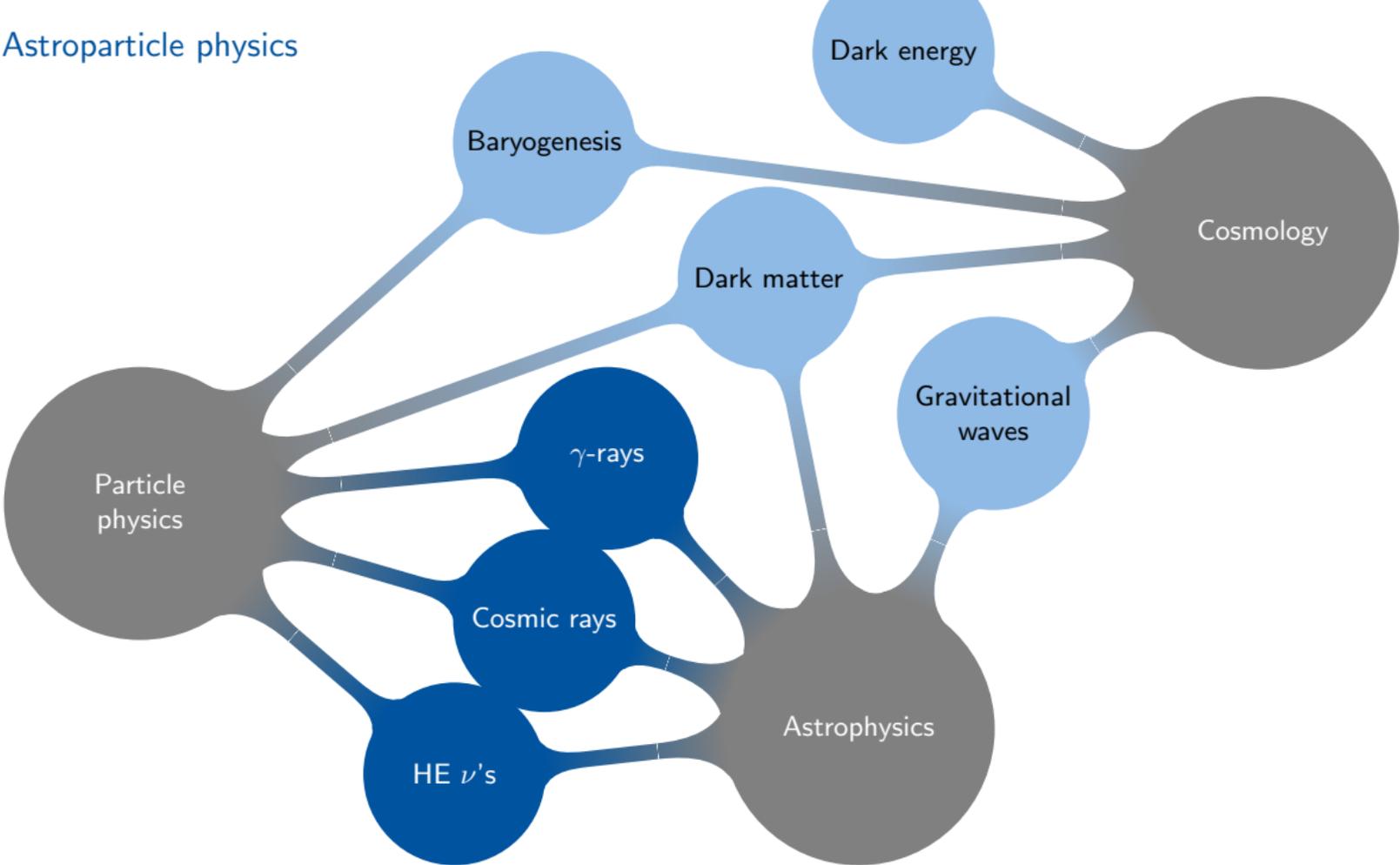


Astroparticle Physics

Philipp Mertsch

ICHEP 2022, Bologna
12 July 2022





Role of cosmic rays



Spectators

- What are their sources?
- Can we find DM in CRs?
- Is there primordial anti-matter in CRs?

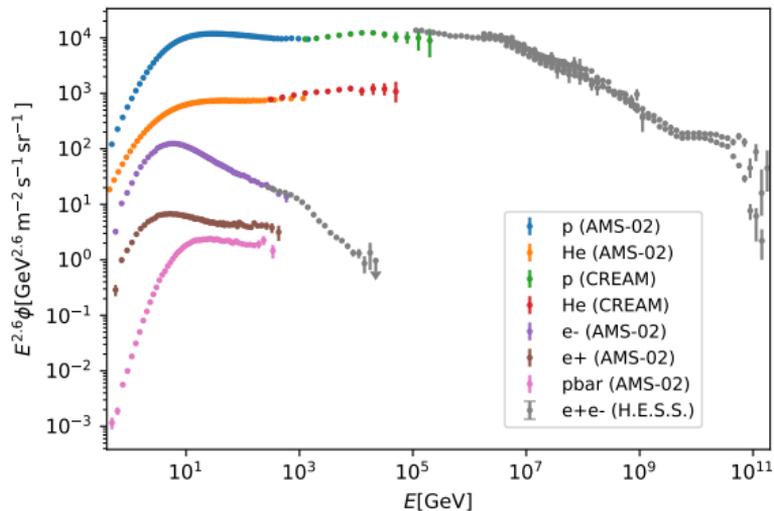


Actors

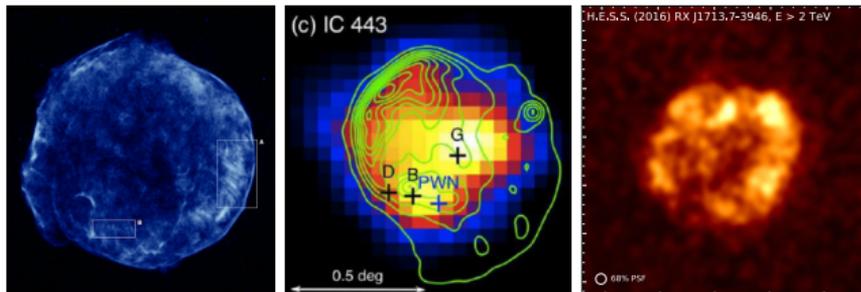
- CRs produce diffuse emission
- CRs contribute to ionisation, heating
- CRs provide gravitational support
- CRs drive winds
- CRs generate turbulence

Origin of cosmic rays

Local observations



Remote sensing



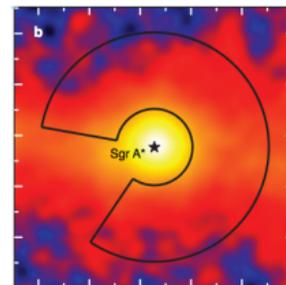
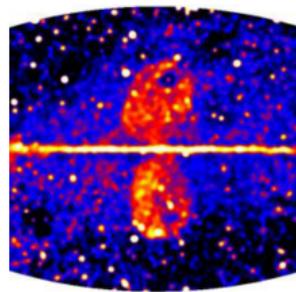
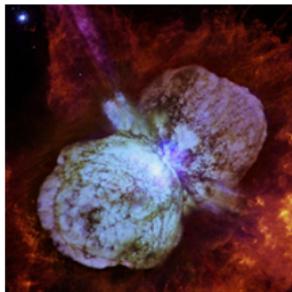
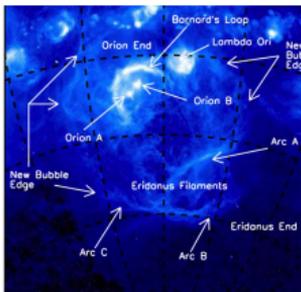
“What is accelerating to $E_{\text{knee}} \sim 3 \times 10^{15}$ eV ?”

Supernova remnants

- $E_{\text{max}} \lesssim 10^{13...14}$ eV for $B \sim B_{\text{ISM}}$
Lagage & Cesarsky (1983)
 - Amplify magnetic fields, non-resonant instability
Bell (2004)
 - Saturation?
- Particle-in-cell simulations

Other sources

- Superbubbles
- Supernovae before shock breakout
- Colliding wind binaries
- Pulsar wind nebulae
- The Fermi bubbles
- The Galactic centre
- Massive star clusters

