Brief overview on (galactic) cosmic rays and their interactions

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APC, Paris

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Overview of the talk -

Cosmic rays: origin and interactions

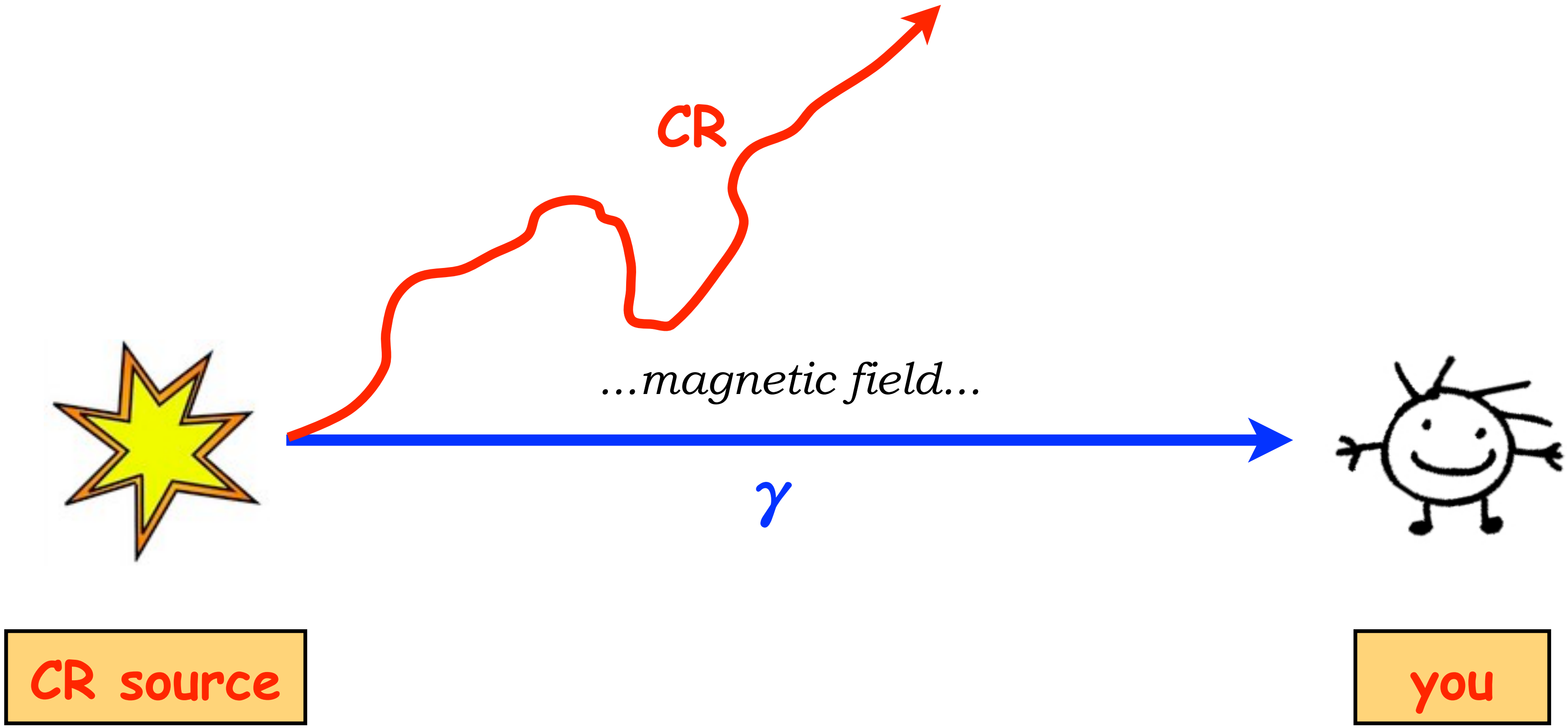
- ☑ Facts on CRs

- ☑ The supernova remnant hypothesis

(see Fabio's talk for a complete review)

- ☑ Interaction of runaway CRs in the ISM

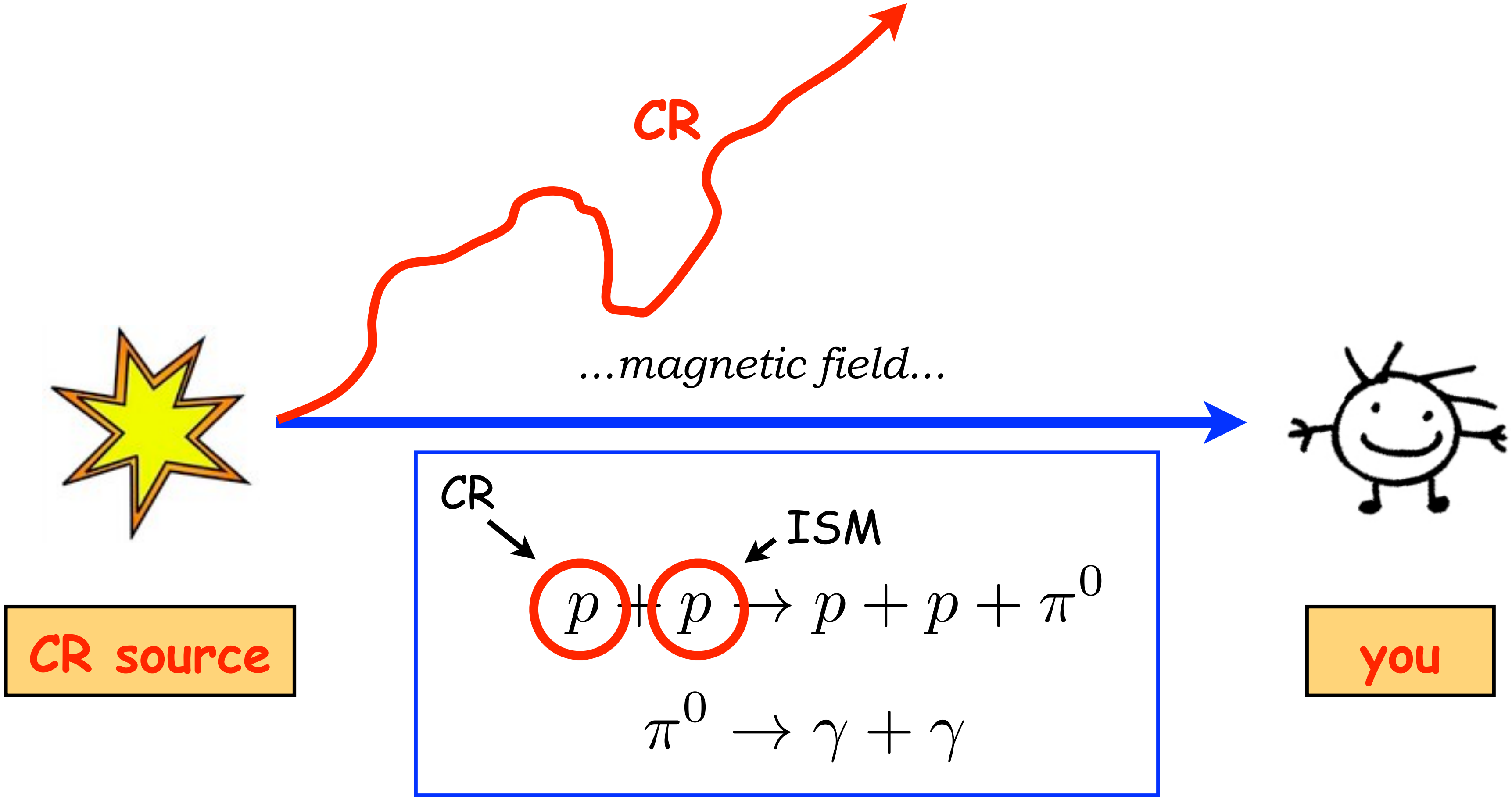
Cosmic ray sources: why is it so difficult?



We cannot do CR Astronomy.

Need for indirect identification of CR sources.

Cosmic ray sources: why is it so difficult?



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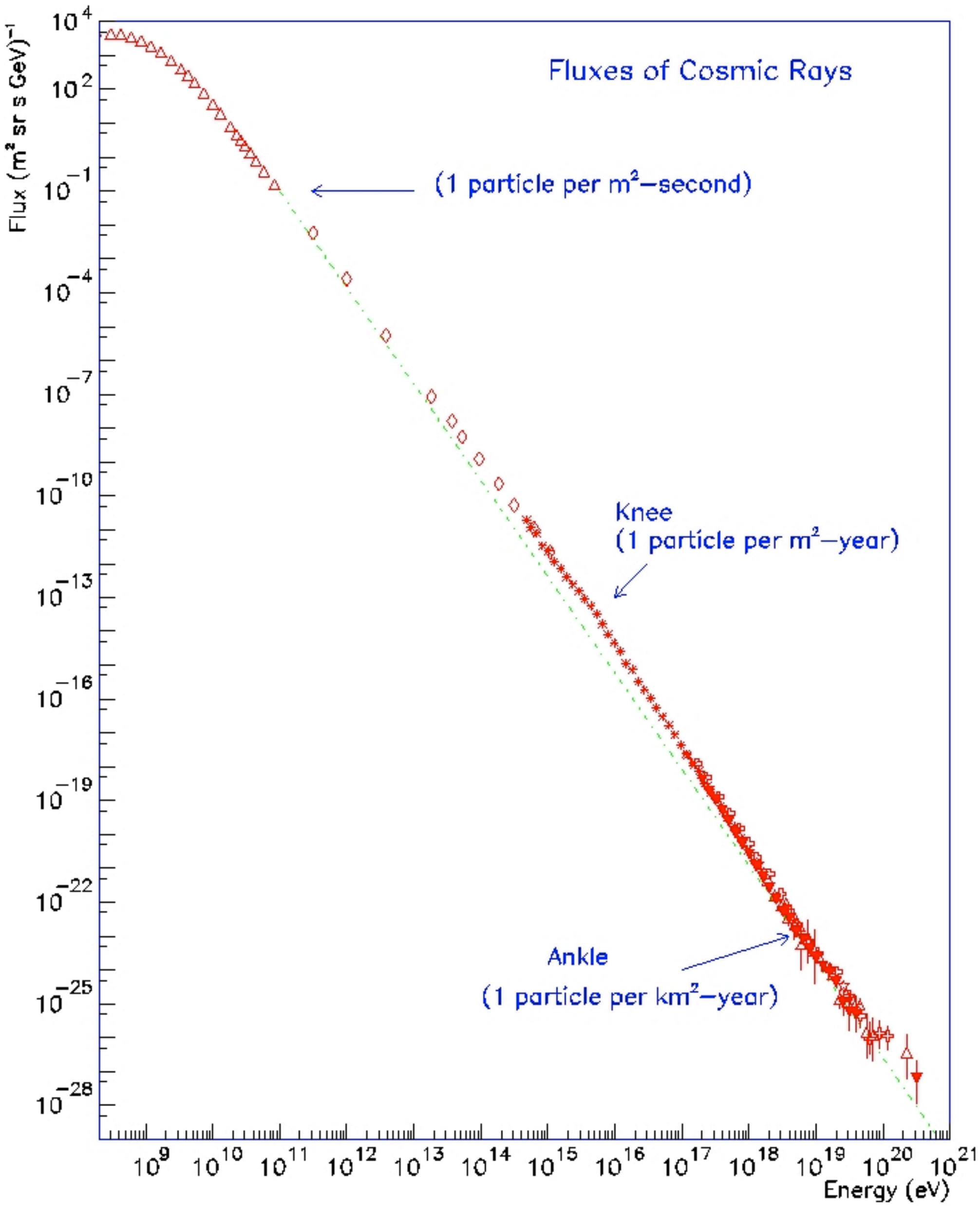
The (local) Cosmic Ray spectrum



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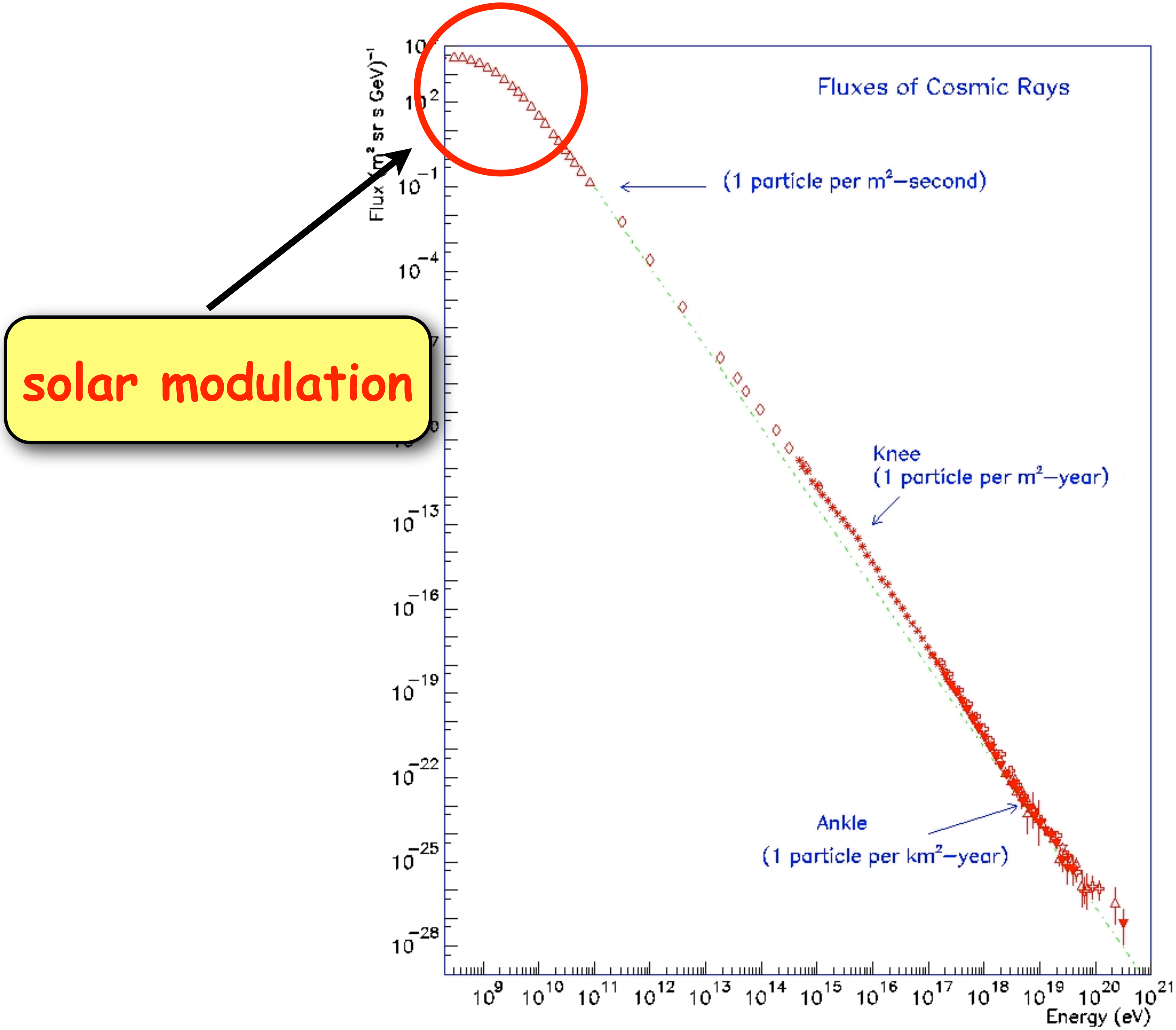

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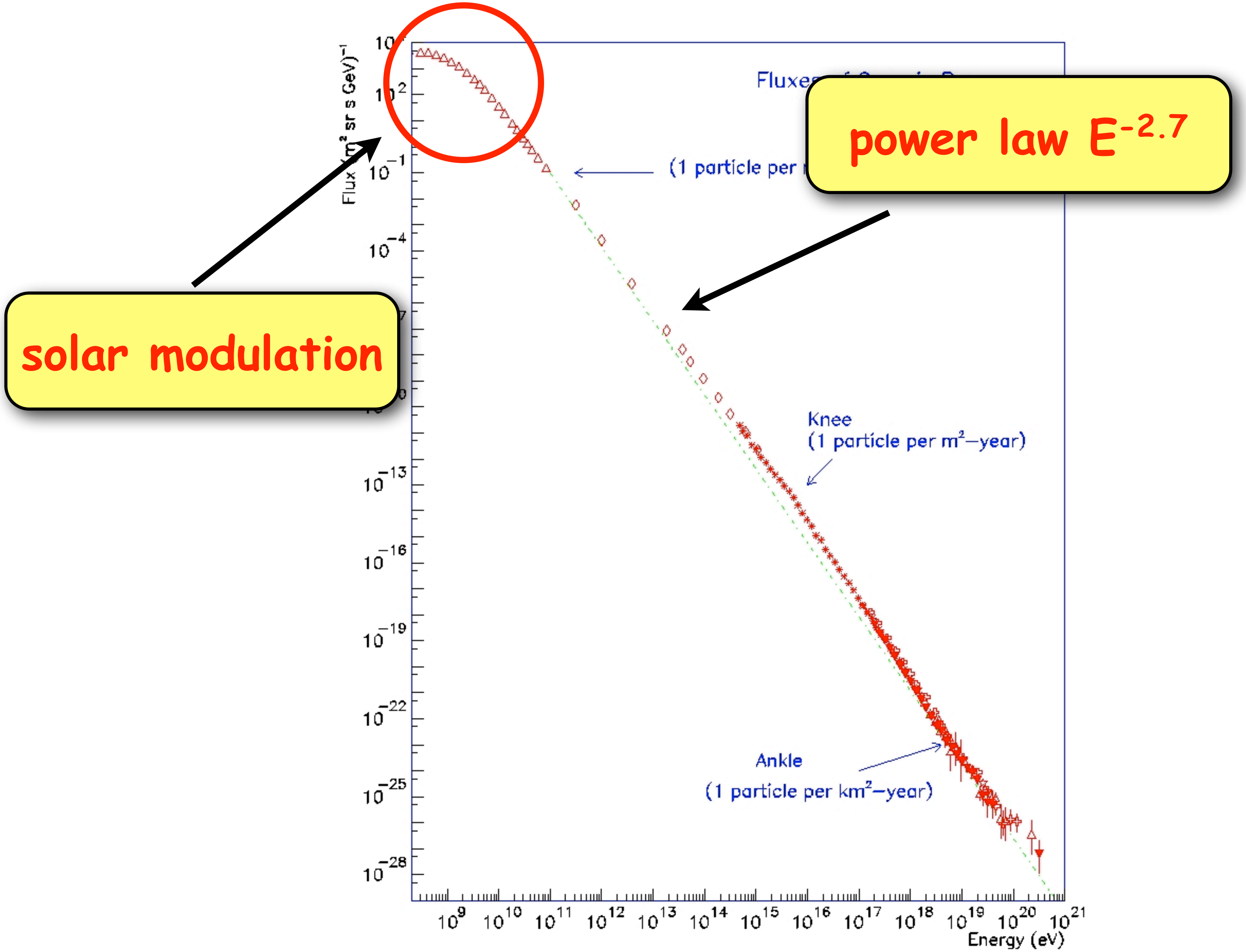

