Transport of Galactic Cosmic-Ray Nuclei

Benedikt Schroer

Carmelo Evoli, Pasquale Blasi, Damiano Caprioli, Oreste Pezzi, Colby Haggerty

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THE UNIVERSITY OF CHICAGO

Content

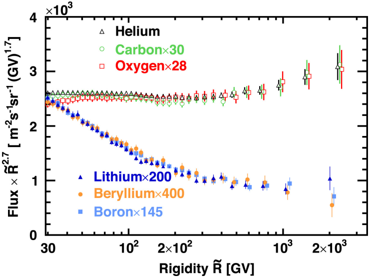
Introduction

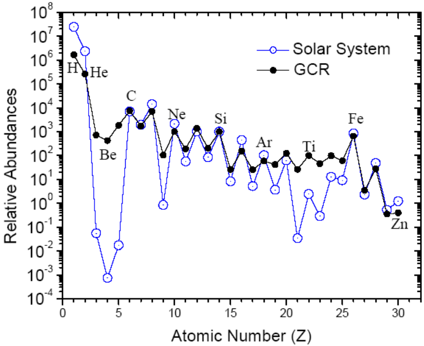
Discovery of CRs

- Cosmic rays are charged particles arriving at Earth from space
- Discovered 100 years ago

[VF Hess Society/Echophysics/Schloss Pöllau/Austria]

Observations





- The overabundant elements show steeper spectra than the other nuclei
- Two classes of CRs: Primaries and Secondaries
- Interpretation of these observations: The secondary CRs are produced via spallation of primaries

[AMS Collaboration 2021; http://www.srl.caltech.edu]

Grammage

- How can we quantify the amount of produced secondaries?

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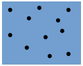
  $\Rightarrow$ Grammage = traversed coulumn density [g/cm^2]
- Grammage in general given by $X = nmcT$



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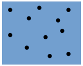
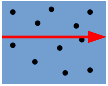


- Grammage in general given by $X = nmcT$
- Several ways to construct T:
  - Ballistic transport: $T = L/c$
  - Diffusive transport: $T = L^2/D(E)$



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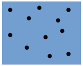

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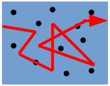

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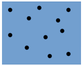

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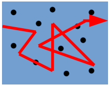
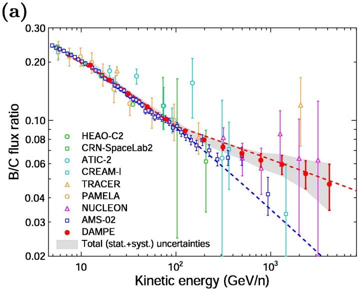


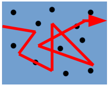
- Can be tested experimentally:
- Secondary over primary ratios let you infer the grammage of CRs on their way to Earth



- Energy dependent quantity $\Rightarrow$ Diffusion ($X = nmcT \propto 1/D(E)$)
- Grammage gives insights about diffusion coefficient and the magnetic turbulence in our Galaxy

[DAMPE Collaboration 2022]

Residence Time



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- What is the propagation volume of CRs? $\Rightarrow$ What is n? Degenerate with T

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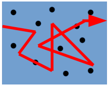

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- Production cross sections of Be isotopes are comparable $\Rightarrow$ expect equal amounts of different Be isotopes

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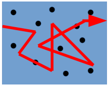

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- $\Rightarrow$ ^{10}Be/^{9}Be ratio depends on confinement time of CRs in the Galaxy

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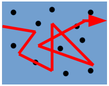

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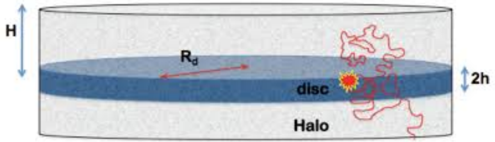
- But ^{10}Be has a half time of $\tau_d \sim 2\,$Myrs
- $\Rightarrow$ ^{10}Be/^{9}Be ratio depends on confinement time of CRs in the Galaxy
- Measurements show this ratio to be roughly ~ 0.1 at $100\,$MeV/n, suggesting a residence time much larger than τ_d [Connell 1998]
- CRs would accumulate the inferred grammage in the disc after $T \sim X/(nmc) \approx 2\,Myrs$ $\Rightarrow$ CRs spend at least part of their life in low density environments

