Extracting physical quantities from cosmic ray and gamma ray observations

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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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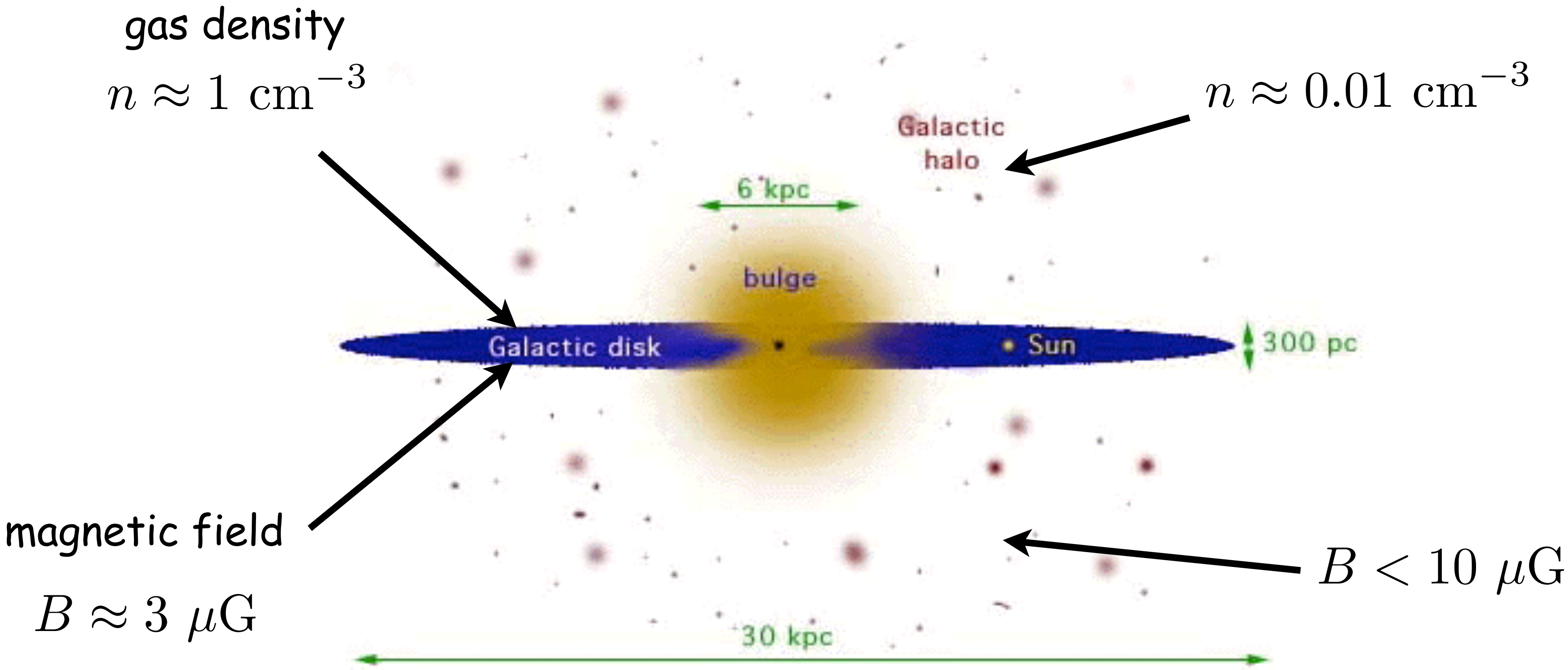
Gamma rays from the Milky Way

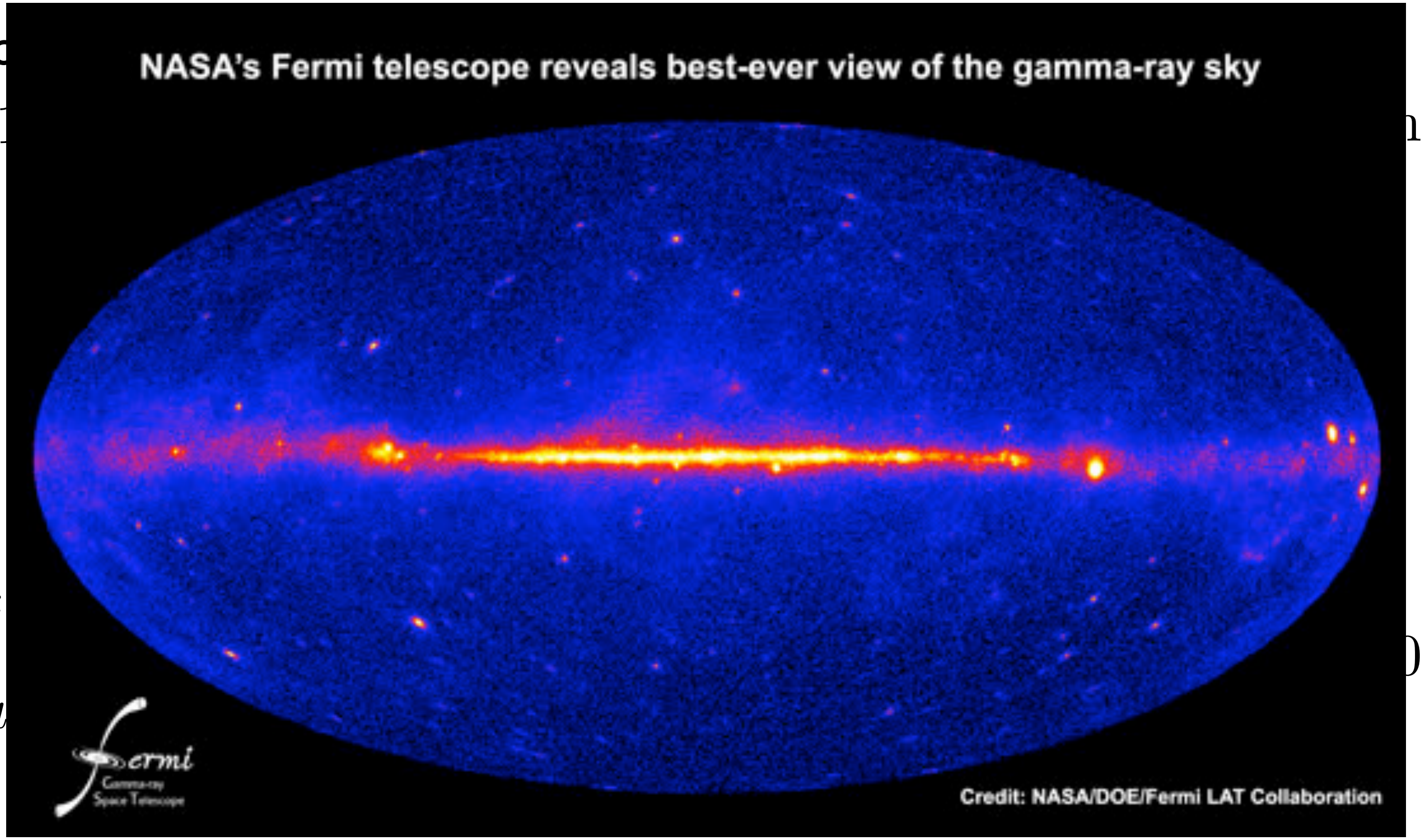


Schematic view of the Milky Way

Gamma rays from the Milky Way

gas c

$n \approx 1$ … m^{-3}



magnetic f

$B \approx 3\ \mu$ … $0\ \mu\mathrm{G}$

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gas density

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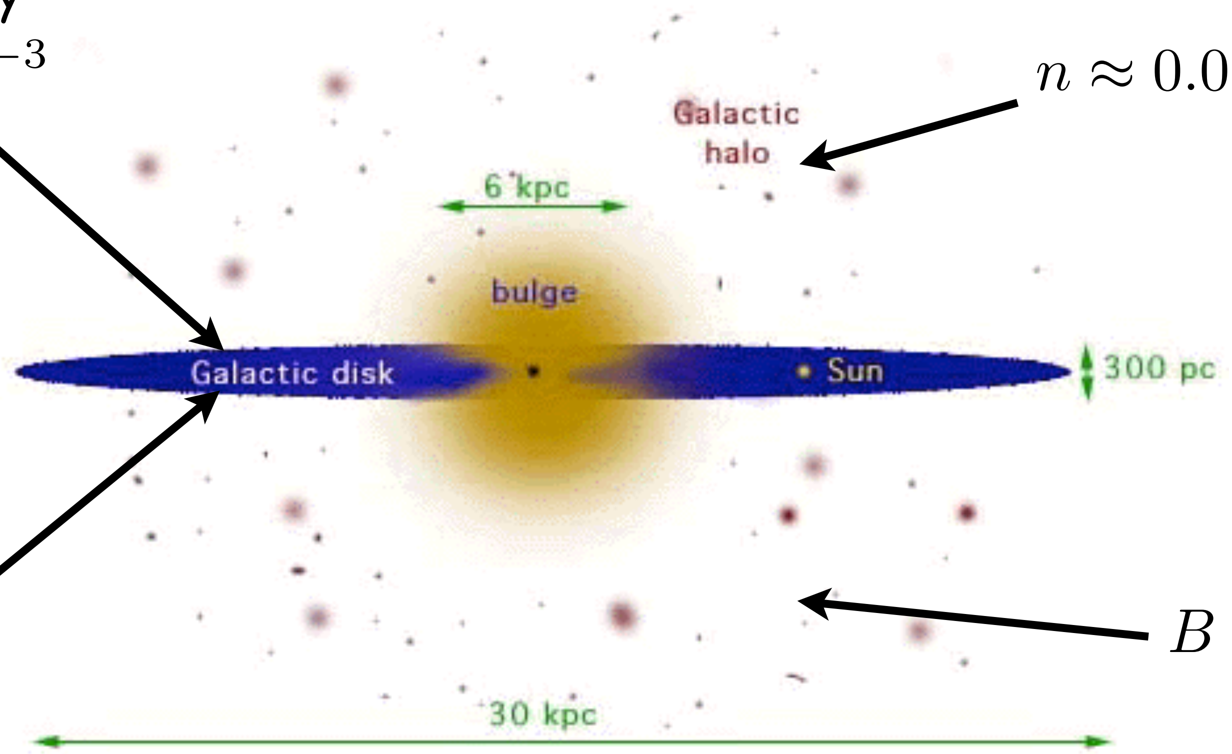
$n \approx 0.01 \text{ cm}^{-3}$



