# Galactic gamma-ray astronomy and cosmic ray origin

Stefano Gabici
APC, Paris

# Overview of the talk

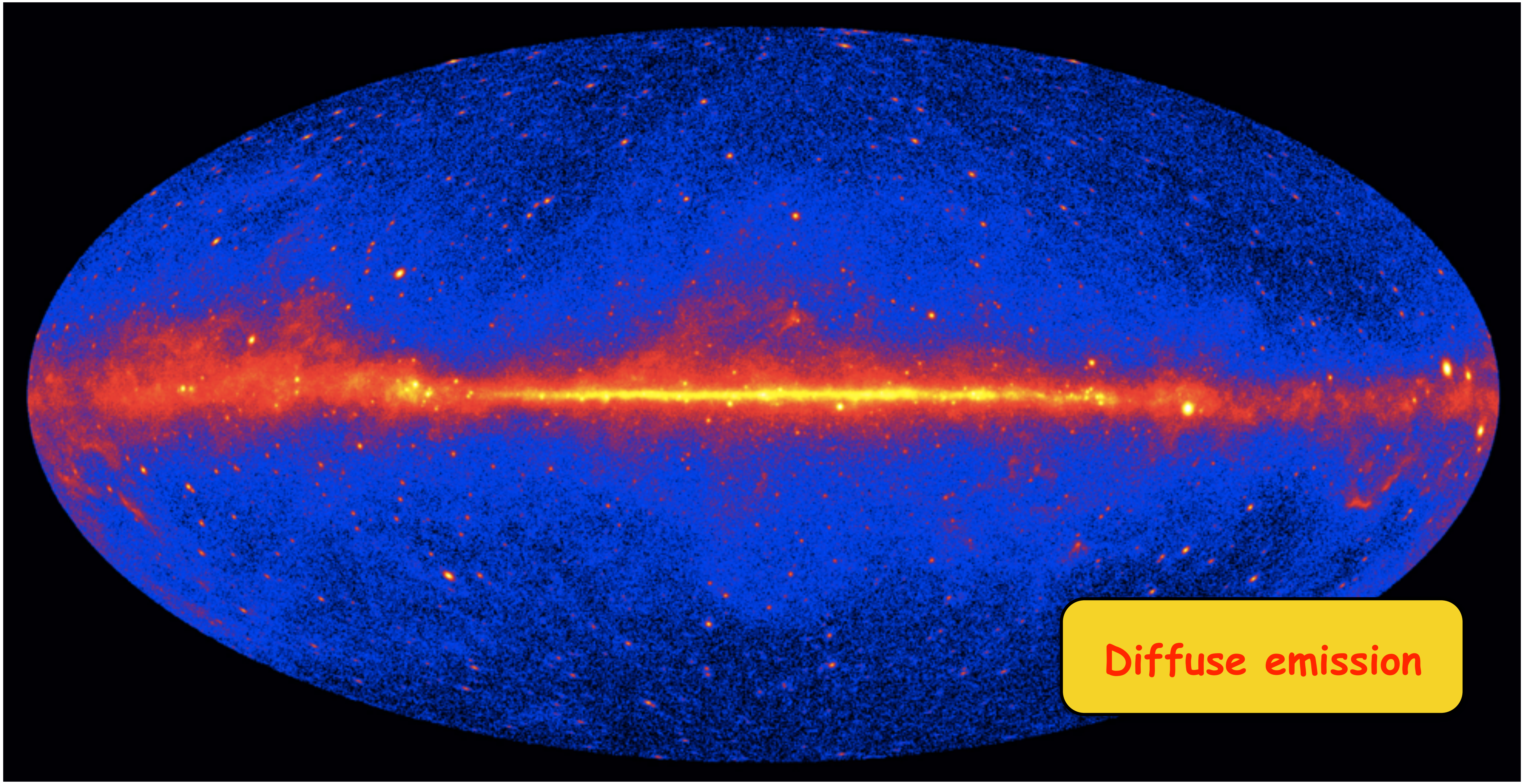
- The GeV and TeV sky look much different
- The link between gamma-ray astronomy and cosmic rays
- SuperNova Remnants in gamma rays:hadronic or leptonic?
- Hadronic/leptonic signatures 1 - the pion bump
- Hadronic/leptonic signatures 2 - the spectral shape(?)
- Hadronic/leptonic signatures 3 - gamma/gas correlations
- Hadronic/leptonic signatures 4 - the multi-TeV domain
- Gamma-ray based tests for the origin of cosmic rays
- What's next? CTA, HAWC, HiScore, LHAASO ...

# Overview of the talk

- The GeV and TeV sky look much different
- The link between gamma-ray astronomy and cosmic rays
- SuperNova Remnants in gamma rays:hadronic or leptonic?
- Hadronic/leptonic signatures 1 - the pion bump
- Hadronic/leptonic signatures 2 - the spectral shape(?)
- Hadronic/leptonic signatures 3 - gamma/gas correlations
- Hadronic/leptonic signatures 4 - the multi-TeV domain
- Gamma-ray based tests for the origin of cosmic rays
- What's next? CTA, HAWC, HiScore, LHAASO ...

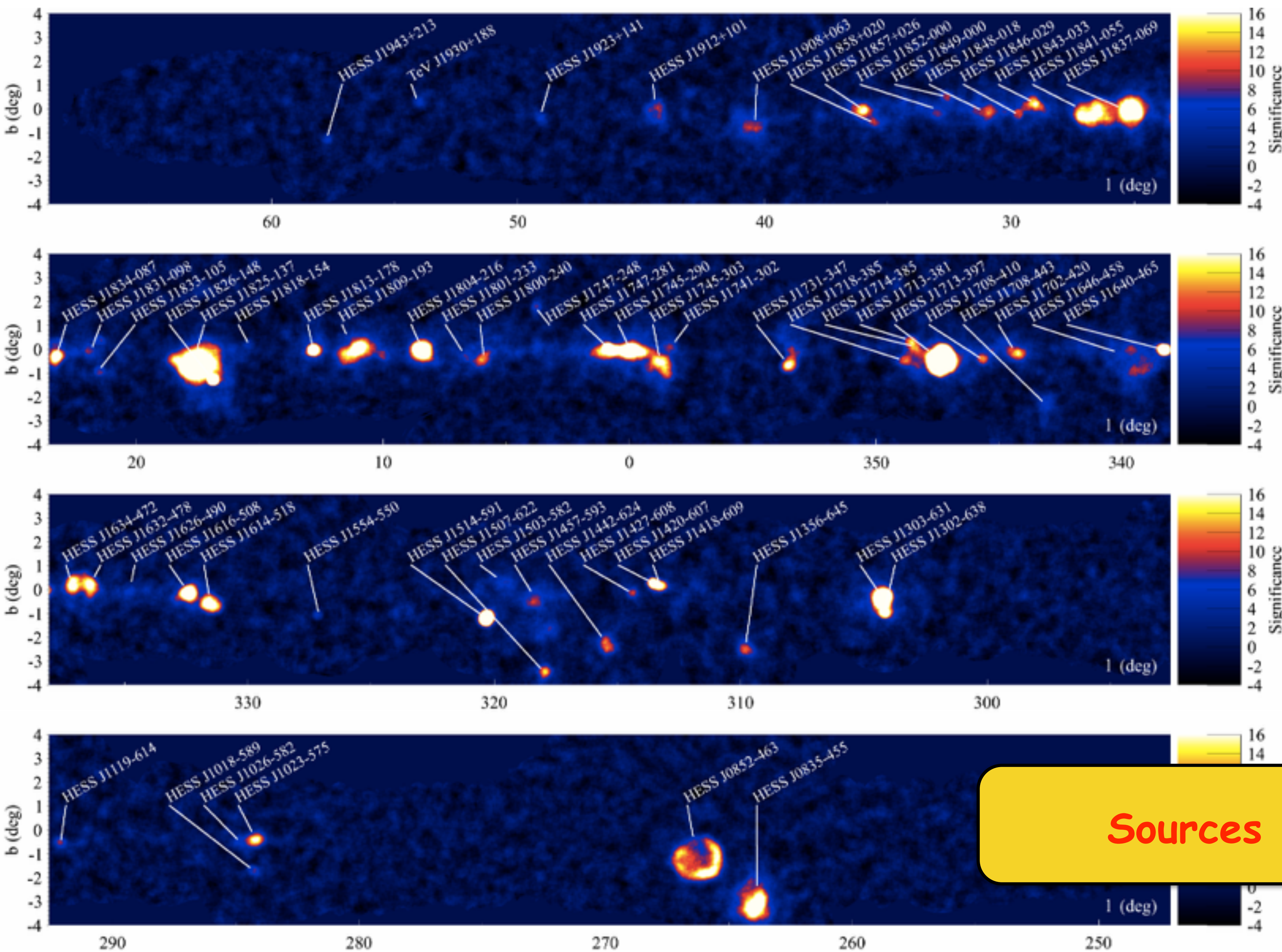
# The gamma-ray sky: GeV domain

## The FERMI sky



# The gamma-ray sky: TeV domain

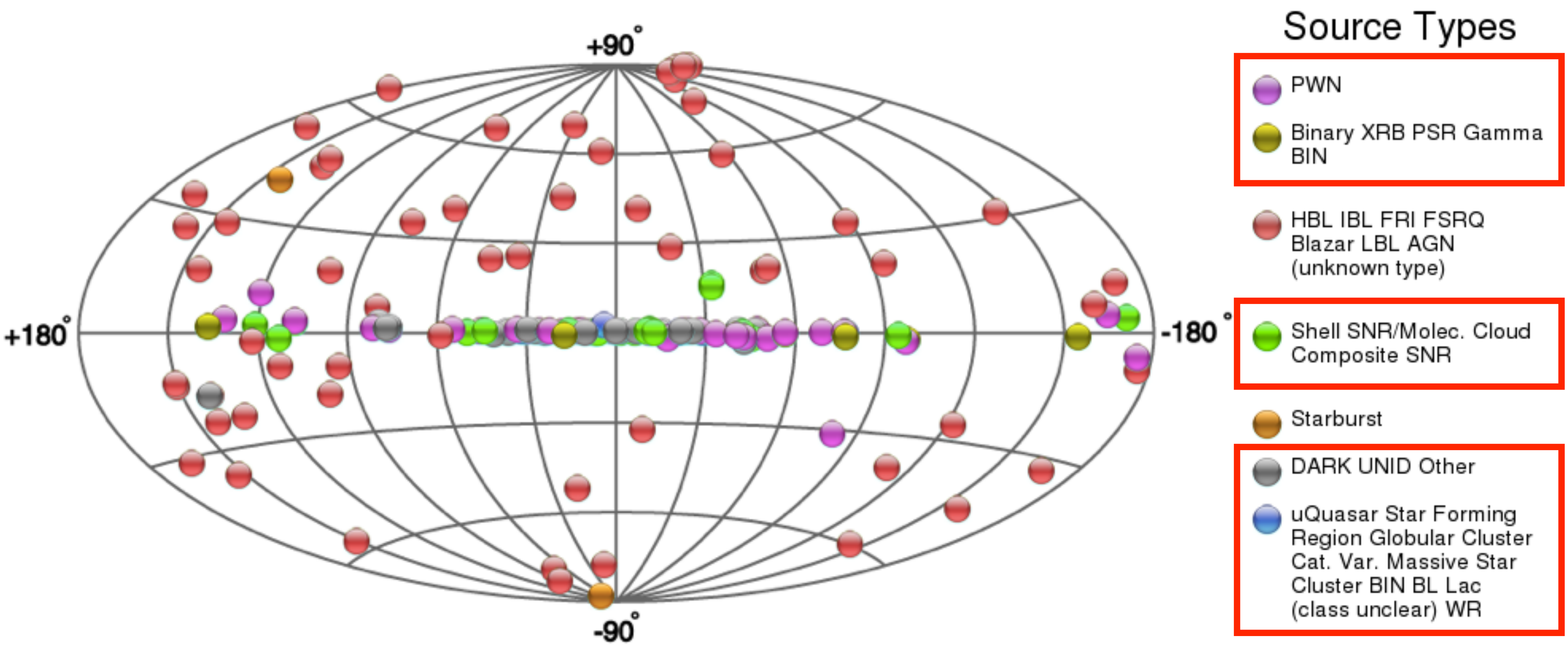
## The HESS survey of the Galactic plane




Sources

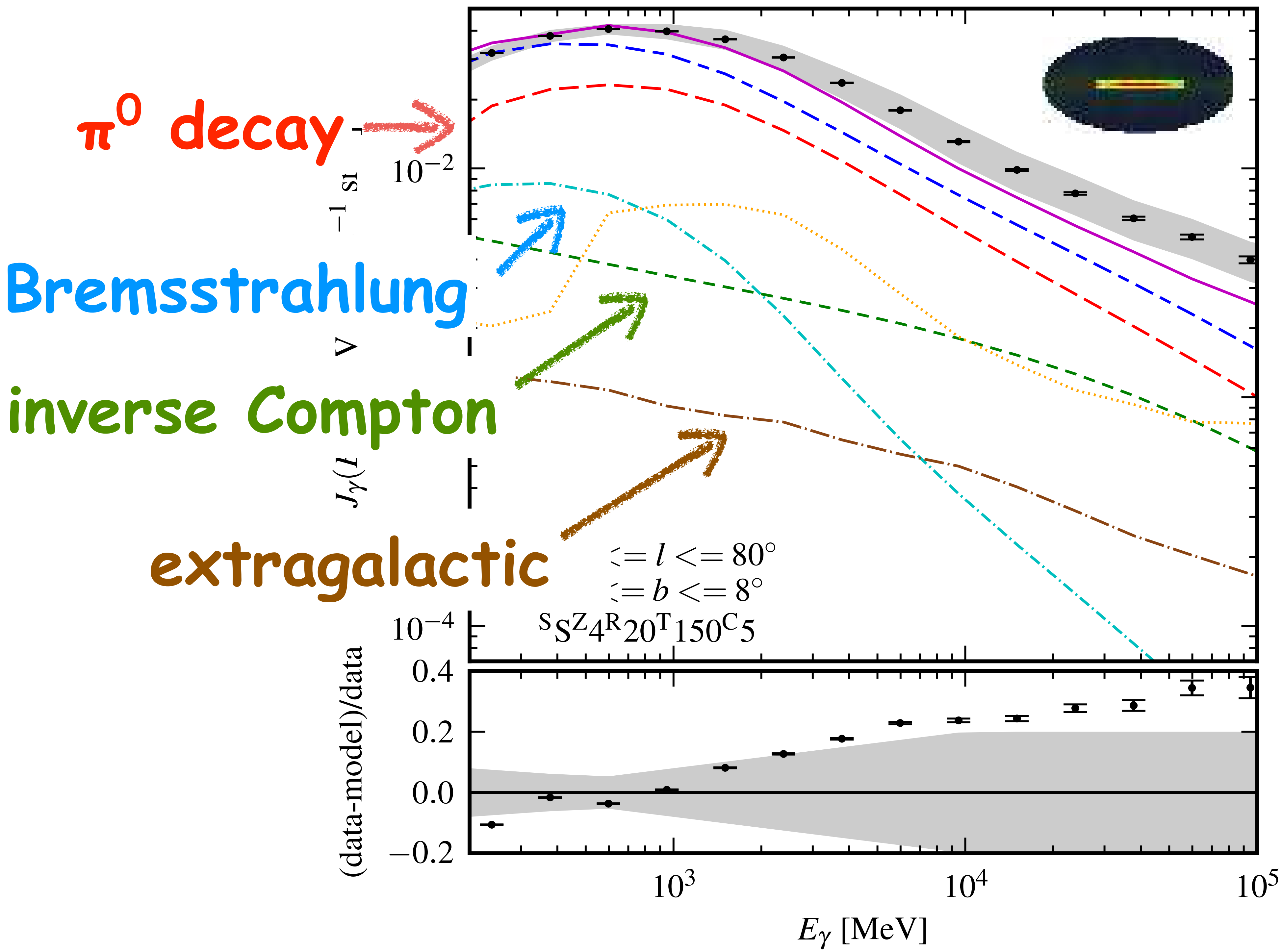
# The gamma-ray sky: TeV domain

## Many types of sources



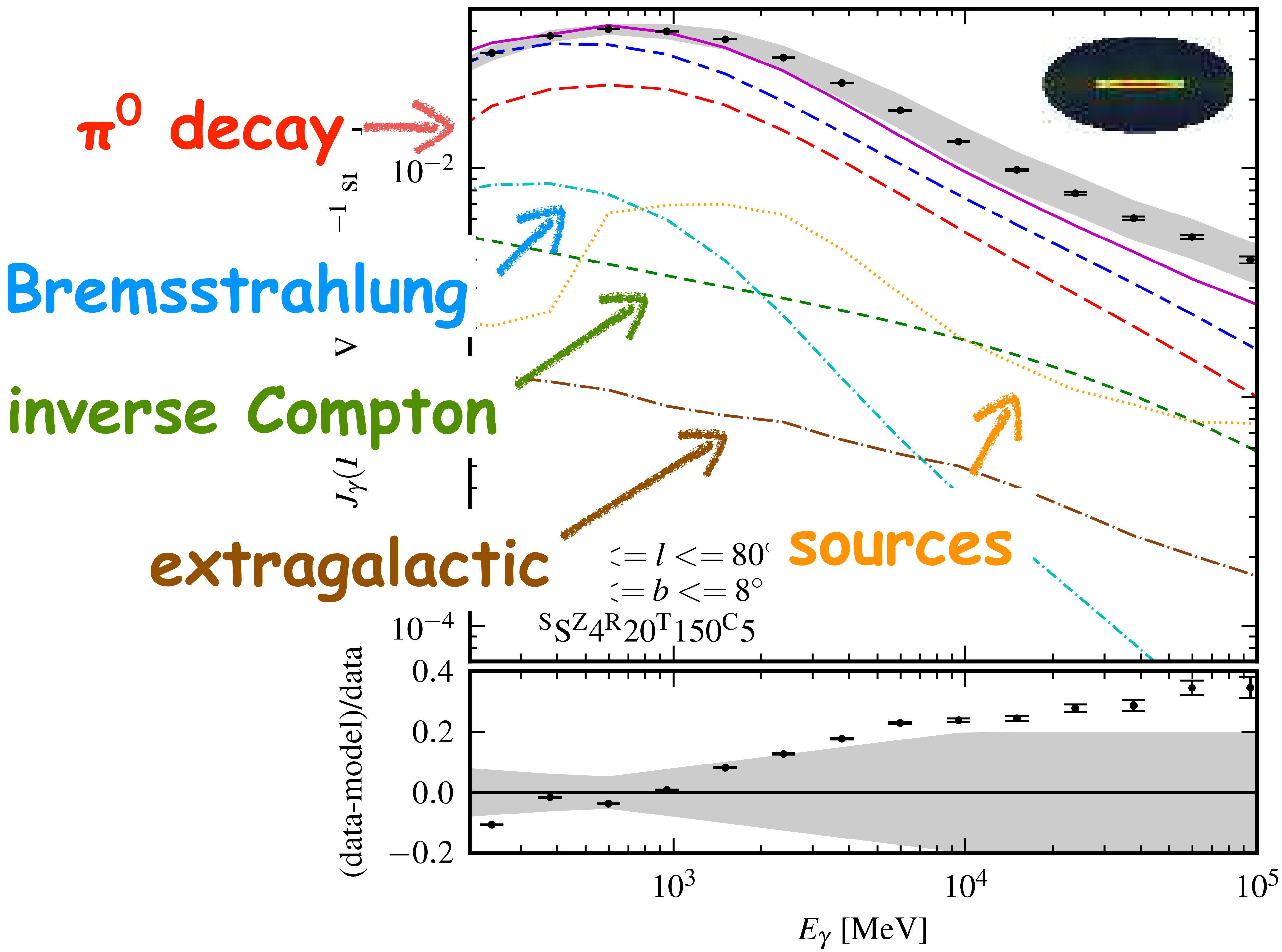

source: TeVCAT

# Diffuse emission versus sources: spectra



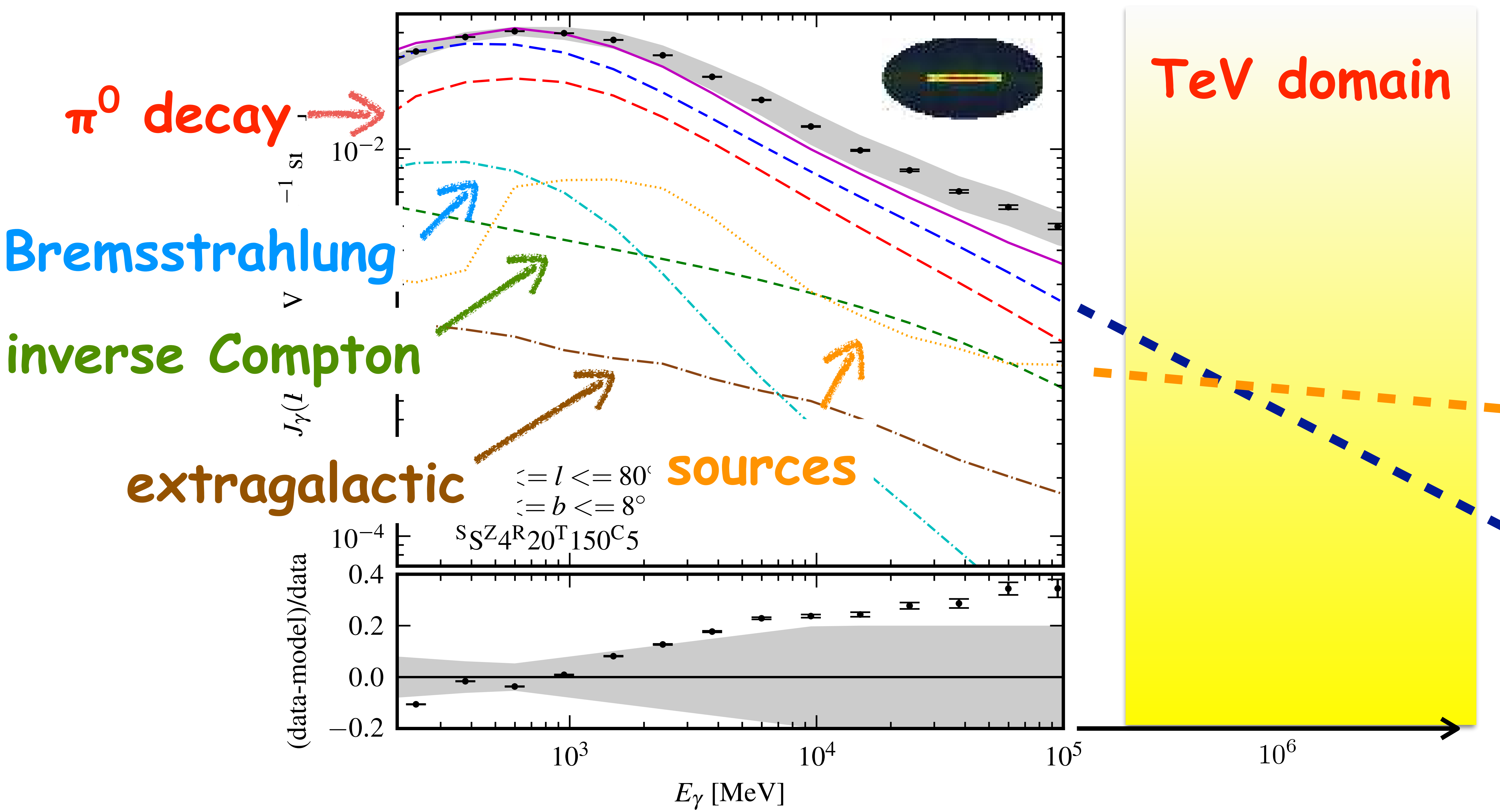

Fermi Collaboration 2012

# Diffuse emission versus sources: spectra




Fermi Collaboration 2012

# Diffuse emission versus sources: spectra

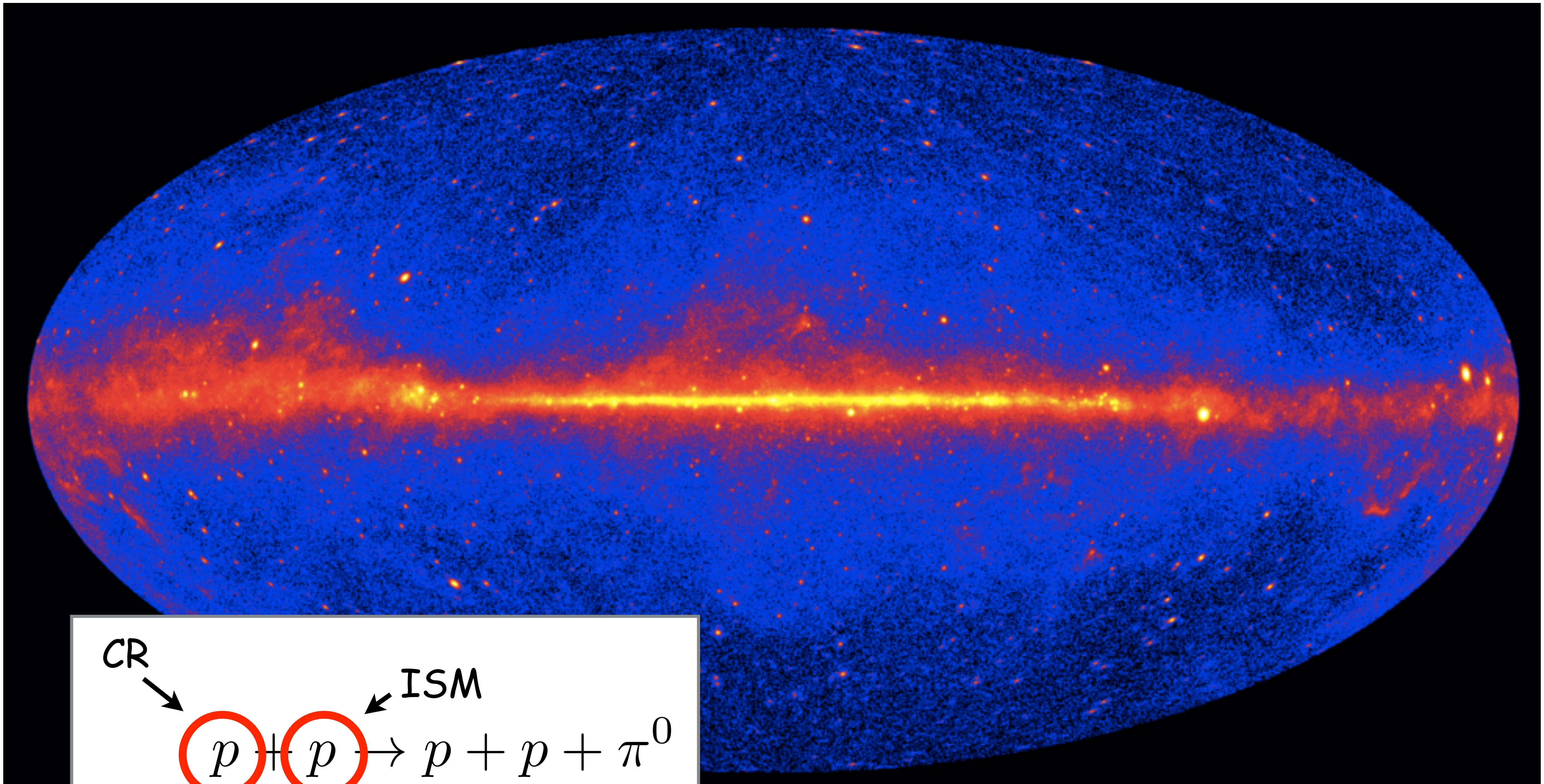



Fermi Collaboration 2012

# Overview of the talk

- The GeV and TeV sky look much different
- The link between gamma-ray astronomy and cosmic rays
- SuperNova Remnants in gamma rays:hadronic or leptonic?
- Hadronic/leptonic signatures 1 - the pion bump
- Hadronic/leptonic signatures 2 - the spectral shape(?)
- Hadronic/leptonic signatures 3 - gamma/gas correlations
- Hadronic/leptonic signatures 4 - the multi-TeV domain
- Gamma-ray based tests for the origin of cosmic rays
- What's next? CTA, HAWC, HiScore, LHAASO …

# Diffuse emission
# from cosmic rays interactions



CR

ISM

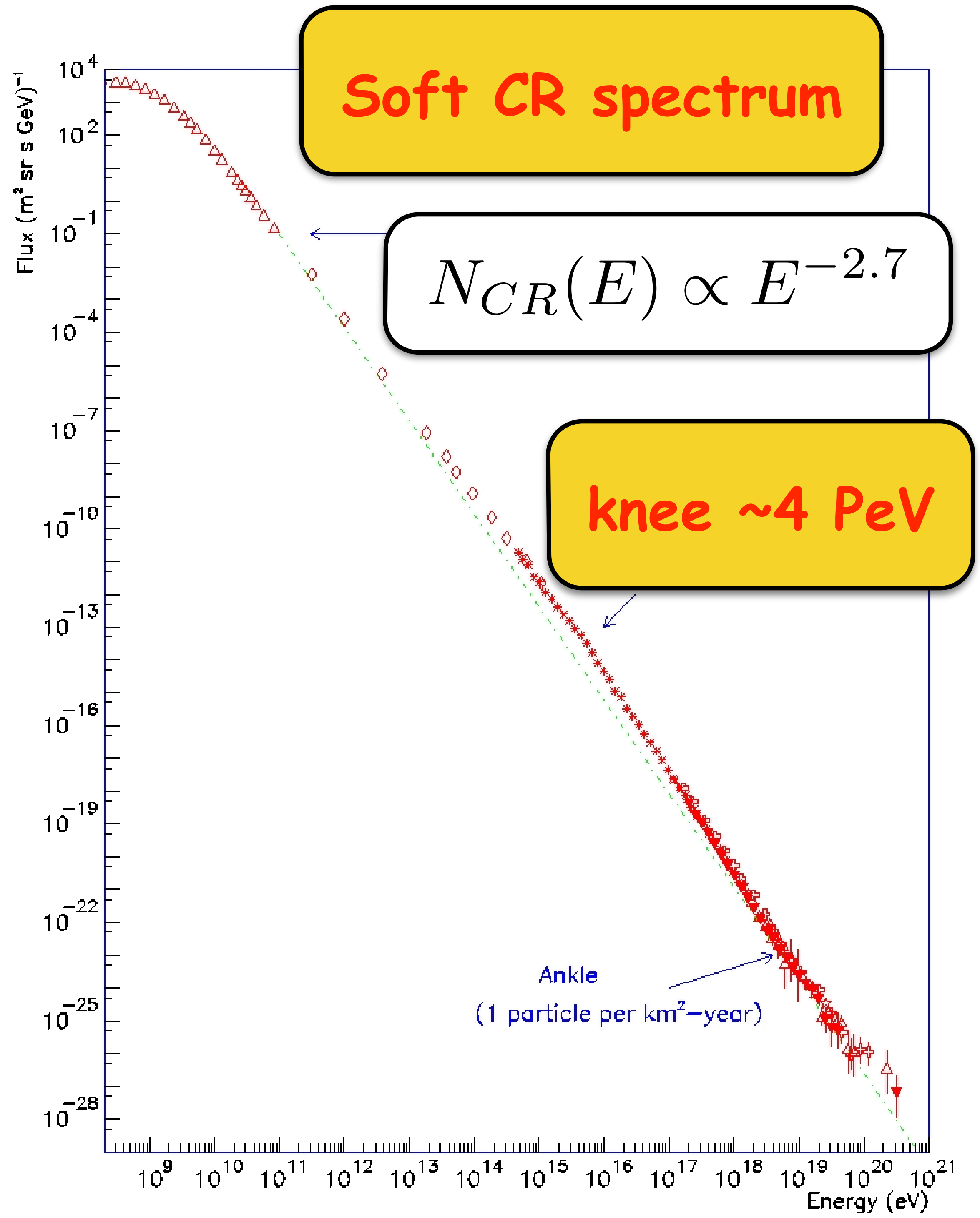
$$p + p \rightarrow p + p + \pi^0$$

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

predicted in the fifties! (Hayakawa 1952)

# The CR spectrum is steep, source spectra are hard

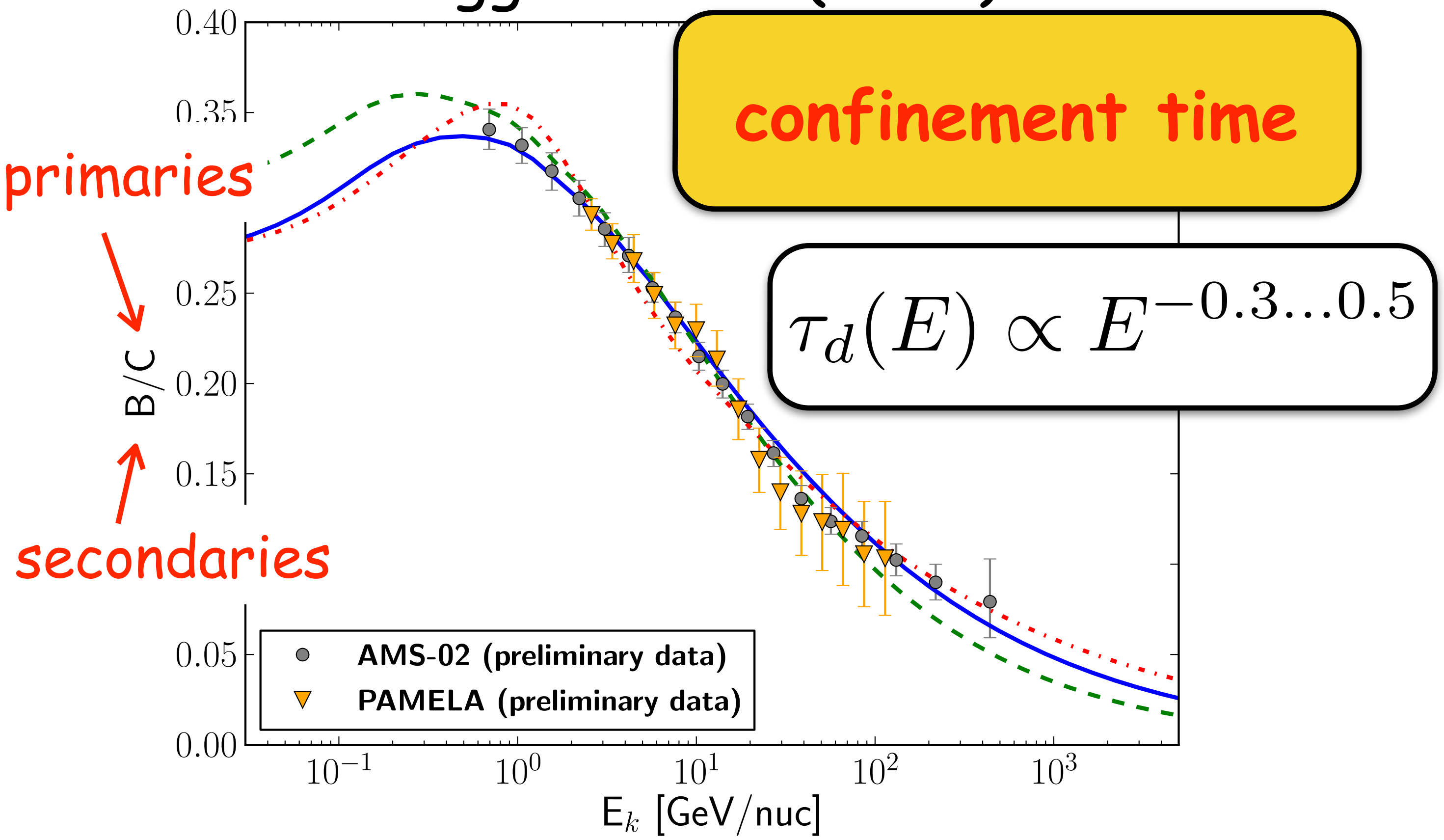
## Energy dependent escape from the Galaxy

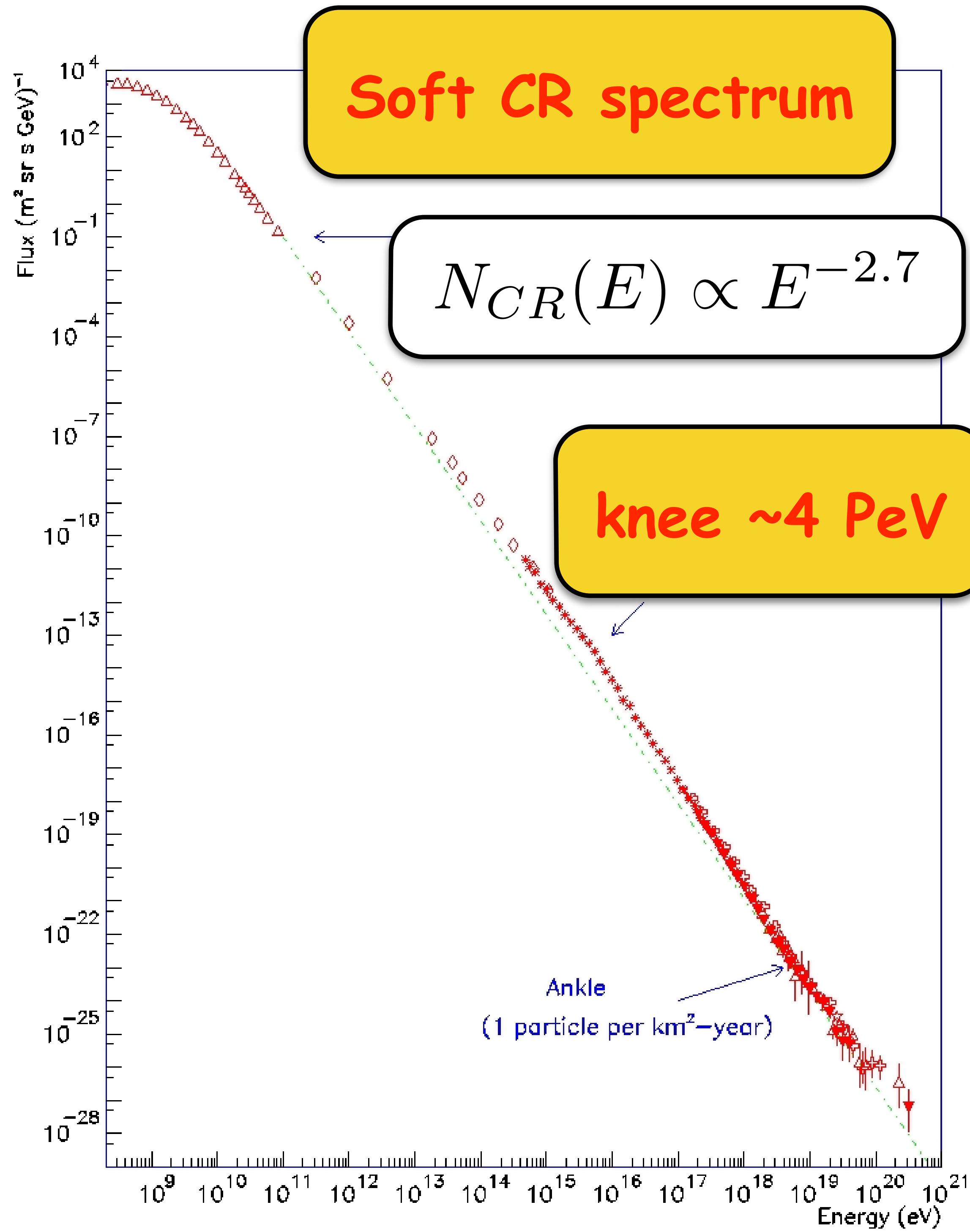


# The CR spectrum is steep, source spectra are hard

## Energy dependent escape from the Galaxy

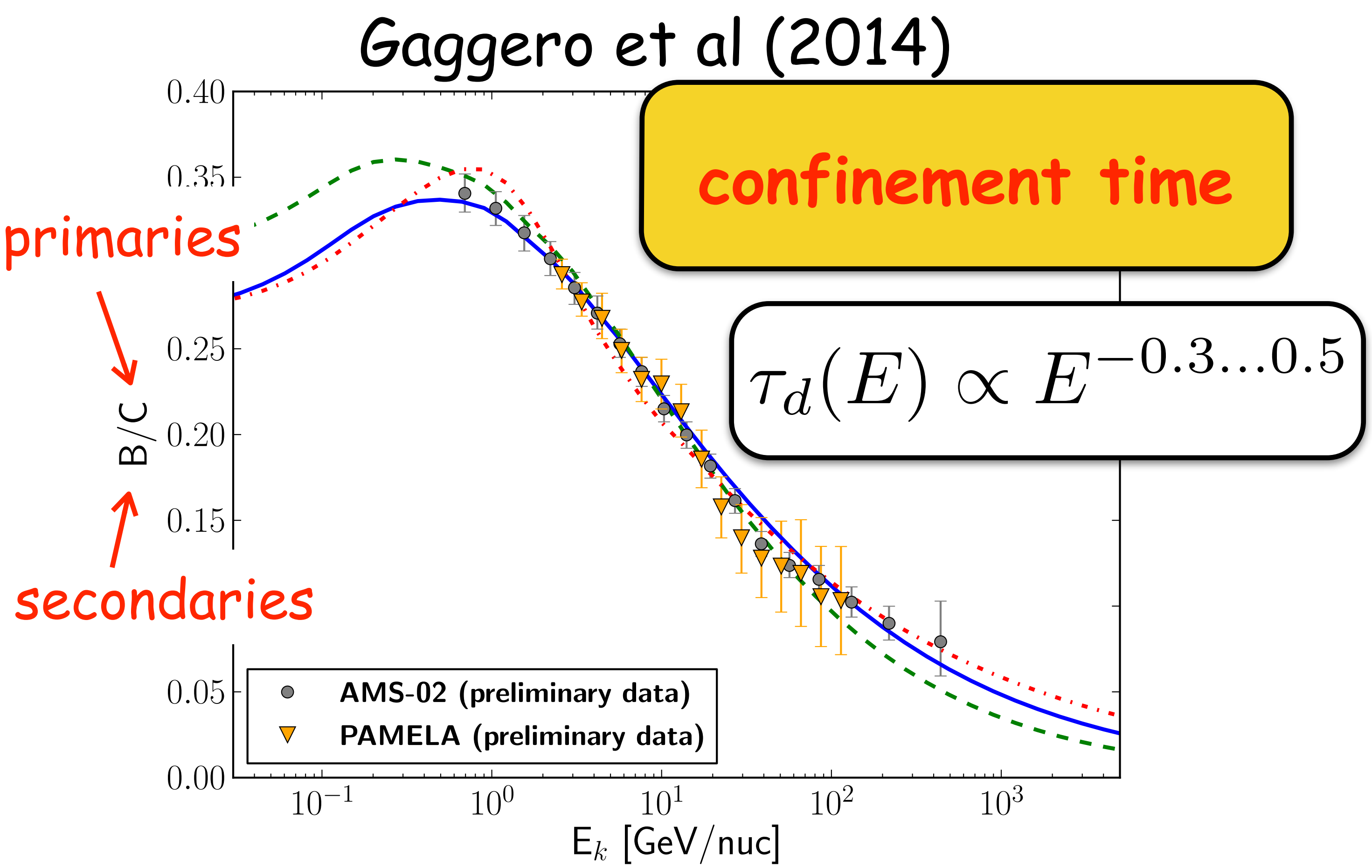
Gaggero et al (2014)

