Probing Local ISM Turbulence using High-Fidelity Measurements of Cosmic Rays

M.A. Malkov

University of California San Diego

Collab.: Pat Diamond, Mingyun Cao (UCSD), Igor Moskalenko (Stanford U),

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Two Power Laws in the Milky Way (Jokipii, Armstrong, Rickett, Spangler...)

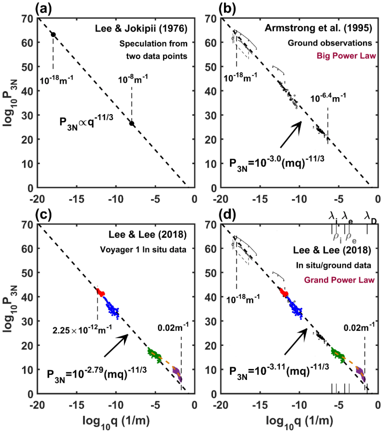
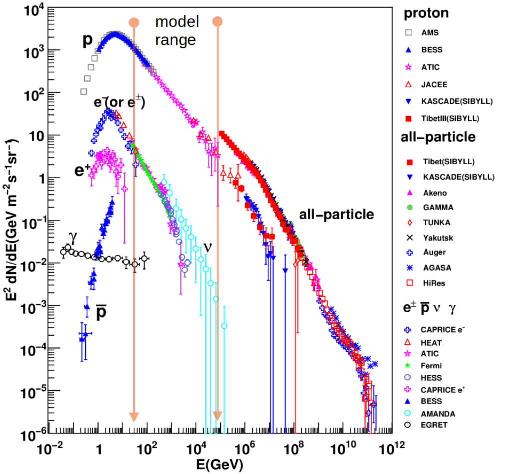


Figure 2 Interstellar turbulence spectra: (a) the Kolmogorov spectrum suggested by Lee & Jokipii (1976), (b) the Big Power Law by Armstrong et al. (1995), (c) the in situ spectrum obtained from Voyager 1 by Lee & Lee (2018), and (d) The Grand Power Law from combination of the ground remote observations (Armstrong et al., 1995; Chepurnov and Lazarian, 2010) and satellite in situ observations (Lee & Lee, 2018).

Lee, K-H. (2018)

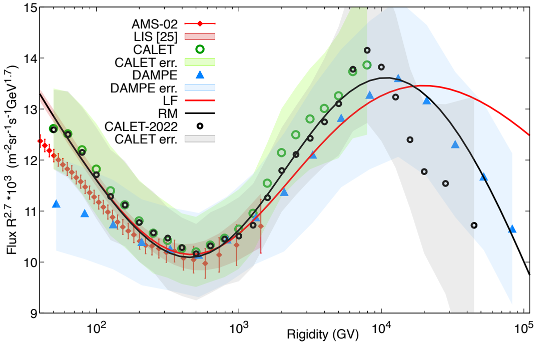
Cosmic Ray Spectra (Hu arxiv:2009.00007)



Outline

- Key three instruments: AMS-02, CALET, DAMPE...
- **10-TeV CR Bump: what is it?**
  - SNRs, ISM propagation? small-scale anisotropy $\equiv$ **means local source, closer than a few m.f.p.**
  - freshly-accelerated particles? secondaries are at least a million-year old
  - Superposition of sources or change in CR diffusivity? - breaks are too sharp
- CR source (reacceleration) is close to the Sun
  - turbulence spectrum in the ISM between the source and observer can be extracted from the CR spectrum
- need of new standards:
  - number of free parameters vs number of descriptors
    - pay due attention to the **fit accuracy**
    - **abandon log-log $\rightarrow$ do log-linear plots!**

New data on the long-suspected CR bump/Calet Update



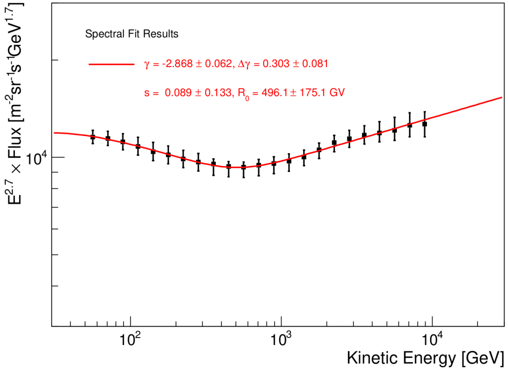
MM & I. Moskalenko, ApJ 2022, These authors ICRC 2023

