The SuperNova Remnant hypothesis for the origin of galactic Cosmic Rays

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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

if $M_{sw} << M_{ej}$ ➡ free expansion phase

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

constant velocity

Evolution of SuperNova Remnants

the free-expansion phase ends when: $M_{ej} \approx M_{sw}$

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uniform medium with density: $\varrho_{gas} \approx 1.7 \times 10^{-24}$ g

shock radius

$$\frac{4\,\pi}{3}\,R_s^3\,\varrho_{gas} = M_{ej} \quad \Rightarrow \quad R_s \approx 2\,\left(\frac{M_{ej}}{M_\odot}\right)^{\frac{1}{3}}\,\mathrm{pc}$$

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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

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

cooling time

$$\tau_c \;\propto\; T^{\frac{1}{2}} \;\gtrsim\; 10^6\ \mathrm{yr}$$

much longer than the SNR age!

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

Evolution of SuperNova Remnants

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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

Sedov solution

$$R_s \approx \left(\frac{E_{SN}}{\varrho_{gas}}\right)^{\frac{1}{5}} t^{\frac{2}{5}} \qquad v_s = \frac{\mathrm{d}R_s}{\mathrm{d}t} \approx \frac{2}{5}\left(\frac{E_{SN}}{\varrho_{gas}}\right)^{\frac{1}{5}} t^{-\frac{3}{5}}$$

$$E_{SN} = 10^{51}\ \mathrm{erg}$$
$$n_{gas} = 1\ \mathrm{cm}^{-3}$$

$$\Rightarrow \begin{cases} R_s \approx 4.5 \left(\dfrac{t}{1000\ \mathrm{yr}}\right)^{\frac{2}{5}} \mathrm{pc} \\[2ex] v_s \approx 1800 \left(\dfrac{t}{1000\ \mathrm{yr}}\right)^{-\frac{3}{5}} \mathrm{km/s} \end{cases}$$

Evolution of SuperNova Remnants

duration of the Sedov phase

t_{age} ↗

Evolution of SuperNova Remnants

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

Evolution of SuperNova Remnants

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

Evolution of SuperNova Remnants

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

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

CR acceleration at SuperNova Remnants

$$\left(\frac{1}{2}\ \varrho_{gas}\ v_s^3\right)$$

energy flux

CR acceleration at SuperNova Remnants

$$\left(\frac{1}{2}\ \varrho_{gas}\ v_s^3\right)\ \left(4\ \pi\ R_s^2\right)$$

shock surface

energy flux

CR acceleration at SuperNova Remnants

$$L_{CR} = \eta \left(\frac{1}{2} \varrho_{gas} v_s^3 \right) (4 \pi R_s^2) \quad \text{erg/s}$$

CR power

CR acceleration efficiency

energy flux

shock surface

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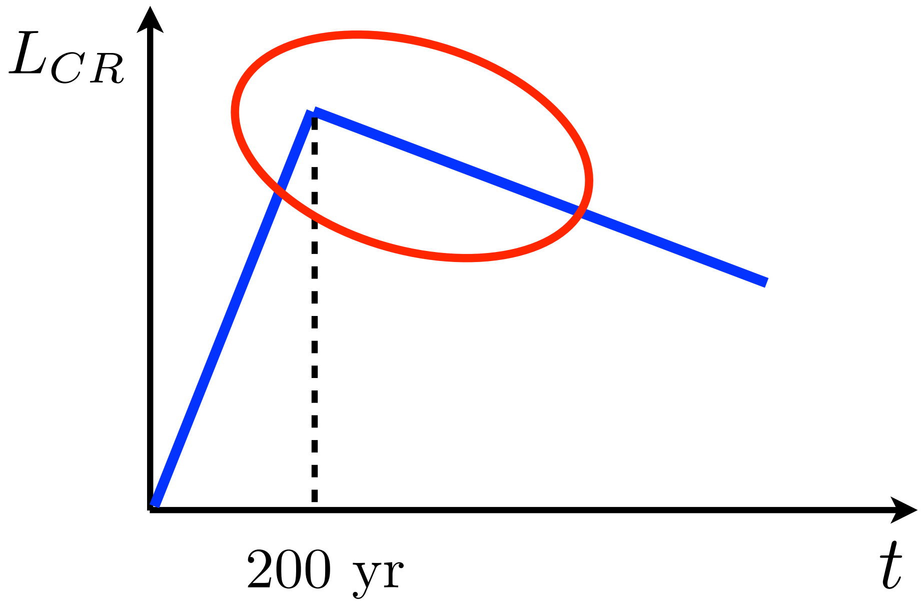
$$L_{CR} \propto v_s^3 R_s^2 \propto t^2$$

free expansion phase

$$\propto t^{-1}$$

Sedov phase



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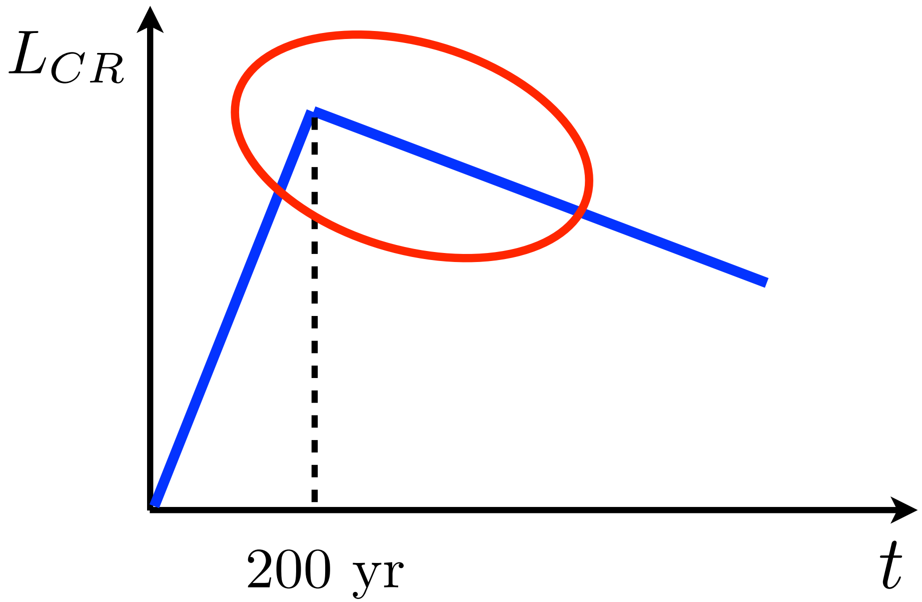
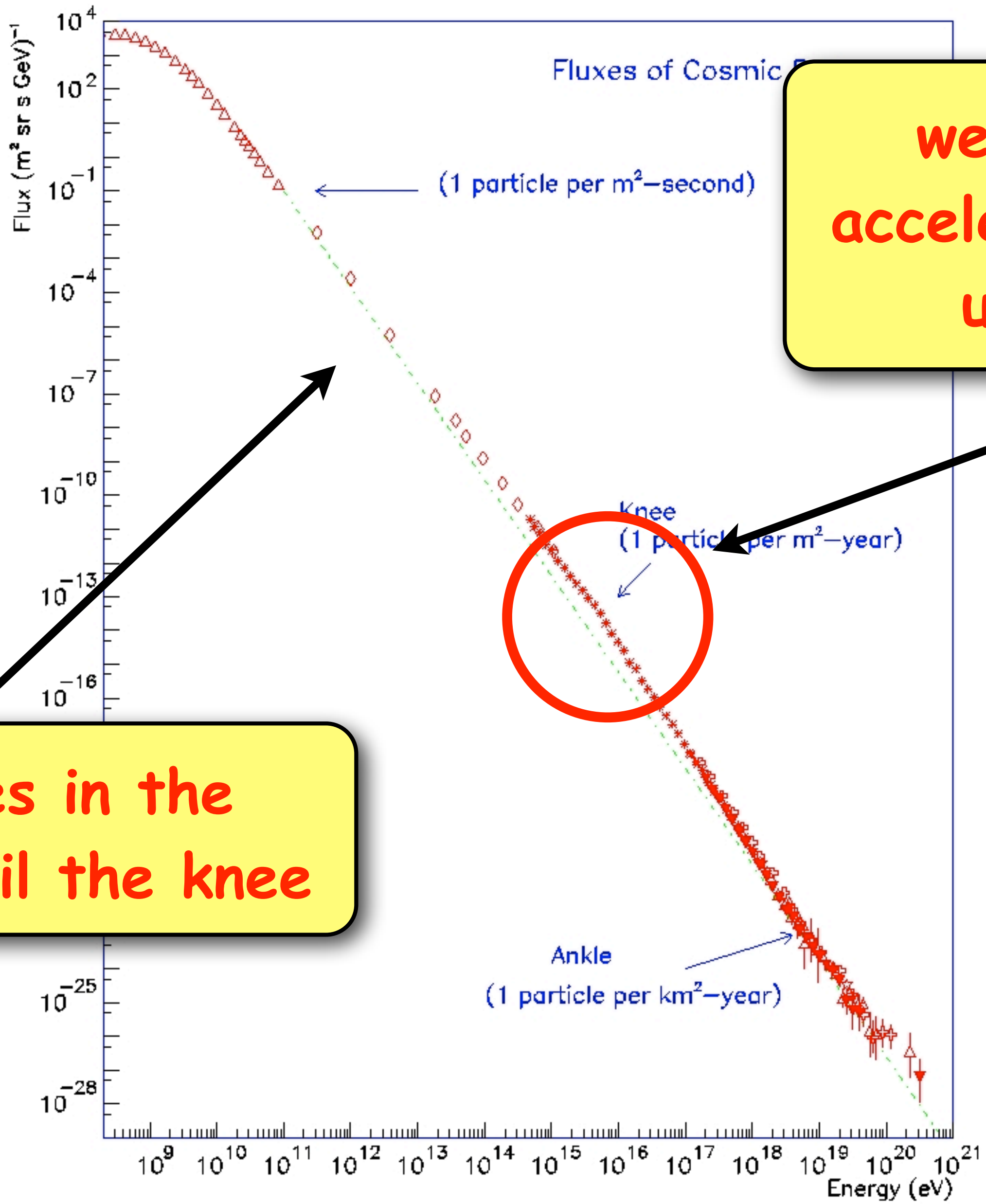


The CR luminosity peaks at the transition between free expansion and Sedov phase

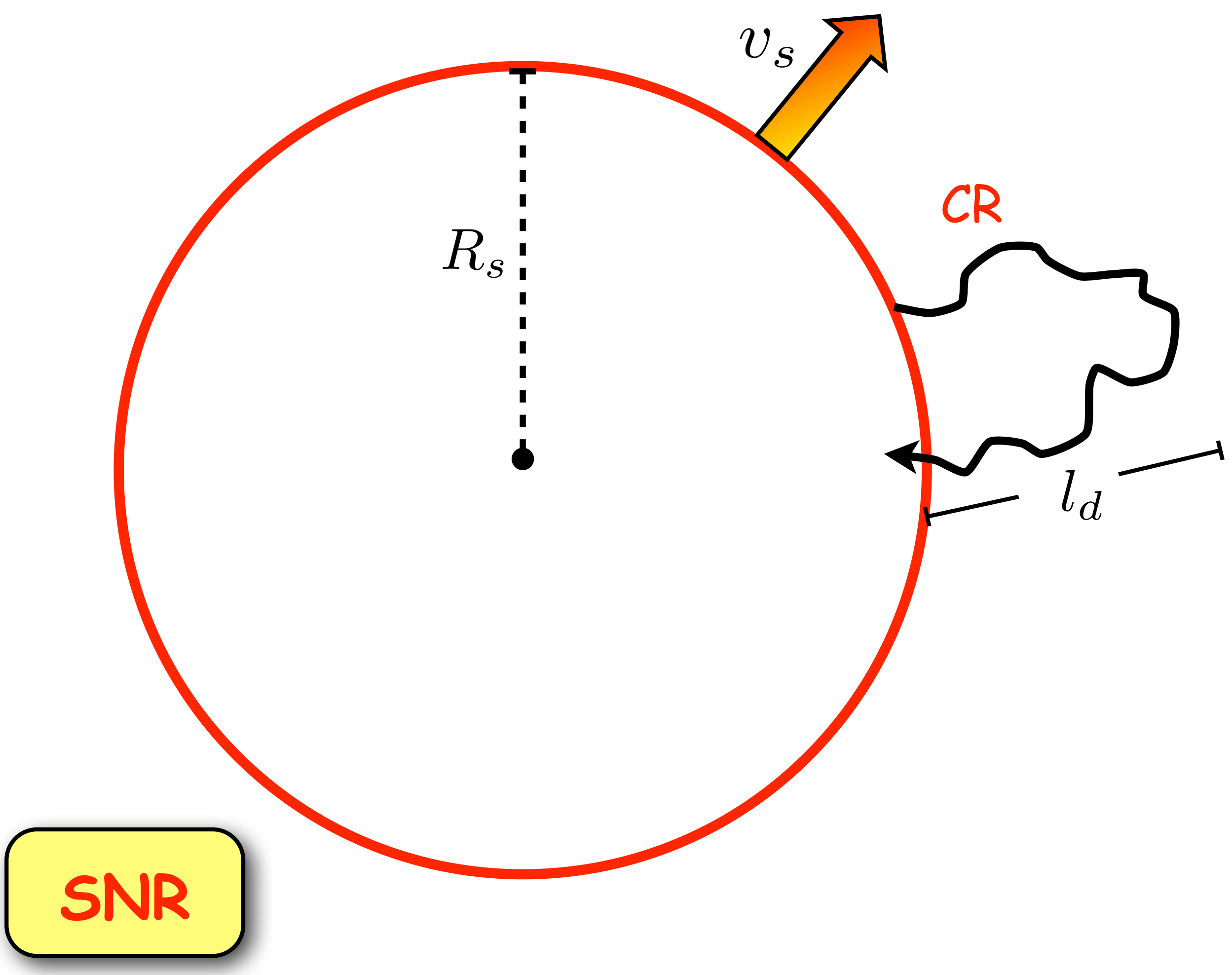
CR acceleration at SuperNova Remnants



we'd like SNRs to accelerate CRs at least up to the knee

no features in the spectrum until the knee

Can SNRs accelerate CRs up to the knee?



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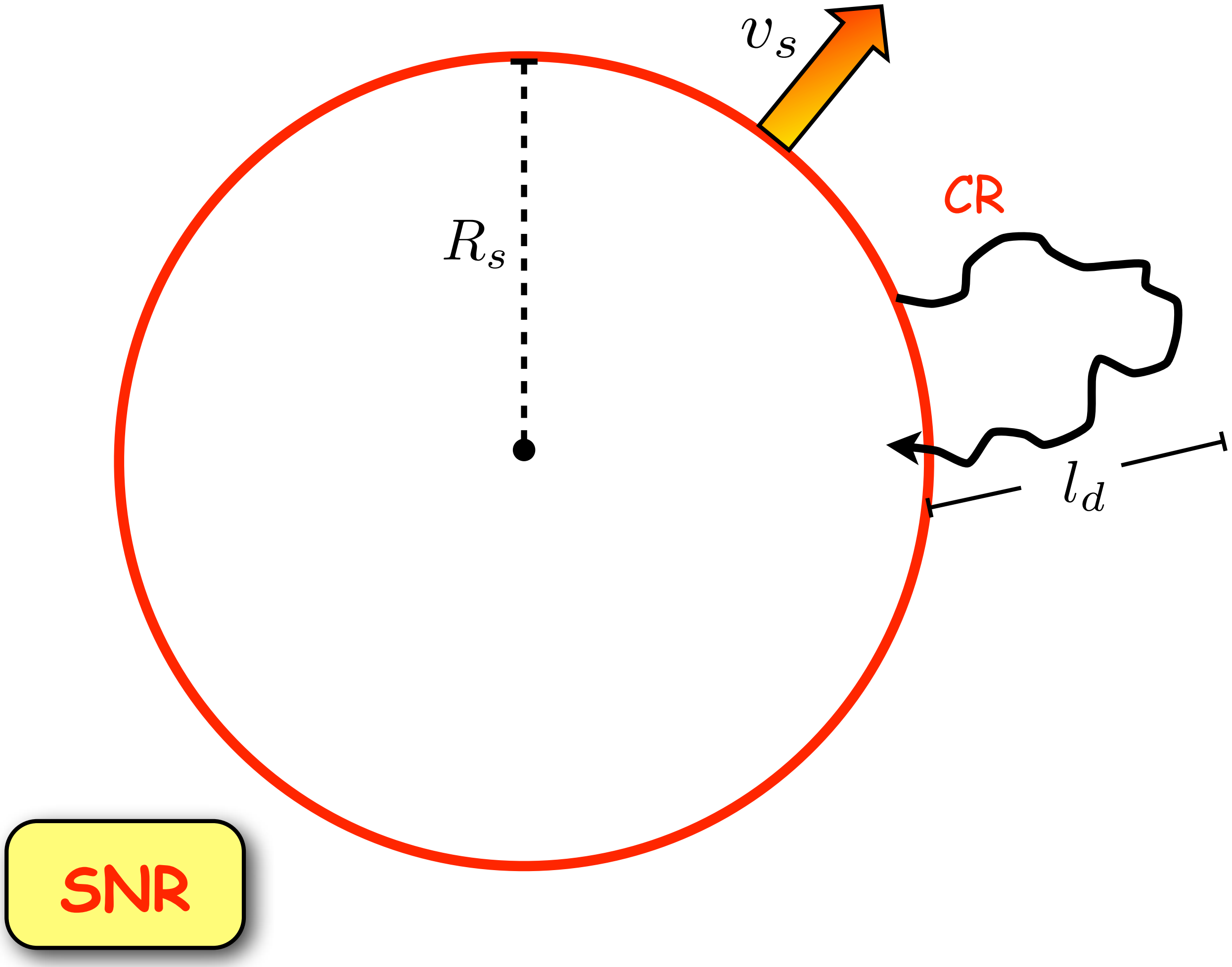

diffusion length

$$l_d = \frac{D}{v_s}$$

acceleration time

$$t_{acc} = \frac{D}{v_s^2}$$

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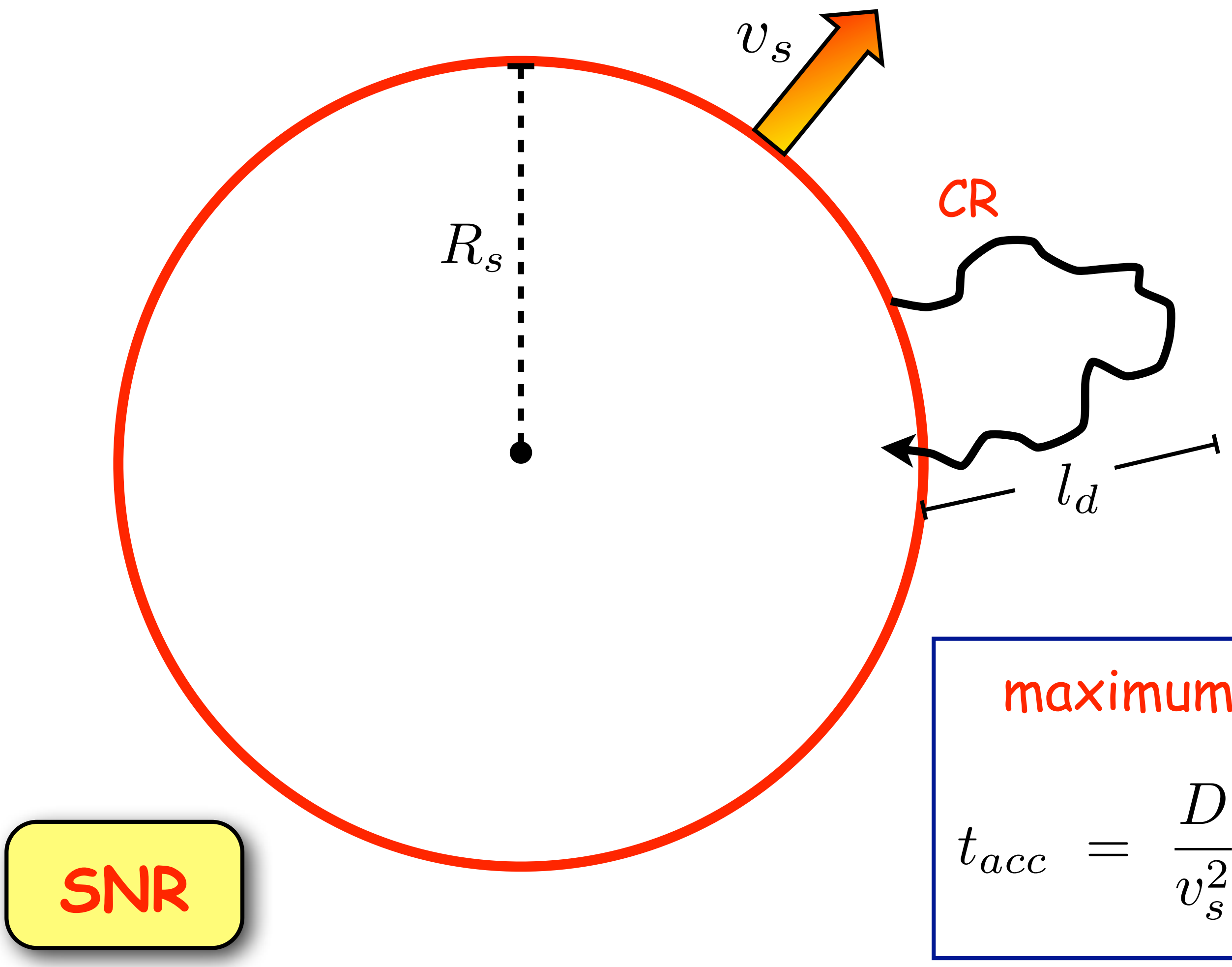

diffusion length

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acceleration time

$$t_{acc} = \frac{D}{v_s^2}$$

maximum CR energy determined by:

$$t_{acc} = \frac{D}{v_s^2} < t_{age} \; / \; l_d = \frac{D}{v_s} < R_s$$

Magnetic field amplification at shocks

WARNING! This would require a long discussion

- the ISM magnetic field (diffusion coefficient) is too weak (large) to accelerate CRs at SNR shocks...
- theoreticians believe that CRs can excite magnetic turbulence at shocks while being accelerated -> **MAGNETIC FIELD AMPLIFICATION**
- X-ray astronomers obtained quite convincing evidence for this fact, and measured magnetic field strength up to **~100 μG ÷ 1 mG** (!)
- theoreticians think that, in the (very) turbulent amplified field the diffusion coefficient is the **Bohm diffusion coefficient**:

$$D = \frac{1}{3} R_L \, c \propto \frac{E}{B}$$

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(1) Free expansion phase

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$$\frac{D(E_{max})}{v_s^2} = t_{age}$$

