Galactic cosmic rays (I)

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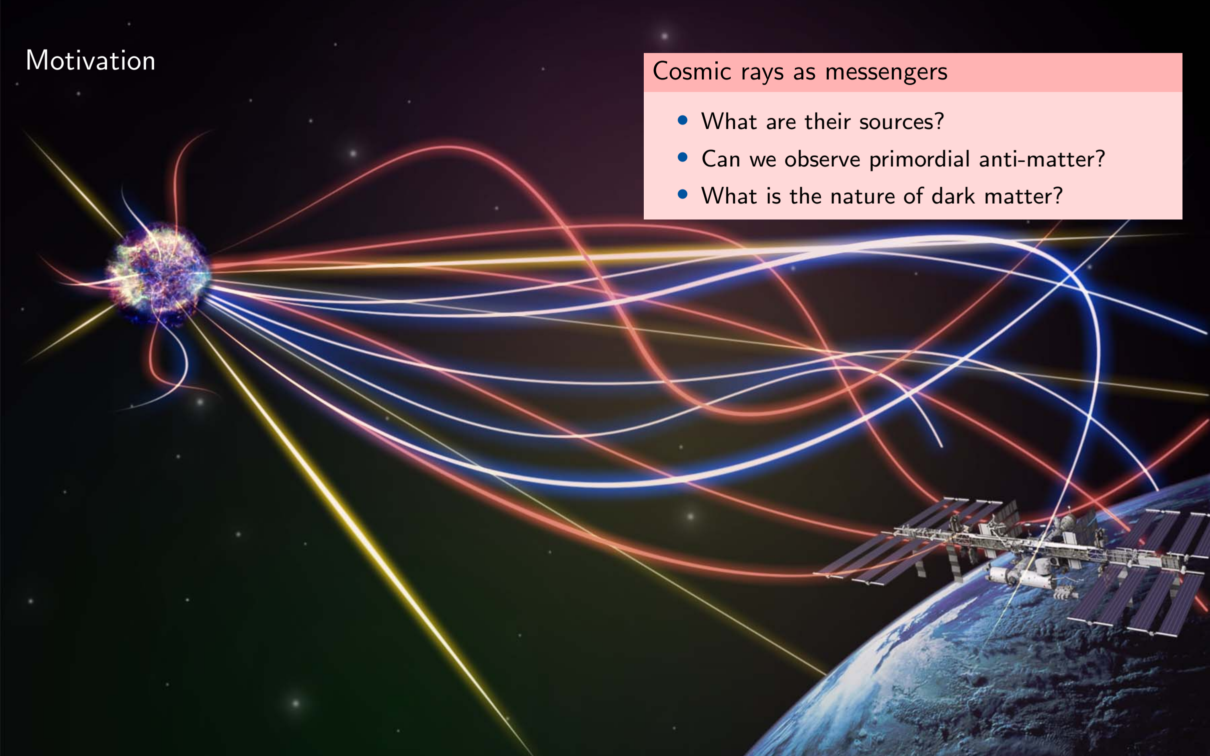
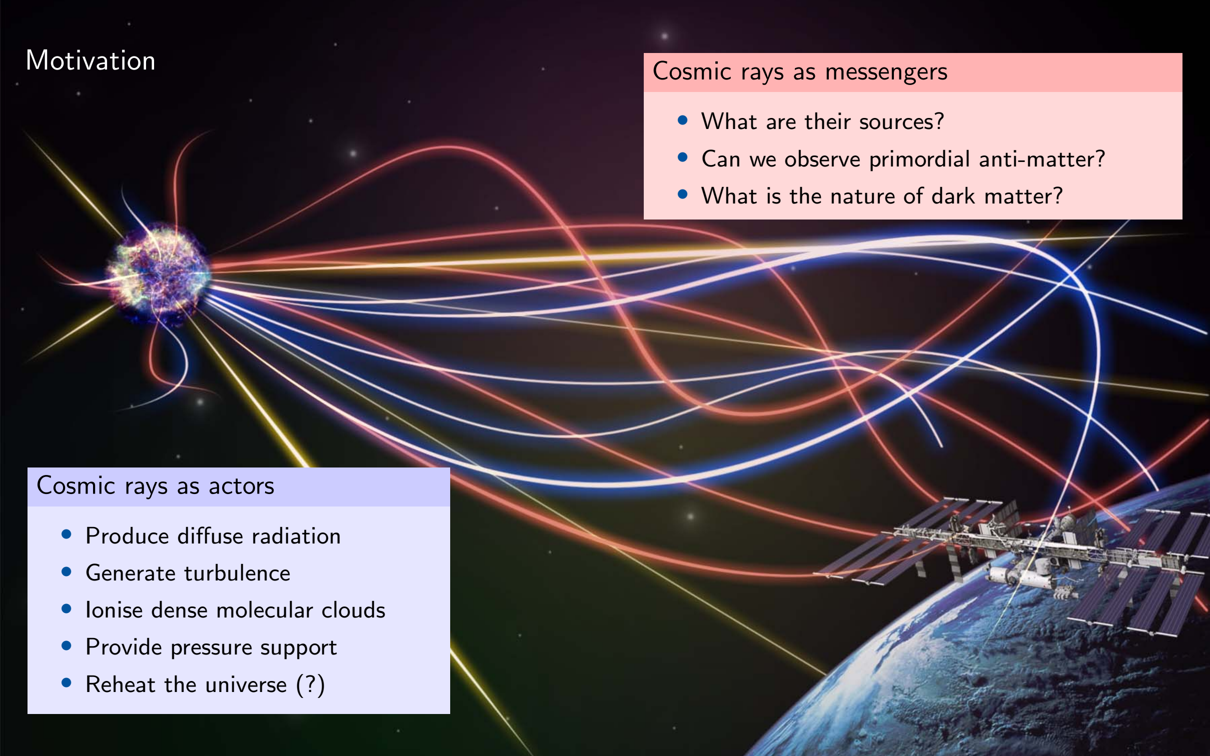
Motivation



Cosmic rays as messengers

- What are their sources?
- Can we observe primordial anti-matter?
- What is the nature of dark matter?



