Gamma Rays from Molecular Clouds and the Origin of Galactic Cosmic Rays

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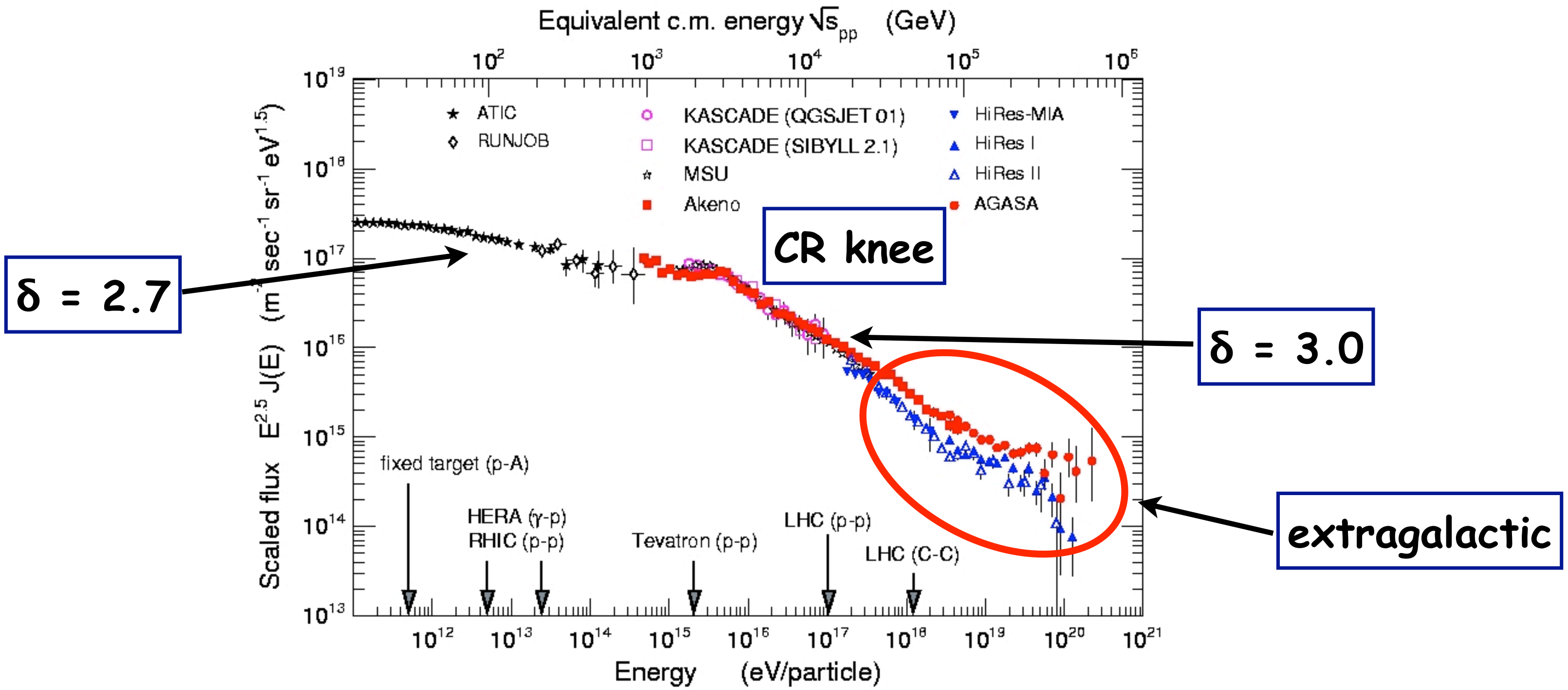
MARIE CURIE ACTIONS

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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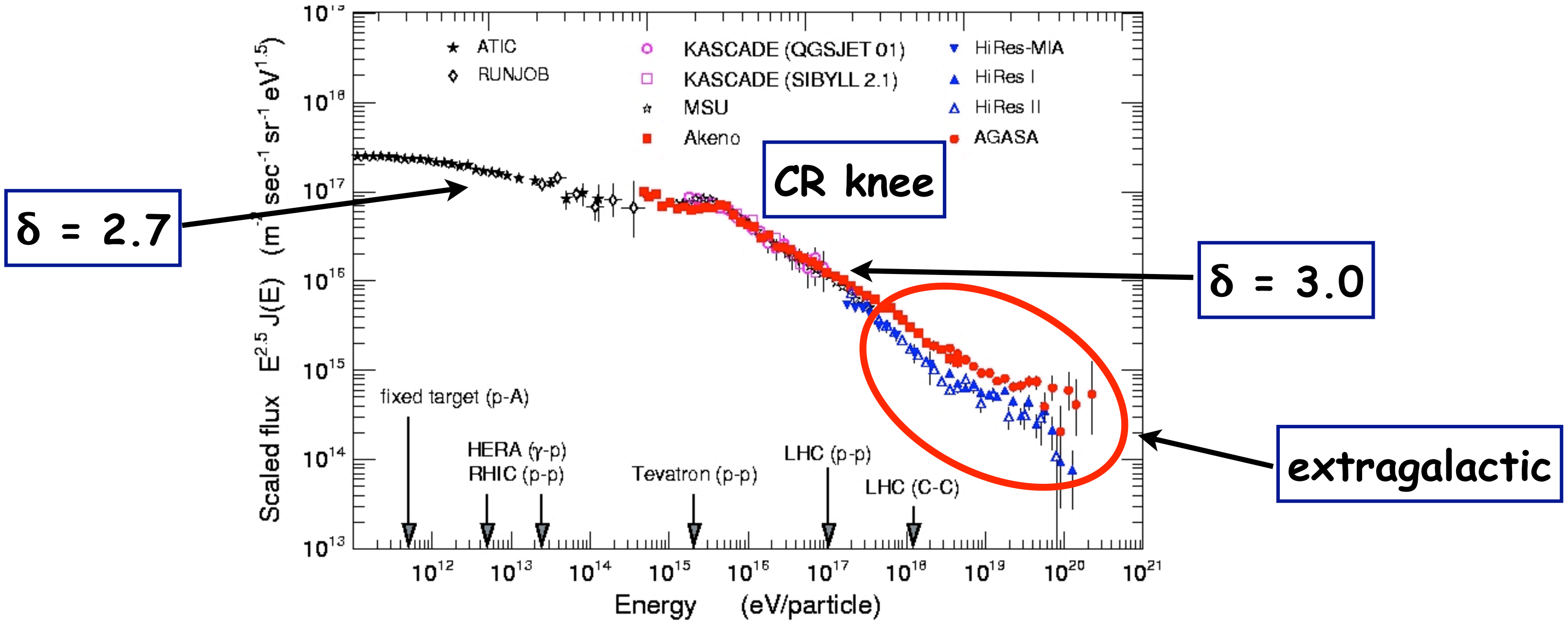
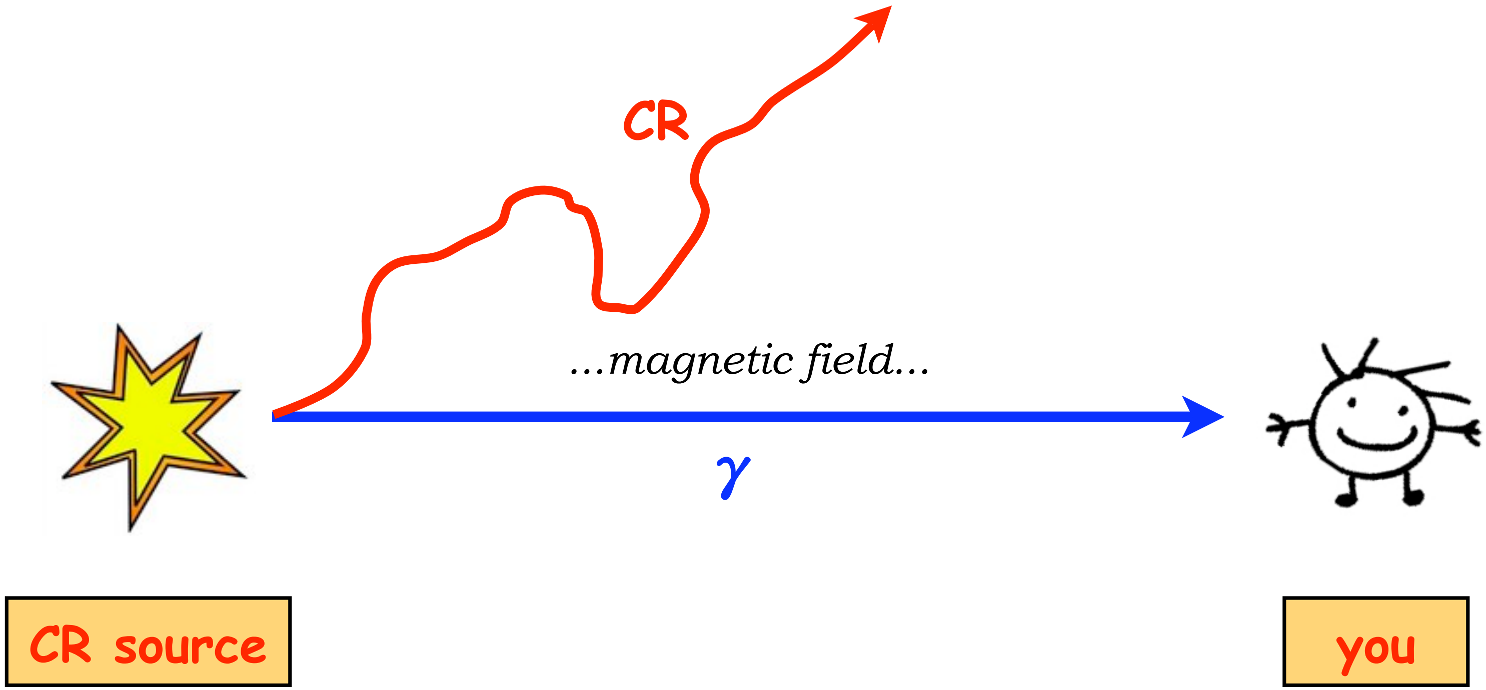
Most popular explanation:

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



Why is it so difficult?



We cannot do CR Astronomy.

Need for indirect identification of CR sources.

