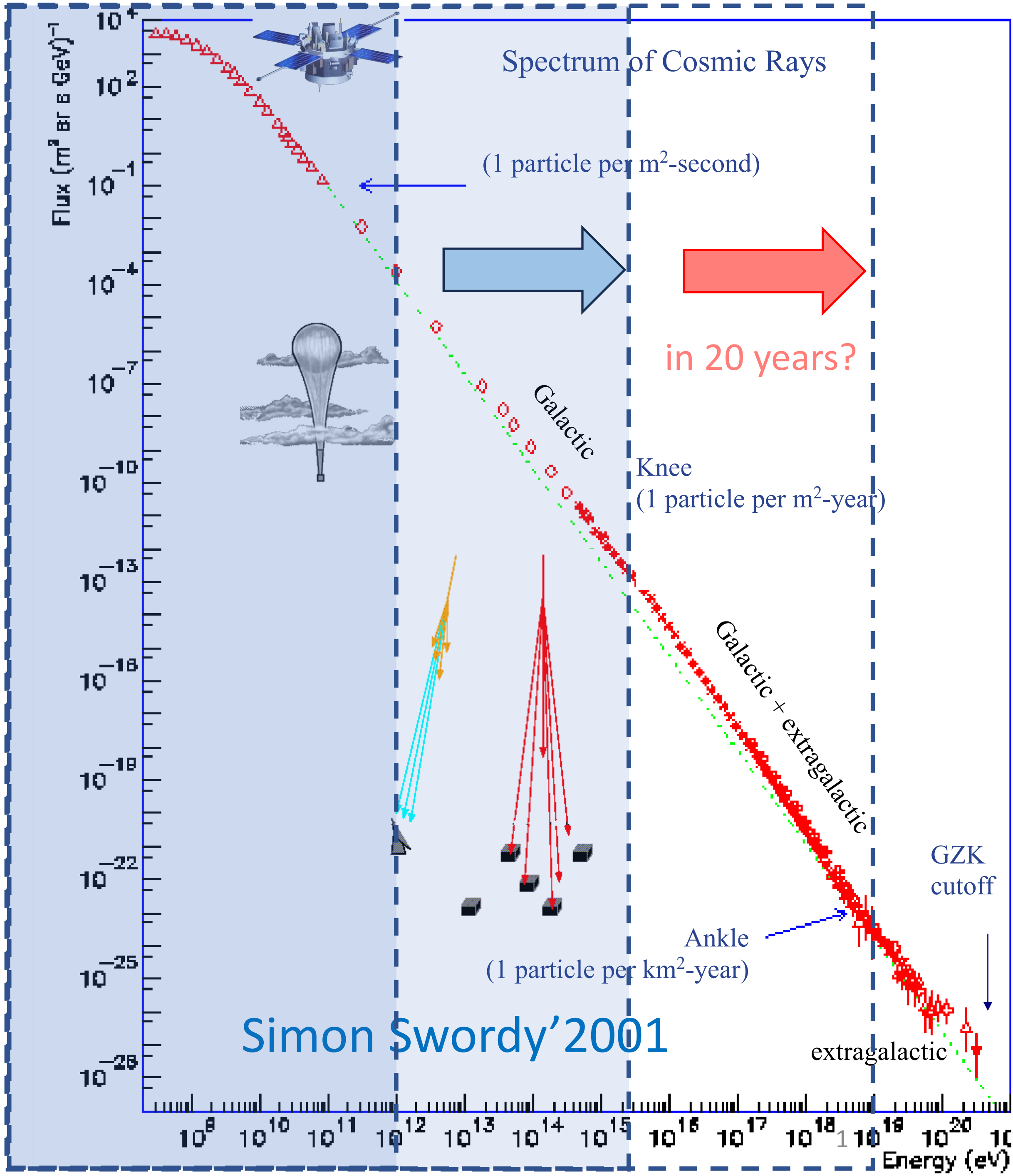
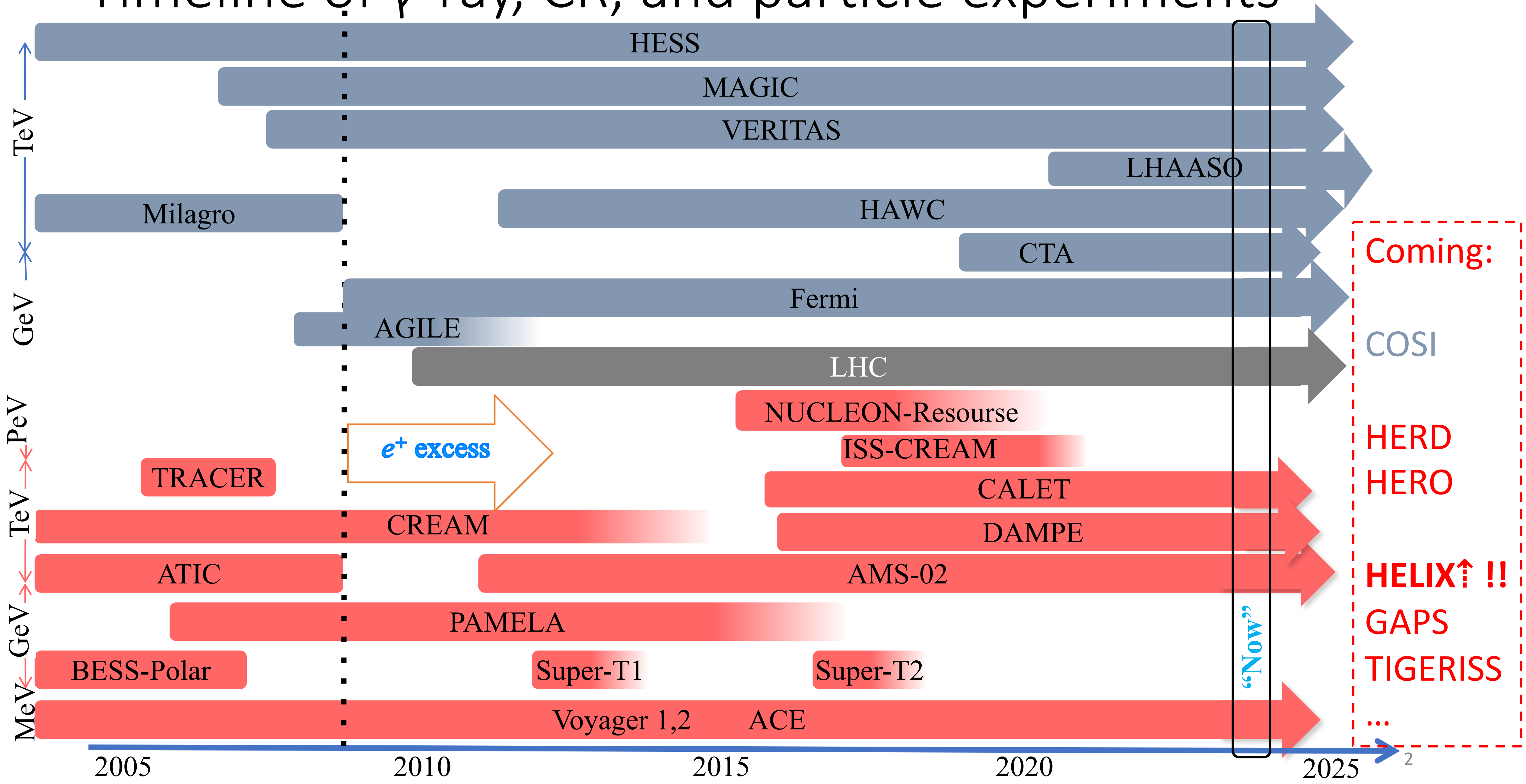
Direct measurements of cosmic rays and their possible interpretations (effects of the local sources)

Igor V Moskalenko / Stanford U.

Ischia, May 26 -June 1, 2024



Timeline of γ-ray, CR, and particle experiments

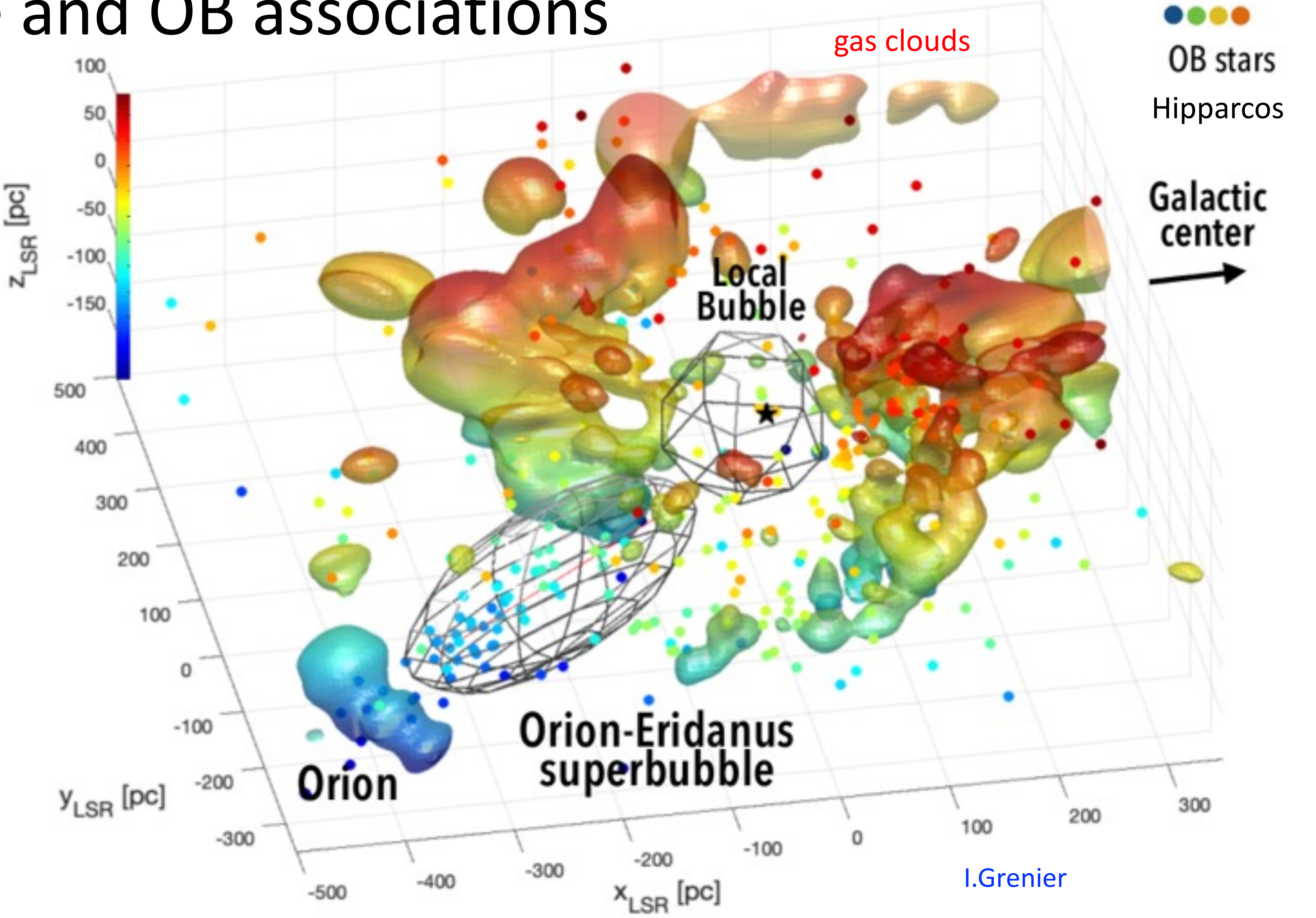


SNR paradigm challenge

Type	Ejecta E_{kin}, erg	Frequency	Observed number (MW)
Supernova remnant	10^{51}	~0.03/year Last was in 1604!	294 (Green Catalogue)
Wolf-Rayet wind	10^{51} -over the lifetime		354
O star wind	10^{50} (0.01 $L_{☆}$)-over 5 Myr winds (2-4)x10^{3} km/s		20,000
Pulsar (Crab)	~4x10^{49} (total E_{rot})		~1500
Nova	10^{45}	~30-40 per year	350
Stellar flare	10^{36}		
Solar flare	10^{32}-10^{33}	Some 10 per year	

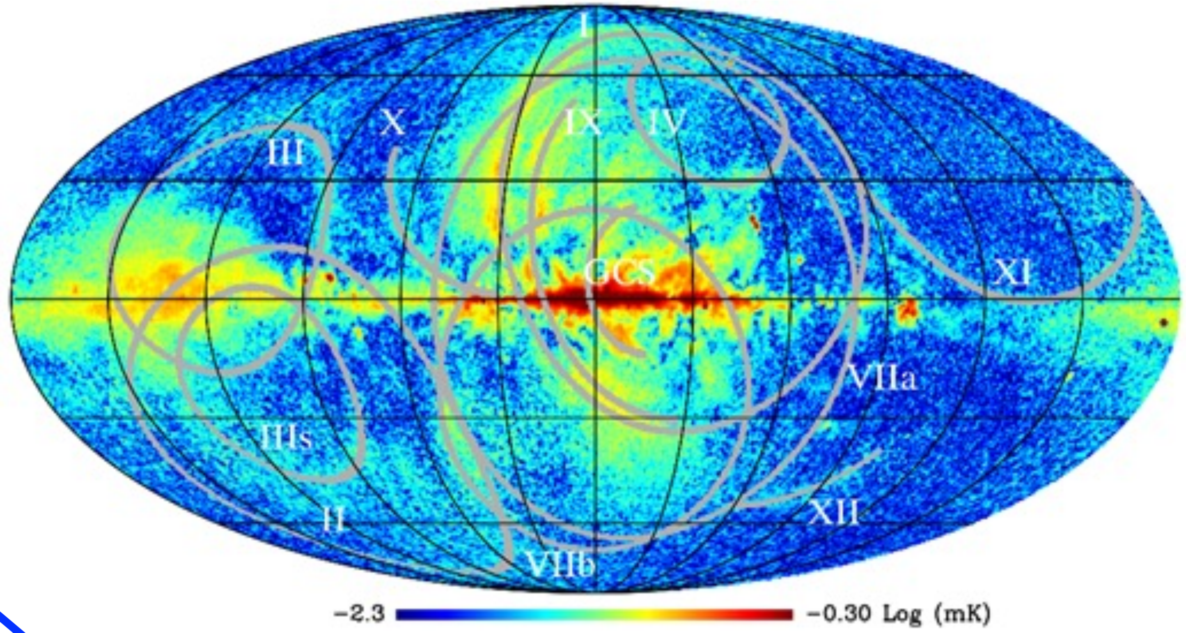
Local Bubble and OB associations

- The Local Bubble – a low-density region of ~200 pc around the Sun filled with hot HI gas is formed in a series of SN explosions (Sfeir+1999, Frish+ 2011)
- A number of OB stars in the vicinity of the solar system, as close as 100 pc
- Yellow/greenish color marks features at the same distance from the Galactic plane as the solar system