magnetic field

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

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

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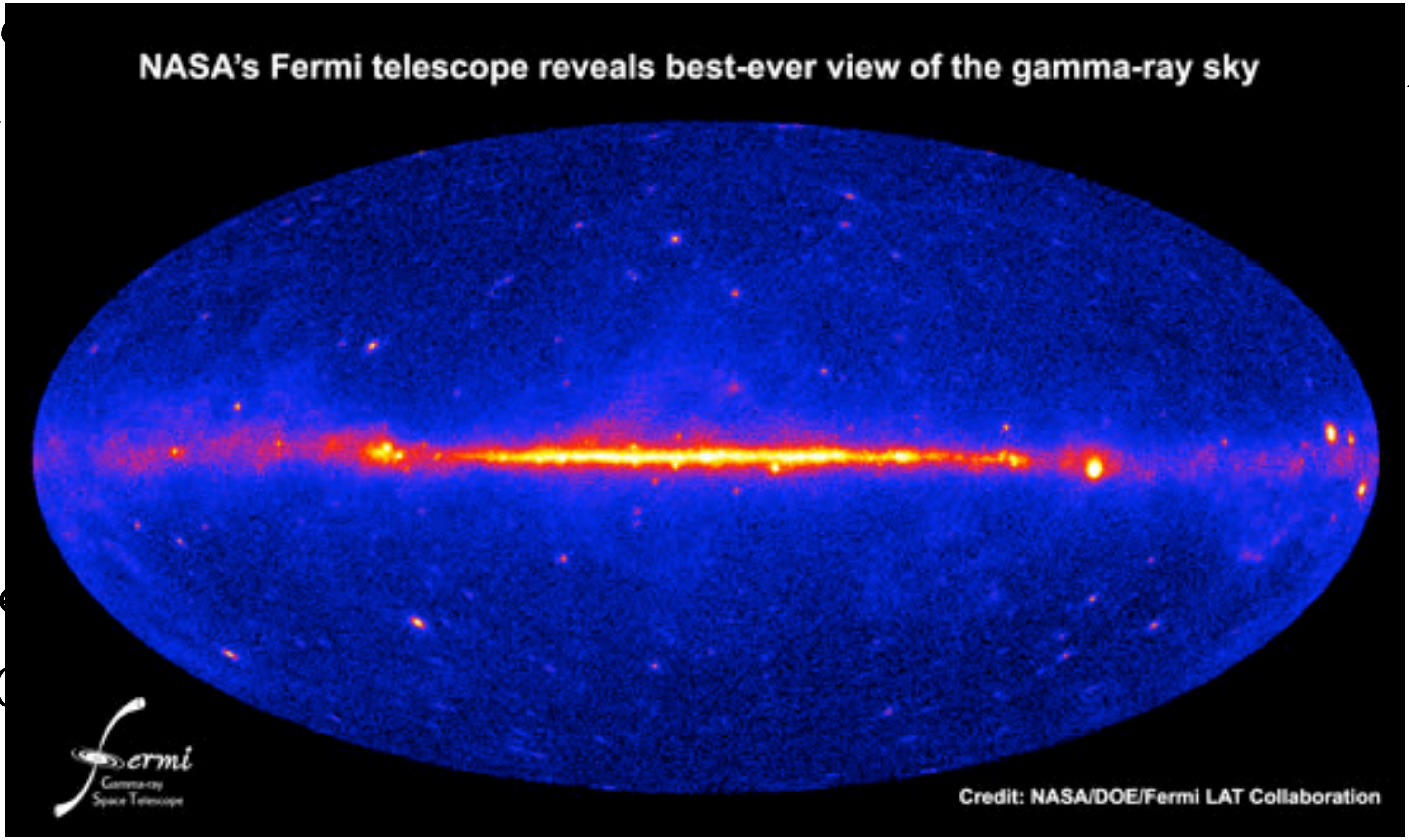

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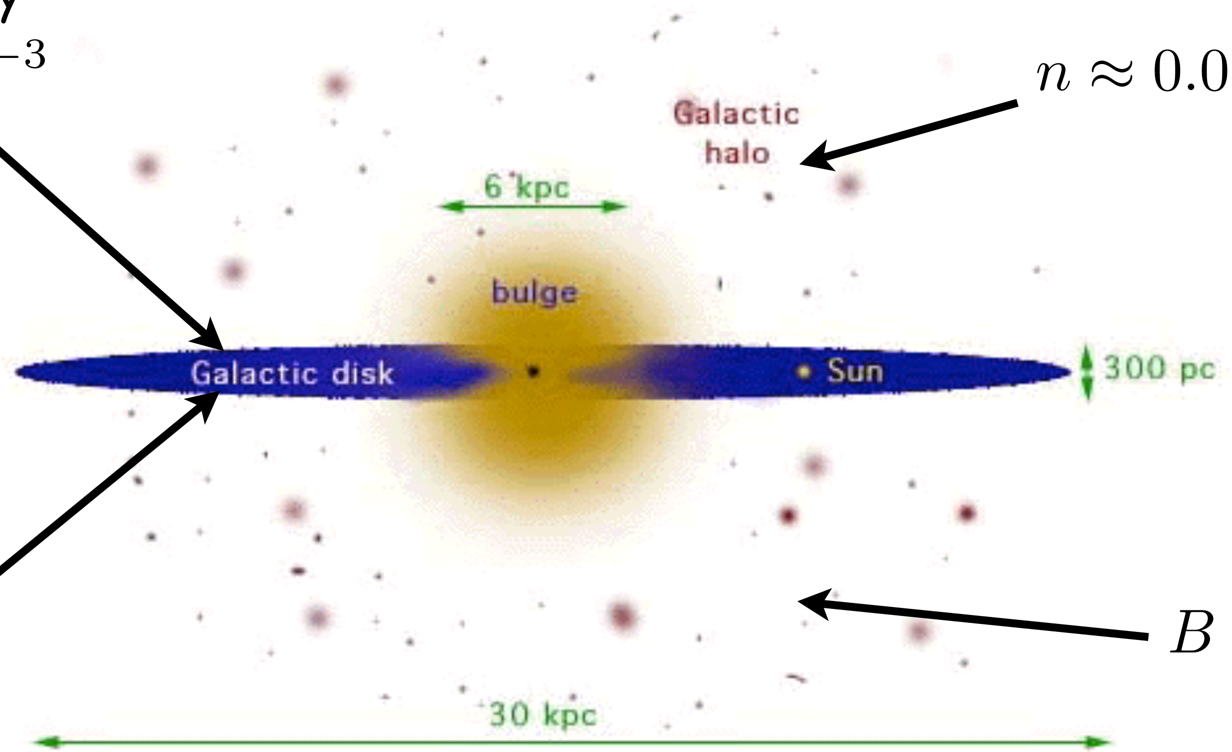

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Gamma rays from the Milky Way

The gamma ray emission from the Milky Way is mainly due to p-p interactions

gamma ray emissivity

$$dn_\gamma(E_\gamma) = \frac{q_\gamma(E_\gamma, \vec{r})}{4\pi r^2}\, d^3\vec{r} = \frac{q_\gamma}{4\pi}\, dr\, d\Omega$$

photon flux at Earth

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$$\frac{\mathrm{d}n_\gamma}{\mathrm{d}\Omega} \;=\; \int_0^{r_{max}} \mathrm{d}r\;\frac{q_\gamma}{4\pi} \;\propto \int_0^{r_{max}} \mathrm{d}r\;N_{CR}(E_{CR},r)\;n_{gas}(r)$$

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measured by EGRET, FERMI...

If we know (we do) the gas distribution in the Milky Way we can use gamma ray observations to constrain spatial variations of the CR intensity

Gamma rays from the Milky Way

NANTEN: CO (J=1-0)
-> tracer of H_2

LAB HI Survey
(Karberla et al 05)

ASSUMPTION:
spatial homogeneity of CRs

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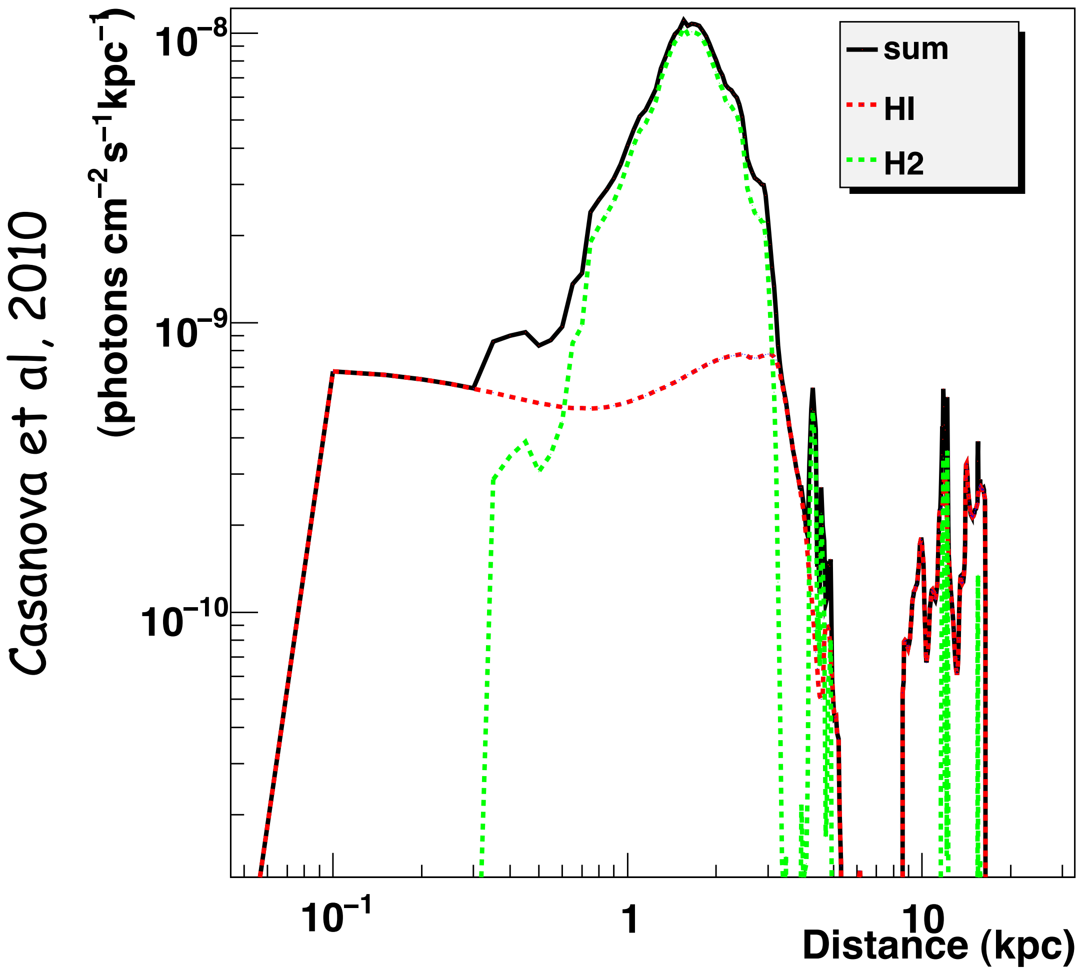

