Acceleration of cosmic rays and gamma-ray emission from supernova remnants and molecular clouds

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APC, Paris

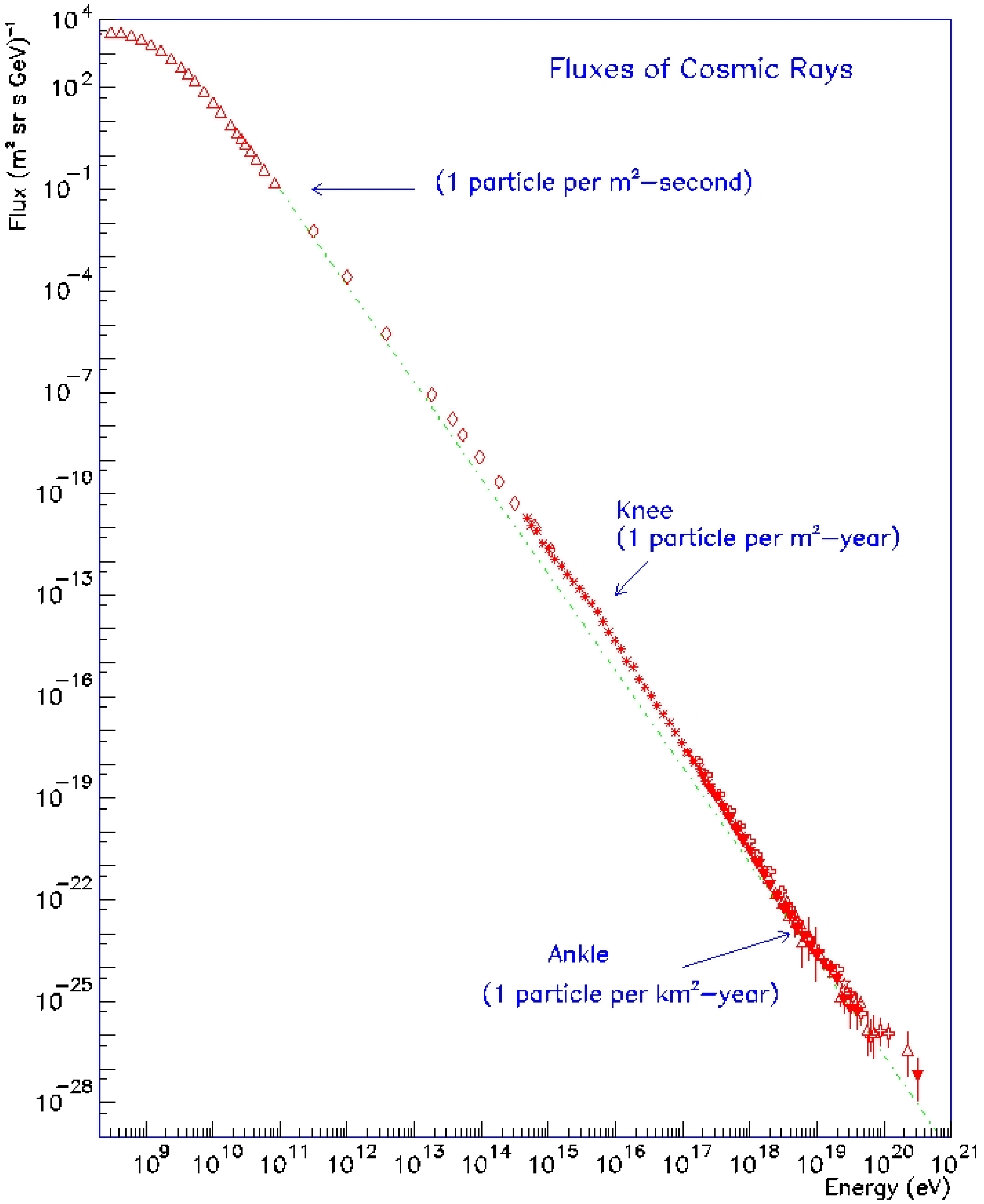
www.cnrs.fr

Overview of the talk

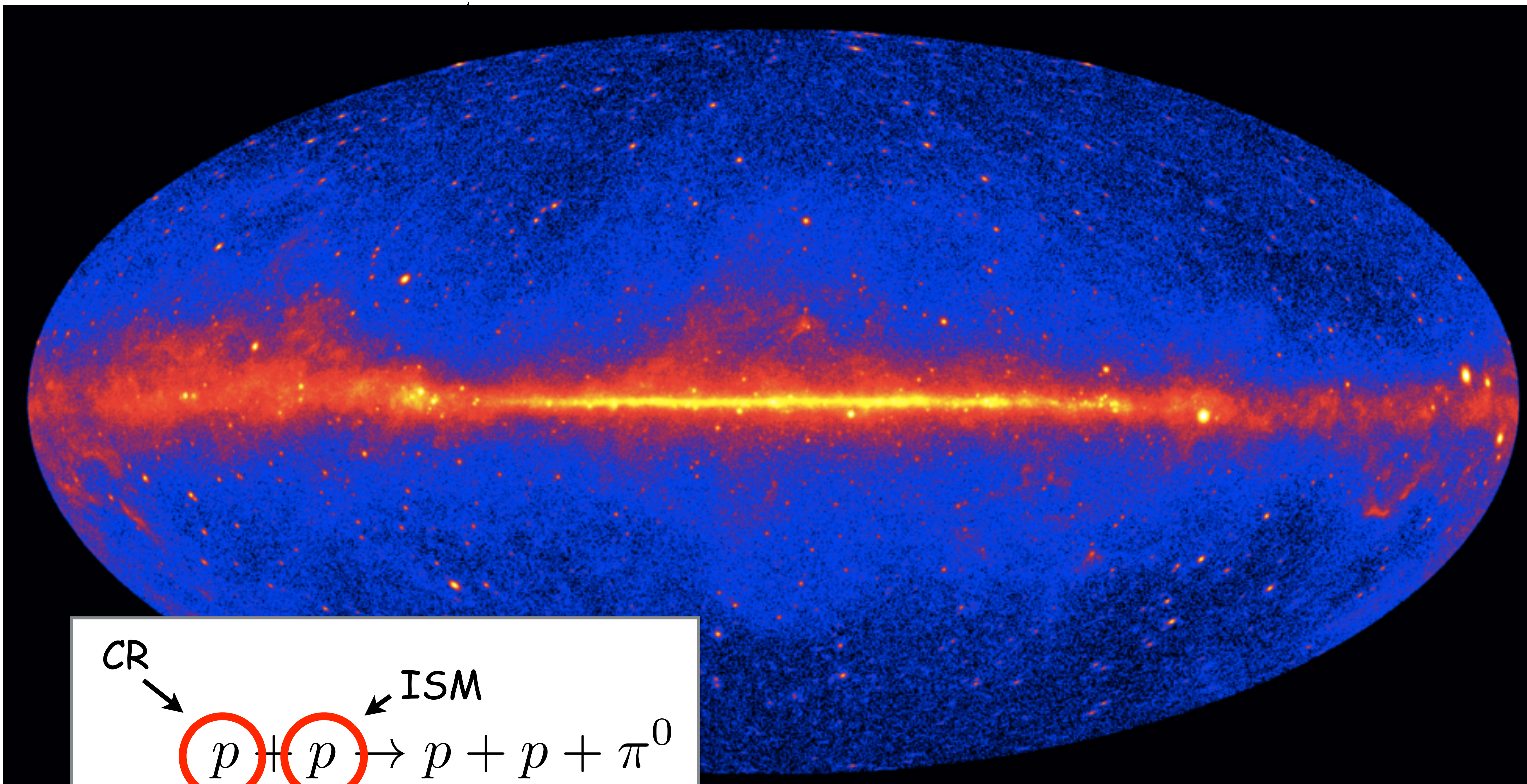
- Galactic cosmic rays, supernova remnants, gamma rays
- Why molecular clouds?
- Molecular clouds shocked by a SNR shock
- Molecular clouds in the vicinity of a SNR shock
- SNR inside MCs (RX J1713?)
- The MeV-TeV connection
- I will NOT talk about isolated clouds (ask Neronov, Dermer, de Oña Wilhelmi …)

Galactic cosmic rays, supernova remnants, gamma rays

Diffuse emission from cosmic rays interactions



Diffuse emission
from cosmic rays interactions



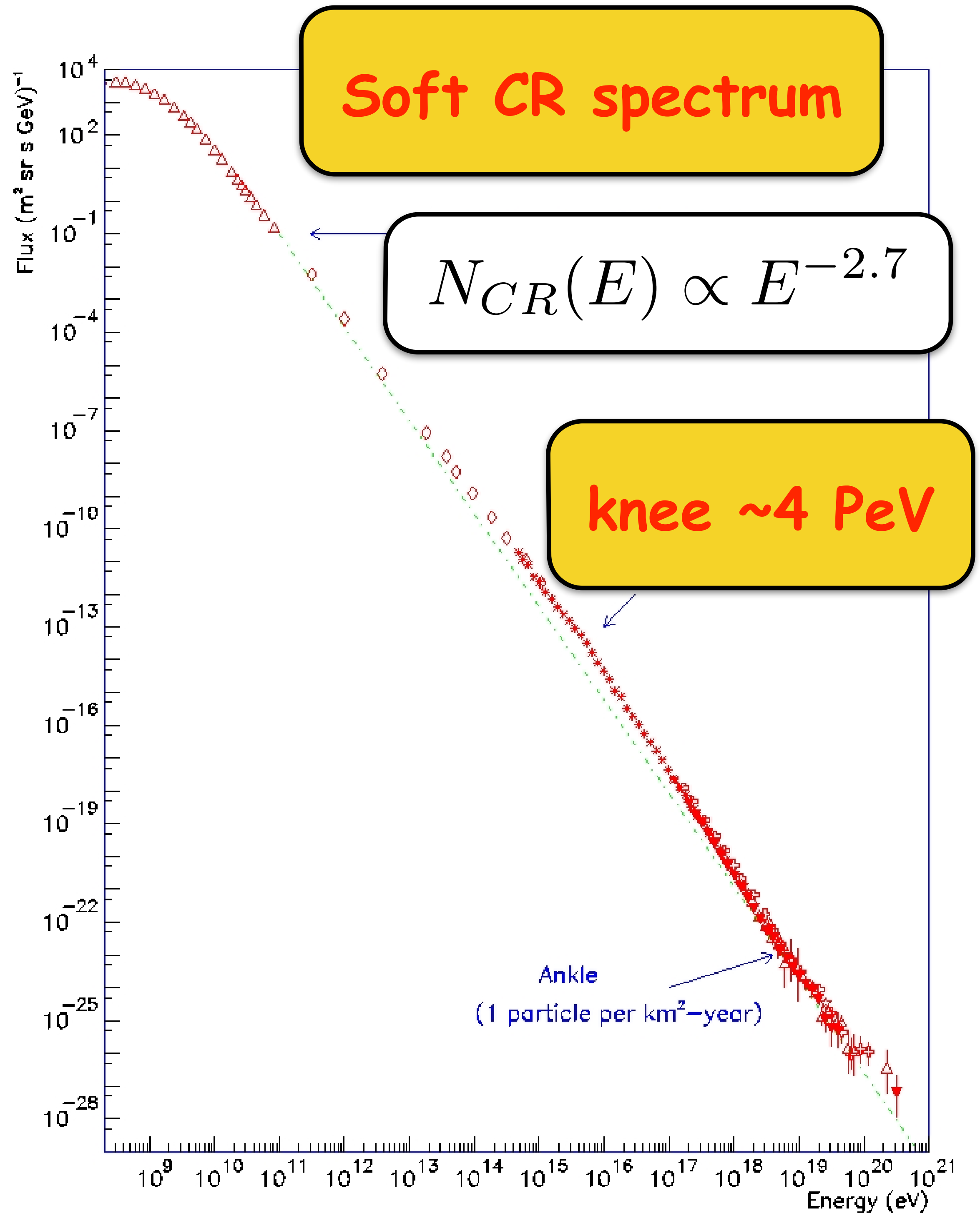
$$\overset{\text{CR}}{p} + \overset{\text{ISM}}{p} \rightarrow p + p + \pi^0$$

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

predicted in the fifties! (Hayakawa 1952)

The CR spectrum is steep, source spectra are hard

Energy dependent escape from the Galaxy



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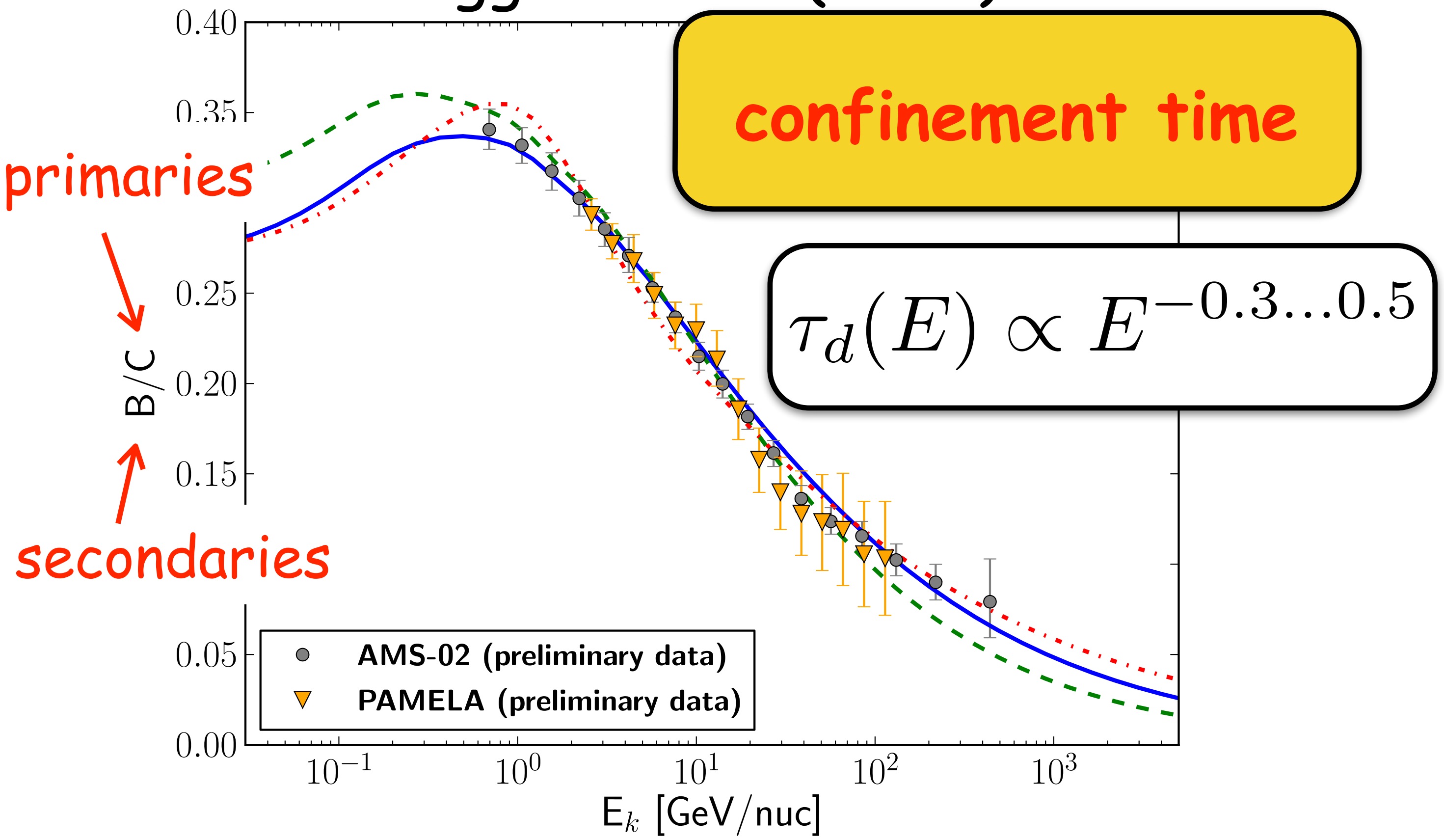
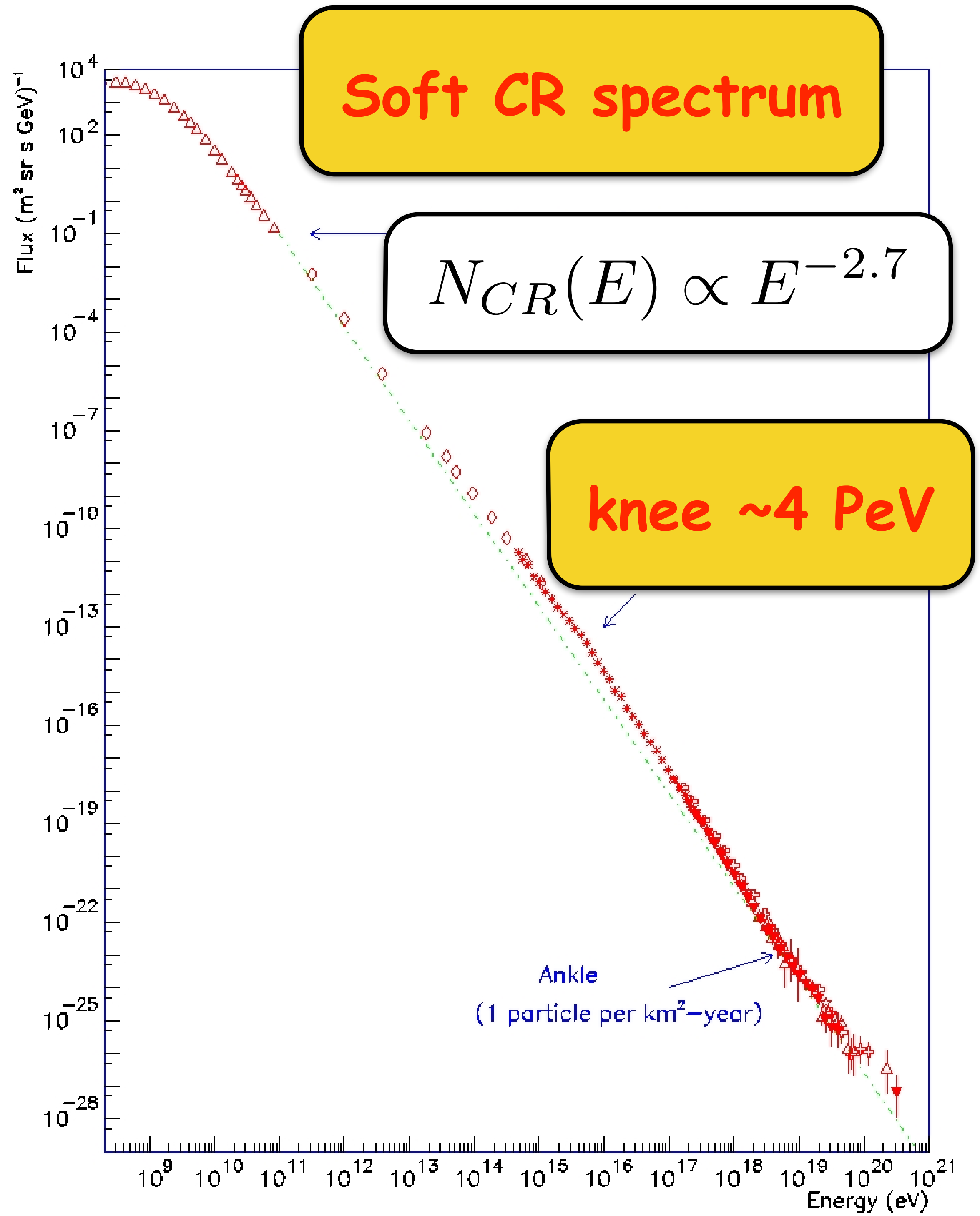
Gaggero et al (2014)





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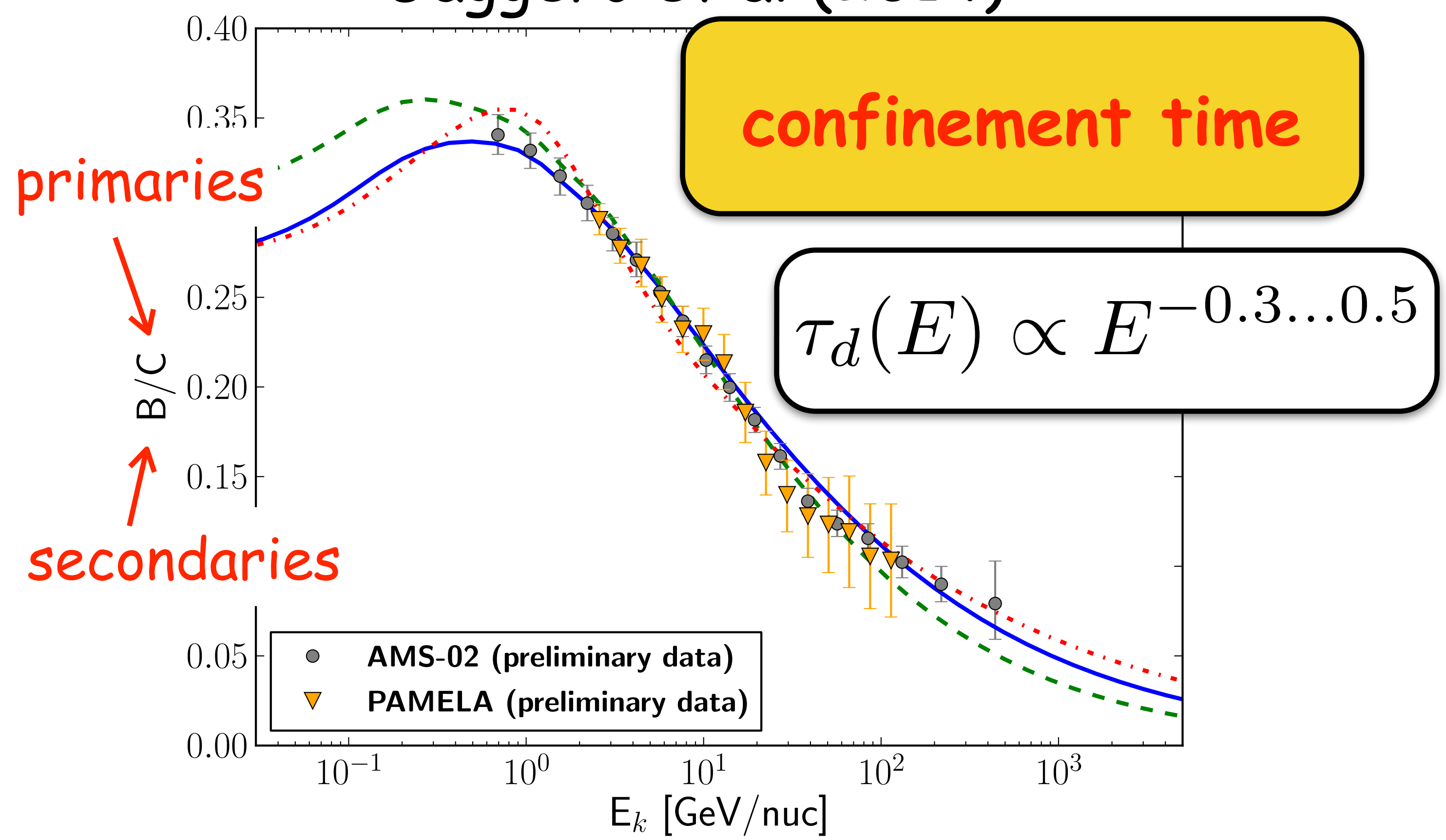

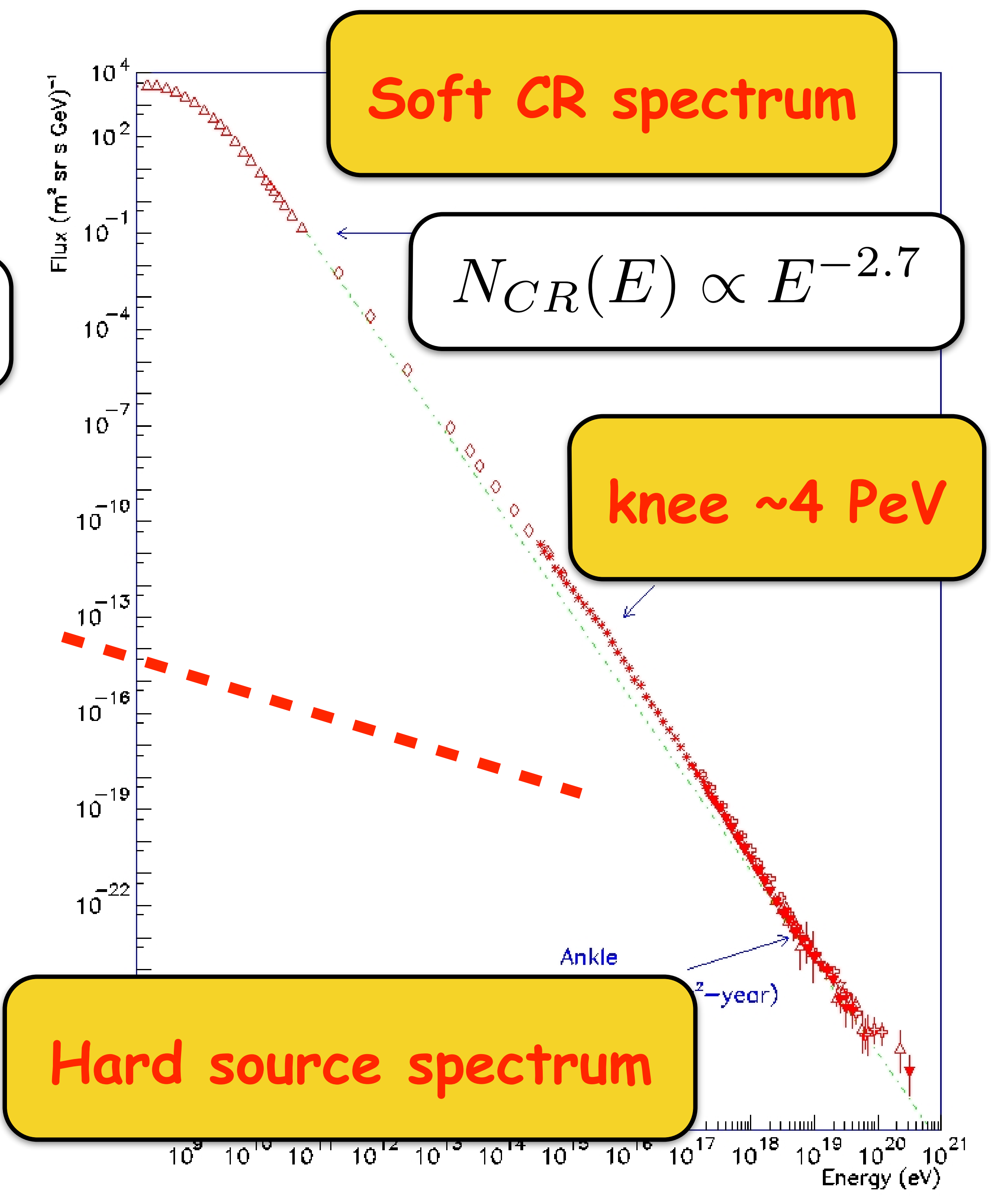

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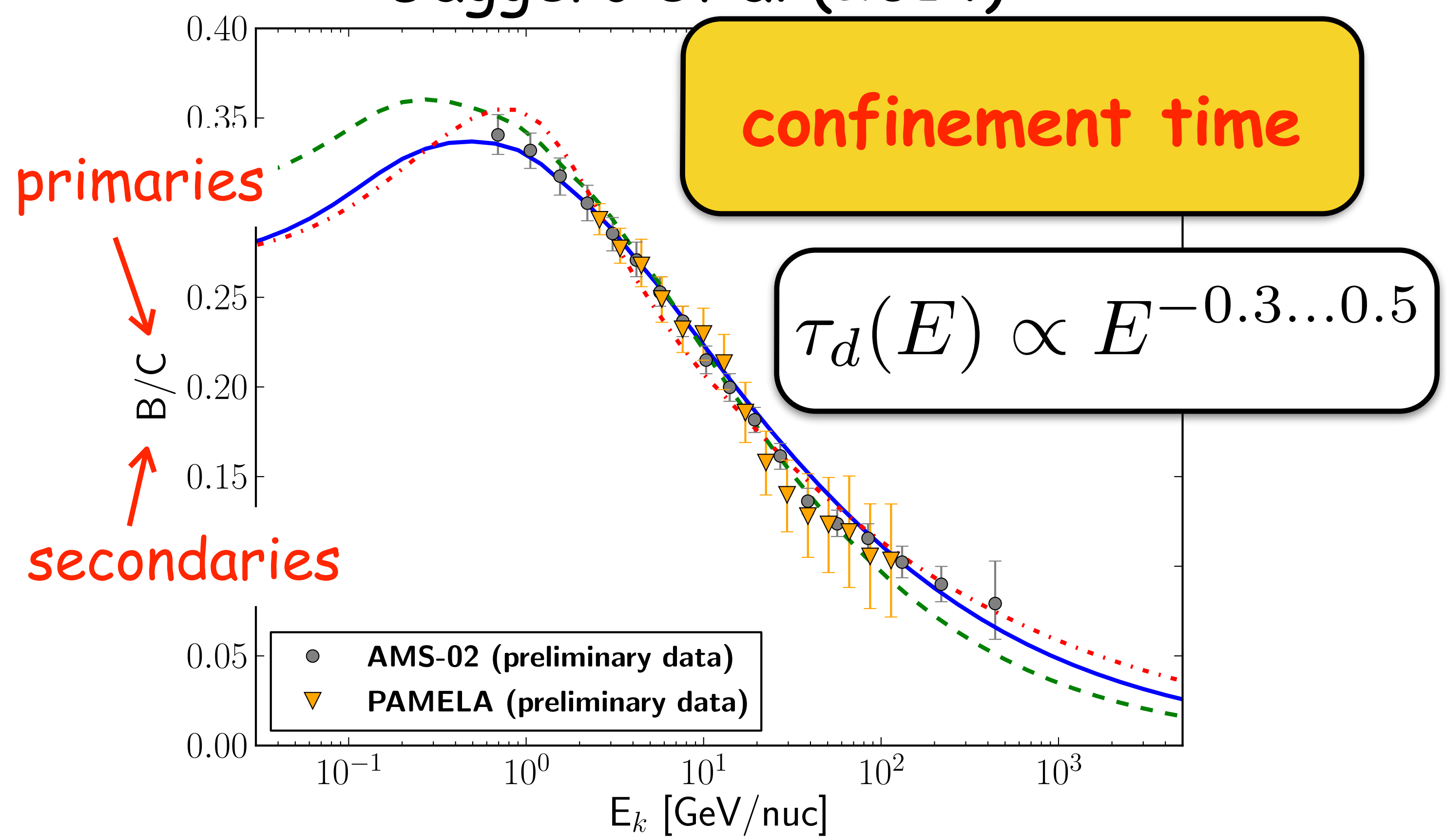
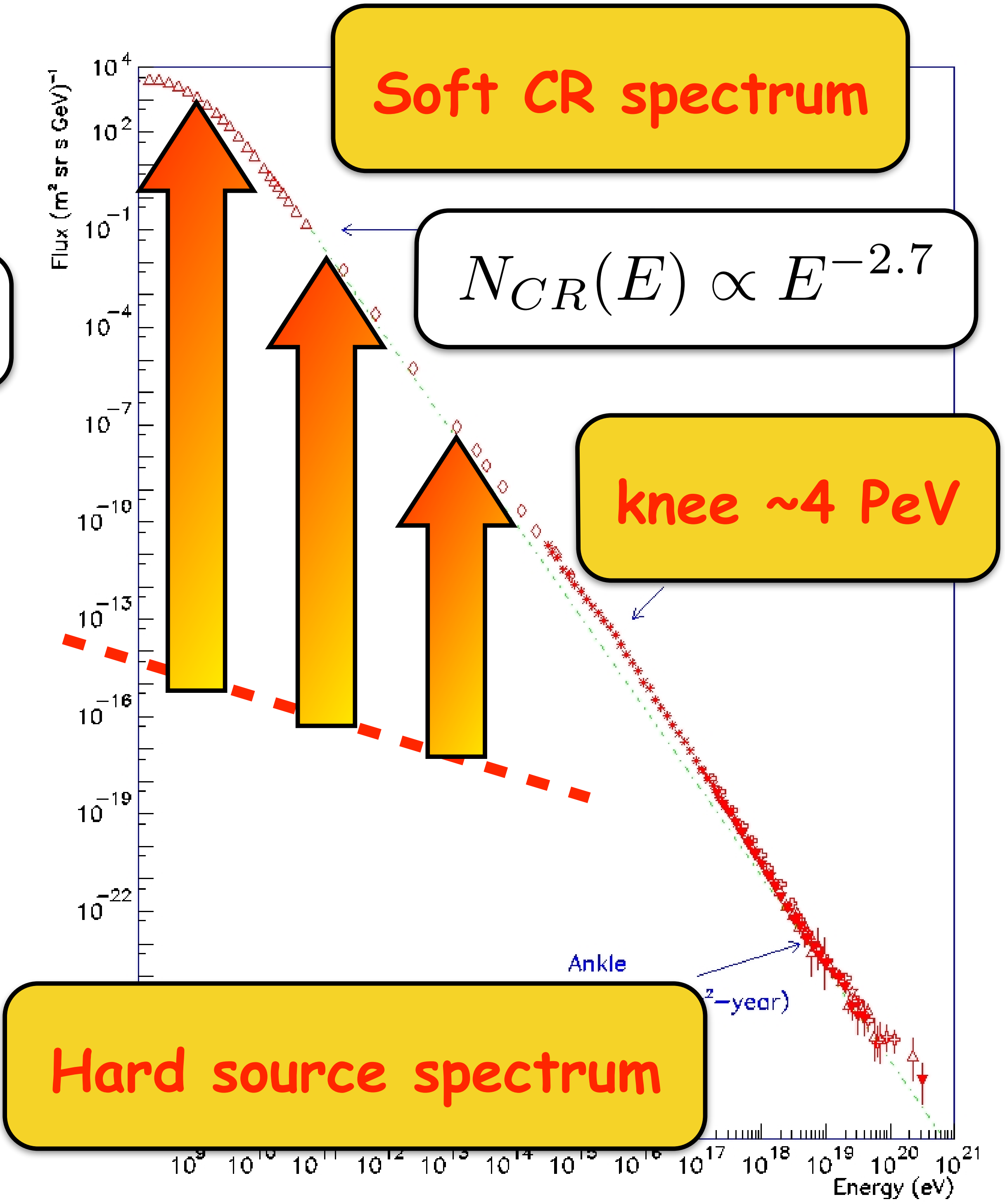




$$N_{CR}(E) = Q_S(E) \times \tau_d(E)$$

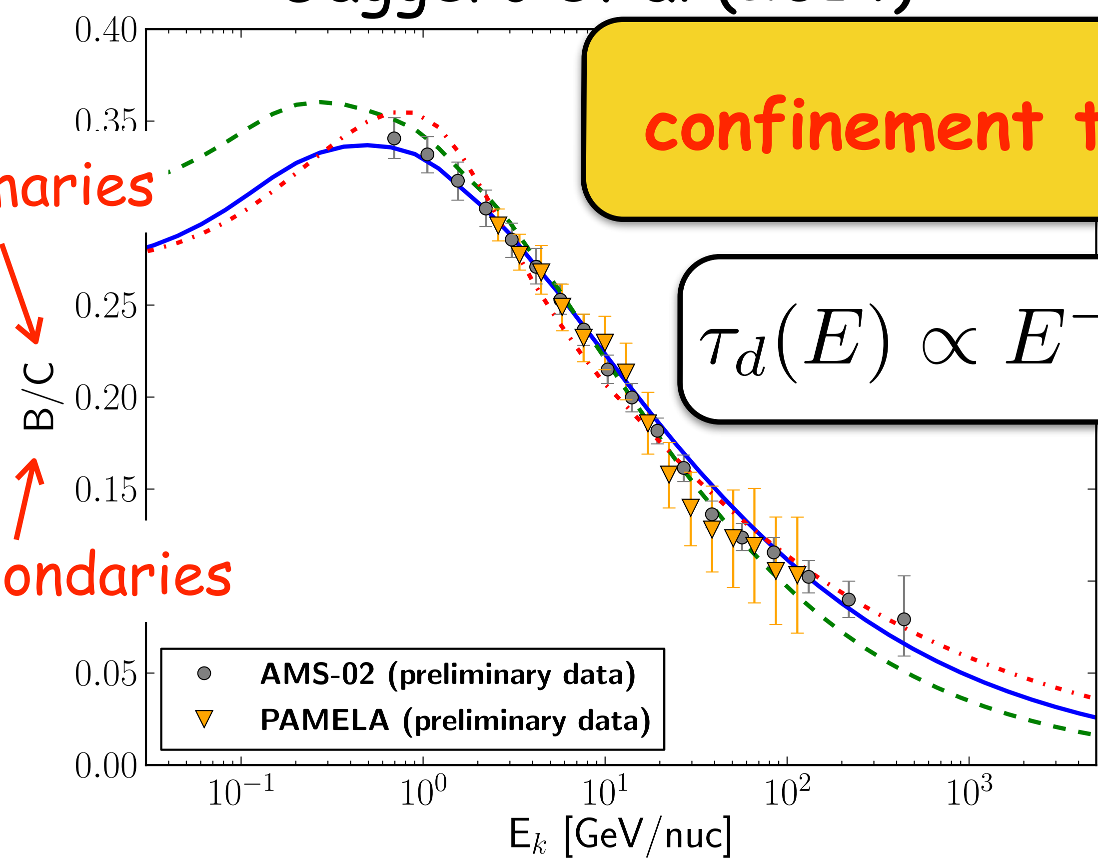
The CR spectrum is steep, source spectra are hard

Energy dependent escape from the Galaxy

Gaggero et al (2014)

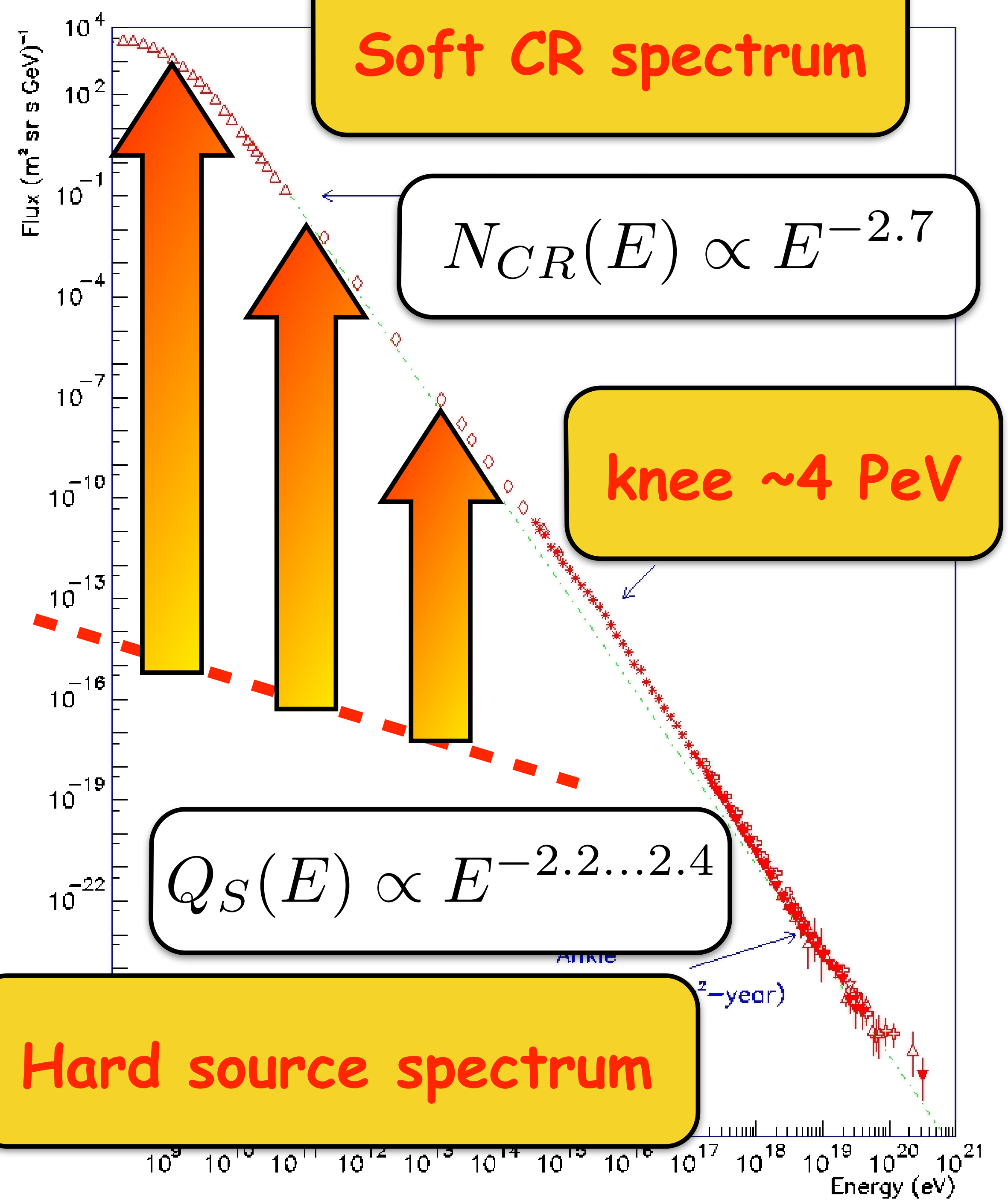
primaries

secondaries



confinement time

$$\tau_d(E) \propto E^{-0.3\ldots0.5}$$



Soft CR spectrum

$$N_{CR}(E) \propto E^{-2.7}$$

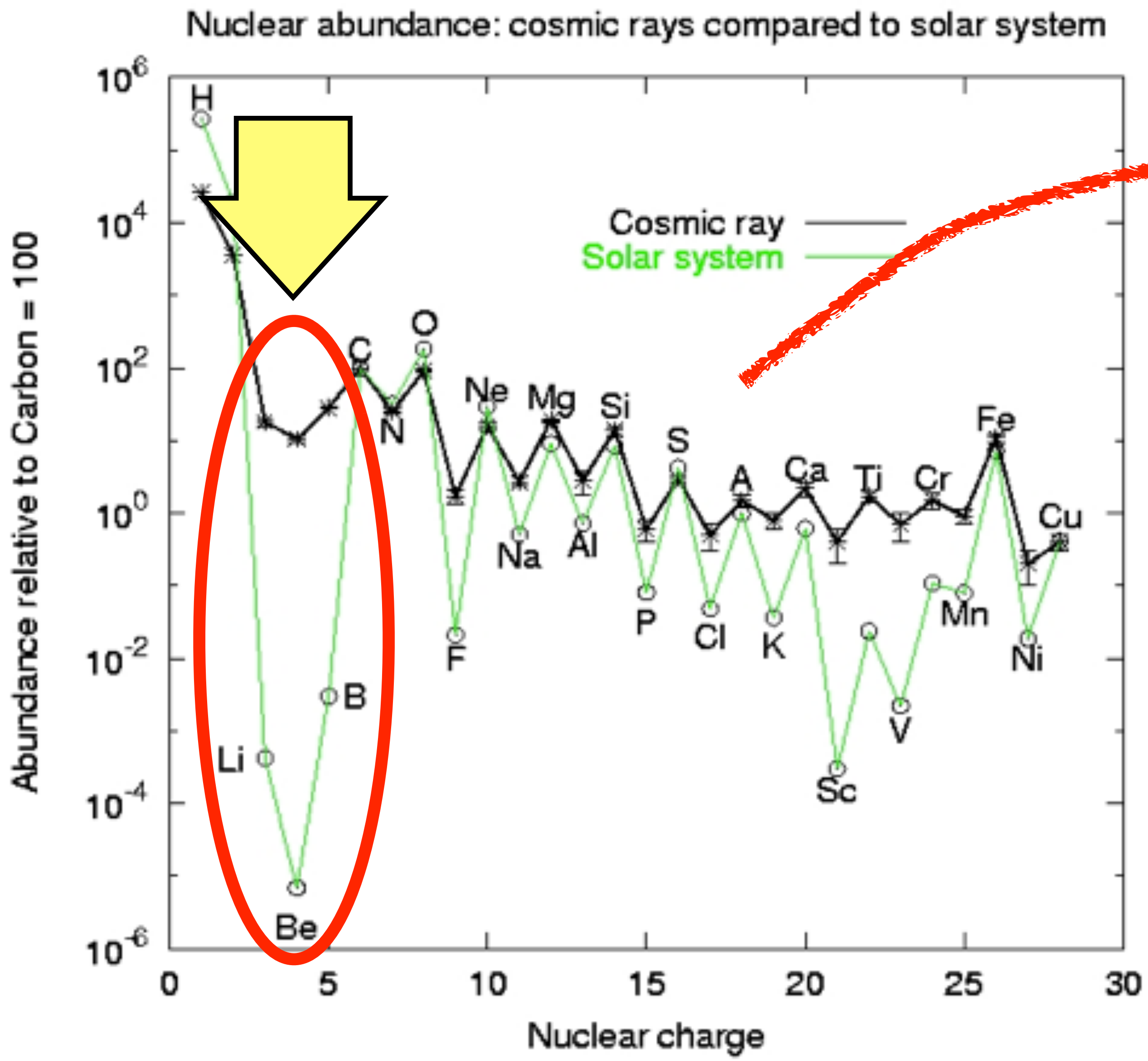
knee ~4 PeV

$$Q_S(E) \propto E^{-2.2\ldots2.4}$$

Hard source spectrum

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

A remarkable “coincidence”



supernovae first proposed by Baade&Zwicky1934

CR escape time

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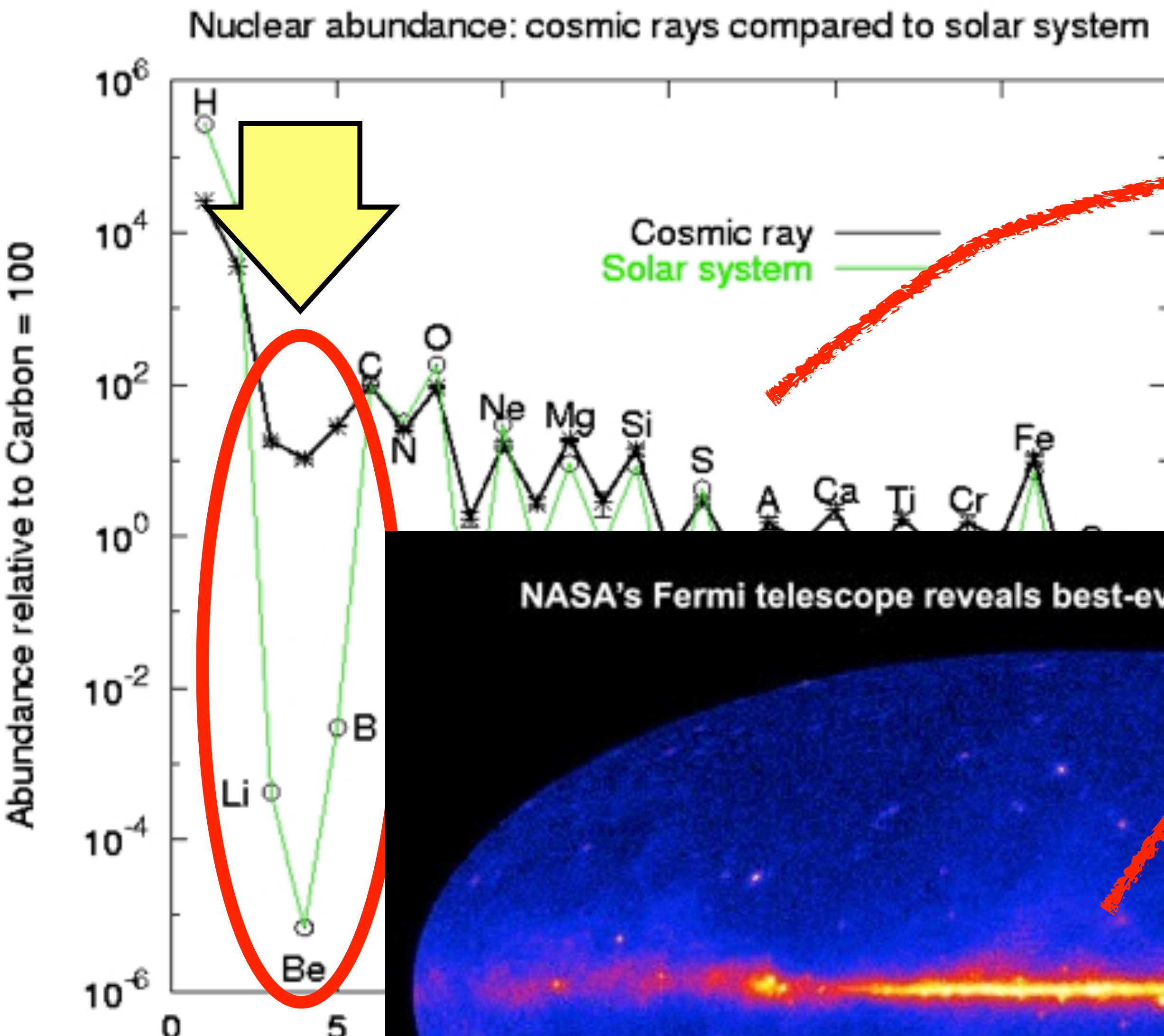
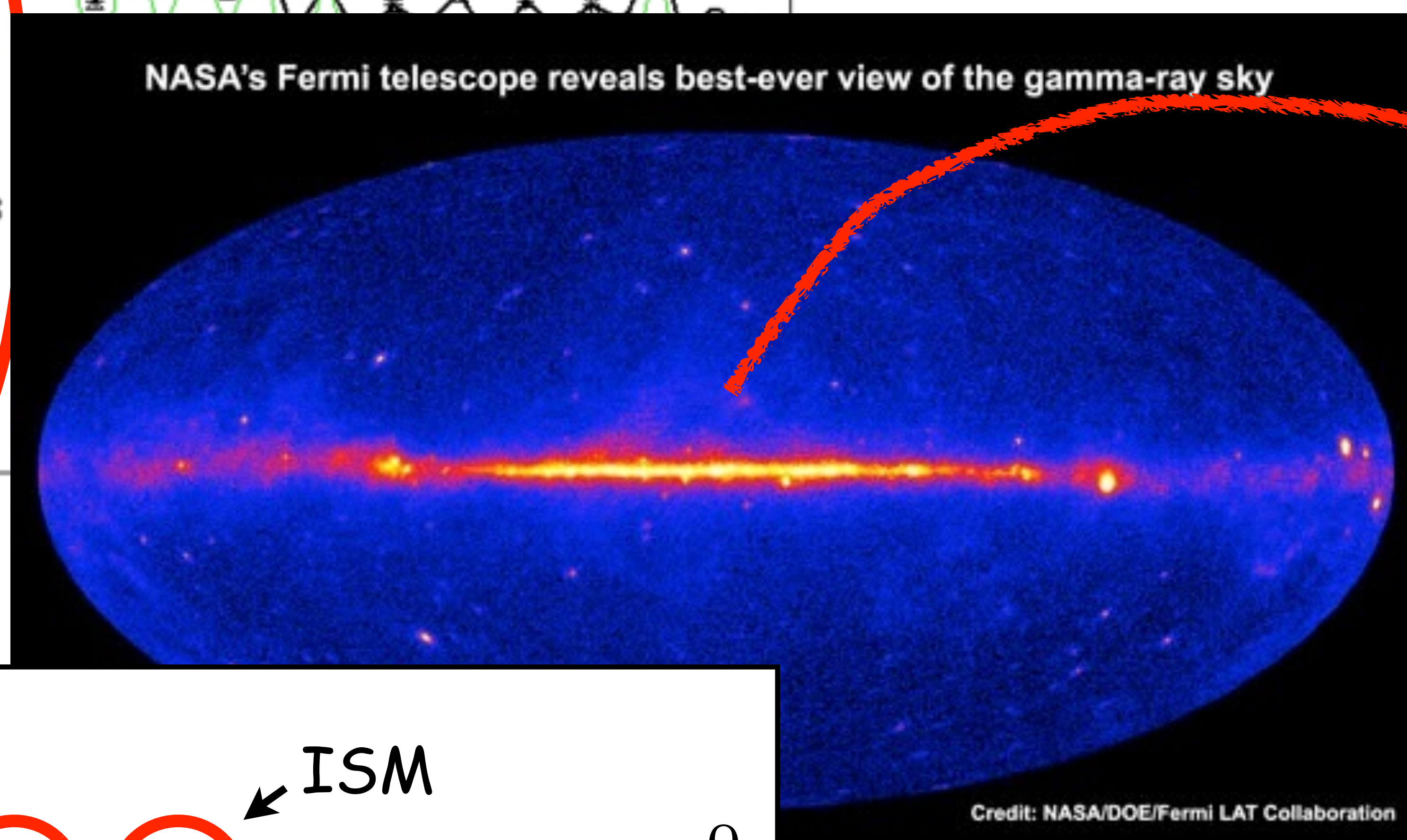


