Galactic cosmic rays

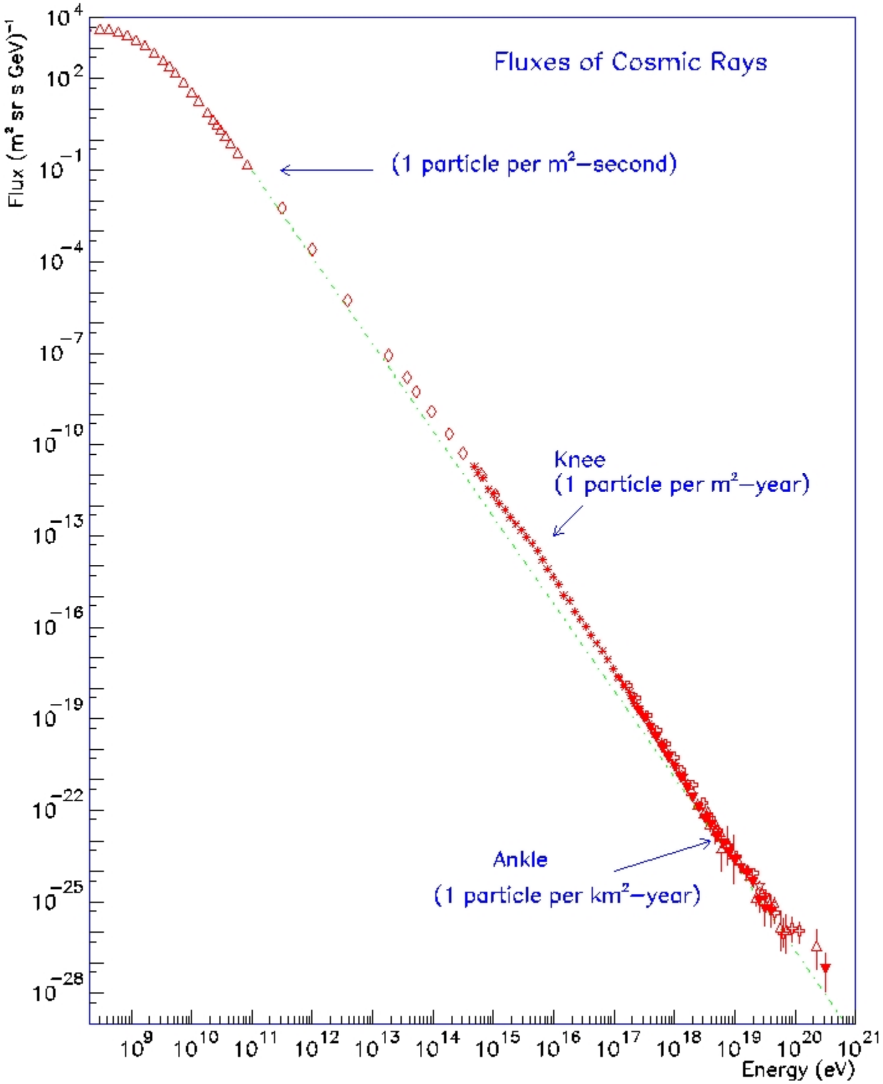
Stefano Gabici
APC, Paris

www.cnrs.fr

Outline of the talk

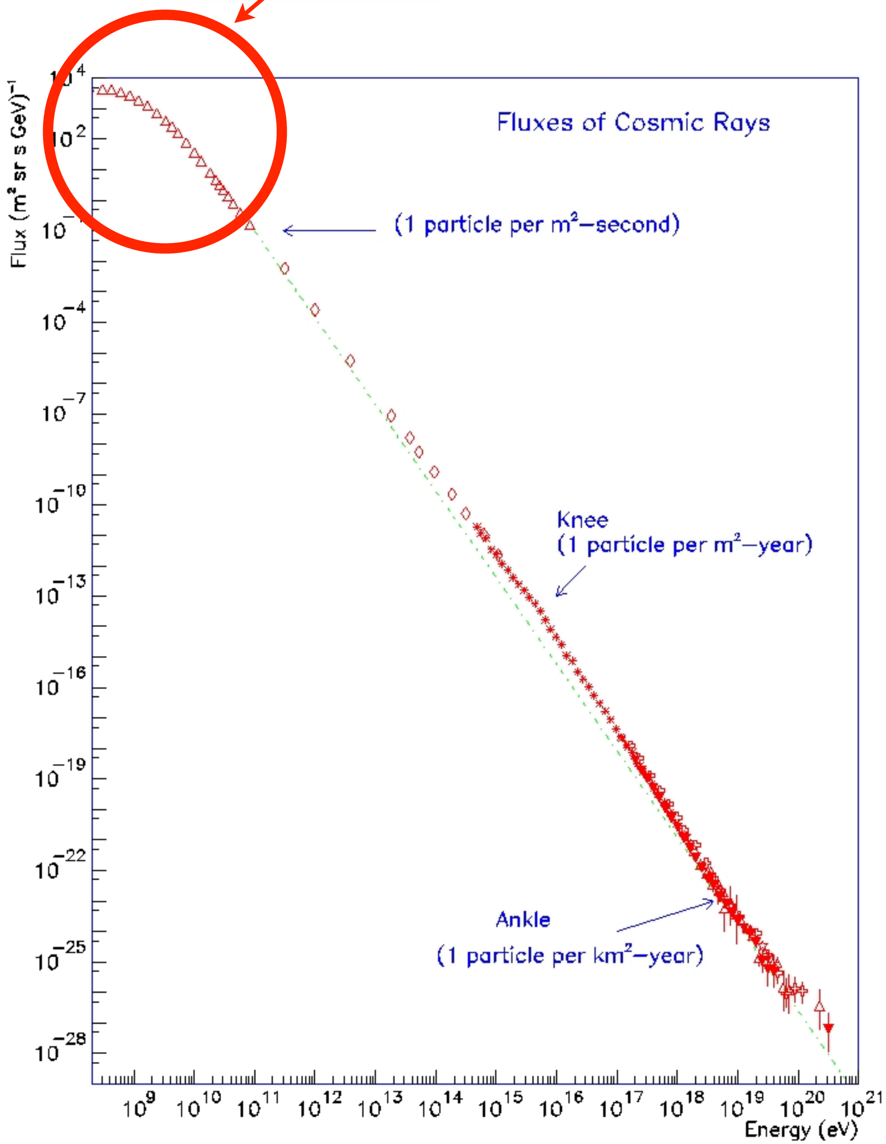
- **The SuperNova Remnant (SNR) paradigm for the origin of Cosmic Rays (CR)**
  - The paradigm: basic ideas
  - Gamma-ray based tests
- **The maximum energy achievable at SNR shocks**
  - Magnetic field amplification at (very?) young SNR shocks
- **The transition between Galactic and extragalactic CRs**
  - various scenarios, second knee, ankle ...
- **(few words) Recent observations that raised a lot of enthusiasm**
  - positrons, breaks in He spectrum ...

Things we have to explain



Things we have to explain

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

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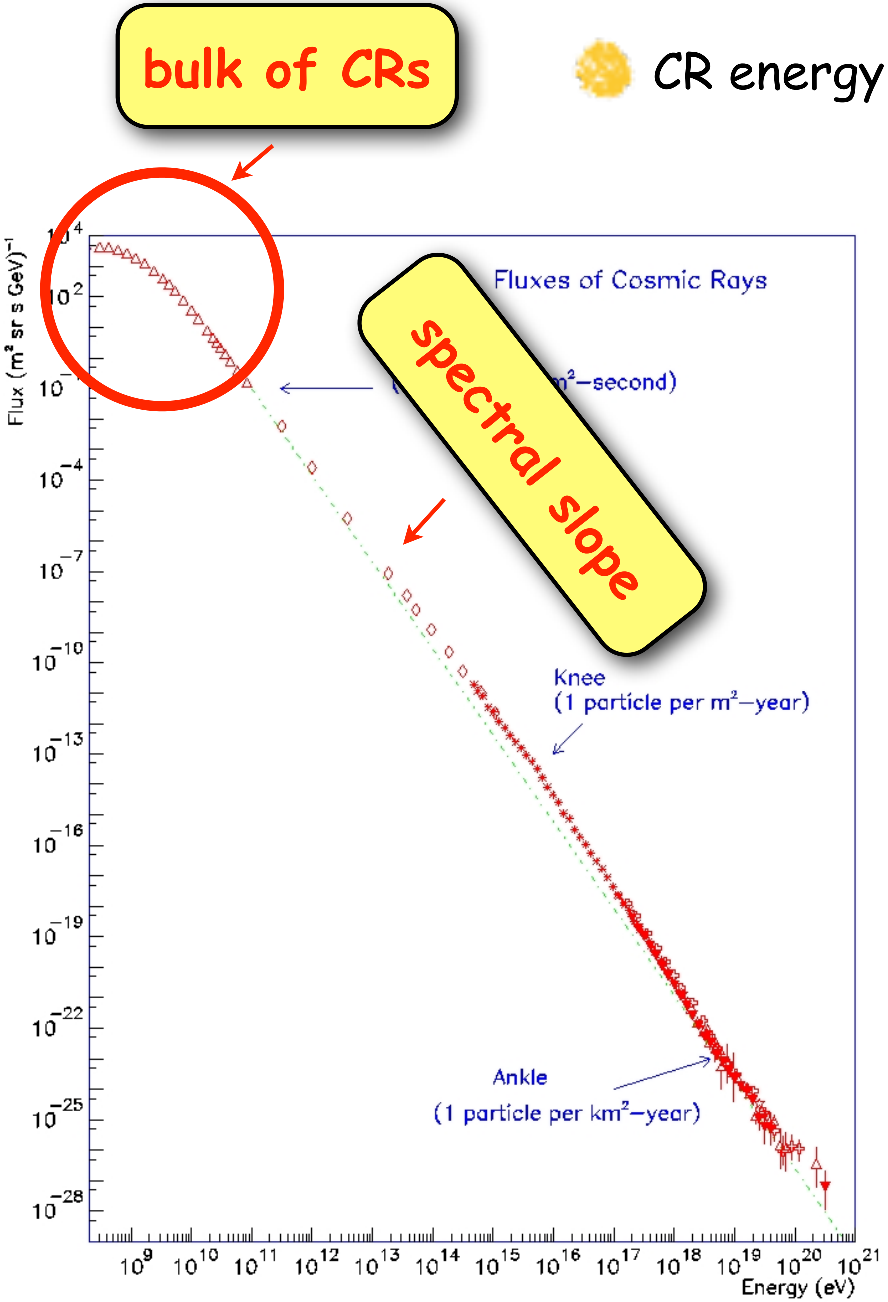

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  + which acceleration mechanism?
  + how is CR propagation affecting this?

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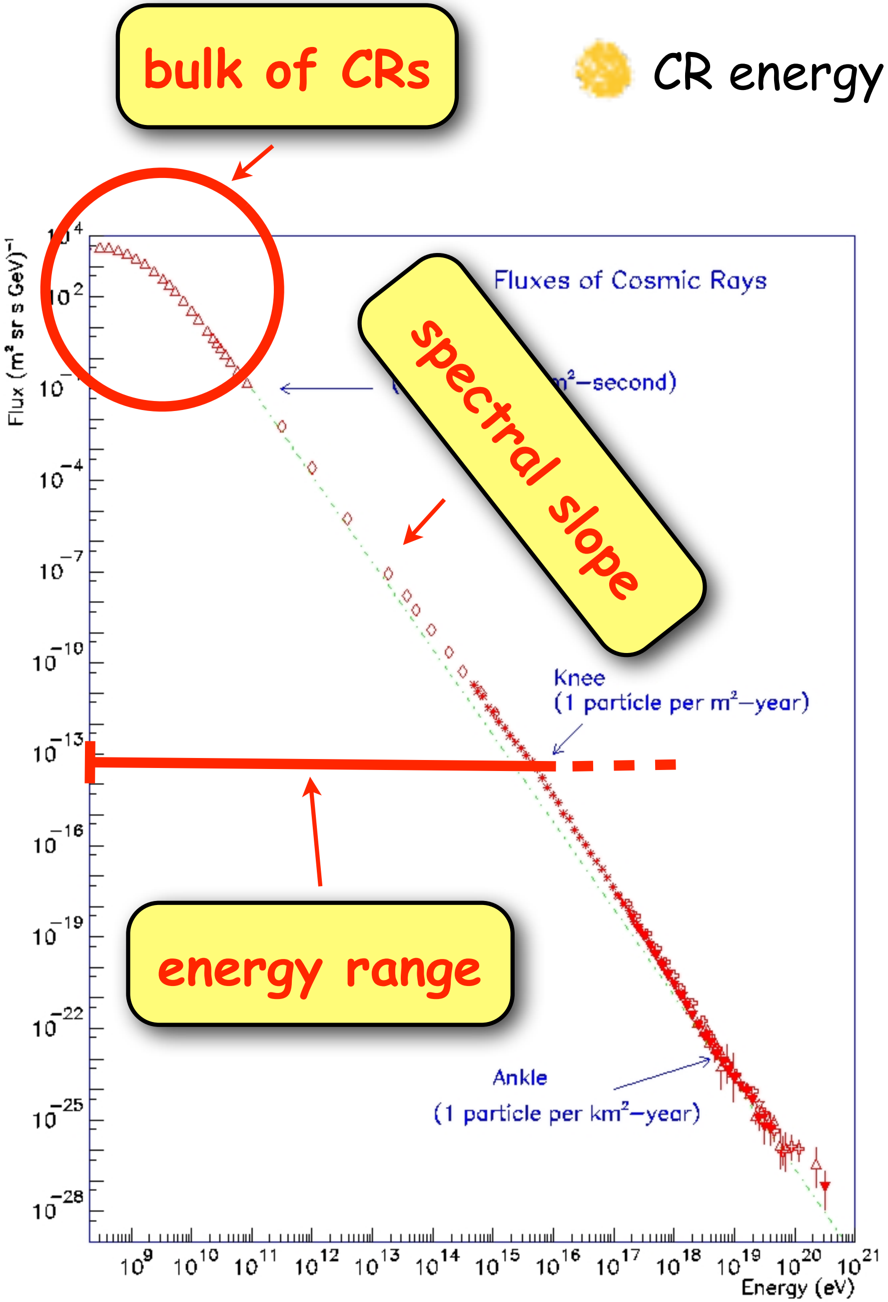

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- energy range

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

  sources must be **PeVatrons**

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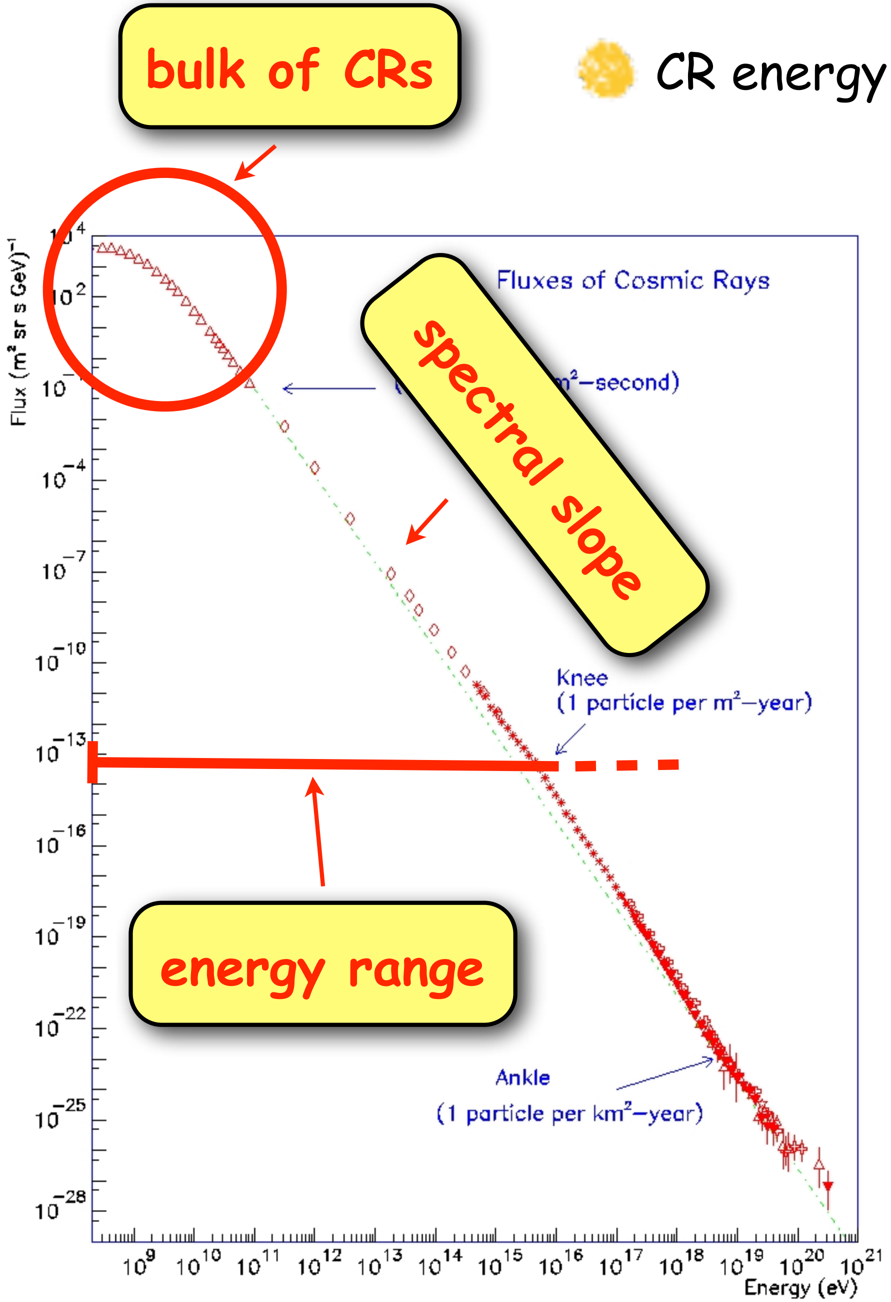

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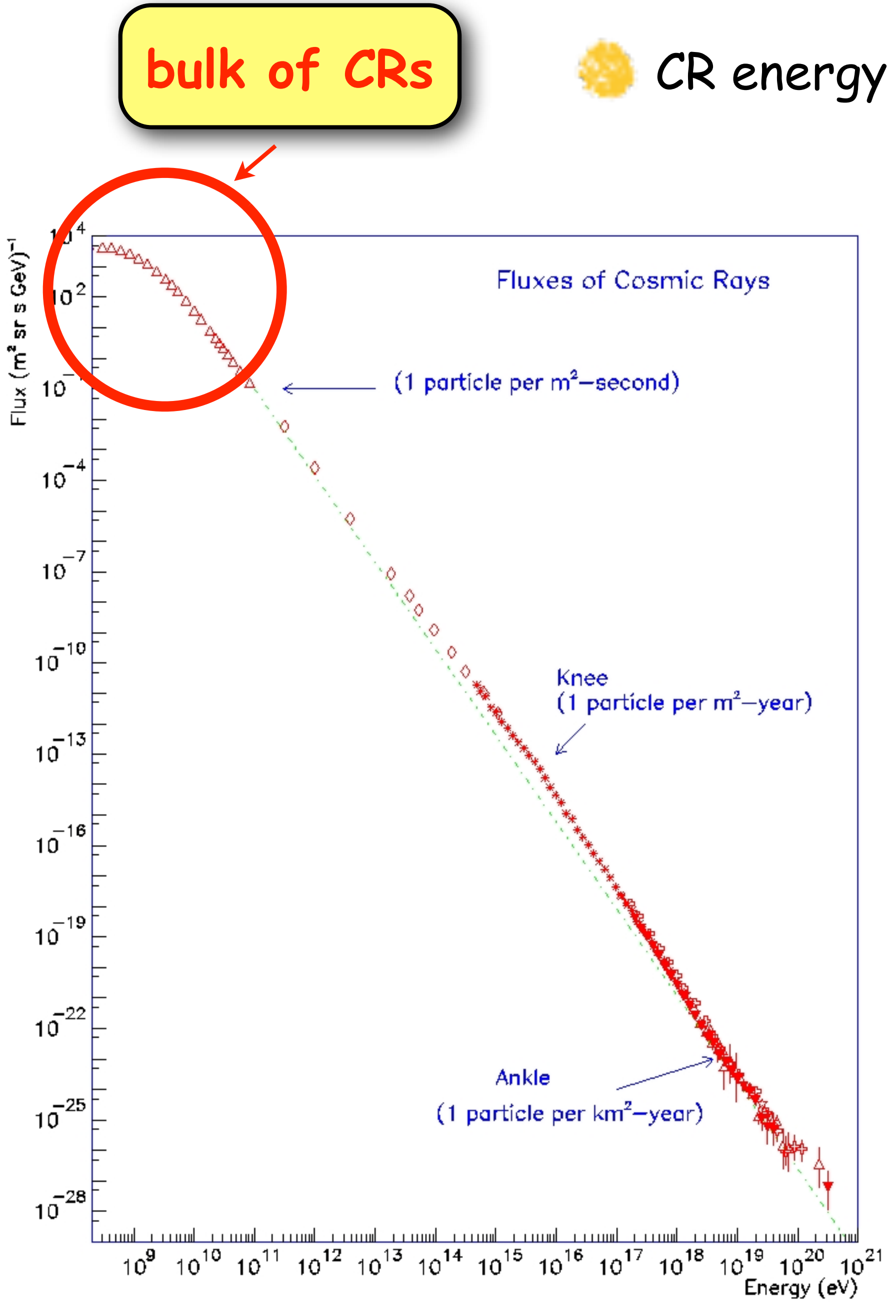
  - sources must be PeVatrons
- more issues -> isotropy & chemical composition

The SuperNova Remnant hypothesis



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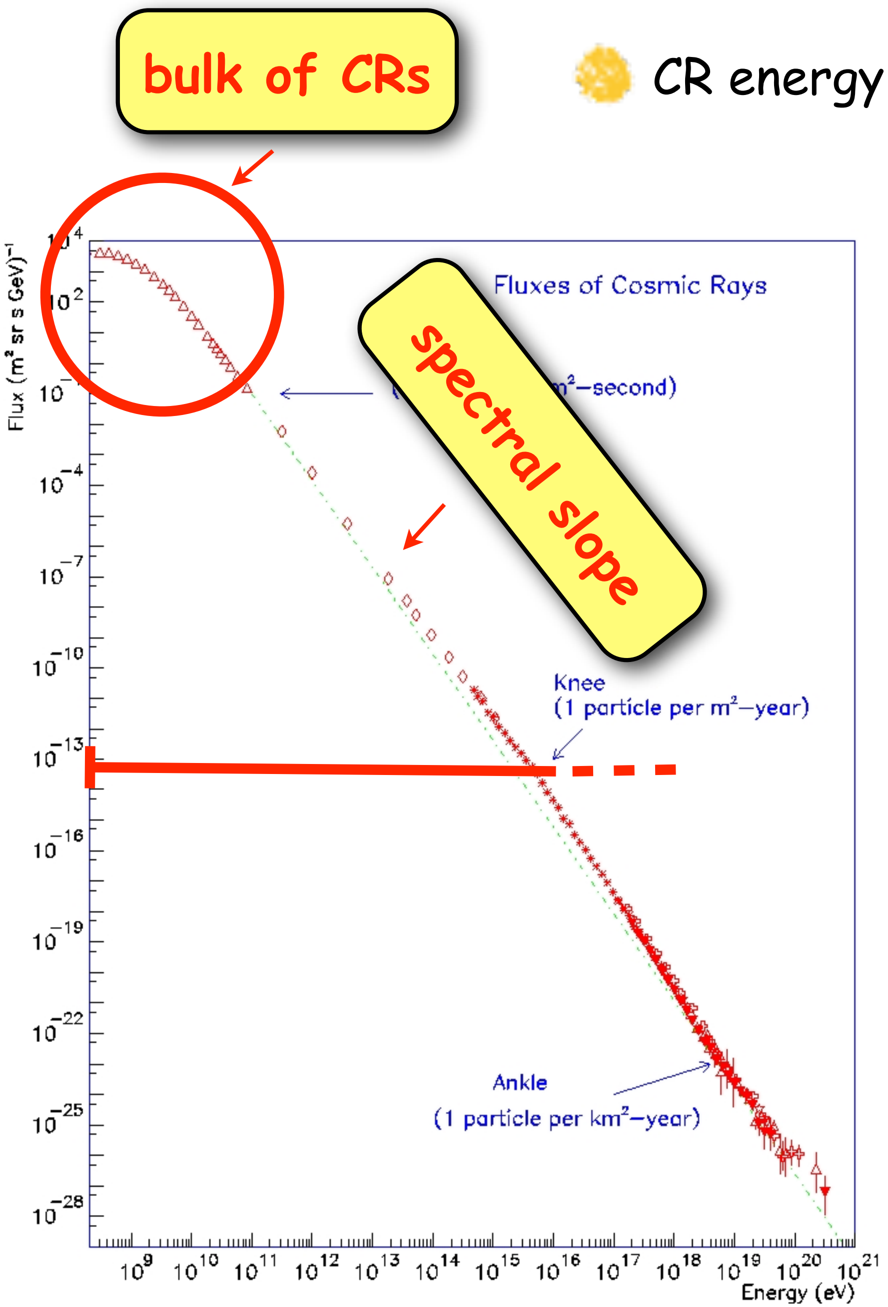

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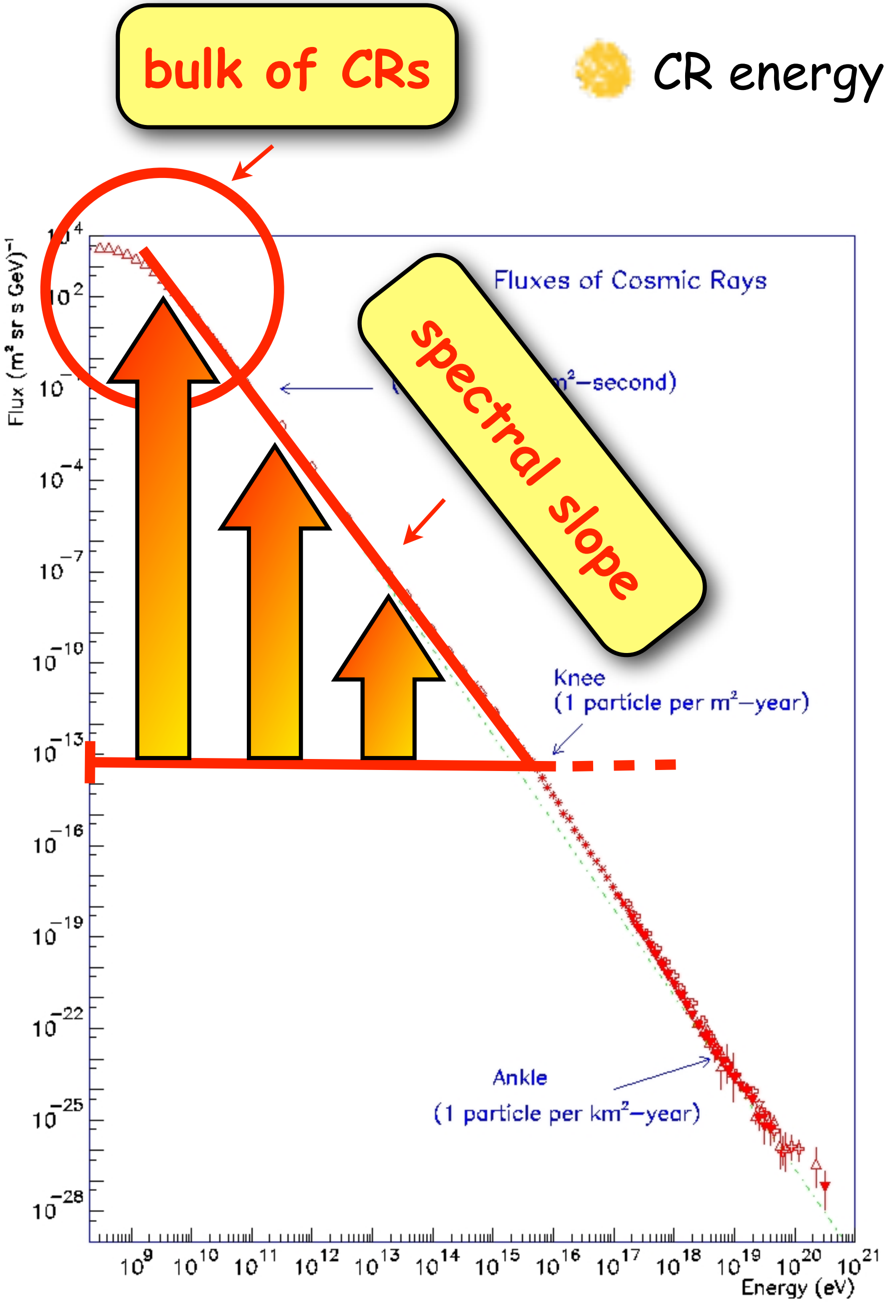

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+ isotropy...

