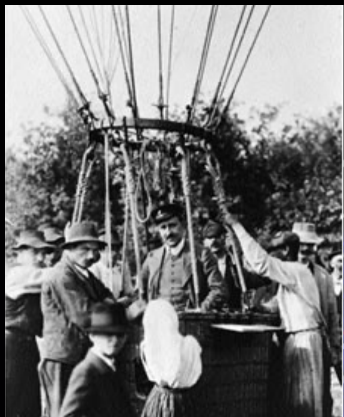
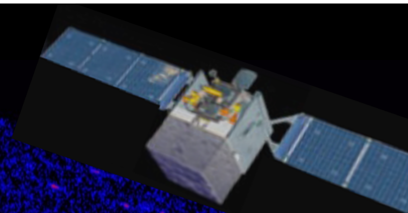




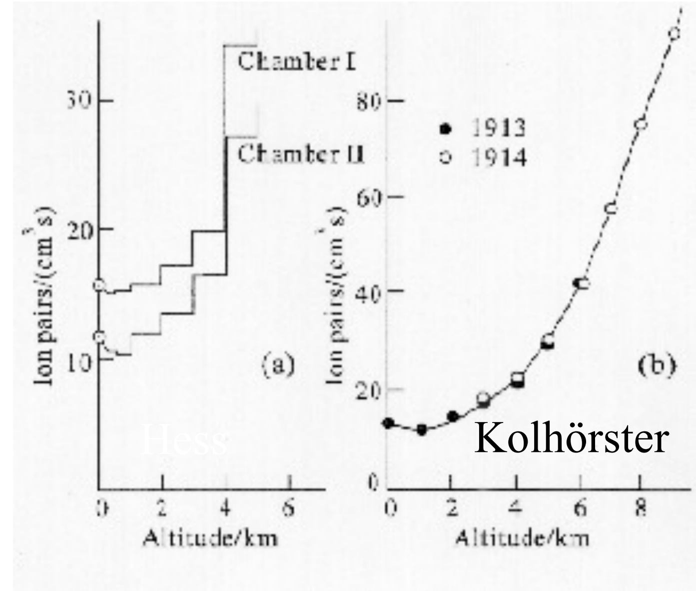
100 years

COSMIC RAYS BELOW 100 TEV IN THE GALAXY AND THE HELIOSPHERE

IGOR V MOSKALENKO – STANFORD

Solar Modulation and Dark Matter Workshop • Trieste • Nov. 15, 2021

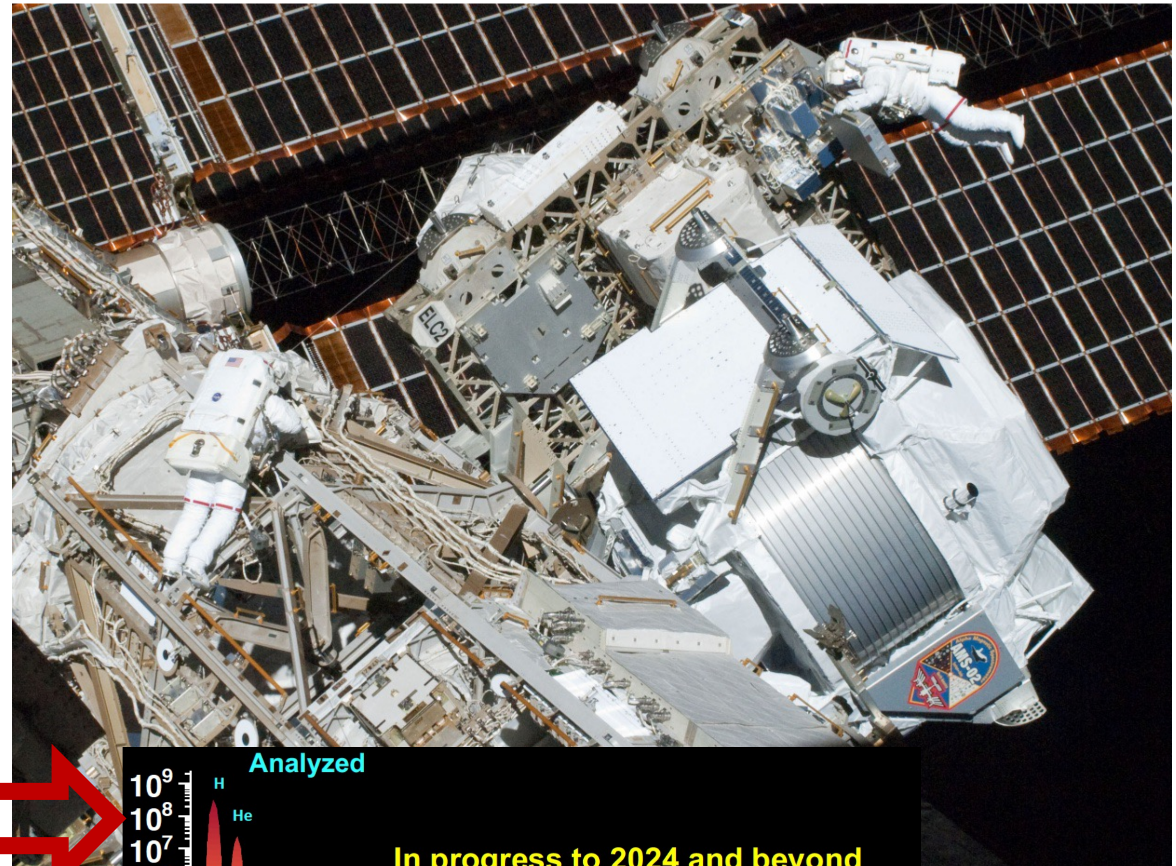
The discovery of cosmic rays

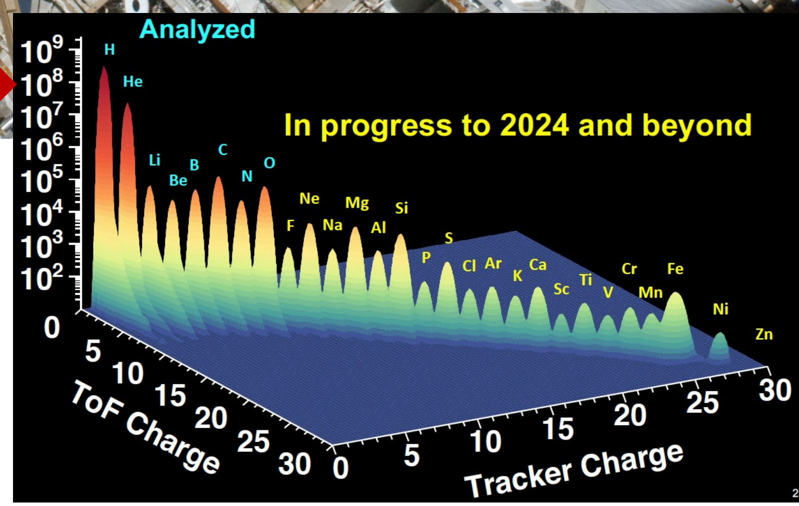


Victor Hess flight on August 7, 1912

- Victor Hess, an Austrian scientist, took a radiation counter (a simple electroscope) on a balloon flight
- He rose to 5200 m (without oxygen) and measured that the amount of radiation increases as the balloon climbed
- Hess correctly concluded that the ionization was caused by highly penetrating radiation coming from outside the atmosphere
- The results by Hess were later confirmed by the Kolhörster in a number of flights up to 9200 m

Notice also a shift in our understanding of the subject of CRs!

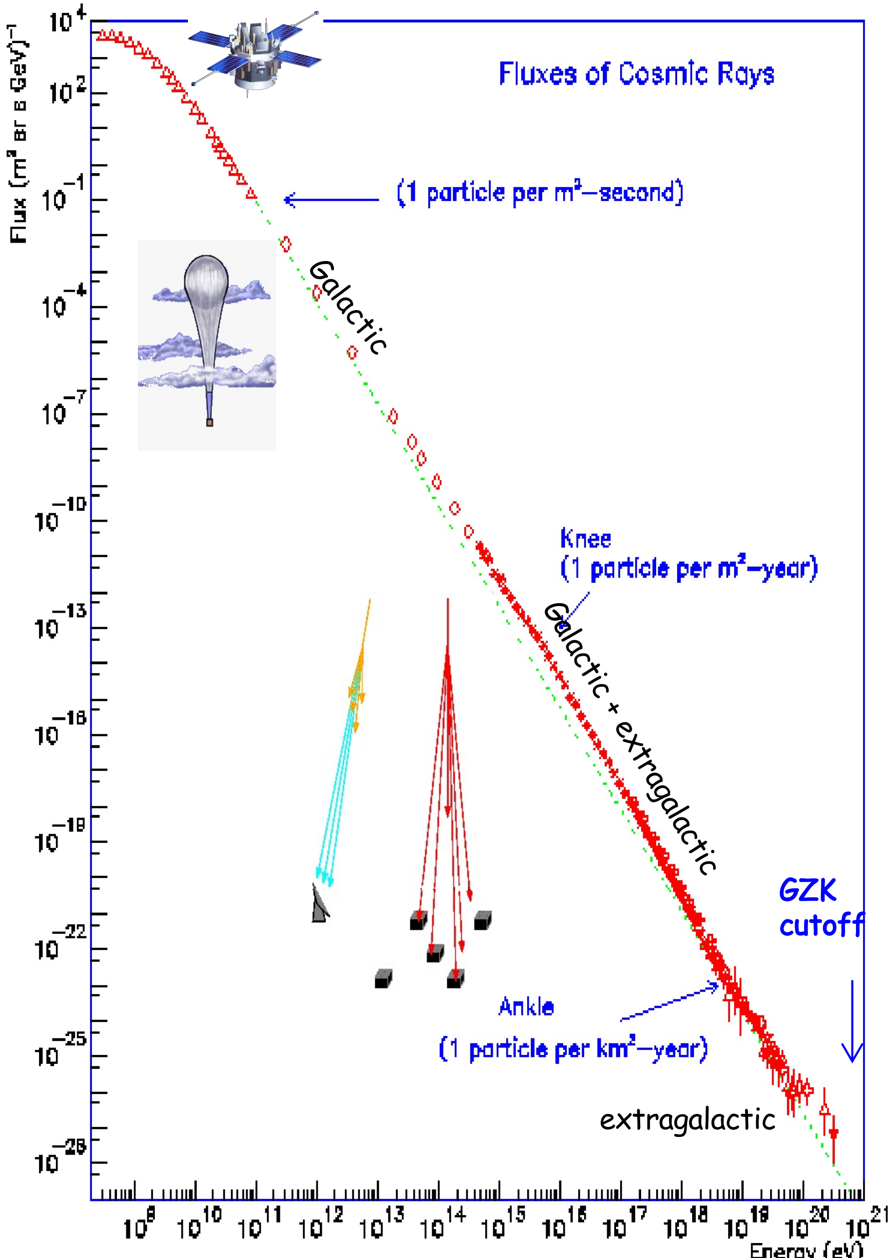




"…this ionization might be attributed to the penetration of the earth's atmosphere from outer space by hitherto unknown radiation of exceptionally high penetrating capacity…" – V. Hess

Spectrum of Cosmic Rays – 20th century

~32 orders of mag

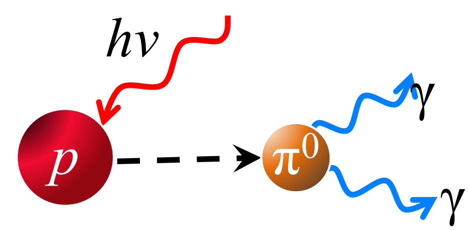


>12 orders of mag

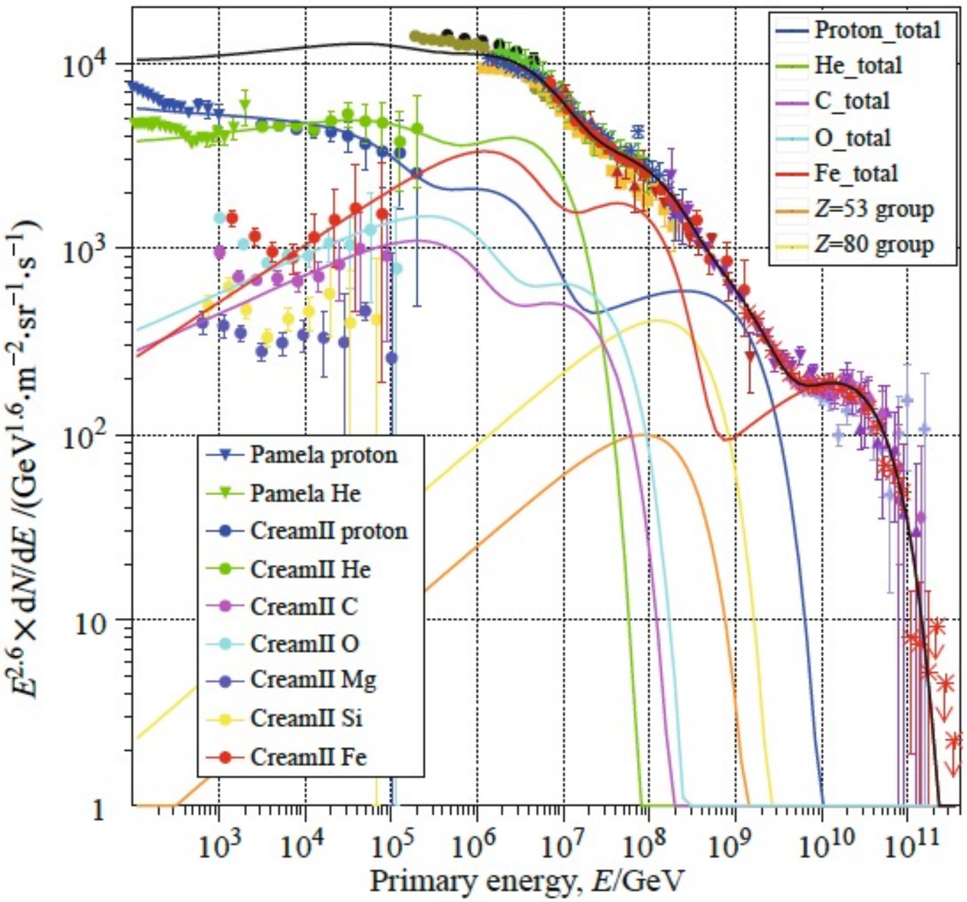
✧ All particle CR spectrum:

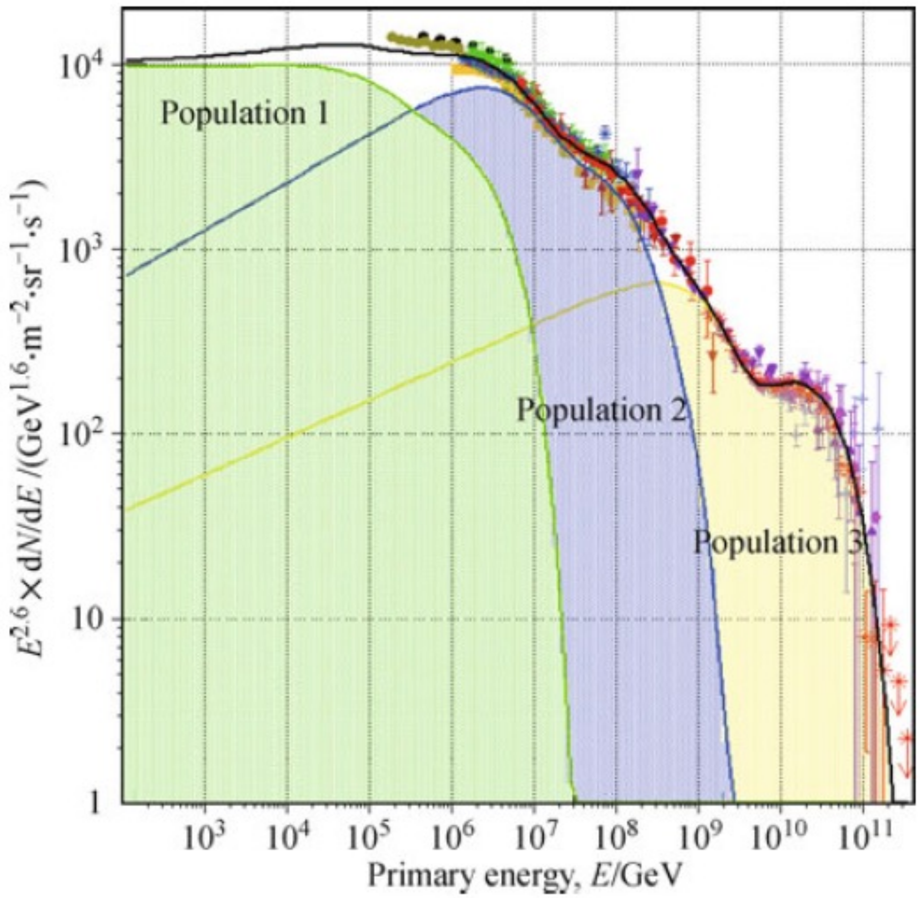
- ✦ The knee (Kulikov & Christiansen 1958)
- ✦ The ankle (Linsley 1963, Fly's eye 1990s)
- ✦ GZK cutoff (predicted Greisen-Zatsepin-Kuzmin 1966)

GZK cutoff:



Spectrum of Cosmic Rays – about now





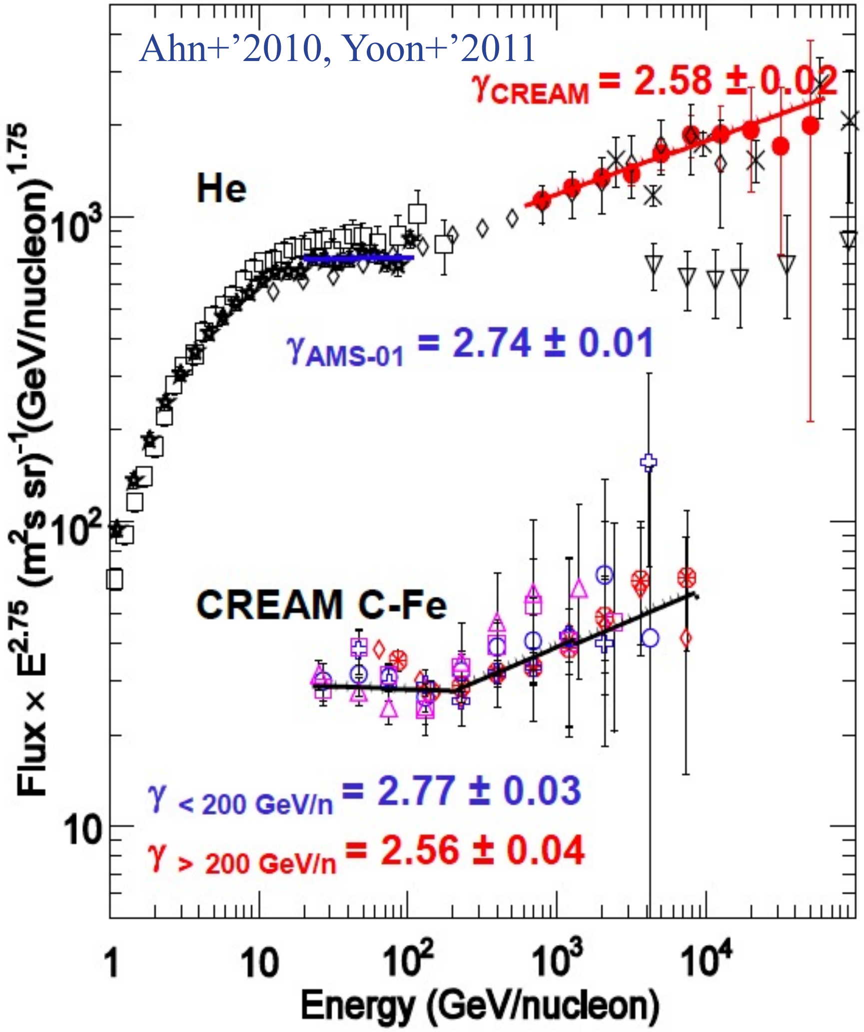
Gaisser, Stanev, Tilav 2013

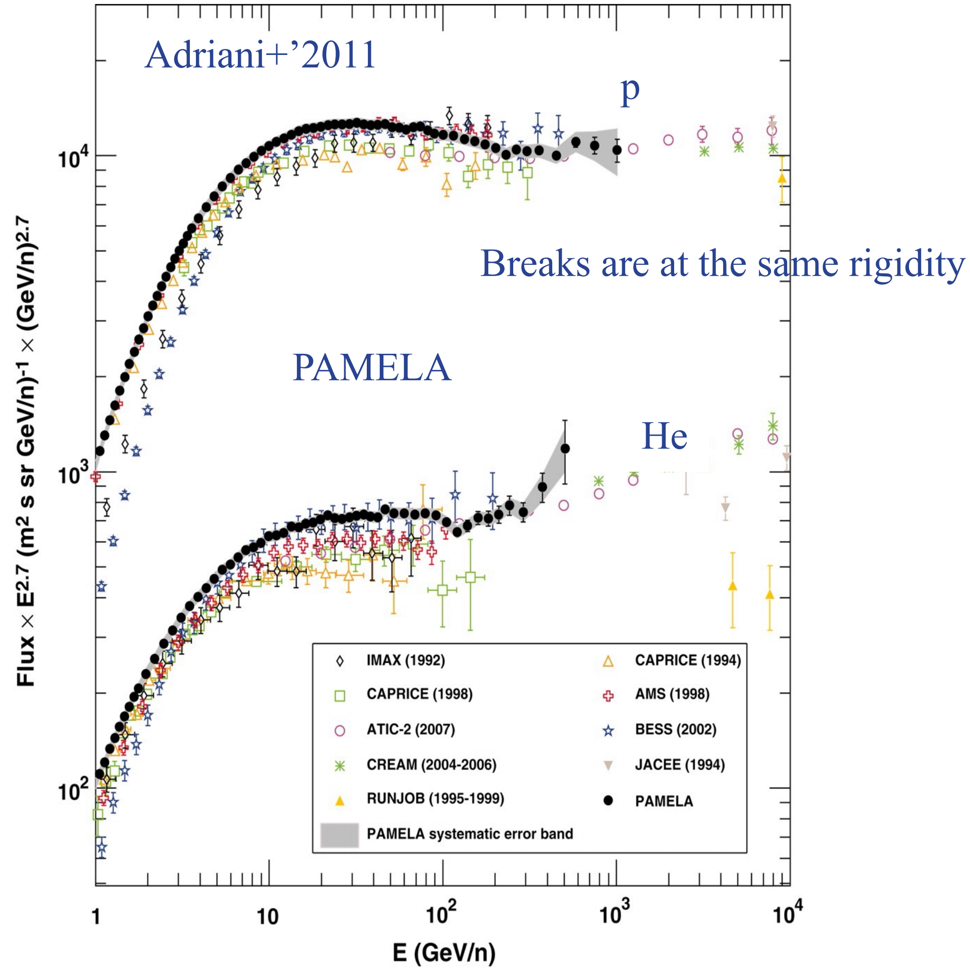
- ✧ Are these features transient?
- ✧ Which types of sources are producing them?
- ✧ Are they typical for the whole Galaxy?
- ✧ What are the consequences if they do or they do not?

Teaser:

Many features recently found in CR spectra have a local origin

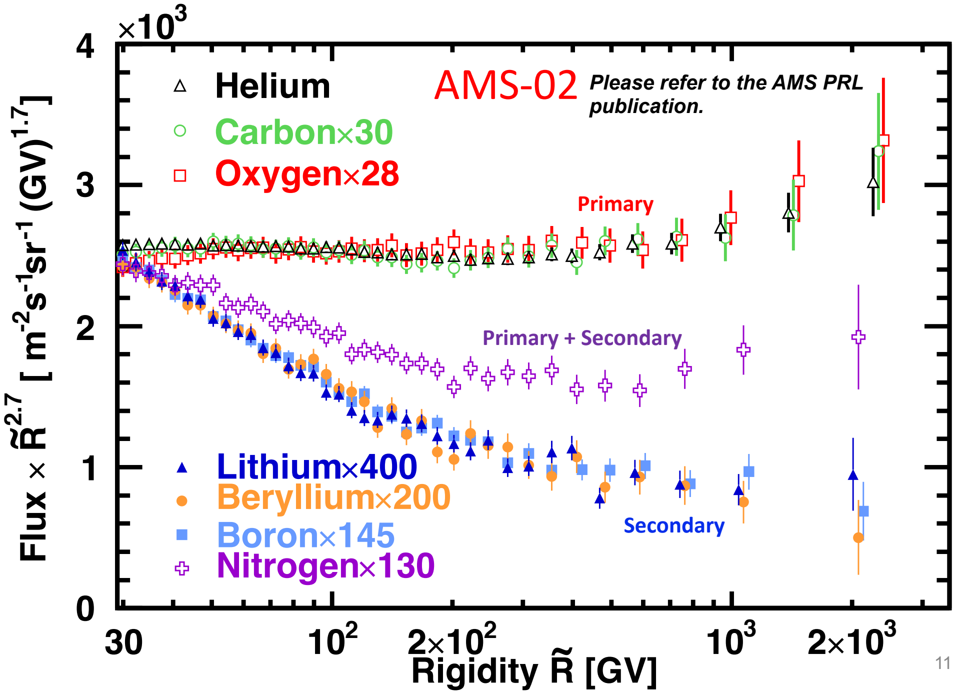
Break in the spectra of CR nucleons





- First noticed in the data by CREAM "*Discrepant hardening observed in cosmic-ray elemental spectra*" (Ahn+'2010) and ATIC-2 (Panov+'2009)
- Initially looked like an energy calibration issue…
- …until it was confirmed by PAMELA and with more statistics by AMS-02

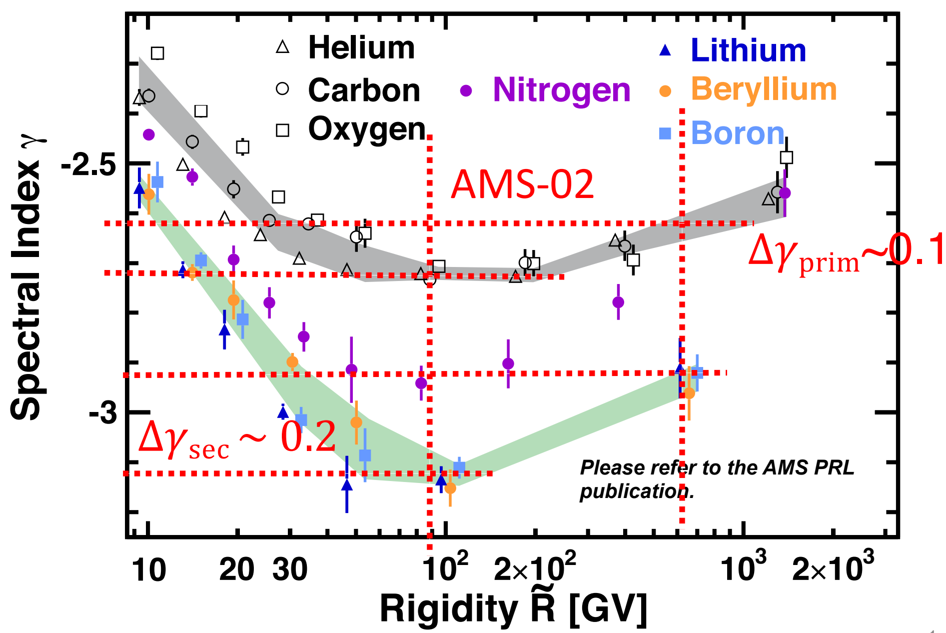
Effect of interstellar propagation

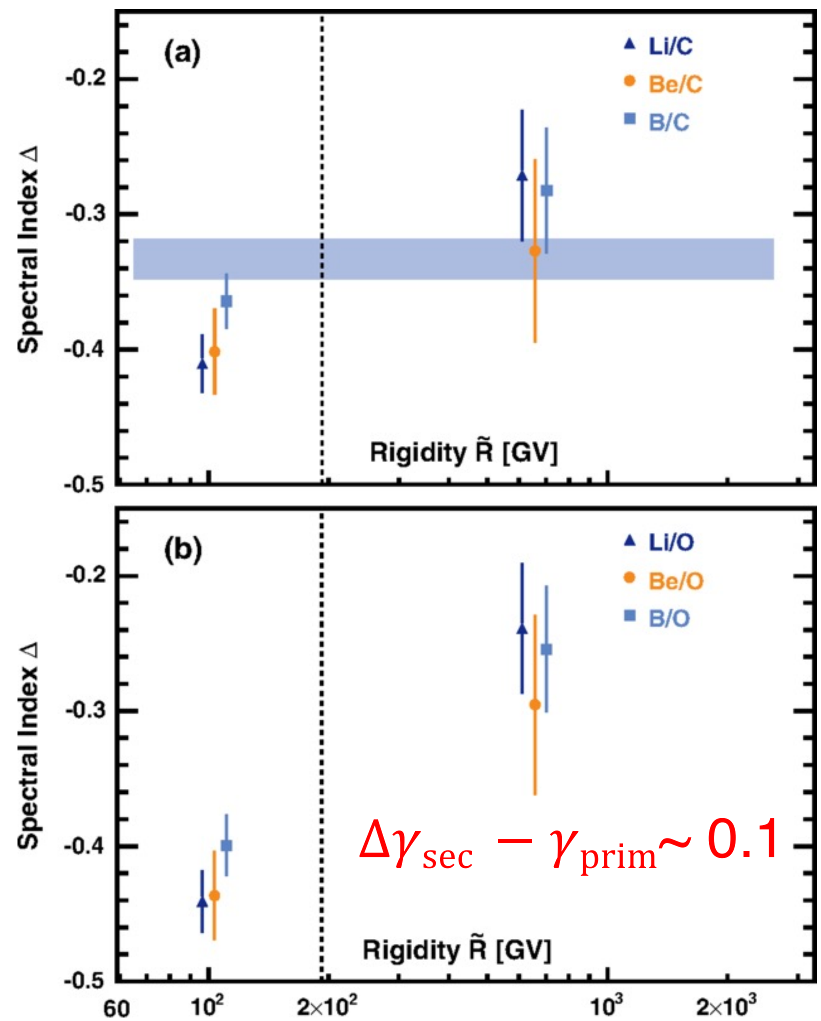


Such behavior was predicted (Vladimirov+'12, Blasi+'12):

$\Delta\gamma_{\rm sec} \sim 2\Delta\gamma_{\rm prim}$

if the break is due to the break in the spectrum of interstellar turbulence

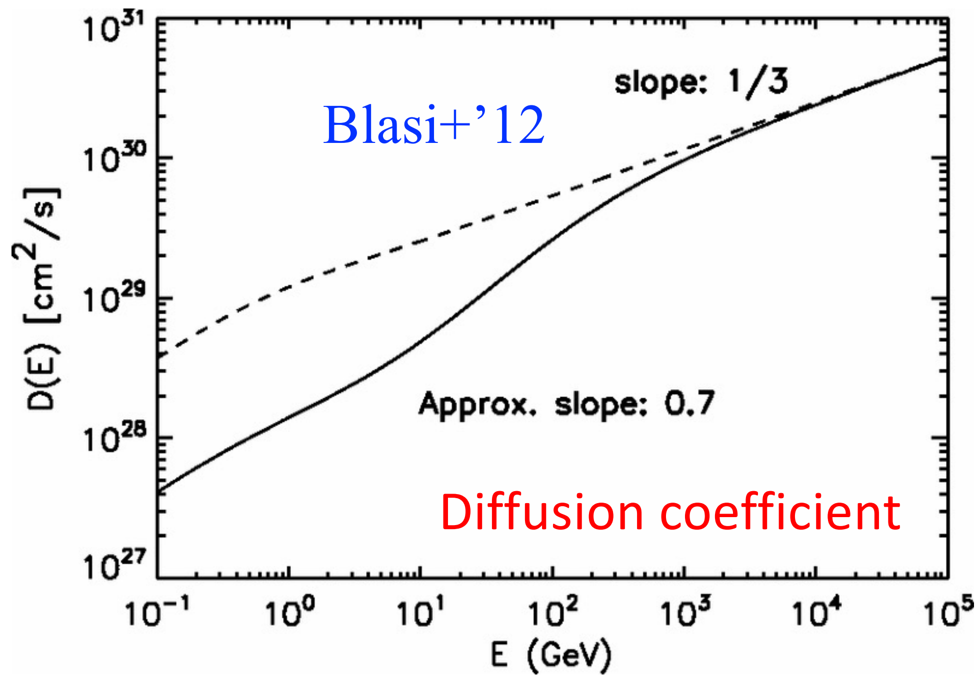


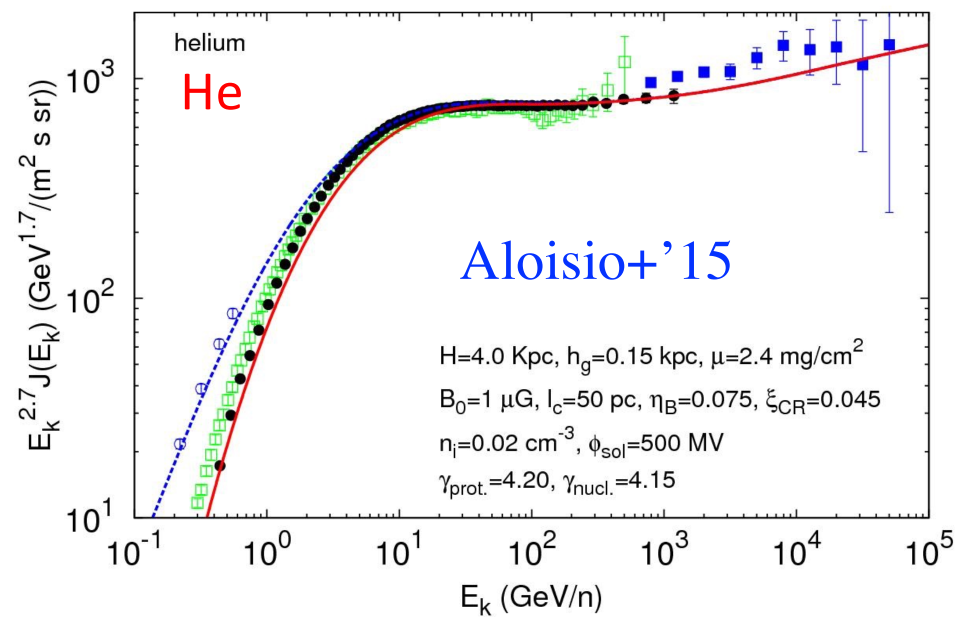


Interstellar turbulence and the diffusion coeff.

