Cosmic ray origin and gamma-ray astronomy above 1 TeV

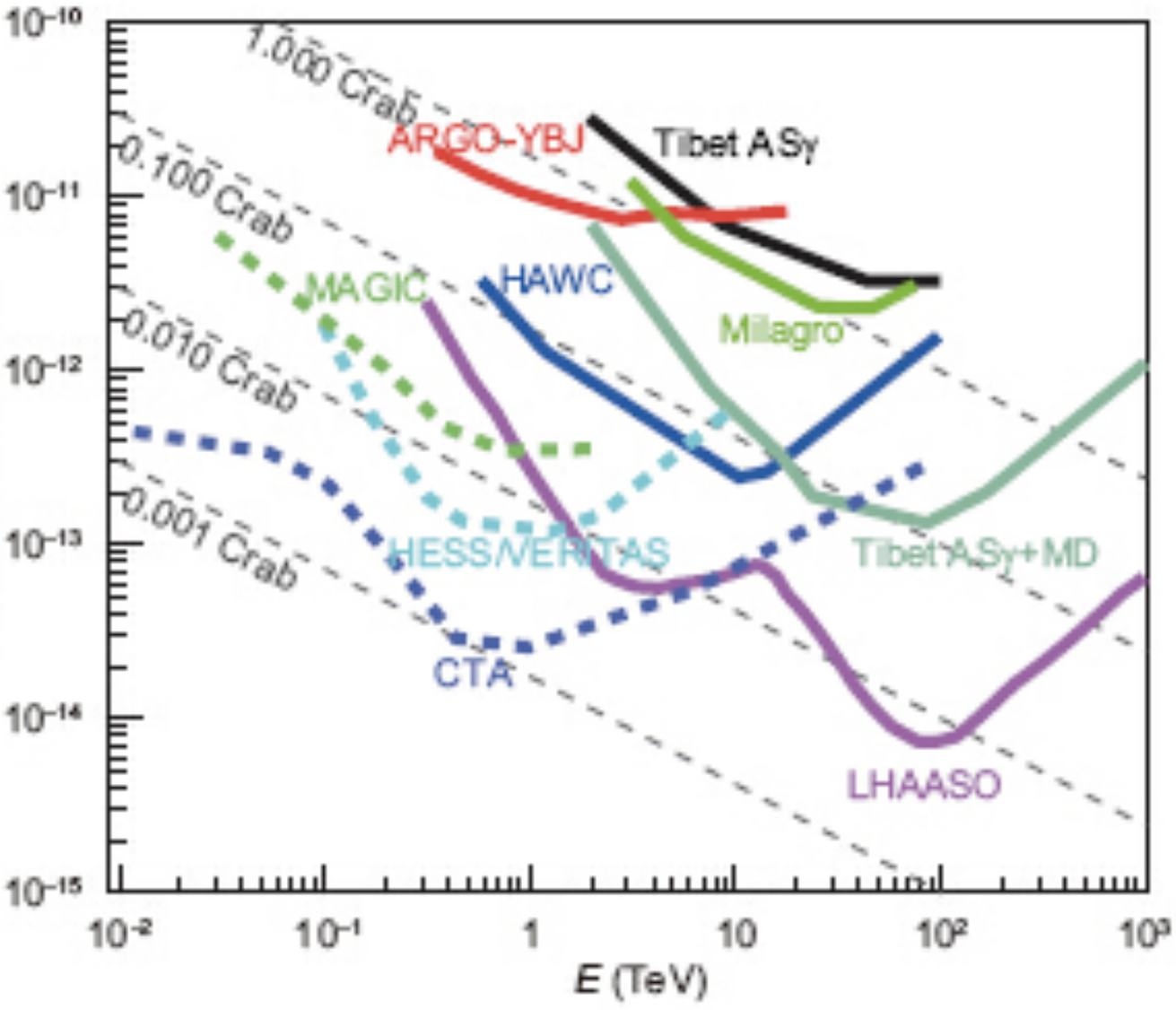
Stefano Gabici
APC, Paris

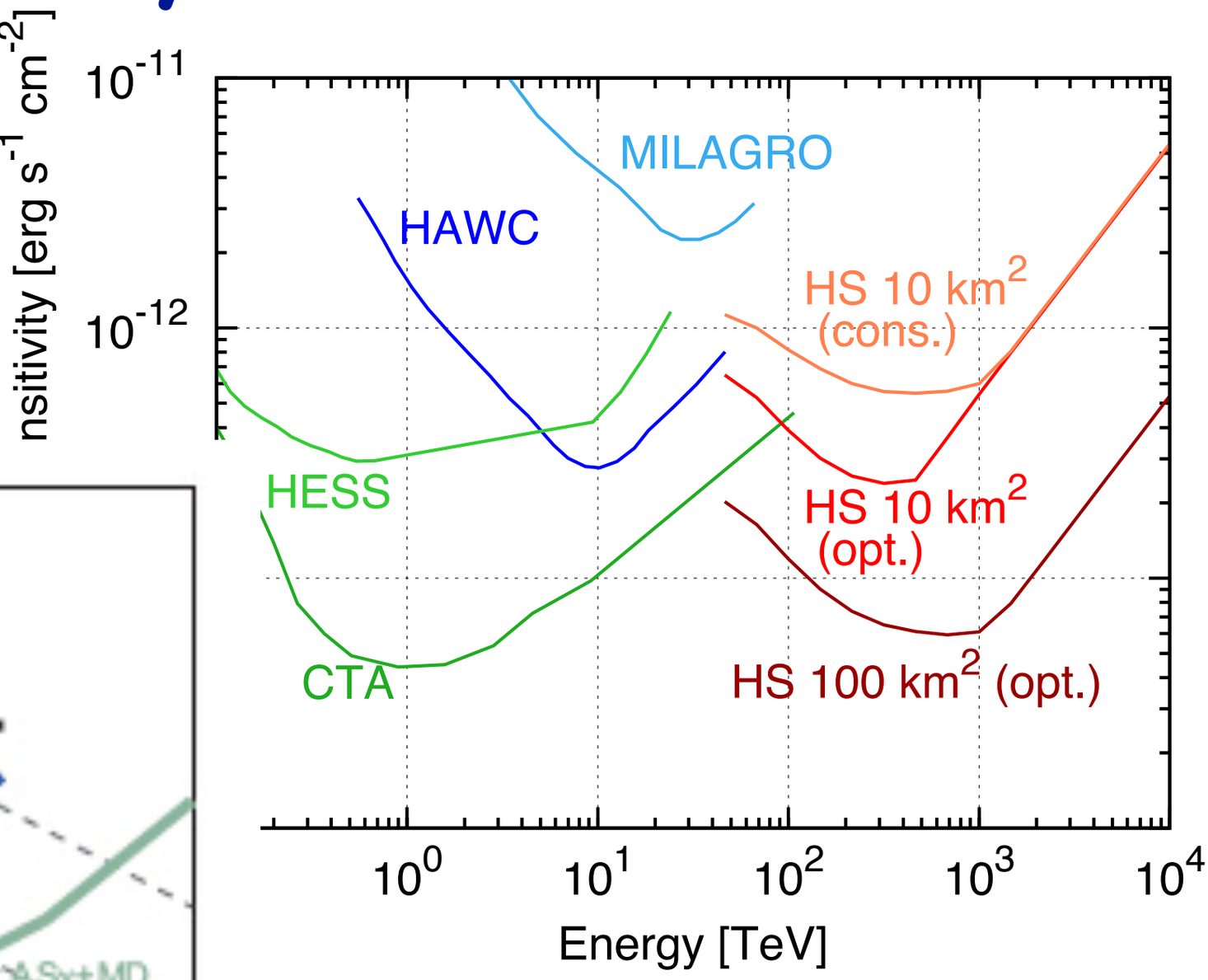
Outline of the talk

Bottom line question: why are instruments like MILAGRO & sons so cool?

- Gamma-ray astronomy: present and future facilities
- Gamma-ray astronomy and the origin of cosmic rays
- Where are CR PeVatrons?
- Diffuse emission in the (multi-)TeV energy domain
- The link with neutrino astronomy

