Extracting physical quantities from cosmic ray and gamma ray observations

Stefano Gabici
APC, Paris

What we have to explain about CRs:

- Energy density
- Energy spectrum
- Chemical composition
- Isotropy
- Stability in time
- Spatial homogeneity (?)

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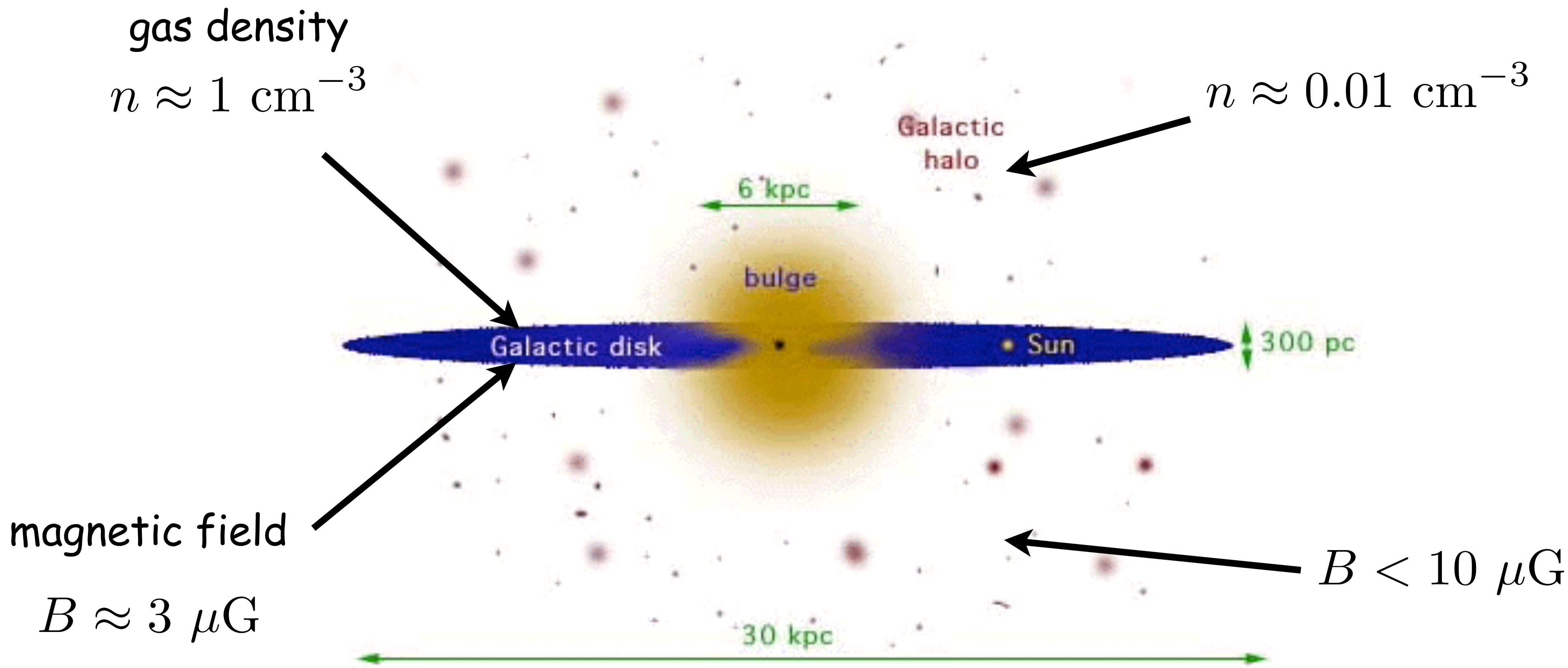
Gamma rays from the Milky Way



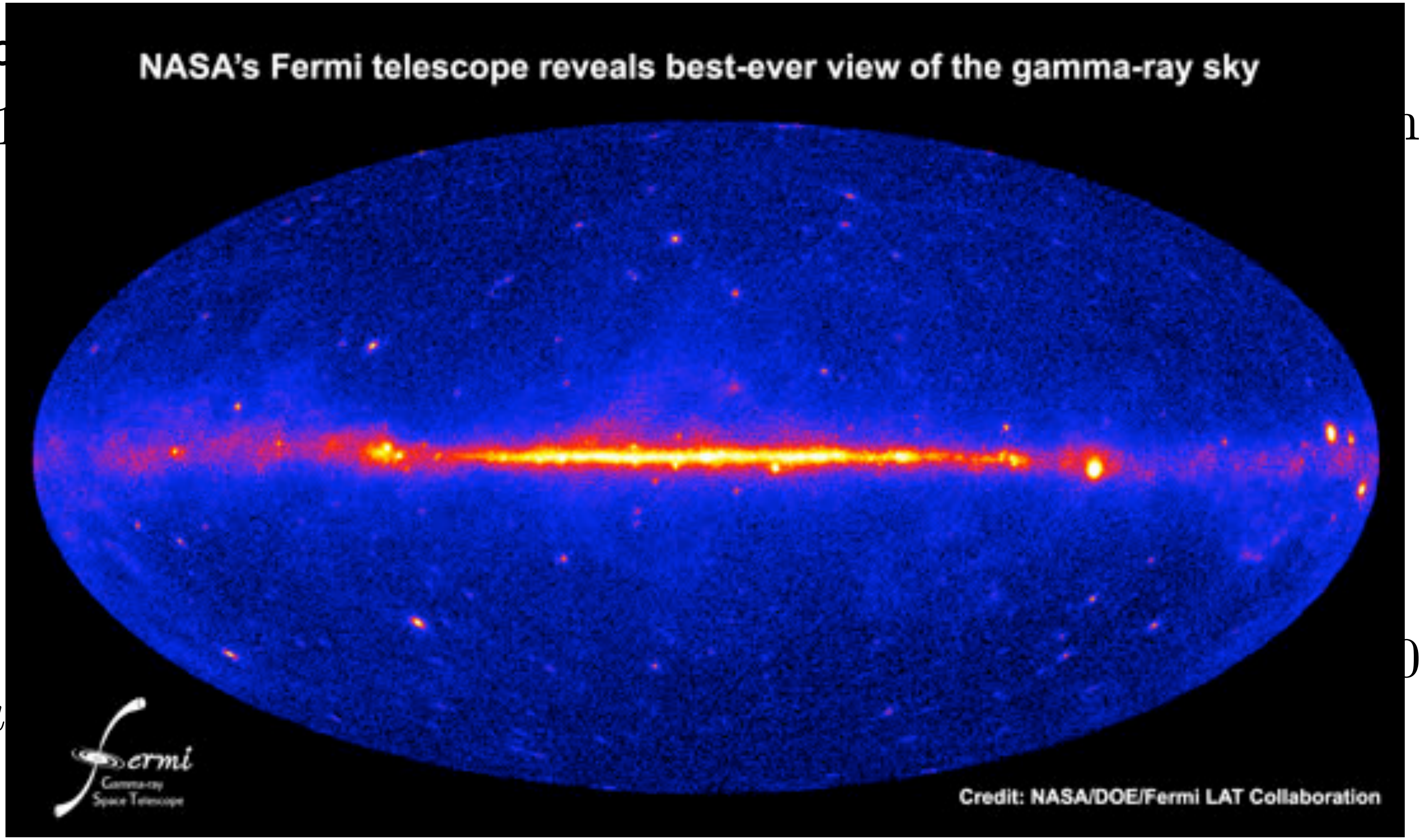
Schematic view of the Milky Way

Gamma rays from the Milky Way

gas d

$n \approx 1$

n^{-3}



magnetic f

$B \approx 3\ \mu$

$0\ \mu\mathrm{G}$

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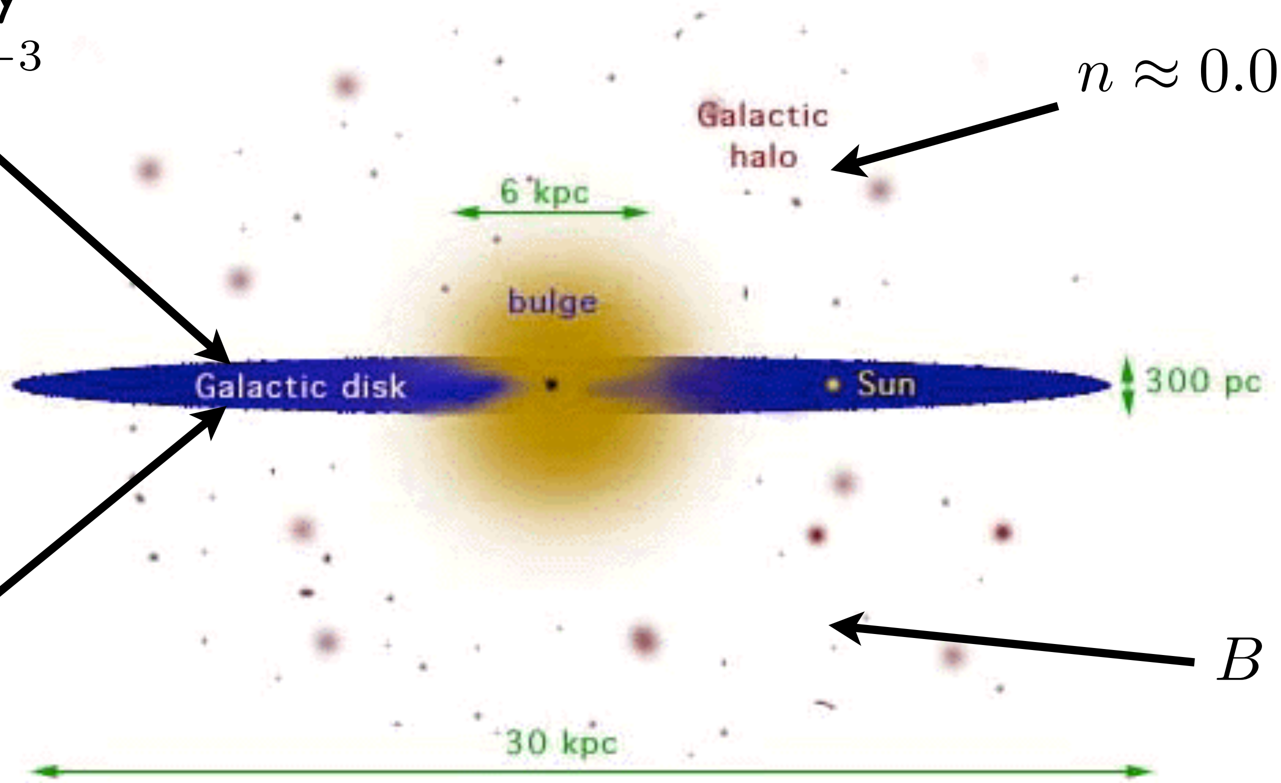
gas density