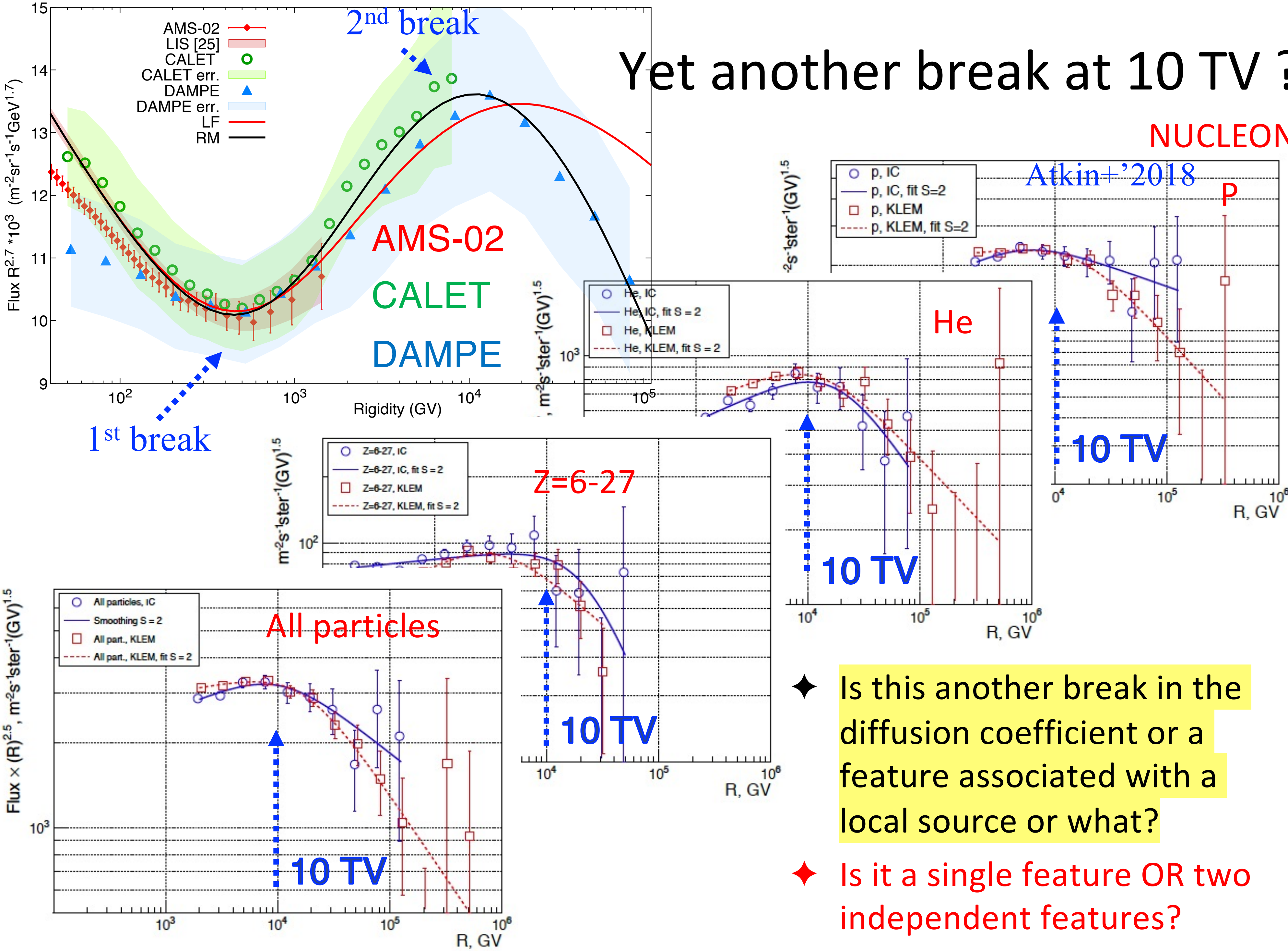
- ✧ 300 GV break: A transition from the self-generated turbulence to the cascading of externally generated turbulence (for instance due to supernova bubbles) from large spatial scales to smaller scales

- ✧ The agreement with AMS-02 data is pretty good, but does not explain the difference between the spectra of *p* and heavier species (He-O)



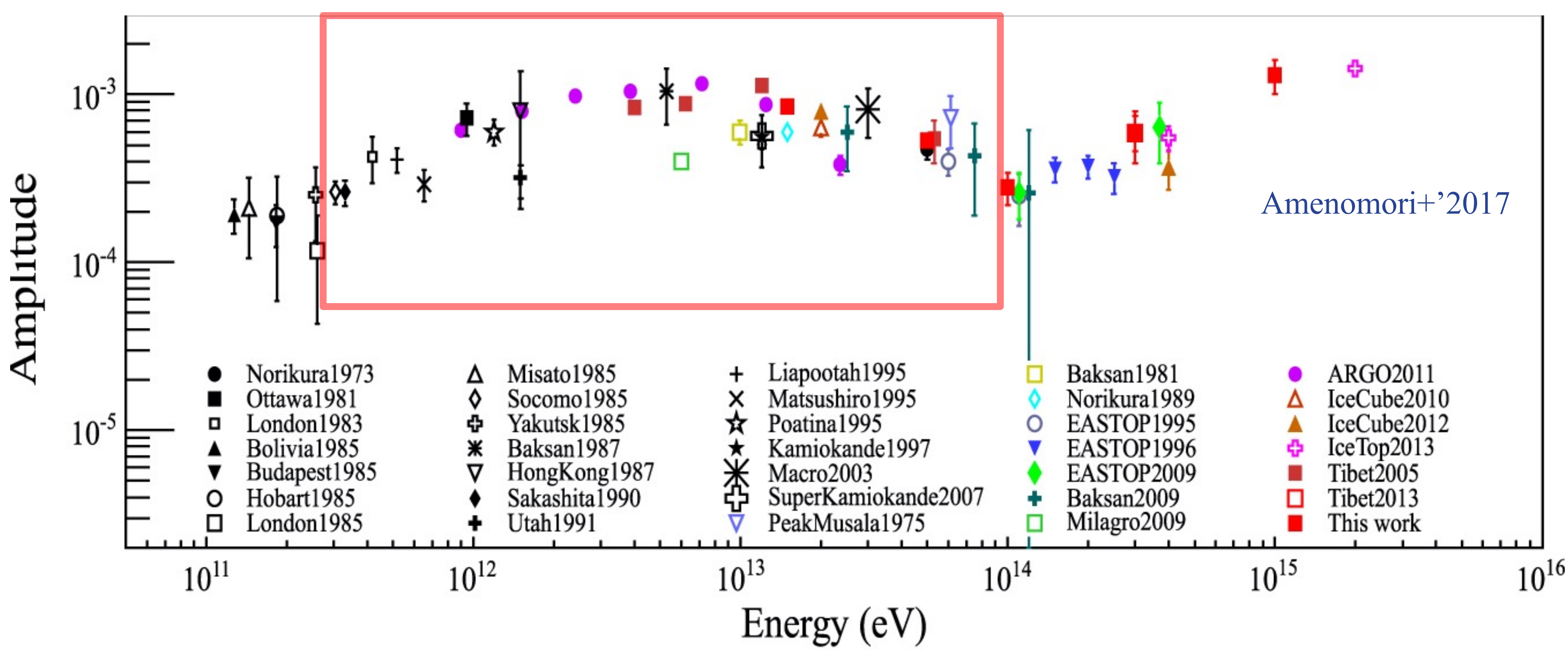


Yet another break at 10 TV ?



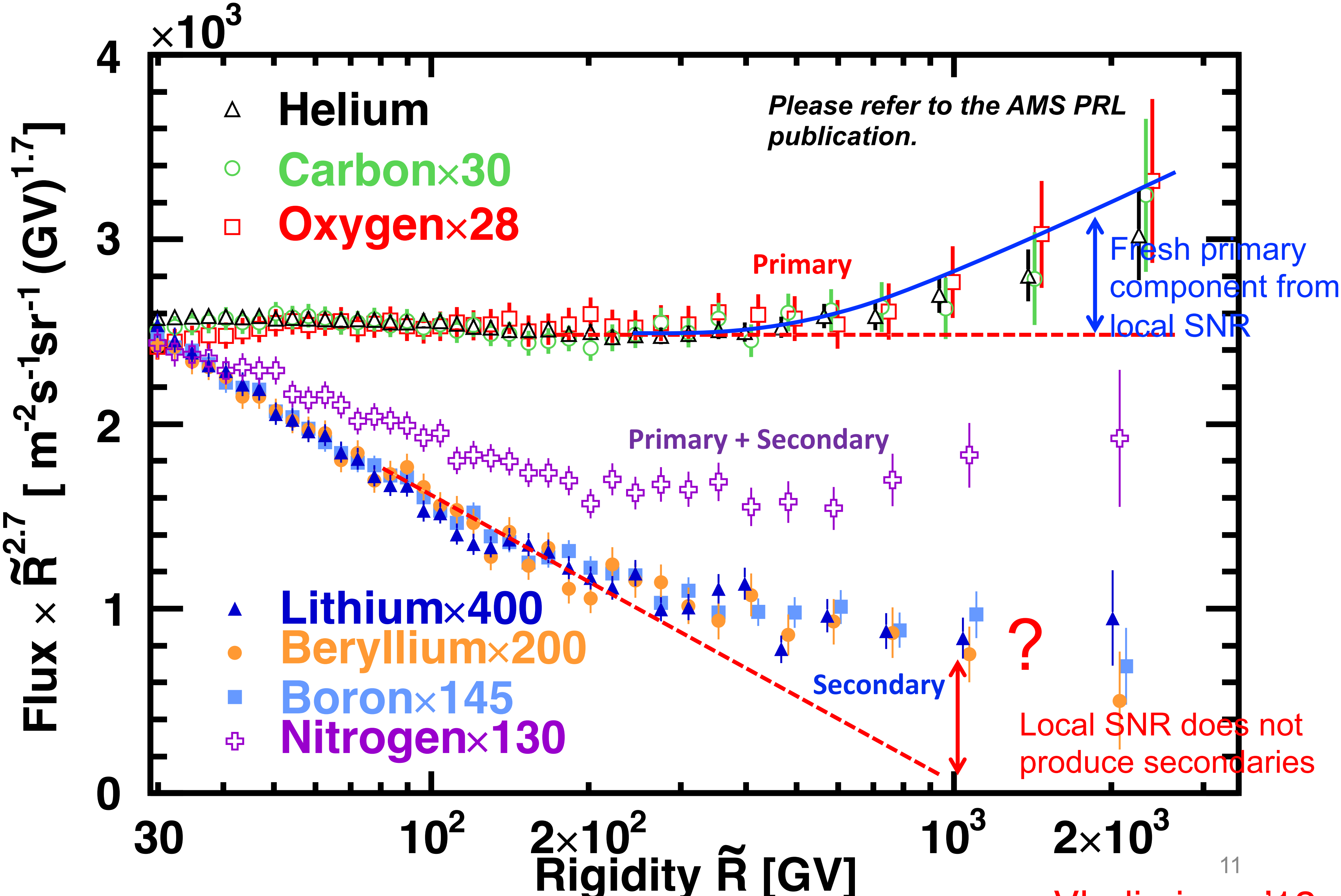
- Is this another break in the diffusion coefficient or a feature associated with a local source or what?
- Is it a single feature OR two independent features?

Anisotropy measurements



- ✧ CR anisotropy has an enhancement in exactly the range of the bump
- ✧ Tells us that it is rather a single feature, not two independent features

Could a local SNR be responsible for this break?

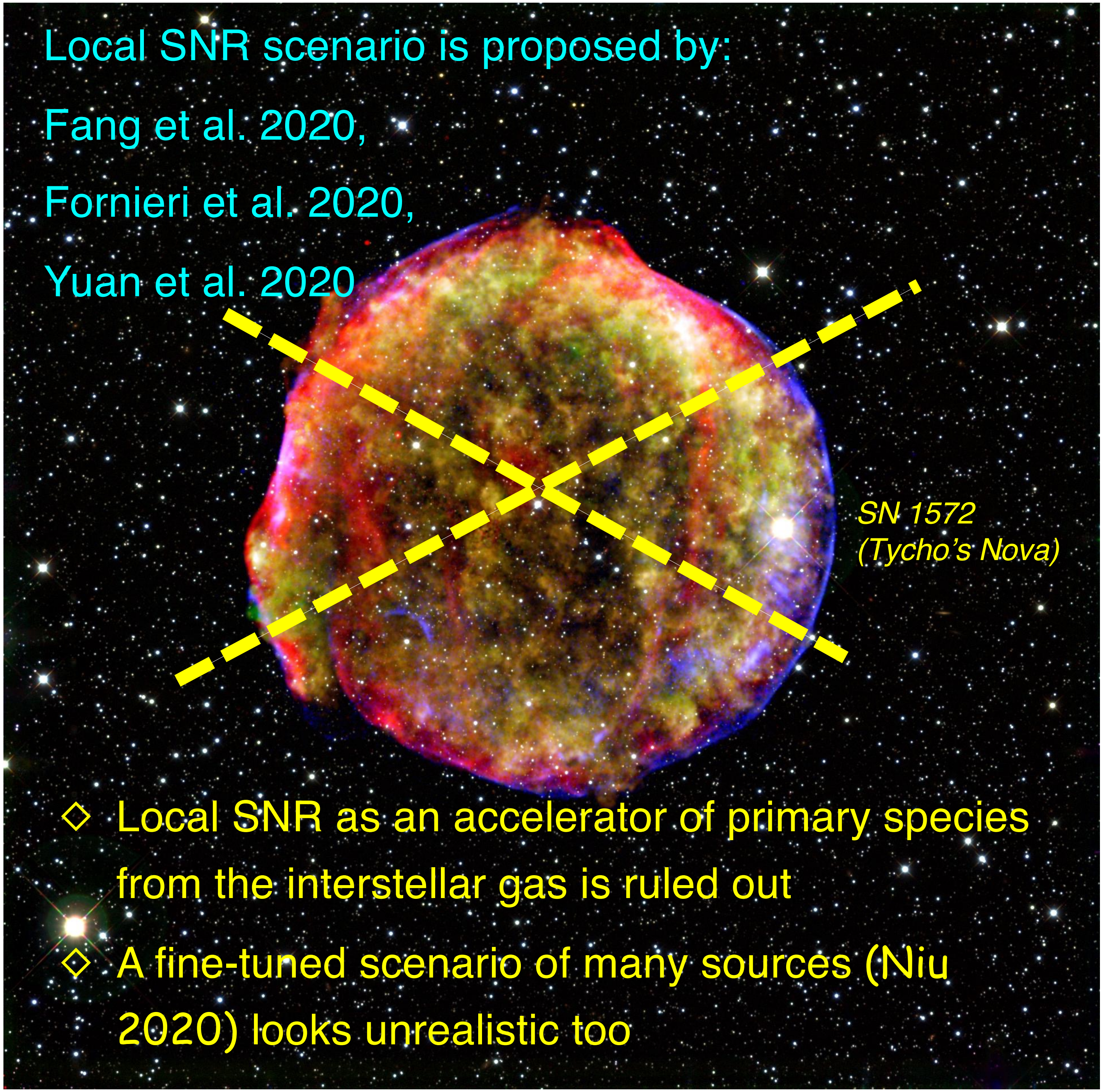


11

Vladimirov+'12

Local SNR?

The TeV bump has to be made of the preexisting CRs with all their primaries and secondaries that have spent millions of years in the Galaxy! – weak local shock that reaccelerates CR particles



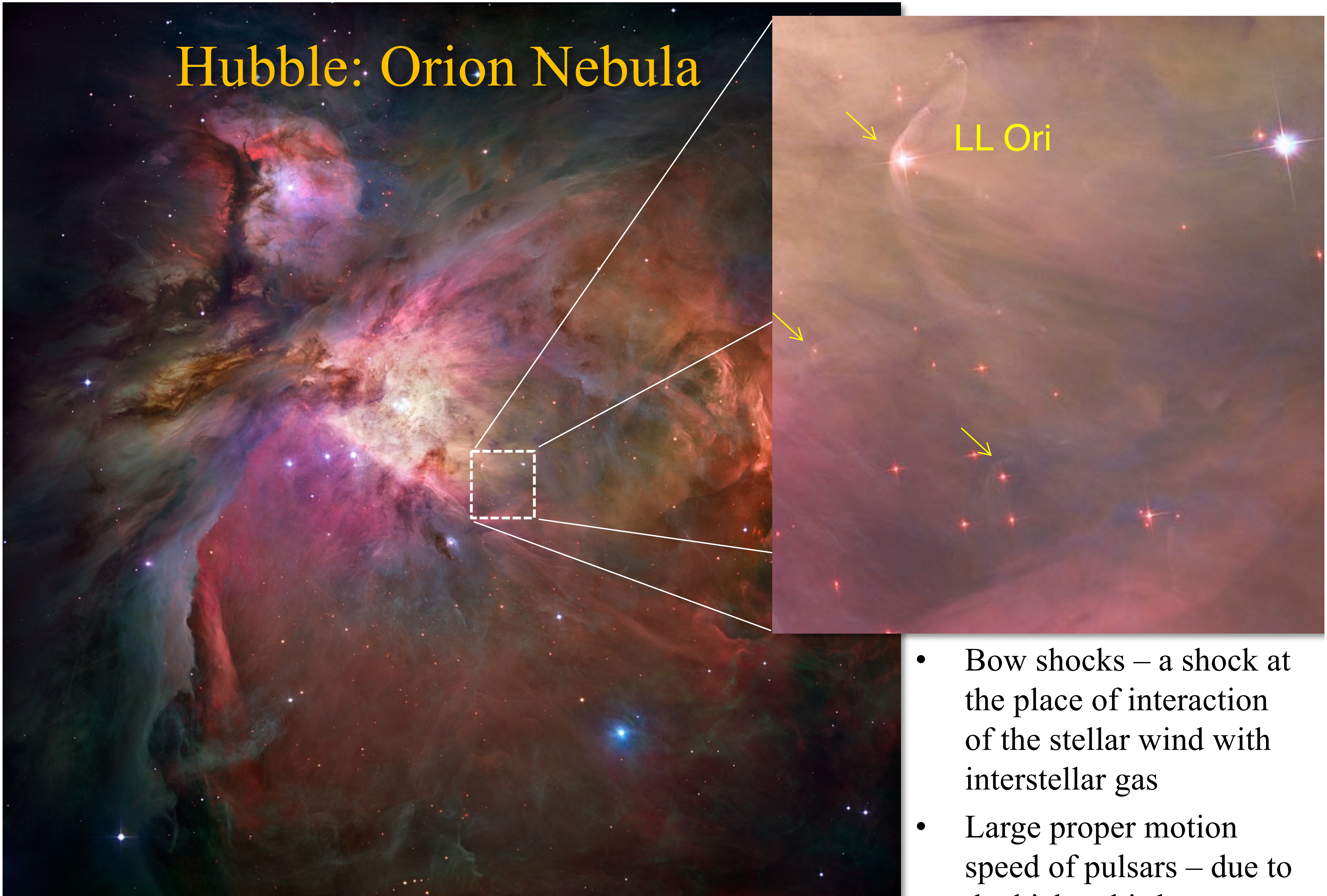
Local SNR scenario is proposed by:

Fang et al. 2020,

Fornieri et al. 2020,

Yuan et al. 2020

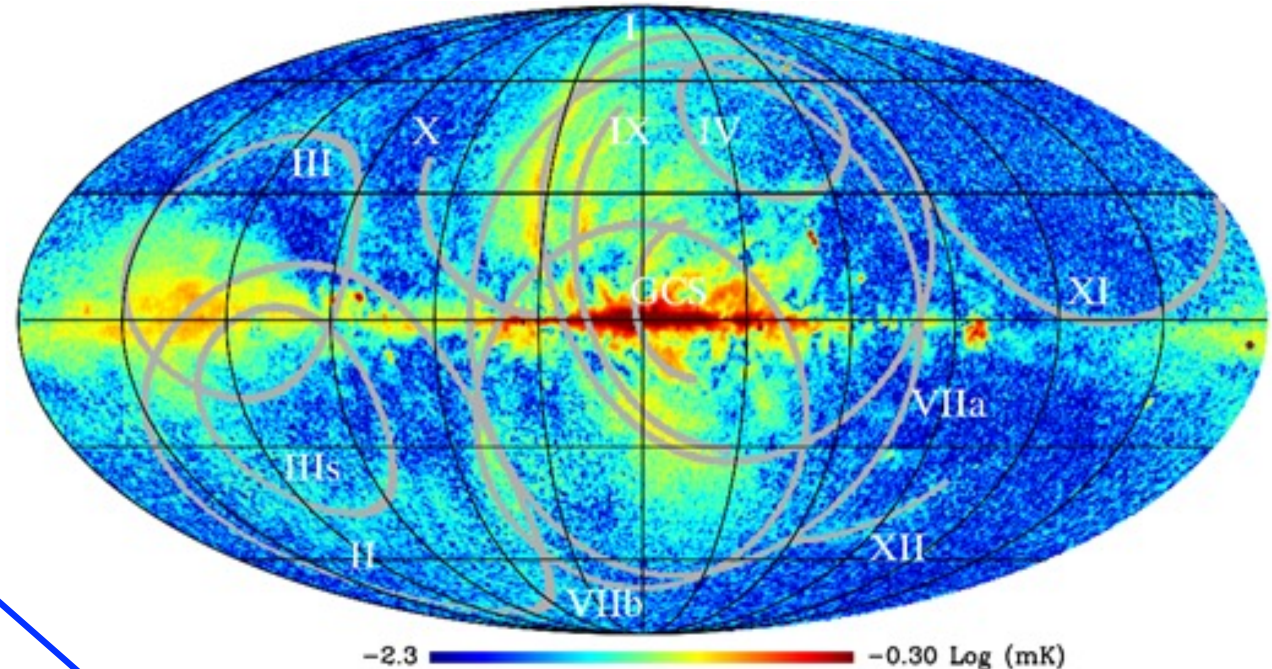
- ◇ Local SNR as an accelerator of primary species from the interstellar gas is ruled out
- ◇ A fine-tuned scenario of many sources (Niu 2020) looks unrealistic too



