Comparing Propagation Models with Local Cosmic Ray Spectra

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ECRS—July 27, 2022

CR Transport Equation

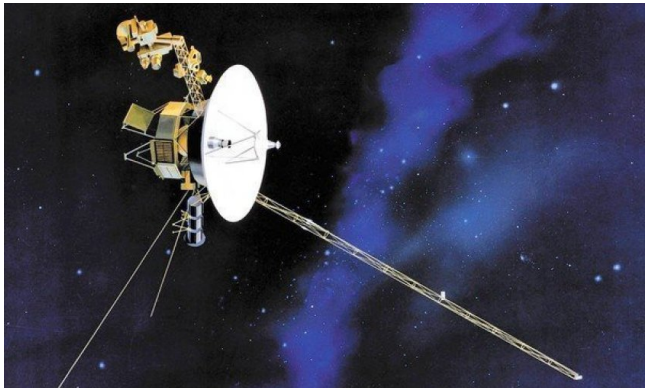
- The GALPROP code simulates cosmic ray (CR) propagation
- GALPROP solves the CR transport equation to simulate local interstellar spectra

$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = \overbrace{q(\vec{r},p,t)}^{\text{Sources}} + \vec{\nabla}\cdot(\overbrace{D_{xx}\vec{\nabla}\psi}^{\text{Diffusion}} - \overbrace{\vec{V}\psi}^{\text{Convection}})$$

$$+ \underbrace{\frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p}\frac{1}{p^2}\psi}_{\text{Re-acceleration}} - \underbrace{\frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right]}_{\text{Energy loss}} - \overbrace{\frac{1}{\tau_f}\psi}^{\text{Spallation/ Fragmentation}} - \underbrace{\frac{1}{\tau_r}\psi}_{\text{Decay}}$$

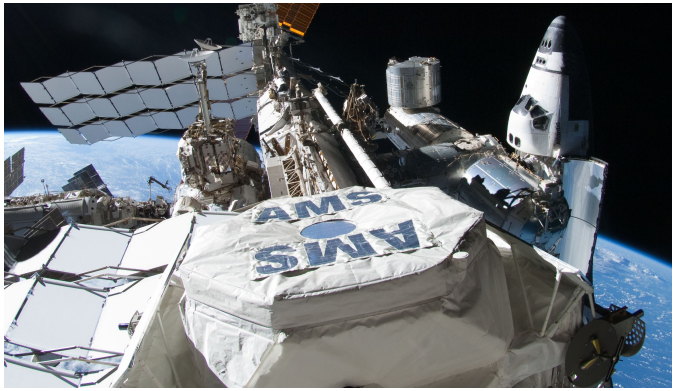
CR Data Sources

Voyager 1



- Probe launched in 1977, now outside the solar system
- Low energy CRs
  - 0.1 to 550 MeV/nucleon
- Unaffected by solar modulation

AMS-02



- Detector installed on the ISS in 2011
- High energy CRs
  - >1 GeV/nucleon
- Unprecedented high precision

Revising CR propagation scenarios

- **DRC**: Diffusion, Reacceleration, Convection
  - **DRC1**: One break in spectral indices
  - **DRC2**: Two breaks in spectral indices
  - **DRC_conv**: Two breaks in spectral indices, stronger convection
- **DRE**: Diffusion, Reacceleration
- **PD**: Plain Diffusion
- **DC**: Diffusion, Convection

Fitting Parameters

- Best-fit parameters found with Minuit2
- B/C ratio strongly constrains parameters of different propagation scenarios

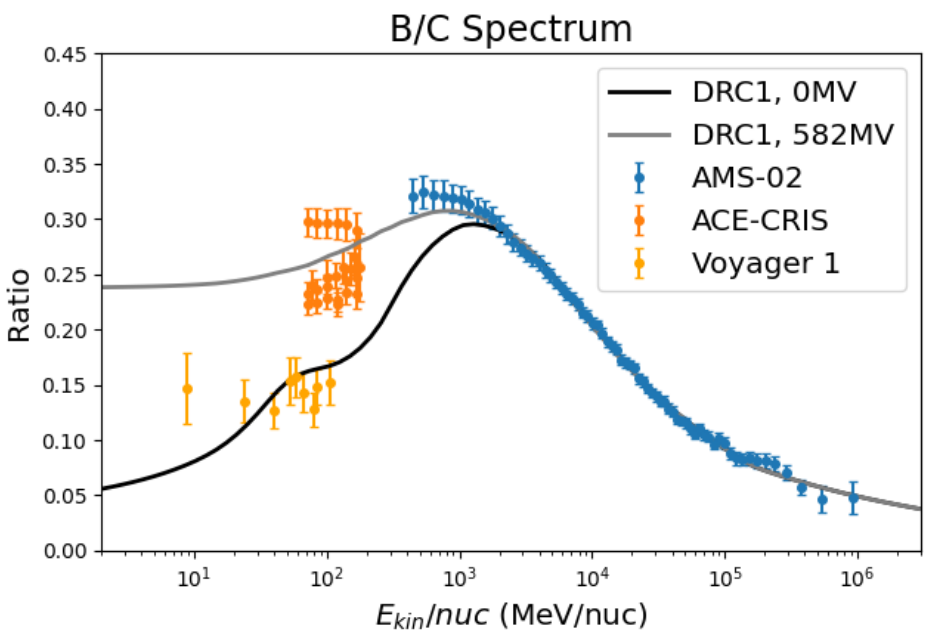
- Our best fit models have:
- 2.7e28 $cm^2 s^{-1} < D_0 < 4.6e28\ cm^2 s^{-1}$ (isotropic)
- One diffusion break at 370 GV for all models:
  - $\delta_1 \sim 0.4$, $\delta_2 \sim 0.2$
- Depending on the scenario:
  - $0\ km\ s^{-1} < V_A < 52\ km\ s^{-1}$
  - $0\ km\ s^{-1}\ kpc^{-1} < dV/dz < 55\ km\ s^{-1}\ kpc^{-1}$

