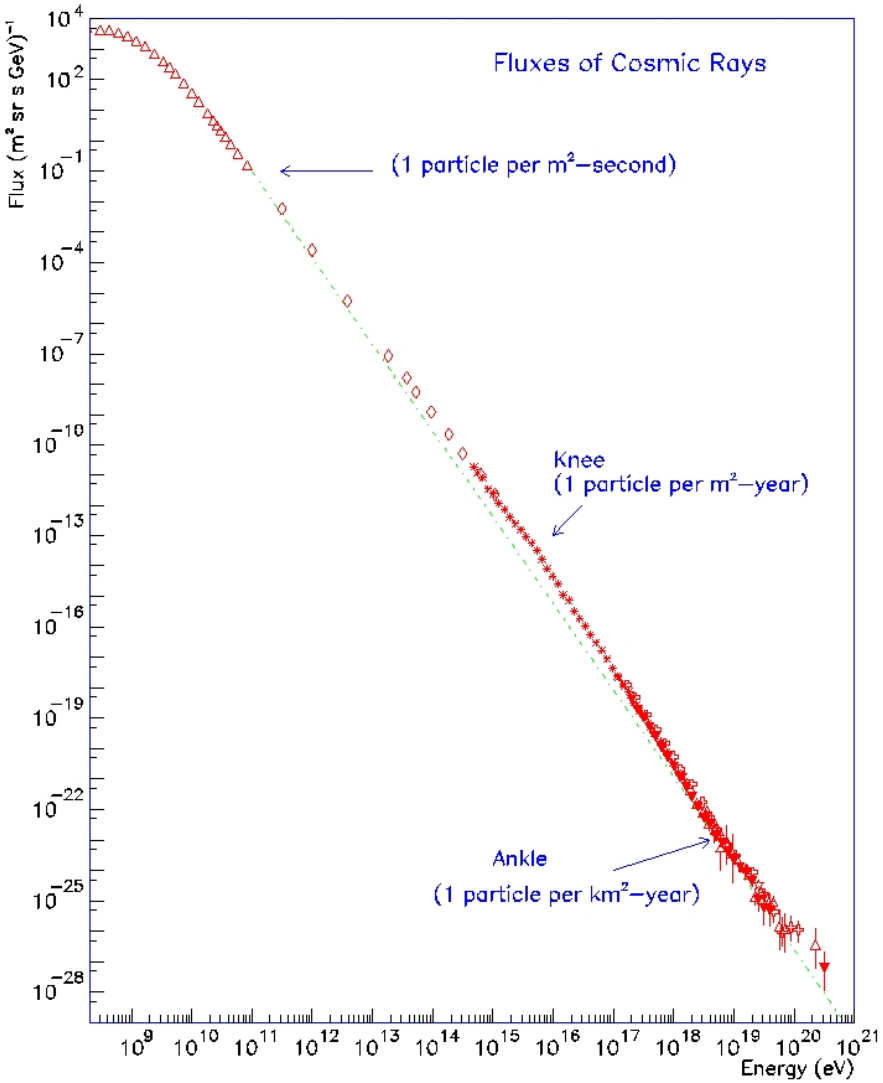
Gamma rays from supernova remnants in clumpy environments

Stefano Gabici
APC, Paris

Overview of the talk

- Galactic cosmic rays
- Gamma rays from supernova remnants
- Hadronic or leptonic?
- The role of gas clumps
- the SNR RX J1713

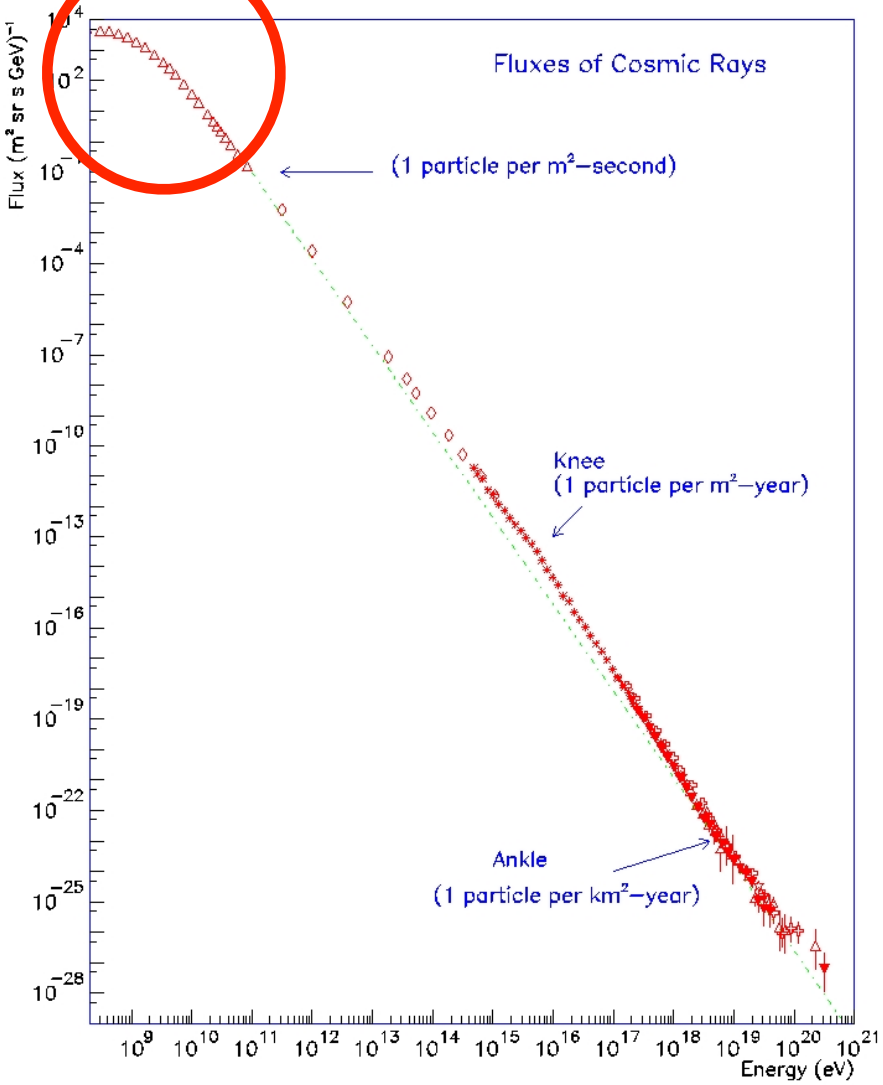
Cosmic rays


Fluxes of Cosmic Rays
(1 particle per m²–second)
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
Flux (m² sr s GeV)⁻¹
Energy (eV)

Cosmic rays

bulk of CRs

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



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

Cosmic rays

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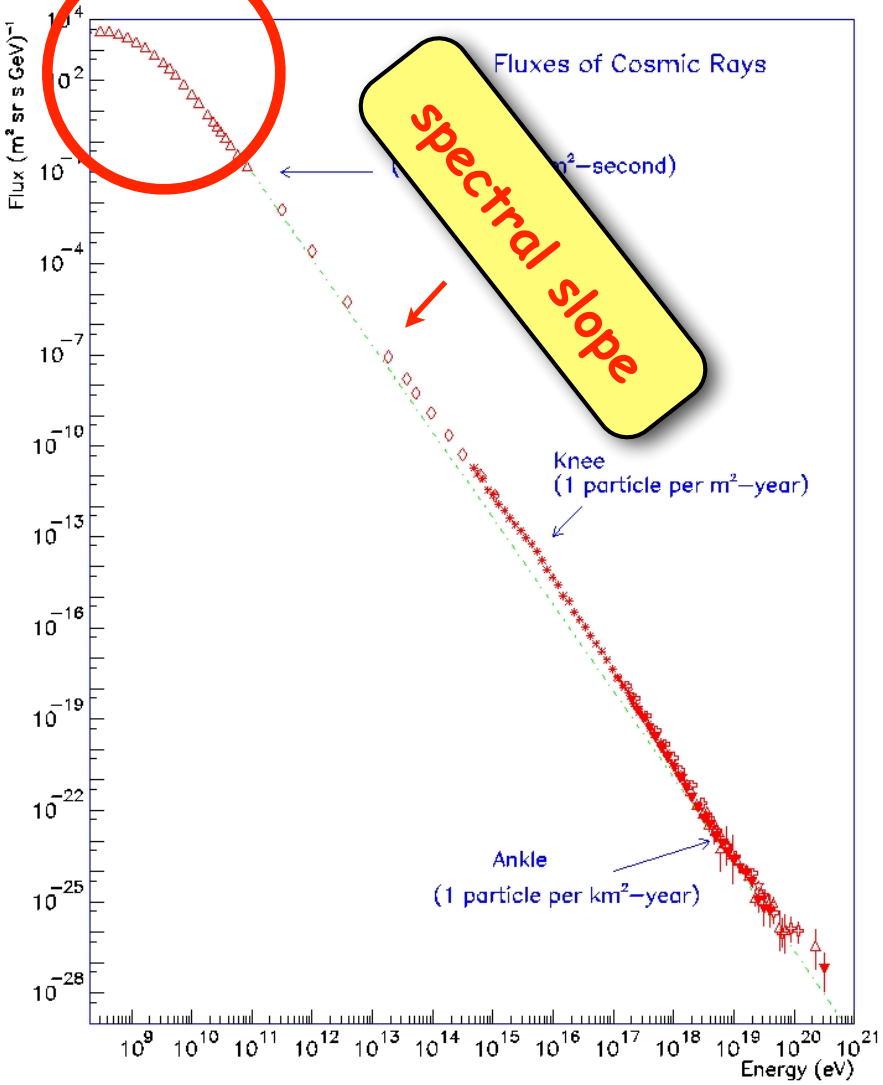

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- spectral shape -> power law ~E$^{-2.7}$
  - + which acceleration mechanism?
  - + how is CR propagation affecting this?

Cosmic rays

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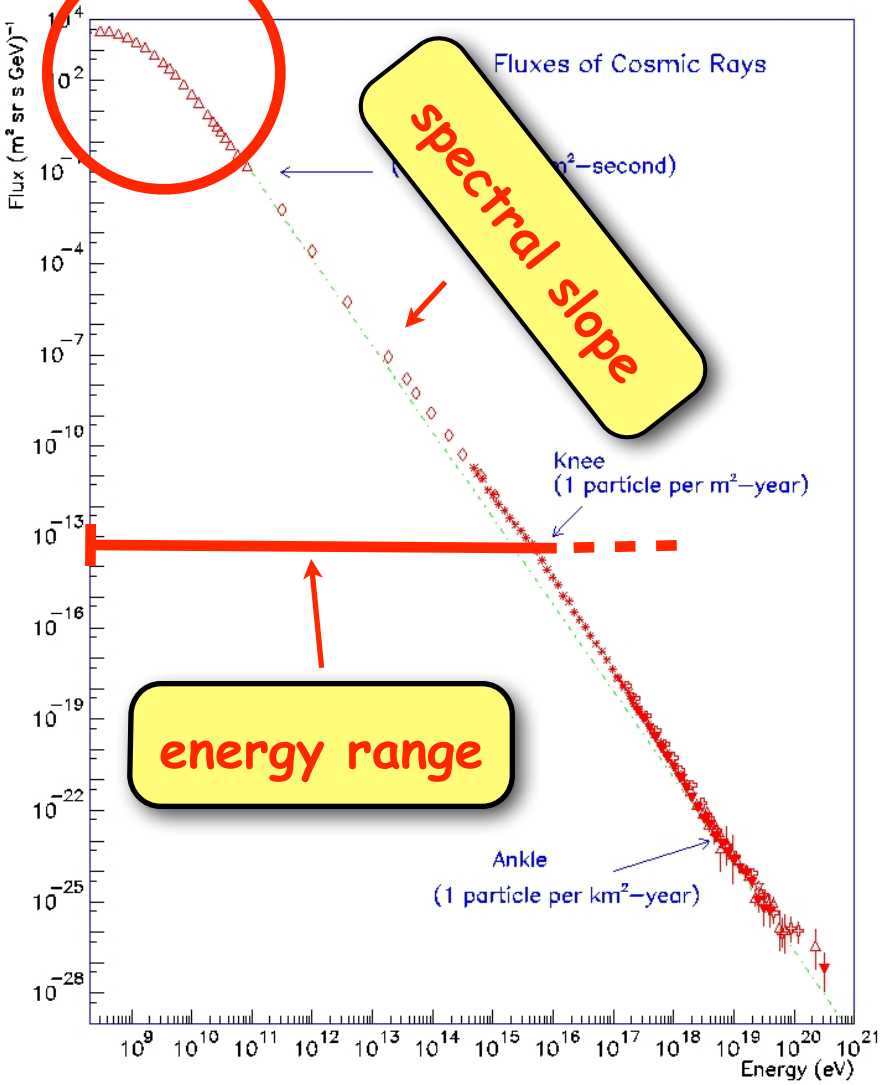

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-> at least up to the knee (~ 4 PeV)

sources must be PeVatrons

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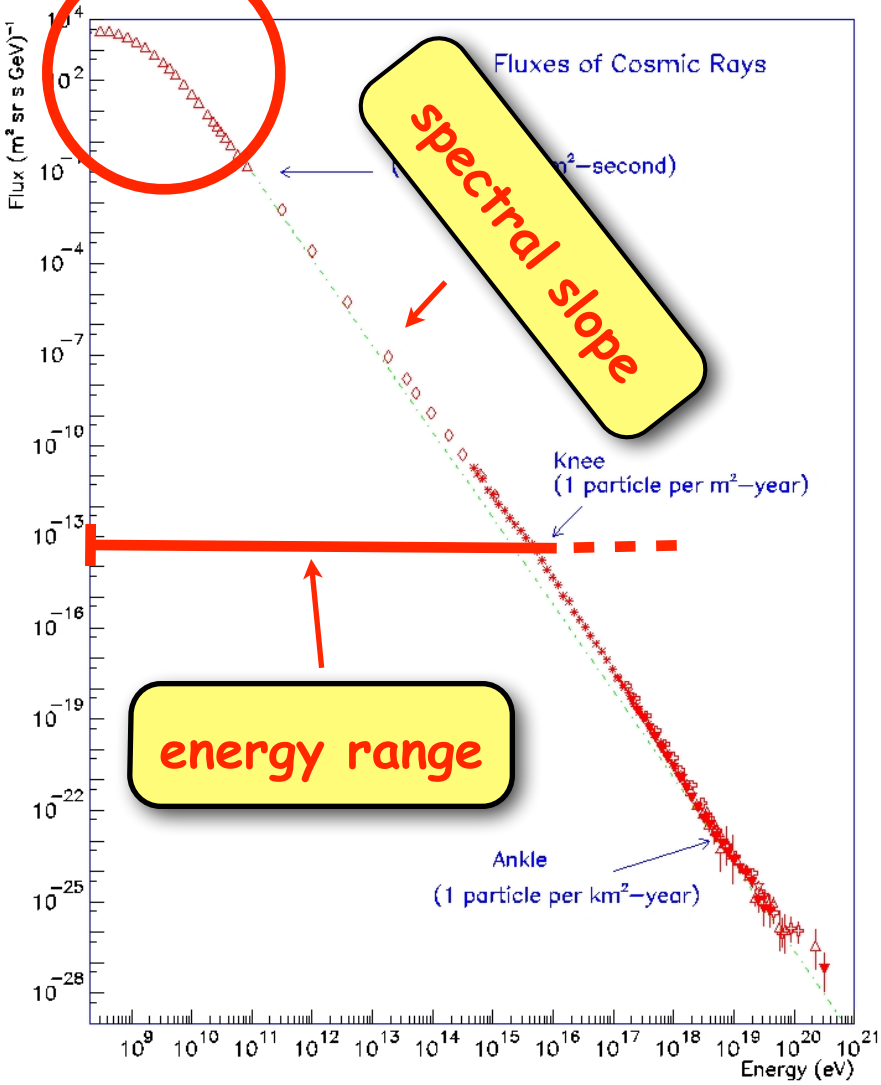

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- more issues -> isotropy & chemical composition

The SuperNova Remnant hypothesis

bulk of CRs

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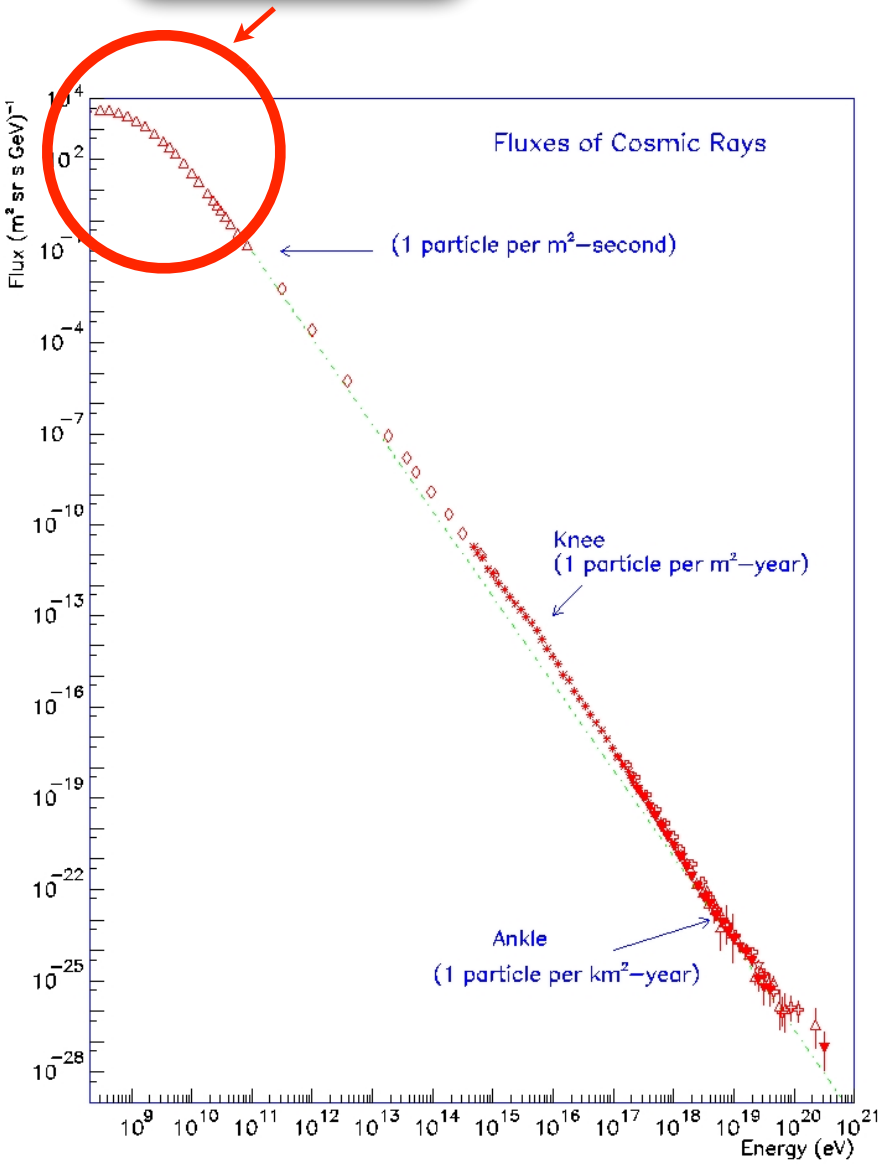

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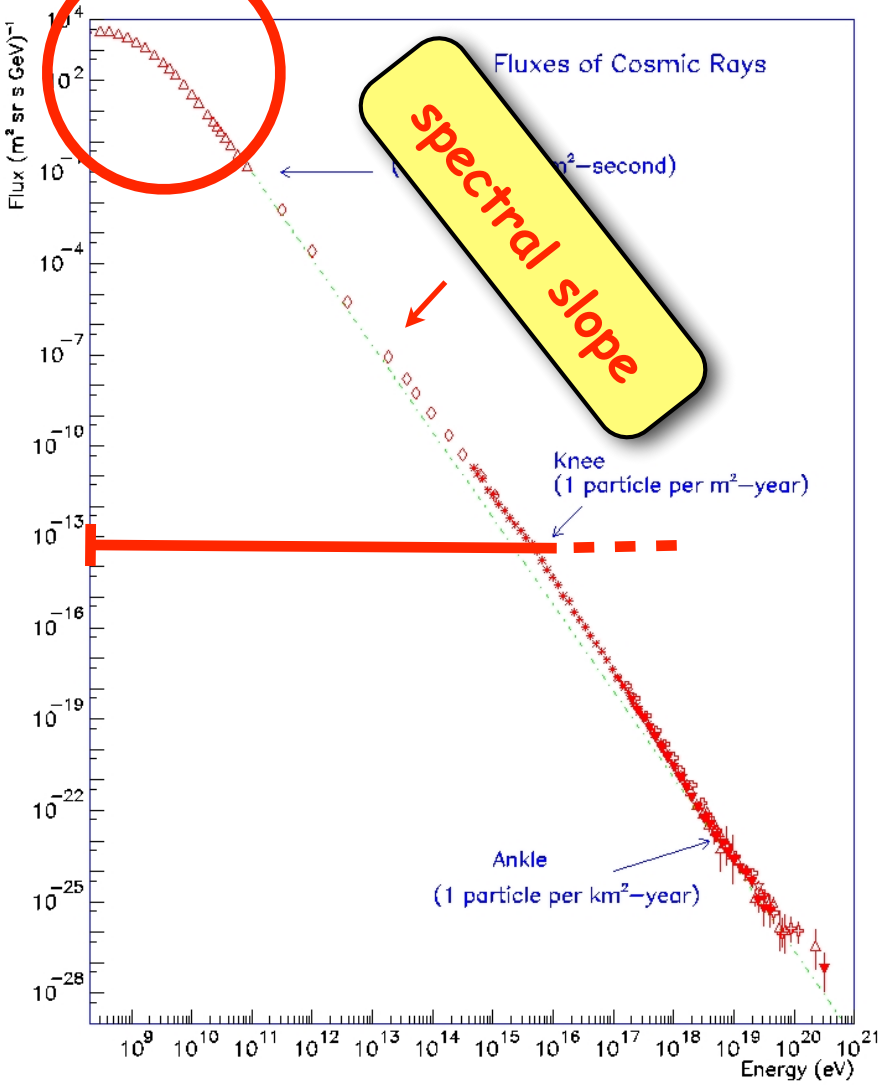