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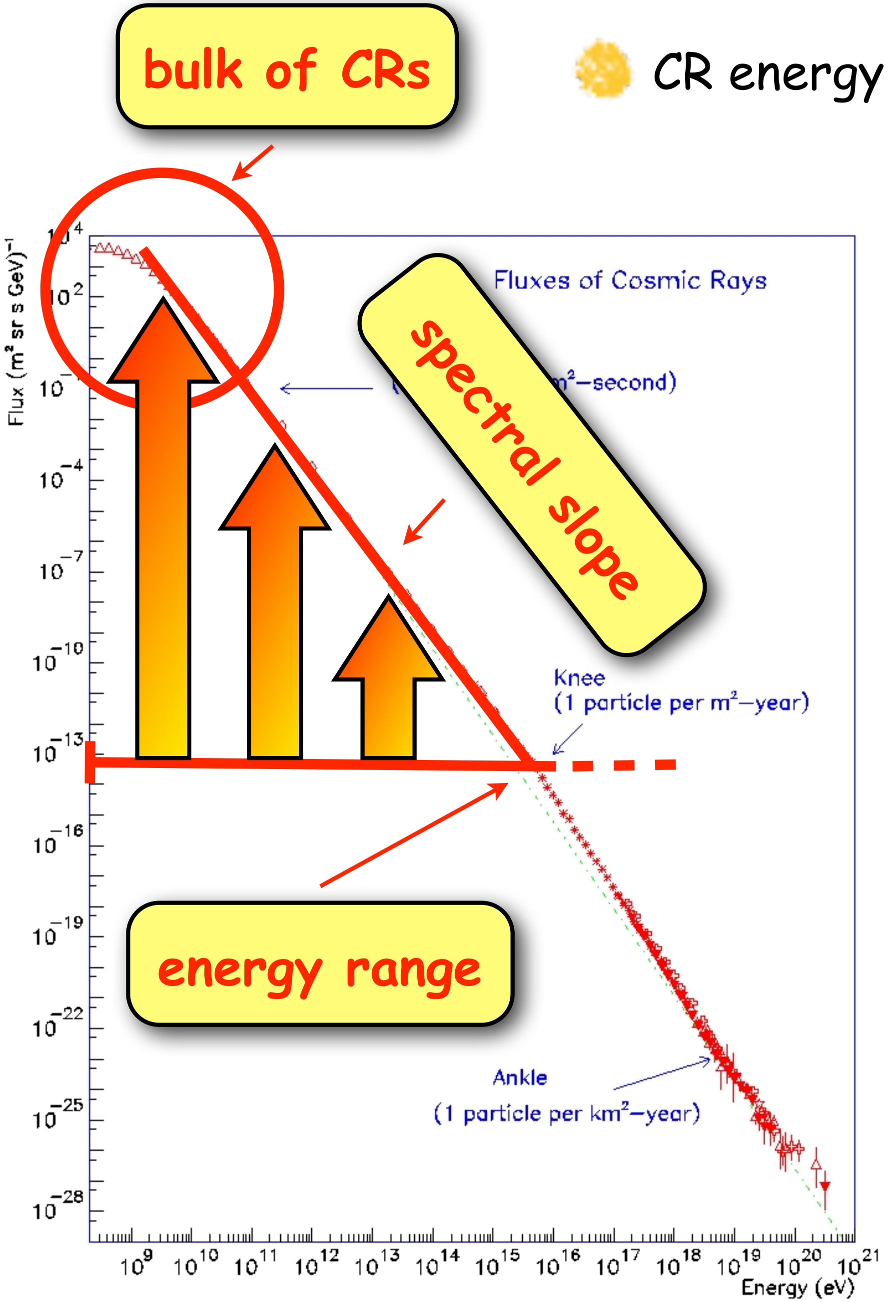

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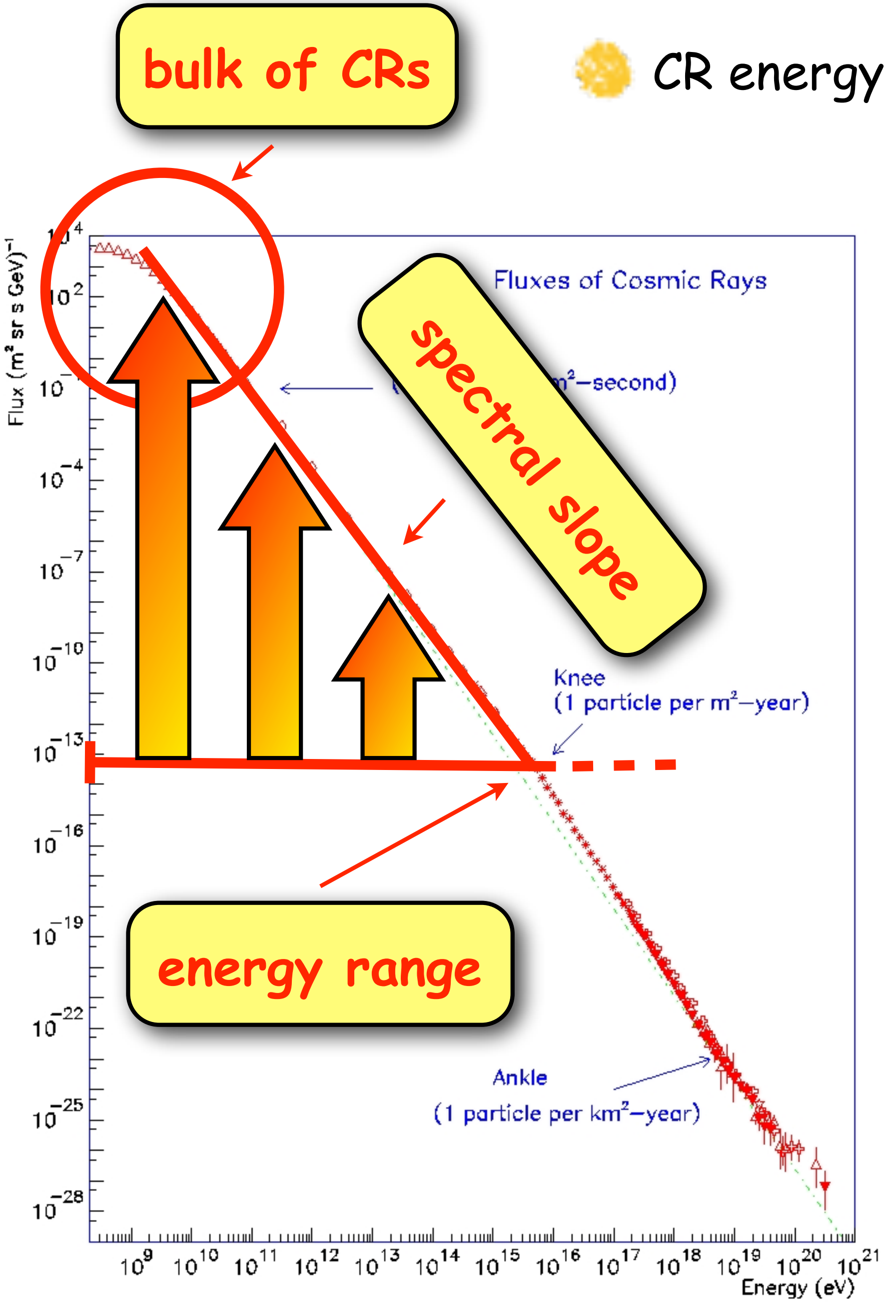

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acceleration

propagation

diffusion

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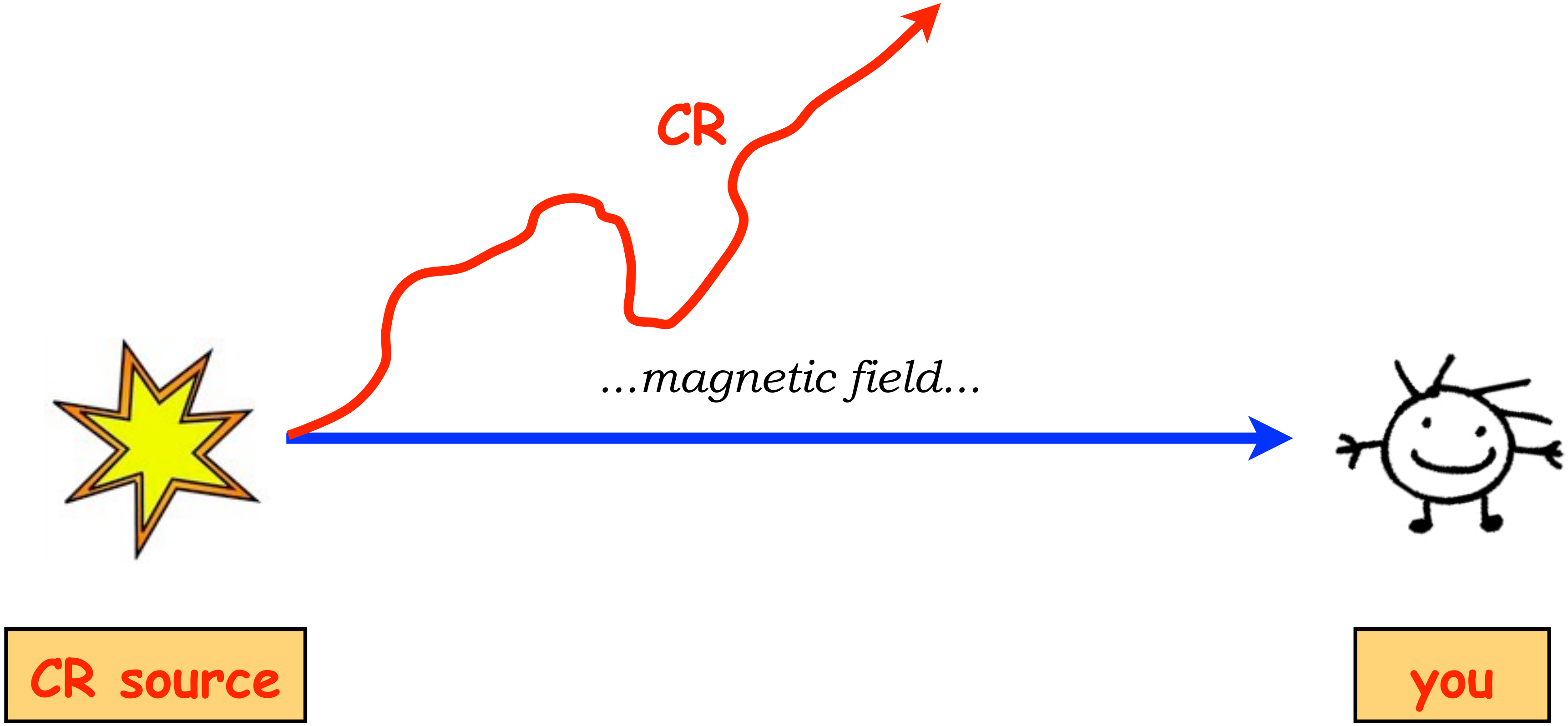
Cosmic ray sources: why is it so difficult?



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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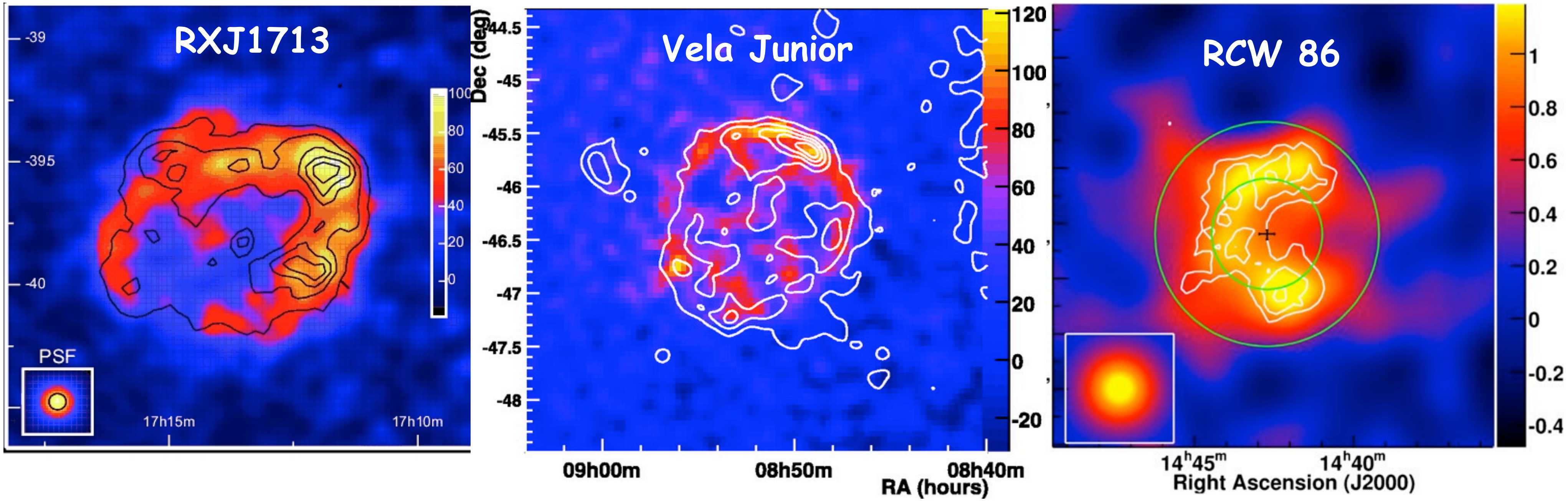

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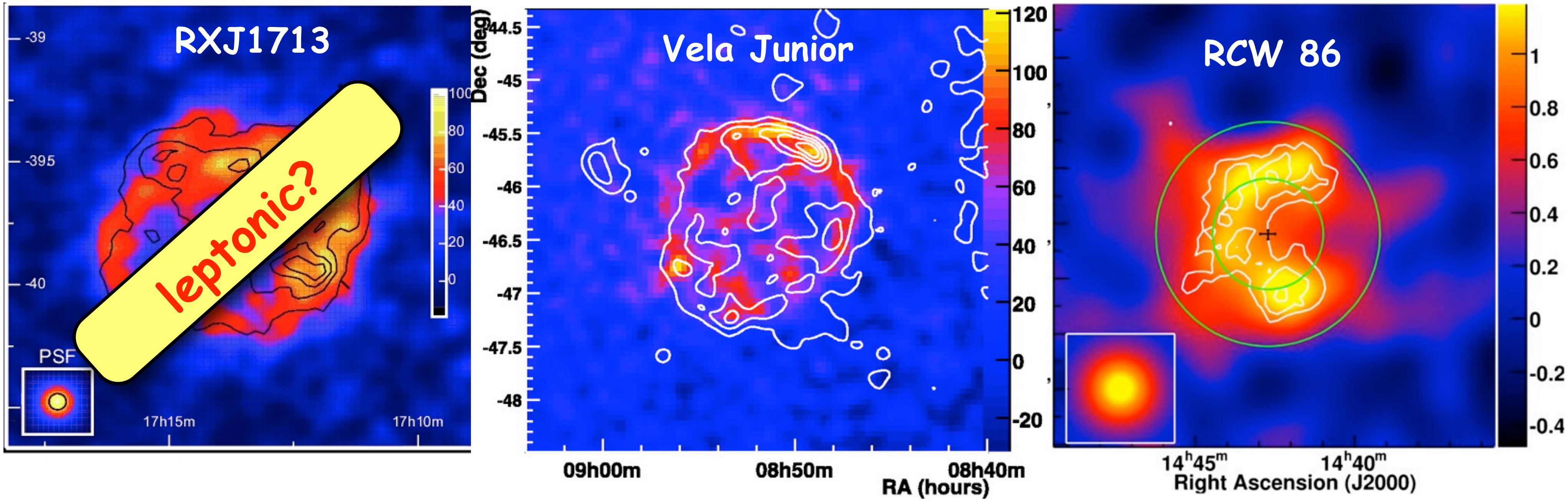
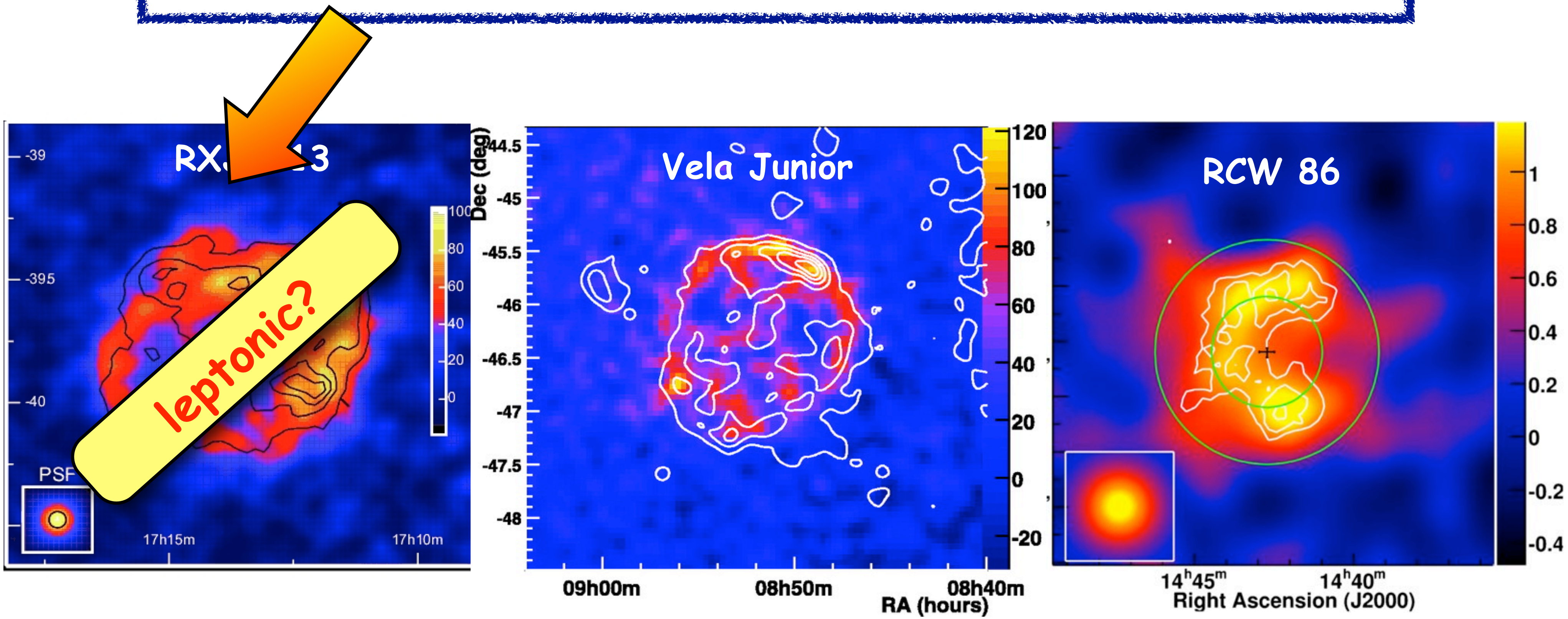


Gamma rays from SNRs: a test for CR origin

Drury, Aharonian & Volk, 1994

this does **NOT** mean that RXJ1713 is not accelerating CRs!
If the ambient gas density is low we can still accommodate up to ~30% of the total SN energy into CRs without significant hadronic emission.



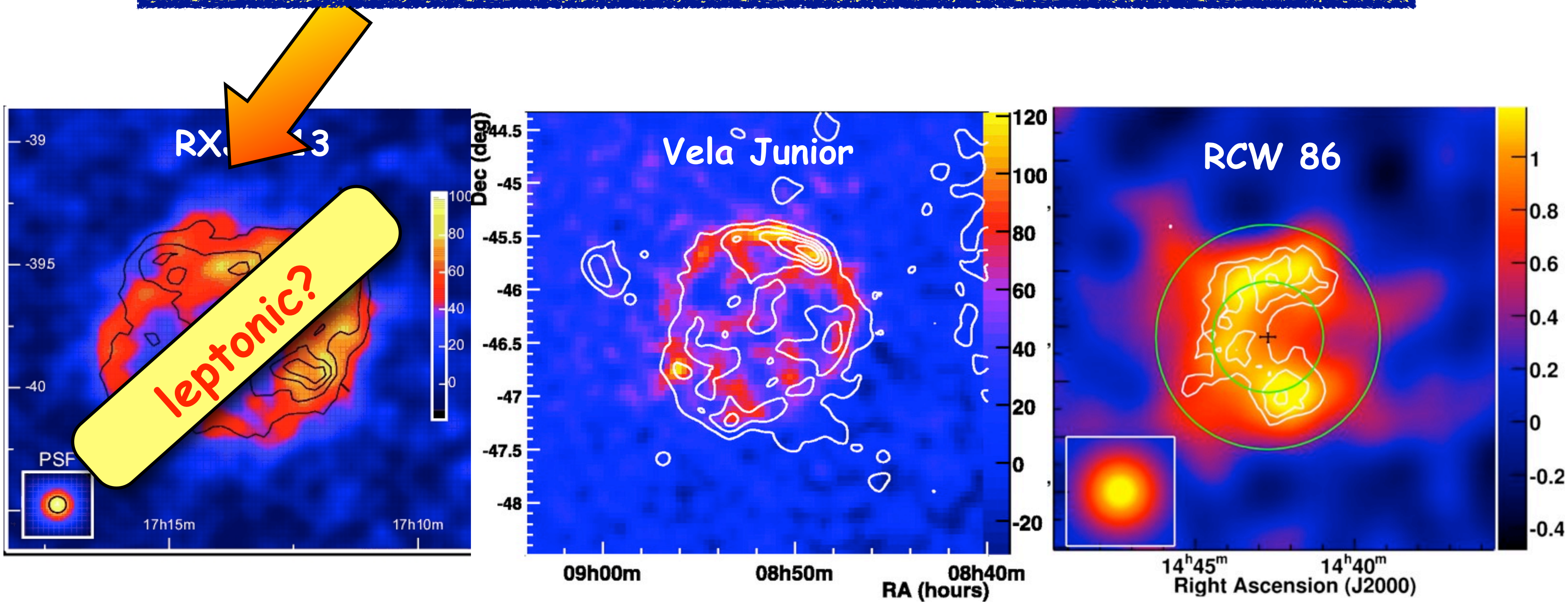
Gamma rays from SNRs: a test for CR origin

Drury, Aharonian & Volk, 1994

we need an unambiguous proof for CR acceleration

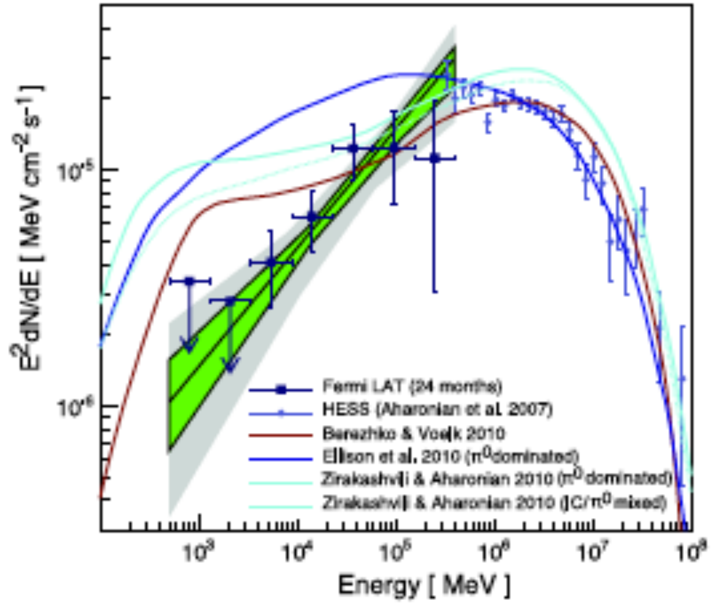
neutrinos are the candidates, but their detection is challenging

-> other gamma-ray based tests?



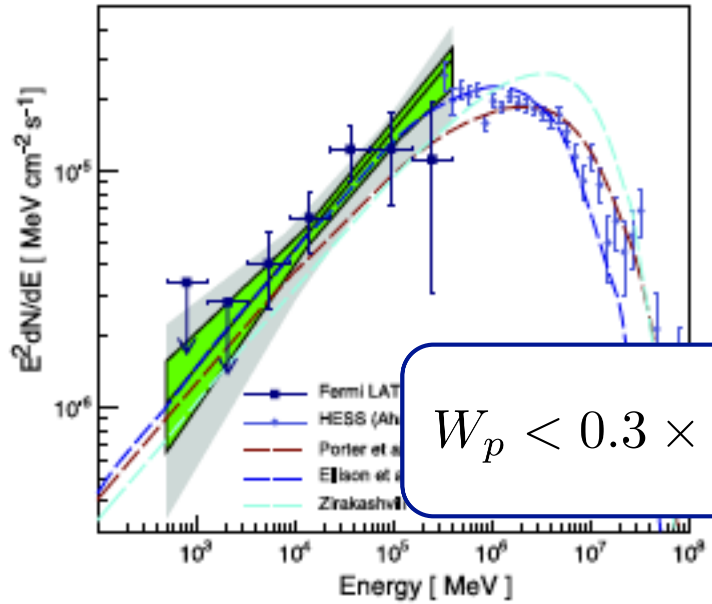
FERMI detects RX J1713

p-p interactions ->



the emission is most likely LEPTONIC

inverse Compton ->



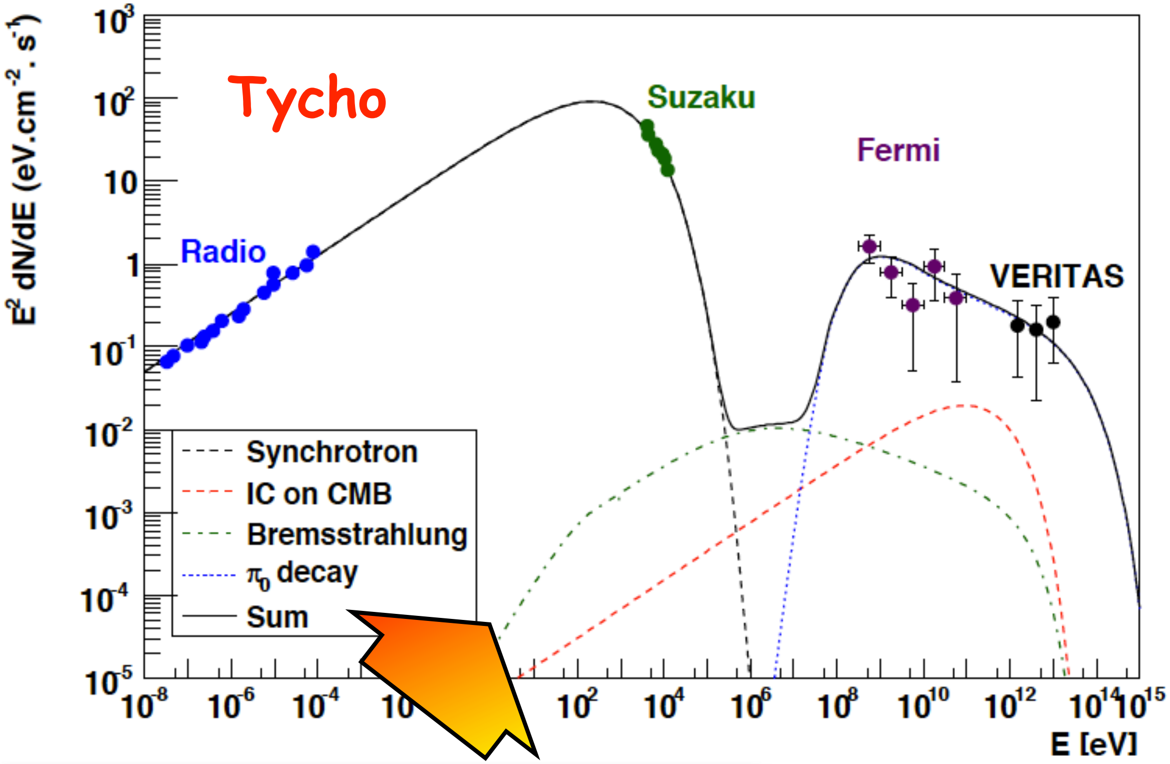
this does NOT mean that there are no protons!!!

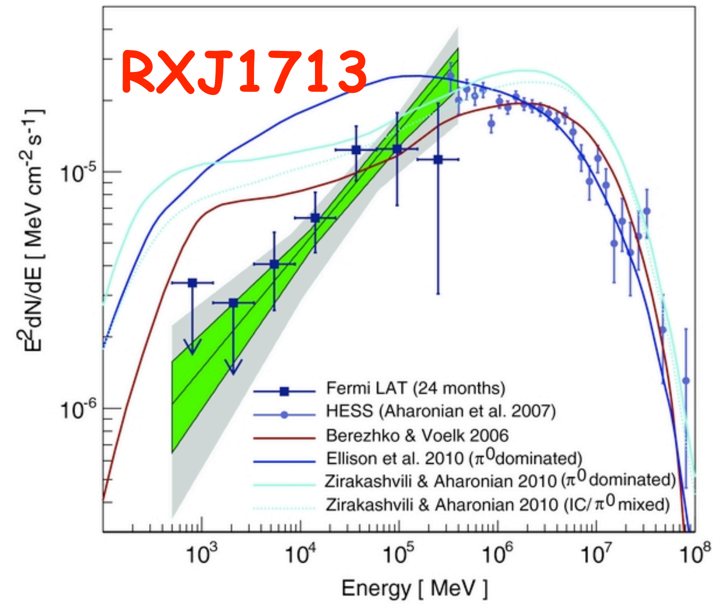
$$W_p < 0.3 \times 10^{51} \left(\frac{n}{0.1 \text{ cm}^{-3})} \right)^{-1} \text{erg}$$

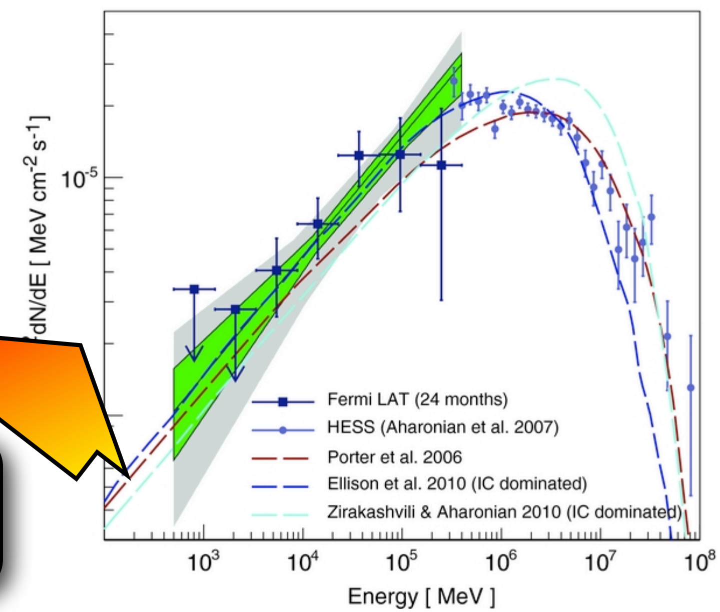
Abdo et al, 2011

Gamma rays from SNRs

(Giordano et al 2011, Morlino&Caprioli 2012)







(Abdo et al 2010)

steep (2.3) -> hadronic?

hard (1.5) -> leptonic?

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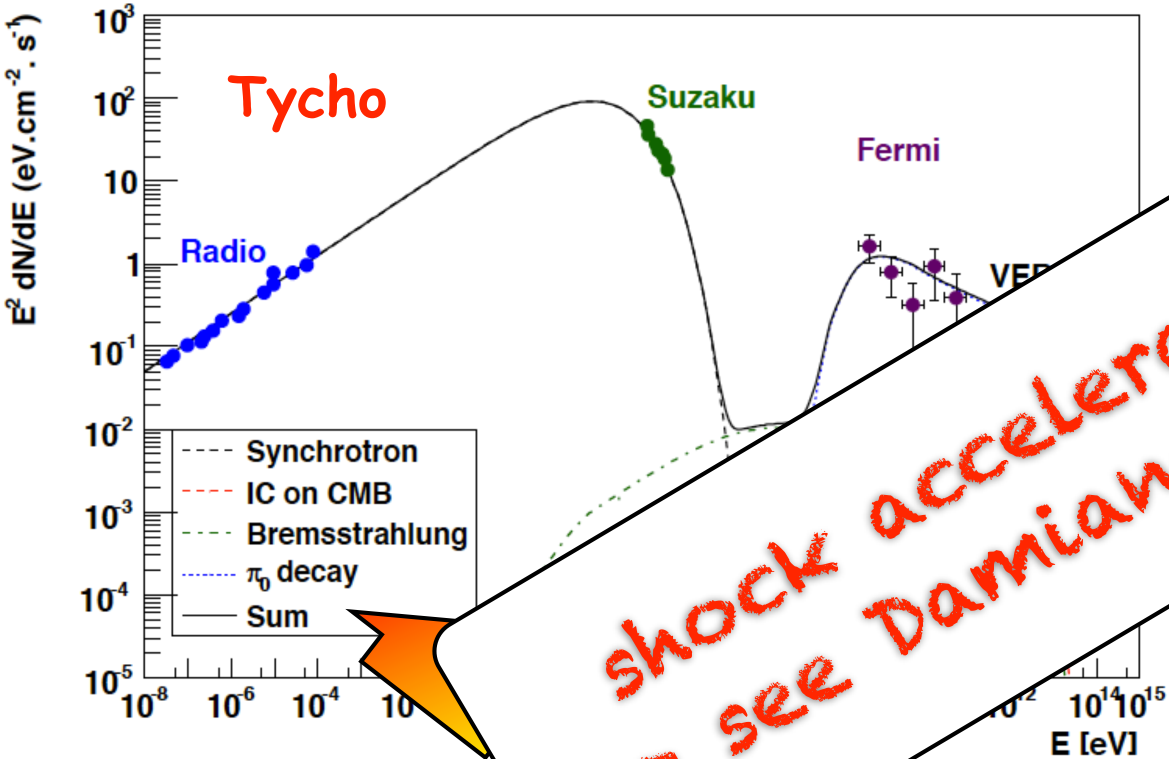
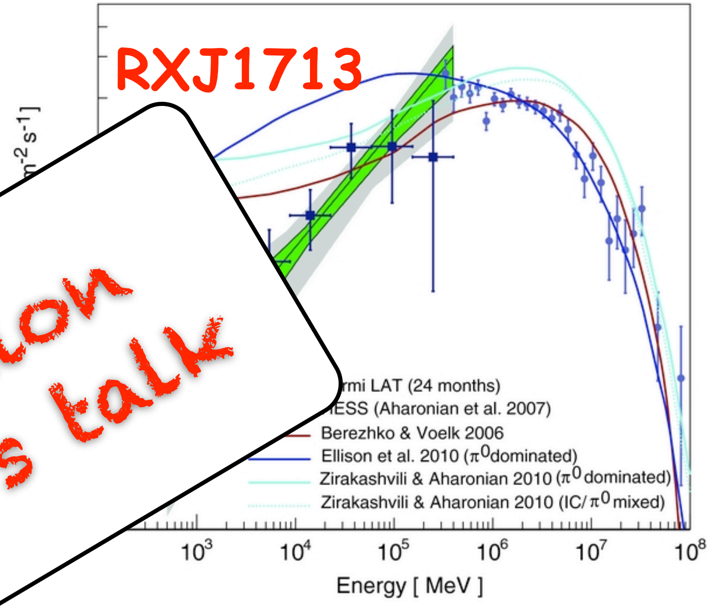
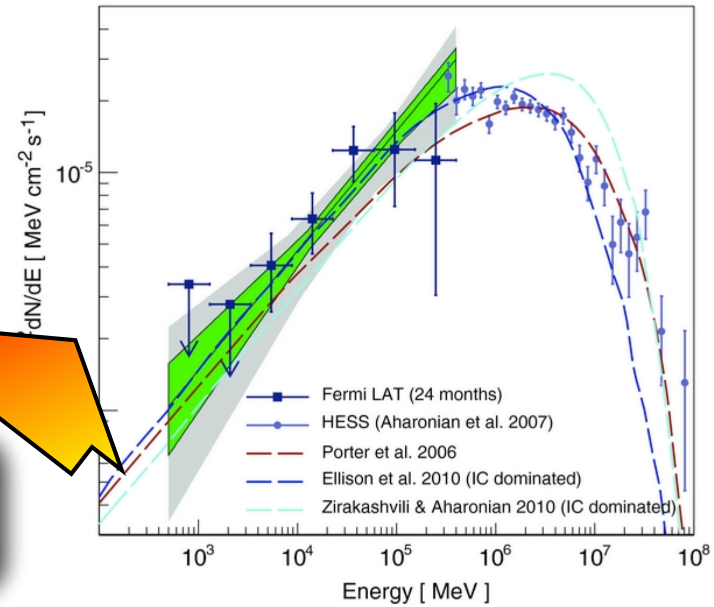






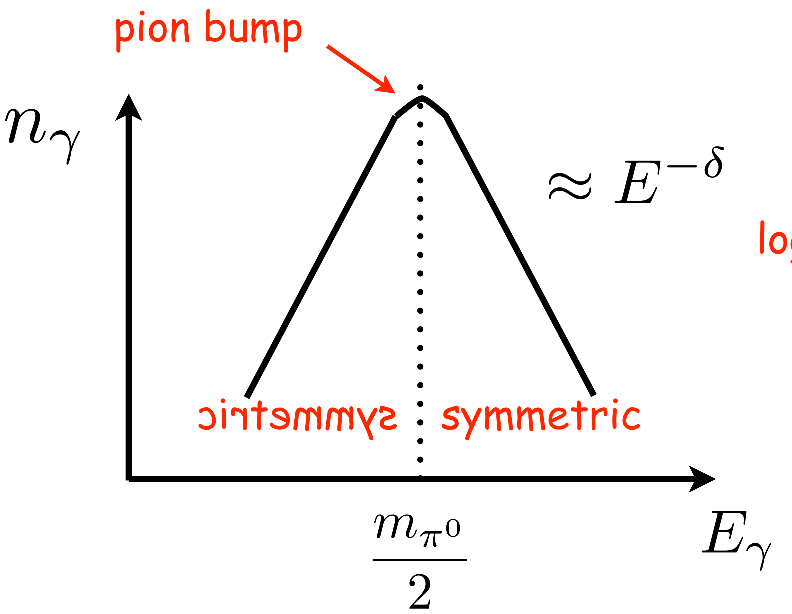
(Abdo et al 2010)

shock acceleration
-> see Damiano's talk

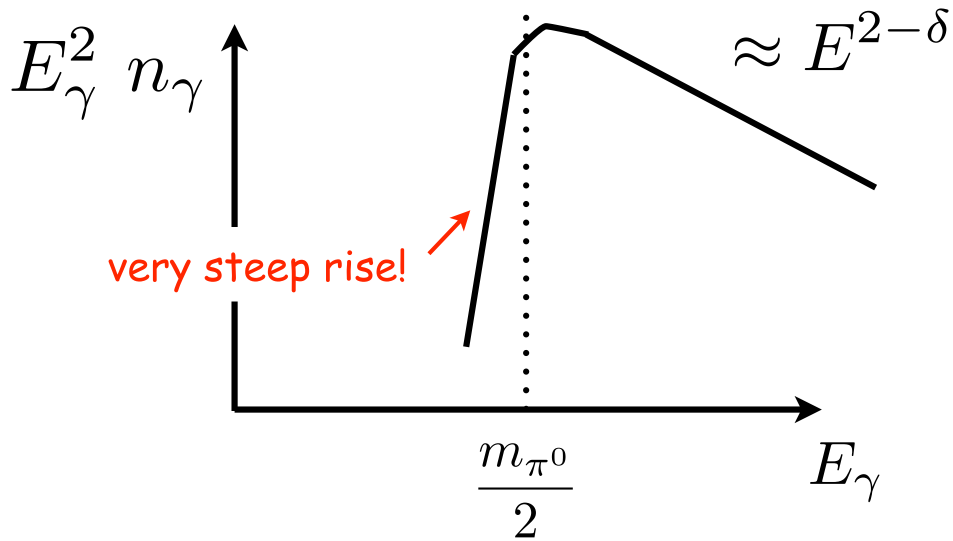
steep (2.3) -> ha

hard (1.5) -> leptonic?