$$D_{xx} = D_0 \beta^{\eta} R^{\delta}$$

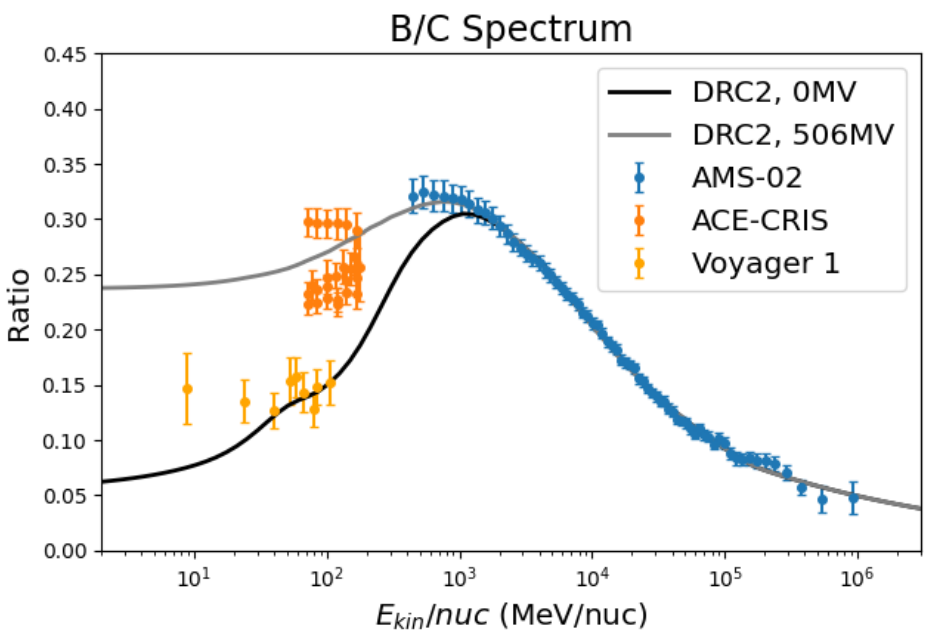
Diffusion coefficient

Best-Fit Models: B/C Ratio

DRC1

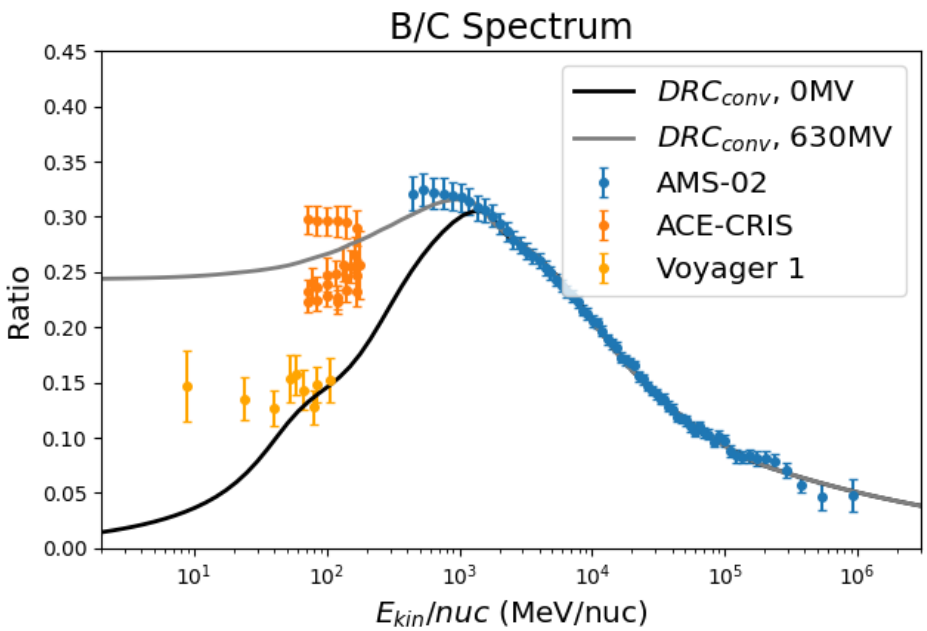


DRC2

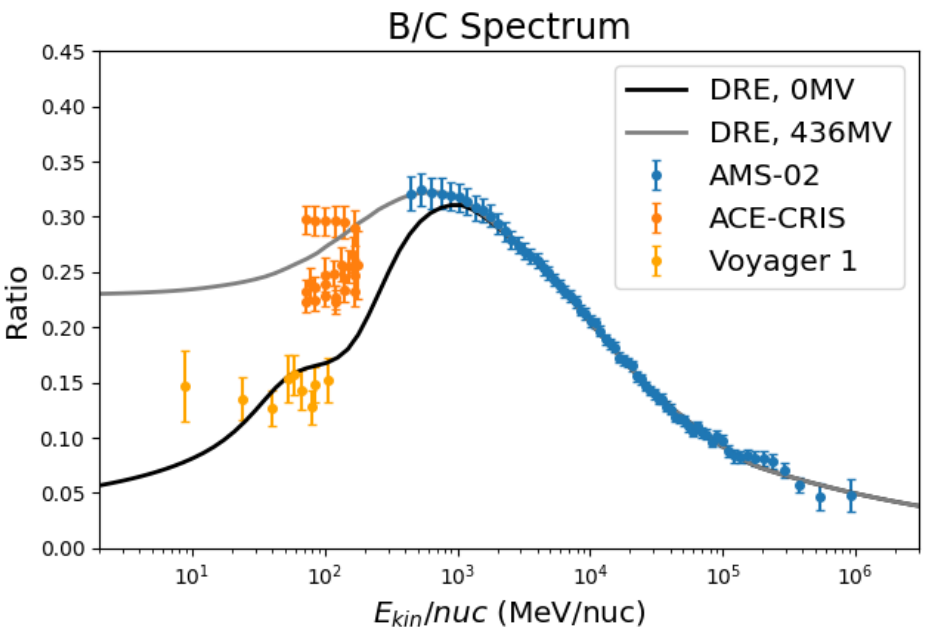


Best-Fit Models: B/C Ratio