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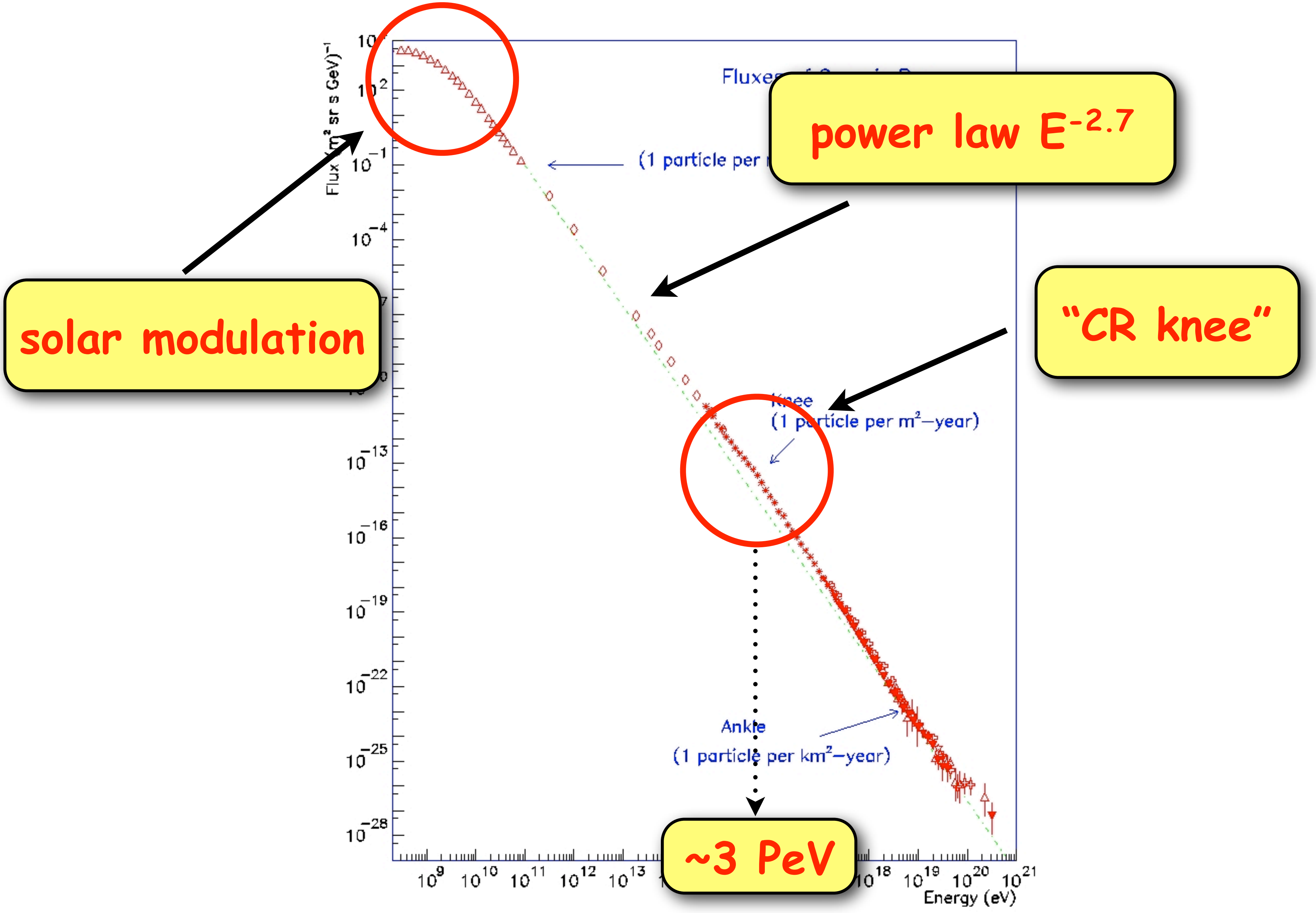

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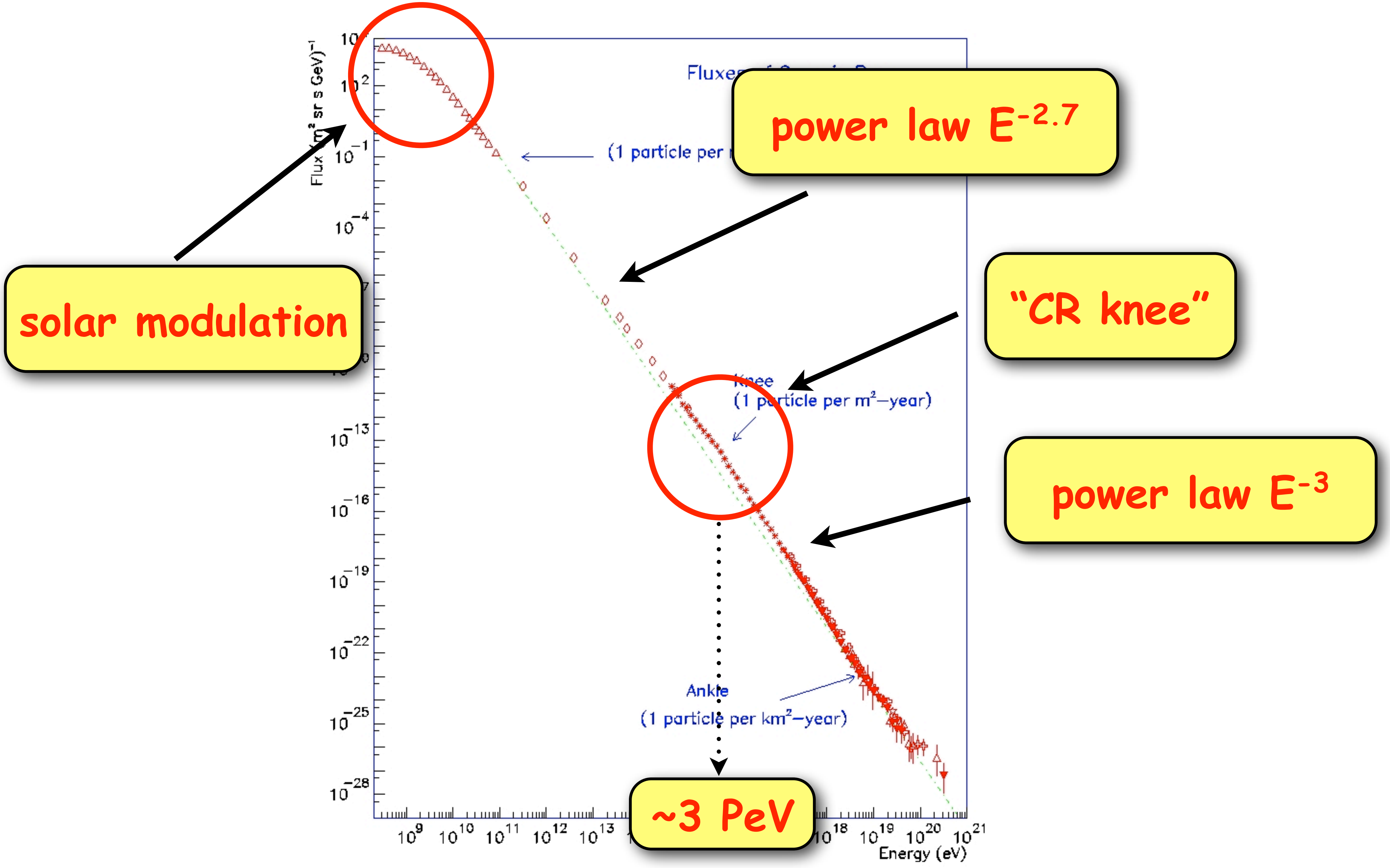

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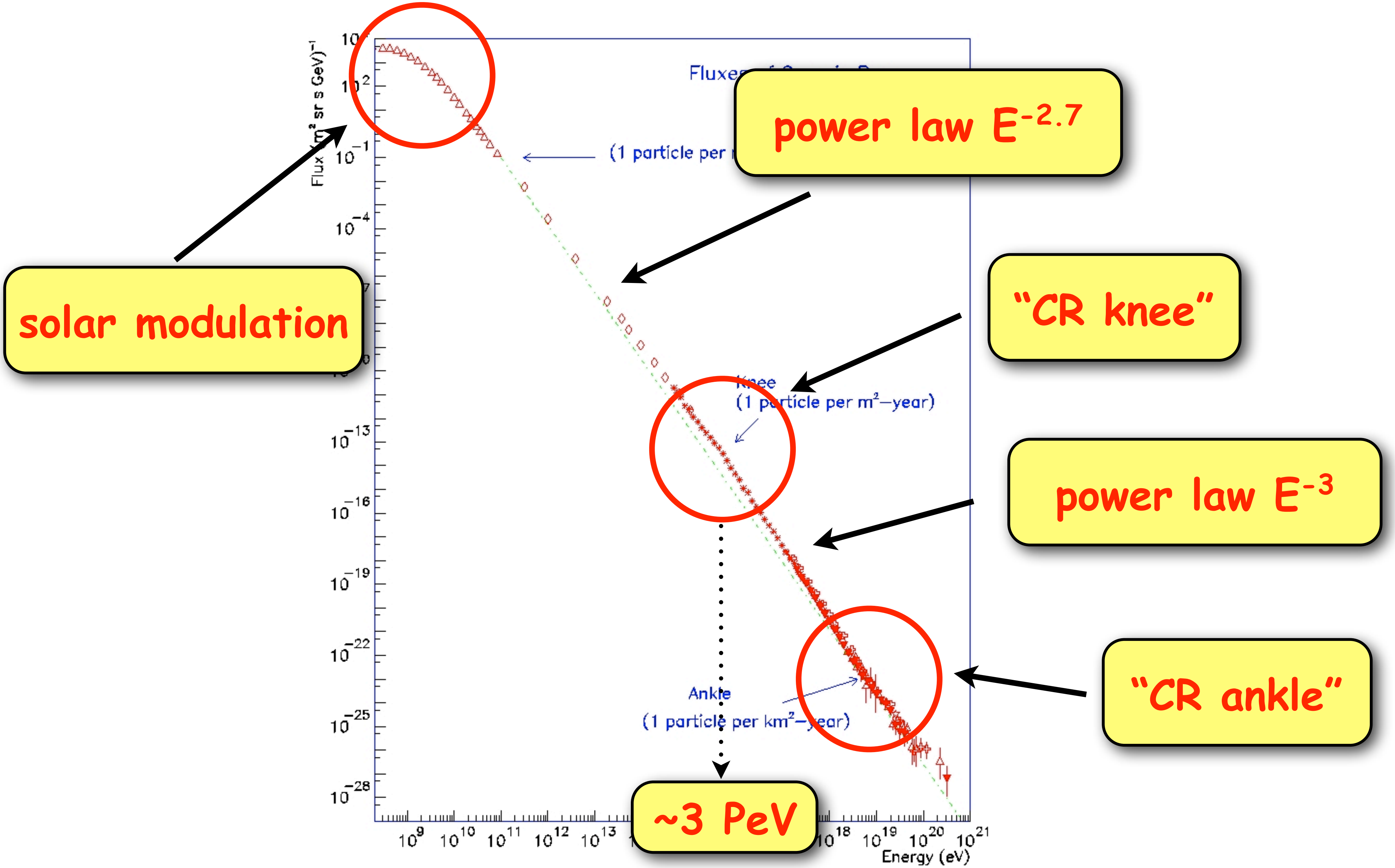

Energy density

Cosmic Ray energy density: $w_{CR} \sim 1 \text{ eV cm}^{-3}$

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Thermal gas energy density: $w_{gas}^{turb} = \varrho_{gas} v_{turb}^2 \sim 1\ \mathrm{eV\ cm^{-3}}$

CRs are dynamically important in the Galaxy

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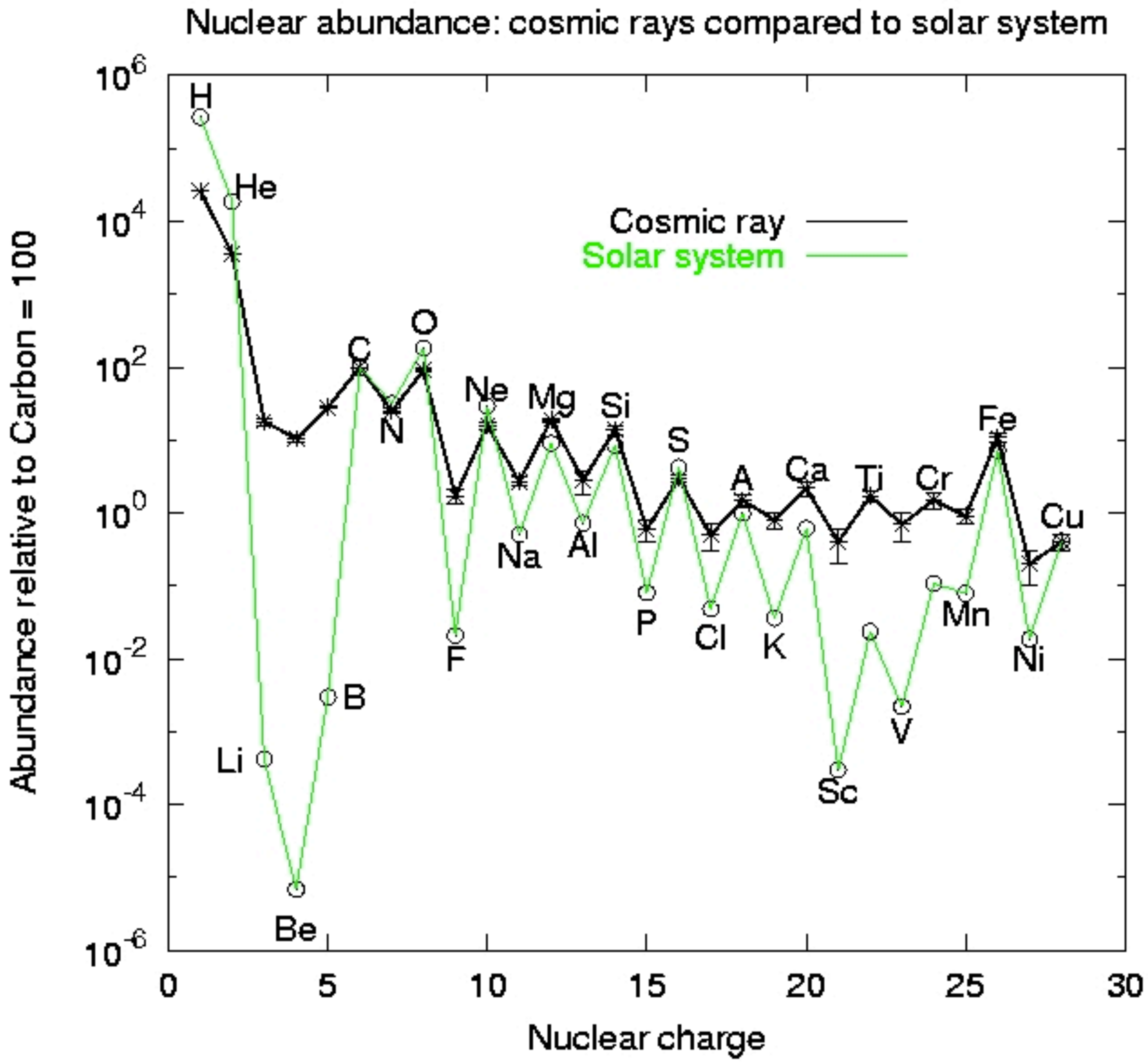
similar to energy density of radiation field -> coincidence or connection?

CRs are dynamically important in the Galaxy

Cosmic Ray composition



Gaisser & Stanev, 2005

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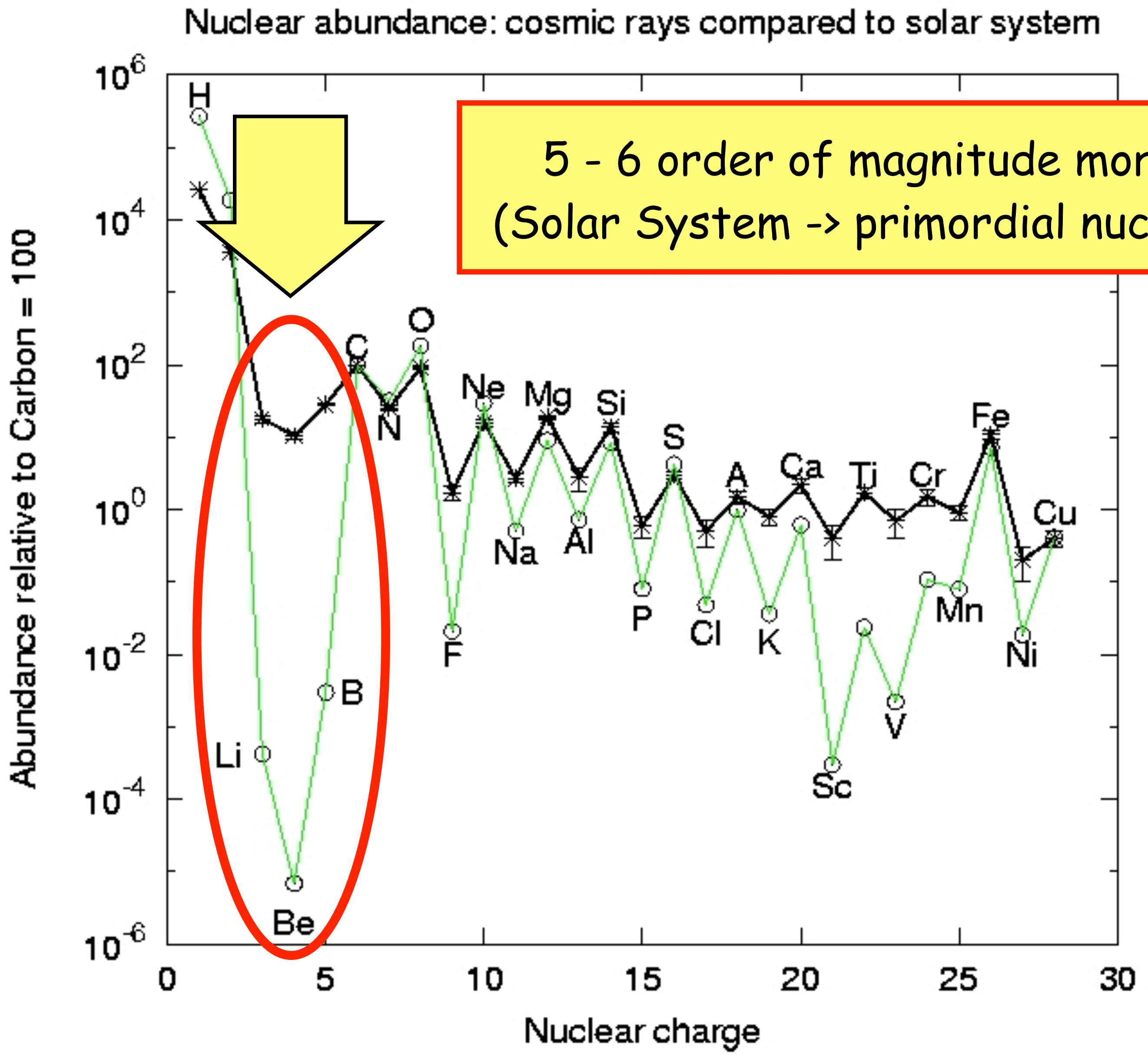

5 - 6 order of magnitude more Li, Be, B!
(Solar System -> primordial nucleosynthesis)

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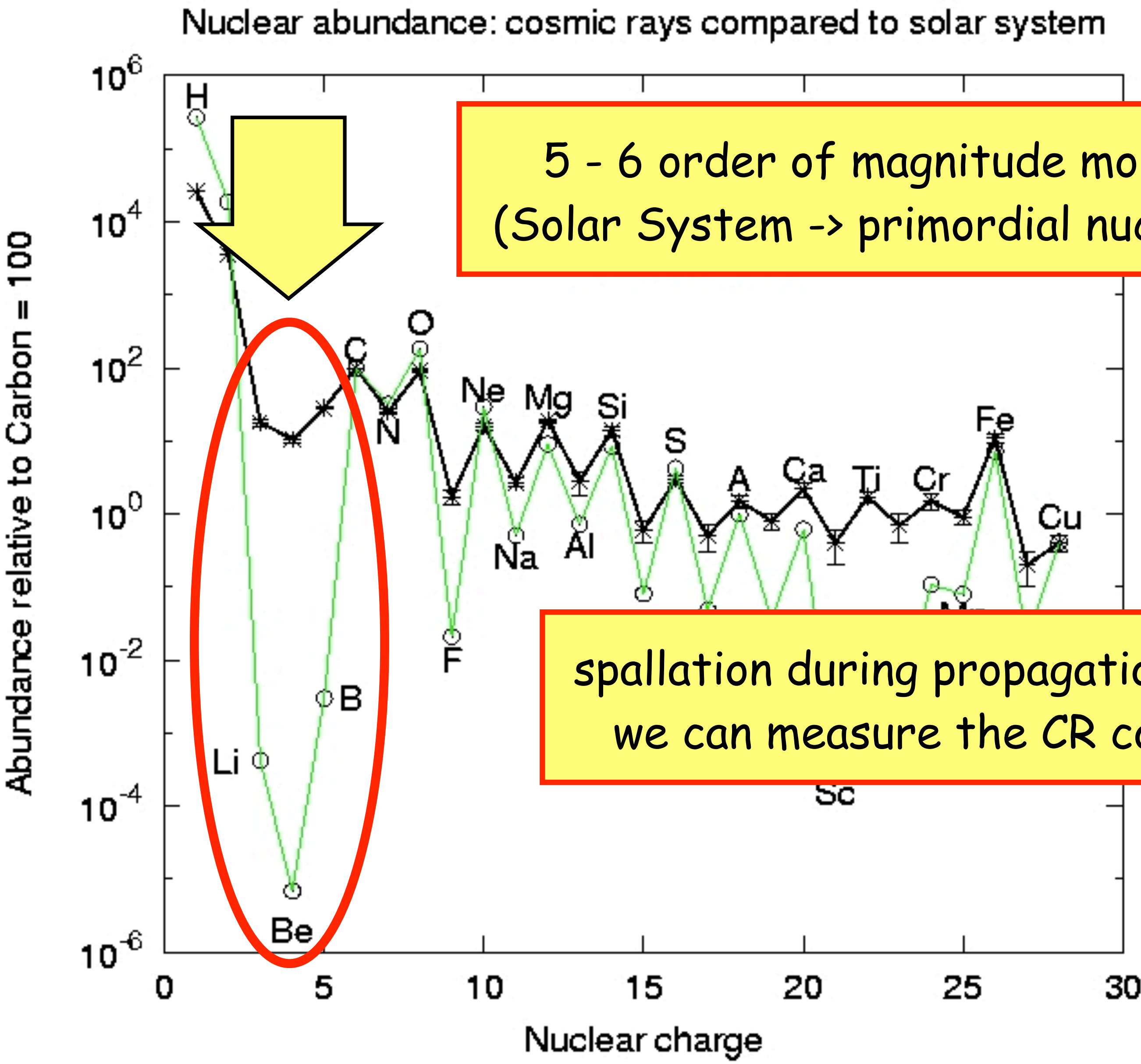