Gamma ray astronomy:where do we stand

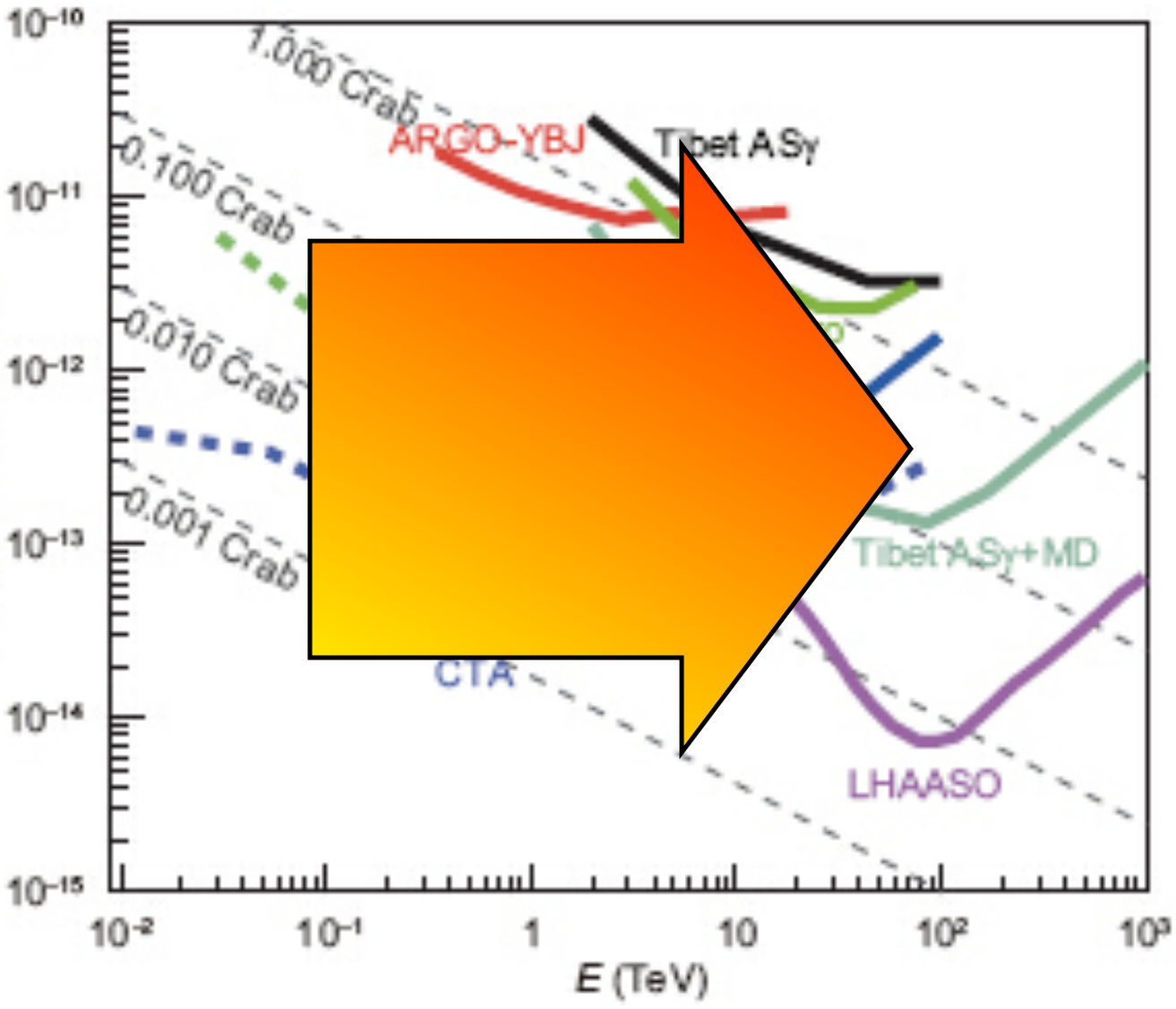


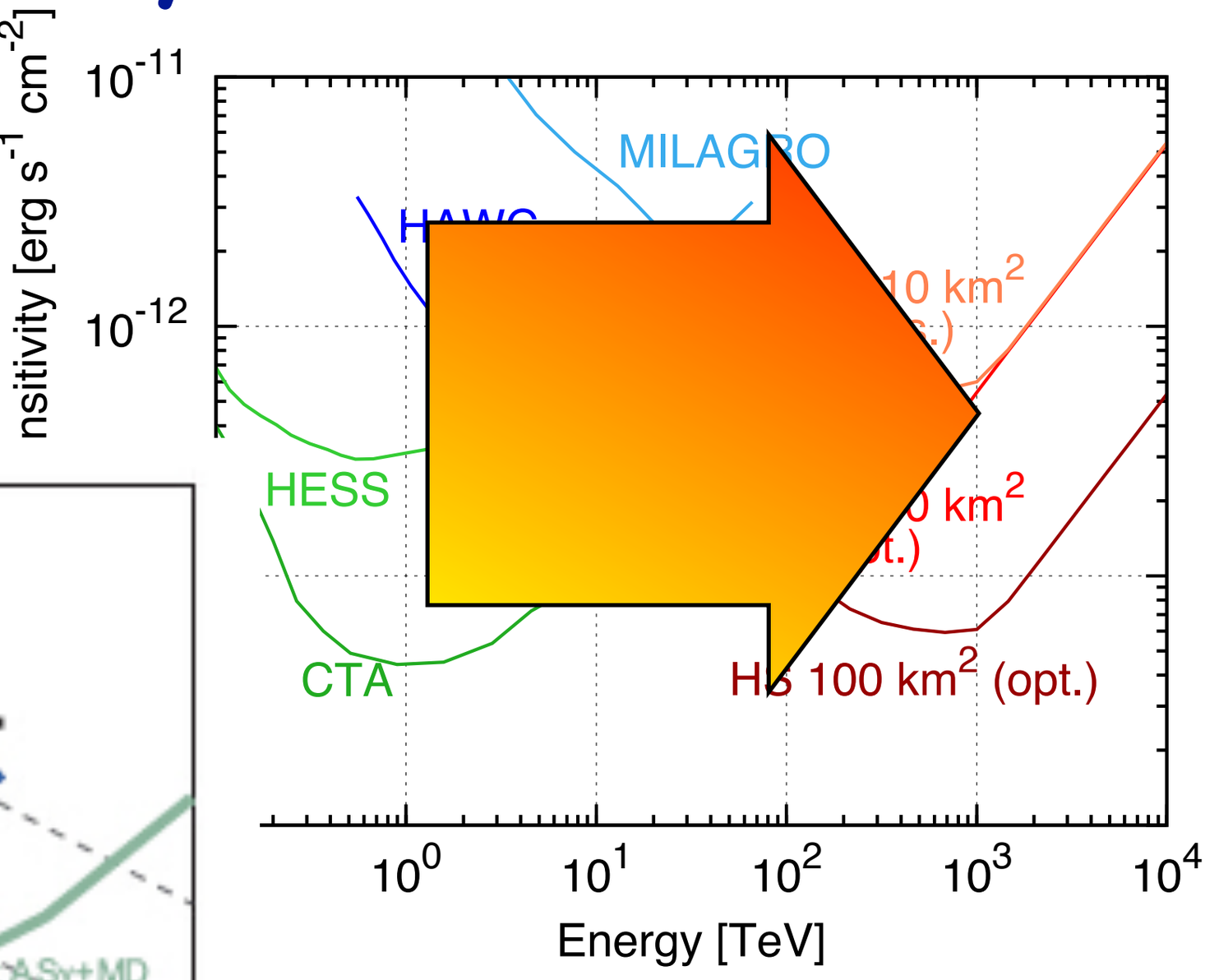


I know, the sensitivity of [name of your instrument] is different than that plotted here…

Gamma ray astronomy:where do we stand

multi-TeV domain





I know, the sensitivity of [name of your instrument] is different than that plotted here…

SuperNova Remnants,Cosmic Rays,γ-rays

SN explosions-> enough power to explain CRs

Baade & Zwicky 1934 (see also Ter Haar 1950)

see Gabici & Montmerle 2015 for a recent review

SuperNova Remnants, Cosmic Rays, γ-rays

SN explosions-> enough power to explain CRs

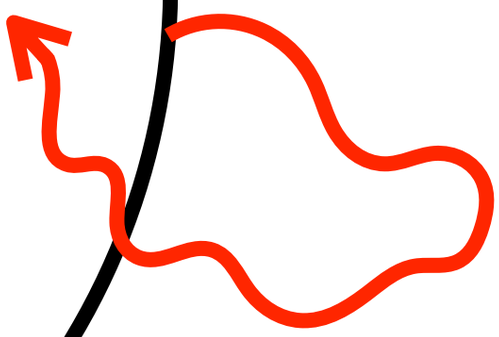
Baade & Zwicky 1934 (see also Ter Haar 1950)