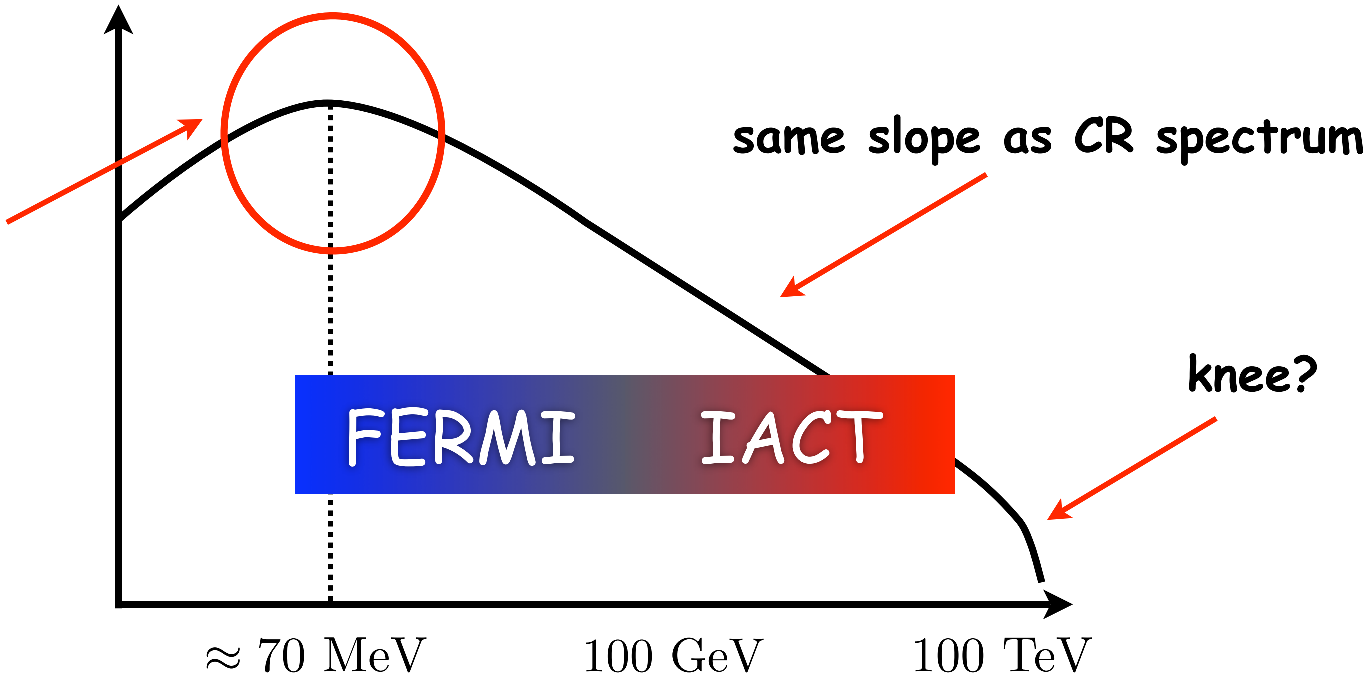
Gamma-ray astronomy

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

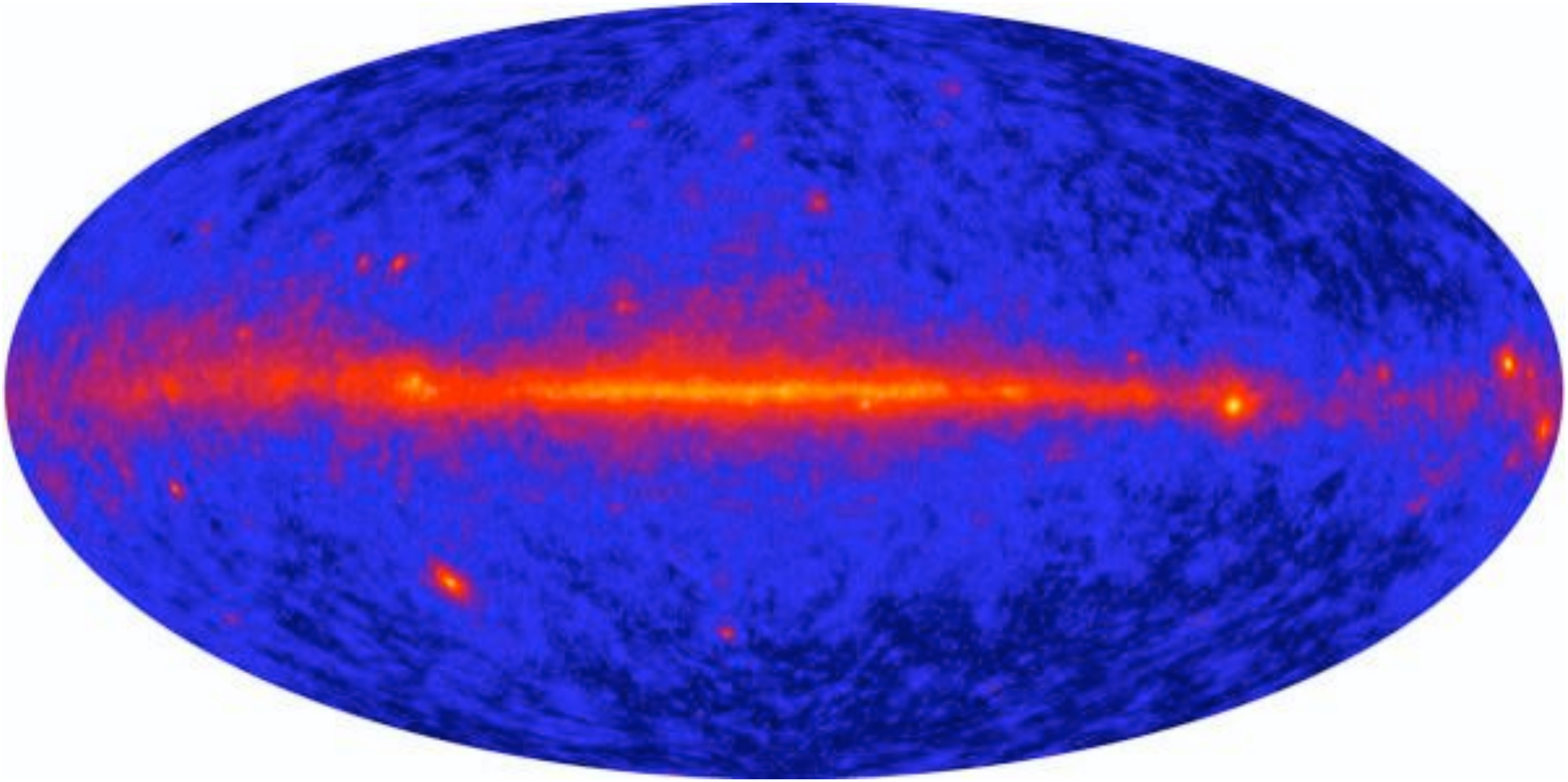
CR ISM

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

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



The sky @ E>100 MeV (FERMI)



We need to know:

Which are the sources of CRs?

- which acceleration mechanism? -> injection spectrum
- total energy in CRs
- maximum energy of accelerated particles

How do CRs propagate?

- magnetic field in the Galaxy
- spatial distribution of sources
- spatial distribution of CRs
- injected -> observed spectrum

Which is the chemical composition of CRs?

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  - magnetic field in the Galaxy
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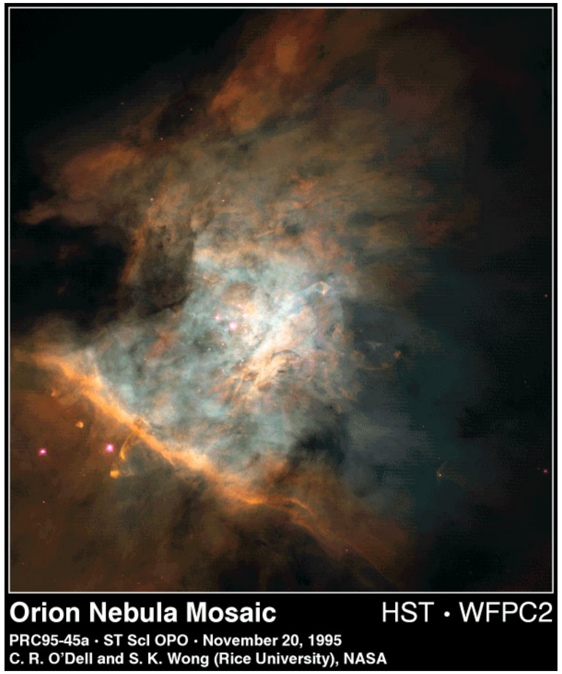
- **Which is the chemical composition of CRs?**

Why molecular clouds?

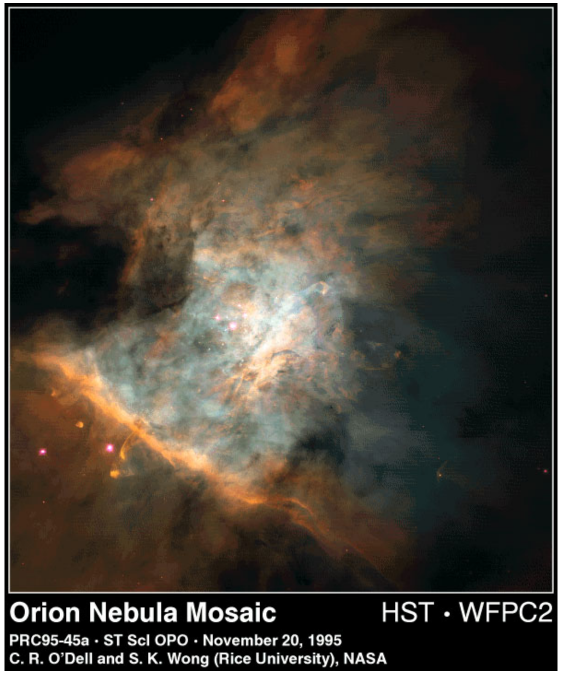


Molecular Clouds -> sites of star formation

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

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

Why molecular clouds?



Molecular Clouds -> sites of star formation

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

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

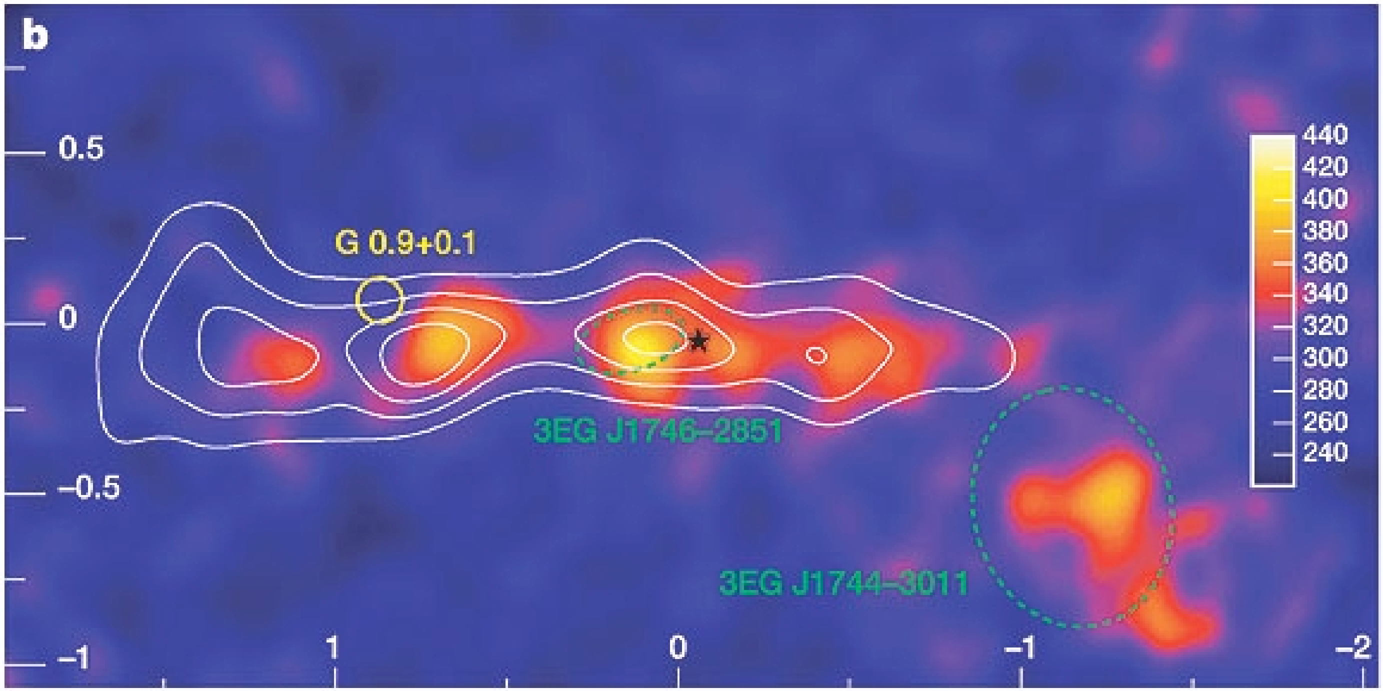
Cloud mass

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

...because they are massive

Molecular Clouds are gamma-ray sources

The galactic centre ridge as seen by HESS

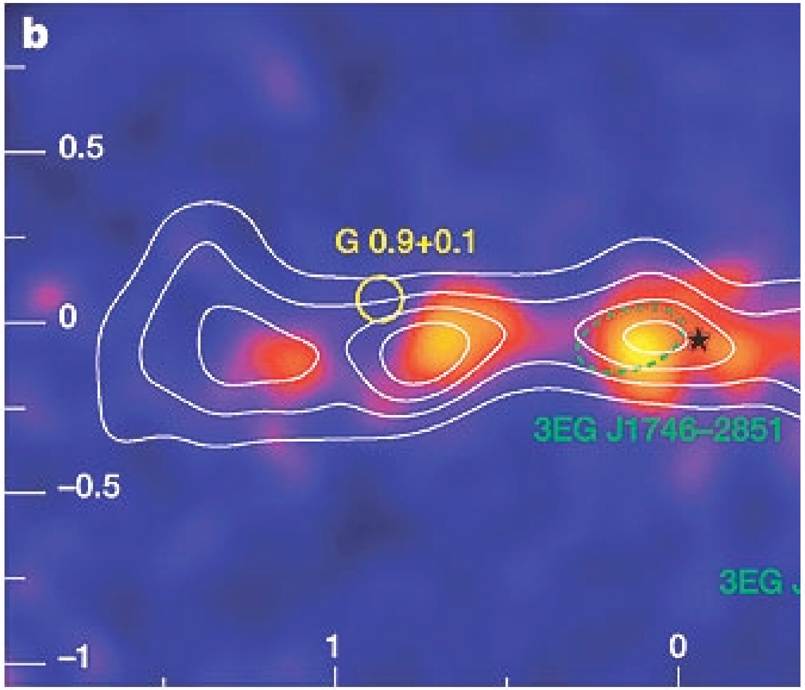


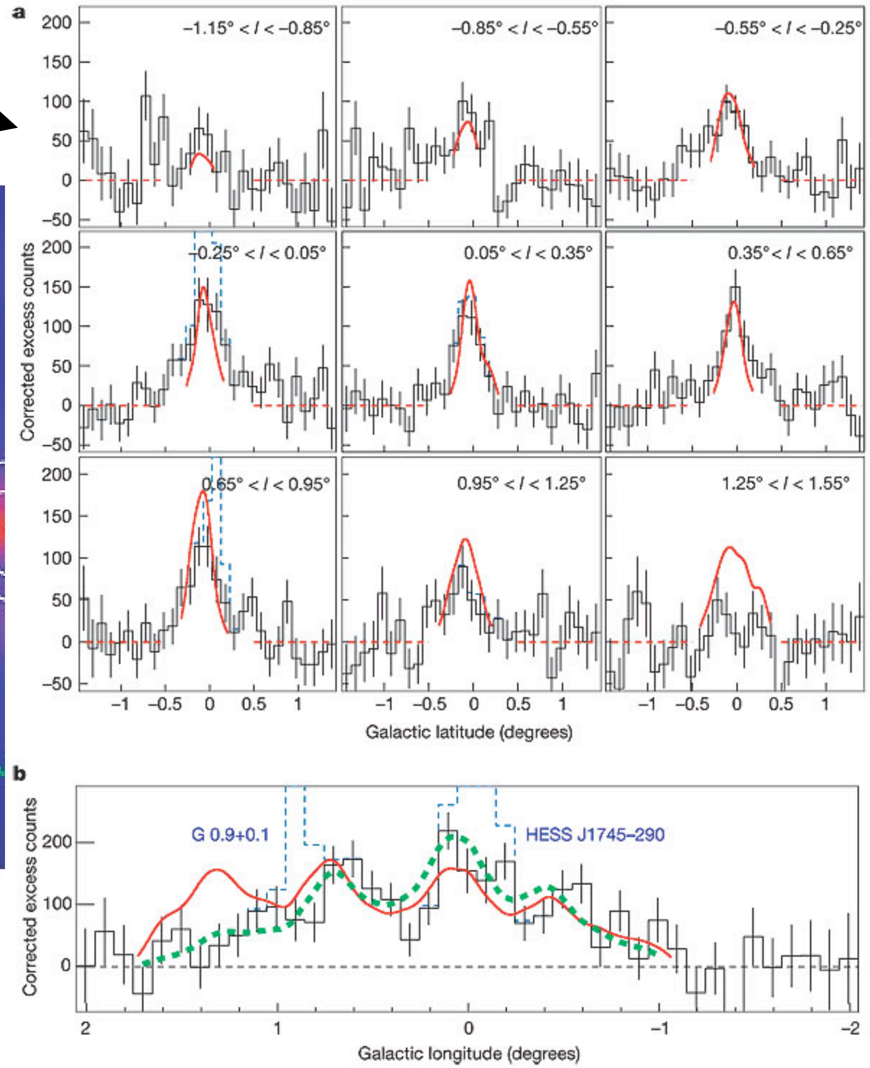
HESS collaboration, 2006

Molecular Clouds are gamma-ray sources

The galactic centre ridge as seen by HESS

good match between CS lines and TeV emission





HESS collaboration, 2006

I - Molecular Clouds as Cosmic Ray Barometers

II - Supernova Remnants/Molecular Clouds associations

III - Some comments on the galactic gamma-ray background

I - Molecular Clouds as Cosmic Ray Barometers

Molecular Clouds as CR barometers

(Issa & Wolfendale, 1981 ; Aharonian, 1991)