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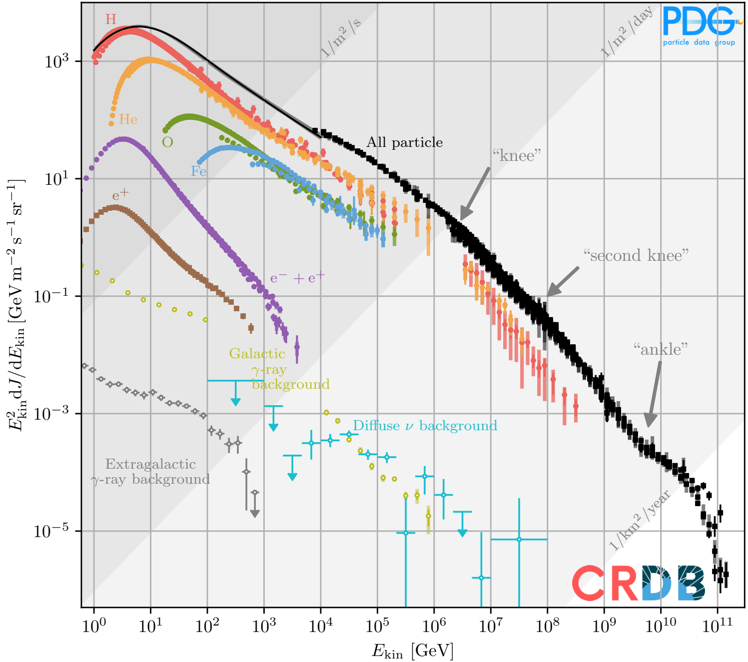
Cosmic rays as actors

- Produce diffuse radiation
- Generate turbulence
- Ionise dense molecular clouds
- Provide pressure support
- Reheat the universe (?)

The cosmic ray spectrum



Intensity $\mathrm{d}J/\mathrm{d}E$

$$\frac{\mathrm{d}J}{\mathrm{d}E} \equiv \frac{(\#\text{particles})}{\Delta t \, \Delta A \, \Delta\Omega \, \Delta E}$$

- $\sim$ 12 orders of magnitude in energy
- $\sim$ power law $\mathrm{d}J/\mathrm{d}E \propto E^{-3}$ with some features

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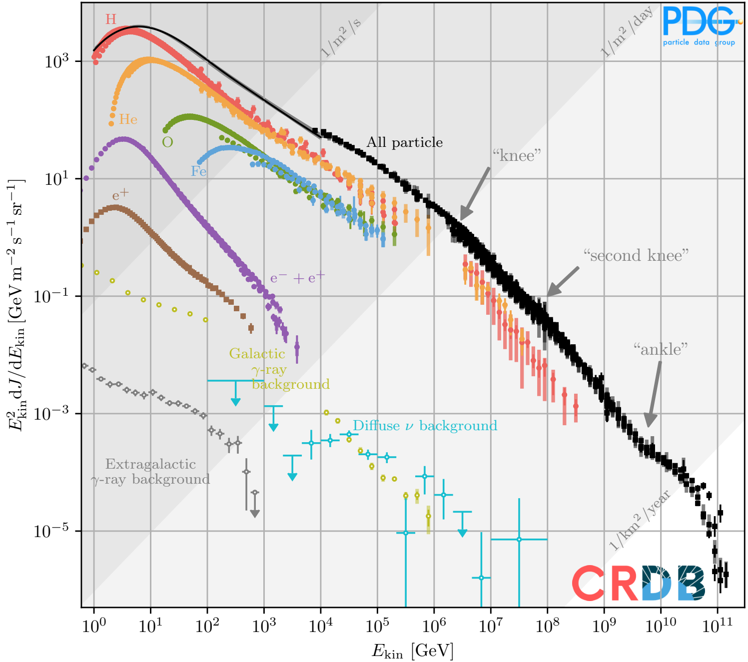

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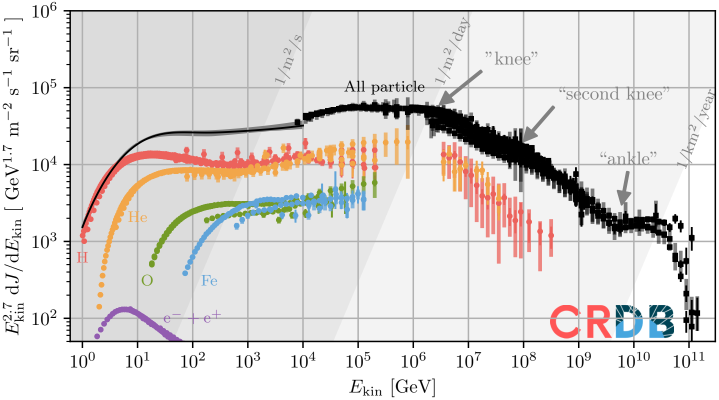
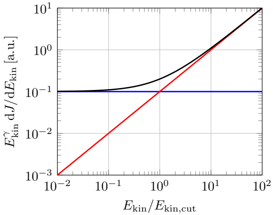
Where is the transition from galactic to extragalactic sources?