Hadronic gamma-rays from old (~10^4yr) SNRs



log scale!



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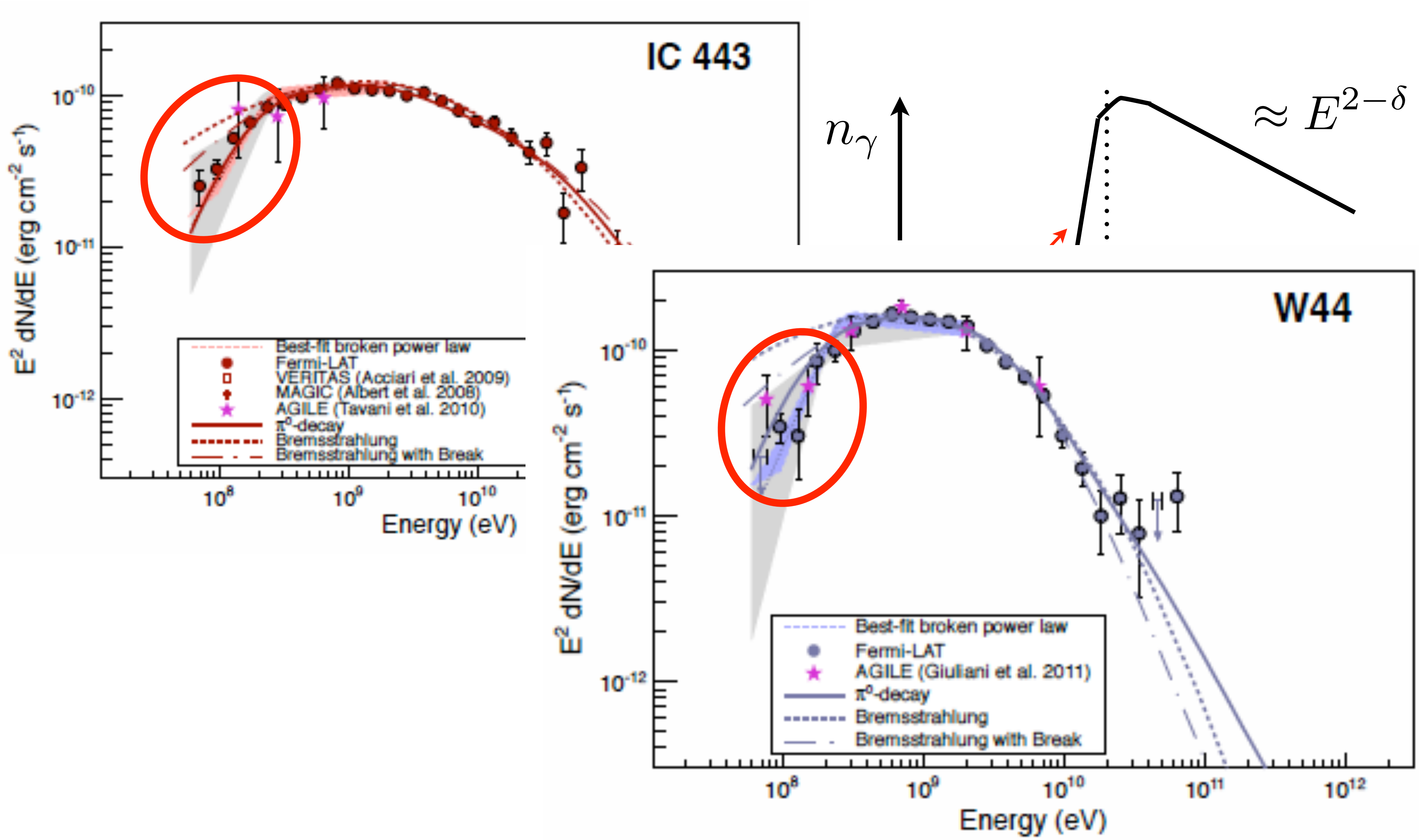
(Ackermann et al 2013)



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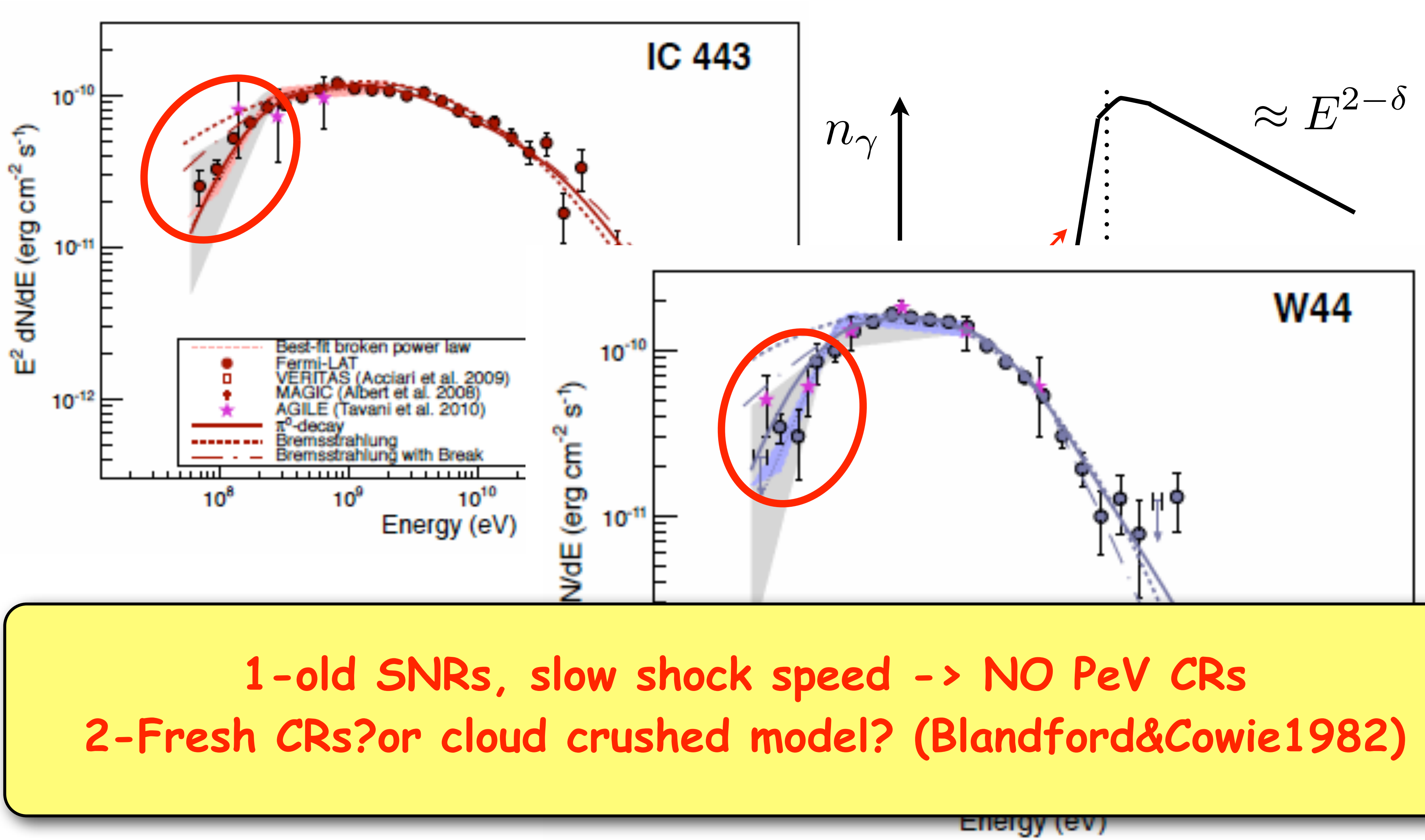

1-old SNRs, slow shock speed -> NO PeV CRs

2-Fresh CRs?or cloud crushed model? (Blandford&Cowie1982)

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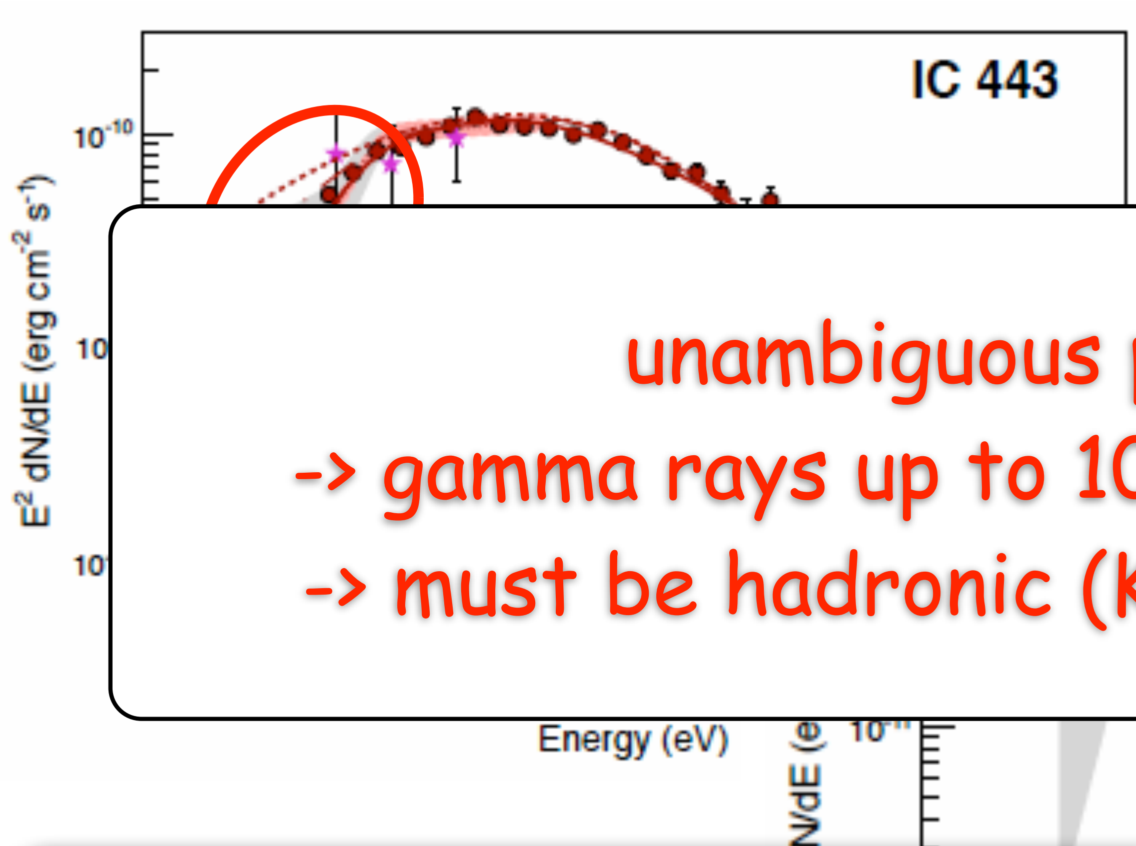
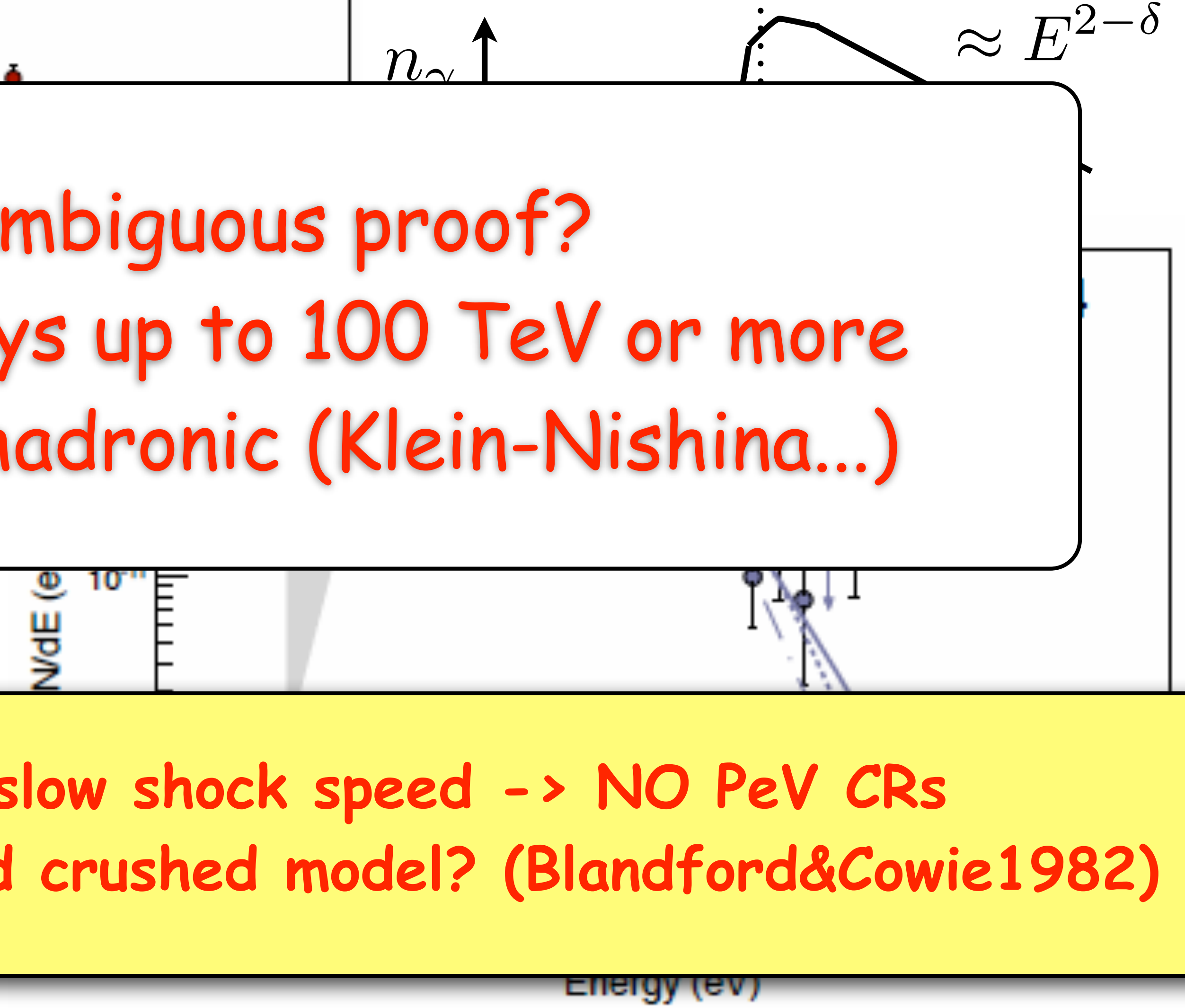




unambiguous proof?

-> gamma rays up to 100 TeV or more

-> must be hadronic (Klein-Nishina...)

1-old SNRs, slow shock speed -> NO PeV CRs

2-Fresh CRs?or cloud crushed model? (Blandford&Cowie1982)

How many SNRs should we see at TeV energies?

Towards population studies of SNRs in very high energy gamma rays

Cristofari et al. 2013

Description of the simulation

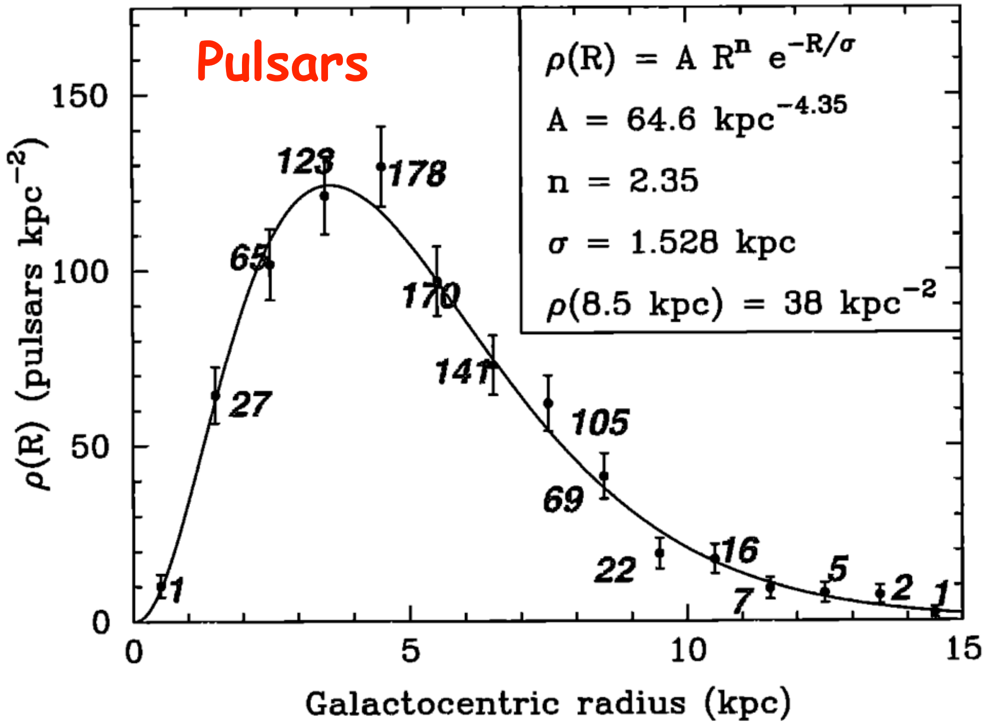
Cristofari et al. 2013

3 SN/century in the MW

-> where and when?

-> core-collapse or thermonuclear

Spatial distribution of SNRs in the MW



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(or Case & Battacharya 1998)

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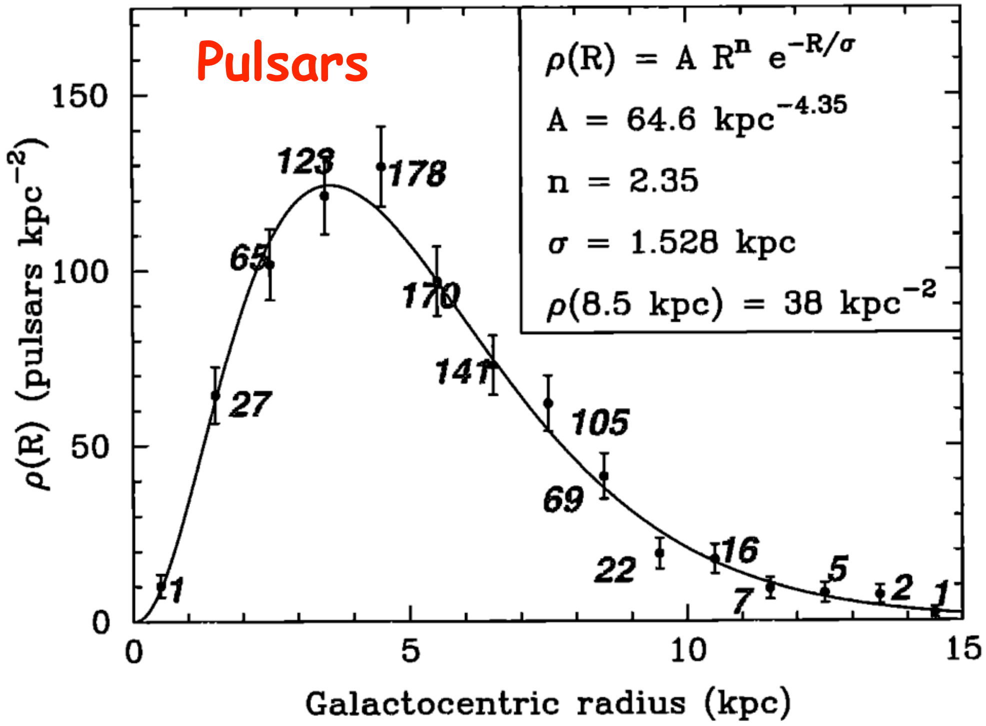

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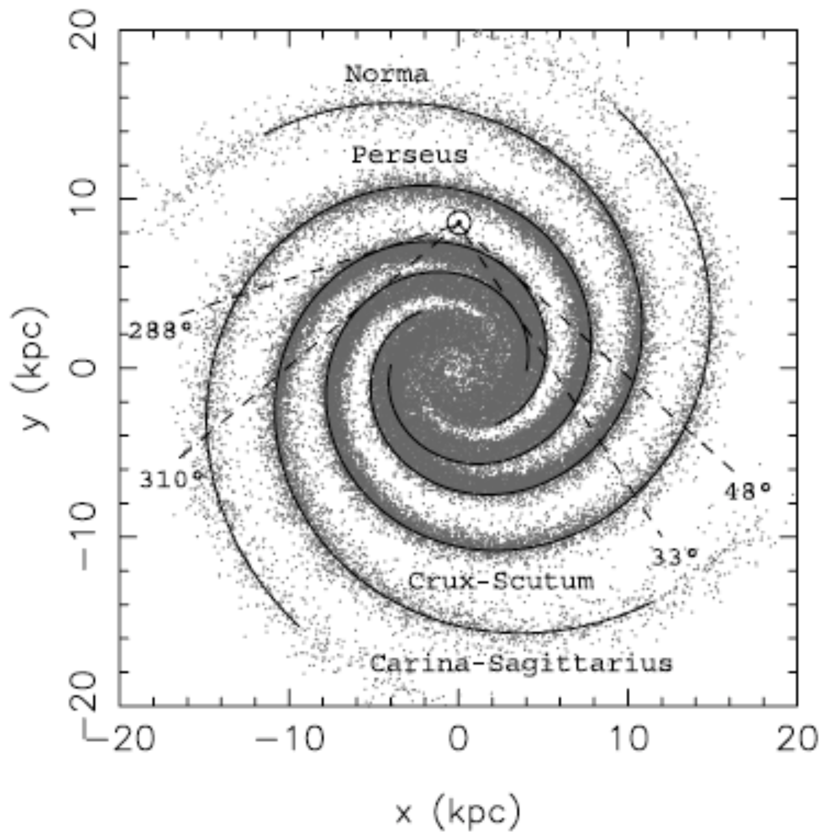

Faucher-Giguère & Kaspi 2006 ->

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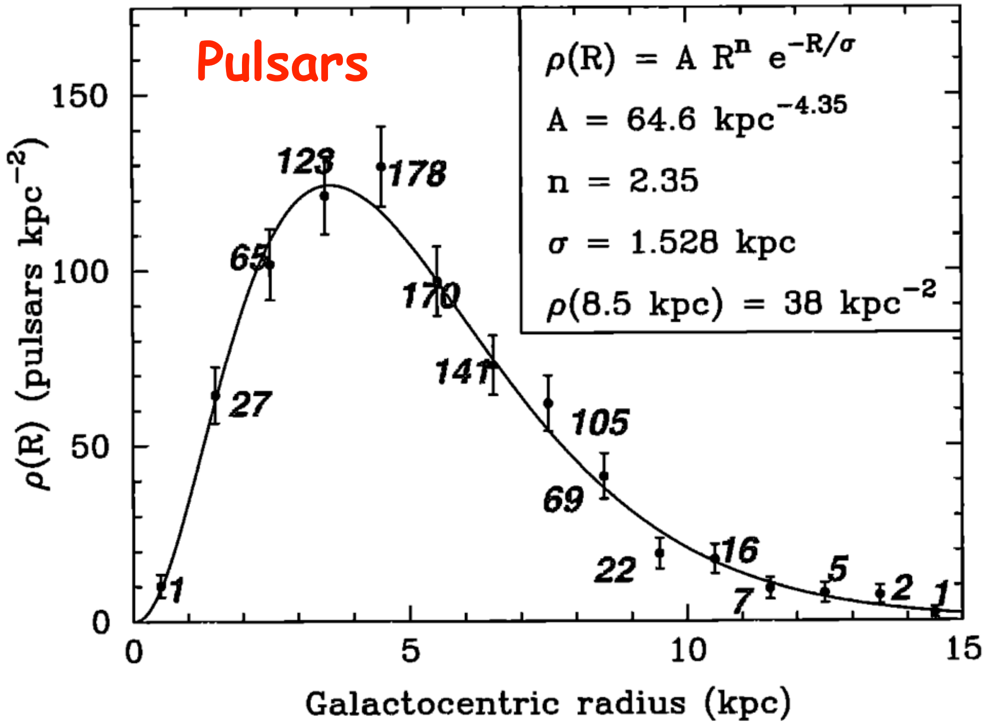

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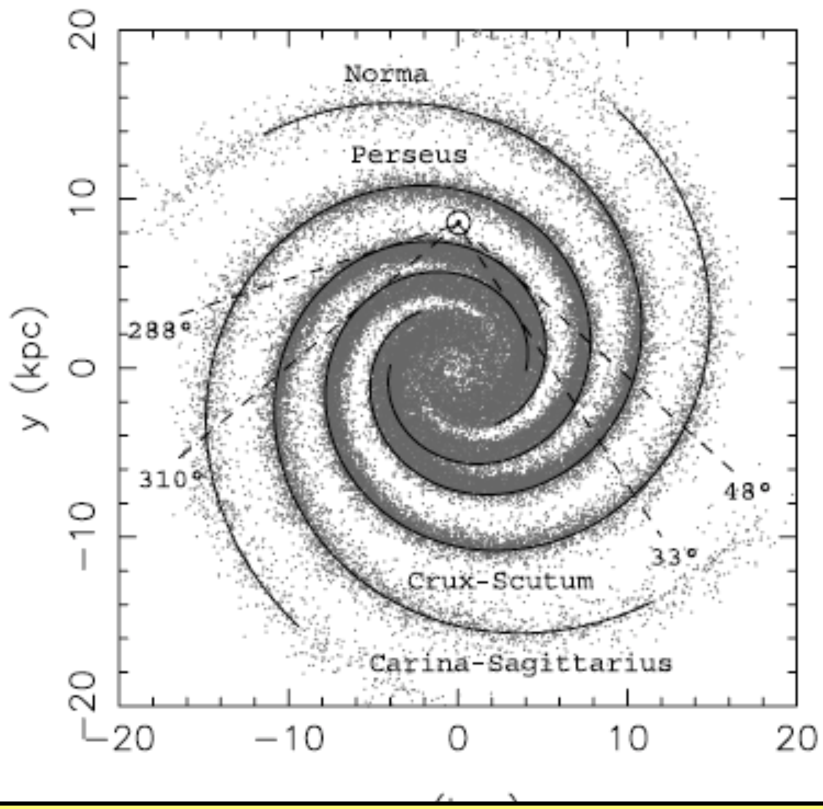


appropriate for core-collapse SNae (~2/3 of total explosions) -> WIND CAVITY
similar distributions exist for thermonuclear SNae (~1/3 of explosions)

Description of the simulation

Cristofari et al. 2013

3 SN/century in the MW

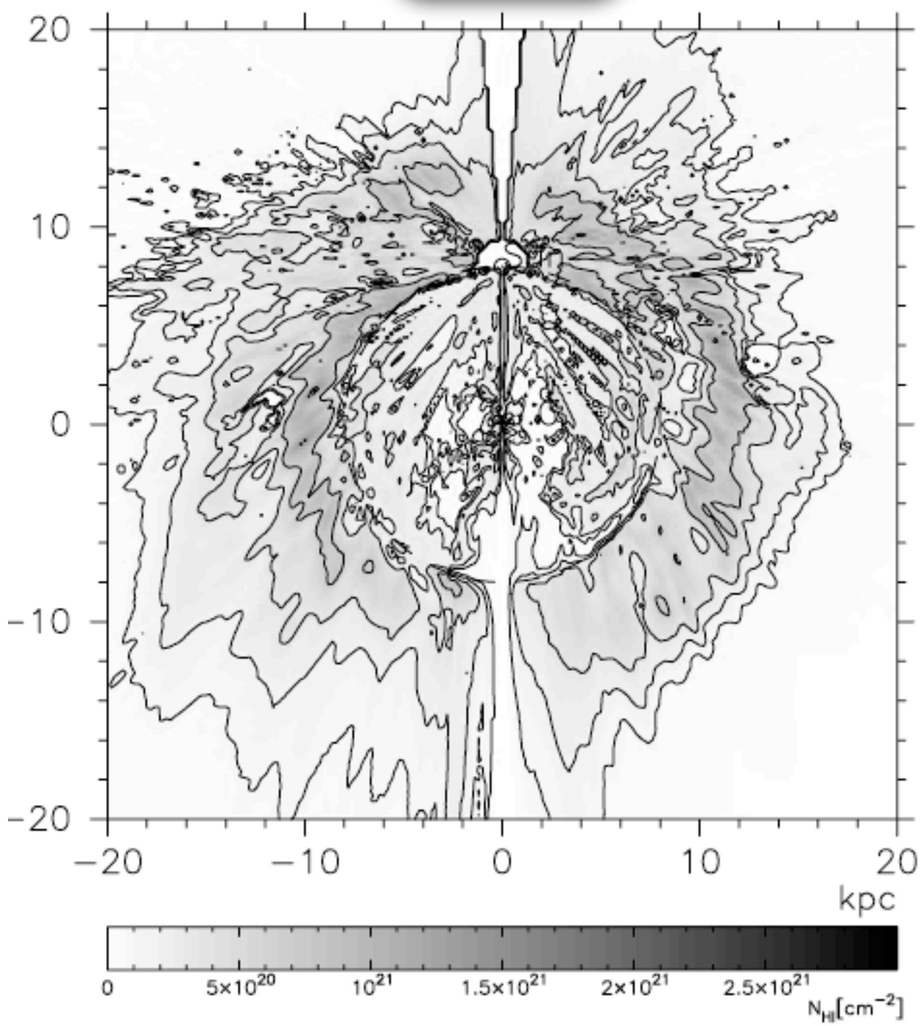
-> where and when?
-> core-collapse or thermonuclear

gas distribution in the MW

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

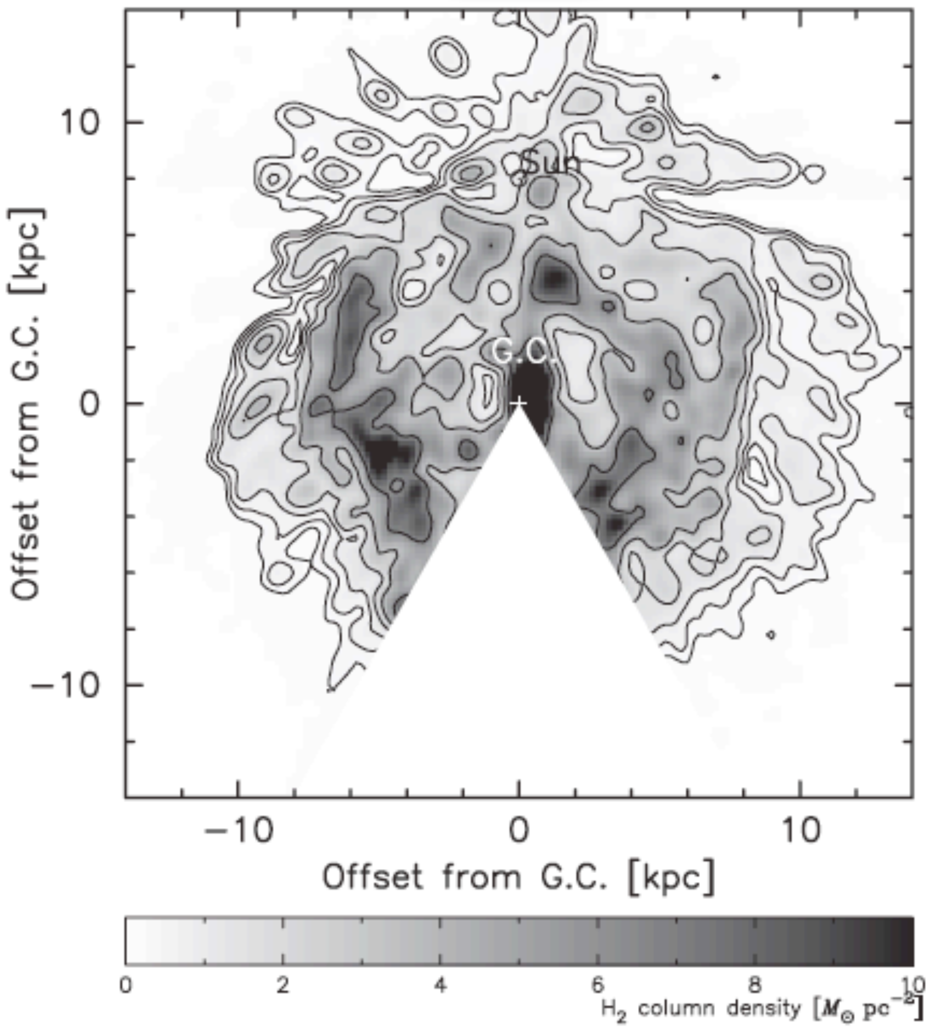
HI and H_2 in the Galaxy

HI



Nakanishi & Sofue 2003

H_2



Nakanishi & Sofue 2006

SN types (+vertical distribution)

thermonuclear

core-collapse

Type	$\mathcal{E}_{51}$	$M_{ej,\odot}$	$\dot{M}_{-5}$	$u_{w,6}$	Rel. rate
Ia	1	1.4	–	–	0.32
IIP	1	8	1	1	0.44
Ib/c	1	2	1	1	0.22
IIb	3	1	10	1	0.02

Table 1. Supernova parameters adopted in the simulation: supernova type (column 1), explosion energy in units of 10^{51} erg (column 2), mass of ejecta in solar masses (column 3), the wind mass loss rate in $M_\odot$/yr (column 4), the wind speed in units of 10 km/s (column 5), and the relative explosion rate (column 6). Values from Ptuskin et al. (2010).

