Gamma rays from molecular clouds (part 2)

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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

(1) Molecular clouds
as cosmic ray barometers

Gamma rays from the Milky Way

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

gamma ray emissivity

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

photon flux at Earth

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

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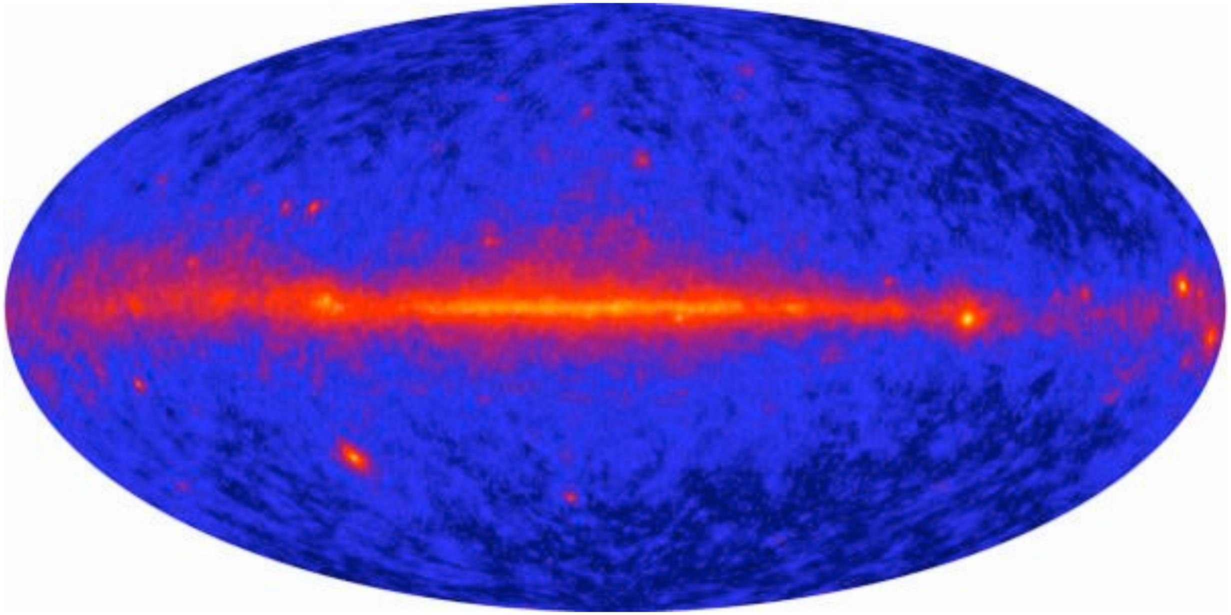
measured by EGRET, FERMI...

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

Molecular Clouds as CR barometers: GeVs



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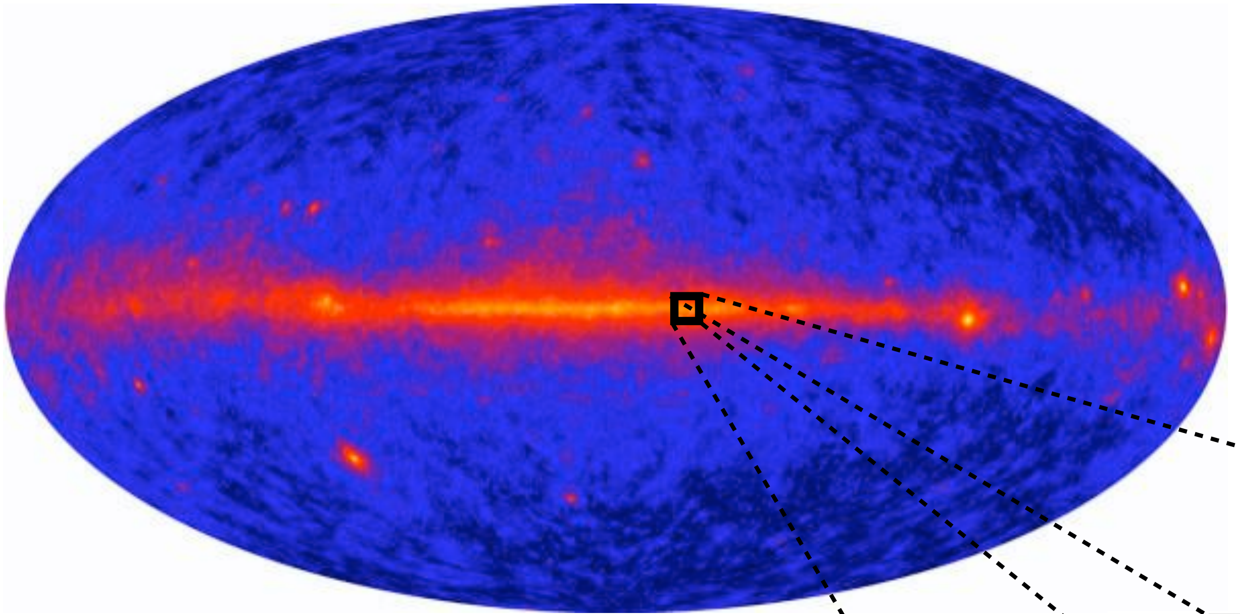

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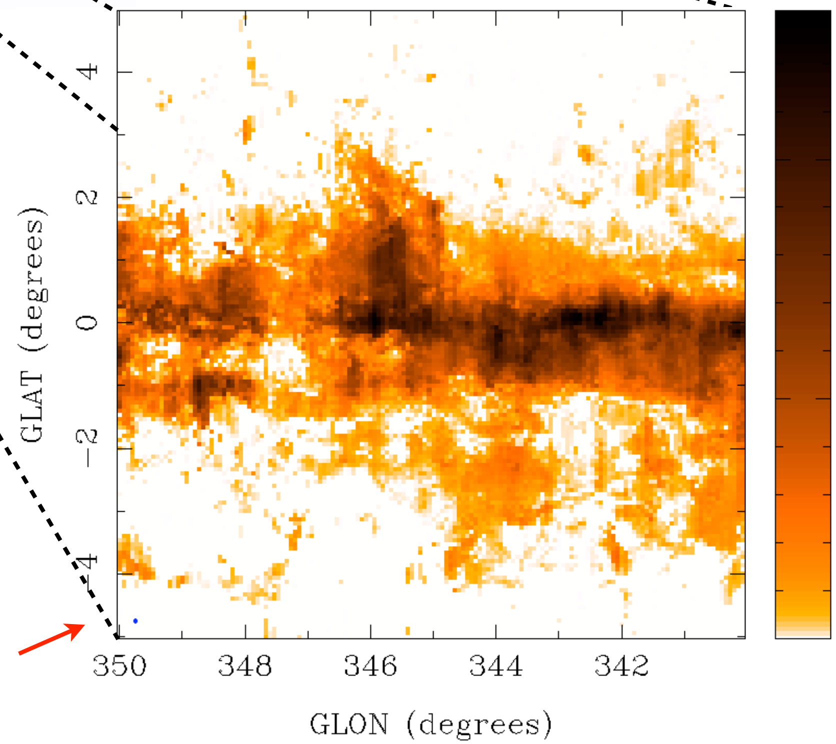
gas column density ->



CO data from NANTEN telescope

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

Gamma rays from the Milky Way

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

LAB HI Survey
(Karberla et al 05)

ASSUMPTION:
spatial homogeneity of CRs

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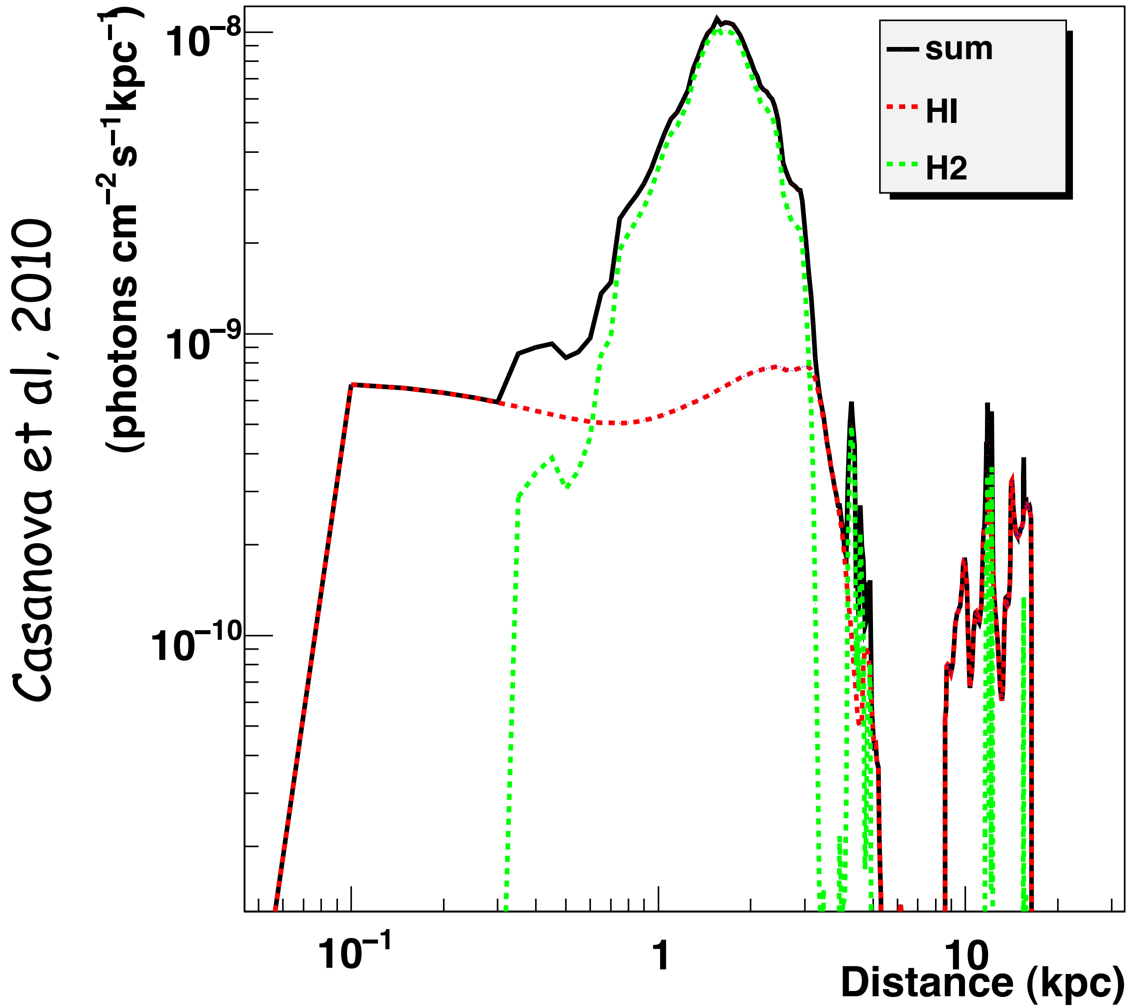

<--- @1 GeV

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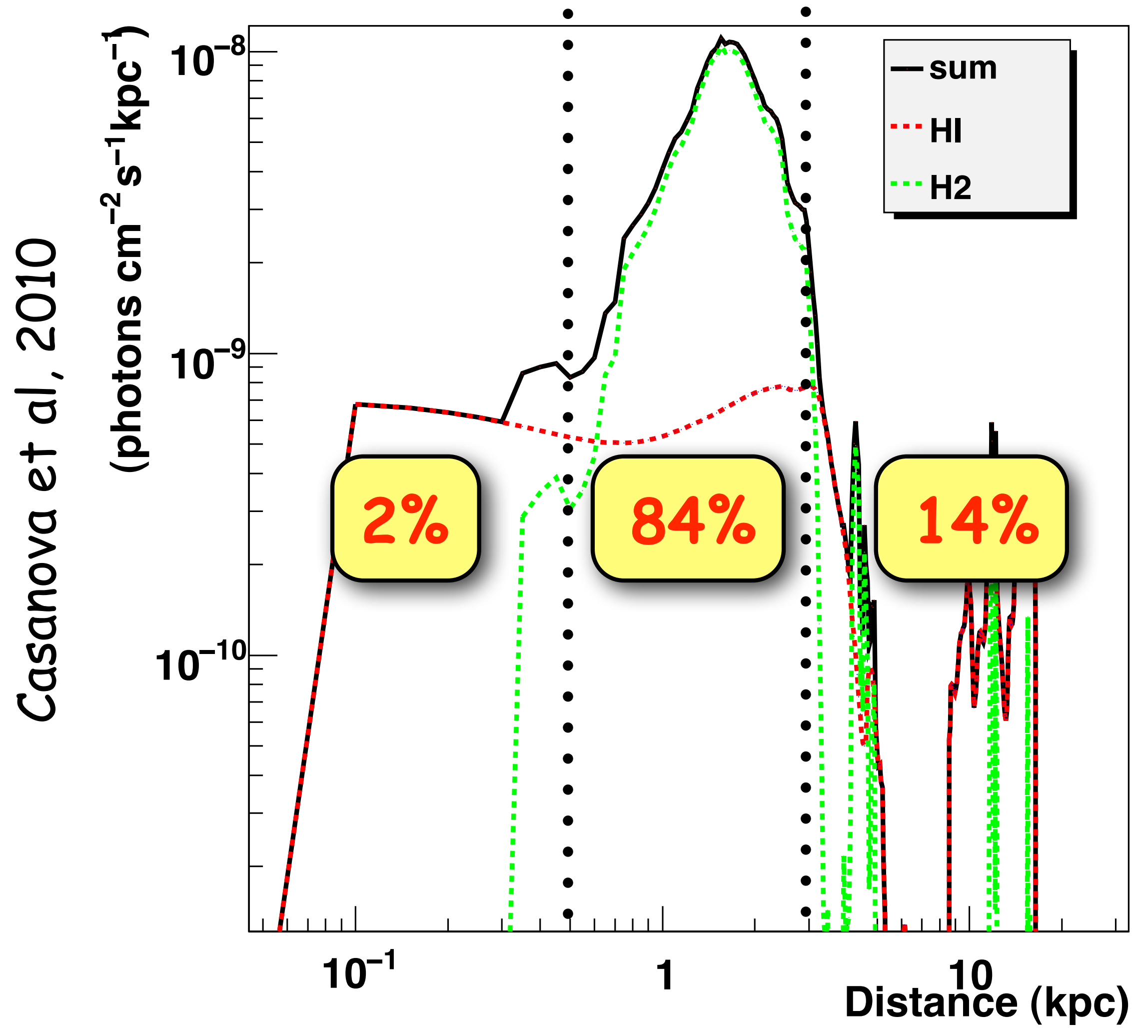

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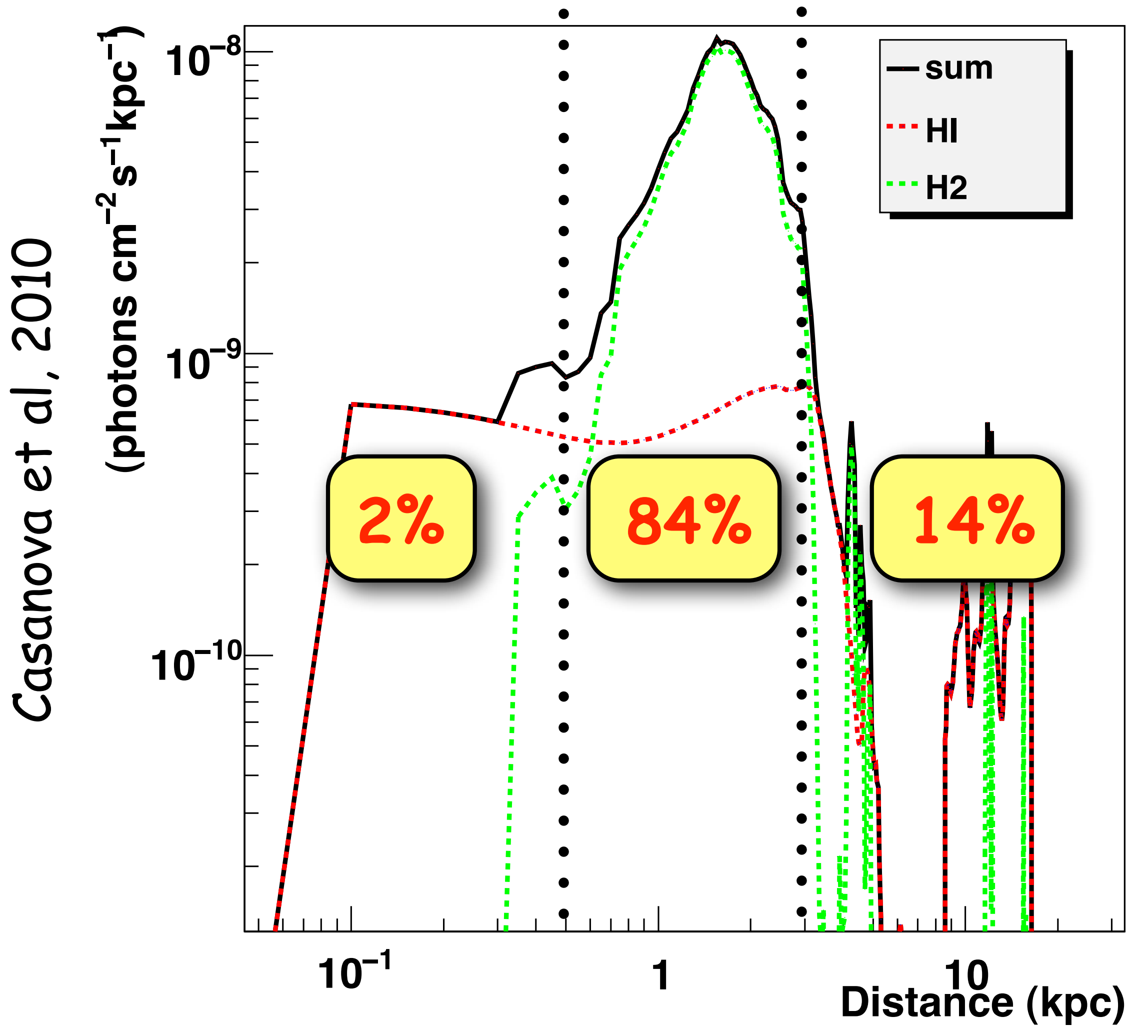

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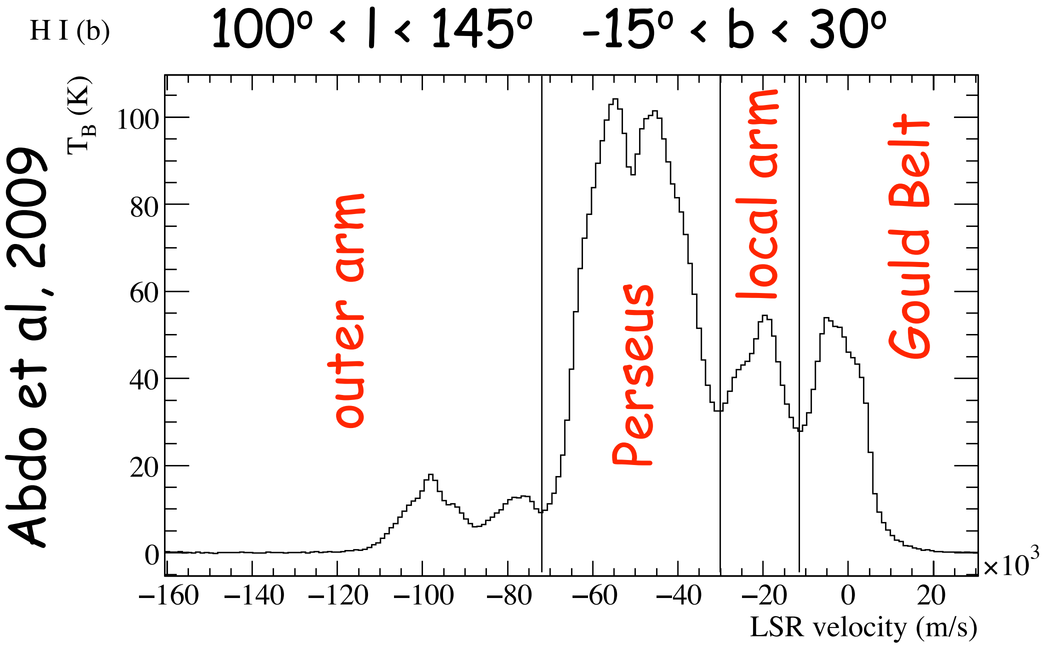
the main contribution to the gamma ray emission comes from ~ 1 kpc. If the CR intensity is different there, we expect a different flux.

-> "Tomography" with gamma rays!

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

Molecular Clouds as CR barometers: GeVs

Recent results from the FERMI collaboration



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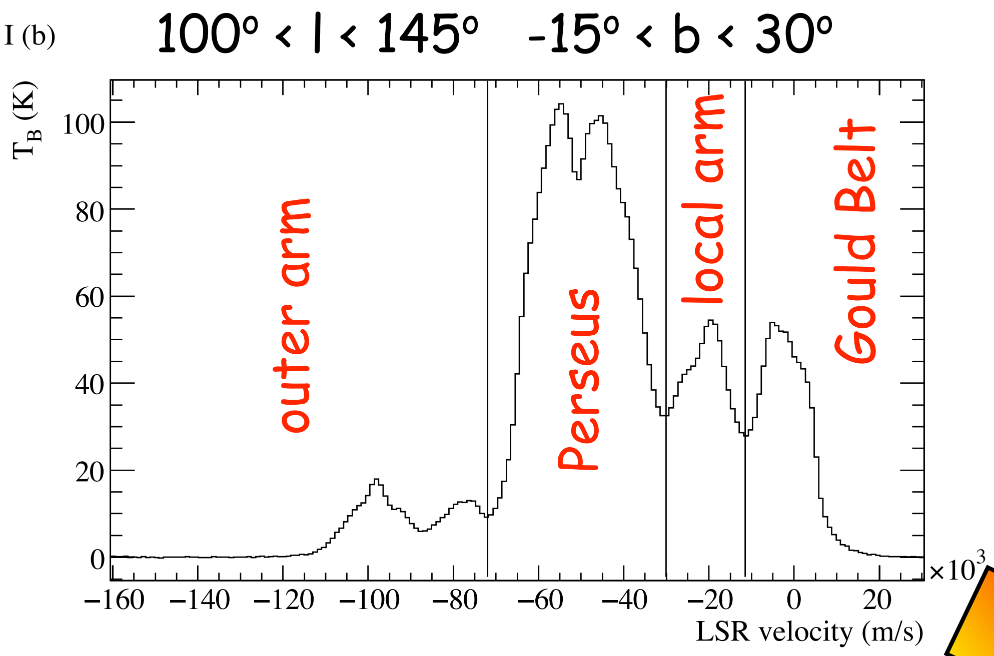
Abdo et al, 2009



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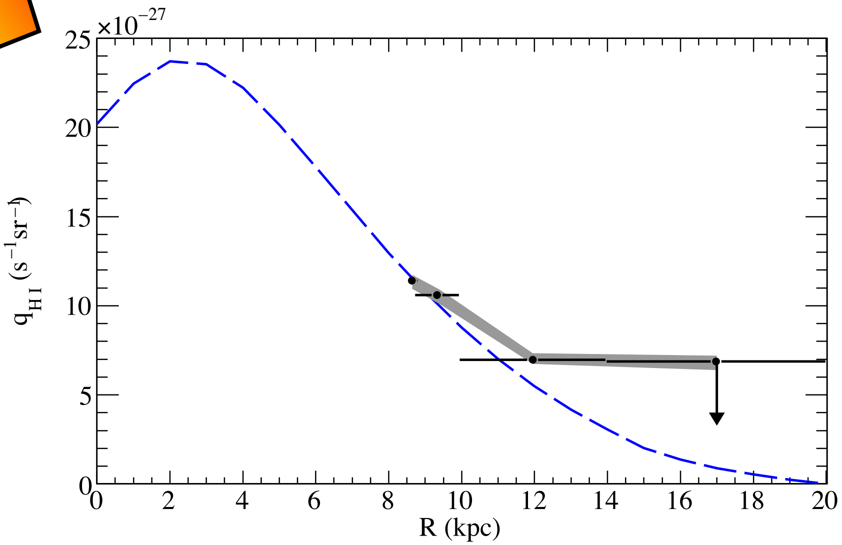
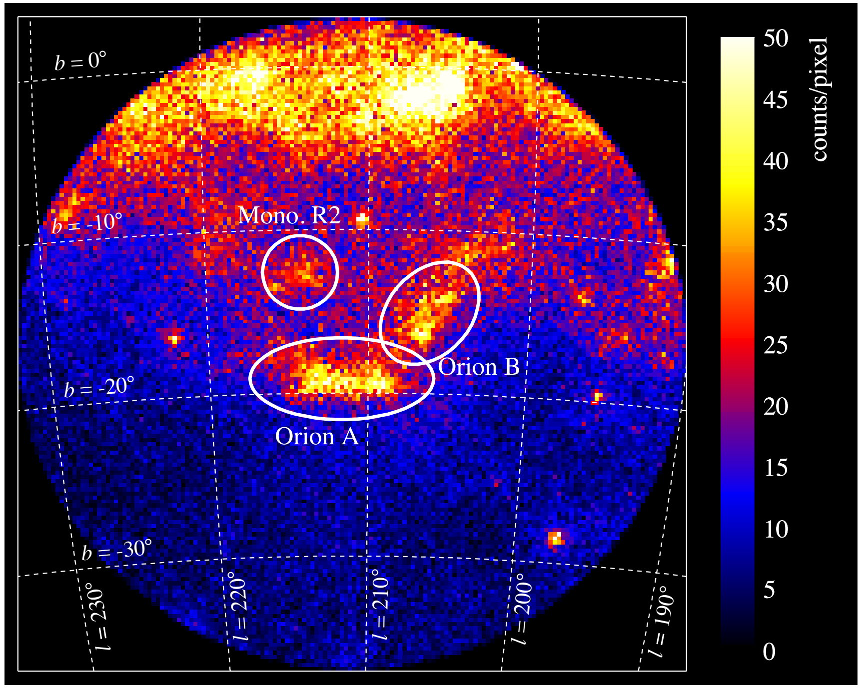
radial profile of gamma ray emissivity ->