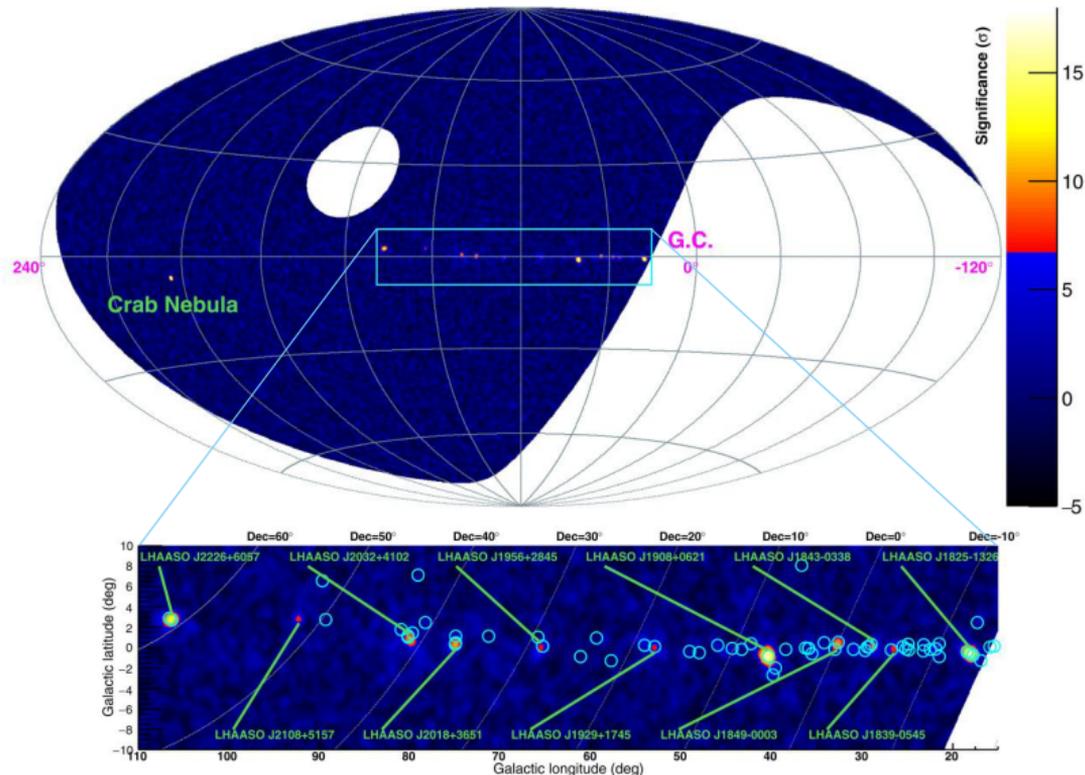


New LHAASO results

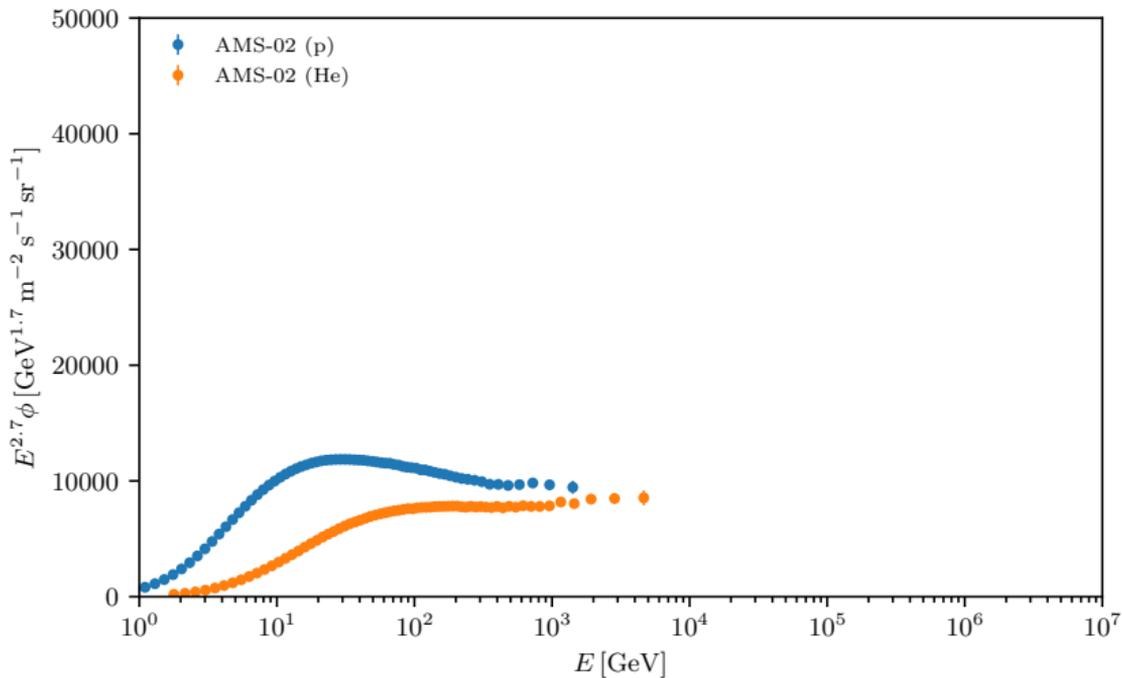
Cao et al. (2021)

- 12 extended sources
- High statistics: 530 γ -rays between 100 TeV and 1.4 PeV
- No sign of cut-off
- No unambiguous association, except Crab

→ PeVatrons at last!

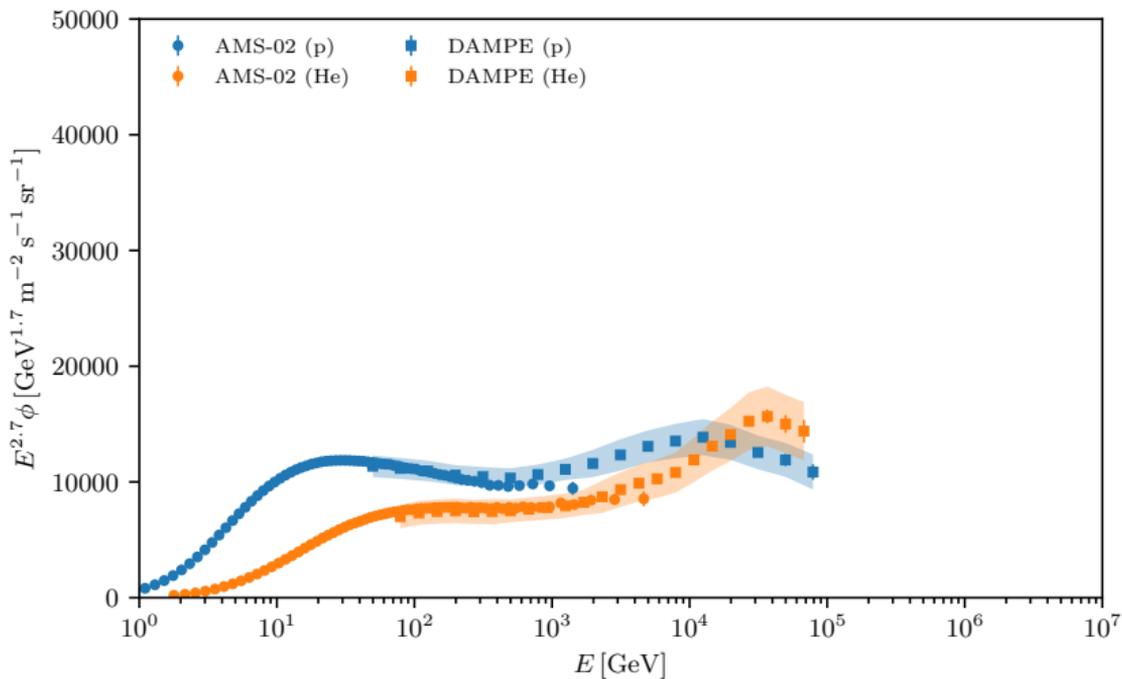


Nuclear spectra



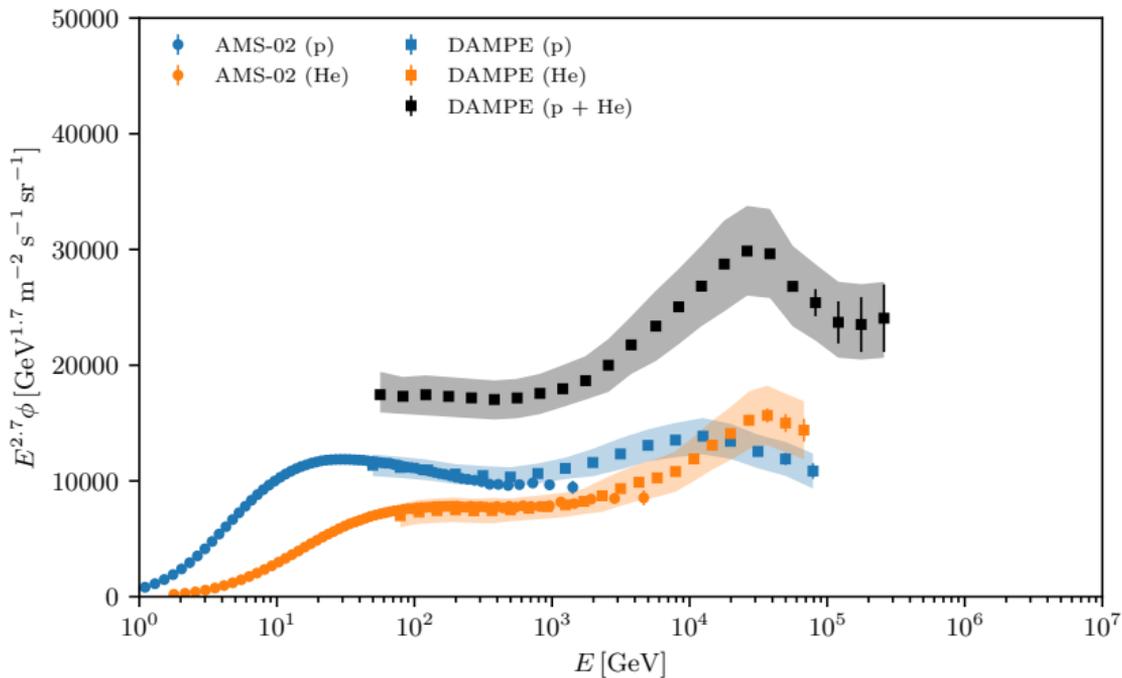
©ICHEP: AMS-02 (Q. Yan), DAMPE (M. Stolpovskiy)

