Gamma ray emission from supernova remnant/molecular cloud associations

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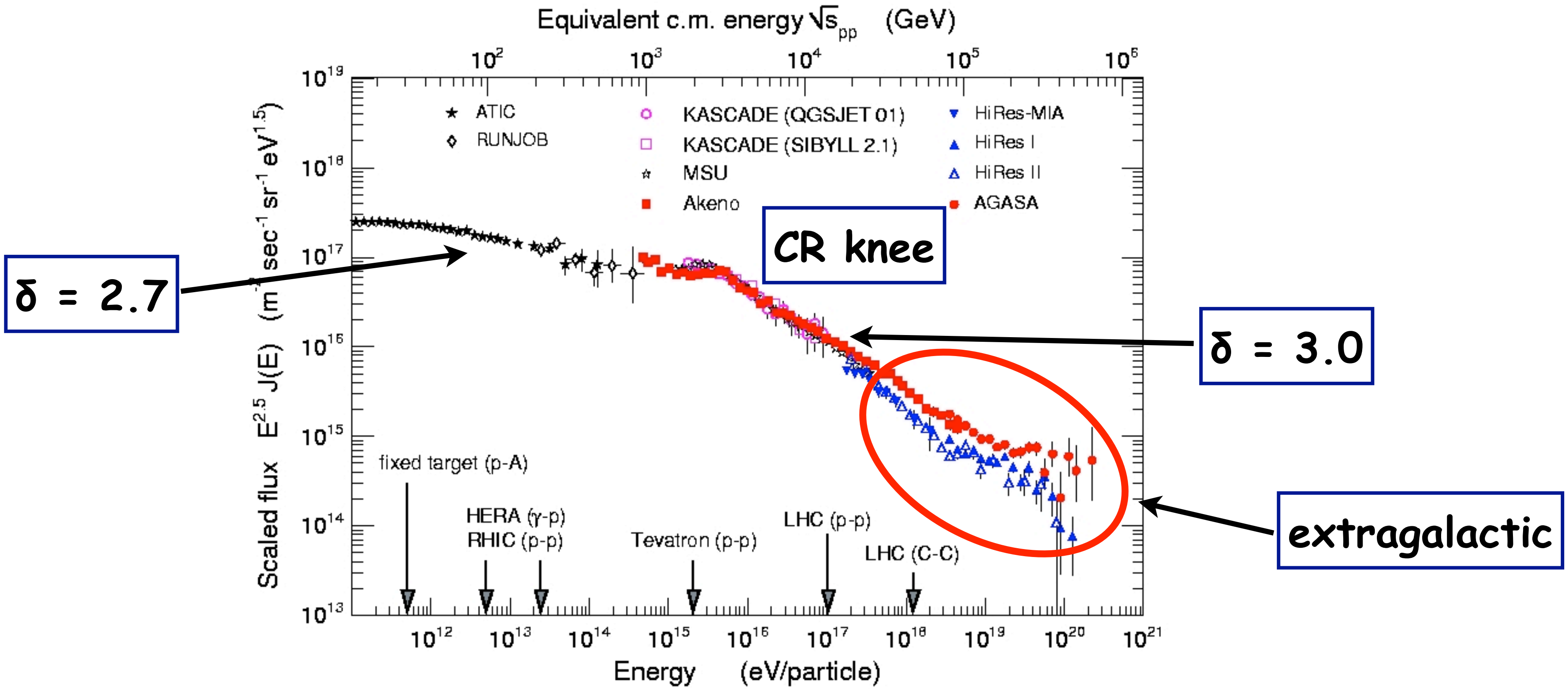
The Origin of galactic Cosmic Rays

☑ **Facts:**

- the spectrum is (ALMOST) a **single power law** -> **CR knee** at few **PeVs**
- extremely **isotropic**, up to very high energies
- energy density -> ω_{CR} **= 1 eV/cm^3**



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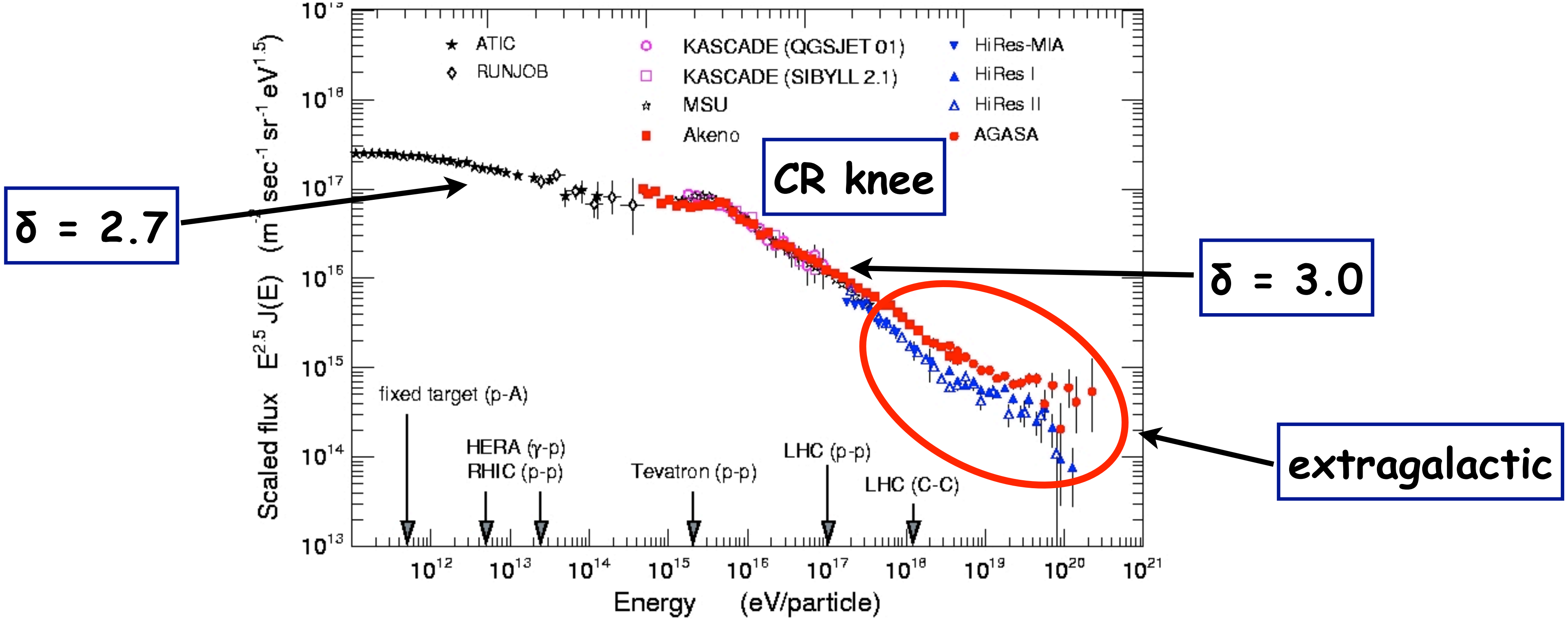
Most popular explanation:

- acceleration in **SuperNovaRemnants** -> CR energy density if efficiency ≥10%
- **diffusive shock acceleration** -> roughly the required spectrum...
- **propagation** in the Galaxy -> isotropy



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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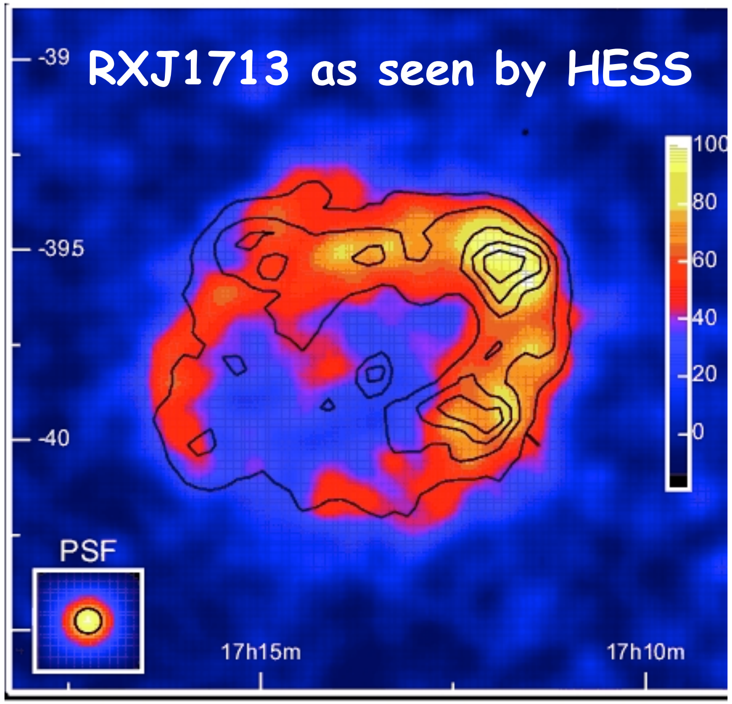
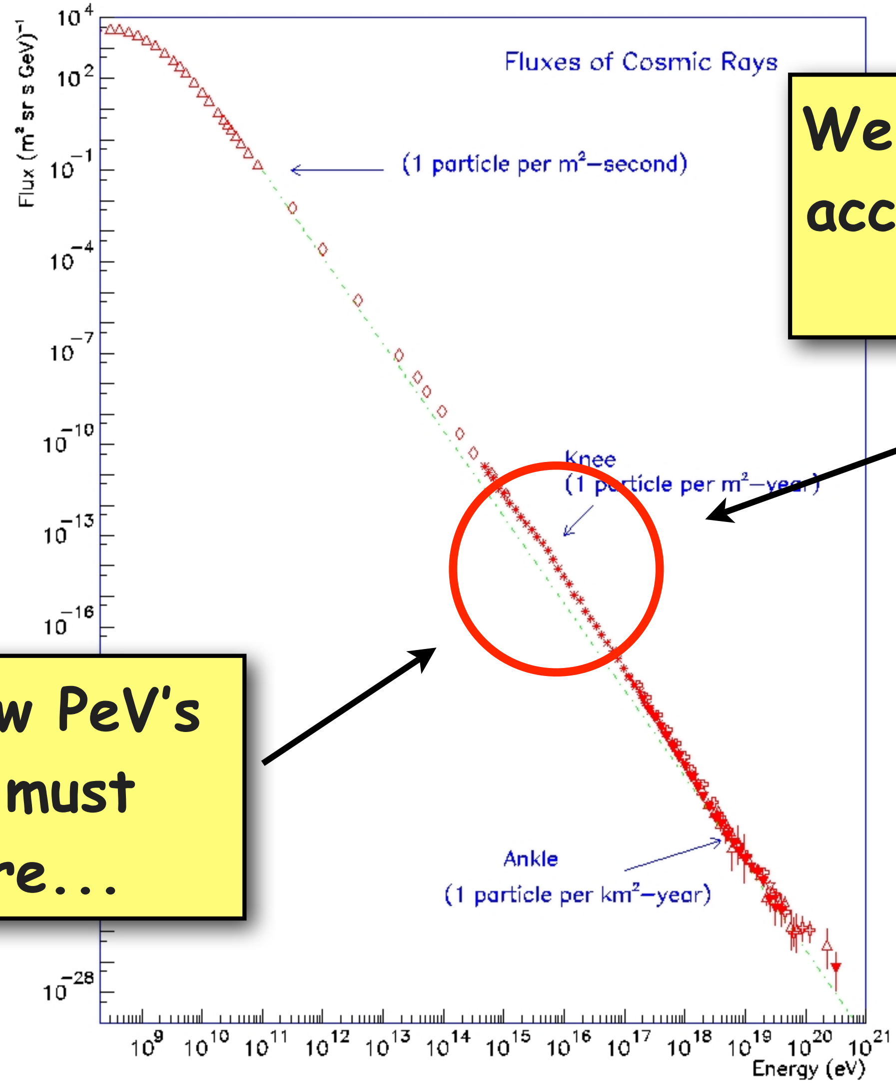
SNRs detected @TeVs ➜ TEST PASSED!

BUT

hadronic or leptonic???



Are SuperNova Remnants CR PeVatrons?



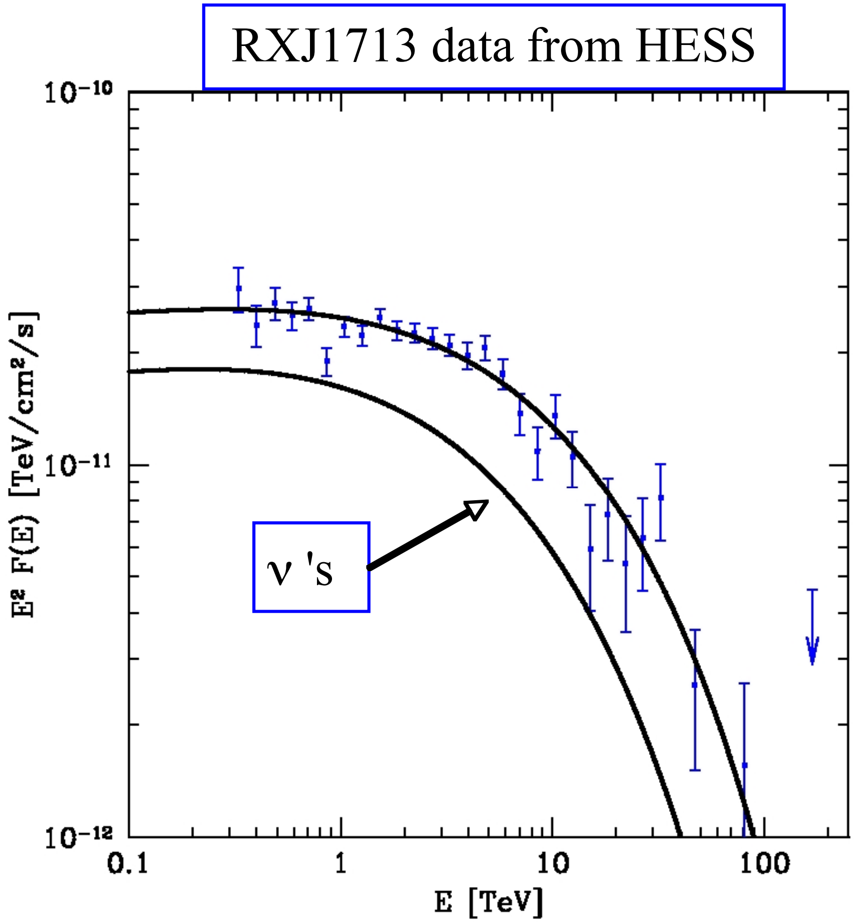
We'd like CR sources to accelerate (at least) up to that energy

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

RXJ1713 does not look like a PeVatron...

We would like SNRs to be CR PeVatrons...

Underlying proton spectrum E^{-2} with exponential cutoff @150 TeV

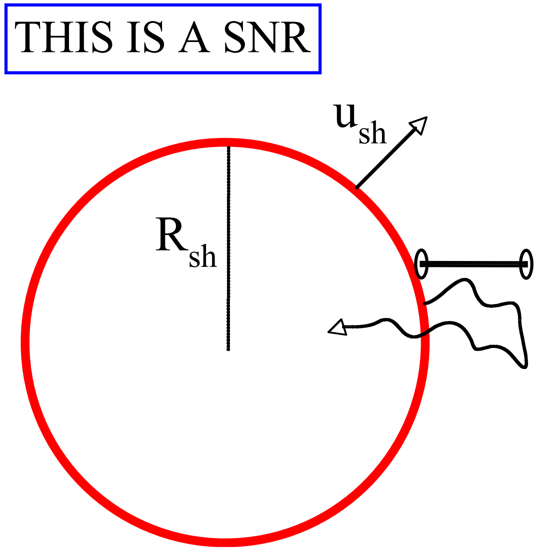


Gabici, 2008

...but RXJ1713 is NOT!!!

RX J1713 probably WAS a PeVatron!

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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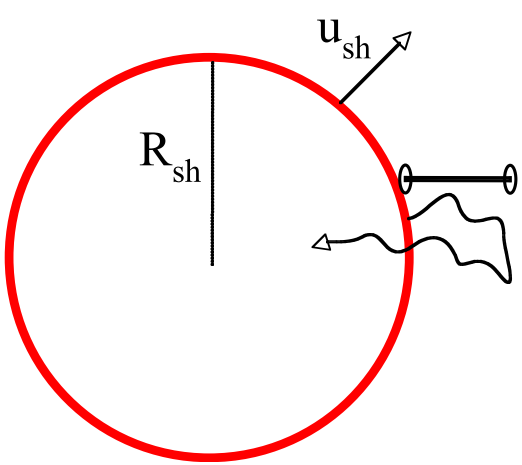
THIS IS A SNR



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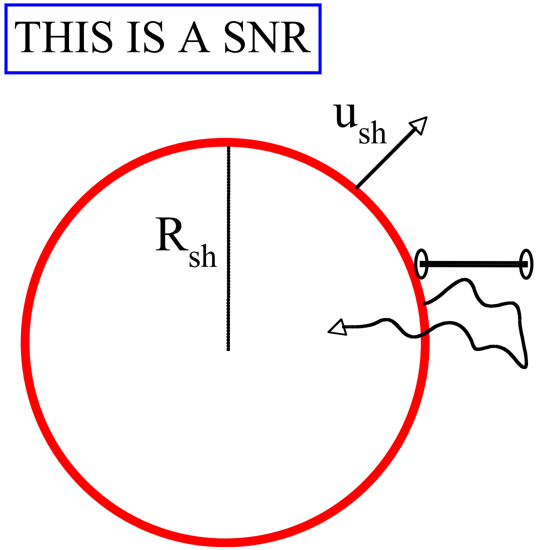

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Sedov phase:

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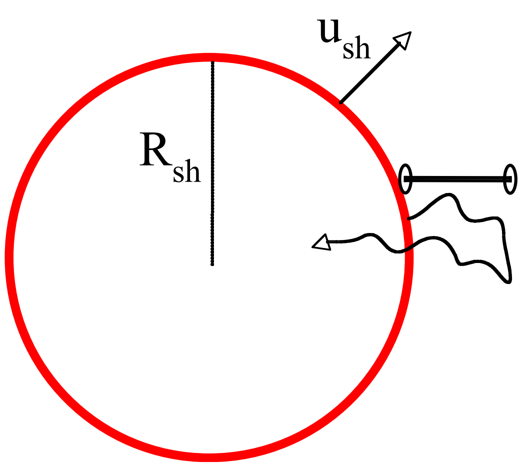

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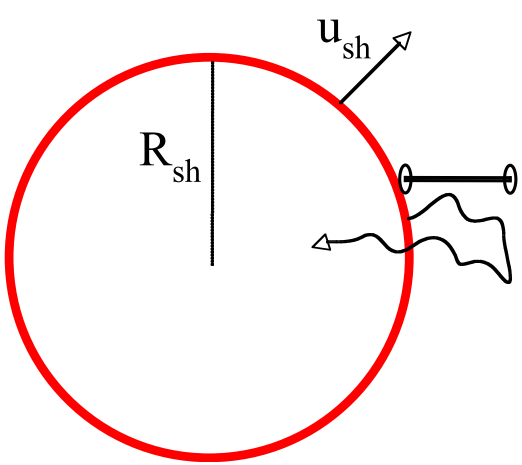

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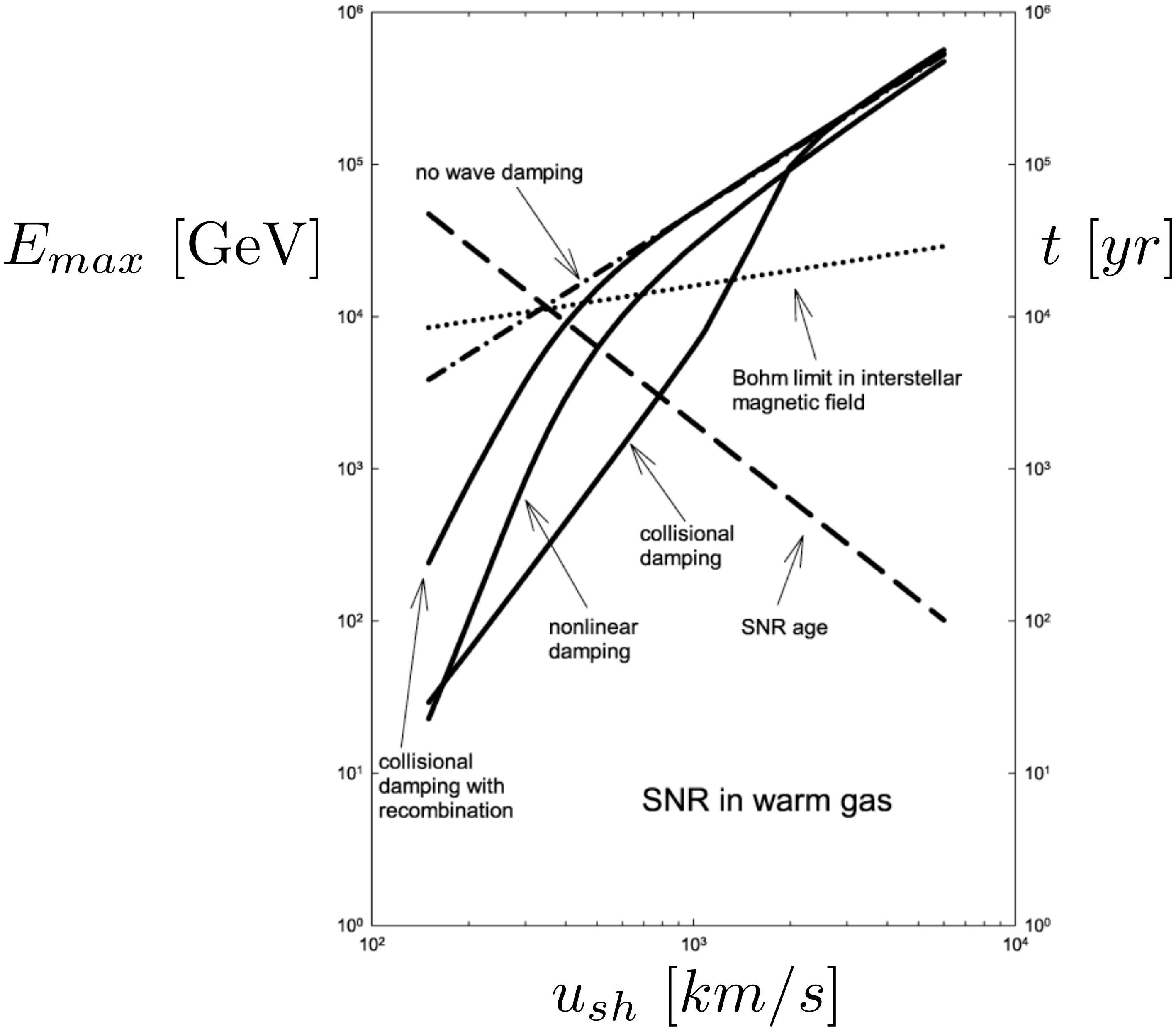
B_{sh} also depends on time

E_{max} decreases with time

Particles with E > E_{max} escape the SNR

Particle escape from SNRs

Ptuskin & Zirakashvili, 2003



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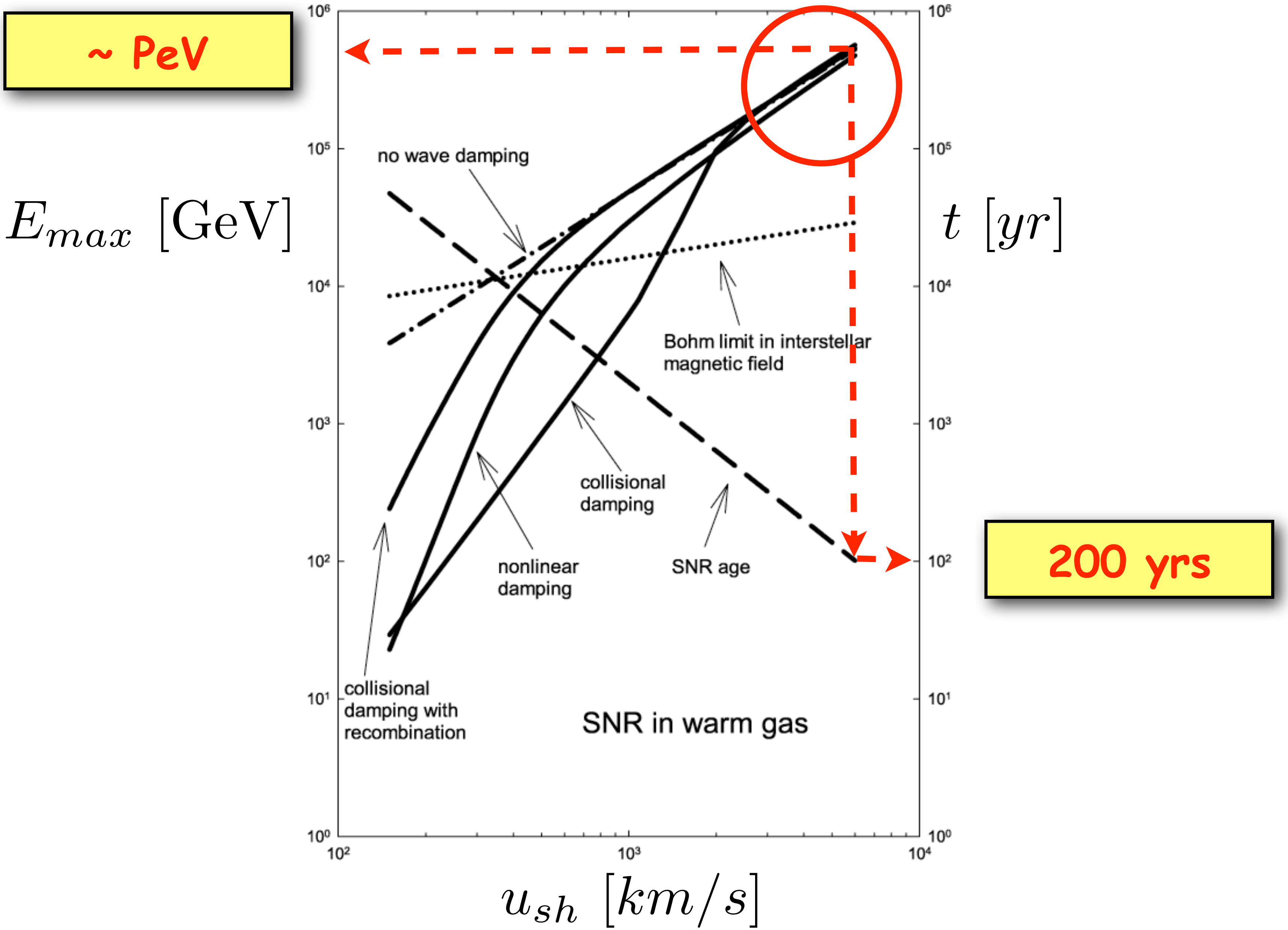