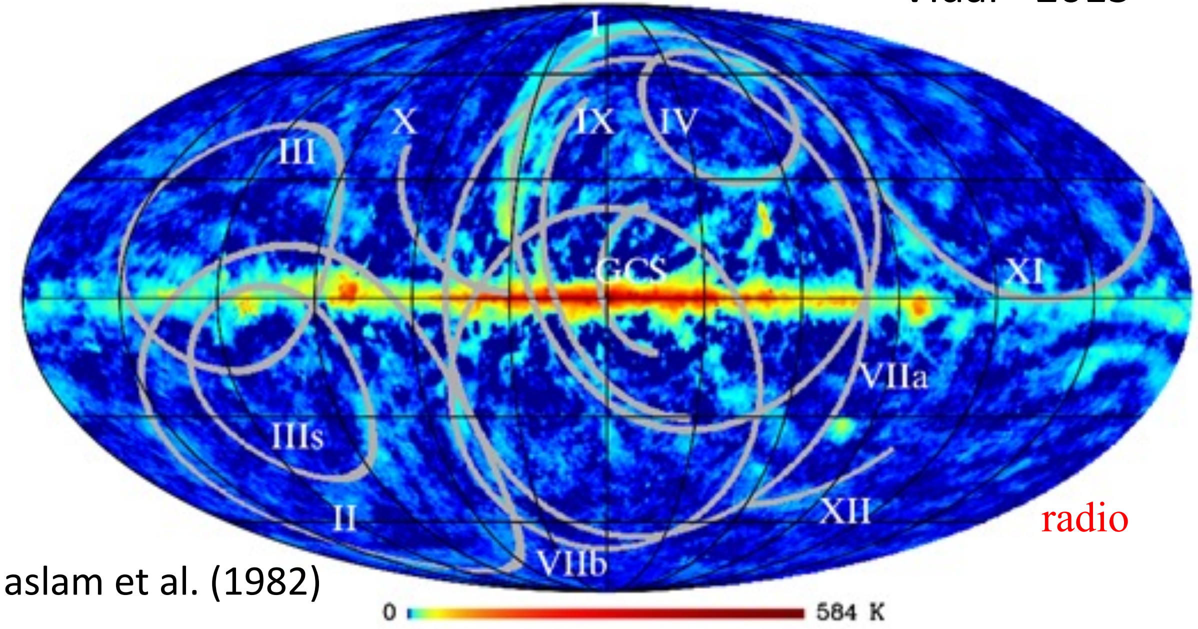
Galactic Loops

- ✧ WMAP *K*-band polarization intensity map
- ✧ Unsharp mask version of the Haslam et al. (1982) map
- ✧ The origin of the Loops is unknown
- ✧ If these are old SNR, accelerated particles may still be present in the shells
- ✧ Signatures of the past (recent?) activity in the Solar neighborhood



WMAP *K*-band polarization intensity map

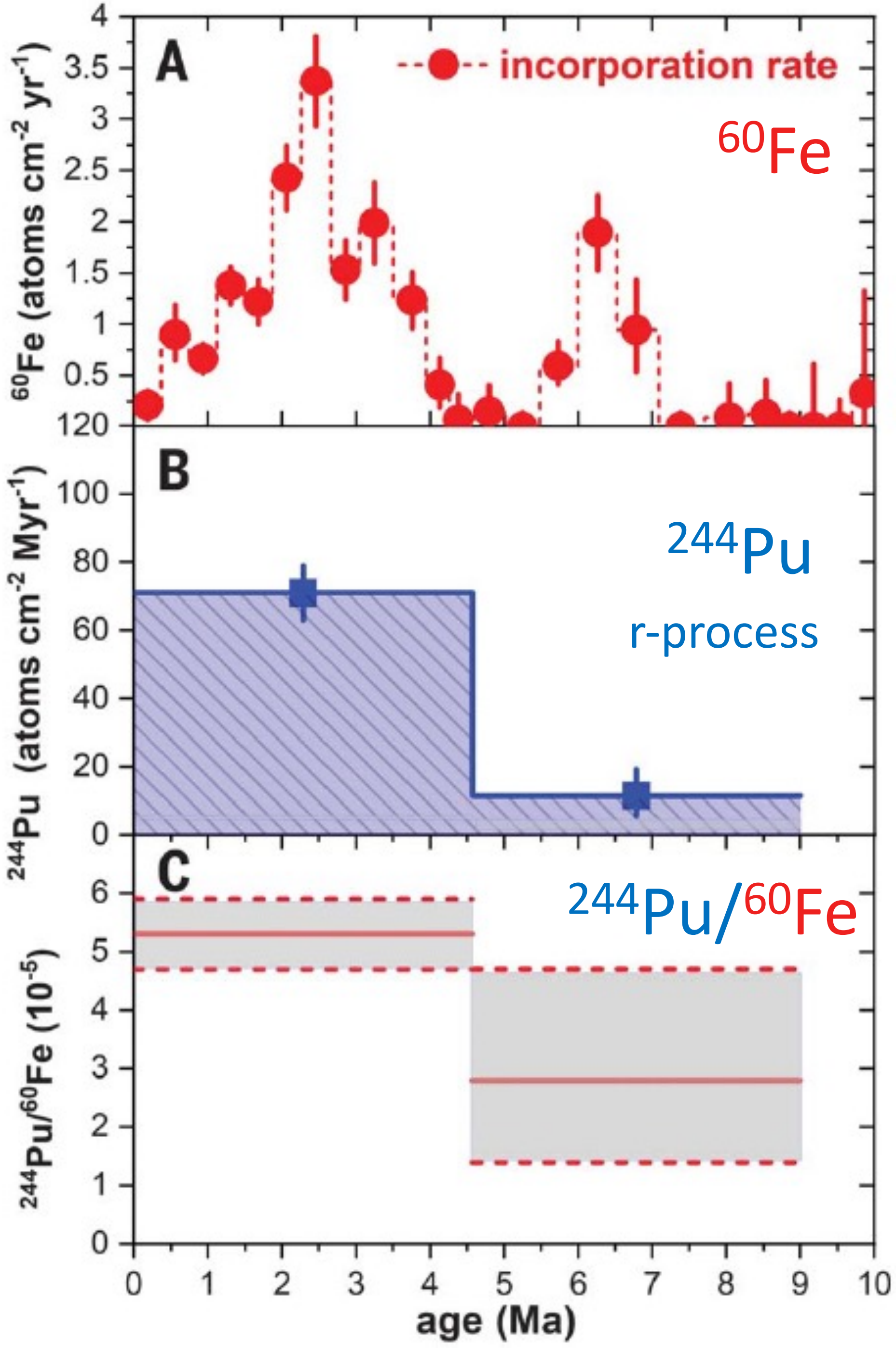
Vidal+'2015



radio

Haslam et al. (1982)

Low-energy features



$\tau_{1/2}$ ~2.6 Myr

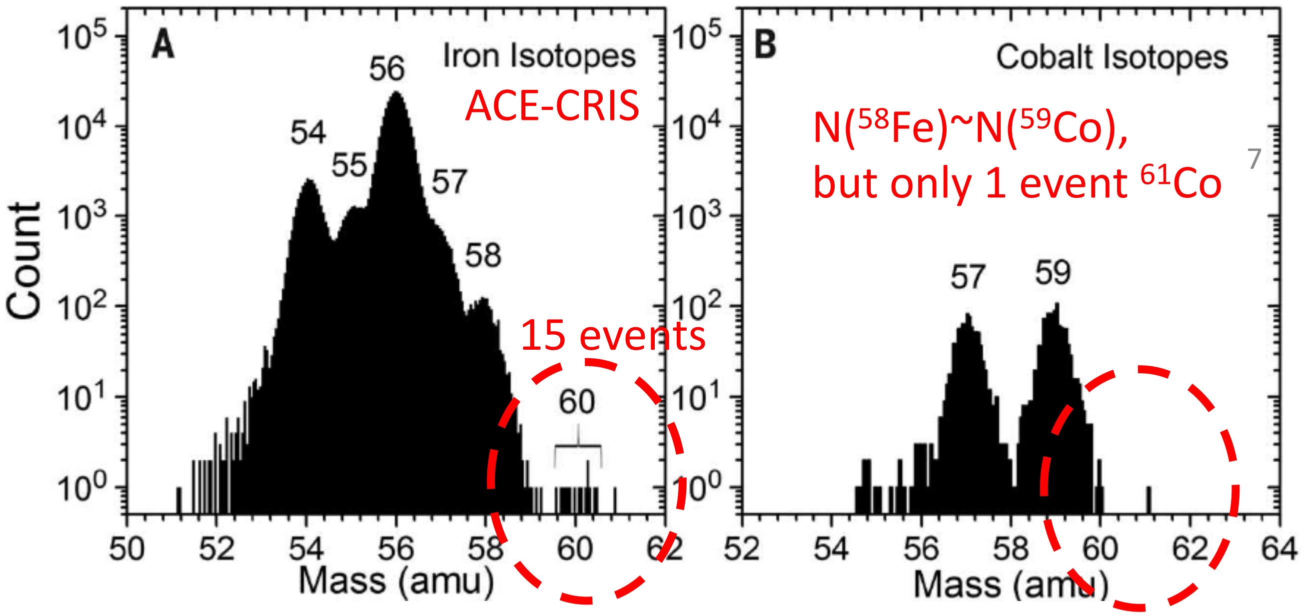
$\tau_{1/2}$ ~80.6 Myr

Wallner+’2021

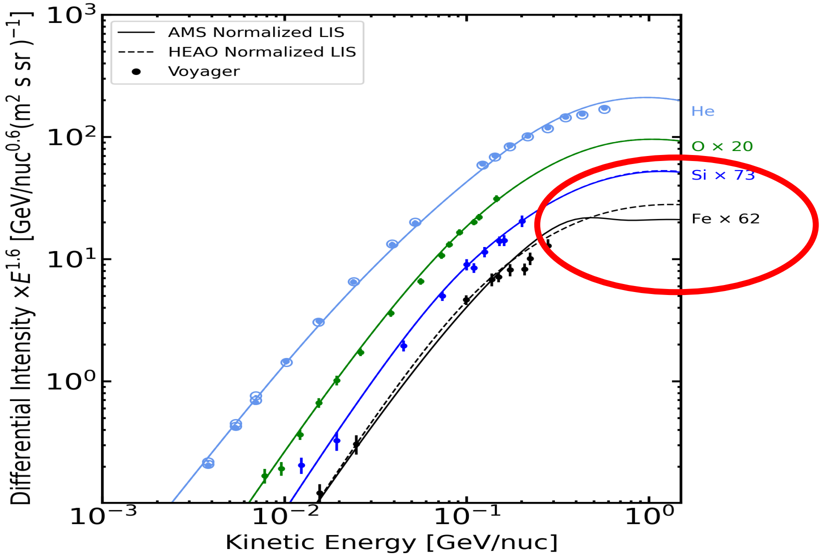
^{60}Fe as a tracer of SN activity in the solar neighborhood

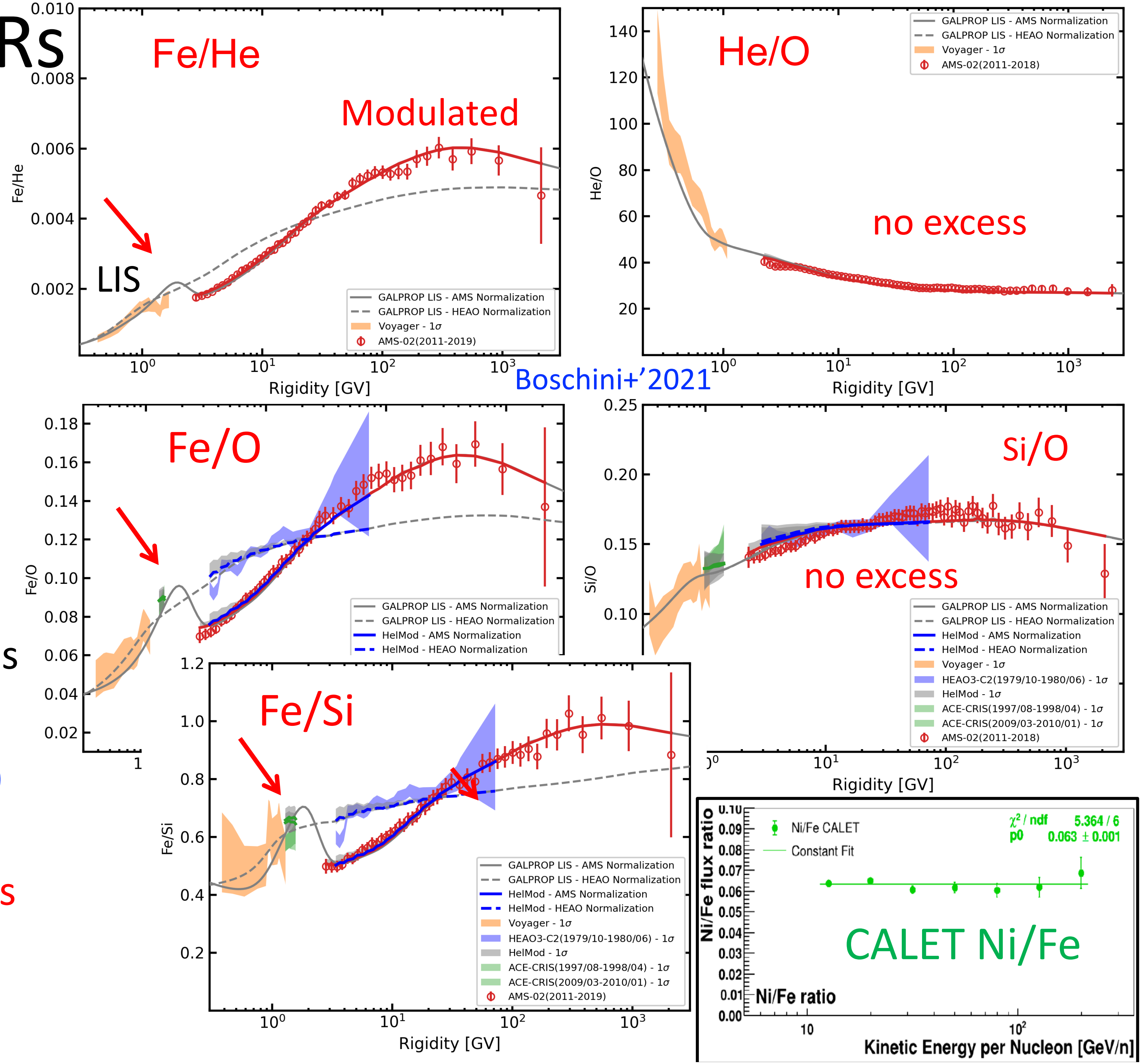
- ✧ The evidence of the past SN activity in the local ISM is abundant (Fry+2015; Wallner+2016,2021; Breitschwerdt+2016)
- ✧ The Local Bubble is a low-density region of the size of ~200 pc filled with hot H II gas that itself was formed in a series of SN explosions
- ✧ Indications of several SNe between ~1.5 and ~3 Myr ago within 100 pc of the Sun

- ✧ ^{60}Fe: a half-life 2.6 Myr, β^{-} decay
- ✧ Excess of radioactive ^{60}Fe in deep ocean sediments (Knie+'1999, 2004; Ludwig+'2016; Wallner+'2016)
- ✧ Antarctic snow (Koll+'2019).
- ✧ Lunar regolith samples (Cook+'2009; Fimiani+'2012, 2014)
- ✧ ACE-CRIS observations of ^{60}Fe (Binns+'2016)



