

Cosmic ray theory (I)

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30 July 2026

Why are cosmic rays interesting?

Cosmic ray origin

- What are the sources of cosmic rays?
- Century-old problem!
- Astrophysical interest

Ingredient

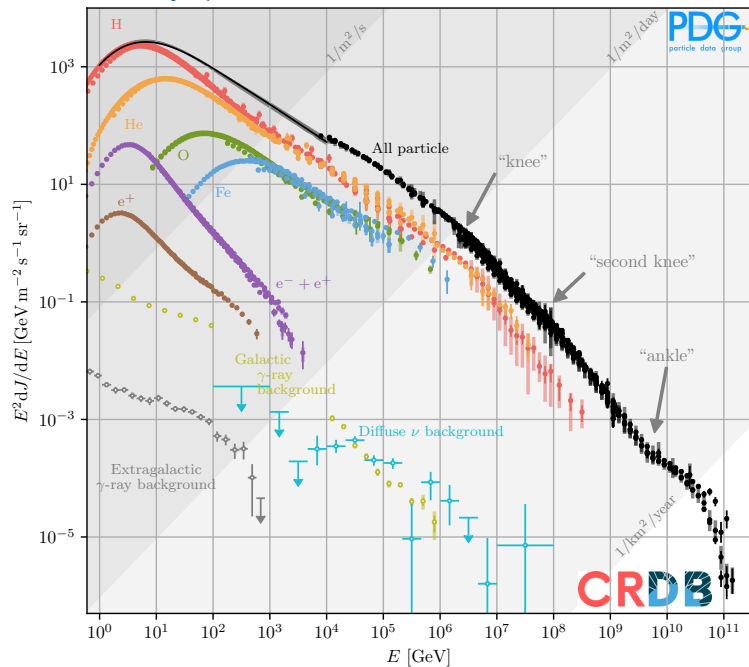
Cosmic rays ...

- produce diffuse emission
- ionise and heat
- provide gravitational support
- drive winds
- generate turbulence

Exotic probe

- Indirect searches of dark matter
- Dark matter cools cosmic rays, cosmic rays scatter dark matter
Bringmann et al. (2019), Ng et al. (2019)
- Primordial anti-matter?

The cosmic ray spectrum

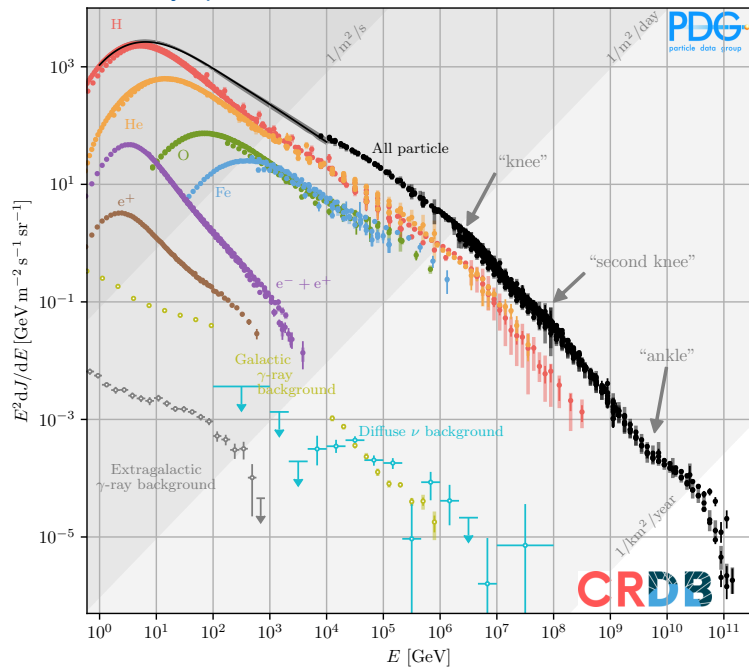


Intensity dJ/dE

$$\frac{dJ}{dE} \equiv \frac{(\# \text{particles})}{\Delta t \Delta A \Delta \Omega \Delta E}$$

- ~ 12 orders of magnitude in energy
- $\sim$ power law $dJ/dE \propto E^{-3}$ with some features

The cosmic ray spectrum



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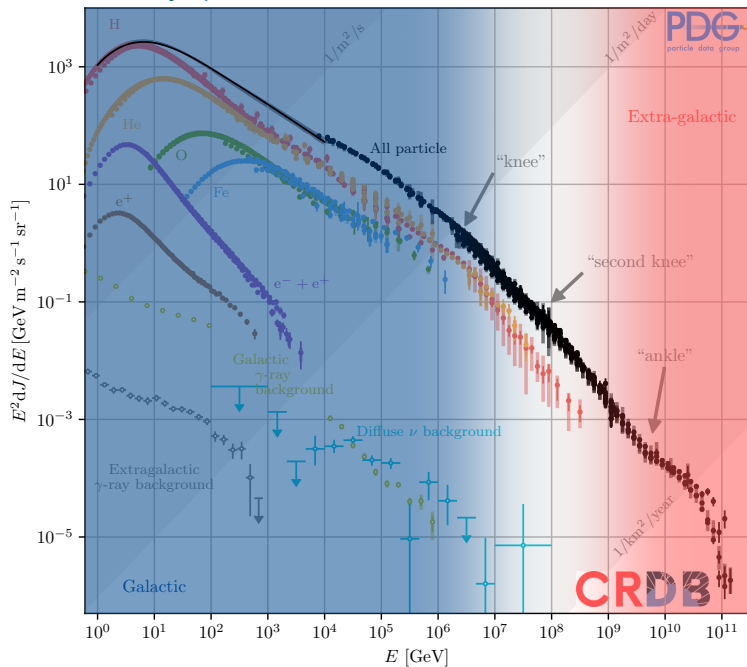
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Where is the transition from galactic to extragalactic sources?