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

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

known constant

Molecular Clouds as CR barometers

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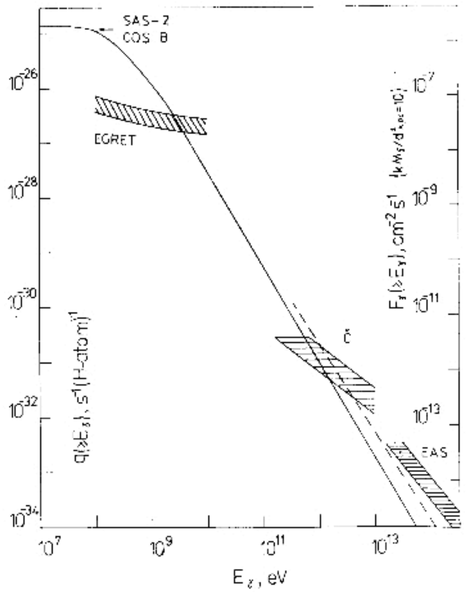


Akharonian, 1991

detectable with EGRET if:

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

- only a few (Orion, Monoceros) -> Digel et al.2001
- we need FERMI

Molecular Clouds as CR barometers

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

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

Two caveats:

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

Detectability at TeV energies: the role of CTA

Gamma-ray flux from the cloud @1TeV

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

flux from a passive cloud

enhancement with respect to passive cloud

mass and distance of the cloud

Gabici, 2008

Detectability at TeV energies: the role of CTA

Sensitivity of CTA @1TeV

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

HESS sensitivity divided by 10

how much CTA is better than HESS

angular resolution

Gabici, 2008

Detectability at TeV energies: the role of CTA

Simplifying assumption:

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

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

Gabici, 2008

Detectability at TeV energies: the role of CTA

Detectability condition:

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

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

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

Gabici, 2008

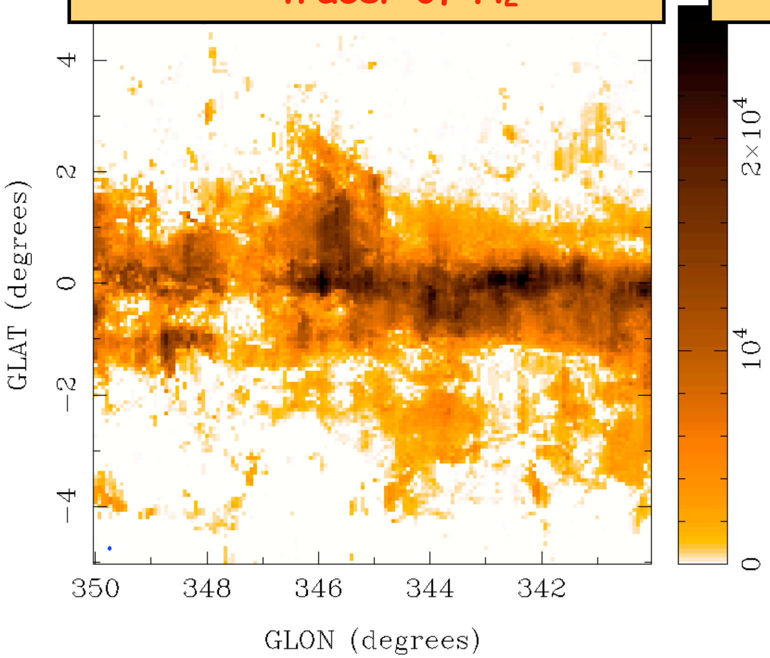
"Tomography" with gamma rays

Casanova ...SG...et al, 2009

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

LAB HI Survey
(Karberla et al 05)

ASSUMPTION:
CR spectrum is universal



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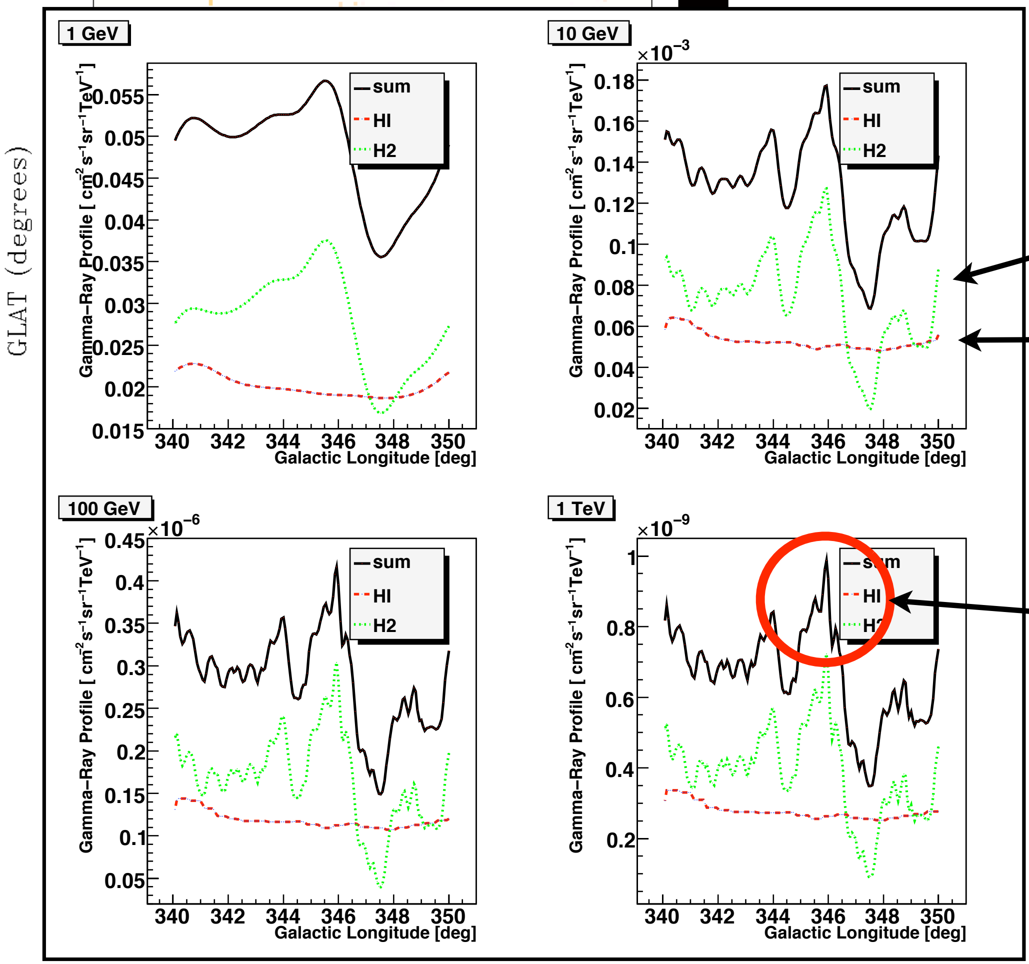


structured (clouds)

smooth (gas)

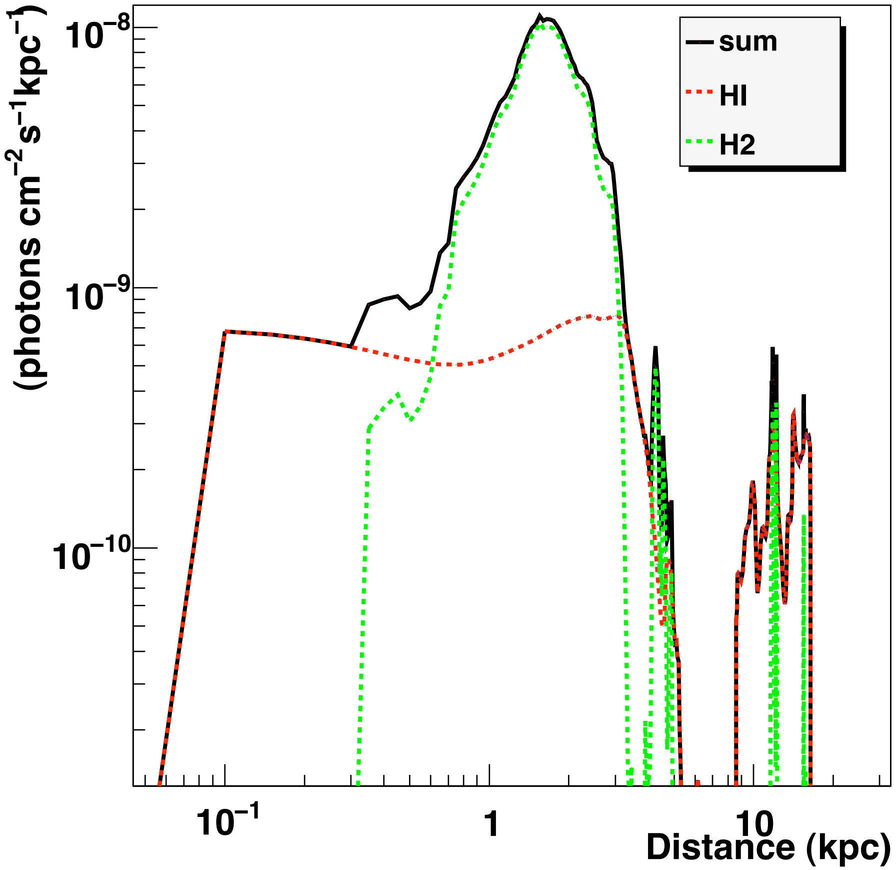
there's a peak here

<- Gamma ray emission

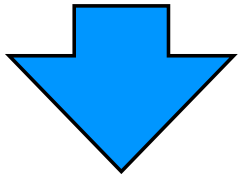
"Tomography" with gamma rays

Casanova ...SG...et al, 2009

@ 1 GeV -> FERMI



most of the emission comes from a relatively small region at D ~ 1-2 kpc



with FERMI data we will be able to use MCs to probe the CR spectrum in specific regions of the Galaxy

II - Supernova Remnants/Molecular Clouds associations

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 cloud is expected

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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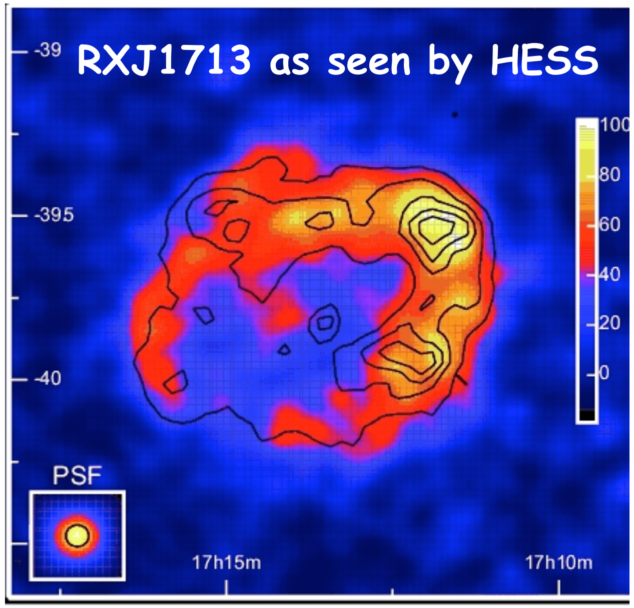


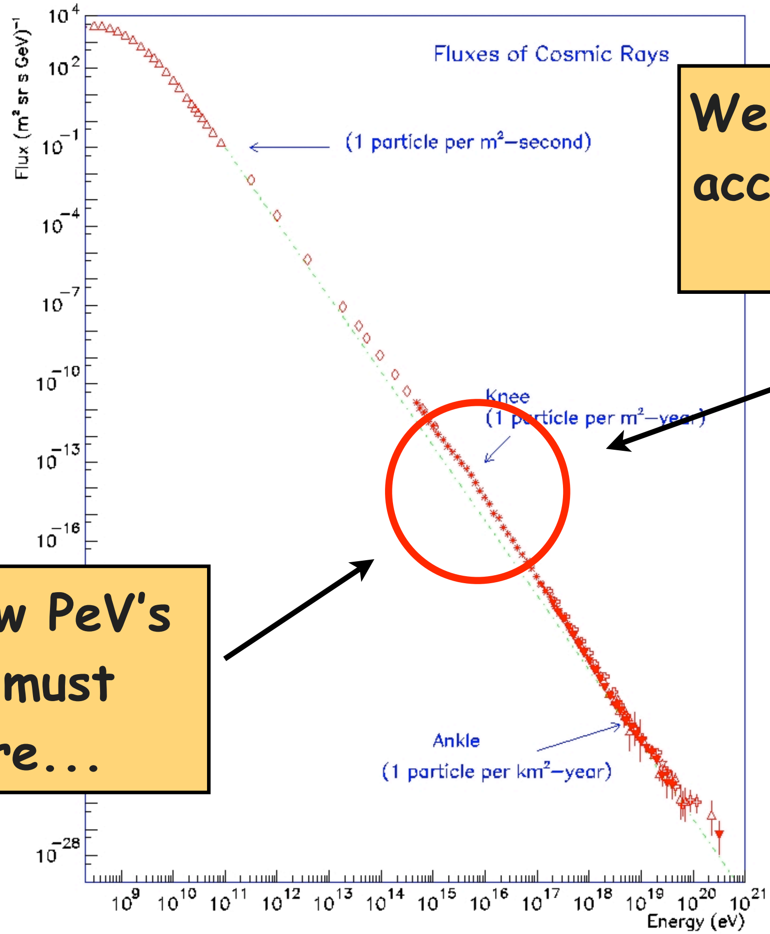
SNRs detected @TeVs ➔ TEST PASSED!

BUT

hadronic or leptonic???

Are SuperNova Remnants CR PeVatrons?

