Gamma ray astronomy and the origin of galactic cosmic rays

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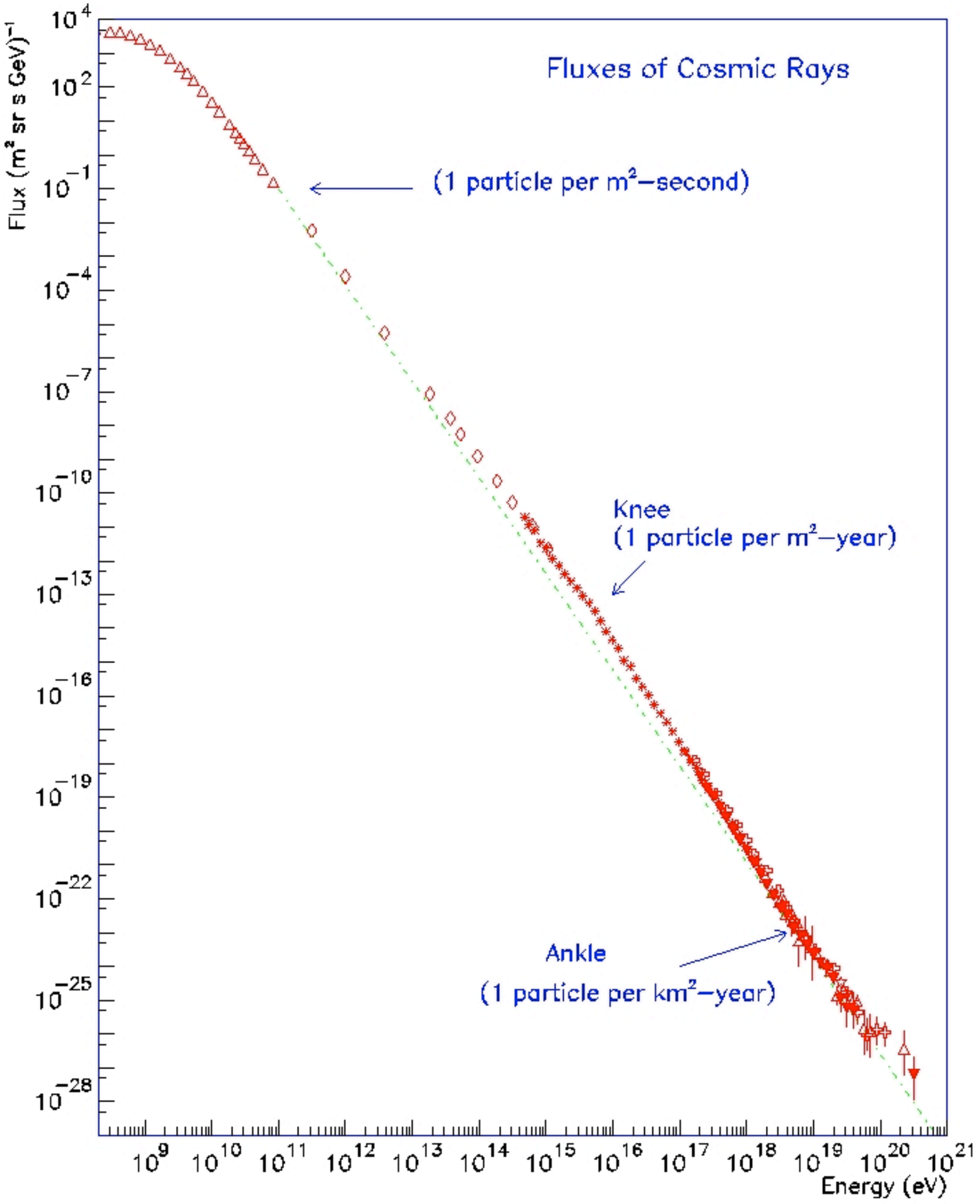
The (local) Cosmic Ray spectrum



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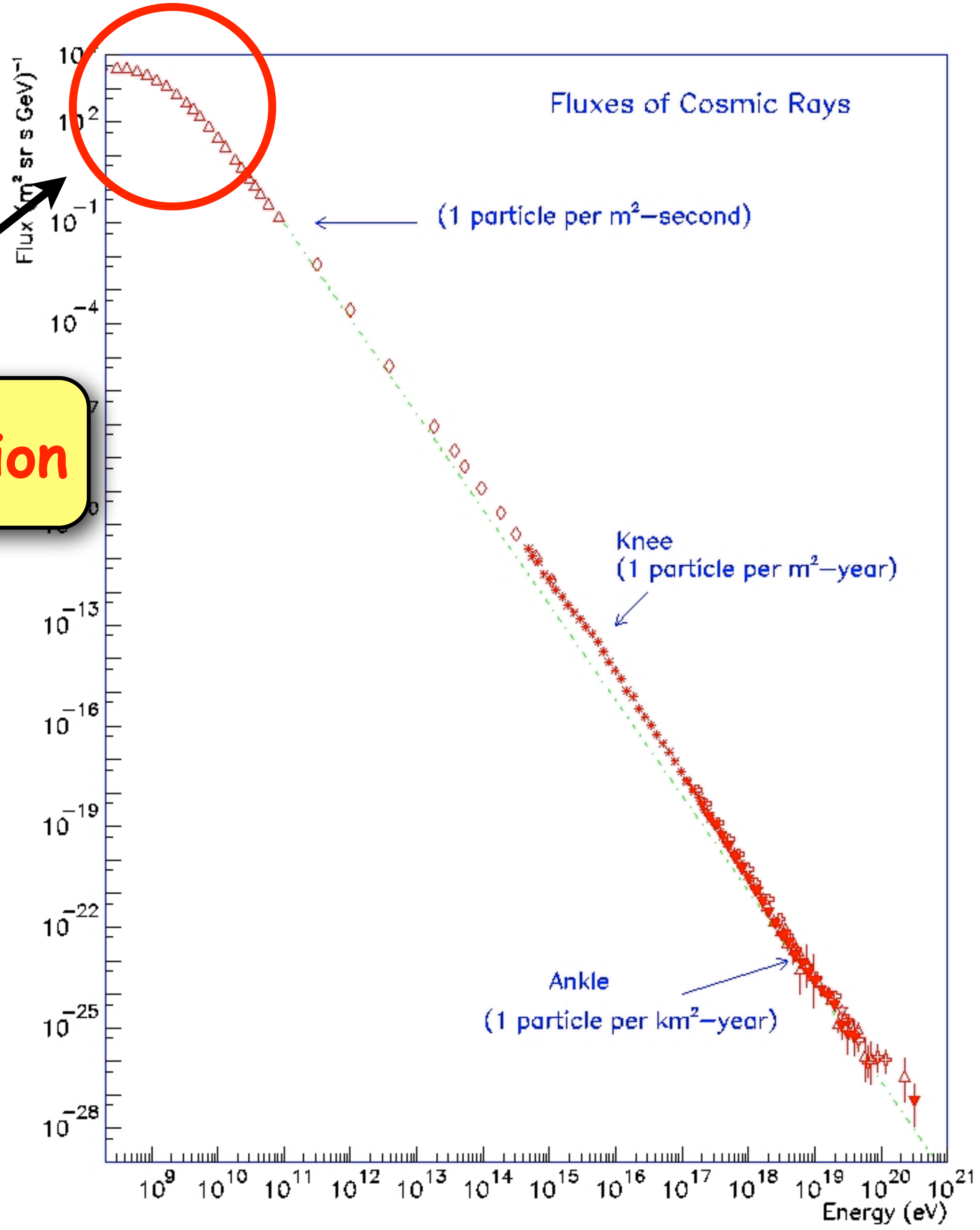

solar modulation

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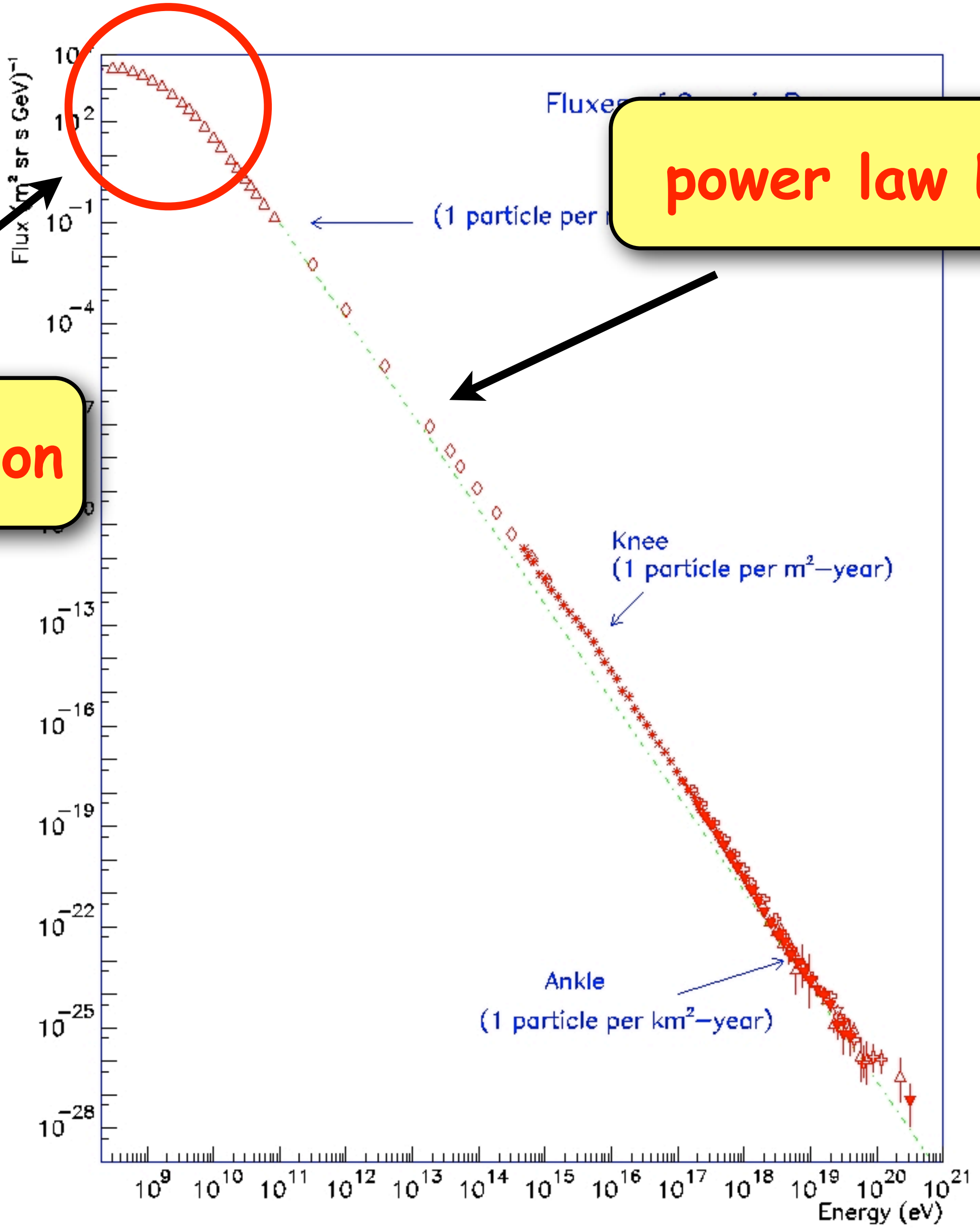

solar modulation

power law $E^{-2.7}$

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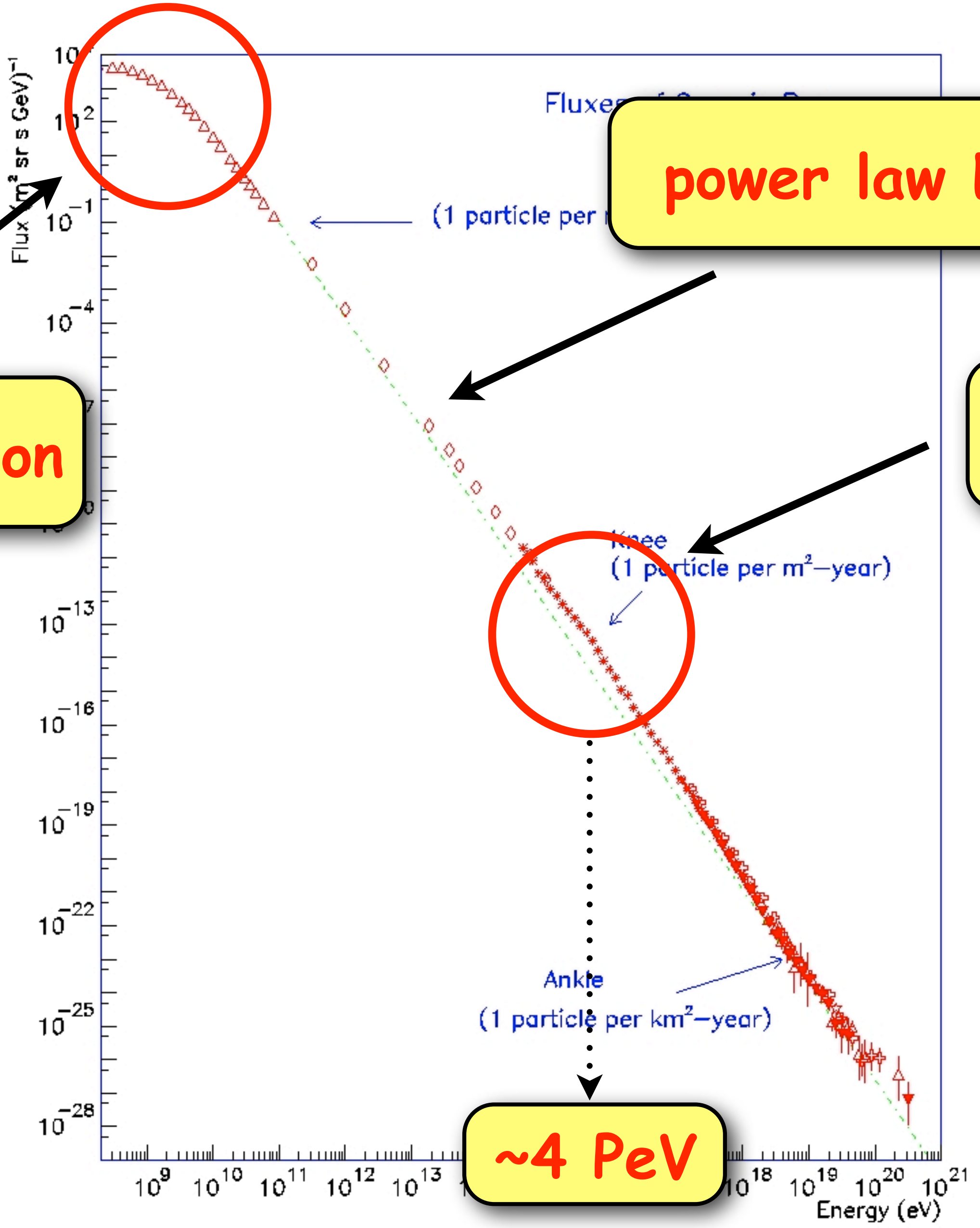

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solar modulation

"CR knee"

~4 PeV

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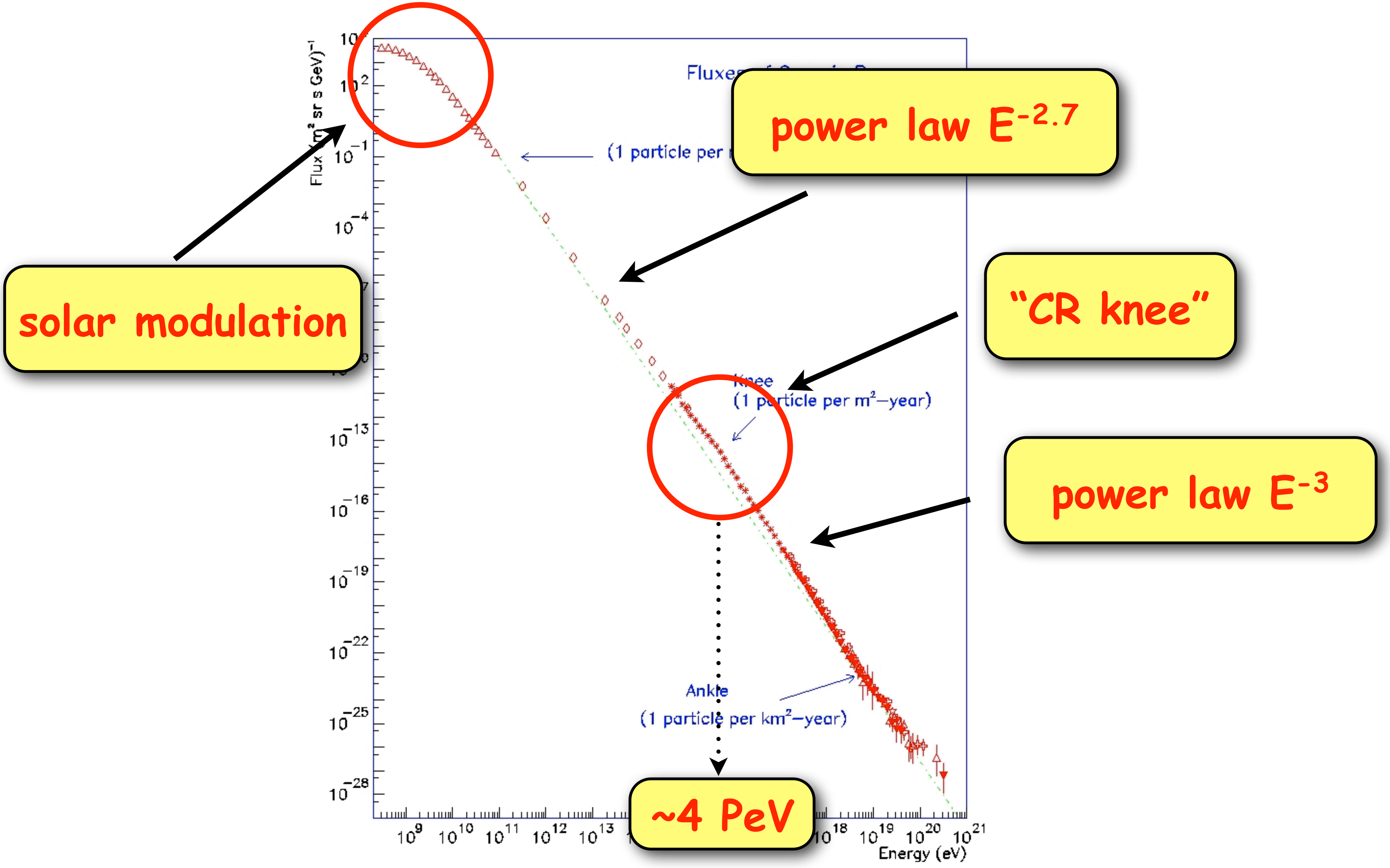

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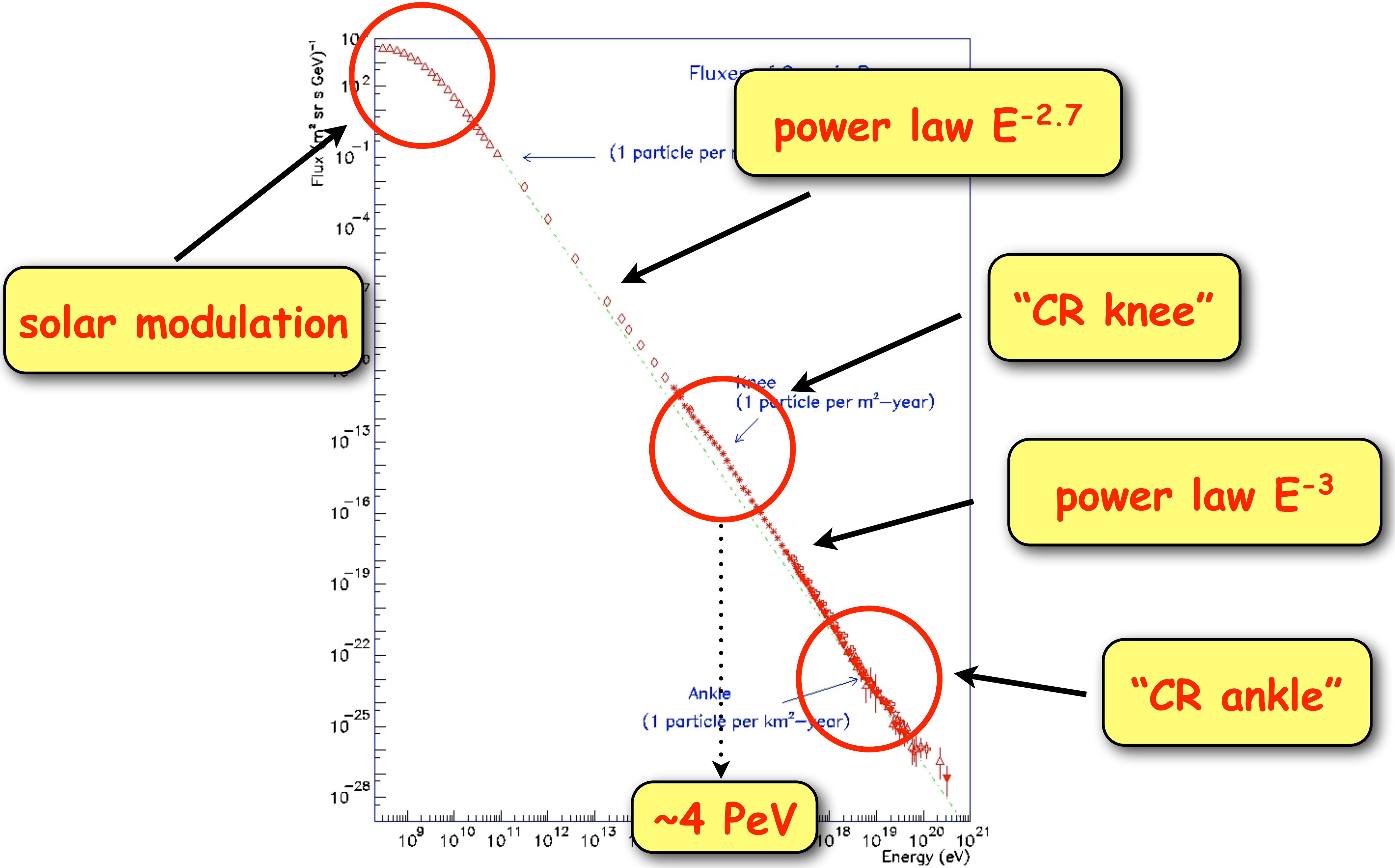

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Energy density

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

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CRs are dynamically important in the Galaxy

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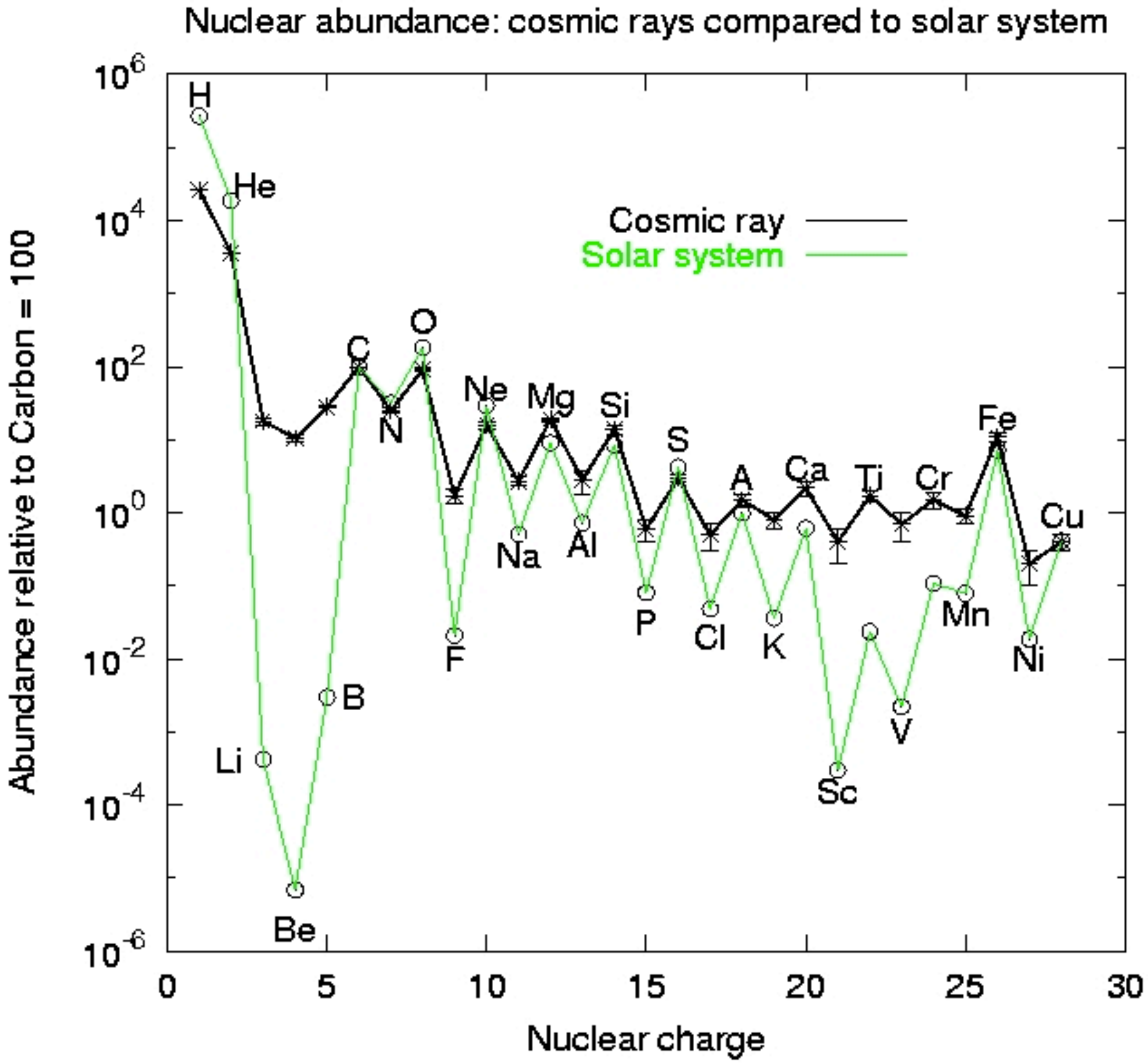
similar to energy density of radiation field -> coincidence or connection?

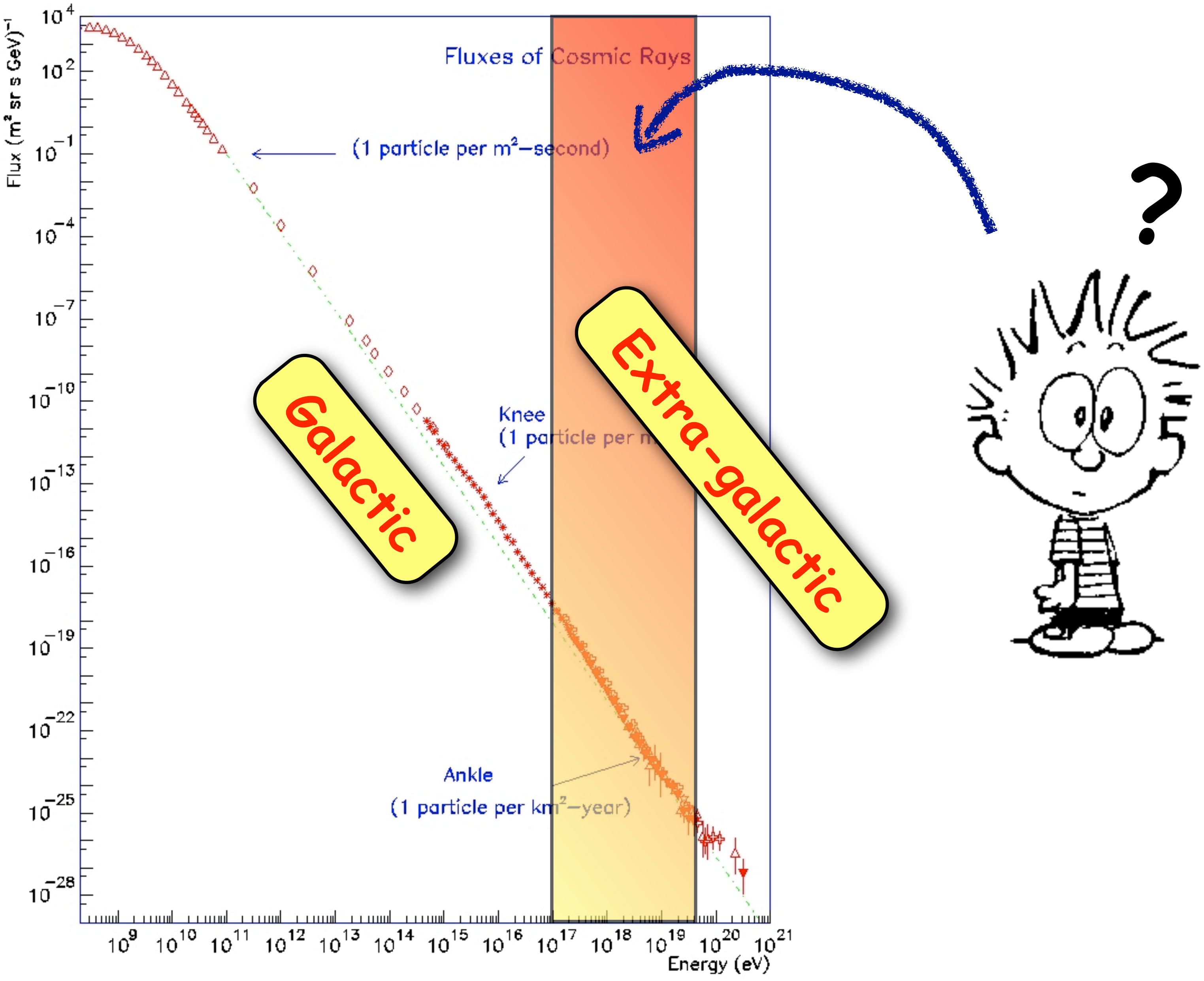
CRs are dynamically important in the Galaxy

Cosmic Ray composition

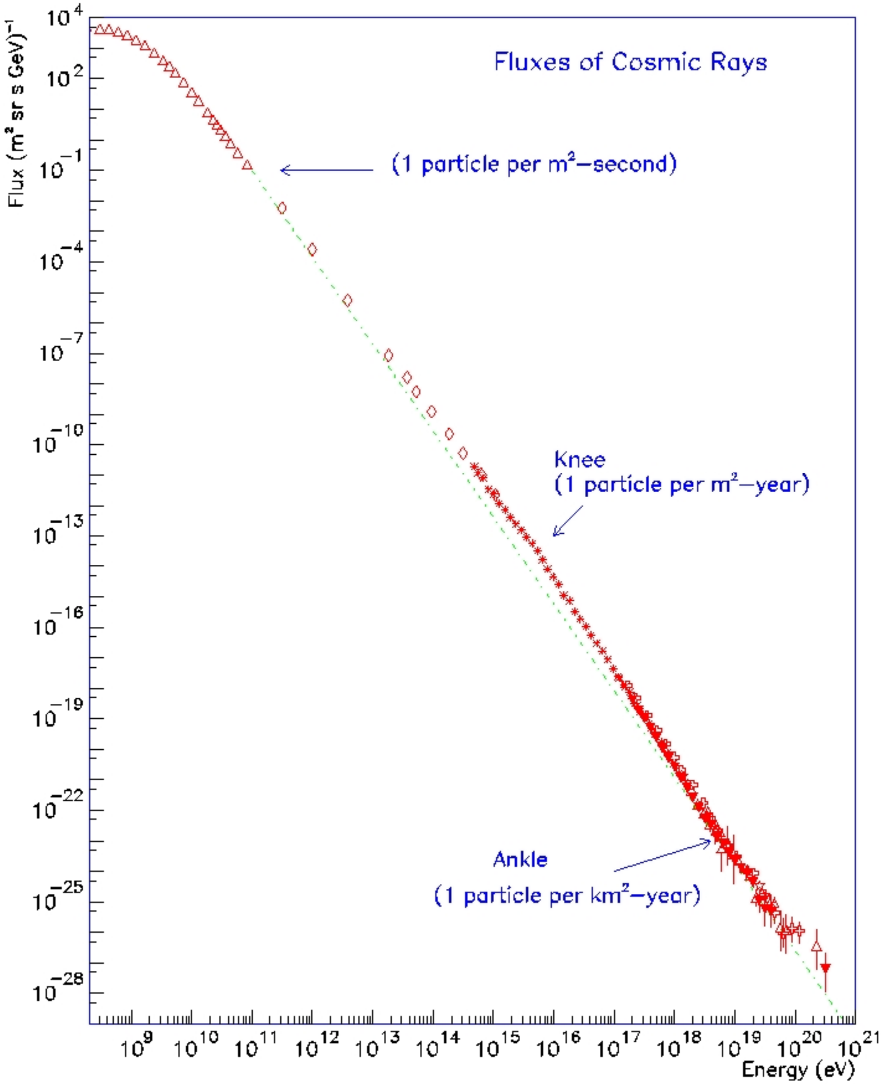


Gaisser & Stanev, 2005

Galactic or extra-galactic?

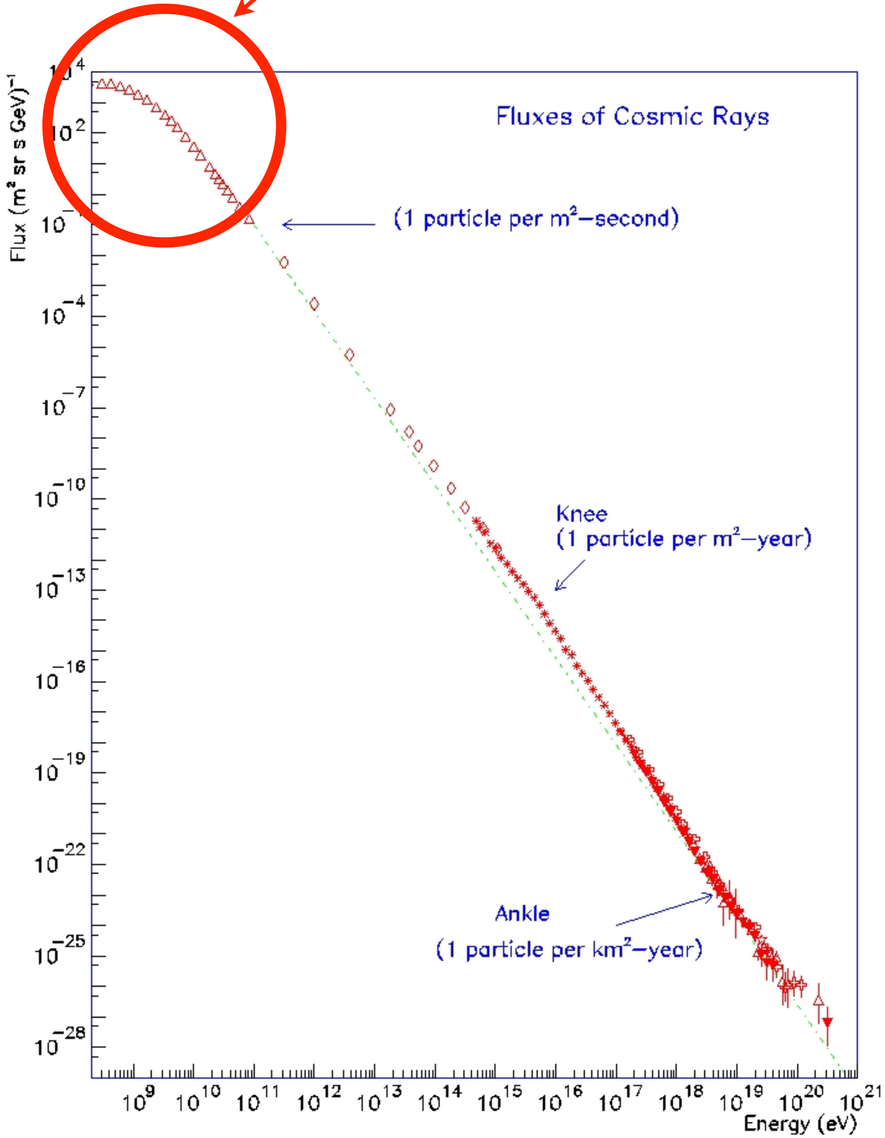


Things we have to explain



Things we have to explain

bulk of CRs



- CR energy density in the Galaxy -> 1 eV/cm^3

- which sources can provide that?
- haw can we identify them?
  - -> gamma rays from CR interactions

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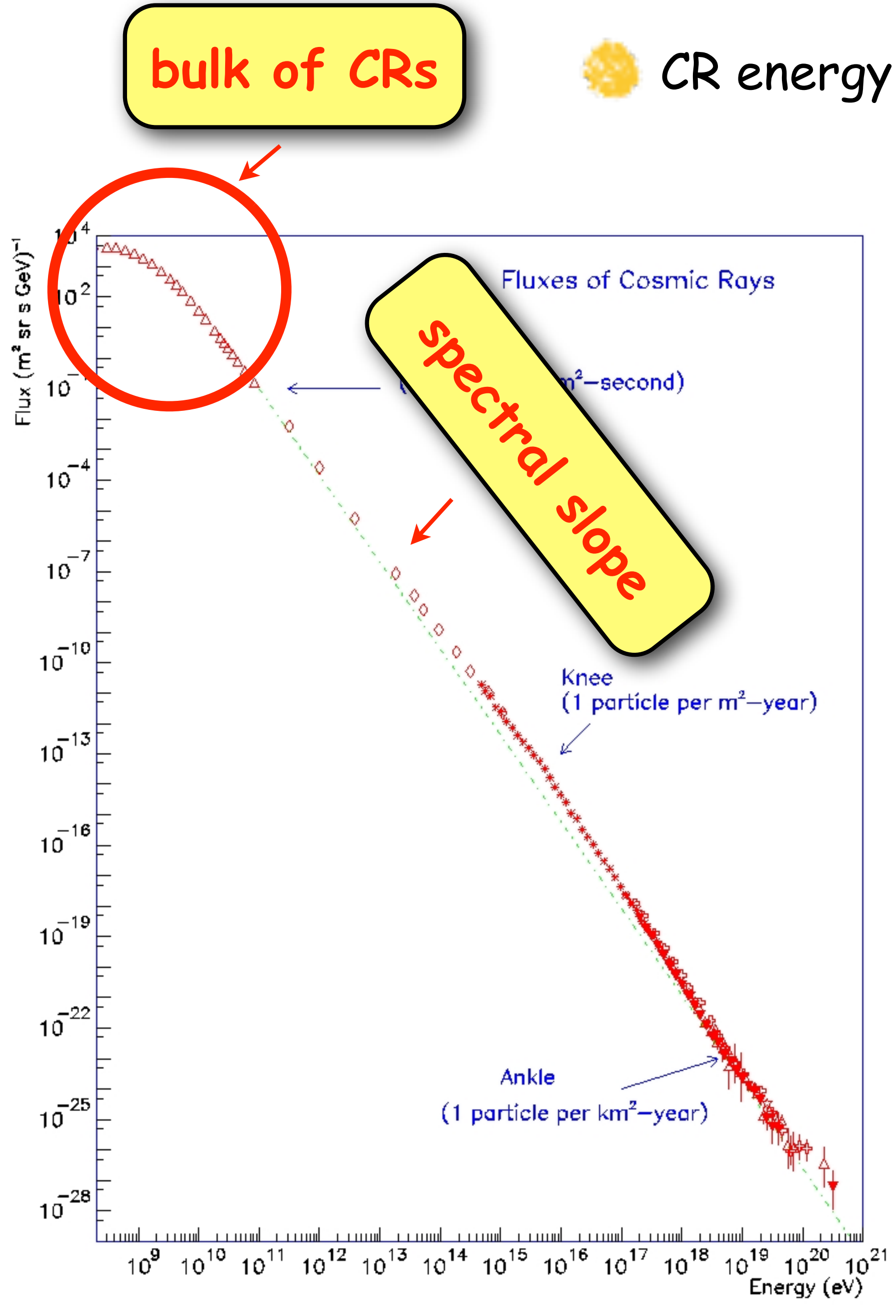

bulk of CRs

spectral slope

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  + which acceleration mechanism?
  + how is CR propagation affecting this?

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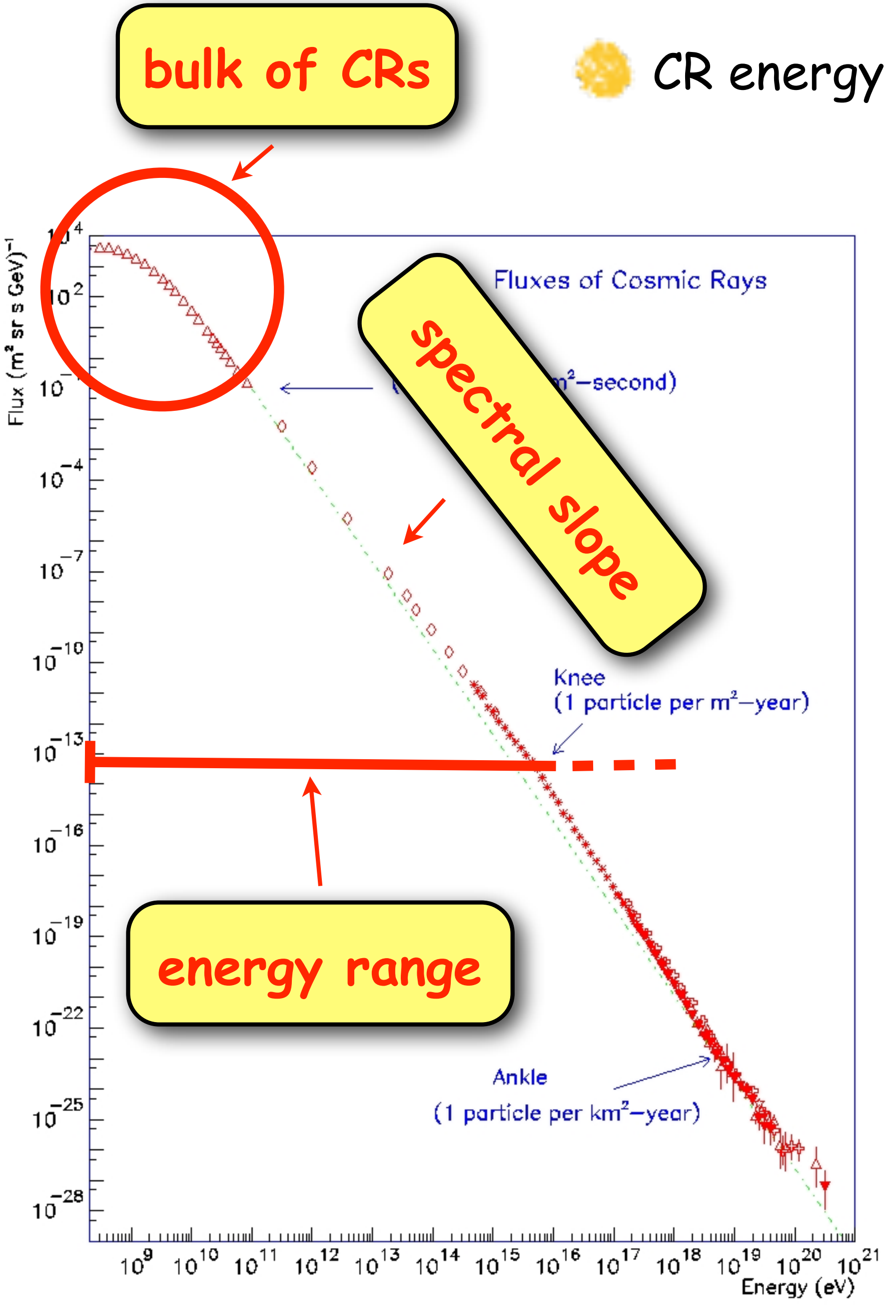

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  -> at least up to the knee (~ 4 PeV)

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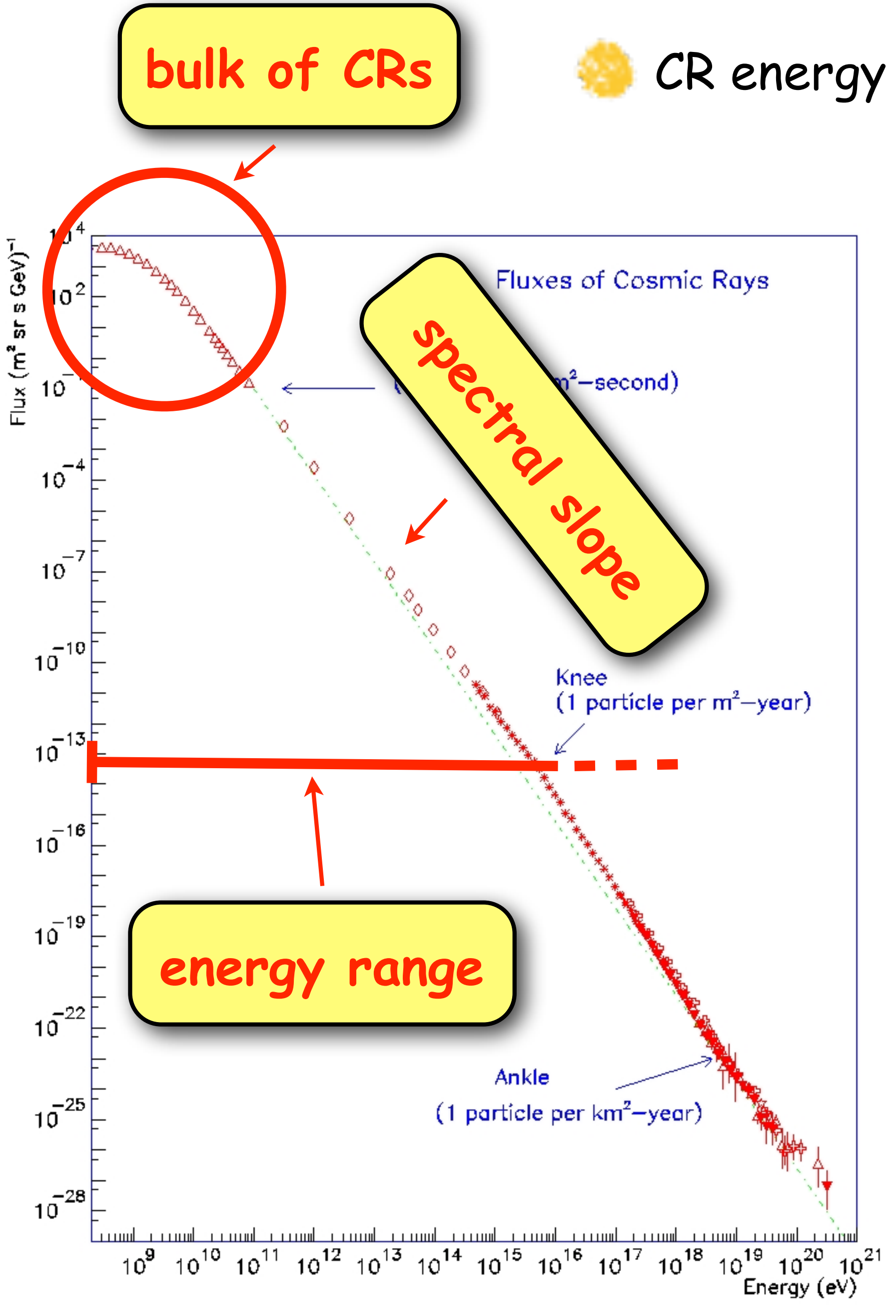

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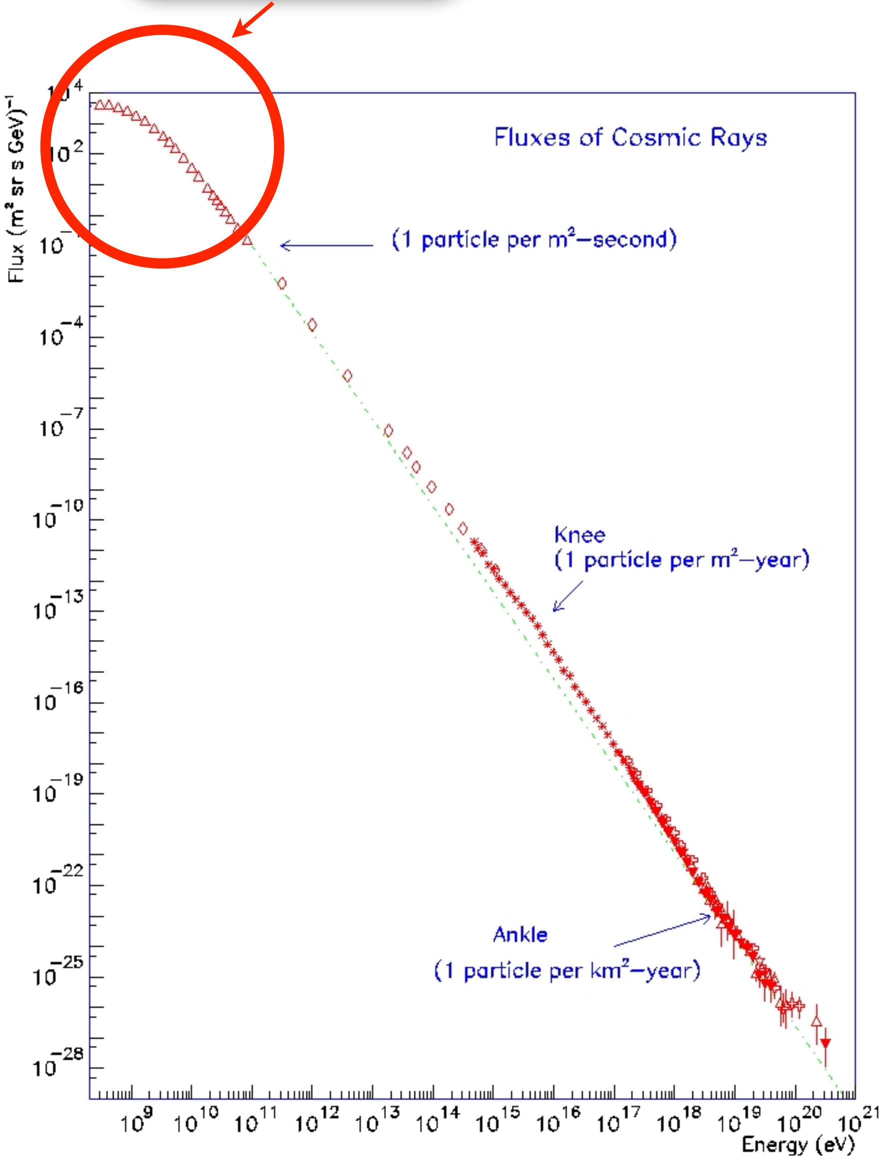
- more issues -> isotropy & chemical composition