CR escape time

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



CR total energy

CR

ISM

$$p + p \to p + p + \pi^0$$

$$\pi^0 \to \gamma + \gamma$$

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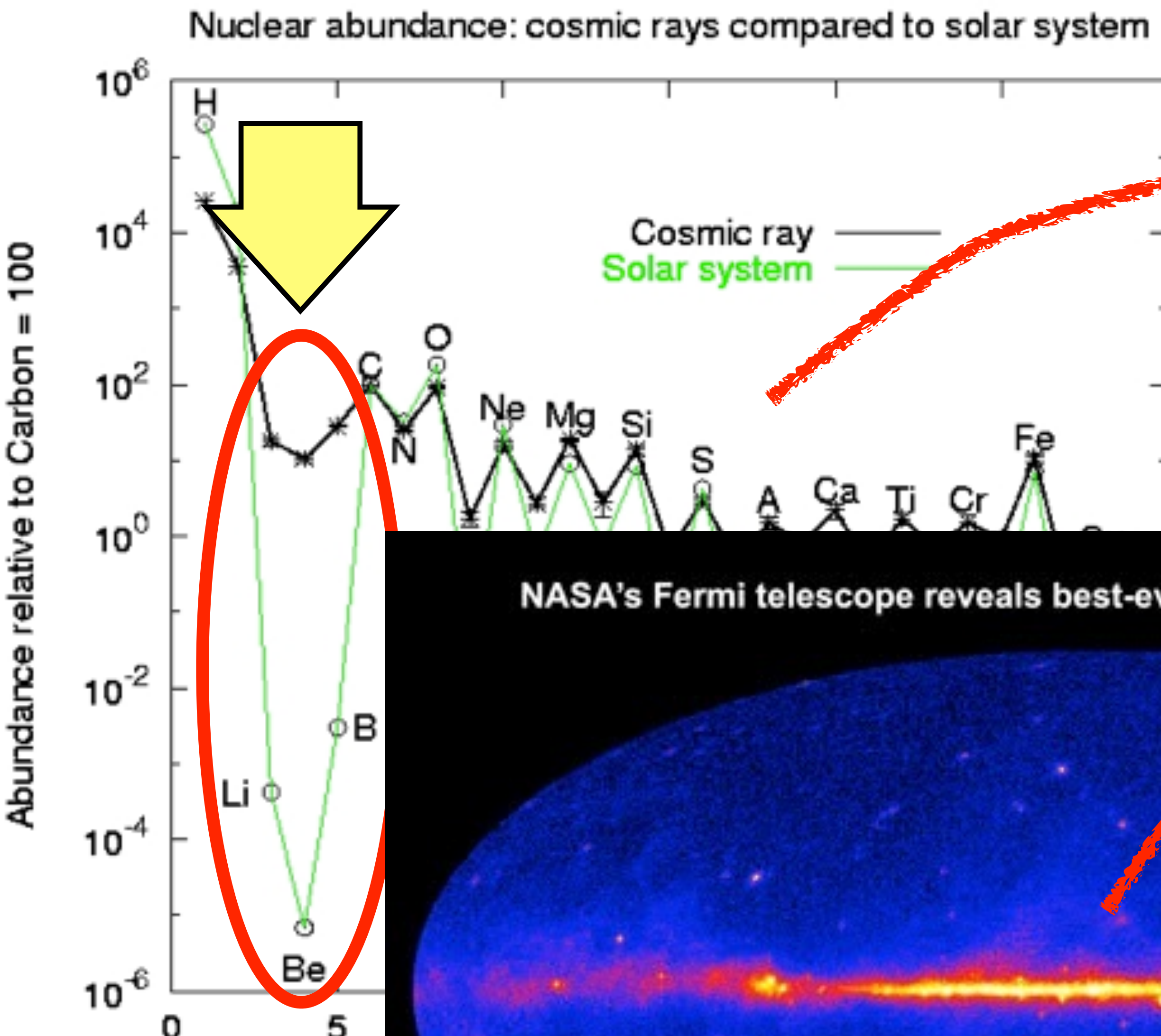

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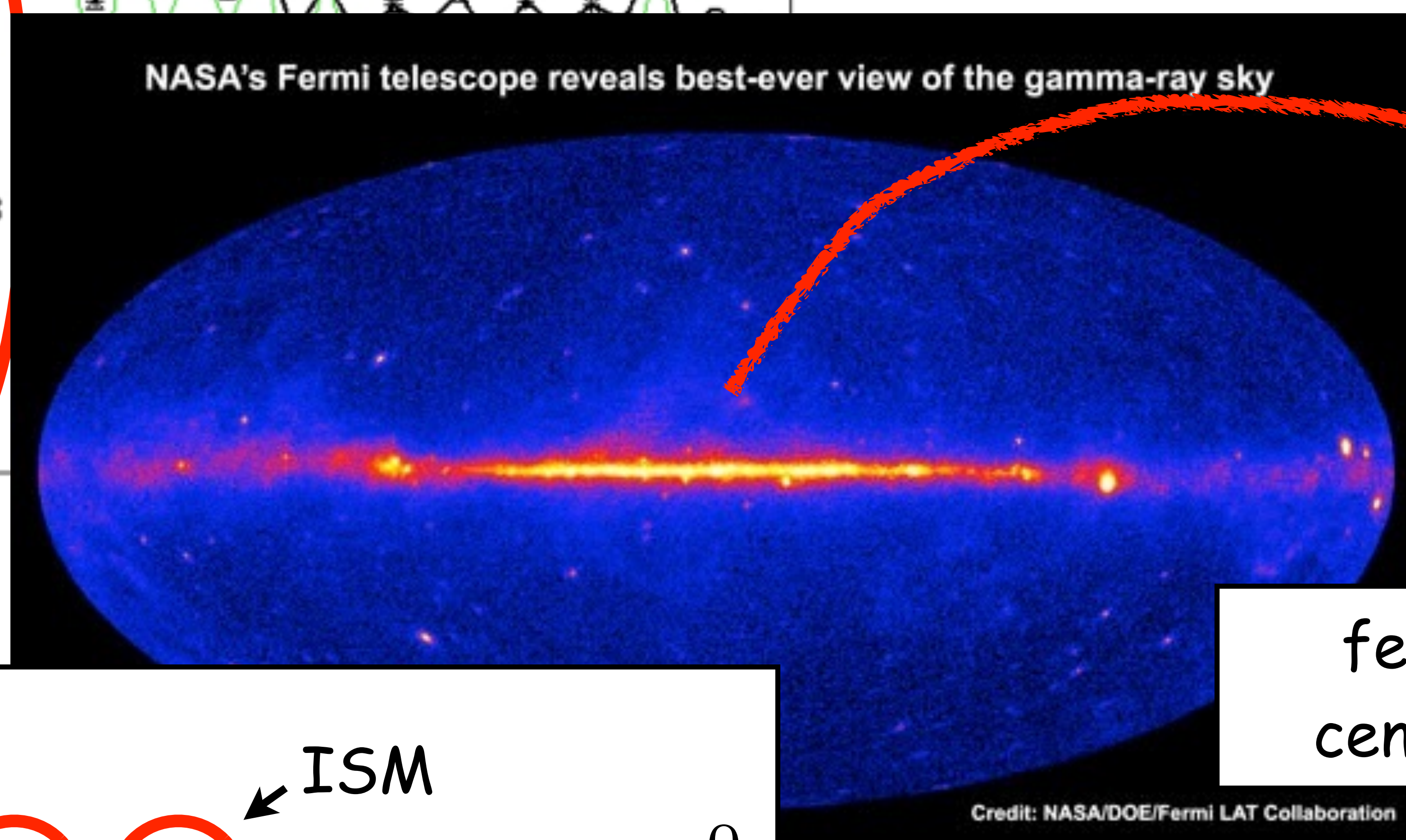

CR total energy

few supernovae per century in the Galaxy

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ISM

$$p + p \to p + p + \pi^0$$

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

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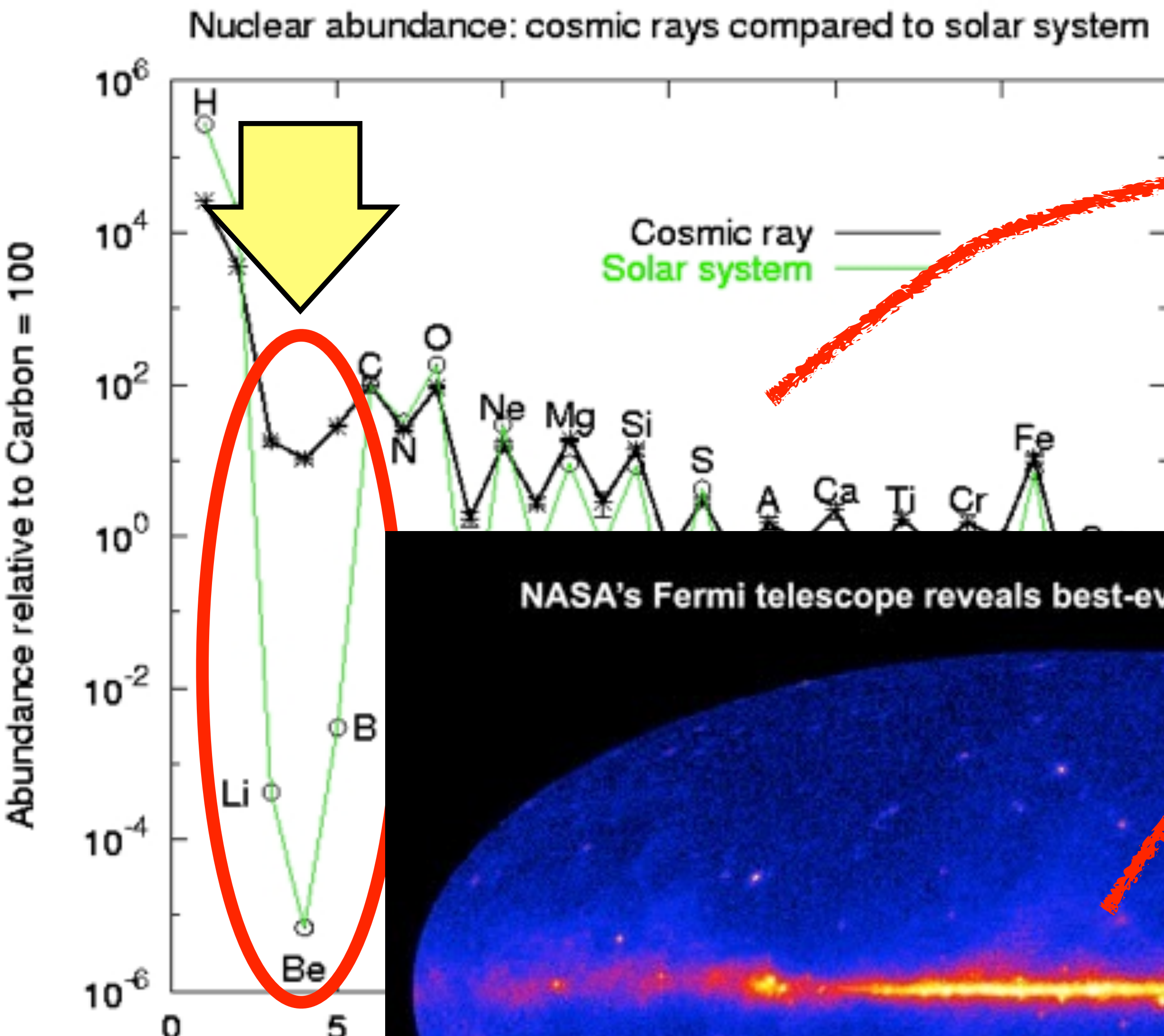

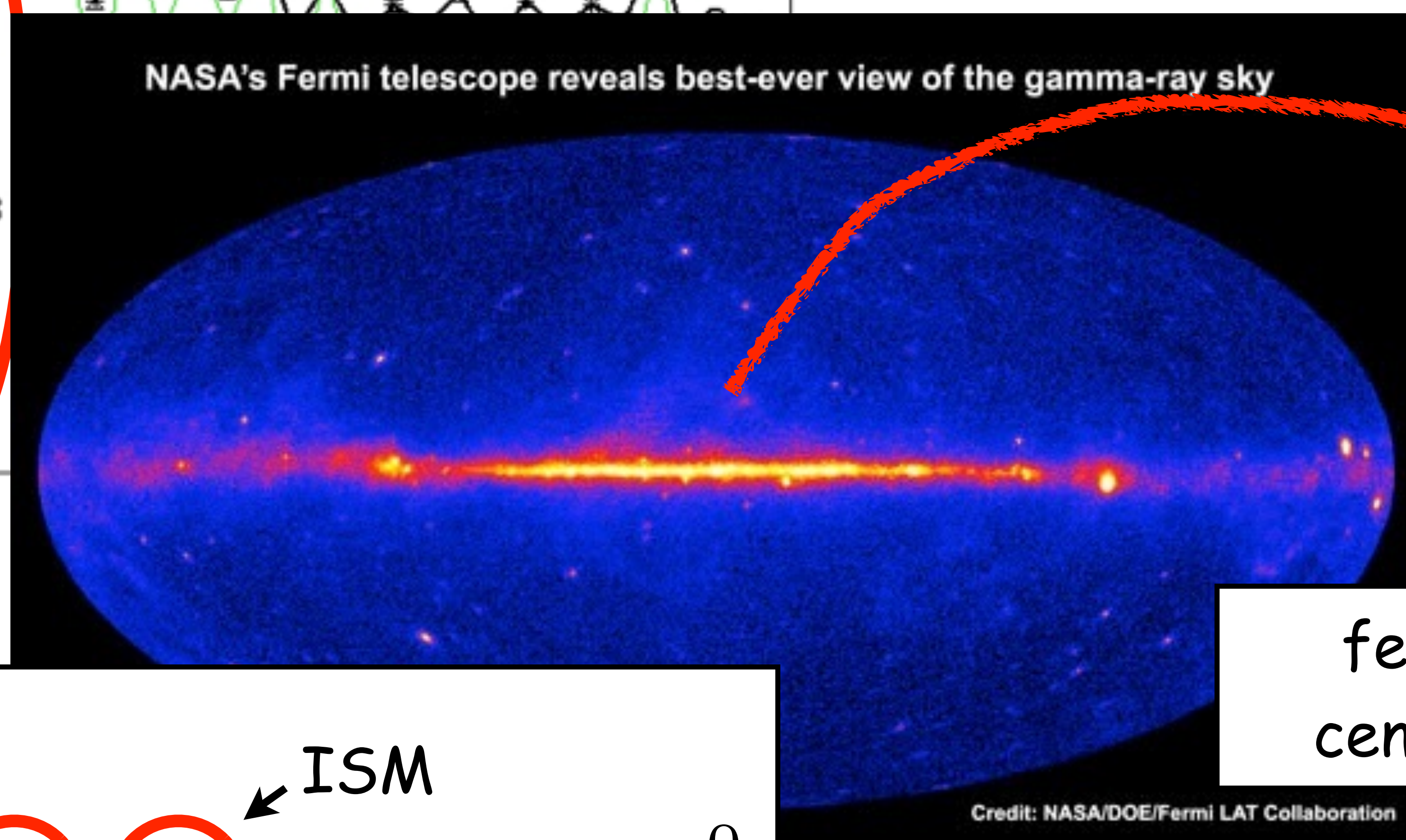

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few supernovae per century in the Galaxy

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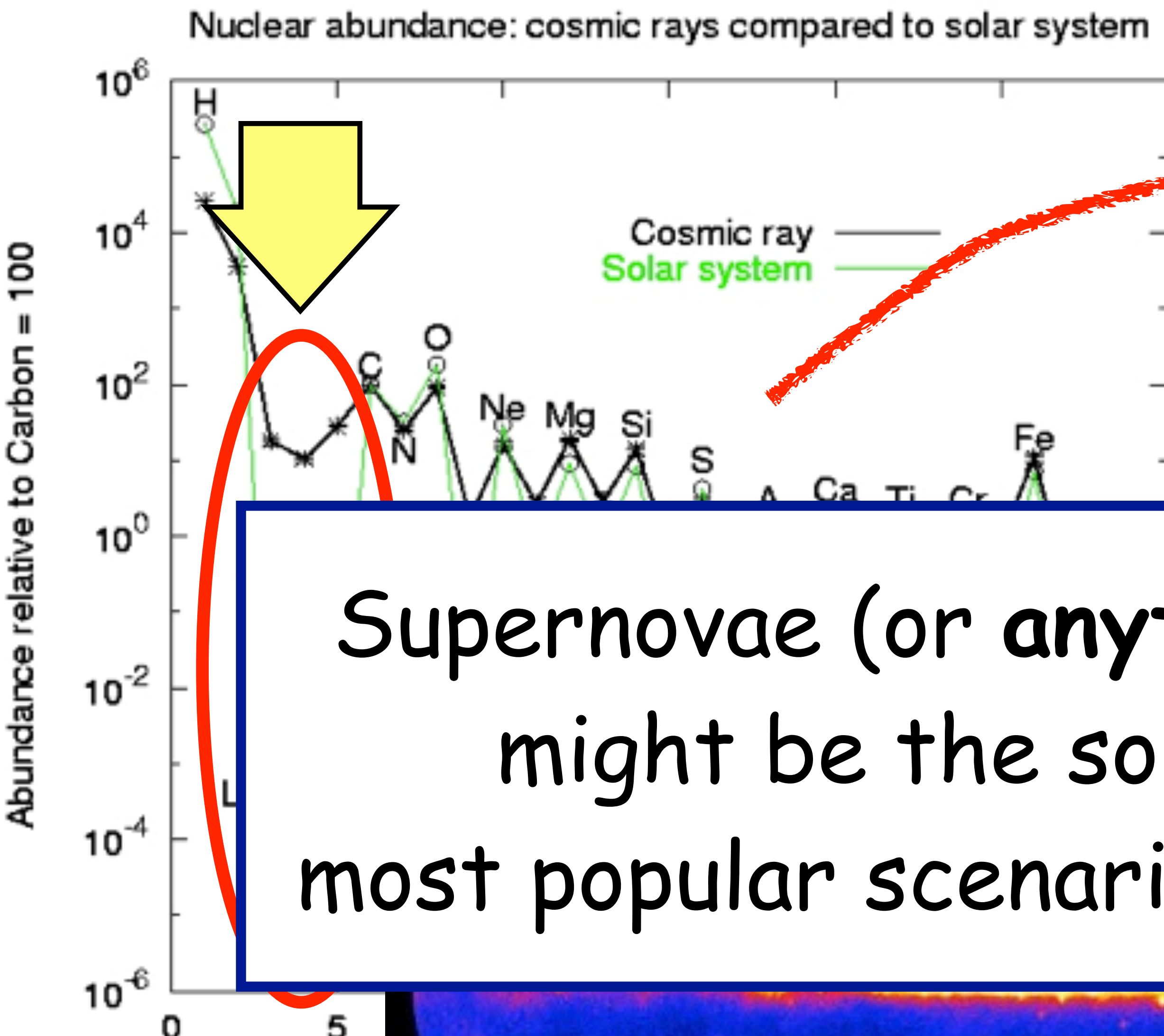
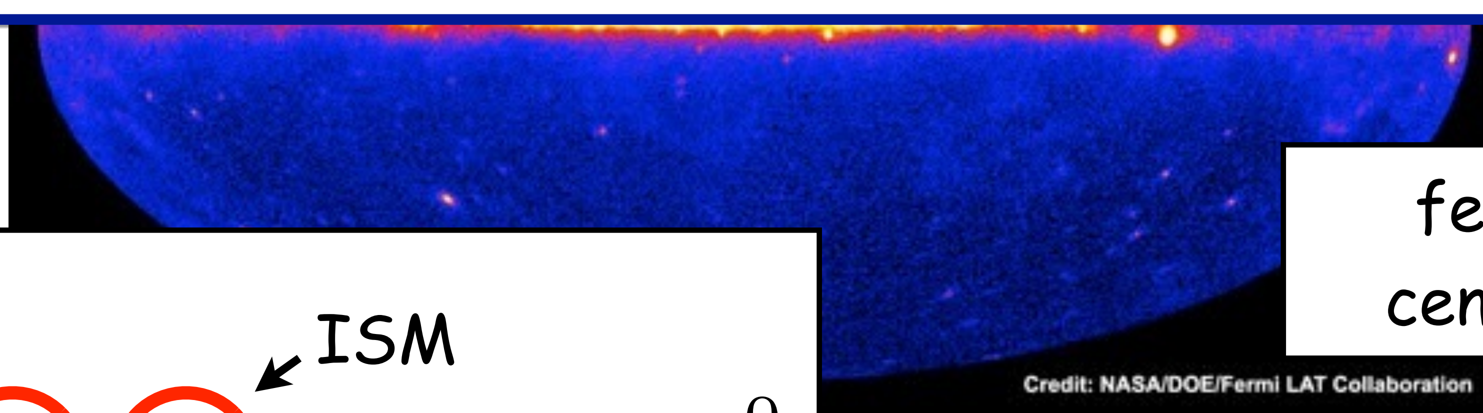


CR escape time

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

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

...nergy



CR ↘ ISM ↙

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few supernovae per century in the Galaxy

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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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SNRs visible in TeV gamma rays

almost model independent

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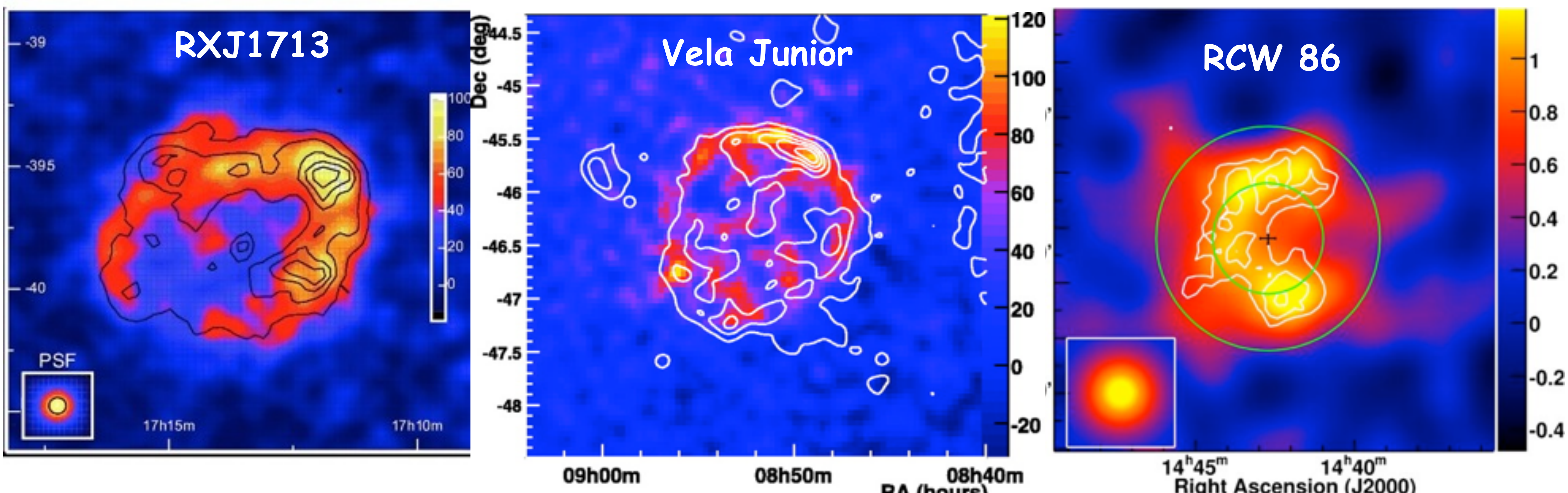


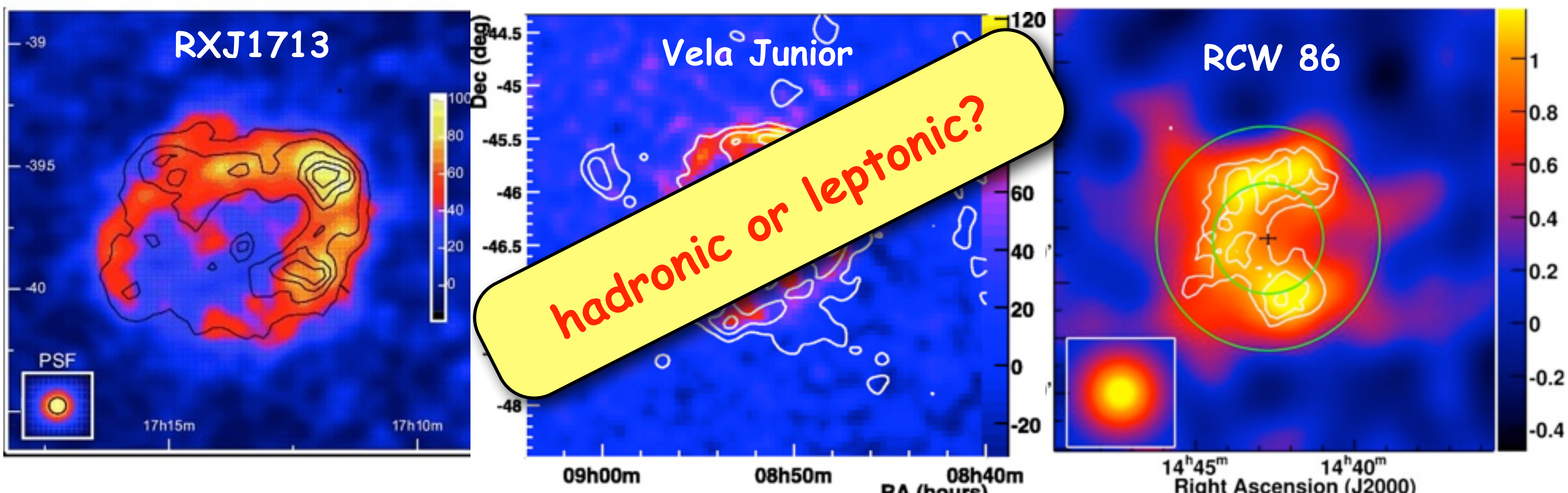
Gamma rays from SNRs: a test for CR origin

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?



Why molecular clouds?

Molecular clouds as cosmic-ray barometers

Black & Fazio 1973, Issa & Wolfendale 1981, Aharonian 1991, Casanova et al. 2010

Gamma ray emission from a molecular cloud

inelasticity

$$L_\gamma(E_\gamma) \approx n_{gas} \; N_{CR}(10\,E_\gamma) \; \sigma_{pp} \; c \; \left(\frac{4\pi}{3} R_{cl}^3\right) \;\; \propto M_{cl} \; N_{CR}(10\,E_\gamma)$$

$$\boxed{F_\gamma(E_\gamma) \;=\; f(\delta) \times N_0 \; E_\gamma^{-\delta} \; \left(\frac{M_{cl}}{d^2}\right)}$$

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gamma ray observations

low energy observations

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CR intensity

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low energy observations

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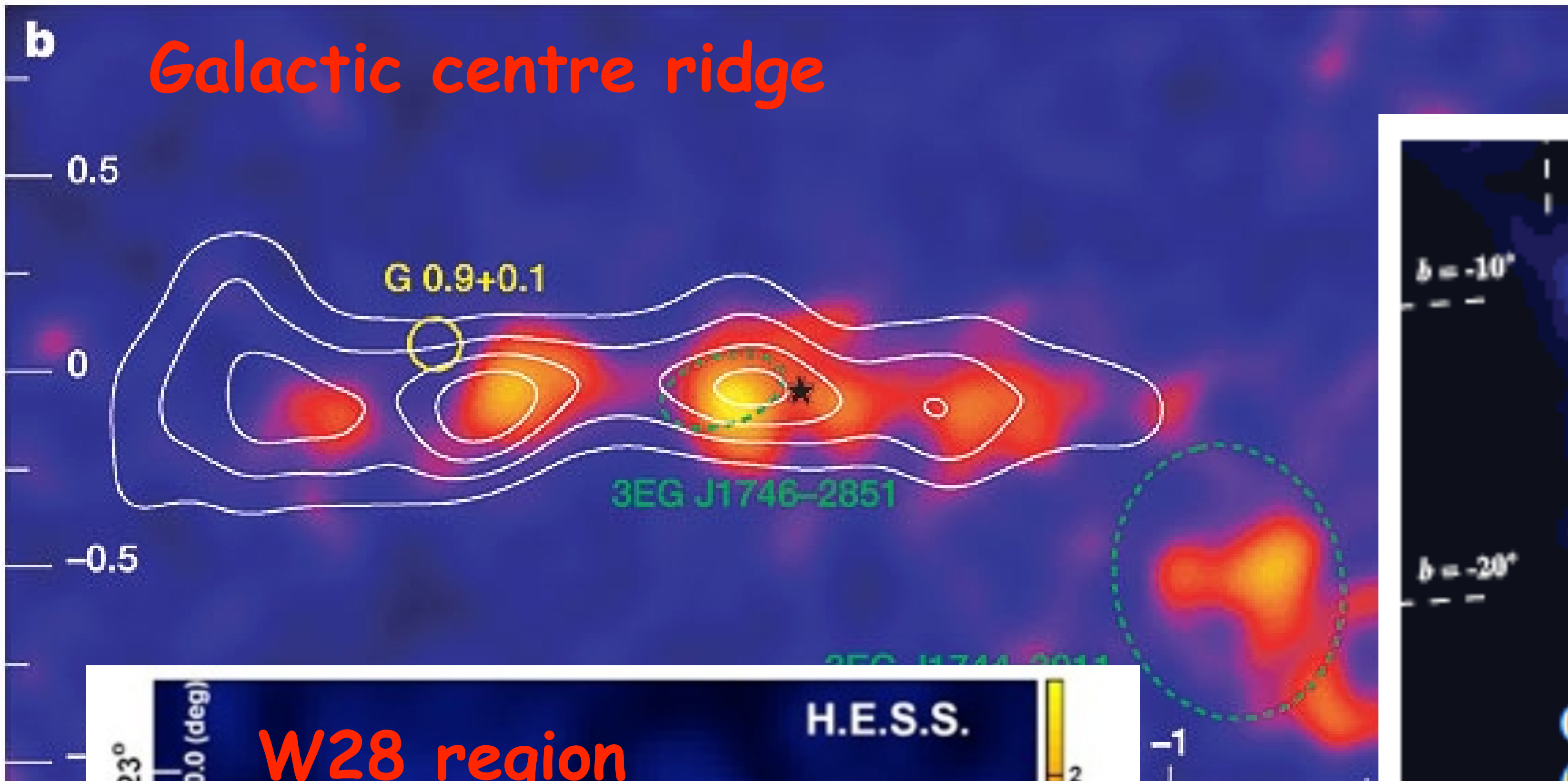
CR intensity

CAVEATS: the determination of the mass depends on the X_{CO} factor

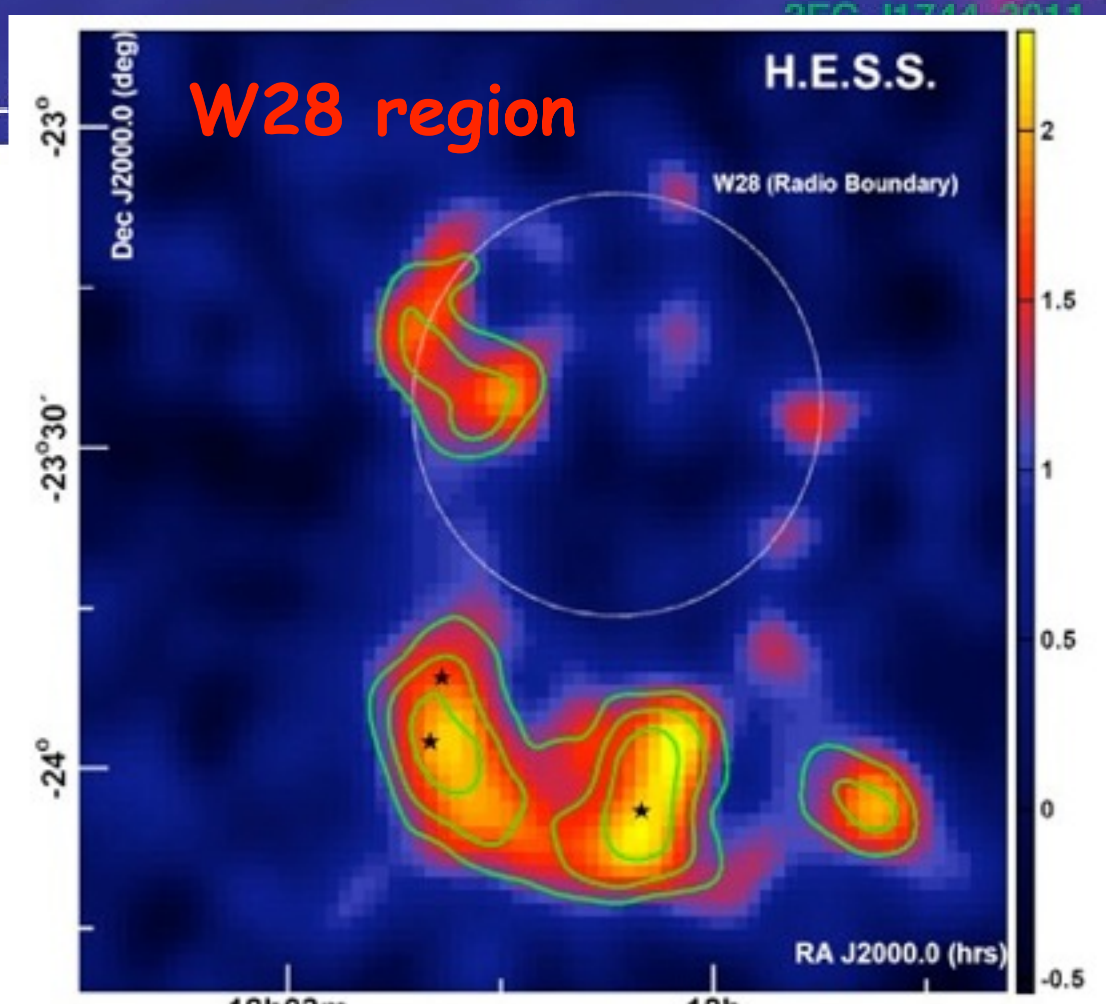
Black & Fazio 1973 -> gamma ray data to infer M_{cl} by assuming a constant CR intensity in the MW

Molecular clouds in gamma-rays

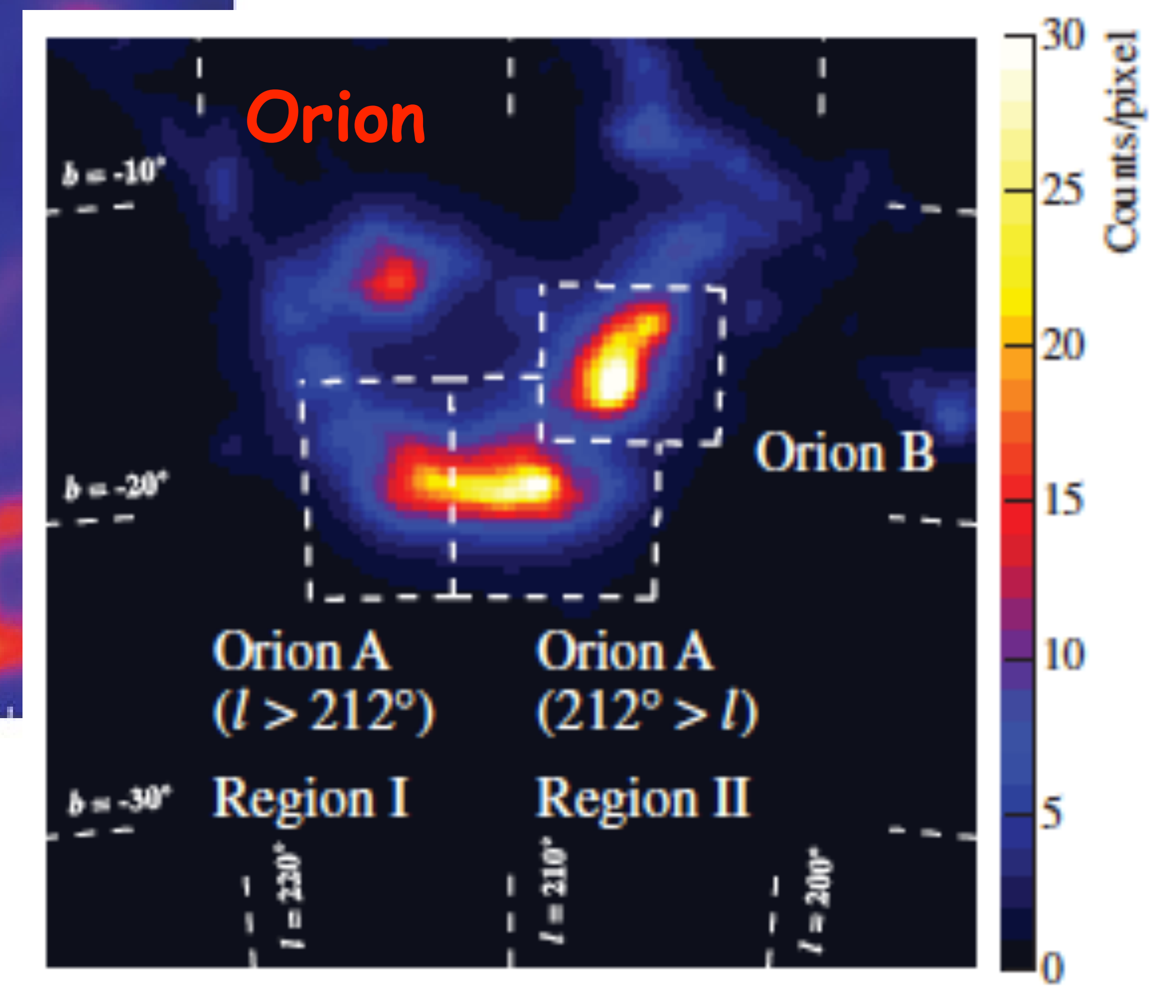
Aharonian et al. 2006



Aharonian et al. 2008



Ackermann et al, 2012



plus many others (especially FERMI), see papers by Neronov+, Dermer, Yang+ etc...

Molecular clouds shocked by a SNR shock

MCs hit by SNRs

MCs overtaken by SN shells -> Aharonian, Drury, Voelk 1994

$$F_\gamma(> 300 \text{ MeV}) \approx 3 \times 10^{-7}\ \theta\ \left(\frac{E_{SN}}{10^{51}\text{erg}}\right) \left(\frac{d}{\text{kpc}}\right)^{-2} \left(\frac{n}{\text{cm}^{-3}}\right) \text{cm}^{-2}\text{s}^{-1}$$

acceleration efficiency

MC density

MCs hit by SNRs

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do we expect turbulence in neutral media?

$F_\gamma(> 300\ \mathrm{MeV}) \simeq 3 \ldots \left(\frac{\ldots}{\mathrm{erg}}\right) \left(\frac{\ldots}{\mathrm{kpc}}\right) \left(\frac{n}{\mathrm{cm}^{-3}}\right) \mathrm{cm}^{-2}\mathrm{s}^{-1}$

acc...

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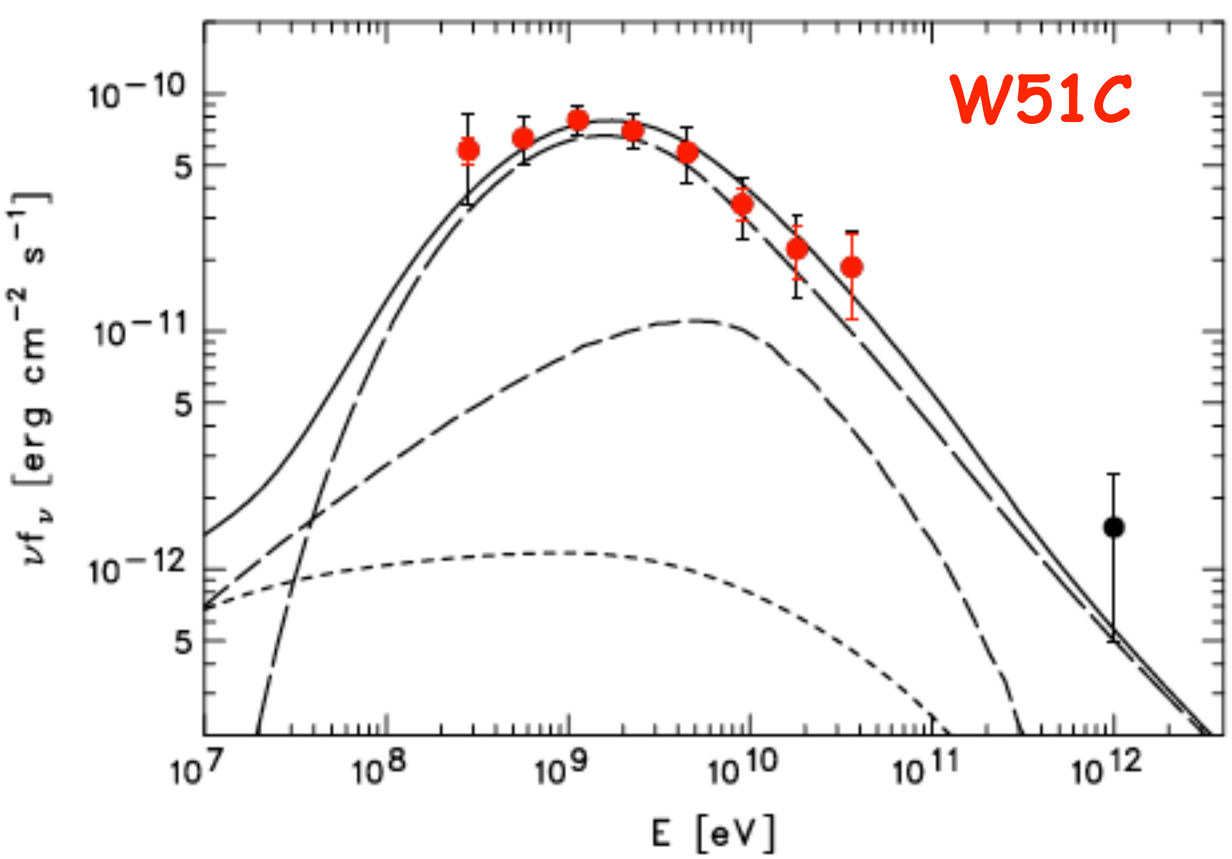
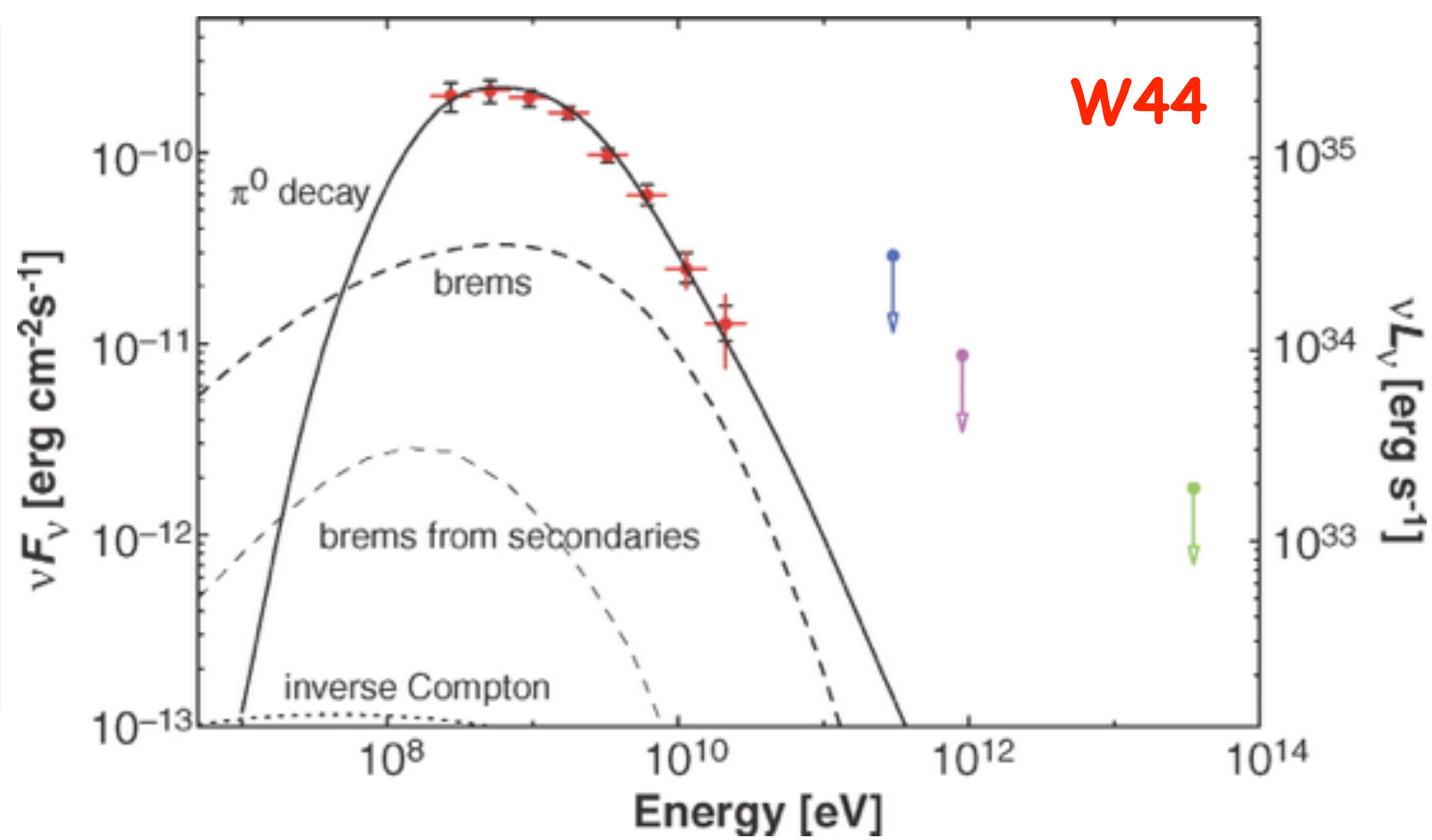
acc... y

MC density

SNR+MC seen by Femri -> old ~10^4 yr, steep spectrum





Abdo et al 2009, 2010

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acc...

