Gamma rays from molecular clouds (part 1)

Stefano Gabici
APC, Paris

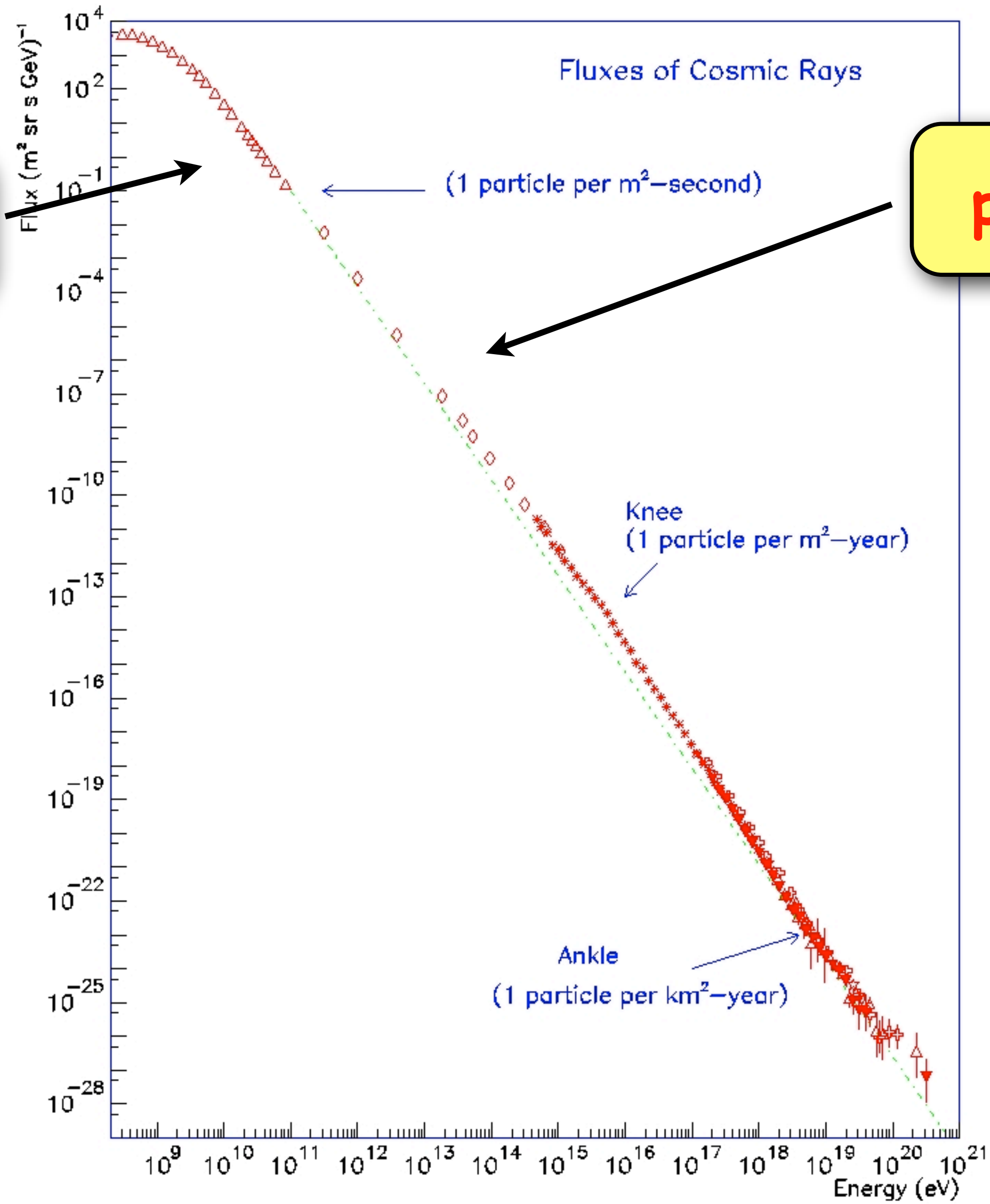
Overview

- ☑ Brief introduction on **cosmic rays**
- ☑ The **supernova remnant hypothesis** for the origin of cosmic rays
- ☑ Why **gamma ray astronomy**?
- ☑ Why **molecular clouds**?
- ☑ Part 1: **Passive Molecular Clouds** -> how to use MCs as cosmic ray barometers
- ☑ Part 2: **Illuminated Molecular Clouds** -> how to use MCs to locate CR sources and constrain CR propagation

Class #2

The (local) Cosmic Ray spectrum

1 eV/cm^3



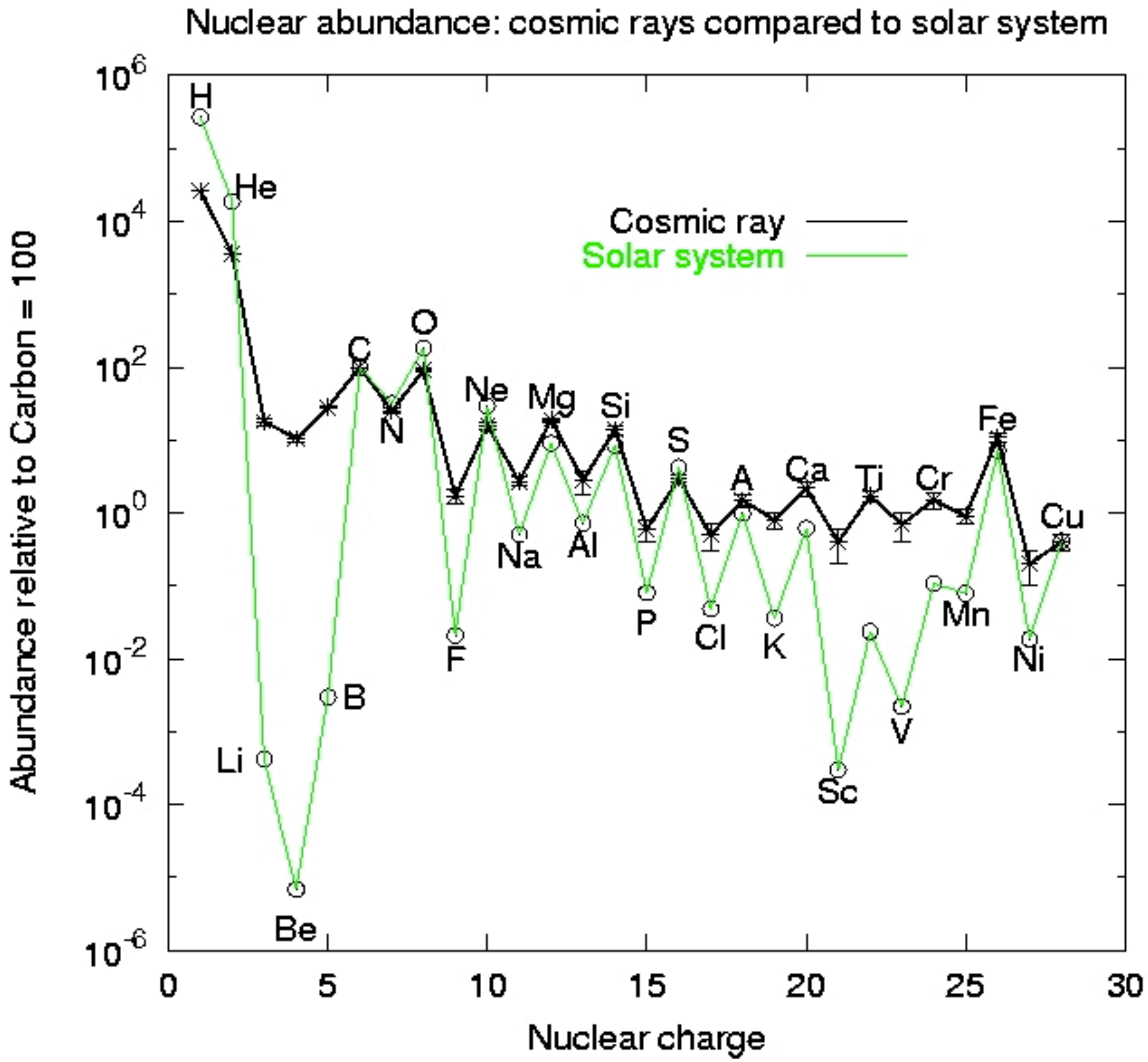
power law

See class by T. Bell on shock acceleration

isotropic

See class by A. Watson

Cosmic Ray composition



Gaisser & Stanev, 2005

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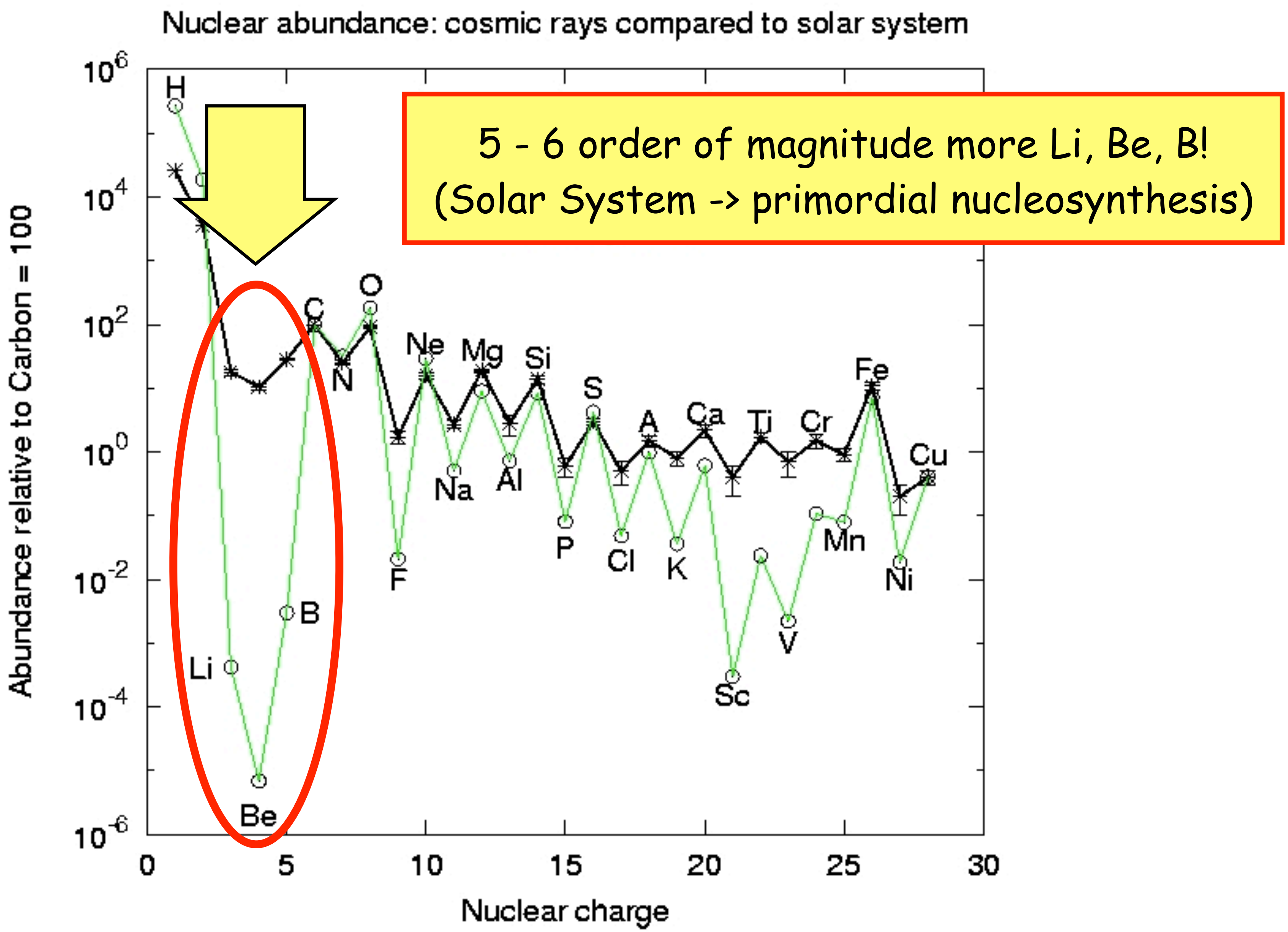

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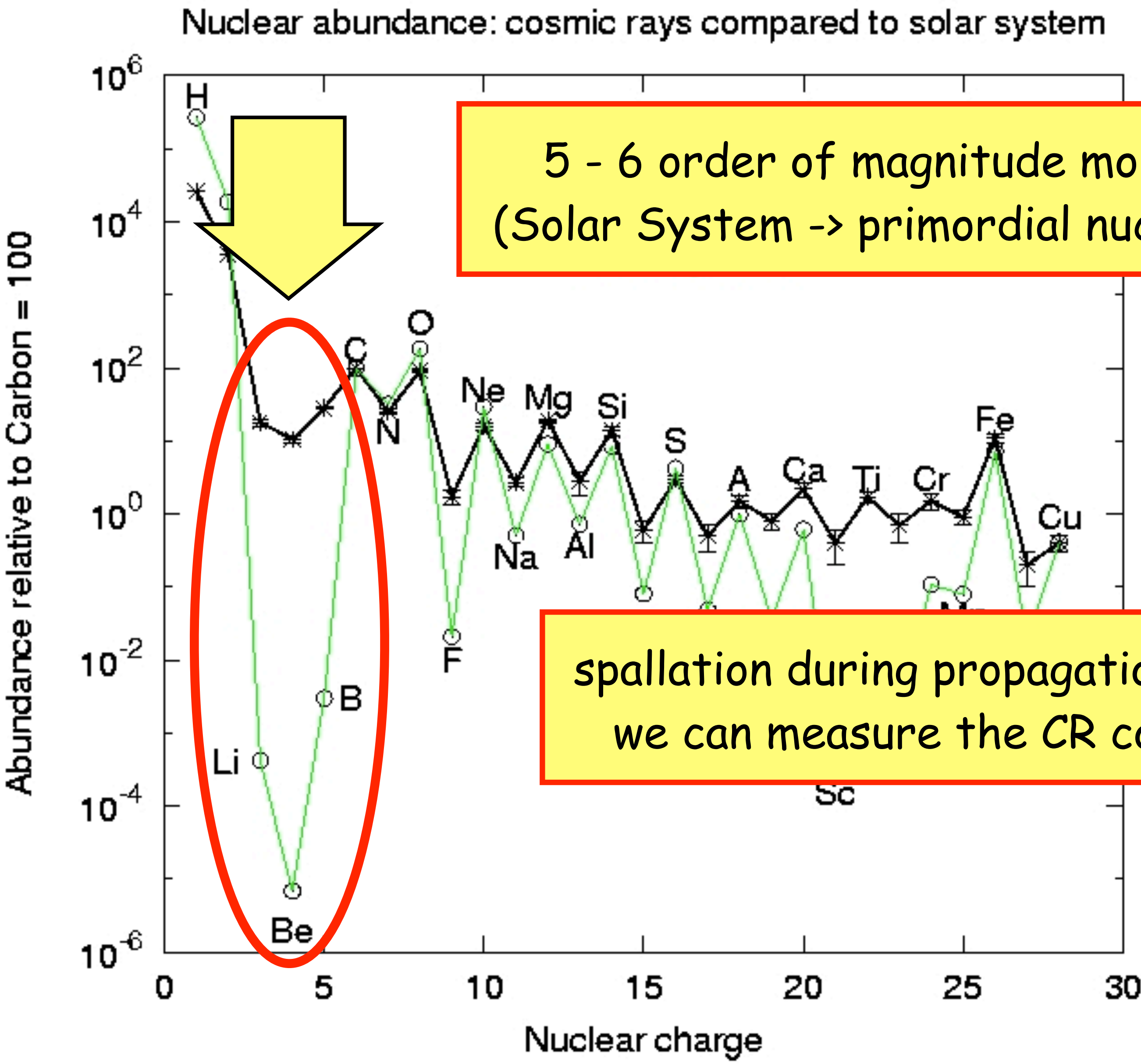


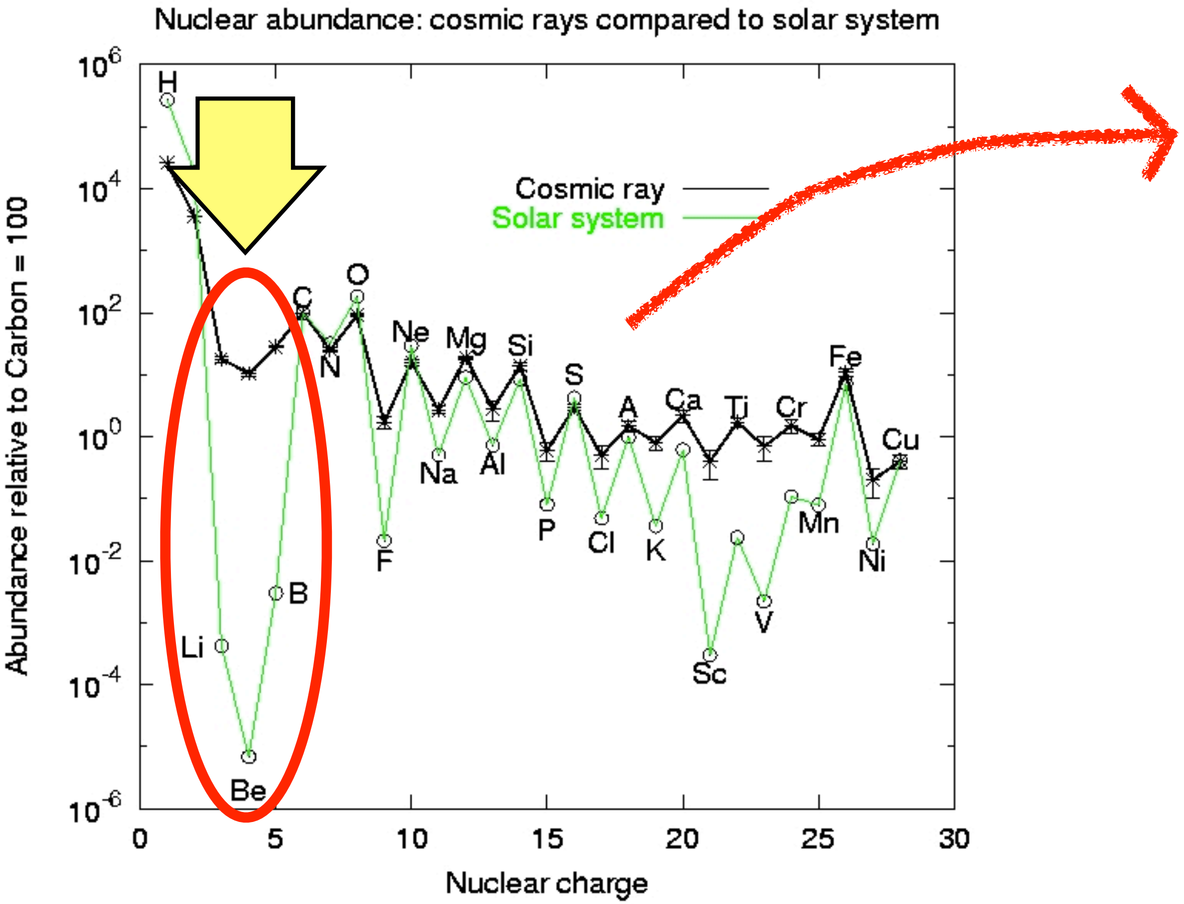
5 - 6 order of magnitude more Li, Be, B!
(Solar System -> primordial nucleosynthesis)

spallation during propagation in the Galaxy ->
we can measure the CR confinement time

Gaisser & Stanev, 2005

A remarkable "coincidence"

~ Baade & Zwicky, 1934



CR escape time

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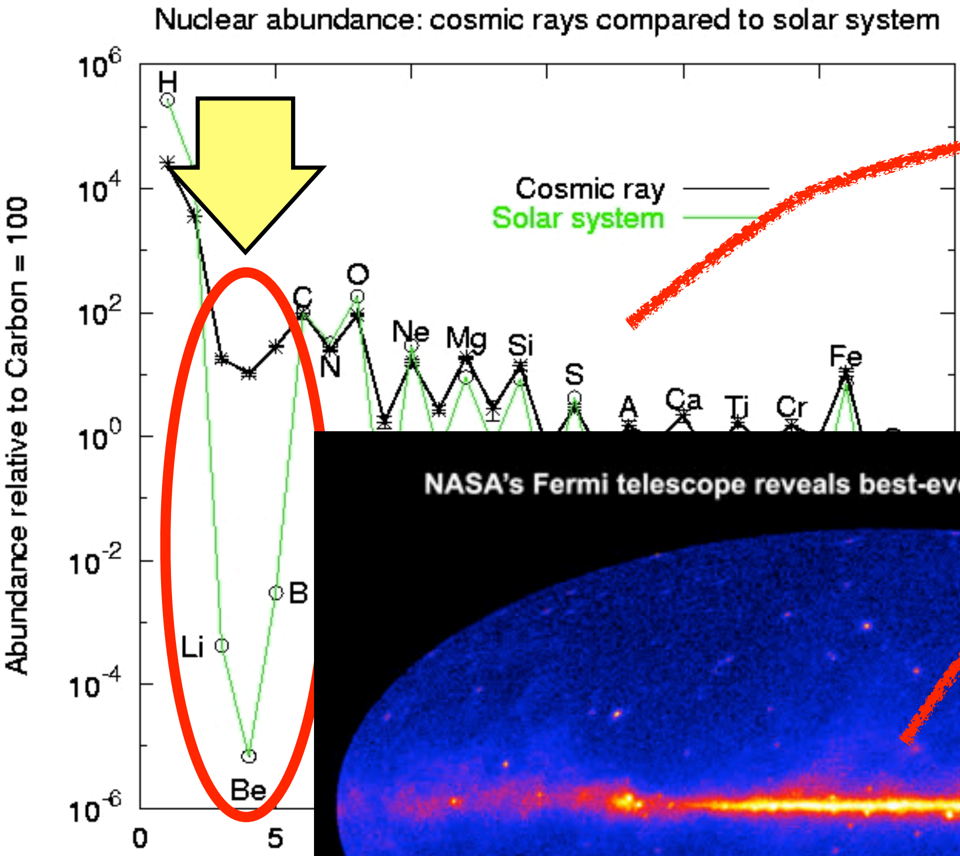