Weighted Slab Model

Standard Picture of CR Transport



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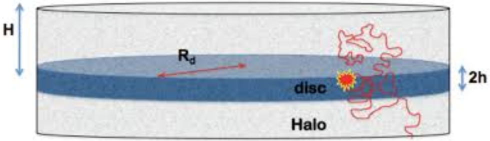

$$-\frac{\partial}{\partial z}\left[D\frac{\partial f_a}{\partial z}\right]+v_A\frac{\partial f_a}{\partial z}\quad-\frac{dv_A}{dz}\frac{p}{3}\frac{\partial f_a}{\partial p}$$

$$+\frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(\frac{dp}{dt}\right)_{a,\mathrm{ion}}f_a\right]+\frac{\mu v(p)\sigma_a}{m}\delta(z)f_a\qquad+\frac{f_a}{\hat{\tau}_{d,a}}$$

$$=\quad 2h_d q_{0,a}(p)\delta(z)\quad+\sum_{a'>a}\frac{\mu\, v(p)\sigma_{a'\to a}}{m}\delta(z)f_{a'}\qquad+\sum_{a'>a}\frac{f_{a'}}{\hat{\tau}_{d,a'}}$$

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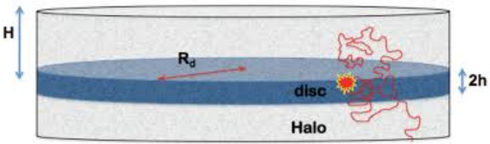

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Diffusion

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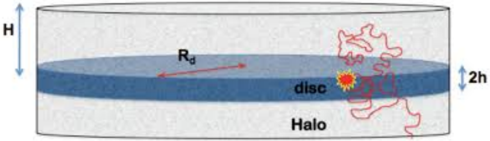

$$-\frac{\partial}{\partial z}\left[D\frac{\partial f_a}{\partial z}\right]\underbrace{}_{\text{Diffusion}} + v_A\frac{\partial f_a}{\partial z}\underbrace{}_{\text{Advection}} - \frac{dv_A}{dz}\frac{p}{3}\frac{\partial f_a}{\partial p}$$

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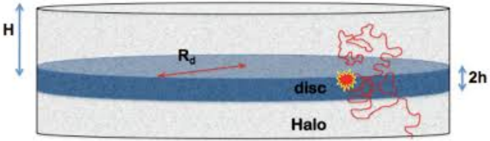

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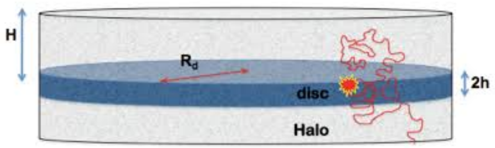

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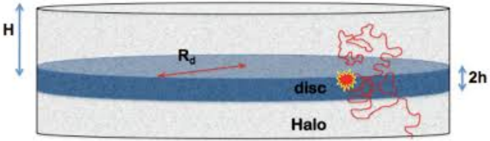

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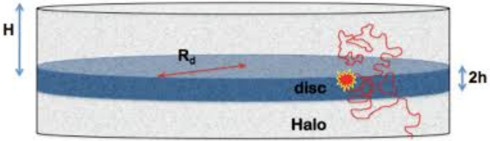

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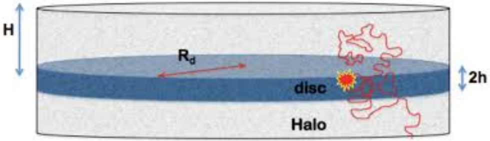

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$$=\underbrace{2h_d q_{0,a}(p)\delta(z)}_{\text{Injection at the sources}}+\sum_{a'>a}\frac{\mu\, v(p)\sigma_{a'\to a}}{m}\delta(z)f_{a'}+\sum_{a'>a}\frac{f_{a'}}{\hat{\tau}_{d,a'}}$$

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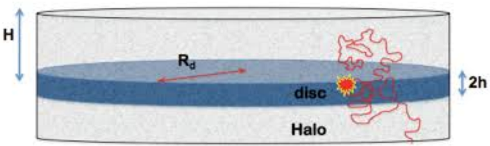

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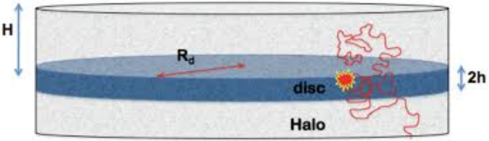

