

# Cosmic Ray Reacceleration in and Propagation from nearby sources

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Eun-Suk Seo (UMD), Vladimir Ptuskin (IZMIRAN) -seminar discussion

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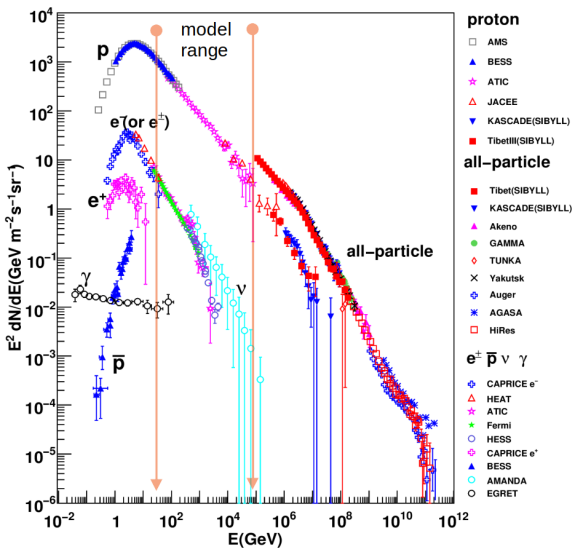
# Why should we turn to local sources?

## New data unveiled features in the CR spectrum in the range 1 – 100 TV:

- breaks in the rigidity spectra that are too sharp to be consistent with:
  - their origin in an SNR or its surroundings
  - superposition of independent sources
  - galactic propagation effects
- stochastic reacceleration in the ISM would smoothen the breaks
- angular anisotropy in CR arrival directions:
  - sharp rise of CR intensity across the local magnetic horizon ( $90^\circ$  pitch angle)
  - sharp field-aligned excess at  $\sim 10$  TV (related to old MILAGRO data?)
- TeV CR bump is seen across the periodic table, including secondaries
  - the bump is made of very old CRs
- **Conclusion:** traditional CR sources (SNRs, superbubbles) or their surroundings cannot be associated with the sharp features of CR bump:
  - sharp spectral breaks
  - steep rise of CR intensity near  $90^\circ$  pitch angle
  - spectral break in secondaries

- Observations of TeV bump in CR spectrum: what it is not?
  - Superposition of sources or change in CR diffusivity? - spectral breaks are too sharp for that
  - freshly-accelerated particles? secondaries are at least a million-year old
  - remote origin? small-scale anisotropy - means local
- what can we learn from the “unexpected” features in the CR spectrum for modeling?
  - need of new standards:
    - ▶ number of free parameters vs number of descriptors
    - ▶ pay due attention to the **fit accuracy**
    - ▶ **abandon log-log → log-linear plots**
- **Model: weak shock in the Local Bubble**
  - CR reacceleration: mechanisms and challenges
  - propagation - turbulent cascades
- distance - shock size relation
  - time dependence of the bump energy?
  - possible objects and mechanism's high bar: termination shock - bow shock combo?
- anisotropy: key CR diagnostics for the years to come

# Observation Overview



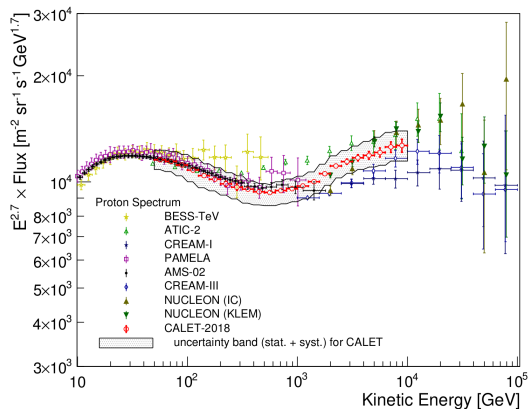
With data rapidly improving

- **DSA@SNRs:** problems with new data
- Key acceleration/propagation ingredients still missing

What causes discrepancies?

- Spectral index: models limited to planar or spherically symmetric, steady shocks
- Chemical composition: injection is key
  - BUT: careful with secondaries
- Maximum energy: escape and self-driven turbulence under realistic shock geometry and dynamical range
- those telltale bumps and dips....

