Do we understand the role of turbulence and diffusion in cosmic ray transport in the heliosphere?

Working Group: 3nd year

Scene-setting speakers: *Dave Ruffolo* (U. Mahidol), *Lingling Zhao* (U. Alabama)
Organizers: *Claudio Corti* (U. Hawaii, NASA/GSFC), *Joe Giacalone* (U. Arizona),
William Matthaeus (U. Delaware), *Ian Richardson* (U. Maryland, NASA/GSFC)

Science Questions

1) How do the parallel and perpendicular mean free paths vary with rigidity at different locations in the heliosphere (e.g. inner vs outer heliosphere, polar vs equatorial regions) based on theory and observations?

2) Can observations of the time-, space-, and rigidity-dependence of cosmic rays be used to constrain different diffusion and turbulence theories?

3) What kind of improvements, both experimental (e.g. better magnetic field measurements) and theoretical (e.g. larger MHD simulations), will help answer the previous questions?

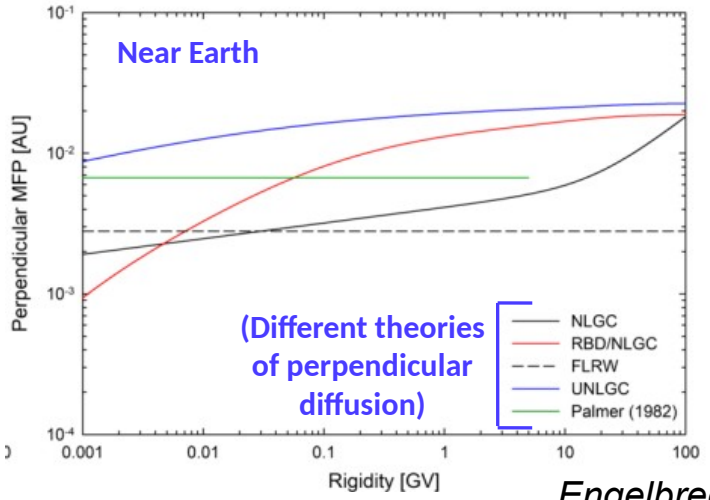
Summary from last SHINE's GCR session

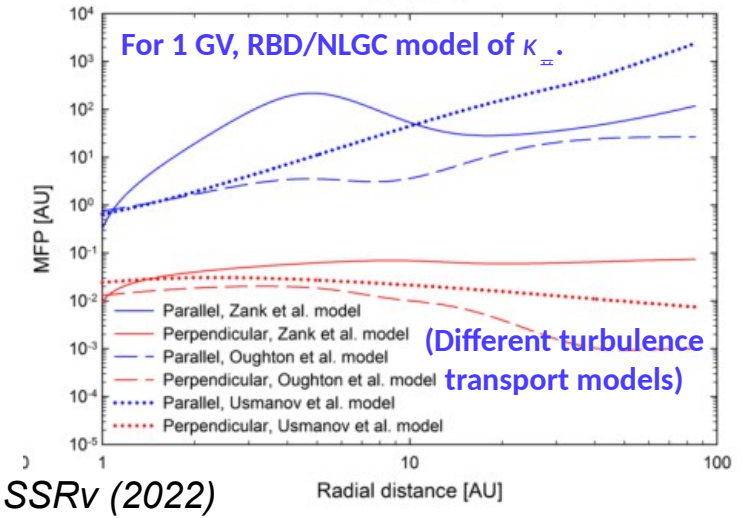
Why this problem is hard:

- Very sparse GCR observations, mostly at 1 AU, very close to the Sun, and often inside Earth's magnetosphere $\rightarrow$ Difficult to derive global picture from local measurements!
- Very few measurements of the same solar wind structure at different locations in the heliosphere.
- We can't measure directly the diffusion coefficient $\rightarrow$ Need to rely on theory....
- ... but perpendicular diffusion is still not completely understood!
- ...drifts, too!

Diffusion from theory (Dave Ruffolo)

- When can we use the diffusion approximation (Parker equation)?
  - SEPs: depends on the type of event
  - GCRs: usually yes, except near shocks and inside flux ropes (Forbush decreases?)
- Parallel diffusion seems a solved problem *[but see latest GCR modeling results!]*
- Multiple theories of perpendicular diffusion: FLWR, NLGC, UNLT, RBD
- MHD models + turbulence transport theories => heliospheric diffusion coefficients