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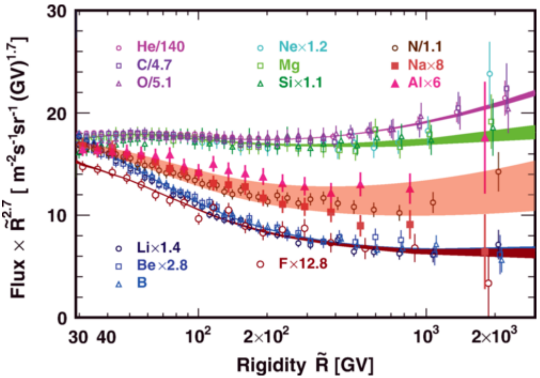
- $\sim$ 90 coupled differential equations

Overview

- Same equation used by different groups with two different approaches: solving the equation numerically [Korsmeier & Cuoco 2021; Boschini et al. 2021; De La Torre Luque et al. 2022] or semianalytically [Evoli et al. 2019; Weinrich et al. 2020; Schroer et al. 2021]
- Big differences can arise from different cross-section models used
- Uncertainties in production cross sections of $\sim 20 - 30\,\%$ are often limiting factor to reach conclusions
- Focus has been on elements lighter than O but since the release of AMS-02 data of heavier nuclei, the whole nucleus chain was incorporated into the models [Boschini et al. 2021; Schroer et al. 2021; De La Torre Luque et al. 2022]
- What are the problems that you can study with this approach?

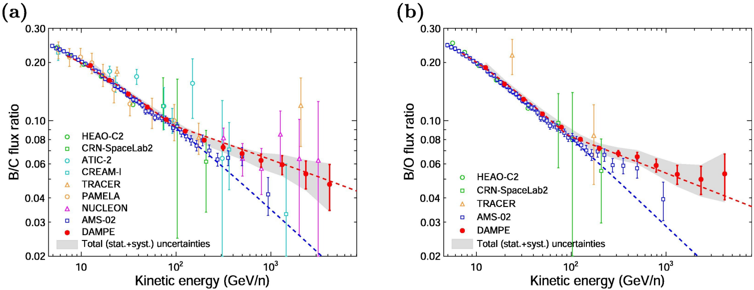
More classes?



- Different slopes measured by AMS for heavier primaries
  $\Rightarrow$ New insights about diffusive shock acceleration?

[AMS Collaboration 2021]

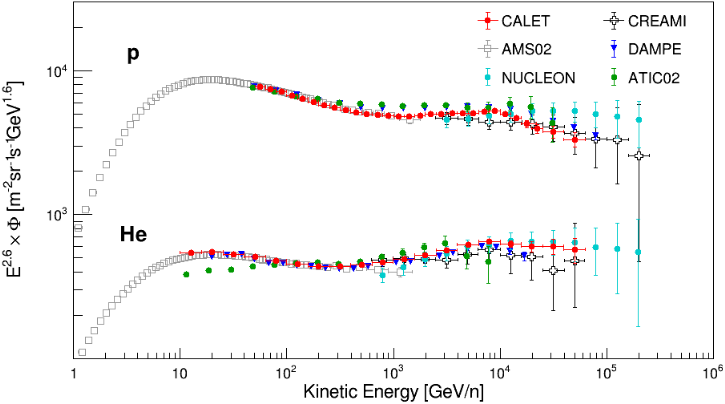
Hardening



- Energy dependence of $D(E)$, change of slope?

[DAMPE Collaboration 2022]

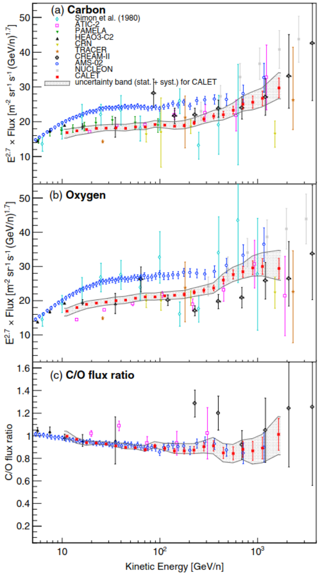
Softening



- 2nd break observed at 10 TeV, maybe a local source [Malkov, Moskalenko 2022] or propagation effect [Chernyshov et al. 2022]

[CALET Collaboration 2023]

There is a Problem



[CALET Collaboration 2020]

- The absolute fluxes of elements heavier than He show significantly different normalizations
- Makes a universal fit using data from different experiments more difficult