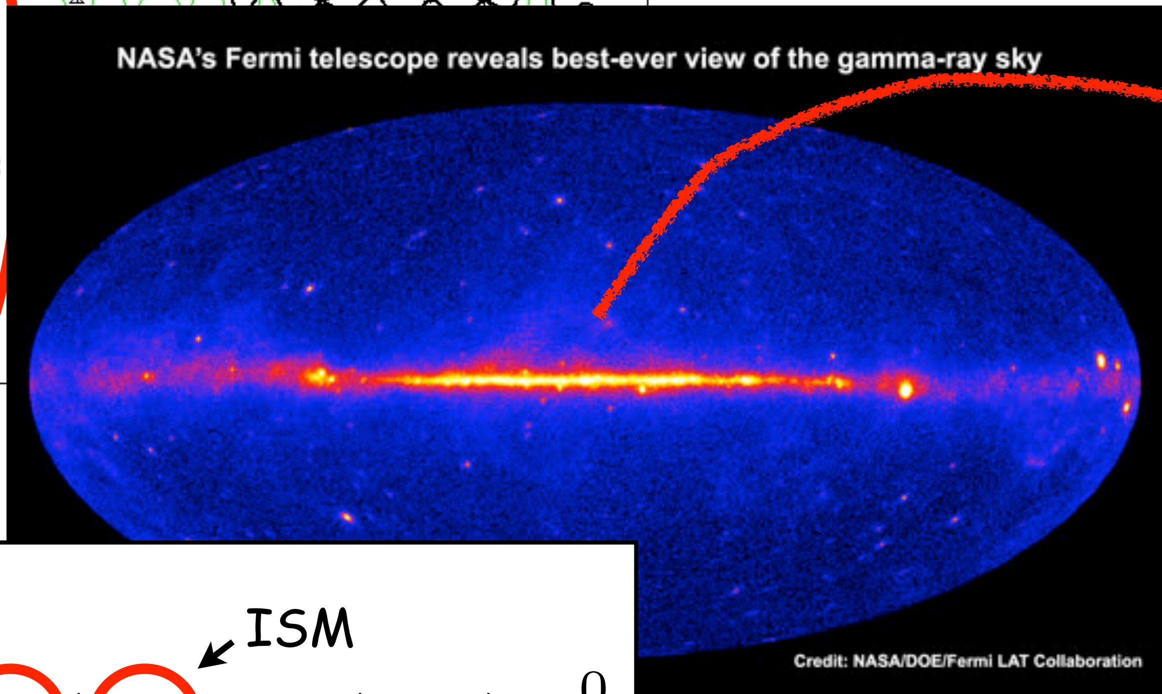

CR escape time

-> power of CR sources 3 x 10^{40} erg/s

CR total energy

CR

ISM

$$p + p \to p + p + \pi^0$$

$$\pi^0 \to \gamma + \gamma$$

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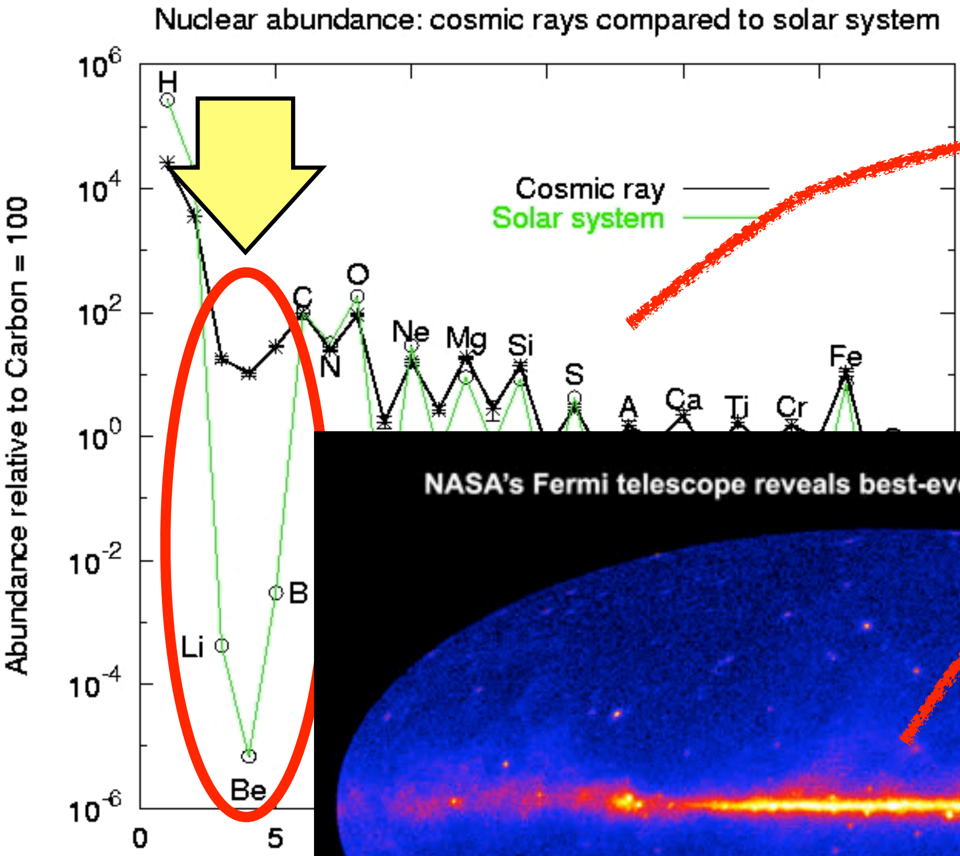

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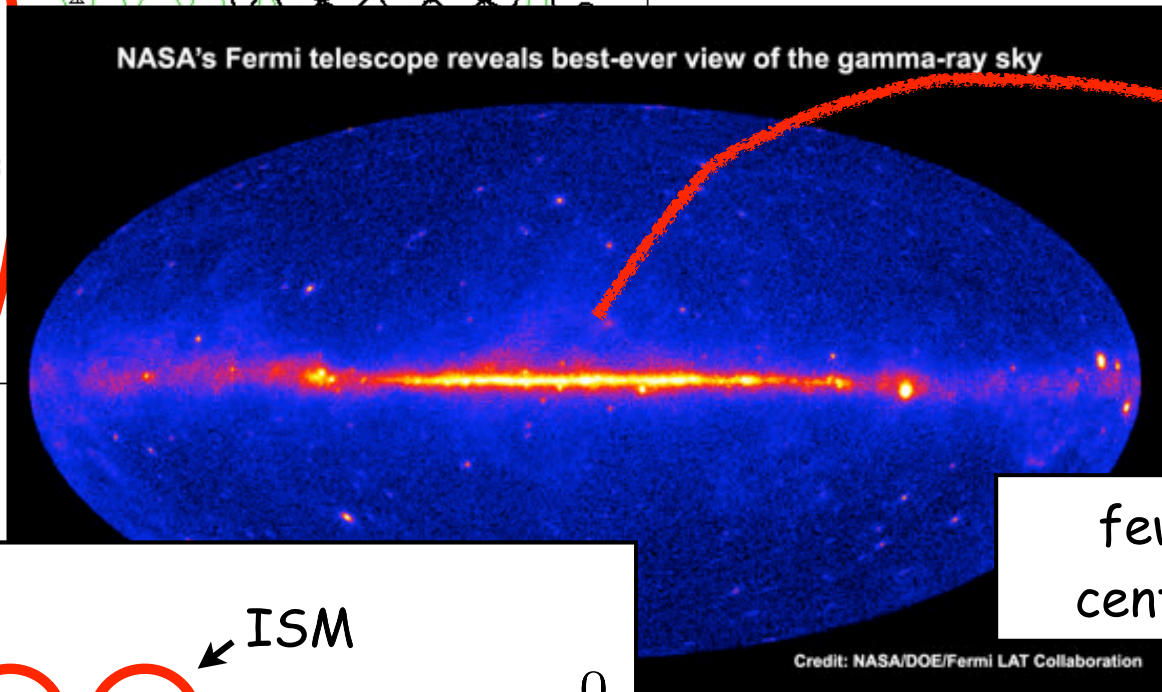

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few supernovae per century in the Galaxy

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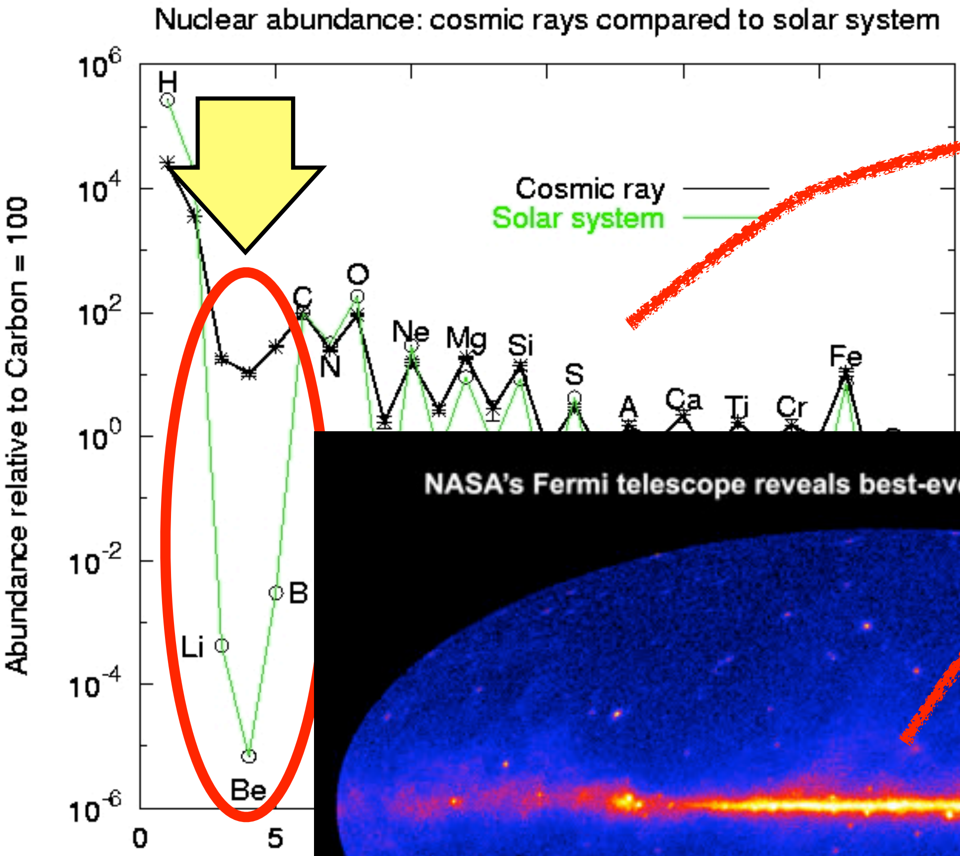

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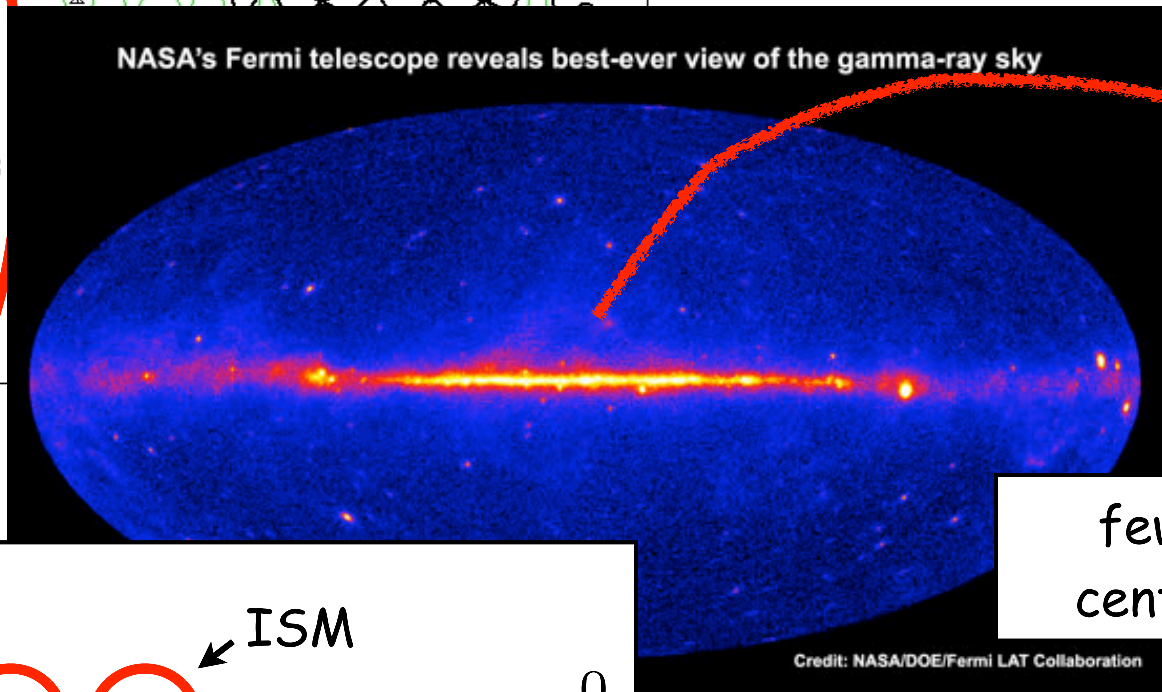

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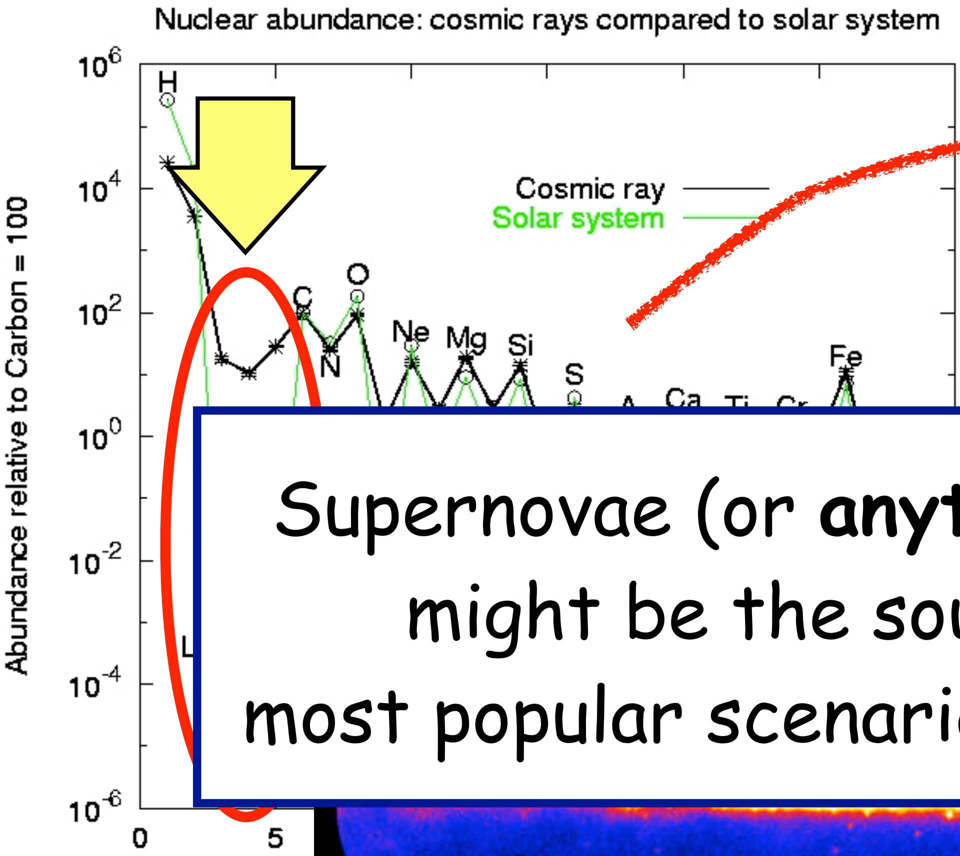

CR escape time

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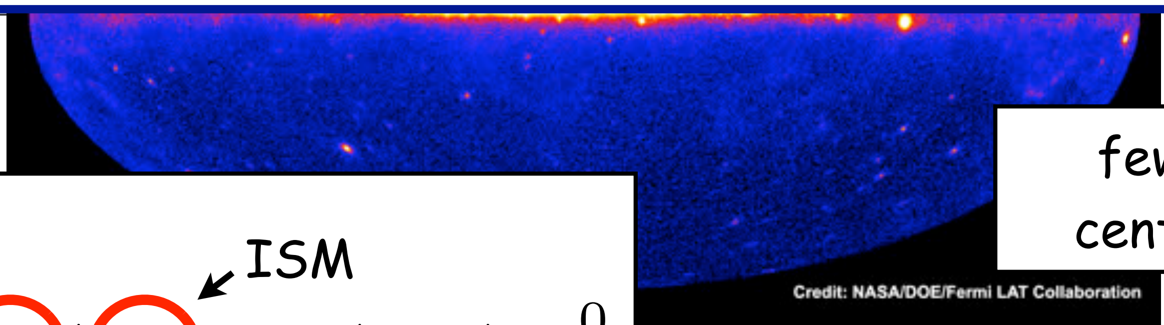
nergy

Supernovae (or **anything** connected to them) might be the sources of cosmic rays:
most popular scenario -> **supernova remnants**



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

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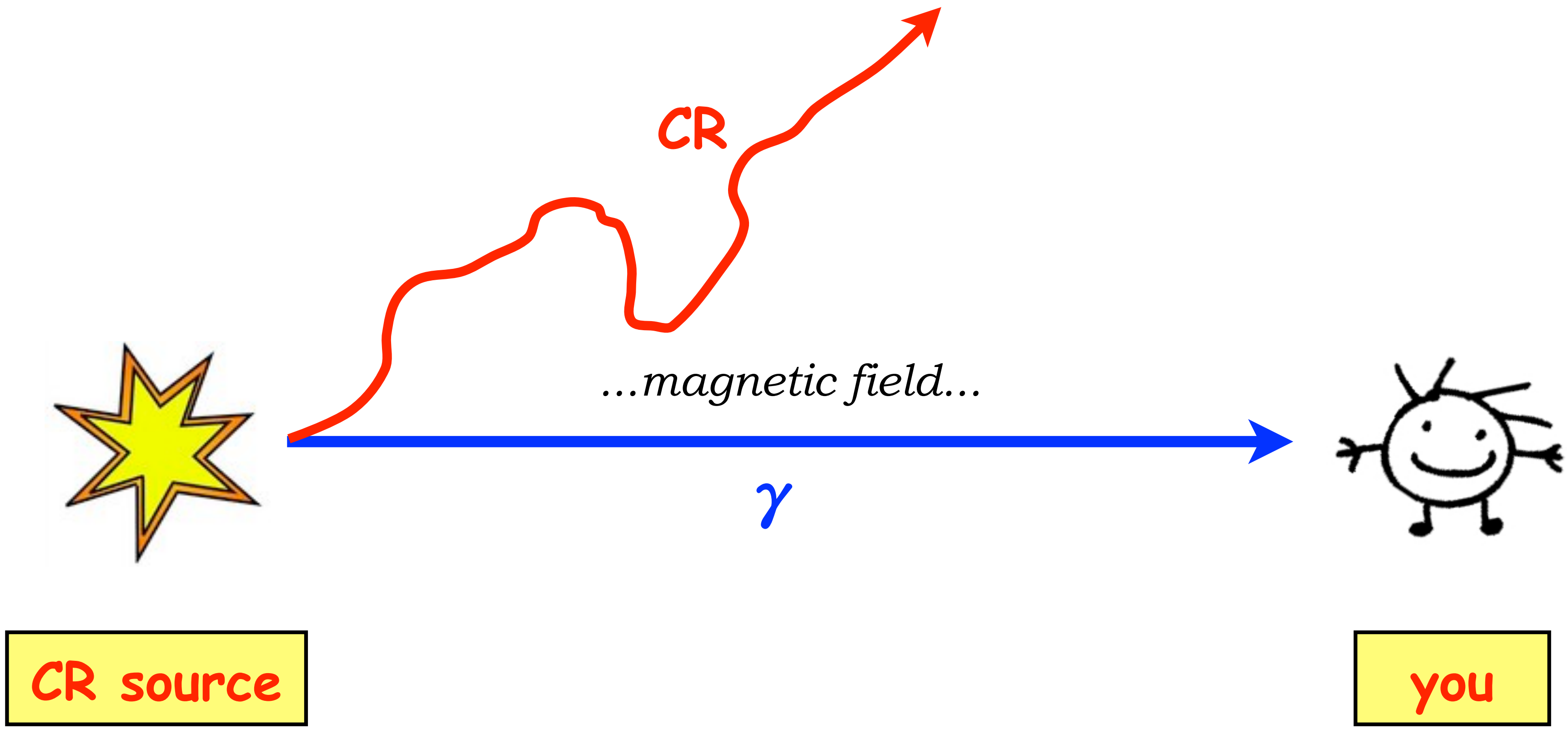
The anomaly is explained if (~ GeV) CRs transverse $\lambda \approx 5 \ \mathrm{g/cm^2}$

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

much larger than the size of the disk!!!