The SuperNova Remnant hypothesis

bulk of CRs



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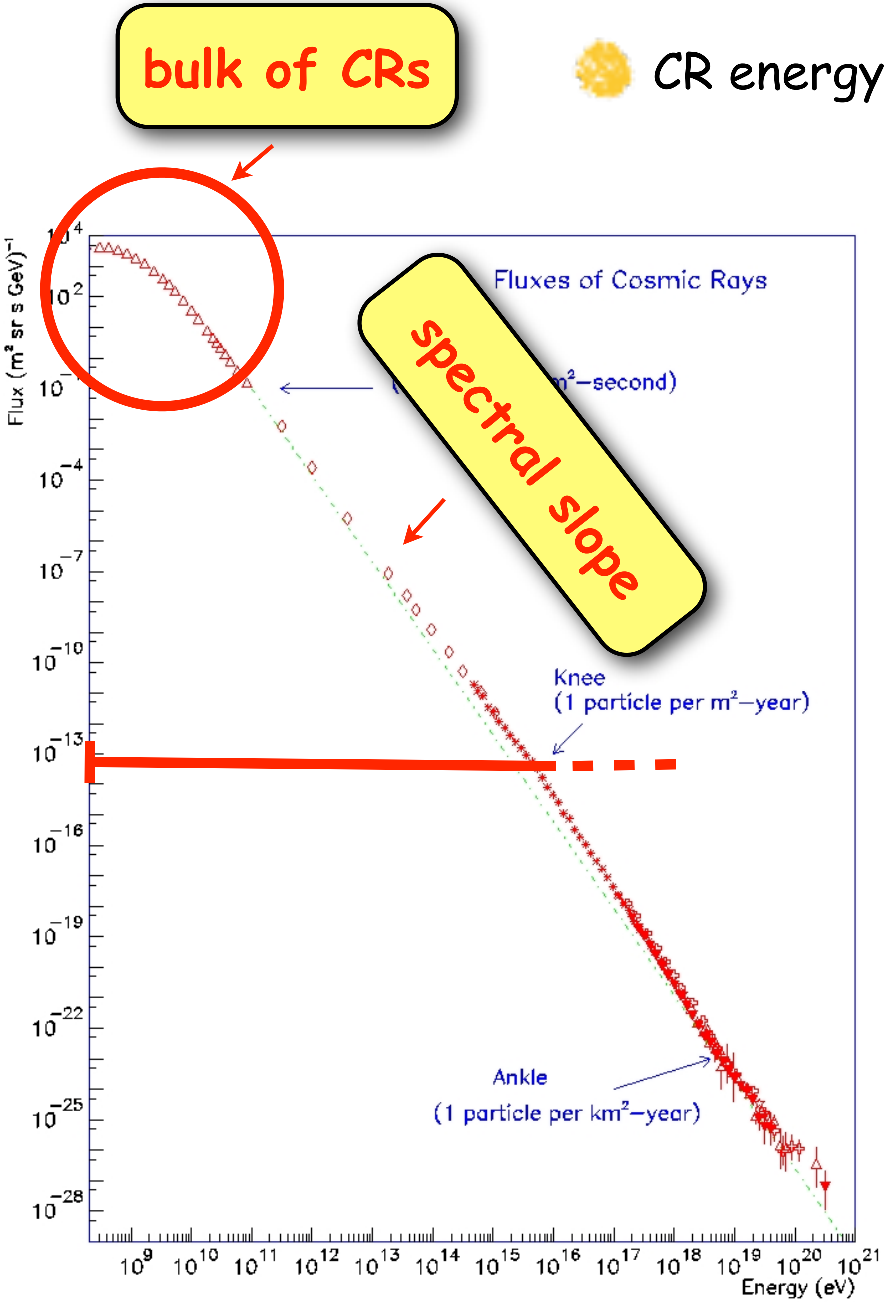

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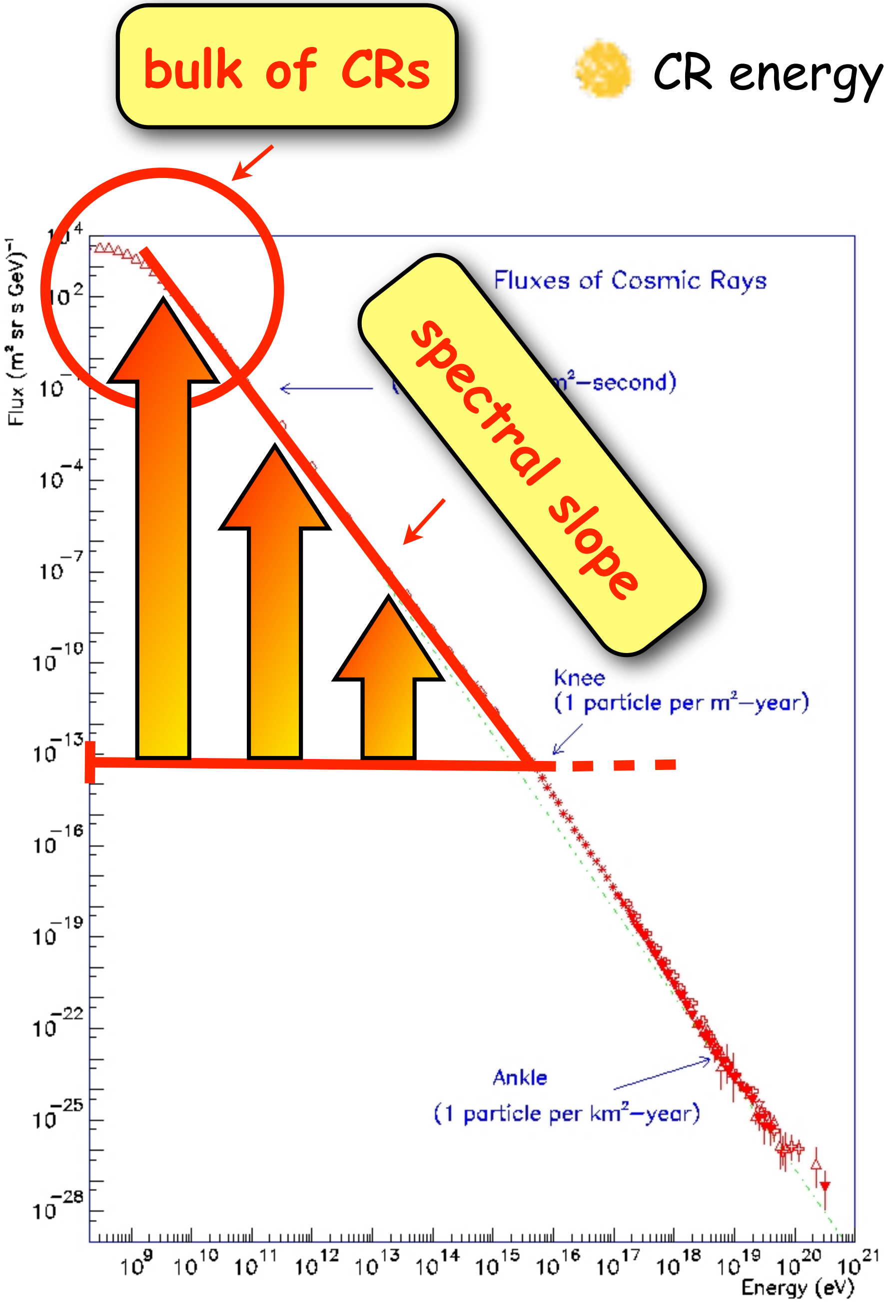

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diffusion

+ higher energy CRs escape faster
+ equilibrium spectrum **~E$^{-2.7}$**

+ isotropy...

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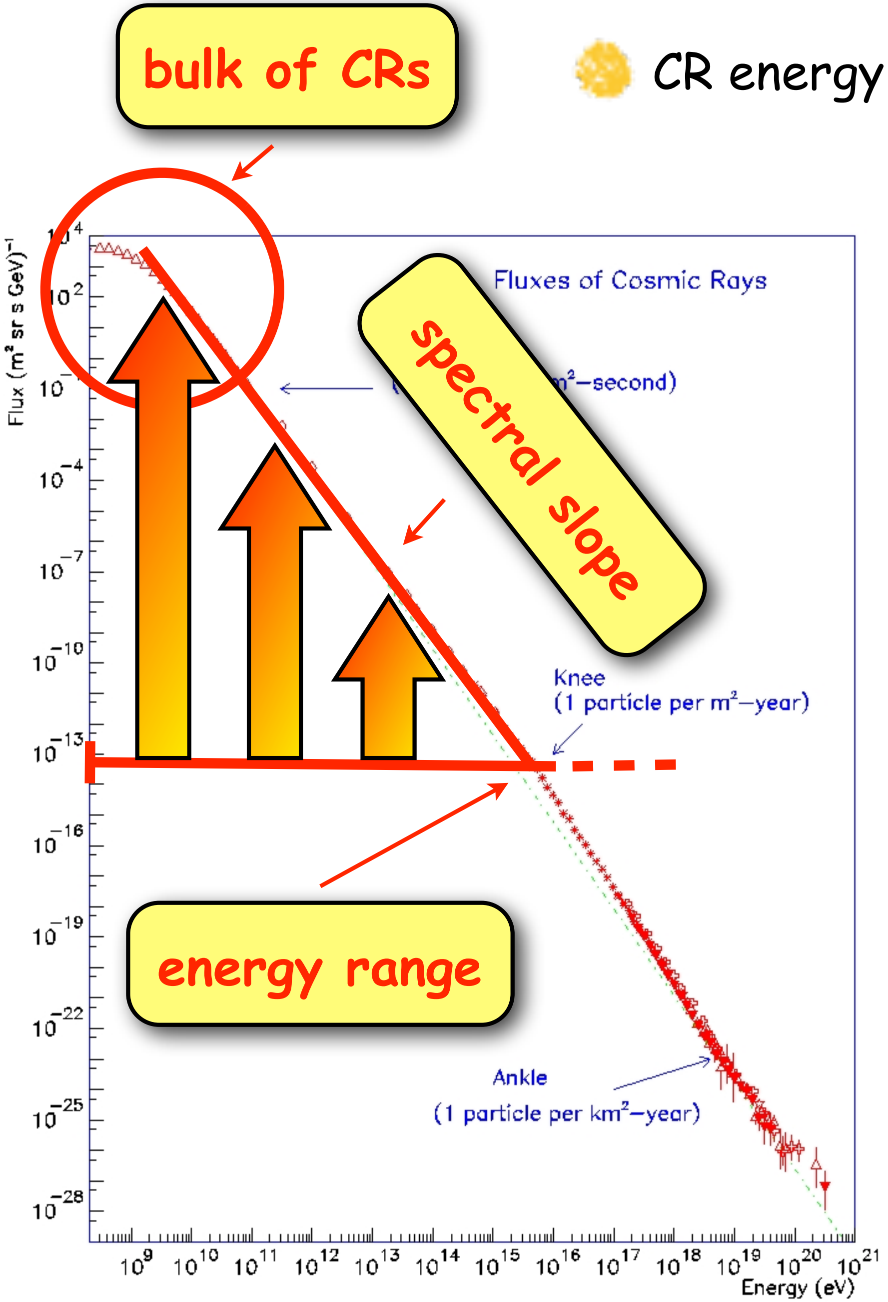

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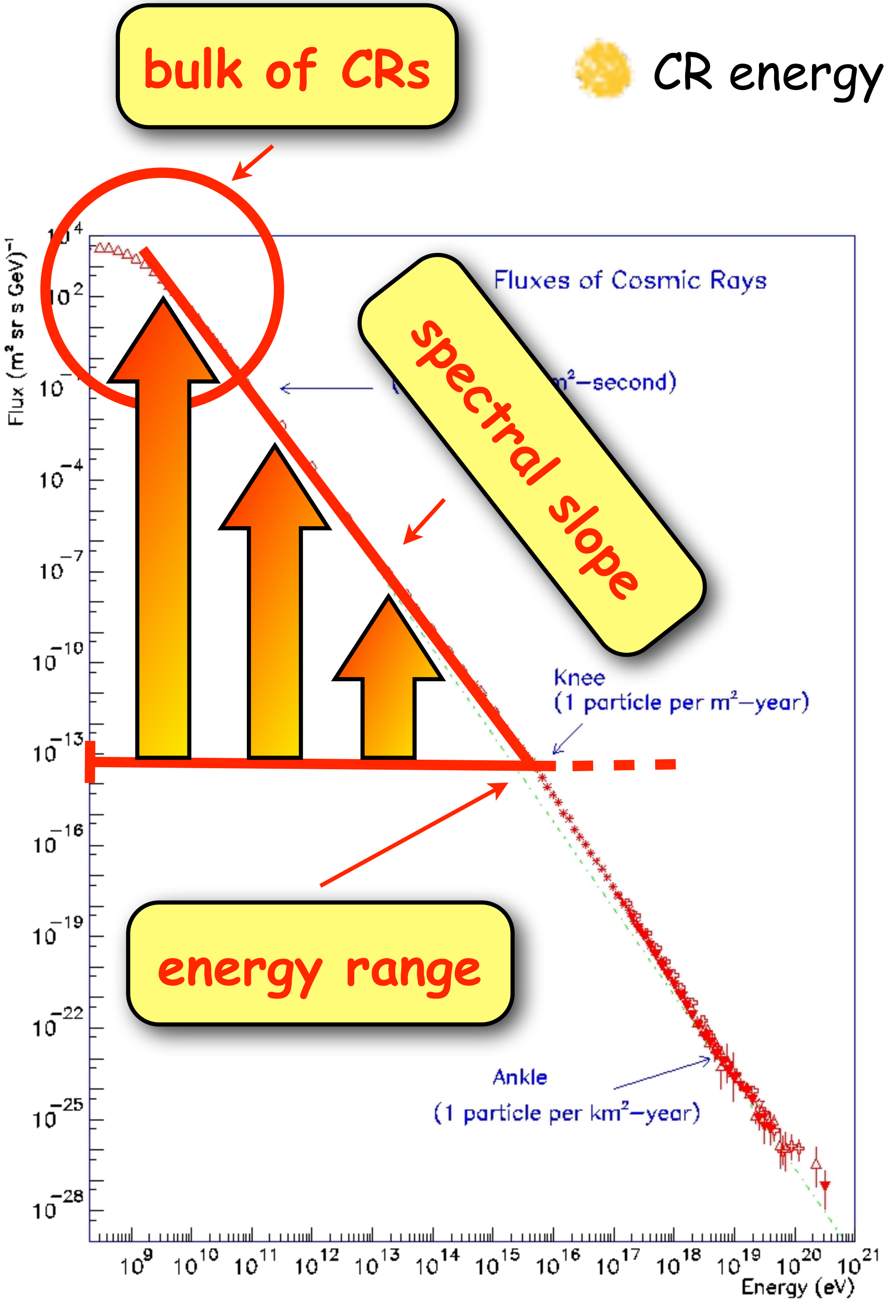

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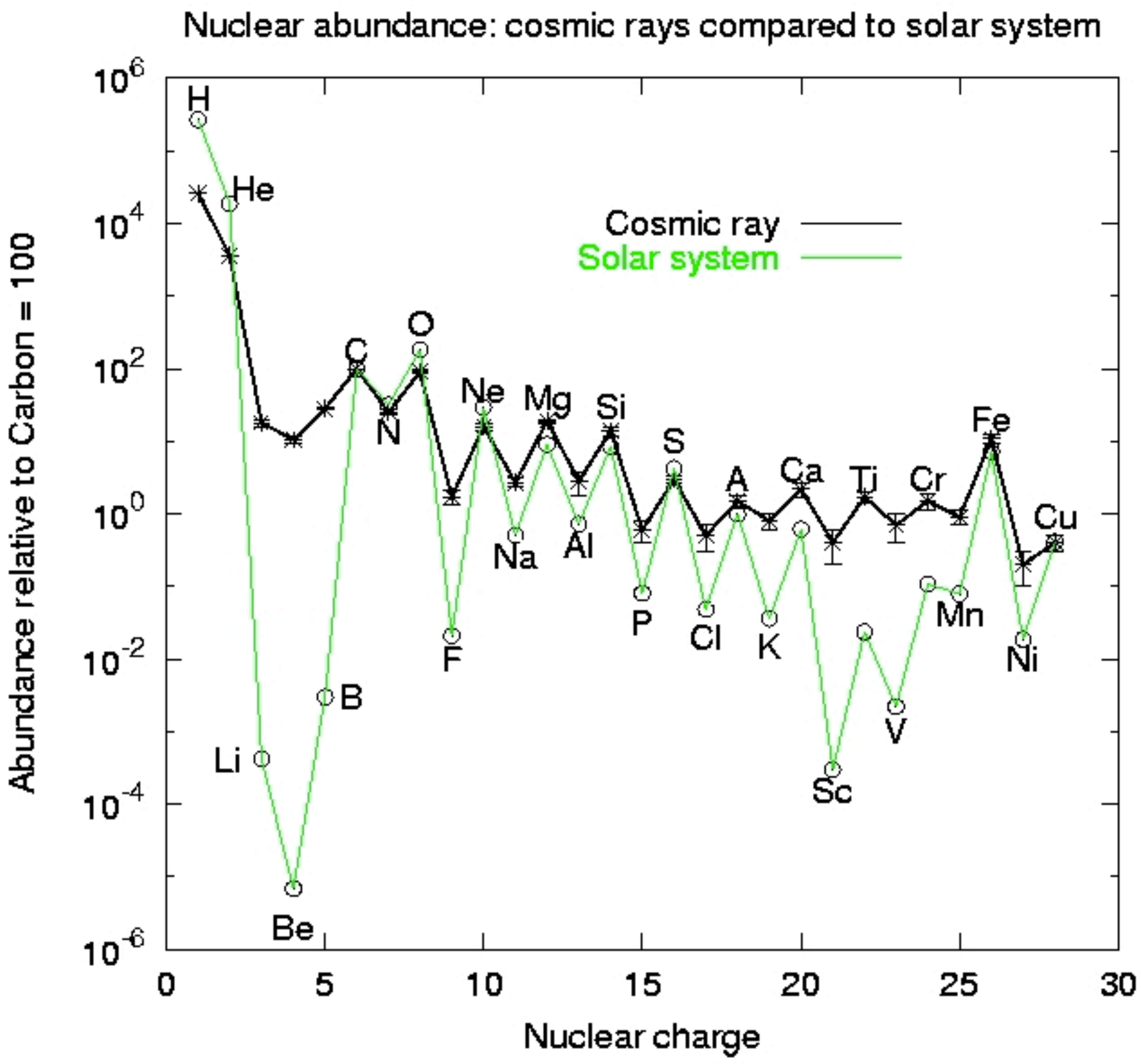

Gaisser & Stanev, 2005

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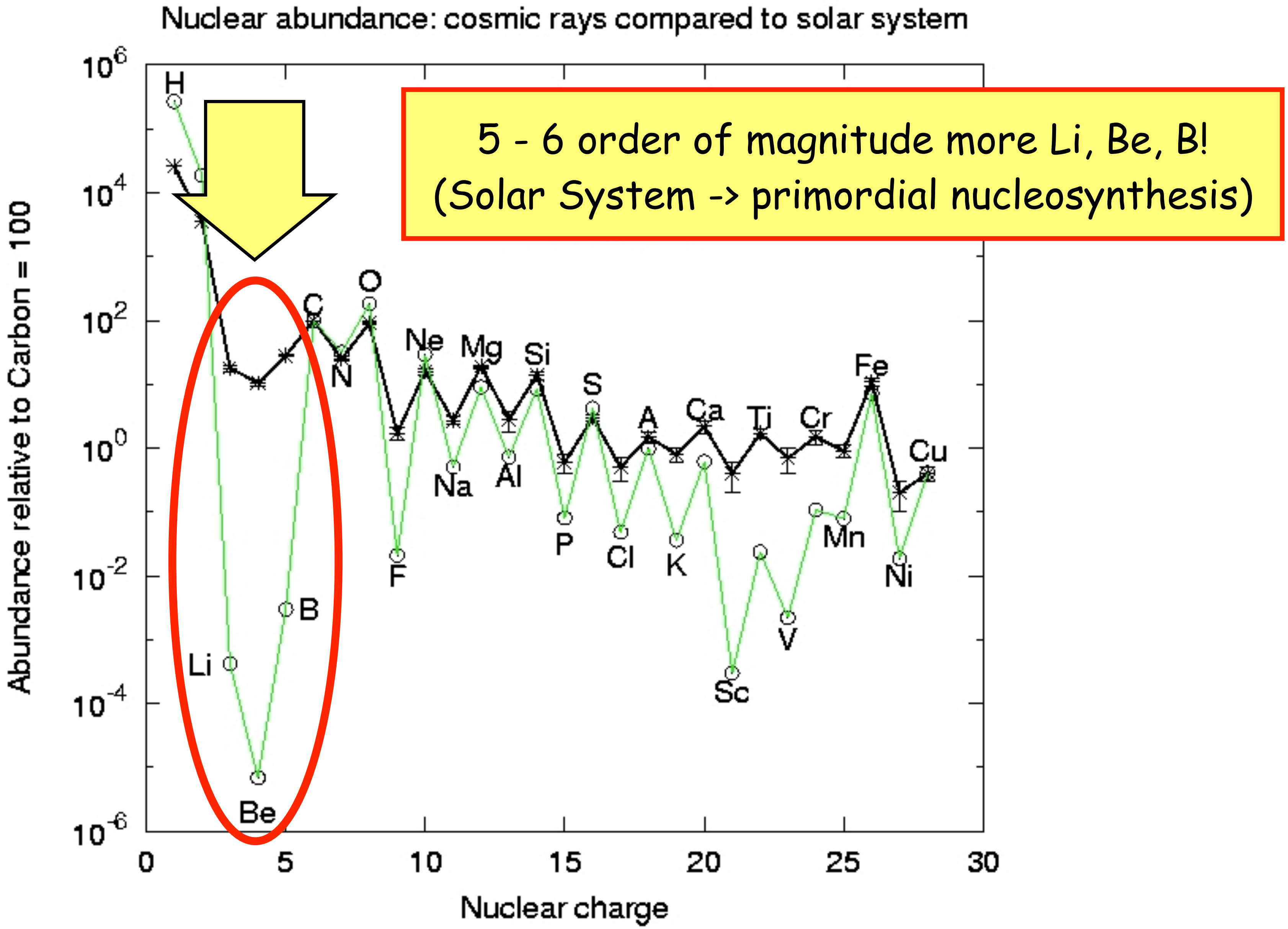

5 - 6 order of magnitude more Li, Be, B!
(Solar System -> primordial nucleosynthesis)

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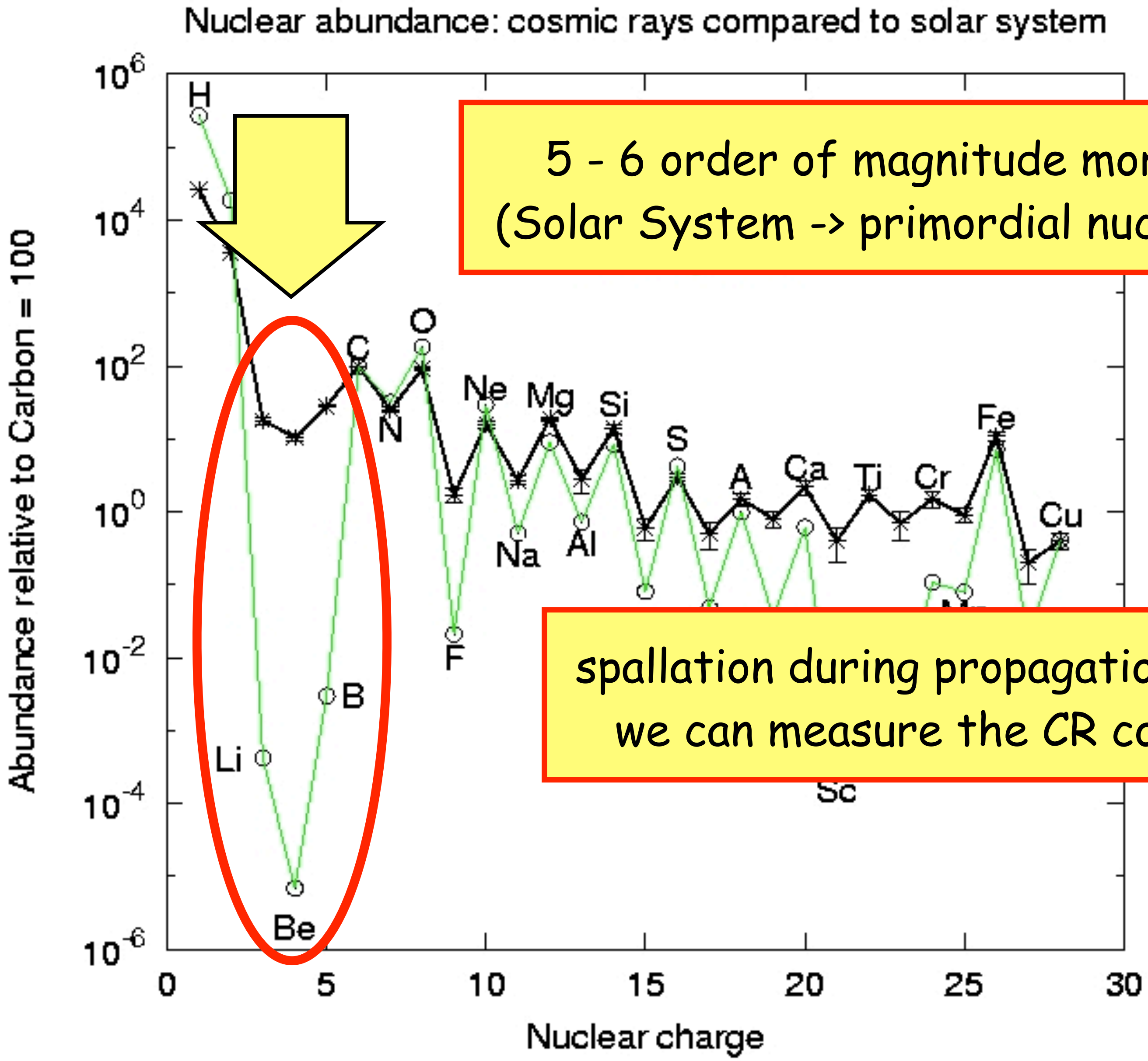

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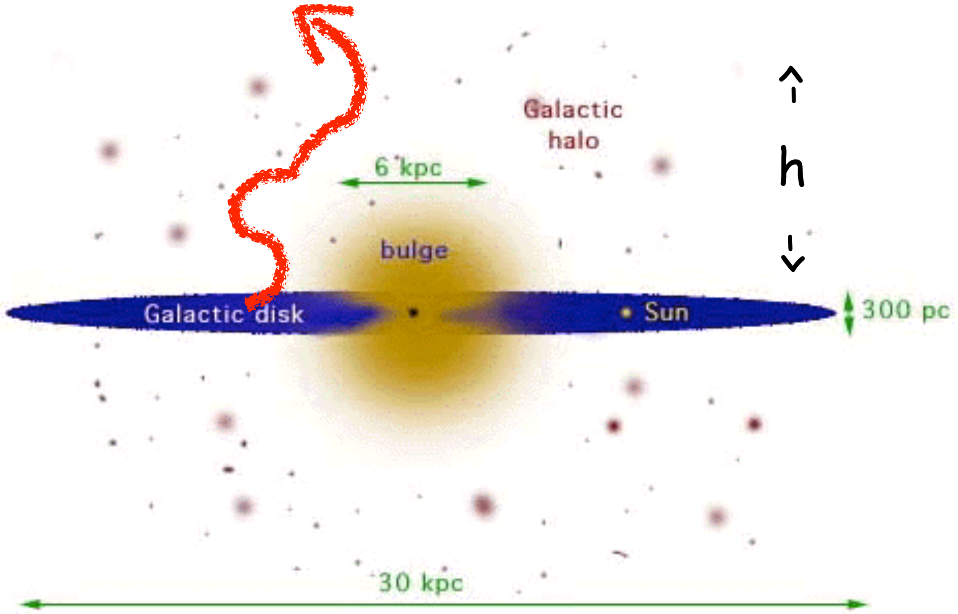
spallation during propagation in the Galaxy ->
we can measure the CR confinement time

Gaisser & Stanev, 2005

Cosmic Ray confinement in the Galaxy



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

$$\delta \approx 0.3 \;...\; 0.6$$

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

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

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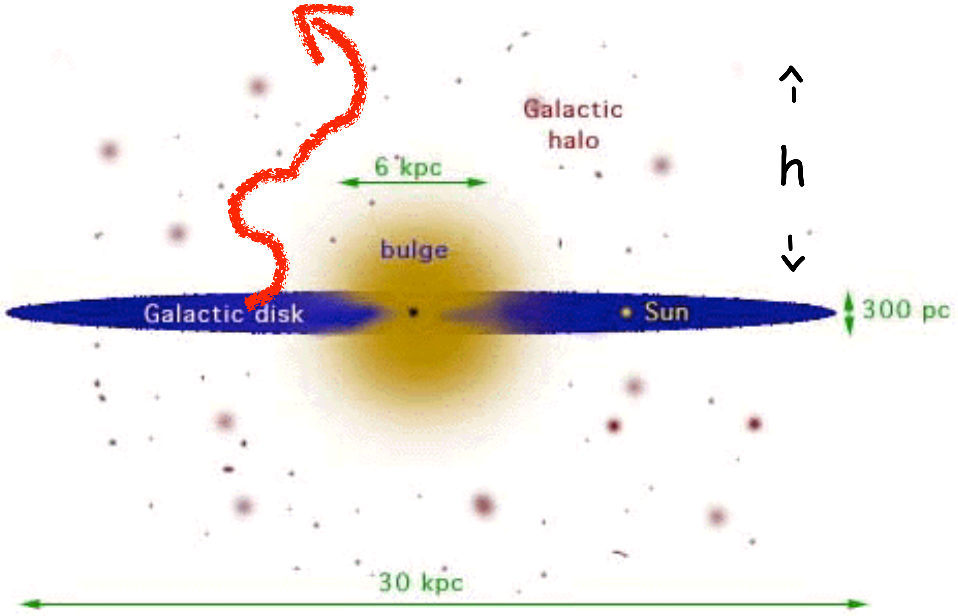

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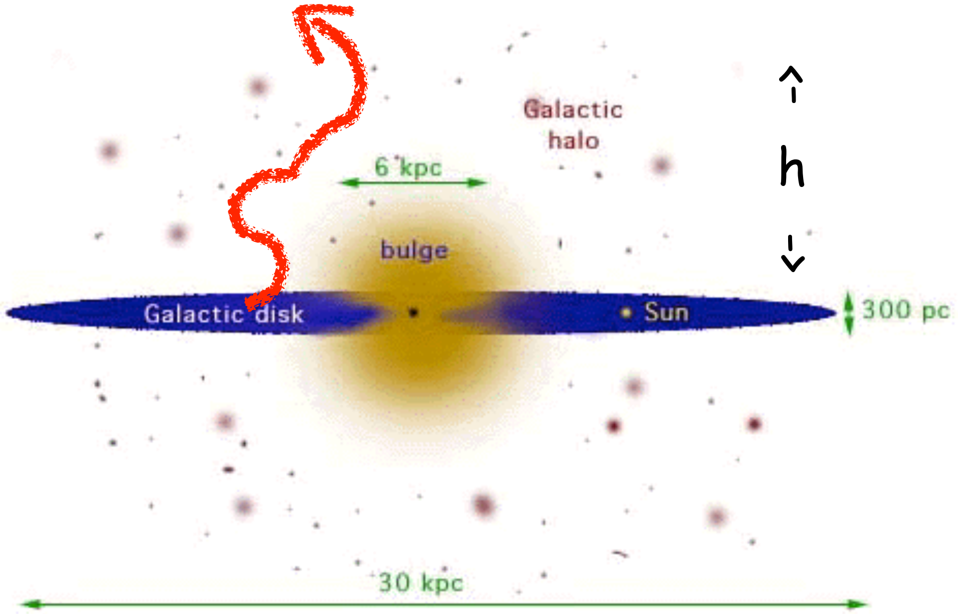

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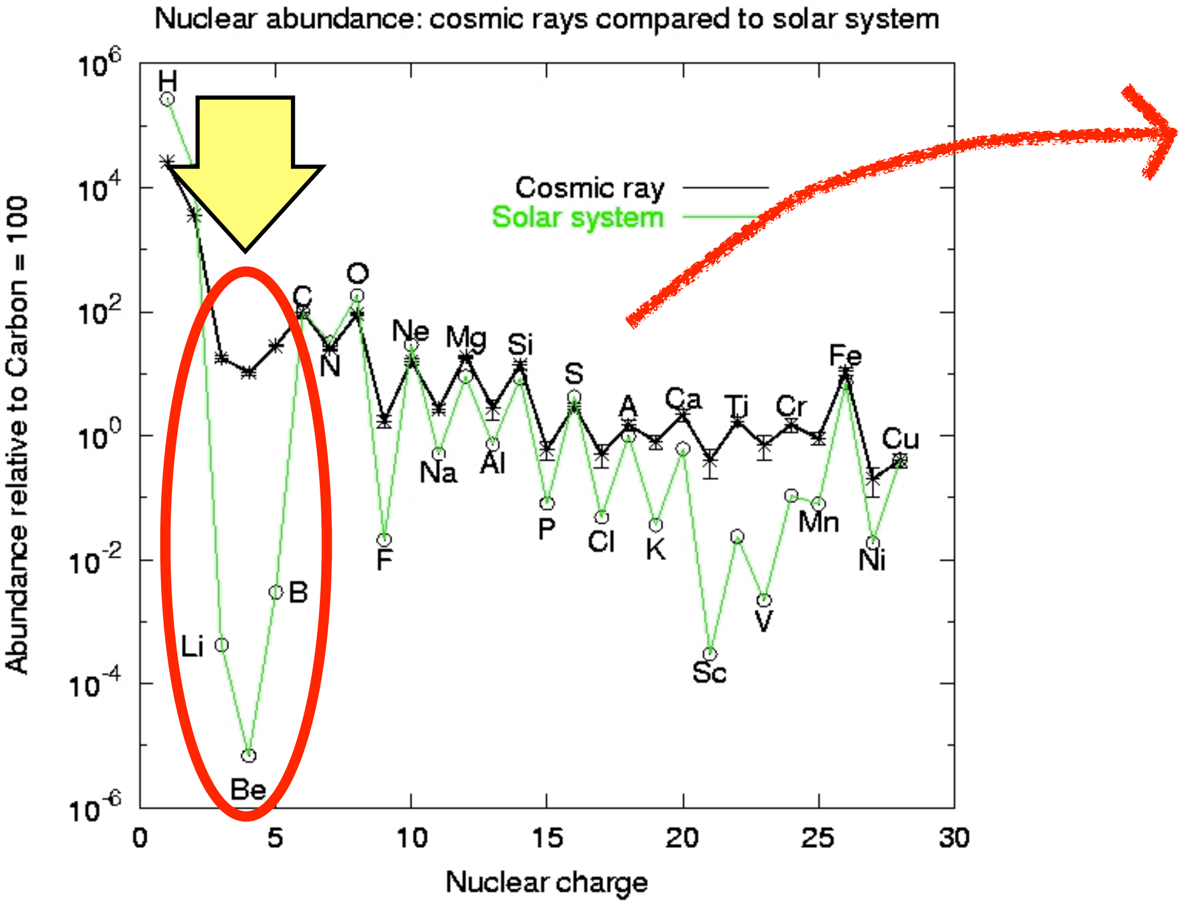
slope close to (or "slightly" steeper than) 2 -> 2.1 ... 2.4

A remarkable "coincidence"

~ Baade & Zwicky, 1934



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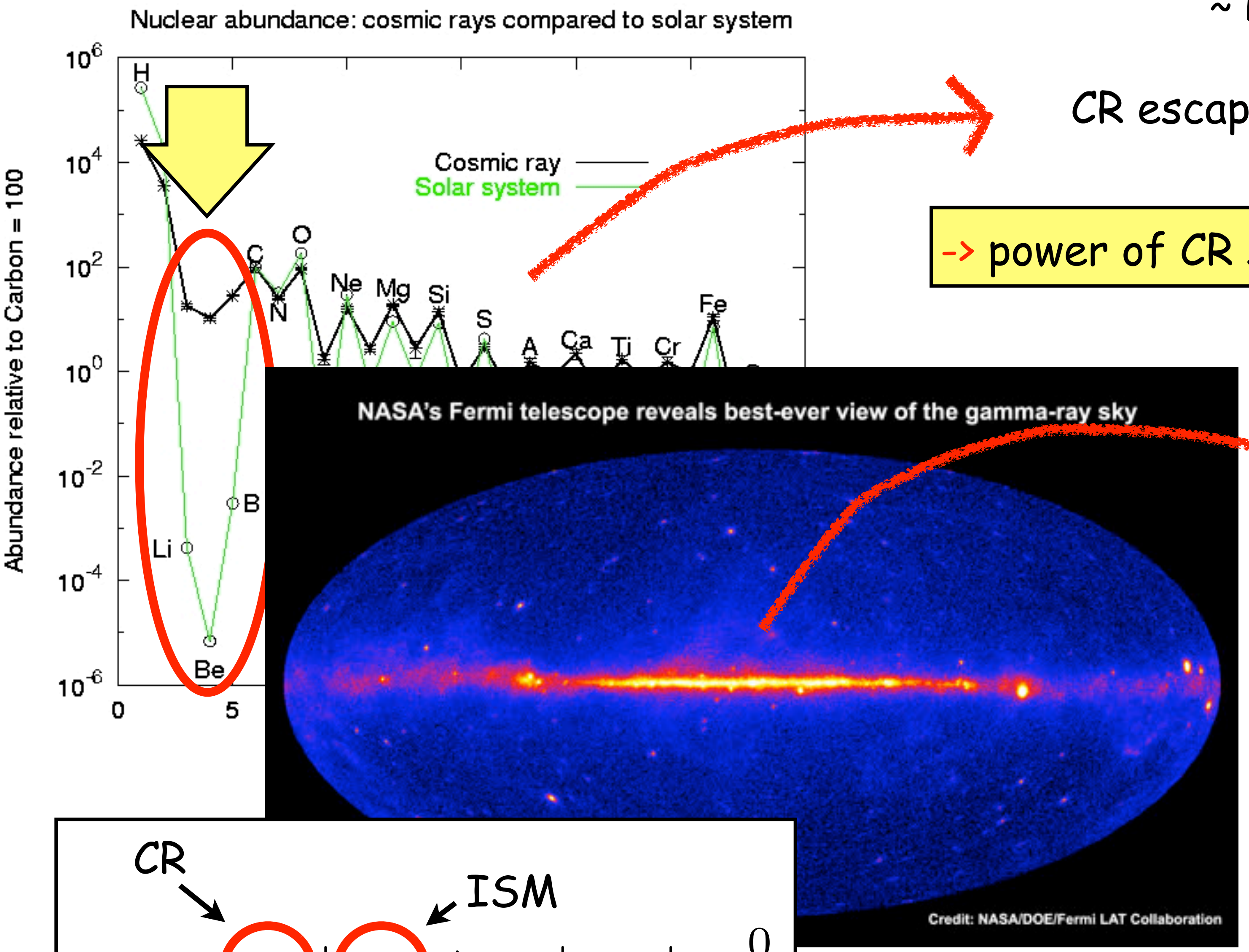

CR escape time

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

CR total energy

$$\overset{\text{CR}}{p} + \overset{\text{ISM}}{p} \rightarrow p + p + \pi^0$$

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

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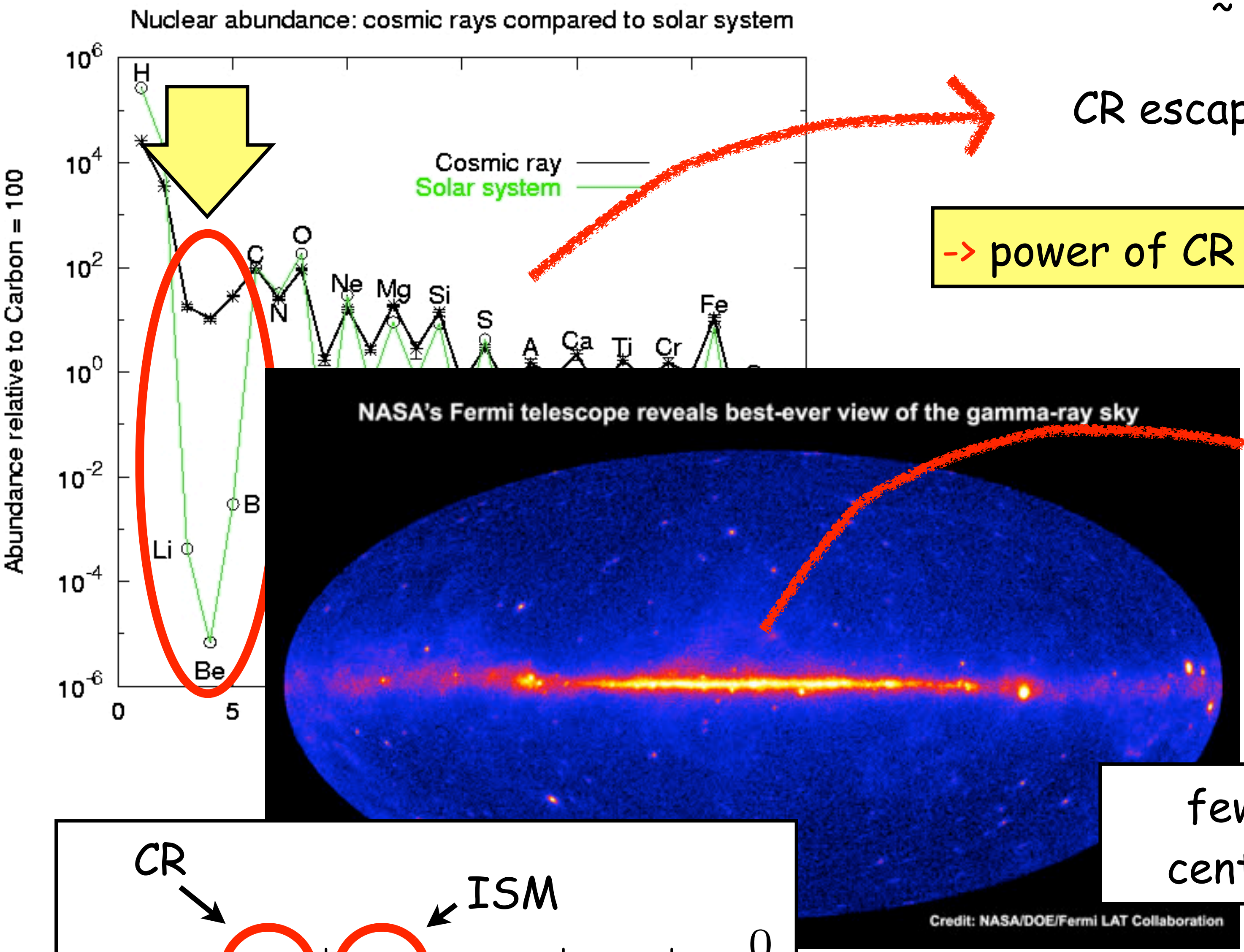

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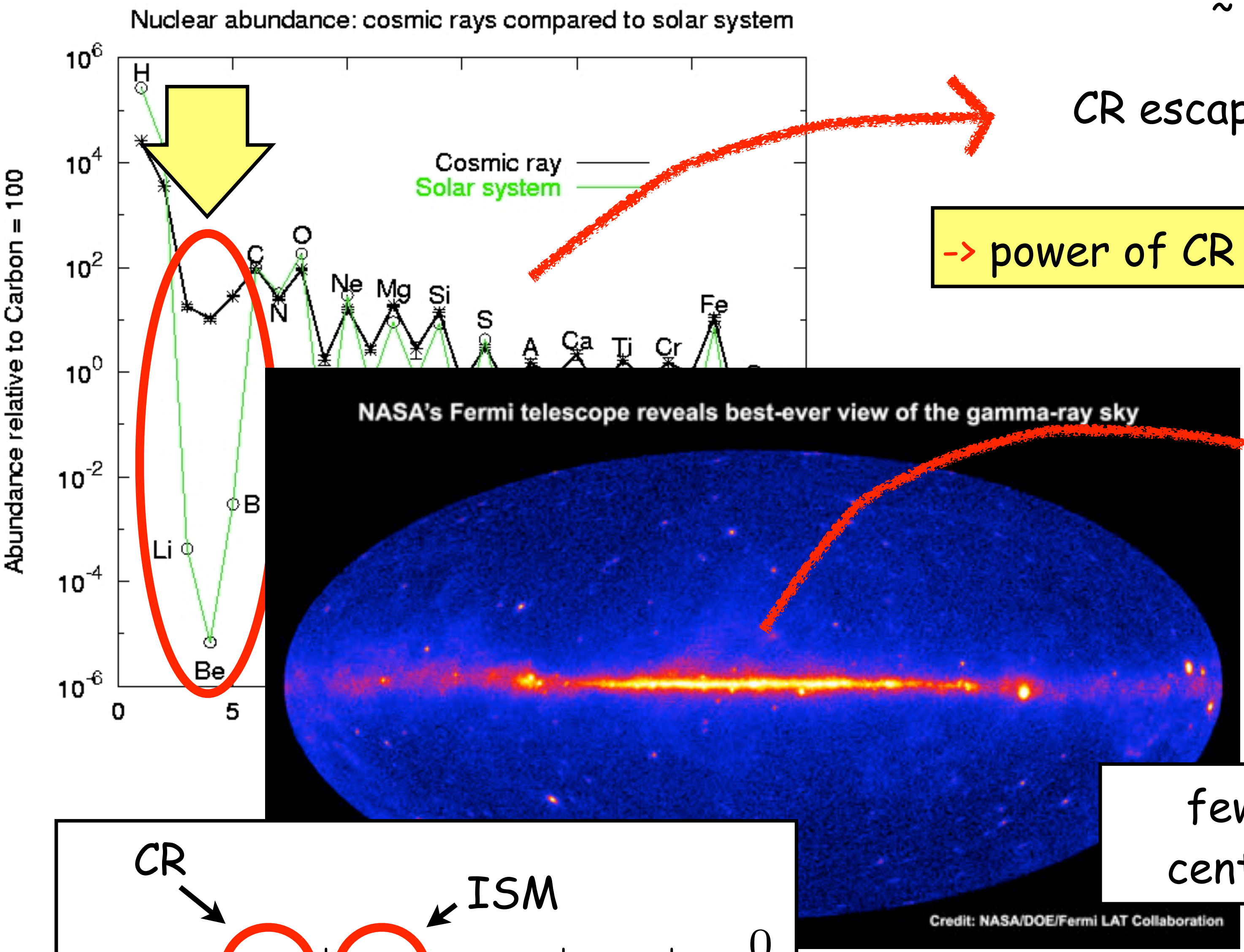

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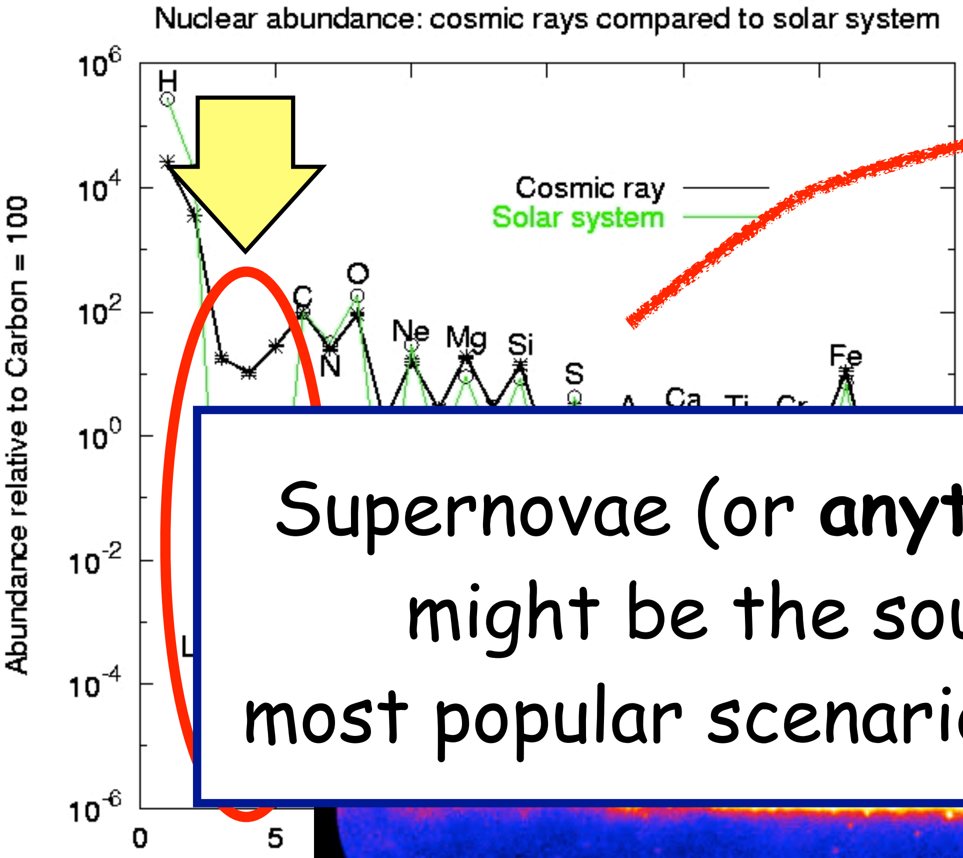
Nuclear abundance: cosmic rays compared to solar system



CR escape time

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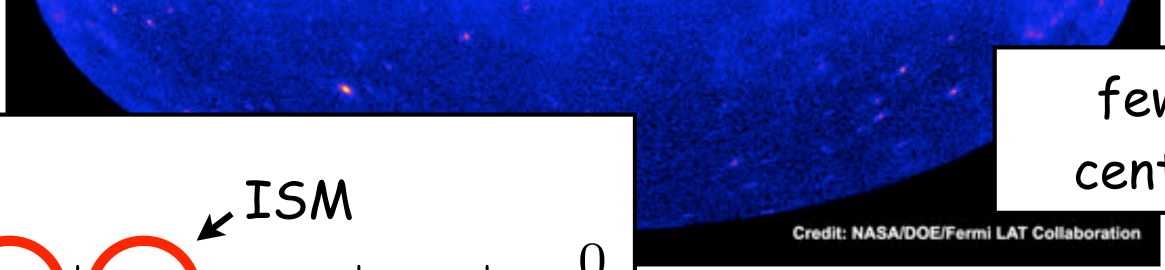
nergy

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



Credit: NASA/DOE/Fermi LAT Collaboration

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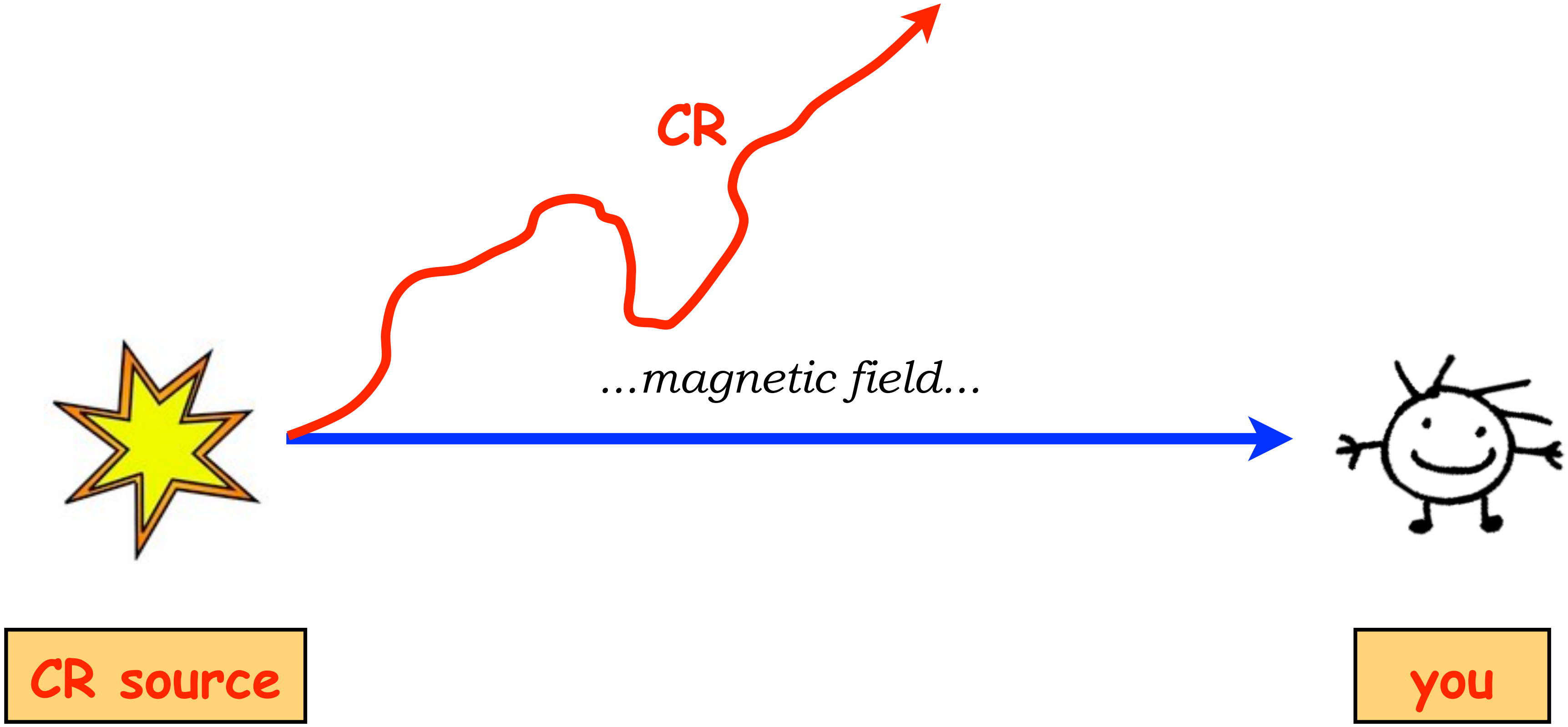
Cosmic ray sources: why is it so difficult?