→ three arguments

The cosmic ray spectrum



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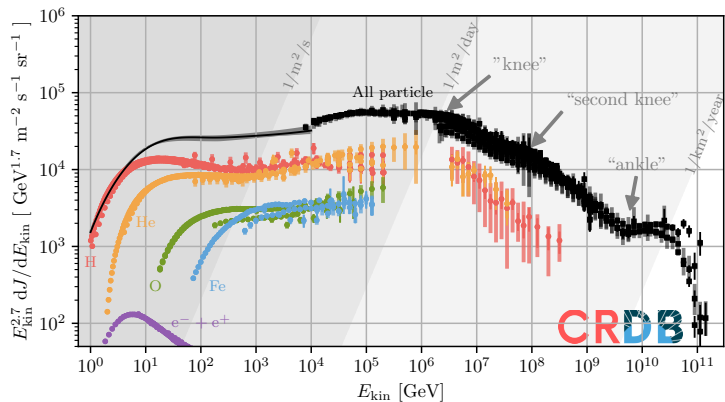
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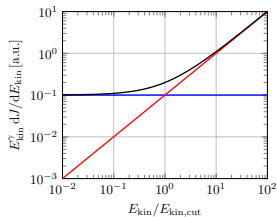
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→ three arguments

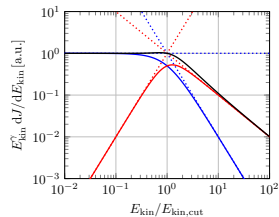
Spectral argument



Hardening



Softening

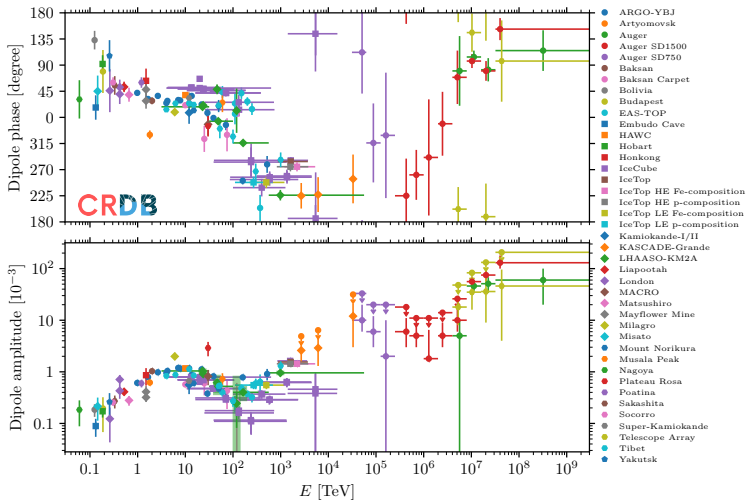


Anisotropy argument (1)

- Angular distribution of CRs is very isotropic
- E.g., the dipole anisotropy $a \equiv \frac{\phi_{\max} - \phi_{\min}}{\phi_{\max} + \phi_{\min}}$

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- Between a few GeV and a PeV: $a = \mathcal{O}(10^{-4} \dots 10^{-3})$

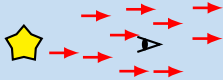


Anisotropy argument (2)

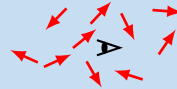


- Sources are discrete
- If CRs were travelling ballistically, would expect $\mathcal{O}(1)$ anisotropy
- See, e.g., electro-magnetic radiation

Anisotropy argument (2)



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Isotropisation by magnetic field requires gyroradius $\leq$ (size of Galaxy)

$$r_g = \frac{pc}{eB} \simeq 1 \text{ pc} \left(\frac{pc}{\text{PeV}} \right) \left(\frac{B}{\mu\text{G}} \right)^{-1} = 1 \text{ kpc} \left(\frac{pc}{\text{EeV}} \right) \left(\frac{B}{\mu\text{G}} \right)^{-1}$$

Can only isotropise CRs with $E \lesssim 10^{18}$ eV

- Shock acceleration:

$$t_{\text{acc}} \approx 10 \frac{\kappa(E)}{U_{\text{shock}}^2}$$

- Diffusion coefficient depends on turbulence level $\eta \leq 1$:

$$\kappa(E) = 3 \times 10^{22} \text{ cm}^2 \text{ s}^{-1} \eta^{-1} \left(\frac{B}{\mu\text{G}} \right)^{-1} \left(\frac{E}{1 \text{ GeV}} \right)$$

- Maximum energy when $t_{\text{acc}} = t_{\text{life}}$:

$$\frac{E_{\max}}{\text{GeV}} \approx \frac{t_{\text{life}} U_{\text{shock}}^2}{10 \kappa(1 \text{ GeV})} \simeq 10^4 \eta \left(\frac{t_{\text{life}}}{10^4 \text{ yr}} \right) \left(\frac{U_{\text{shock}}}{1000 \text{ km s}^{-1}} \right)^2 \left(\frac{B}{\mu\text{G}} \right)$$

Lagage & Cesarsky (1983)

→ Amplification of magnetic fields, e.g. non-resonant instability Bell (2004)

Acceleration in SNRs: $E_{\max} \lesssim 10^{15} \text{ eV}$

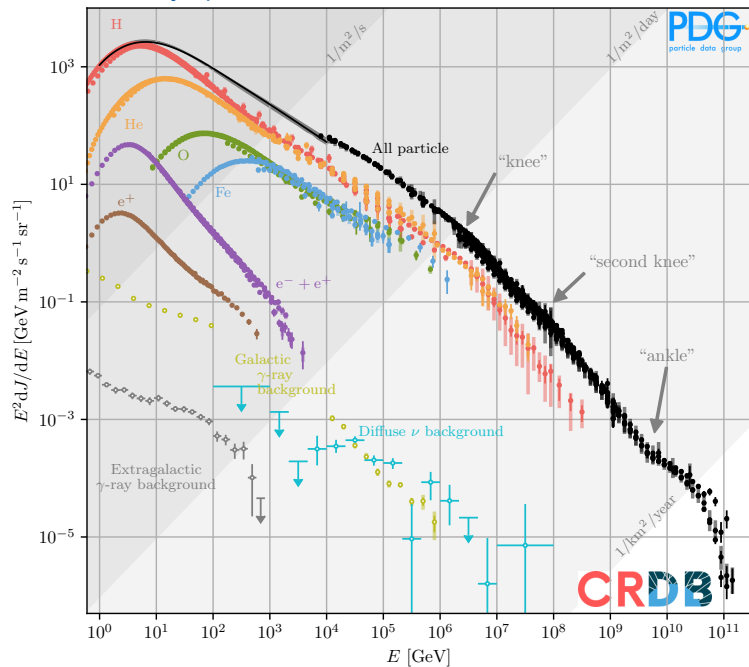
Transition summary

- Spectral argument: $E_{\text{trans}} \sim 5 \times 10^{18} \text{ eV}$
- Anisotropy argument: $E_{\text{trans}} \lesssim 10^{18} \text{ eV}$
- E_{max} argument: $E_{\text{trans}} \lesssim 10^{15} \text{ eV}$

Working definition:

Galactic CRs $\equiv$ CRs with energies $E \lesssim 10^{15} \text{ eV}$

The cosmic ray spectrum

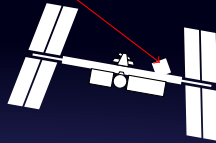


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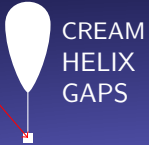
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Space experiments: AMS-02, CALET, DAMPE, *Fermi*-LAT