$n \approx 1 \text{ cm}^{-3}$

$n \approx 0.01 \text{ cm}^{-3}$



magnetic field

$B \approx 3\ \mu\text{G}$

$B < 10\ \mu\text{G}$

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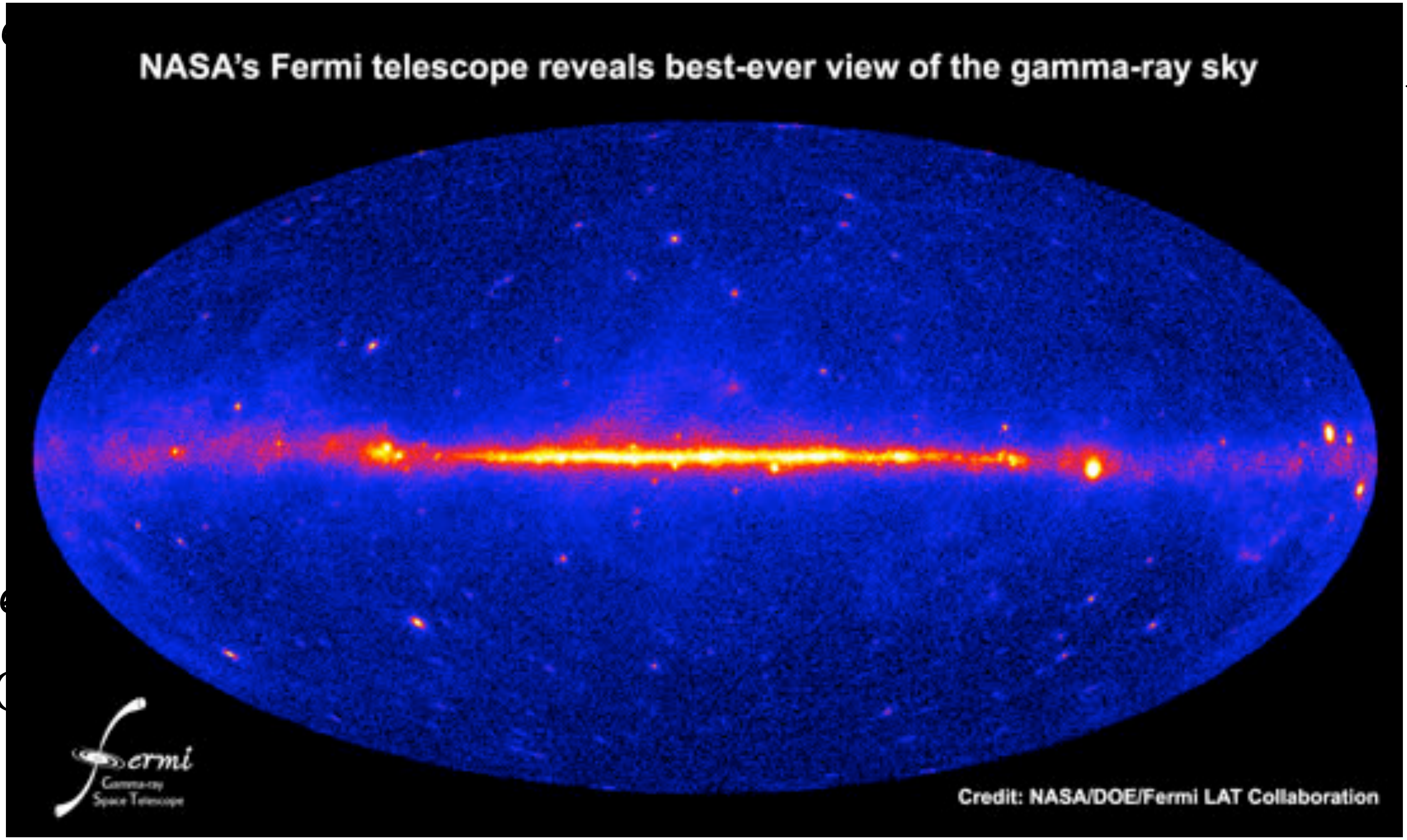

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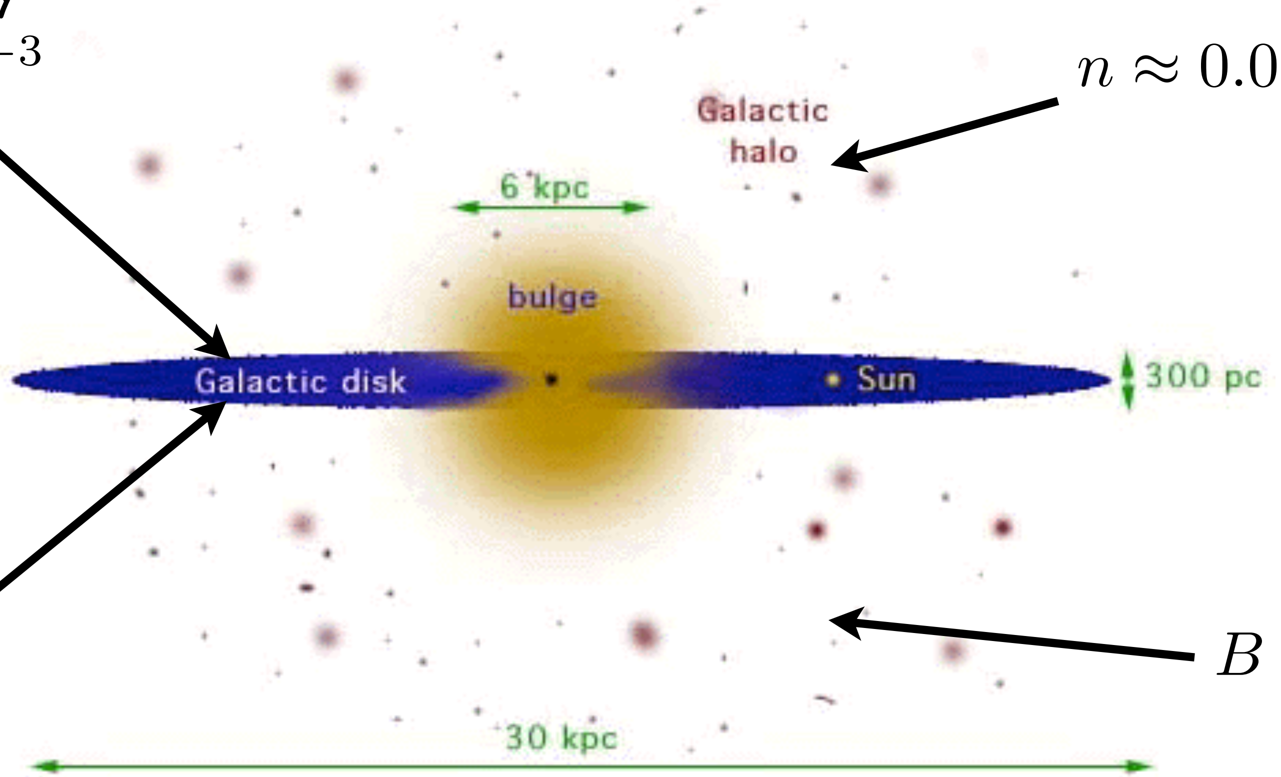

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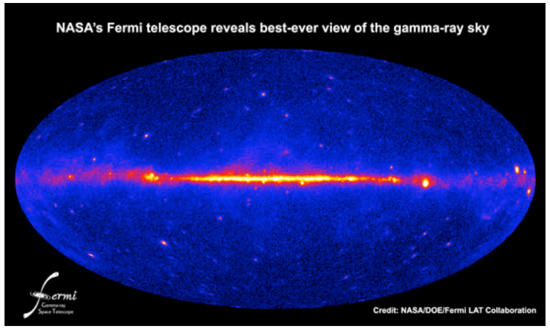
from gamma ray observations

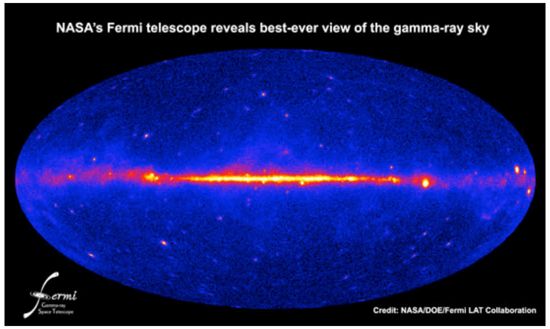
Are CRs universal?



Cosmic rays are homogeneously distributed in the galactic disk.

Hypothesis: are they homogeneously distributed in the whole Universe?

Are CRs universal?



Cosmic rays are homogeneously distributed in the galactic disk.
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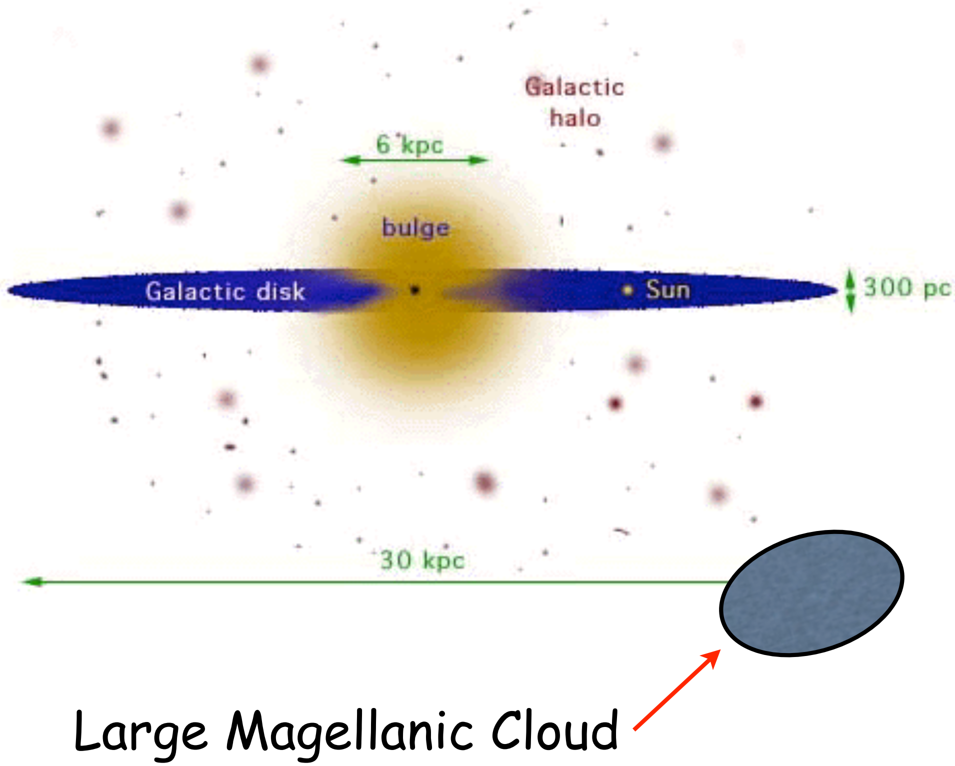
We play the same game with the Large Magellanic Cloud.
Total gas mass -> expected gamma rays