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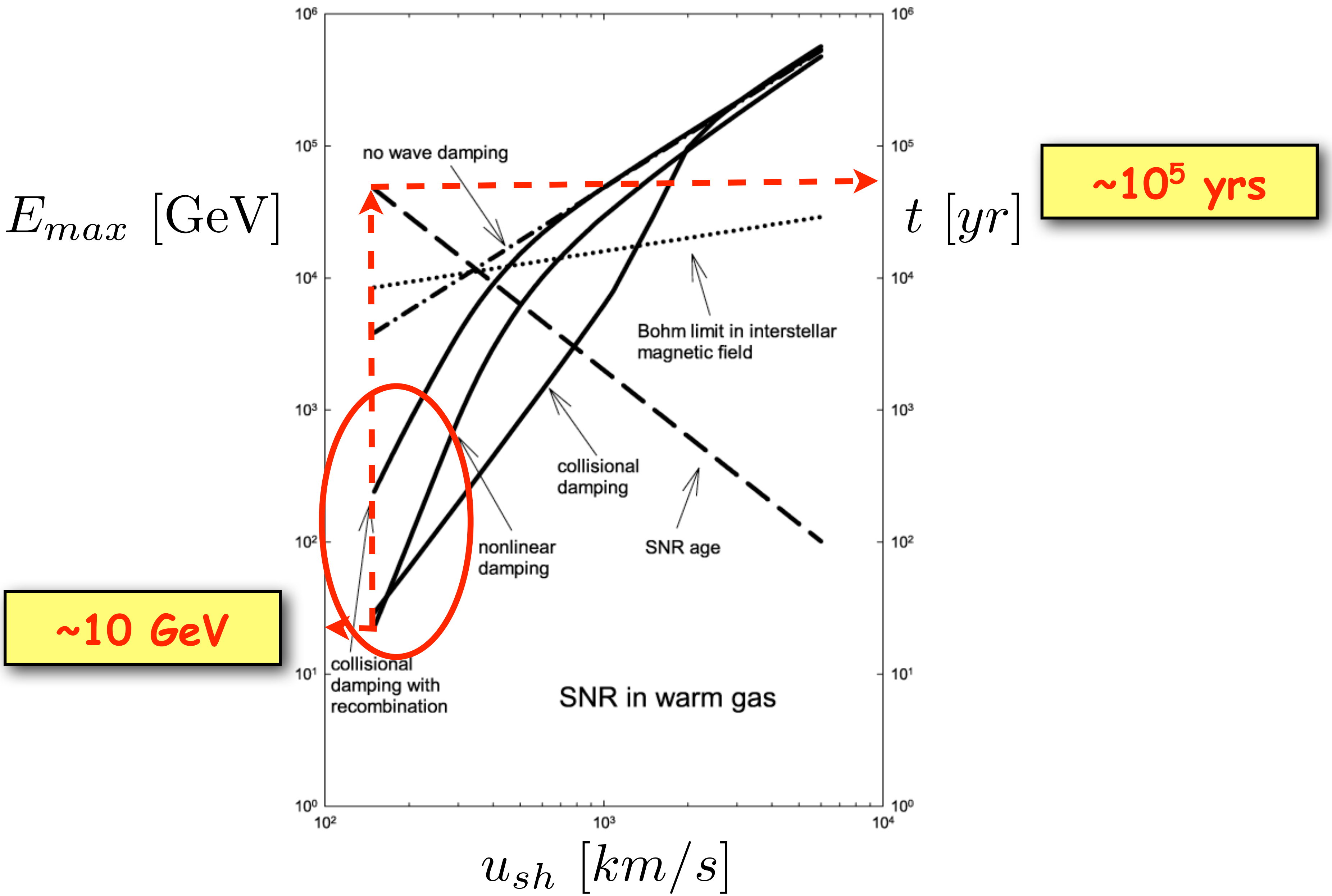

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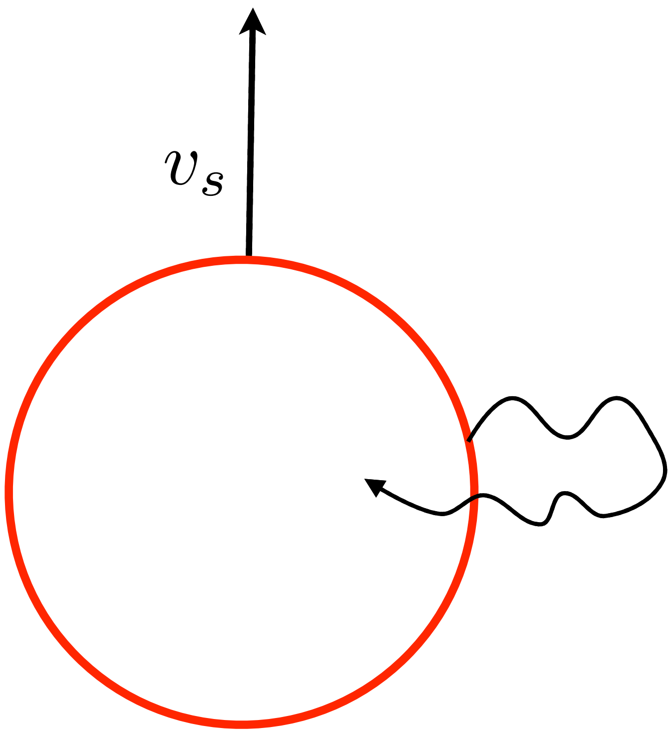

This is a supernova remnant

RXJ1713 WAS a CR PeVatron

- PeV particles are accelerated at the beginning of Sedov phase (~200yrs), when the shock speed is high!

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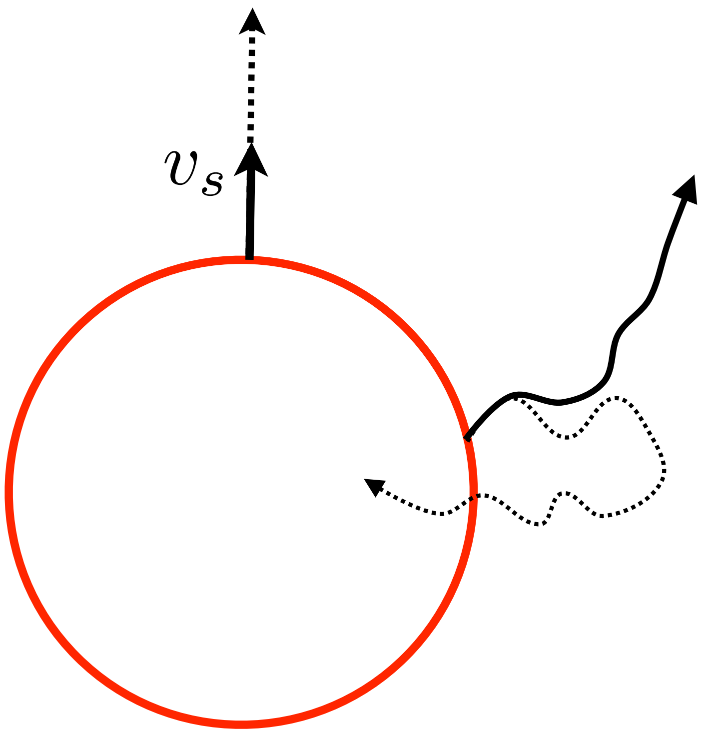

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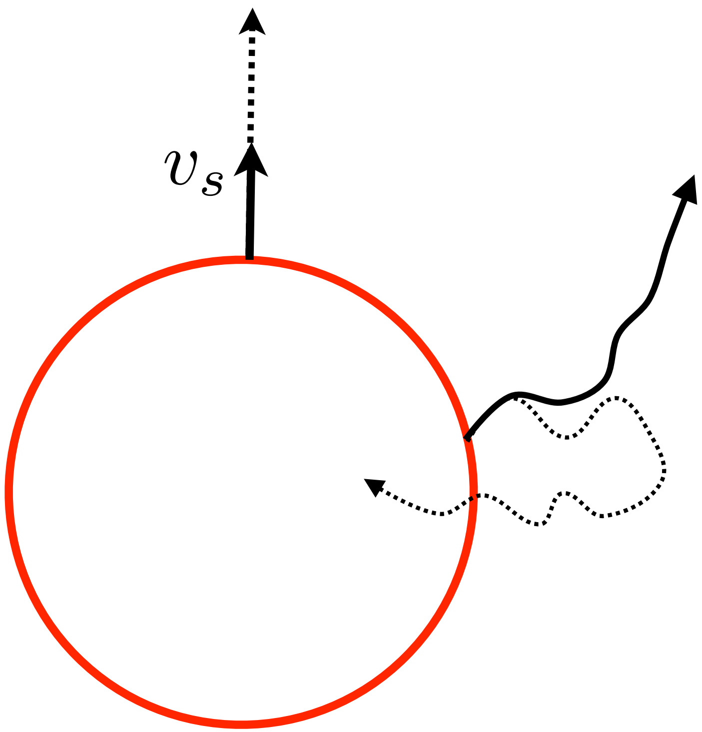

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- a SNR is a PeVatron for a very short time

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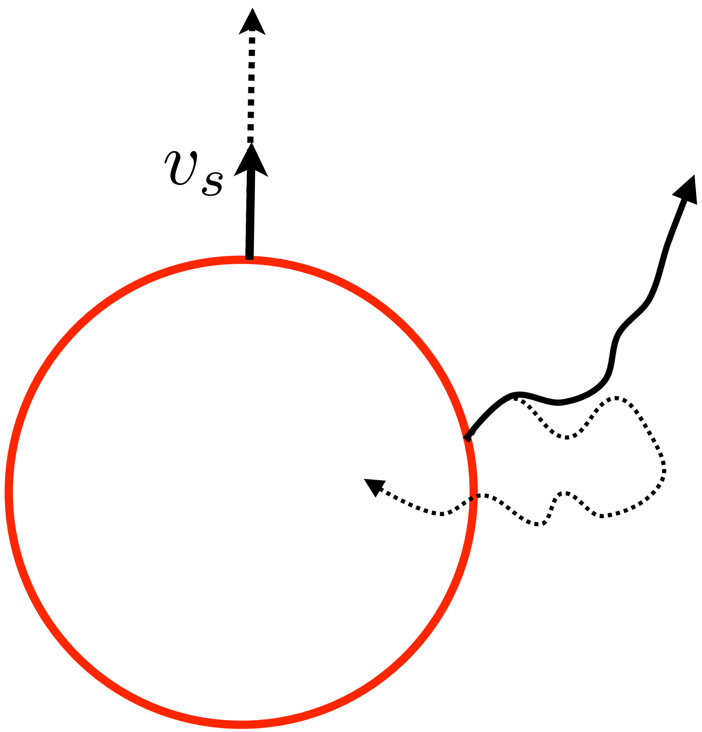

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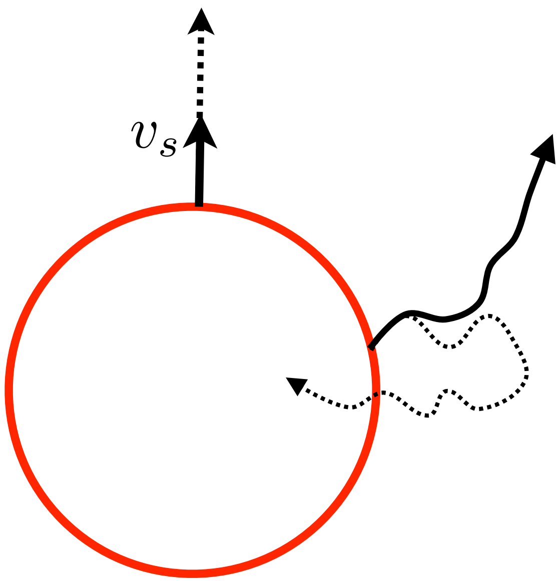
- still no evidence for the existence of escaping CRs

Particle escape from SNRs



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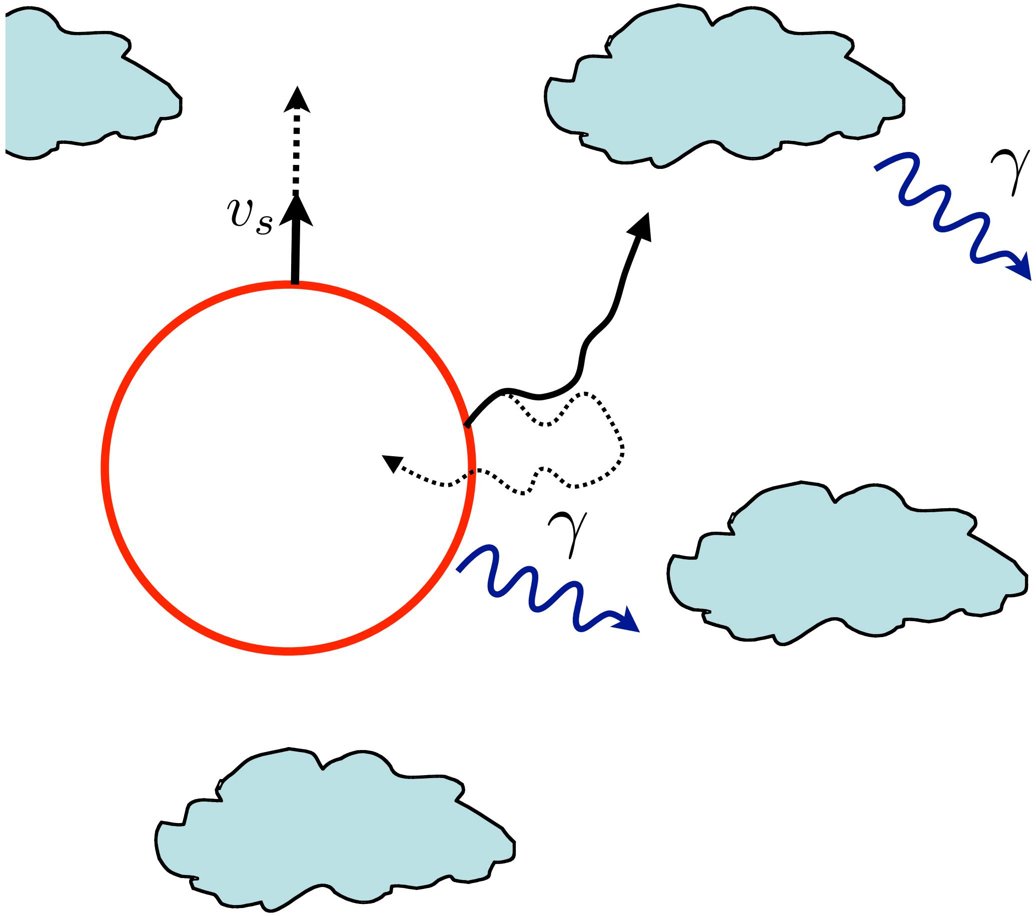
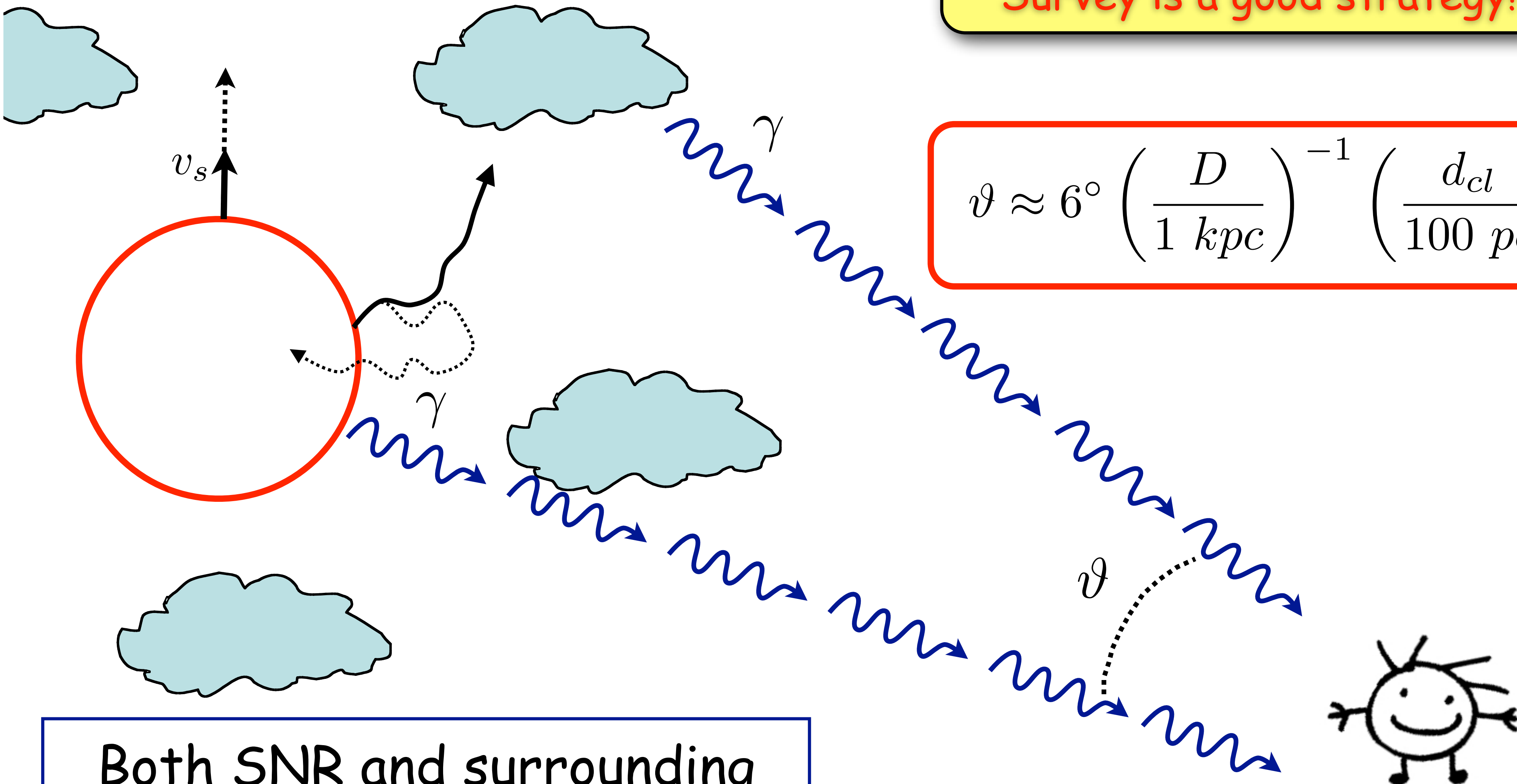


Both SNR and surrounding molecular clouds emit gammas

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

Montmerle's SNOBs

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!

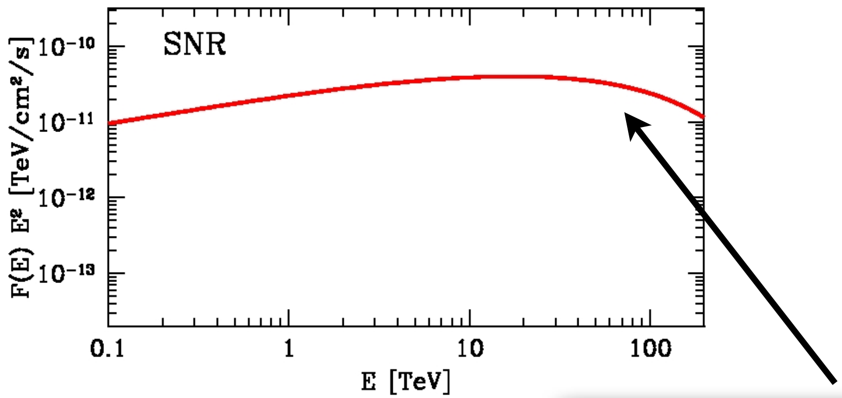
An association between cosmic ray sources and molecular clouds is expected

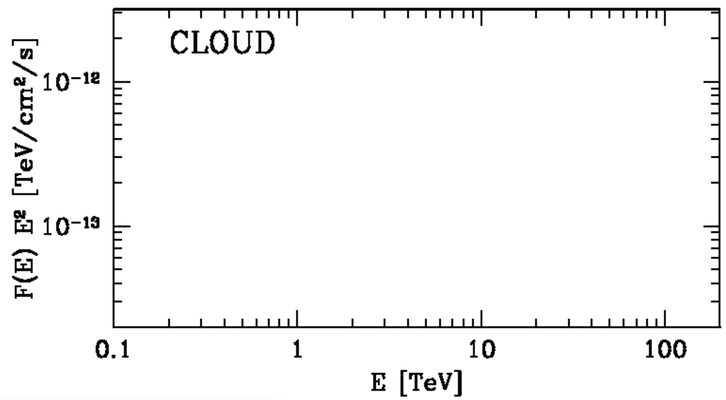
Gamma rays from MCs illuminated by CRs

t = 400 yr

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

SNR **Cloud**





PeVatron!!!
but for short time!

Gabici&Aharonian(2007)

Gamma rays from MCs illuminated by CRs

t = 2000 yr

$d = 1\ kpc$
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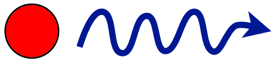
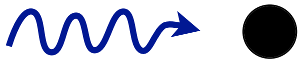
$D_{PeV} = 3\ 10^{29} cm^2/s$

100 TeV

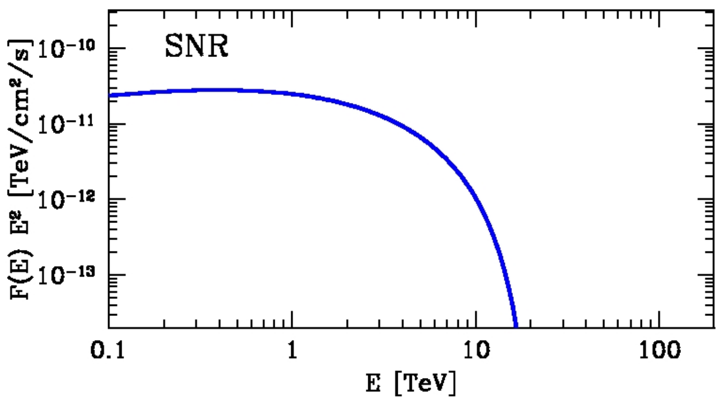


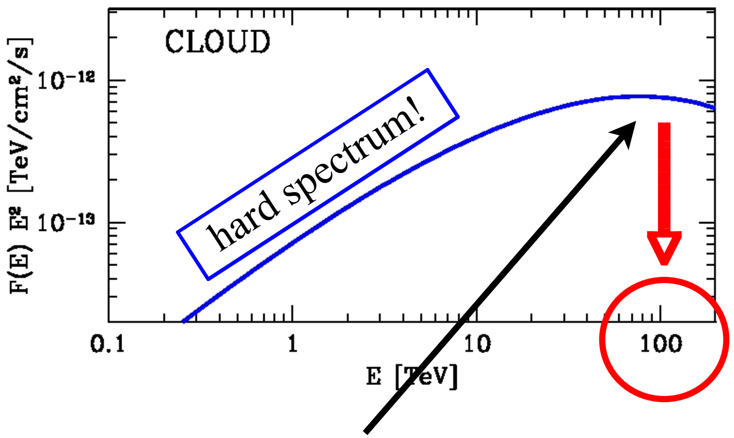
1 PeV



SNR

Cloud





Gabici&Aharonian(2007)

HESS remnant

Indirect detection of a PeVatron! Emission lasts longer!