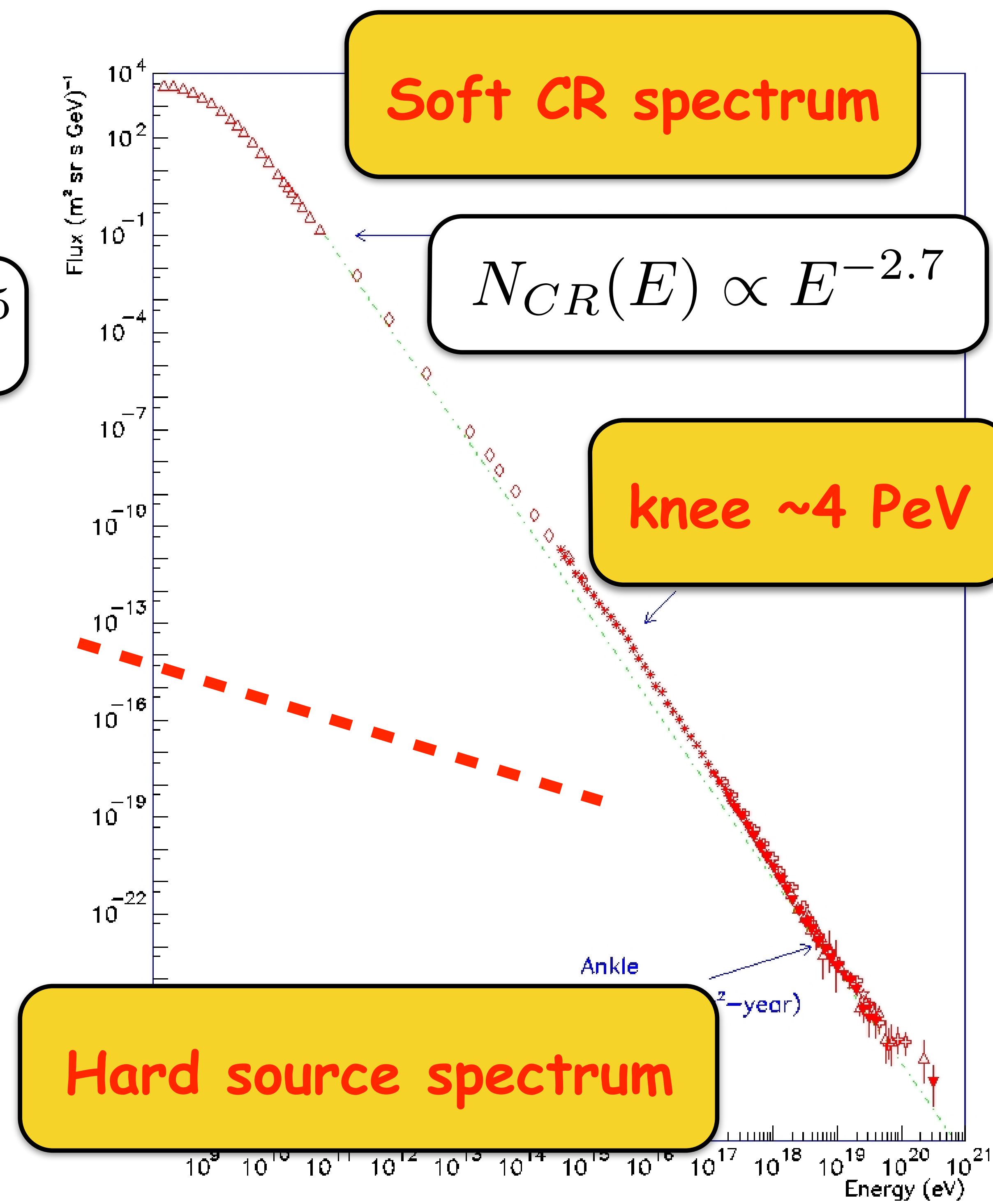


# The CR spectrum is steep, source spectra are hard

## Energy dependent escape from the Galaxy

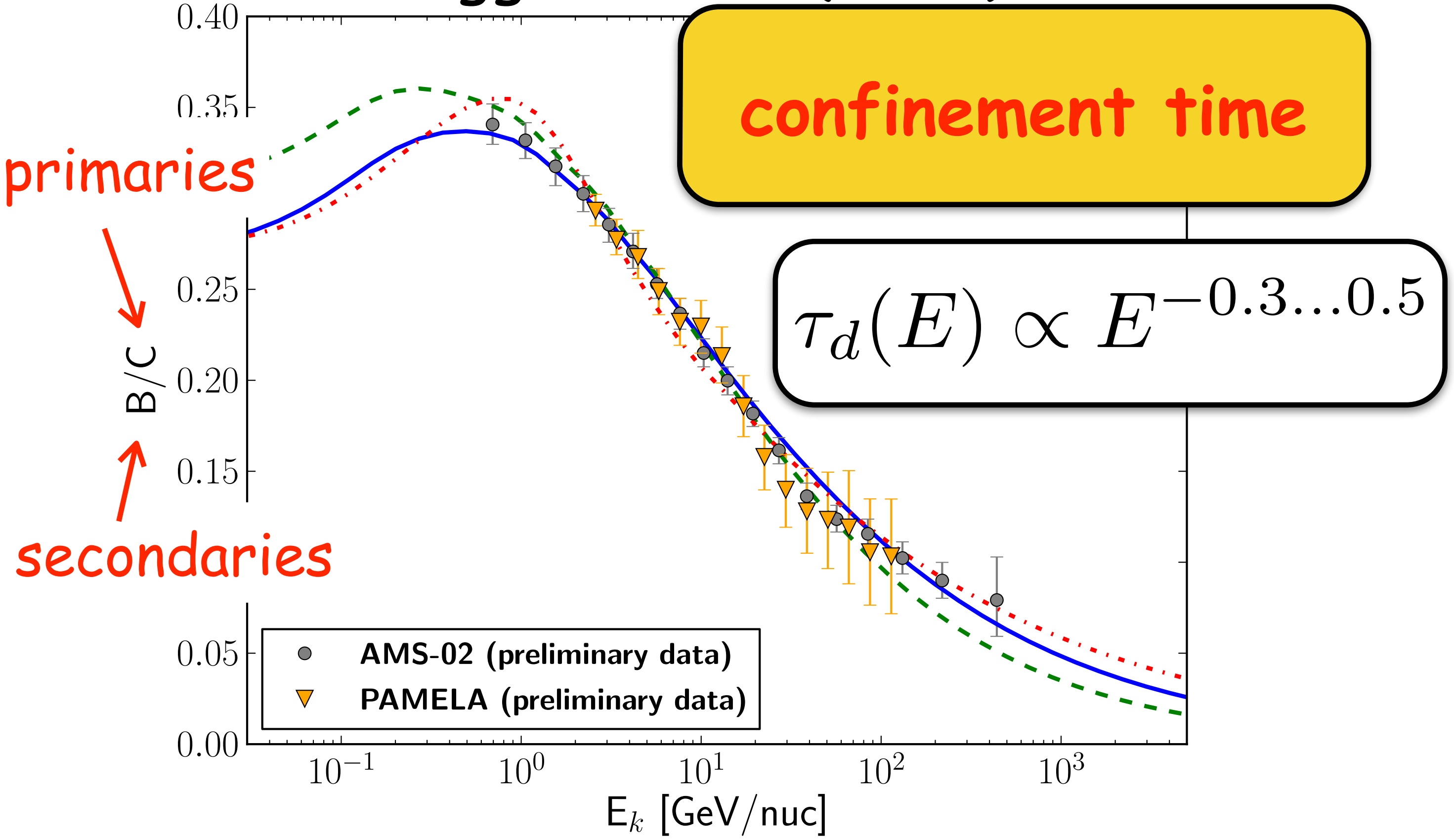


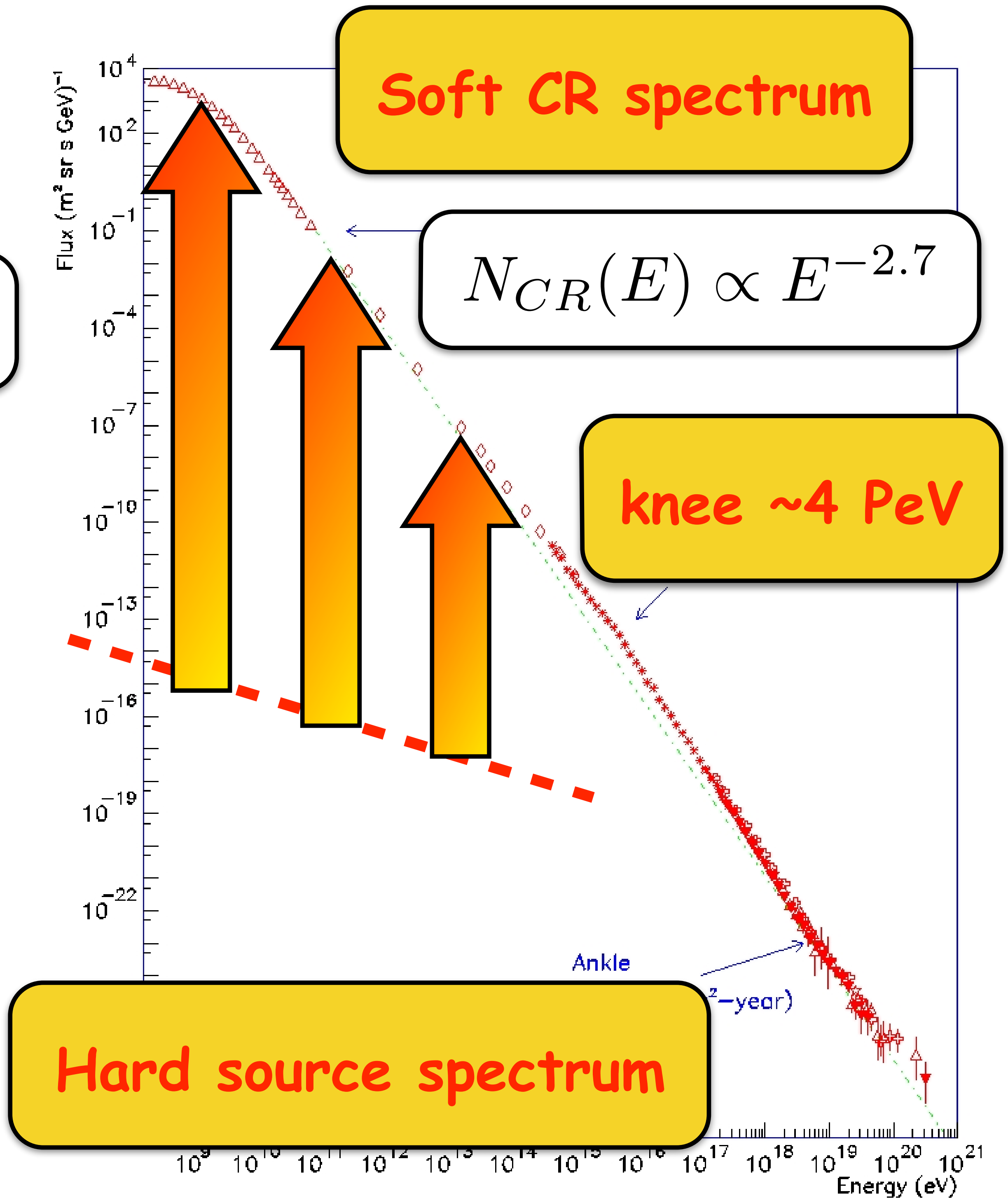



# The CR spectrum is steep, source spectra are hard

## Energy dependent escape from the Galaxy

Gaggero et al (2014)



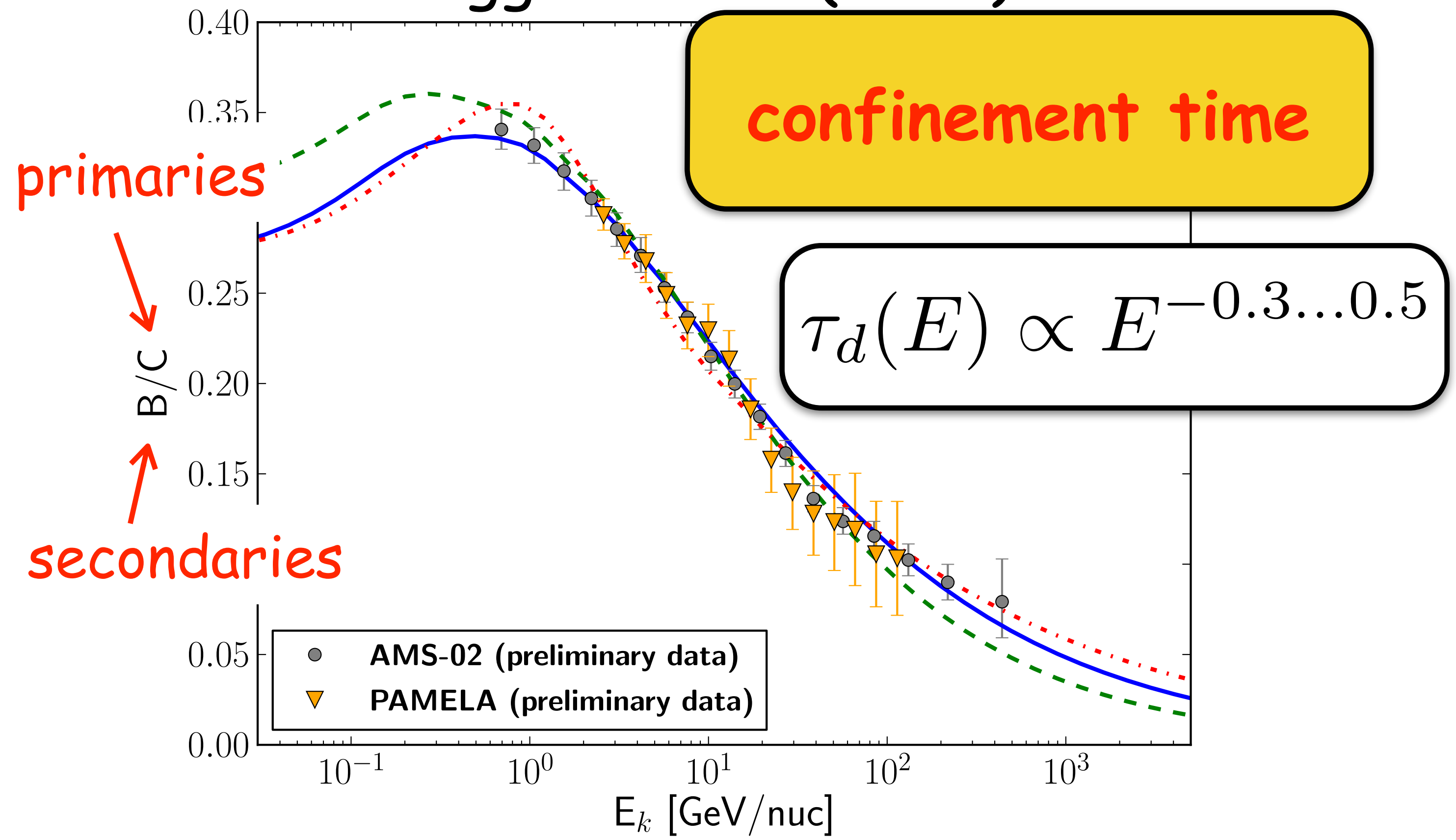



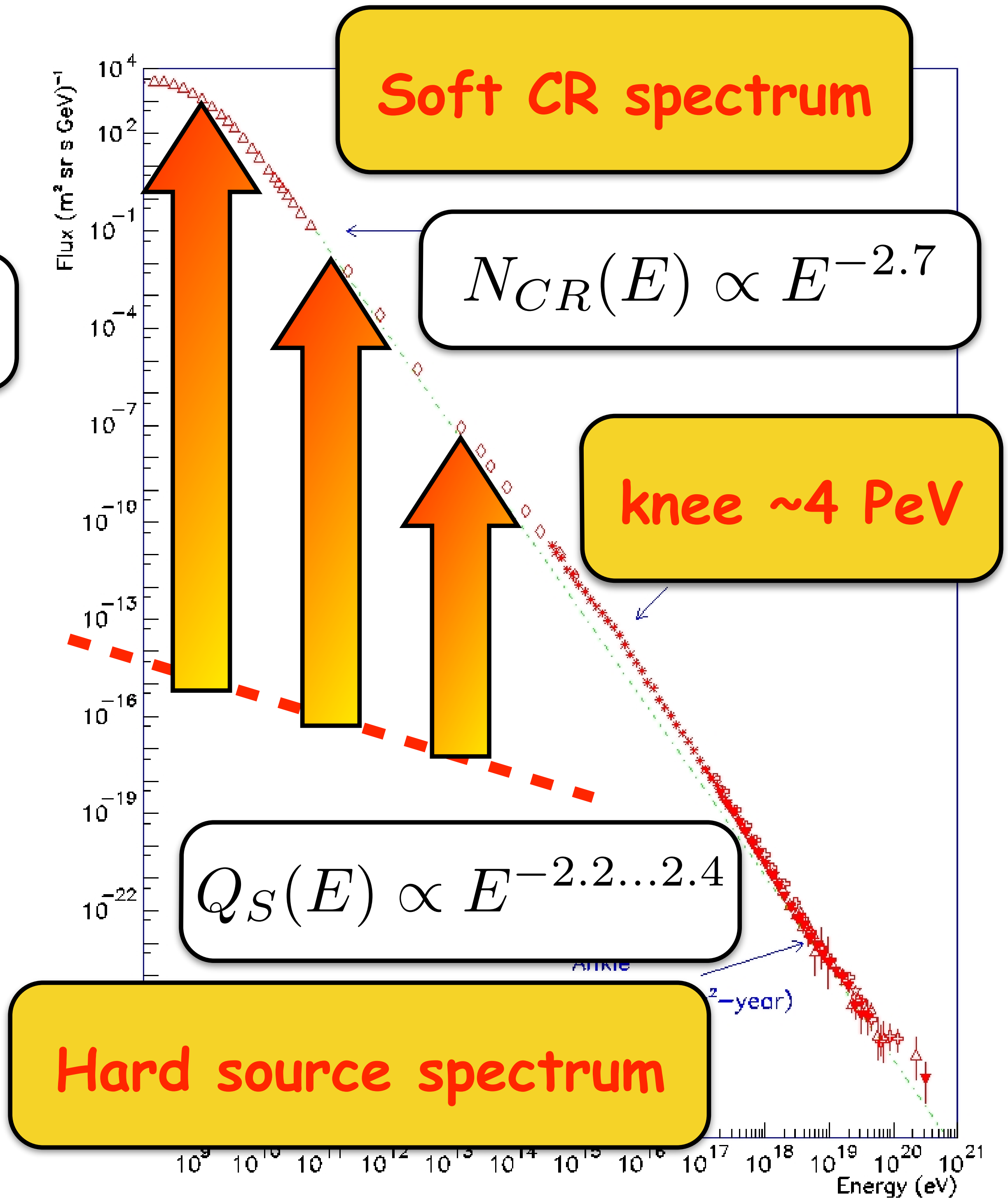

$$N_{CR}(E) = Q_S(E) \times \tau_d(E)$$

# The CR spectrum is steep, source spectra are hard

## Energy dependent escape from the Galaxy

Gaggero et al (2014)

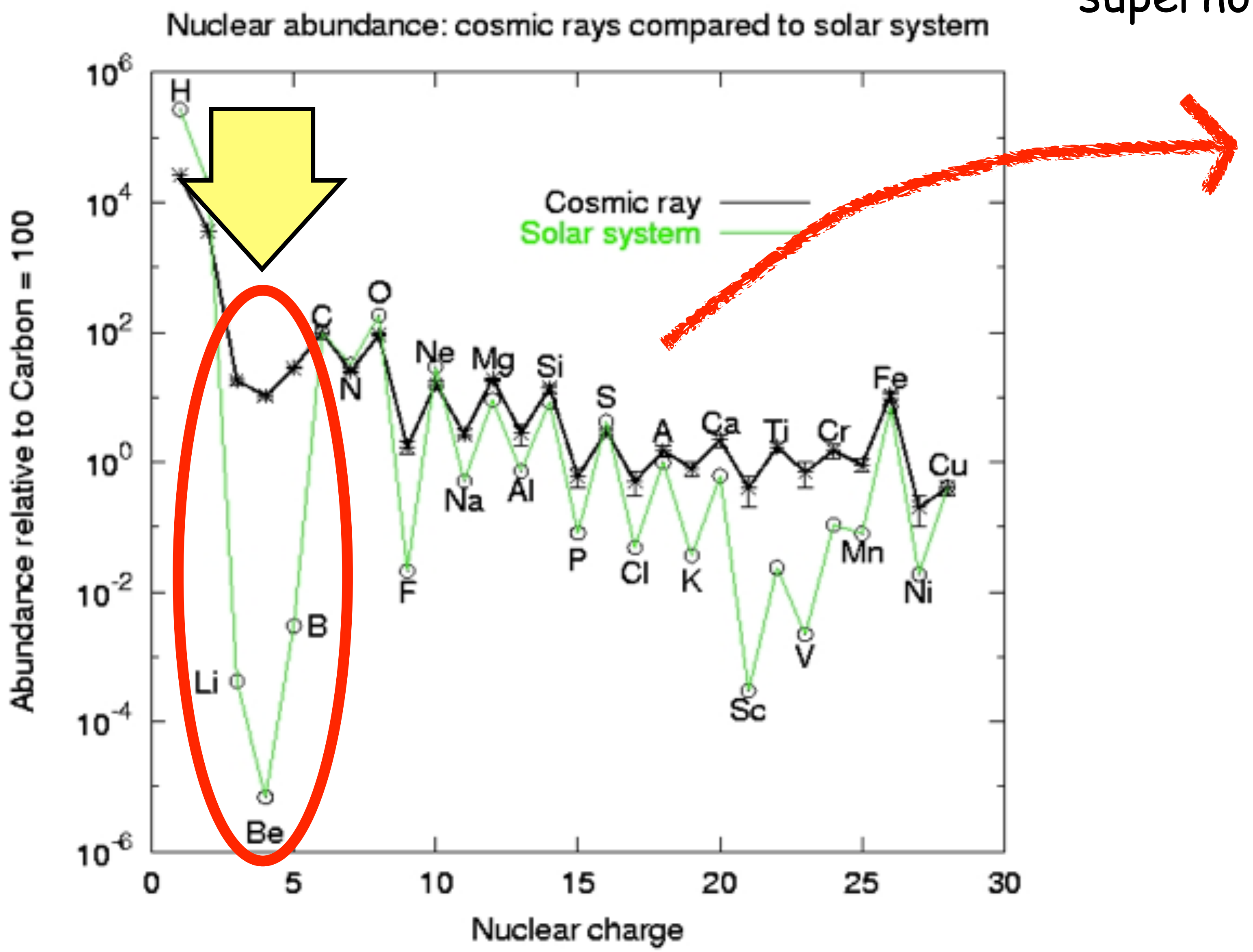



$$N_{CR}(E) = Q_S(E) \times \tau_d(E)$$

# A remarkable "coincidence"

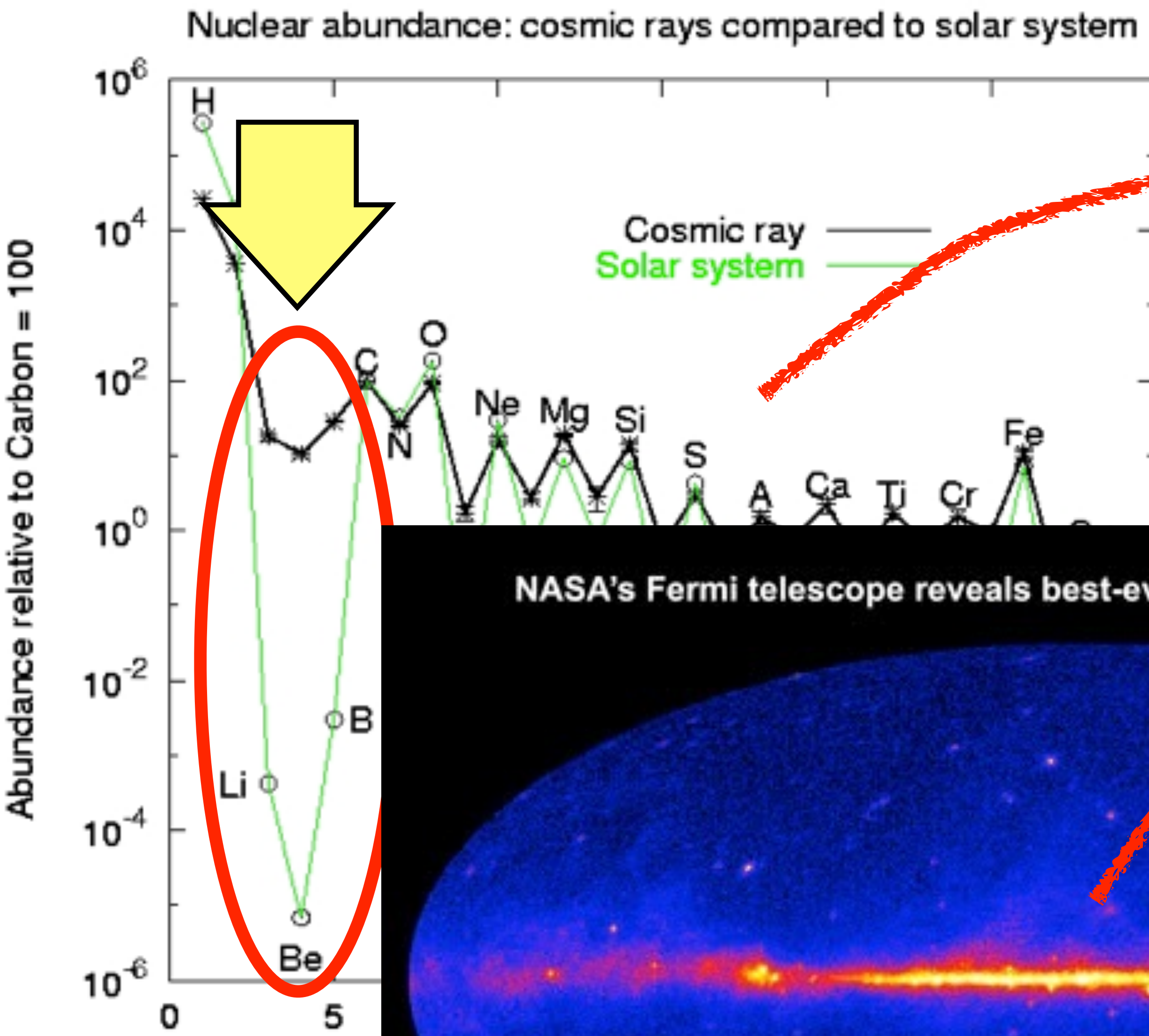
supernovae first proposed by Baade&Zwicky1934




CR escape time

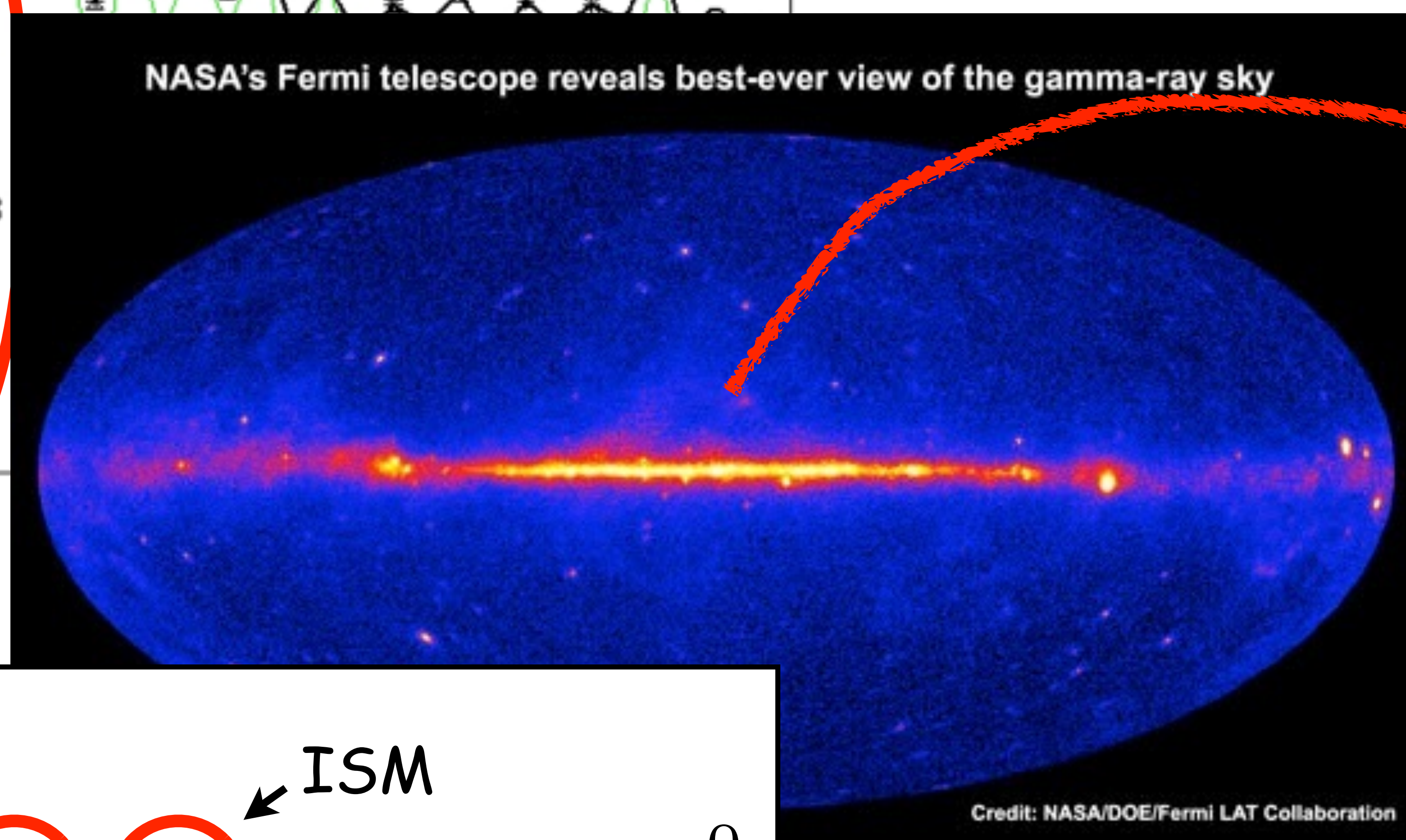
# A remarkable "coincidence"

supernovae first proposed by Baade&Zwicky1934




CR escape time

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




CR total energy

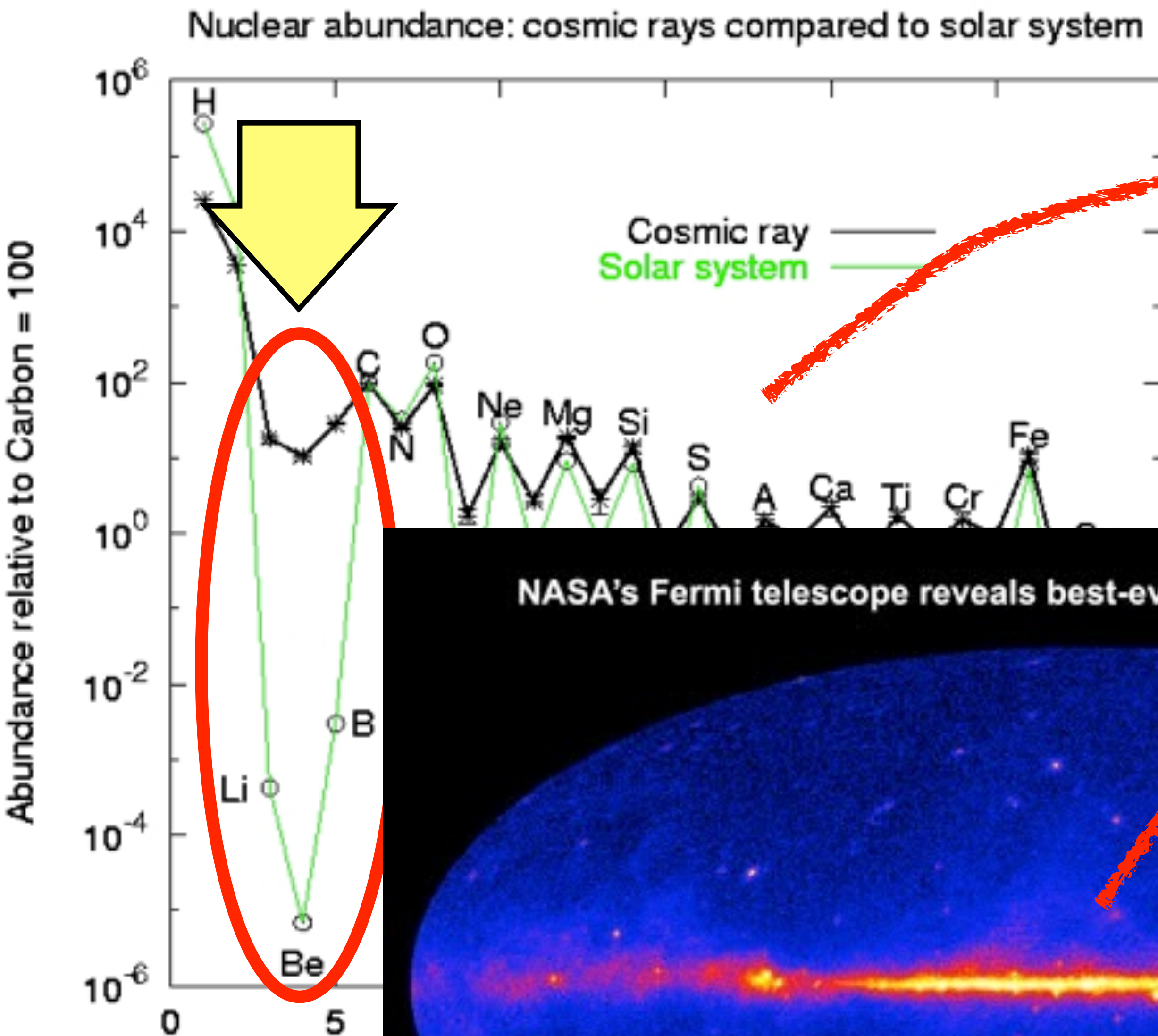
CR ISM

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

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

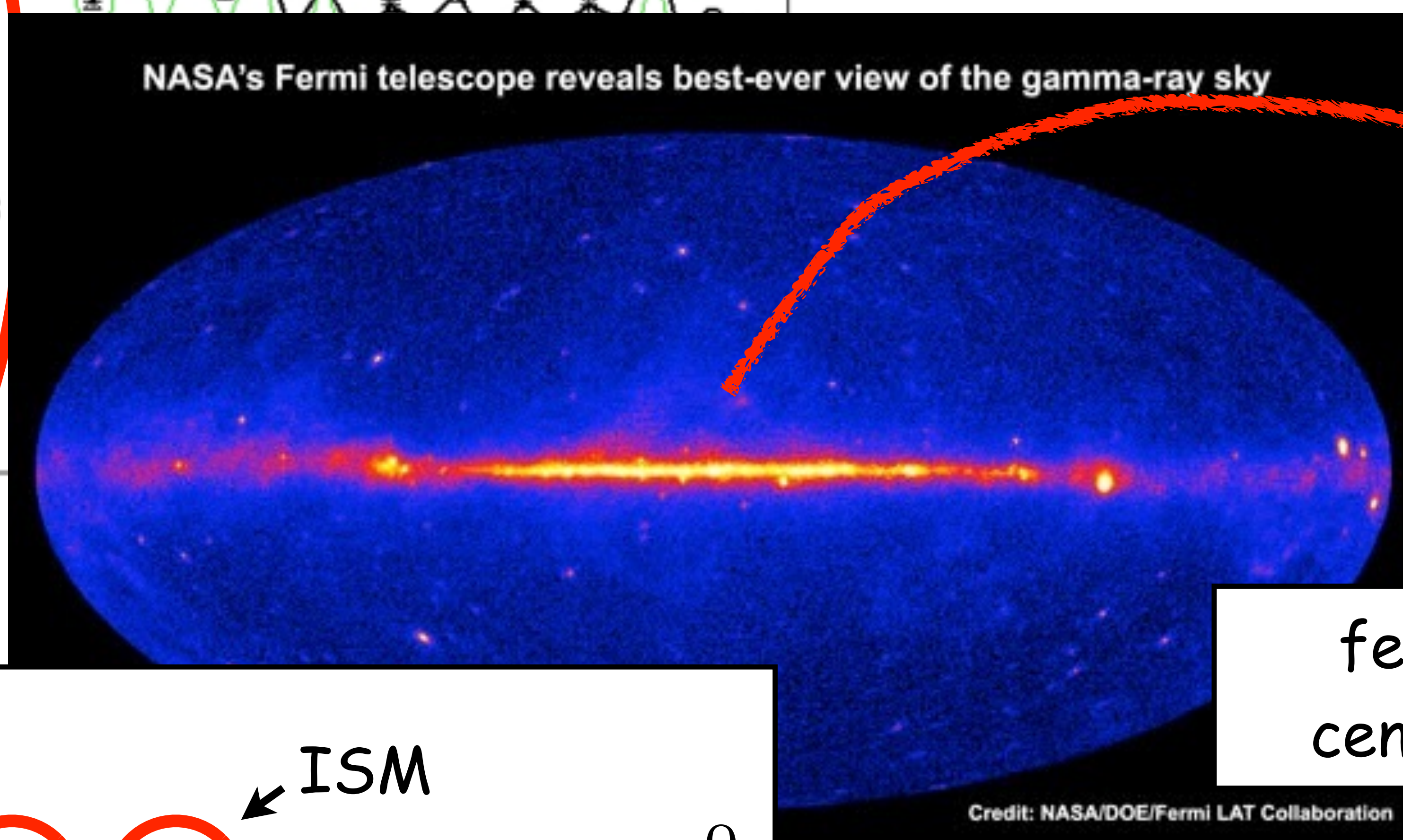
# A remarkable "coincidence"