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spallation during propagation in the Galaxy ->
we can measure the CR confinement time

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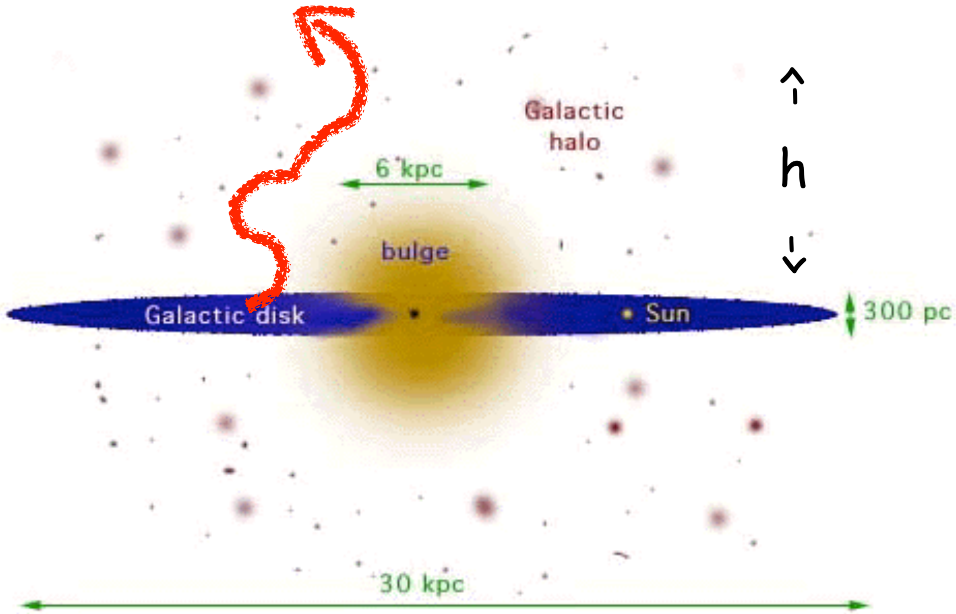
Cosmic Ray confinement in the Galaxy



$$t_{esc} \propto E^{-\delta}$$

$$\delta \approx 0.3 \ldots 0.6$$

$$h \approx \sqrt{D\, t_{esc}}$$

$$\boxed{D \approx 10^{28} \left(\frac{E}{10 \text{ GeV}} \right)^{\delta} \text{cm}^2/\text{s}}$$

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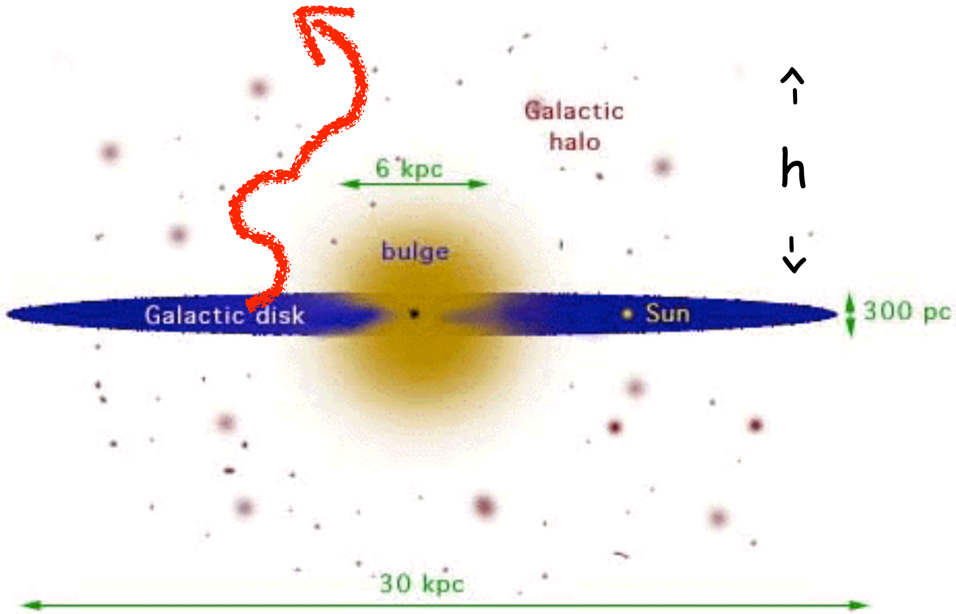

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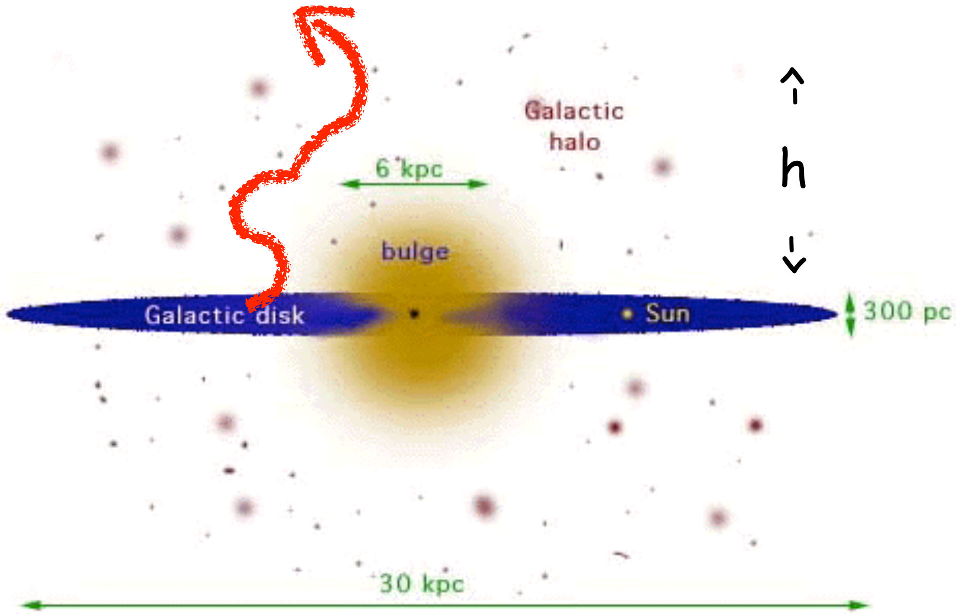

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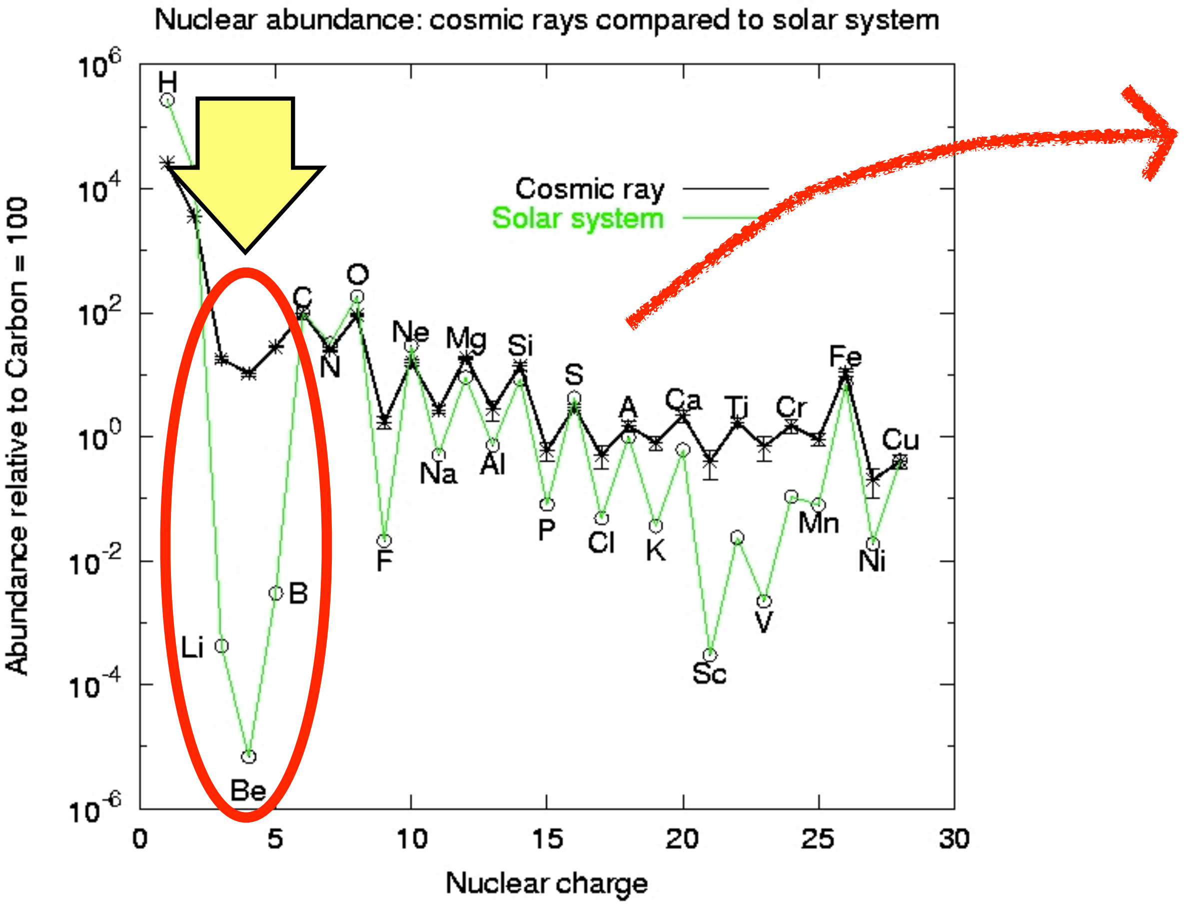
slope close to (or "slightly" steeper than) 2

A remarkable "coincidence"

~ Baade & Zwicky, 1934



CR escape time

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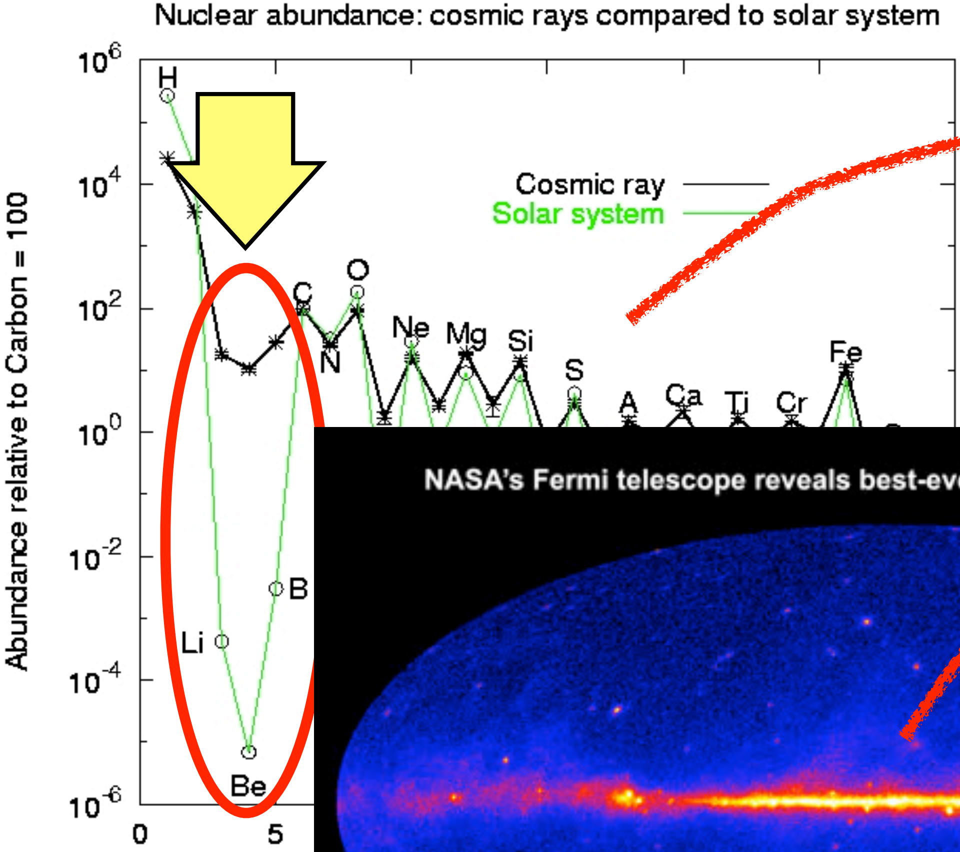
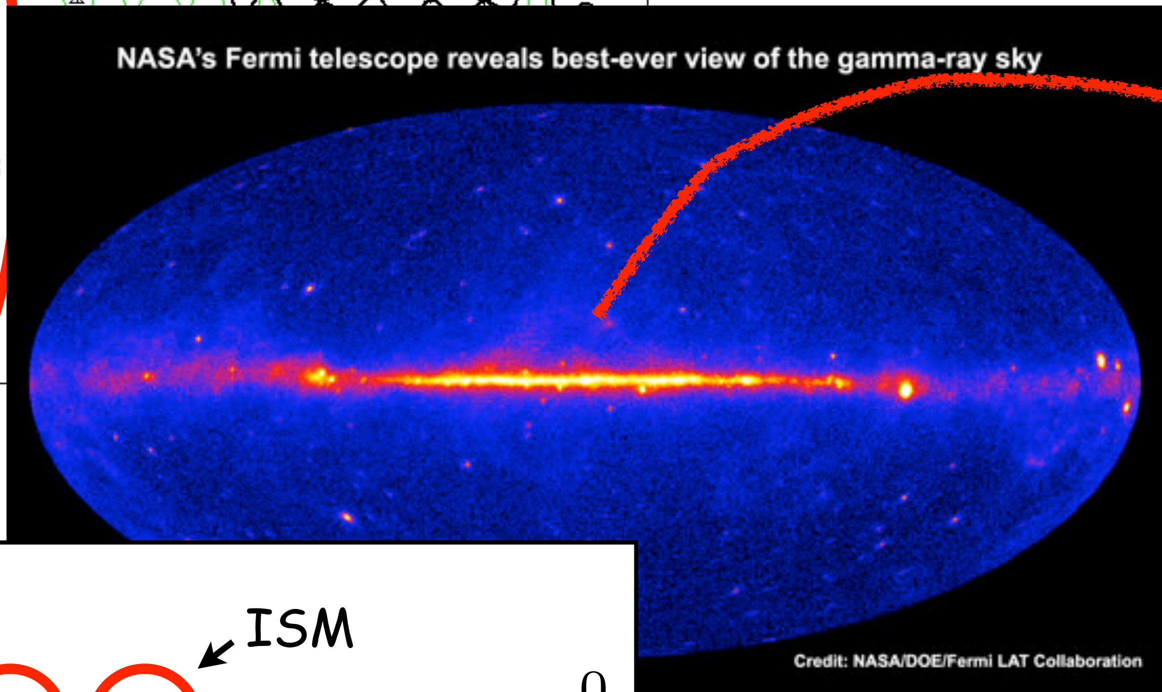


CR escape time

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



CR total energy

CR

ISM

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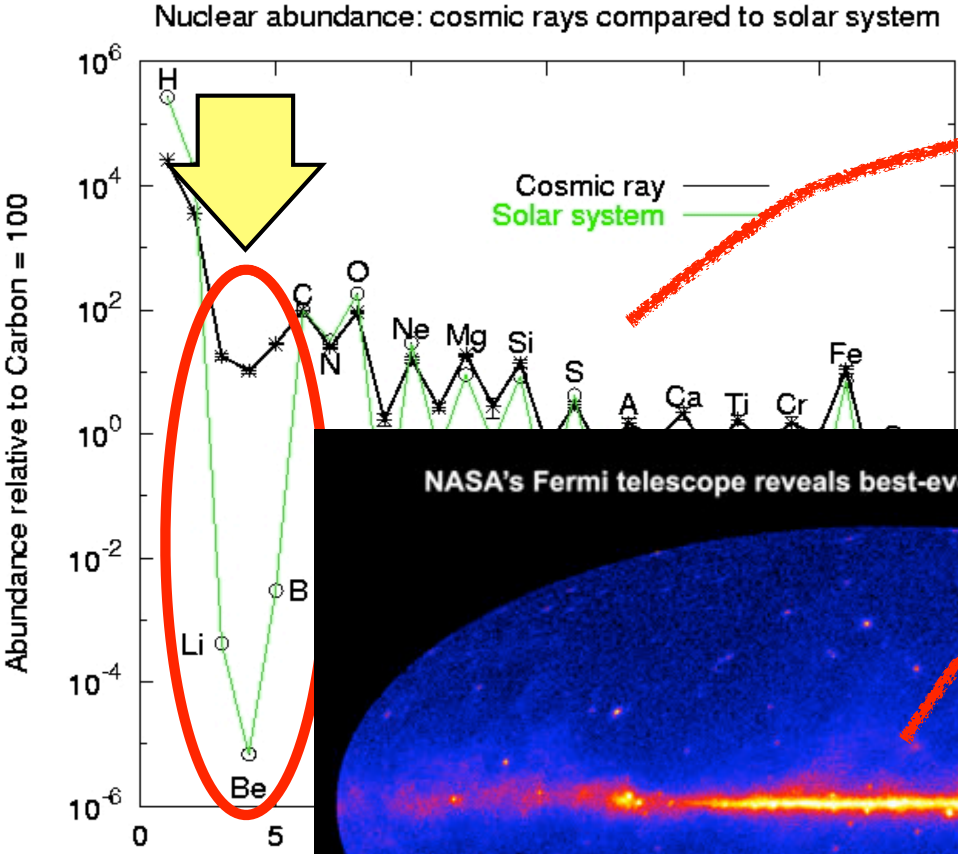

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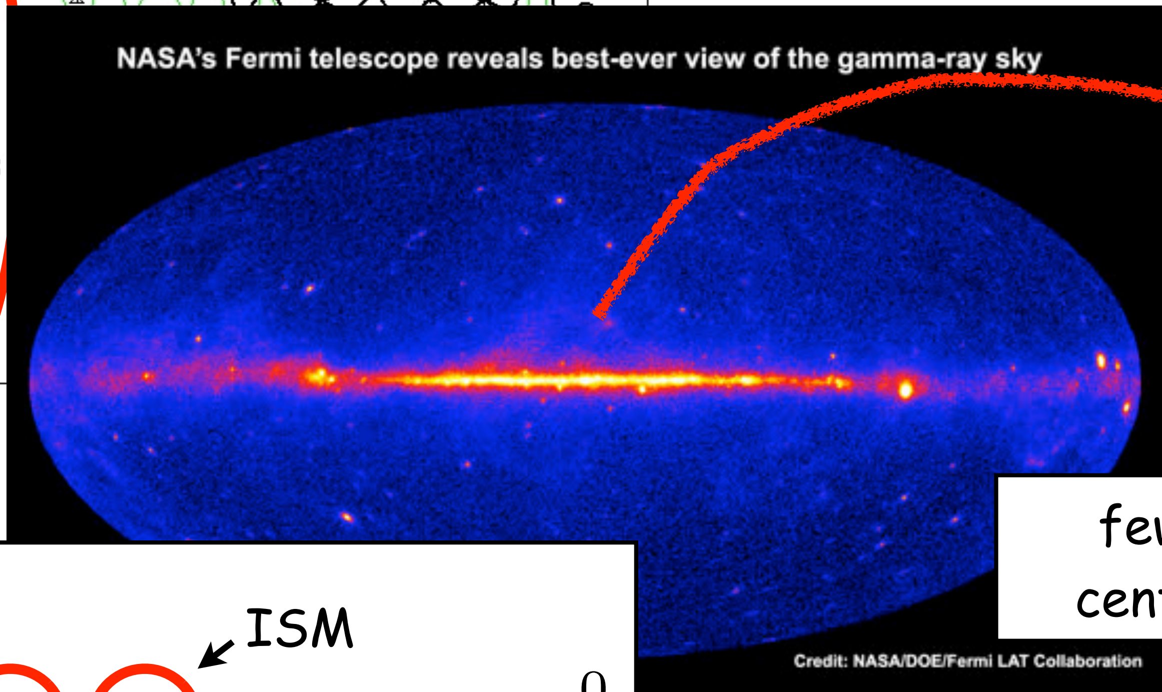