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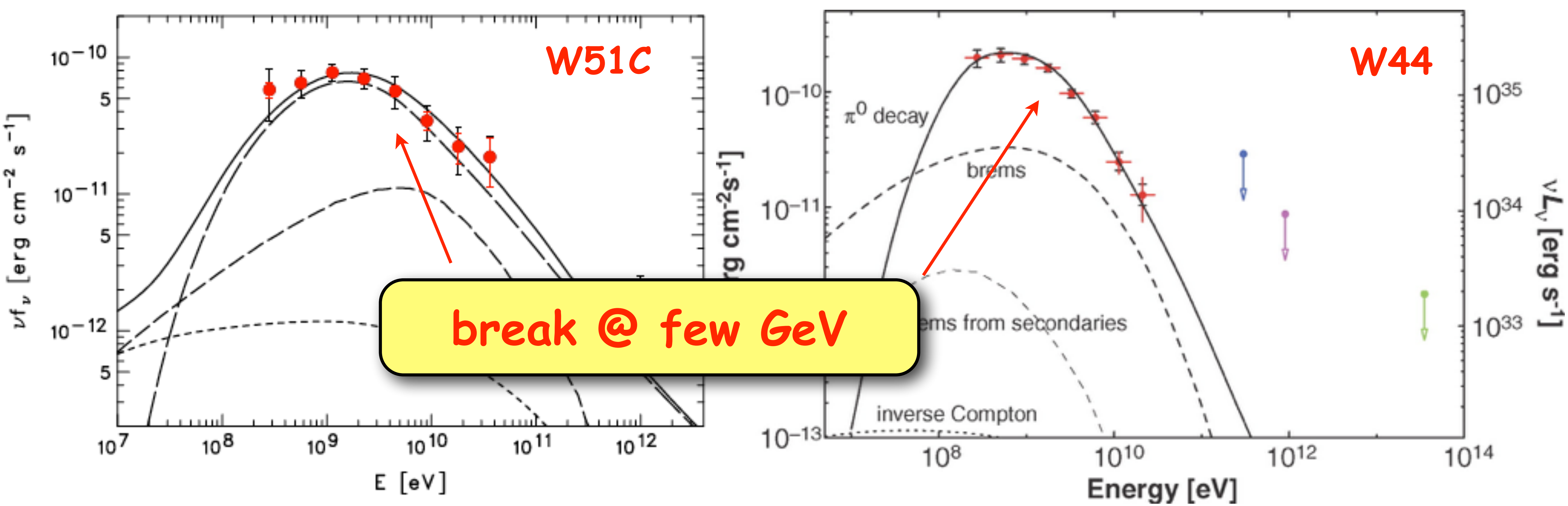

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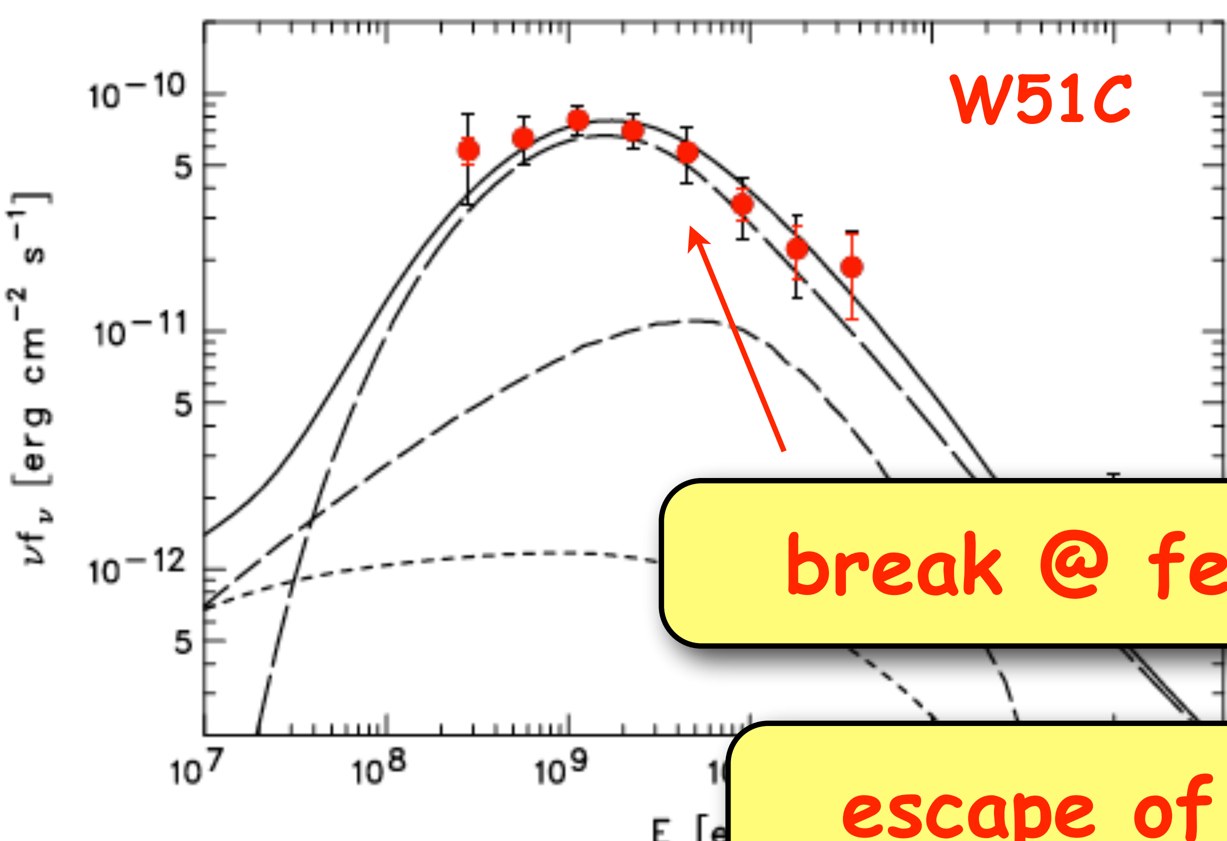
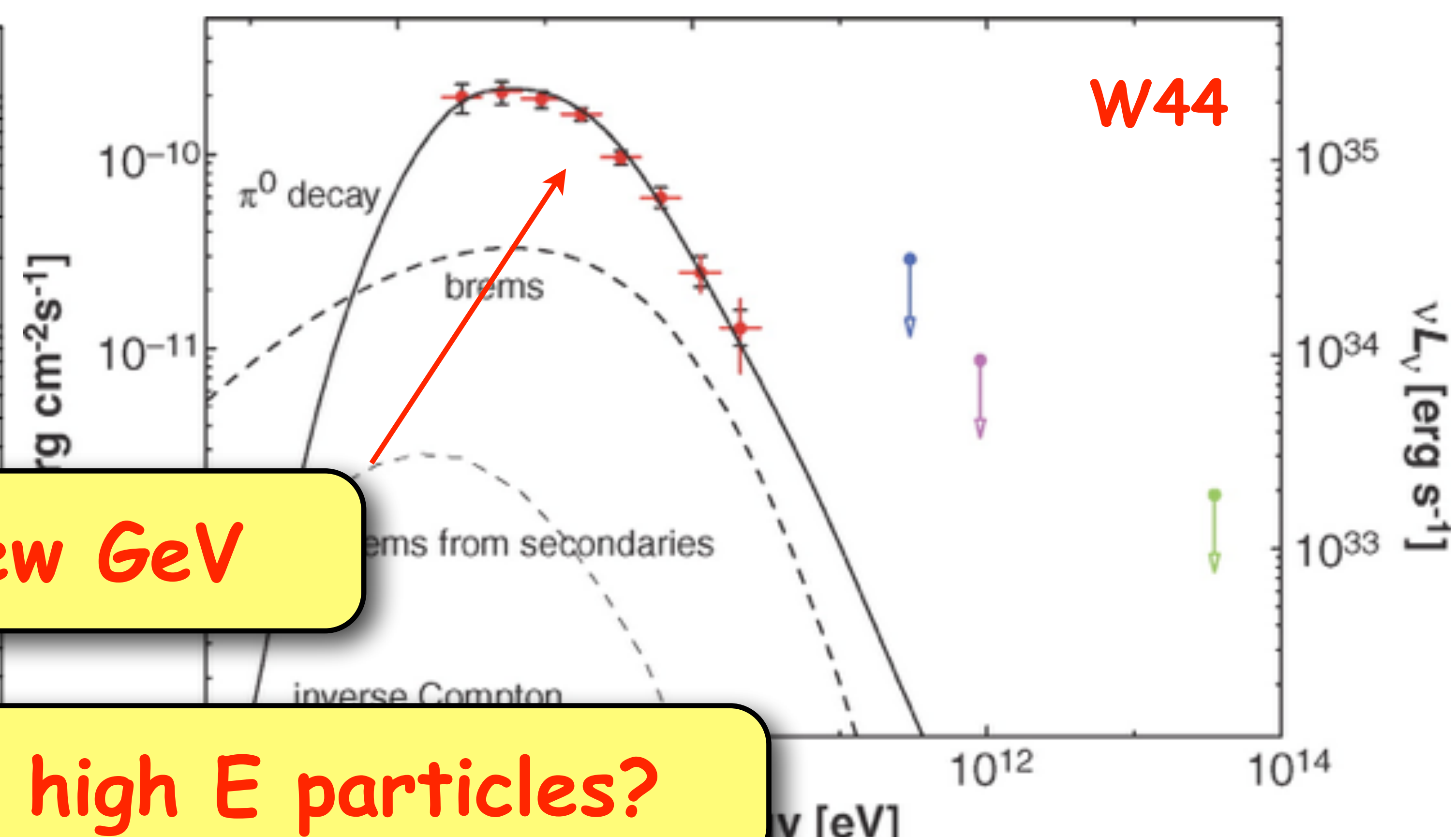


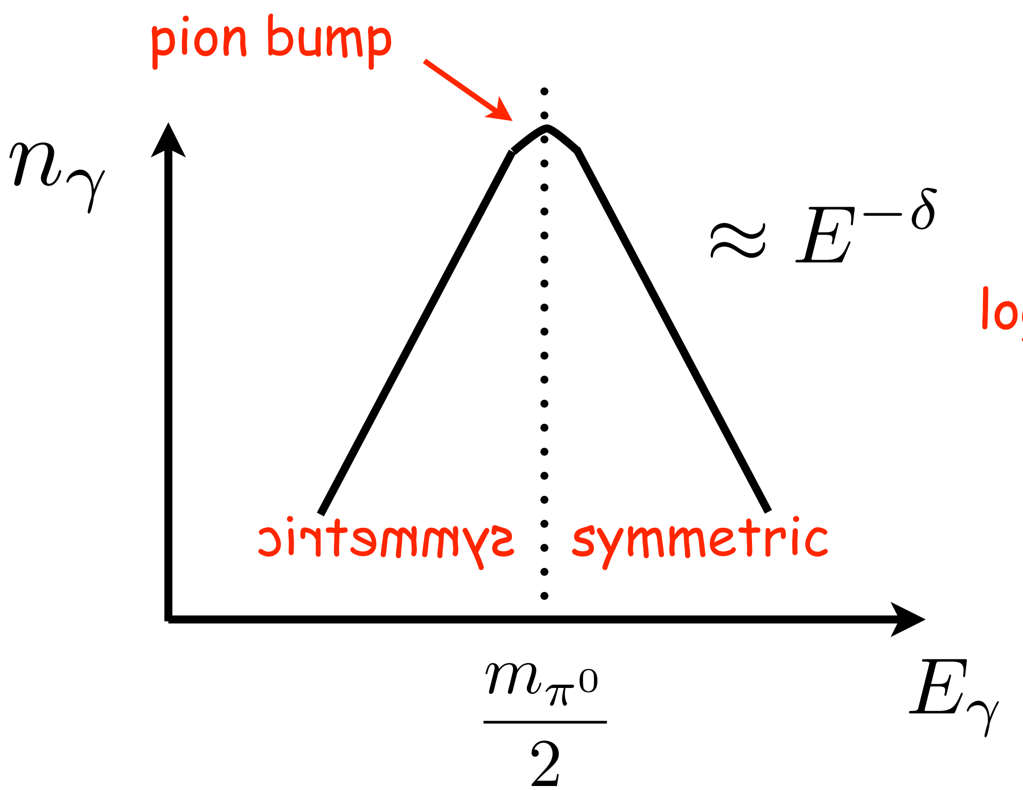


break @ few GeV

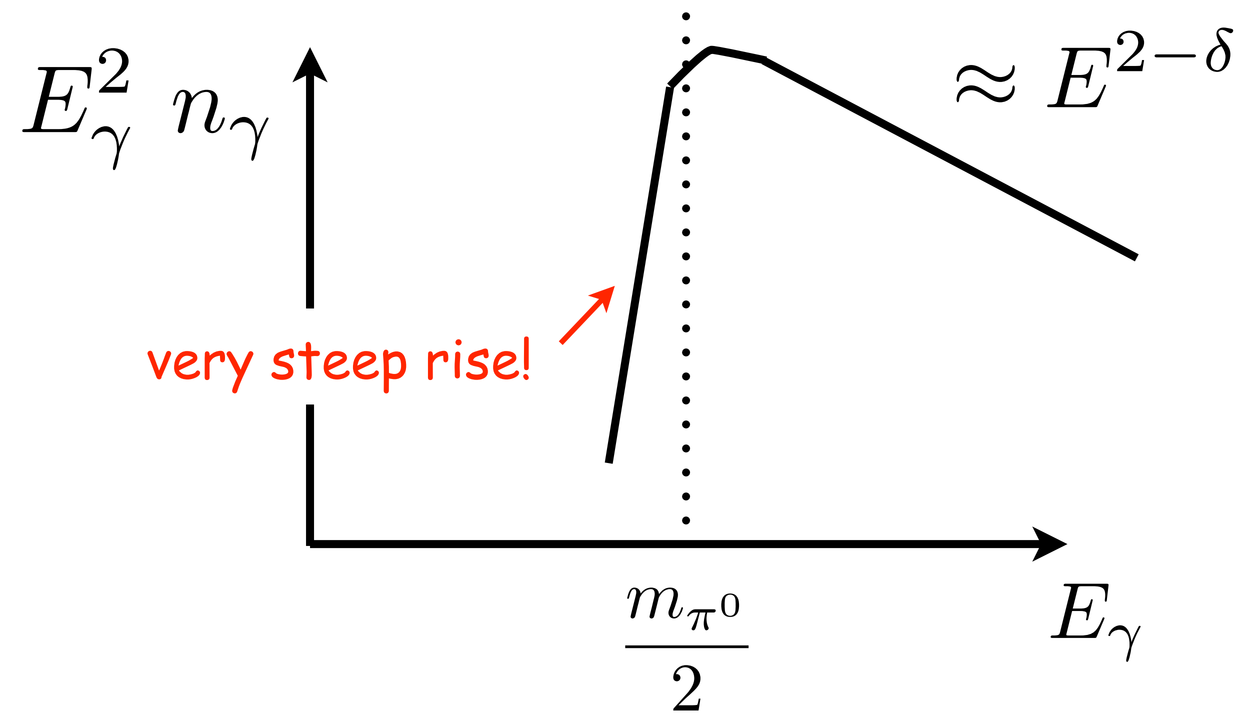
escape of high E particles?

Abdo et al 2009, 2010

Do SNRs accelerate protons?



log scale!

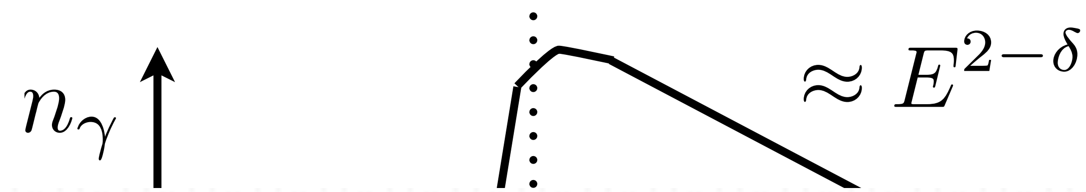


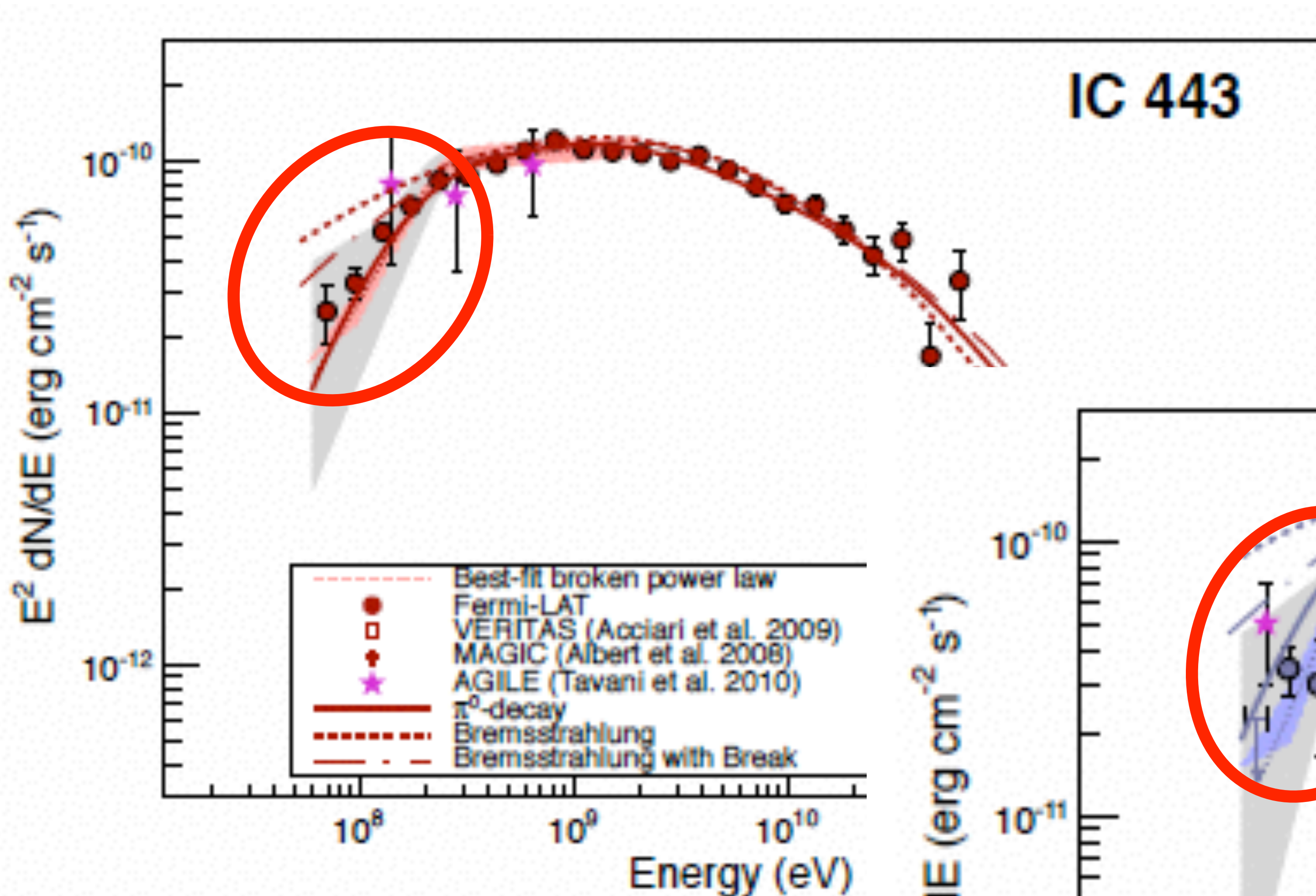
Do SNRs accelerate protons?

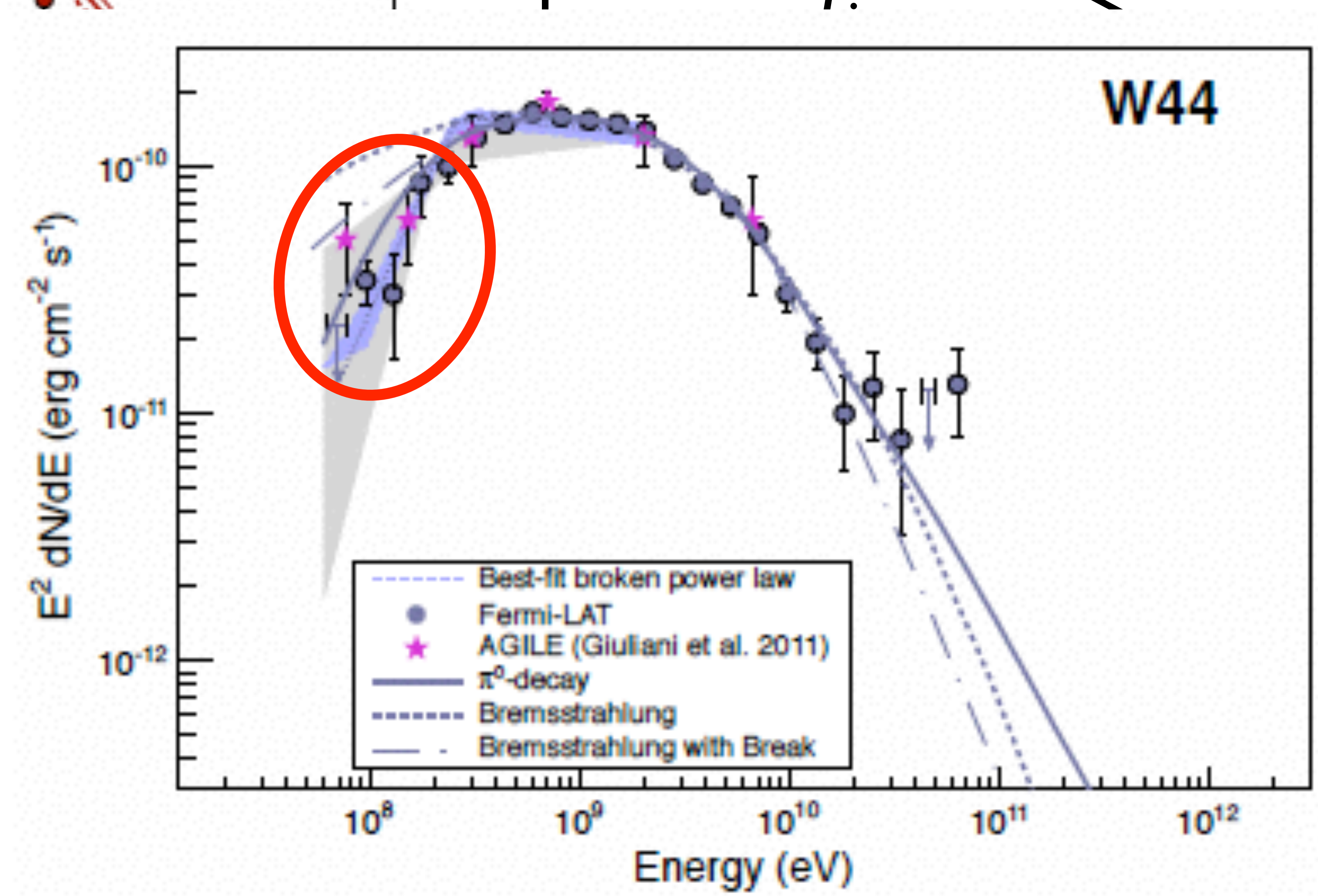
(Ackermann et al 2013)

FERMI (and **AGILE**)

(Giuliani+, Cardillo+)







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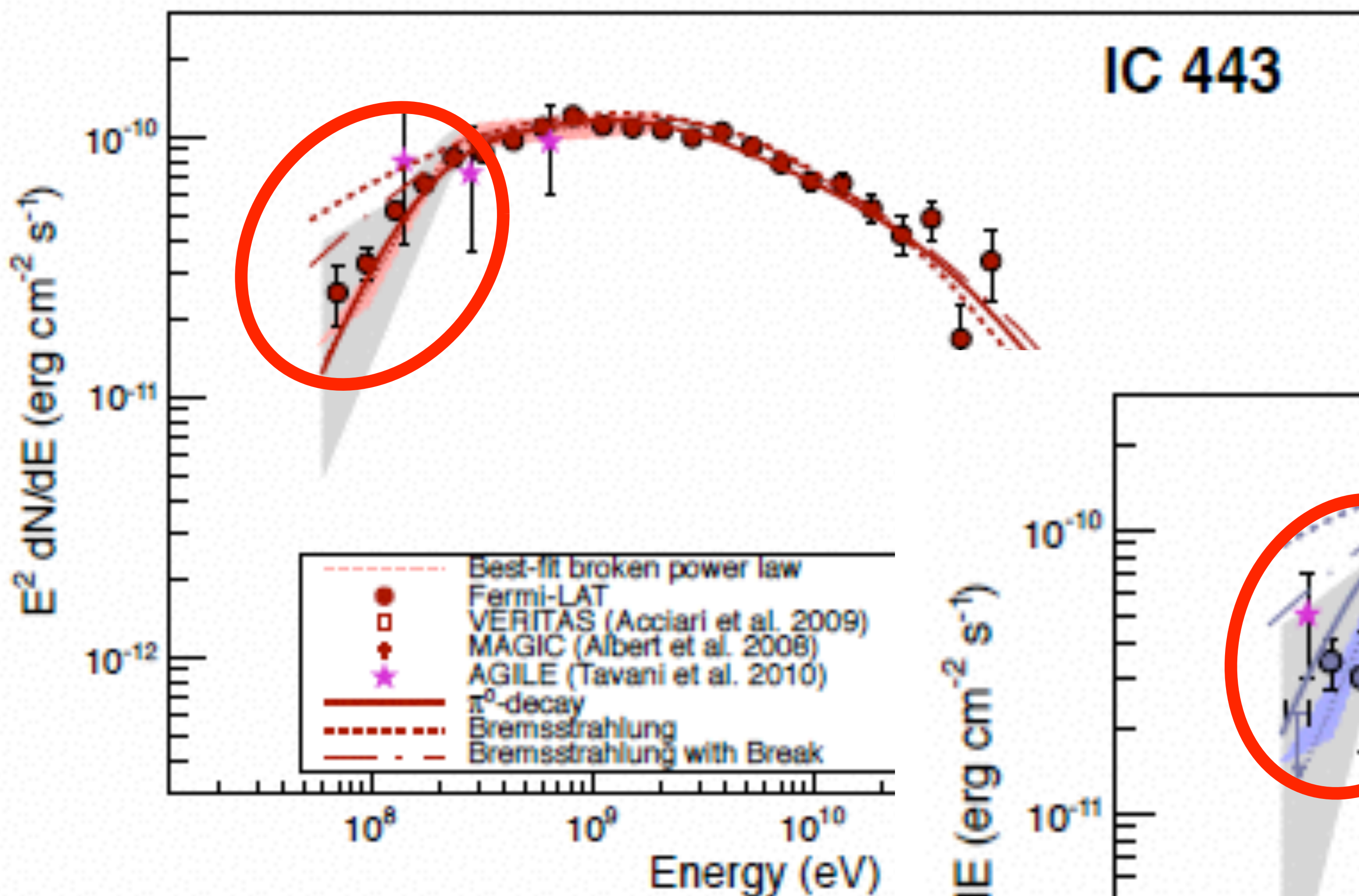

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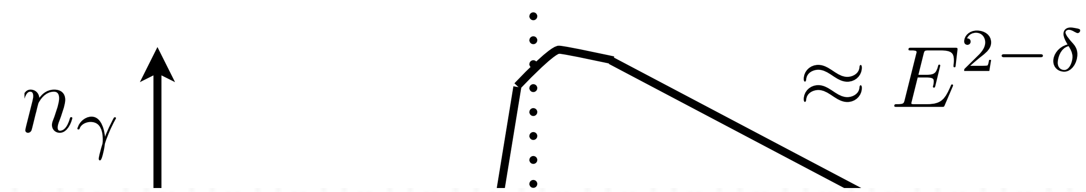
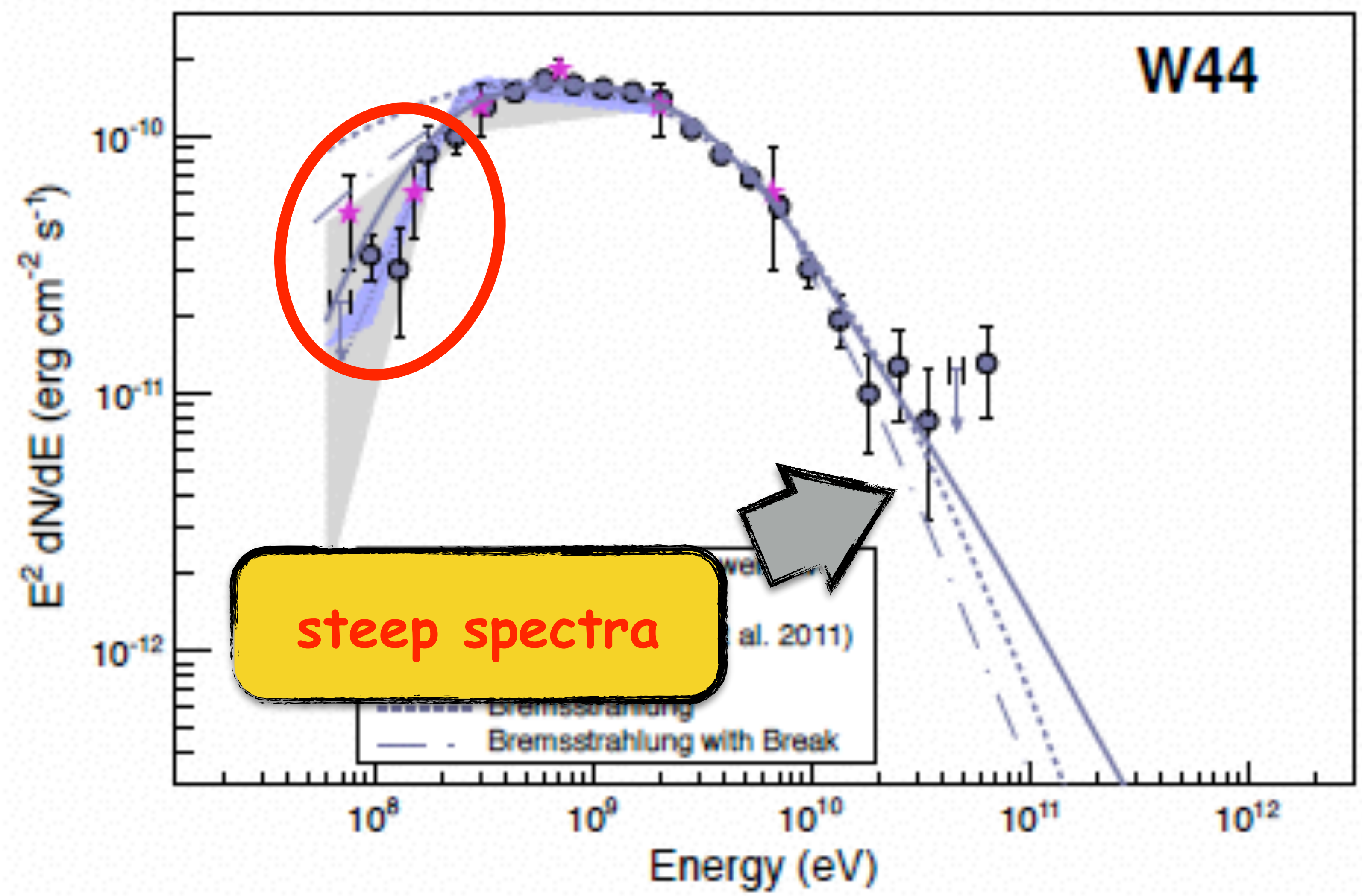


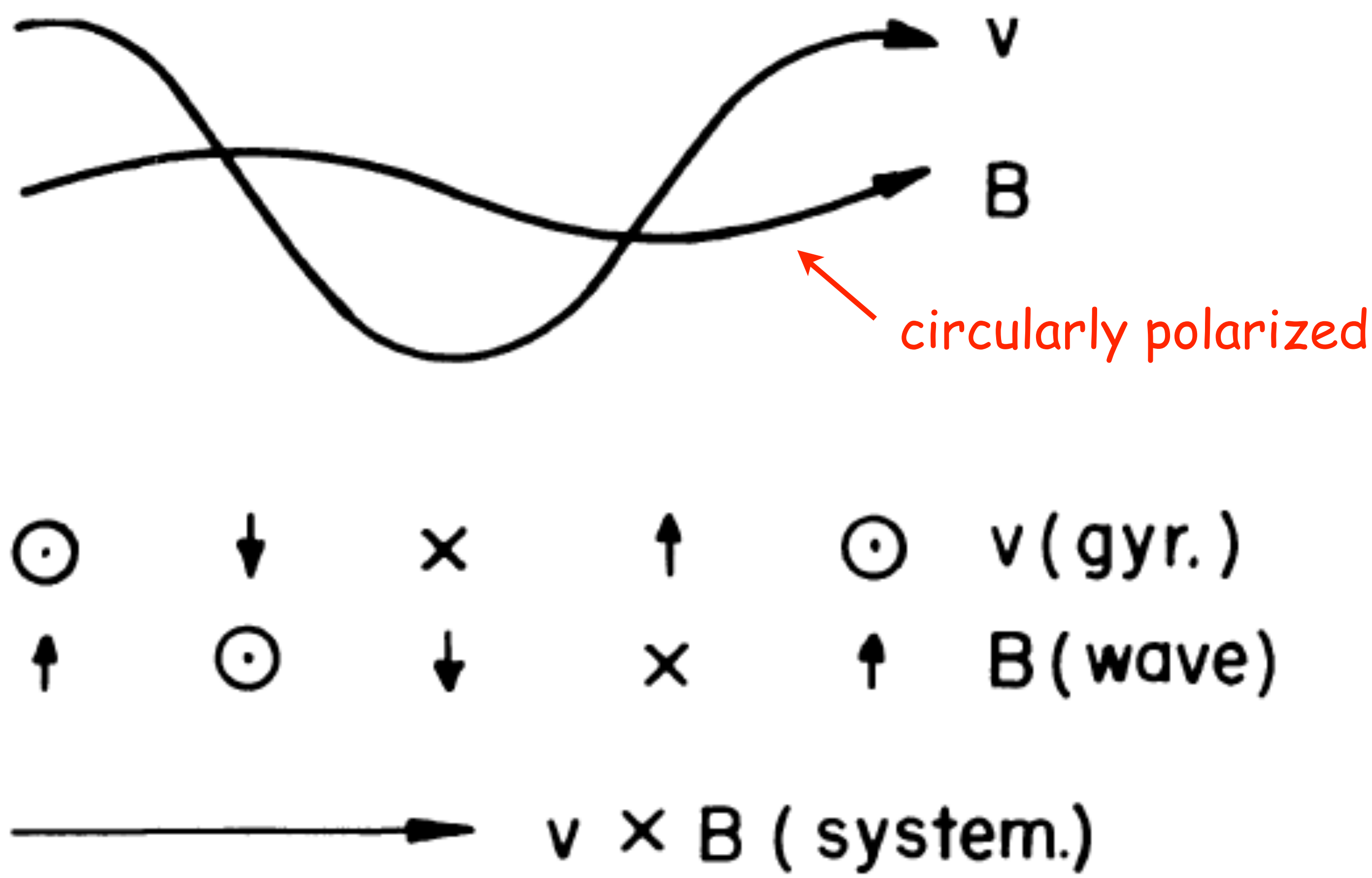


steep spectra

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

CRs & Alfven waves: resonant interactions

Fig. from Wentzel 1972



static field -> pitch angle scattering only

$E_{before} = E_{after}$

resonant condition
(in the frame moving with the waves!)

$$\lambda = \frac{2\pi}{k} = \left(\frac{2\pi}{\Omega_g}\right) v_z \approx 2\pi R_L \longrightarrow k \approx \frac{1}{R_L}$$

Wentzel 1974

MCs hit by SNRs: effect of neutrals

SNR+MC seen by Fermi are usually old ~10^4 yrs -> slow shock speed -> radiative

GeV flux -> reacceleration of background CRs + compression (Blandford&Cowie1981)

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break @few GeV -> limited confinement of particles due to ion-neutral damping of Alfven waves (Malkov et al 2011)

$$\omega \gg \nu_{i-n} \qquad\qquad \omega \ll \nu_{i-n}$$

$$V_A = \frac{B}{\sqrt{4\ \pi\ \rho_i}} \qquad\qquad V_A = \frac{B}{\sqrt{4\ \pi\ \rho_n}}$$

k

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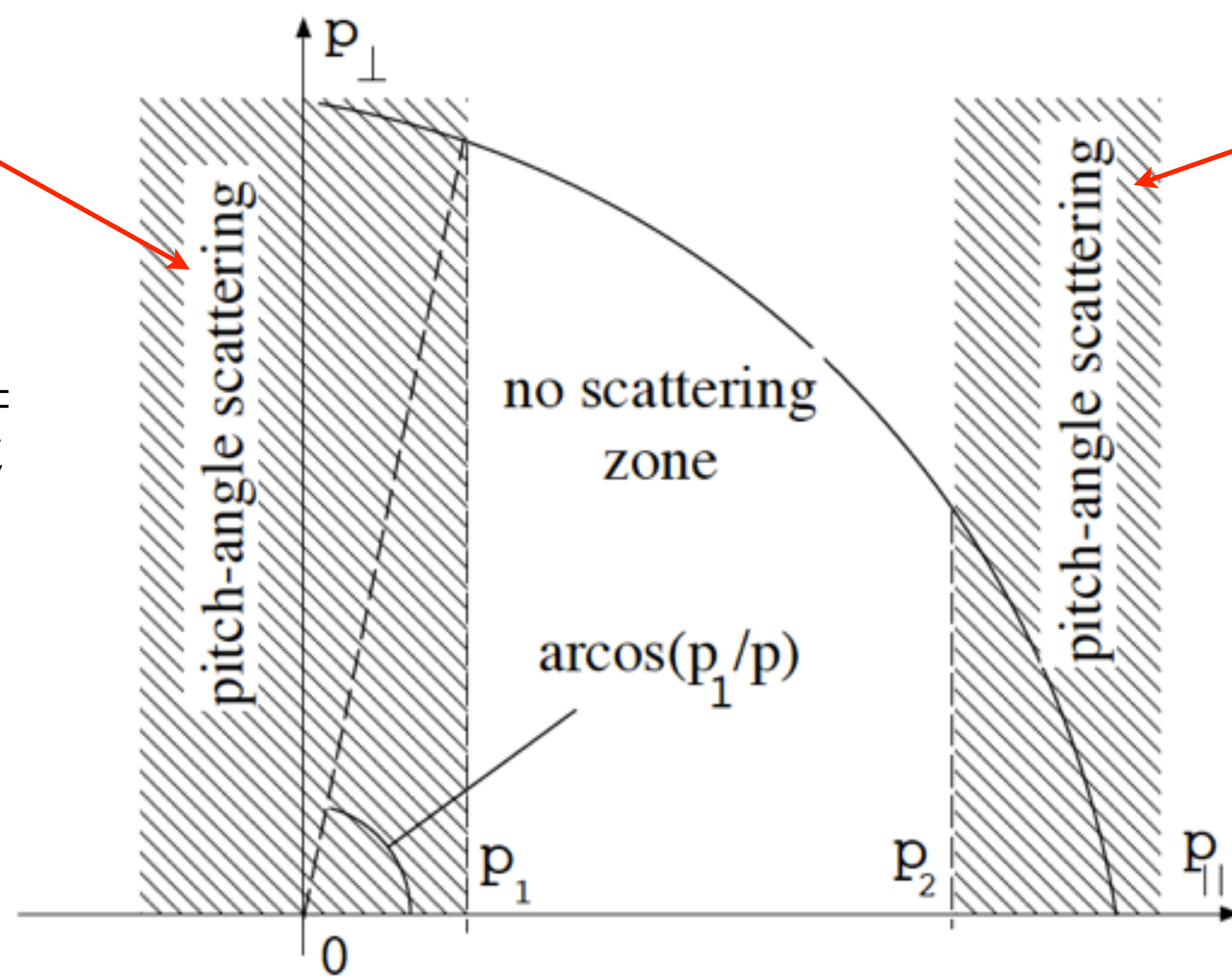

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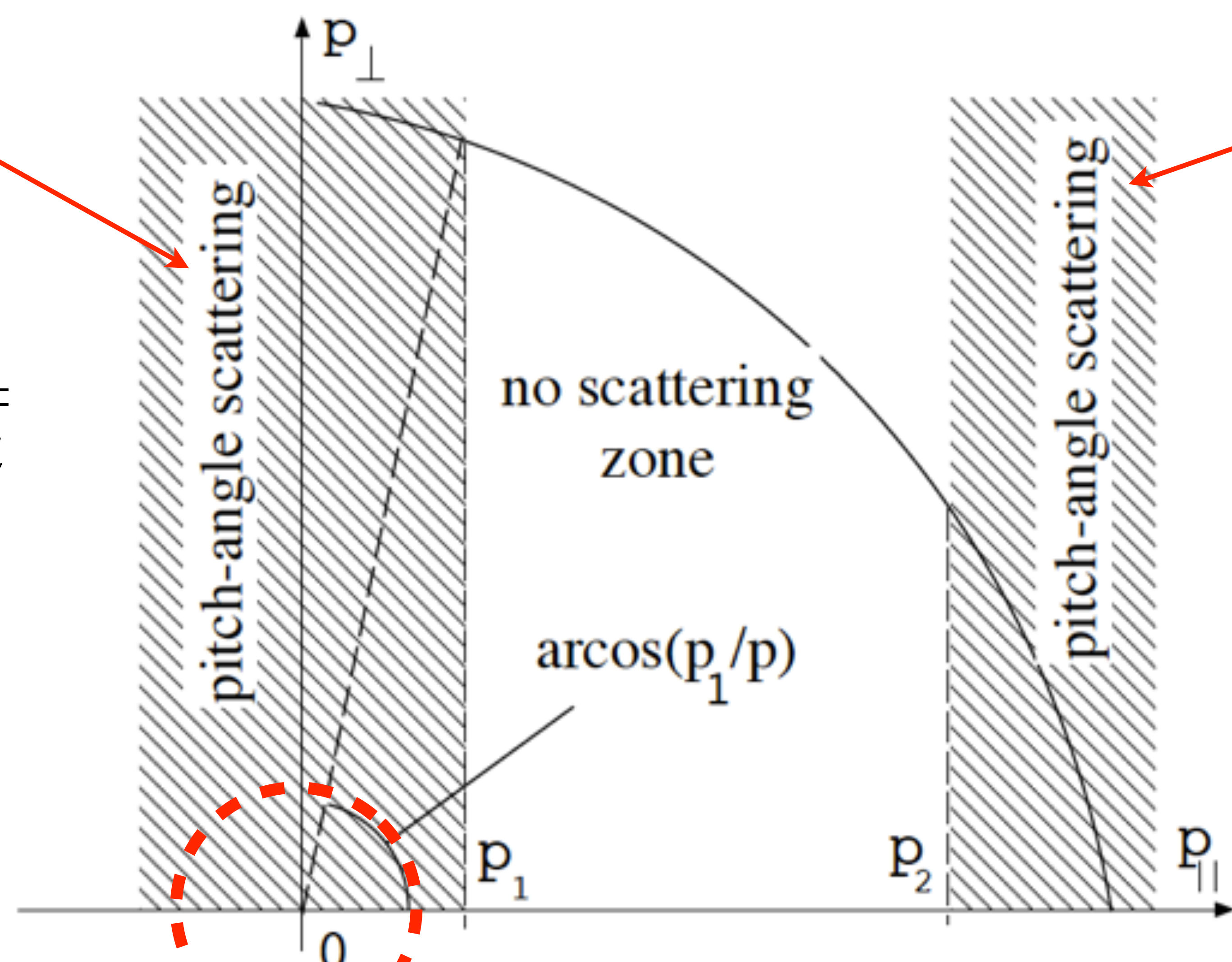

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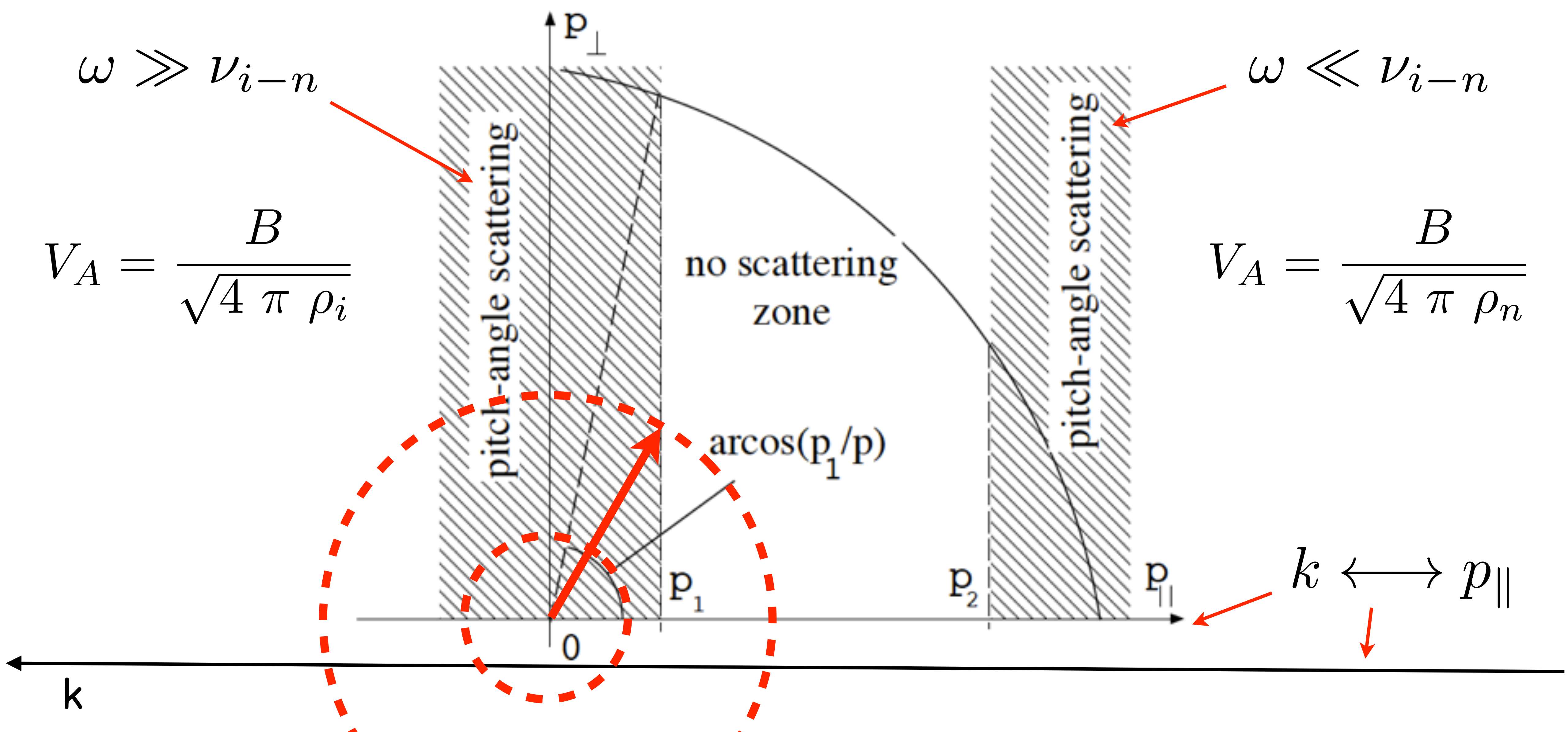

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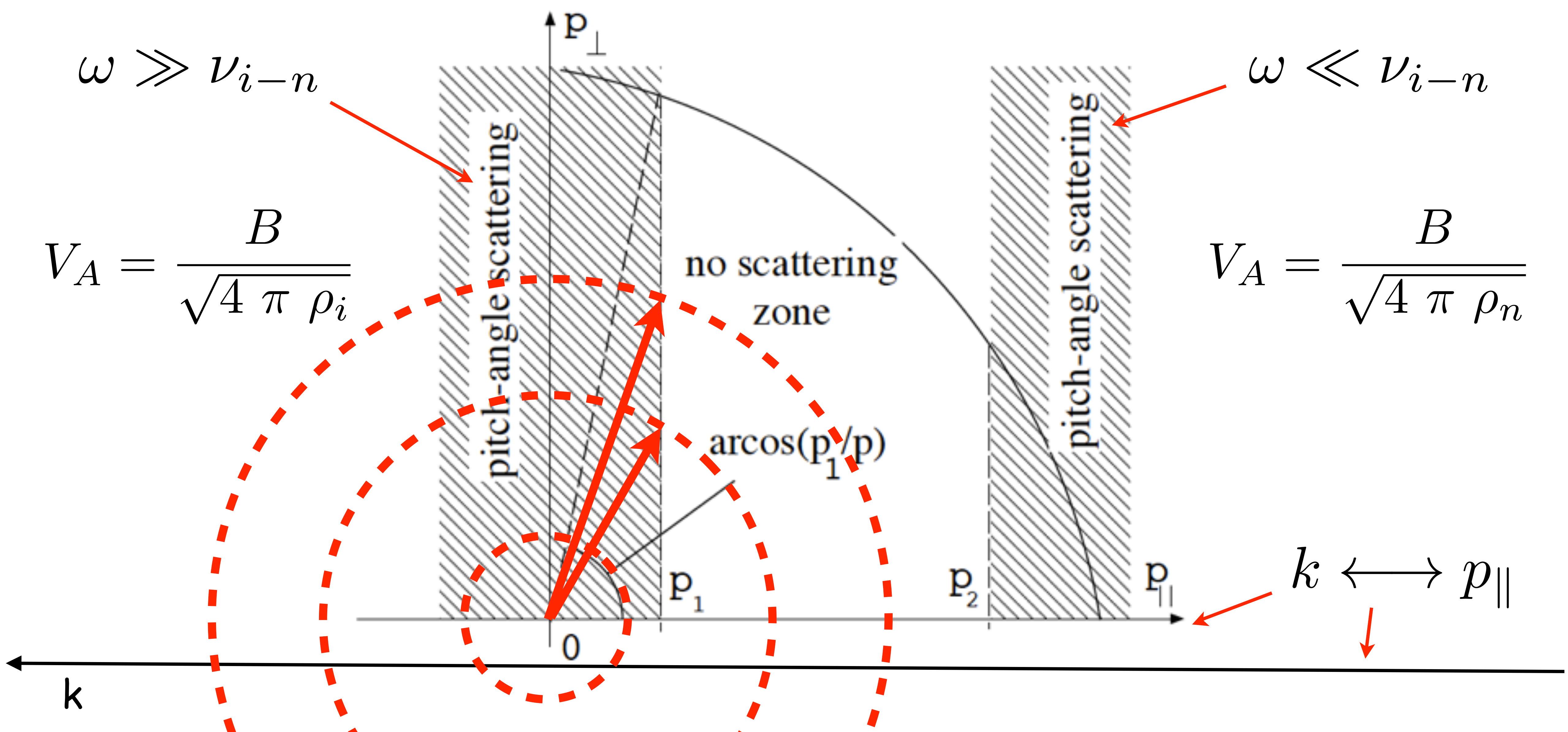