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

Why is it so difficult?



We cannot do CR Astronomy.

Need for indirect identification of CR sources.

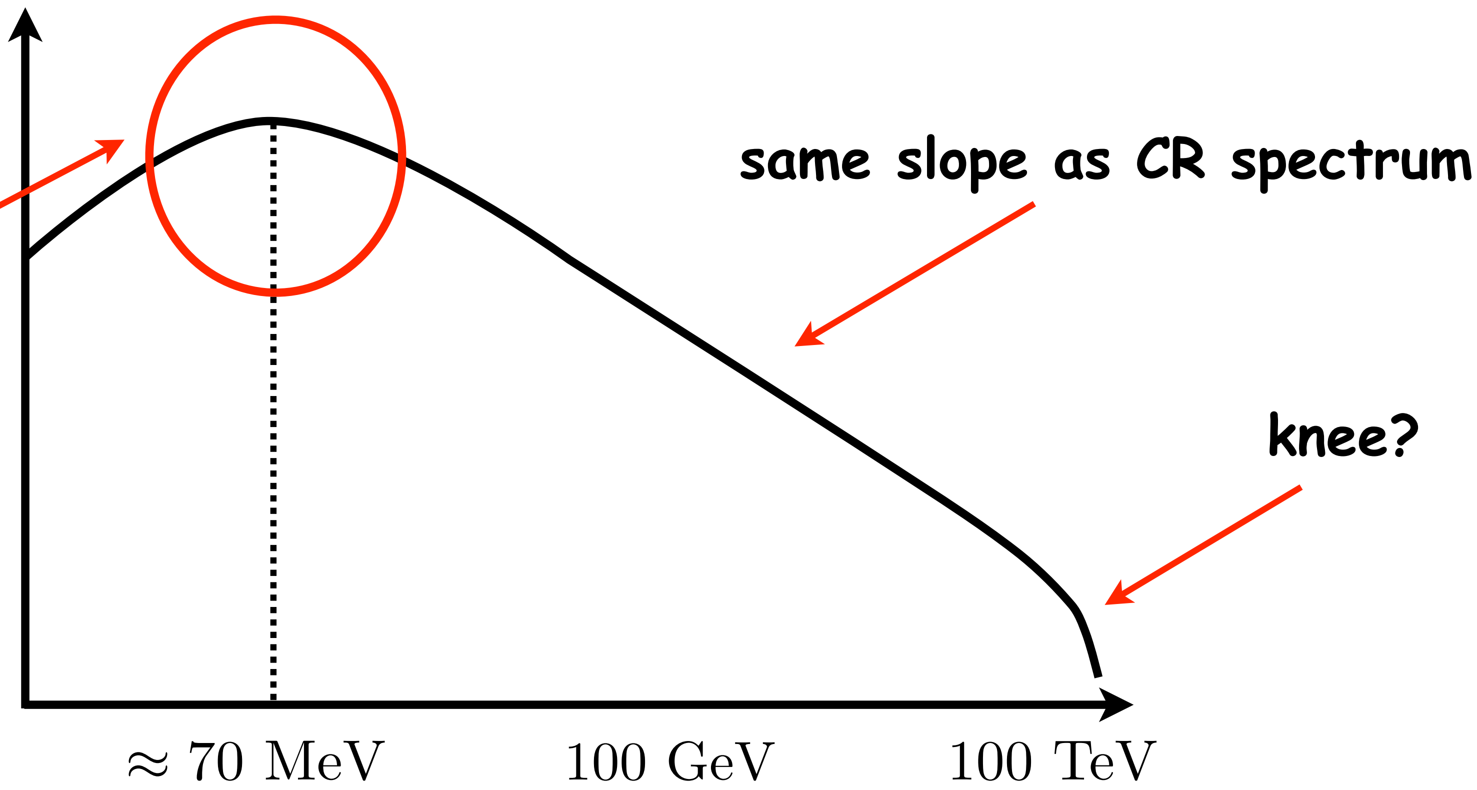
Gamma-ray astronomy

$$p + p \rightarrow p + p + \pi^0 \qquad \pi^0 \rightarrow \gamma + \gamma$$

CR ISM

$$\boxed{\langle E_\gamma \rangle \approx E_{CR}/10}$$

$$E_{peak} = \frac{m_{\pi^0}}{2}$$



See class by D. Kanghoulyan

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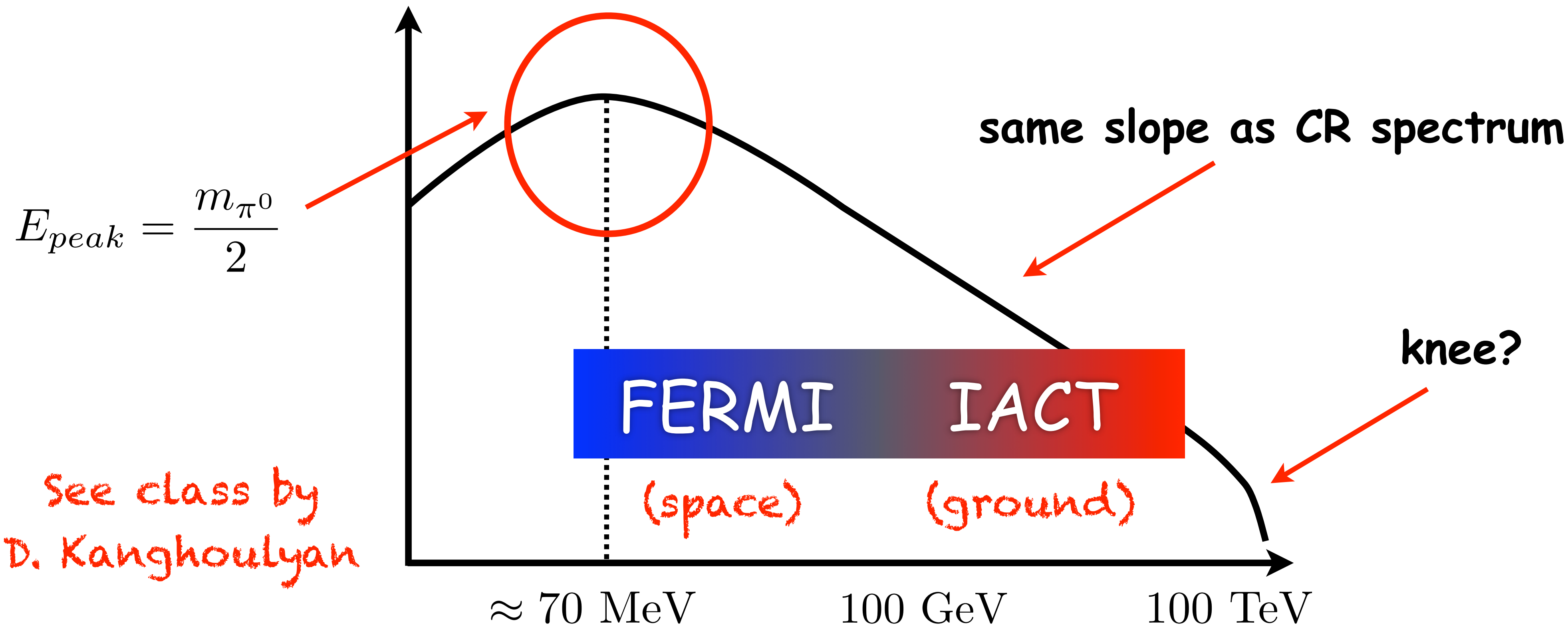

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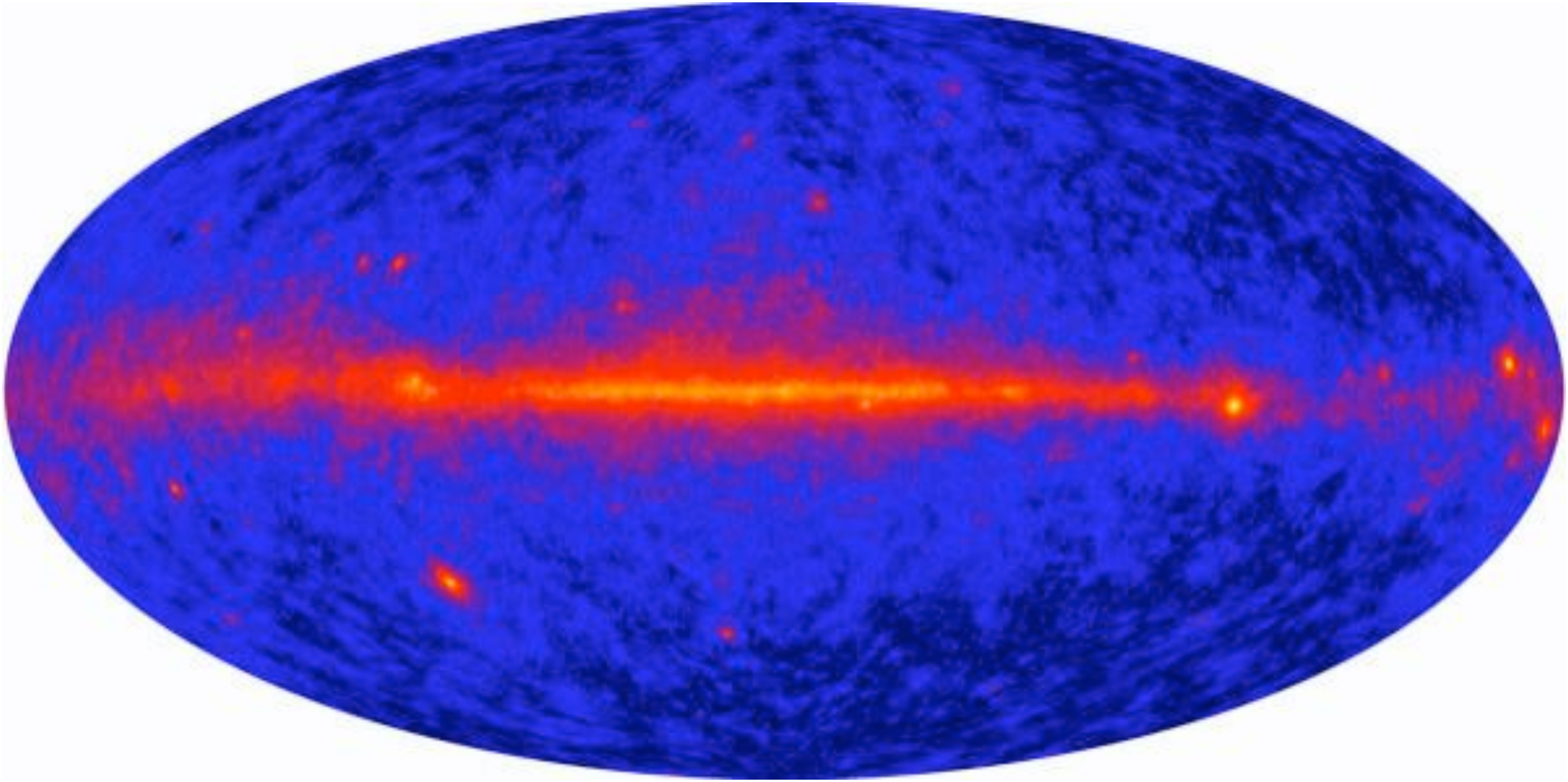
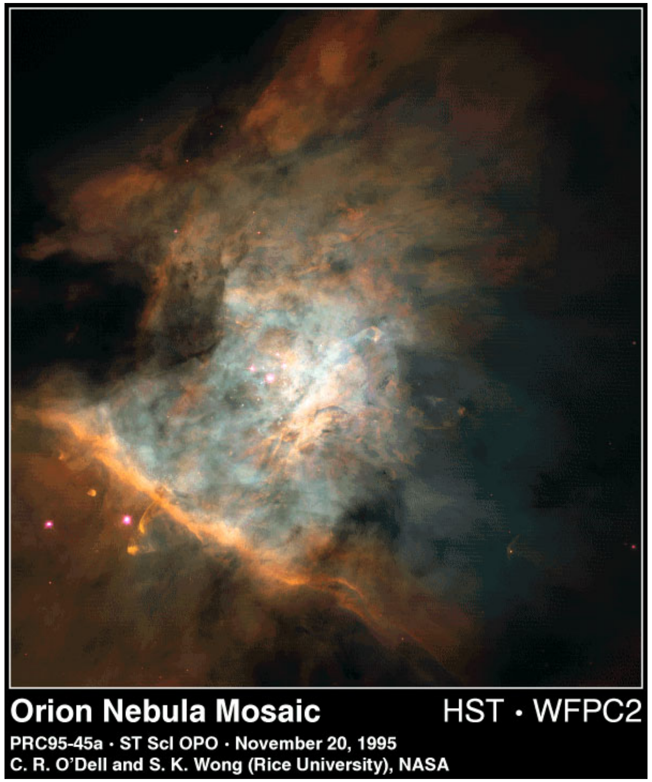
The sky @ E>100 MeV (FERMI)



Why molecular clouds?

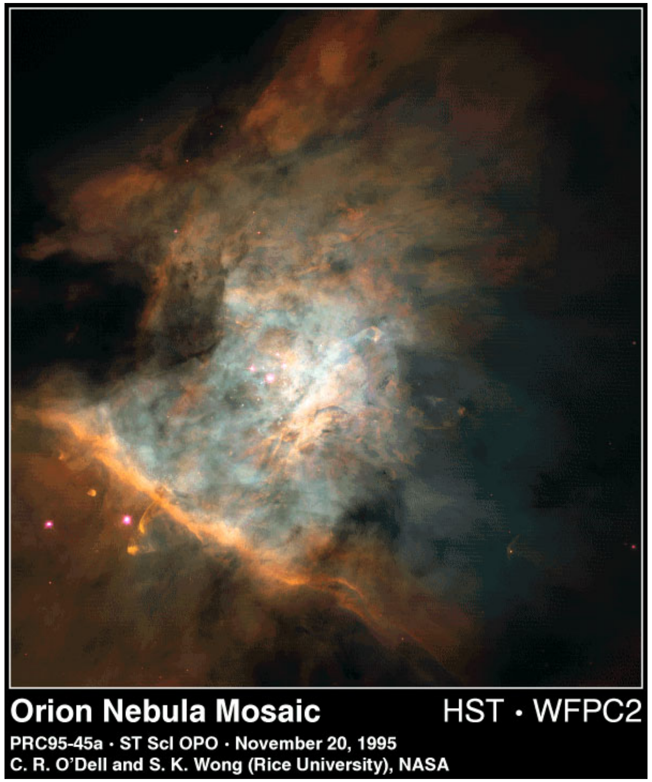


Molecular Clouds -> sites of star formation

dense -> $n \sim 100\ \mathrm{cm}^{-3}$

massive -> Mass up to $10^6\ M_\odot$

Why molecular clouds?



Molecular Clouds -> sites of star formation

dense -> n ~ 100 cm^{-3}

massive -> Mass up to 10^6 $M_\odot$

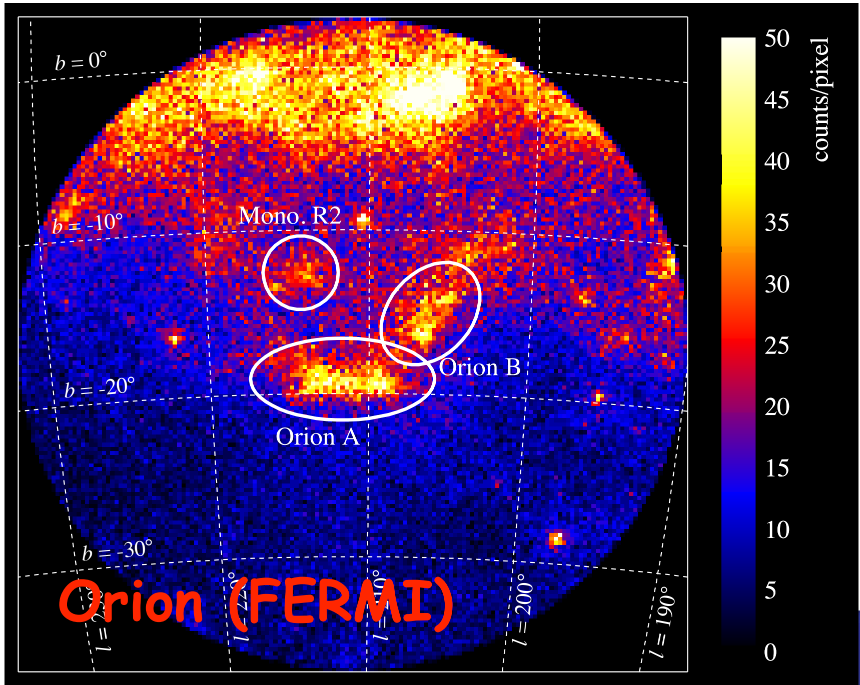
Cloud mass

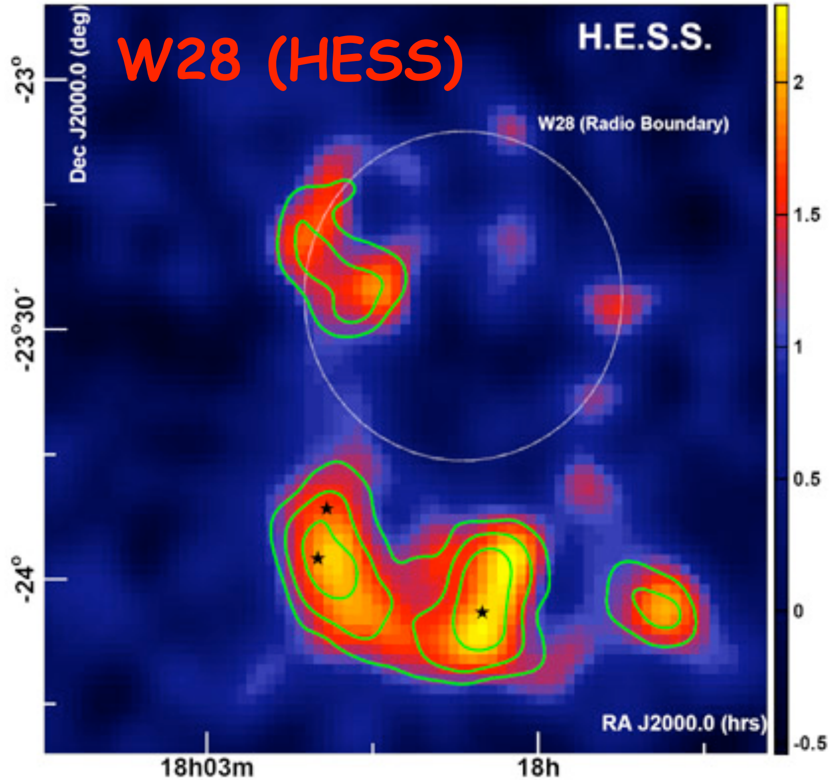
$$L_\gamma \approx \sigma\, c \int dV\, n_{CR}\, n_{ISM} = \sigma\, c\, n_{CR} \boxed{\int dV\, \cancel{n_{CR}}\, n_{ISM}} \propto M_{cl}$$