<-- @1 GeV

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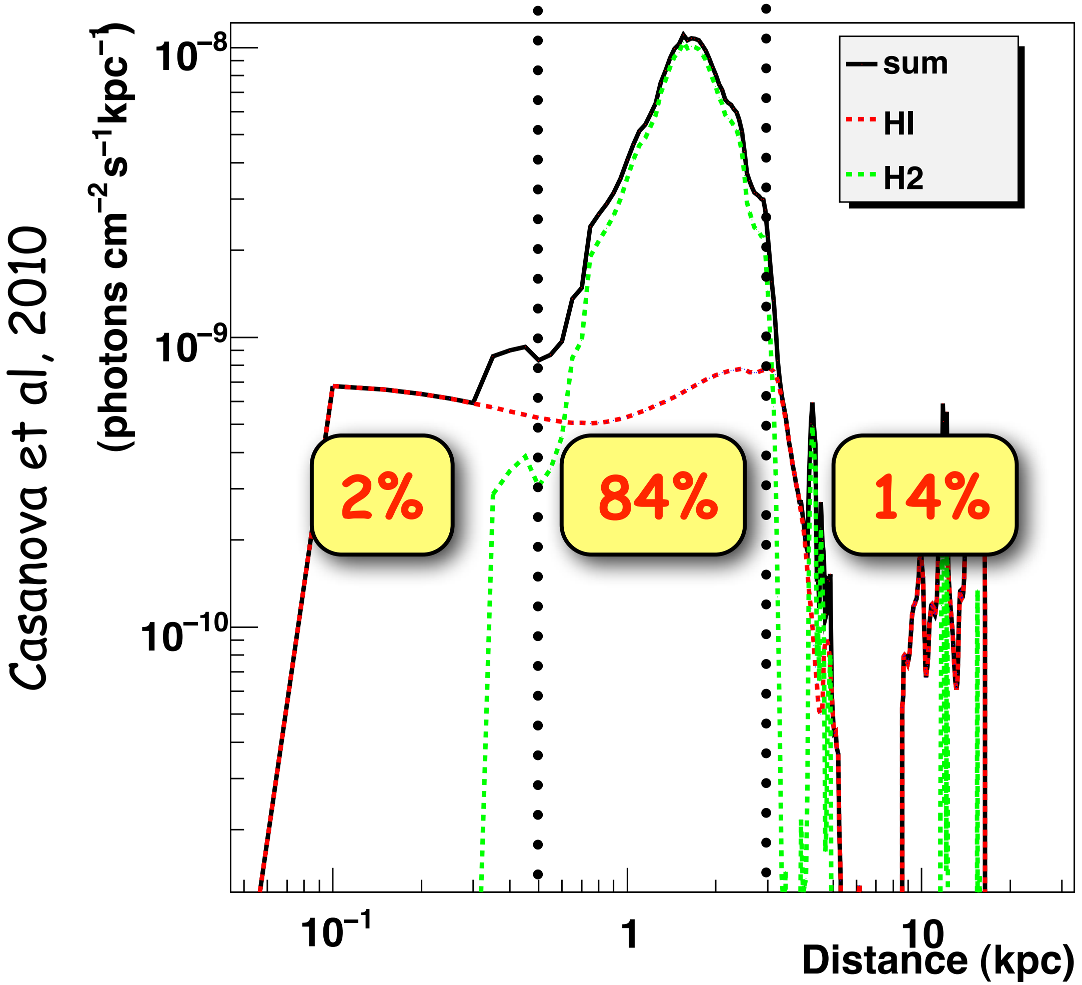

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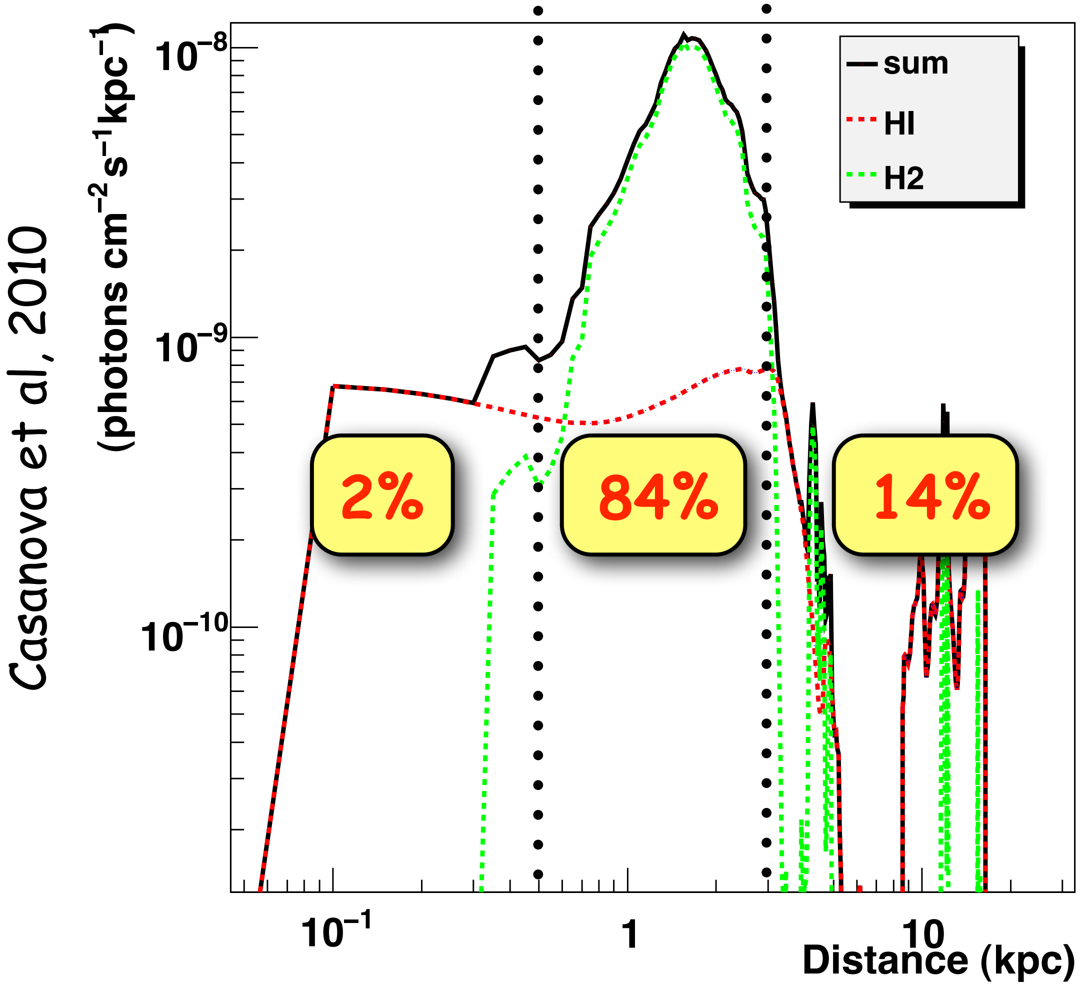

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the main contribution to the gamma ray emission comes from ~ 1 kpc. If the CR intensity is different there, we expect a different flux.

-> "Tomography" with gamma rays!

CR are, on large scales, homogeneously distributed in the MW (EGRET)

What we have to explain about CRs:

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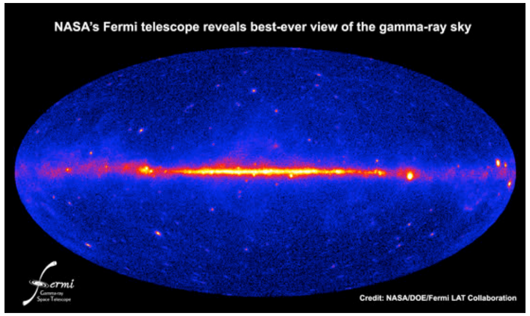
from gamma ray observations

Are CRs universal?



Cosmic rays are homogeneously distributed in the galactic disk.

Hypothesis: are they homogeneously distributed in the whole Universe?