# A closer look at the CR bump



Calet team PRL, 2019

- At first (CREAM, ATIC, PAMELA 2006-2011) detected a **dip** around  $R_{\text{br}} \sim 200 - 300$  GV, both for  $p$  and He. Initially perceived as a device calibration problem, but not in a few instruments (?).
- confirmed later by AMS-02, but shifted to  $R_{\text{br}} \approx 450$  GV
- improved observations revealed a **second break** (softening), at  $\gtrsim 10$  TV.
- without this break, it would be difficult to connect to the knee, without a significant deviation from the power-law

# New data on the CR bump

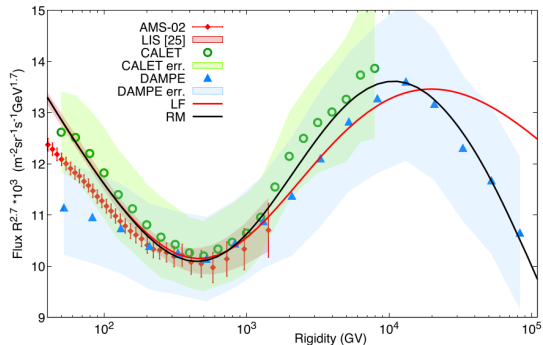
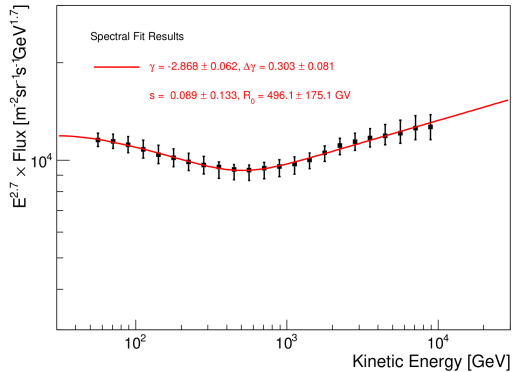


**Figure 1.** Proton rigidity spectrum from AMS-02, CALET, and DAMPE (Adriani et al. 2019; An et al. 2019; Aguilar et al. 2021). CALET and DAMPE data were modified to adjust for systematic differences between the three instruments, see text for details. The curves show the model calculations,

MM & Moskalenko, ApJ 2022

- At first (CREAM, ATIC, PAMELA 2006-2011) detected a **dip** around  $R_{br} \sim 200 - 300$  GV, both for  $p$  and He. Initially perceived as a device calibration problem, but not in a few instruments (?).
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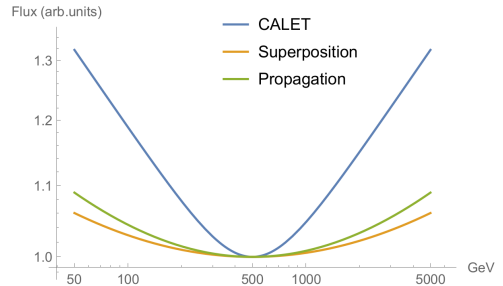
# Parameters of the first break



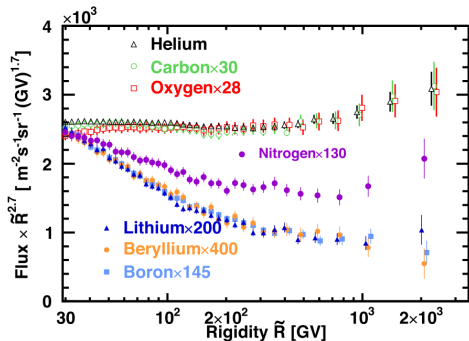
$$F \propto E^{-\gamma} \left[ 1 + (E/500)^{\Delta\gamma/s} \right]^s$$