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few supernovae per century in the Galaxy

-> power of SuperNovae 3 x 10^{41} erg/s

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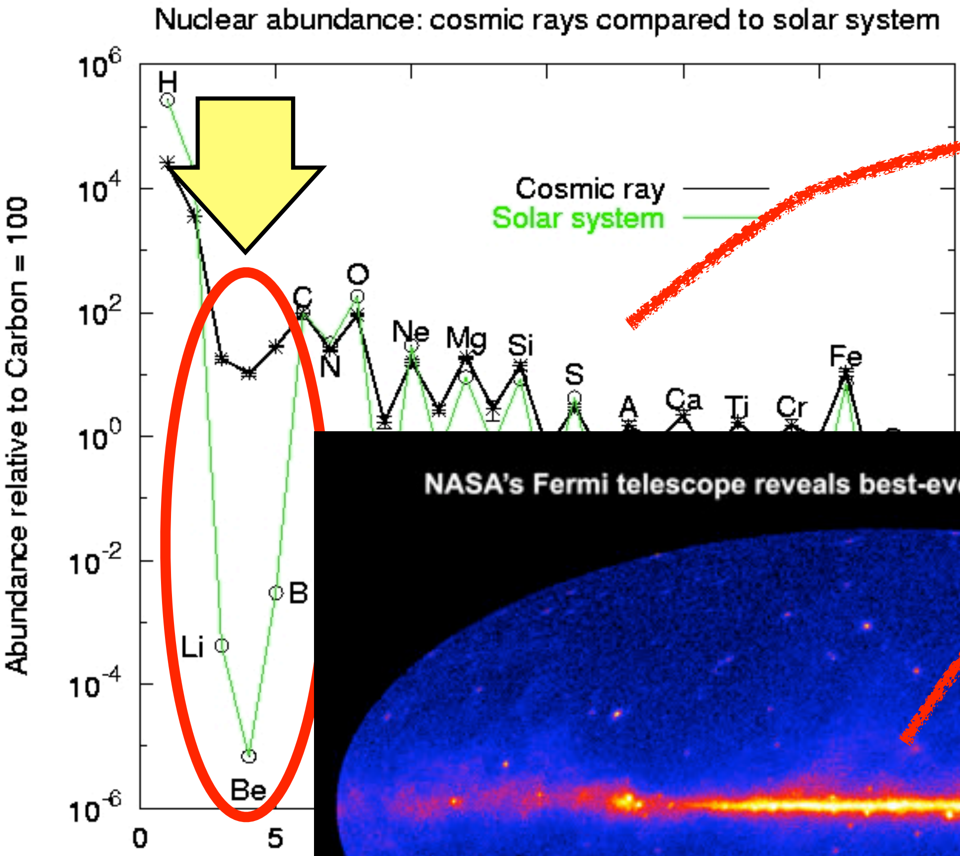

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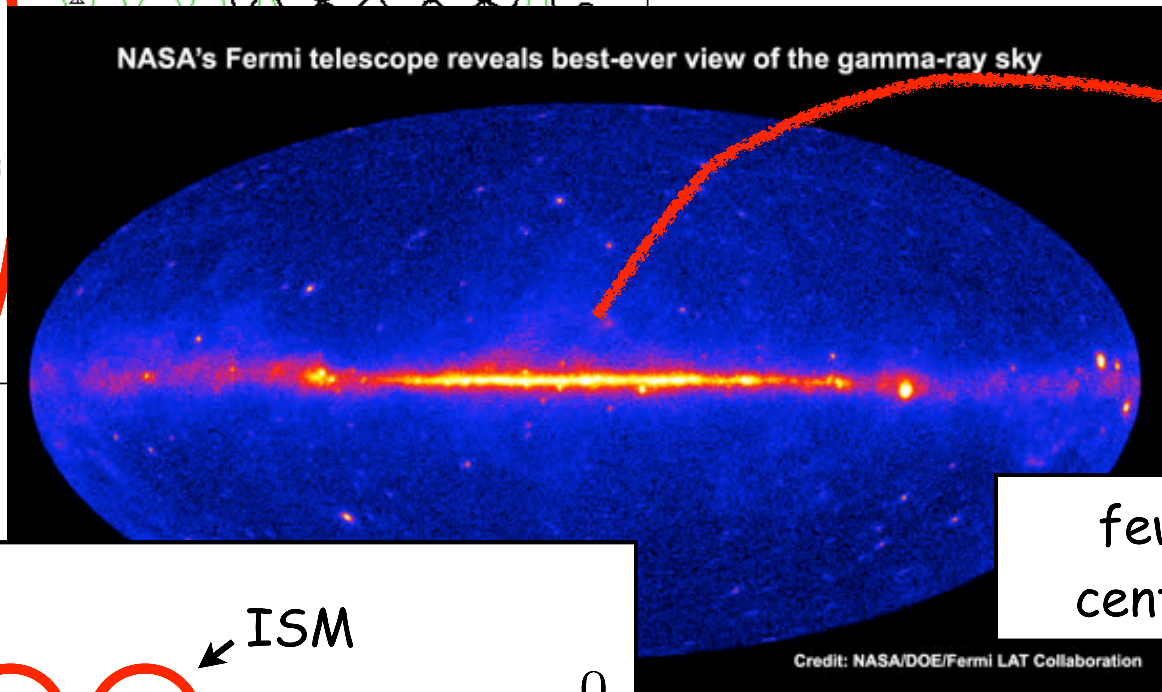

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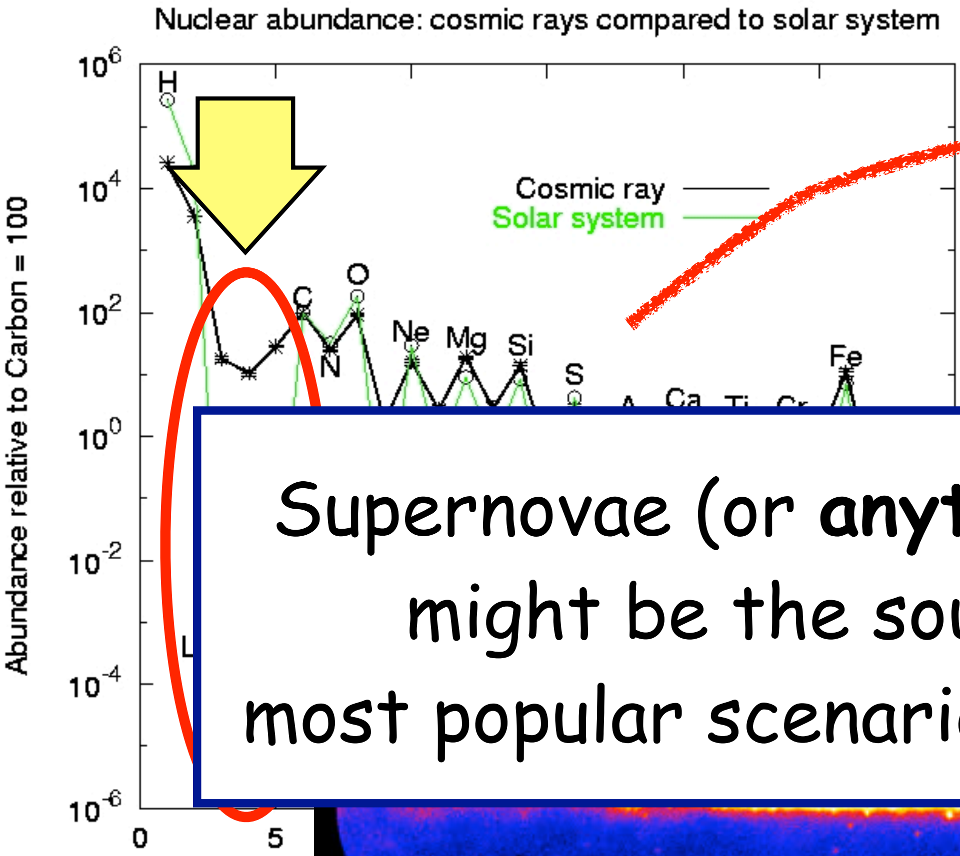

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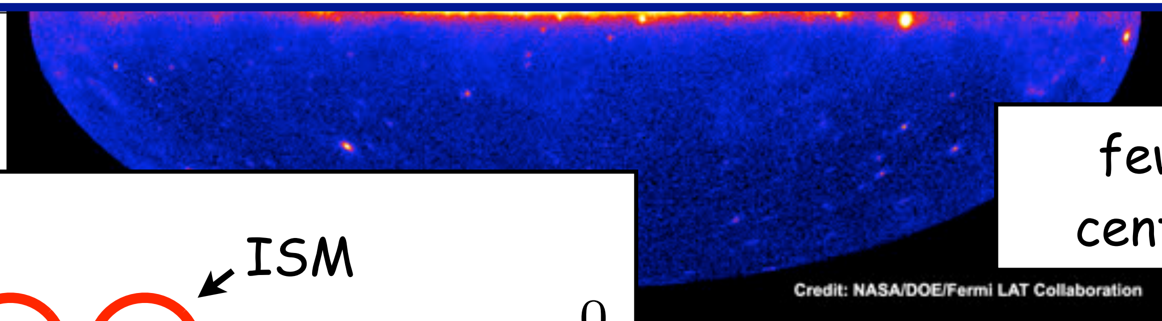
Supernovae (or **anything** connected to them) might be the sources of cosmic rays:
most popular scenario -> **supernova remnants**



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Gamma rays from SNRs: a test for CR origin

Drury, Aharonian & Volk, 1994

- CR observations -> CR power of the Galaxy
- Supernova rate in the Galaxy (≈3 per century)

⇨ ≳10% of SNR energy MUST be converted into CRs

- ISM density $n \approx 0.1 \div 1\ cm^{-3}$
- proton-proton interactions

⇨ SNRs visible in TeV gamma rays

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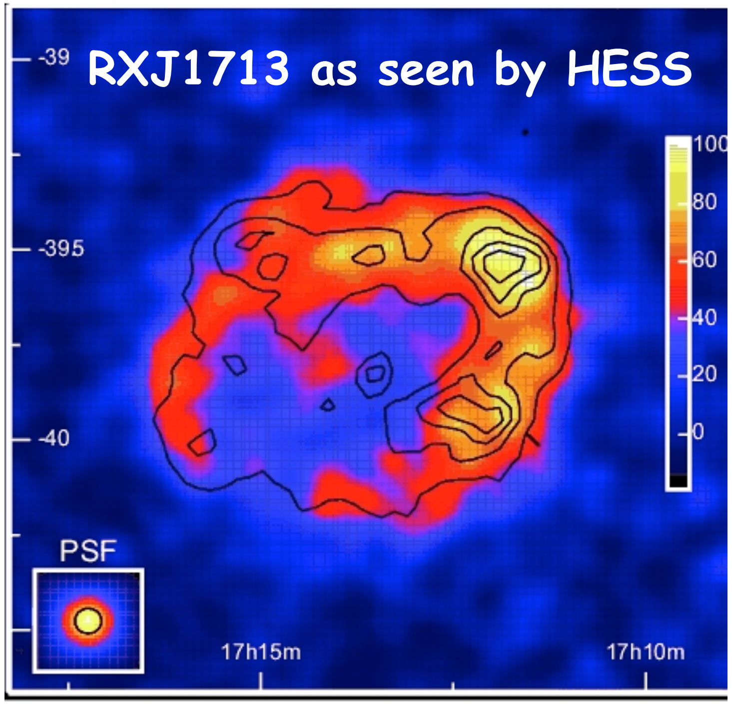
BUT

hadronic or leptonic???



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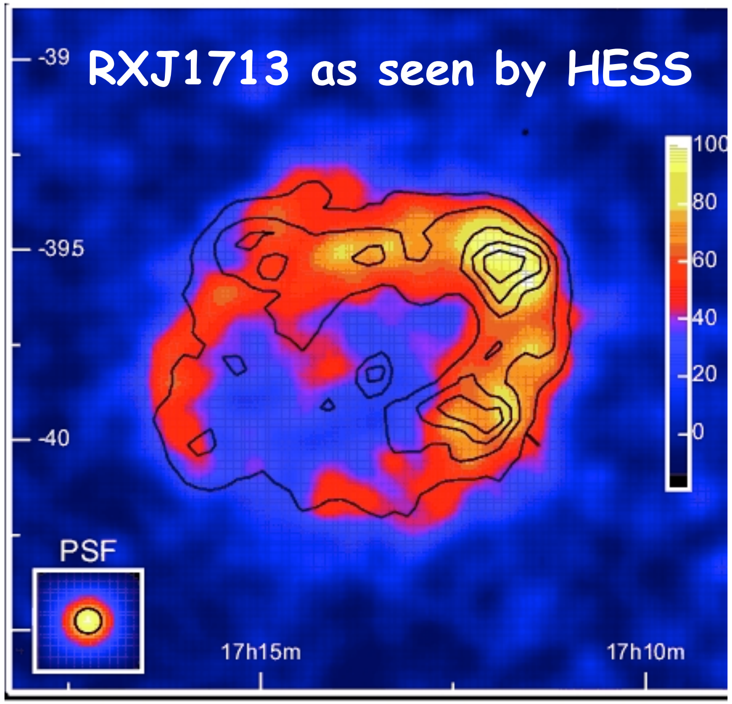
almost model independent



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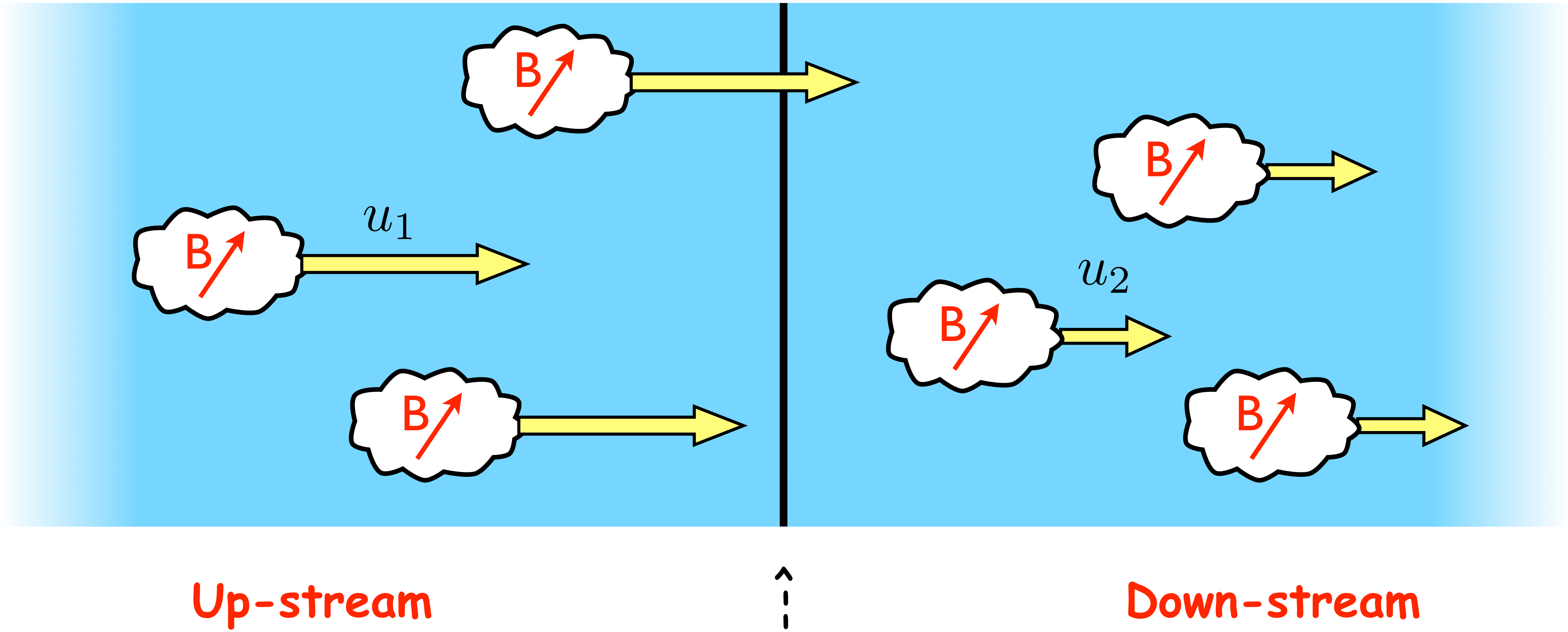
Diffusive Shock Acceleration