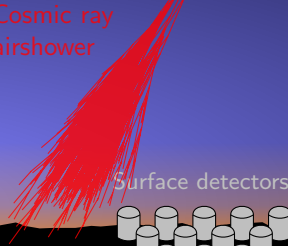


Balloon experiments:



CREAM
HELIX
GAPS

Cosmic ray
airshower



Cherenkov telescopes:
HESS, VERITAS, MAGIC



Fluorescence detectors:

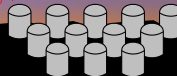
Auger, TA



IceCube



Surface detectors:



HAWC, IceTop, Auger, TA, LHAASO

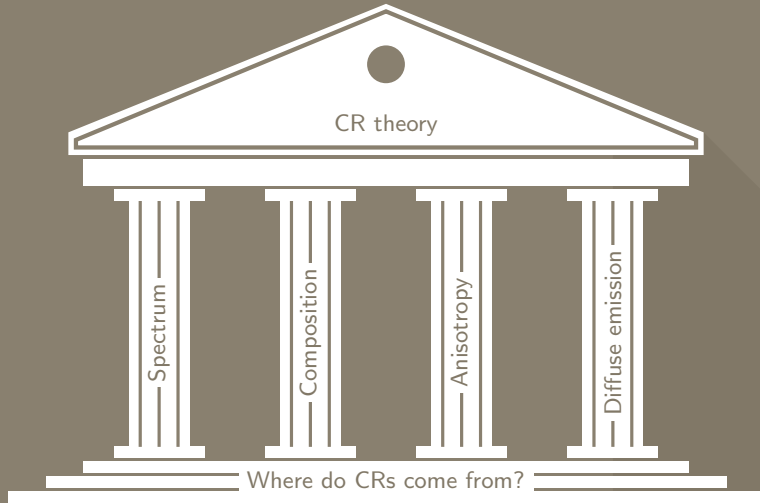
Outline

- ① Motivation
- ② Fundamental observations
 - Spectrum
 - Anisotropy
 - Composition
- ③ Key insights
 - Grammage
 - Cosmic ray clocks
 - Rigidity-dependence
 - Source candidates
- ④ Cosmic-ray transport
 - The transport equation
 - Diffusion
 - Other processes
 - Galactic transport
- ⑤ Shock acceleration
 - Shocks
 - Macroscopic approach
 - Microscopic approach
 - Additional effects
- ⑥ Solar modulation
 - Heliosphere
 - Solar cycles
 - Force-field model
 - Drift effects
- ⑦ Measurements and interpretation
 - Spectral breaks
 - Non-universality
 - Spectral coincidences
 - Electrons and positrons

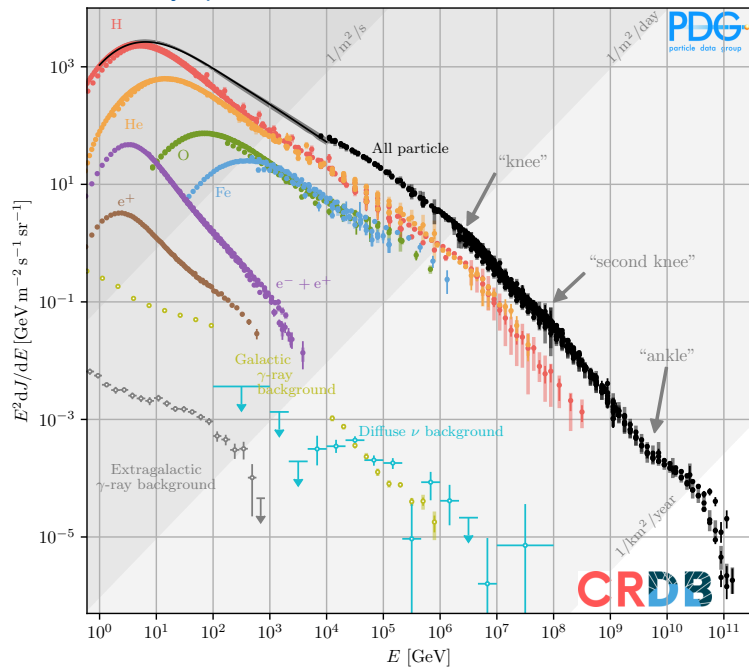
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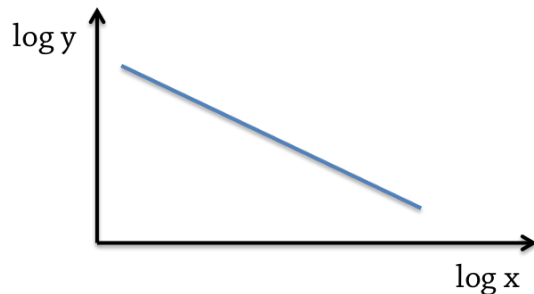
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Scale invariance

$$y = f(x) = Ax^\beta$$
$$f(\lambda x) = A\lambda^\beta x^\beta \propto x^\beta$$

Examples

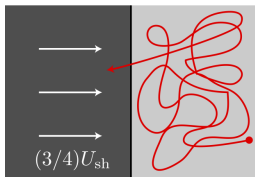
- Spectrum of density perturbations in early universe
- Initial mass function of stars
- Power spectrum of (magneto-)hydrodynamic turbulence
- Energy or frequency spectra of astrophysical sources
- ...

A gambling analogy

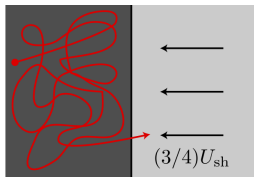
- Amount p ; probability of not having lost N
- Chance of losing q : $N_{i+1} = N_i(1 - q)$
- Fractional gain g : $p_{i+1} = p_i(1 + g)$
- Probability of having more than p_n : $N(> p_n)$

$$\left. \begin{aligned} \ln N(> p_n)/N_0 &= \ln(1 - q)^n \simeq -nq \\ \ln p_n/p_0 &= \ln(1 + g)^n \simeq ng \end{aligned} \right\} \Rightarrow N(> p_n) = N_0 \left(\frac{p_n}{p_0} \right)^{-q/g} = \int_{p_0}^{p_n} dp \frac{dN}{dp}$$

$$\frac{dN}{dp} \propto \left(\frac{p}{p_0} \right)^{-(1+q/g)}$$



upstream rest frame



downstream rest frame

Diffusive shock acceleration

- Prob. of escape: $q = \frac{U_{sh}}{v}$
- fractional gain: $g = \frac{\Delta p}{p} = \frac{U_{sh}}{v}$
- spectrum: $\frac{dN}{dp} \propto p^{-2}$