supernovae first proposed by Baade&Zwicky1934




CR escape time

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




CR total energy

few supernovae per century in the Galaxy

-> power of SuperNovae $10^{42}$ erg/s

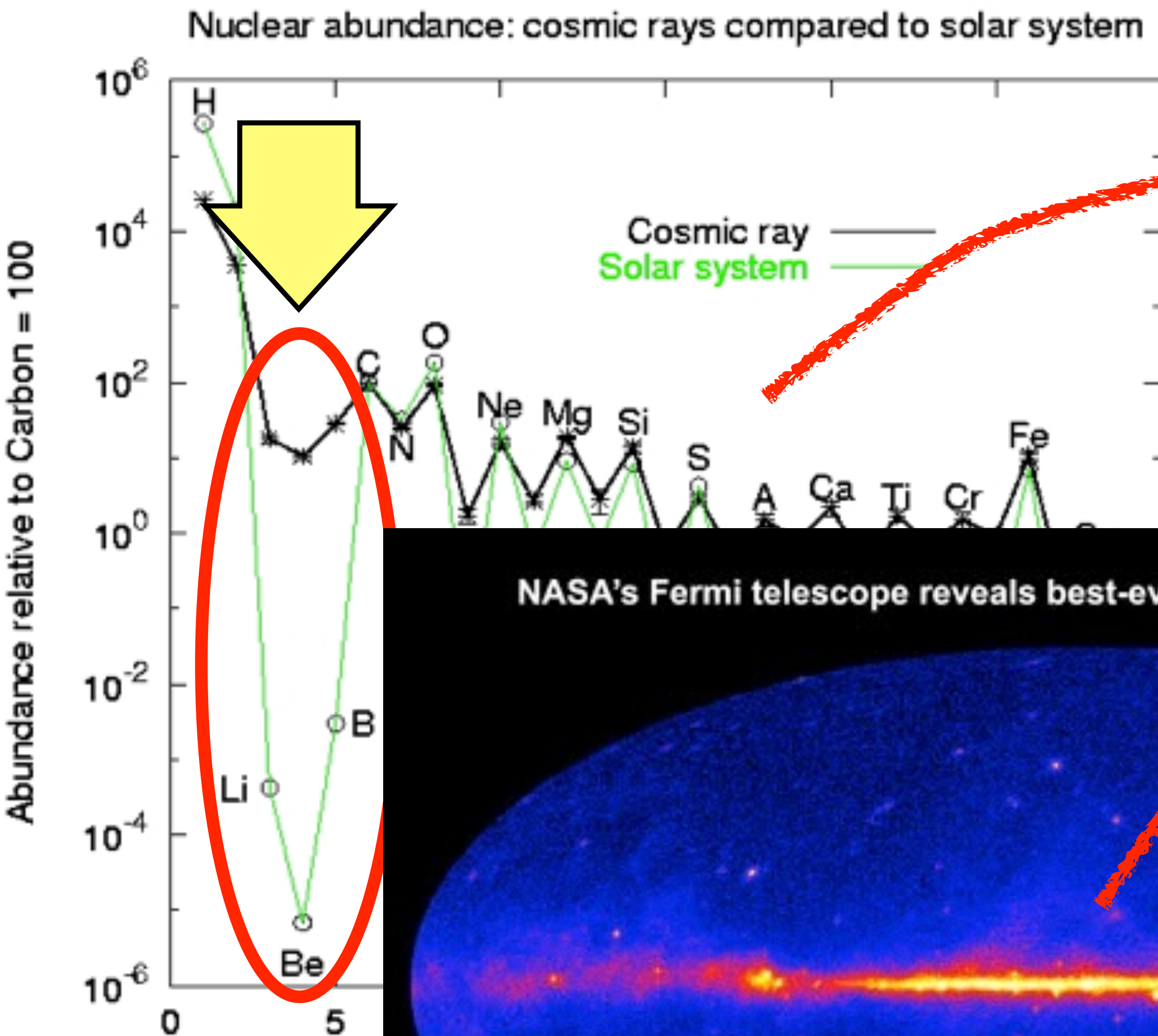
CR → ISM

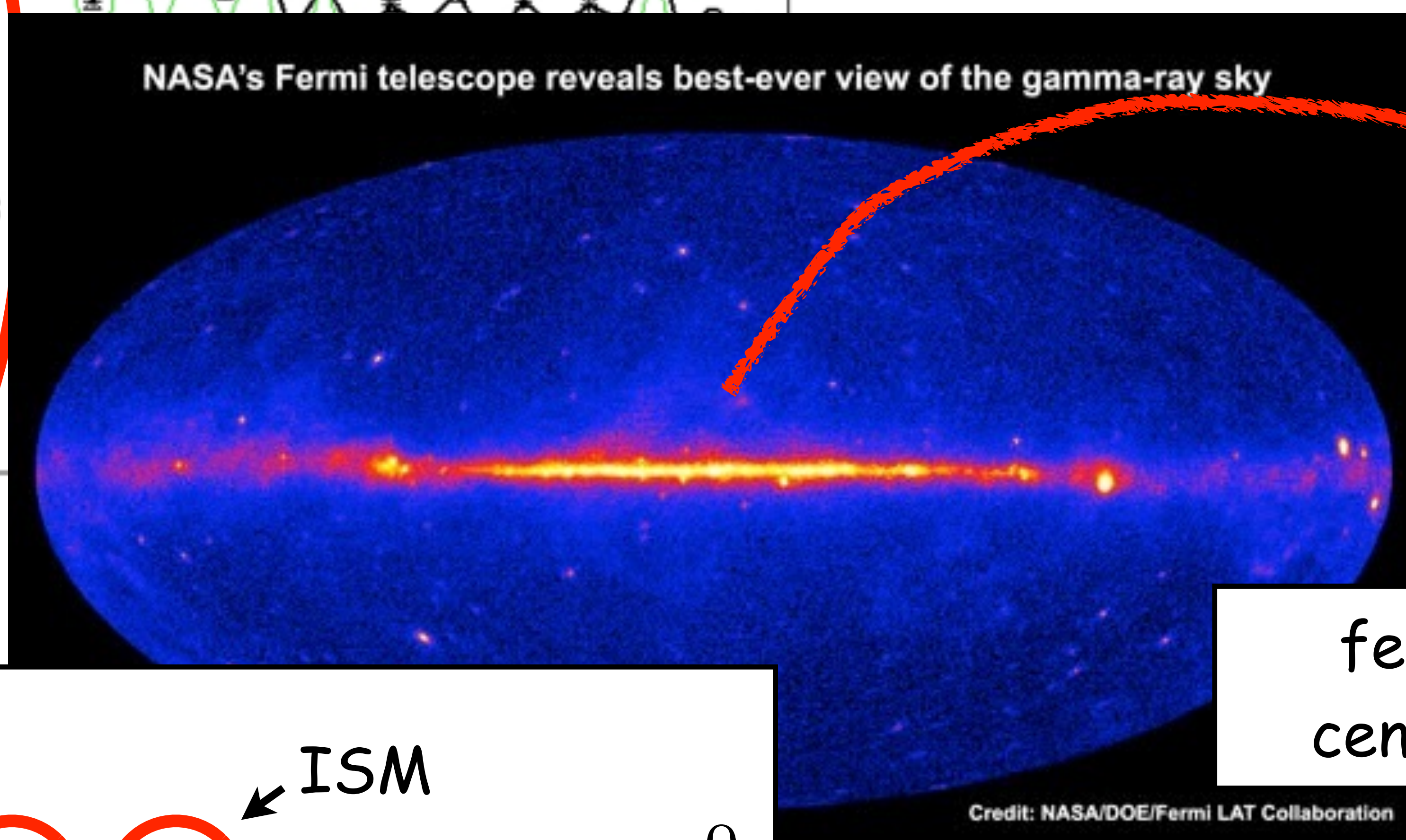
$$p + p \rightarrow p + p + \pi^0$$

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

# A remarkable "coincidence"

supernovae first proposed by Baade&Zwicky1934




CR escape time

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

CR total energy

few supernovae per century in the Galaxy

-> power of SuperNovae $10^{42}$ erg/s

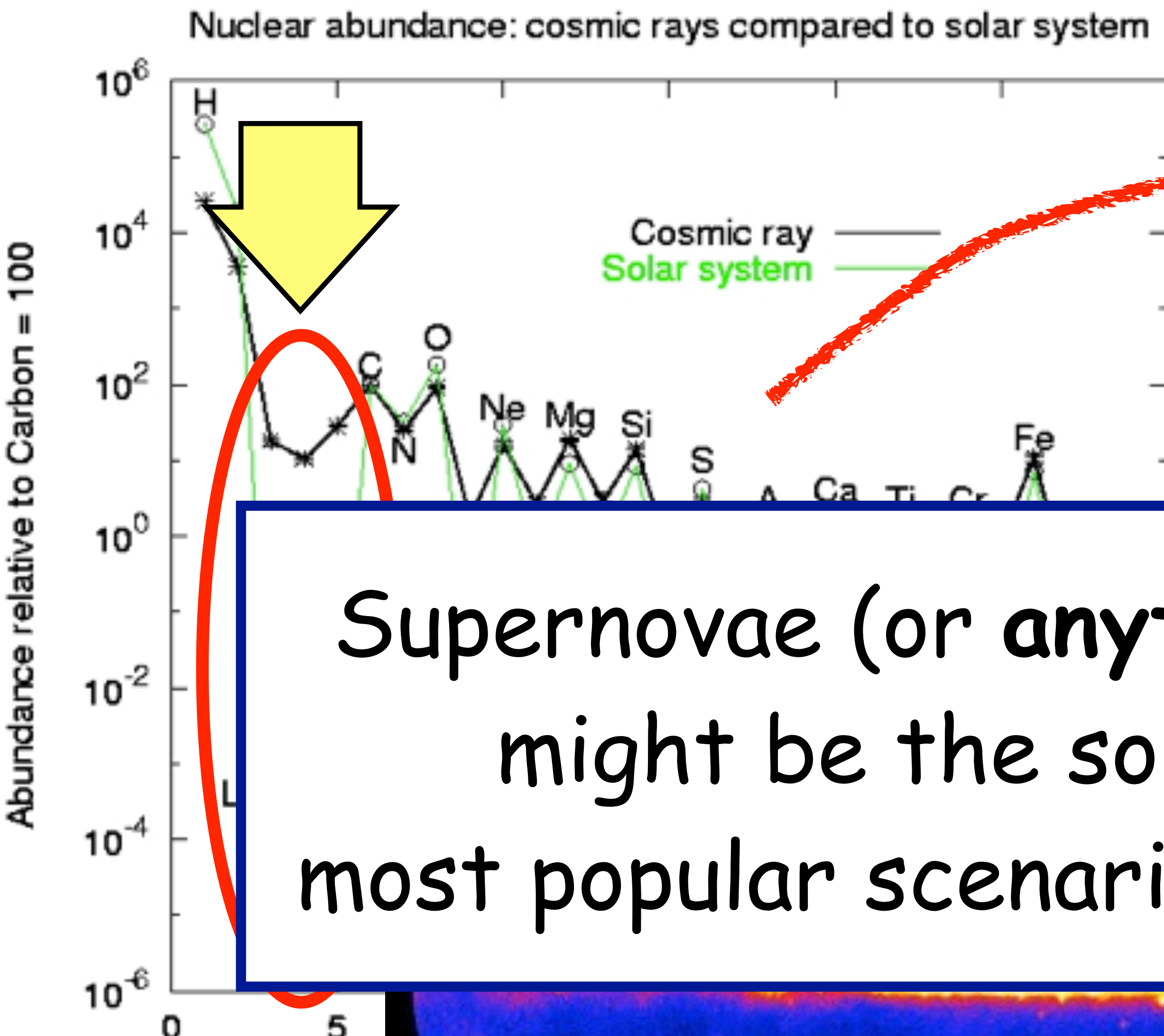
CR → ISM

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

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

# A remarkable "coincidence"

supernovae first proposed by Baade&Zwicky1934



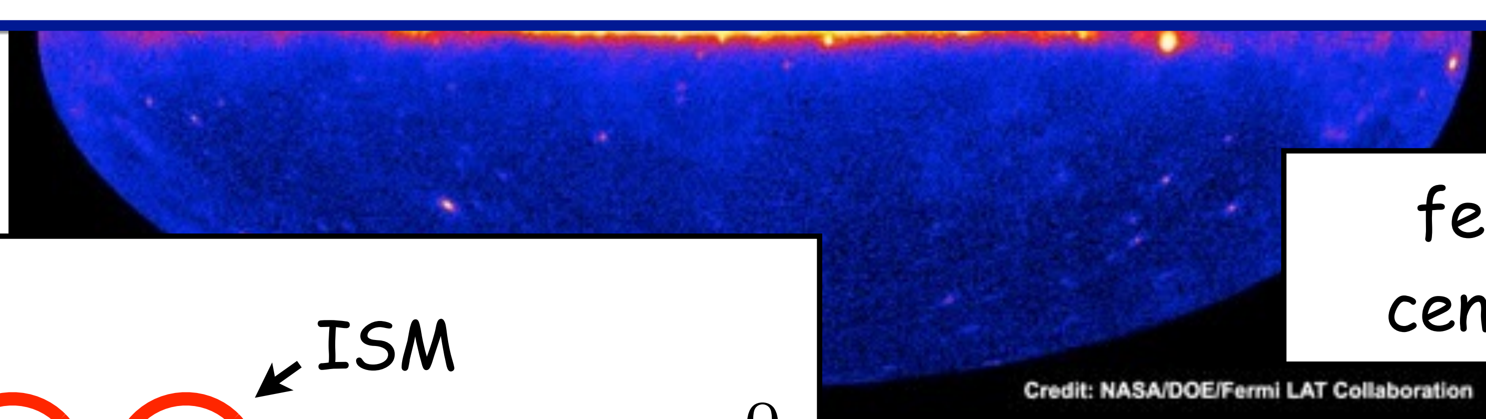

CR escape time

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

nergy

Supernovae (or **anything** connected to them) might be the sources of cosmic rays:

most popular scenario -> **supernova remnants**




few supernovae per century in the Galaxy

CR → ← ISM

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

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

-> power of SuperNovae $10^{42}$ erg/s

# Overview of the talk

- The GeV and TeV sky look much different
- The link between gamma-ray astronomy and cosmic rays
- SuperNova Remnants in gamma rays:hadronic or leptonic?
- Hadronic/leptonic signatures 1 - the pion bump
- Hadronic/leptonic signatures 2 - the spectral shape(?)
- Hadronic/leptonic signatures 3 - gamma/gas correlations
- Hadronic/leptonic signatures 4 - the multi-TeV domain
- Gamma-ray based tests for the origin of cosmic rays
- What's next? CTA, HAWC, HiScore, LHAASO ...

# 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**

# Gamma rays from SNRs: a test for CR origin

Drury, Aharonian & Volk, 1994

- CR observations -> CR powe... e Galaxy
- Supernova rate in the ... (≈3 per century)

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

- ISM density n ... 1 $cm^{-3}$
- proton-pro... eractions

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

**almost model independent**

# Gamma rays from SNRs: a test for CR origin

Drury, Aharonian & Volk, 1994

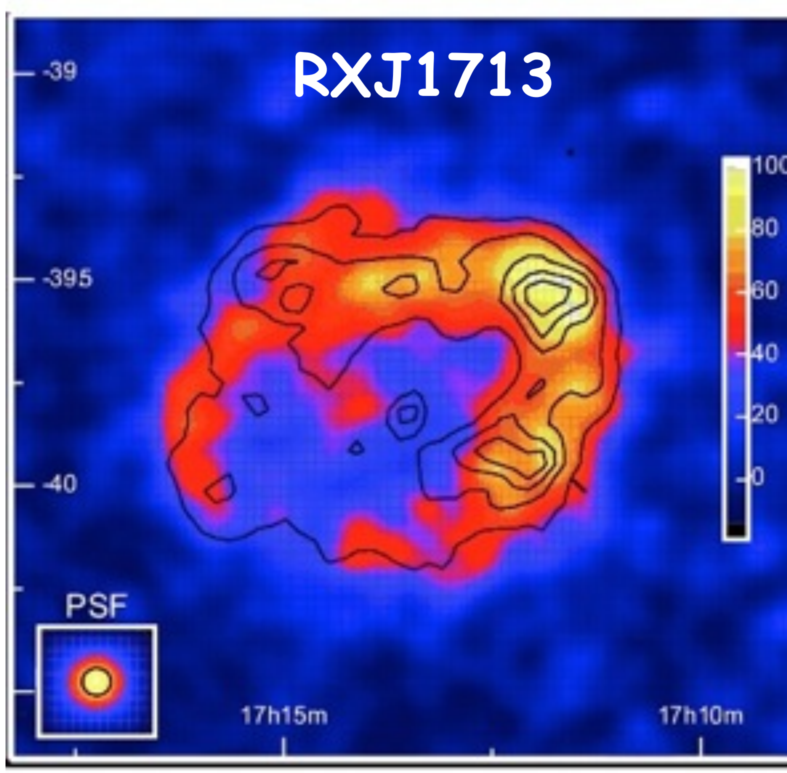
almost model independent

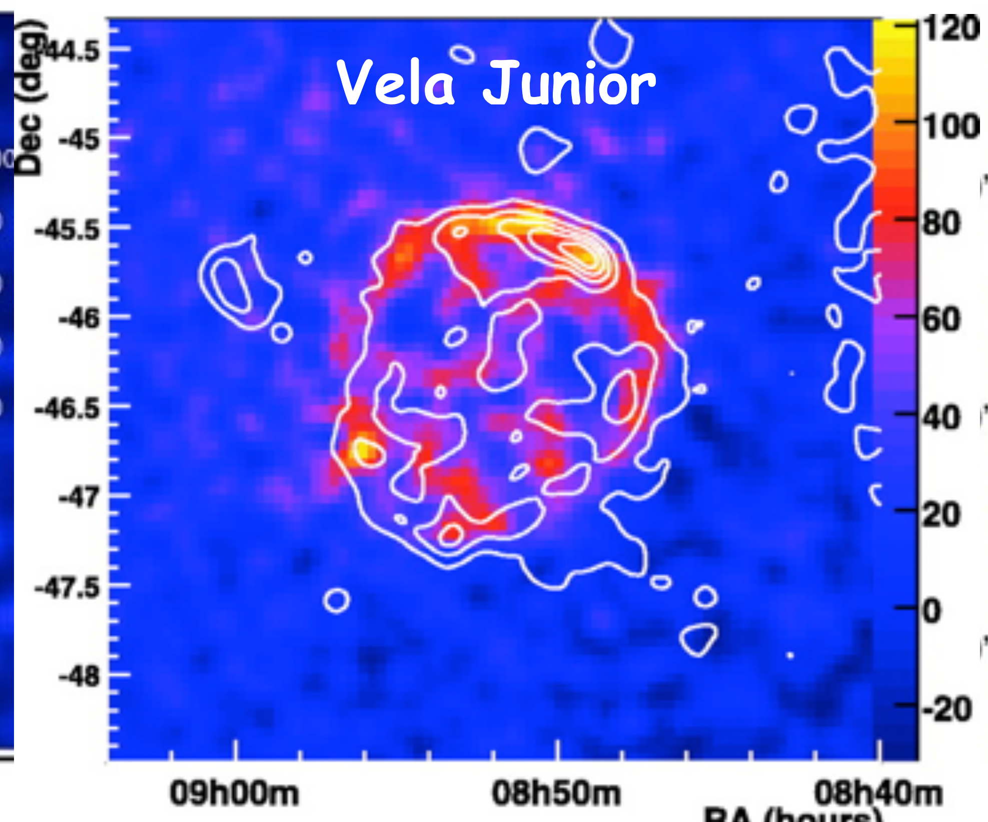
- CR observations -> CR powe... e Galaxy
- Supernova rate in the ... ($\approx$3 per century)

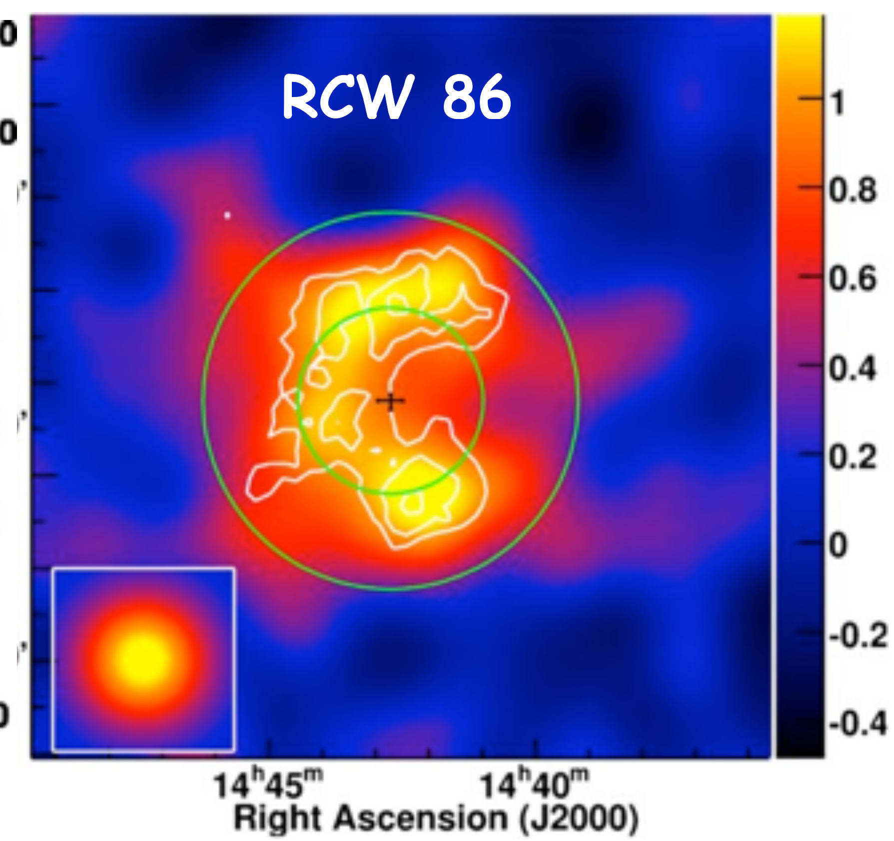
$\Rightarrow$ $\gtrsim$10% of SNR energy MUST be converted into CRs

- ISM density n ... 1 $cm^{-3}$
- proton-pro... eractions

$\Rightarrow$ SNRs visible in TeV gamma rays



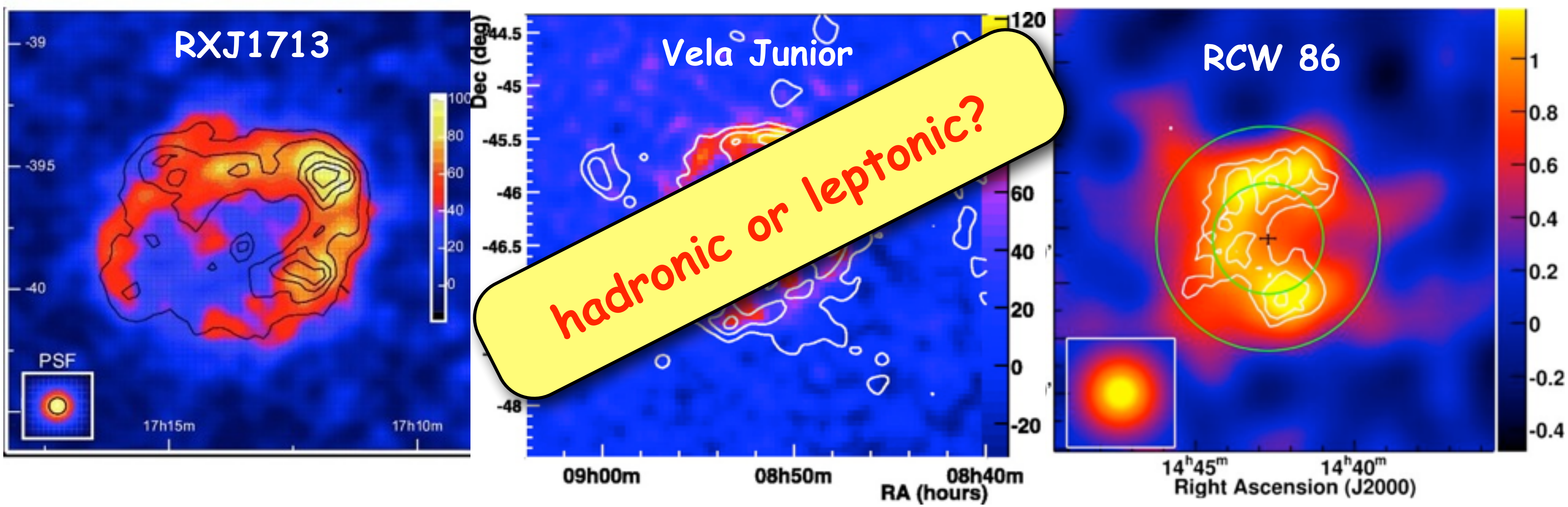
# Gamma rays from SNRs: a test for CR origin

Drury, Aharonian & Volk, 1994

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

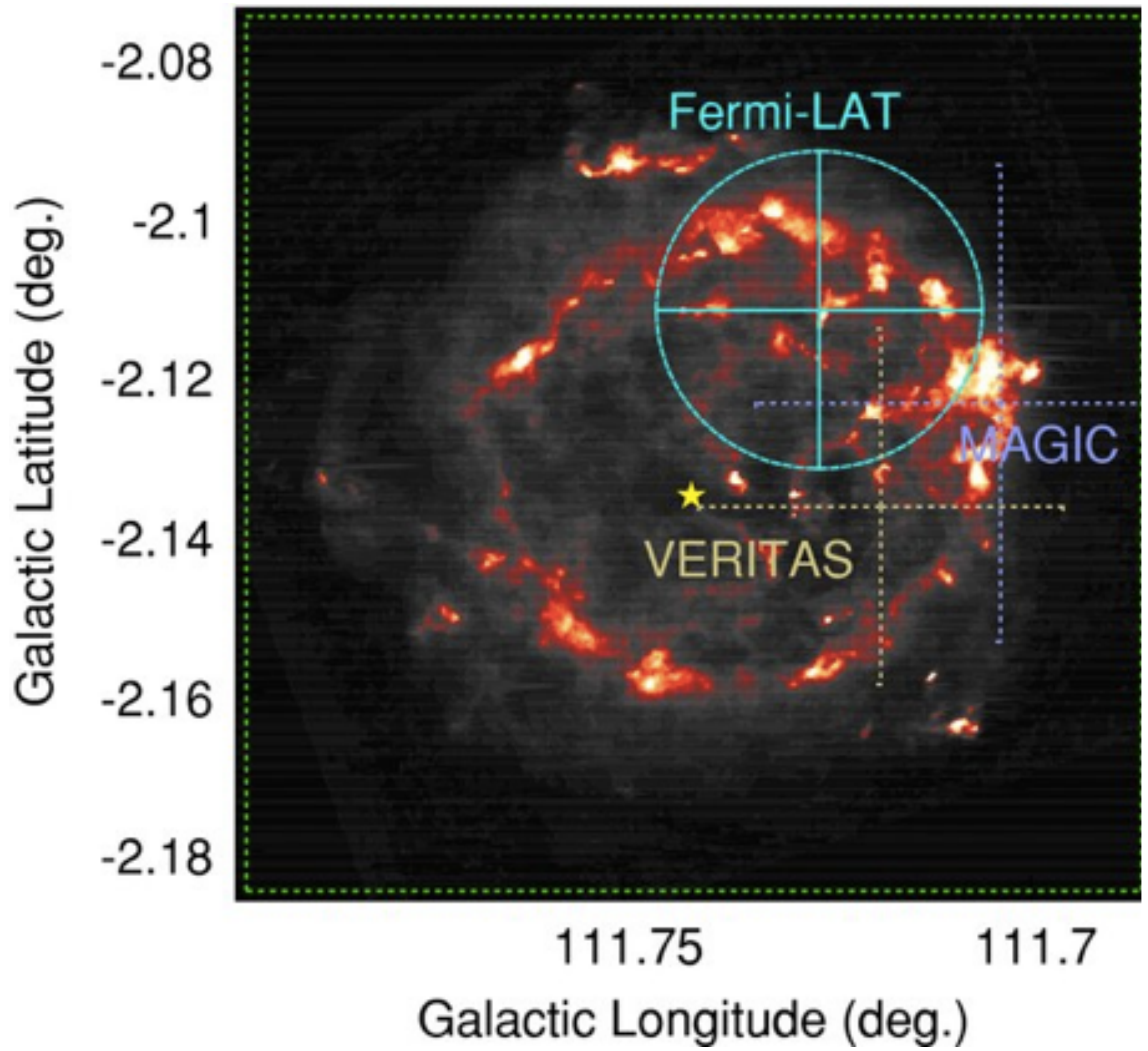
**neutrinos** are the candidates, but their detection is challenging

**-> other gamma-ray based tests?**



# Hadronic or leptonic?

SNR Cas A

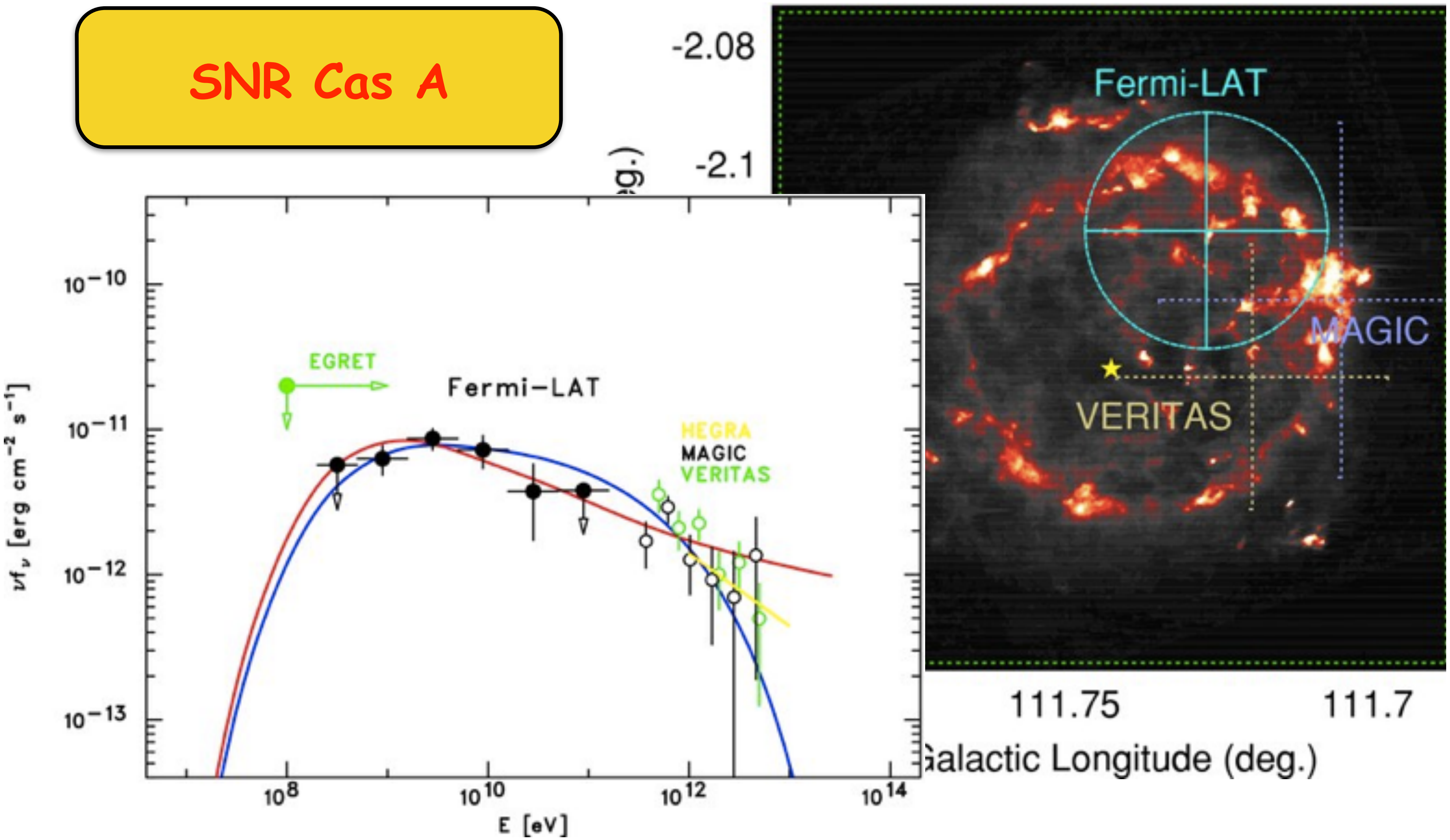



FERMI coll. (2010)

# Hadronic or leptonic?

SNR Cas A

FERMI coll. (2010)



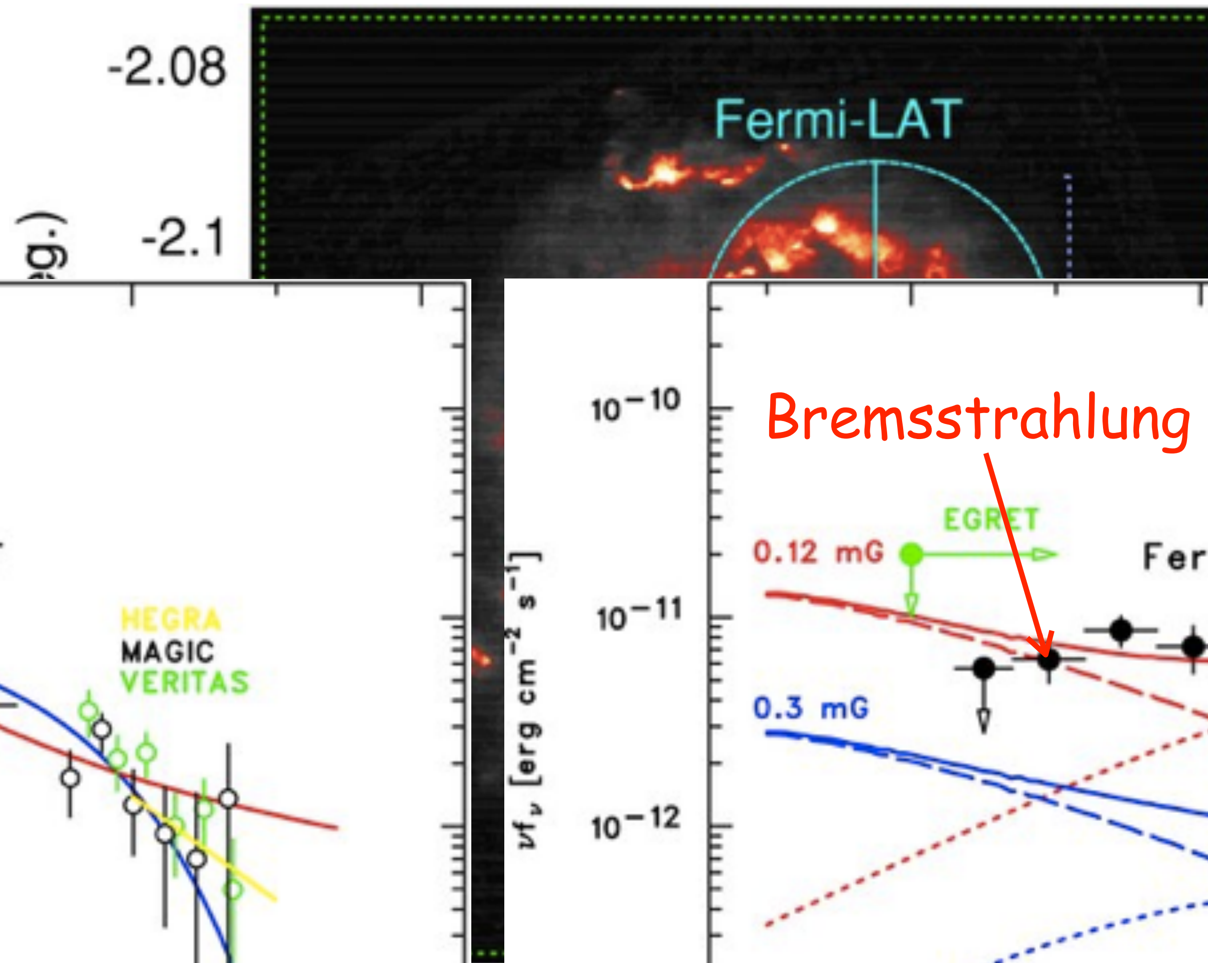

**proton-proton:**

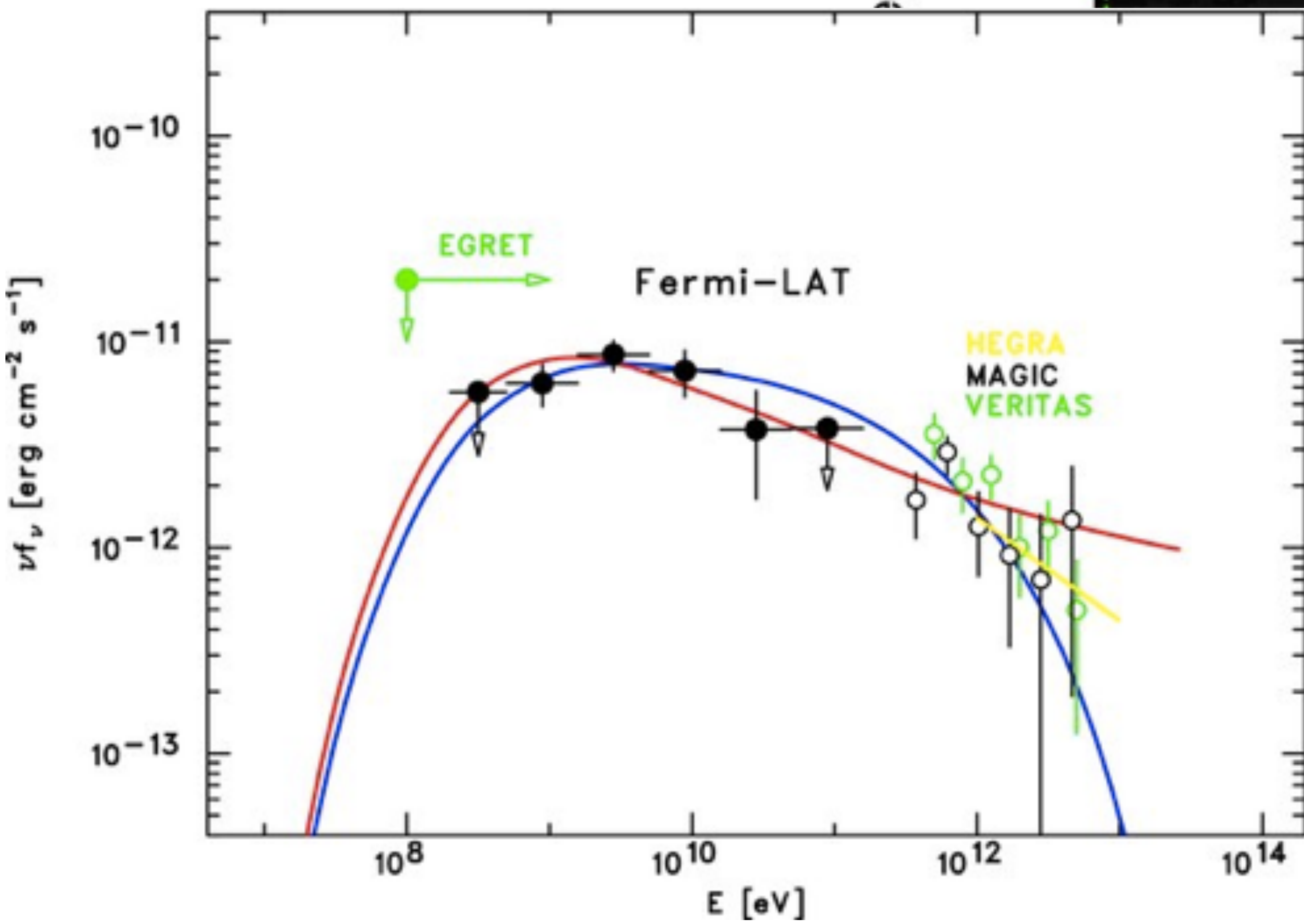
$$E_\gamma \approx 0.1 \times E_p$$

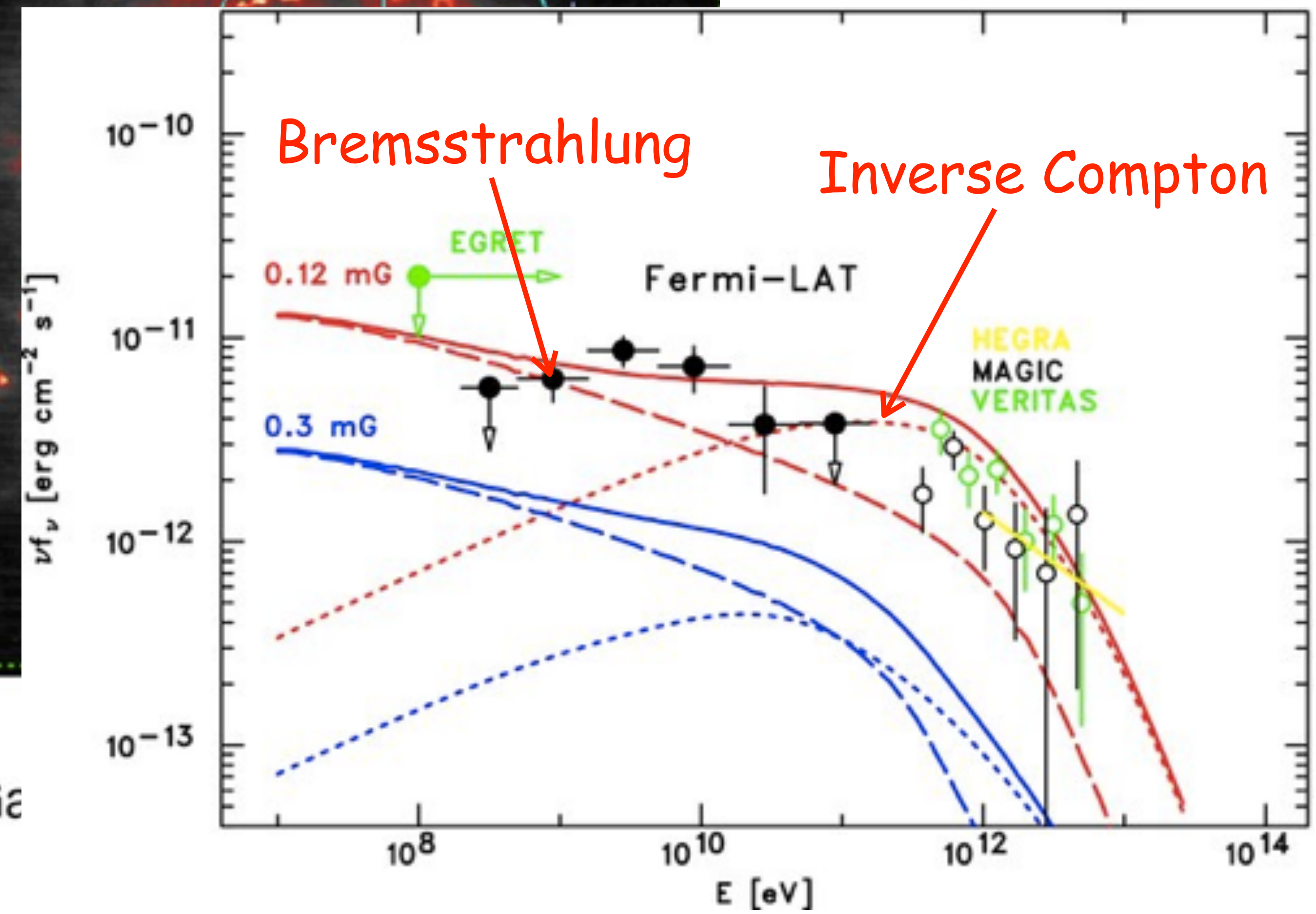
# Hadronic or leptonic?

