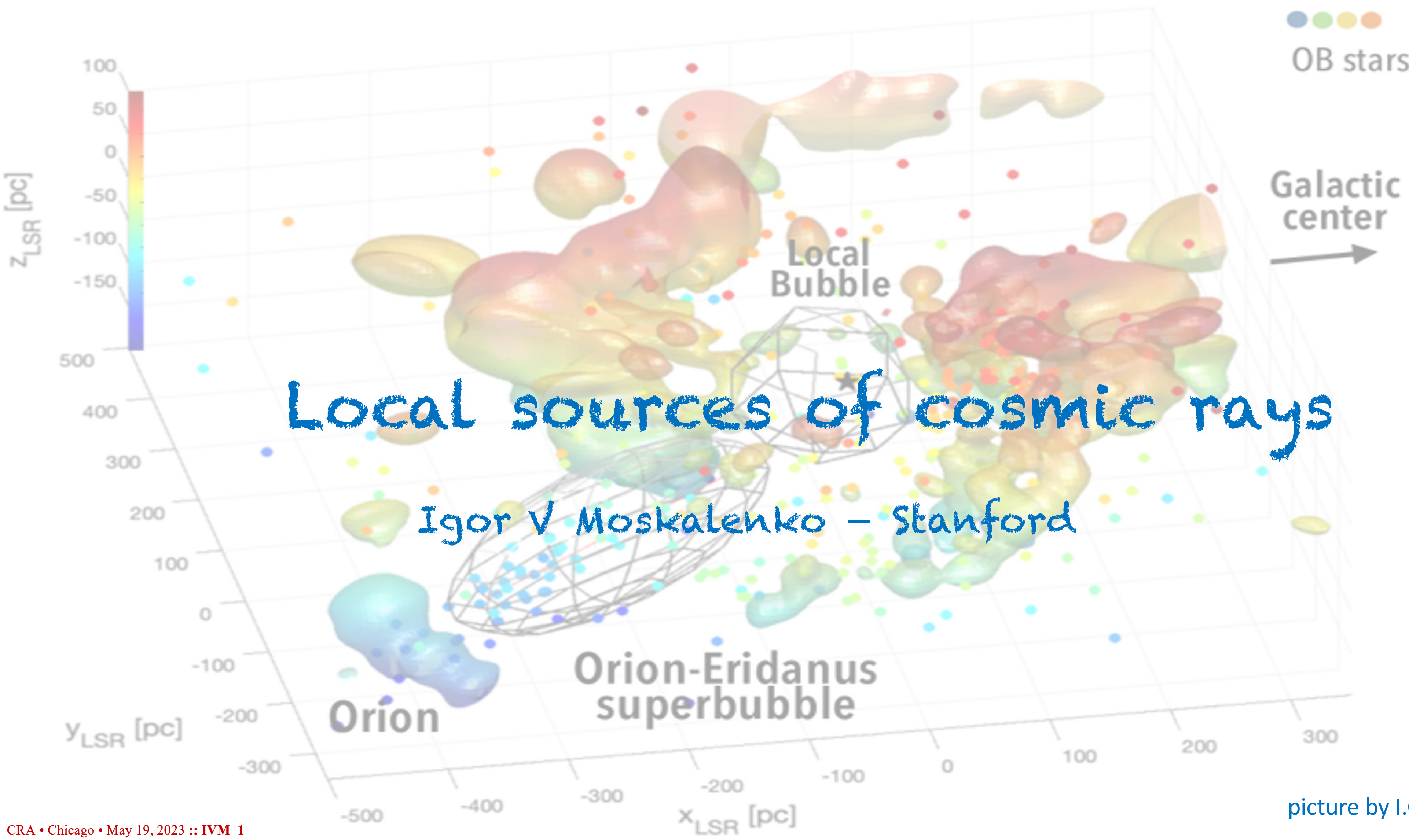
Local sources of cosmic rays

Igor V Moskalenko – Stanford



picture by I.Grenier

Inventory of Galactic cosmic ray sources

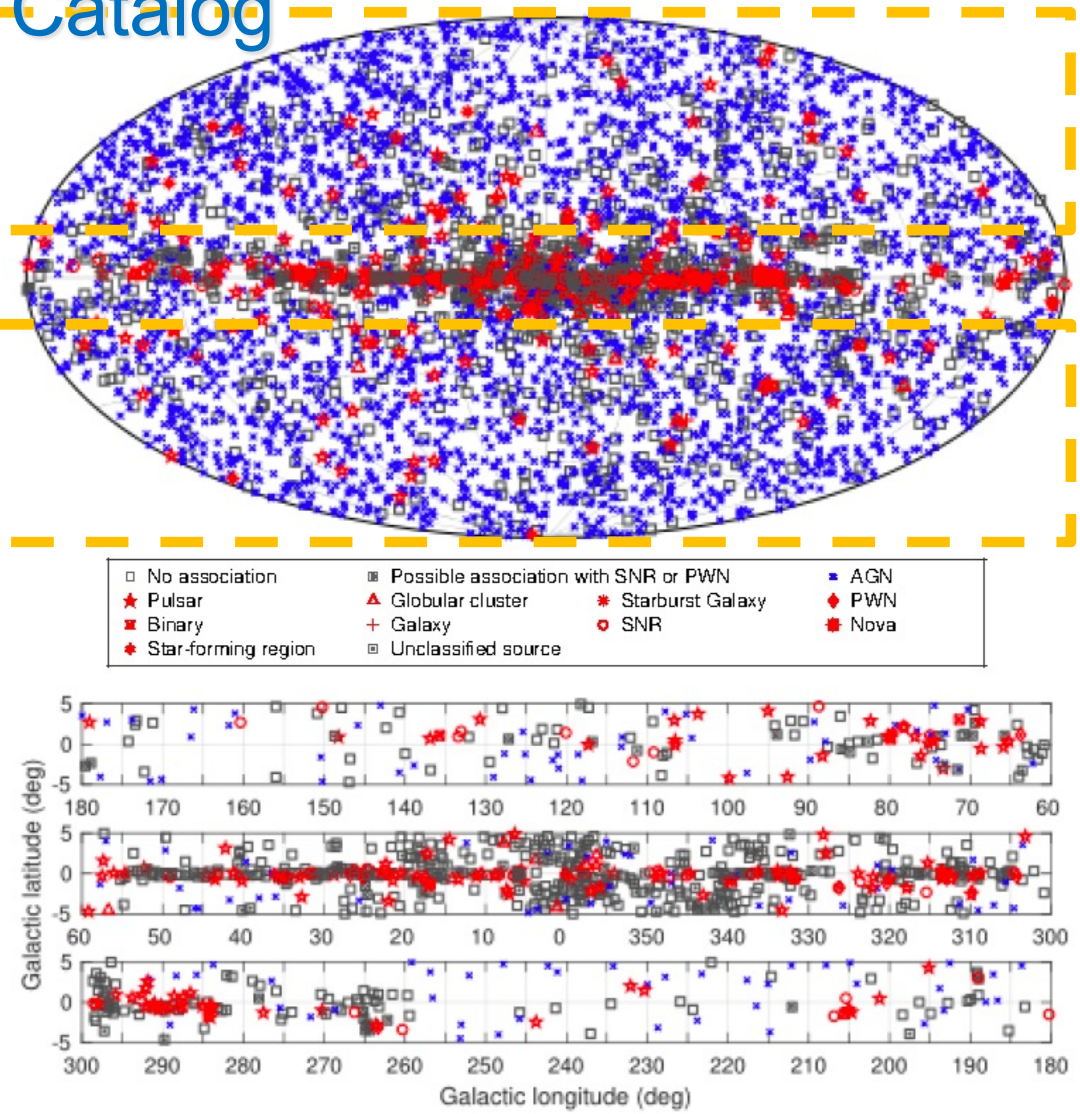
Type	Ejecta E_{kin}, erg	Frequency	Observed number (MW)
Supernova	10^{51}	~0.03/year Last 1604	294 (Green Catalogue)
Wolf-Rayet wind	10^{51} -over the lifetime		354
O star wind	10^{50} (0.01 $L_{☆}$)-over 5 Myr winds (2-4)x10^{3} km/s		20,000
Pulsar (Crab)	~4x10^{49} (total E_{rot})		~1500
Nova	10^{45}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

4th Fermi-LAT Catalog

- 8 years of observations
- 50 MeV – 1 TeV
- 5065 sources above 4σ
- 75 extended sources
- 354 identified
- >3130 identified or associated sources are active galaxies (blazars)
- SMC, LMC, and M 31
- 7 Starburst galaxies
- 239 – pulsars
- Other Galactic sources:
  - 40 SNRs
  - 17 PWNe
  - 30 Globular clusters
  - 6 High-mass binaries
  - 3 Star-Forming Regions
  - 2 Low-mass Binaries
  - η Carinae (binary)
  - 1 Nova V5668 Sagittarii, other novae not included
- 1337 sources do not have any counterparts at other wavelength

Red – are mostly Galactic srs but a few SF galaxies

High latitude Galactic sources (pulsars, globular clusters) are most likely local



Nova distribution

A sample of Novae with reddening (distance) estimates

Some of them within ~1 kpc distance from the Sun

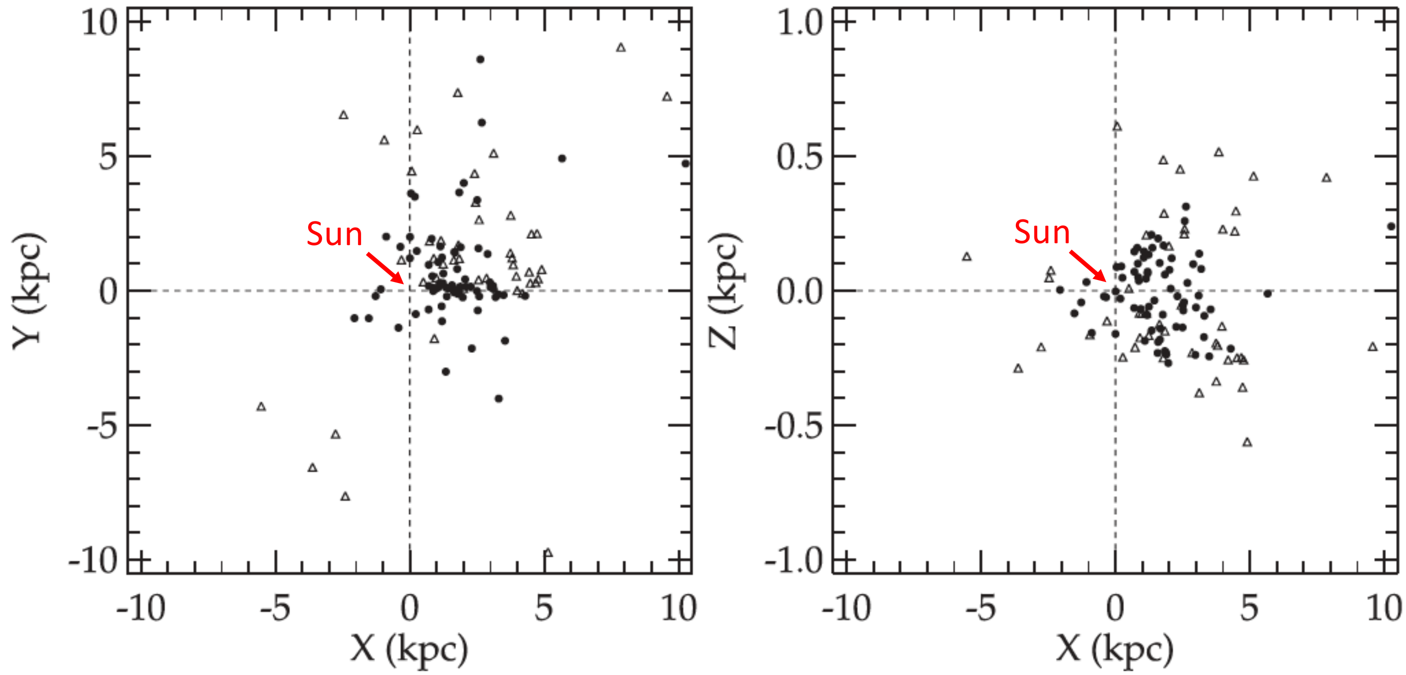
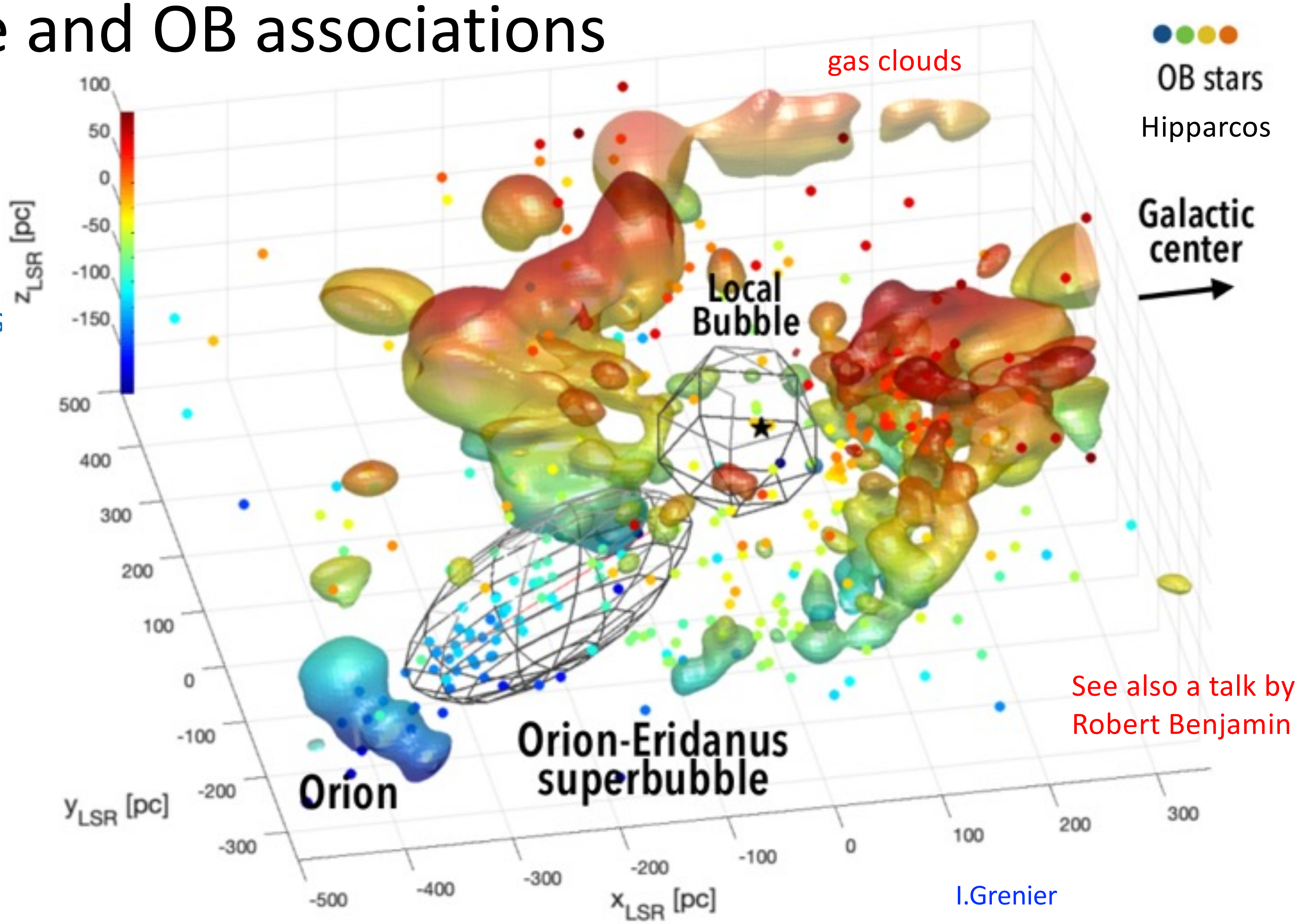


Figure 8. The heliocentric rectangular Galactic distances. (●) for which the distances are obtained, (△) only lower limits calculated.