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

- 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



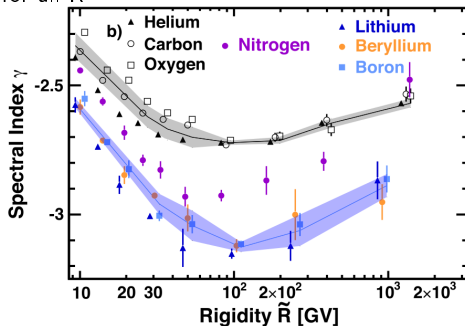
# Secondary Elements Test



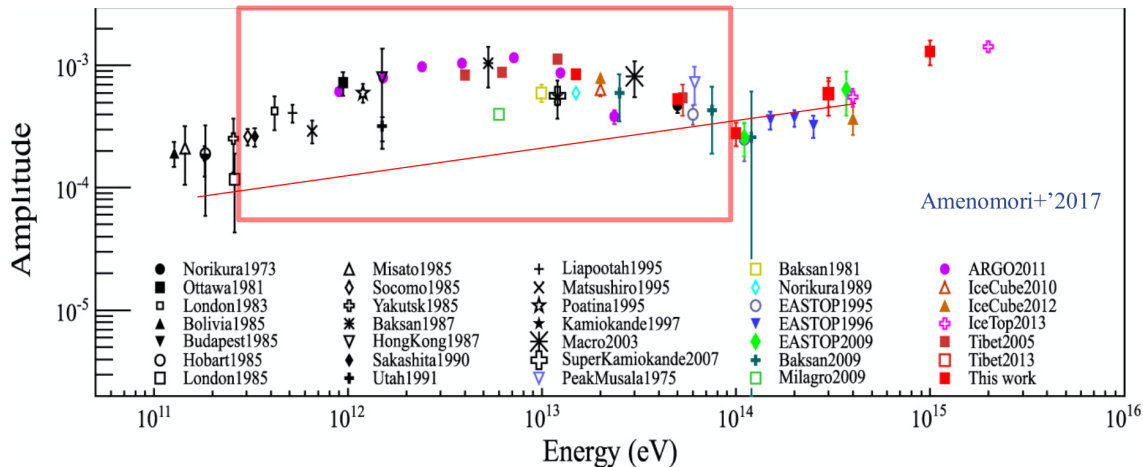
AMS-02, PhRep, 2021

- 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



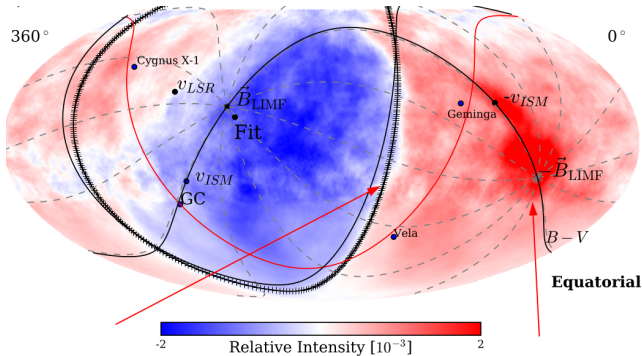
# Dipole Anisotropy in the Bump Area



$$\bullet \quad \mathbf{v} \cdot \nabla f \sim \frac{\partial}{\partial \mu} D \frac{\partial f}{\partial \mu} \rightarrow \quad \kappa \sim \frac{c^2}{D}$$

$$\bullet \quad \frac{1}{f} \frac{\partial f}{\partial \mu} \sim \frac{\kappa}{c L_{\text{source}}} \sim \frac{3}{c} \cdot \frac{10^{26} - 10^{28}}{3 - 300 \text{ pc}} \sim 10^{-3}$$

# 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

# INITIAL Model Assumptions: Weak Shock in the Local Bubble

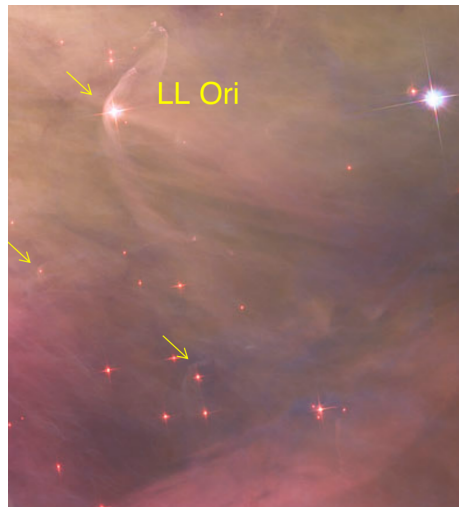
- distance to the shock within 3-10 pc
- $T \sim 10^6 K$ , a 100 km/s shock  $\rightarrow M = 1.4 - 1.7$
- rarefied plasma,  $n \sim 0.01$ ,  $\beta \sim 2$
- can be a fragment of old SNR shock (radiative shell, e.g., Chevalier 1974)
- can be a bow-shock of rapid star, produced by the outer Lindblad 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



# Solution at a Shock for and Propagation Upstream of reaccelerated CRs

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

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

where shock index  $q = (r + 2)/(r - 1) > \gamma_s$  (bg CR index), and  $r = u_1/u_2$ ,  $R$  -particle rigidity

- extend the path integral beyond the shock precursor, with  $\kappa$  increasing outside, as the turbulence level decreases

