Acceleration of cosmic ray secondaries inside old supernova remnants

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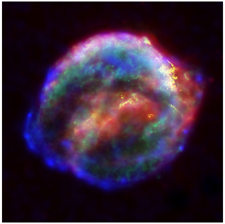
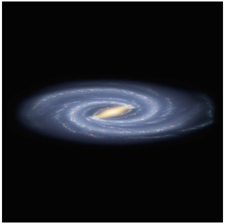
Secondaries from the source?

Common belief: secondaries from propagation dominate since the grammage in the ISM is larger than in the source



$$\langle \tau_{\mathrm{src}} \rangle \lesssim \tau_{\mathrm{SNR}} \approx 10^{4\ldots5}\,\mathrm{yr}$$
$$n_{\mathrm{src}} \lesssim 10\,\mathrm{cm}^{-3}$$
$$\Rightarrow X_{\mathrm{src}} \approx 0.2\,\mathrm{g\,cm}^{-2}$$



$$\langle \tau_{\mathrm{ISM}} \rangle \sim \tau_{\mathrm{esc}} \approx 10^{7}\,\mathrm{yr}$$
$$n_{\mathrm{ISM}} \approx 0.1\,\mathrm{cm}^{-3}$$
$$\Rightarrow X_{\mathrm{ISM}} \approx \mathrm{few\,g\,cm}^{-2}$$

However, secondaries from source can have a harder spectrum!

The transport equation

$$\frac{\partial \psi_j}{\partial t} = \nabla \cdot (\kappa \cdot \nabla \psi_j - \mathbf{u}\, \psi_j)$$
spatial diffusion and advection

$$+ \frac{\partial}{\partial p} \left(p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_j \right)$$
momentum diffusion

$$+ \frac{\partial}{\partial p} \left(- \frac{\mathrm{d}p}{\mathrm{d}t} \psi_j + \frac{p}{3} (\nabla \cdot \mathbf{u})\, \psi_j \right)$$
momentum change incl. adiabatic

$$- v n_{\mathrm{gas}} \sigma_j \psi_j - \frac{\psi_j}{\tau_j}$$
spallation and decay

$$+ v n_{\mathrm{gas}} \sum_{k>j} \sigma_{k \to j} \psi_k + \sum_{k>j} \frac{\psi_k}{\tau_{k \to j}}$$
spallation and decay

$$+ S_j$$
primary sources

The transport equation

for shock acceleration

$$\frac{\partial \psi_j}{\partial t} = \nabla \cdot (\kappa \cdot \nabla \psi_j - \mathbf{u}\, \psi_j)$$ spatial diffusion and advection

$$+ \frac{\partial}{\partial p} \left(p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_j \right)$$ momentum diffusion

$$+ \frac{\partial}{\partial p} \left(- \frac{\mathrm{d}p}{\mathrm{d}t} \psi_j + \frac{p}{3} (\nabla \cdot \mathbf{u})\, \psi_j \right)$$ momentum change incl. adiabatic

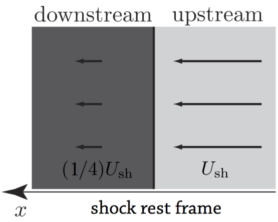
$$- v n_{\text{gas}} \sigma_j \psi_j - \frac{\psi_j}{\tau_j}$$ spallation and decay

$$+ v n_{\text{gas}} \sum_{k>j} \sigma_{k \to j} \psi_k + \sum_{k>j} \frac{\psi_k}{\tau_{k \to j}}$$ spallation and decay

$$+ S_j$$ primary sources

Macroscopic approach

Seminal papers in 1977/78 by Krymsky; Axford, Leer, Skaldron; Blandford, Ostriker; also Bell



- Consider steady-state transport equation for phase-space density f_i:

$$u \frac{\partial f_i}{\partial x} - \frac{\partial}{\partial x} \kappa \frac{\partial f_i}{\partial x} - \frac{p}{3} \frac{\mathrm{d}u}{\mathrm{d}x} \frac{\partial f_i}{\partial p} = 0$$