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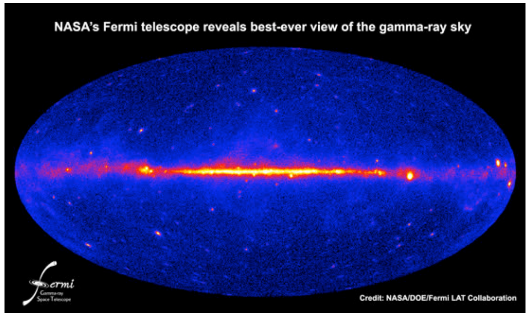

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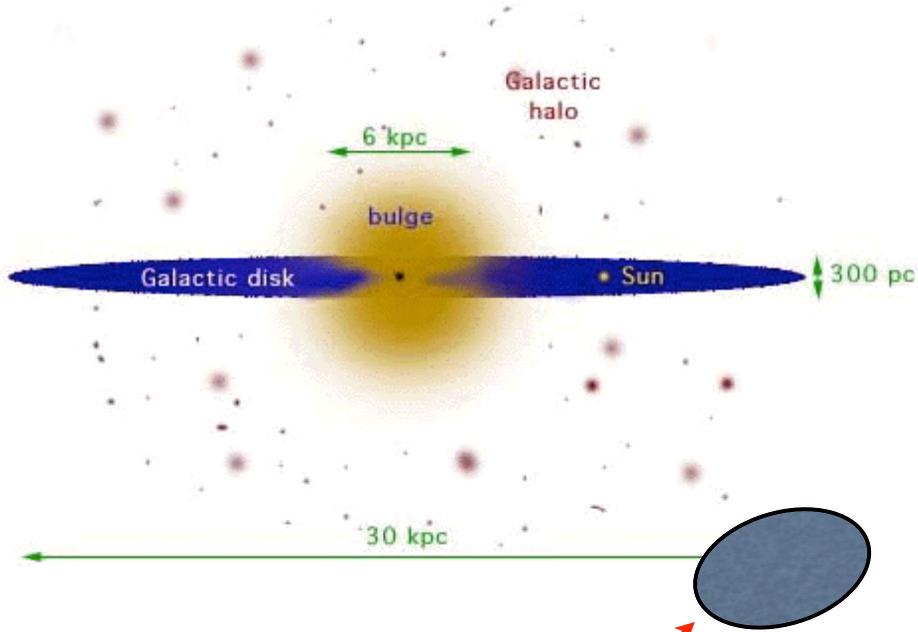
We play the same game with the Large Magellanic Cloud.
Total gas mass -> expected gamma rays

We observe less gammas than expected!

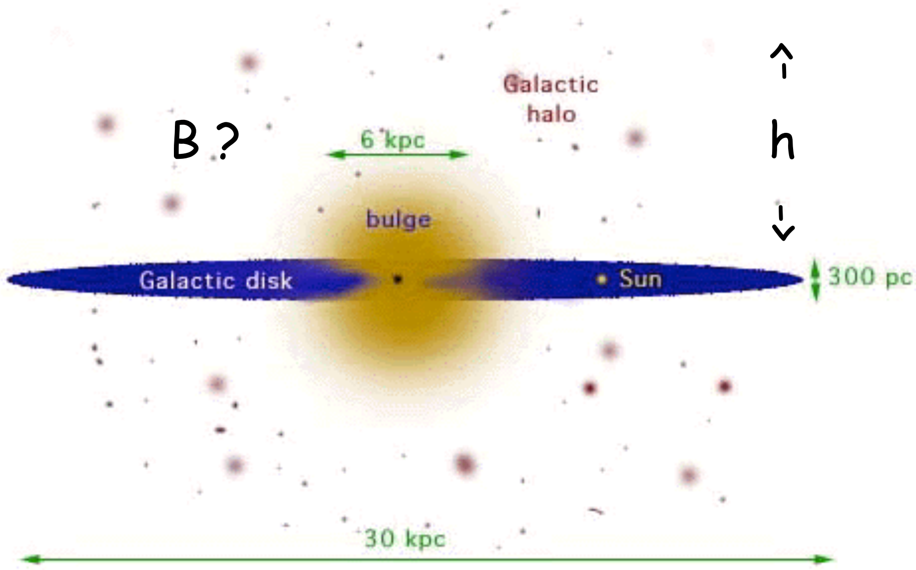


Large Magellanic Cloud

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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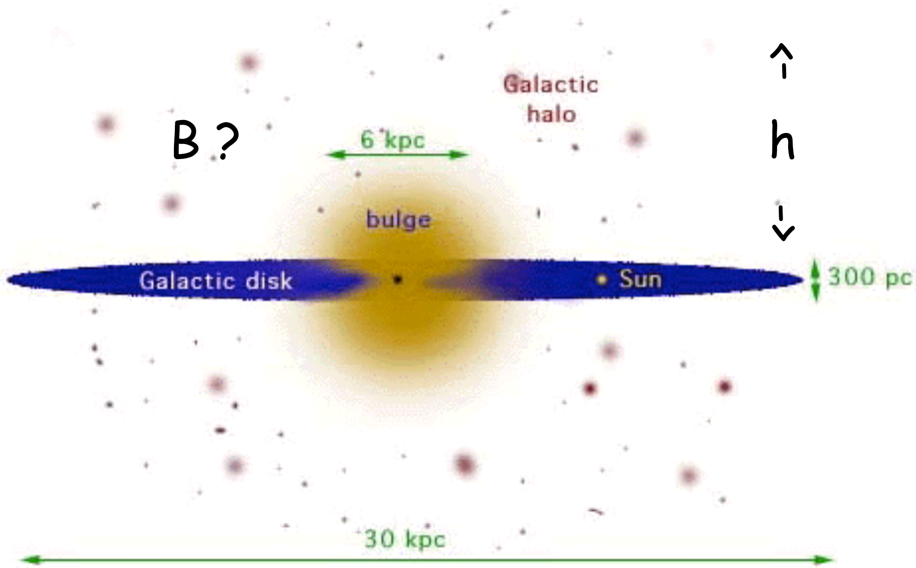

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Confinement condition:

$$R_L < h$$

Larmor radius

halo size

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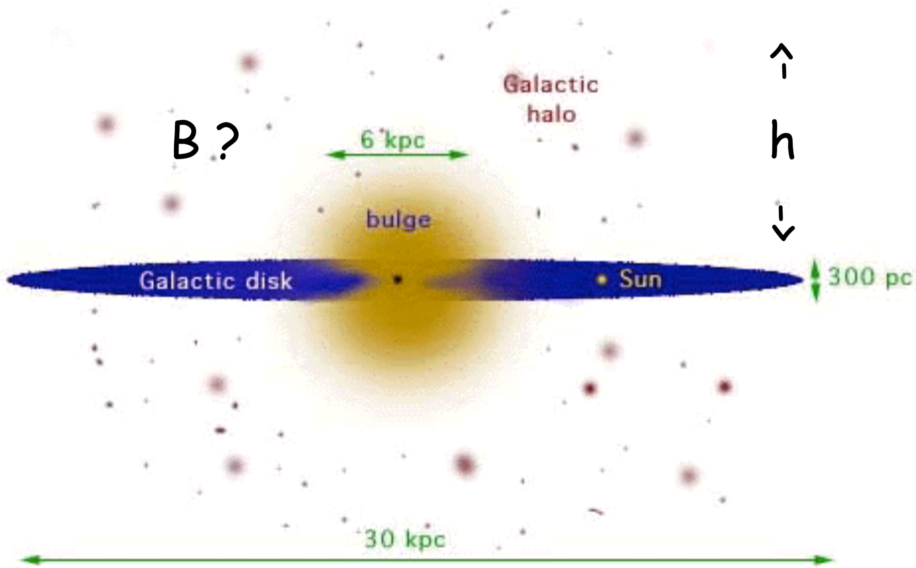

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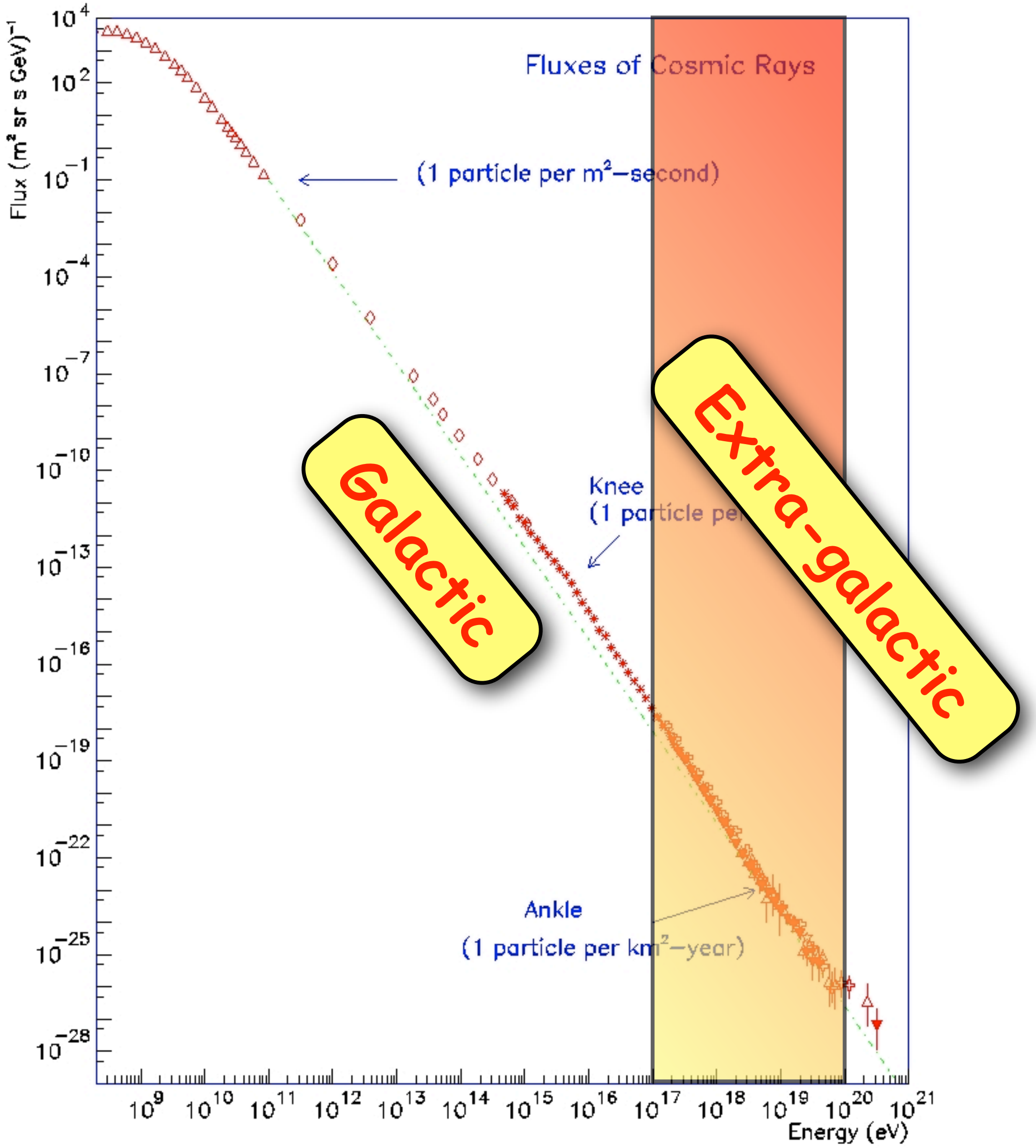
Confinement condition:

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

(cm) — Larmor radius — halo size — h: 1 - 10 — B: 0.1 - 10

Galactic or extra-galactic?