Molecular clouds at GeV energies: FERMI

Orion molecular clouds

Okumura et al, 2009



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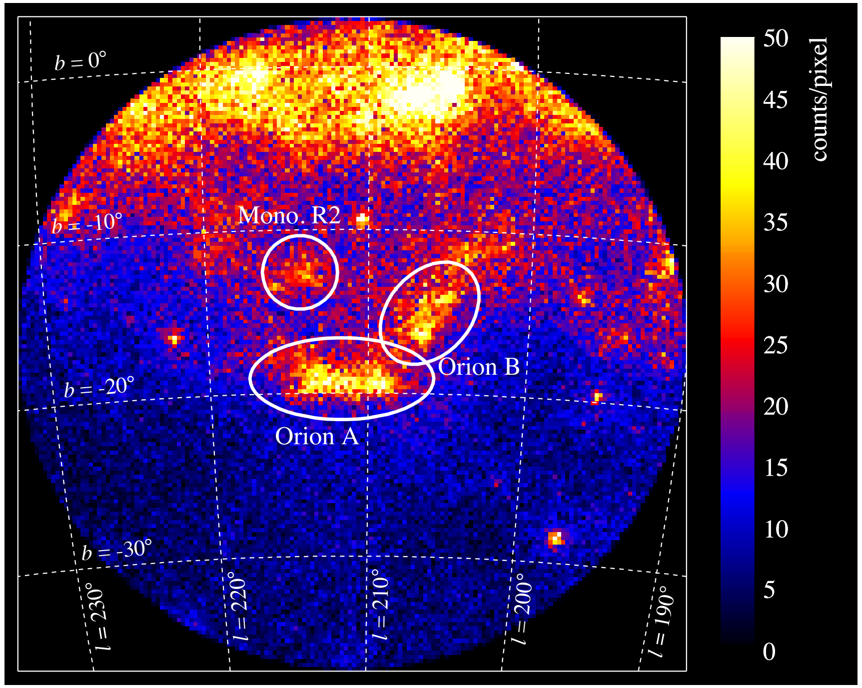

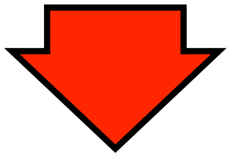

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CR spectrum from GALPROP
(8% less than local CRs)

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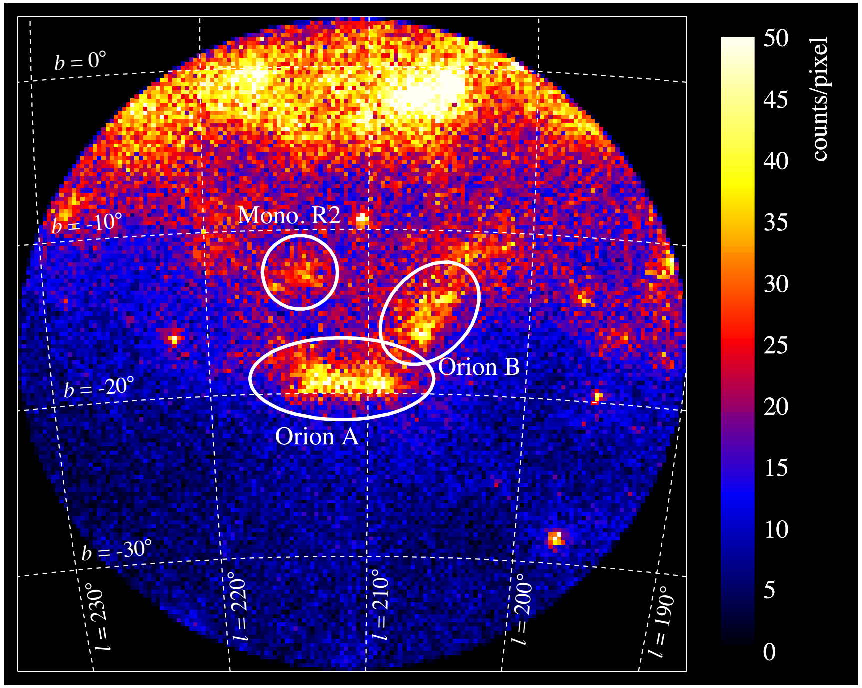

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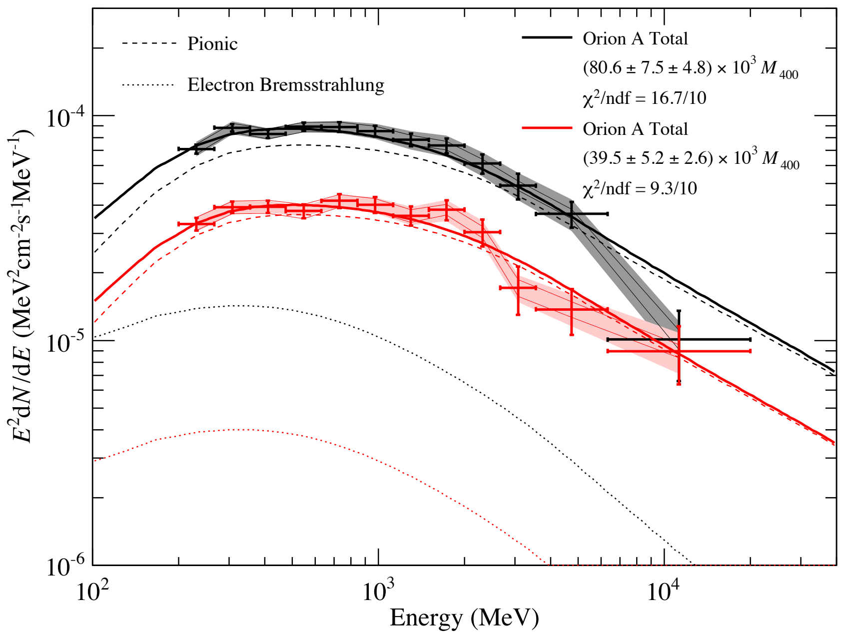

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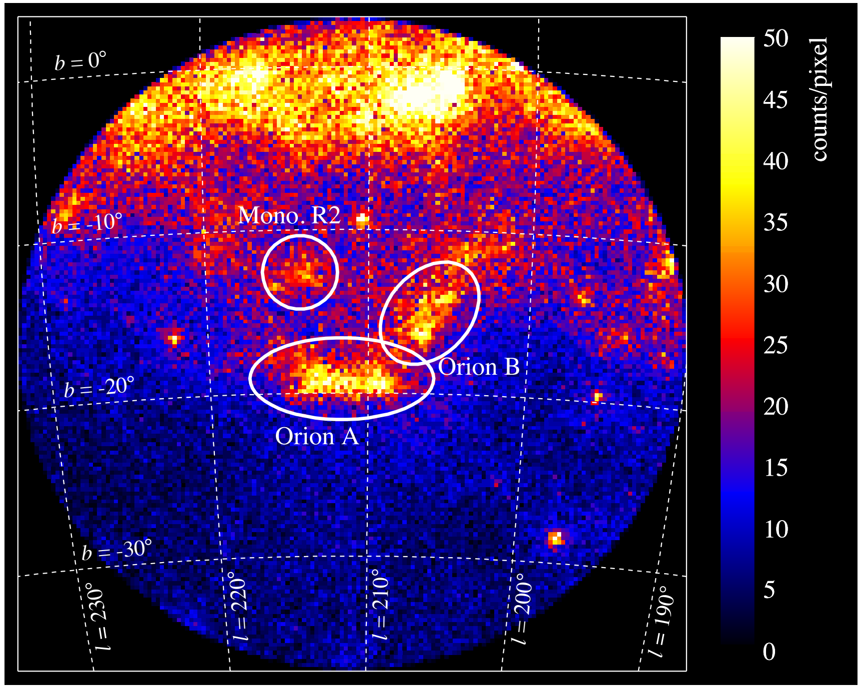

$$M_A \sim 8.1 \times 10^4 M_\odot$$
$$M_B \sim 4.0 \times 10^4 M_\odot$$

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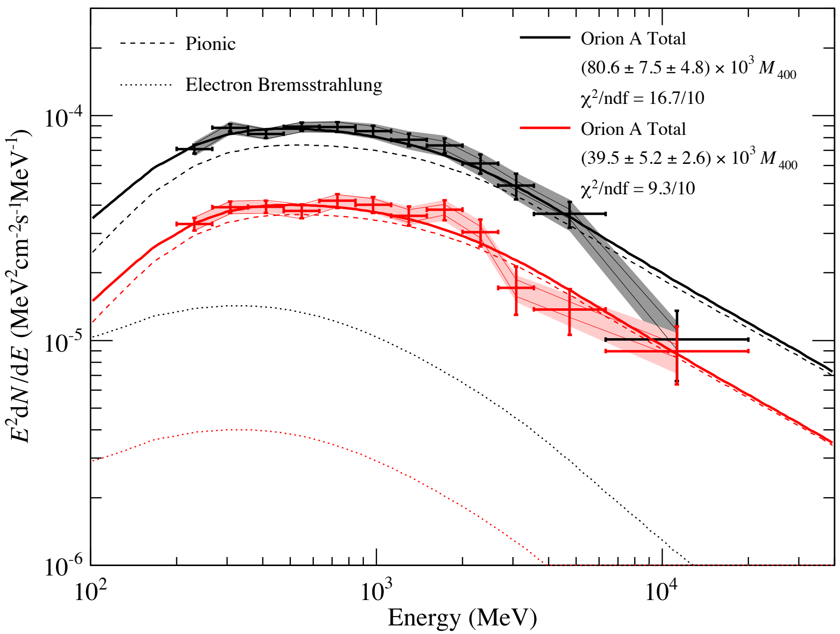

(2) Illuminated molecular clouds (MC/SNR associations)

Evolution of SuperNova Remnants

SN -> Explosion in a cold, uniform medium

Explosion energy: $E_{SN} = 10^{51}\ E_{51}\ \mathrm{erg}$

Mass of ejecta: $M_{ej} \approx 1 \div 10\ M_{\odot}$

M_{sw} -> mass swept up by the shock

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$$E_{SN} = \frac{1}{2}\ M_{ej}\ v^2 \quad \Rightarrow \quad \boxed{v \ = \ 10^9\ E_{51}^{1/2} \left(\frac{M_{ej}}{M_\odot}\right)^{1/2} \mathrm{cm/s}}$$

constant velocity

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shock radius

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duration of the free expansion phase: $t \approx \frac{R_s}{v} \approx 200 \left(\frac{M_{ej}}{M_\odot} \right)^{-\frac{1}{6}} \text{yr}$

Evolution of SuperNova Remnants

$M_{sw} >> M_{ej}$ -> the shock slows down

we want to find a relation between R_s and t

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let's start by considering the shock heating of the gas

$$k_b T_2 = \frac{3}{16} m u_1^2 \gtrsim 1 \text{ keV}$$

cooling time → $$\tau_c \propto T^{\frac{1}{2}} \gtrsim 10^6 \text{ yr}$$ ← much longer than the SNR age!

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- SNRs emit X-rays
- the SNR in this phase conserves the total energy!

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we can built a non dimensional quantity -> $\left(\frac{E_{SN}}{\varrho_{gas}}\right)\frac{t^2}{R_s^5}$

$$R_s \approx \left(\frac{E_{SN}}{\varrho_{gas}}\right)^{\frac{1}{5}} t^{\frac{2}{5}}$$

Sedov solution

Evolution of SuperNova Remnants

duration of the Sedov phase

t_{age} ↗

Evolution of SuperNova Remnants

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$t_{age} \nearrow$ $\quad v_s \propto t^{-\frac{3}{5}} \searrow$ $\quad T_2 \propto v_s^2 \searrow$ $\quad \tau_c \propto T_2^{\frac{1}{2}} \searrow$

Evolution of SuperNova Remnants

duration of the Sedov phase

t_{age} ↗ $v_s \propto t^{-\frac{3}{5}}$ ↘ $T_2 \propto v_s^2$ ↘ $\tau_c \propto T_2^{\frac{1}{2}}$ ↘

when $t_{age} \sim \tau_c$ -> radiative losses become important

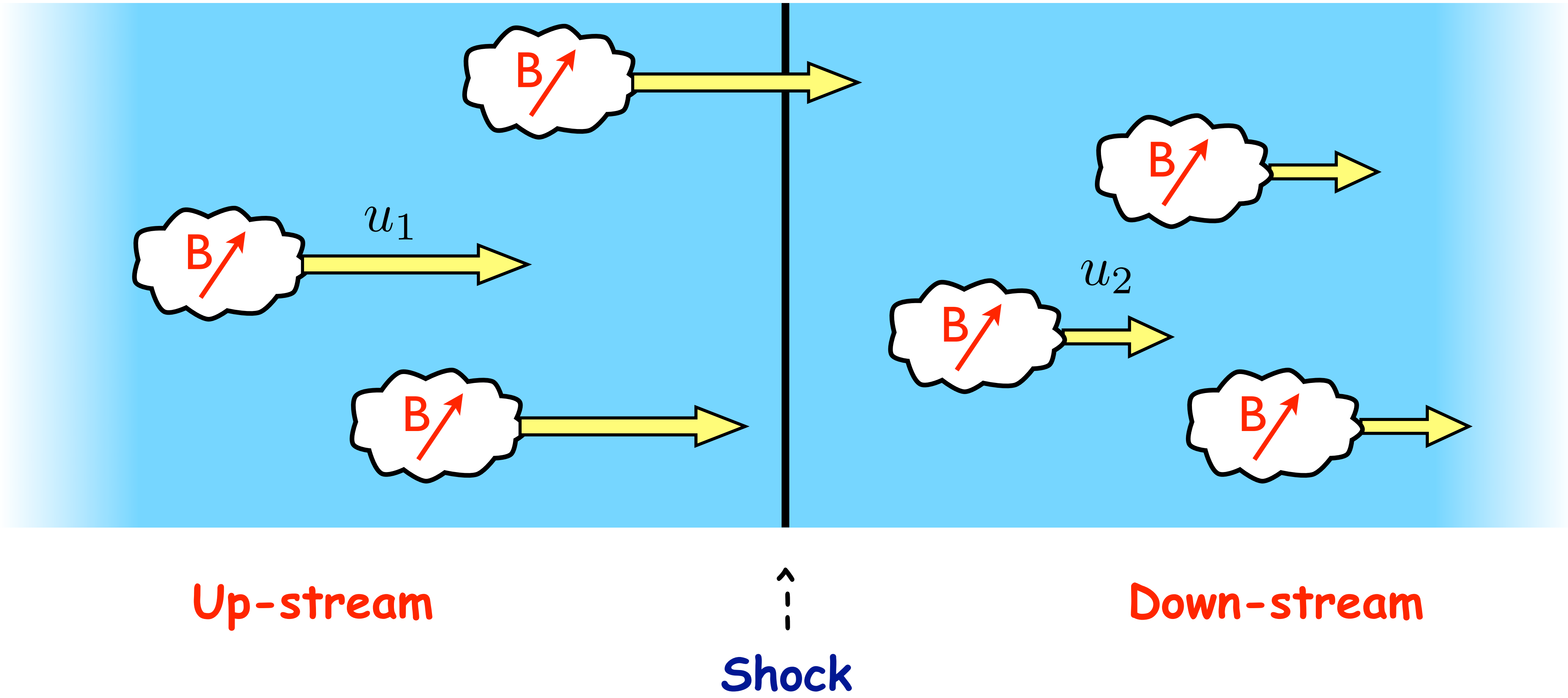
this happens at $t_{age} \sim 5 \times 10^4 \text{ yr}$

$$\begin{cases} R_s^{end} \approx 20 \text{ pc} \\ v_s^{end} \approx 200 \text{ km/s} \end{cases}$$

Diffusive Shock Acceleration

Shock rest frame

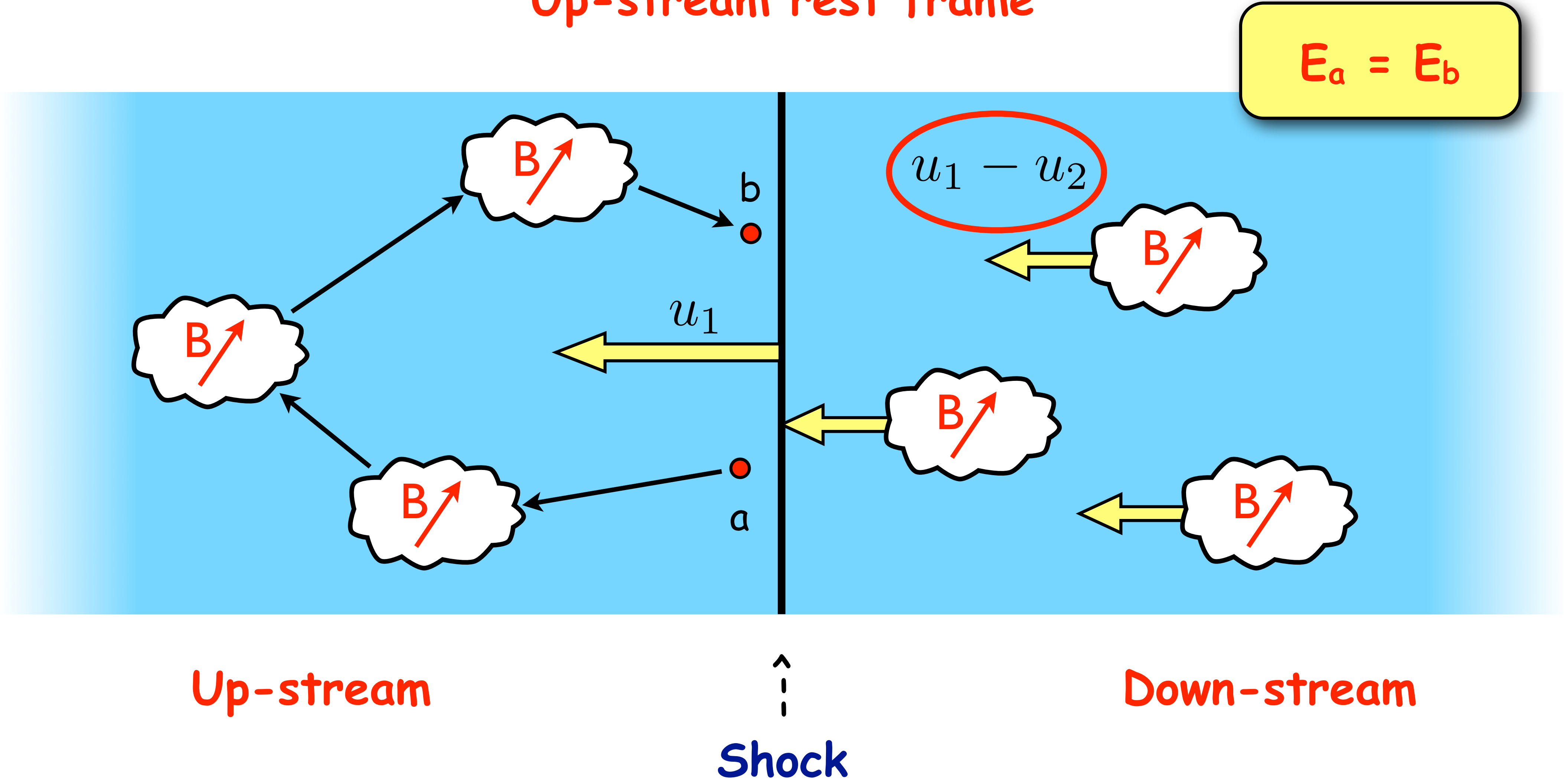
See class by T. Bell



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

Diffusive Shock Acceleration

Up-stream rest frame



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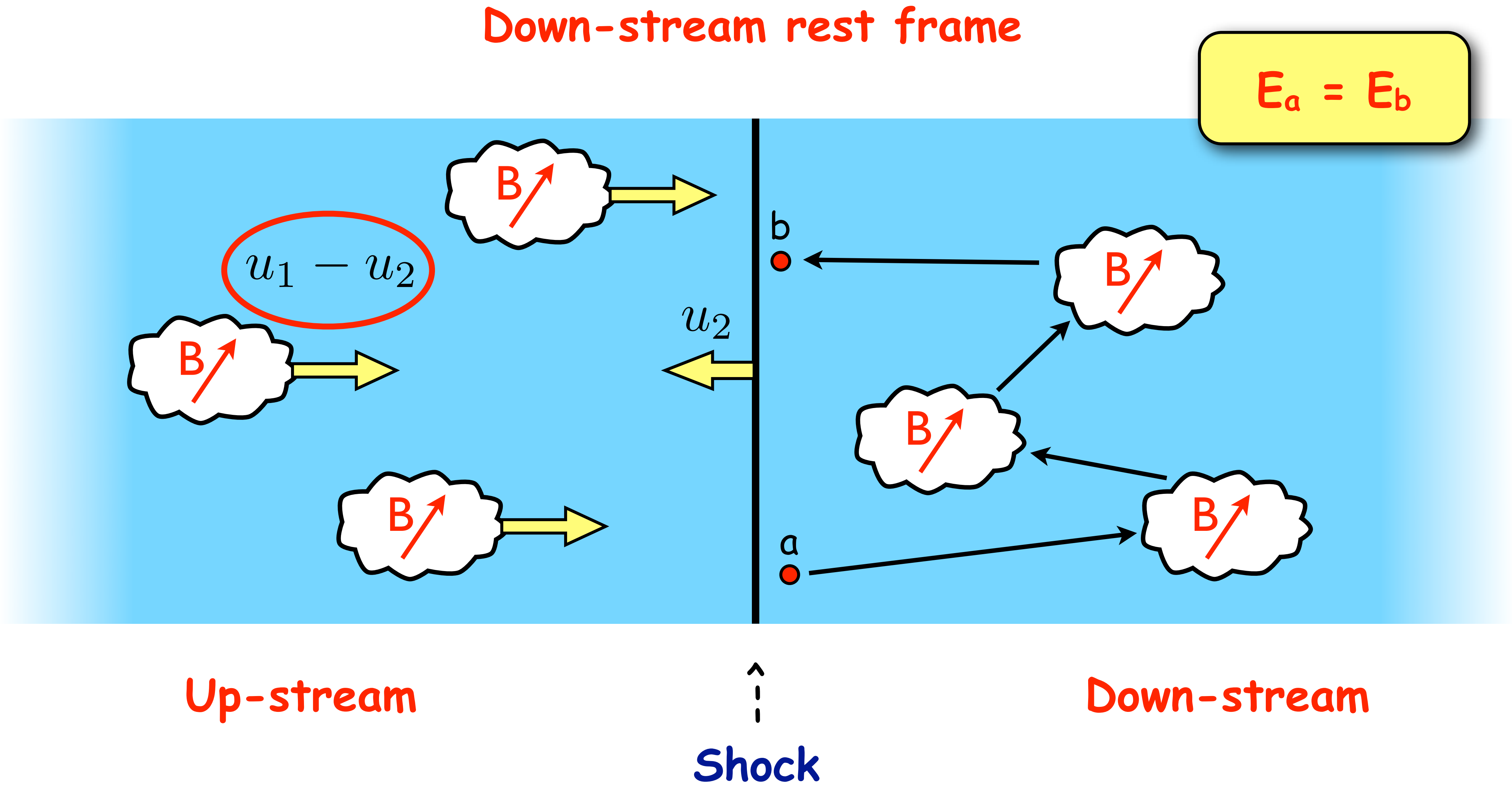
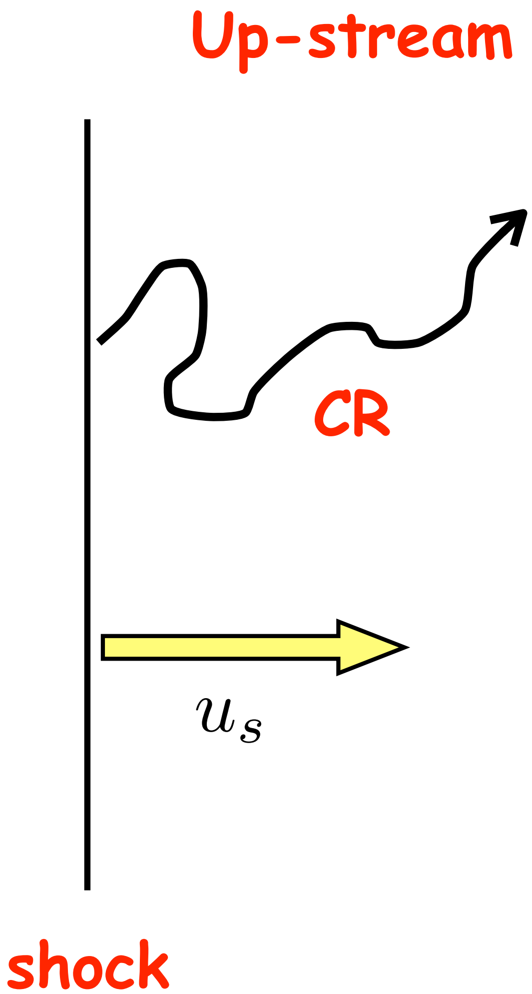