SNR shocks-> acceleration sites

Shklovsky 1954, Ginzburg & Syrovatskii 1964

see Gabici & Montmerle 2015 for a recent review

SuperNova Remnants, Cosmic Rays, γ-rays



SN explosions-> enough power to explain CRs

Baade & Zwicky 1934 (see also Ter Haar 1950)

SNR shocks-> acceleration sites

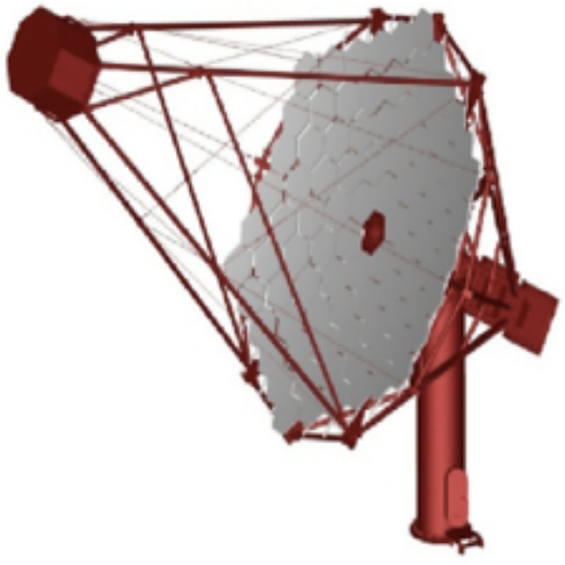
Shklovsky 1954, Ginzburg & Syrovatskii 1964

Diffusive Shock Acceleration

BOBALSKy 1977-1978 (Blandford, Ostriker, Bell, Axford, Leer, Skadron, Krymskii)

see Gabici & Montmerle 2015 for a recent review

SuperNova Remnants, Cosmic Rays, γ-rays



SN explosions-> enough power to explain CRs

Baade & Zwicky 1934 (see also Ter Haar 1950)

SNR shocks-> acceleration sites

Shklovsky 1954, Ginzburg & Syrovatskii 1964

Diffusive Shock Acceleration

BOBALSKy 1977-1978 (Blandford, Ostriker, Bell, Axford, Leer, Skadron, Krymskii)

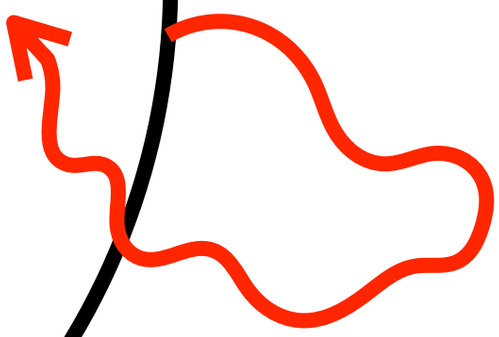
γ-rays from pp interactions

Drury, Aharonian & Völk 1994

<- Cherenkov telescope

see Gabici & Montmerle 2015 for a recent review

SuperNova Remnants, Cosmic Rays, γ-rays



very popular but not proven yet!

SN explosions-> enough power to explain CRs

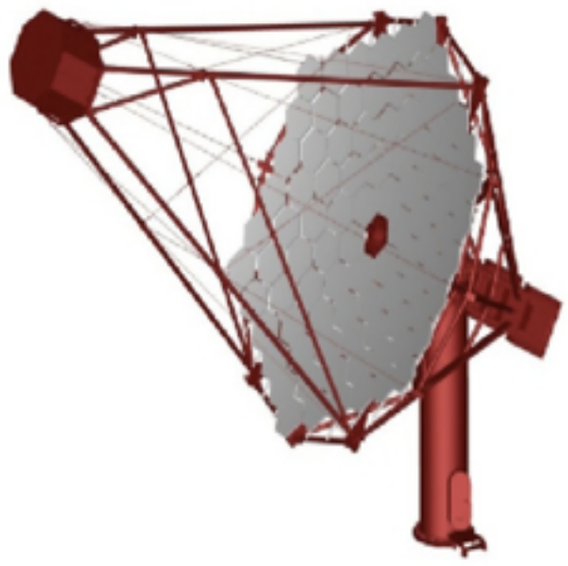
Baade & Zwicky 1934 (see also Ter Haar 1950)

SNR shocks-> acceleration sites

Shklovsky 1954, Ginzburg & Syrovatskii 1964

Diffusive Shock Acceleration

BOBALSKy 1977-1978 (Blandford, Ostriker, Bell, Axford, Leer, Skadron, Krymskii)