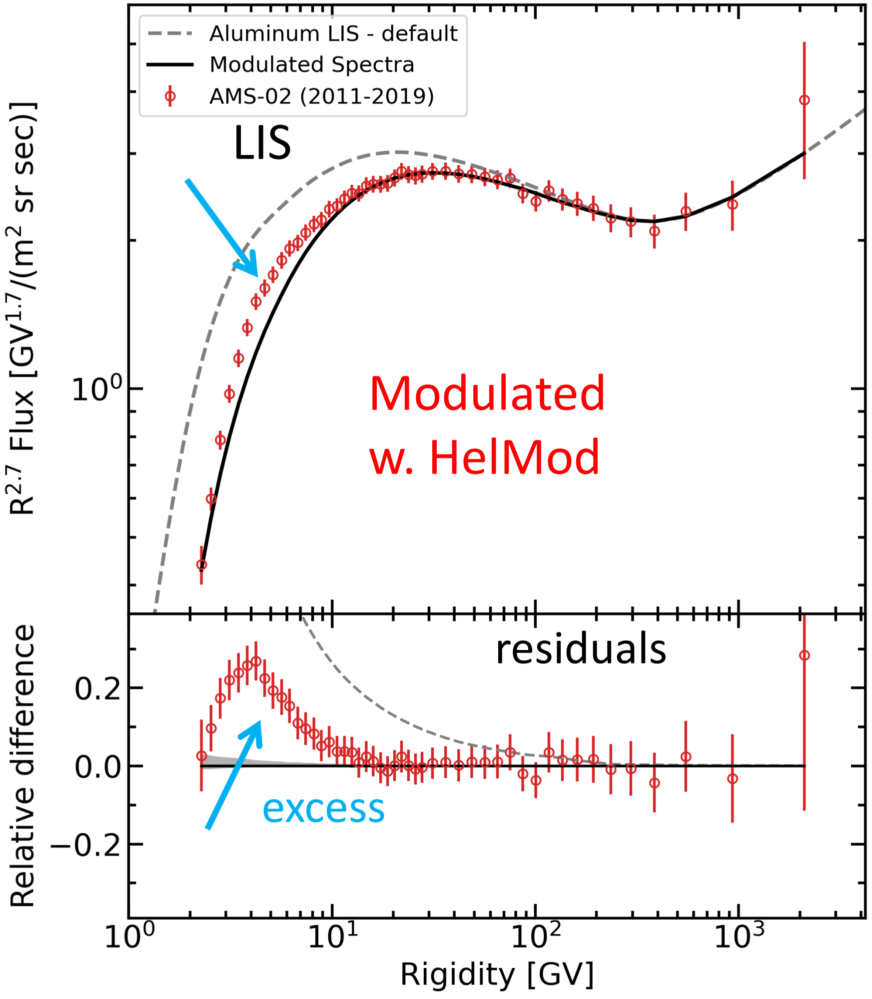
Iron excess/deficit in CRs



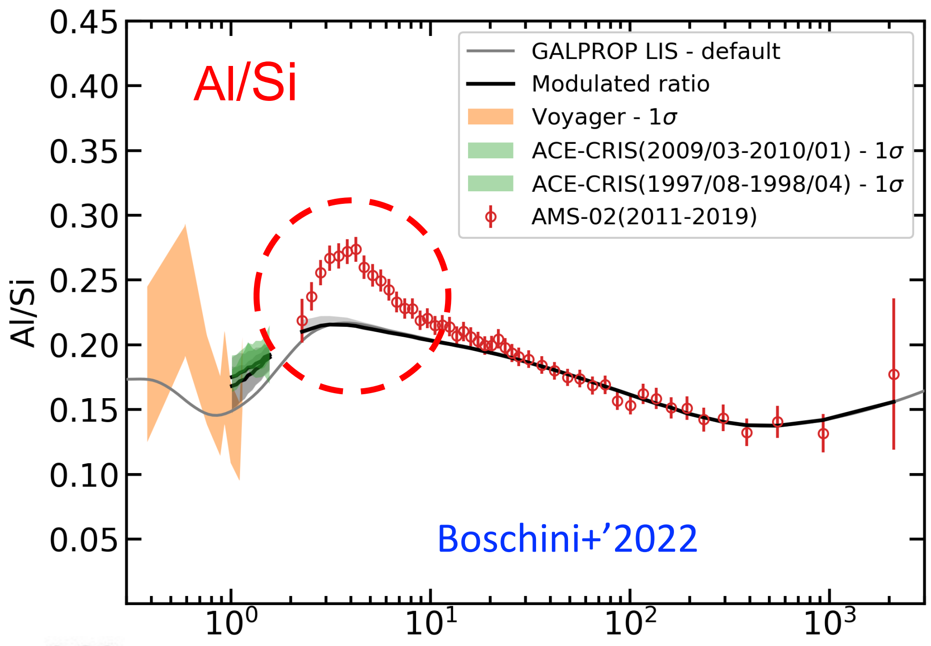


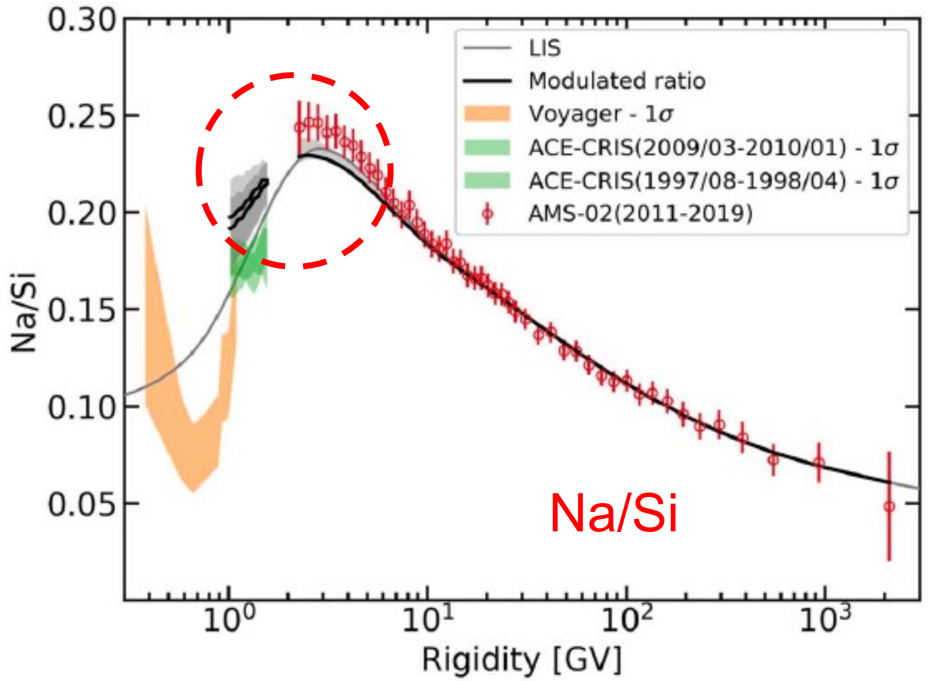
- ✧ The excess in iron – comparison of Voyager 1, ACE-CRIS, and AMS-02 data
- ✧ Most visible in Fe/He, Fe/O, Fe/Si ratios
- ✧ Absent in He/O and Si/O ratios
- ✧ Falls in line with other evidences (^{60}Fe)
- ✧ Local sources: large fragmentation cross sections and fast ionization losses
- ✧ Fe group: Ni/Fe = const (CALET)
- ✧ Important to measure sub-Fe/Fe ratio

Aluminum excess



- An excess in aluminum becomes clearly visible when we compare the Al/Si ratio with model predictions
- A similar feature in Na/Si ratio is absent
- The excess is observed in a narrow region 3-10 GV (~0.8-4 GeV/n), where the production cross sections are mostly flat
- Indicates a presence of low-energy Al component, perhaps associated with local sources (massive stars?)





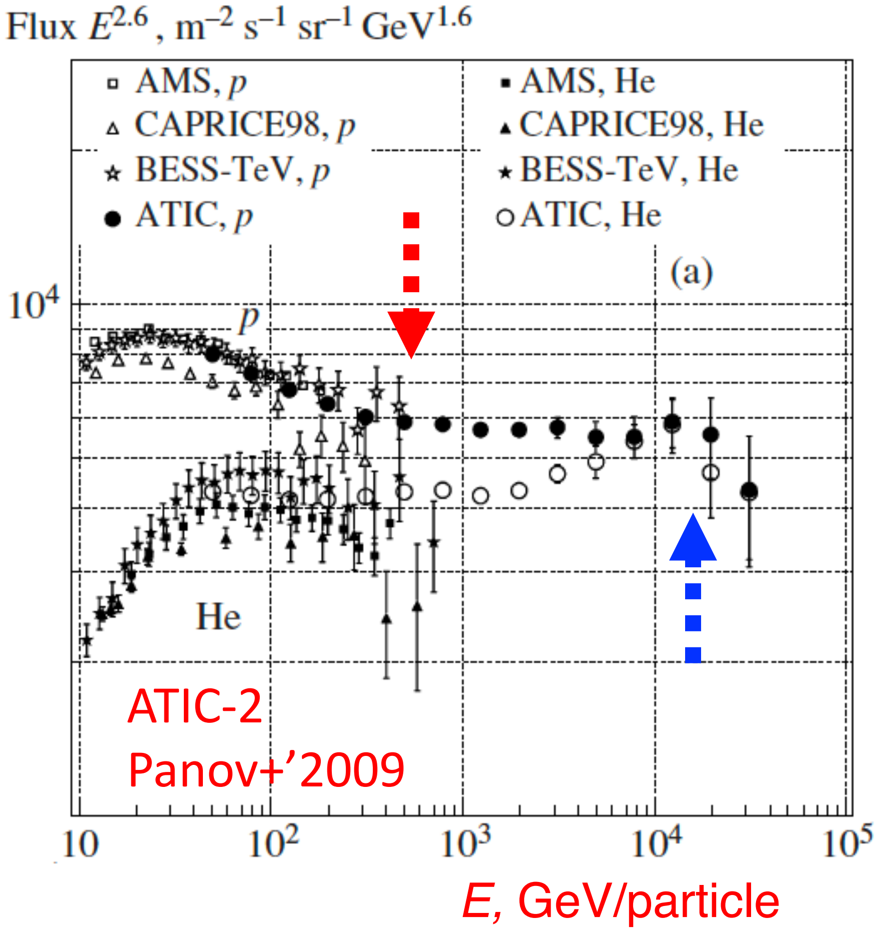
There are more low-energy excesses observed (Li, F) and even more is coming in 2024…

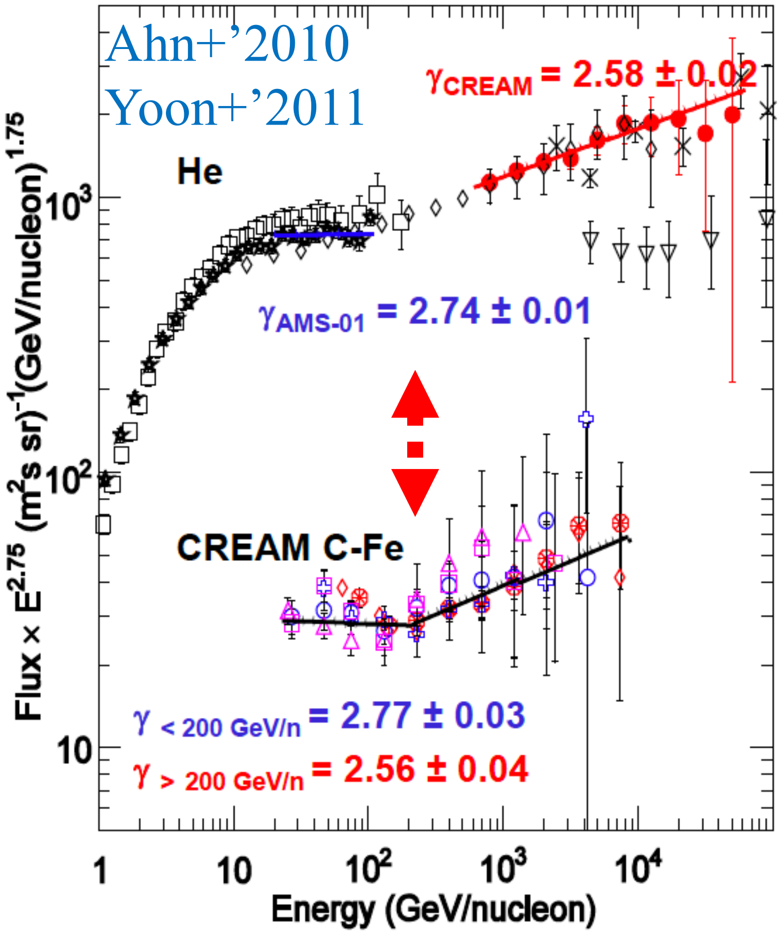
Stay tuned!

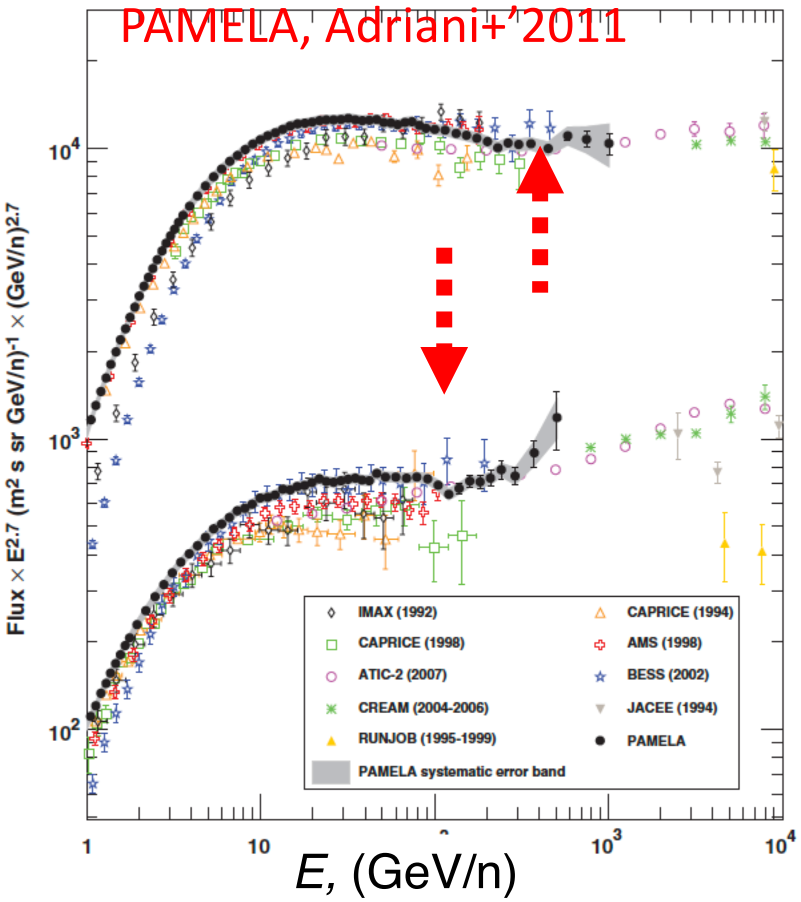
The TV bump

200 GV break in spectra of CR species

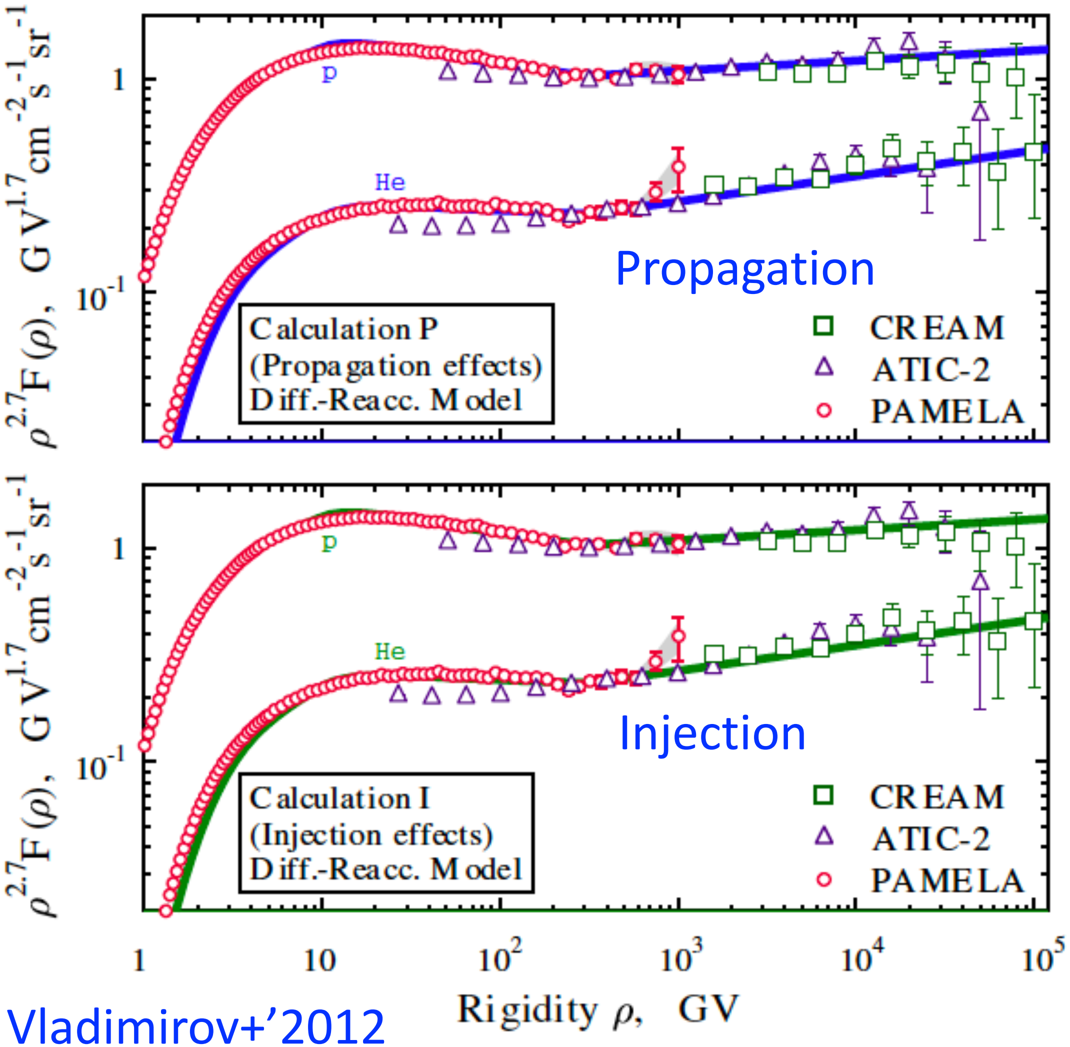
- ATIC-2 (Panov+'2009) and CREAM "*Discrepant hardening observed in cosmic-ray elemental spectra*" (Ahn+'2010)
- Initially looked like a calibration issue between <200 GeV and >200 GeV instruments, which used different techniques
- Beautifully outlined by PAMELA (went up to 1 TeV)
- Do not be confused, plots have different units: GeV/particle, GeV/nucleon