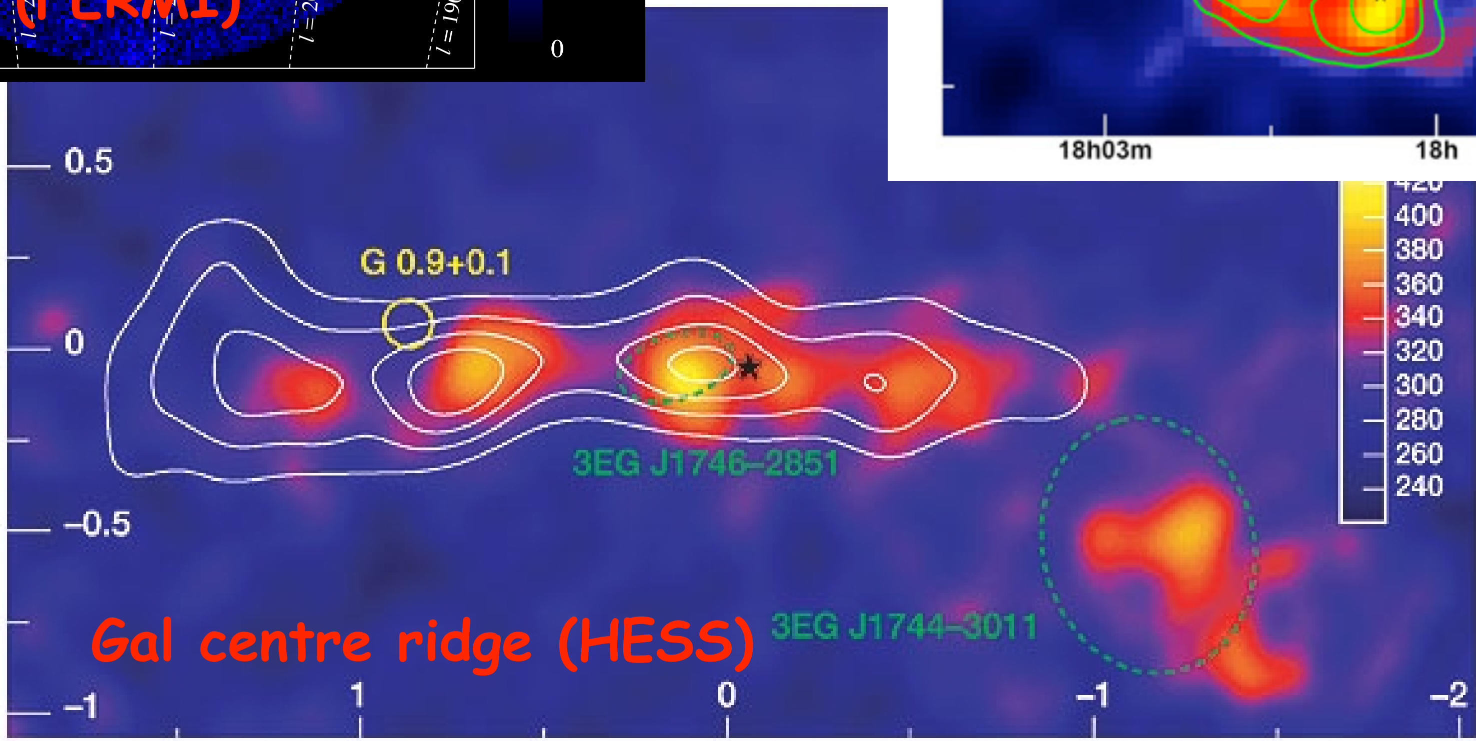
...because they are massive

Molecular clouds are gamma ray sources

Okumura et al, 2009







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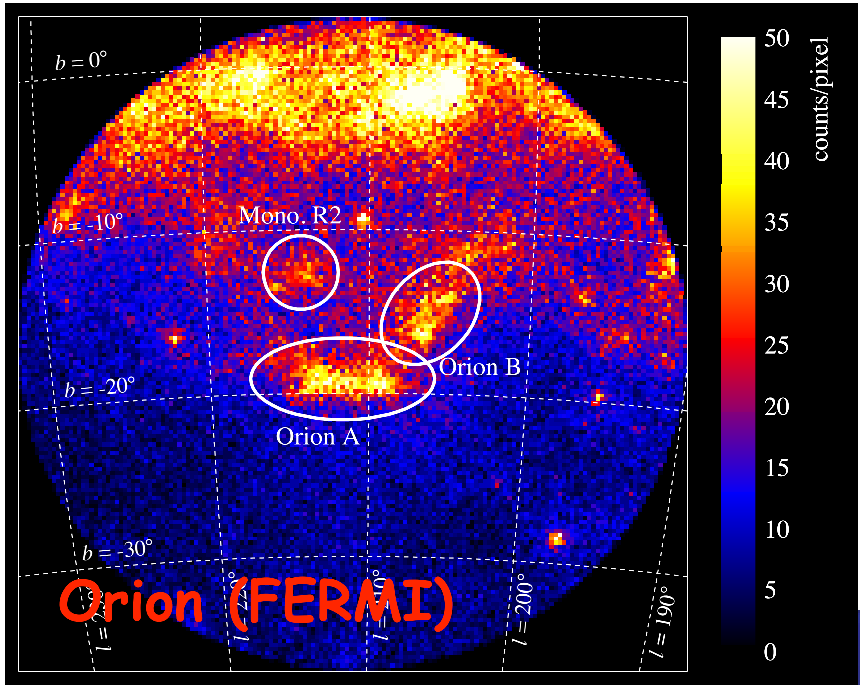
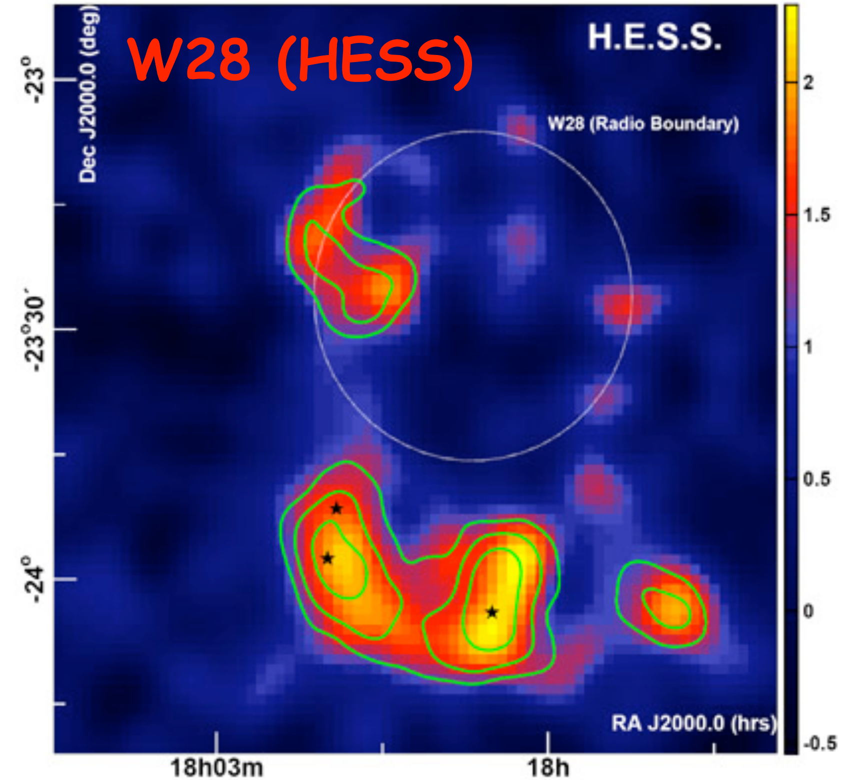
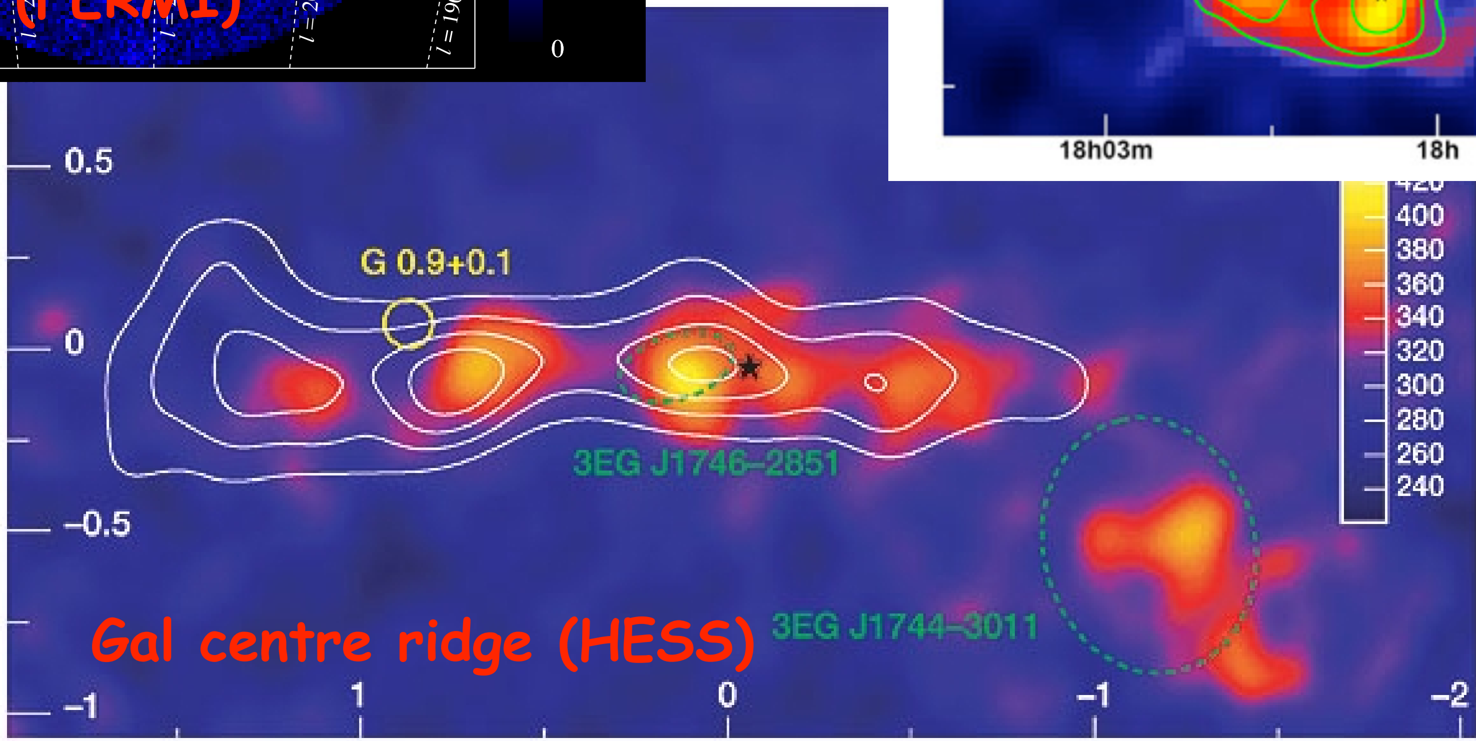




Aharonian et al, 2008

Aharonian et al, 2006



(1) Molecular clouds as cosmic ray barometers

Molecular Clouds as CR barometers

(Issa & Wolfendale, 1981 ; Aharonian, 1991)

Zero-th order approximation: the CR spectrum everywhere in the Galaxy is identical to the spectrum we observe at Earth

$$\Longrightarrow \qquad F_\gamma = A \left(\frac{M_{cl}}{d^2} \right)$$

known constant

Molecular Clouds as CR barometers

$$\boxed{F_\gamma = A \left(\frac{M_{cl}}{d^2} \right)}$$

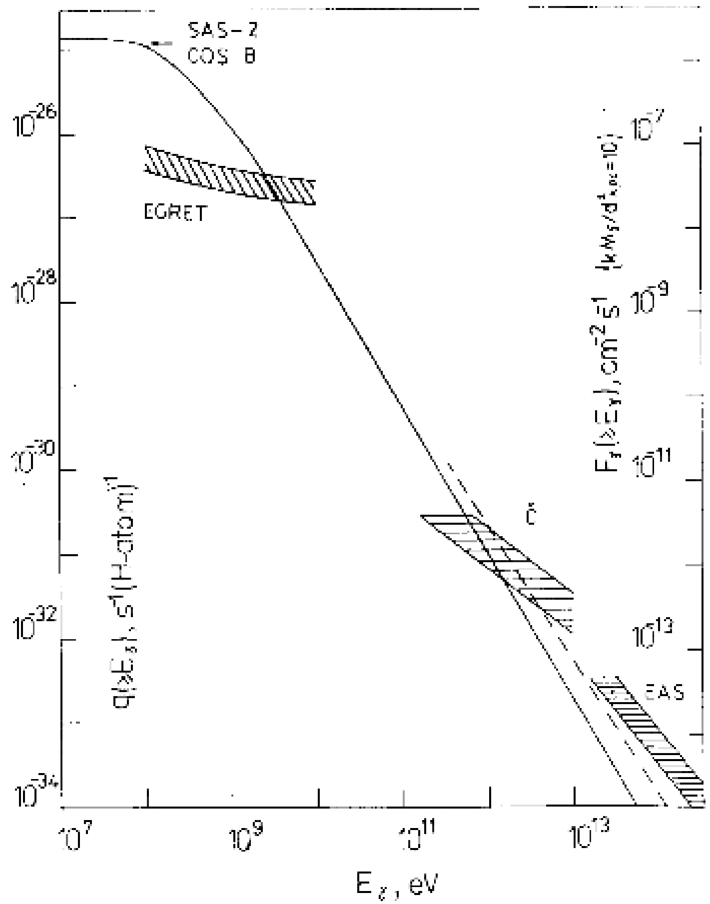
Conversely, if we know M_{cl} and d (from CO measurements) we can derive A and estimate both the normalization and spectrum of CRs at the cloud -> Molecular Clouds are CR Barometers

Two caveats:

- error in the determination of the mass (CO -> H2 conversion)
- effective penetration of CR into the cloud (if not see Gabici et al. 2007)

Molecular Clouds as CR barometers: GeVs

Akharonian, 1991



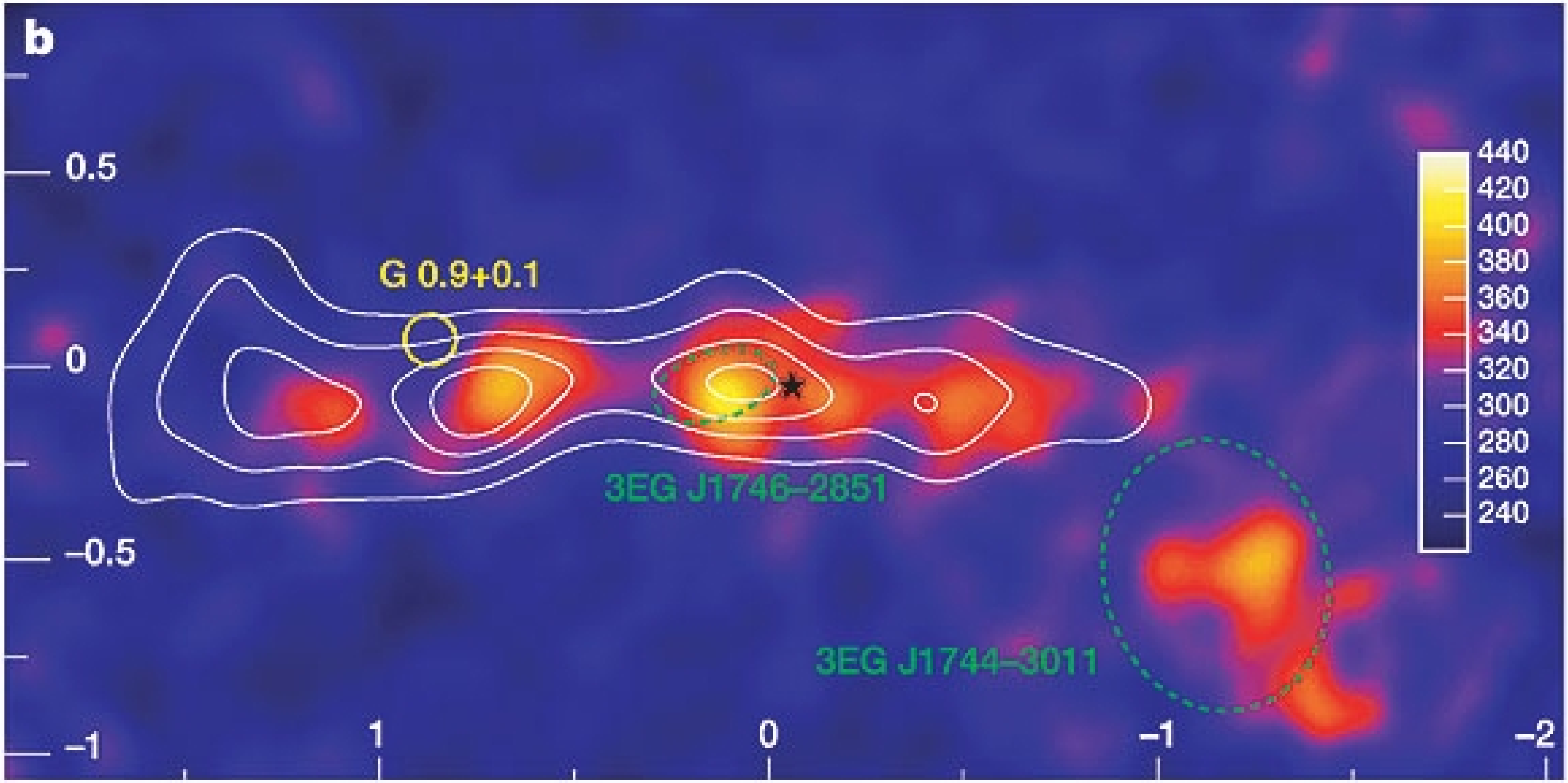
detectable with EGRET if:

$$\boxed{\frac{M_5}{d_{kpc}^2} > 10}$$

- only a few (Orion, Monoceros) -> Digel et al.2001
- we need **FERMI**
- gamma ray spectrum -> steep power law from GeV to TeV energies

Molecular Clouds as CR barometers: TeVs

The galactic centre ridge as seen by HESS



HESS collaboration, 2006

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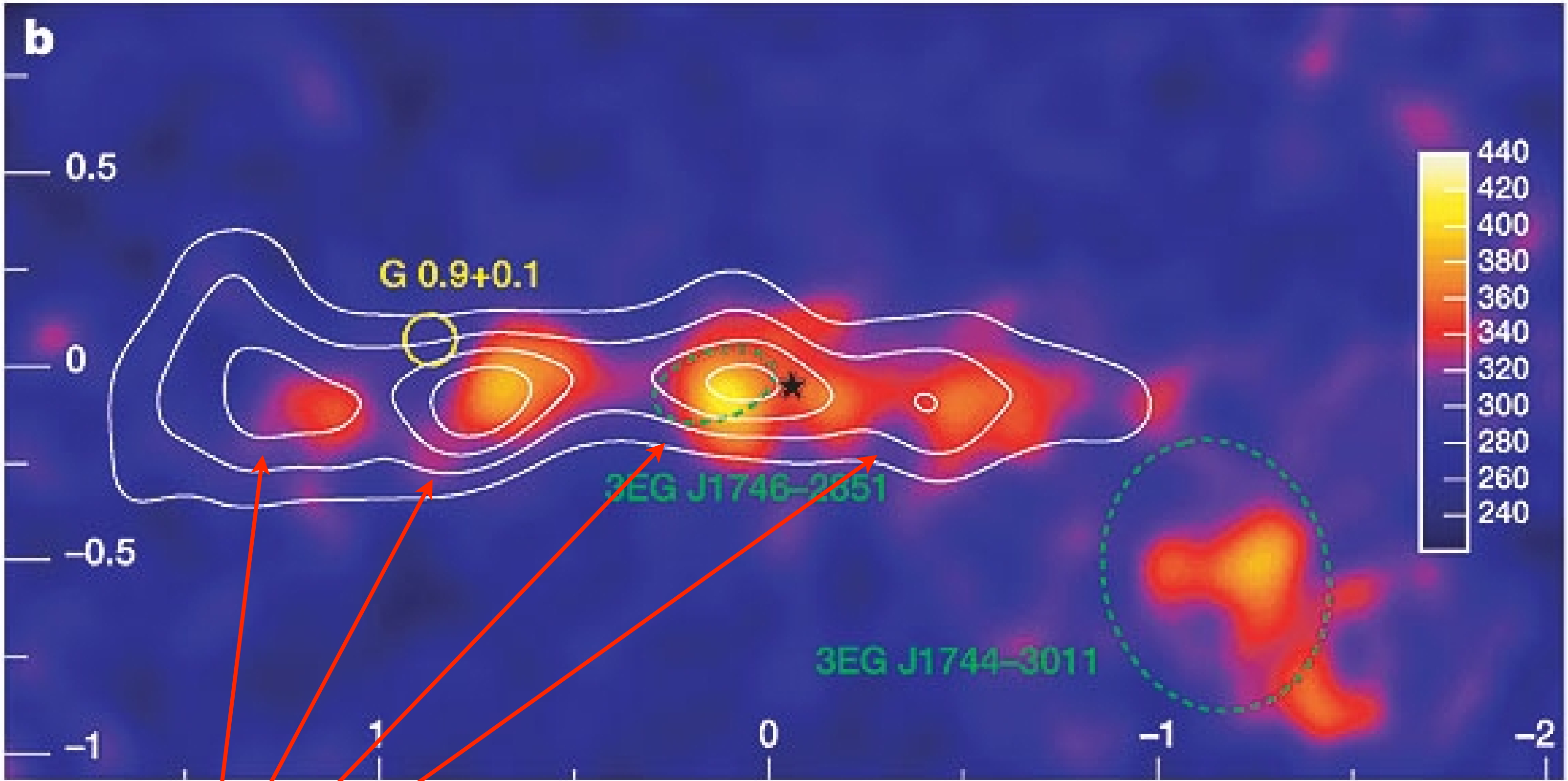

mass of the clouds
measured from
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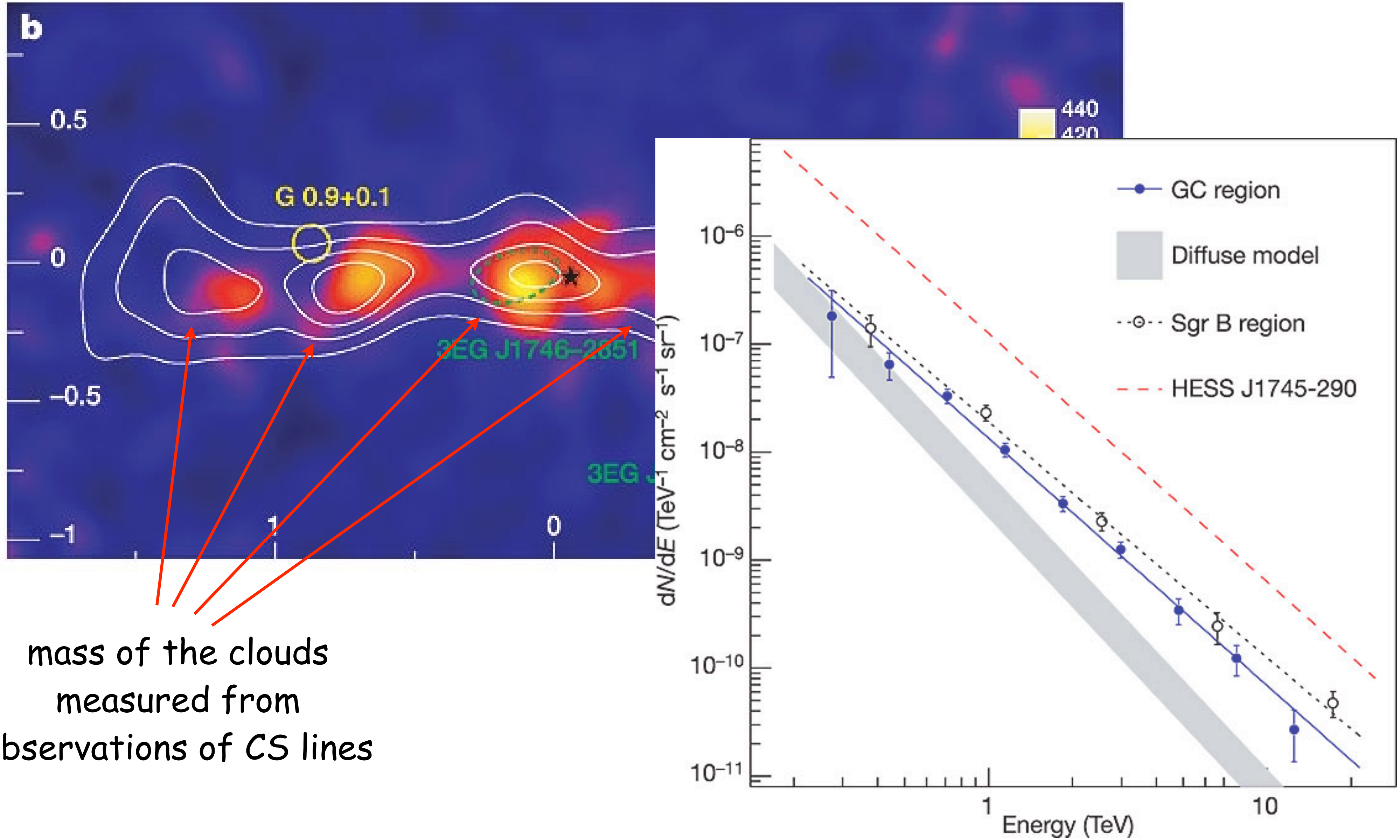
HESS collaboration, 2006