$\omega \ll \nu_{i-n}$

$$V_A = \frac{B}{\sqrt{4\ \pi\ \rho_n}}$$

$k \longleftrightarrow p_{||}$

MCs hit by SNRs: effect of neutrals

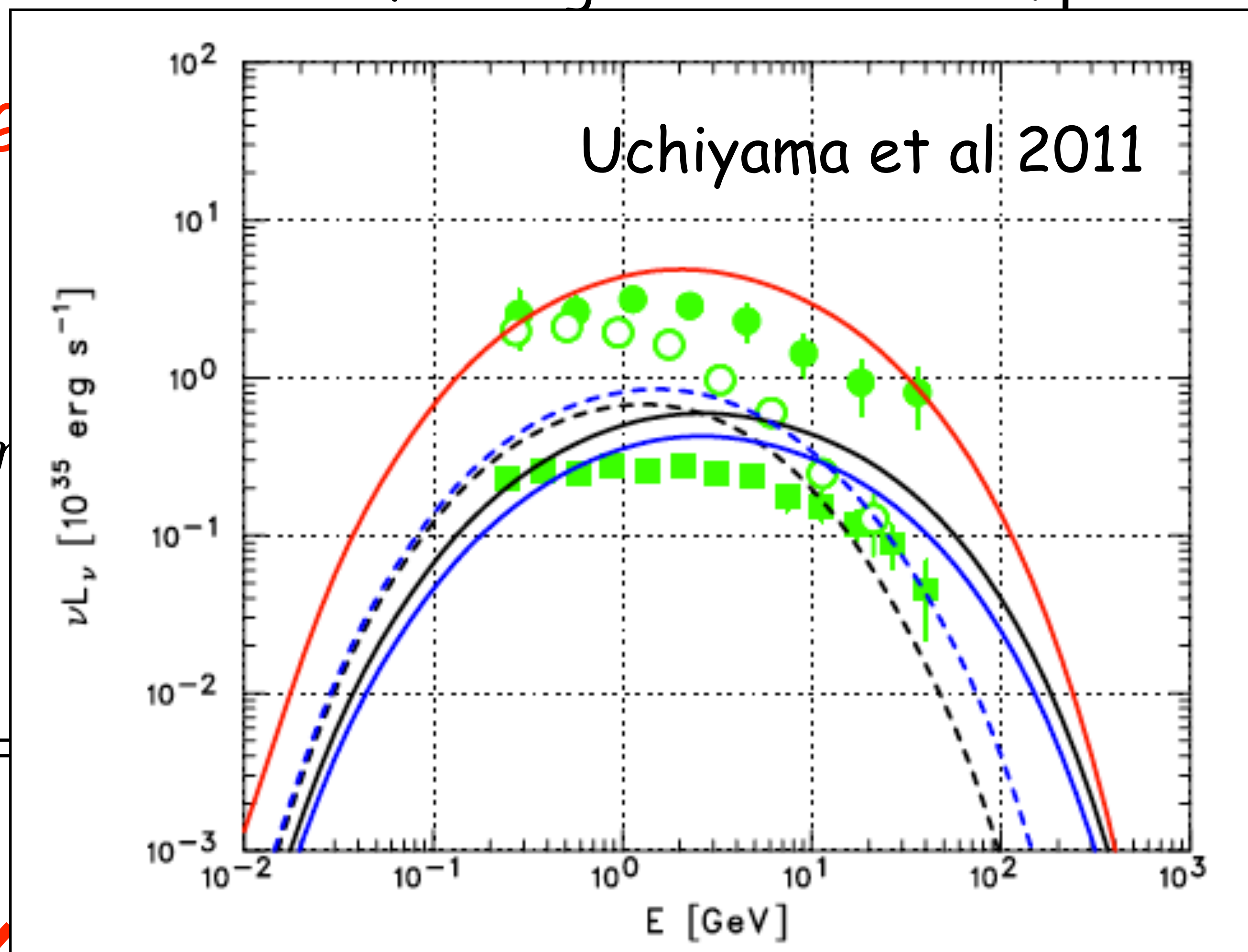
SNR+MC seen by Fermi are usually old ~10^4 yrs -> slow shock speed -> radiative

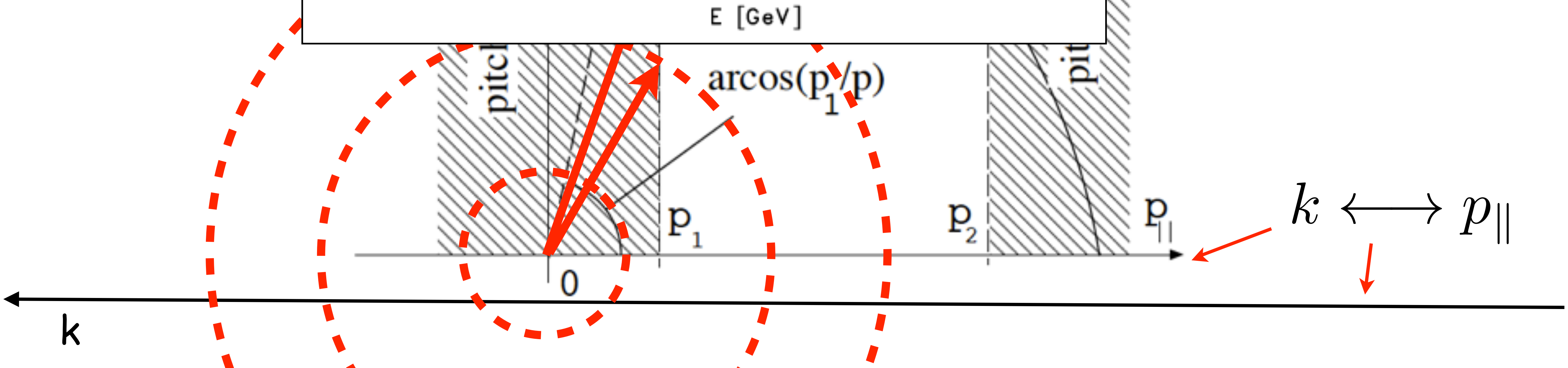
GeV flux -> reacceleration of background CRs + compression (Blandford&Cowie1981)

break @few G ... o ion-neutral damping of

$\omega \gg \nu_{i-n}$ ... $\omega \ll \nu_{i-n}$

$V_A = \frac{B}{\sqrt{4\pi ...}}$ ... $V_A = \frac{B}{\sqrt{4\pi\rho_n}}$

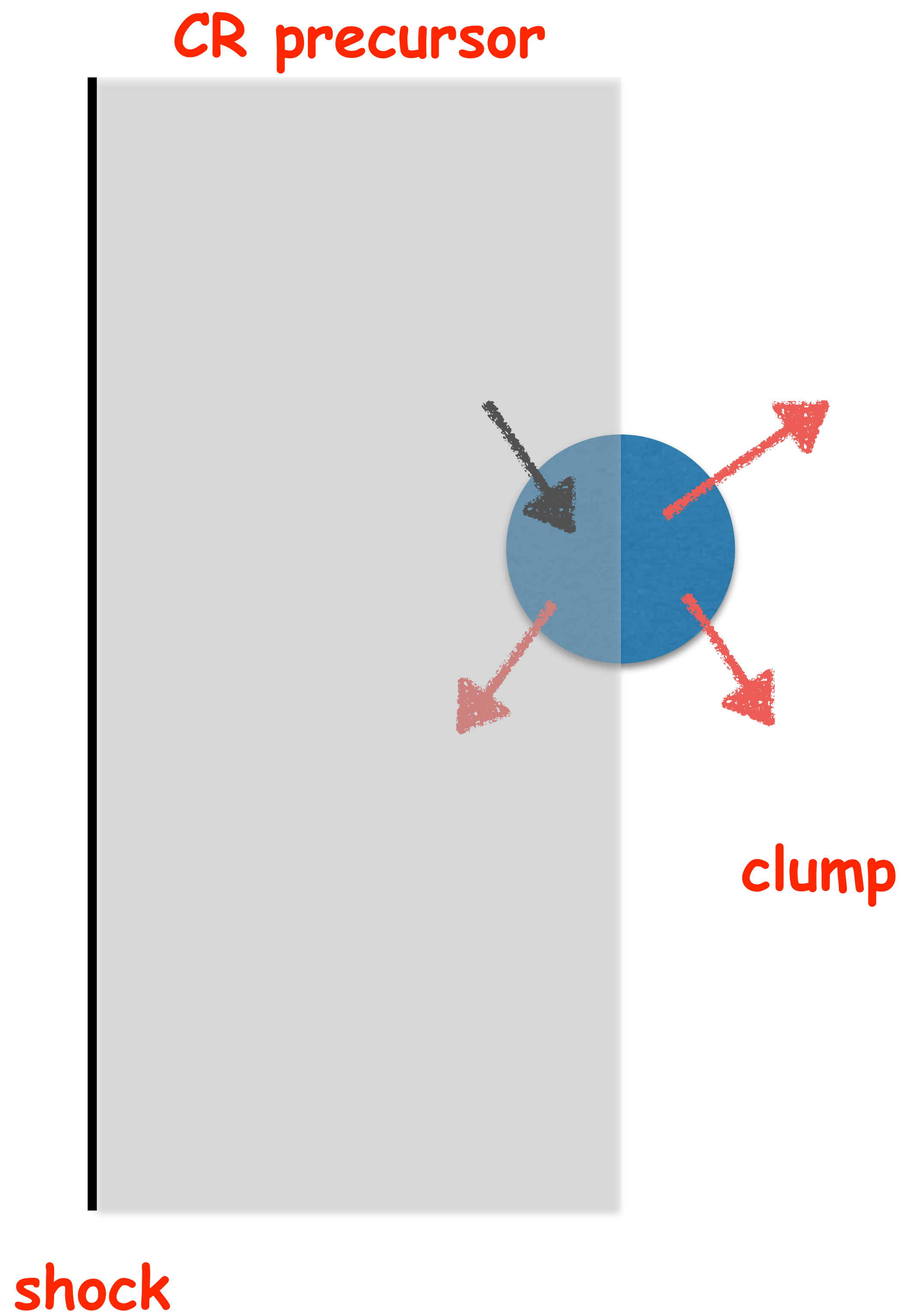




Effect of neutrals: spectral breaks

clump

Effect of neutrals: spectral breaks



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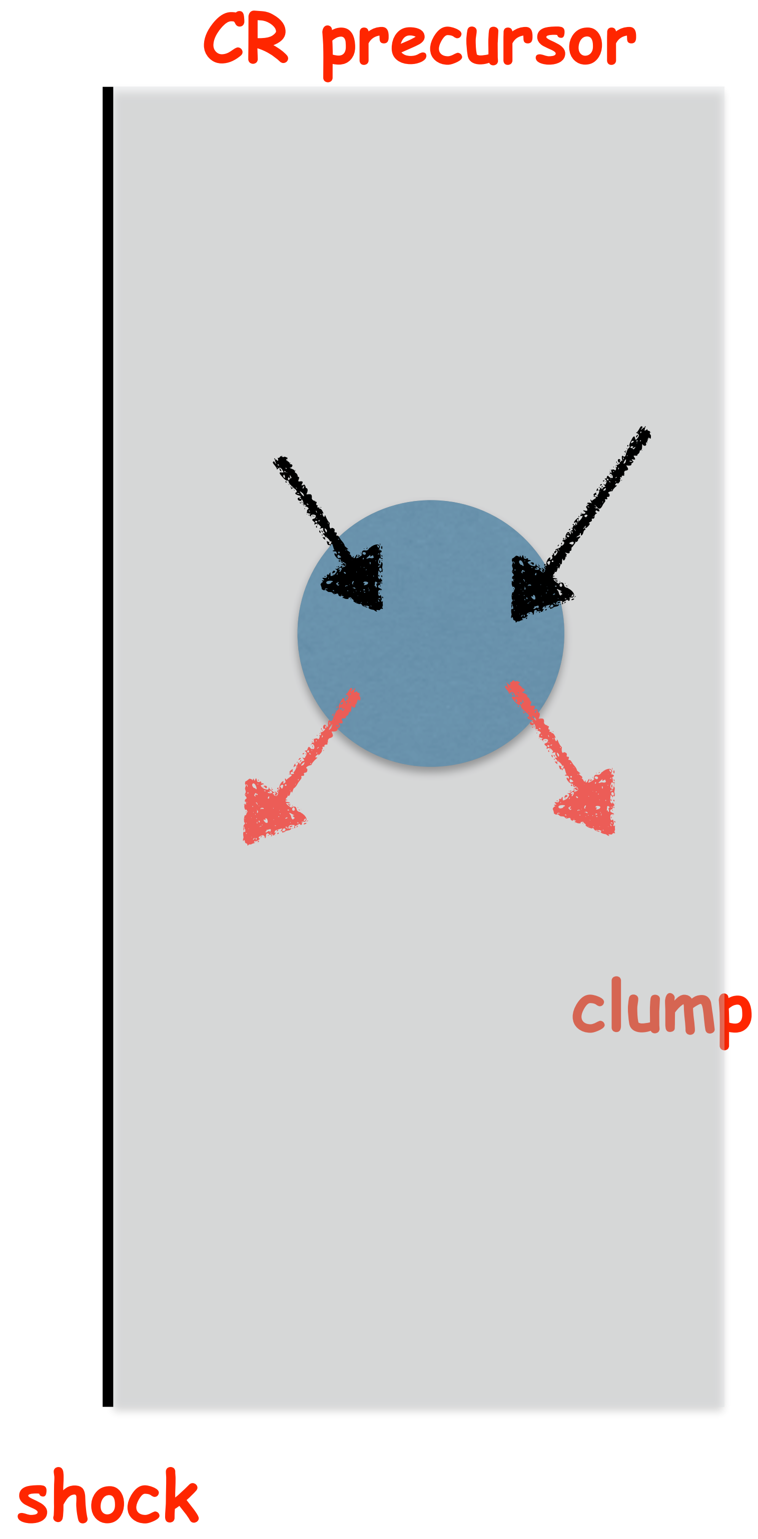

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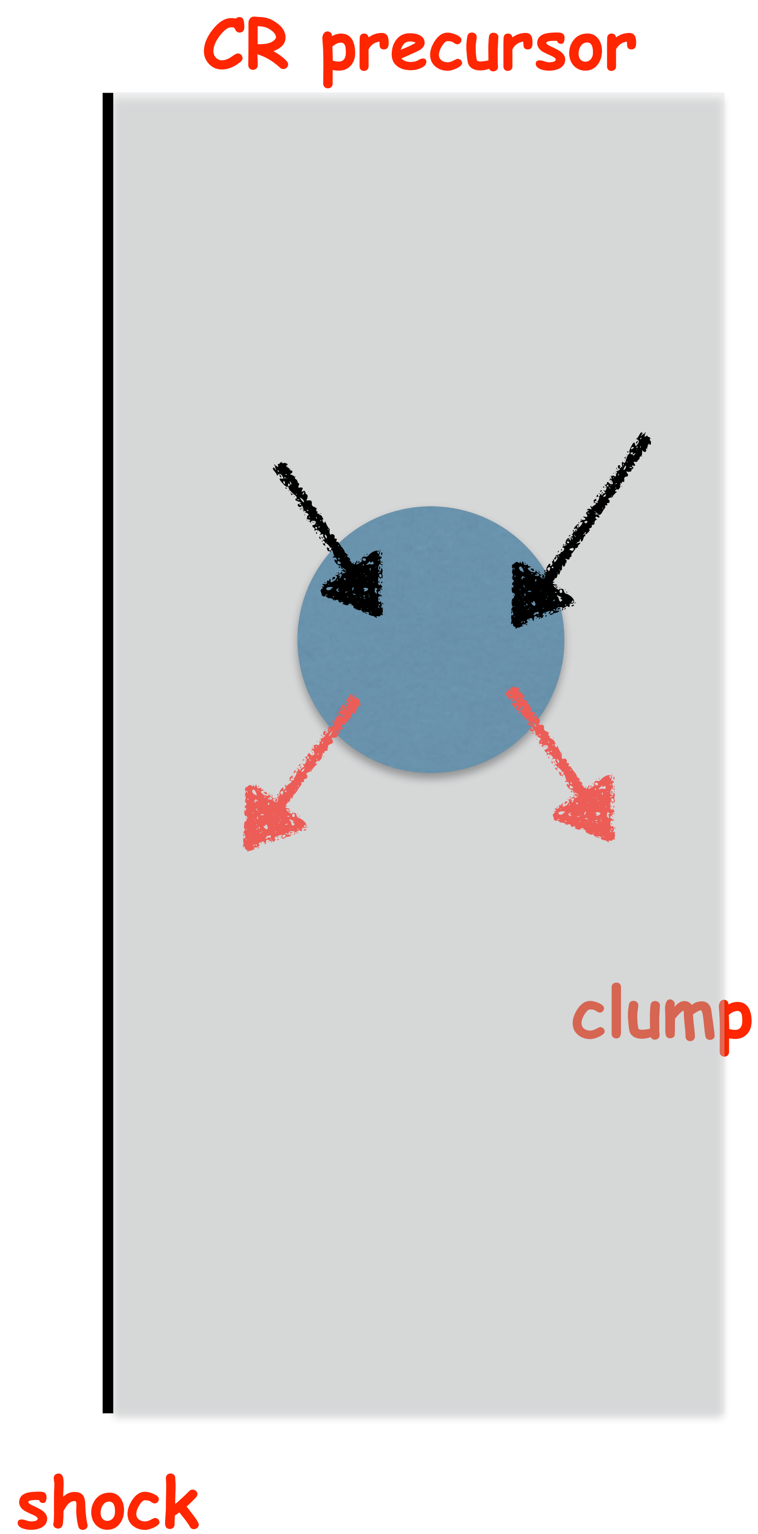


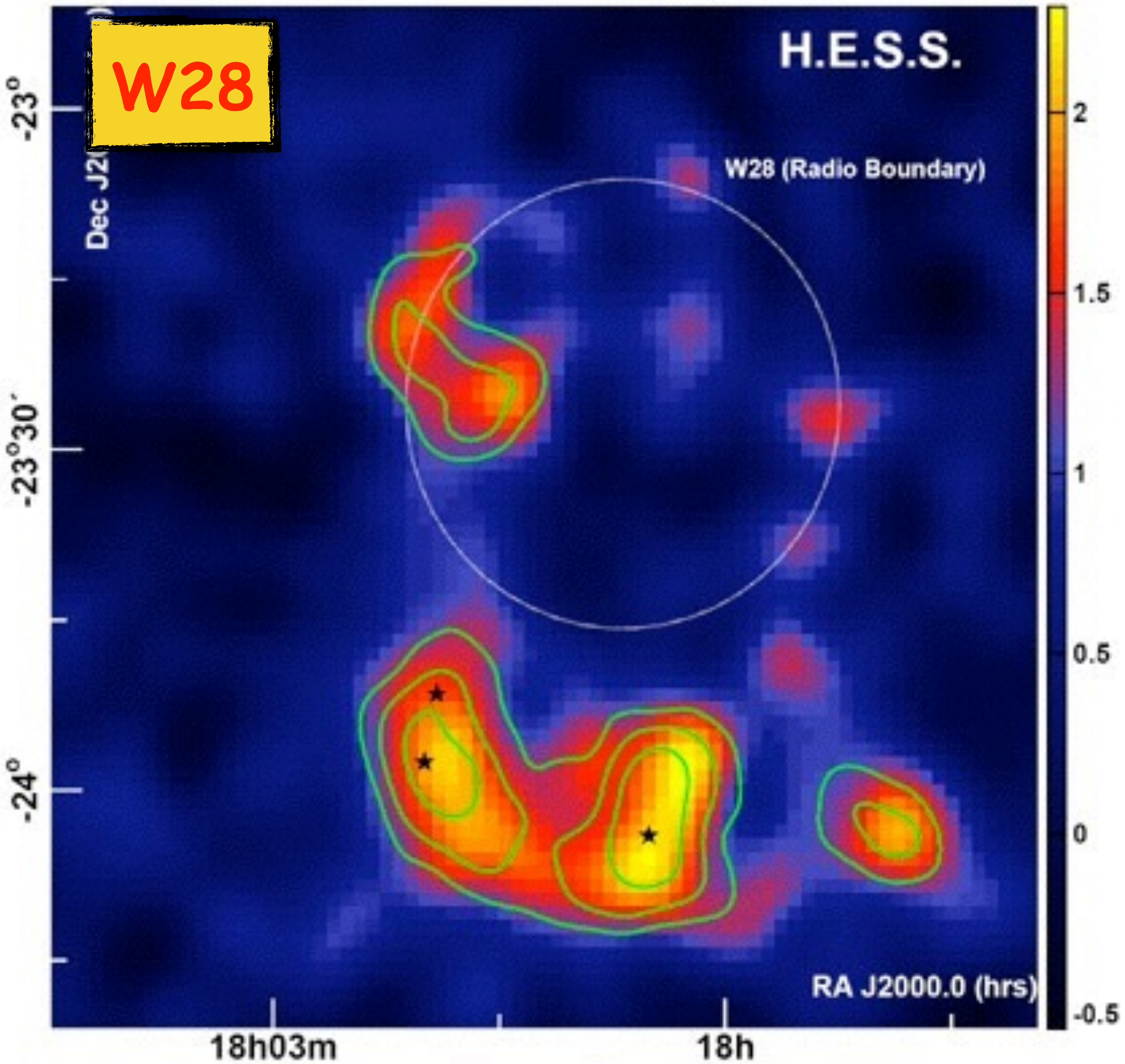
fine tuning?

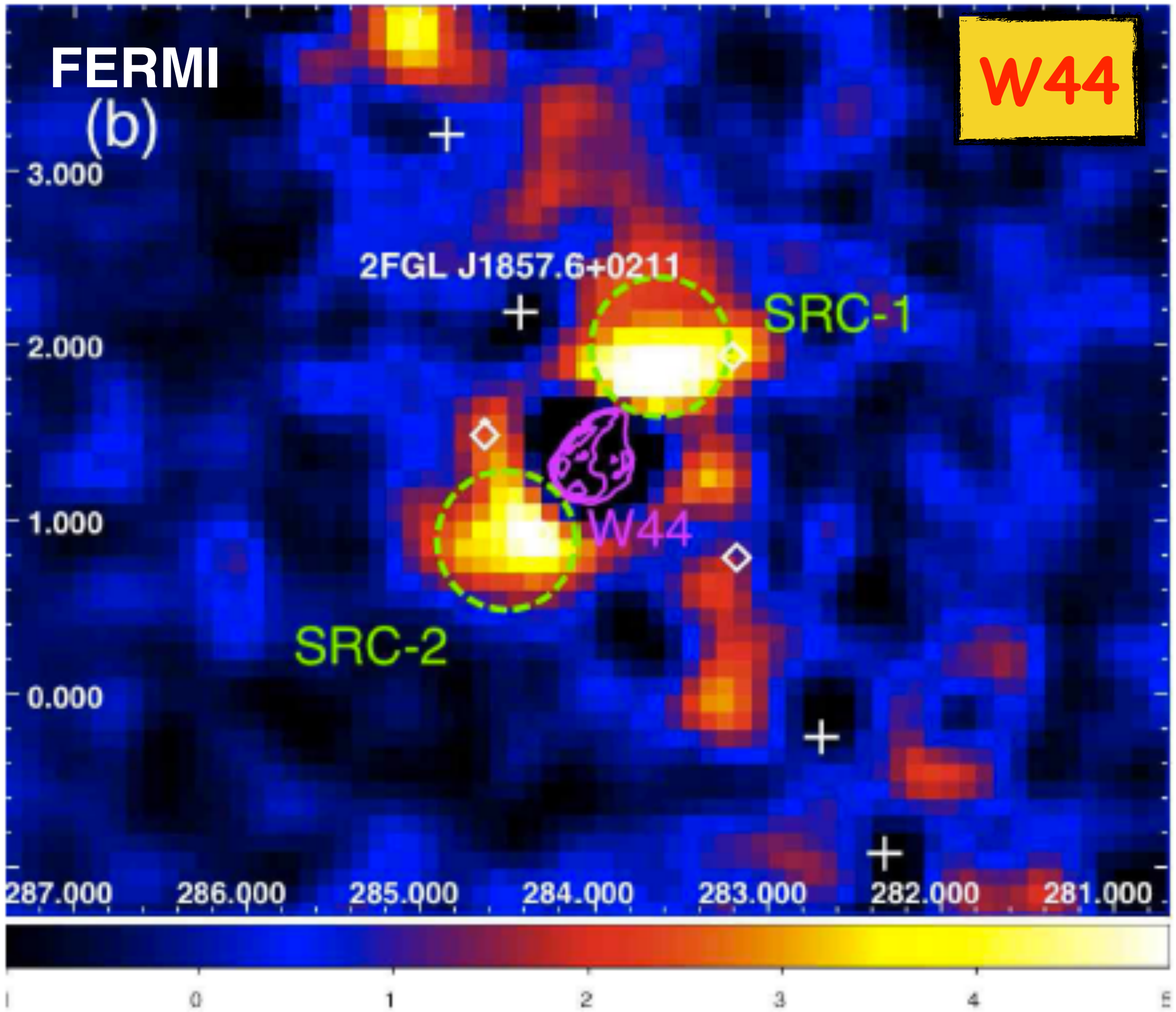
could work (?) in the cloud crushed model (acceleration and reacceleration happen in a clump)

Molecular clouds in the vicinity of a SNR shock

Indirect evidence for protons: molecular clouds

Aharonian et al. 2008





Uchiyama et al. 2012

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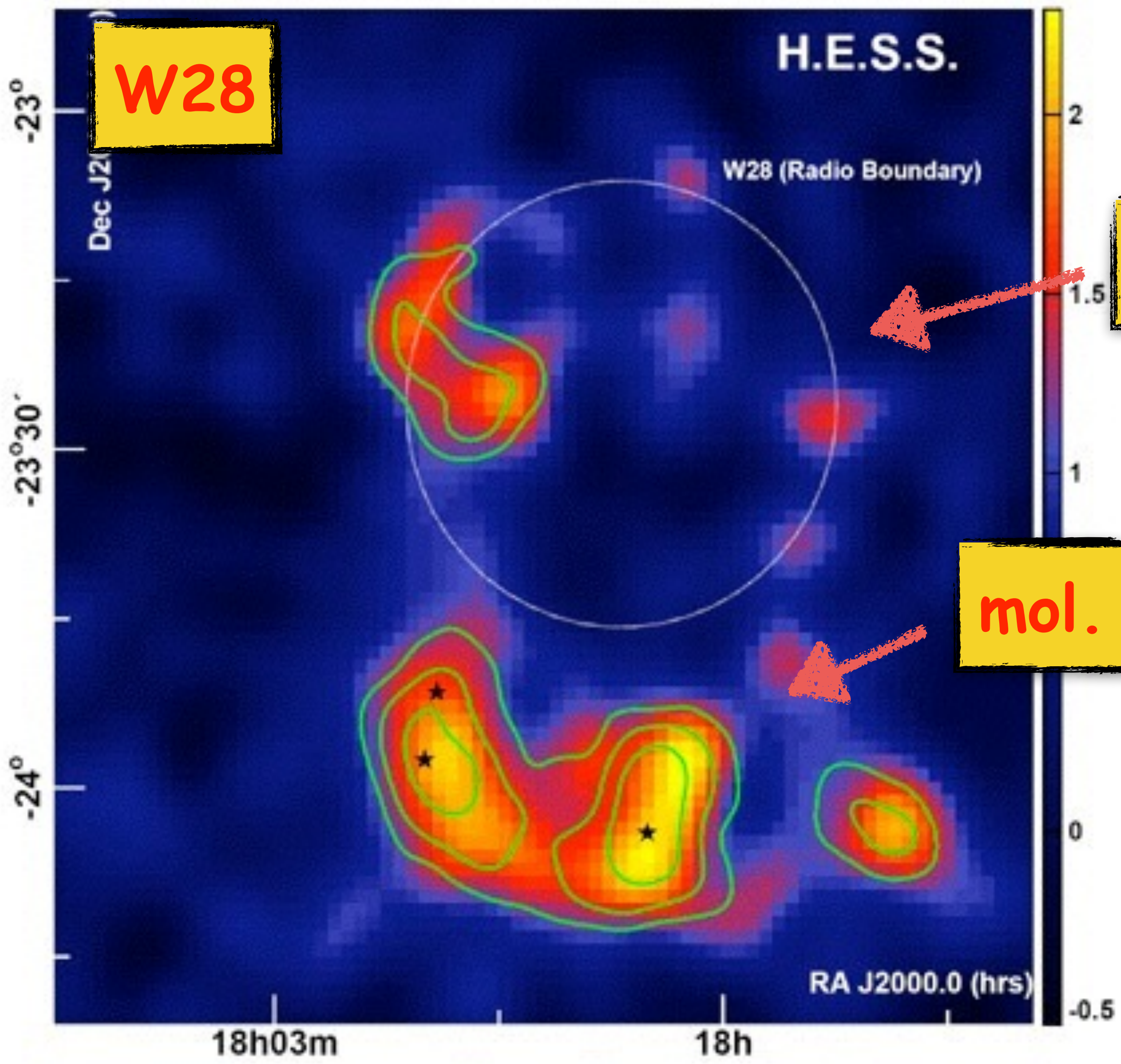

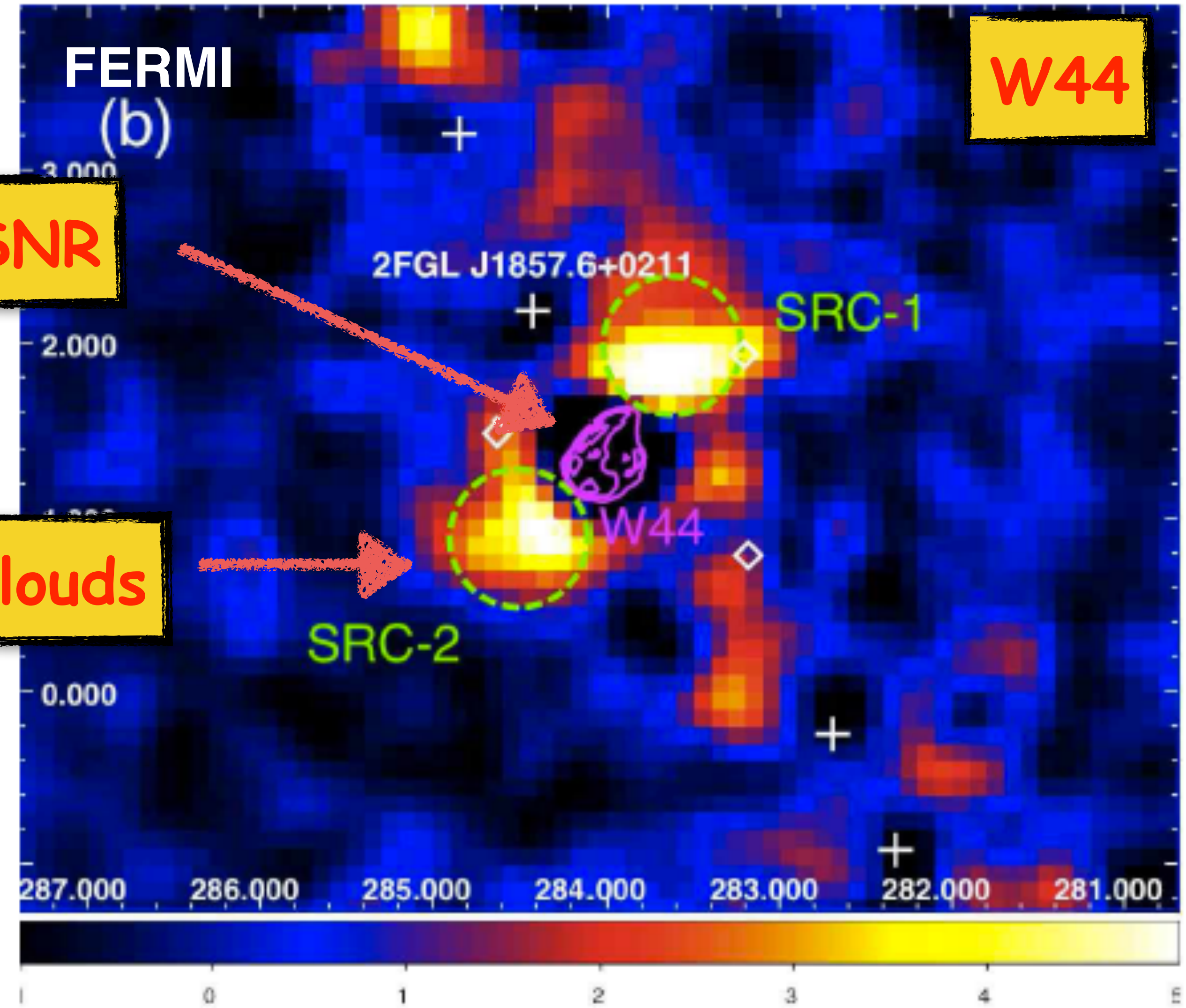

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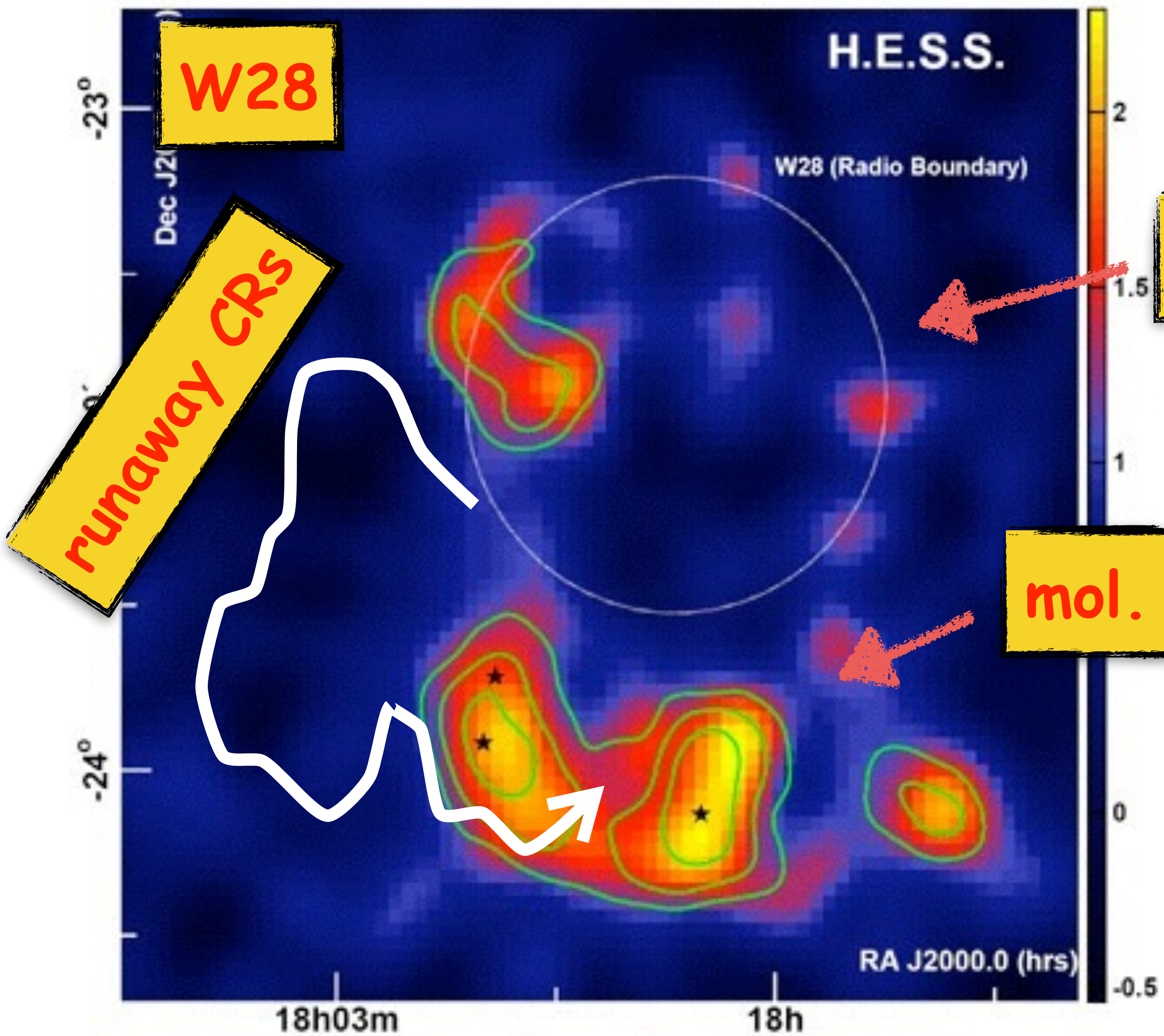

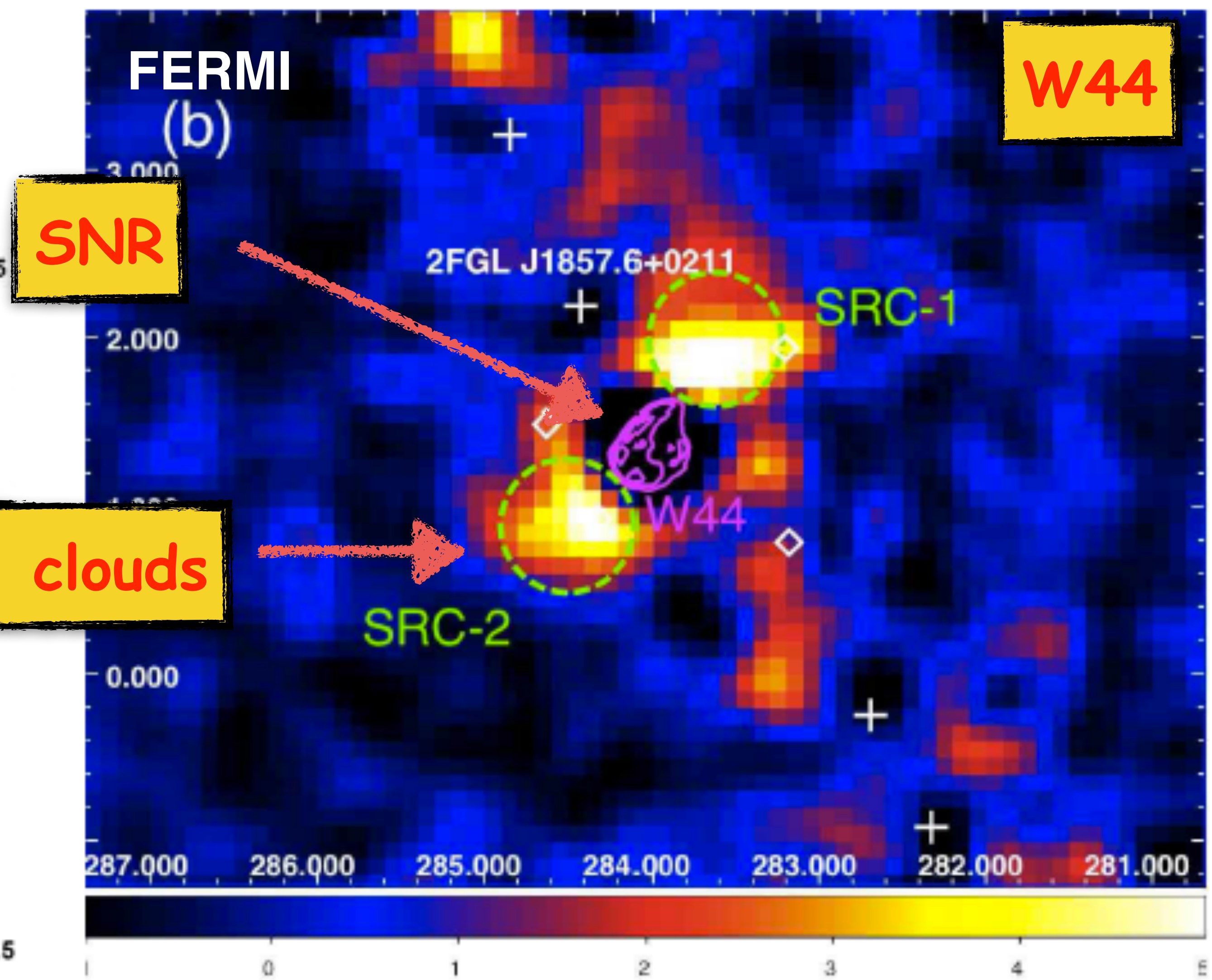

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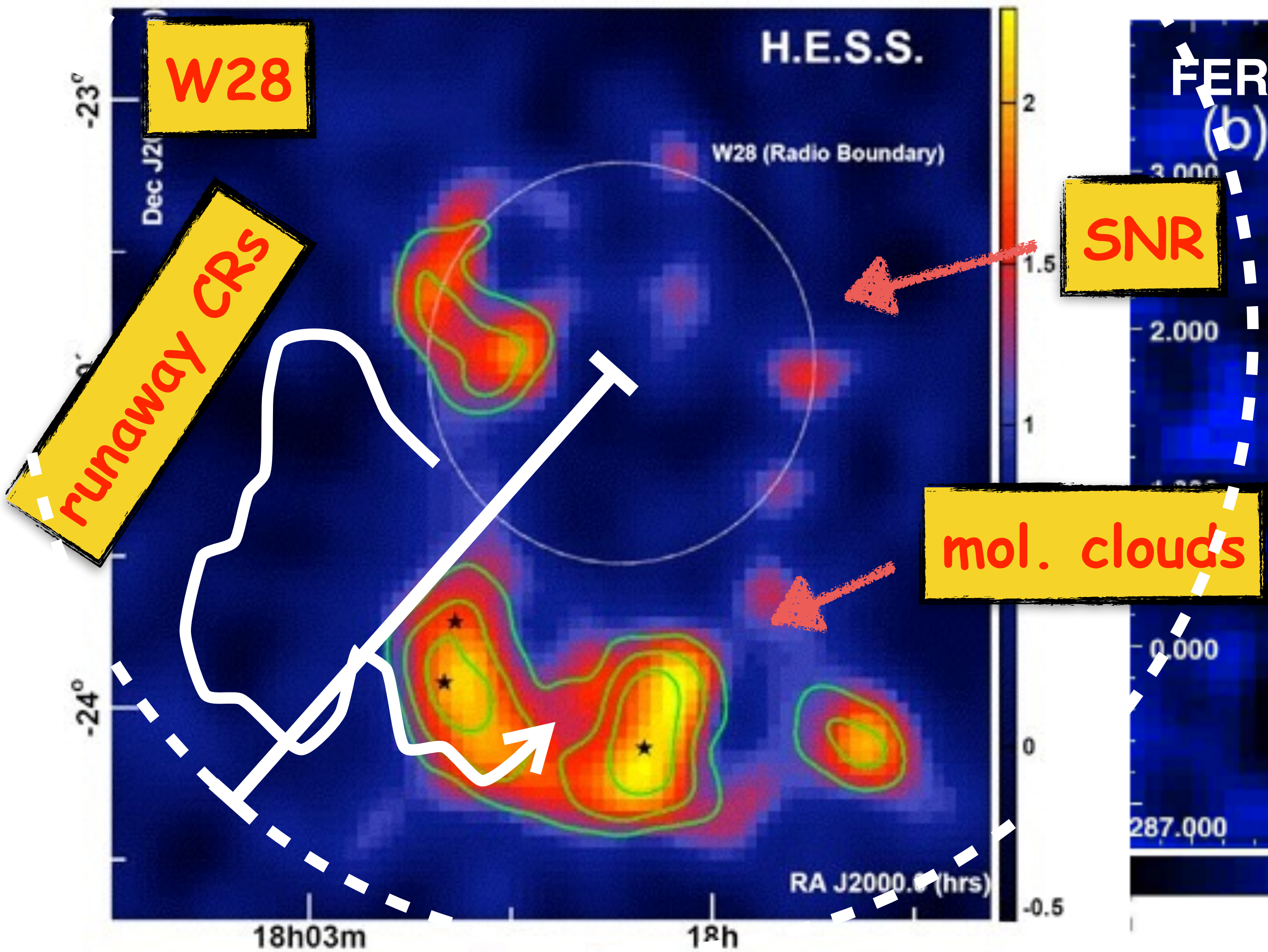
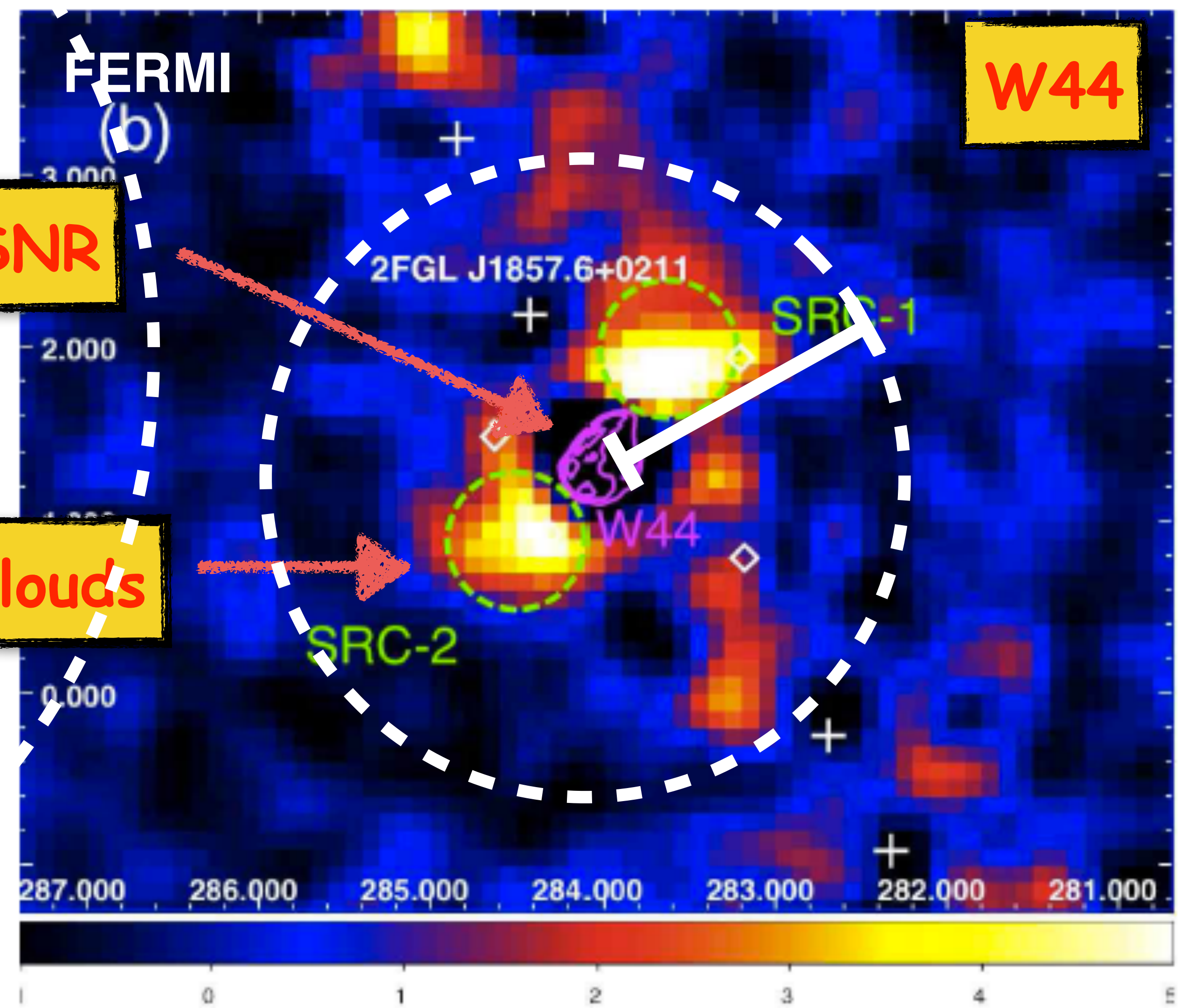


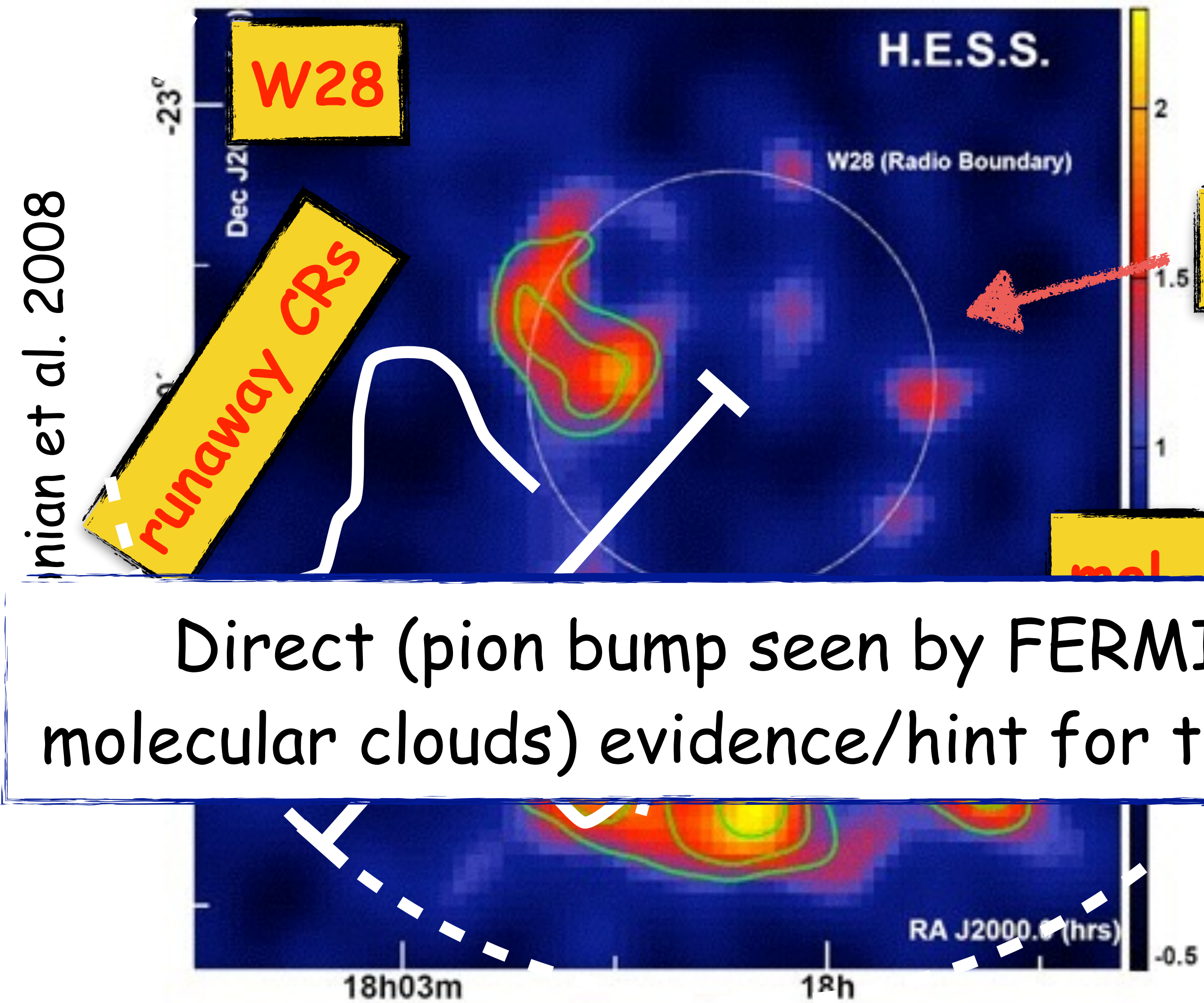


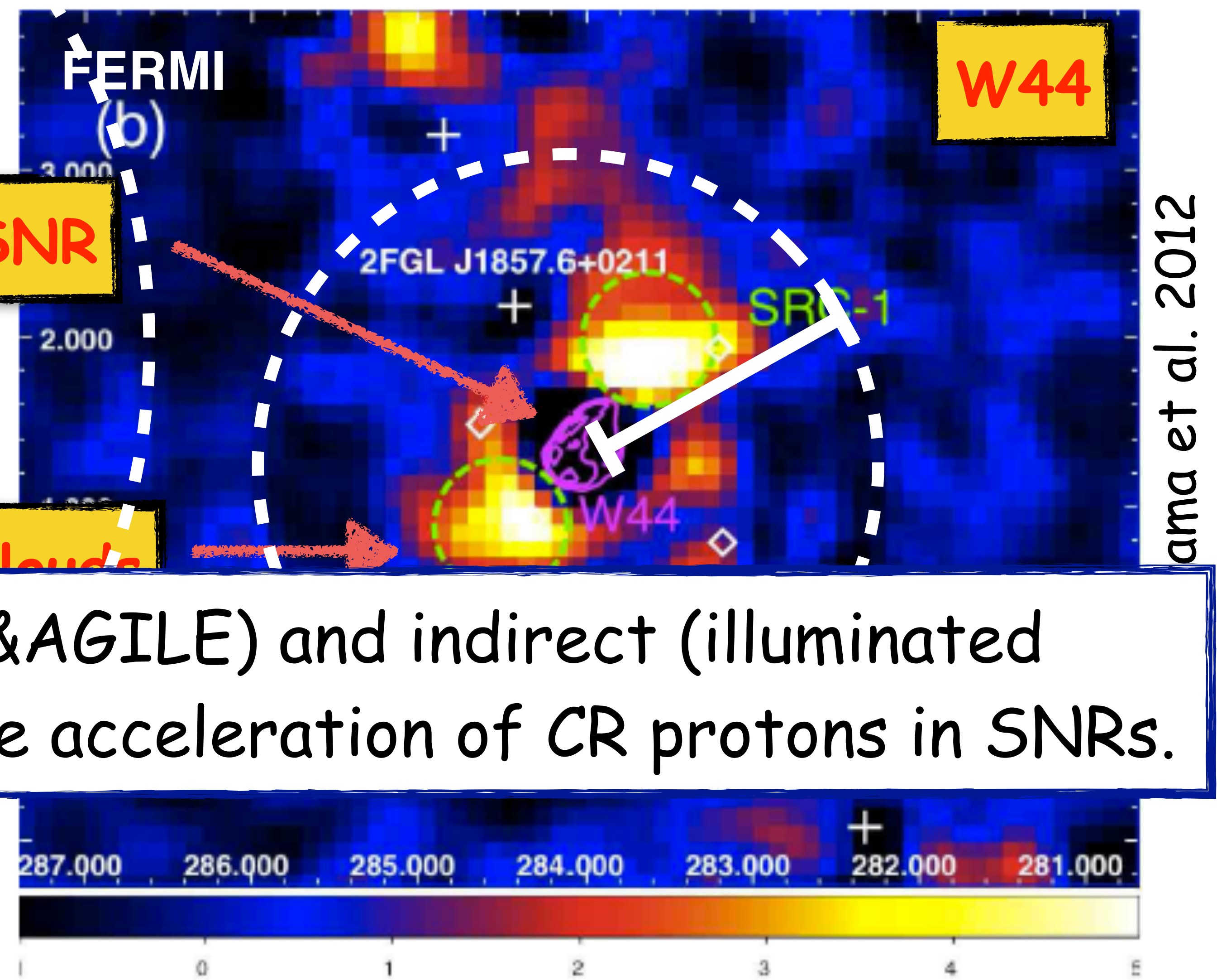
Uchiyama et al. 2012

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

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

Indirect evidence for protons: molecular clouds





Direct (pion bump seen by FERMI&AGILE) and indirect (illuminated molecular clouds) evidence/hint for the acceleration of CR protons in SNRs.