- Bow shocks – a shock at the place of interaction of the stellar wind with interstellar gas
- Large proper motion speed of pulsars – due to the kick at birth

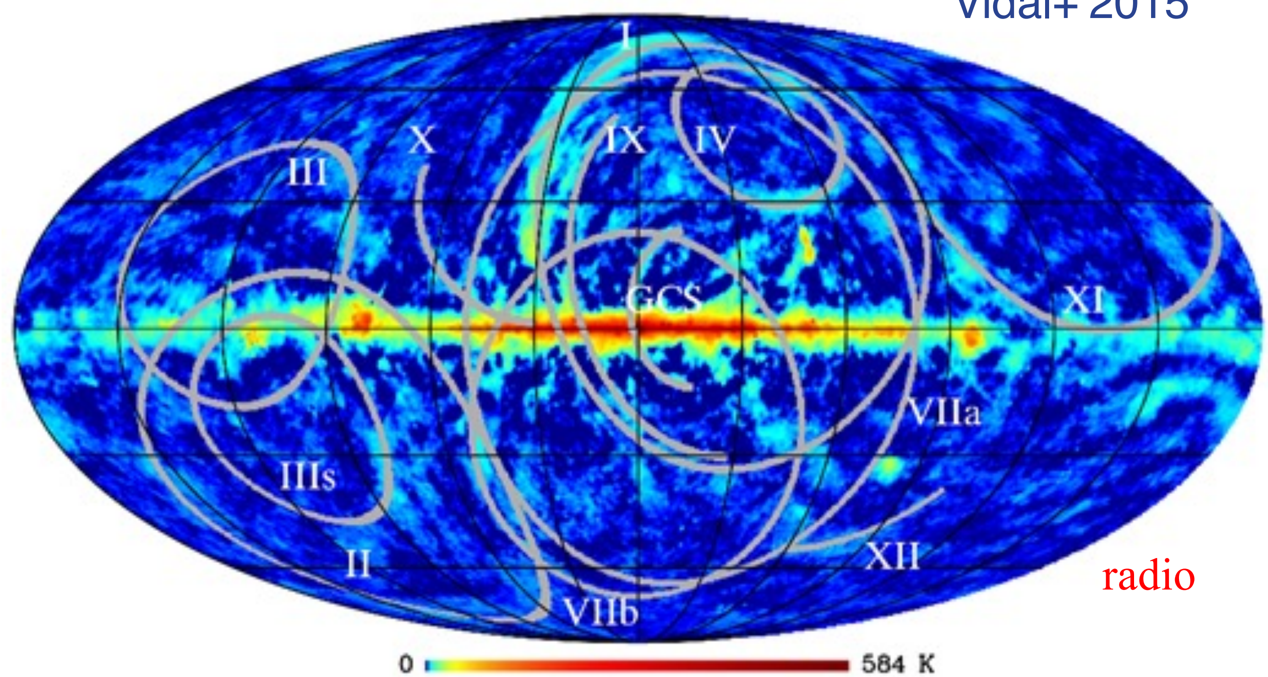
Galactic Loops

- 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 SNRs, accelerated particles may still be present in the shell
- Signatures of the past (recent?) activity in the Solar neighborhood
- How strong does this past activity affect the current fluxes of CR species?



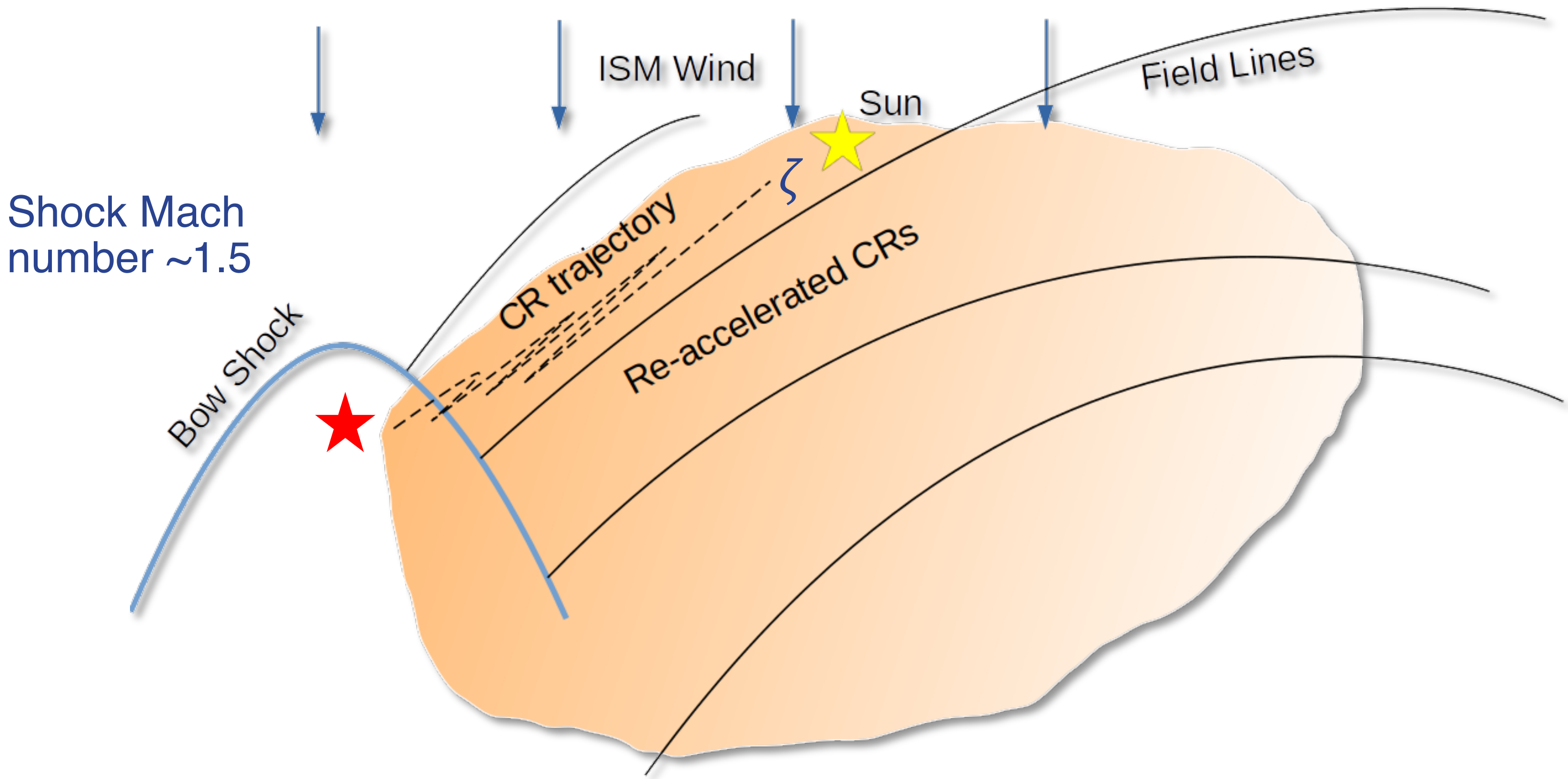
WMAP *K*-band polarization intensity map

Vidal+'2015



radio

Bow shock of a passing star

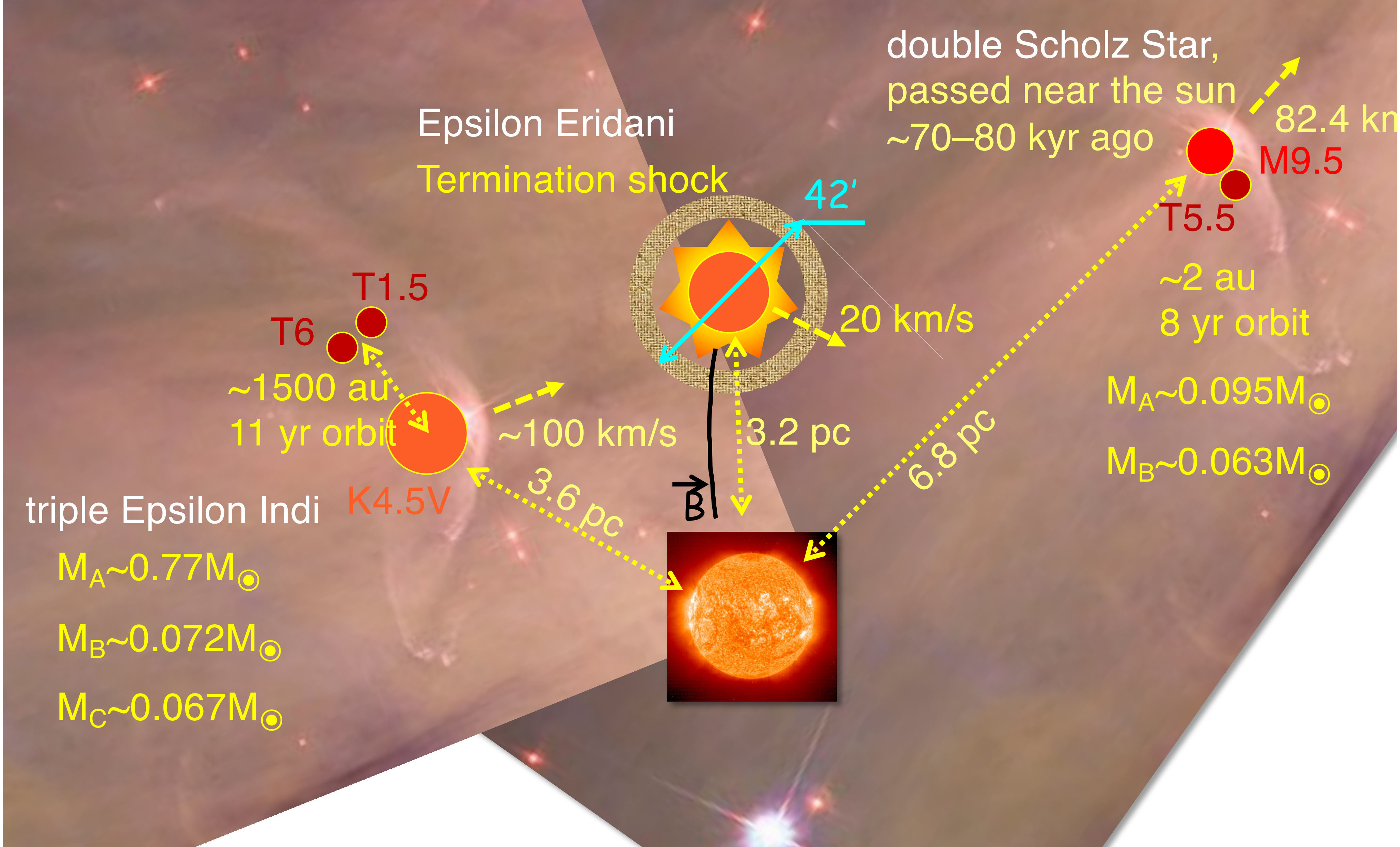


CRs propagate along the magnetic flux tube while self-generating turbulence;

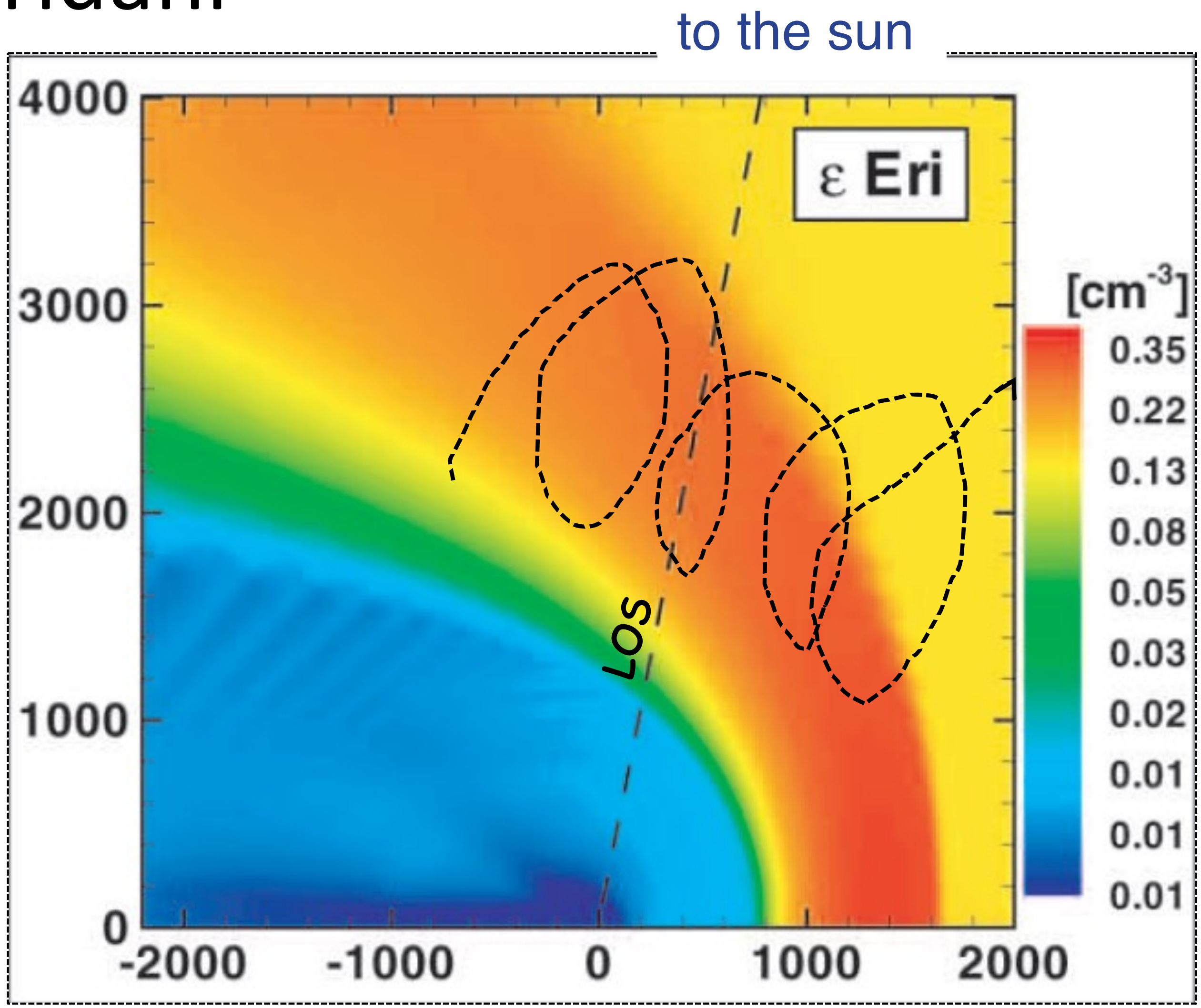
Distance-size relationship $\zeta_{\rm obs}({\rm pc}) \sim 10^2 \sqrt{l_\perp\,({\rm pc})}$;

Assuming $l_\perp = 10^{-3}$-10^{-2} pc, we find the path length along the magnetic field lines of $\zeta_{\rm obs}$ = 3-10 pc.

Passing Stars:
Scholtz Star, Epsilon Indi, Epsilon Eridani

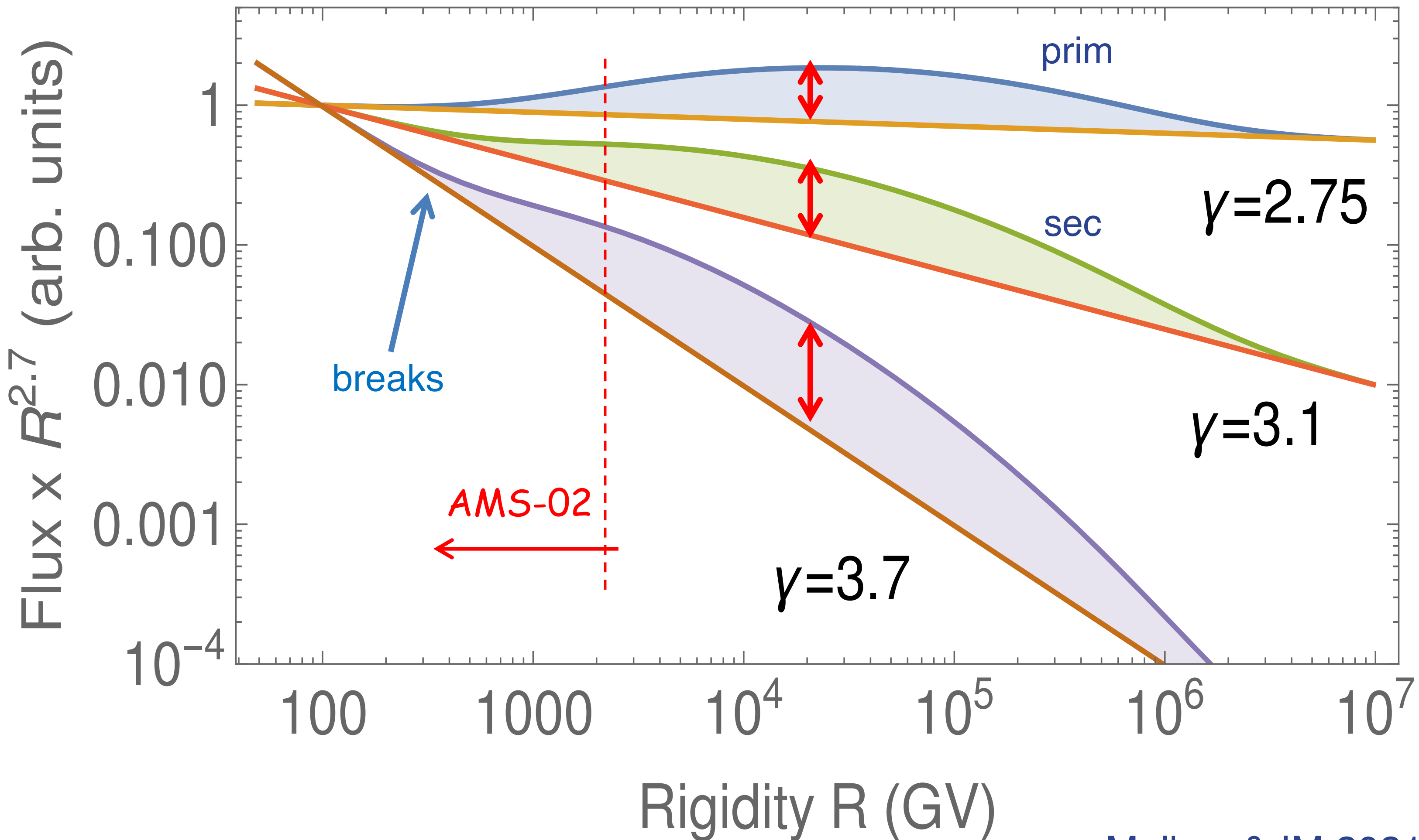


Case of Epsilon Eridani



- ✧ Distance 3.2 pc
- ✧ Velocity ~20 km s^{-1}
- ✧ The sun is upstream
- ✧ Magnetically connected with the Sun: just ~6.7 deg off of the magnetic field direction in the solar neighborhood
- ✧ Huge astrosphere ~8000 AU (42’ on the sky – larger than the Moon!)