Ozdonmez+ 2016

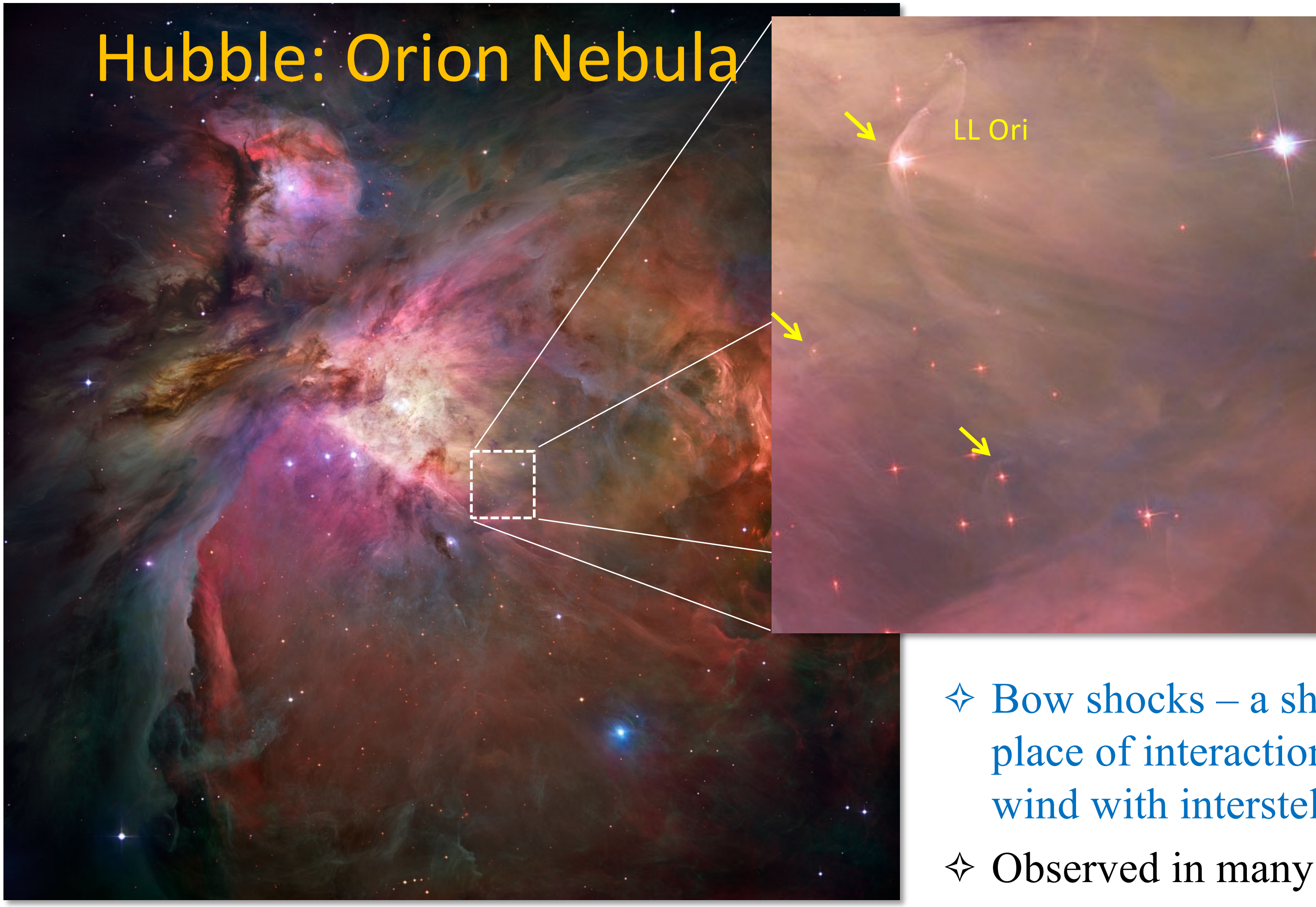
Local Bubble and OB associations

- 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



See also a talk by Robert Benjamin

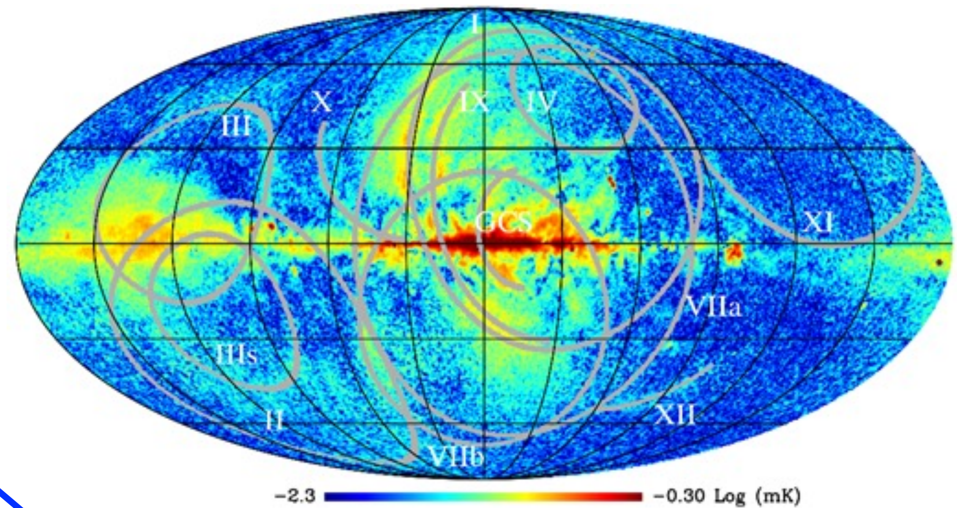
I.Grenier



- Bow shocks – a shock at the place of interaction of the stellar wind with interstellar gas
- Observed in many systems

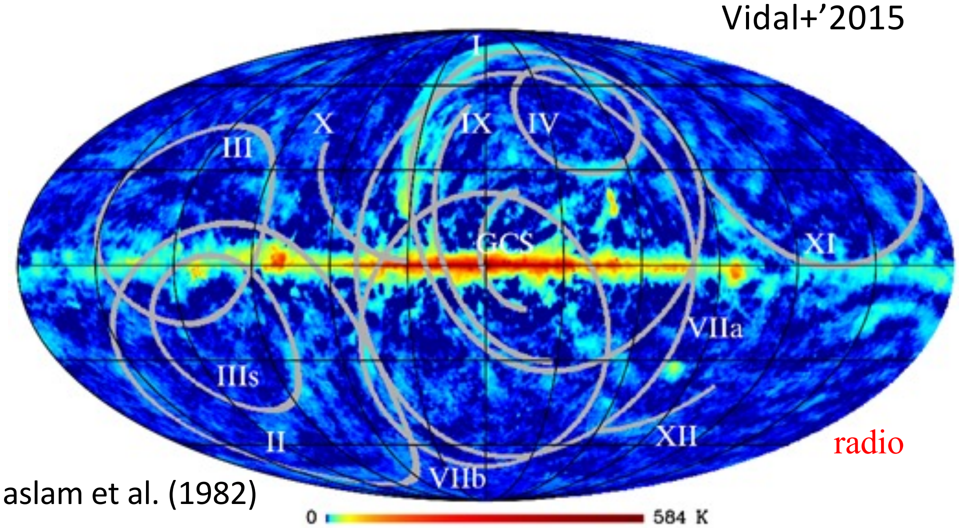
Galactic Loops

- 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

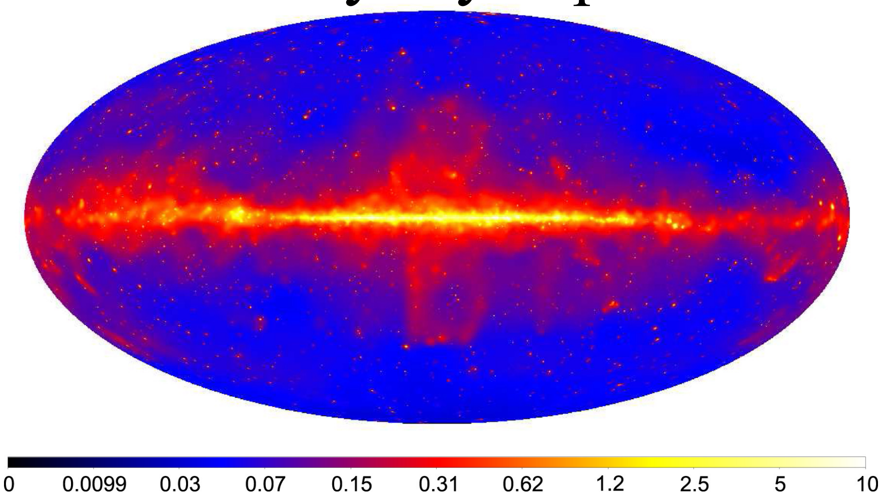
Vidal+’2015

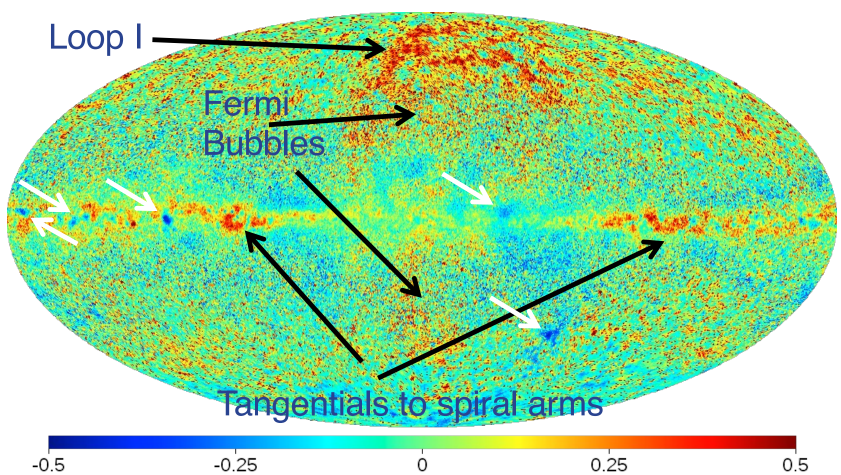


radio

Haslam et al. (1982)

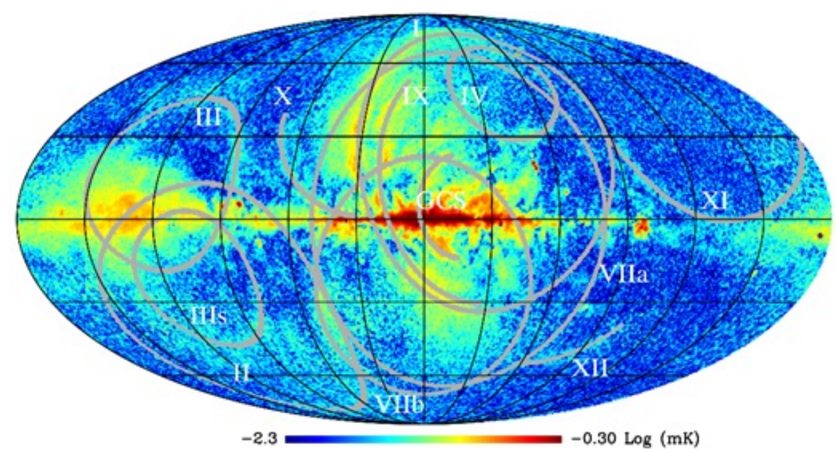
Gamma-ray skymap residuals





✧ Fermi-LAT skymap >1 GeV

- ✧ Details of the Galactic structure are clearly seen in residual maps
  - ✦ Spiral arms
  - ✦ Fermi Bubbles
  - ✦ Excesses & Deficits
  - ✦ Loops & Spurs



✧ WMAP *K*-band polarization intensity map

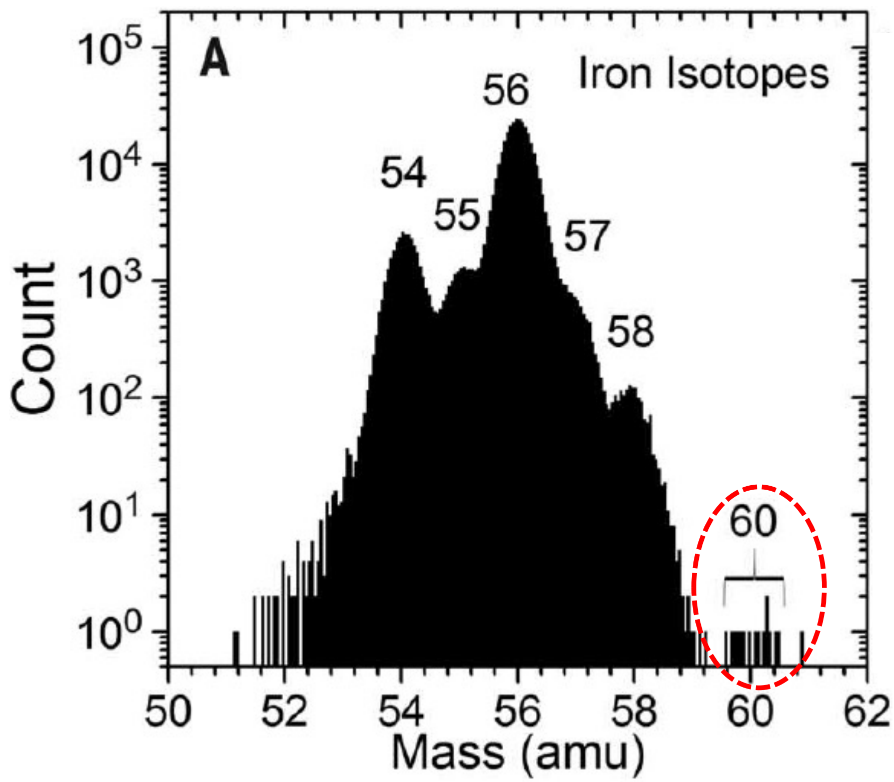
Signatures of recent SN activity

- ✧ ^{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)
- ✧ Lunar regolith samples (Cook+'2009; Fimiani+'2012, 2014)
- ✧ Antarctic snow (Koll+'2019).
- ✧ ACE-CRIS observations of ^{60}Fe (Binns+'2016)