-Incredibly sharp second break at ~ 10TV measured by CALET (!)

still consistent with DAMPE and the model with particle losses from the magnetic flux tube

- At first (CREAM, ATIC, **PAMELA** 2006-2011) detected a **dip** around $R_{br} \sim 200 - 300$ GV
- improved observations revealed a **second break** (softening), at $\gtrsim 10$ TV, initially by DAMPE, only
- now confirmed by CALET but much sharper!
- PAMELA's first break was even sharper than the current CALET's second break
- confirmed later by AMS-02, but shifted to $R_{br} \approx 450$GV and **smoothed!**

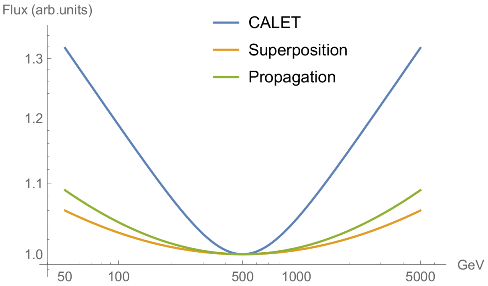
Parameters of the first break



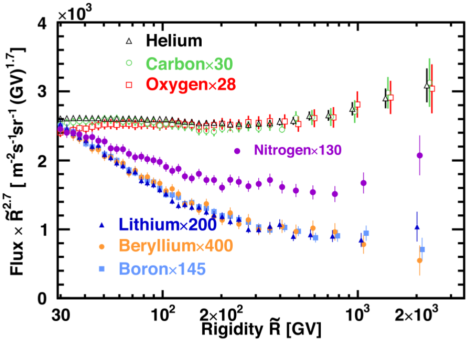
$$F \propto E^{-\gamma}\left[1 + (E/500)^{\Delta\gamma/s}\right]^{s}$$

$$\Delta\gamma = 0.3, \qquad s = 0.1$$

- Attempts to fit Calet data to a superposition of two sources or by breaking the CR diffusion scaling with energy result in a very smooth transition between the two power-laws



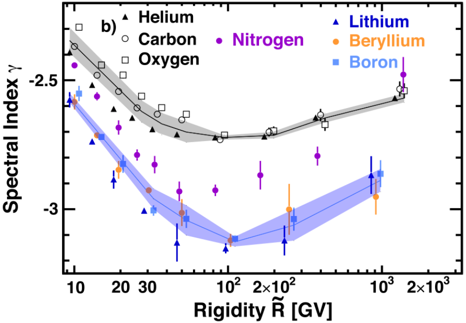
Secondary Elements Test



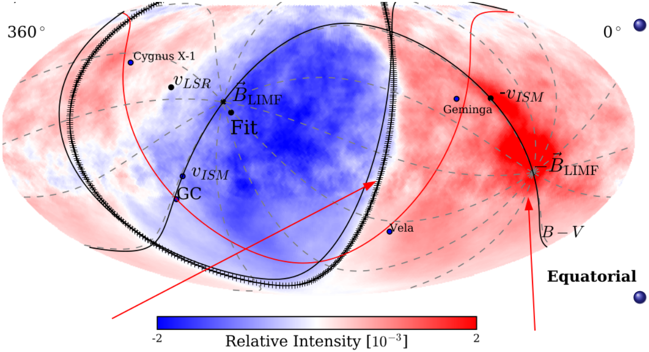
AMS-02, PhRep, 2021

- Were the flattening coming from a different source with harder spectrum, it wouldn't be the same for all the primaries and all the secondaries
  - fragmentation and production cross sections are different

- Spectral shapes of primaries are similar
- Spectral shapes of secondaries are also similar, but different from the primaries
- spectra of secondaries are steeper than primaries for all R