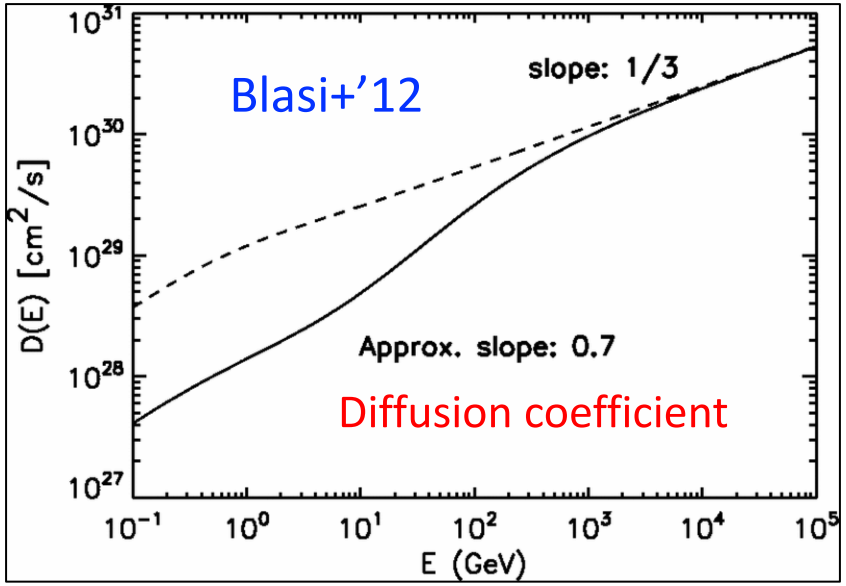


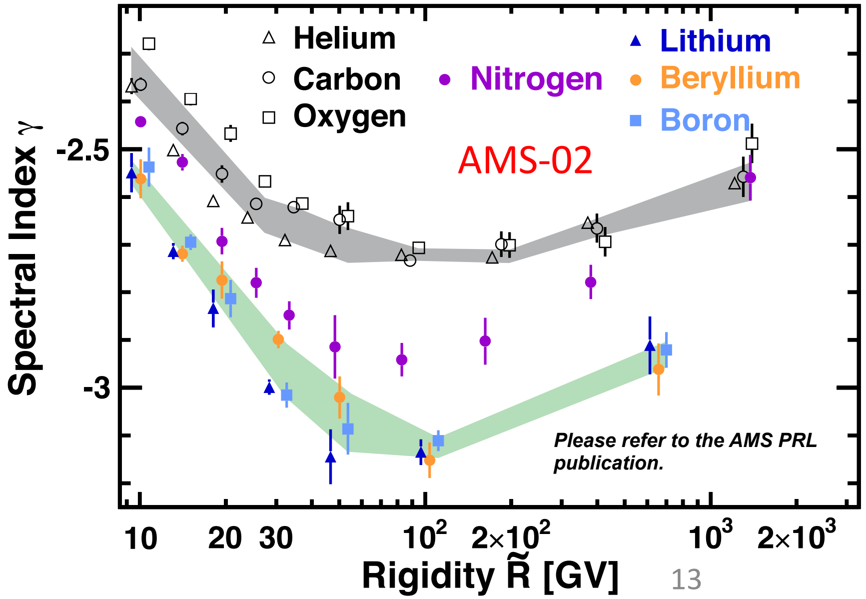
Early hypotheses of the origin of ~200 GV break



Vladimirov+'2012

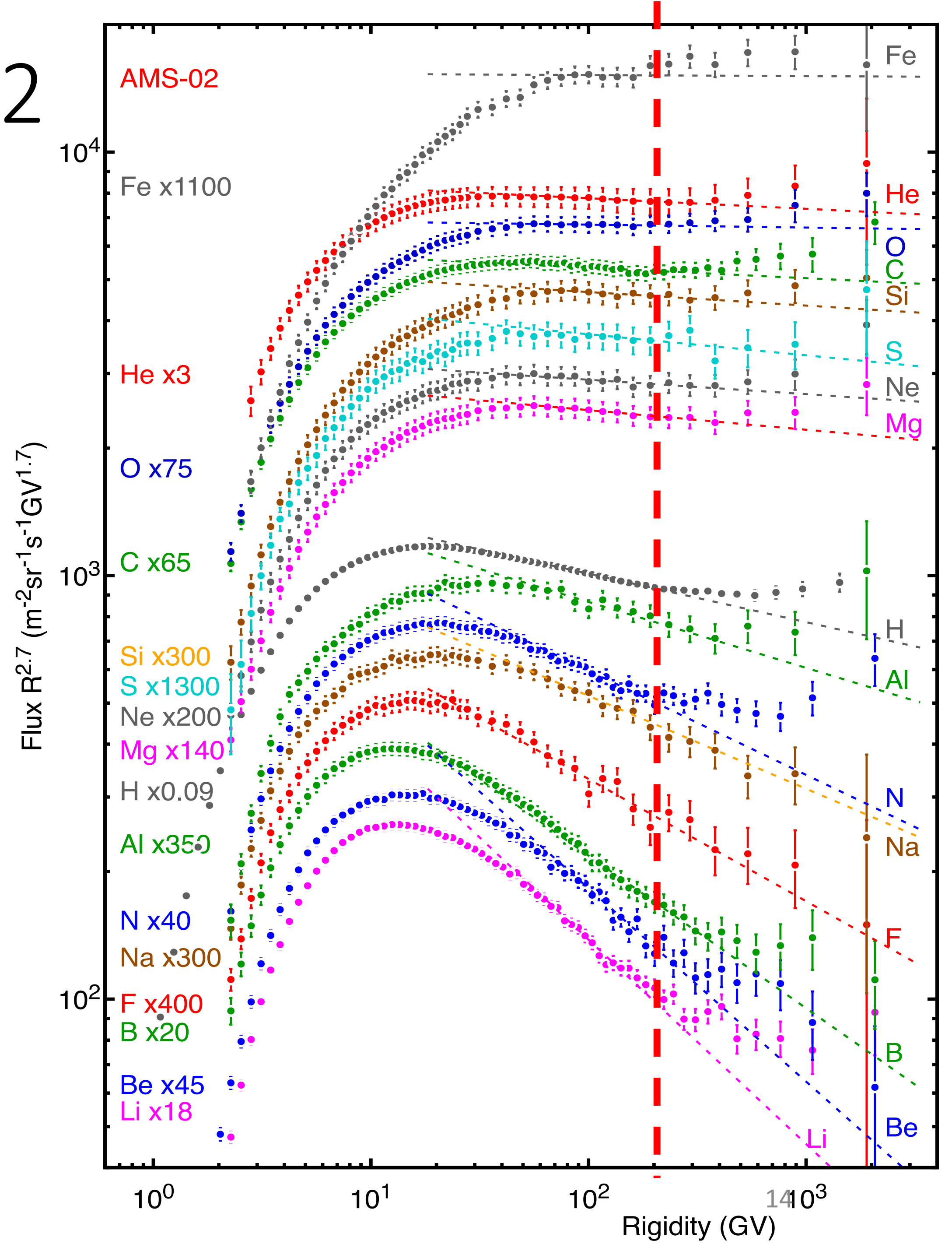
- Vladimirov+2012 proposed 4 distinct scenarios: Propagation, Injection, Local Source at low or high energies. Propagation scenario (break in the diffusion coeff.) was a favorite
- Blasi+12 proposed physical motivation for the break in the diffusion coefficient
- The diffusion coeff. scenario reproduced the observed difference between spectra of primary and secondary species



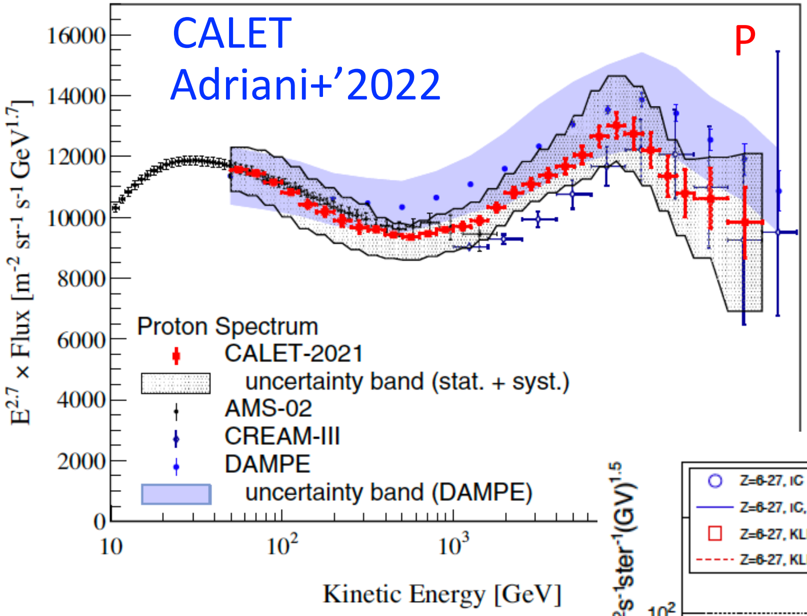


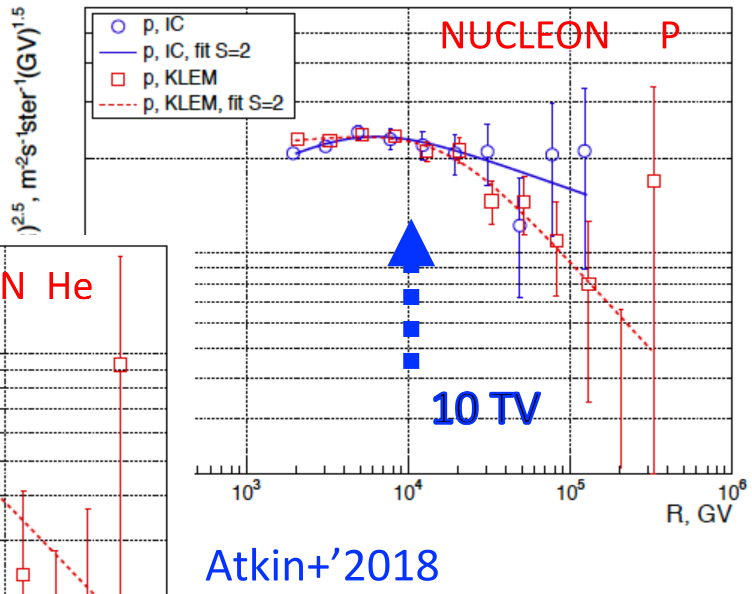
Alpha Magnetic Spectrometer-02 (AMS-02) measurements of the 200 GV break

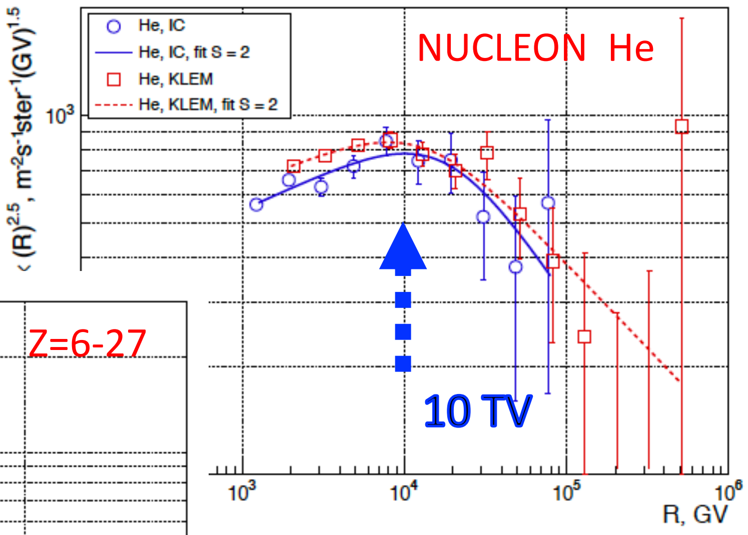
- It is most clearly seen in AMS-02 data, which cover this range
- CR species are sorted by approximate order of their spectral index in 50-200 GV range
- Fe has the flattest spectrum followed by He, O, C, and then Si, S, Ne, Mg
- The steeper spectra are observed in H, Al, N, Na, F, B, Be, and the steepest is Li (partly tertiary)
- Fluorine is flatter than Boron, and may indicate a different origin or a presence of the primary component