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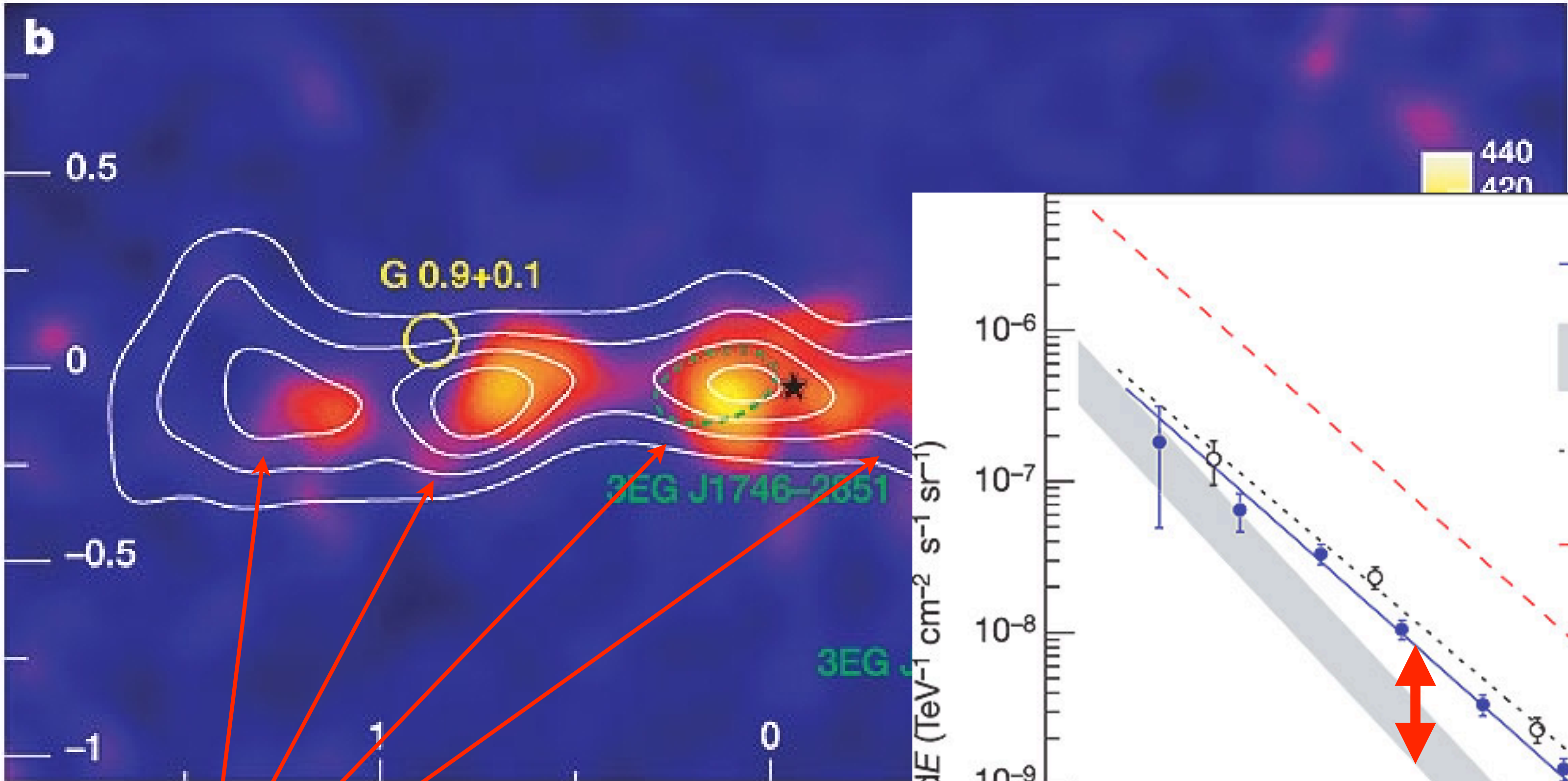
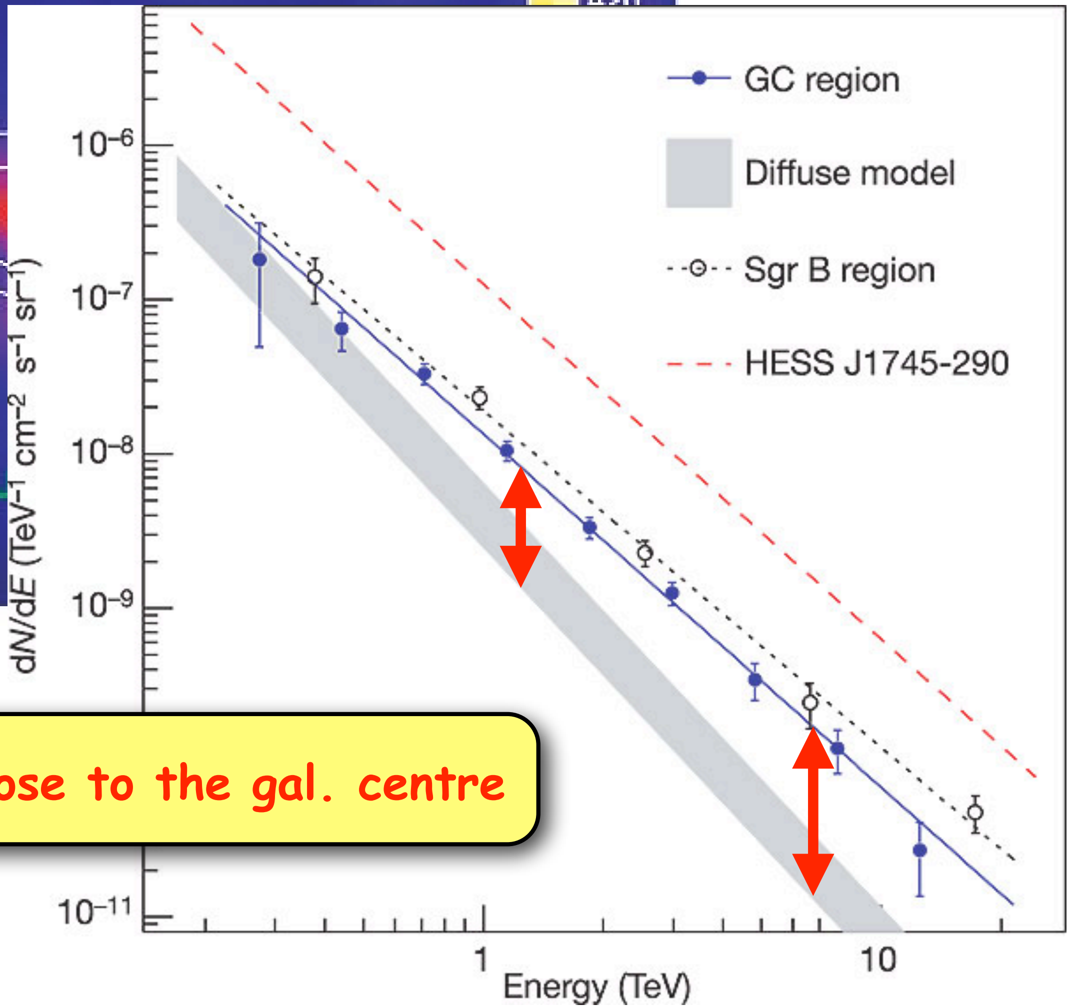




mass of the clouds measured from observations of CS lines

CR excess close to the gal. centre

Detectability at TeV energies: the role of CTA

Gamma-ray flux from the cloud @1TeV

$$2 \times 10^{-13}\, \delta\, \frac{M_5}{d_{kpc}^2}\ TeV/cm^2/s\ >\ 10^{-14} \left(\frac{\epsilon_{CTA}}{0.1}\right) \left(\frac{\theta}{0.1^\circ}\right)\ TeV/cm^2/s$$

flux from a passive cloud

enhancement with respect to passive cloud

mass and distance of the cloud

Gabici, 2008

Detectability at TeV energies: the role of CTA

Sensitivity of CTA @1TeV

$$2 \times 10^{-13}\ \delta\ \frac{M_5}{d_{kpc}^2}\ TeV/cm^2/s\ >\ 10^{-14}\ \left(\frac{\epsilon_{CTA}}{0.1}\right)\ \left(\frac{\theta}{0.1^\circ}\right)\ TeV/cm^2/s$$

HESS sensitivity divided by 10

how much CTA is better than HESS

angular resolution

Gabici, 2008

Detectability at TeV energies: the role of CTA

Simplifying assumption:

$$2 \times 10^{-13}\ \delta\ \frac{M_5}{d_{kpc}^2}\ TeV/cm^2/s\ >\ 10^{-14}\ \left(\frac{\epsilon_{CTA}}{0.1}\right)\ \left(\frac{\theta}{0.1^\circ}\right)\ TeV/cm^2/s$$

all the clouds have the same density (~ 100 cm^{-3}): $\theta \approx 1^\circ\ \frac{M_5^{1/3}}{d_{kpc}}$

Gabici, 2008

Detectability at TeV energies: the role of CTA

Detectability condition:

$$d_{kpc} < \ 2 \ \delta \ M_5^{2/3}$$

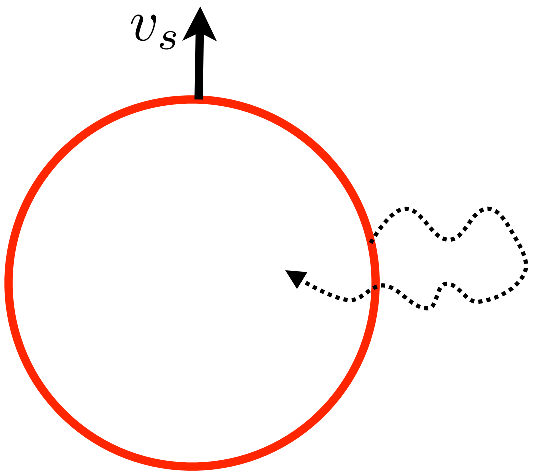
- **HESS** cannot detect passive clouds
- **CTA** will be able to detect local passive clouds (~ kpc distance scale)
- **CTA (HESS)** will probe the Cosmic Ray pressure in regions of the Galaxy

where $\delta \gg 1$ ($\delta \gg 10$)

Gabici, 2008

(2) Illuminated molecular clouds (MC/SNR associations)

How to use Molecular Clouds...

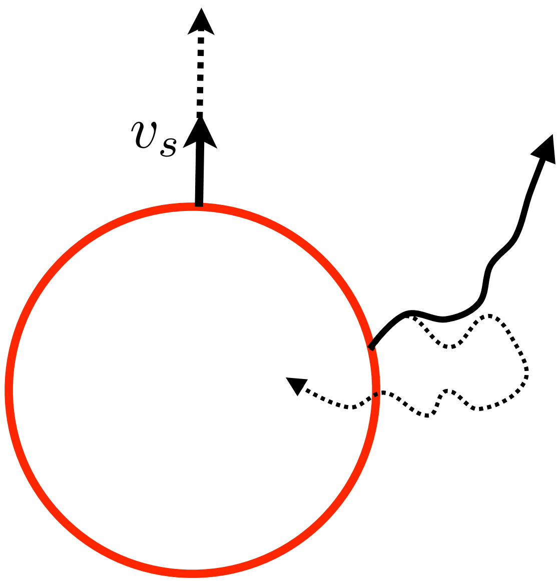


SNRs accelerate CRs

Aharonian&Atoyan 1996, SG&Aharonian, 2007

How to use Molecular Clouds...

CRs “somehow” escape the SNR



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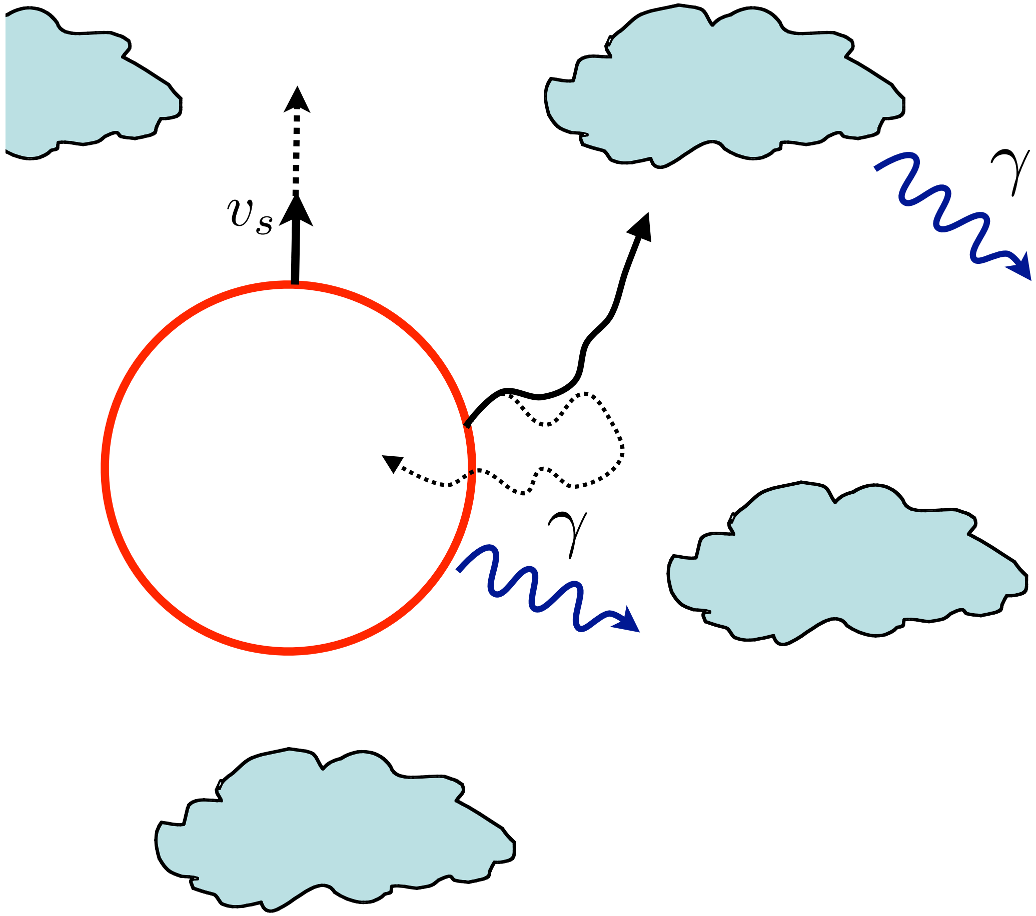
MCs enhance the gamma ray emission



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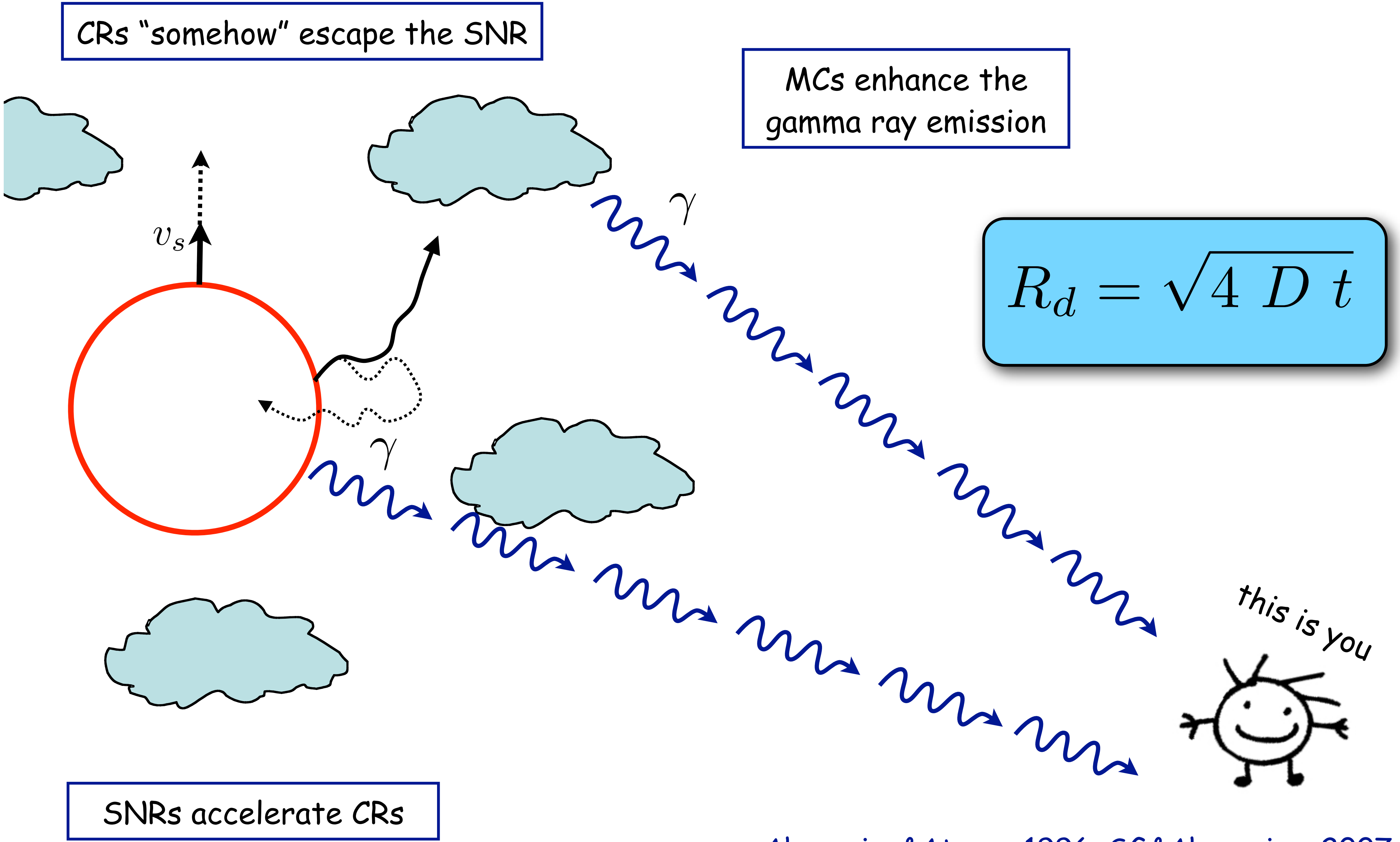