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- [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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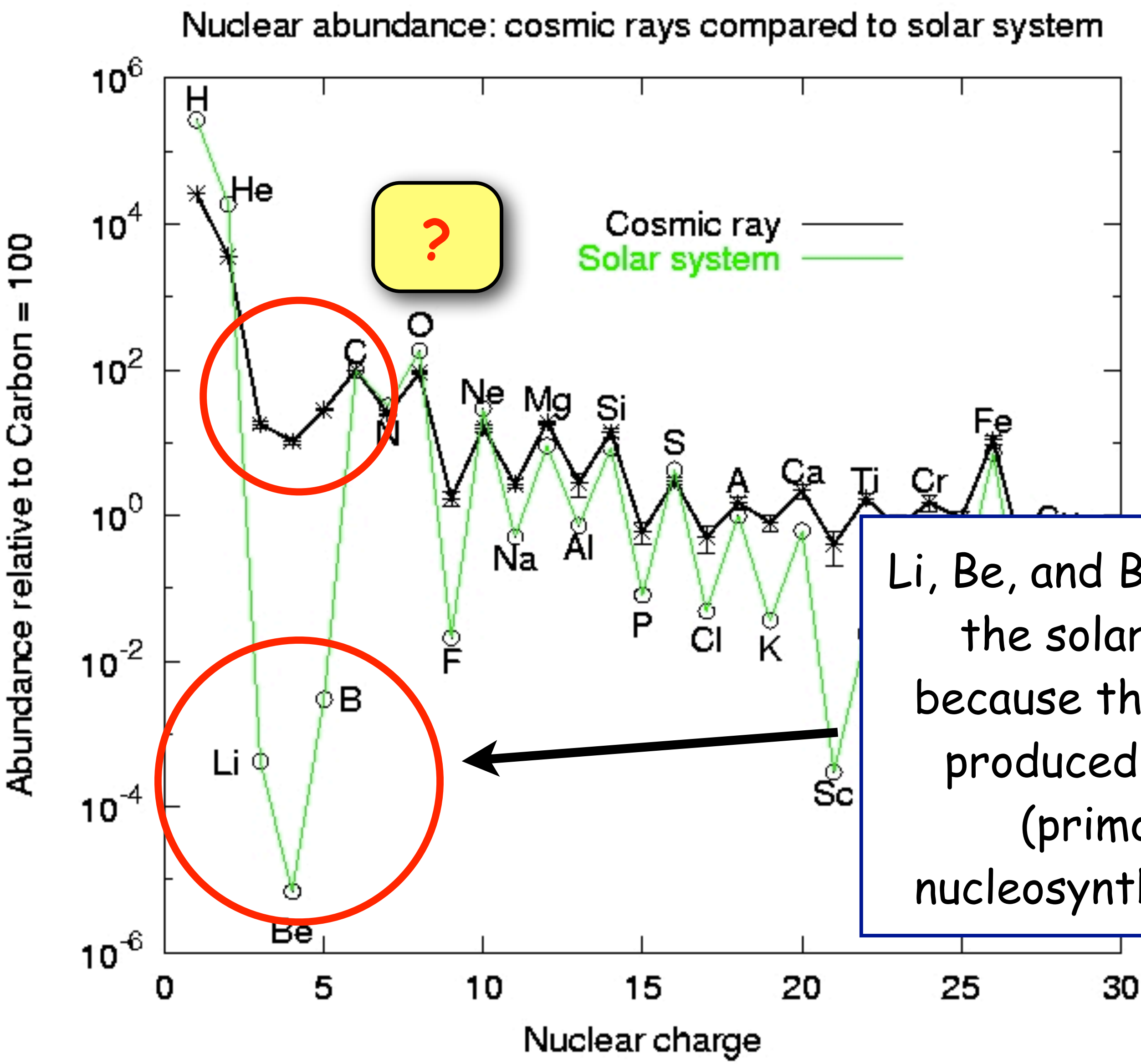
Cosmic Ray composition



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 CRs transverse $\lambda \approx 5 \text{ g/cm}^2$

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The anomaly is explained if CRs transverse $\lambda \approx 5 \text{ g/cm}^2$

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

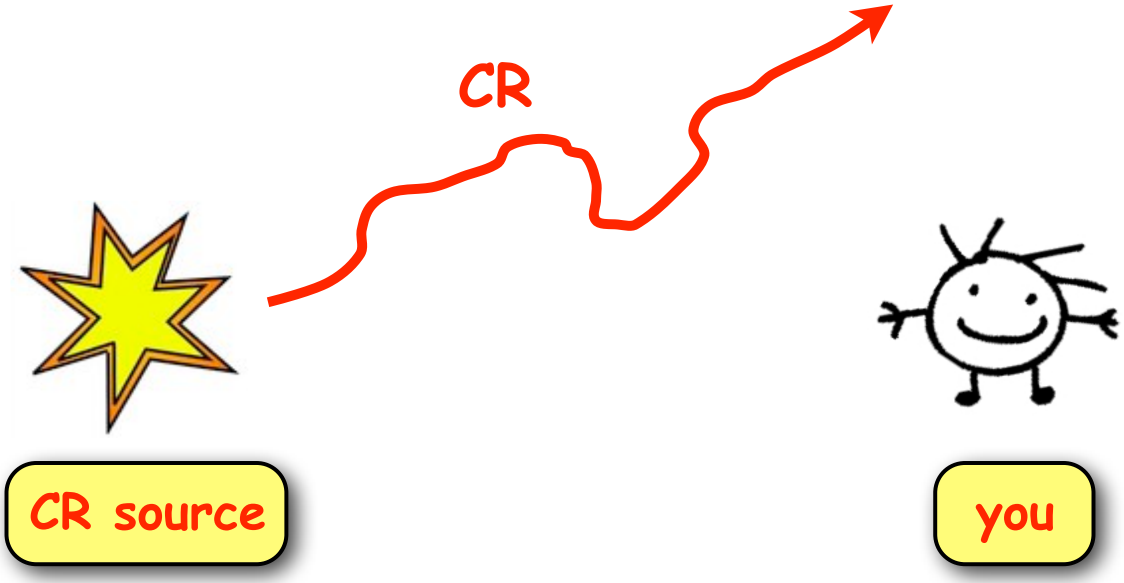
much larger than the size of the disk!!!

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

CRs don't go straight: consequences

(1) We cannot do
CR astronomy

-> difficult to identify
sources



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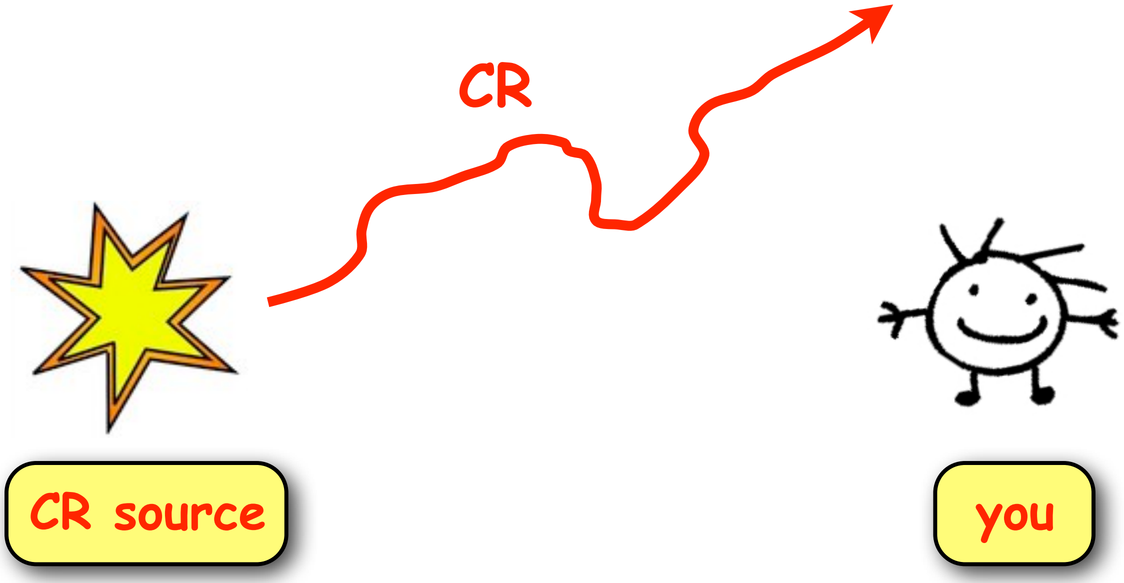
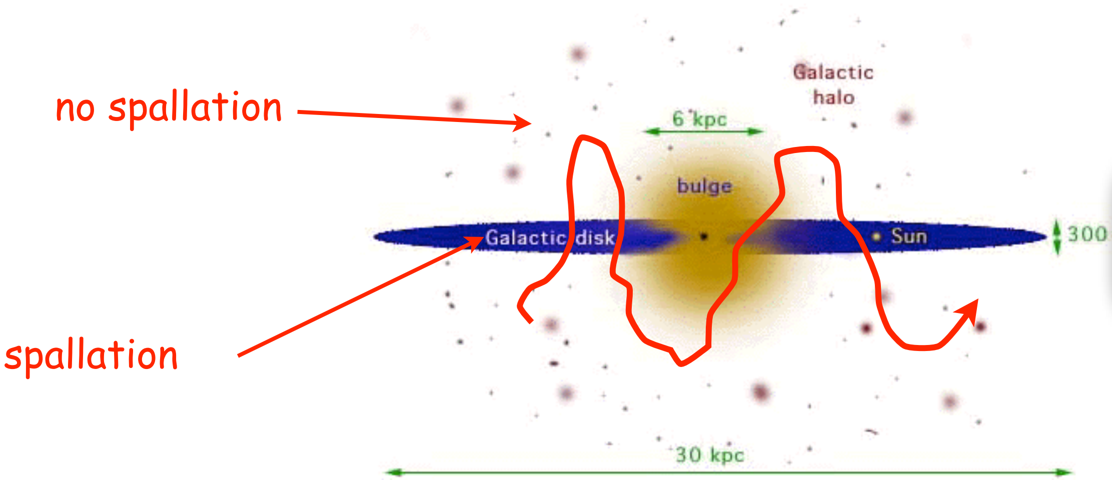