NO ICS -> Klein-Nishina

Gamma rays from MCs illuminated by CRs

t = 8000 yr

$d = 1\ kpc$

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

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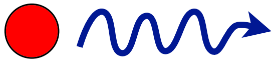
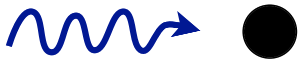
1 TeV

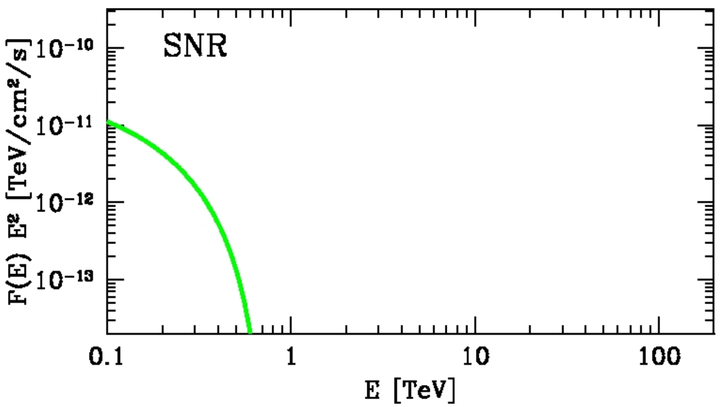


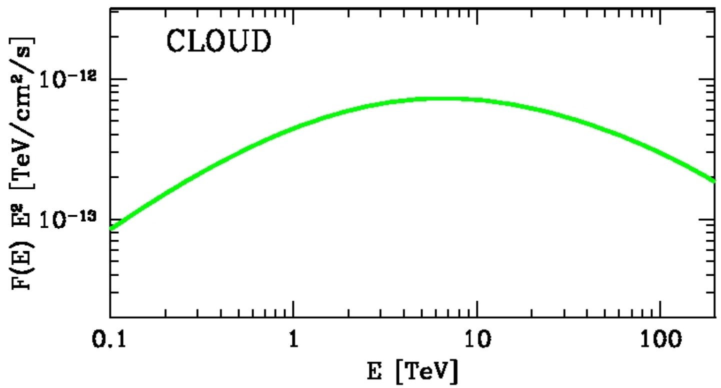
100 TeV



SNR

Cloud





Gabici&Aharonian(2007)

GLAST remnant?

HESS and MILAGRO unidentified sources?

Gamma rays from MCs illuminated by CRs

t = 32000 yr

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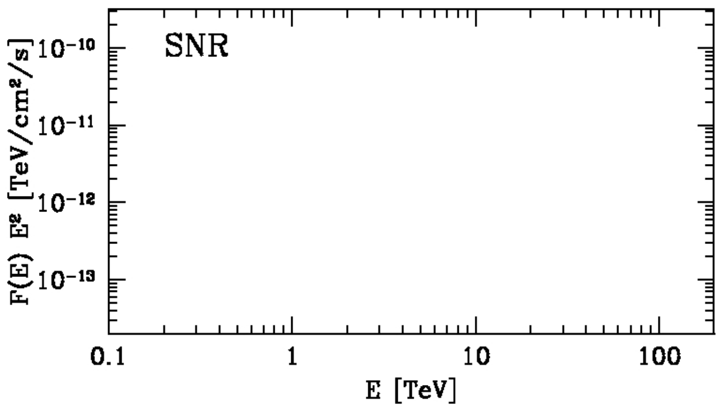

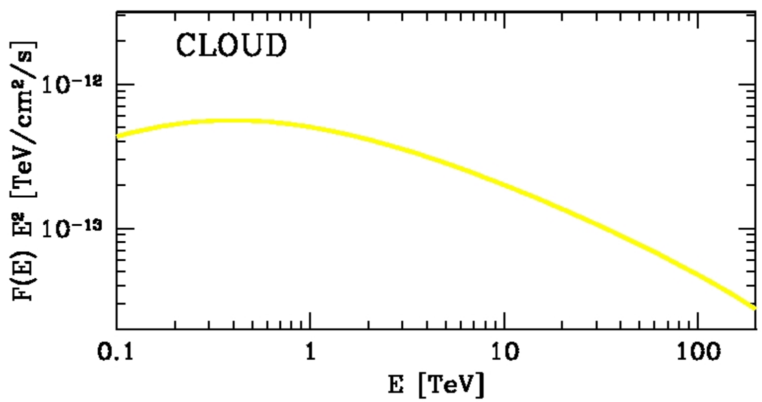

Gabici&Aharonian(2007)

no emission

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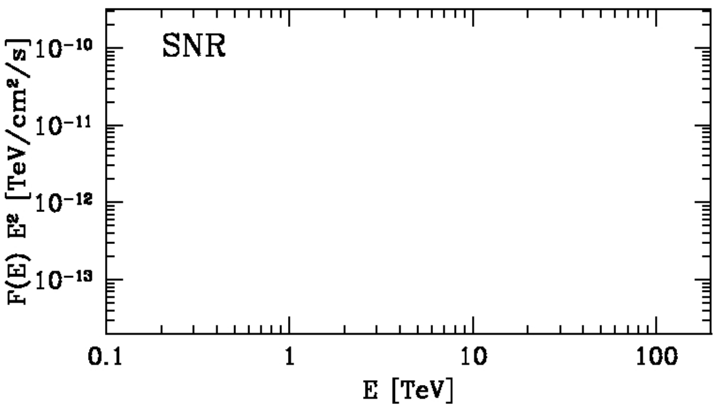
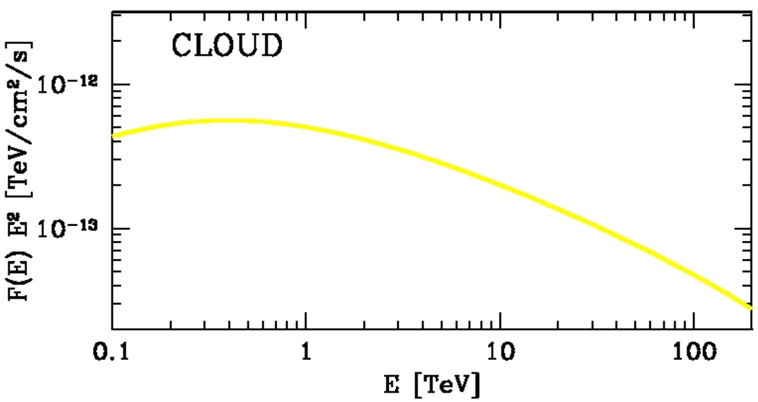
100 GeV

10 TeV

SNR

Cloud





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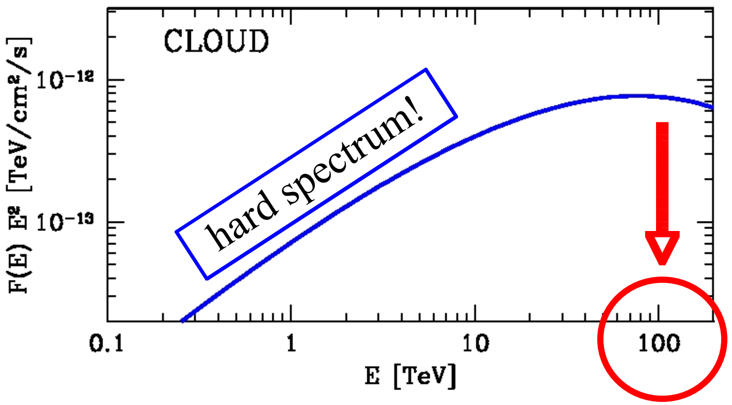
Naive statistics



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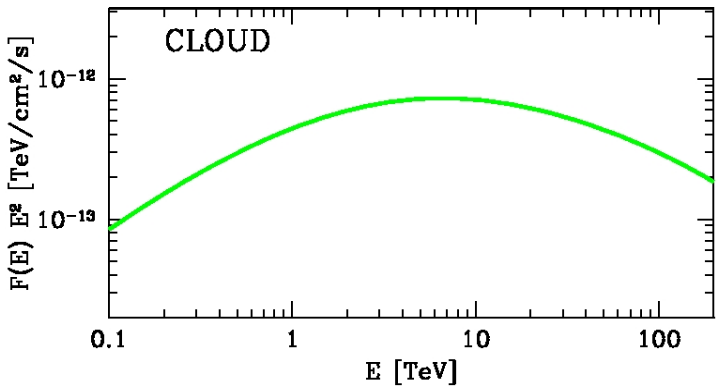

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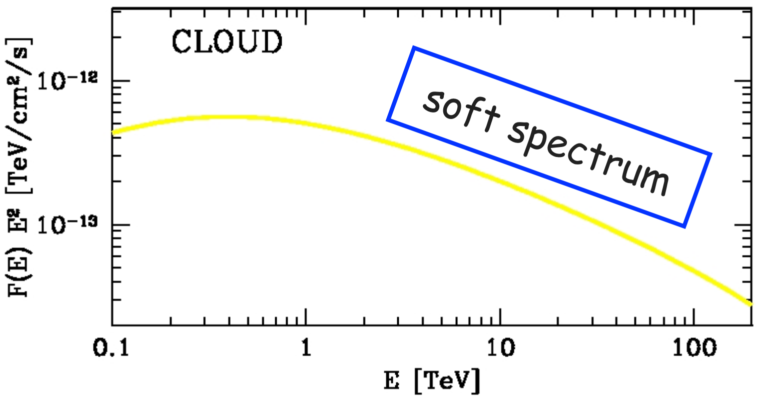

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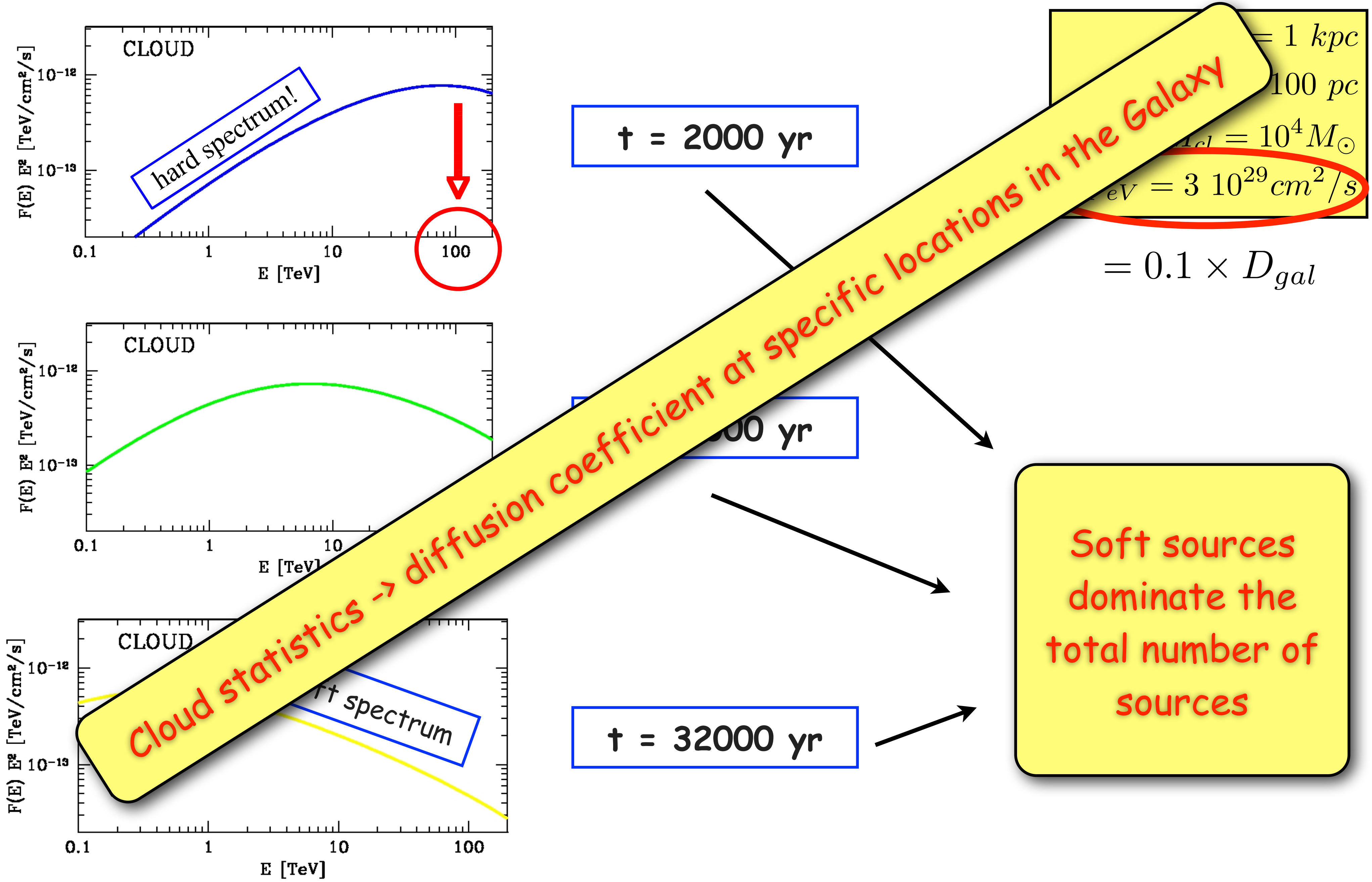
$= 0.1 \times D_{gal}$

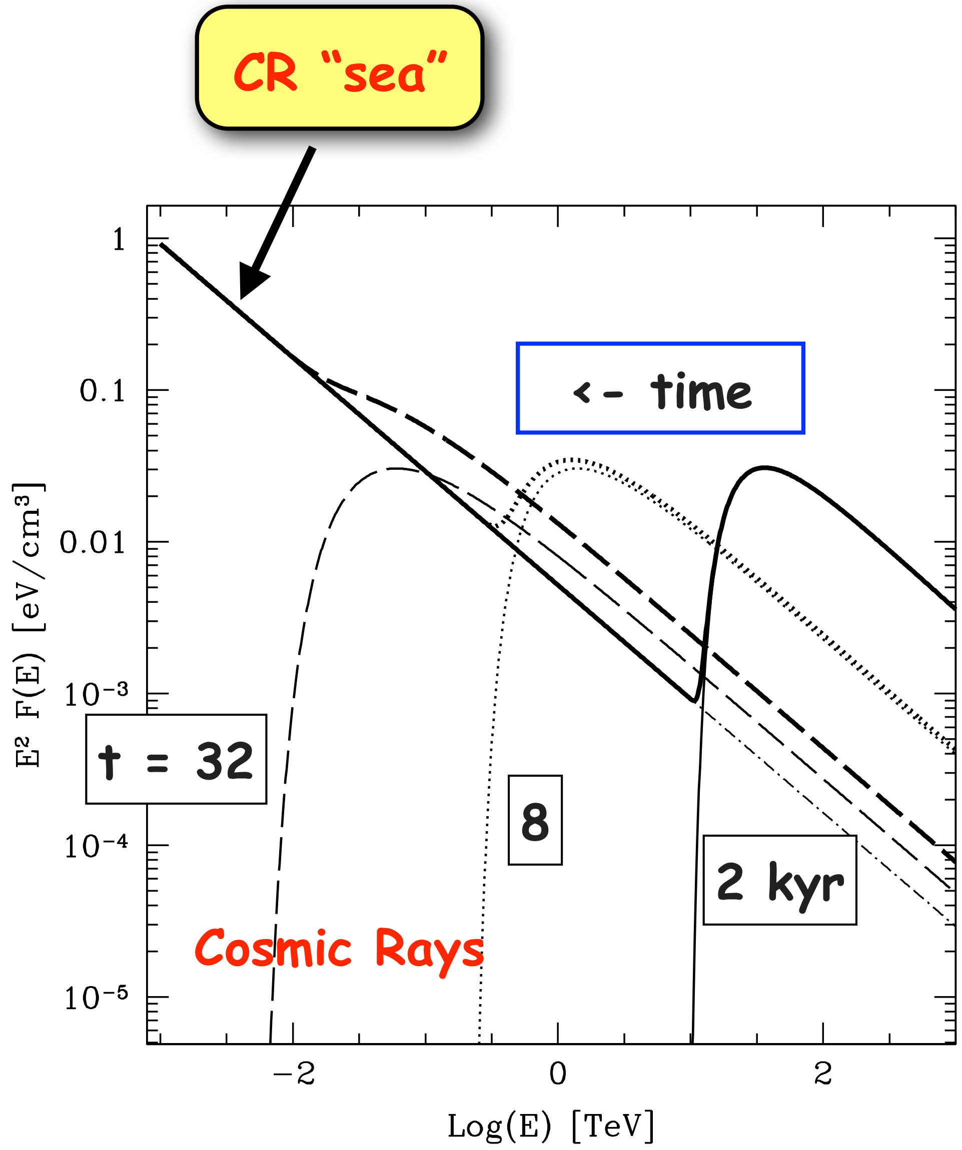
Soft sources dominate the total number of sources

Naive statistics



MultiWaveLength implications

$M=10^5\ M_\odot$; D=1kpc ; $D_{10}=10^{28} cm^2/s$; d = 100 pc



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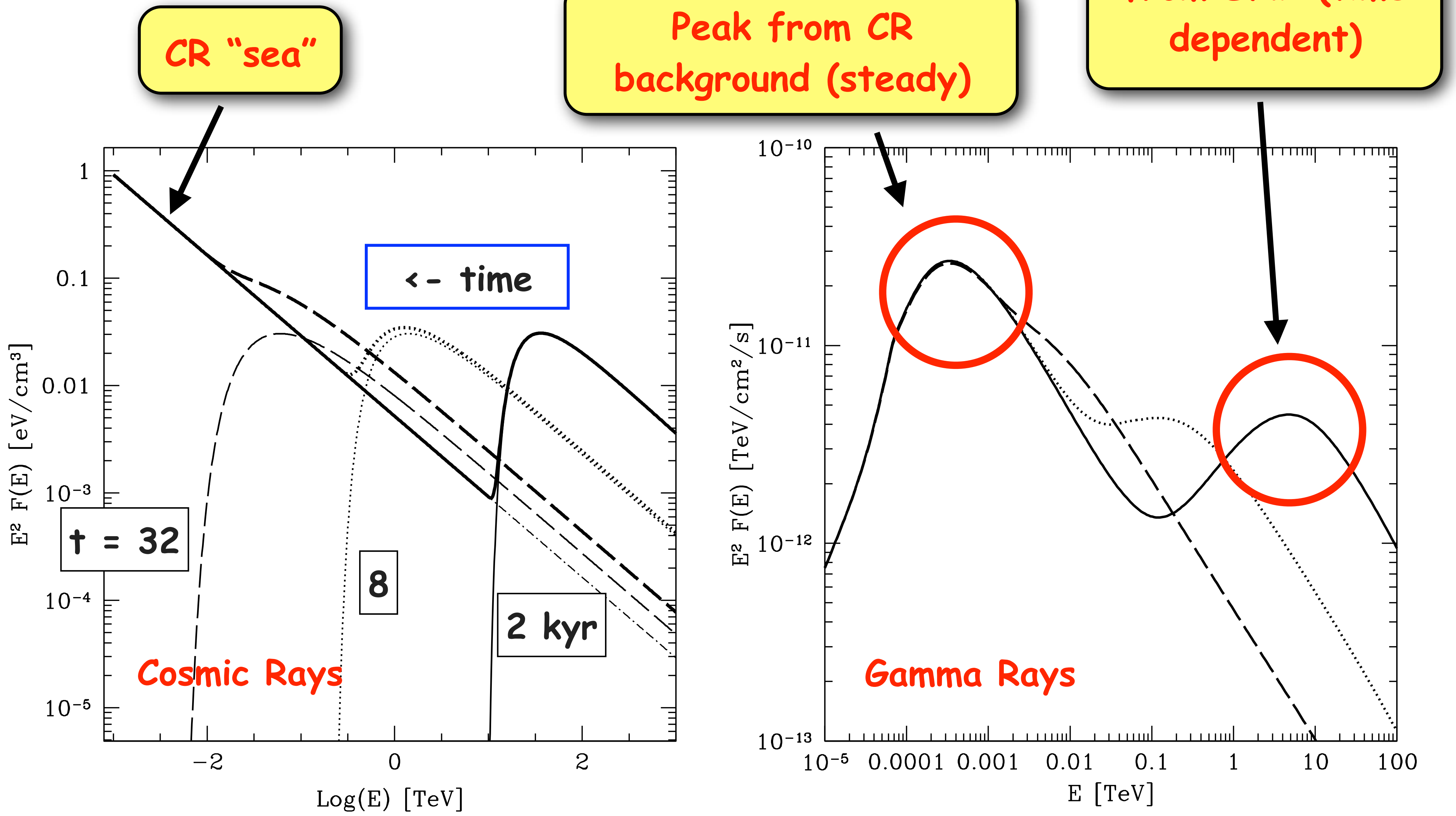

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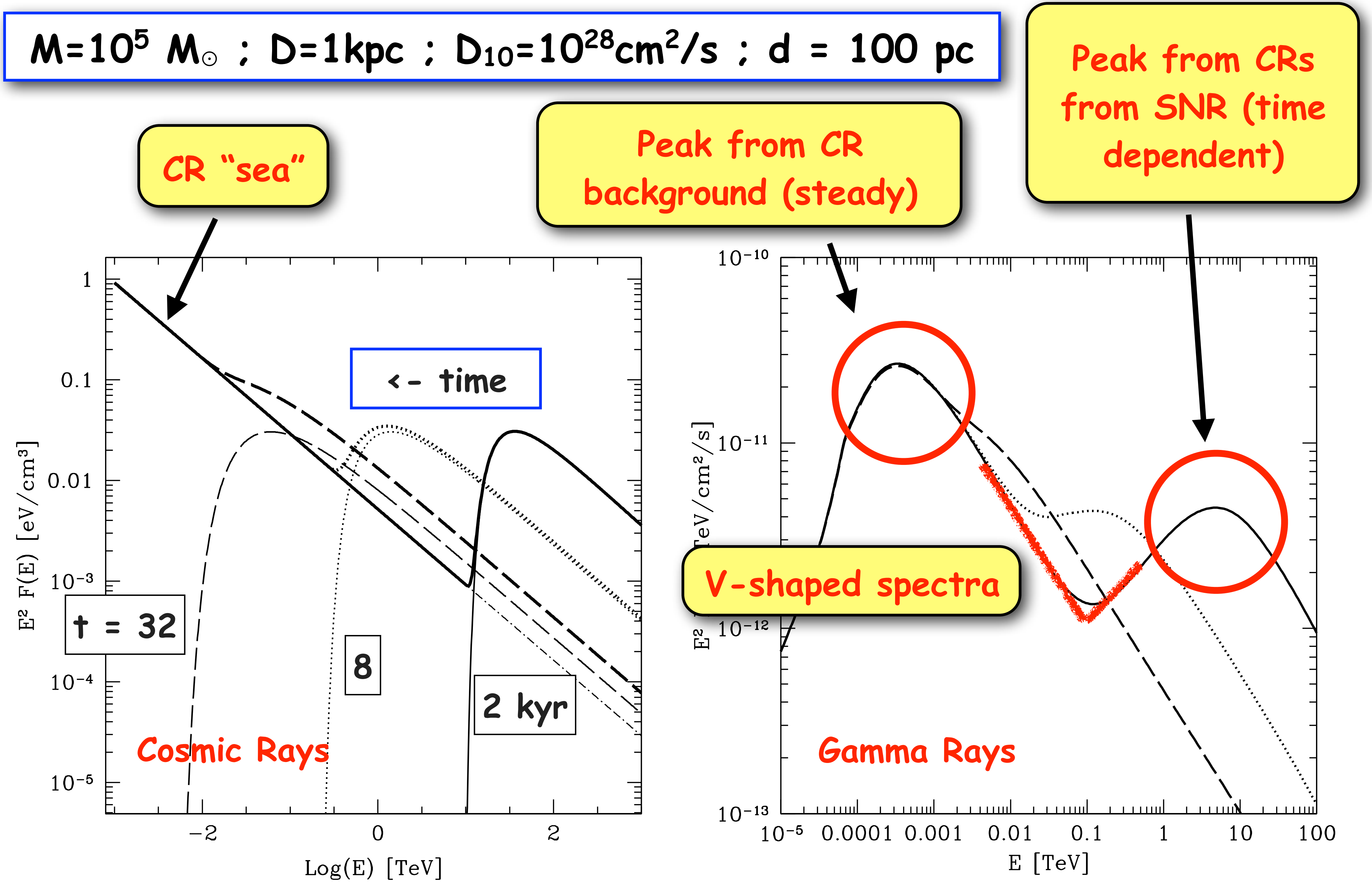