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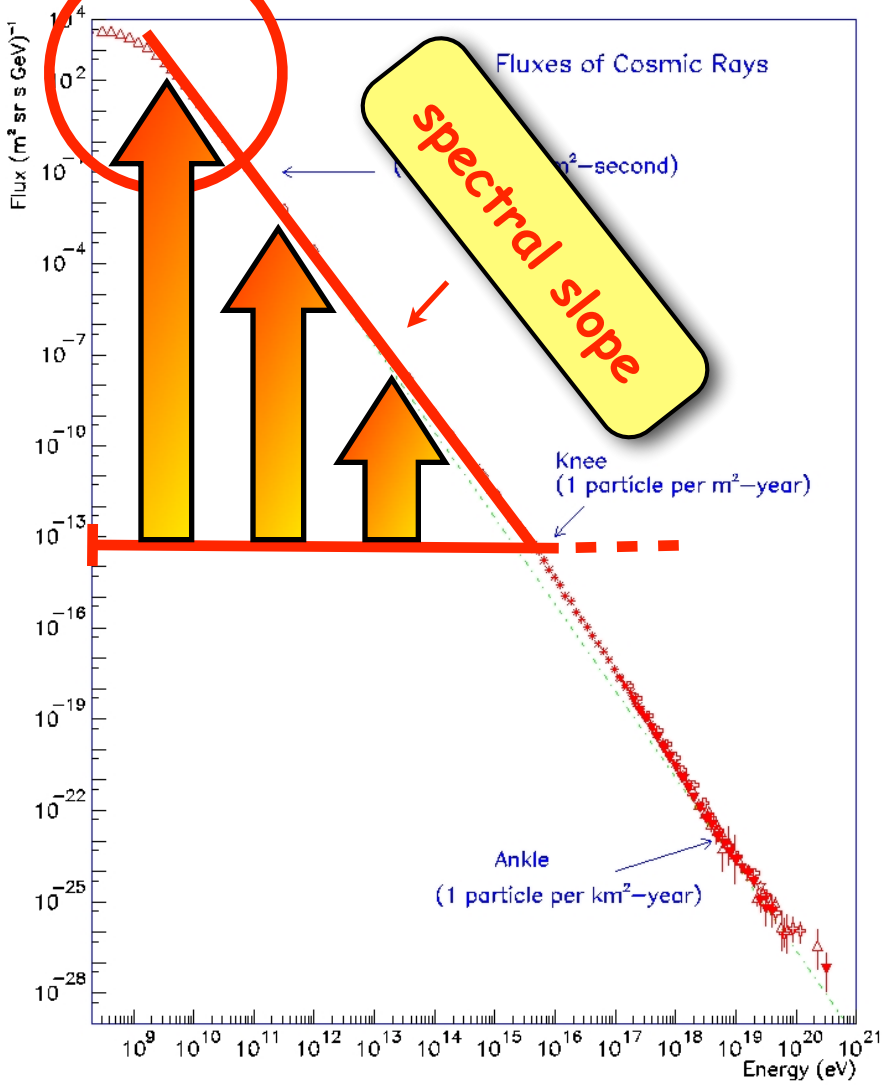

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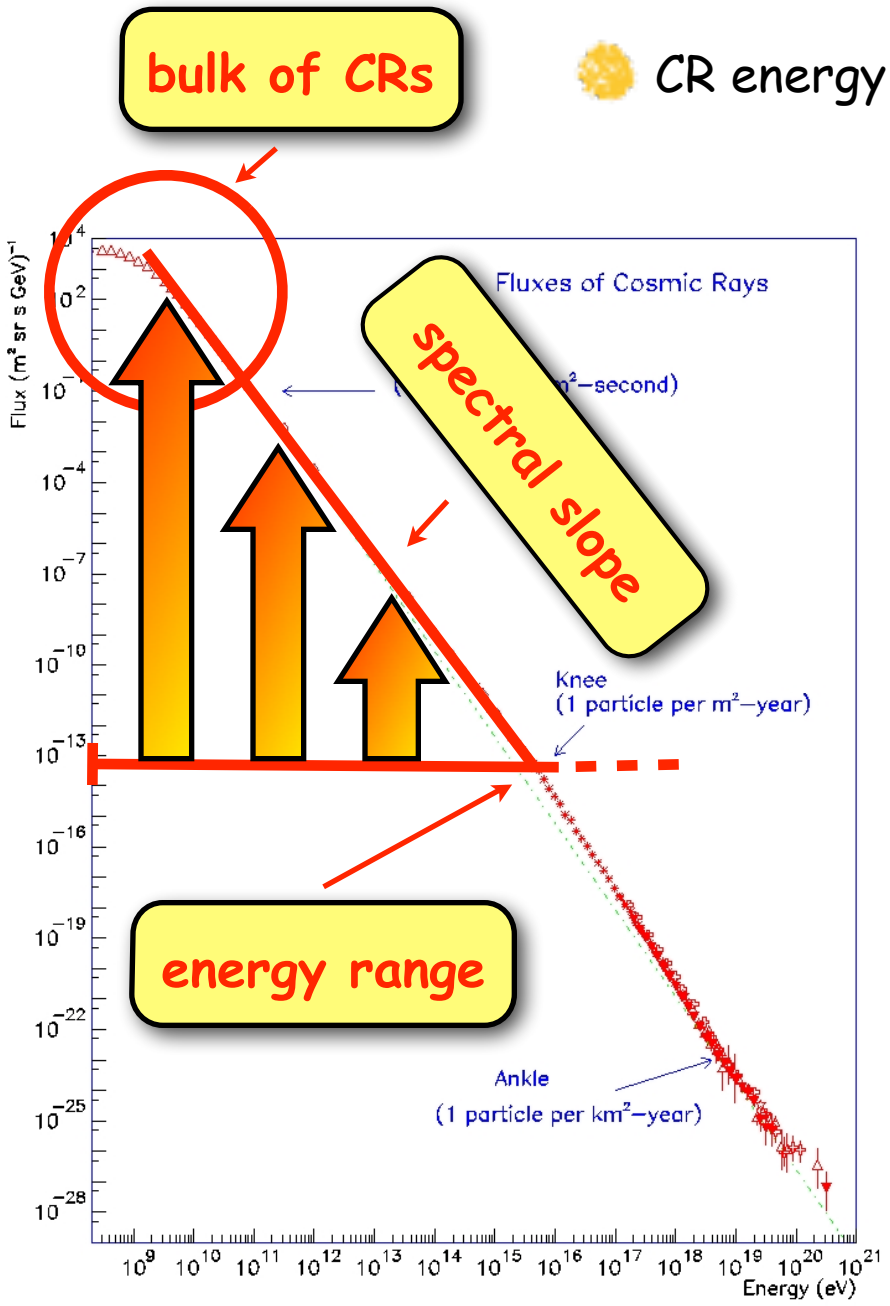

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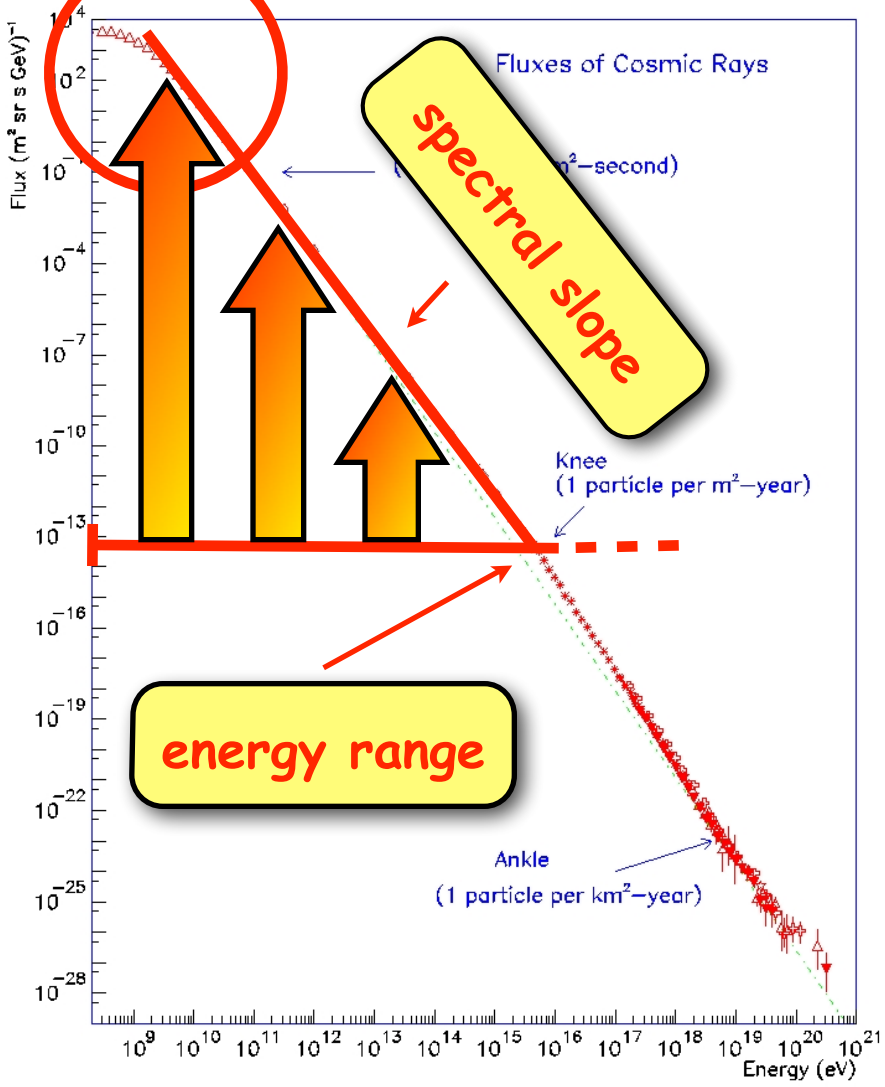

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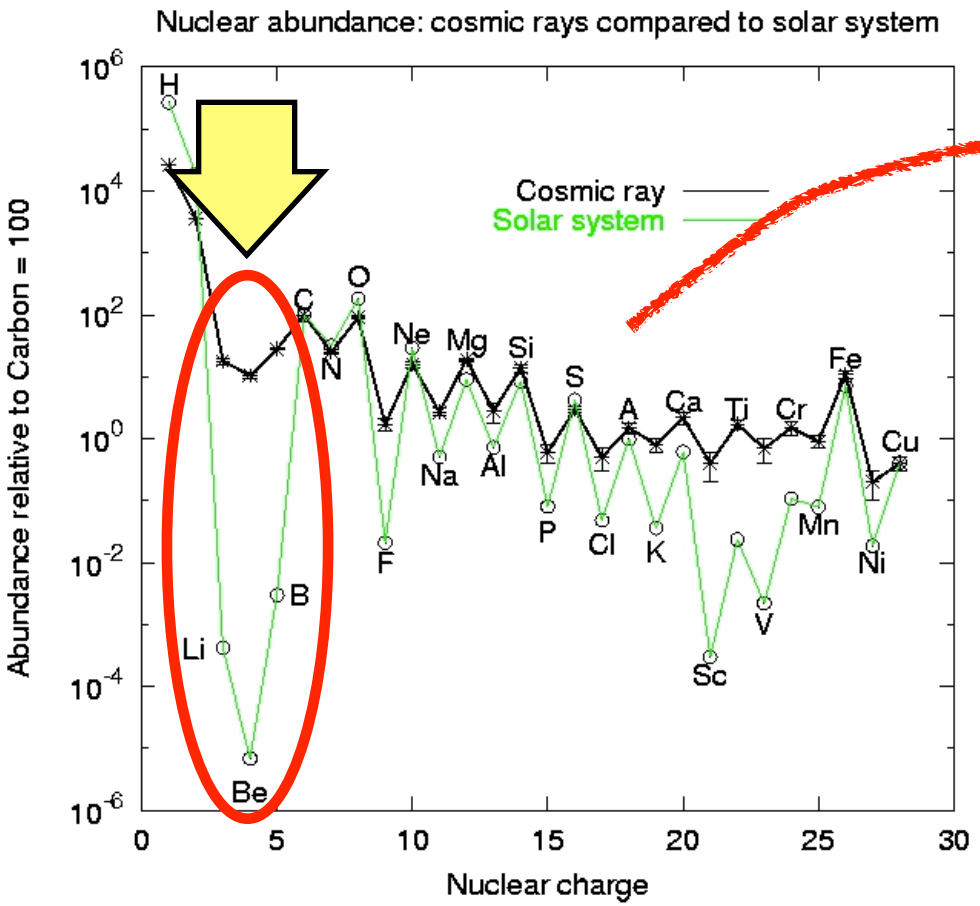
supernovae first proposed by Baade&Zwicky1934



CR escape time

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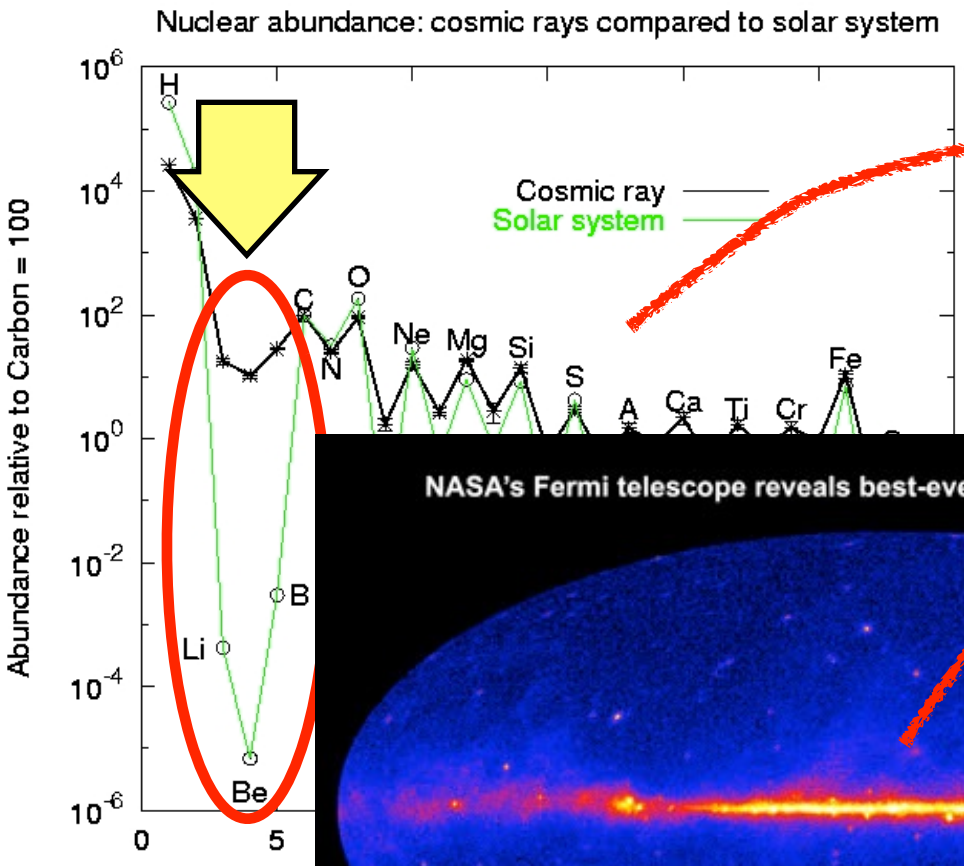
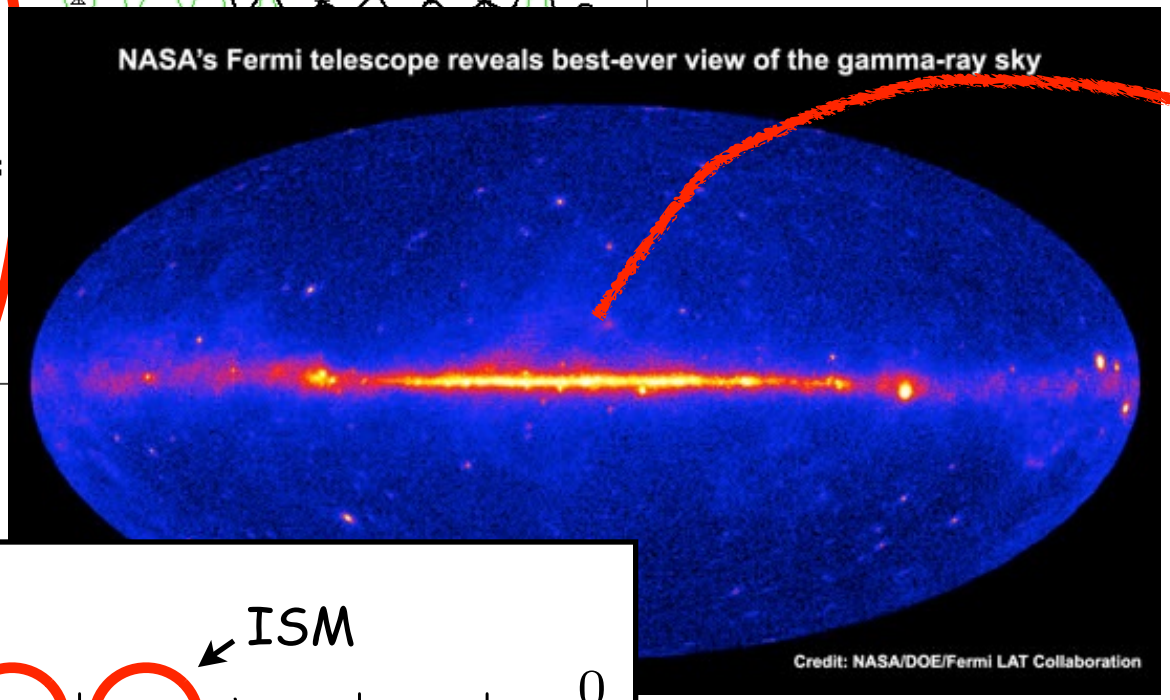


CR escape time

-> power of CR sources 10^{41} erg/s



CR total energy

CR ISM

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

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

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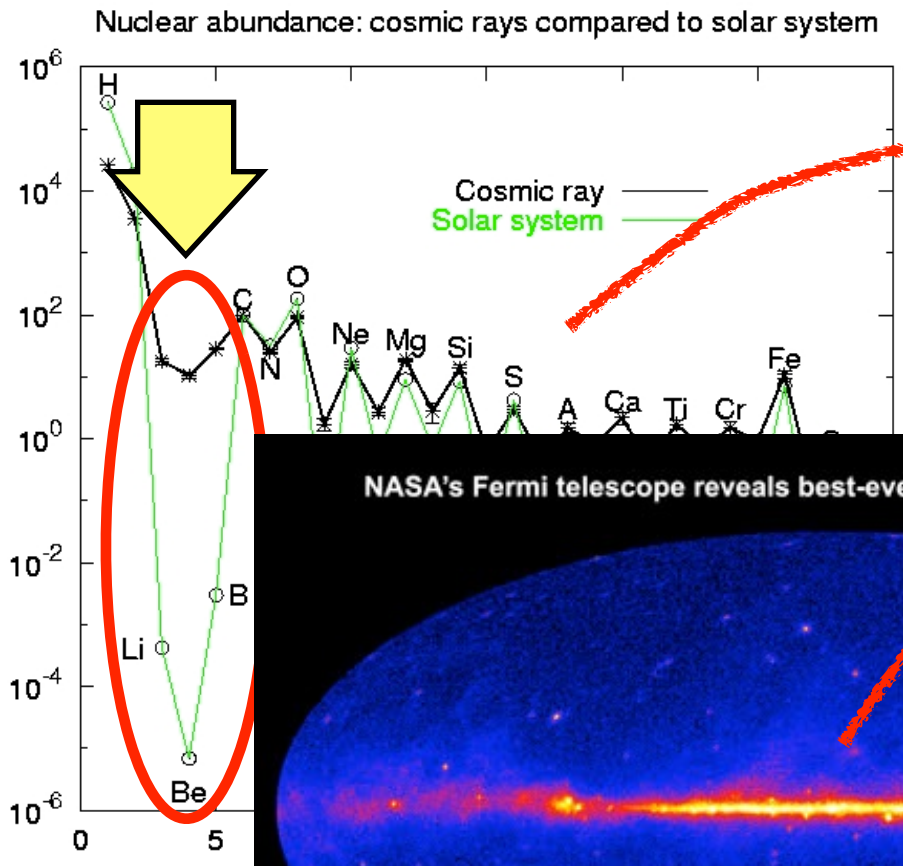

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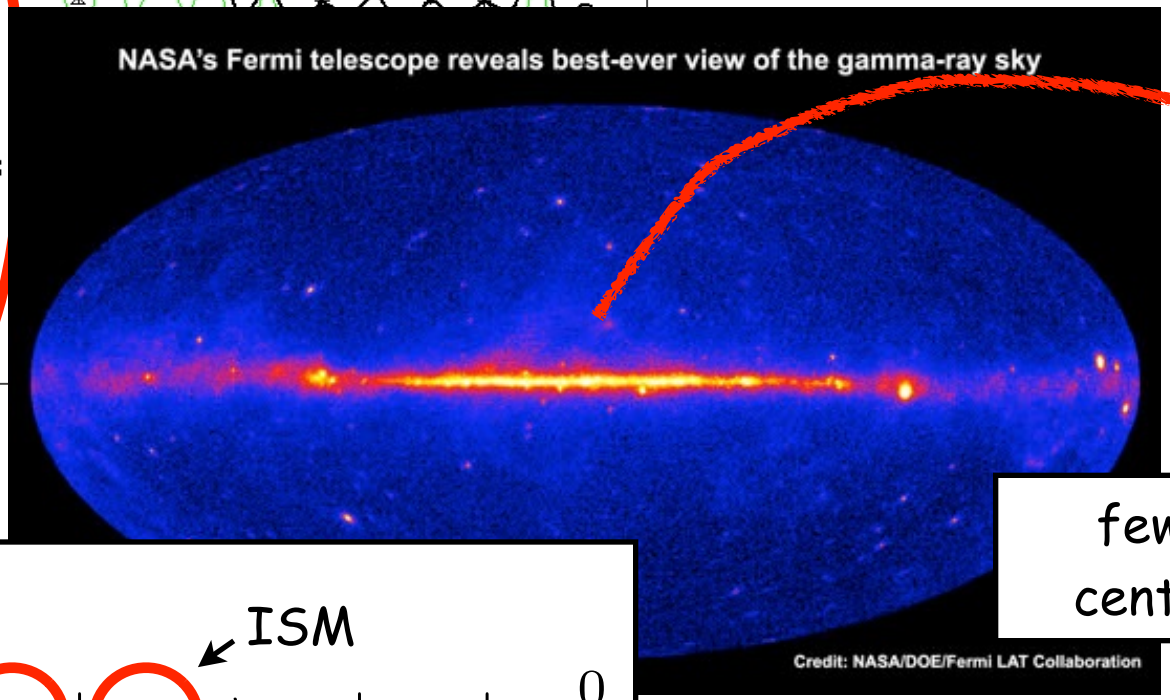
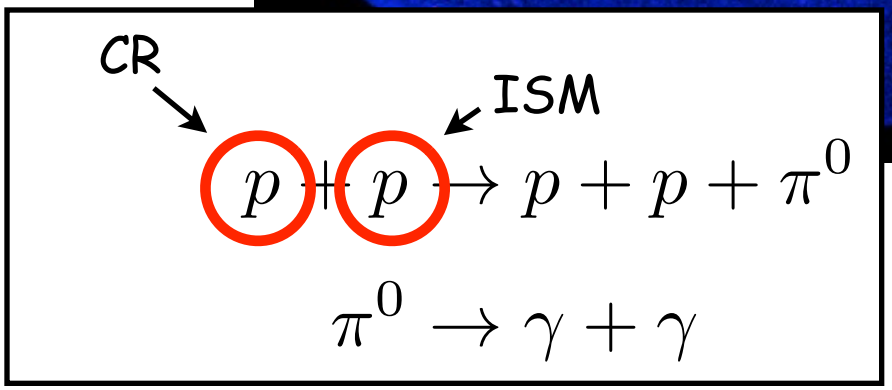