$\rightarrow$ three arguments

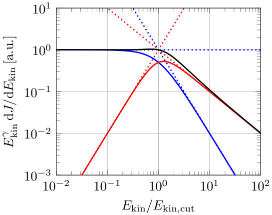
Spectral argument



Hardening



Softening



Anisotropy argument (1)

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

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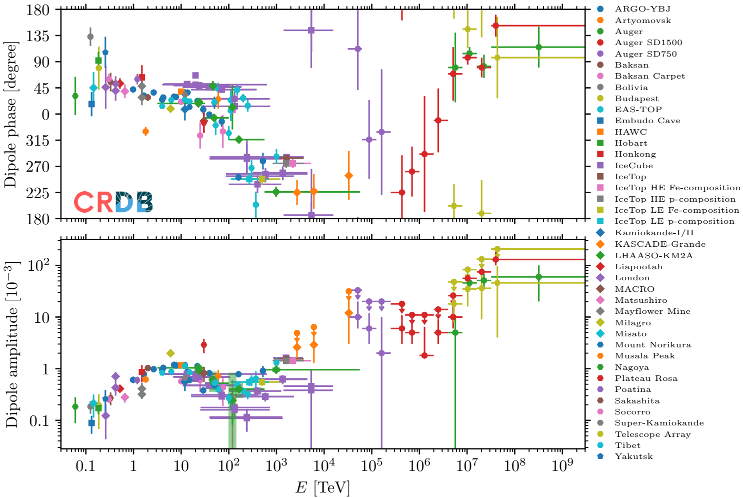
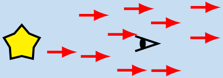


Anisotropy argument (2)



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

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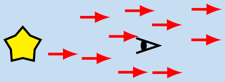

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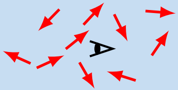

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$\rightarrow$ Need to isotropise CRs

- (Coulomb) collisions with interstellar matter too infrequent

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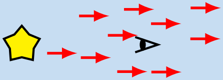

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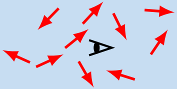

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Isotropisation by magnetic field requires gyroradius $\leq$ (size of Galaxy)

$$r_{\mathrm{g}} = \frac{pc}{eB} \simeq 1\,\mathrm{pc} \left(\frac{pc}{\mathrm{PeV}} \right) \left(\frac{B}{\mu\mathrm{G}} \right)^{-1} = 1\,\mathrm{kpc} \left(\frac{pc}{\mathrm{EeV}} \right) \left(\frac{B}{\mu\mathrm{G}} \right)^{-1}$$

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

$E_{\rm max}$ argument

- Shock acceleration:

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

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

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

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

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

Lagage & Cesarsky (1983)

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

Acceleration in SNRs: $E_{\rm max} \lesssim 10^{15}\,\mathrm{eV}$

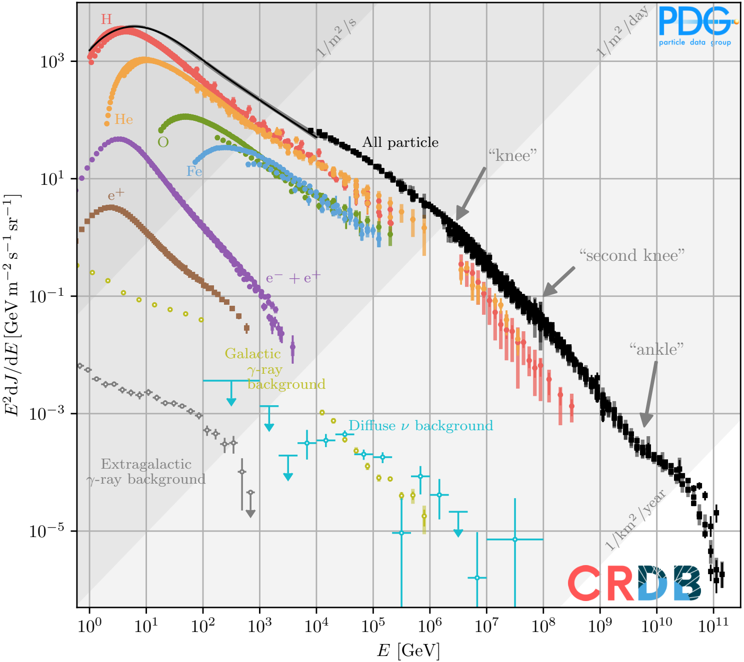
Transition summary

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

Working definition:

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

The cosmic ray spectrum



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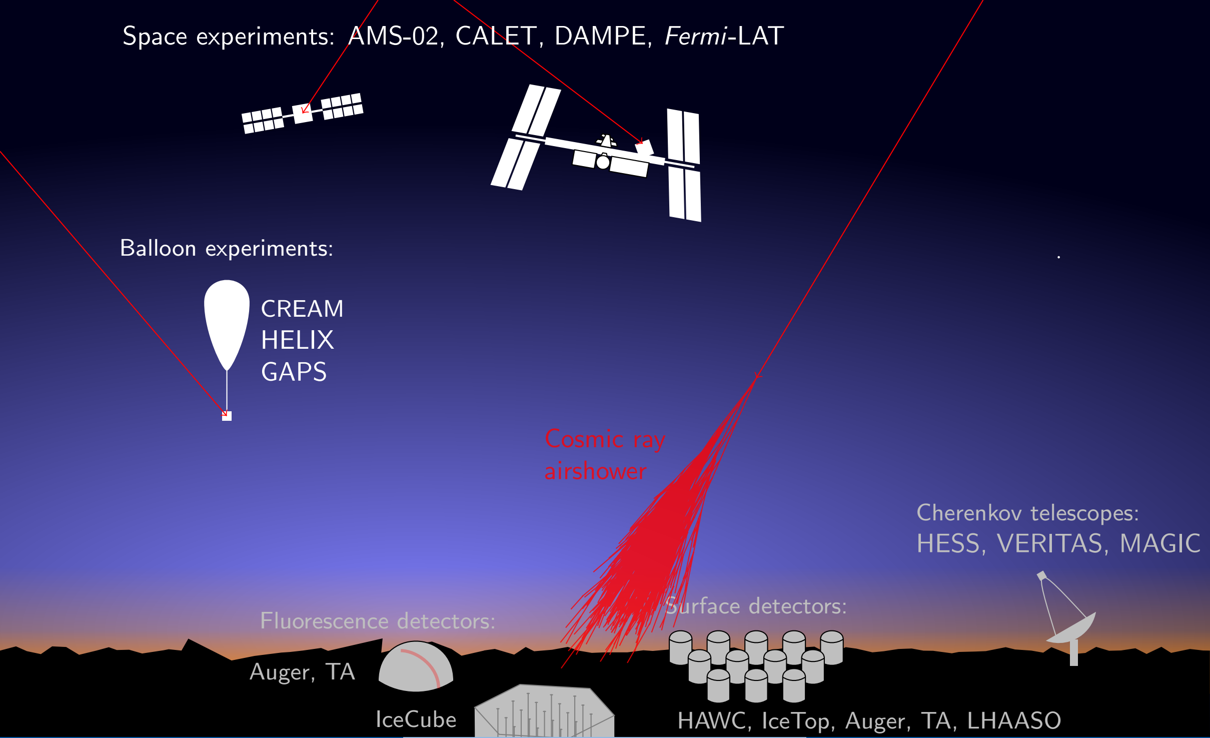
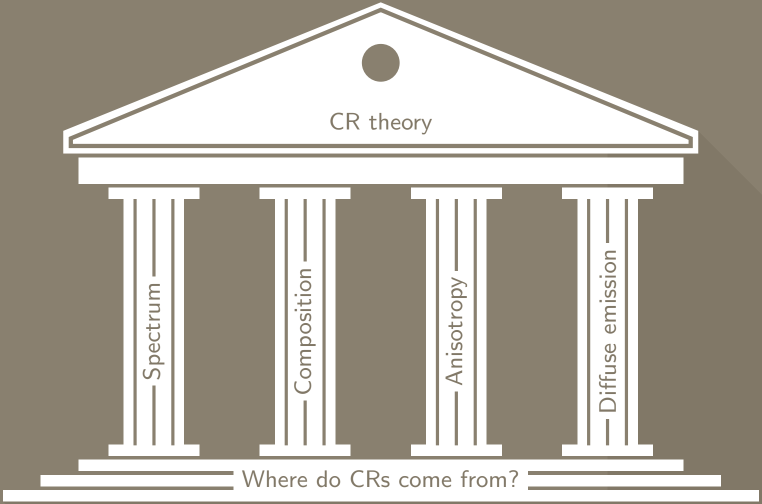


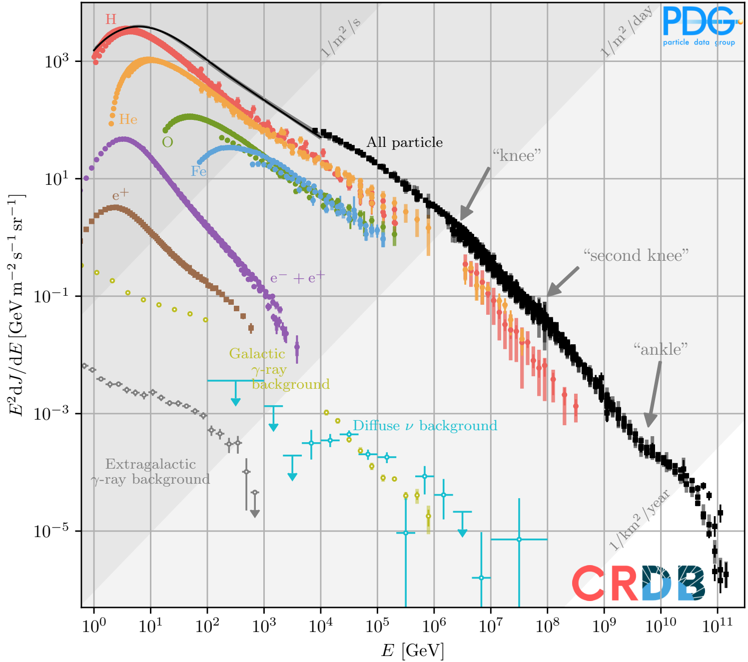
Space experiments: AMS-02, CALET, DAMPE, *Fermi*-LAT
Balloon experiments:
CREAM
HELIX
GAPS
Cosmic ray airshower
Cherenkov telescopes:
HESS, VERITAS, MAGIC
Fluorescence detectors:
Auger, TA
Surface detectors:
HAWC, IceTop, Auger, TA, LHAASO
IceCube

Outline

Outline


CR theory
Spectrum
Composition
Anisotropy
Diffuse emission
Where do CRs come from?