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

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

Constraints on propagation

average diffusion coefficient in the MW (use with caution!)

$$D(E) \approx 10^{28} \left(\frac{E}{10 \text{ GeV}} \right)^{0.5} \text{cm}^2/\text{s} \longrightarrow D(1 \text{ TeV}) \approx 10^{29} \text{cm}^2/\text{s}$$

- **W28** - $t_{age} \sim 4.4 \times 10^4$ yr - D(1 TeV) $\sim 3\text{-}9 \times 10^{27}$ cm^2/s - Gabici et al 2010
- **W44** - $t_{age} \sim 1.0 \times 10^4$ yr - D(10 GeV) $\gtrsim 10^{27}$ cm^2/s - Uchiyama etal2012
- - $t_{age} \sim 2.0 \times 10^4$ yr - D(10 GeV) $\gtrsim 5 \times 10^{26}$ cm^2/s - Uchiyama etal2012
- **IC443** - $t_{age} \sim 3.0 \times 10^4$ yr - D(1 TeV) $\sim 1 \times 10^{27}$ cm^2/s - Torres et al 2010
- **GCR** - $t_{age} \sim 1 \times 10^4$ yr - D(~10 TeV) $< 10^{30}$ cm^2/s - HESS coll. 2006
- **W51C** - $t_{age} \sim 3.2 \times 10^4$ yr - D(1 TeV) $\sim 3 \times 10^{27}$ cm^2/s - Ohira et al 2011
- **9SNRs** - $t_{age} \sim .2\text{-}1 \times 10^4$ yr - D(10GeV) $\sim .4\text{-}5 \times 10^{26}$ cm^2/s - Li & Chen 2012
- **G35.6** - $t_{age} \sim 3. \times 10^4$ yr - D(1 TeV) $< 1. \times 10^{28}$ cm^2/s - Torres et al 2012

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diffusion coefficient suppressed?

Constraints on propagation

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GCR - $t_{age} \sim 1 \times 10^4$ yr - D(~1 … V) < 10^{30} … 6

W51C - $t_{age} \sim 3.2 \times 10^4$ yr - D … V) ~ 3 x 10^{27} … 1

9SNRs - $t_{age} \sim .2\text{-}1 \times 10^4$ yr - … 0GeV) ~ .4-5x1 …

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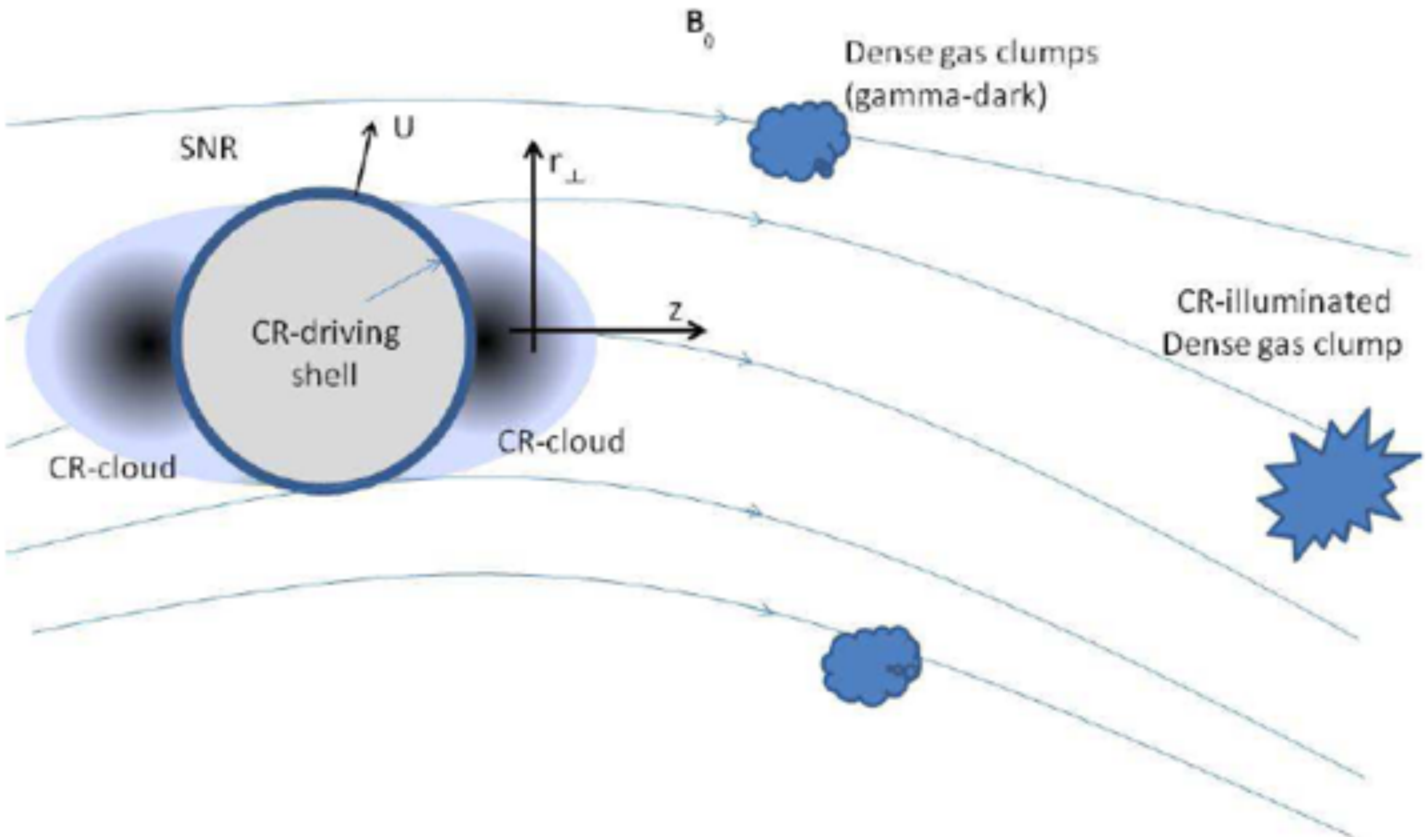
Dor (LMC)
$t_{age} \sim 3 \times 10^6$ yr
D(1 GeV) ~ 10^{27} cm^2/s
Murphy et al 2012

diffusion coefficient suppressed?

Anisotropic diffusion

first paper in this direction is probably Ptuskin et al 2007 -> streaming instability+damping

Malkov et al 2012



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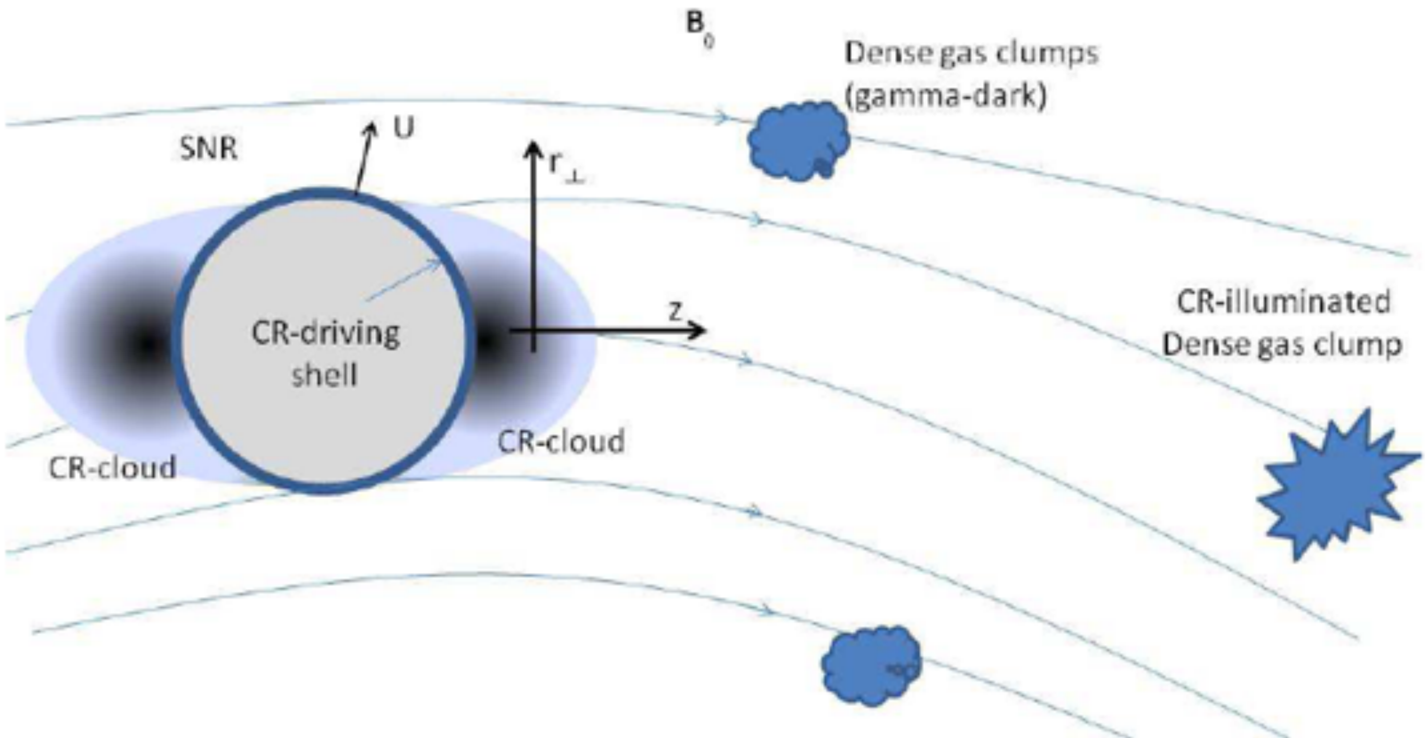

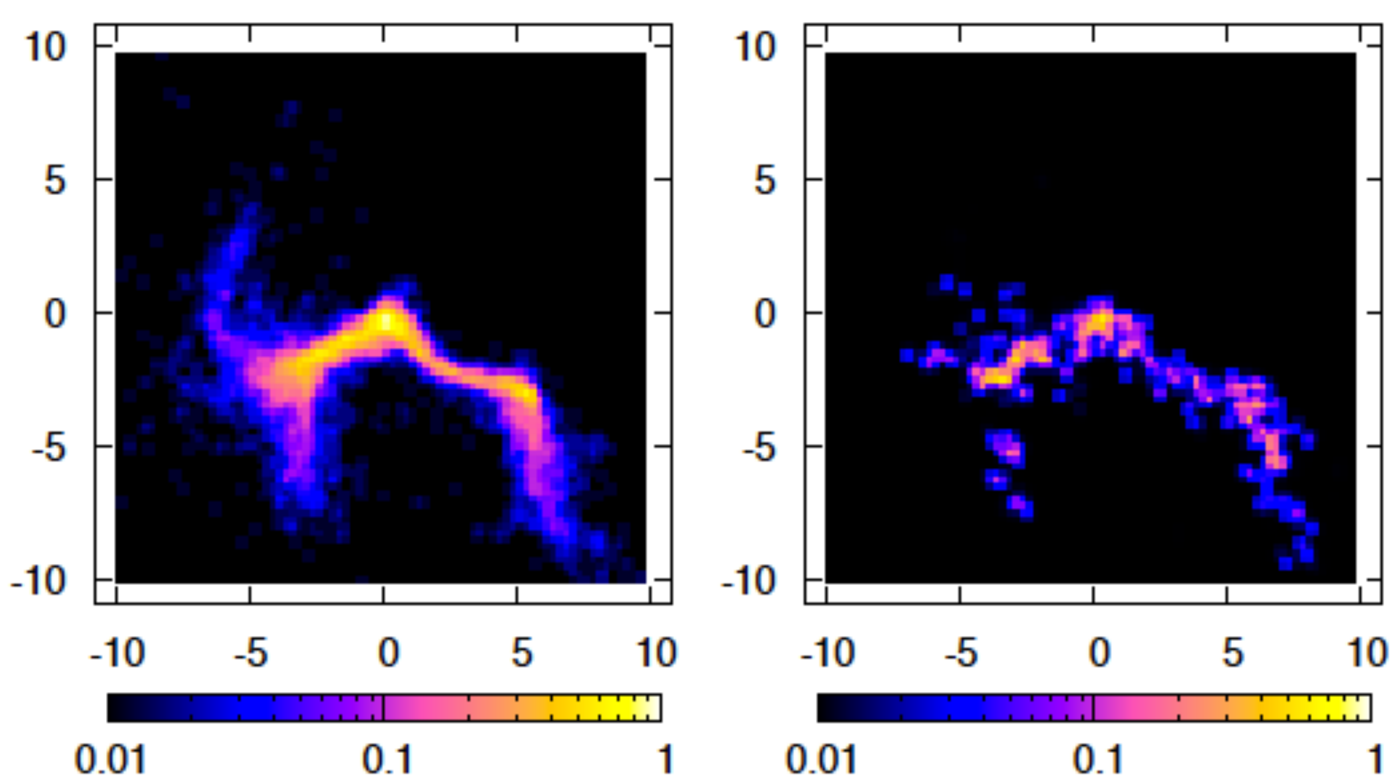

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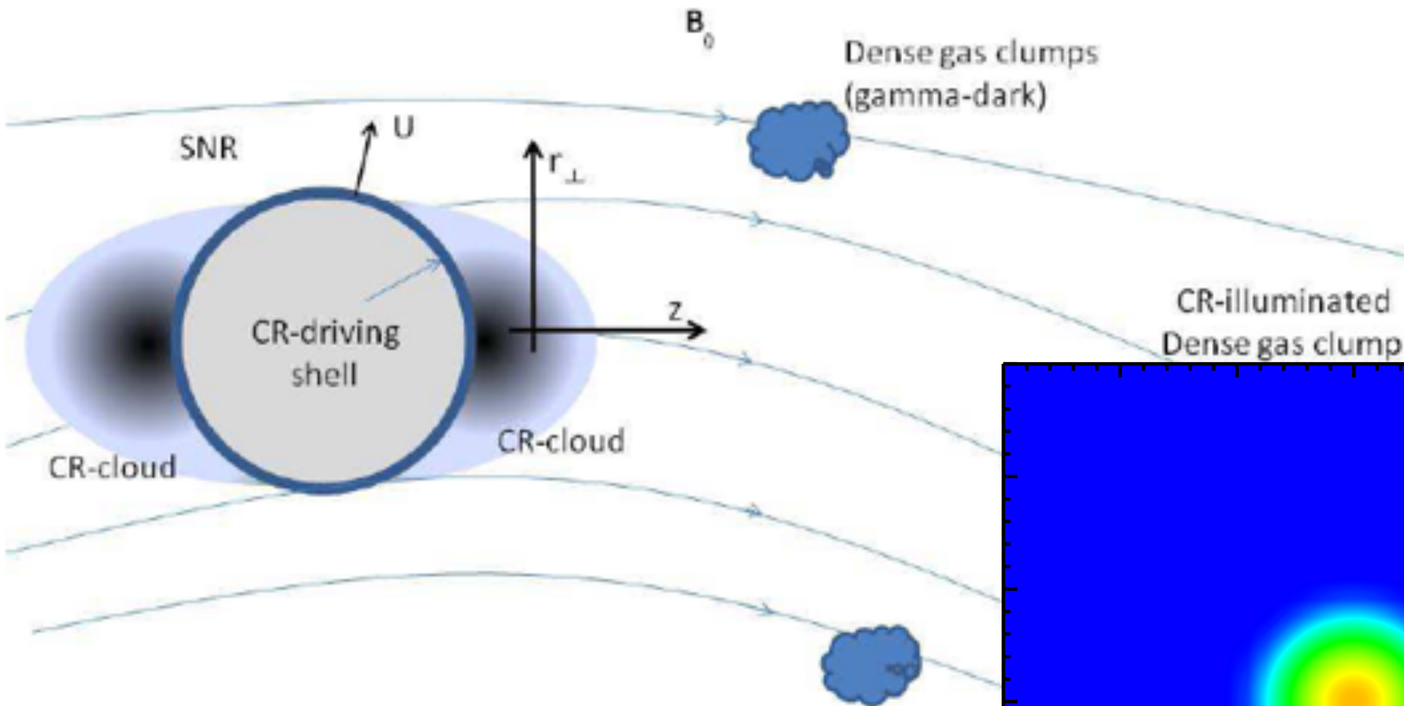
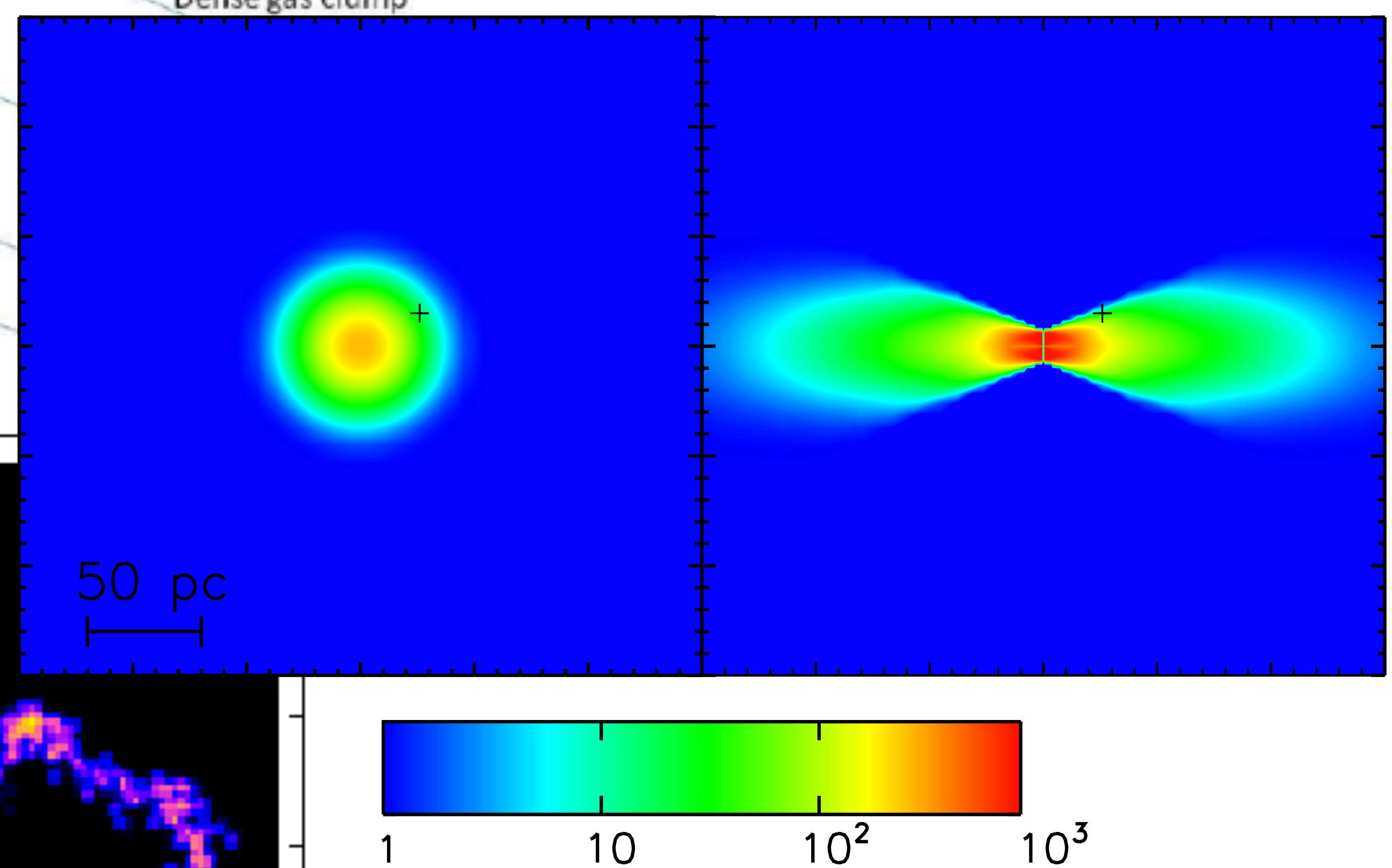
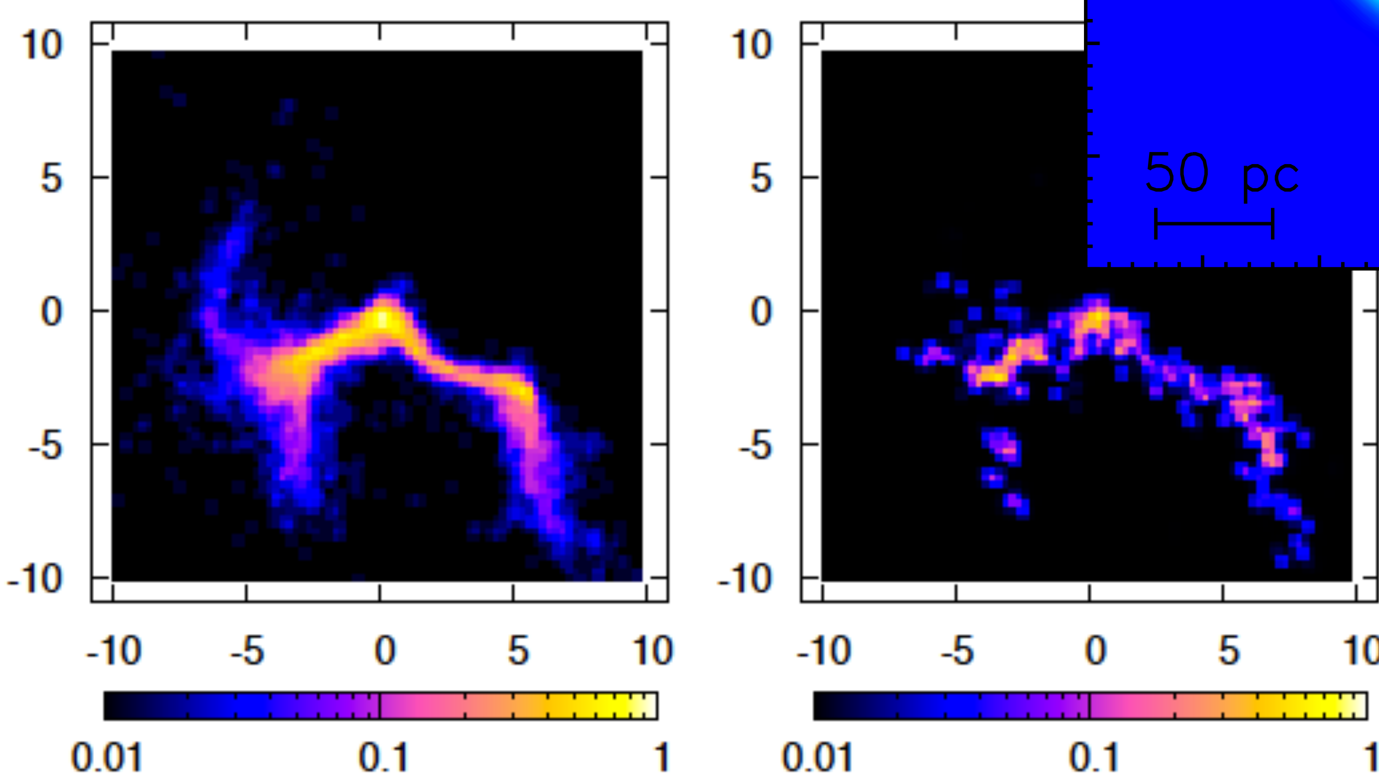




Nava & Gabici 2012



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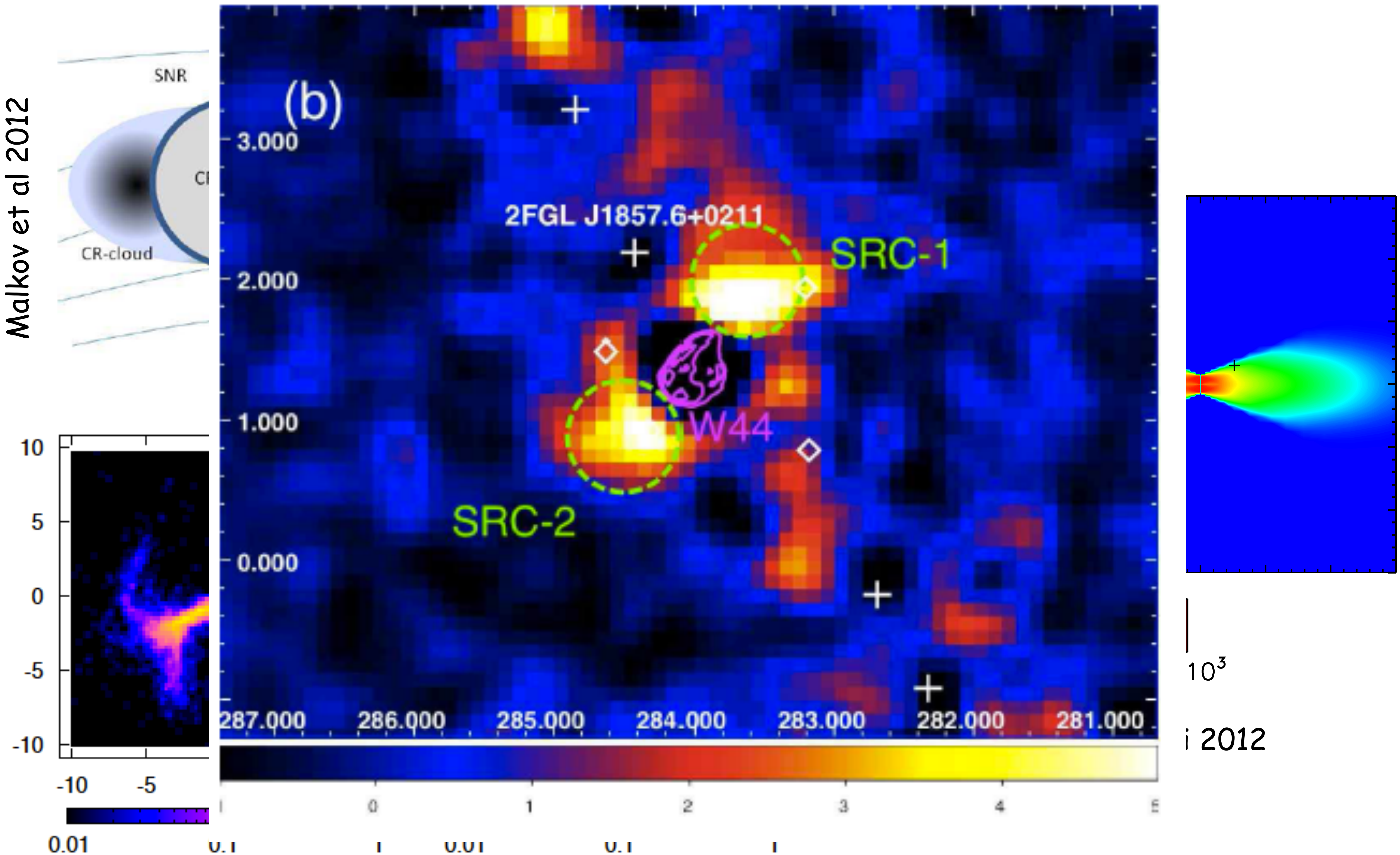

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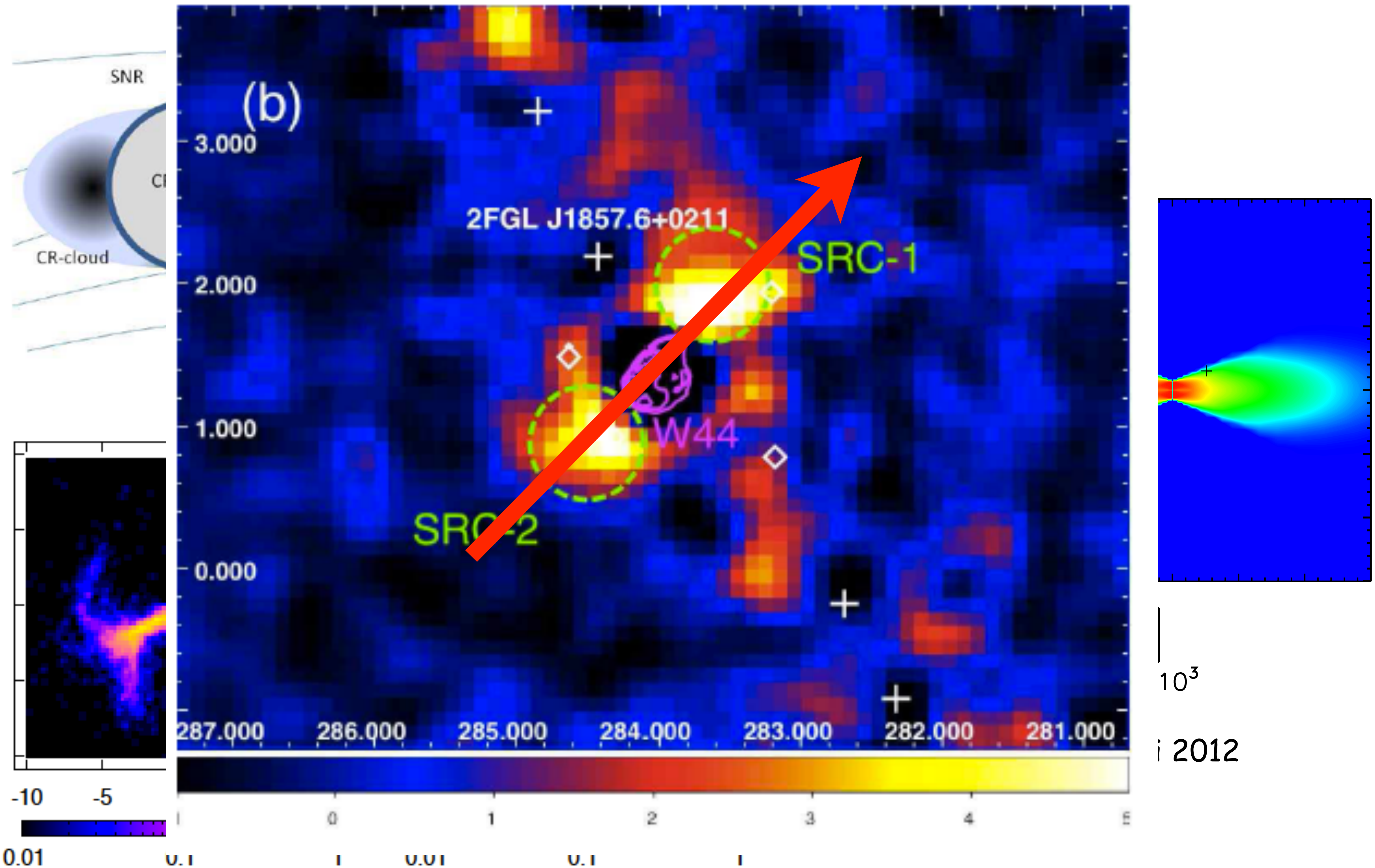


Giacinti et al. 2012

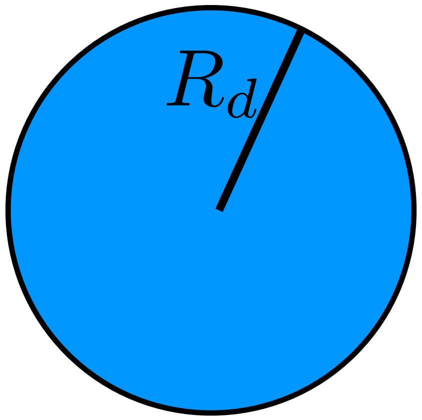
Anisotropic diffusion: general considerations

Nava & Gabici 2012

reminder on isotropic D ->

$$n_{CR} \approx \frac{N_{CR}}{R_d^3}$$

$$R_d \approx \sqrt{D \times t}$$



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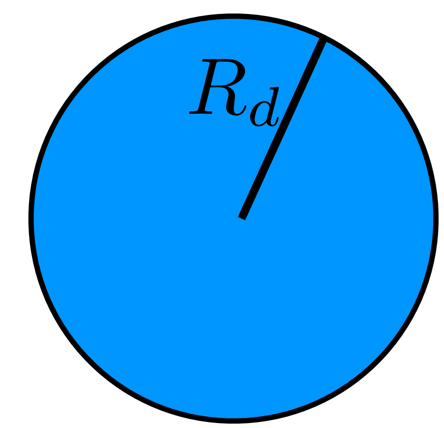
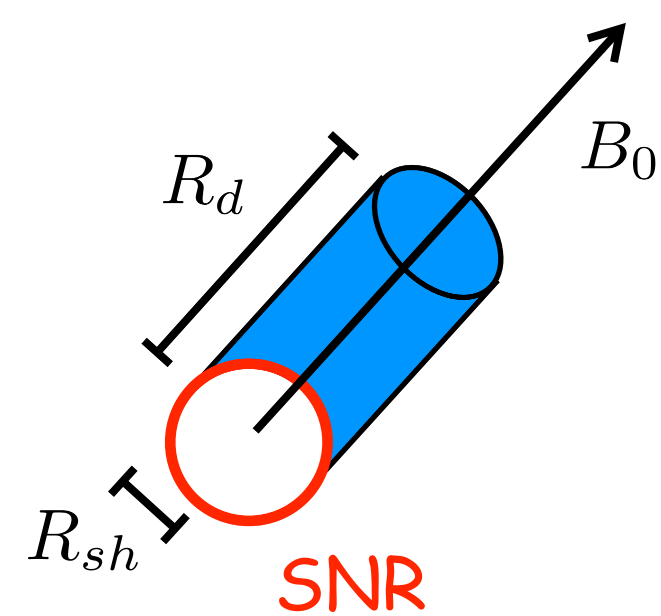


strictly anisotropic D

$$n_{CR} \approx \frac{N_{CR}}{R_d \, R_{sh}^2}$$



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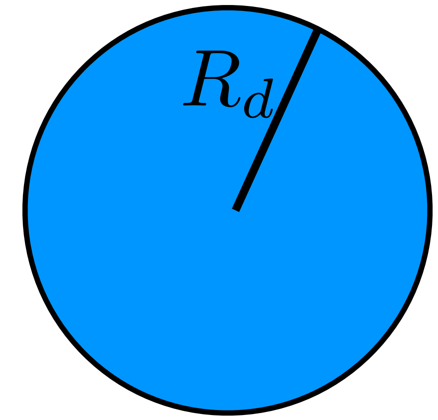
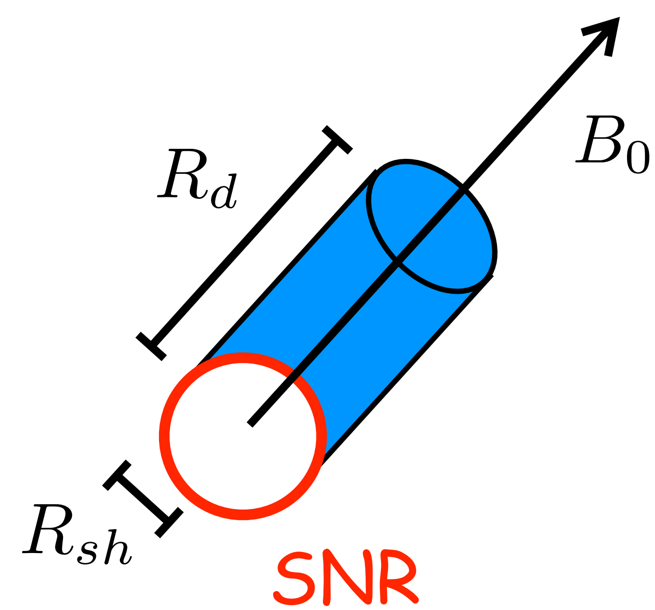


strictly anisotropic D

$$n_{CR} \approx \frac{N_{CR}}{R_d\, R_{sh}^2} \approx \frac{N_{CR}}{R_d^3} \left(\frac{R_d}{R_{sh}} \right)^2$$



isotropic

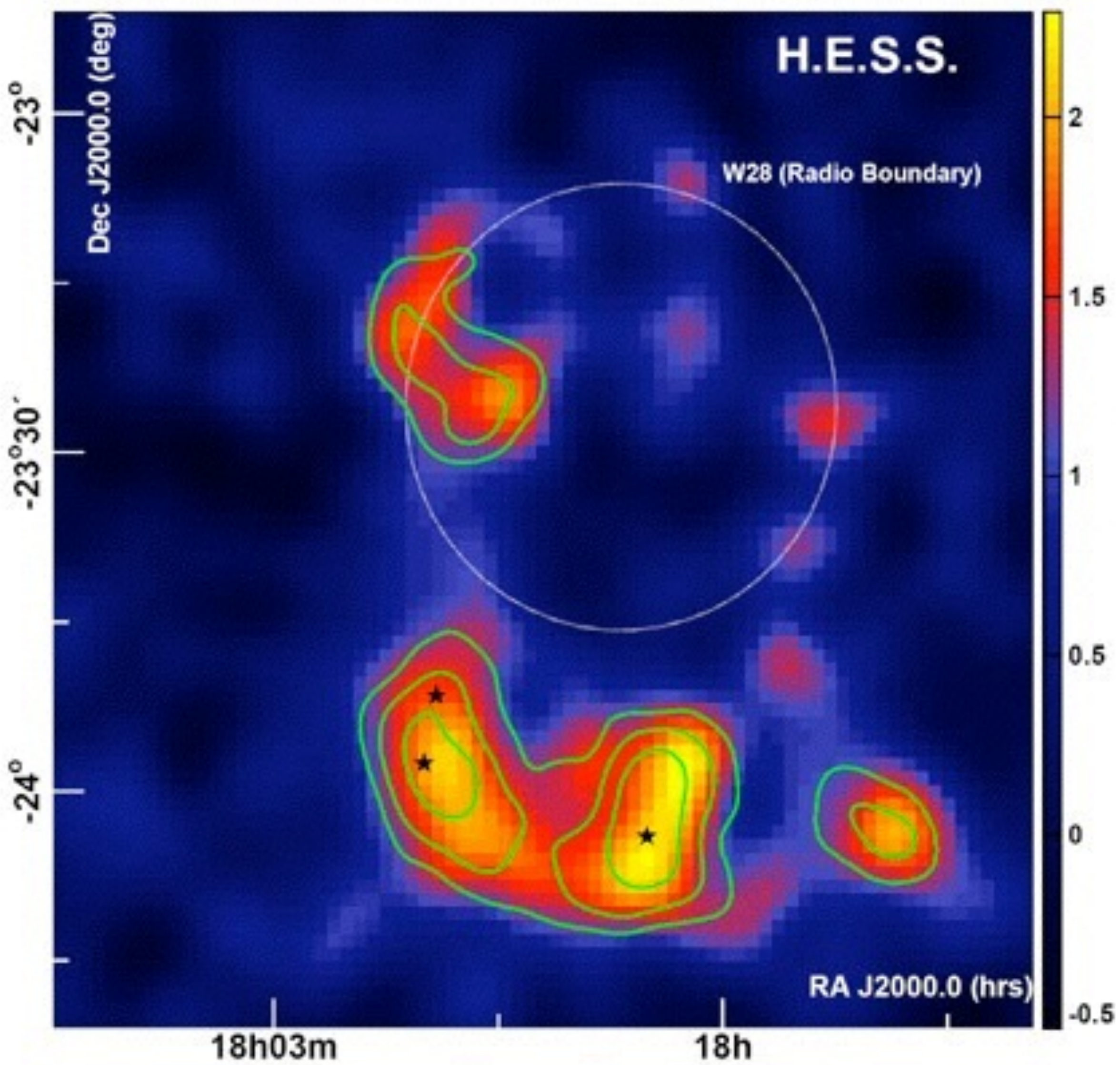
~100 pc

$$\boxed{D = D_0 \left(\frac{R_d}{R_{sh}} \right)^{4/3}}$$

~10 pc

much larger D for anisotropic diffusion

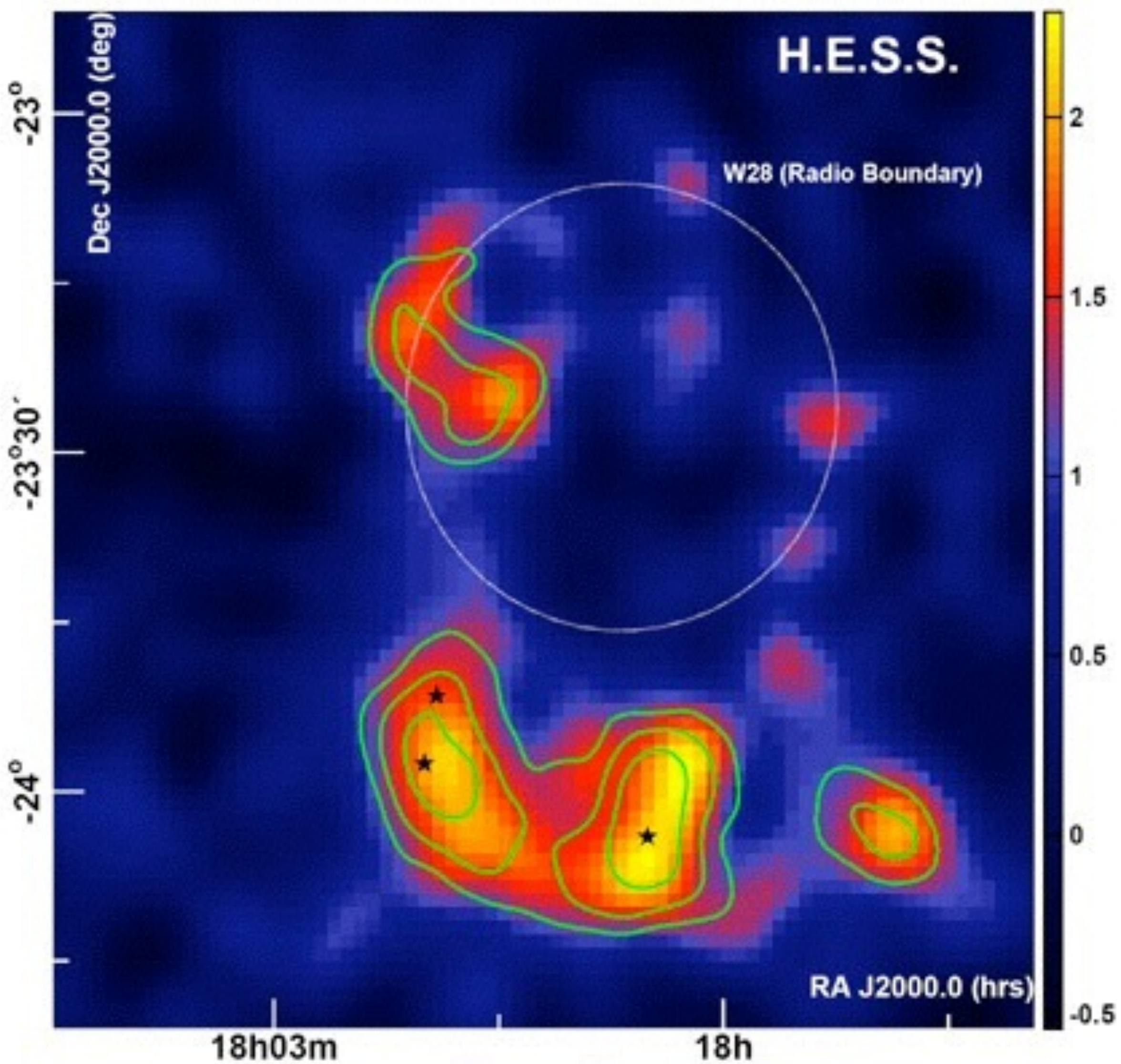
Example: the SNR W28



isotropic D -> $$D(1\ \mathrm{TeV}) = 10^{27}...10^{28}\mathrm{cm}^2/\mathrm{s}$$ ~0.01-0.1 galactic

anisotropic D -> $$D(1\ \mathrm{TeV}) \approx 10^{29}\mathrm{cm}^2/\mathrm{s}$$ ~galactic

Example: the SNR W28



intrinsic uncertainty of 1-2 orders of magnitude in the determination of D, related to our "ignorance" on how diffusion proceeds. to this you have to add the "astrophysical" uncertainties (mass estimates, flux estimate, distance, etc...)

isotropic D -> $D(1\ \mathrm{TeV}) = 10^{27}...10^{28}\mathrm{cm}^2/\mathrm{s}$ ~0.01-0.1 galactic

anisotropic D -> $D(1\ \mathrm{TeV}) \approx 10^{29}\mathrm{cm}^2/\mathrm{s}$ ~galactic

Can we see PeVatrons? Clouds...