Observations

- These measurements led to many interesting discoveries:
  - Spectral hardening at 300 GV
  - Spectral softening around 10 TV
  - ...
- Each new measurement has the potential to unveil a new, unexpected aspect of CR transport which will ultimately lead to an increasingly complete picture
- Requires careful analysis of what is the origin of the feature, e.g., hardening due to a change of slope in $D(E)$
- This can be motivated by a spatially dependent diffusion coefficient [Tomassetti 2012] or transition of scattering of self-generated to extrinsic turbulence [Blasi et al. 2012]

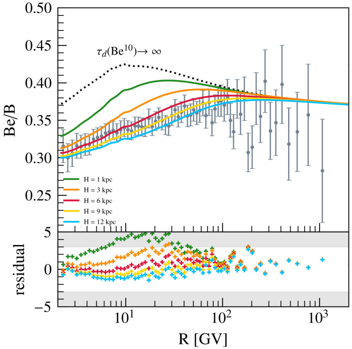
Our Model

One can rewrite as equation in terms of grammage and flux $I_a(E) = 4\pi A p^2 f_a(p)$:

$$\frac{I_a(E)}{X_a(E)} + \frac{\mathrm{d}}{\mathrm{d}E}\left(\left[\left(\frac{\mathrm{d}E}{dx}\right)_{ad} + \left(\frac{\mathrm{d}E}{dx}\right)_{ion,a}\right] I_a(E)\right)$$
$$+\frac{I_a(E)}{X_{\mathrm{cr,a}}} = 2h\frac{A_a p^2 q_a(p)}{\mu v} + \sum_{a'>a}\frac{I_{a'}(E)}{m}\sigma_{a'\to a}$$

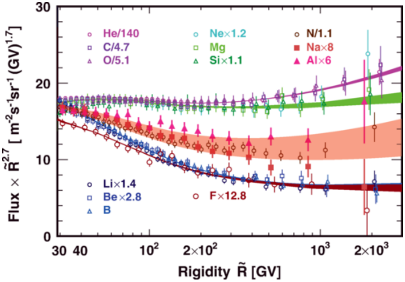
- where we introduced the critical grammage $X_{\mathrm{cr,a}} := \frac{m}{\sigma_a}$ and the grammage traversed by nuclei a $X_a(E) := \frac{\mu v}{2v_A}\left(1 - e^{-\frac{v_A H}{D}}\right)$
- Solutions only sensitive to ratio $\frac{H}{D}$
- Without energy losses primaries $I_a(E) \propto E^{-\gamma+2-\delta}$ and secondaries $I_a(E) \propto E^{-\gamma+2-2\delta}$
- $\Rightarrow$ Secondary over primary ratios $\propto E^{-\delta}$

Determining the Halo size



- For radioactive nuclei $X_a(E) \approx \frac{\mu v}{2}\sqrt{\frac{\tau_d}{D}}$ for $\tau_d \ll \min\left(\frac{H^2}{D}, \frac{H}{v_A}\right)$
- With our model a Halo size $H \geq 5\,\mathrm{kpc}$ is preferred [Evoli et al. 2020]
- Influenced by cross section uncertainties
- Compatible within uncertainties with $\sim 5\,\mathrm{kpc}$ found by [Weinrich et al. 2020] and $\sim 4\,\mathrm{kpc}$ by [Boschini et al. 2020; Maurin et al. 2022]
- In the following, we fix $H = 7\,\mathrm{kpc}$ in our model

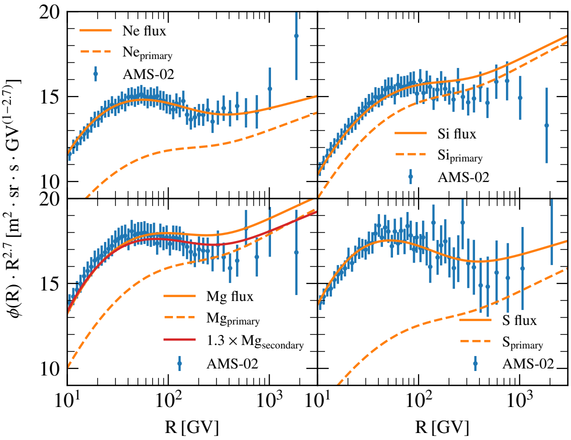
Intermediate-Mass Nuclei



- AMS-02 measures different slopes for different nuclei
- Good fits have been achieved using different injection slopes for different primary CRs [Boschini et al. 2020; De La Torre Luque et al. 2022]
- However, is it possible to fit the data using the same injection slope?