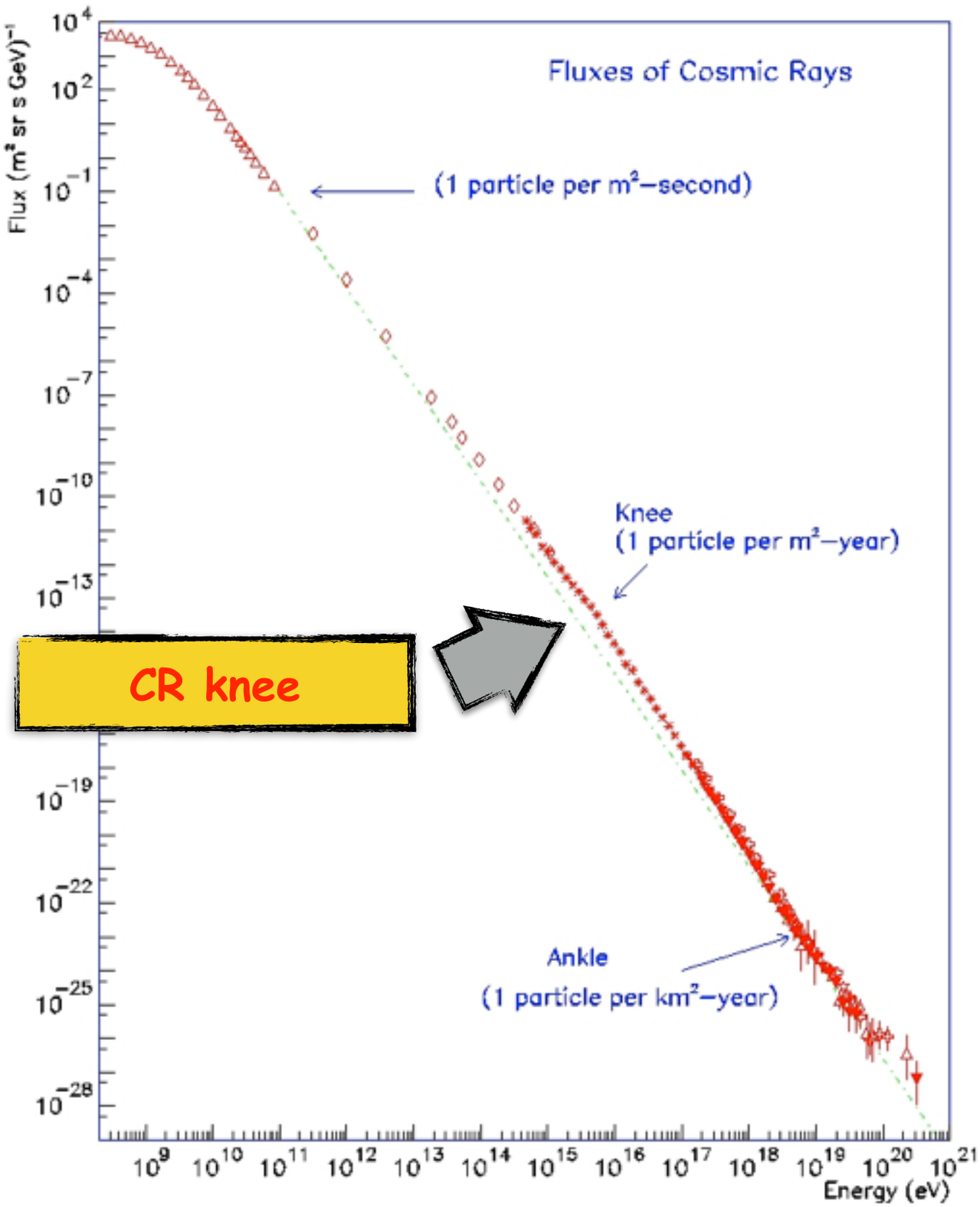
γ-rays from pp interactions

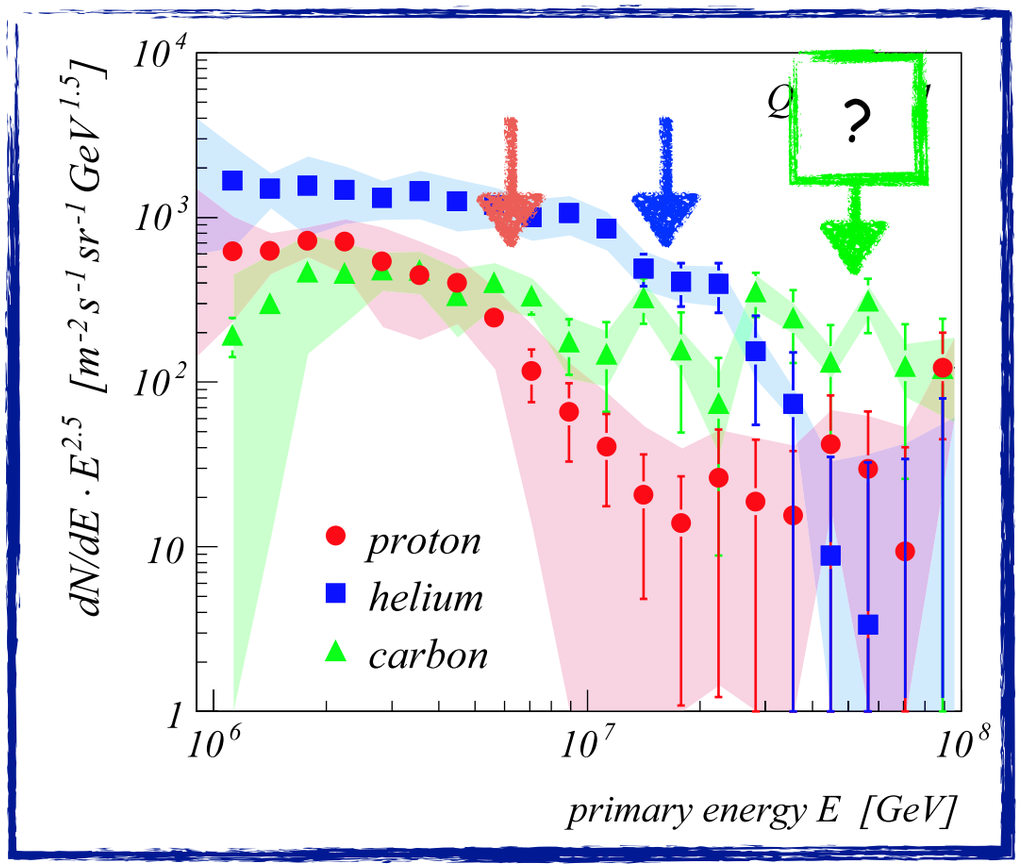
Drury, Aharonian & Völk 1994