CR total energy

few supernovae per century in the Galaxy



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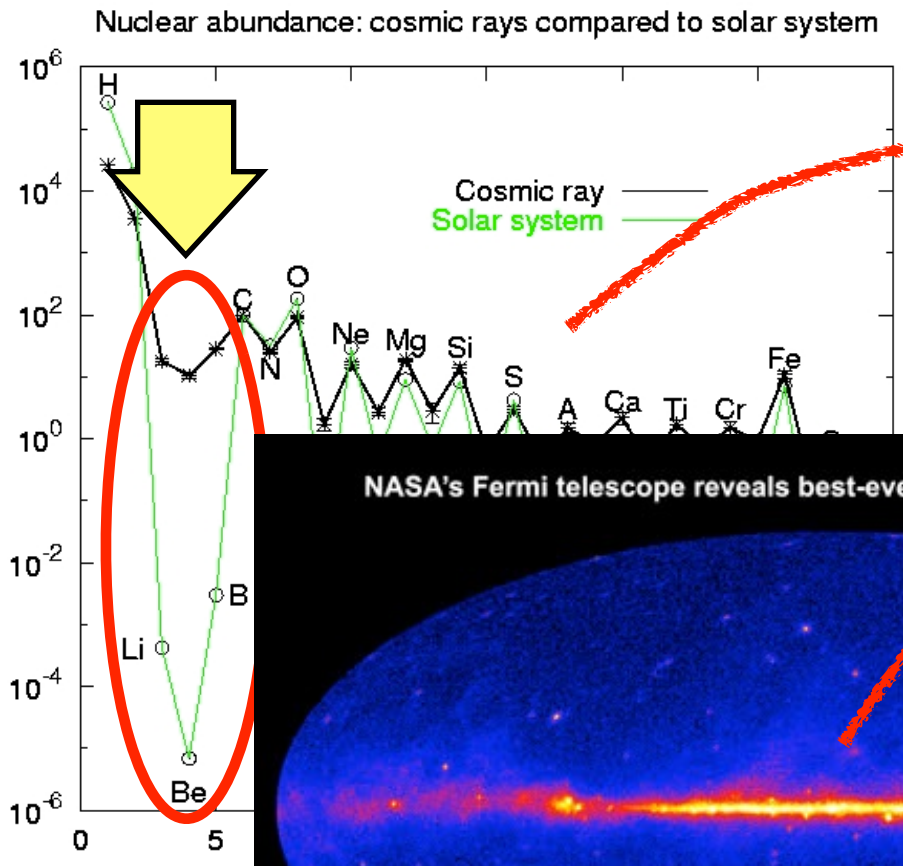

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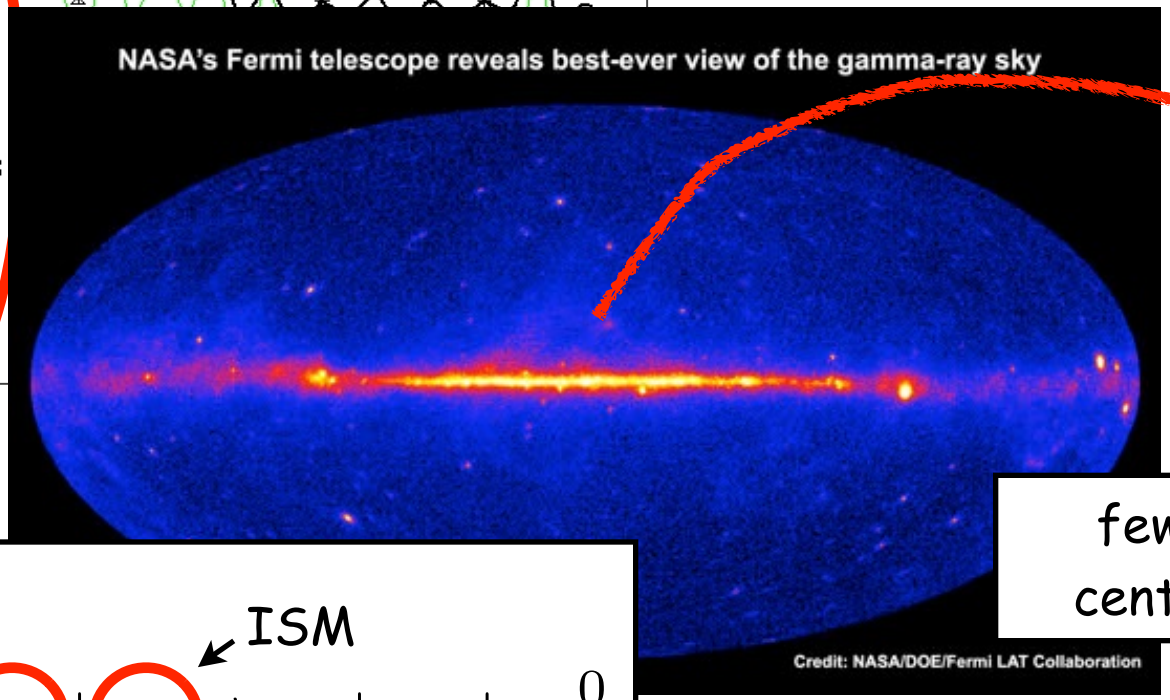

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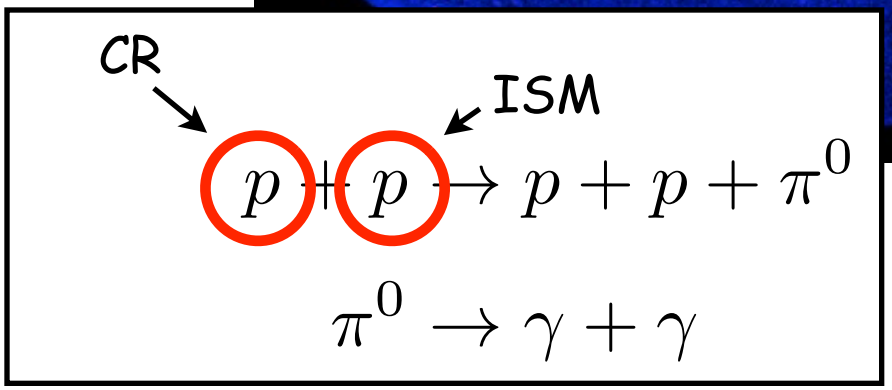

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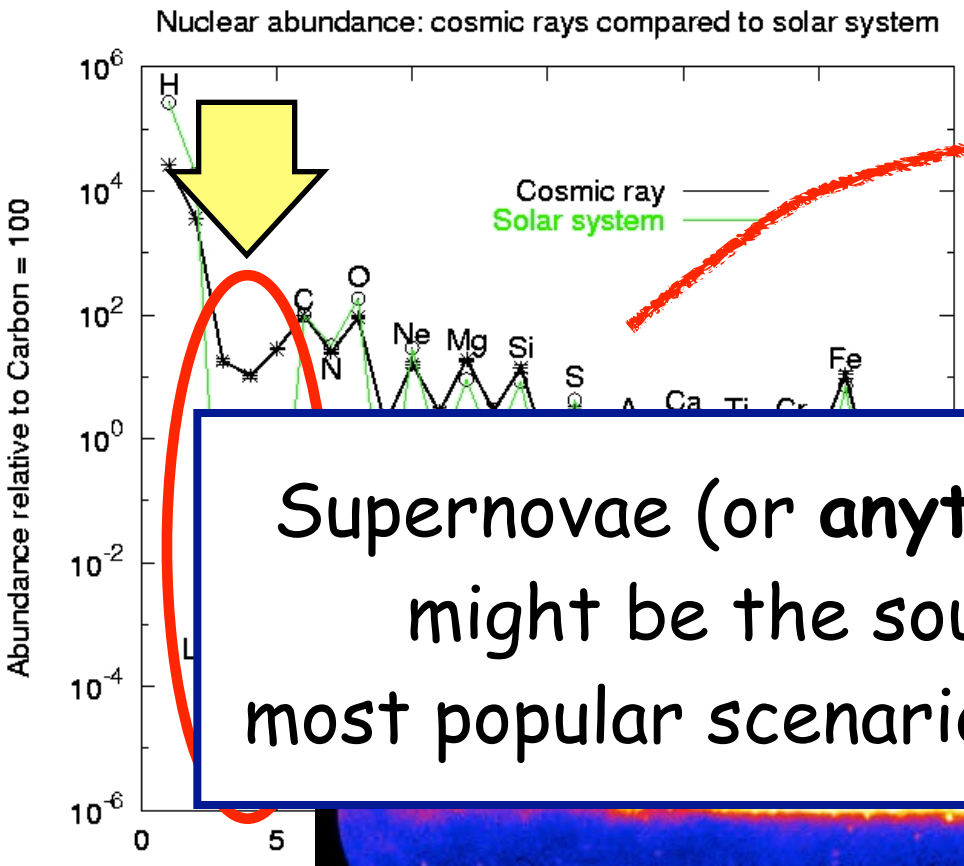

CR escape time

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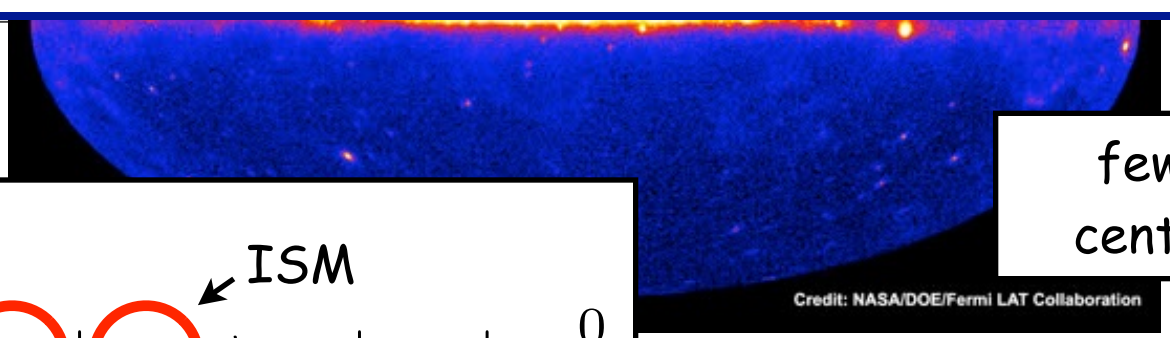
Supernovae (or **anything** connected to them) might be the sources of cosmic rays:
most popular scenario -> **supernova remnants**

nergy



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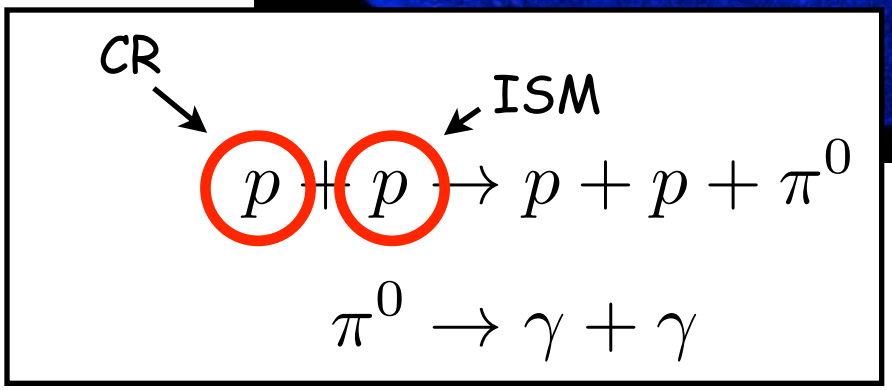

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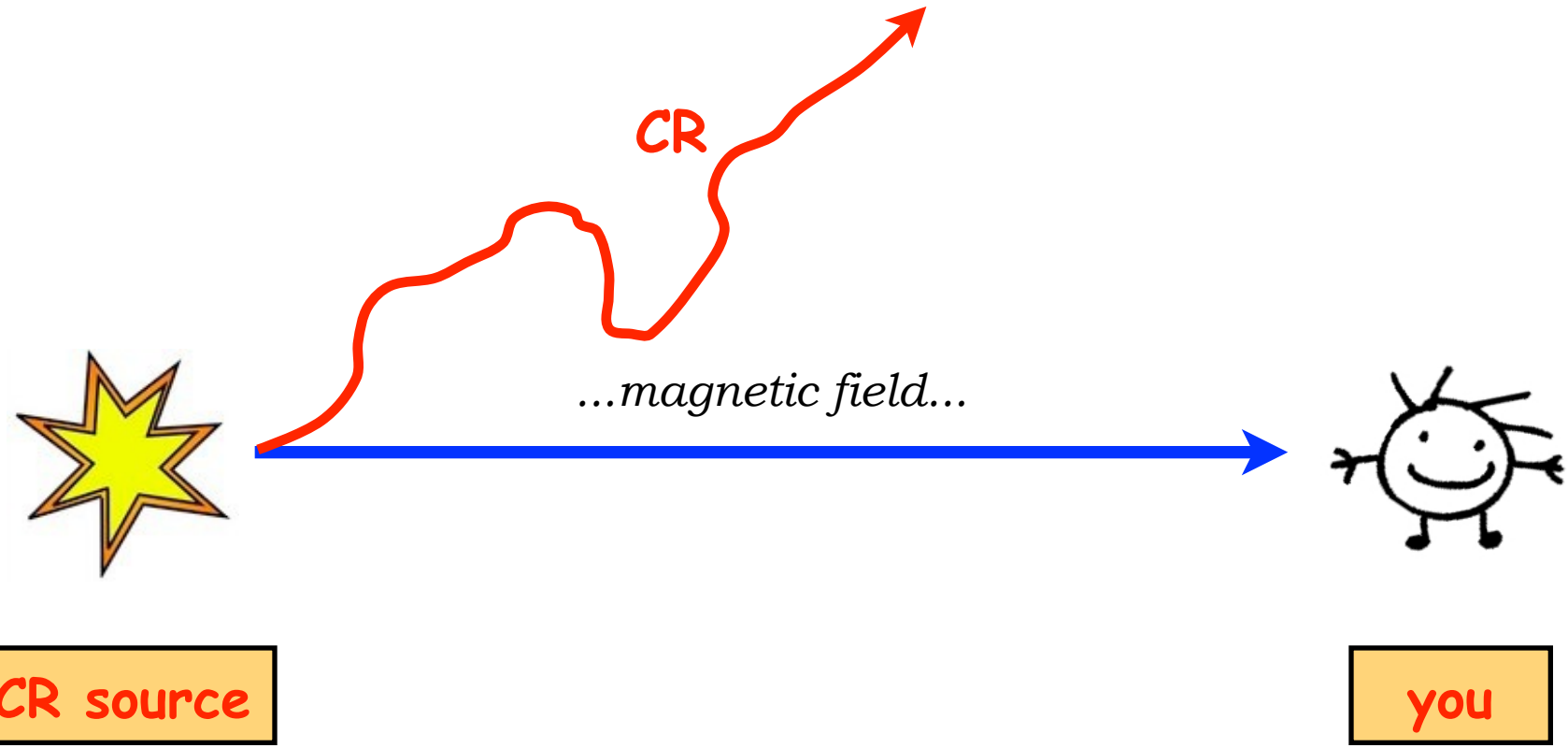
Cosmic ray sources: why is it so difficult?



We cannot do CR Astronomy.

Need for indirect identification of CR sources.

Gamma rays from SNRs: a test for CR origin

Drury, Aharonian & Volk, 1994

- CR observations -> CR power of the Galaxy
- Supernova rate in the Galaxy (≈3 per century)

} ⇨ ≳10% of SNR energy MUST be converted into CRs

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

} ⇨ **SNRs visible in TeV gamma rays**

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almost model independent

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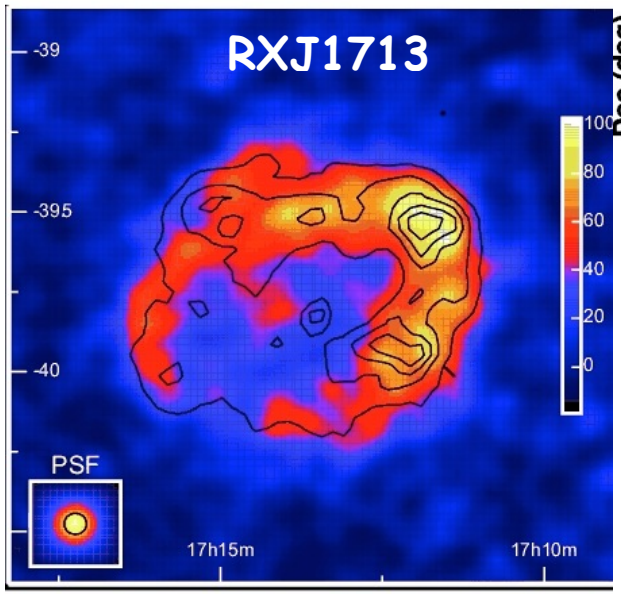
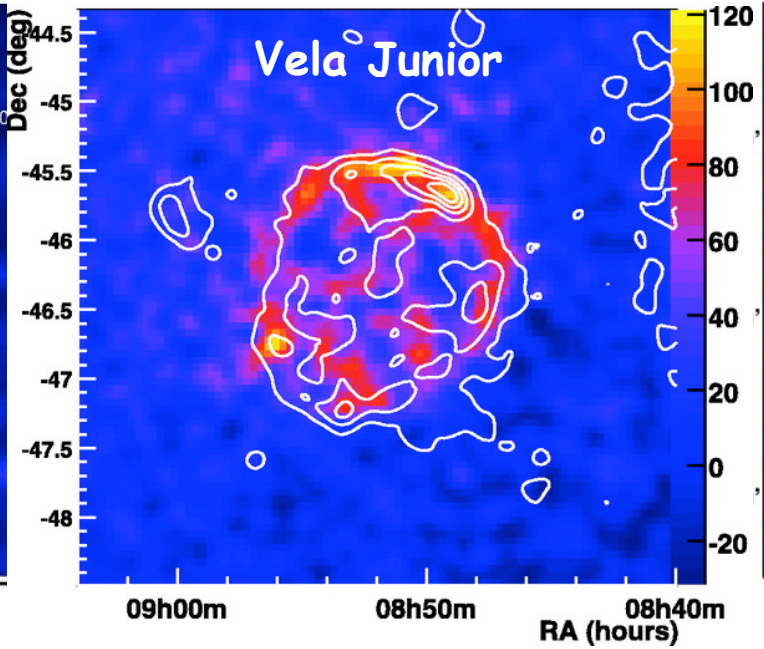
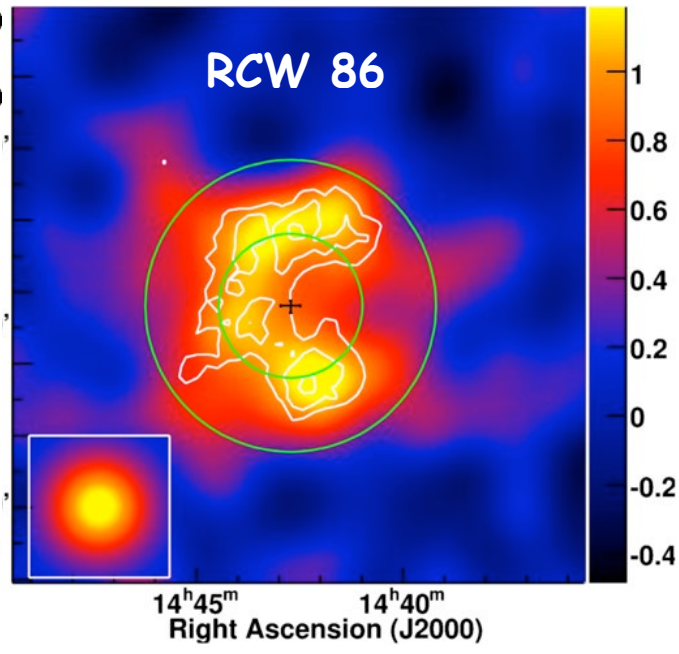






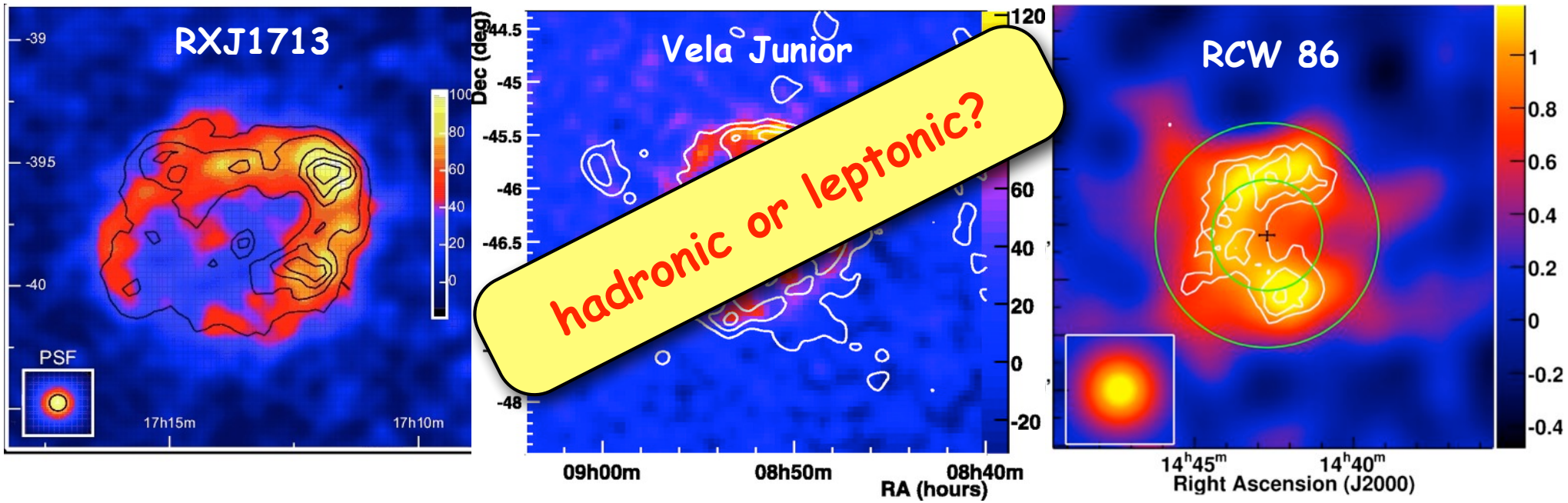
Gamma rays from SNRs: a test for CR origin