The cosmic ray spectrum



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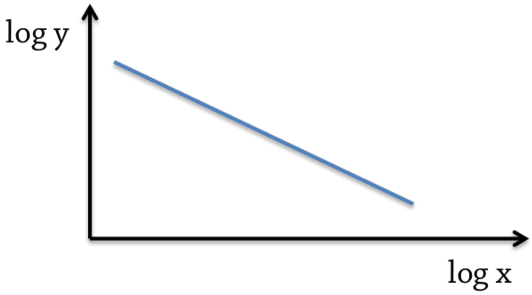
Powerlaws in astrophysics



Scale invariance

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

Examples

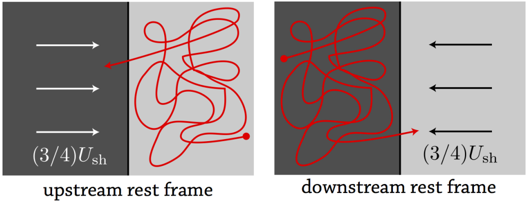
- Spectrum of density perturbations in early universe
- Initial mass function of stars
- Power spectrum of (magneto-)hydrodynamic turbulence
- Energy or frequency spectra of astrophysical sources
- ...

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: $N(>p_n) = N_n$

$$\left.\begin{array}{rcl} \ln N(>p_n) & = & \ln(1-q)^n \simeq -nq \\ \ln p_n/p_0 & = & \ln(1+g)^n \simeq ng \end{array}\right\} \Rightarrow N(>p_n) = \left(\frac{p_n}{p_0}\right)^{-q/g} = \int_{p_0}^{p_n} \mathrm{d}p \, \frac{\mathrm{d}N}{\mathrm{d}p}$$

$$\frac{\mathrm{d}N}{\mathrm{d}p} \propto \left(\frac{p}{p_0}\right)^{-(1+q/g)}$$

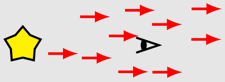


Diffusive shock acceleration

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

Anisotropy

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



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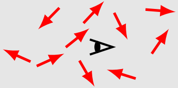

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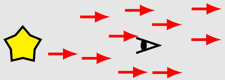

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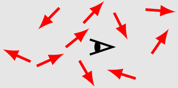

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- Scattering of charged particles with turbulent magnetic field isotropises particle directions

$\rightarrow$ 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

Rigidity

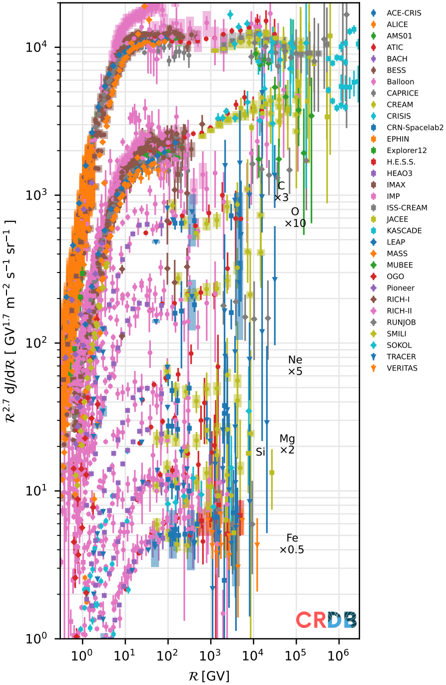
- Charged particles subject to Lorentz force:

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

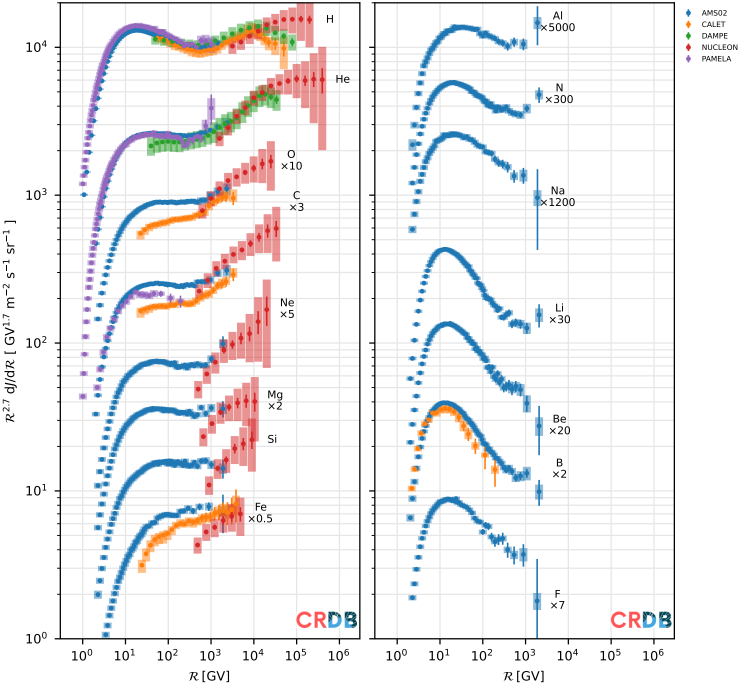
- Here, $R = \frac{pc}{Ze}$ is called the rigidity and $s = vt$ is the path length
- For relativistic nuclei, rigidity $= 2 \times$ (energy per nucleon):