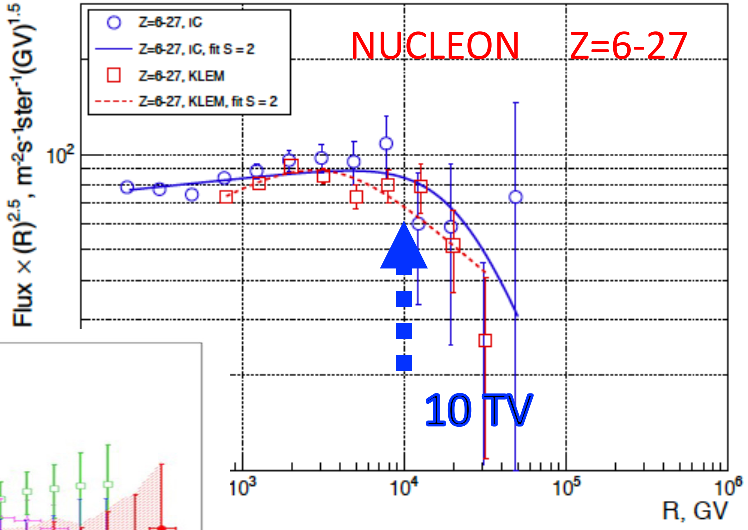


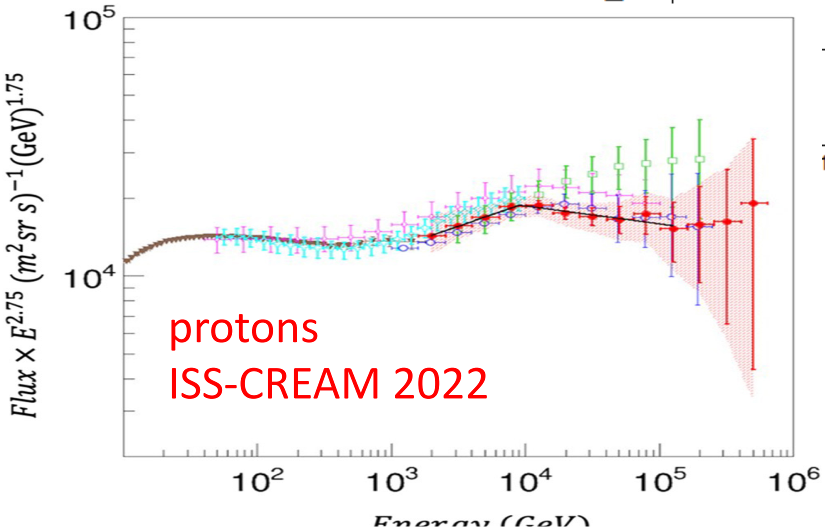
Yet another break at 10 TV

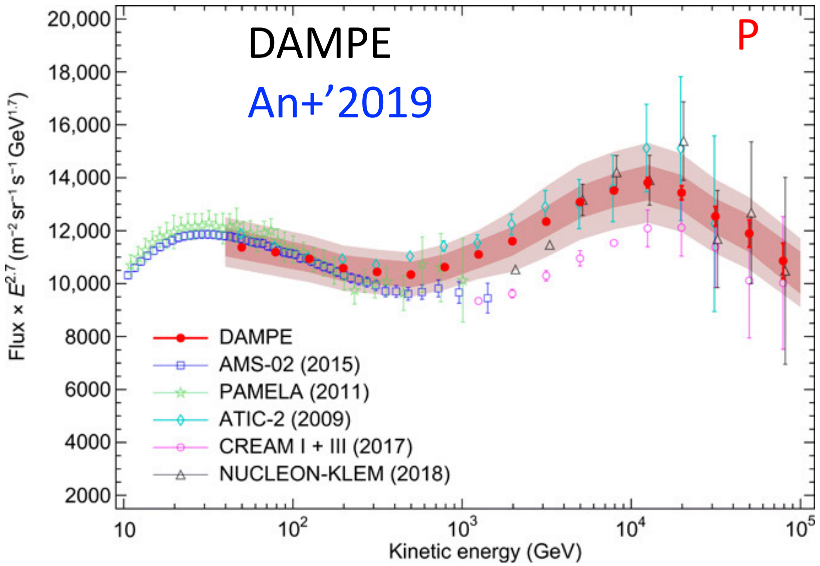








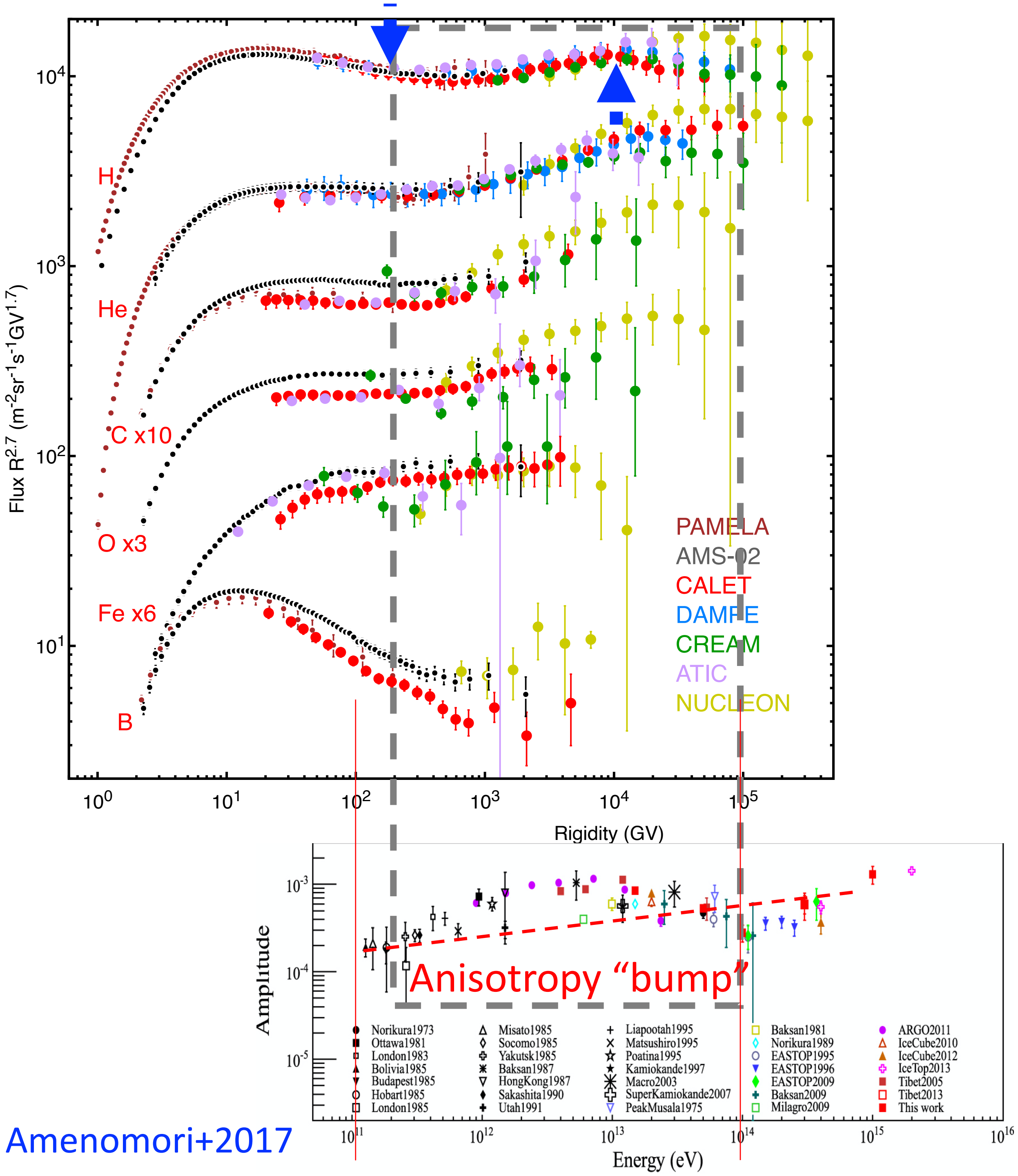




- Was also observed by ATIC, but no claim was made

TeV bump

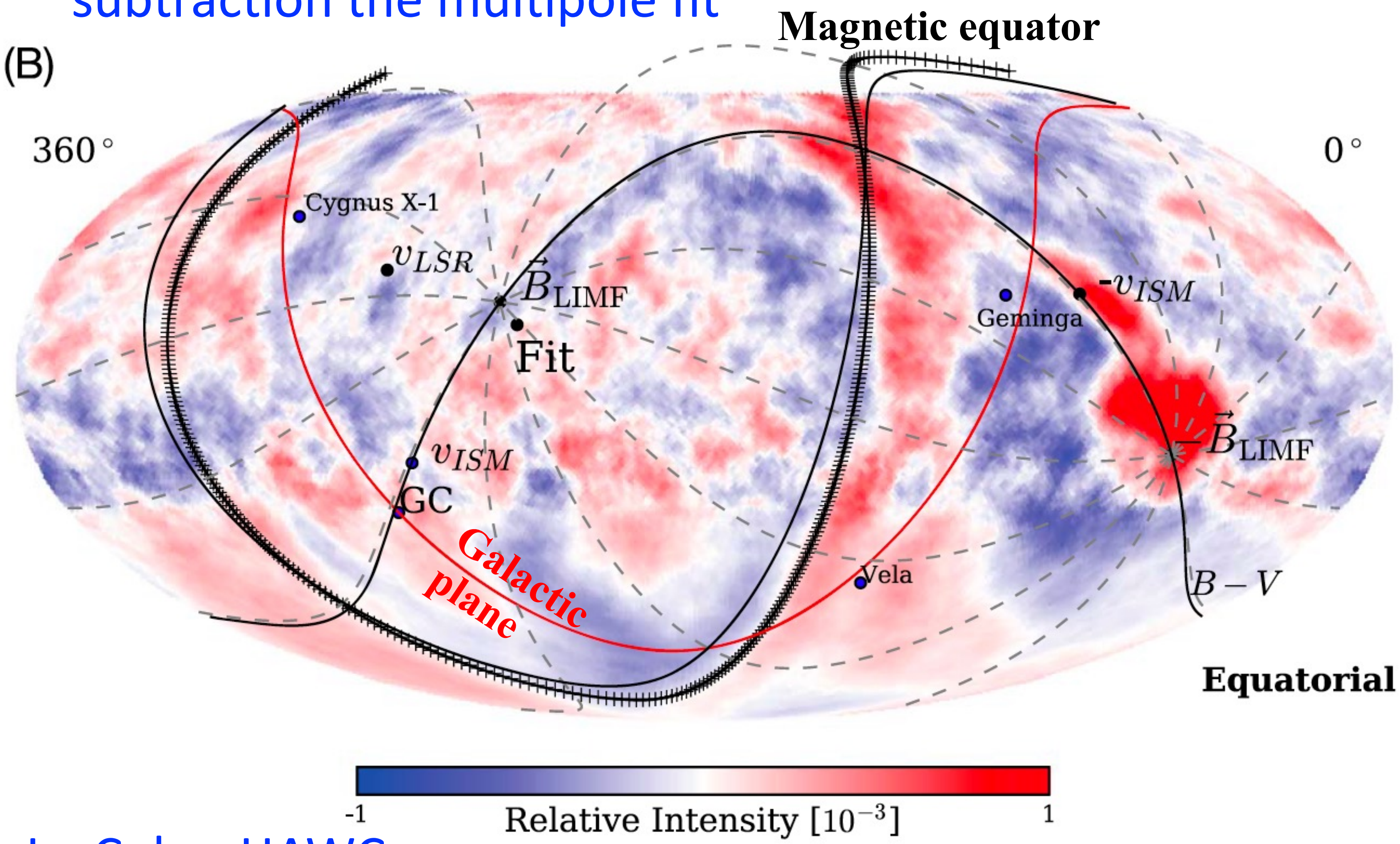
- The TeV bump is now confirmed by several instruments
- The two breaks, at ~0.2 TV and 10 TV, plus anisotropy increase indicate a single structure rather than two separate features
- Protons are dominant: Rigidity ≈ Kinetic Energy per Particle (in TeV range)



Amenomori+2017

Small-scale anisotropy @ 10 TeV & local B field

Relative intensity after subtraction the multipole fit

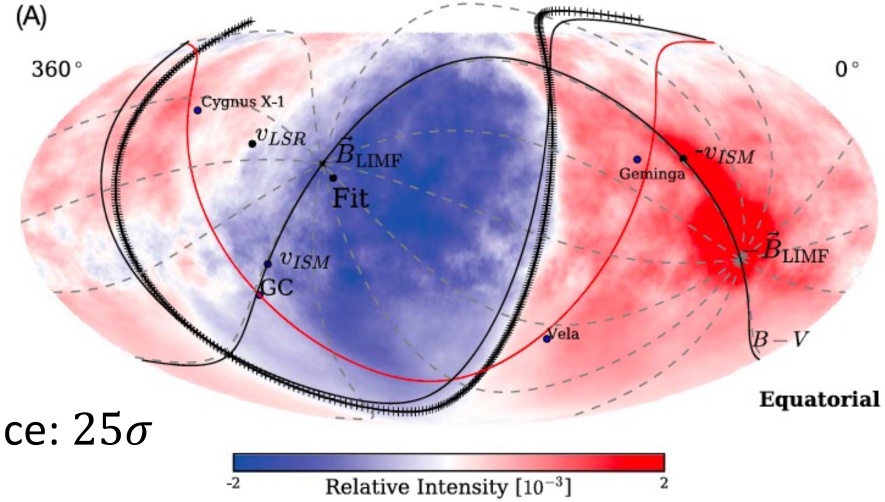


IceCube+HAWC

Abeysekara+2019

- Very sharp jump in anisotropy across the magnetic equator – a hint at the proximity of the source
- The direction to the source coincides with the Galactic anticenter, the direction of the local B-field, and about 45° off the "tail" of the heliosphere