Particle acceleration during the free expansion phase



$$l_d = \sqrt{D\,t}$$

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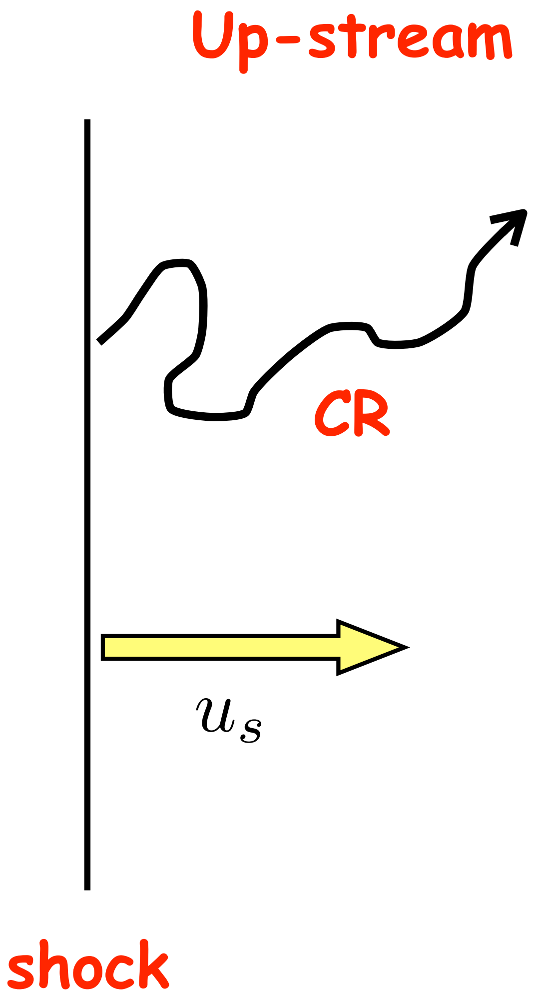

$$l_d = \sqrt{D\, t}$$

equating...

$$l_d = u_s\, t$$

$$t = \frac{D}{u_s^2} \propto E$$

Bohm diffusion -> $\lambda = R_L$

$$D \approx \lambda c \rightarrow D \propto E$$

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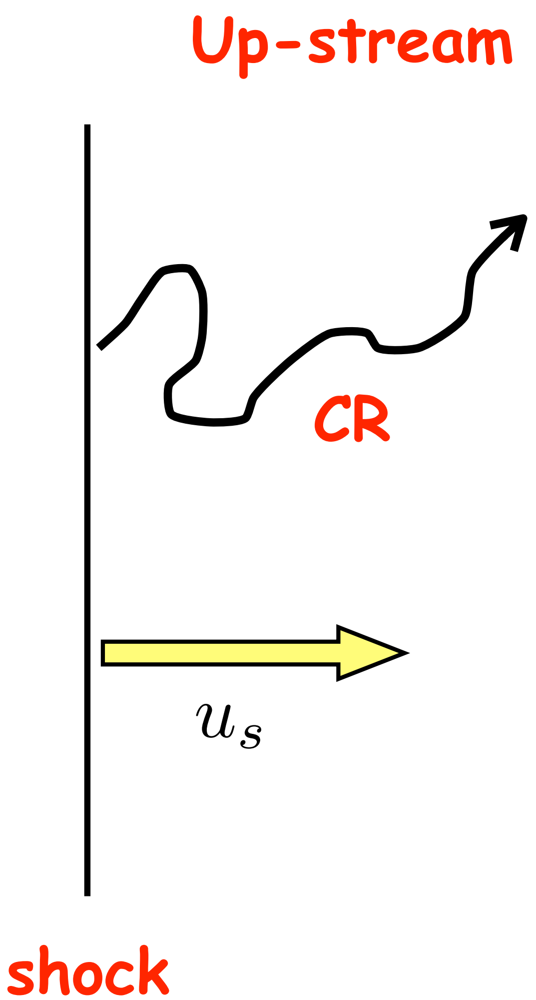

max energy increases w. time

$$l_d = \sqrt{D\, t}$$

equating...

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$$t_{age} = \frac{D}{u_s^2} \propto E_{max}$$

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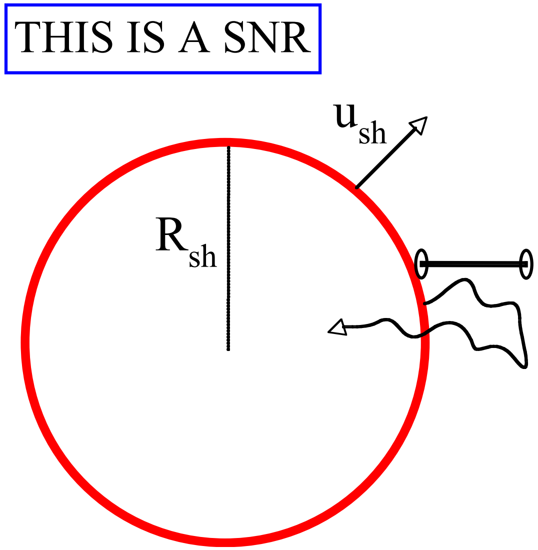
Particles escape from SNRs

see e.g. Ptuskin & Zirakashvili, 2003

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



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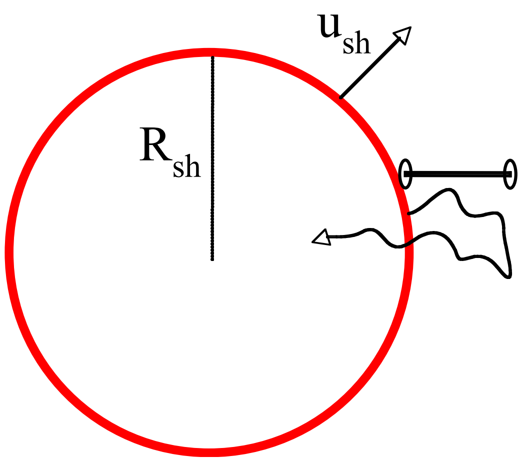

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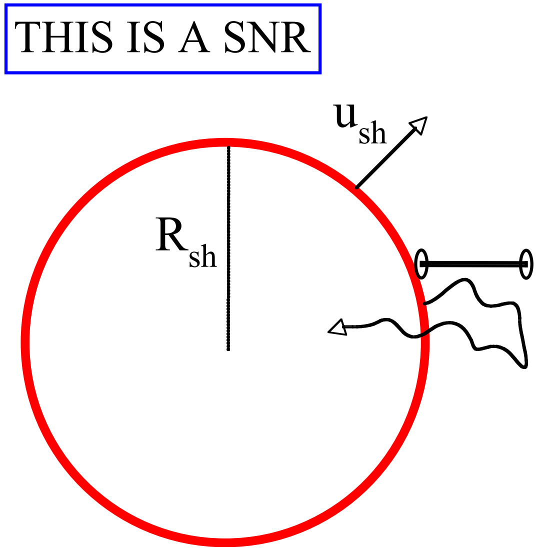

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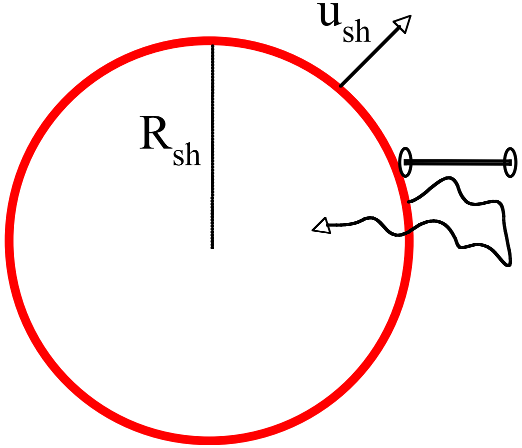

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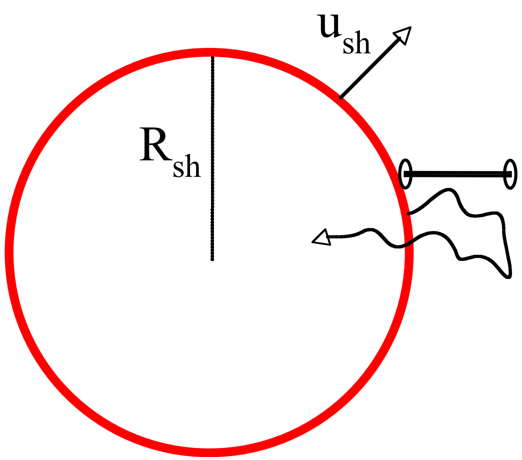

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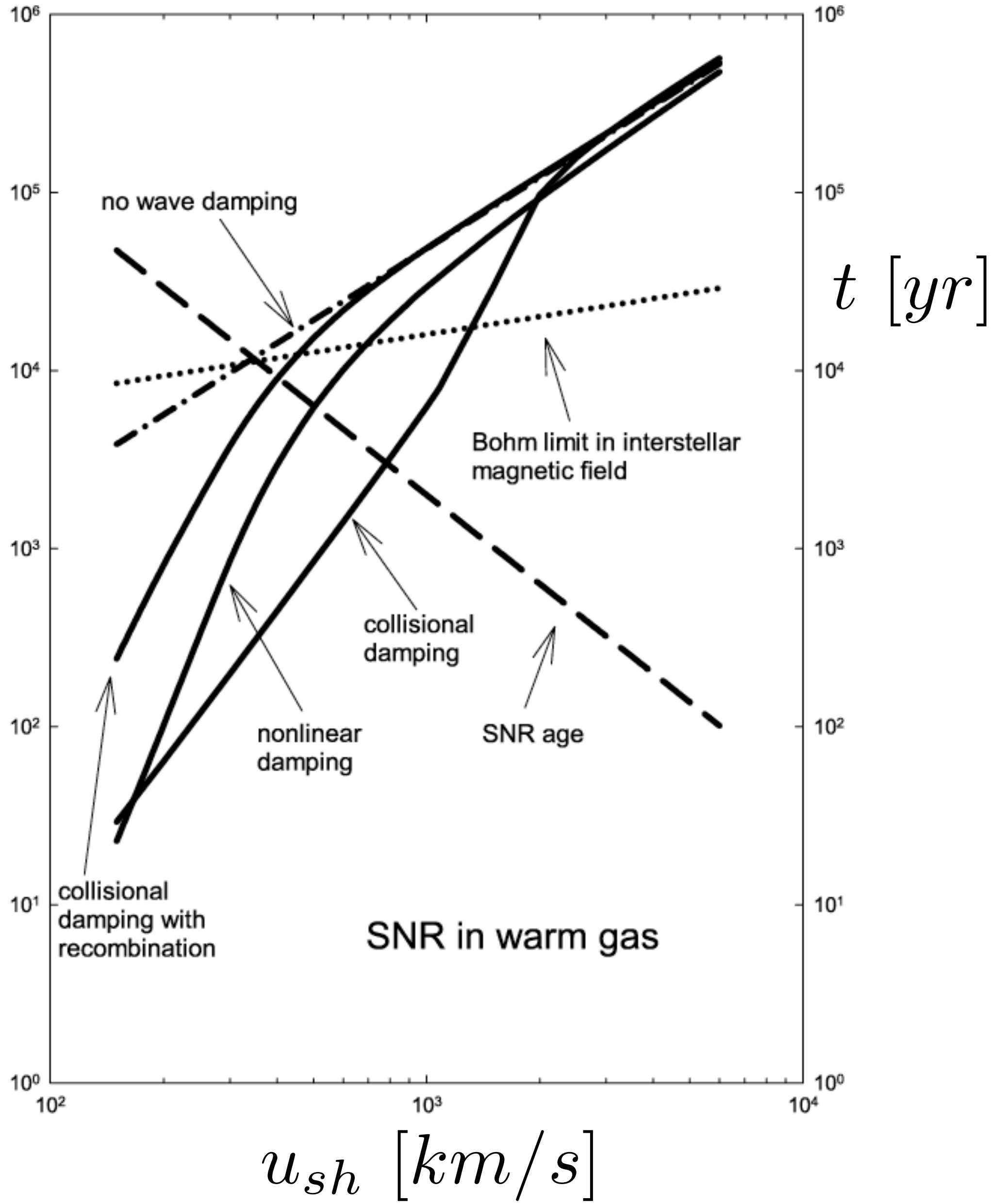
B_{sh} also depends on time

E_{max} decreases with time

Particles with E > E_{max} escape the SNR

Particle escape from SNRs

Ptuskin & Zirakashvili, 2003



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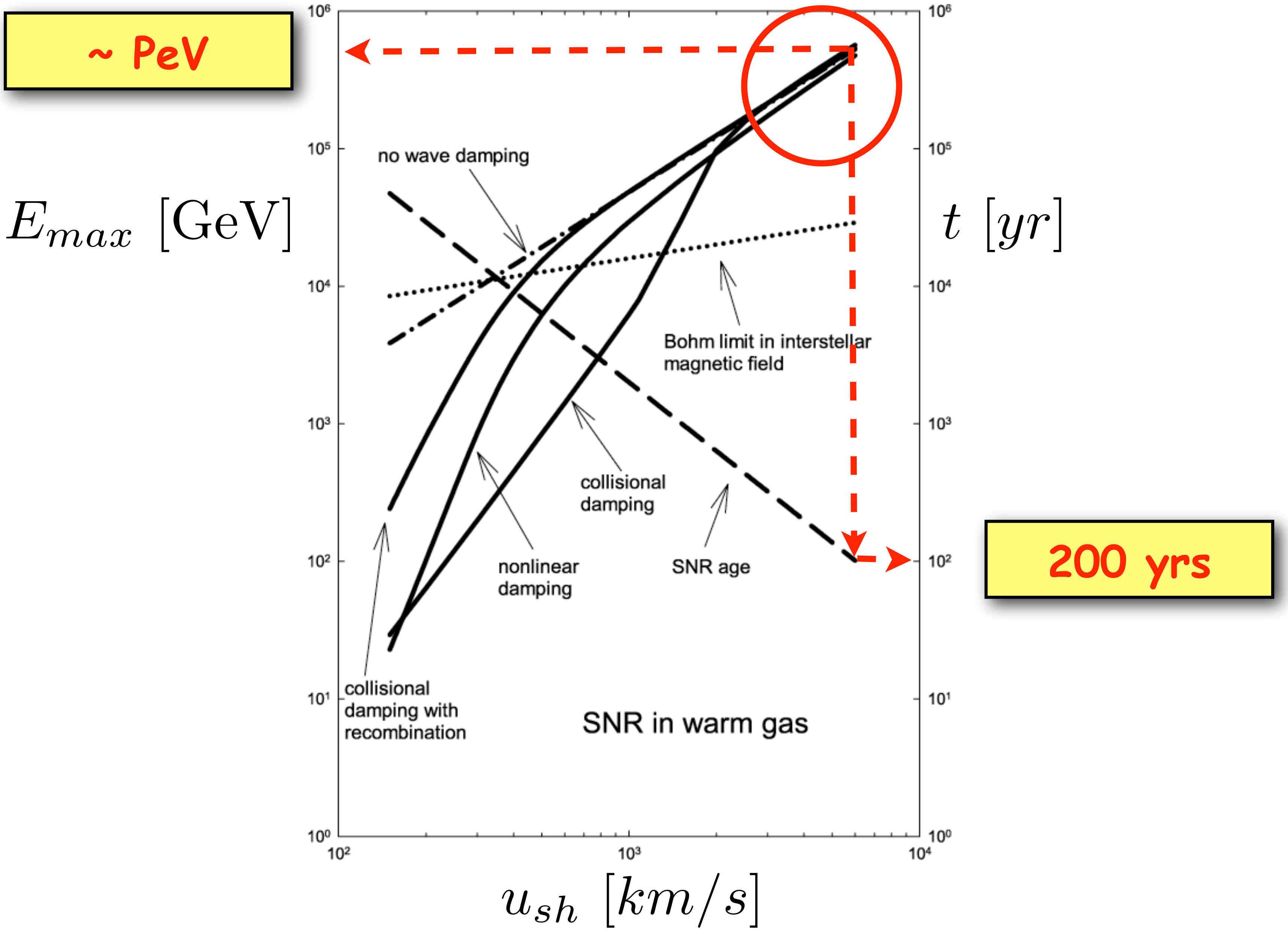

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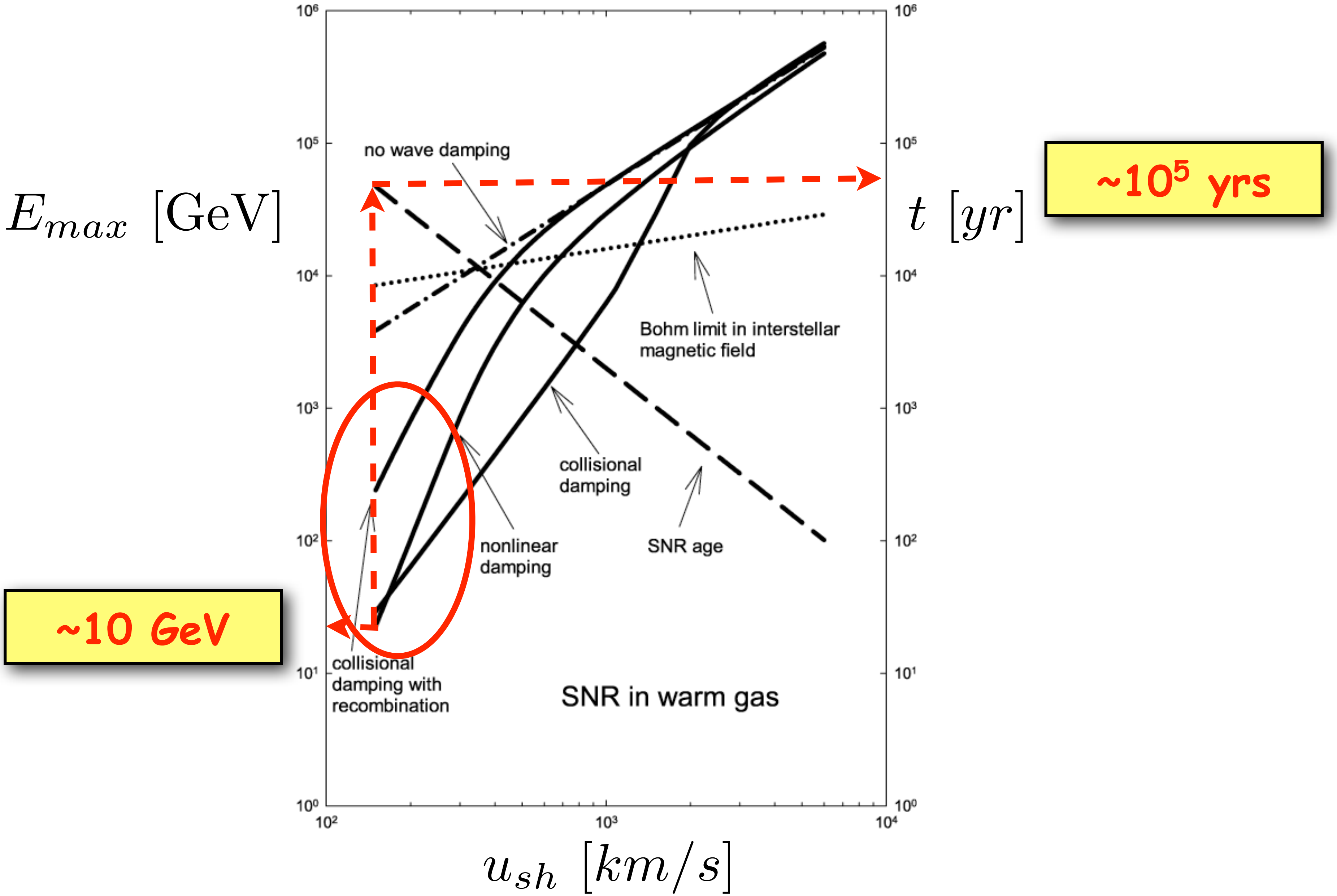