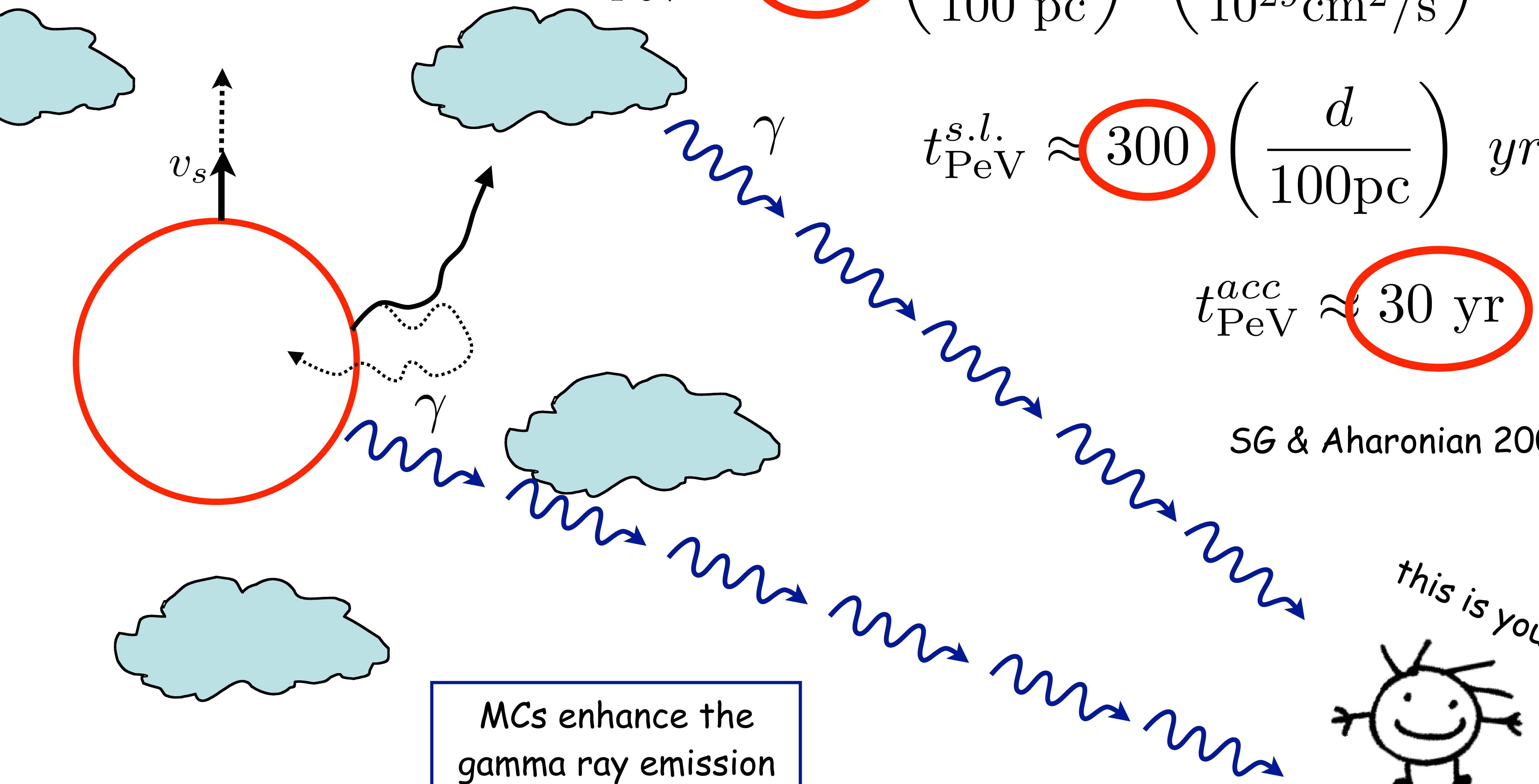
CRs escape the SNR

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

$$t^{s.l.}_{\mathrm{PeV}} \approx 300 \left(\frac{d}{100\mathrm{pc}}\right)\ yr$$

$$t^{acc}_{\mathrm{PeV}} \approx 30\ \mathrm{yr}$$

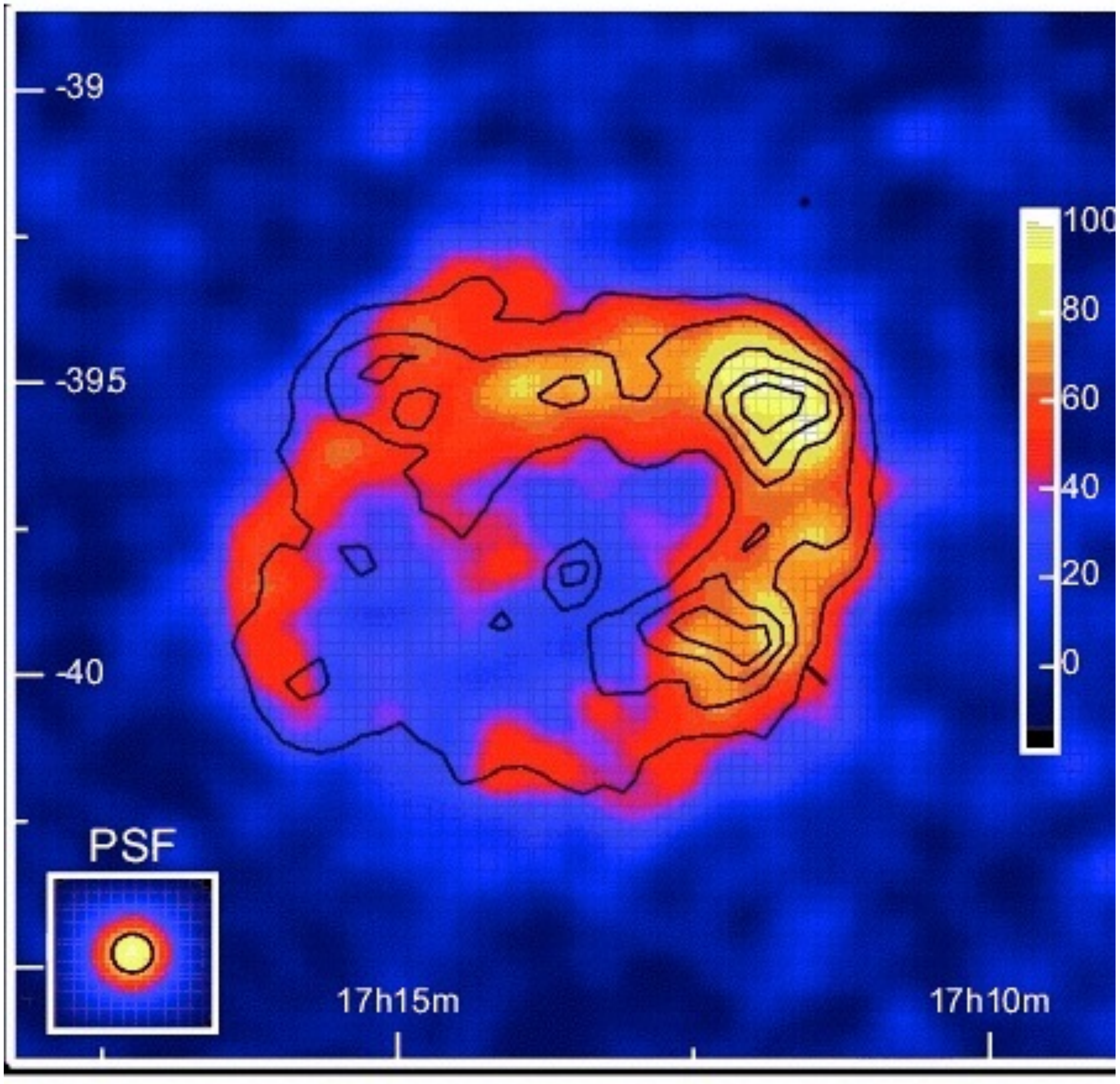
SG & Aharonian 2007



MCs enhance the gamma ray emission

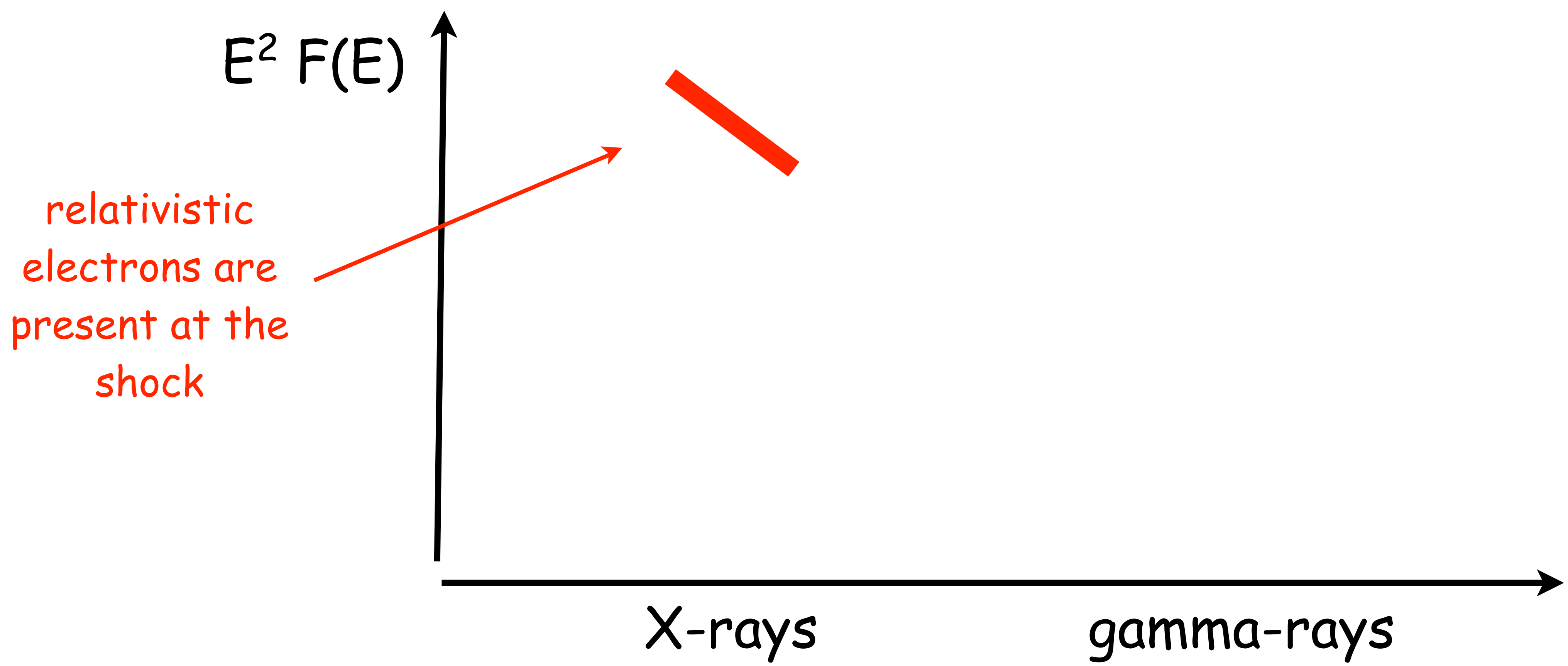
Supernova remnants inside molecular clouds

RXJ 1713: a type II SN in a MC?



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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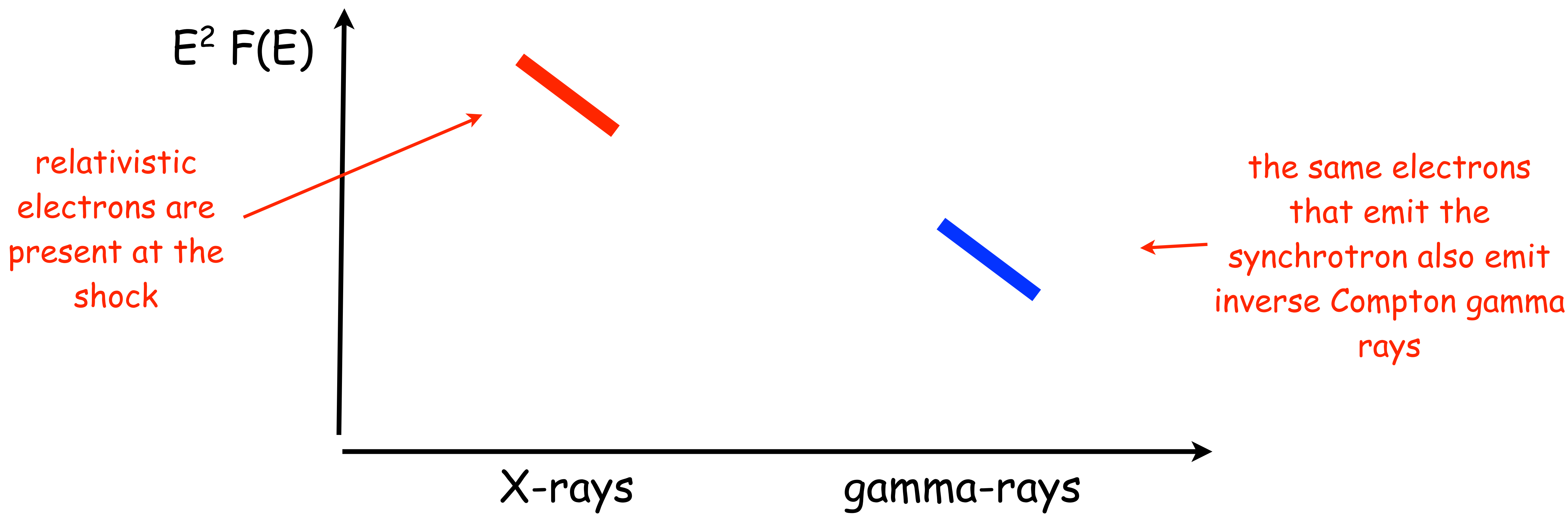
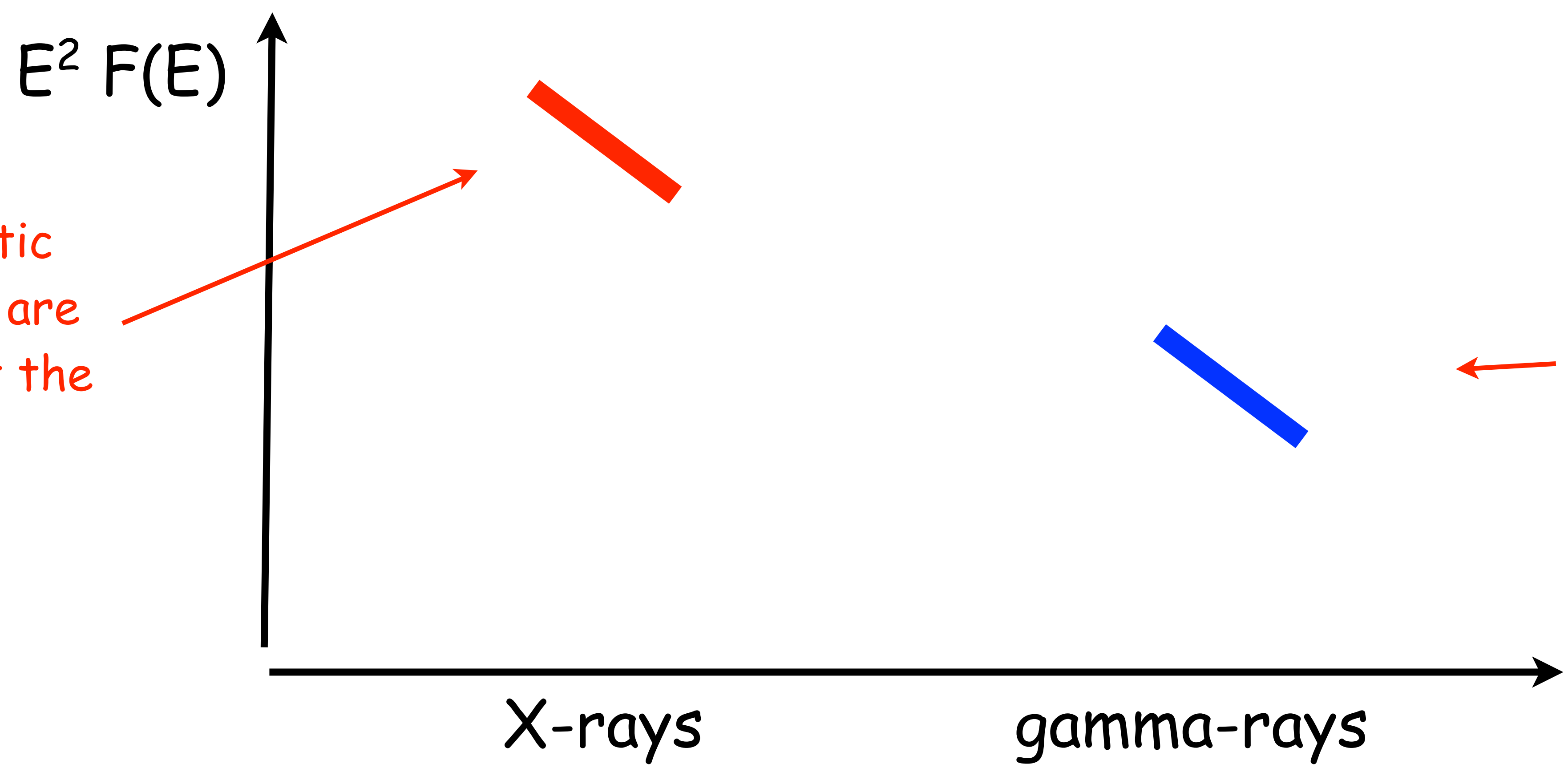


Hadronic versus leptonic emission: the role of the magnetic field

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

relativistic electrons are present at the shock



the same electrons that emit the synchrotron also emit inverse Compton gamma rays

synchrotron -> $F_s \propto n_e B^\beta$

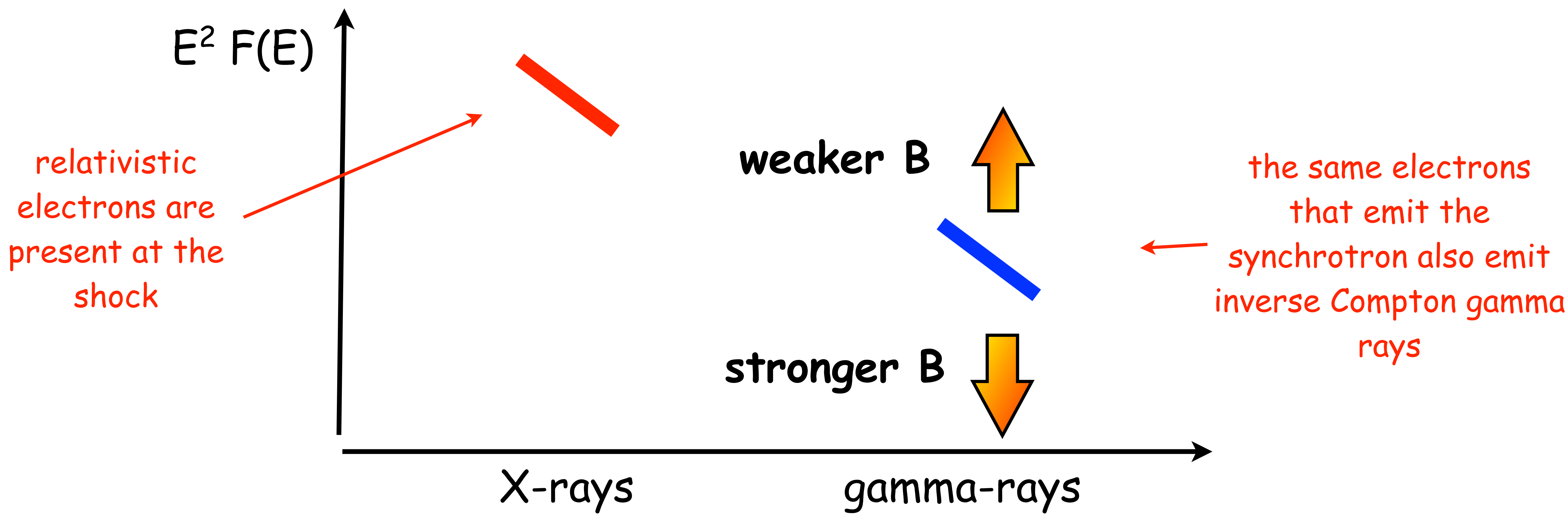
this product is fixed by X-ray obs.

inverse Compton -> $F_{IC} \propto n_e w_{soft}$

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...)



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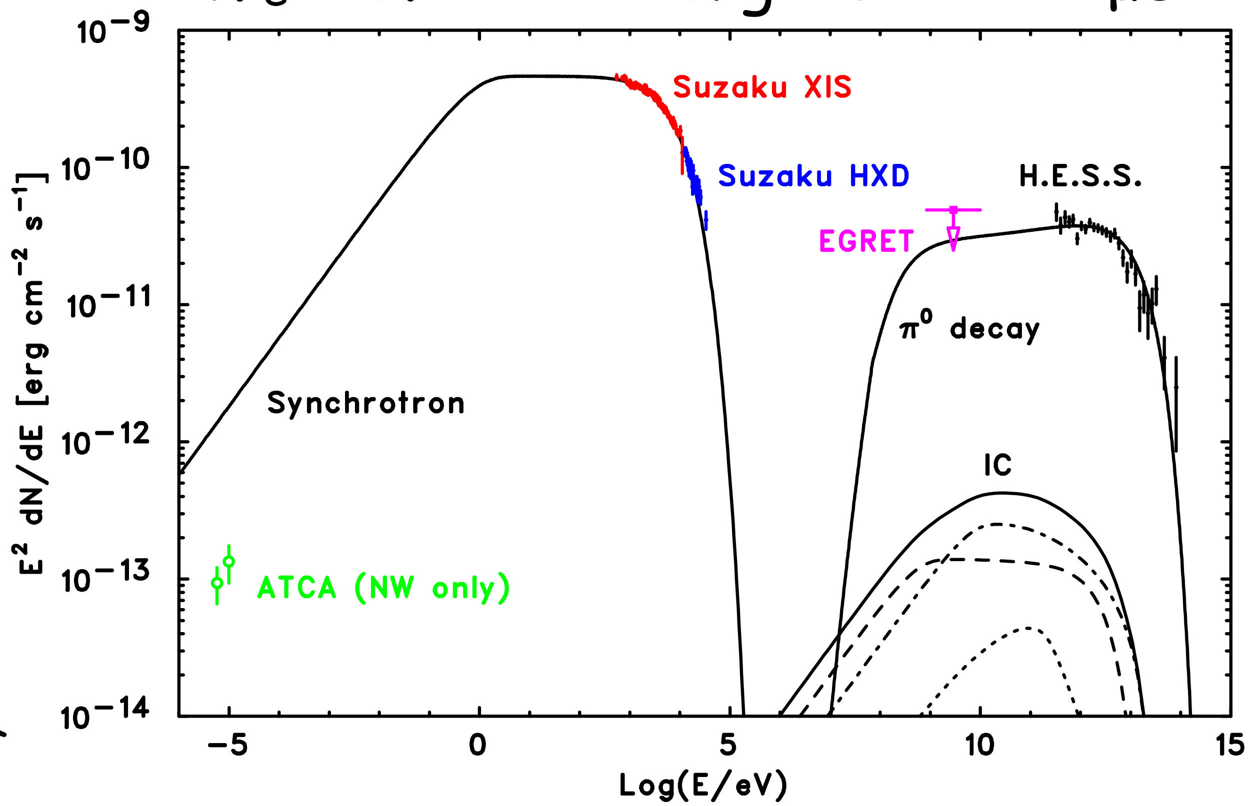
Hadronic versus leptonic emission

RXJ1713: hadronic and leptonic models

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

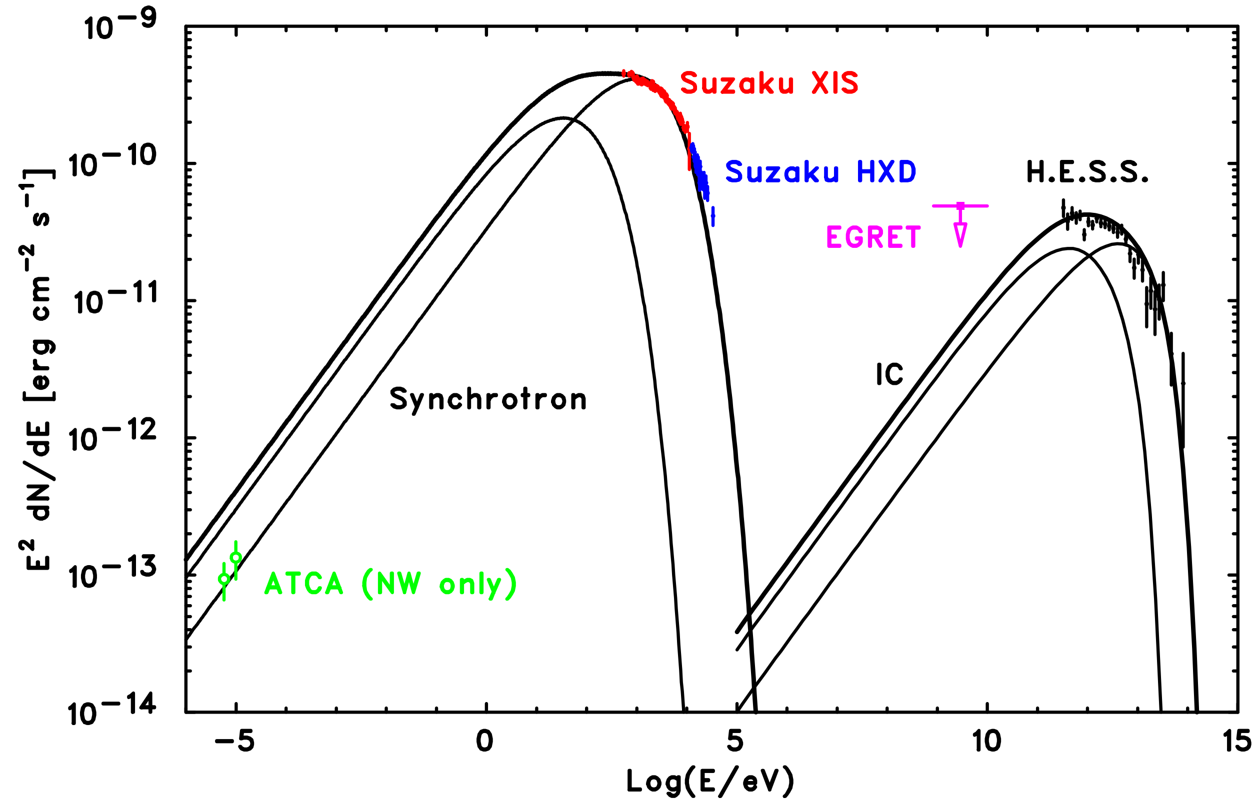
Leptonic: low B field -> synchrotron losses negligible -> electron spectrum E^{-2} -> inverse Compton scattering -> gamma ray spectrum $E^{-1.5}$

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

Hadronic versus leptonic emission

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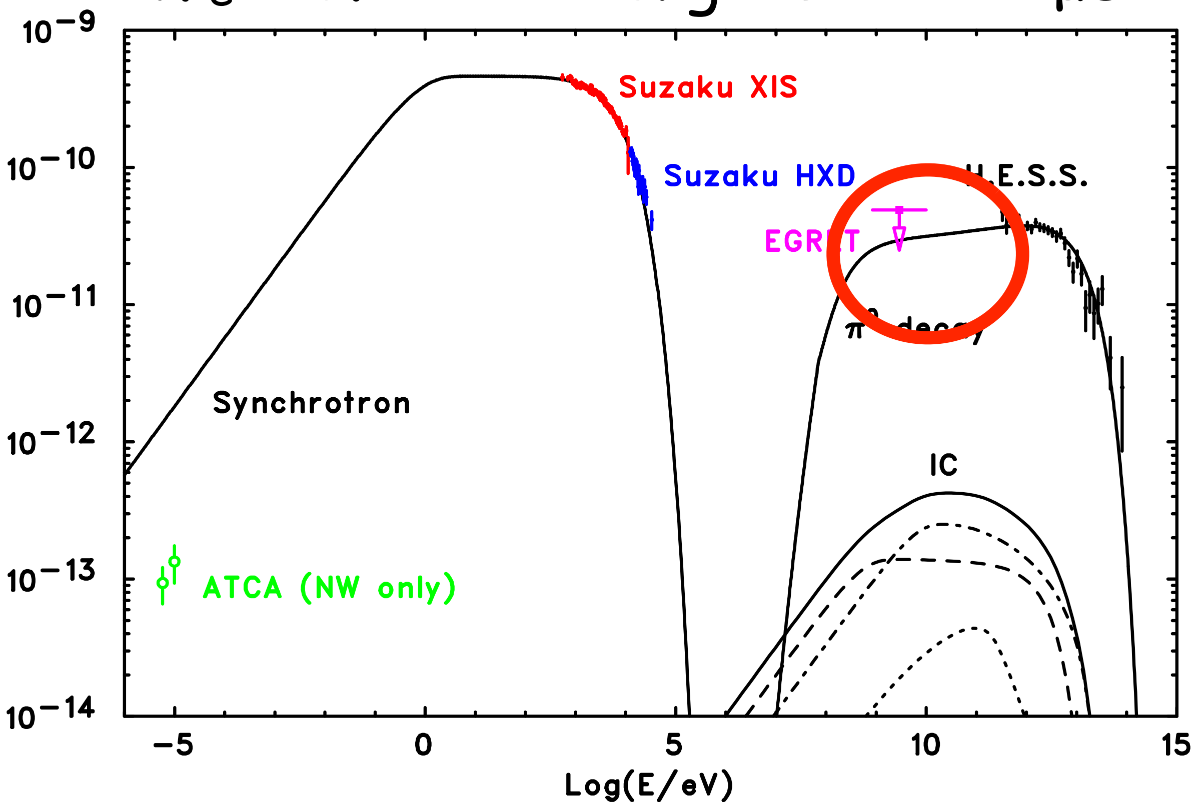

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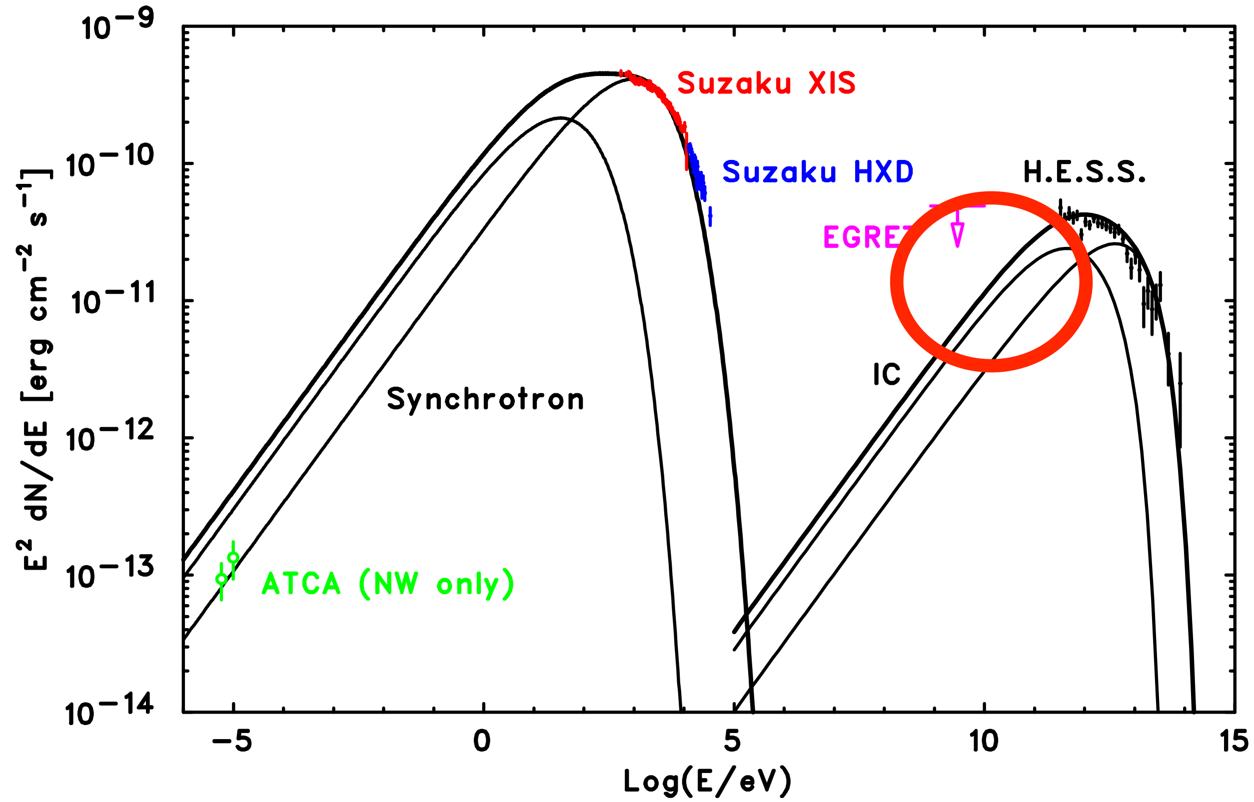
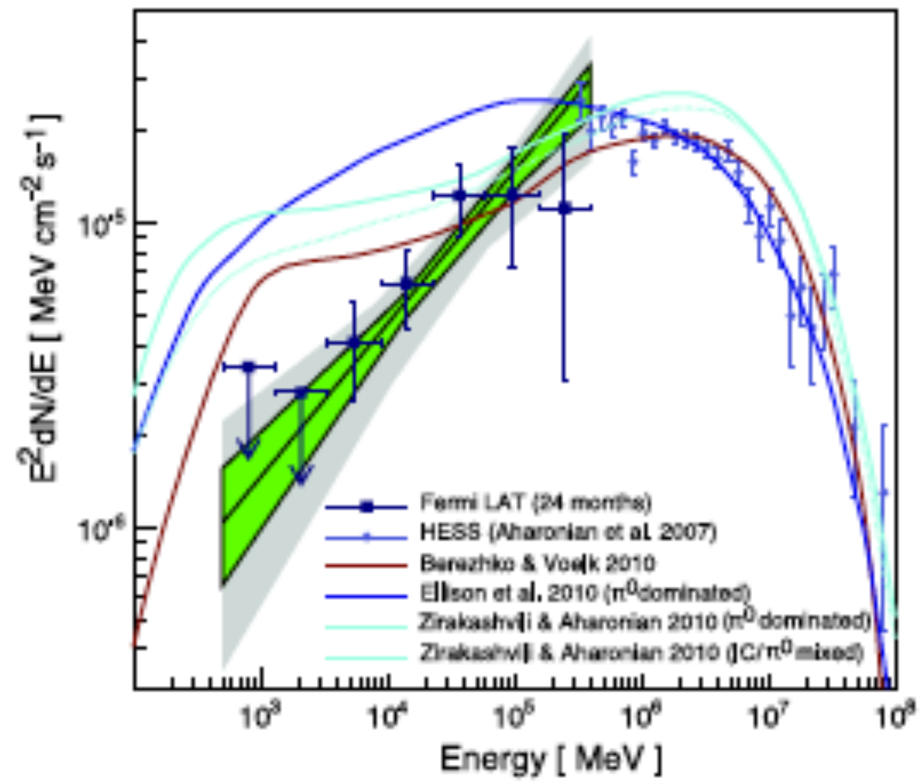


Leptonic

Tanaka et al., 2008

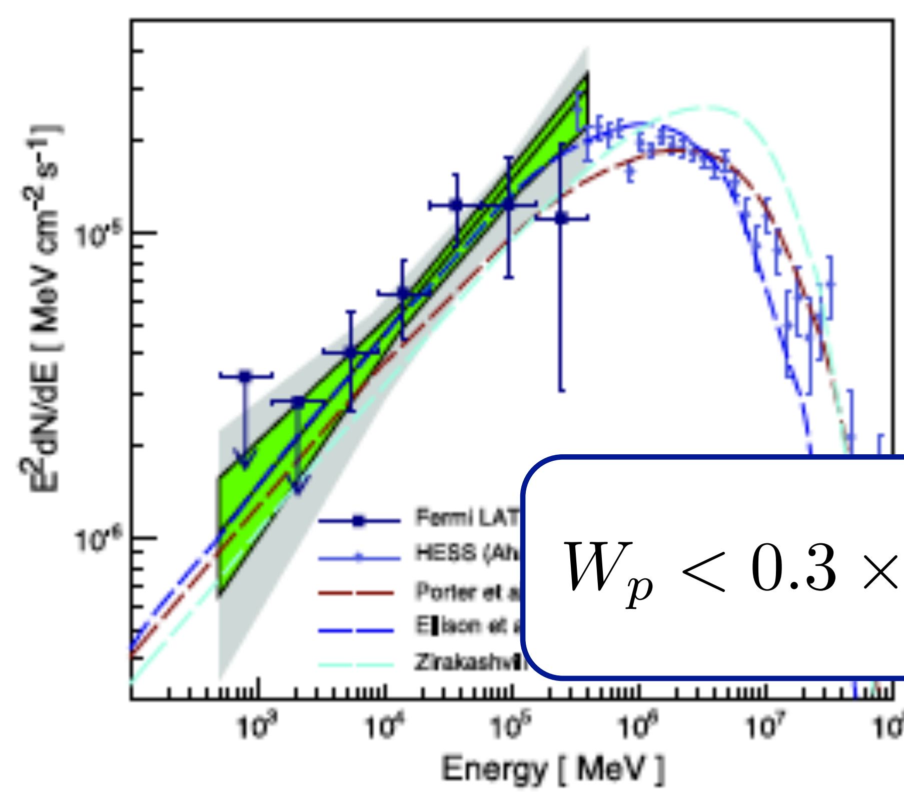
FERMI detects RX J1713

p-p interactions ->



emission most likely LEPTONIC?

inverse Compton ->

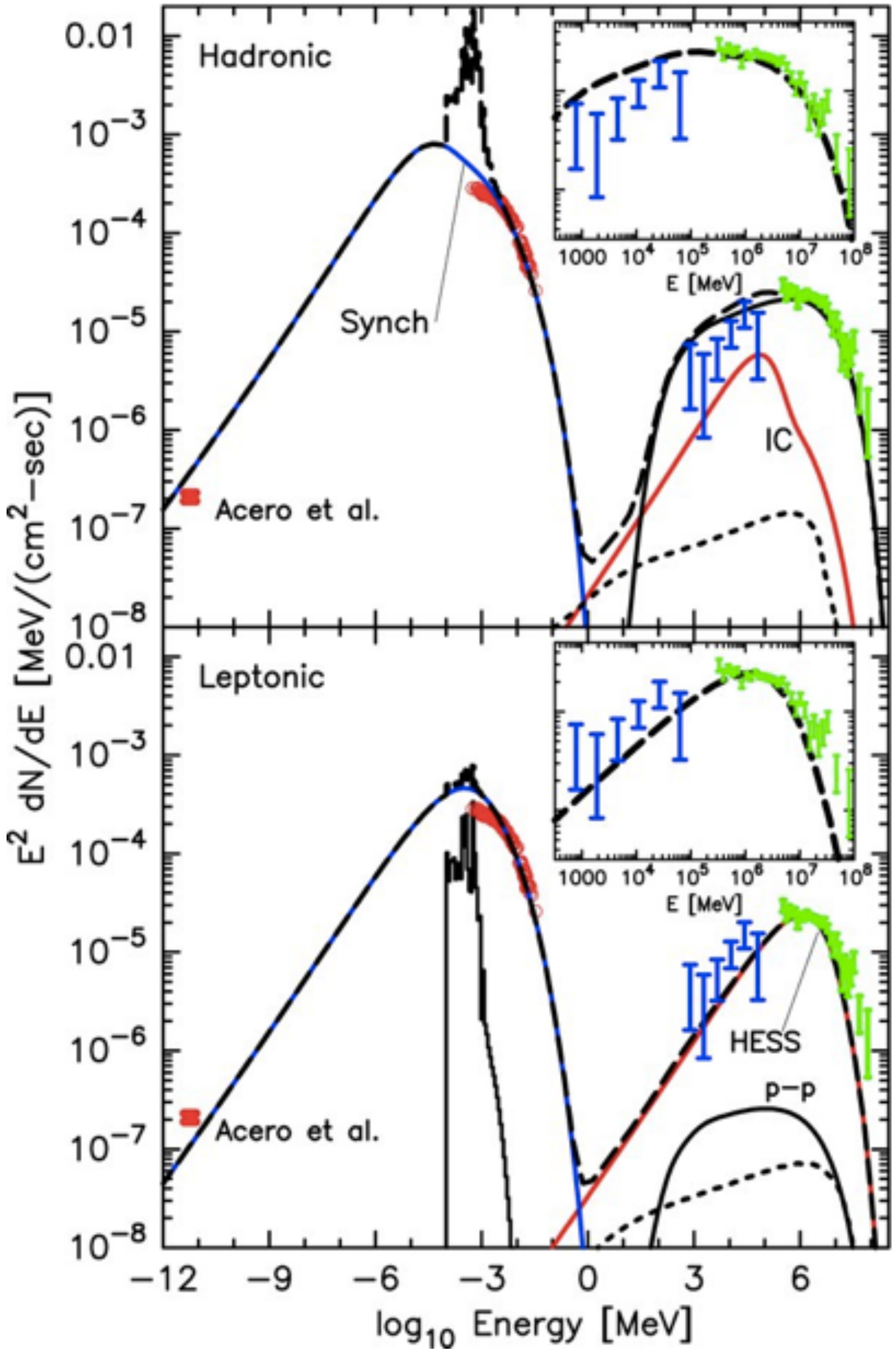


this does NOT mean that there are no protons!!!

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

Abdo et al, 2011

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



(Ellison et al 2010)

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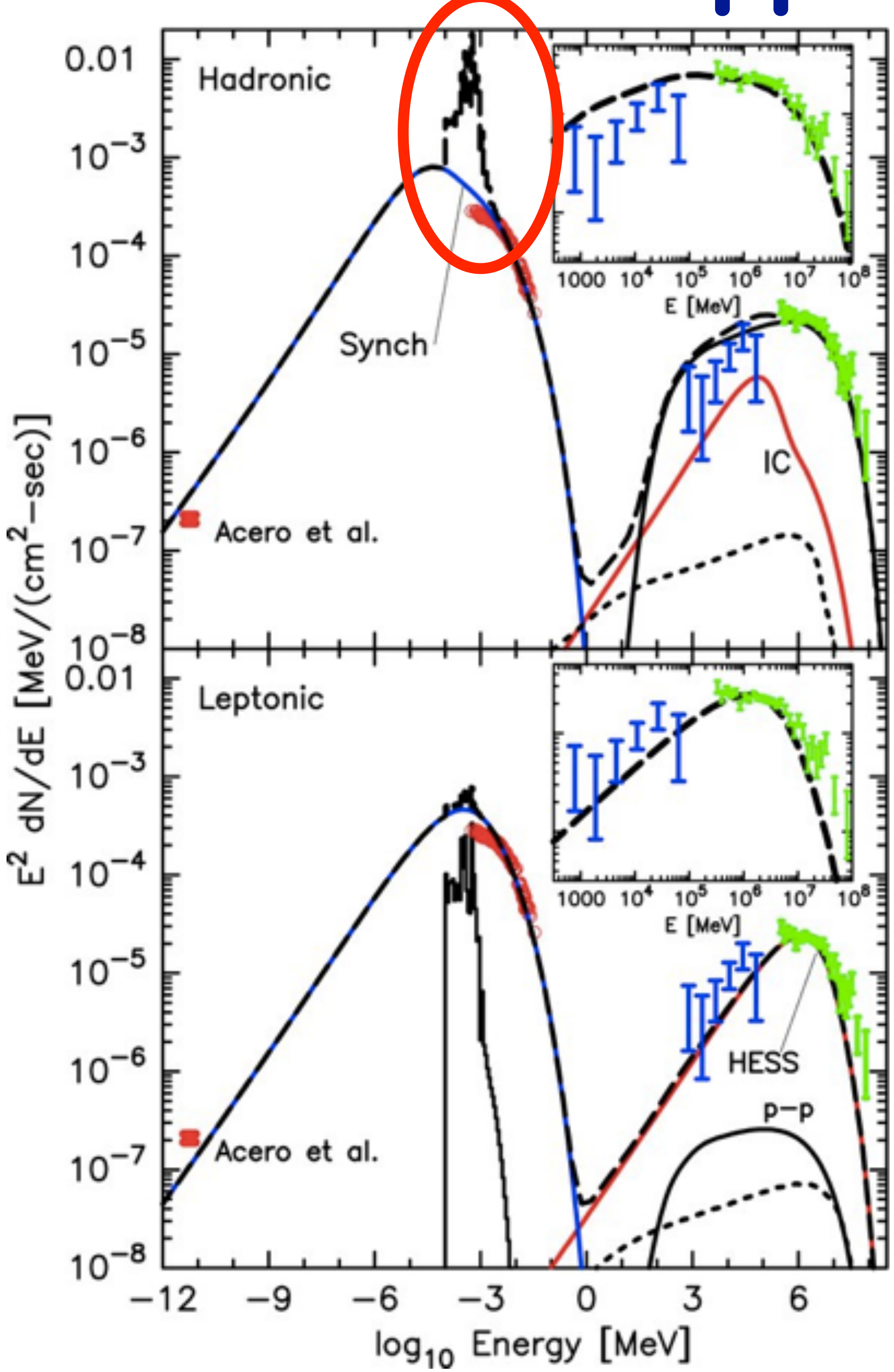

hadronic

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

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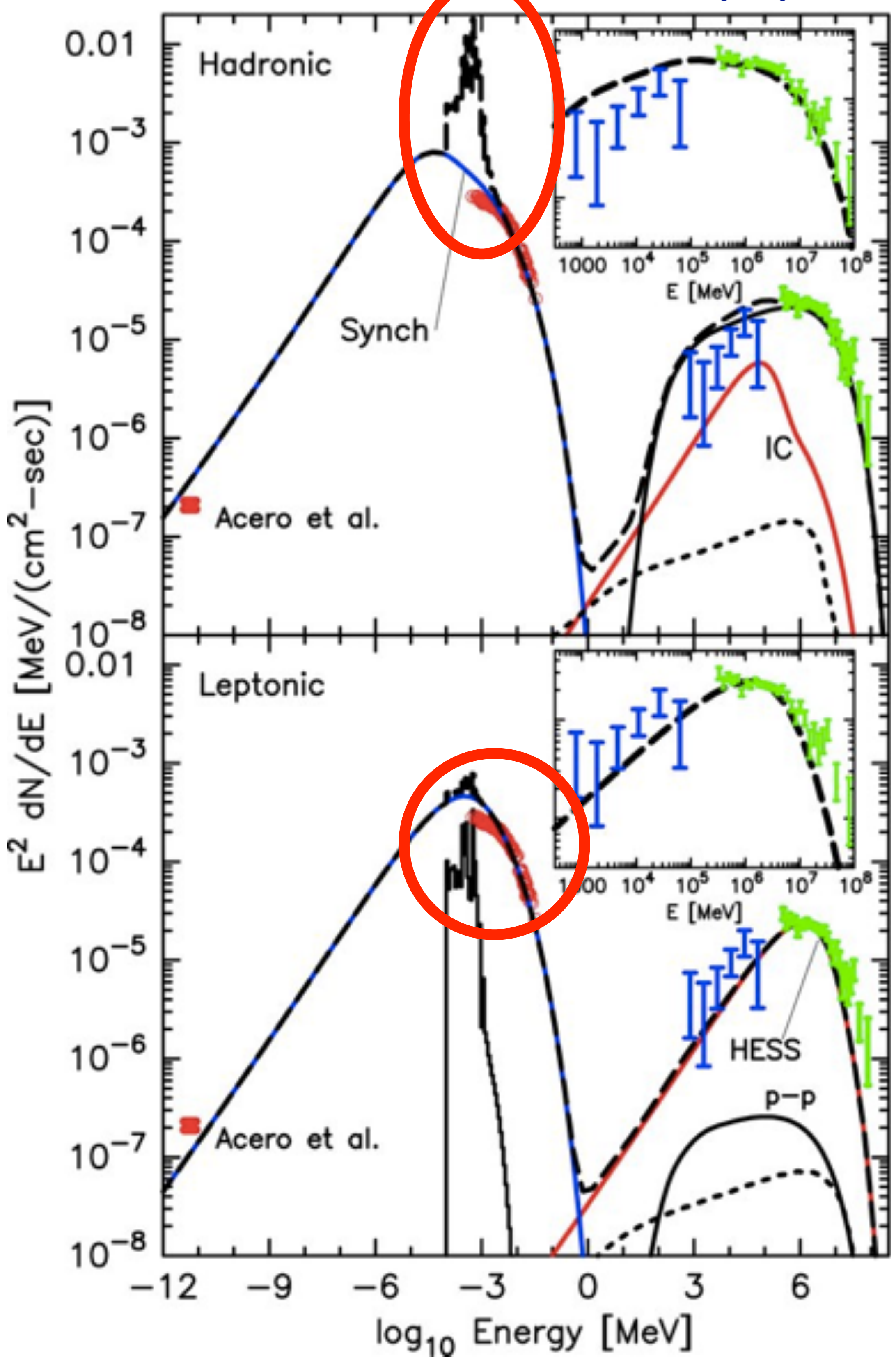

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hadronic

high gas density + shock heating
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-> NOT OBSERVED
(see also Katz&Waxman2008)

leptonic

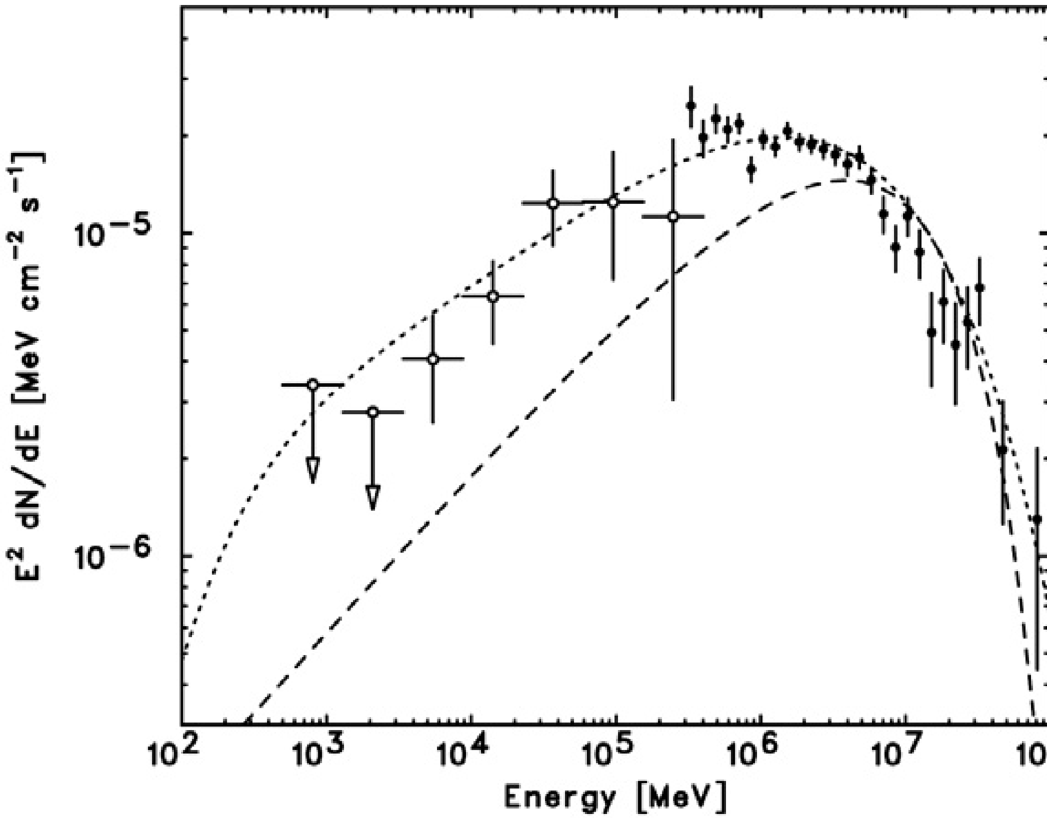
gas density is not a crucial parameter so one can tune it not to violate X-ray constraints