Nuclear spectra



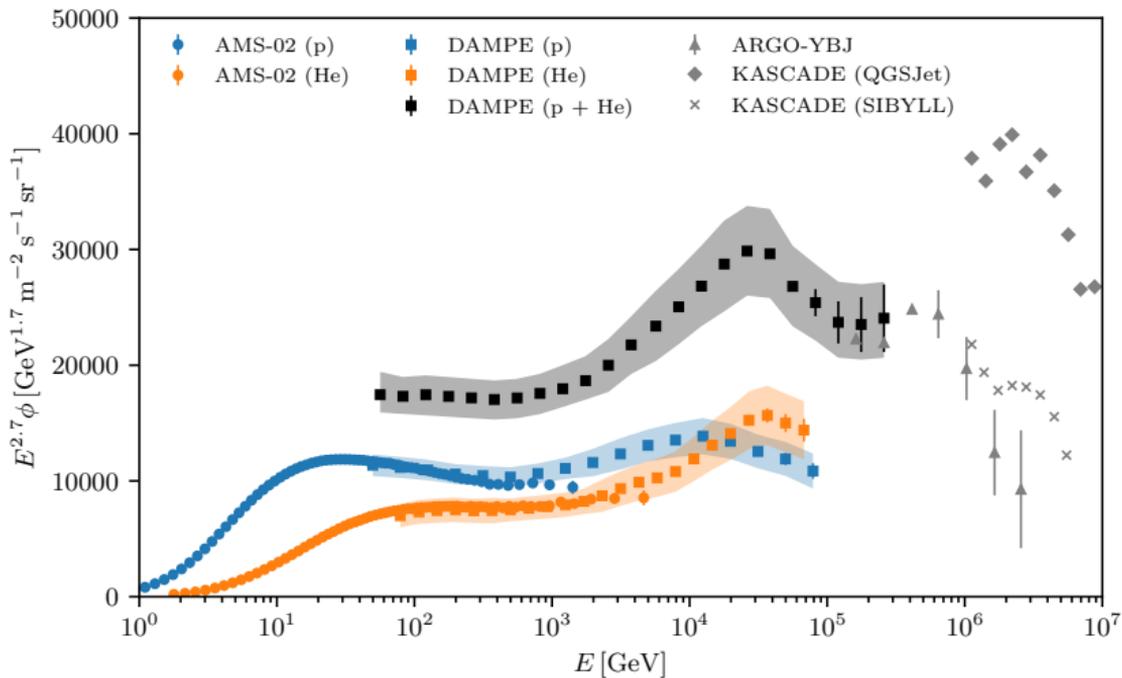
©ICHEP: AMS-02 (Q. Yan), DAMPE (M. Stolpovskiy)

Nuclear spectra



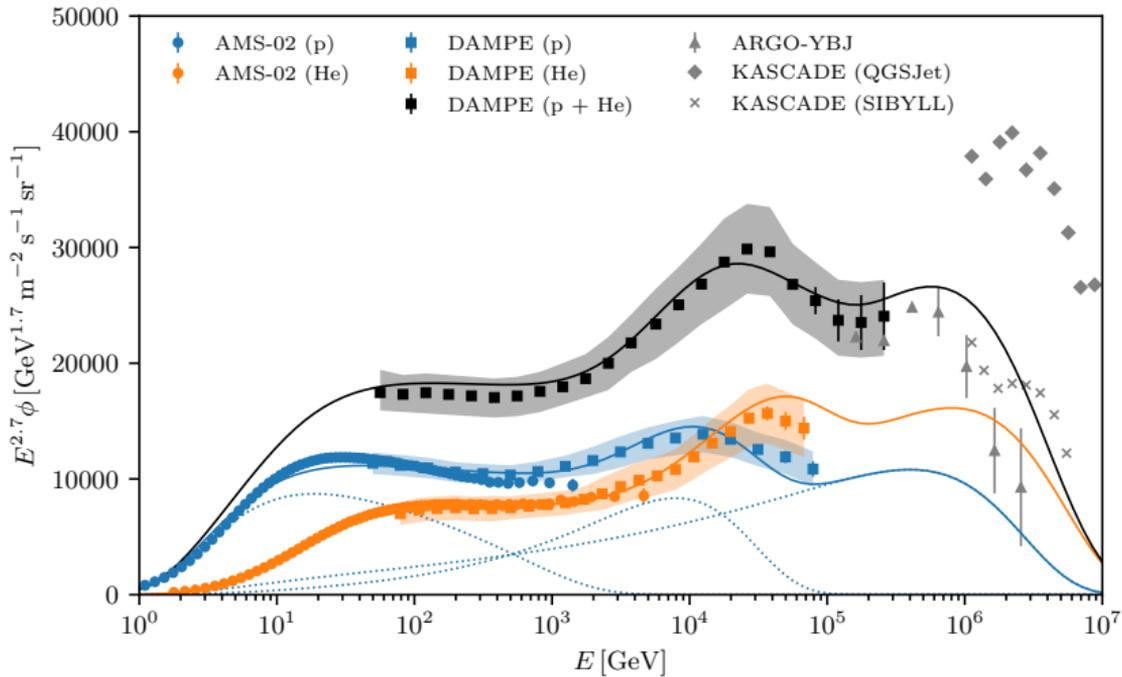
©ICHEP: AMS-02 (Q. Yan), DAMPE (M. Stolpovskiy)

Nuclear spectra



@ICHEP: AMS-02 (Q. Yan), DAMPE (M. Stolpovskiy)

Nuclear spectra



@ICHEP: AMS-02 (Q. Yan), DAMPE (M. Stolpovskiy)

Bump hunting

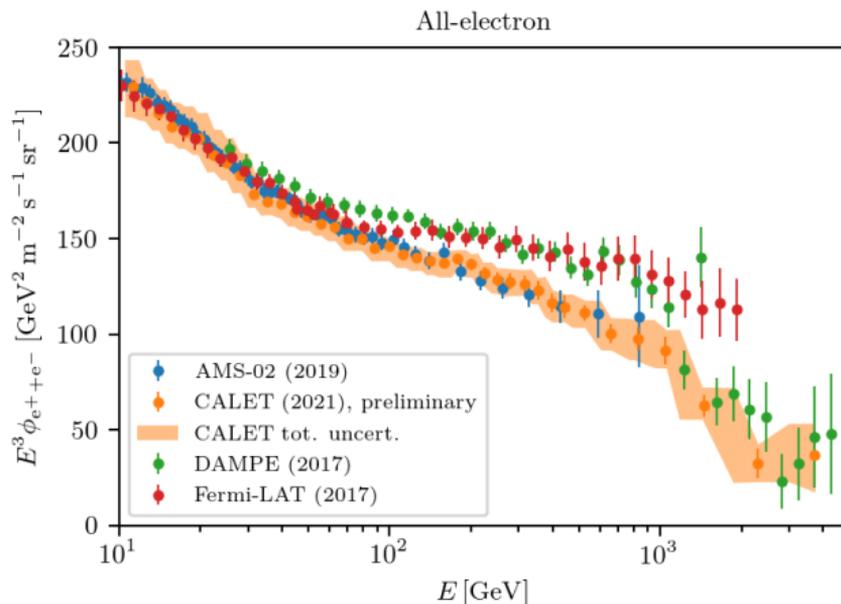
- Bump can be parametrised: broken power law, log-parabola, but what does it mean?

Individual source

- Shape determined by
 - source spectrum
 - age of source
 - distance of source
- Power law source spectra and diffusion coefficient, impulsive injection → broad bumps
- Statistical interpretation?!

New population

- Position in energy of spectral feature related to environmental parameters
- How much variance expected?

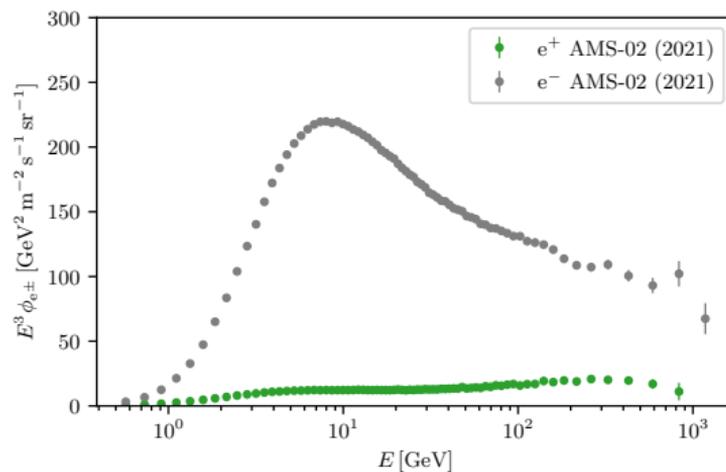


Between ~ 50 GeV and 1 TeV, two groups: $\left\{ \begin{array}{l} \text{Fermi-LAT and DAMPE} \\ \text{AMS-02 and CALET} \end{array} \right.$

@ICHEP: Extension of DAMPE analysis ongoing (M. Stolpovskiy);
see also AMS-02 (D. Krasnopevtsev)

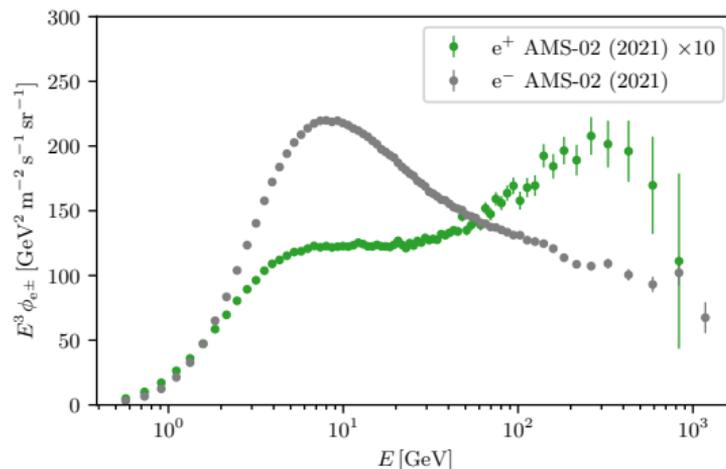
The positron excess

Aguilar *et al.* (2021)