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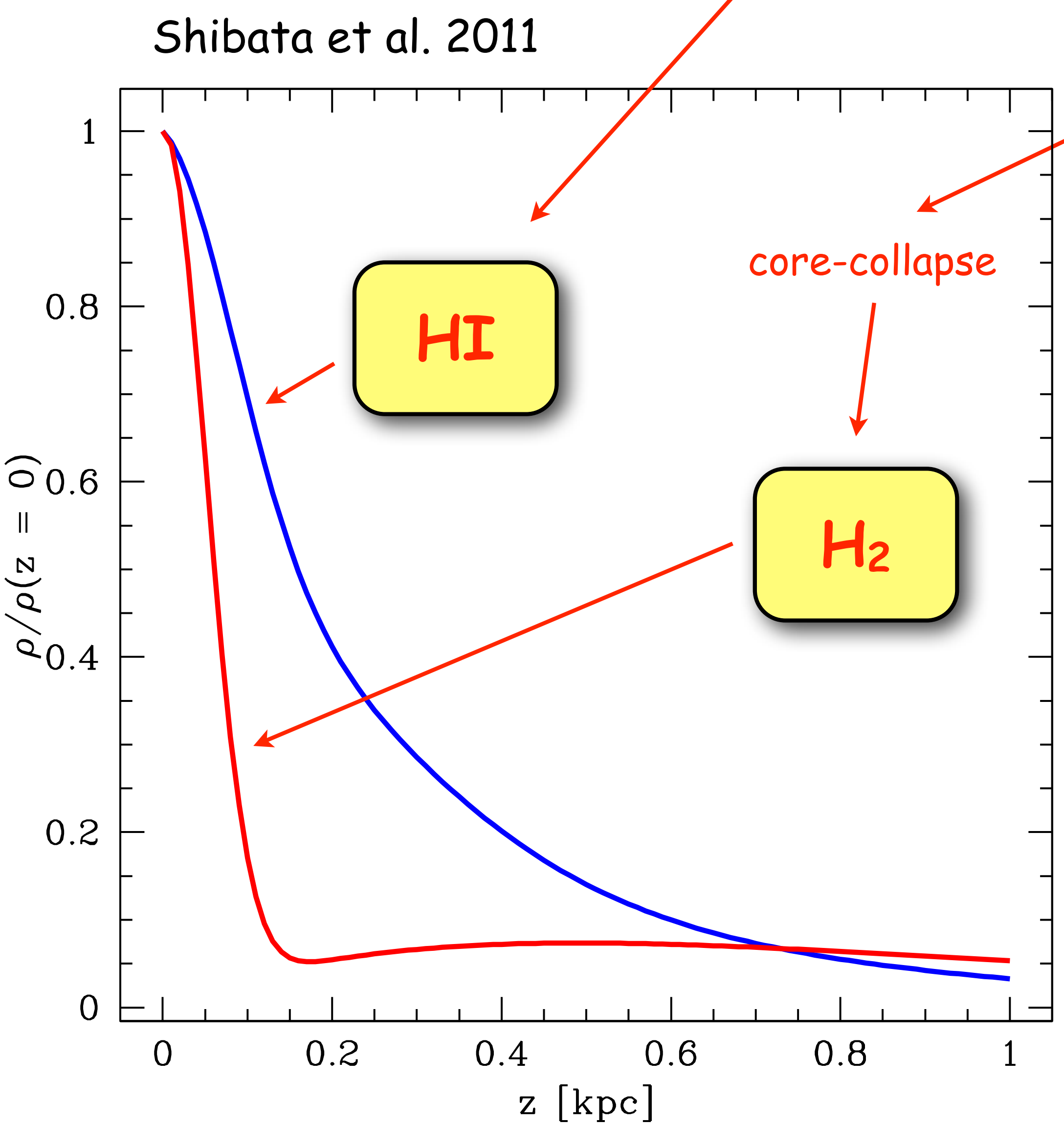

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hydro evolution of SNRs

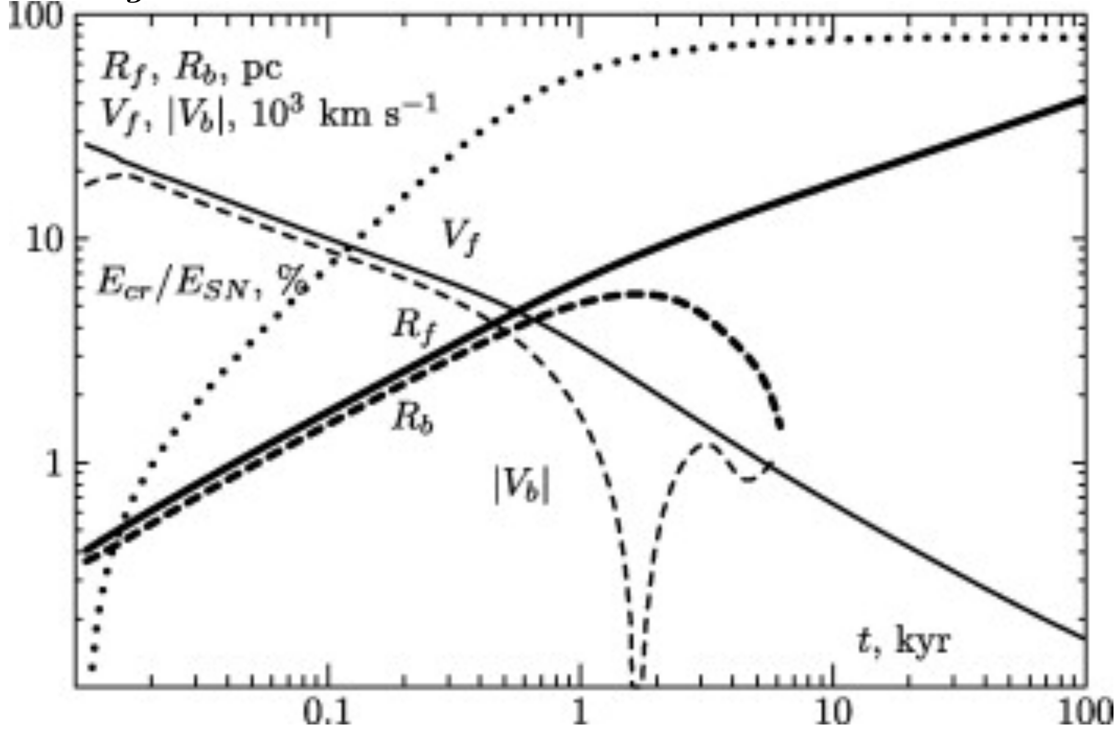
-> shock radius .vs. time
-> shock velocity .vs. time

Evolution of SNRs

10^{51} erg

$R_{sh}(t)$, $u_{sh}(t)$ depend ONLY on E_{SN}, $n_{gas}(R)$, M_{ej}

$n_{gas} = 0.1\ \mathrm{cm}^{-3}$



Zirakashvili & Ptuskin 2012

Evolution of SNRs

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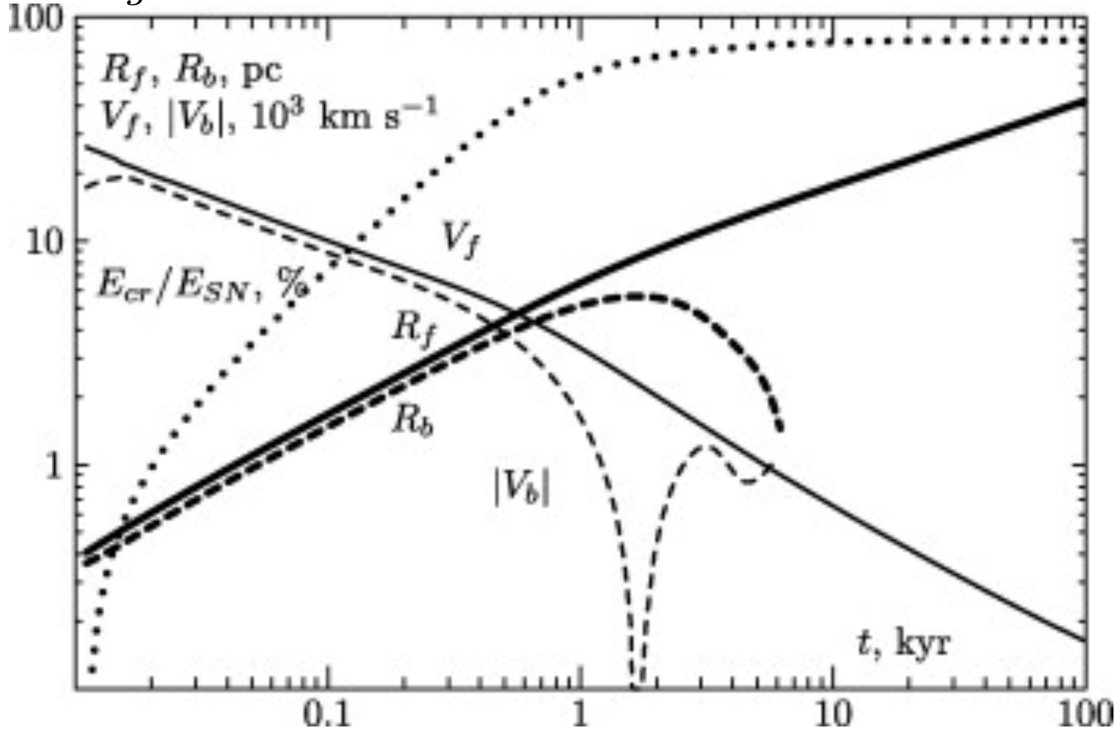

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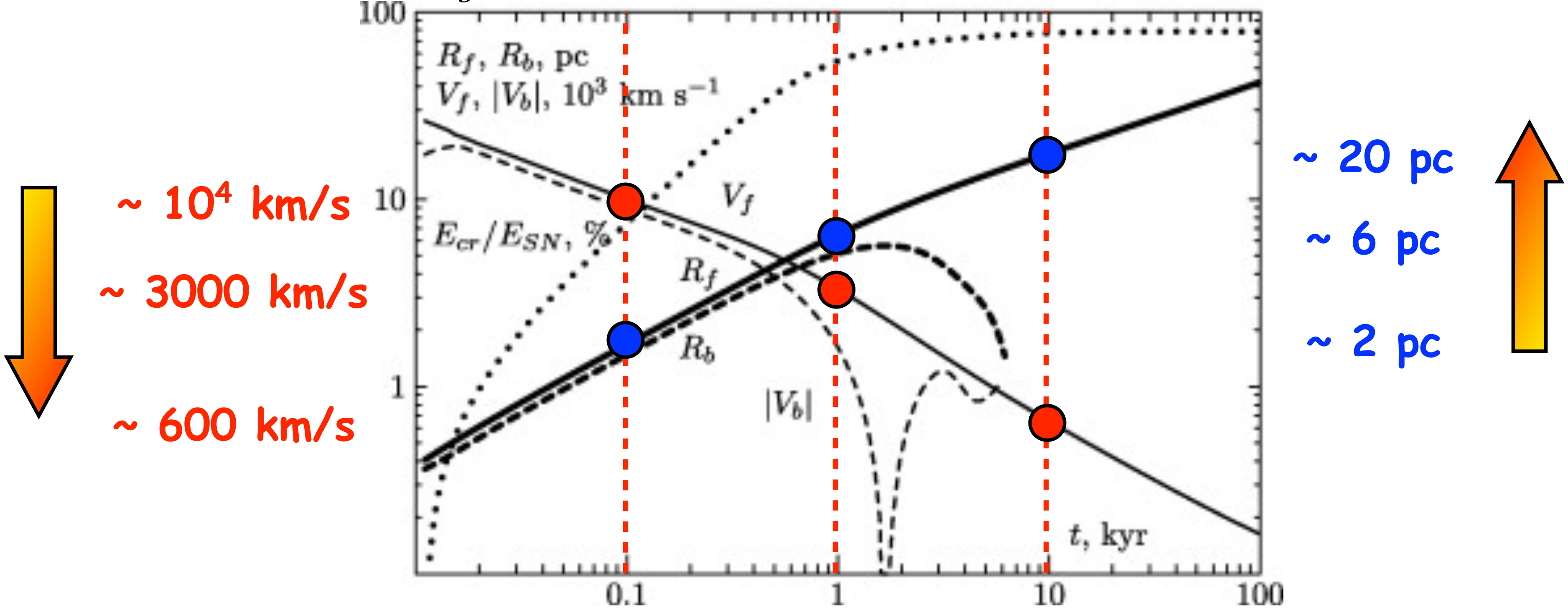

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Evolution of SNRs

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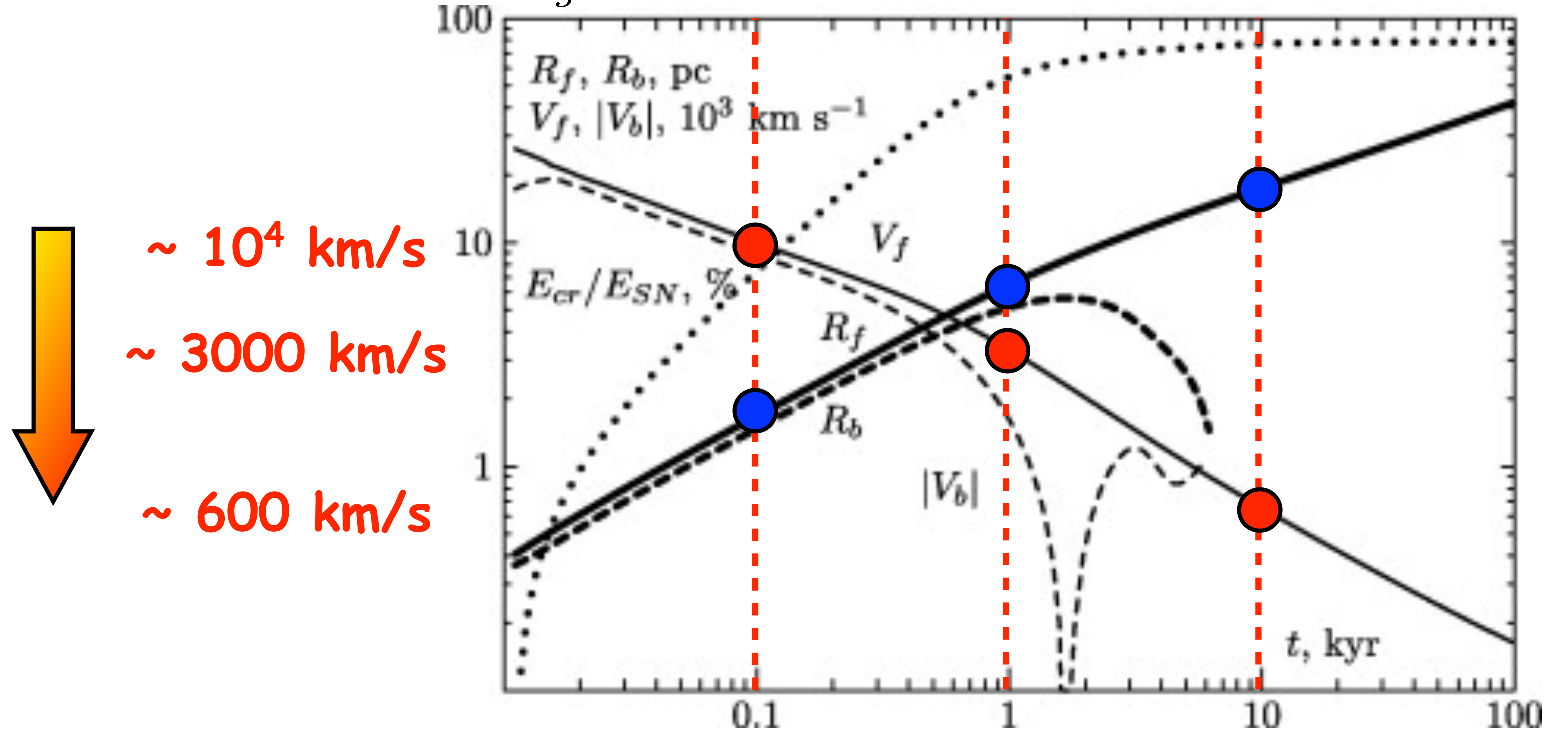
Sedov phase ($M_{sw} \gg M_{ej}$) -> $\left(\frac{E_{SN}^2}{n_{gas}}\right)^{1/5}$

much lower density for core-collapse (wind cavity) → $n_{gas} = 0.1\ \mathrm{cm}^{-3}$



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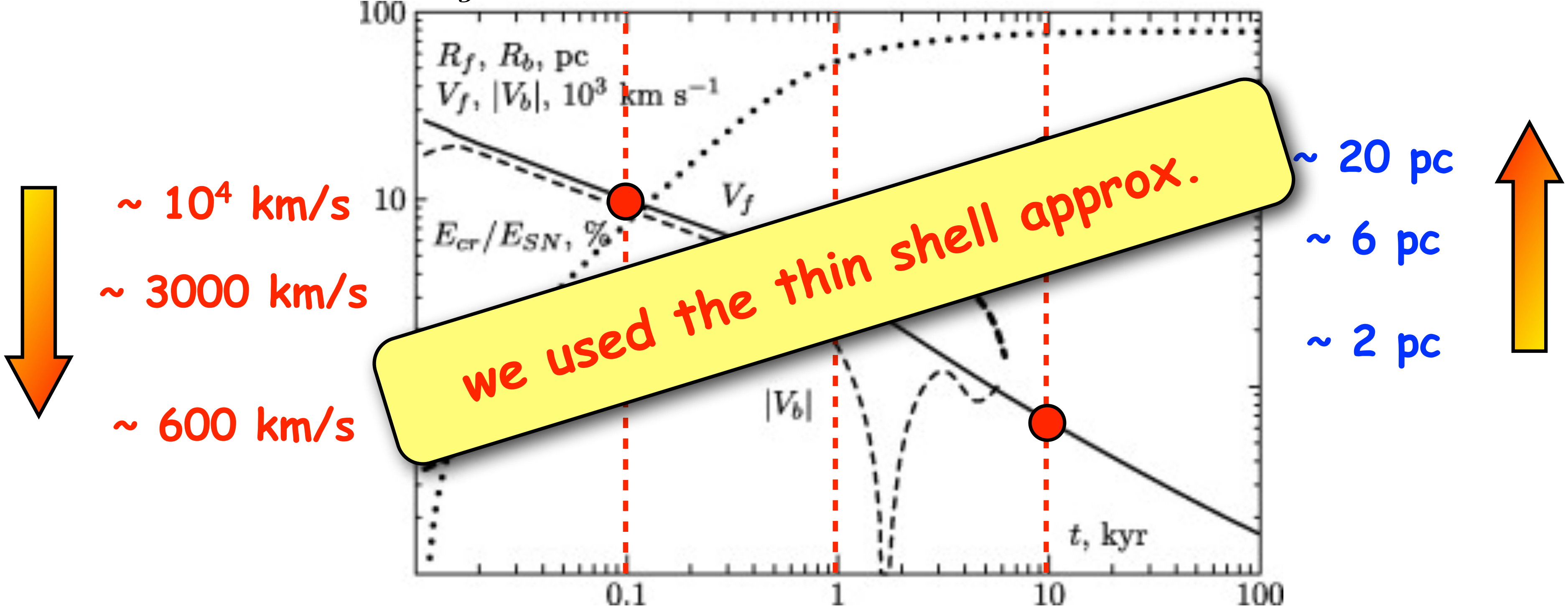

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-> atomic hydrogen (HI)
-> molecular hydrogen (H_2)

CR acceleration

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

hydro evolution of SNRs

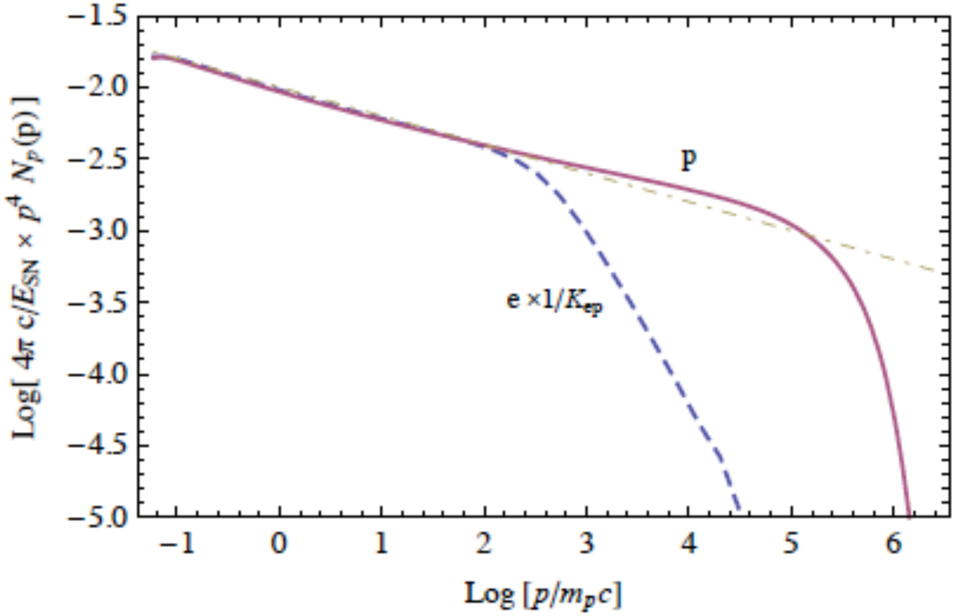
-> shock radius .vs. time
-> shock velocity .vs. time

Particle acceleration (protons+electrons)
Acceleration efficiency & Spectrum

~10% acceleration efficiency + Power law in momentum:

slope is a free parameter -> range from ~4.1 to 4.4

Morlino & Caprioli 2011



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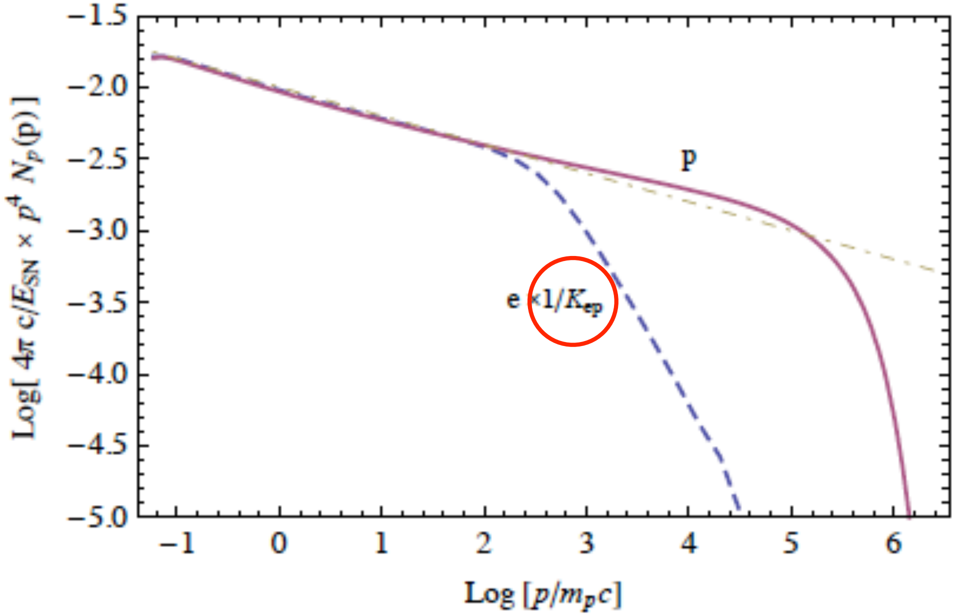

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$$\tau_{sync} \approx 1.8 \times 10^3 \left(\frac{E_e}{\text{TeV}}\right)^{-1} \left(\frac{B_2}{100\ \mu\text{G}}\right)^{-2} \text{yr}$$

break

one power steeper here

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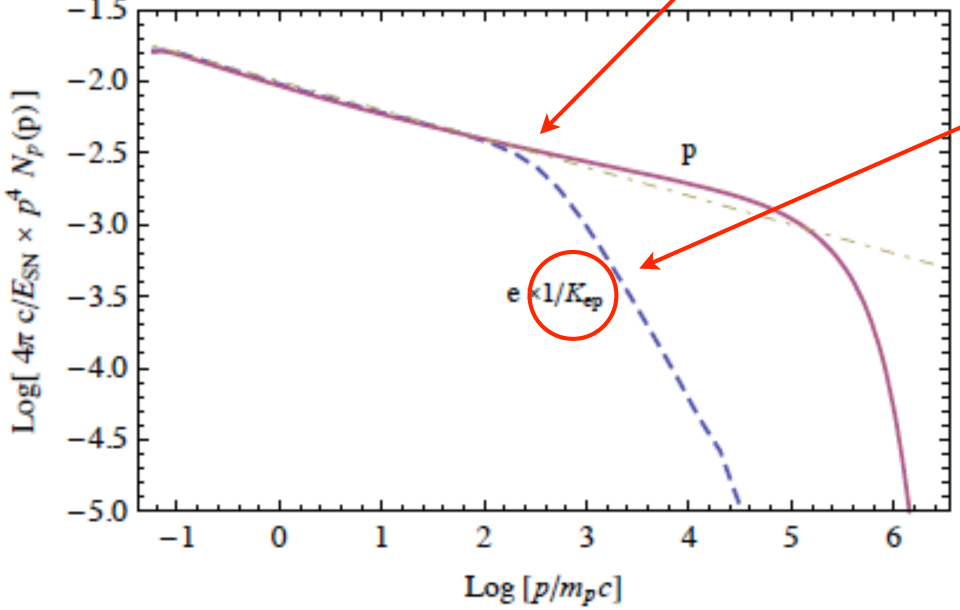

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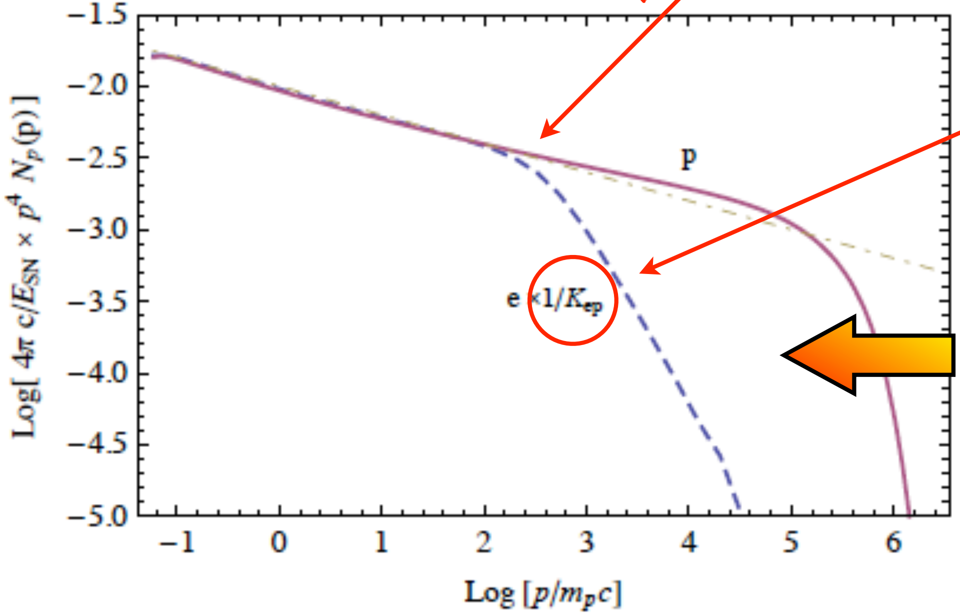


Hillas-like criterium for E_{max}

$$E^p_{max} \approx u_{sh}\ R_{sh}\ B_{sh}\ \propto\ t^{-4/5}$$

amplified field as in Bell et al. 2013
(+ damping downstream)

Description of the simulation

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

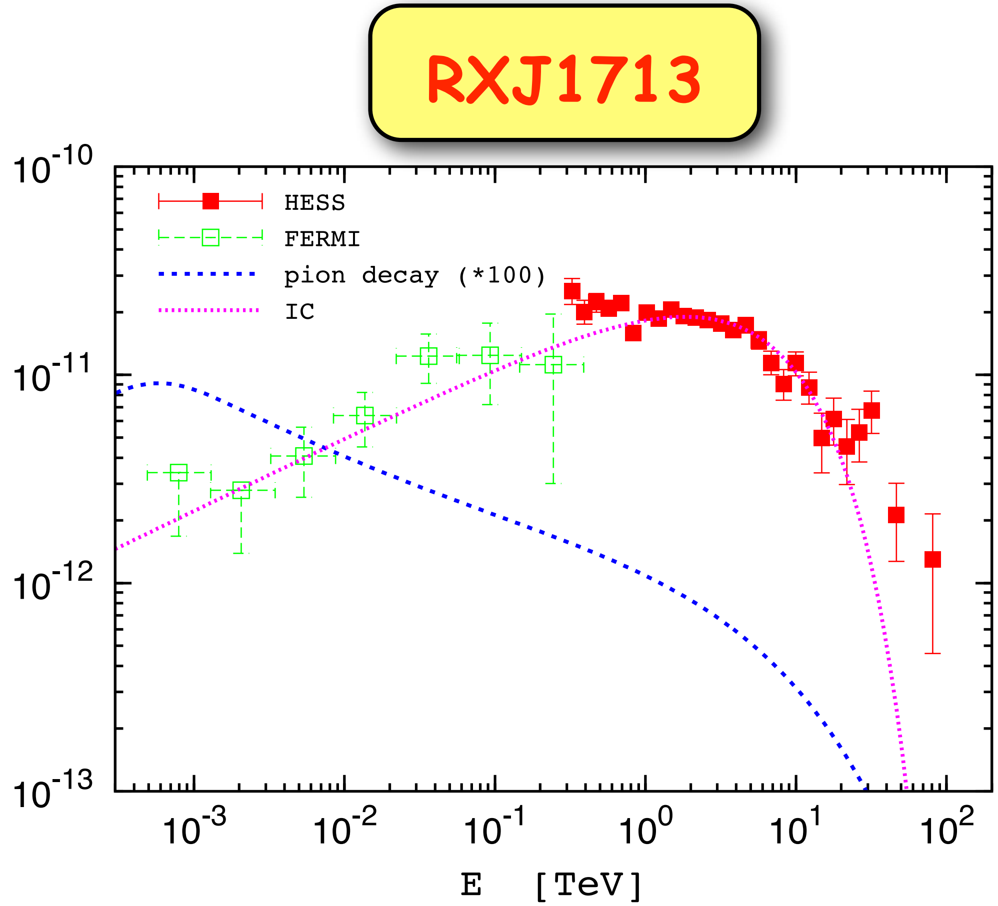
hydro evolution of SNRs

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

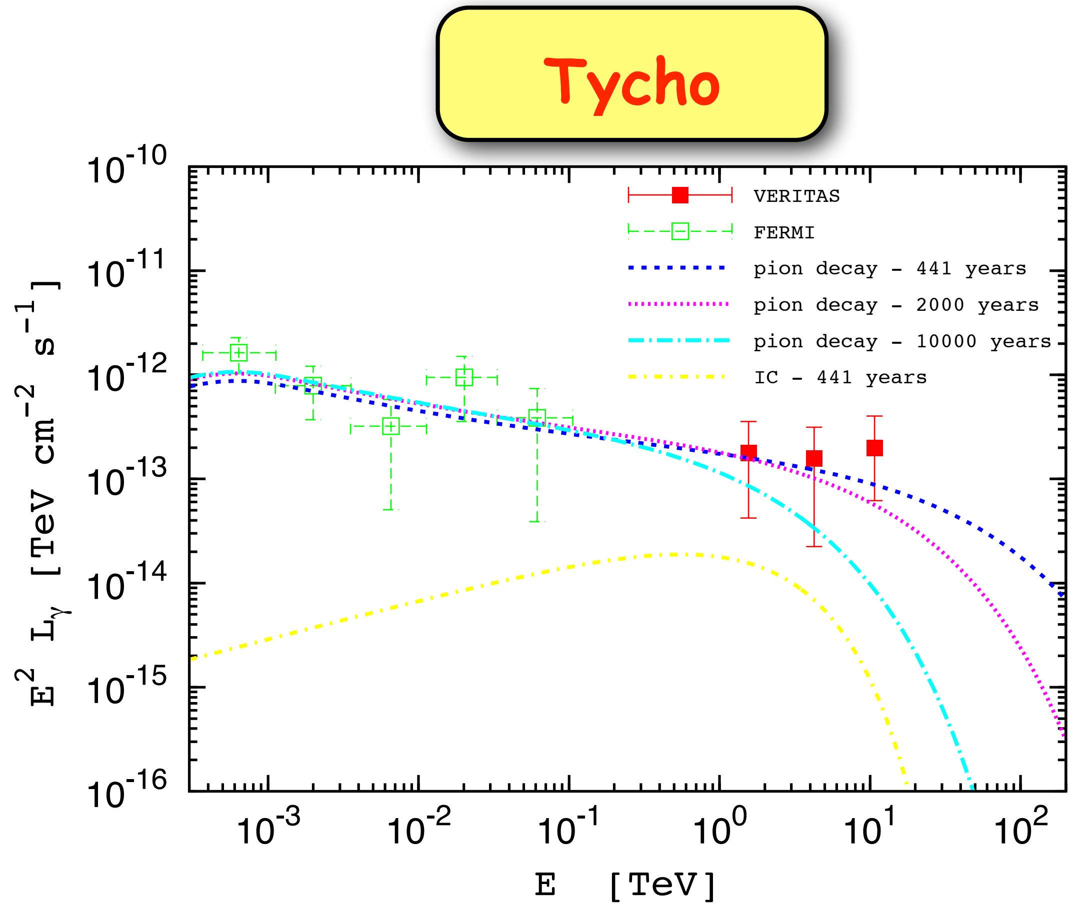
gamma-ray emission

-> hadronic+leptonic

Does this work?