<- Cherenkov telescope

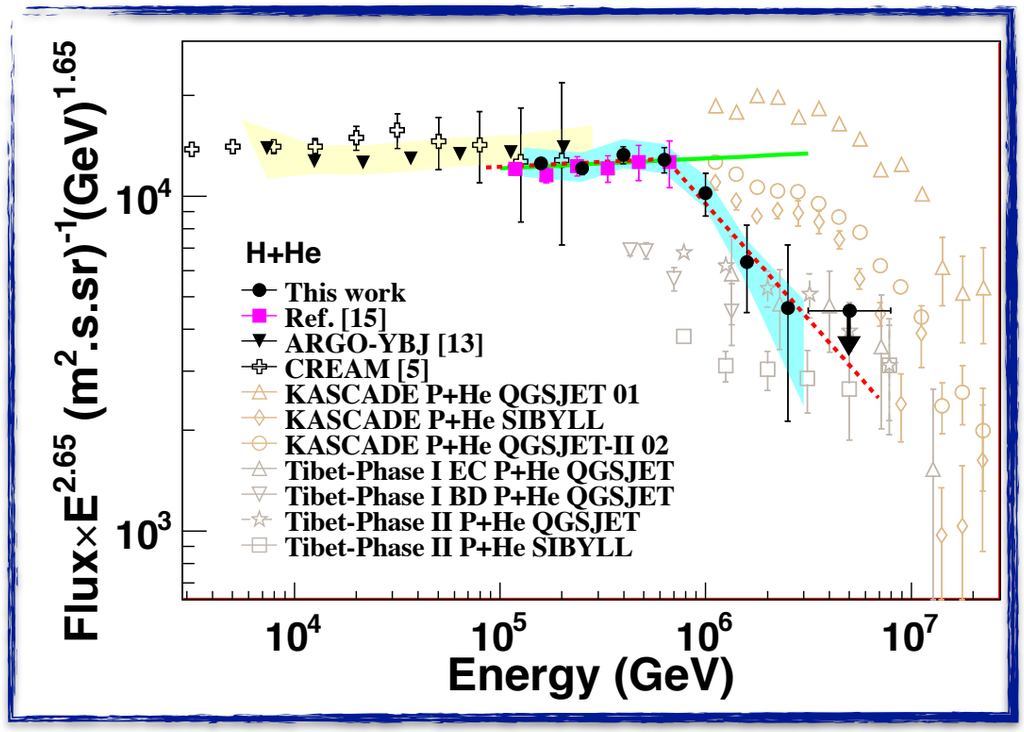
see Gabici & Montmerle 2015 for a recent review