Reacceleration at Sub-TeV–TeV energies

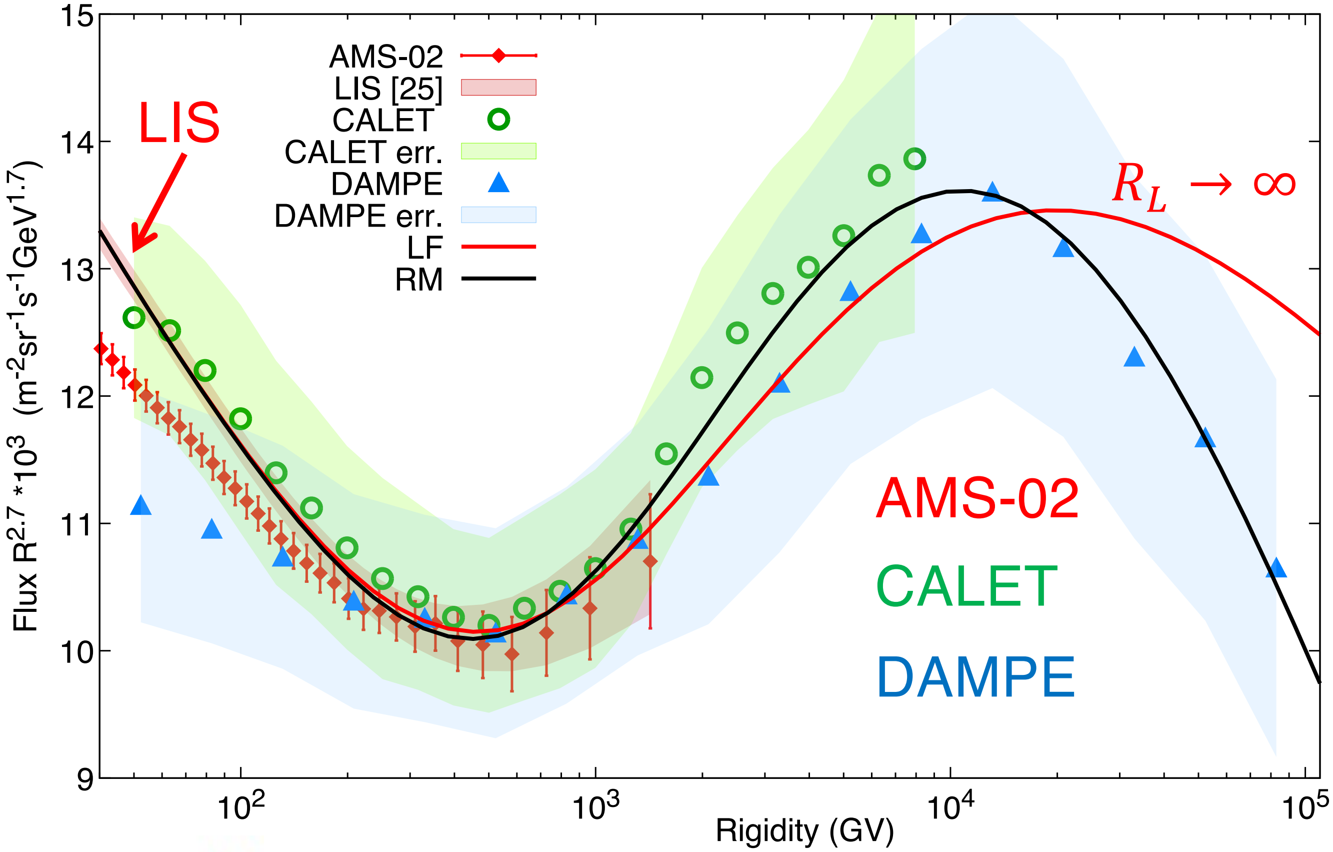


Malkov & IM 2021

- ✧ Primary and secondary species have different bumps
- ✧ The bump is more pronounced in the case of a steeper spectrum
- ✧ The LIS spectral index at ~0.1 TV defines the spectral behavior at 0.1-100 TV!

Sub-TeV–TeV energies

- ✧ Parameters are fixed from the proton spectrum: q, R_0 (and possibly R_L)
- ✧ γ_s is the LIS spectral index at ~100 GV (from Boschini+ 2020)
- ✧ Spectra of all other CR species are reproduced automatically



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

Malkov & IM 2021

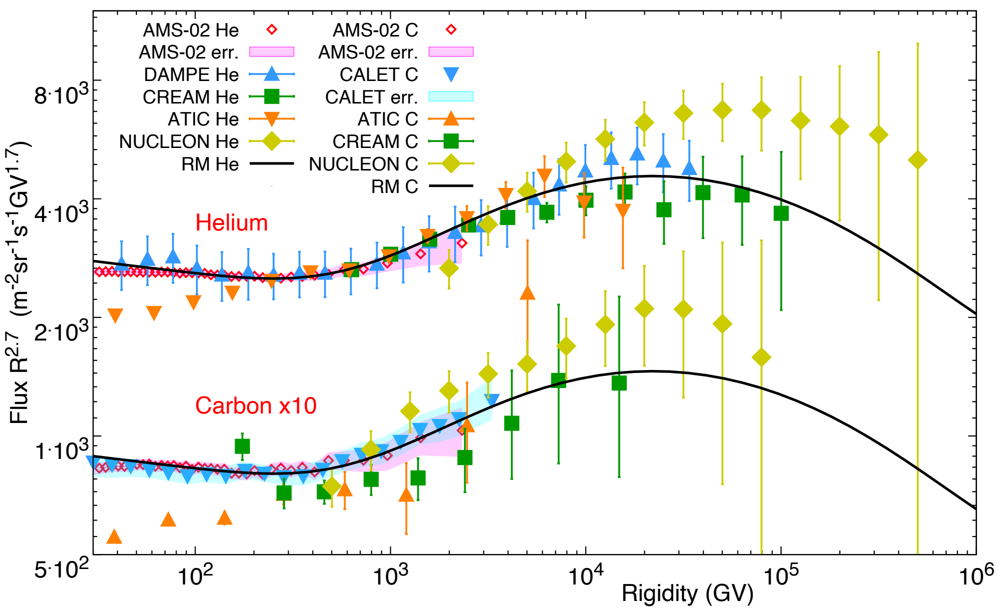
Table I. Model parameters and fit results for the proton spectrum.

Parameter (St. err. %)	R_0(GV)	R_L(GV)	q	$K = (\gamma+2)/(q-\gamma)$	χ^2_{min}/dof	dof
Realistic Model (RM)	5878 (3.5%)	2.24×10^5 (28%)	4.2	3.59 (4.9%)	0.10	76-3
Loss-Free Model (LF)	4795 (3.2%)	∞	4.7	2.58 (2.9%)	0.19	76-2

Examples of He, C, B/C

Only 2 fixed parameters per species:

- γ_s – the LIS spectral index at ~100 GV (from Boschini et al. 2020)
- A_s – the normalization



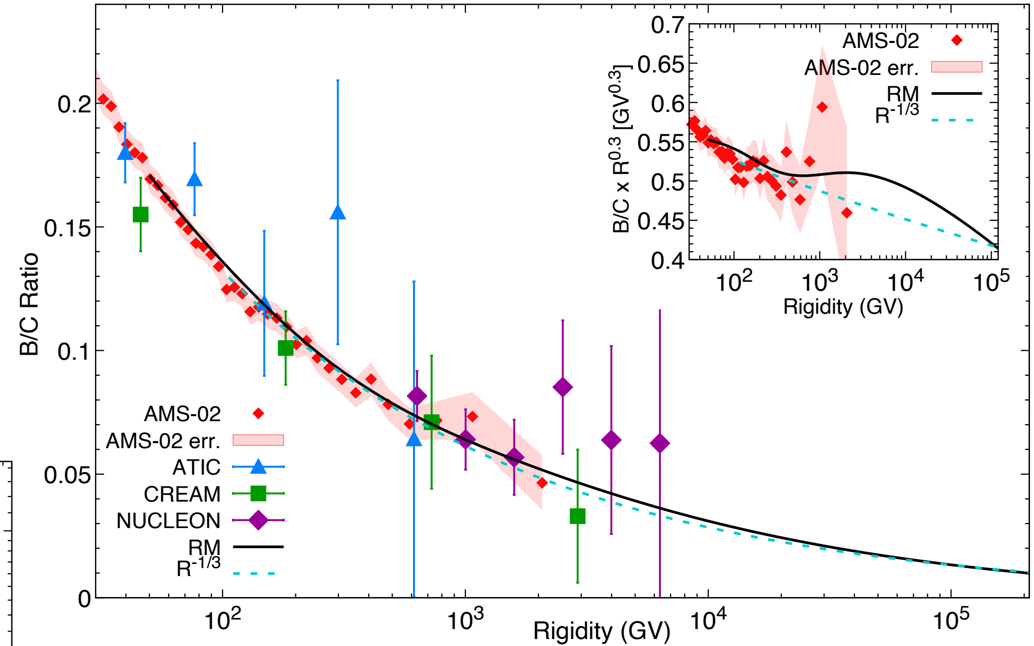


Table II. Input parameters for CR species derived from their LIS [25].

Parameters	protons	helium	boron	carbon
A_s ($m^{-2}\,s^{-1}\,sr^{-1}\,GV^{-1}$)	2.32×10^4	3410	79	109
γ_s	2.85	2.76	3.1	2.76

Malkov & IM 2021

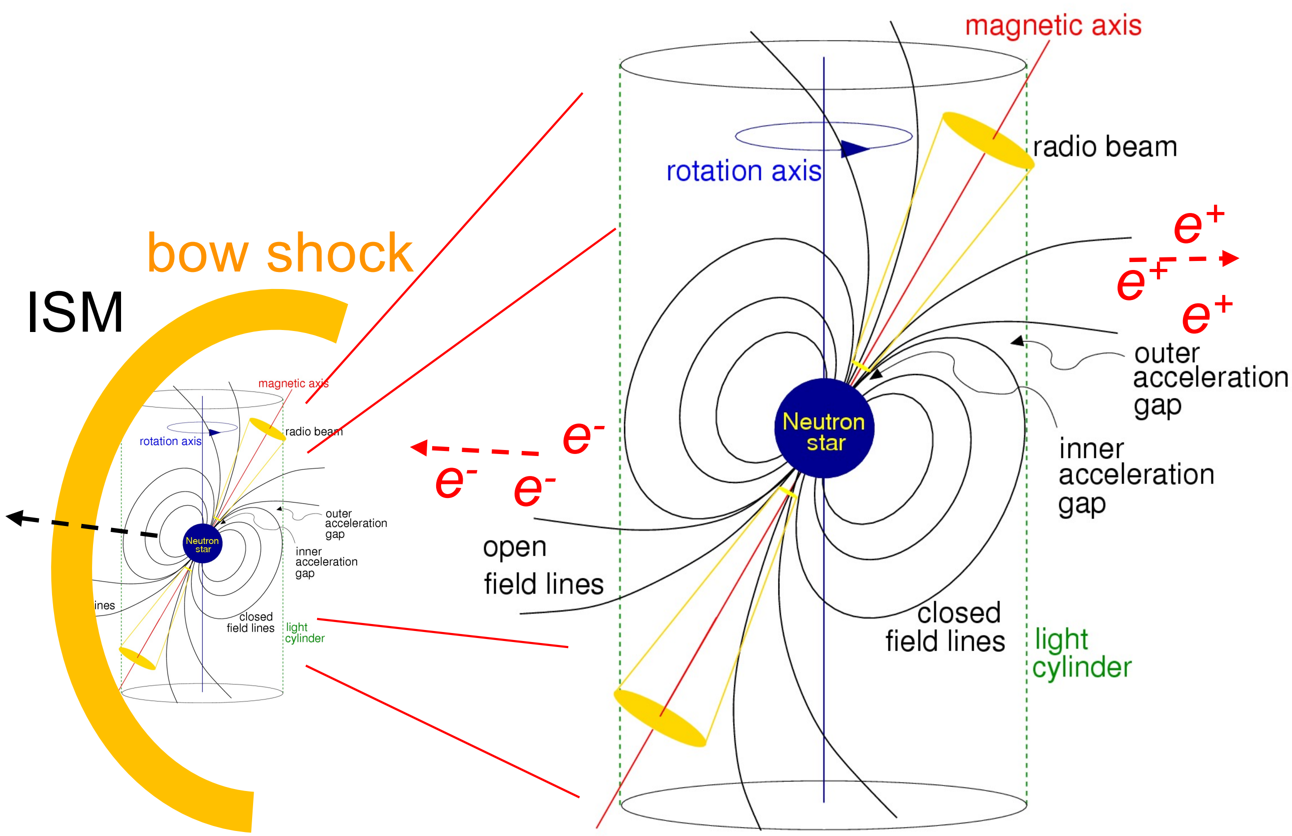
The most accurate AMS-02 data are critical!

Possible time dependence

- ✧ Lateral gradient scale of the flux tube: 10^{15}-10^{16} cm ~100-1000 au
- ✧ Relative speed of the Sun and the star ~100 km/s
- ✧ Expected time dependence is 3-30 years
- ✧ Early reports of the GeV break: ATIC (2002-2003), CREAM (2004-2005), PAMELA (2006-2008) – break rigidity ~200-240 GV
- ✧ AMS-02 (2011-2014) – break rigidity ~450 GV
- ✧ Situation with ~10 TV break is unclear as the error bars are large

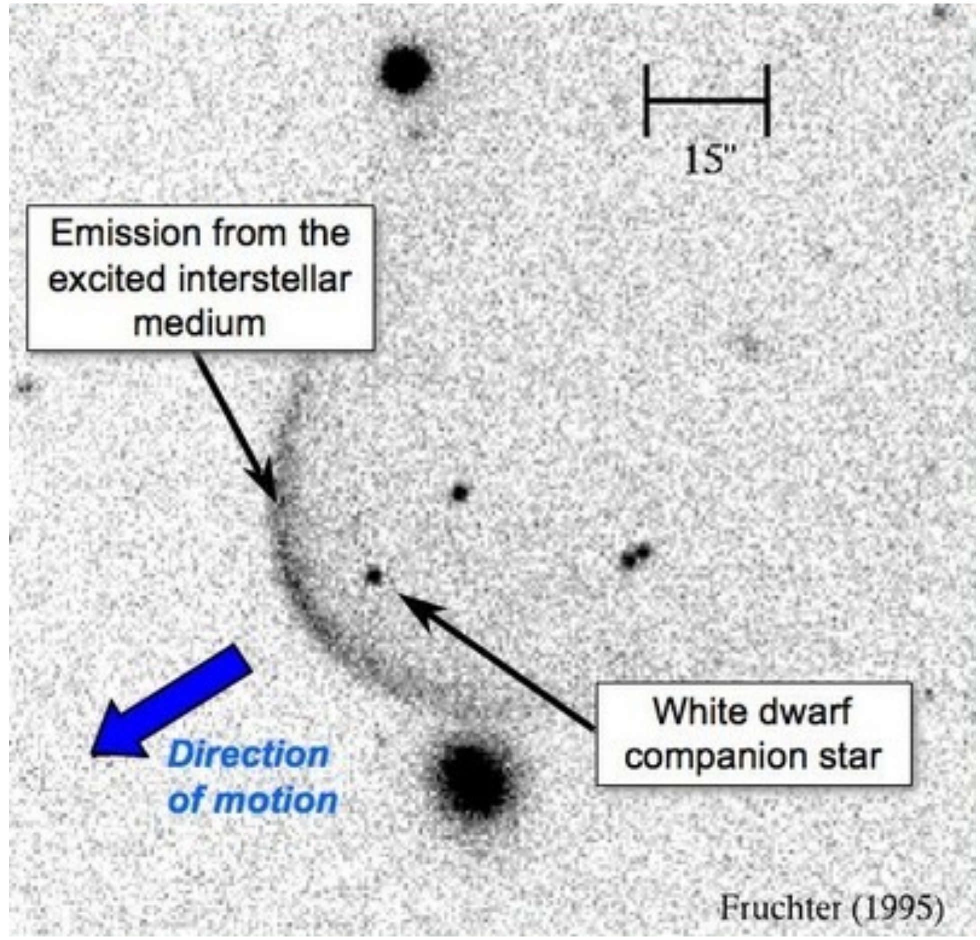
Pulsar bow shock model by A. Bykov et al. (2017)

- Pulsars with high spin-down power produce relativistic winds
- Some of the PWNe are moving relative to the ambient ISM with supersonic speeds producing bow shocks
- Ultrarelativistic particles accelerated at the termination surface of the pulsar wind may undergo reacceleration in the converging flow system → produces universal spectrum, same as for protons
- Similar spectra for electrons and positrons



The 5.7 millisecond pulsar PSR J0437-4715

- ◇ Distance: 156.79±0.25pc
- ◇ Closest and brightest millisecond pulsar (MSP), in a binary system with a white dwarf companion and an orbital period of 5.7 days
- ◇ Velocity ~100 km/s
- ◇ Observed in optical, far-ultraviolet (FUV), and X-ray bands
- ◇ It exhibits the greatest long-term rotational stability of any pulsar
- ◇ It is the first pulsar for which the full three-dimensional orientation of the binary orbit was determined, enabling a new test of General Relativity