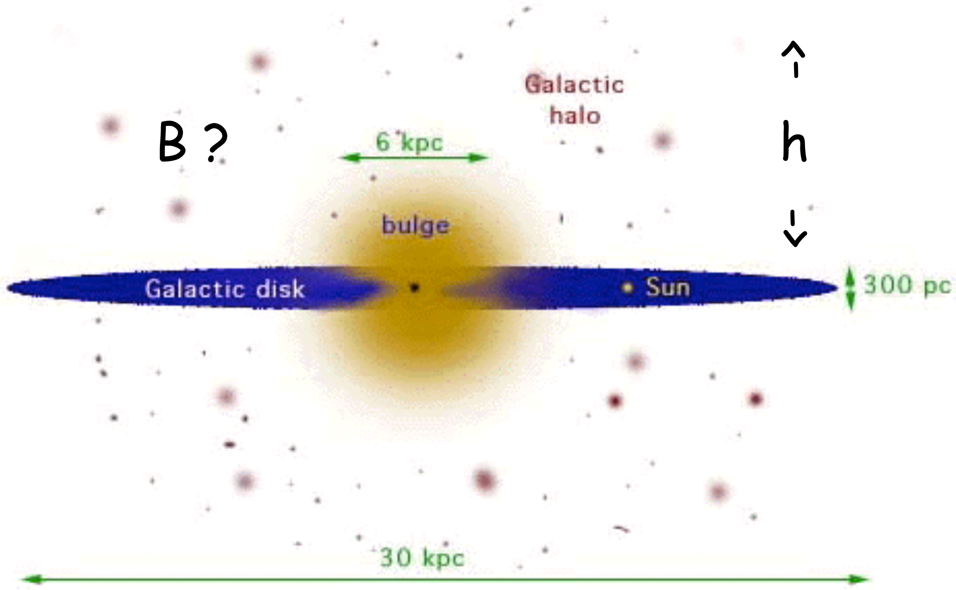
We observe less gammas than expected!

CRs come from the Galaxy



Galactic or extra-galactic?

Which CRs are confined in the Galaxy?



It depends on the values of the magnetic field and thickness of the halo (both poorly constrained...)

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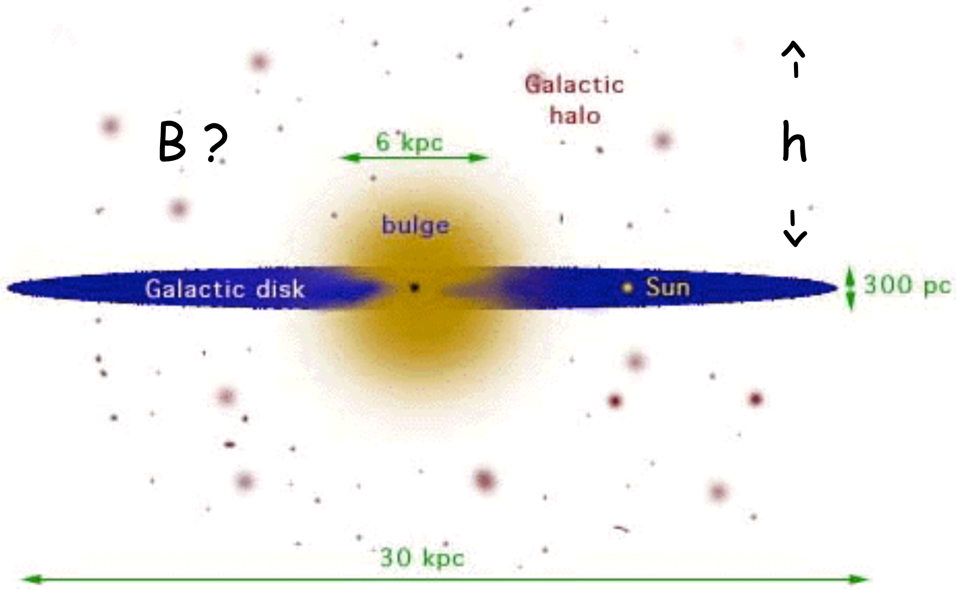

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Confinement condition:

$$R_L < h$$

Larmor radius

halo size

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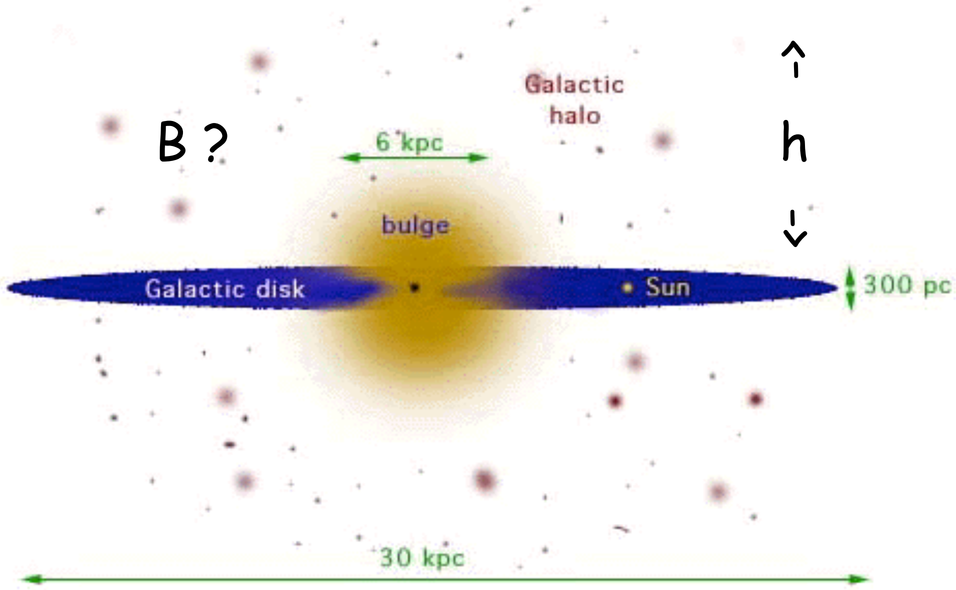

It depends on the values of the magnetic field and thickness of the halo (both poorly constrained...)

Confinement condition:

$$\frac{E(\mathrm{eV})}{300\ B(\mathrm{G})} = R_L < h \Rightarrow E < 10^{18}\left(\frac{h}{\mathrm{kpc}}\right)\left(\frac{B}{\mu\mathrm{G}}\right)\mathrm{eV} = 10^{17} \div 10^{20}\ \mathrm{eV}$$

(cm) Larmor radius halo size 1 - 10 0.1 - 10

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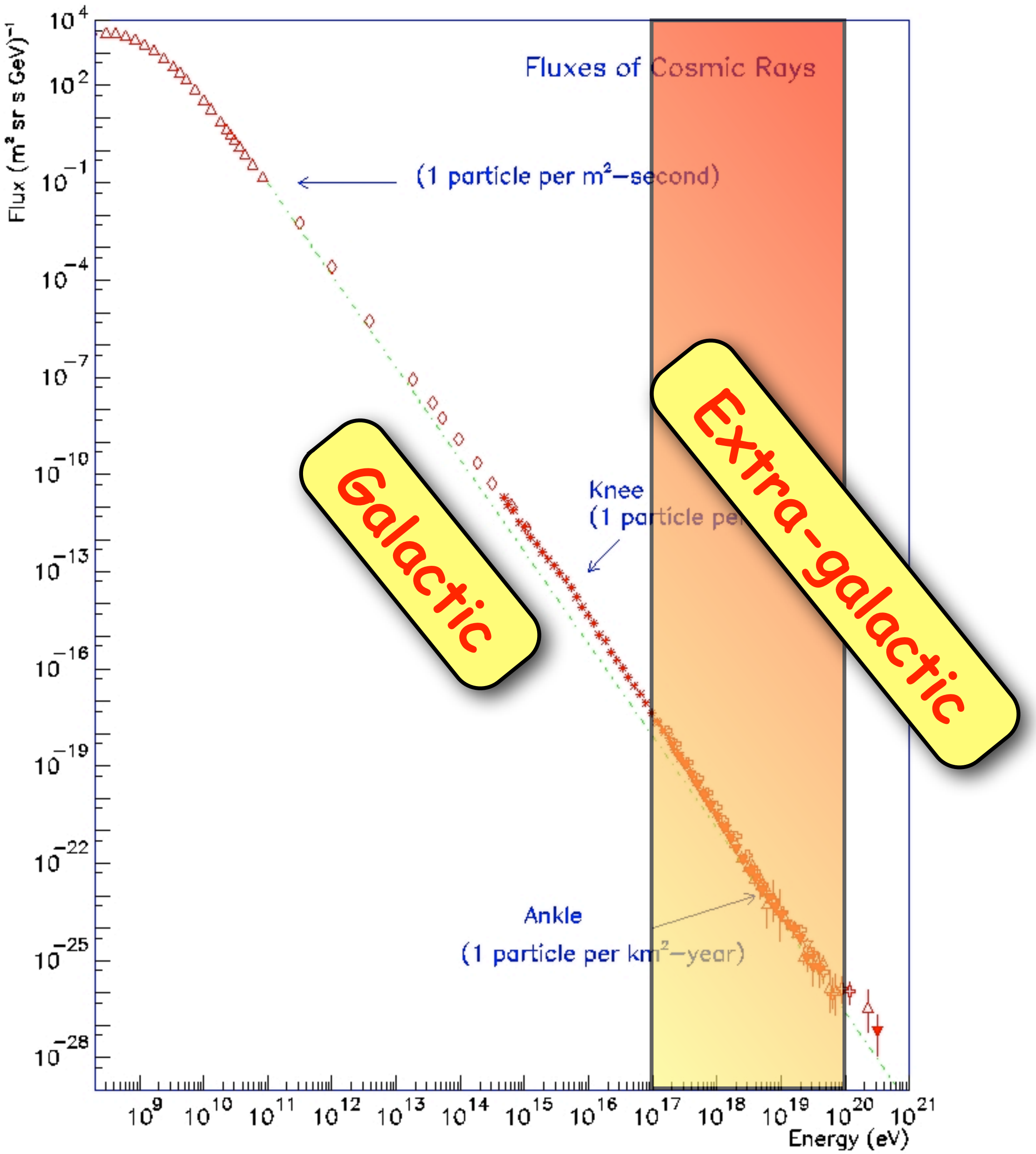