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

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



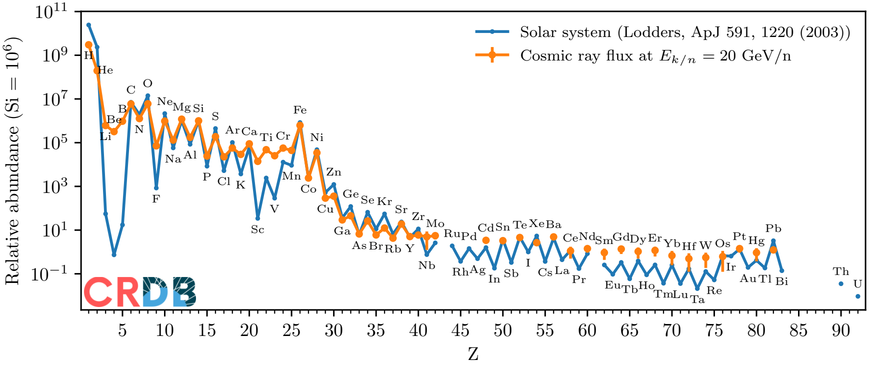
$\mathcal{R}^{2.7}$ dJ/d$\mathcal{R}$ [GV$^{1.7}$ m^{-2} s^{-1} sr^{-1}]
$\mathcal{R}$ [GV]
C ×3
O ×10
Ne ×5
Mg ×2
Si
Fe ×0.5
CRDB
ACE-CRIS
ALICE
AMS01
ATIC
BACH
BESS
Balloon
CAPRICE
CREAM
CRISIS
CRN-Spacelab2
EPHIN
Explorer12
H.E.S.S.
HEAO3
IMAX
IMP
ISS-CREAM
JACEE
KASCADE
LEAP
MASS
MUBEE
OGO
Pioneer
RICH-I
RICH-II
RUNJOB
SMILI
SOKOL
TRACER
VERITAS



Spectral universality,
but ∼ two groups

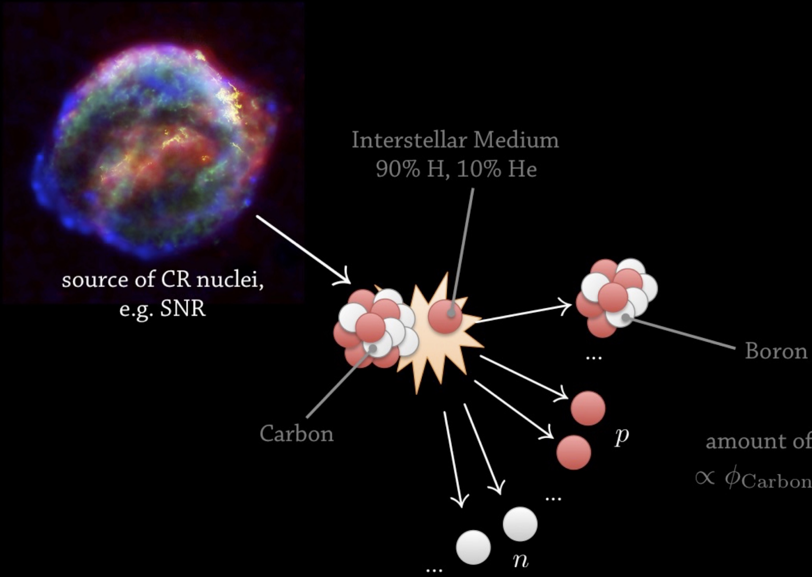
Composition

- 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

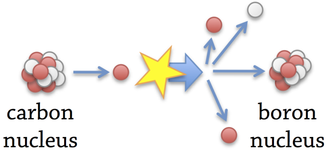


amount of Boron

$\propto \phi_{\mathrm{Carbon}}\, \sigma_{\mathrm{spall}}\, n_{\mathrm{gas}}$

Approximation

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



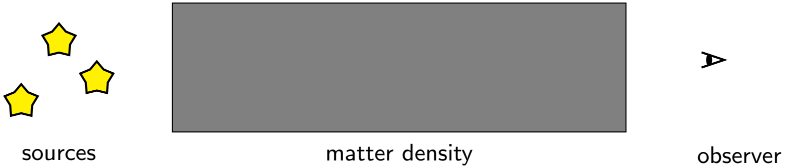
$$E_{\mathrm{kin,B}} = 11 E_{\mathrm{n,B}} = 11 E_{\mathrm{n,C}} = \frac{11}{12} E_{\mathrm{kin,C}}$$

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

$$\frac{\mathrm{d}^2 N_{\mathrm{B}}}{\mathrm{d}E_{\mathrm{n}}\,\mathrm{d}t} = -\frac{\mathrm{d}^2 N_{\mathrm{C}}}{\mathrm{d}E_{\mathrm{n}}\,\mathrm{d}t}$$