Between a few GeV and a PeV: $a = \mathcal{O}(10^{-4} \dots 10^{-3})$



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- Scattering of charged particles with turbulent magnetic field isotropises particle directions
- Particles perform a random walk in space:

$$\langle (\Delta r)^2 \rangle \propto \Delta t$$

- The constant of proportionality is called the **diffusion coefficient** κ

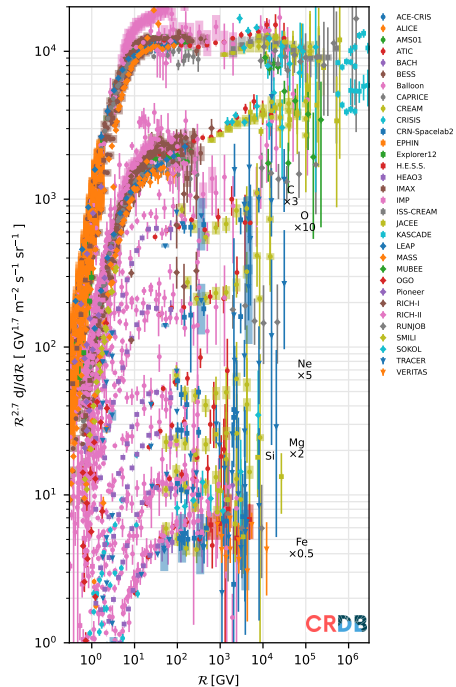
- Charged particles subject to Lorentz force:

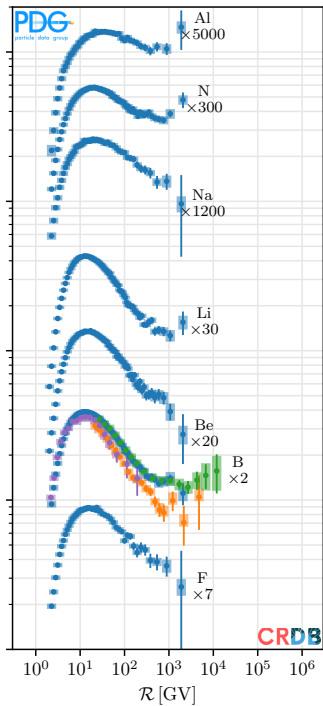
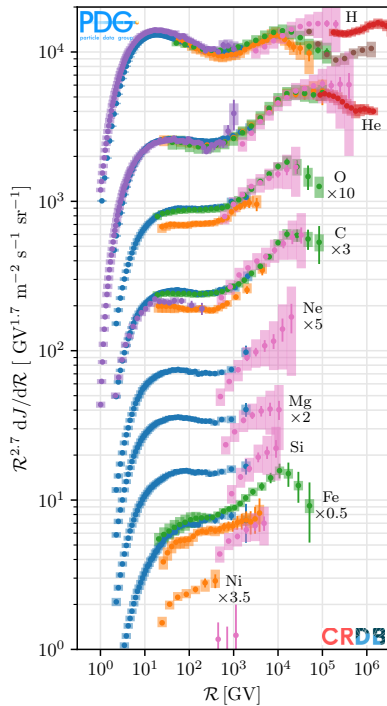
$$\begin{aligned}\frac{d\mathbf{p}}{dt} &= \frac{Ze}{c}(\mathbf{v} \times \mathbf{B}) \\ \Leftrightarrow m\gamma v \frac{d\hat{\mathbf{v}}}{dt} &= \frac{Ze}{c}vB(\hat{\mathbf{v}} \times \hat{\mathbf{B}}) \\ \Leftrightarrow \frac{1}{B} \underbrace{\frac{pc}{Ze}}_{\equiv R} \frac{d\hat{\mathbf{v}}}{ds} &= \hat{\mathbf{v}} \times \hat{\mathbf{B}} \quad \text{with } s = vt\end{aligned}$$

- Here, $R = \frac{pc}{Ze}$ is called the **rigidity** and $s = vt$ is the path length
- For relativistic nuclei, rigidity = $2 \times$ (energy per nucleon):

$$eR = \frac{pc}{Z} \simeq \frac{E}{Z} = \frac{A}{Z} \frac{E}{A} \simeq 2 \frac{E}{A}$$

Particle spectra should look the same in rigidity or energy per nucleon



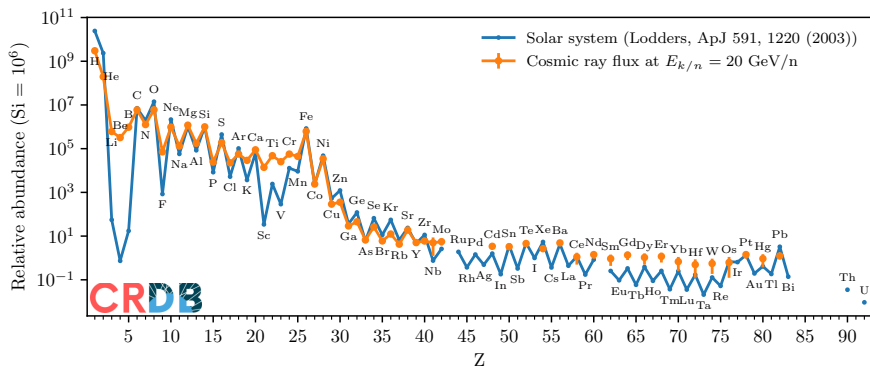


- AMS02
- CALET
- DAMPE
- GRAPES-3
- LHAASO-KM2A
- NUCLEON
- PAMELA

Spectral universality,
but $\sim$ two groups

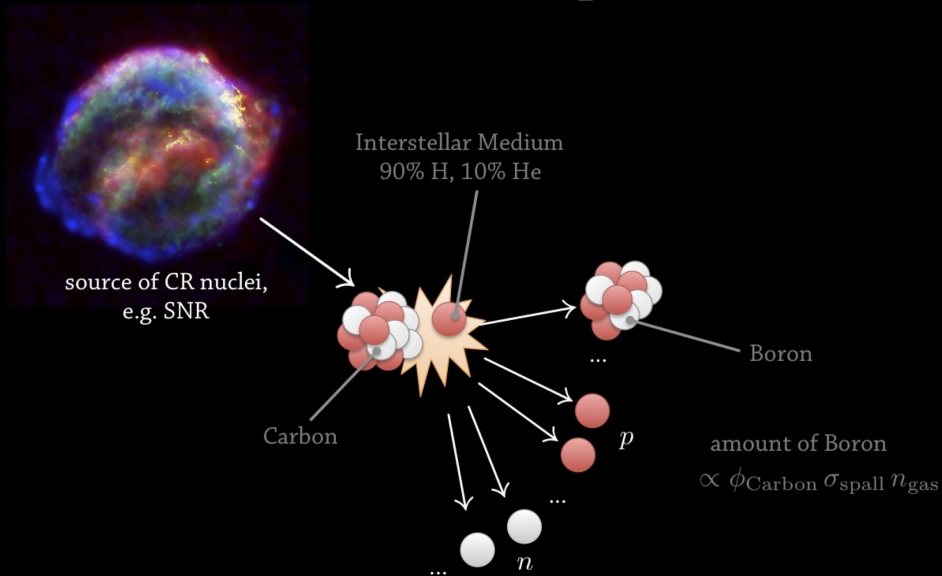
Composition

- Some species have same abundances in CRs and in solar system → **primaries**
- Other species are overabundant with respect to solar abundances:

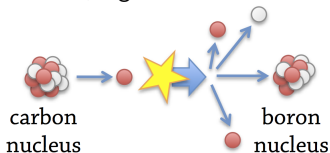


→ Must have been produced during the transport → **secondaries**

Secondaries from spallation



- Work in the “straight-ahead-approximation”: momentum or kinetic energy is equally shared among constituent nucleons, e.g.:



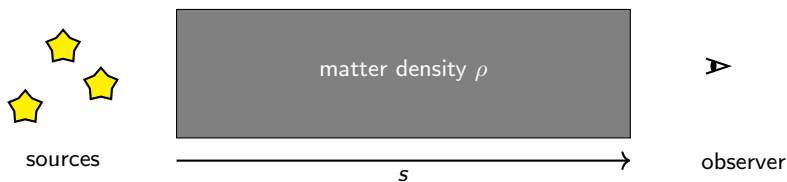
$$E_{\text{kin},B} = 11E_{n,B} = 11E_{n,C} = \frac{11}{12}E_{\text{kin},C}$$

- If we formulate our eqs. in terms of energy per nucleon E_n , can directly relate the production of boron with destruction of carbon:

$$\frac{d^2 N_B}{dE_n dt} = -\frac{d^2 N_C}{dE_n dt}$$

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- Somewhat model-independent way of quantifying the confinement

$$\text{grammage } X \equiv \int ds \, \rho(s) = s\bar{\rho}$$

→ Amount of matter ρ that CRs traverse

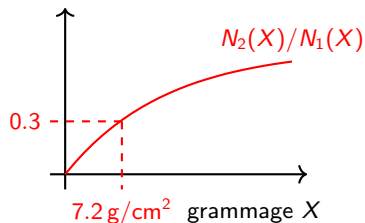
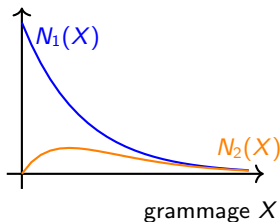
- Consider number of primary and secondary CRs, N_1 and N_2 :

$$\begin{aligned}\frac{dN_1}{dX} &= -\frac{N_1}{\lambda_1} \\ \frac{dN_2}{dX} &= -\frac{N_2}{\lambda_2} + \text{BR}_{1 \rightarrow 2} \frac{N_1}{\lambda_1}\end{aligned}$$

with $1/\lambda_{1,2} = \sigma_{1,2}/m$ the specific cross-section and $\text{BR}_{1 \rightarrow 2}$ is the branching ratio.

- Let $N_1(0) = N_0$, $N_2(0) = 0$ and solve for secondary-to-primary ratio:

$$\frac{N_2}{N_1} = \text{BR}_{1 \rightarrow 2} \frac{\lambda_2}{\lambda_2 - \lambda_1} \left(\exp \left[-\frac{X}{\lambda_2} + \frac{X}{\lambda_1} \right] - 1 \right)$$



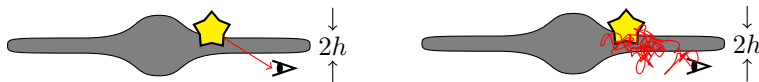
Example: Boron-to-carbon ratio

- We know the cross-sections, $\lambda_C \simeq 6.7 \text{ g cm}^{-2}$, $\lambda_B \simeq 10 \text{ g cm}^{-2}$ and branching ratio, $\text{BR}_{C \rightarrow B} \simeq 0.35$
 - At low energies, $N_2/N_1 \simeq 0.3$
- $X \simeq 7.2 \text{ g cm}^{-2}$

- Where does the grammage come from?
- If CRs traverse the Galactic disk, every crossing contributes

$$\Delta X \sim h m_N n_{\text{gas}} \simeq (100 \text{ pc})(1.7 \times 10^{-24} \text{ g})(1 \text{ cm}^{-3}) \simeq 5 \times 10^{-4} \text{ g cm}^{-2}$$

- ($1 \text{ pc} \simeq 3.1 \times 10^{18} \text{ cm}$)



CRs must cross the disk many times, e.g. through **diffusion**

- Residence time in disk:

$$t_{\text{esc}} = \frac{s}{v} = \frac{X}{v \bar{\rho}} = \frac{X}{v m_N \bar{n}_{\text{gas}}} \simeq 3 \times 10^6 \text{ yr}$$

for $n_{\text{gas}} = 1 \text{ cm}^{-3}$

- Three processes:
 - Escape at rate $1/t_{\text{esc}}$
 - Production by spallation $\Gamma_{j \rightarrow i} = v \bar{n}_{\text{gas}} \sigma_{j \rightarrow i} = v \bar{n}_{\text{gas}} \sigma_j \text{BR}_{j \rightarrow i}$
 - Destruction by spallation $\Gamma_i = v \bar{n}_{\text{gas}} \sigma_i$

→ Coupled set of equations for $N_{1,2}$:

$$\begin{aligned}\frac{dN_1}{dt} &= -\frac{N_1}{t_{\text{esc}}} - N_1 \Gamma_1 + Q_1 \\ \frac{dN_2}{dt} &= -\frac{N_2}{t_{\text{esc}}} - N_2 \Gamma_2 + \Gamma_{1 \rightarrow 2} N_1\end{aligned}$$

- In steady state ($dN_i/dt \equiv 0$):

$$\begin{aligned}N_1 &= \frac{Q_1}{1/t_{\text{esc}} + \Gamma_1} \\ N_2 &= \frac{\Gamma_{1 \rightarrow 2}}{1/t_{\text{esc}} + \Gamma_2} N_1 = \frac{\sigma_j \text{BR}_{1 \rightarrow 2}}{1/(v t_{\text{esc}} \bar{n}_{\text{gas}}) + \sigma_2} N_1\end{aligned}$$

→ How to break degeneracy between t_{esc} and $\bar{n}_{\text{gas}}$?