Science 2016

Observation of the ^{60}Fe nucleosynthesis-clock isotope in galactic cosmic rays

W. R. Binns,[1*] M. H. Israel,[1*] E. R. Christian,[2] A. C. Cummings,[3] G. A. de Nolfo,[2] K. A. Lave,[1] R. A. Leske,[3] R. A. Mewaldt,[3] E. C. Stone,[3] T. T. von Rosenvinge,[2] M. E. Wiedenbeck[4]

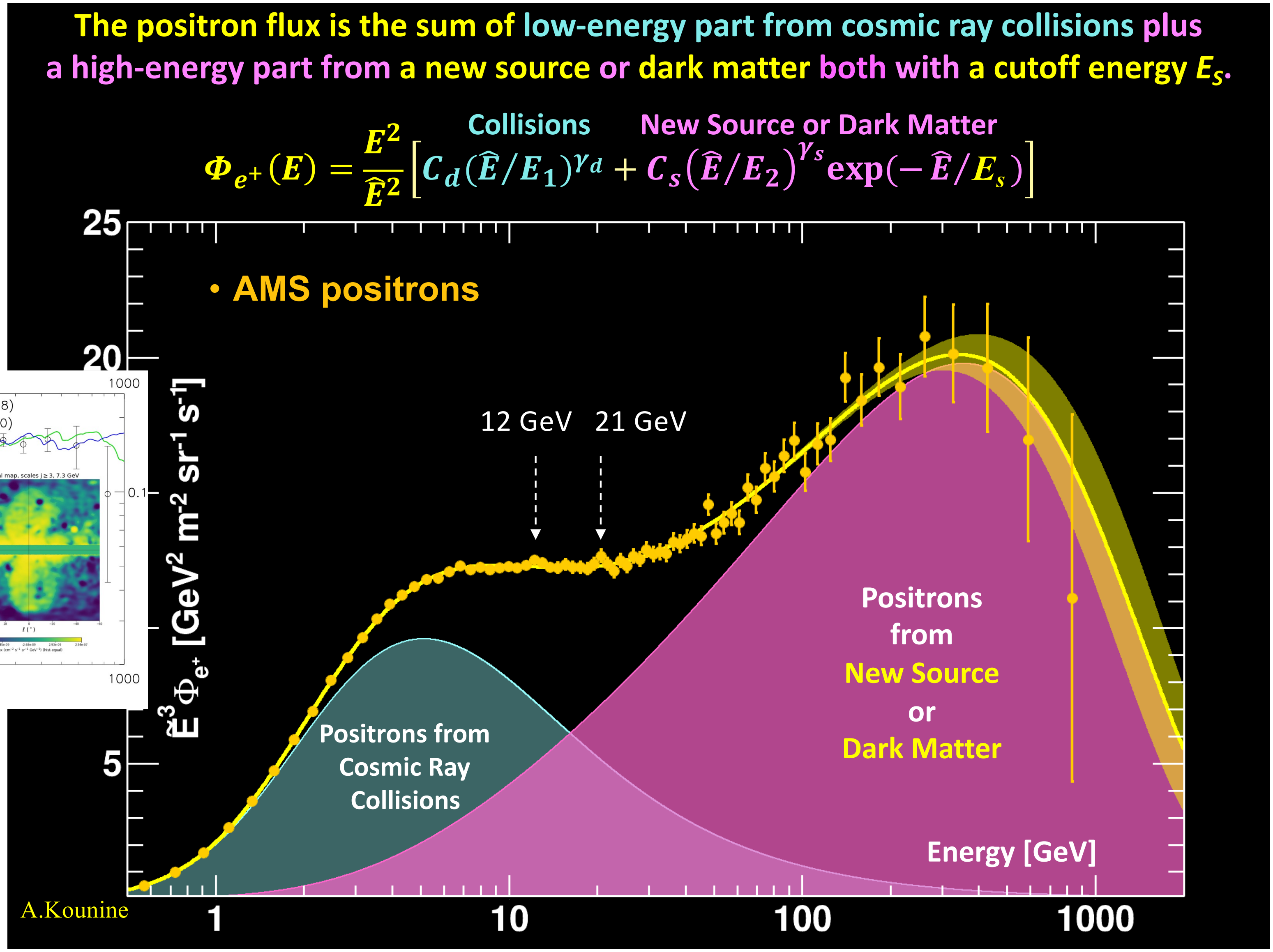


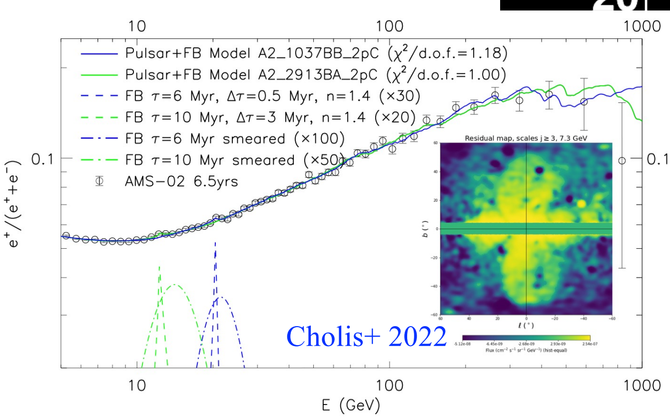
CR signatures of local sources

- Anomalous isotopic composition (low energies)
- Changes in the elemental composition vs rigidity
- Spectral bumps
- Spectral breaks
- All sorts of excesses (and deficits?)
- Unexpected spectral behavior of some species
- Anisotropy (high energies)

- Some (all ?) of them are difficult to identify because we do not have a reference system

Unexpected Positrons

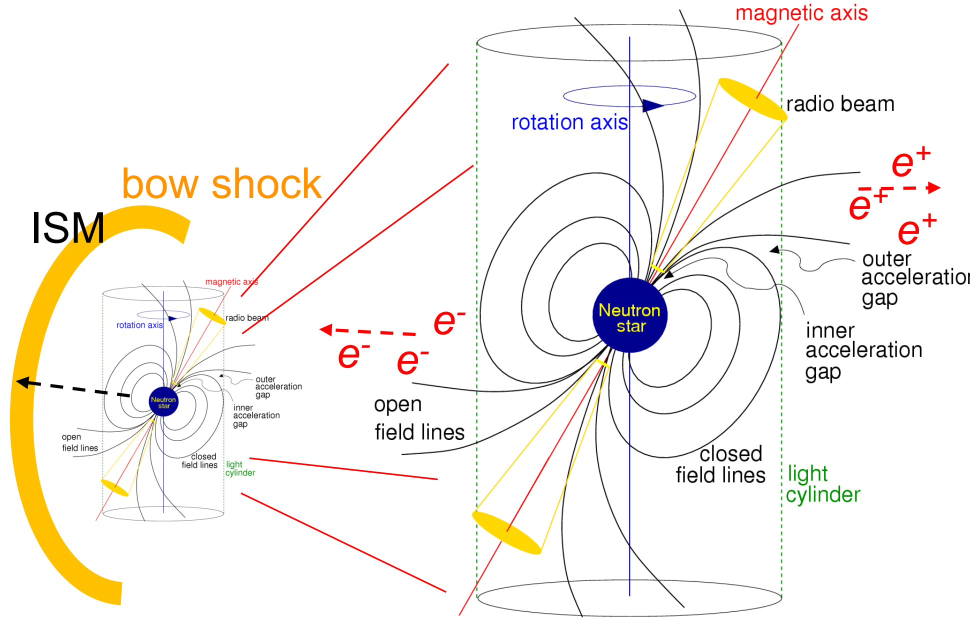




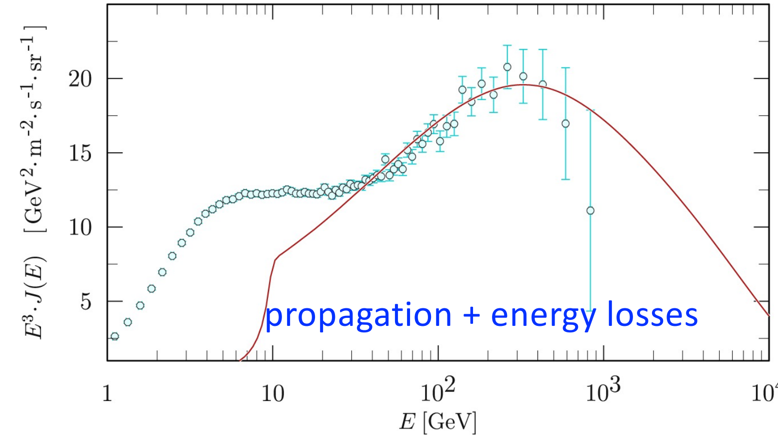
Pulsar bow shock model by A. Bykov et al. (2017)

- 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

See also Bykov+'2019, Petrov'+2020

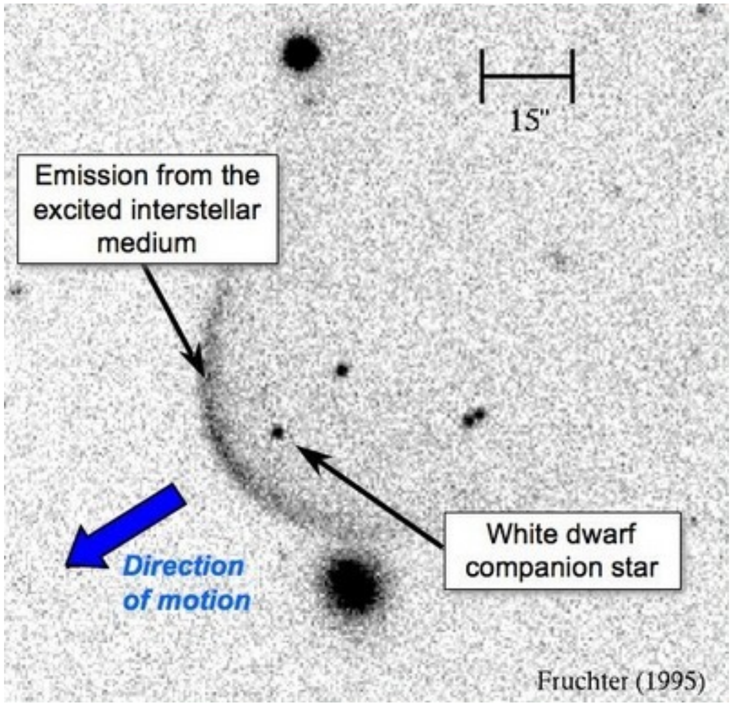


positrons from a millisecond pulsar PSR J0437-4715



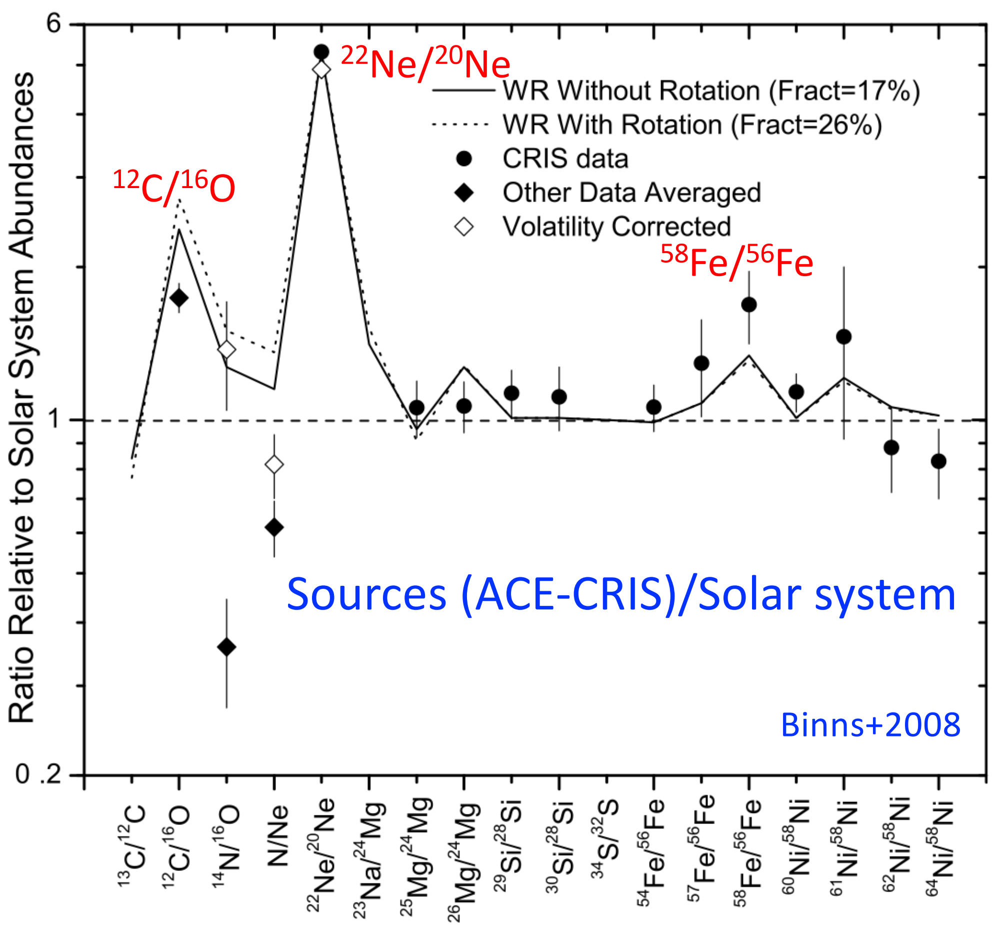
The 5.7 millisecond pulsar PSR J0437-4715