Drury, Aharonian & Volk, 1994

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

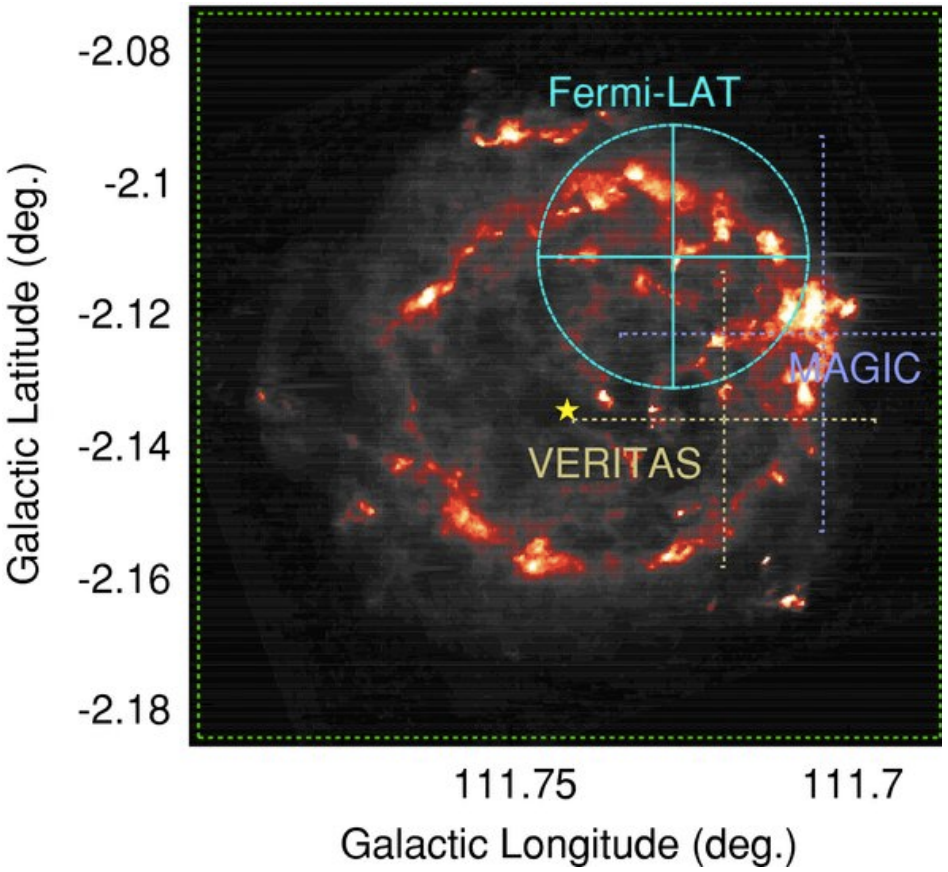
neutrinos are the candidates, but their detection is challenging

-> other gamma-ray based tests?



Hadronic or leptonic?

SNR Cas A



FERMI coll. (2010)

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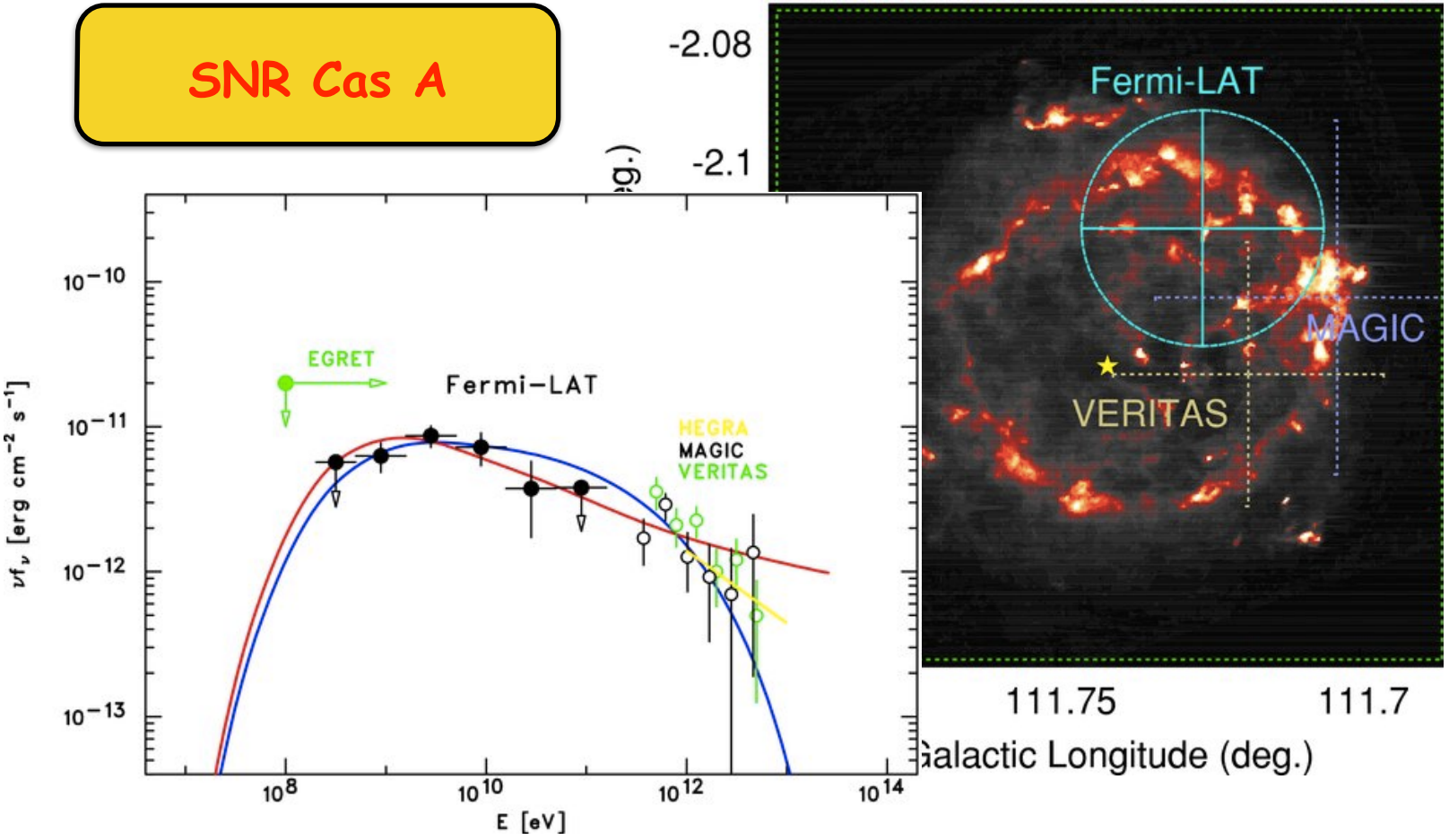

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proton-proton:

$$E_\gamma \approx 0.1 \times E_p$$

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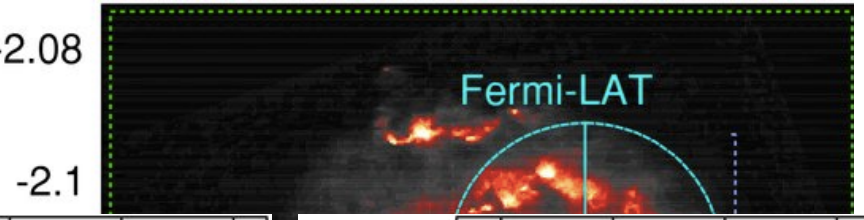

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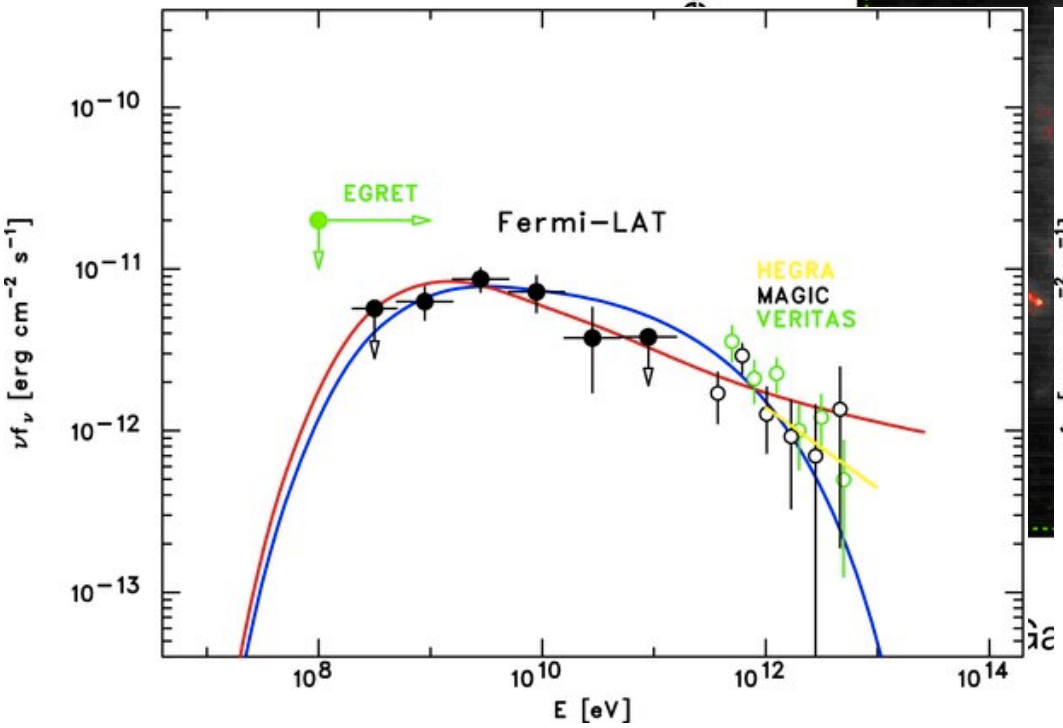

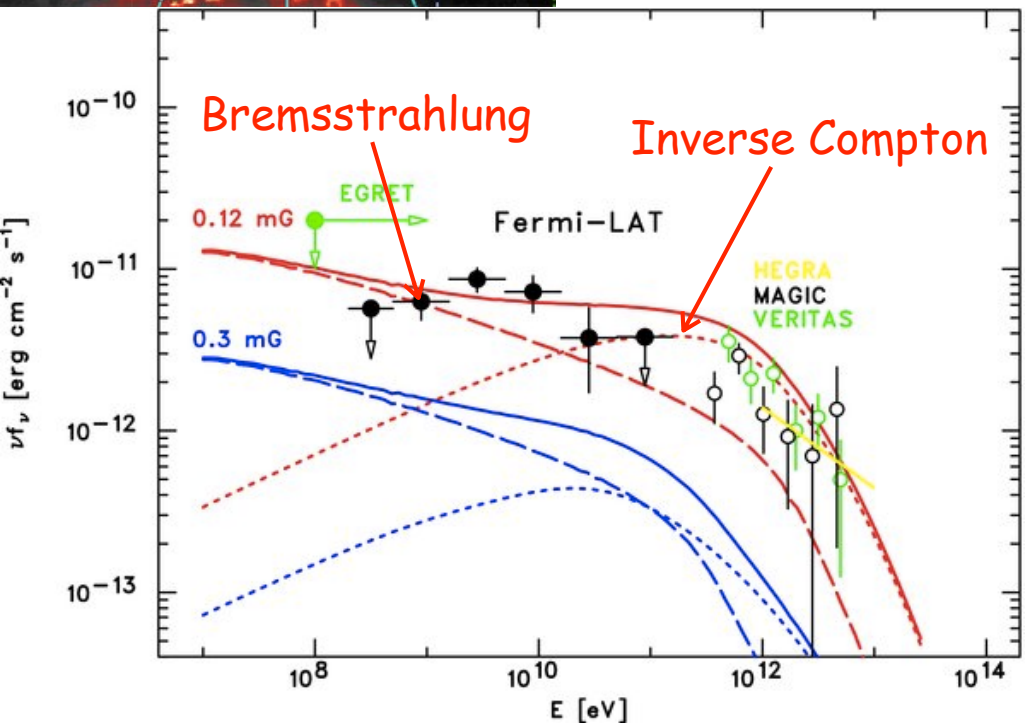

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Inverse Compton on CMB $E_\gamma \approx 1 \left(\frac{E_e}{20\ \mathrm{TeV}} \right)^2 \mathrm{TeV}$

Bremsstrahlung $E_\gamma \approx E_e$

Hadronic or leptonic?

SNR Cas A

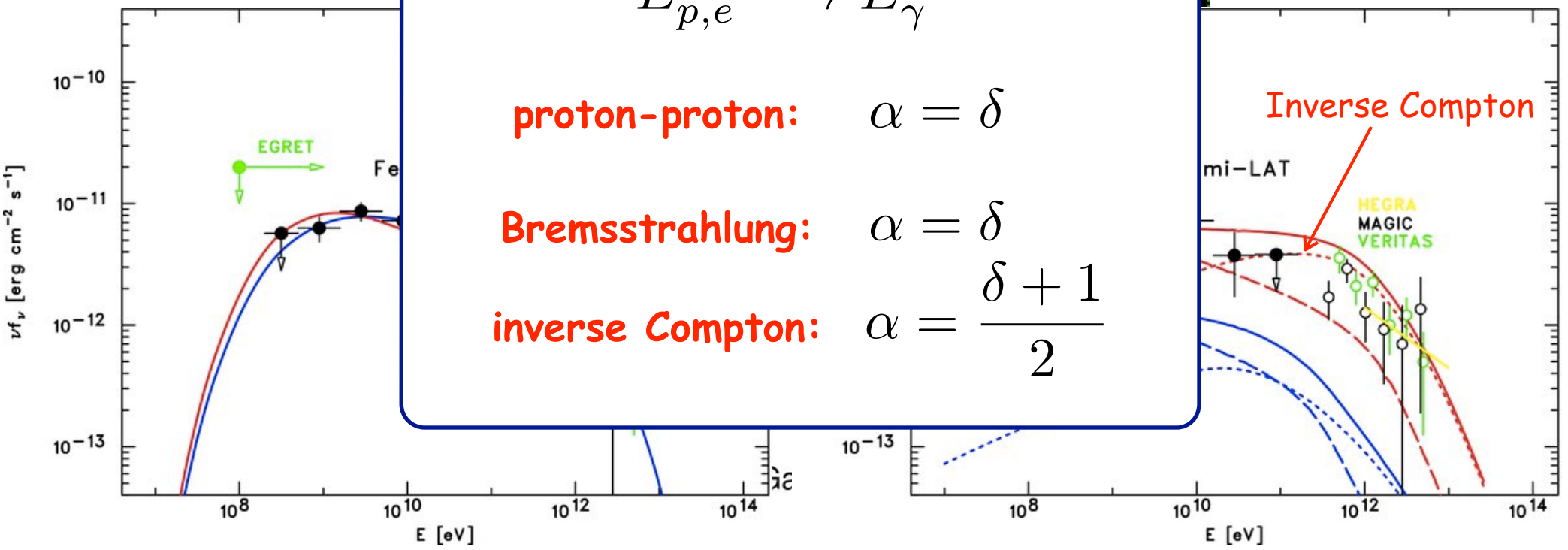
FERMI coll. (2010)

$$E_{p,e}^{-\delta} \longrightarrow E_{\gamma}^{-\alpha}$$

proton-proton: $\alpha = \delta$

Bremsstrahlung: $\alpha = \delta$

inverse Compton: $\alpha = \dfrac{\delta + 1}{2}$



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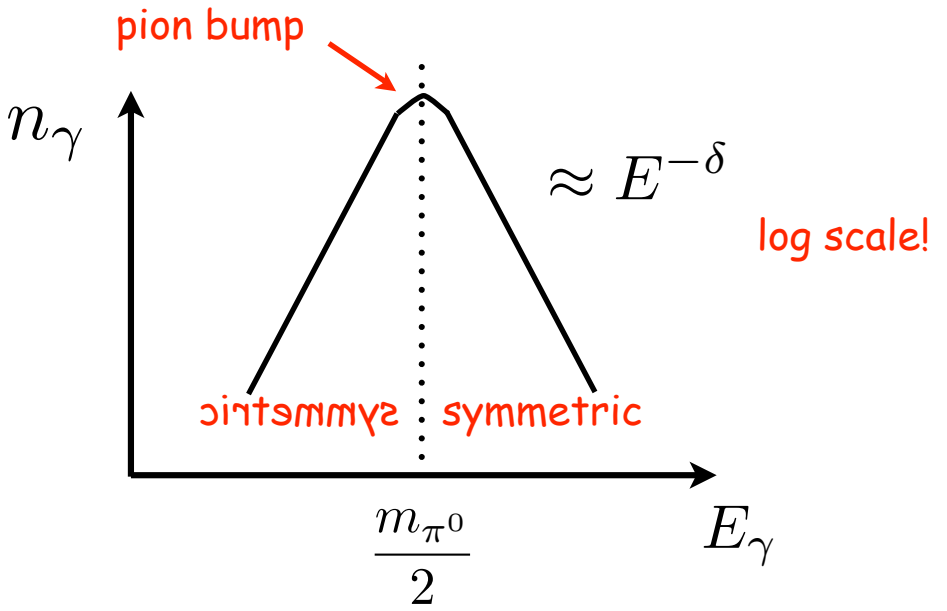
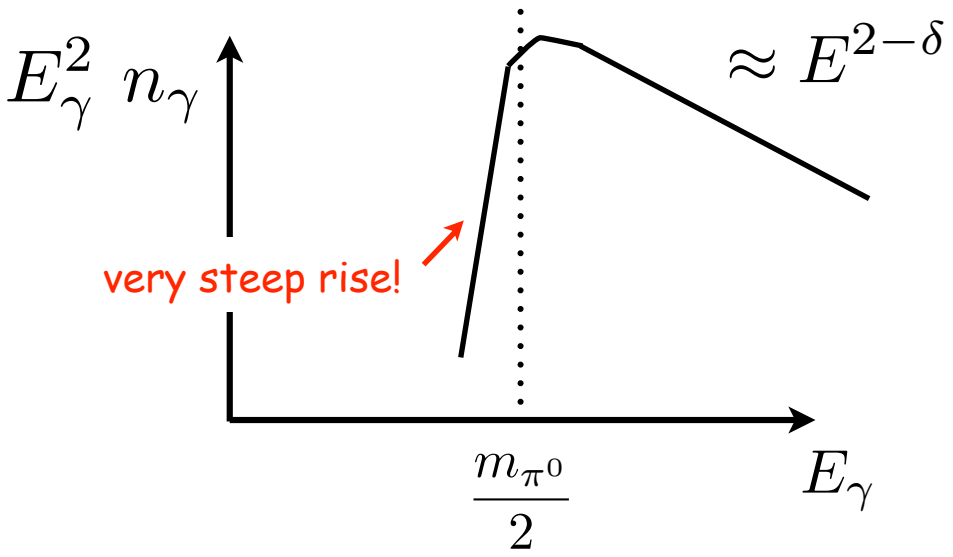


log scale!