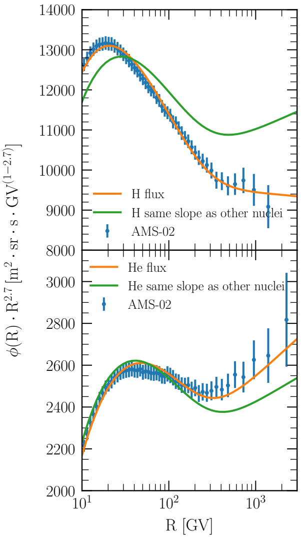
[AMS Collaboration 2021]

Our Results



- Requiring the same slope leads to reasonably good fits
- Possible tensions can be lifted with cross-section uncertainties (see Mg) and possibly source grammage plays a role as well

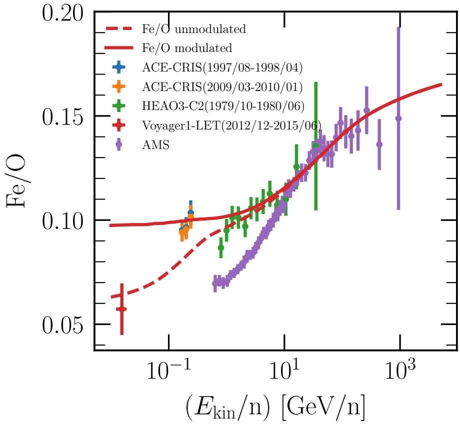
[Schroer et al. 2021]



[Schroer et al. 2021]

- H and He require a different slope than other nuclei and each other, confirms result of previous study [Evoli et al. 2019] and independently confirmed by [Weinrich et al. 2020]
- Puzzling result as even theories that explain different slope of H and He predict same slope of He and heavier nuclei [Malkov et al. 2012]

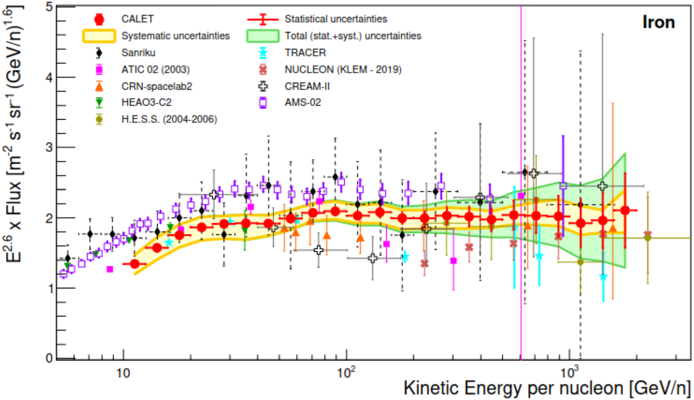
One Exception



- Our model is compatible with all available data except AMS-02
- Fe data might require to incorporate a new or so far neglected effect into our model

[Schroer et al. 2021]

CALET Fe Measurement



- CALET measurement shows different normalization than AMS-02, but confirms slope
- However does not cover the part of the spectrum where we see the large deviations from our model and other experiments

[CALET Collaboration 2021]

Possible Caveats

We tested different possible shortcomings of our model:

- Iron suffers severe energy losses, maybe ionization or spallation are not properly accounted for.