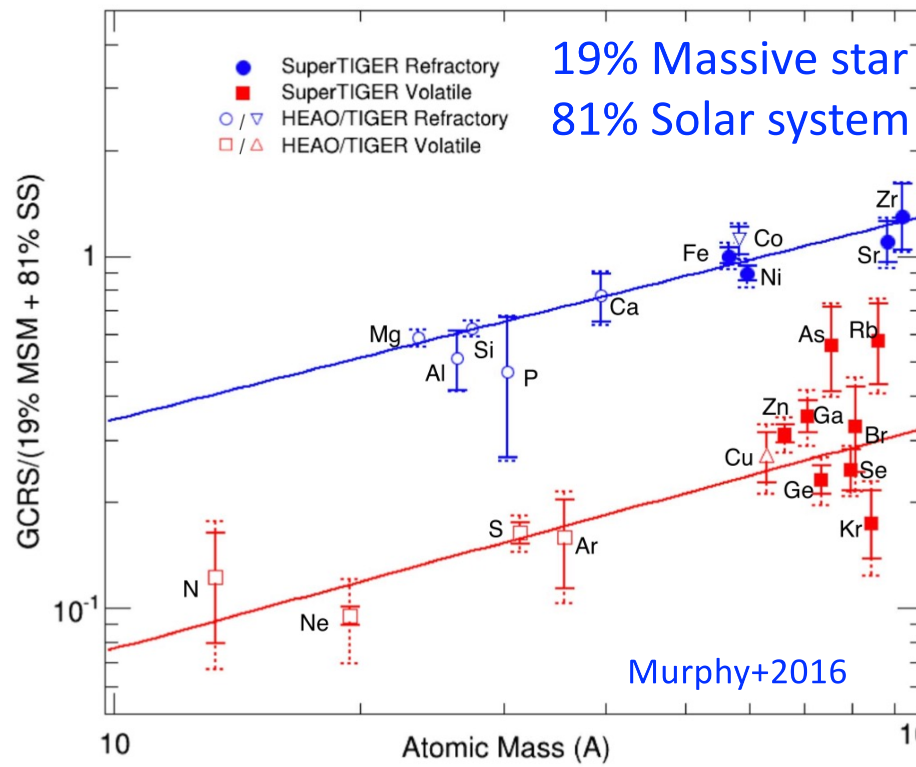
- ◇ Distance: 156.79±0.25 pc
- ◇ Closest and brightest millisecond pulsar (MSP), in a binary system with a white dwarf companion and an orbital period of 5.7 days
- ◇ Velocity ~100 km/s
- ◇ Observed in optical, far-ultraviolet (FUV), and X-ray bands
- ◇ It exhibits the greatest long-term rotational stability 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

Anomalies in the source isotopic composition





- Overabundance of certain isotopes and source abundances of refractory and volatiles hints at ~20% contribution of massive star material

Excesses in low-energy cosmic rays

Precise spectra of CR species by AMS-02 reveal excesses when compared to ACE-CRIS and Voyager 1 measurements

Boschini+’2019, 2020, 2021, 2022

(GalProp + HelMod framework)

So far spectral features/excesses were found in the spectra of:

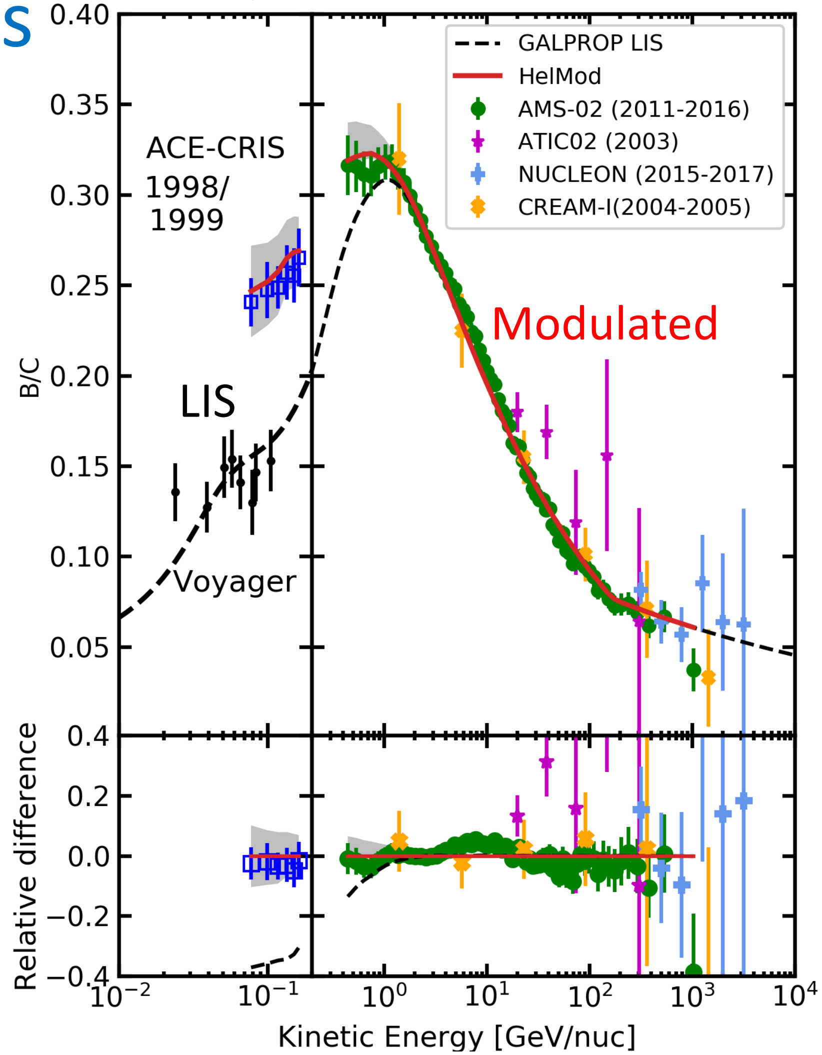
✧ Iron (primary)

✧ Aluminum (50-50 sec.-prim.)

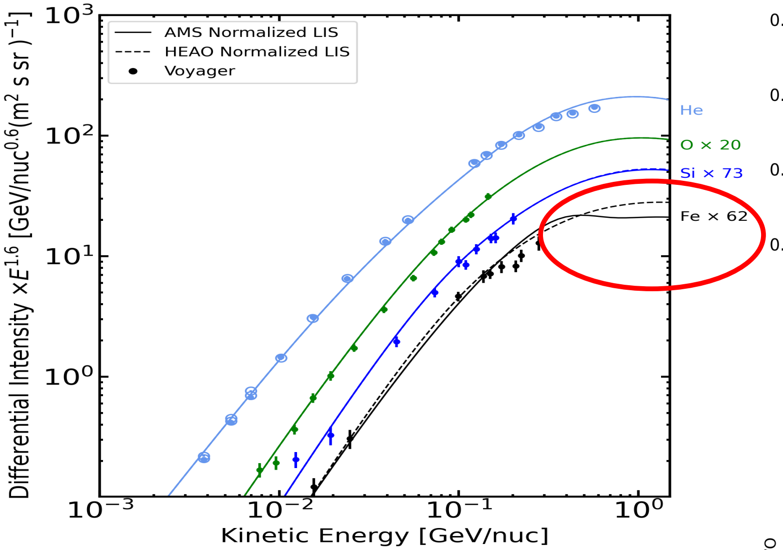
✧ Lithium (secondary)

✧ Fluorine (secondary)

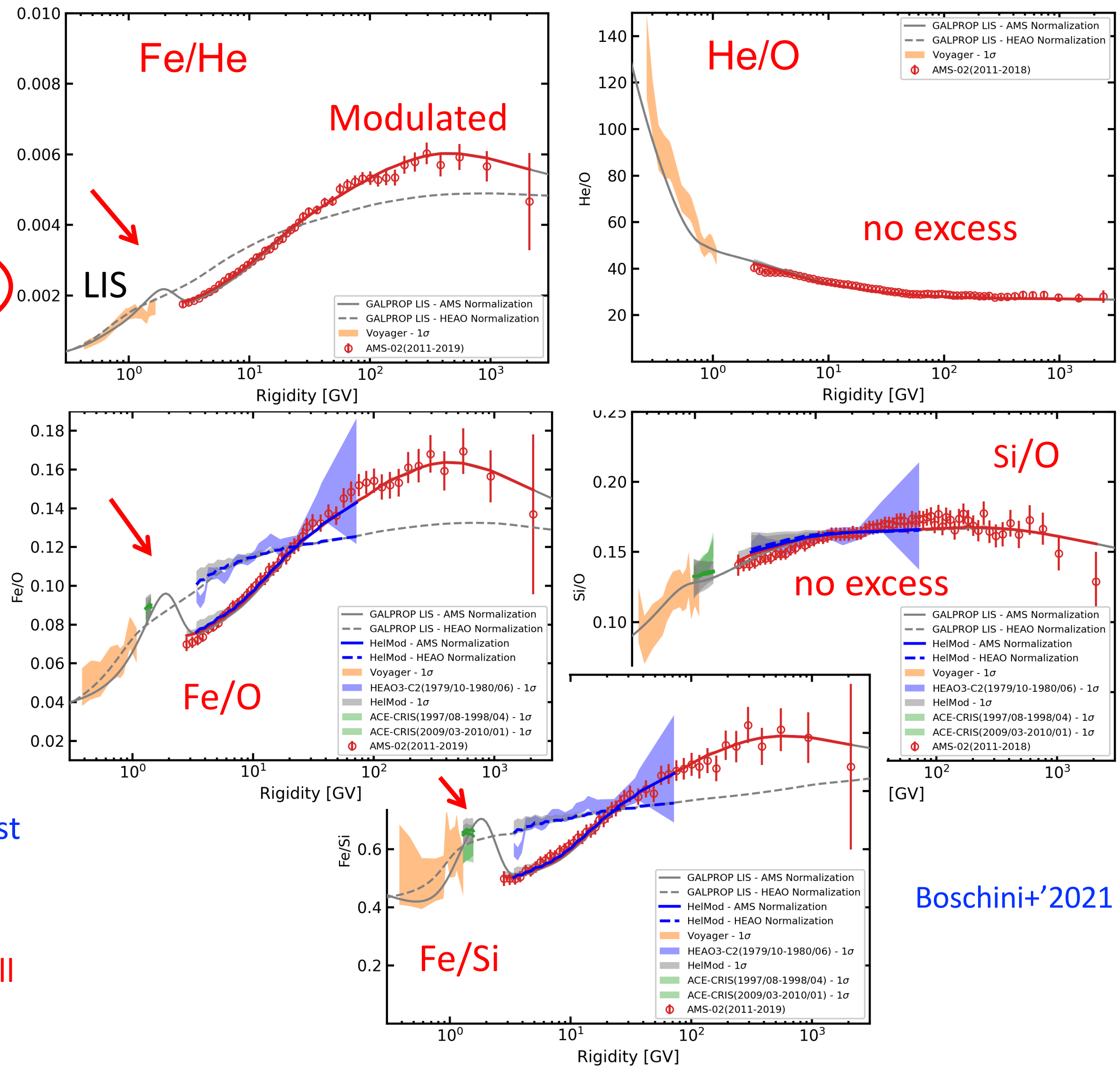
B/C tuned to the data



Iron excess/deficit



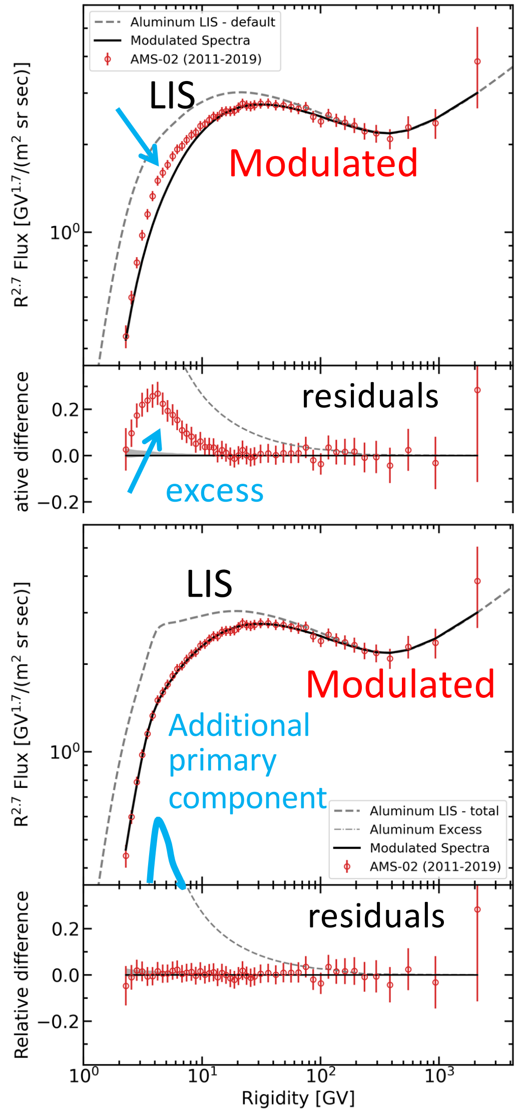
- ✧ Most visible in Fe/He, Fe/O, Fe/Si ratios (arrows)
- ✧ Such features are absent in He/O and Si/O ratios
- ✧ The excess in iron – follows from consistency between Voyager 1, ACE-CRIS, and AMS-02 data
- ✧ The likely source of the excess CR iron are the past consequent explosions of SNe – falls in line with other evidences
- ✧ Important that these accelerated particles are still present in CRs!