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- Use unstable nuclei: life time breaks the degeneracy!
- ${}^9\text{Be}$ is stable, ${}^{10}\text{Be}$ has a half life $\tau_{10} \simeq 1.4 \times 10^6$ yr and decays to ${}^{10}\text{B}$
- Equation for ${}^9\text{Be}$

$$N_9 = \frac{\Gamma_{\text{CNO} \rightarrow 9}}{1/t_{\text{esc}} + \Gamma_9} N_{\text{CNO}}$$

- Equation for ${}^{10}\text{Be}$

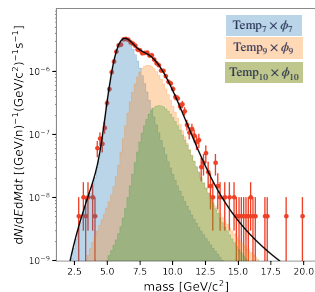
$$N_{10} = \frac{\Gamma_{\text{CNO} \rightarrow 10}}{1/t_{\text{esc}} + \Gamma_{10} + 1/\tau_{10}} N_{\text{CNO}}$$

- and so the ratio is

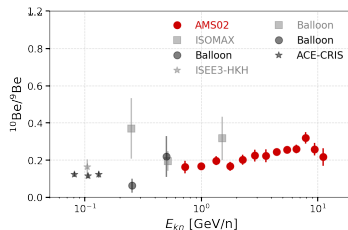
$$\frac{N_{10}}{N_9} = \frac{\Gamma_{\text{CNO} \rightarrow 10}}{\Gamma_{\text{CNO} \rightarrow 9}} \frac{1/t_{\text{esc}} + \Gamma_9}{1/t_{\text{esc}} + \Gamma_{10} + 1/\tau_{10}}$$

Comparison with data: $\bar{n}_{\text{gas}} \sim 0.1 \text{ cm}^{-3}$, much lower than in disk
⇒ CRs spend only fraction of time in disk, rest of time
in extended **CR halo**, $z_{\text{max}}/h \sim 10$

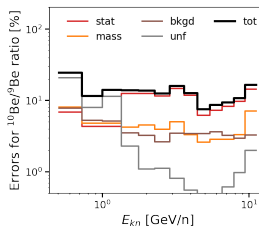
- $\Delta M \simeq 1 \text{ amu}$
- no event-by-event analysis, but use shape of mass distribution



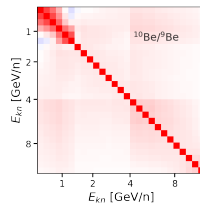
Flux ratios



Errors



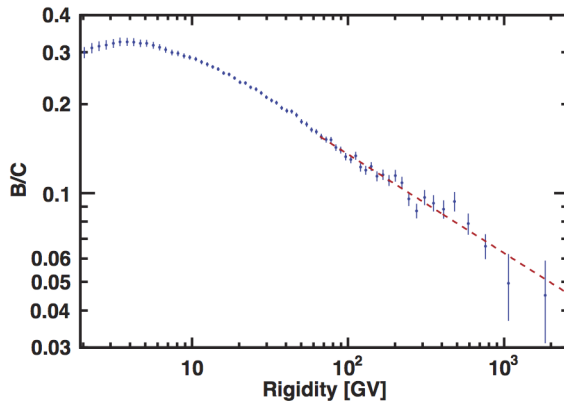
Total correlation matrices



- Also $^2\text{H}/^1\text{H}$ and $^3\text{He}/^4\text{He}$

Rigidity-dependent grammage

Aguilar *et al.*, PRL 117 (2016) 231102



- While $B/C \sim 0.3$ at a few GV, it decreases with increasing rigidity

$$\Rightarrow X(R) \sim 7.2 \text{ g cm}^{-2} \left(\frac{R}{10 \text{ GV}} \right)^{-0.3}$$

- If interpreted as residence time:

$$\text{in disk: } t_{\text{res}} = \frac{s}{v} = \frac{X}{v \bar{\rho}} = \frac{X}{v m_N \bar{n}_{\text{gas}}}$$

$$\text{in halo: } t_{\text{res}} = \frac{X}{v m_N \bar{n}_{\text{gas}}} \frac{z_{\text{max}}}{h}$$

↖ halo height
↖ disk height

- In a diffusion model with diffusion coefficient κ ,

$$t_{\text{res}} \sim \frac{z_{\text{max}}^2}{\kappa}$$

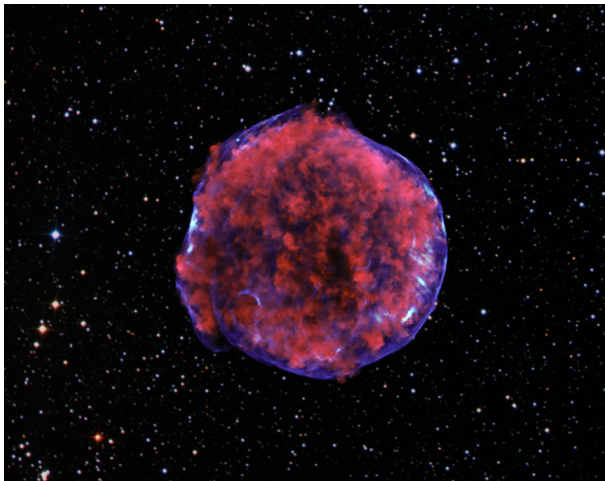
→ faster diffusion at higher energies: $\kappa = \kappa(p) \sim p^{1/3}$

What are the sources of (galactic) CRs?