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$$\frac{D_0 \; E_{max}}{B \; v_s^2} = \frac{D(E_{max})}{v_s^2} = t_{age}$$

$$E_{max} \propto t_{age}$$

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(2) Sedov phase

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$$t_{acc} = \frac{D}{v_s^2} < t_{age}$$

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most stringent constrain

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most stringent constrain

$$\frac{D_0 \ E_{max}}{B \ v_s} = \frac{D(E_{max})}{v_s} = R_s$$

$$E_{max} \propto B \ v_s \ R_s$$

$B \propto t_{age}^{-\alpha}$, $v_s \propto t_{age}^{-\frac{3}{5}}$, $R_s \propto t_{age}^{\frac{2}{5}}$

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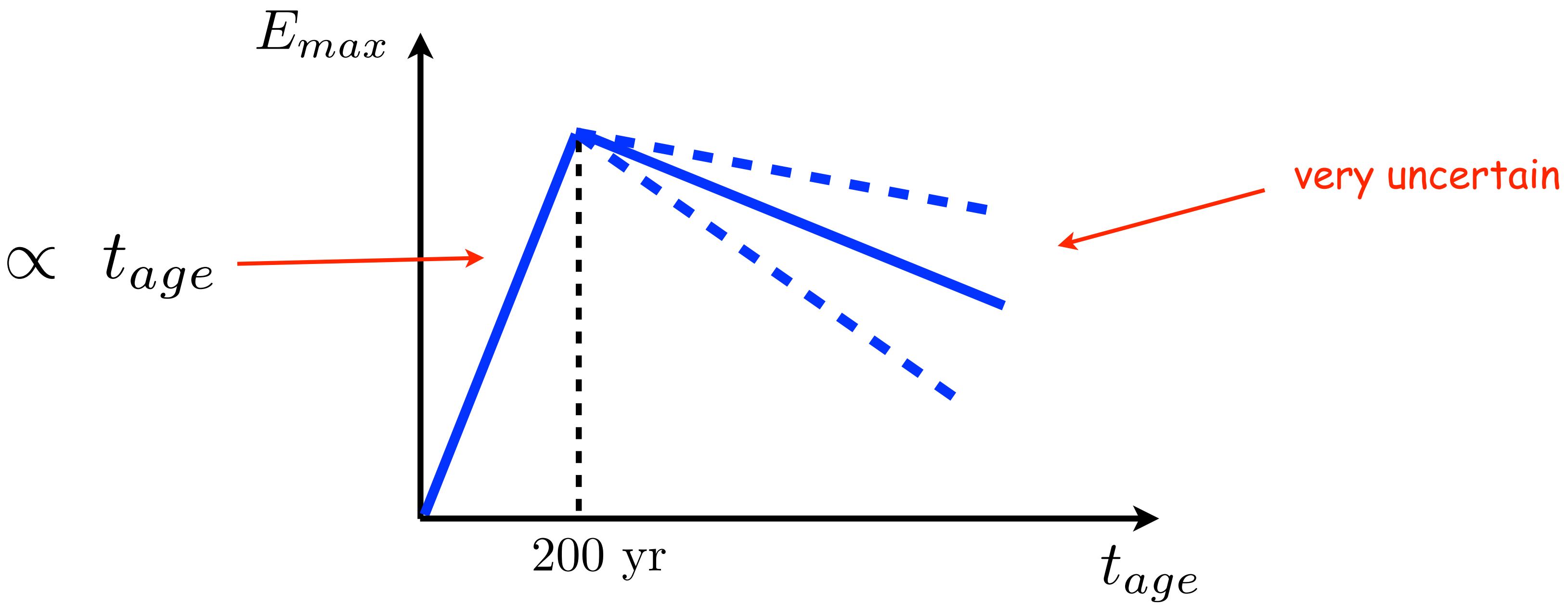
$$E_{max} \propto \underbrace{B}_{t_{age}^{-\alpha}}\ \underbrace{v_s}_{t_{age}^{-\frac{3}{5}}}\ \underbrace{R_s}_{t_{age}^{\frac{2}{5}}}$$

$$E_{max} \propto t_{age}^{-\frac{1}{5}-\alpha}$$

the maximum energy decreases with time

Can SNRs accelerate CRs up to the knee?



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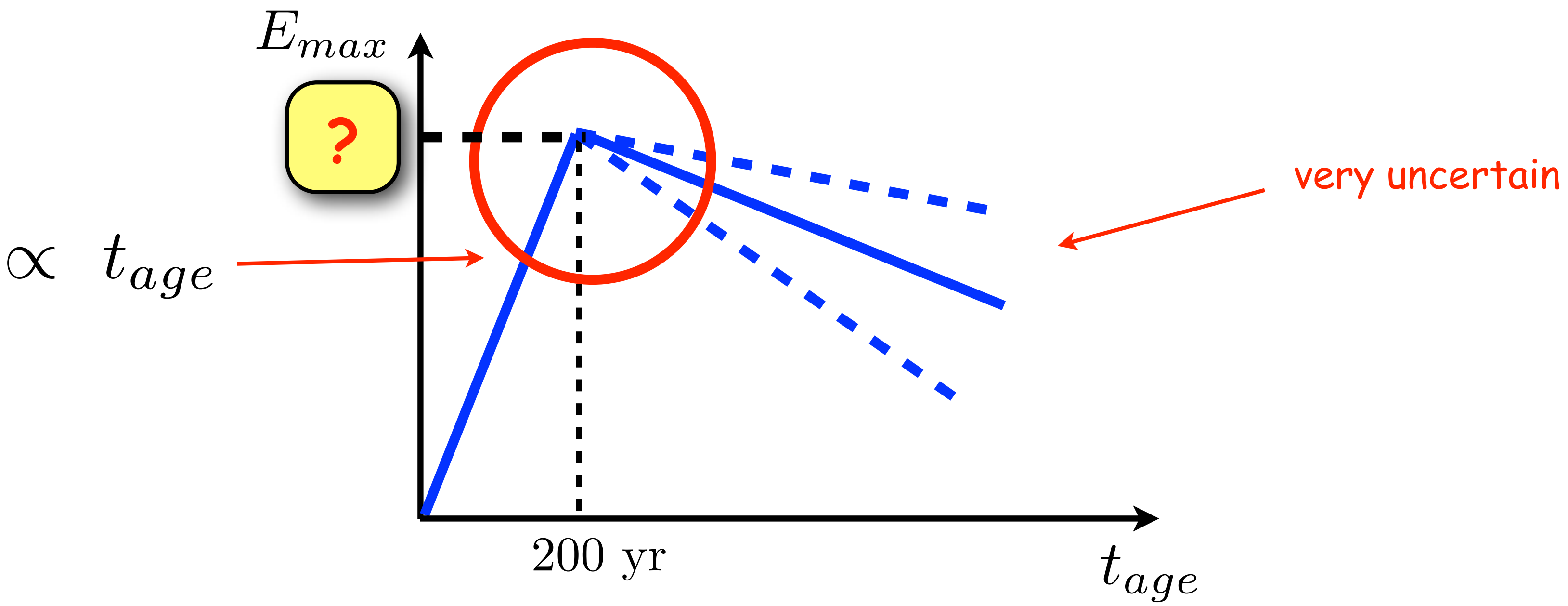

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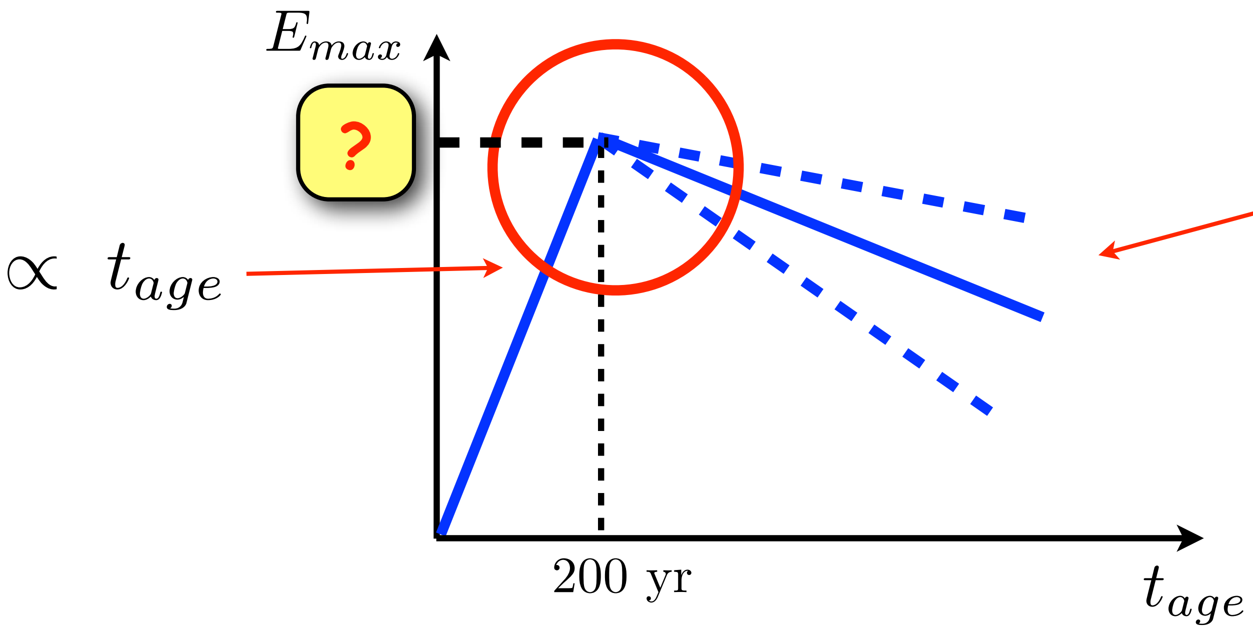
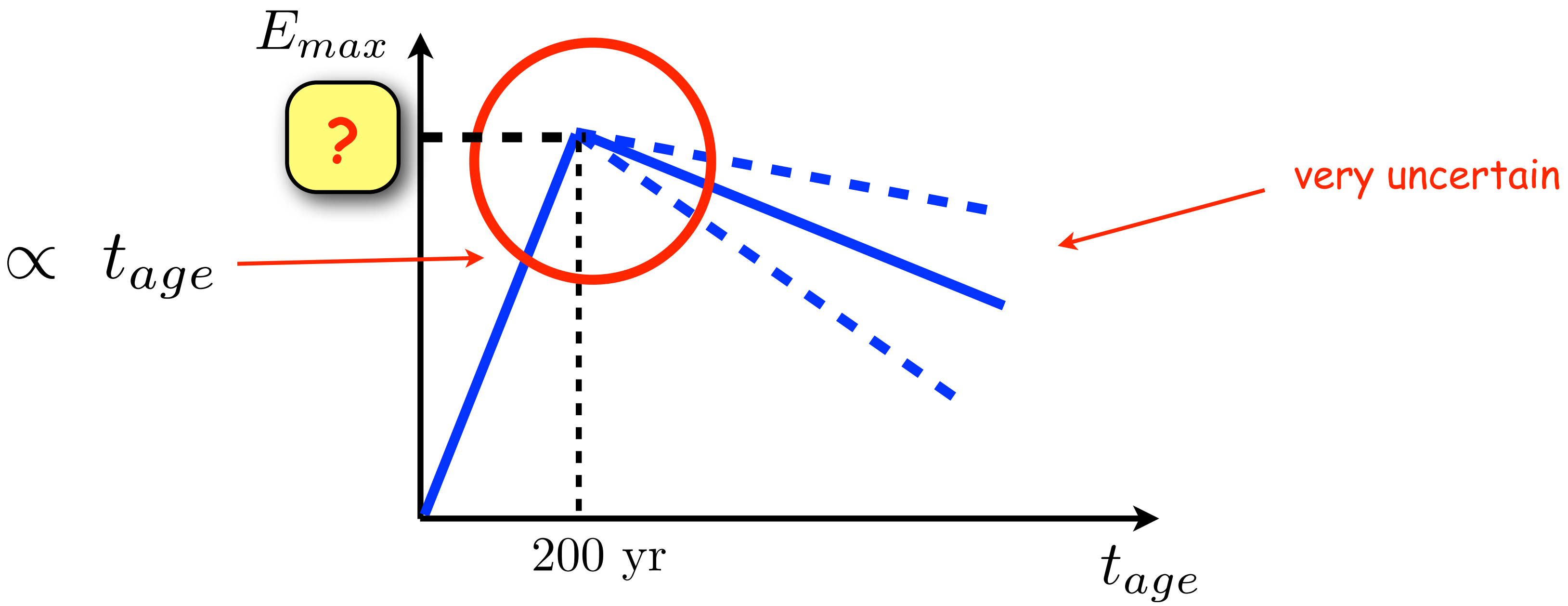


$$\frac{D_B(E_{max})}{v_{FE}^2} = t_{Sedov}$$

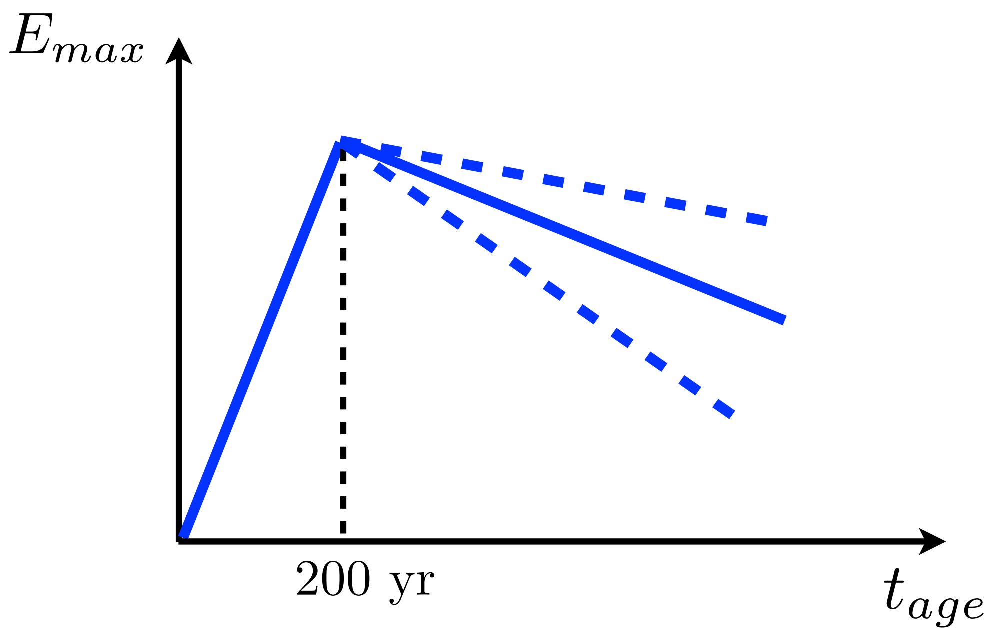
Can SNRs accelerate CRs up to the knee? YES!



$$\frac{D_B(E_{max})}{v_{FE}^2} = t_{Sedov}$$

$$E_{max} \approx 20 \left(\frac{B}{100\ \mu\mathrm{G}}\right)\left(\frac{v_{FE}}{10^9\ cm/s}\right)^2\left(\frac{t_{Sedov}}{200\ \mathrm{yr}}\right) PeV$$