DRC_conv

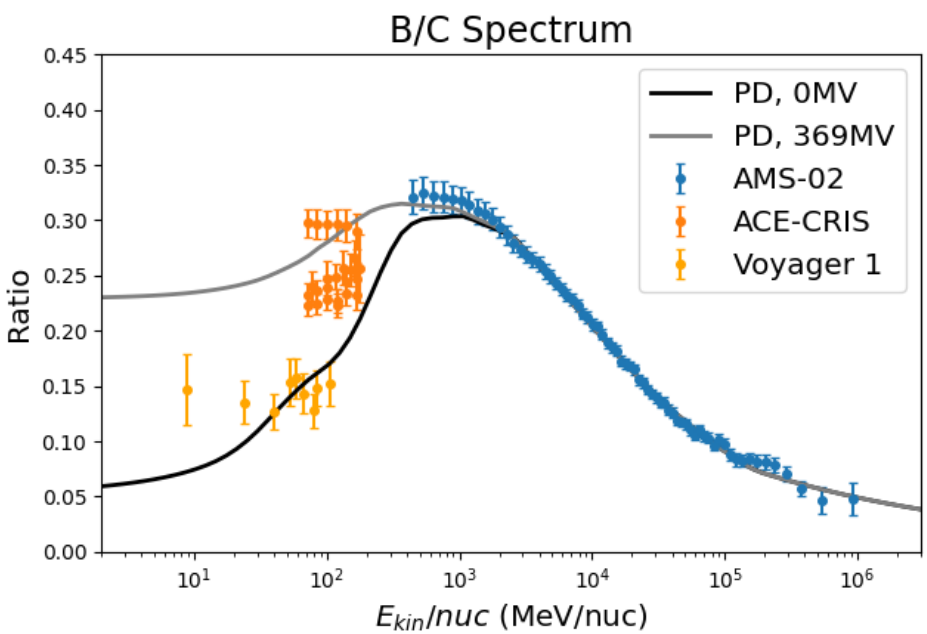


DRE

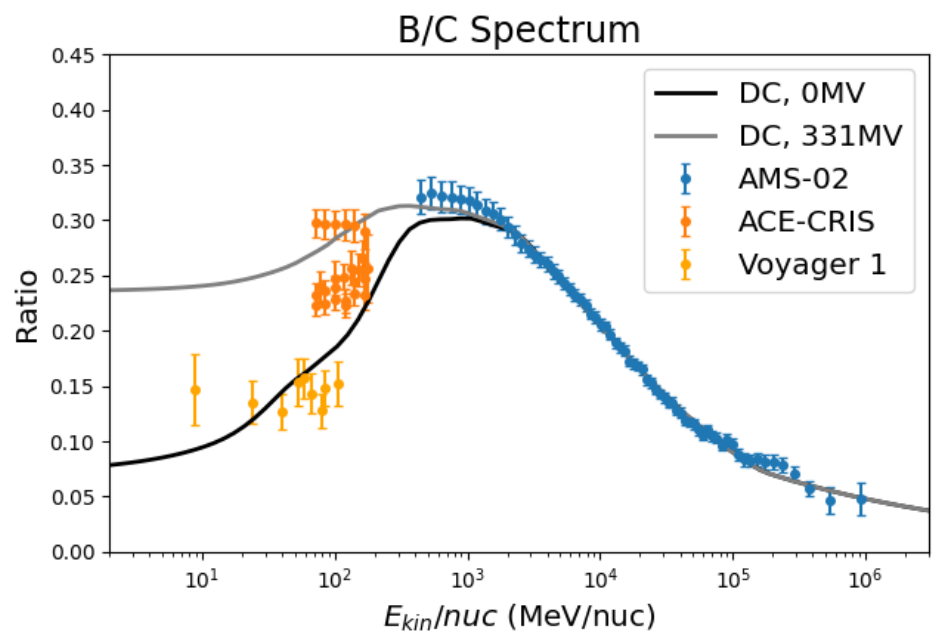


Best-Fit Models: B/C Ratio

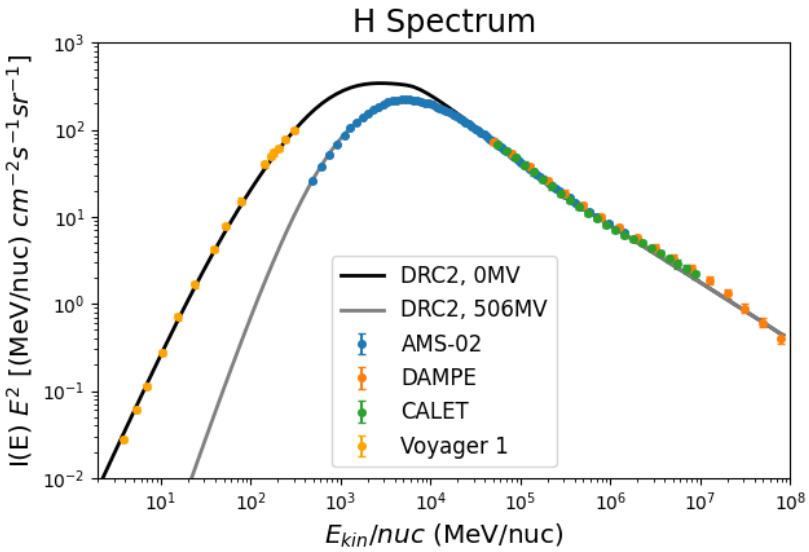
PD

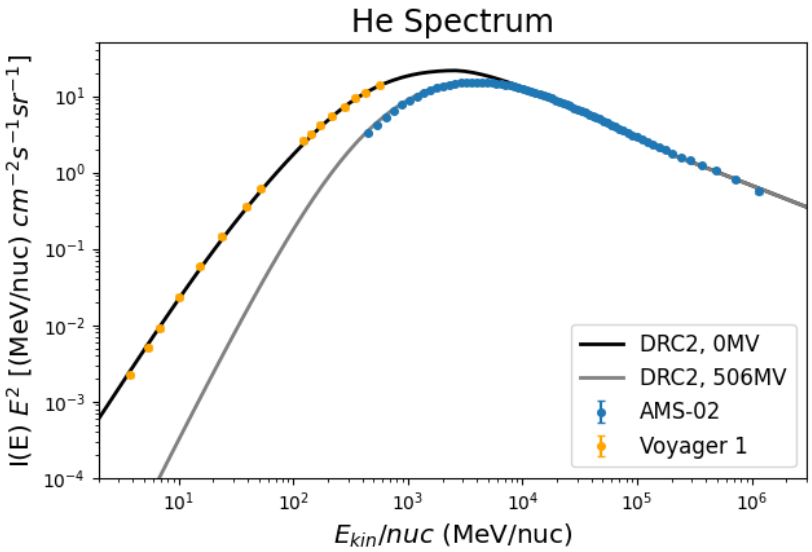


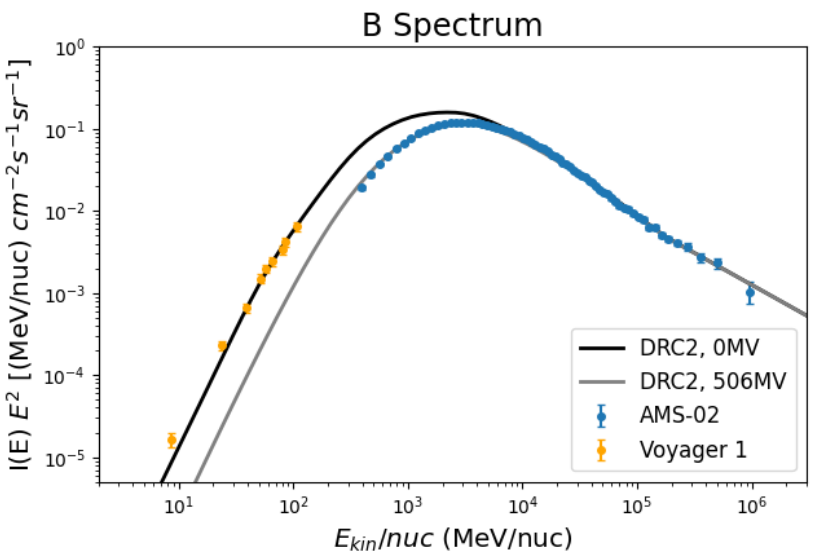
