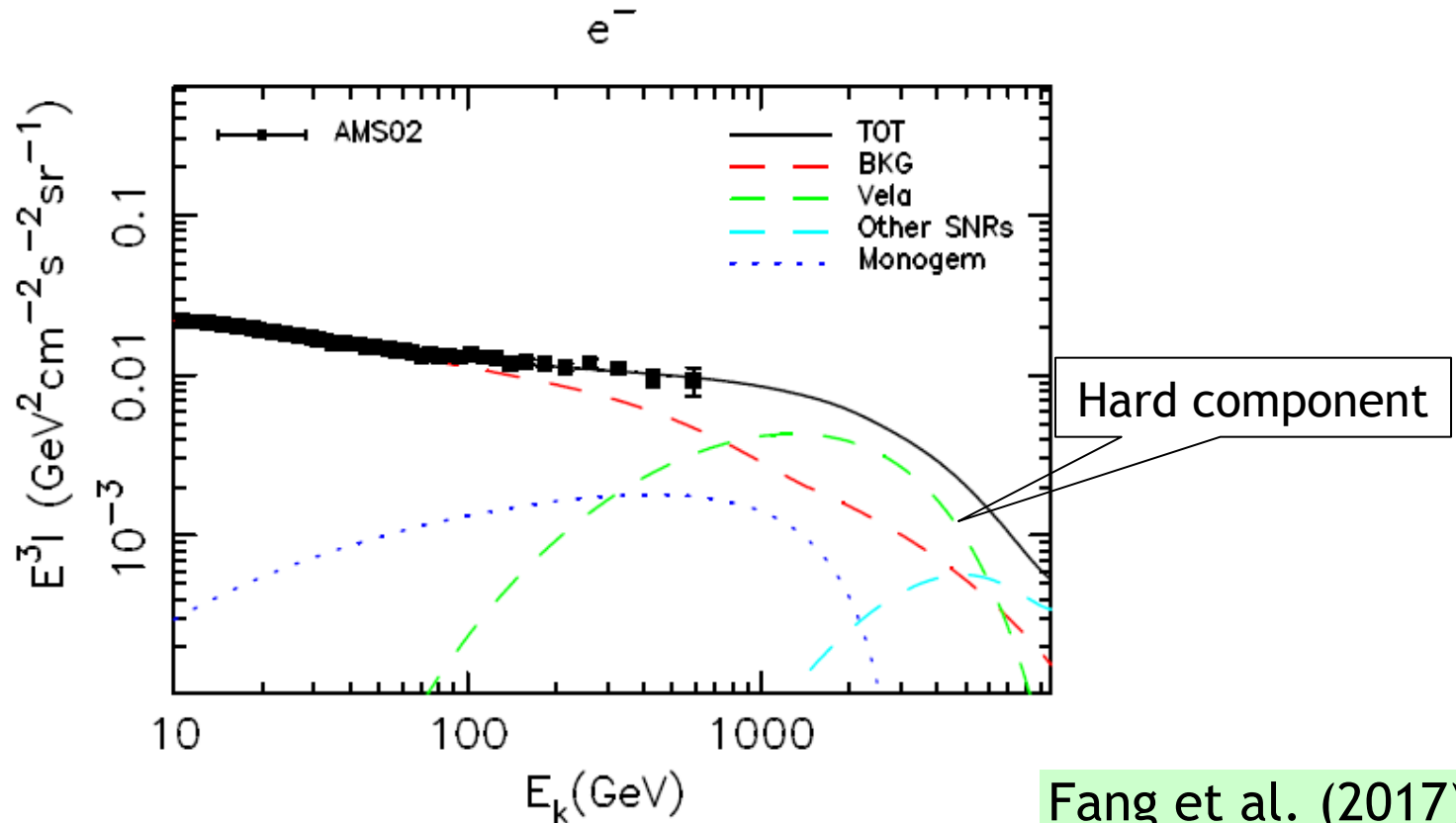


	Two breaks						One break					
	$\frac{\chi^2}{\text{d.o.f}}$	χ^2	$\frac{e^+}{e^++e^-}$	$e^+ + e^-$	e^-	e^+	$\frac{\chi^2}{\text{d.o.f}}$	χ^2	$\frac{e^+}{e^++e^-}$	$e^+ + e^-$	e^-	e^+
Pulsar	1.1	287.1	48.57	99.02	60.03	79.45	2.75	725.2	132.7	271.8	211.7	109.0
μ	1.12	293.4	40.7	113.8	61.0	77.95	3.01	797.9	242.4	245.5	206.9	103.1
τ	1.11	291.0	42.62	106.4	63.38	78.6	2.94	779.9	213.9	252.2	209.9	103.9

Lin, QY, Bi (2015)

Physics of the electron spectral hardening

- Nearby source effect (Bernard et al. 2013; Gaggero et al. 2013; Di Mauro et al. 2014; Fang et al. 2017a, 2017b)
- Superposition of source population (YQ et al. 2011)
- Charge asymmetry of the electron/positron sources (Feng & Kang 2013)



Conclusion

- AMS-02 B/C data set effective constraints on the propagation models (and parameters): a class of reacceleration models are favored
- Spectral hardenings of cosmic rays could be interpreted by source spectral dispersion, or a time-dependent particle acceleration of SNRs
- Spectral hardenings of electrons could be hint of nearby sources

Thank you!