We cannot do CR Astronomy.

Need for indirect identification of CR sources.

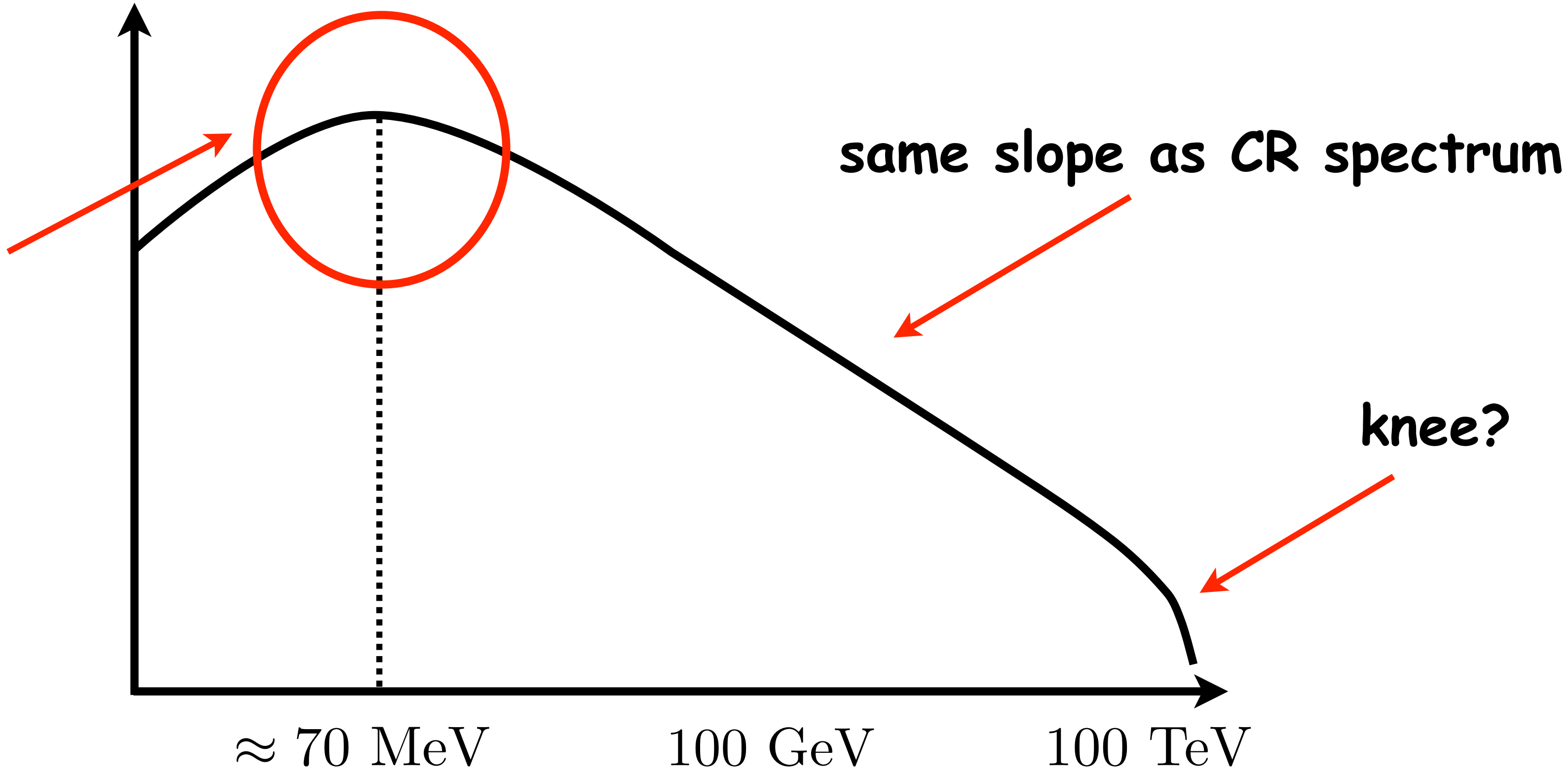
Gamma-ray astronomy

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

CR **ISM**

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

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



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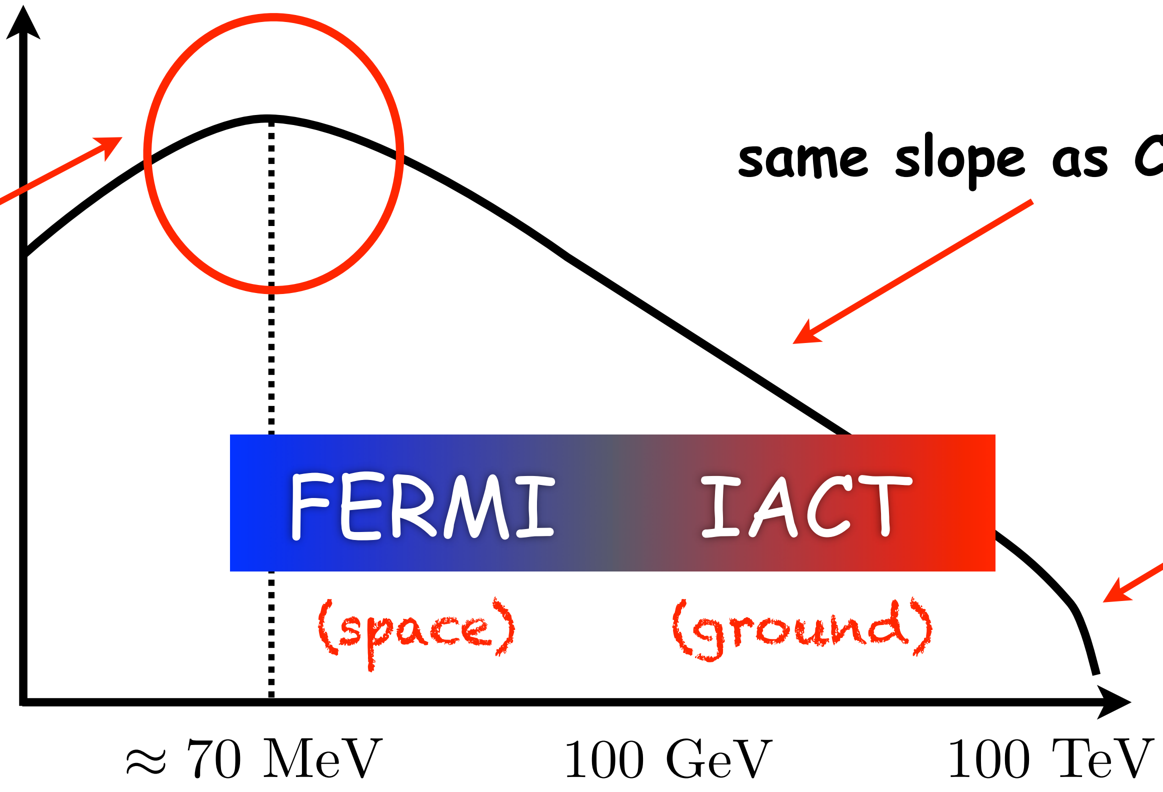

same slope as CR spectrum

knee?

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 ≈ 0.1 ÷ 1 cm^{-3}
- proton-proton interactions

⇨ **SNRs visible in TeV gamma rays**

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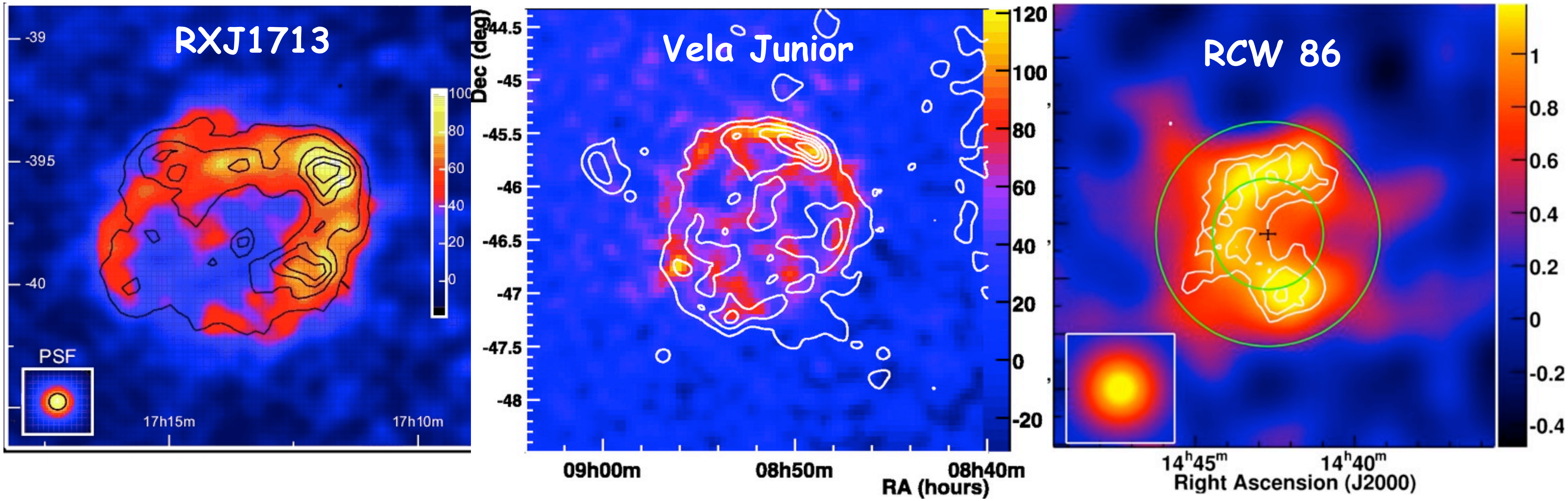

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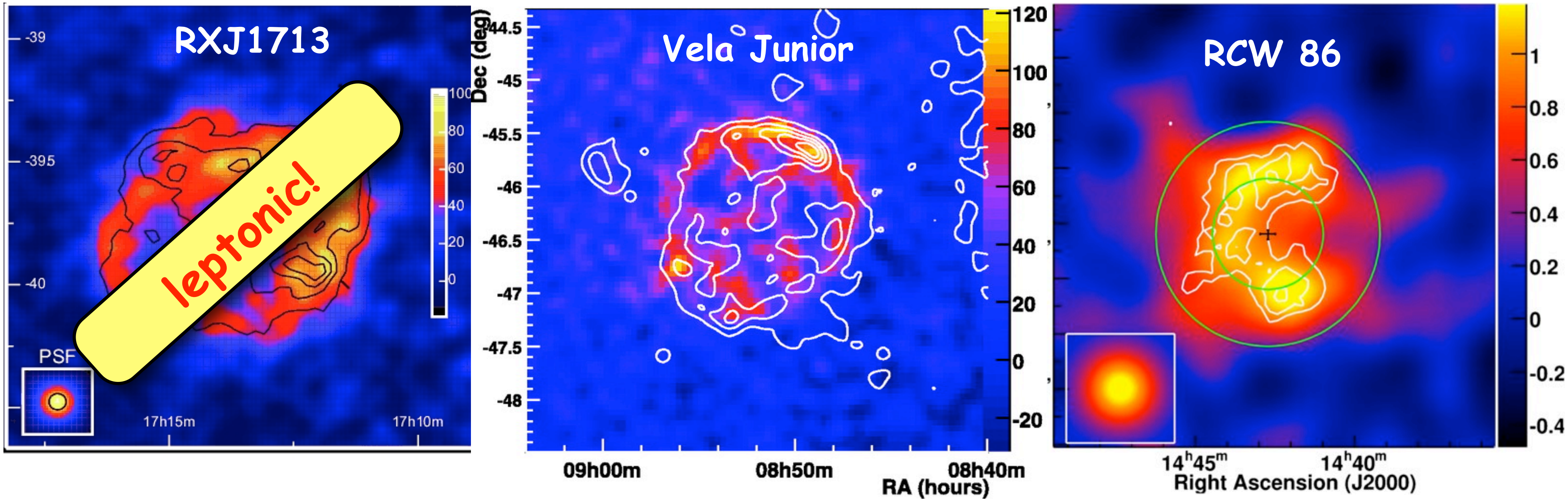

leptonic!

Gamma rays from SNRs:
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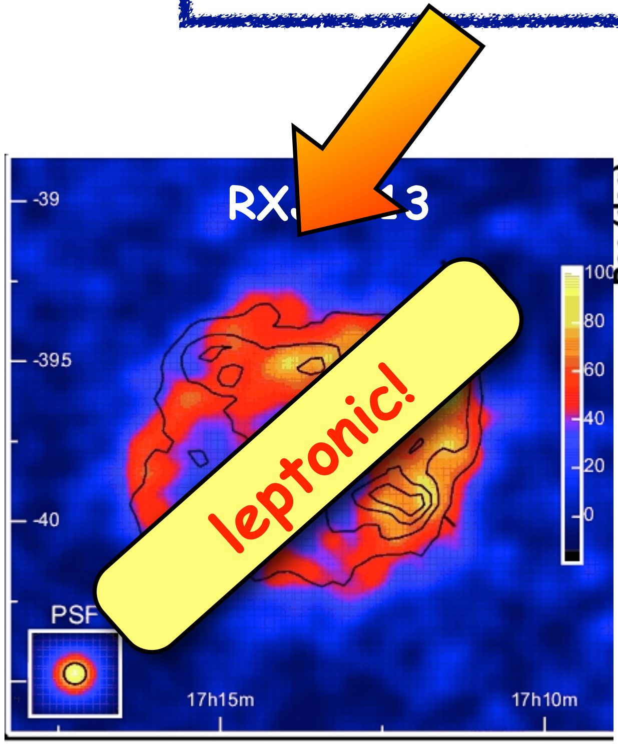
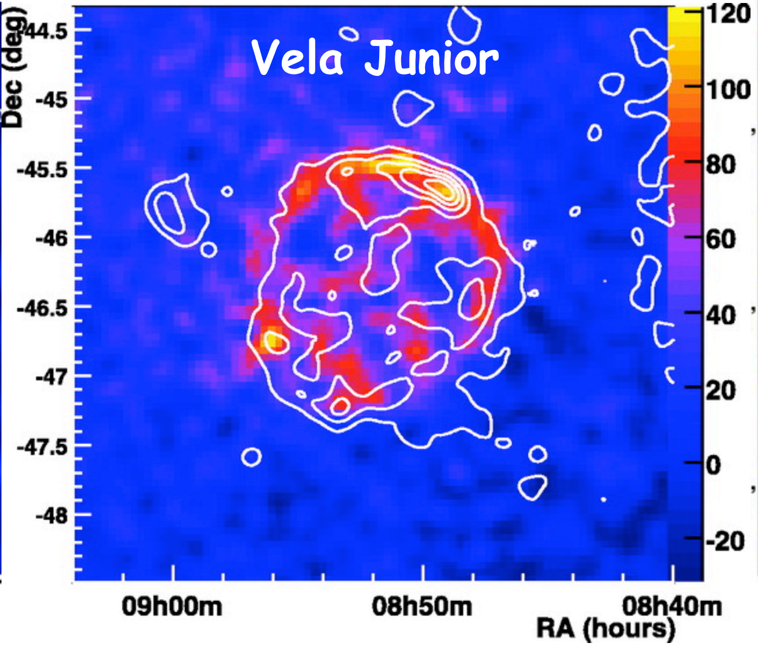
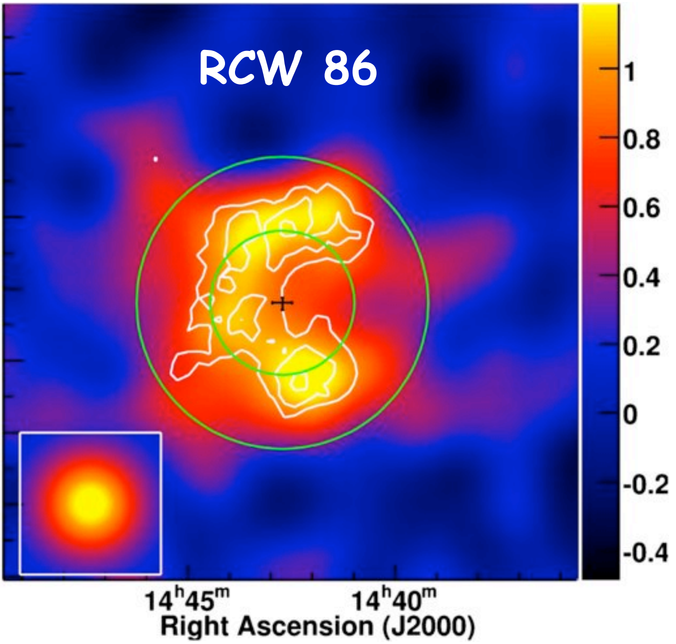
Drury, Aharonian & Volk, 1994

this does NOT mean that RXJ1713 is not accelerating CRs!
If the ambient gas density is low we can still accommodate up to ~30% of the total SN energy into CRs without significant hadronic emission.







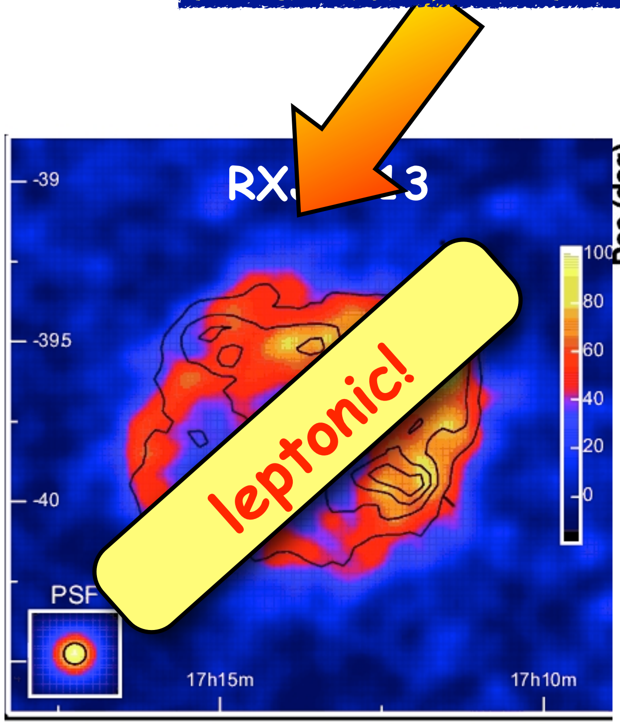
Gamma rays from SNRs: a test for CR origin

Drury, Aharonian & Volk, 1994

we need an **unambiguous proof for CR acceleration**

neutrinos are the candidates, but their detection is challenging

-> other gamma-ray based tests?



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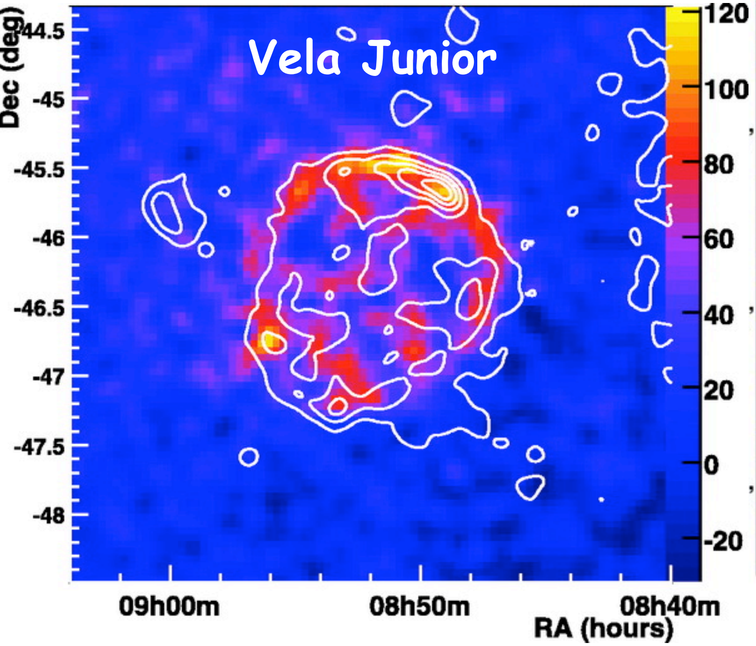
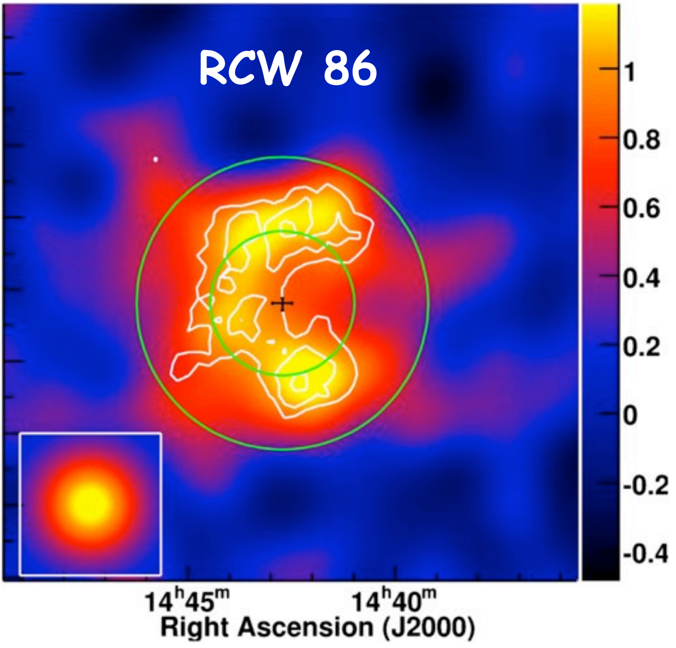
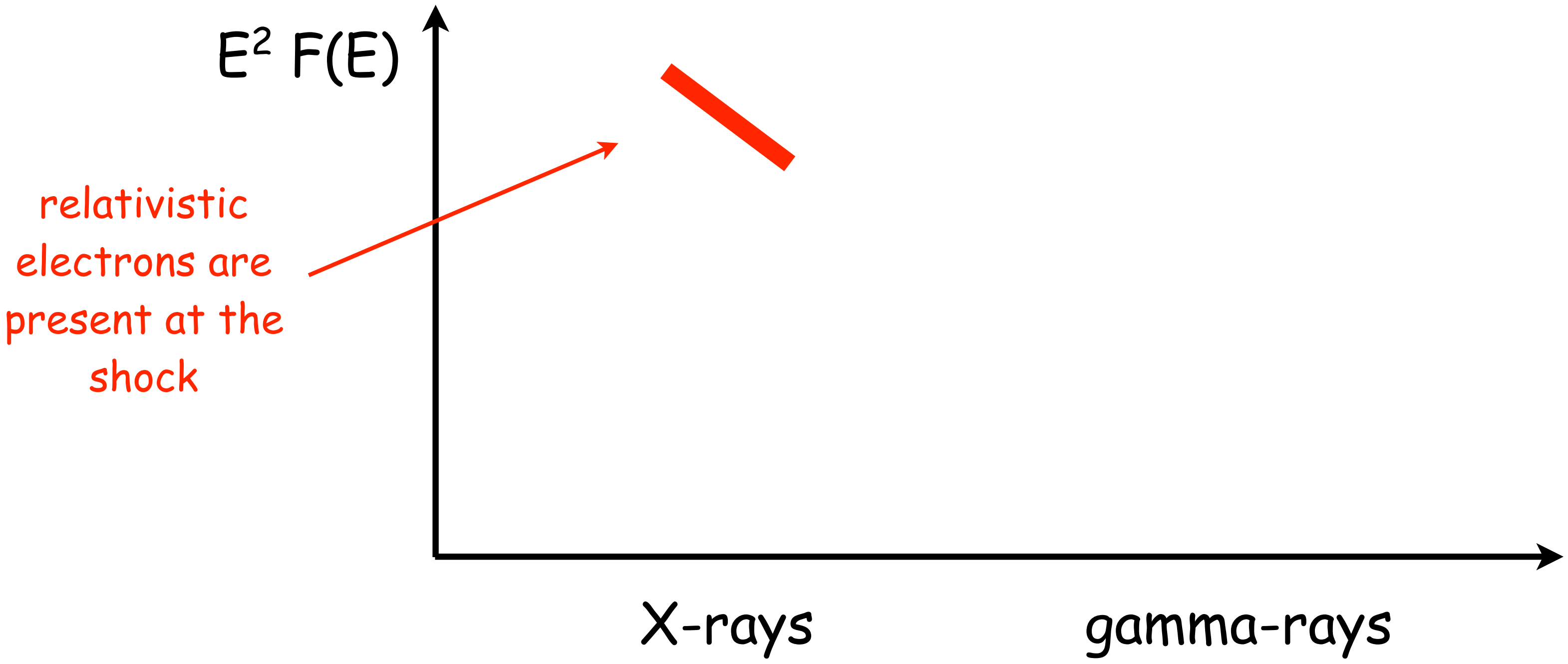




Hadronic versus leptonic emission

X-ray synchrotron emission is observed from some TeV SNRs
(RXJ1713, Vela Junior...)



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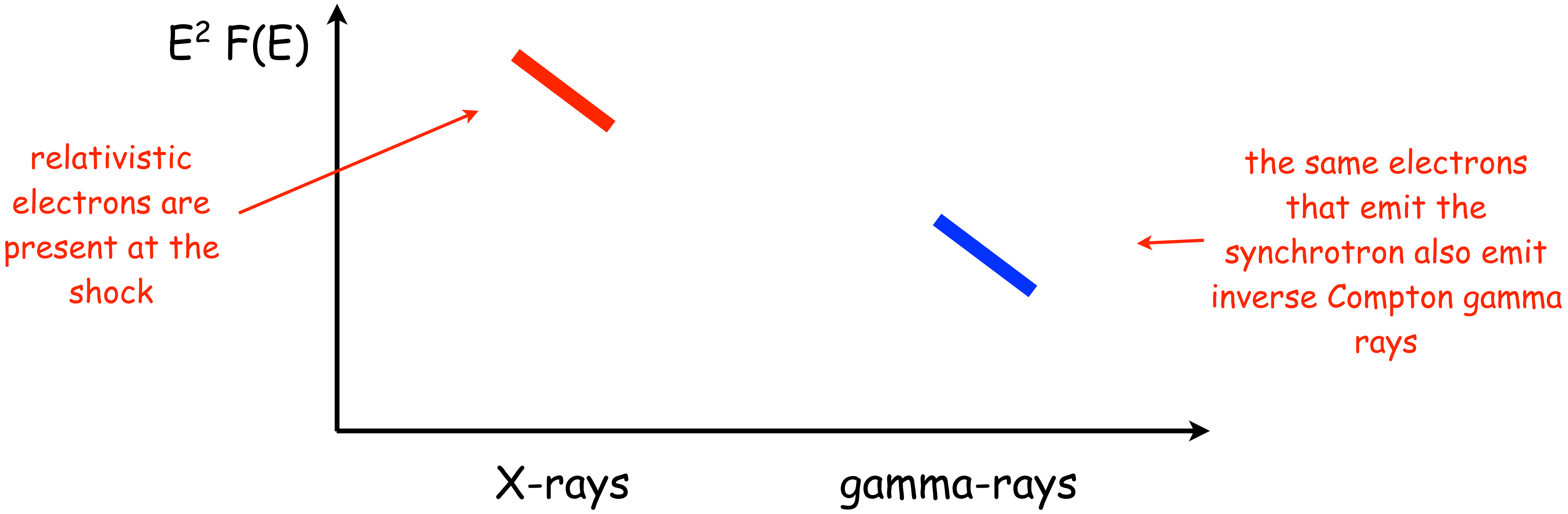
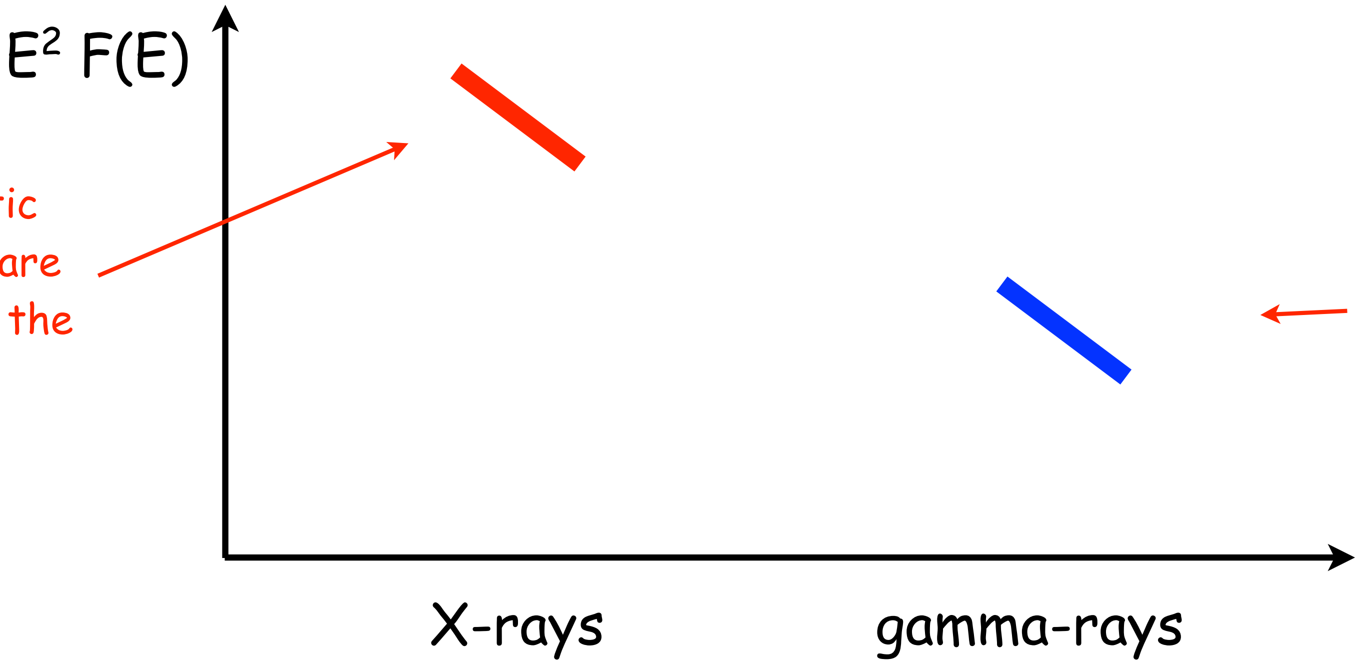


relativistic electrons are present at the shock

the same electrons that emit the synchrotron also emit inverse Compton gamma rays

Hadronic versus leptonic emission

X-ray synchrotron emission is observed from some TeV SNRs
(RXJ1713, Vela Junior...)



relativistic electrons are present at the shock

the same electrons that emit the synchrotron also emit inverse Compton gamma rays

synchrotron -> $F_s \propto n_e B^\beta$

this product is fixed by X-ray obs.

inverse Compton -> $F_{IC} \propto n_e w_{soft}$

we know this

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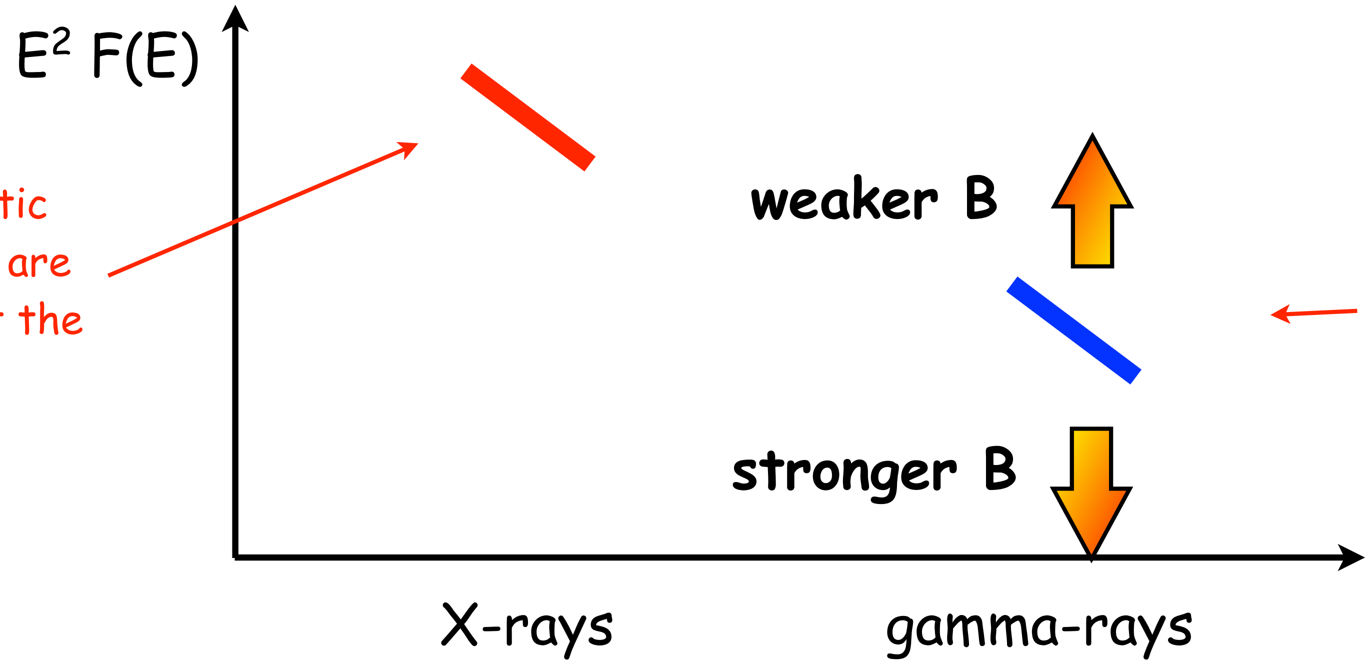

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Hadronic versus leptonic emission: from particle to photon spectra

p-p interactions ->

$$N_p \propto E^{-\delta} \longrightarrow N_\gamma \propto E^{-\delta}$$

inverse Compton ->

$$N_e \propto E^{-\delta} \longrightarrow N_\gamma \propto E^{-\frac{\delta+1}{2}}$$

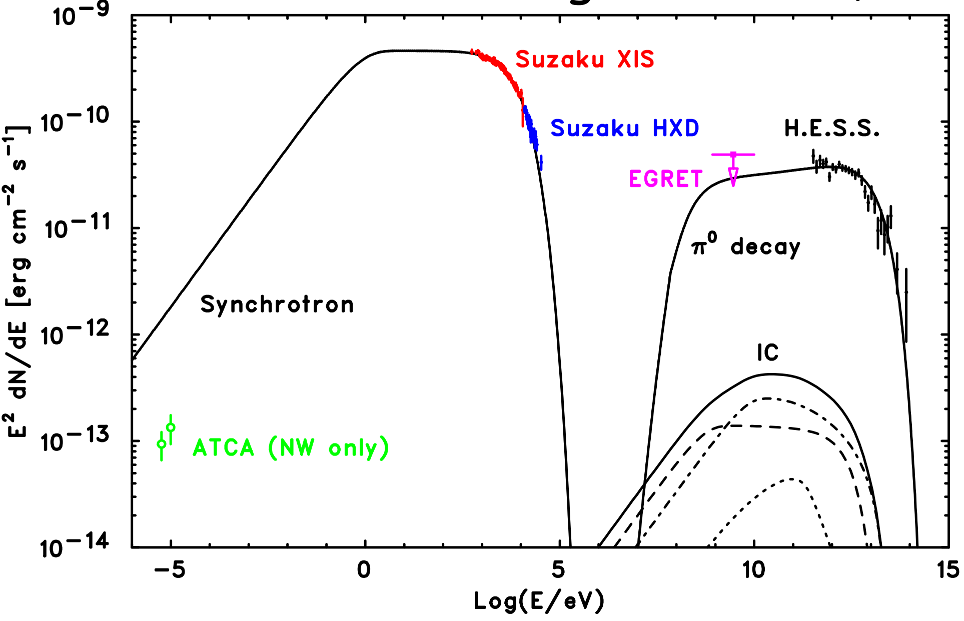
Hadronic versus leptonic emission

RXJ1713: hadronic and leptonic models

Hadronic: proton spectrum E^{-2} -> p-p interactions -> gamma ray spectrum E^{-2}

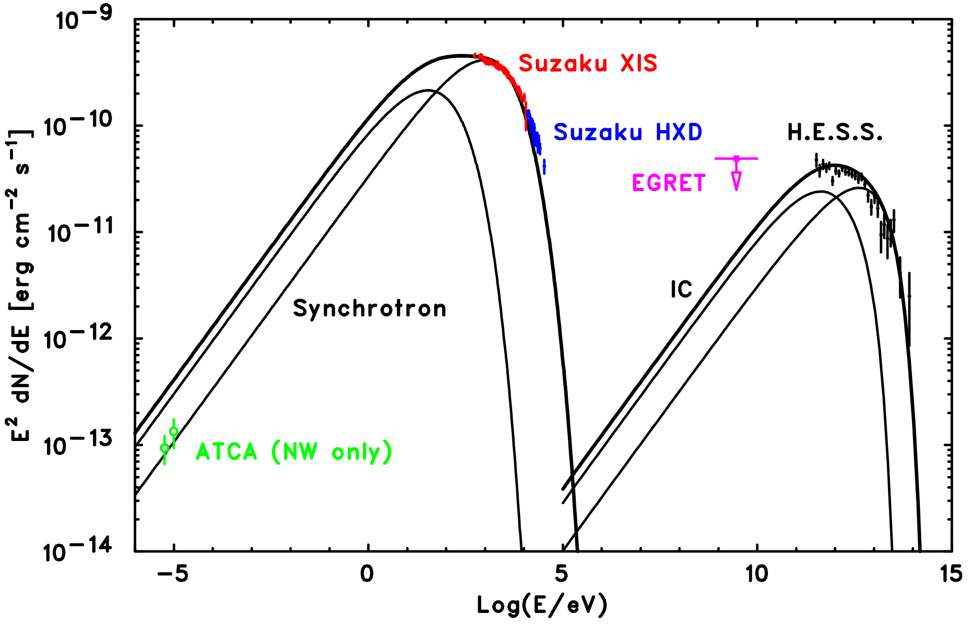
Leptonic: low B field -> synchrotron losses negligible -> electron spectrum E^{-2} -> inverse Compton scattering -> gamma ray spectrum $E^{-1.5}$

$W_p = 2{,}7 \times 10^{50}\ (n/cm^{-3})^{-1}$ erg
$W_e = 3.1 \times 10^{46}$ erg + B = 200 μG



Hadronic

$W_e = 4.8 \times 10^{47}$ erg + B = 14 μG



Leptonic

Tanaka et al., 2008

Hadronic versus leptonic emission

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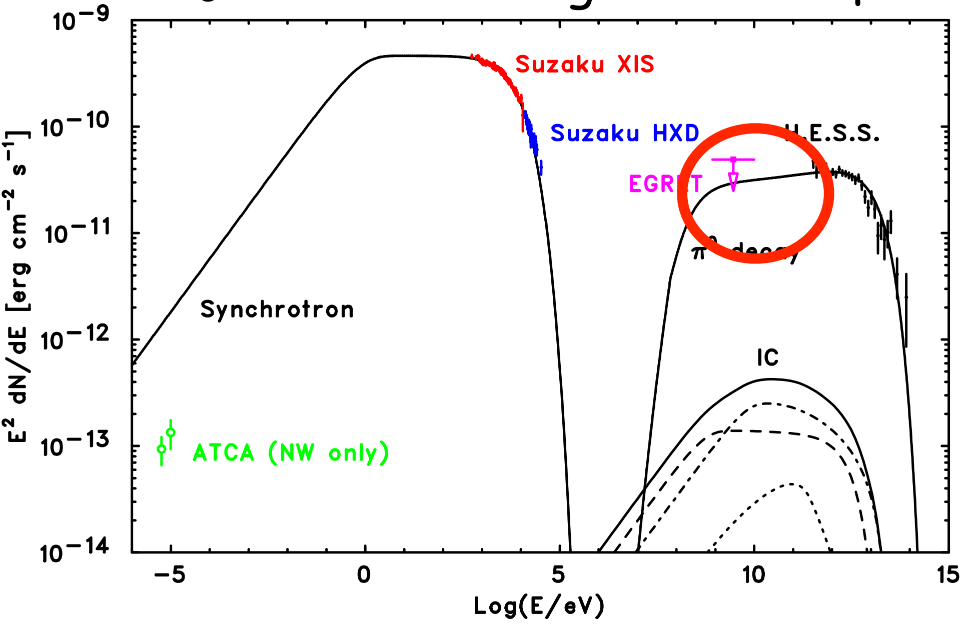

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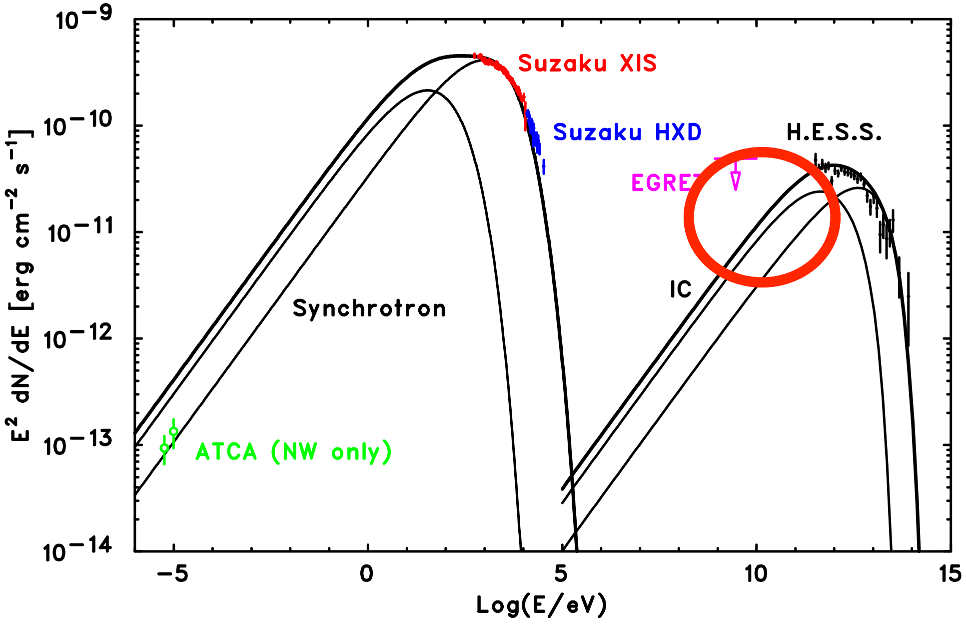
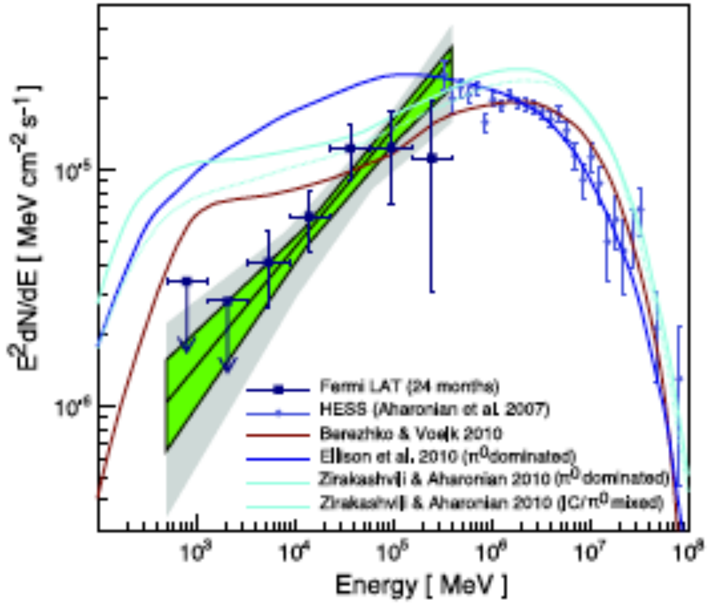


Leptonic

Tanaka et al., 2008

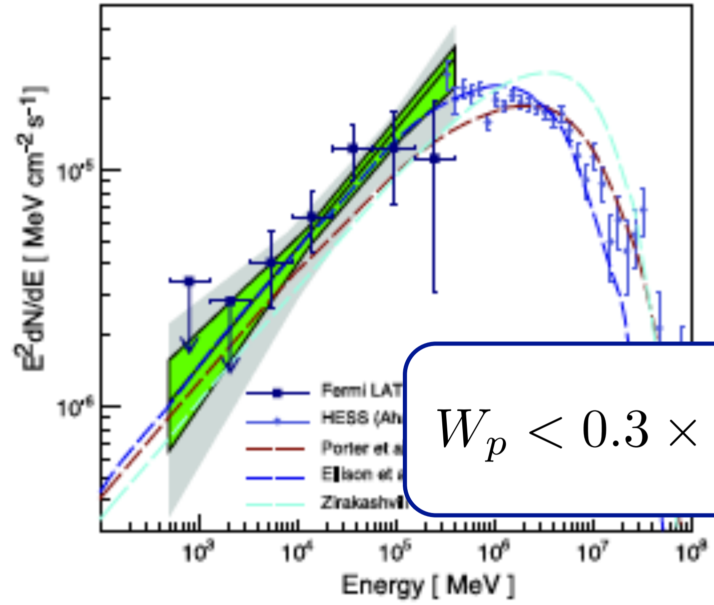
FERMI detects RX J1713

p-p interactions ->



the emission is most likely LEPTONIC

inverse Compton ->



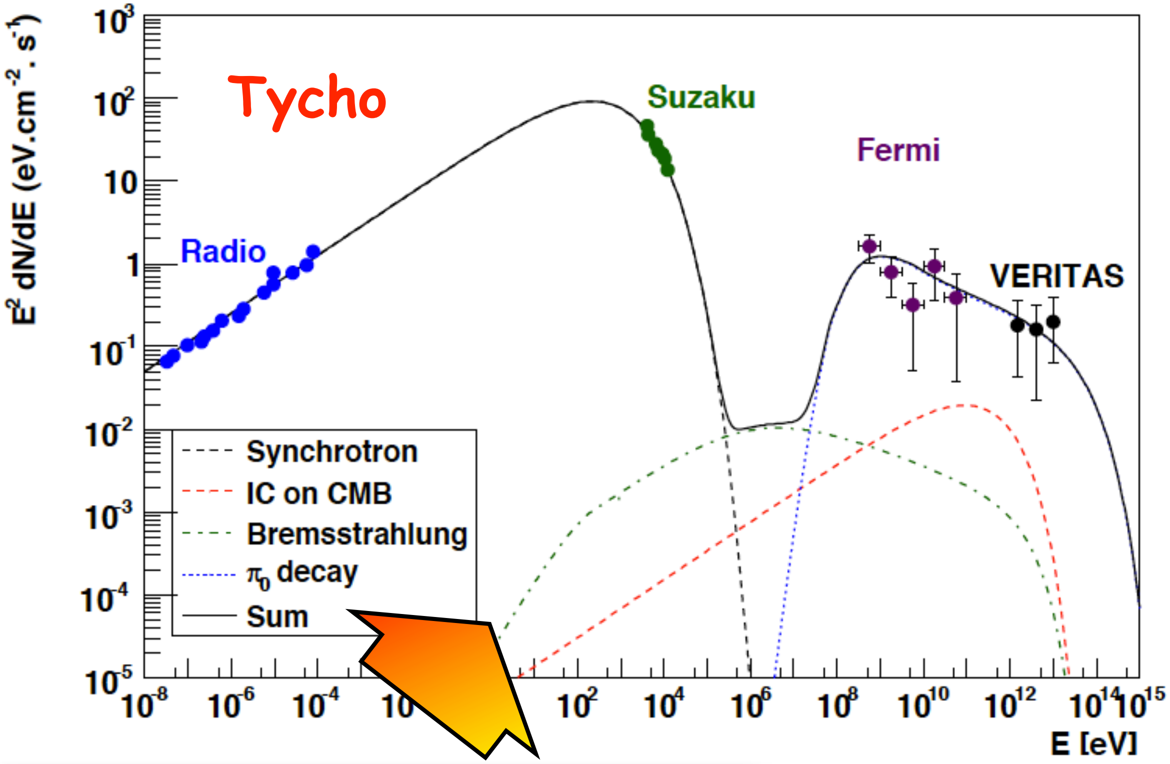
this does NOT mean that there are no protons!!!