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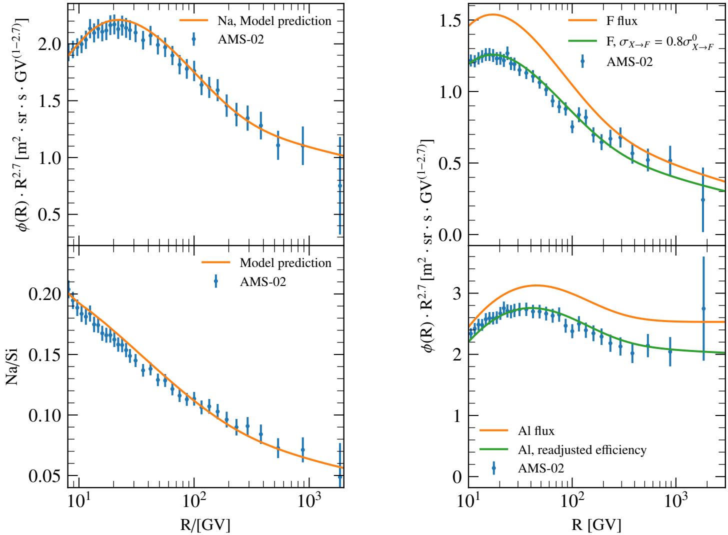
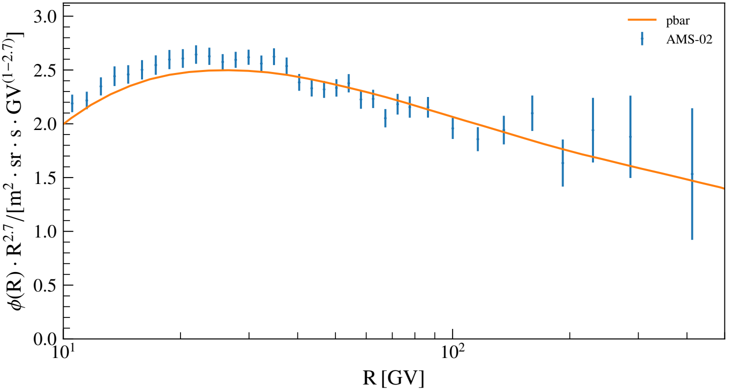
- ~~Iron could have another injection slope~~ Does not give a satisfying fit either

Model Predictions vs. Measurements



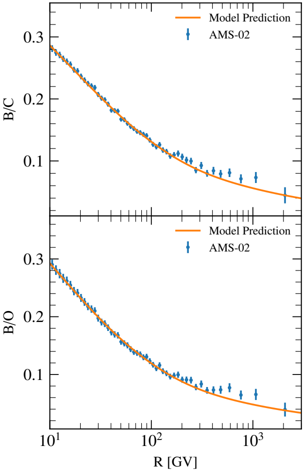
- Prediction for Na agrees perfectly while Al and F require slight modifications

Preliminary Results for Antiprotons



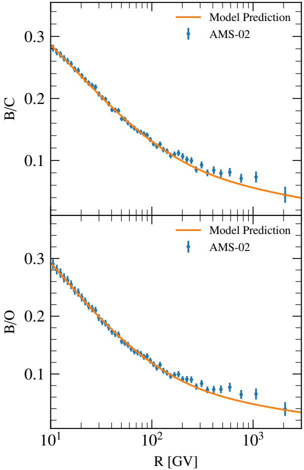
- We use the up-to-date, differential cross section by [Korsmeier et al. 2018]
- Preliminary results seem promising, no need of new physics

Fit to light Ratios



[Schroer et al. 2021]

Fit to light Ratios



- Source grammage can improve agreement at high energies [Evoli et al. 2019; Bresci et al. 2019]

[Schroer et al. 2021]

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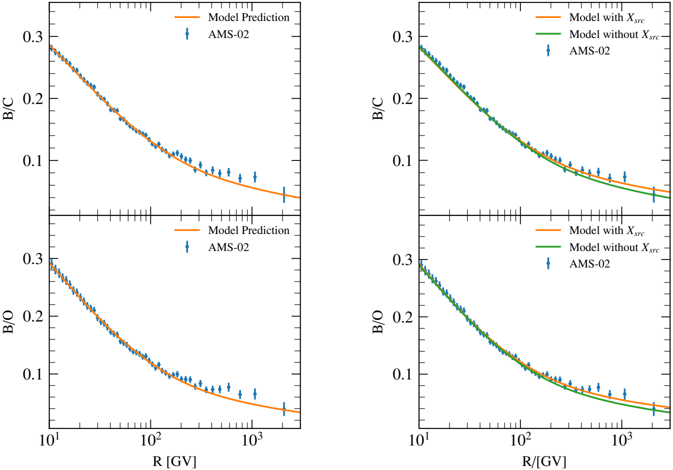


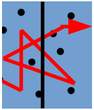
- Source grammage can improve agreement at high energies [Evoli et al. 2019; Bresci et al. 2019]
- Even more important at higher energies probed by DAMPE and CALET

[Schroer et al. 2021]

CRs escaping SNRs

CR Acceleration at SNR

- CRs are accelerated at shocks
- Gain energy every time they pass the shock
- Highest energy particles leave acceleration region



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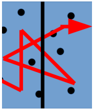
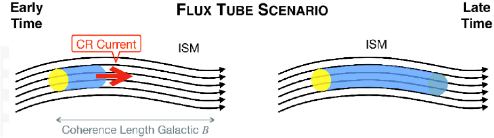