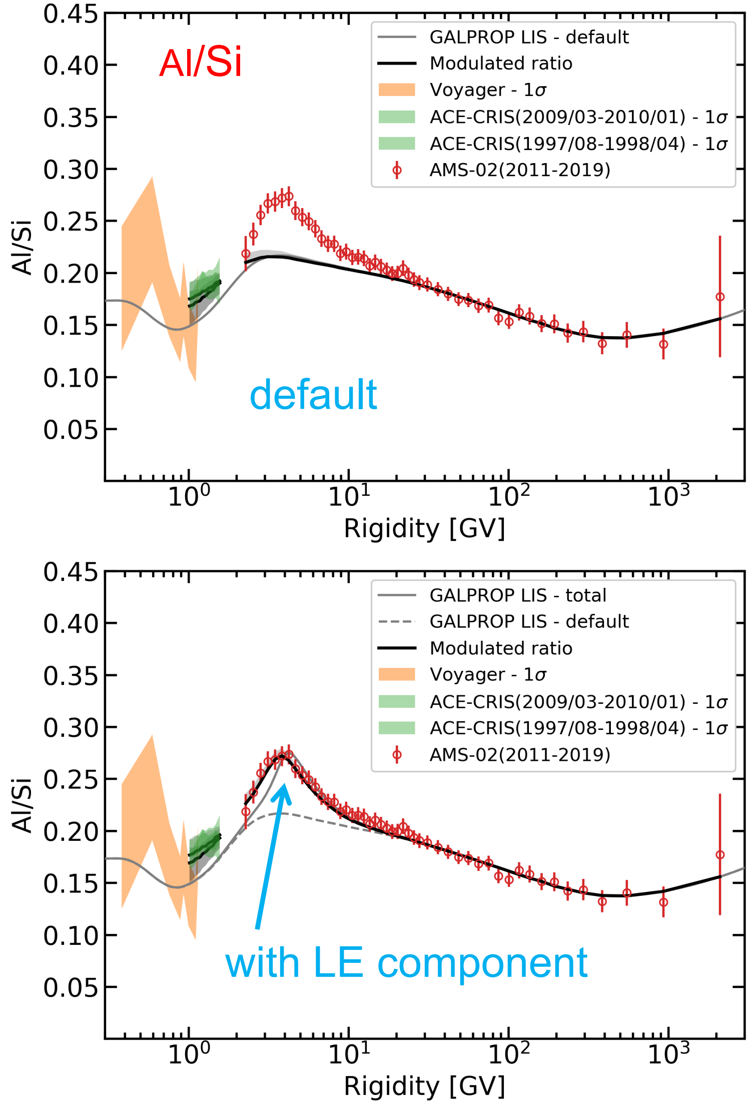


Boschini+'2021

Aluminum excess

- ✧ The sources of cosmic Al are numerous, and are simultaneously also the sources of other rare isotopes, such as ^{19}F
- ✧ Possible contribution of massive stars proposed to explain the observed anomalous ^{22}Ne/^{20}Ne ratio and other observed ratios, ^{12}C/^{16}O, and ^{58}Fe/^{56}Fe, in CRs (Binns+'2008)

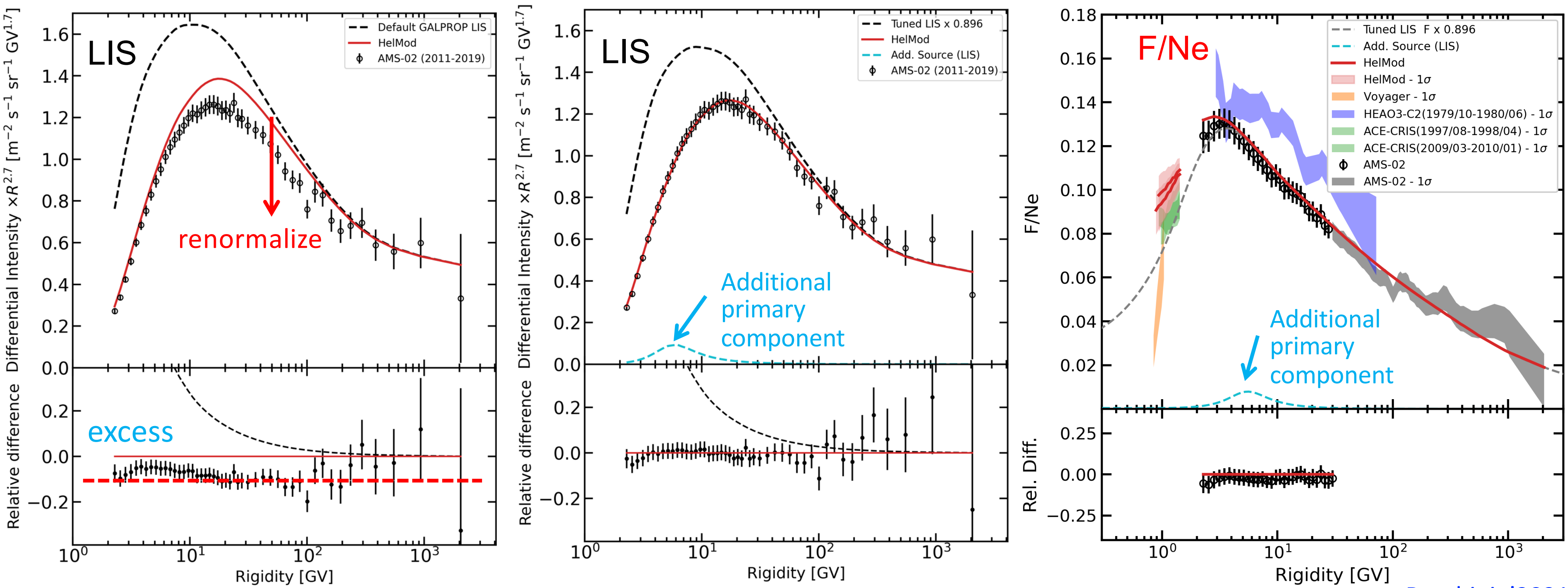




Boschini+'2022

Fluorine excess

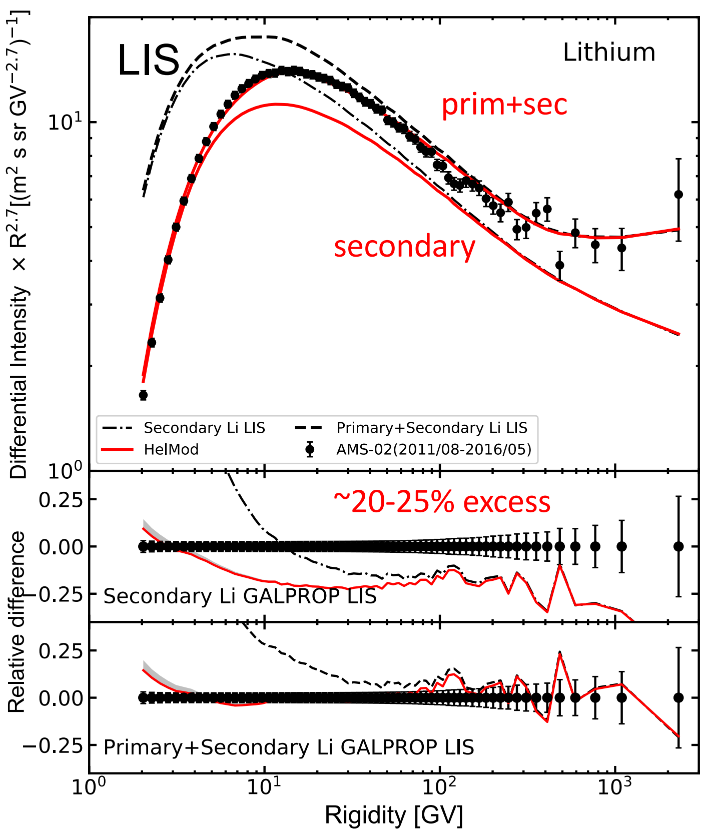
1. Deficit of secondary F, most likely a production cross section issue
2. After renormalization, we see a low-energy excess



Boschini+'2021

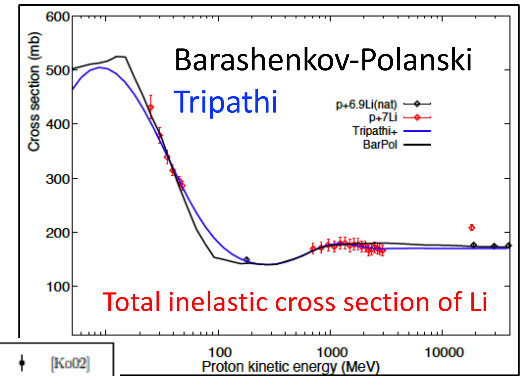
- ✧ The ISM abundance of fluorine is anomalously low – it is easily destroyed in stars through p- or α-captures
- ✧ The origin of cosmic fluorine is still not well constrained
- ✧ Source of fluorine: SN type II, WR stars, and the asymptotic giant branch (AGB) of intermediate-mass stars

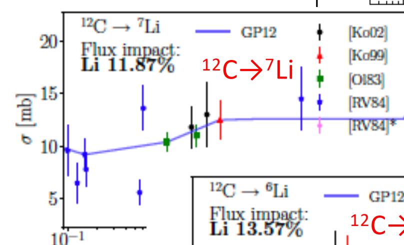
Primary Lithium



Boschini+'2020

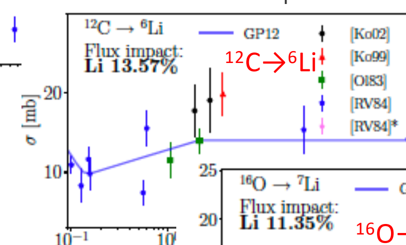
- ✧ Classical novae – new type of ^{7}Li source
- ✧ Blue-shifted absorption lines of partly ionized ^{7}Be (->^{7}Li) (half-life 53.22 days) in the spectrum of a classical nova V339 Del ~40–50 days after the explosion (Tajitsu et al. 2015)
- ✧ ^{7}Be lines also observed from other novae, V1369 Cen, V5668 Sgr, V2944 Oph, ASASSN-16kt [V407 Lupi], V838 Her
- ✧ The total mass of ^{7}Li per novae: ~10^{-9}–$6\times10^{-9} M_{\odot}$

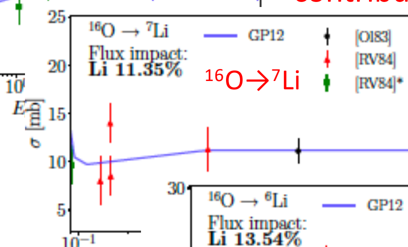




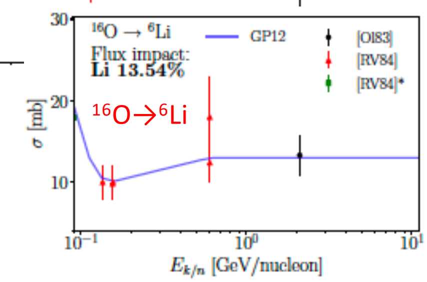
✧Main cross sections, contributing at 10% level each

✧Many others contributing ≤1%



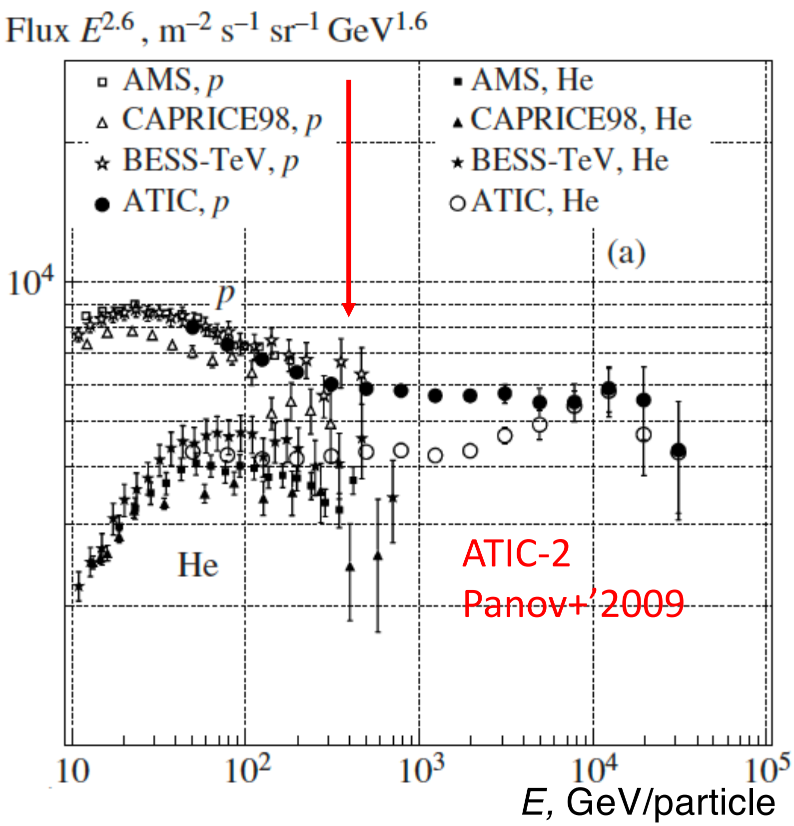


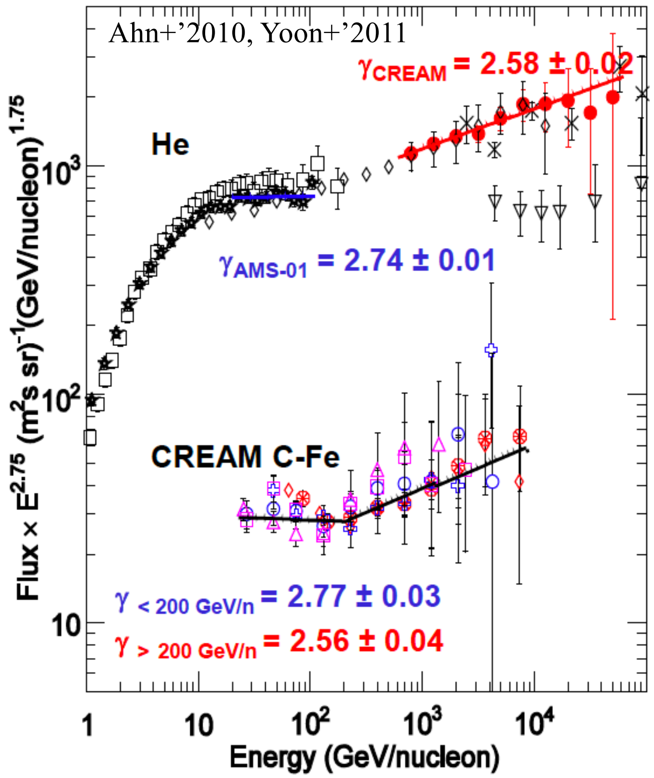
✧Cross section hypothesis requires all cross sections to be biased on the same side



High-energy break in the spectra of CR nucleons

- ATIC-2 (Panov+'2009) & CREAM *"Discrepant hardening observed in cosmic-ray elemental spectra"* (Ahn+'2010)
- Initially looked like an energy calibration issue…





Interpretation of the break at ~300-400 GV

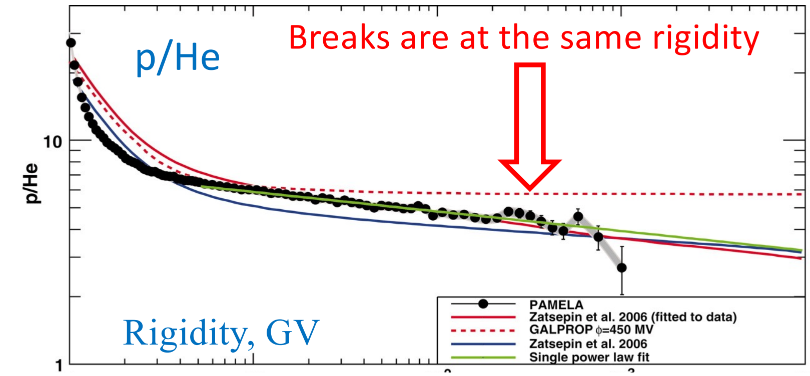
Based on PAMELA data Vladimirov+'2012 considered 6 scenarios of the break:

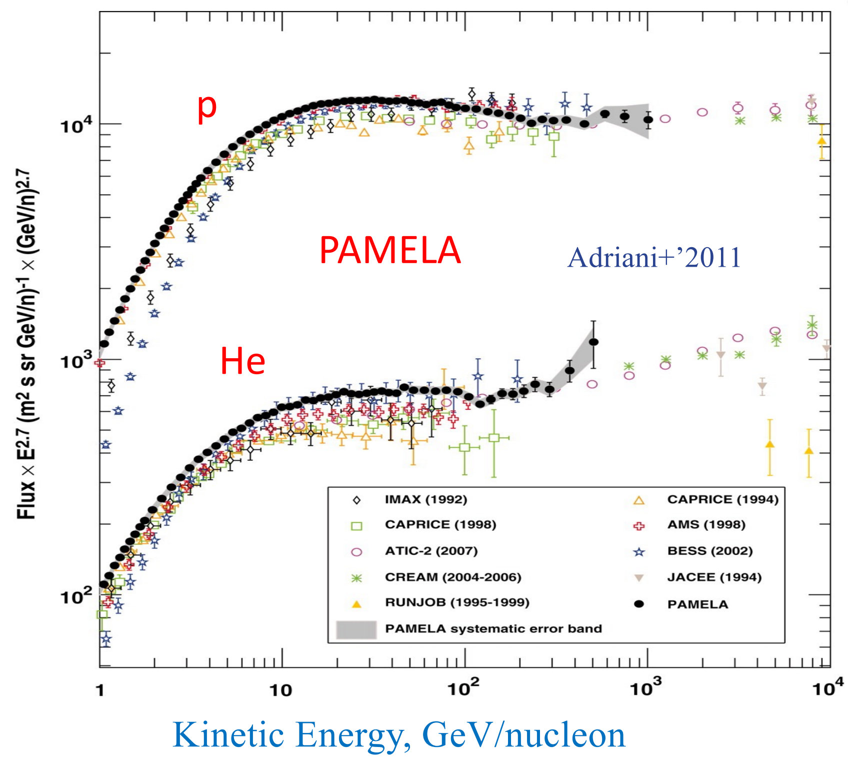
✧Injection scenario: associated with injection

- ✧prediction for secondaries – change in the spectral index below/above the break $\Delta\gamma_{\mathrm{sec}} \sim \Delta\gamma_{\mathrm{prim}}$

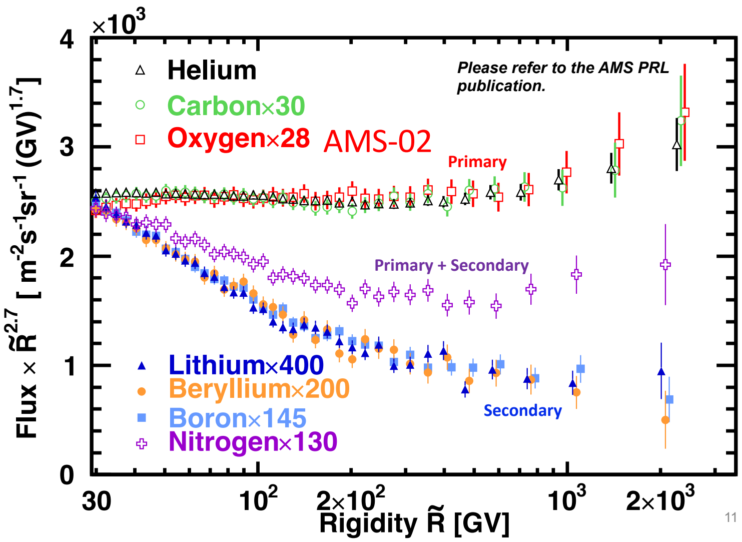
✧Propagation scenario: result of the diffusion (preferred)

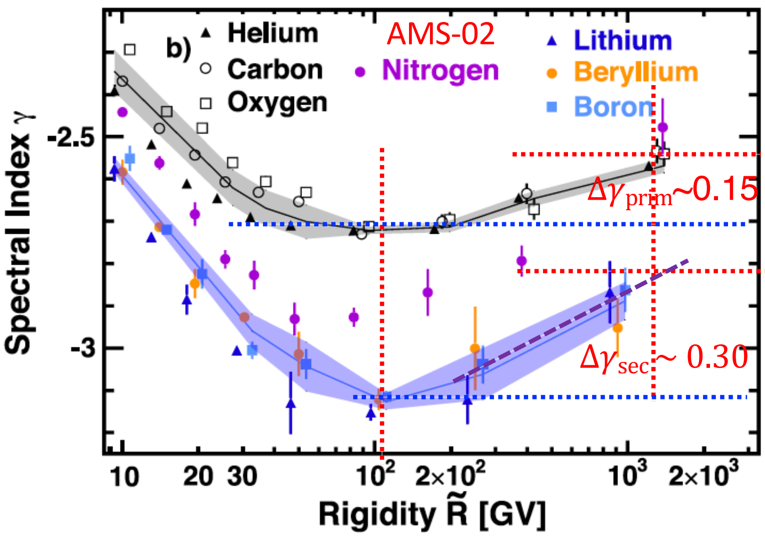
- ✧The ratio p/He shows no break
- ✧Prediction for secondaries – change in the spectral index below/above the break $\Delta\gamma_{\mathrm{sec}} \sim 2\Delta\gamma_{\mathrm{prim}}$
- ✧Index of the diffusion coeff.: $\delta \sim \gamma_{\mathrm{sec}} - \gamma_{\mathrm{prim}}$

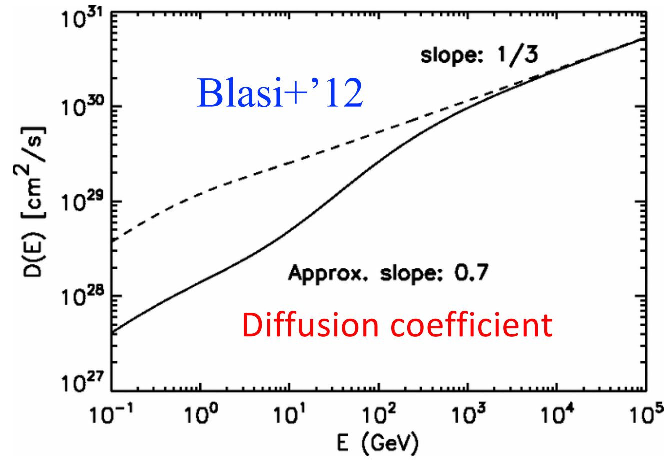


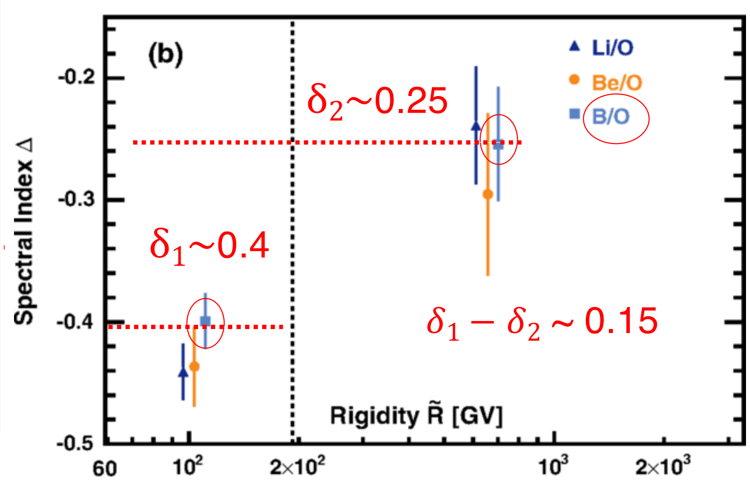


Effect of interstellar propagation









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

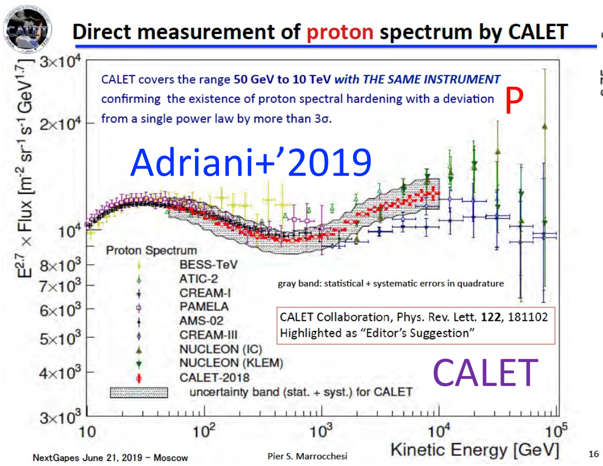
$$\Delta\gamma_{sec} \sim 2\Delta\gamma_{prim}$$

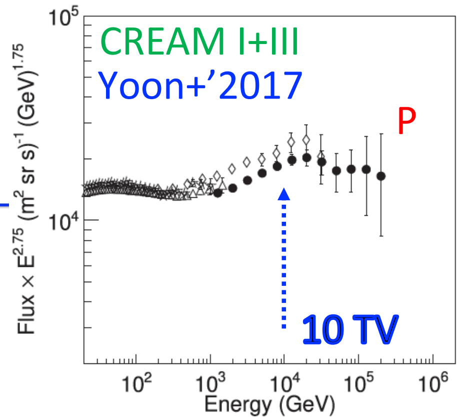
– if the break is due to the break in the spectrum of interstellar turbulence;

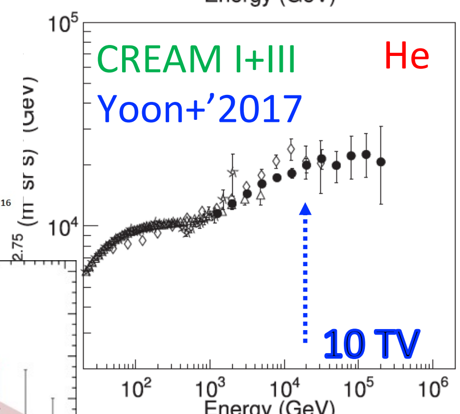
Index of the diffusion coefficient:

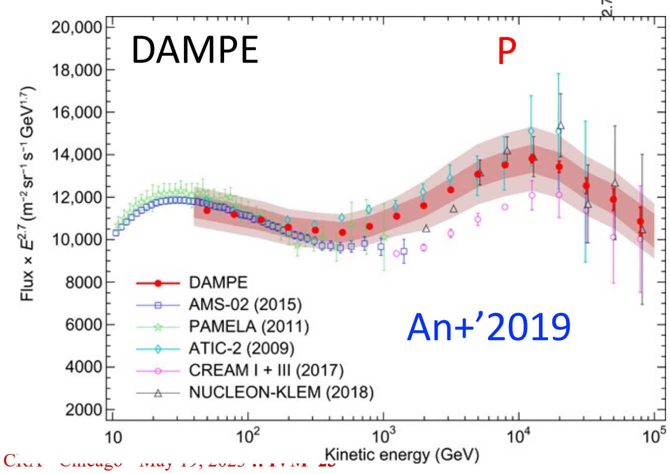
$$\delta = |\gamma_{sec} - \gamma_{prim}|$$

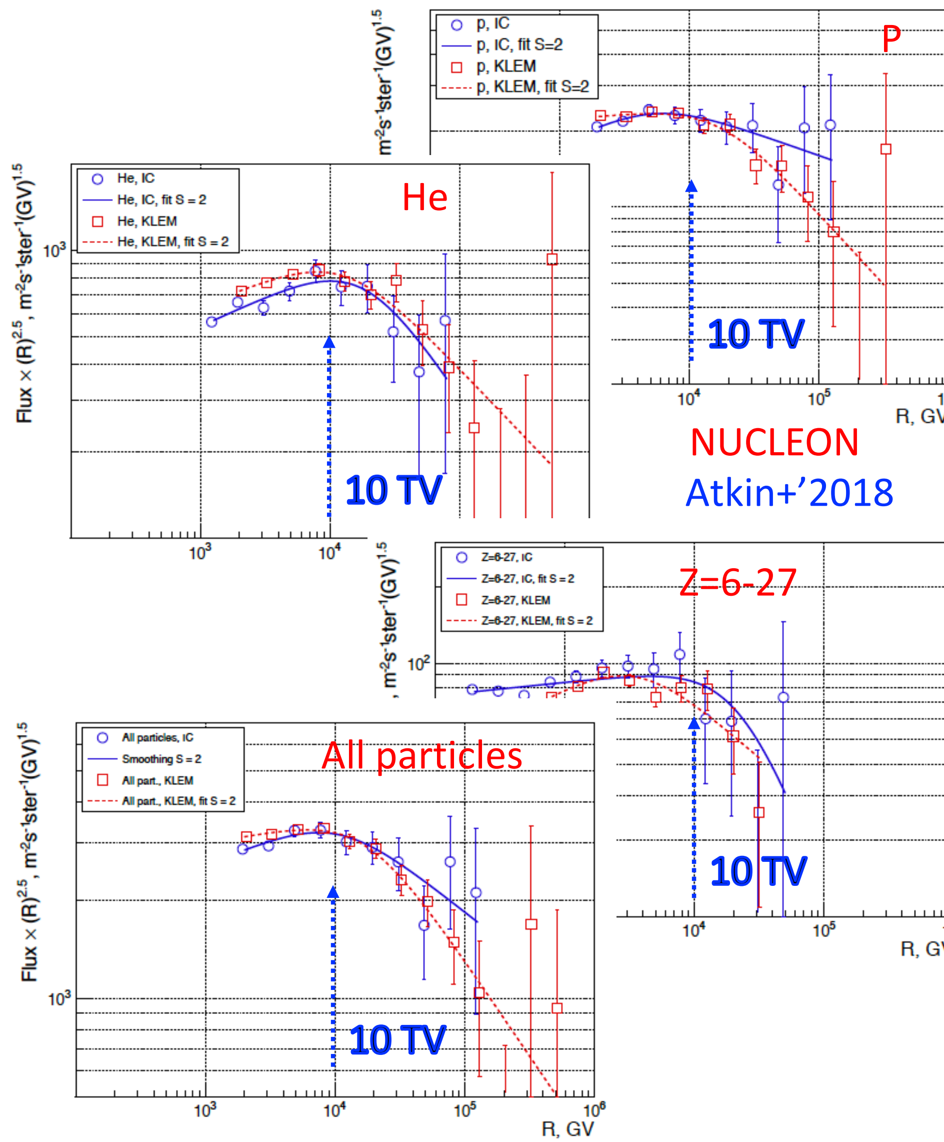
Yet another break at 10 TV?