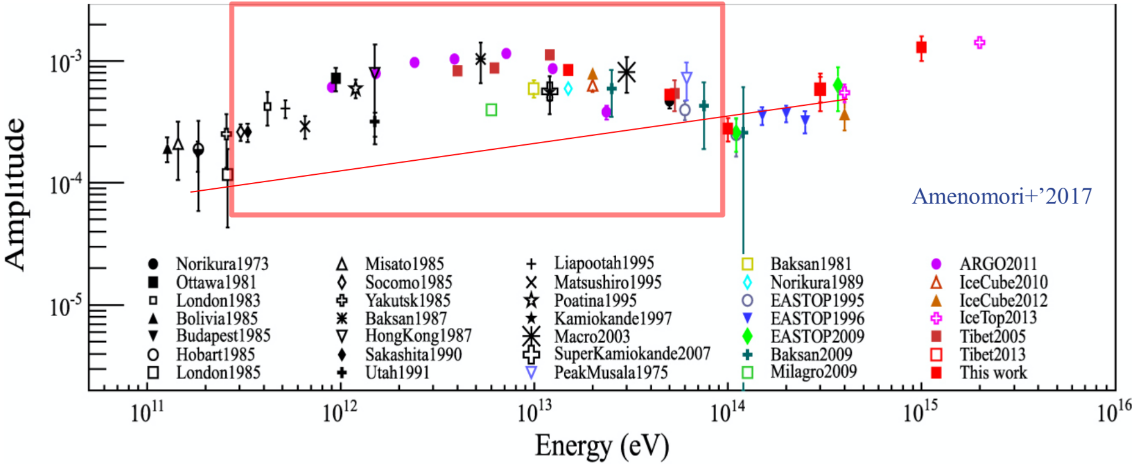


Small-Scale Anisotropy



- Observations (Abeysekara+ 2019)
- two key signatures constraining the distance to their source:
  - CR intensity jump across magnetic horizon $\mu = \cos\vartheta \approx 0$
  - enhancement in the field direction $\mu \approx 1$
- Note, that a similar field-aligned CR proton beam in the 10 TV range has been observed by Milagro

Dipole Anisotropy in the Bump Area



- $v \cdot \nabla f \sim \frac{\partial}{\partial \mu} D \frac{\partial f}{\partial \mu} \rightarrow \quad \kappa \sim \frac{c^2}{D}$
- $\frac{1}{f}\frac{\partial f}{\partial \mu} \sim \frac{\kappa}{cL_{\mathrm{source}}} \sim \frac{3}{c} \cdot \frac{10^{26}-10^{28}}{3-300\mathrm{pc}} \sim 10^{-3}$

INITIAL Model Assumptions: Weak Shock in the Local Bubble

- distance to the shock within 3-10 pc
- $T \sim 10^6 K$, a 100 km/s shock $\rightarrow$ $M = 1.4 - 1.7$
- rarefied plasma, $n \sim 0.01$, $\beta \sim 2$
- can be old SNR (radiative shell, e.g., Chevalier 1974)
- bow-shock of a rapid star, via outer Lindblad resonant scattering (Dehnen 1999)
- can be a termination shock of strong stellar wind. **Reacceleration**

Example:
Hubble image of Orion Nebula $\rightarrow$

- As CR-reaccelerating shock and Heliosphere are moving through the ISM, only the CRs with sufficient rigidity can reach us

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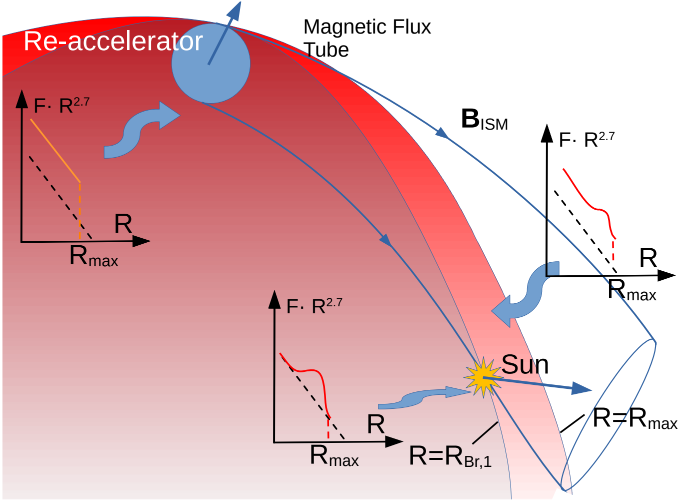


Solution at a Shock for and Propagation Upstream of reaccelerated CRs

- start with the solution upstream of a bow-shock (Blandford&Ostriker, 1978)

$$f(x,R)=f_{\infty}\left\{1+\frac{\gamma_s+2}{q-\gamma_s}\exp\left[-u_1\int_0^x\frac{dx'}{\kappa(x',R)}\right]\right\}$$

shock index $q=(r+2)/(r-1)>\gamma_s$ (bg CR index), and $r=u_1/u_2$, R -particle rigidity, $f_{\infty}\propto R^{-\gamma_s}$

- NB: steeper source spectra $\rightarrow$ stronger reacceleration! Recall secondaries
  - κ increases along the CR path, as the turbulence decays.