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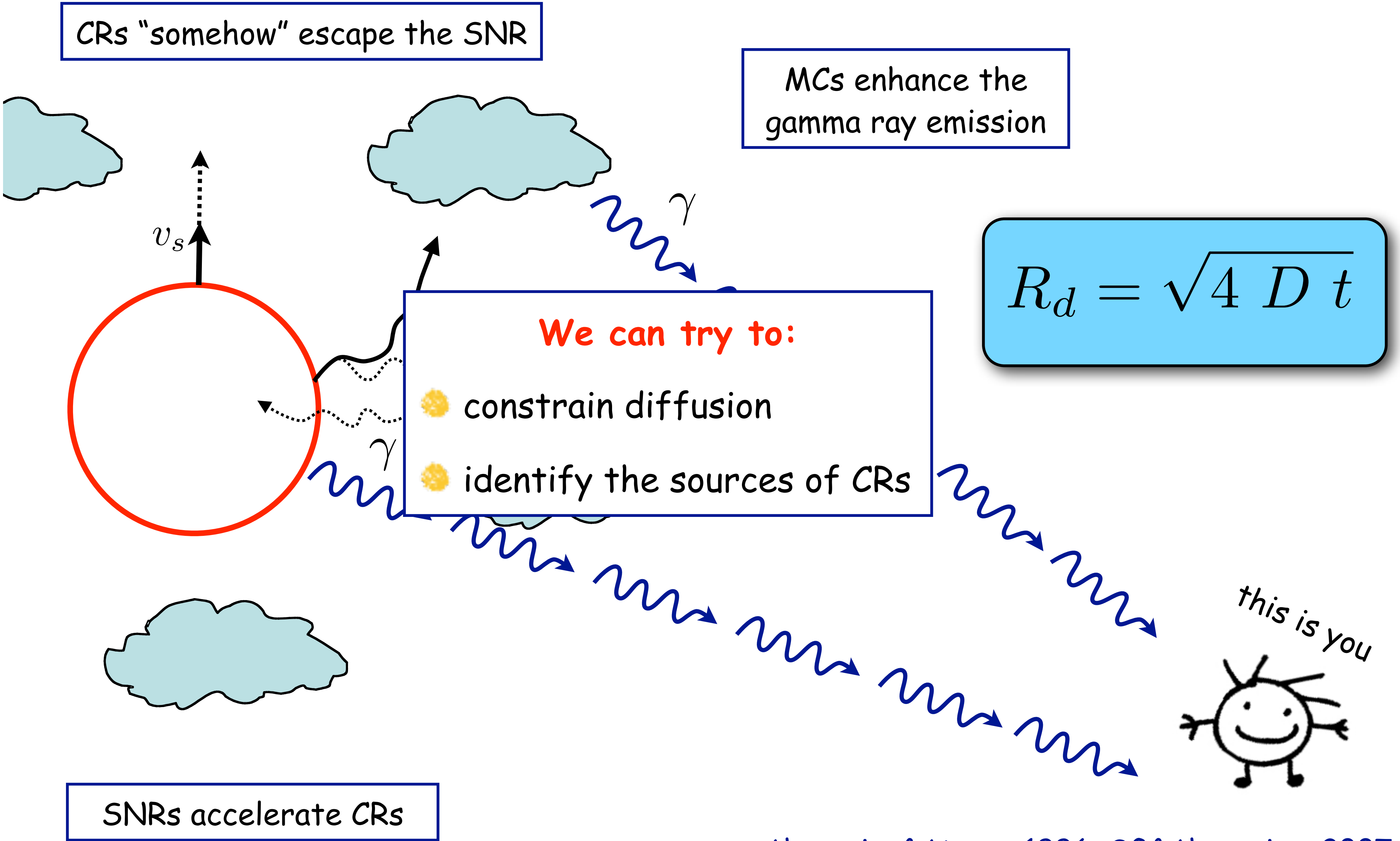

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The diffusion of CRs

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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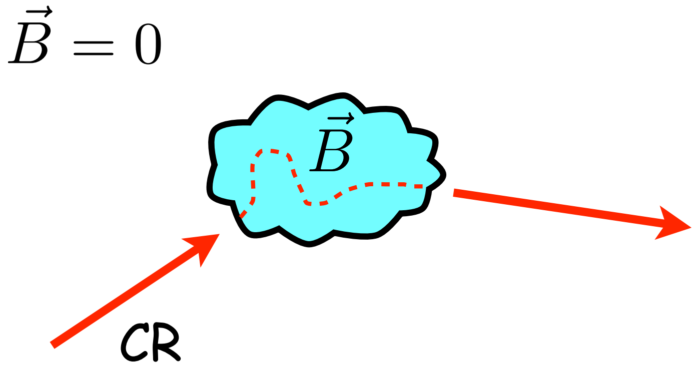
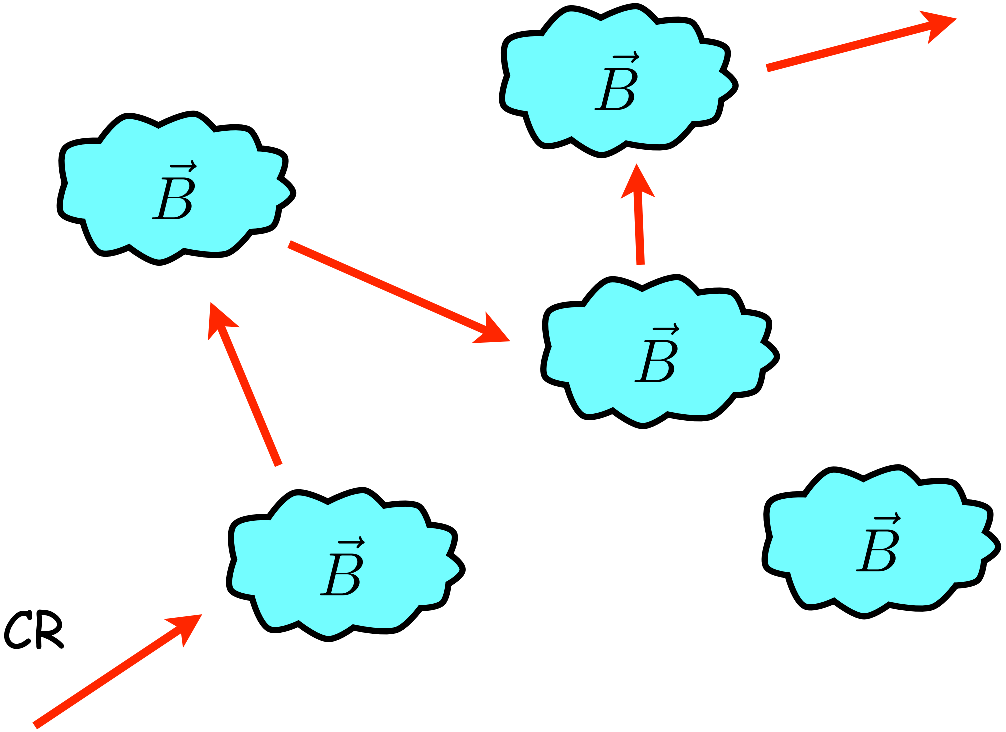
(Oversimplified picture)

magnetized cloudlets in an unmagnetized background



the particle energy is unchanged (Lorentz force)

The diffusion of CRs



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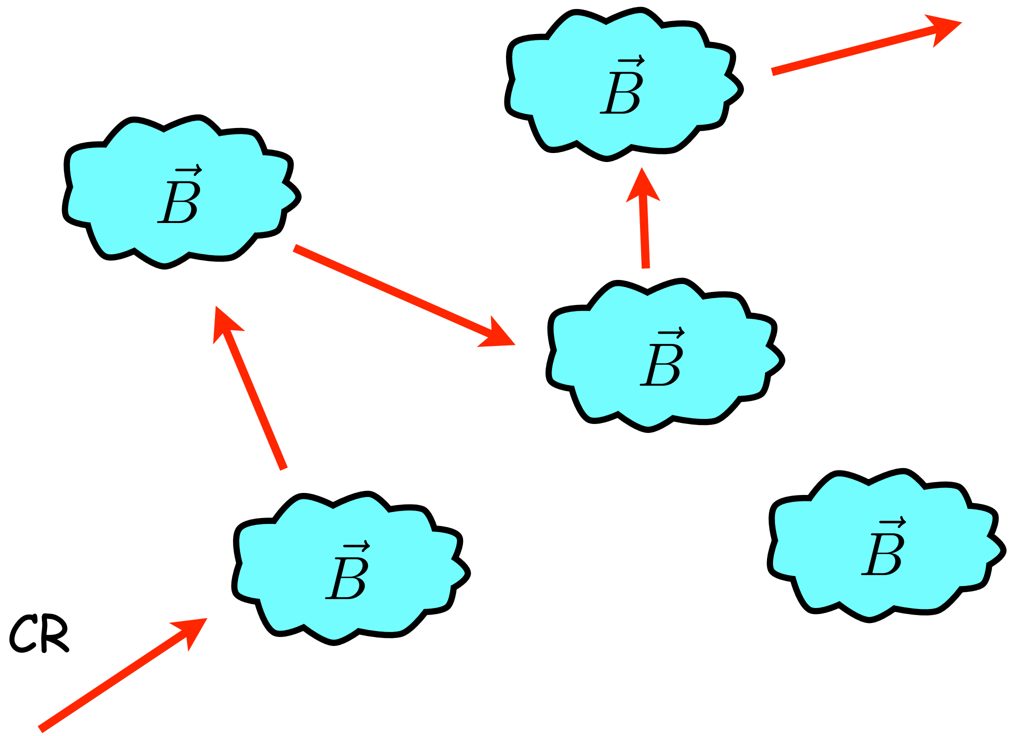
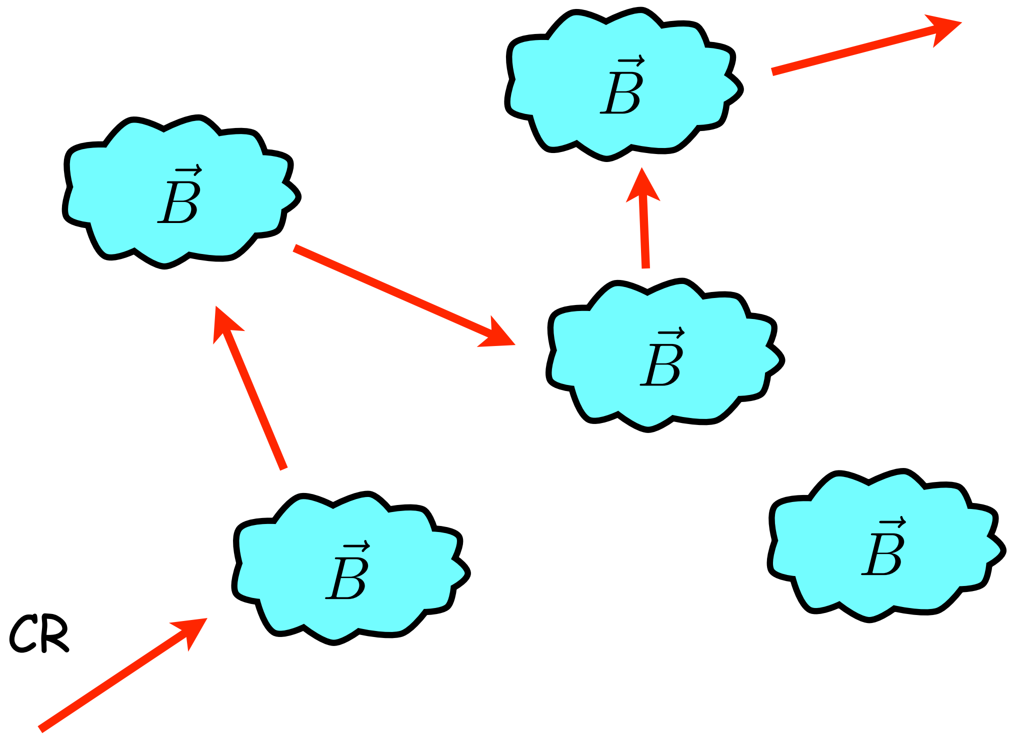


λ -> mean free path

The diffusion of CRs



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

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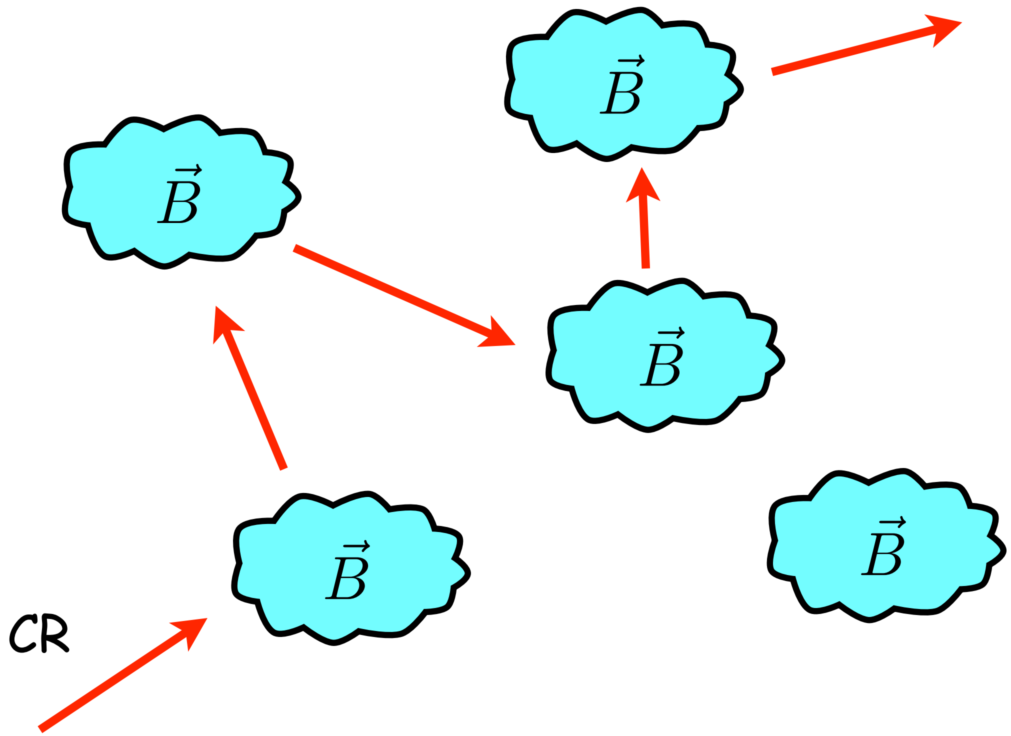

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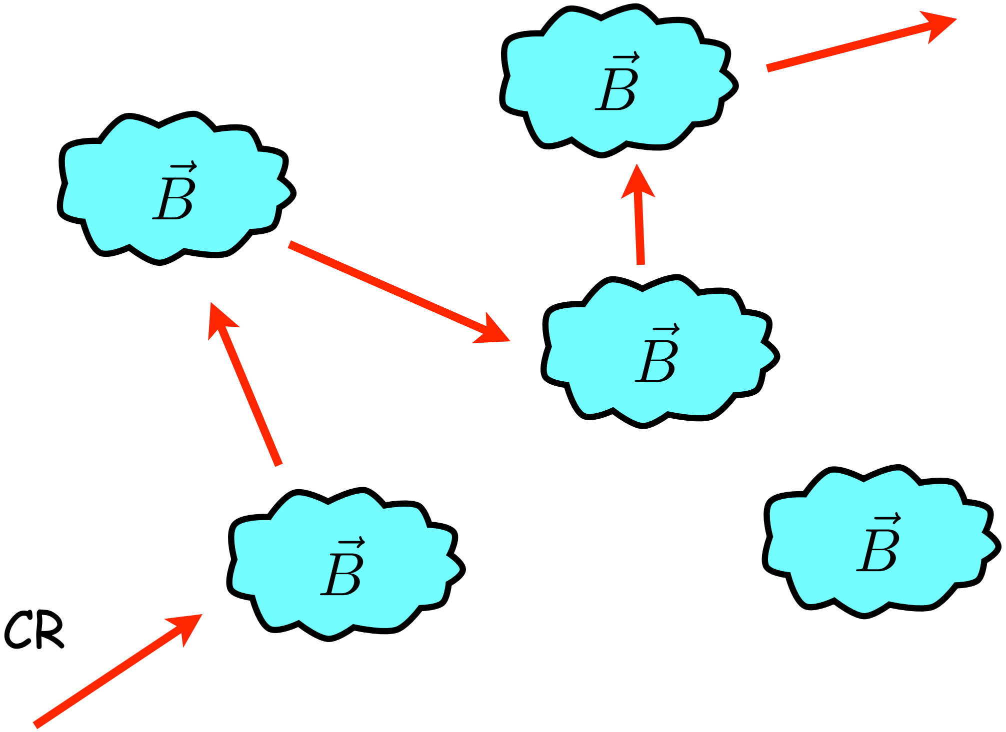

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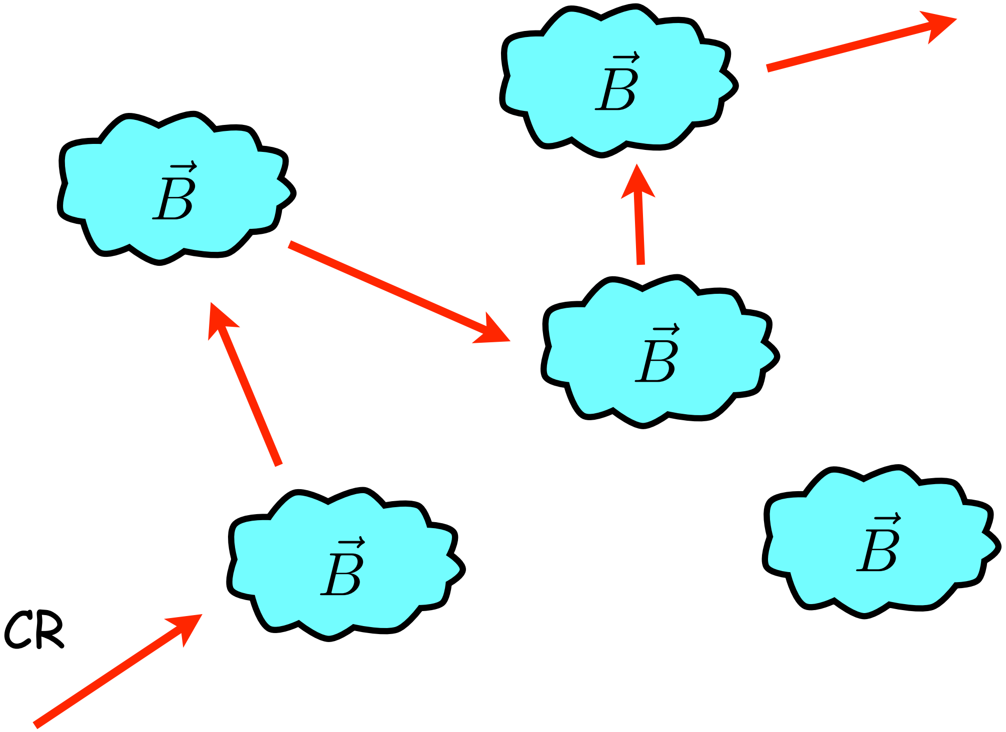
random walk

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

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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

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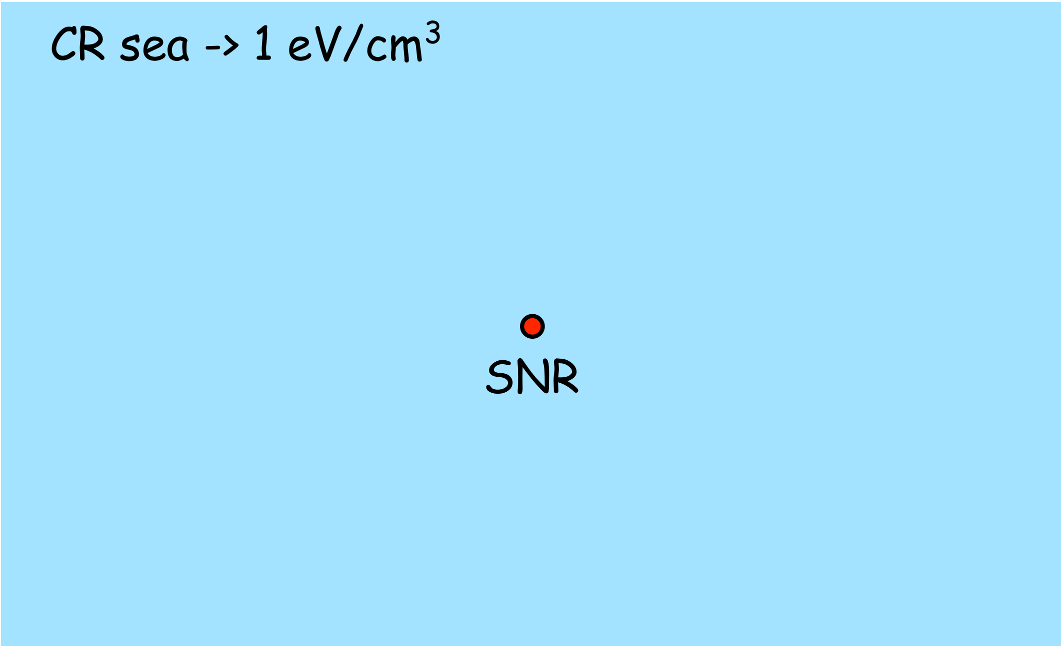
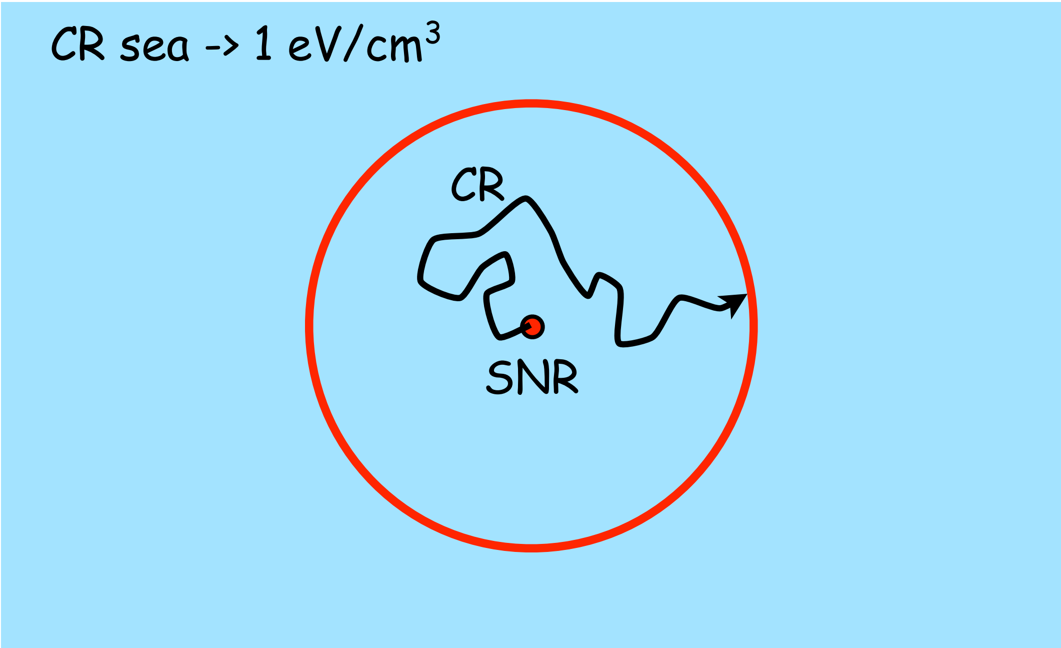
Energy dependent -> $D \propto E^{0.6}$