- CRs are accelerated at shocks
- Gain energy every time they pass the shock
- Highest energy particles leave acceleration region
- $\Rightarrow$ Electric current grows magnetic fields trapping lower energy particles [Bell et al. 2013; Caprioli et al. 2009; Reville et al. 2009]
- At zeroth order $X_{src} \approx n_{SNR} mc T_{SNR}$ accumulated while confined in the remnant
- In principle, X_{src} can have other contributions as well

Source in the ISM

- Once particles leave the source they diffuse on Galactic scales
- interstellar magnetic field is coherent on scales of 10-50pc [Ptuskin et al. 2008]
- mean free path $\lambda = \frac{3D}{v} \approx 1 \cdot E_{\mathrm{GeV}}^{1/2}\,\mathrm{pc} \Rightarrow$ ballistic escape initially



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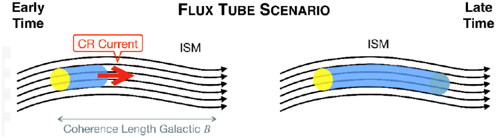

- $\Rightarrow$ CR escape preferentially along magnetic field lines and are ballistic above a certain energy $\Rightarrow$ 1D problem
- Under the flux tube approximation analytical solutions [Ptuskin et al. 2008; Malkov et al. 2013] were derived for a CR cloud expanding in a tube and exciting the resonant streaming instability, corresponding to a faded accelerator

Flux Tube Approximation

- Analytical and numerical solutions investigated the excitation of the **resonant streaming instability** [Malkov et al. 2013; D'Angelo et al. 2016; Nava et al.2016 & 2019; Recchia et al. 2022]
- Strong self-confinement in the circum-source region is found, becoming less effective towards higher energies
- As a result particles acquire a grammage in the circum-source region, while being trapped
- Estimates of this grammage range from it being negligible [Nava et al. 2019; Recchia et al. 2022] to being significant [D'Angelo et al. 2016]
- Strongly depends on relevant damping mechanisms

Non-resonant Streaming Instability

- Inject a flux of particles into a flux tube with the injected flux = flux escaping the shock
- Growth Condition: [Bell 2004]

$$\frac{\phi_{CR}(E > E_0)}{c} E_0 \gg \frac{B_0^2}{4\pi}$$

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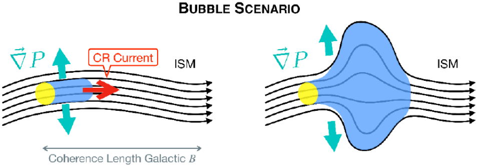
- For typical, young SNR $\frac{4\pi \phi_{CR} E_0}{c B_0^2} \approx 100$ [Schroer et al. 2021, ApJL]
- very fast growing mode $\gamma_{max}^{-1} \approx 1.1(\mathrm{E}/2.5\mathrm{TeV})\,\mathrm{yr}$, saturates after $\sim 5 - 10\gamma_{max}^{-1}$
- happens in very short time compared to typical age of SNR $\sim 10^{4..6}$ yr

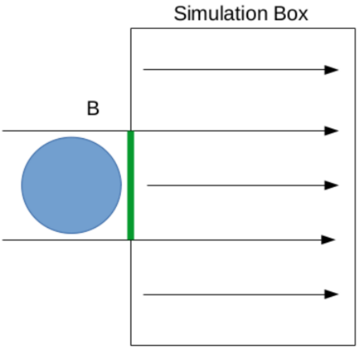
Consequences

- When particles start to diffusive, number density and pressure increase
- $\Rightarrow$ pressure in CR exceeds gas pressure $\rightarrow$ breaks 1D geometry because overpressurized region will expand in transverse direction

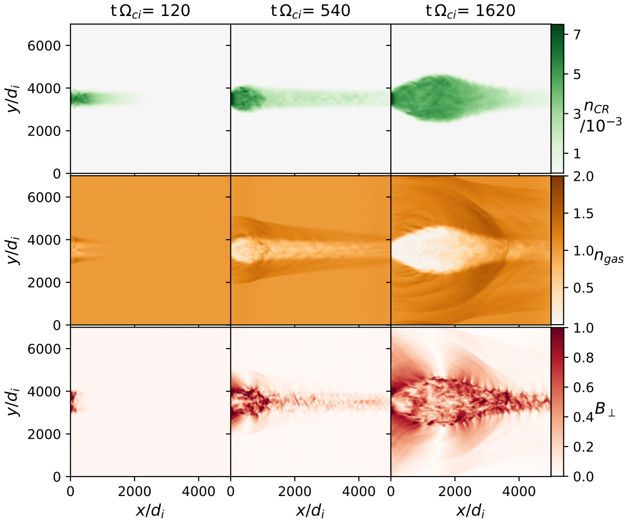


Simulation

- Hybrid particle in cell simulation with `dHybridR` [Haggerty & Caprioli 2019]
- Solve Maxwell equations and equations of motion for macroparticles
- Electromagnetic fields from the motion of the particles