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

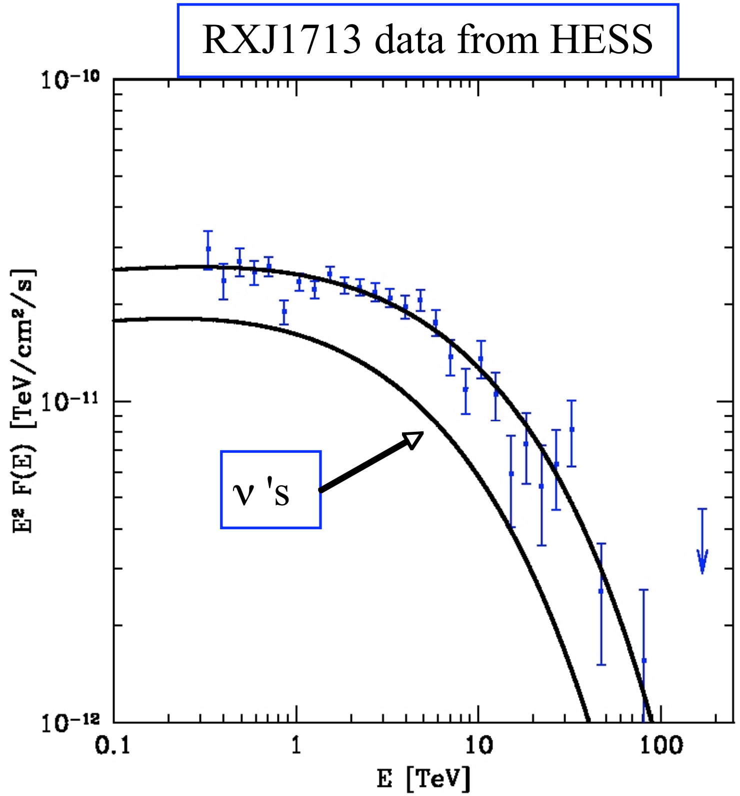


CR knee @few PeV's
Something must
happen here...

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

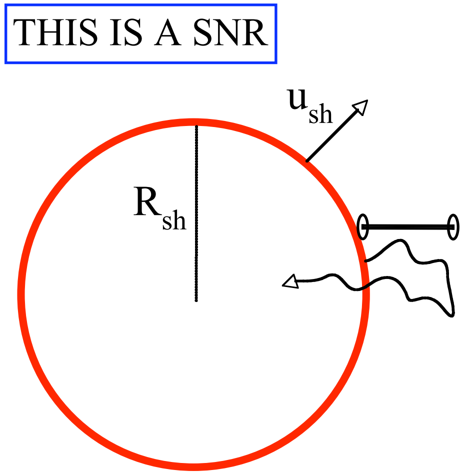


Gabici, 2008

...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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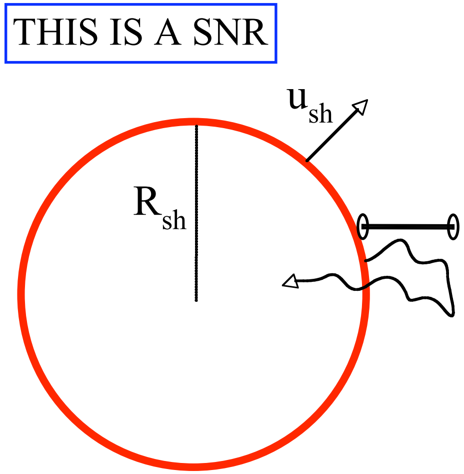

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Confinement condition:

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

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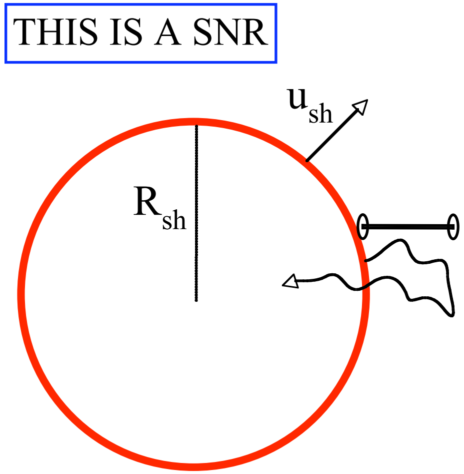

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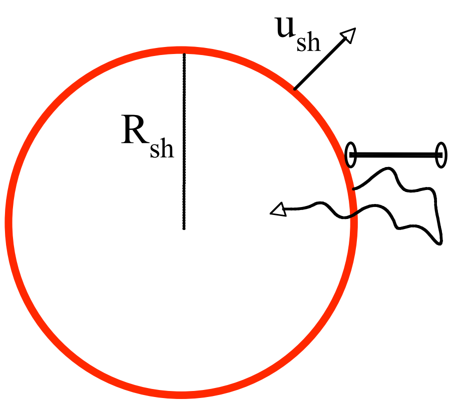
Sedov phase:

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

RX J1713 probably WAS a PeVatron!

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

THIS IS A SNR



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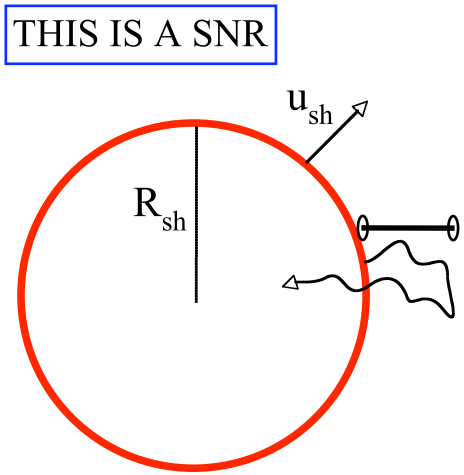

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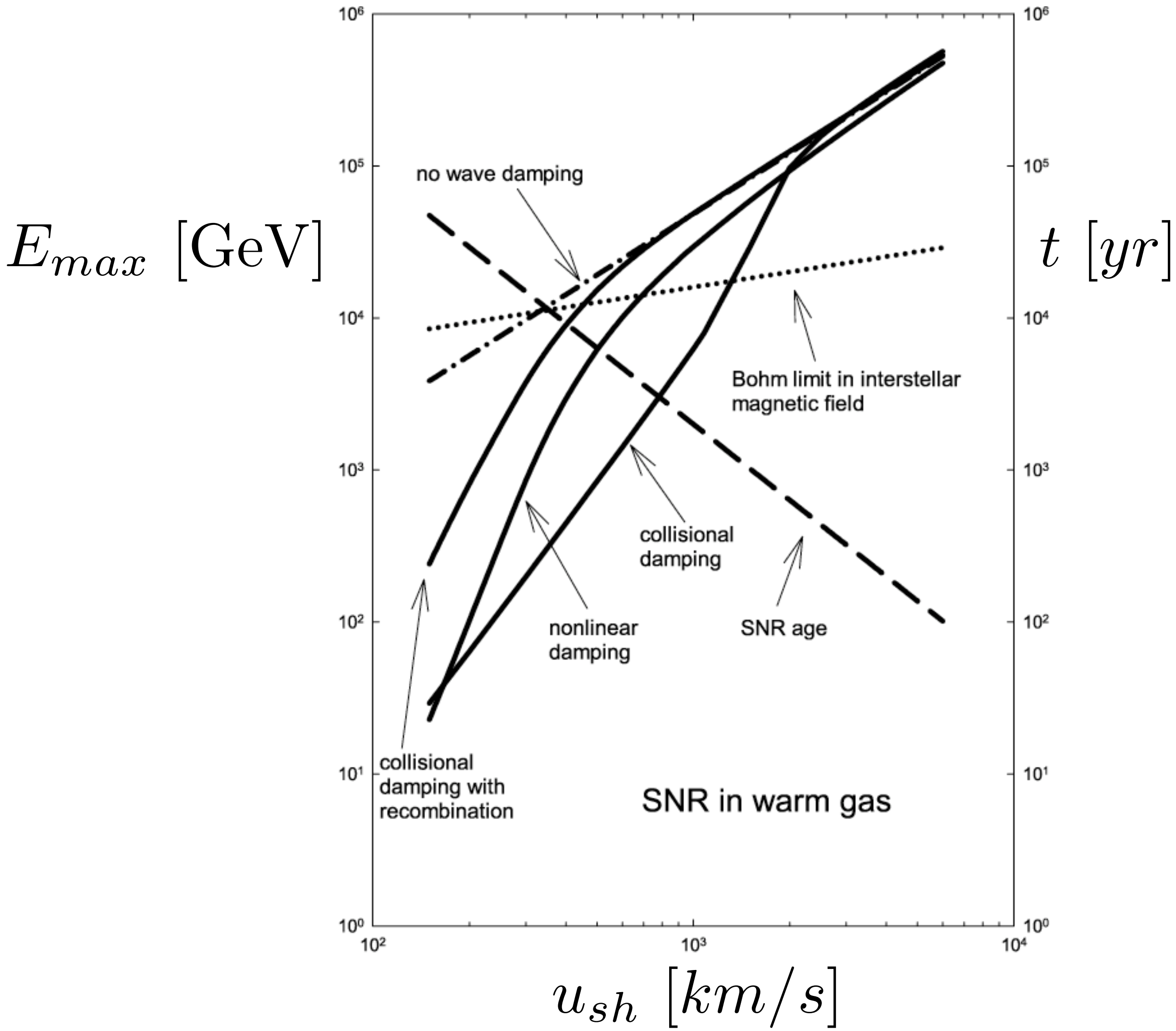
$$E_{max} \propto B_{sh} t^{-1/5}$$

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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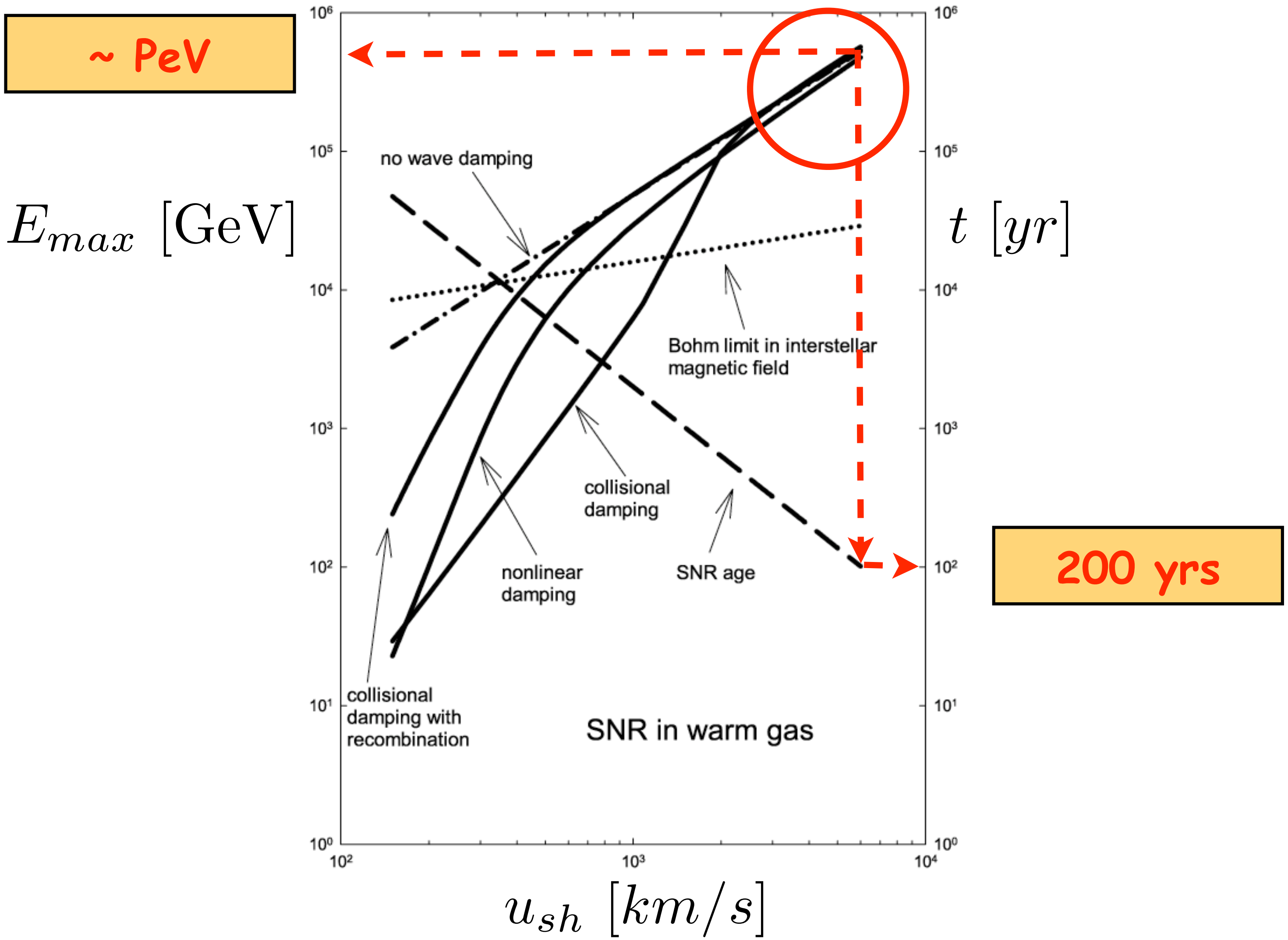