What we have to explain about CRs:

- [ ] Energy density
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- [ ] Isotropy
- [ ] Stability in time
- [x] Spatial homogeneity ( )

  (in the Milky Way)

-> in the Galaxy

-> Galactic up to the knee and above

-> many sources

from gamma ray observations

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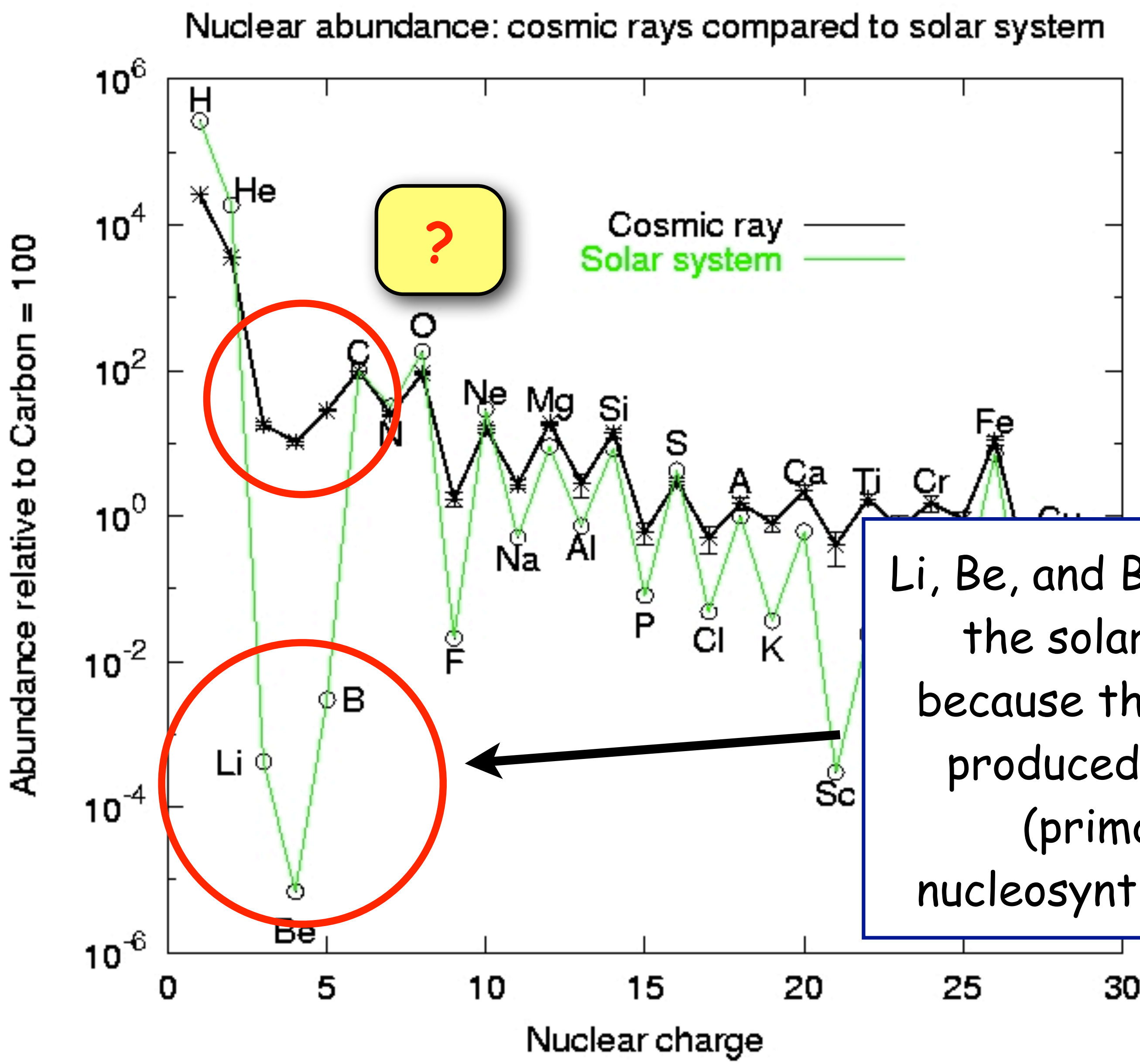
Cosmic Ray composition



Li, Be, and B are rare in the solar system because they are not produced by stars (primordial nucleosynthesis only)

Cosmic Ray composition: spallation

Spallation: production of light elements as fragmentation products of the interaction of high energy particles with cold matter.

The anomaly is explained if (~ GeV) CRs transverse $\lambda \approx 5 \ \mathrm{g/cm^2}$

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Assuming propagation in the galactic disk: $l_s = \dfrac{\lambda}{\varrho_{ISM}} \approx 1 \text{ Mpc}$

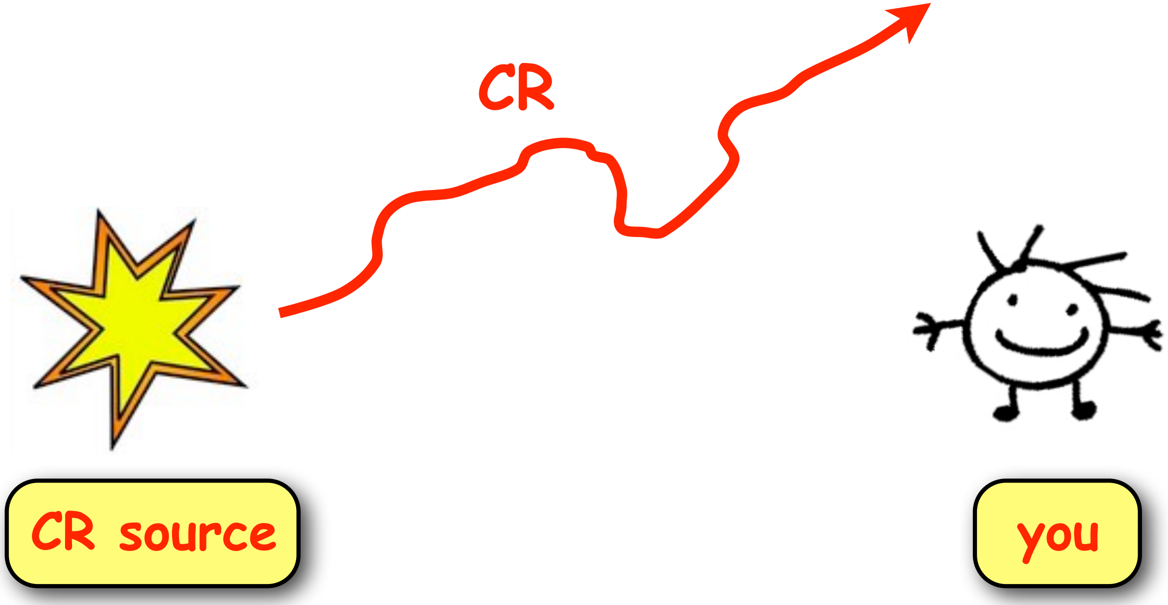
much larger than the size of the disk!!!

CRs don't go straight but are confined in the disk -> diffusive behavior -> isotropy!

CRs don't go straight: consequences

(1) We cannot do CR astronomy

-> difficult to identify sources



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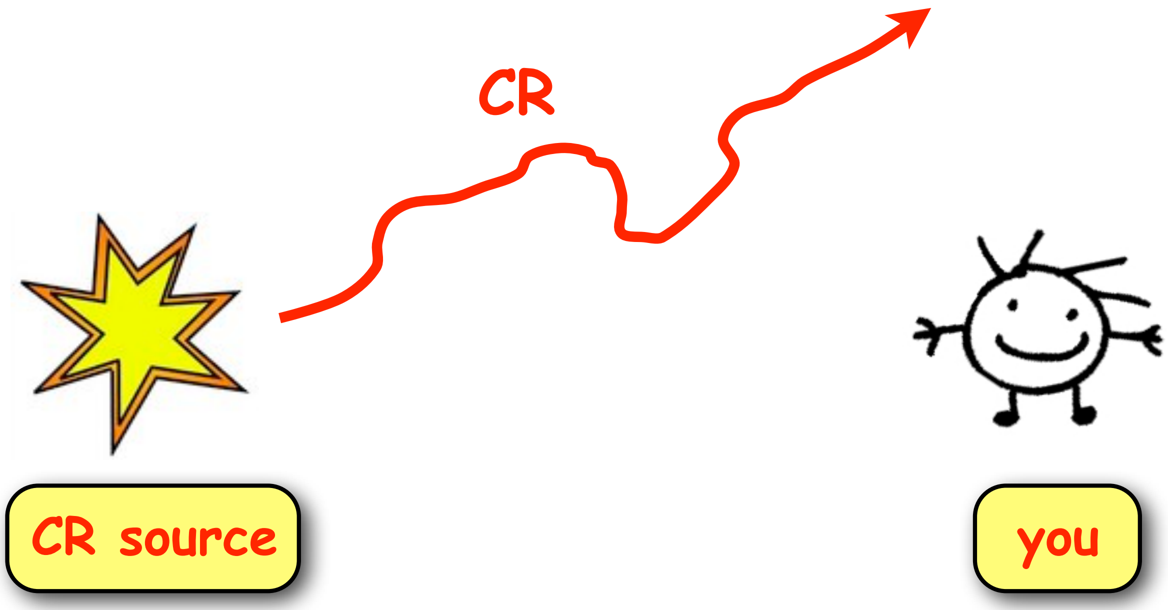
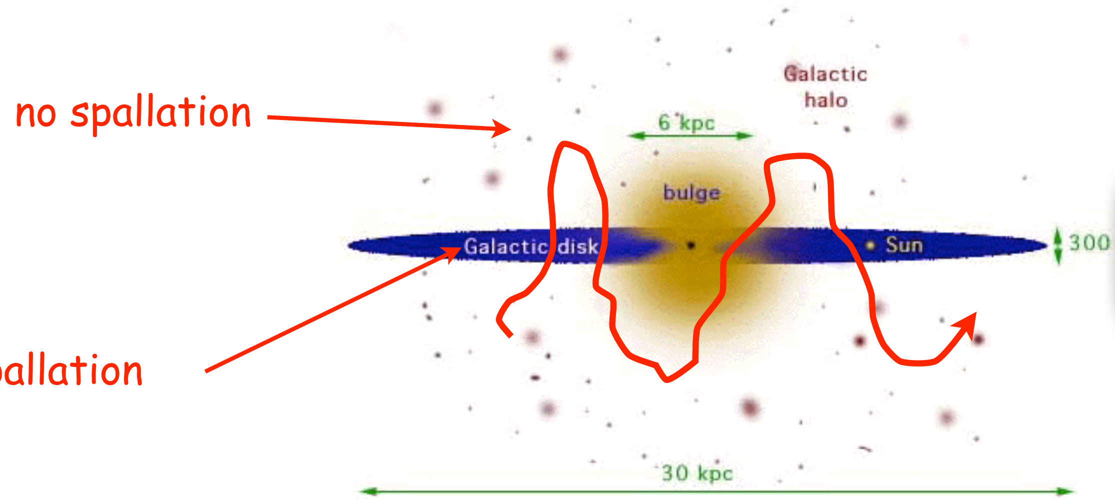