SNR Cas A

FERMI coll. (2010)




**proton-proton:**

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

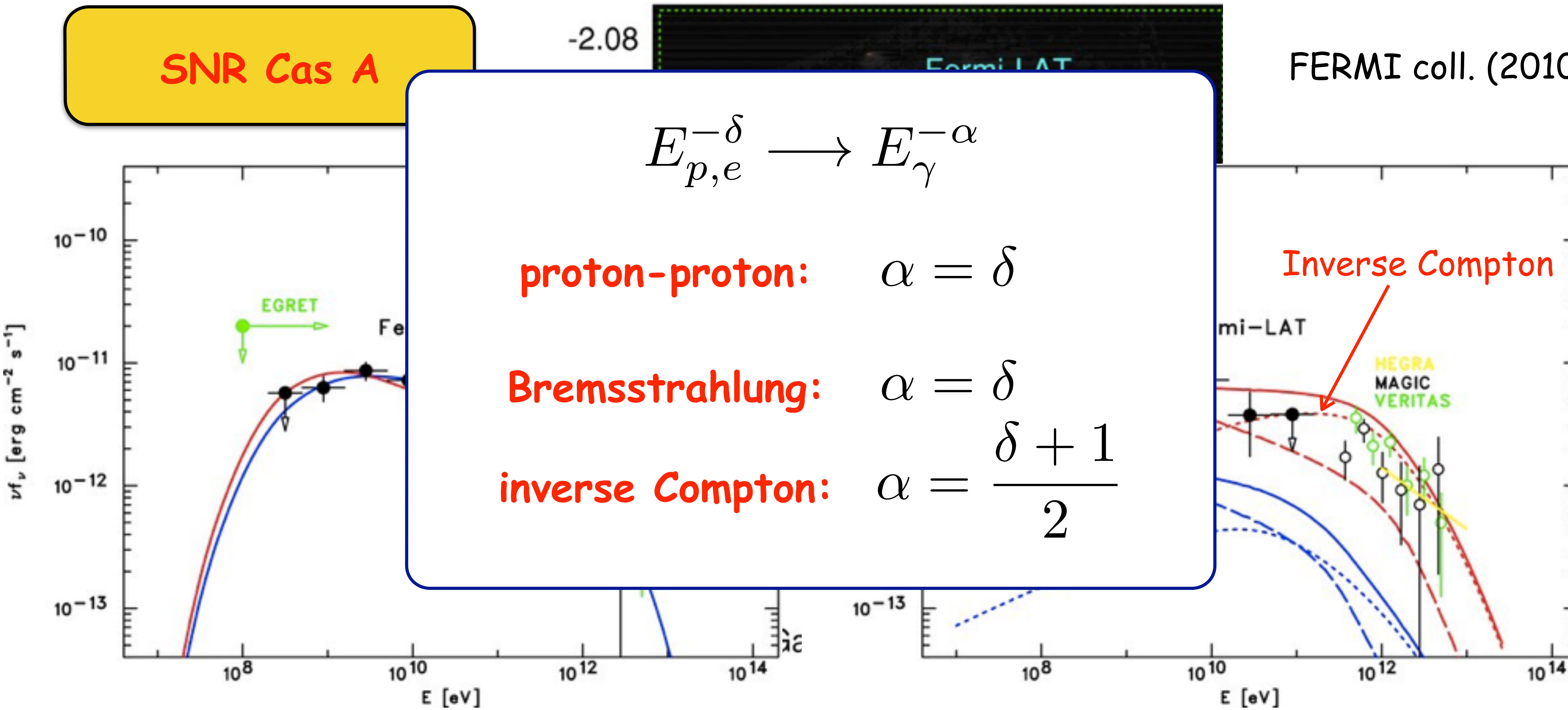
**Inverse Compton on CMB** $E_\gamma \approx 1 \left( \frac{E_e}{20\ \text{TeV}} \right)^2 \text{TeV}$

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

proton-proton:

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

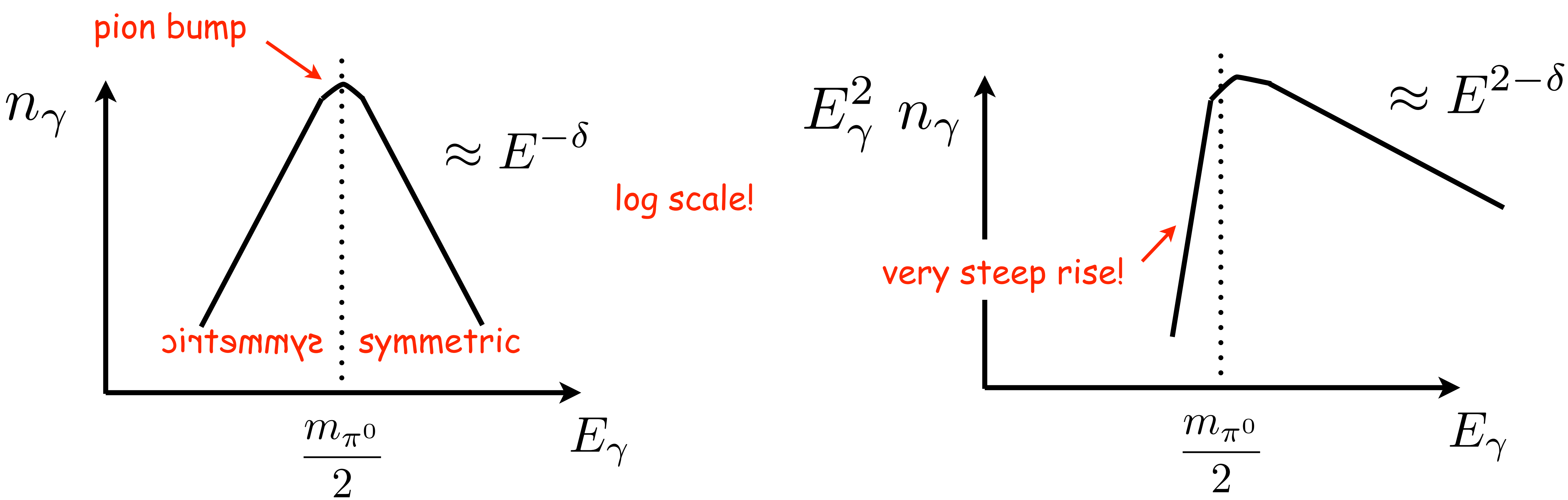
Inverse Compton on CMB $E_\gamma \approx 1 \left( \dfrac{E_e}{20\ \text{TeV}} \right)^2 \text{TeV}$

Bremsstrahlung $E_\gamma \approx E_e$

# Overview of the talk

- The GeV and TeV sky look much different
- The link between gamma-ray astronomy and cosmic rays
- SuperNova Remnants in gamma rays:hadronic or leptonic?
- Hadronic/leptonic signatures 1 - the pion bump
- Hadronic/leptonic signatures 2 - the spectral shape(?)
- Hadronic/leptonic signatures 3 - gamma/gas correlations
- Hadronic/leptonic signatures 4 - the multi-TeV domain
- Gamma-ray based tests for the origin of cosmic rays
- What's next? CTA, HAWC, HiScore, LHAASO ...

# Hadronic or leptonic?
# The pion bump

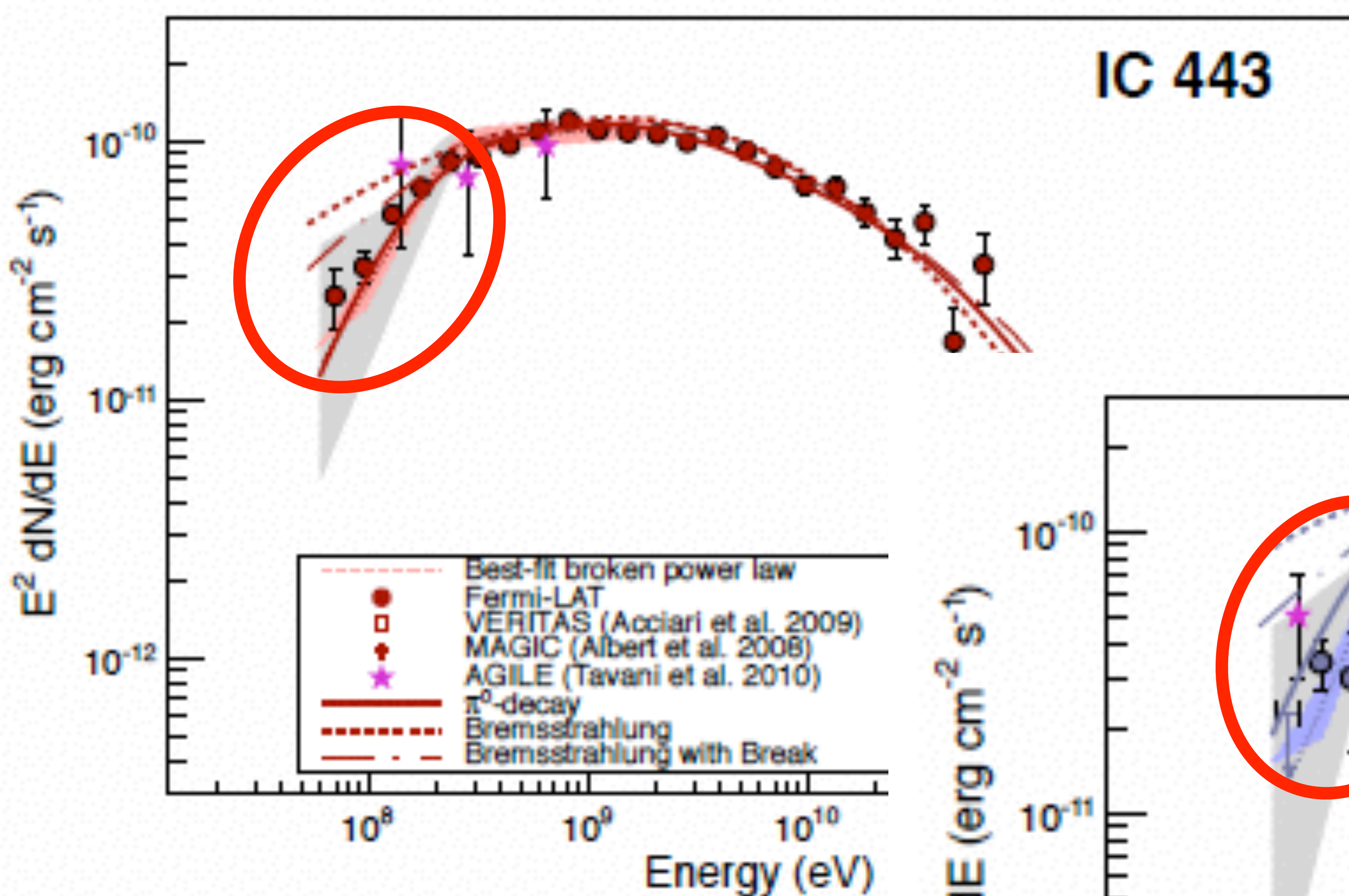


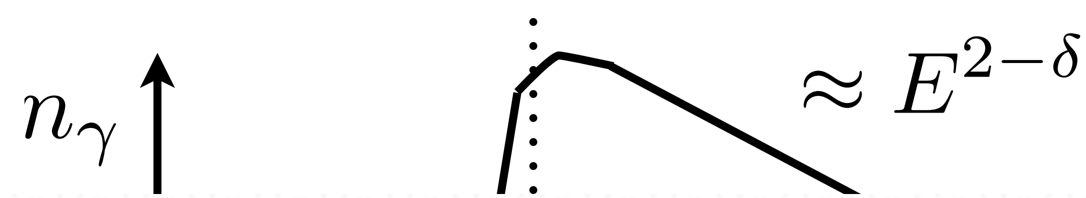
# Hadronic or leptonic?
# The pion bump

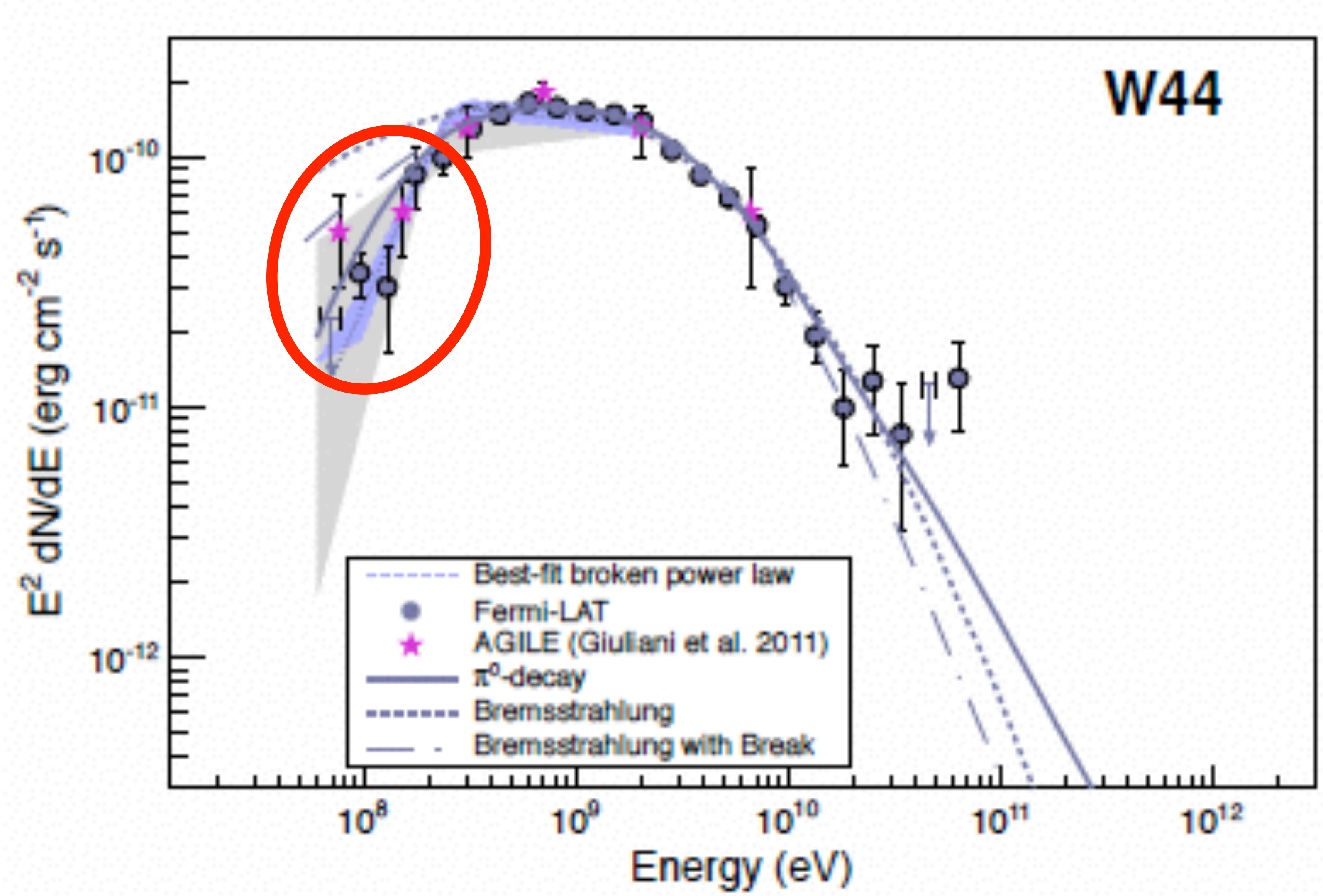
(Ackermann et al 2013)

**FERMI** (and **AGILE**)

(Giuliani+, Cardillo+)



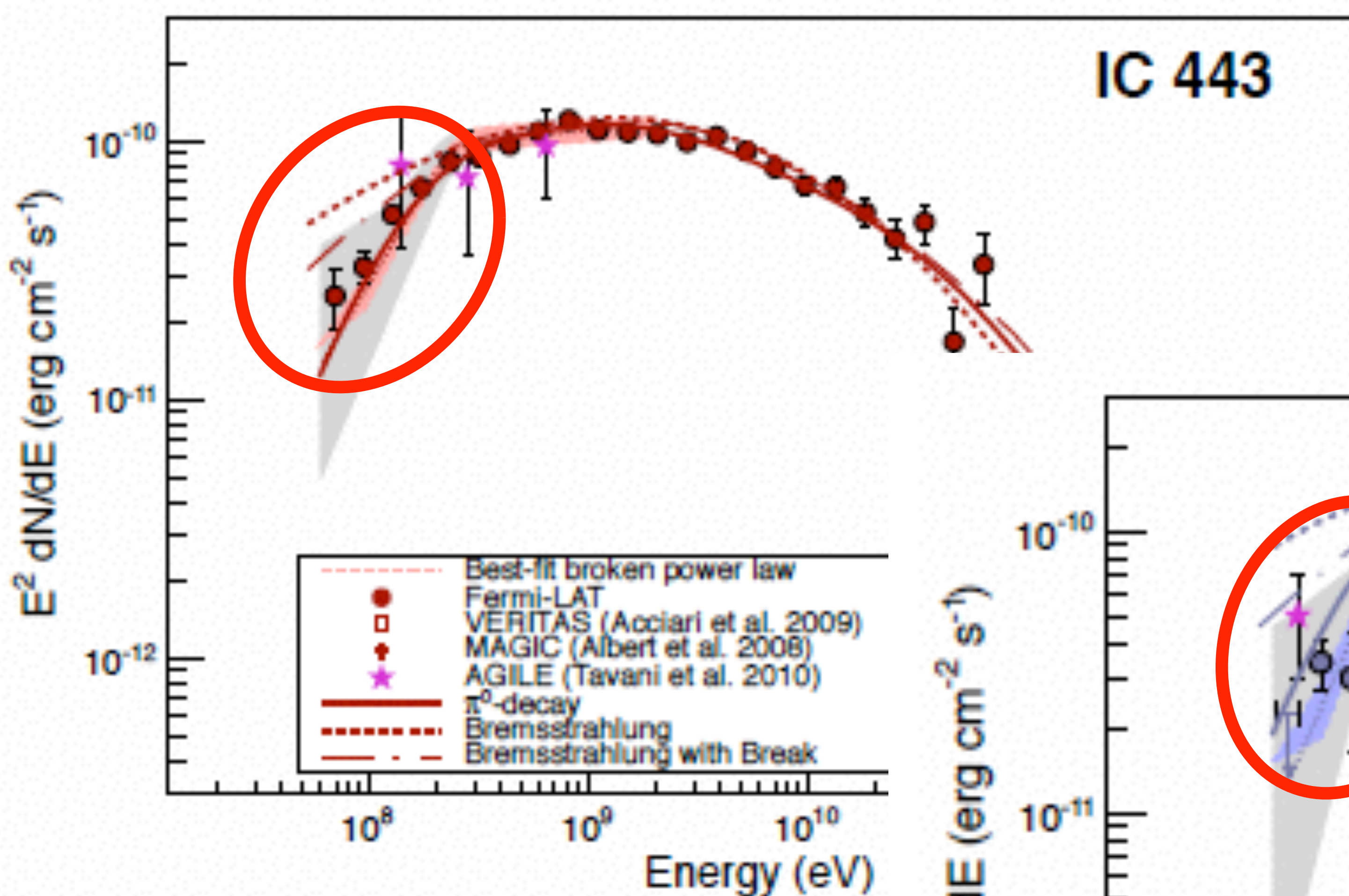



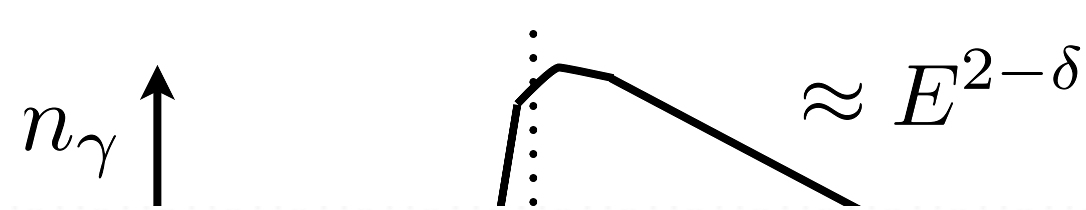
# Hadronic or leptonic?
# The pion bump

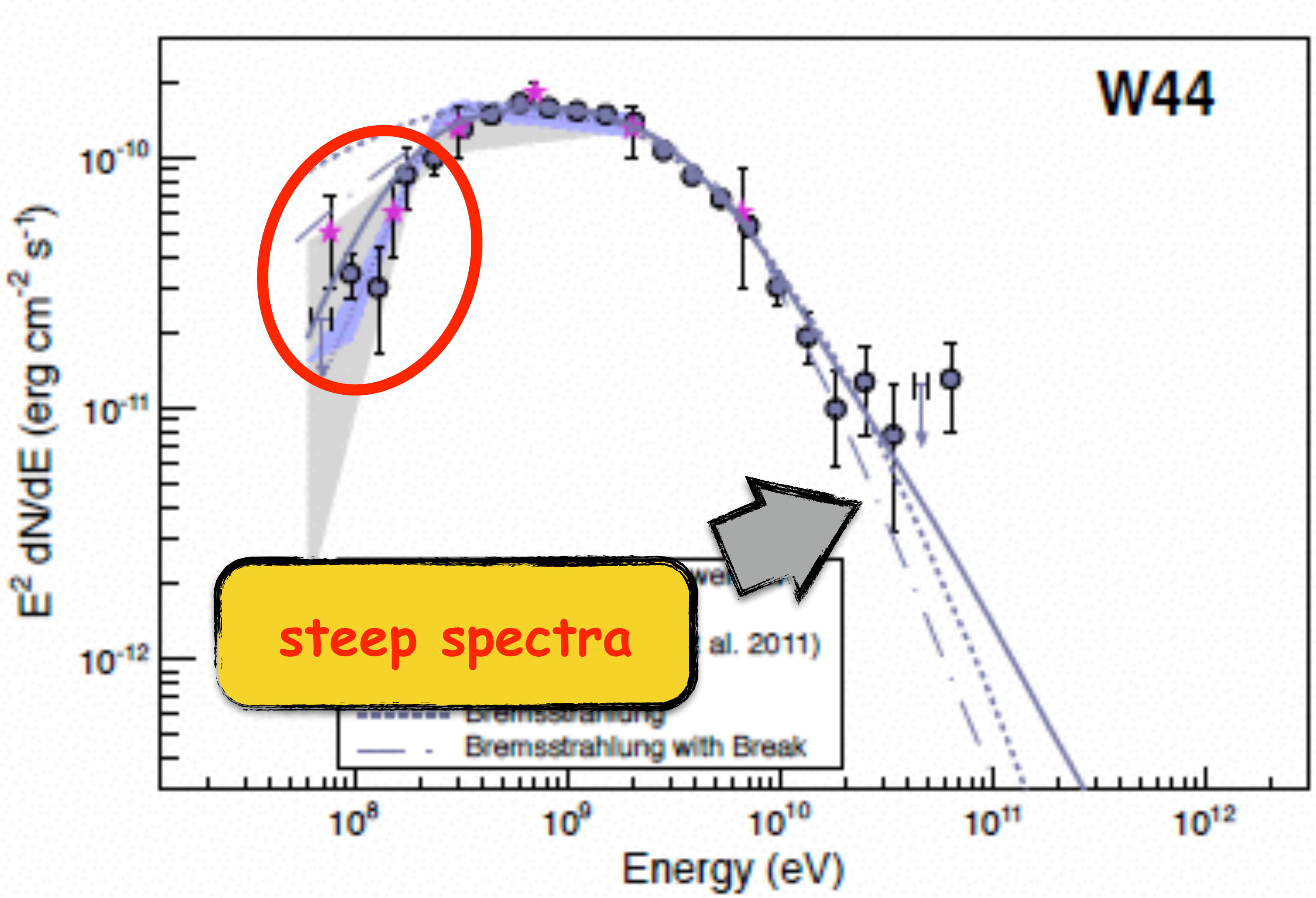
(Ackermann et al 2013)

FERMI (and AGILE )

(Giuliani+, Cardillo+)



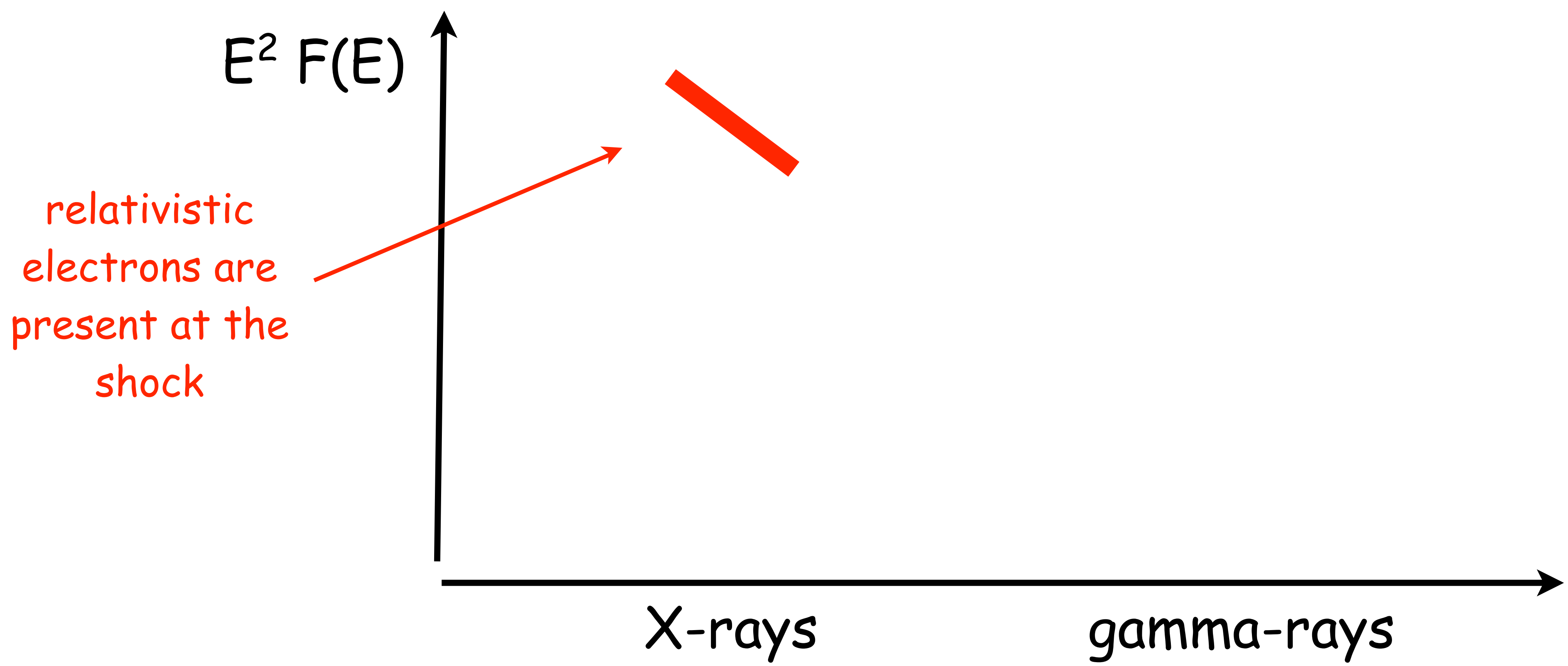

GeV CR are present
-> we want SNR to be
PeVatrons -> additional
evidence required

# Overview of the talk

- The GeV and TeV sky look much different
- The link between gamma-ray astronomy and cosmic rays
- SuperNova Remnants in gamma rays:hadronic or leptonic?
- Hadronic/leptonic signatures 1 - the pion bump
- Hadronic/leptonic signatures 2 - the spectral shape(?)
- Hadronic/leptonic signatures 3 - gamma/gas correlations
- Hadronic/leptonic signatures 4 - the multi-TeV domain
- Gamma-ray based tests for the origin of cosmic rays
- What's next? CTA, HAWC, HiScore, LHAASO ...

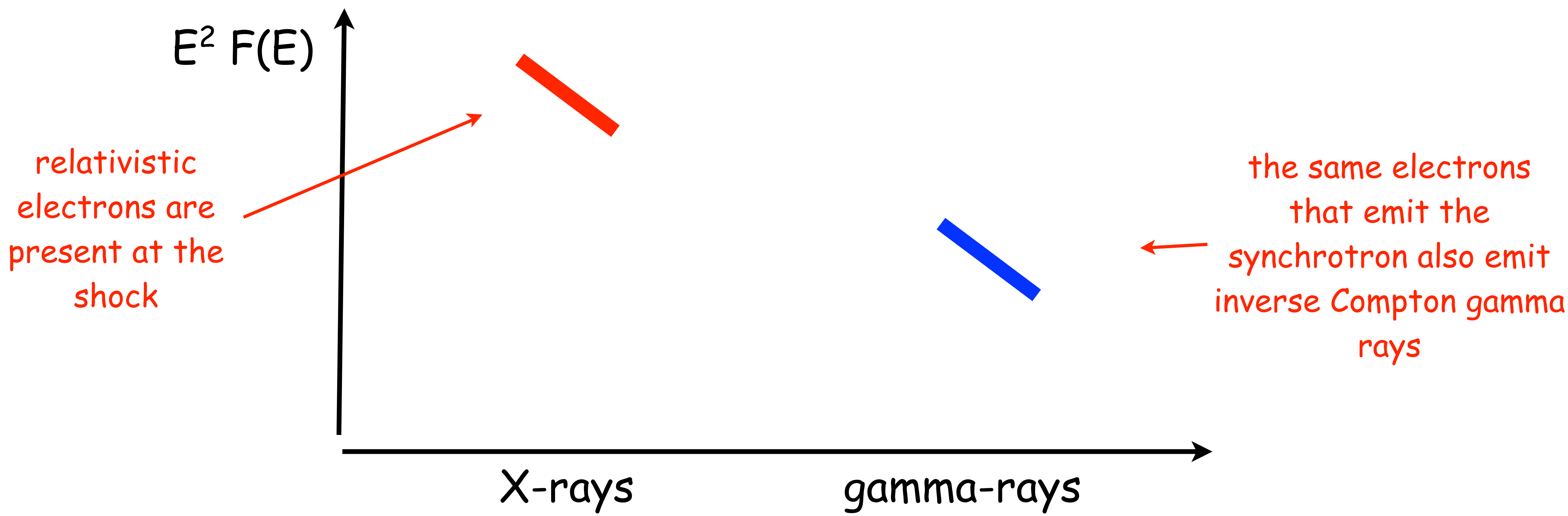
# Hadronic versus leptonic emission: the role of the magnetic field

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



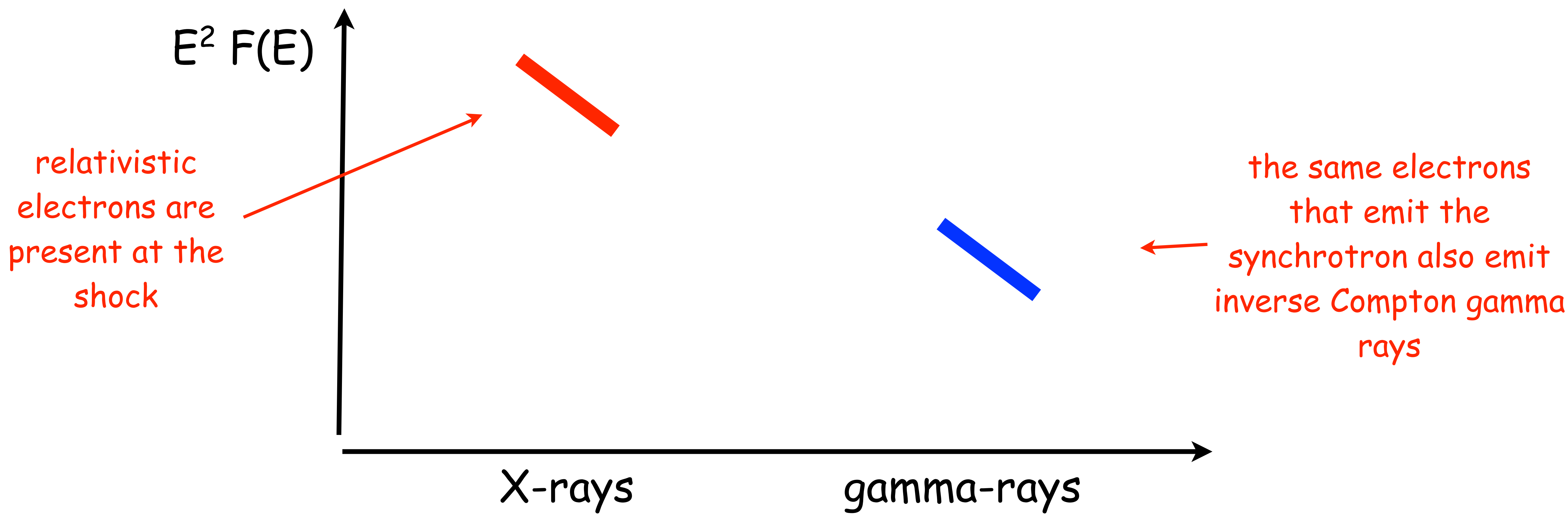
# Hadronic versus leptonic emission: the role of the magnetic field

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



# Hadronic versus leptonic emission: the role of the magnetic field

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

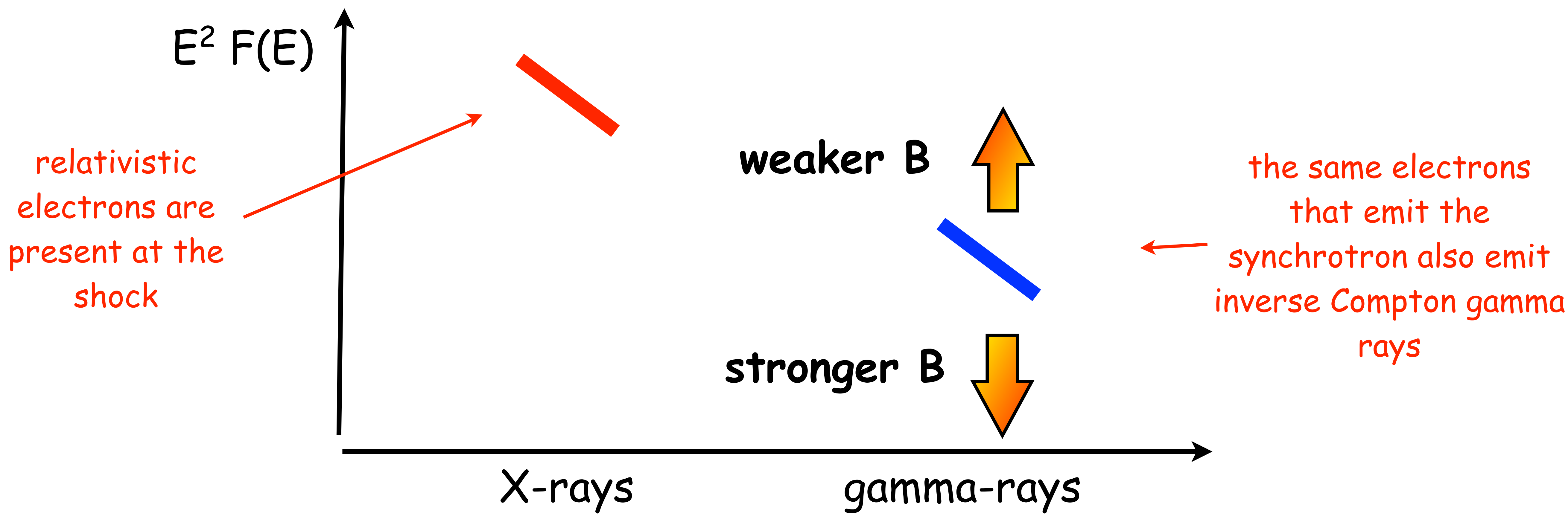



synchrotron -> $F_s \propto n_e B^\beta$ inverse Compton -> $F_{IC} \propto n_e w_{soft}$

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

# Hadronic versus leptonic emission: the role of the magnetic field

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




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

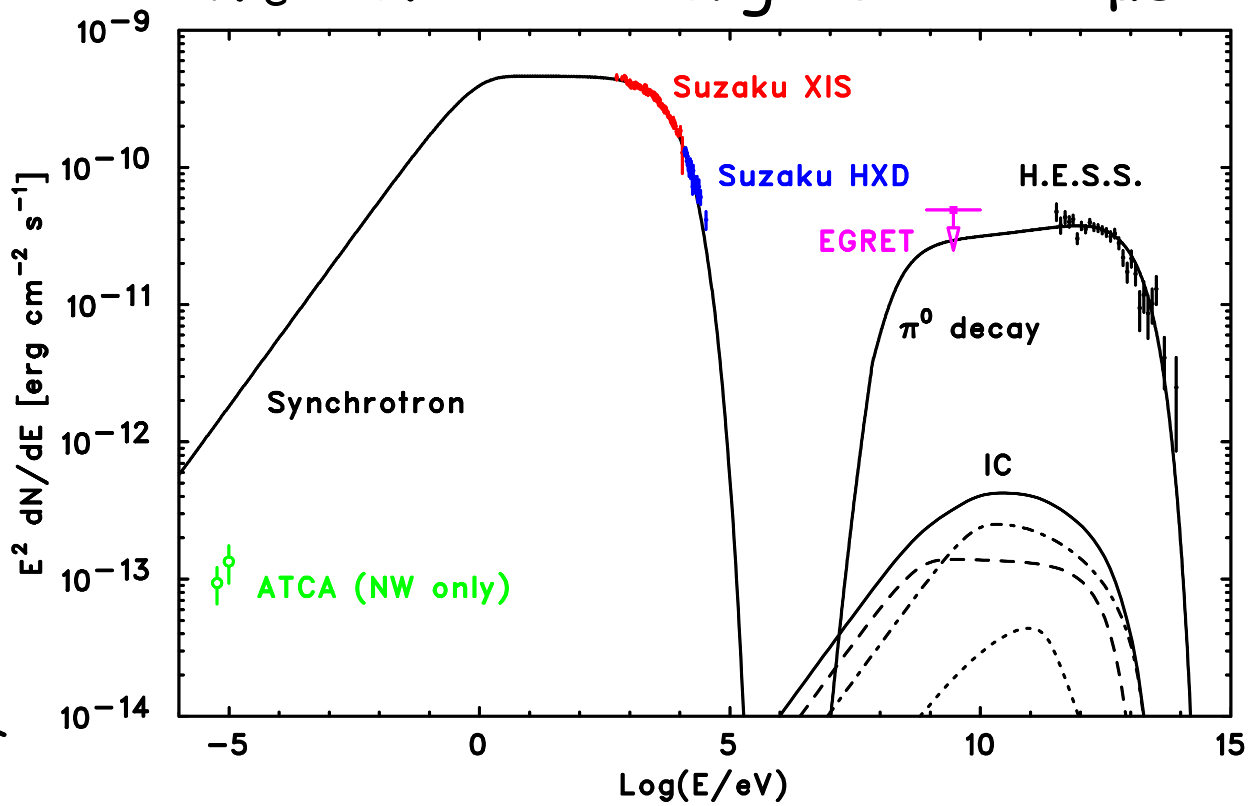
# Hadronic versus leptonic emission

## RXJ1713: hadronic and leptonic models

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

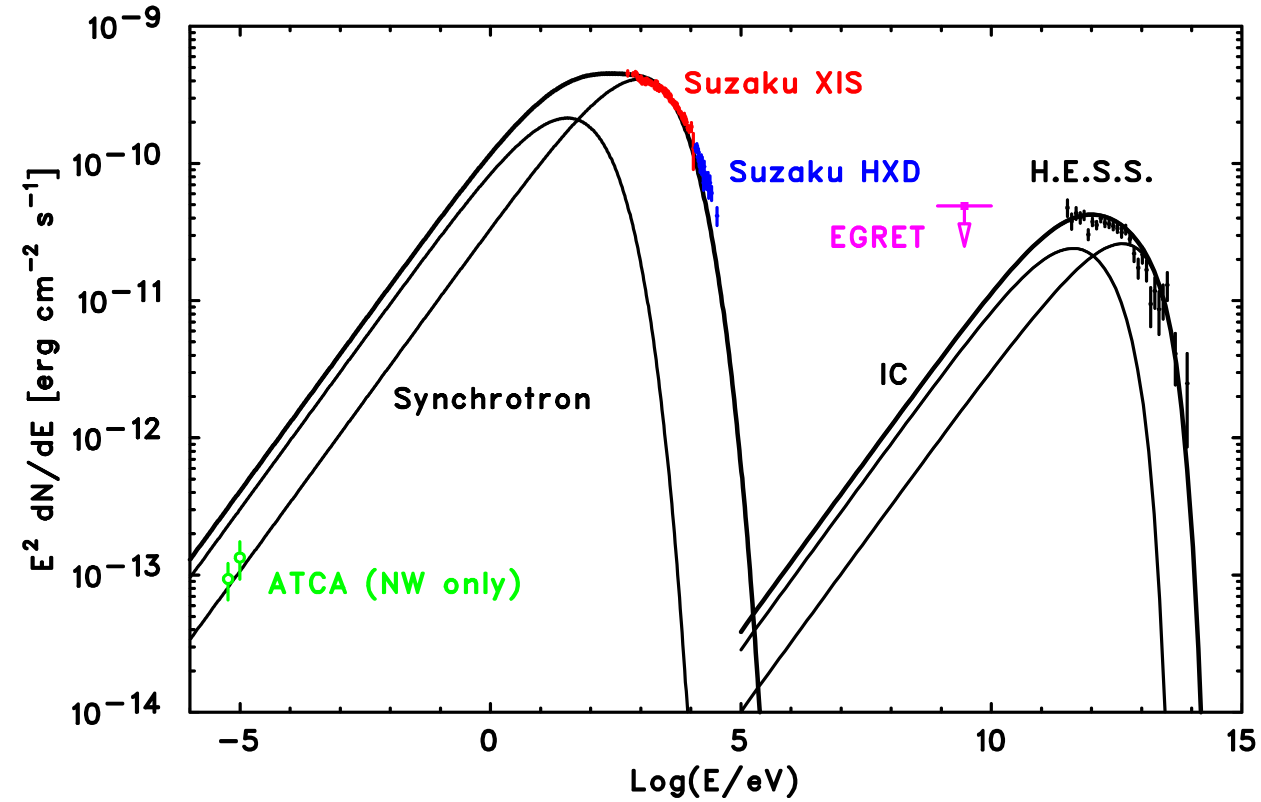
**Leptonic:** low B field -> synchrotron losses negligible -> electron spectrum $E^{-2}$ -> inverse Compton scattering -> gamma ray spectrum $E^{-1.5}$