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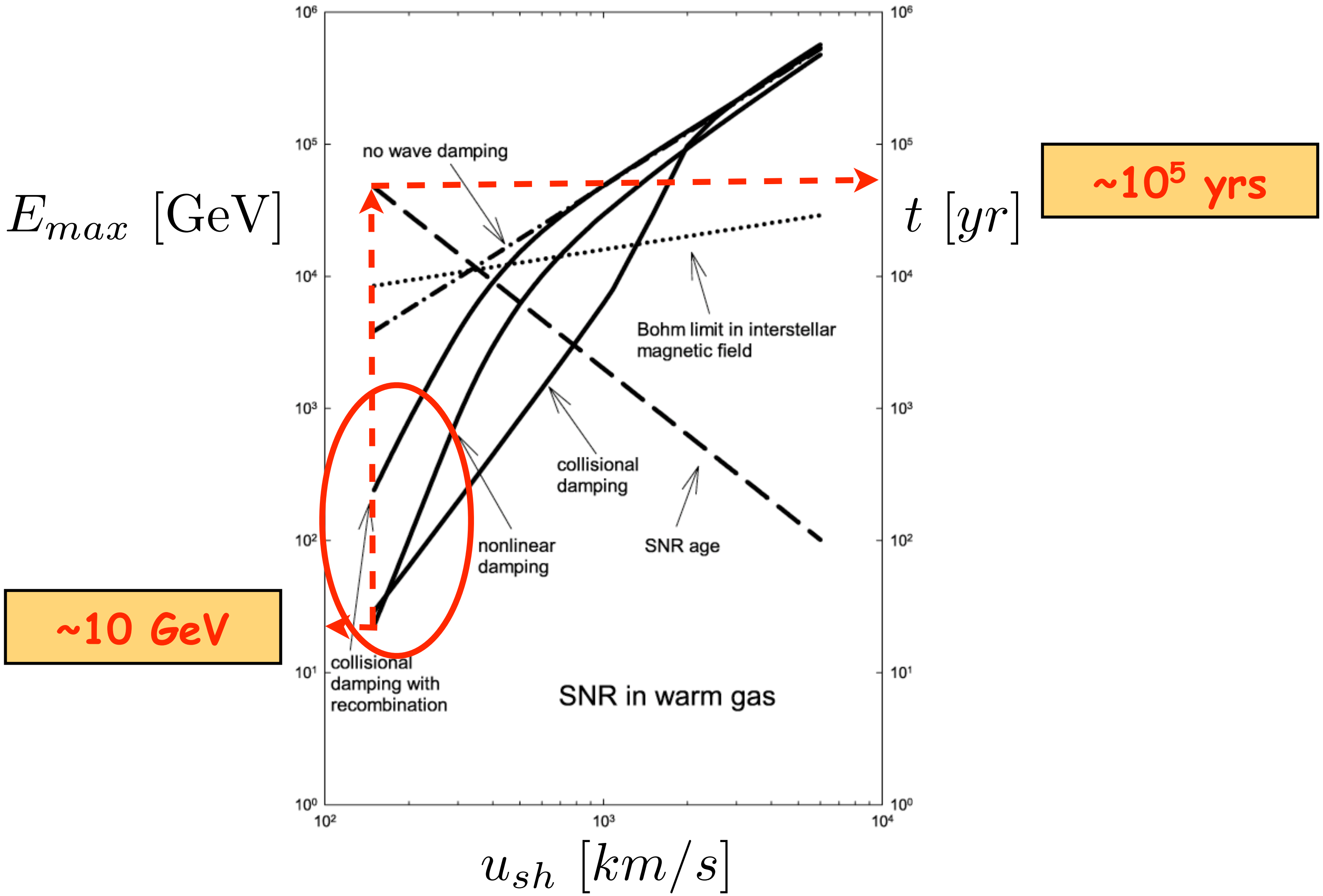

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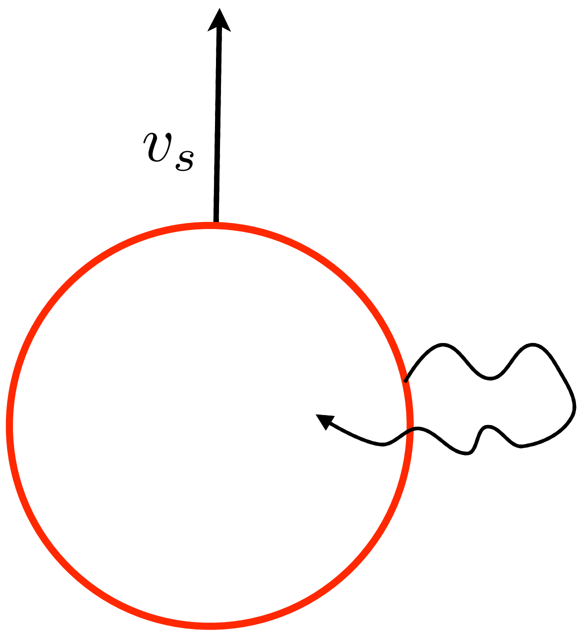
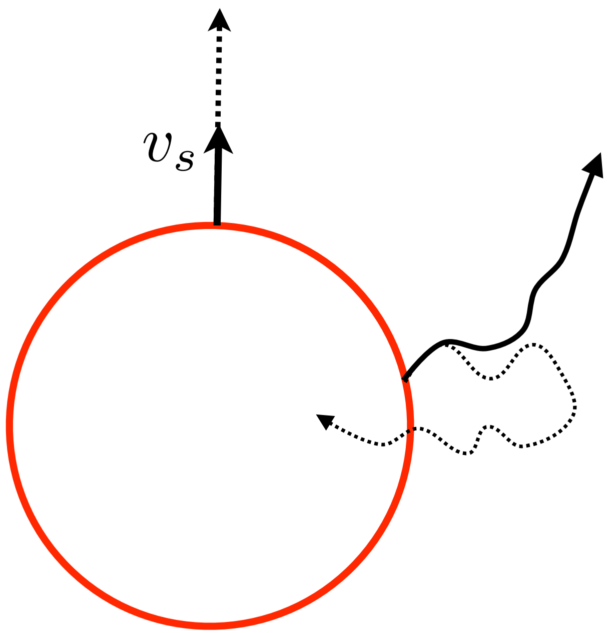


This is a supernova remnant

RXJ1713 WAS a CR PeVatron

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

Particle escape from SNRs



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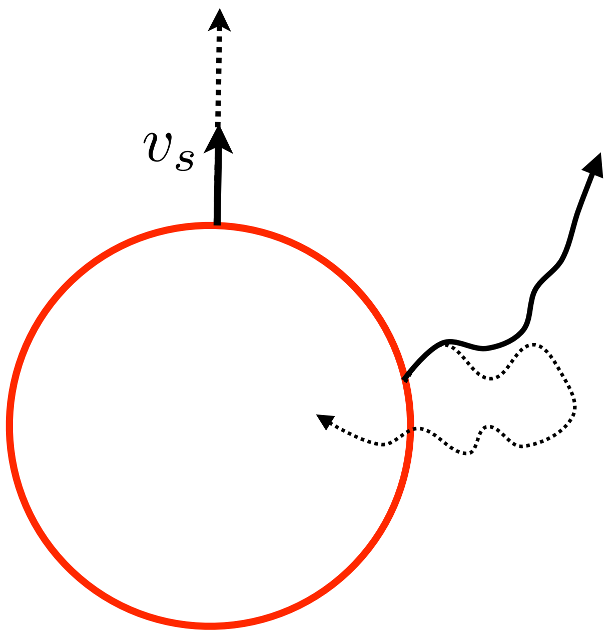

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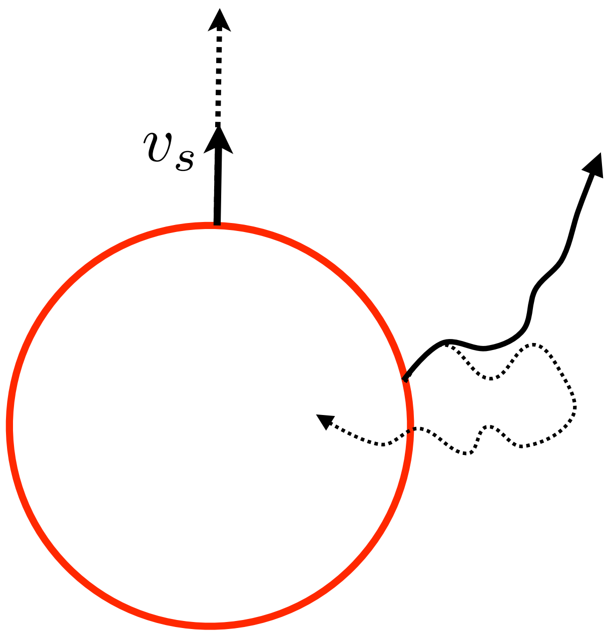
- Highest energy particles are released first, and particles with lower and lower energy are progressively released later
- a SNR is a PeVatron for a very short time

Particle escape from SNRs



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RXJ1713 <u>WAS</u> a CR PeVatron

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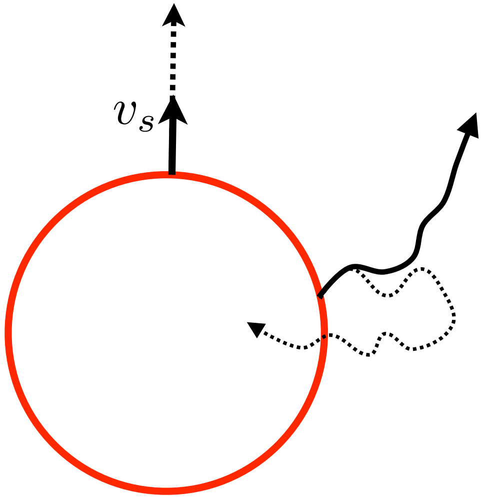
- they quickly escape as the shock slows down
- Highest energy particles are released first, and particles with lower and lower energy are progressively released later
- a SNR is a PeVatron for a very short time
- still no evidence for the existence of escaping CRs

Particle escape from SNRs



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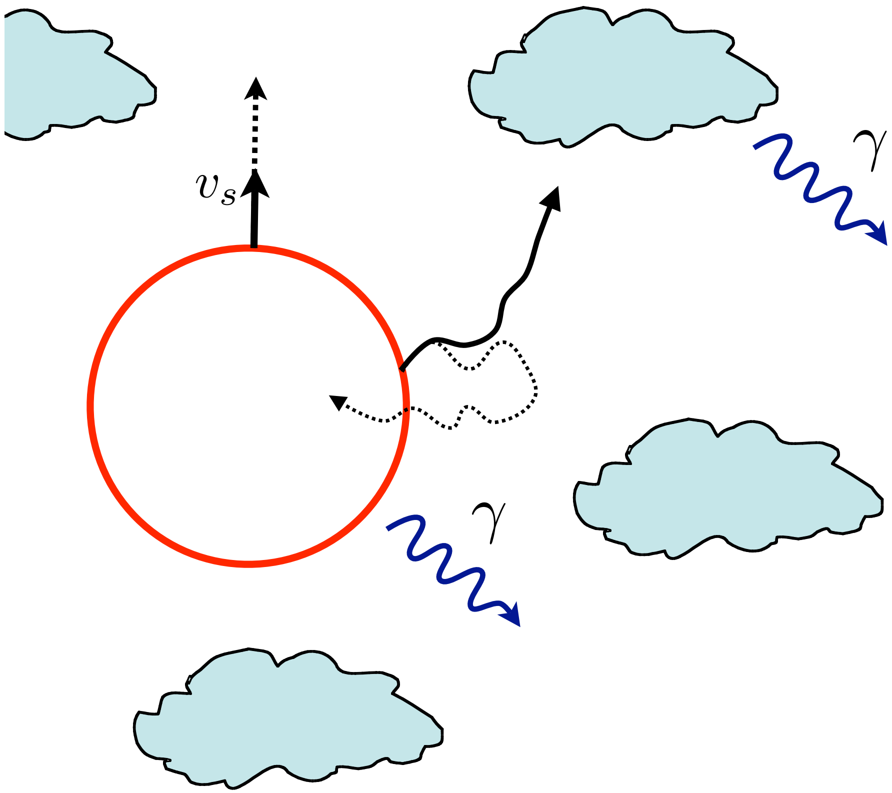
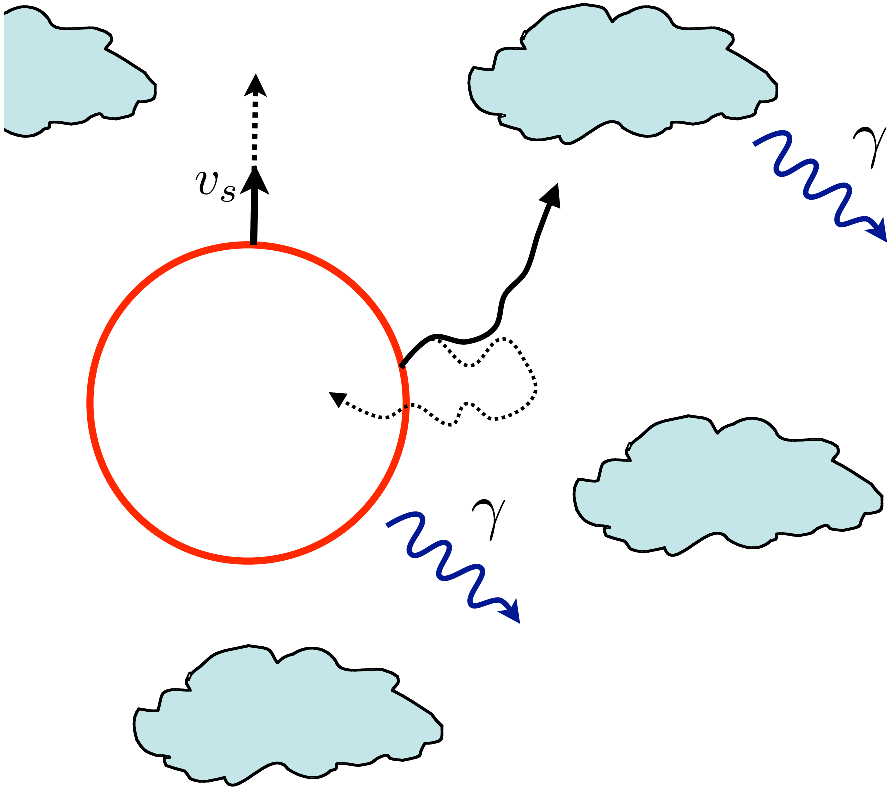


Both SNR and surrounding molecular clouds emit gammas

Particle escape from SNRs



Gamma rays from escaping particles:
Aharonian & Atoyan, 1996 (**CR accelerator**)
Gabici & Aharonian, 2007 (**SNRs**)
Follow up papers:
Torres et al, 2008
Rodriguez-Marrero et al, 2008
Gabici et al, 2009