type II
age = 1630 yr
slope 4.3
d = 1 kpc
B_2 = 5 μG
ξ_{CR} = 0.4
$K_{ep} = 10^{-2}$



type Ia
age = 1630 yr
slope 4.25
d = 3.5 kpc
ξ_{CR} = 0.18
$K_{ep} = 10^{-4}$
$n_0 = 0.24\ cm^{-3}$

A comparison with the HESS scan

Gast et al. 2011

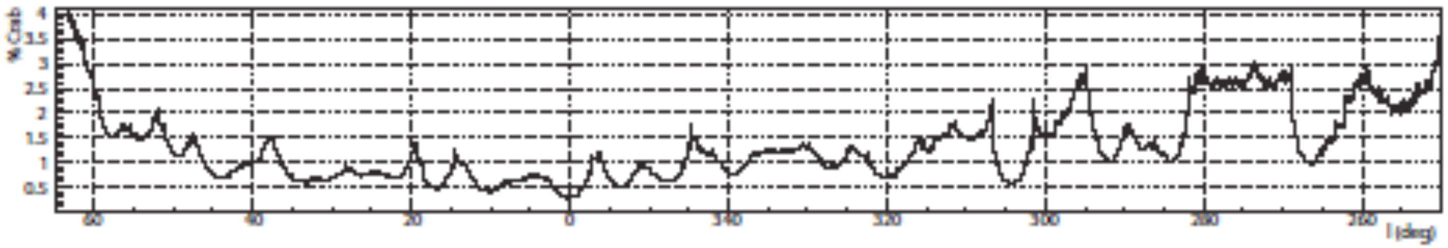


Figure 2: Sensitivity of H.E.S.S. to point-like γ-ray sources with an assumed spectral index of 2.5, for a detection level of 5σ pre-trial, at $b = -0.3^\circ$, the approximate average latitude of Galactic sources. The sensitivity is expressed in units of the Crab integral flux $F(\geq 1\,\mathrm{TeV})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

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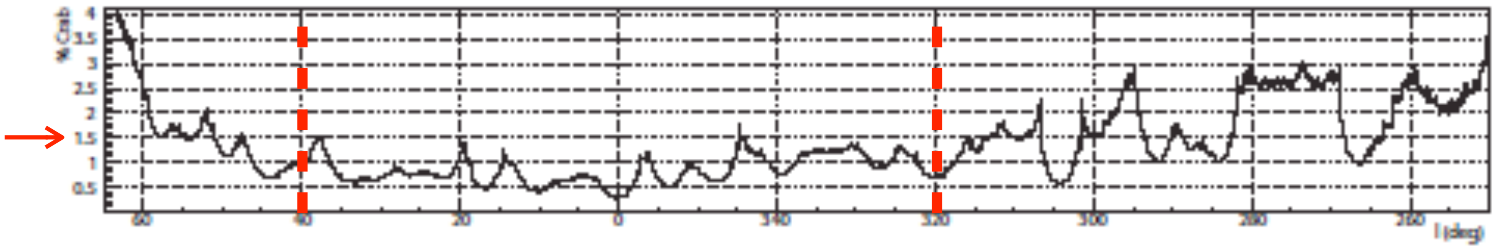

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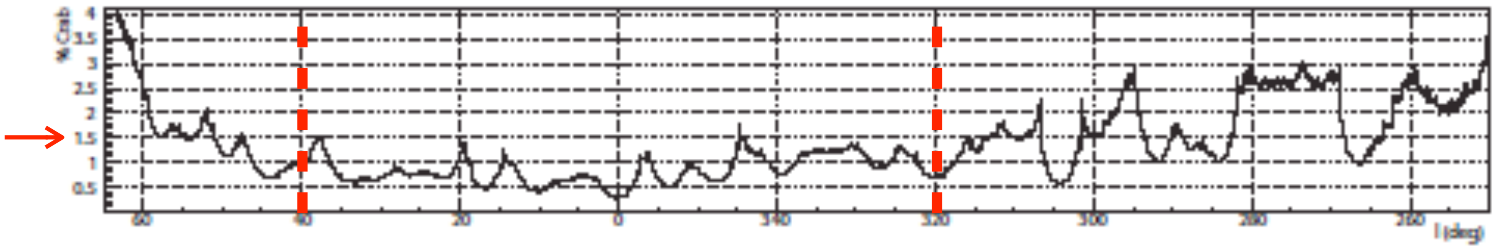

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$$-3^\circ < b < 3^\circ$$

- sensitivity scales as source extension
- PSF = 0.1 degrees

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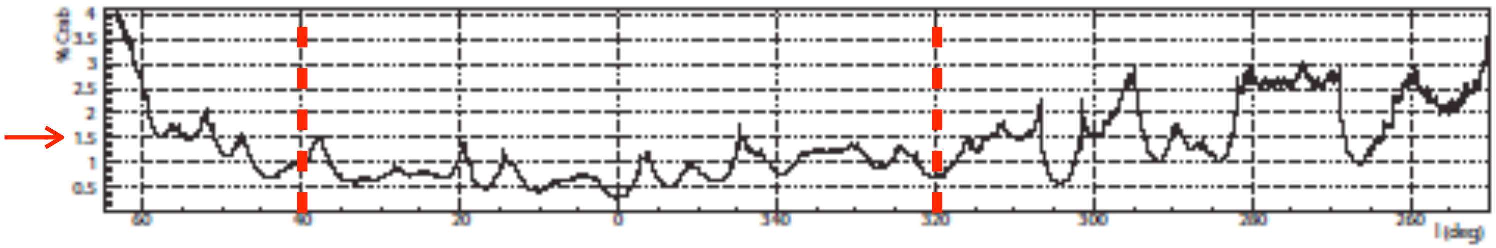

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Name	$F(> 1\ \mathrm{TeV})$ $[10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	d [kpc]	age [kyr]	radius [°]	Ref.
RX J1713.7–3946	15.5	1	1.6	0.65	1,2,3
HESS J1731–347	6.9	2.4...4	27	0.25	4,5
CTB 37B	0.4	13.2	0.3...3	0.03	6,7

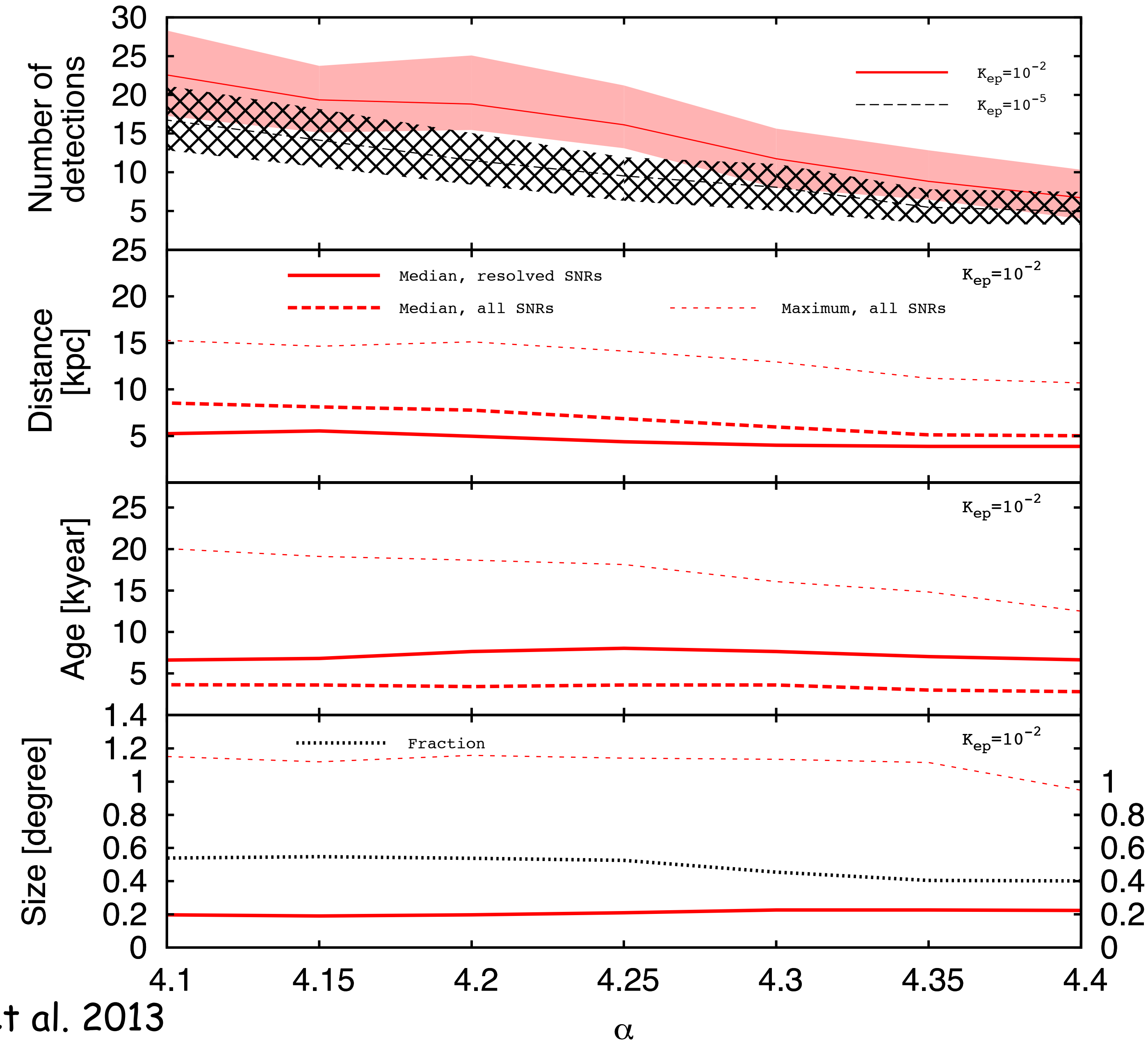
Table 3. Gamma–ray fluxes, distances, ages and apparent sizes of the three SNR shells detected by H.E.S.S. in the region $|l| < 40°$, $|b| < 3.5°$ at a flux level above 1.5% of the Crab. *References:* 1) Aharonian et al. 2006b; 2) Moriguchi et al. 2005; 3) Wang et al. 1997; 4) Abramowski et al. 2011;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



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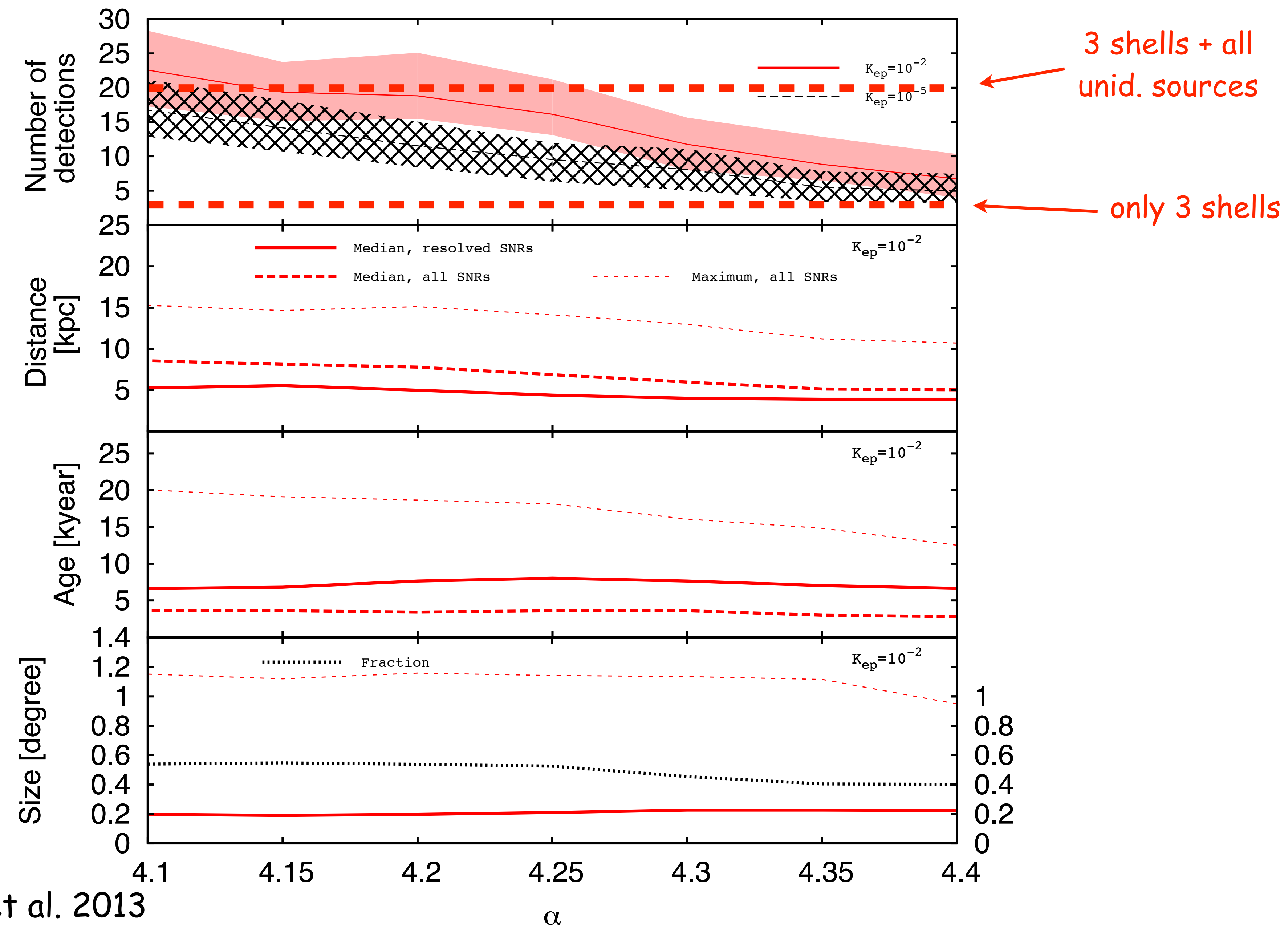

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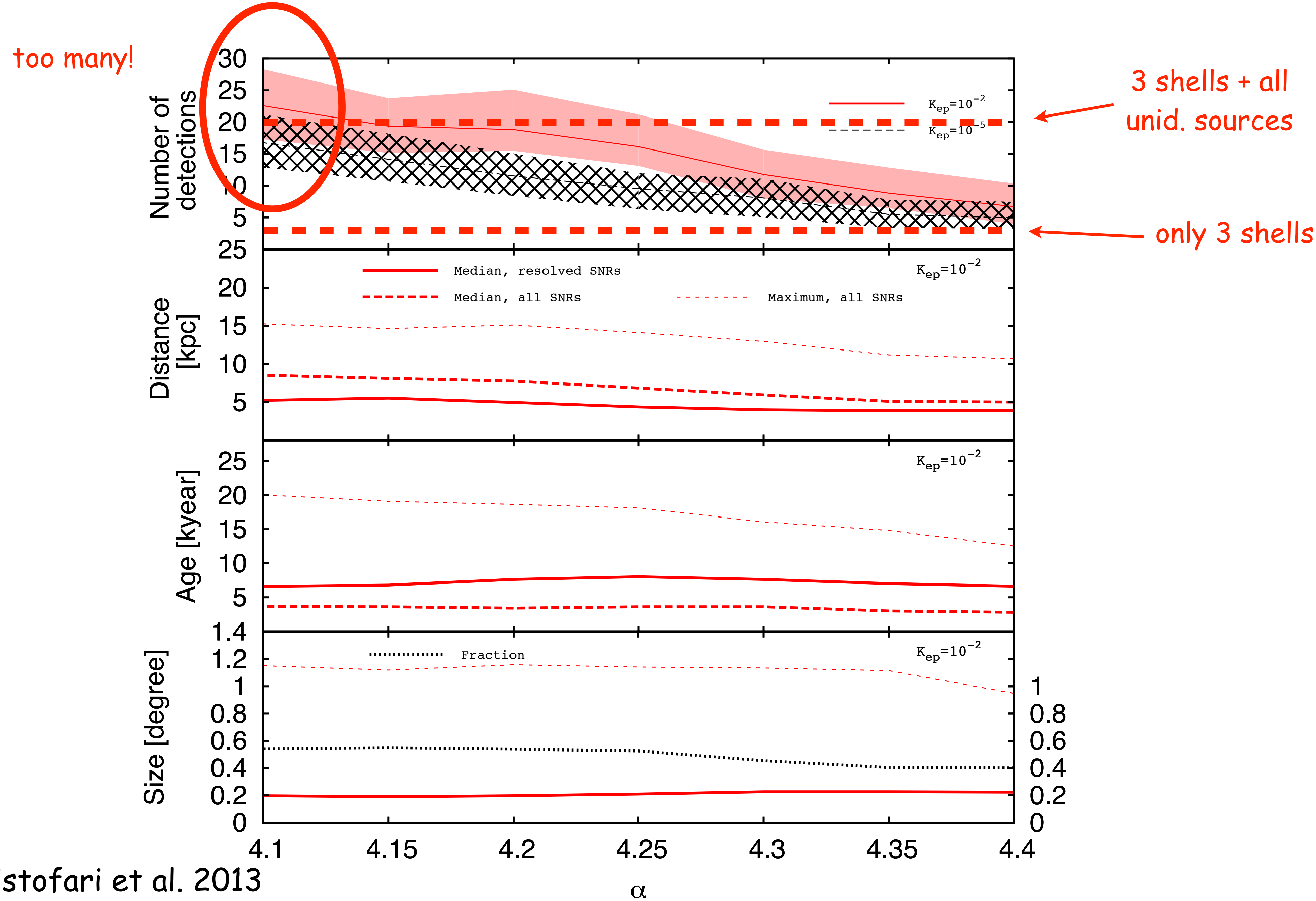

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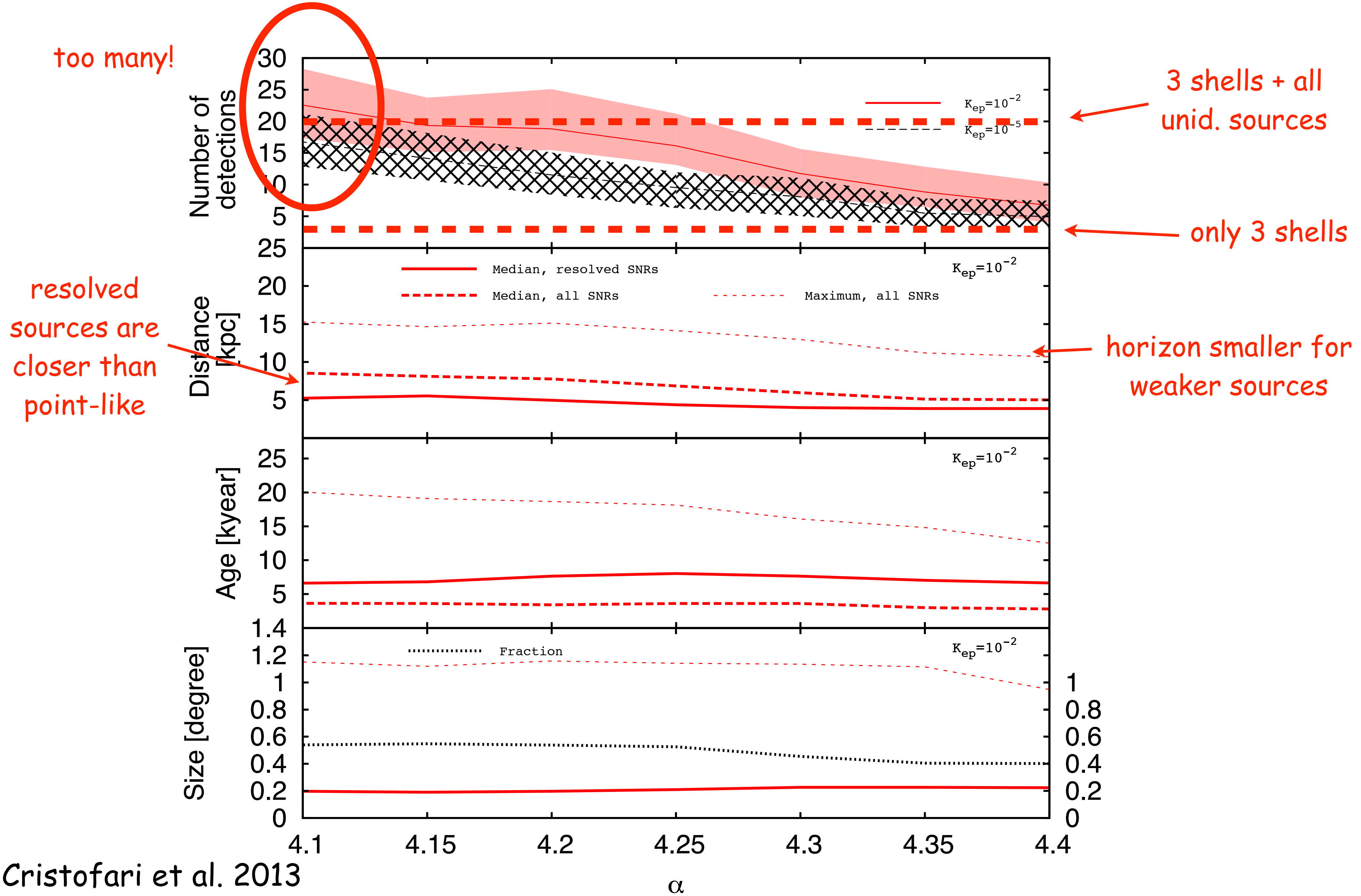

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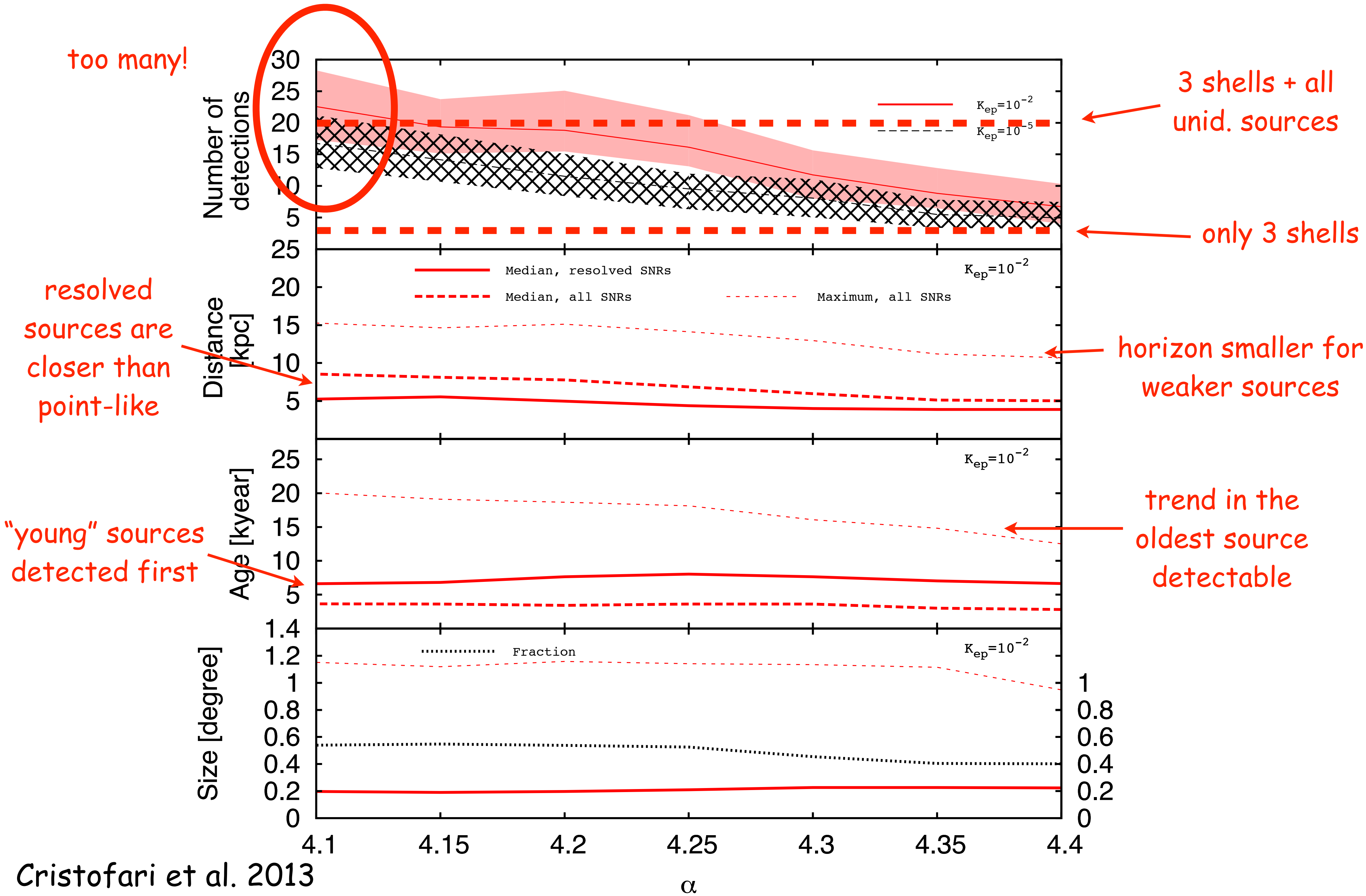
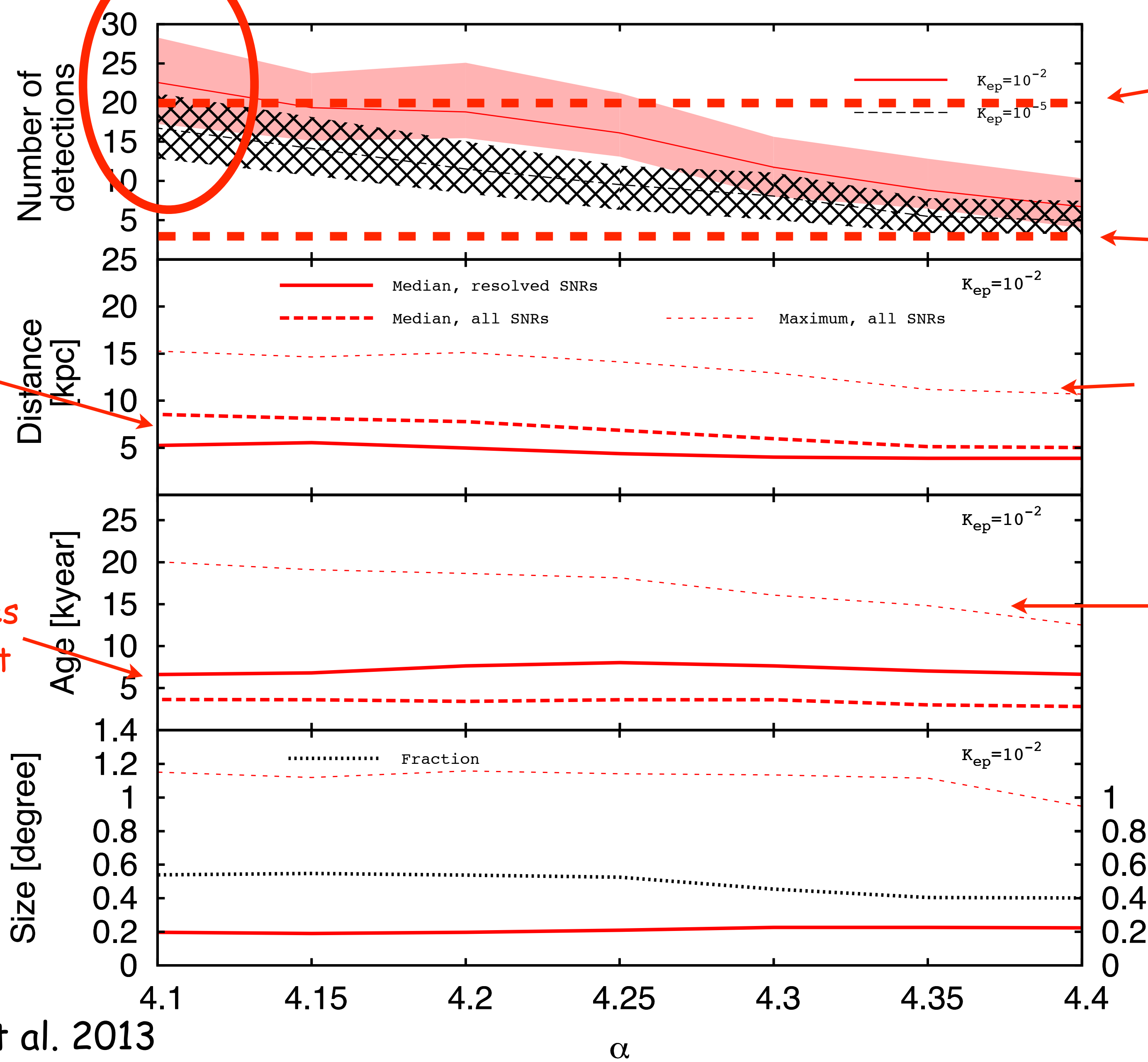


Cristofari et al. 2013

A comparison with the HESS scan

too many!



3 shells + all unid. sources

only 3 shells

resolved sources are closer than point-like

horizon smaller for weaker sources

"young" sources detected first

trend in the oldest source detectable

~50%-50% extended and point like

Cristofari et al. 2013

Conclusions on gamma-ray based tests

HESS -> TeV gamma ray emission

-> consistent with 1994 predictions (Drury et al)

-> hadronic or leptonic?

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-> no complete catalogue of SNRs available at TeV energies

-> hard spectra ($\sim E^{-2}$) are hardly consistent with data (too many sources) -> slope must be 2.1 or steeper -> same conclusion is reached from studies of CR propagation

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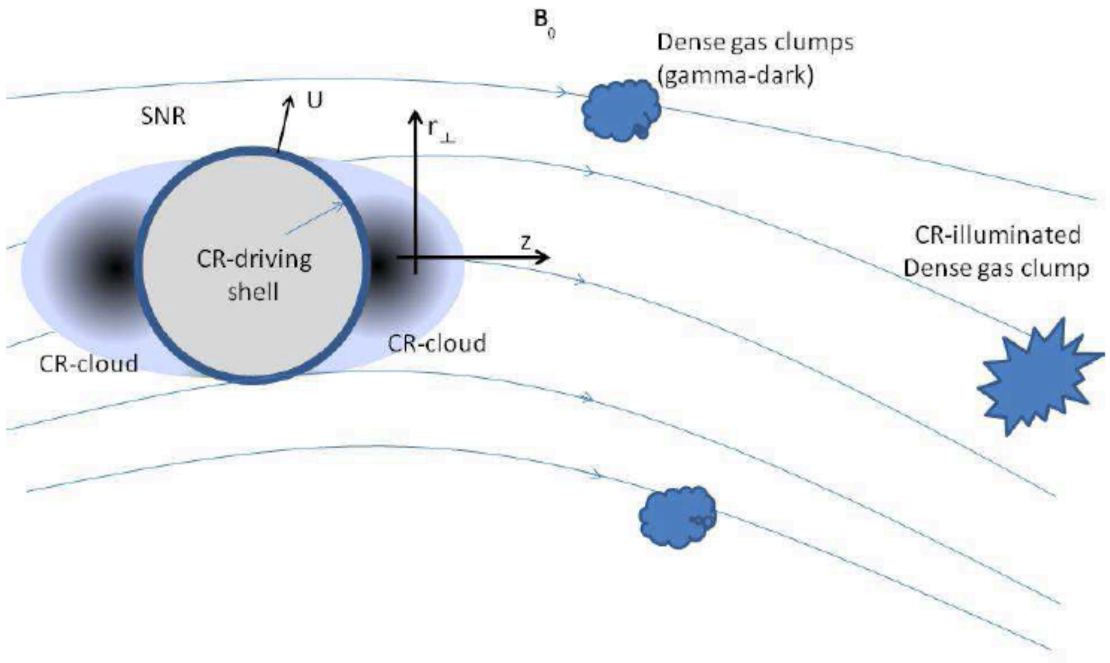
SNR+Mol clouds -> gamma rays -> diffusion coefficient

Gamma rays from the vicinity of SNRs

Aharonian&Atoyan1996, Gabici&Aharonian2007, Gabici et al. 2009,2010, Casanova et al. 2011 ...