(2) CRs are confined in the Galactic disk $t_{disk} = \frac{l_s}{c} \approx 3 \times 10^6 \text{ yr}$



$t_{halo} \approx 10 \times 10^6 \text{ yr}$

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-> diffusive behavior
-> confinement time -> 10 Myrs
-> NO CR Astronomy

- [ ] Stability in time
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Cosmic Ray power in the Galaxy

CR energy density

total CR energy in the disk

MW disk volume

$$w_{CR} \sim 1\,\mathrm{eV/cm^3} \longrightarrow \mathcal{E}_{CR} = w_{CR}\,V_{disk}$$

<u>spatial homogeneity</u>

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$$\frac{\mathrm{d}\mathcal{E}_{CR}}{\mathrm{d}t} = P_{CR} - \frac{\mathcal{E}_{CR}}{t_{disk}}$$

CR power from CR sources in the disk

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CR power from CR sources in the disk

$$P_{CR} = \frac{\mathcal{E}_{CR}}{t_{disk}} = \frac{w_{CR} V_{disk}}{t_{disk}} = 3 \times 10^{40} \text{ erg/s}$$

Is this correct?

CRs interact with the gas -> $p + p \rightarrow p + p + \pi^0$

Should we use this equation instead?

$$\frac{\mathrm{d}\mathcal{E}_{CR}}{\mathrm{d}t} = P_{CR} - \frac{\mathcal{E}_{CR}}{t_{disk}} - \dot{\mathcal{E}}_{pp}$$

energy loss term due to p-p interactions

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Energy loss rate:

$$t_{pp} = (n_{gas}\ \sigma_{pp}\ c\ k)^{-1}$$

4×10^{-26} cm^2

0.45

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$$\frac{\mathrm{d}\mathcal{E}_{CR}}{\mathrm{d}t} = P_{CR} - \frac{\mathcal{E}_{CR}}{t_{disk}} - \cancel{\frac{\mathcal{E}_{CR}}{t_{pp}}}$$

energy loss term due to p-p interactions

Energy loss rate:

$$t_{pp} = (n_{gas}\ \sigma_{pp}\ c\ k)^{-1} \approx 60 \left(\frac{n_{gas}}{\mathrm{cm}^{-3}}\right)^{-1} \mathrm{Myr} >> t_{disk} = 3\ \mathrm{Myr}$$

4×10^{-26} cm^2 0.45

We can safely neglect CR energy losses

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- ☑ Energy density -> power of CR sources 3 x 10^{40} erg/s
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- ☑ Chemical composition
- ☑ Isotropy

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-> diffusive behavior
-> confinement time -> 10 Myrs
-> impossible to identify sources

- ☑ Stability in time
- ☑ Spatial homogeneity ✗
  (in the Milky Way)

-> in the Galaxy
-> Galactic up to the knee and above
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from gamma ray observations

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The diffusion of CRs

Spallation measurements tell us that cosmic rays follow tortuous paths before escaping the Galaxy. **Why?**

The galactic magnetic field or, better, **irregularities in the Galactic magnetic field** are responsible for the diffusive propagation of cosmic rays.

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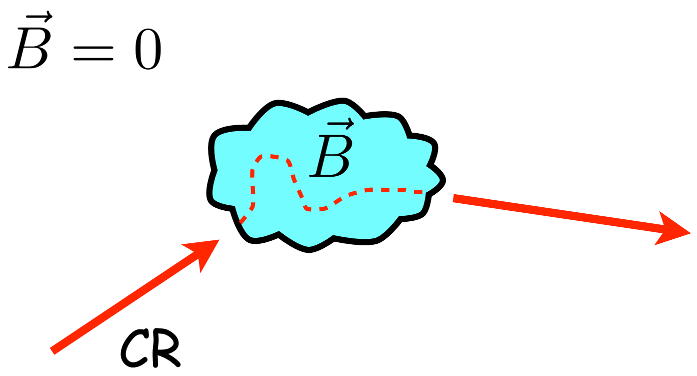
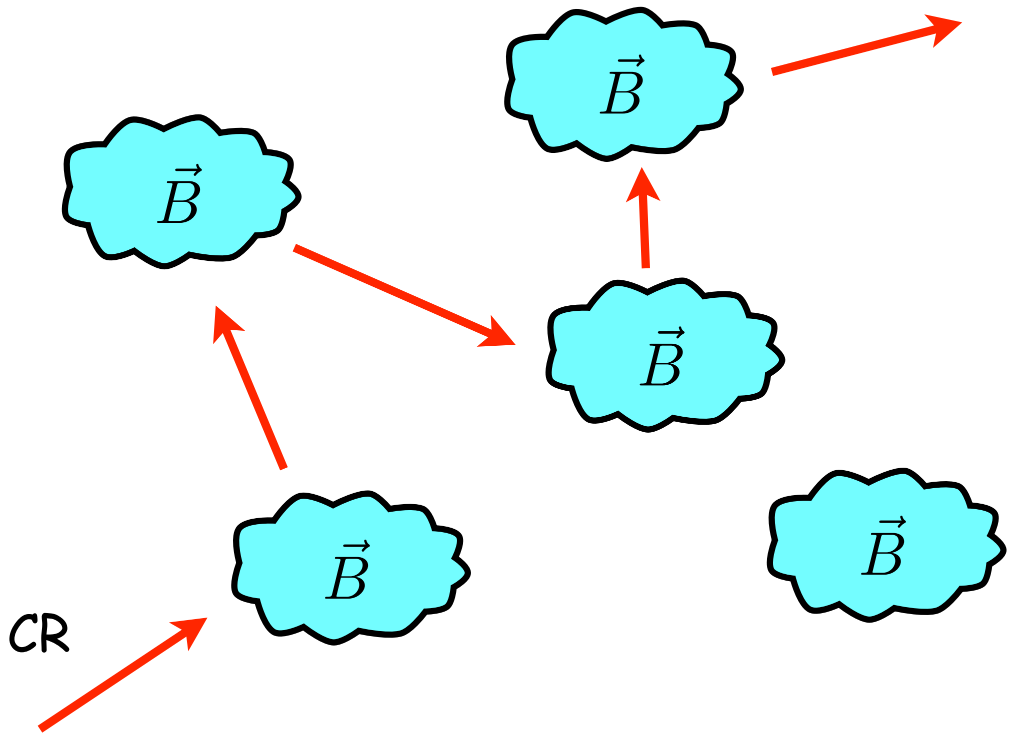
(Oversimplified picture)

magnetized cloudlets in an unmagnetized background

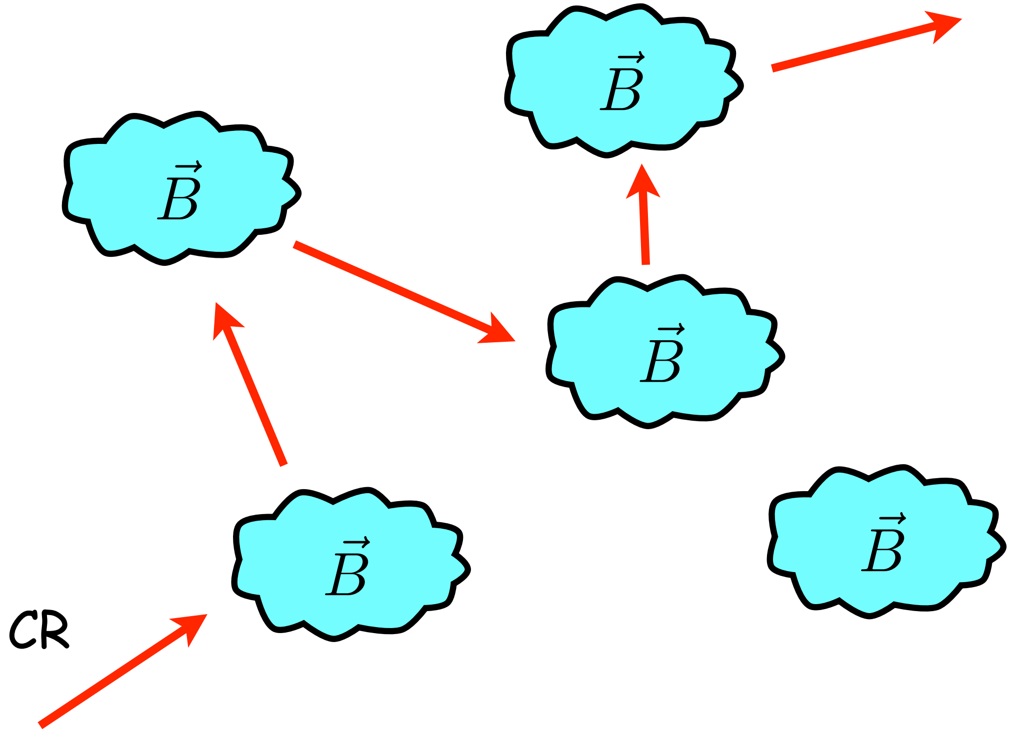


the particle energy is unchanged (Lorentz force)