DC

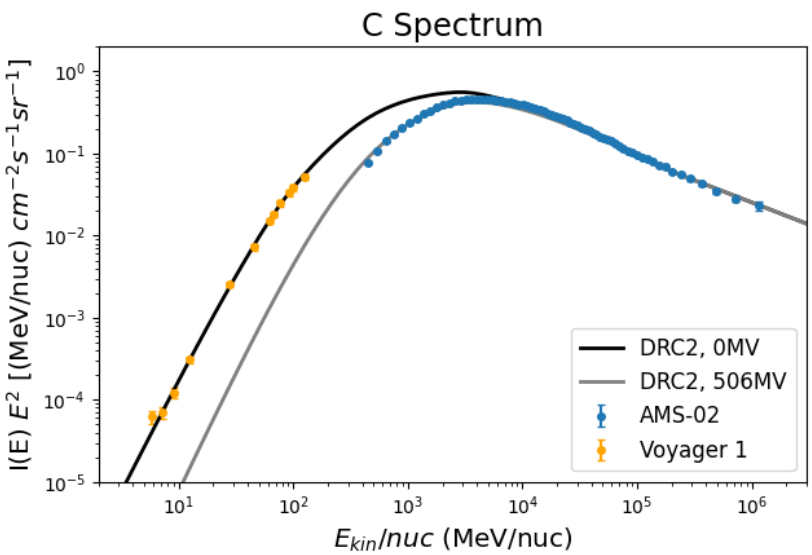


DRC2: H, He, B, C

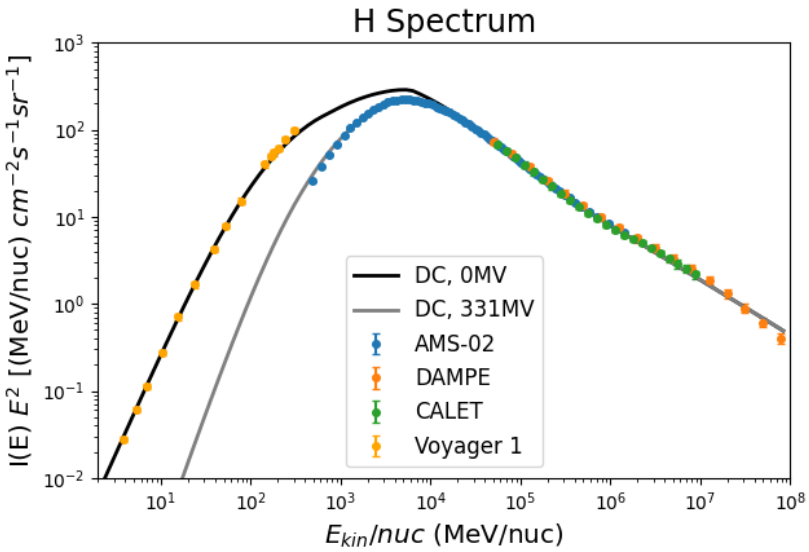

H Spectrum
I(E) E^2 [(MeV/nuc) $cm^{-2}s^{-1}sr^{-1}$]
E_{kin}/nuc (MeV/nuc)
DRC2, 0MV
DRC2, 506MV
AMS-02
DAMPE
CALET
Voyager 1