Malkov et al 2012



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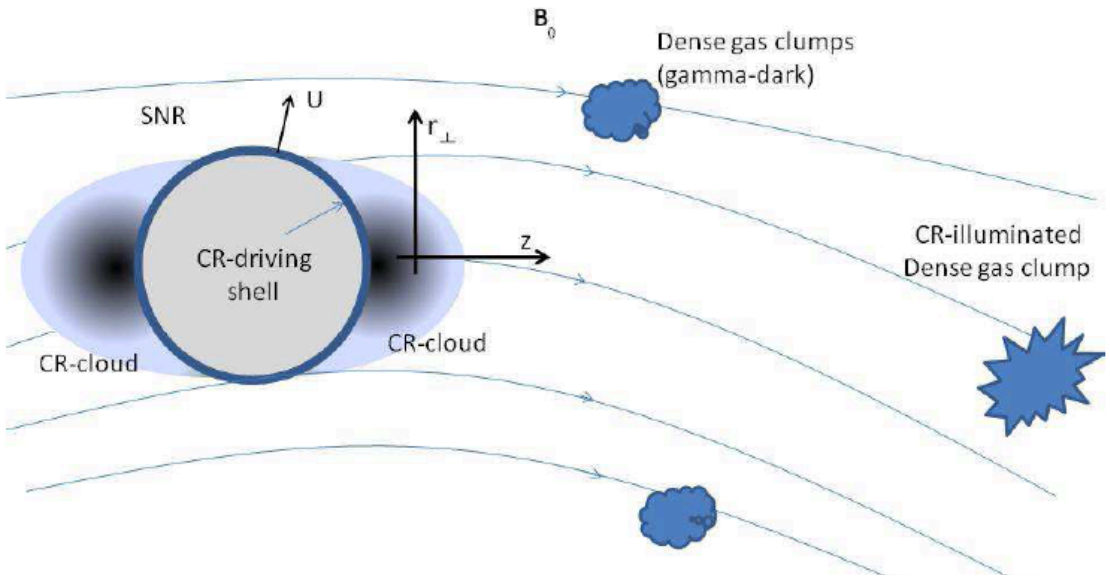

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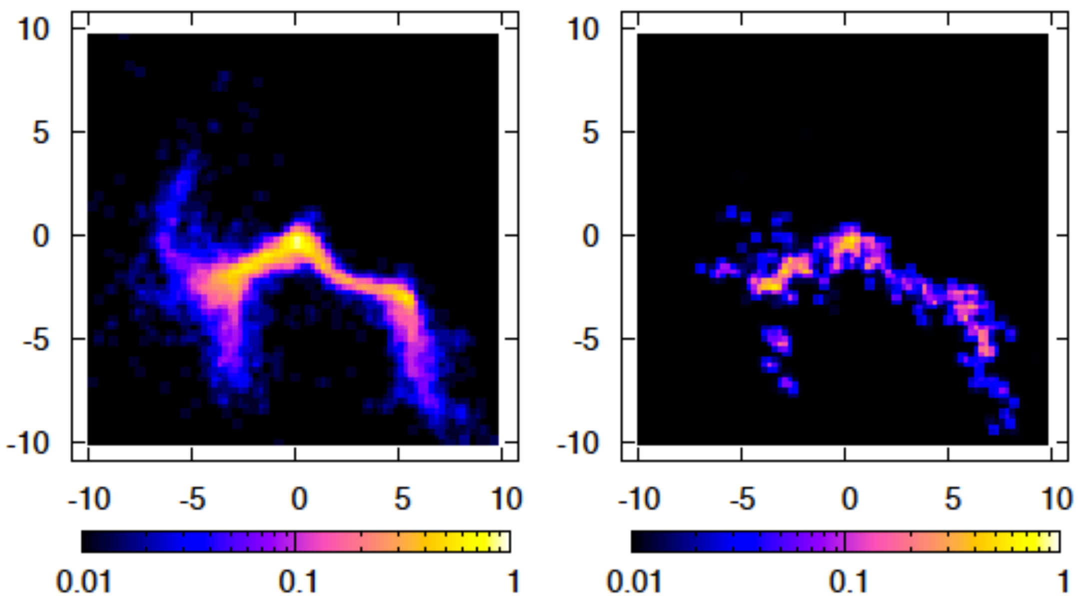

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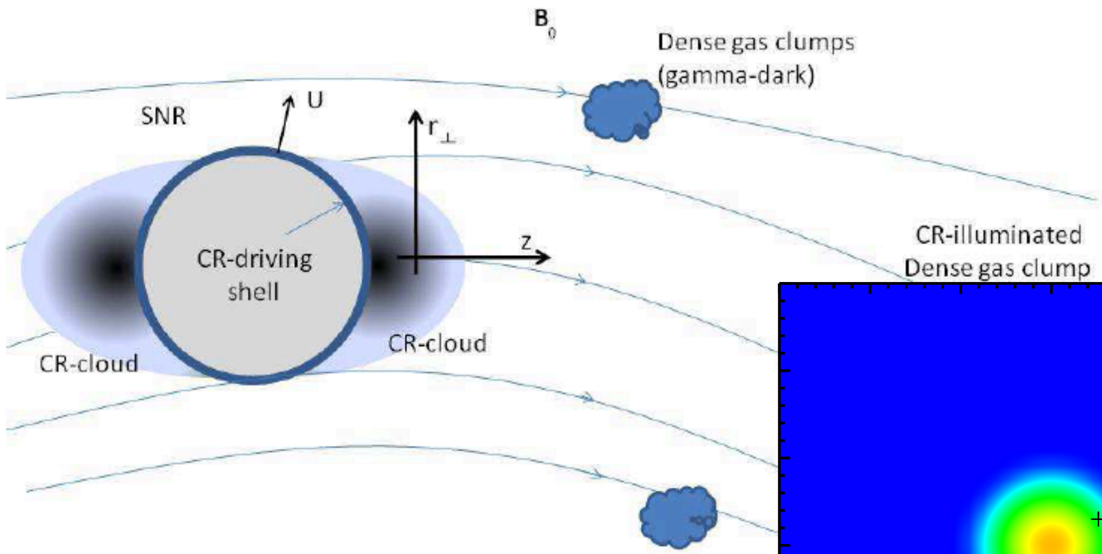

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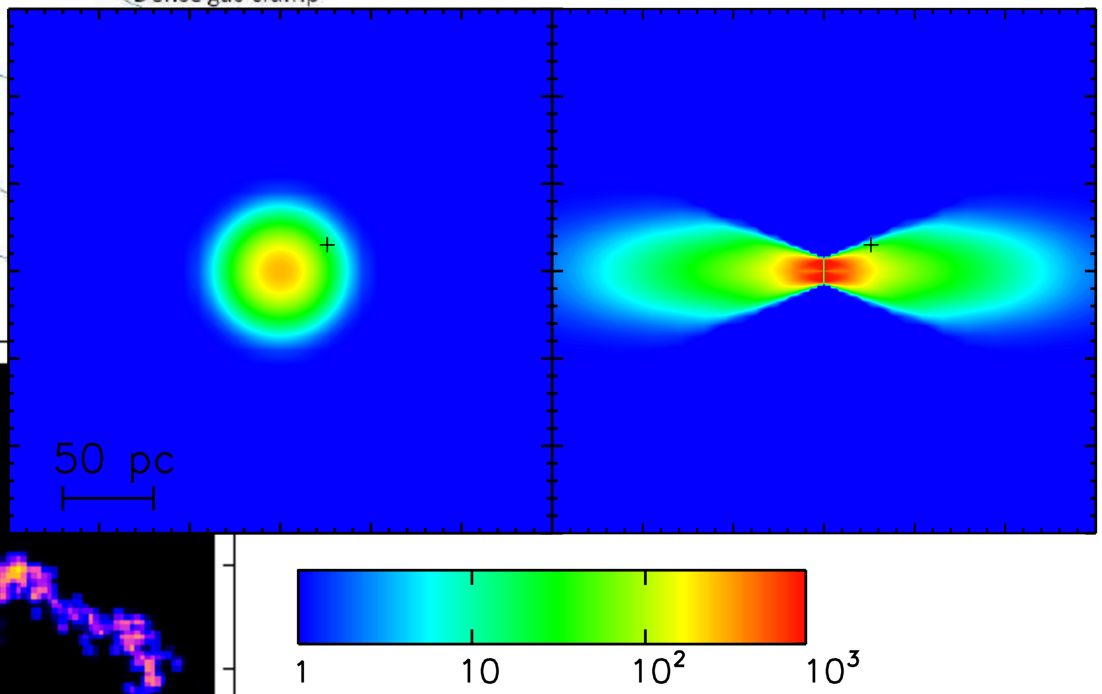
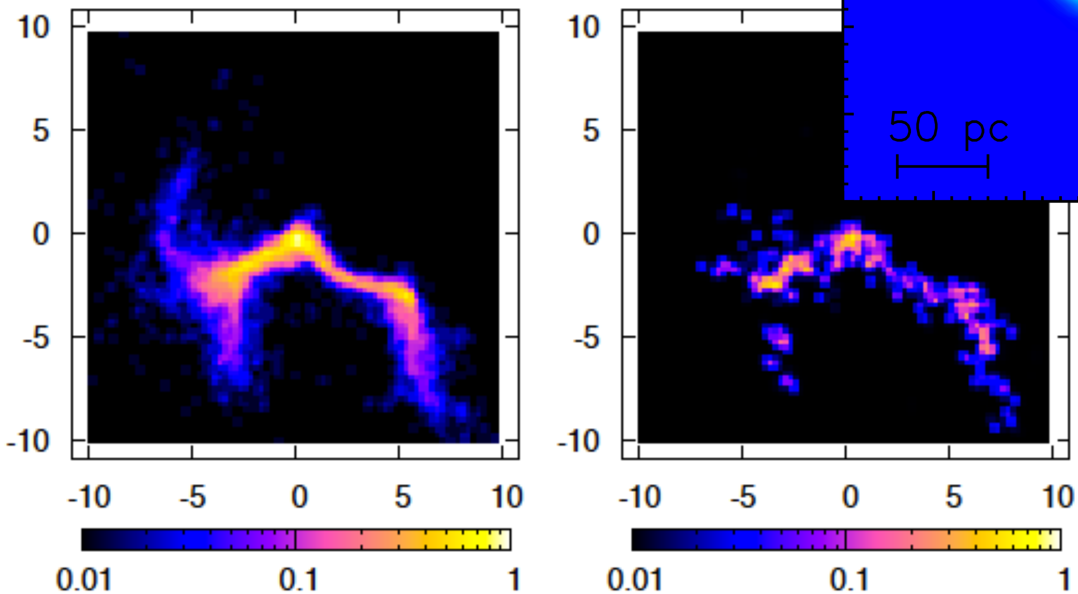


Nava & Gabici 2012



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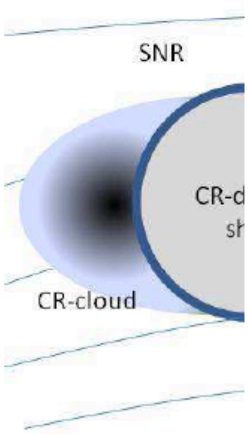

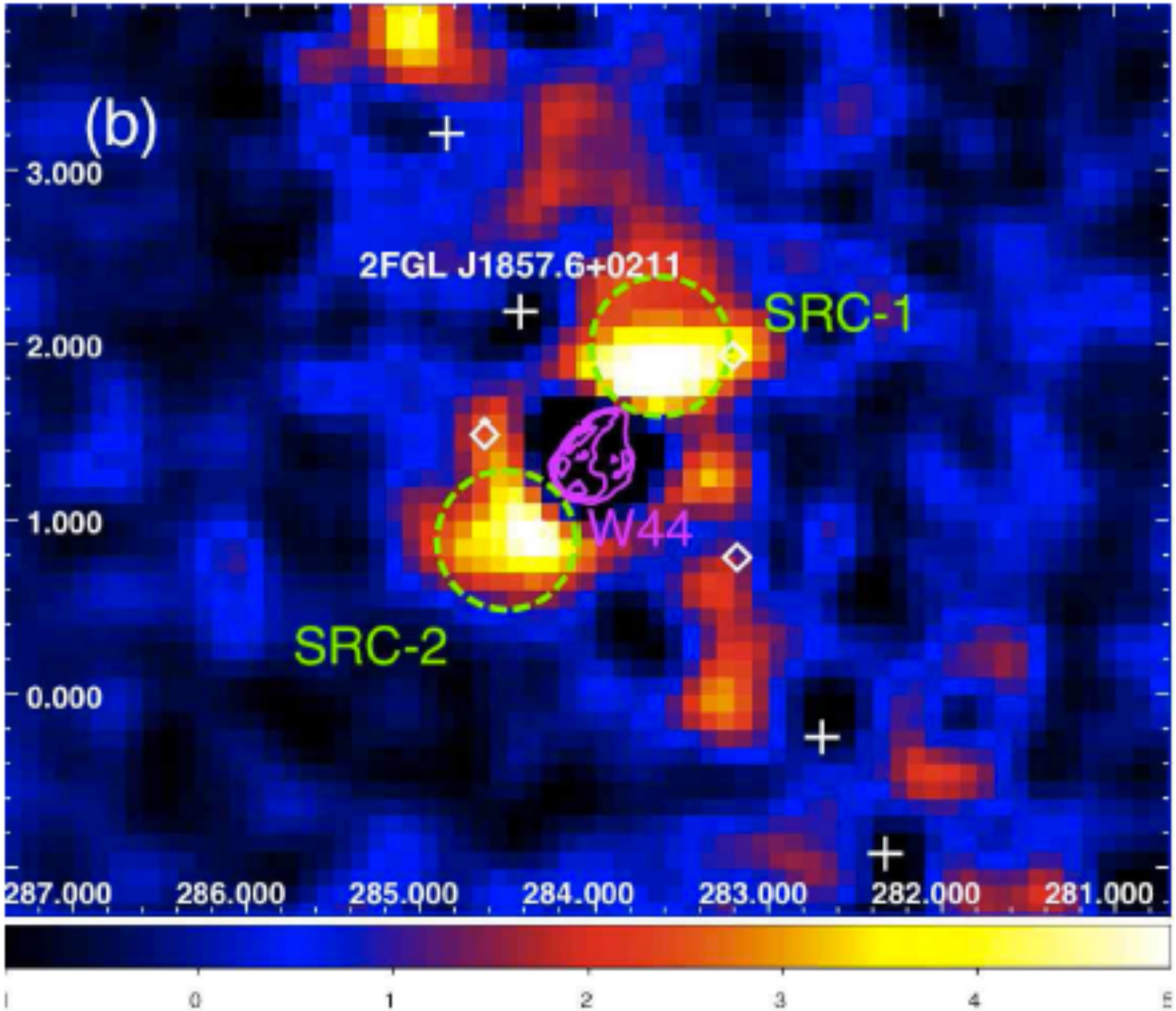

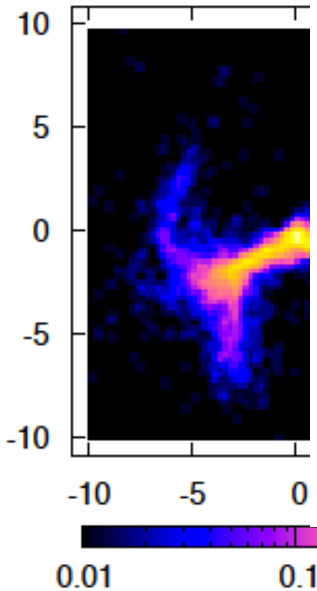

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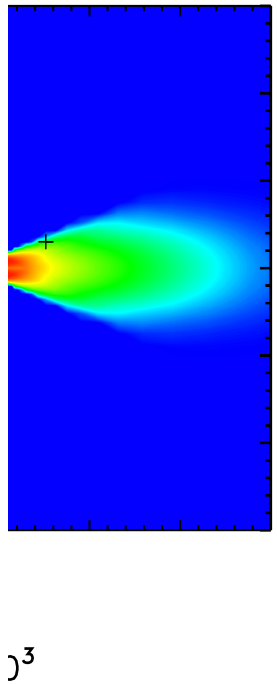

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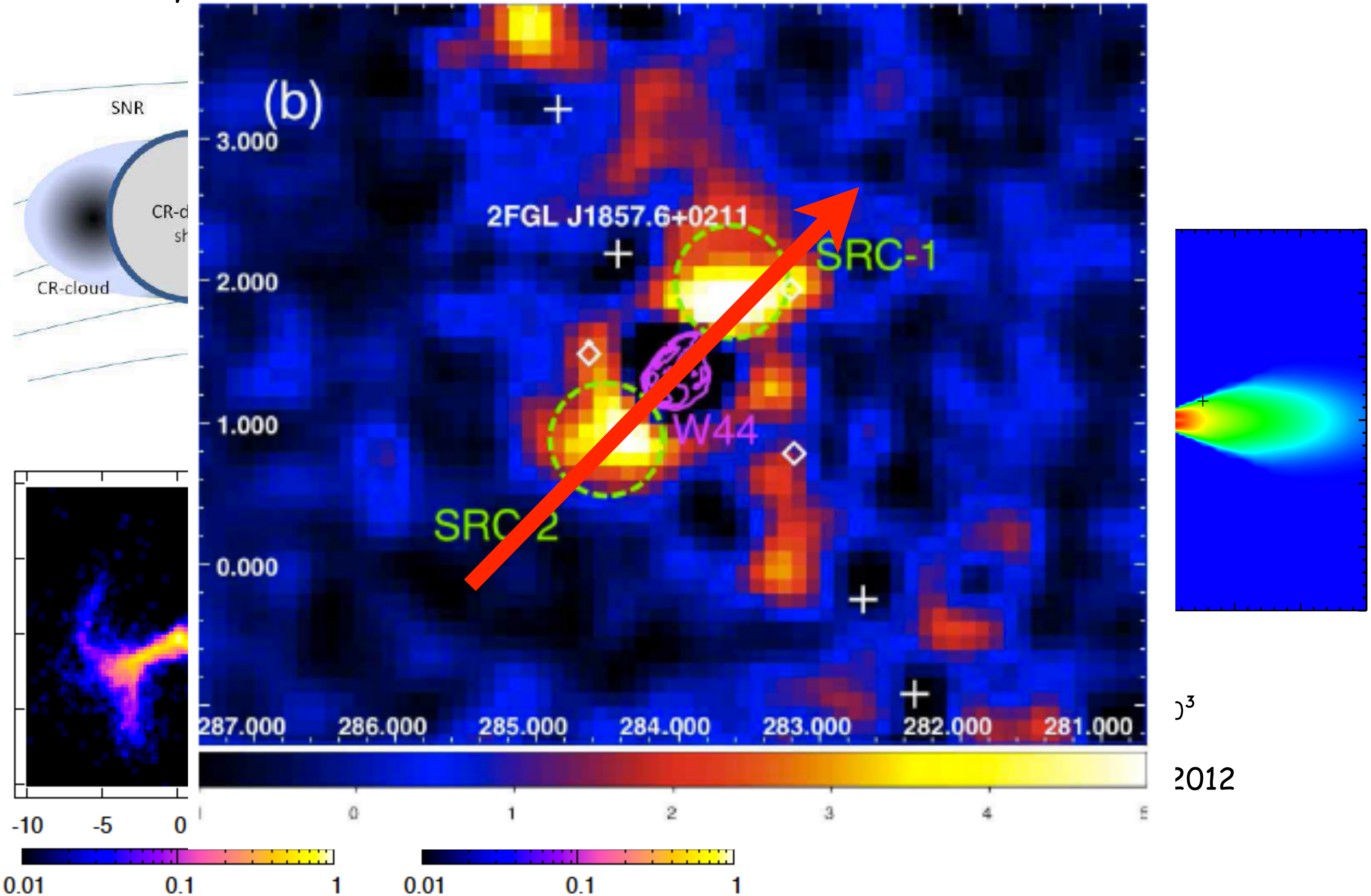

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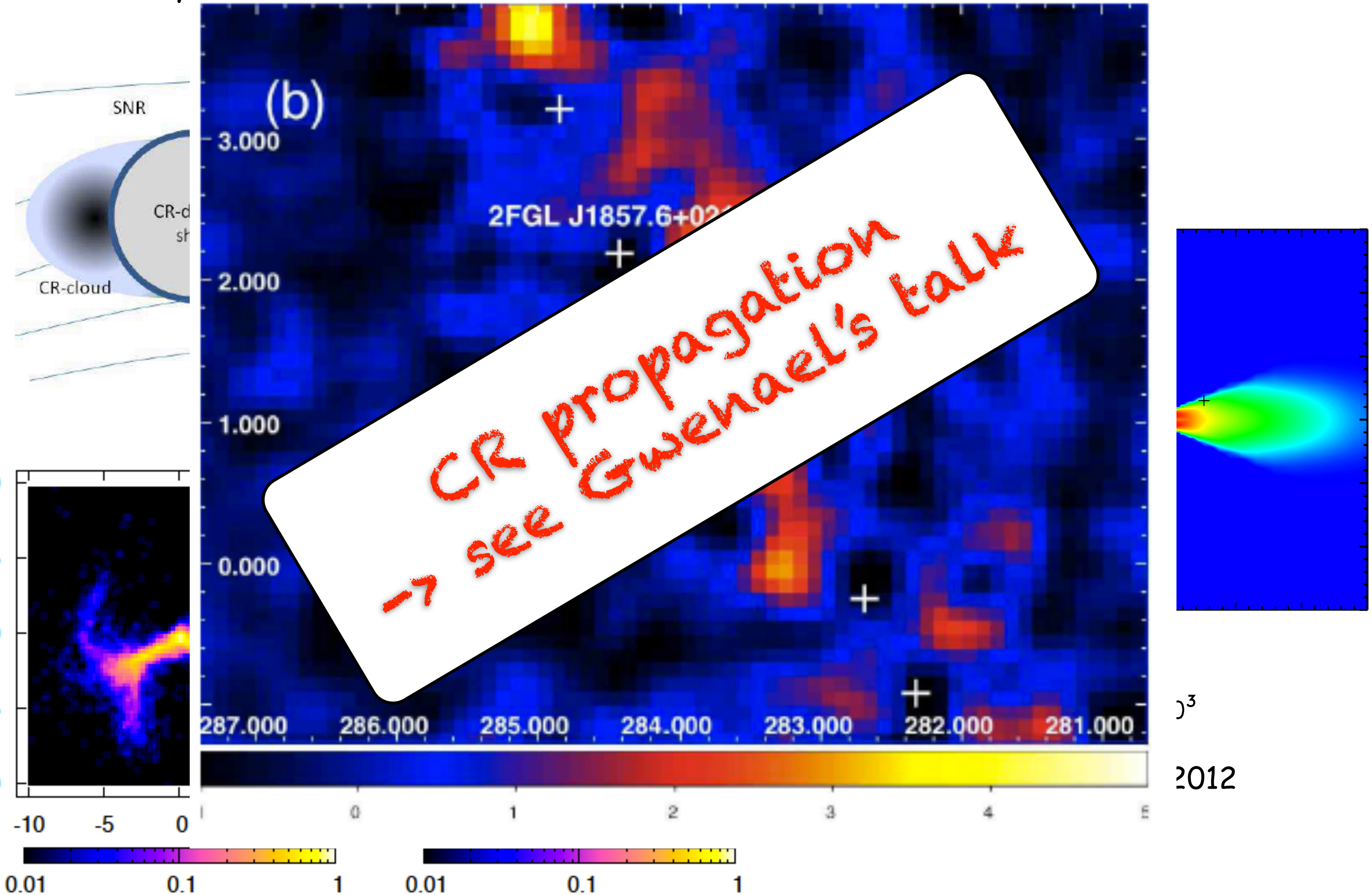

Giacinti et al. 2012

Shock acceleration: maximum energy

velocity

size

magnetic field

Hillas criterium -> $$E_{max} \approx u\ R\ B$$

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In numbers...

$$E_{max} \approx 1 \left(\frac{u}{1000\ \mathrm{km/s}} \right) \left(\frac{R}{\mathrm{pc}} \right) \left(\frac{B}{\mu \mathrm{G}} \right) \mathrm{TeV}$$

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~10 ~3 ~3

Lagage & Cesarsky 1983 -> $$E_{max} \approx 100 \text{ TeV}$$

well below the knee

Shock acceleration: maximum energy

velocity, size, magnetic field

Hillas criterium -> $$E_{max} \approx u\ R\ B$$

In numbers...

$$\left(\frac{B}{\mu \mathrm{G}}\right) \mathrm{TeV}$$

~10 ~3 ~3

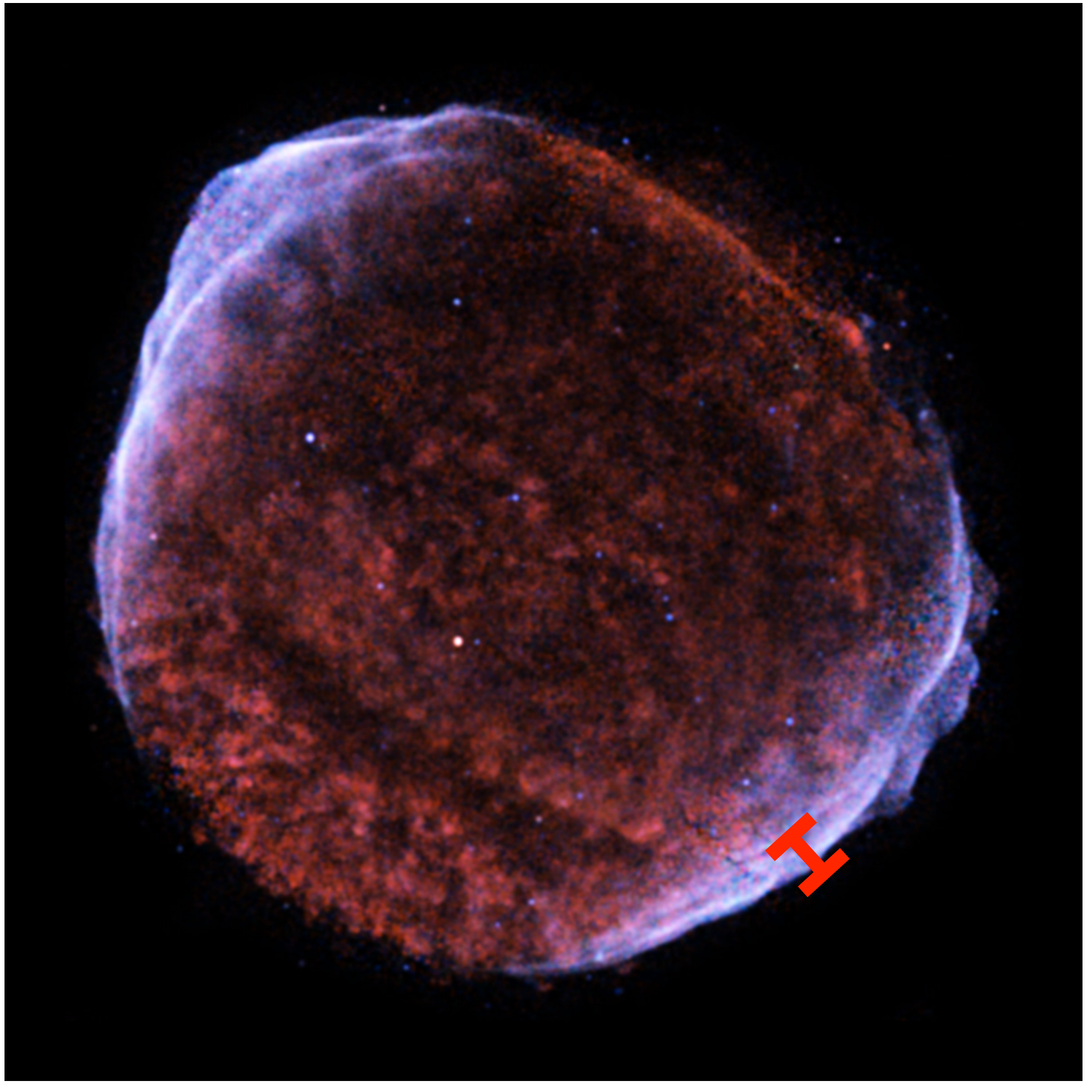
B is the only parameter we can play with

Lagage & Cesarsky 1983 -> $$E_{max} \approx 100\ \mathrm{TeV}$$

well below the knee

Magnetic field amplification: observations

Hughes et al.



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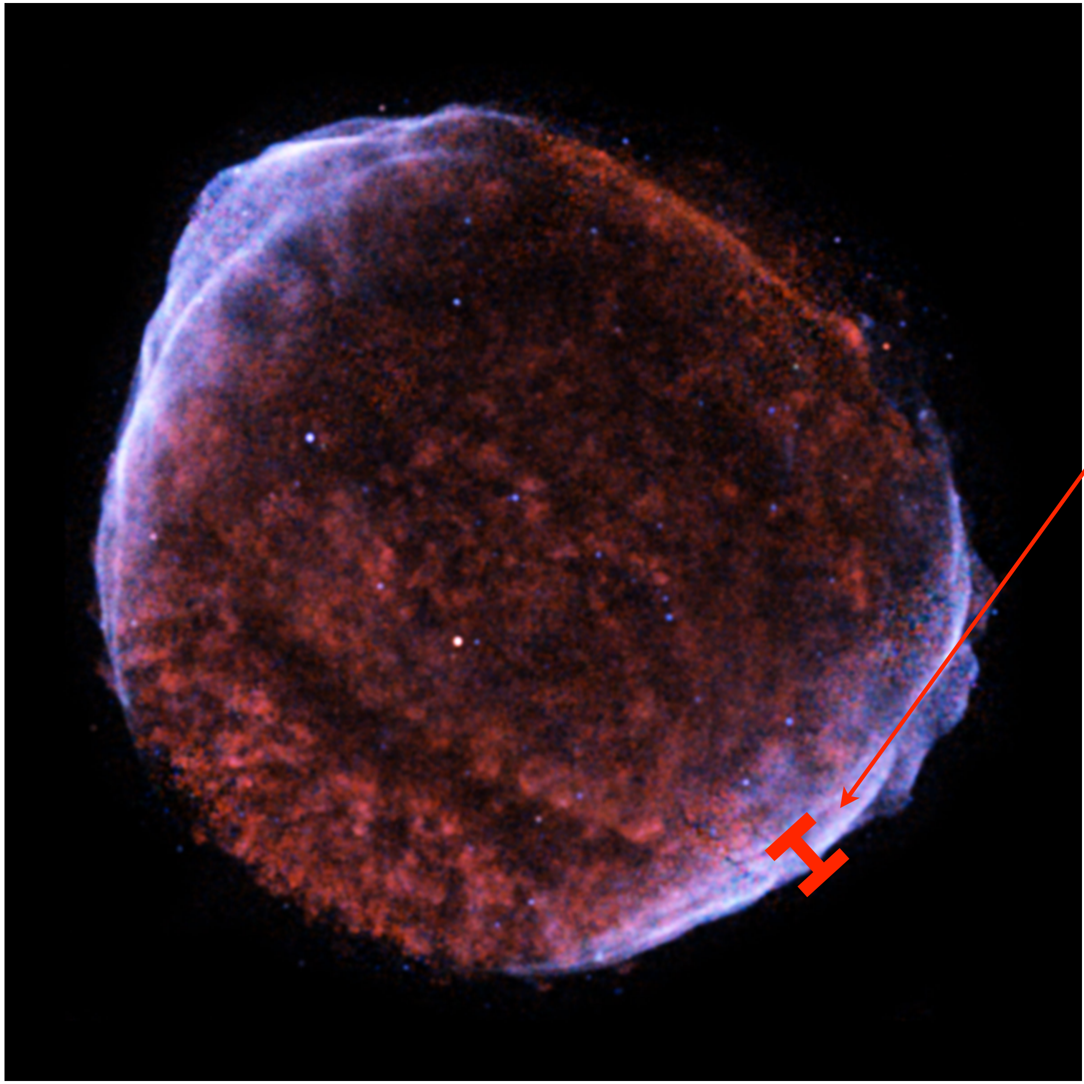


Hughes et al.

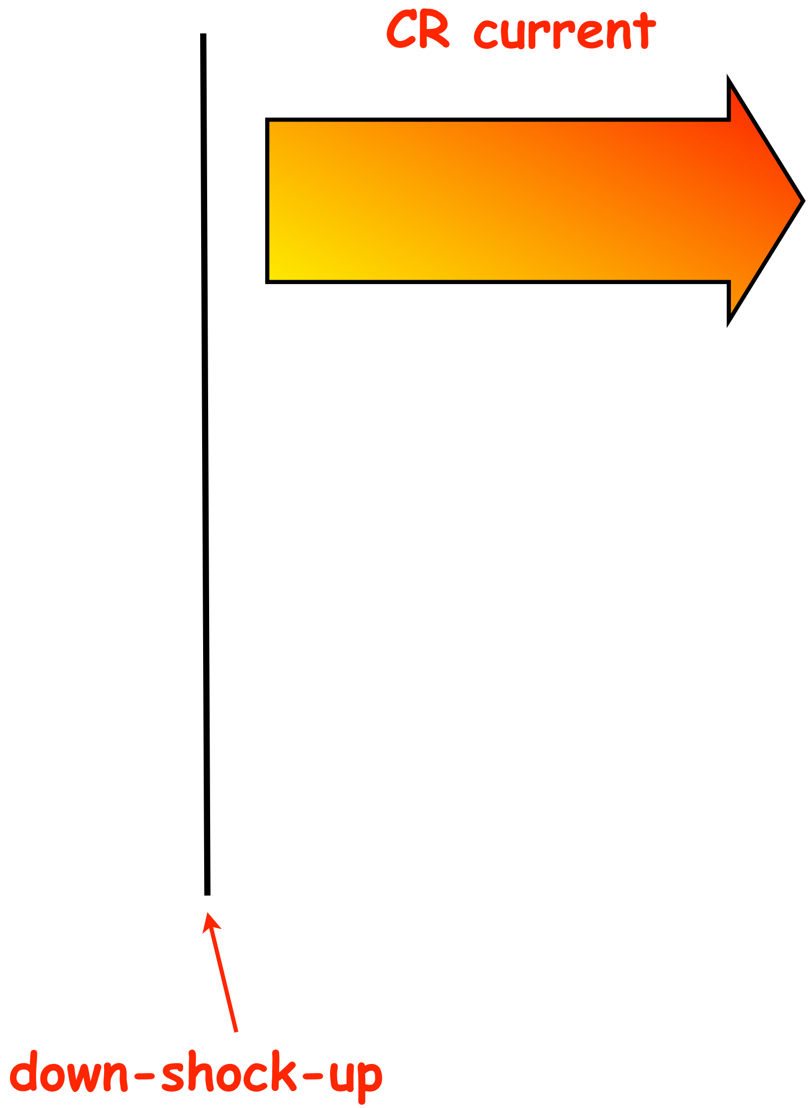
thickness (or, better, thinness, of the X-ray filaments
-> fast synchrotron losses
-> large B-field)

$$B \approx 100 \div 1000 \ \mu\mathrm{G}$$

Vink & Laming, Bamba et al., Uchiyama & Aharonian ...