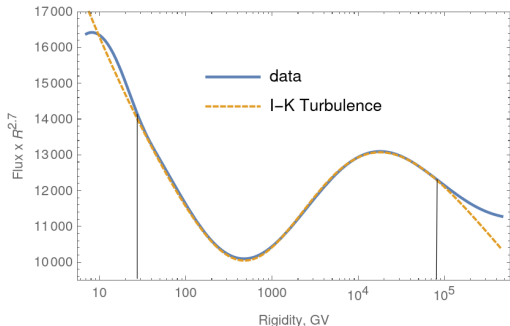
$$\Phi(x, R) = u_1 \int_0^x \frac{dx'}{\kappa(x', R)} \rightarrow \Phi_1 + u \int_{x_0}^{\zeta} \frac{dx'}{\kappa_{\text{prop}}(x', R)}$$

- 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,  $\Phi(R)$  takes the form (MM & I.Moskalenko, ApJ 2022)

$$\Phi(R) = (R_0/R)^a + (R/R_L)^{1/2}$$

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

# Spectrum Fit (Synthetic Data)



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

- 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  $a = 1/2$  (IK-spectrum), and find  $R_0$ ,  $K$  from the fit.

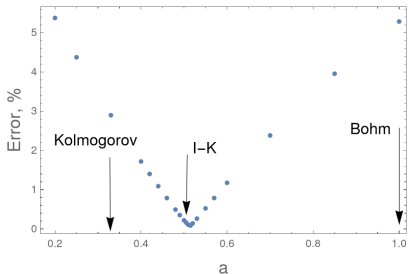
$$\sqrt{R_0} \simeq \frac{3u}{c\sqrt{r_{GV}l_\perp}} \int_0^{\zeta_{\text{obs}}} \sqrt{\frac{P_{\text{CR}}}{\rho C_s V_A}} dz$$

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

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

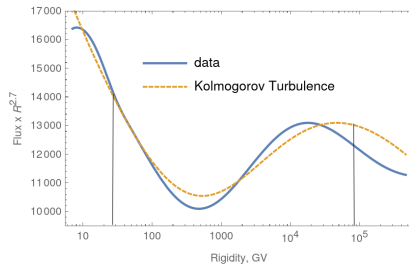
MM & I. Moskalenko, [ApJ 2022](#)

# Unknown Problem Parameters Inferred from best Fit



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

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

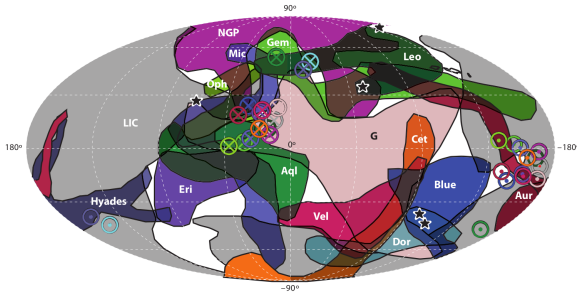


- Parameters inferred from the fit
  - Mach number:  $M = 1.55$
  - reaccelerated CRs/background ratio:  $K = 2.4$
  - Distance -size relation  $\zeta_{\text{obs}}[\text{pc}] \sim 10^2 \sqrt{l_{\perp} [\text{pc}]}$

# Possible Source of Reaccelerated CRs: Local Interstellar Environment: CLIC

- Typical astrosphere  $l_{\perp} \sim 10^{16}$  cm, using estimate  $\zeta_{\text{obs}}[\text{pc}] \sim 10^2 \sqrt{l_{\perp} [\text{pc}]}$
- Look for an object (e.g., stellar bow-shock or termination shock) **within 10 pc**

## Complex Local Interstellar Clouds (CLIC)



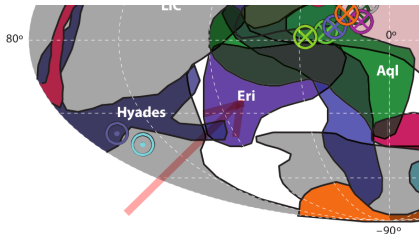
- Using 157 stars (abs. lines) within 100 pc around the Sun
- 15 partially ionized WIM clouds identified  $T = (4 - 10) \cdot 10^3 K$
- Fill a volume within 15 parsecs of the Sun
- Four clouds are currently interacting with the heliosphere
- Sun will leave the LIC (local interstellar cloud) in 3000 years and enter the intercloud space
- This region has a higher temperature and lower gas density than the WIM.