- For $x \neq 0$,

$$f_i(x,p) = \begin{cases} g_i(p) \exp\left[\frac{x}{\kappa(p)/u}\right] + Y_i \delta(p - p_{\rm inj}) & \text{for } x < 0 \\ f_{i,0}(p) & \text{for } x > 0 \end{cases}$$

Macroscopic approach

Seminal papers in 1977/78 by Krymsky; Axford, Leer, Skaldron; Blandford, Ostriker; also Bell

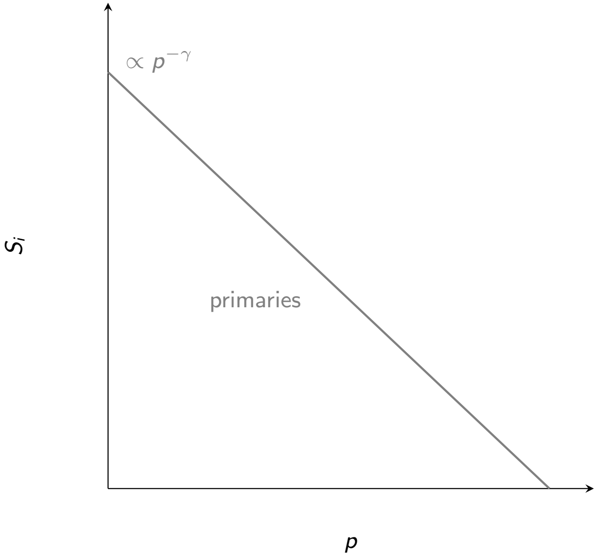
- Can derive matching conditions and find for the spectrum at shock,

$$f_{i,0}(p) = \gamma p^{-\gamma} \int_0^p \mathrm{d}p' \, p'^{\gamma-1} Y_i \delta(p' - p_{\mathrm{inj}}) + \text{const.} \times p^{-\gamma}$$

  with spectral index $\gamma \equiv \frac{3r}{r-1}$
- With $r \simeq 4$: $f_{i,0}(p) \propto p^{-4} \quad \Rightarrow \quad \psi_i(p) = 4\pi p^2 f_{i,0}(p) \propto p^{-2}$

Strong ($r = 4$) shock accelerates CRs to p^{-2} spectrum!

Primaries only



DSA with secondaries

Blasi (2009); Blasi & Serpico (2009); Mertsch & Sarkar (2009); Ahlers *et al.* (2010); Tomassetti & Donato (2012); Cholis & Hooper (2012); Mertsch & Sarkar (2014); Cholis *et al.* (2017); Mertsch, Vittino, Sarkar (2020); Kawanak & Lee (2021)

- Transport equation

$$u \frac{\partial f_i}{\partial x} - \frac{\partial}{\partial x} \kappa \frac{\partial f_i}{\partial x} - \frac{p}{3} \frac{\mathrm{d}u}{\mathrm{d}x} \frac{\partial f_i}{\partial p} + \Gamma_i f_i = q_i \quad \text{with} \quad \underbrace{\Gamma_i = vn \sum_{j<i} \sigma_{i \to j}}_{\text{spallation loss}}, \; \underbrace{q_i = vn \sum_{j>i} \sigma_{j \to i} f_j}_{\text{spallation production}}$$