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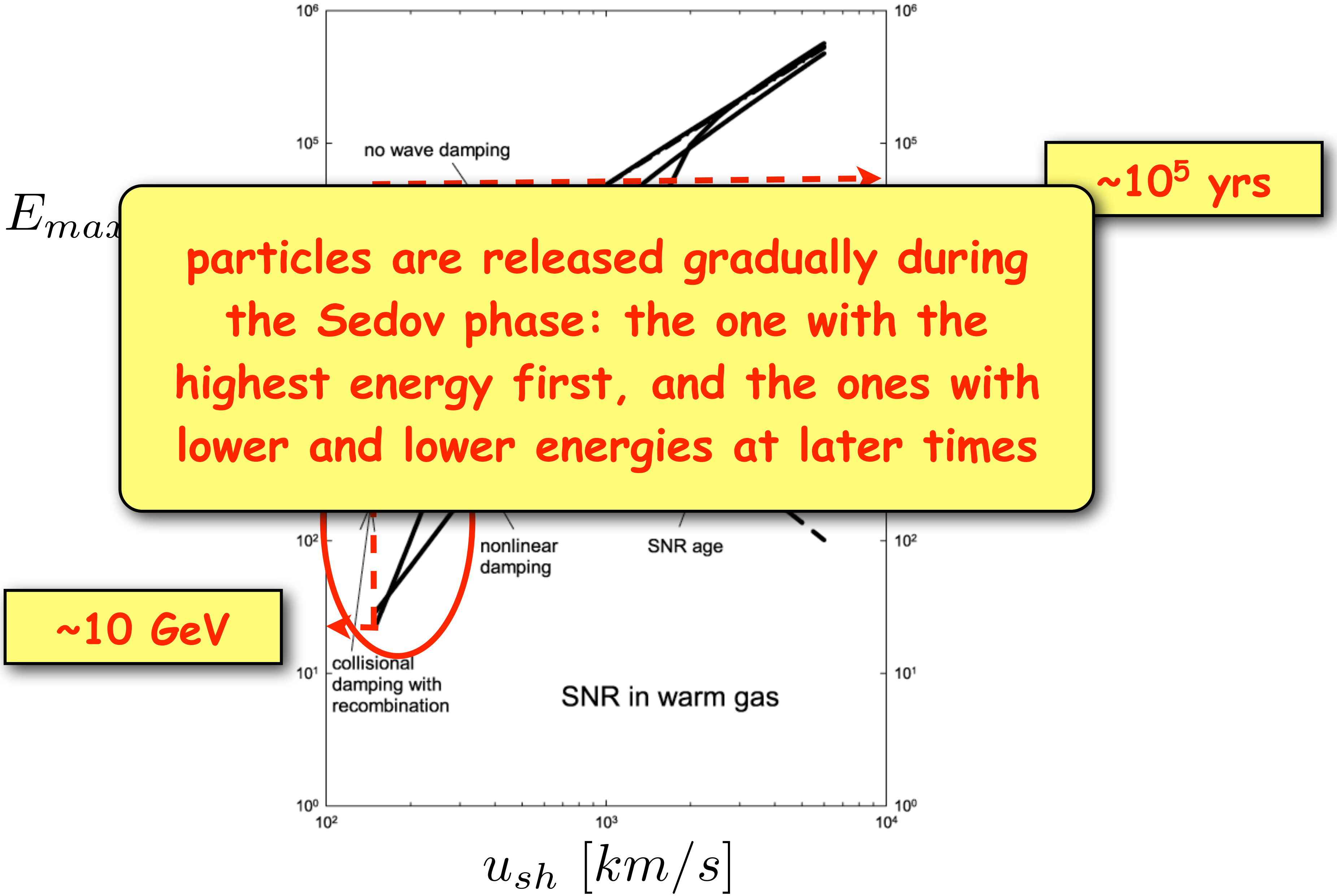
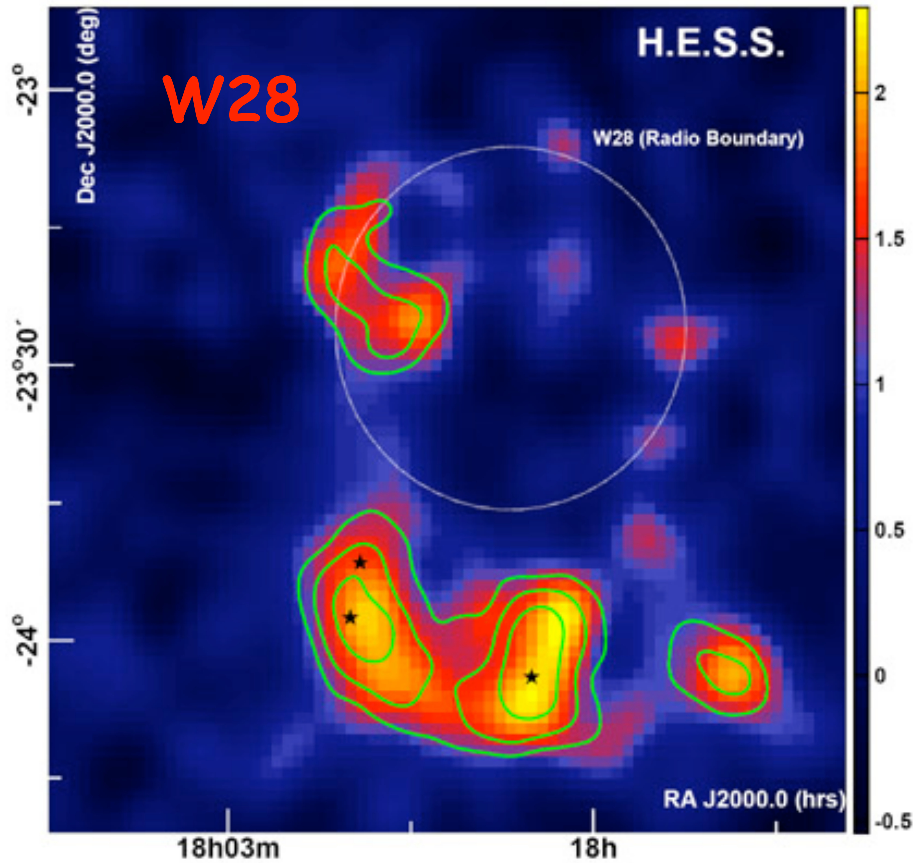


particles are released gradually during the Sedov phase: the one with the highest energy first, and the ones with lower and lower energies at later times

The W28 region in gammas, CO, & radio



HESS - TeV emission

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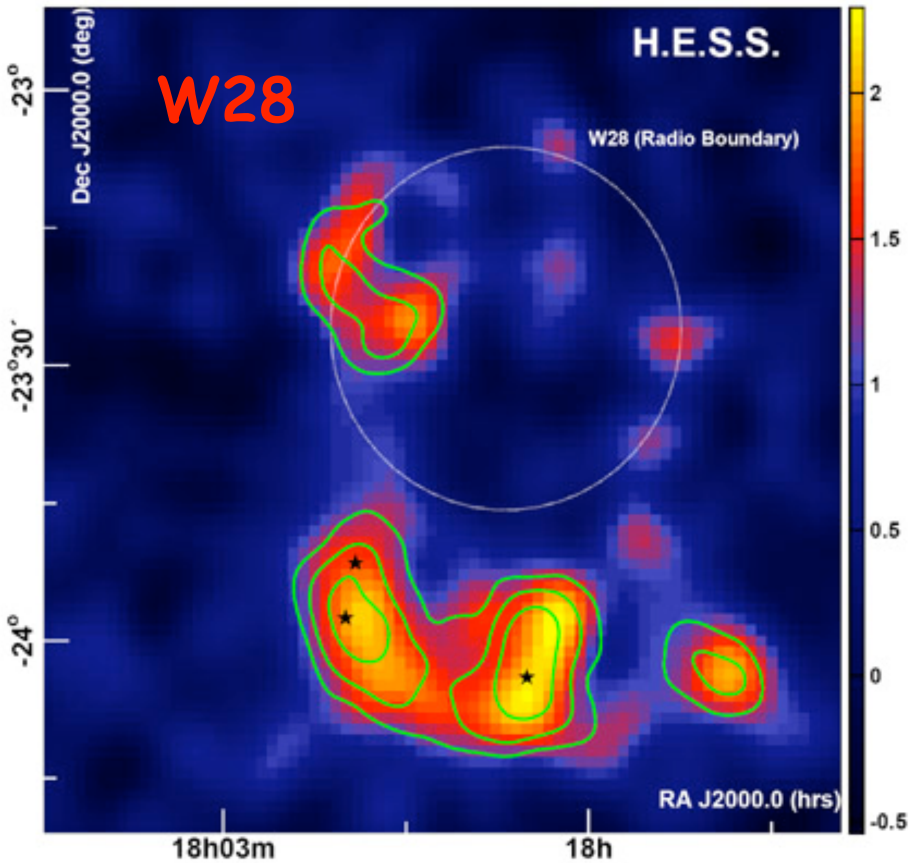

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Aharonian et al, 2008

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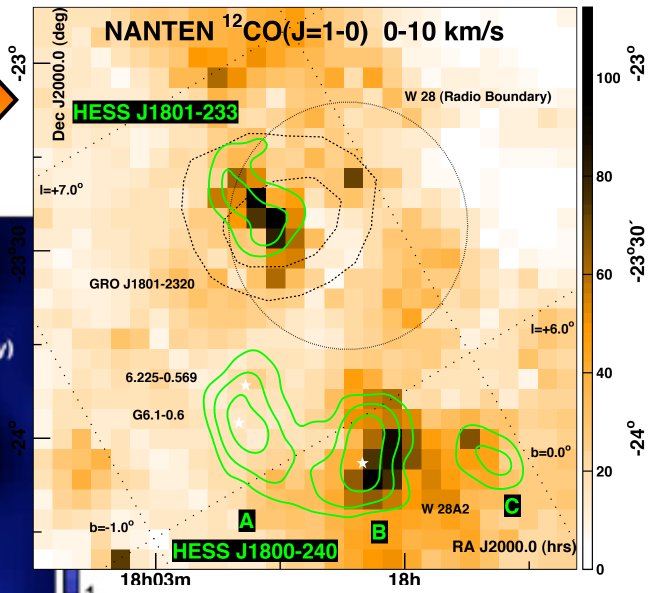
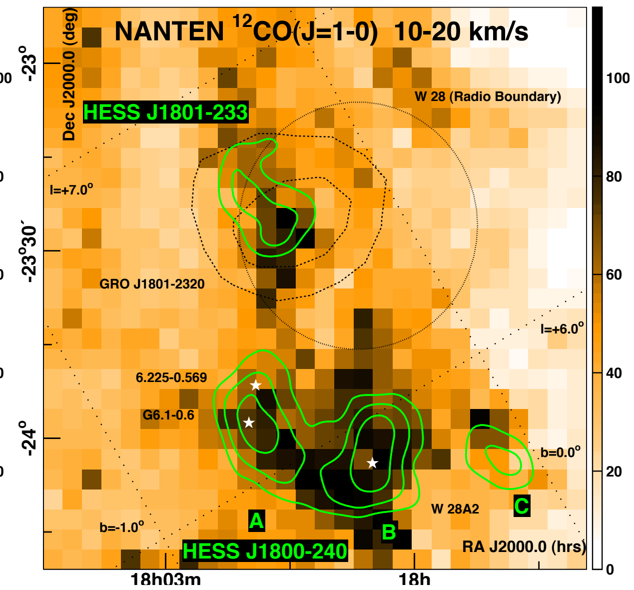
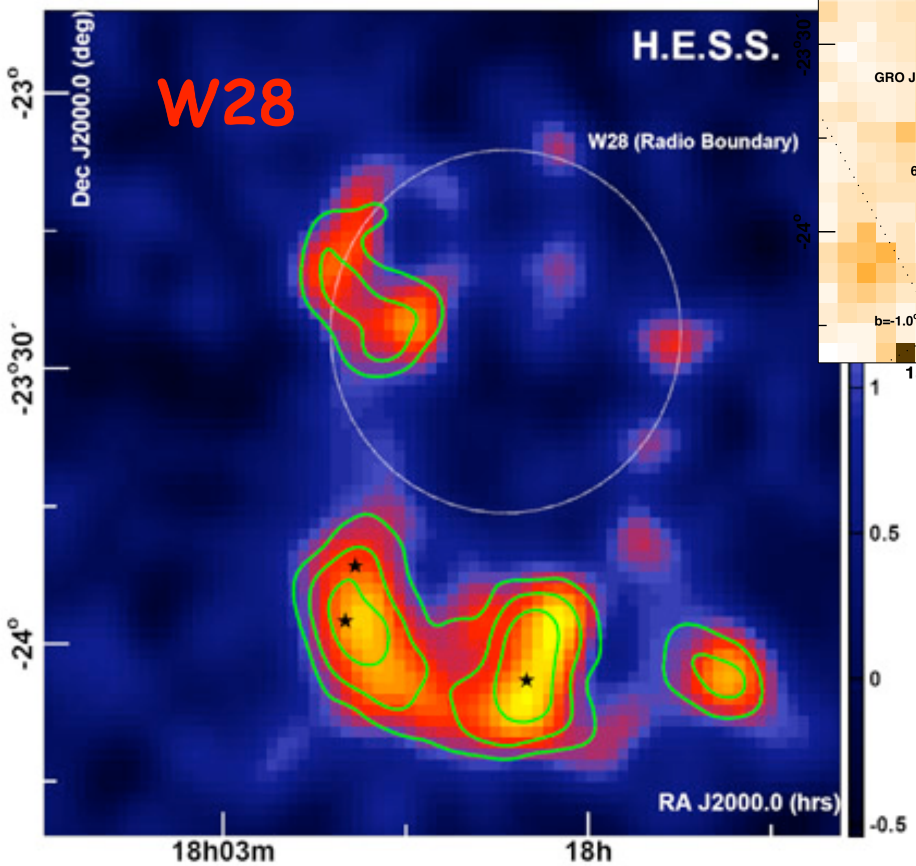
NANTEN data - CO line







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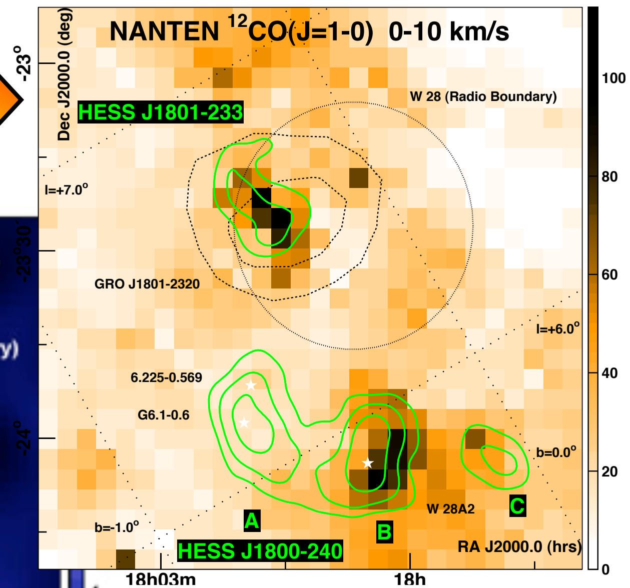
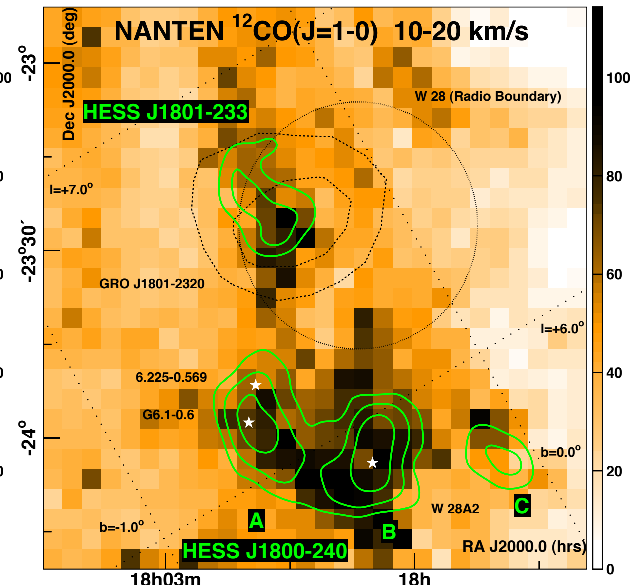
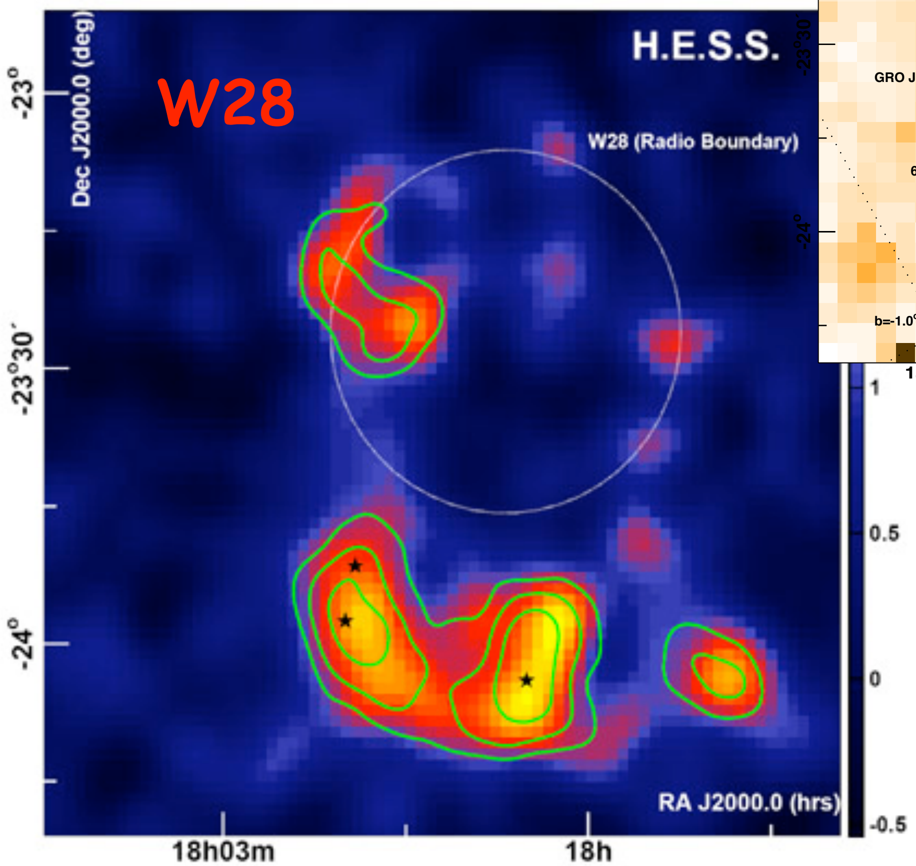
NANTEN data - CO line

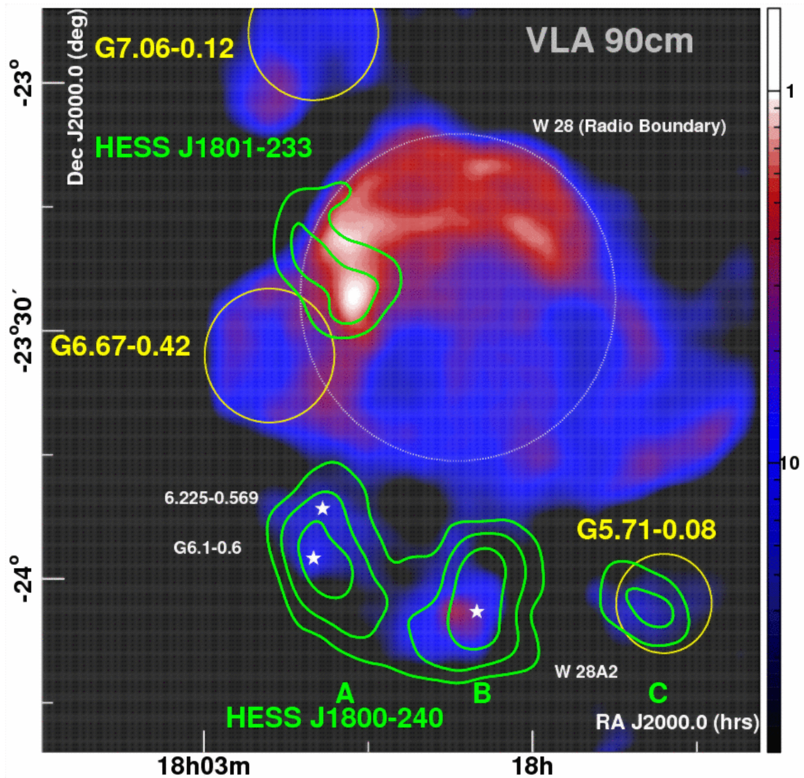






HESS - TeV emission

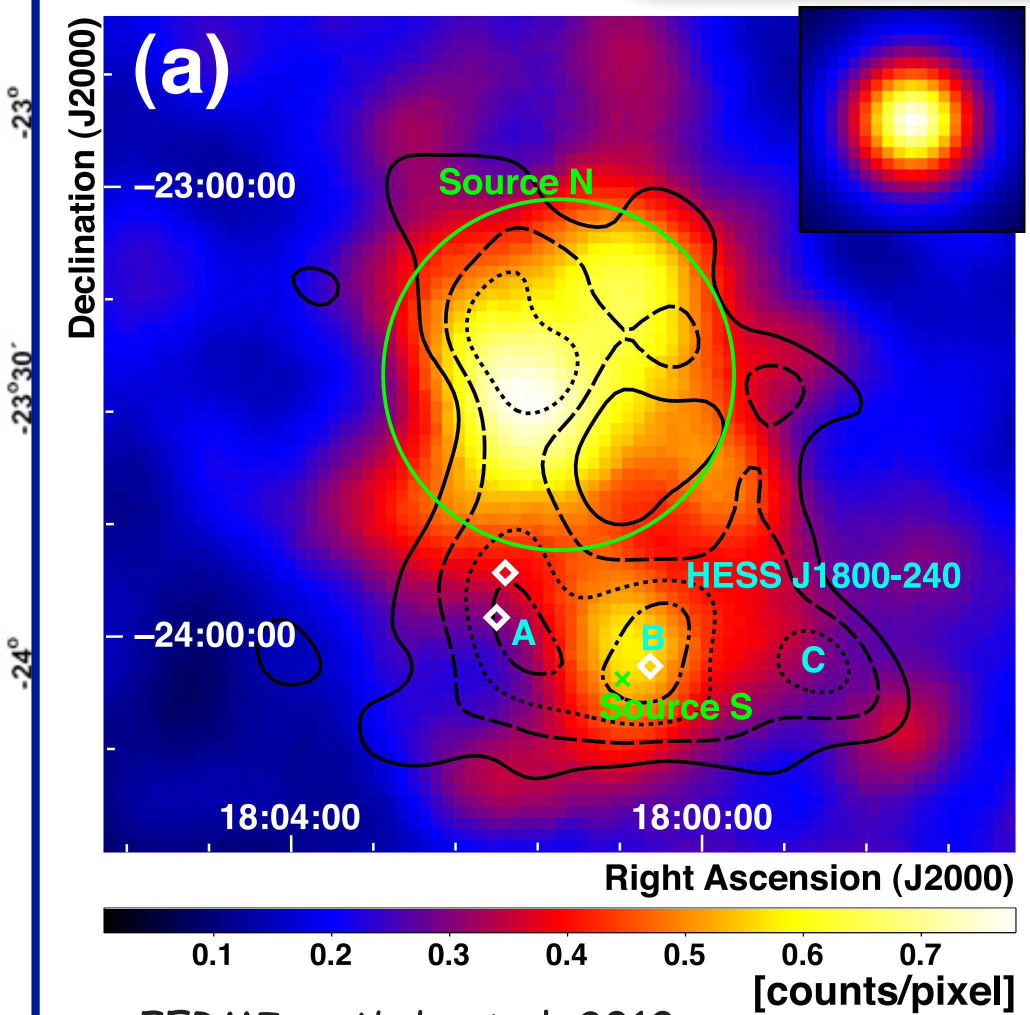
Aharonian et al, 2008



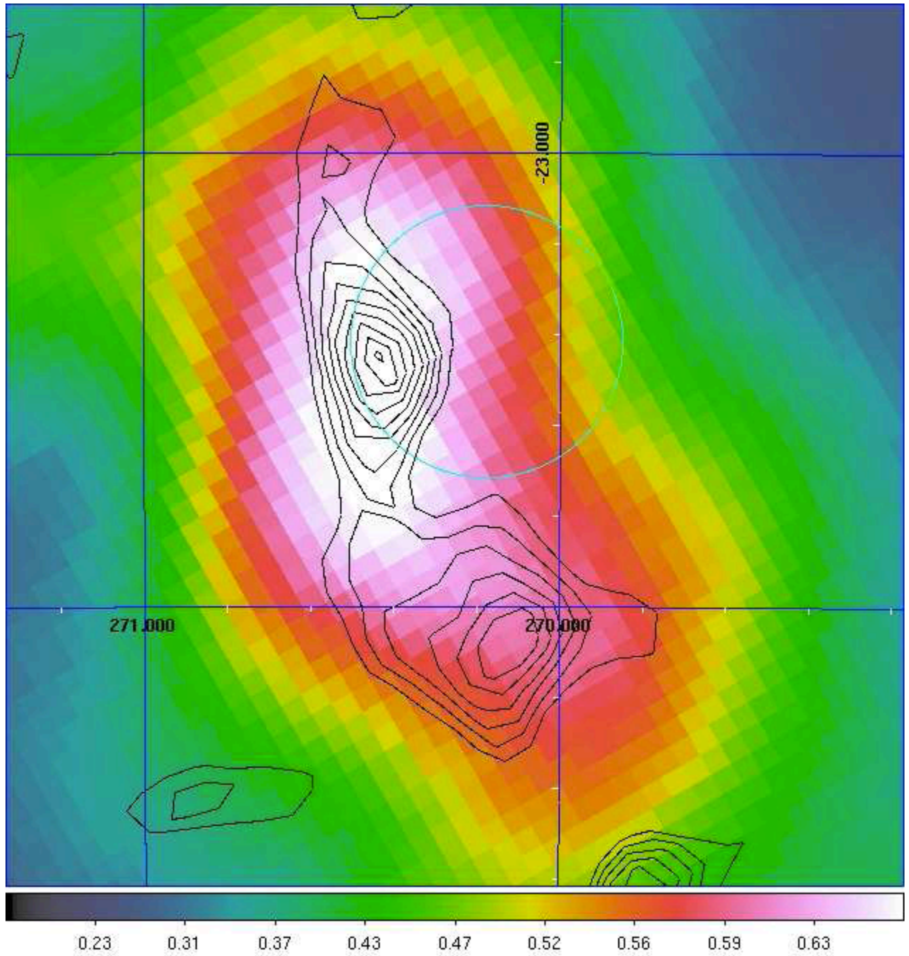
Radio (Dubner et al 2000)

The W28 region in gammas, CO, & radio

FERMI and AGILE - GeV emission

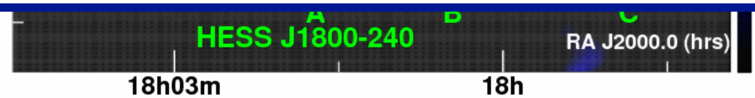


FERMI -> Abdo et al, 2010

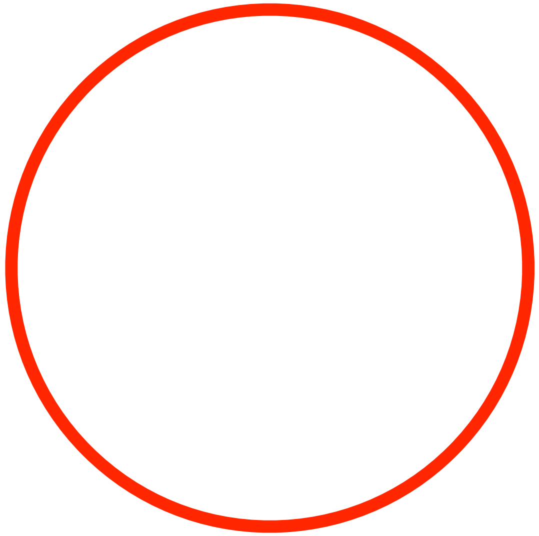


AGILE -> Giuliani et al, 2010

Aharonian et al, 2008



W28: a cartoon



SNR shell

radio emission

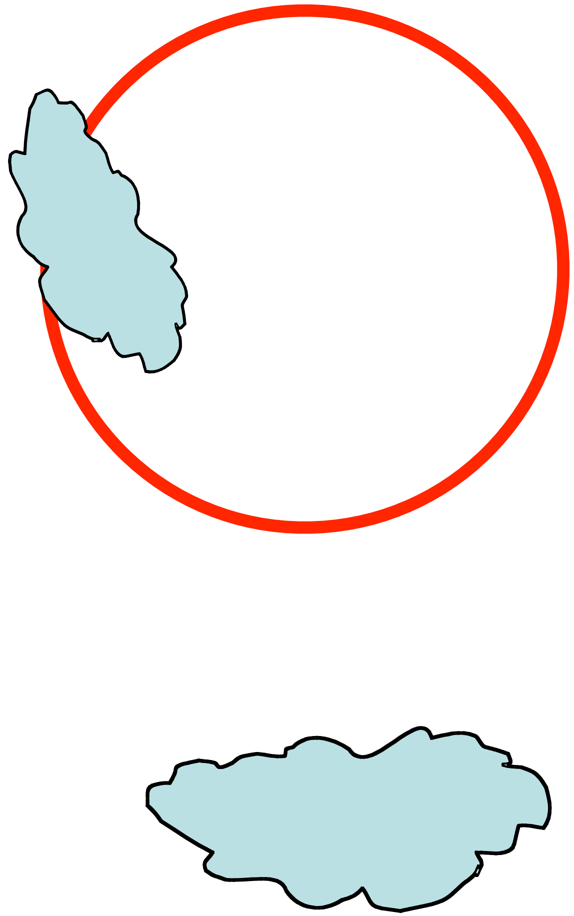
-> GeV electrons

-> ongoing (re)acceleration?