Implications of the SNR hypothesis



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

Implications of the SNR hypothesis



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

volume affected by CRs from the SNR

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

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

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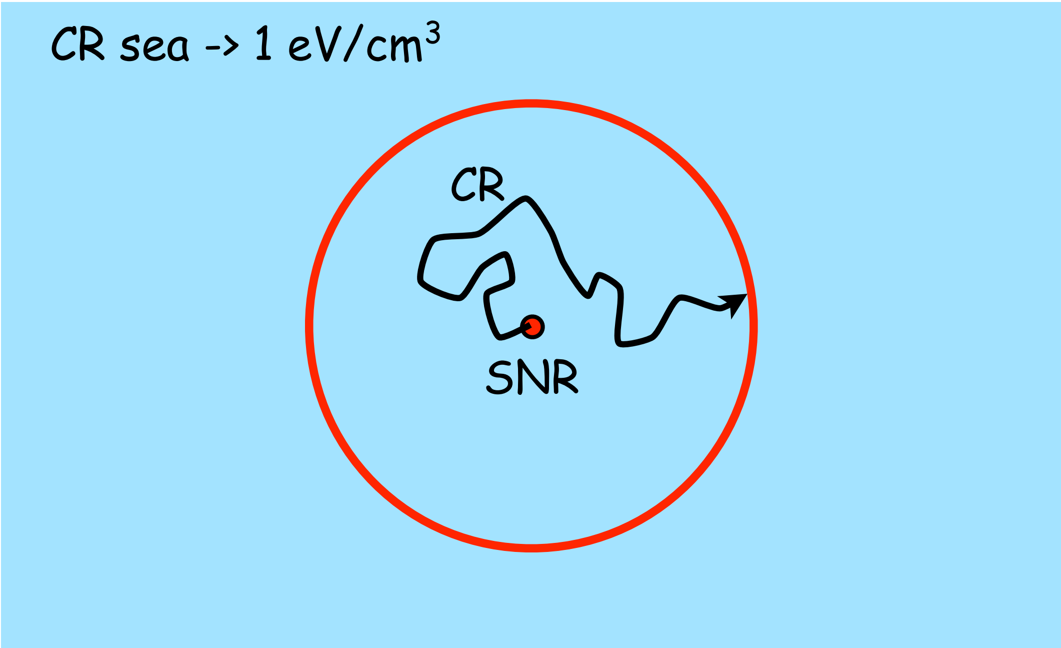

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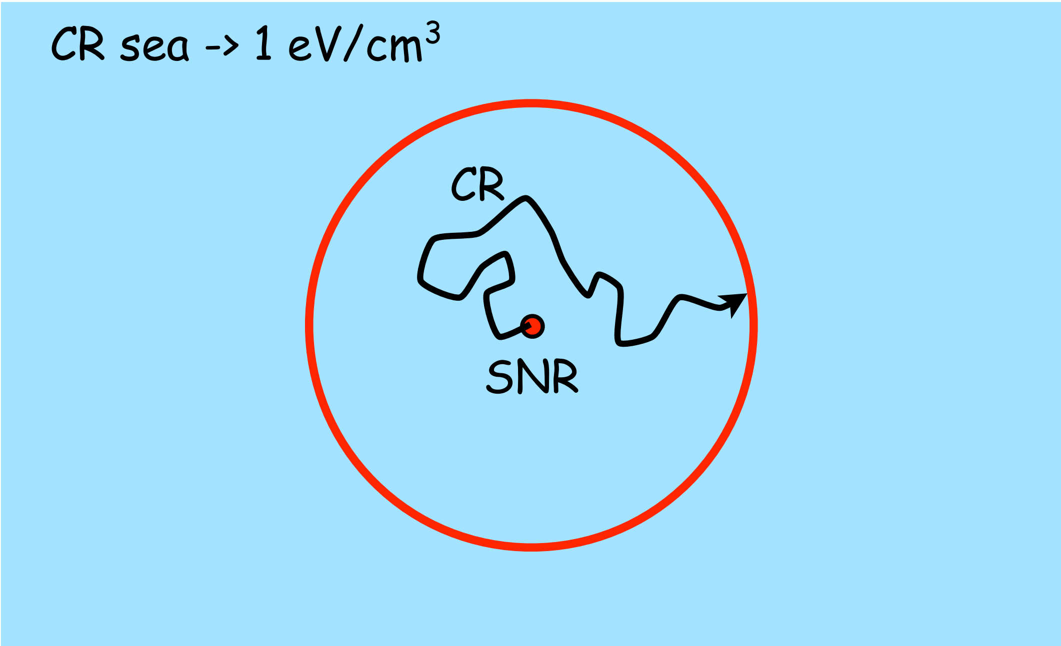
Implications of the SNR hypothesis

Very rough!



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Montmerle's SNOBs

adapted from Montmerle, 1979 ; Casse & Paul, 1980

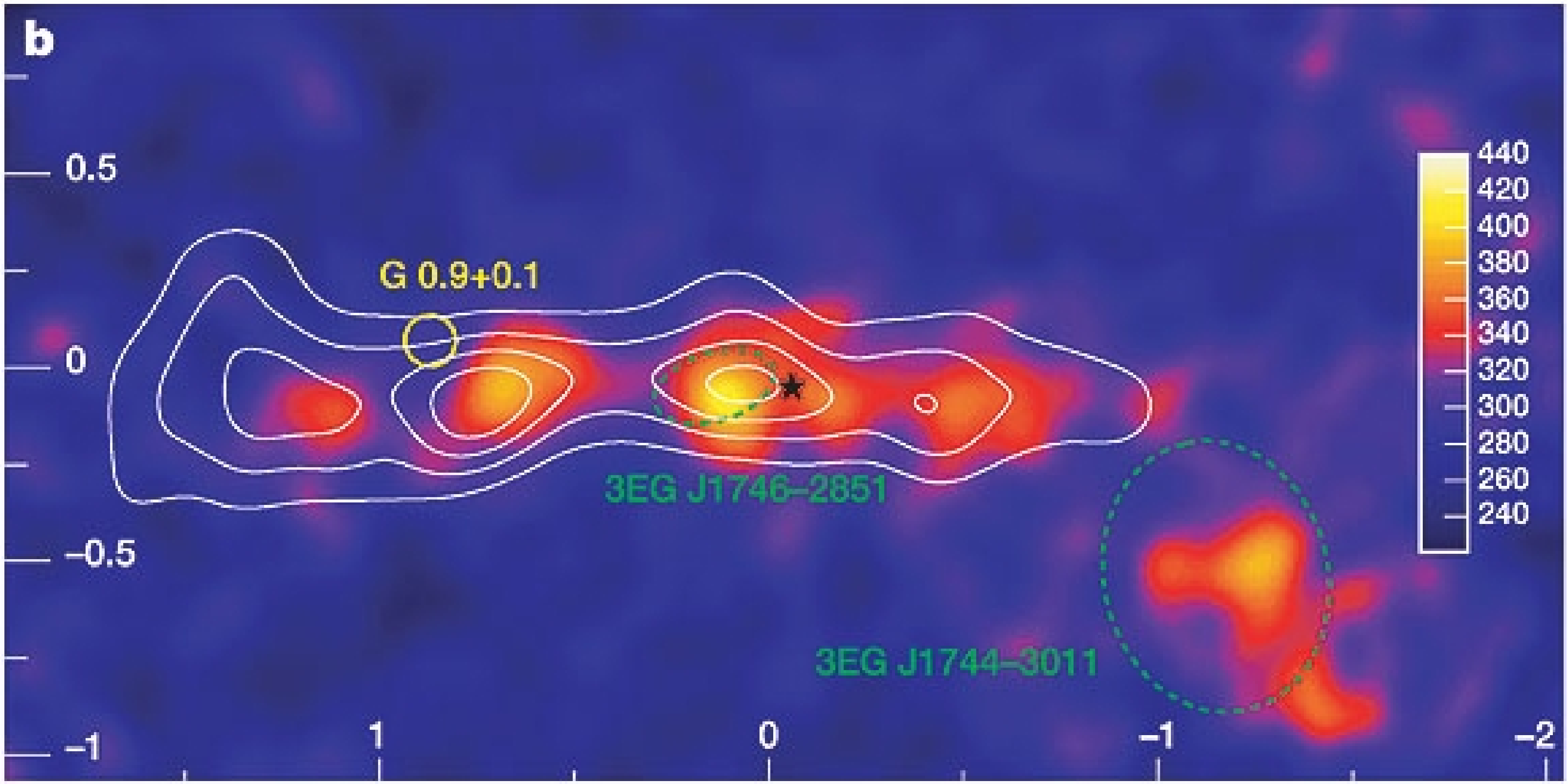
Super Novae-OB stars associations

- **Massive (OB) stars** form in dense regions -> **molecular cloud complexes**
- **OB stars** evolve rapidly and eventually explode forming **SNRs**
- **SNR** shocks accelerate ***COSMIC RAYS***
- **CRs** escape from their sources and diffuse away in the DENSE circumstellar material -> **molecular cloud complex**
- ...and produce there ***gamma rays!***

An association between cosmic ray sources and molecular cloud is expected

Example: the galactic centre ridge

The galactic centre ridge as seen by HESS

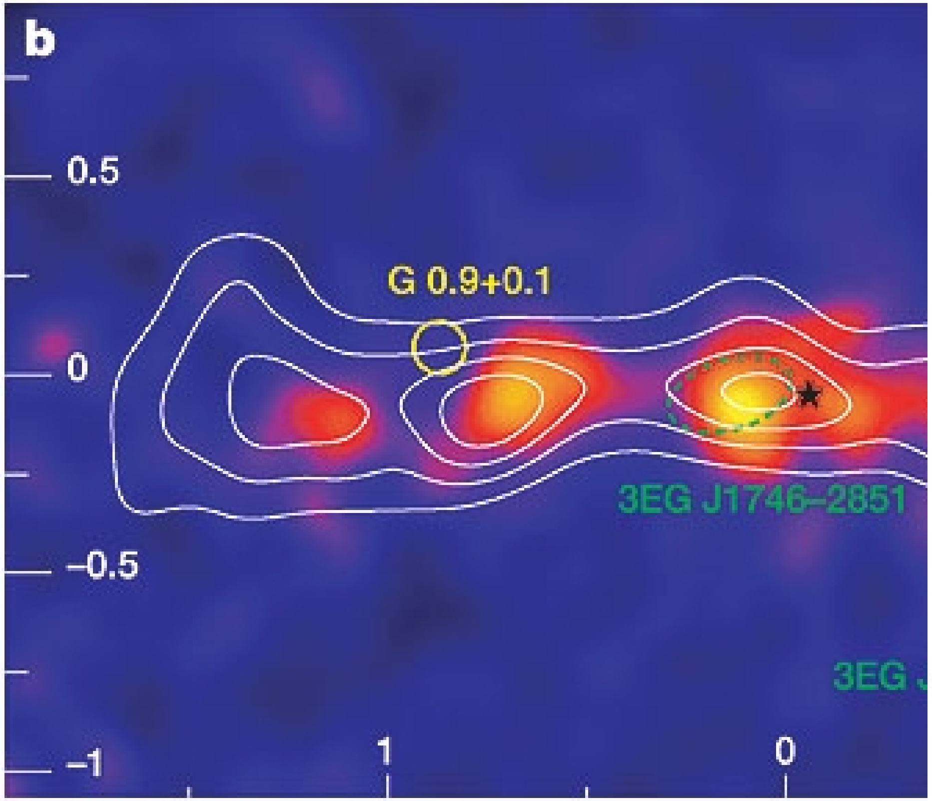


HESS collaboration, 2006

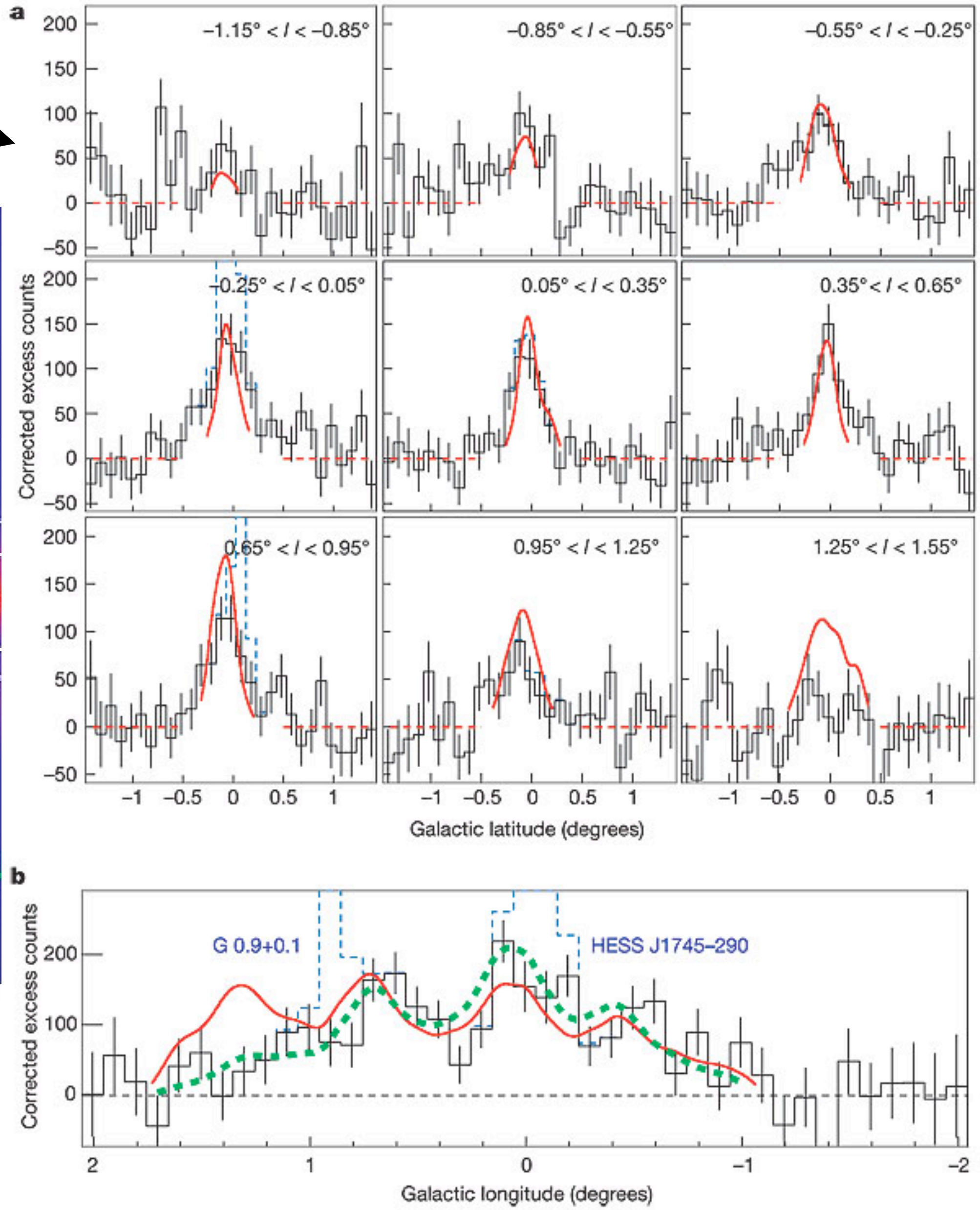
Example: the galactic centre ridge

The galactic centre ridge as seen by HESS

good match between CS lines and TeV emission



HESS collaboration, 2006



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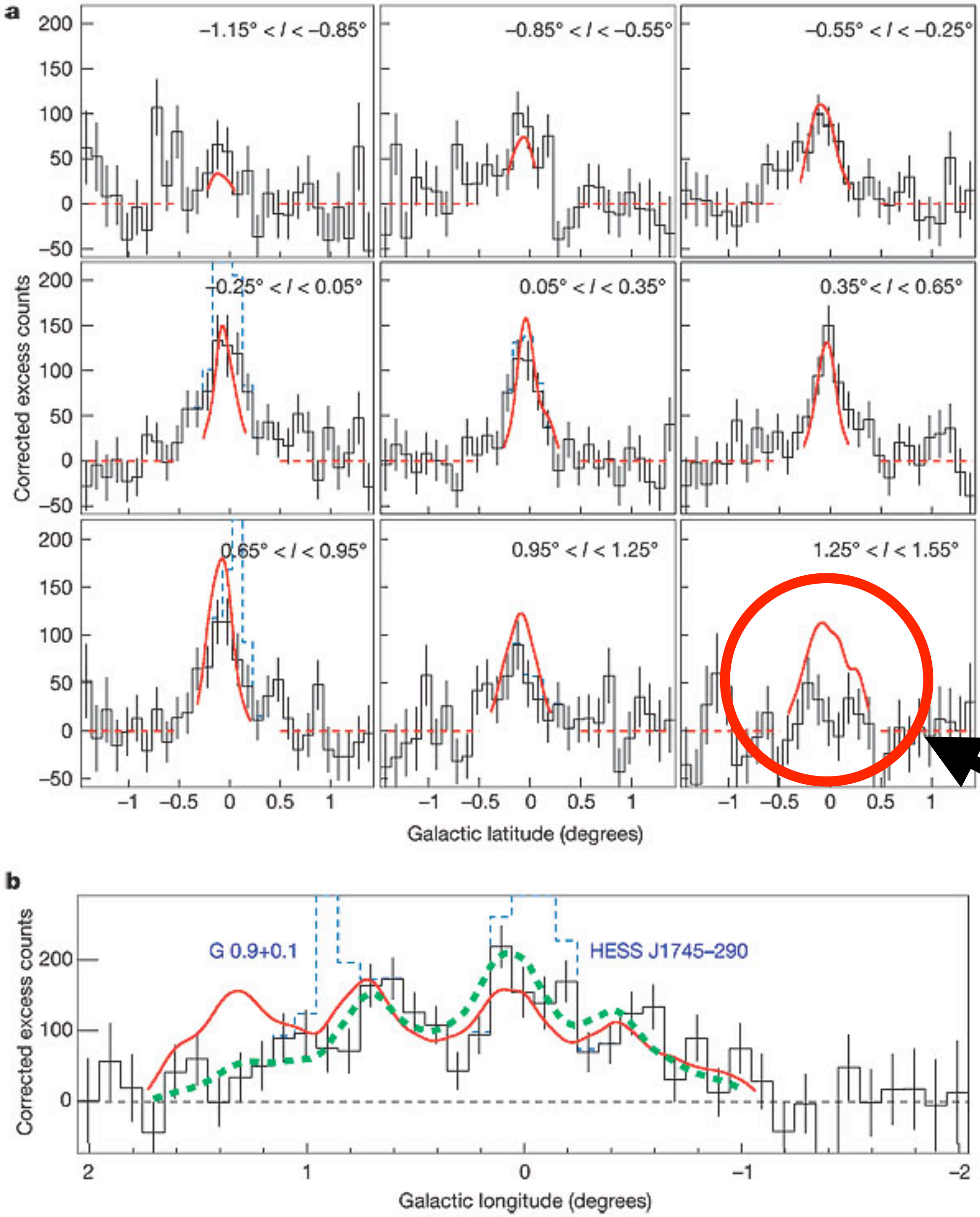
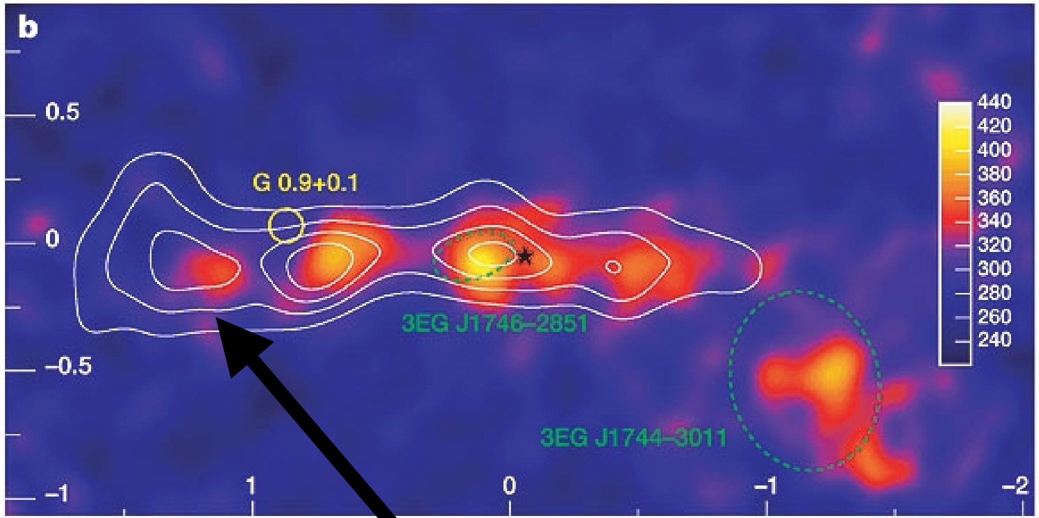
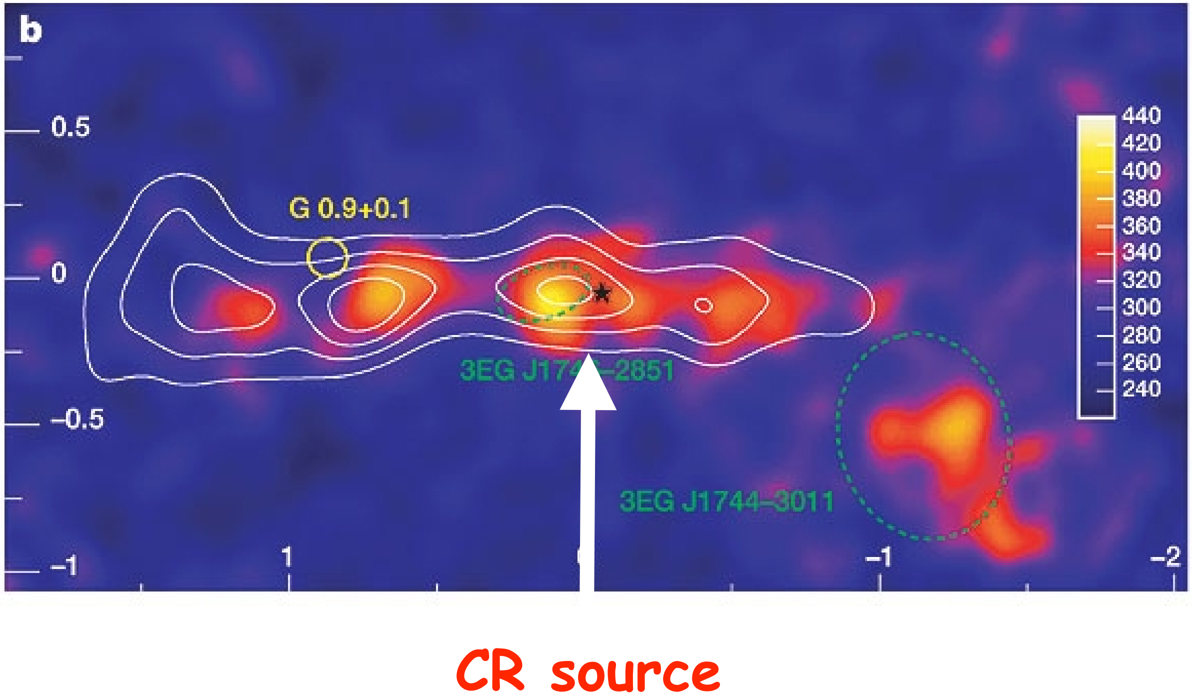




the correlation between gamma ray intensity and gas density is worse for the cloud which is the farthest away from the galactic centre