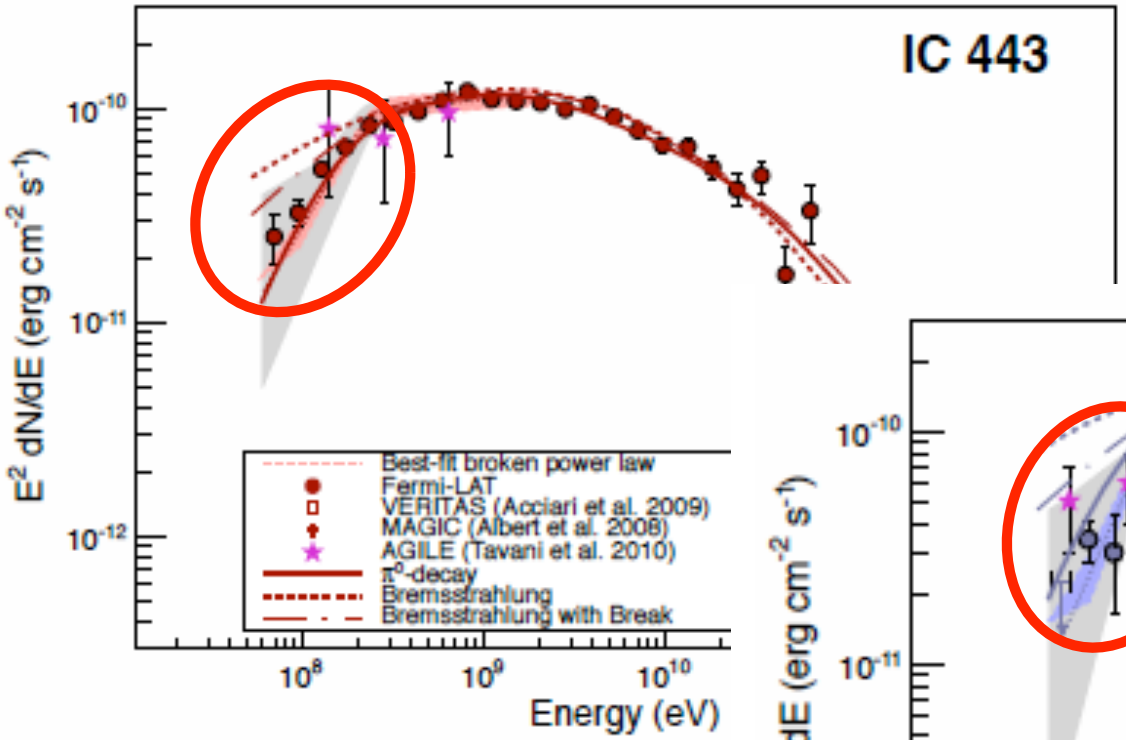


Hadronic or leptonic?
The pion bump

(Ackermann et al 2013)

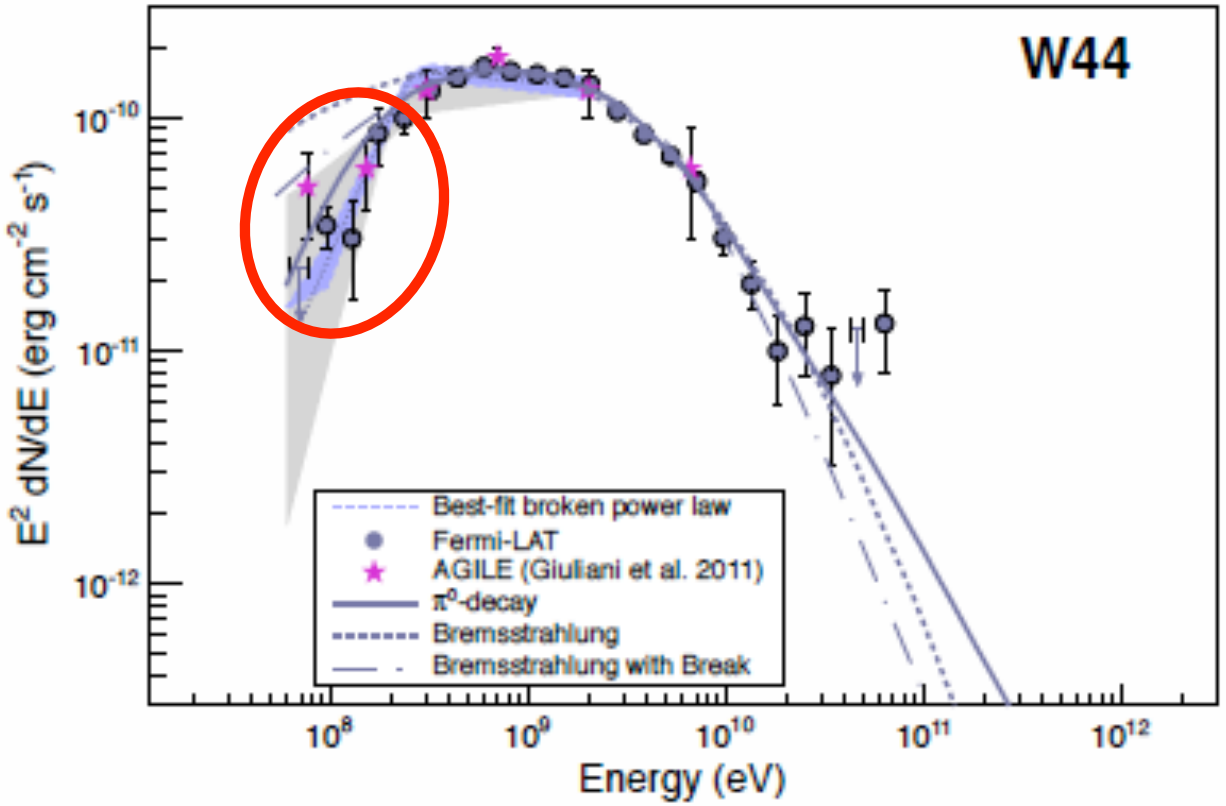
FERMI (and AGILE)

(Giuliani+, Cardillo+)



n_γ

$\approx E^{2-\delta}$



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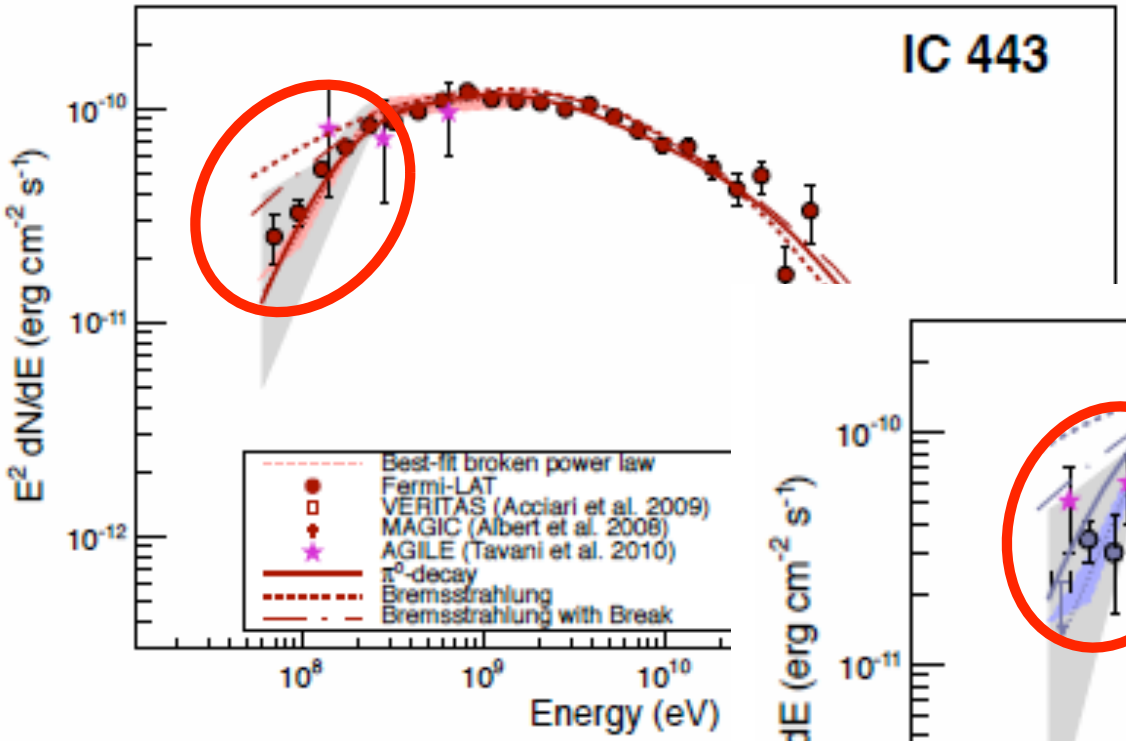

FERMI (and **AGILE**)

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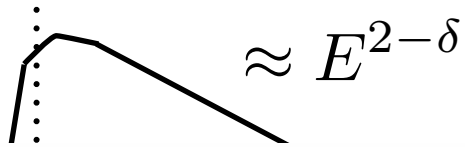
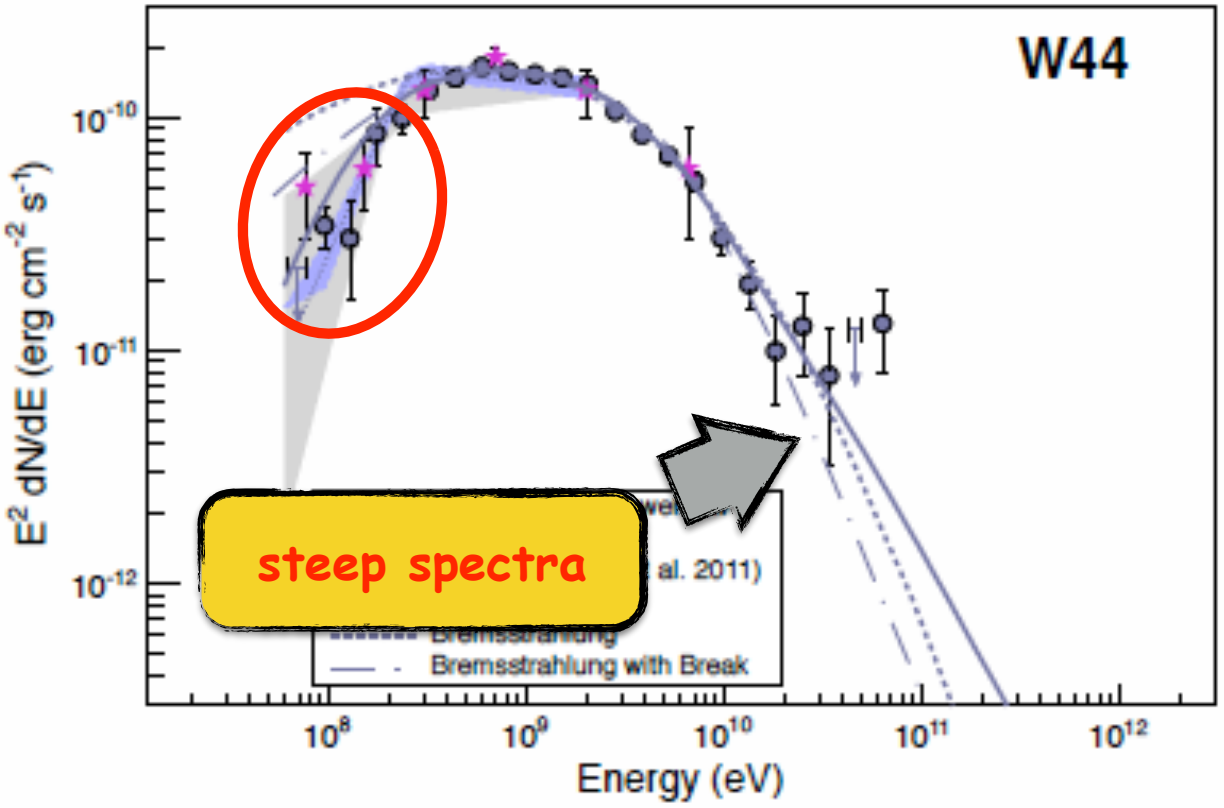
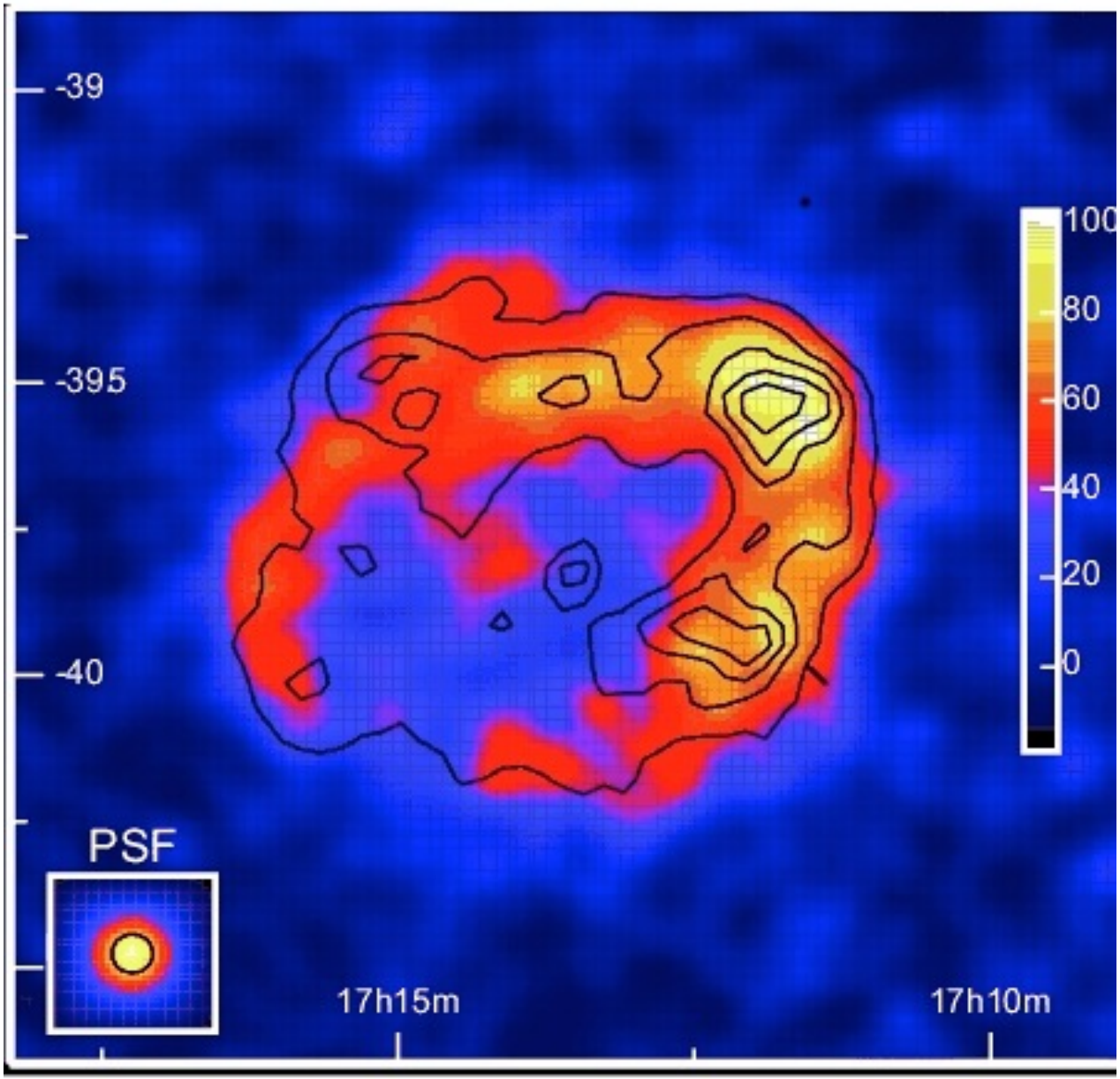
n_γ ↑





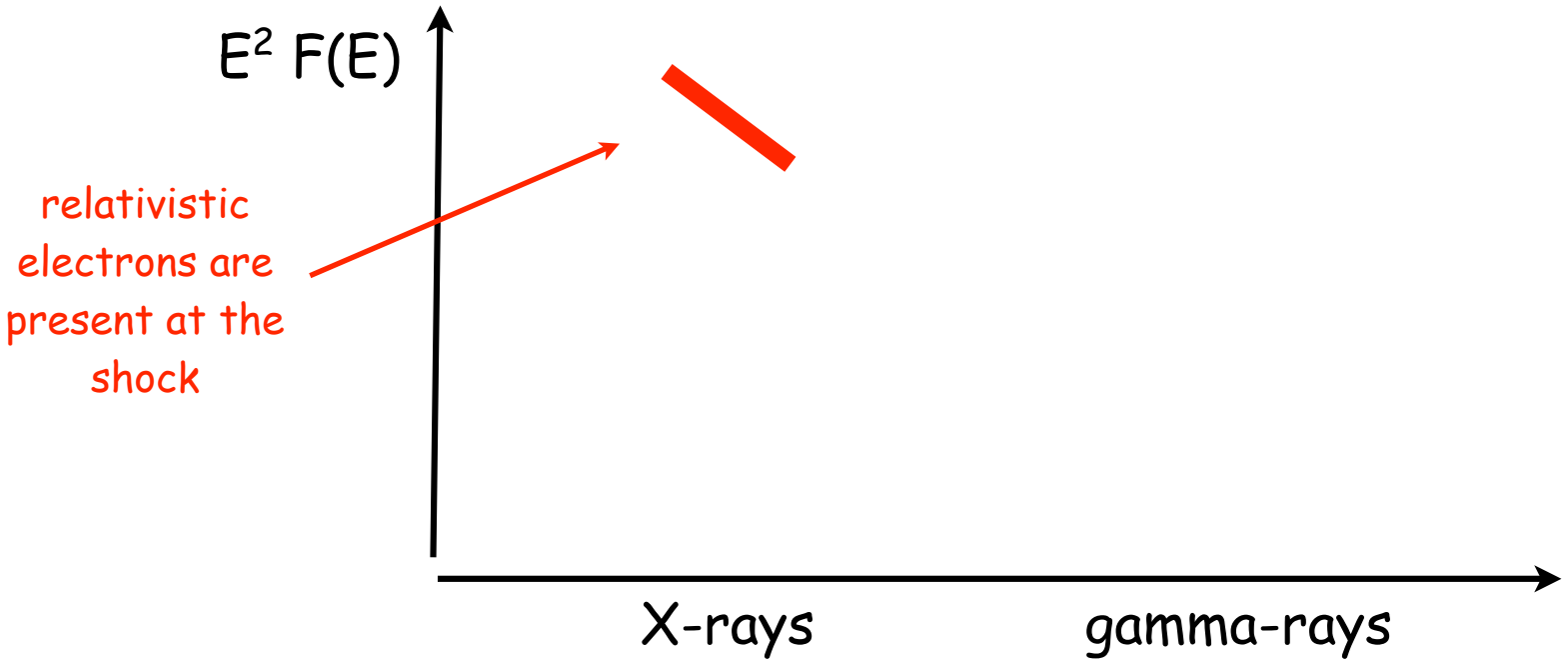
GeV CR are present
-> we want SNR to be **PeVatrons** -> additional evidence required

The SNR RXJ 1713



Hadronic versus leptonic emission: the role of the magnetic field

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



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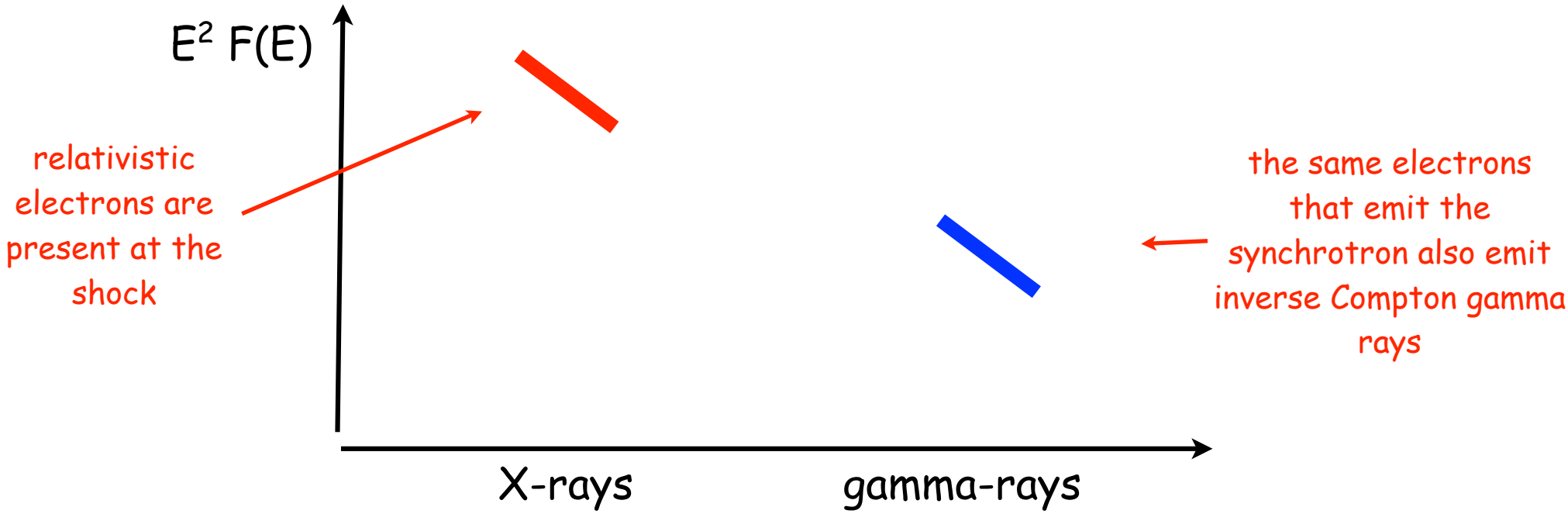

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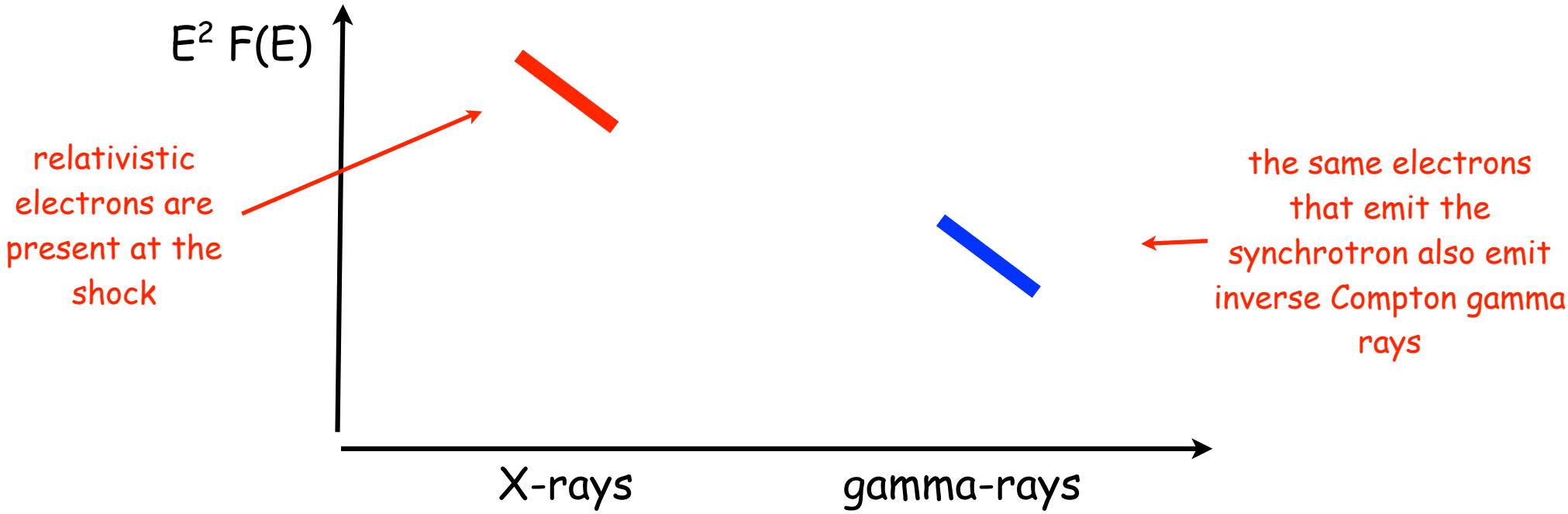