W28: a cartoon

SNR shell

Molecular clouds



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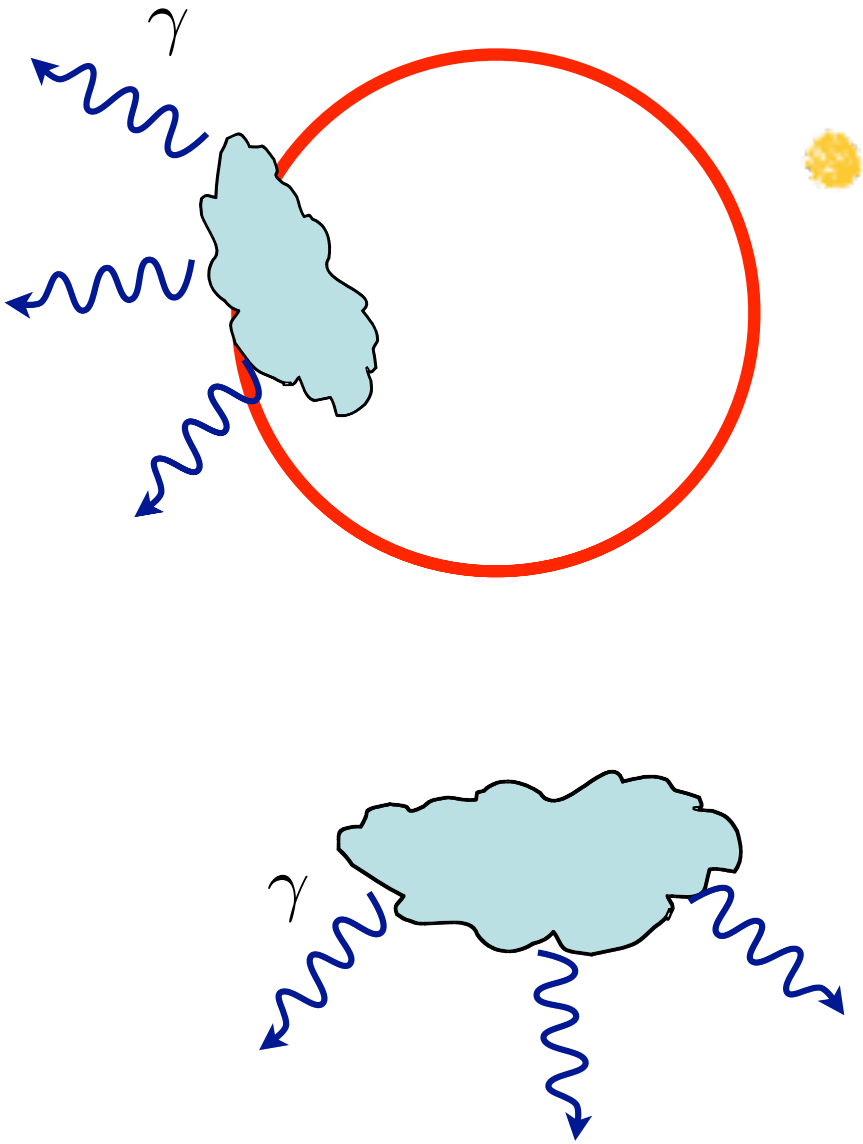

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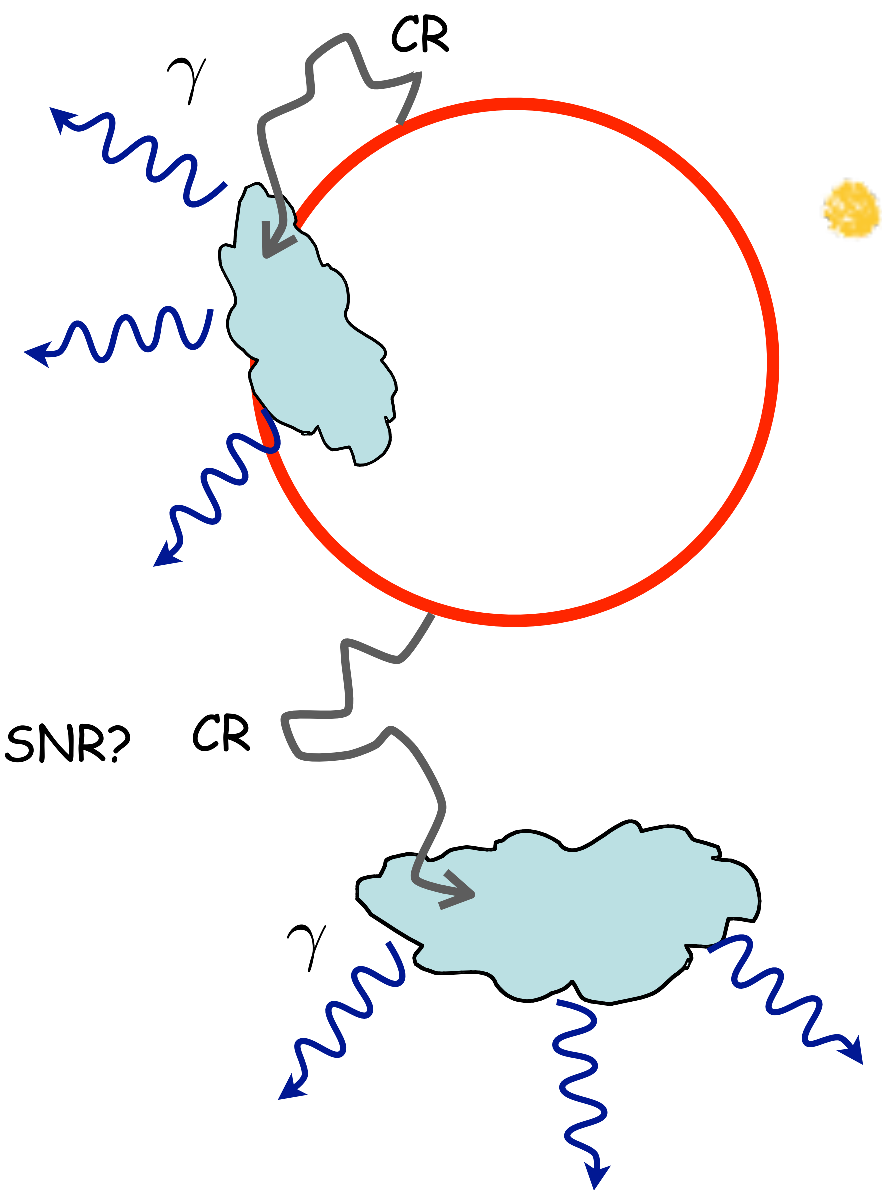

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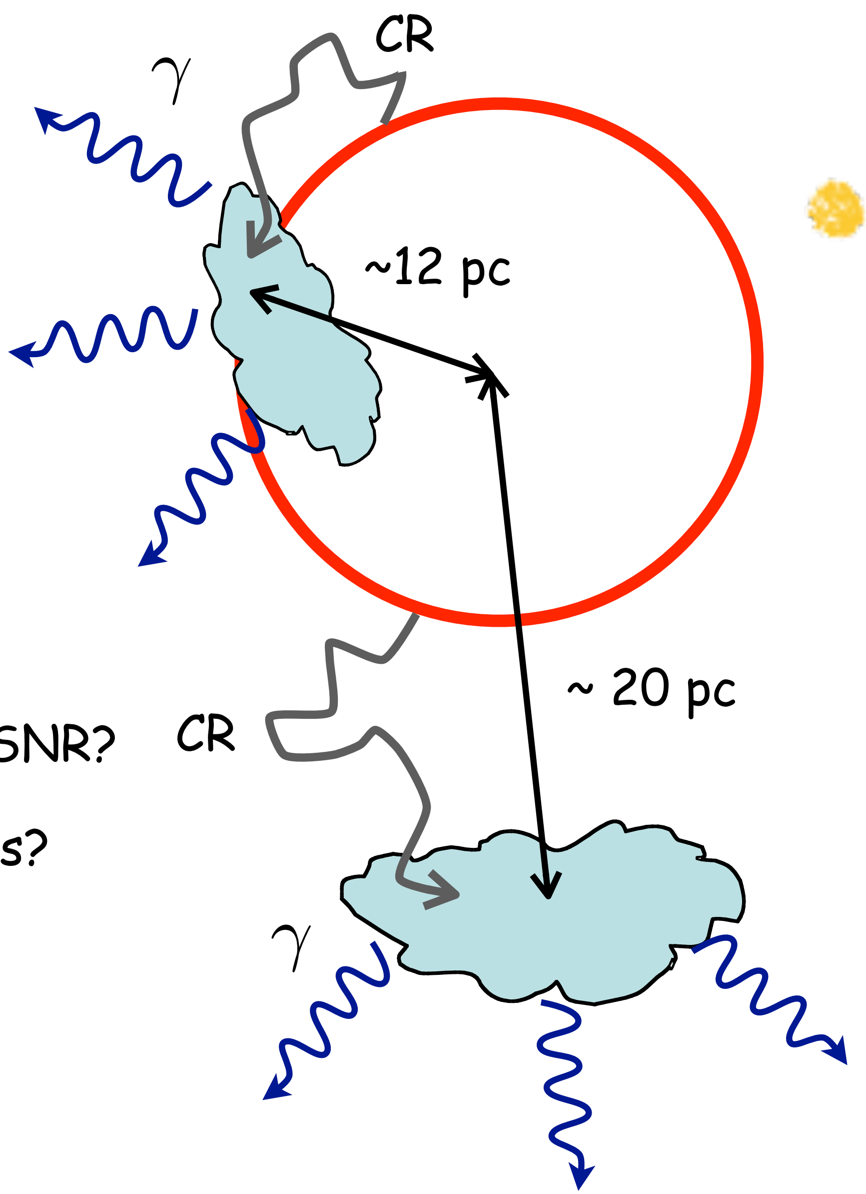

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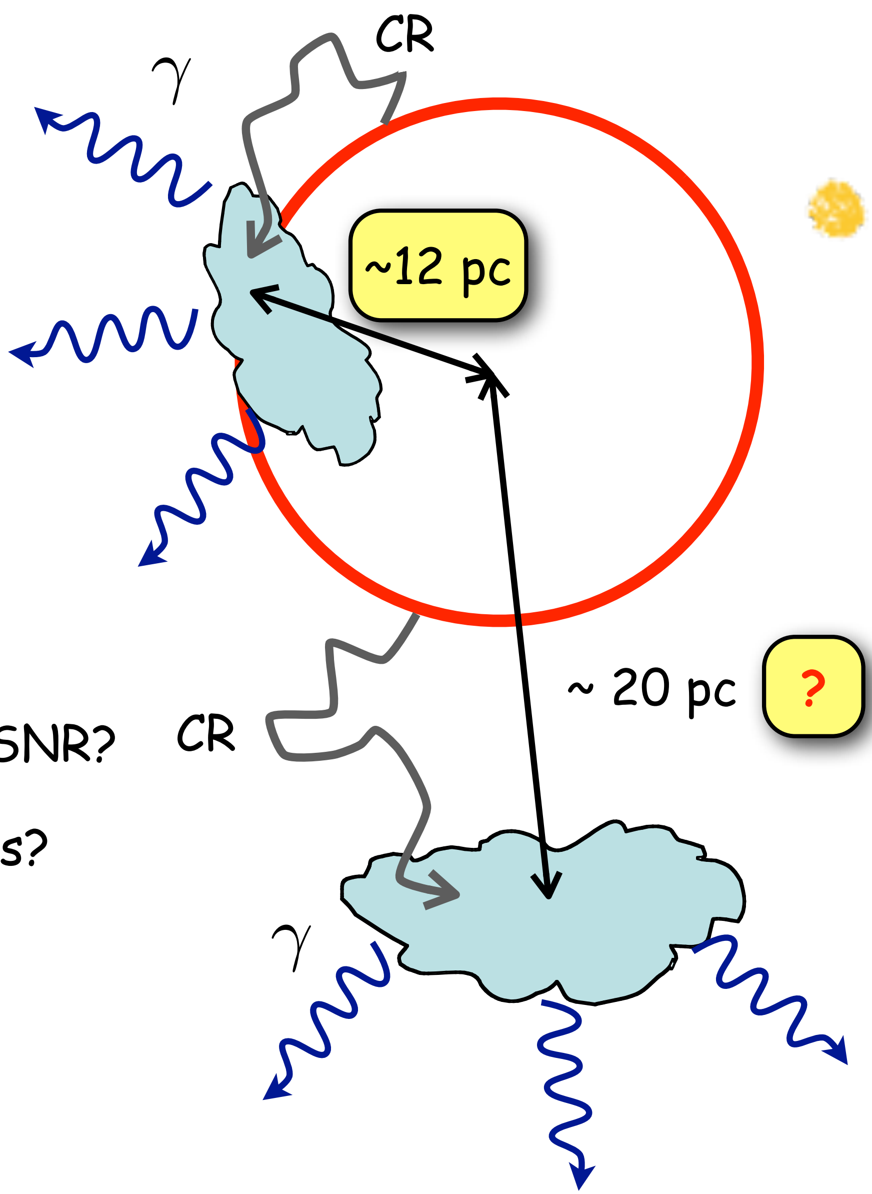
    - + masers



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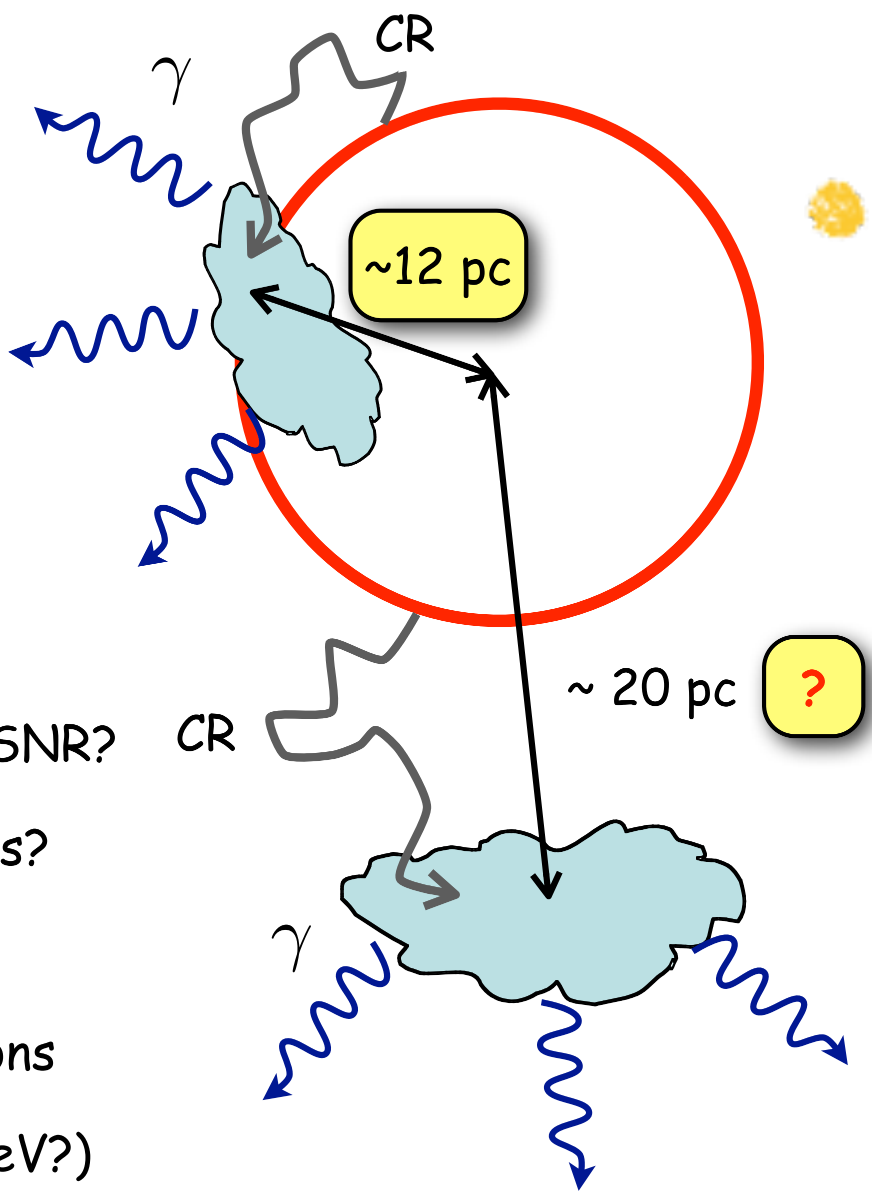

- radio emission
  - -> GeV electrons
  - -> ongoing (re)acceleration?

- gamma rays + gas
  - -> CR protons?
  - -> coming from the SNR?
  - -> projection effects?
    - + masers
  - -> most of the protons already escaped (> GeV?)

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

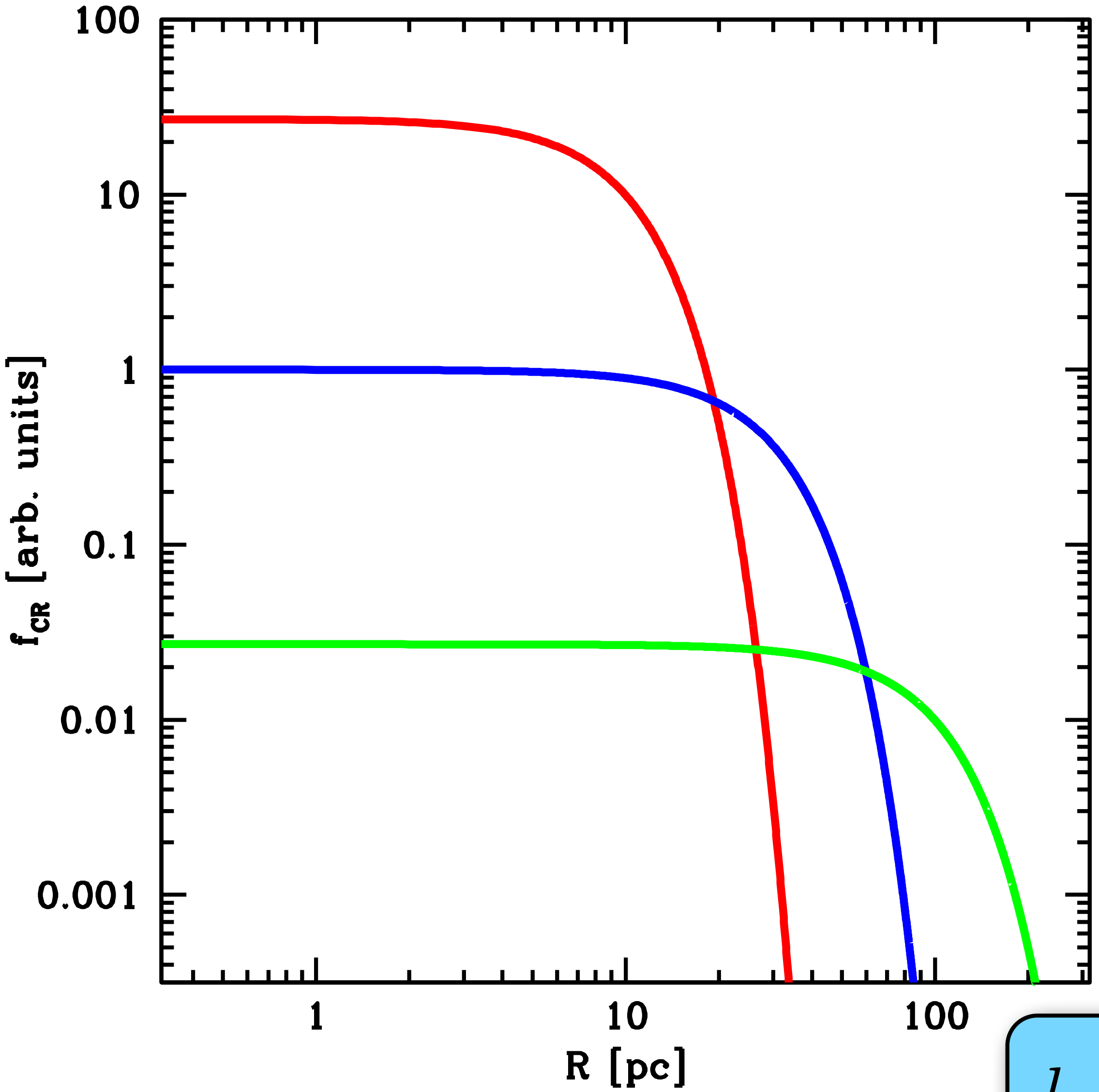
? model dependent...