- Cosmic ray nuclei produce soft flux of e^\pm by spallation
- Positron fraction should fall

@ICHEP: AMS-02 (D. Krasnopevtsev)



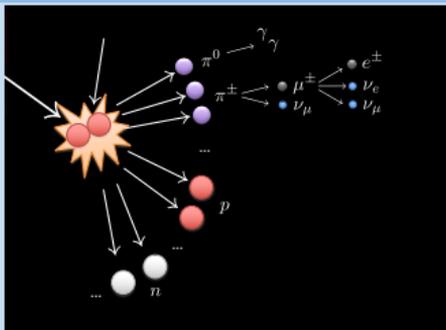
- Cosmic ray nuclei produce soft flux of e^\pm by spallation
- Positron fraction should fall
- Rise above ~ 7 GeV
- Exponential cut-off at ~ 800 GeV

Adriani *et al.* (2009), Ackermann *et al.* (2011), Aguilar *et al.* (2013)

@ICHEP: AMS-02 (D. Krasnopevtsev)

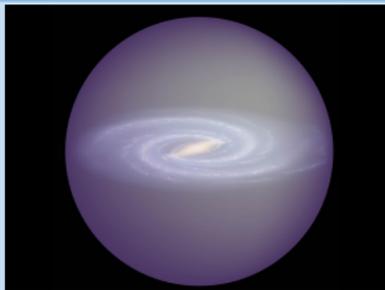
Sources of positrons

Secondaries



“Exotic scenarios” Lipari (2017)
in tension with data

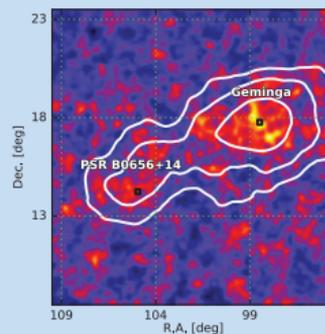
Dark matter



Strongly constrained by γ -rays, \bar{p} , CMB!

Pulsars/PWNe

Abeysekera et al. (2017)



Must be contributing at some level?!

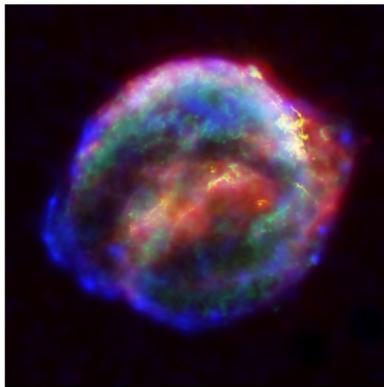
Others

- SNR in *nearby* dense cloud Fujita et al. (2009)
- Compact binary millisecond pulsars
Linares & Kachelrieß (2020)
- ...

Secondaries from the source?

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, *accepted* (2021); Kawanaka & Lee (2021)

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



$$\langle \tau_{\text{src}} \rangle \lesssim \tau_{\text{SNR}} \approx 10^{4\dots 5} \text{ yr}$$

$$n_{\text{src}} \lesssim 10 \text{ cm}^{-3}$$

$$\Rightarrow X_{\text{src}} \approx 0.2 \text{ g cm}^{-2}$$



$$\langle \tau_{\text{ISM}} \rangle \sim \tau_{\text{esc}} \approx 10^7 \text{ yr}$$

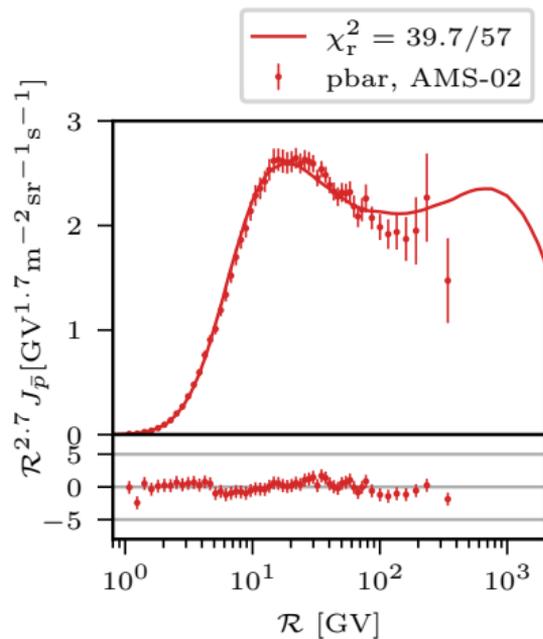
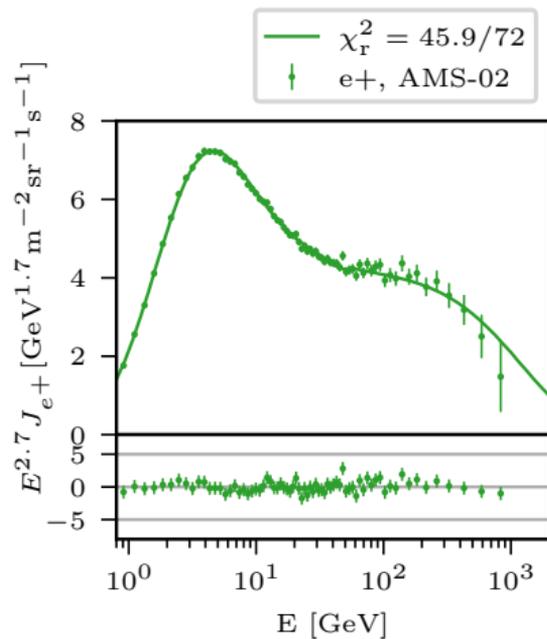
$$n_{\text{ISM}} \approx 0.1 \text{ cm}^{-3}$$

$$\Rightarrow X_{\text{ISM}} \approx \text{few g cm}^{-2}$$

However, secondaries from source can have a harder spectrum!

Acceleration of secondaries

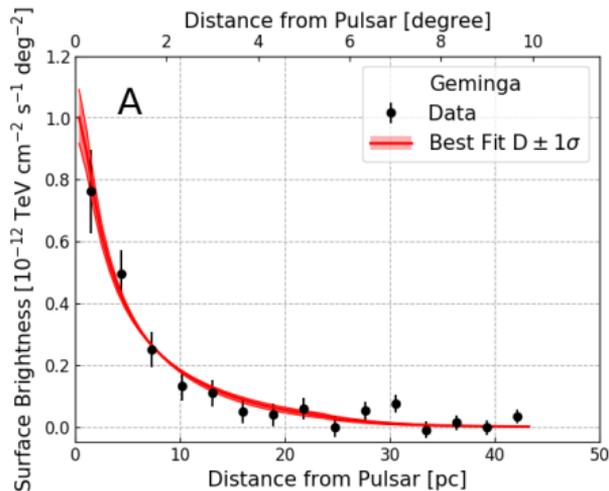
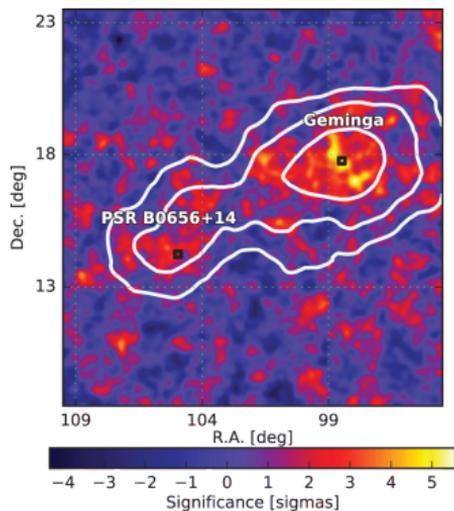
Mertsch, Vittino, Sarkar (2021)



Protons, helium, boron, carbon, nitrogen, oxygen. equally well reproduced

Gamma-ray halos

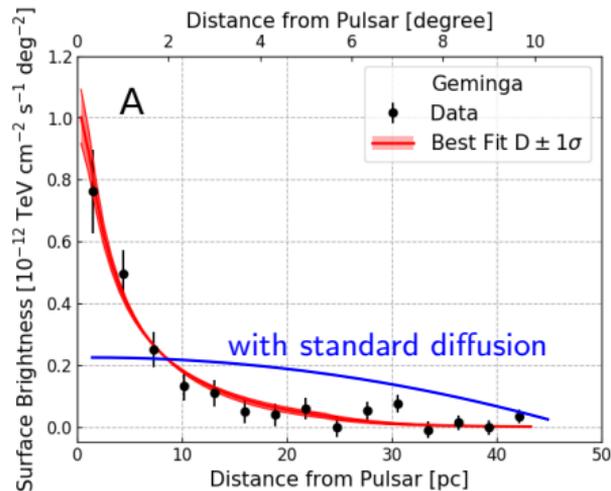
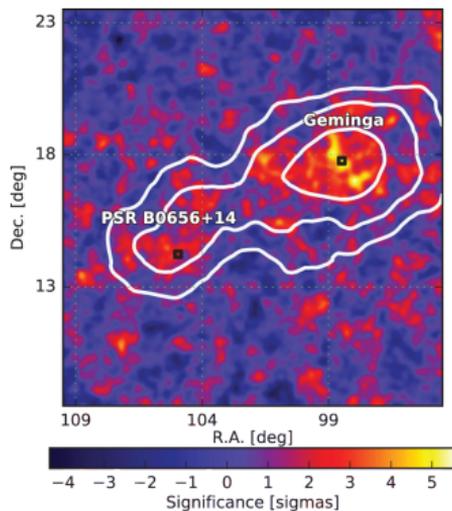
Abeyssekara *et al.* (2017)