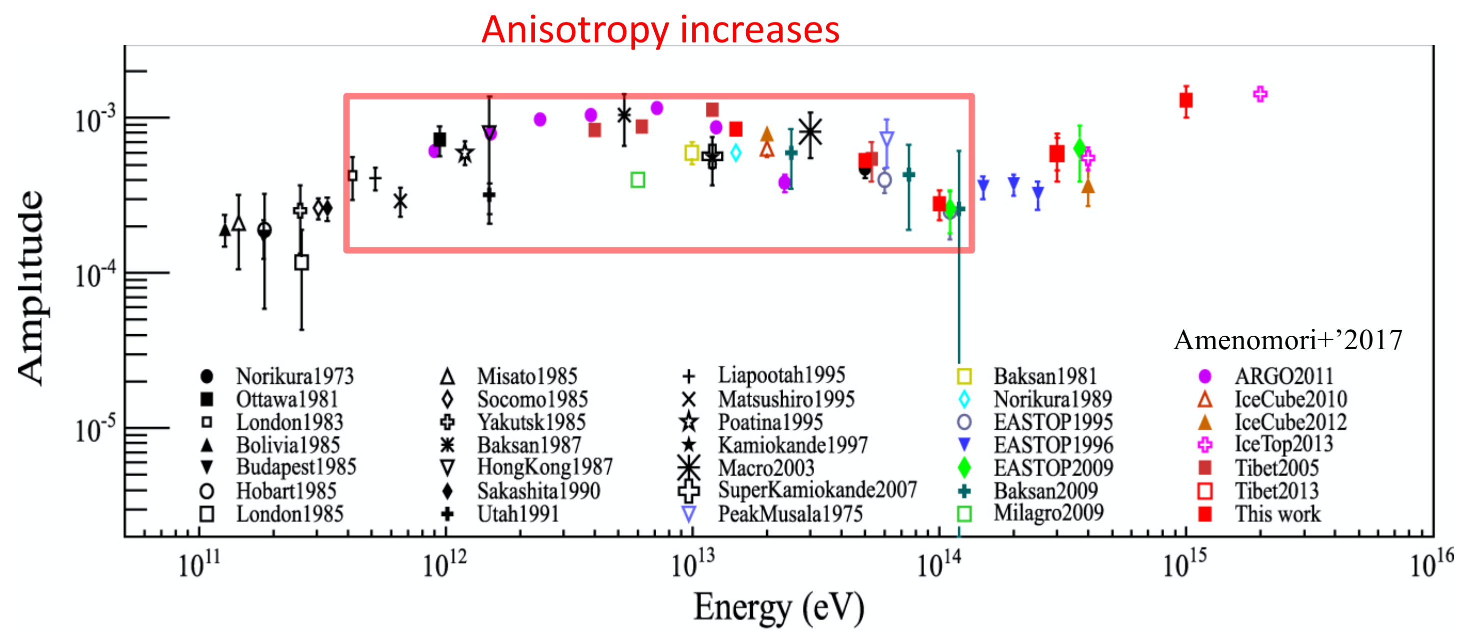








CR Anisotropy

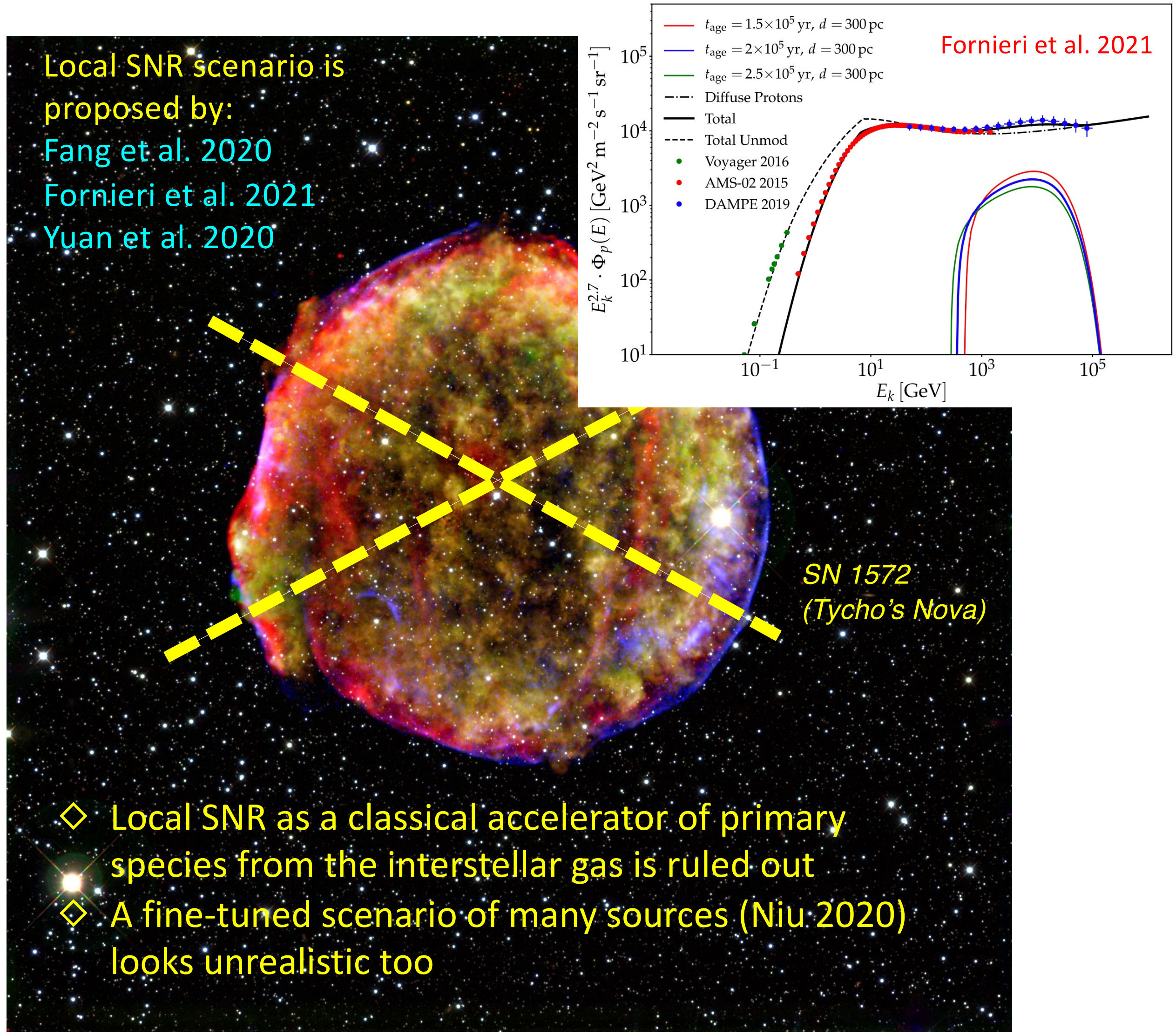


✧ CR anisotropy has an enhancement in exactly the range of the bump

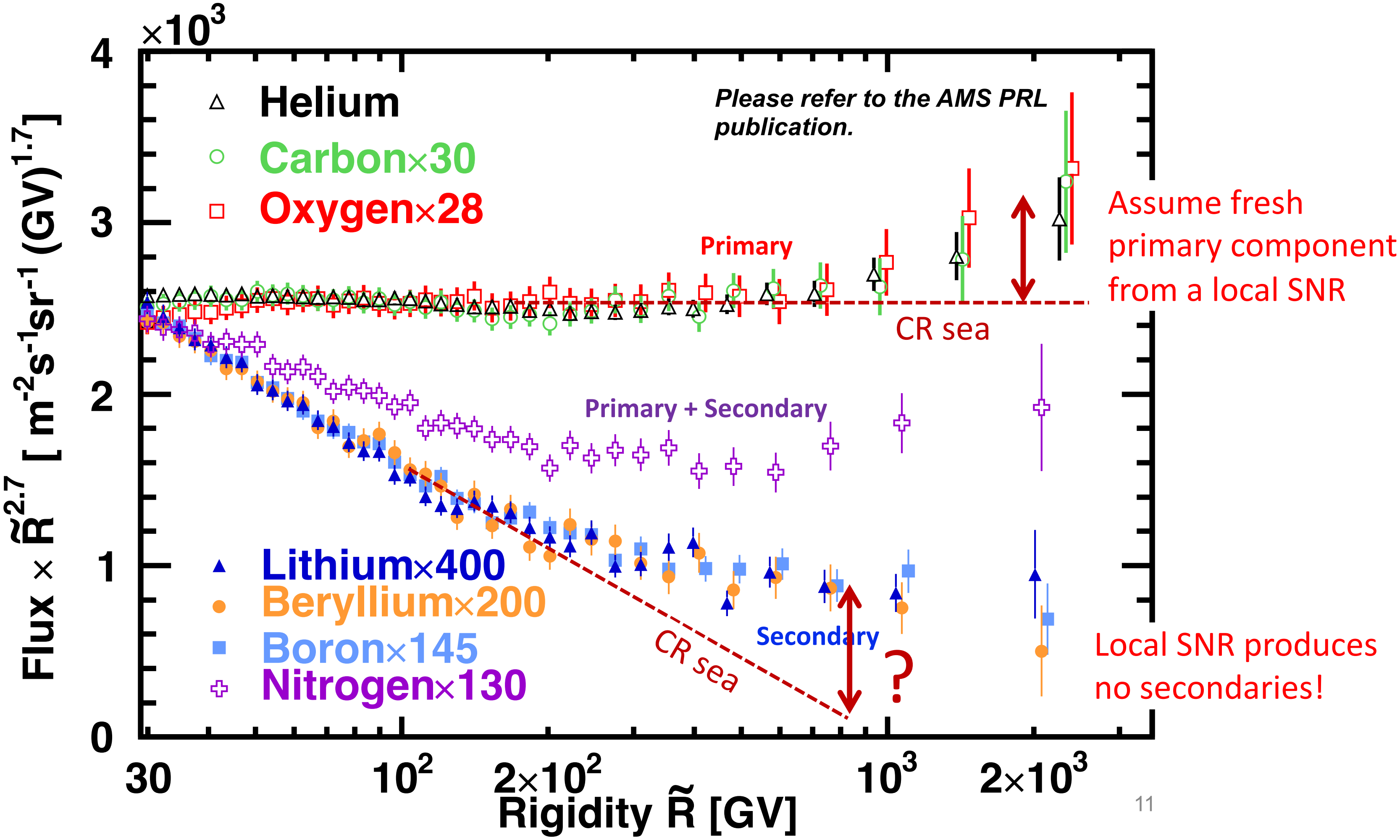
✧ Indicates the local origin of the bump

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!
- ✧ => CR particle reacceleration in a weak local shock

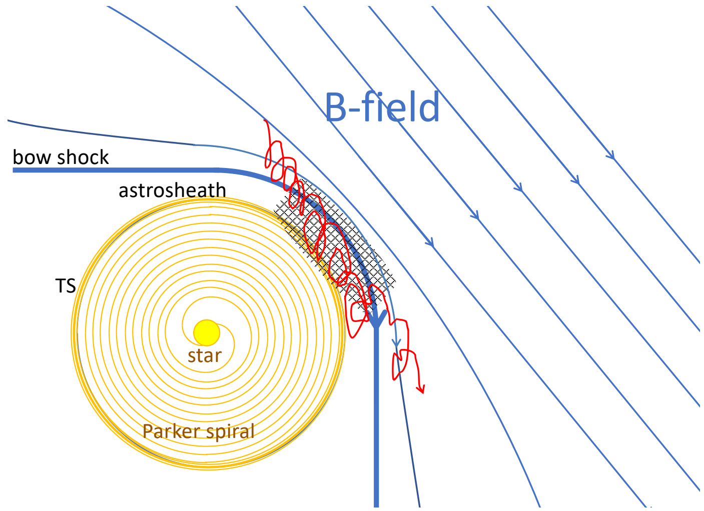


Local SNR scenario vs reacceleration

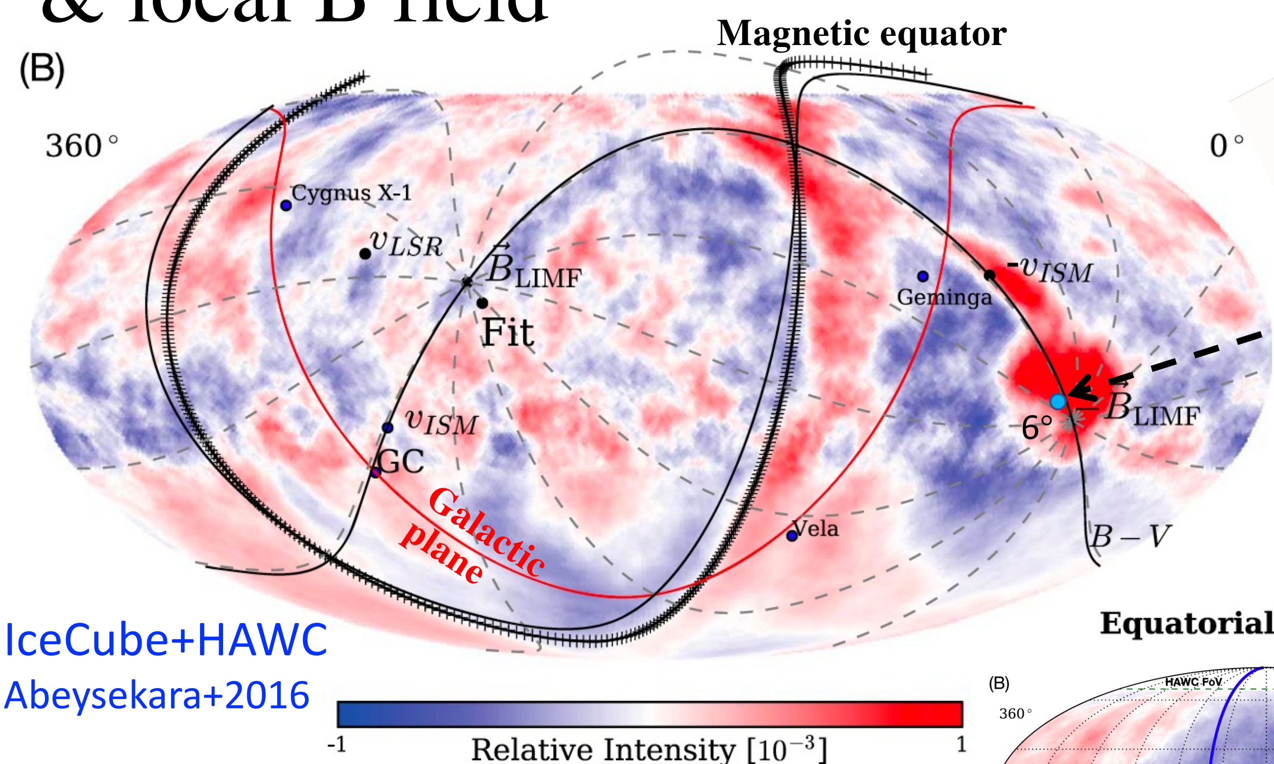


Epsilon Eridani and passing stars

- 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)
- ε Eri: K2 dwarf (5 000 K), 0.82 $M_\odot$, 0.74 $R_\odot$ (preferred)
- Distance – 3.2 pc
- Speed – 20 km/s (a bit small, but has a strong stellar wind)
- Well aligned with the direction of the local magnetic field – within 6.7°
- Huge astrosphere – 8000 au, 47' as seen from Earth (larger than the Moon!)
- Mass loss rate – 30 $\dot{M}_\odot$
- ε Indi: triplet K4.5V (0.77 $M_\odot$) + T1.5 (0.072 $M_\odot$) + T6 (0.067 $M_\odot$)
- Distance – 3.6 pc
- Speed – 40.4 km/s (radial)
- Scholz's Star: duplet M9.5 (0.095 $M_\odot$) + T5.5 (0.063 $M_\odot$)
- Distance – 6.8 pc
- Speed – 82.4 km/s (radial)
- Any local shock with a small Mach number