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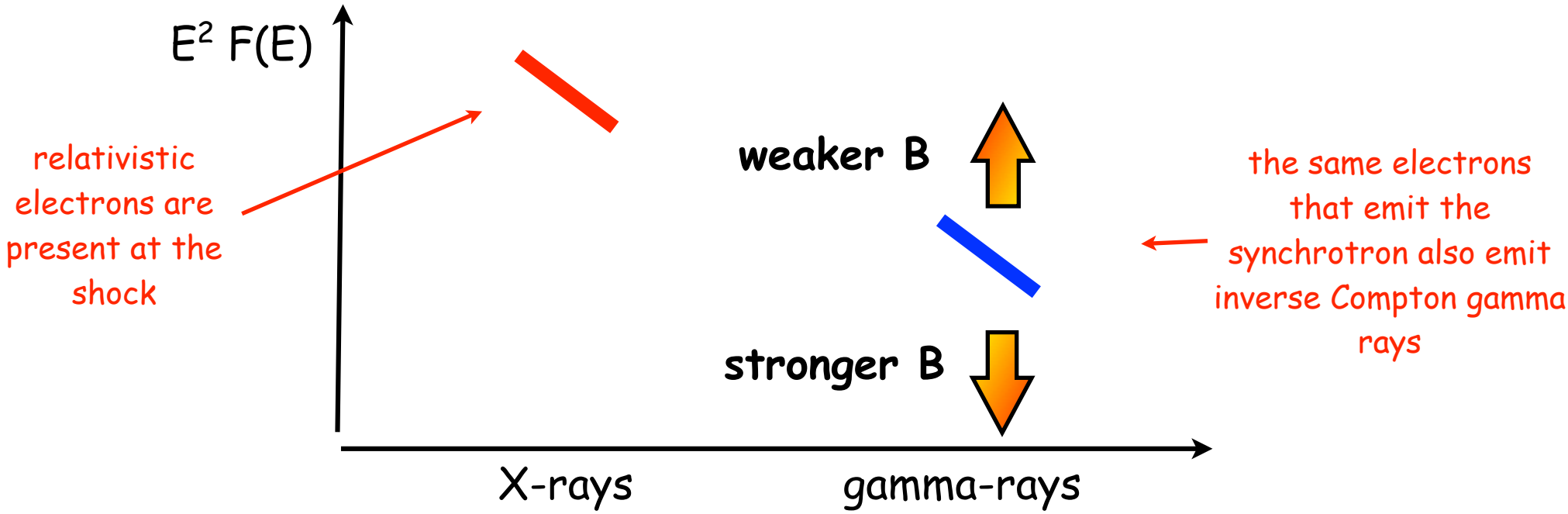

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Hadronic versus leptonic emission

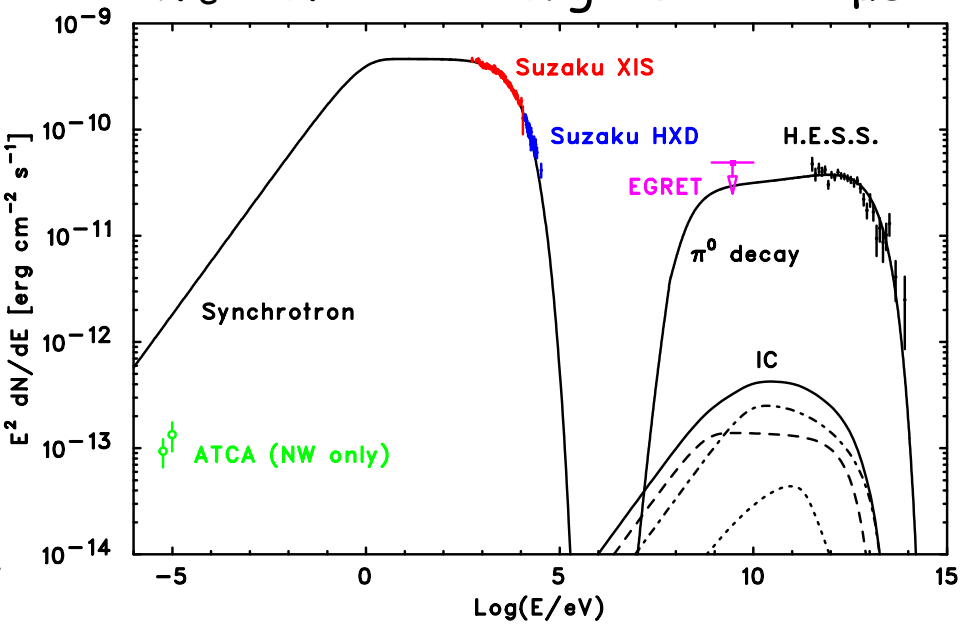
RXJ1713: hadronic and leptonic models

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 $E^{-1.5}$

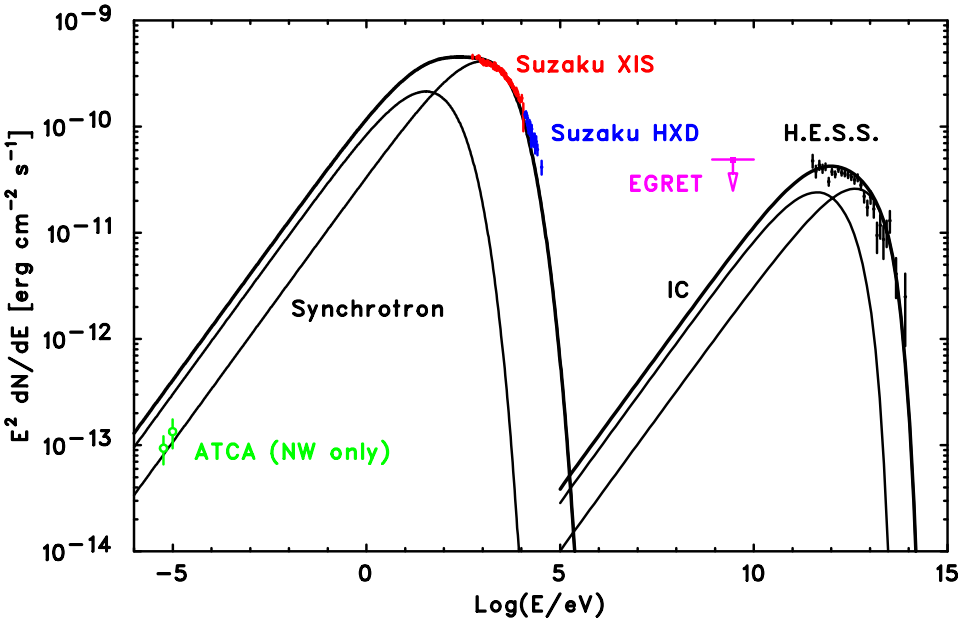
$W_p = 2{,}7 \times 10^{50}\ (n/cm^{-3})^{-1}$ erg

$W_e = 3.1 \times 10^{46}$ erg + B = 200 μG



Hadronic

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



Leptonic

Tanaka et al., 2008

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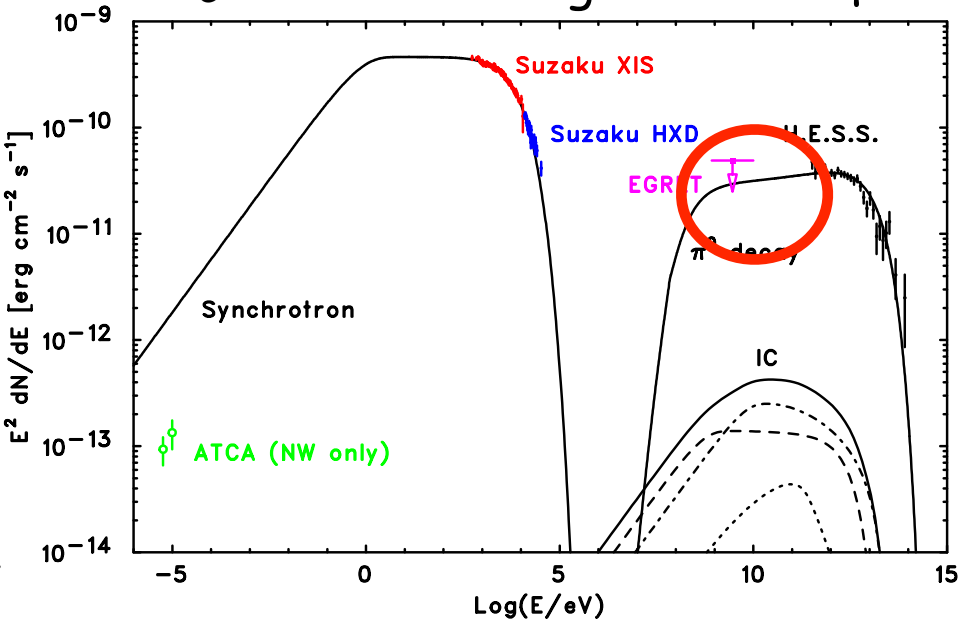

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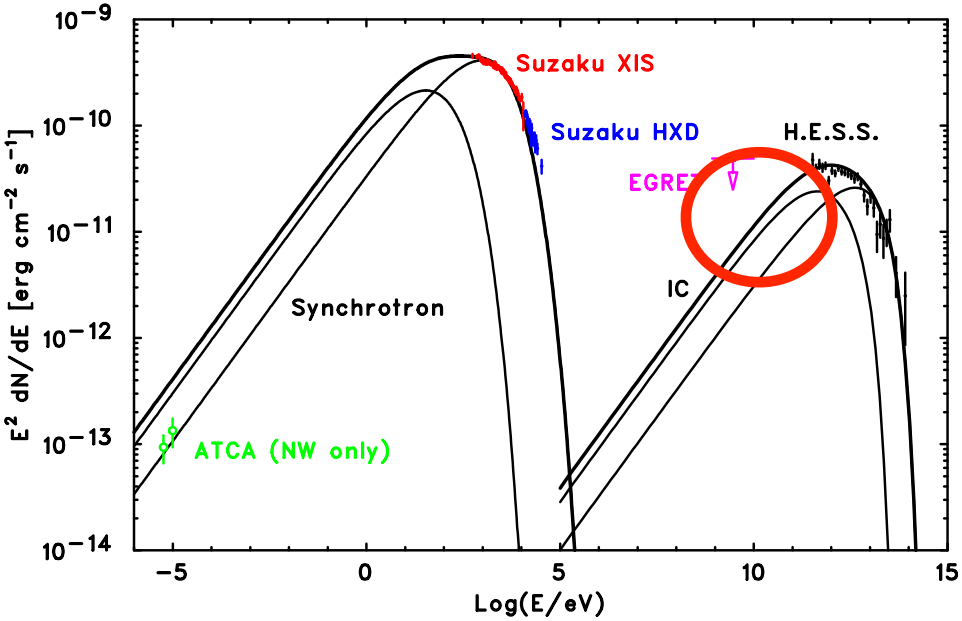
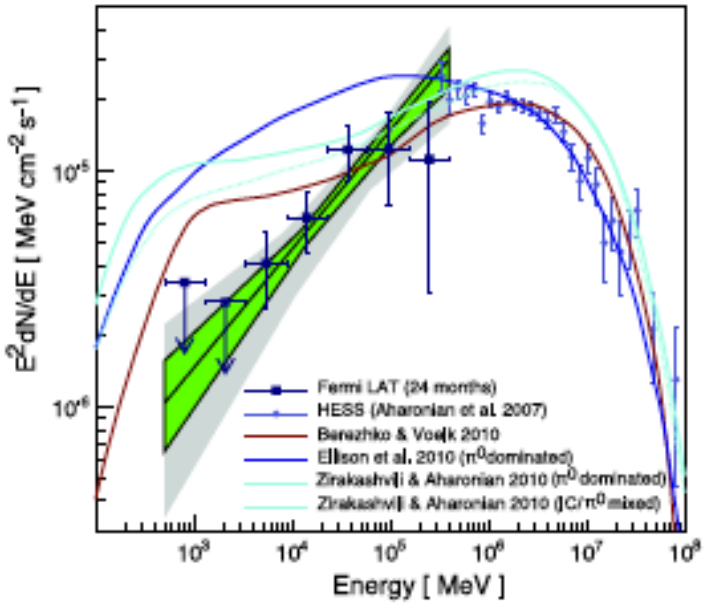


Leptonic

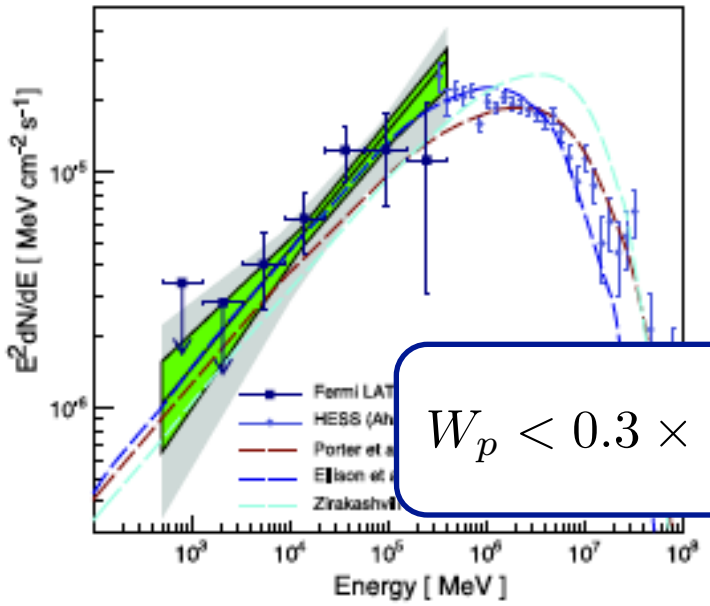
FERMI detects RX J1713

p-p interactions ->



emission most likely LEPTONIC?

inverse Compton ->

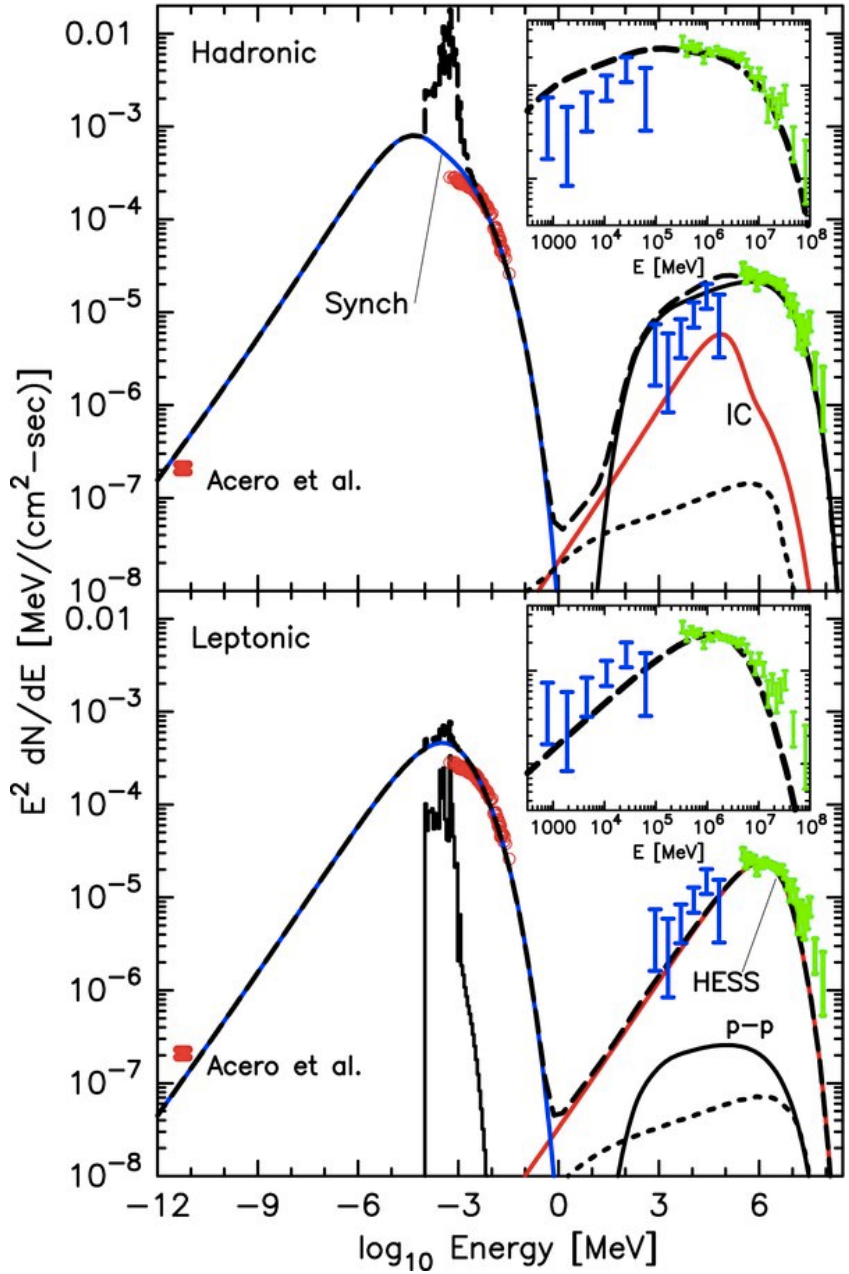


this does NOT mean that there are no protons!!!

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

Abdo et al, 2011

No thermal emission from RXJ1713: further support to IC scenario?



(Ellison et al 2010)

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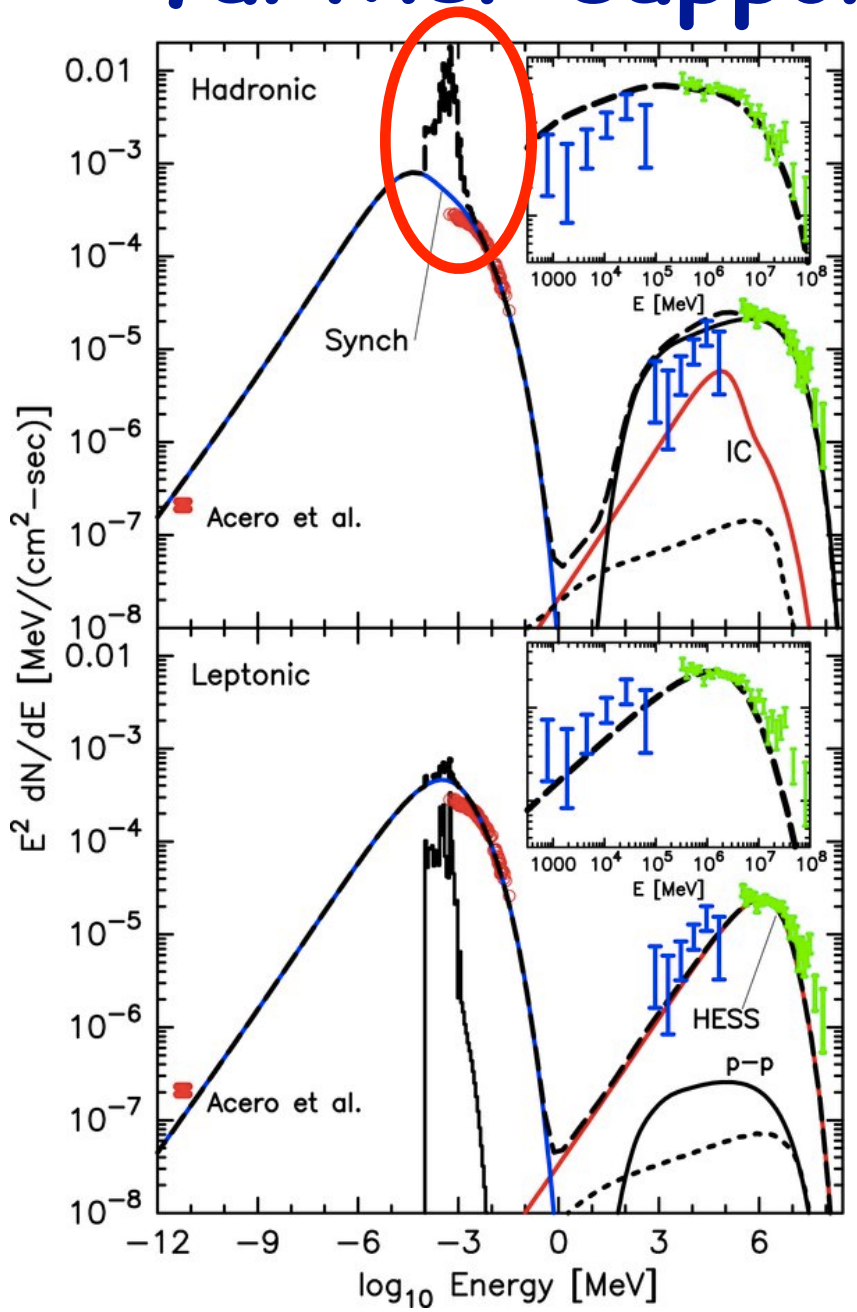

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high gas density + shock heating

-> bright X-ray thermal emission (lines)

-> NOT OBSERVED

(see also Katz&Waxman2008)

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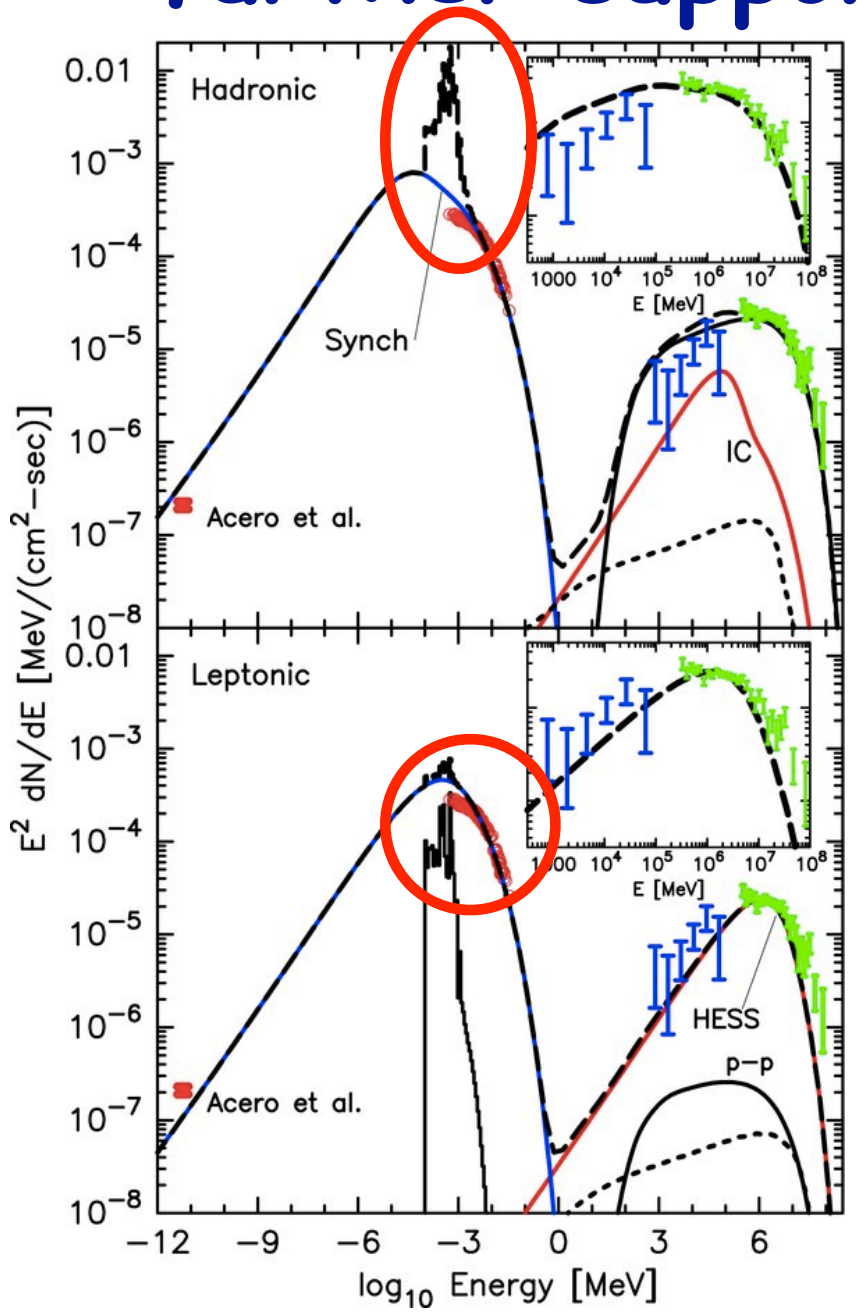