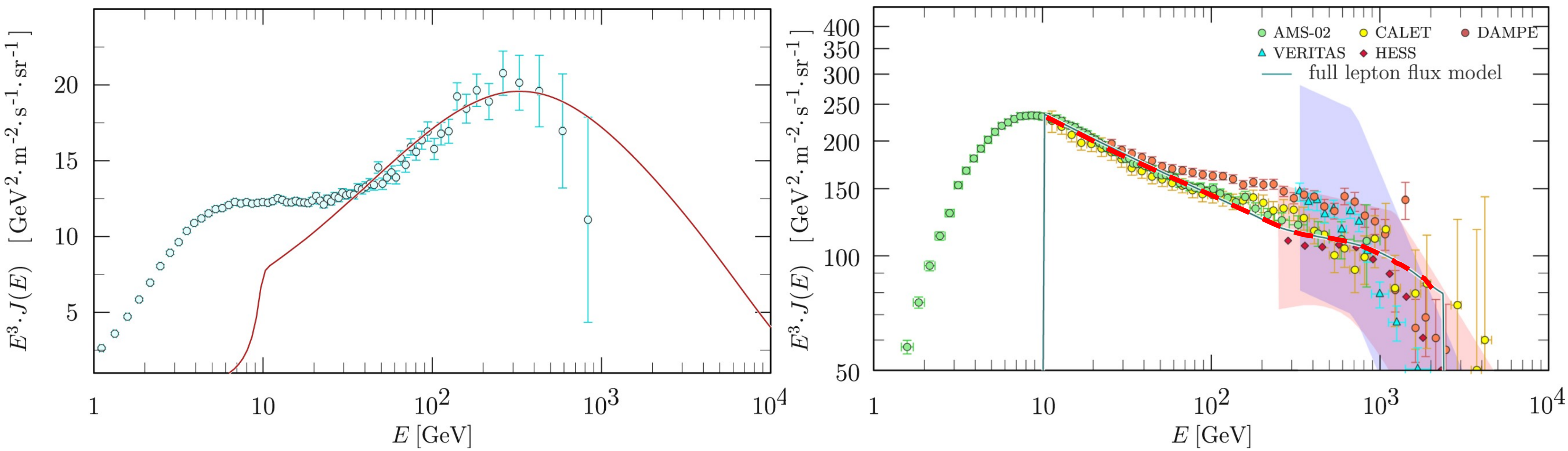


Optical image of the binary system containing PSR J0437-4715

The Astrophysical Journal Letters, 876:L8 (6pp), 2019 May 1
https://doi.org/10.3847/2041-8213/ab1922

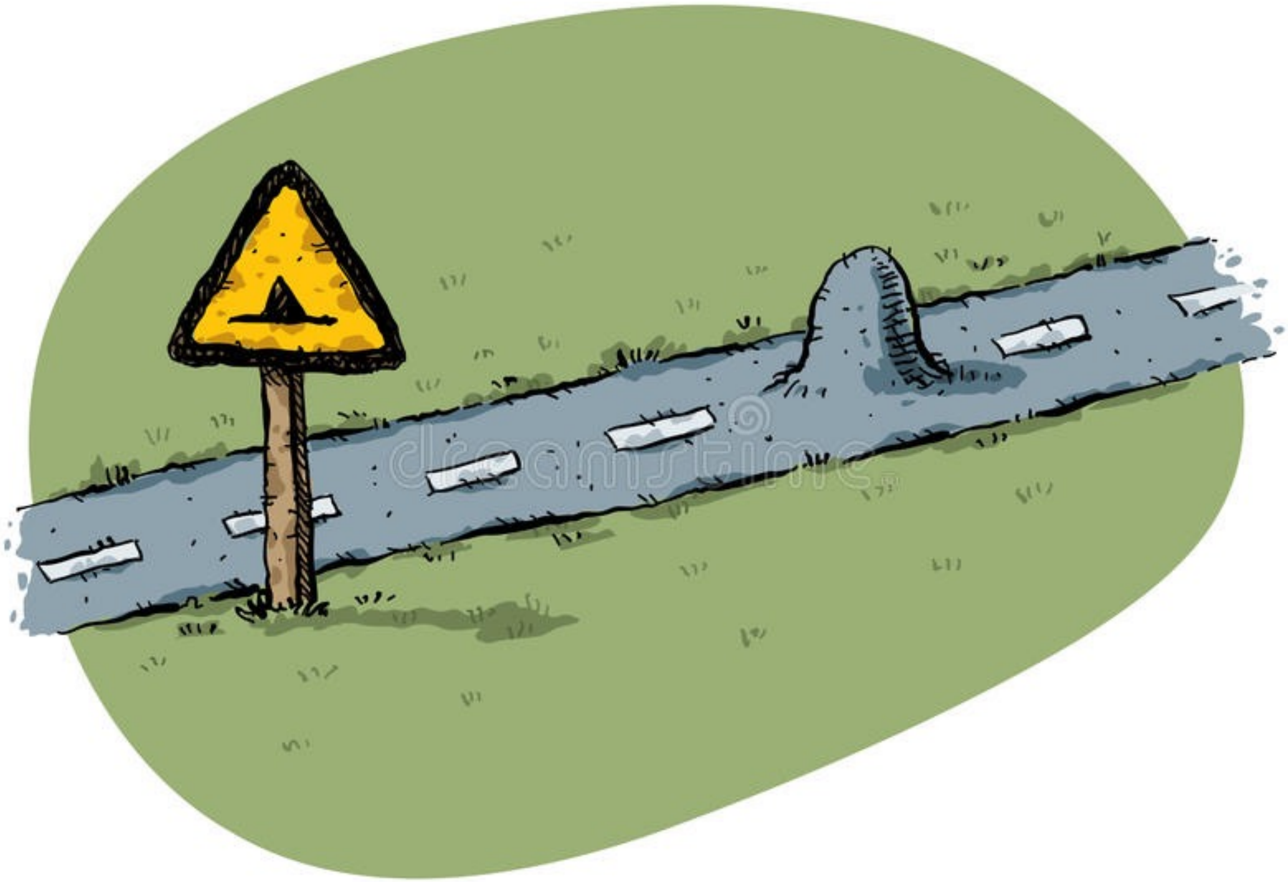
GeV–TeV Cosmic-Ray Leptons in the Solar System from the Bow Shock Wind Nebula of the Nearest Millisecond Pulsar J0437–4715

A. M. Bykov[1,2,3], A. E. Petrov[1], A. M. Krassilchtchikov[1], K. P. Levenfish[1], S. M. Osipov[1], and G. G. Pavlov[4]



Accelerated leptons from the nebula of PSR J0437-4715 can be responsible both for:

- the enhancement of the positron fraction above a few GeV detected by PAMELA and AMS-02 spectrometers
- the TeV range lepton fluxes observed with H.E.S.S., VERITAS, Fermi, CALET, and DAMPE



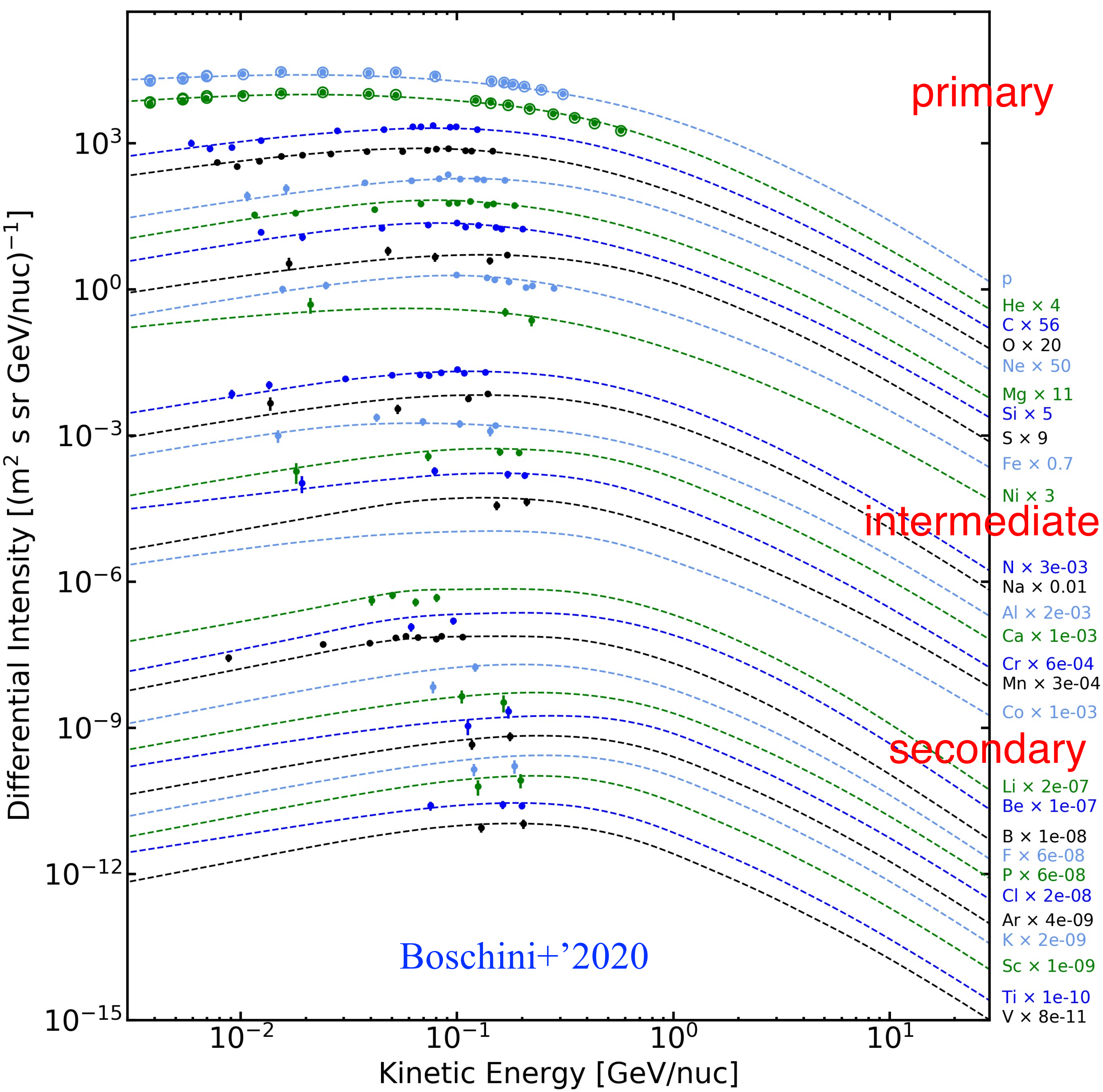
Let’s talk about low-energy ~~bumps~~ excesses in Li, F, Fe

Low energy ≡ local (fast ionization losses)

We use the GALPROP—HELMOD framework

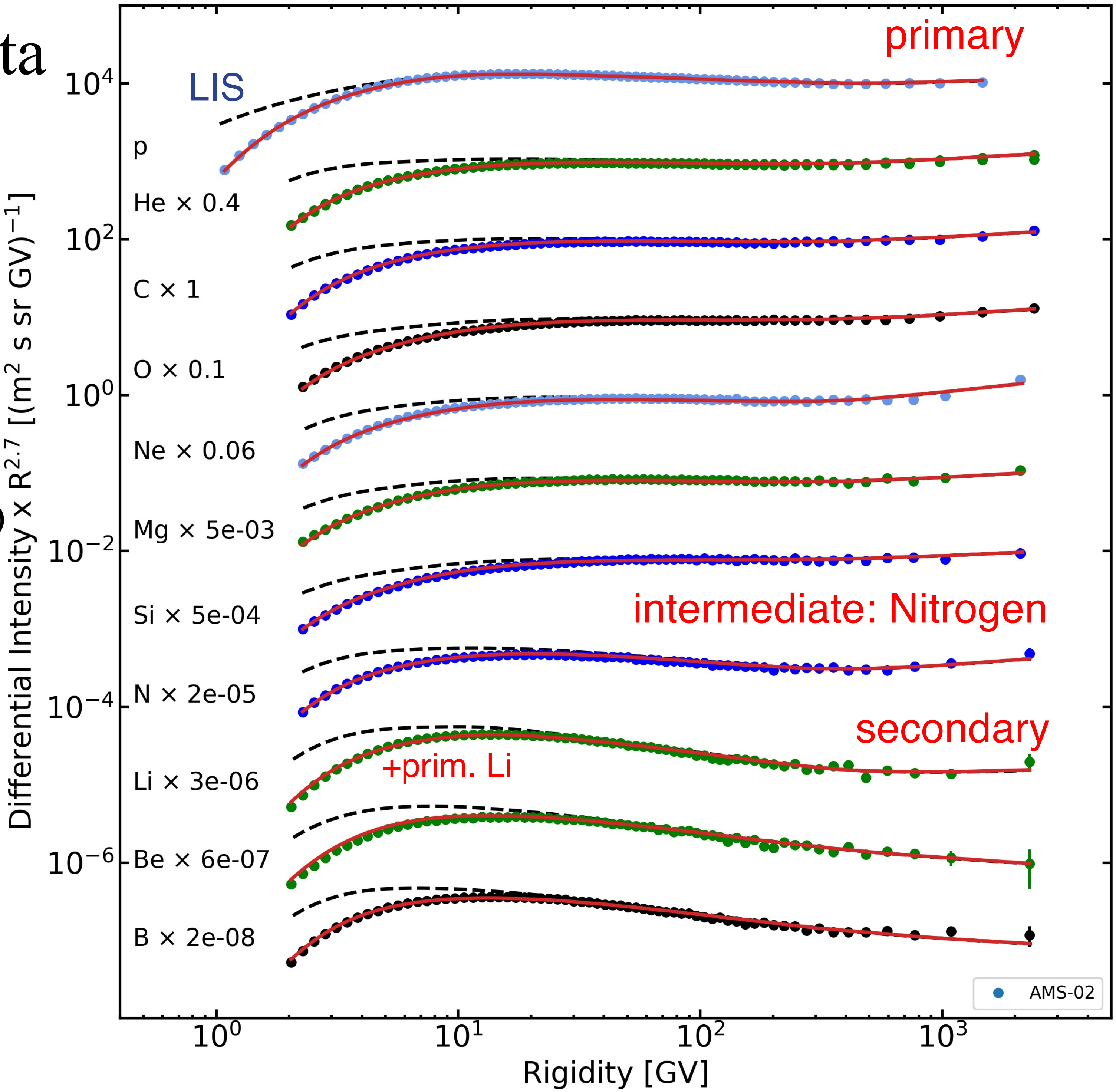
Voyager 1

- ✧ Spectra tuned to Voyager 1, ACE-CRIS, AMS-02
- ✧ Spectra of primary and secondary species are well aligned >1 GeV/n
- ✧ Intermediate: have significant secondary contribution
- ✧ At lower energies spectra exhibit some irregular behavior due to the energy losses, fragmentation and local sources



AMS-02 data

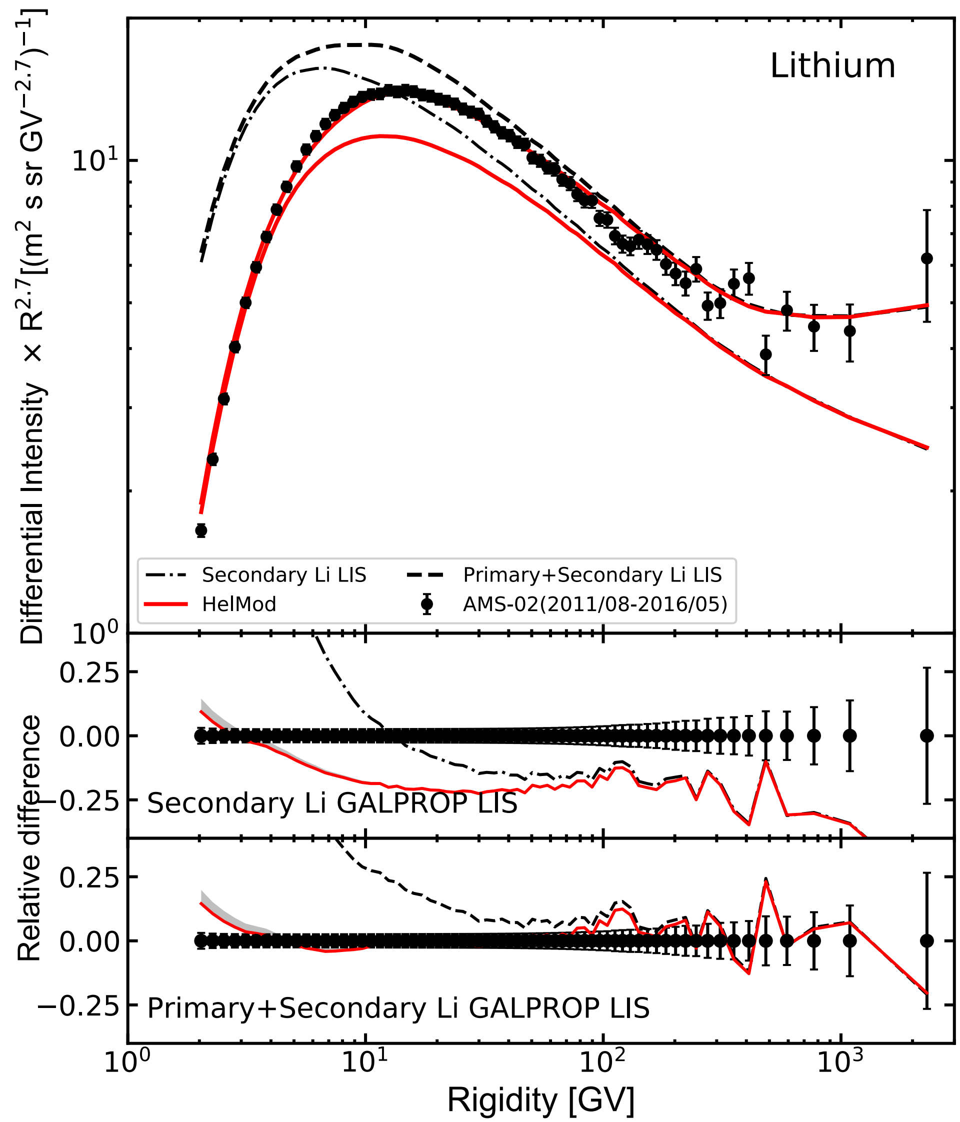
- ✧ Spectra of CR species from AMS-02:
  - ✦ Primary
  - ✦ Intermediate
  - ✦ Secondary (steeper spectra)
- ✧ Local Interstellar Spectra (LIS) – dashed lines
- ✧ Heliospheric propagation – HELMOD