(2) CRs are confined in the Galactic disk

$$t_{disk} = \frac{l_s}{c} \approx 3 \times 10^6 \text{ yr}$$



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

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Cosmic Ray power in the Galaxy

CR energy density

total CR energy in the disk

MW disk volume

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

spatial homogeneity

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CR power from CR sources in the disk

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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:

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

σ_{pp}: 4×10^{-26} cm^2 ; k: 0.45

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energy loss term due to p-p interactions

Energy loss rate:

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

σ_{pp}: 4×10^{-26} cm^2 k: 0.45

We can safely neglect CR energy losses

What we have to explain about CRs:

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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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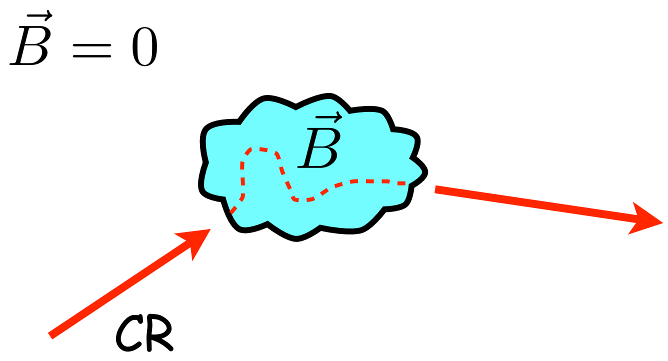
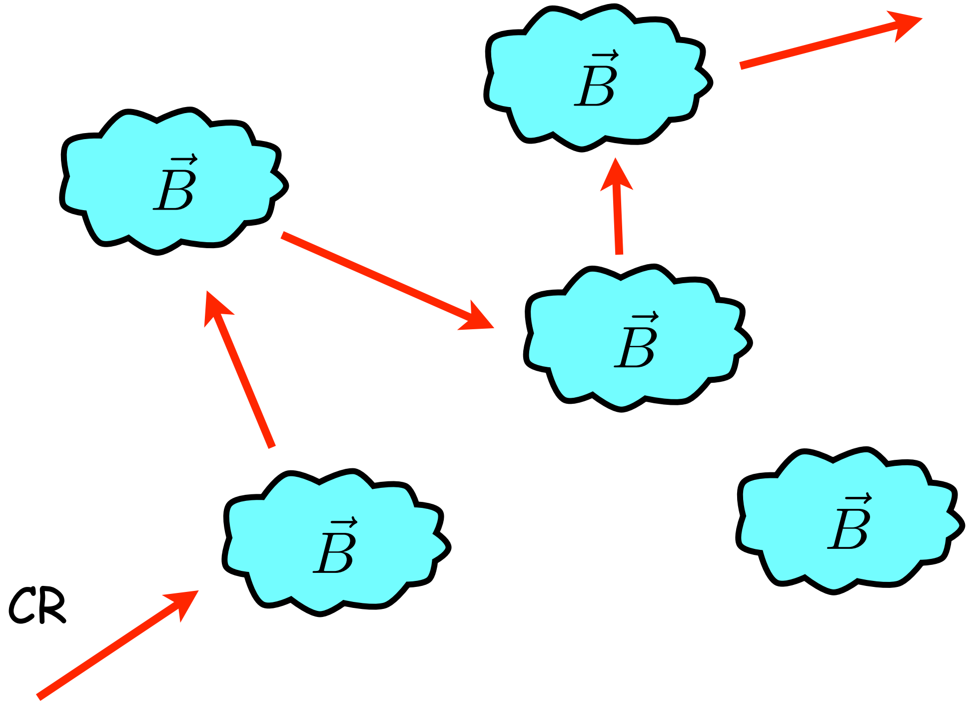
(Oversimplified picture)



magnetized cloudlets in an unmagnetized background

the particle energy is unchanged (Lorentz force)

The diffusion of CRs



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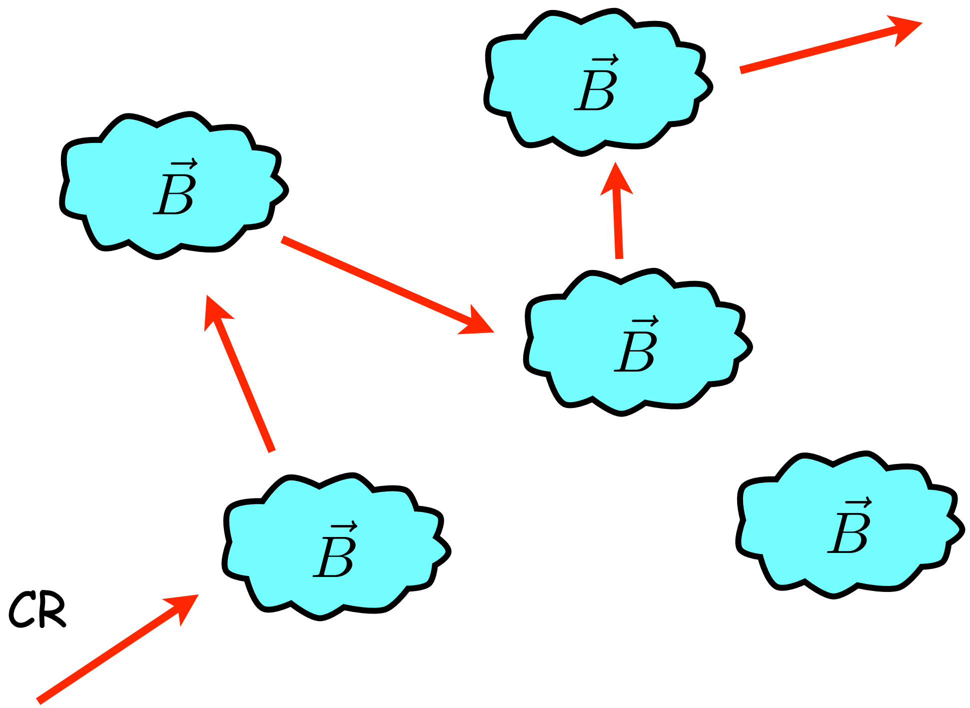

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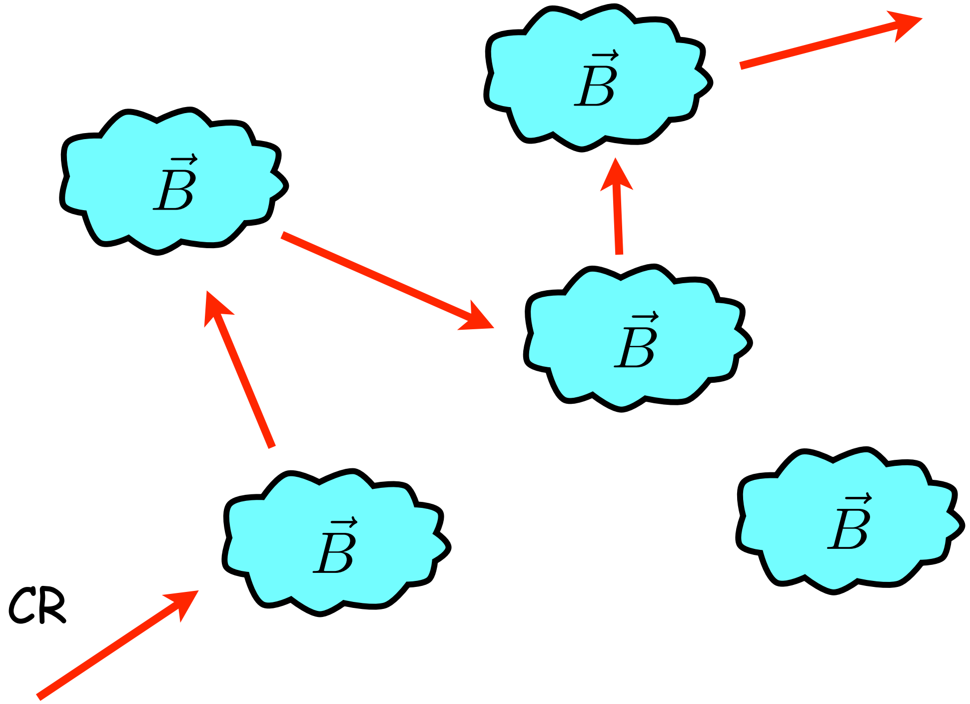

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$$\tau_c = \frac{\lambda}{c}$$ -> collision time

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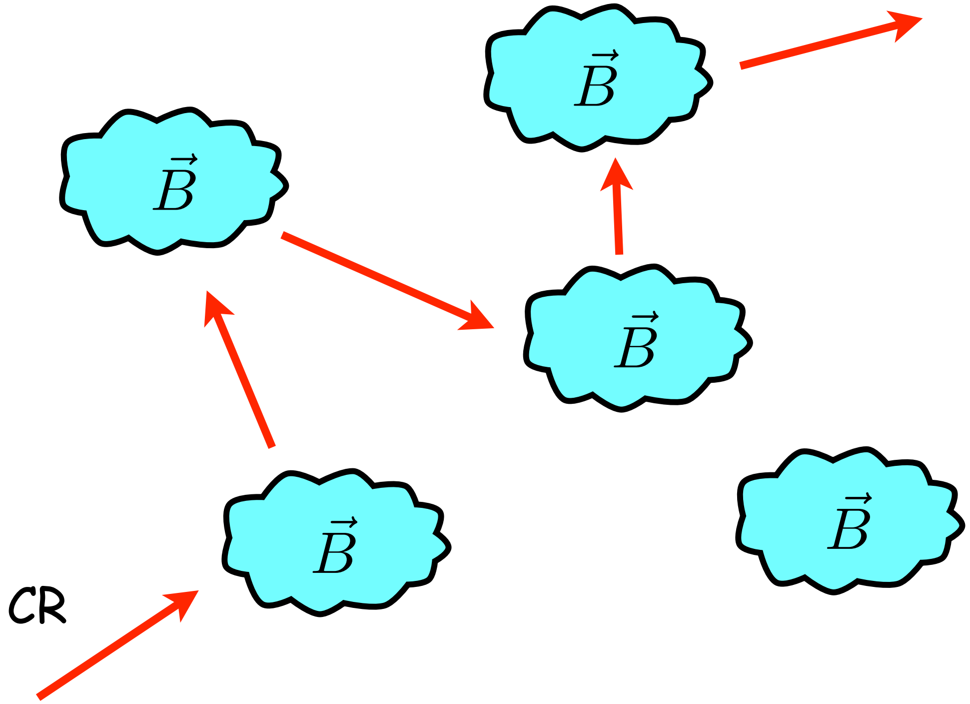