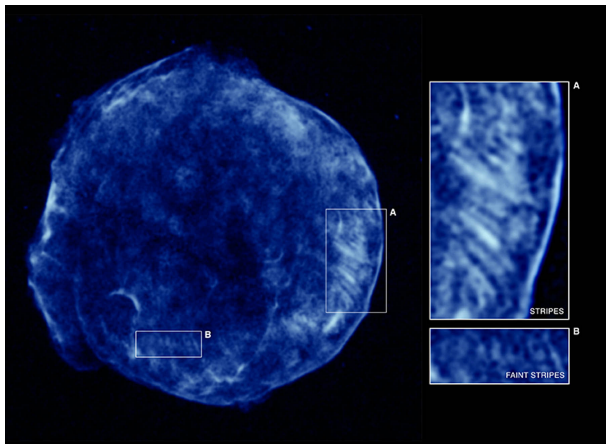


- Already Baade & Zwicky suggested supernovae (SNe)
 - SN liberates much of gravitational energy of star, typically 10^{51} erg
 - ($1 \text{ erg} = 10^{-7} \text{ J} \simeq 624 \text{ GeV}$)
- However, particles accelerated in SN event suffer from adiabatic losses

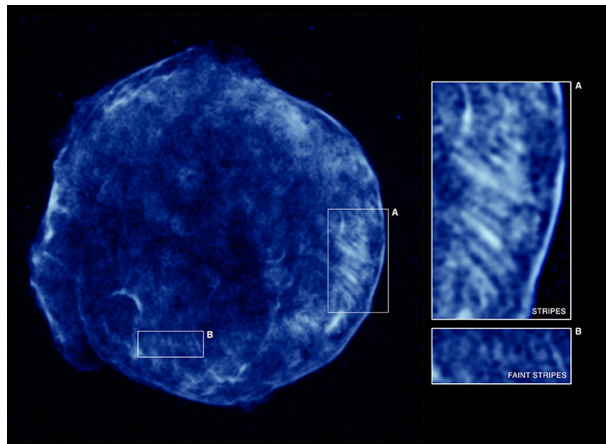
Example: Tycho SNR



Example: Tycho SNR



Example: Tycho SNR



Also sources of hadronic cosmic rays?

The case for supernova remnants

Ginzburg & Syrovatskii

- 1 Presence of strong shocks
- 2 Observation of PeV particles

3 Energetics:

$$\text{CR energy density:} \quad \varepsilon = 0.3 \text{ eV cm}^{-3} \simeq 5 \times 10^{-13} \text{ erg cm}^{-3}$$

$$\text{Volume of CR halo:} \quad V = \pi (10 \text{ kpc})^2 (3 \text{ kpc}) \simeq 3 \times 10^{67} \text{ cm}^3$$

$$\text{Total CR energy:} \quad \varepsilon V = 10^{55} \text{ erg}$$

$$\text{Residence time:} \quad t_{\text{res}} = 10^7 \text{ yr}$$

$$\text{Power needed:} \quad \varepsilon V / t_{\text{res}} = 10^{48} \text{ erg yr}^{-1}$$

$$\text{Galactic supernova rate:} \quad R = 0.03 \text{ yr}^{-1}$$

$$\text{Contribution from one supernova:} \quad \varepsilon V / (R t_{\text{res}}) = 3 \times 10^{49} \text{ erg}$$

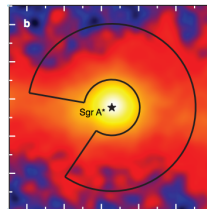
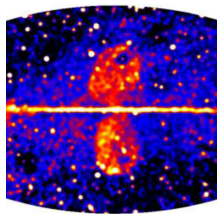
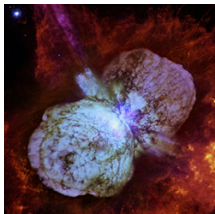
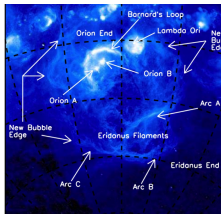
“What is accelerating to $E_{\text{knee}} \sim 3 \times 10^{15} \text{ eV}$?”

Supernova remnants

- $E_{\text{max}} \lesssim 10^{13\dots14} \text{ eV}$ for $B \sim B_{\text{ISM}}$
Lagage & Cesarsky (1983)
 - Amplify magnetic fields, non-resonant instability
Bell (2004)
 - Saturation?
- Particle-in-cell simulations

Other sources

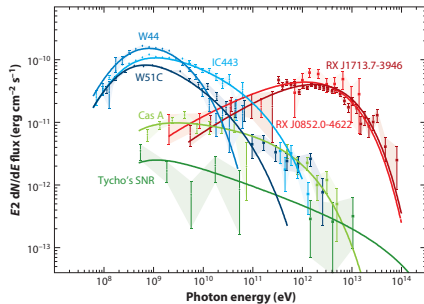
- Superbubbles
- Supernovae before shock breakout
- Colliding wind binaries
- Pulsar wind nebulae
- The Fermi bubbles
- The Galactic centre
- Massive star clusters



Any questions?

LHAASO disfavors supernova remnants as PeVatrons

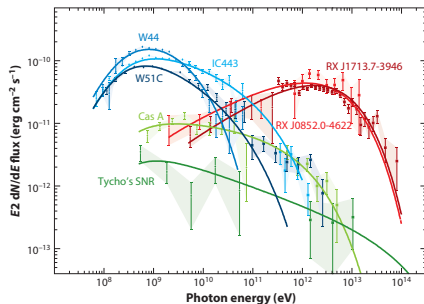
Funk et al. (2015)



- LHAASO Galactic plane survey
- Majority of sources: pulsars/pulsar wind nebulae
- Supernova remnants have very soft spectra

LHAASO disfavors supernova remnants as PeVatrons

Funk et al. (2015)

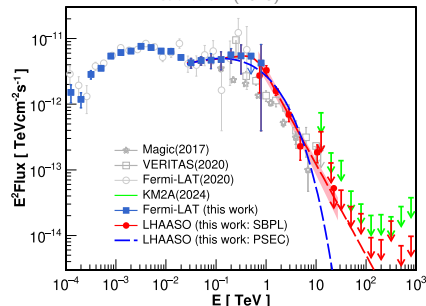


Cas A

- Very bright in radio
- 350 yr
- Possibly a PeVatron?

- LHAASO Galactic plane survey
- Majority of sources: pulsars/pulsar wind nebulae
- Supernova remnants have very soft spectra

Cao et al. (2025)



Star cluster winds could be sources of $\simeq$ PeV cosmic rays

Adjusted from Peron (2025)



Young massive star clusters (YMSCs)