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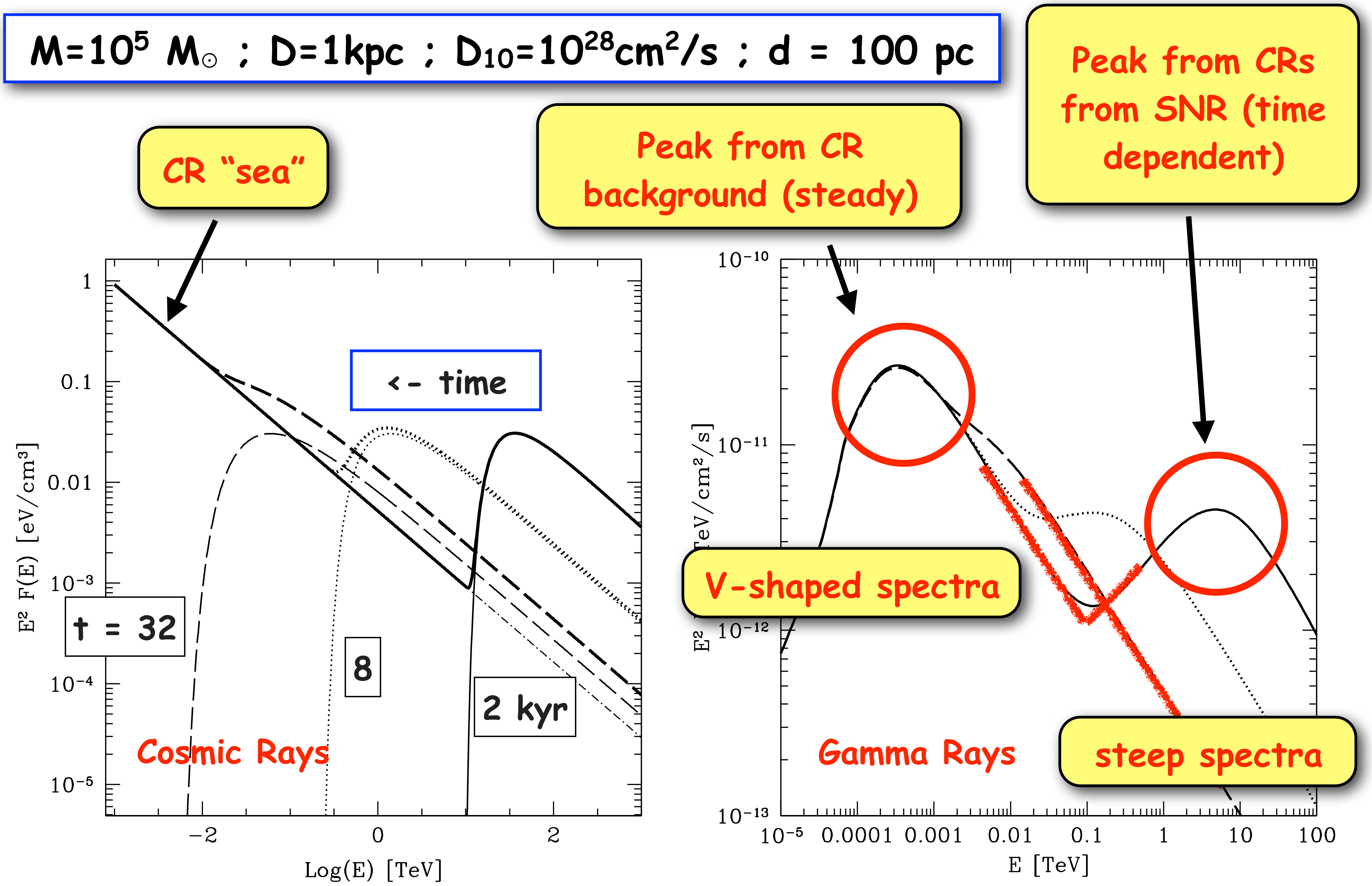
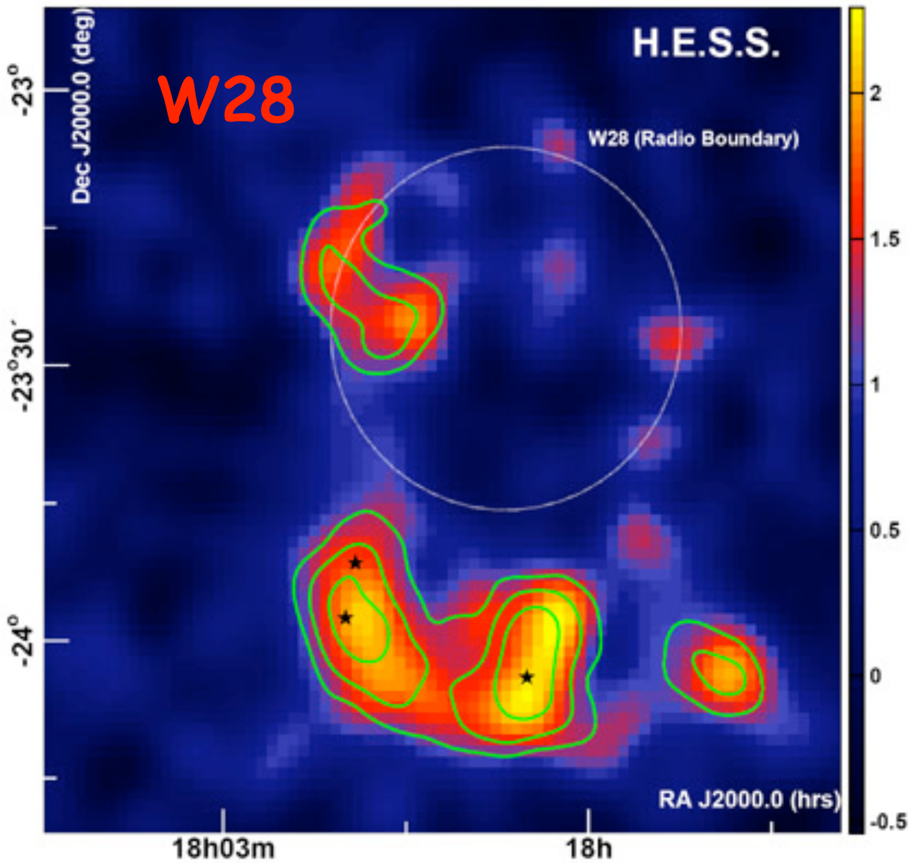


The W28 region in gammas, CO, & radio



HESS - TeV emission

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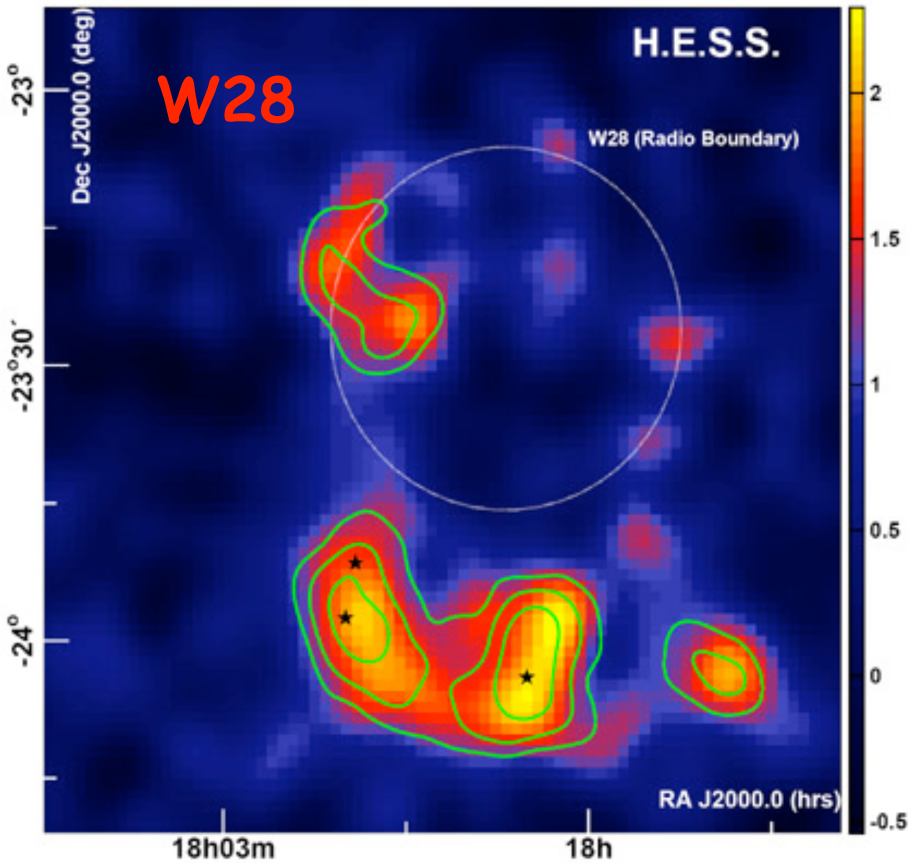

HESS - TeV emission

Aharonian et al, 2008

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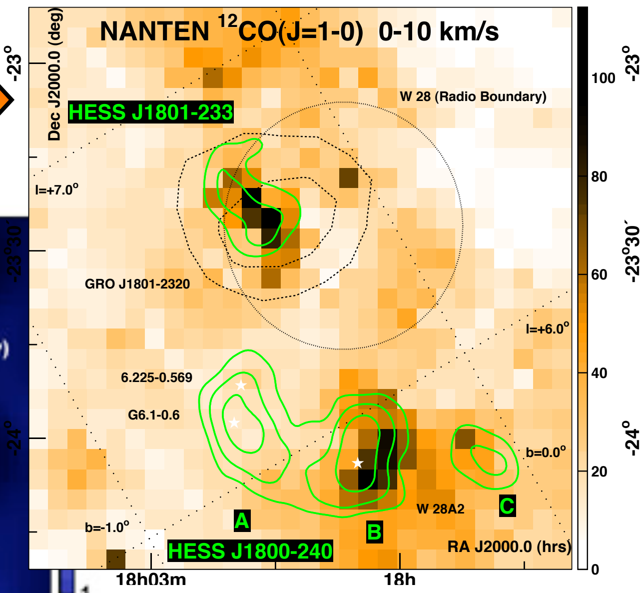
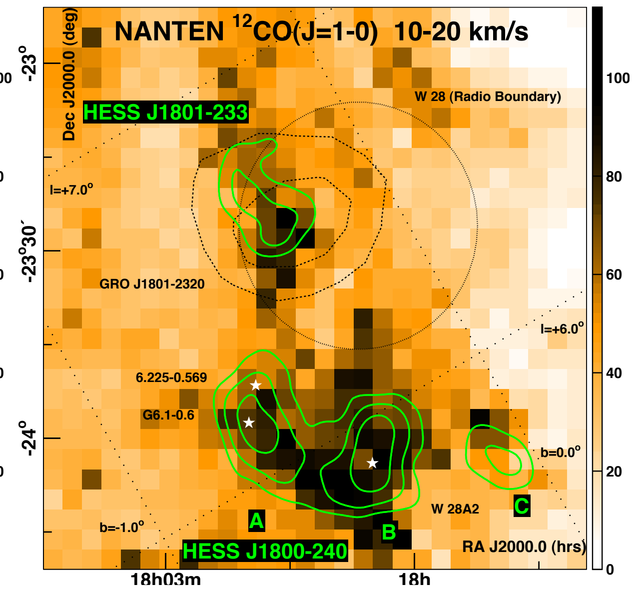
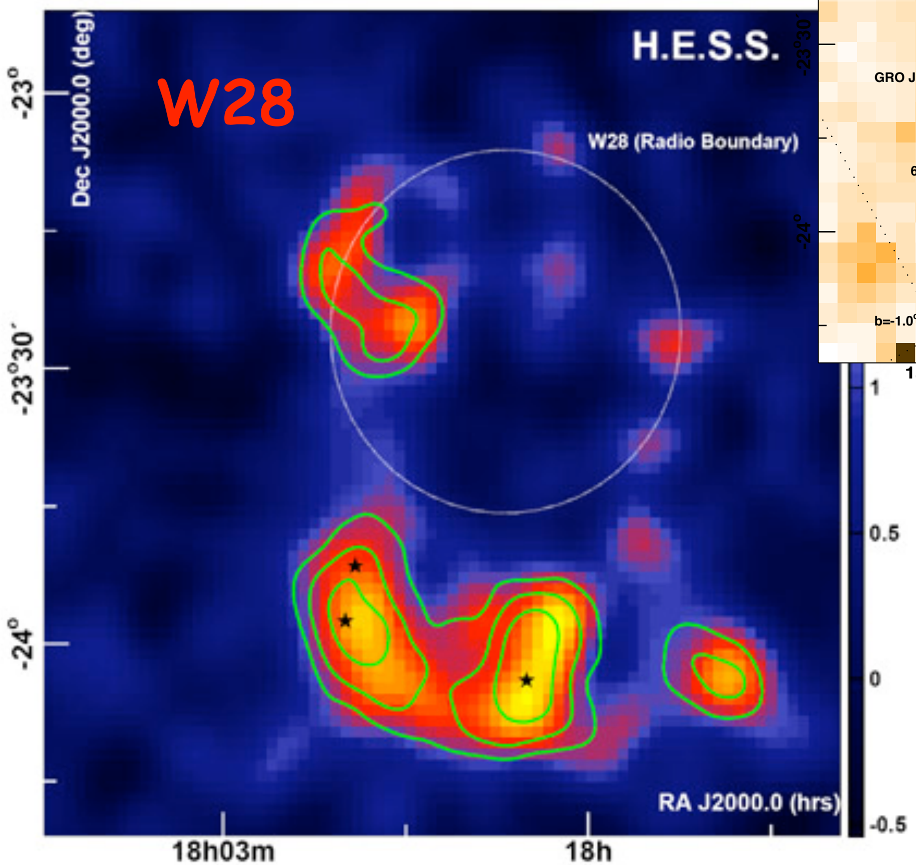
NANTEN data - CO line







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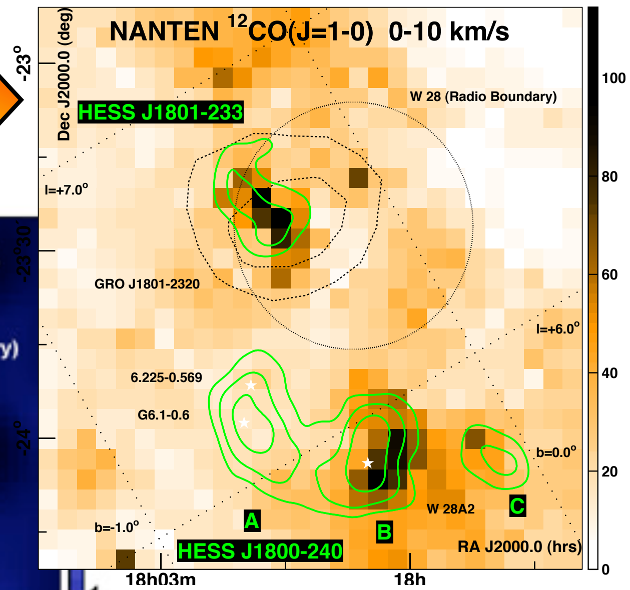
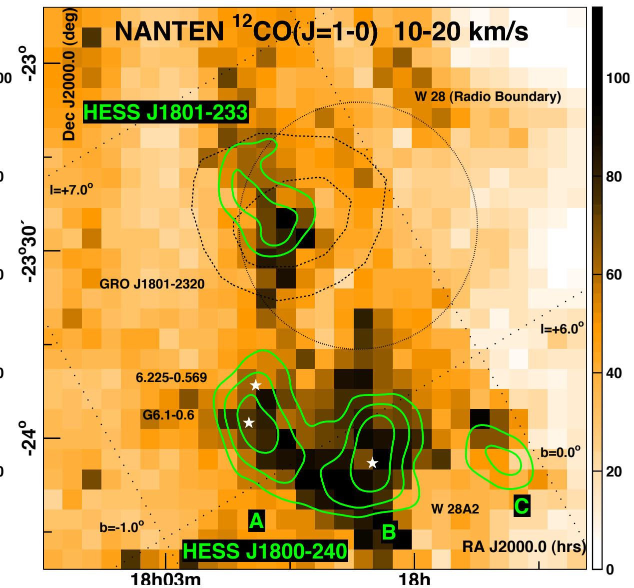
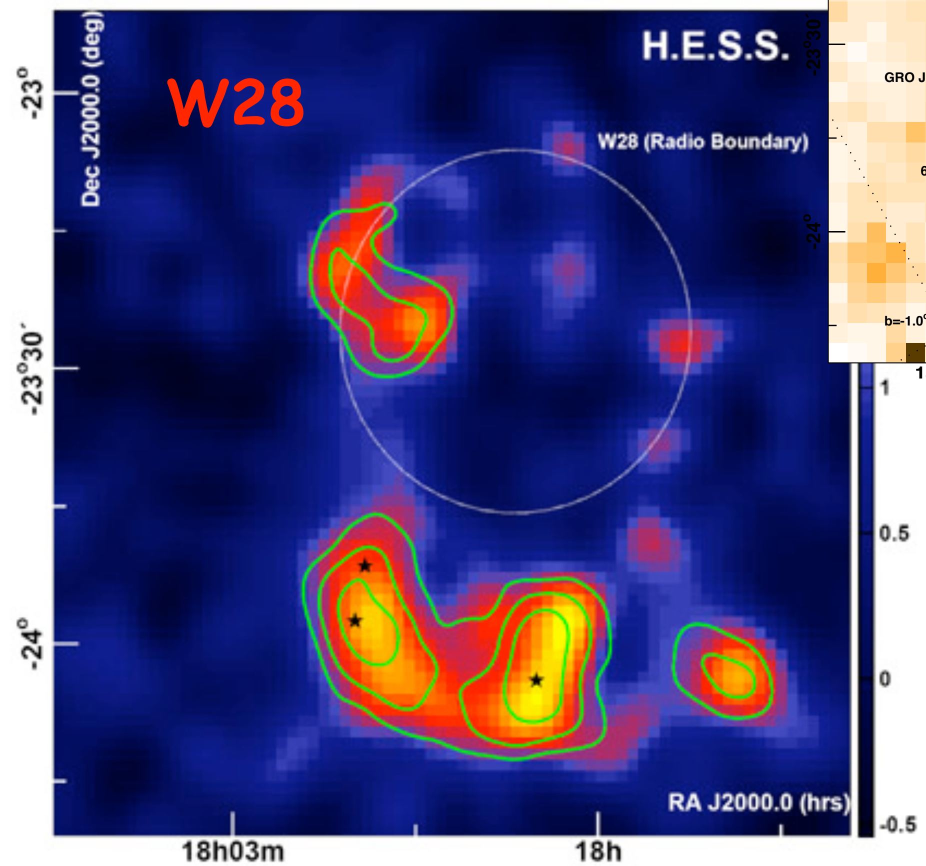
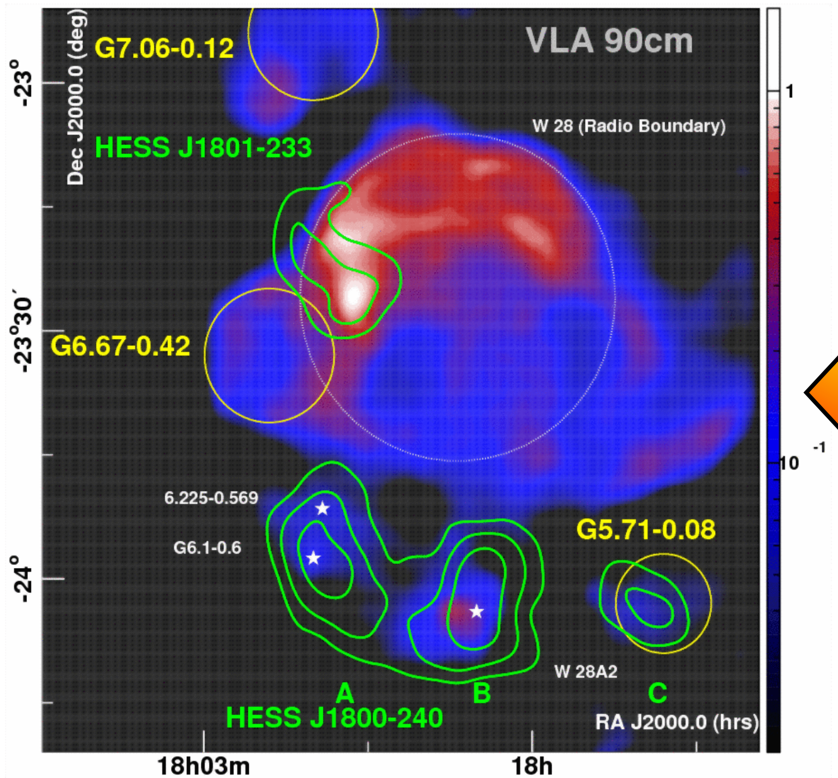








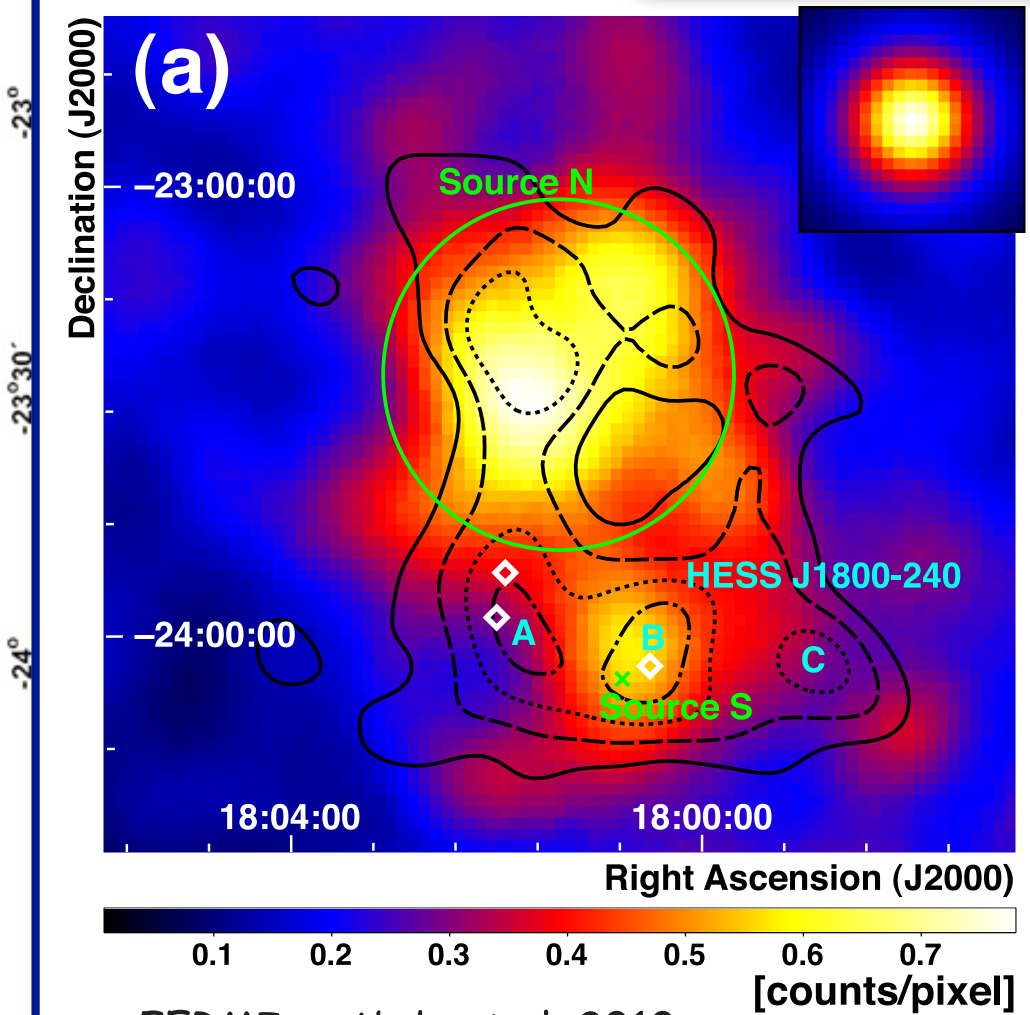
Radio (Dubner et al 2000)

HESS - TeV emission

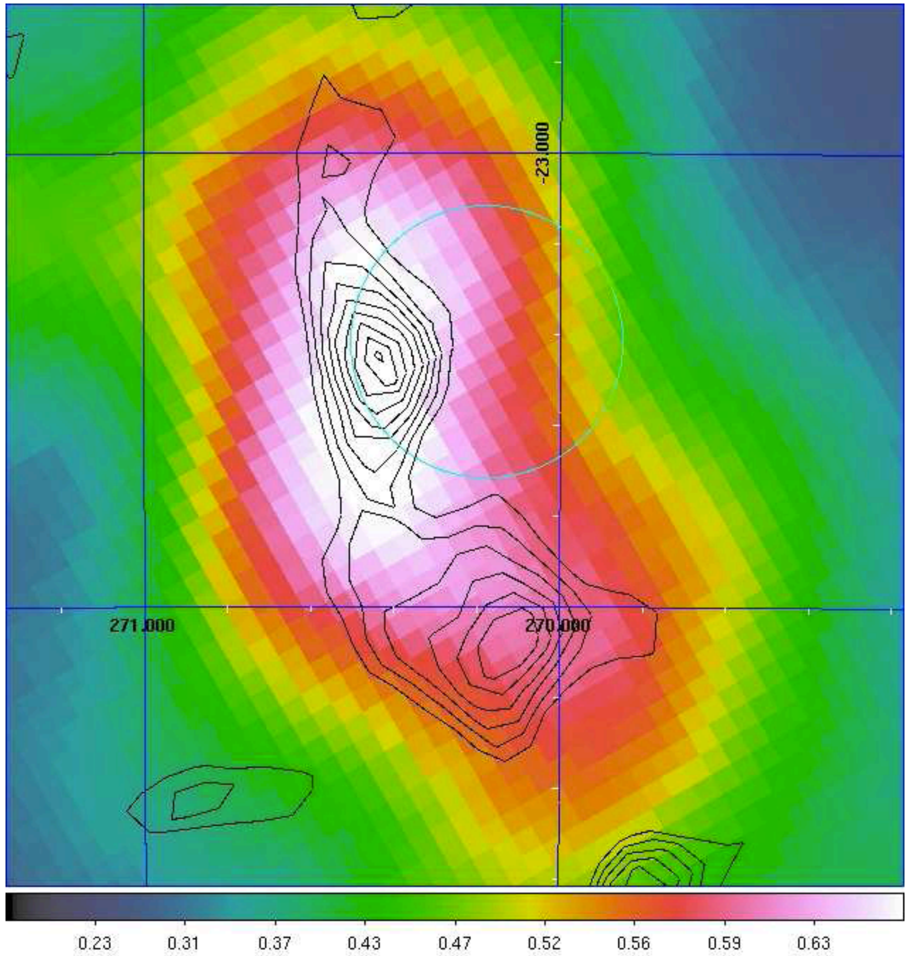
Aharonian et al, 2008

The W28 region in gammas, CO, & radio

FERMI and AGILE - GeV emission

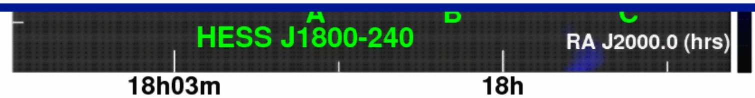


FERMI -> Abdo et al, 2010



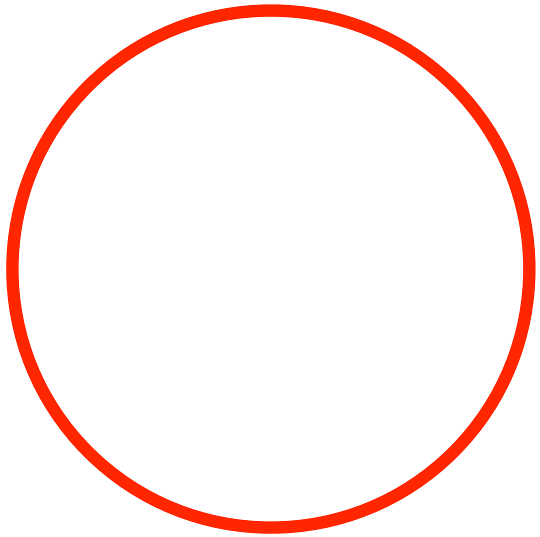
AGILE -> Giuliani et al, 2010

Aharonian et al, 2008



W28 as seen by a theoretician

SNR shell



- radio emission

  -> GeV electrons

  -> ongoing (re)acceleration?