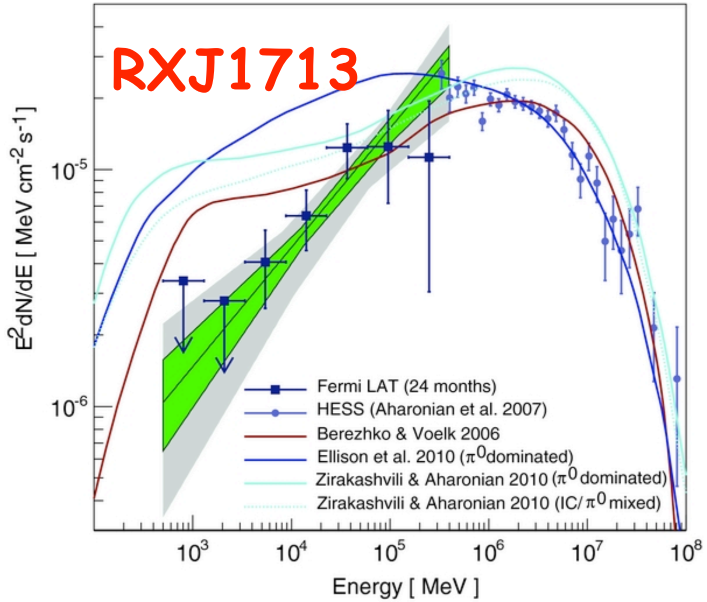
$$W_p < 0.3 \times 10^{51} \left(\frac{n}{0.1 \text{ cm}^{-3})} \right)^{-1} \text{erg}$$

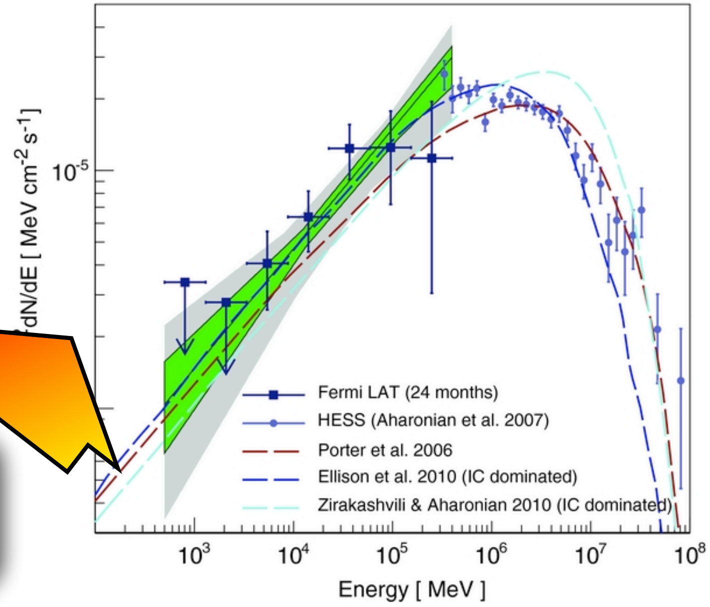
Abdo et al, 2011

Gamma rays from SNRs

(Giordano et al 2011)







(Abdo et al 2010)

steep (2.3) -> hadronic?

hard (1.5) -> leptonic?

Molecular clouds, if detected in gamma rays, can be used to probe the level of the cosmic ray intensity at various locations in the Galaxy and thus:

1) reveal spatial variations of cosmic rays in the Galaxy,
2) identify cosmic ray sources and
3) constrain cosmic ray propagation.

Molecular clouds as cosmic-ray barometers

Black & Fazio 1973, Issa & Wolfendale 1981, Aharonian 1991, Casanova...SG... et al. 2010

Gamma ray emission from a molecular cloud

$$L_\gamma(E_\gamma) \approx n_{gas}\ N_{CR}(10\,\overset{\text{inelasticity}}{\swarrow}E_\gamma)\ \sigma_{pp}\ c\ \left(\frac{4\pi}{3}R_{cl}^3\right)\ \propto M_{cl}\ N_{CR}(10\,E_\gamma)$$

$$\boxed{F_\gamma(E_\gamma)\ =\ f(\delta)\times N_0\ E_\gamma^{-\delta}\ \left(\frac{M_{cl}}{d^2}\right)}$$

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gamma ray observations

low energy observations

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CR intensity

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low energy observations

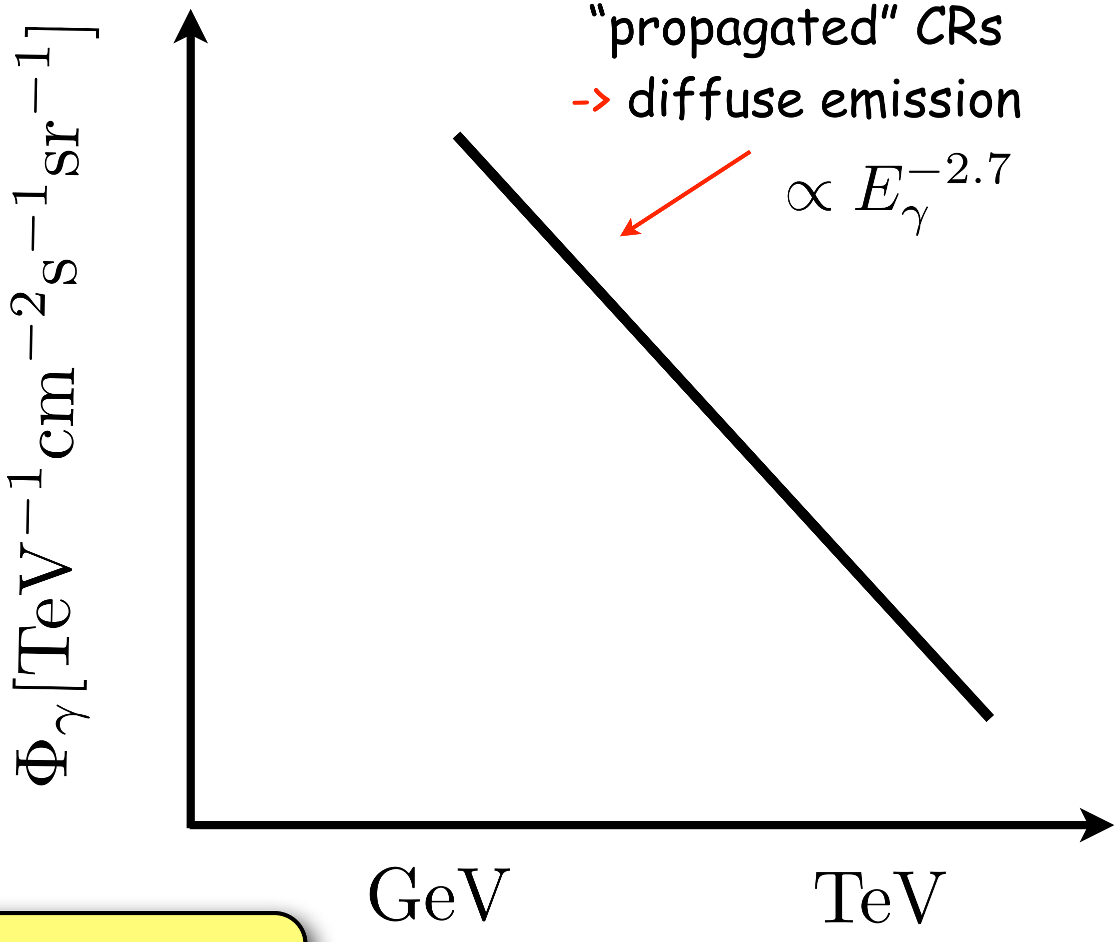
CR intensity

CAVEATS: the determination of the mass depends on the X_{CO} factor

Black & Fazio 1973 -> gamma ray data to infer M_{cl} by assuming a constant CR intensity in the MW

Molecular Clouds .vs. Diffuse Emission

gamma ray emission from MCs -> reveal the presence of a CR accelerator



diffuse emission

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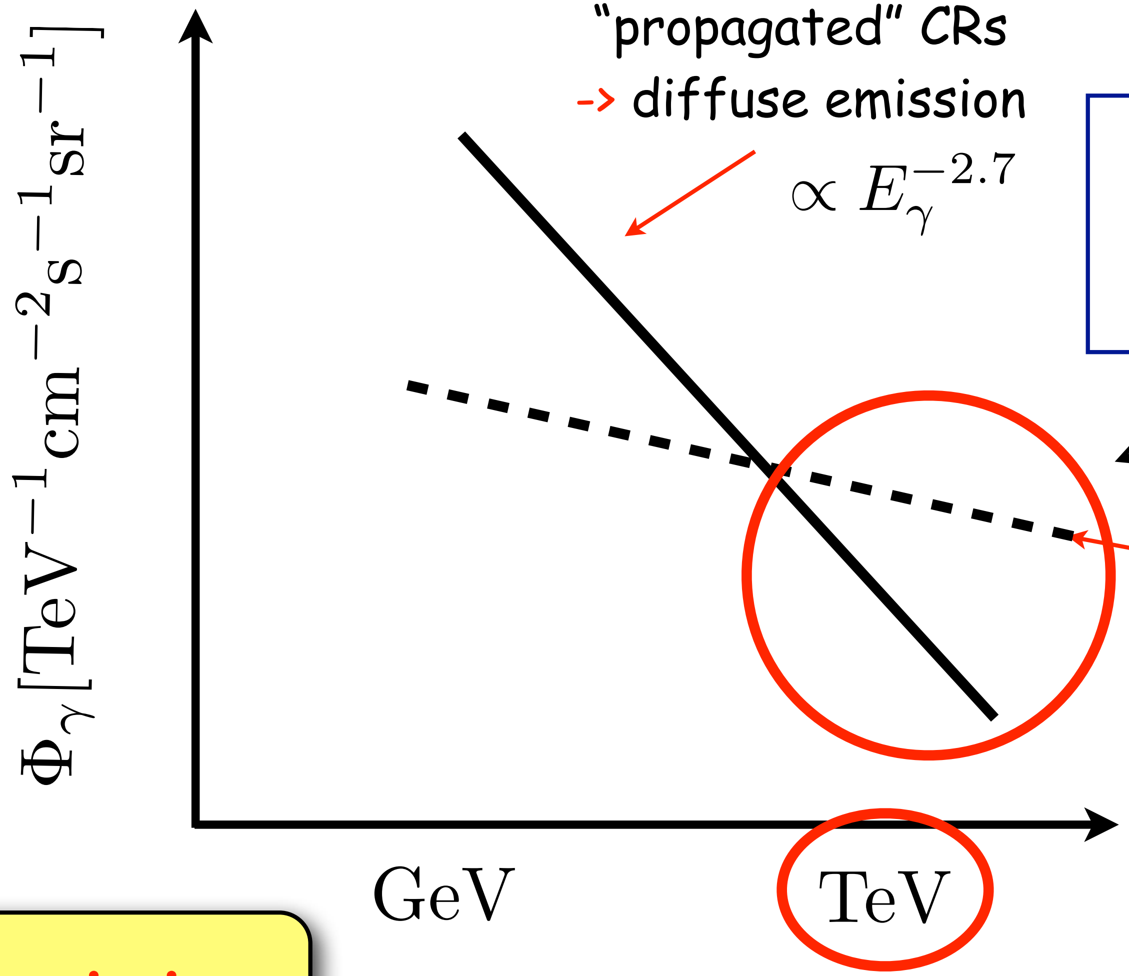


"propagated" CRs
-> diffuse emission

$\propto E_\gamma^{-2.7}$

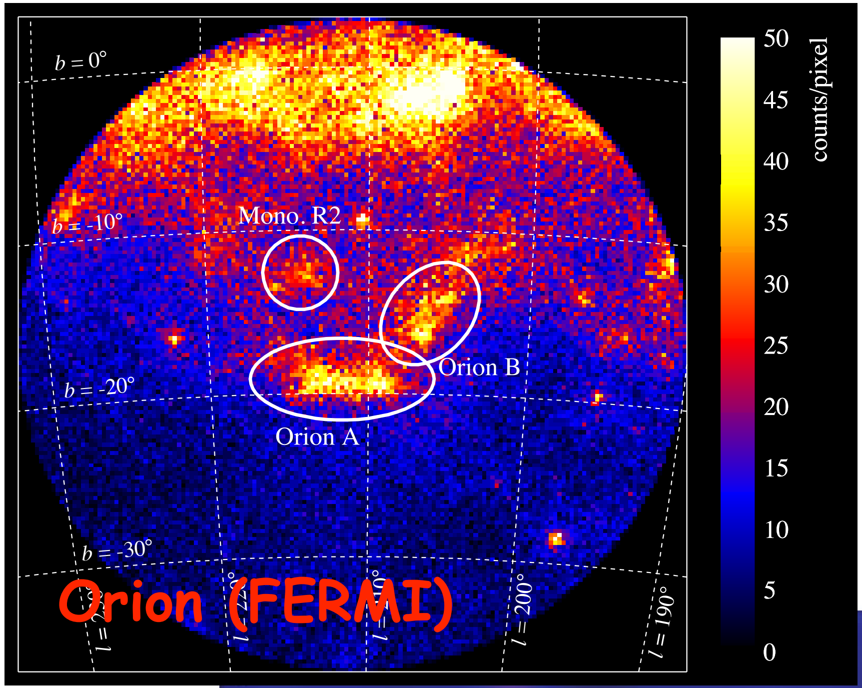
excesses show up more easily at high energies -> **TeV**

"fresh" CRs
-> hard spectrum

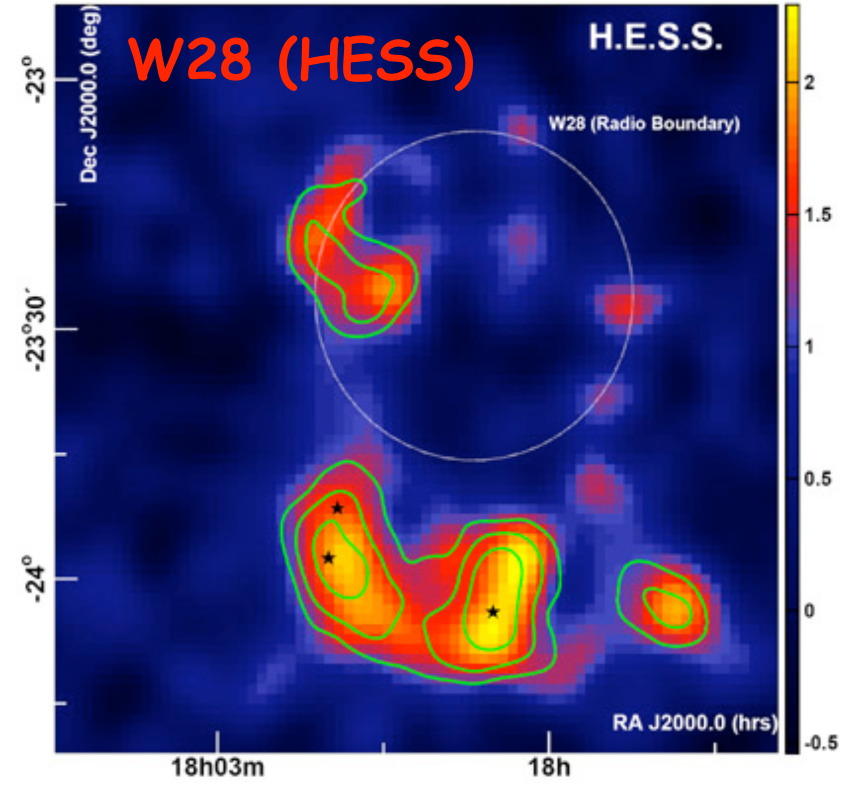
diffuse emission

Molecular clouds are gamma ray sources

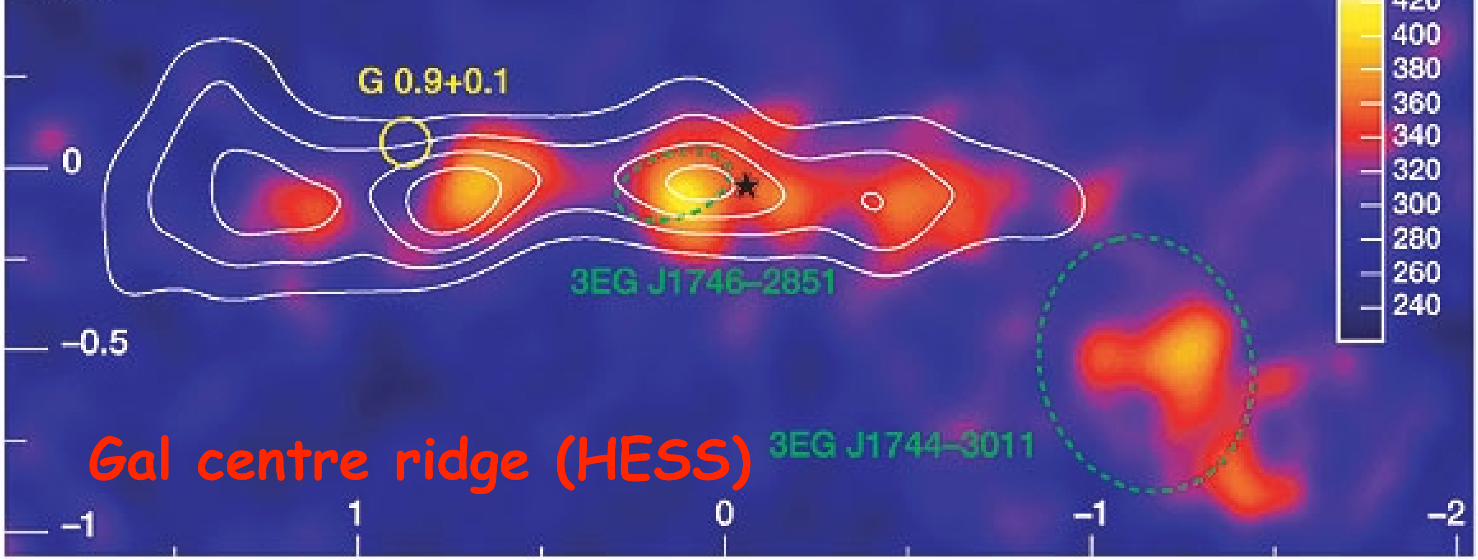
Okumura et al, 2009



Orion (FERMI)



W28 (HESS)



Gal centre ridge (HESS)

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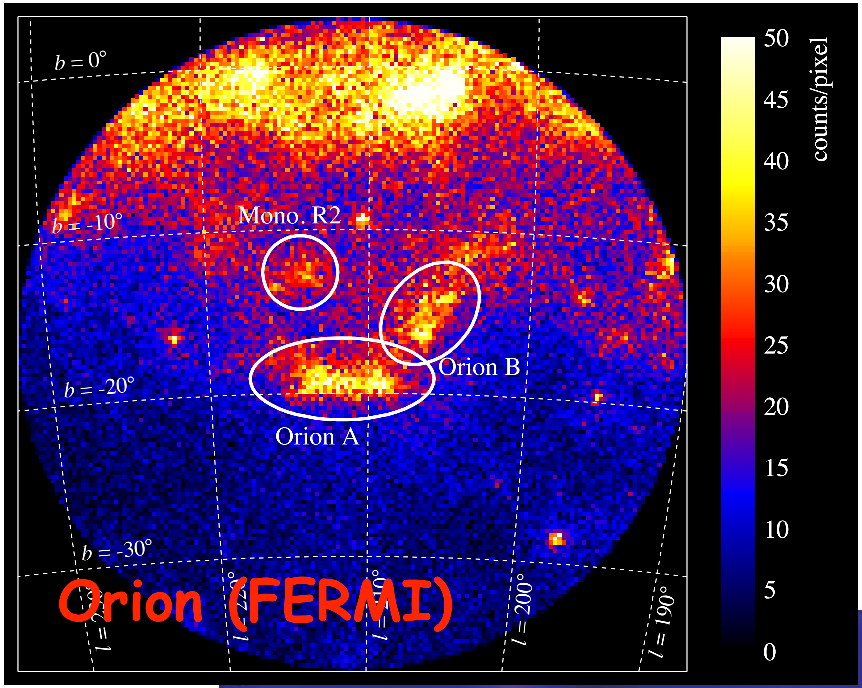
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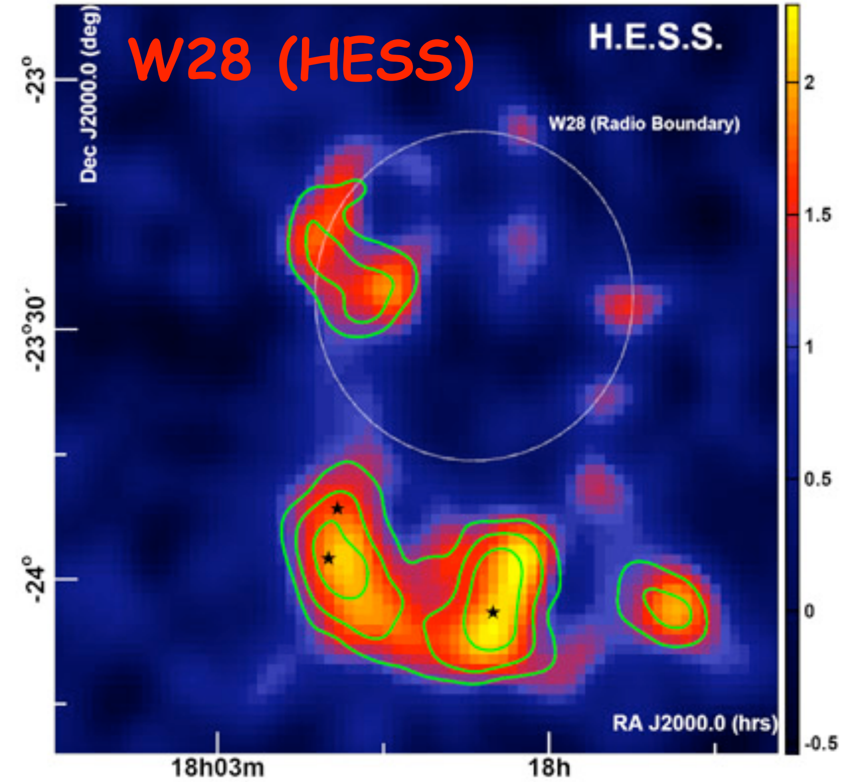
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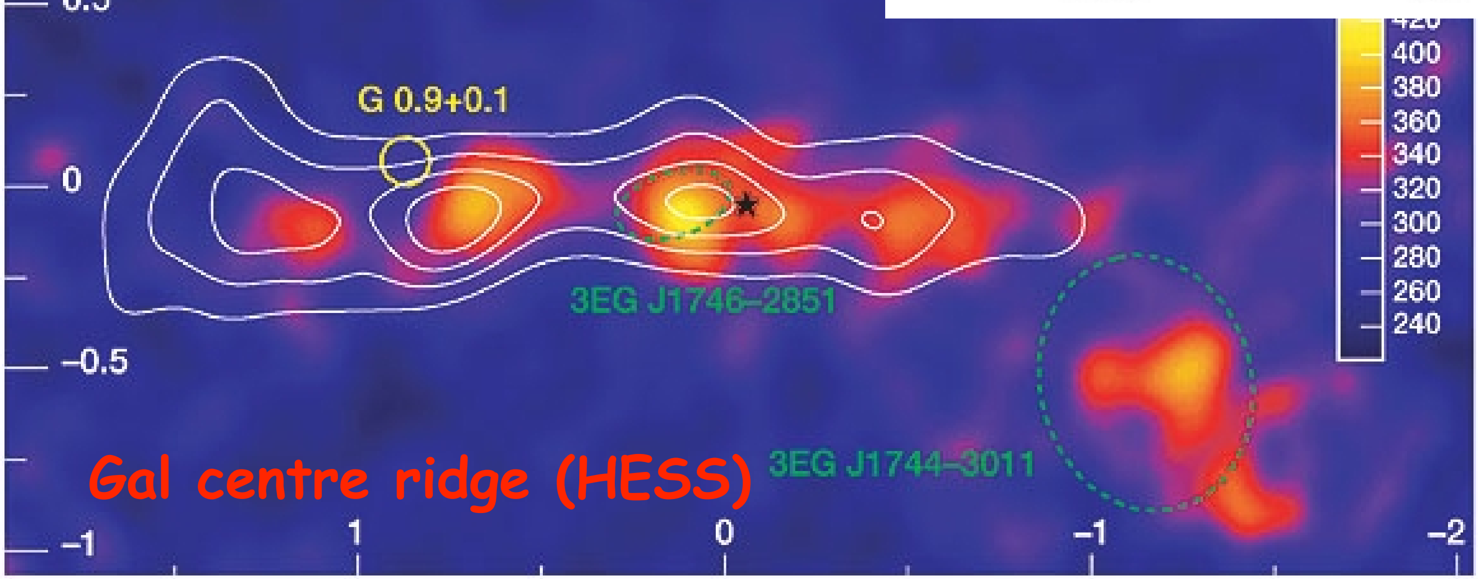
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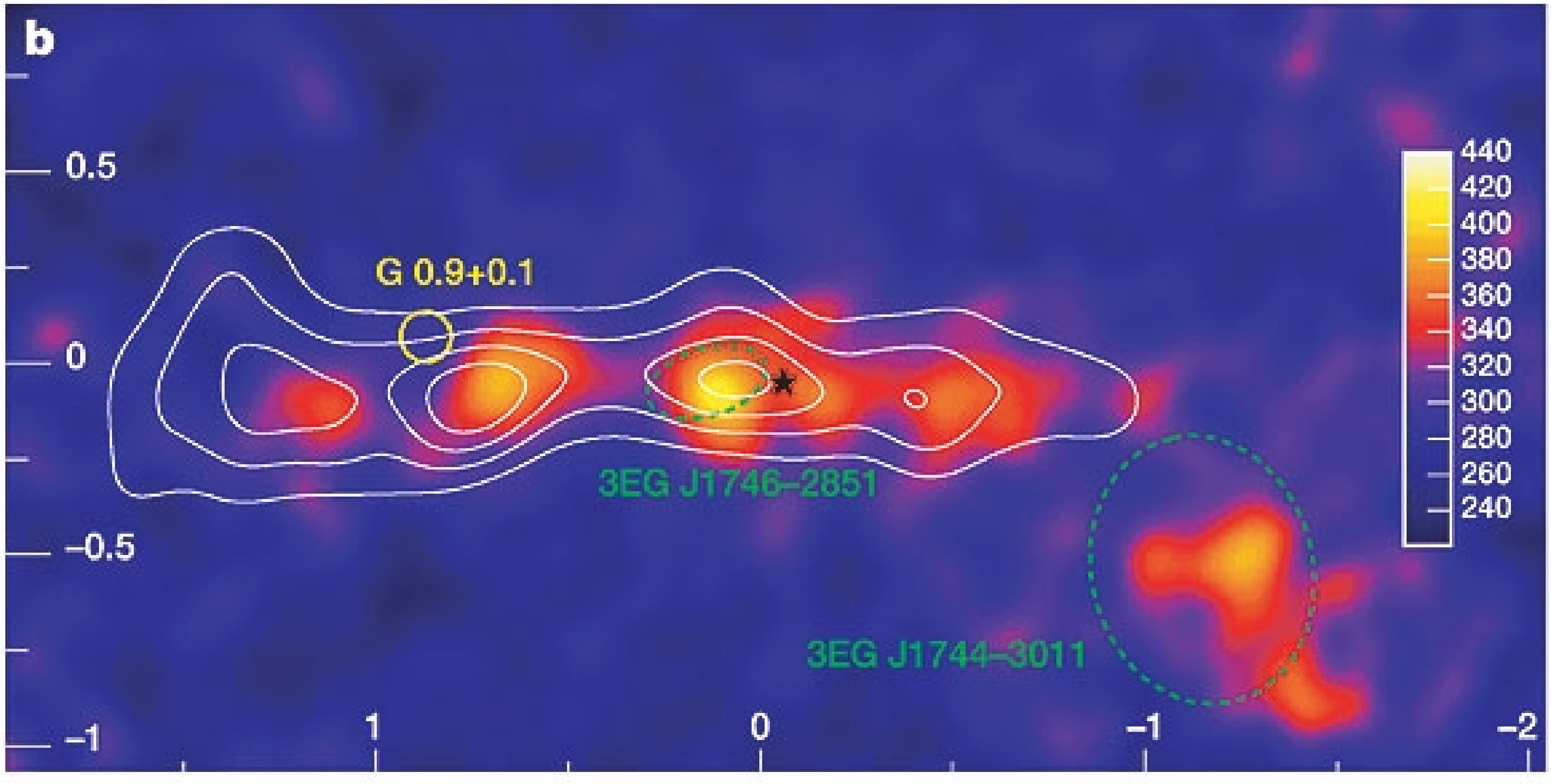
MCs probe the level of the CR sea: TeVs

The galactic centre ridge as seen by HESS



HESS collaboration, 2006

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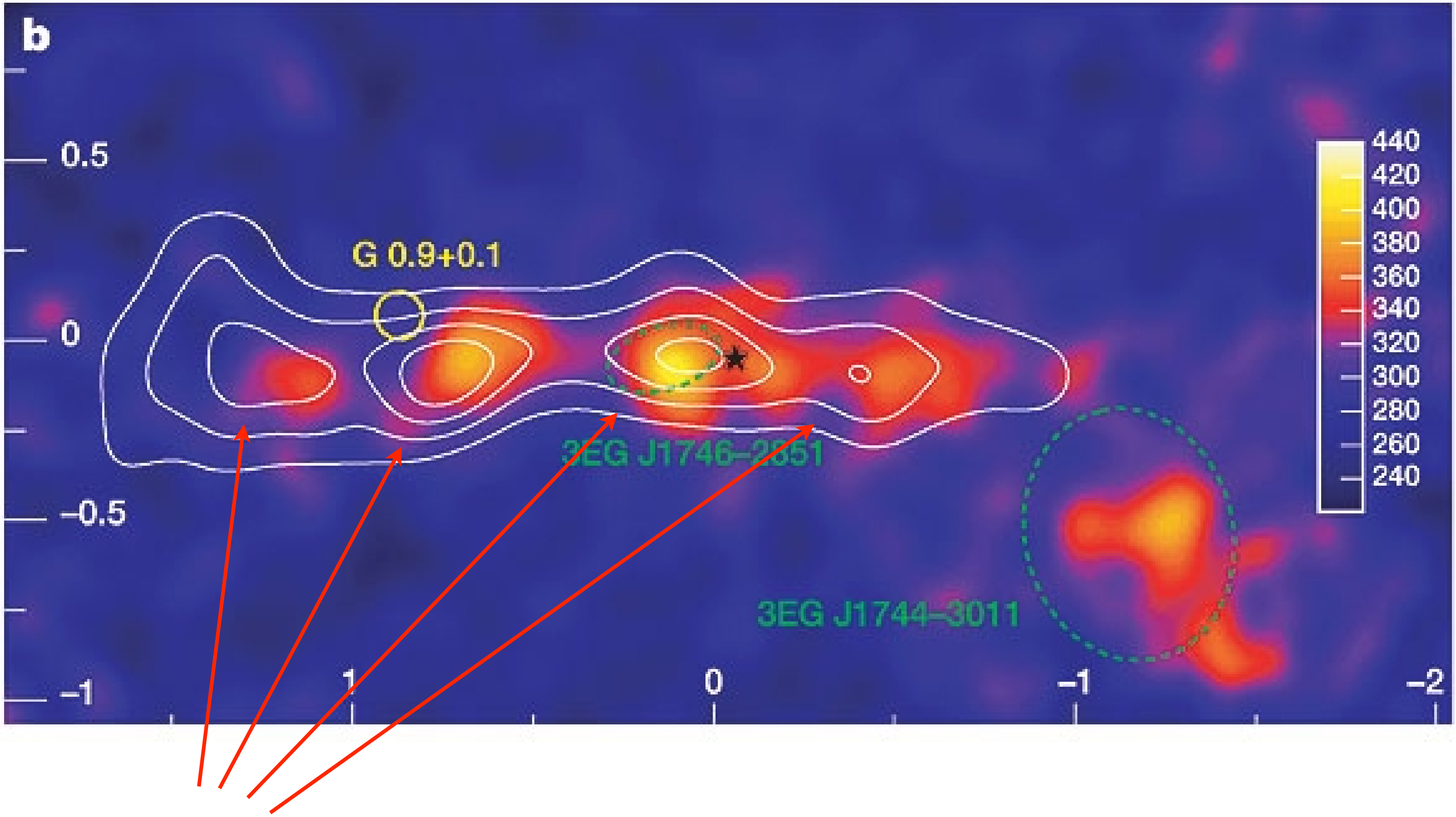

HESS collaboration, 2006

mass of the clouds
measured from
observations of CS lines

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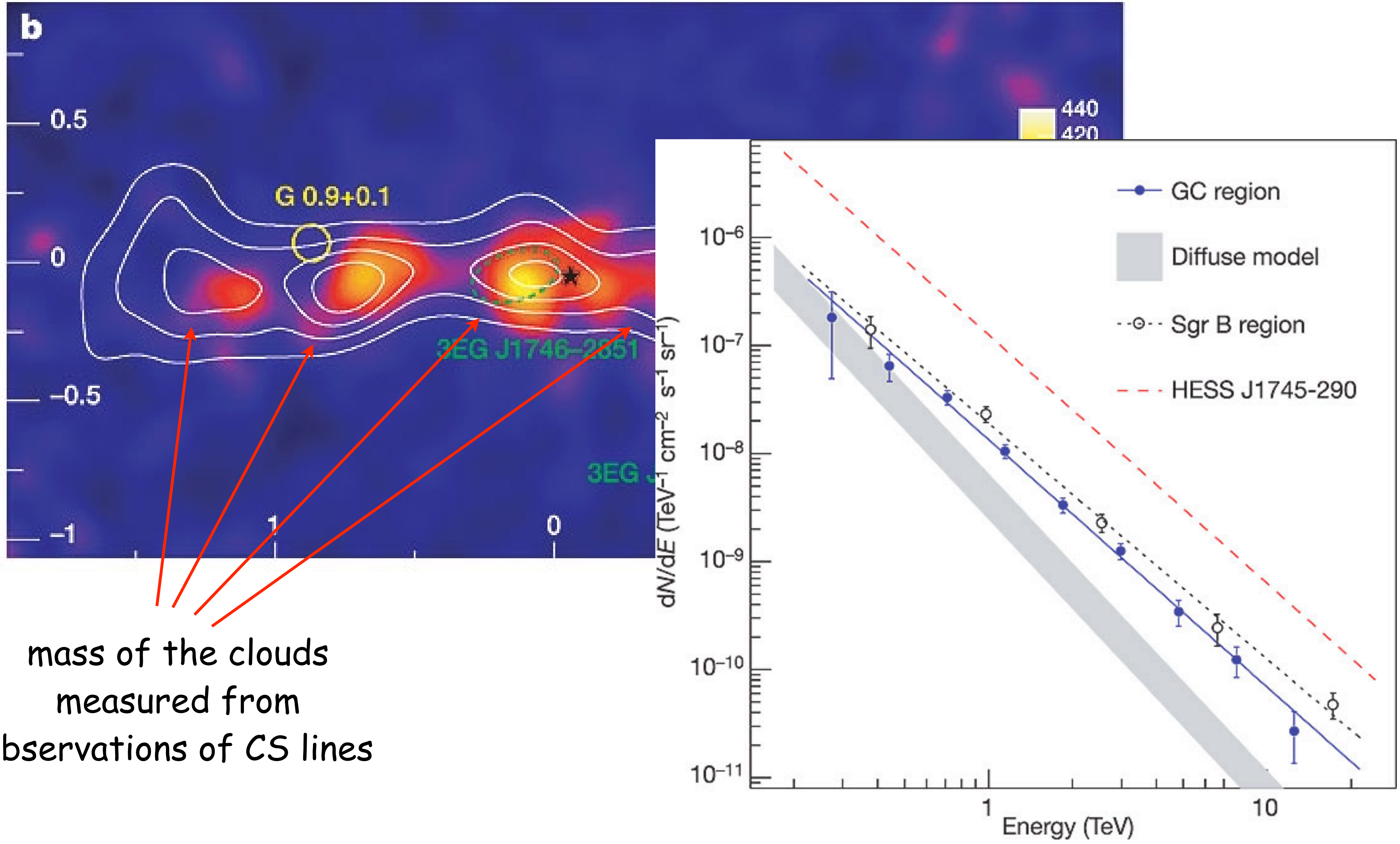

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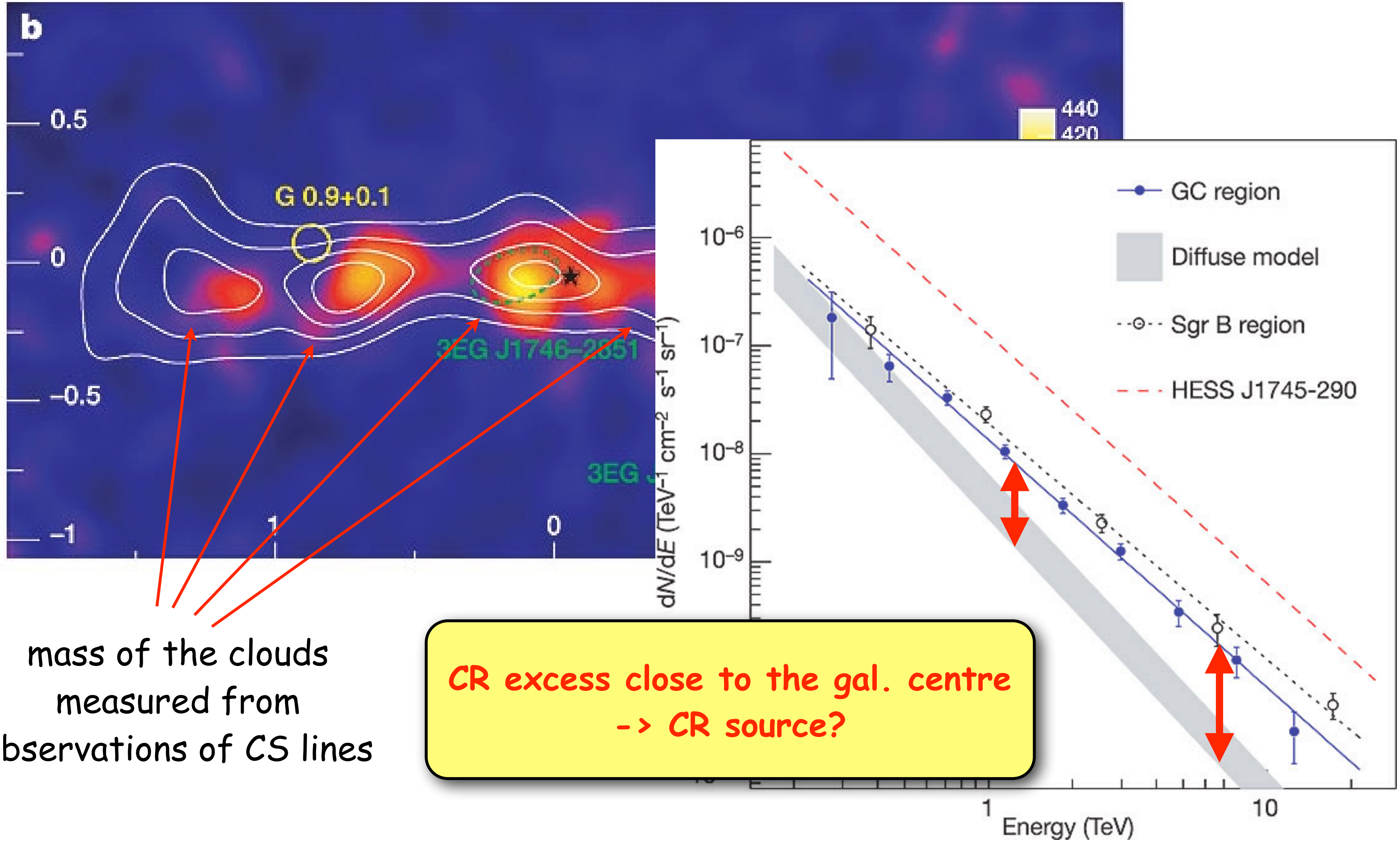

mass of the clouds
measured from
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CR excess close to the gal. centre
-> CR source?

Identifying CR sources: Montmerle's SNOBs

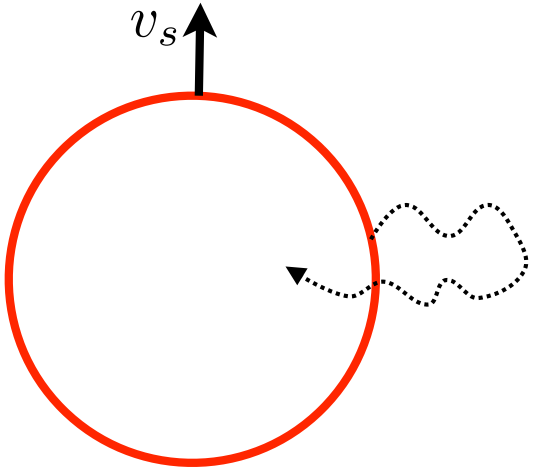
Super Novae-OB stars associations

adapted from Montmerle, 1979 ; Casse & Paul, 1980

- ☑ **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 clouds is expected

How to use Molecular Clouds...

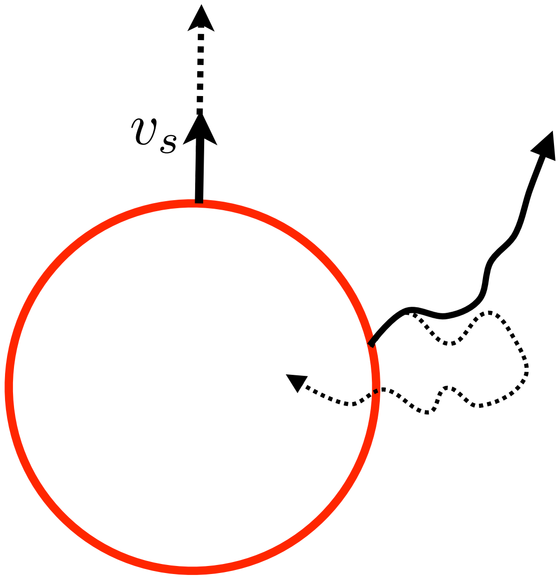


SNRs accelerate CRs

Aharonian&Atoyan, 1996; SG&Aharonian, 2007

How to use Molecular Clouds...