Relative intensity

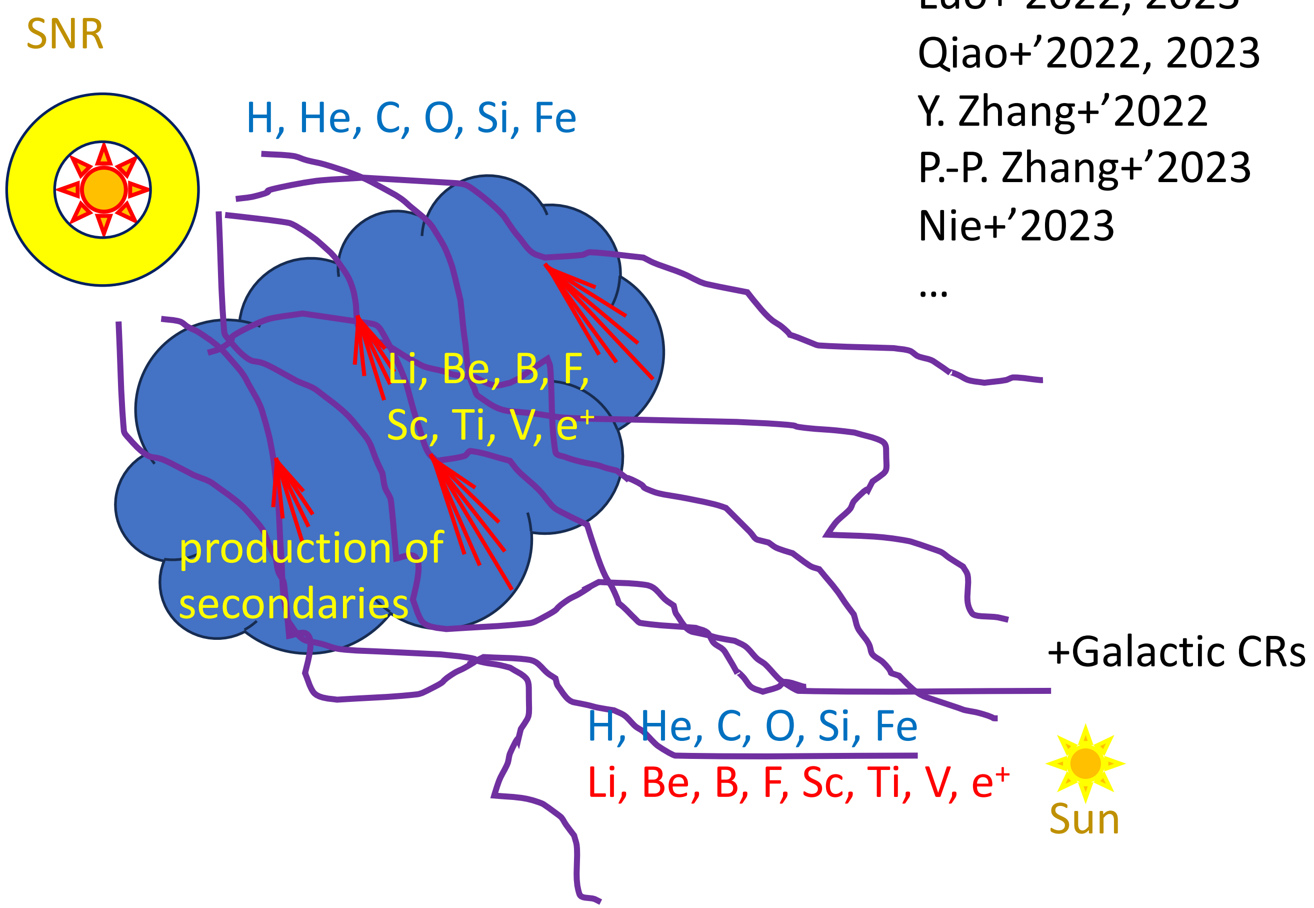


Significance: 25σ

Models of the TeV bump

Local SNR + gas cloud models

Claimed to reproduce all observed features in CR nuclei, $e^{\pm}$, pbars

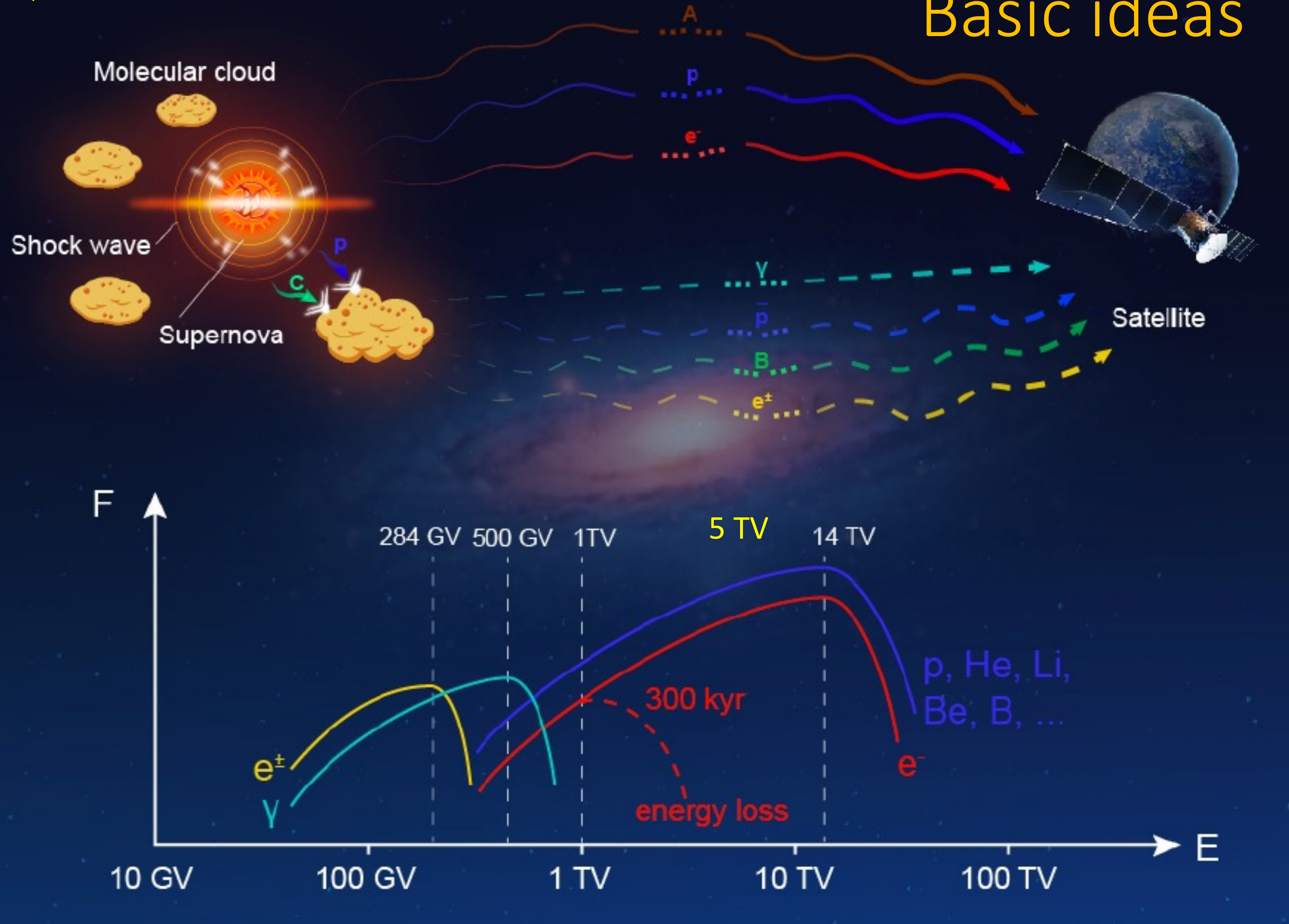


Yang & Aharonian'2019
Liu+'2019
Fang+'2021
Fornieri+'2021
Yuan+'2021
Zhao+'2022, 2022
Luo+'2022, 2023
Qiao+'2022, 2023
Y. Zhang+'2022
P.-P. Zhang+'2023
Nie+'2023
…

- Many models are speculating on the idea of a local SNR (~300 pc, Geminga SNR)
- Consider a combination of the Galactic CRs with concave spectra + sharp peak from the local SNR
- Secondary species are produced in gas cloud(s)
- Propose to reproduce antiprotons, electrons, positrons
- Proposed to reproduce CR anisotropy

Basic ideas

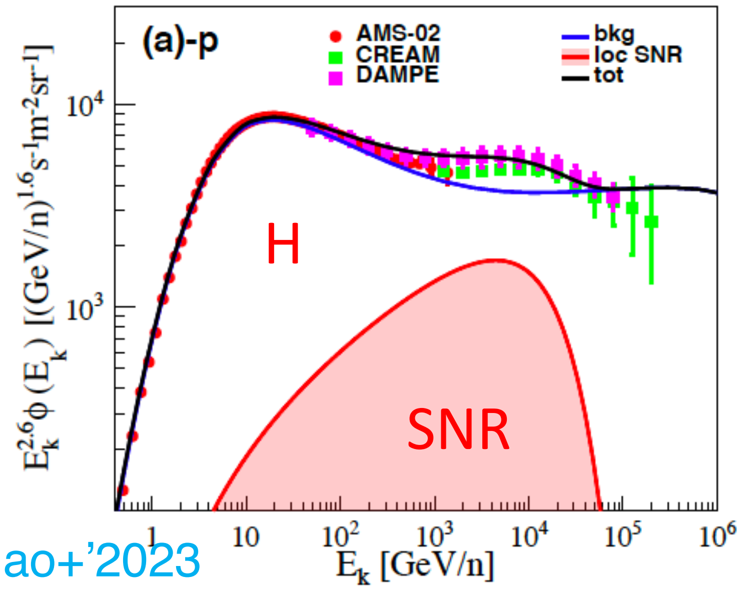
Qiao+'2023

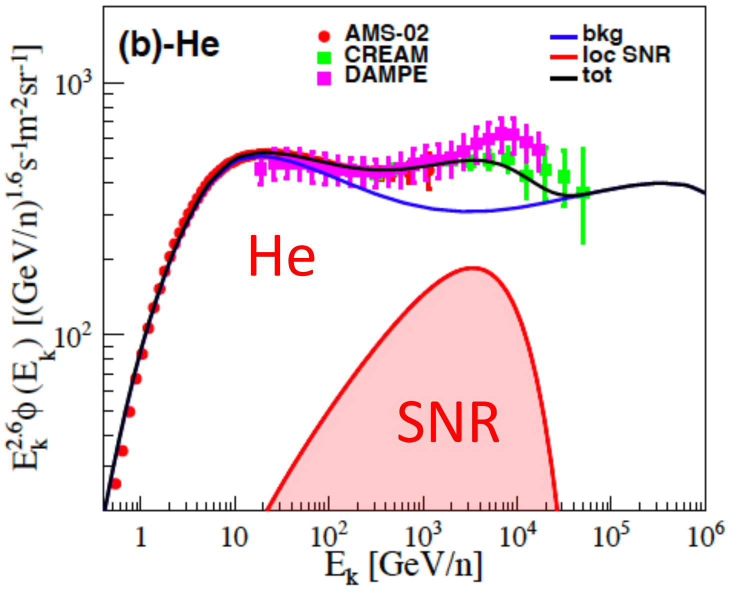


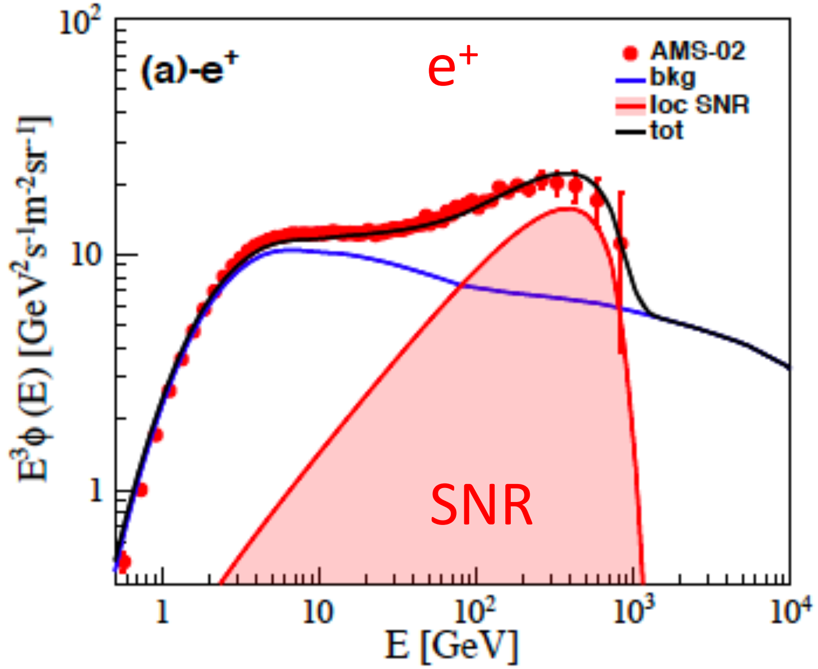
- SNR accelerates particles (primary nuclei, e^-) with a cutoff at 5 TV
- They produce secondaries (LiBeB, $e^{\pm}$) in the cloud
- Primary e^- loose energy to make a break at 1 TV
- $e^{\pm}$ are produced with a cutoff at 300 GV (5 TV cutoff in protons)
- Proposed source Geminga SNR, age 330 kyr at 330 pc

Example spectra in the SNR model

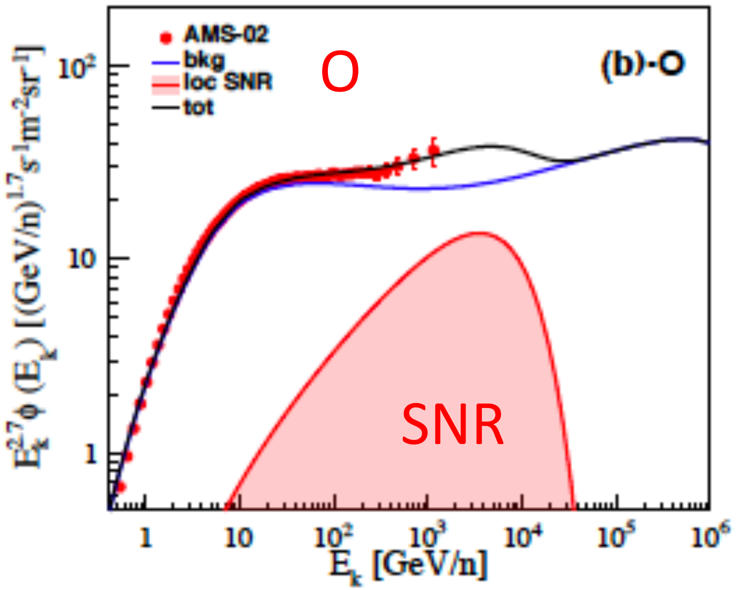
Red area shows SNR contribution

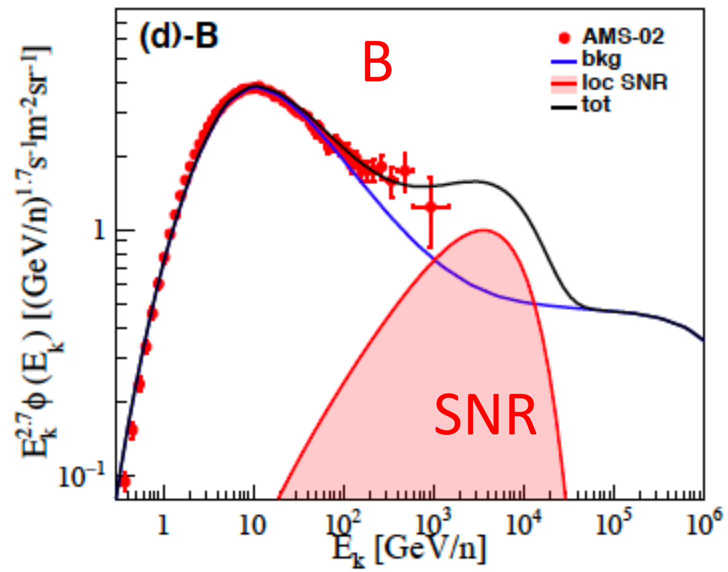


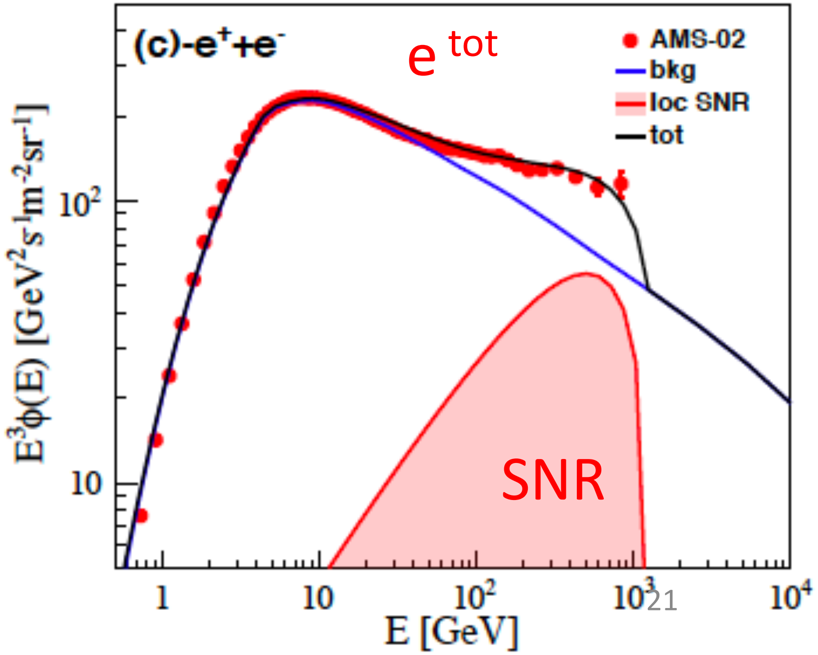




Qiao+'2023

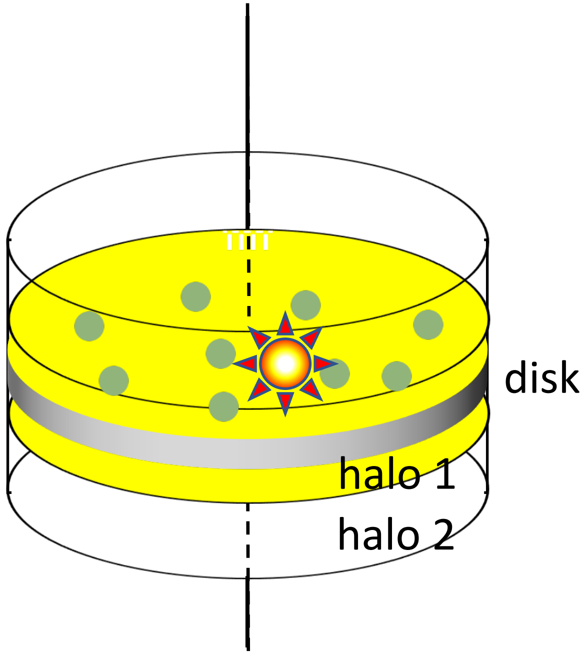






Some issues with local SNR model

- A lot of fine tuning
- To make a room for the SNR component, one has to make a concave spectrum of the Galactic CRs. I.e. one has to make a dip in the Galactic CR spectrum and a peak in SNR component at the same energy simultaneously
- Used a modified Tomassetti's (2015) two-halo scenario with two different rigidity dependence of the diffusion coefficient
- 8 transport parameters + 6 spectral parameters + individual normalization for SNR (28) components for each species + 7 parameters for e^{-} + gas cloud grammage ≈ 45-50 free parameters
- Cannot reproduce the sharp jump in anisotropy along the magnetic equator

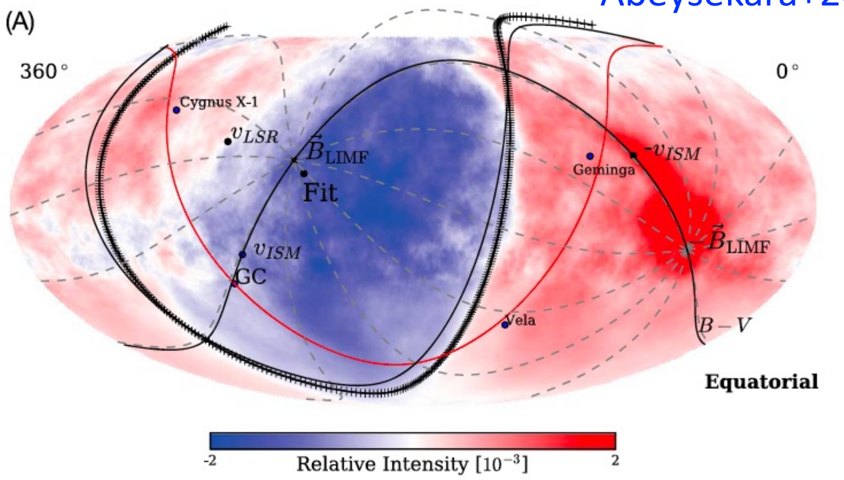


Galaxy with two halos and a local source

Diffusion length and anisotropy

- The gyroradius of a particle with rigidity 10 TV in the interstellar 3 μG magnetic field is 600-700 AU ~ (3-4) ×10^{-3} pc
- Geminga SNR is at ~330 pc
- This is ~10^5 mean free paths – there is no way to see such sharp anisotropy at such a distance
- The observed anisotropy exhibits very sharp break at the magnetic equator
- All global models of the TV bump have this problem
- Conclusion: the source should be close