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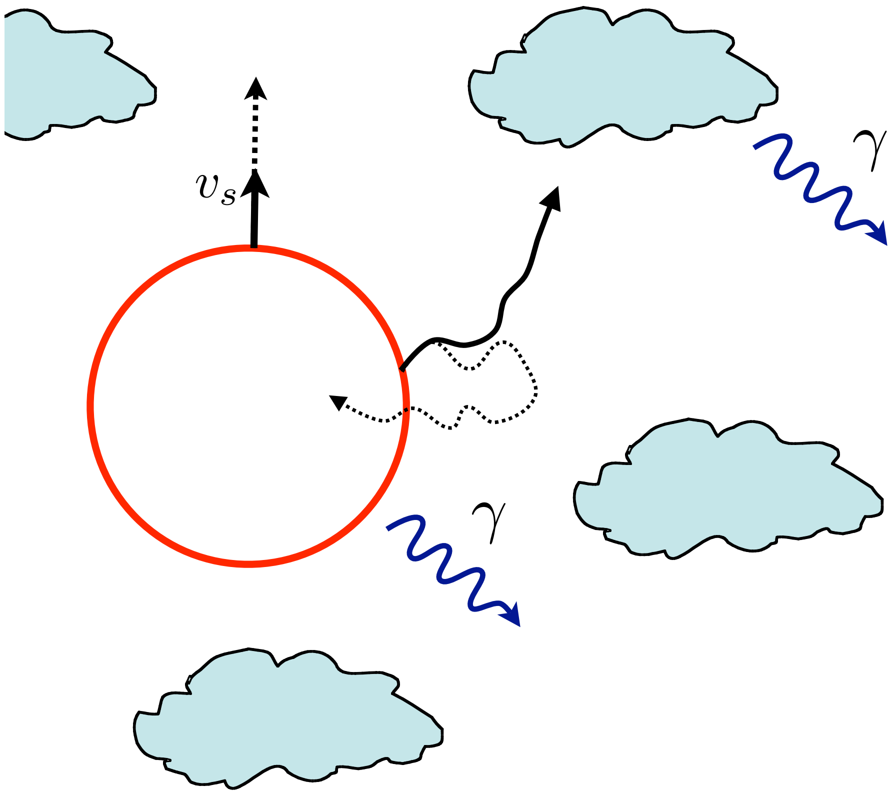
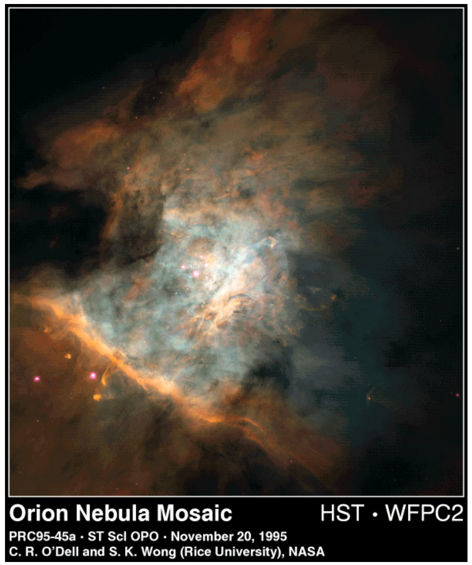


Both SNR and surrounding molecular clouds emit gammas

Molecular Clouds, sites of star formation



$10^3 M_\odot \lesssim M \lesssim 10^6 M_\odot$ $0.5\ \mathrm{pc} \lesssim R \lesssim 20\ \mathrm{pc}$

Gamma rays from MCs illuminated by CRs

t = 400 yr

1 PeV

SNR

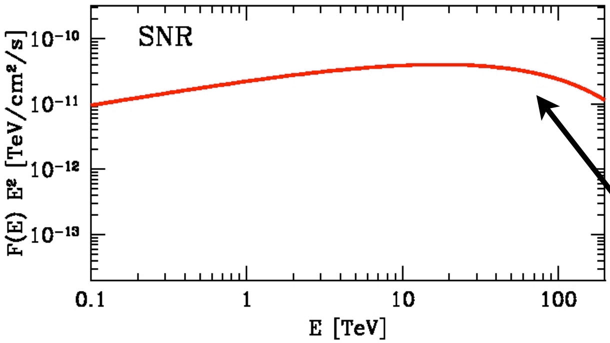
Cloud

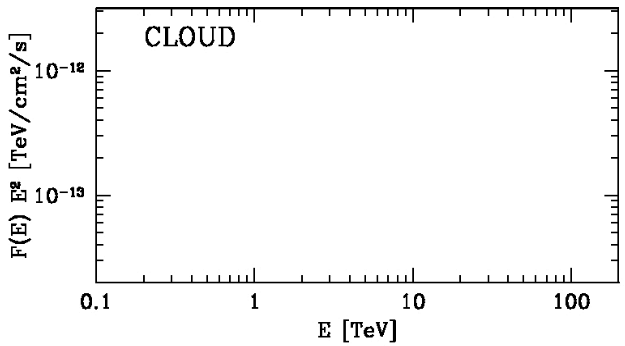
$d = 1\ kpc$

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

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

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





PeVatron!!!
but for short time!

Gabici&Aharonian(2007)

Gamma rays from MCs illuminated by CRs

t = 2000 yr

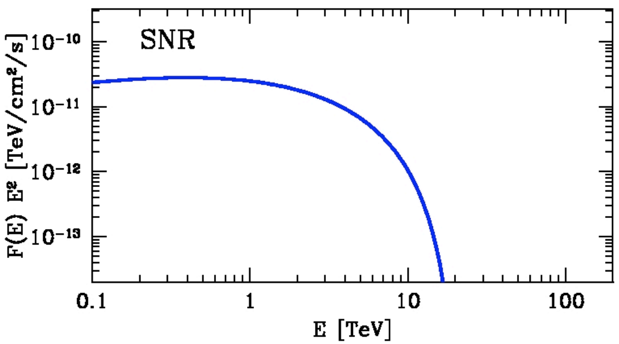
$$d = 1\ kpc$$
$$d_{snr/cl} = 100\ pc$$
$$M_{cl} = 10^4 M_\odot$$
$$D_{PeV} = 3\ 10^{29} cm^2/s$$

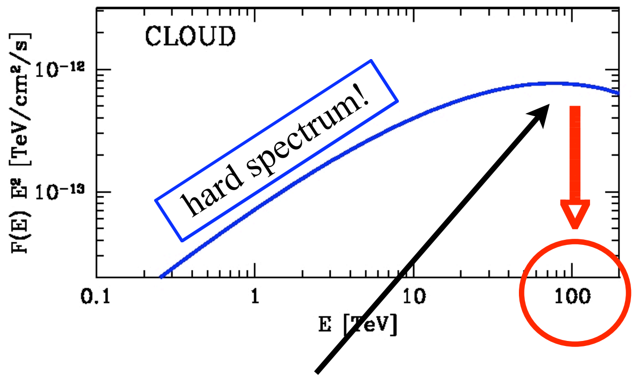
100 TeV

1 PeV

SNR

Cloud





Gabici&Aharonian(2007)

HESS remnant

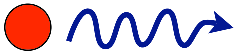
Indirect detection of a PeVatron! Emission lasts longer!

NO ICS -> Klein-Nishina

Gamma rays from MCs illuminated by CRs

t = 8000 yr

1 TeV



SNR

100 TeV

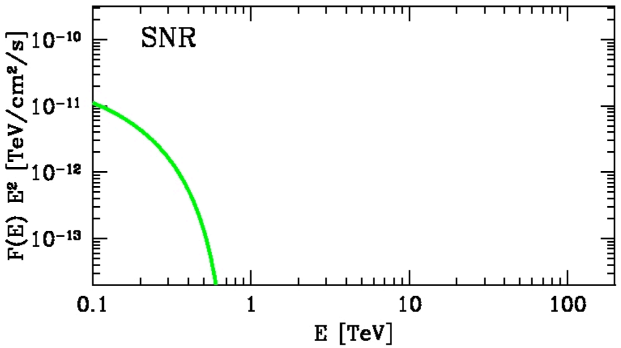
Cloud

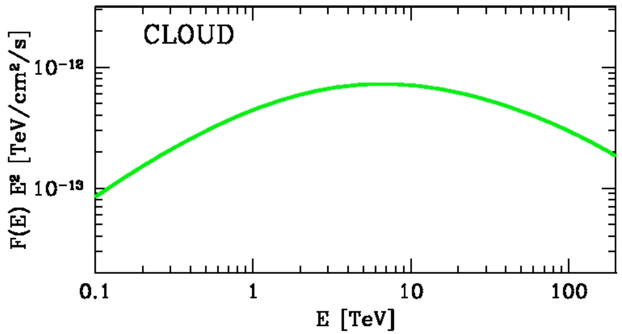
$d = 1\ kpc$

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

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

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





Gabici&Aharonian(2007)

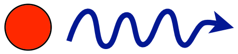
GLAST remnant?

HESS and MILAGRO unidentified sources?

Gamma rays from MCs illuminated by CRs

t = 32000 yr

100 GeV



10 TeV

$d = 1\ kpc$

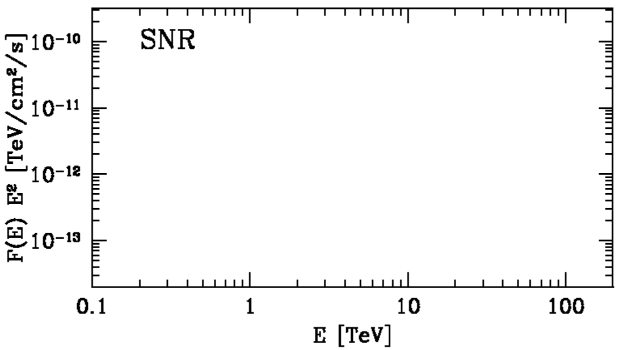
$d_{snr/cl} = 100\ pc$

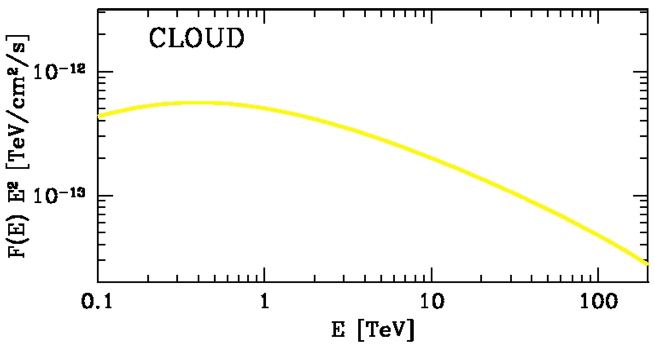
$M_{cl} = 10^4 M_{\odot}$

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

SNR

Cloud





Gabici&Aharonian(2007)

no emission

HESS and MILAGRO unidentified sources?

Gamma rays from MCs illuminated by CRs

t = 32000 yr

100 GeV

10 TeV

$d = 1\ kpc$

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

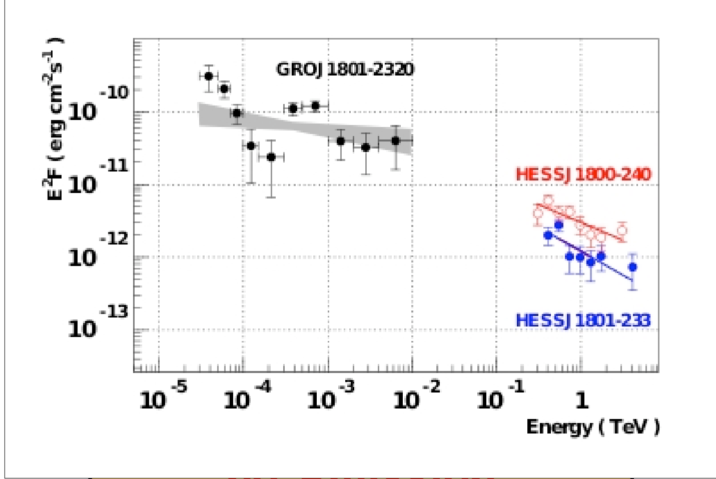
$M_{cl} = 10^4 M_\odot$

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

SNR

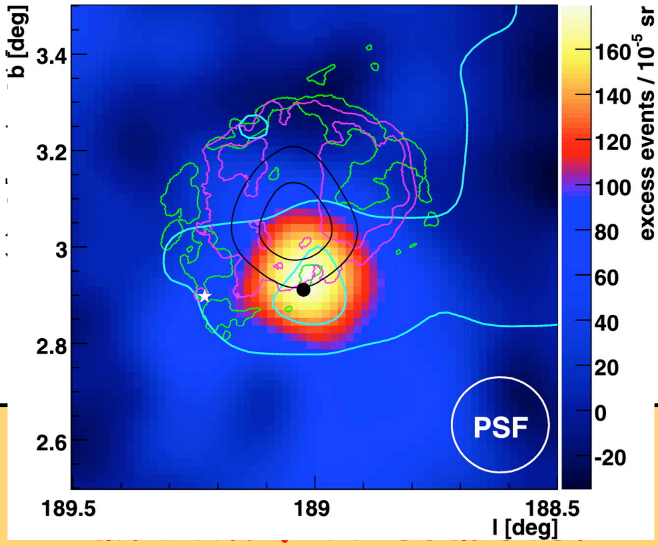
Cloud

HESS: clouds in W28 field



no emission

MAGIC: IC443 (see Torres2008)

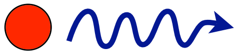


Gabici&Aharonian(2007)