CRs "somehow"
escape the SNR



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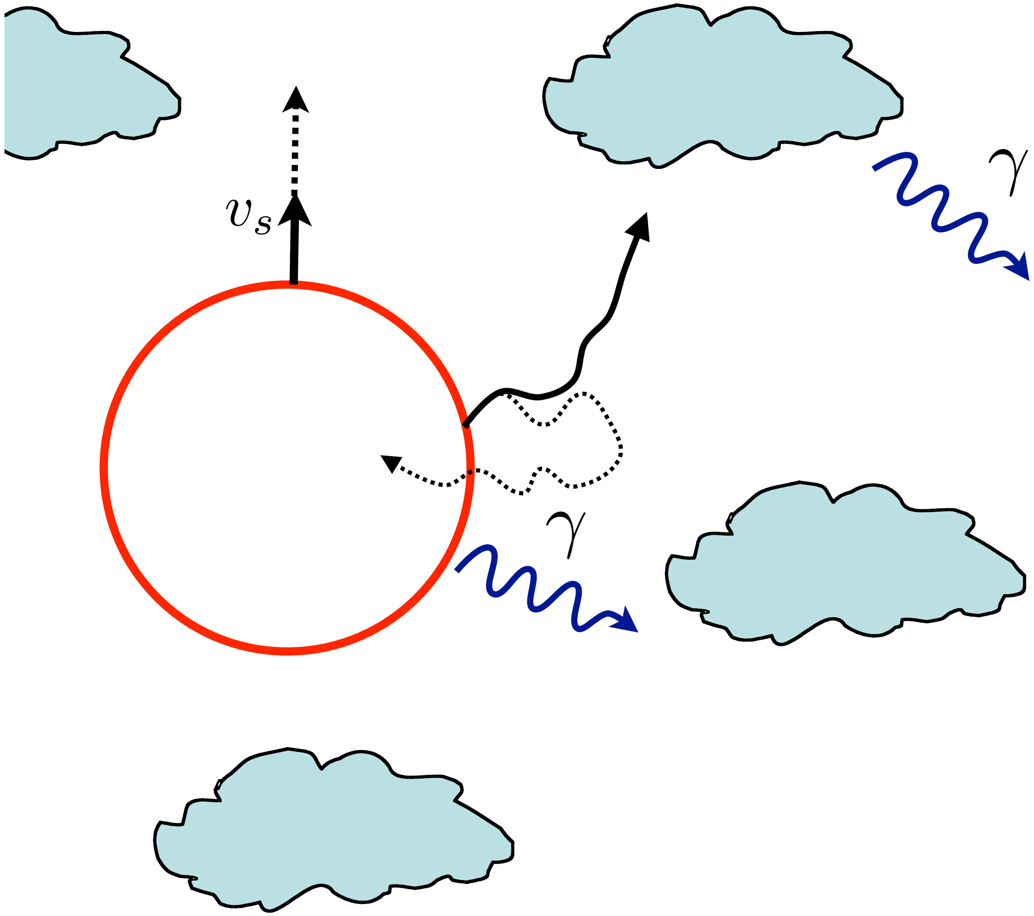

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MCs enhance the gamma ray emission

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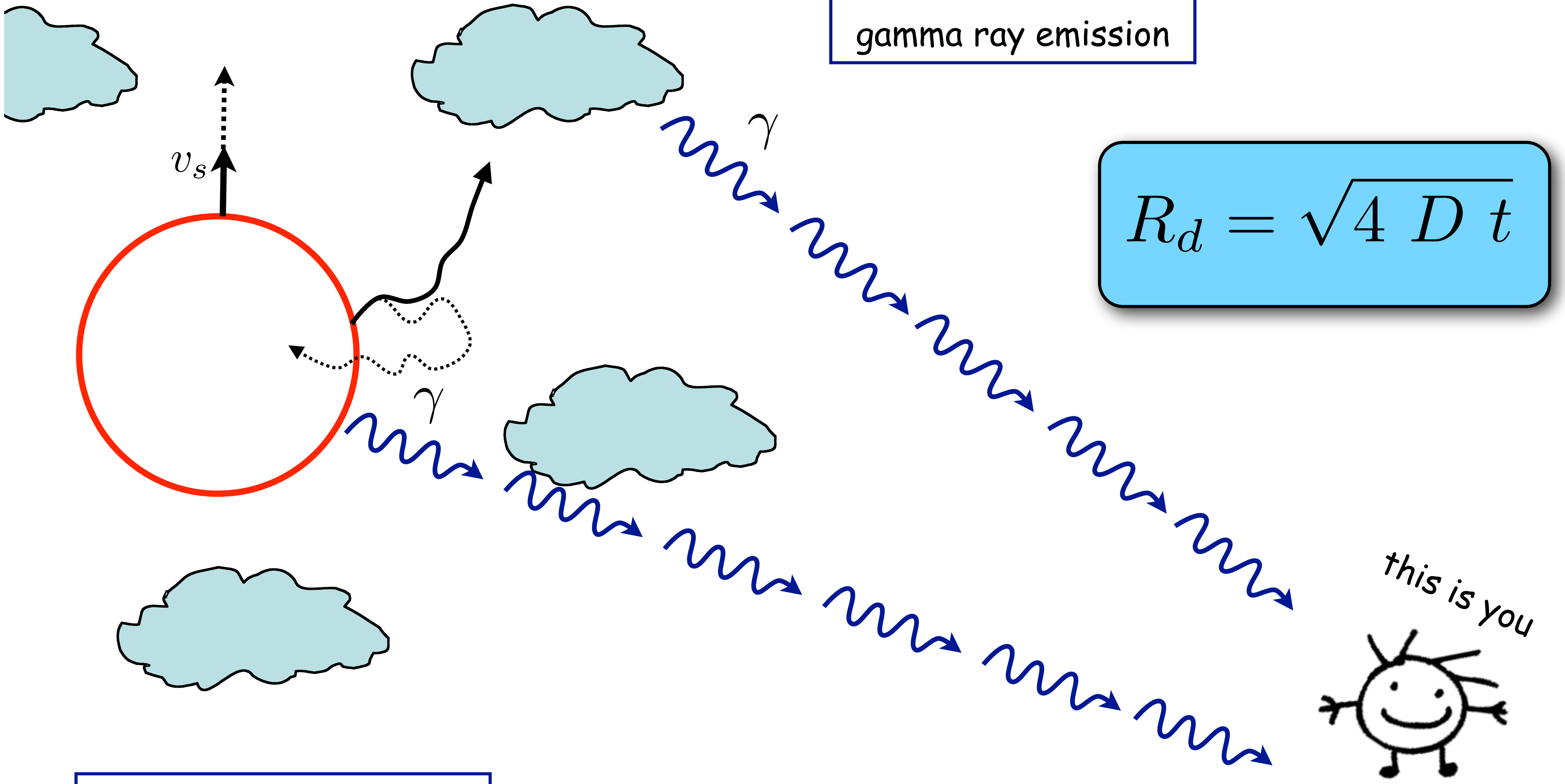

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$$R_d = \sqrt{4\ D\ t}$$

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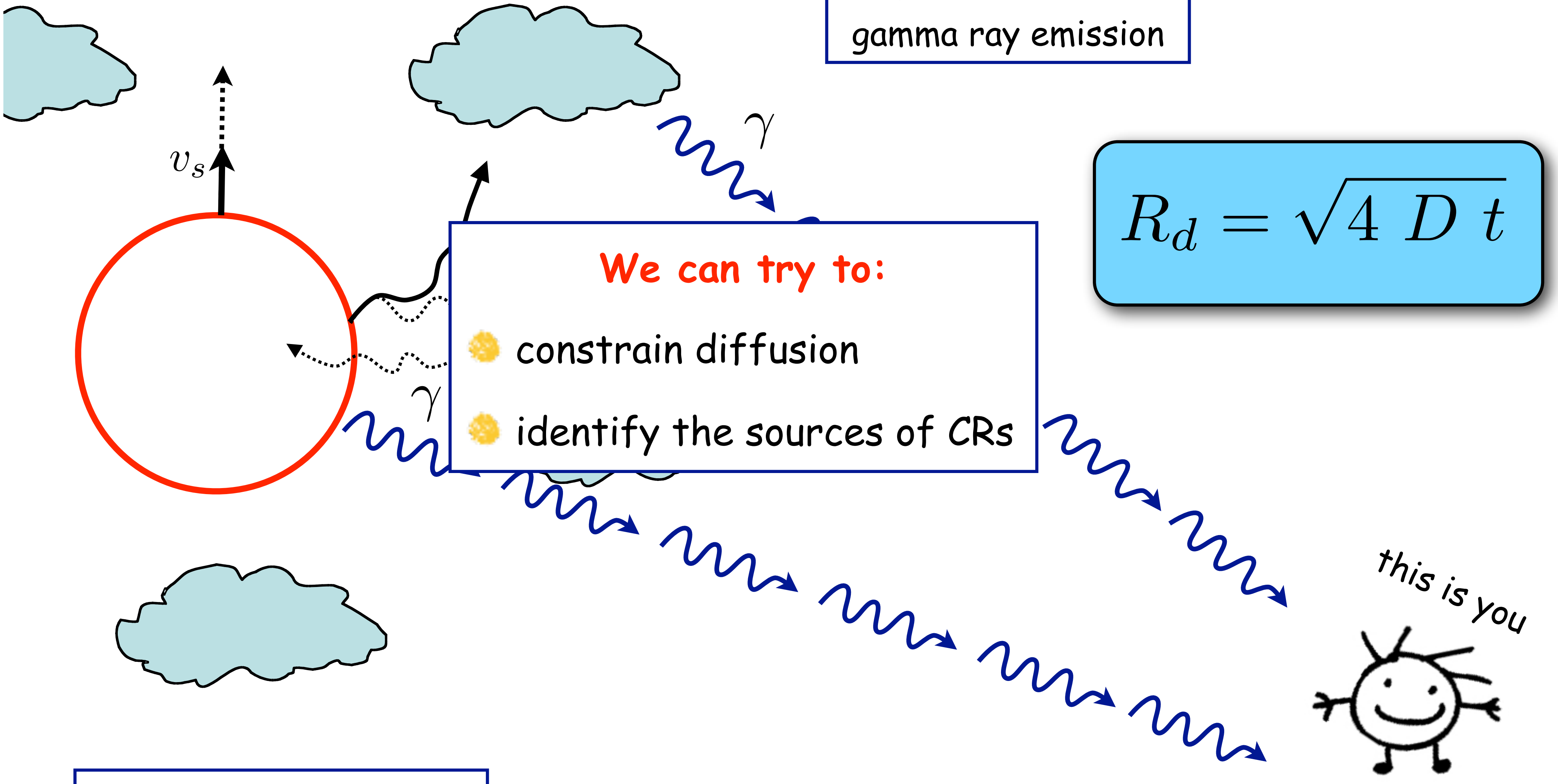


CRs “somehow” escape the SNR

MCs enhance the gamma ray emission

$$R_d = \sqrt{4\ D\ t}$$

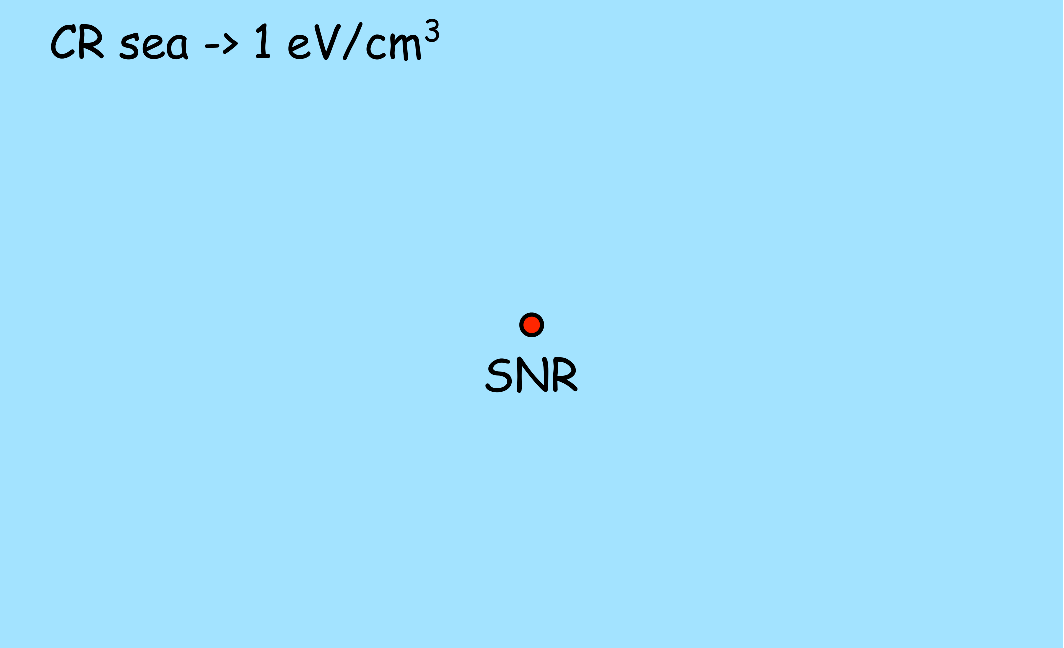
We can try to:

- constrain diffusion
- identify the sources of CRs

SNRs accelerate CRs

Aharonian&Atoyan, 1996; SG&Aharonian, 2007

Implications of the SNR hypothesis

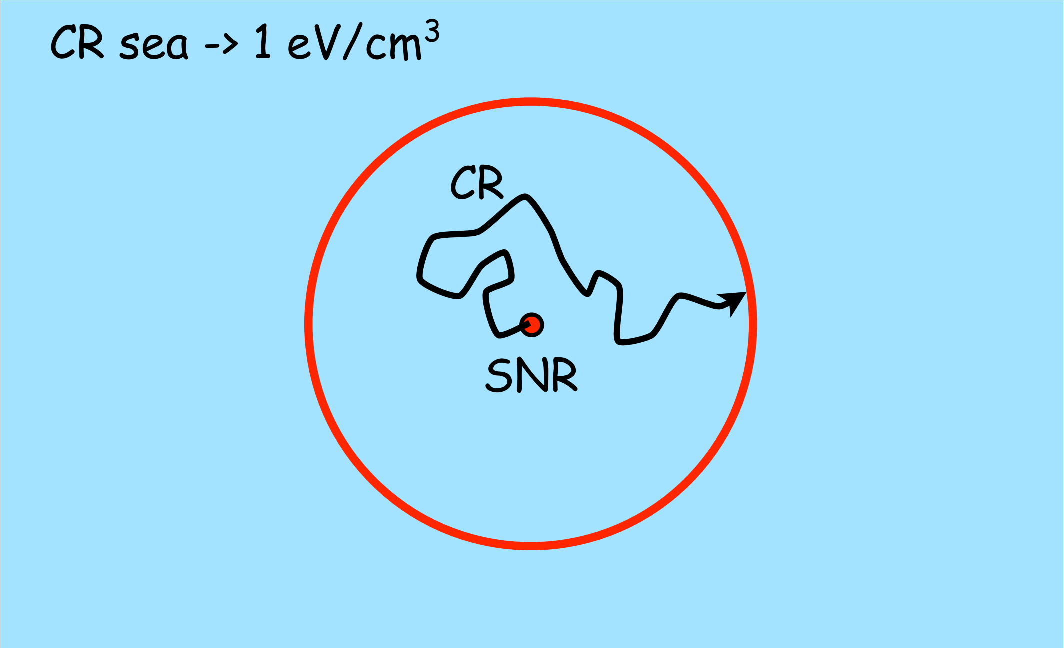


CR sea -> 1 eV/cm^3

SNR

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

Implications of the SNR hypothesis



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volume affected by CRs from the SNR

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

➡ $R_{CR} \approx 100\ \text{pc}$

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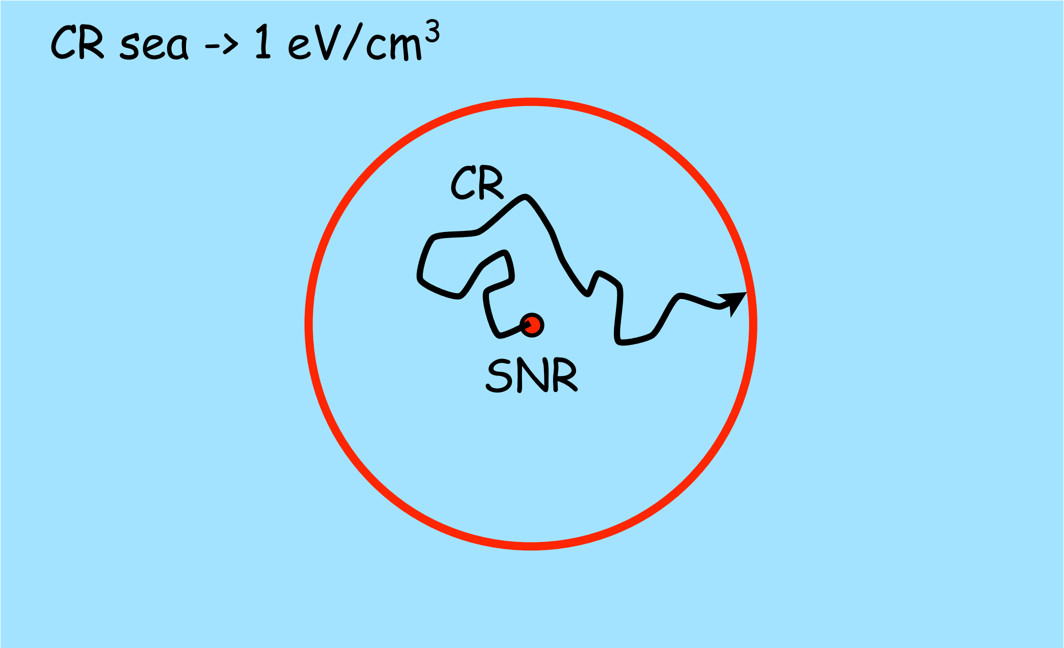

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$$\Rightarrow \quad R_{CR} \approx 100 \mathrm{~pc}$$

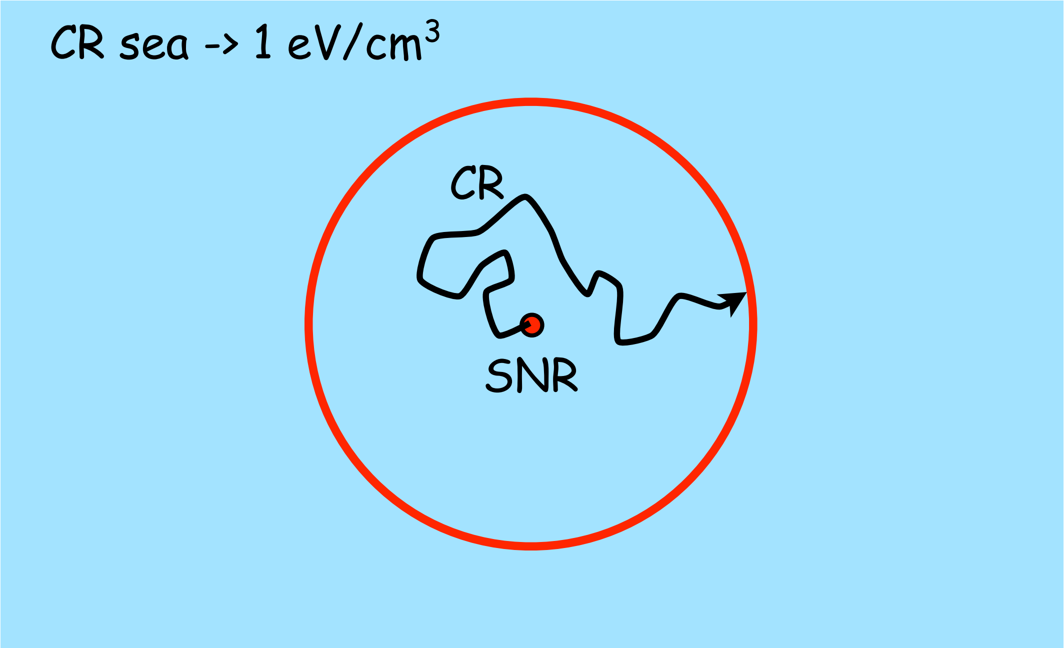
such a volume is affected for a time:

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

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

Implications of the SNR hypo is

Very rough!



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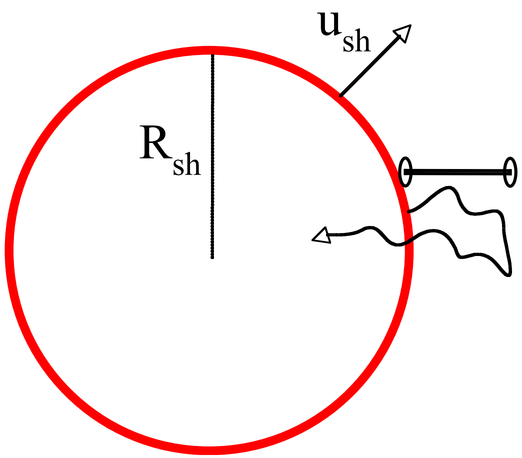
When do CRs escape SNRs?

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

THIS IS A SNR



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

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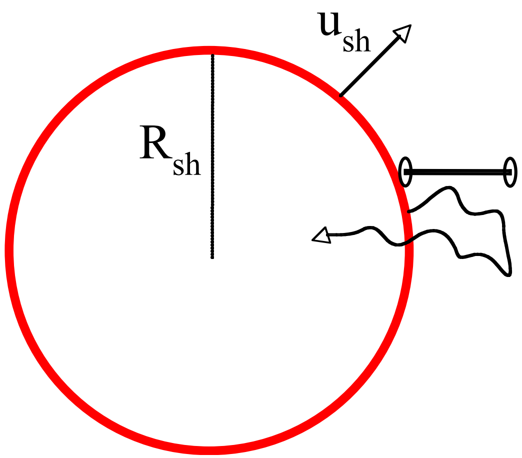

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$$\frac{D(E)}{u_{sh}(t)} < R_{sh}(t) \;\; \rightarrow \;\; E_{max} \sim B_{sh}\, u_{sh}(t)\, R_{sh}(t)$$

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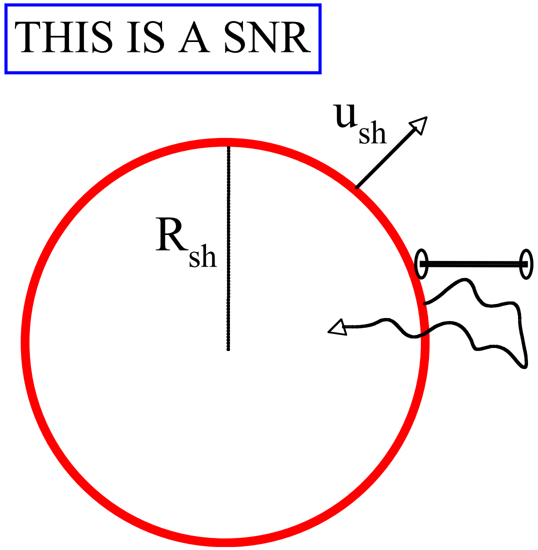

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Sedov phase:

$$R_{sh}(t) \propto t^{2/5}$$
$$u_{sh}(t) \propto t^{-3/5}$$

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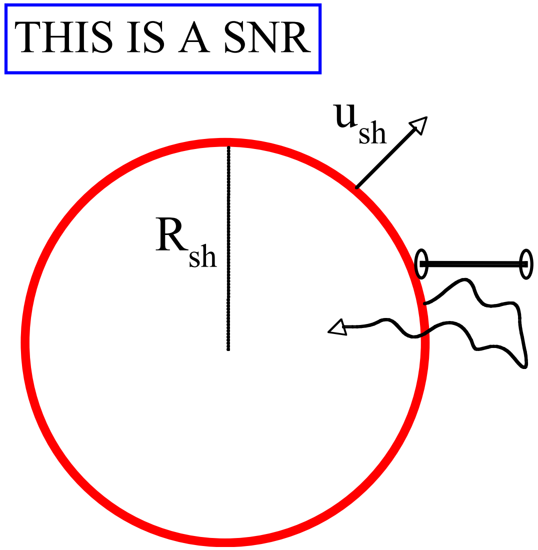

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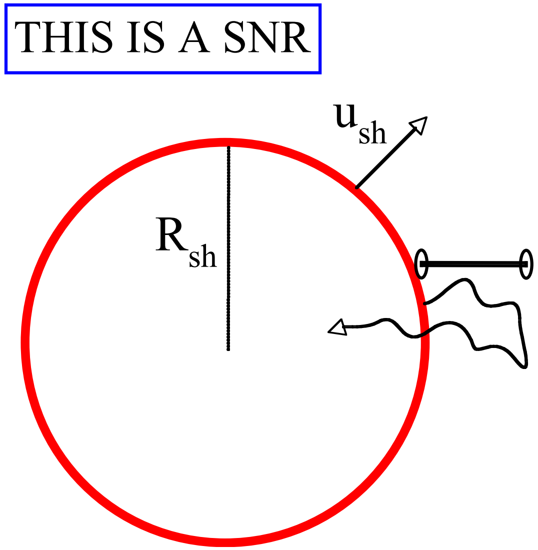

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$$E_{max} \propto B_{sh} t^{-1/5}$$

B

Sedov phase:

$$R_{sh}(t) \propto t^{2/5}$$
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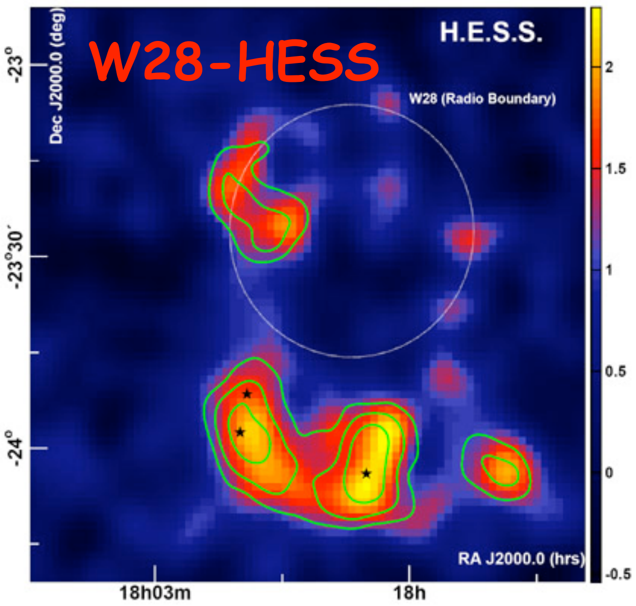
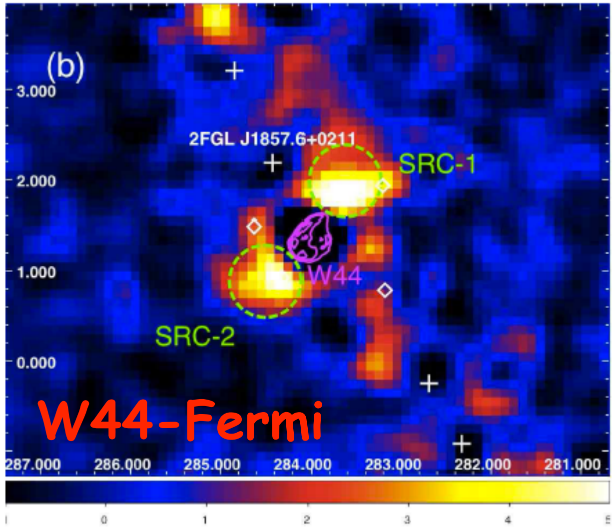
Emax decreases with time

Particles with E > Emax escape the SNR

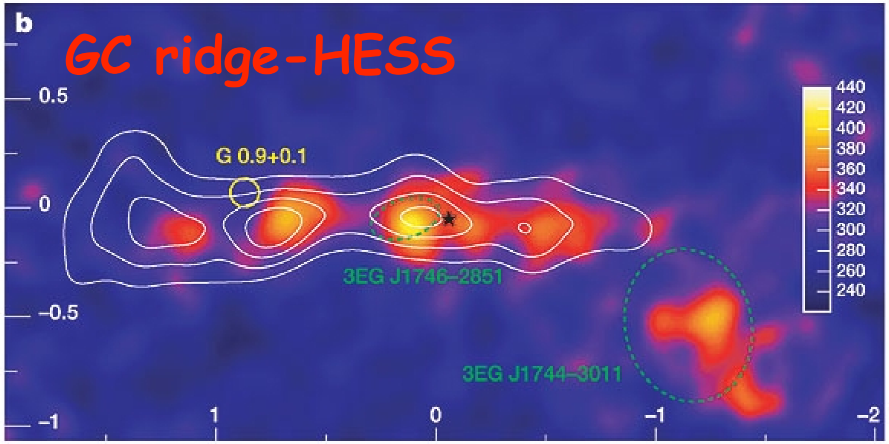
Identifying CR sources now: HESS, MAGIC, VERITAS, FERMI, AGILE



Aharonian et al, 2008



Uchiyama et al, 2012



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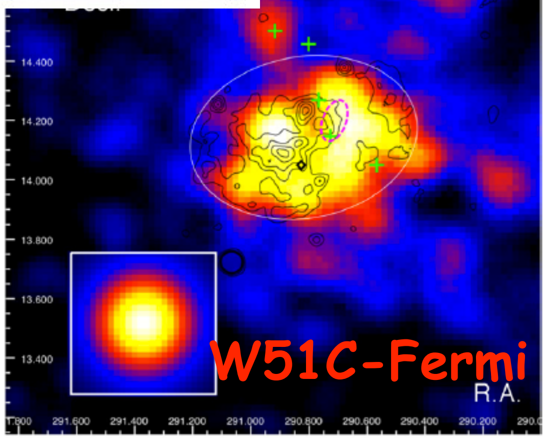

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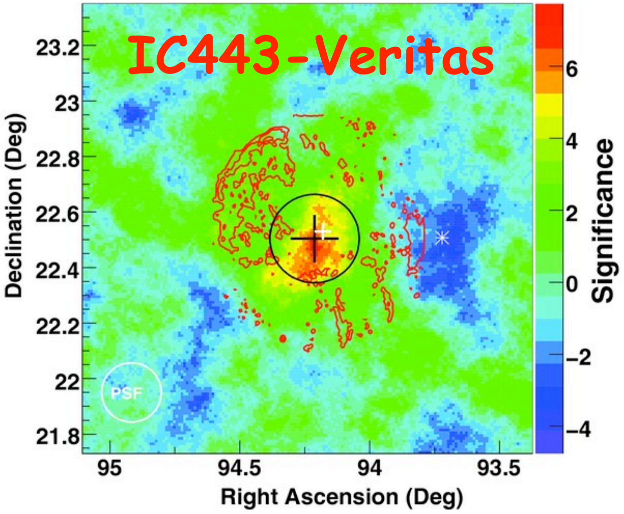
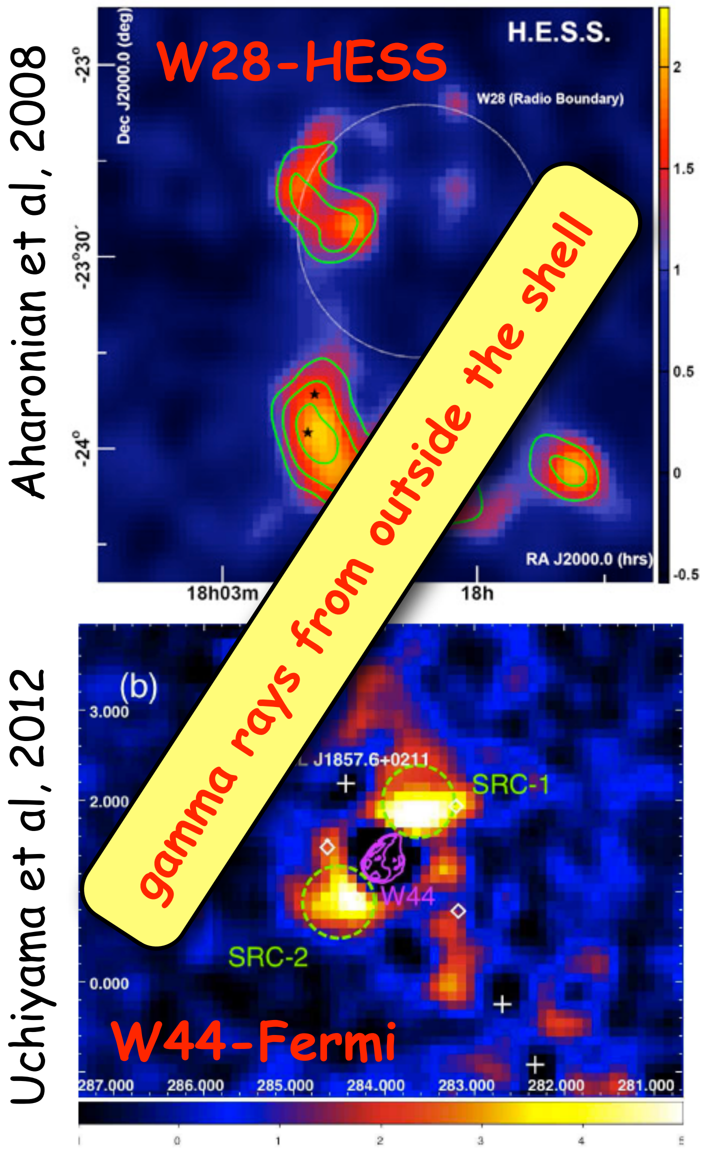


Acciari et al, 2009

+others

Identifying CR sources now: HESS, MAGIC, VERITAS, FERMI, AGILE



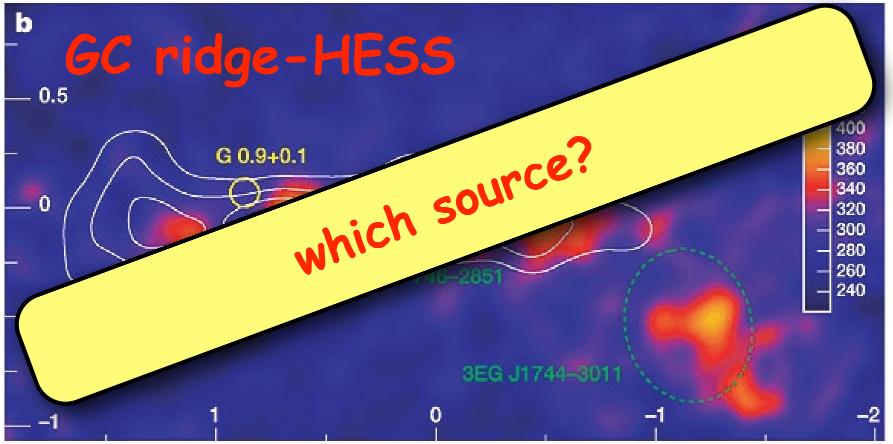
Aharonian et al, 2008

W28-HESS

Uchiyama et al, 2012

W44-Fermi

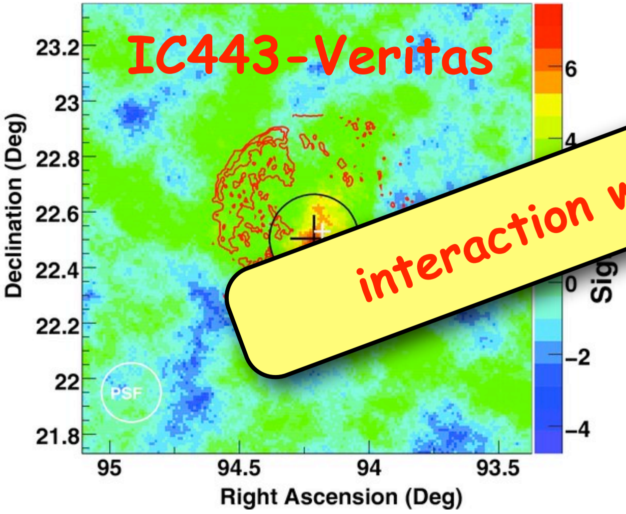
gamma rays from outside the shell



GC ridge-HESS

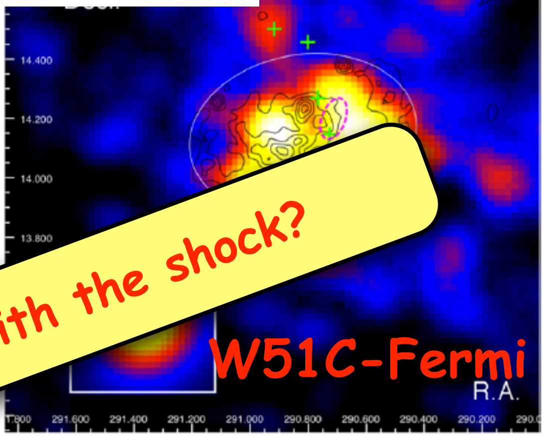
which source?

Aharonian et al, 2006



IC443-Veritas

Acciari et al, 2009



W51C-Fermi

Abdo et al, 2009

interaction with the shock?

+others

Gamma rays from MCs illuminated by CRs

t = 400 yr

1 PeV

SNR

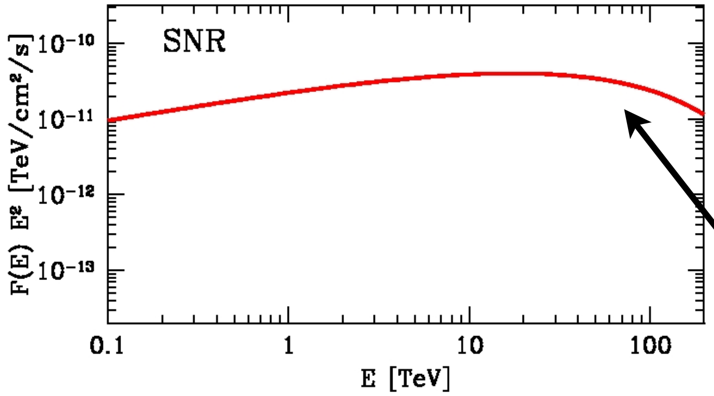
Cloud

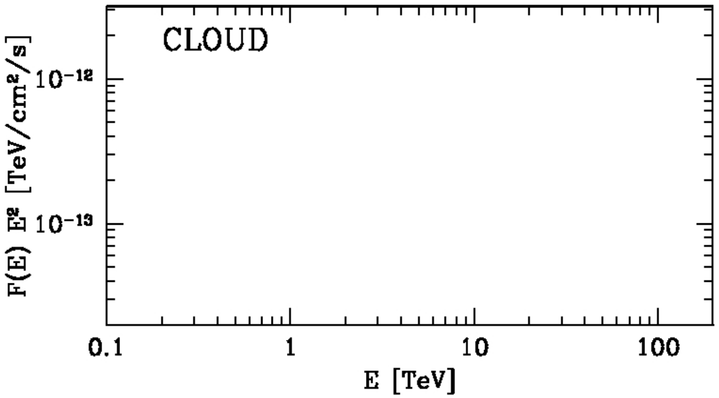
$d = 1\ kpc$

$d_{snr/cl} = 100\ pc$

$M_{cl} = 10^4 M_\odot$

$D_{PeV} = 3\ 10^{29} cm^2/s$





PeVatron!
but for short time!

Gabici&Aharonian(2007)

Gamma rays from MCs illuminated by CRs

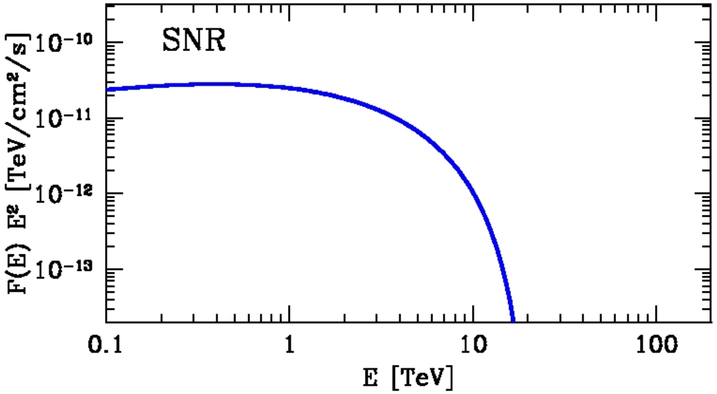
t = 2000 yr

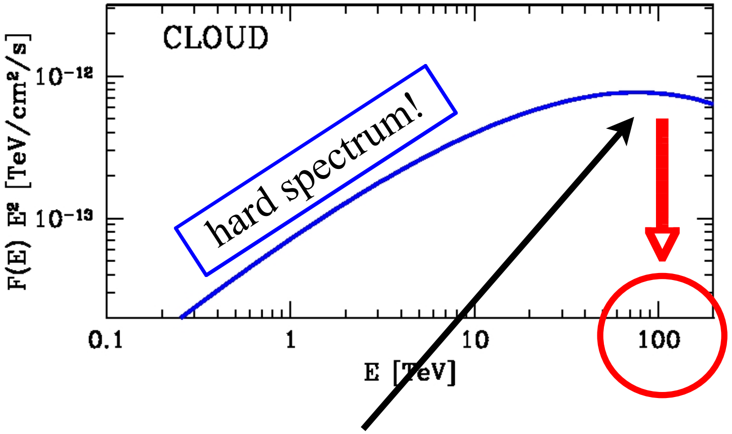
$d = 1\ kpc$

$d_{snr/cl} = 100\ pc$

$M_{cl} = 10^4 M_\odot$

$D_{PeV} = 3\ 10^{29} cm^2/s$





Gabici&Aharonian(2007)

HESS remnant?

Indirect detection of a PeVatron.
Emission may last longer.

NO ICS -> Klein-Nishina

Gamma rays from MCs illuminated by CRs

t = 8000 yr

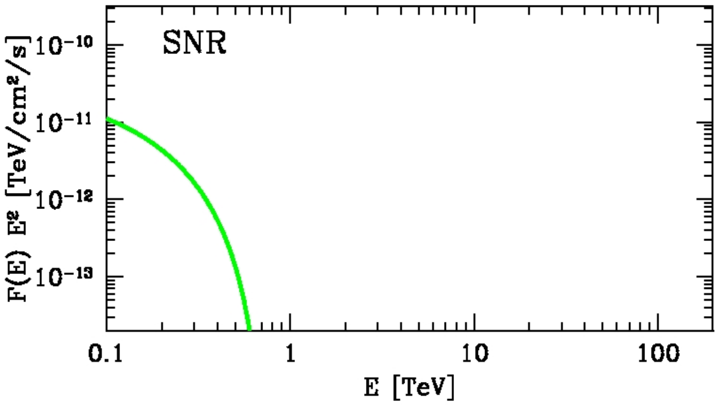
$$d = 1\ kpc$$
$$d_{snr/cl} = 100\ pc$$
$$M_{cl} = 10^4 M_{\odot}$$
$$D_{PeV} = 3\ 10^{29} cm^2/s$$

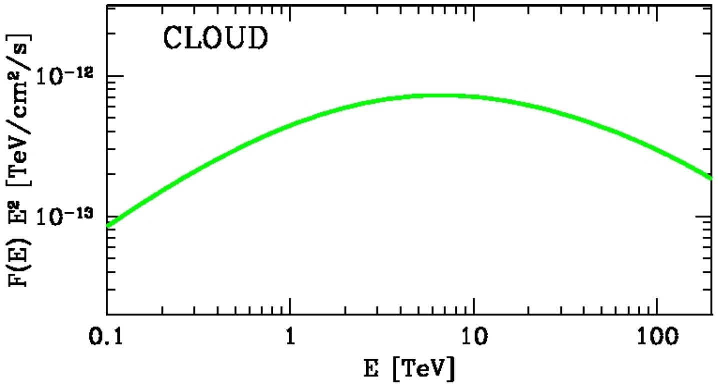
1 TeV

100 TeV

SNR

Cloud





Gabici&Aharonian(2007)

FERMI?

HESS and MILAGRO unidentified sources?

Gamma rays from MCs illuminated by CRs

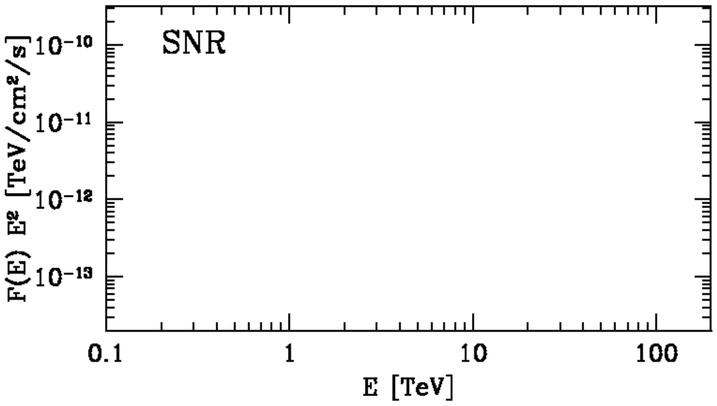
t = 32000 yr

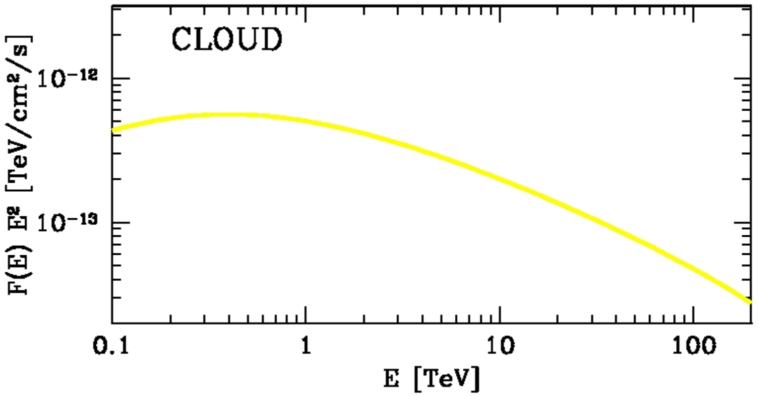
$d = 1\ kpc$

$d_{snr/cl} = 100\ pc$

$M_{cl} = 10^4 M_\odot$

$D_{PeV} = 3\ 10^{29} cm^2/s$



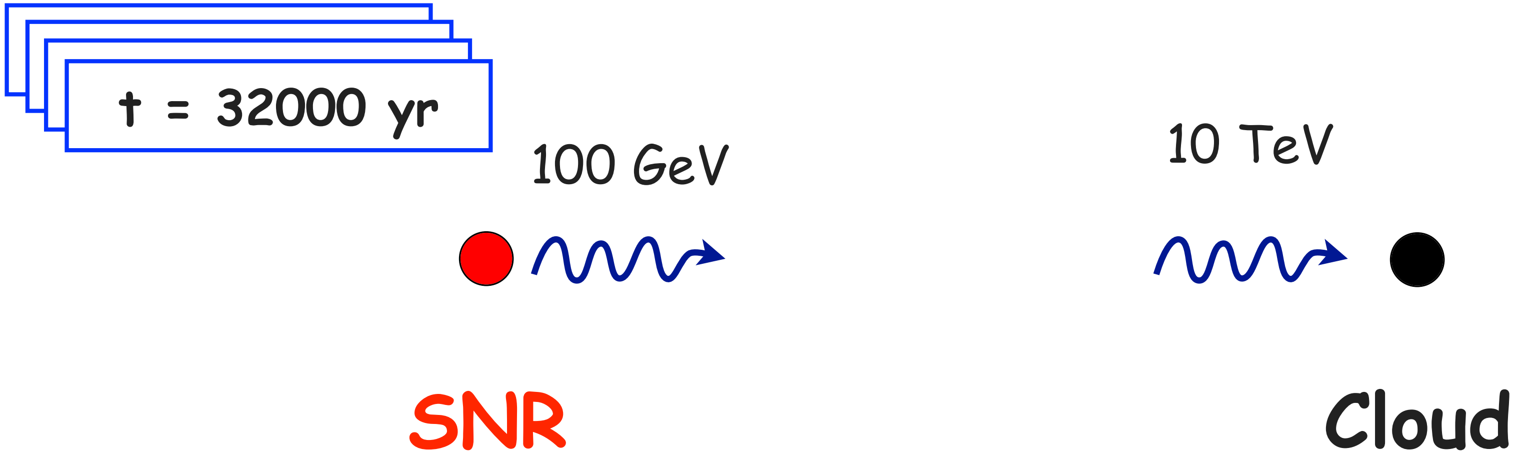


Gabici&Aharonian(2007)

no emission

HESS and MILAGRO unidentified sources?

Gamma rays from MCs illuminated by CRs



t = 32000 yr

100 GeV

10 TeV

SNR

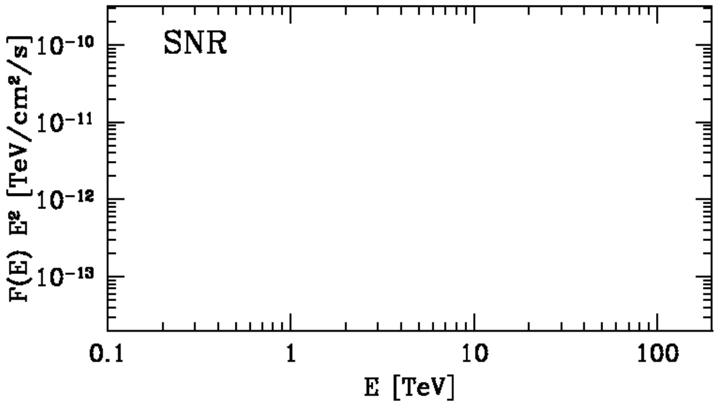
Cloud

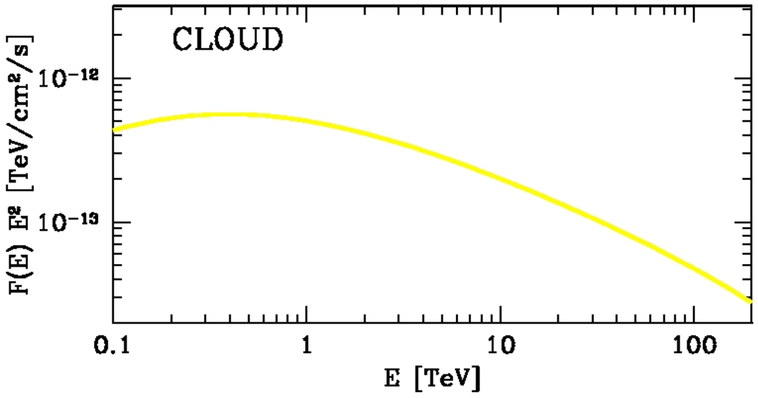
$d = 1\ kpc$

$d_{snr/cl} = 100\ pc$

$M_{cl} = 10^4 M_\odot$

$D_{PeV} = 3\ 10^{29} cm^2/s$





Gabici&Aharonian(2007)

no emission

HESS and MILAGRO
unidentified sources?

Gamma rays from MCs illuminated by CRs

t = 32000 yr

100 GeV

10 TeV

$d = 1\ kpc$

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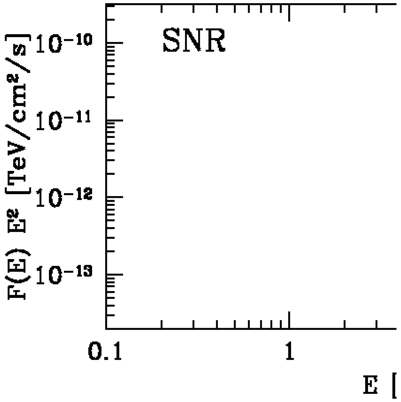
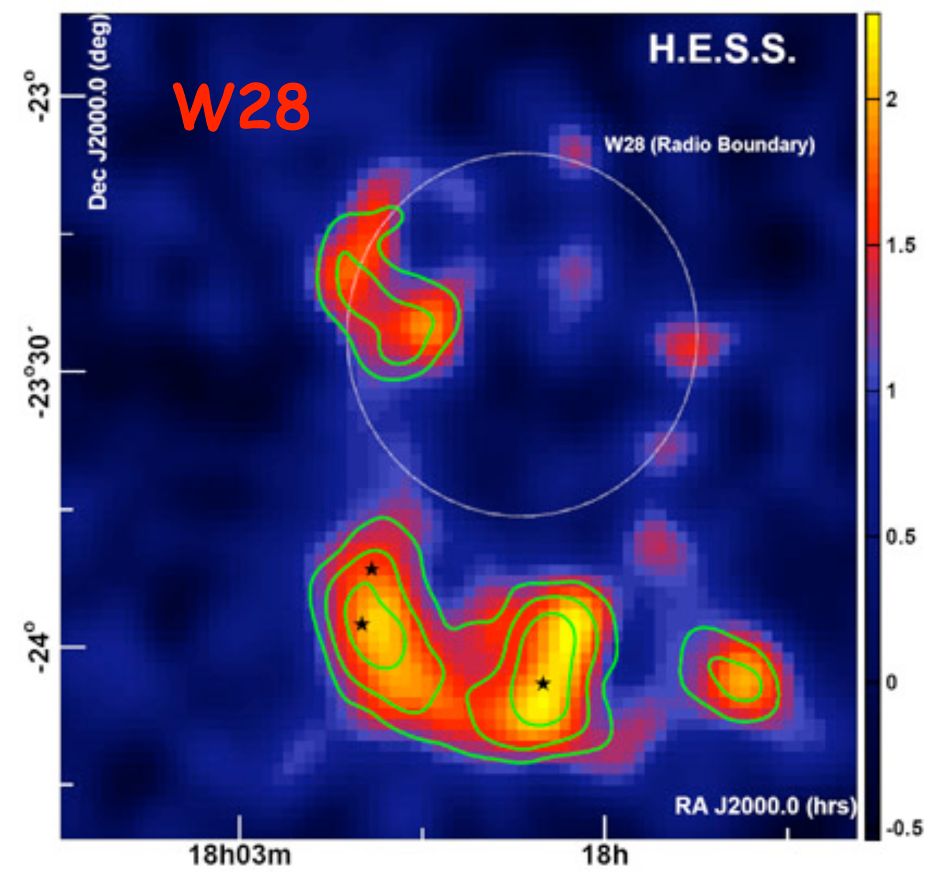
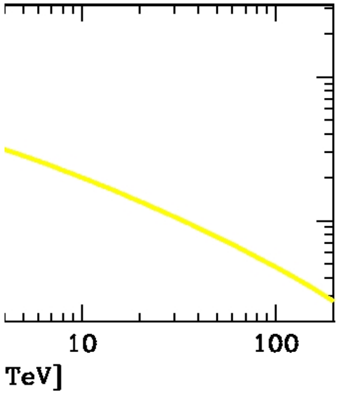
SN

id







Gabici&Aharonian(2007)

no emission

MILAGRO
unidentified sources?