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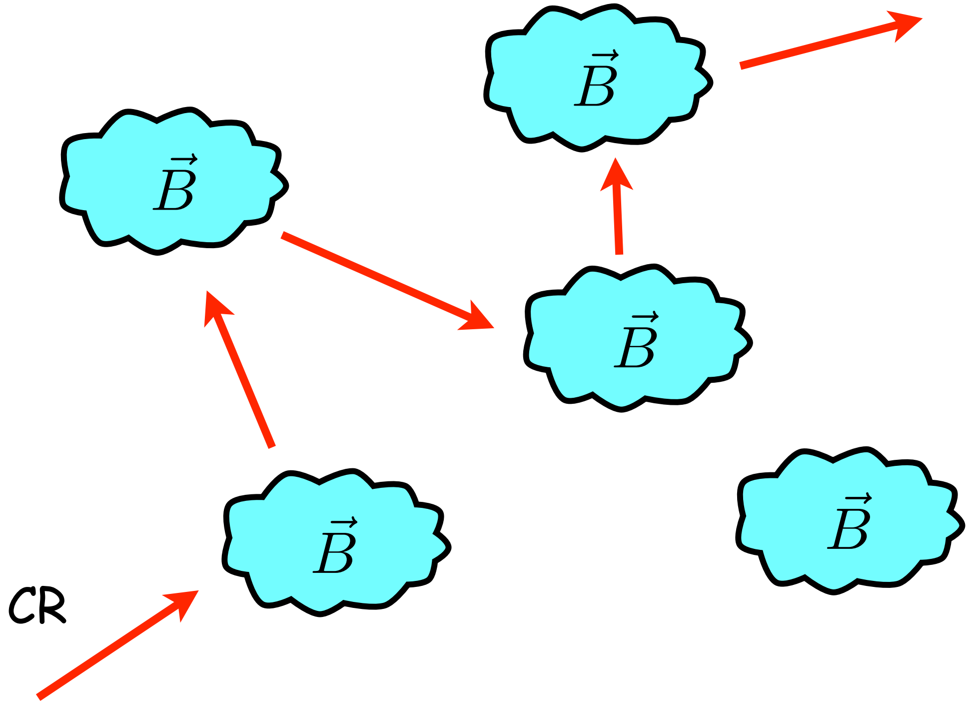

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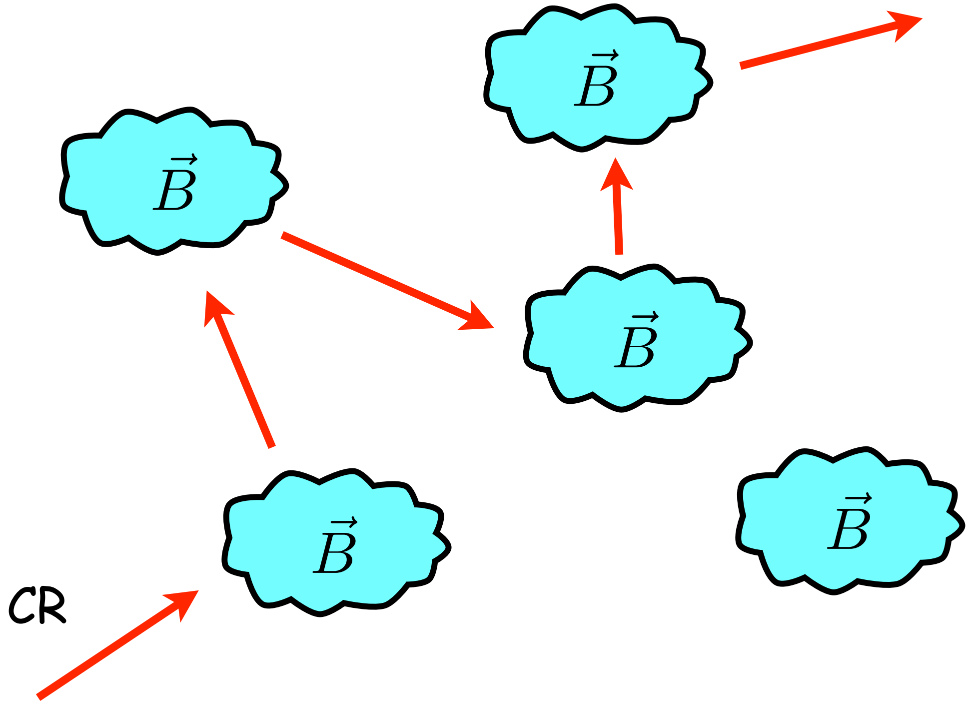
diffusion length -> $$l_d = \lambda \sqrt{N}$$

random walk

The diffusion of CRs



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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

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

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

~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

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

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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
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from gamma ray observations

A remarkable coincidence

Total CR power in the Galaxy ->

$$P_{CR} = 3 \times 10^{40} \text{ erg/s}$$

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 ->

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

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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  - ...ional tests

Diffusive Shock Acceleration

SNR shocks

see next class

TeV gamma ray astronomy

see next slide

TeV emission from SNRs: a test for CR origin

Detectability condition for HESS

$$W_{CR} > 10^{49} \, n_{gas}^{-1} \, d_{kpc}^{2} \, \mathrm{erg}$$

above ~ 10 TeV

TeV emission from SNRs: a test for CR origin

Detectability condition for HESS

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- up to the knee (5×10^{15} eV)

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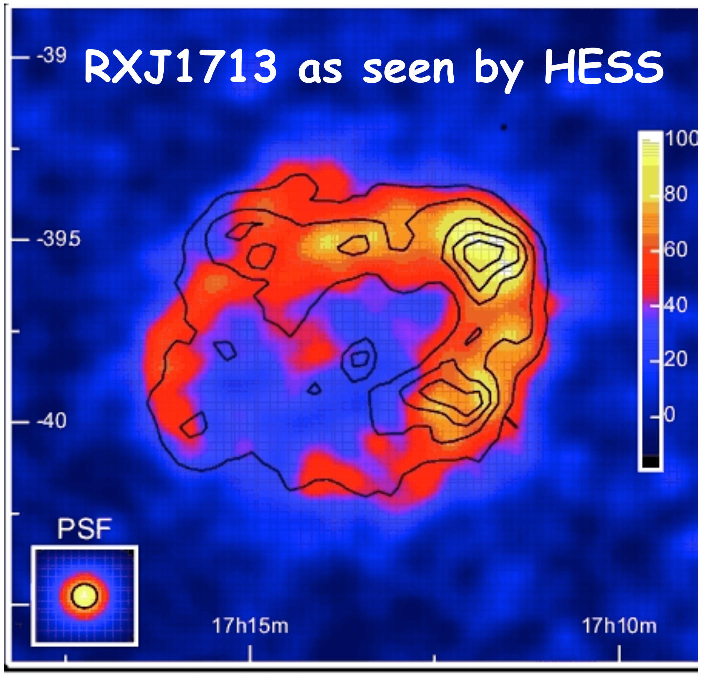
If **SuperNova Remnants** indeed are the sources of galactic Cosmic Rays they MUST be visible in **TeV gamma rays**
(Drury, Aharonian, and Voelk, 1994)

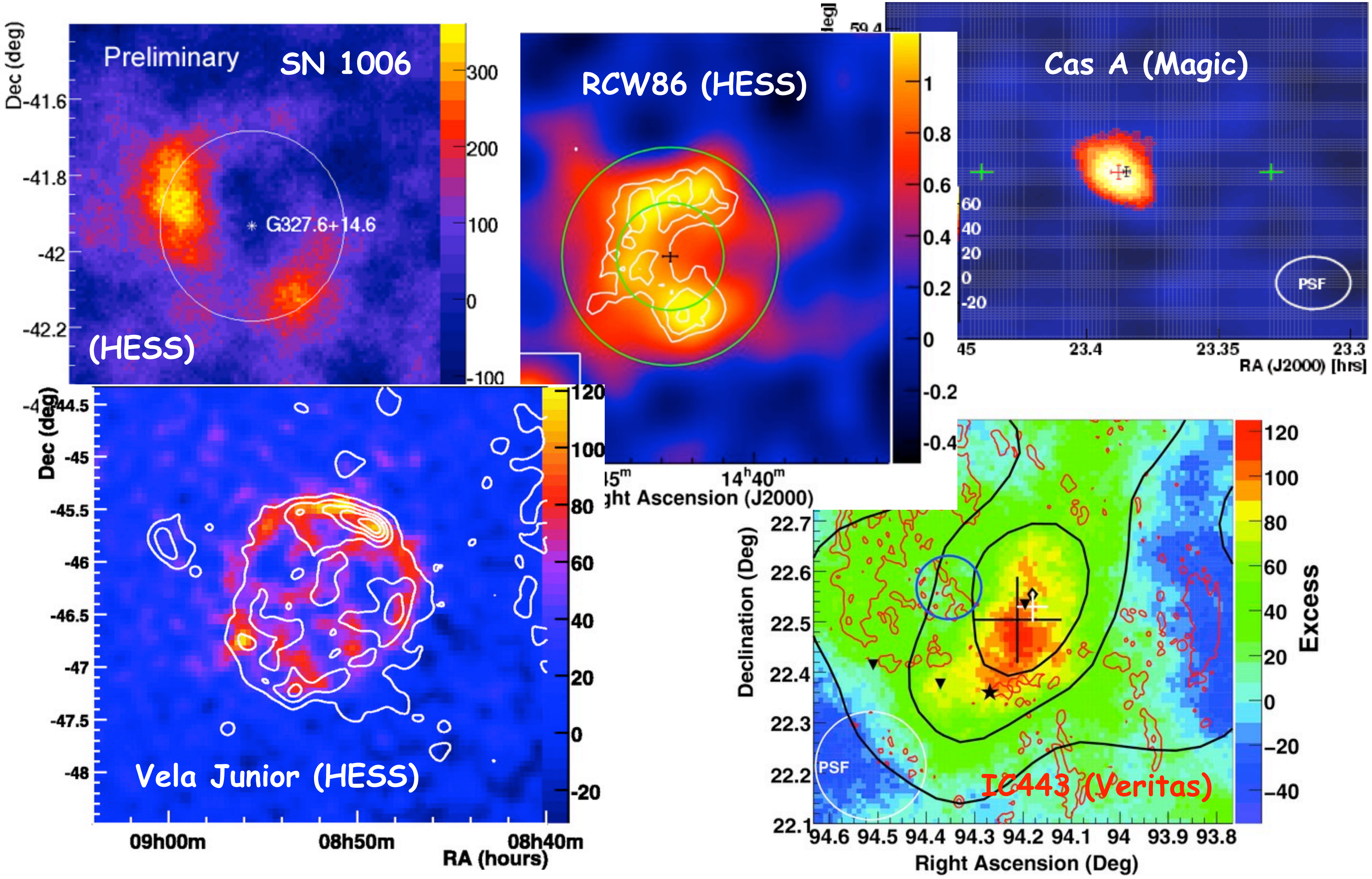
TeV emission from SNRs:
a test for CR origin