Particle escape from SNRs



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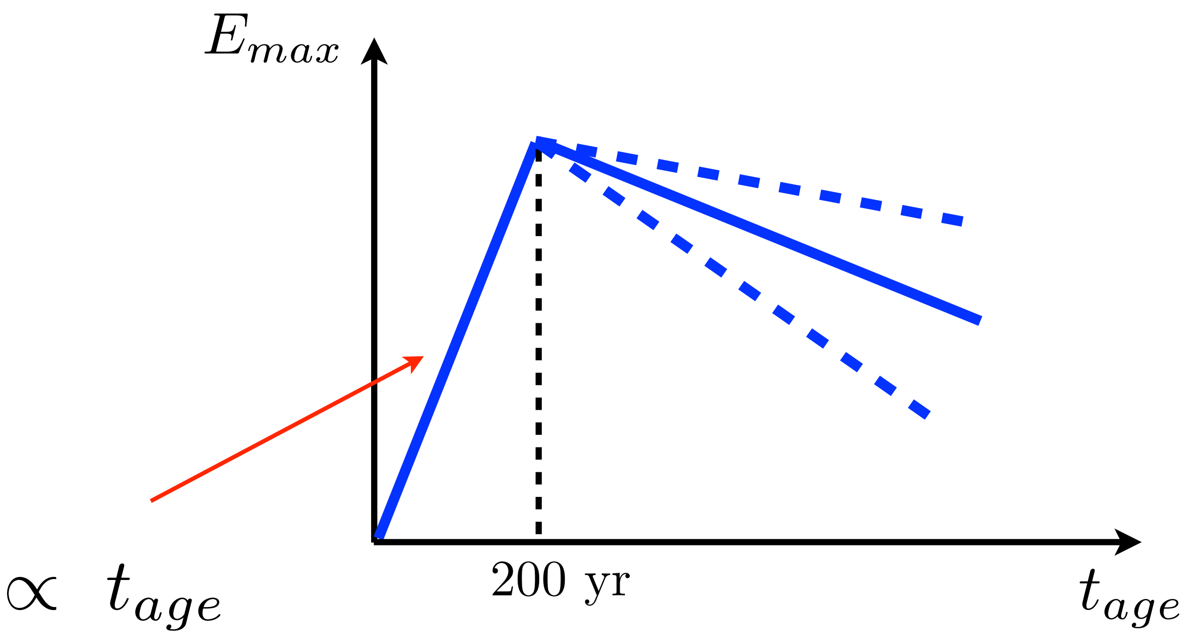
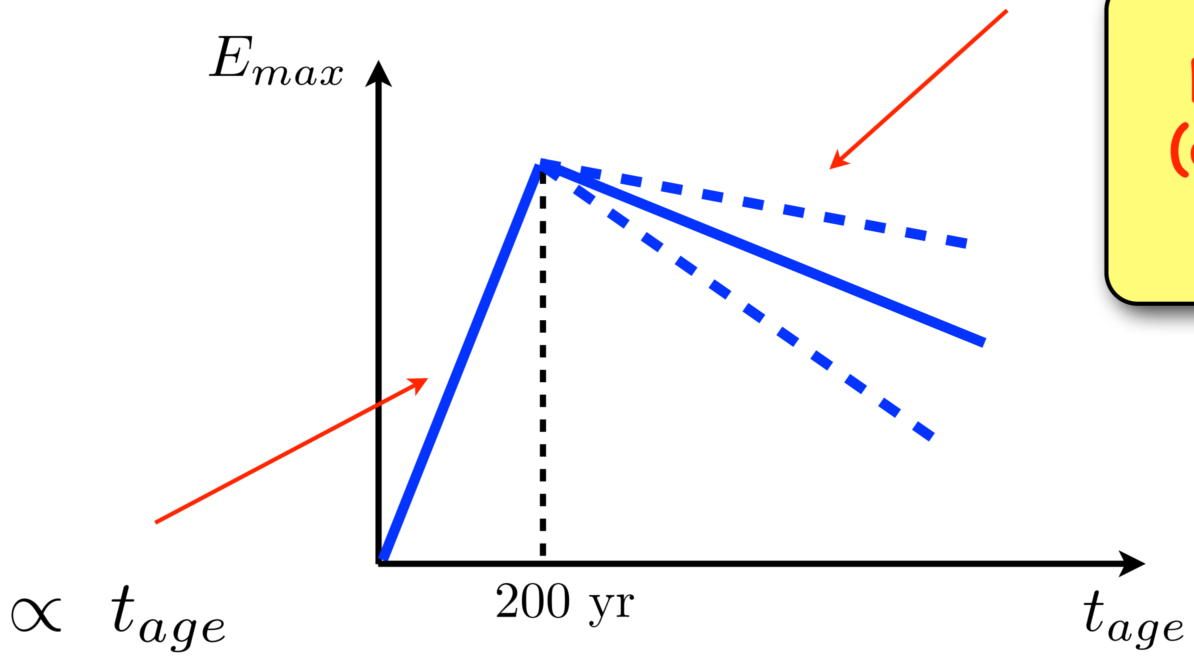


no particle escape

Particle escape from SNRs

$$E_{max} \propto t_{age}^{-\delta}$$

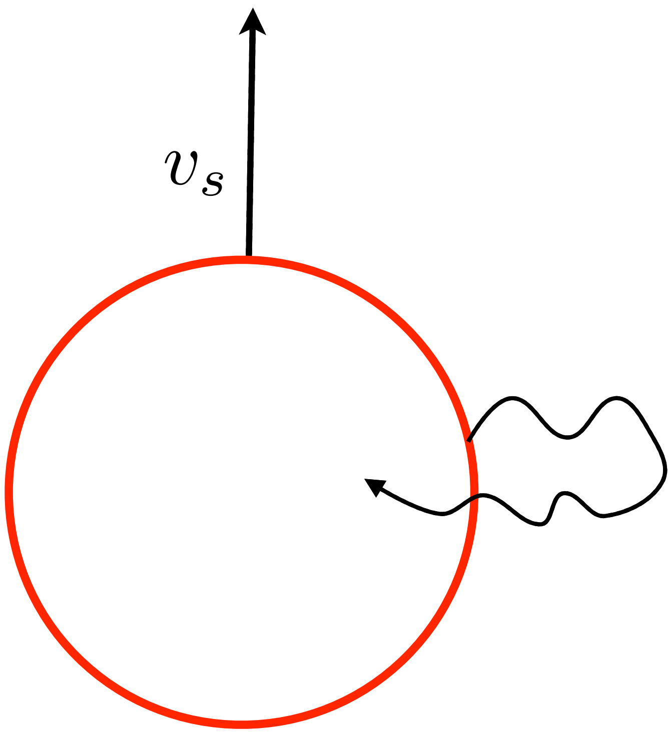
δ is basically unknown



particles with $E>E_{max}$ (accelerated at $t<t_{age}$) escape the SNR

no particle escape

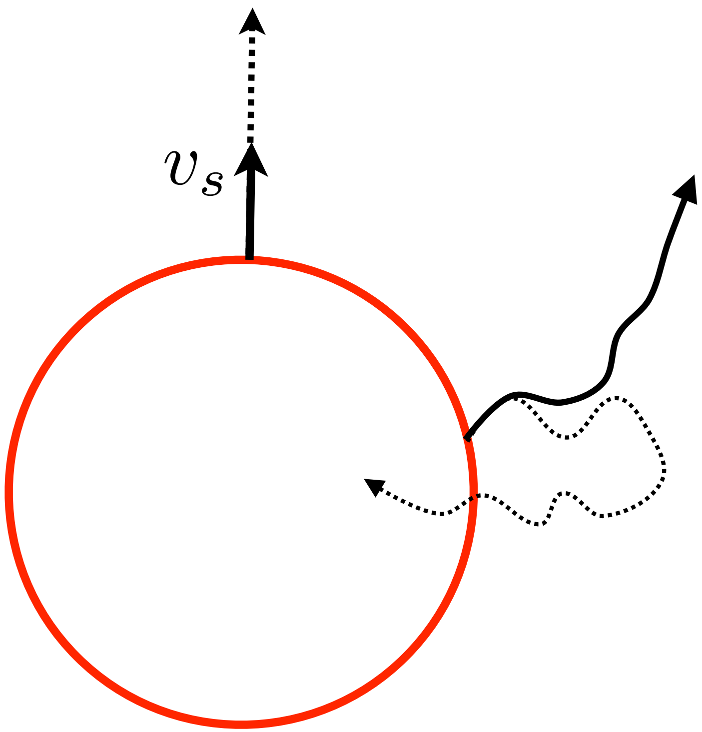
Particle escape from SNRs



- **PeV particles** are accelerated at the beginning of Sedov phase (~200yrs), when the shock speed is high!
- they **quickly escape** as the shock slows down

This is a supernova remnant

Particle escape from SNRs



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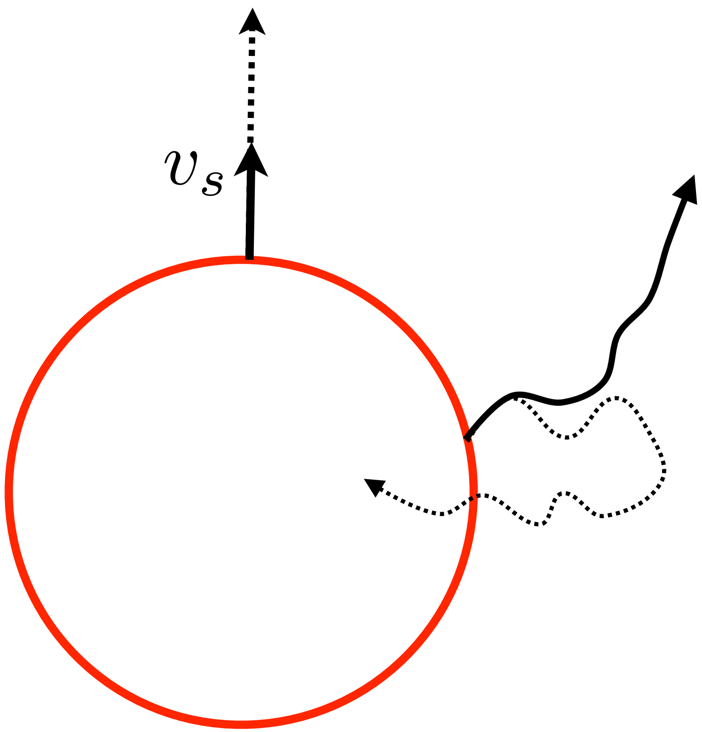

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- they quickly escape as the shock slows down
- Highest energy particles are released first, and particles with lower and lower energy are progressively released later
- a SNR is a PeVatron for a very short time
- still no evidence for the existence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

Injection spectrum of CRs from SNRs

Which CR spectrum is injected by a SNR during the whole Sedov phase?

particles are released in the ISM at a time: $E \propto t^{-\delta}$ ← unknown

CRs are accelerated at a rate: $L_{CR} \propto t^{-1}$

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$$\mathrm{d}\mathcal{E}_{CR \to ISM} \propto L_{CR} \, \mathrm{d}t$$

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$$\frac{\mathrm{d}t}{\mathrm{d}E} = -\frac{1}{\delta} E^{-\frac{1}{\delta}-1}$$

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$$N_{CR}(E) \propto \frac{\frac{\mathrm{d}\mathcal{E}_{CR \to ISM}}{\mathrm{d}E}}{E} \propto E^{-2}$$ ← **OK!**

A bit more general solution...

a fraction η_{cr} of the shock kin. energy L_k -> CRs with spectrum: $Q_{CR} \propto E^{-s}$

Ohira et al 2010

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$$F_{esc} = \int Q_{esc}(E)\ E\ \mathrm{d}E \propto Q_{CR}(E_{max})\ E^2_{max}$$

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(a) s < 2 -> $\eta_{CR} L_k \approx Q_{CR}(E_{max}) E_{max}^2$ → $N_{esc} \propto E^{-2}$

escaping energy flux

Ohira et al 2010

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escaping energy flux

(b) Soft spectrum -> s > 2

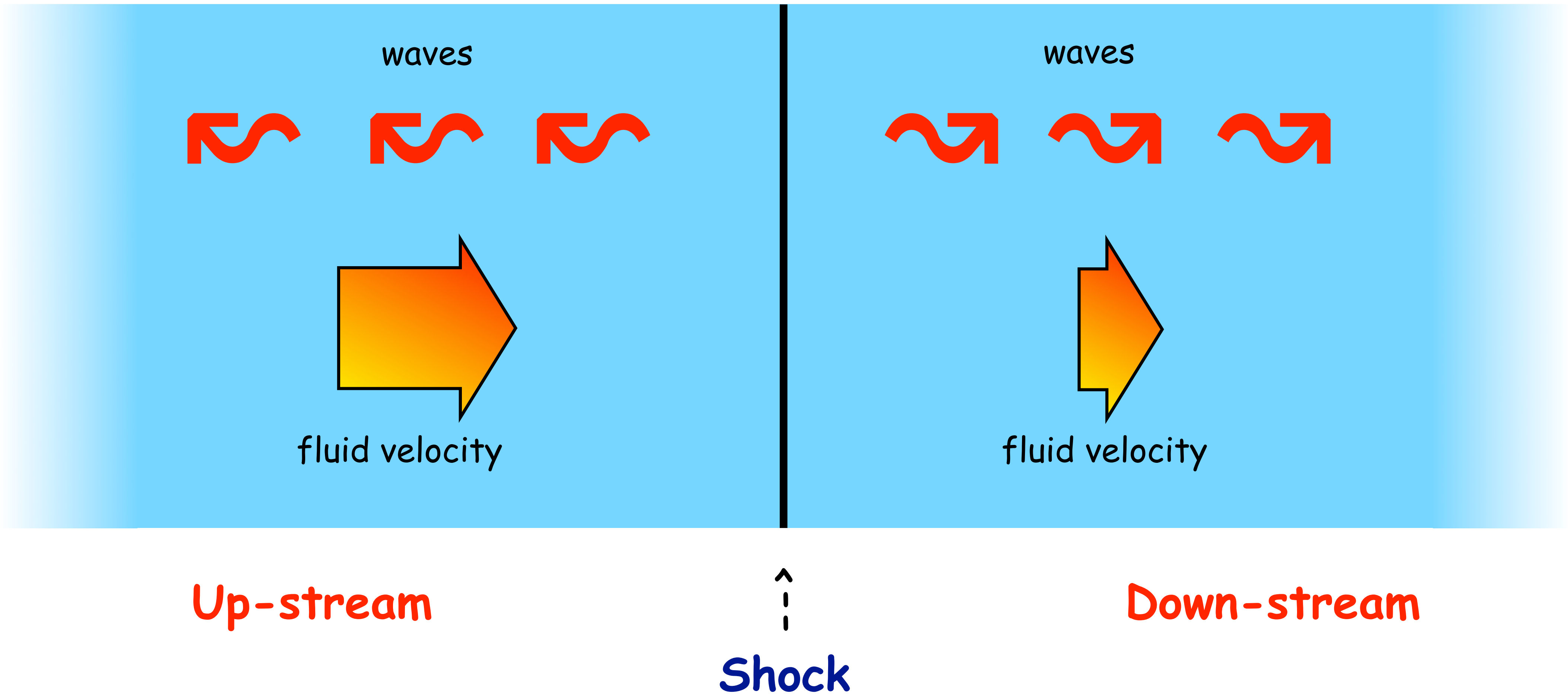
$$\eta_{CR} L_k \approx Q_{CR}(E_0) E_0^2 \propto Q_{CR}(E_{max}) E_{max}^2 \left(\frac{E_0}{E_{max}}\right)^{2-s}$$

→ $N_{esc} \propto E^{-s}$

Ohira et al 2010

Alfven drift

Zirakashvili & Ptuskin 2008



CRs "feel" a smaller compression ratio -> softer spectrum!!!

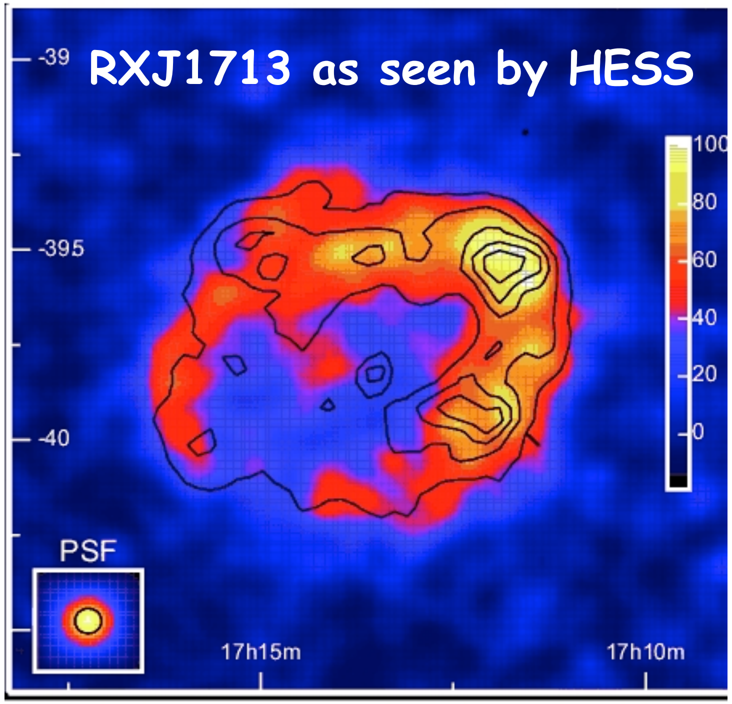
Summarizing:

SNRs are good candidate sources for CRs because:

- they can provide the right amount of energy in form of CRs (if **~10% efficiency**)
- they inject CRs in the ISM with (roughly) the spectrum needed to explain CR observations (**$\sim E^{-2.1...2.4}$**)
- they can accelerate CRs (at least) up to the energy of the CR knee (**$\sim 5 \times 10^{15}$ eV**)

Further
Gamma-Ray based Tests
for Cosmic Ray Origin

TeV emission from SNRs: a test for CR origin



Test passed!

This is still not a conclusive proof -> hadronic or leptonic emission?

Test (0): neutrinos

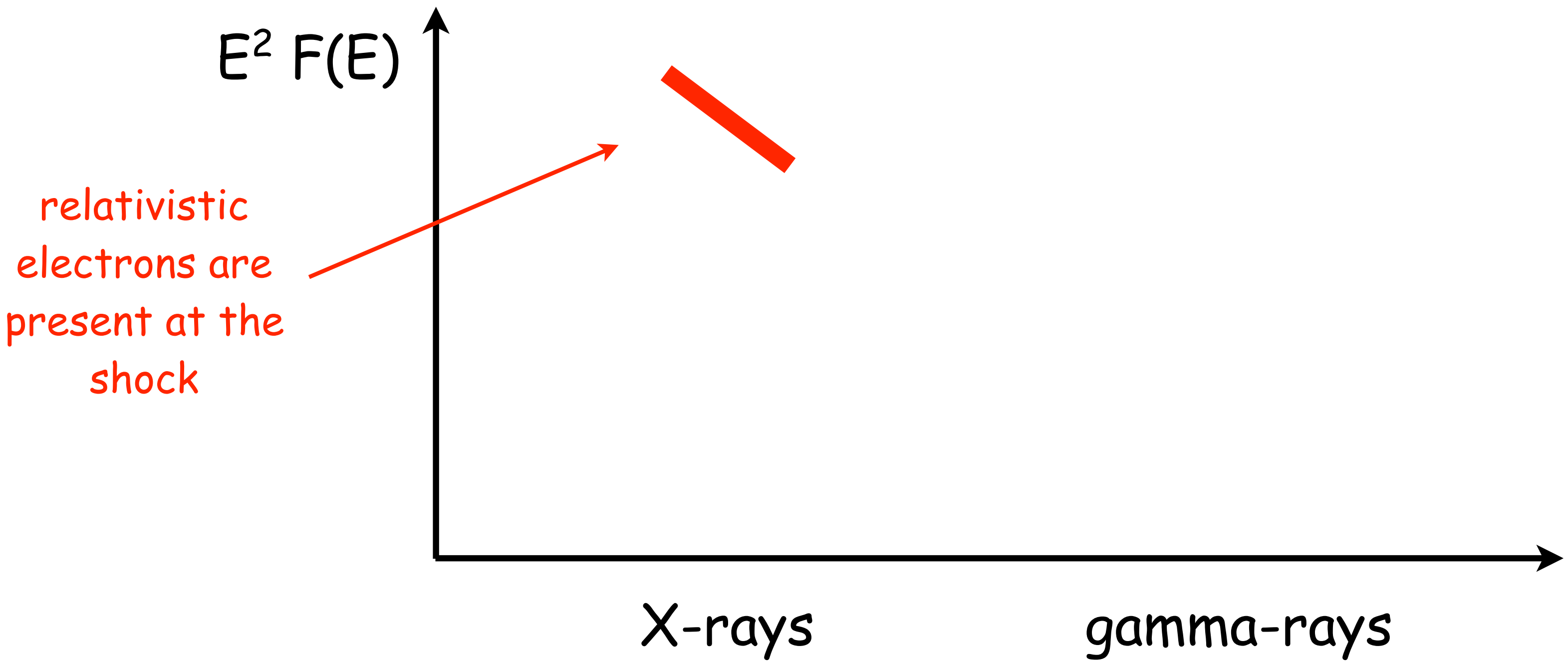
Good thing: Detection of neutrinos = hadronic interactions

Bad thing: Neutrino telescopes have a very poor sensitivity...

Thus: we'd better search for gamma-ray-based tests!