HESS collaboration, 2006

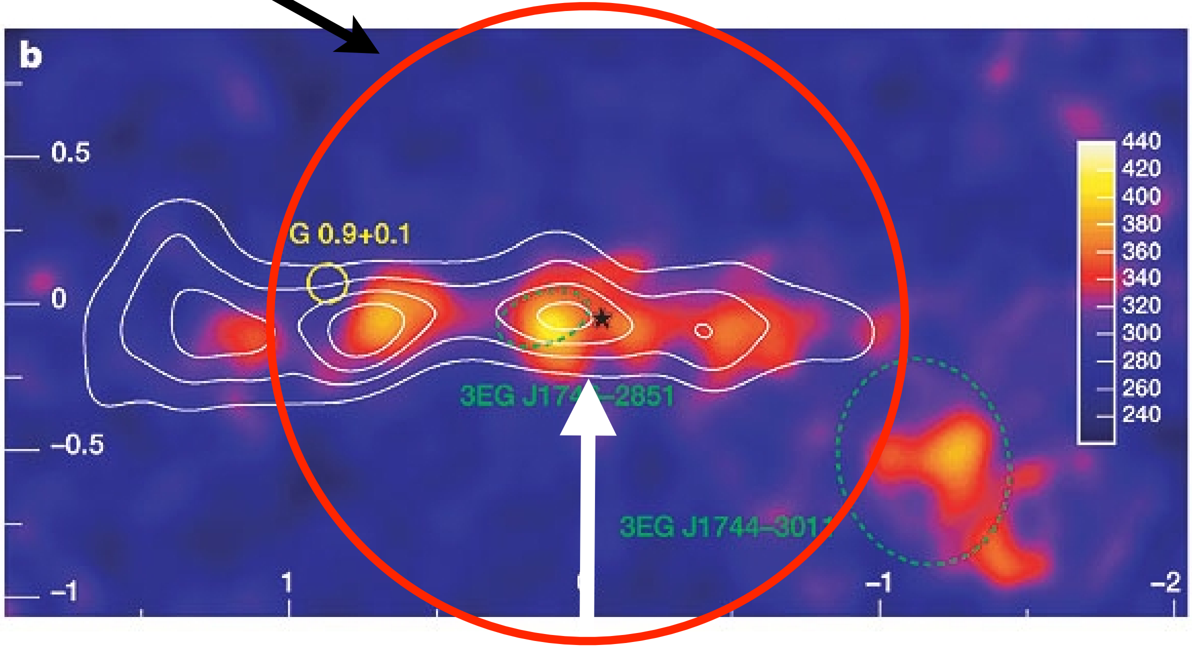
Example: the galactic centre ridge



HESS collaboration, 2006

Example: the galactic centre ridge

after a time t_{diff} CRs fill a volume like this



CR source

HESS collaboration, 2006

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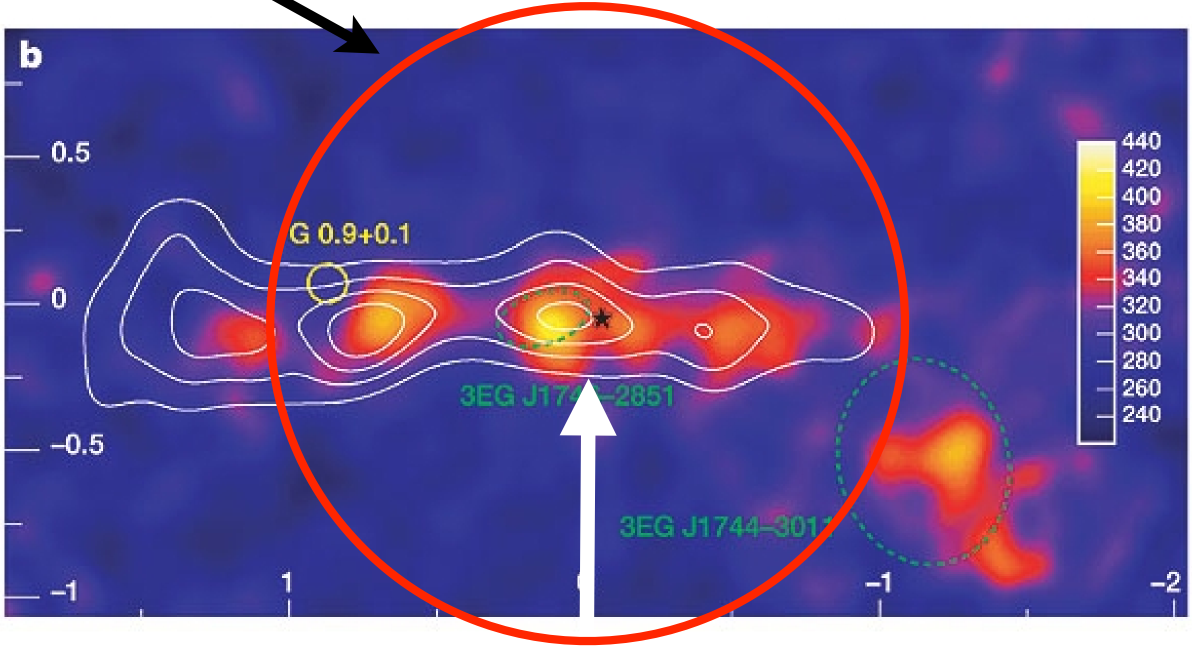


CR source

$$t_{diff} \approx \frac{l^2}{D}$$

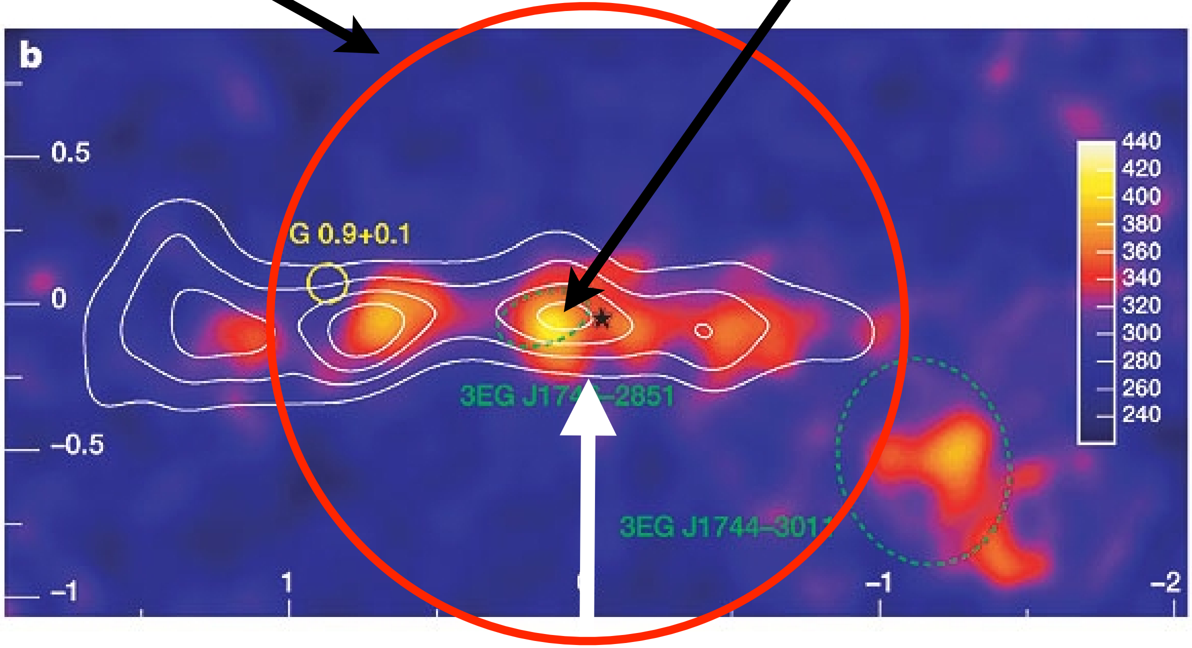
if we know the age of the source we can estimate the diffusion coefficient!

HESS collaboration, 2006

Example: the galactic centre ridge

after a time t_{diff} CRs fill a volume like this

SNR SgrA East -> t ~ 10^4 yr
(though quite uncertain)



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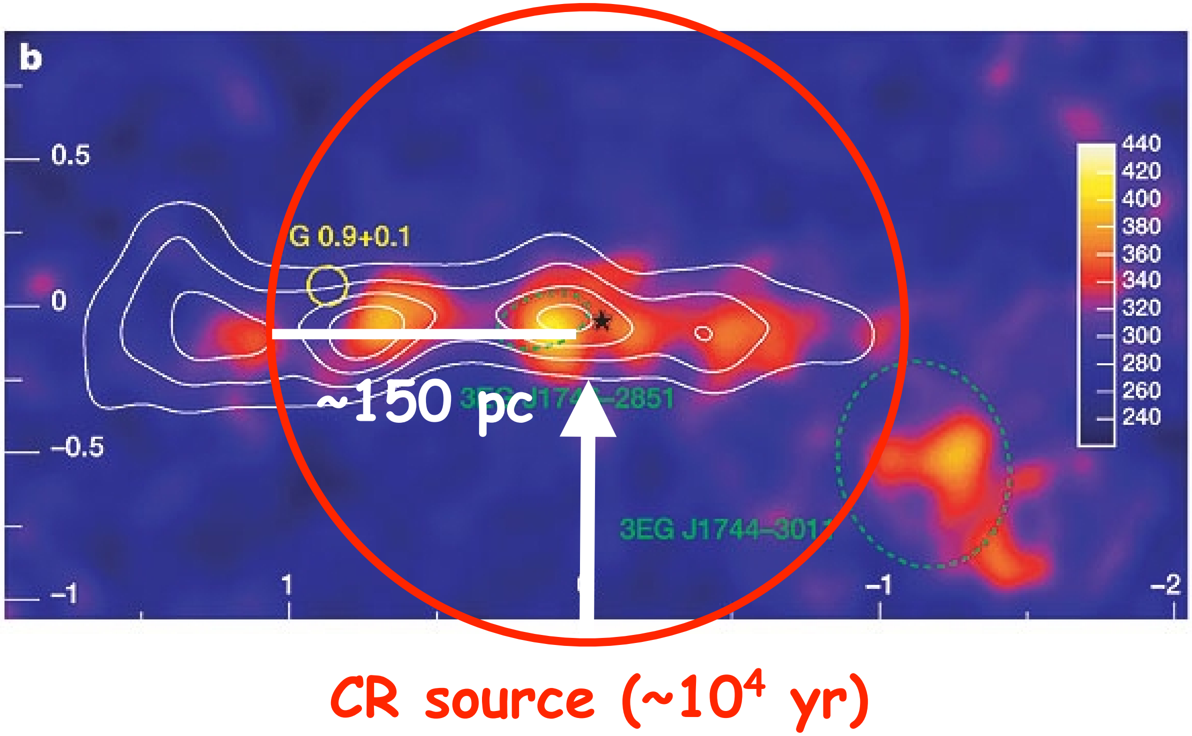

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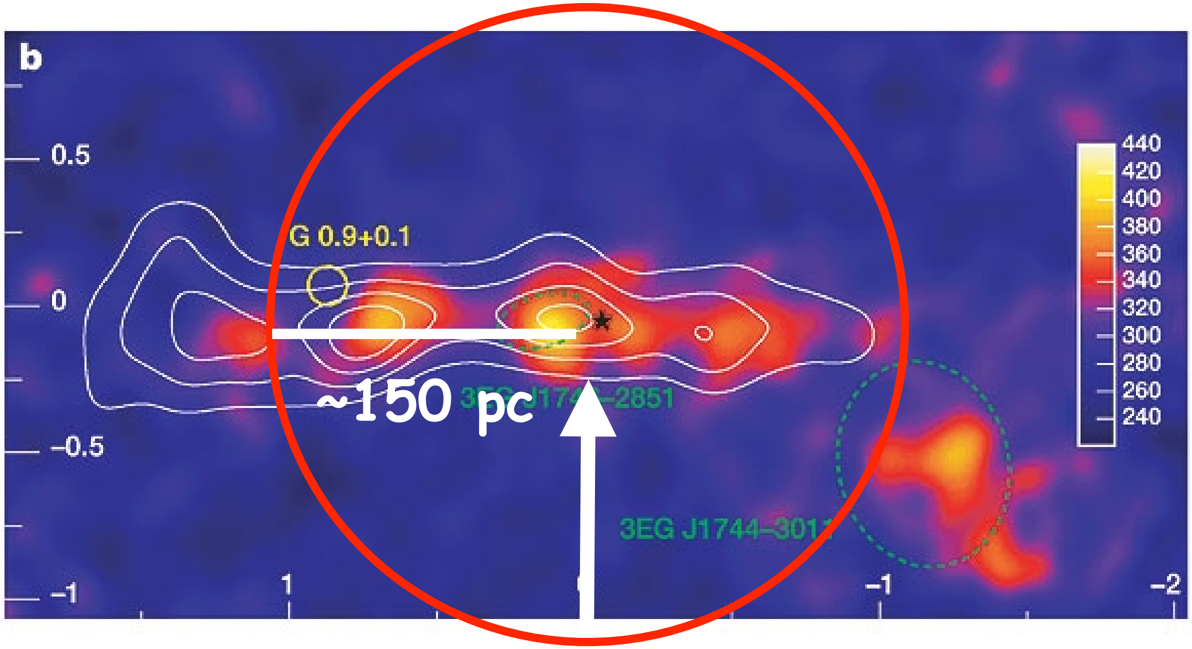


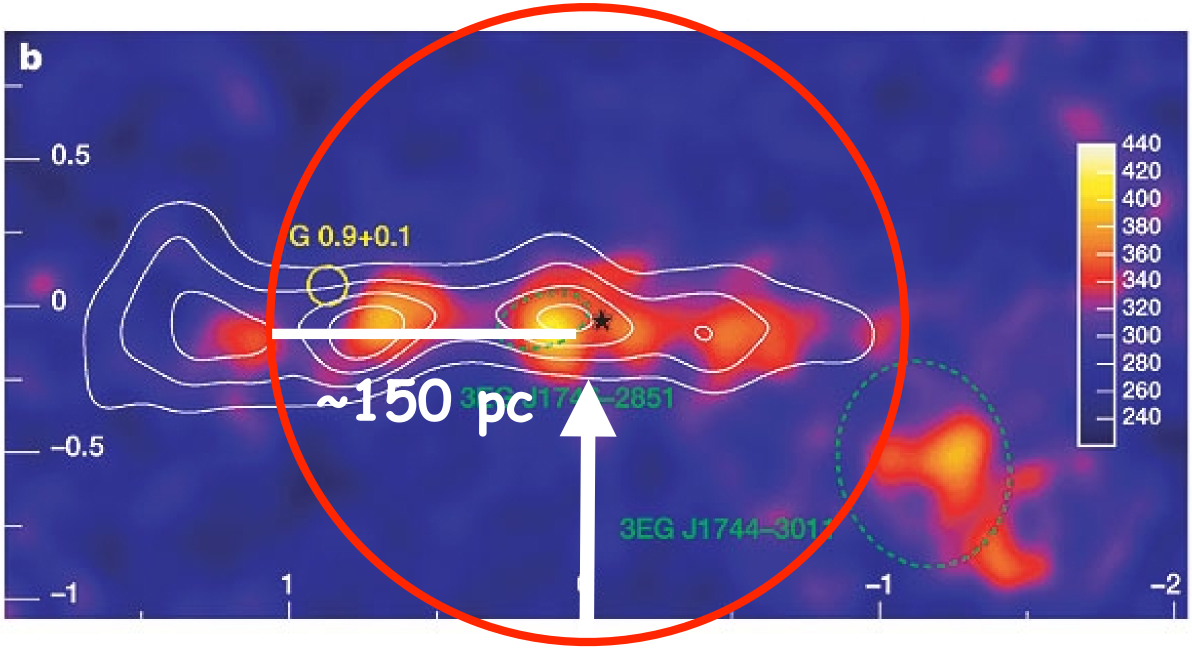
CR source (~10^4 yr)

$$t_{diff} \approx \frac{l^2}{D}$$

$$D \lesssim 7 \times 10^{29} \mathrm{cm}^2/\mathrm{s}$$

not too different from the average diffusion coefficient in the Galaxy

Example: the galactic centre ridge



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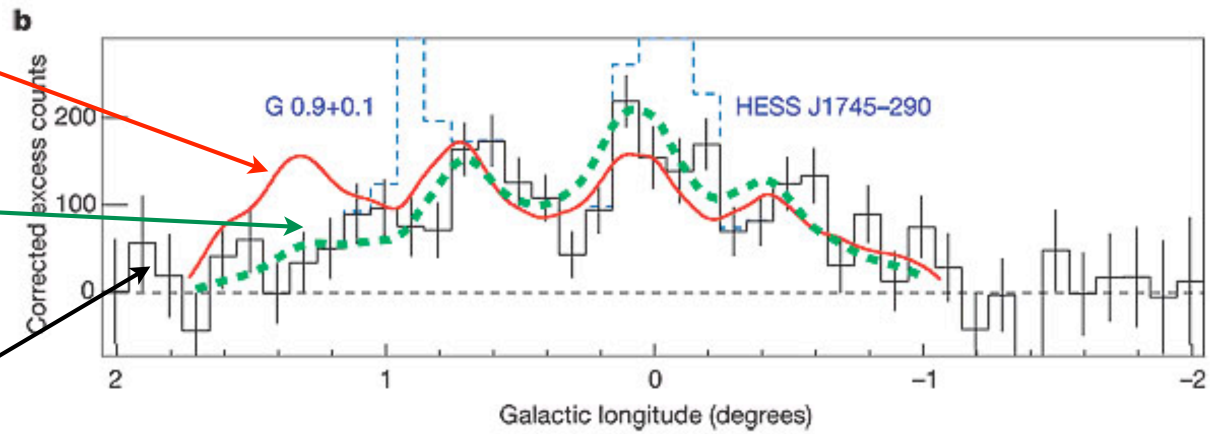
density

predicted gamma rays (diffusion from a source in the Galactic centre)

observed gamma rays



Take-home messages

- Molecular clouds are massive -> lots of gammas expected
- MCs -> massive stars -> SNRs -> CR acceleration&escape -> gamma rays!
- can be used to probe the CR intensity throughout the Galaxy
- and/or to identify the sources of CRs and constrain the diffusion coefficient