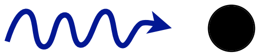
Gamma rays from MCs illuminated by CRs

t = 32000 yr

100 GeV



10 TeV



$d = 1\ kpc$

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

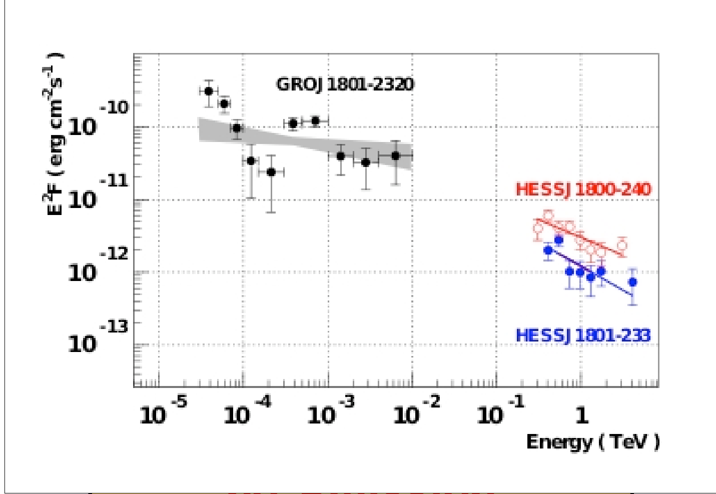
$M_{cl} = 10^4 M_\odot$

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

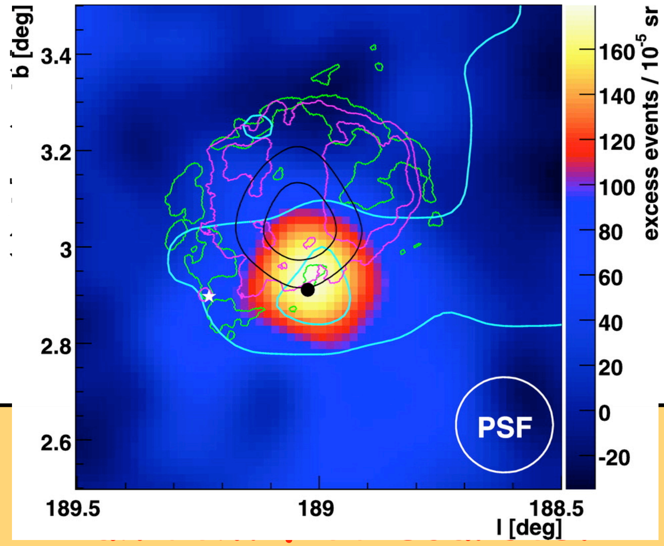
SNR

Cloud

HESS: clouds in W28 field



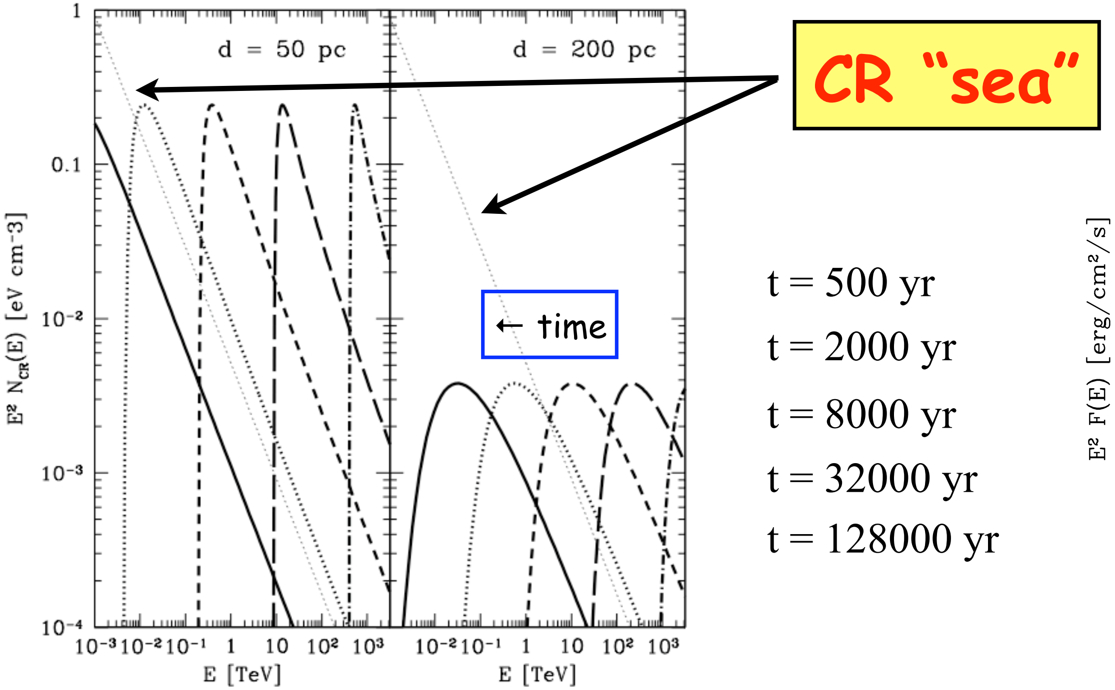
MAGIC: IC443 (see Torres2008)



Gabici&Aharonian(2007)

MWL implications

GeV-TeV connection... ...and PeV-hard X connection



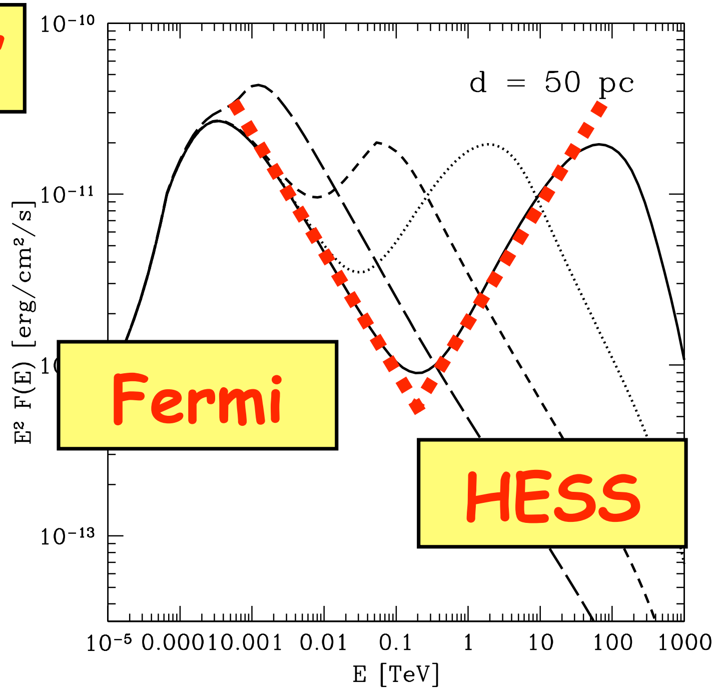
t = 500 yr

t = 2000 yr

t = 8000 yr

t = 32000 yr

t = 128000 yr



Gabici, Aharonian & Casanova, 2009

MWL implications

GeV-TeV connection... ...and PeV-hard X connection

PeV cosmic rays in a molecular cloud...

$$p\ p \rightarrow p\ p\ \pi^+\ \pi^-\ \pi^0$$
$$\hookrightarrow \mu^-$$
$$\hookrightarrow e^-$$

$$E_e \approx 100\ TeV$$

$$\epsilon_{syn} \sim 20 \left(\frac{B}{30\mu G}\right)\left(\frac{E}{100TeV}\right)^2 keV$$

We can search for PeVatrons in X-rays!

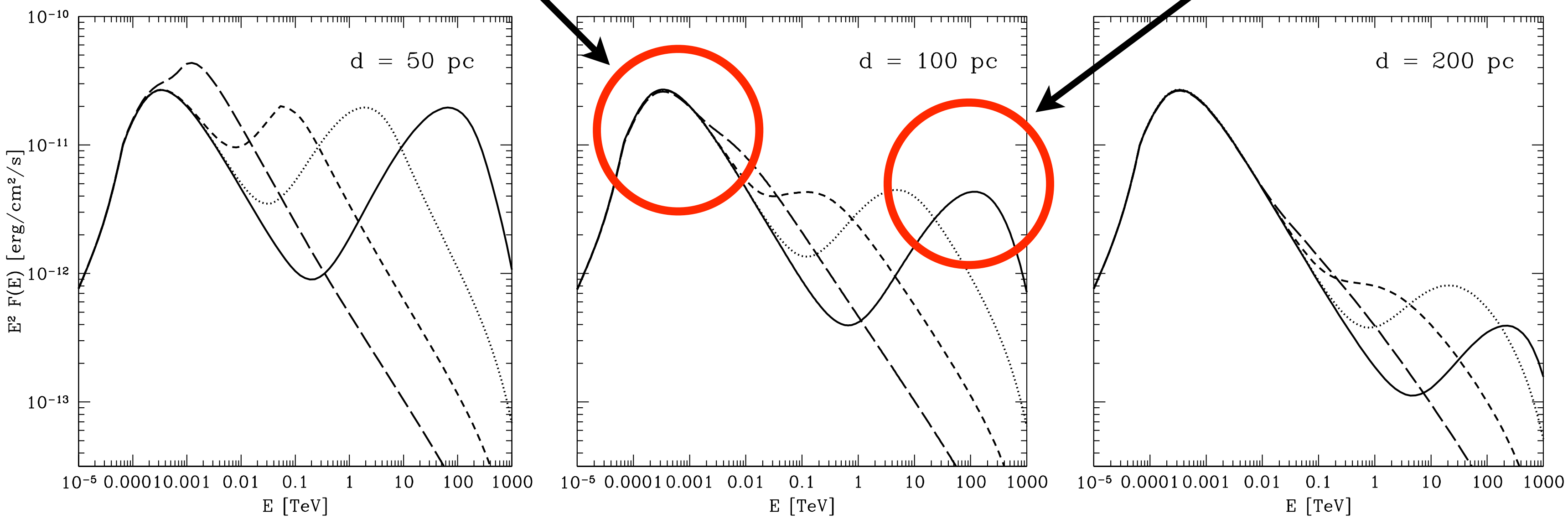
Gabici, Aharonian & Casanova, 2009

MWL implications

$M=10^5\ M_\odot$; $R=20pc$; $n=120cm^{-3}$; $B=20\mu\ G$; $D=1kpc$; $D_{10}=10^{28}cm^2/s$

Peak from CR background (steady)

Peak from CR from SNR (time dependent)



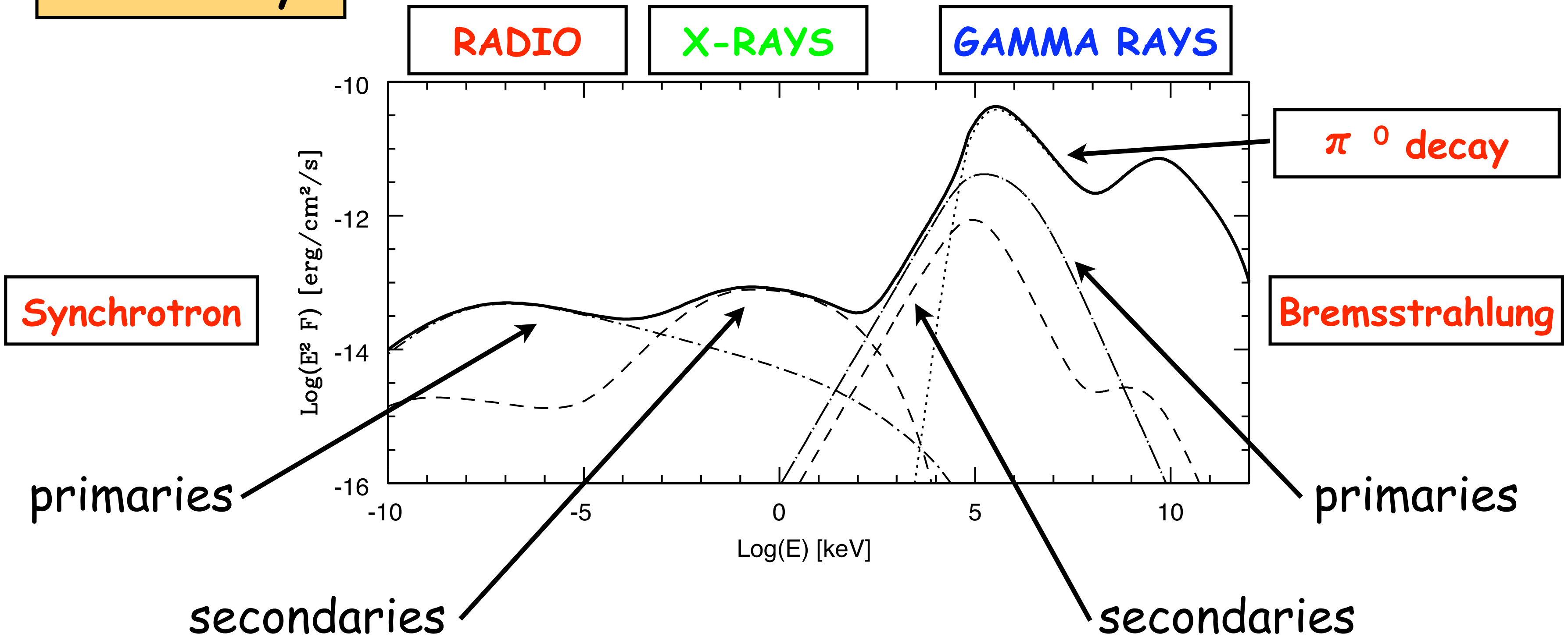
A great variety of spectra are expected

Gabici, Aharonian & Casanova, 2009

MWL implications

M=10^5 $M_\odot$; R=20pc ; n=120cm^{-3} ; B=20μ G ; $d_{SNR/MC}$=100pc ; D=1kpc

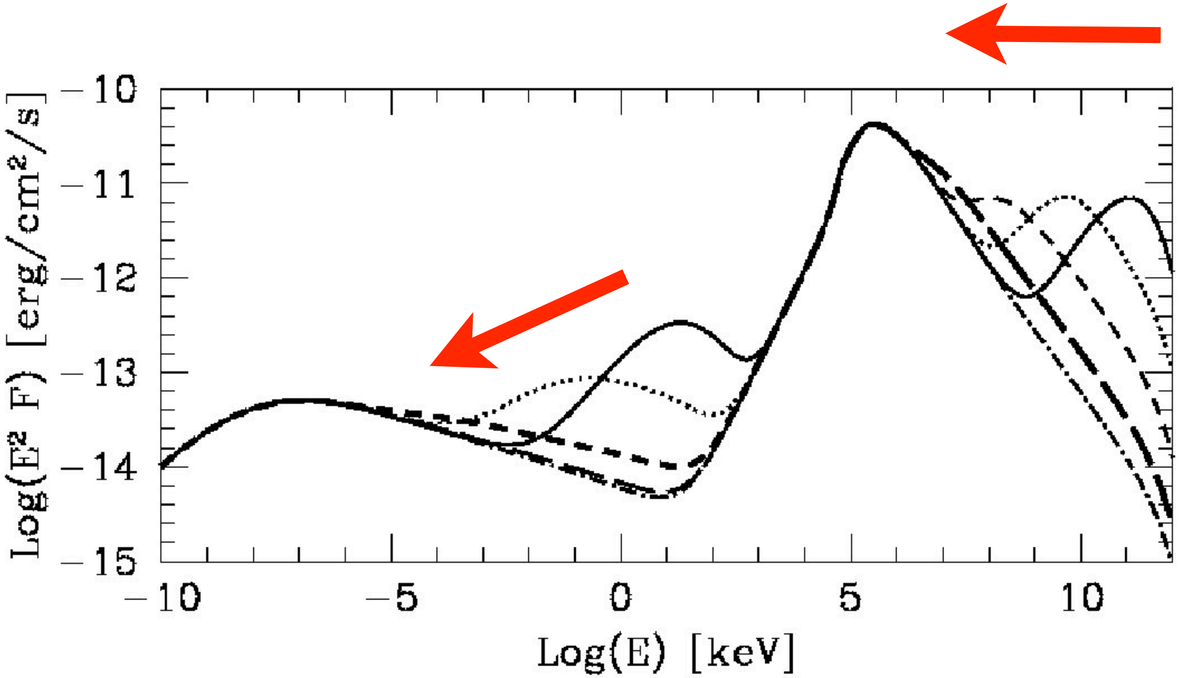
t = 2000 yr



Gabici, Aharonian & Casanova, 2009

MWL implications

$M=10^5\ M_\odot$; $R=20pc$; $n=120cm^{-3}$; $B=20\mu\ G$; $d_{SNR/MC}=100pc$; $D=1kpc$