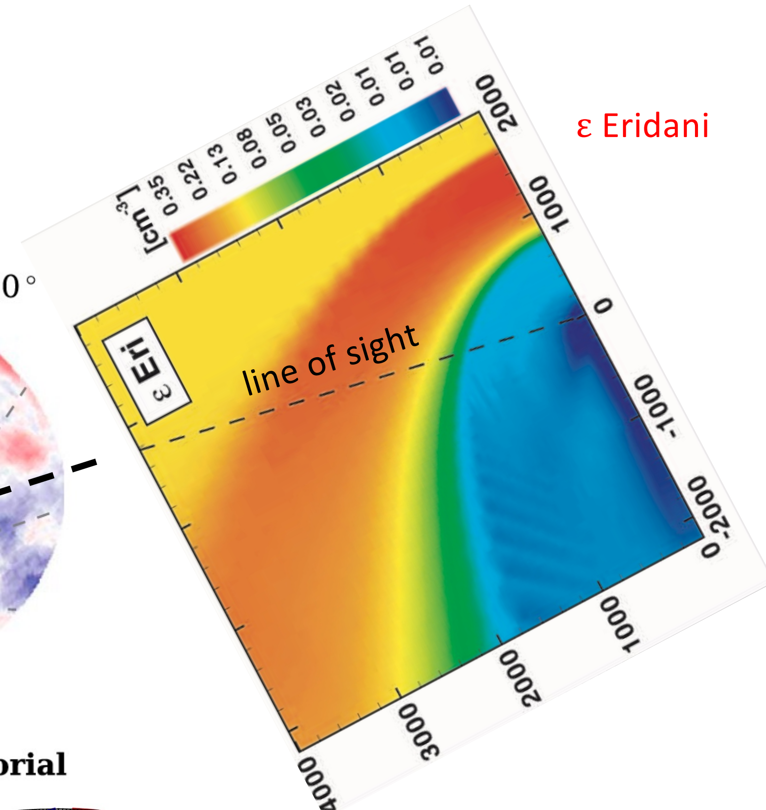
Small-scale anisotropy @ 10 TeV & local B field

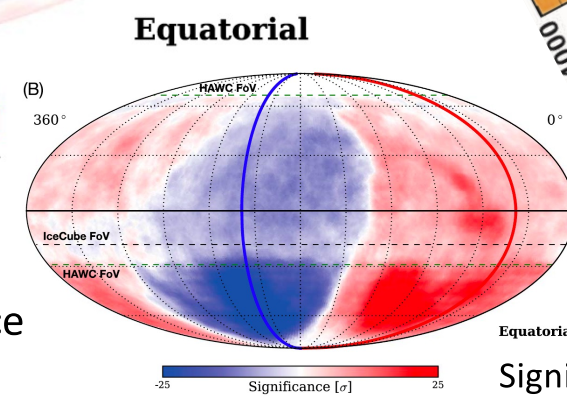


IceCube+HAWC

Abeysekara+2016

ε Eridani





Significance ± 25

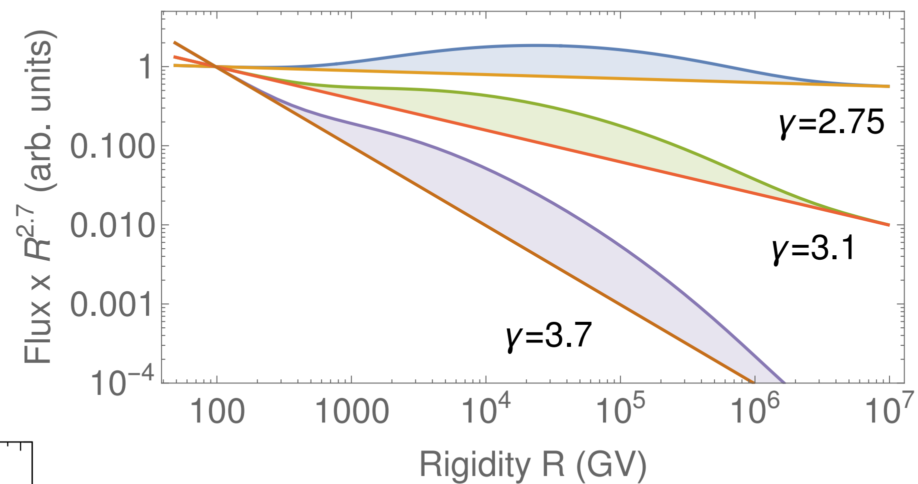
Very sharp jump in anisotropy across the magnetic equator – another hint at the proximity of the source

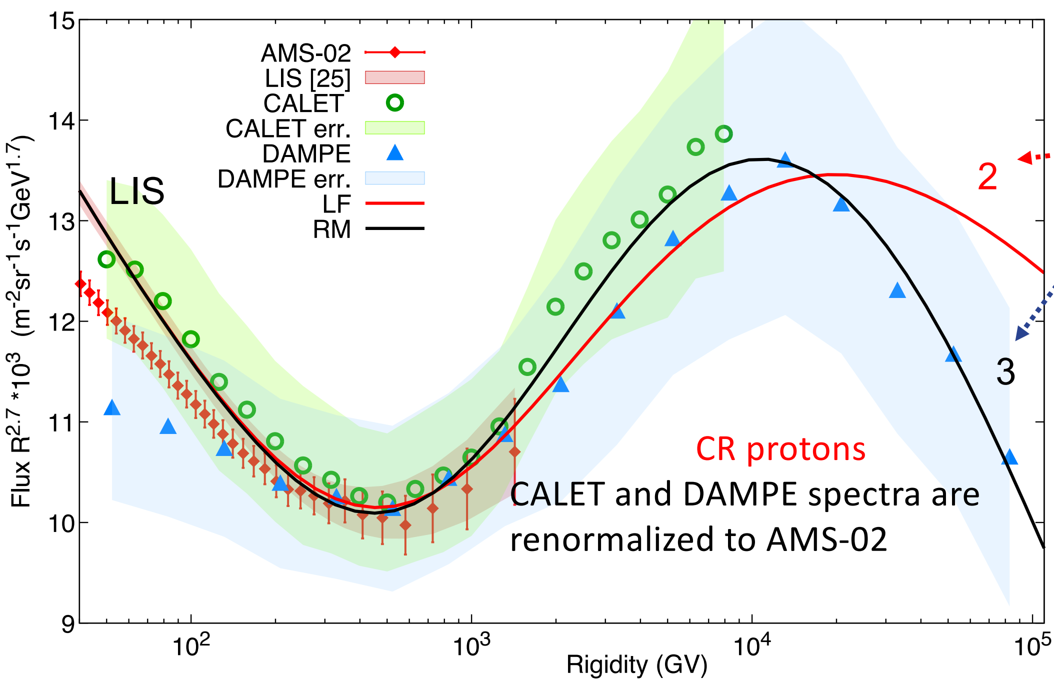
Bump formation

✧ Moderate reacceleration by ×1.5-2

✧ Low-energy particles do not reach the observer as they are convected downstream by the ISM flow

✧ High-energy particle loss from the flux tube





✧ Only 2 (3) free parameters – fixed from CR proton spectrum

✧ Use local interstellar spectrum (LIS) below the bump

✧ The steeper the spectrum of ambient particles – that larger the bump

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Parameters

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

Parameter (St. err. %)	R_0(GV)	R_L(GV)	q	$K=(\gamma+2)/(q-\gamma)$	$\chi^2_{\min}$/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

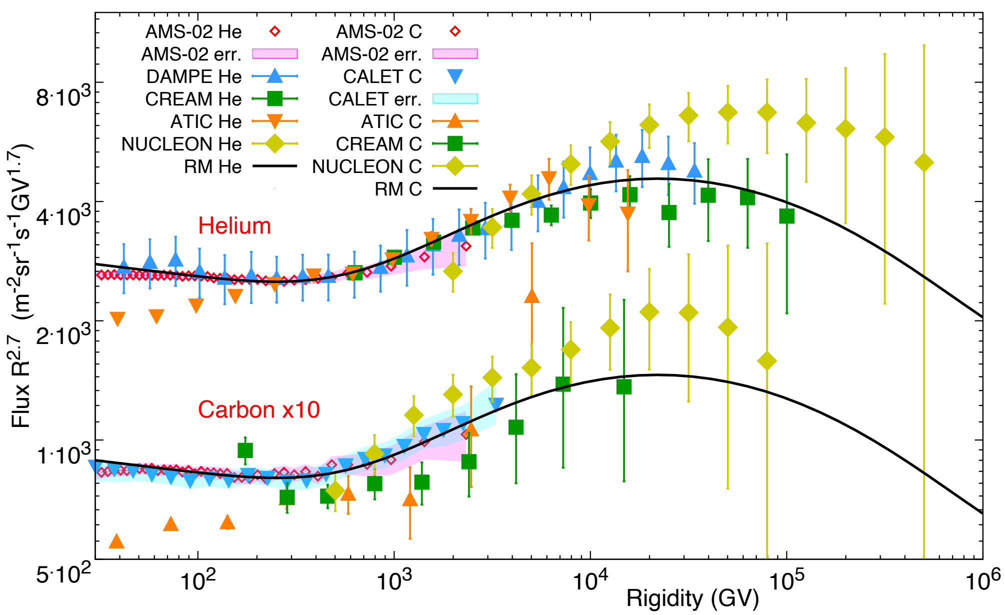
q=3r/(r-1)

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

◯ - parameters fixed from CR proton spectrum

Table 2. Input parameters for CR species derived from their LIS (Boschini et al. 2020b).

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



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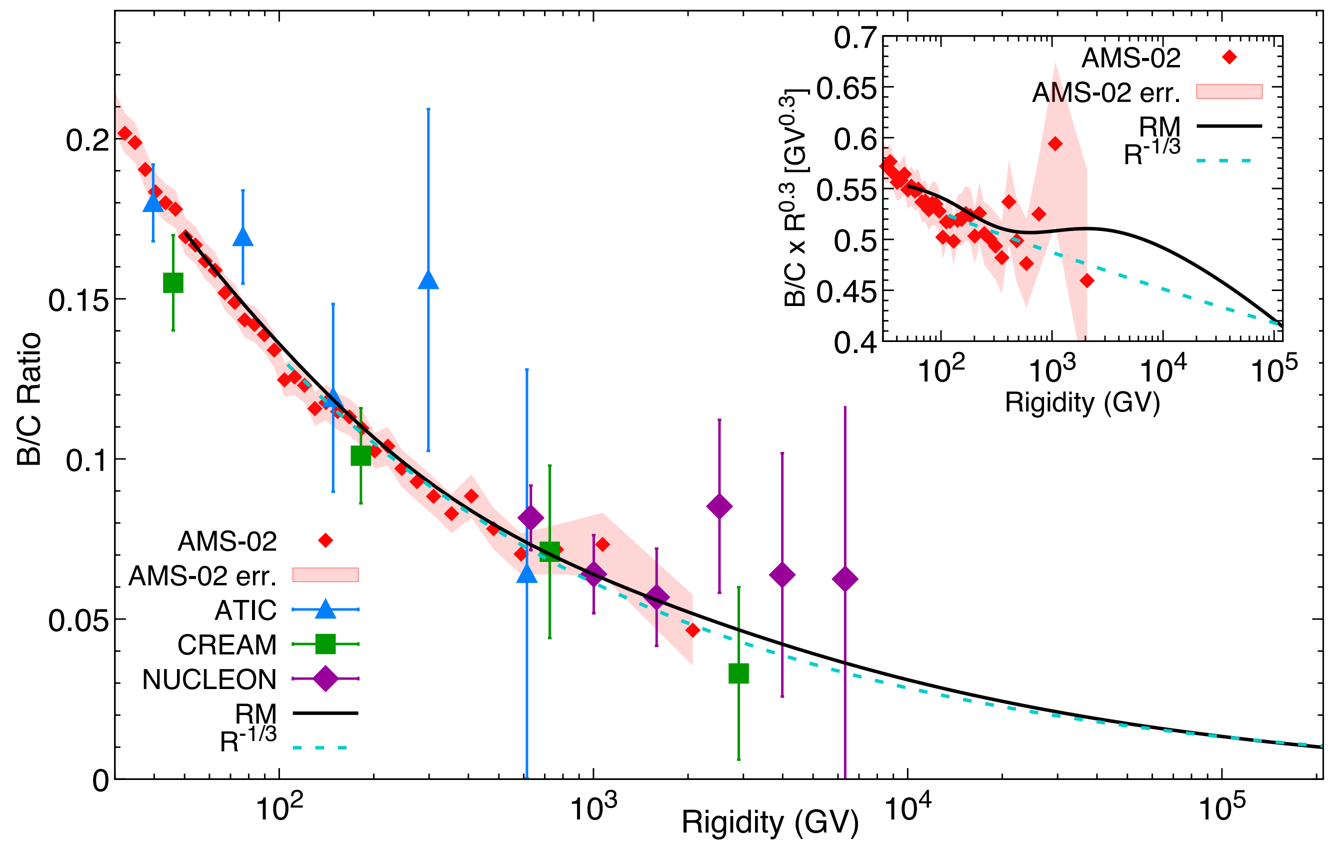
- ✧ A_s, γ_s – fixed normalization and spectral index of the LIS below the bump (individual for each species)
- ✧ LIS for H-Ni are given in Boschini+'2020
- ✧ Model reproduces spectra of ALL CR species with only 2 (3) parameters fixed from the proton spectrum

Example: B/C ratio

B/C is better measured than the spectrum of Boron



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Conclusion

At the end, stars may be affecting our lives indeed 🙂

Thanks!!