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

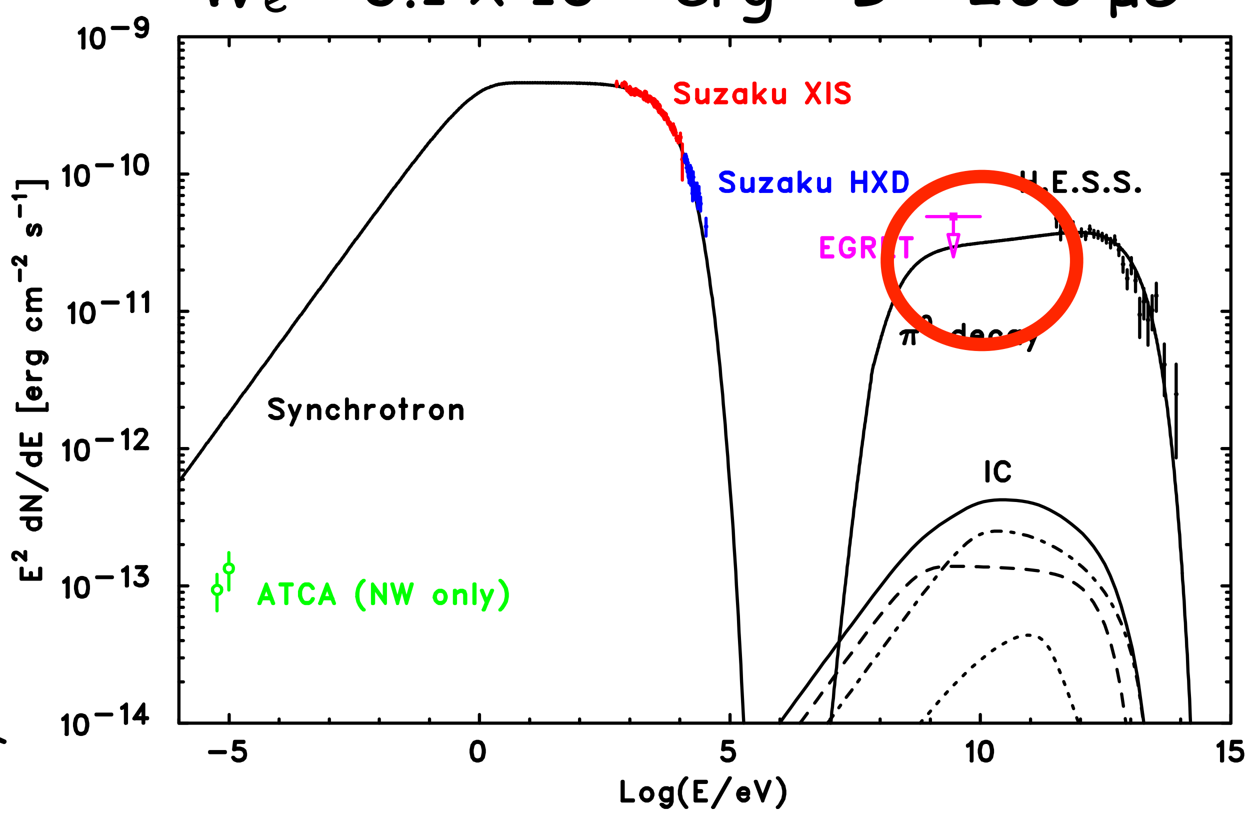
# Hadronic versus leptonic emission

## RXJ1713: hadronic and leptonic models

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

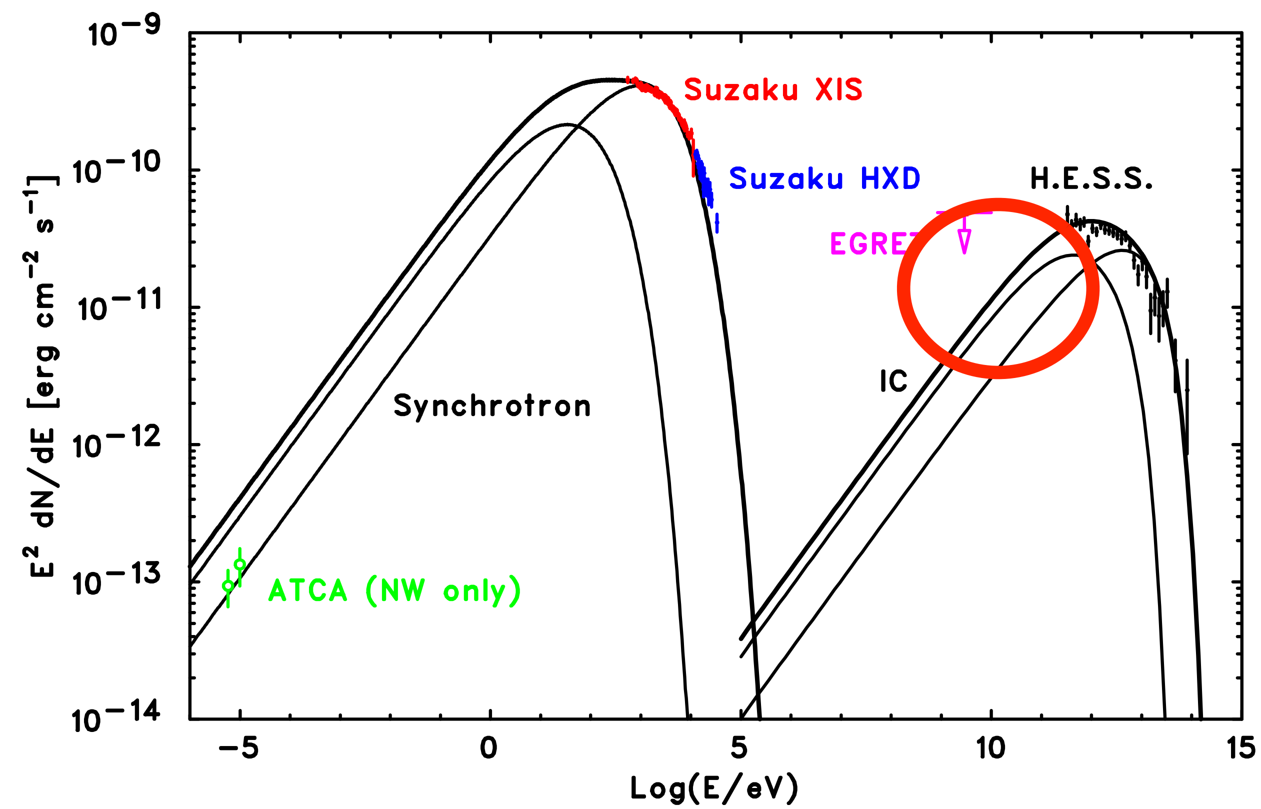
**Leptonic:** low B field -> synchrotron losses negligible -> electron spectrum $E^{-2}$ -> inverse Compton scattering -> gamma ray spectrum $E^{-1.5}$

$W_p = 2{,}7 \times 10^{50}\ (n/cm^{-3})^{-1}$ erg
$W_e = 3.1 \times 10^{46}$ erg + B = 200 μG




**Hadronic**

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

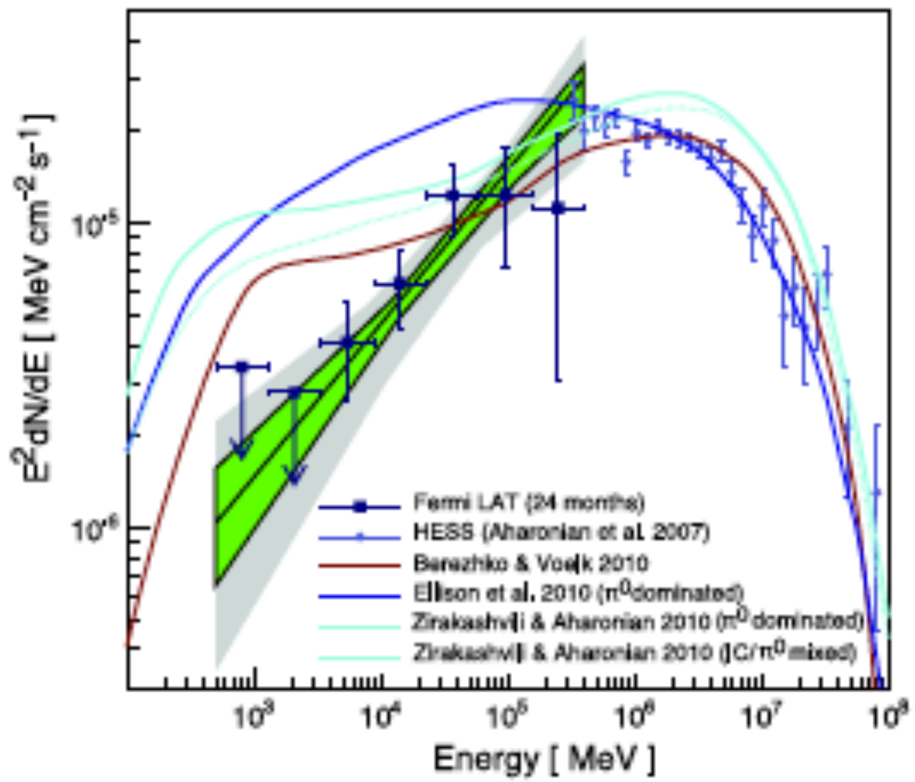



**Leptonic**

Tanaka et al., 2008

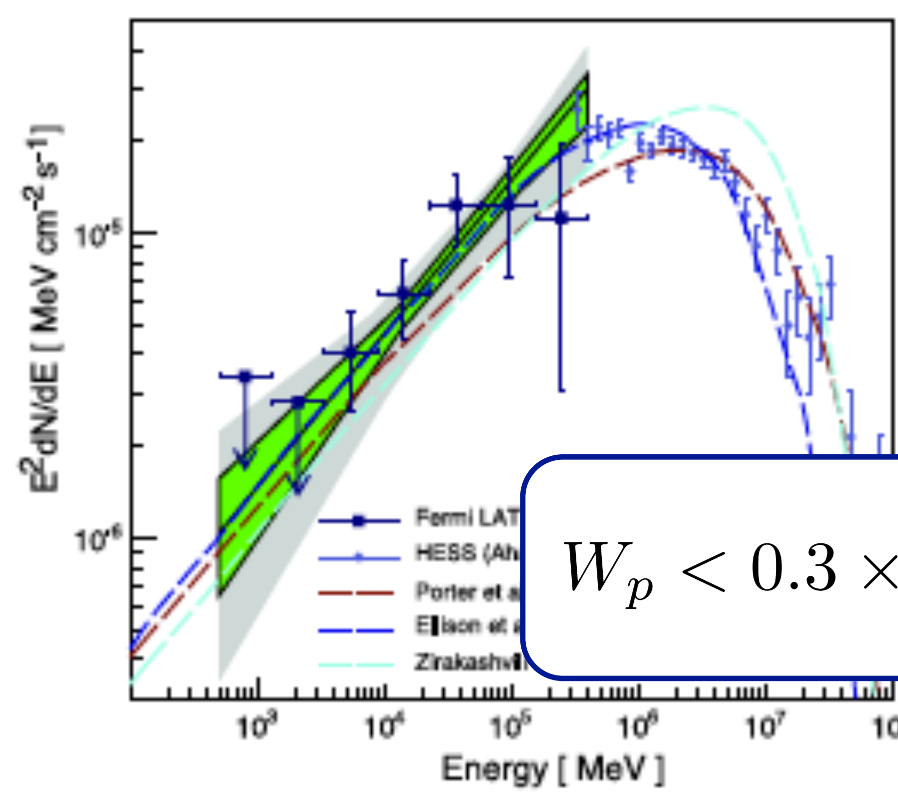
# FERMI detects RX J1713

p-p interactions ->




emission most likely LEPTONIC?

inverse Compton ->

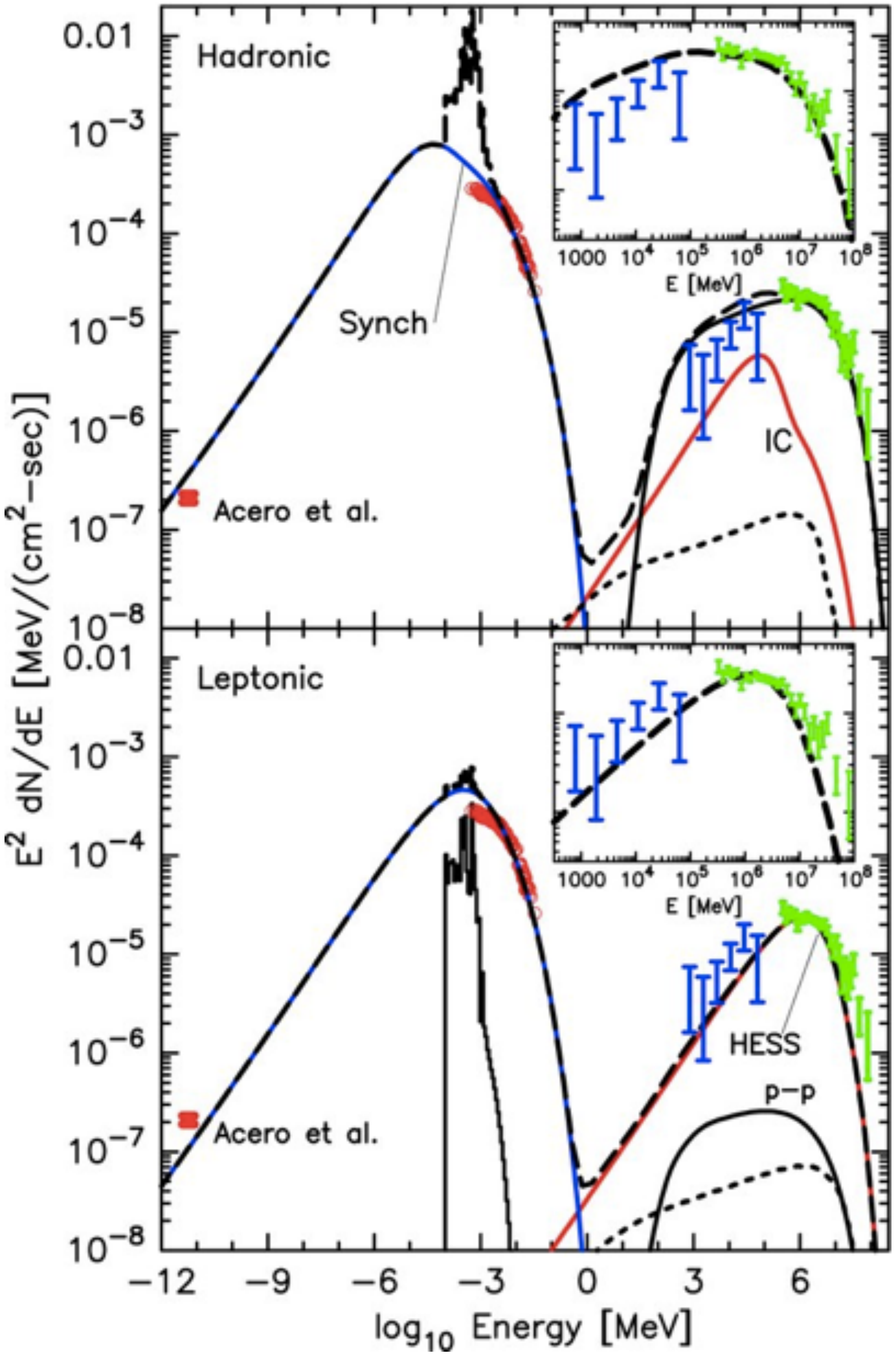



this does NOT mean that there are no protons!!!

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

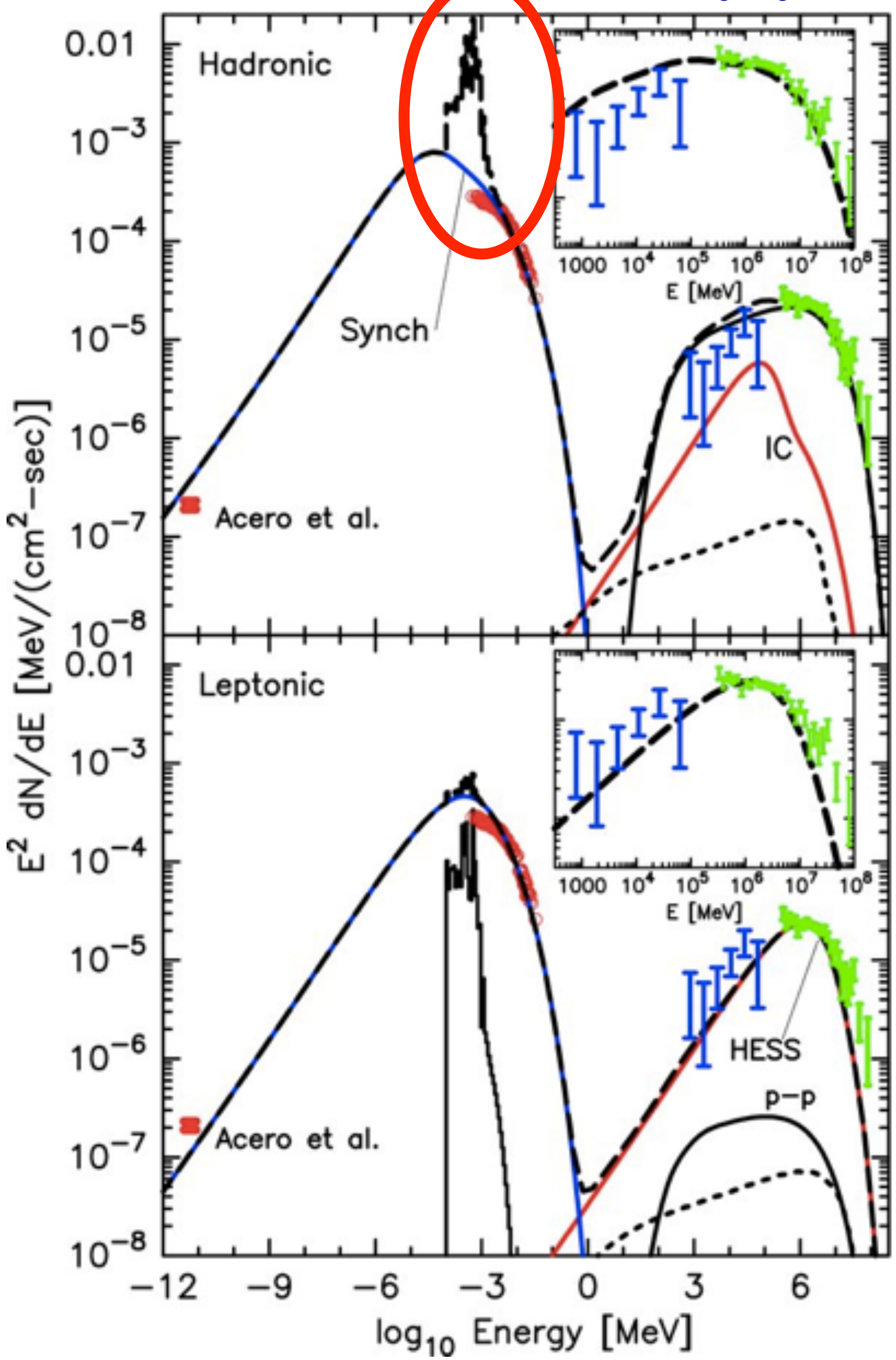
Abdo et al, 2011

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




(Ellison et al 2010)

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



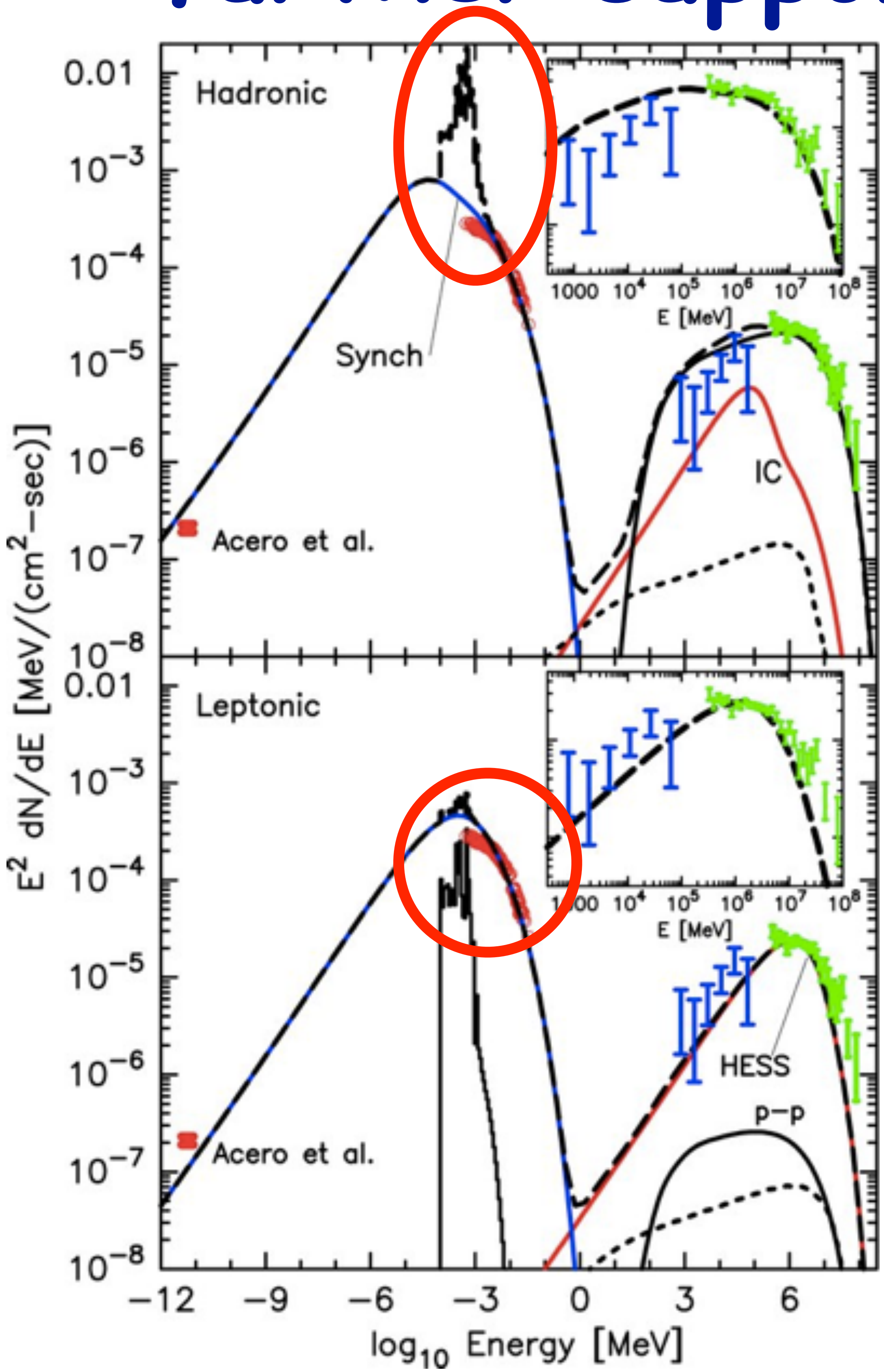

(Ellison et al 2010)

hadronic

high gas density + shock heating
-> bright X-ray thermal emission (lines)
-> NOT OBSERVED
(see also Katz&Waxman2008)

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

(Ellison et al 2010)




**hadronic**

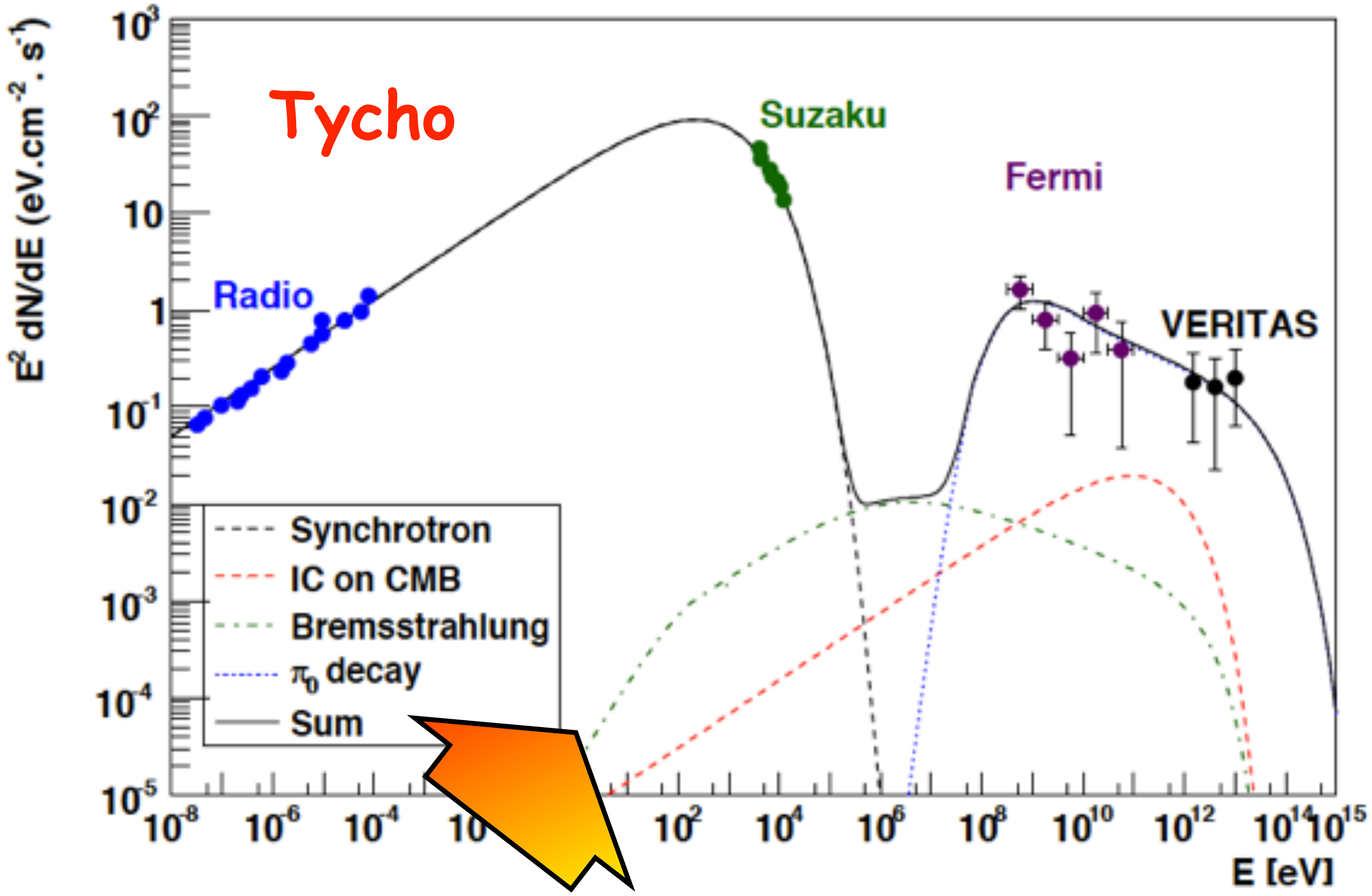
high gas density + shock heating
-> bright X-ray thermal emission (lines)
**-> NOT OBSERVED**
(see also Katz&Waxman2008)

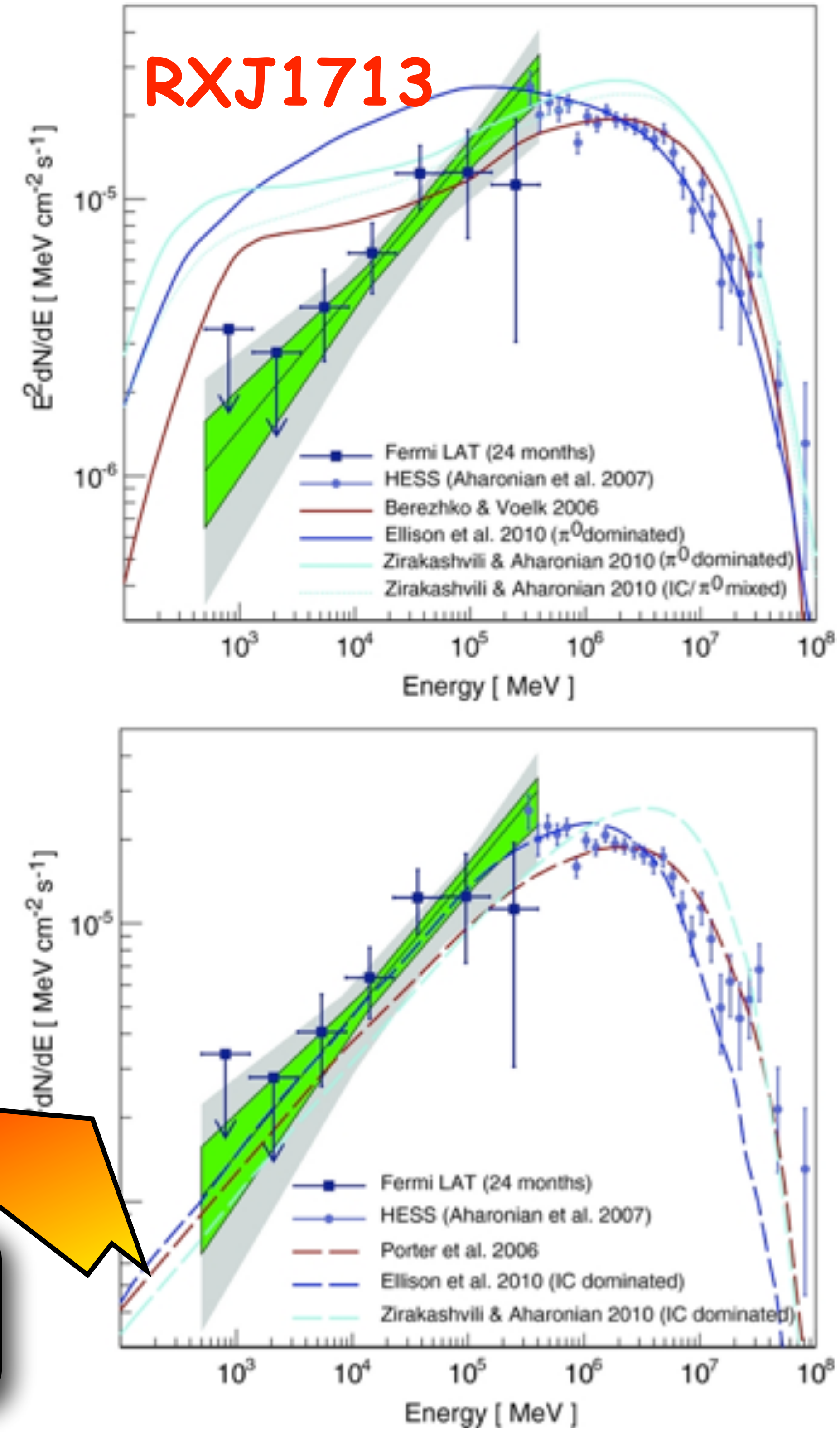
**leptonic**

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)




(Abdo et al 2010)

steep (2.3) -> hadronic?

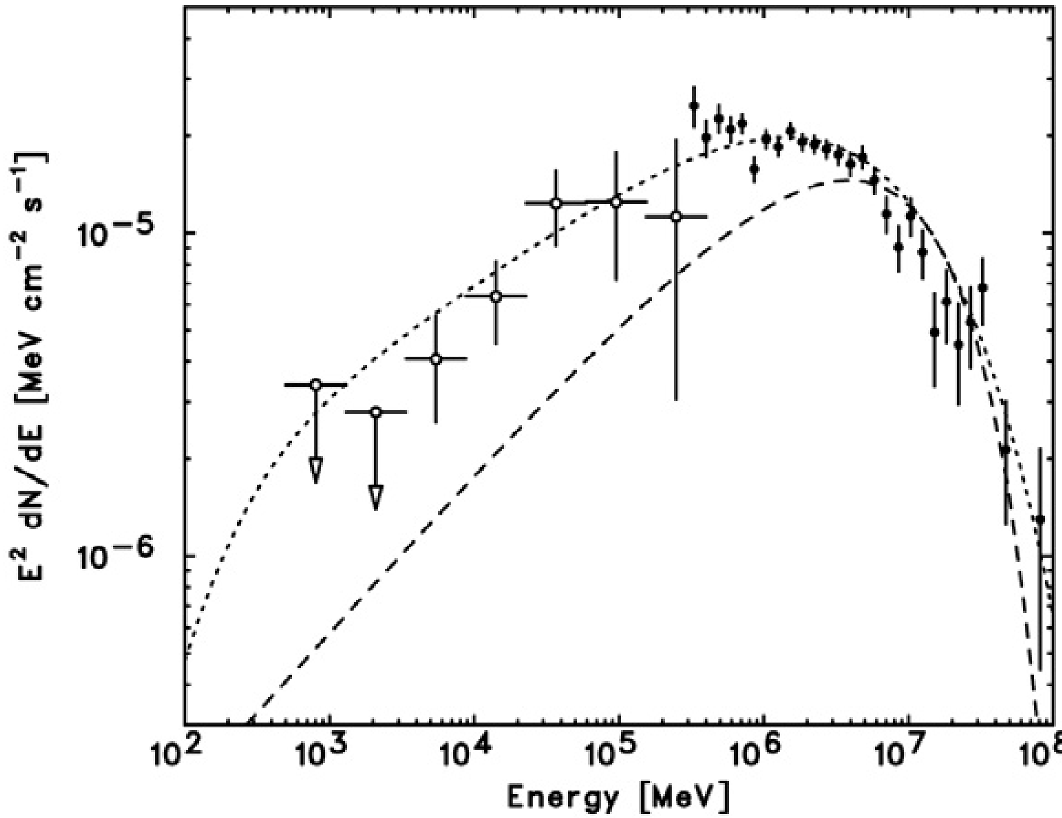
hard (1.5) -> leptonic?

# 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 $E_{cool}$



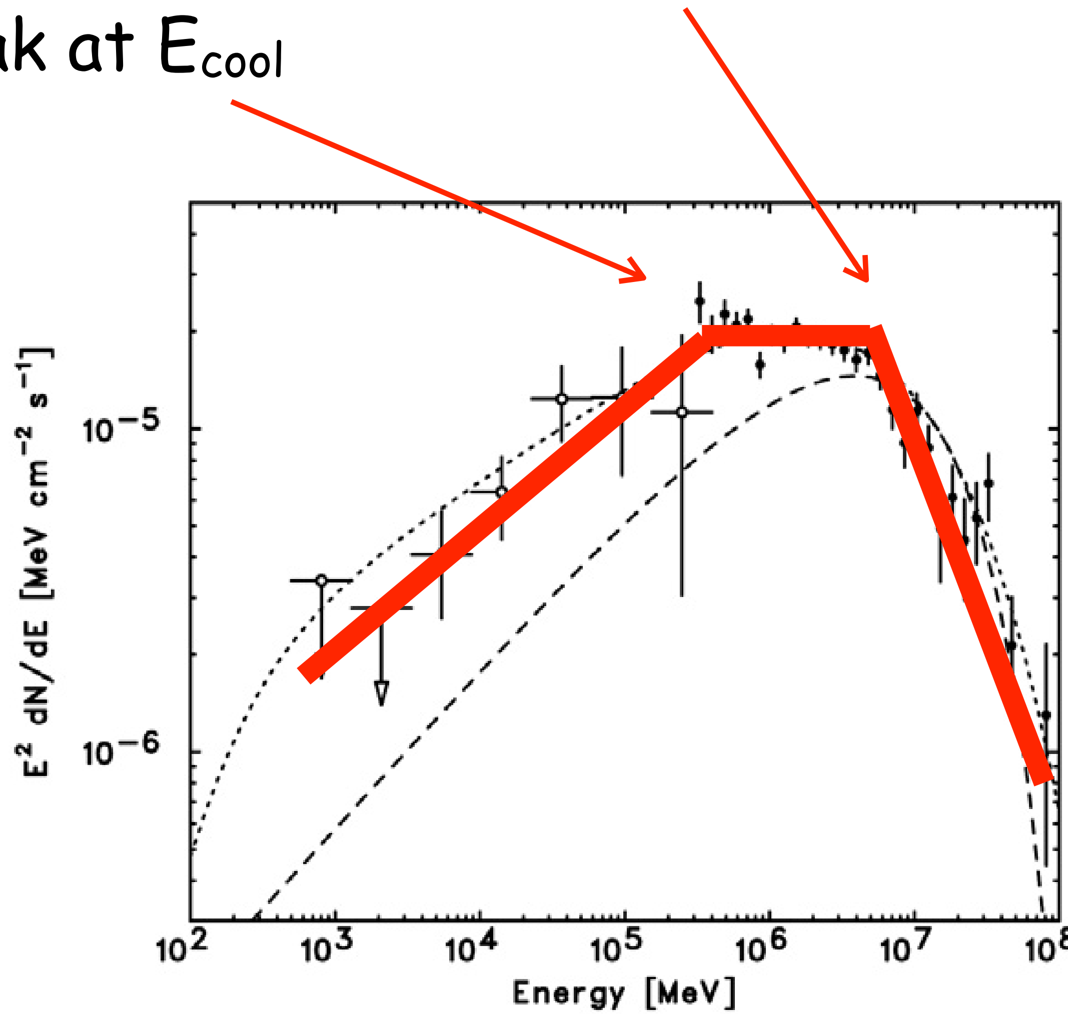

(Aharonian 2013)

# 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 $E_{cool}$




(Aharonian 2013)

# RXJ1713: difficulties of one-zone leptonic models

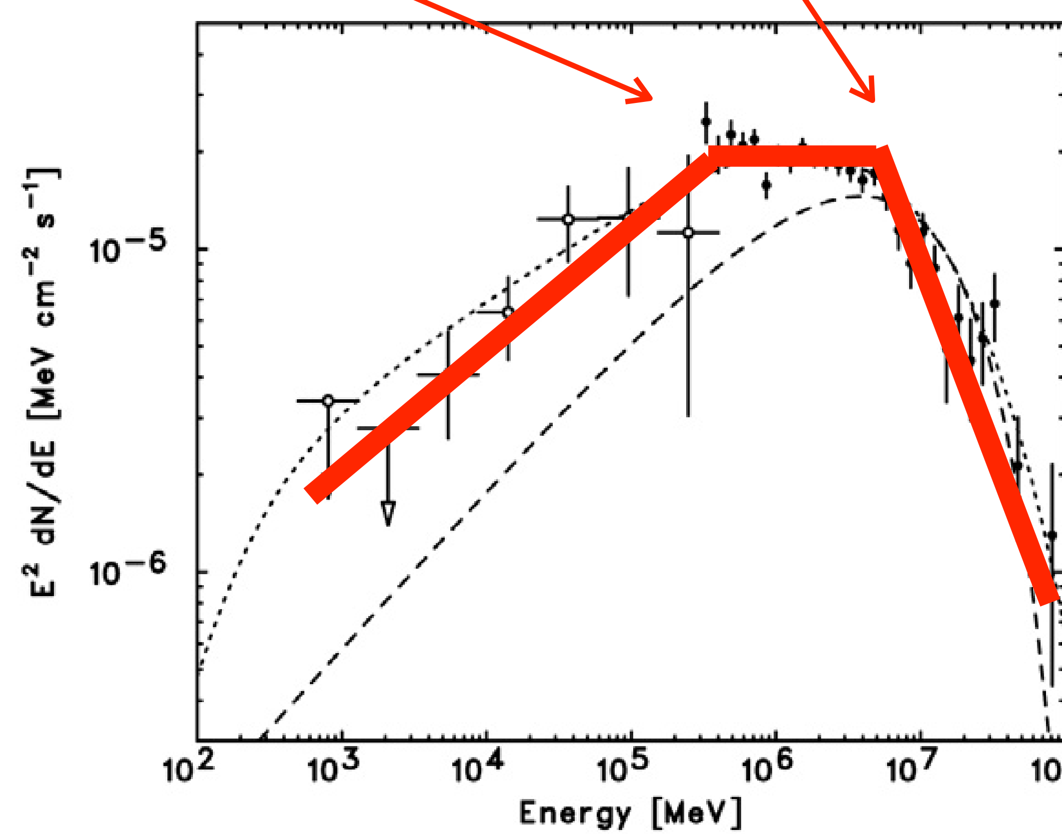
**two features in the electron spectrum:**

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

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

**BUT!**

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



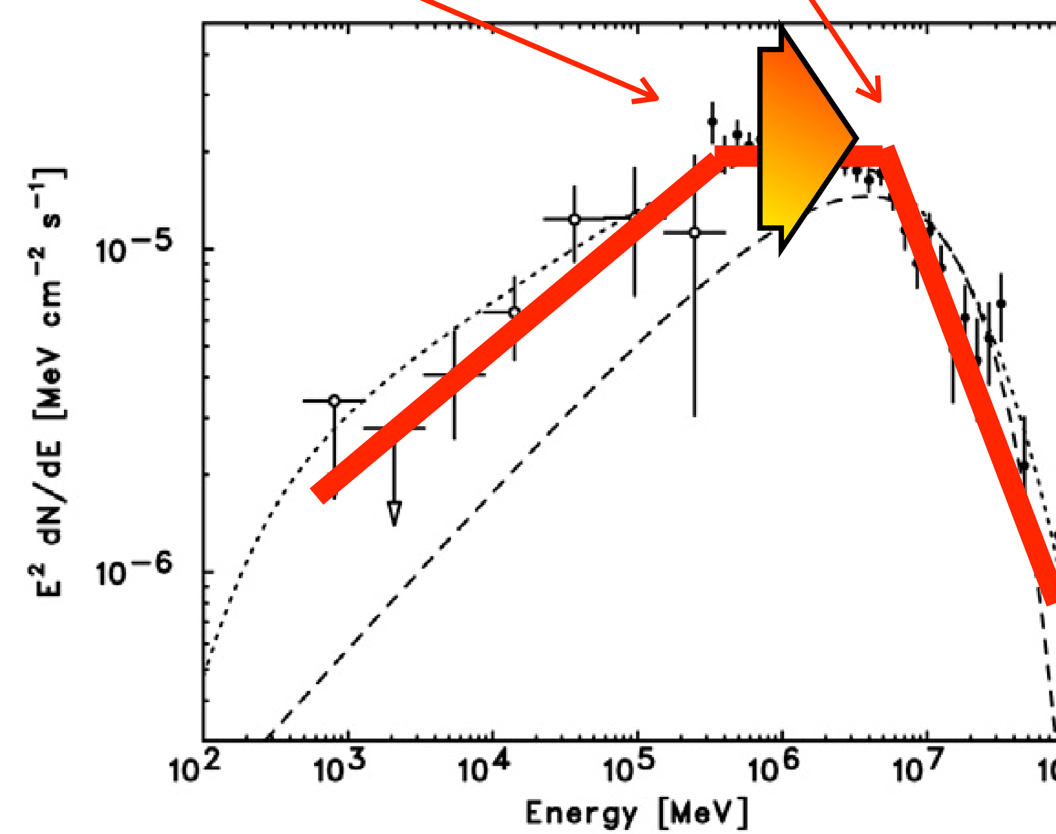

(Aharonian 2013)

# 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 $E_{cool}$




(Aharonian 2013)

BUT!