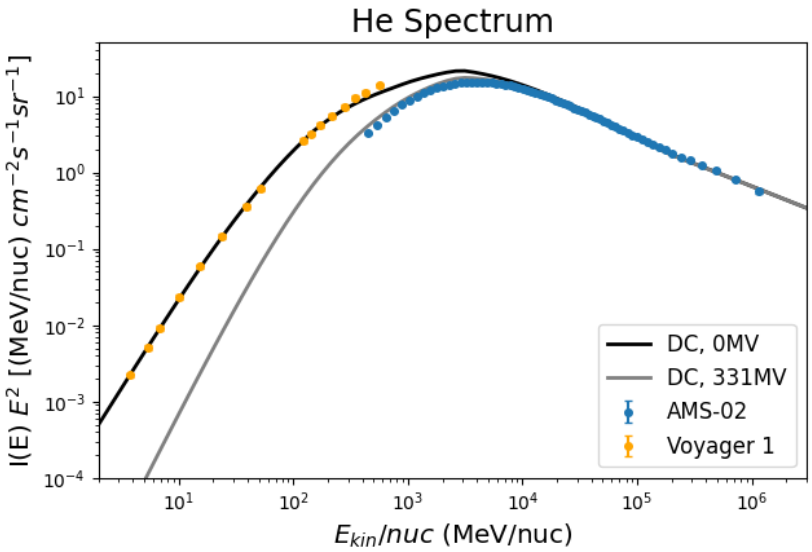

He Spectrum
I(E) E^2 [(MeV/nuc) $cm^{-2}s^{-1}sr^{-1}$]
E_{kin}/nuc (MeV/nuc)
DRC2, 0MV
DRC2, 506MV
AMS-02
Voyager 1

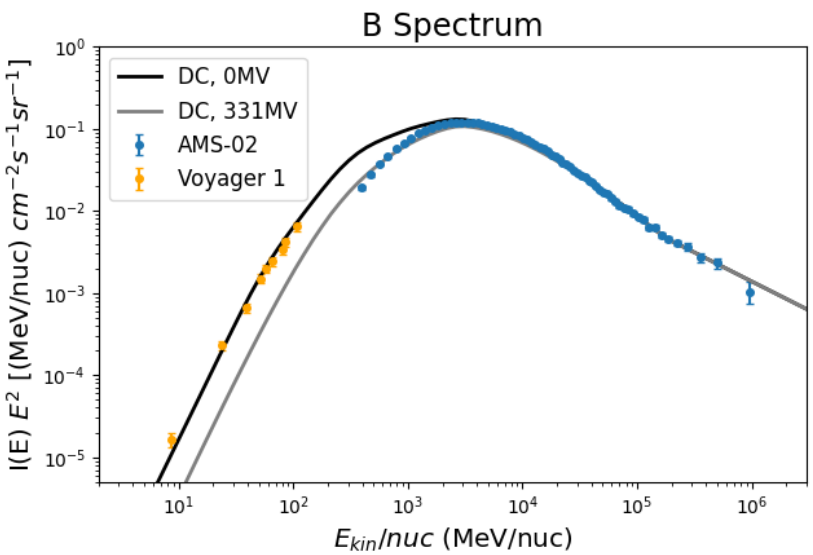

B Spectrum
I(E) E^2 [(MeV/nuc) $cm^{-2}s^{-1}sr^{-1}$]
E_{kin}/nuc (MeV/nuc)
DRC2, 0MV
DRC2, 506MV
AMS-02
Voyager 1

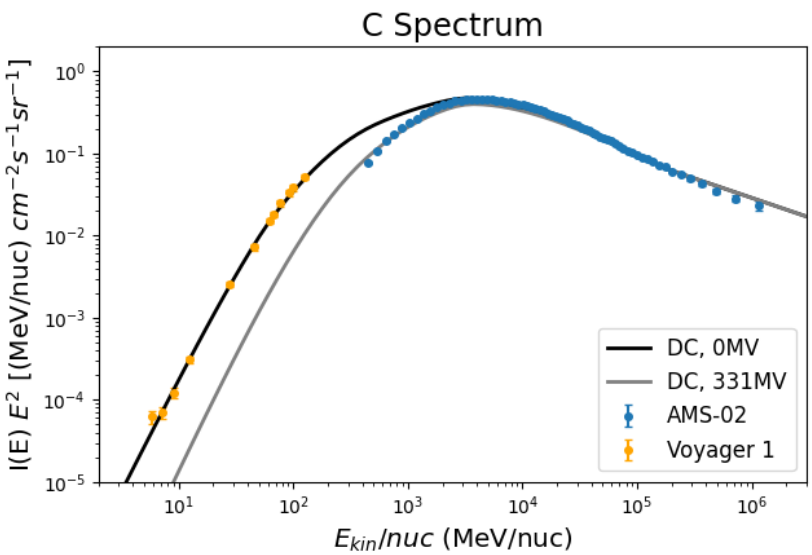

C Spectrum
I(E) E^2 [(MeV/nuc) $cm^{-2}s^{-1}sr^{-1}$]
E_{kin}/nuc (MeV/nuc)
DRC2, 0MV
DRC2, 506MV
AMS-02
Voyager 1