Naive statistics

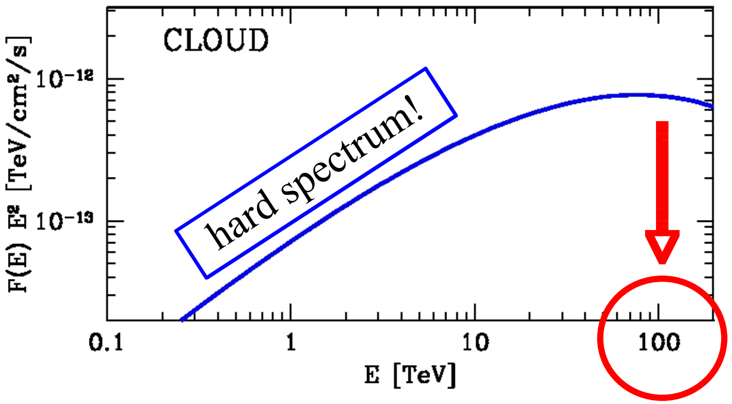
$$d = 1\ kpc$$

$$d_{snr/cl} = 100\ pc$$

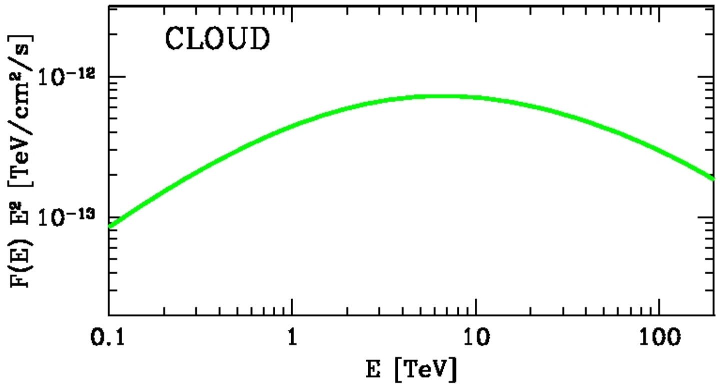
$$M_{cl} = 10^4 M_\odot$$

$$D_{PeV} = 3\ 10^{29} cm^2/s$$

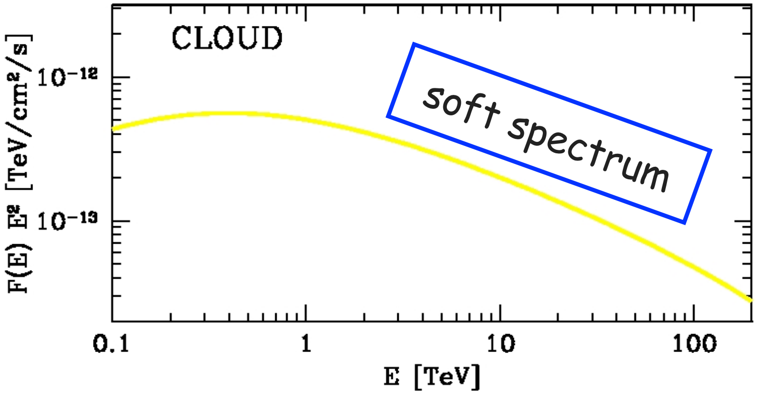
$$= 0.1 \times D_{gal}$$



t = 2000 yr



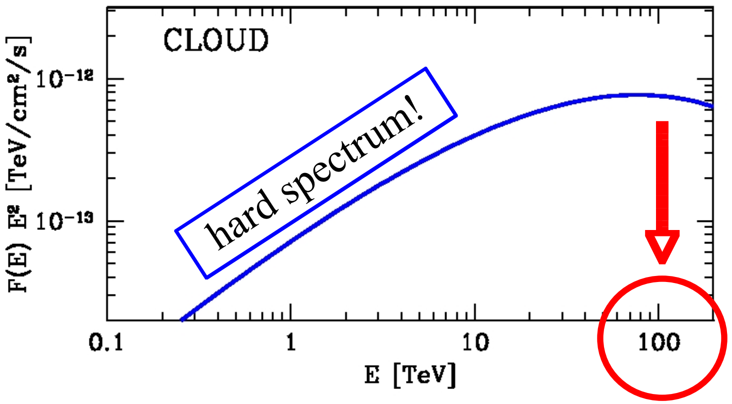
t = 8000 yr



t = 32000 yr

Soft sources dominate the total number of sources

Naive statistics



t = 2000 yr

$= 1\ kpc$

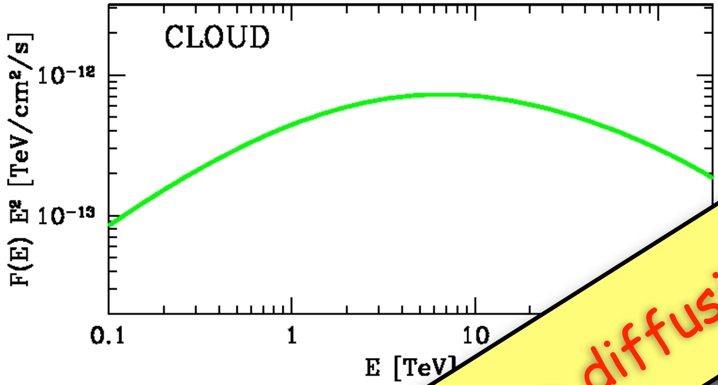
$100\ pc$

$_{cl} = 10^4 M_\odot$

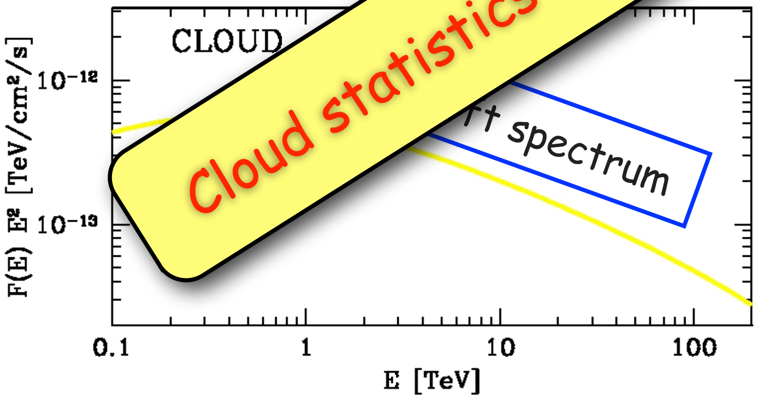
$_{eV} = 3\ 10^{29} cm^2/s$

$= 0.1 \times D_{gal}$

Cloud statistics -> diffusion coefficient at specific locations in the Galaxy



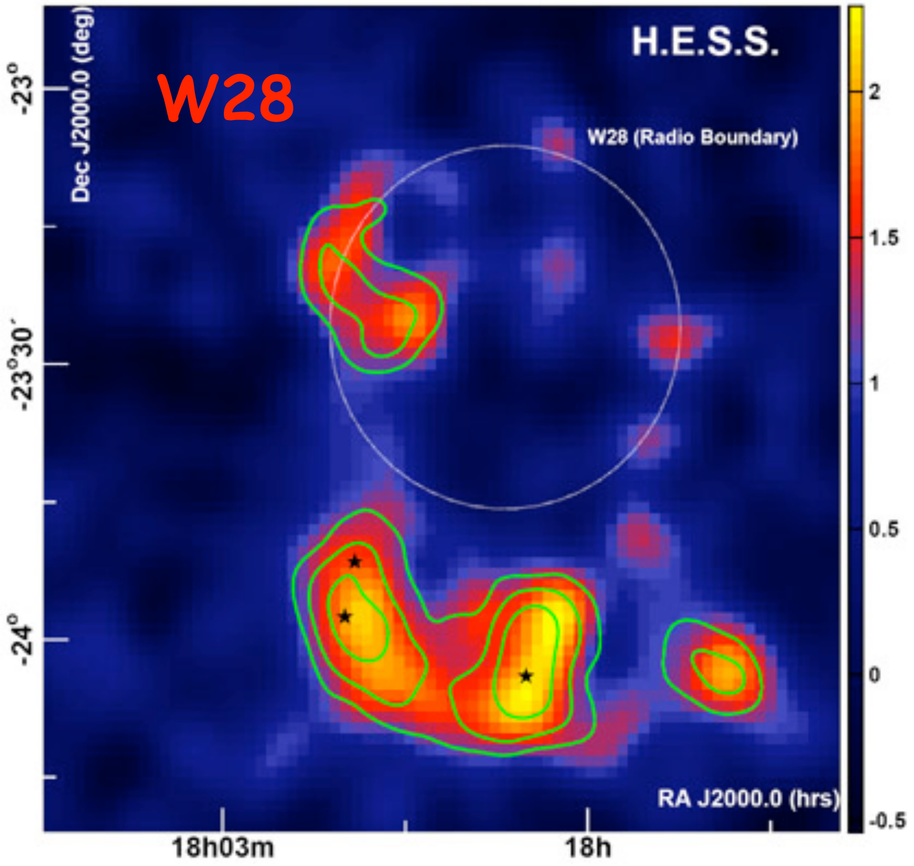
00 yr



t = 32000 yr

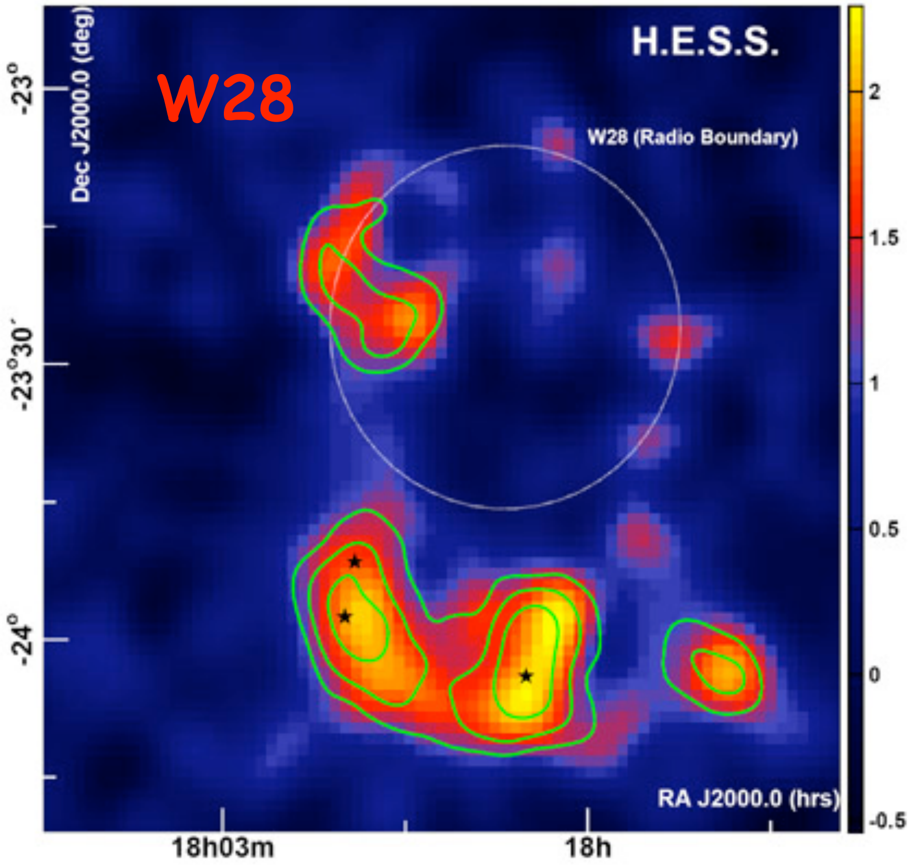
Soft sources dominate the total number of sources

The W28 region in gammas, CO, & radio



HESS - TeV emission

The W28 region in gammas, CO, & radio

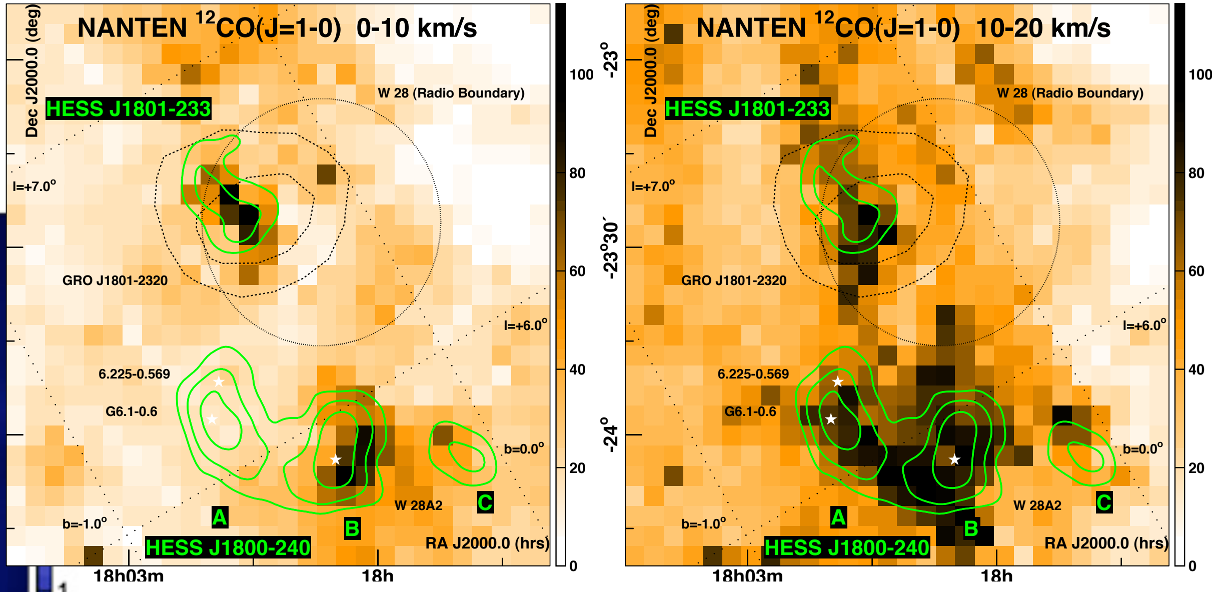


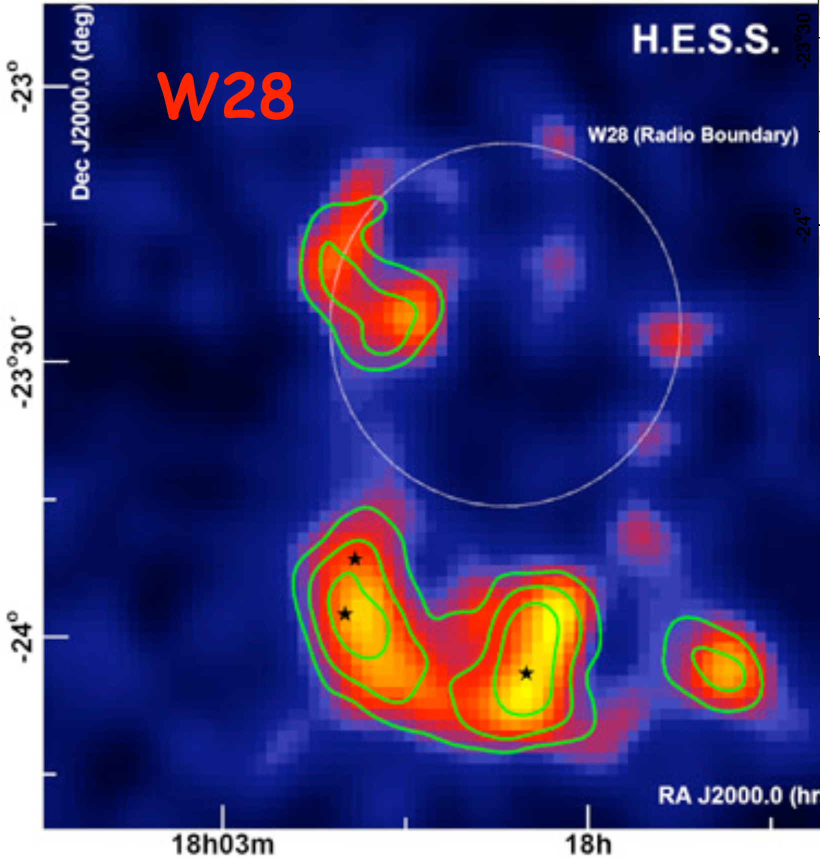
HESS - TeV emission

Aharonian et al, 2008

The W28 region in gammas, CO, & radio

NANTEN data - CO line



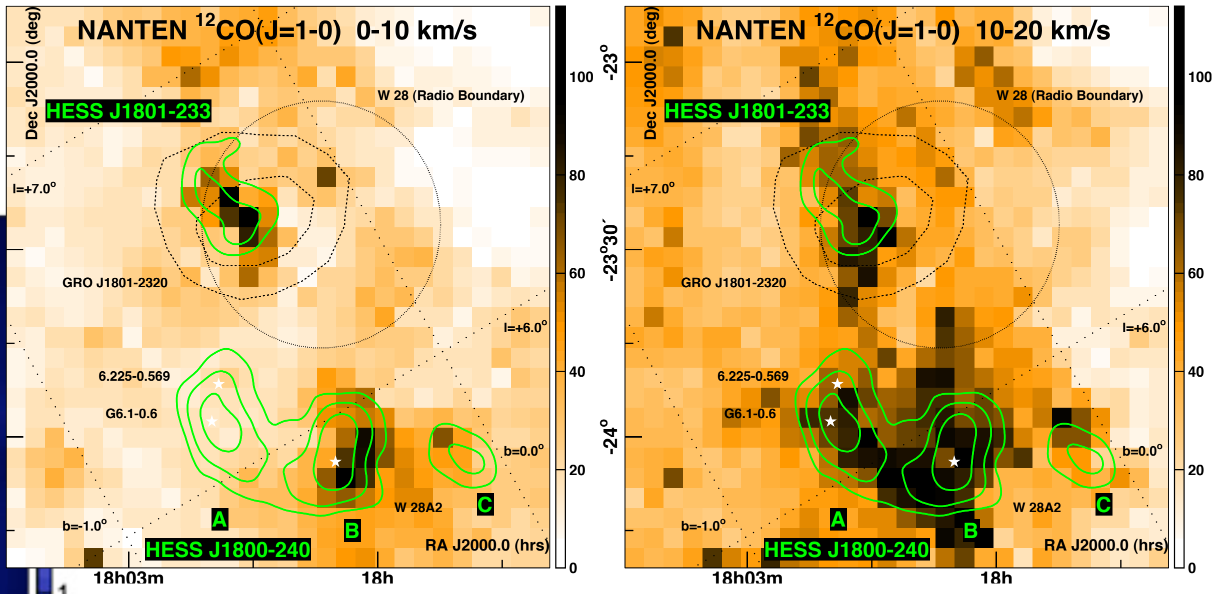


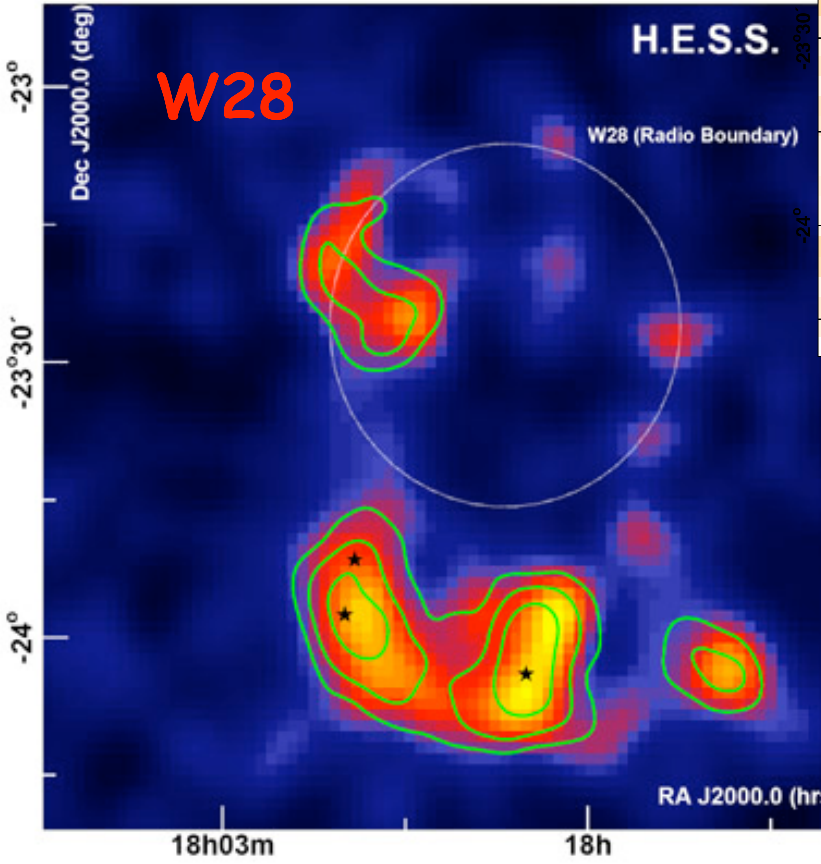
HESS - TeV emission

Aharonian et al, 2008

The W28 region in gammas, CO, & radio

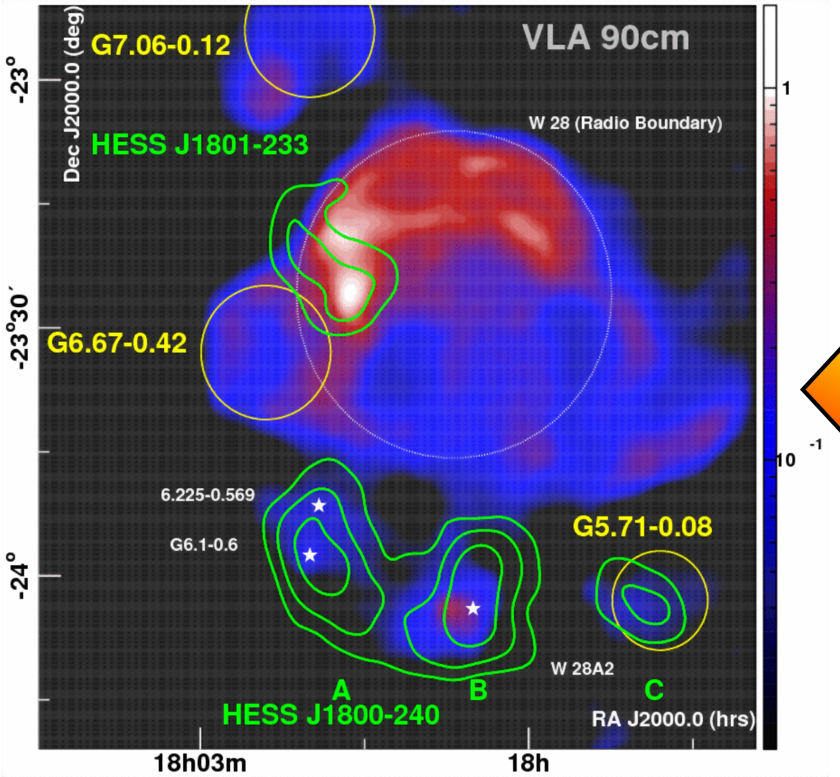
NANTEN data - CO line





HESS - TeV emission

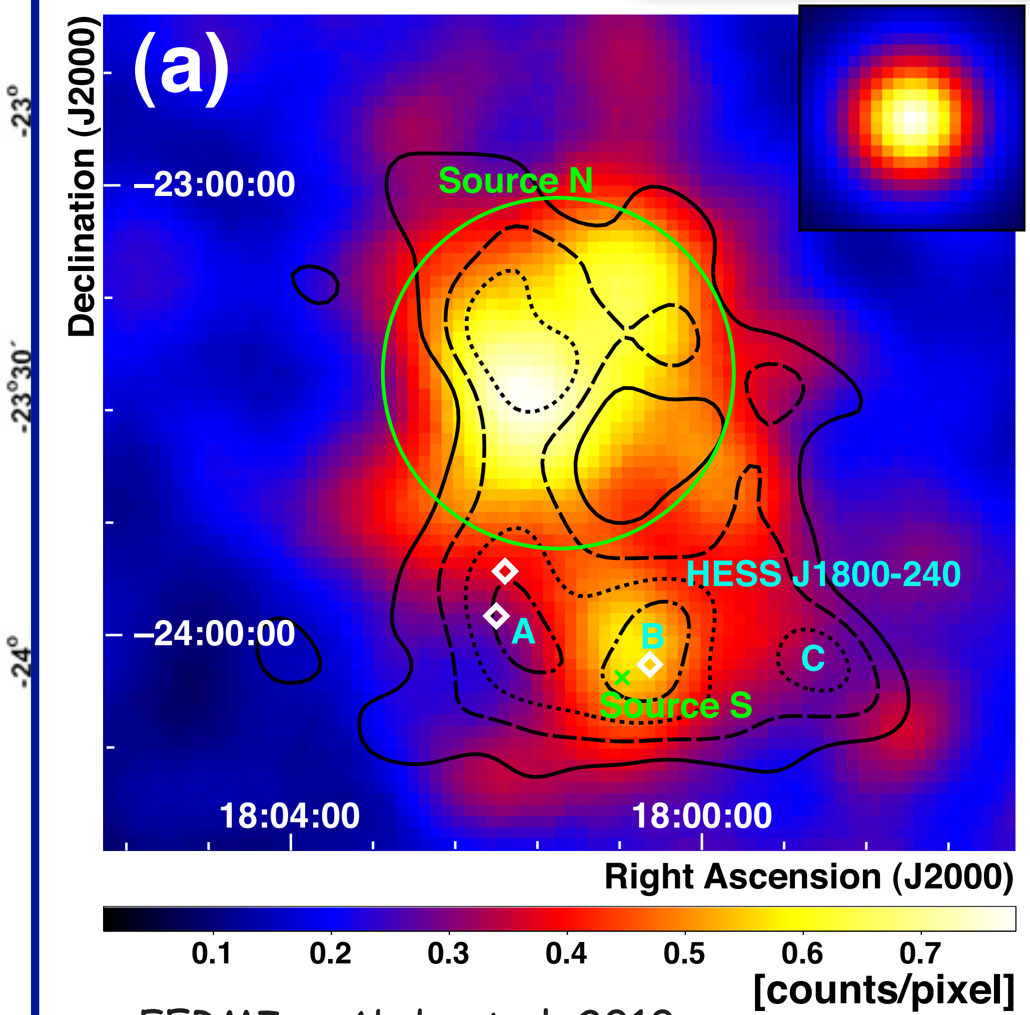
Aharonian et al, 2008



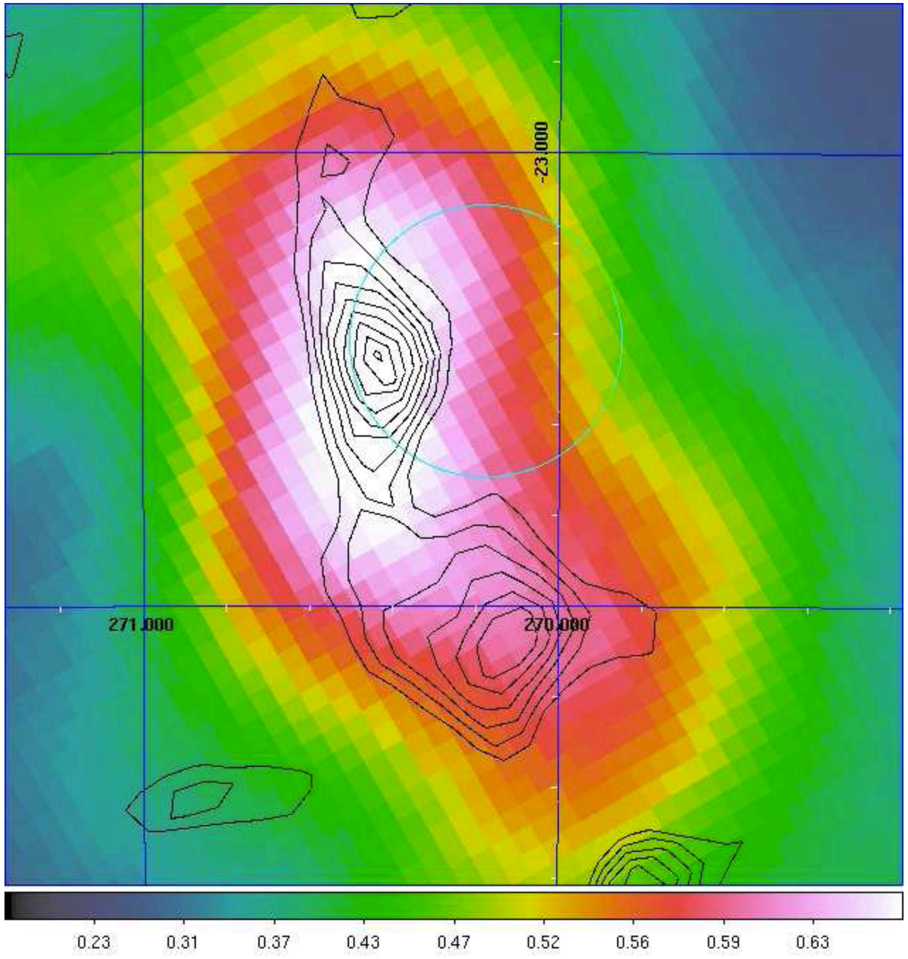
Radio (Dubner et al 2000)

The W28 region in gammas, CO, & radio

FERMI and AGILE - GeV emission

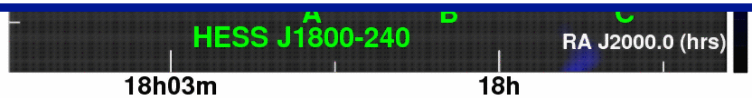


FERMI -> Abdo et al, 2010

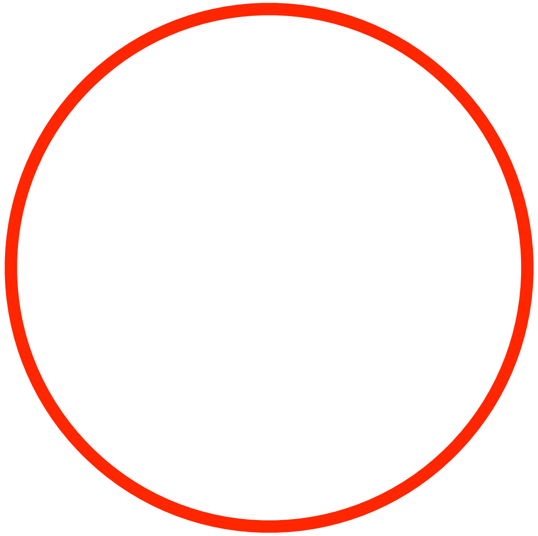


AGILE -> Giuliani et al, 2010

Aharonian et al, 2008



W28: a cartoon



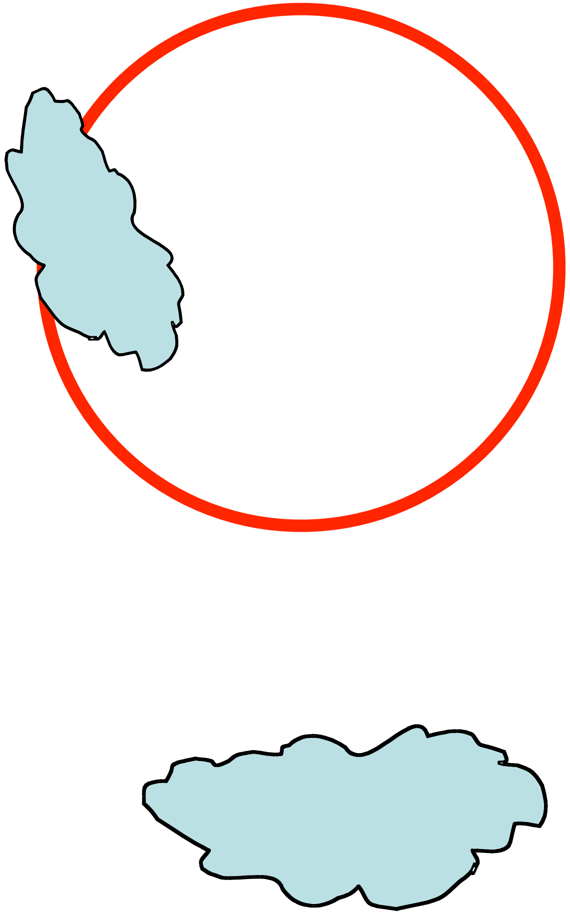
SNR shell

- radio emission

  -> GeV electrons

  -> ongoing (re)acceleration?

W28: a cartoon



SNR shell

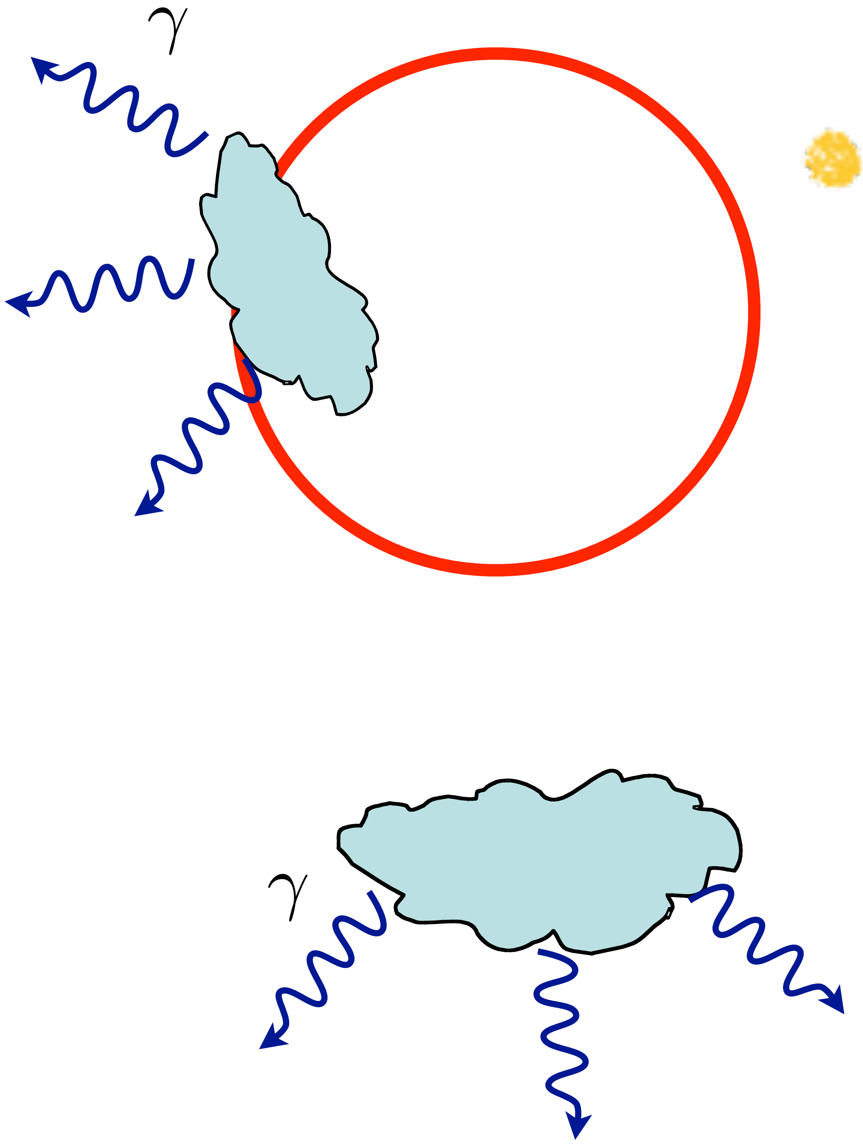
Molecular clouds

● radio emission

-> GeV electrons

-> ongoing (re)acceleration?

W28: a cartoon



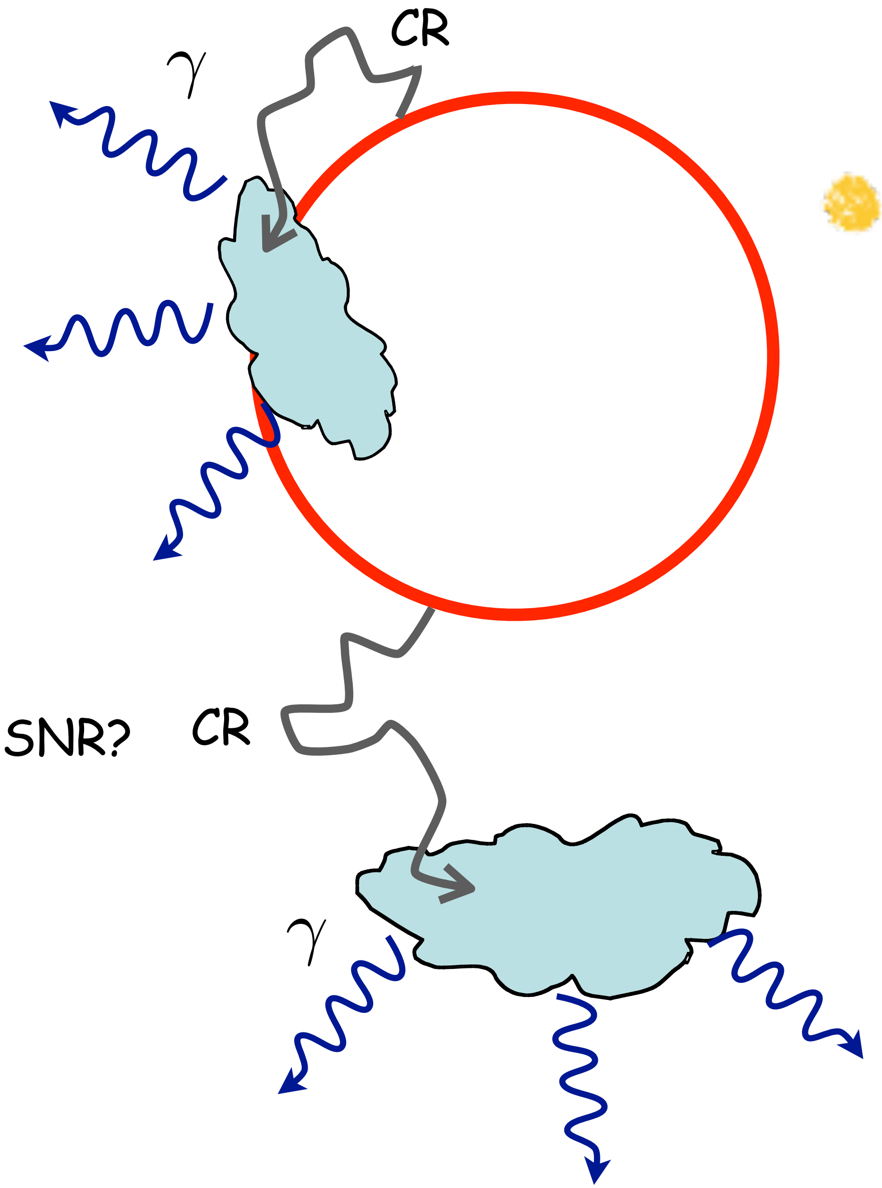
Molecular clouds

- gamma rays + gas
  - -> CR protons?

SNR shell

- radio emission
  - -> GeV electrons
  - -> ongoing (re)acceleration?

W28: a cartoon



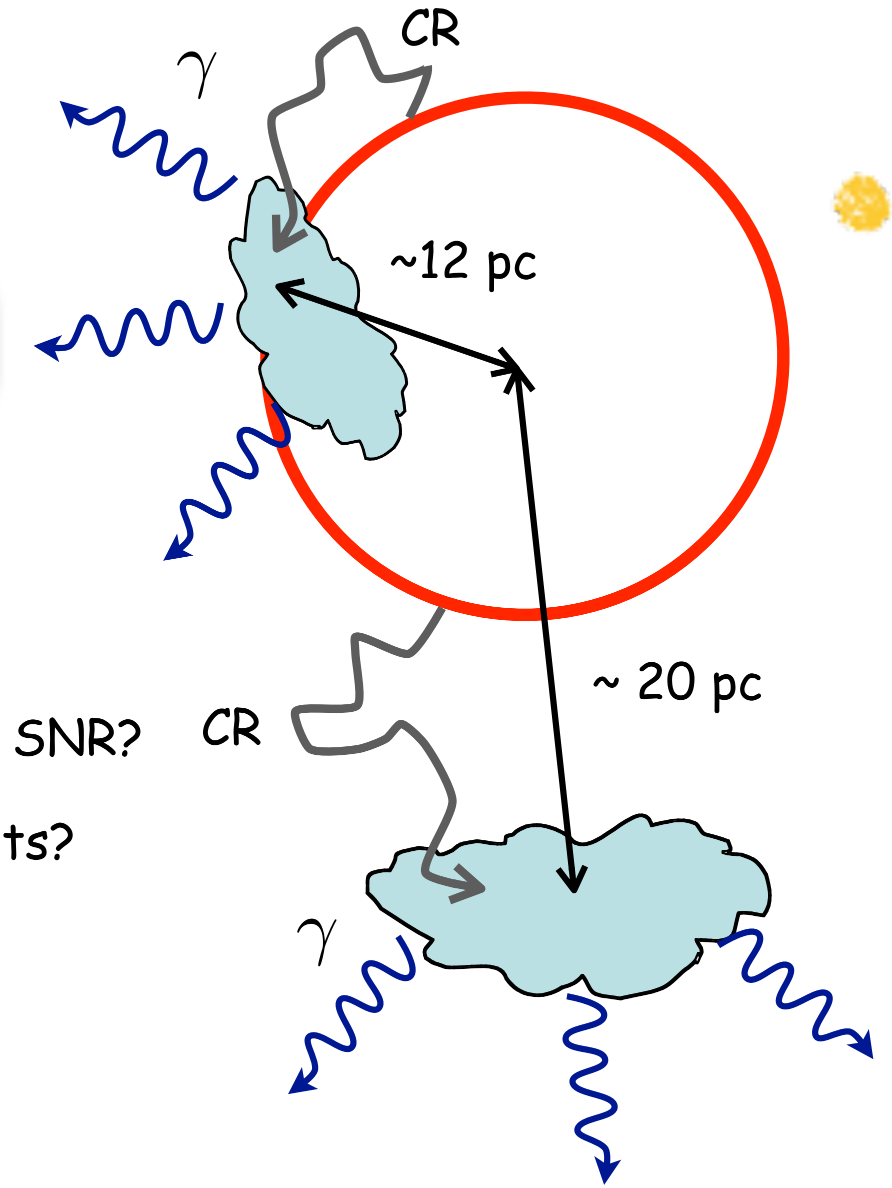
Molecular clouds

- gamma rays + gas
  - -> CR protons?
  - -> coming from the SNR?

SNR shell

- radio emission
  - -> GeV electrons
  - -> ongoing (re)acceleration?

W28: a cartoon



Molecular clouds

- gamma rays + gas
  - -> CR protons?
  - -> coming from the SNR?
  - -> projection effects?

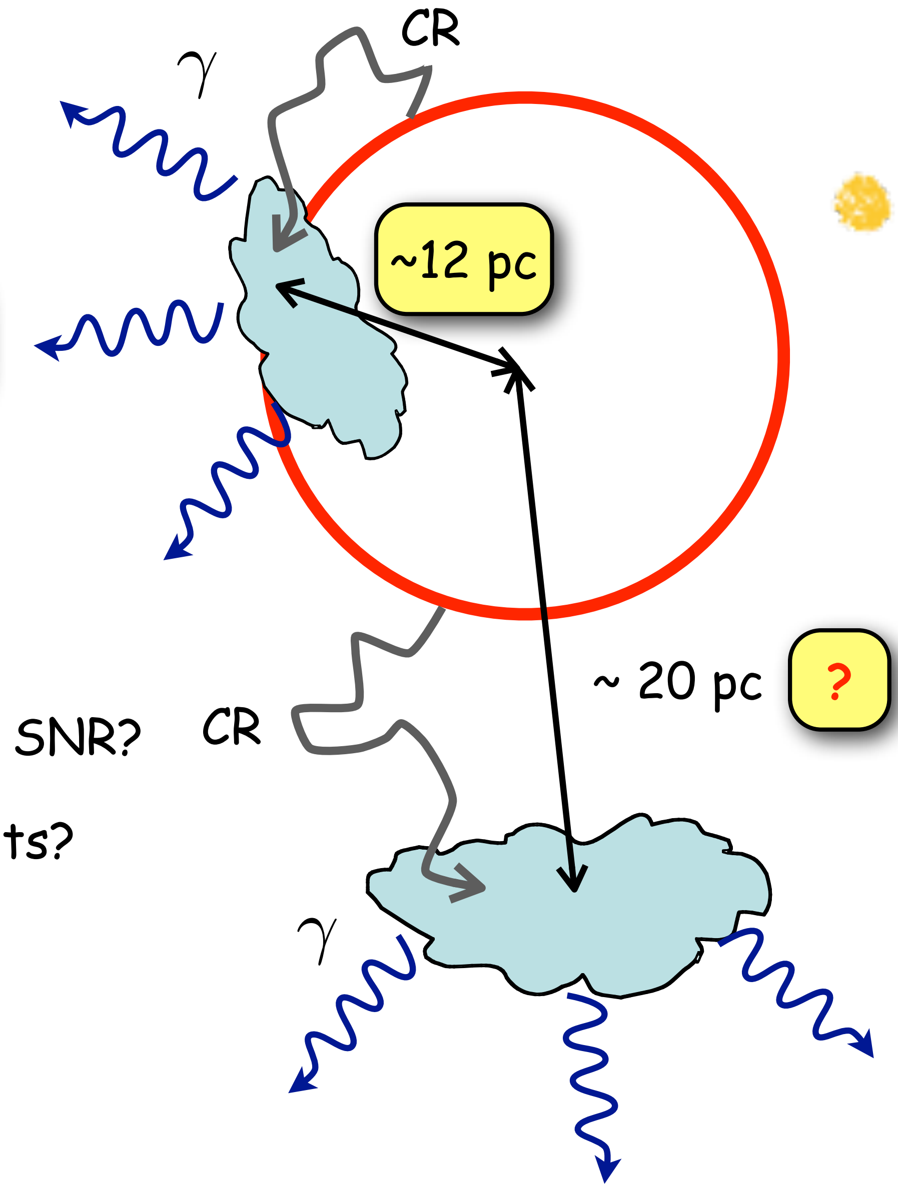
SNR shell

- radio emission
  - -> GeV electrons
  - -> ongoing (re)acceleration?

W28: a cartoon

Molecular clouds

- gamma rays + gas
  - -> CR protons?
  - -> coming from the SNR?
  - -> projection effects?
    - + masers



SNR shell

- radio emission
  - -> GeV electrons
  - -> ongoing (re)acceleration?

W28: a cartoon

Molecular clouds

- gamma rays + gas

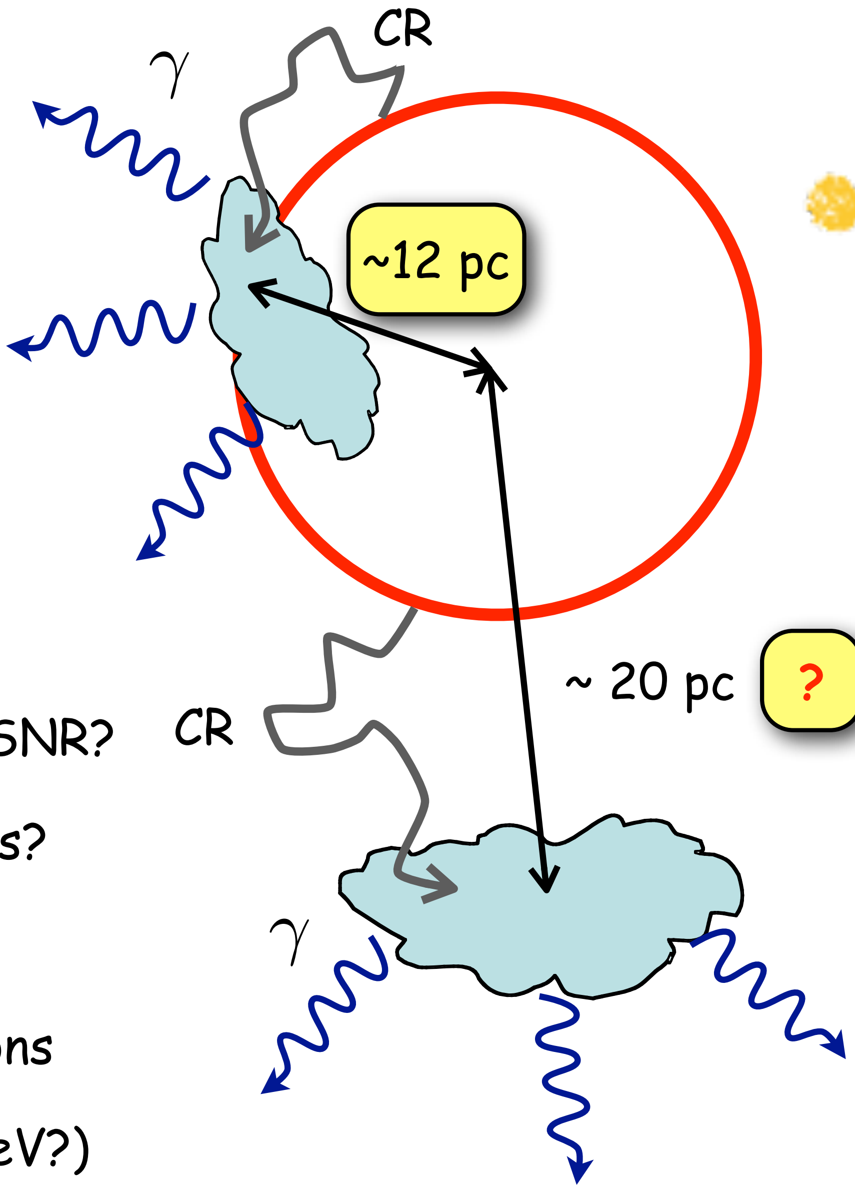
-> CR protons?

-> coming from the SNR?

-> projection effects?

  + masers

-> most of the protons already escaped (> GeV?)



SNR shell

- radio emission

-> GeV electrons

-> ongoing (re)acceleration?

Escaping particles

- assumptions
  - -> point like explosion
  - -> (isotropic) diffusion coefficient independent on position
  - -> particles with energy E escape after a time: $t_{out} \propto E^{-\delta}$

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this is just a parametrization

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when the SNR is smaller

higher energy particles are released first

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Escaping particles

- assumptions

-> point like explosion

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-> particles with energy E escape after a time: $t_{out} \propto E^{-\delta}$

when the SNR is smaller

higher energy particles are released first

this is just a parametrization

diffusion length

$$l_d \approx (D\ t)^{1/2}$$

$$t = t_{age} - t_{out}$$

? model dependent...