Boschini+'2020

Primary Li in cosmic rays

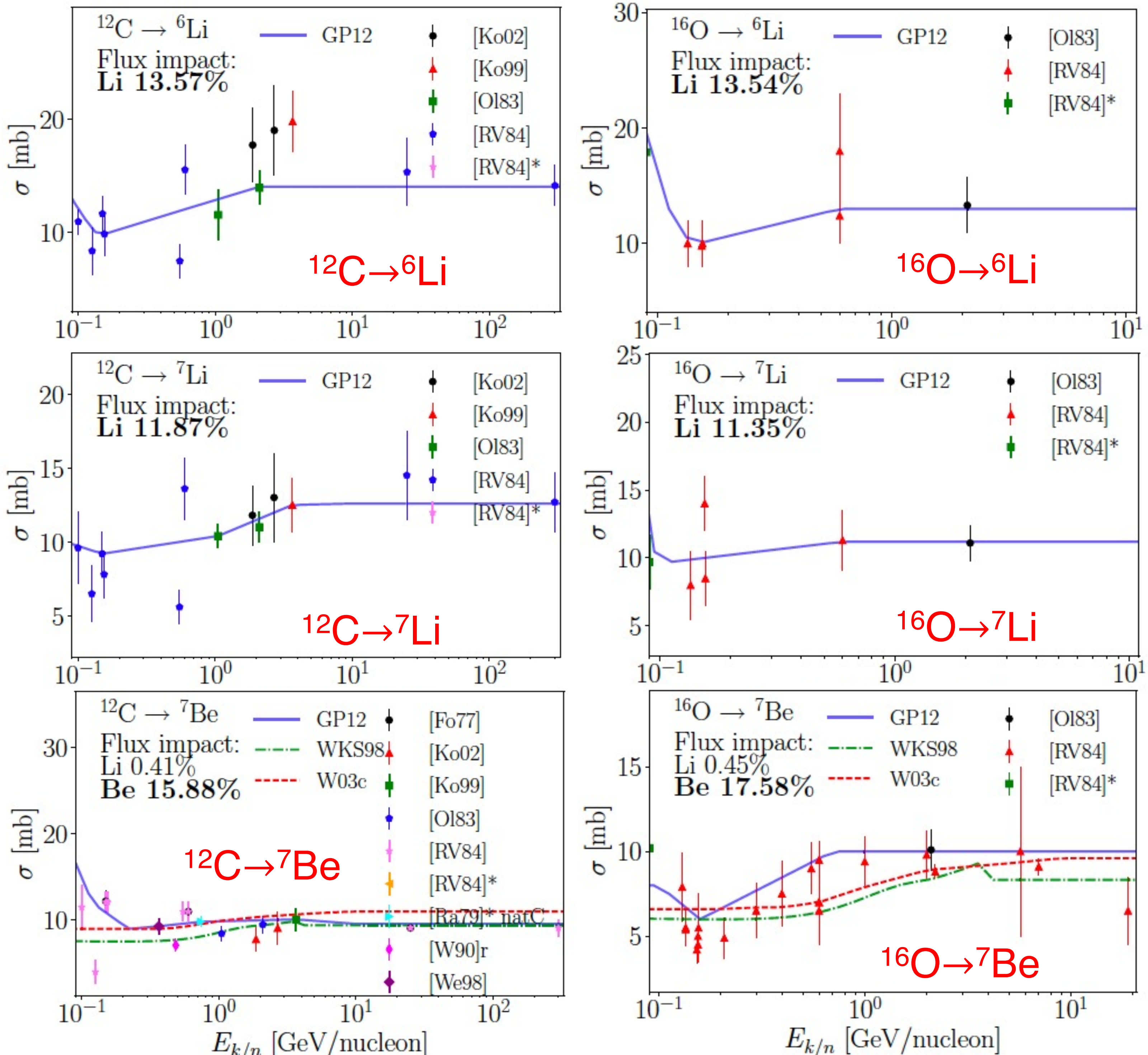
- Calculations with only secondary Li show 25% lithium excess
- Examination of the ^{6}Li and ^{7}Li production shows that the main reaction channels are well-constrained
- 25% discrepancy requires the same bias for all cross sections
- We concluded that this is an indication of primary Li in CRs



Boschini+'20

Li cross sections

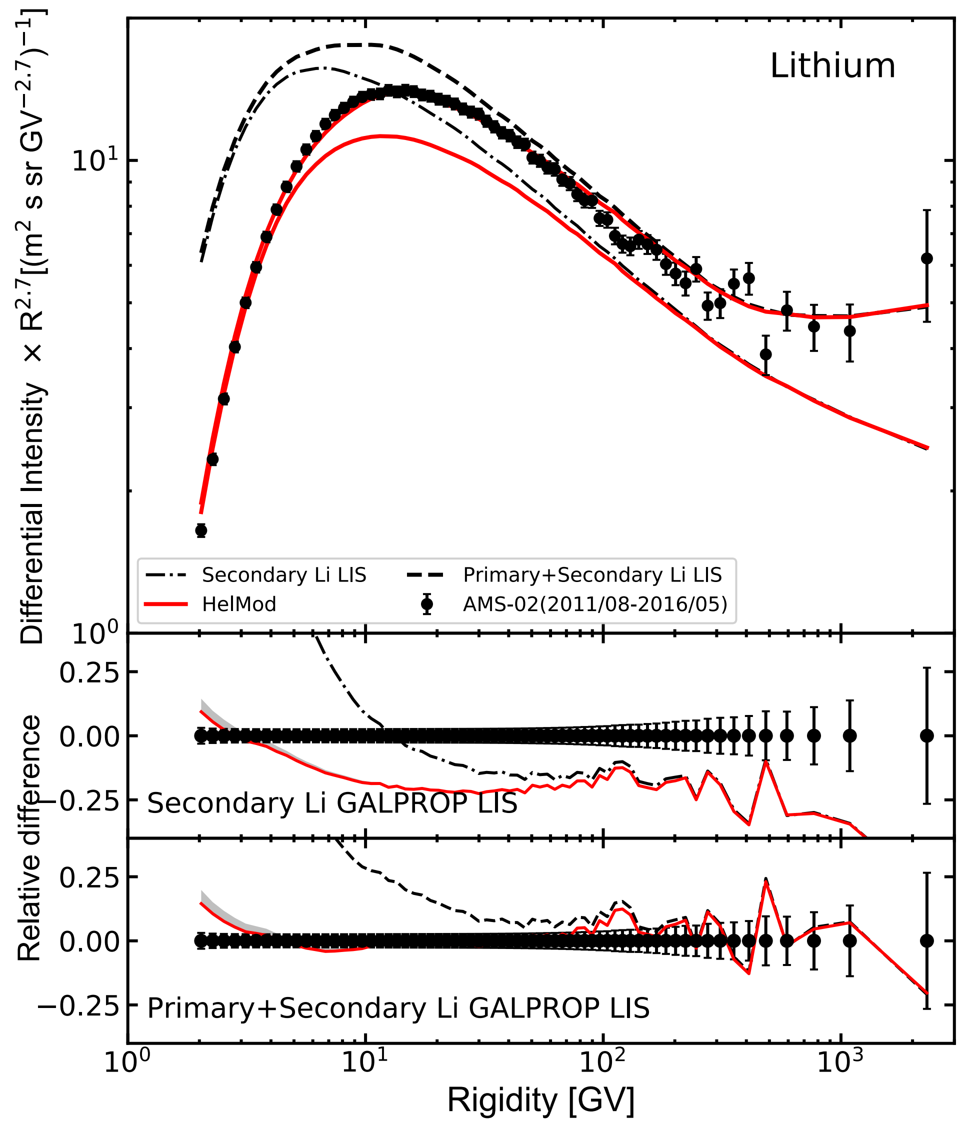
- Even if one of the main channels is wrong by 50%, the effective error is only ~6%
- 25% discrepancy requires the same bias for all cross sections



Sources of primary Li

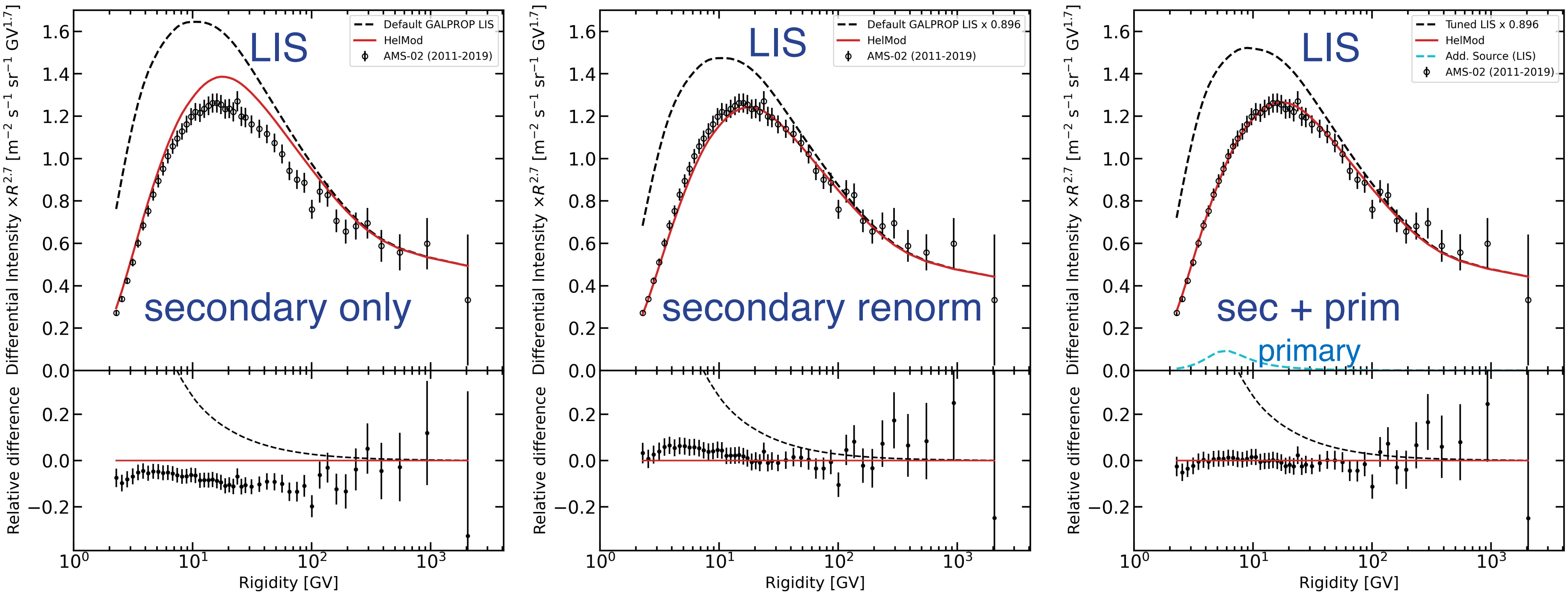
Evidence of primary ^{7}Li

- Cameron-Fowler mechanism (1971):
  - $^{3}He(\alpha,\gamma)^{7}Be$
  - transport of ^{7}Be into cooler layers
  - ^{7}Be decay (53.22 days) → ^{7}Li
- Observation of blue-shifted absorption lines of partly ionized ^{7}Be in the spectrum of a classical nova V339 Del about 40-50 days after the explosion is the first observational evidence that the mechanism proposed in 1970s is working indeed
- Consequent observations of other novae (V1369 Cen, V5668 Sgr and V2944 Oph,, ASASSN-16kt [V407 Lupi], V838 Her) also reveal the presence of 7Be lines in their spectra testifying that classical novae is the new type of sources of ^{7}Li



Boschini+'20

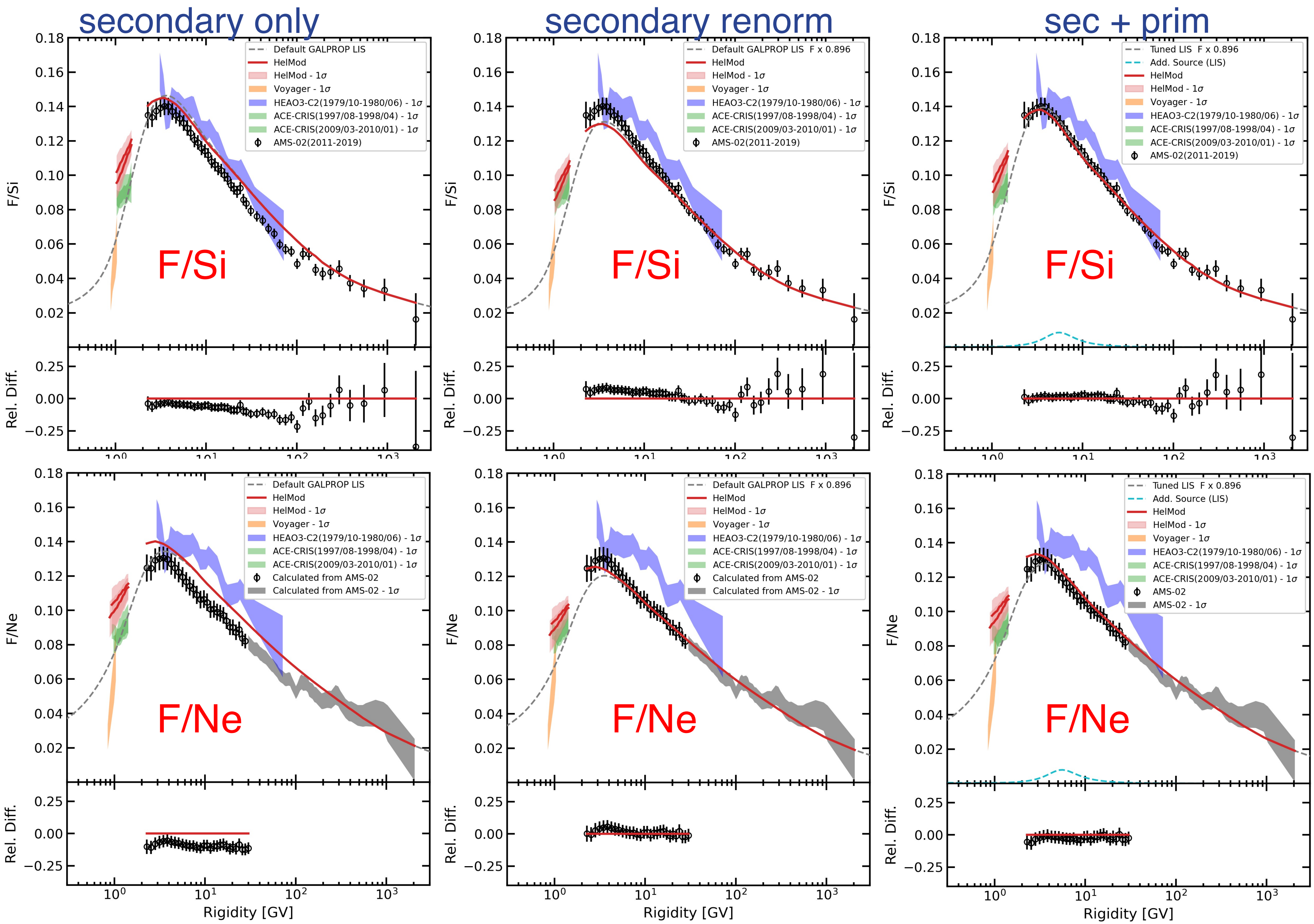
Primary fluorine



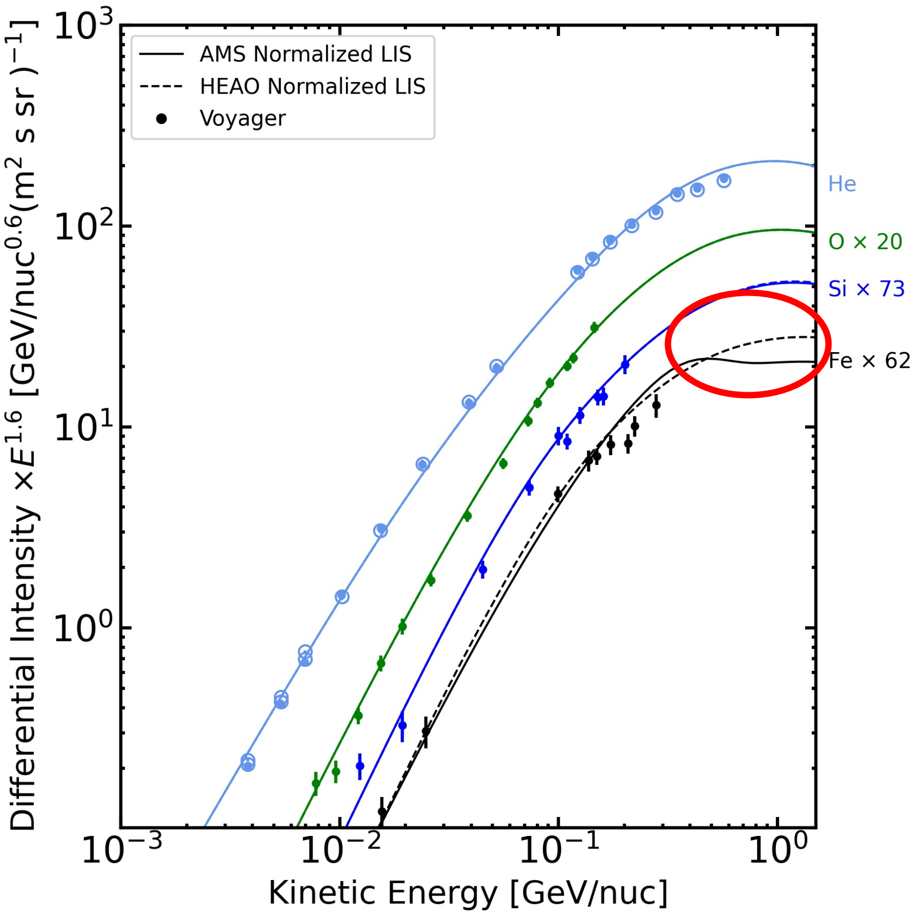
- Overall normalization (x0.896) due to possible errors in the production cross sections
- Remaining excess <10 GV is treated as a primary component