1. Downstream $(+)$ solution is not const. anymore:

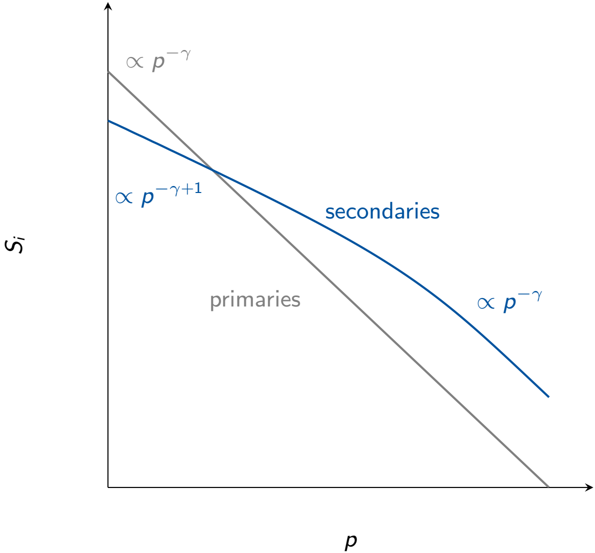
$$f_i^+(x, p) \simeq f_i^0(p) + r \Big(\underbrace{q_i^0(p)}_{\propto p^{-\gamma}} - \Gamma_i^+ f_i^0(p) \Big) \frac{x}{u_+}$$

2. Spectrum at shock is not $\propto p^{-\gamma}$ anymore:

$$f_i^0(p) = \gamma p^{-\gamma} \int_0^p \mathrm{d}p' \, p'^{\gamma - 1} \left(\underbrace{Y_i \delta(p' - p_{\text{inj}})}_{\to p^{-\gamma}} + (1 + r^2) \mathrm{e}^{-p'/p_\Gamma} \underbrace{\underbrace{\frac{\kappa(p')}{u_-^2}}_{\propto p'} \underbrace{q_i^0(p')}_{\propto p'^{-\gamma}}}_{\to p^{-\gamma+1}} \right)$$

DSA with secondaries

Mertsch, Vittino, Sarkar (2020)



The transport equation

for galactic transport

$$\frac{\partial \psi_j}{\partial t} = \nabla \cdot \left(\kappa \cdot \nabla \psi_j - \mathbf{u} \psi_j \right)$$ spatial diffusion and advection

$$+ \frac{\partial}{\partial p} \left(p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_j \right)$$ momentum diffusion

$$+ \frac{\partial}{\partial p} \left(- \frac{\mathrm{d}p}{\mathrm{d}t} \psi_j + \frac{p}{3} \left(\nabla \cdot V \right) \psi_j \right)$$ momentum change incl. adiabatic

$$- v n_{\mathrm{gas}} \sigma_j \psi_j - \frac{\psi_j}{\tau_j}$$ spallation and decay

$$+ v n_{\mathrm{gas}} \sum_{k>j} \sigma_{k \to j} \psi_k + \sum_{k>j} \frac{\psi_k}{\tau_{k \to j}}$$ spallation and decay

$$+ S_j$$ primary sources

Challenges

Mertsch, Vittino, Sarkar (2020)

Large number of free parameters

- Unknown parameters:
  - source spectrum: γ_1^{p}, γ_2^{p}, $\mathcal{R}_{\mathrm{br}}^{\mathrm{p}}$, s^{p}, γ_2^{He}, γ_2^{C}, γ_2^{nuc}
  - gal. transport: κ_0, $\mathcal{R}_{12}$, $\mathcal{R}_{23}$, s_{12}, s_{23}, δ_1, δ_2, δ_3, v_{A}
  - solar modulation: ϕ_{p}, ϕ_{e^+}, $\phi_{\bar{\mathrm{p}}}$, ϕ_{nuc}
  - accn. of secs.: τ_{SNR}, K_{B}, $\mathcal{R}_{\mathrm{max}}$, α