The diffusion of CRs

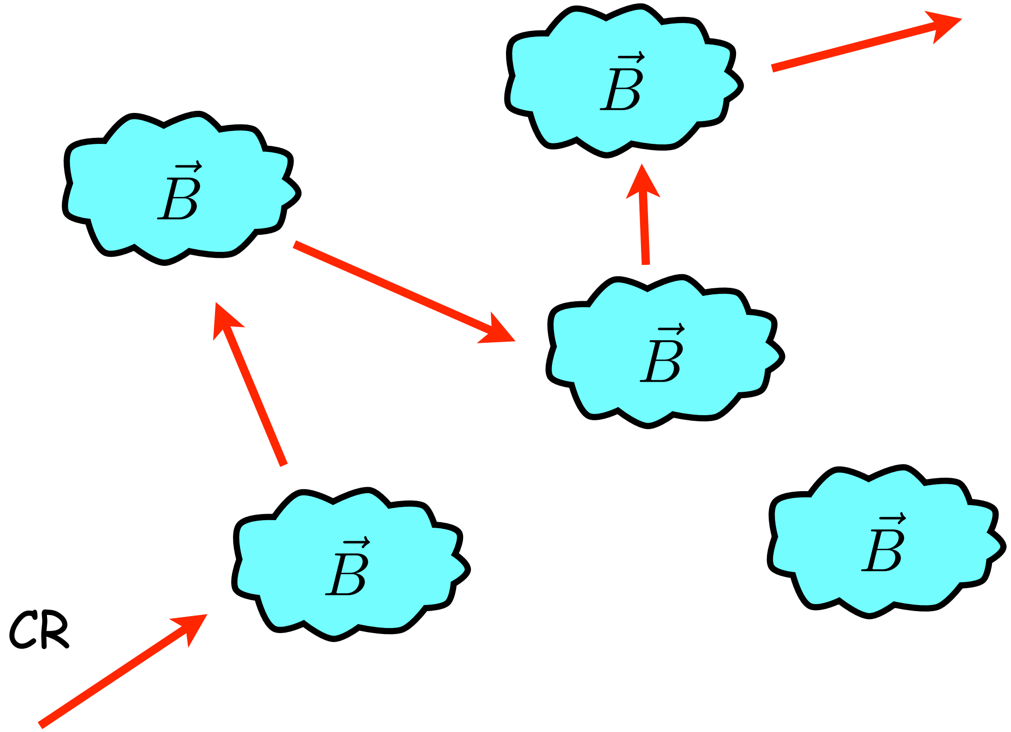


The diffusion of CRs



λ -> mean free path

The diffusion of CRs



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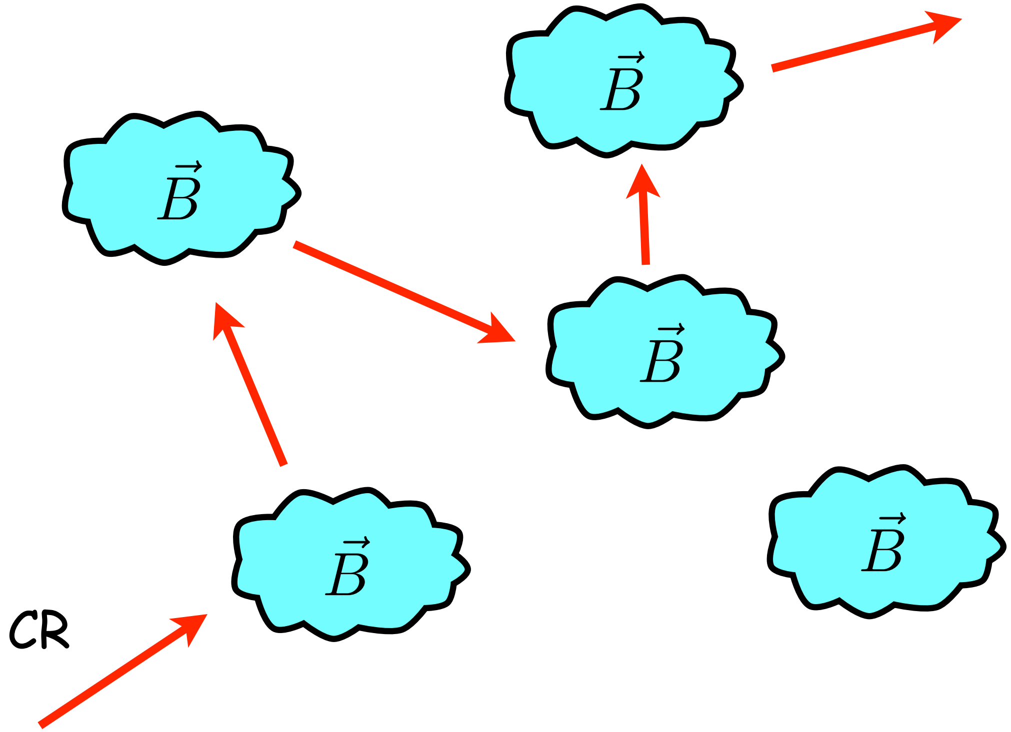
$$\tau_c = \frac{\lambda}{c}$$ -> collision time

The diffusion of CRs



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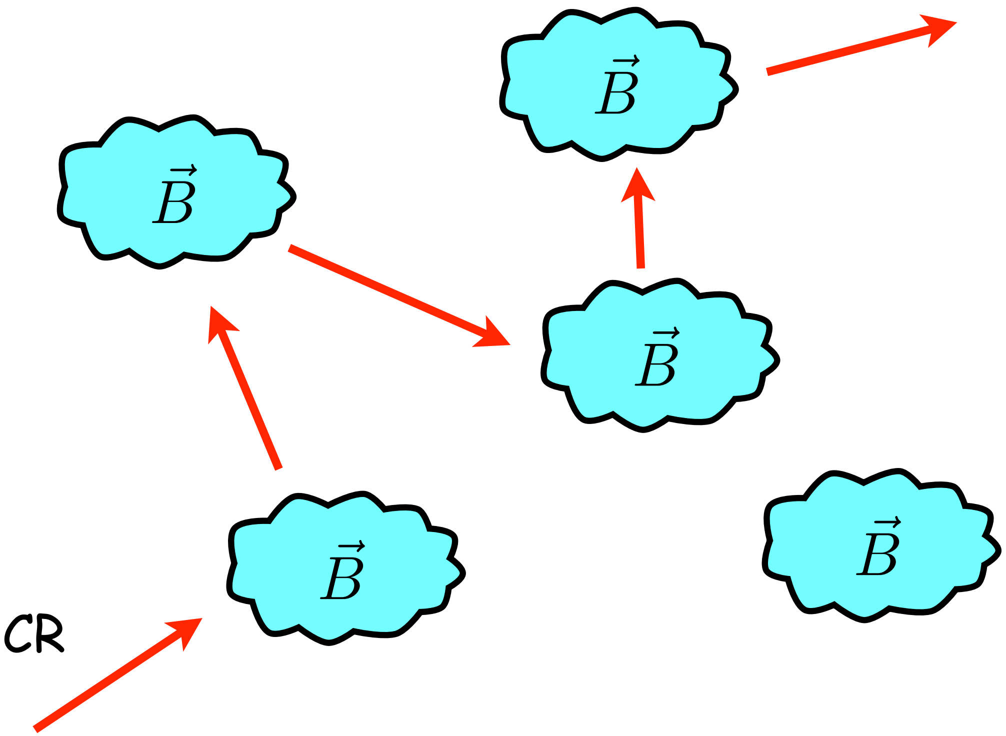

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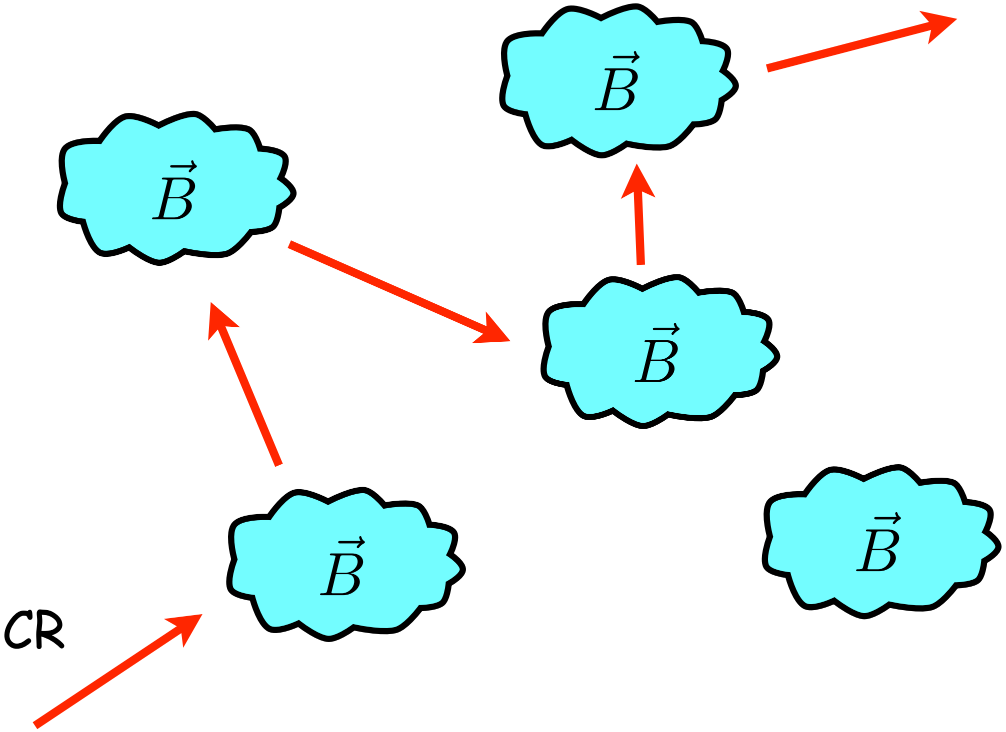
diffusion length -> $l_d = \lambda \sqrt{N}$

random walk

The diffusion of CRs



λ -> mean free path

$$\tau_c = \frac{\lambda}{c}$$ -> collision time

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diffusion length -> $$l_d = \lambda \sqrt{N} = \lambda \sqrt{\frac{t}{\tau_c}} = \lambda \sqrt{\frac{t\, c}{\lambda}} = \sqrt{\lambda\, c\, t}$$

random walk

this product determines the diffusion properties of the particle

The diffusion of CRs

It is convenient to define the quantity $D = \lambda\ c$ called **diffusion coefficient**

diffusive propagation -> $$l_d = \sqrt{D\ t} \propto \sqrt{t}$$

straight line propagation -> $$l_{sl} = c\ t \propto t$$

The diffusion of CRs

It is convenient to define the quantity $D = \lambda\, c$ called **diffusion coefficient**