Hadronic versus leptonic emission

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



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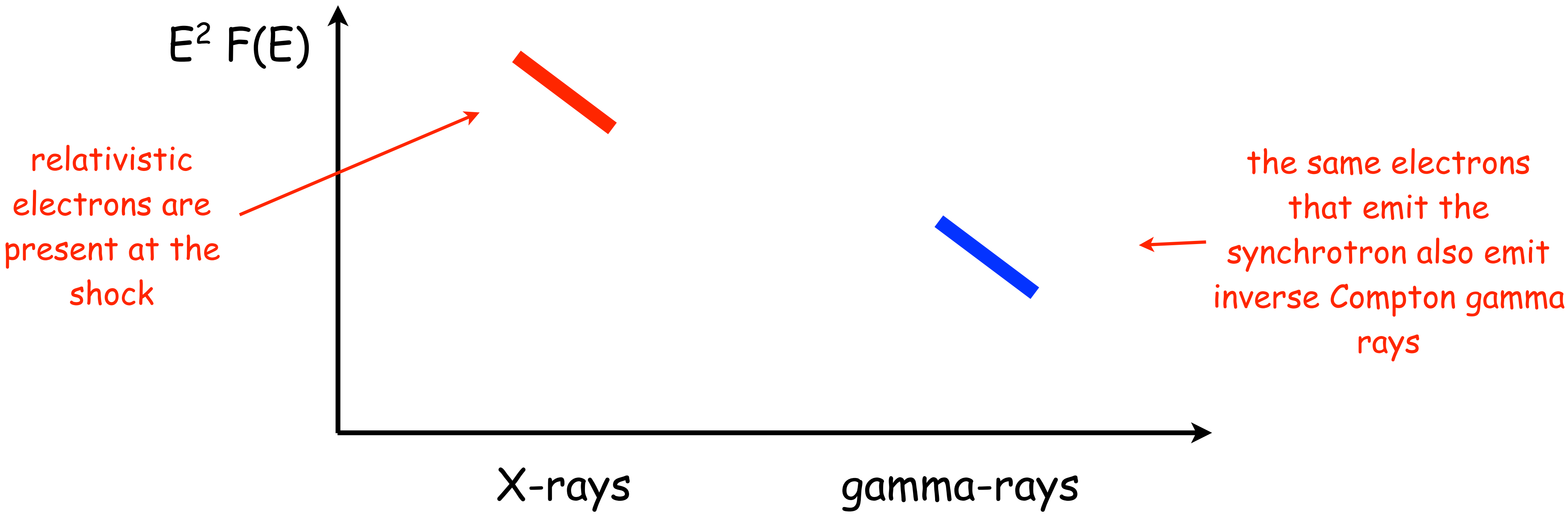

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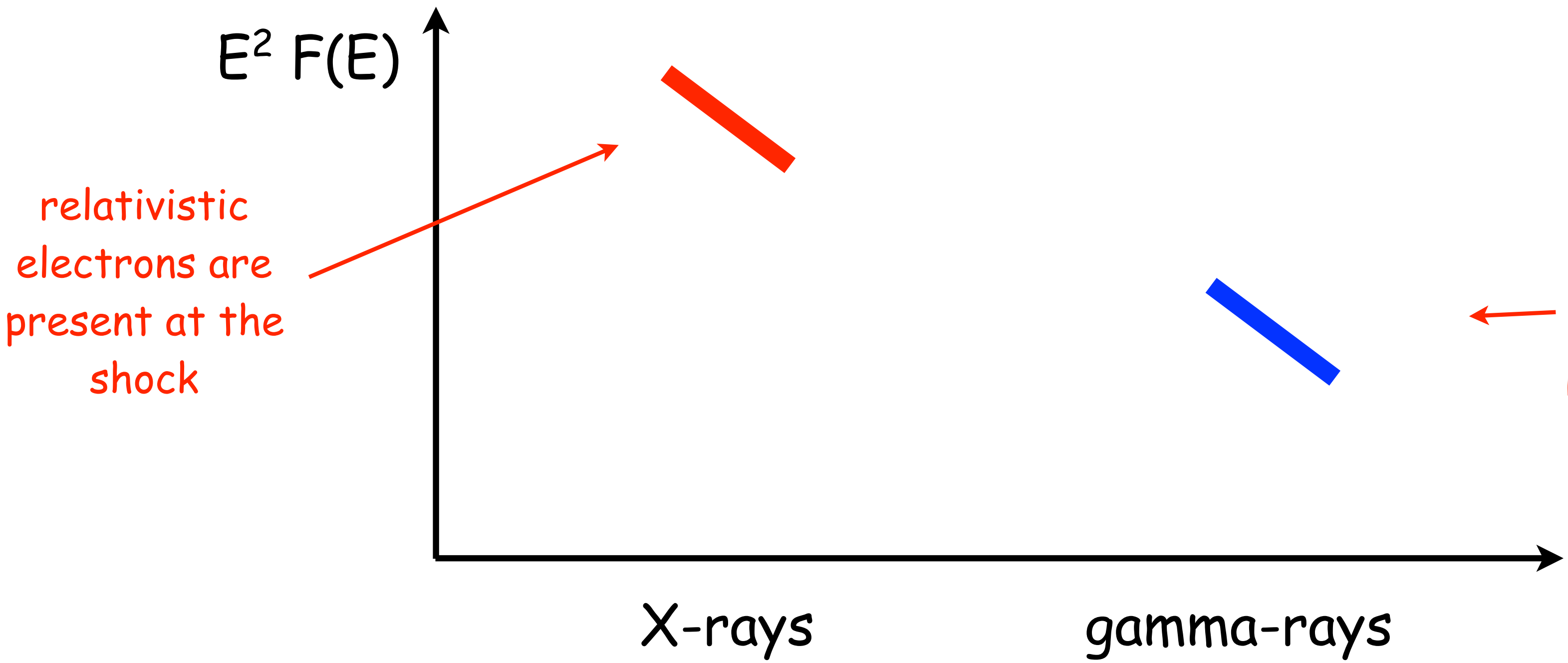

synchrotron -> $F_s \propto n_e B^\beta$ inverse Compton -> $F_{IC} \propto n_e w_{soft}$

this product is fixed by X-ray obs. we know this

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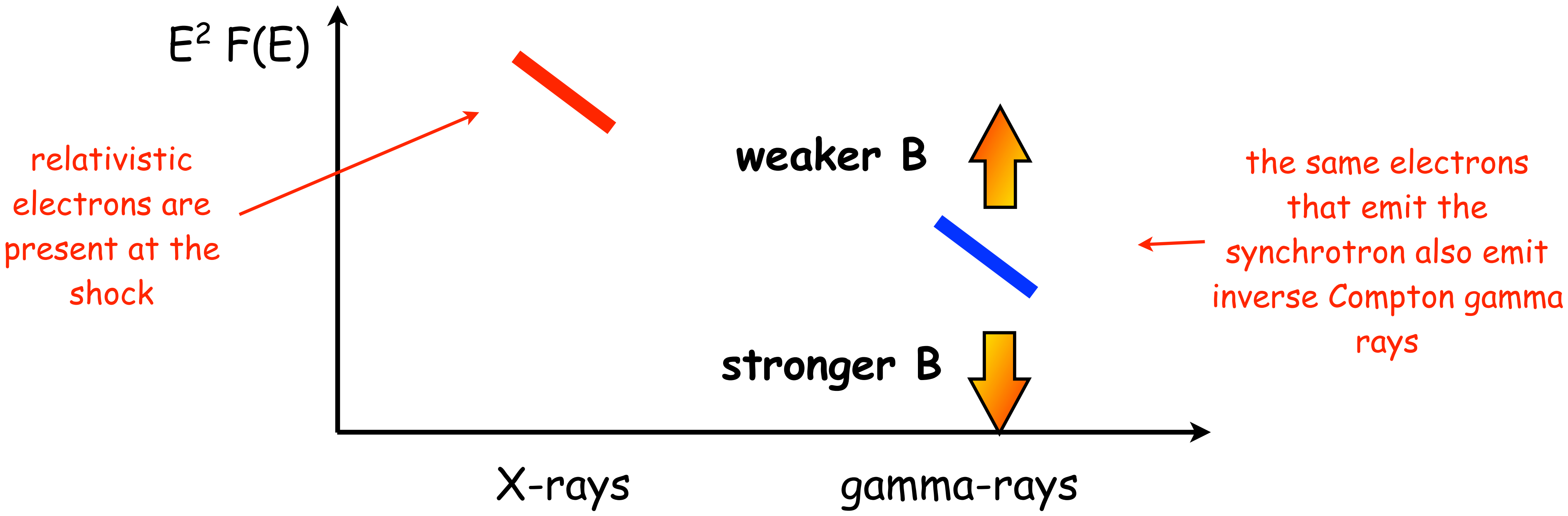

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this product is fixed by X-ray obs.   we know this

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 ->

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

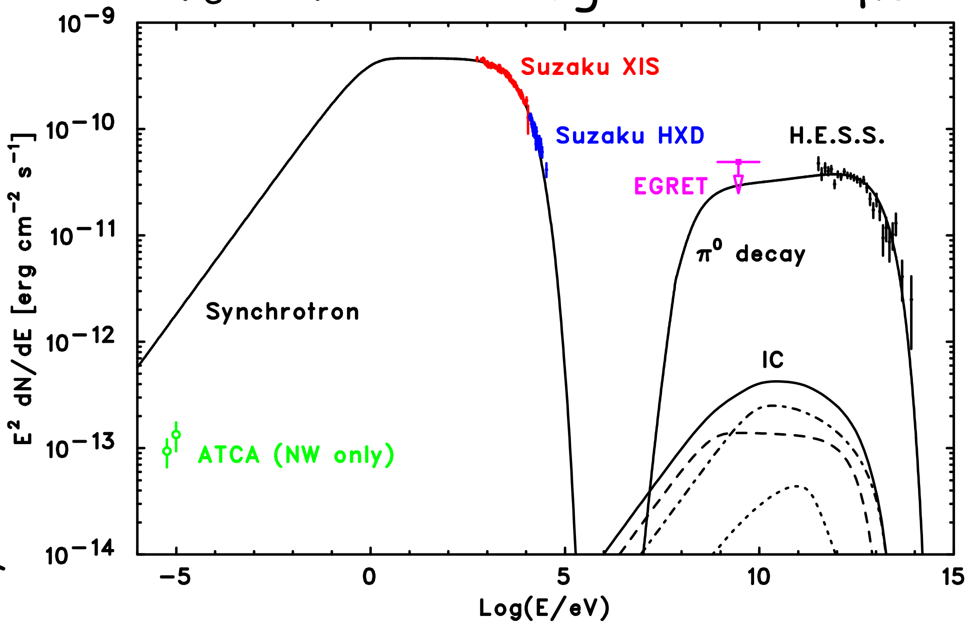
Hadronic versus leptonic emission

RXJ1713: hadronic and leptonic models

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

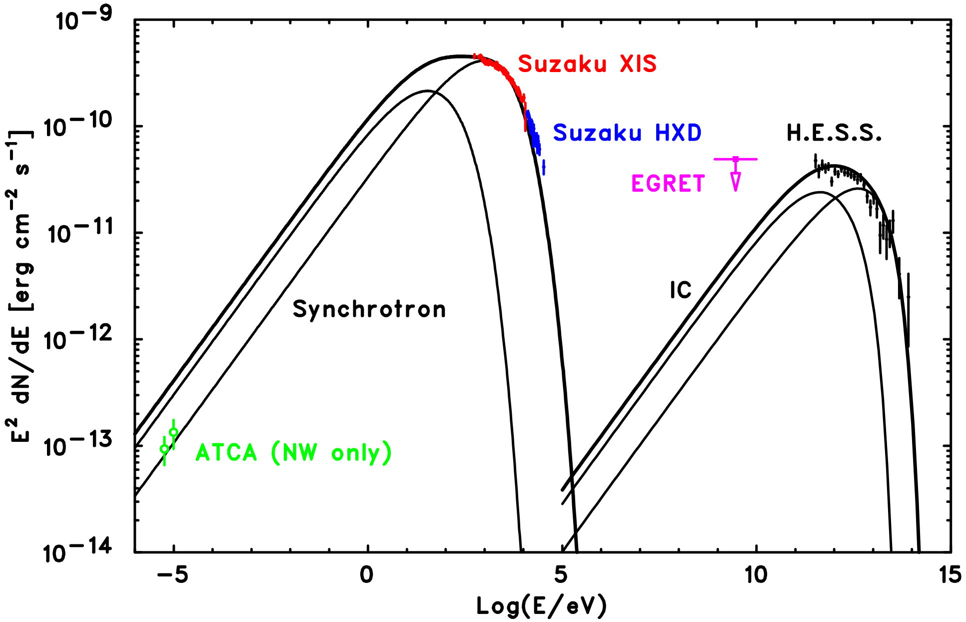
Leptonic: low B field -> synchrotron losses negligible -> electron spectrum E^{-2} -> inverse Compton scattering -> gamma ray spectrum $E^{-1.5}$

$W_p = 2{,}7 \times 10^{50}\ (n/cm^{-3})^{-1}$ 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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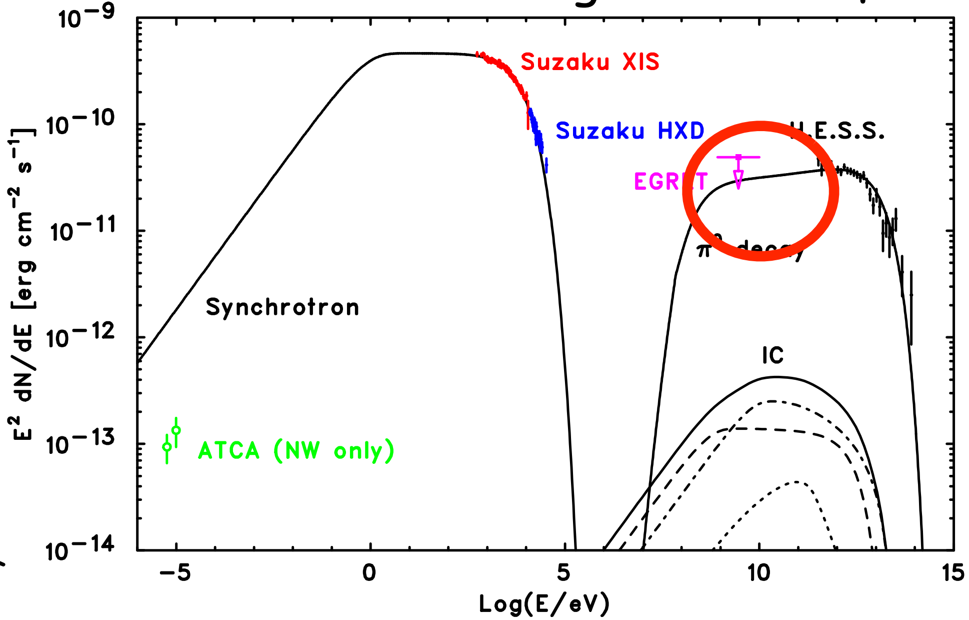

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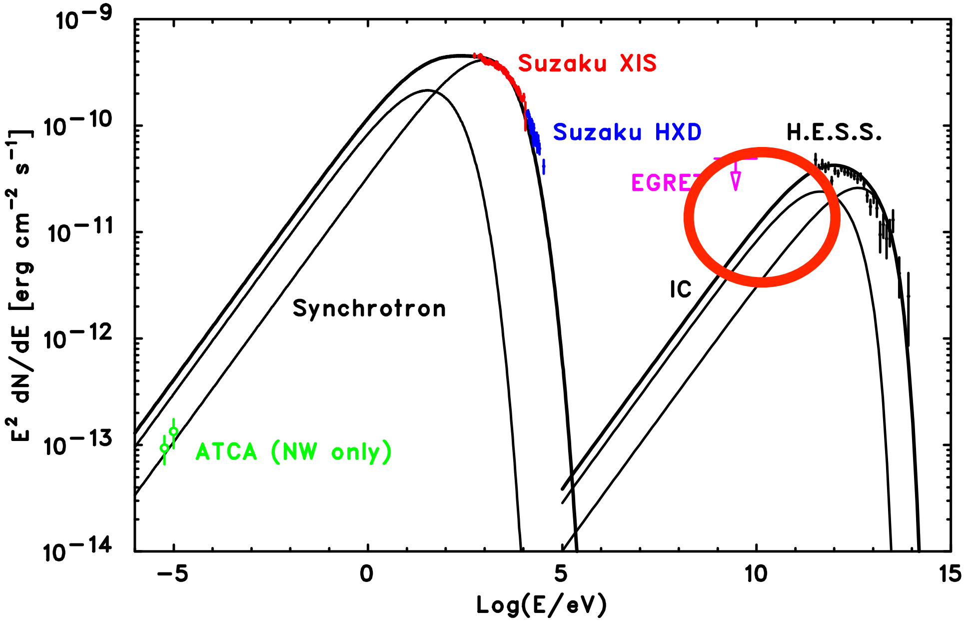
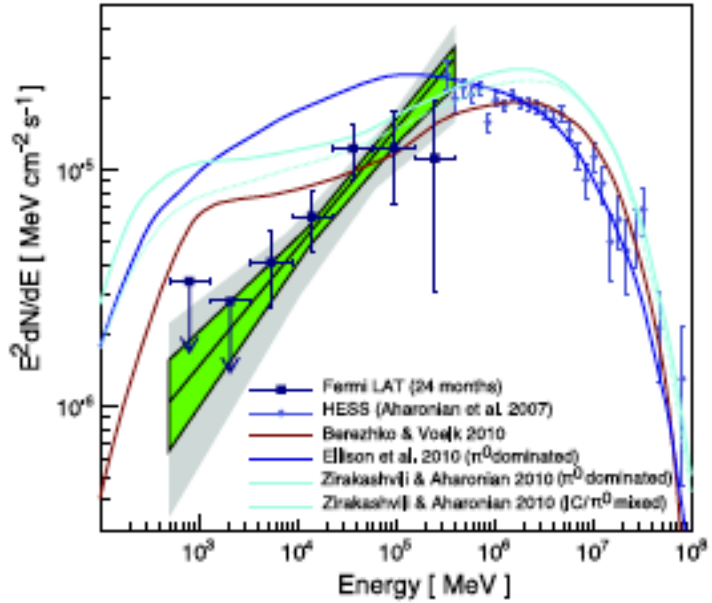


Leptonic

Tanaka et al., 2008

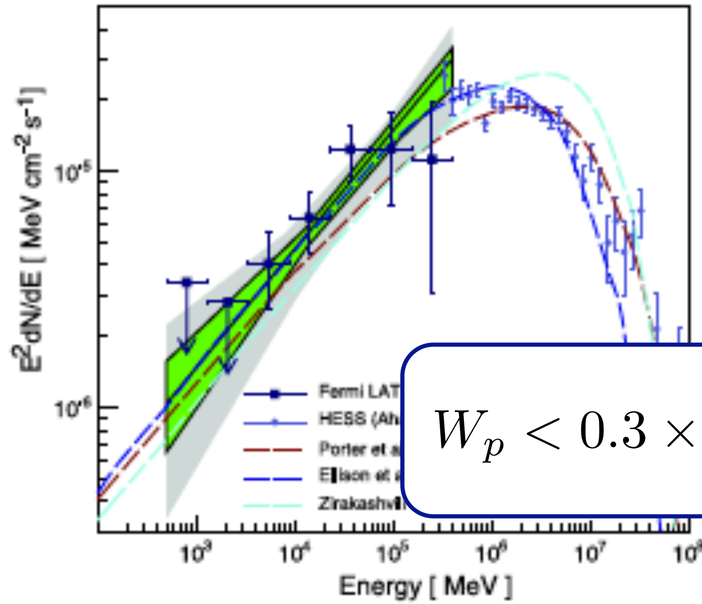
Test (1) FERMI detects RX J1713

p-p interactions ->



the emission is most likely LEPTONIC

inverse Compton ->



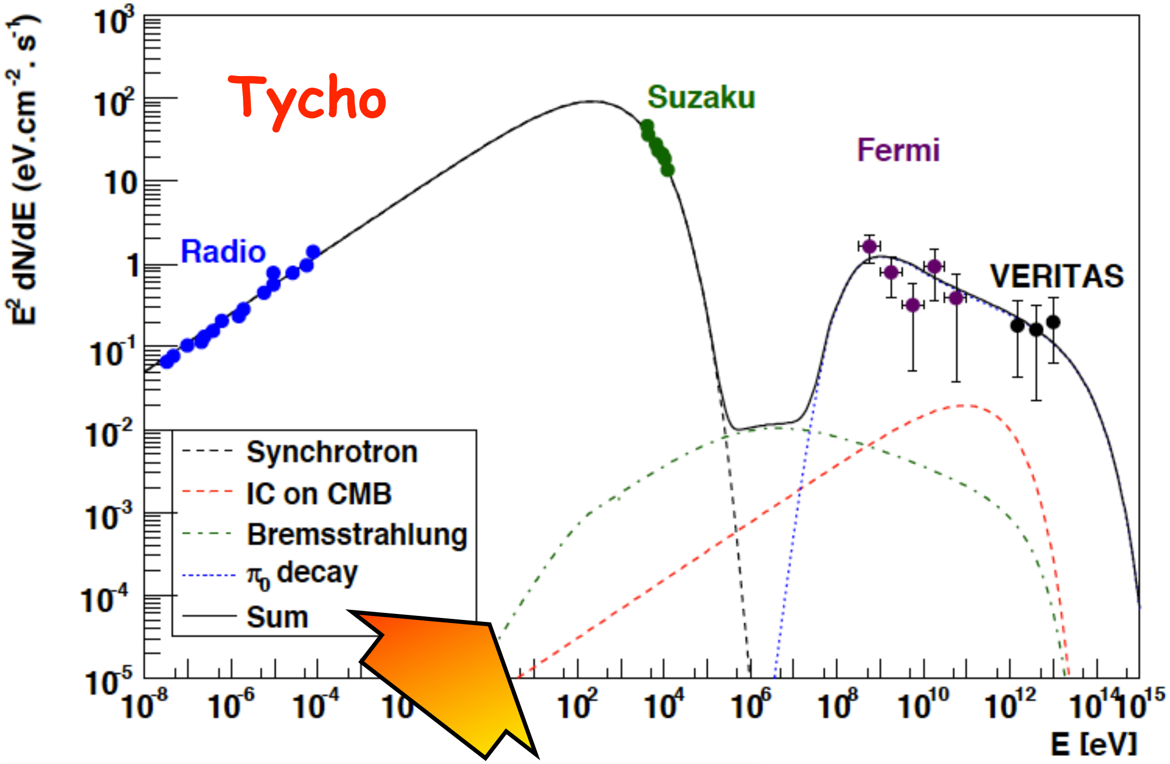
this does NOT mean that there are no protons!!!