Outline

Slab model



- Somewhat model-independent way of quantifying the confinement

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

→ Amount of matter ρ that CRs traverse

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

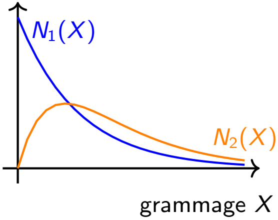
$$\frac{\mathrm{d}N_1}{\mathrm{d}X} = -\frac{N_1}{\lambda_1}$$
$$\frac{\mathrm{d}N_2}{\mathrm{d}X} = -\frac{N_2}{\lambda_2} + \mathrm{BR}_{1\to 2}\frac{N_1}{\lambda_1}$$

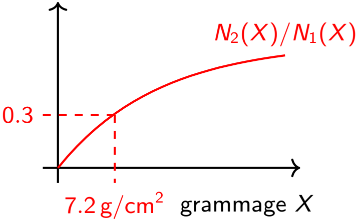
where $\lambda_{1,2} = (\sigma_{1,2}/m)^{-1}$ is the inverse of the specific cross-section and $\mathrm{BR}_{1\to 2}$ is the branching ratio.

Grammage

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

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





Example: Boron-to-carbon ratio

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

$\to$ $X \simeq 7.2\,\mathrm{g\,cm^{-2}}$

Grammage

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

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

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

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

- Residence time in disk:

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

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

Leaky box model

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

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

$$\frac{\mathrm{d}N_1}{\mathrm{d}t} = -\frac{N_1}{t_{\mathrm{esc}}} - N_1 \Gamma_1 + Q_1$$
$$\frac{\mathrm{d}N_2}{\mathrm{d}t} = -\frac{N_2}{t_{\mathrm{esc}}} - N_2 \Gamma_2 + \Gamma_{1 \to 2} N_1$$

- In steady state $(\mathrm{d}N_i/\mathrm{d}t \equiv 0)$:

$$N_1 = \frac{Q_1}{1/t_{\mathrm{esc}} + \Gamma_1}$$
$$N_2 = \frac{\Gamma_{1 \to 2}}{1/t_{\mathrm{esc}} + \Gamma_2} N_1 = \frac{\sigma_j \mathrm{BR}_{1 \to 2}}{1/(v t_{\mathrm{esc}} \bar{n}_{\mathrm{gas}}) + \sigma_2} N_1$$

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

Cosmic ray clocks

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

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

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

- Equation for ^{10}Be

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

- and so the ratio is

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

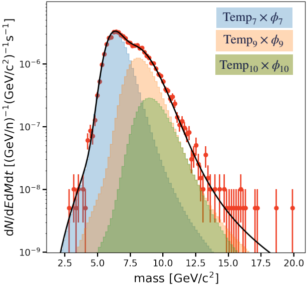
Comparison with data: $\bar{n}_{gas} \sim 0.1\,\mathrm{cm}^{-3}$, much lower than in disk
⇒ CRs spend only fraction of time in disk, rest of time
in extended **CR halo**, $z_{max}/h \sim 10$

Isotopes

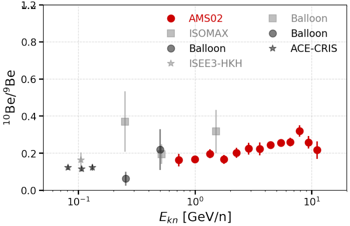
Derome *et al.*, PoS (ICRC2021) 119

- $\Delta M \simeq 1\,\mathrm{amu}$

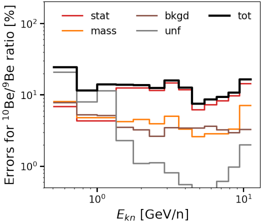
$\rightarrow$ no event-by-event analysis,
but use shape of mass distribution



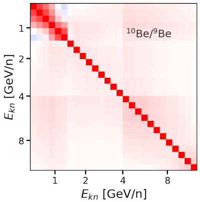
Flux ratios



Errors



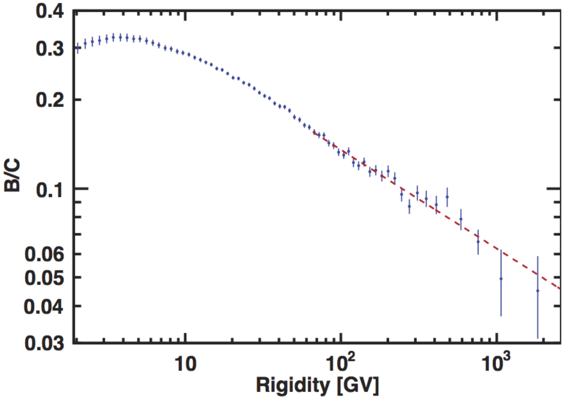
Total correlation matrices



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

Rigidity-dependent grammage

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



Rigidity-dependent grammage

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

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

- If interpreted as residence time:

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

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

($z_{\max}$: halo height; h: disk height)