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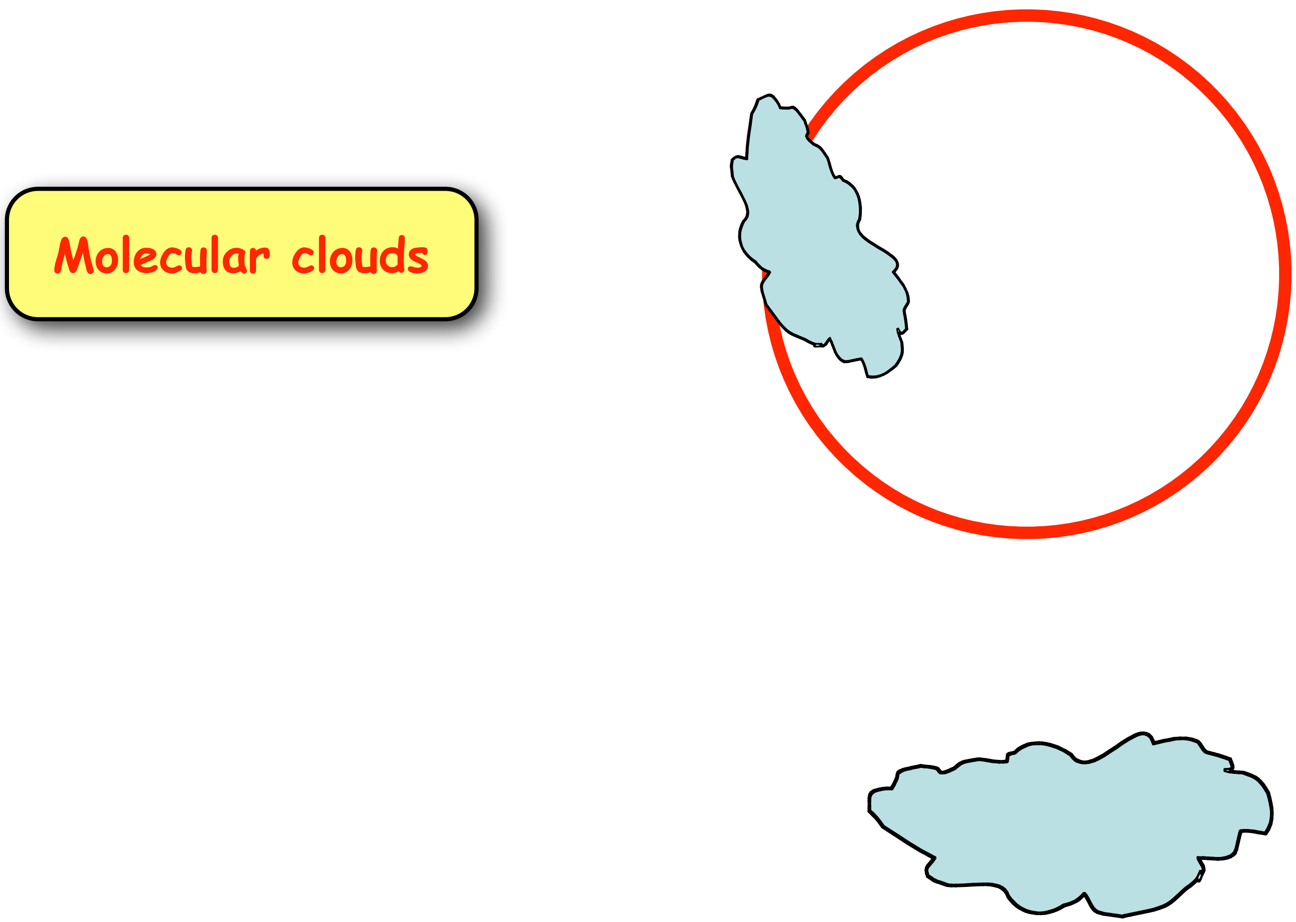

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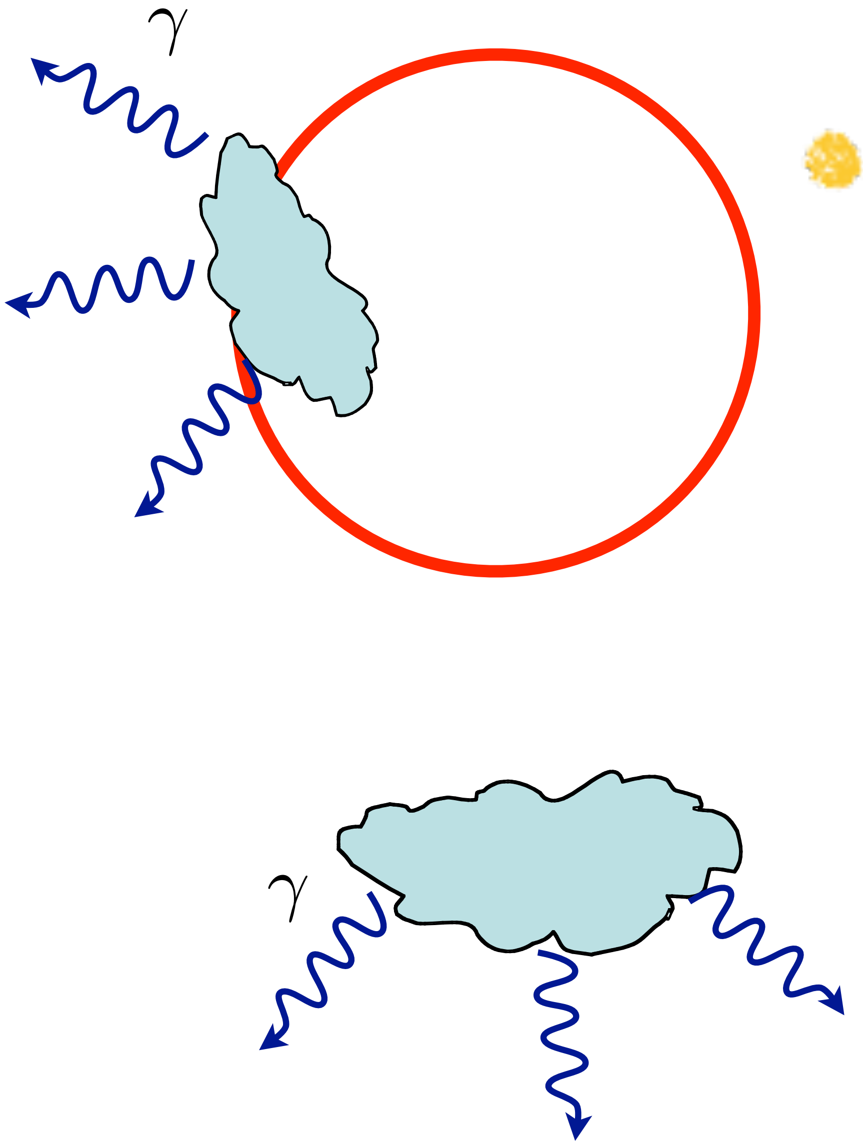
Molecular clouds

- gamma rays + gas
  - -> CR protons?



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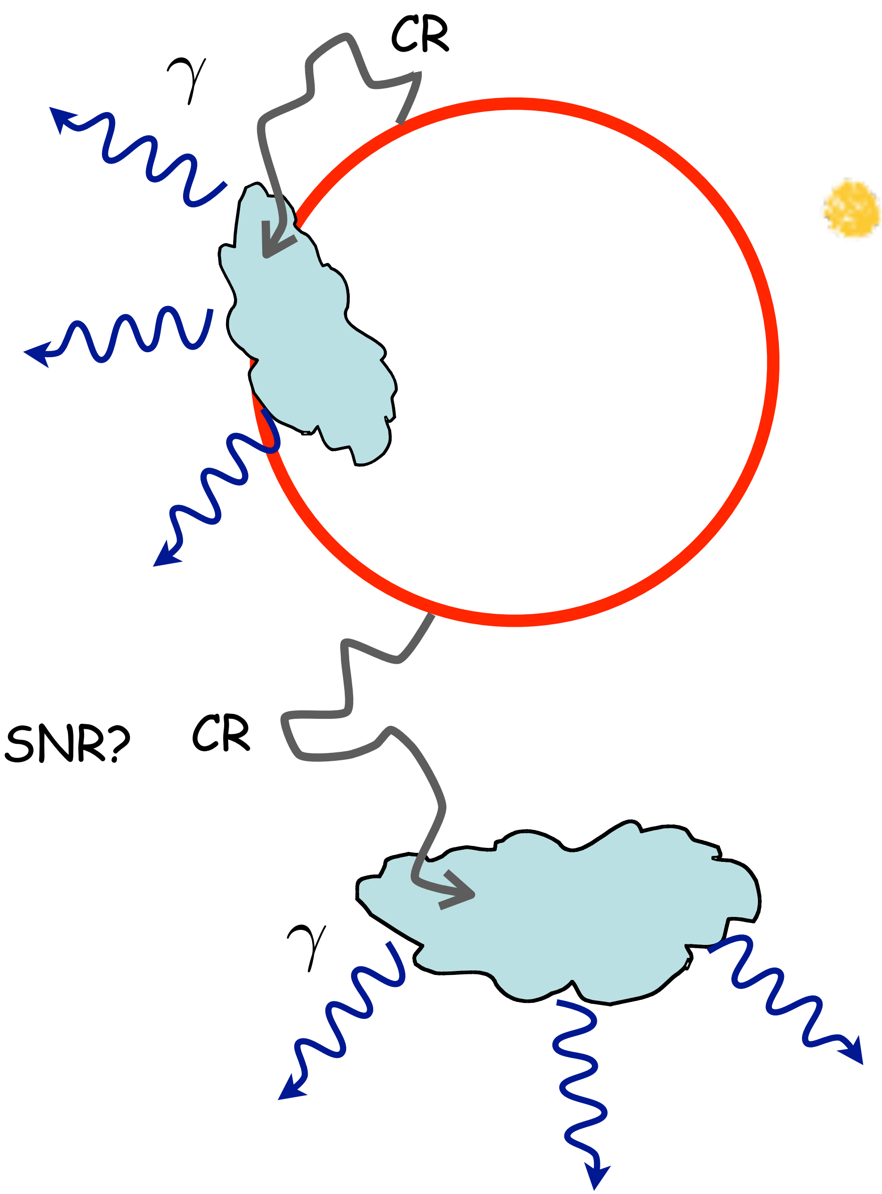

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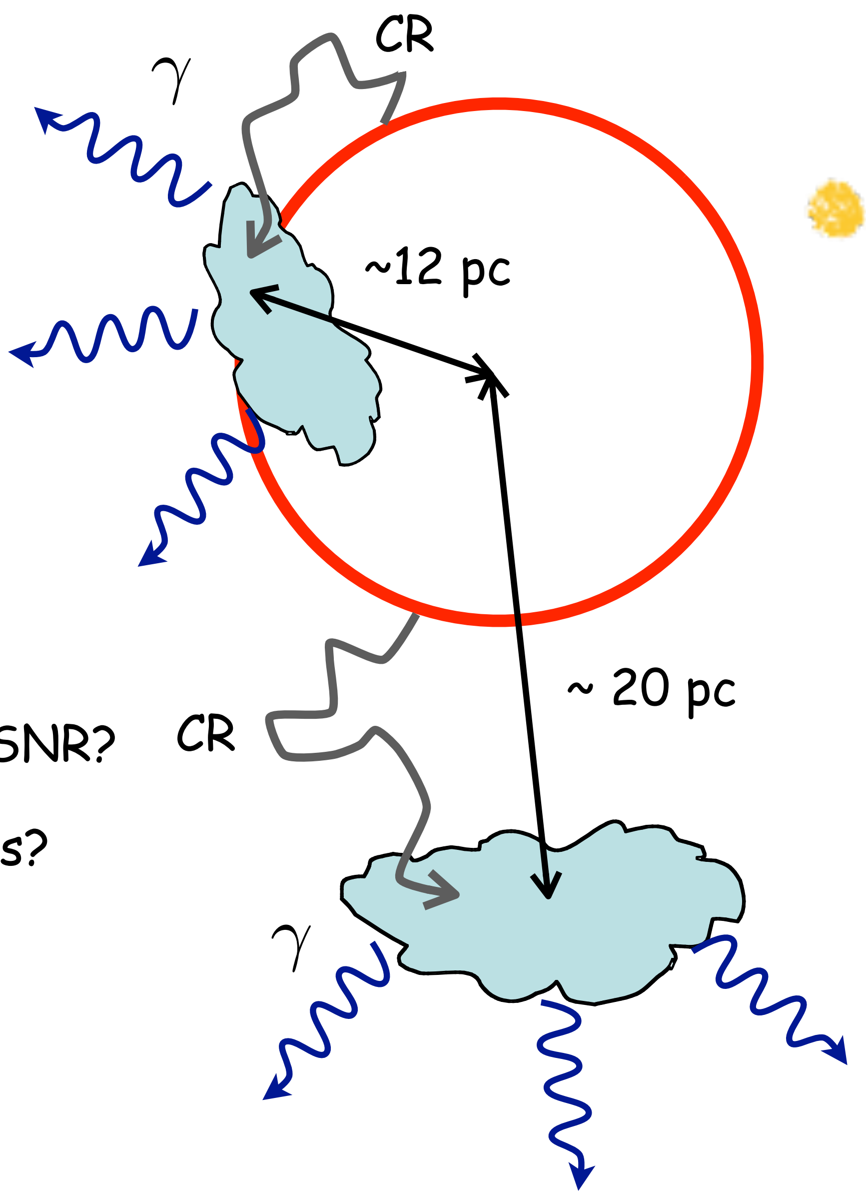

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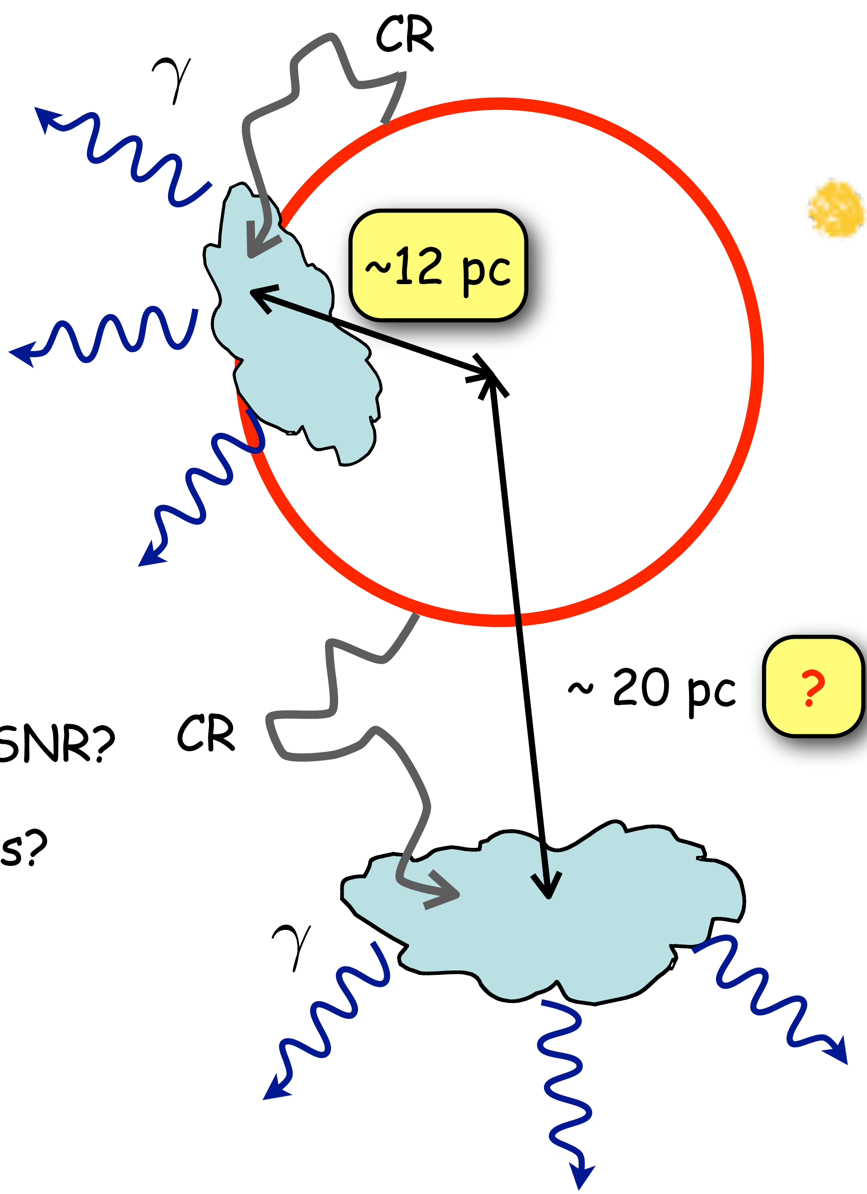

SNR shell

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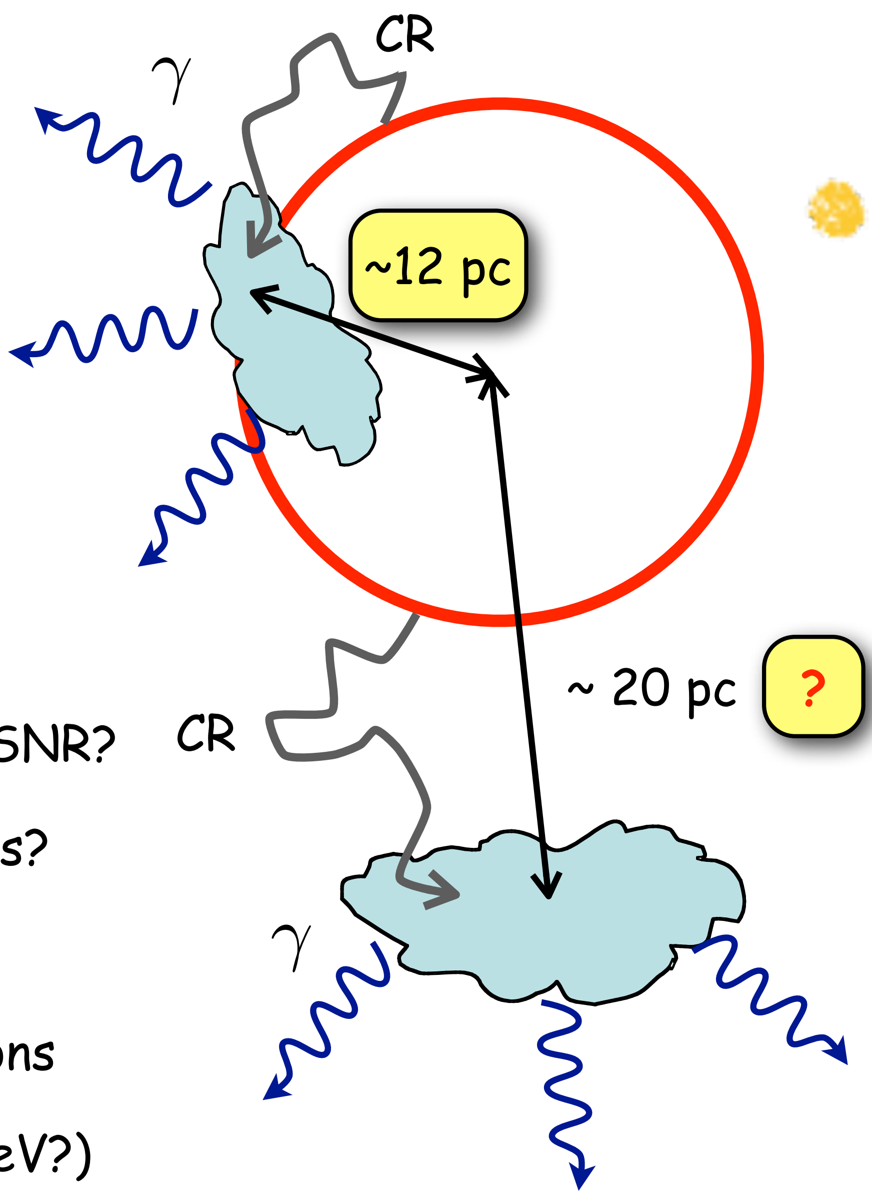
W28 as seen by a theoretician

Molecular clouds

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



SNR shell

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Escaping particles

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

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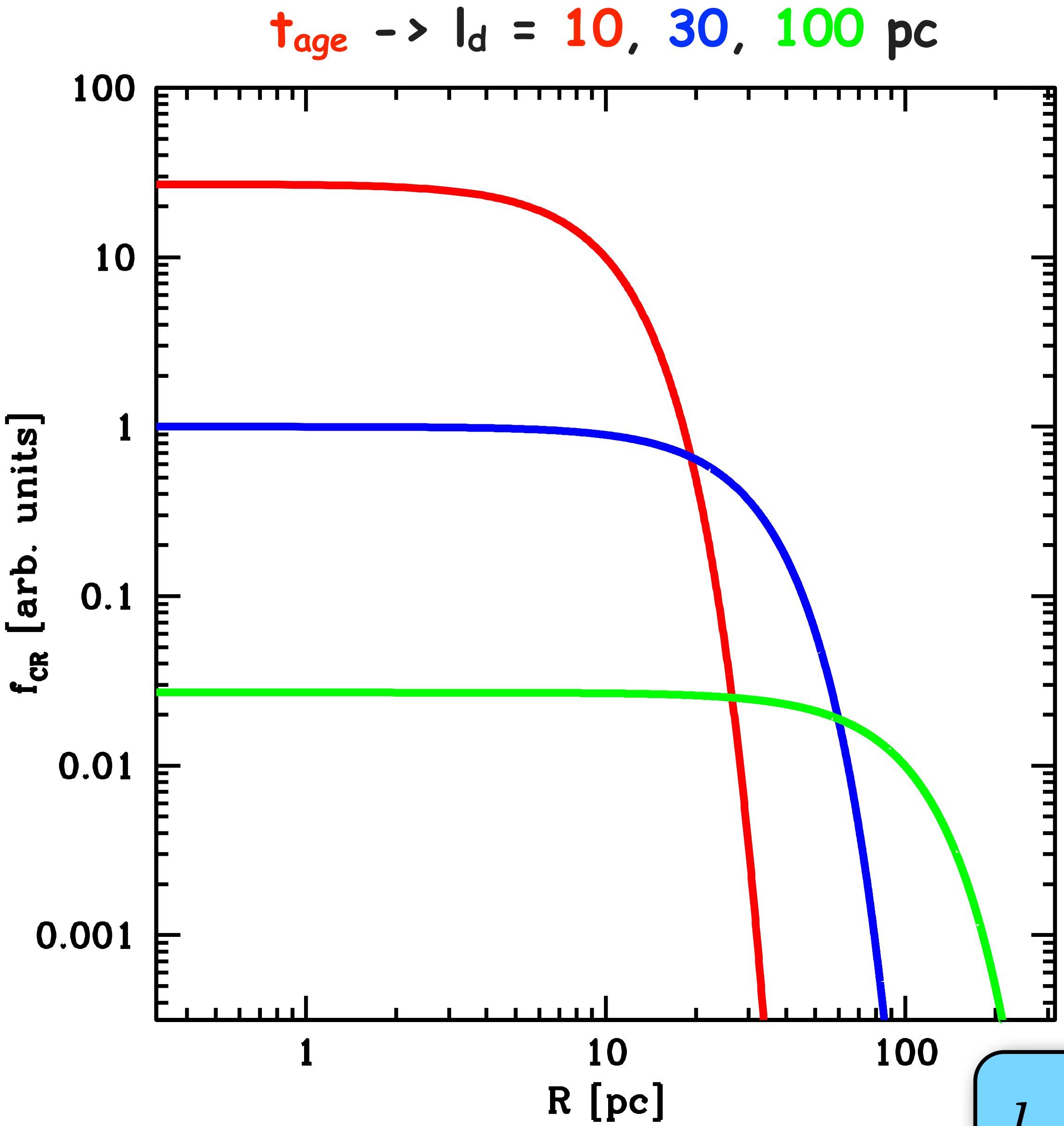
$$t = t_{age} - t_{out}$$