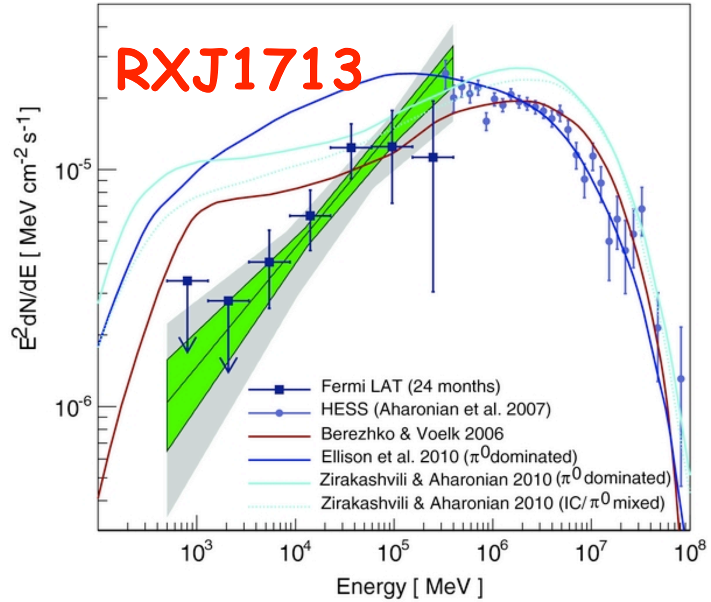
$$W_p < 0.3 \times 10^{51} \left(\frac{n}{0.1 \text{ cm}^{-3})} \right)^{-1} \text{erg}$$

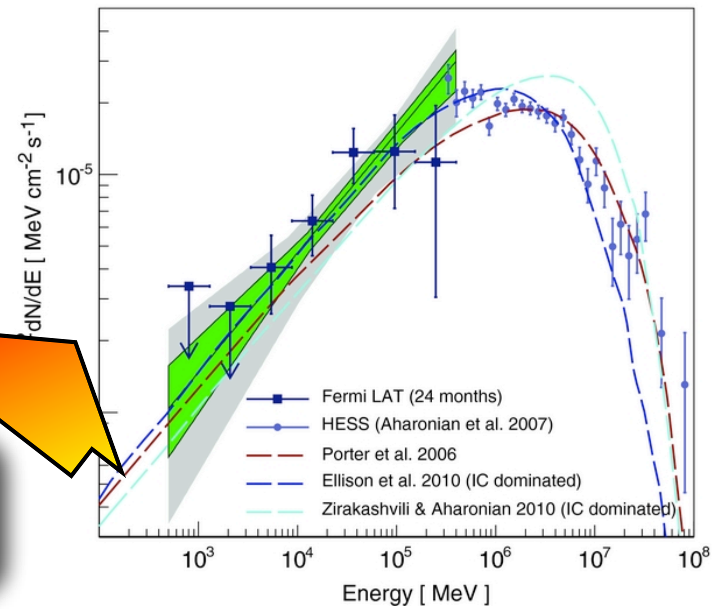
Abdo et al, 2011

Gamma rays from SNRs

(Giordano et al 2011)







(Abdo et al 2010)

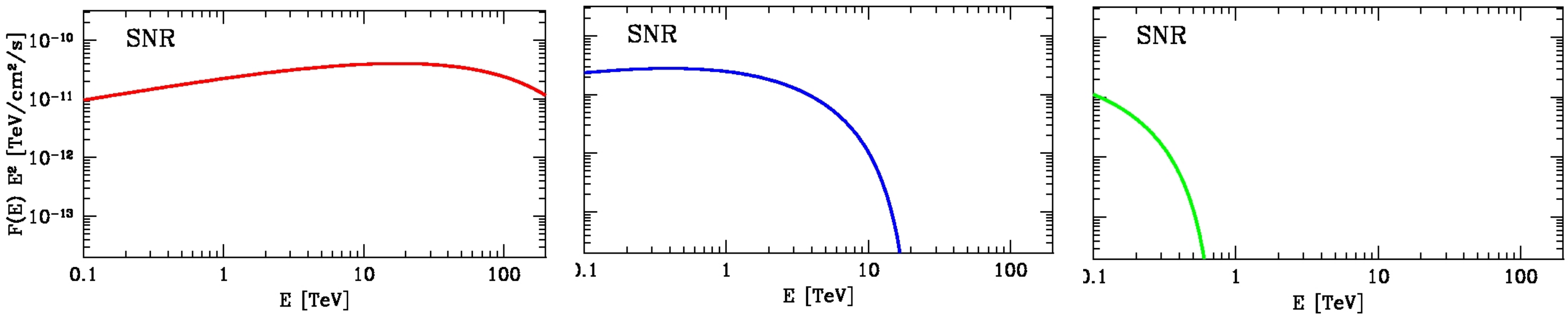
steep (2.3) -> hadronic?

hard (1.5) -> leptonic?

Test (2): multi-TeV emission from SNRs

The TeV emission depends on the SNR age
-> RXJ1713 is already too old to look like a PeVatron

time after the explosion.....



t = 400 yr

t = 2000 yr

t = 8000 yr

the actual behavior depends on gas density, explosion energy, magnetic field evolution, diffusion coefficient...

Gabici & Aharonian, 2007

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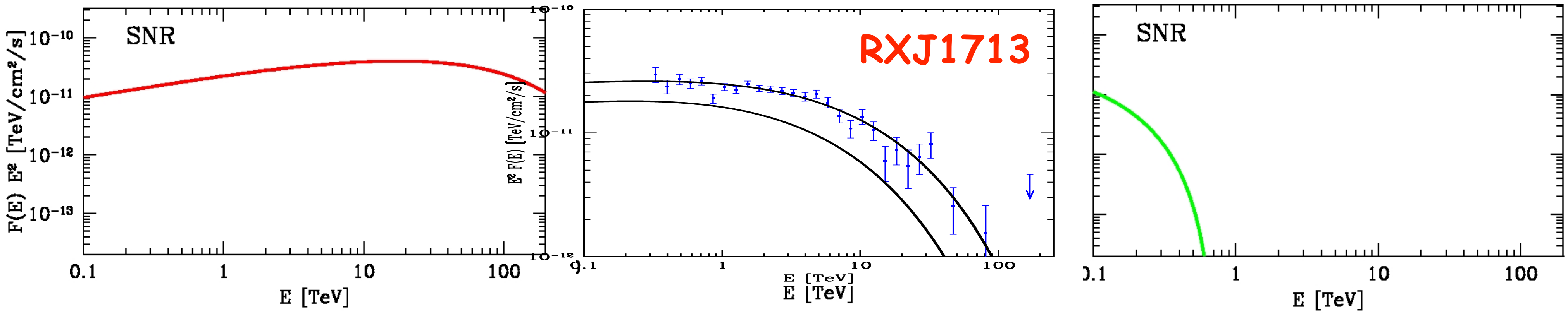

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Gabici & Aharonian, 2007

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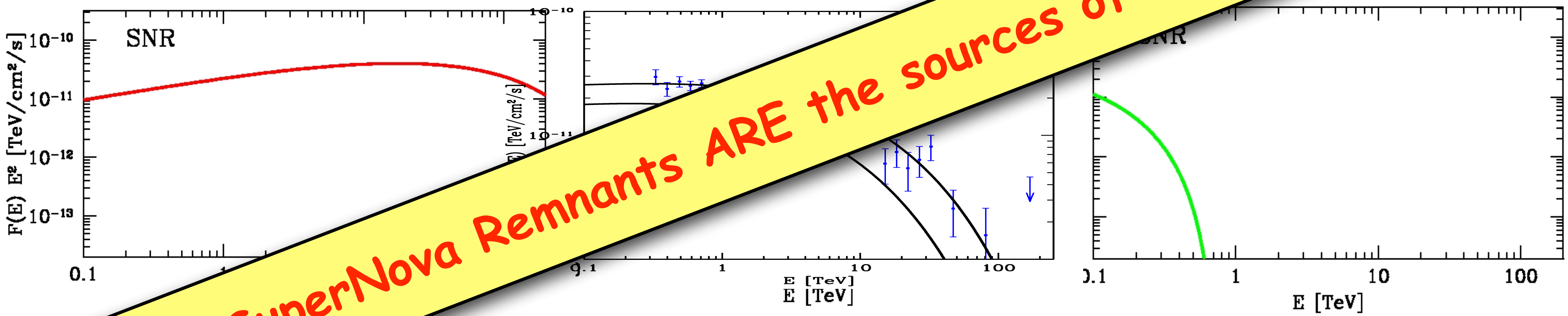


If SuperNova Remnants ARE the sources of Cosmic Rays

= 400 yr

t = 2000 yr

t = 8000 yr

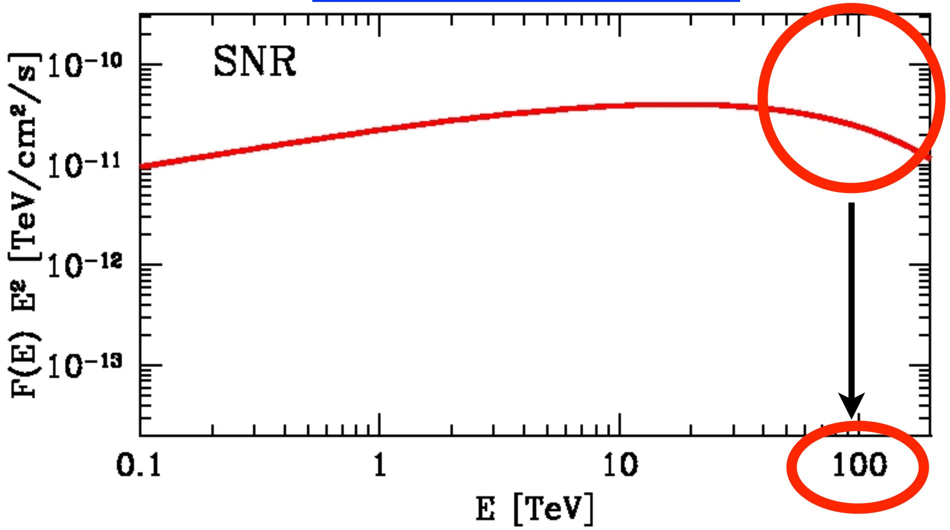
the actual behavior depends on gas density, explosion energy, magnetic field evolution, diffusion coefficient...

Gabici & Aharonian, 2007

Are SuperNova Remnants CR PeVatrons?

Hadronic versus leptonic contribution to the gamma ray emission

t = 400 yr



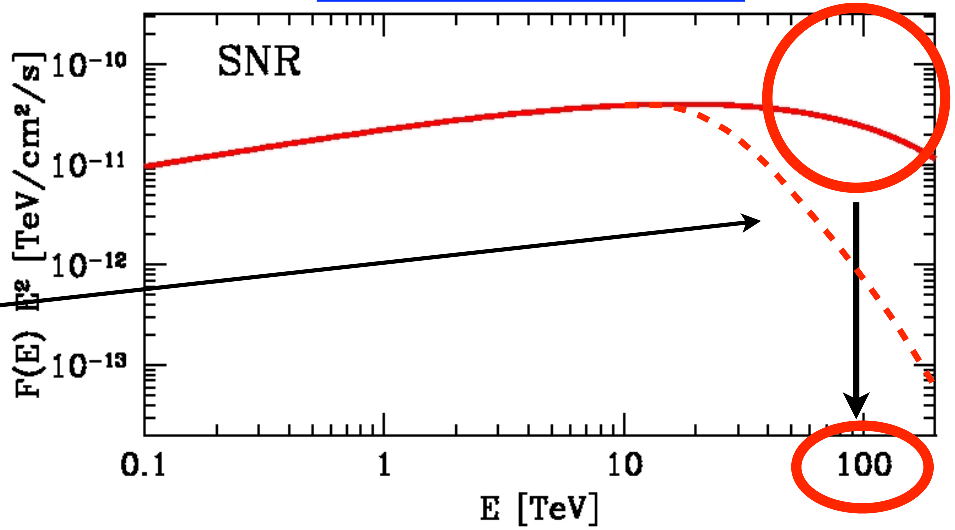
hard spectrum up to ~100 TeV, if hadronic implies the presence of ~PeV Cosmic Rays

-> PeVatron!

Are SuperNova Remnants CR PeVatrons?

Hadronic versus leptonic contribution to the gamma ray emission

t = 400 yr



can we expect to see a spectrum like this one due to inverse Compton?
NO->Klein-Nishina cutoff!

hard spectrum up to ~100 TeV, if hadronic implies the presence of ~PeV Cosmic Rays
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Are SuperNova Remnants CR PeVatrons?

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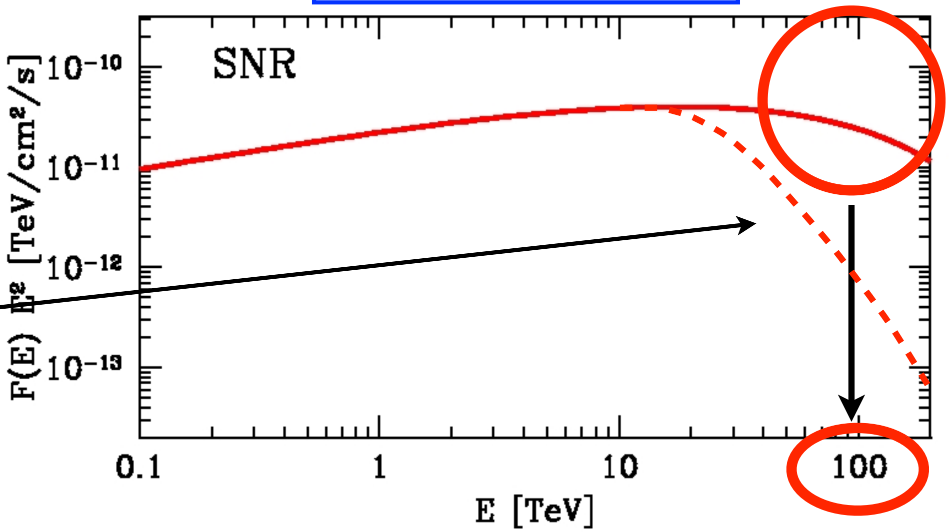

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Hard spectrum up to >100 TeV -> PeVatron!

Are SuperNova Remnants CR PeVatrons?

Hadronic versus leptonic contribution to the gamma ray emission

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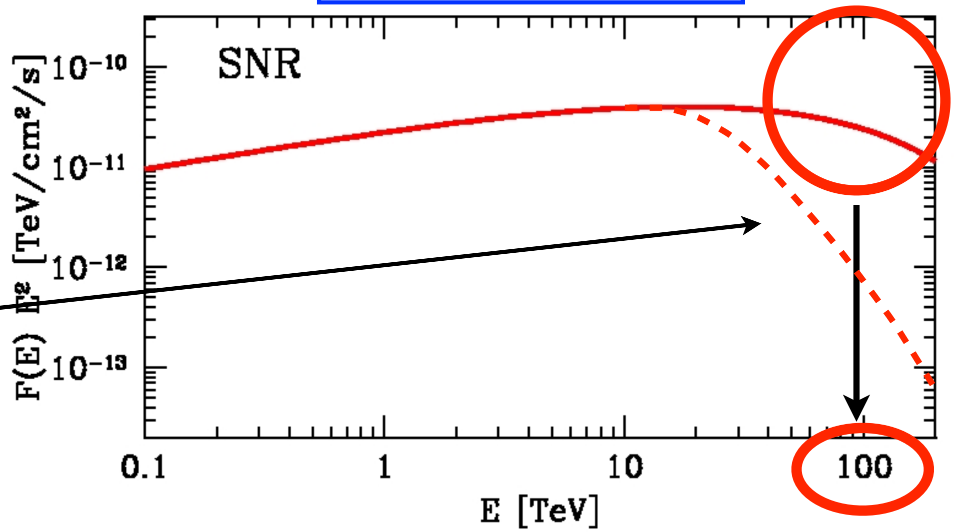

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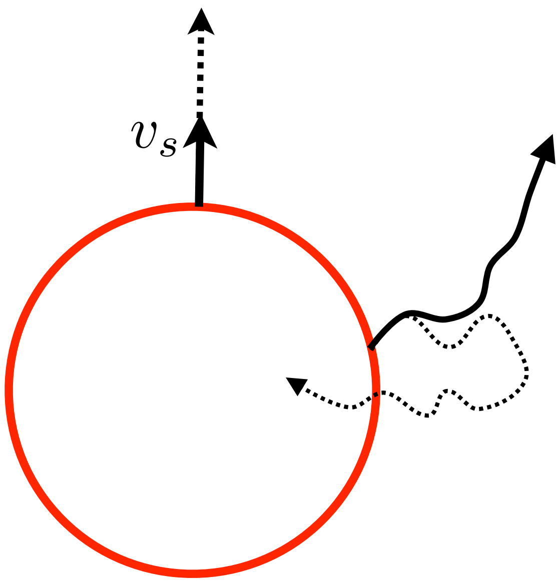
hard spectrum up to ~100 TeV, if hadronic implies the presence of ~PeV Cosmic Rays
-> PeVatron!

Hard spectrum up to >100 TeV -> PeVatron!