Magnetic field amplification: theory

Non-resonant instability



Bell 2004

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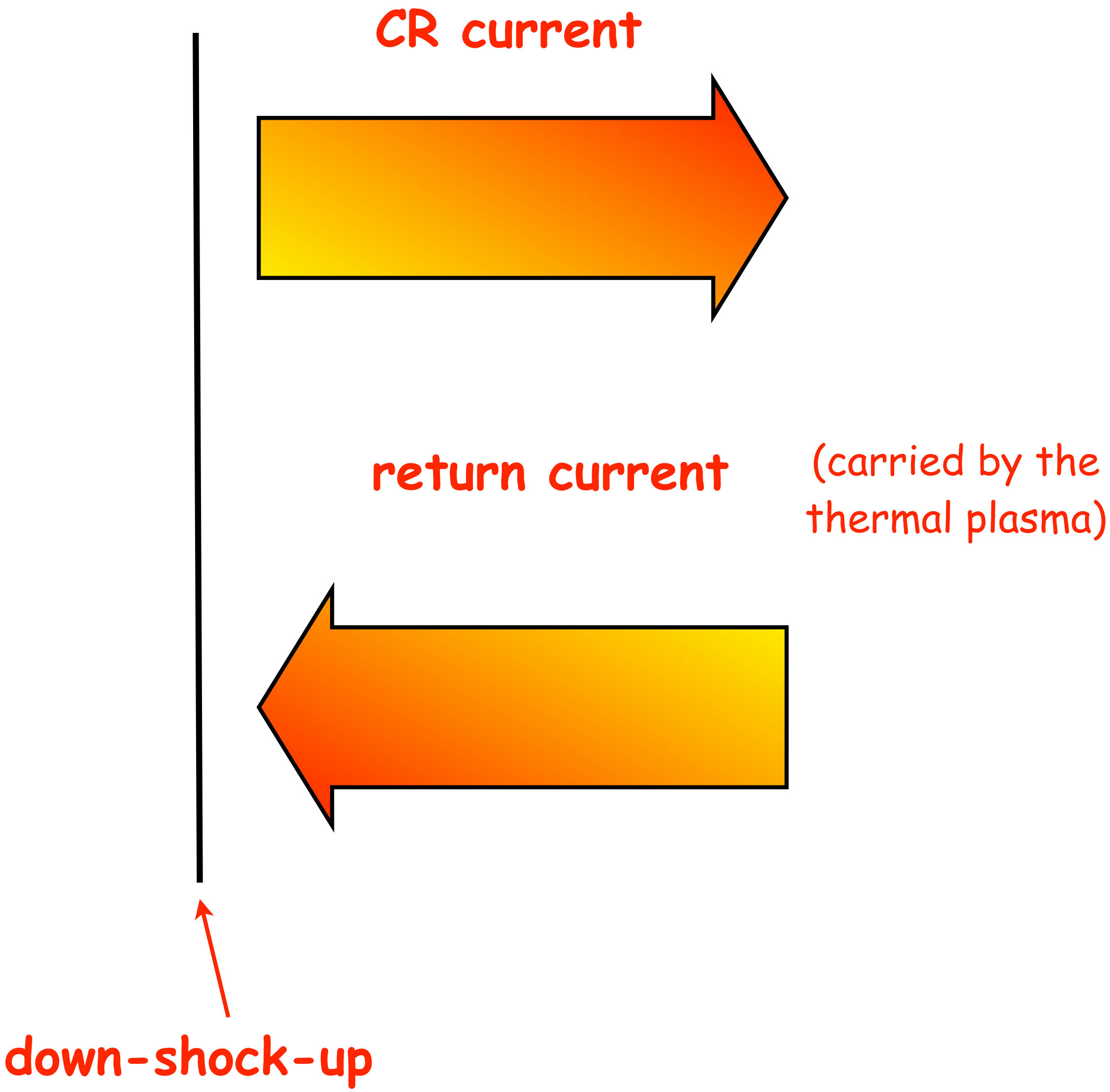

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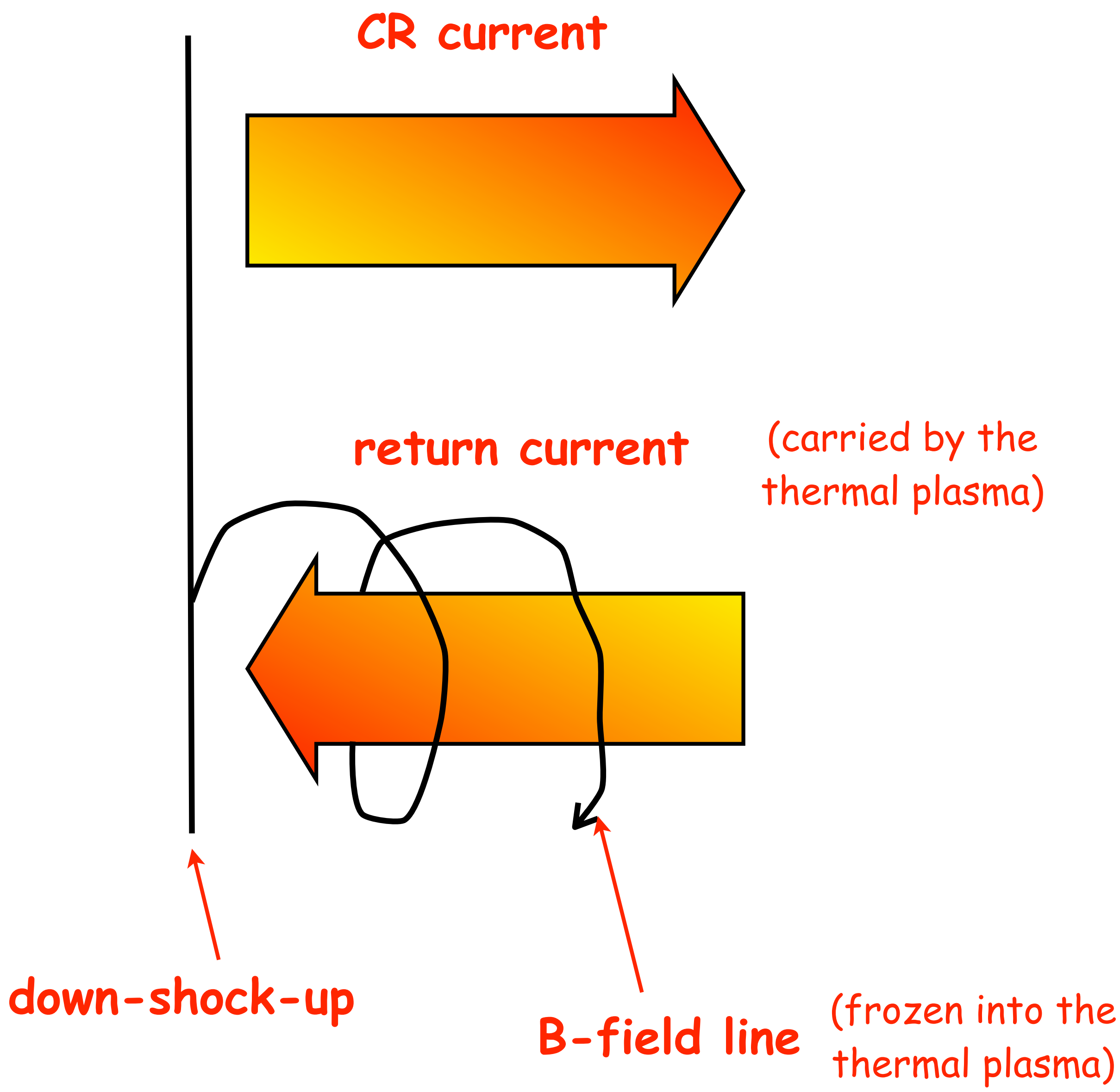

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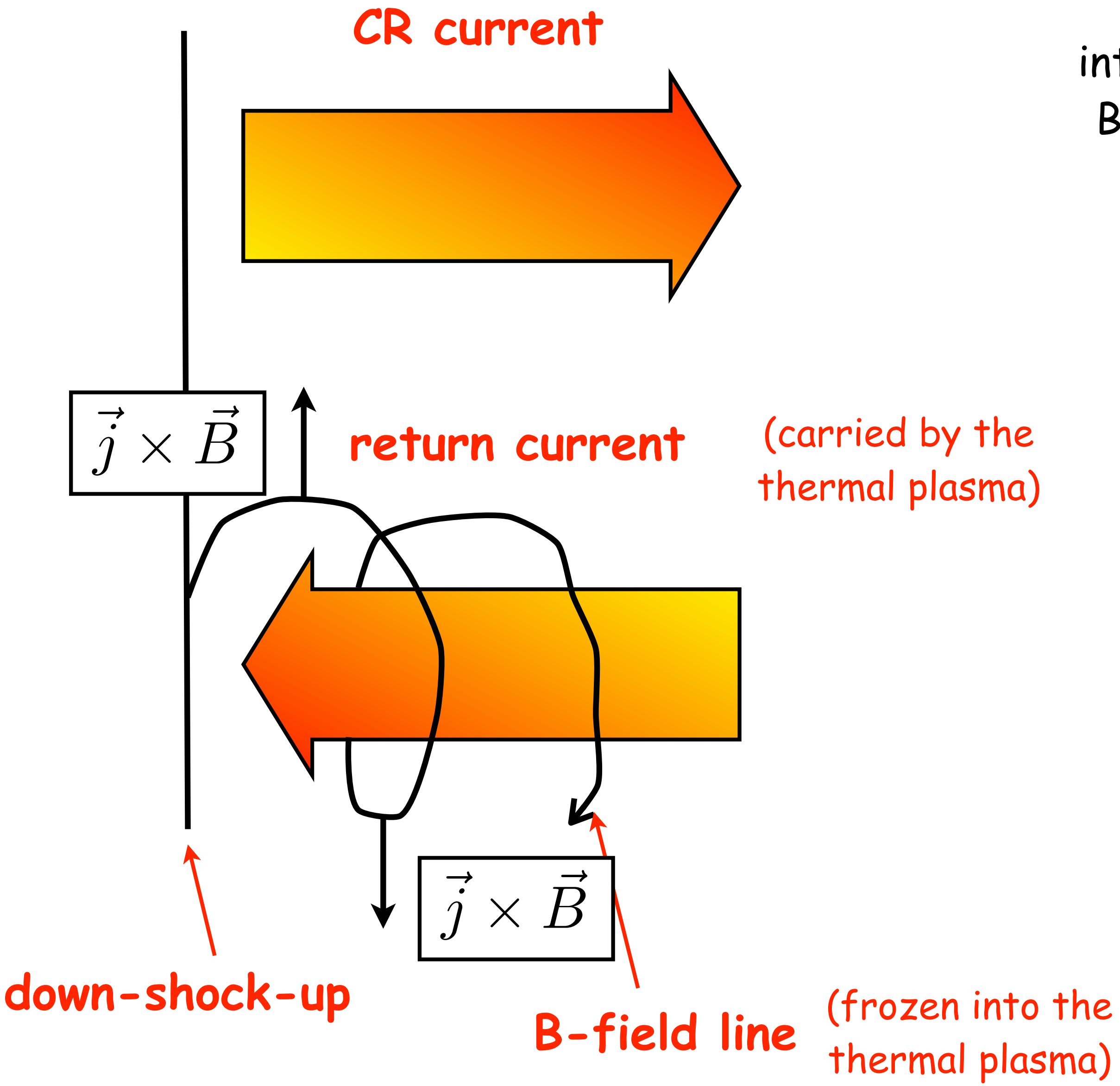

interaction between return current and B-field sets the background plasma in motion and drives the instability

Bell 2004

Magnetic field amplification: theory

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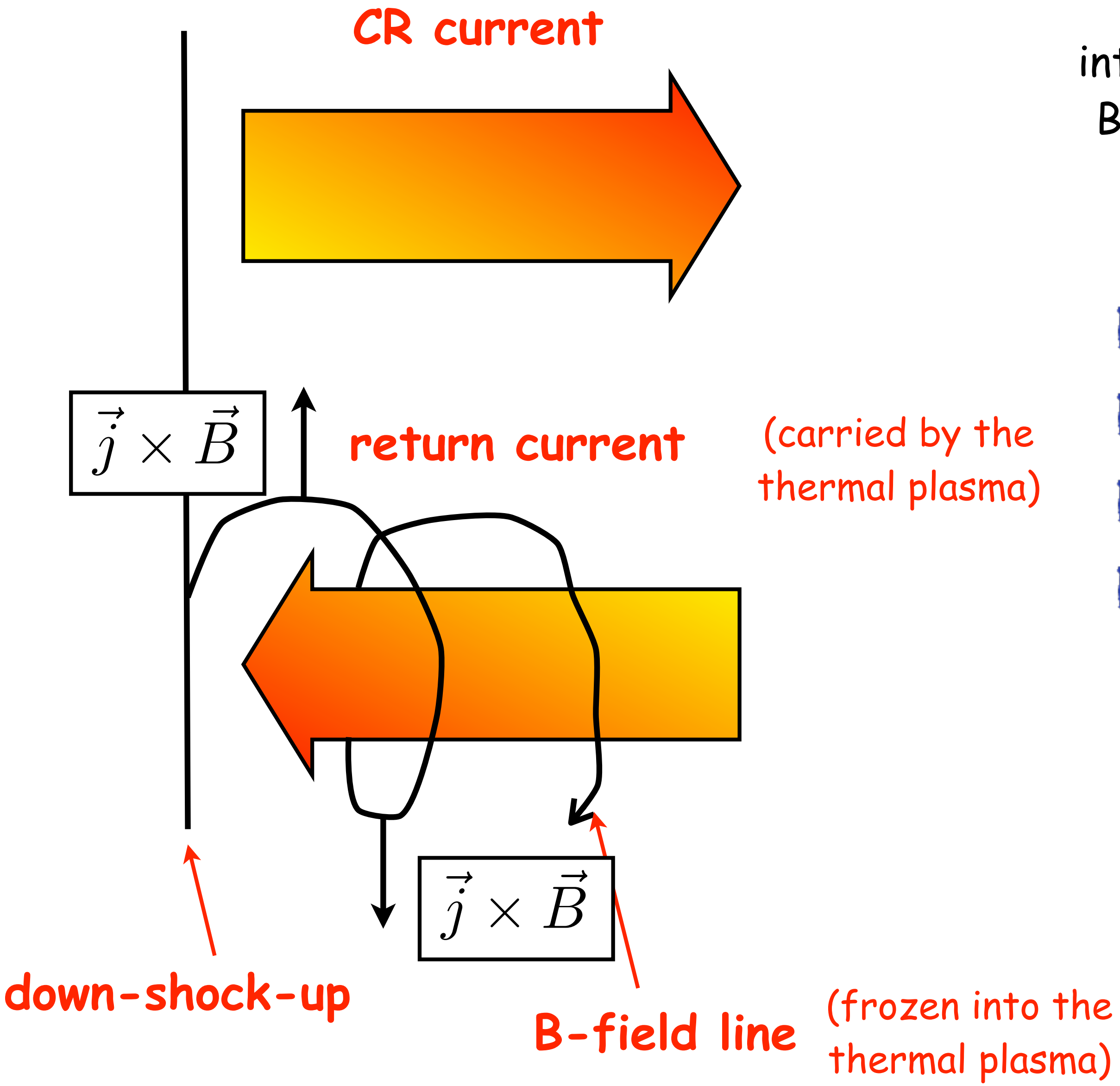

interaction between return current and B-field sets the background plasma in motion and drives the instability

- ☑ j x B force expands the spiral
- ☑ lengthens B-field lines
- ☑ increases B-field
- ☑ increase j x B force!

instability!

Bell 2004

Maximum energy

B-field amplification (observed/predicted) up to a factor of 100-1000

Simple minded approach-> $E_{max} \approx u \, R \, B$ x 100

up to the knee

keep this in mind

Physical approach

$$E_{max} \approx 230 \ \eta_{0.03} \left(\frac{n_e}{\mathrm{cm}^{-3}} \right)^{1/2} \left(\frac{u}{10000 \ km/s} \right)^2 \left(\frac{R_{sh}}{\mathrm{pc}} \right) \ \mathrm{TeV}$$

historical SNRs (CasA,Tycho,SN1006 are too old (!) to accelerate up to the knee! -> PeVatrons are very young (< 100 yr)

Bell et al. 2013

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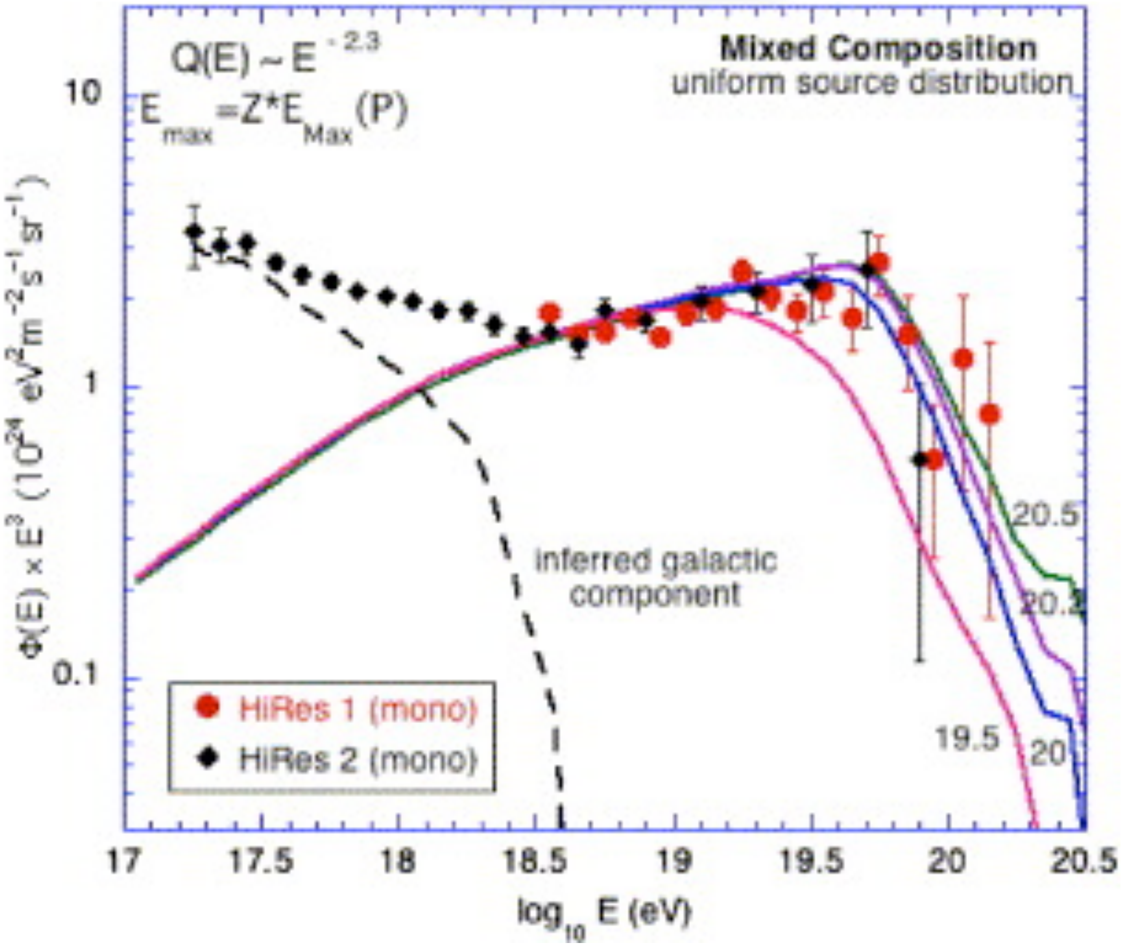
~1 PeVatron in the Galaxy :-(

historical SN… …006 are too old (!) to accelerate up to th… …evatrons are very young (< 100 yr)

Bell et al. 2013

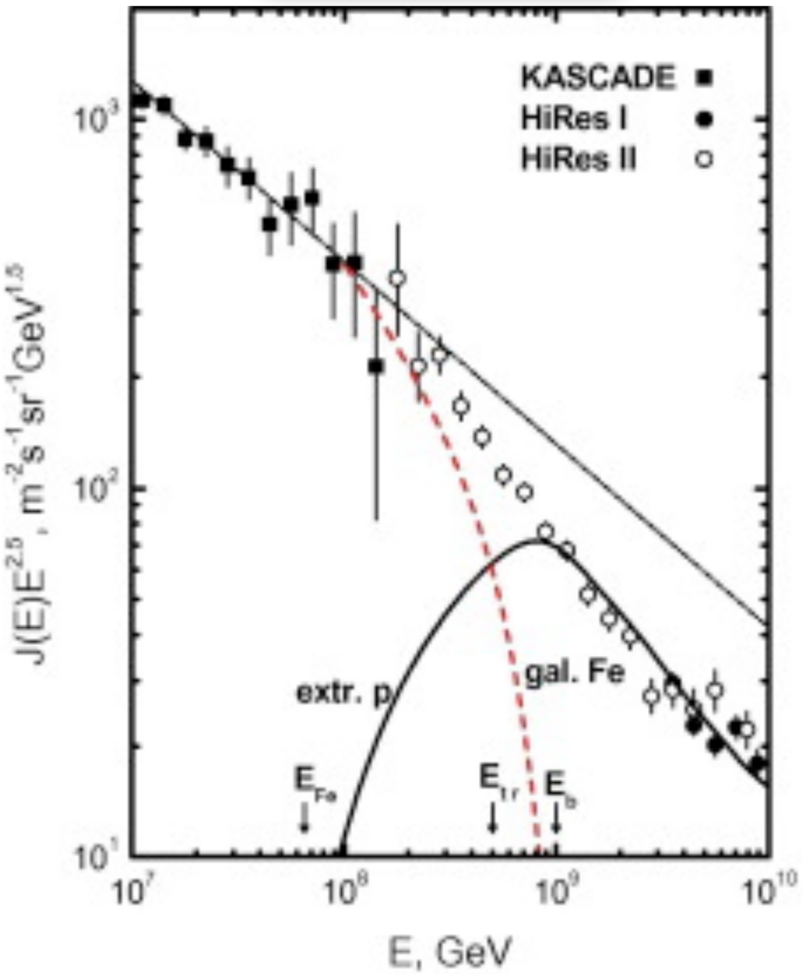
Where is the transition?

ankle



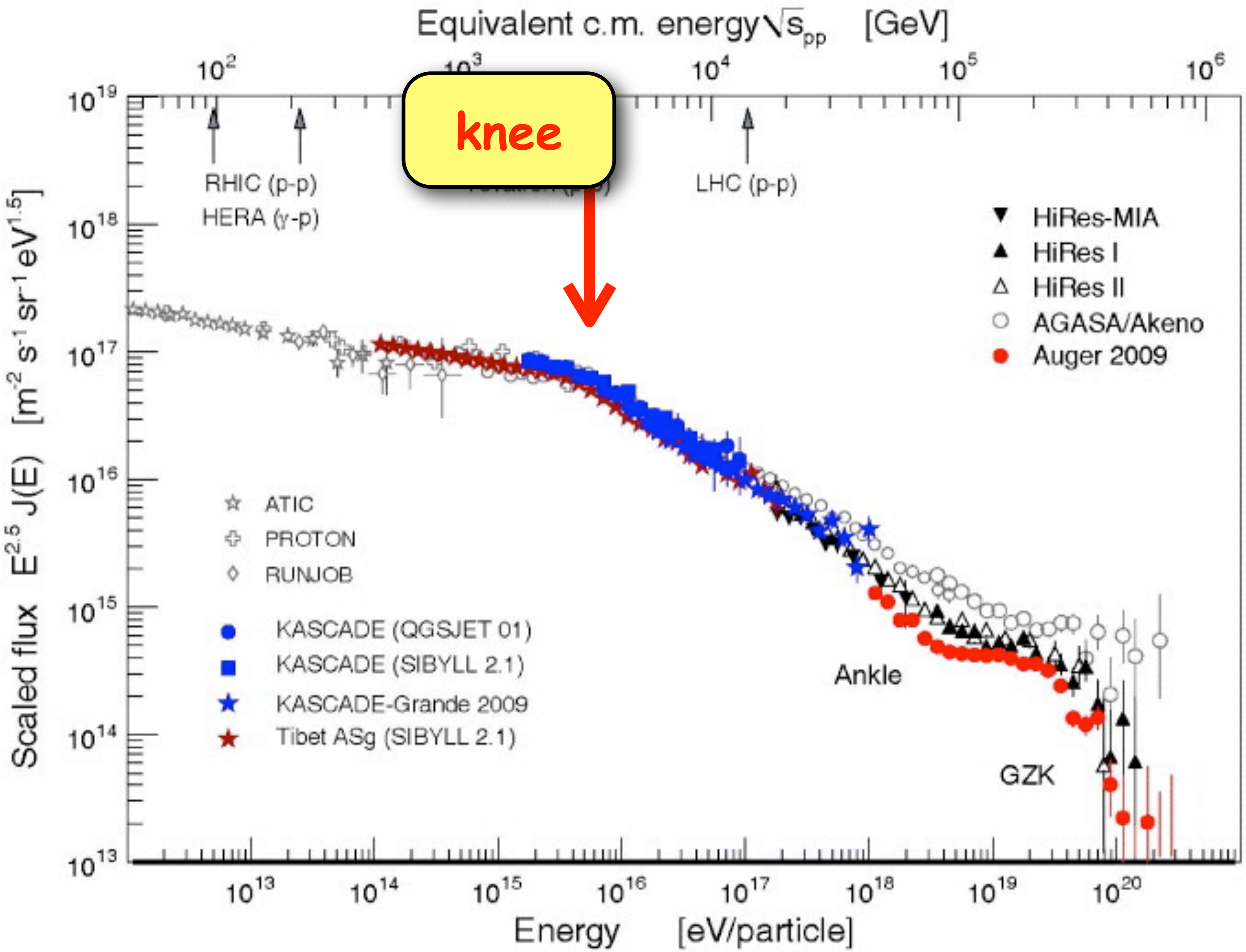
Allard et al.

second knee



Aloisio et al.

How far can SNRs go?



is this a problem for the ankle scenario?

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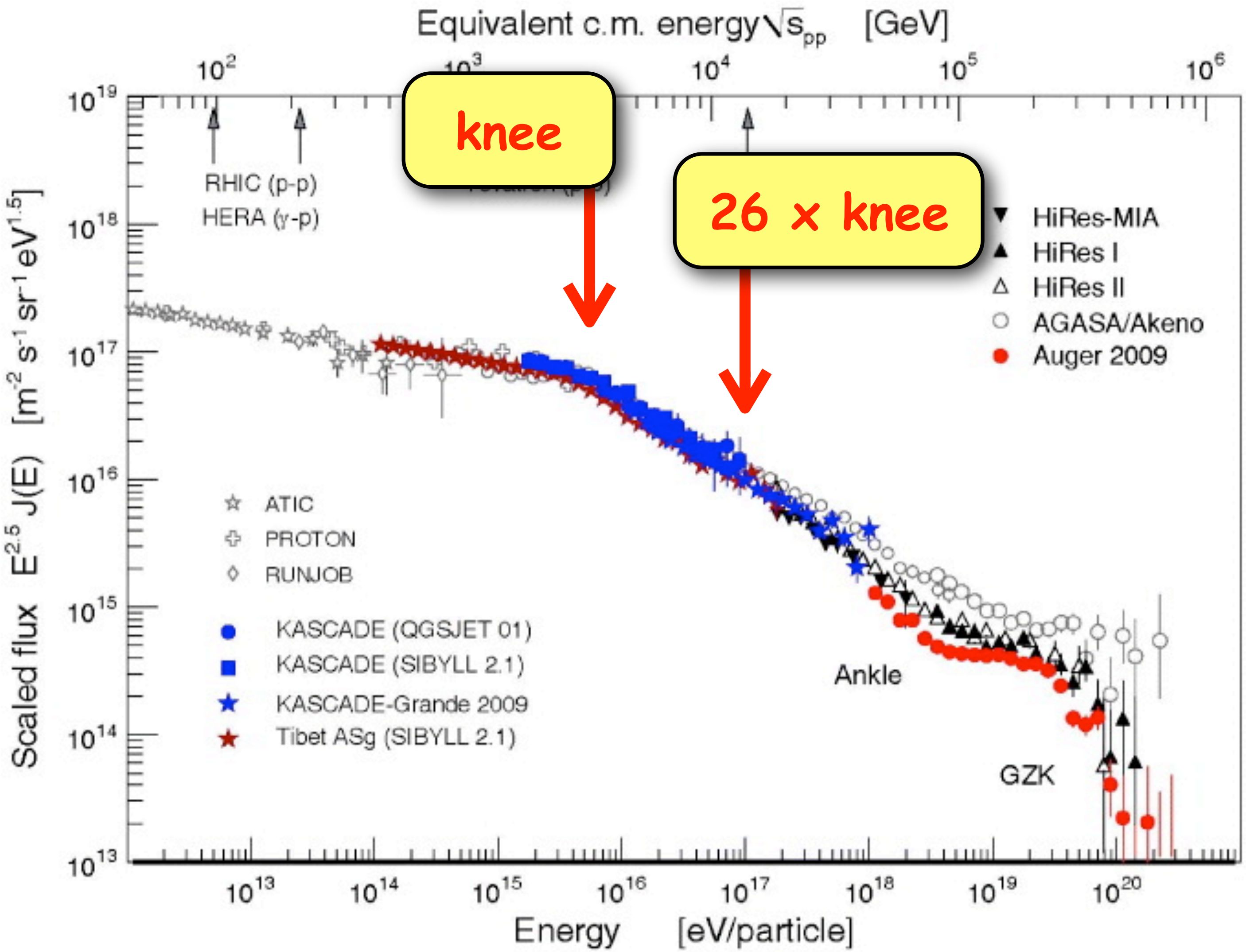

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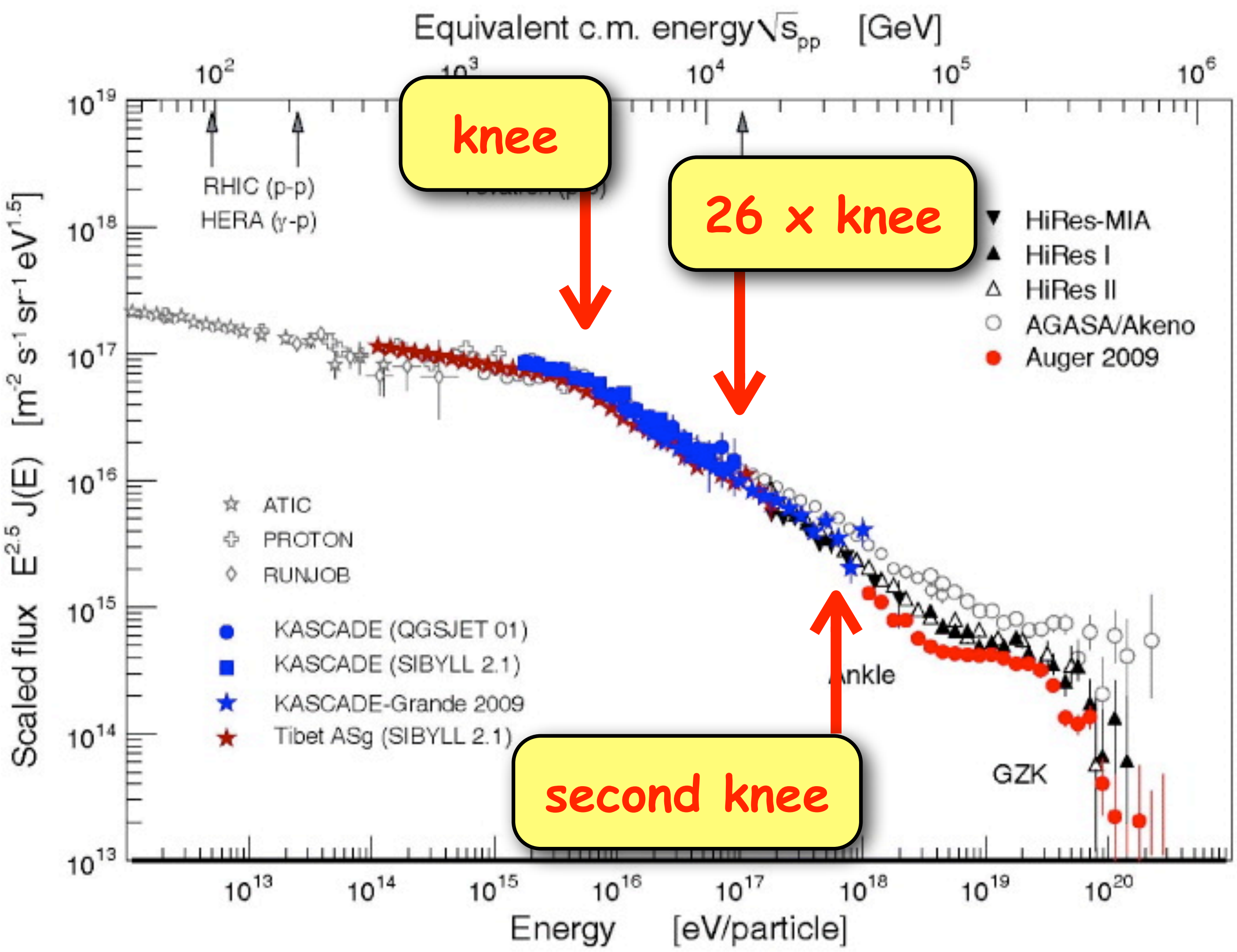