- Gamma-ray emission around two nearby pulsars
- Emission from e^\pm much more confined than expected
- Ambient diffusion coefficient suppressed by factor ~ 100
- Self-confinement of high-energy e^\pm

Gamma-ray halos

Abeyssekara *et al.* (2017)



- Gamma-ray emission around two nearby pulsars
- Emission from e^\pm much more confined than expected
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- Self-confinement of high-energy e^\pm

Cosmic ray self-confinement

Ptuskin, Zirakashvili, Plesser (2008); Malkov *et al.* (2013); Nava *et al.* (2016)

$$\partial_t P_{\text{CR}} + v_A \partial_z P_{\text{CR}} = \partial_z (D_{zz}(z, p) \partial_z P_{\text{CR}})$$

$$D_{zz}(z, p) \sim \left. \frac{D_B(p)}{I(k)} \right|_{k=1/r_g}$$

- CR pressure $P_{\text{CR}} = p^4 f$
- Diffusion coefficient $D_{zz}(z, p)$
- Bohm value $D_B(p)$
- Turbulence spectral energy density $I(k)$

Cosmic ray self-confinement

Ptuskin, Zirakashvili, Plesser (2008); Malkov *et al.* (2013); Nava *et al.* (2016)

$$\partial_t P_{\text{CR}} + v_A \partial_z P_{\text{CR}} = \partial_z (D_{zz}(z, \rho) \partial_z P_{\text{CR}})$$

$$D_{zz}(z, \rho) \sim \left. \frac{D_B(\rho)}{l(k)} \right|_{k=1/r_g}$$

$$\Gamma_{\text{CR}}(z, k) = -\frac{v_A}{l} \partial_z P_{\text{CR}}$$

$$\partial_t l + v_A \partial_z l = 2\Gamma_{\text{CR}}(z, k)l - 2\Gamma_d l + Q$$

- CR pressure $P_{\text{CR}} = p^4 f$
- Diffusion coefficient $D_{zz}(z, \rho)$
- Bohm value $D_B(\rho)$
- Turbulence spectral energy density $l(k)$
- Growth rate $\Gamma_{\text{CR}}(z, k)$
- Damping rate Γ_d

Cosmic ray self-confinement

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- Bohm value $D_B(\rho)$
- Turbulence spectral energy density $l(k)$
- Growth rate $\Gamma_{\text{CR}}(z, k)$
- Damping rate Γ_d

Around supernova remnants:

Nava & Gabici (2013), D'Angelo *et al.* (2016, 2018),
Nava *et al.* (2019), Brahimi *et al.* (2020), Brose *et al.* (2021),
Schroer *et al.* (2021), Recchia *et al.* (2022),
Jacobs, Mertsch, Phan (2022)

Around pulsar wind nebulae:

Evoli, Linden, Morlino (2018), Linden & Mukhopadhyay (2022)

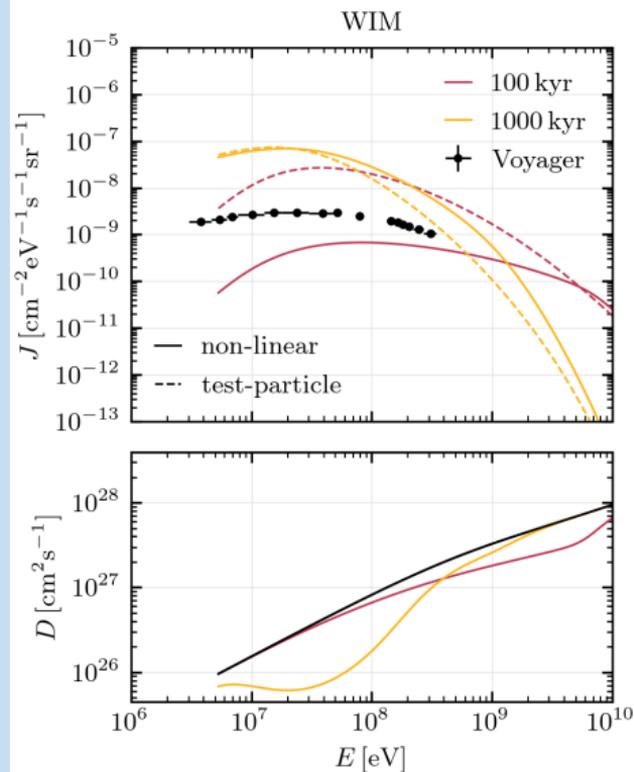
On Galaxy scales:

Amato, Blasi, Serpico (2012), Evoli *et al.* (2016)

Cosmic ray self-confinement

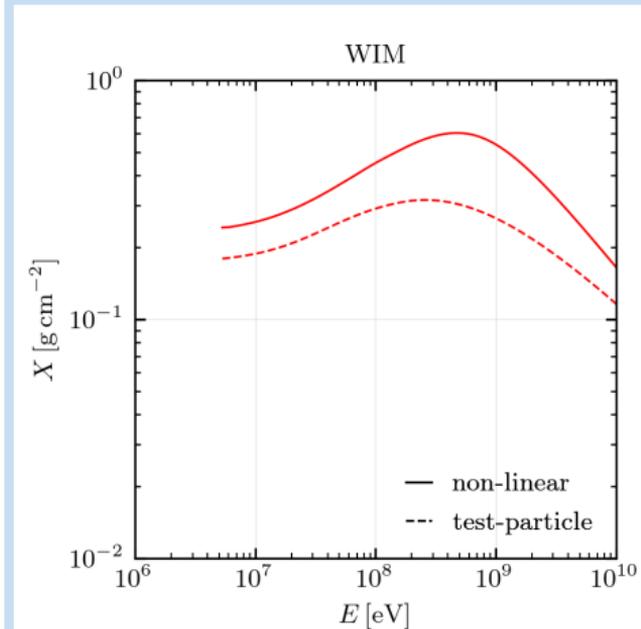
Jacobs, Mertsch, Phan (2022)

Spectra



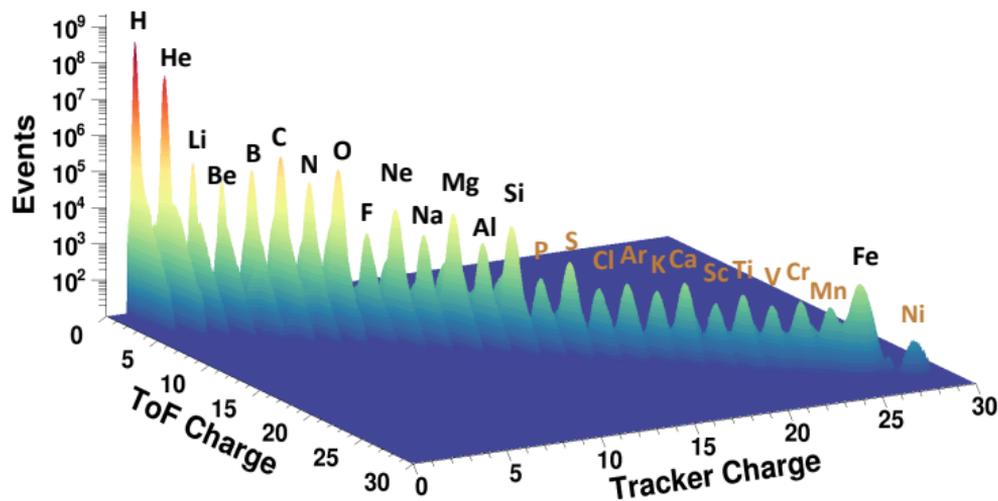
Grammage

i.e. the amount of matter experienced inside the source



Chemical composition

- Unprecedented charge resolution, e.g. from AMS-02:



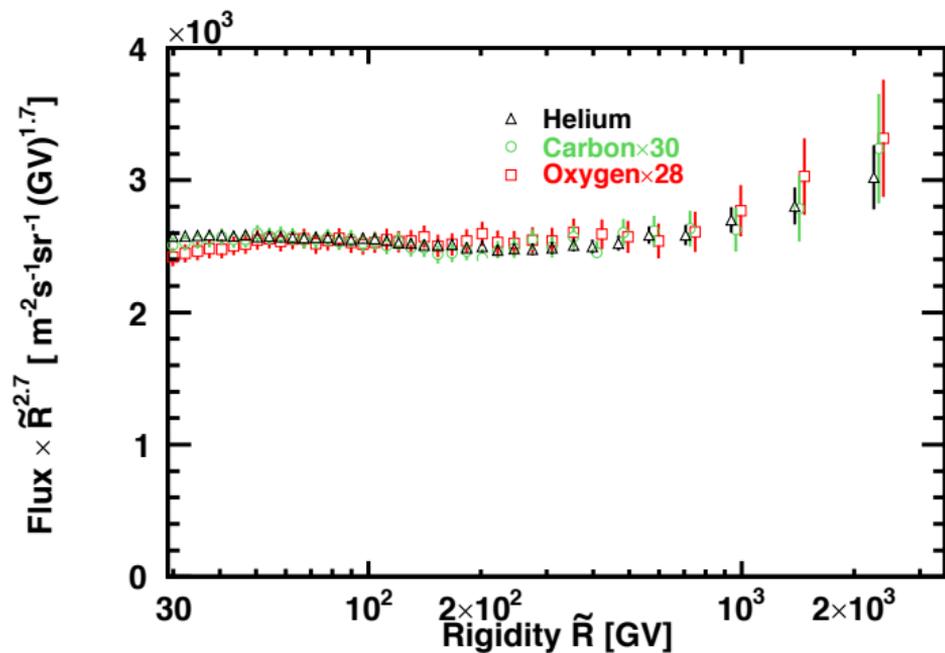
Relevance

- Precision: more statistics \rightarrow better constraints
- Origin: composition contains clue on sources
- Serendipity: expect the unexpected!