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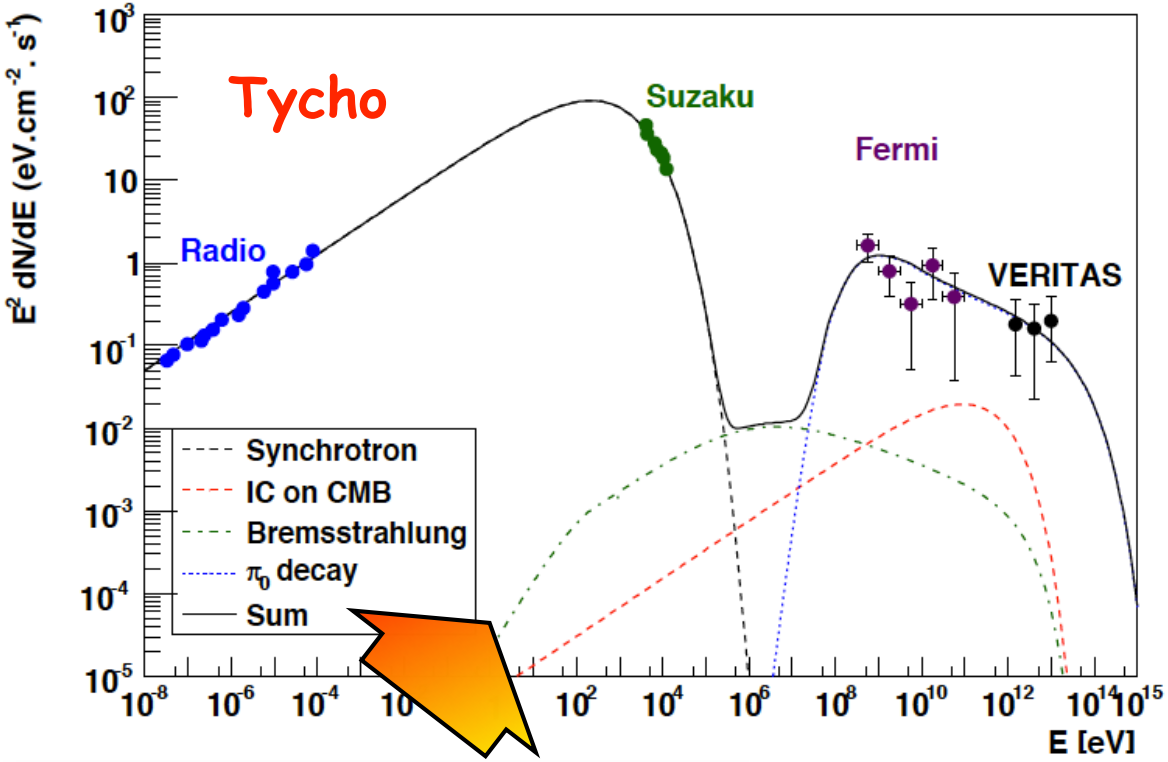
leptonic

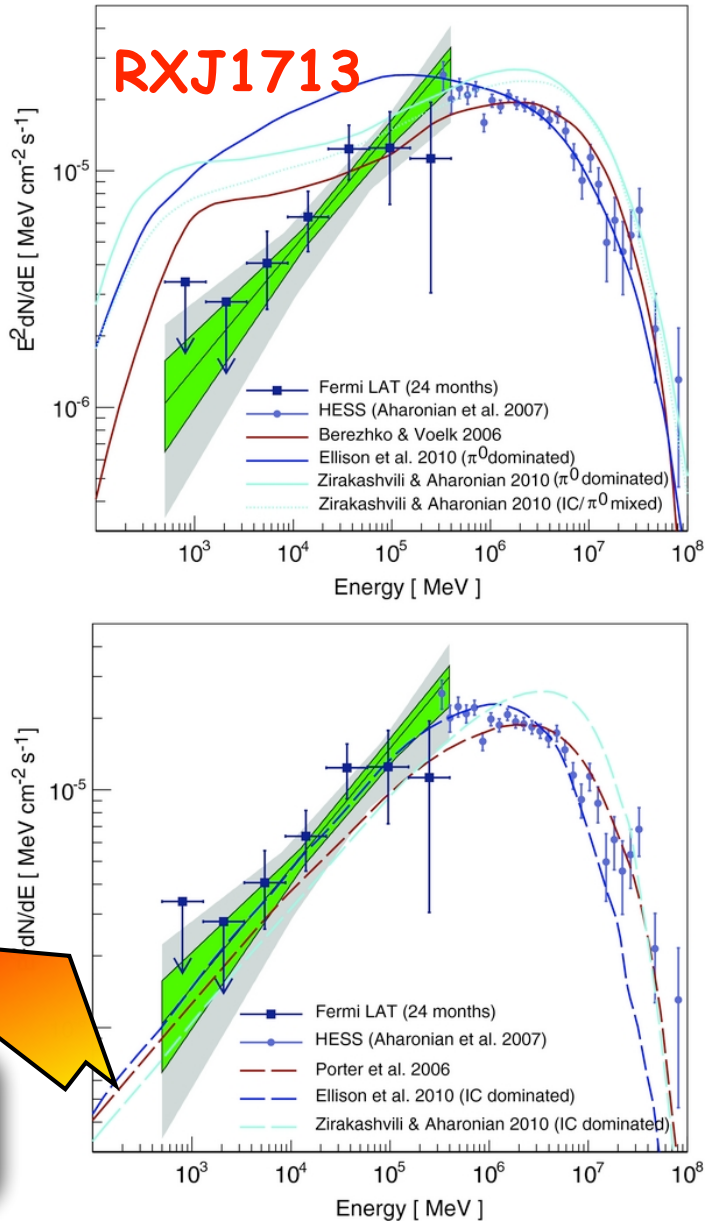
gas density is not a crucial parameter so one can tune it not to violate X-ray constraints

Gamma rays from SNRs

(Giordano et al 2011)



steep (2.3) -> hadronic?



(Abdo et al 2010)

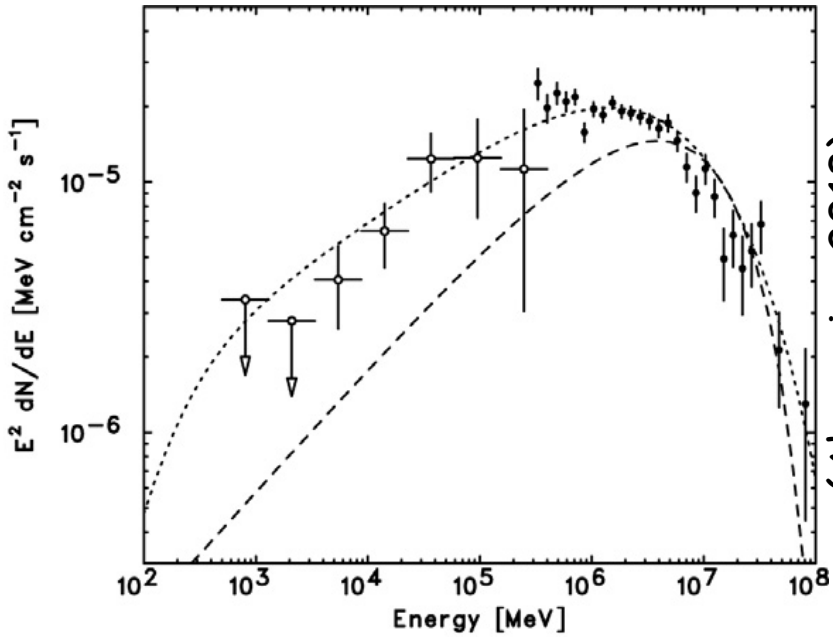
hard (1.5) -> leptonic?

RXJ1713: difficulties of one-zone leptonic models

two features in the electron spectrum:

acceleration time = synchrotron loss time -> acceleration cutoff at E_{max}

SNR age = synchrotron loss time -> cooling break at E_{cool}



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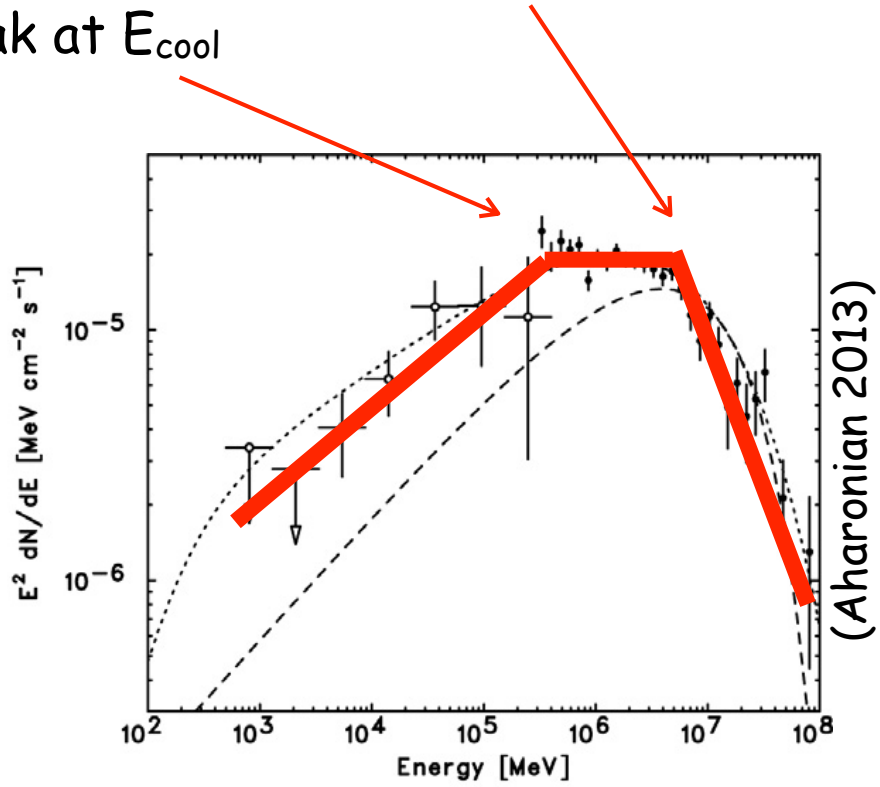

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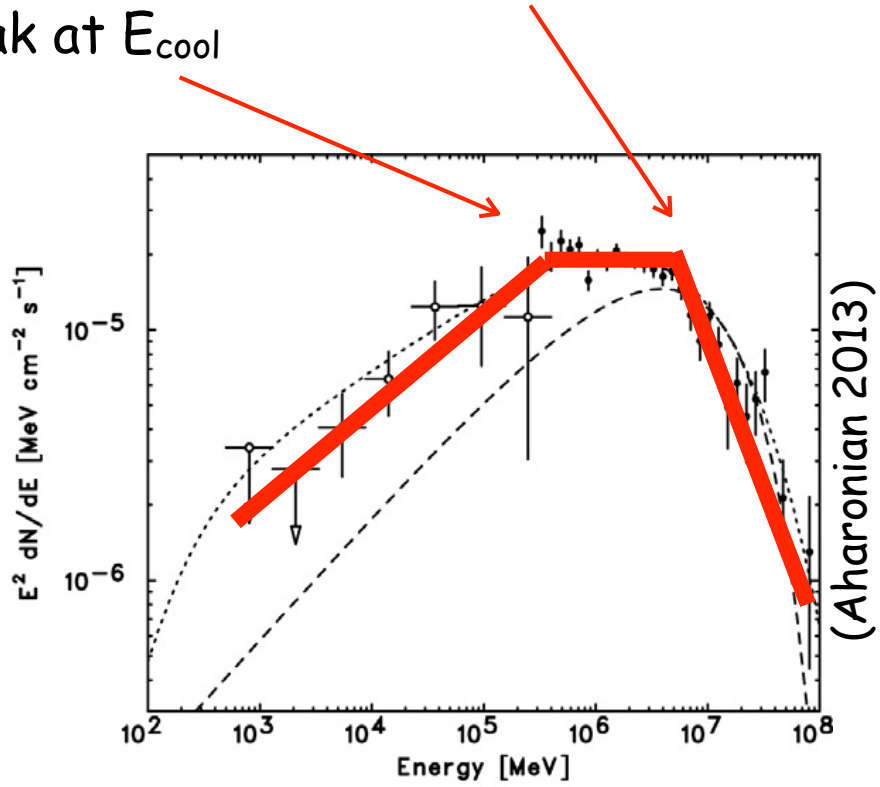
to fit simultaneously X and gamma rays with electrons the magnetic field MUST be **at most ~10 microGauss**



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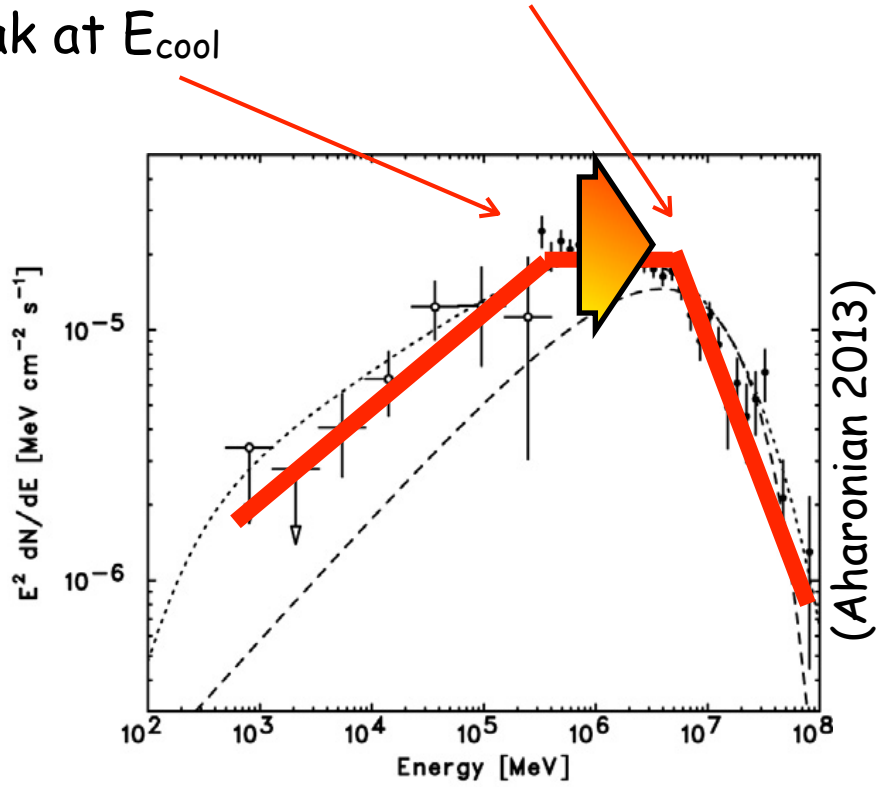

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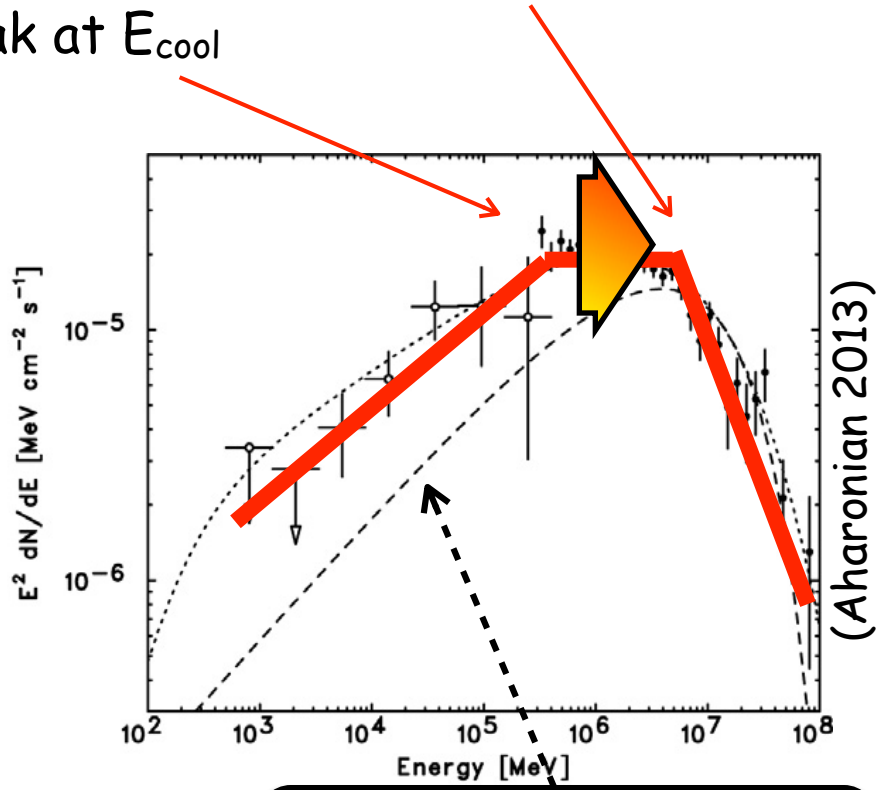
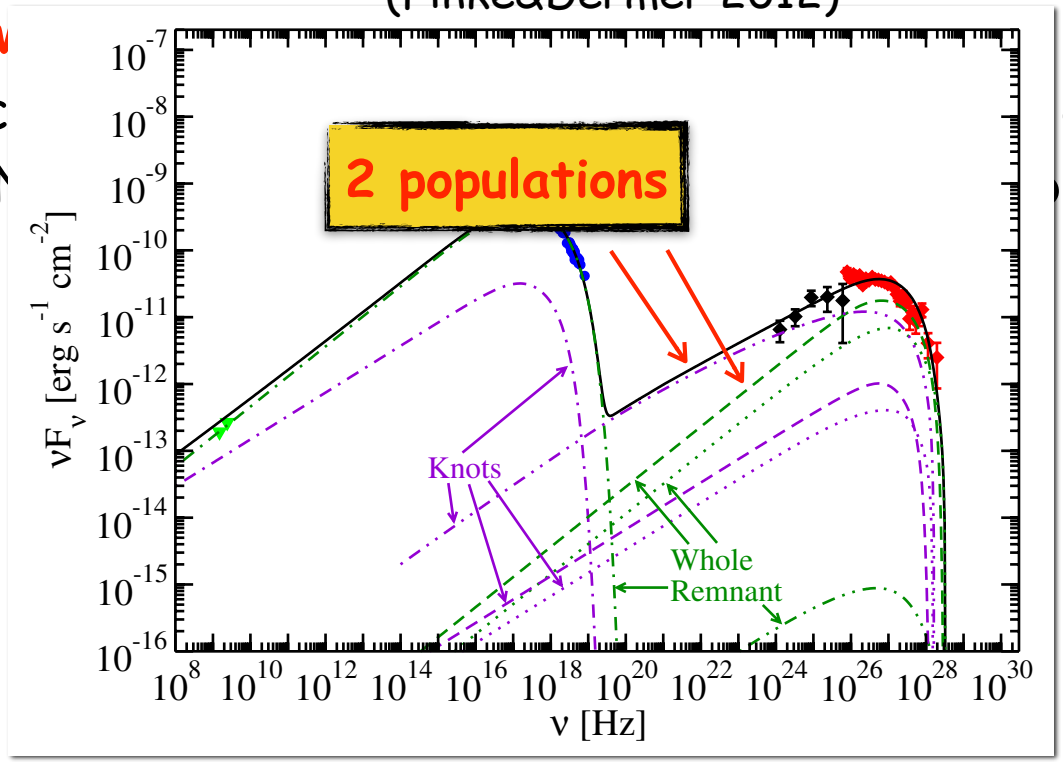


one-zone IC model

RXJ1713: difficulties of one-zone leptonic models

(Finke&Dermer 2012)



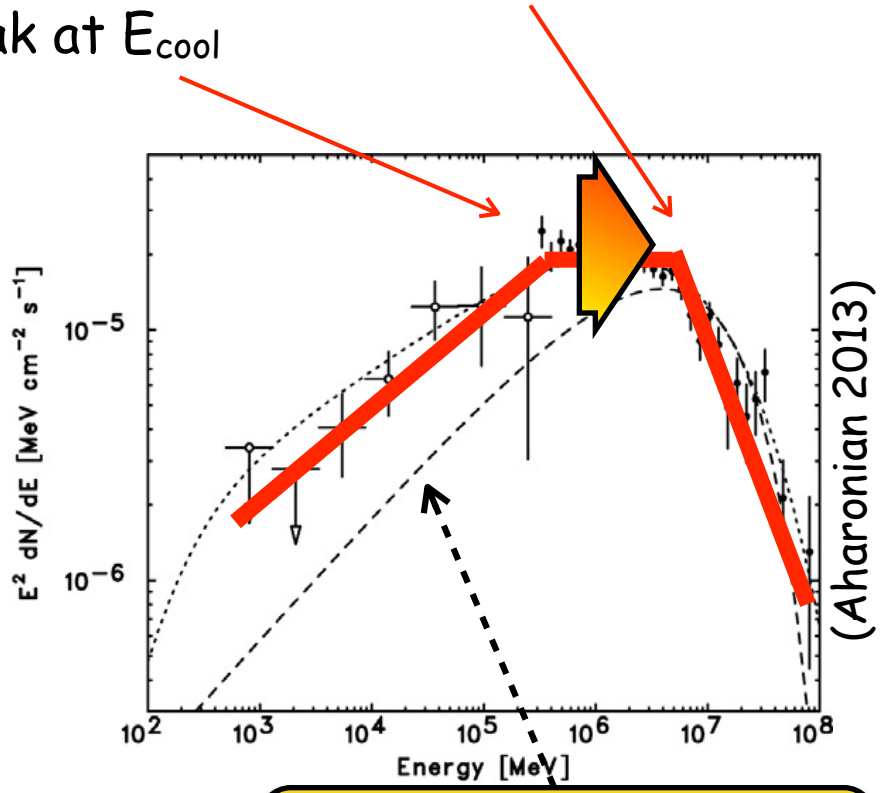
tw

ac

SN

acceleration cutoff at E_{max}

break at E_{cool}



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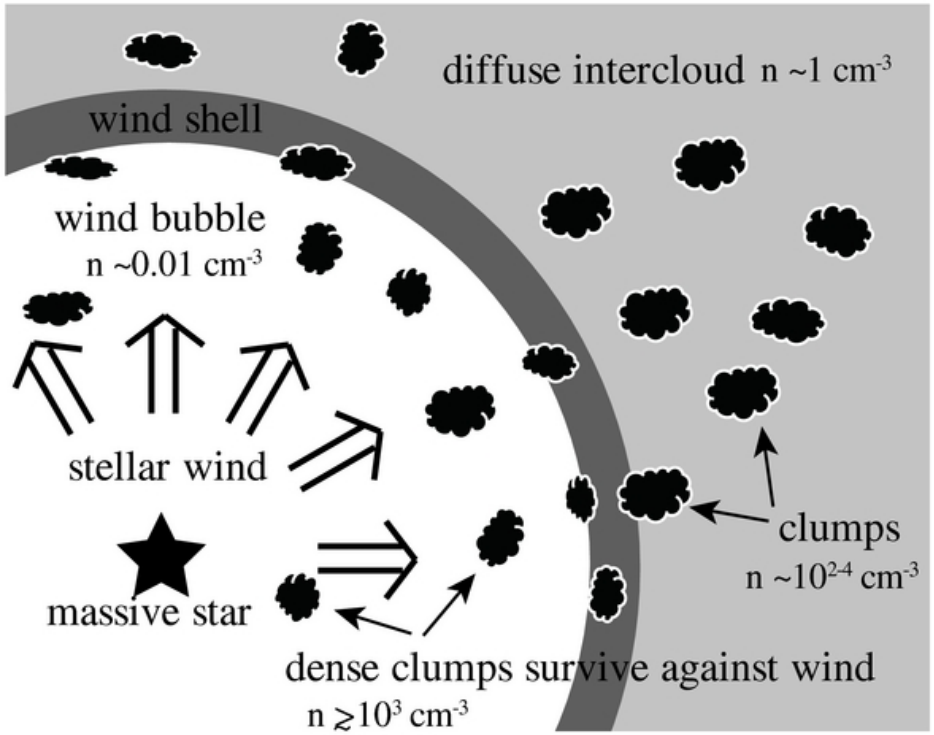
one-zone IC model

A hadronic model for RXJ1713

(Zirakashvili & Aharonian 2010, Inoue et al. 2012, Gabici & Aharonian 2014)

SNR in a dense (and clumpy!) environment



stellar wind sweeps the gas and creates a cavity

dense clumps survive [unshocked -> $u_c \sim u_s (n_h/n_c)^{1/2}$] both the stellar wind and the SNR shock

no thermal X-rays!