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

THUS...

**no cooling break** is expected...

# RXJ1713: difficulties of one-zone leptonic models

**two features in the electron spectrum:**

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

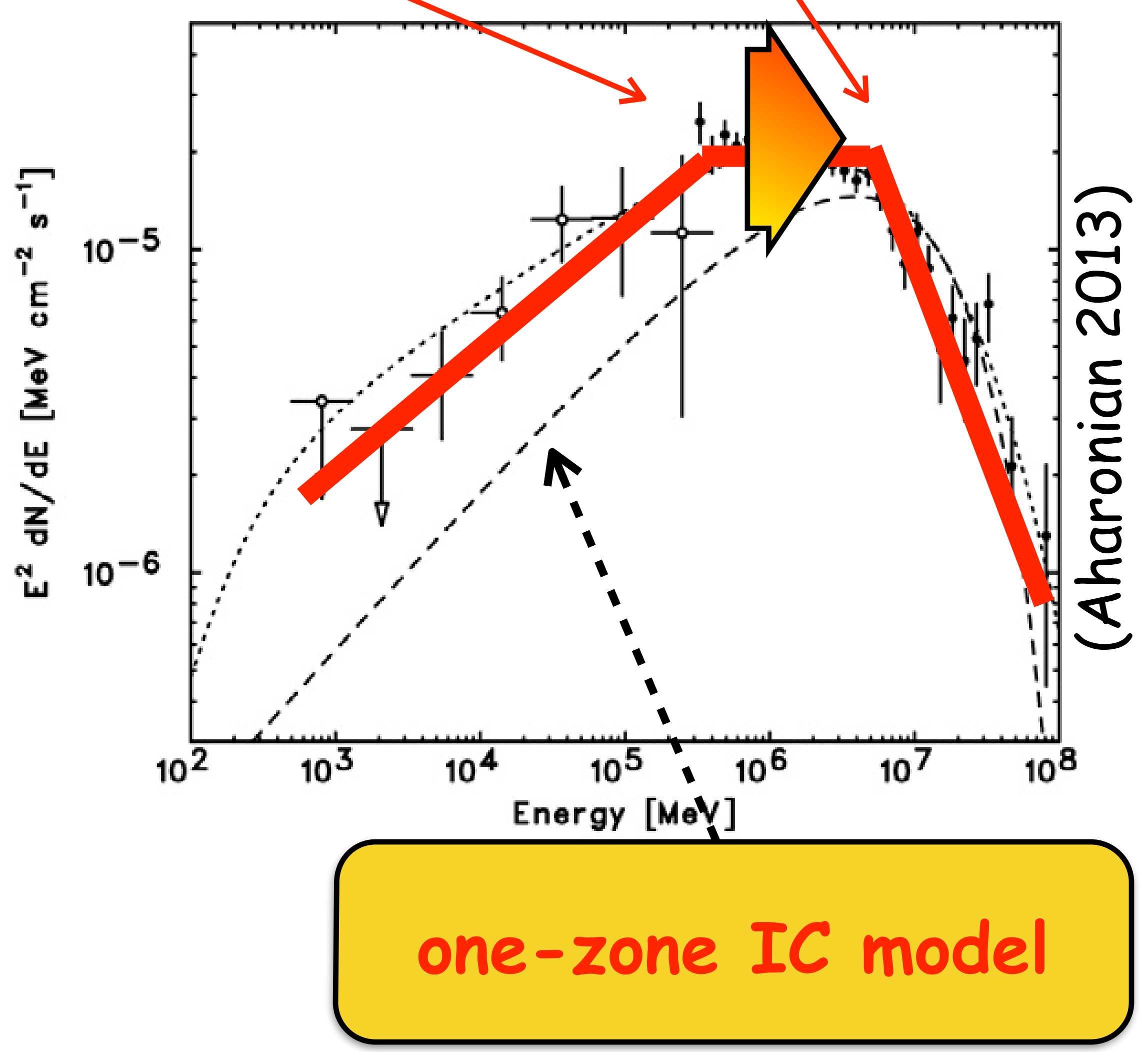
SNR age = synchrotron loss time -> cooling break at $E_{cool}$

BUT!

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

THUS...

**no cooling break** is expected...



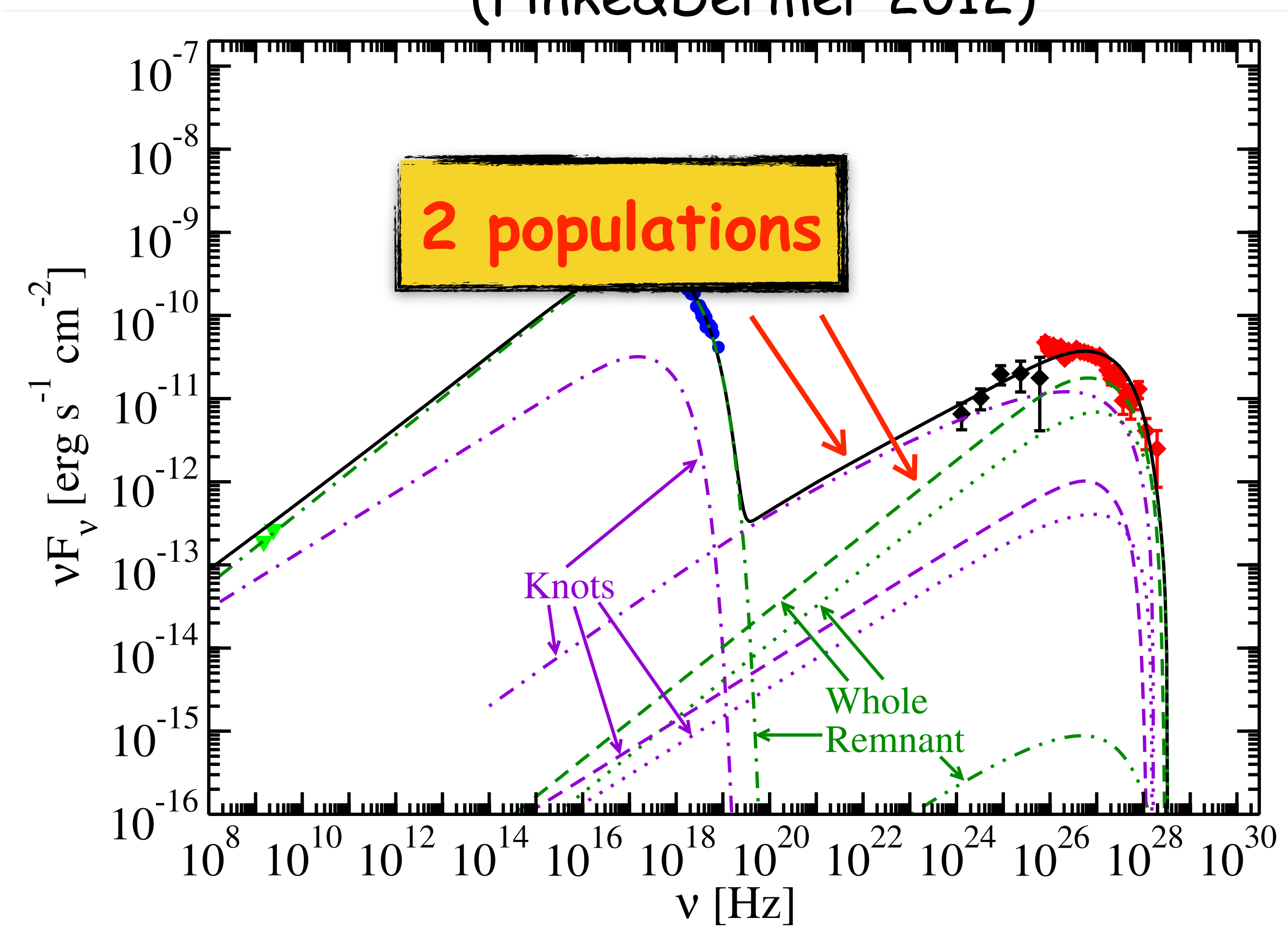
# RXJ1713: difficulties of one-zone leptonic models

(Finke&Dermer 2012)

tw

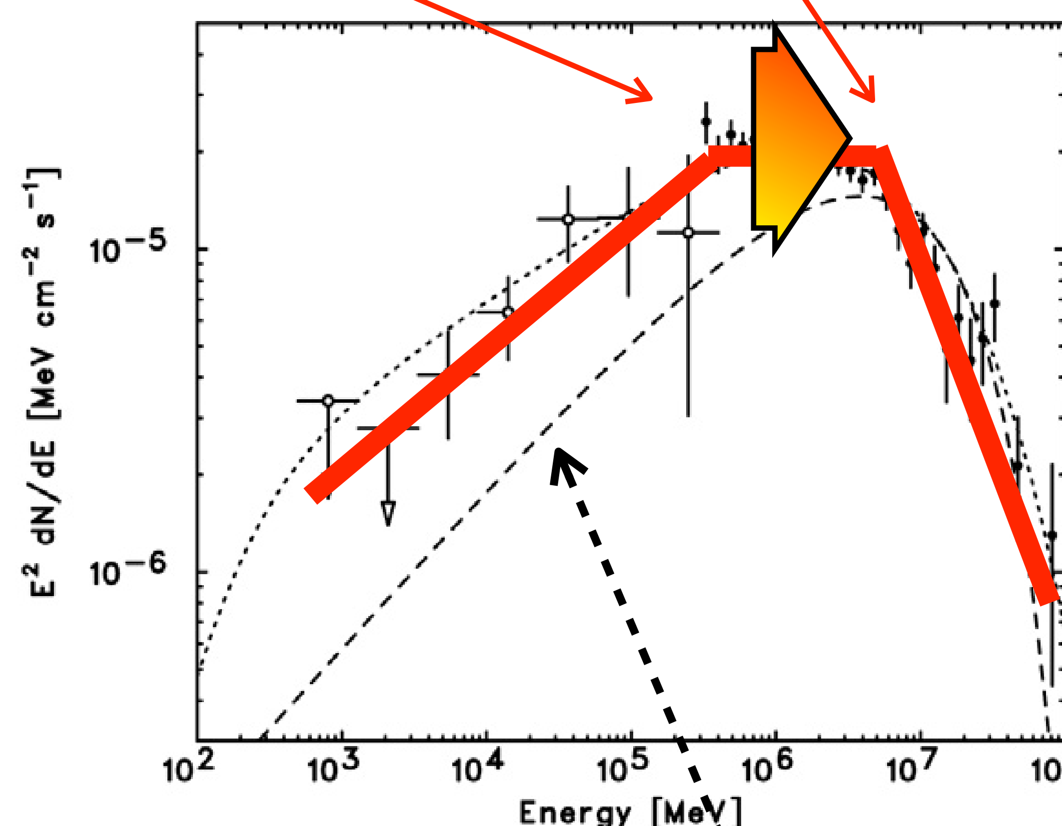
ac

SN




acceleration cutoff at $E_{max}$

break at $E_{cool}$




(Aharonian 2013)

one-zone IC model

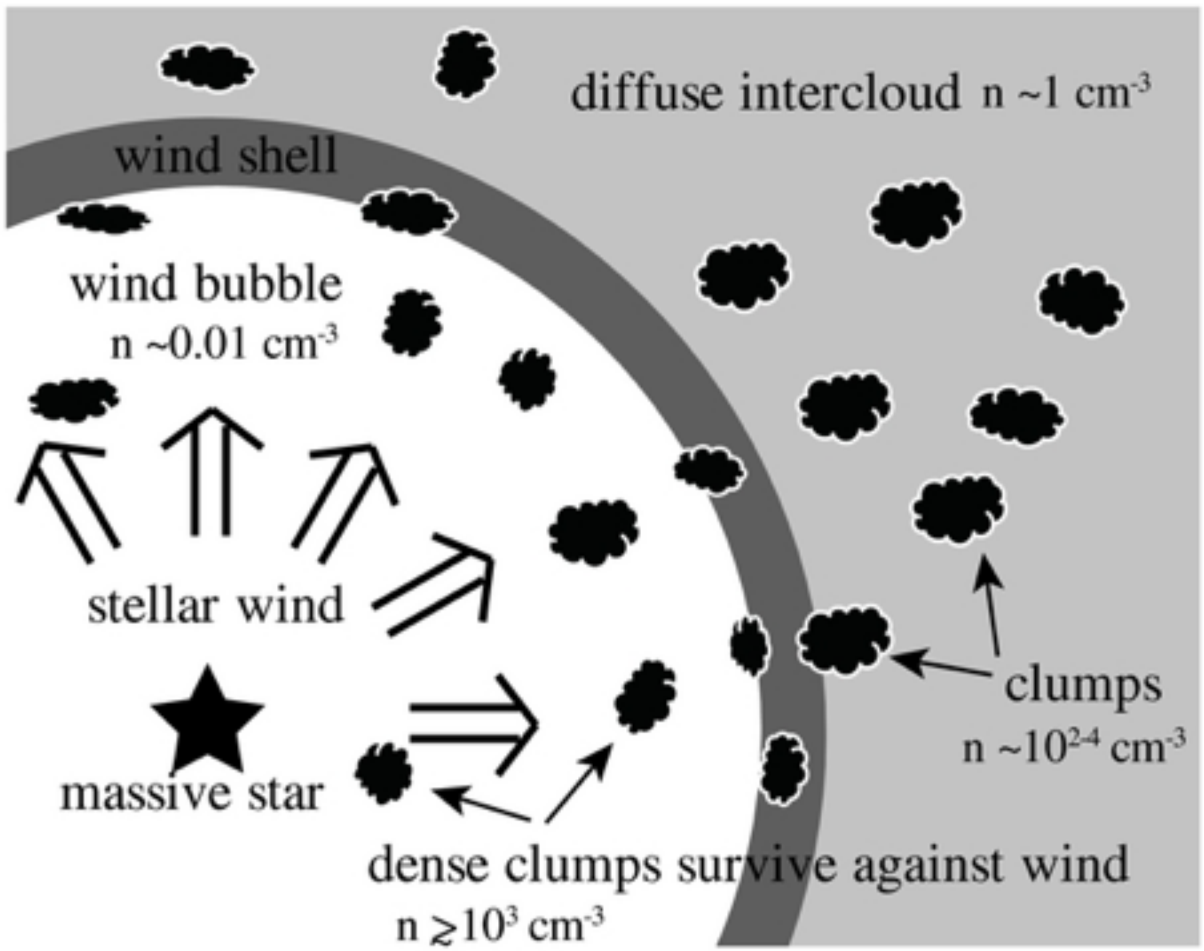
THUS...

no cooling break is expected...

# 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

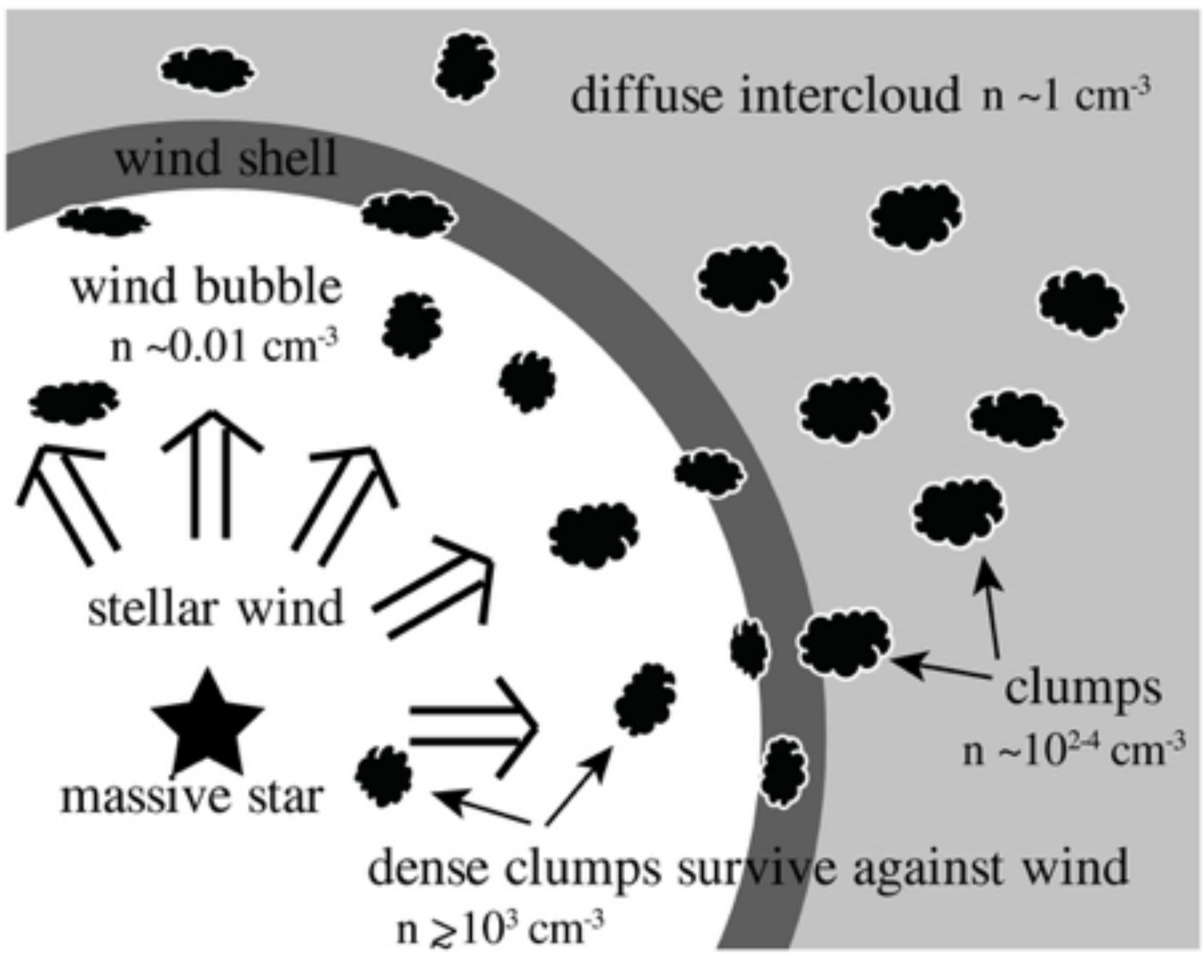
dense clumps survive (unshocked) both the stellar wind and the SNR shock

**no thermal X-rays!**

# A hadronic model for RXJ1713

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

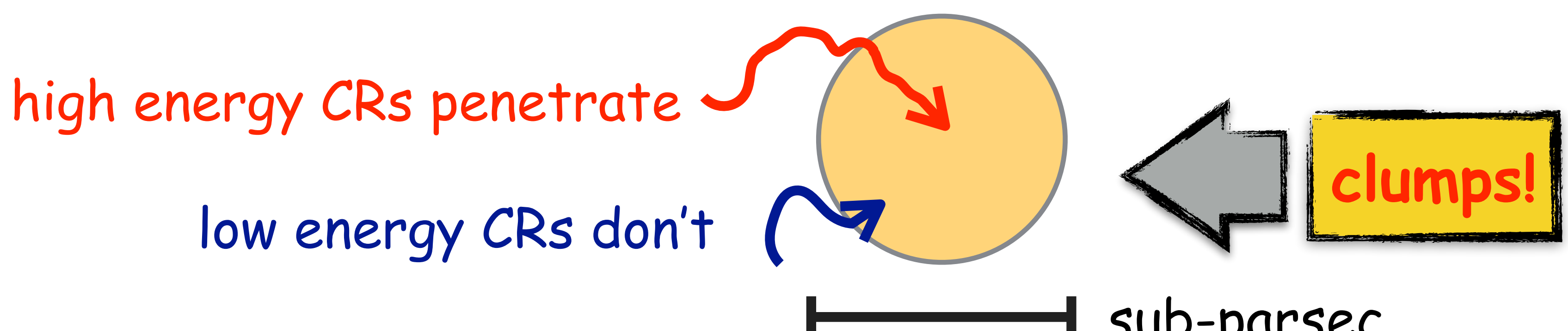
**SNR in a dense (and clumpy!) environment**




stellar wind sweeps the gas and creates a cavity

dense clumps survive (unshocked) both the stellar wind and the SNR shock

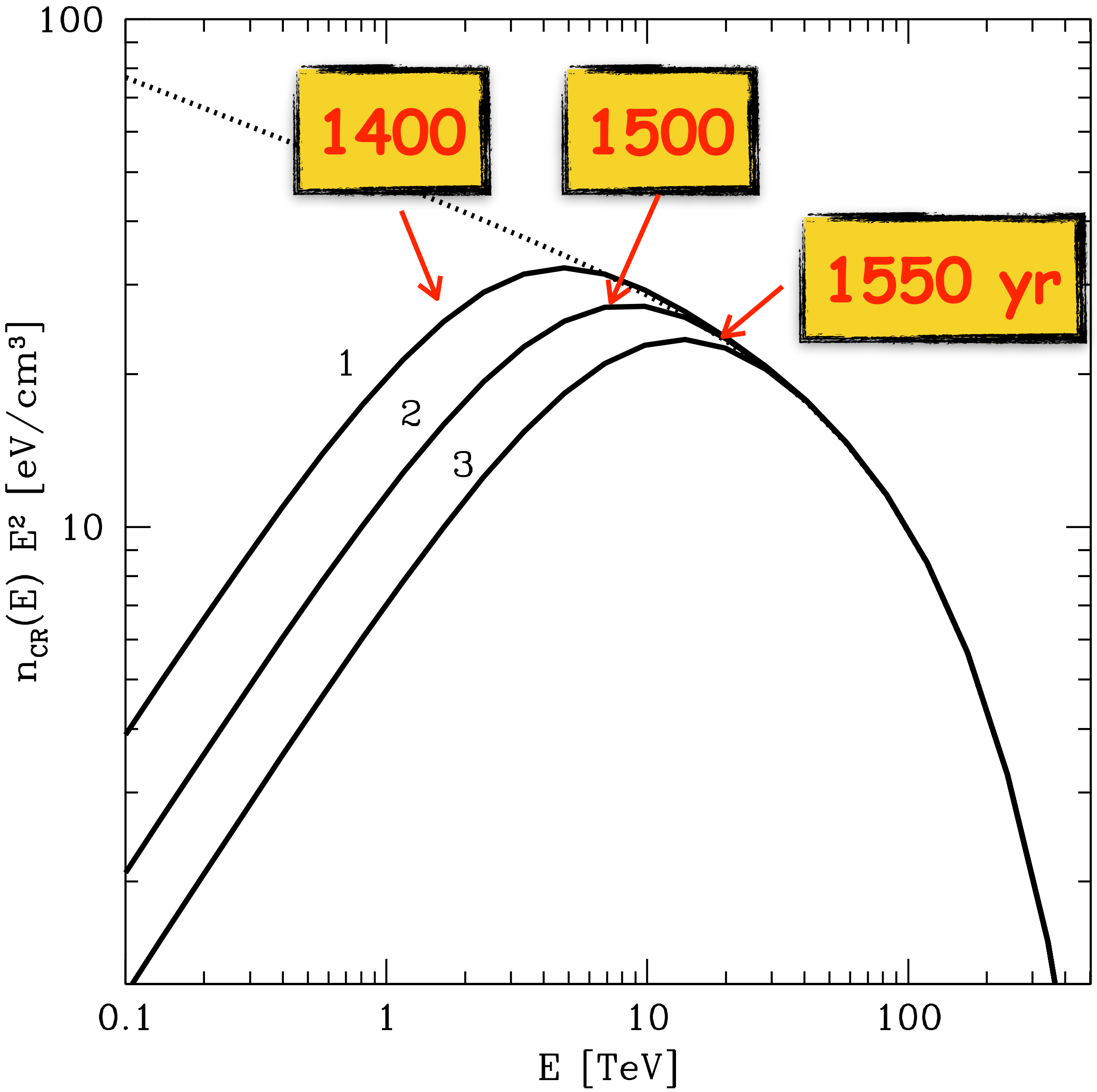
**no thermal X-rays!**

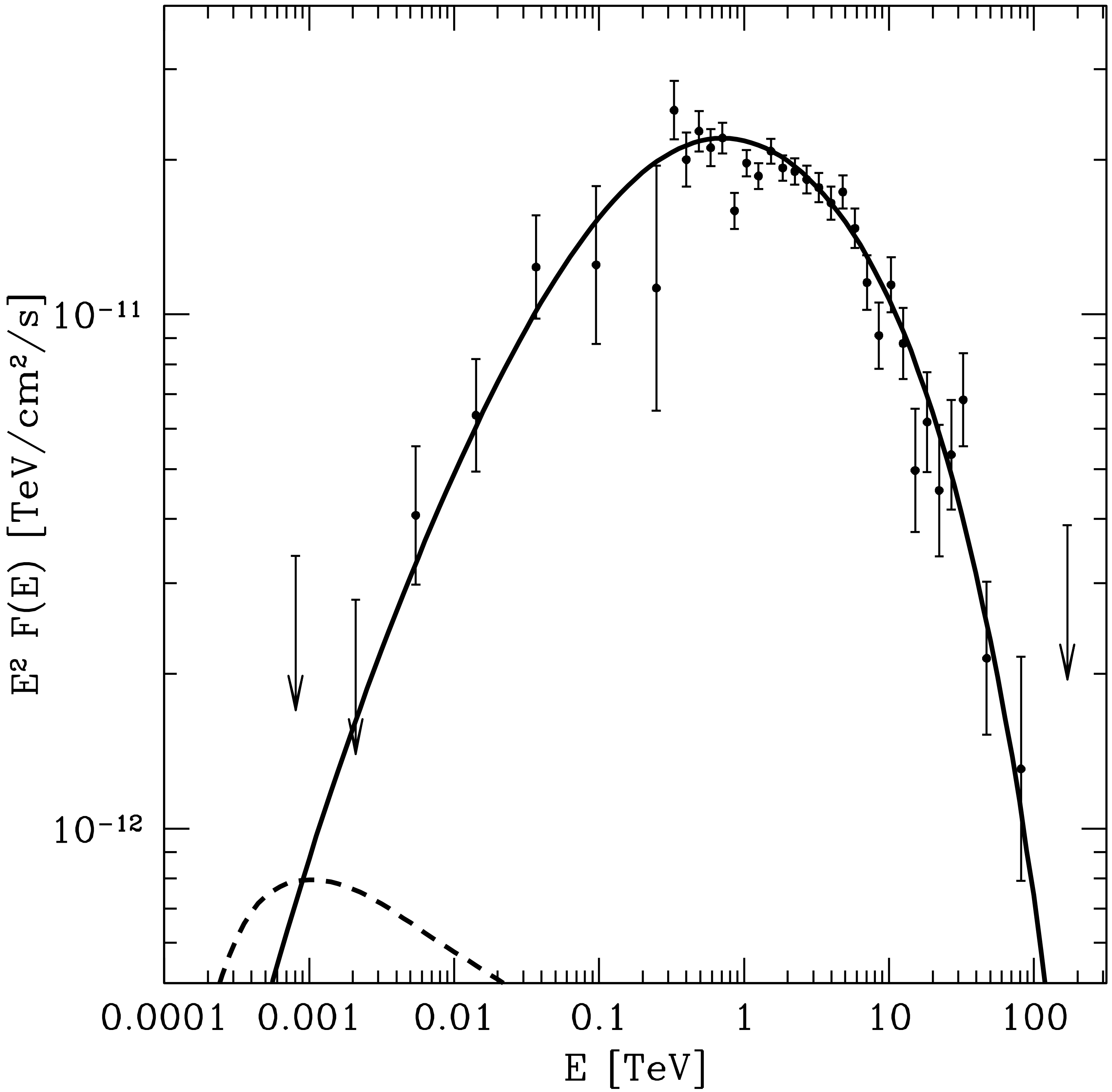


# A hadronic model for RXJ1713

Gabici & Aharonian 2014

age -> ~1620 yr

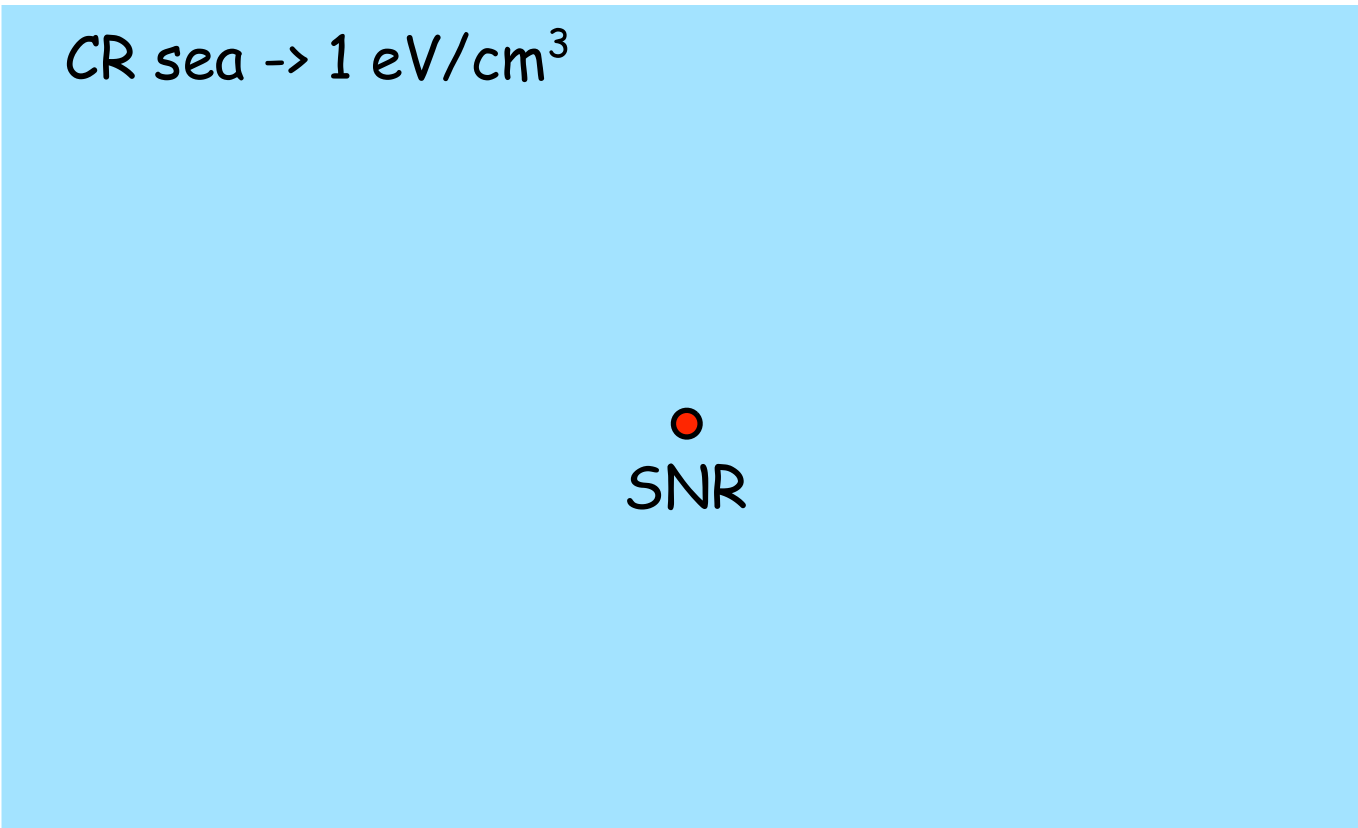


# Overview of the talk

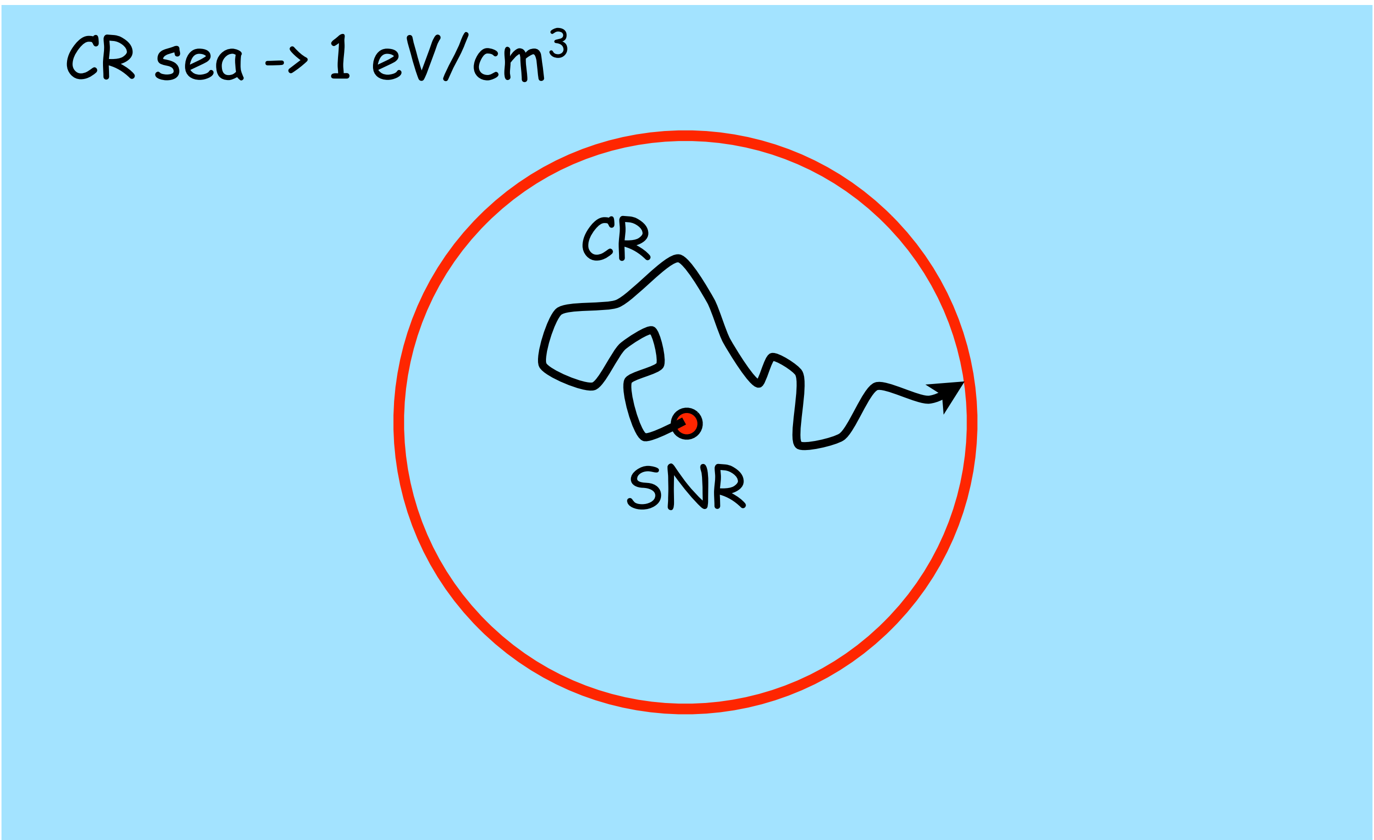
- The GeV and TeV sky look much different
- The link between gamma-ray astronomy and cosmic rays
- SuperNova Remnants in gamma rays:hadronic or leptonic?
- Hadronic/leptonic signatures 1 - the pion bump
- Hadronic/leptonic signatures 2 - the spectral shape(?)
- Hadronic/leptonic signatures 3 - gamma/gas correlations
- Hadronic/leptonic signatures 4 - the multi-TeV domain
- Gamma-ray based tests for the origin of cosmic rays
- What's next? CTA, HAWC, HiScore, LHAASO …

# At some point CRs escape SNRs




$$E_{CR}^{SNR} = \ 10^{50} \mathrm{erg}$$

# At some point CRs escape SNRs



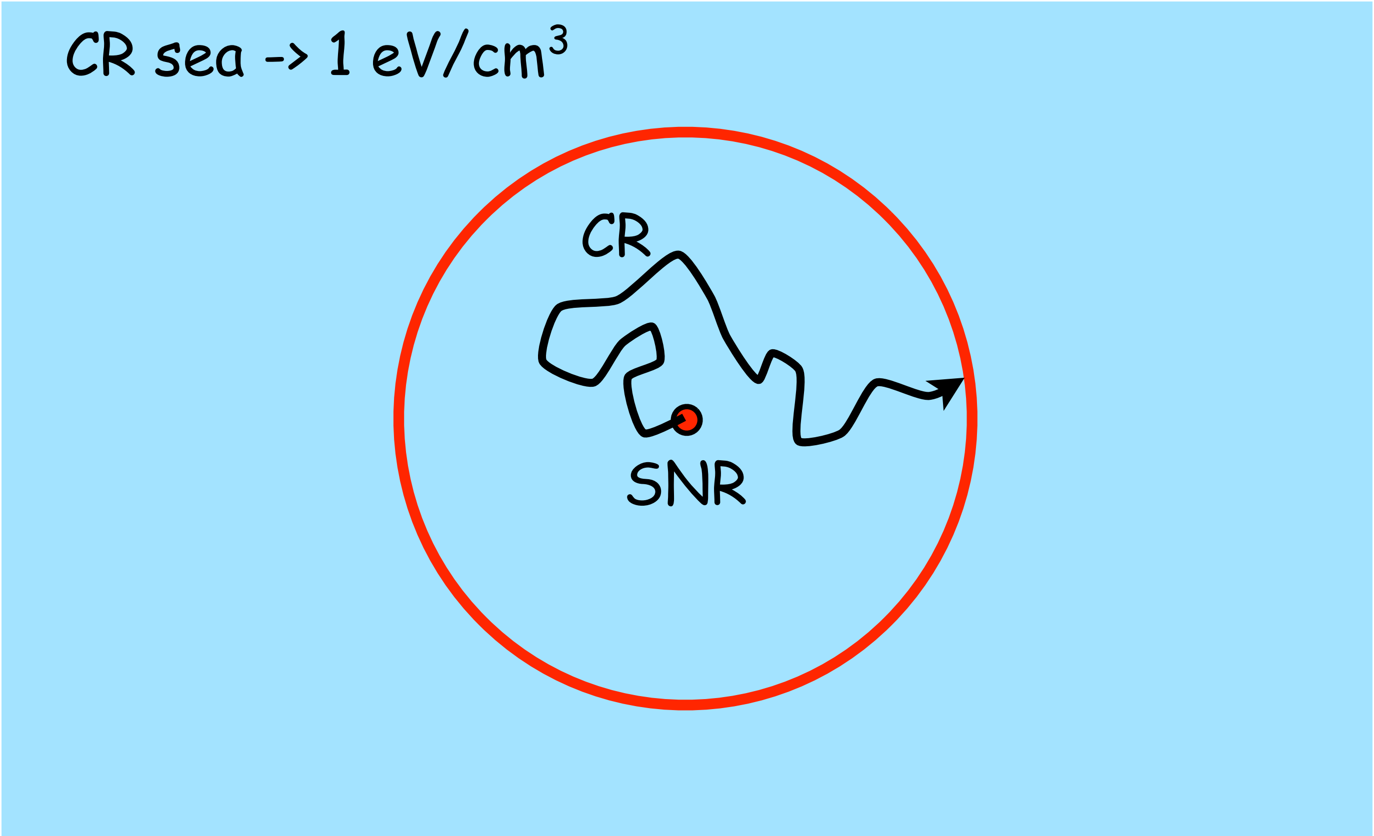

$$E_{CR}^{SNR} = 10^{50} \mathrm{erg}$$

volume affected by CRs from the SNR

$$\frac{E_{CR}^{SNR}}{\left(\frac{4\pi}{3} R_{CR}^3\right)} = 1 \ \mathrm{eV/cm^3}$$

$$\Rightarrow \quad R_{CR} \approx 100 \ \mathrm{pc}$$

# At some point CRs escape SNRs




$$E_{CR}^{SNR} = 10^{50}\text{erg}$$

volume affected by CRs from the SNR

$$\frac{E_{CR}^{SNR}}{\left(\frac{4\pi}{3}\ R_{CR}^3\right)} = 1\ \text{eV/cm}^3$$

$$\Rightarrow \quad R_{CR} \approx 100\ \text{pc}$$

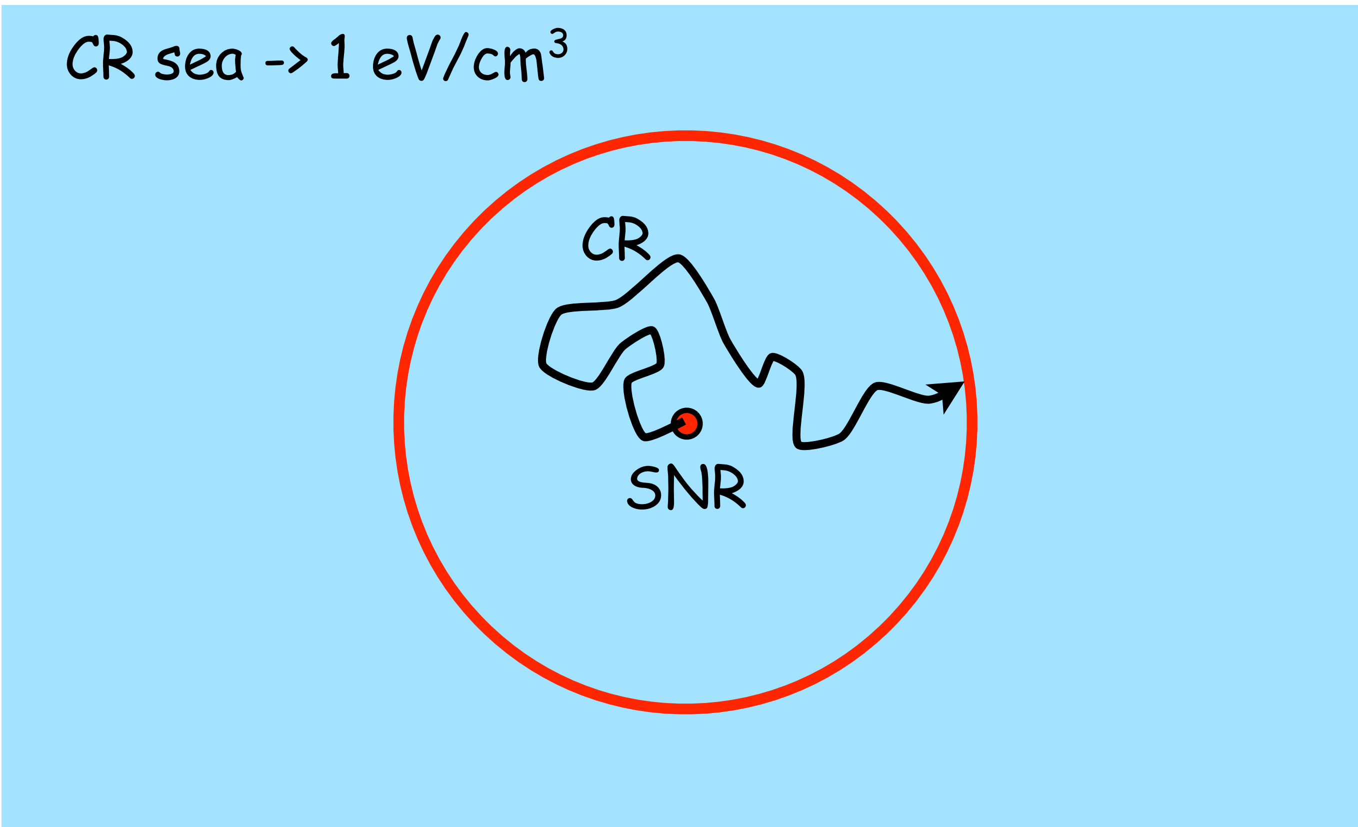
such a volume is affected for a time:

$$D = 10^{28}\left(\frac{E}{10\ \text{GeV}}\right)^{0.6}\text{cm}^2/\text{s} \quad \Rightarrow \quad D(1\ \text{TeV}) \approx 2\times 10^{29}\ \text{cm}^2/\text{s}$$

$$t \approx \frac{R_{CR}^2}{D} \approx 10^4\ \text{yr}$$

# At some point CRs escape SN

Very rough!