DC: H, He, B, C

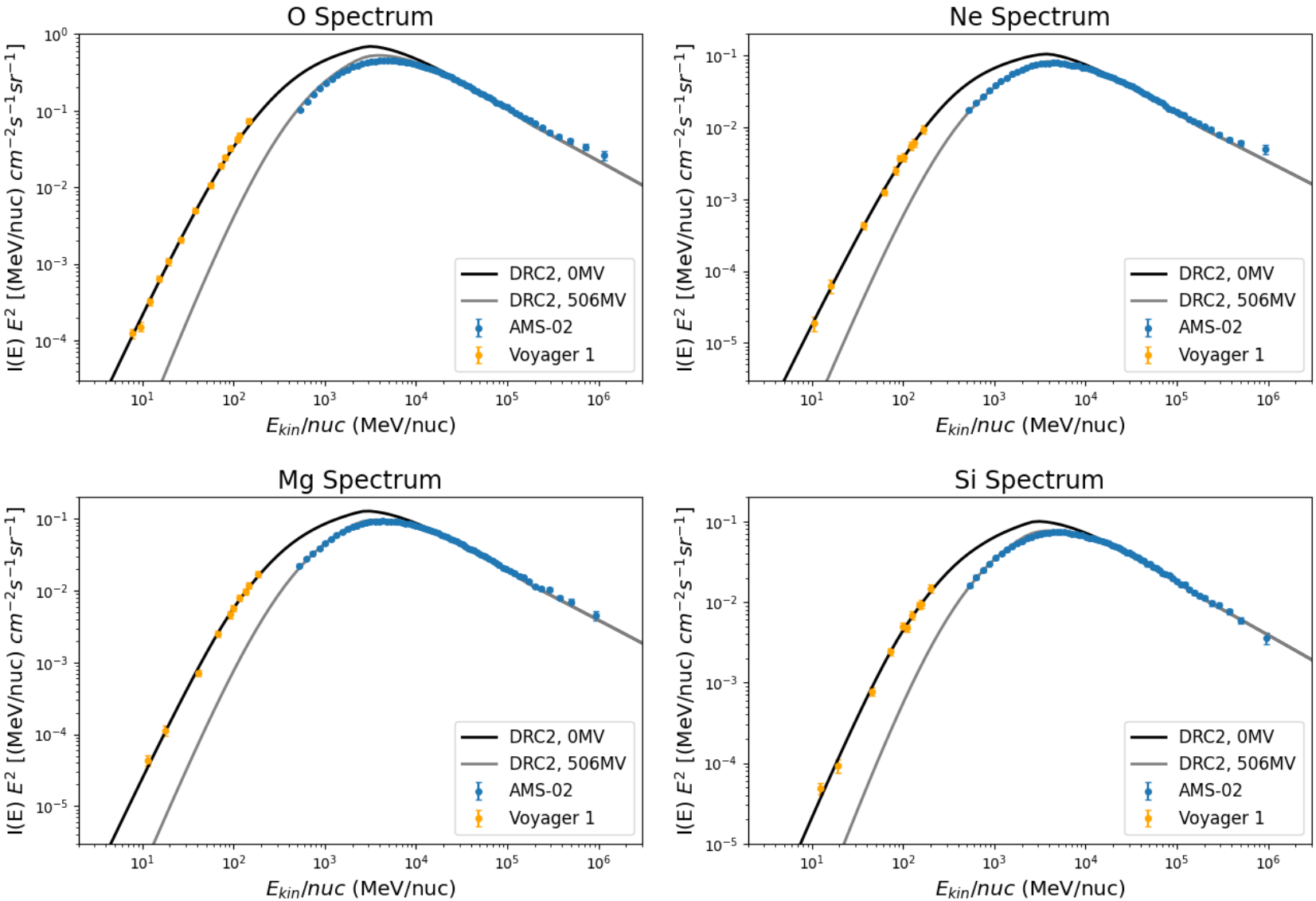

H Spectrum
DC, 0MV
DC, 331MV
AMS-02
DAMPE
CALET
Voyager 1
I(E) E^2 [(MeV/nuc) $cm^{-2}s^{-1}sr^{-1}$]
E_{kin}/nuc (MeV/nuc)


He Spectrum
DC, 0MV
DC, 331MV
AMS-02
Voyager 1
I(E) E^2 [(MeV/nuc) $cm^{-2}s^{-1}sr^{-1}$]
E_{kin}/nuc (MeV/nuc)

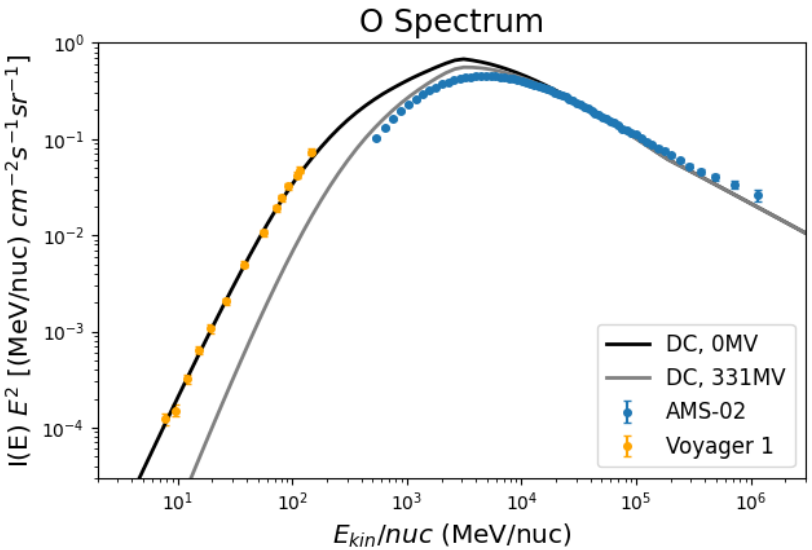

B Spectrum
DC, 0MV
DC, 331MV
AMS-02
Voyager 1
I(E) E^2 [(MeV/nuc) $cm^{-2}s^{-1}sr^{-1}$]
E_{kin}/nuc (MeV/nuc)

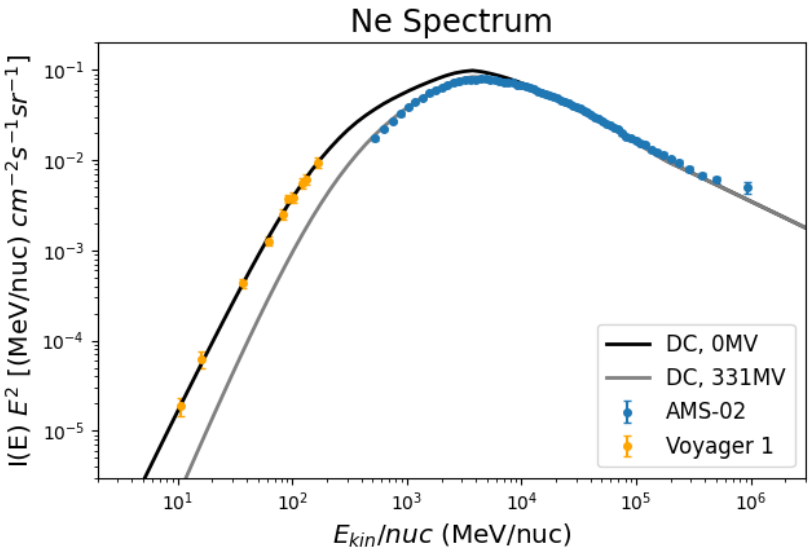

C Spectrum
DC, 0MV
DC, 331MV
AMS-02
Voyager 1
I(E) E^2 [(MeV/nuc) $cm^{-2}s^{-1}sr^{-1}$]
E_{kin}/nuc (MeV/nuc)