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Spallation measurements allow us to measure the average diffusion coefficient in the Galaxy

$$l_{disk} = \sqrt{D\,t_{disk}} \longrightarrow D = \frac{l_{disk}^2}{t_{disk}} = 10^{28}\ \mathrm{cm}^2/\mathrm{s}$$

~300 pc

3 Myr (from spallation)

@ 10 GeV

CR diffusion is energy dependent

Spallation measurements at different energies -> $t_{disk} \propto E^{-0.6}$

which corresponds to -> $D \propto E^{0.6}$

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We can now constrain the CR injection spectrum in the Galaxy

$$\frac{\mathrm{d}N_{CR}(E)}{\mathrm{d}t} = Q_{CR}(E) - \frac{N_{CR}(E)}{t_{disk}}$$

CRs injected from sources in the disk

escape rate from the disk

CR diffusion is energy dependent

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stability in time

CRs injected from sources in the disk

escape rate from the disk

$$Q_{CR}(E) = \frac{N_{CR}(E)}{t_{disk}} \propto N_{CR}(E)\, D(E) \propto E^{-2.1}$$

measured -> $E^{-2.7}$

What we have to explain about CRs:

- ☑ Energy density -> power of CR sources 3 x 10^{40} erg/s
- ☑ Energy spectrum -> sources inject spectra close to E^{-2}
- ☑ Chemical composition
- ☑ Isotropy
  - -> diffusive behavior
  - -> confinement time -> 10 Myrs
  - -> impossible to identify sources
- ☑ Stability in time
- ☑ Spatial homogeneity (in the Milky Way)
  - -> in the Galaxy
  - -> Galactic up to the knee and above
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from gamma ray observations

A remarkable coincidence

Total CR power in the Galaxy -> $P_{CR} = 3 \times 10^{40}$ erg/s

A **SuperNova** is the explosion of a massive star that releases ~10^{51} ergs in form of kinetic energy. In the Galaxy the observed supernova rate is of the order of 1/30 - 1/100 yr^{-1}.

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Total SN power in the Galaxy ->

$$P_{SN} = 3 \times 10^{41} \ \mathrm{erg/s}$$

SuperNovae alone could maintain the CR population provided that about **10%** of their kinetic energy is **somehow converted into CRs**

The SN hypothesis for CR origin

SuperNovae alone could maintain the CR population provided that about 10% of their kinetic energy is somehow converted into CRs

- total energy --> OK
- "somehow converted"
  - which acceleration mechanism?
  - correct spectrum? (roughly E^{-2}?)
  - correct energy range? (at least up to the knee?)
- can we falsify this hypothesis?
  - need for observational tests

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SNR shocks

Diffusive Shock Acceleration

see next class

TeV gamma ray astronomy

see next slide

TeV emission from SNRs: a test for CR origin

Detectability condition for HESS

$$\boxed{W_{CR} > 5 \times 10^{47} \left(\frac{n_{gas}}{4 \text{ cm}^{-3}} \right)^{-1} d_{kpc}^2 \text{ erg}}$$

above ~ 10 TeV

TeV emission from SNRs: a test for CR origin

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Assumptions...

- 10% efficiency -> 10^{50} erg in CRs
- $E^{-2.1}$ spectrum
- up to the knee (5×10^{15} eV)

above ~ 10 TeV

$$W_{CR} \approx 3 \times 10^{49} \text{ erg}$$

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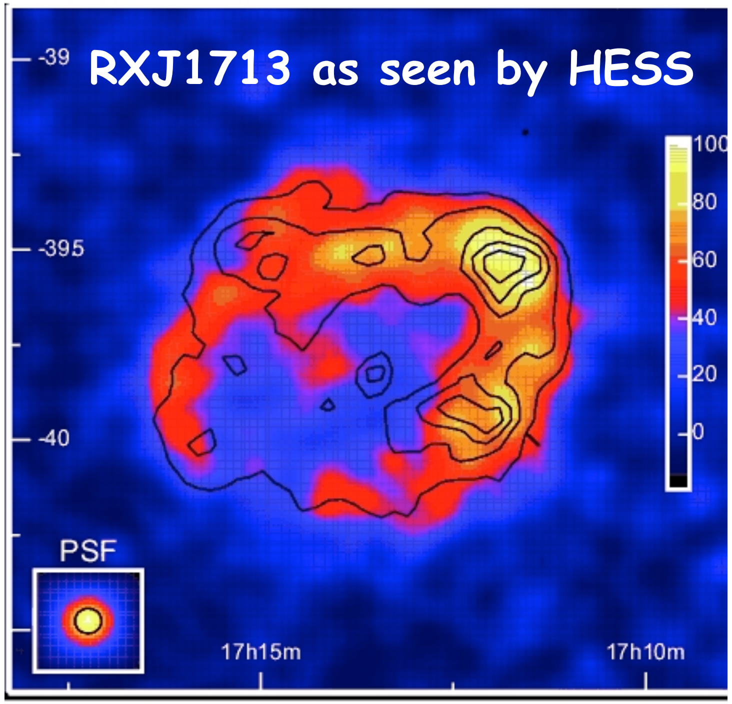
If **SuperNova Remnants** indeed are the sources of galactic Cosmic Rays they MUST be visible in **TeV gamma rays**
(Drury, Aharonian, and Voelk, 1994)

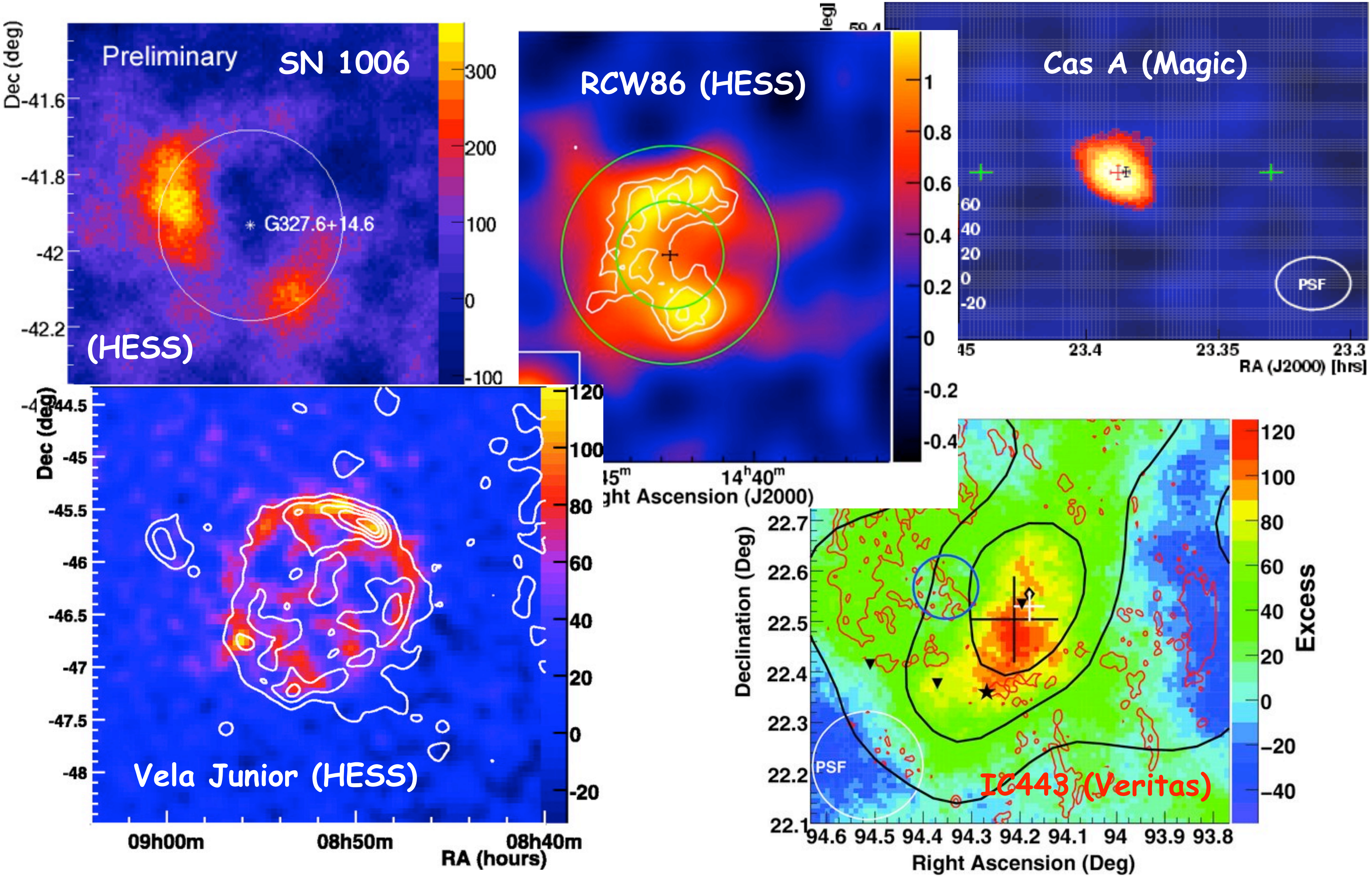
TeV emission from SNRs: a test for CR origin



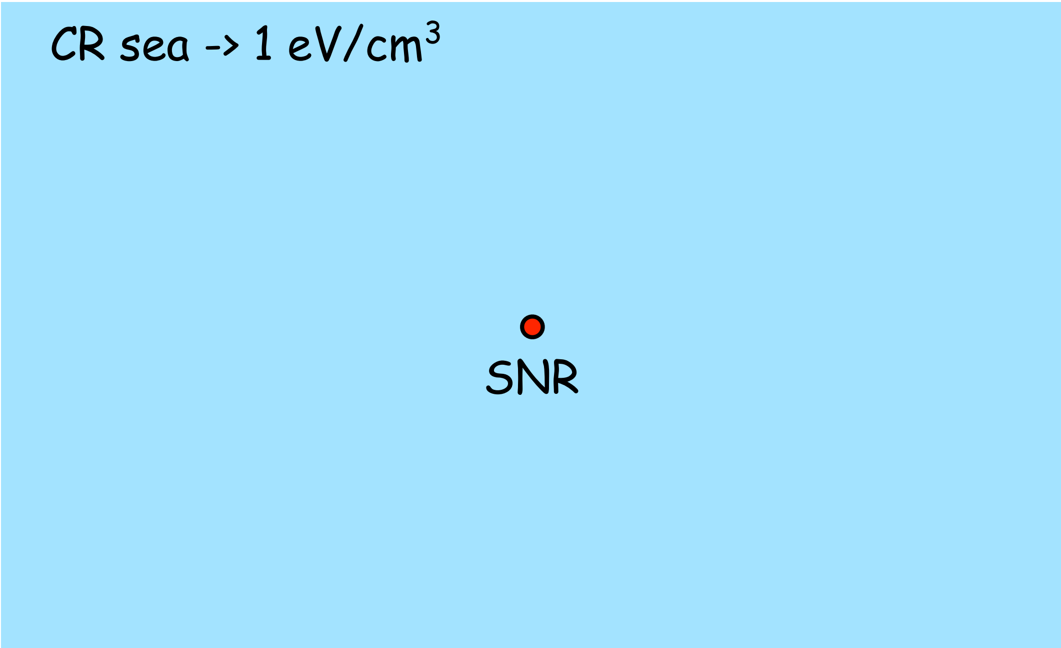
Test passed!