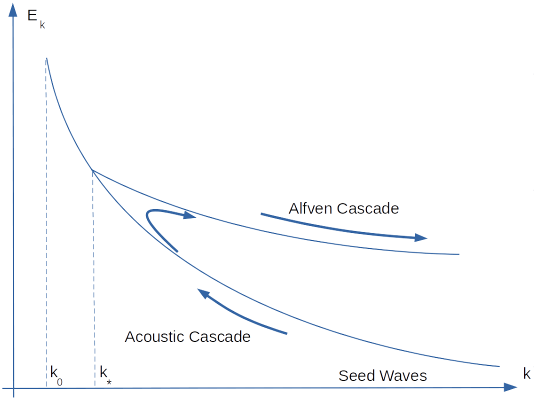
$$\Phi(x,R)=u_1\int_0^x\frac{dx'}{\kappa(x',R)}\rightarrow\Phi_1+u\int_{x_0}^{\zeta}\frac{dx'}{\kappa_{\rm prop}(x',R)}$$

- it can be shown that the main contribution comes from the second term, $x_0\rightarrow 0$. With lateral particle losses from the flux tube added, $\Phi(R)$ takes the form (MM & I.Moskalenko, ApJ '21,22)

$$\Phi(R)=(R_0/R)^a+(R/R_L)^b,\quad a=2-q_{\rm turb},\quad b=q_{\rm turb}-1$$

The 10-TV bump results from a local elevation of the CR spectrum by reacceleration and convecting CRs with $R\lesssim 1$ TV away with the ISM flow

Turbulent Cascades: What to plug in as q_{turb}?



- acoustic waves steepen into shocks, and the acoustic cascade is fully determined by ∇P_{CR}
- ∇P_{CR} drives shock merger, @ γ_D -rate

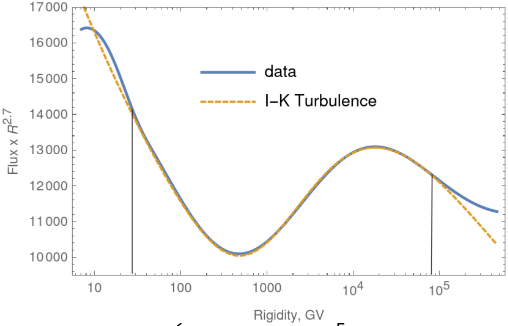
$$E_k^s = \frac{2\pi^2}{3\left(\gamma+1\right)^2 \rho_0^2 C_s^2}\left(\frac{\partial \overline{P}_{\text{CR}}}{\partial r}\right)^2 \cdot \frac{1}{k^3} = \frac{\gamma_D^2}{k^3}$$

- acoustic inverse cascade is intercepted by direct Alfvenic cascade

- acoustic cascade starts from short MS seed waves, resonantly driven by CR anisotropy

$$E_k^A \sim \frac{\sqrt{\gamma_D} V_A^{3/2}}{k^{3/2}} \propto \frac{\delta B_k^2}{B^2}, \quad \to a = \frac{1}{2}$$

Spectrum Fit: Idealized Data (no errors)



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

- Parameter R_0 can be related to CR pressure and flux tube size, $l_\perp$ (loss-free fit, $R_L = \infty$ here)

- use synthetic data from Boschini+, ApJ 2020 (analytic curve, demodulated)
- we know $a = b = 1/2$ (IK-spectrum), and find R_0, $K = (\gamma_s + 2) / (q - \gamma_s)$ from the fit.

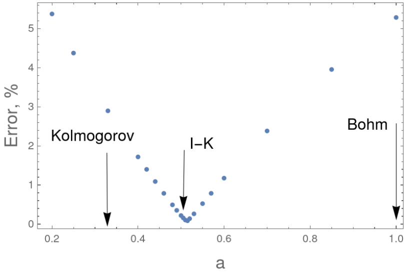
$$\sqrt{R_0} \simeq \frac{3u}{c\sqrt{r_{GV} l_\perp}} \int_0^{\zeta_{obs}} \sqrt{\frac{P_{CR}}{\rho C_s V_A}} dz$$

- K defines Mach number, M; R_0 relates the distance ζ_{obs} to $l_\perp$, here $r_{GV} \equiv r_g(1GV)$
- from the best fit we find $a = 0.515, K = 2.39, R_0 = 4434GV$.