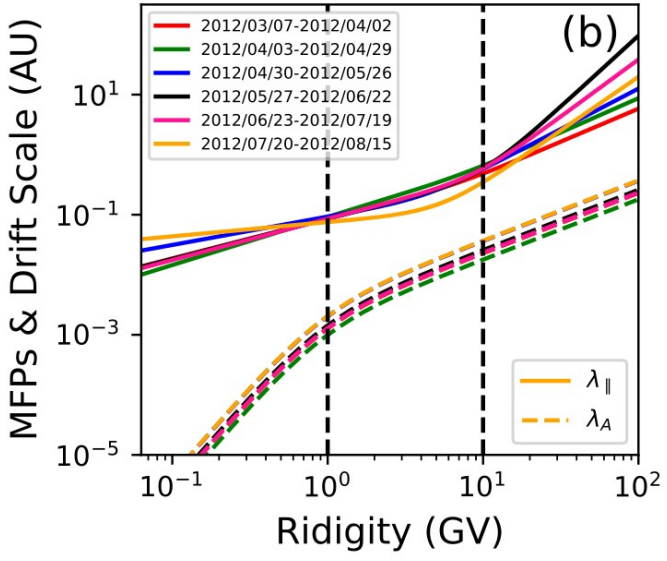


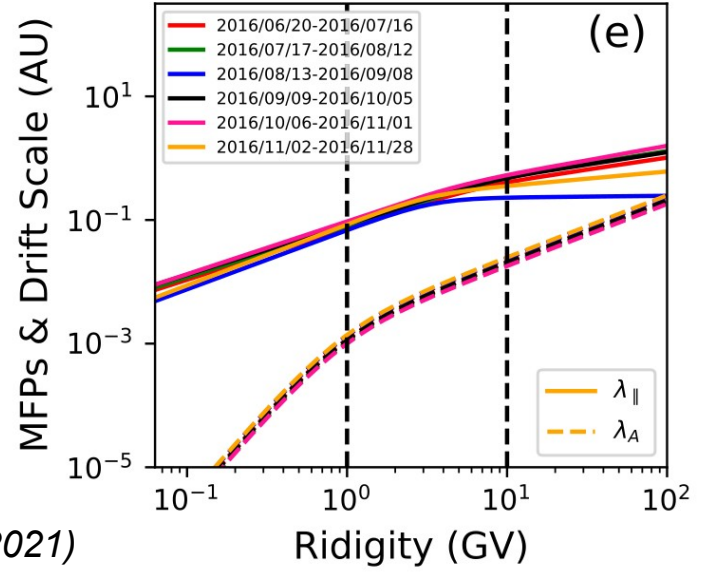


Engelbrecht et al., SSRv (2022)

Diffusion from observations (Dave Ruffolo)

- Anisotropy and time profiles of SEPs and GLEs yields mean free paths and pitch-angle distributions, but only for inner heliosphere and specific events
- GCR anisotropies from different NMs yields mean free paths and radial gradients, but only for 1 AU and local solar wind structures
- Modeling of PAMELA and AMS protons in GCRs leads to puzzling rigidity dependence of parallel mean free paths

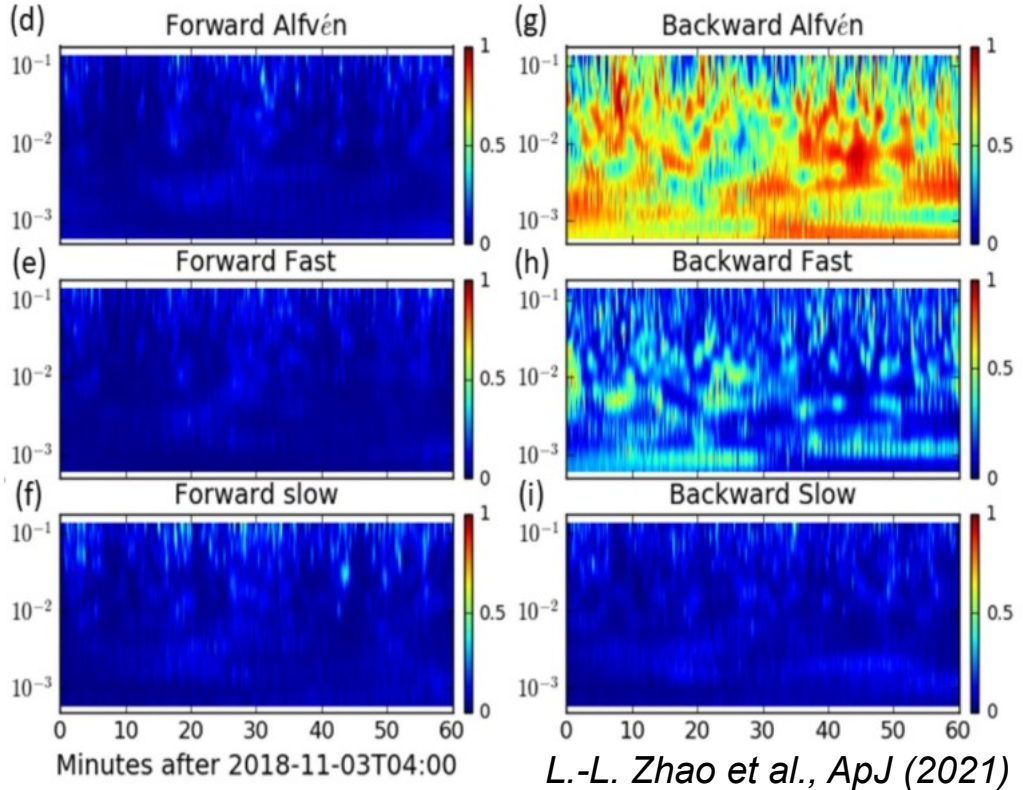




Song et al., ApJSS (2021)