$$E_{CR}^{SNR} = 10^{50}\text{erg}$$

volume affected by CRs from the SNR

$$\frac{E_{CR}^{SNR}}{\left(\frac{4\pi}{3} R_{CR}^3\right)} = 1 \text{ eV/cm}^3$$

$$\Rightarrow \quad R_{CR} \approx 100 \text{ pc}$$

such a volume is affected for a time:

$$D = 10^{28} \left(\frac{E}{10 \text{ GeV}}\right)^{0.6} \text{cm}^2/\text{s} \quad \Rightarrow \quad D(1 \text{ TeV}) \approx 2 \times 10^{29} \text{ cm}^2/\text{s}$$

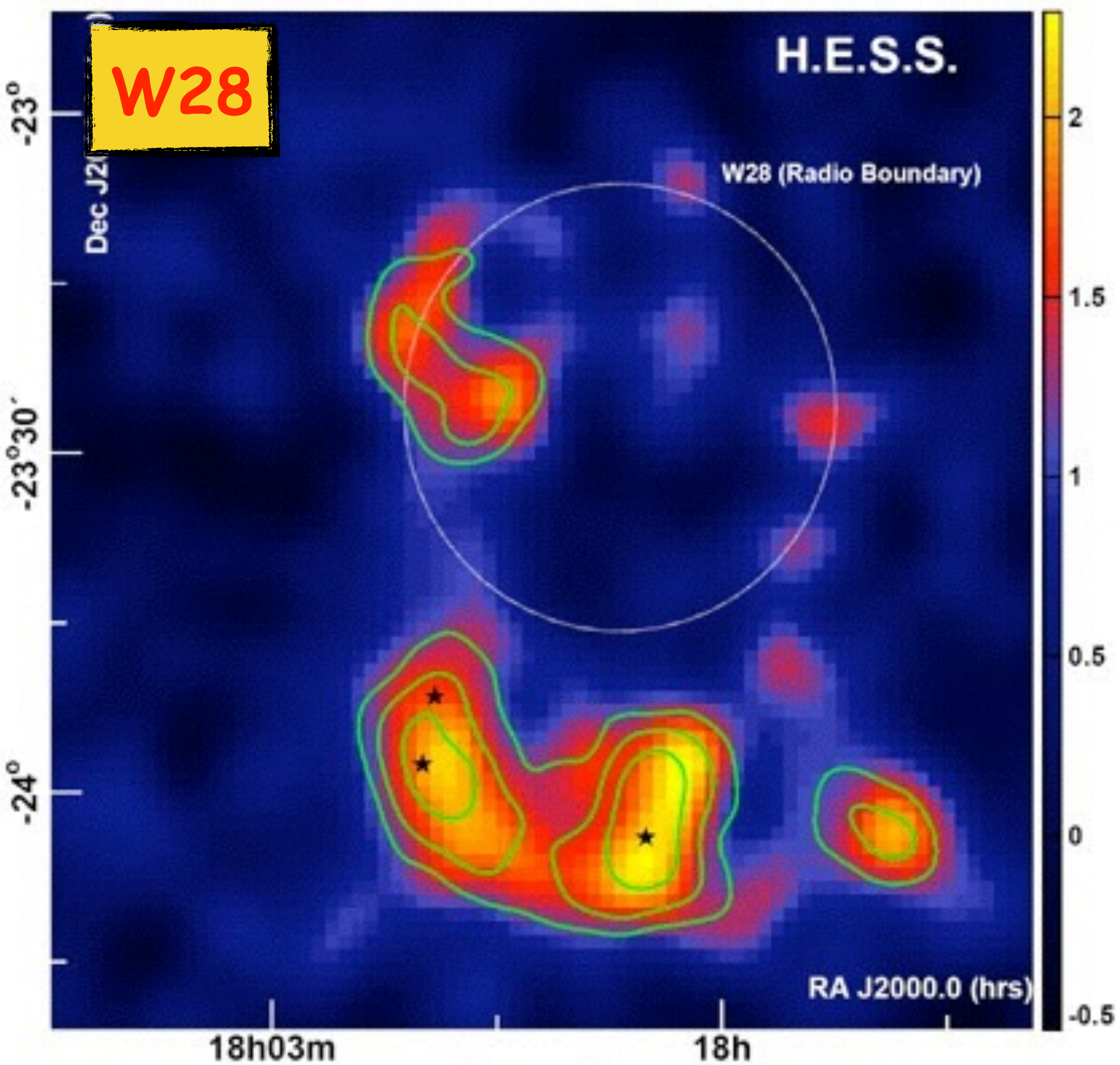
$$t \approx \frac{R_{CR}^2}{D} \approx 10^4 \text{ yr}$$

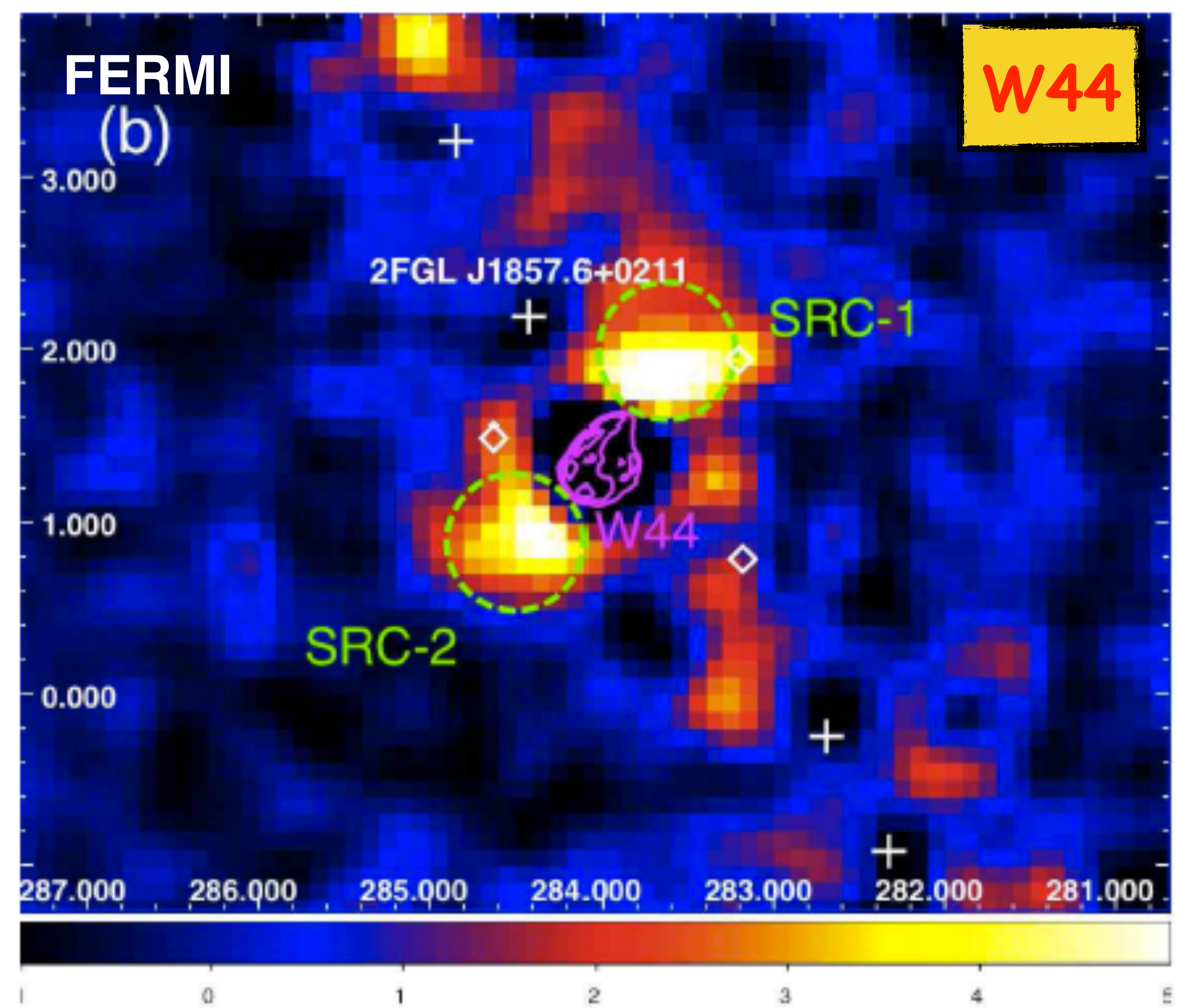
# Indirect evidence for protons: clouds

two oldish (several $10^4$ yr) SNRs

for a review see Gabici 2013

Aharonian et al. 2008



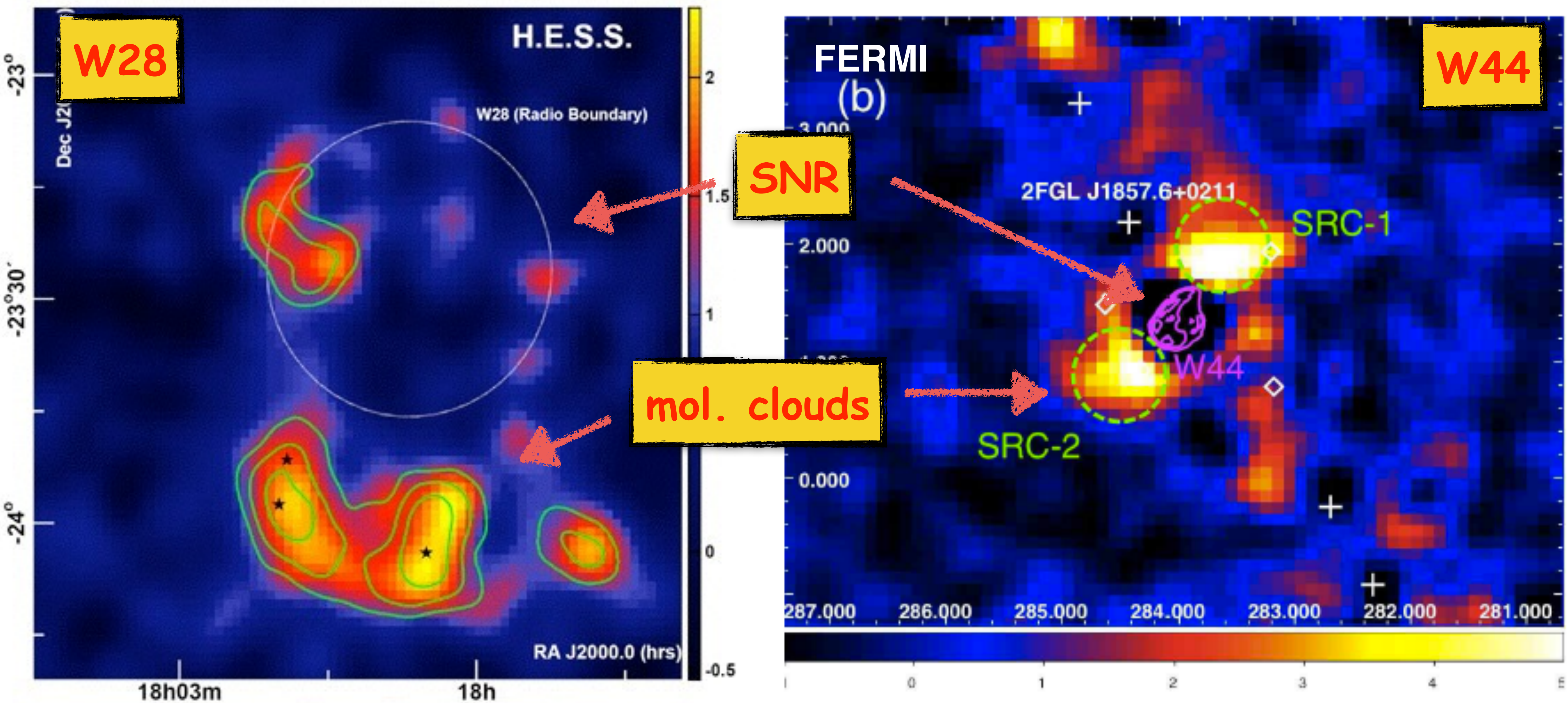

Uchiyama et al. 2012

# Indirect evidence for protons: clouds

two oldish (several $10^4$ yr) SNRs

for a review see Gabici 2013

Aharonian et al. 2008



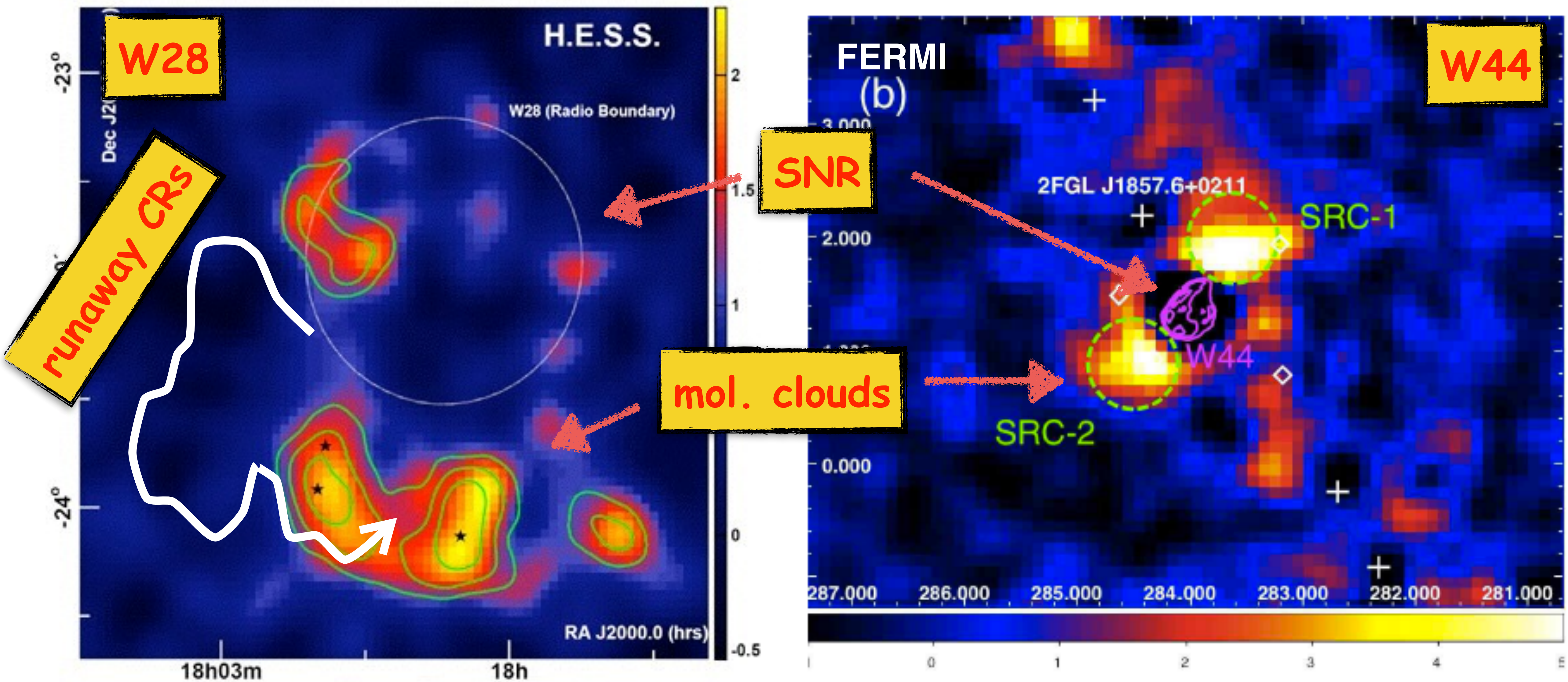

Uchiyama et al. 2012

# Indirect evidence for protons: clouds

**two oldish (several $10^4$ yr) SNRs**

for a review see Gabici 2013

Aharonian et al. 2008



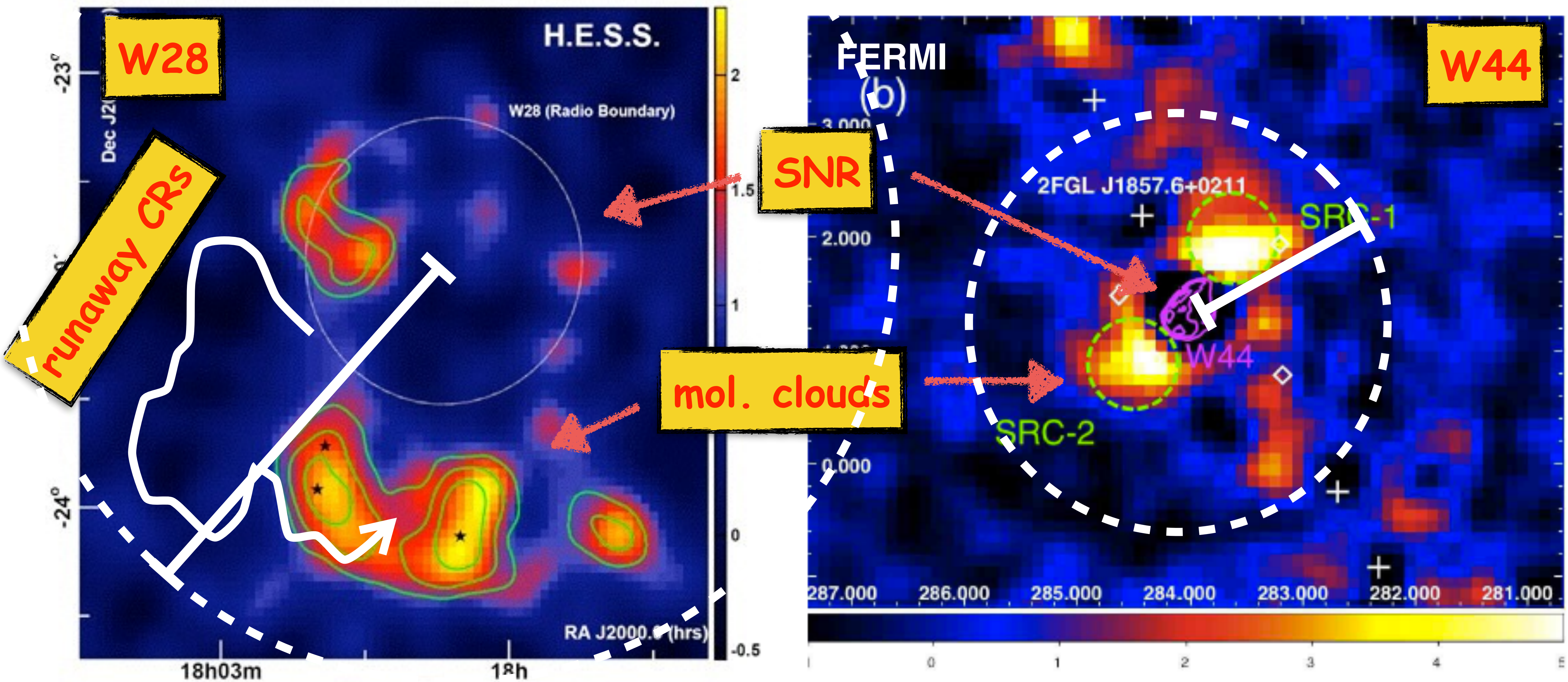

Uchiyama et al. 2012

# Indirect evidence for protons: clouds

two oldish (several $10^4$ yr) SNRs

for a review see Gabici 2013

Aharonian et al. 2008




Uchiyama et al. 2012

$$R_{diff} = \sqrt{6\ D\ t}$$

for theoretical modeling see Aharonian & Atoyan, Gabici+, Casanova+, Nava & Gabici, Torres+, Li & Chen, Ohira+, Fujita+, Ellison&Bykov ...

# Overview of the talk

- The GeV and TeV sky look much different
- The link between gamma-ray astronomy and cosmic rays
- SuperNova Remnants in gamma rays:hadronic or leptonic?
- Hadronic/leptonic signatures 1 - the pion bump
- Hadronic/leptonic signatures 2 - the spectral shape(?)
- Hadronic/leptonic signatures 3 - gamma/gas correlations
- Hadronic/leptonic signatures 4 - the multi-TeV domain
- Gamma-ray based tests for the origin of cosmic rays
- What's next? CTA, HAWC, HiScore, LHAASO ...

# The PeV domain:can we get to the knee?

Let's assume SNRs do accelerate up to the knee

p-p interactions -> $E^{p}_{max} \approx 4 \times 10^{15} \mathrm{eV} \longrightarrow E^{\gamma}_{max} \approx 400 \mathrm{TeV}$

inverse Compton-> suppressed above several tens of TeV (Klein-Nishina effect)

# The PeV domain:can we get to the knee?

Let's assume SNRs do accelerate up ...

p-p interactions -> $E^p$ ... eV $\longrightarrow E^{\gamma}_{max} \approx 400\mathrm{TeV}$

inver... ...ppressed above several tens of TeV (Klein-Nishina effect)

**testable with future gamma ray facilities: CTA, HAWC, HiSCORE, LHAASO**

# The PeV domain:can we get to the knee?

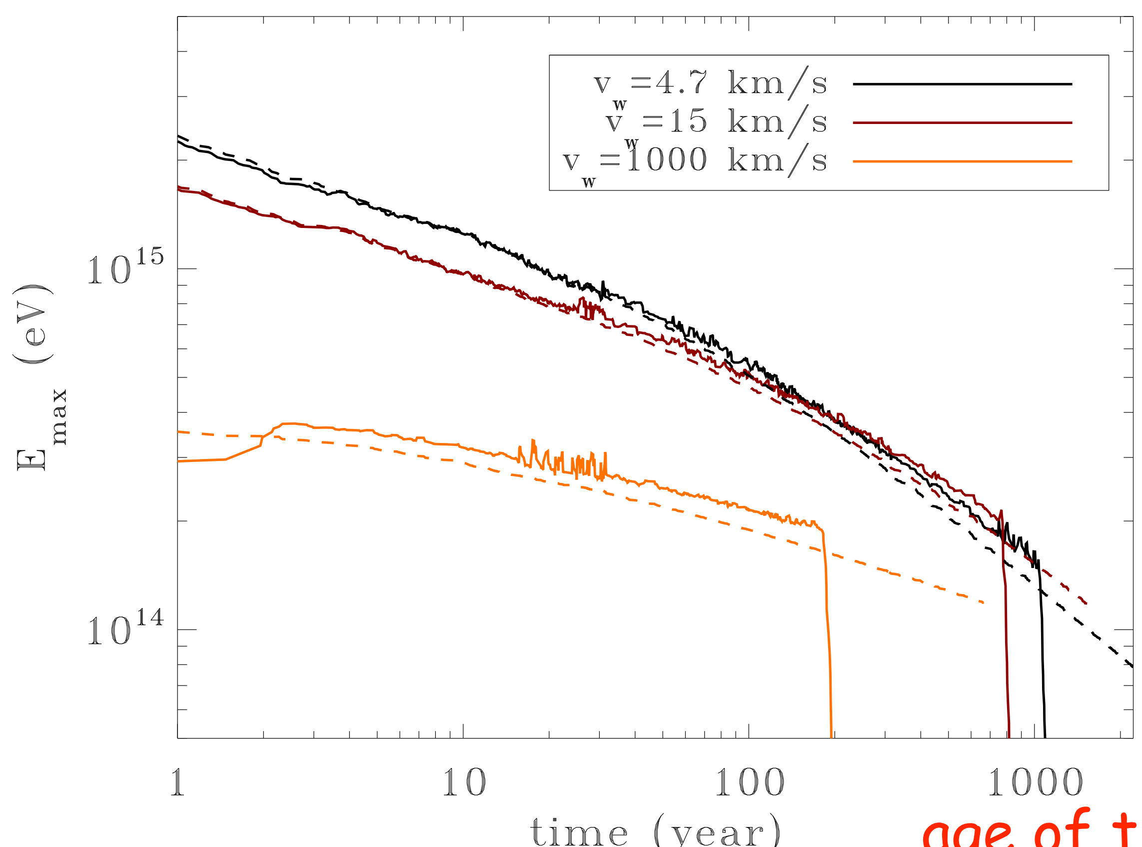
Let's assume SNRs do accelerate up...

p-p interactions -> $E^p$ ... eV $\longrightarrow E^{\gamma}_{max} \approx 400\text{TeV}$

inver... ...uppressed above several tens of TeV (Klein-Nishina effect)

testable with future gamma ray facilities: CTA, HAWC, HiSCORE, LHAASO

Theory




age of the SNR

Schure & Bell 2013/2014

# The PeV domain:can we get to the knee?

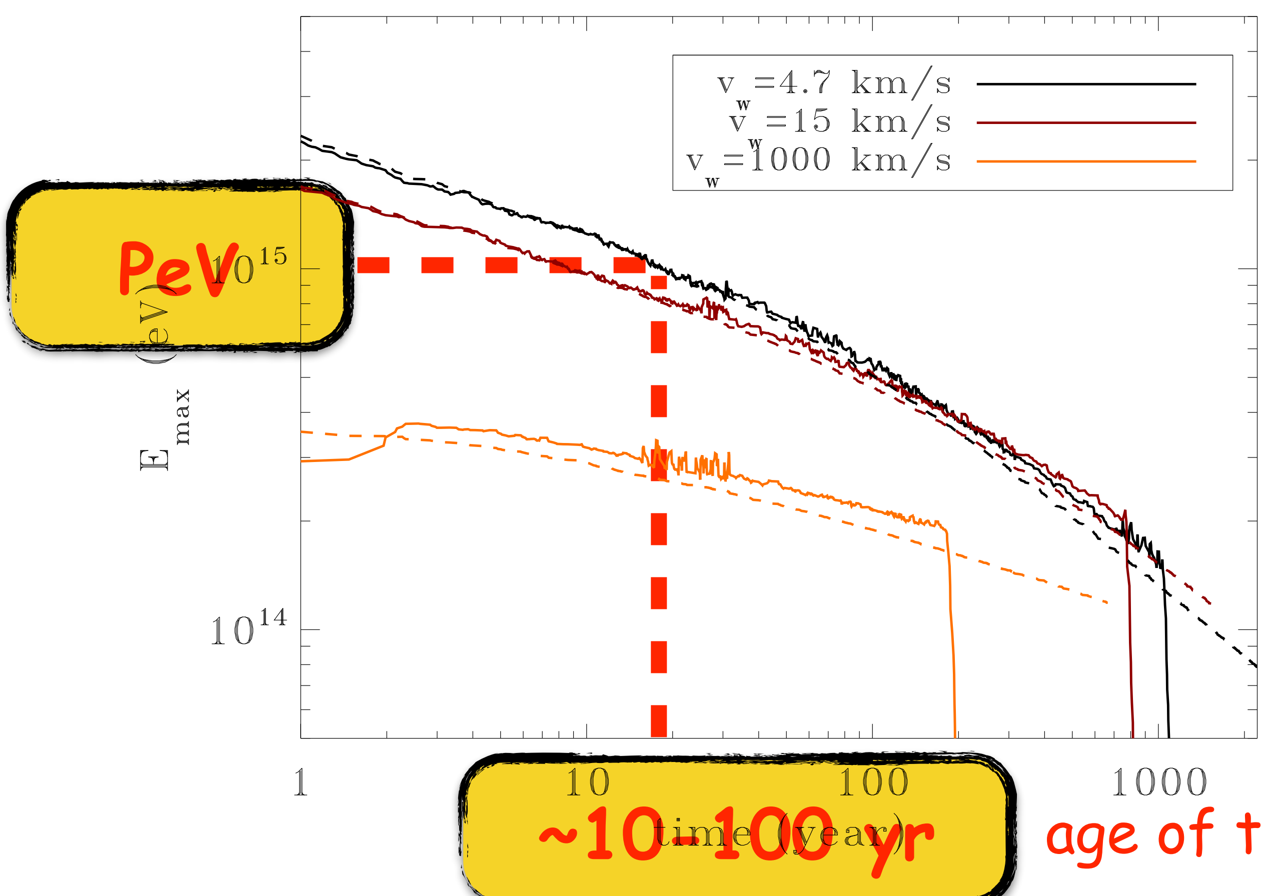
Let's assume SNRs do accelerate up ...

p-p interactions -> $E^p$ ... eV $\longrightarrow E^{\gamma}_{max} \approx 400\text{TeV}$

inver... ...ppressed above several tens of TeV (Klein-Nishina effect)

testable with future gamma ray facilities: CTA, HAWC, HiSCORE, LHAASO

Theory




age of the SNR

Schure & Bell 2013/2014

# The PeV domain: can we get to the knee?

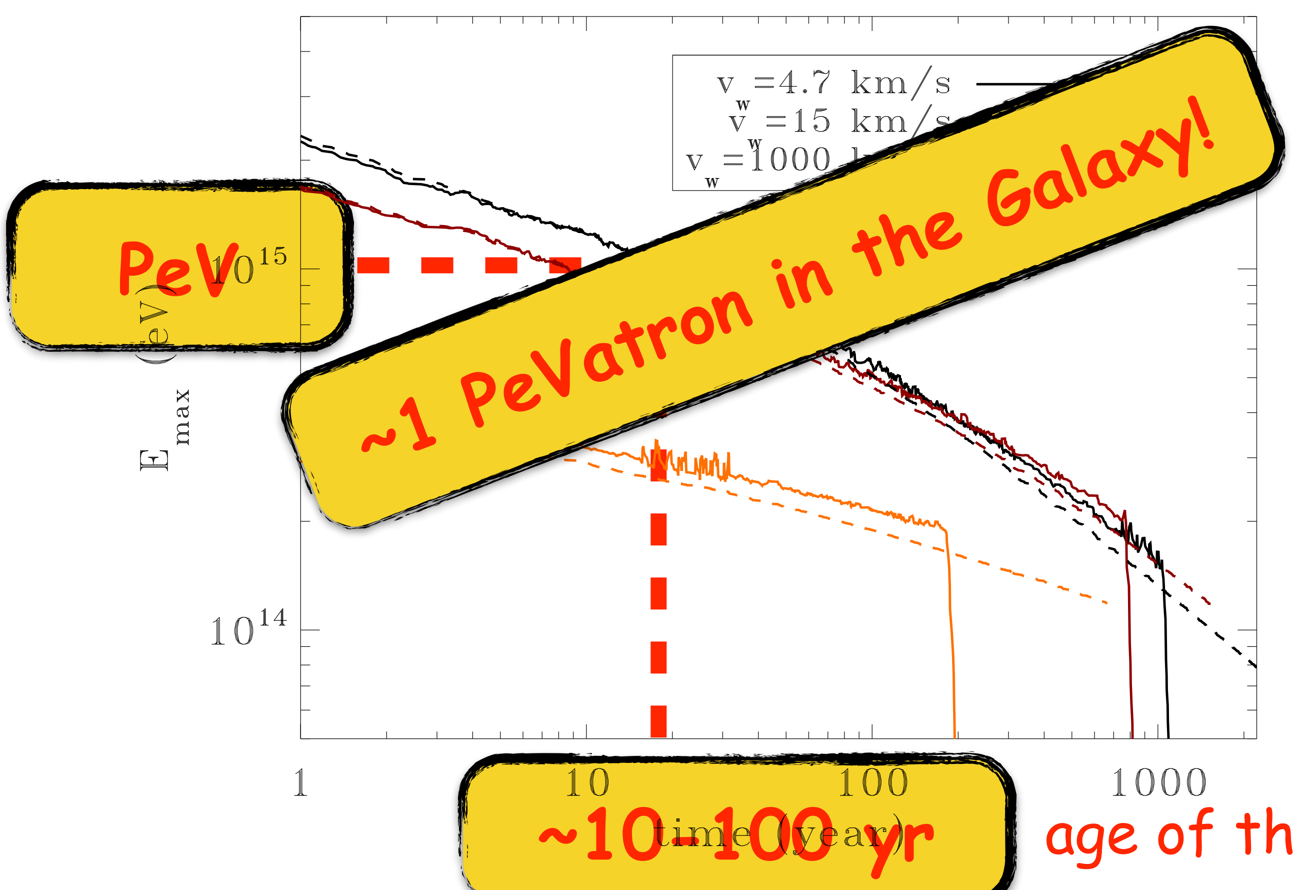
Let's assume SNRs do accelerate up ...

p-p interactions -> $E^p$ ... eV $\longrightarrow E^{\gamma}_{max} \approx 400\text{TeV}$

inve... ...uppressed above several tens of TeV (Klein-Nishina effect)

testable with future gamma ray facilities: CTA, HAWC, HiSCORE, LHAASO

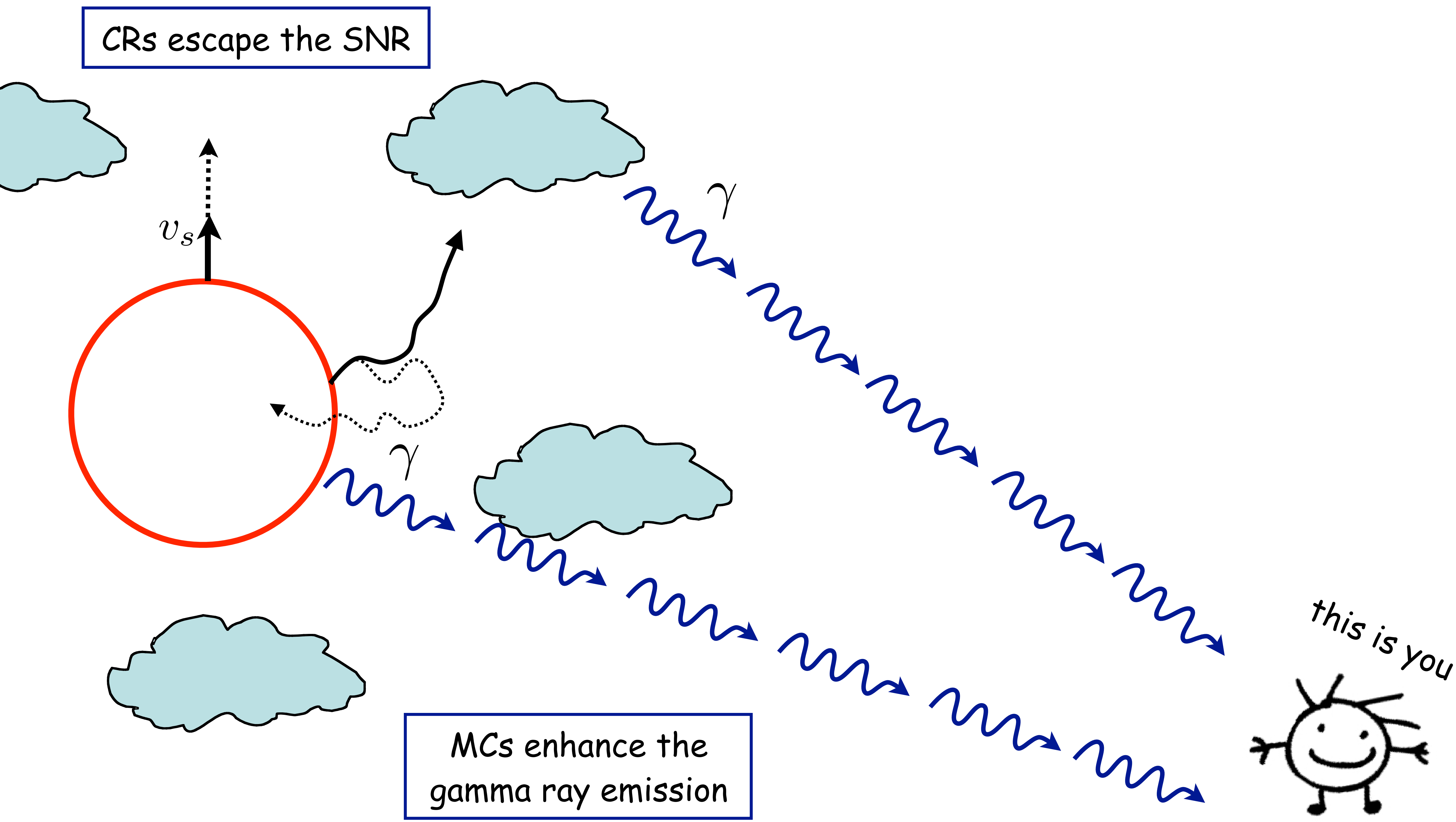
Theory




age of the SNR

Schure & Bell 2013/2014

# Indirect detection of PeVatrons?



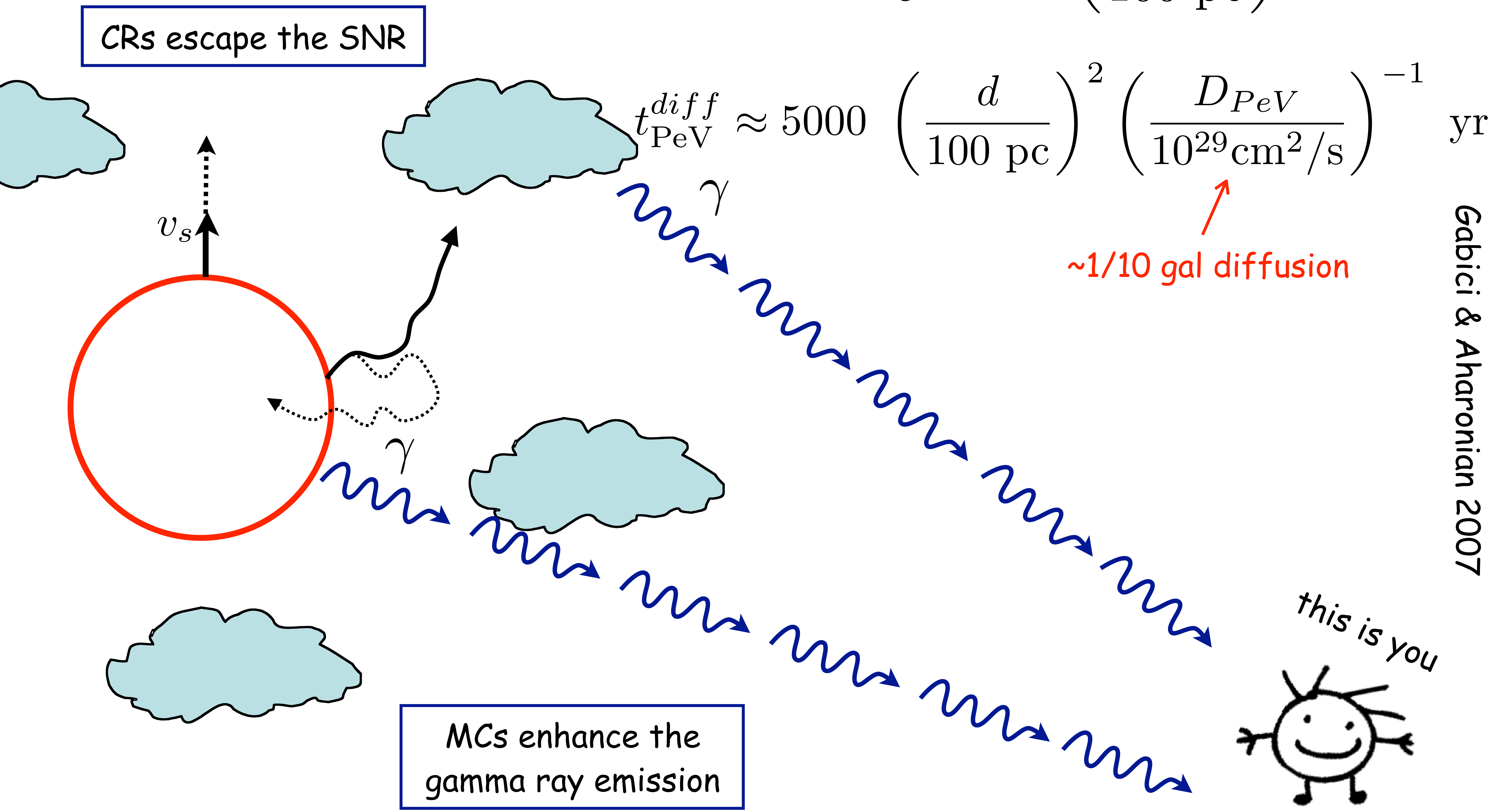

Gabici & Aharonian 2007

# Indirect detection of PeVatrons?

$$t_{ballistic} = \frac{d}{c} \approx 300 \left( \frac{d}{100 \text{ pc}} \right) \text{yr}$$

$$t_{\text{PeV}}^{diff} \approx 5000 \left( \frac{d}{100 \text{ pc}} \right)^2 \left( \frac{D_{PeV}}{10^{29} \text{cm}^2/\text{s}} \right)^{-1} \text{yr}$$

~1/10 gal diffusion



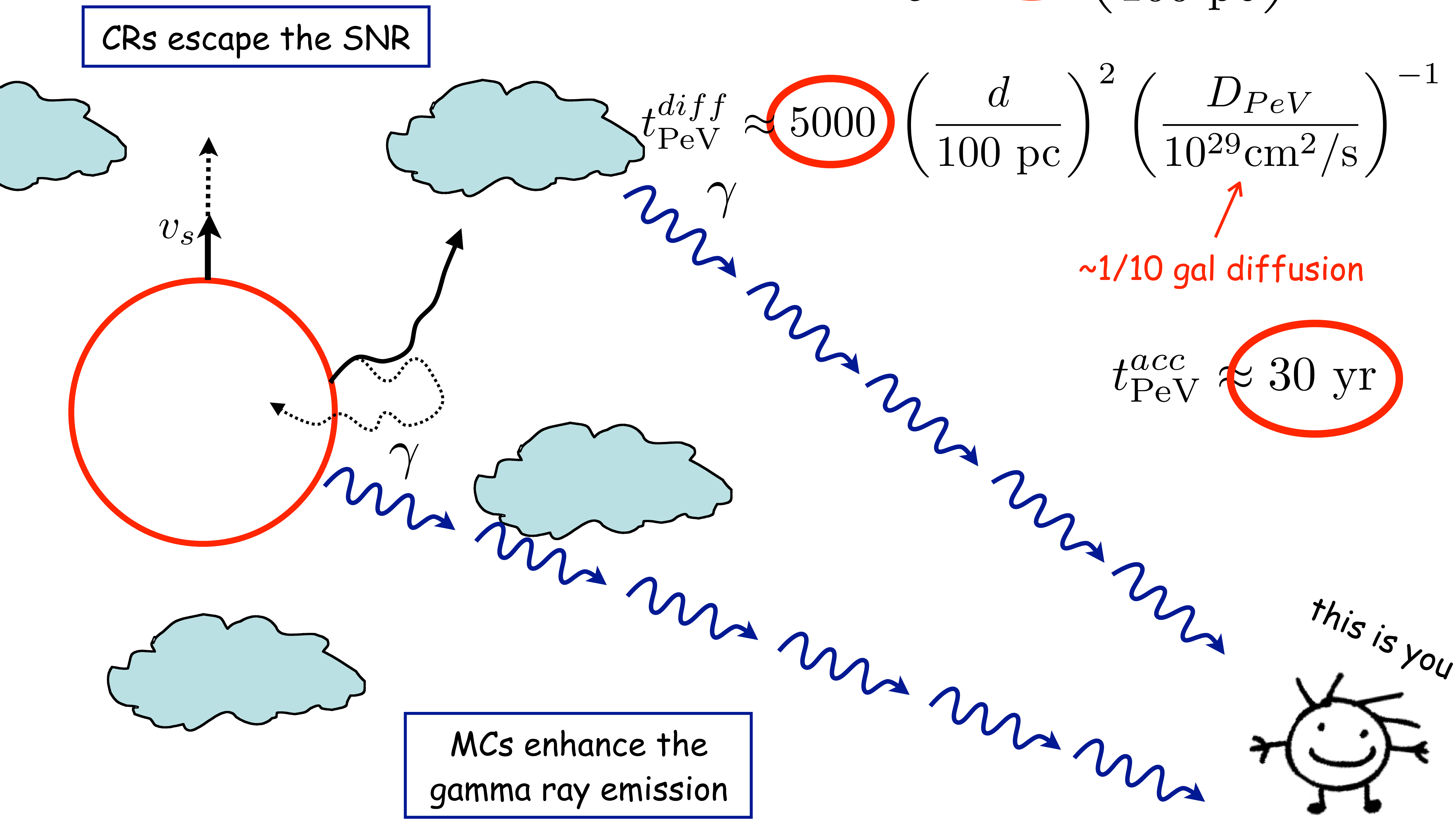
# Indirect detection of PeVatrons?

$$t_{ballistic} = \frac{d}{c} \approx 300 \left( \frac{d}{100 \text{ pc}} \right) \text{yr}$$

$$t_{\rm PeV}^{diff} \approx 5000 \left( \frac{d}{100 \text{ pc}} \right)^2 \left( \frac{D_{PeV}}{10^{29} \text{cm}^2/\text{s}} \right)^{-1} \text{yr}$$

~1/10 gal diffusion

$$t_{\rm PeV}^{acc} \approx 30 \text{ yr}$$




Gabici & Aharonian 2007

# Overview of the talk

- The GeV and TeV sky look much different
- The link between gamma-ray astronomy and cosmic rays
- SuperNova Remnants in gamma rays:hadronic or leptonic?
- Hadronic/leptonic signatures 1 - the pion bump
- Hadronic/leptonic signatures 2 - the spectral shape(?)
- Hadronic/leptonic signatures 3 - gamma/gas correlations
- Hadronic/leptonic signatures 4 - the multi-TeV domain
- Gamma-ray based tests for the origin of cosmic rays
- What's next? CTA, HAWC, HiScore, LHAASO ...