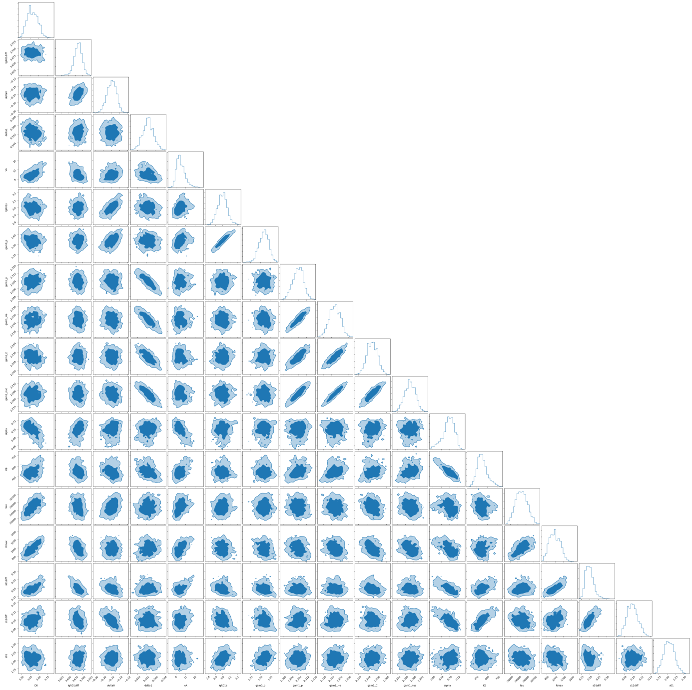
  $\Big\}\ \mathcal{O}(20)$
- Cannot adopt values from other studies

$\rightarrow$ Need to efficiently scan parameter space

- Used affine-invariant MC sampler `emcee`

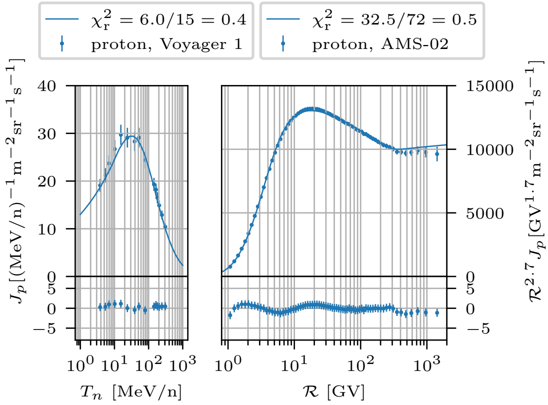
Cross-section uncertainty

- For e^+: Dermer, Kamae *et al.*, Huang *et al.*
- For $\bar{p}$: Winkler, Feng *et al.*, Kachelriess *et al.*, Tan & Ng
- Some needed to be implemented in `GALPROP`


D0
lgR01diff
delta0
delta1
vA
lgR01s
gam0_p
gam1_p
gam1_He
gam1_C
gam1_nuc
alpha
KB
tau
Rmax
s01diff
s12diff
s01

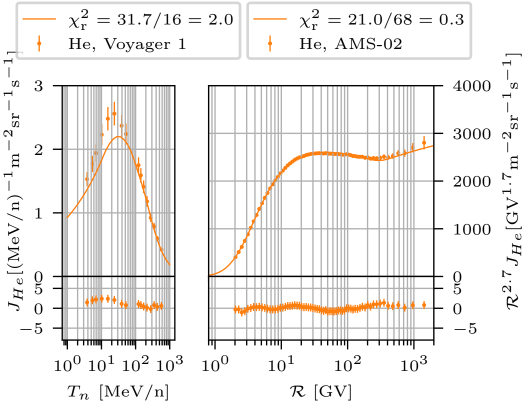
Results: proton

Mertsch, Vittino, Sarkar (2020)



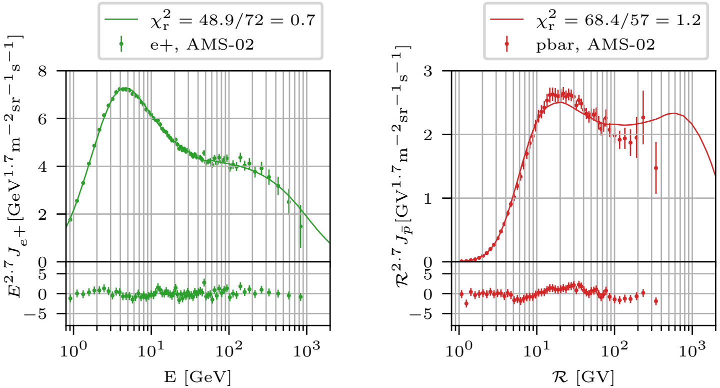
Results: helium

Mertsch, Vittino, Sarkar (2020)