Shock rest frame



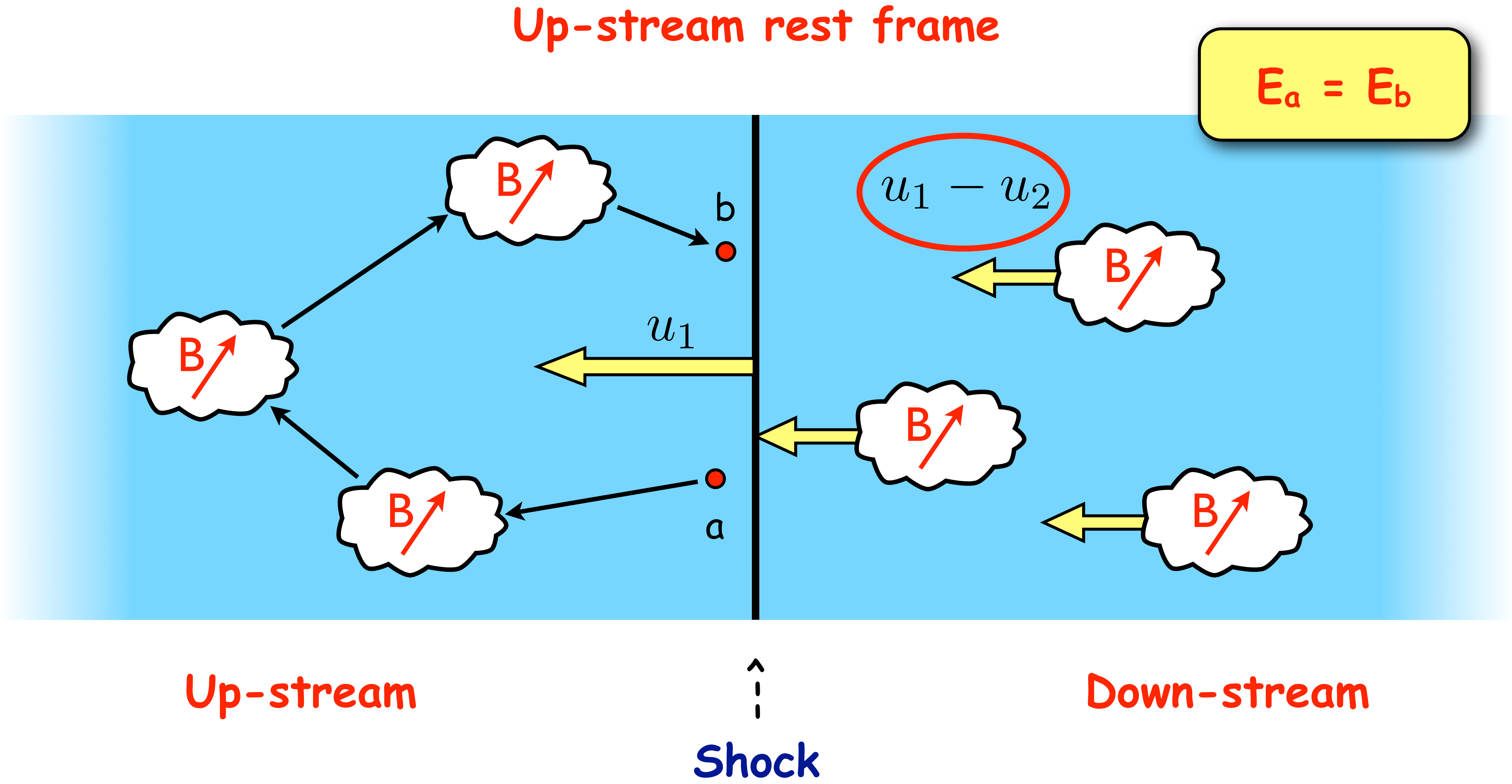
Up-stream

Shock

Down-stream

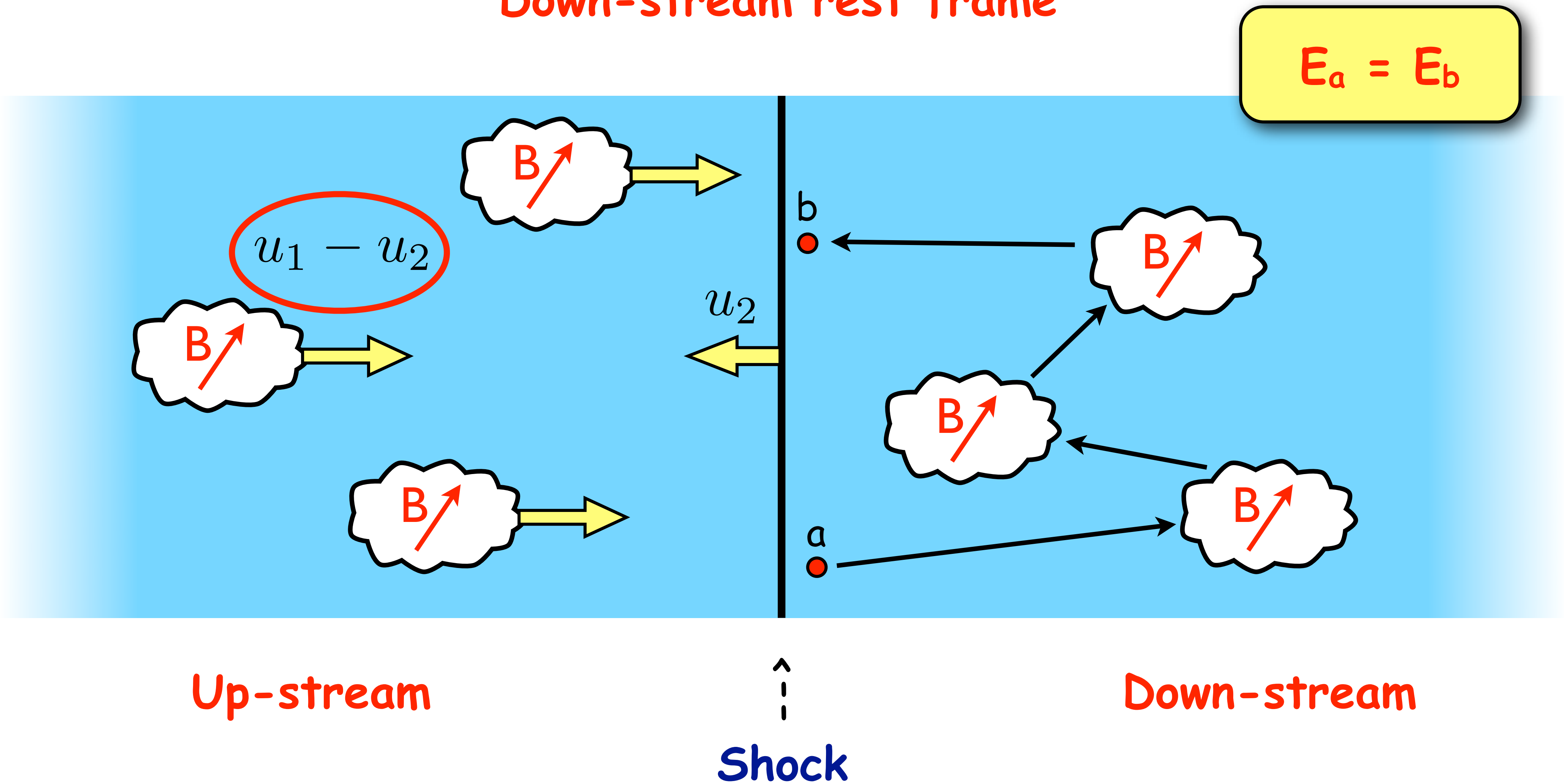
Krymskii 1977, Axford et al. 1977, Blandford & Ostriker 1978, Bell 1978

Diffusive Shock Acceleration



Diffusive Shock Acceleration

Down-stream rest frame



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Every time the particle crosses the shock (up -> down or down -> up), it undergoes an head-on collision with a plasma moving with velocity u_1-u_2

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Asymmetry

(Infinite and plane shock:) Upstream particles always return the shock, while downstream particles may be advected and never come back to the shock

Diffusive Shock Acceleration

Symmetry

Every

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u_2

U

Solution: power law spectrum

$$n(E) \propto E^{-\alpha} \qquad \alpha = \frac{r+2}{r-1}$$

strong shock -> r = 4 -> $\boxed{n(E) \propto E^{-2}}$

(Infinite and plane shock:) Upstream particles always return the shock, while downstream particles may be advected and never come back to the shock

Diffusive Shock Acceleration at SuperNova Remnants and the origin of Galactic Cosmic Rays

(1) Spallation measurements of Cosmic Rays suggest that CR sources have to inject in the Galaxy a spectrum close to E^{-2}.

(2) Strong shocks at SNRs can indeed accelerate E^{-2} spectra.

-> Thus SNRs are good candidates as sources of Galactic CRs.

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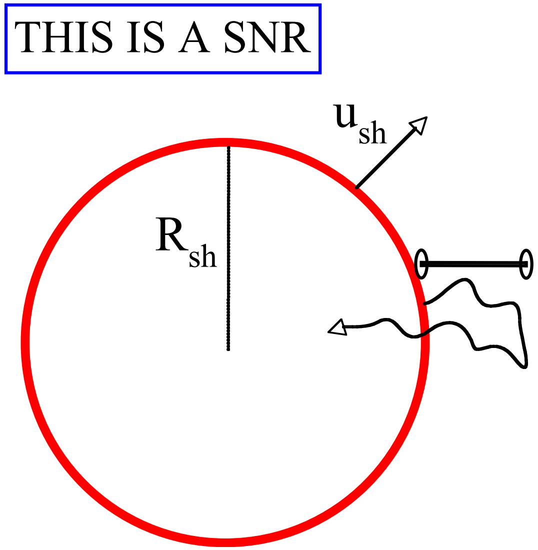
E^{-2} is the spectrum at the shock, not the one released in the ISM!

When do CRs escape SNRs?

We need to know a bit of shock acceleration theory...



Diffusion length: $$l_{diff} \sim \frac{D(E)}{u_{sh}} \propto \frac{E}{B_{sh} u_{sh}}$$

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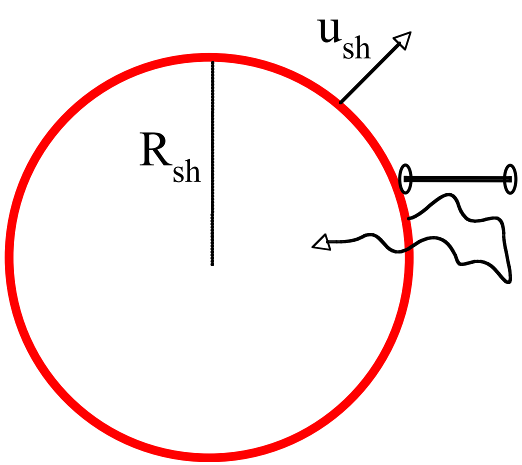
THIS IS A SNR



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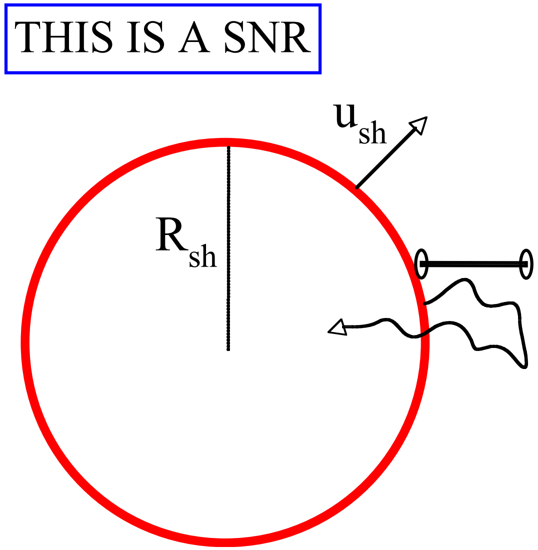

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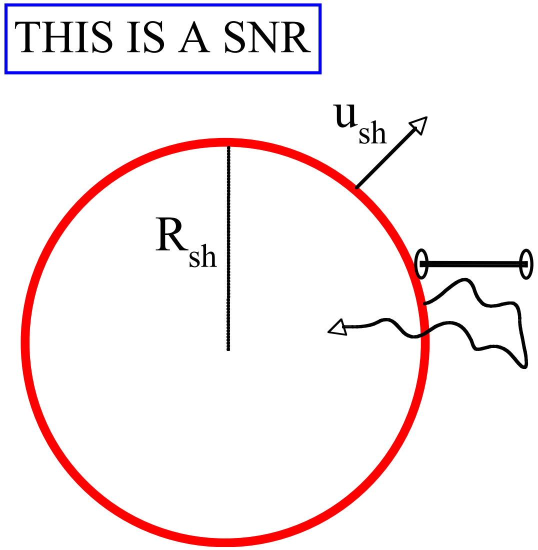

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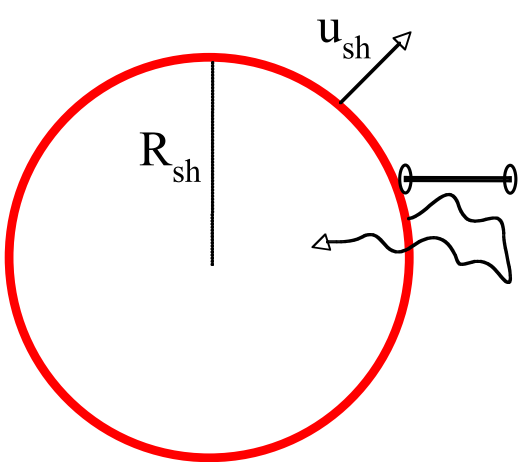

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B_{sh} also depends on time

E_{max} decreases with time
Particles with E > E_{max} escape the SNR

CRs are (probably) released gradually...

very naive summary of: Ptuskin & Zirakashvili 2003, 2005

Assumption 1: particles of energy E are released at a time defined by -> $E \propto t^{-\delta}$

SNR in Sedov phase: $R_s \propto t^{\frac{2}{5}}$ $u_s \propto t^{-\frac{3}{5}}$

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Assumption 2: a fixed fraction of L_k is released in form of CRs

$$\frac{dN_{CR}}{dE} = \frac{dN_{CR}}{dt}\frac{dt}{dE} \propto \frac{L_k}{E} \times \frac{t}{E}\left(\frac{E}{t}\frac{dt}{dE}\right) \propto E^{-2}$$

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again!

$1/t$

const

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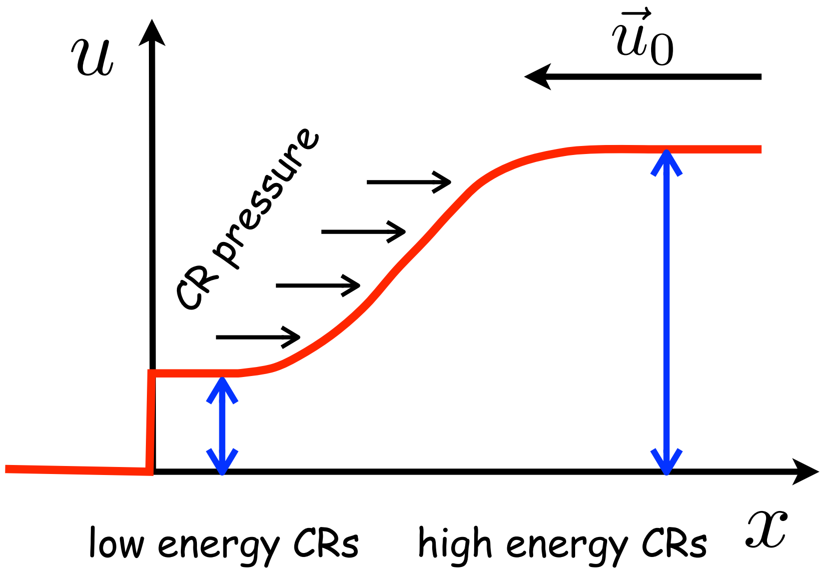
Non-linear Diffusive Shock Acceleration

Non-linear DSA: what happens if the acceleration efficiency is high (~1)?

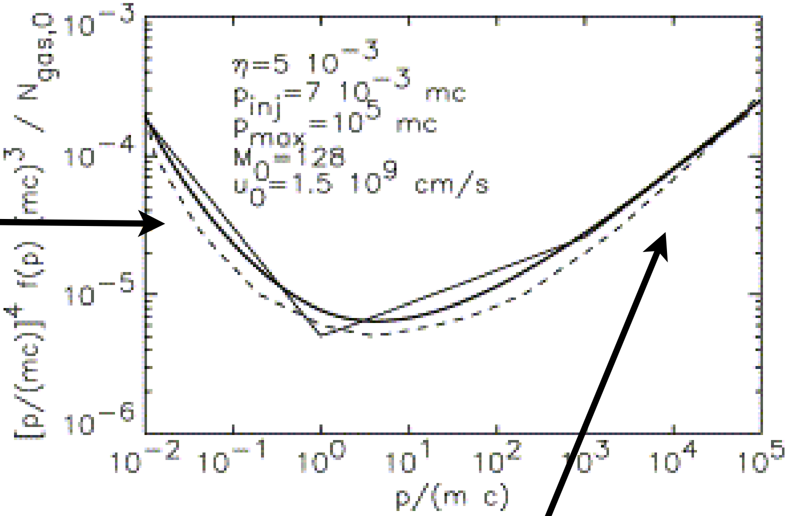
shock acceleration is intrinsically efficient ➜ cosmic ray pressure is slowing down the upstream flow ➜ formation of a precursor



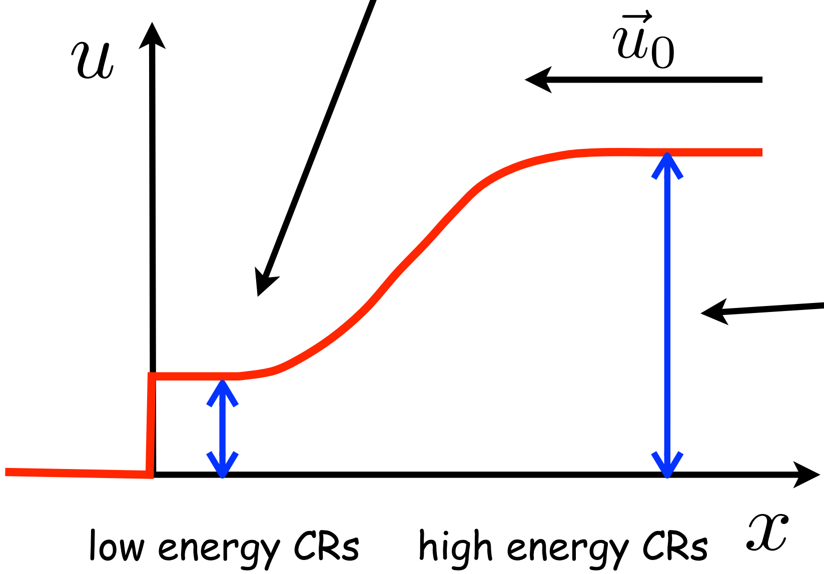
Eichler 79, Blandford 80, Drury&Volk 81, Kang&Jones 91, Malkov 99, Berezhko&Ellison 99, Blasi 02 ...

Non-linear Diffusive Shock Acceleration

Non-linear DSA: what happens if the acceleration efficiency is high (~1)?



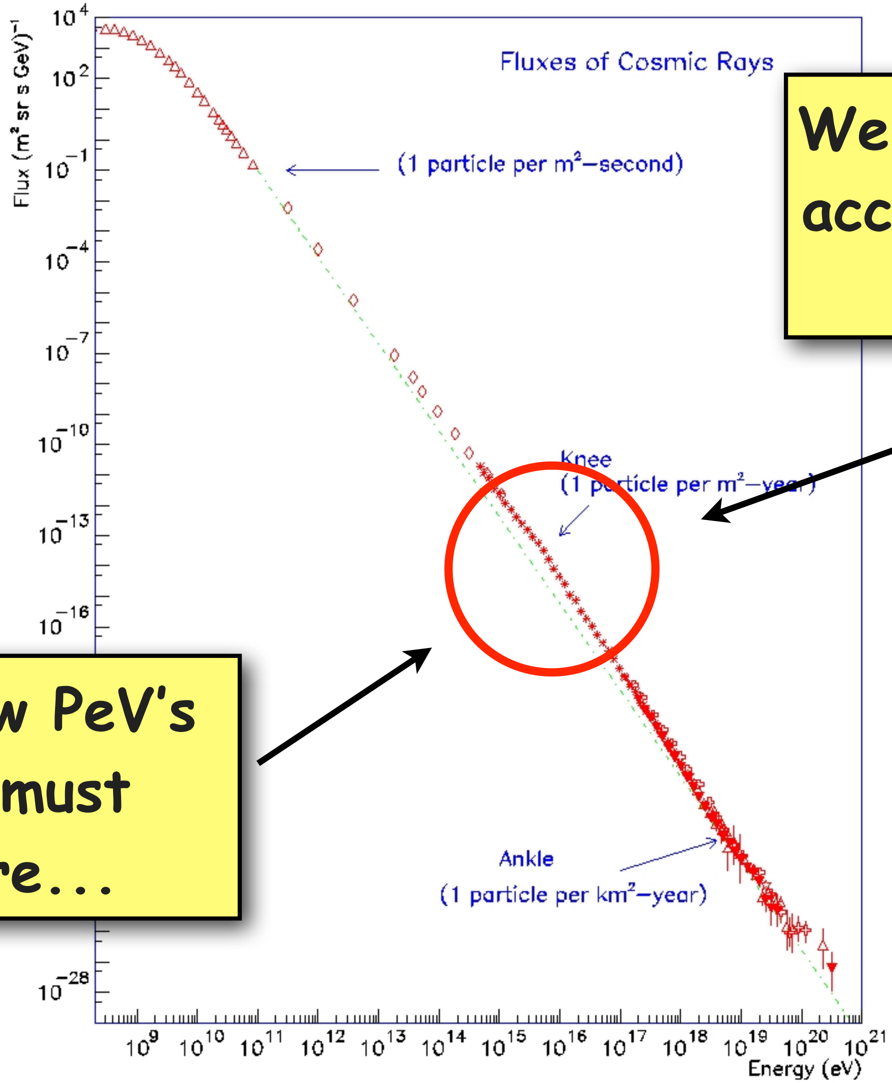
Low energy CRs
R < 4
slope > 4



High energy CRs
R > 4
slope < 4

Eichler 79, Blandford 80, Drury&Volk 81, Kang&Jones 91, Malkov 99, Berezhko&Ellison 99, Blasi 02 ...

Are SuperNova Remnants CR PeVatrons?



We'd like CR sources to accelerate (at least) up to that energy

CR knee @few PeV's
Something must happen here...