Escaping particles

- assumptions

-> point like explosion

when the SNR is smaller

-> (isotropic) diffusion coefficient independent on position

-> particles with energy E escape after a time: $t_{out} \cancel{\;\;} E^{-\delta}$

higher energy particles are released first

this is just a parametrization

diffusion length

$$l_d \approx (D\ t)^{1/2} \approx (D\ t_{age})^{1/2}$$

$$t = t_{age} - \cancel{t_{out}}$$

? model dependent...

high energy particles

Escaping particles

assumptions

- -> point like explosion
- -> (isotropic) diffusion coefficient independent on position
- -> particles with energy E escape after a time: $t_{out} \cancel{\propto} E^{-\delta}$

when the SNR is smaller

higher energy particles are released first

this is just a parametrization

diffusion length

$$l_d \approx (D\ t)^{1/2} \approx (D\ t_{age})^{1/2}$$

$$t = t_{age} - \cancel{t_{out}}$$

? model dependent...

high energy particles

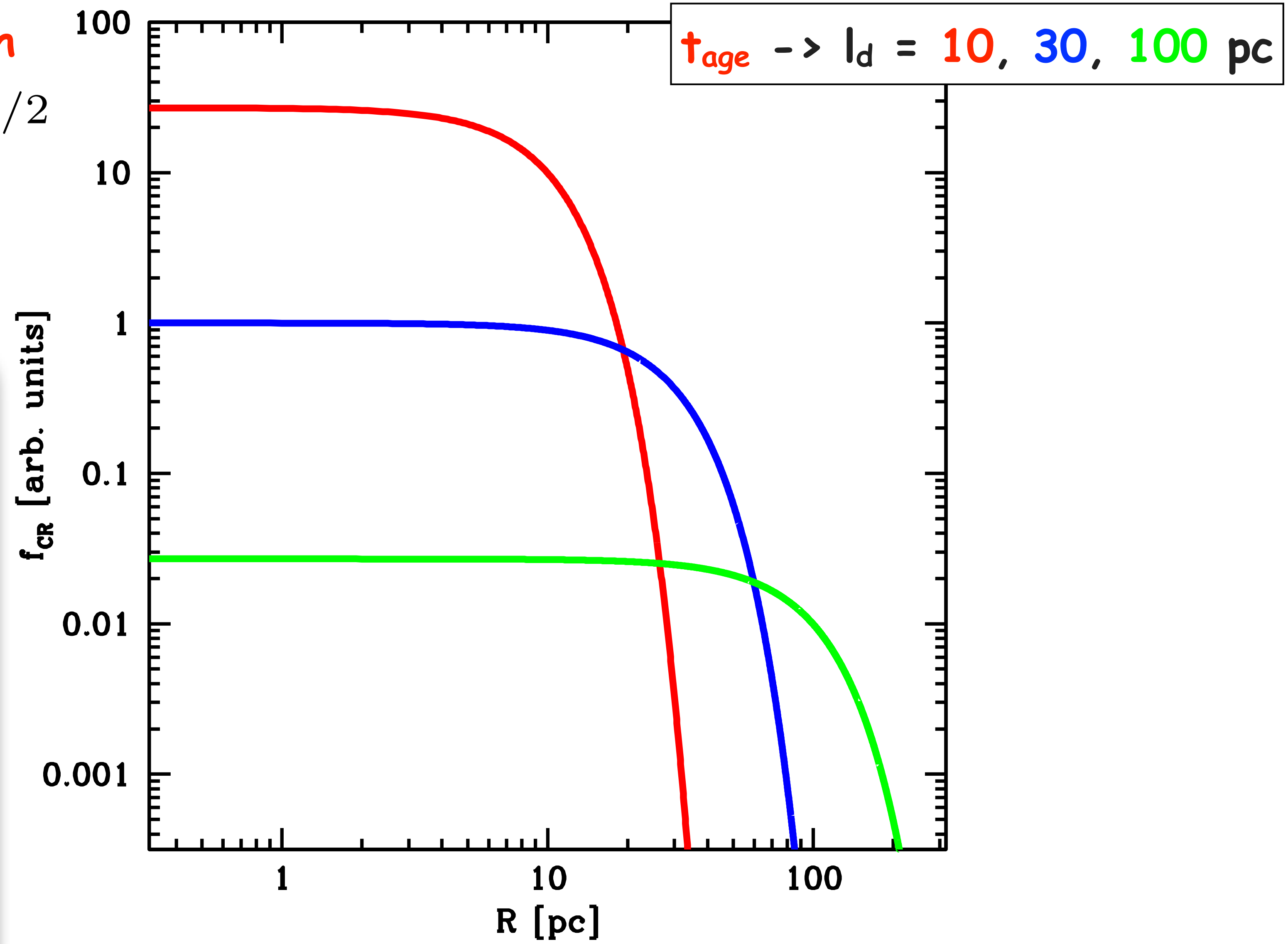
lower energies -> point-like approx not so good + model dependent (t_{out} ~ t_{age})

Escaping particles: CR spectrum

Isotropic diffusion -> main motivation: it's simple...

diffusion length

$$l_d \approx (D\ t)^{1/2}$$



Aharonian&Atoyan 1996;SG et al 2007,2009,2010;Torres et al 2008,2010;Rodriguez Marrero et al 2008;Lee et al 2008;Fujita et al 2009;Casanova...SG... et al 2010;Li&Chen 2010;Ohira et al 2011;Ellison&Bikov 2011 ...

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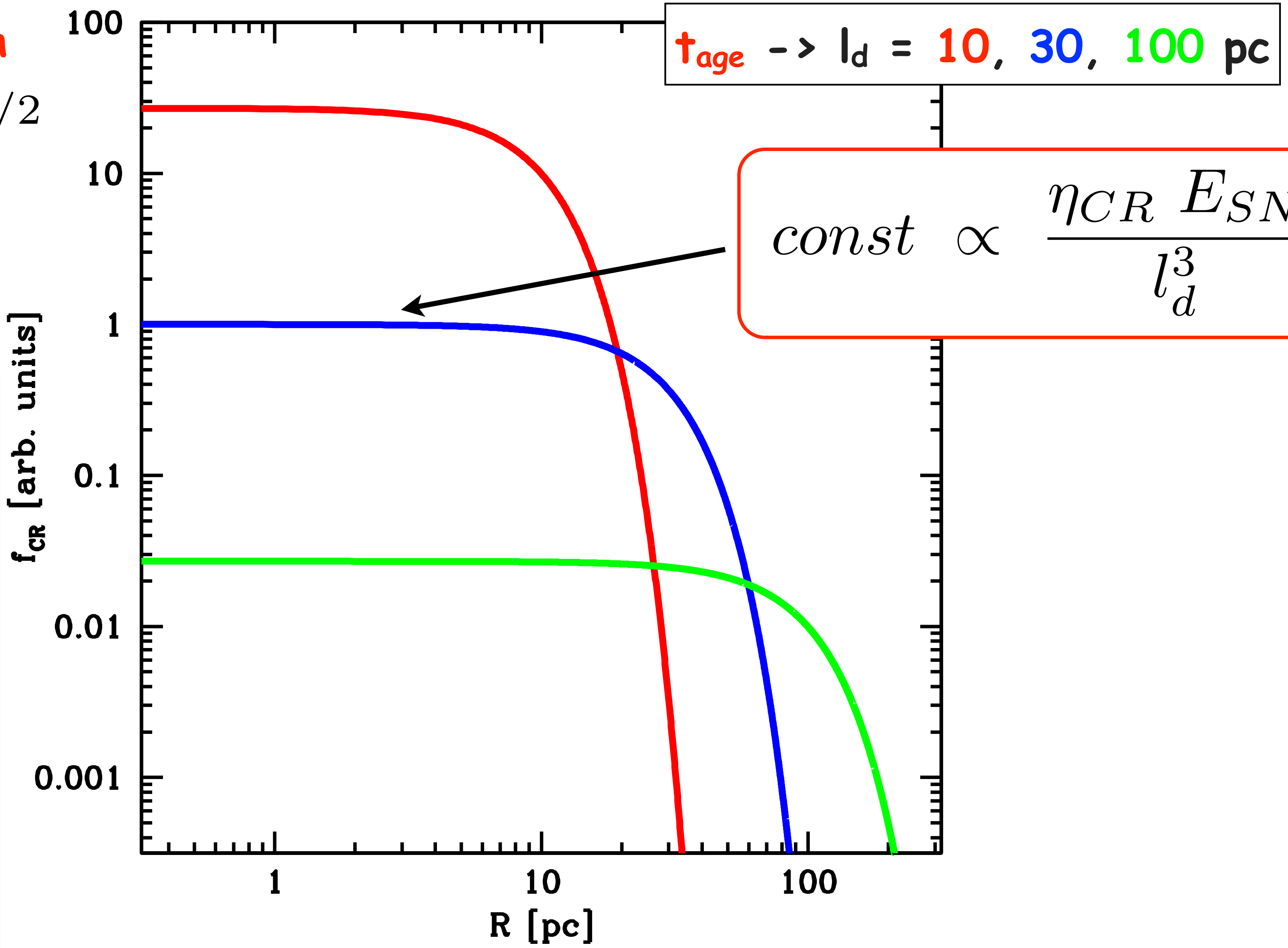


$$const \ \propto \ \frac{\eta_{CR}\ E_{SN}}{l_d^3}$$

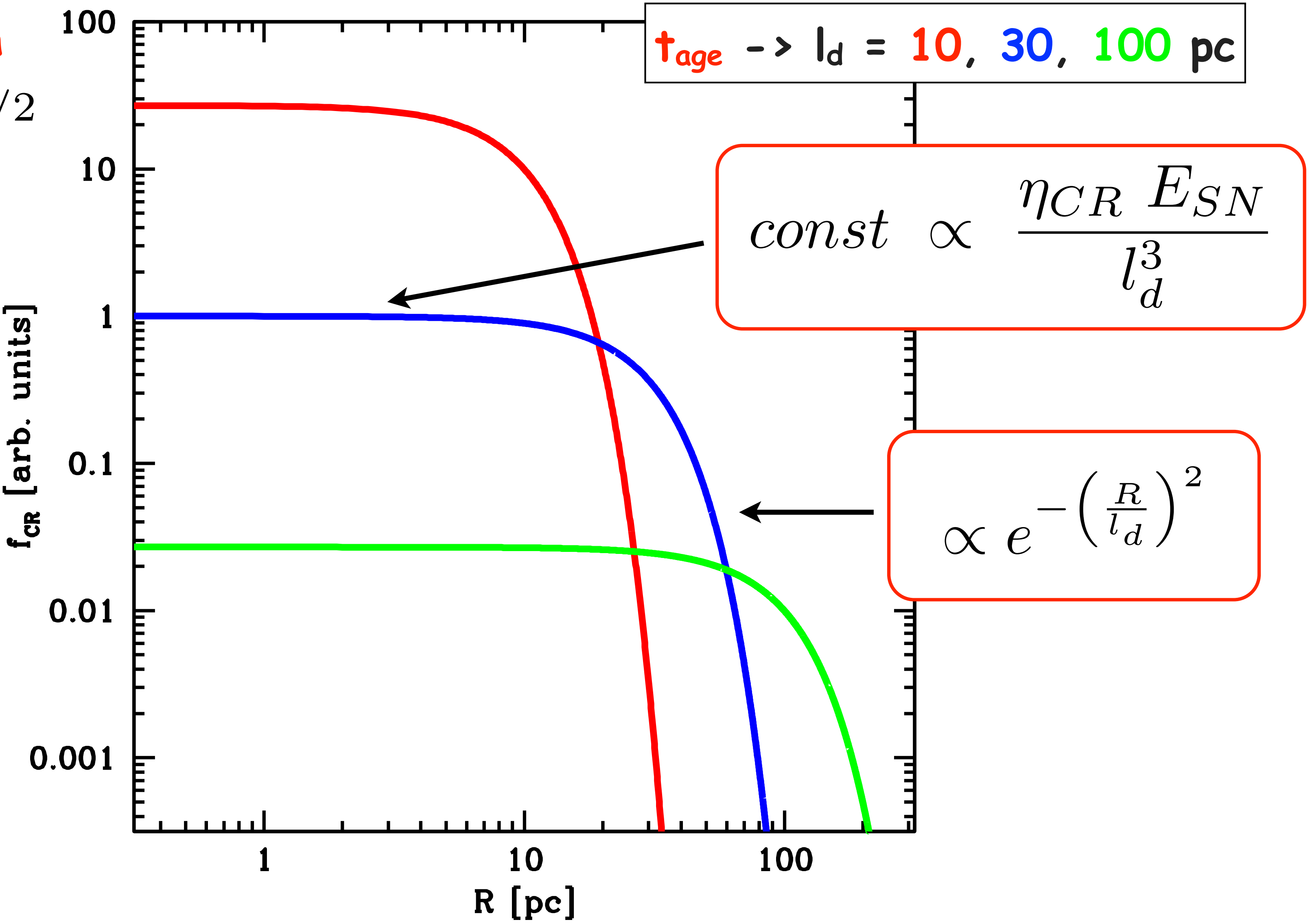
Escaping particles: CR spectrum

Isotropic diffusion -> main motivation: it's simple...

diffusion length

$$l_d \approx (D\ t)^{1/2}$$

Aharonian&Atoyan 1996;SG et al 2007,2009,2010;Torres et al 2008,2010;Rodriguez Marrero et al 2008;Lee et al 2008;Fujita et al 2009;Casanova...SG... et al 2010;Li&Chen 2010;Ohira et al 2011;Ellison&Bikov 2011 ...



$$const\ \propto\ \frac{\eta_{CR}\ E_{SN}}{l_d^3}$$

$$\propto e^{-\left(\frac{R}{l_d}\right)^2}$$

Escaping particles: CR spectrum

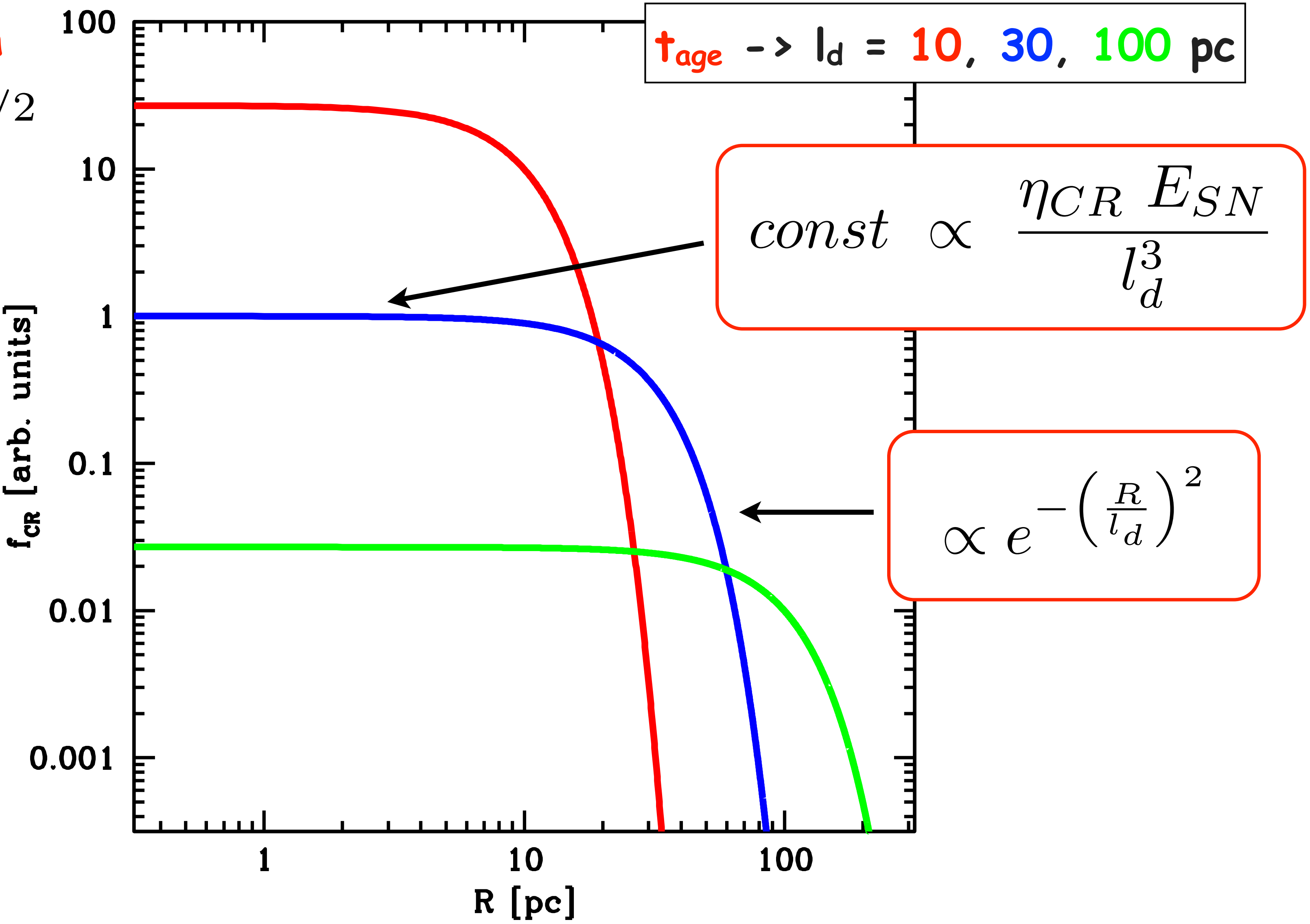
Isotropic diffusion -> main motivation: it's simple...

diffusion length

$$l_d \approx (\boxed{D}\, t)^{1/2}$$

badly constrained

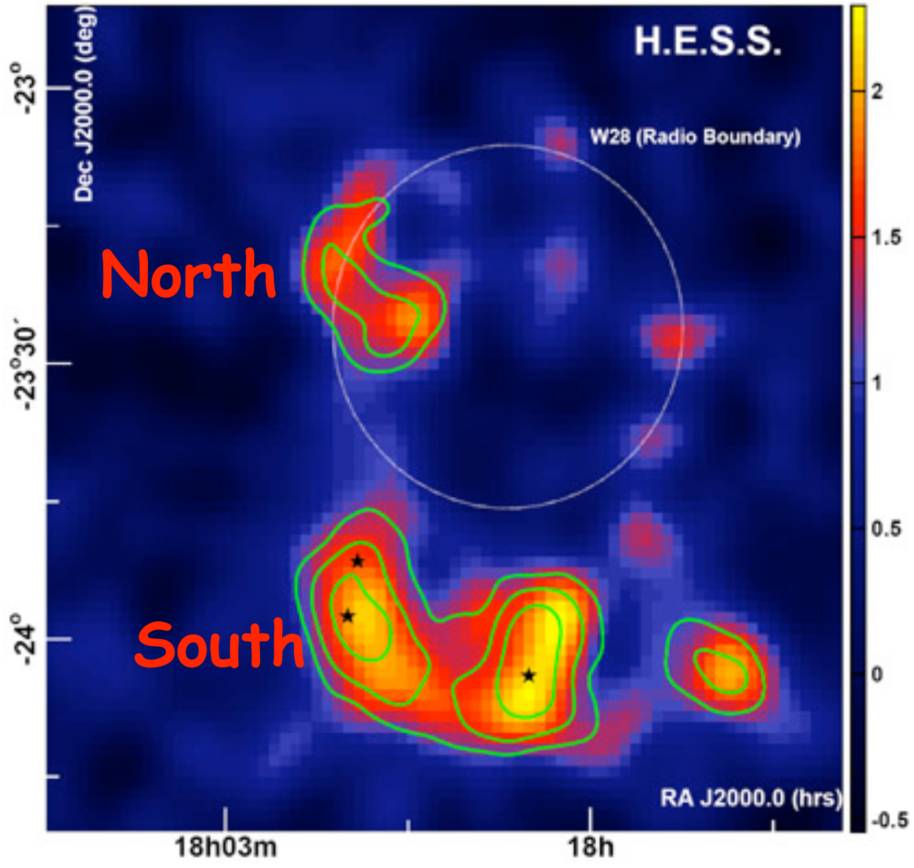
Aharonian&Atoyan 1996;SG et al 2007,2009,2010;Torres et al 2008,2010;Rodriguez Marrero et al 2008;Lee et al 2008;Fujita et al 2009;Casanova...SG... et al 2010;Li&Chen 2010;Ohira et al 2011;Ellison&Bikov 2011 ...



$$const \;\propto\; \frac{\eta_{CR}\, E_{SN}}{l_d^3}$$

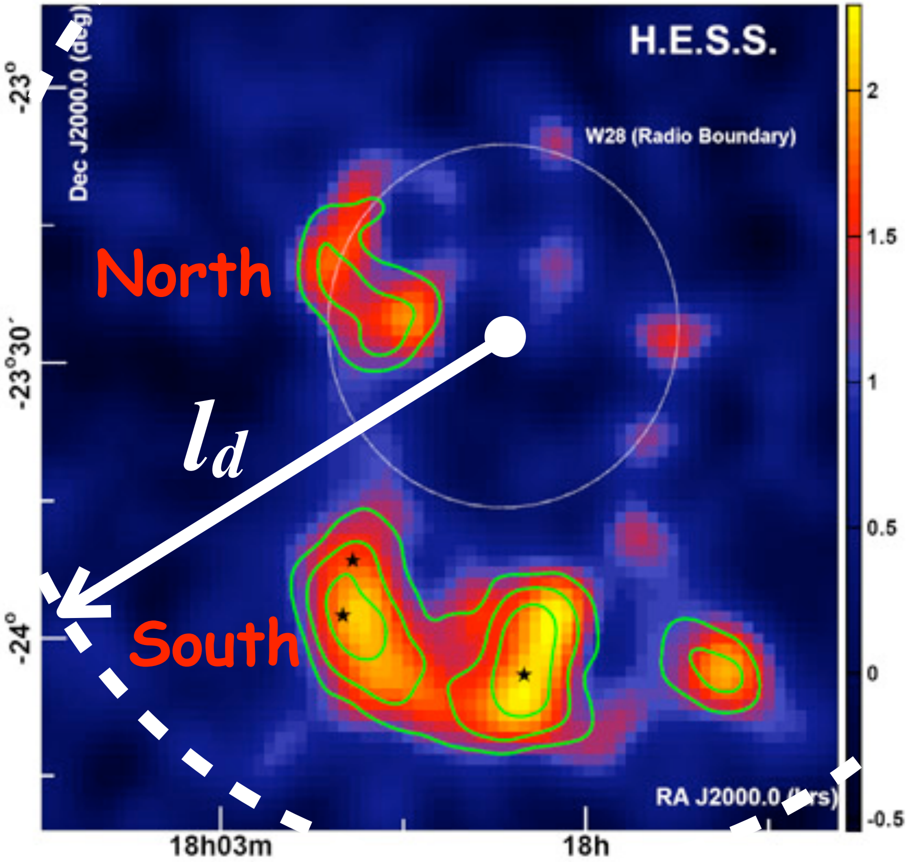
$$\propto e^{-\left(\frac{R}{l_d}\right)^2}$$

Escaping particles: W28



$$\left(\frac{F_\gamma}{M_{cl}}\right)_{North} \approx \left(\frac{F_\gamma}{M_{cl}}\right)_{South}$$

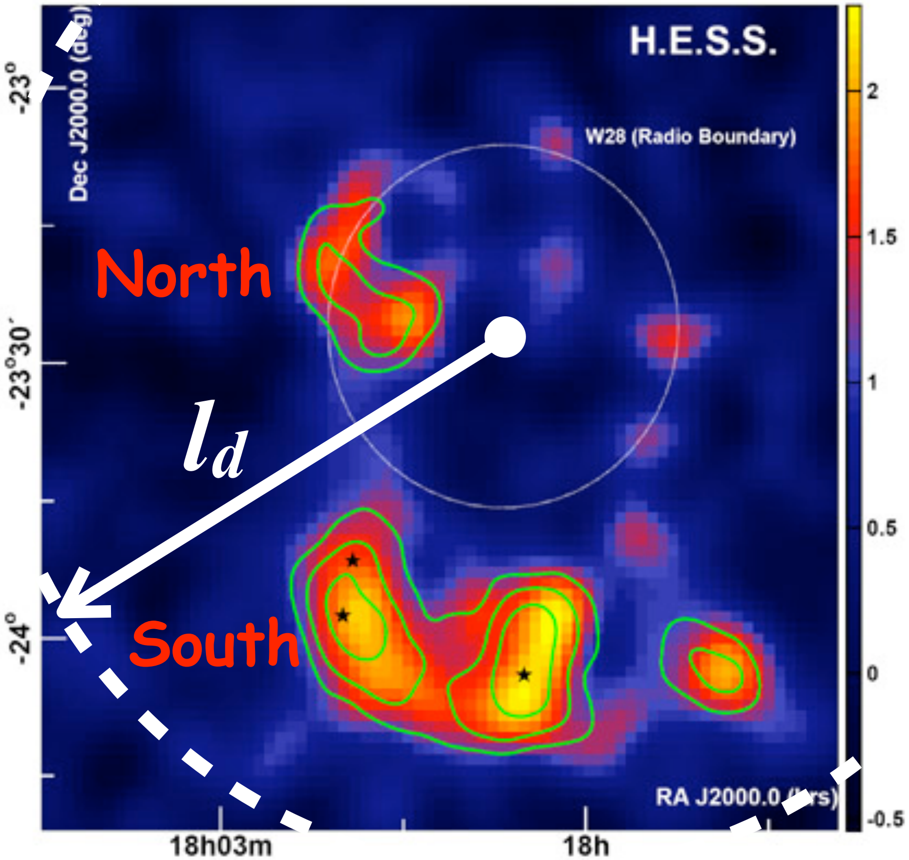
Escaping particles: W28



$$\left(\frac{F_\gamma}{M_{cl}}\right)_{North} \approx \left(\frac{F_\gamma}{M_{cl}}\right)_{South}$$

both clouds within a distance l_d

Escaping particles: W28

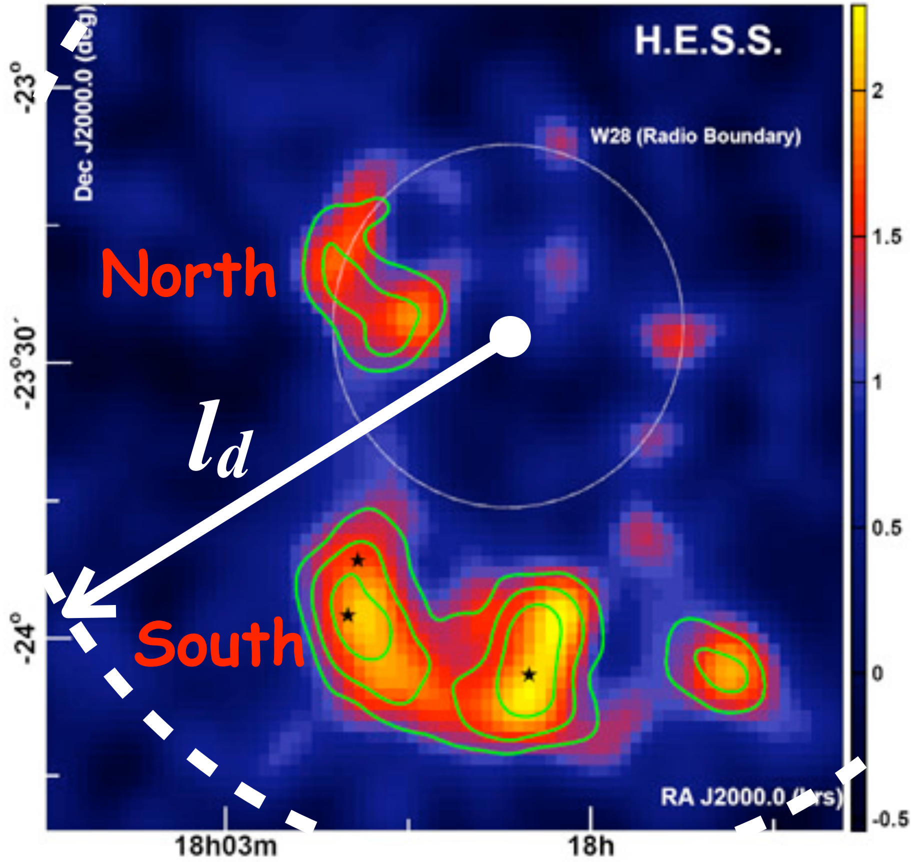


$$\left(\frac{F_\gamma}{M_{cl}}\right)_{North} \approx \left(\frac{F_\gamma}{M_{cl}}\right)_{South}$$

both clouds within a distance l_d

$$F_\gamma \propto \frac{f_{CR}\, M_{cl}}{d^2}$$

Escaping particles: W28



$$\left(\frac{F_\gamma}{M_{cl}}\right)_{North} \approx \left(\frac{F_\gamma}{M_{cl}}\right)_{South}$$

both clouds within a distance l_d

$$F_\gamma \propto \frac{f_{CR}\, M_{cl}}{d^2} \propto \frac{\eta_{CR}\, E_{SN}}{(D\ t_{age})^{3/2}} \left(\frac{M_{cl}}{d^2}\right)$$

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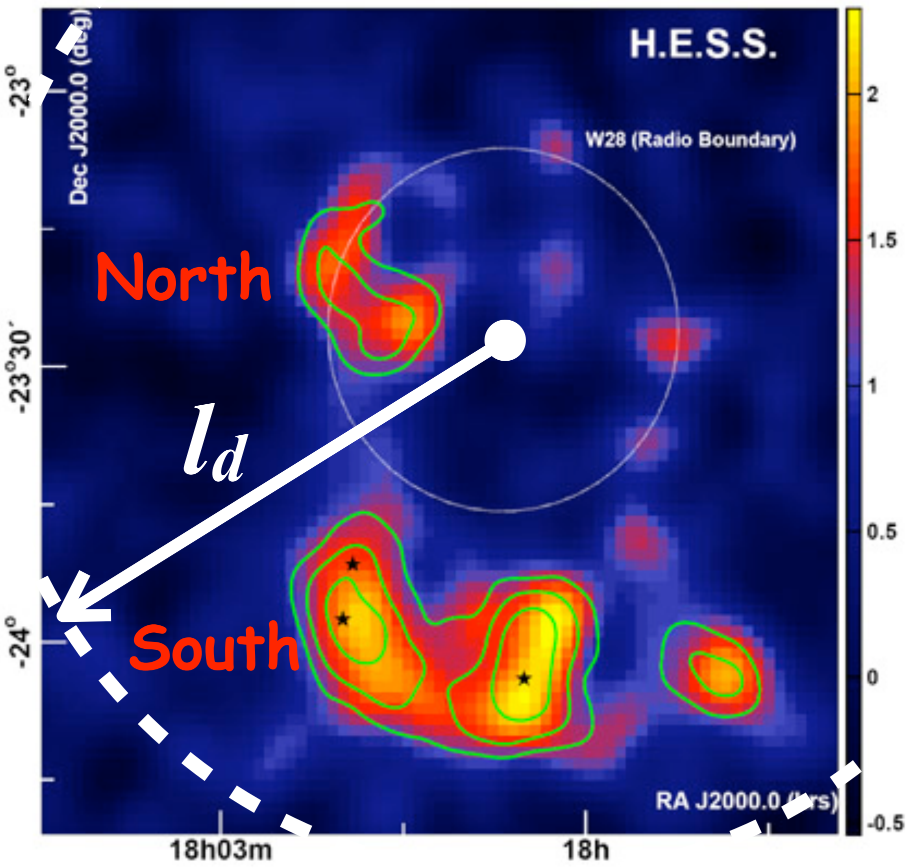

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$$F_\gamma \propto \frac{f_{CR}\ M_{cl}}{d^2} \propto \frac{\eta_{CR}\ E_{SN}}{(D\ t_{age})^{3/2}} \left(\frac{M_{cl}}{d^2}\right)$$

and we get... ->

$$D \propto \left(\frac{\eta_{CR} E_{SN}\ M_{cl}}{F_\gamma d^2}\right)^{2/3} t_{age}^{-1}$$

W28: numbers

☑ **Measured quantities:**

- apparent size: ~ 45′-50′, distance ~ 2 kpc -> R_s ~ 12 pc
- ratio OIII/Hβ -> v_s = 80 km/s

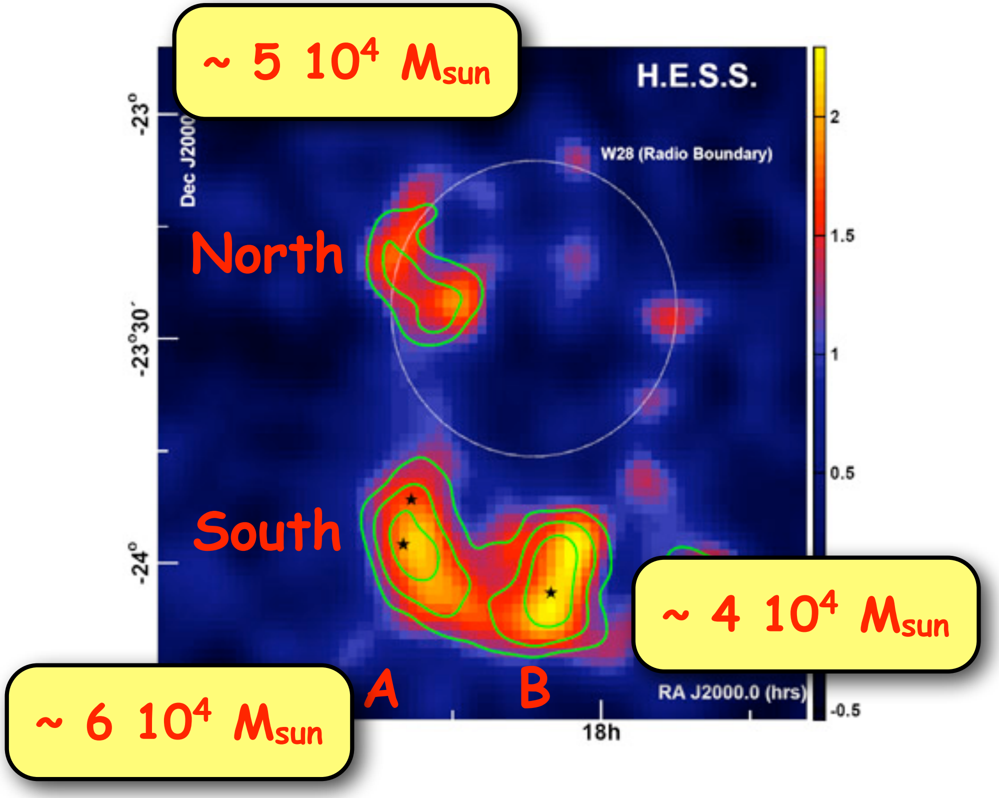
☑ **Assumptions:**

- mass of ejecta -> M_{ej} ~ 1.4 M_{sun}
- ambient density -> n ~ 5 cm^{-3}

☑ **Derived quantities (Cioffi et al 1989 model):**

- explosion energy -> E_{SN} ~ 0.4 x 10^{51} erg
- initial velocity -> v_0 ~ 5500 km/s
- SNR age -> 4.4 x 10^4 yr (radiative phase)

W28: TeV emission

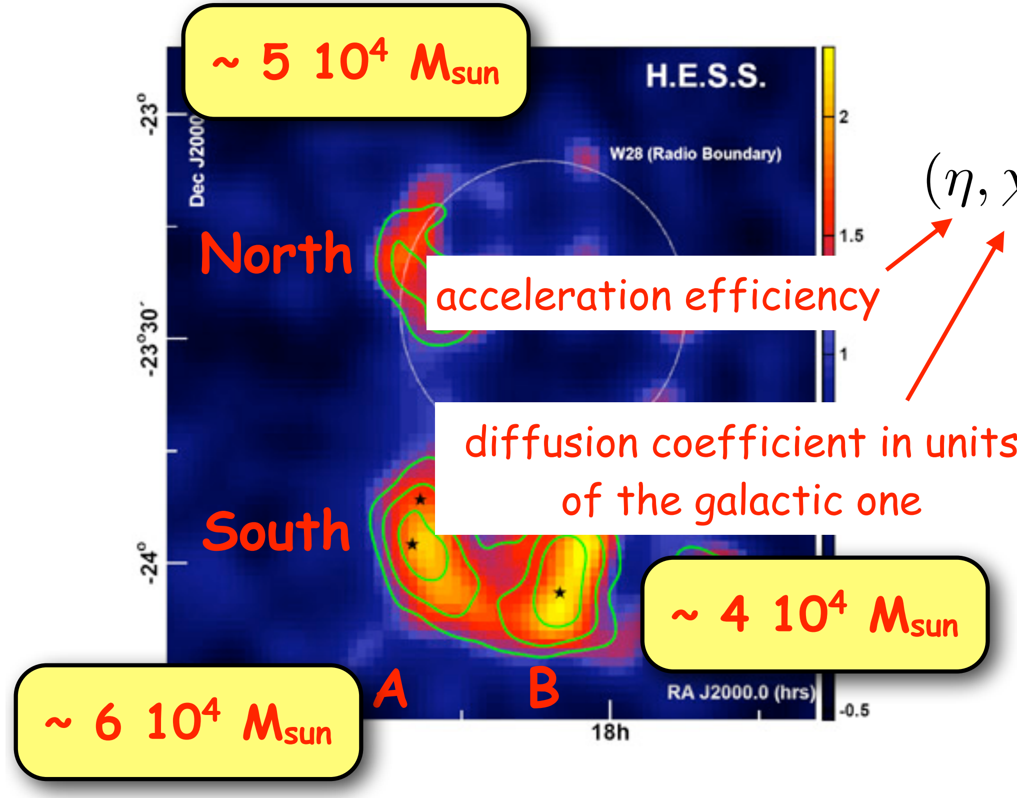


~ 5 10^4 M_{sun}

~ 4 10^4 M_{sun}

~ 6 10^4 M_{sun}

W28: TeV emission

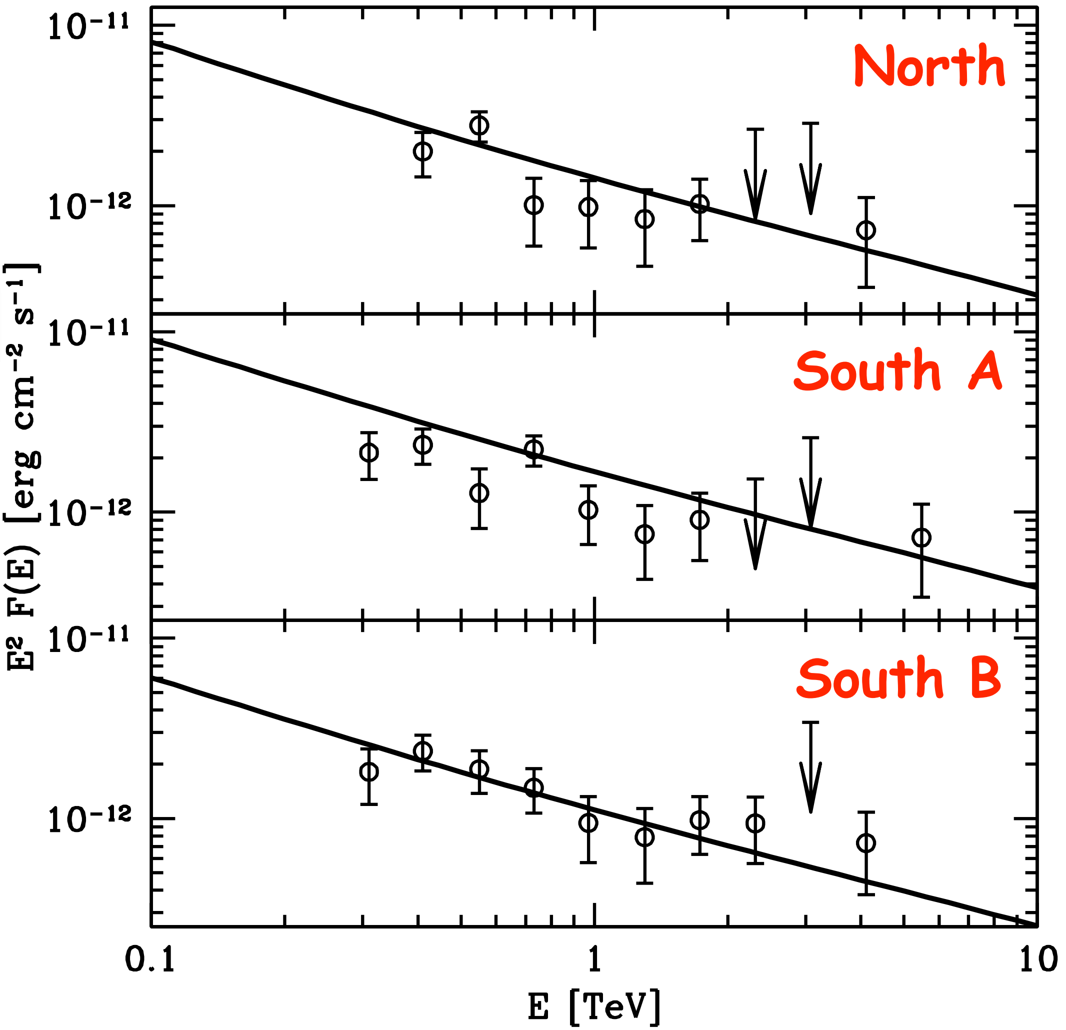


acceleration efficiency

diffusion coefficient in units of the galactic one

virtually the same curves for:

$$(\eta, \chi) = (10\%, 0.028); (30\%, 0.06); (50\%, 0.085)$$



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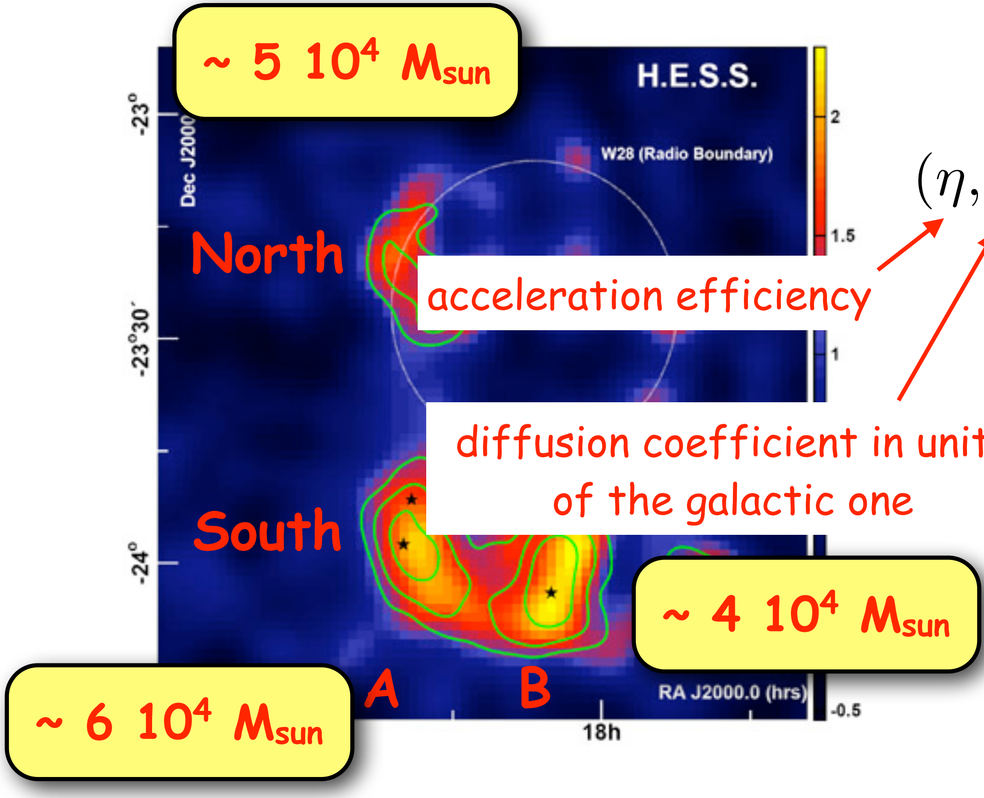

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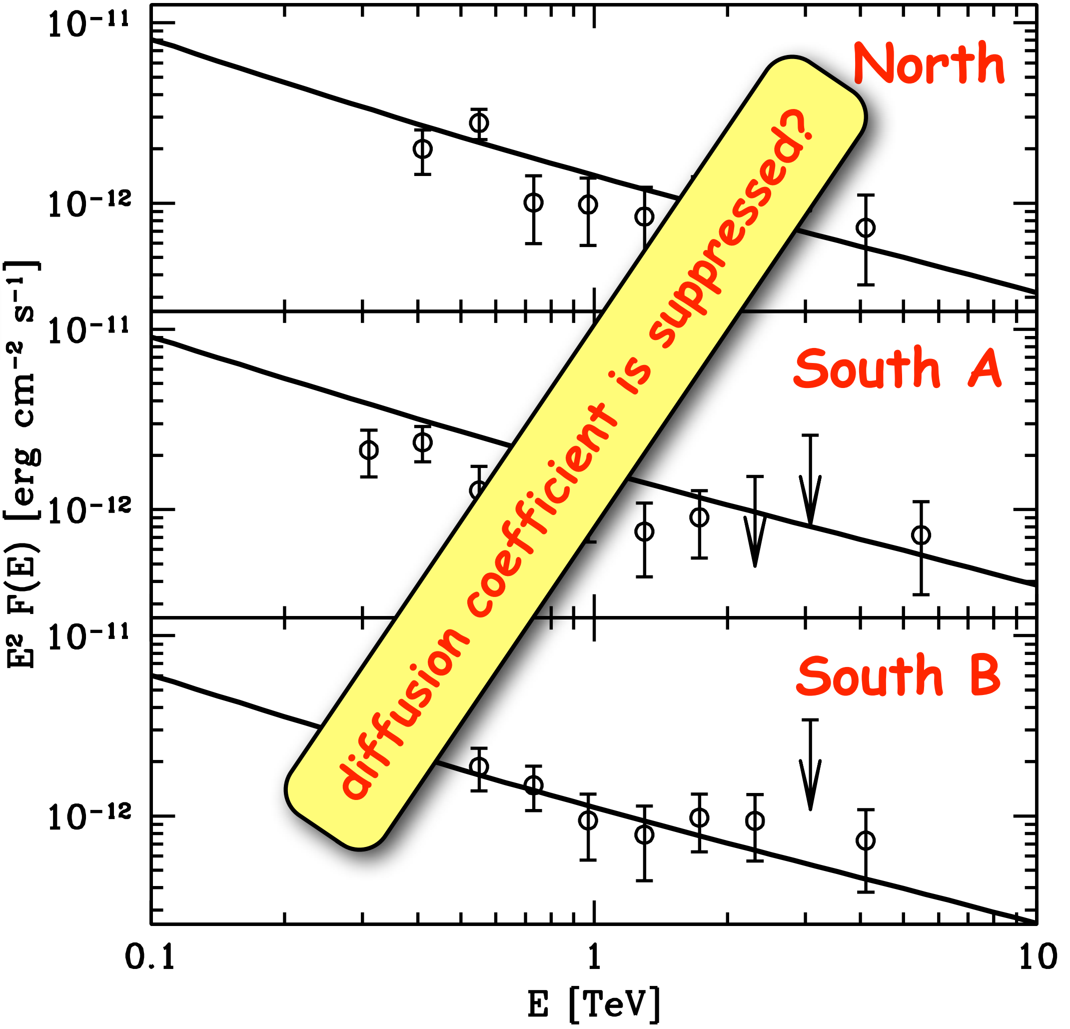
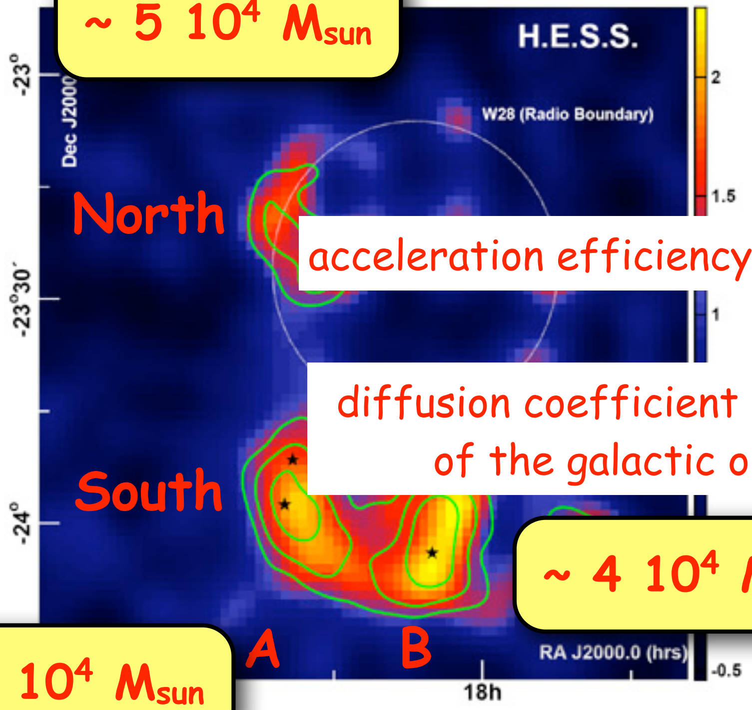


diffusion coefficient is suppressed?