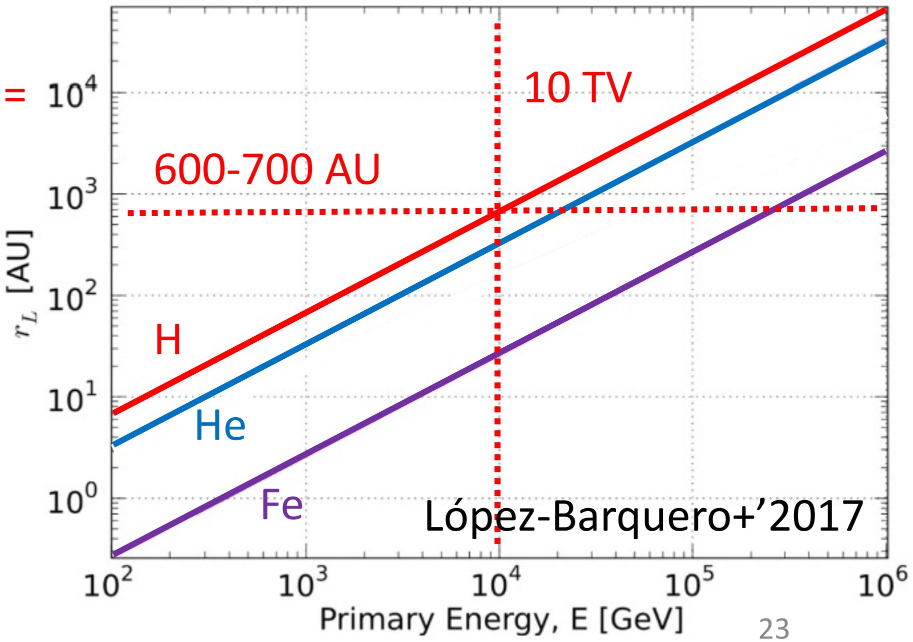
IceCube+HAWC
Abeysekara+2019



Relative intensity

Gyroradius in B=3 μG

0.0485pc =



Reacceleration in a local shock

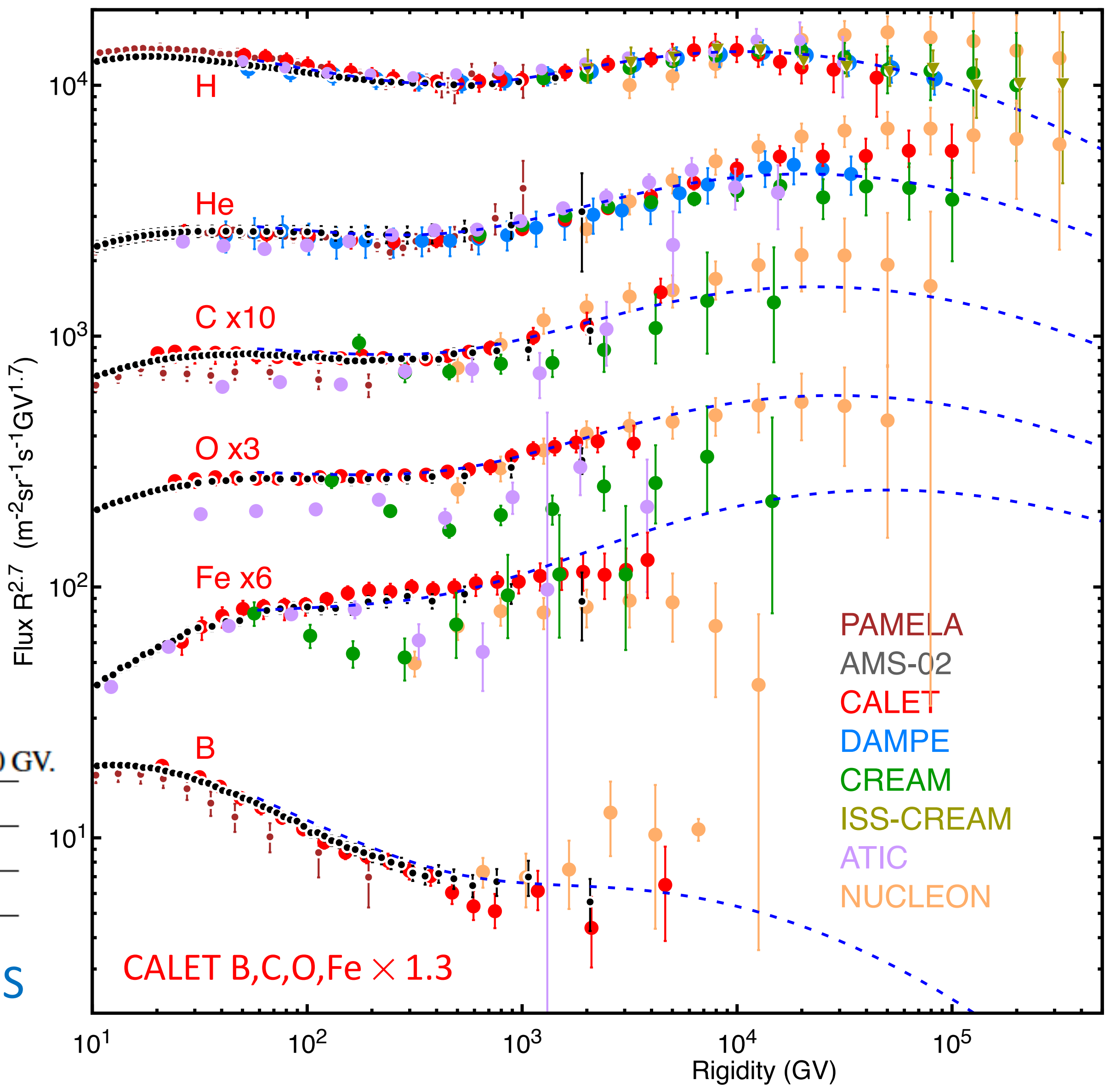
- Assumes all CR species exist in the ISM and have power-law spectra with no breaks
- No free parameters but the parameters of the shock
- Matches the AMS-02 data with tiny error bars

Table 2. Input parameters for CR species derived from their LIS (Boschini et al. 2020, 2021) at ≈100 GV.

Parameters	H	He	B	C	O	Fe
A_b ($\mathrm{m^{-2}\,s^{-1}\,sr^{-1}\,GV^{-1}}$)	2.32×10^4	3631	70.2	111	108	11.6
γ_b	2.85	2.77	3.09	2.75	2.73	2.66

✧ A_s, γ_s – fixed normalization and spectral index of the LIS below the bump (individual for each species)

✧ LIS for H-Ni are given in Boschini+'2020



Malkov & IVM

Shock parameters

Derived from best measured proton spectrum – 3 parameters

fixed below the break for each species

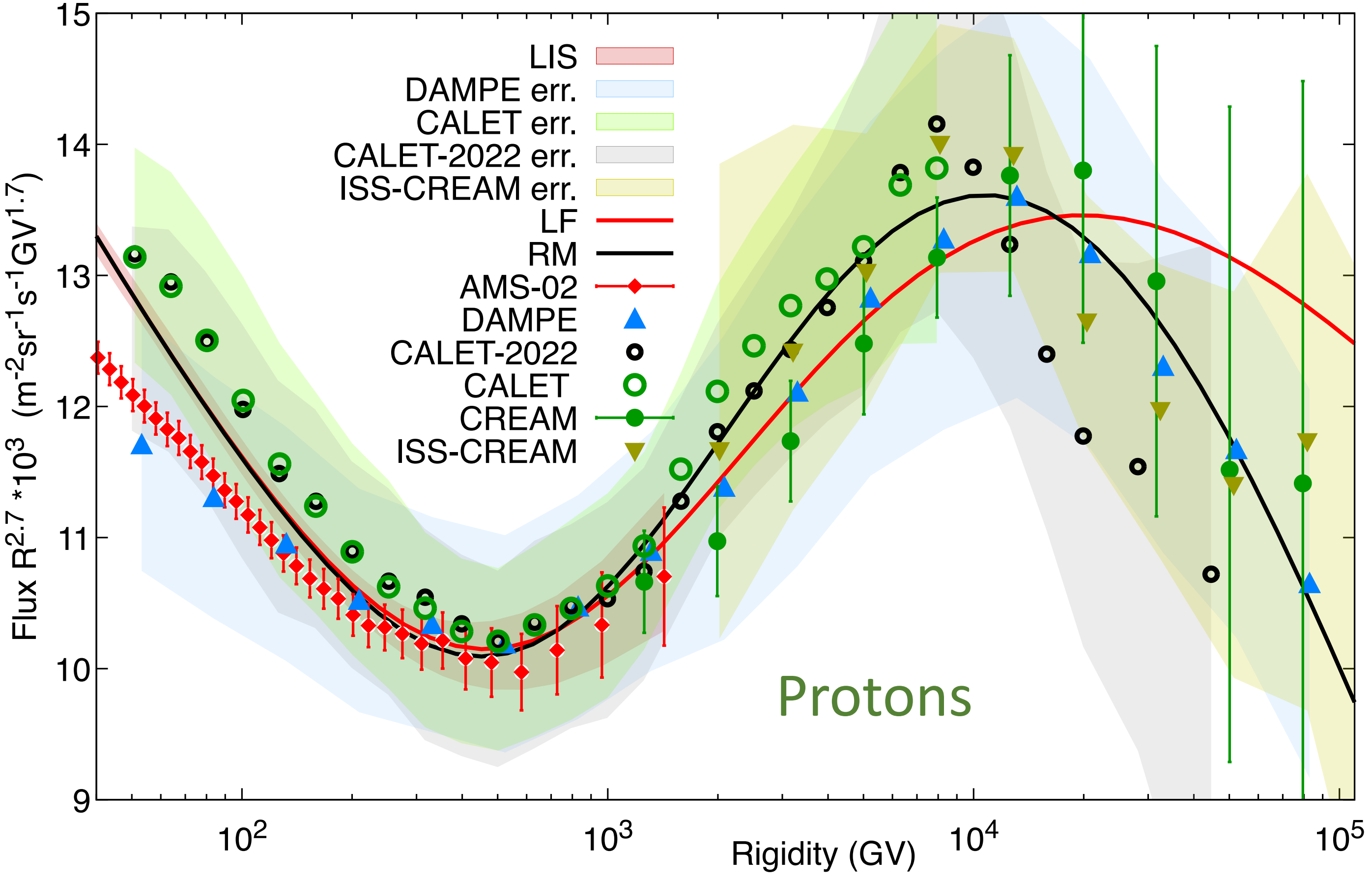
$$f_s(R) = A_s R^{-\gamma_s}\left\{1+\frac{\gamma_s+2}{q-\gamma_s}\exp\left[-\sqrt{\frac{R_0}{R}}-\sqrt{\frac{R}{R_L}}\right]\right\}$$

○ - parameters fixed from CR proton spectrum

$q_s = (r+2)/(r-1)$ – shock spectral index,
r – the compression ratio

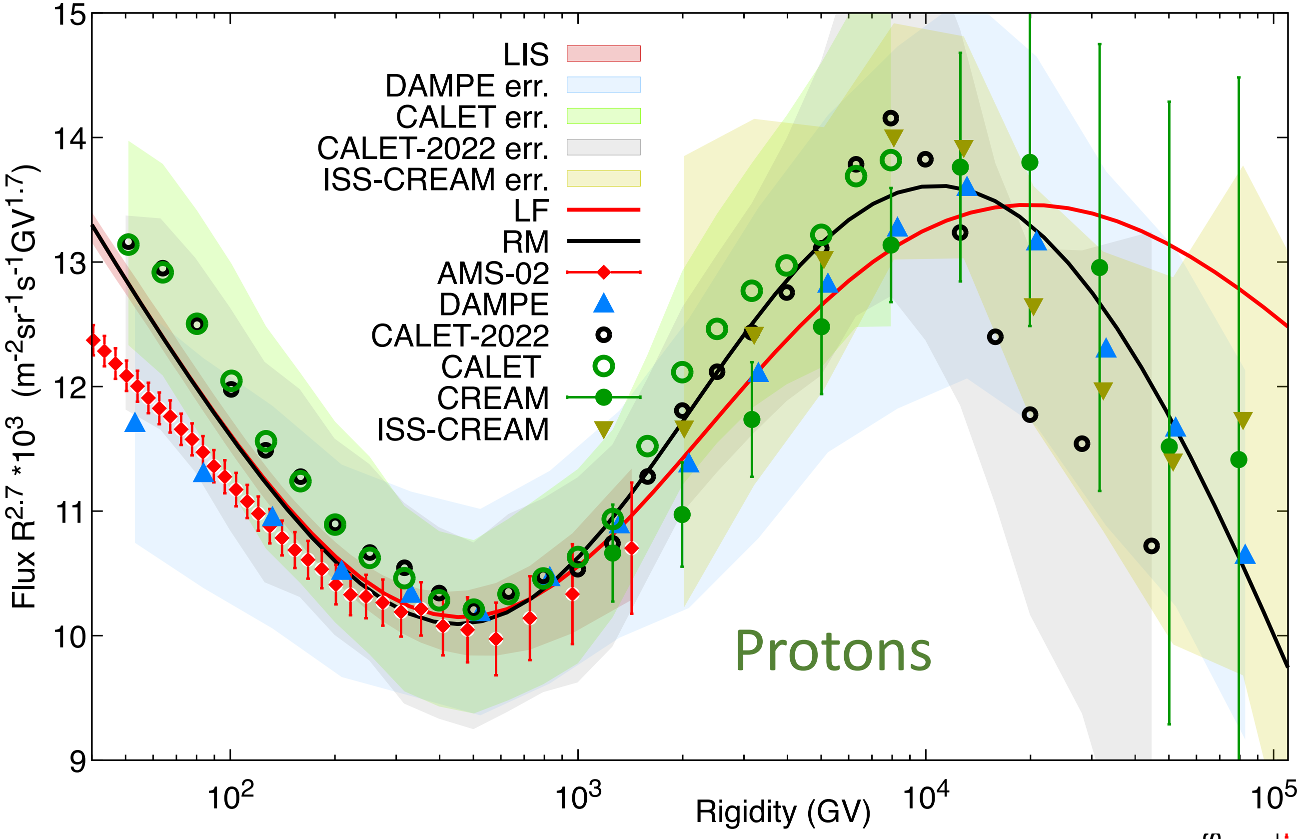
Table 1. Model parameters and fit results for the proton spectrum.