$$M = 1.55, \quad \frac{\zeta_{obs}}{\sqrt{r_{GV} l_\perp}} \approx 2.2 \cdot 10^2 \frac{c}{u} \sqrt{\frac{\rho C_s V_A}{P_\infty}}$$

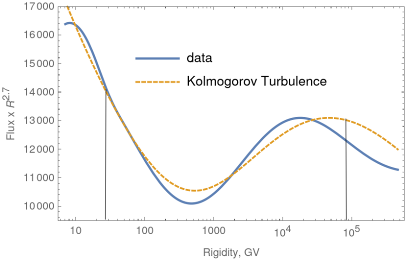
MM & I.Moskalenko, ApJ '21, 22

Unknown Problem Parameters Inferred from best Fit



- nominal value for $a = 1/2$ (Iroshnikov-Kraichnan)
- best fit value $a = 0.515$, rel. error $\Delta \approx 9.1 \cdot 10^{-4}$

$$\Delta = \int_{R_1}^{R_2} |f - f_d| \, dR \Big/ \int_{R_1}^{R_2} f_d \, dR$$

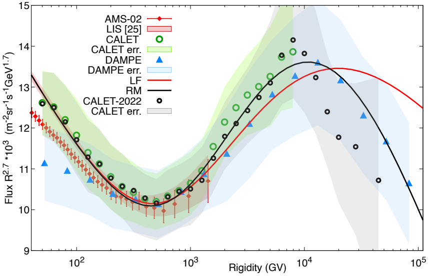


- Parameters inferred from the fit
  - Mach number: $M = 1.55$
  - reaccelerated CRs/background ratio: $K = 2.4$
  - Distance -size relation $\zeta_{obs}[\mathrm{pc}] \sim 10^2 \sqrt{l_\perp\,[\mathrm{pc}]}$

Spectrum Fit: Real Data adjusted for systematic errors

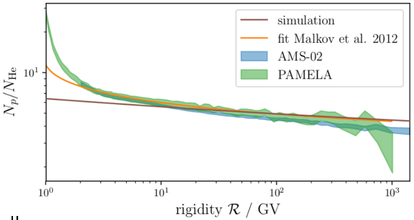
Parameter (St. err. %)	R_0(GV)	R_L(GV)	q	$K = (\gamma+2)/(q-\gamma)$	$\chi^2_{\min}$/dof	dof
Realistic model (RM)	5878 (3.5%)	2.24×10^5 (28%)	4.2	3.59 (4.9%)	0.10	76-3
Loss-free model (LF)	4795 (3.2%)	∞	4.7	2.58 (2.9%)	0.19	76-2

- data benchmarked by spectral minima to demodulated AMS-02 data of Boschini+ ApJ 2020
- $R = \tilde{R}/1.12$, Flux= $\widetilde{\mathrm{Flux}} \times 1.09$ -CALET
- $R = \tilde{R}/0.95$, Flux= $\widetilde{\mathrm{Flux}} \times 0.98$ -DAMPE



MM & Moskalenko, ApJ 2022

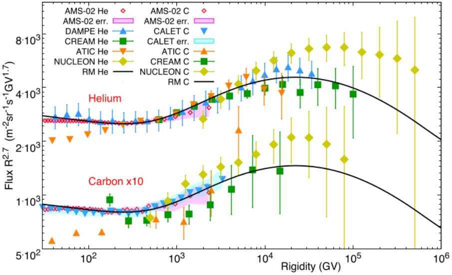
- Using the shock and propagation parameters obtained from the proton fit, (Table) we fit the spectra of other species
- He,C,O and all other SNR-accelerated elements with $\langle A/Q \rangle \approx 2$ have flatter than proton spectra by ≈ 0.1 (MM 1998, MM, Diamond and Sagdeev, Hanusch, Liseykina, MM, 2019)

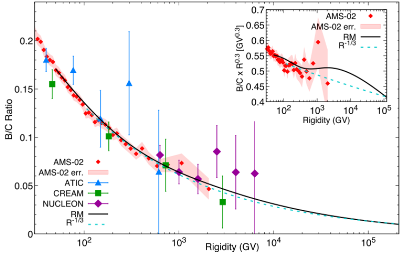


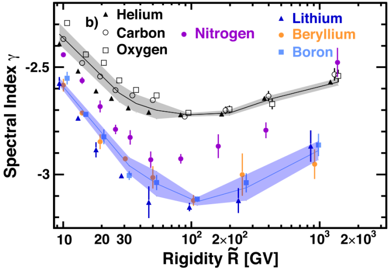
Spectrum Fit: Secondaries and B/C

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

- q -shock spectral index fixed by the proton fit
- γ_s background spectrum of He and C
- γ_s (proton) $>$ γ_s (He,C) $\rightarrow$ the CR break is less pronounced for He,C
- $\gamma_s\left(B, Be, Li\right) > \gamma_s\left(p\right) \rightarrow$ CR break is stronger