Turbulence from observations (Lingling Zhao)

- Parallel and perpendicular fluctuations behave differently in solar wind: power anisotropy, spectral index anisotropy, fast vs slow solar wind
- PSP data suggests that power in 2D fluctuations becomes smaller closer to the Sun.
- Discussion of methods for MHD wave decomposition of solar wind data and in simulation: in some opinions, decomposition in wave modes may be incomplete and misleading.



L.-L. Zhao et al., ApJ (2021)

Turbulence-plasma-particle couplings at shocks (Lingling Zhao)

- Energetic particles modify shock structure, leading to non-linear diffusive shock acceleration
- Multi-fluid model equations including cosmic ray pressure and viscous stress predicts large differences in the diffusion coefficient between upstream and downstream
- These models are complementary to PIC simulation of SN shocks and can be applied to interplanetary shocks as well
- Multi-fluid models that include effects from cosmic rays should also include injection and acceleration at the shock, which are key aspects of shock dissipation.

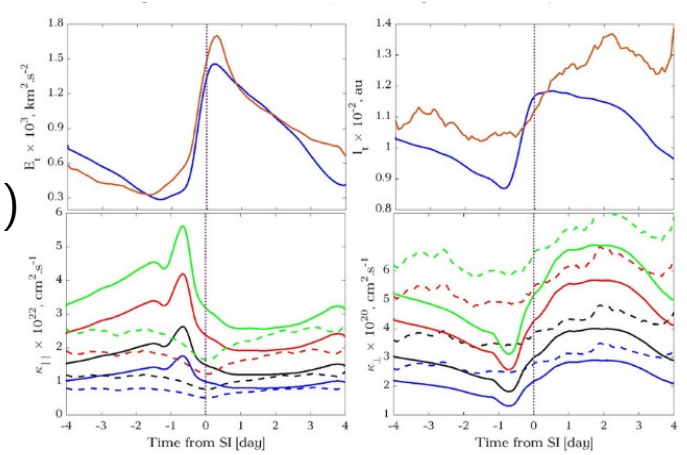
Poster contributions & Discussions

Turbulence in CIRs (Keyvan Ghanbari, #107)

- Differences in correlation lengths between MHD model and data

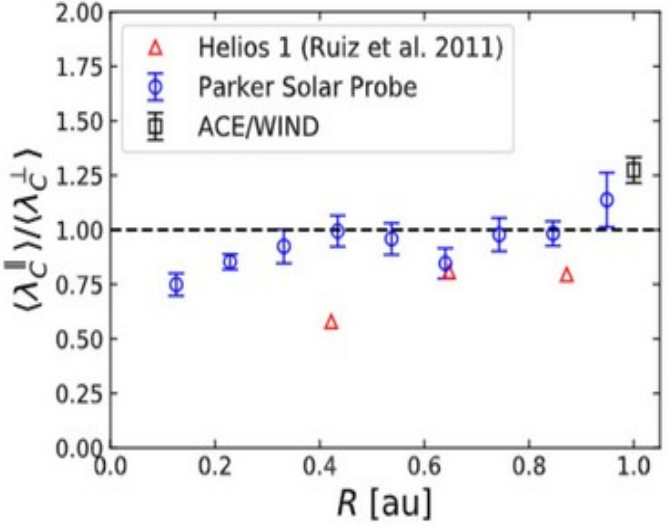
Radial evolution of turbulence anisotropy (Manuel Cuesta, #221)

- Anisotropy seems to disappear after 0.4 AU
- Systematic analysis of Voyager and Ulysses data is needed to derive radial and latitudinal evolution throughout the heliosphere



Lots of discussion: ratio of parallel/perp correlation lengths, and power density ratio in 2D and slab fluctuations

- different definitions of correlation scale (spectrum or correlation function), how data sample sizes are chosen, how ensemble averages are performed....
- ***Technical, but these questions can influence parallel and perp mean free paths!***



Future outlook

- We need to incorporate advancements of MHD + turbulence transport models in GCR modeling: **can we reproduce data with basically no free parameters in the diffusion coefficients?**
- **We need more magnetic field measurements across all heliosphere** to validate turbulence transport models, this includes multi-spacecraft measurements in order to determine the spatial dependence of the vector magnetic field.