@ICHEP: CALET has measured Ni flux (F. Stolzi)

Nuclear spectra

@ICHEP: AMS-02 (Q. Yan, A. Oliva, Y. Chen)

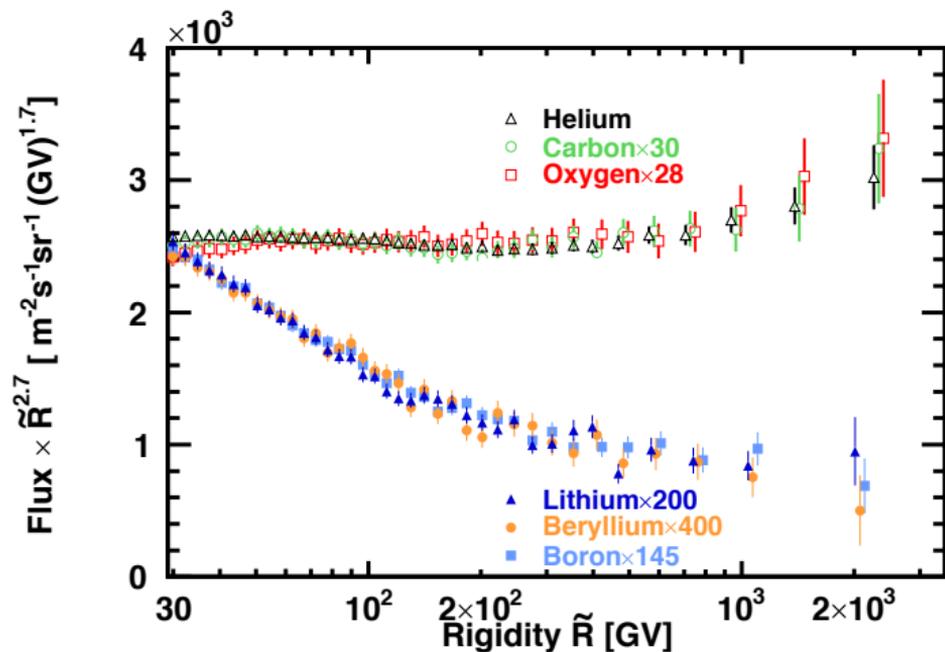


Primaries

Accelerated in sources, $\propto E^{-2.7}$

Nuclear spectra

@ICHEP: AMS-02 (Q. Yan, A. Oliva, Y. Chen)



Primaries

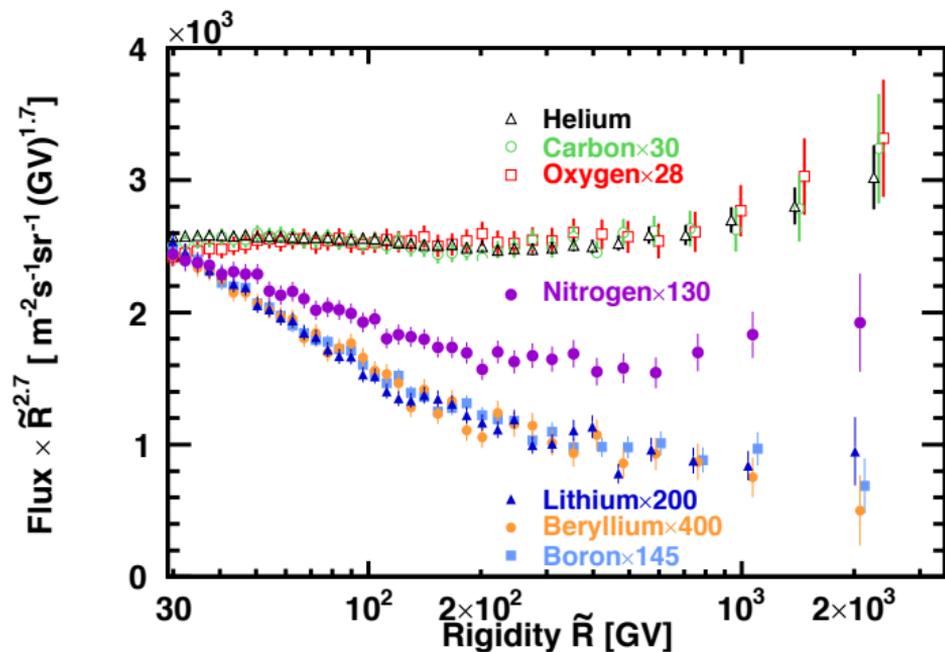
Accelerated in sources, $\propto E^{-2.7}$

Secondaries

Produced during transport, $\propto E^{-3}$

Nuclear spectra

@ICHEP: AMS-02 (Q. Yan, A. Oliva, Y. Chen)



Primaries

Accelerated in sources, $\propto E^{-2.7}$

Third group

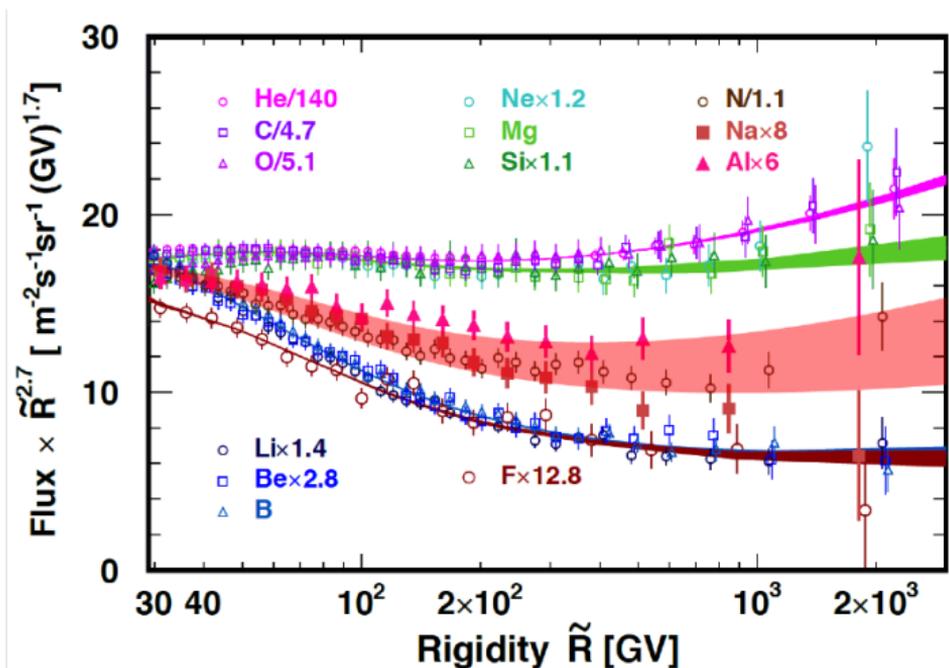
Primary and secondary contributions

Secondaries

Produced during transport, $\propto E^{-3}$

Nuclear spectra

@ICHEP: AMS-02 (Q. Yan, A. Oliva, Y. Chen)



Primaries

Accelerated in sources, $\propto E^{-2.7}$

Fourth group?

Universality?!

Third group

Primary and secondary contributions

Secondaries

Produced during transport, $\propto E^{-3}$

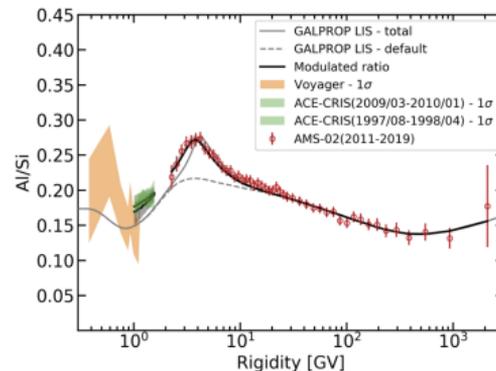
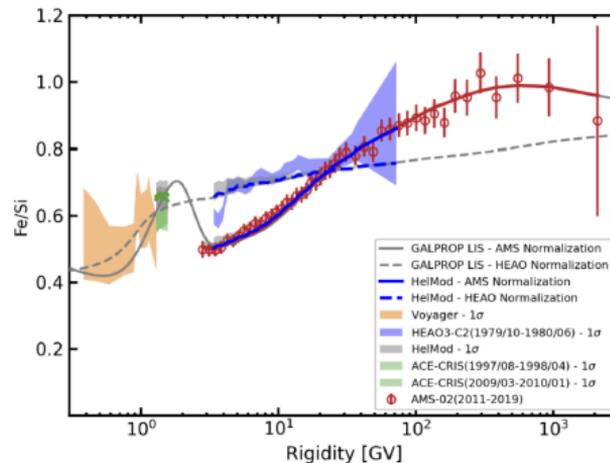
Interpretation of chemical composition