- In a diffusion model with diffusion coefficient κ,

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

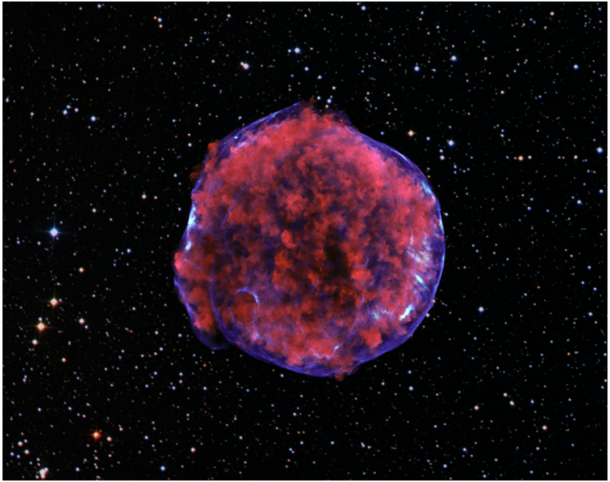
$\rightarrow$ faster diffusion at higher energies: $\kappa = \kappa(p) \sim p^{1/3}$

What are the sources of (galactic) CRs?

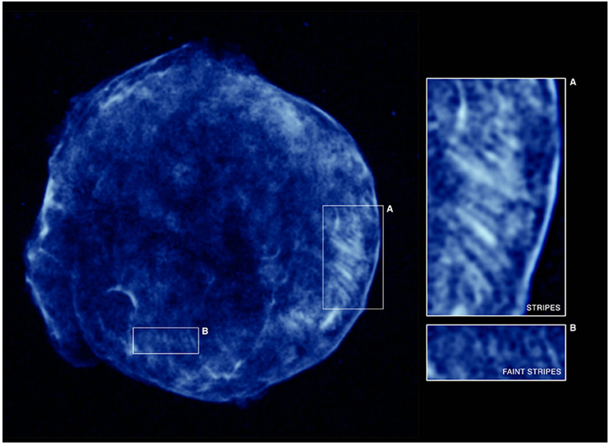
- Already Baade & Zwicky suggested supernovae (SNe)
- SN liberates much of gravitational energy of star, typically 10^{51} erg
- ($1\,\mathrm{erg} = 10^{-7}\,\mathrm{J} \simeq 624\,\mathrm{GeV}$)

- However, particles accelerated in SN event suffer from adiabatic losses

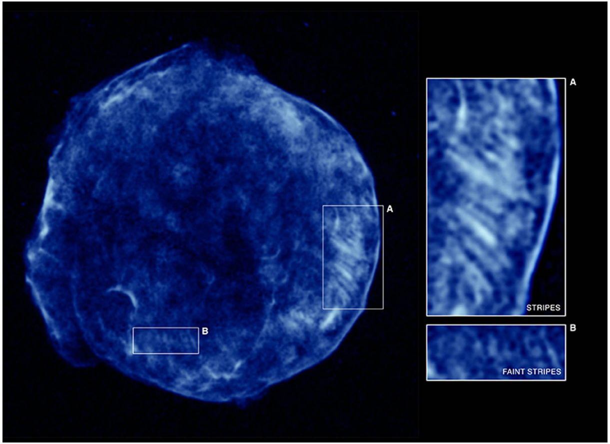
Example: Tycho SNR



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:

CR energy density:	ε	$= 0.3\,\mathrm{eV\,cm^{-3}} \simeq 5\times10^{-13}\,\mathrm{erg\,cm^{-3}}$
Volume of CR halo:	V	$= \pi(10\,\mathrm{kpc})^2(3\,\mathrm{kpc}) \simeq 3\times10^{67}\,\mathrm{cm^3}$
Total CR energy:	εV	$= 10^{55}\,\mathrm{erg}$
Residence time:	t_{res}	$= 10^7\,\mathrm{yr}$
Power needed:	$\varepsilon V/t_{\mathrm{res}}$	$= 10^{48}\,\mathrm{erg\,yr^{-1}}$
Galactic supernova rate:	R	$= 0.03\,\mathrm{yr^{-1}}$
Contribution from one supernova:	$\varepsilon V/(R t_{\mathrm{res}})$	$= 3\times10^{49}\,\mathrm{erg}$

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

Supernova remnants

- $E_{\text{max}} \lesssim 10^{13 \ldots 14}$ eV for $B \sim B_{\text{ISM}}$

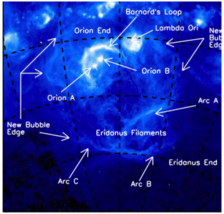
  Lagage & Cesarsky (1983)
- Amplify magnetic fields, non-resonant instability

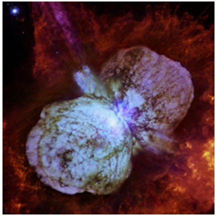
  Bell (2004)
- Saturation?

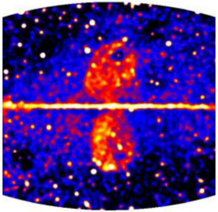
$\rightarrow$ Particle-in-cell simulations

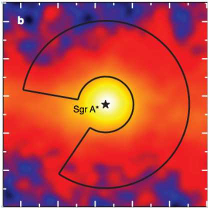
Other sources

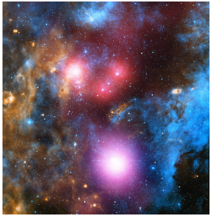
- Superbubbles
- Supernovae before shock breakout
- Colliding wind binaries
- Pulsar wind nebulae
- The Fermi bubbles
- The Galactic centre
- Massive star clusters











Any questions?