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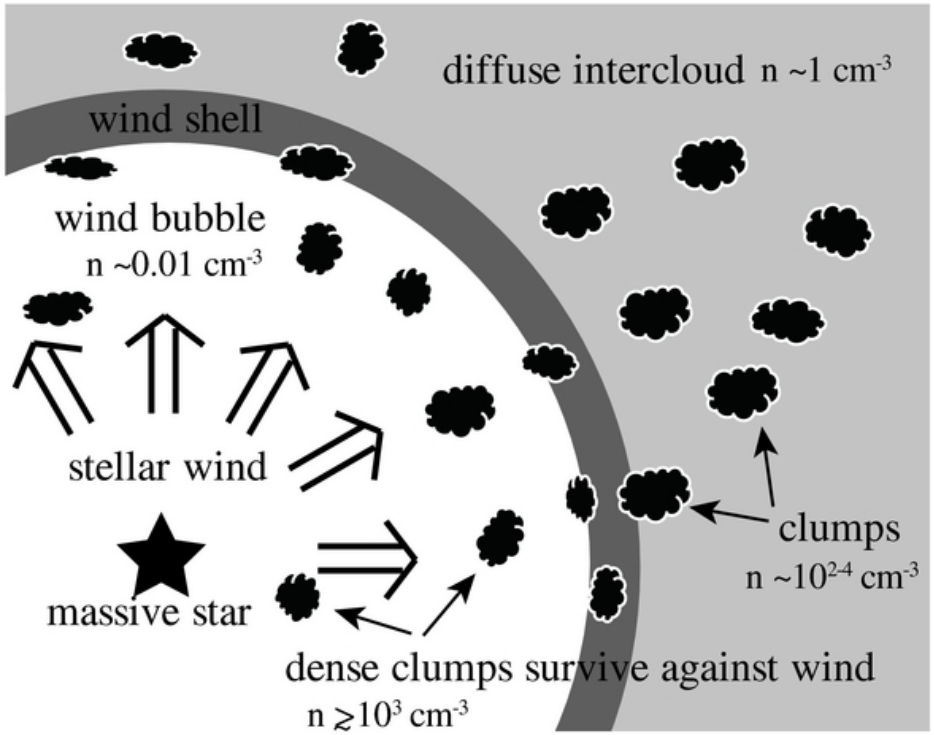

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high energy CRs penetrate

low energy CRs don't

clumps!

sub-parsec

Requirements

Inoue et al. 2012, Gabici & Aharonian 2014

- mass in clumps >> mass in diffuse hot gas
- sub-pc scale clumps, density ~10^3 cm^{-3}
- hot tenuous medium in the bubble n~10^{-2} cm^{-3}
- turbulent layer between clumps and hot medium

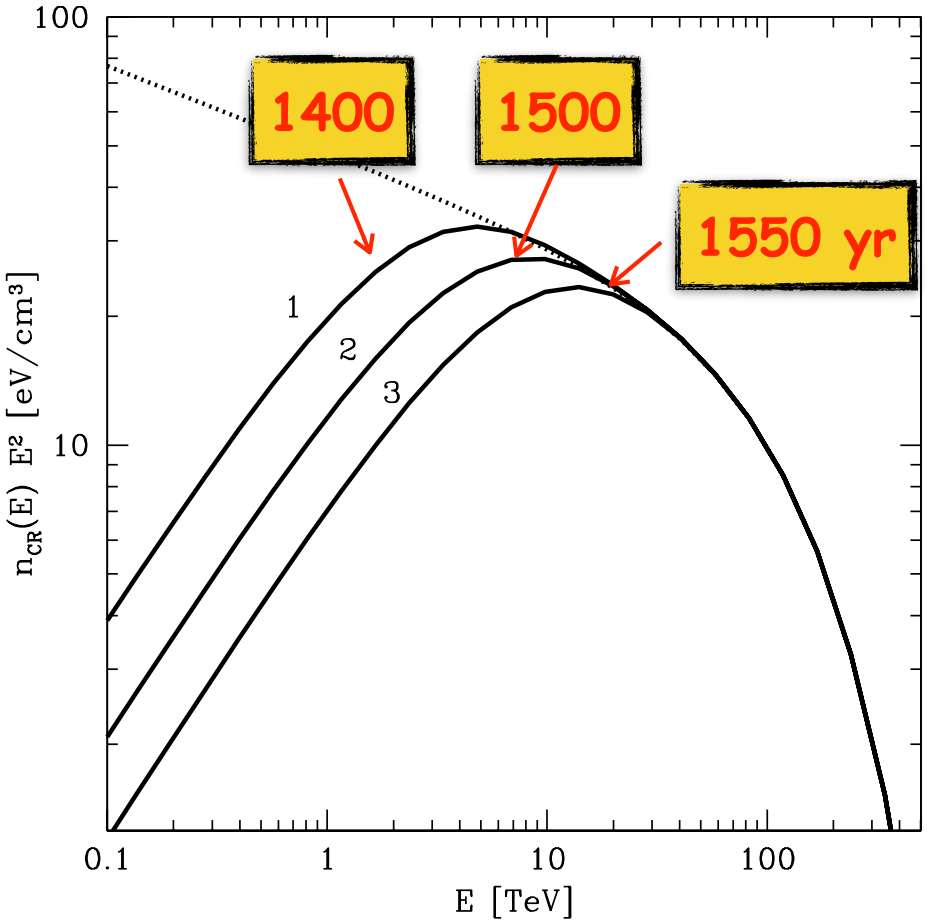
(~0.05 pc) with B~100 microGauss

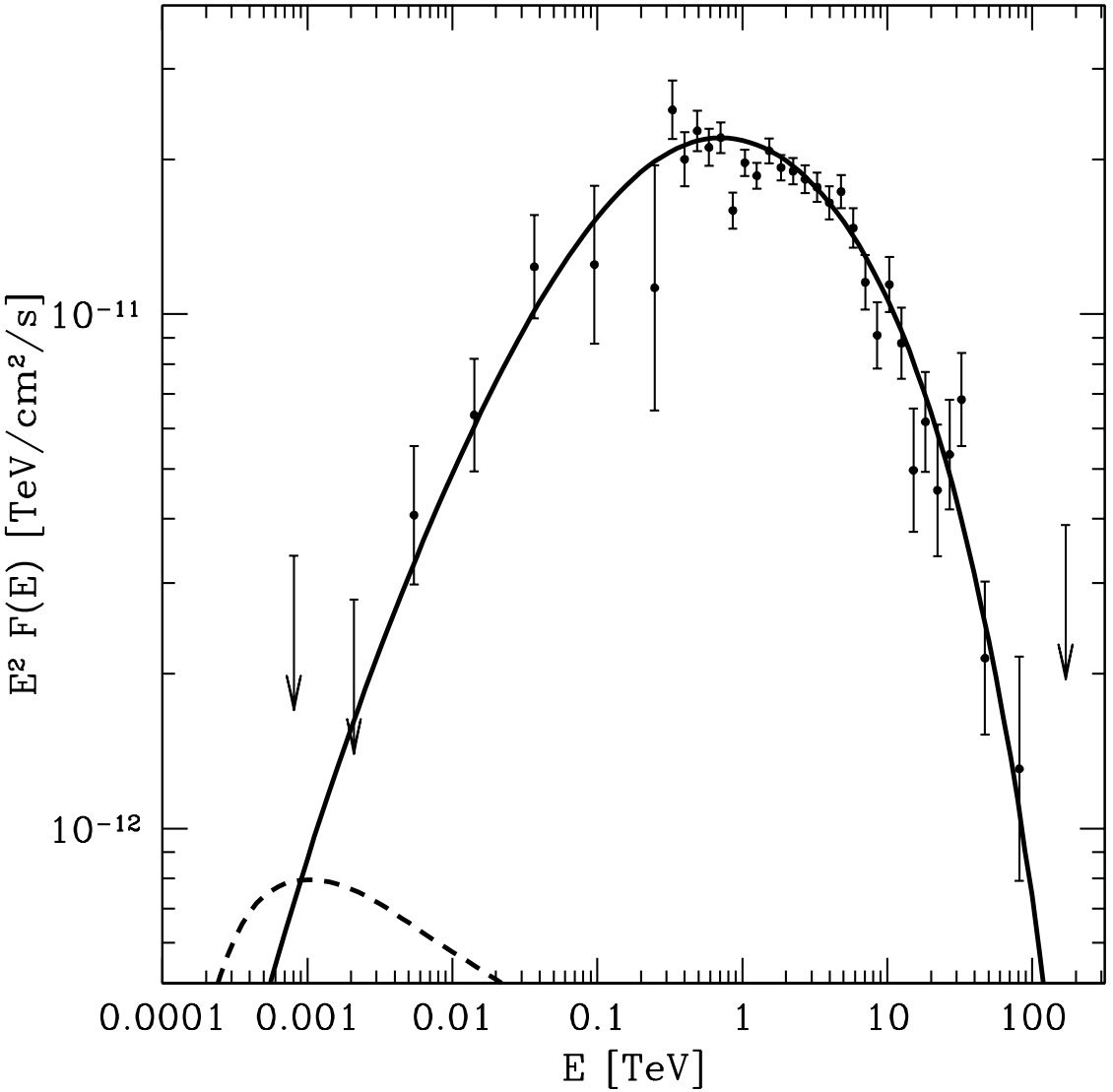
- Bohm diffusion coefficient

A hadronic model for RXJ1713

Gabici & Aharonian 2014

age -> ~1620 yr





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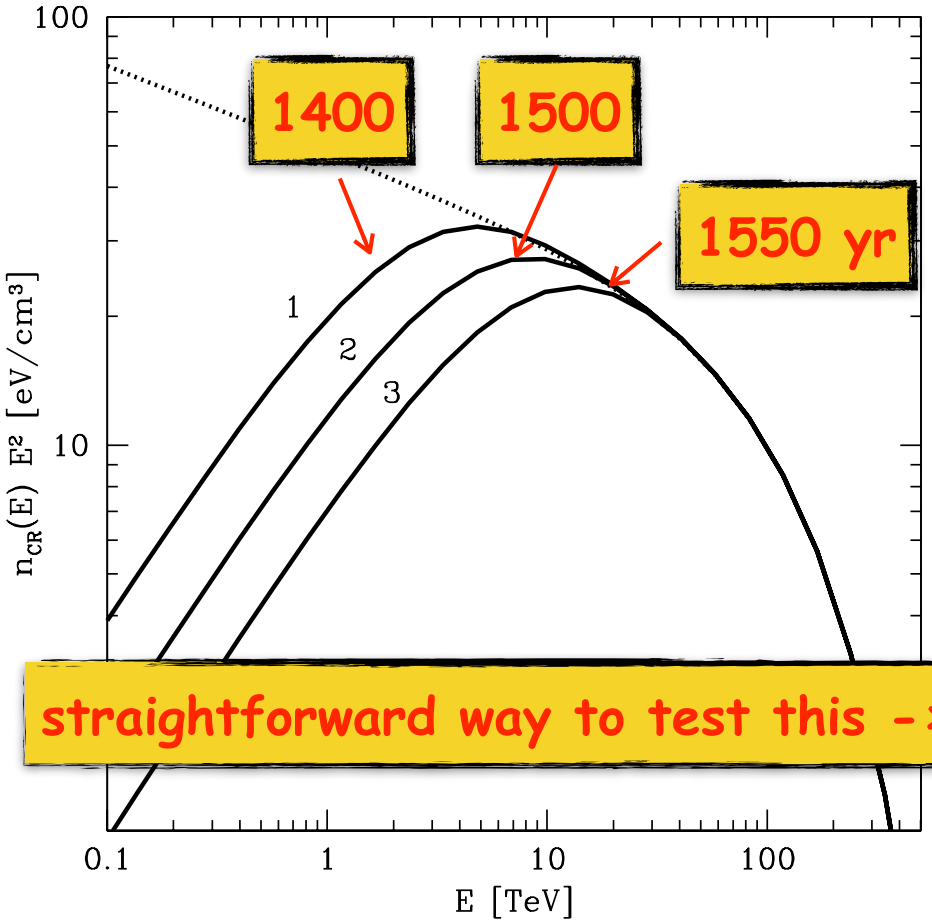
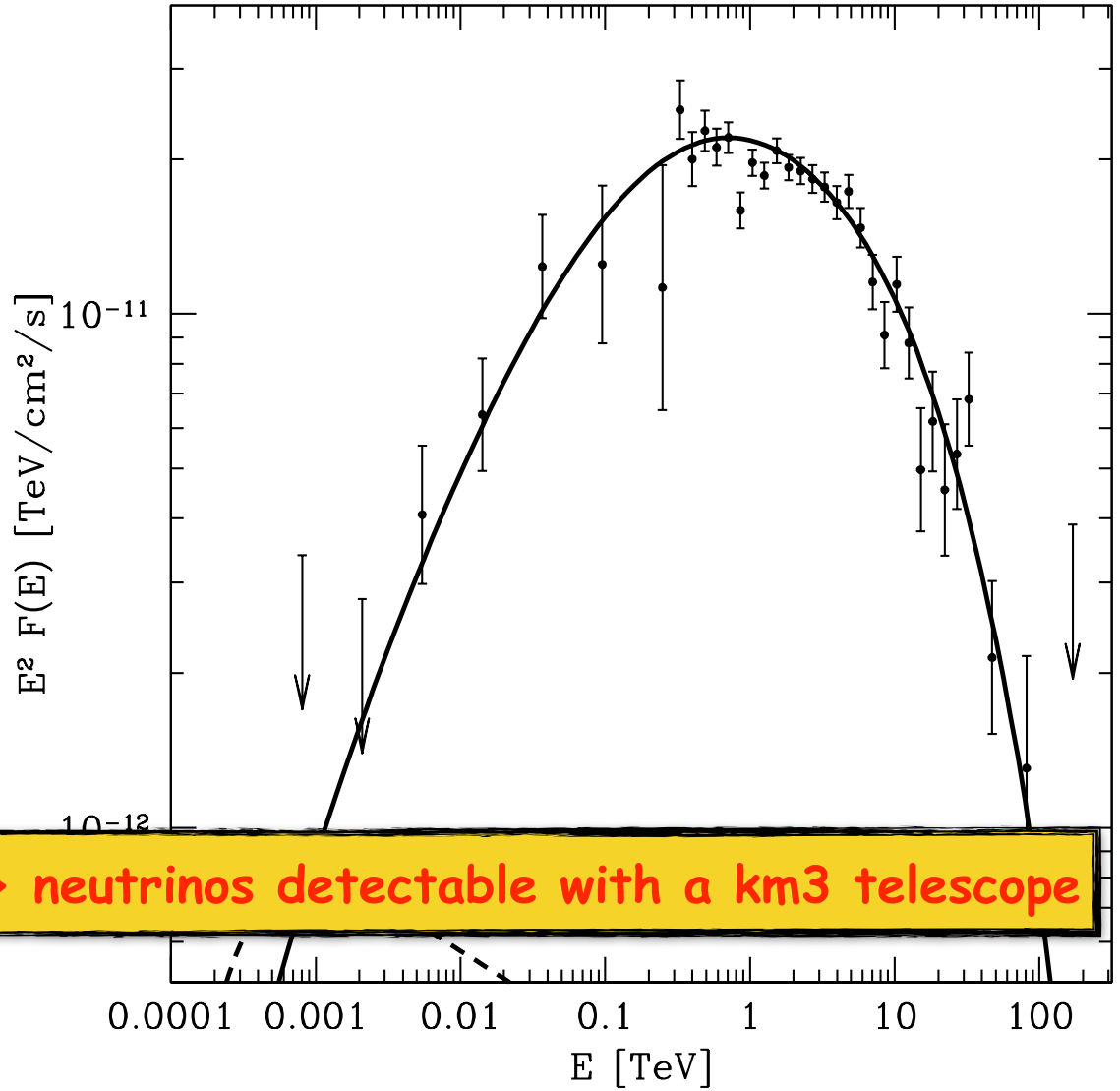
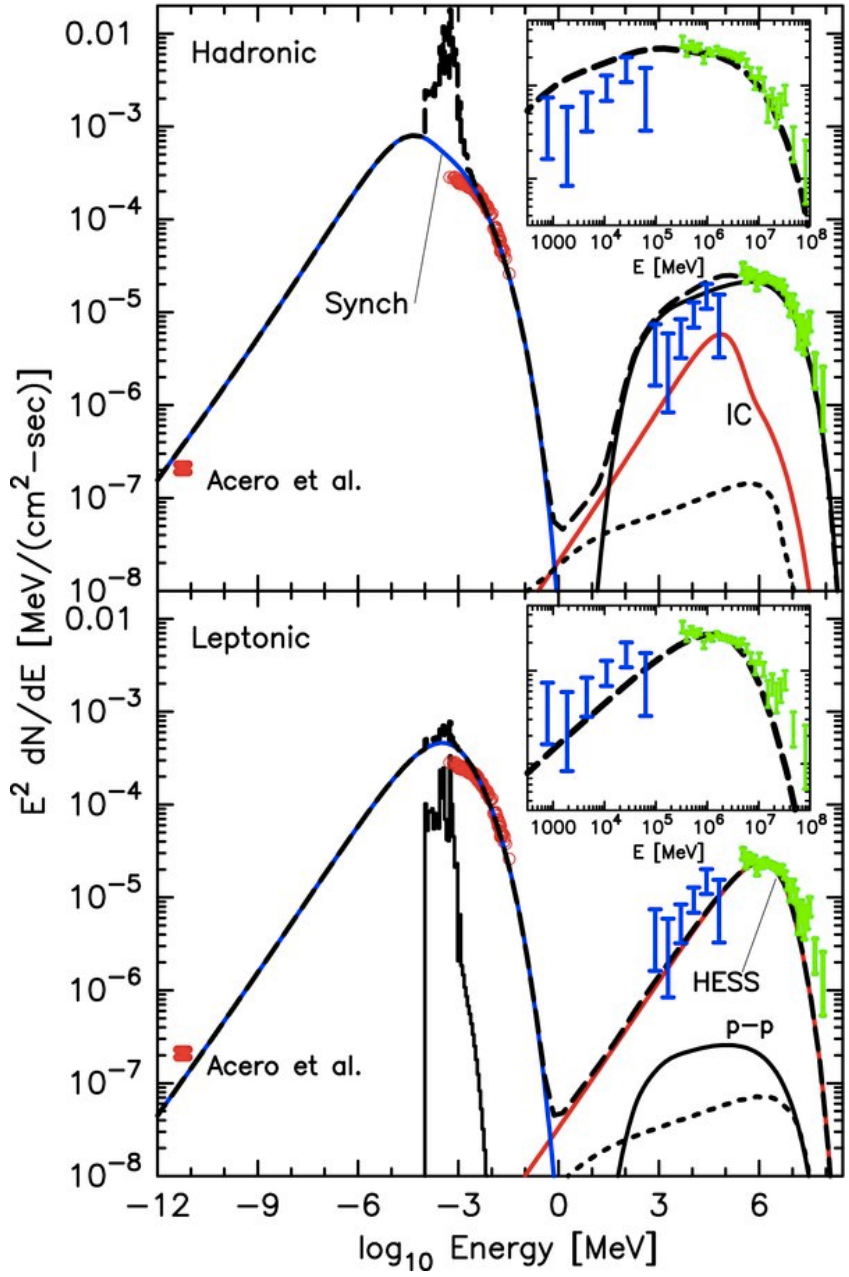




straightforward way to test this -> neutrinos detectable with a km3 telescope

Hadronic or leptonic?

(Ellison et al 2010)



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