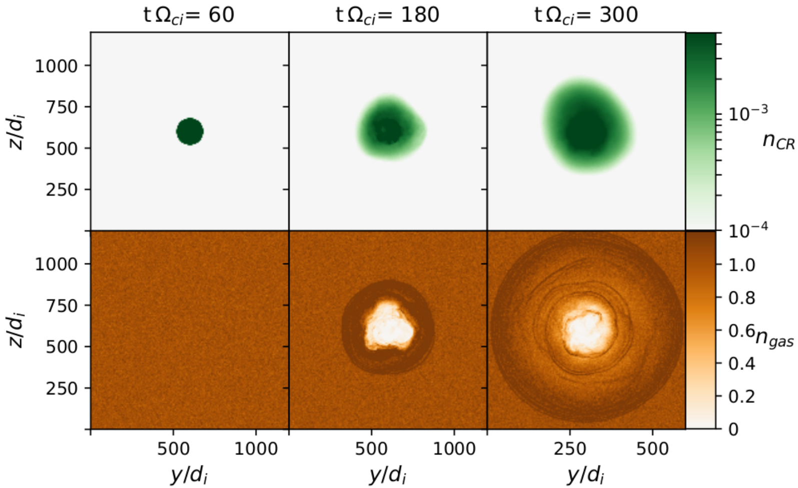


Evolution in 2D



[Schroer et al. 2021, ApJL]

Evolution in 3D



[Schroer et al. PoS(ICRC2021)]

Implications

- What are the observational consequences?

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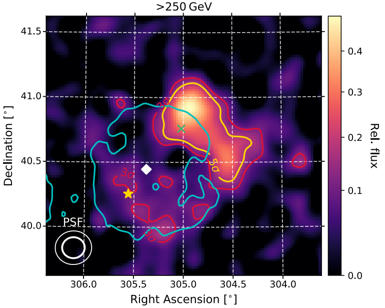
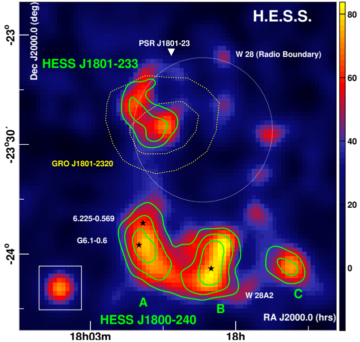
- What are the observational consequences?
- Strong particle trapping influences the grammage accumulated by the particles
- Strongly dependent on achieved suppression of diffusion coefficient ξ and the gas density inside the bubble w.r.t. the ISM density η

$$\frac{X_{bubble}}{X_{Galactic}} \approx \frac{3 \times 10^{-1}\eta}{(\xi/10^{-2})} \left(\frac{L}{50pc}\right)^2$$

- $\Rightarrow$ With $\eta = 1$ this gives $\sim 10\%$, contributes an additional grammage component to the fits of CR nuclei, but not the major part





- Hints for strongly reduced diffusion coefficient observed near SNRs [Fujita et al. 2009; Gabici et al. 2010]
- Difficult task to detect due to specific necessary conditions, like presence of nearby molecular clouds

[MAGIC Collaboration 2010; HESS Collaboration 2008]

Conclusions

Conclusions

- Many different groups with similar approaches able to fit AMS-02 data of lighter nuclei
- Cross section uncertainties play an important role for dectecting physical anomalies
- Our model is able to reproduce flux of all intermediate-mass to light elements using a single injection slope for all nuclei heavier than He reducing heavily the amount of free parameters compared to other studies like [Boschini et al. 2020; De La Torre Luque et al. 2022] who fit all nuclei simultaneously
- Able to give predictions which are compatible with new data without refitting the model
- There seems to be an issue with Fe, that we still need to understand

Conclusions

- Source grammage might improve the fits
- Particles leaving a SNR generate magnetic instabilities
- Form bubbles of low diffusivity where particles stay trapped for long time