How to estimate the maximum CR energy

in the scenario proposed by e.g. Ptuskin & Zirakashvili 2003, 2005 the maximum particle energy is reached at the transition between the free expansion and the Sedov phase...

acceleration time ->

$$t_{acc} \approx \frac{D}{u_s^2}$$

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acceleration time ->

$$t_{acc} \approx \frac{D}{u_s^2}$$

mean value in the ISM from spallation

naive assumption ->

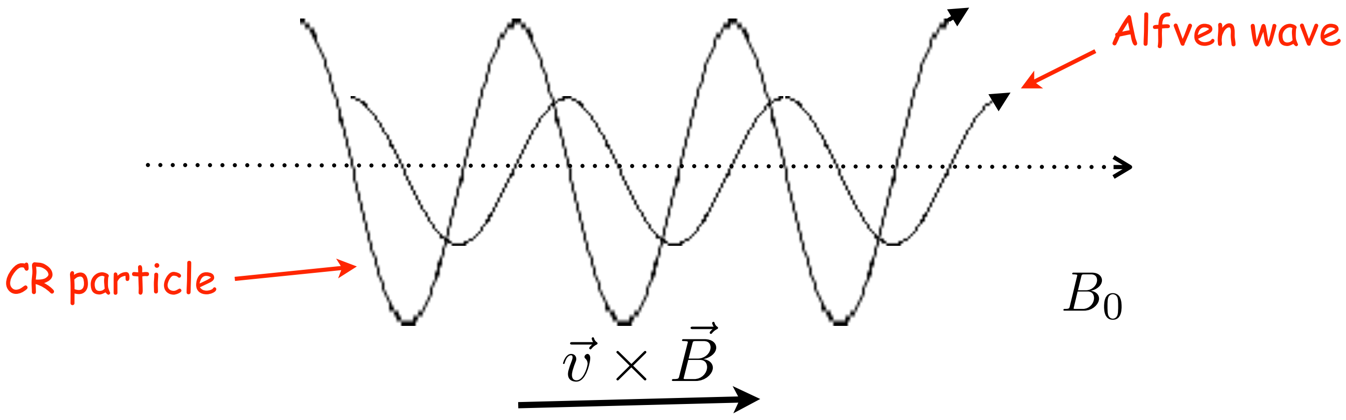
$$D \approx 10^{28} \left(\frac{E}{10 \text{ GeV}} \right)^{\delta} \text{cm}^2/\text{s}$$

$$\boxed{E_{max} \approx 1 \left(\frac{u_s}{10^9 \text{ cm/s}} \right)^2 \left(\frac{t}{1000 \text{ yr}} \right) \text{GeV}}$$

this is very optimistic

The role of CR streaming instability

e.g. Wentzel 1972, 1974



resonant interaction between CRs and Alfven waves

$$\boxed{R_L \sim \frac{1}{k}}$$

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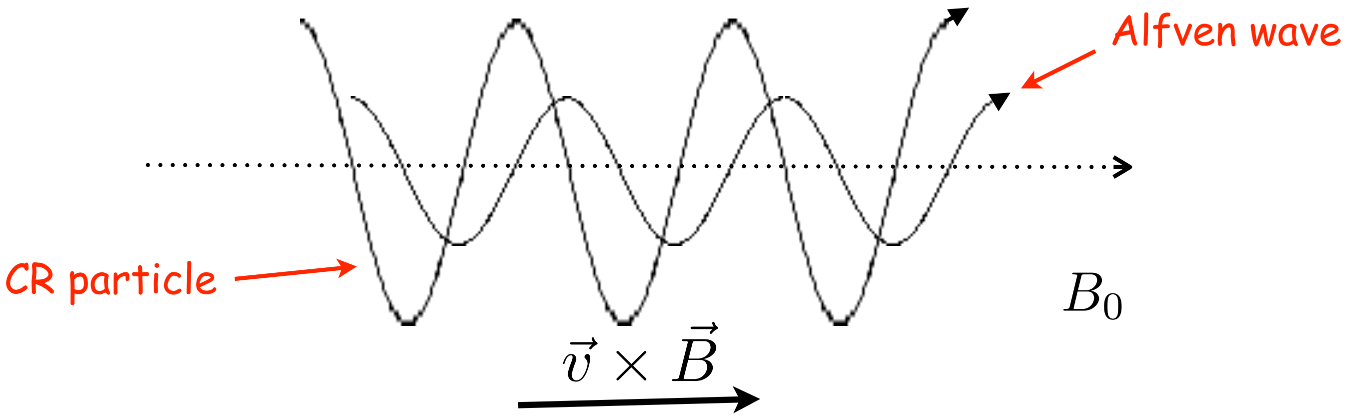

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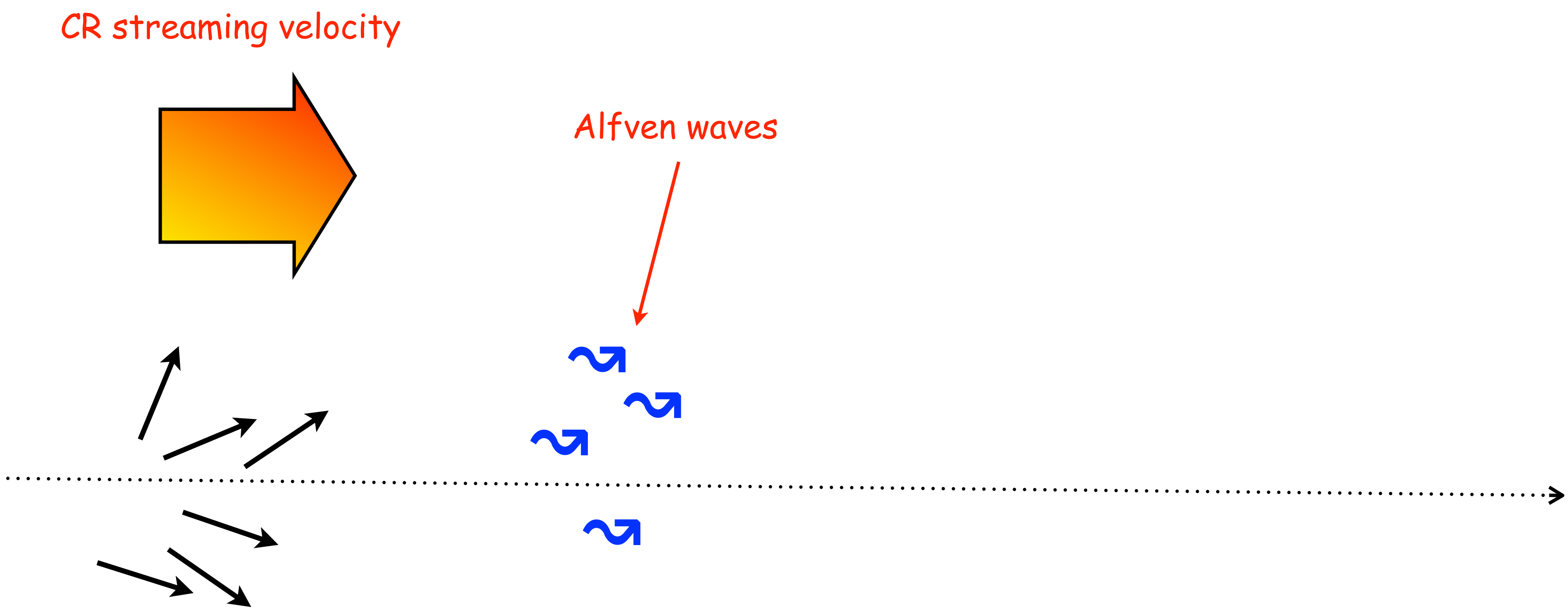

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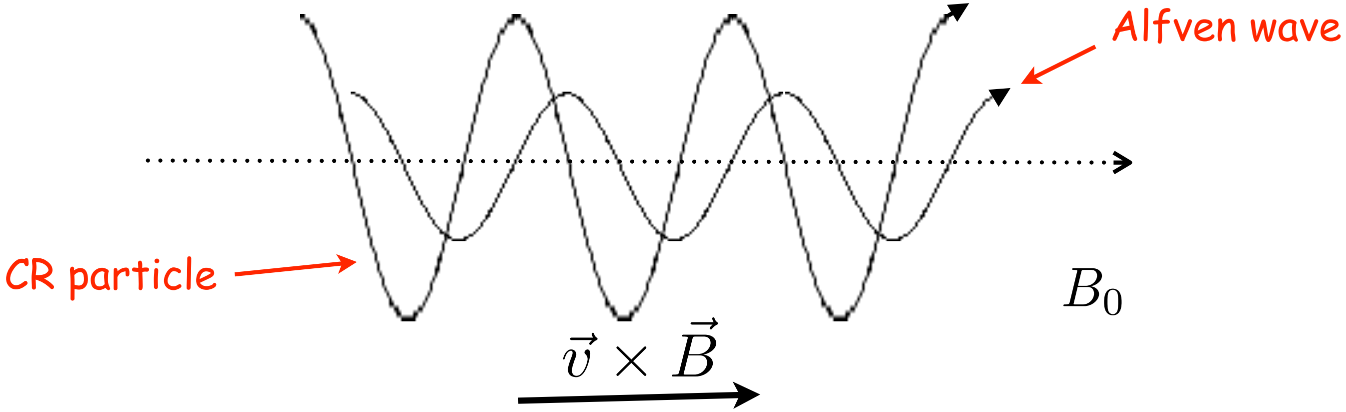
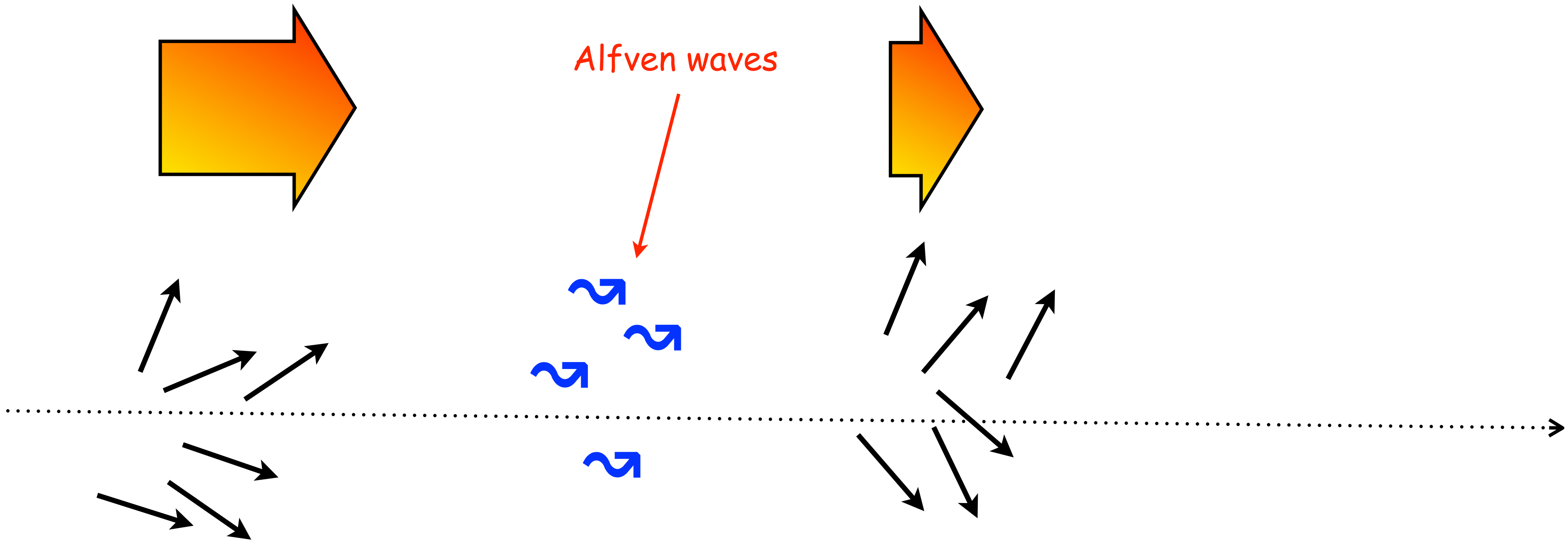


resonant interaction between CRs and Alfven waves

$$R_L \sim \frac{1}{k}$$

CR streaming velocity

momentum -> waves



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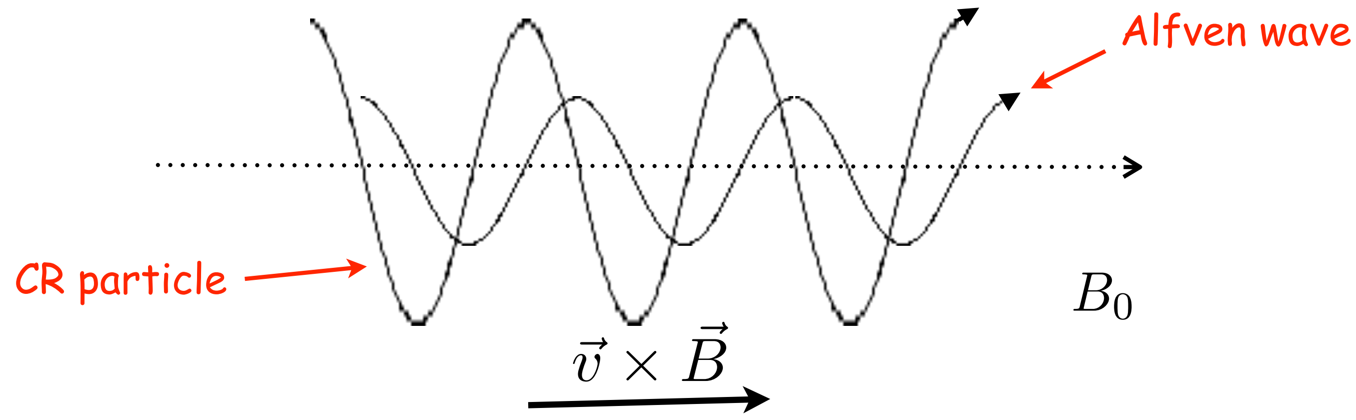

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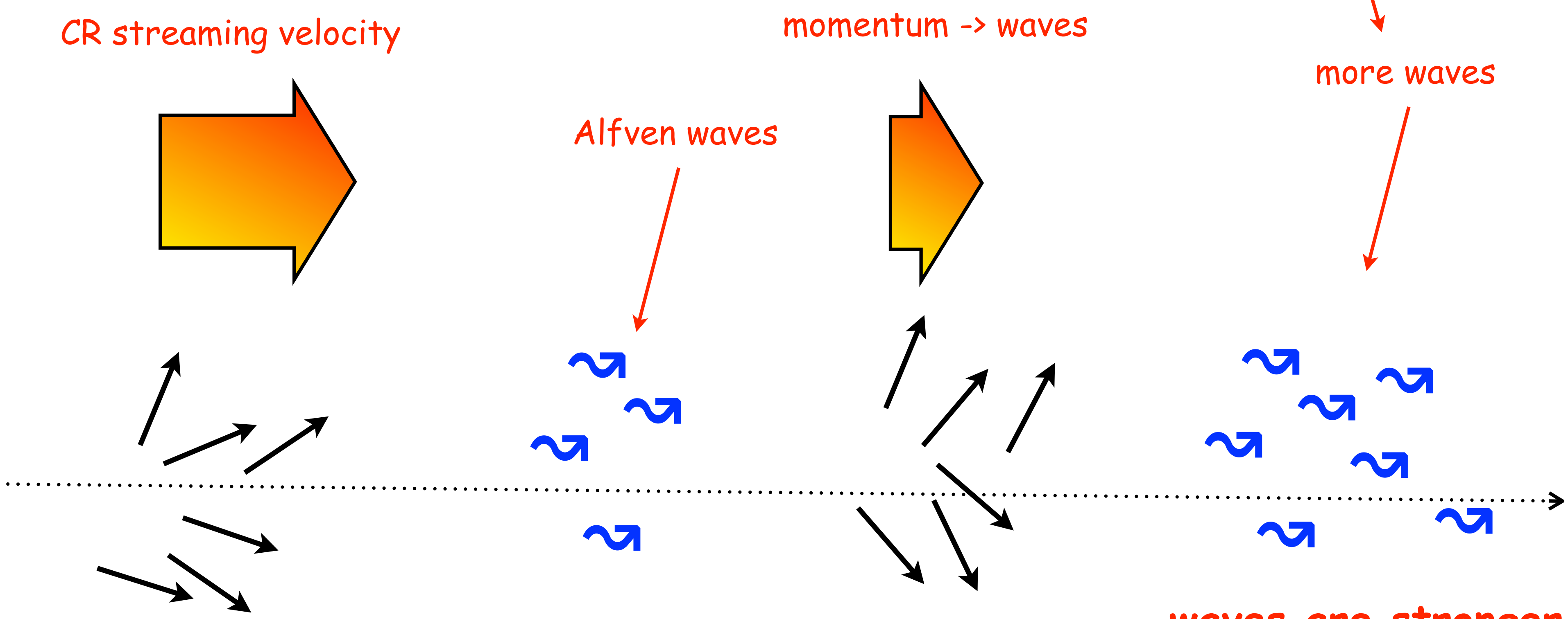

waves are stronger

How to estimate the maximum CR energy

Lagage & Cesarsky 1983

field saturation -> $$\frac{\delta B}{B_0} \sim 1$$

mean free path = Larmor radius

Bohm diffusion-> $$D = \frac{1}{3} R_L \; c$$

$$t_{acc} \approx \frac{D}{u_s^2}$$

acceleration time

this is well below the knee!!!

atomic number

$$E_{max} \approx B \; R_s \; u_s \; Z \approx 10^{14} \; \mathrm{eV}$$

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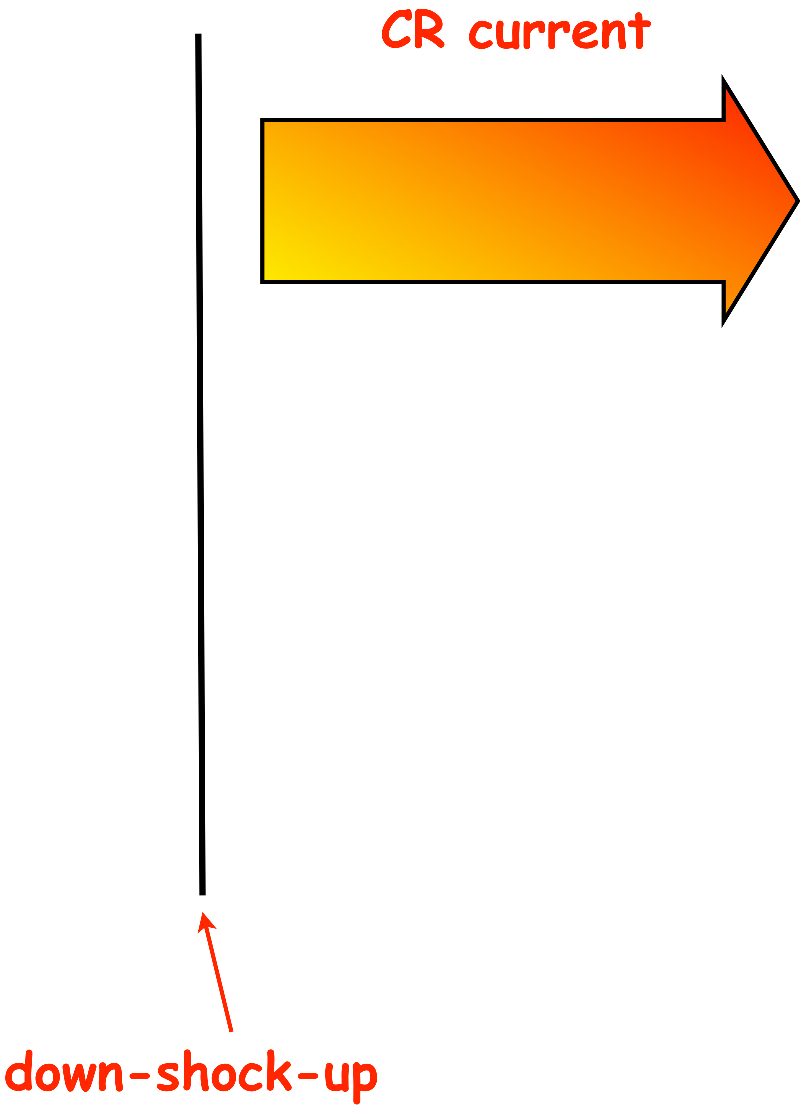
(Non resonant) current driven instability

CRs stream at the shock velocity relative to the background plasma



Bell 2004

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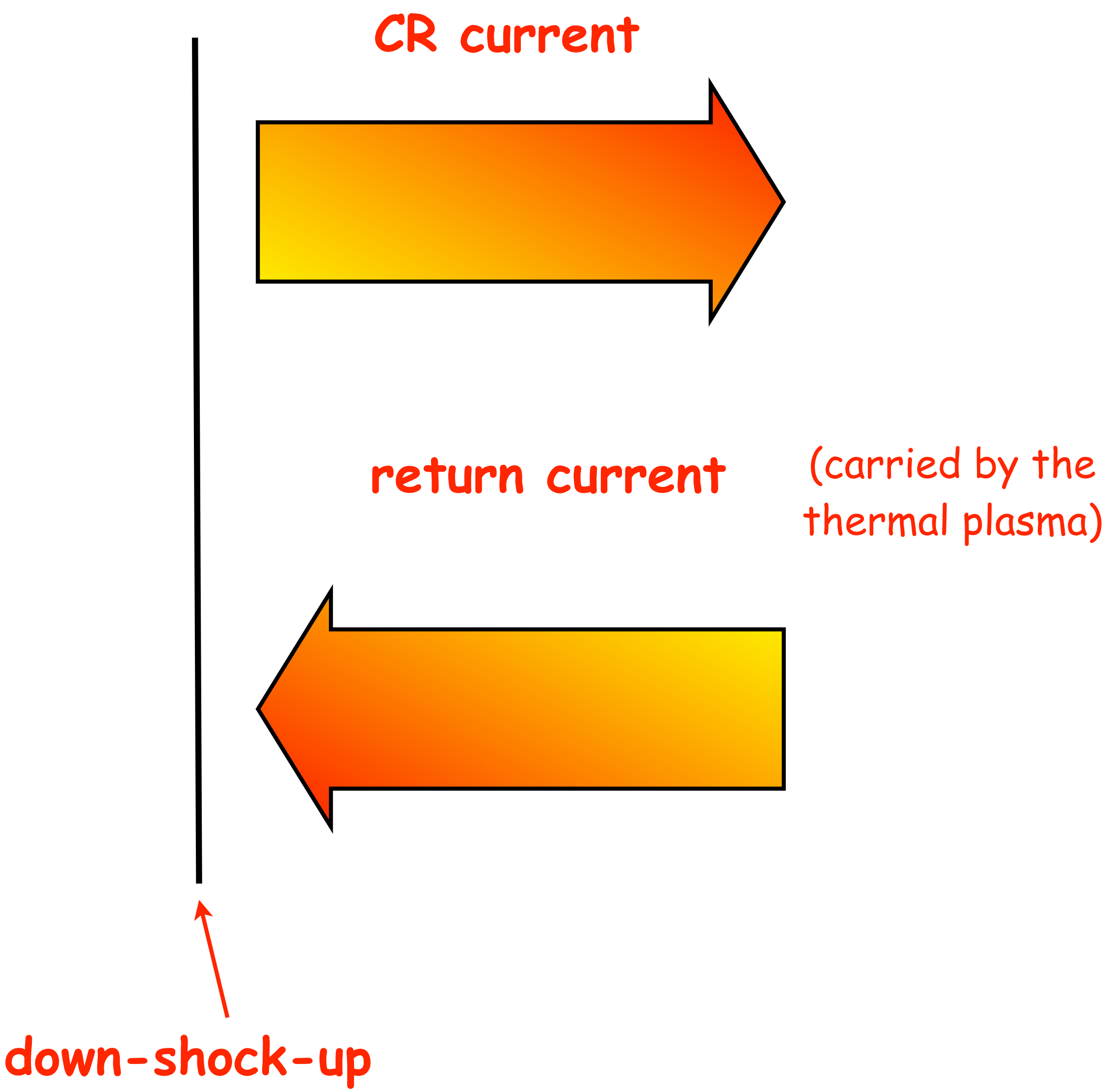