# How many SNRs should we see in TeV gamma rays?

Cristofari et al. 2013

**3 SN/century in the MW**

-> where and when?
-> core-collapse or thermonuclear

**gas distribution in the MW**

-> atomic hydrogen (HI)
-> molecular hydrogen ($H_2$)

**CR acceleration**

-> efficiency, spectrum, B-field
-> both protons & electrons

**hydro evolution of SNRs**

-> shock radius .vs. time
-> shock velocity .vs. time

**gamma-ray emission**

-> hadronic+leptonic

# A comparison with the HESS scan

Gast et al. 2011

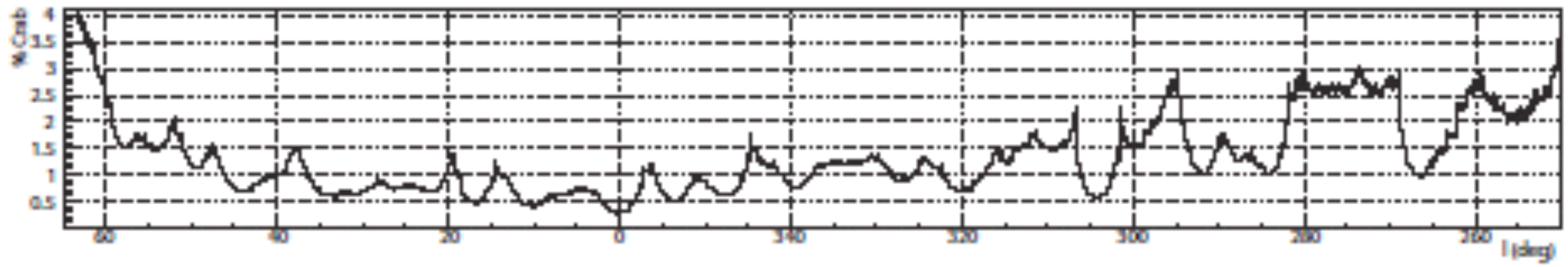



Figure 2: Sensitivity of H.E.S.S. to point-like $\gamma$-ray sources with an assumed spectral index of 2.5, for a detection level of $5\sigma$ pre-trial, at $b = -0.3°$, the approximate average latitude of Galactic sources. The sensitivity is expressed in units of the Crab integral flux $F(\geq 1\,\mathrm{TeV}) = 2.26 \cdot 10^{-7}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}$.

# A comparison with the HESS scan

Gast et al. 2011

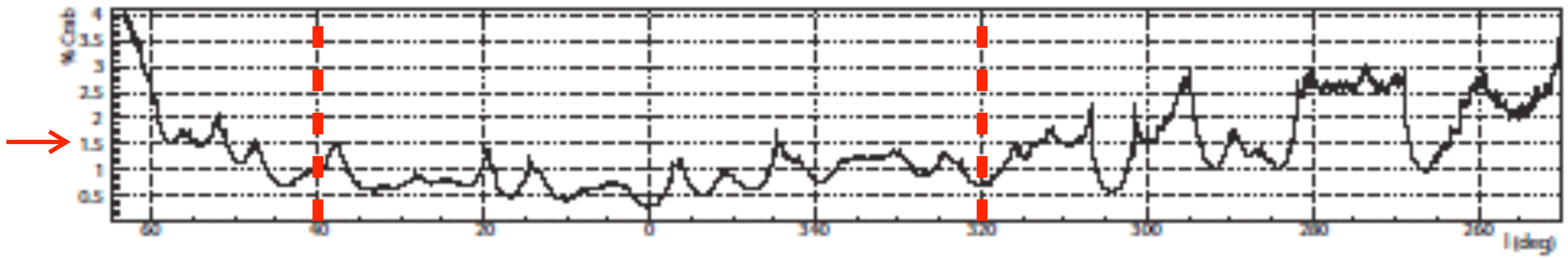



Figure 2: Sensitivity of H.E.S.S. to point-like $\gamma$-ray sources with an assumed spectral index of 2.5, for a detection level of $5\sigma$ pre-trial, at $b = -0.3°$, the approximate average latitude of Galactic sources. The sensitivity is expressed in units of the Crab integral flux $F(\geq 1\,\mathrm{TeV}) = 2.26 \cdot 10^{-7}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}$.

# A comparison with the HESS scan

Gast et al. 2011

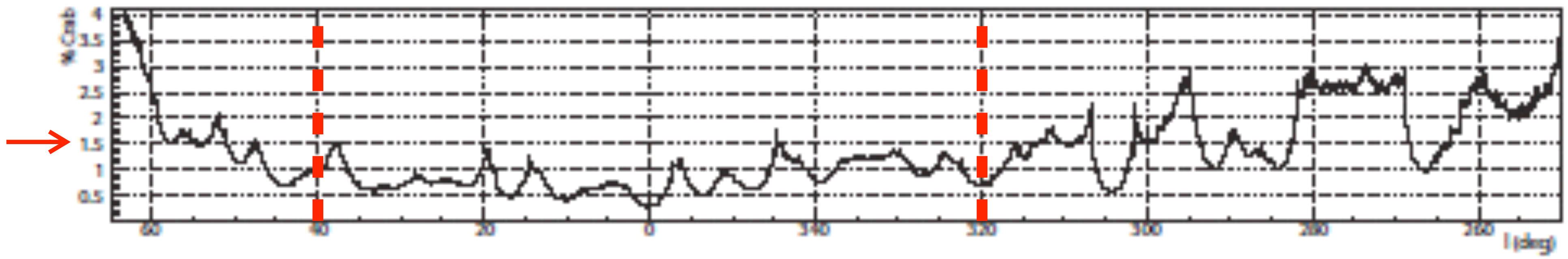



Figure 2: Sensitivity of H.E.S.S. to point-like $\gamma$-ray sources with an assumed spectral index of 2.5, for a detection level of $5\sigma$ pre-trial, at $b = -0.3°$, the approximate average latitude of Galactic sources. The sensitivity is expressed in units of the Crab integral flux $F(\geq 1\,\mathrm{TeV}) = 2.26 \cdot 10^{-7}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}$.

$$-3^\circ < b < 3^\circ$$

- sensitivity scales as source extension
- PSF = 0.1 degrees

# A comparison with the HESS scan

Gast et al. 2011

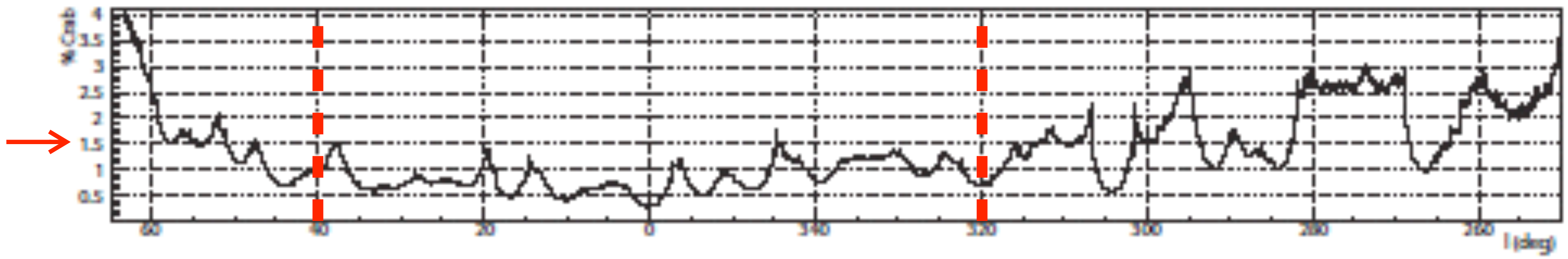



Figure 2: Sensitivity of H.E.S.S. to point-like $\gamma$-ray sources with an assumed spectral index of 2.5, for a detection level of $5\sigma$ pre-trial, at $b = -0.3°$, the approximate average latitude of Galactic sources. The sensitivity is expressed in units of the Crab integral flux $F(\geq 1\,\mathrm{TeV}) = 2.26 \cdot 10^{-7}\,\mathrm{m^{-2}\,s^{-1}}$.

$$-3^\circ < b < 3^\circ$$

- sensitivity scales as source extension
- PSF = 0.1 degrees

| Name | $F(> 1\ \mathrm{TeV})$ $[10^{-12}\mathrm{cm^{-2}s^{-1}}]$ | d [kpc] | age [kyr] | radius [°] | Ref. |
|---|---|---|---|---|---|
| RX J1713.7–3946 | 15.5 | 1 | 1.6 | 0.65 | 1,2,3 |
| HESS J1731–347 | 6.9 | 2.4...4 | 27 | 0.25 | 4,5 |
| CTB 37B | 0.4 | 13.2 | 0.3...3 | 0.03 | 6,7 |

**Table 3.** Gamma-ray fluxes, distances, ages and apparent sizes of the three SNR shells detected by H.E.S.S. in the region $|l| < 40°$, $|b| < 3.5°$ at a flux level above 1.5% of the Crab. *References:* 1) Aharonian et al. 2006b; 2) Moriguchi et al. 2005; 3) Wang et al. 1997; 4) Abramowski et al. 2011; 5) Tian et al. 2008; 6) Aharonian et al. 2008a; 7) Nakamura et al. 2009

**+ 3 SNR/MC (CTB 37A, W28, HESS J1731) -> ???**

**+ 17 unidentified sources**

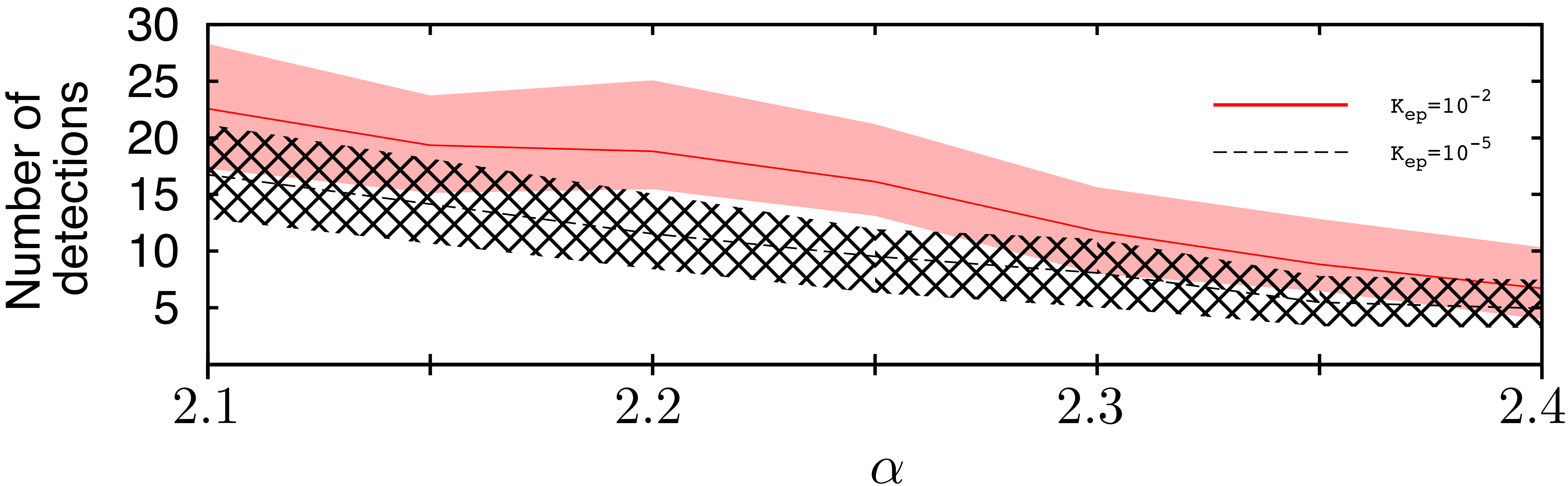
Cristofari et al. 2013

# A comparison with the HESS scan

Cristofari et al. 2013

CR spectrum escaping from SNRs -> $$N_{CR}(E) = N_0 \; E^{-\alpha}$$

RED and BLACK regions -> with or without Inverse Compton contribution

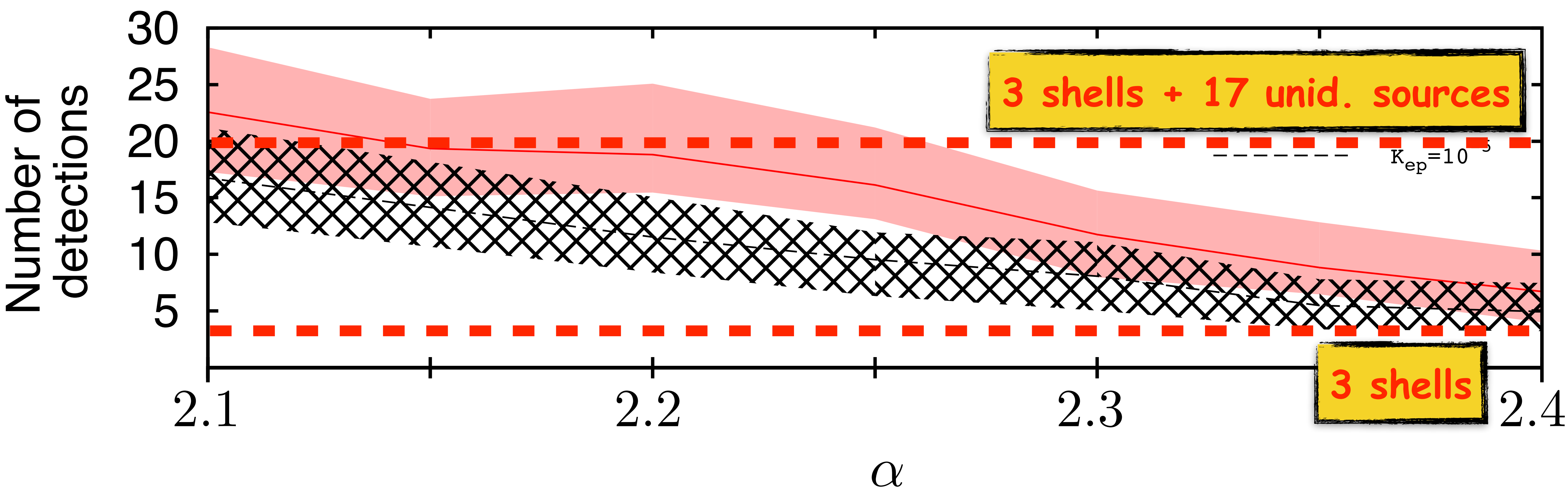


# A comparison with the HESS scan

Cristofari et al. 2013

CR spectrum escaping from SNRs -> $$N_{CR}(E) = N_0 \; E^{-\alpha}$$

RED and BLACK regions -> with or without Inverse Compton contribution

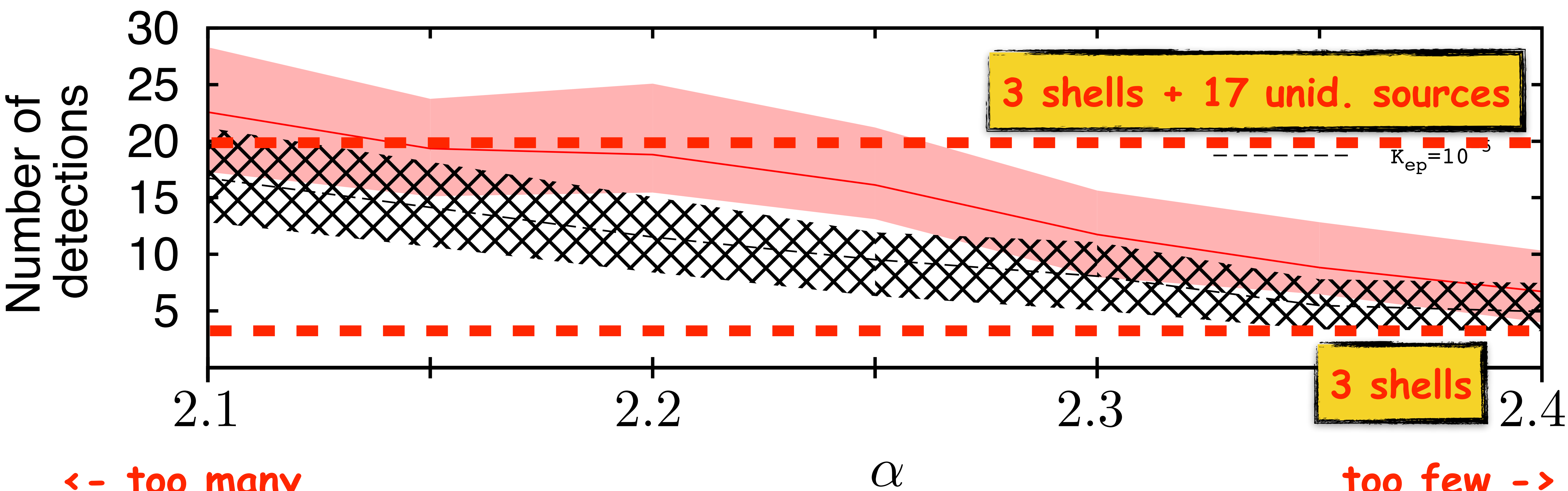


# A comparison with the HESS scan

Cristofari et al. 2013

CR spectrum escaping from SNRs -> $N_{CR}(E) = N_0 \; E^{-\alpha}$

RED and BLACK regions -> with or without Inverse Compton contribution




<- too many

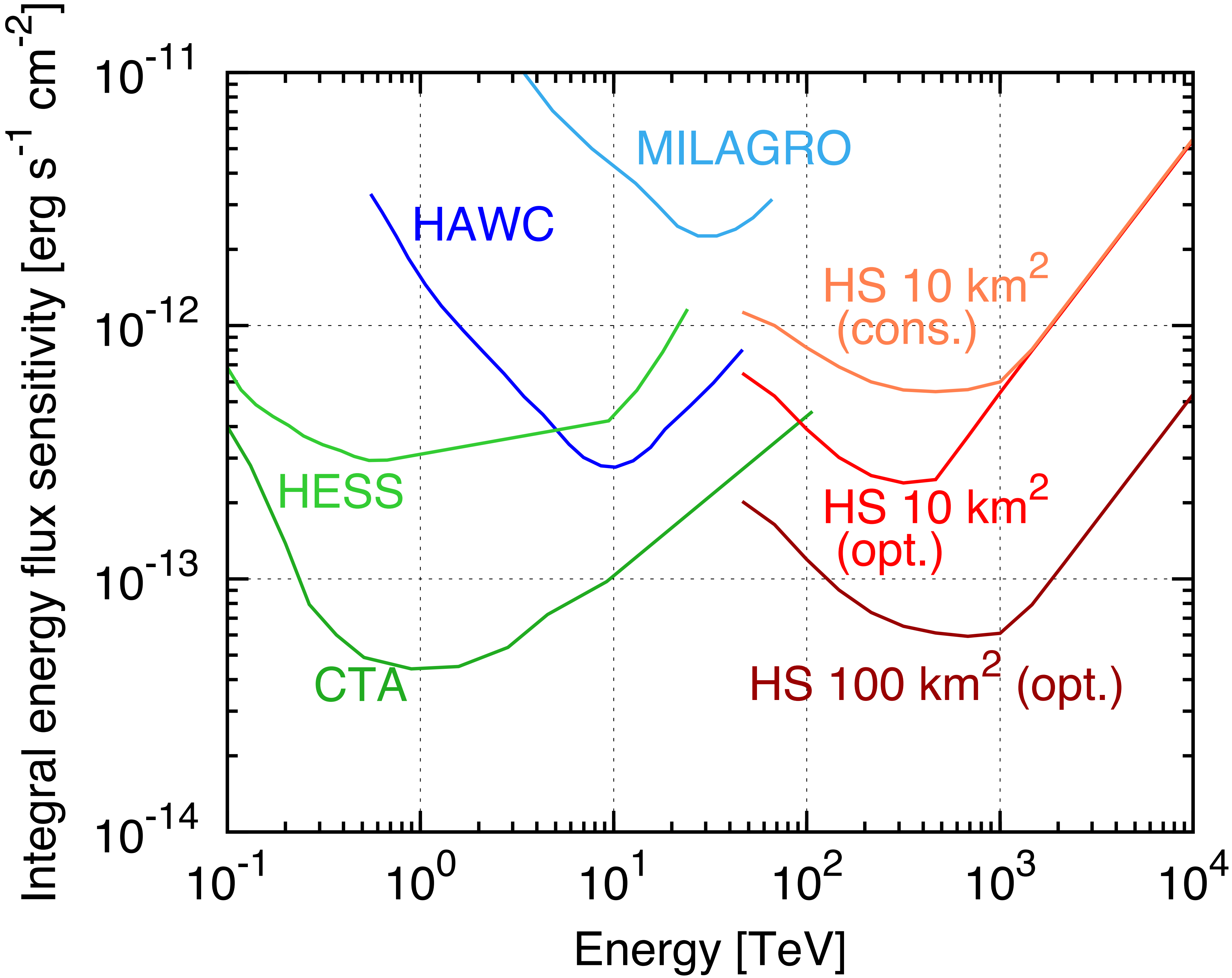
too few ->

allowed range of spectral slopes from CR propagation studies!

# Overview of the talk

- The GeV and TeV sky look much different
- The link between gamma-ray astronomy and cosmic rays
- SuperNova Remnants in gamma rays:hadronic or leptonic?
- Hadronic/leptonic signatures 1 - the pion bump
- Hadronic/leptonic signatures 2 - the spectral shape(?)
- Hadronic/leptonic signatures 3 - gamma/gas correlations
- Hadronic/leptonic signatures 4 - the multi-TeV domain
- Gamma-ray based tests for the origin of cosmic rays
- What's next? CTA, HAWC, HiScore, LHAASO ...

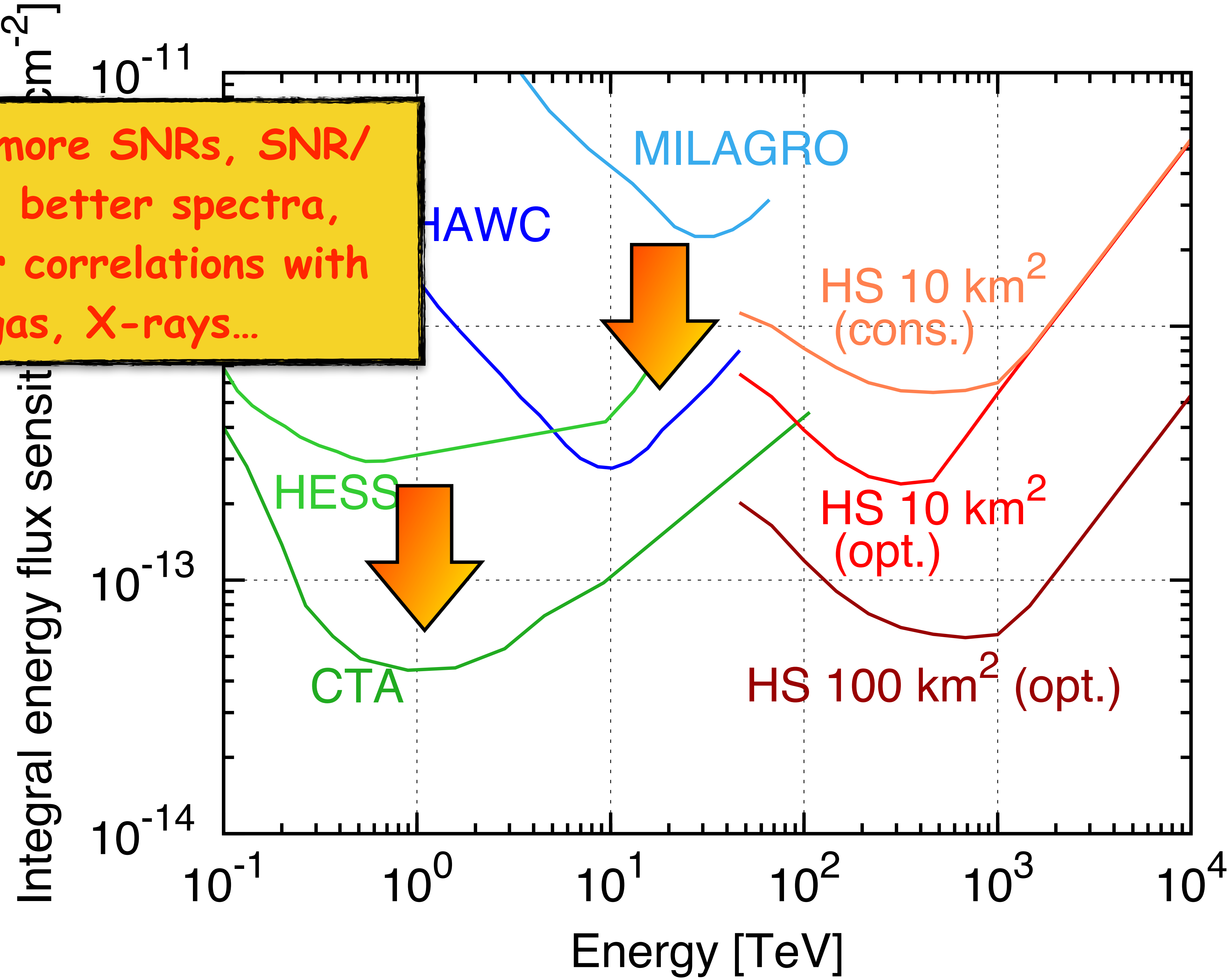
# What's next? Conclusions...




Hampf et al. 2013

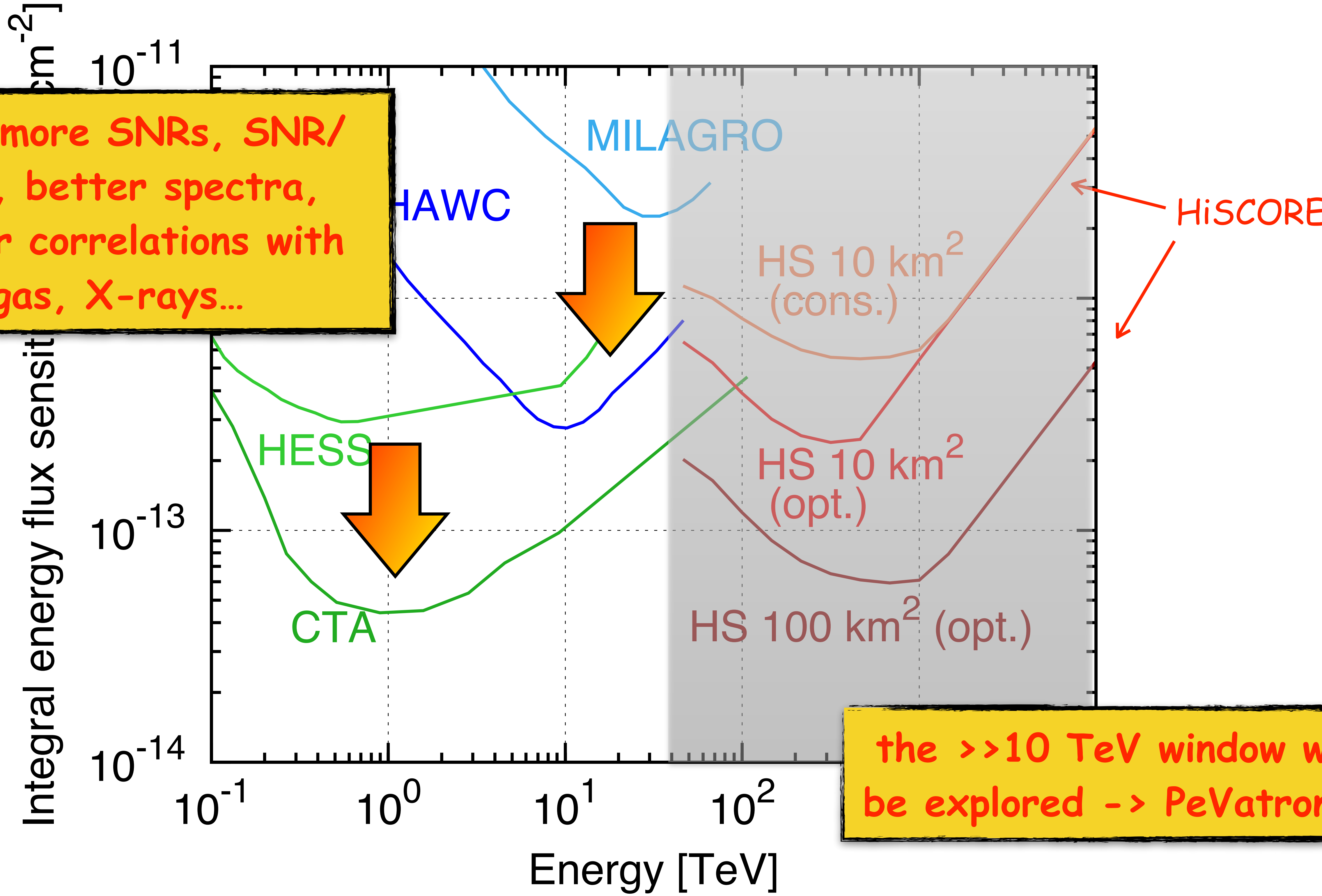
# What's next? Conclusions…

many more SNRs, SNR/ MCs, better spectra, better correlations with gas, X-rays…




Hampf et al. 2013

# What's next? Conclusions…




many more SNRs, SNR/MCs, better spectra, better correlations with gas, X-rays…

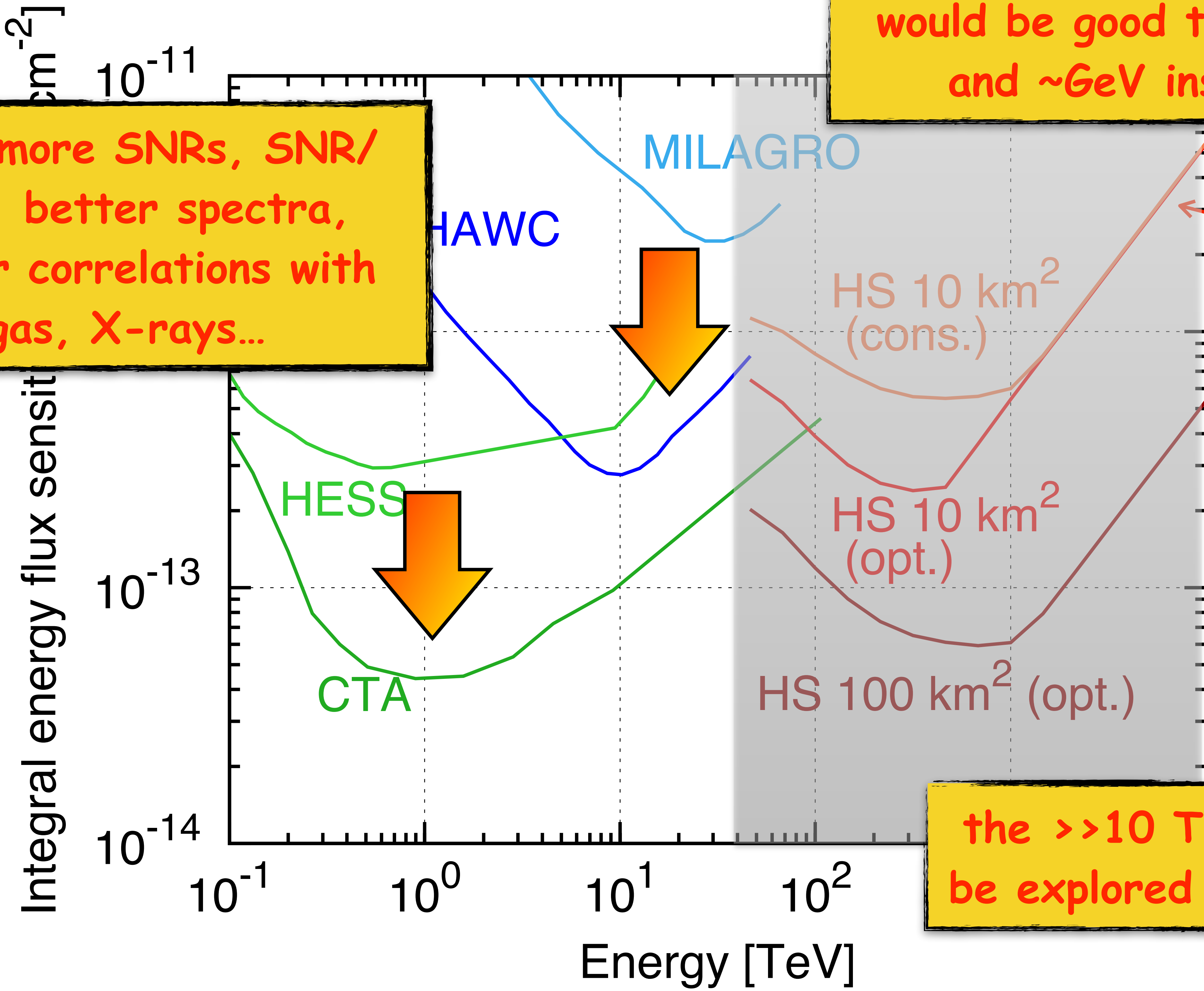
the >>10 TeV window will be explored -> PeVatrons?

Hampf et al. 2013

# What's next? Conclusions...

many more SNRs, SNR/MCs, better spectra, better correlations with gas, X-rays...

would be good to have ~MeV and ~GeV instruments




the >>10 TeV window will be explored -> PeVatrons?

Hampf et al. 2013

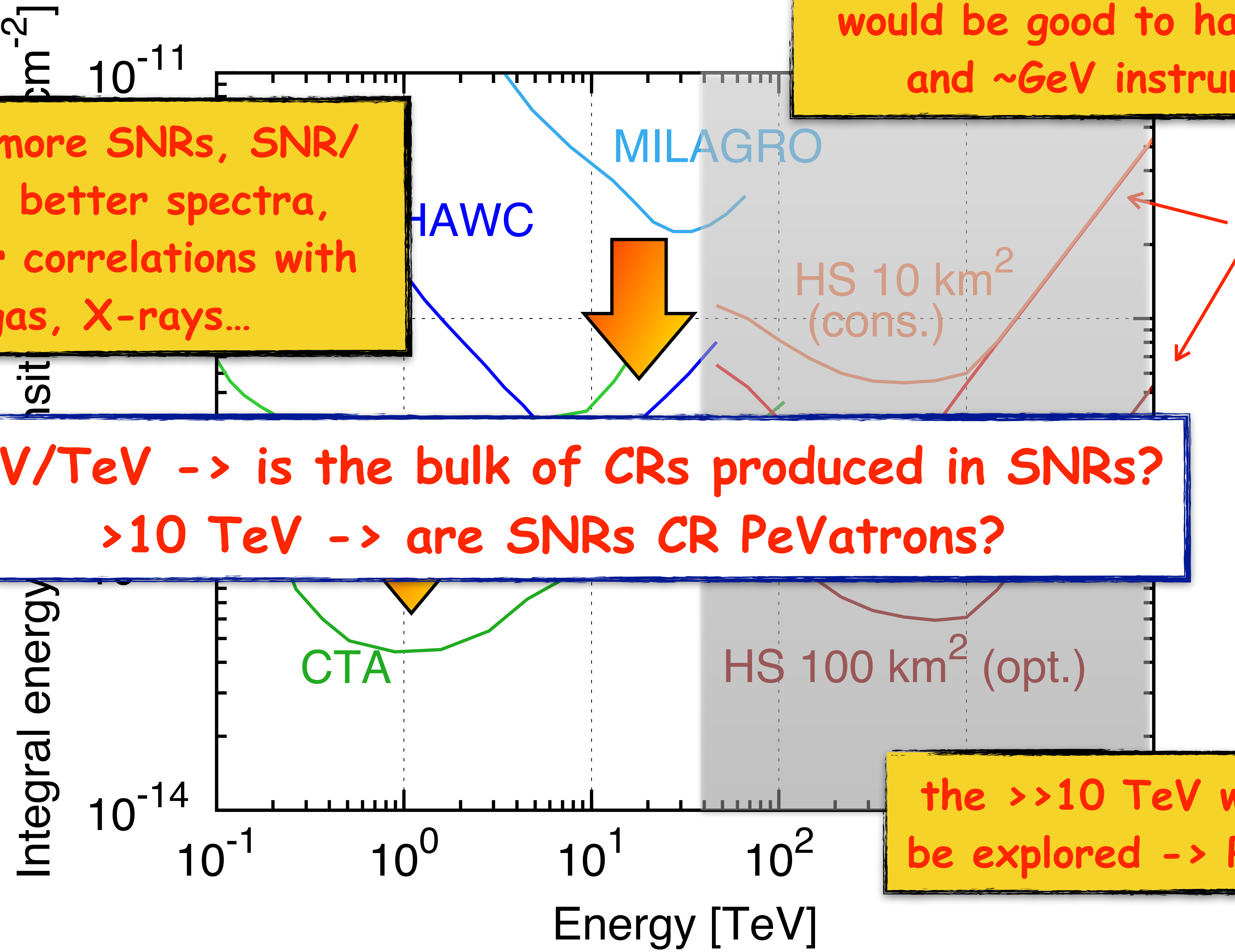
# What's next? Conclusions…

would be good to have ~MeV and ~GeV instruments

many more SNRs, SNR/MCs, better spectra, better correlations with gas, X-rays…

GeV/TeV -> is the bulk of CRs produced in SNRs?
>10 TeV -> are SNRs CR PeVatrons?

the >>10 TeV window will be explored -> PeVatrons?




Hampf et al. 2013