From Frisch+ 2011 review

# Local Interstellar Environment: Magnetic Connectivity

- Key evidence for the CR bump association with a star if they are in the same flux tube with the heliosphere
- **Epsilon Eridani** is only a small turn of  $\approx 6.7^\circ$  away from the local field direction

## Complex Local Interstellar Clouds (CLIC)

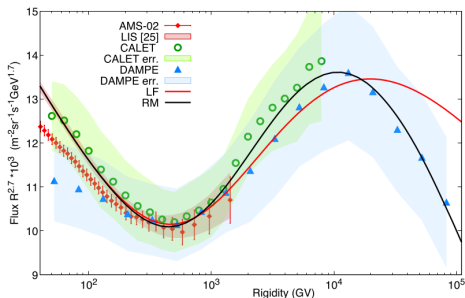


- $\epsilon$ -Eri is located at 3.2 pc of the Sun and possesses a huge astrosphere
- The chance to find a suitable candidate star within  $6.7^\circ$  of the local field direction is only  $\approx 0.3\%$ , assuming that its position on the sky is random
- Sample 3-4 stars that have detectable astrospheres (bow shocks) of a size  $>1000$  au (to exceed a 10-TeV CR Larmor radius) within 5 pc of the Sun
- The probability of at least one of them to be found in such a narrow solid angle is not larger than **one percent**

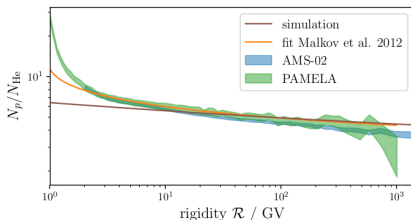
# Spectrum Fit: Real Data adjusted for systematic errors

| Parameter (St. err. %) | $R_0(\text{GV})$ | $R_L(\text{GV})$         | $q$ | $K = (\gamma + 2)/(q - \gamma)$ | $\chi^2_{\min}/\text{dof}$ | dof  |
|------------------------|------------------|--------------------------|-----|---------------------------------|----------------------------|------|
| Realistic model (RM)   | 5878 (3.5%)      | $2.24 \times 10^5$ (28%) | 4.2 | 3.59 (4.9%)                     | 0.10                       | 76-3 |
| Loss-free model (LF)   | 4795 (3.2%)      | $\infty$                 | 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 =  $\widetilde{\text{Flux}} \times 1.09$  - CALET
- $R = \tilde{R}/0.95$ , Flux =  $\widetilde{\text{Flux}} \times 0.98$  - DAMPE



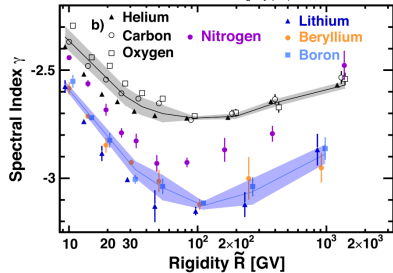
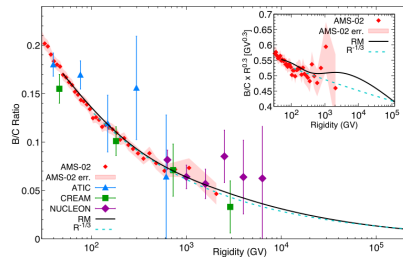
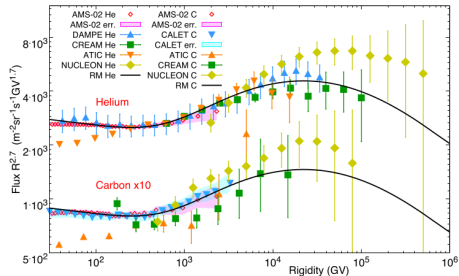
- Using the shock and propagation parameters obtained from the proton fit, (Table) we fit the spectra of other species
- He, C, O and all other SNR-accelerated elements with  $\langle A/Q \rangle \approx 2$  have flatter than proton spectra by  $\approx 0.1$  ([MM 1998](#), [MM](#), [Diamond and Sagdeev](#),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



# Spectrum Fit: Secondaries and B/C

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

- $q$  -shock spectral index fixed by the proton fit
- $\gamma_s$  background spectrum of He and C
- $\gamma_s(\text{proton}) > \gamma_s(\text{He, C}) \rightarrow$  the CR bump is less pronounced for He, C