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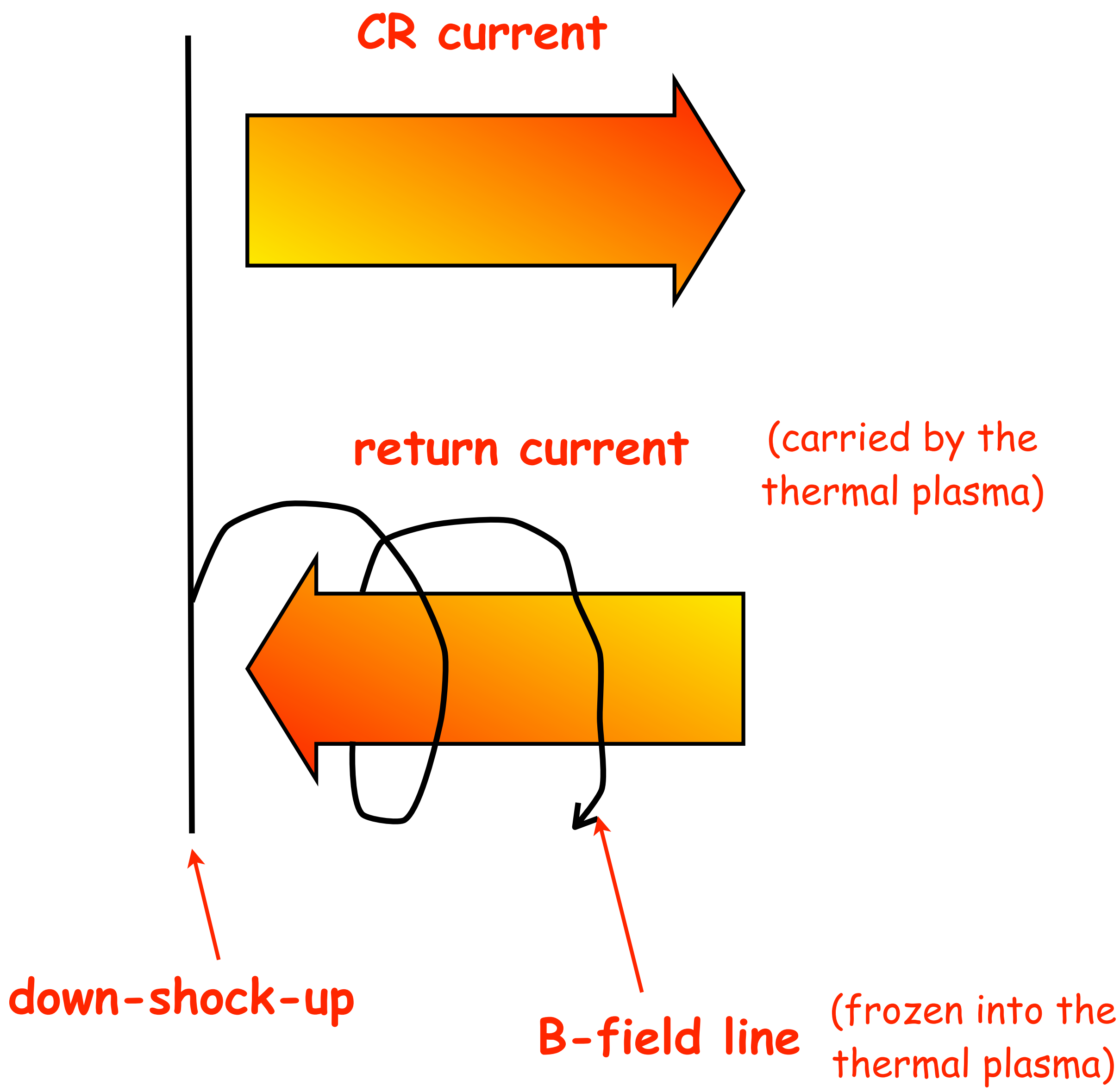

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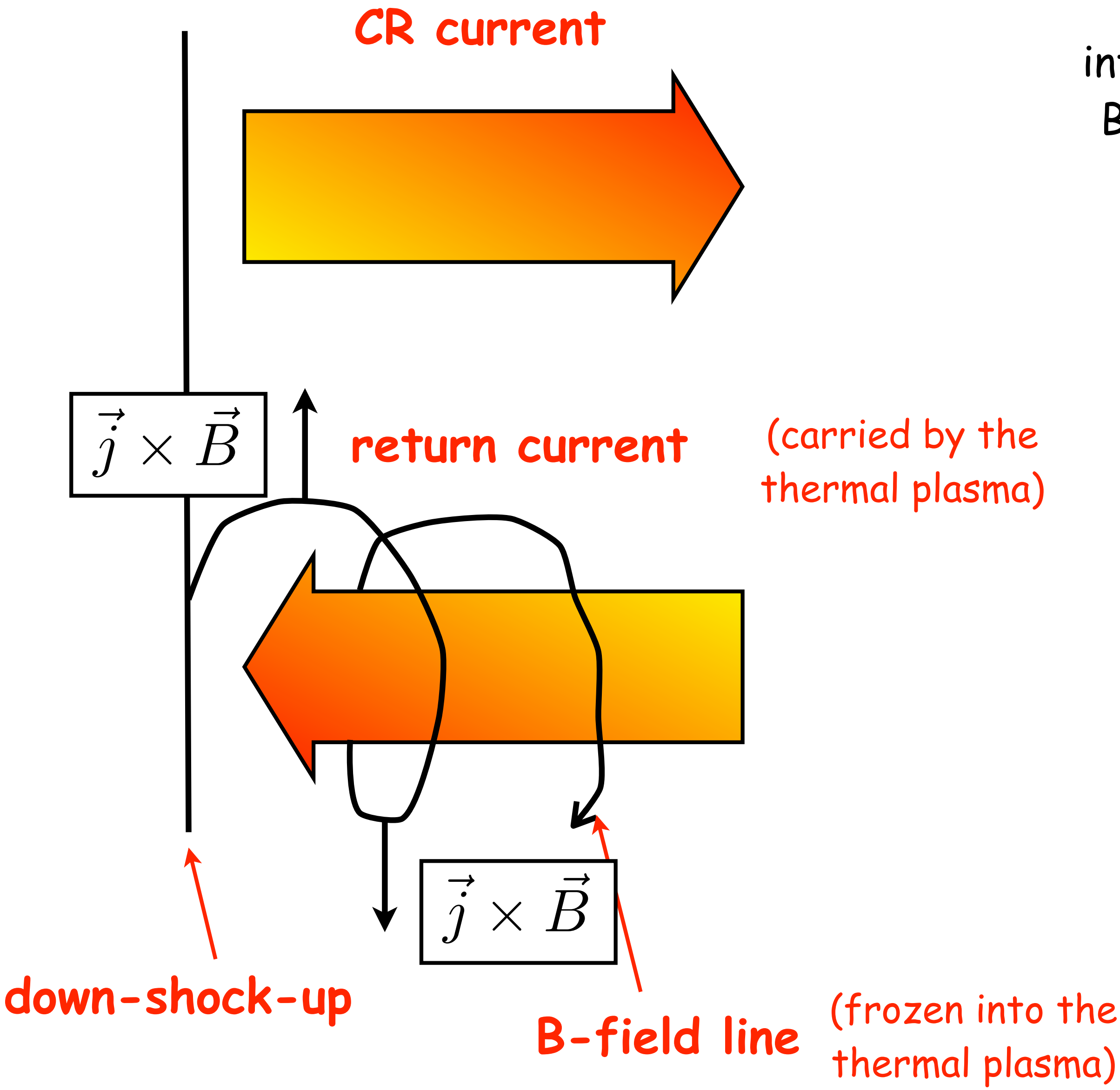

interaction between return current and B-field sets the background plasma in motion and drives the instability

Bell 2004

(Non resonant) current driven instability

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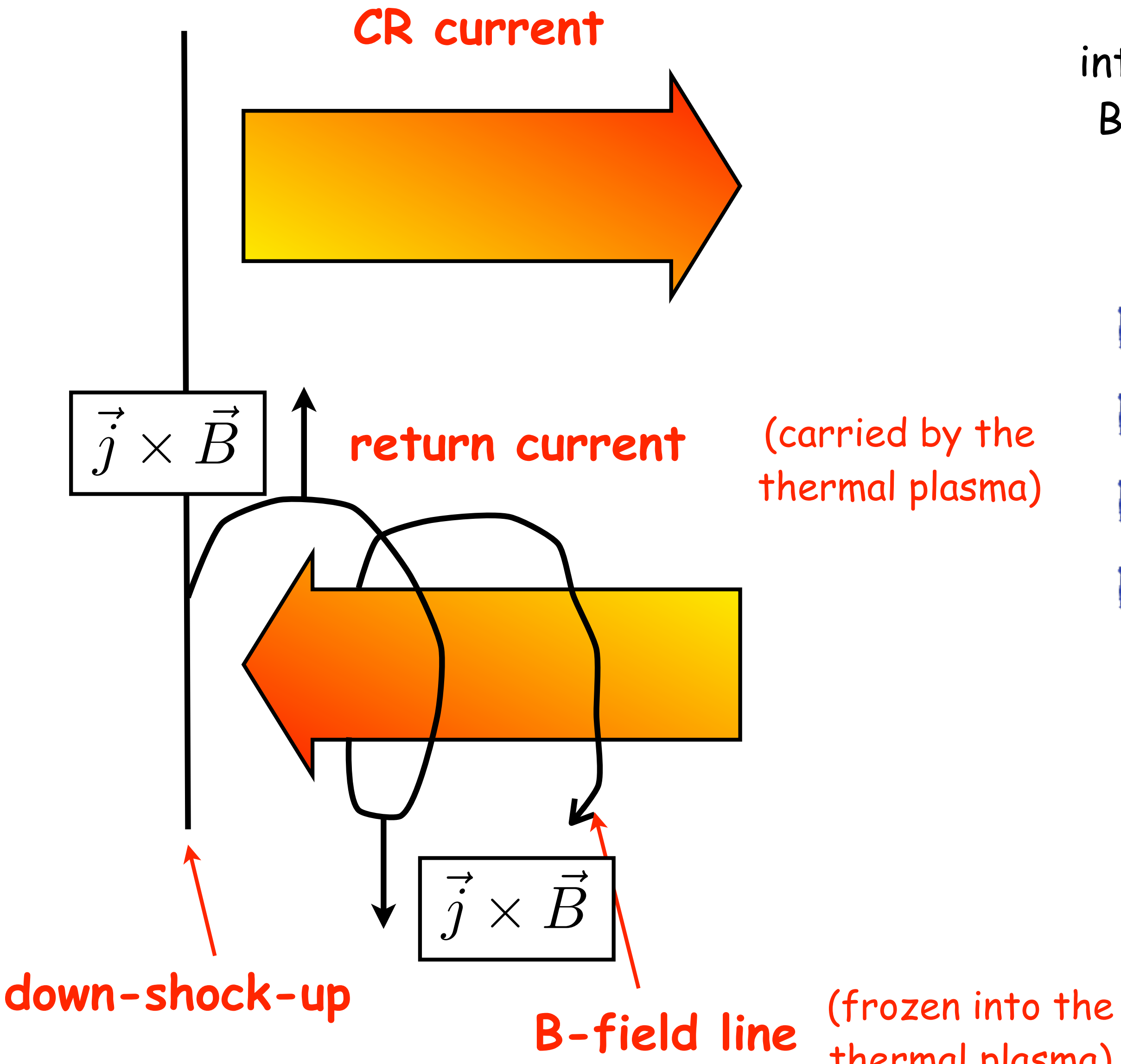


interaction between return current and B-field sets the background plasma in motion and drives the instability

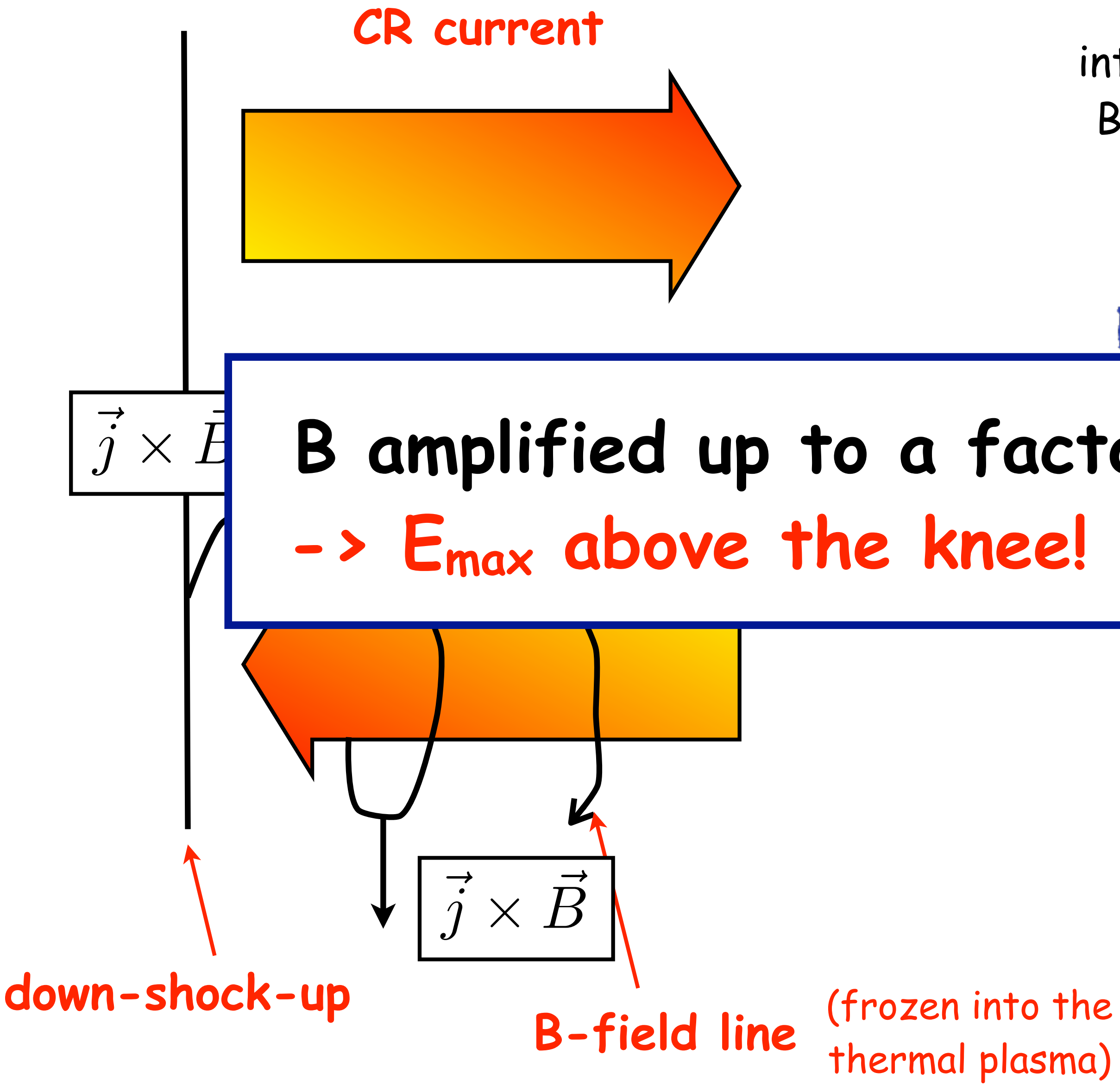
- ☑ j x B force expands the spiral
- ☑ lengthens B-field lines
- ☑ increases B-field
- ☑ increase j x B force!

instability!

Bell 2004

(Non resonant) current driven instability

CRs stream at the shock velocity relative to the background plasma



interaction between return current and B-field sets the background plasma in motion and drives the instability

☑ j x B force expands the spiral

B amplified up to a factor of 100-1000

-> E_{max} above the knee! (naive estimate)

instability!

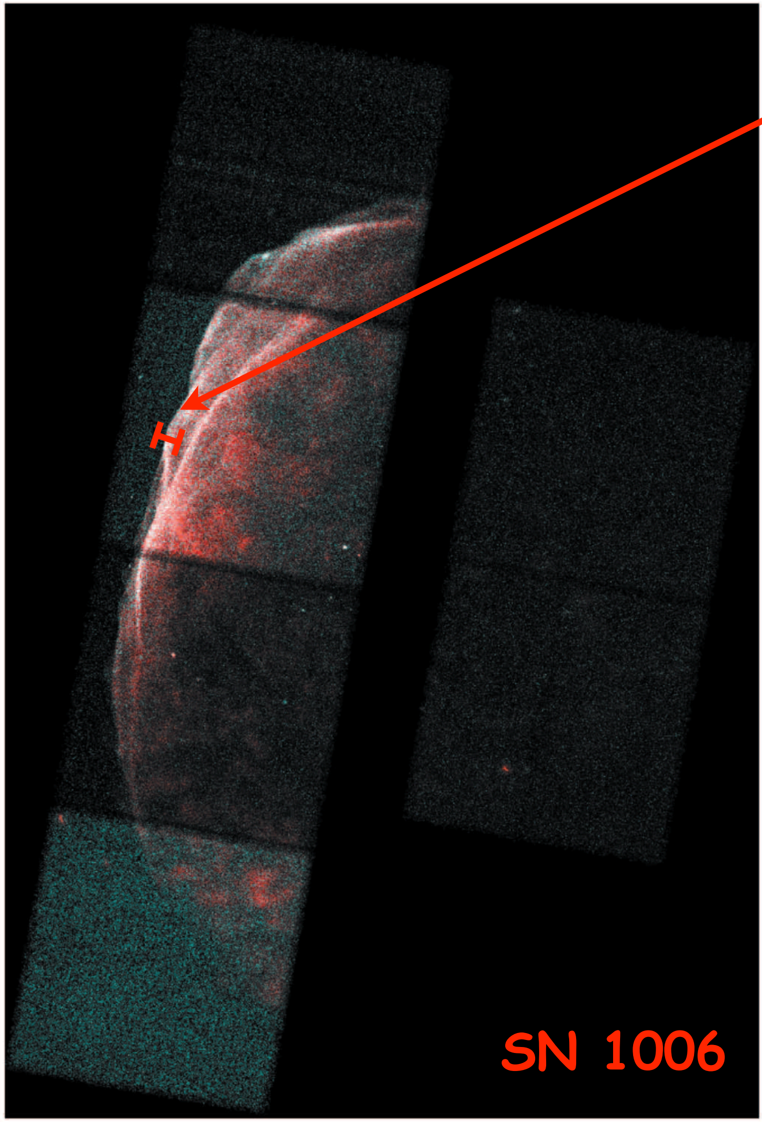
Bell 2004

Evidences for B-field amplification

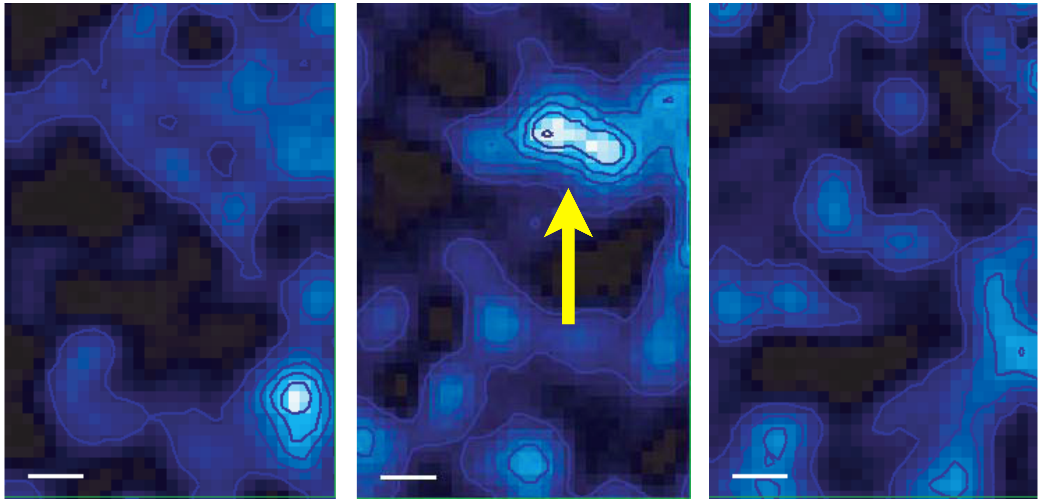
e.g. Vink & Laming 2003, Bamba et al 2003, Volk et al 2005, Uchiyama et al 2007 ...