W28: TeV emission



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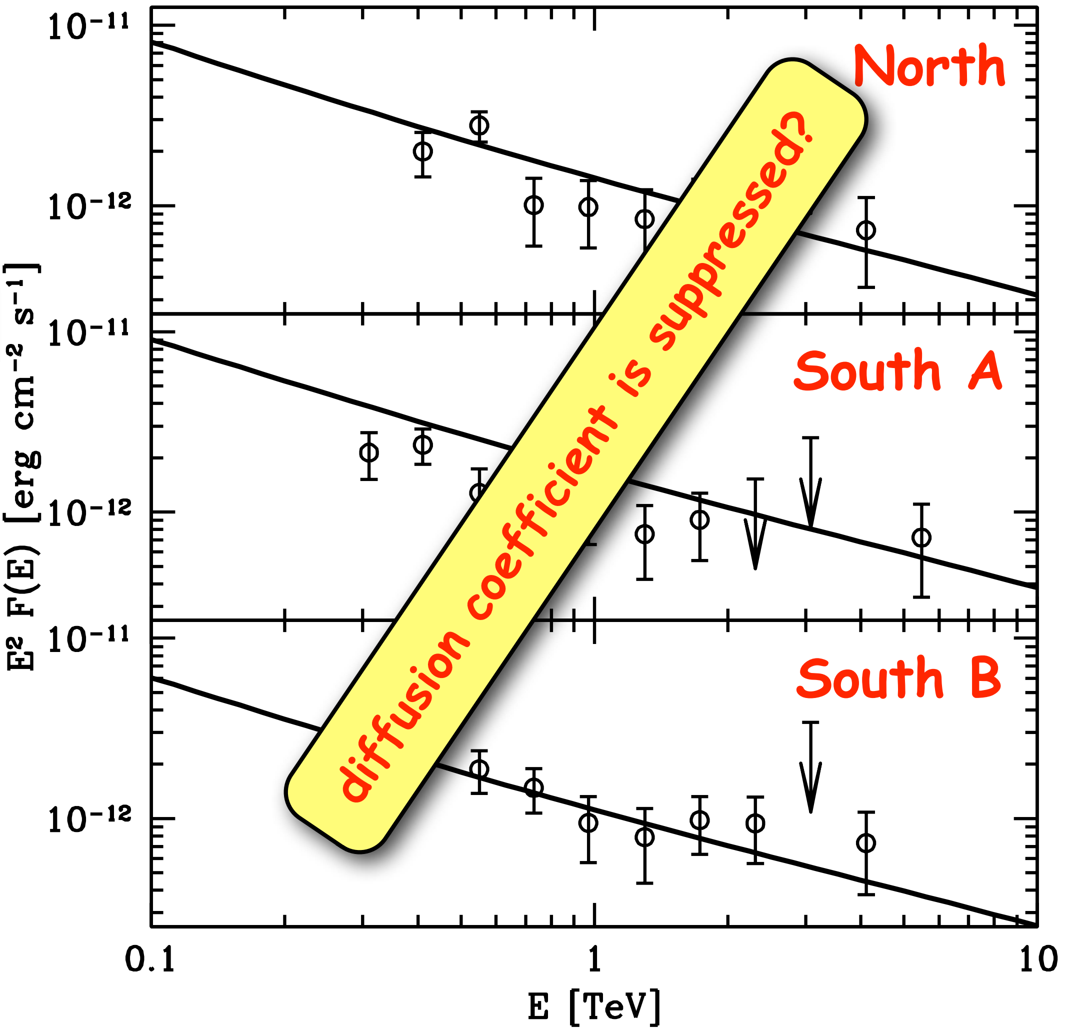
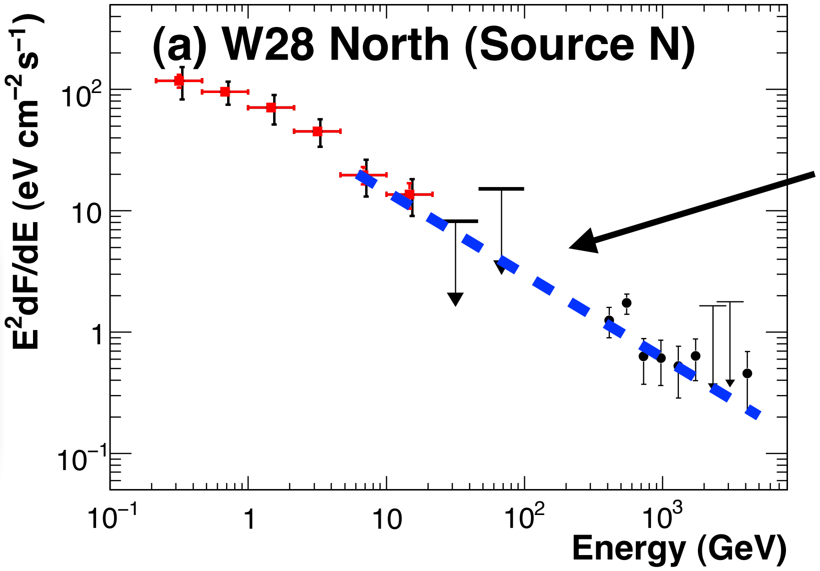


diffusion coefficient is suppressed?

size of “CR bubble” @3 TeV

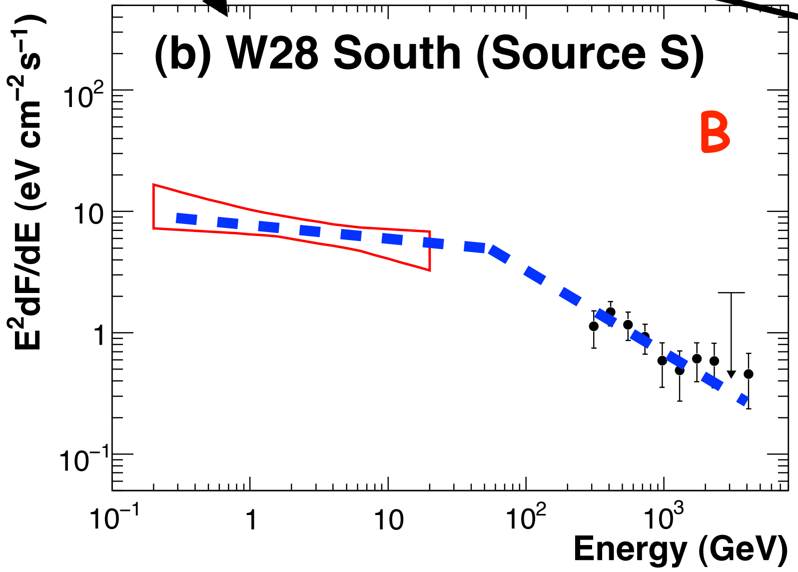
$$l_d \approx 70 \text{ pc} \rightarrow \chi = 0.028$$
$$\approx 95 \text{ pc} \rightarrow \chi = 0.06$$
$$\approx 115 \text{ pc} \rightarrow \chi = 0.085$$

W28: GeV emission

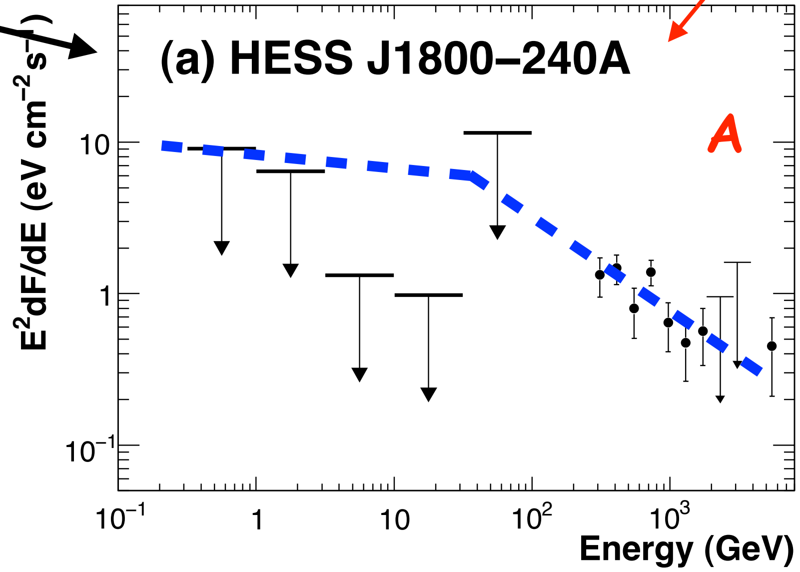


if the cloud is within the "CR bubble" [$d < l_d(E)$]

if cloud A and B are at the same distance -> same spectrum

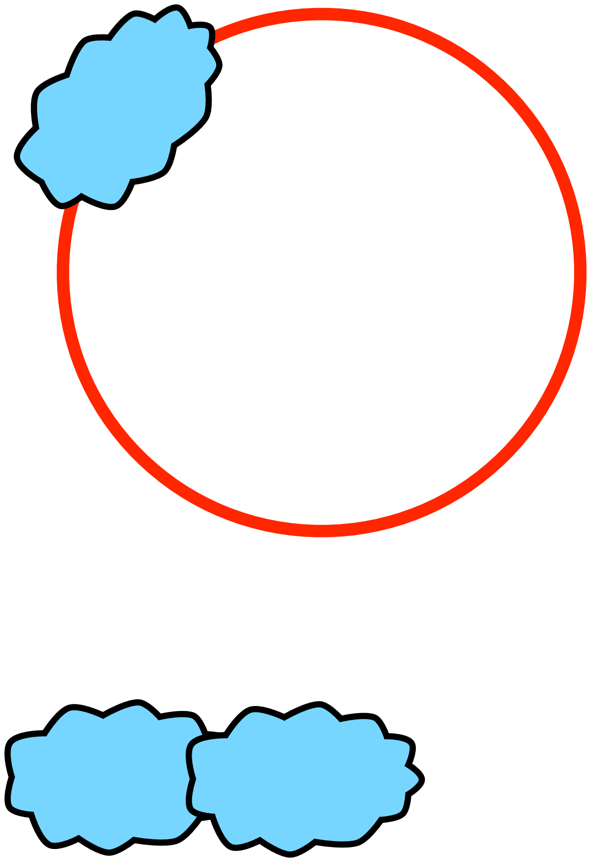


cloud A might not be physically associated with the W28 system

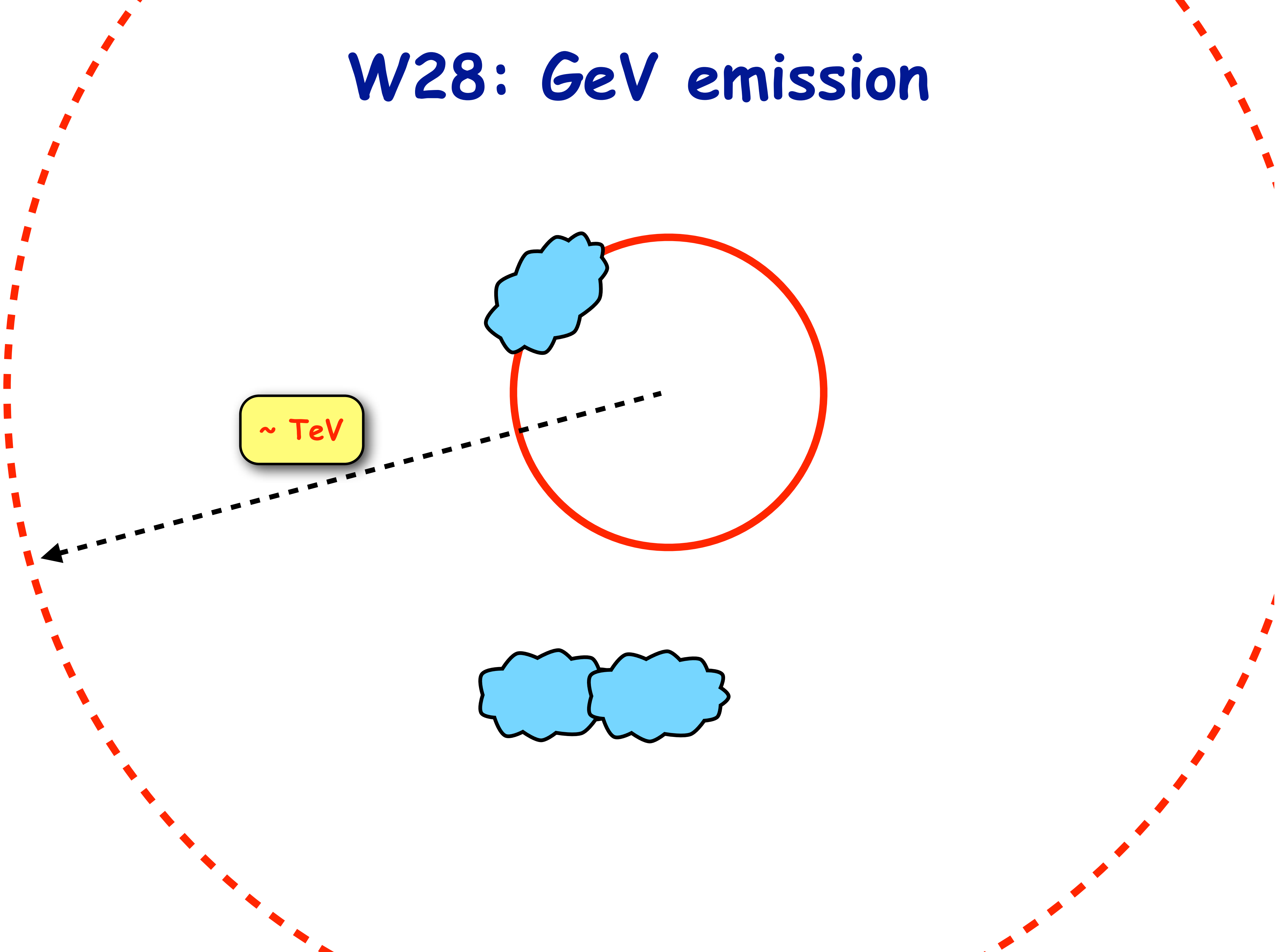


FERMI -> Abdo et al, 2010

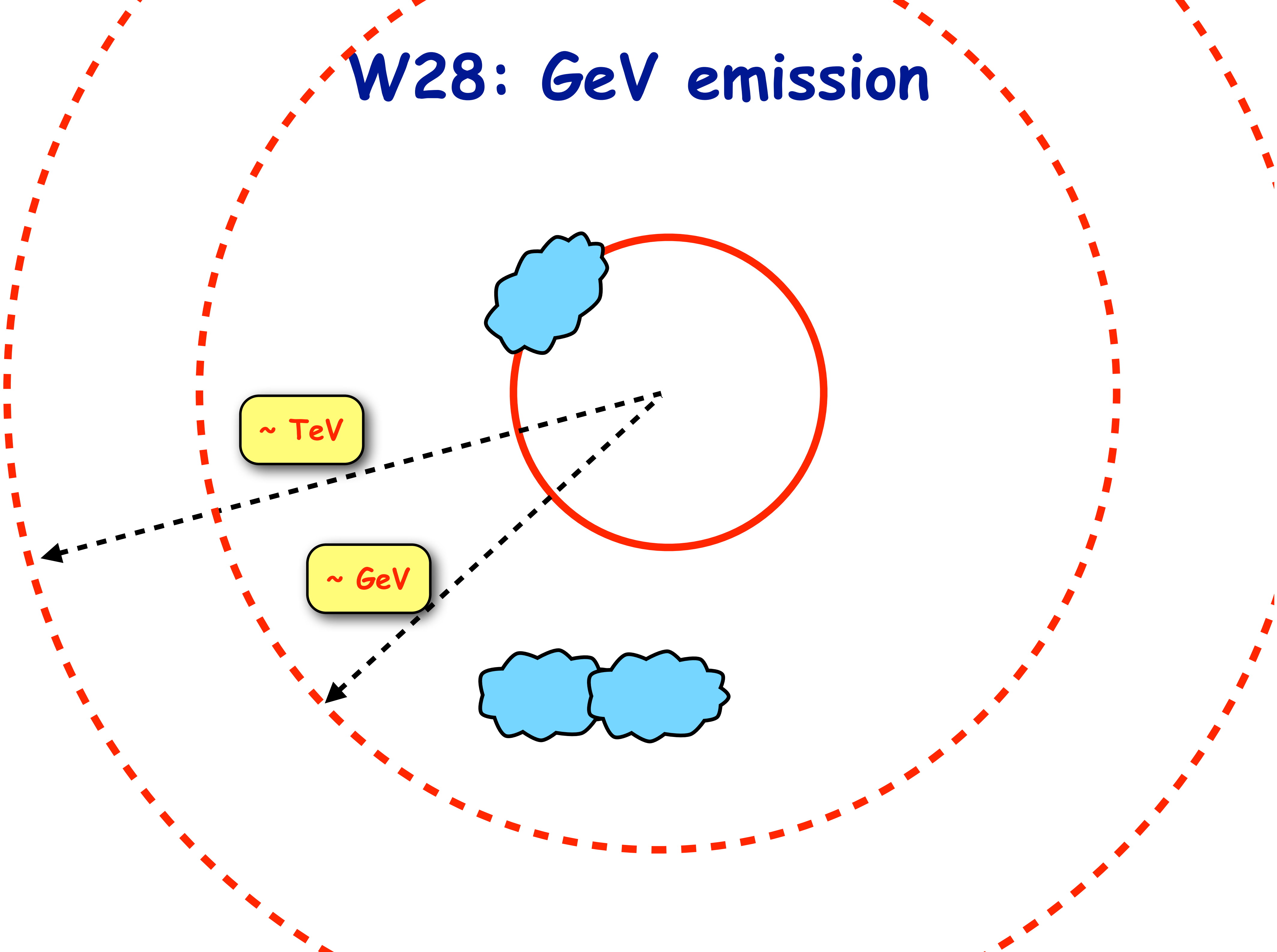
W28: GeV emission



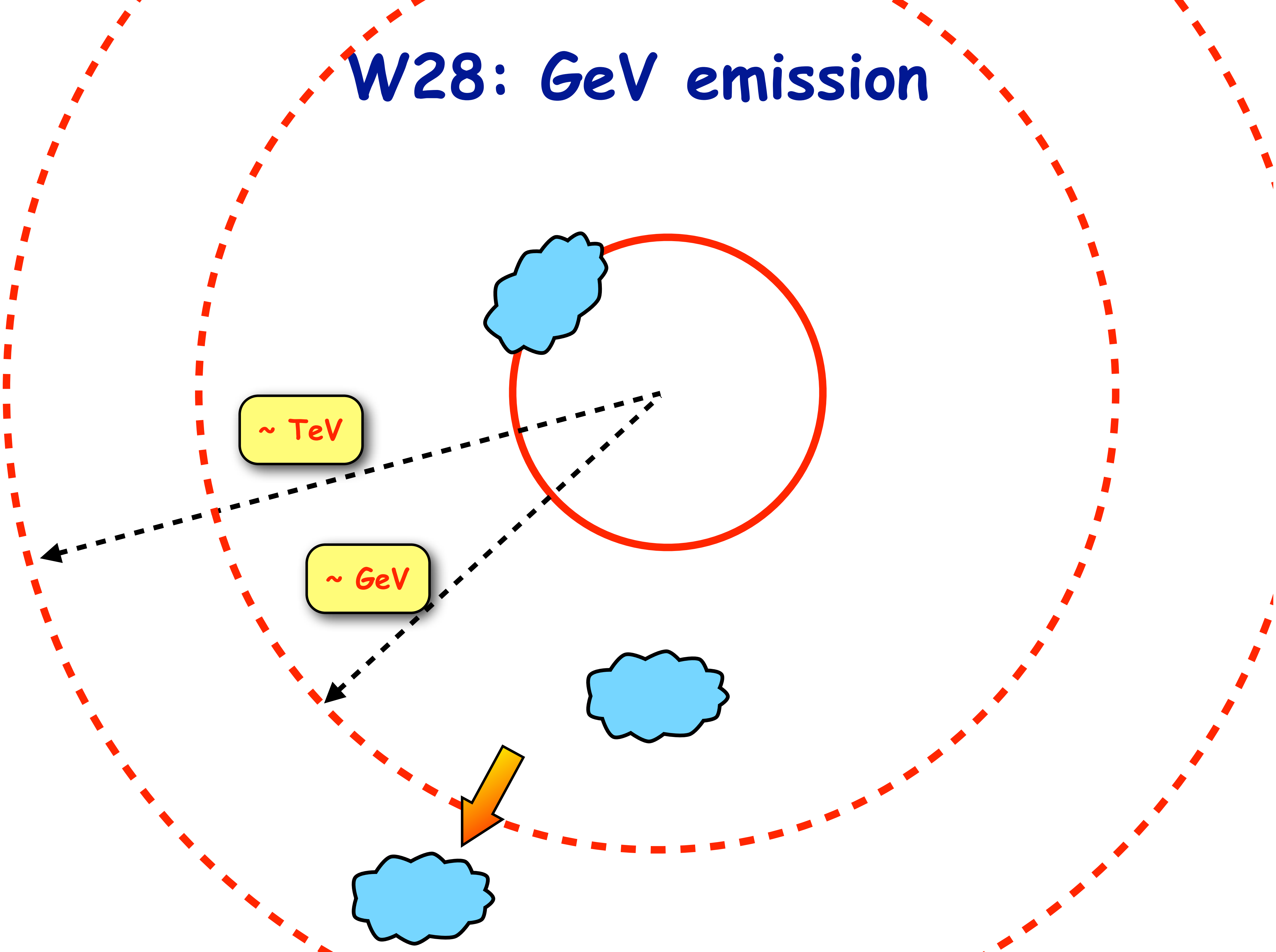
W28: GeV emission



W28: GeV emission



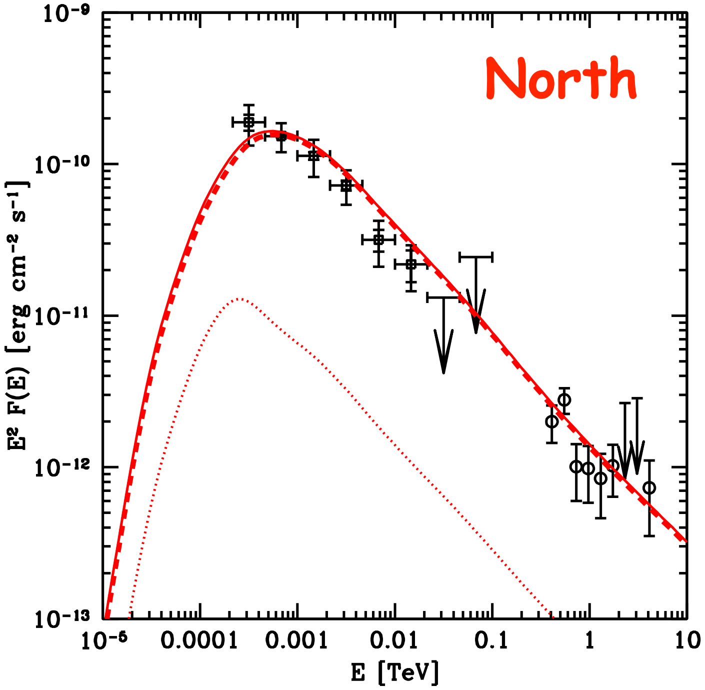
W28: GeV emission



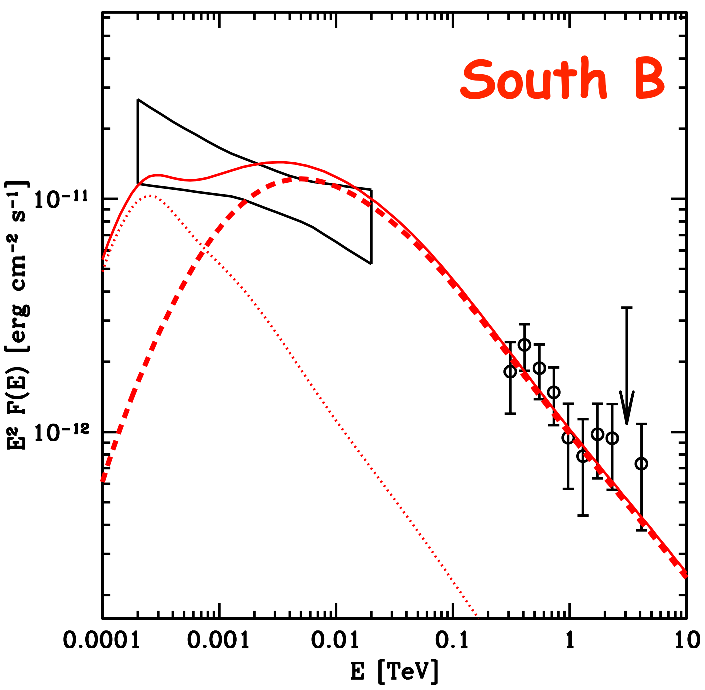
W28: GeV emission

$$\eta = 30\%$$

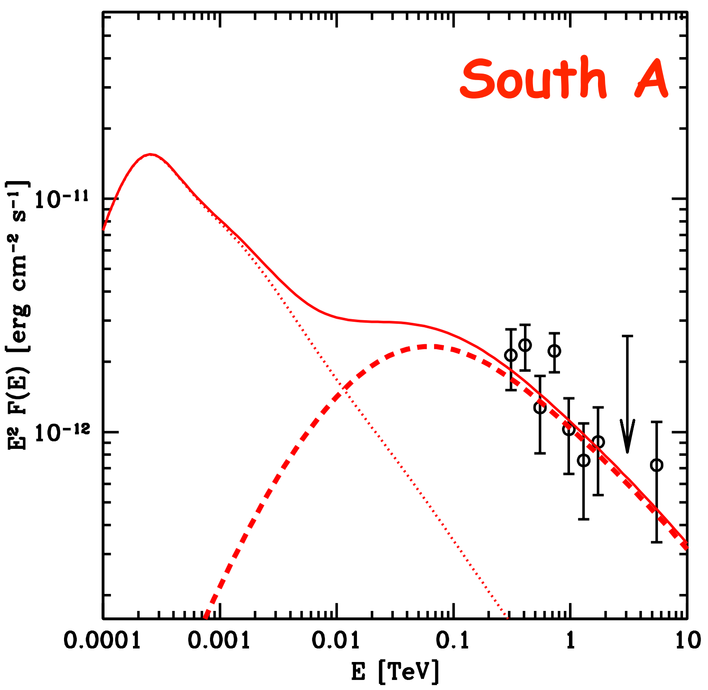
$$\chi = 0.06$$



d = 12 pc



d = 32 pc

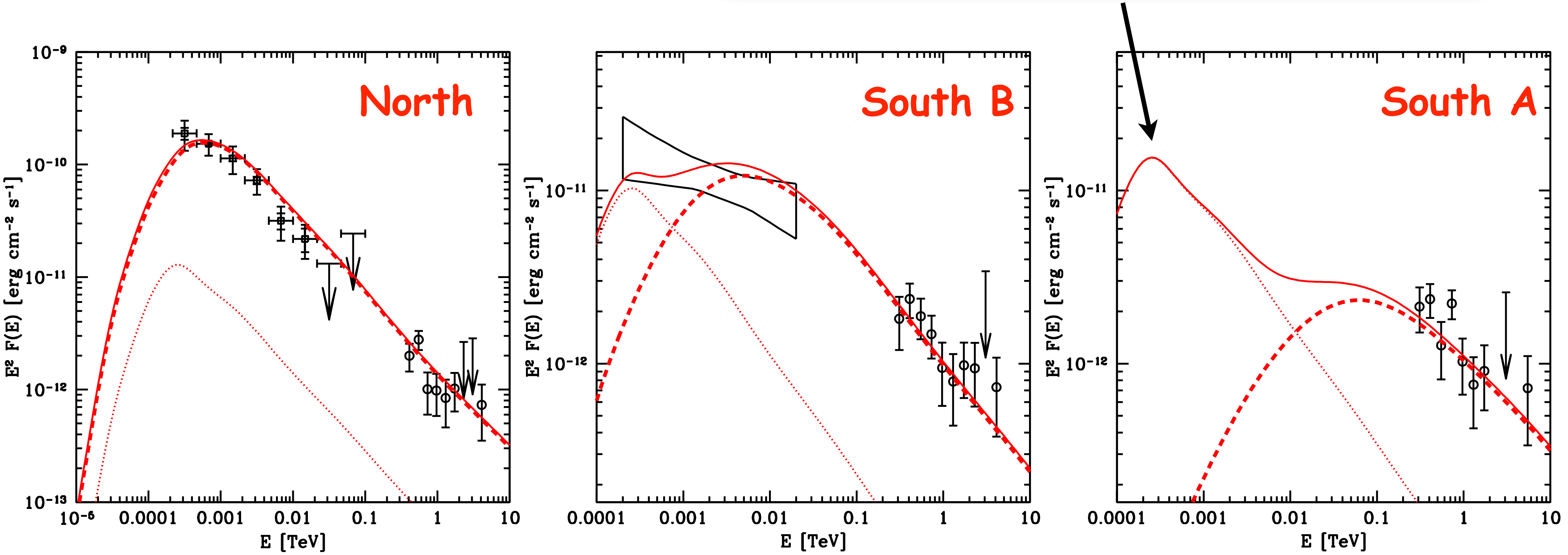


d = 65 pc

W28: GeV emission

$$\eta = 30\%$$

$$\chi = 0.06$$



d = 12 pc

d = 32 pc

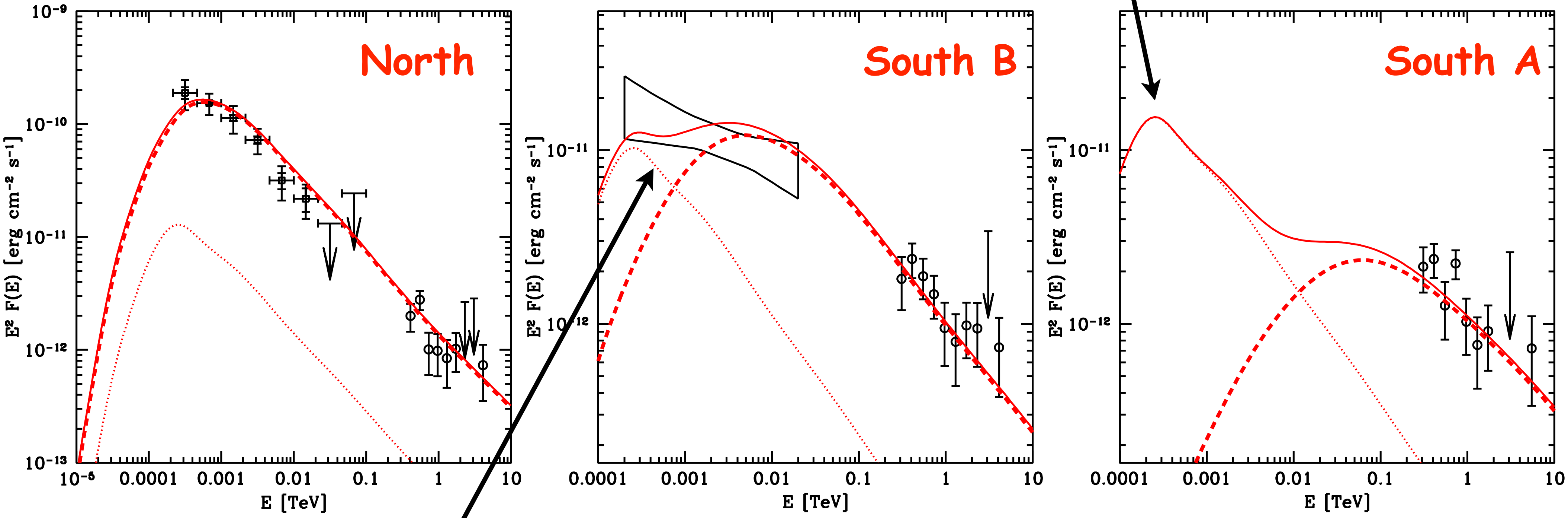
d = 65 pc

W28: GeV emission

$$\eta = 30\%$$

$$\chi = 0.06$$

this peak is removed as background



d = 12 pc

d = 32 pc

d = 65 pc

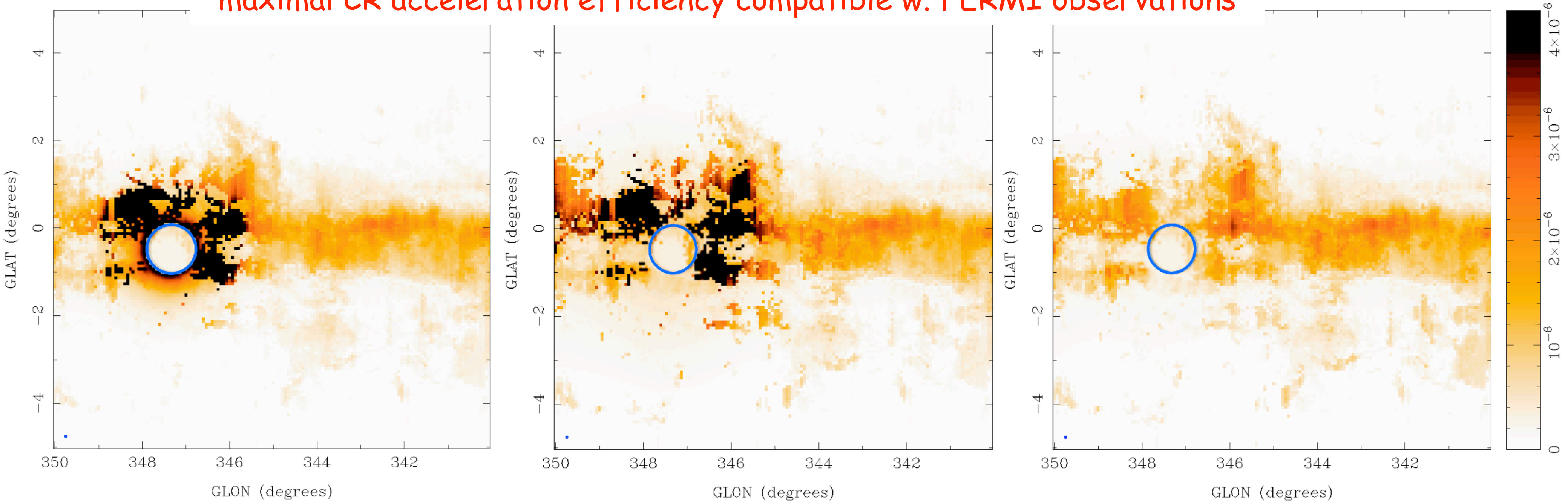
some problems here...

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

Identifying CR sources:
Diffuse emission around RX J1713

Simulated emission at 1 TeV = H_2 and HI (NANTEN+LAB survey) + runaway CRs

maximal CR acceleration efficiency compatible w. FERMI observations



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

average diffusion coefficient in the Galaxy
from spallation measurements

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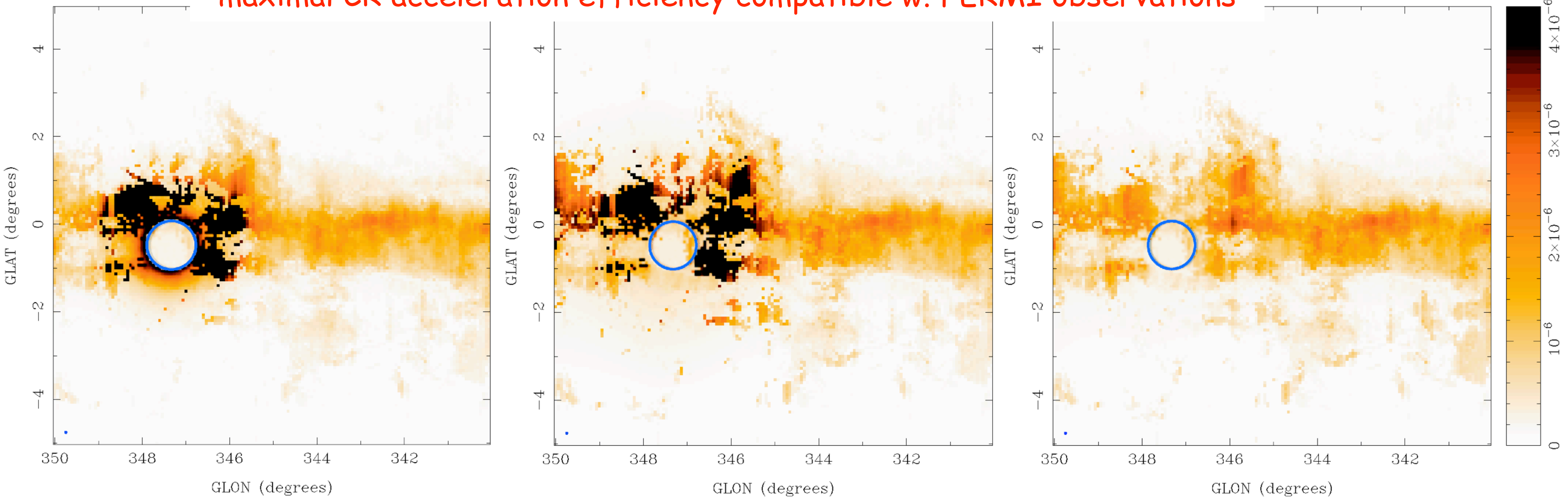

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Casanova...SG...et al, 2010

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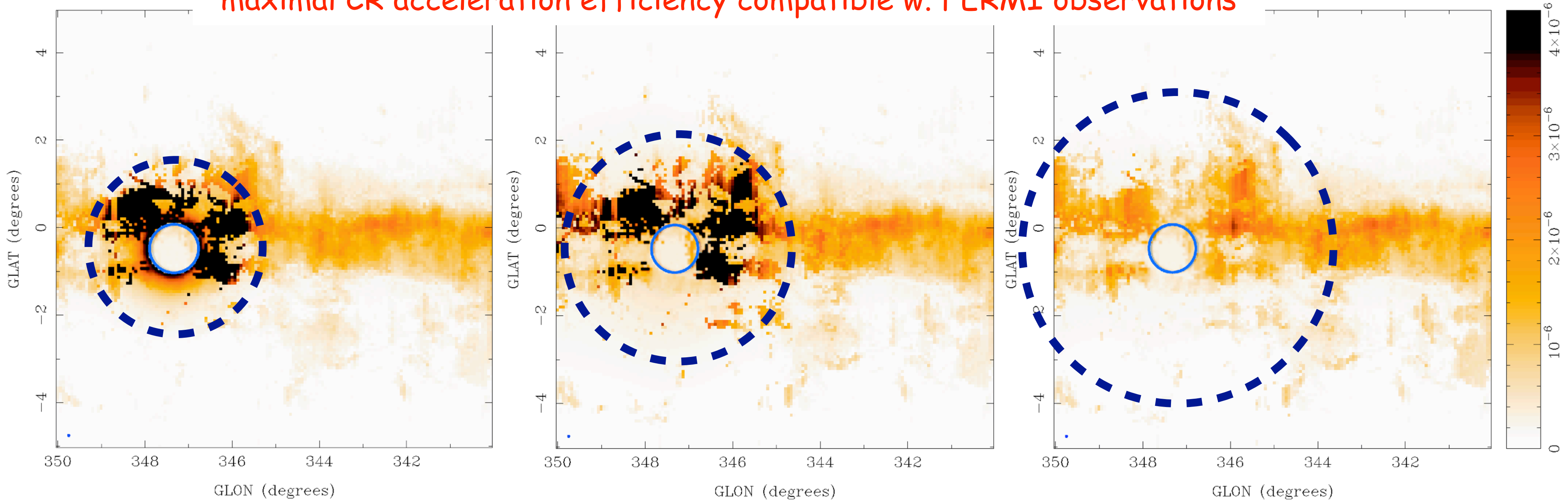

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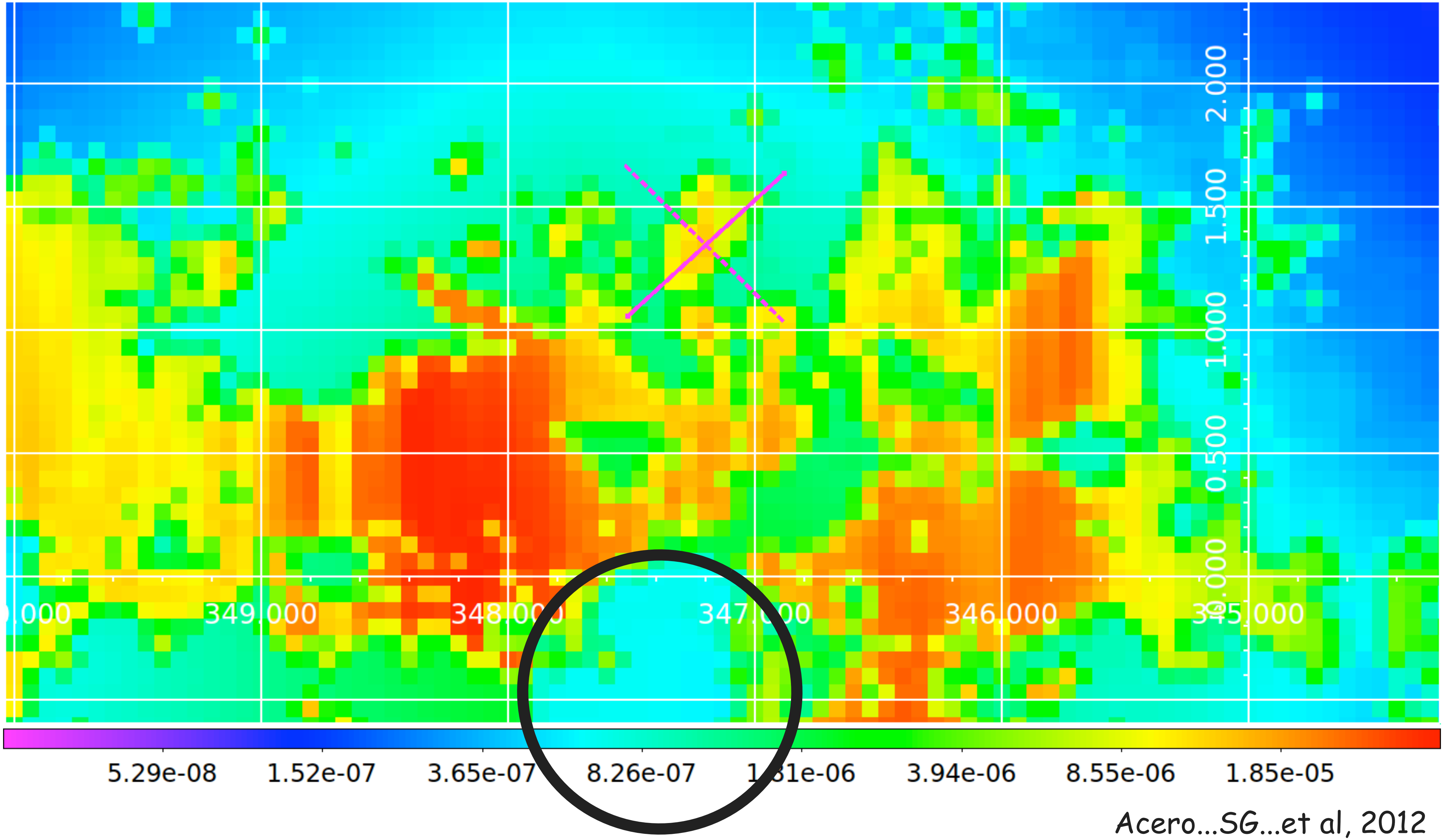
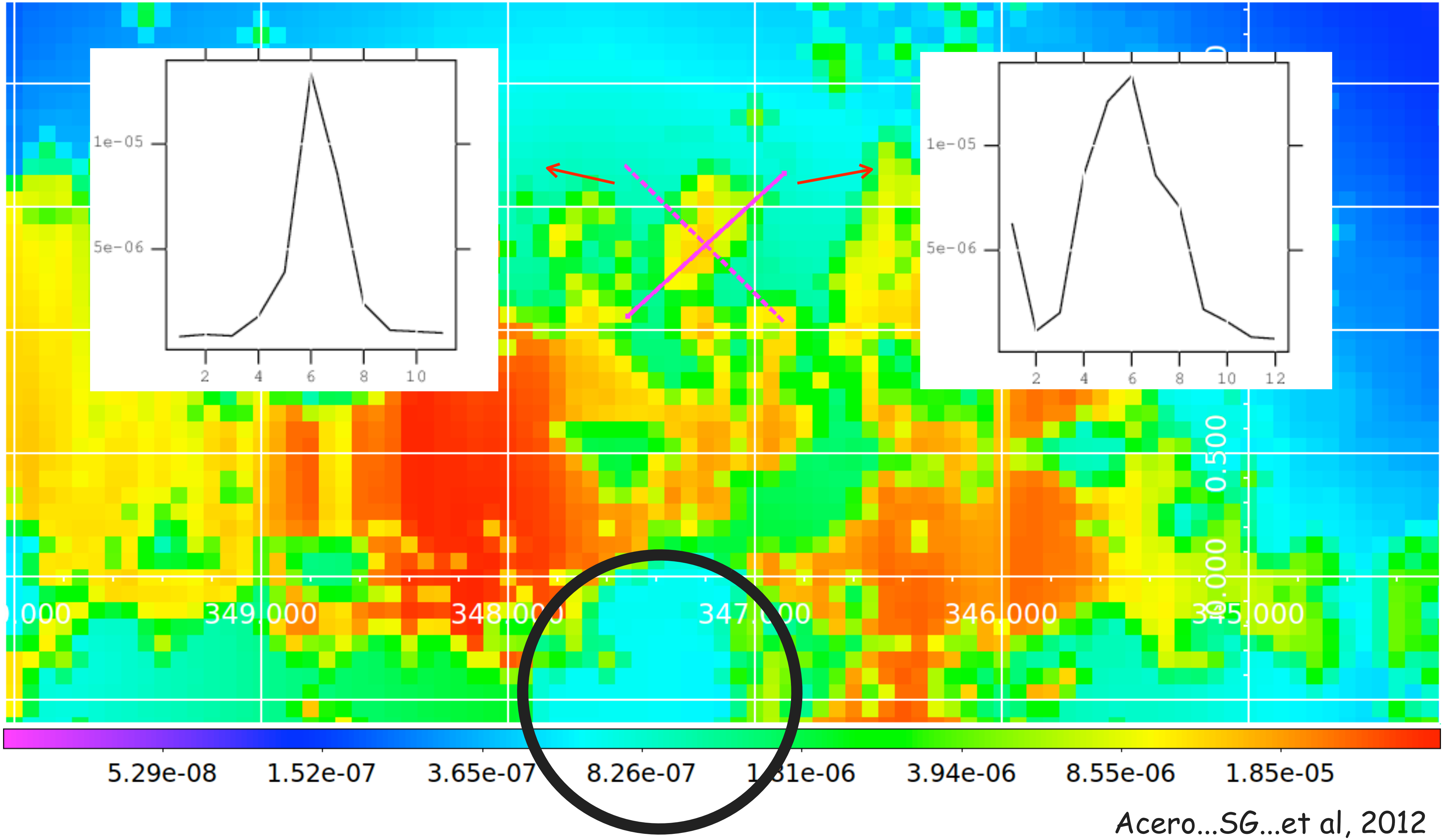
Identifying CR sources: diffuse emission around RX J1713 with CTA



Acero...SG...et al, 2012

Identifying CR sources: diffuse emission around RX J1713 with CTA



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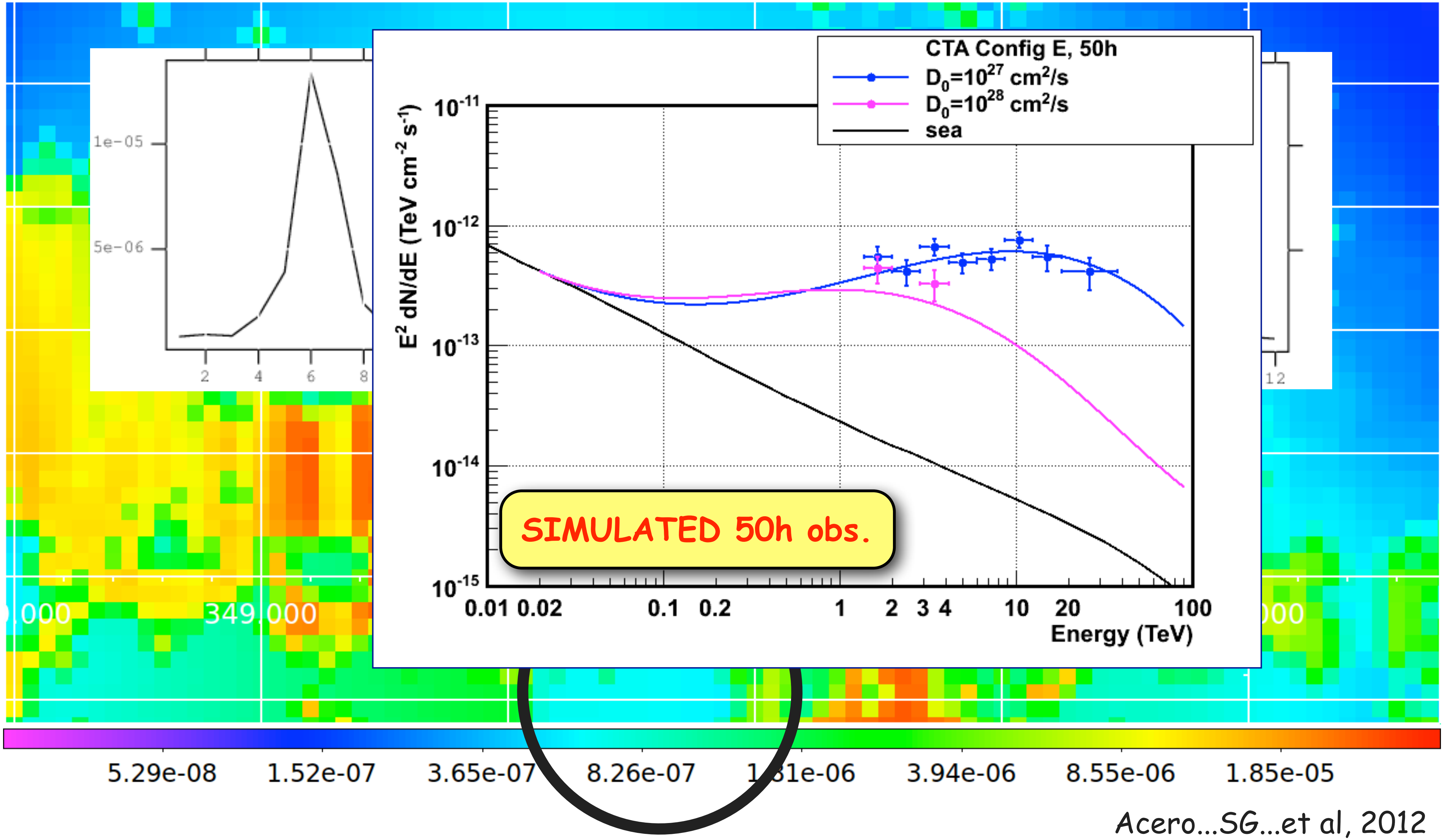

SIMULATED 50h obs.

Acero...SG...et al, 2012

Constraints on propagation

average diffusion coefficient in the MW (use with caution!)

$$D(E) \approx 10^{28} \left(\frac{E}{10 \text{ GeV}} \right)^{0.5} \text{cm}^2/\text{s} \longrightarrow D(1 \text{ TeV}) \approx 10^{29} \text{cm}^2/\text{s}$$

W28 - t_{age} ~ 4.4 x 10^4 yr - D(1 TeV) ~ 3-9 x 10^{27} cm^2/s - Gabici et al 2010

W44 - t_{age} ~ 1.0 x 10^4 yr - D(10 GeV) $\gtrsim$ 10^{27} cm^2/s - Uchiyama etal2012

- t_{age} ~ 2.0 x 10^4 yr - D(10 GeV) $\gtrsim$ 5 x 10^{26}cm^2/s - Uchiyama etal2012

IC443 - t_{age} ~ 3.0 x 10^4 yr - D(1 TeV) ~ 1 x 10^{27} cm^2/s - Torres et al 2010

GCR - t_{age} ~ 1 x 10^4 yr - D(~10 TeV) < 10^{30} cm^2/s - HESS coll. 2006

W51C - t_{age} ~ 3.2 x 10^4 yr - D(1 TeV) ~ 3 x 10^{27} cm^2/s - Ohira et al 2011

9SNRs - t_{age} ~ .2-1 x 10^4 yr - D(10GeV) ~ .4-5x10^{26}cm^2/s - Li & Chen 2012

G35.6 - t_{age} ~ 3. x 10^4 yr - D(1 TeV) < 1. x 10^{28}cm^2/s - Torres et al 2012

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W44	$t_{age} \sim 1.0 \times 10^4$ yr	D(10 GeV) ≳ 1 … ²/s	Uchiyama etal2012
	$t_{age} \sim 2.0 \times 10^4$ yr	D(10 GeV) … 10^{26}cm²/s	Uchiyama etal2012
IC443	$t_{age} \sim 3.0 \times 10^4$ yr	D(1 Te … x 10^{27} cm²/s	Torres et al 2010
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diffusion coefficient suppressed?

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- t_{age} ~ 2.0 x 10^4 yr - D(10 GeV) x 10^{26}cm^2/s - Uchiyama etal2012

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GCR - t_{age} ~ 1 x 10^4 yr - D(~1 V) < 10^{30} 6

W51C - t_{age} ~ 3.2 x 10^4 yr - D V) ~ 3 x 10^2 1

9SNRs - t_{age} ~ .2-1 x 10^4 yr 0GeV) ~ .4-5x1

G35.6 - t_{age} ~ 3. x 10^4 yr - D(1 TeV) < 1. x 10^{28}cm^2/s - Torres et al 2012

diffusion coefficient suppressed?

Dor (LMC)
t_{age} ~ 3 x 10^6 yr
D(1 GeV) ~ 10^{27} cm^2/s
Murphy et al 2012

Conclusions

☑ **Gamma rays from molecular clouds**

- probe the level of CR sea -> possible now with Fermi

  -> in the future with CTA?

- identify CR accelerators -> Fermi, HESS and Co.

- constrain CR diffusion coefficient

  -> hints for suppression of D close to sources

  -> why? CR induced turbulence (streaming instability?)

  -> few sources now -> more sources with CTA