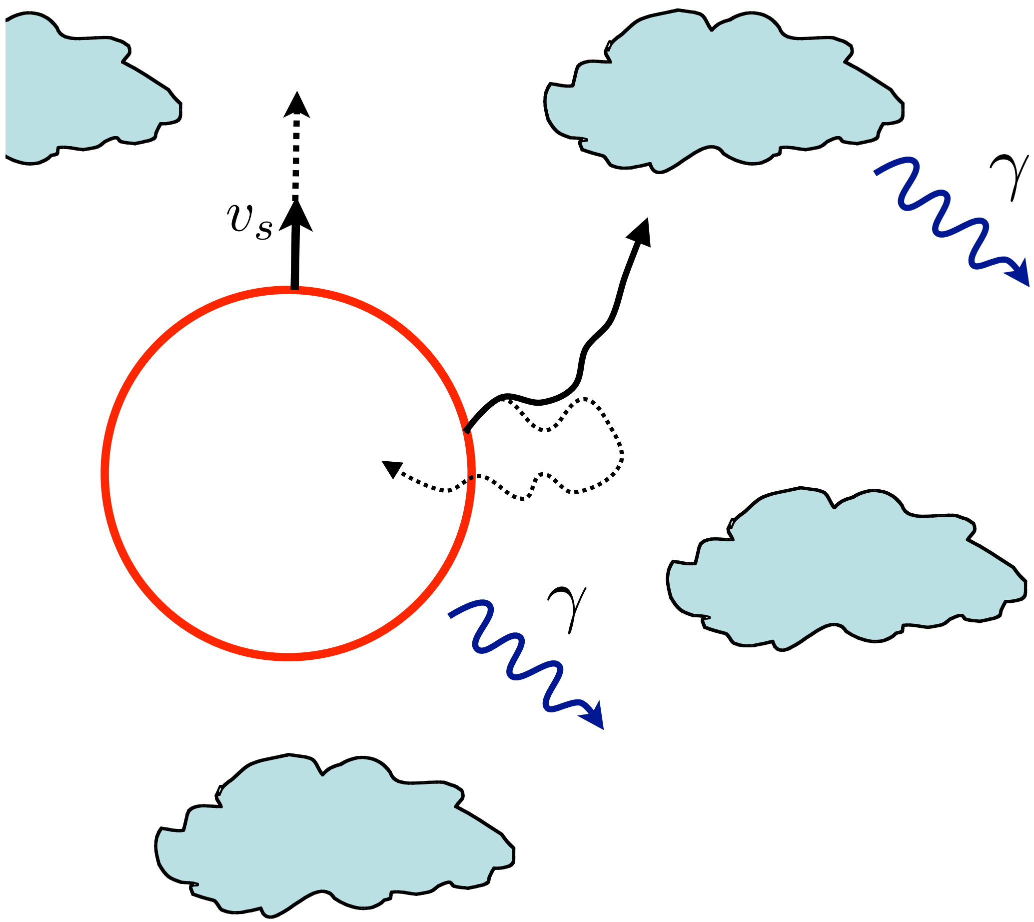
unambiguous evidence of the fact that SNRs accelerate CRs up to the knee

the emission lasts for a very short time
(400 yrs -> <10 SNRs)

The role of Molecular Clouds

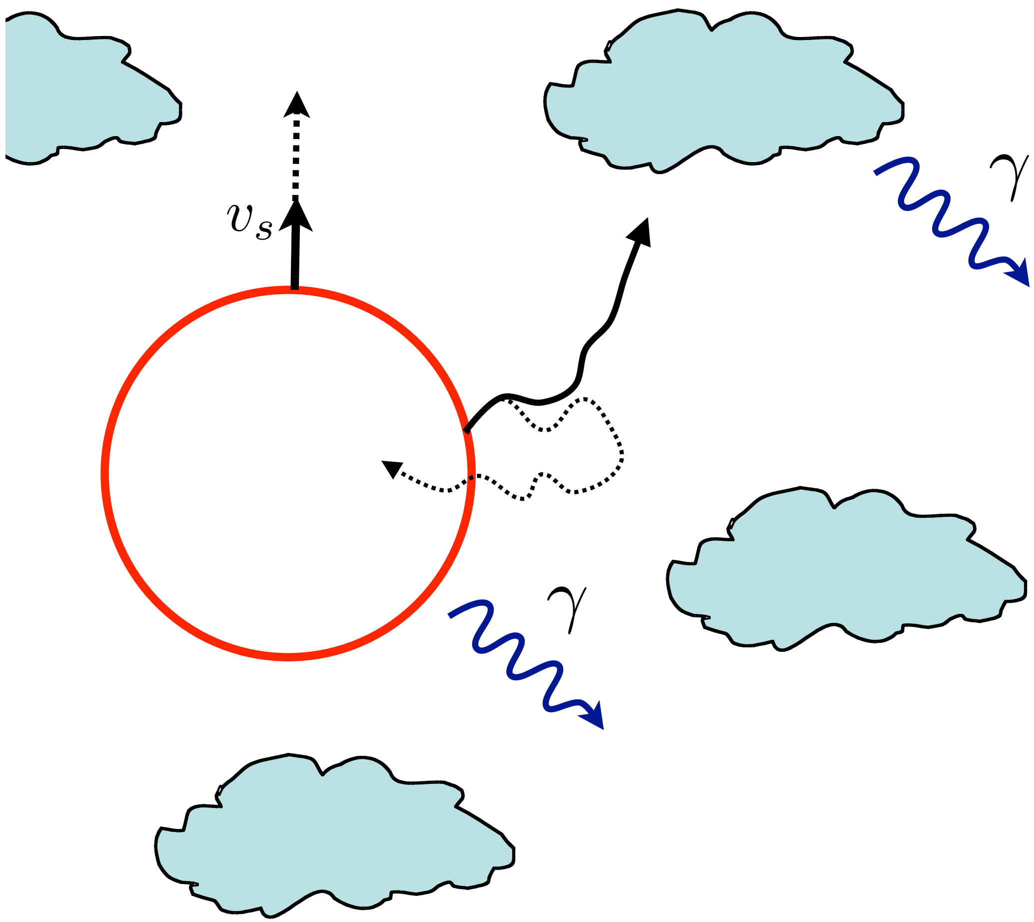


The role of Molecular Clouds



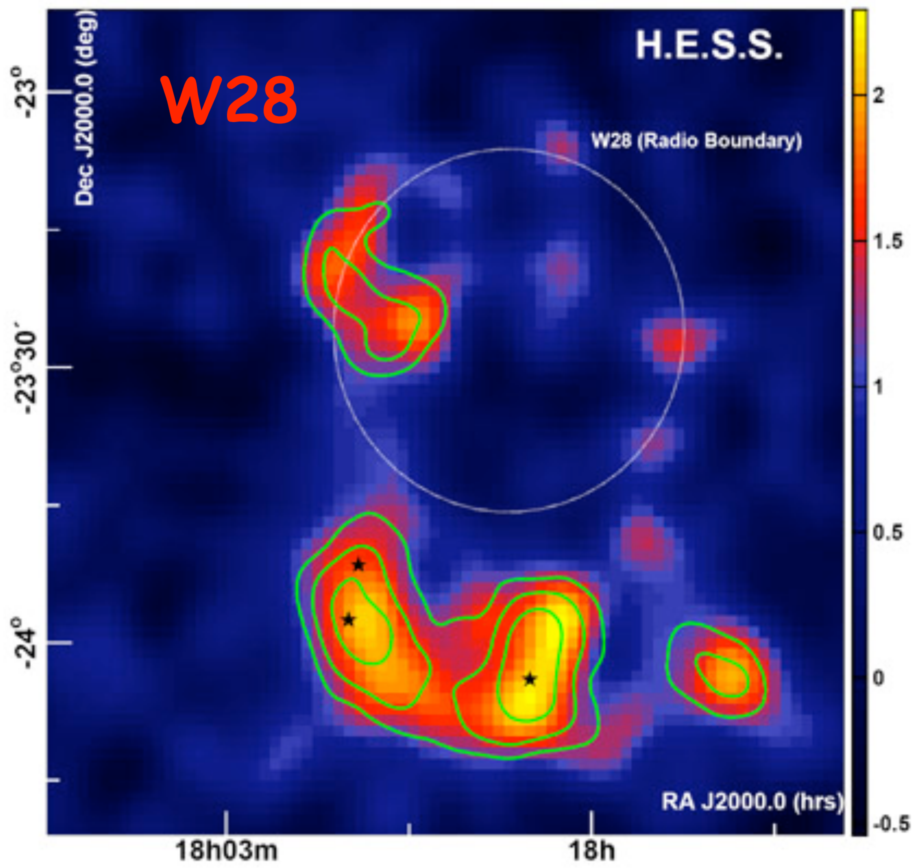
Both SNR and surrounding molecular clouds emit gammas

The role of Molecular Clouds



Both SNR and surrounding molecular clouds emit gammas

Maybe something like that has been already detected...



Gamma rays from MCs illuminated by CRs

t = 400 yr

$d = 1\ kpc$

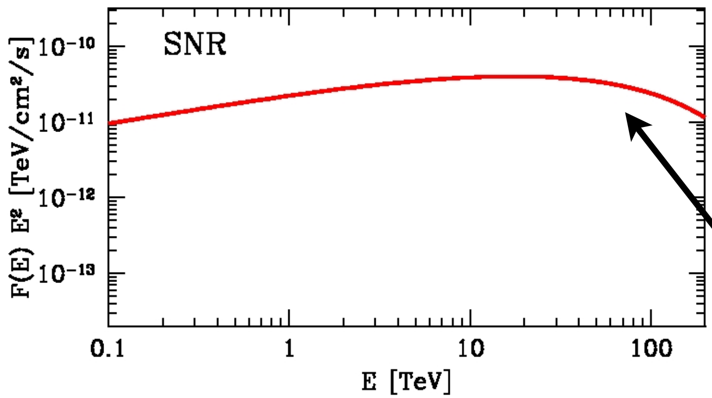
$d_{snr/cl} = 100\ pc$

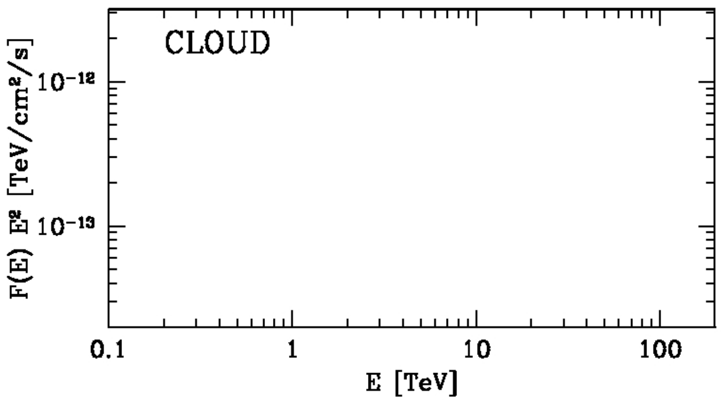
$M_{cl} = 10^4 M_\odot$

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

SNR

Cloud





Gabici&Aharonian(2007)

PeVatron!!!

but for short time!

Gamma rays from MCs illuminated by CRs

t = 2000 yr

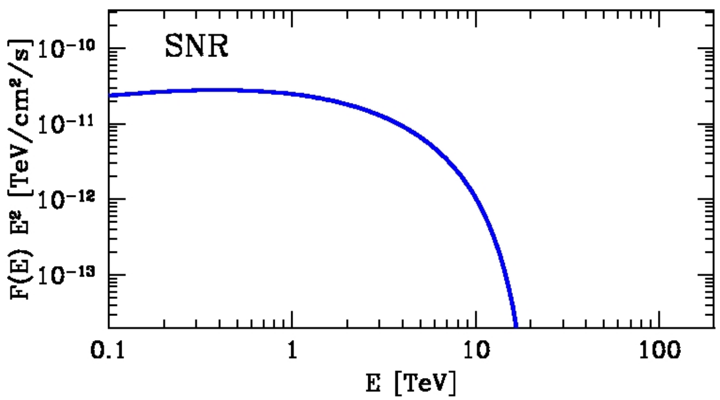
100 TeV

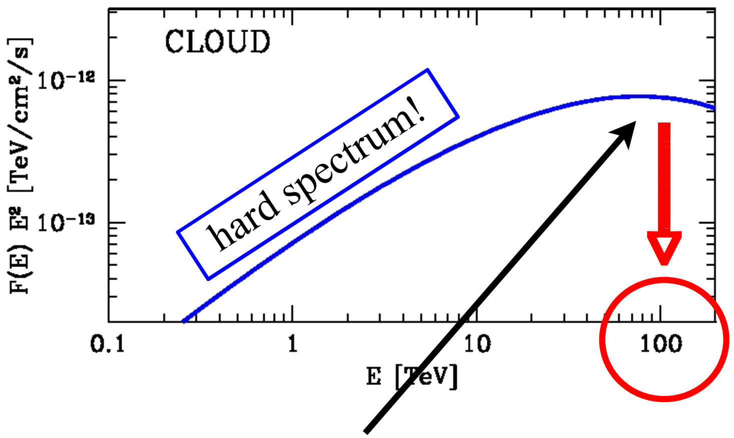
1 PeV

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

SNR

Cloud





Gabici&Aharonian(2007)

HESS remnant

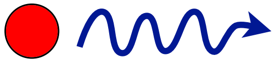
Indirect detection of a PeVatron! Emission lasts longer!

NO ICS -> Klein-Nishina

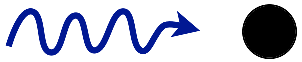
Gamma rays from MCs illuminated by CRs

t = 8000 yr

1 TeV



100 TeV



$$d = 1\ kpc$$
$$d_{snr/cl} = 100\ pc$$
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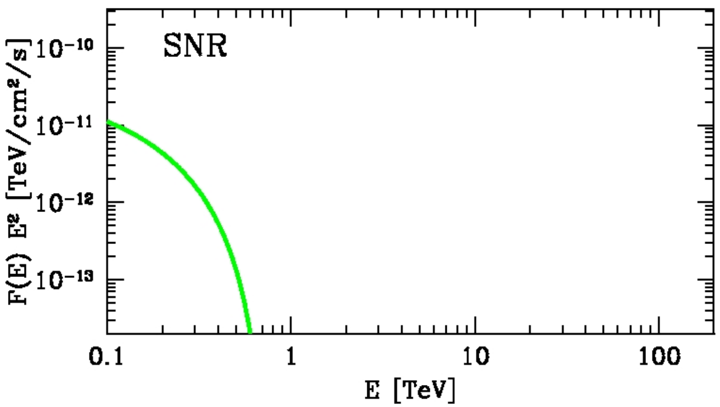
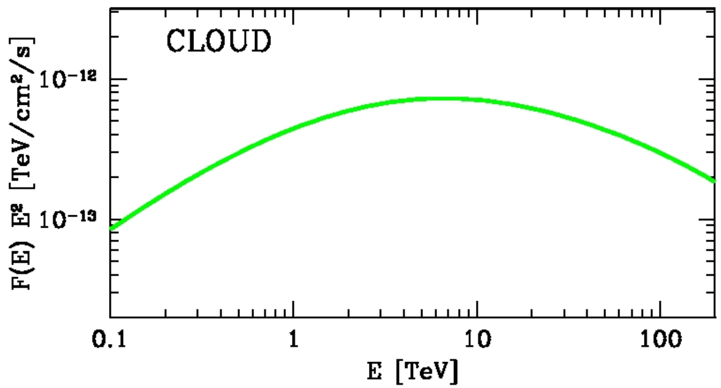
SNR

Cloud





Gabici&Aharonian(2007)

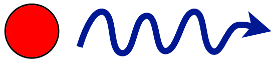
GLAST remnant?

HESS and MILAGRO unidentified sources?

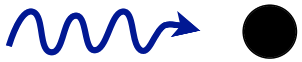
Gamma rays from MCs illuminated by CRs

t = 32000 yr

100 GeV



10 TeV



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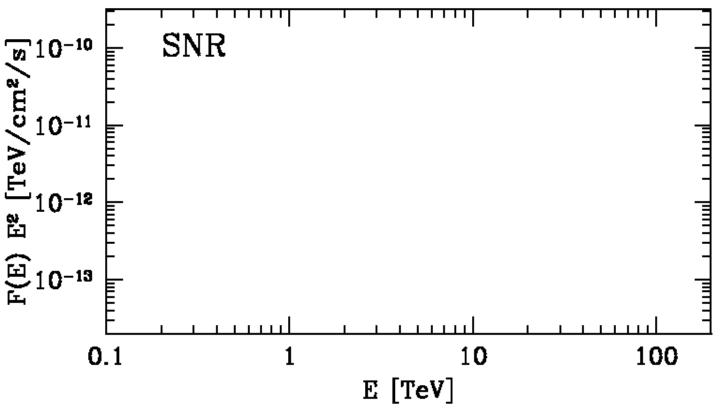
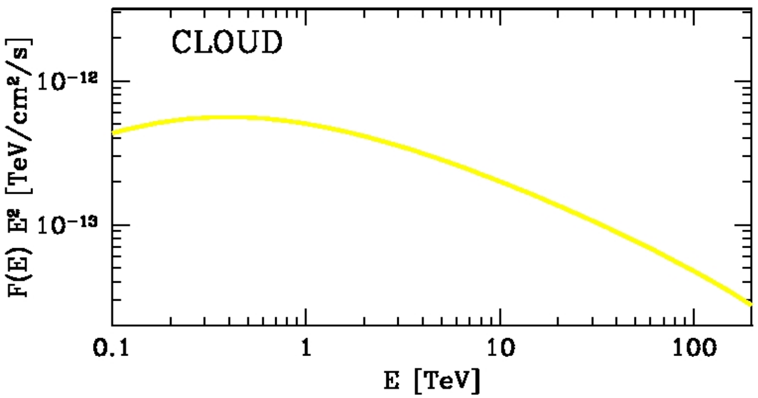
SNR

Cloud





no emission

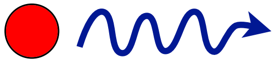
HESS and MILAGRO unidentified sources?