t = 500 yr

t = 2000 yr

t = 8000 yr

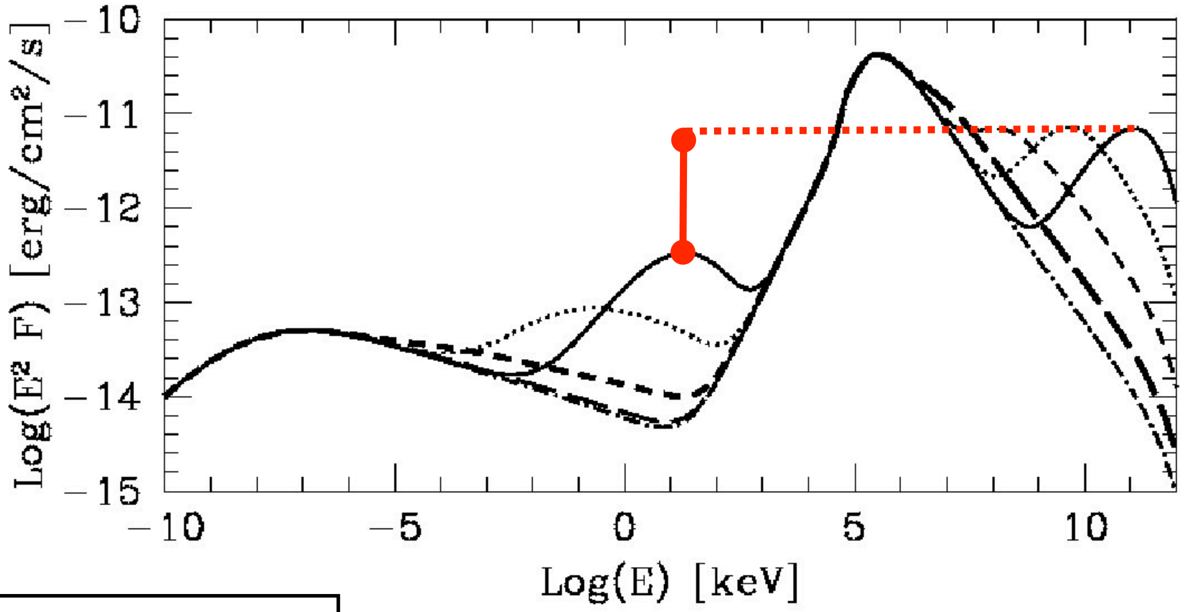
t = 32000 yr

t = ∞ yr

Gabici, Aharonian & Casanova, 2009

MWL implications

$M=10^5\ M_\odot$; $R=20pc$; $n=120cm^{-3}$; $B=20\mu\ G$; $d_{SNR/MC}=100pc$; $D=1kpc$



t = 500 yr

t = 2000 yr

t = 8000 yr

t = 32000 yr

t = ∞ yr

UNIDENTIFIED
"DARK" TeV SOURCES

Gabici, Aharonian & Casanova, 2009

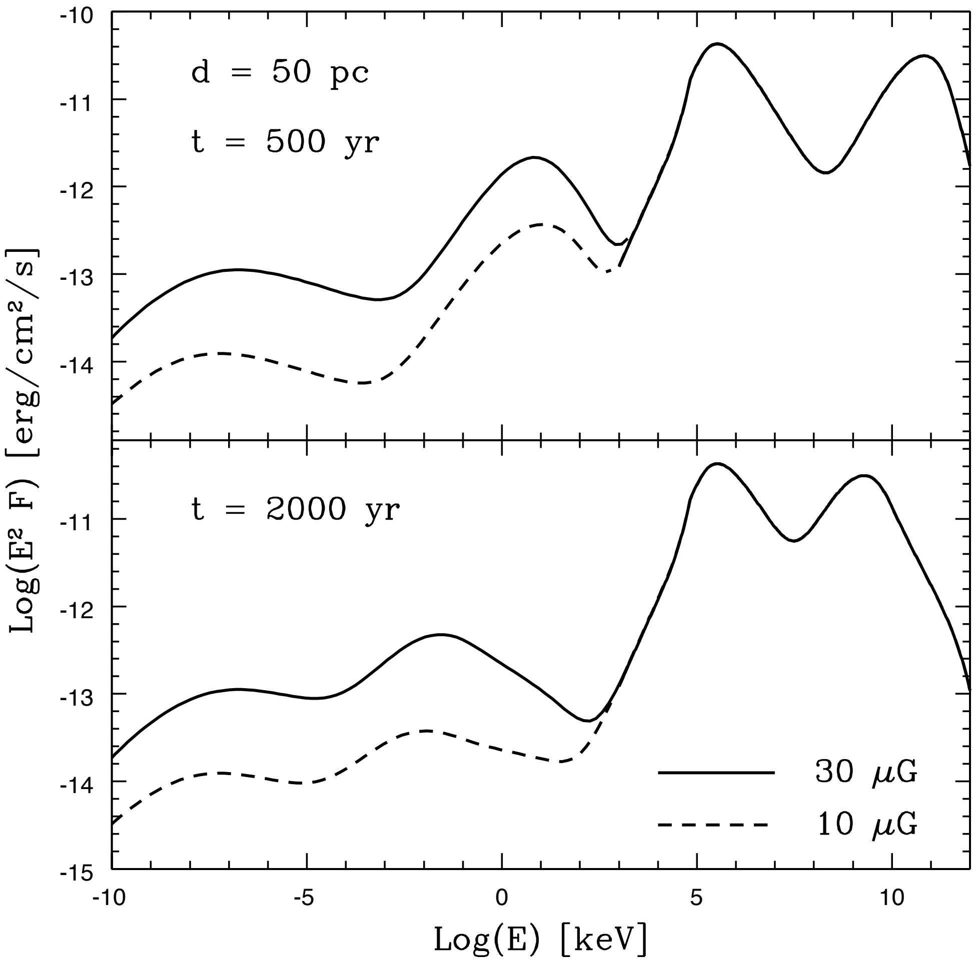
The role of the magnetic field

We cannot increase the field arbitrarily...

Mag. energy < Grav. energy

$$\frac{B^2}{8\pi} \times V = W_B < W_G = \frac{3}{5} \frac{G M_{cl}^2}{R_{cl}}$$

$$B_{cl} \leq 30 \left(\frac{M}{10^5 M_\odot} \right) \left(\frac{R_{cl}}{20 \text{ pc}} \right)^{-2} \mu G$$

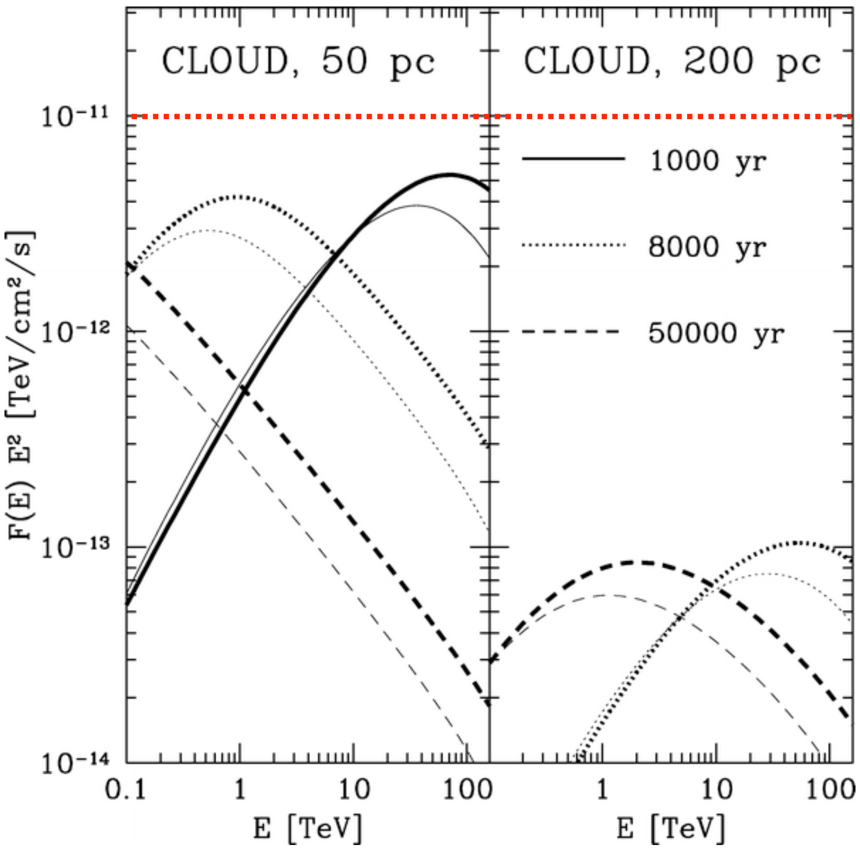


Gabici, Aharonian & Casanova, 2009

Multimessenger observations -> neutrinos

Gabici&Aharonian(2007)

To detect sources with neutrino telescope we need ~1 Crab



$d = 1\ kpc$

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

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

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

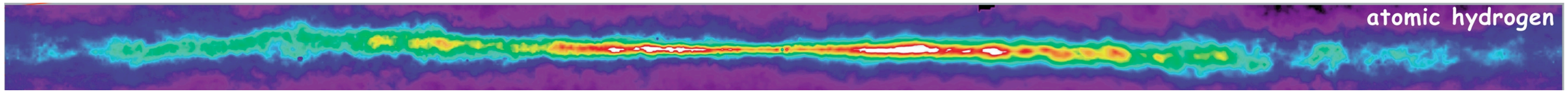
thick -> gammas
thin -> neutrinos

Detection -> very massive MC very close to the SNR

III - Some comments on the galactic gamma-ray background

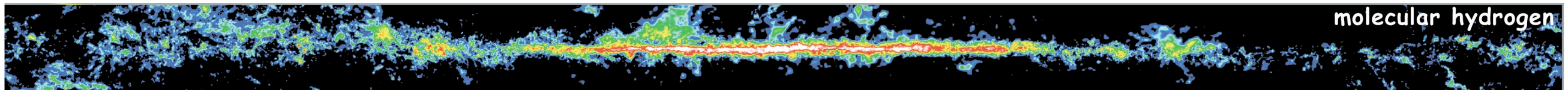
Galactic gamma-ray background

Atomic hydrogen



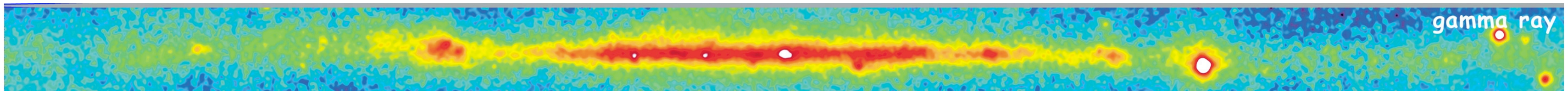
column density -> $10^{21} \div 2.3\ 10^{22}$ cm^{-2} **diffuse**

Molecular hydrogen



column density -> $1.2\ 10^{21} \div 2.85\ 10^{22}$ cm^{-2} **clouds**

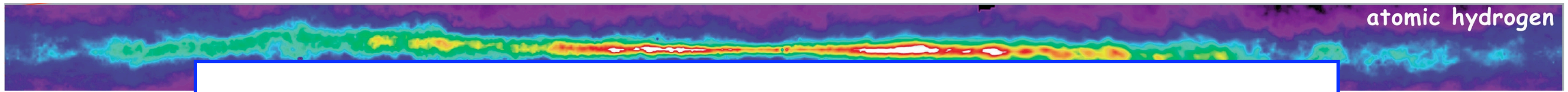
Gamma rays



gamma = **CRs** X (**diffuse** + **clouds**)

Galactic gamma-ray background

Atomic hydrogen



co

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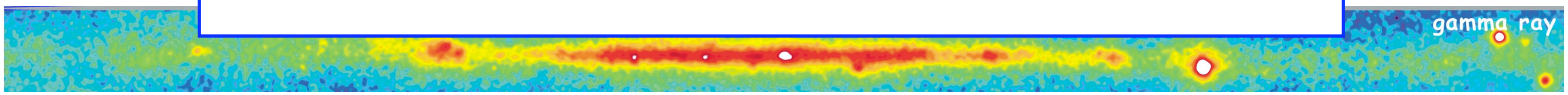

gamma = CRs X (diffuse + clouds)

Molecular clouds: are we dealing with sources or diffuse emission?

or

What is the background?

Conclusions