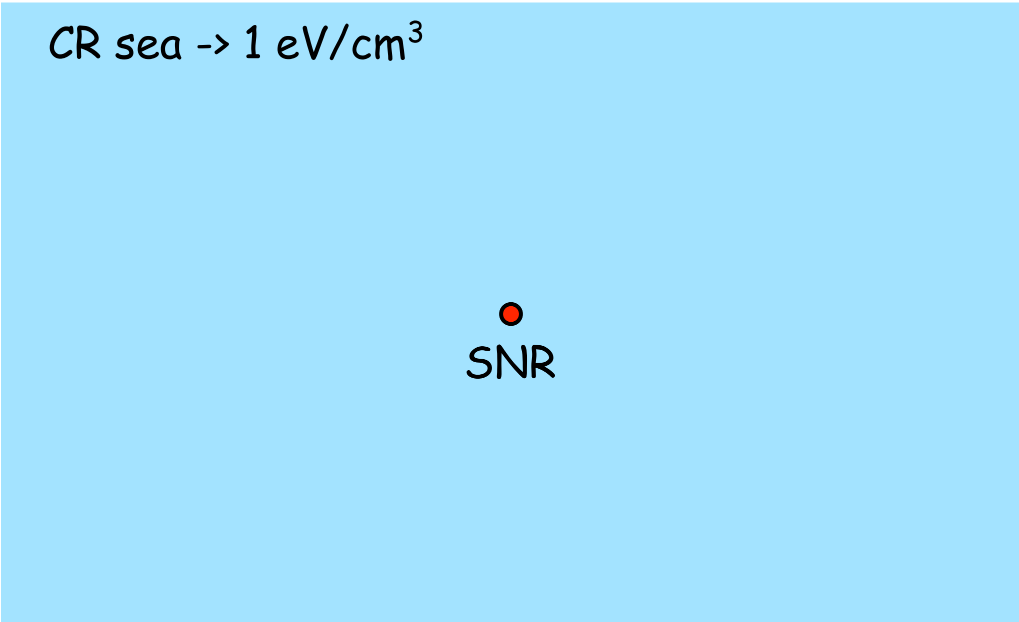
Test passed!

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

SNRs in gamma rays



Implications of the SNR hypothesis



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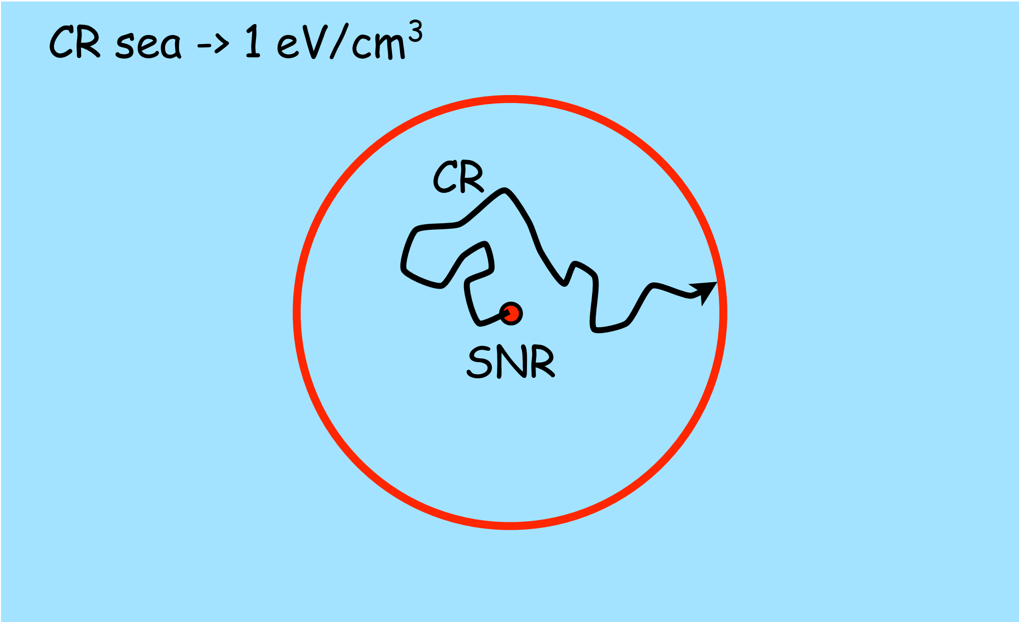

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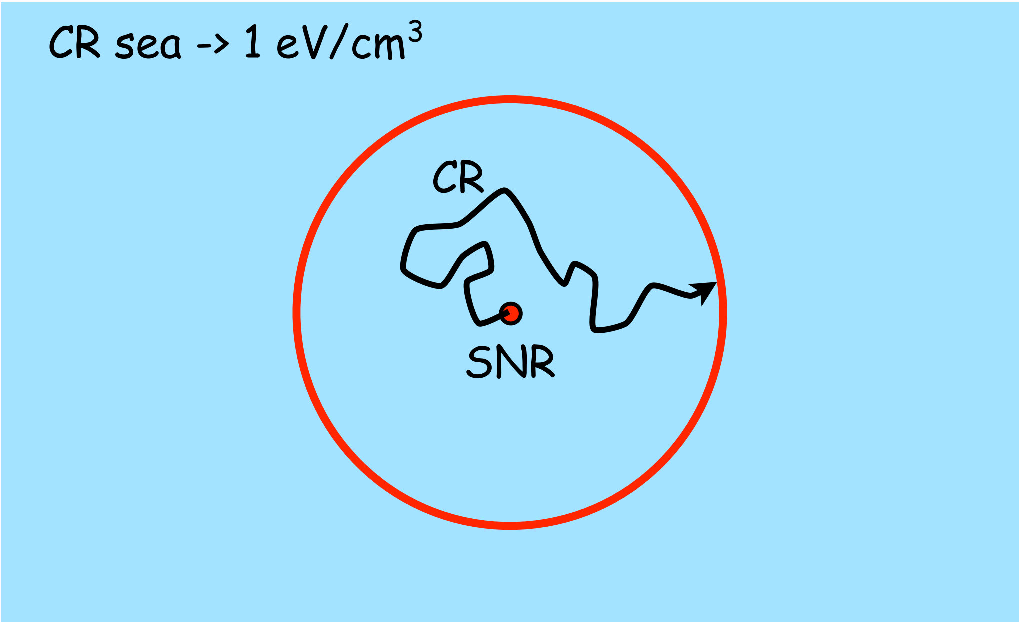

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$$D = 10^{28} \left(\frac{E}{10 \text{ GeV}}\right)^{0.6} \text{cm}^2/\text{s} \quad \Rightarrow \quad D(1 \text{ TeV}) \approx 2 \times 10^{29} \text{ cm}^2/\text{s}$$

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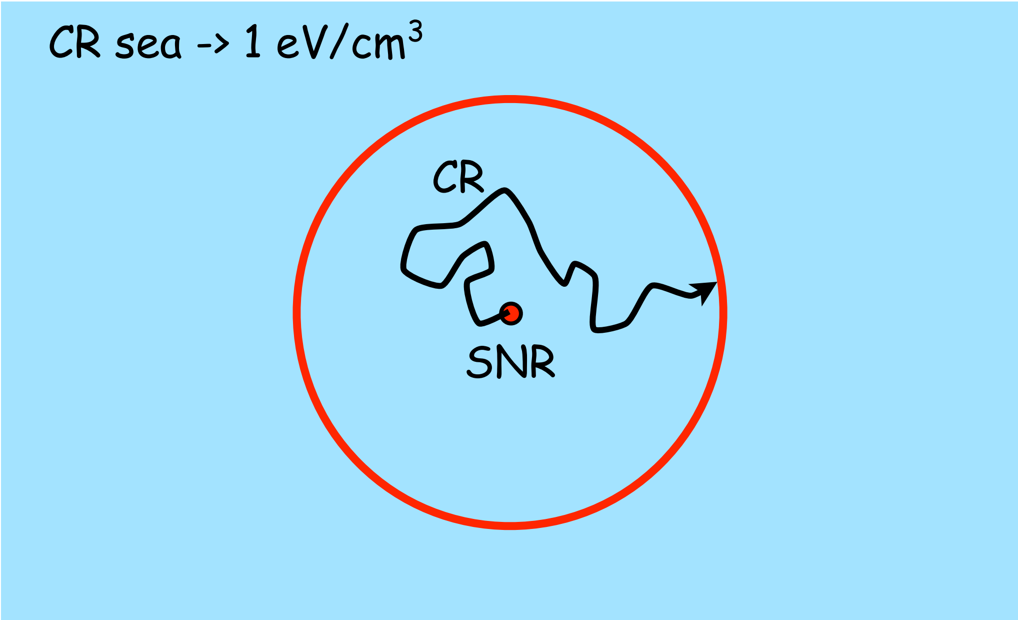
Implications of the SNR hypothesis

Very rough!



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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