- Energetics:

$$\sum_{\text{gal. YMSCs}} P \approx \sum_{\text{gal. SNRs}} P$$

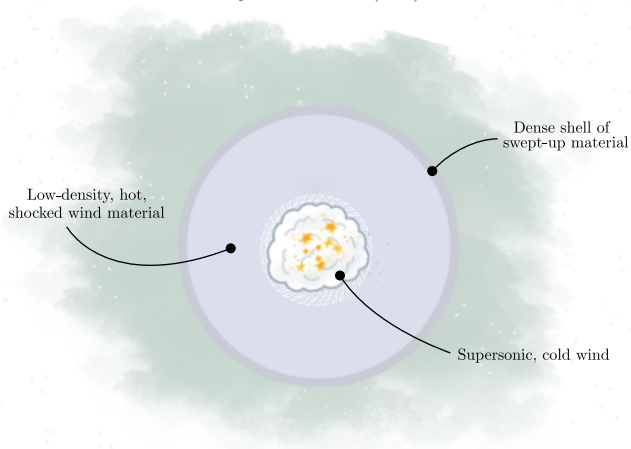
- Interaction of multiple stellar winds

→ turbulence

→ shock acceleration, stochastic acceleration

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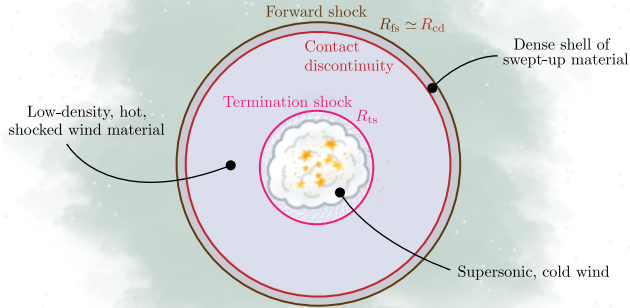
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$$\frac{\kappa}{U_{\text{sh}}} \simeq R_{\text{ts}}$$

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$$\text{Kraichnan : } E_{\max} \simeq 2.84 \left(\frac{\eta_B}{0.1} \right)^{\frac{1}{2}} \left(\frac{\dot{M}}{10^{-4} M_{\odot} \text{ yr}^{-1}} \right)^{-\frac{5}{10}} \left(\frac{L_w}{10^{39} \text{ erg s}^{-1}} \right)^{\frac{13}{10}} \left(\frac{\rho_0}{20 m_p \text{ cm}^{-3}} \right)^{-\frac{3}{10}} \left(\frac{t_{\text{age}}}{3 \text{ Myr}} \right)^{\frac{2}{5}} \left(\frac{L_{\text{inj}}}{2 \text{ pc}} \right)^{-1} \text{ PeV},$$

$$\text{Bohm : } E_{\max} \simeq 20 \left(\frac{\eta_B}{0.1} \right)^{\frac{1}{2}} \left(\frac{\dot{M}}{10^{-4} M_{\odot} \text{ yr}^{-1}} \right)^{-\frac{1}{4}} \left(\frac{L_w}{10^{39} \text{ erg s}^{-1}} \right)^{\frac{3}{4}} \text{ PeV},$$

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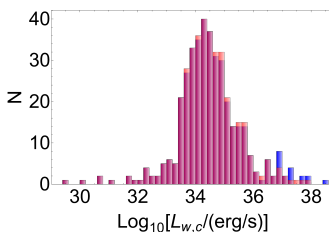
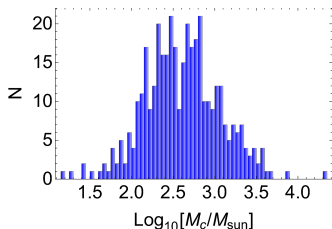
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Celli et al. (2024)

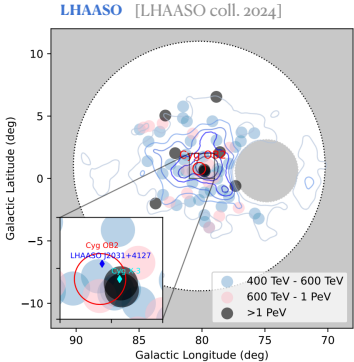
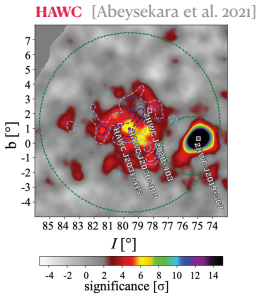
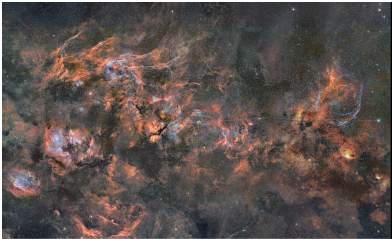
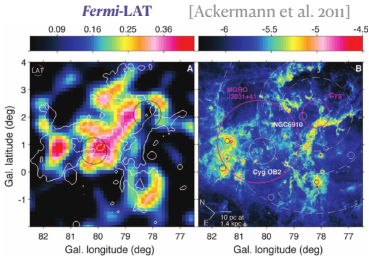
YMSCs as gamma-ray sources I

Peron (2025)

How many do we know?

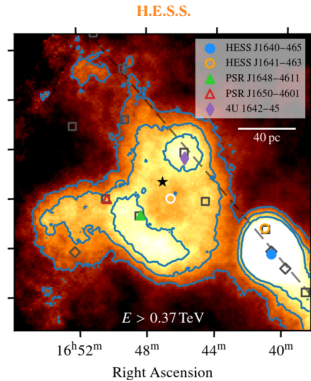
Cygnus Region

- Complex Star forming region: OB associations (OB2, but also OB1...9), PSRs, SNRs, background MQs (Cyg X-3)
- Hadronic emission up to PeV!



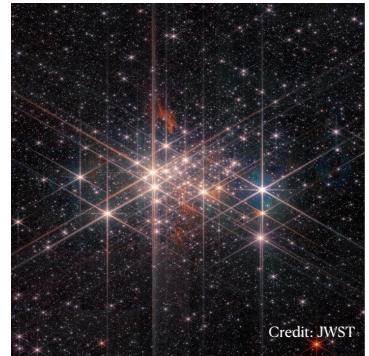
How many do we know?

Westerlund 1



[Aharonian et al. 2022]

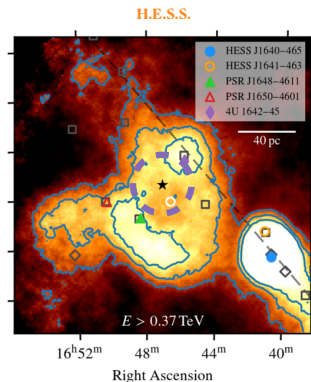
- Most powerful SC in the Galaxy
- $\sim 4\text{-}5$ Myr old
- Contains ~ 20 WRs !
- No dense surrounding gas
- Emission predominantly *leptonic* [Härer et al. 2023]



YMSCs as gamma-ray sources II

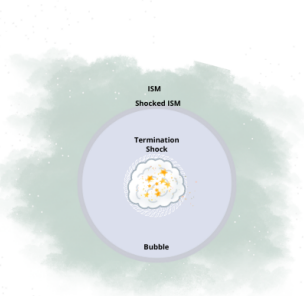
Peron (2025)

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[Aharonian et al. 2022]

Westerlund 1



Accelerated electrons at the edge of the TS interacting with high radiation field of the cluster

[Härer et al. 2023]