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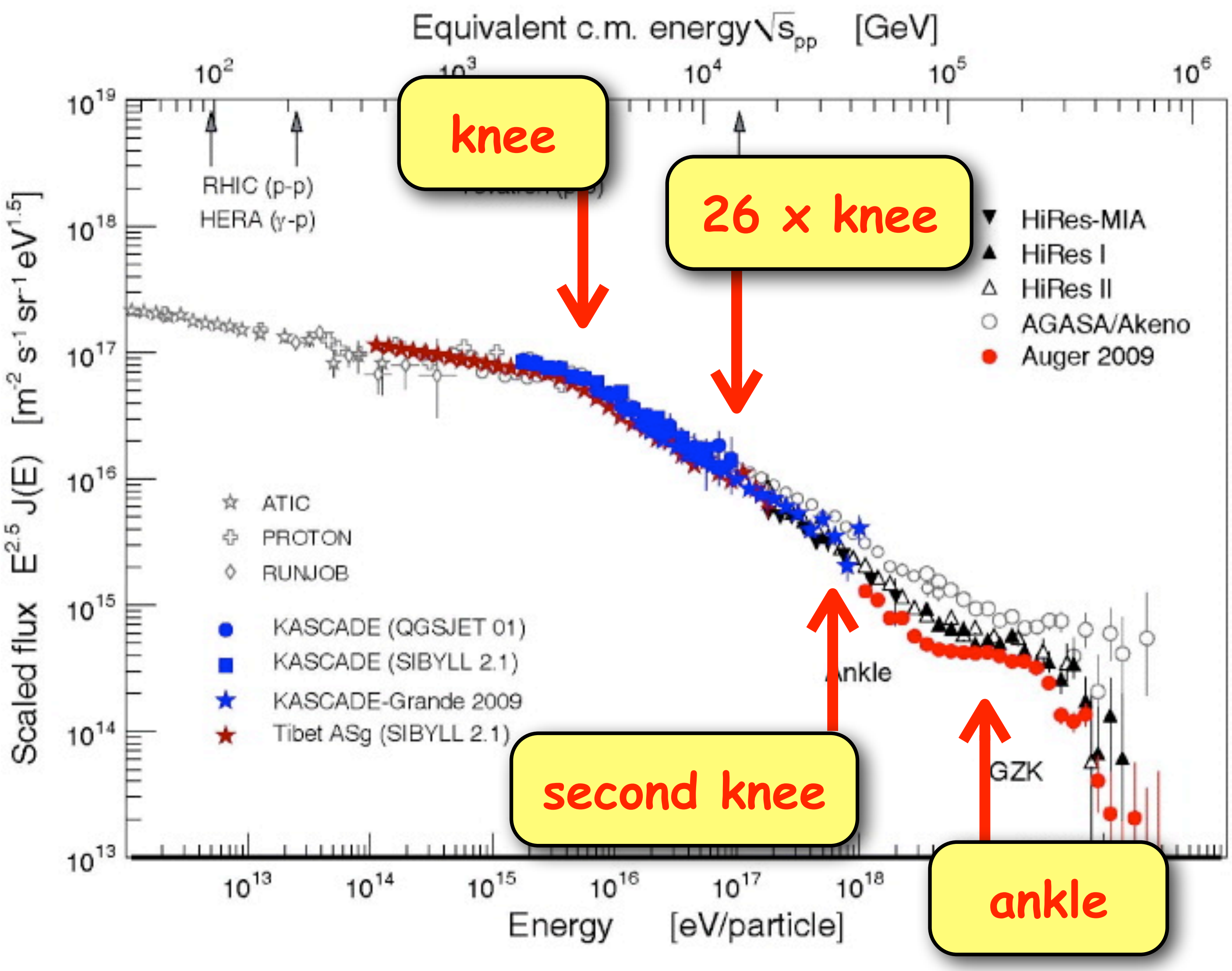
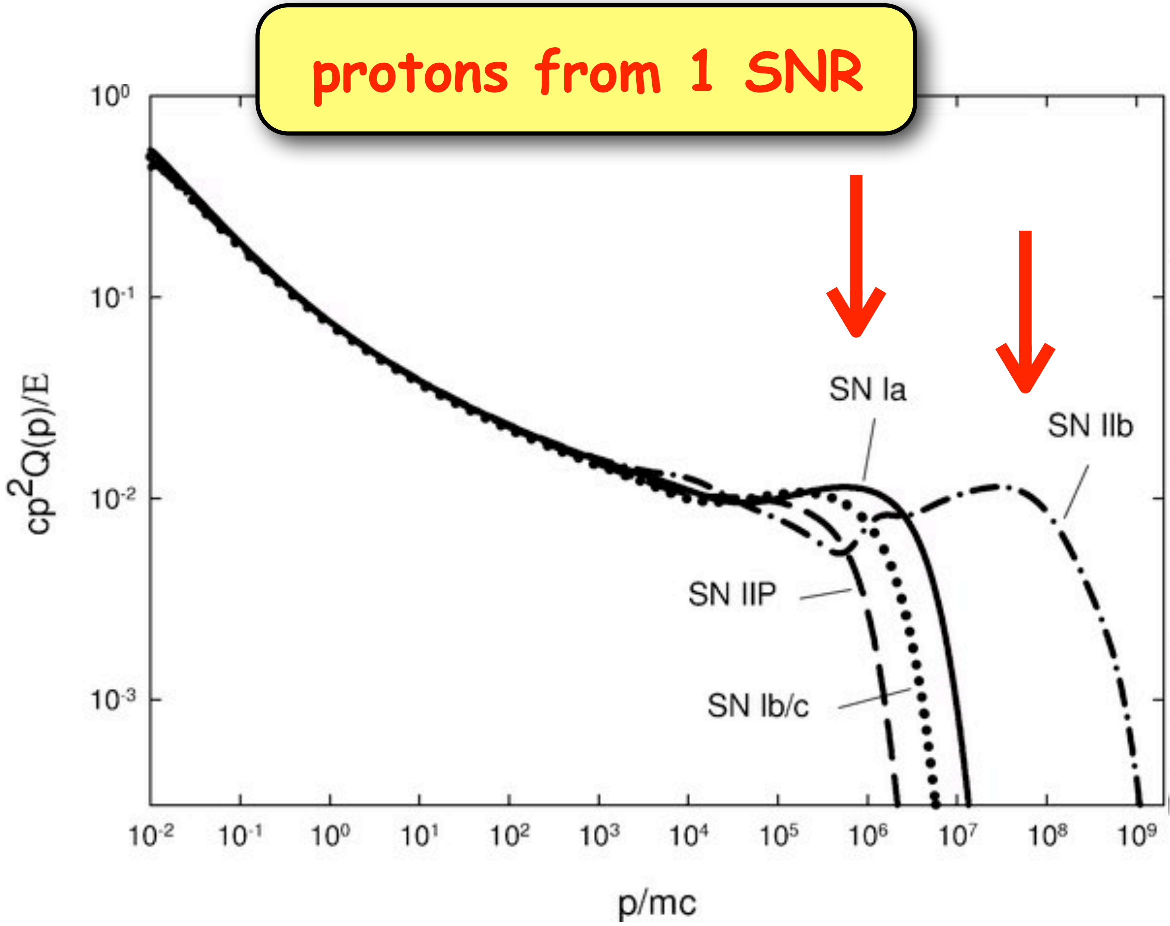


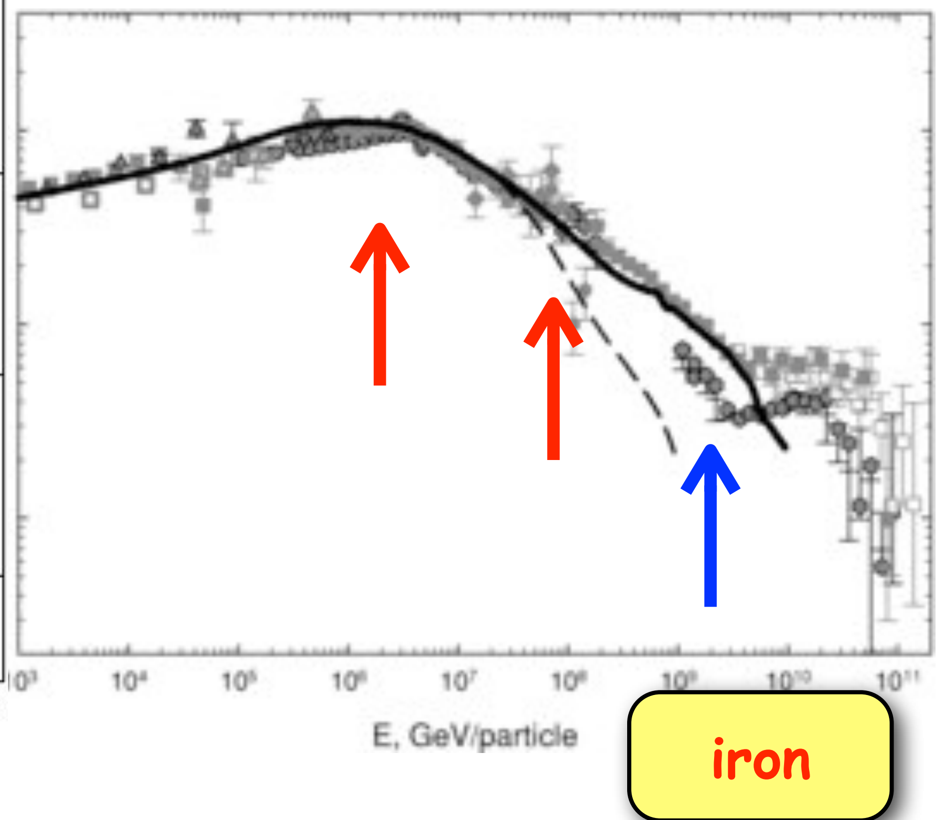
is this a problem for the ankle scenario?

Possible solution: SNe IIb

quite small explosion rate... but...

SN IIb explode in a very dense wind -> $E_{max} \propto n_{gas}^{1/2}$



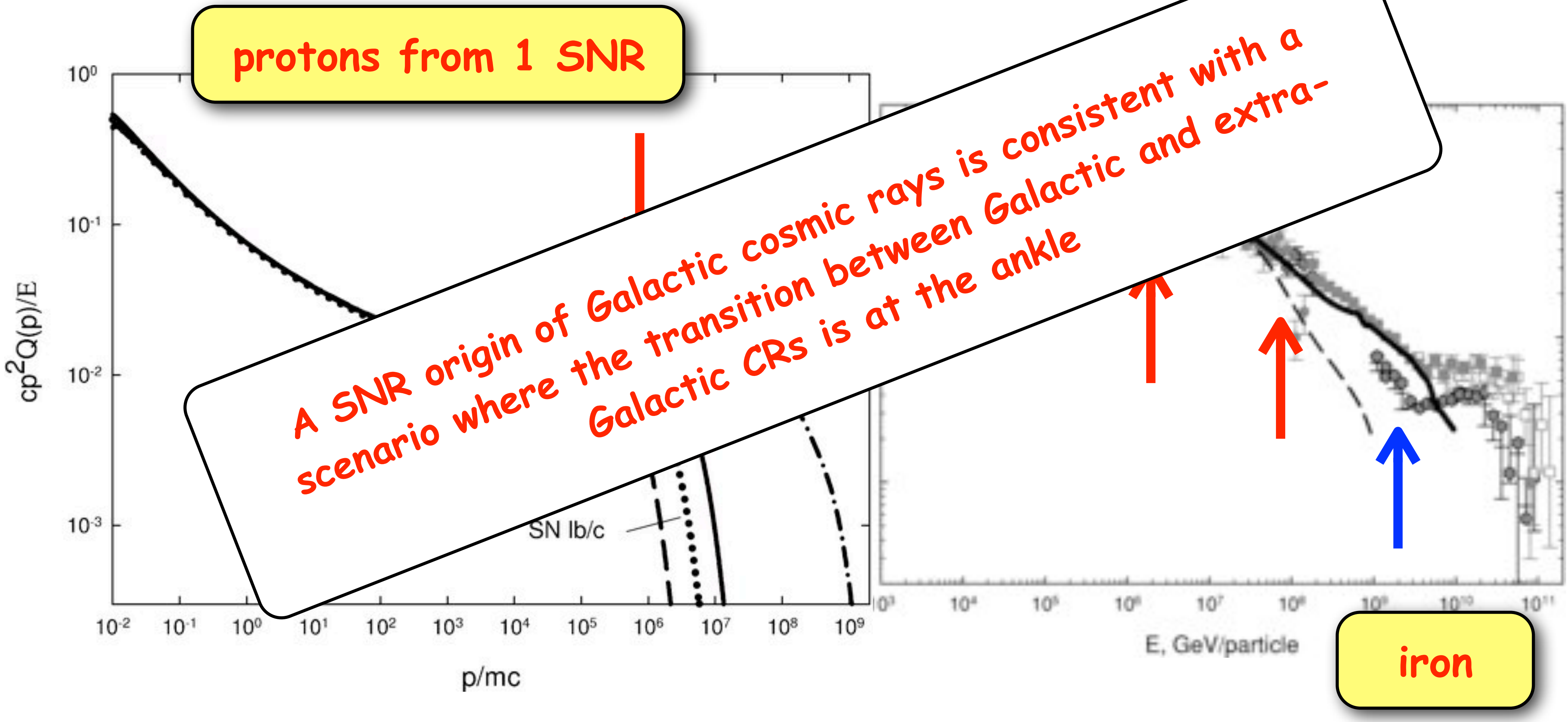


Ptuskin et al. 2010

Possible solution: SNe IIb

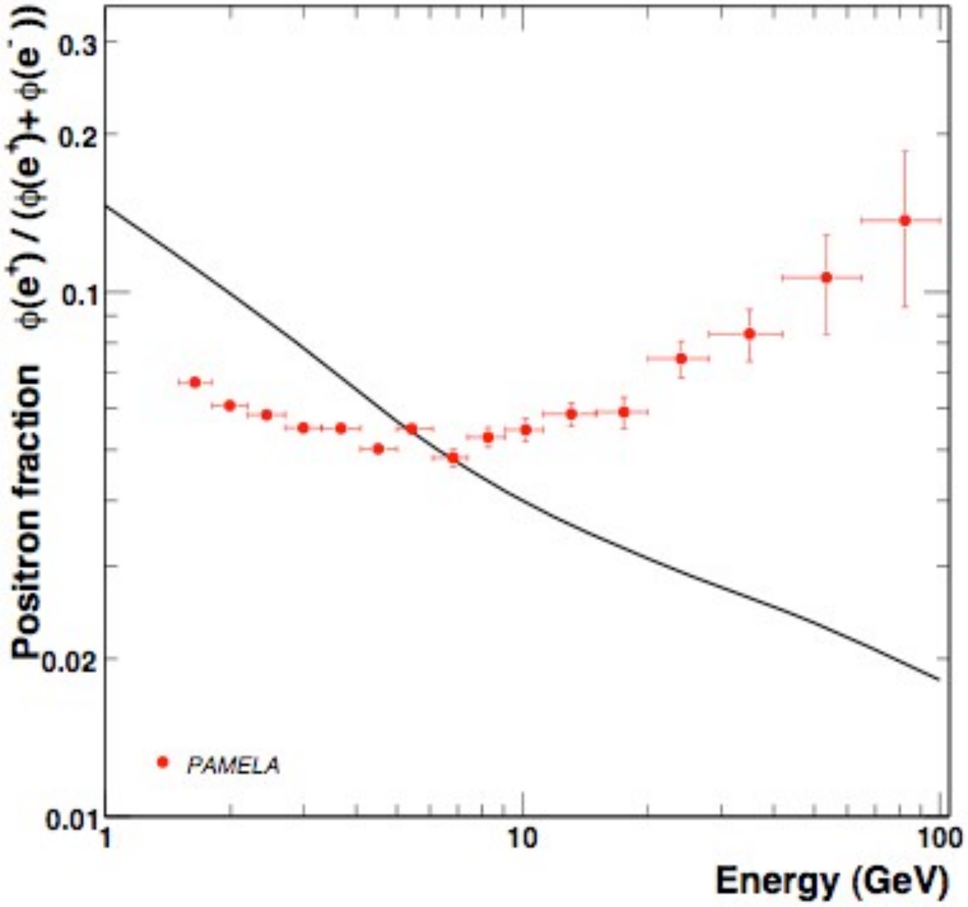
quite small explosion rate... but...

SN IIb explode in a very dense wind -> $E_{max} \propto n_{gas}^{1/2}$



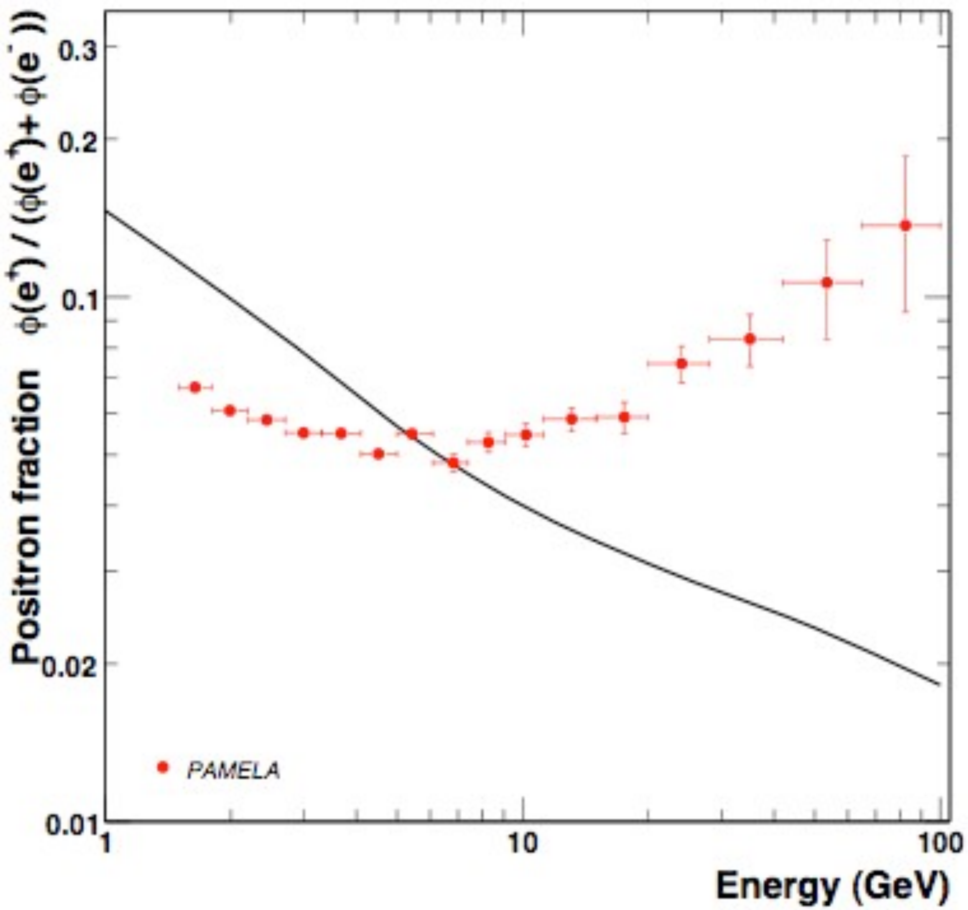
Ptuskin et al. 2010

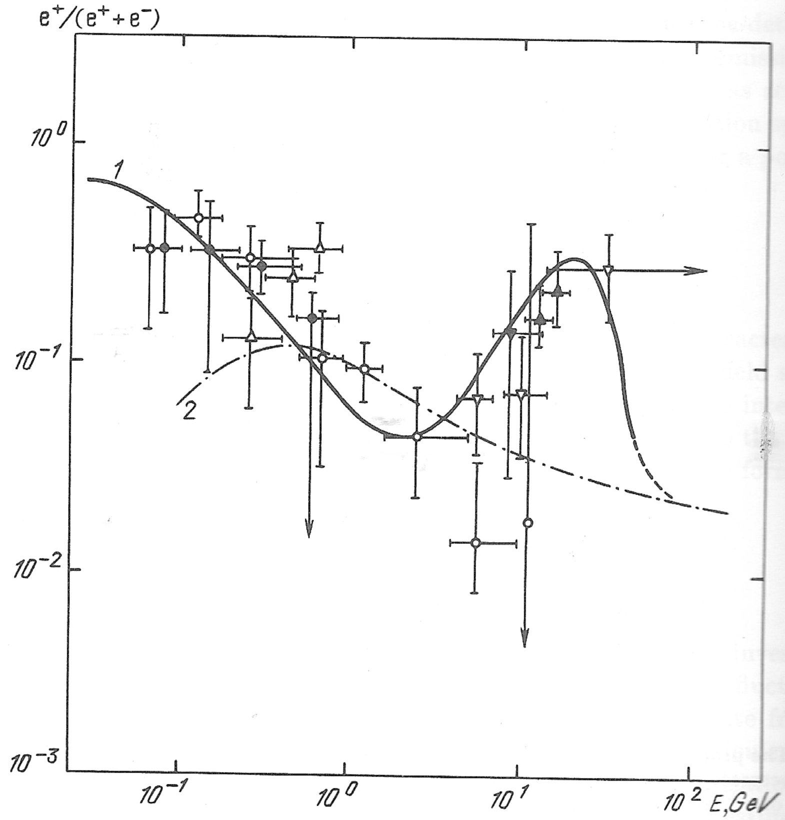
Positron fraction excess



Adriani et al. 2009

Positron fraction excess



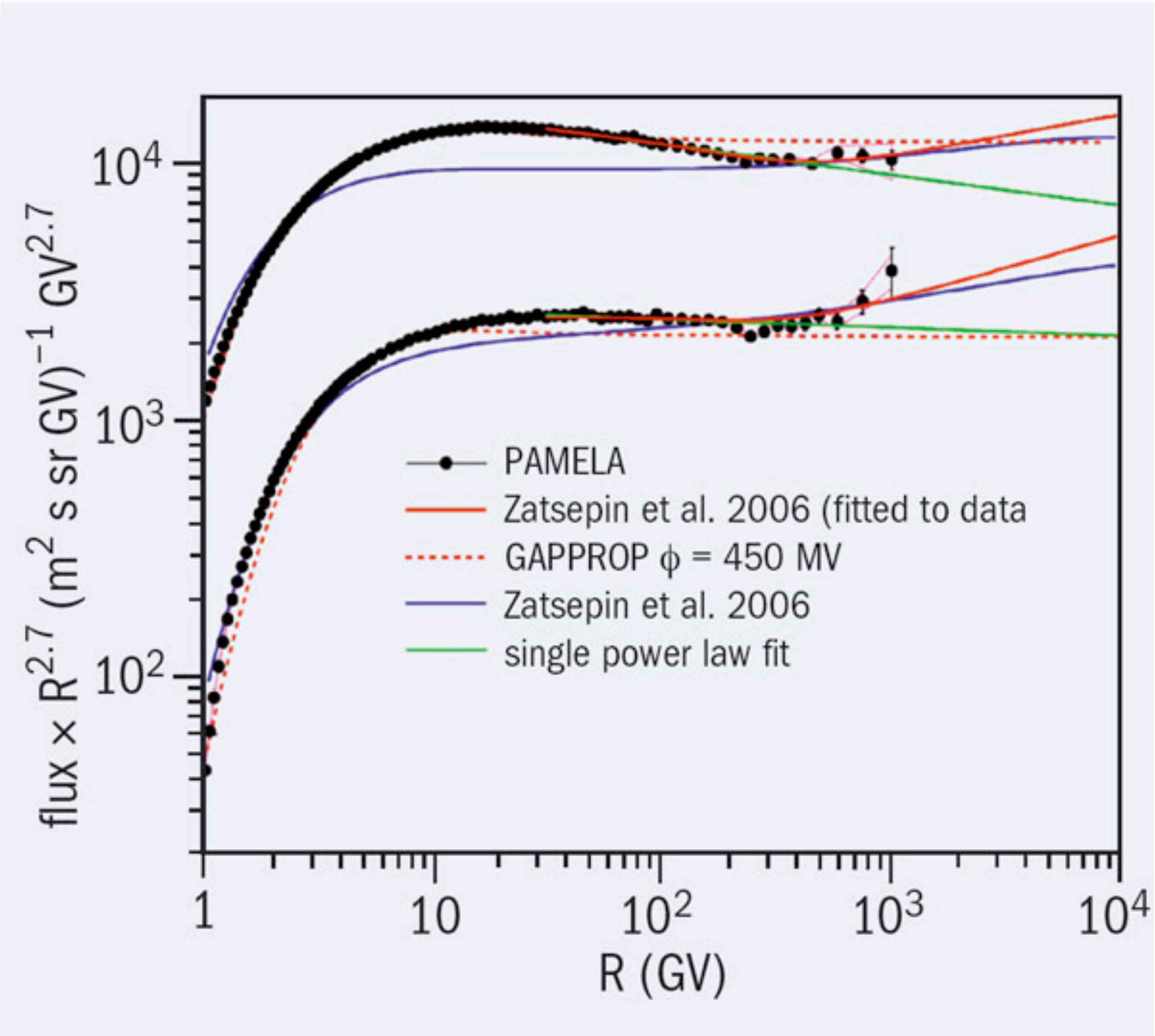


;. 5.28. The observed and the calculated ratio of the positron density (e^+) to the sum of the ;itron and electron densities ($e^+ + e^-$) close to the Earth. Curve 2 corresponds to the calculations in the framework of the standard diffusion model, and curve 1 to the calculation in the framework of a diffusion model with acceleration of the particles in molecular clouds.

Adriani et al. 2009

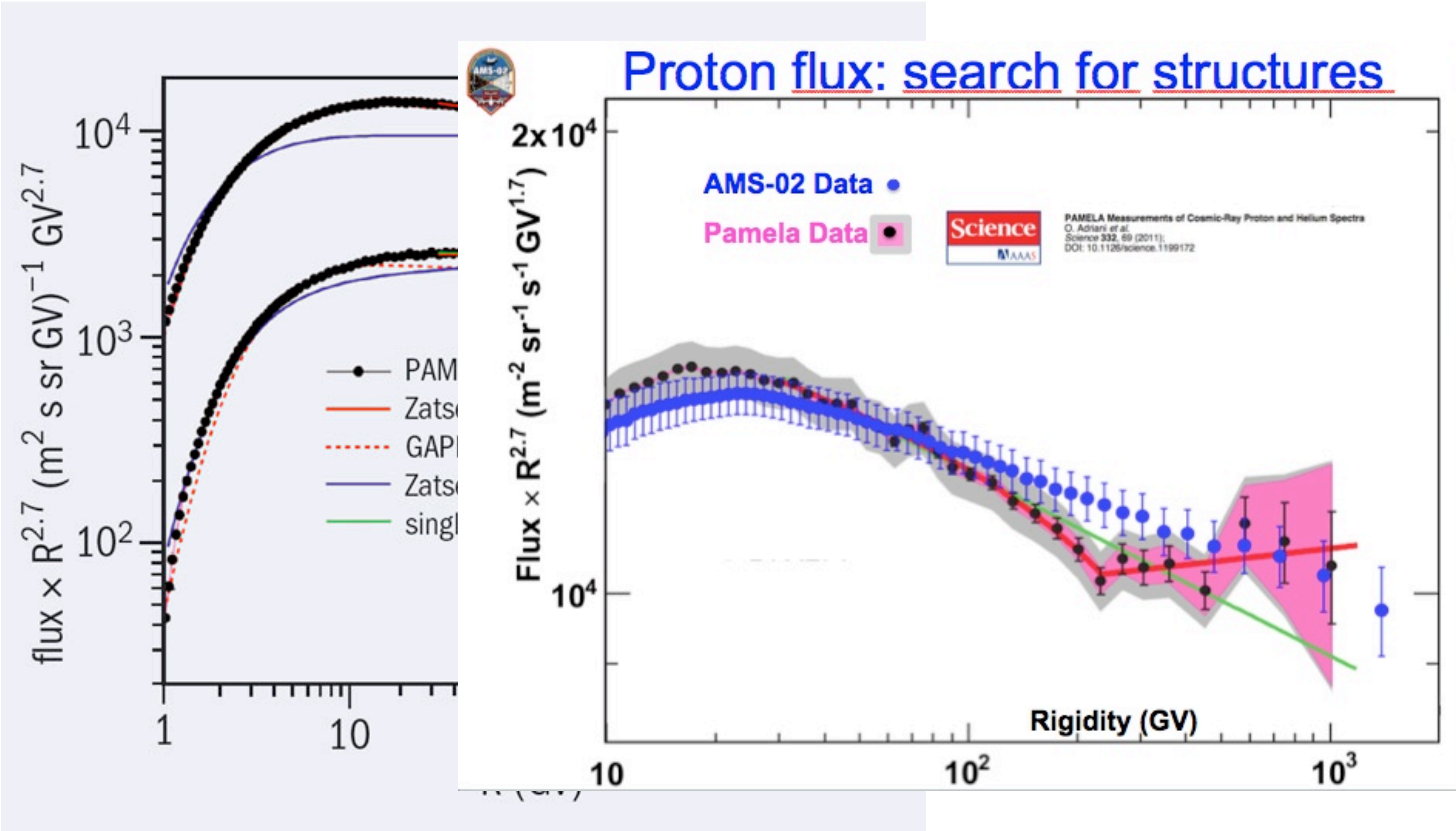
Berezinskii et al. 1990

Breaks in H and He spectra



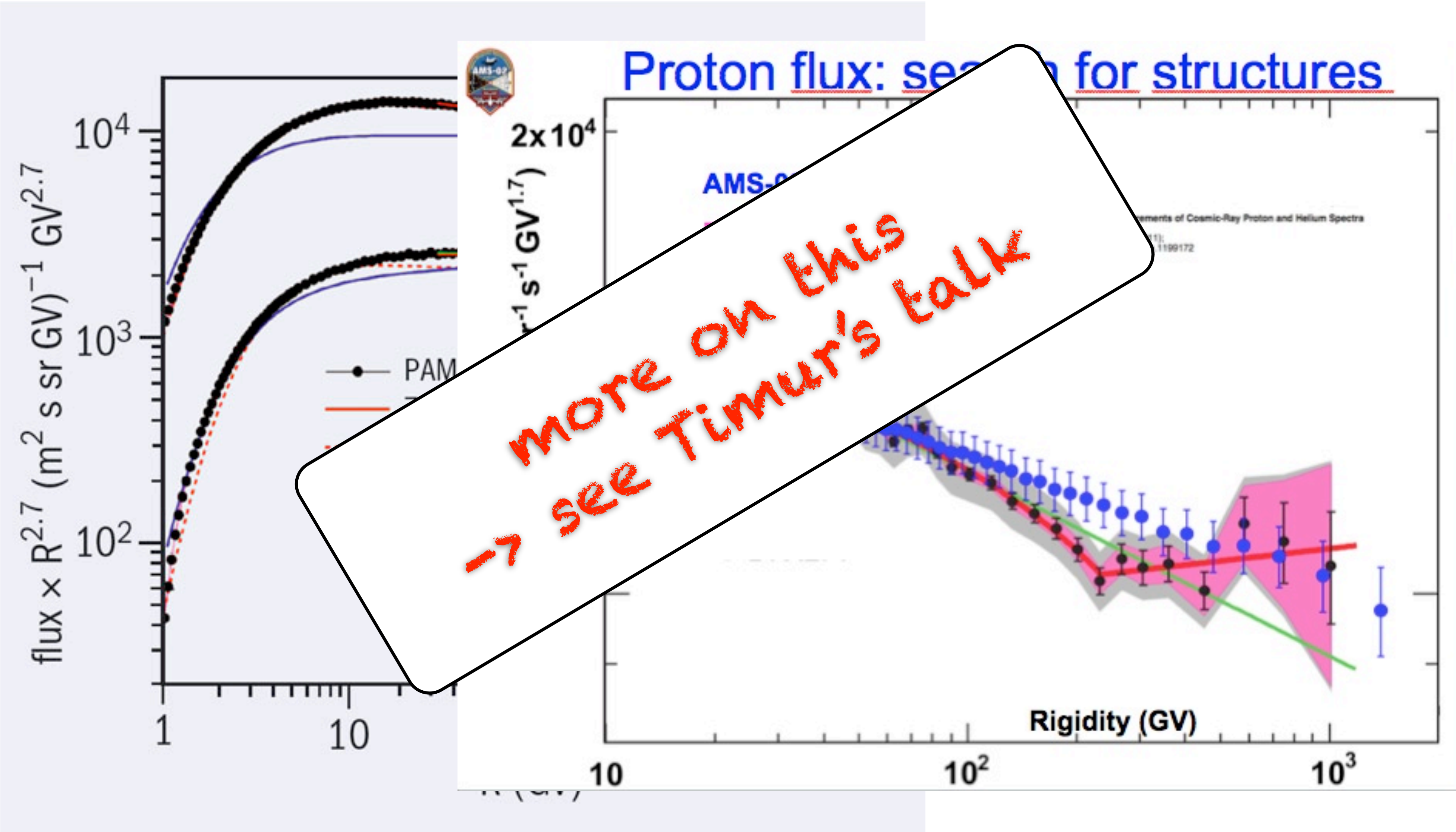
Adriani et al. 2011

Breaks in H and He spectra



Adriani et al. 2011

Breaks in H and He spectra



Adriani et al. 2011

Conclusions

what we know

-> SNRs accelerates particles (electrons up to ~100 TeV)
-> SNRs are bright VHE gamma-ray sources (Drury et al test -> passed)
-> current Cherenkov telescopes detected an "appropriate" number of SNRs (another test passed)
-> some SNRs seem to accelerate protons (e.g. Tycho, also W44 & IC443 but this is another story)

do SNRs accelerate CRs up to the knee?

-> we don't know (no direct observational evidence yet)
-> we think they might (Bell instability, X-ray filaments)
-> possible test: detect 100 TeV photons (or neutrinos...)
-> doable? (~1 PeVatron in the MW)
-> other ways? -> molecular clouds? X-rays? other ideas?