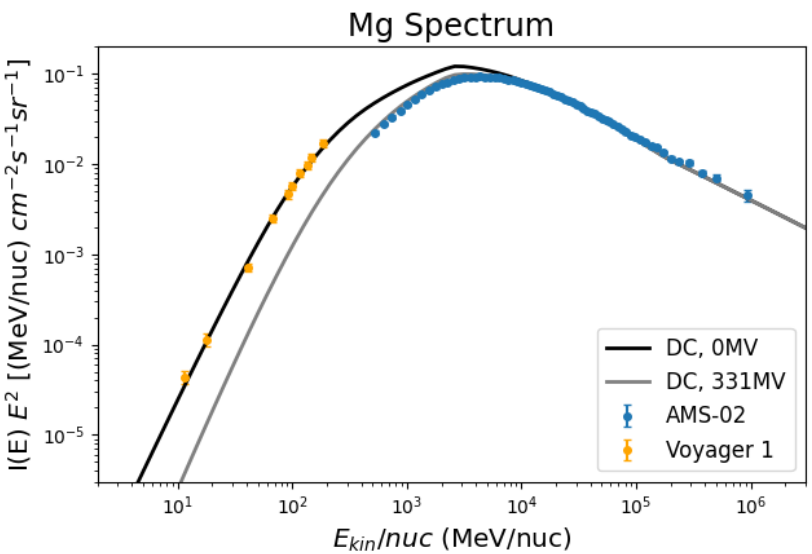
DRC2: O, Ne, Mg, Si

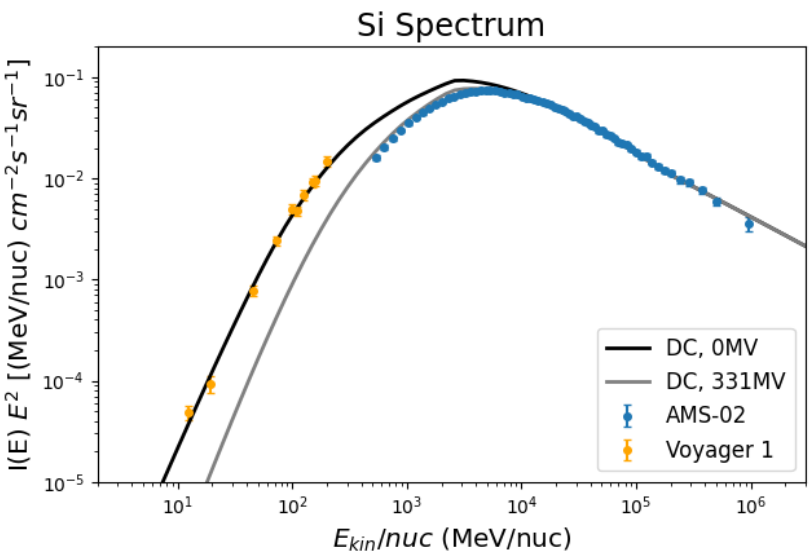


DC: O, Ne, Mg, Si

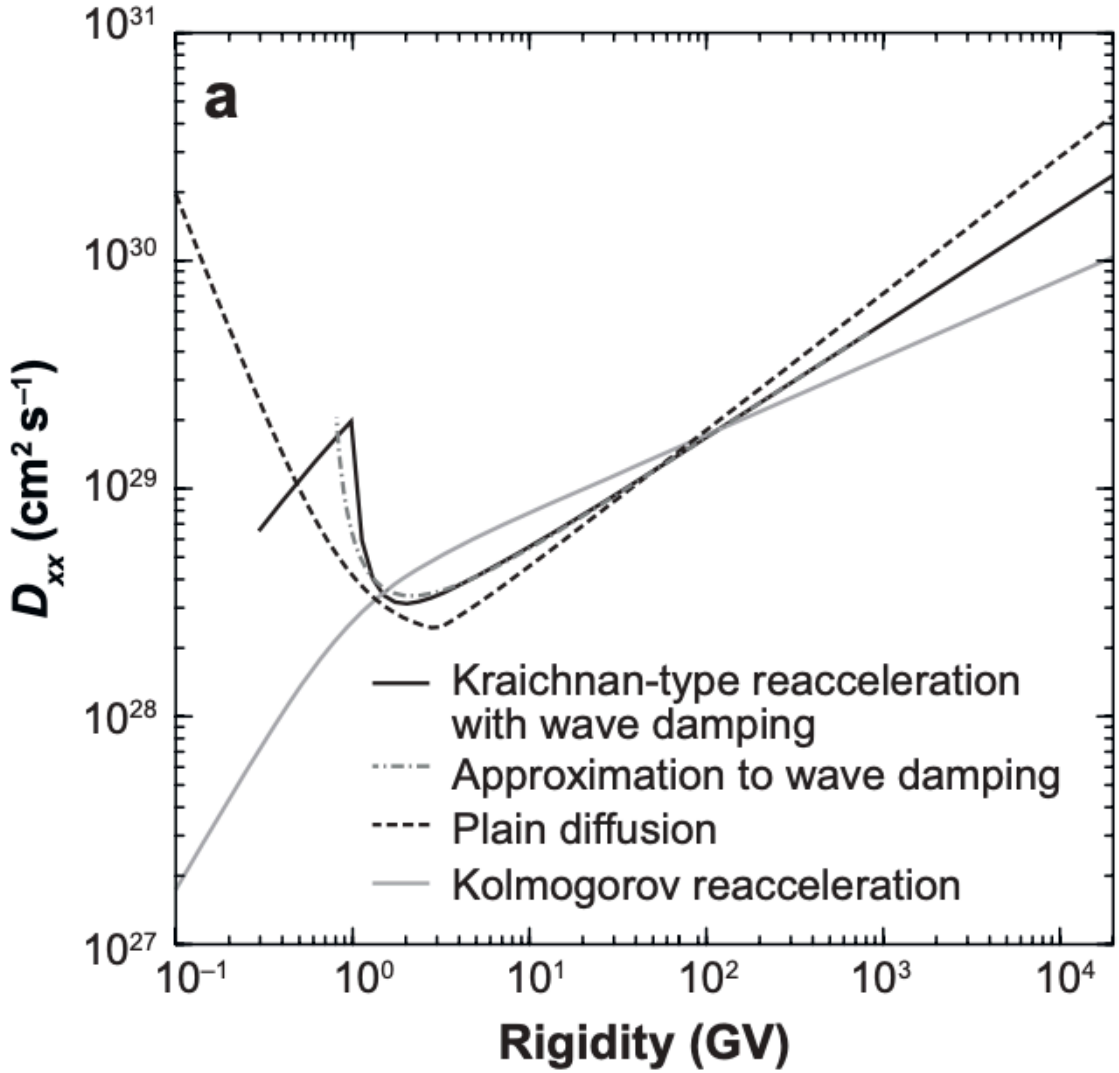

O Spectrum
I(E) E^2 [(MeV/nuc) $cm^{-2}s^{-1}sr^{-1}$]
E_{kin}/nuc (MeV/nuc)
DC, 0MV
DC, 331MV
AMS-02
Voyager 1


Ne Spectrum
I(E) E^2 [(MeV/nuc) $cm^{-2}s^{-1}sr^{-1}$]
E_{kin}/nuc (MeV/nuc)
DC, 0MV
DC, 331MV
AMS-02
Voyager 1

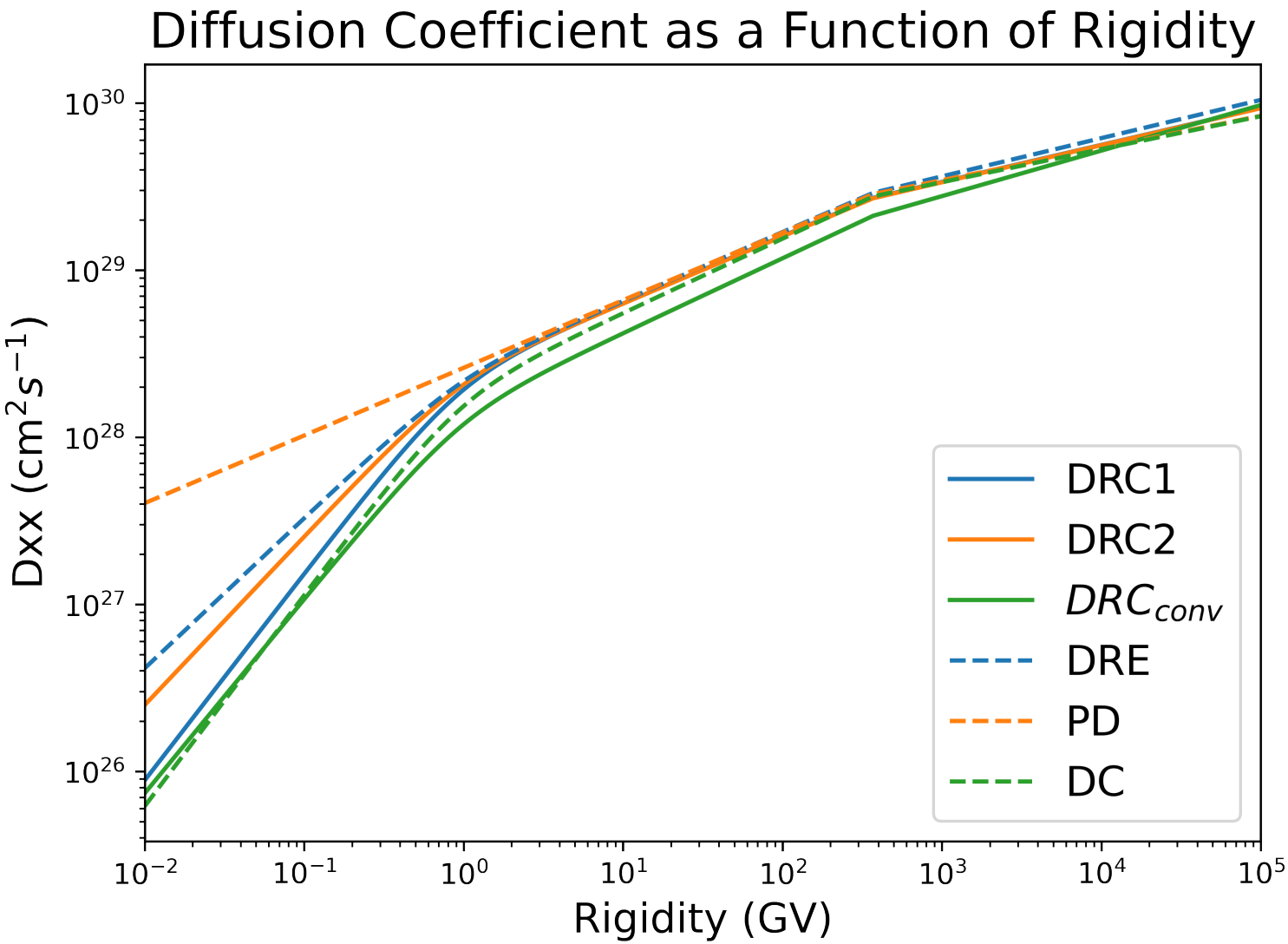

Mg Spectrum
I(E) E^2 [(MeV/nuc) $cm^{-2}s^{-1}sr^{-1}$]
E_{kin}/nuc (MeV/nuc)
DC, 0MV
DC, 331MV
AMS-02
Voyager 1


Si Spectrum
I(E) E^2 [(MeV/nuc) $cm^{-2}s^{-1}sr^{-1}$]
E_{kin}/nuc (MeV/nuc)
DC, 0MV
DC, 331MV
AMS-02
Voyager 1

Typical Diffusion Models (Strong et al. 2007)



Diffusion Coefficient



Conclusions

- We revise the various propagation scenarios with latest CR measurements
- DRC models with two breaks in the spectral indices perform the best
- Effects of including:
  - Convection and reacceleration
  - One vs. two breaks in spectral indices
- PD models exist with no need for a low-energy diffusion break where Dxx turns upwards at low energies
- DC models and DRC models with dV/dz (conv) > 50 km/s/kpc are disfavored by data