high energy particles

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

Escaping particles: CR spectrum

t_{age} -> l_d = 10, 30, 100 pc



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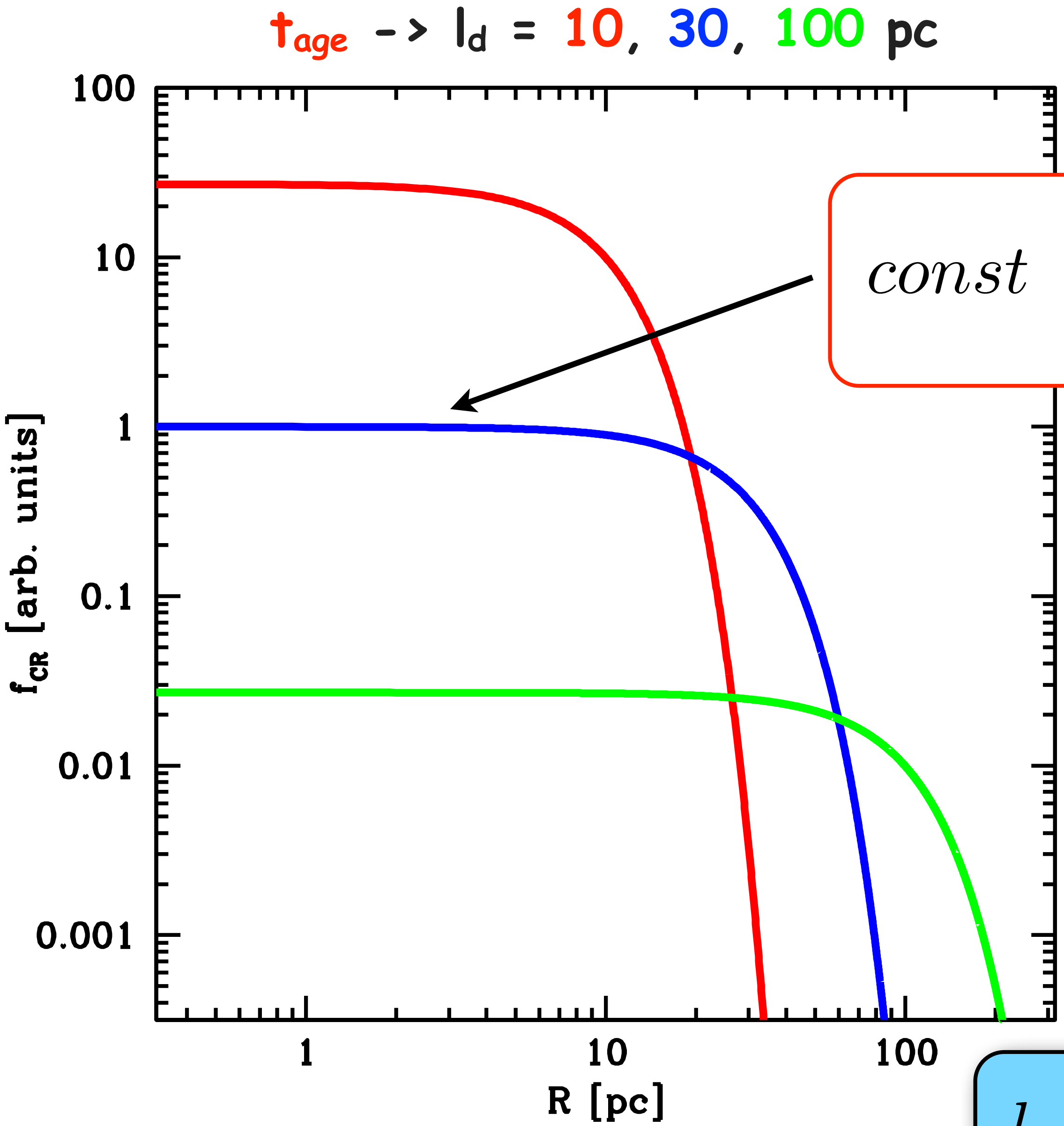

$$const \propto \frac{\eta_{CR}\, E_{SN}}{l_d^3}$$

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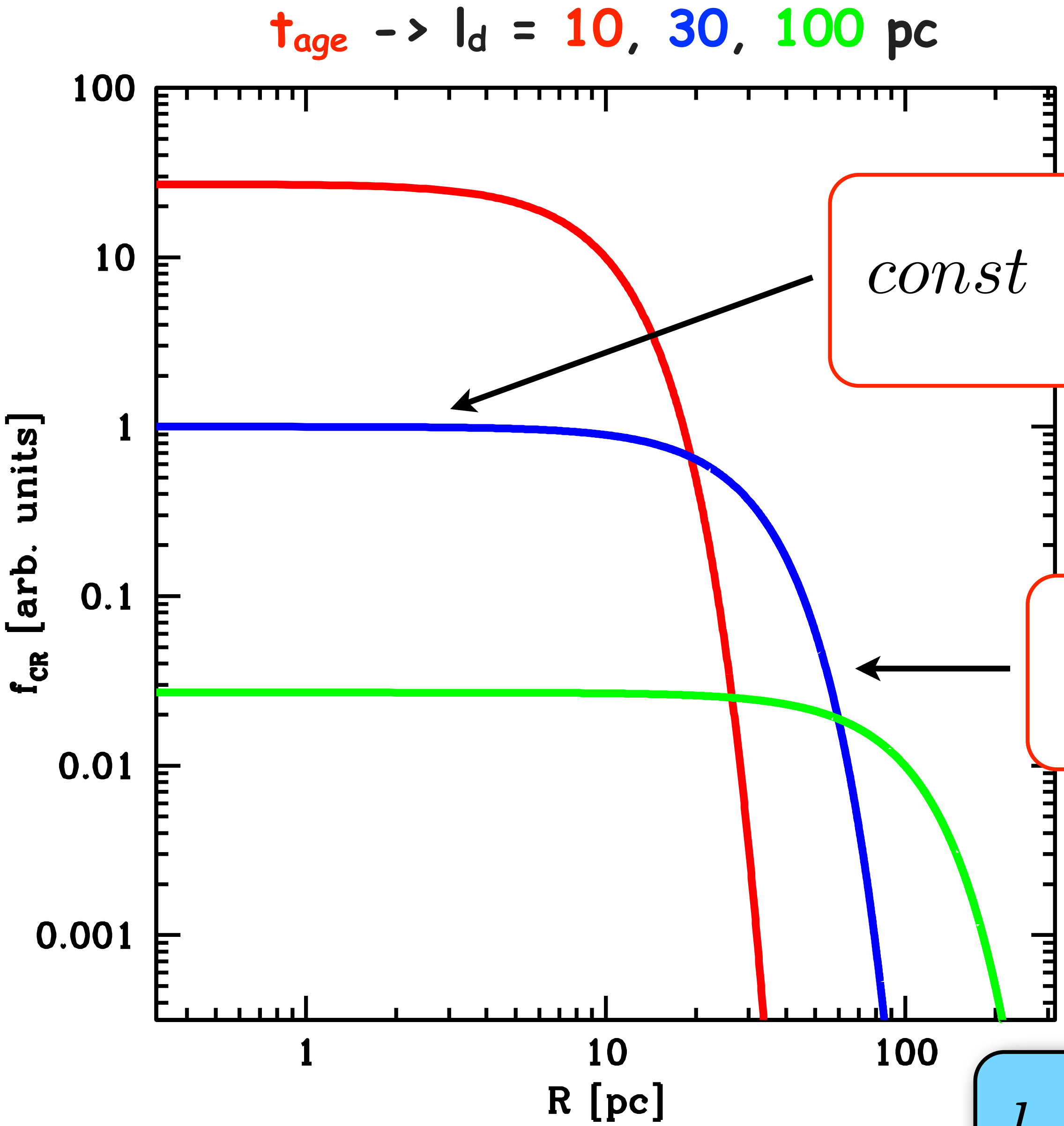
Escaping particles: CR spectrum



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

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

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

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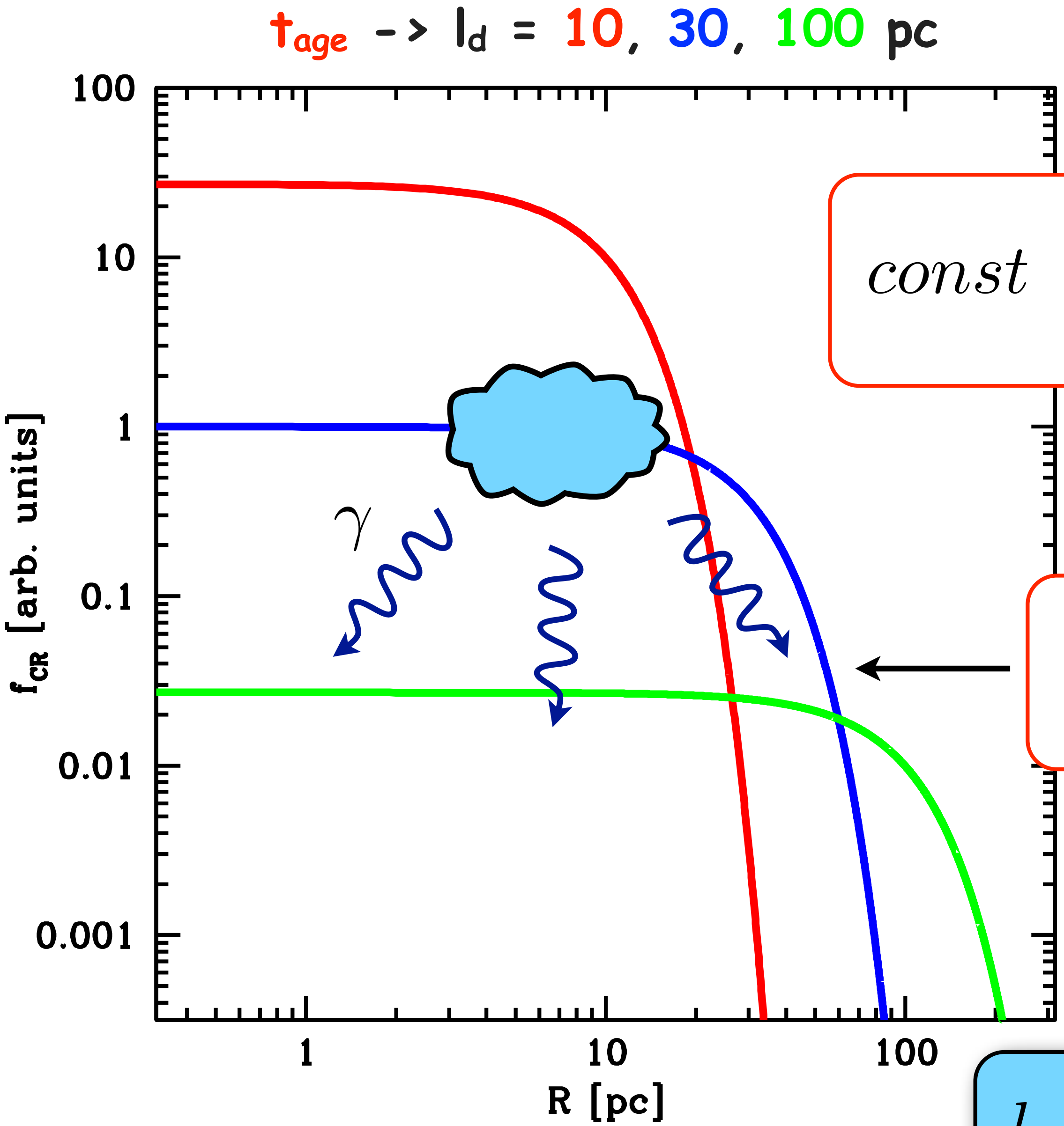

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Escaping particles: CR spectrum

if we want SNRs to be the sources of CRs...

$$0.1 \lesssim \eta_{CR} \lesssim 1$$

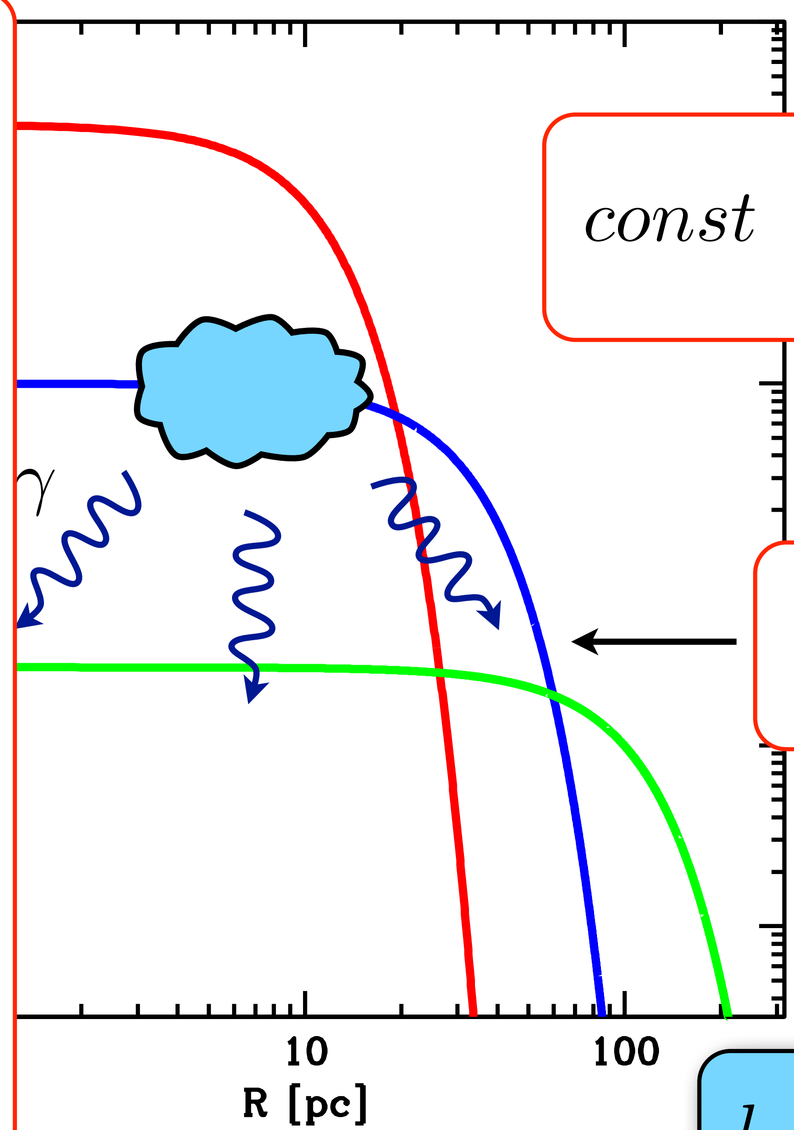
$$t_{age} \approx 3 \times 10^4 \div 10^5 \text{yr}$$

$$E_{SN} \gtrsim 2 \div 4 \times 10^{50} \text{erg}$$

$$M_{cl}^N \approx 5 \times 10^4 M_\odot$$

estimate D?

t_{age} -> l_d = 10, 30, 100 pc

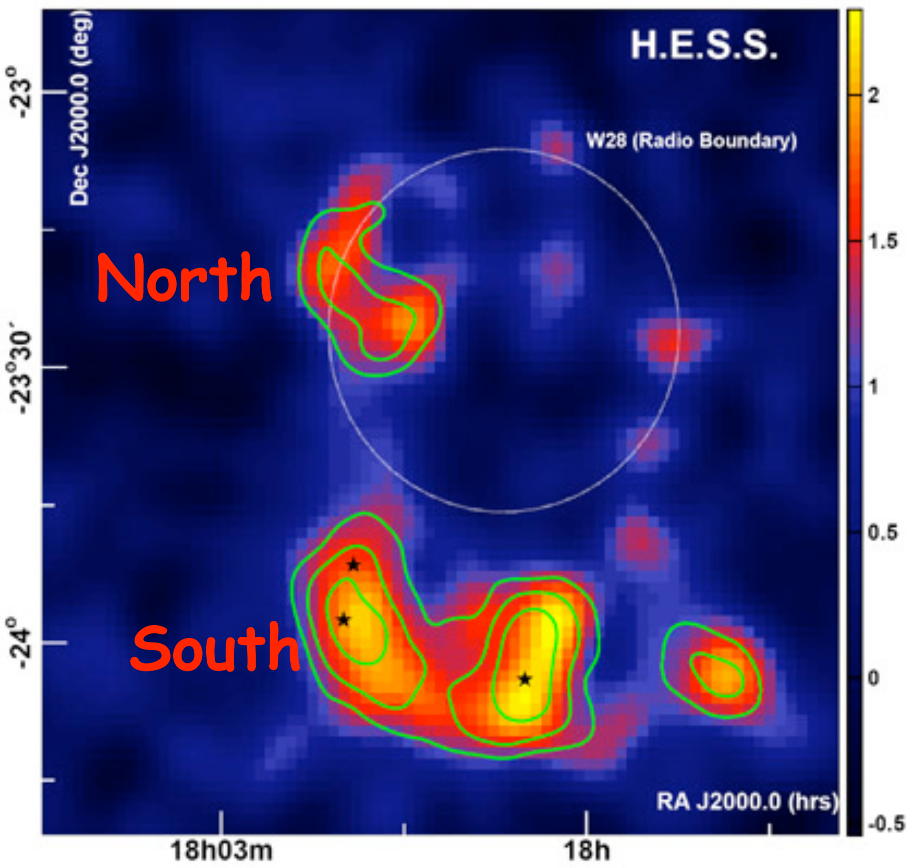


$$const \propto \frac{\eta_{CR} E_{SN}}{l_d^3}$$

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

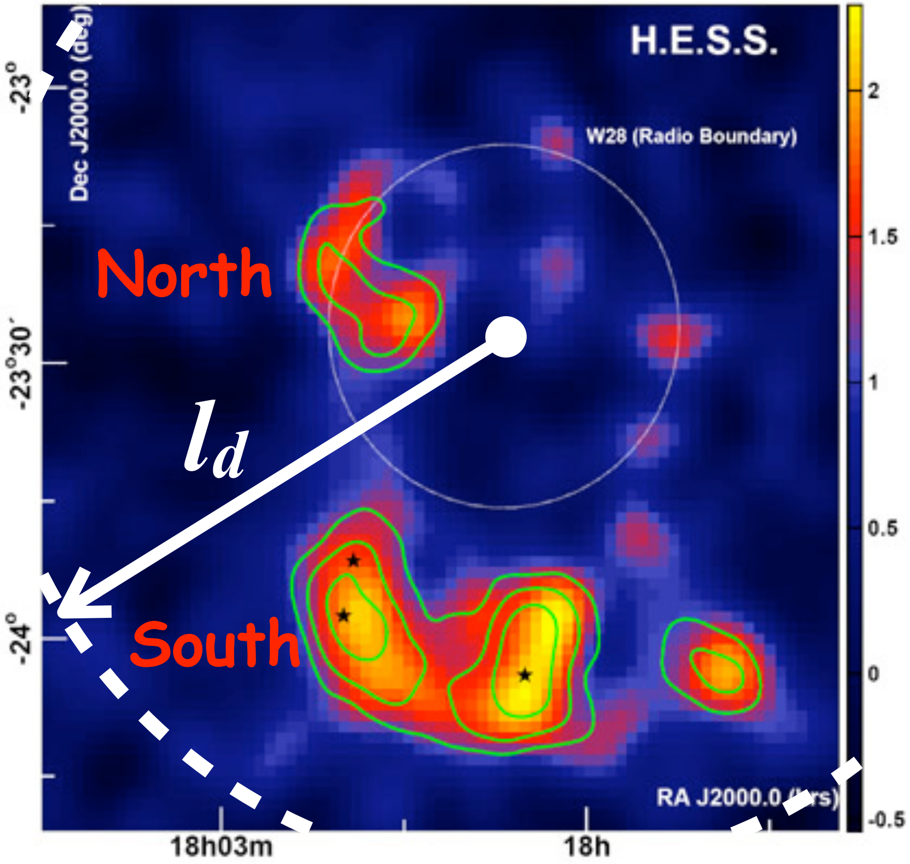
$$l_d \approx (D\ t_{age})^{1/2}$$

Escaping particles: W28



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

Escaping particles: W28



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both clouds within a distance l_d

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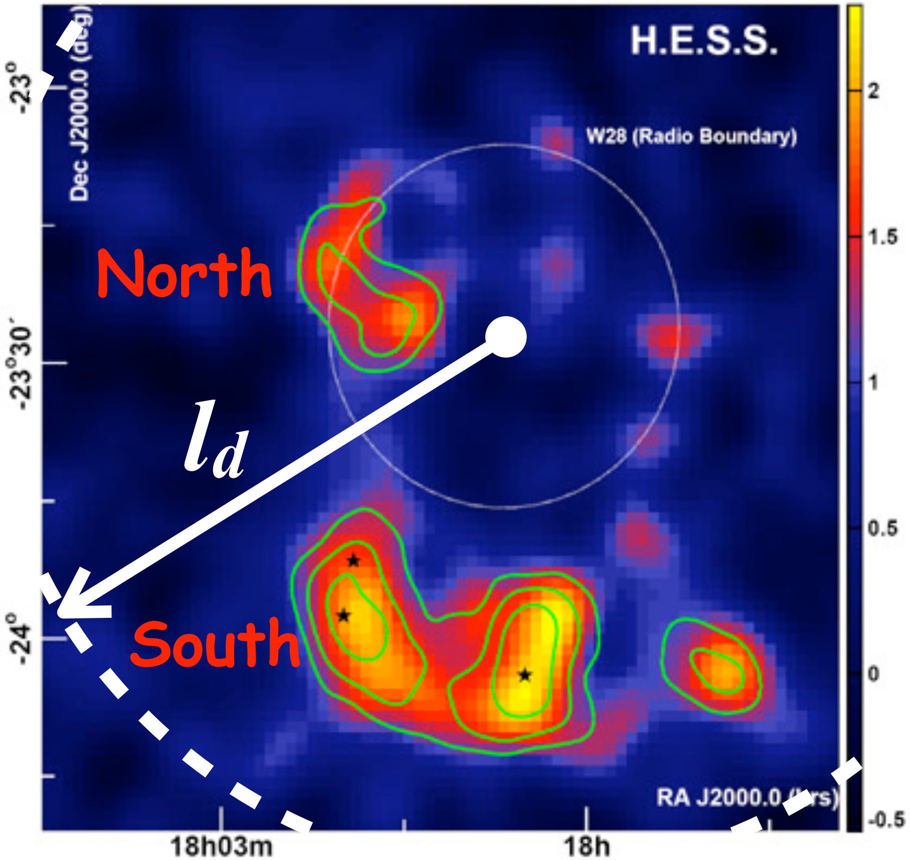

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$$F_\gamma \propto \frac{f_{CR}\, M_{cl}}{d^2}$$

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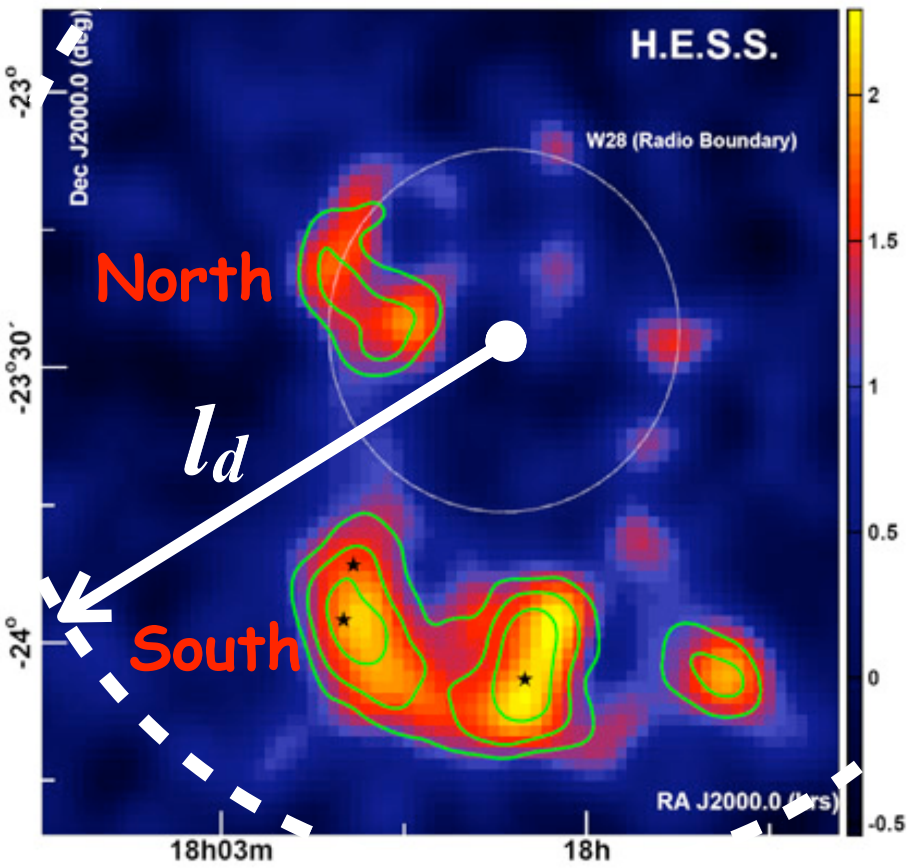
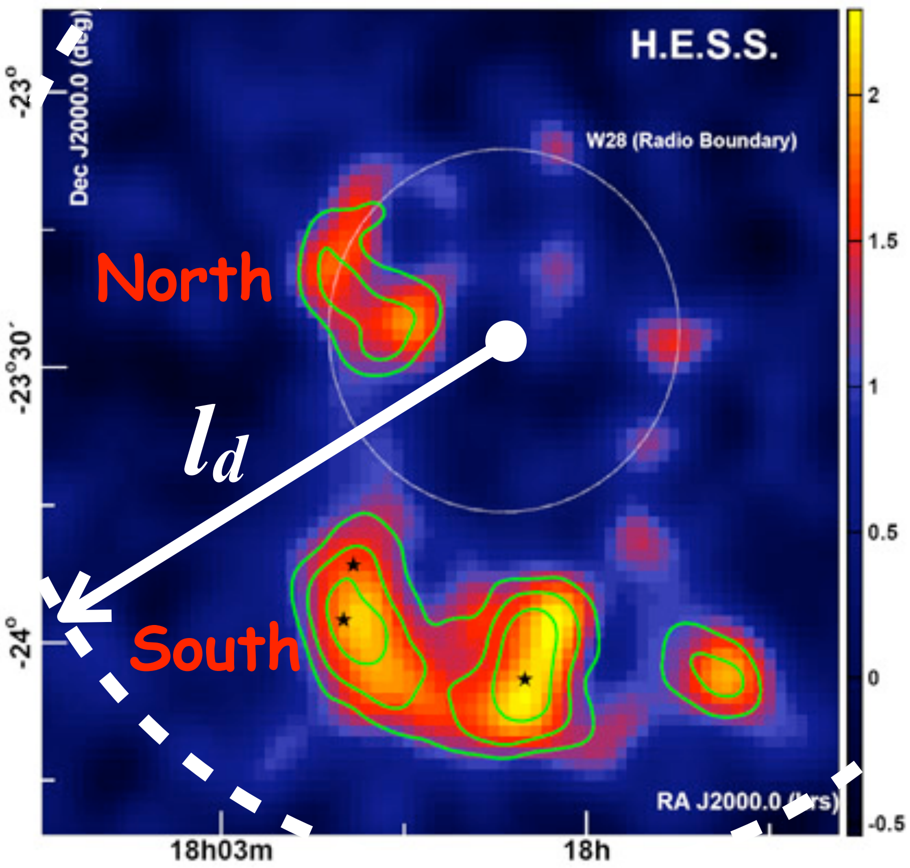


$$\left(\frac{F_\gamma}{M_{cl}}\right)_{North} \approx \left(\frac{F_\gamma}{M_{cl}}\right)_{South}$$

both clouds within a distance l_d

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

Escaping particles: W28



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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