- Source abundances depend on
 - composition of source reservoir
 - ISM phase (ionisation state)
 - dust content
- Measure chemical composition to infer the environments for CR acceleration

Lessons

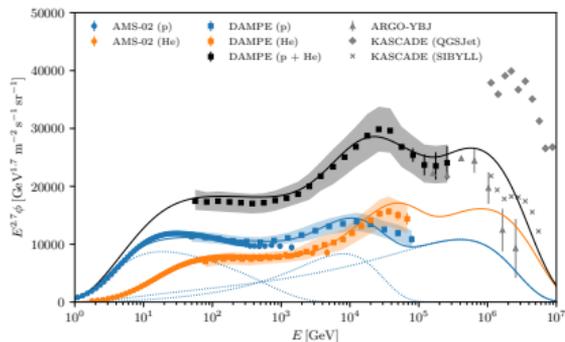
Tatischeff *et al.* (2021)

- 1 Mainly super bubble origin, supernova remnants in warm ISM contribute $< 30\%$
- 2 Overabundance of ^{22}Ne
→ wind termination shocks of massive stars



@ICHEP: Additional sources? (N. Masi)

Summary



Experiment

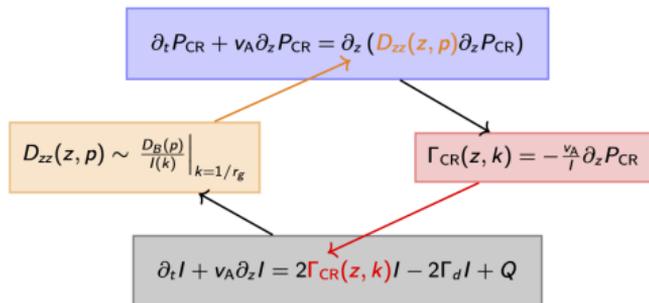
Rich phenomenology of:

- Cosmic ray spectra
- Cosmic ray composition
- Spatial distribution

Theory

Either:

- Identify new source classes
- Or new microphysics



Backup slides

The transport equation

$$\begin{aligned} \frac{\partial \psi_j}{\partial t} = & \nabla \cdot (\kappa \cdot \nabla \psi_j - \mathbf{u} \psi_j) && \text{spatial diffusion and advection} \\ & + \frac{\partial}{\partial p} \left(p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_j \right) && \text{momentum diffusion} \\ & + \frac{\partial}{\partial p} \left(-\frac{dp}{dt} \psi_j + \frac{p}{3} (\nabla \cdot \mathbf{u}) \psi_j \right) && \text{momentum change incl. adiabatic} \\ & - v n_{\text{gas}} \sigma_j \psi_j - \frac{\psi_j}{\tau_j} && \text{spallation and decay} \\ & + v n_{\text{gas}} \sum_{k>j} \sigma_{k \rightarrow j} \psi_k + \sum_{k>j} \frac{\psi_k}{\tau_{k \rightarrow j}} && \text{spallation and decay} \\ & + S_j && \text{primary sources} \end{aligned}$$

The transport equation

for shock acceleration

$$\begin{aligned} \frac{\partial \psi_j}{\partial t} = & \nabla \cdot (\kappa \cdot \nabla \psi_j - \mathbf{u} \psi_j) && \text{spatial diffusion and advection} \\ & + \frac{\partial}{\partial p} \left(p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_j \right) && \text{momentum diffusion} \\ & + \frac{\partial}{\partial p} \left(-\frac{dp}{dt} \psi_j + \frac{p}{3} (\nabla \cdot \mathbf{u}) \psi_j \right) && \text{momentum change incl. adiabatic} \\ & - v n_{\text{gas}} \sigma_j \psi_j - \frac{\psi_j}{\tau_j} && \text{spallation and decay} \\ & + v n_{\text{gas}} \sum_{k>j} \sigma_{k \rightarrow j} \psi_k + \sum_{k>j} \frac{\psi_k}{\tau_{k \rightarrow j}} && \text{spallation and decay} \\ & + S_j && \text{primary sources} \end{aligned}$$

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, *accepted* (2021); Kawanaka & Lee (2021)

- Transport equation

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

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

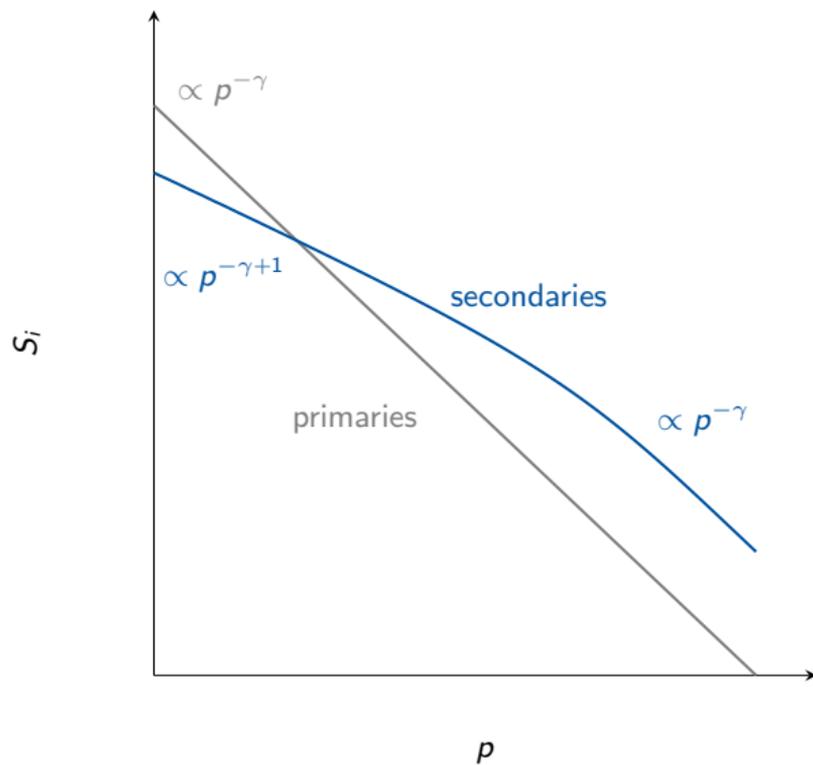
$$f_i^+(x, p) \simeq f_i^0(p) + r \left(\underbrace{q_i^0(p)}_{\propto p^{-\gamma}} - \Gamma_i^- f_i^0(p) \right) \frac{x}{u_+}$$

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

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

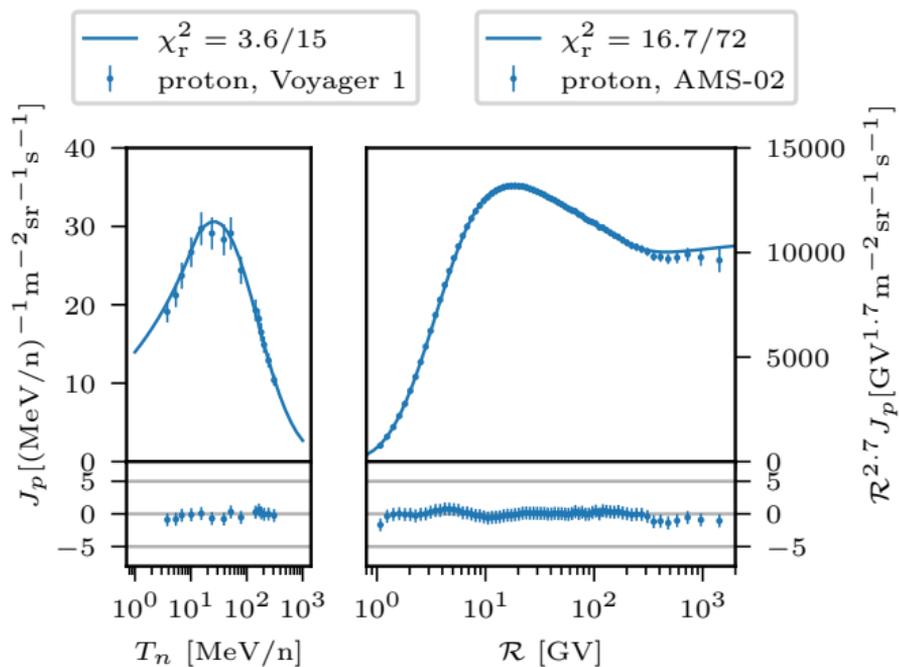
DSA with secondaries

Mertsch, Vittino, Sarkar (2021)



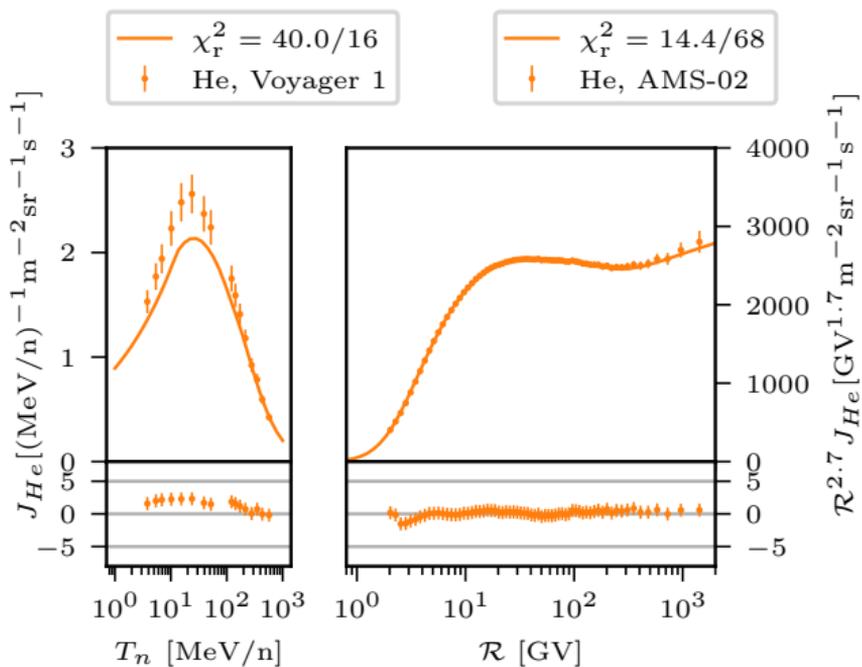
Results: protons

Mertsch, Vittino, Sarkar (2021)