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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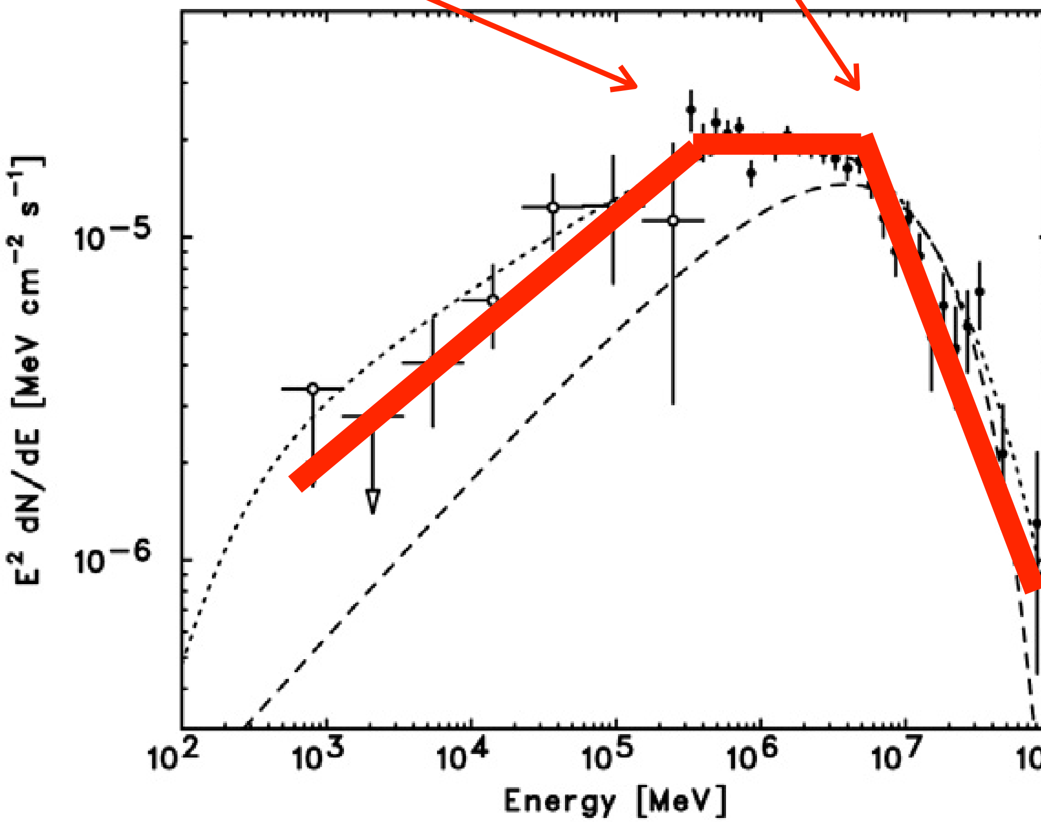

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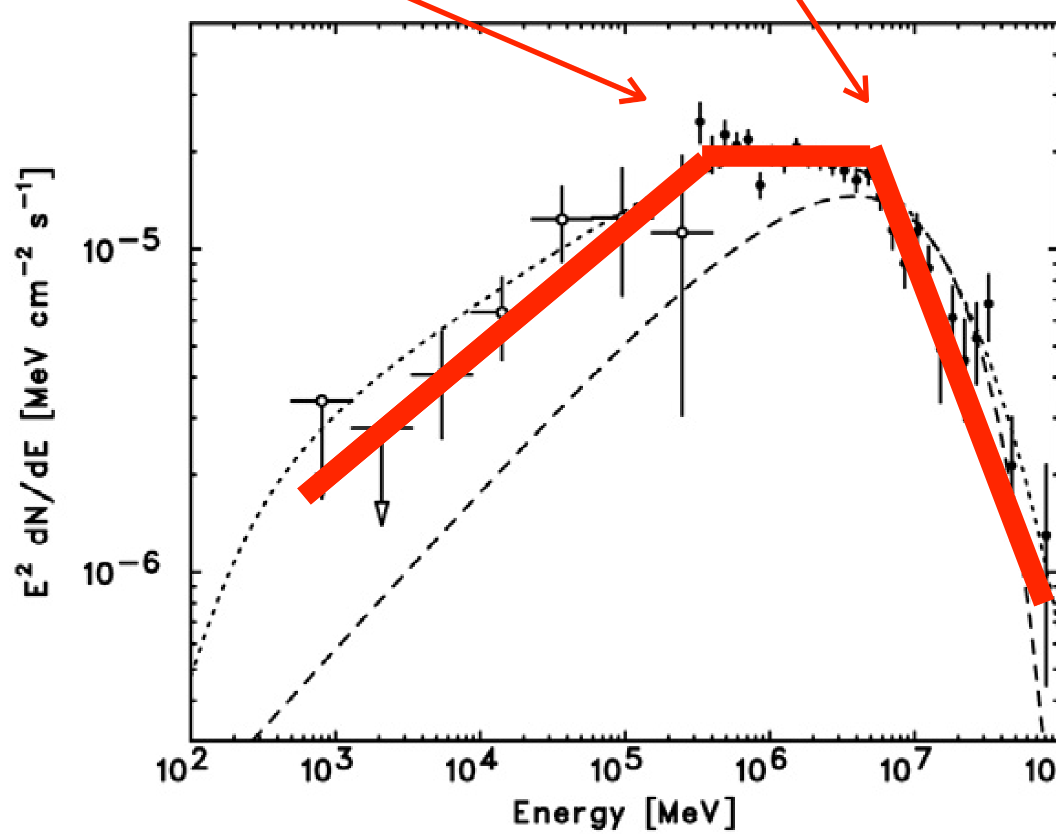
to fit simultaneously X and gamma rays with electrons the magnetic field MUST be **at most ~10 microGauss**



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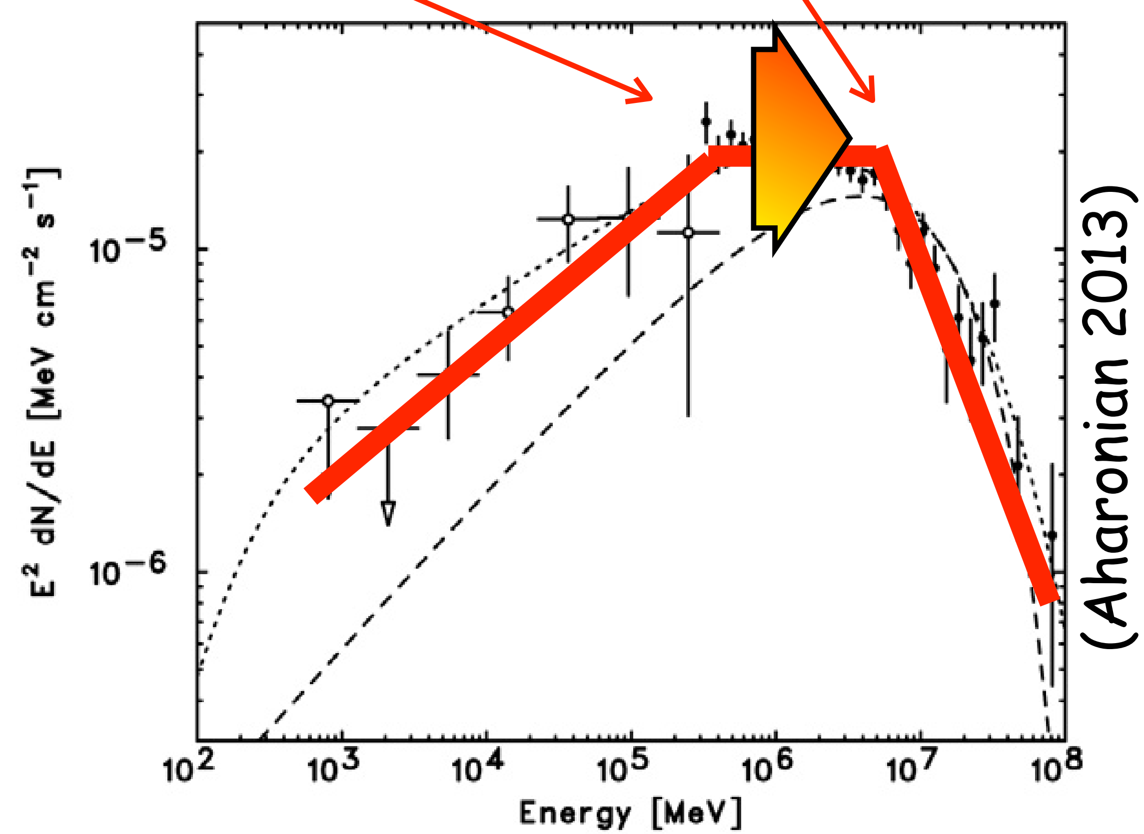

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no cooling break is expected...

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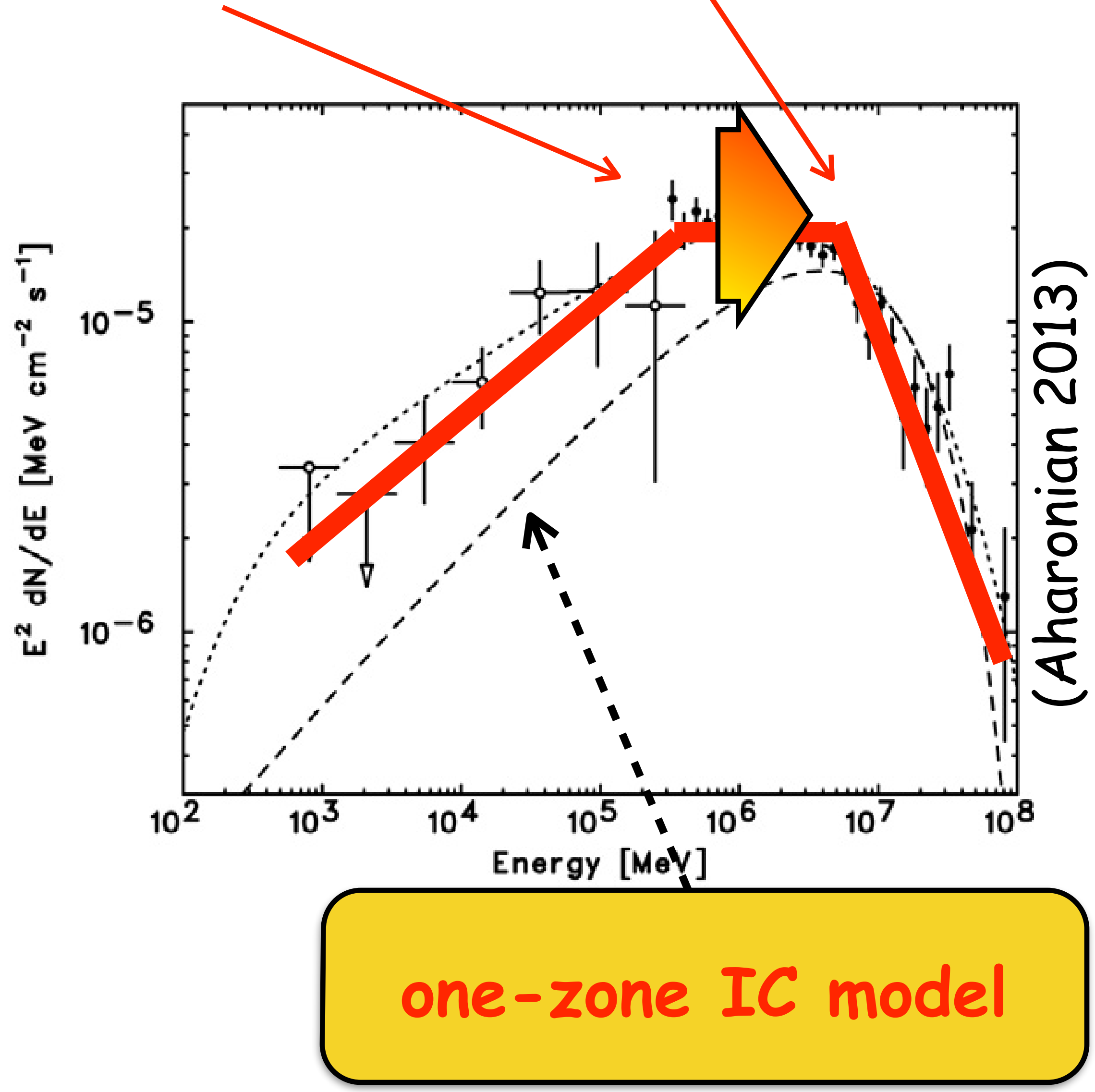

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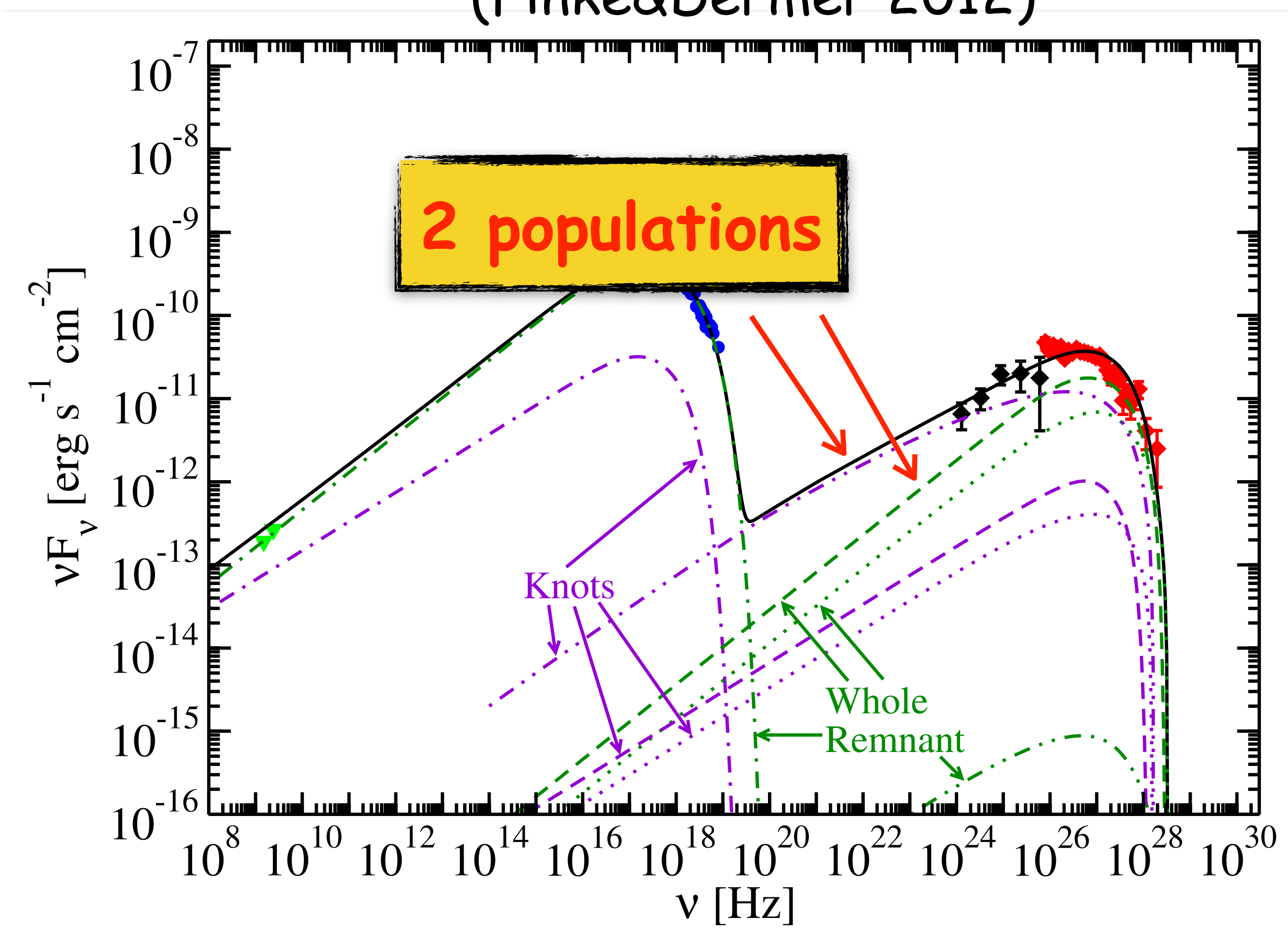
RXJ1713: difficulties of one-zone leptonic models

(Finke&Dermer 2012)

tw

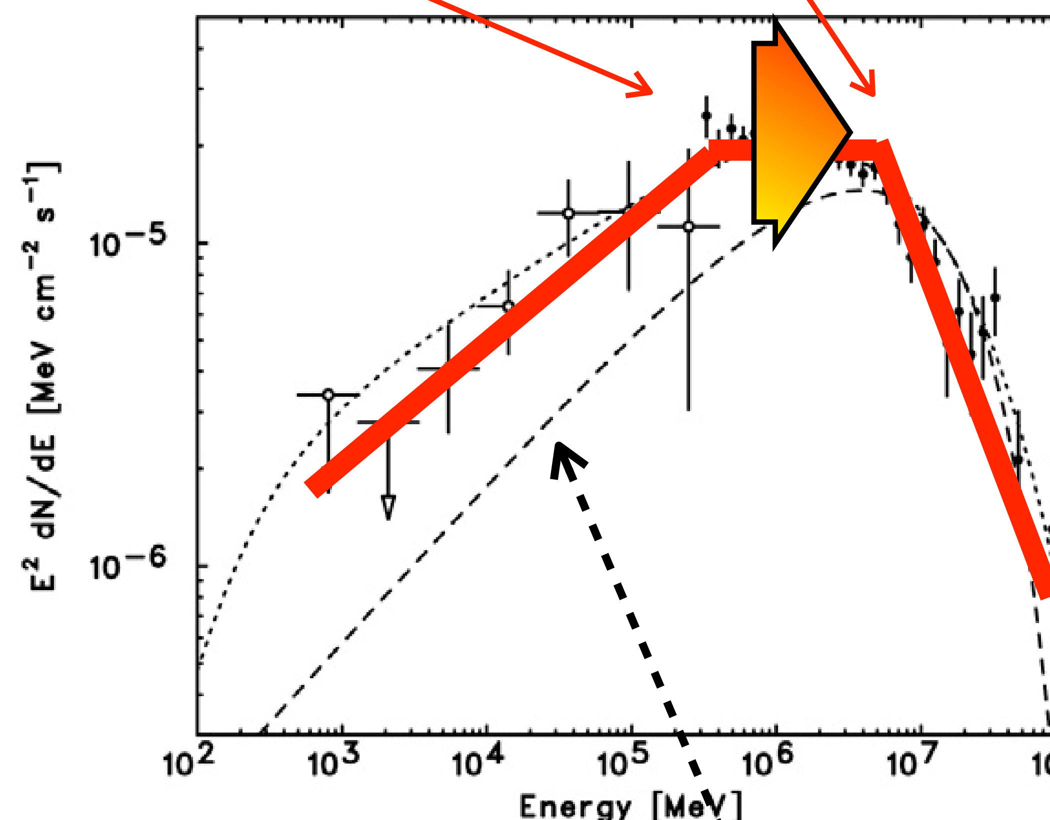
ac

SN



acceleration cutoff at E_{max}

reak at E_{cool}



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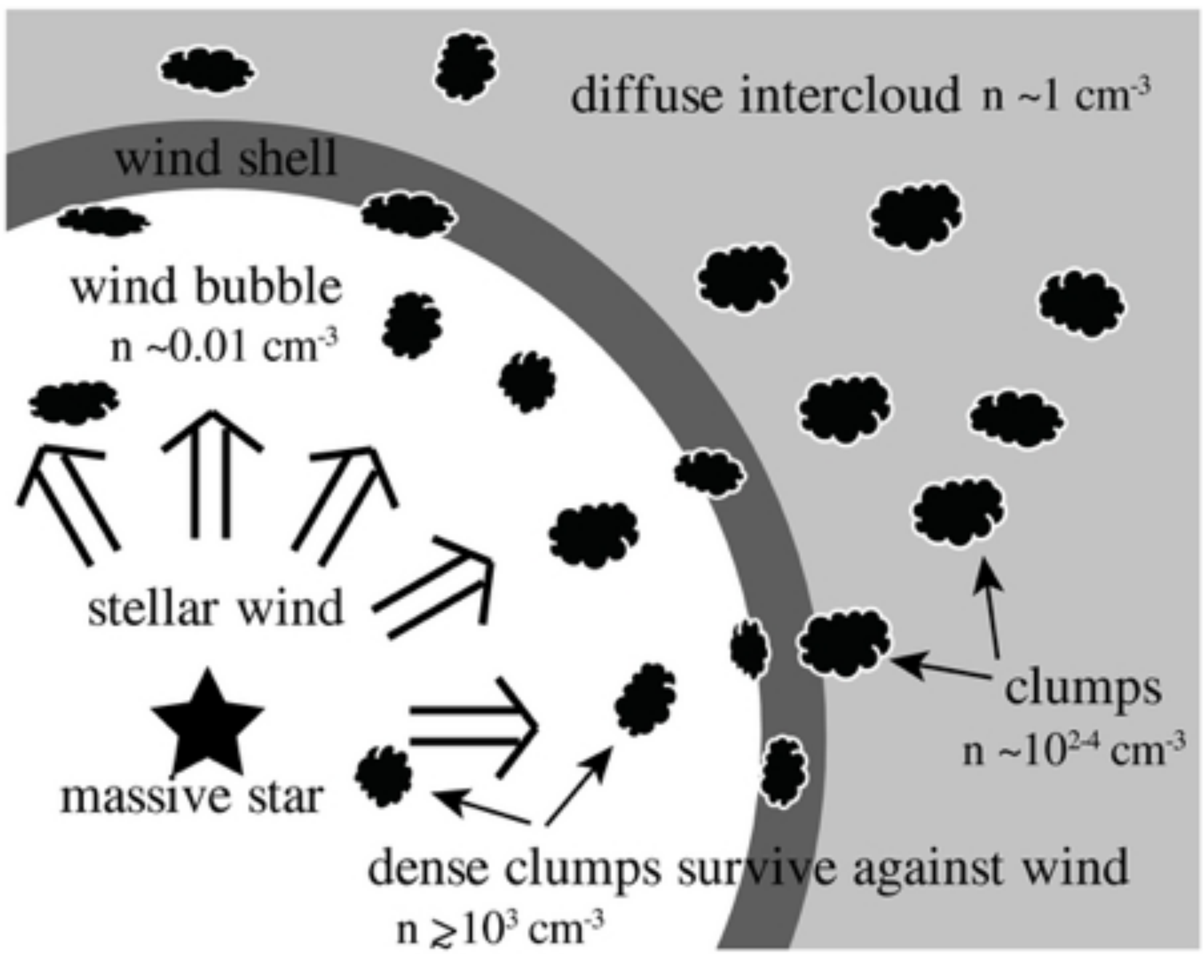
one-zone IC model

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

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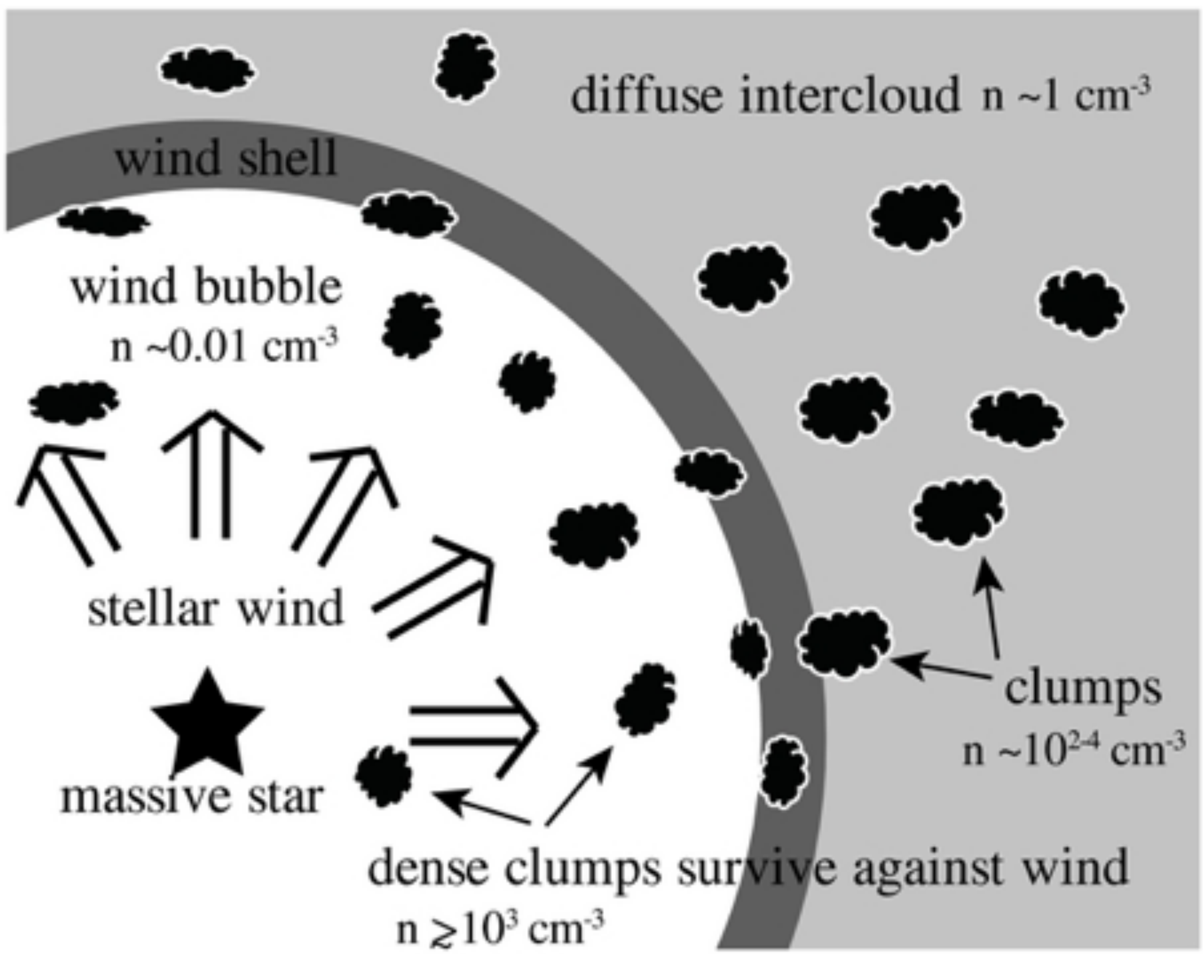

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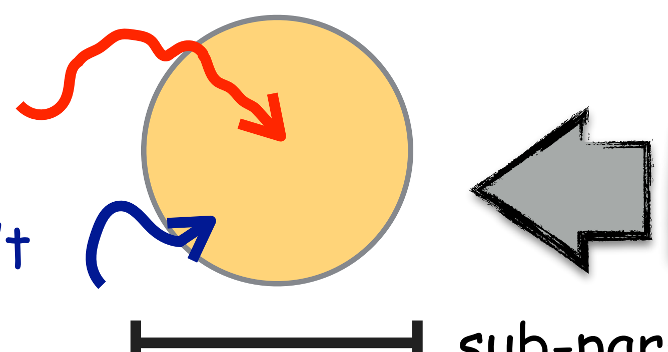
high energy CRs penetrate

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 $\sim 10^3$ cm^{-3}
- hot tenuous medium in the bubble $n \sim 10^{-2}$ cm^{-3}
- turbulent layer between clumps and hot medium (~0.05 pc) with B~100 microGauss
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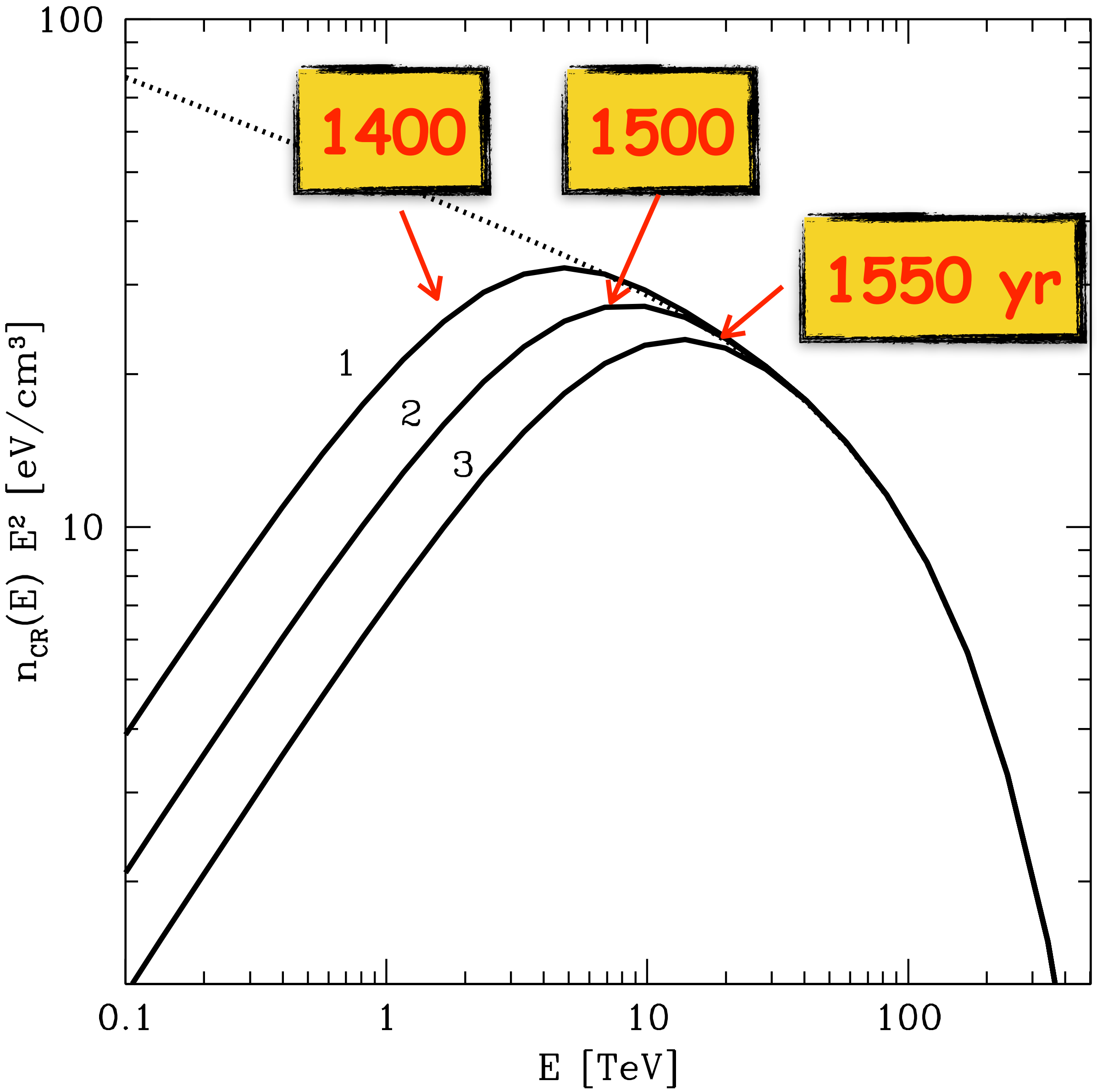
suggested by simulations

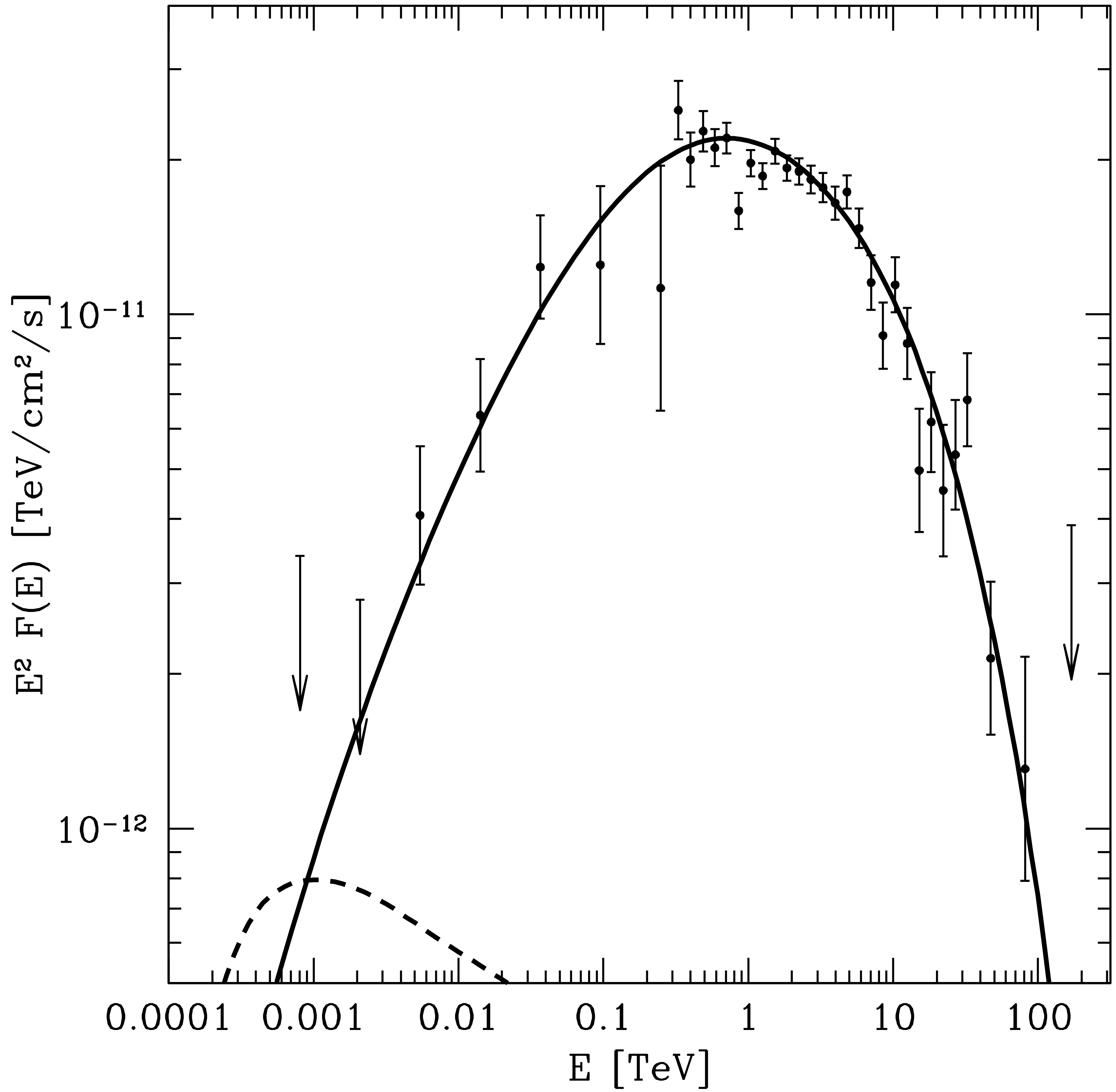
assumption

A hadronic model for RXJ1713

Gabici & Aharonian 2014

age -> ~1620 yr





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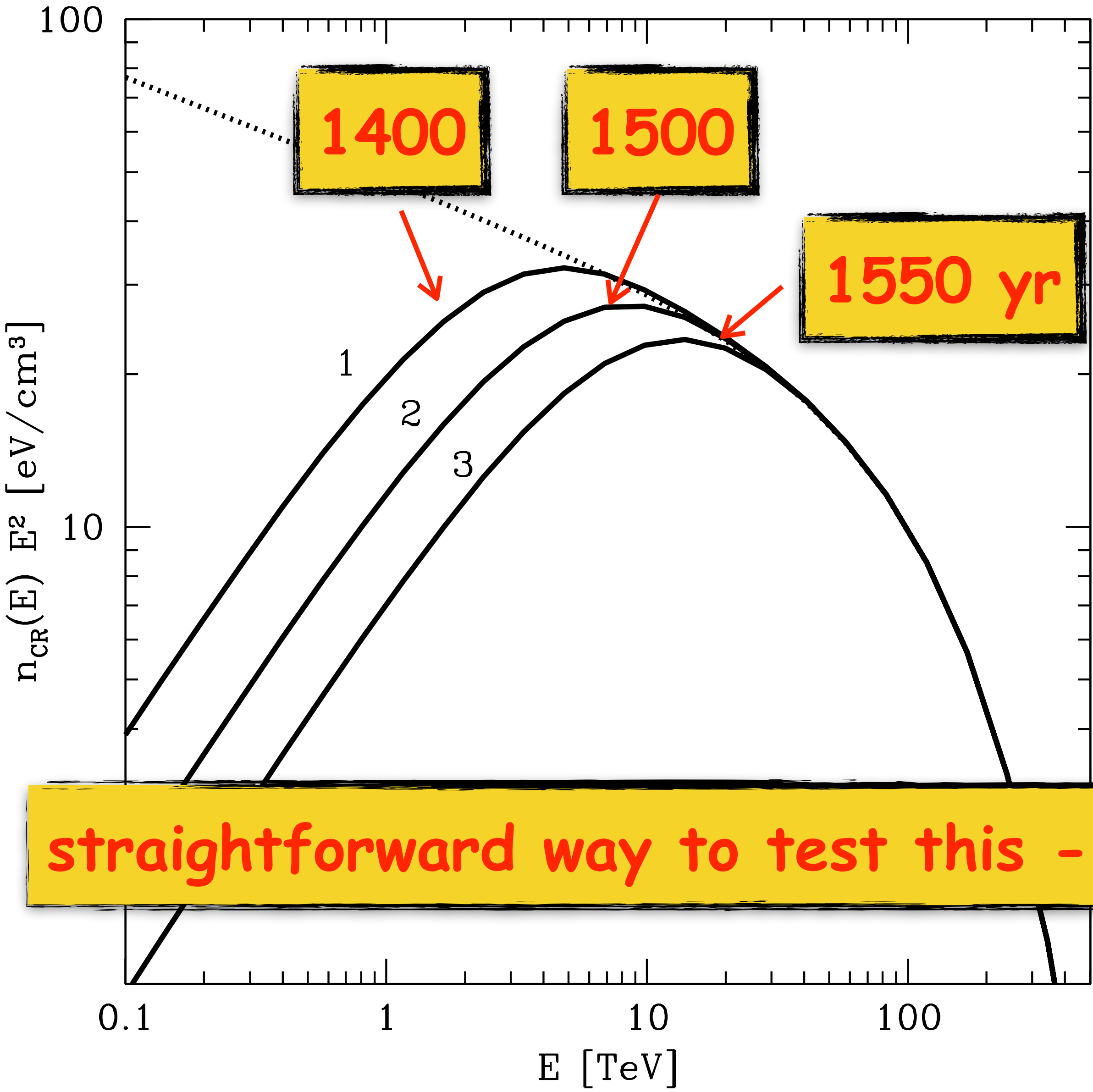
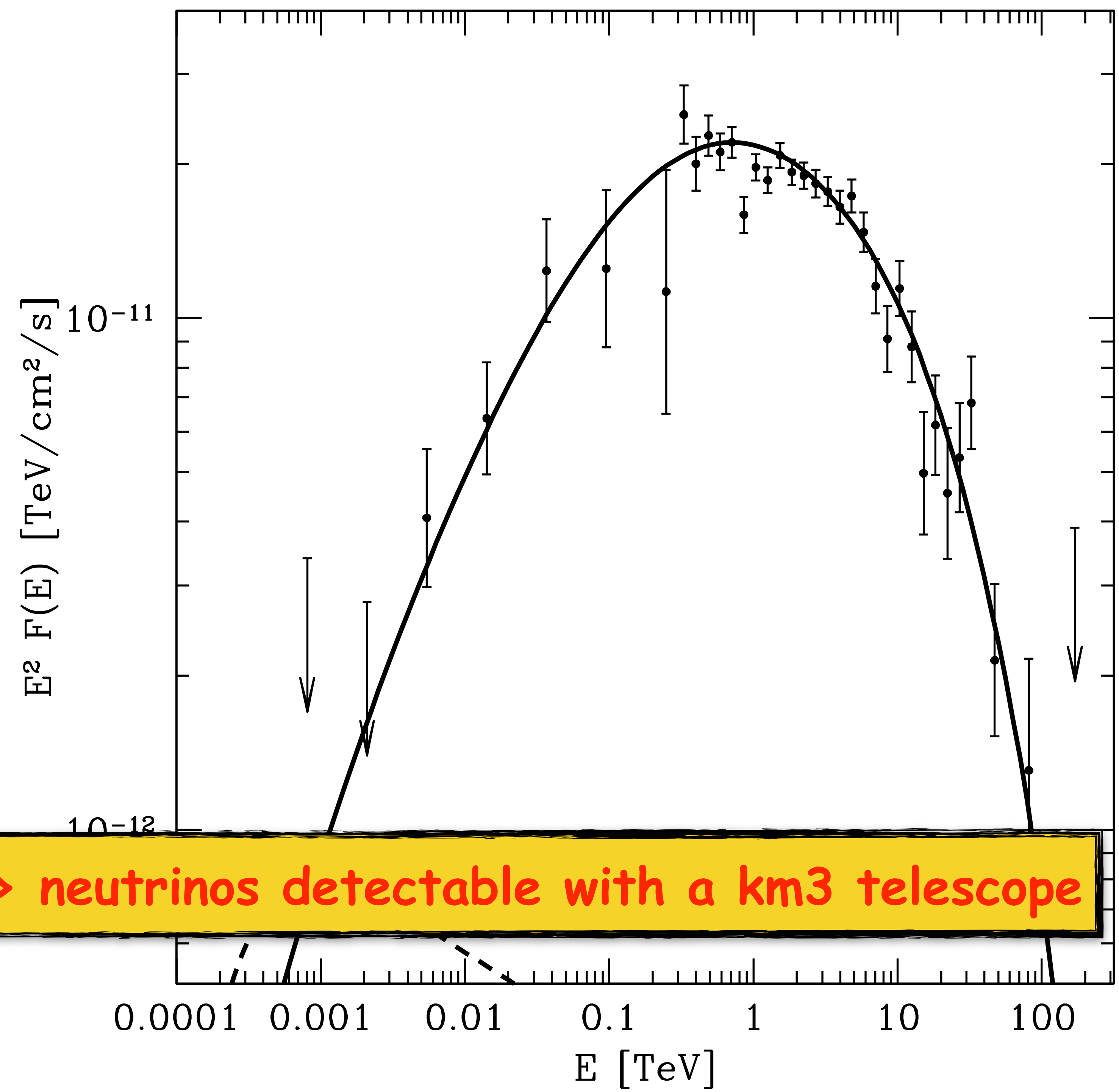
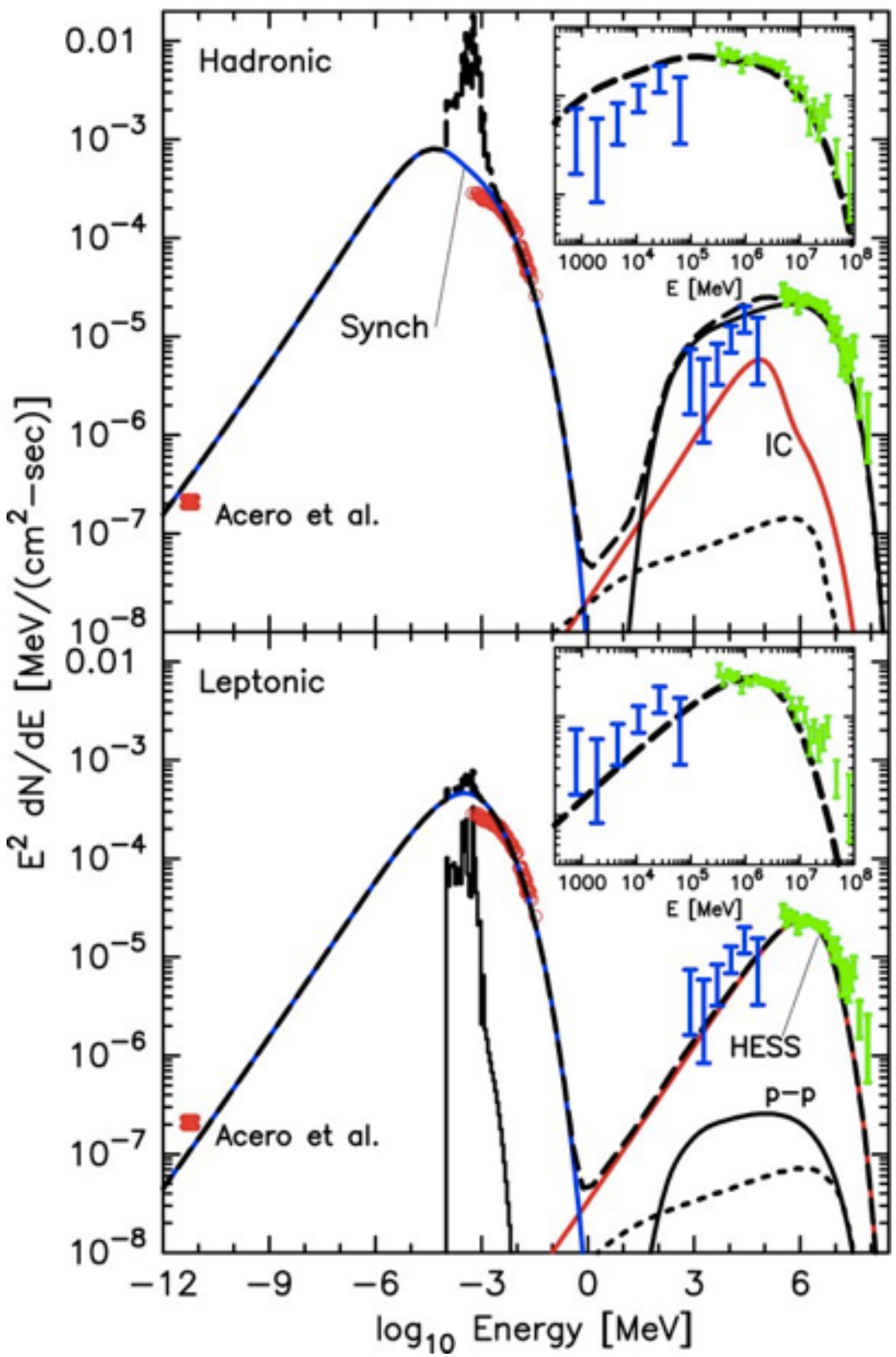




straightforward way to test this -> neutrinos detectable with a km3 telescope

Hadronic or leptonic?