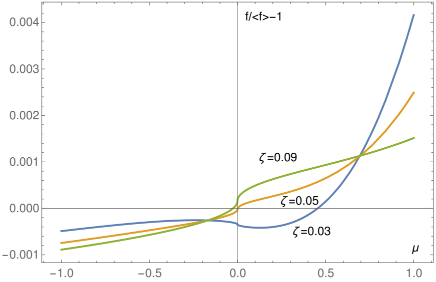
MM & Moskalenko, ApJ 2022

Small-Scale Anisotropy: FP Solution vs. Observations

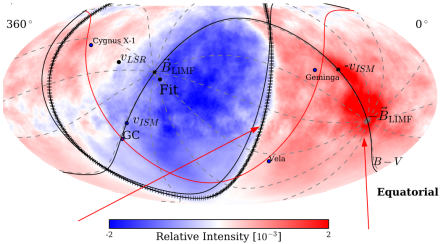
- FP Dominant terms: **prediction**

$$f(\zeta,\mu)=\sum_{n=0}^{\infty}C_n f_n(\mu\cdot\mathrm{sgn}\zeta)\,e^{-\lambda_n|\zeta|}\qquad n=0,1$$

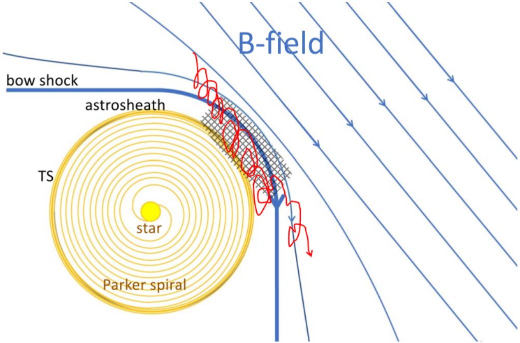
- Eigenvalues λ_n rapidly increase with $n>0$: $\lambda_0\approx 2\sqrt{5\nu_\perp}\ll 1$, $\lambda_{n>0}\sim 10^2$($\nu_\perp$ lateral losses from the flux tube)
- More subtle anisotropy effects associated with the turbulence spectrum (IK), see MM & Moskalenko, ApJ '21



- **Observations** (Abeysekara+ 2019)
- two key signatures consistent with $\zeta\approx 0.05$ distance predictions:
  - jump across magnetic horizon $\mu\approx 0$
  - enhancement in the field direction $\mu\approx 1$



Bowshock -Termination Shock Reacceleration Mechanism



- Likely object: ϵ-Eri star, 3.2 pc of the Sun, $\dot{M} > 30\dot{M}_{\odot}$, 10^4au astrosphere, $\lesssim 7^{\circ}$- magnetic connectivity with the Sun

- Space between TS and BS is overpressured by reaccelerated CRs
  - thermal plasma with frozen in B-field is partially expelled
  - magnetic bottle forms
    - CRs are trapped and can be accelerated more efficiently being trapped between the termination- and bowshock
- Acceleration mechanism - work in progress (MM&M.Lemoine, PRE 2023, MM&I.Moskalenko, ApJ 2022)

Conclusions

- High-precision data on primaries and secondaries CRs aroung the 10-TeV bump, including angular distributions, can be explained assuming:
    - Sun is crossing a magnetic flux tube filled with reaccelerated CRs
    - ϵ-Eridani (Ran) star is the primary candidate for the CR bump because of its exceptional magnetic connectivity with the heliosphere, large astroshpere, and powerful stellar wind
- Iroshnikov-Kraichnan MHD turbulence, driven by the CR-bump overpressure, is derived and required to fit the data
- Sharp increase of the bump CR intensity across magnetic horizon derived from IK
    - it indicates no CR mirroring $\rightarrow$ incompressible turbulence
- earlier CR bump position: 240 GV (ATIC, Pamela, 2006-2010) $\rightarrow$ 450 GV (current) may point to <u>a time variability, not the calibration issues</u>
- time dependence at 10-30 years suggested
- small-scale anisotropy: key CR diagnostics for the years to come