# Small-Scale Anisotropy from Magnetically Connected CR Source

- Source proximity and magnetic connectivity must impact the CR arrival direction distribution (anisotropy, large- and small-scale)
- Observed for a long time, e.g. Milagro “hot spots”, IceCube, HAWC
- Use Fokker-Planck equation: along the field,  $\zeta$ - direction, lateral losses  $\nu'_{\perp}$

$$\frac{\partial f}{\partial t} + c\mu \frac{\partial f}{\partial \zeta} + \nu'_{\perp} f = \frac{\partial}{\partial \mu} (1 - \mu^2) D(p, \mu) \frac{\partial f}{\partial \mu} + Q(p, \mu) \delta(\zeta)$$

scattering frequency

$$D = \left. \frac{\pi^2 c}{|\mu| r_g^2 B_0^2} \rho_0 E_k^A \right|_{k=1/r_g |\mu|} \equiv 4\nu_{\text{IK}}(p) |\mu|^{1/2}, \quad \nu_{\text{IK}} = \frac{\pi}{16} \sqrt{\frac{\gamma D}{V_A r_g}}$$

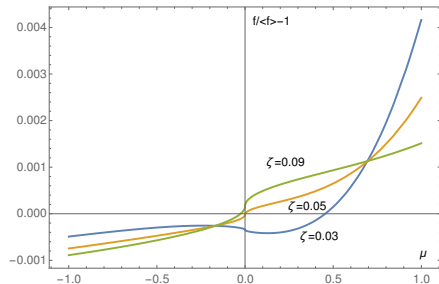
$$f(\zeta, \mu) = \sum_{n=0}^{\infty} C_n f_n(\mu \cdot \text{sgn} \zeta) e^{-\lambda_n |\zeta|} \quad \text{rescaled vars: } \nu_{\text{IK}} t, \quad \frac{\nu_{\text{IK}}}{c} \zeta \equiv \frac{\zeta}{\lambda_{\text{CR}}}, \quad \frac{f}{Q_0}$$

# Small-Scale Anisotropy: FP Solution vs. Observations

- FP Dominant terms: **prediction**

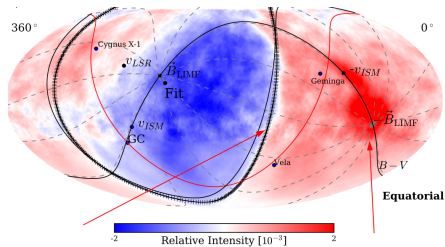
$$f(\zeta, \mu) = \sum_{n=0}^{\infty} C_n f_n(\mu \cdot \text{sgn} \zeta) e^{-\lambda_n |\zeta|} \quad n = 0, 1$$

- Eigenvalues  $\lambda_n$  rapidly increase with  $n > 0$ :  
 $\lambda_0 \approx 2\sqrt{5\nu_{\perp}} \ll 1$ ,  $\lambda_{n>0} \sim 10^2$

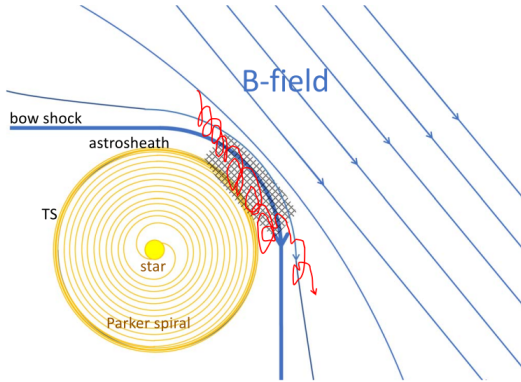


- Observations** (Abeysekara+ 2019)

- 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



- 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, to be submitted, MM&I.Moskalenko, ApJ 2022)

- CRs probe the Local Bubble increasingly well
- Current data on primaries and secondaries CRs can be explained assuming:
  - Sun is crossing a magnetic flux tube filled with reaccelerated CRs
  - $\epsilon$ -Eridani (Ran) star is the primary candidate for the CR bump because of its exceptional magnetic connectivity with the heliosphere
- back-and-forth about the CR rigidity bump position: 240 GV (ATIC, Pamela, 2006-2010 )  
→450 GV (AMS-02 + other new instruments, NOW) may point to a time variability, not the calibration issues
- time dependence at 3-30 years suggested
- good data at 10 TV needed, including arrival directions