This is still not a conclusive proof -> hadronic or leptonic emission?

SNRs in gamma rays



Implications of the SNR hypothesis



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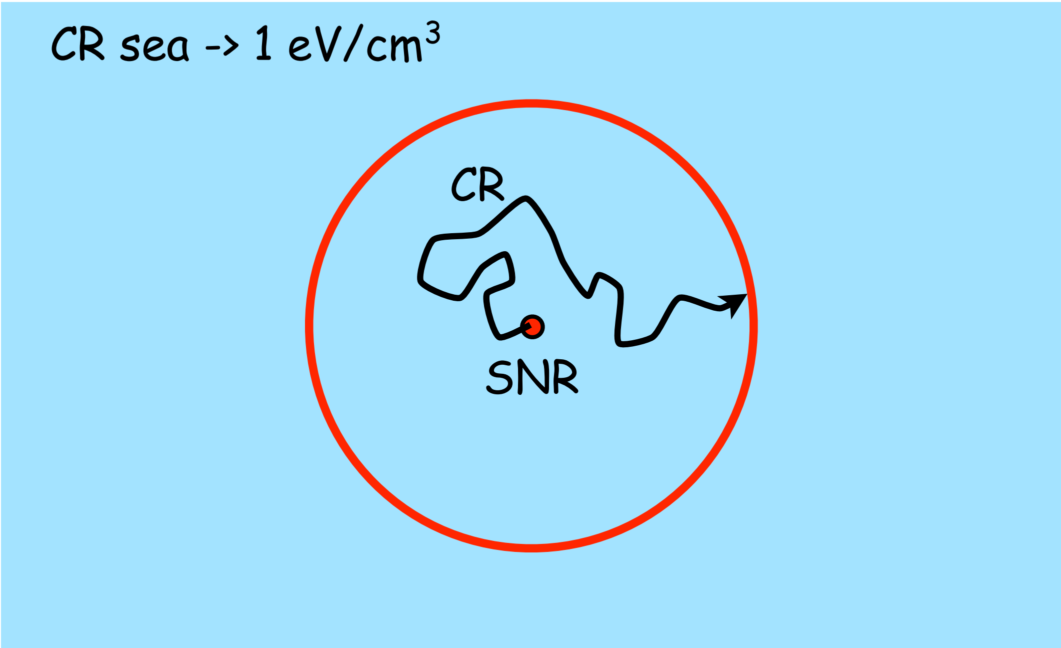


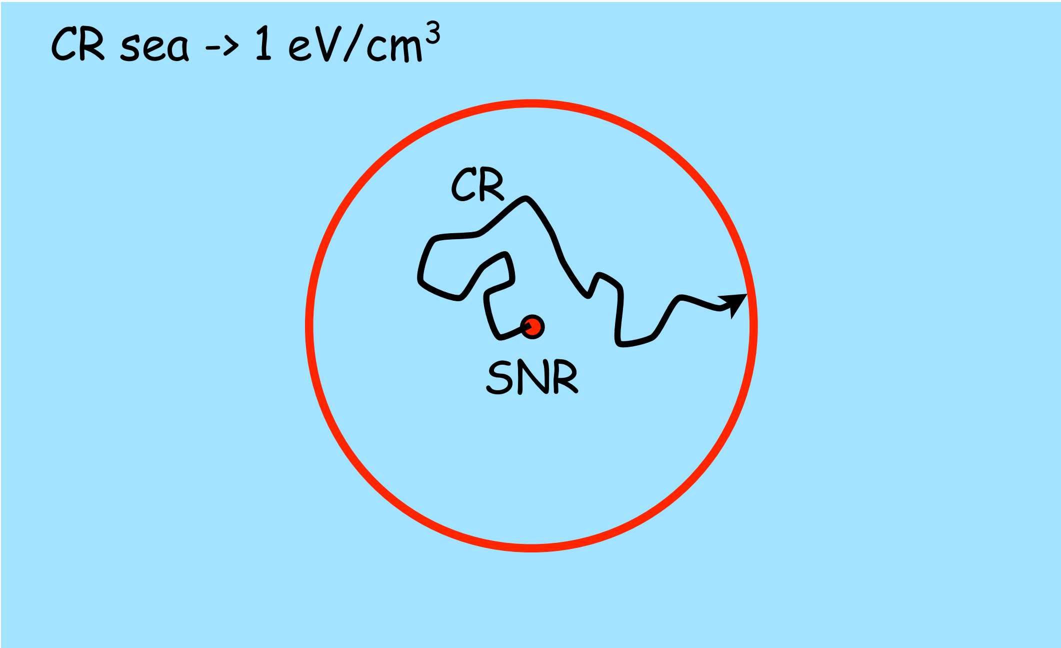
$$E_{CR}^{SNR} = \ 10^{50} \mathrm{erg}$$

volume affected by CRs from the SNR

$$\frac{E_{CR}^{SNR}}{\left(\frac{4\pi}{3}\ R_{CR}^3\right)} = \ 1\ \mathrm{eV/cm}^3$$

$$\Rightarrow \quad R_{CR} \approx 100\ \mathrm{pc}$$

Implications of the SNR hypothesis



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volume affected by CRs from the SNR

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$$\Rightarrow \quad R_{CR} \approx 100 \text{ pc}$$

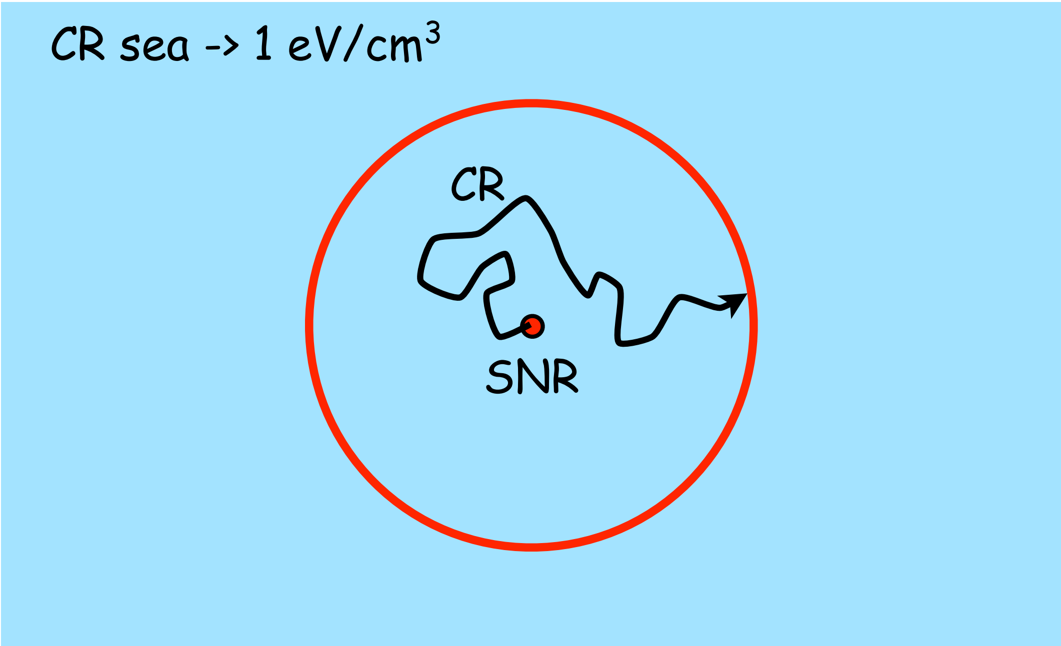
such a volume is affected for a time:

$$D = 10^{28} \left(\frac{E}{10 \text{ GeV}}\right)^{0.6} \text{cm}^2/\text{s} \quad \Rightarrow \quad D(1 \text{ TeV}) \approx 2 \times 10^{29} \text{ cm}^2/\text{s}$$

$$t \approx \frac{R_{CR}^2}{D} \approx 10^4 \text{ yr}$$

Implications of the SNR hypothesis

Very rough!



$$E_{CR}^{SNR} = 10^{50} \mathrm{erg}$$

volume affected by CRs from the SNR

$$\frac{E_{CR}^{SNR}}{\left(\frac{4\pi}{3} R_{CR}^3\right)} = 1 \ \mathrm{eV/cm^3}$$

$$R_{CR} \approx 100 \ \mathrm{pc}$$

such a volume is affected for a time:

$$D = 10^{28} \left(\frac{E}{10 \ \mathrm{GeV}} \right)^{0.6} \mathrm{cm^2/s} \qquad D(1 \ \mathrm{TeV}) \approx 2 \times 10^{29} \ \mathrm{cm^2/s}$$

$$t \approx \frac{R_{CR}^2}{D} \approx 10^4 \ \mathrm{yr}$$

What we have to explain about CRs:

☑ Energy density	-> power of CR sources 3 x 10^{40} erg/s
☑ Energy spectrum	-> sources inject spectra close to E^{-2}
☑ Chemical composition ☑ Isotropy	-> diffusive behavior -> confinement time -> 10 Myrs -> impossible to identify sources
☑ Stability in time	-> R >> 100 pc, t >> 10^4 yr (if SNRs)
☑ Spatial homogeneity () (in the Milky Way)	-> -> in the Galaxy -> Galactic up to the knee and above -> many sources (-> SNR?)

from gamma ray observations