? model dependent...

high energy particles

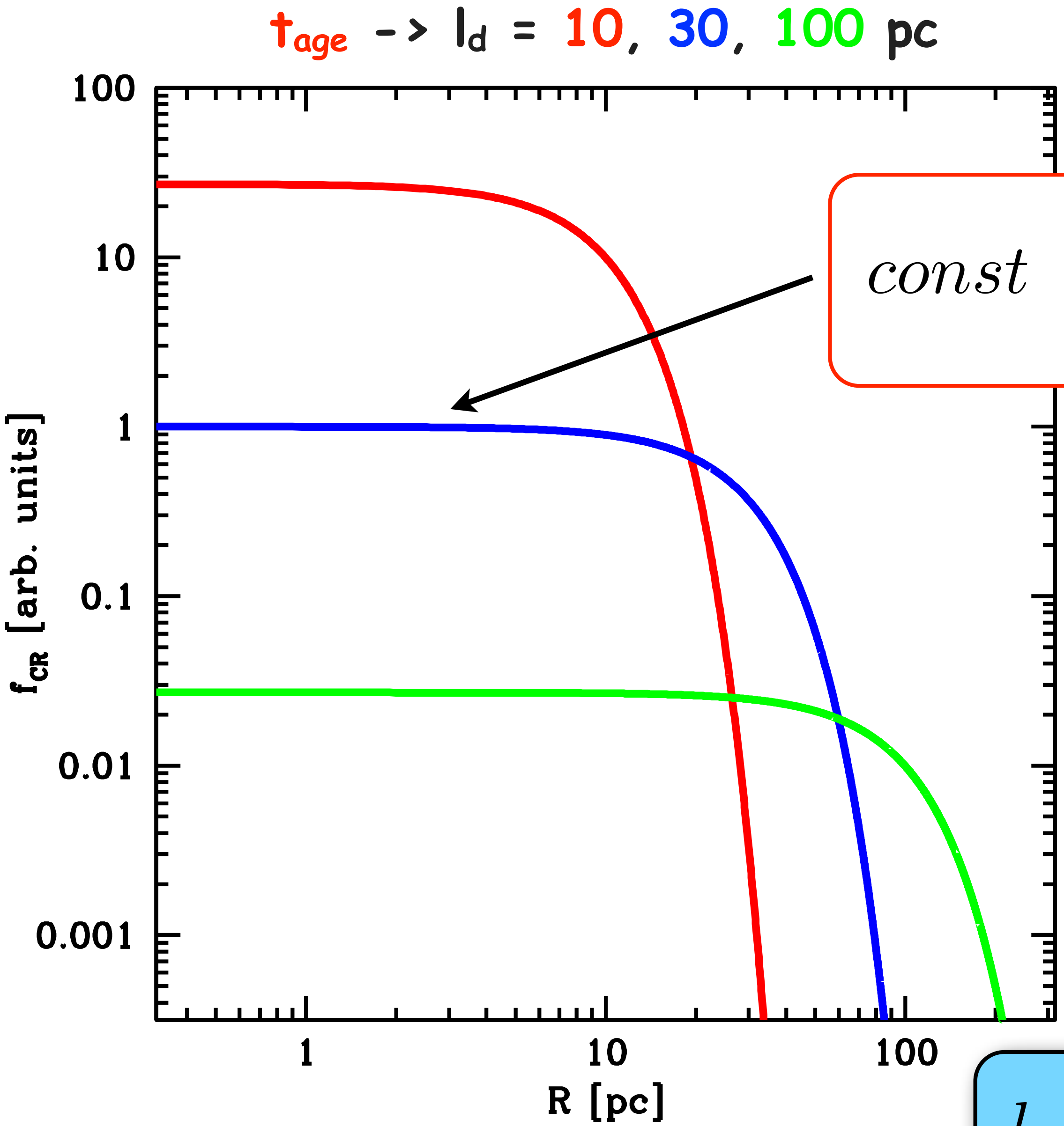
lower energies -> point-like approx not so good + model dependent ($t_{out} \sim t_{age}$)

Escaping particles: CR spectrum



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

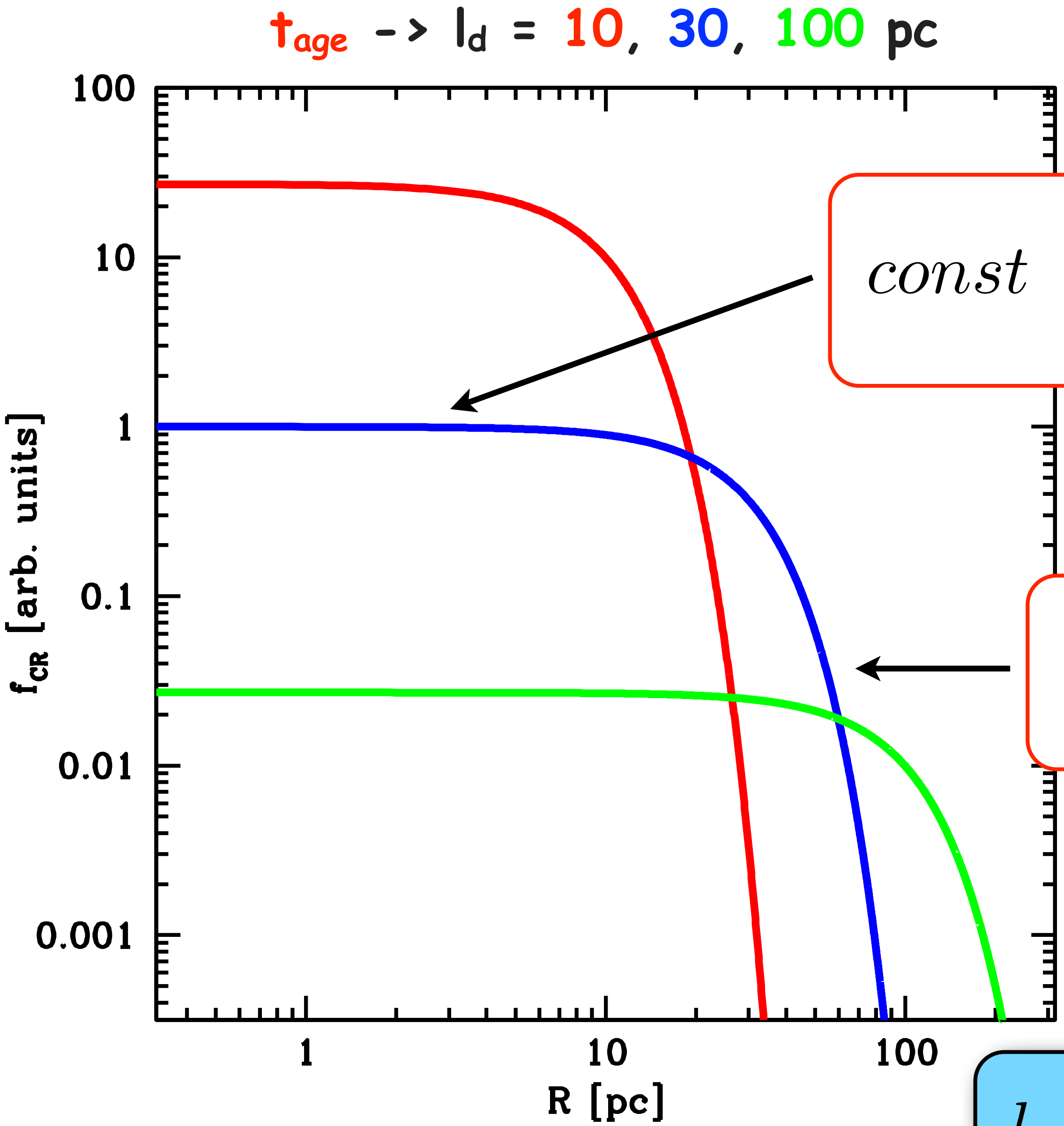
Escaping particles: CR spectrum



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

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

Escaping particles: CR spectrum



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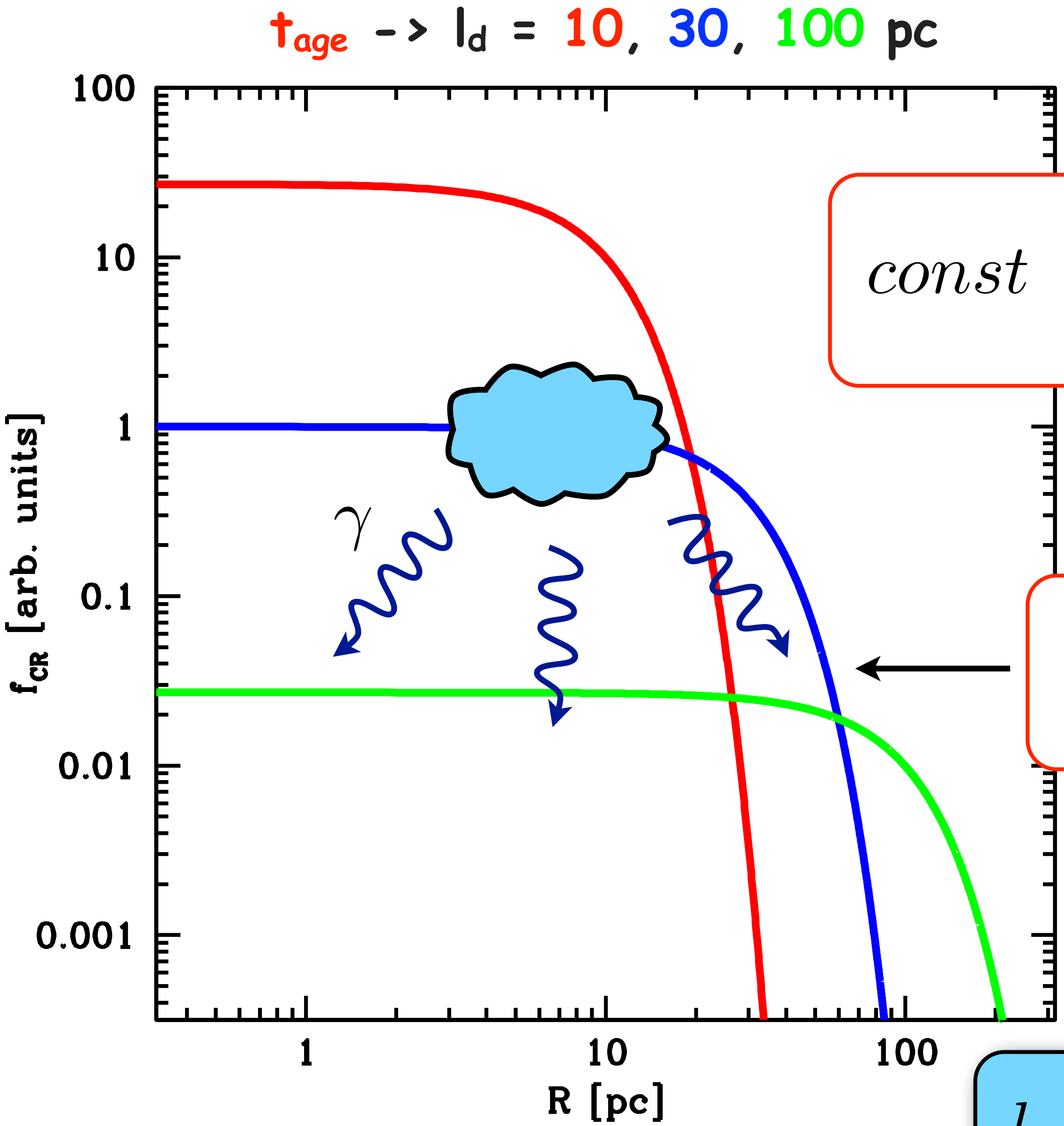

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Escaping particles: CR spectrum

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

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

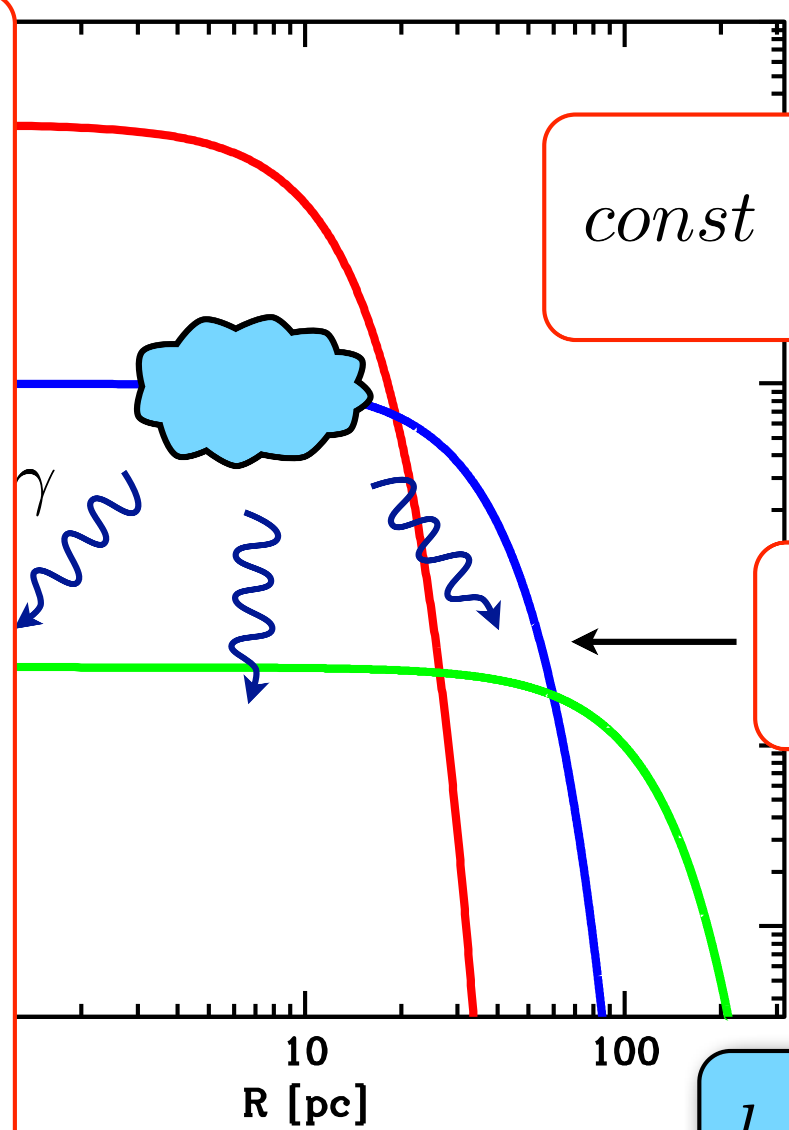
$$t_{age} \approx 3 \times 10^4 \div 10^5 \text{yr}$$

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

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

estimate D?

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



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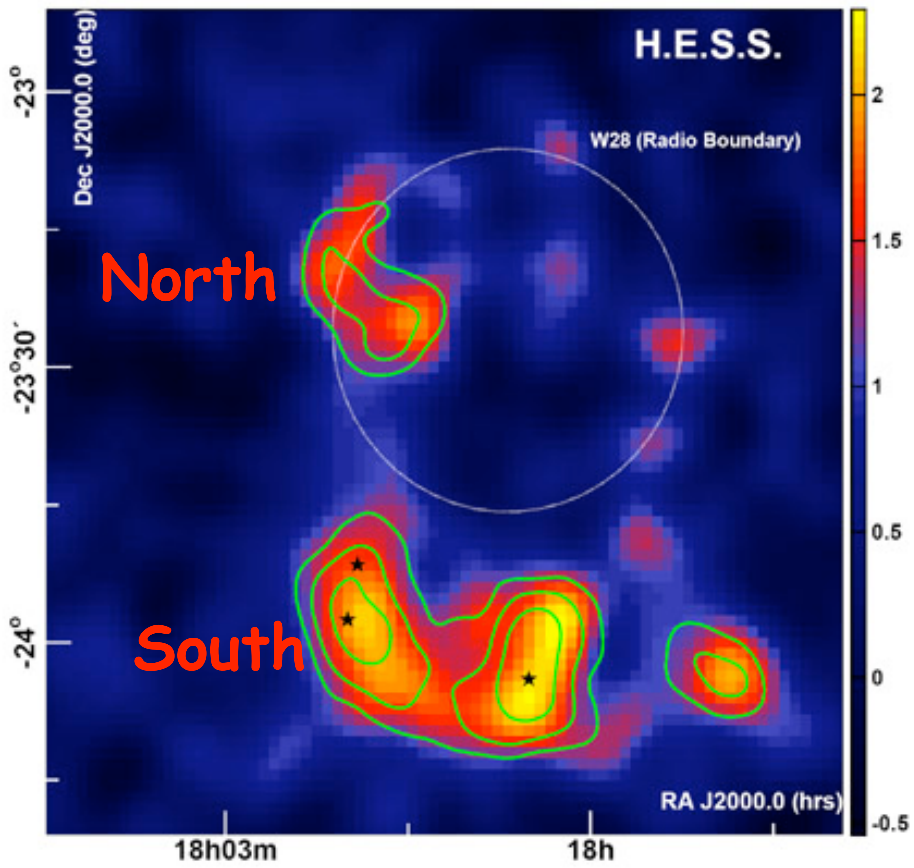
Escaping particles: W28



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

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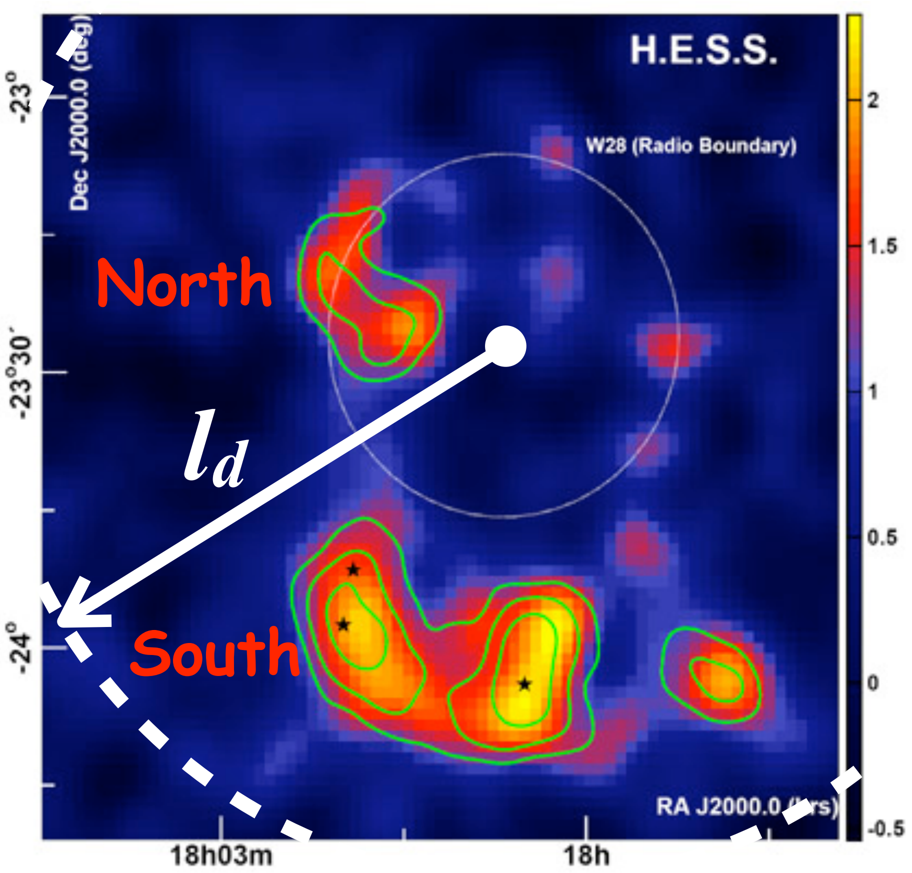

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both clouds within a distance l_d

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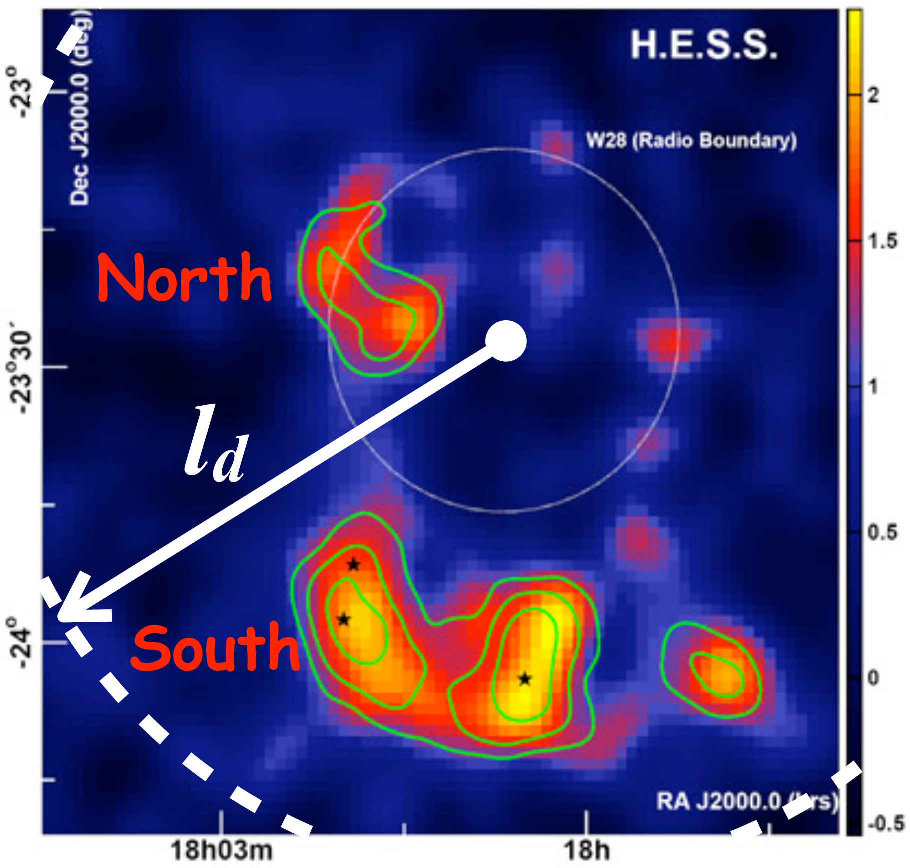