X-ray filaments

B ~ few hundreds microGauss



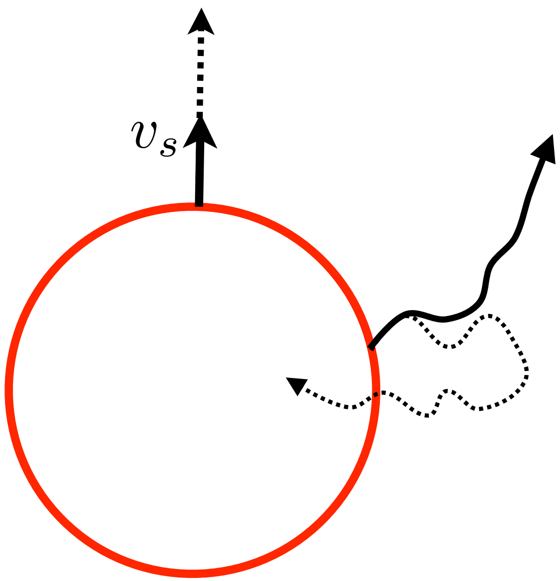
fast X-ray variability



RX J1713

B ~ milliGauss

Particle escape from SNRs



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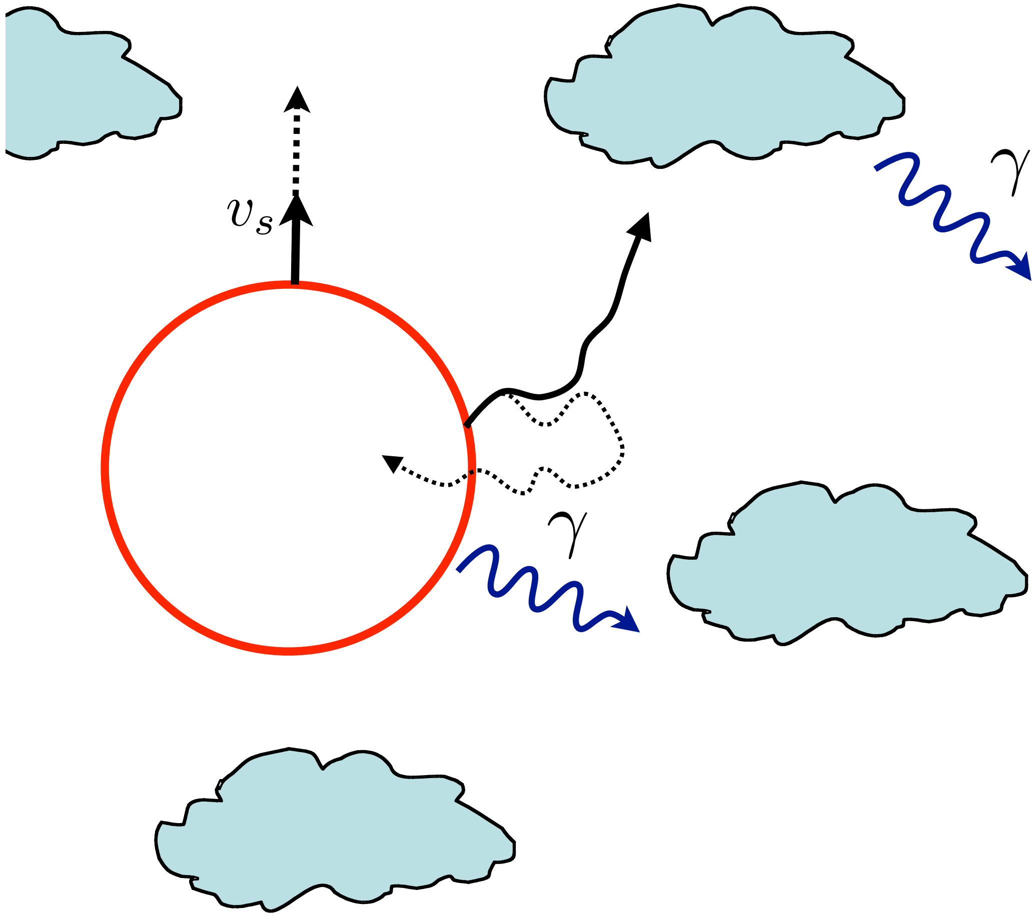
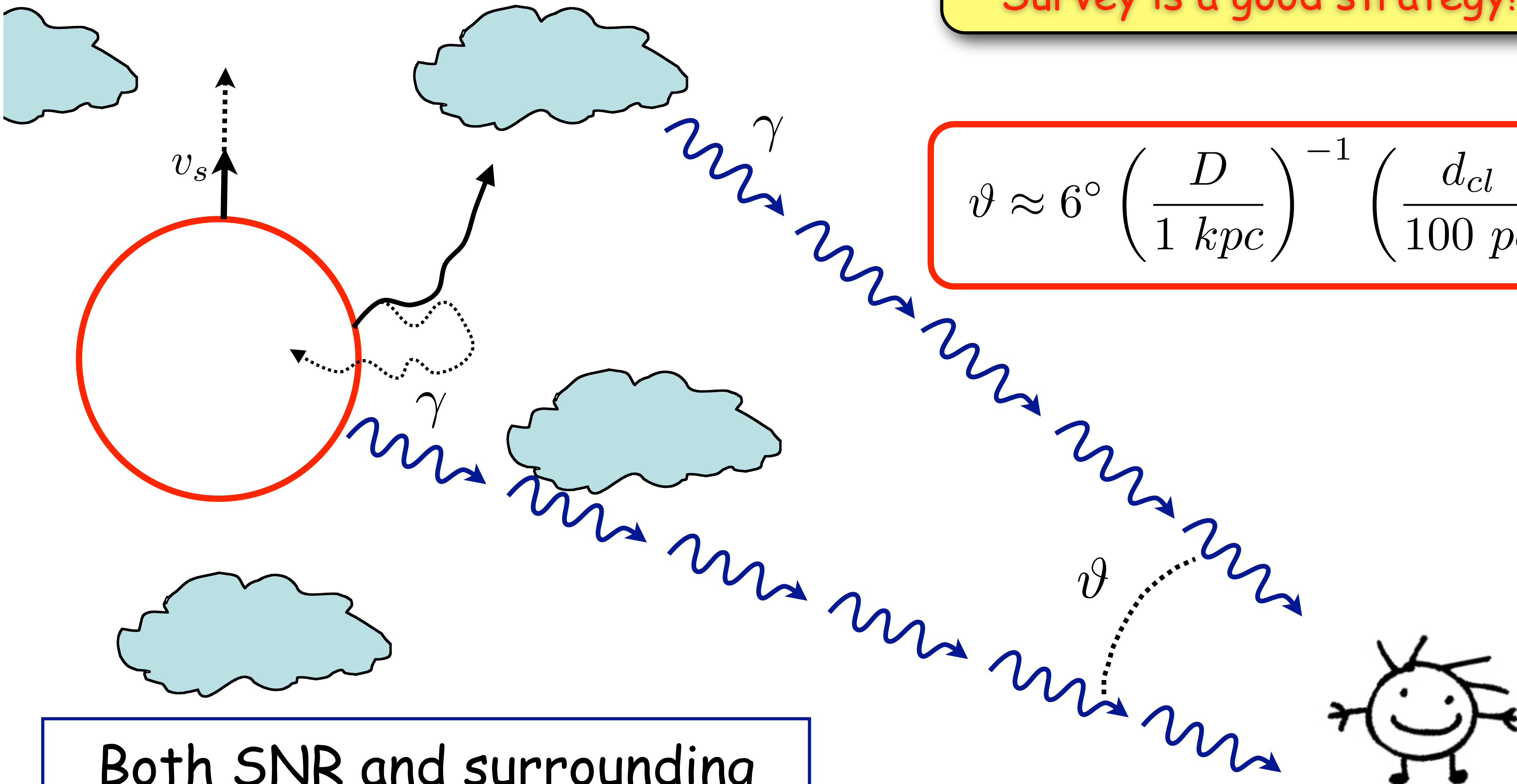


Both SNR and surrounding molecular clouds emit gammas

Particle escape from SNRs

Survey is a good strategy!

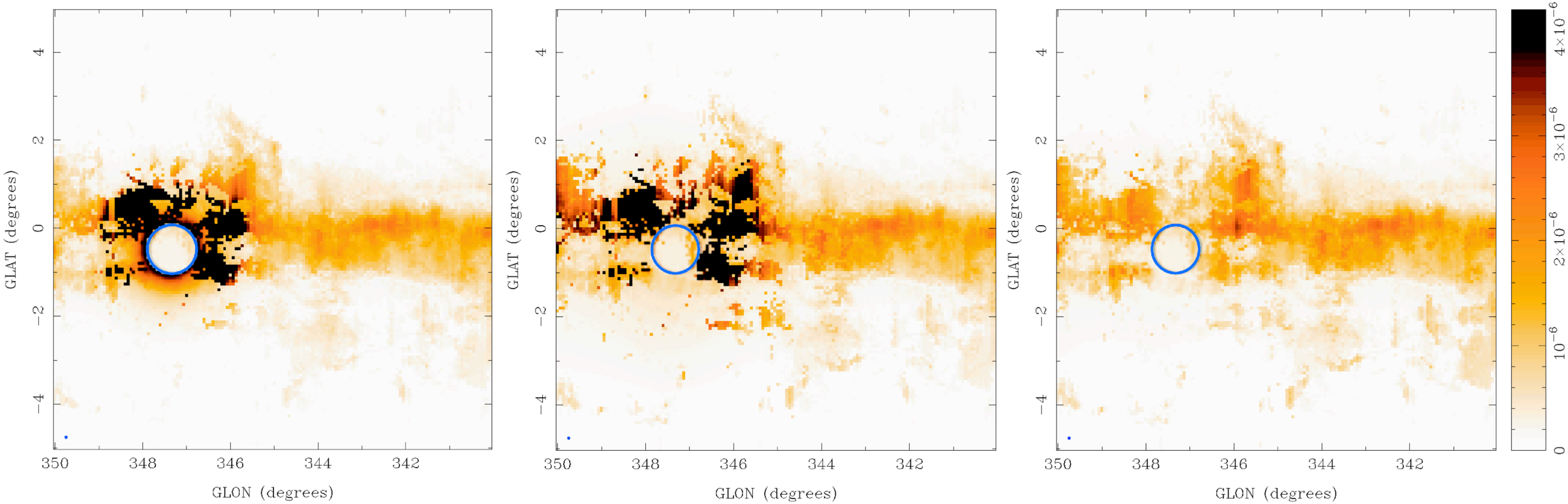
$$\vartheta \approx 6^\circ \left(\frac{D}{1\ kpc} \right)^{-1} \left(\frac{d_{cl}}{100\ pc} \right)$$



Both SNR and surrounding molecular clouds emit gammas

Diffuse emission around RX J1713

Emission at 1 TeV = mol. and atomic gas (NANTEN+LAB survey) + runaway CRs



$$D = 10^{26}\left(\frac{E}{10\mathrm{GeV}}\right)^{0.5}\ \mathrm{cm}^2/\mathrm{s} \qquad D = 10^{27}\left(\frac{E}{10\mathrm{GeV}}\right)^{0.5}\ \mathrm{cm}^2/\mathrm{s} \qquad D = 10^{28}\left(\frac{E}{10\mathrm{GeV}}\right)^{0.5}\ \mathrm{cm}^2/\mathrm{s}$$

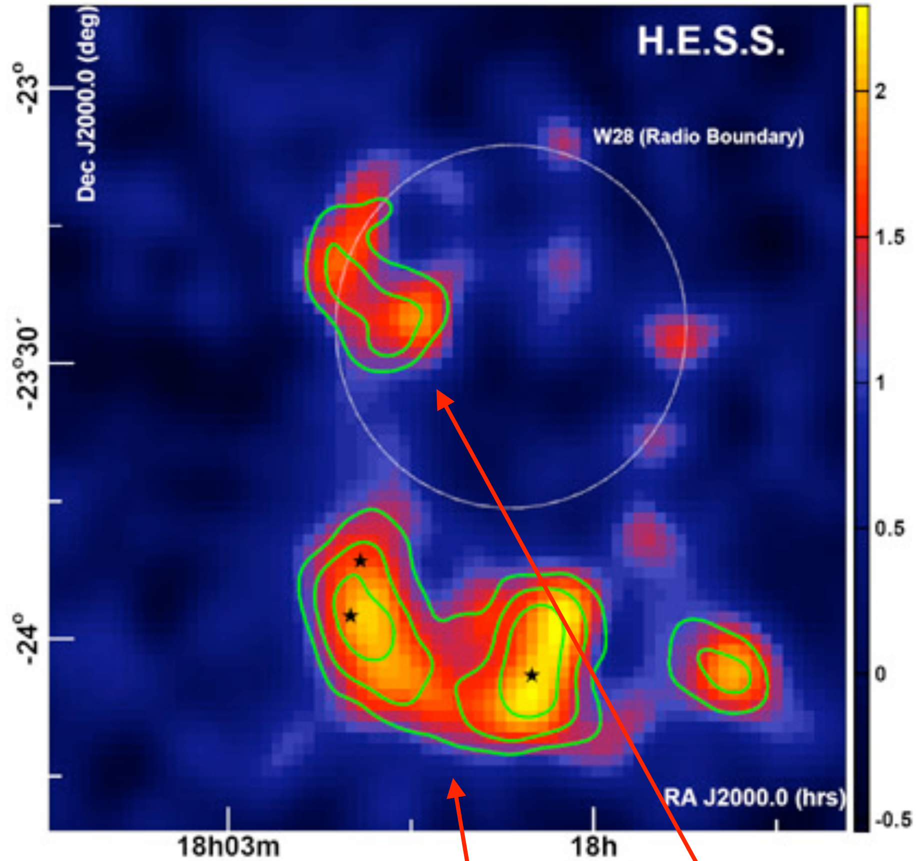
average diffusion coefficient in the Galaxy
from spallation measurements

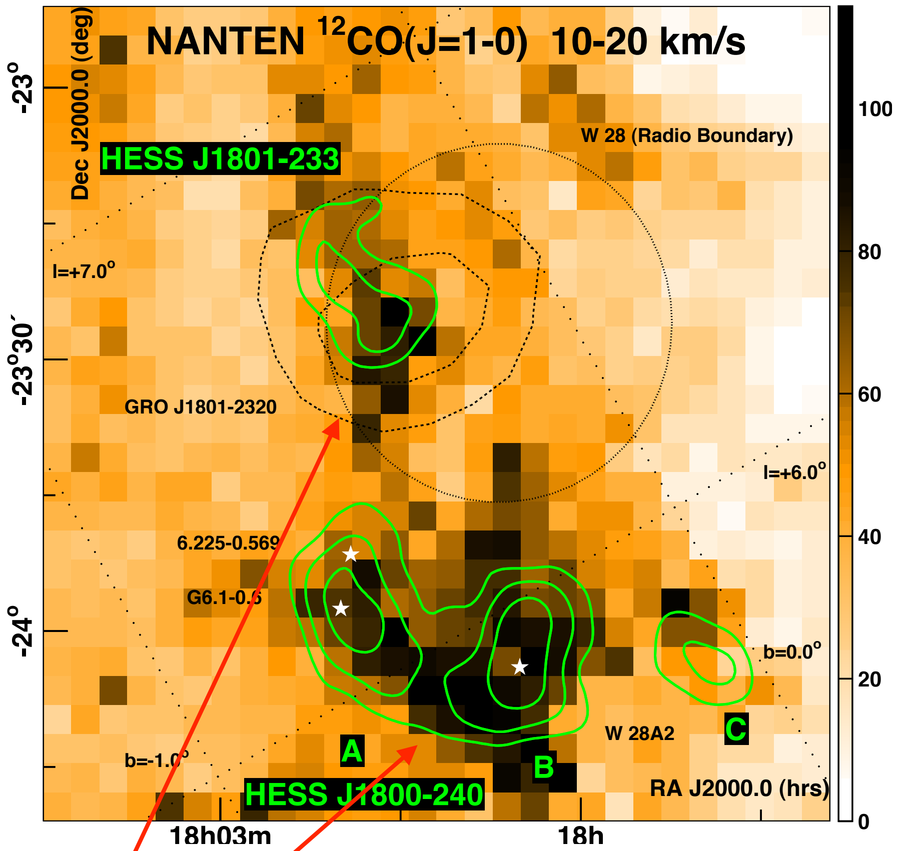
Casanova et al, 2010

W28: gamma rays from runaway particles?

TeV emission

gas distribution





good match between TeV emission and gas density distribution

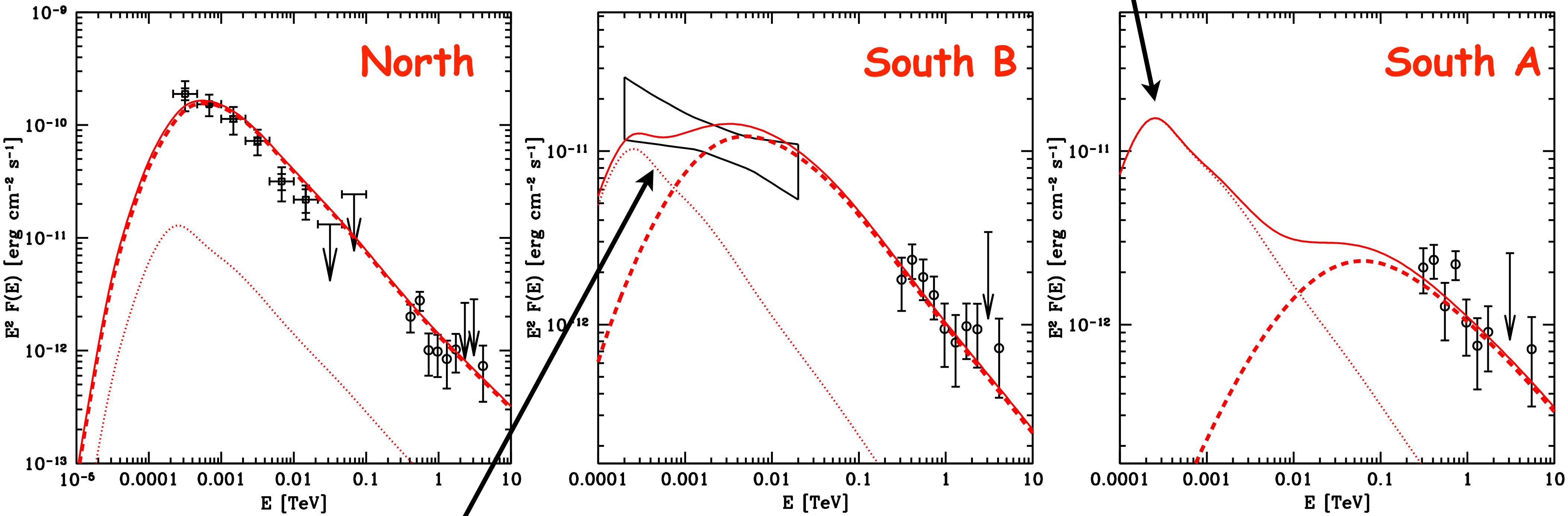
HESS coll., 2008

W28: GeV & TeV emission

Gabici et al, 2010

$$\eta = 30\%$$
$$\chi = 0.06$$

this peak is removed as background



d = 12 pc

d = 32 pc

d = 65 pc

some problems here...

+ some of the approximations are not very good at low energies
+ subtraction of the background?
+ other contributions? (Bremsstrahlung)

SNRs as CR sources: summary

SNRs can provide:

- ☑ the total energy
- ☑ (more or less) the correct spectrum
- ☑ the maximum CR energy needed to reach the knee and beyond...
- ☑ indirect evidence from CR interactions in the surrounding ISM?

(-> mol clouds...)

to explain the observed CR spectrum

...but we are still missing a convincing proof of that

Tomorrow: how to distinguish between
hadronic and leptonic origin of the gamma ray emission