Results: positrons, antiprotons

Mertsch, Vittino, Sarkar (2020)



Future improvements

Reminder: steady-state spectrum at shock:

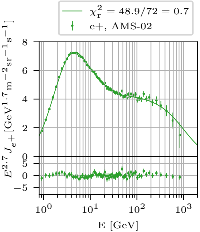
$$f_i^0(p) = \gamma p^{-\gamma} \int_0^p \mathrm{d}p' \, p'^{\gamma-1} \left(\underbrace{Y_i \delta(p' - p_{\mathrm{inj}})}_{\to p^{-\gamma}} + (1 + r^2) \mathrm{e}^{-p'/p_\Gamma} \underbrace{\underbrace{\frac{\kappa(p')}{u_-^2}}_{\propto p'} \underbrace{q_i^0(p')}_{\propto p'^{-\gamma}}}_{\to p^{-\gamma+1}} \right)$$

Additional effects

- Time-dependence, e.g. for shock speed — hydro, t_{dyn}
- Self-consistent $\kappa(p)$ — kinetic, t_{gyro}
- Escape — hydro-kinetic, ?

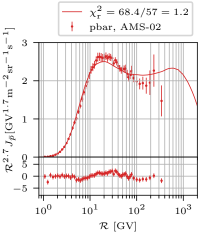
$\rightarrow$ A multi-scale problem!

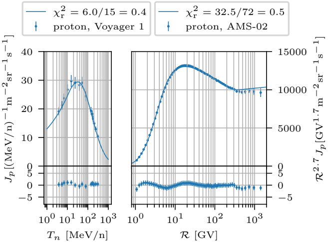
Summary



- Secondary CRs get shock accelerated inside supernova remnants
- Can explain the e^+ excess, the hard $\bar{p}$ spectrum, . . .
- No need for new class of sources!

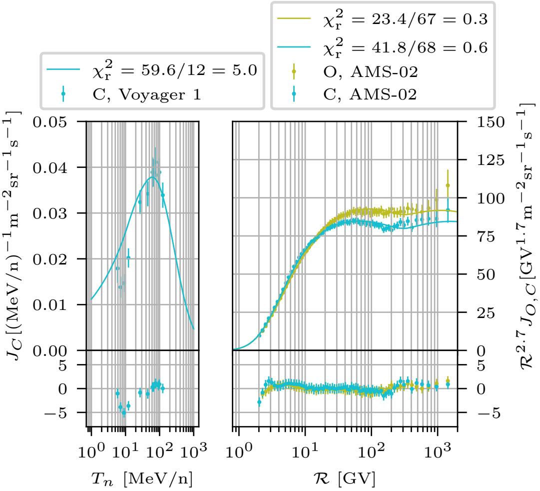
Mertsch, Vittino, Sarkar (2020), arXiv:2012.12853





Results: carbon, oxygen

Mertsch, Vittino, Sarkar (2020)



Results: boron, nitrogen

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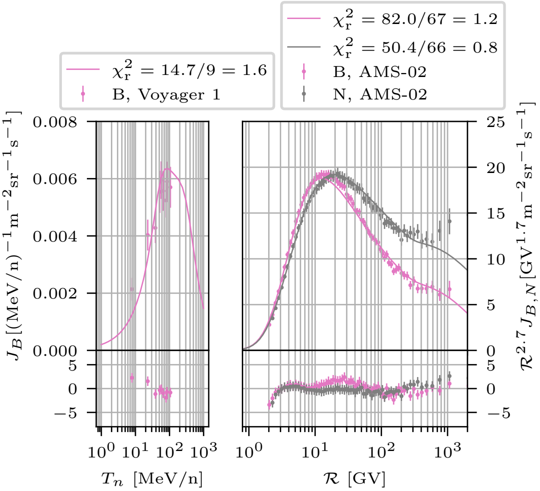

Results: boron-to-carbon ratio

Mertsch, Vittino, Sarkar (2020)