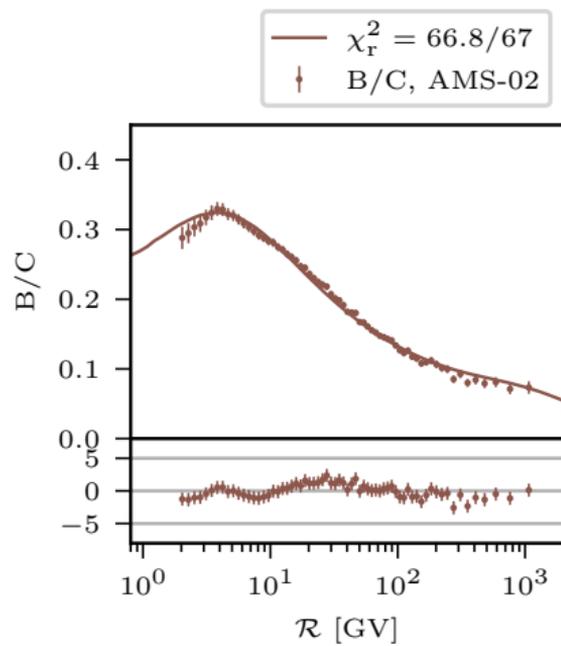
Results: helium

Mertsch, Vittino, Sarkar (2021)



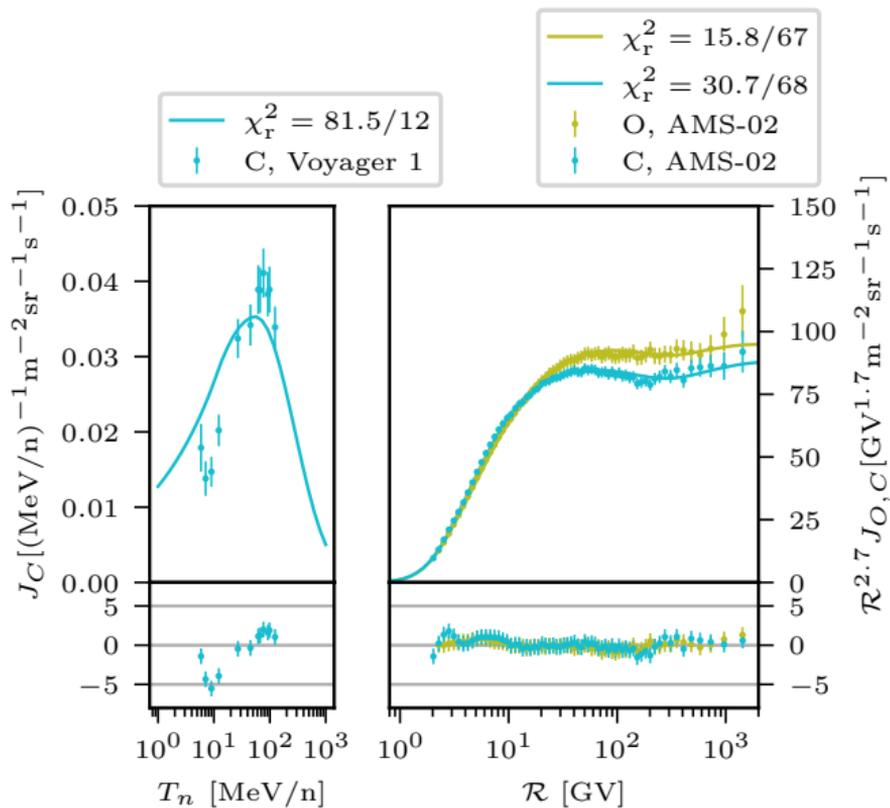
Results: boron-to-carbon ratio

Mertsch, Vittino, Sarkar (2021)



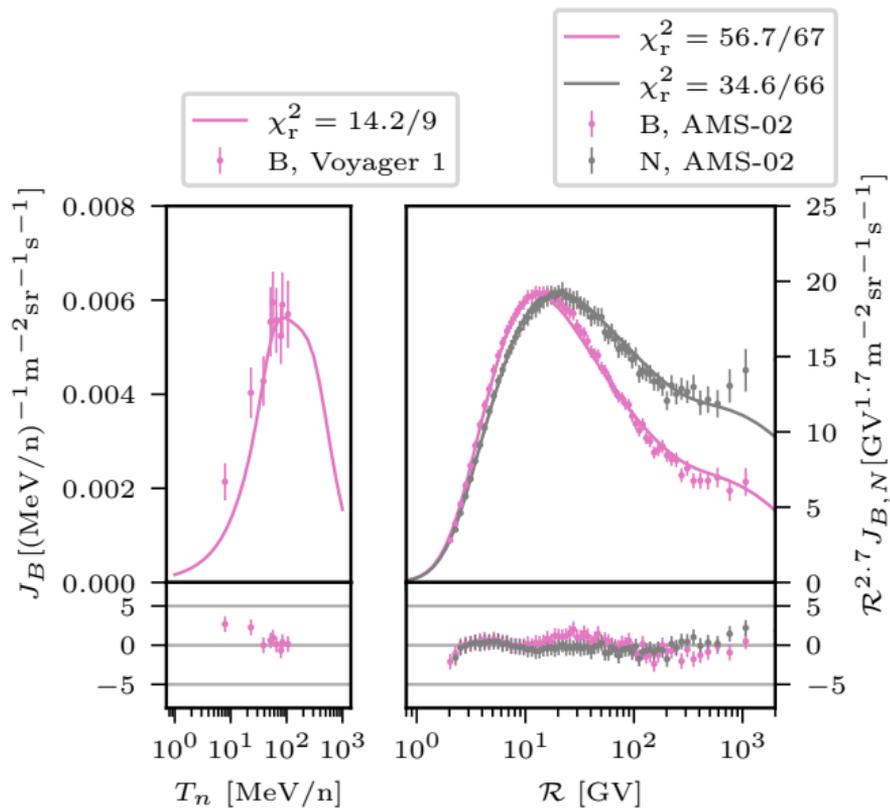
Results: carbon, oxygen

Mertsch, Vittino, Sarkar (2021)



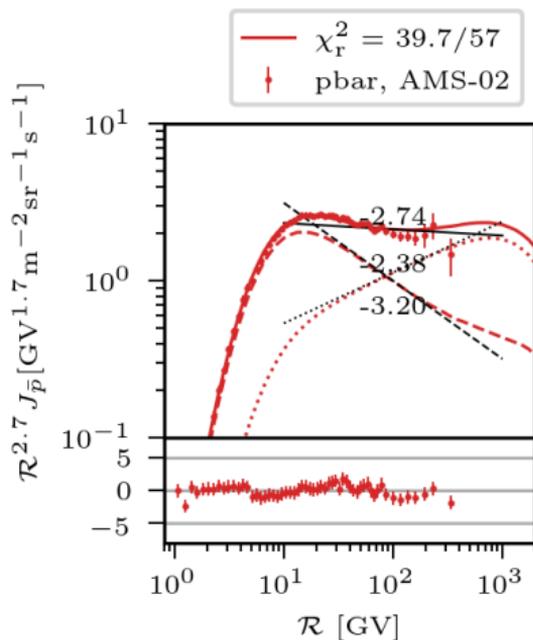
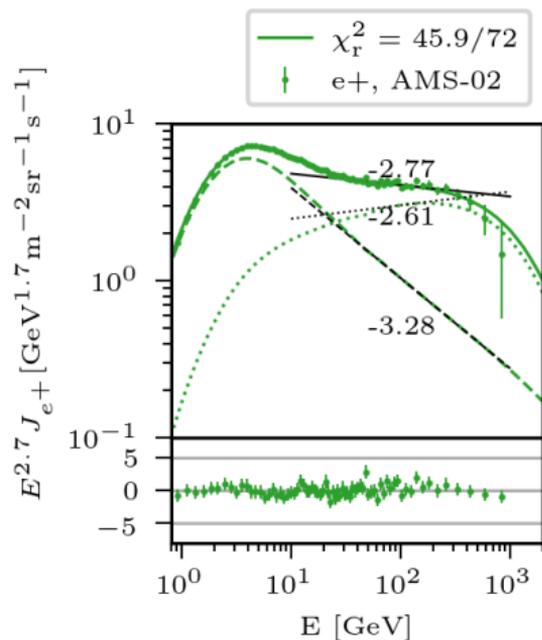
Results: boron, nitrogen

Mertsch, Vittino, Sarkar (2021)



Acceleration of secondaries

Mertsch, Vittino, Sarkar (2021)



Protons, helium, boron, carbon, nitrogen, oxygen. equally well reproduced

AMS-100

Schael *et al.* (2019)