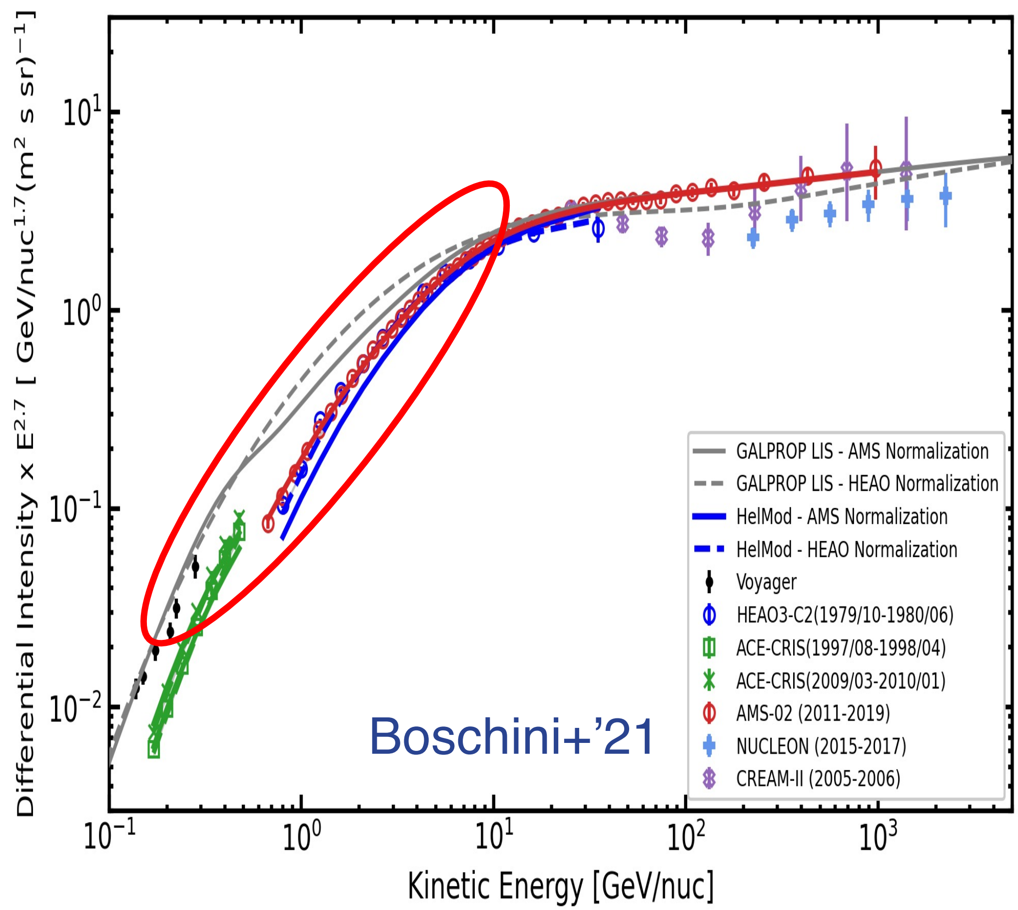
Boschini+'21, in press

F/Si and F/Ne ratios



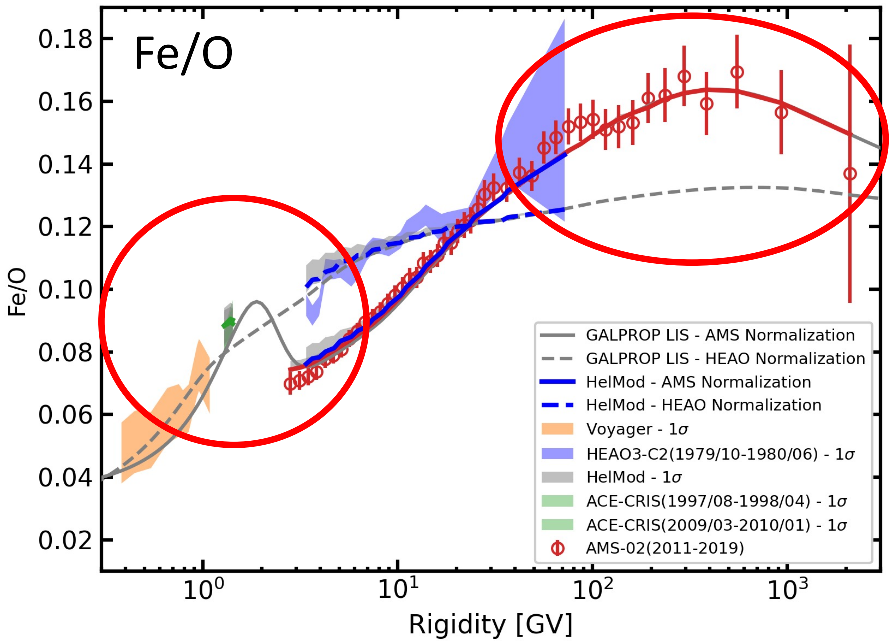
Low-energy excess in CR iron

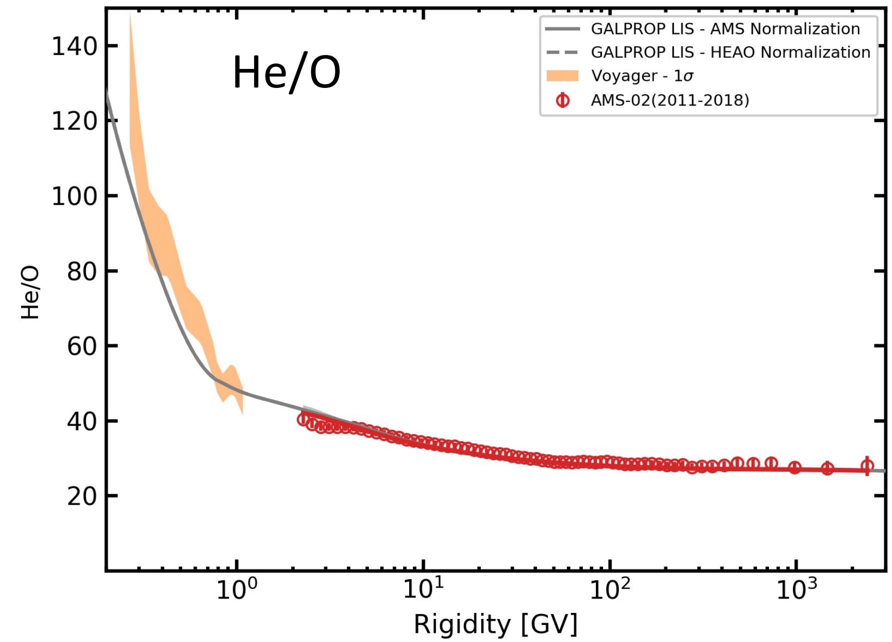


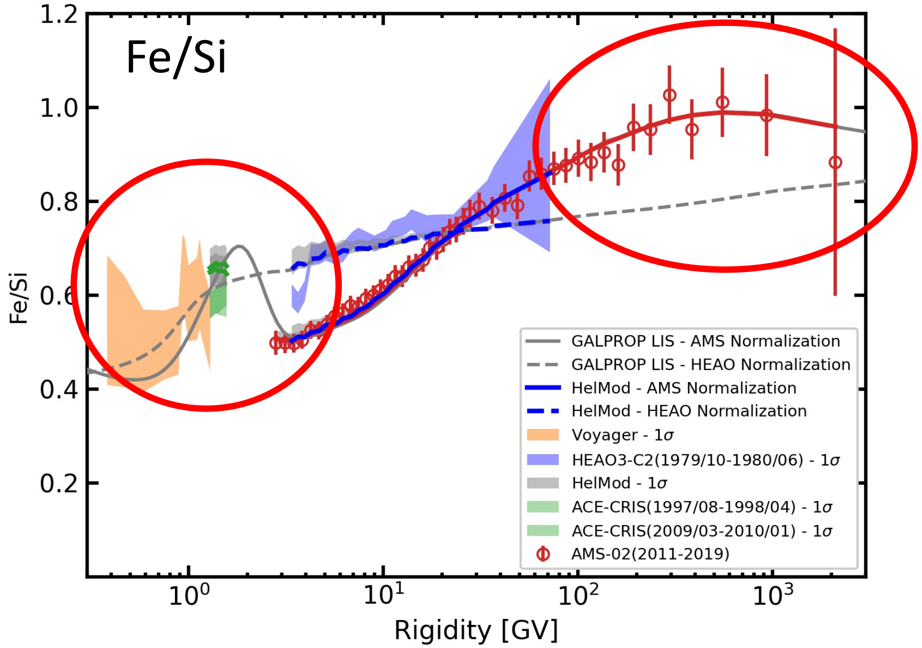


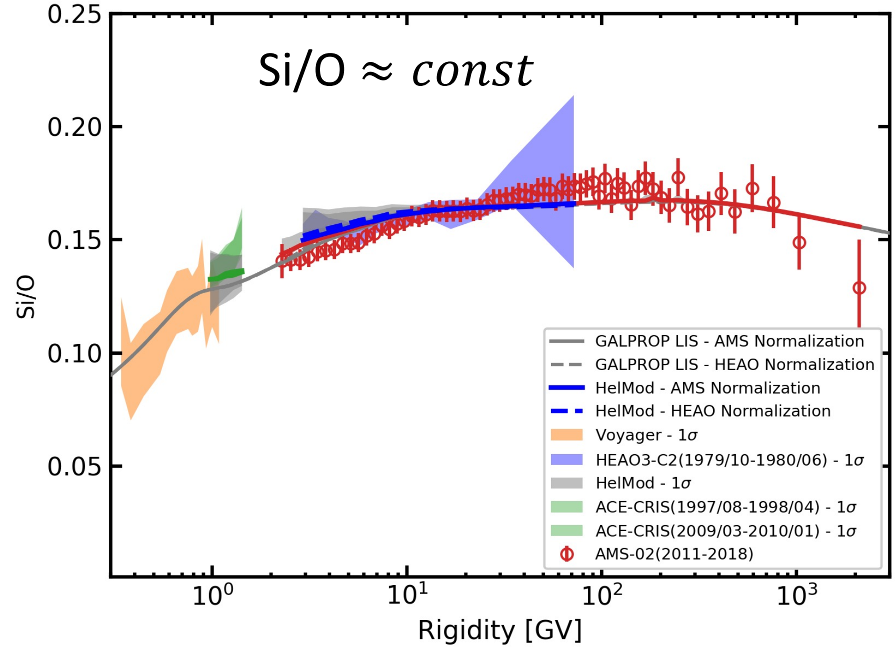
- Modulation level during HEAO-3 mission was higher than during AMS-02, but the data are overlap -> miscalibration of HEAO-3
- Misfit between AMS-02 and ACE-CRIS & Voyager 1 data indicates a spectral feature

Fe excess at Low & High energies







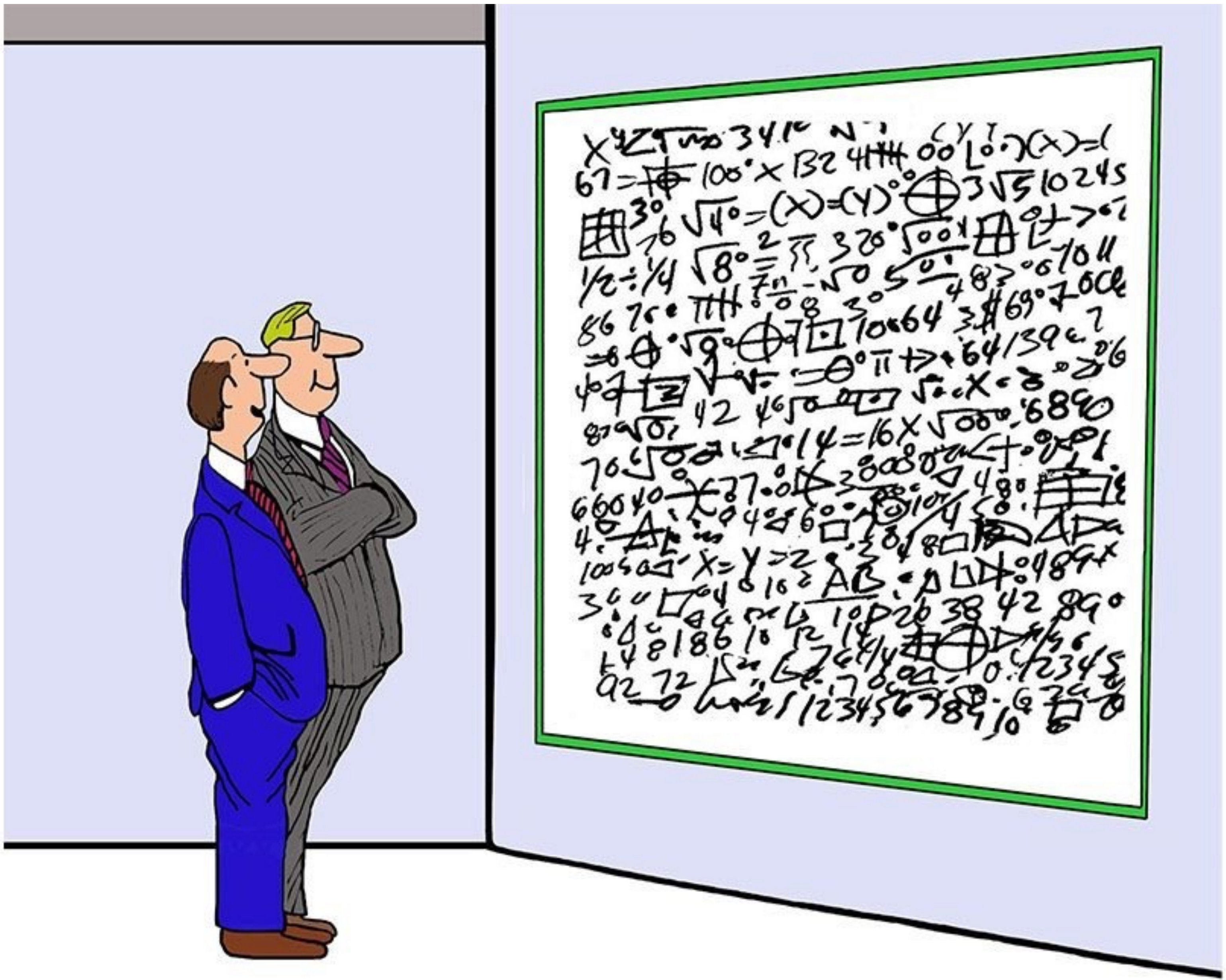


Possible origin of Fe excess

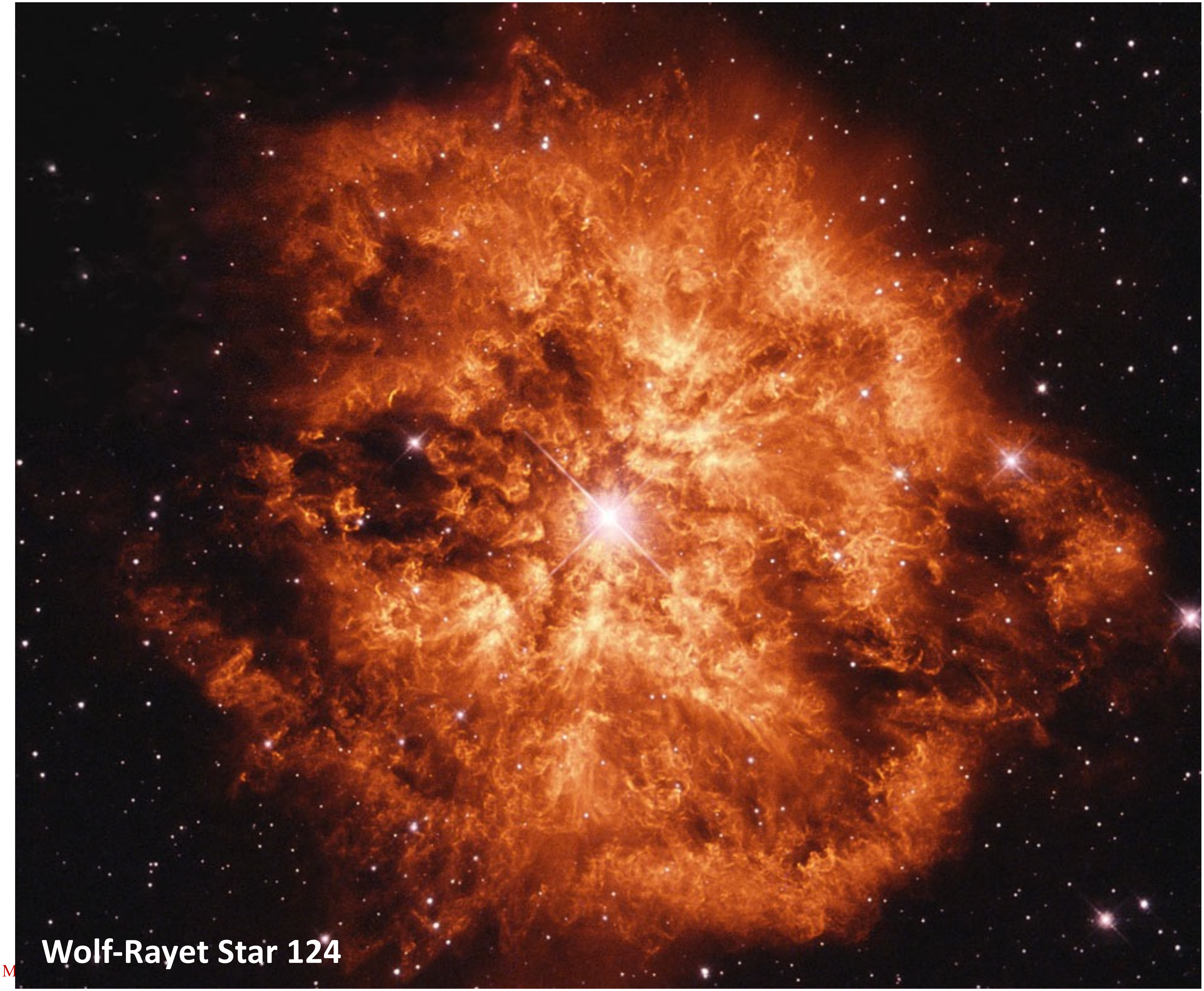
The likely source of the excess CR iron are old SN remnants

- ◊ Evidence of past SN activity in the local ISM is abundant
- ◊ The Local Bubble is formed in a series of SN explosions
- ◊ Multiple reports of an excess of radioactive ^{60}Fe:
  - ✦ Deep ocean sediments (Knie et al. 1999, 2004; Ludwig et al. 2016; Wallner et al. 2016)
  - ✦ Lunar regolith samples (Cook et al. 2009; Fimiani et al. 2012, 2014)
  - ✦ Antarctic snow (Koll et al. 2019)
  - ✦ In CRs by ACE-CRIS (Binns et al. 2016) – implies that the low-energy CRs from the most recent SN are still around

Thanks!



When you put it like this, it makes complete sense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