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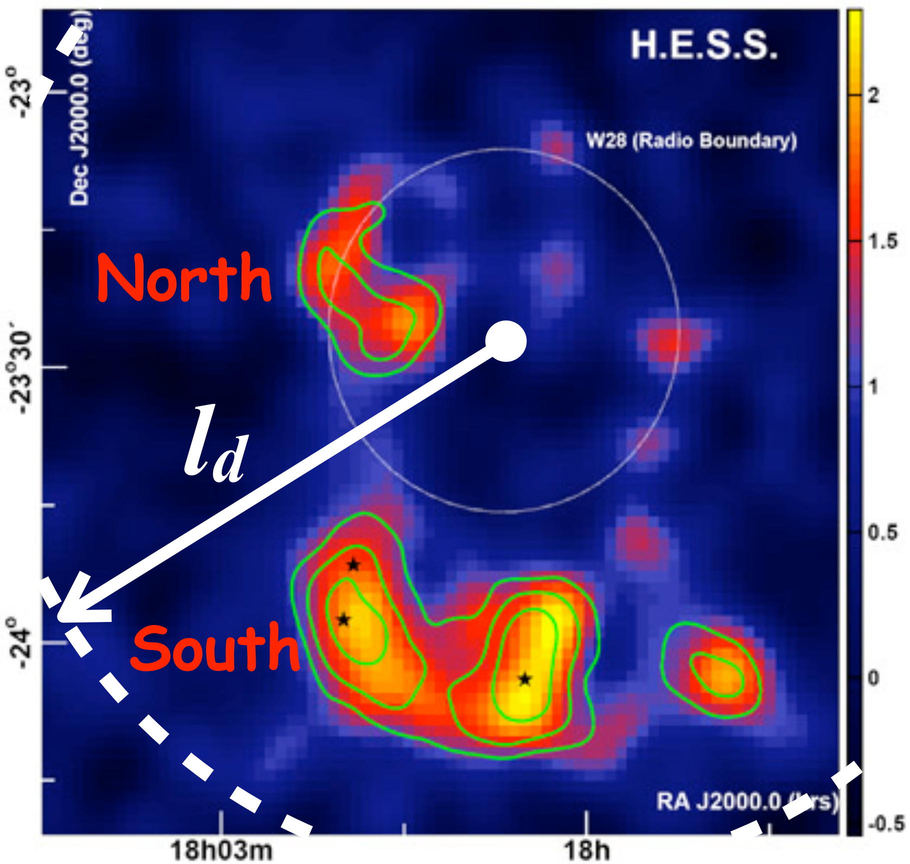

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$$F_\gamma \propto \frac{f_{CR}\, M_{cl}}{d^2} \propto \frac{\eta_{CR}\, E_{SN}}{(D\ t_{age})^{3/2}} \left(\frac{M_{cl}}{d^2}\right)$$

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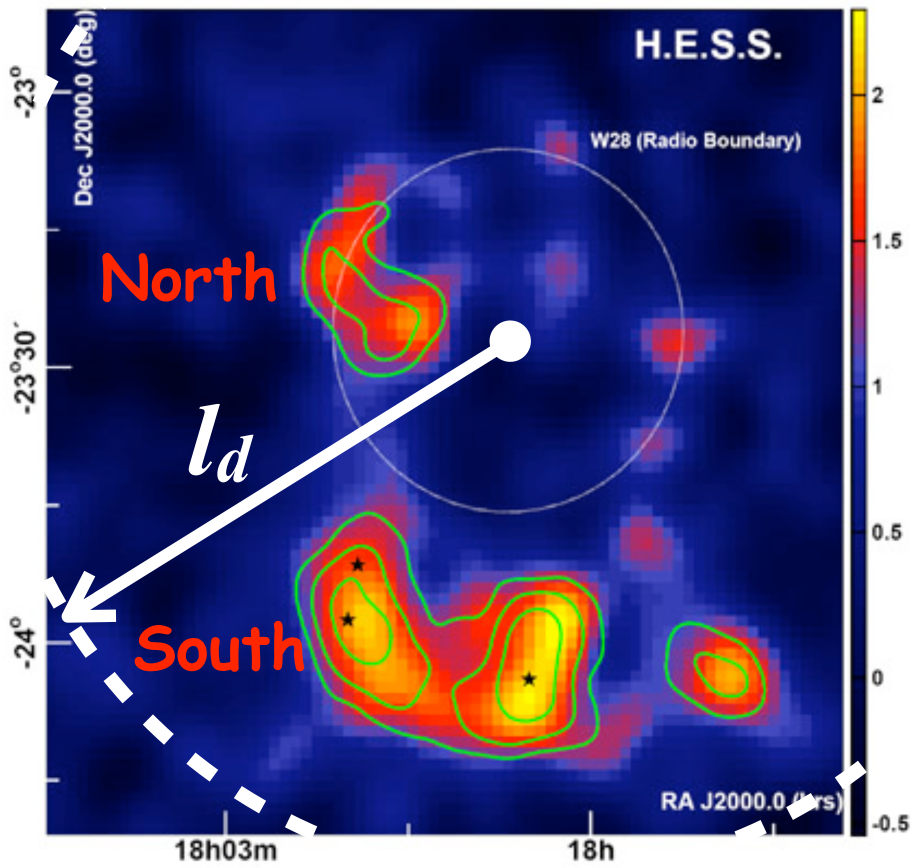

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$$F_\gamma \propto \frac{f_{CR}\, M_{cl}}{d^2} \propto \frac{\eta_{CR}\, E_{SN}}{(D\ t_{age})^{3/2}} \left(\frac{M_{cl}}{d^2}\right)$$

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

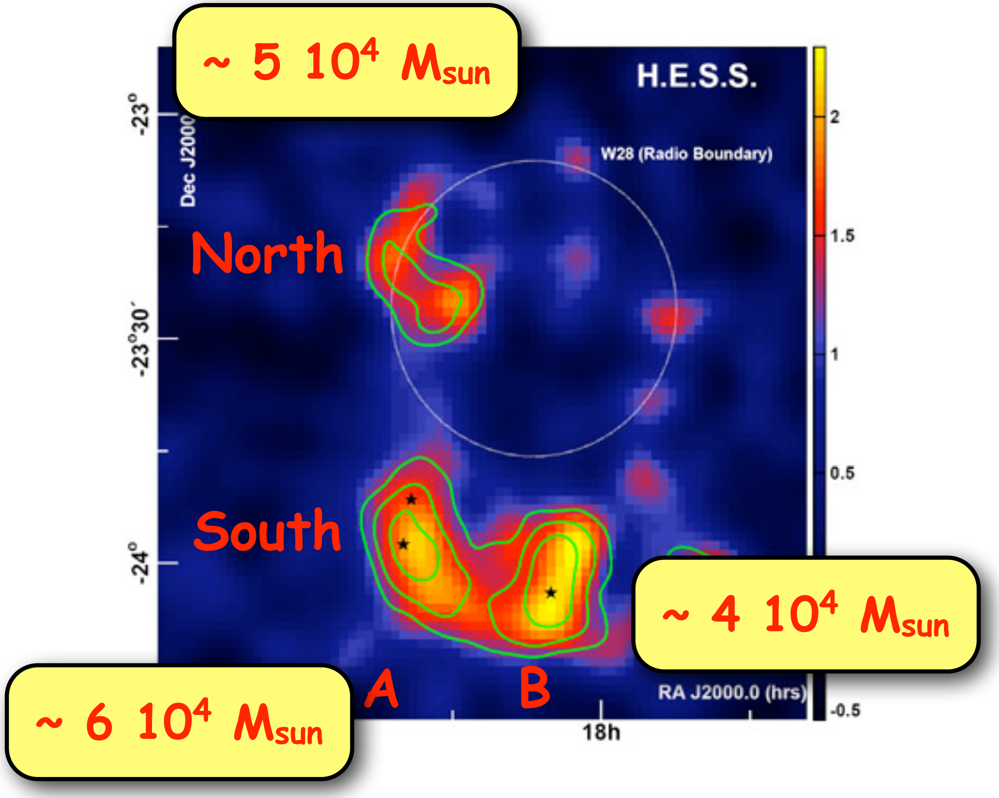
Assumptions:

- 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



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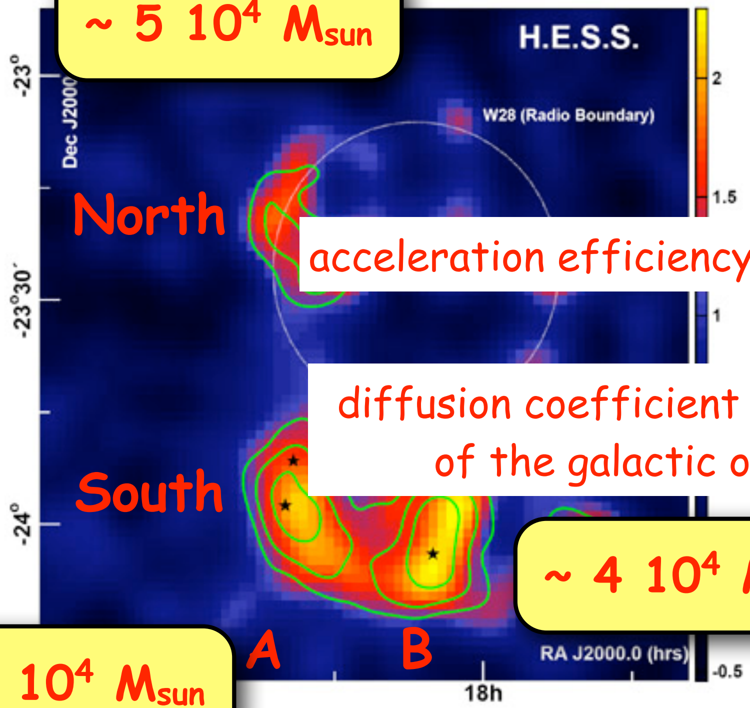


~ 5 10^4 M_{sun}

North

South

A

B

~ 4 10^4 M_{sun}

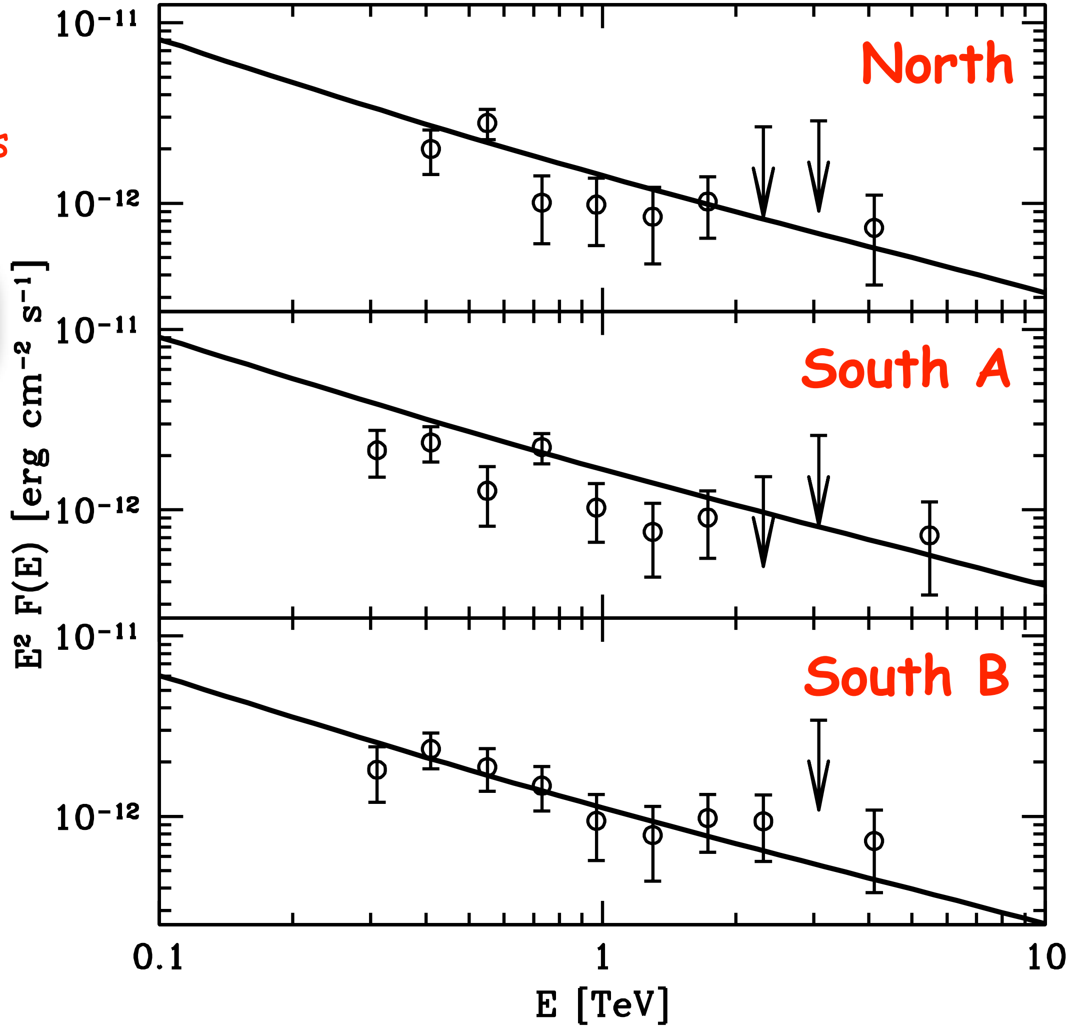
~ 6 10^4 M_{sun}

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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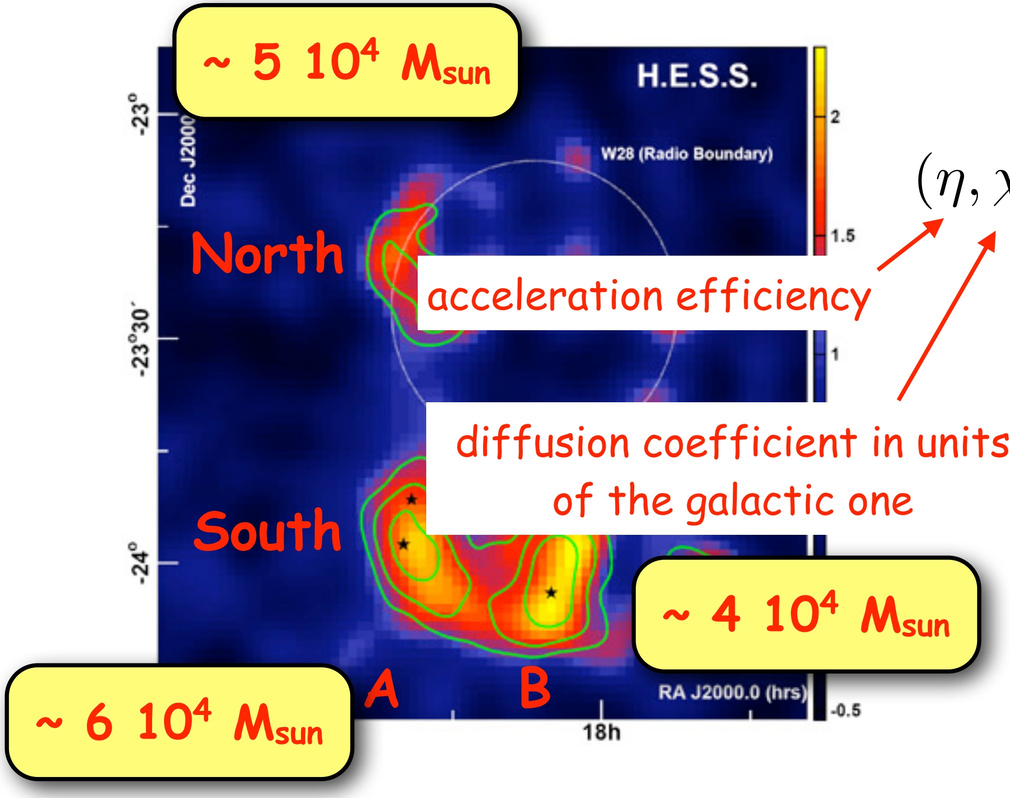

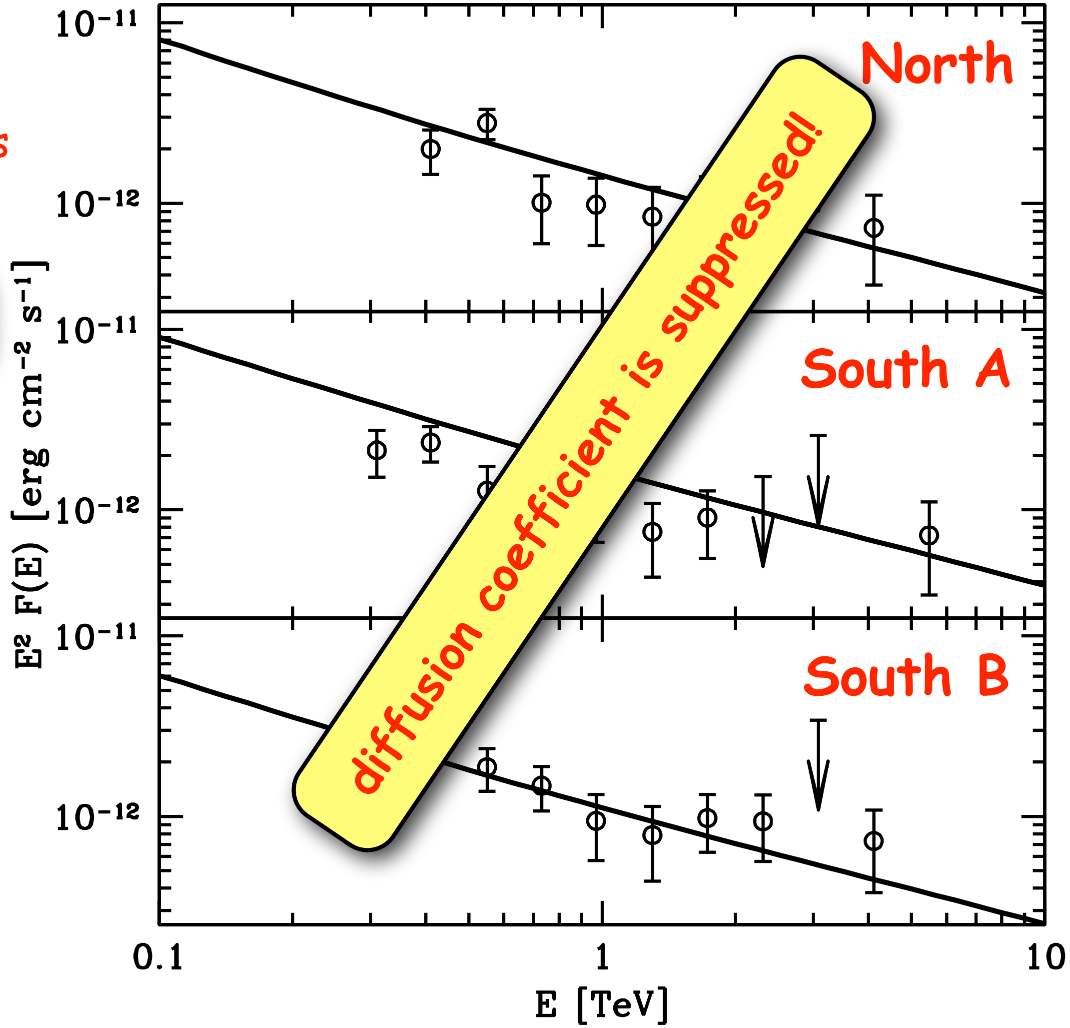

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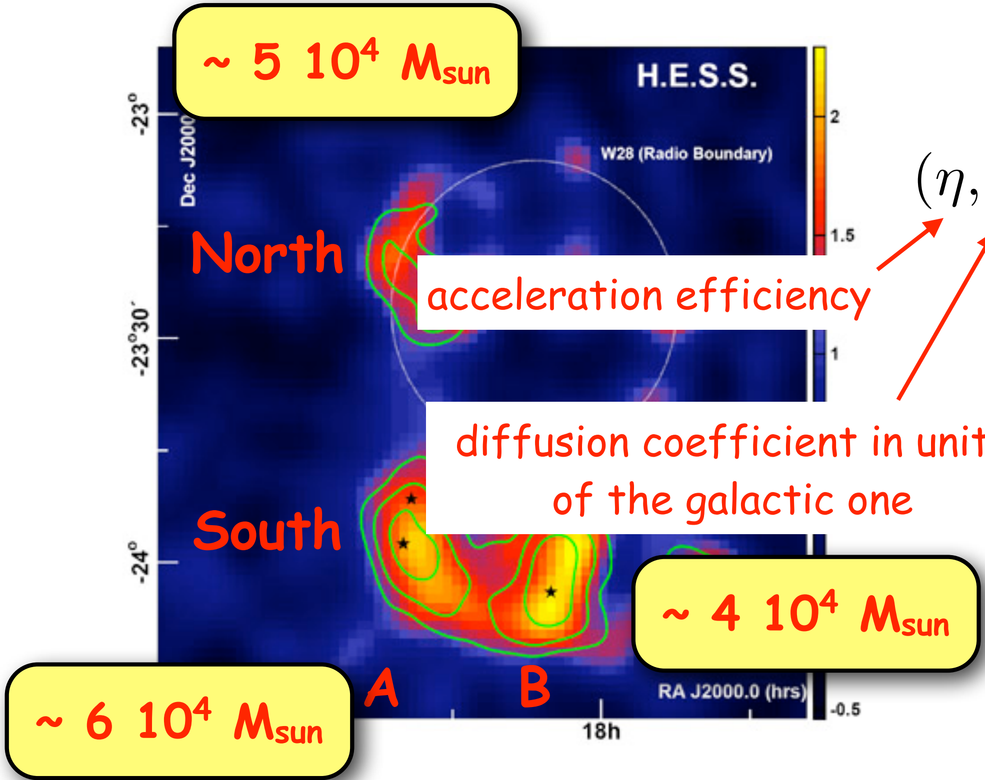

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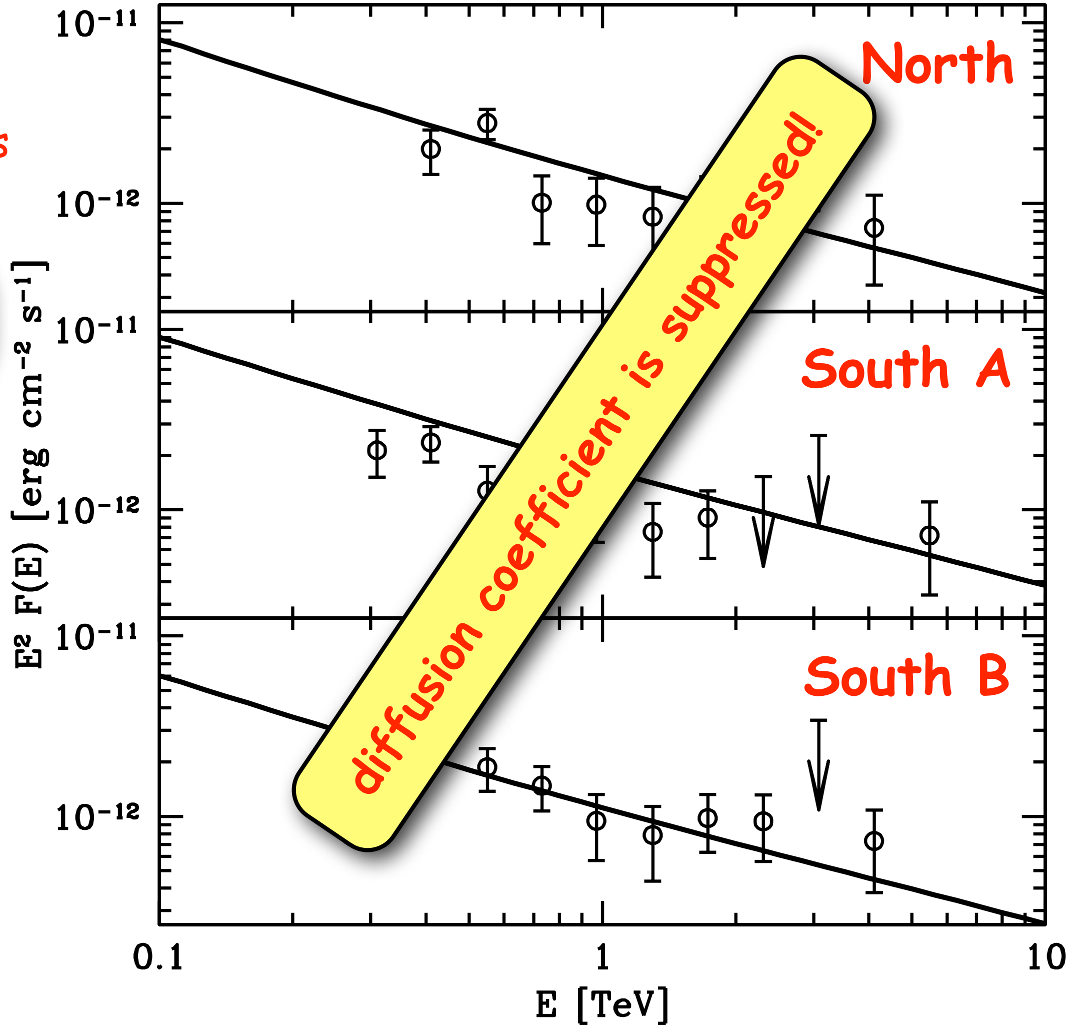


size of "CR bubble" @3 TeV

$$l_d \approx 70 \text{ pc} \rightarrow \chi = 0.028$$

$$\approx 95 \text{ pc} \rightarrow \chi = 0.06$$

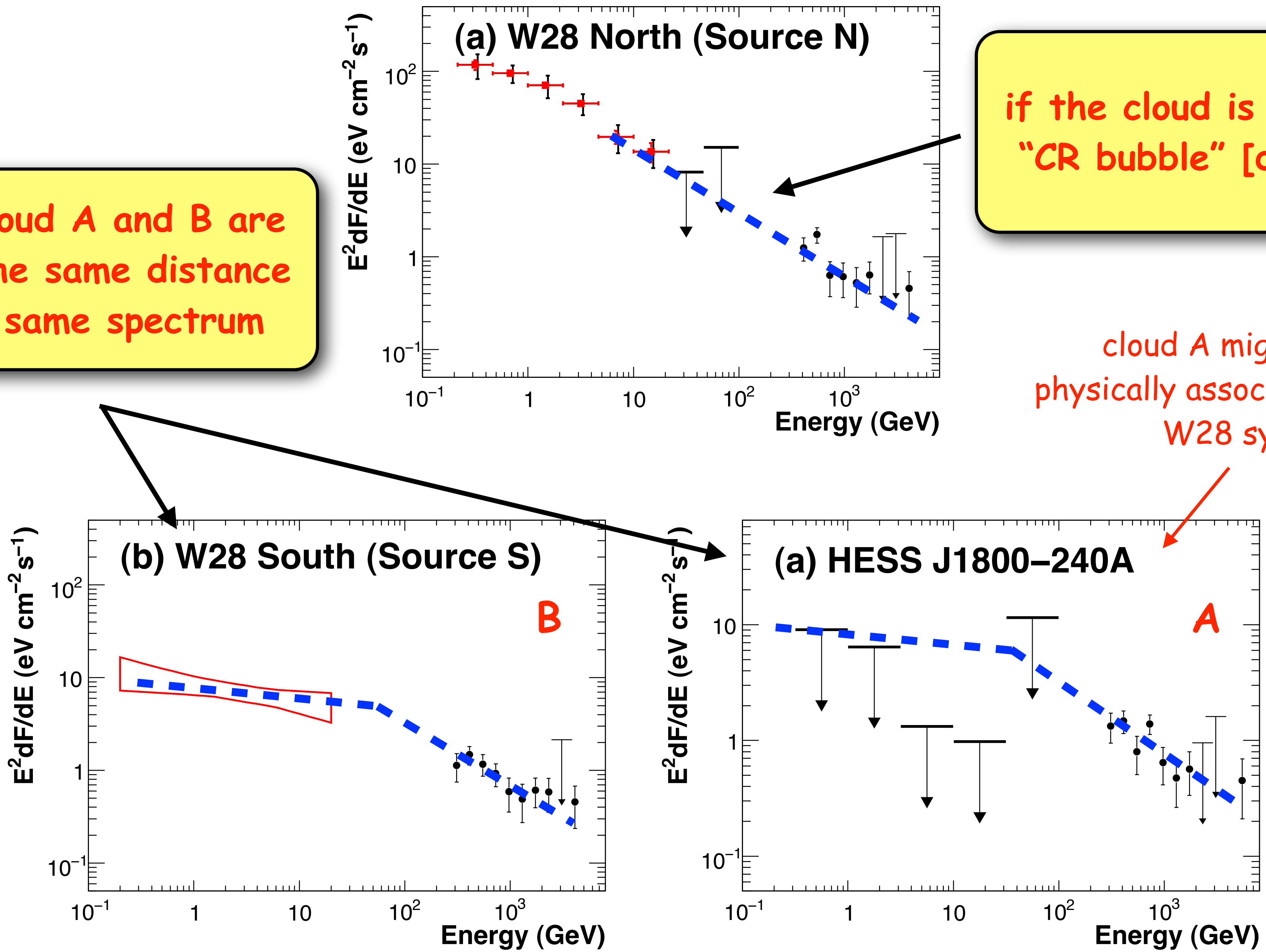
$$\approx 115 \text{ pc} \rightarrow \chi = 0.085$$