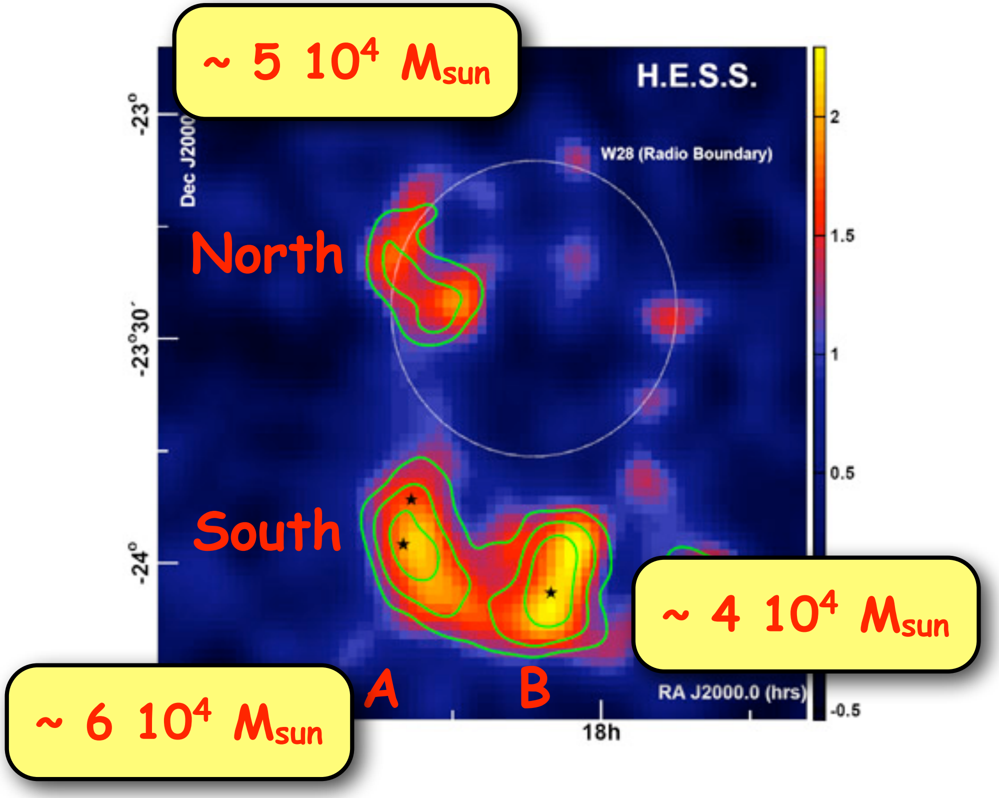
Assumptions:

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

W28: TeV emission

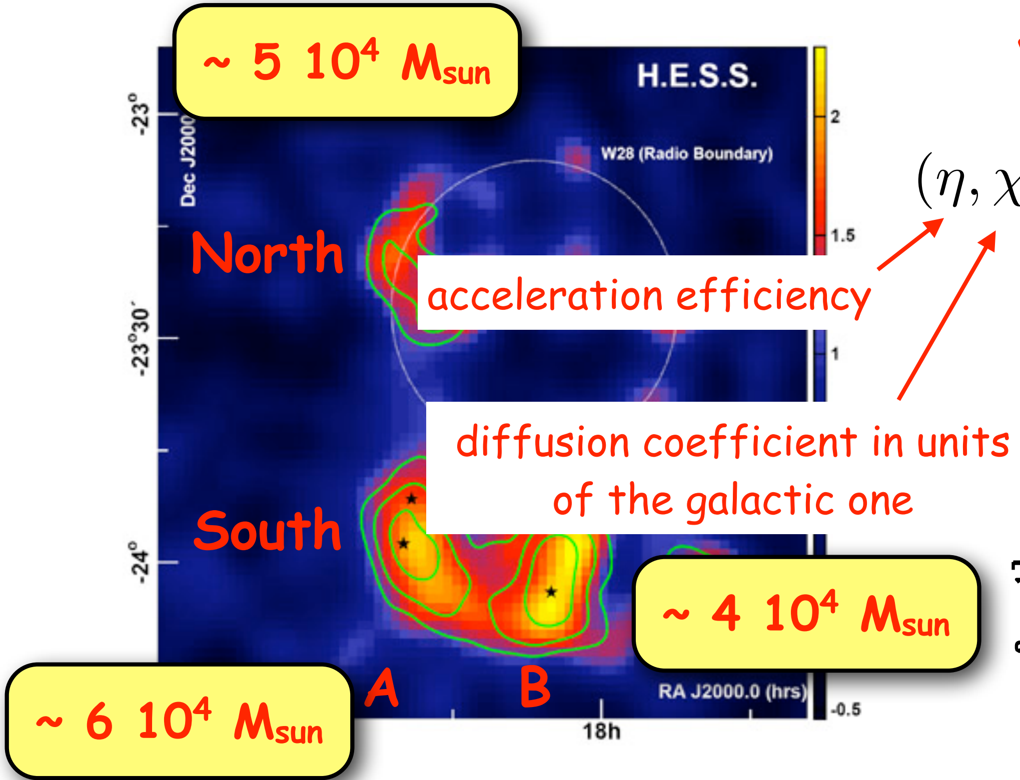


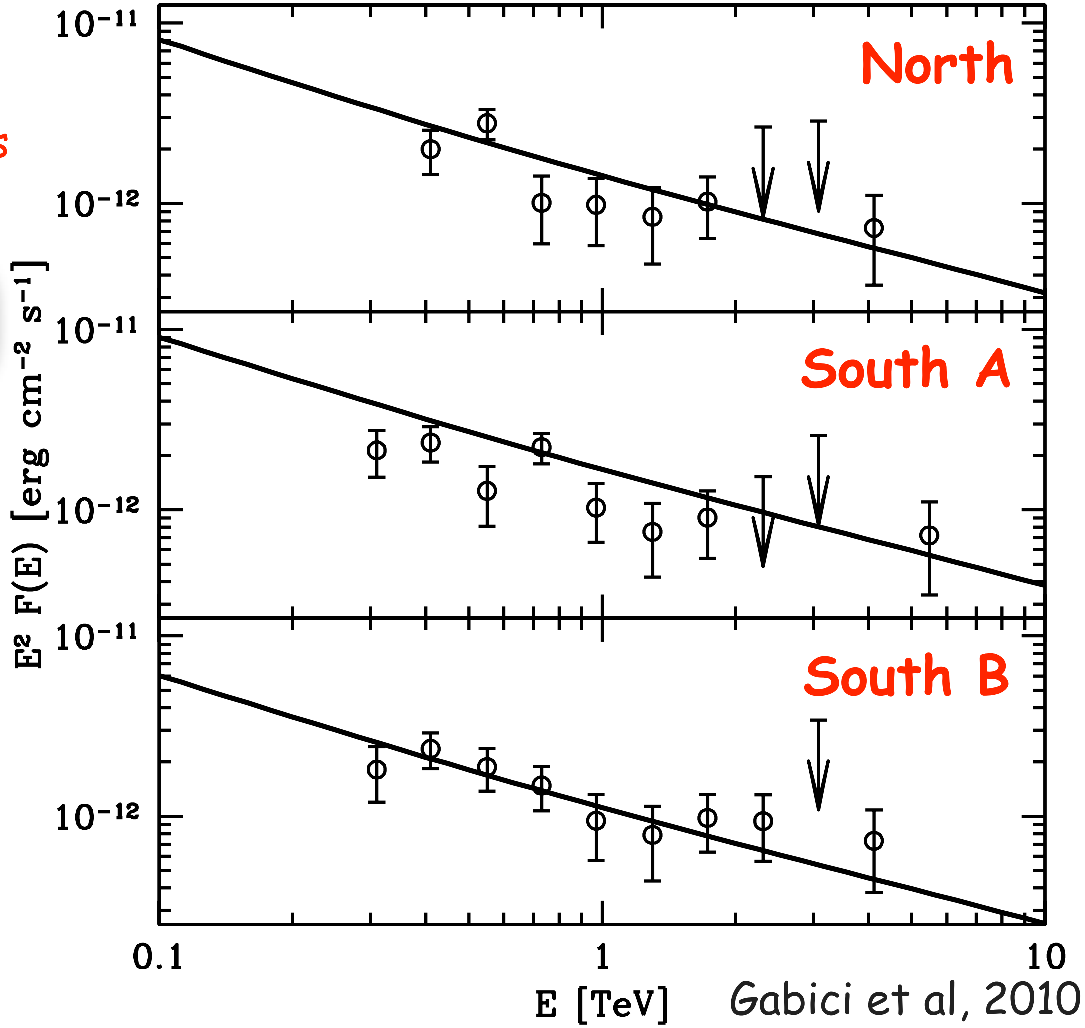
Gabici et al, 2010

W28: TeV emission

virtually the same curves for:

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





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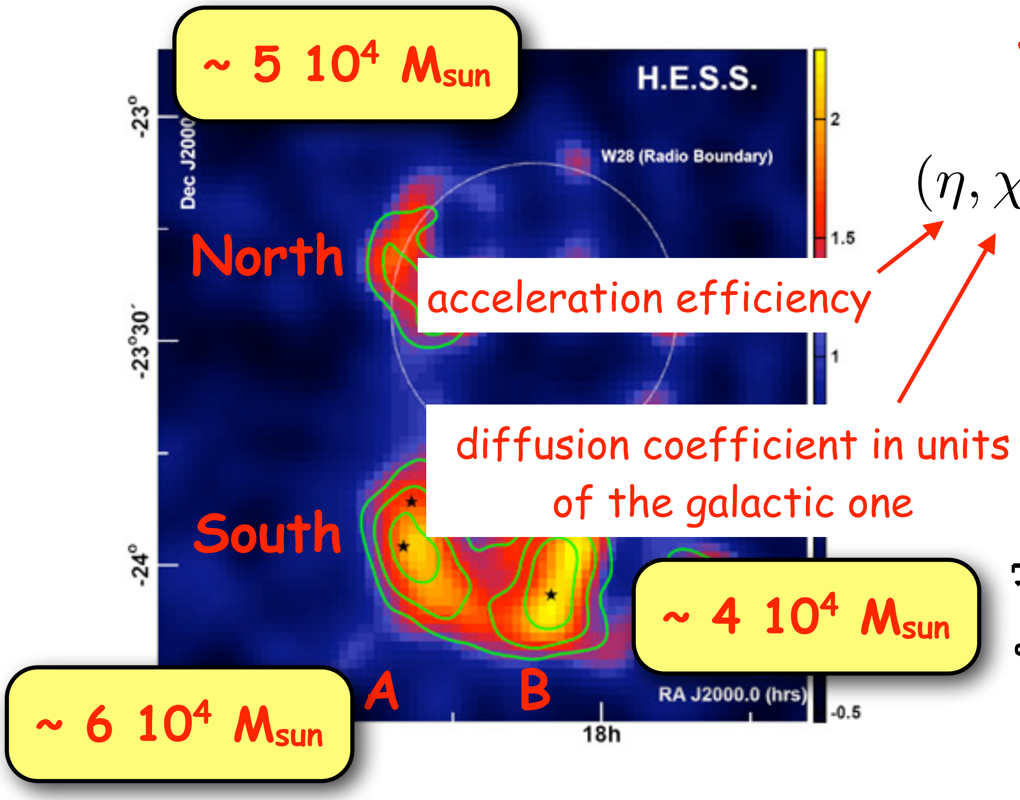

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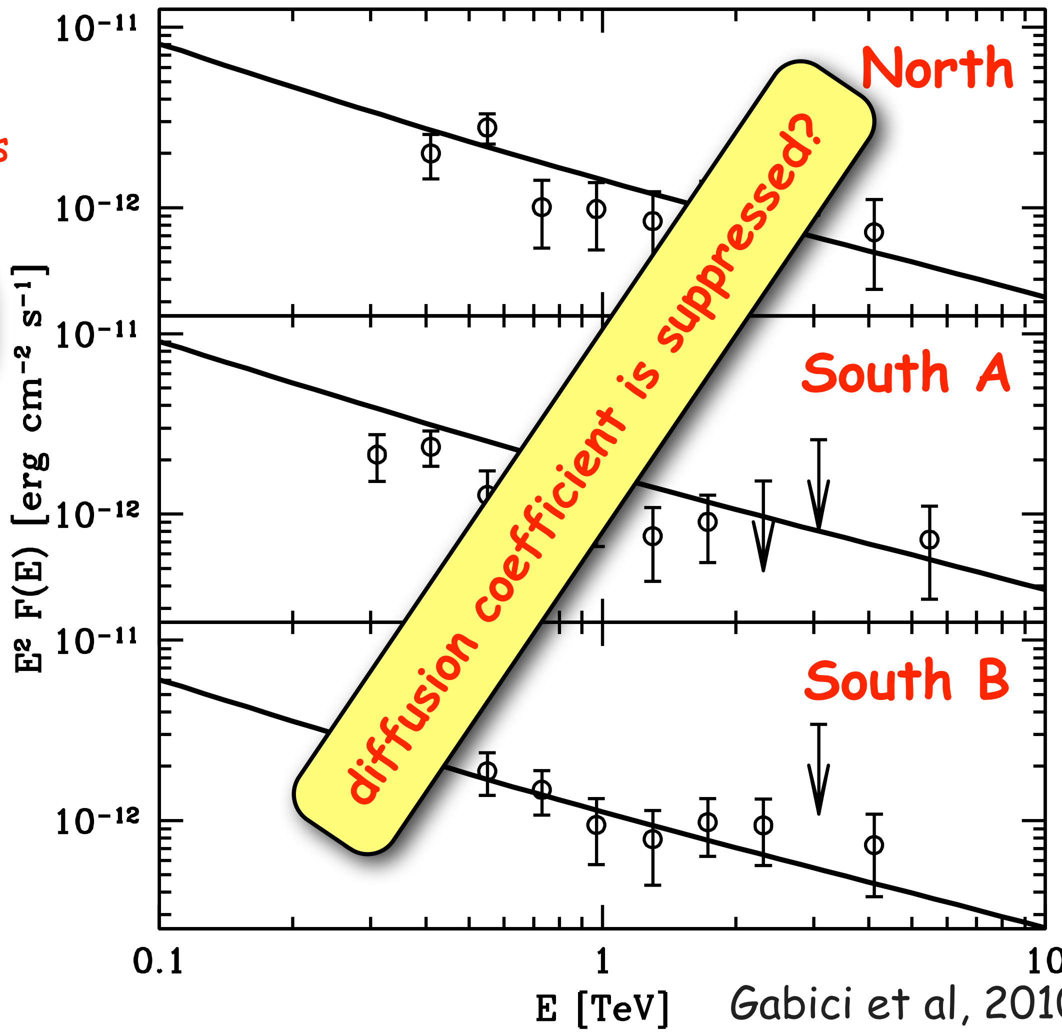

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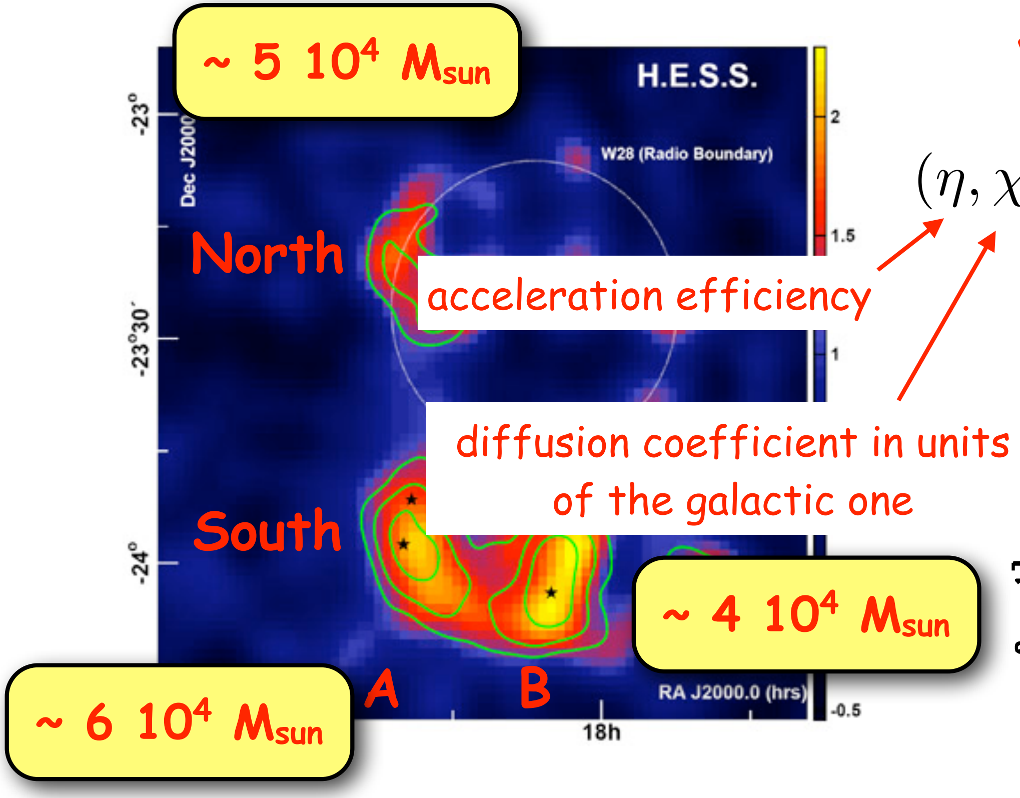

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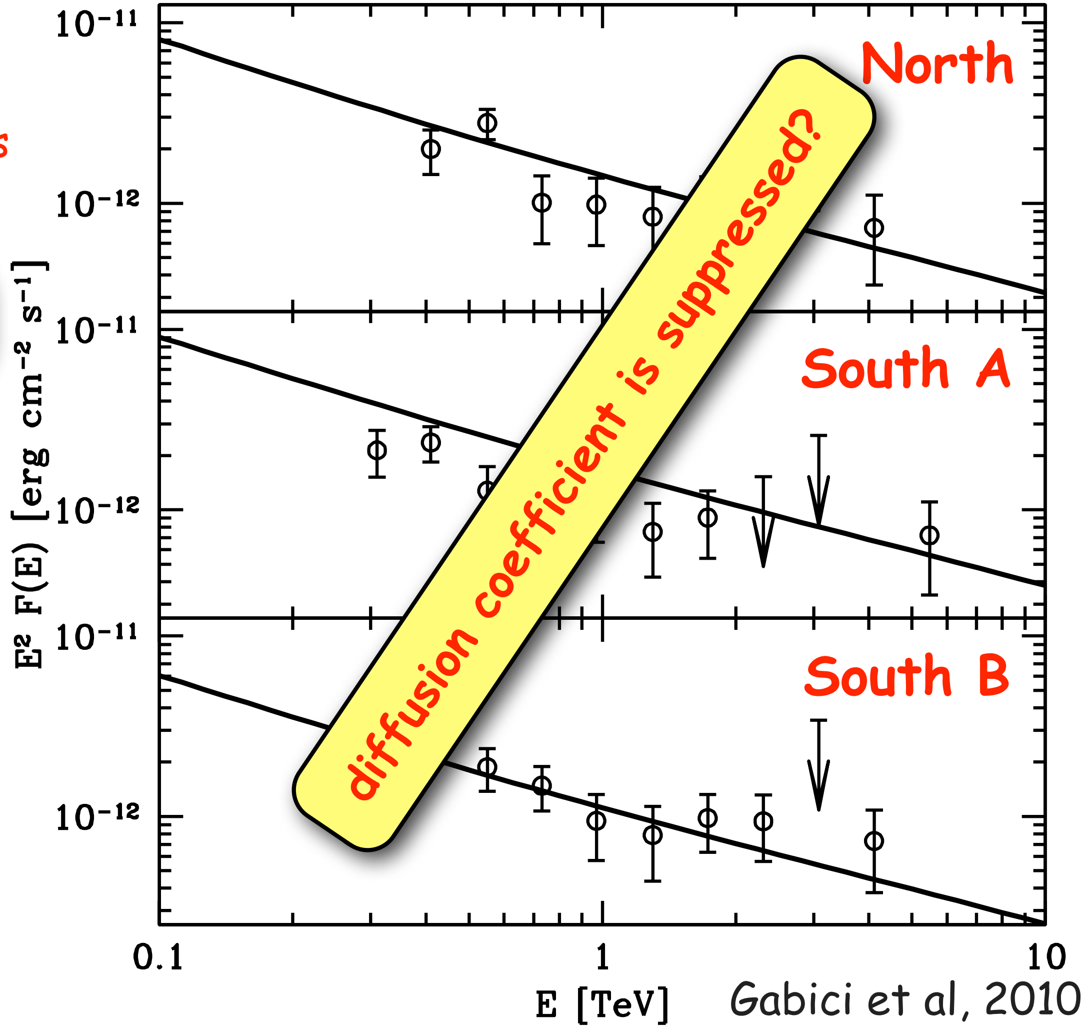
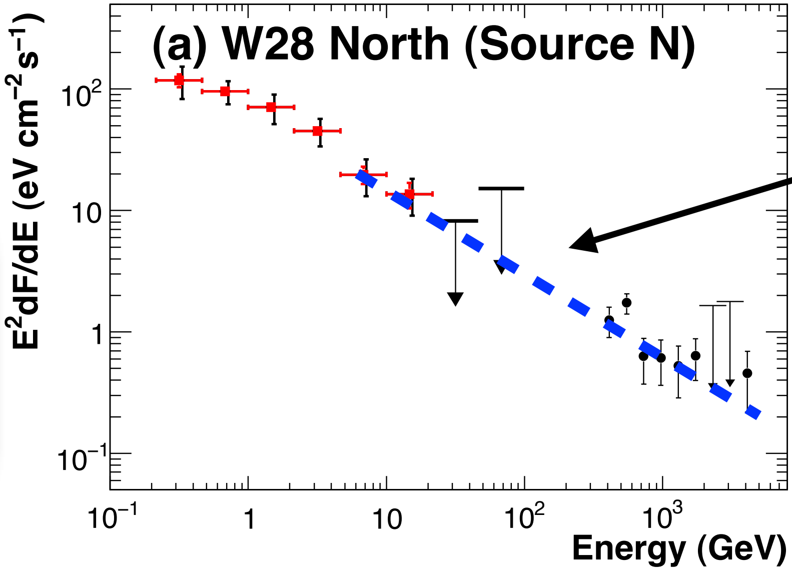