Gabici&Aharonian(2007)

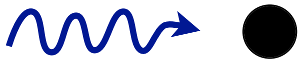
Gamma rays from MCs illuminated by CRs

t = 32000 yr

100 GeV



10 TeV



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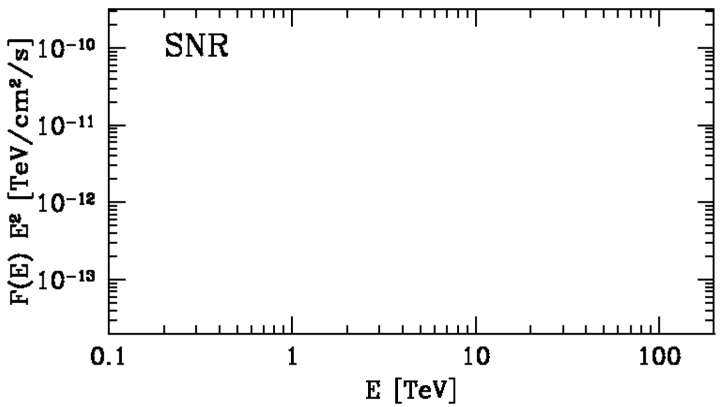

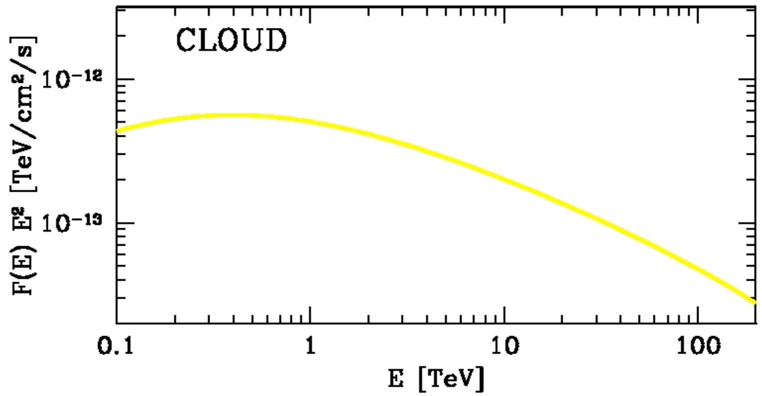

Gabici&Aharonian(2007)

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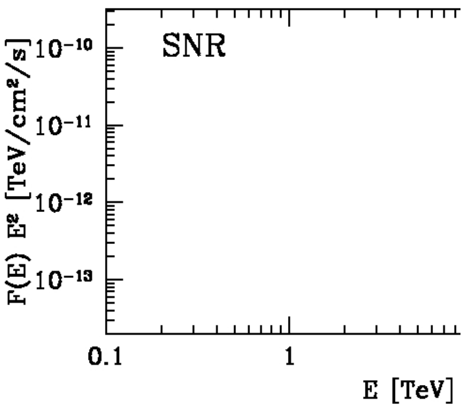
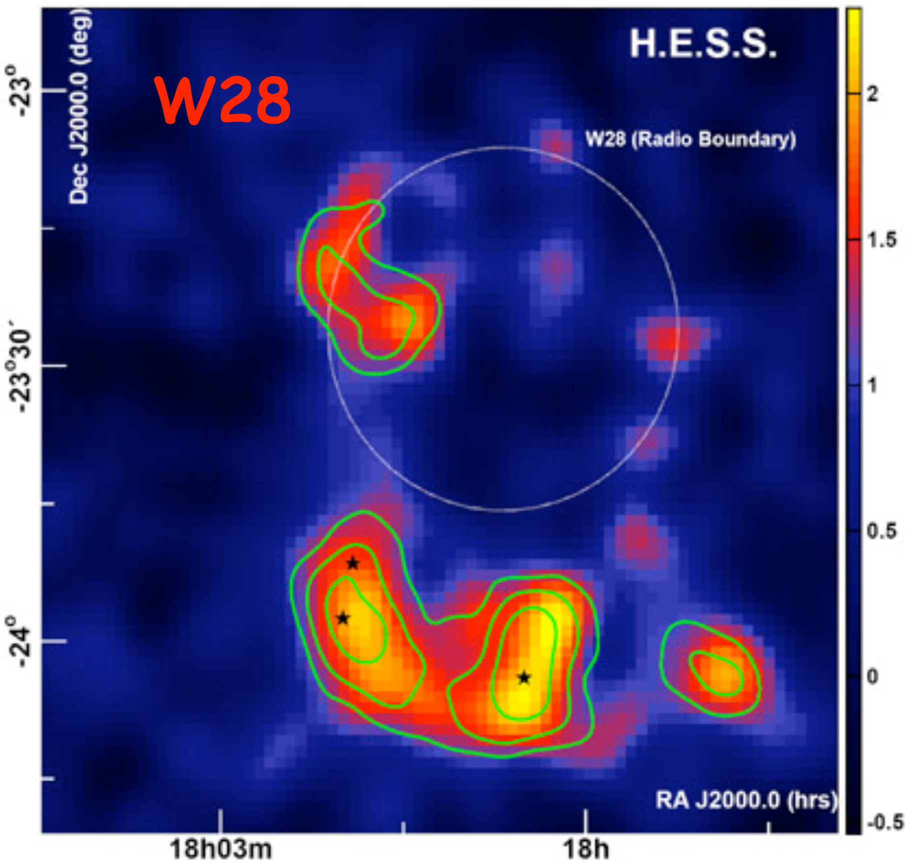
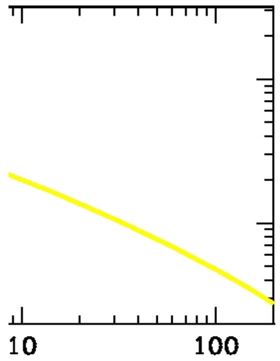






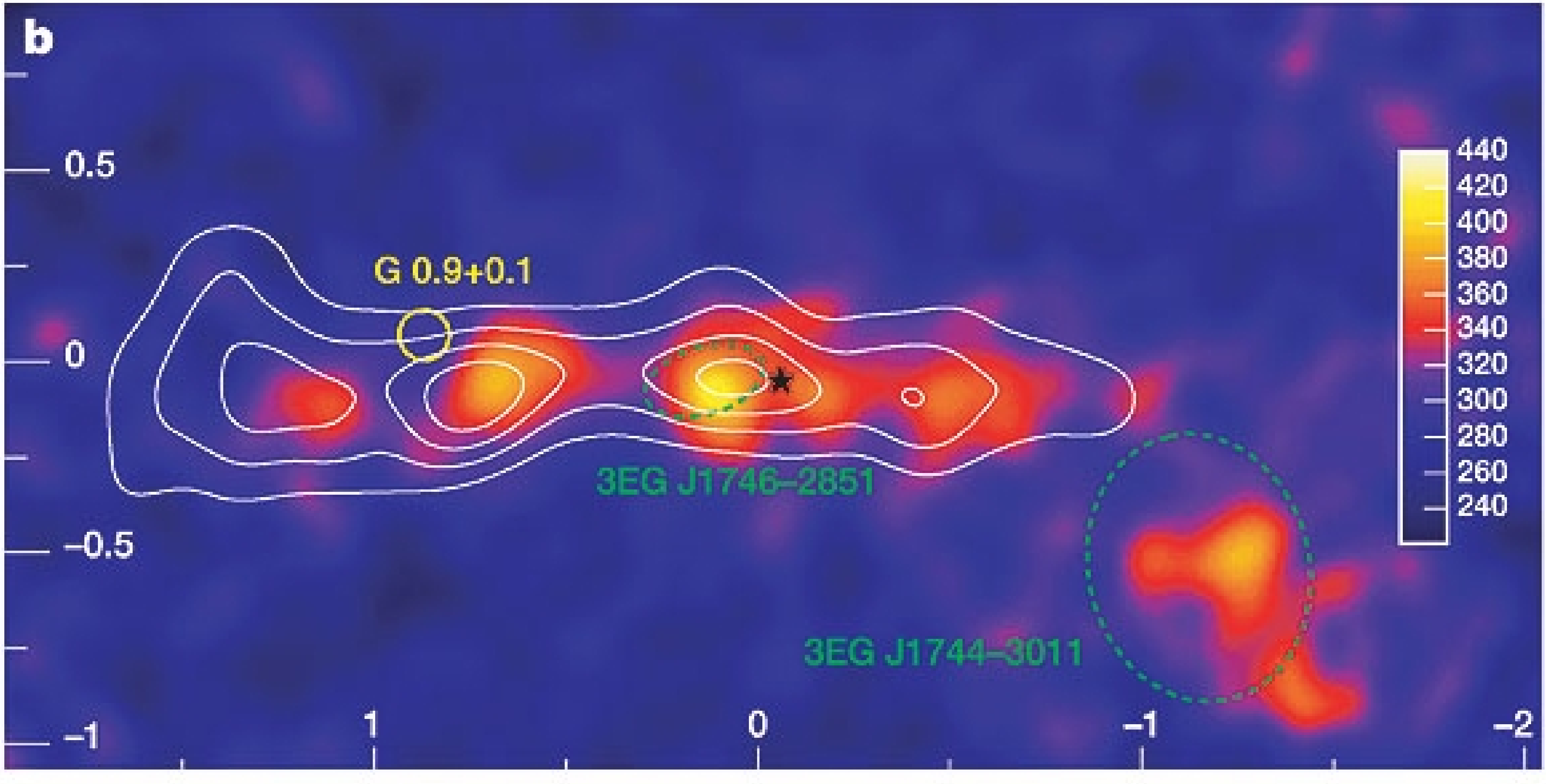
Gabici&Aharonian(2007)

no emission

LAGRO
unidentified sources?

Example: the galactic centre ridge

The galactic centre ridge as seen by HESS

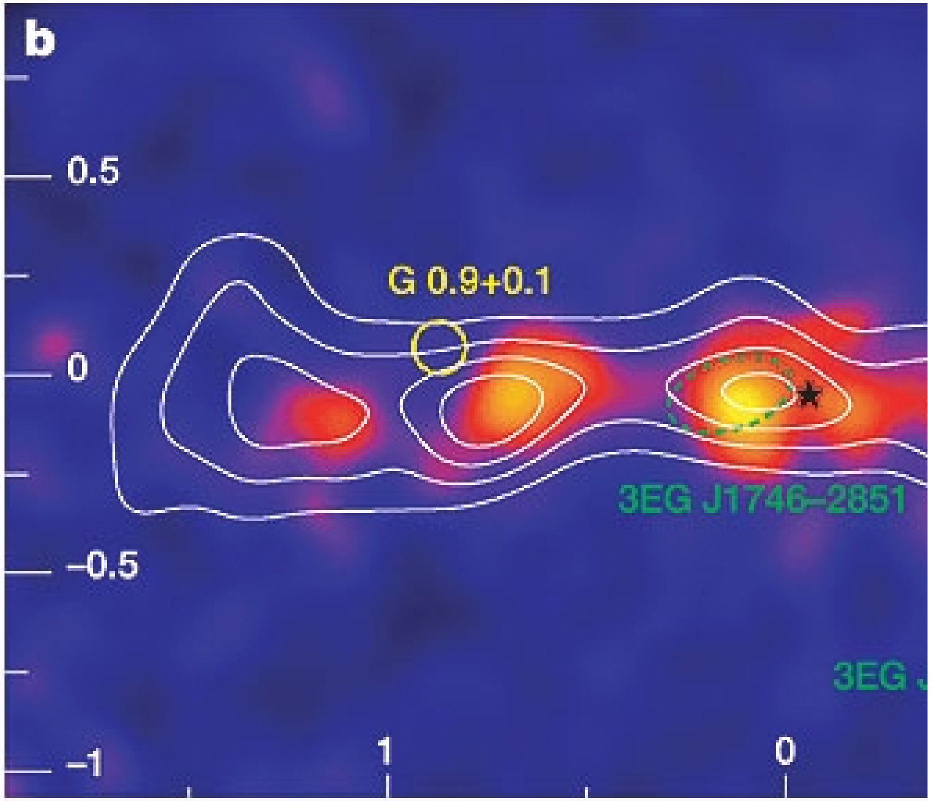


HESS collaboration, 2006

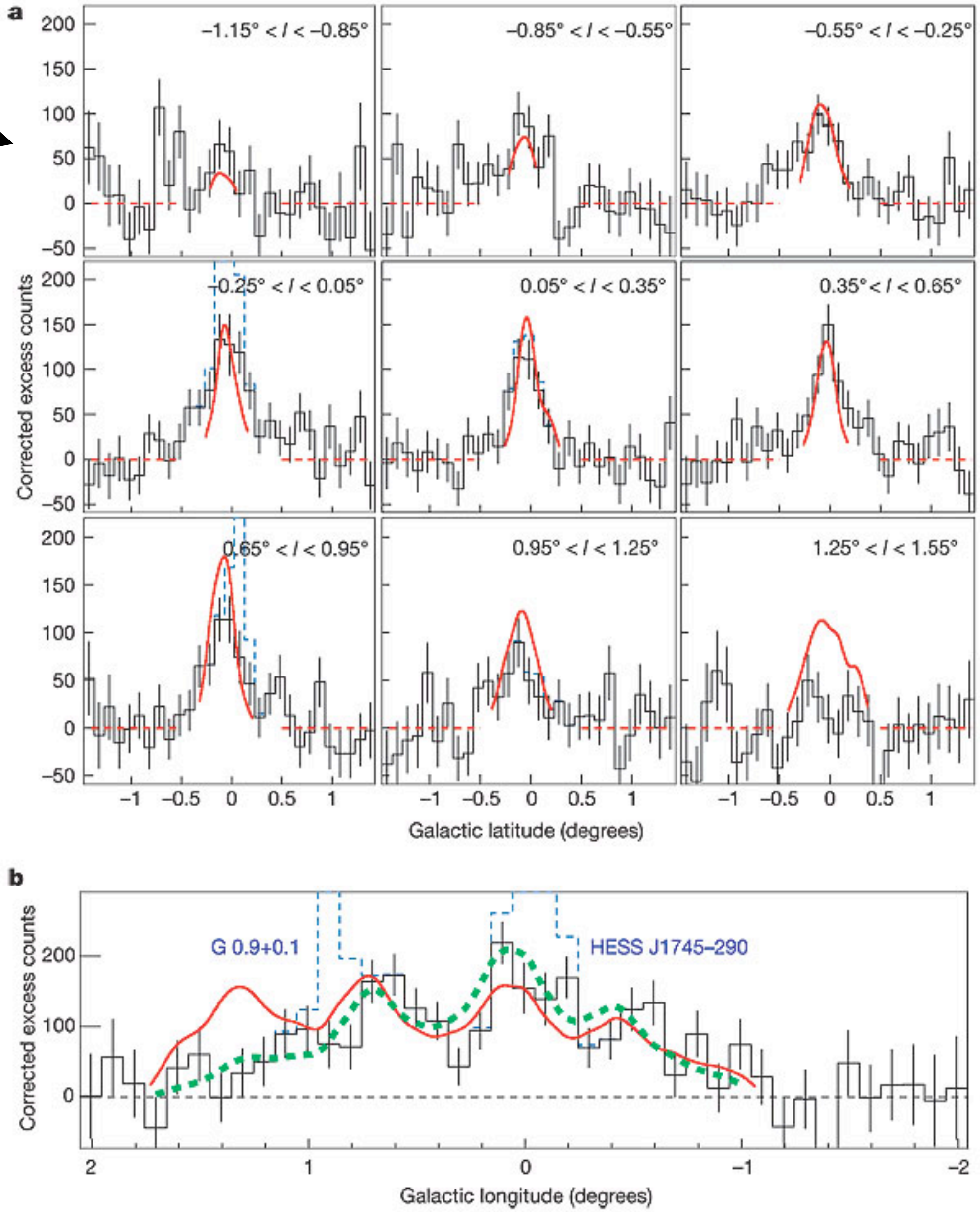
Example: the galactic centre ridge

The galactic centre ridge as seen by HESS

good match between CS lines and TeV emission



HESS collaboration, 2006



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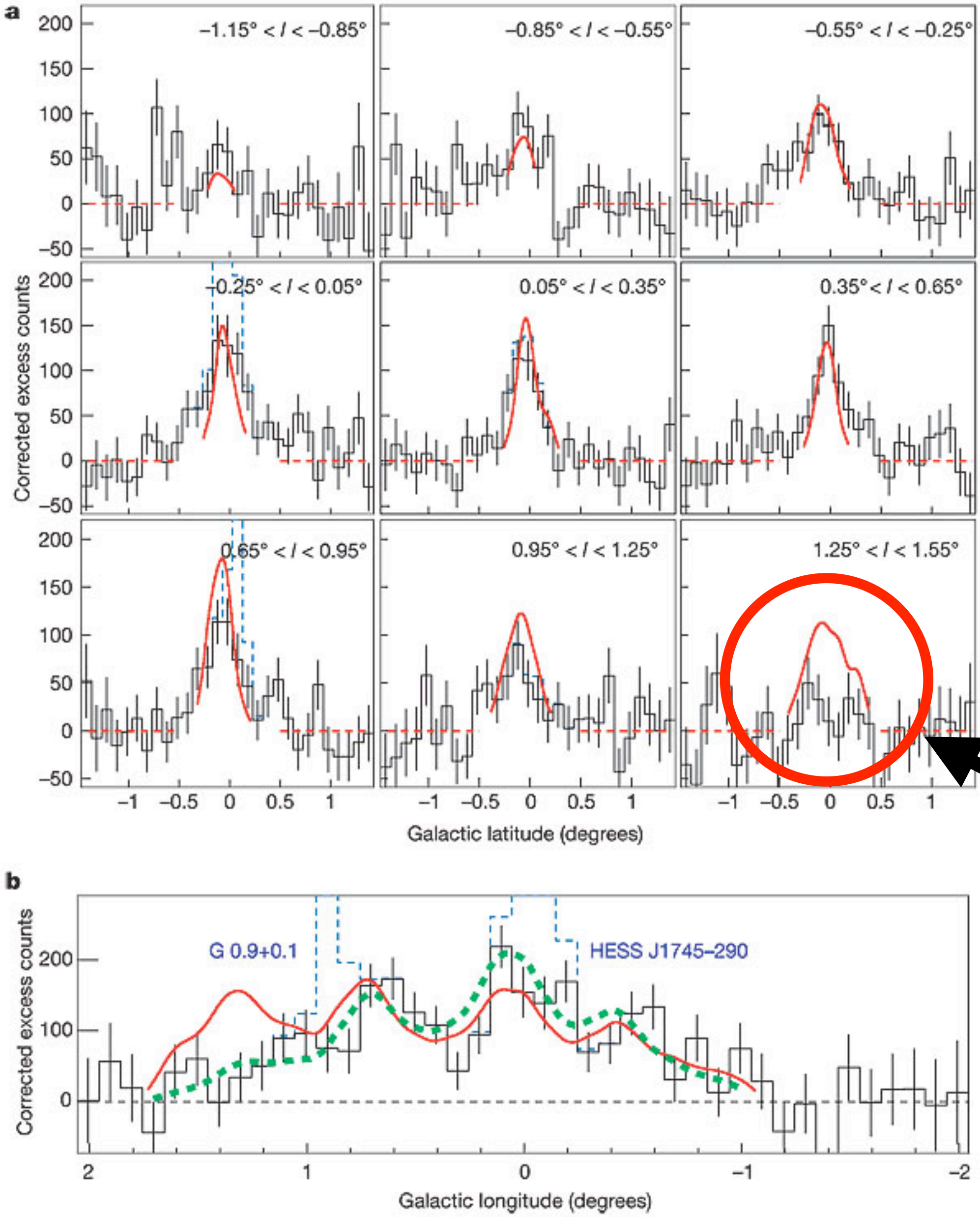
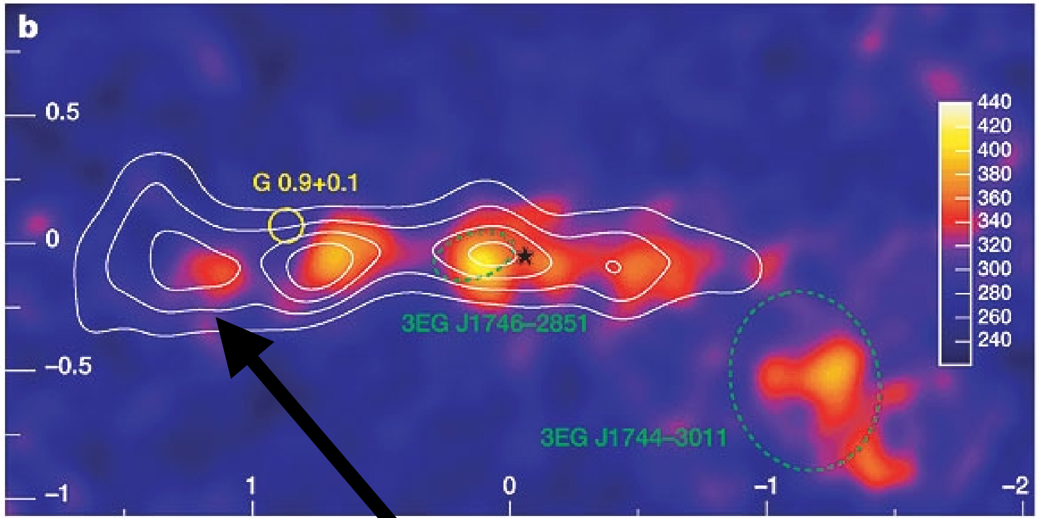
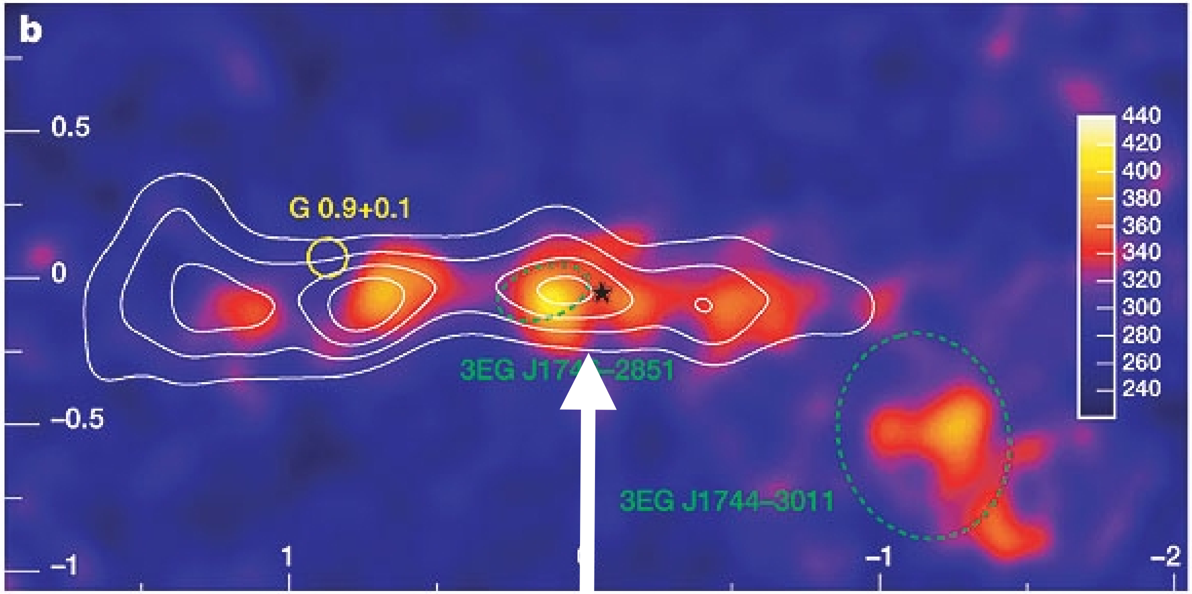




the correlation between gamma ray intensity and gas density is worse for the cloud which is the farthest away from the galactic centre