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

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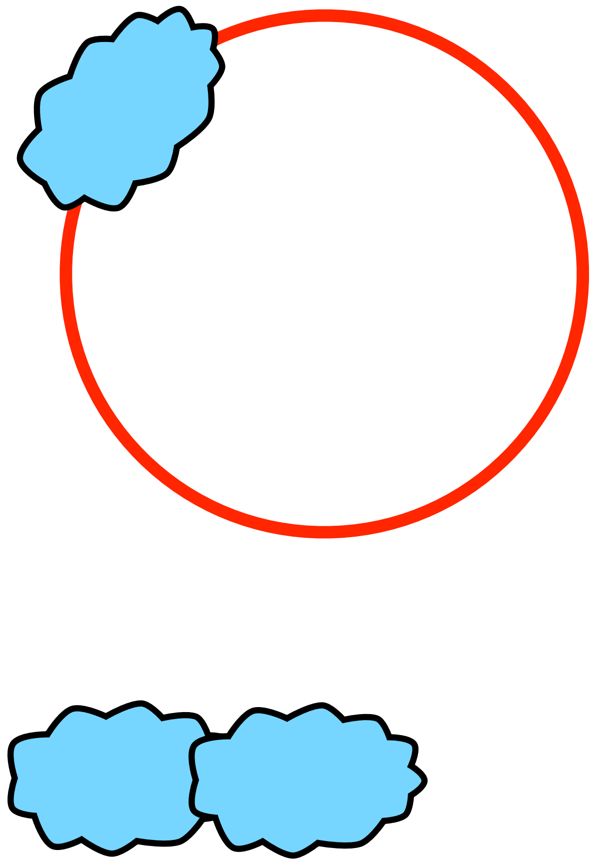

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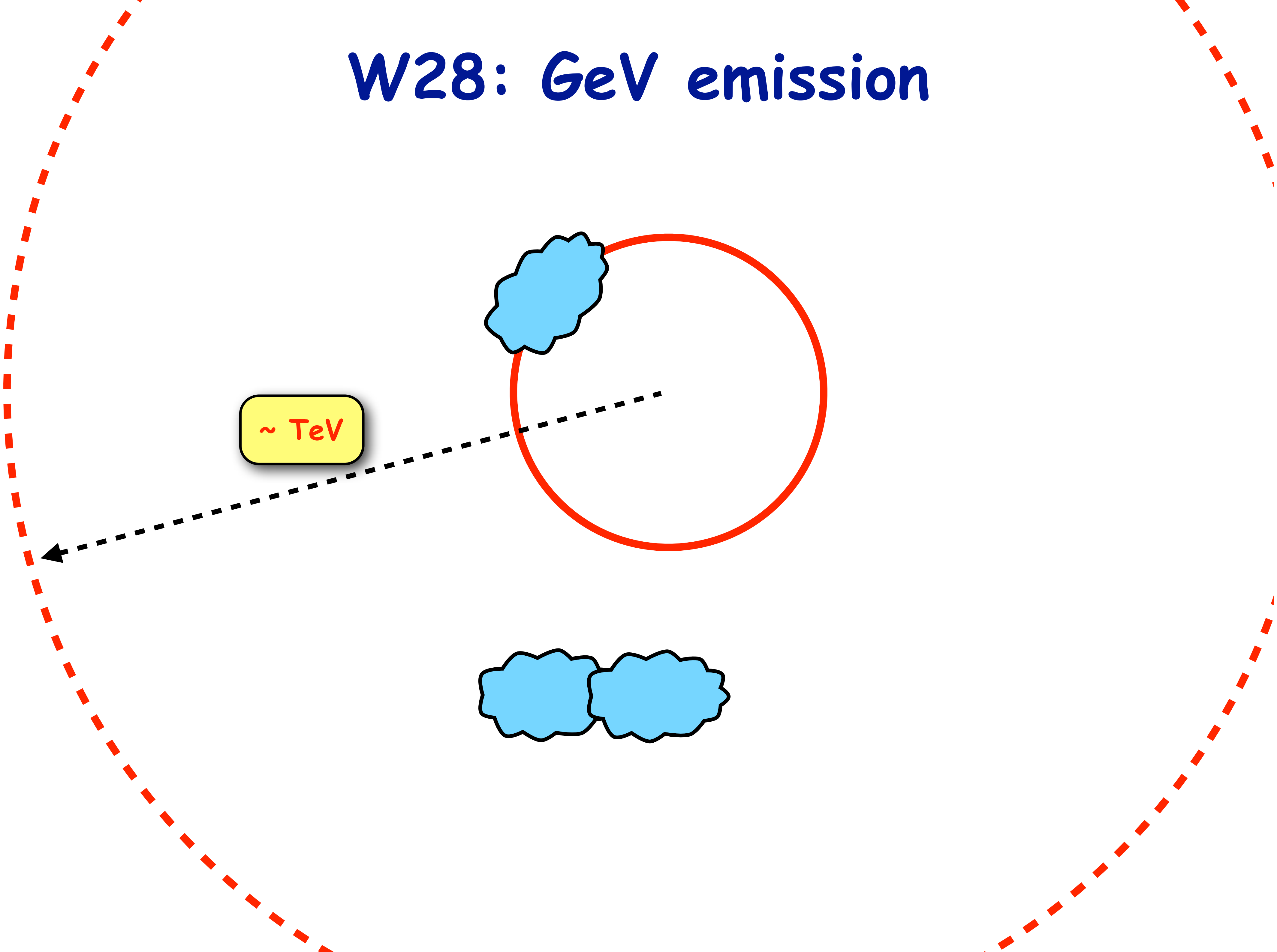

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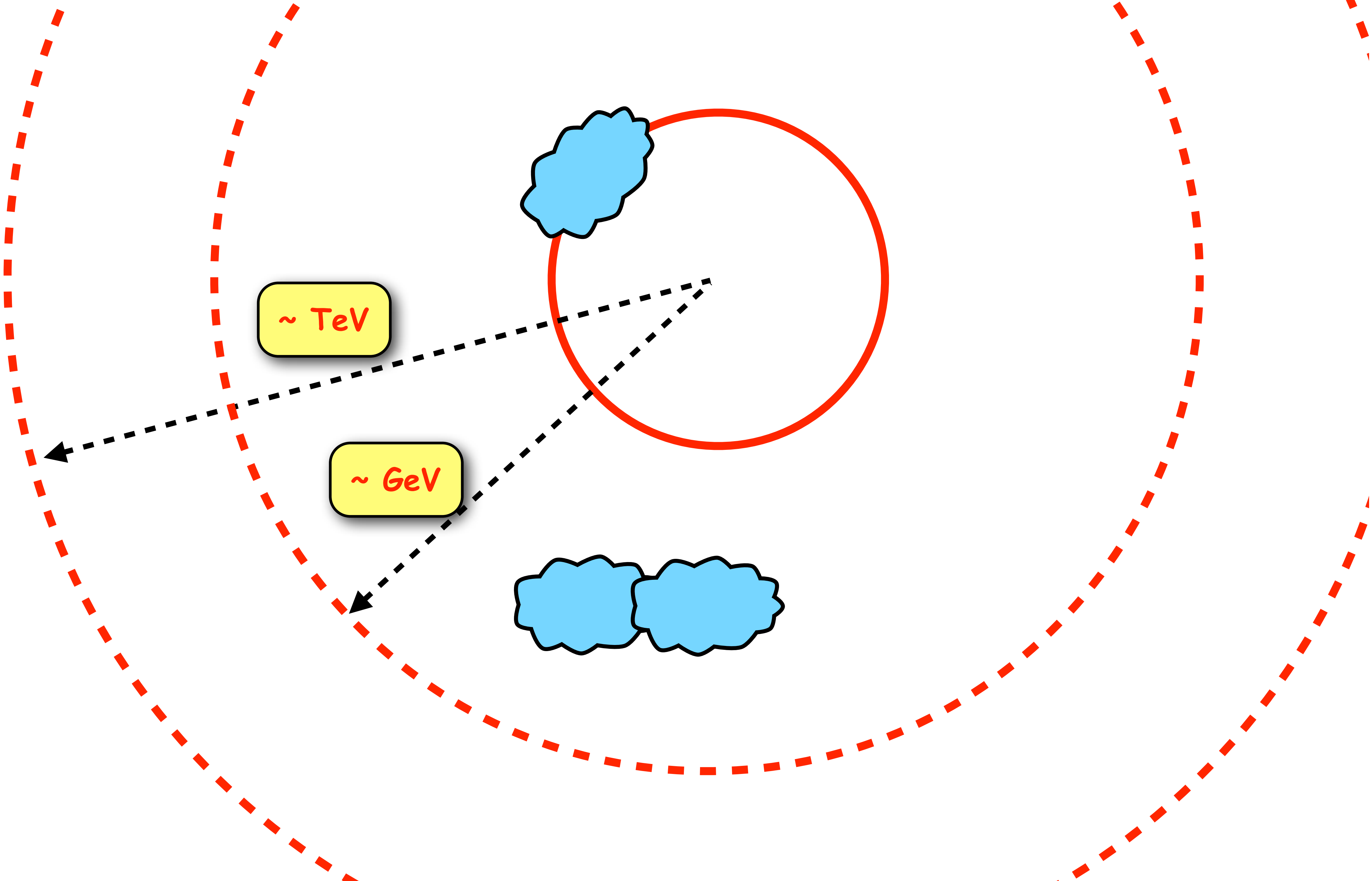

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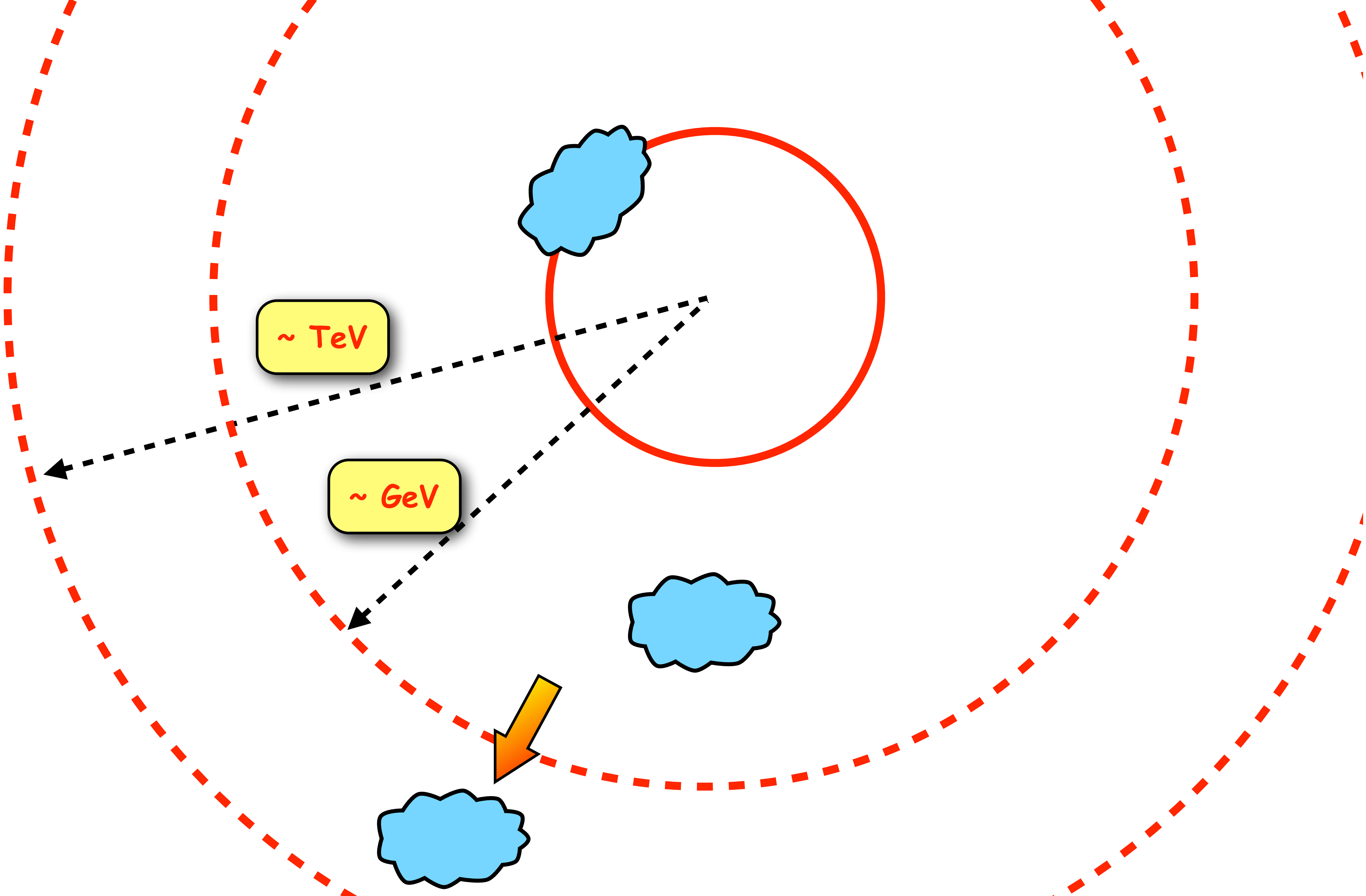
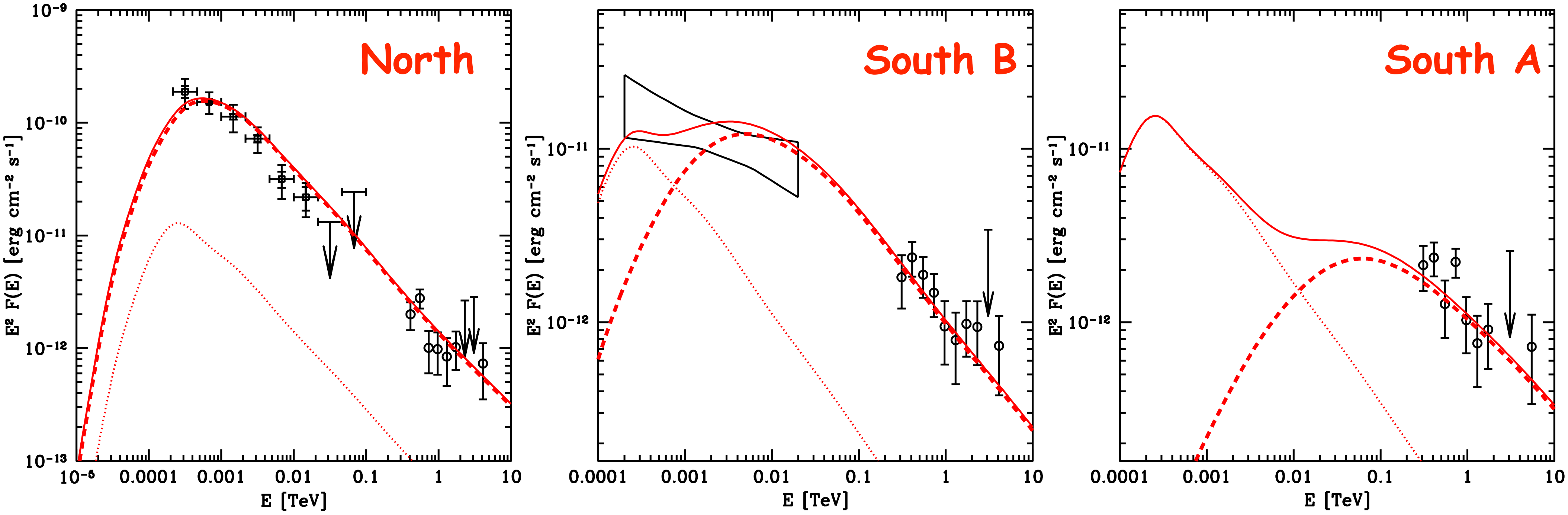


W28: GeV emission

$$\eta = 30\%$$

$$\chi = 0.06$$



d = 12 pc

d = 32 pc

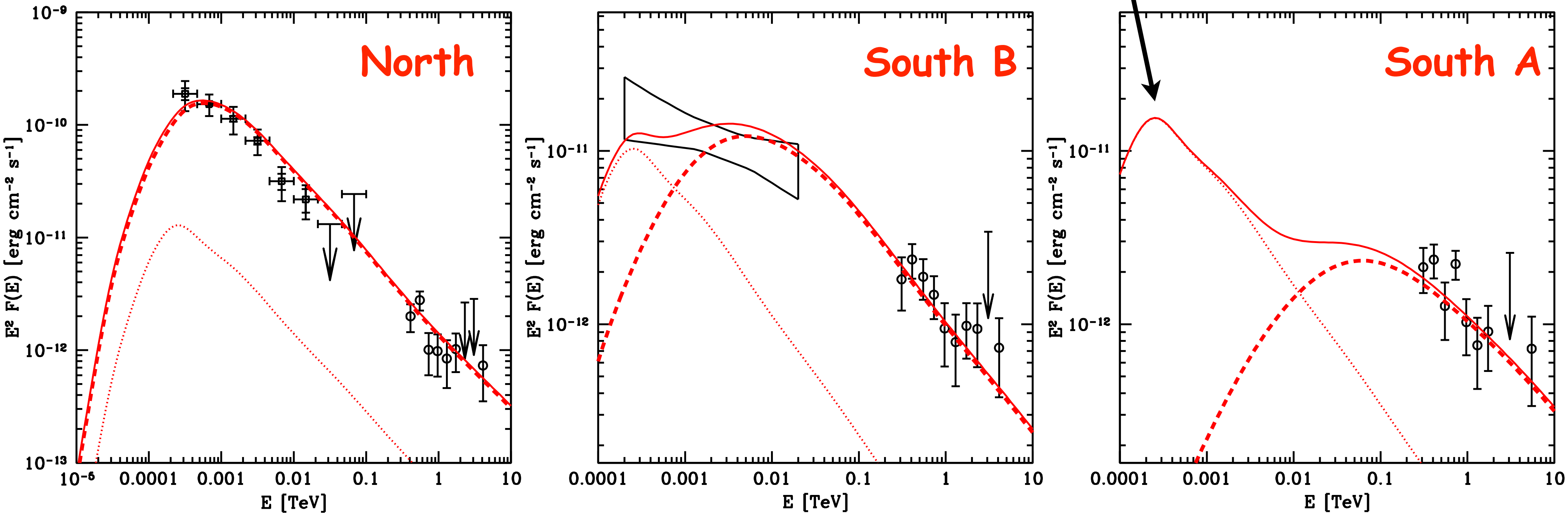
d = 65 pc

W28: GeV emission

$\eta = 30\%$

$\chi = 0.06$

this peak is removed as background



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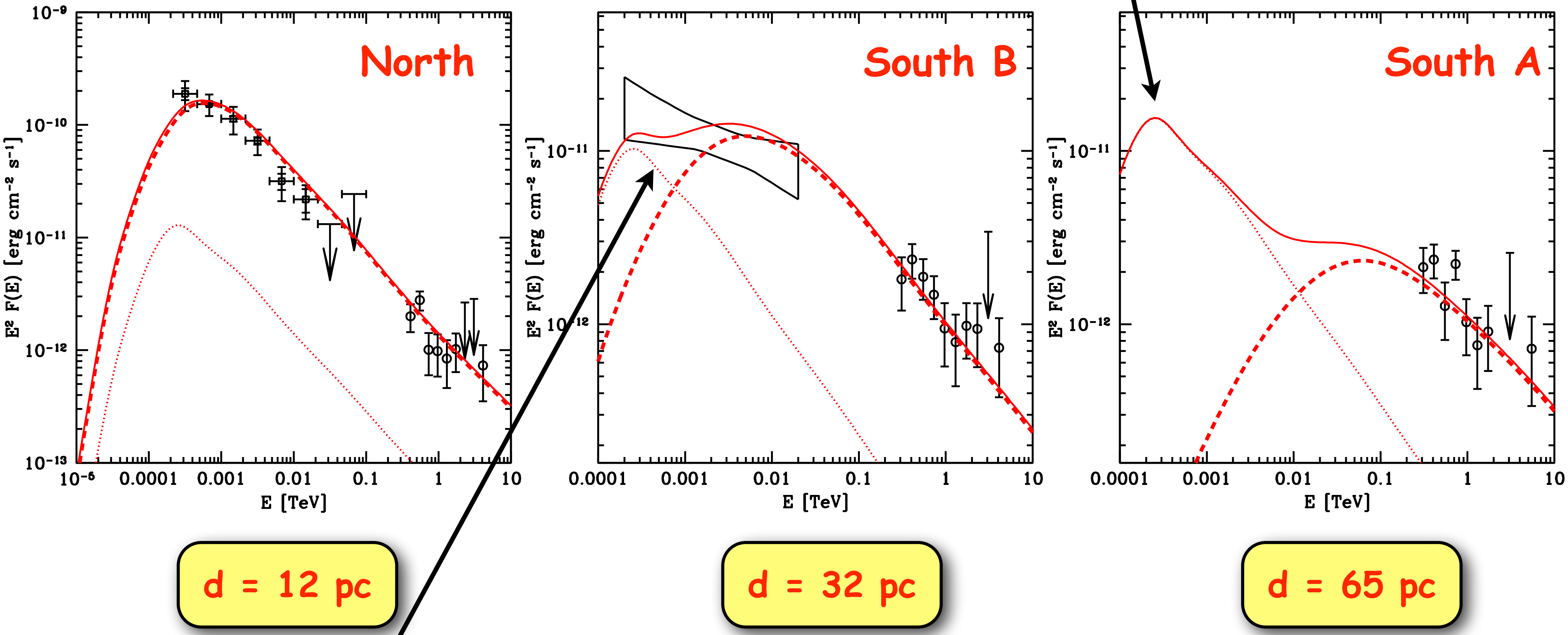

some problems here...

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

Conclusions (problems)

Can we estimate the diffusion coefficient?

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- by a factor of ~ 10-100
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-> more data from HESS, Fermi, and CTA