Parameter (St. err. %)	R_0(GV)	R_L(GV)	q_s
Realistic Model (RM)	5878 (3.5%)	2.24×10^5 (28%)	4.20
Loss-Free Model (LF)	4794 (3.2%)	∞	4.73



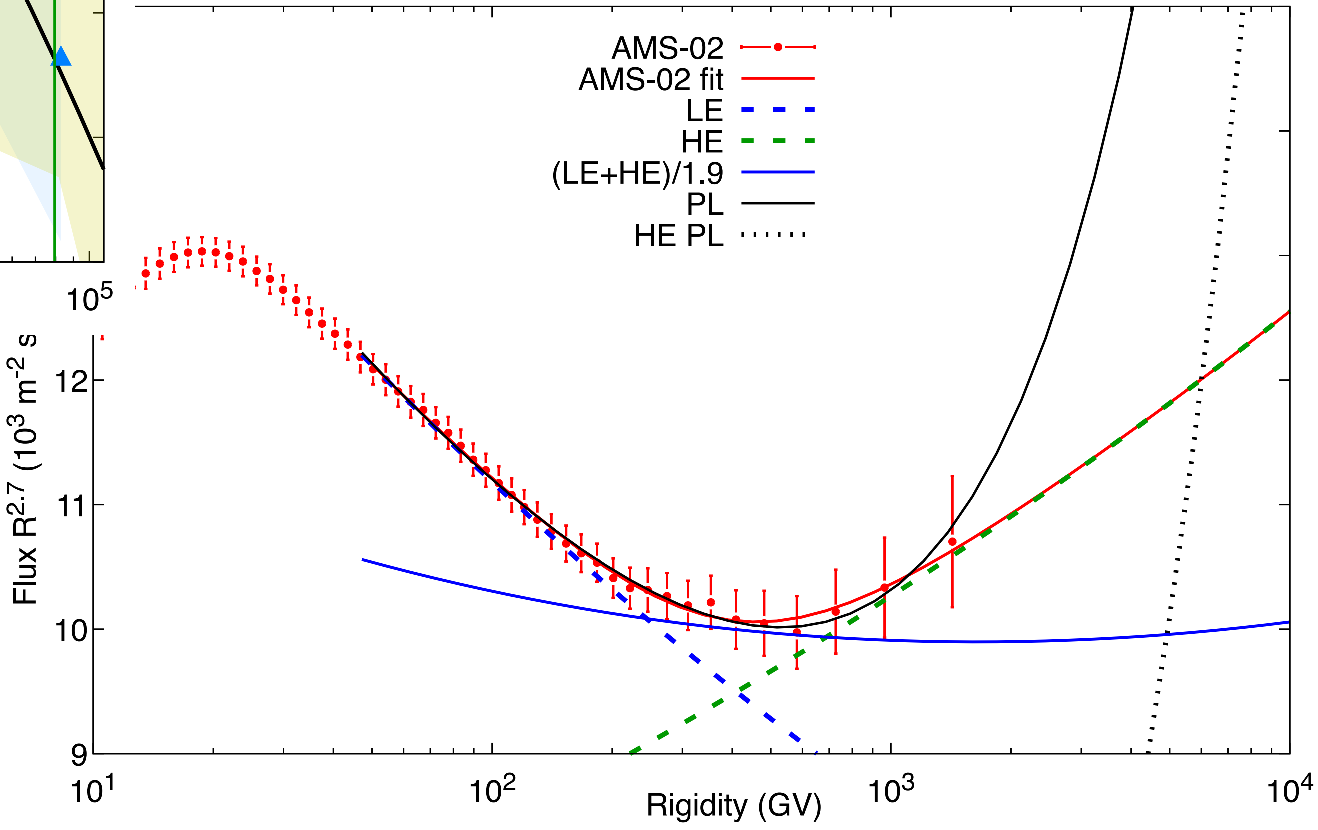
- ✧ Moderate reacceleration, Mach number ~1.5
- ✧ Low-energy particles do not reach us as they are convected downstream by the ISM flow
- ✧ High-energy particles lost from the flux tube

Sum of two power laws



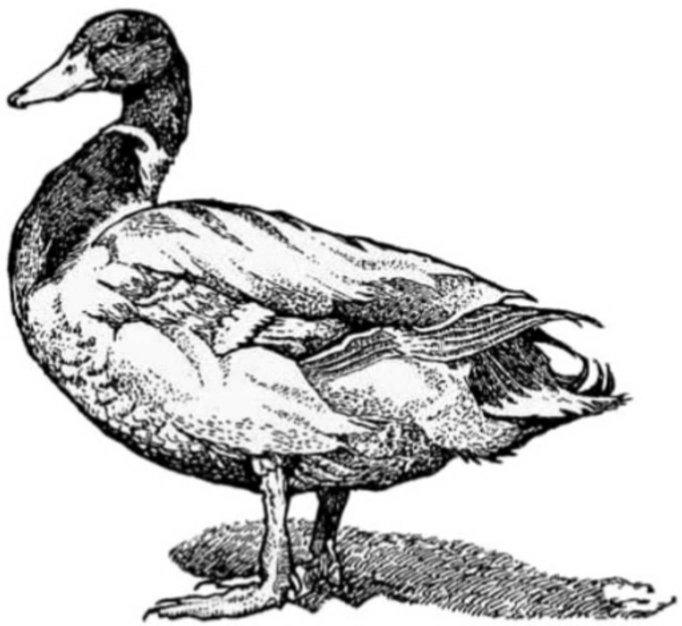
The break is too sharp for a sum of two power-laws

Note a LINEAR Flux scale



Duck test

If it looks like a local shock, has only 3 free parameters, and provides the simplest interpretation of several types of (precise) data

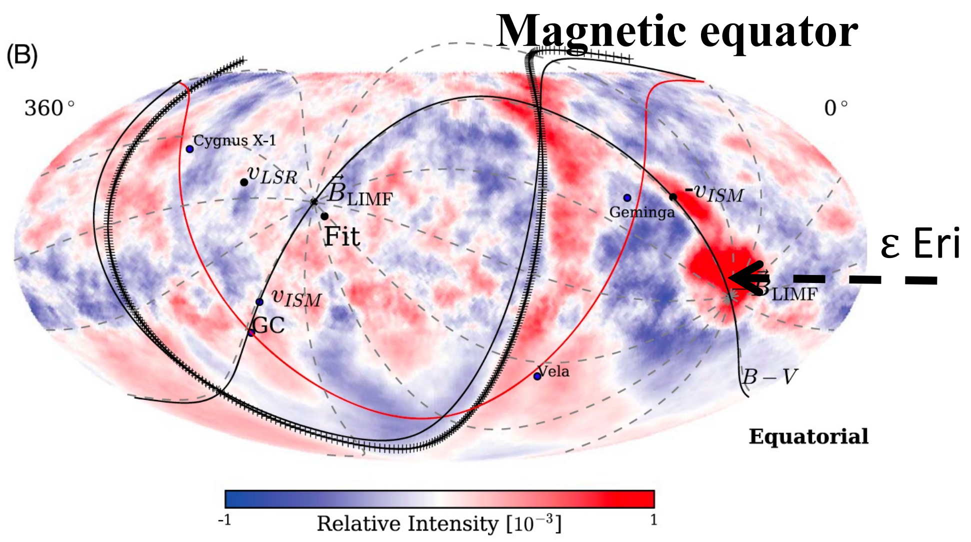


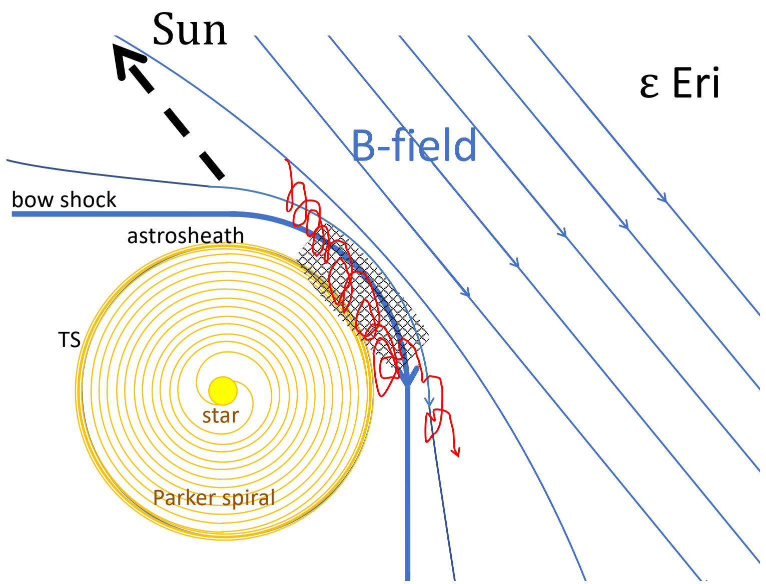
then it is likely a local shock

Epsilon Eridani star

- Distance-shock-size relation: $\zeta_{obs}(pc) \sim 100\sqrt{L_{\perp}(pc)}$; for sufficiently large bow shocks, $L_{\perp} = 10^{-3}$-10^{-2} pc, then the distance is ζ_{obs} = 3-10 pc
  (Malkov & IVM'2021, 2022)
- Any local shock with a small Mach number ~1.5 fits
- ε Eri: K2 dwarf (5 000 K), 0.82 $M_{\odot}$, 0.74 $R_{\odot}$ (preferred)
- Well aligned with the direction of the local magnetic field – within 6.7° !
- Distance – 3.2 pc
- Mass loss rate – 30-1500 $\dot{M}_{\odot}$!
- Huge astrosphere – 8000 au, 47' as seen from Earth (larger than the Moon!)
- Proper velocity – 20 km/s (a bit small, but has a strong stellar wind)

IceCube+HAWC
Abeysekara+2016



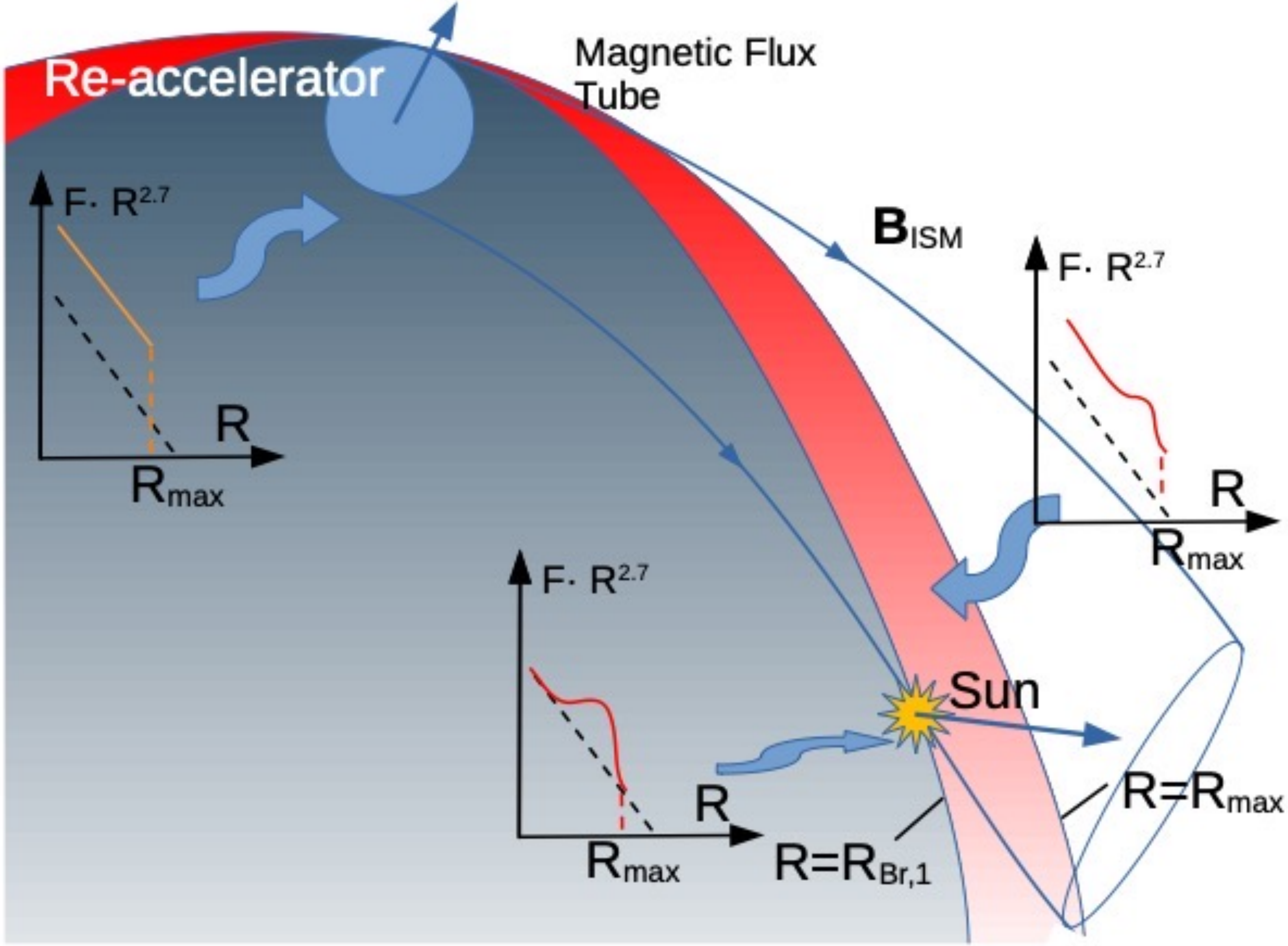


ε Eridani star

CR spectrum depends on position of the observer

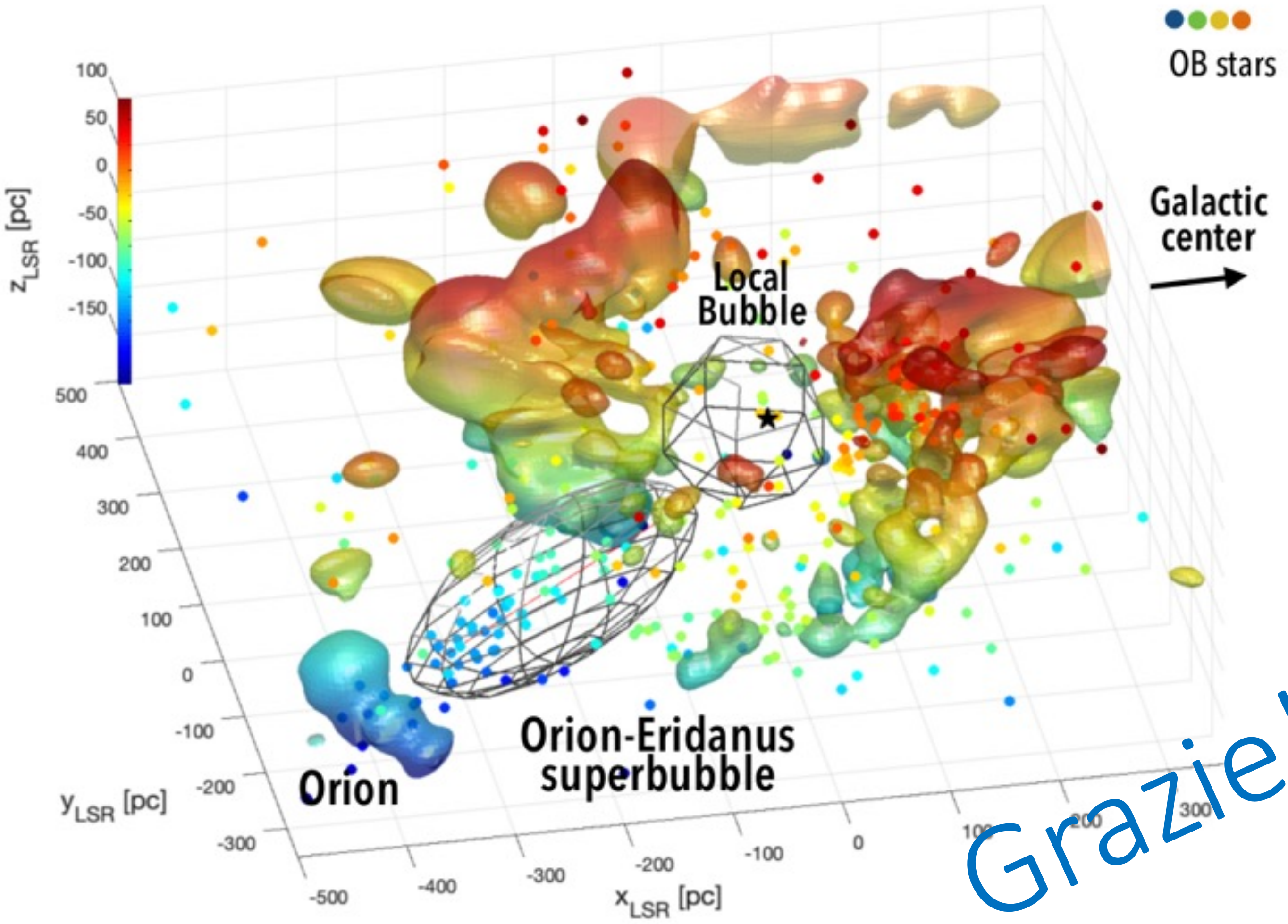
ε Eridani star and the Sun are moving, and the configuration changes

THEREFORE, the position of the break should change with time



Conclusion

- We are just in the beginning in our understanding of the influence of our local Galactic environment onto the observed CR fluxes
- We used to think about Galactic CR fluxes as stable on the scales of kyr-Myr, but watch for possible changes on 10-30 yr scale
- The precise direct measurements are the keys



Grazie!