Gabici et al, 2010

size of "CR bubble" @3 TeV

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

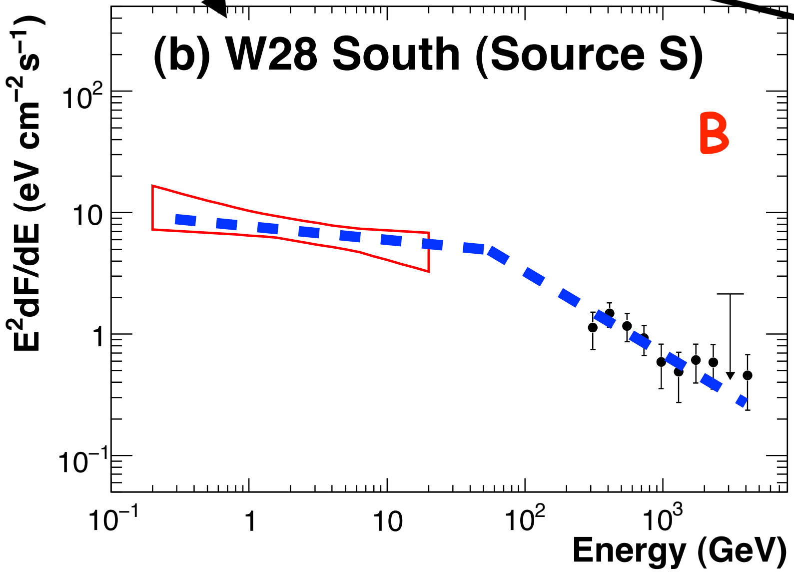
W28: GeV emission

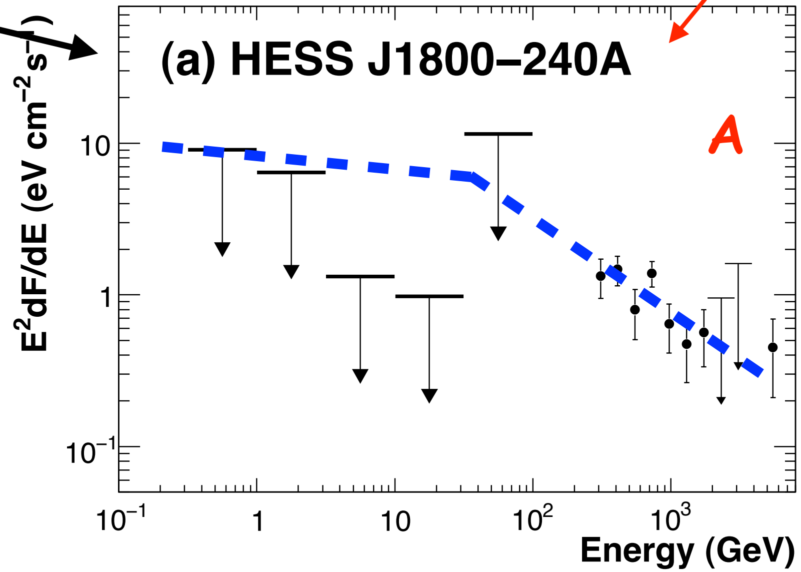


if the cloud is within the "CR bubble" [d < $l_d(E)$]

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

cloud A might not be physically associated with the W28 system





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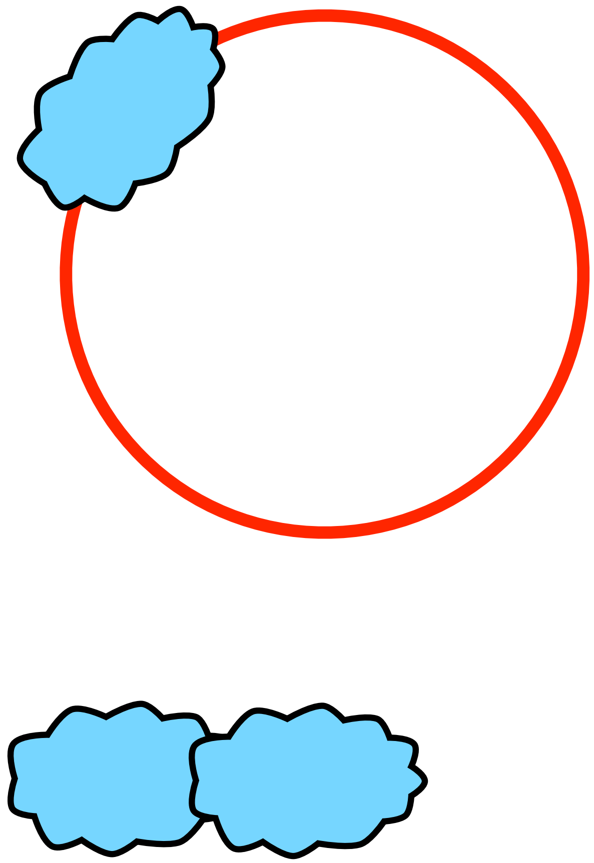

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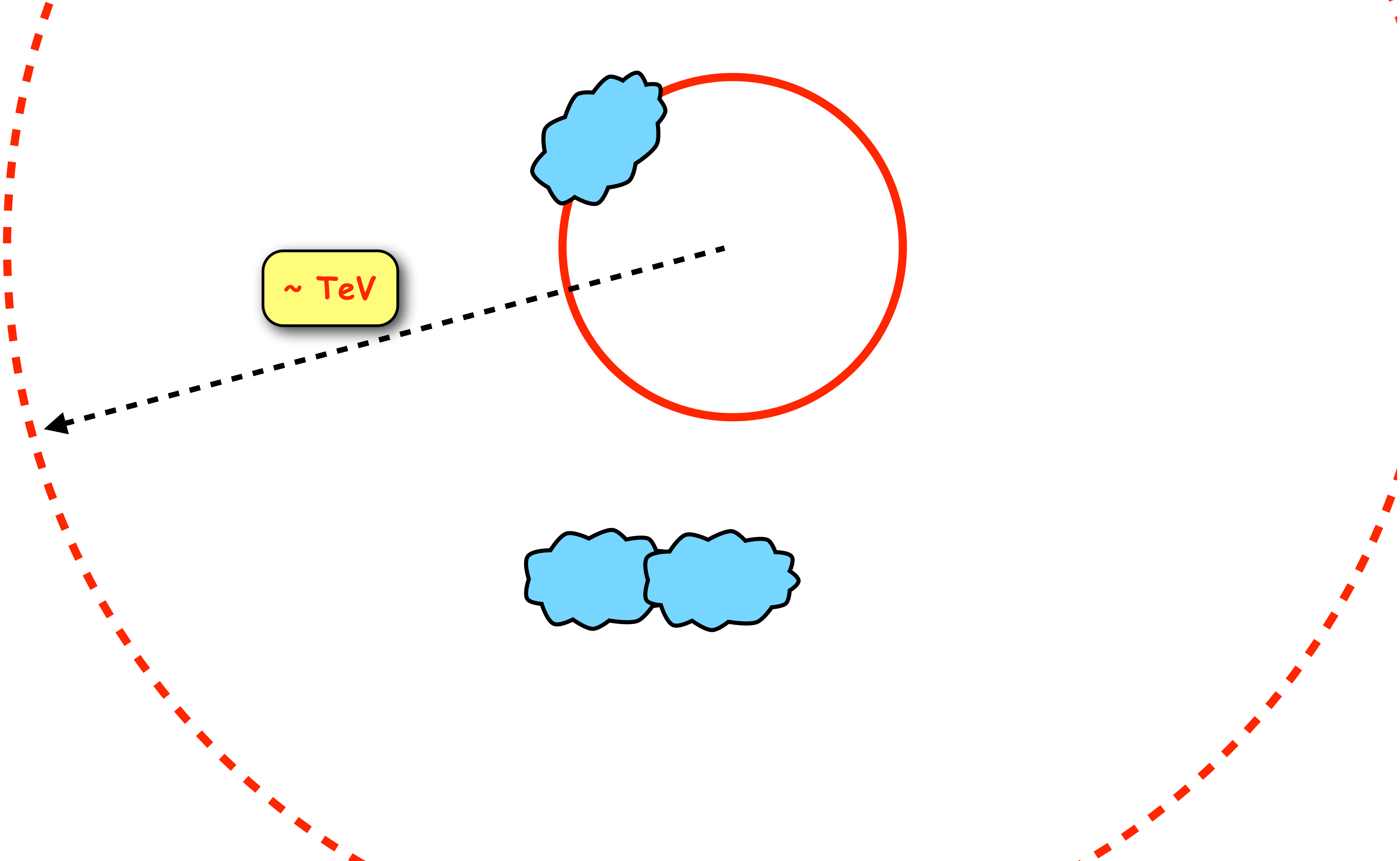

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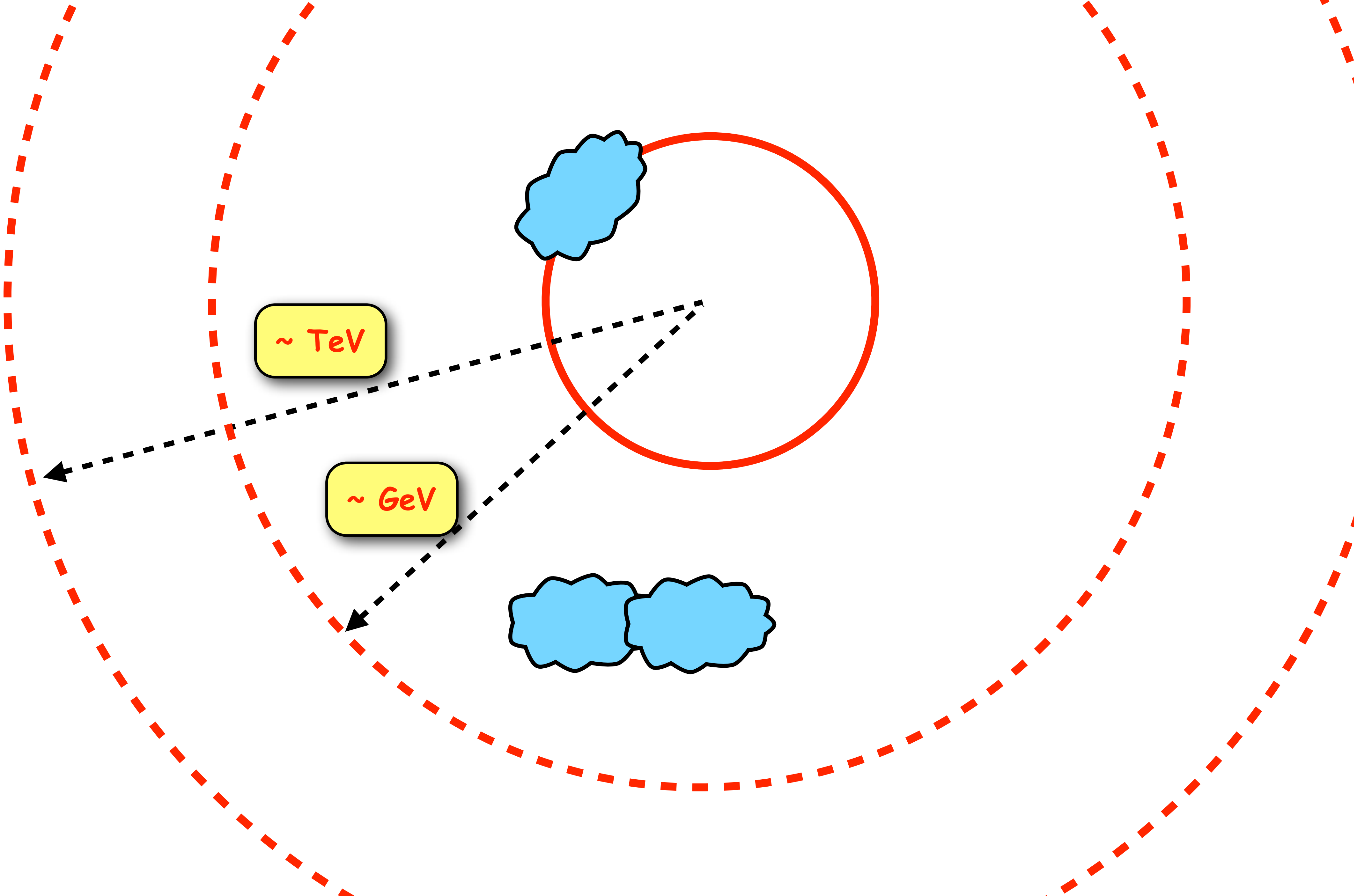

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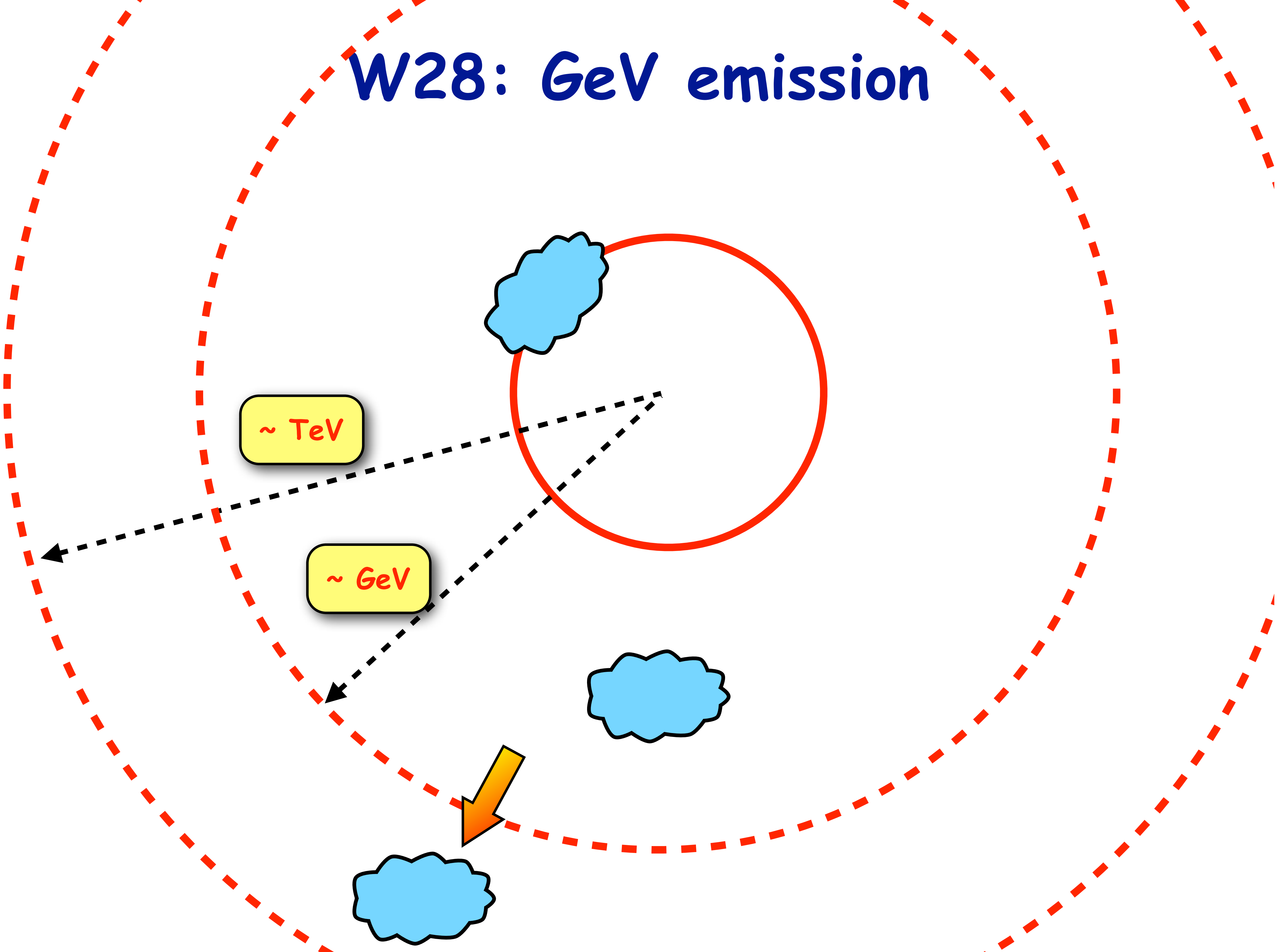
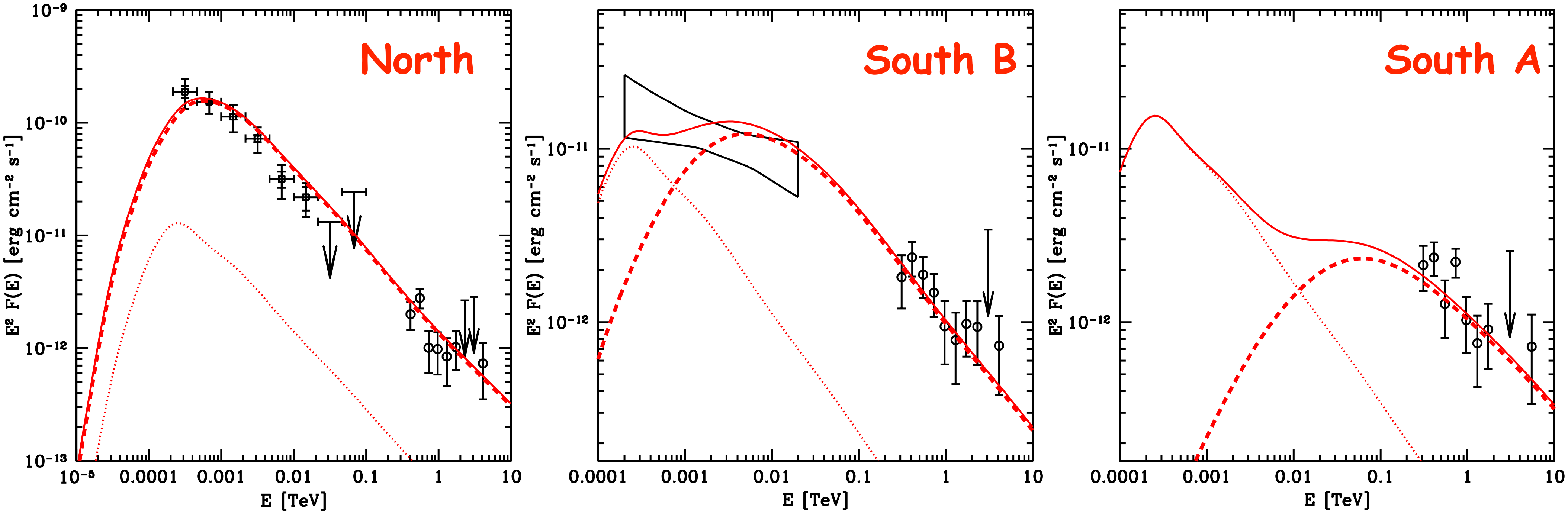


W28: GeV emission

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



d = 12 pc

d = 32 pc

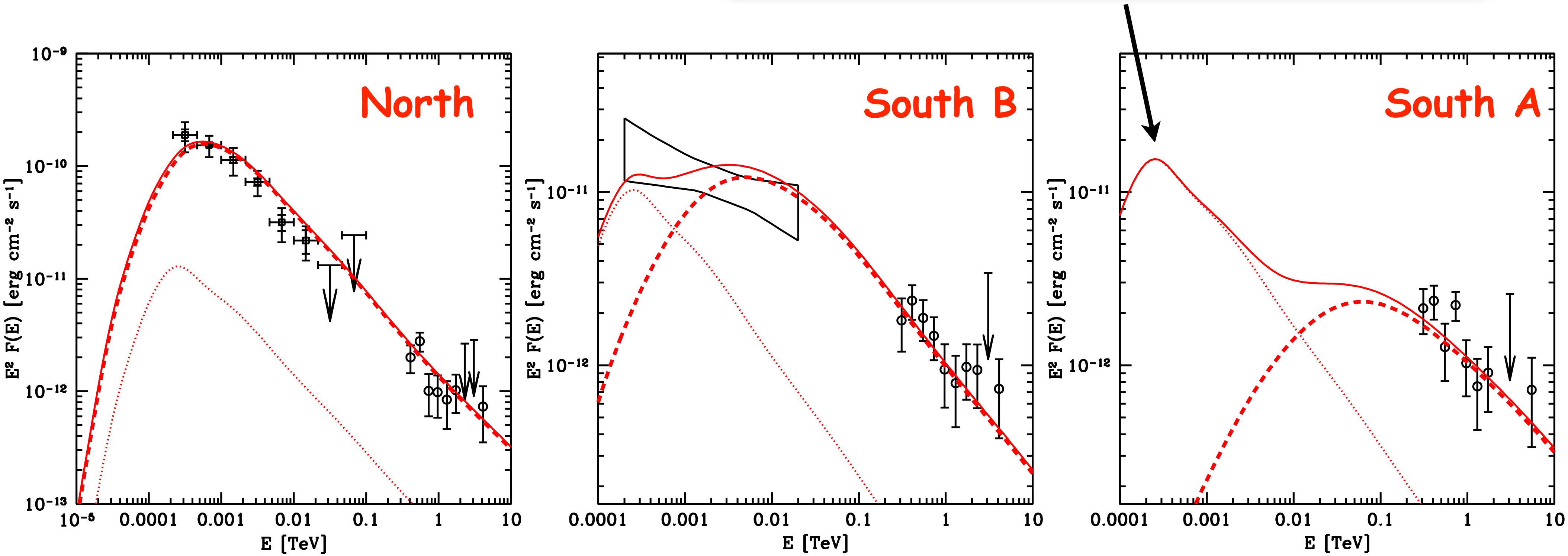
d = 65 pc

W28: GeV emission

$\eta = 30\%$

$\chi = 0.06$

this peak is removed as background



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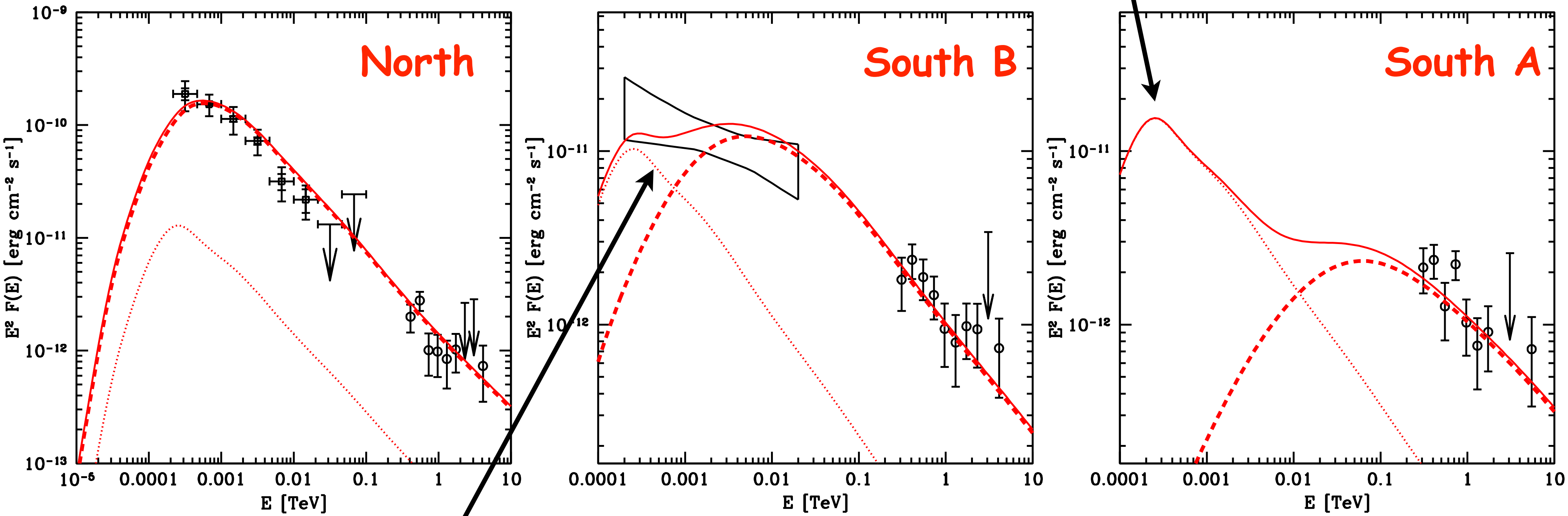

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d = 65 pc

some problems here...

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

Take-home message

- ☑ Current observations of **MCs in gamma rays** can be used to probe the **CR intensity** at different locations within the Galaxy (i.e. Gal centre ridge, orion cloud, W28) -> **indirect identification of CR sources**

- ☑ For MC located close to the (supposed) CR accelerator, estimates of the **local CR diffusion coefficient** can be made.

- ☑ Future observations (Fermi, HESS/MAGIC/VERITAS, but most of all CTA) will increase the number of detected clouds and make the results presented here more (or less?) solid