(Ellison et al 2010)



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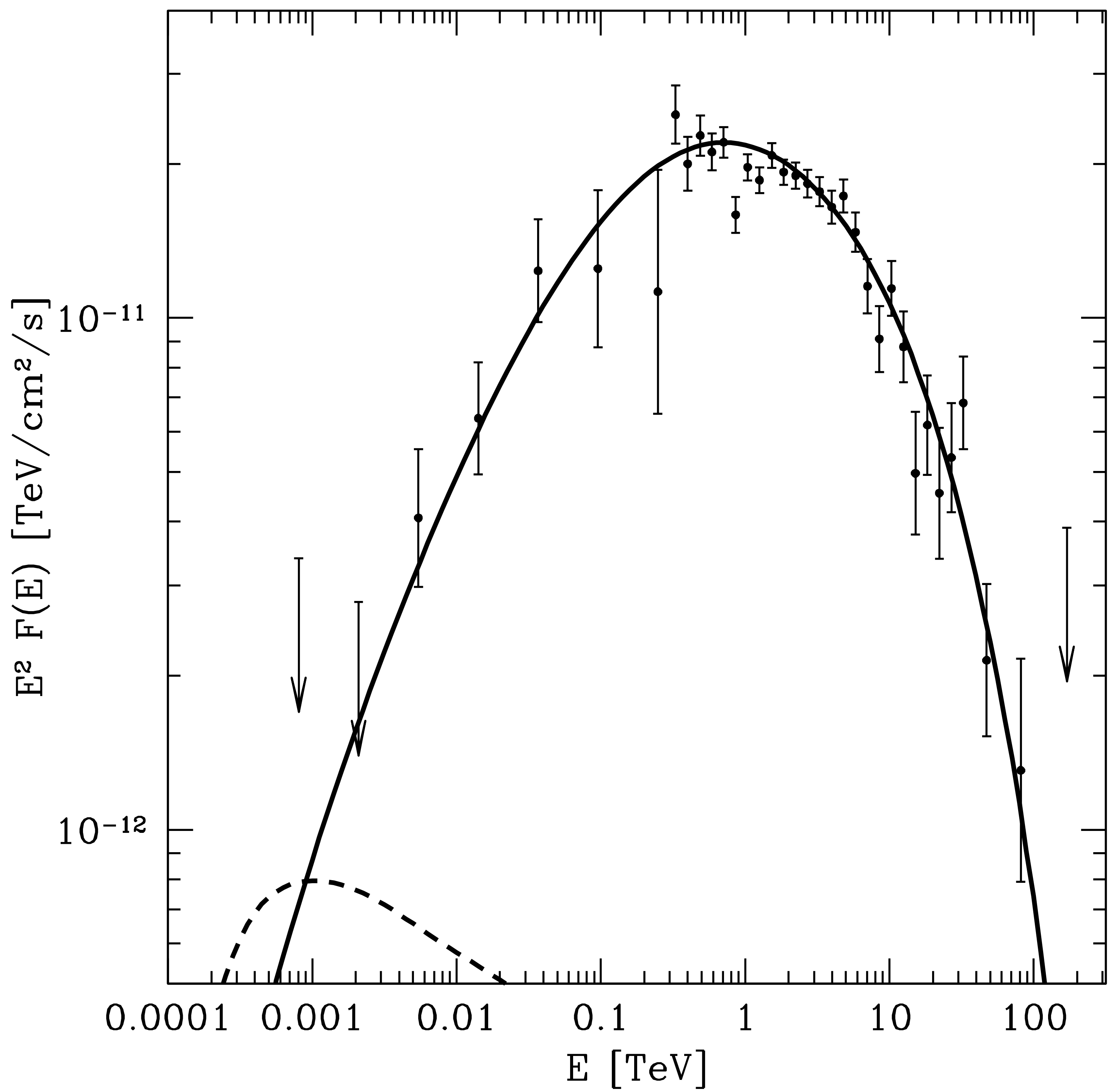
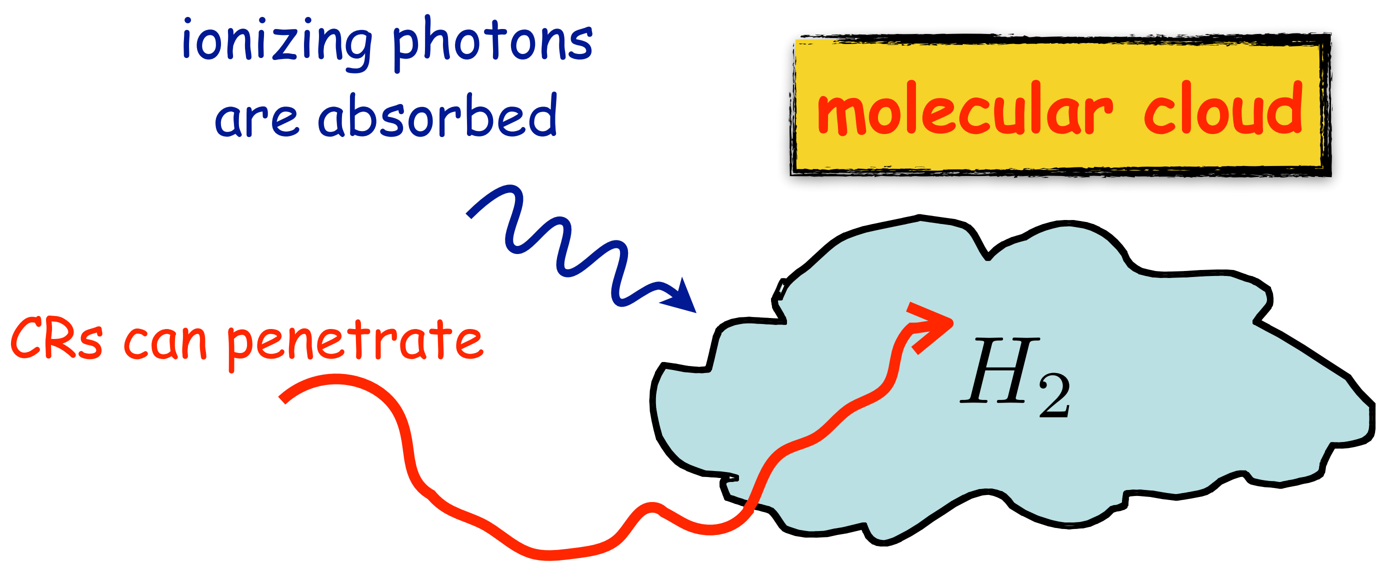


The MeV-TeV connection

The MeV domain: CR ionization

(see Padovani et al. 2009 for a recent review)



$$H_2 + CR \longrightarrow H_2^+ + e^-$$

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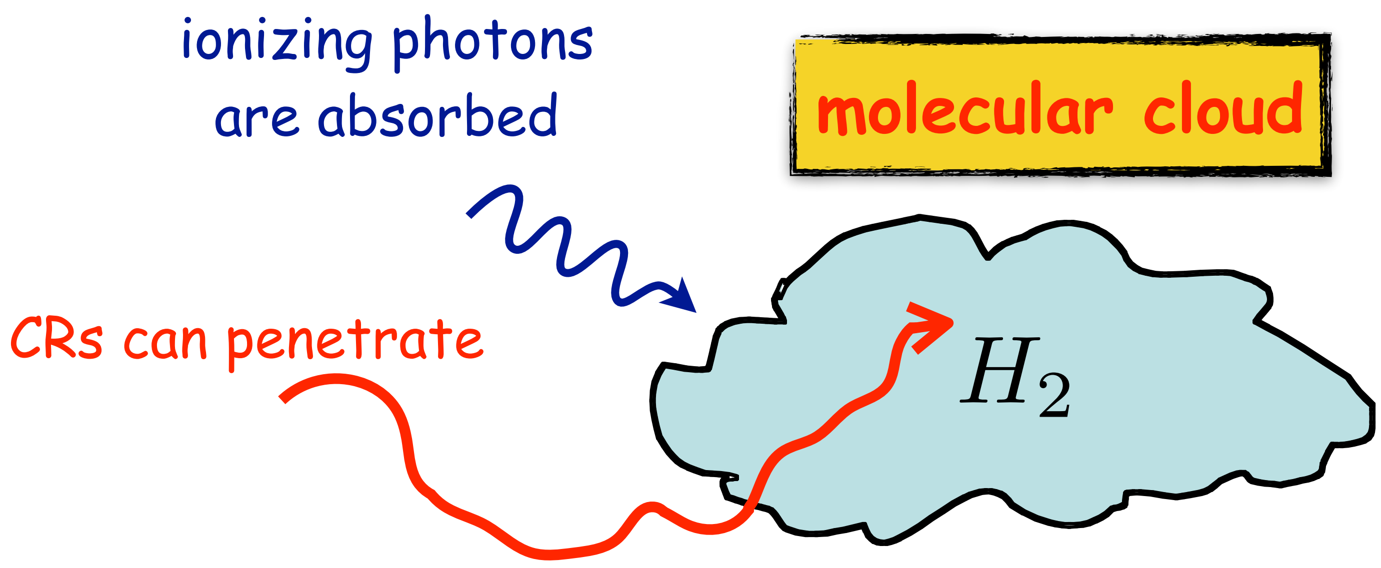

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chemistry

$$H_3^+, HCO^+, DCO^+ \ldots$$

see papers by McCall, Indriolo, Ceccarelli, Vaupré ...

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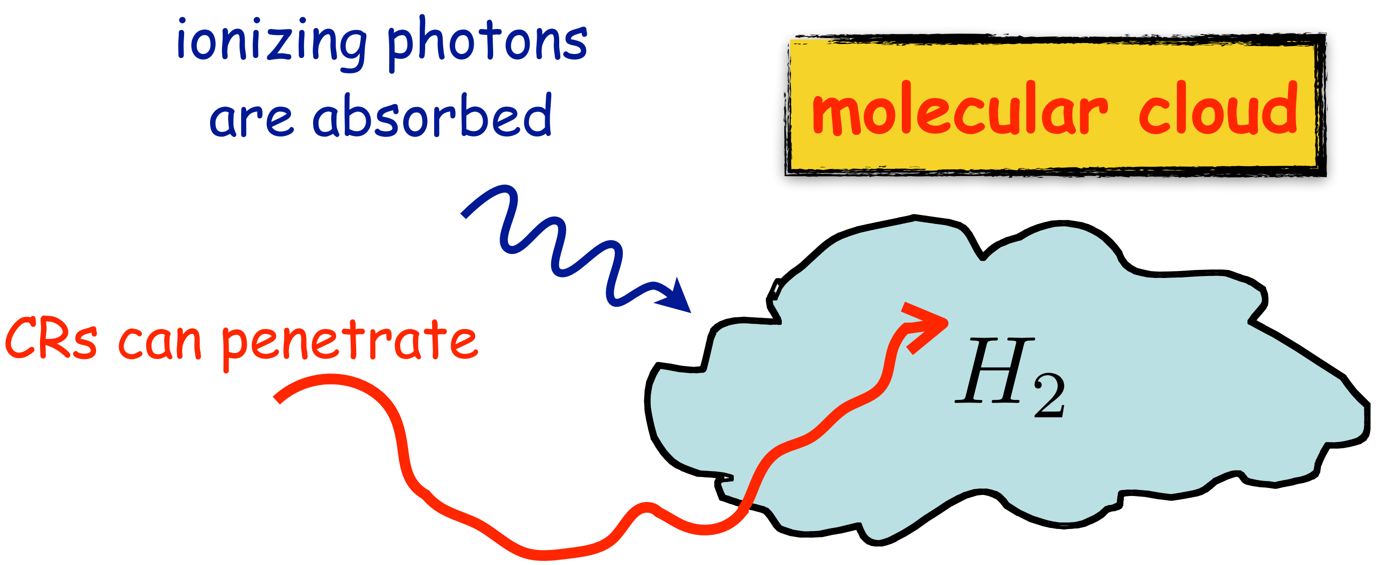

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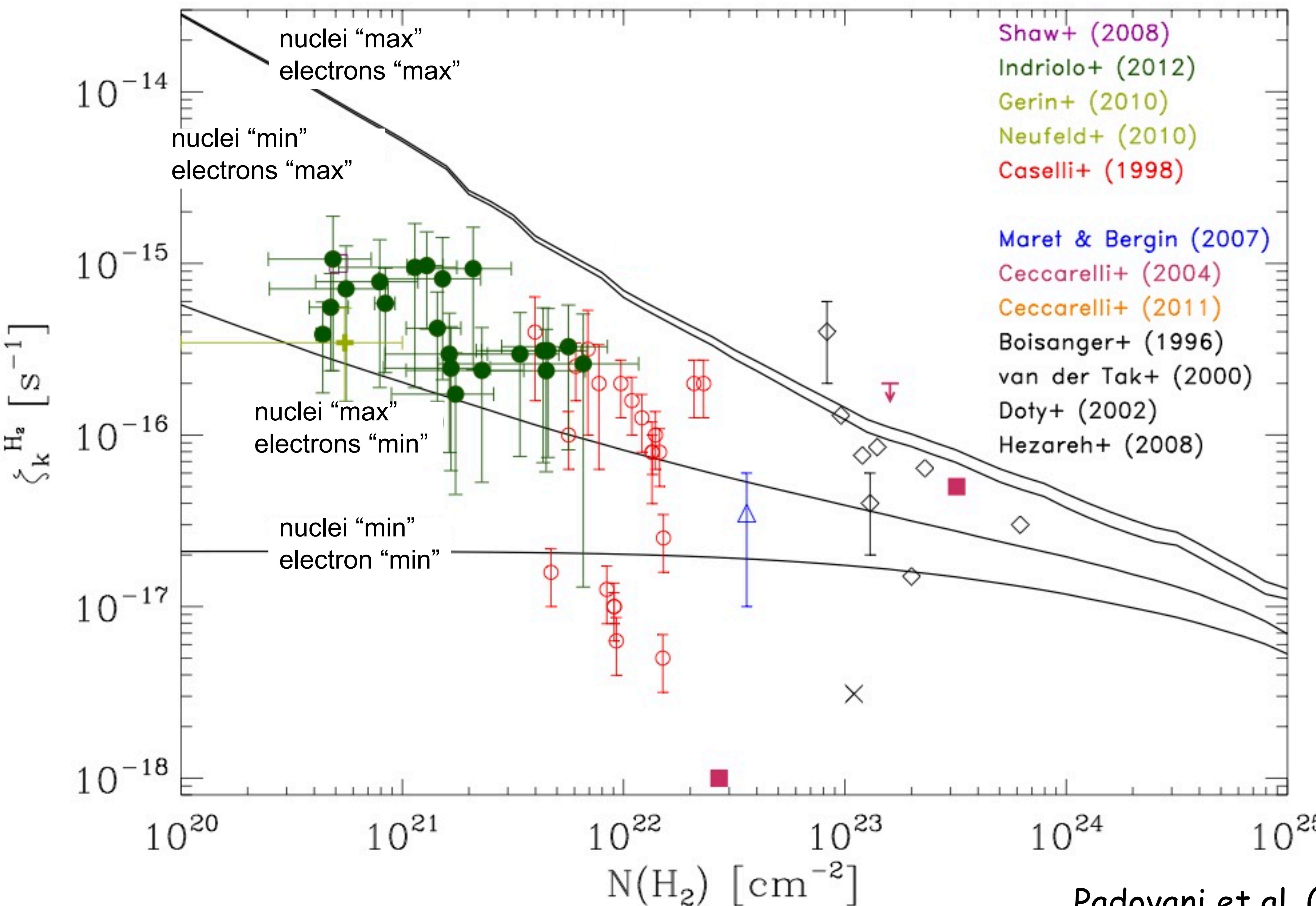
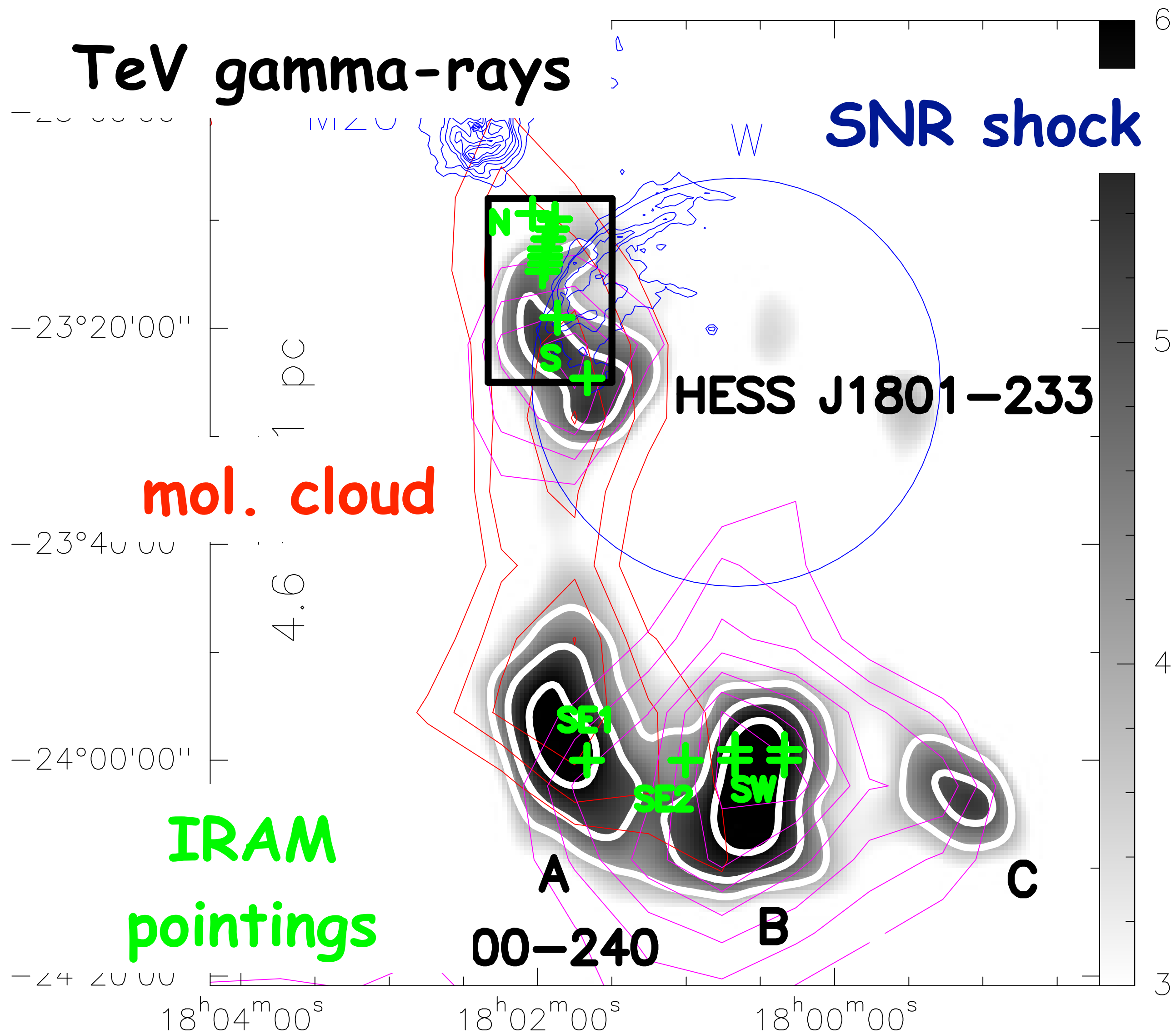
CR ionization rate: isolated clouds



Padovani et al. (2009)

CR ionization: the SNR W28

Vaupré, Hily-Blant, Ceccarelli, Dubus, SG, Montmerle (2014)



TeV + gas -> multi-TeV CR protons

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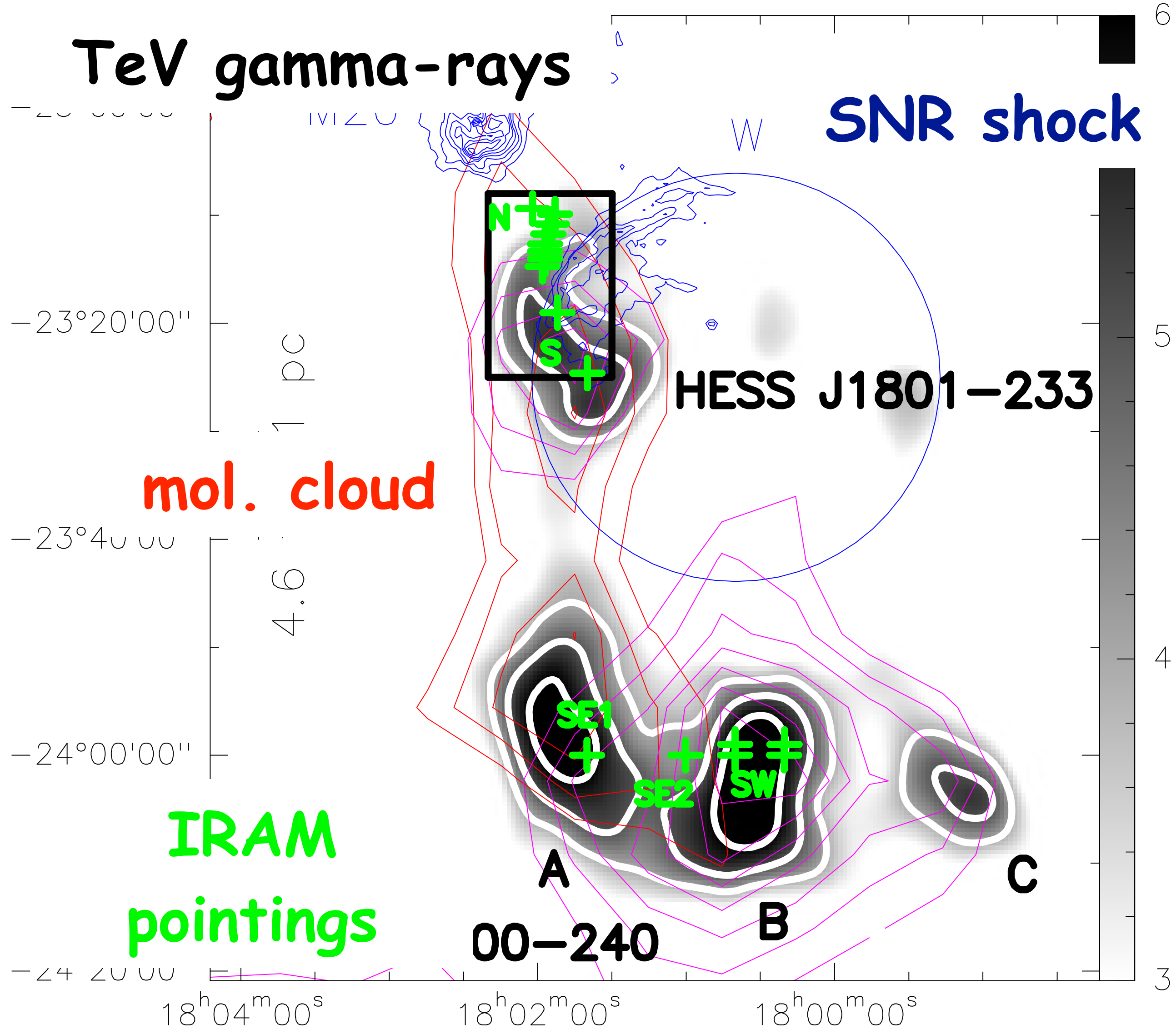

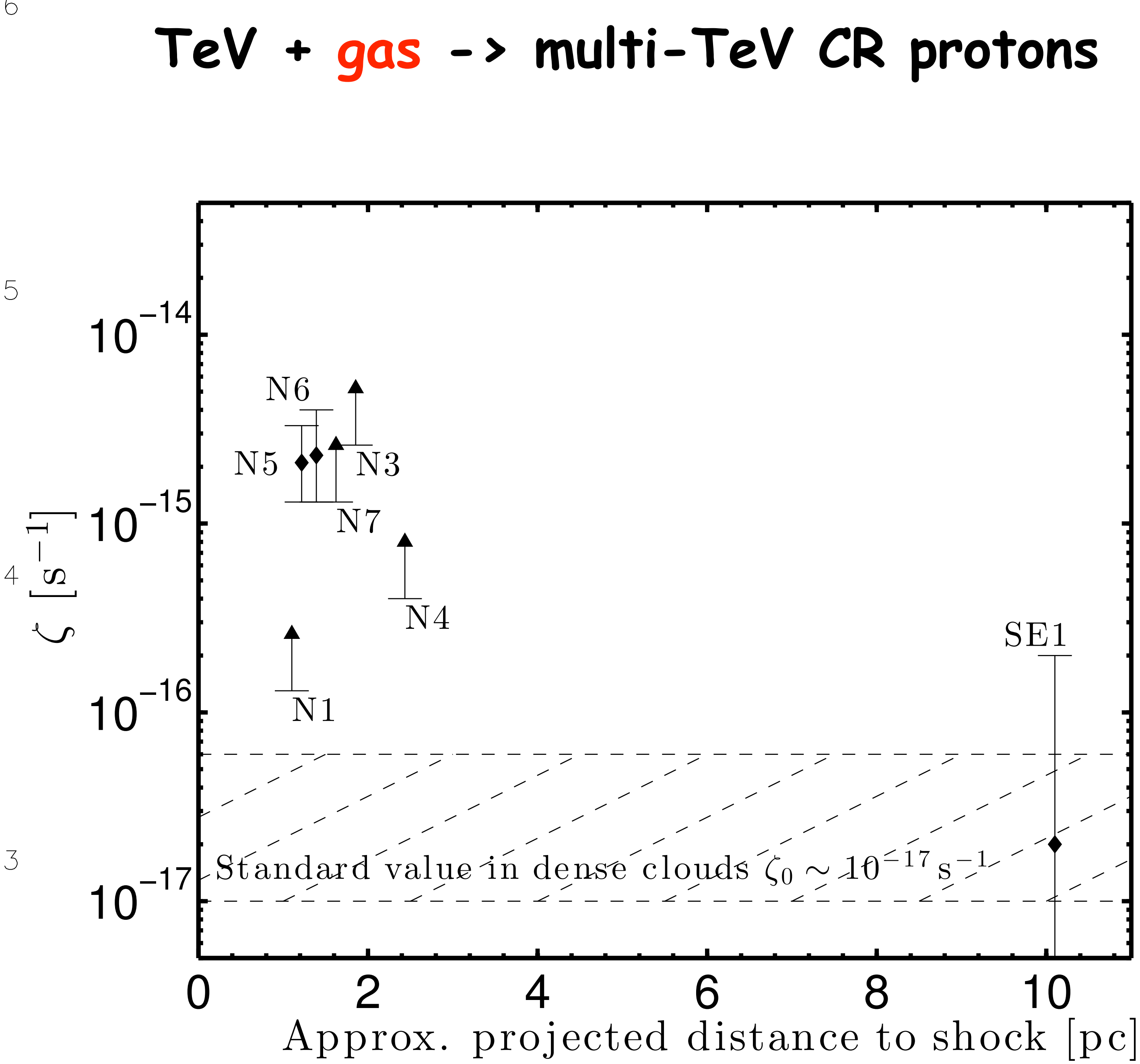

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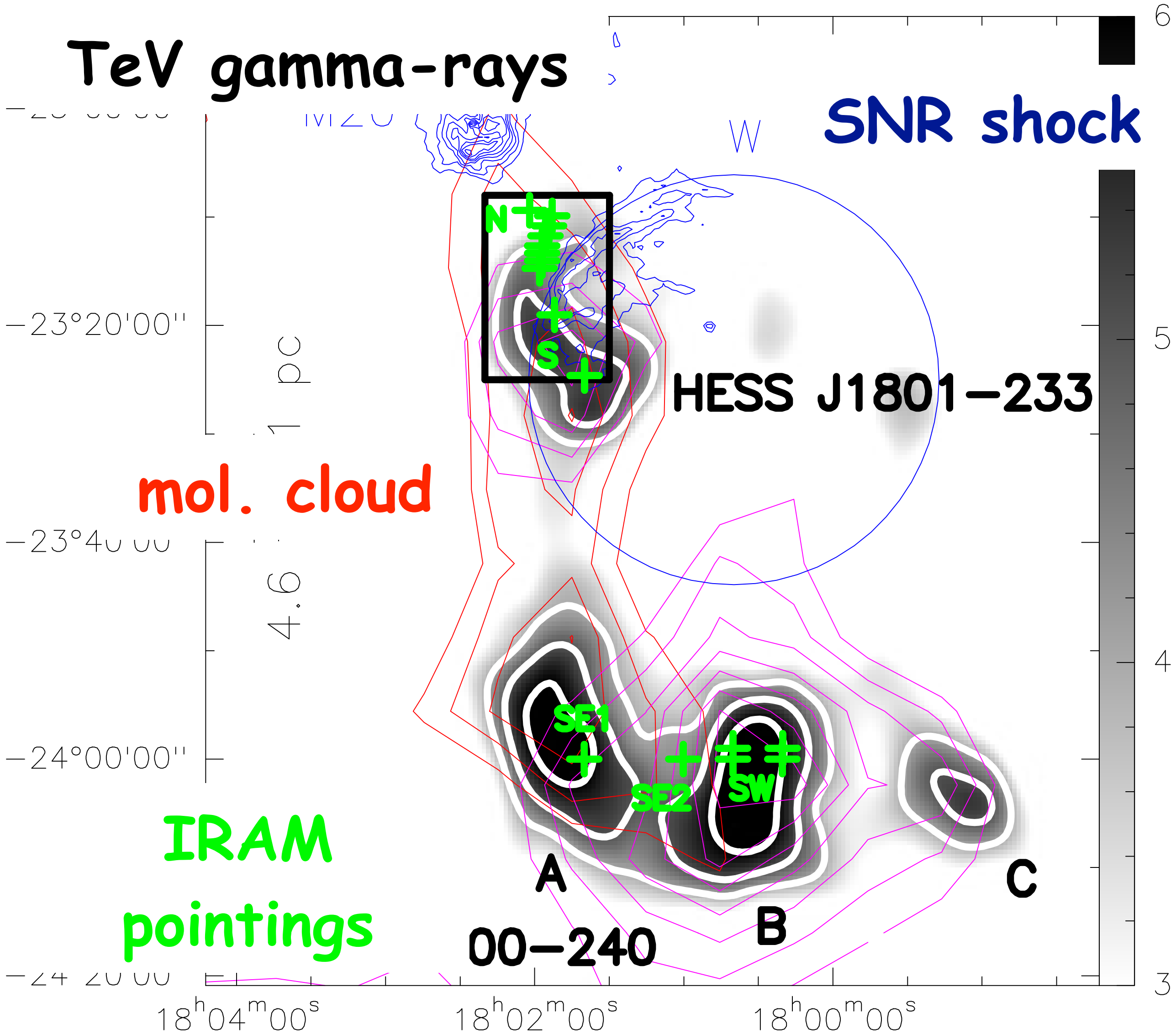

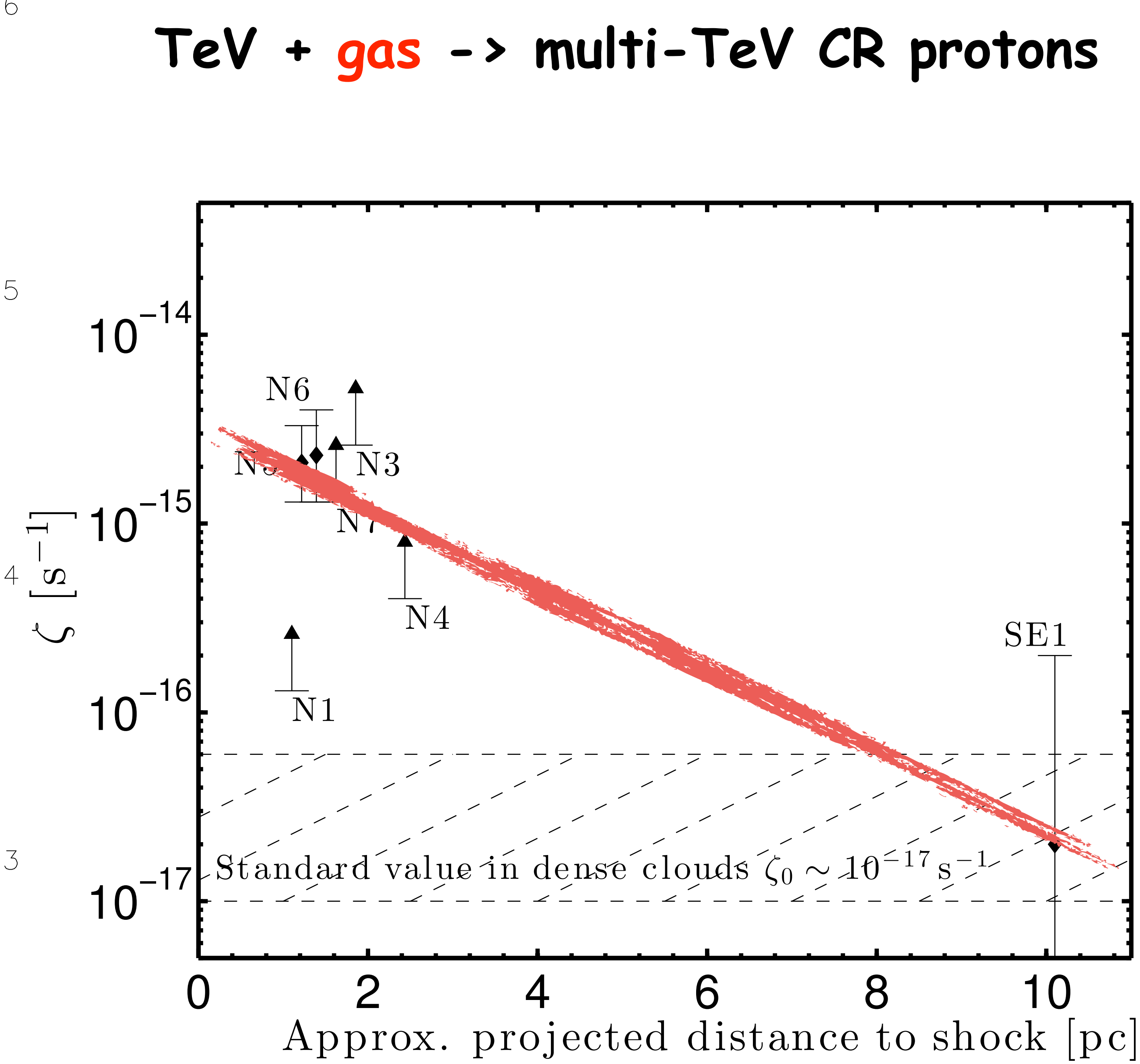

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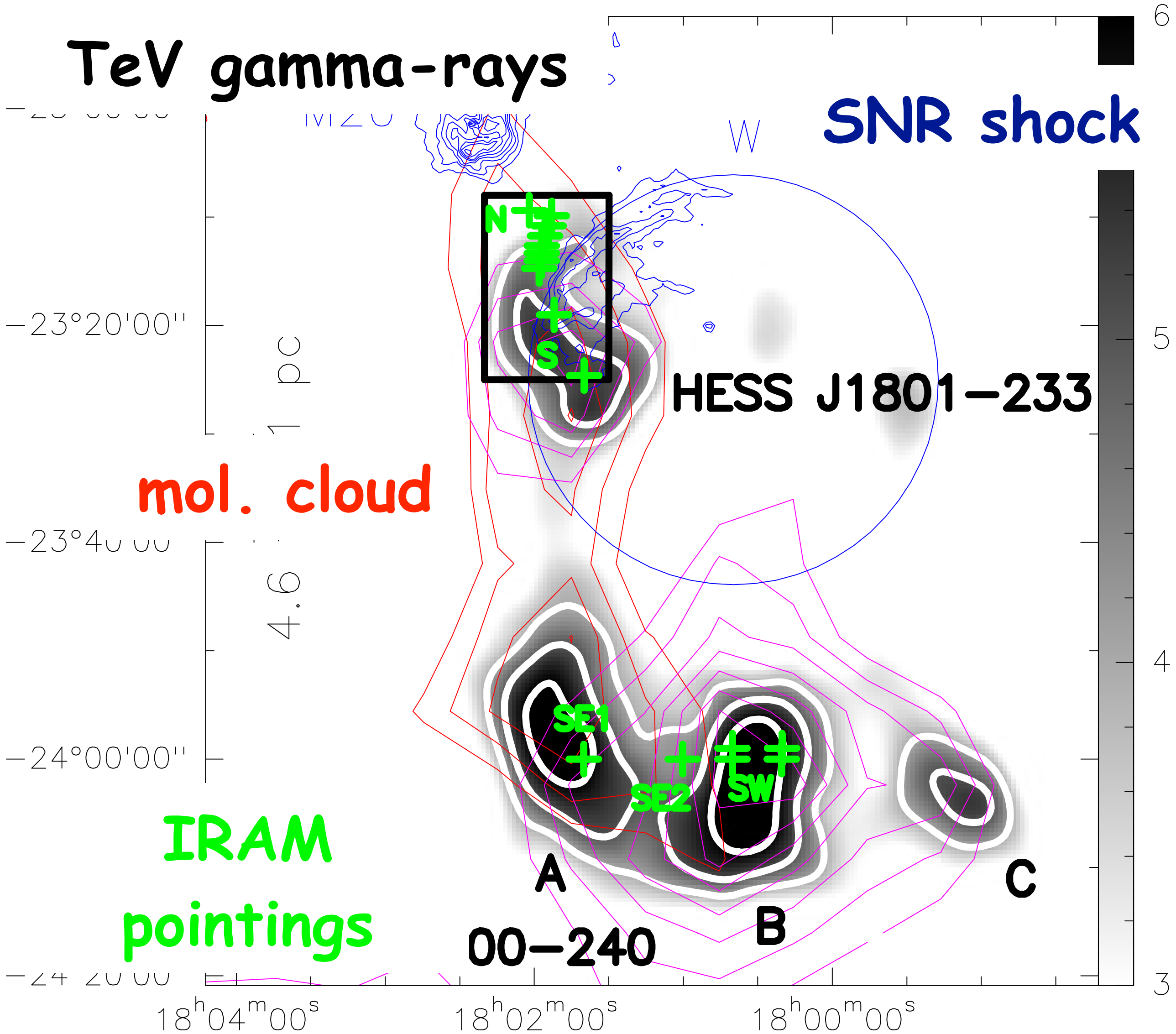
TeV gamma-rays



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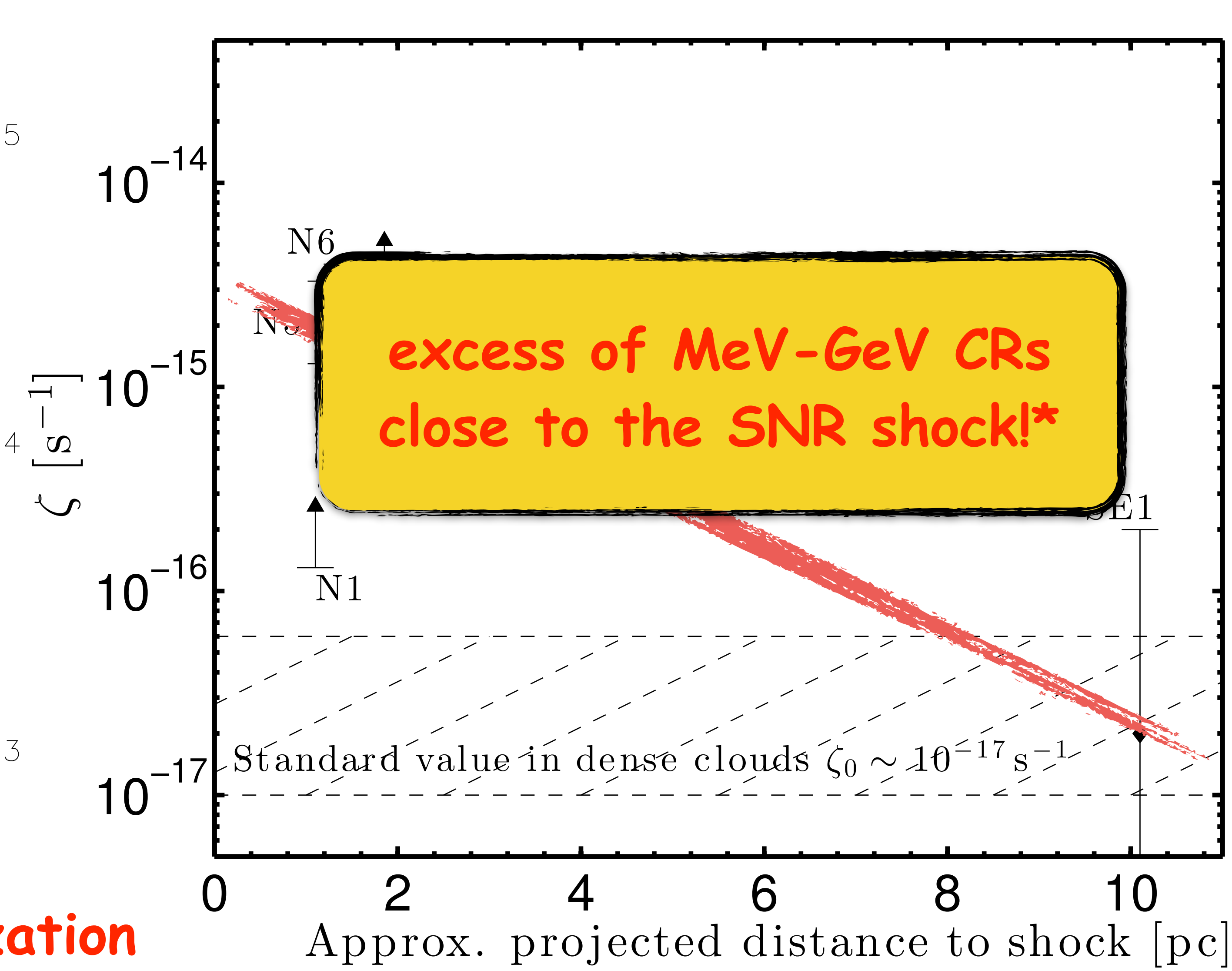

* also CR electrons contribute to ionization

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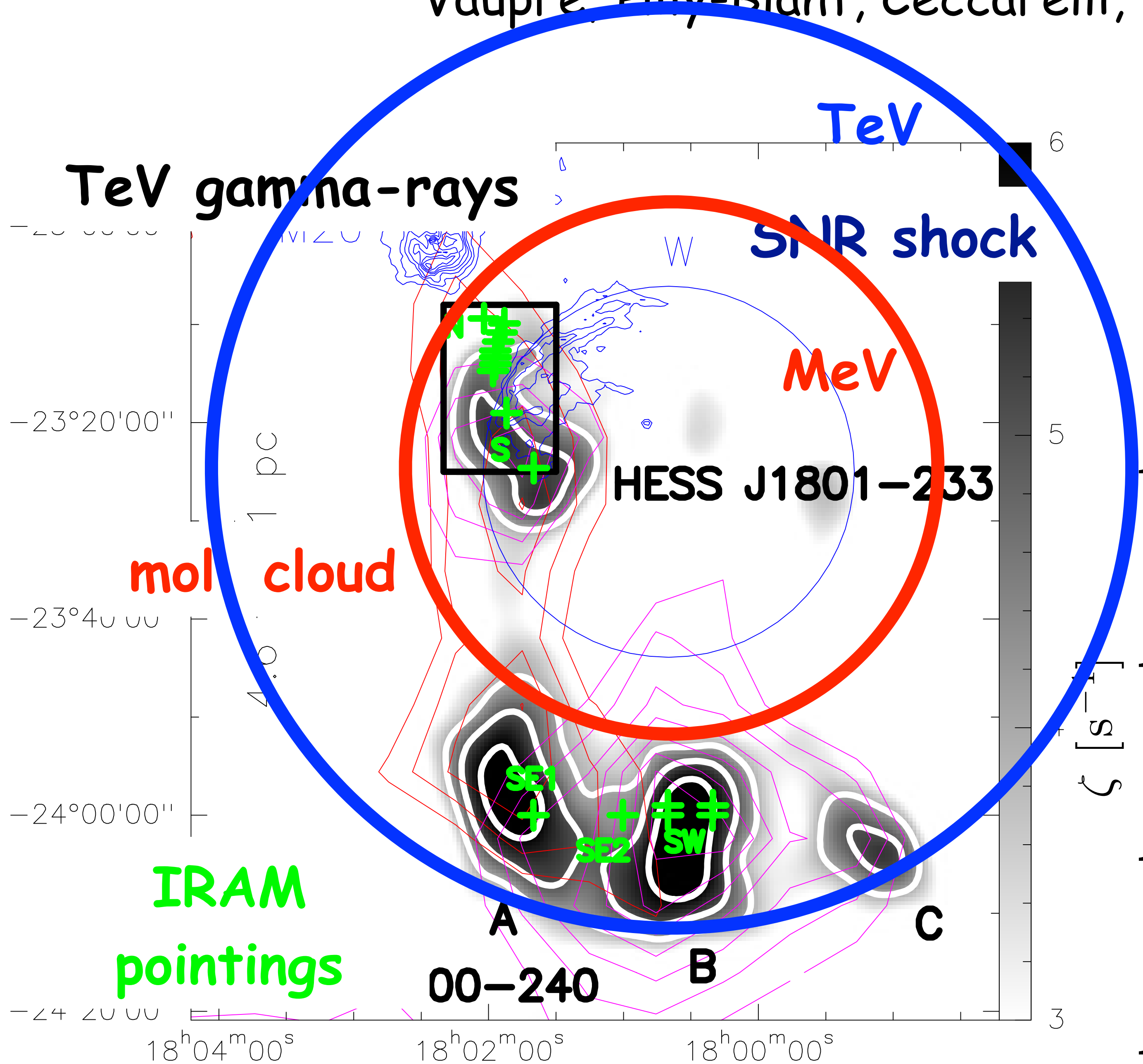

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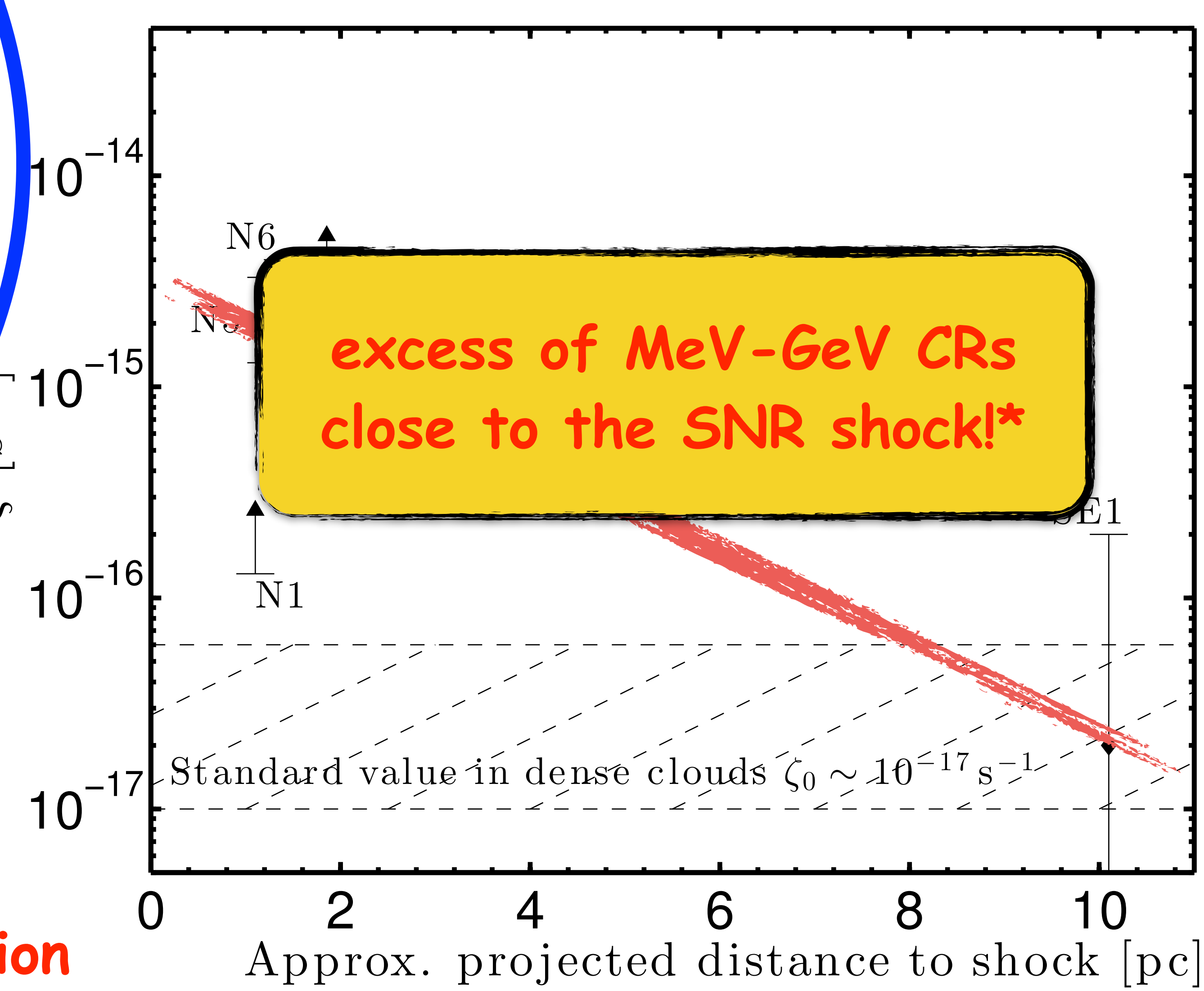

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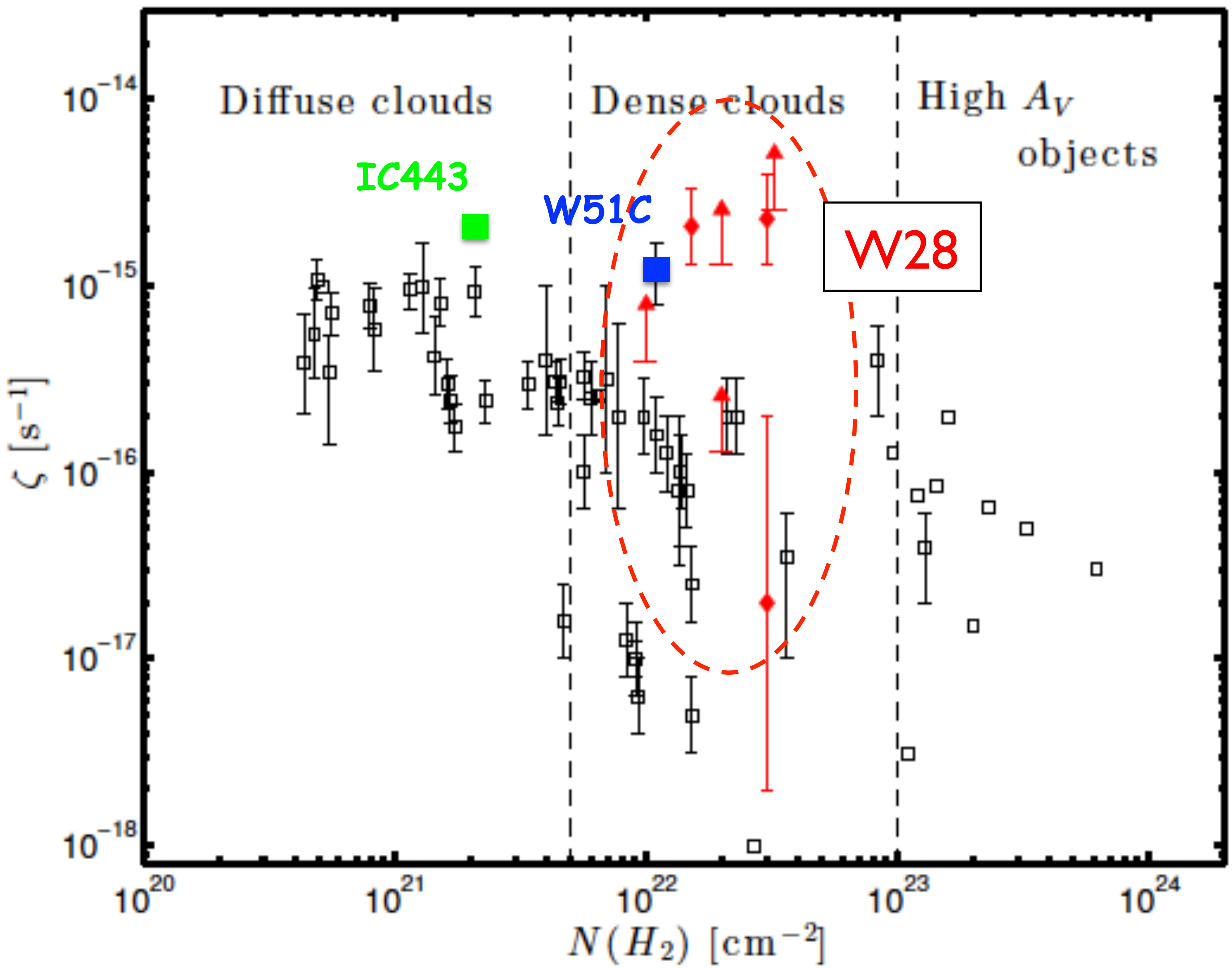
CR ionization: W28, W51C, and IC 443

Vaupré et al 2014 - Ceccarelli et al 2011 - Indriolo et al 2010



Low energy CRs in SNRs

Good things

- finally, observations can constrain the spectrum of CRs well below GeV energies -> getting closer to injection energy

Bad things

- these are integral constraints -> no direct information on the spectral shape
- protons or electrons?

Conclusion

- Molecular clouds are cosmic ray barometers
- We can use them to:
  - enhance the emission from SNRs (interacting systems)
  - indirectly infer the acceleration of hadrons up to PeV (SNR/MC associations)
  - estimate the diffusion coefficient in the vicinity of CR accelerators (SNR/MC associations)
  - probe the ~MeV part of the CR spectrum (ionization)
- Hadronic or leptonic? Not solved yet also for best studied SNRs