HESS collaboration, 2006

Example: the galactic centre ridge

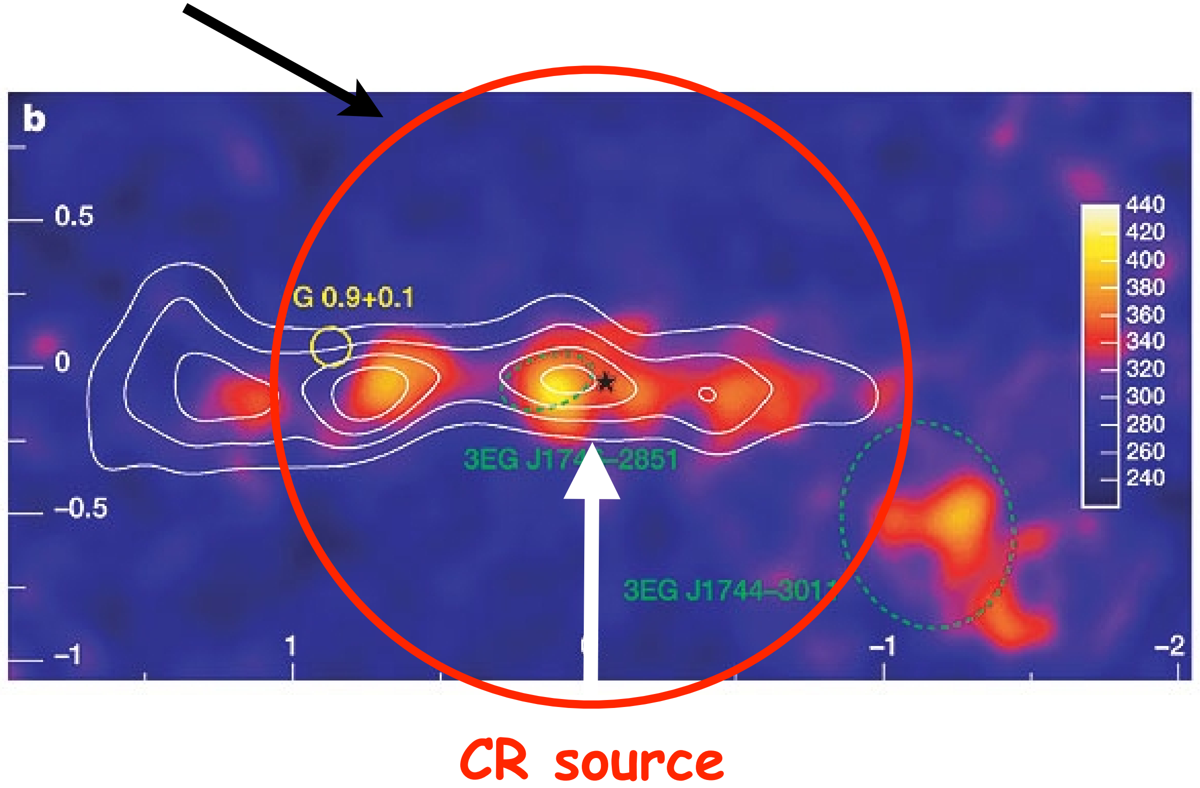


CR source

HESS collaboration, 2006

Example: the galactic centre ridge

after a time t_{diff} CRs fill a volume like this



HESS collaboration, 2006

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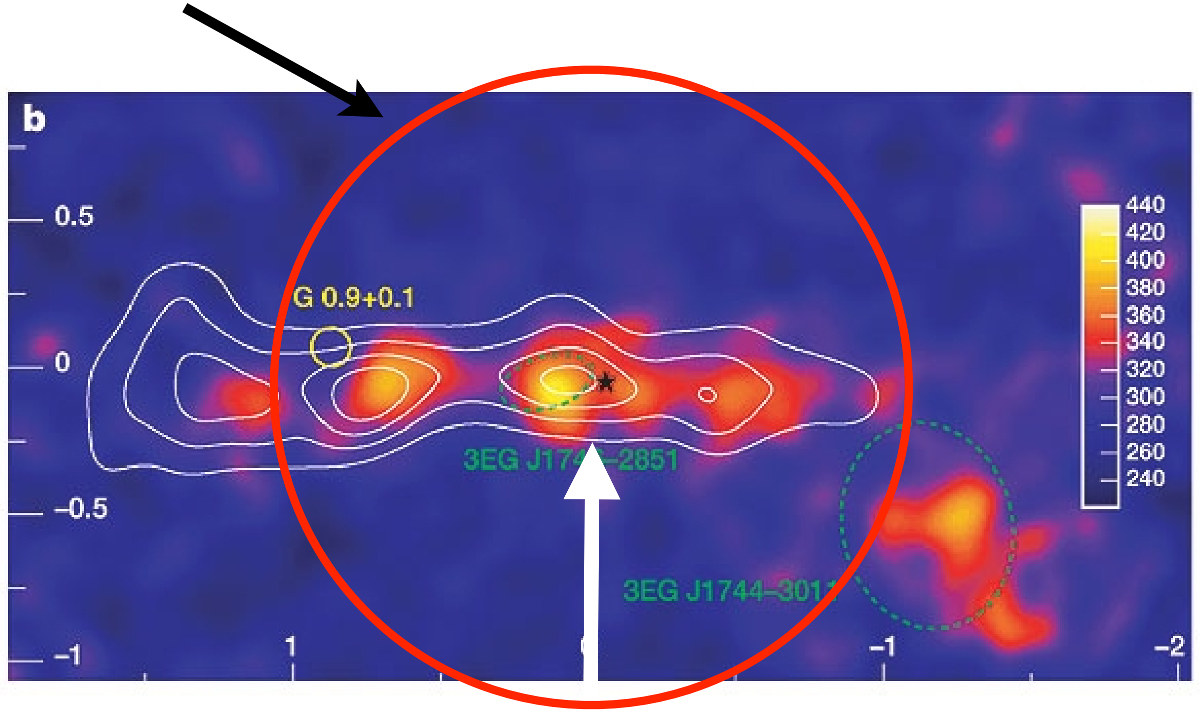


CR source

$$t_{diff} \approx \frac{l^2}{D}$$

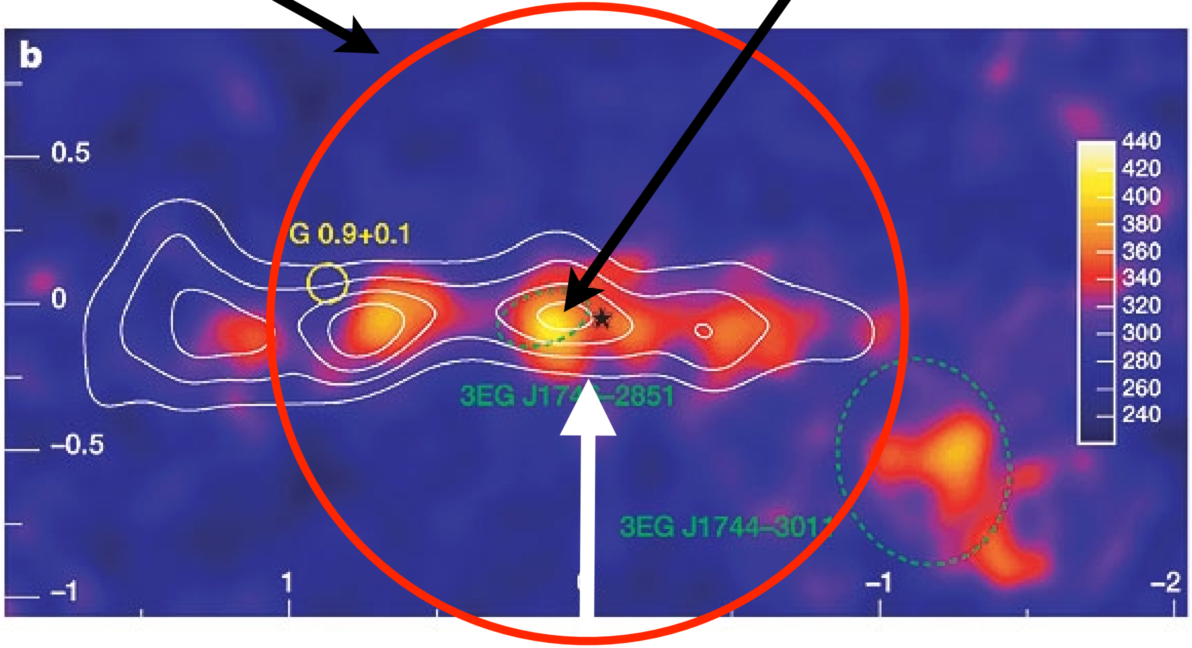
if we know the age of the source we can estimate the diffusion coefficient!

HESS collaboration, 2006

Example: the galactic centre ridge

after a time t_{diff} CRs fill a volume like this

SNR SgrA East -> t ~ 10^4 yr
(though quite uncertain)



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HESS collaboration, 2006

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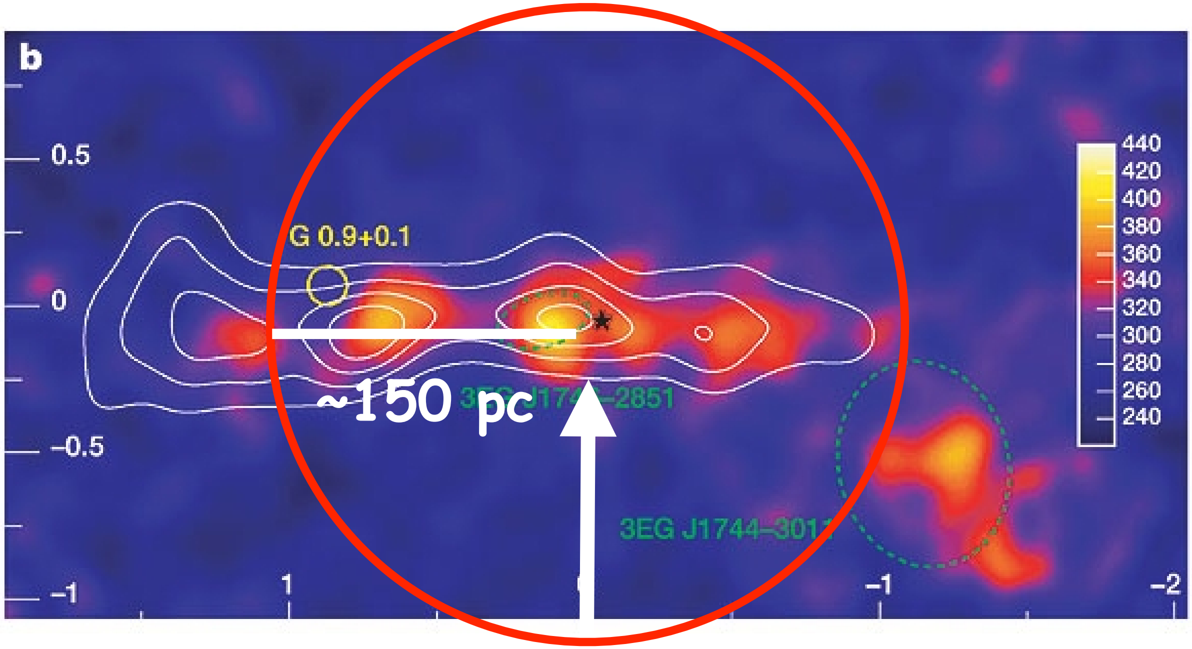
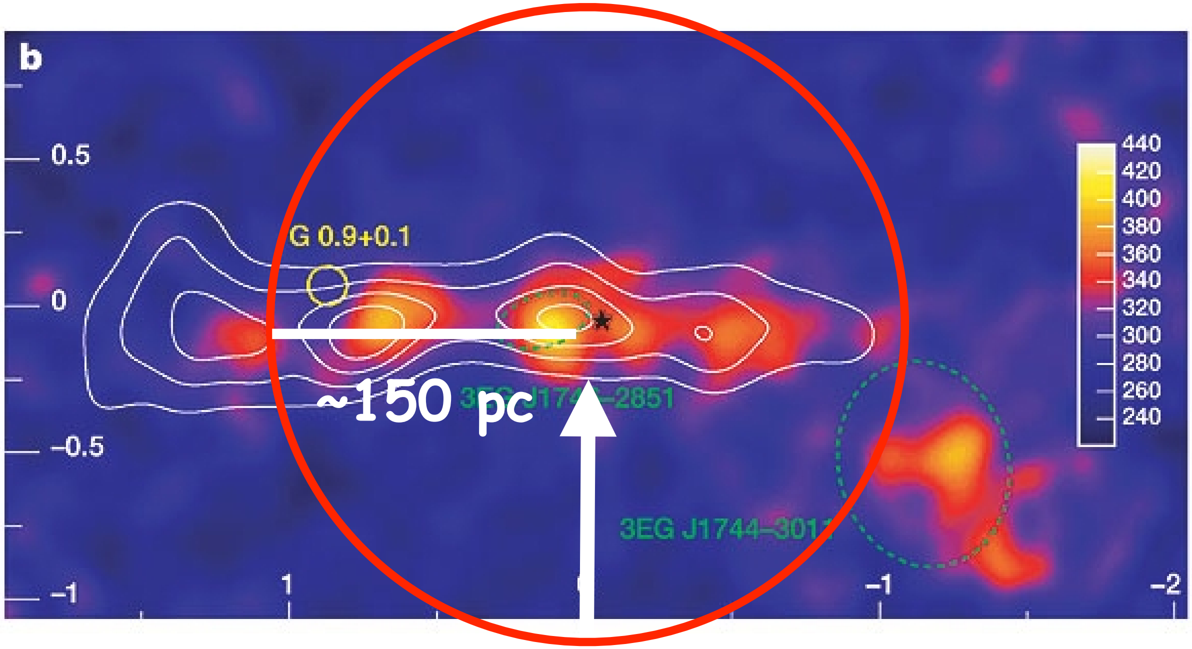


CR source (~10^4 yr)

$$t_{diff} \approx \frac{l^2}{D}$$

Example: the galactic centre ridge



CR source (~10^4 yr)

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$$D \lesssim 7 \times 10^{29} \mathrm{cm}^2/\mathrm{s}$$

possibly smaller than the average diffusion coefficient in the Galaxy

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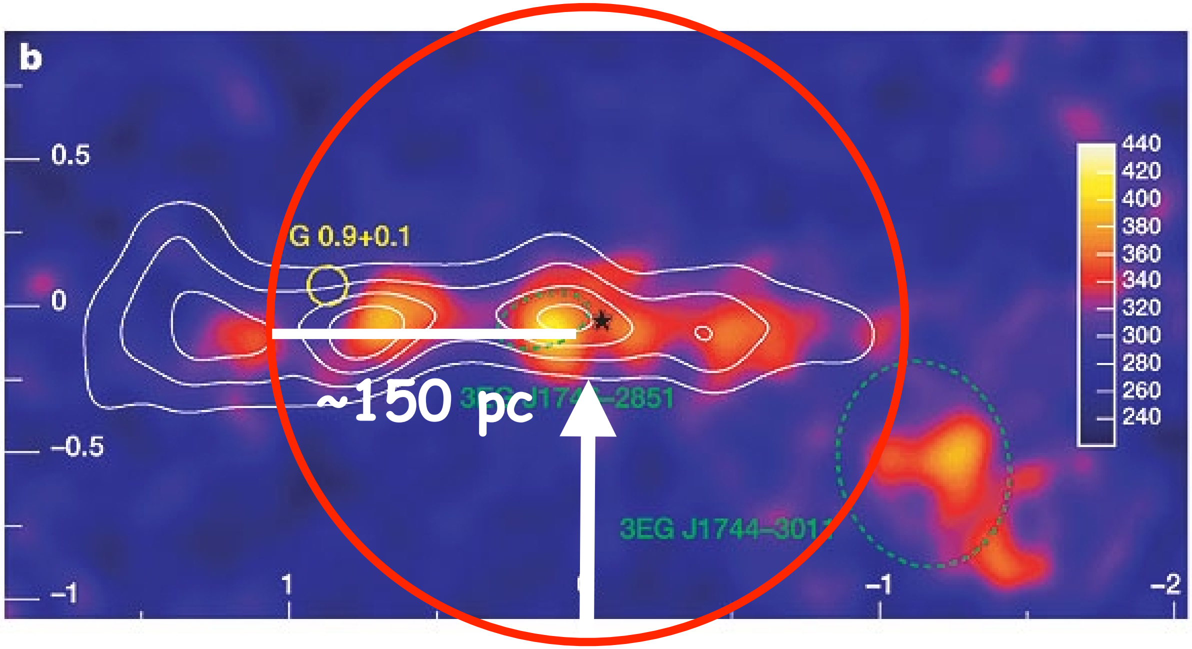

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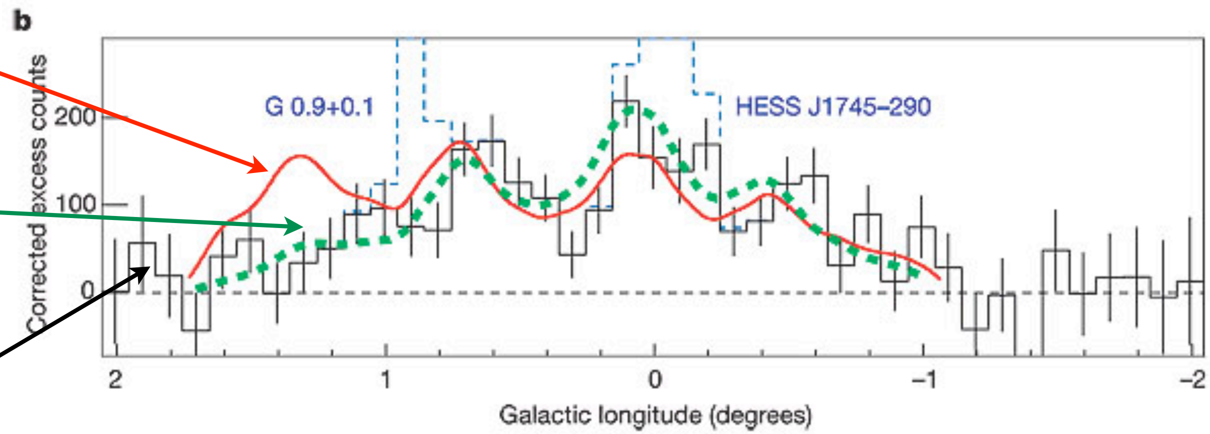
density

predicted gamma rays (diffusion from a source in the Galactic centre)

observed gamma rays



Conclusions

- We still don't know which are the sources of galactic **CRs**;
- We have many reasons to believe that **SNRs** might be the sources of CRs;
- A tight connection between CR physics and gamma-ray astronomy exists (**CR+ISM -> Gamma-rays**);
- Four gamma ray based **tests** for CR origin:
  - [x] TeV emission from SNRs -> necessary but not sufficient condition
  - [ ] GeV-TeV spectrum of SNRs -> FERMI -> **hadronic or leptonic?**
  - [ ] multi-TeV emission from SNRs -> future Cherenkov telescopes (Cherenkov Telescope Array, TenTen ...) -> **PeVatrons!**
  - [ ] Molecular clouds

Thanks!