We need proton PeVatrons





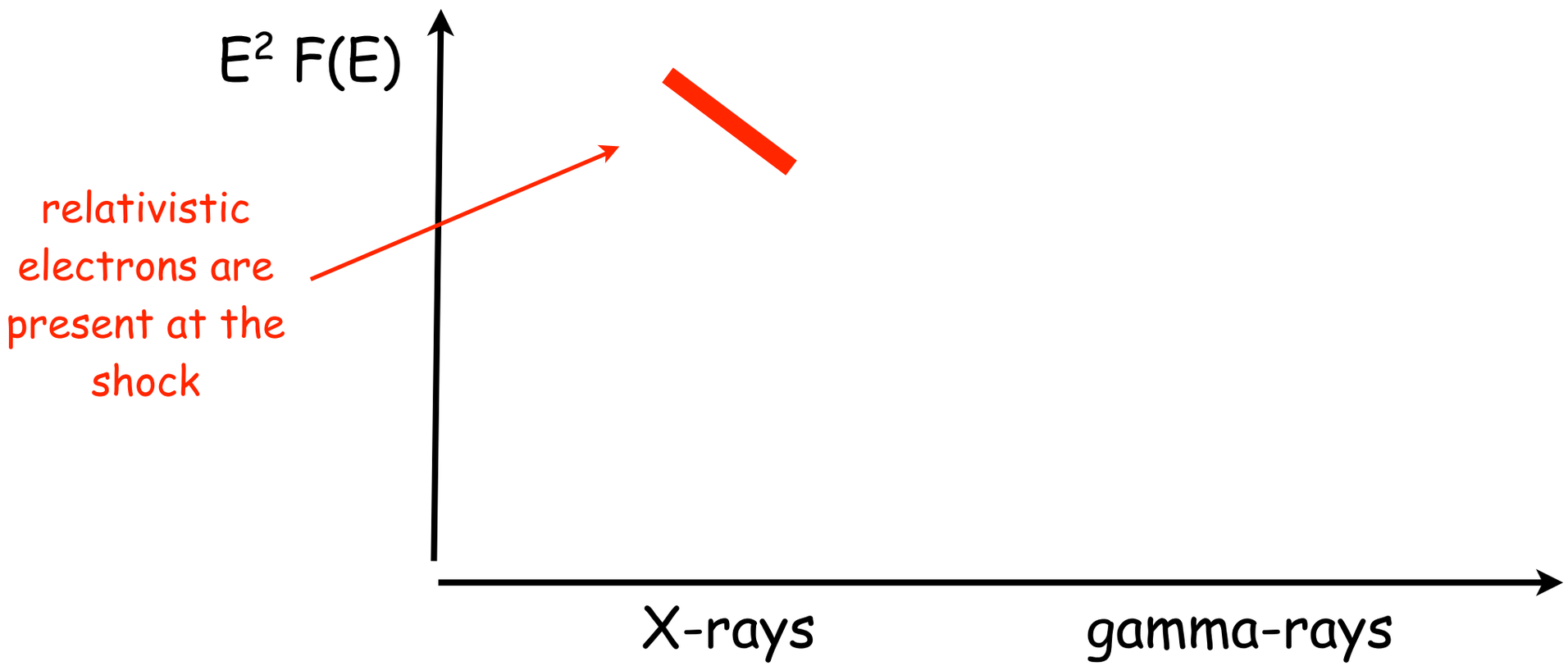
KASCADE coll. 2005



ARGO coll. 2015

Hadronic or leptonic?

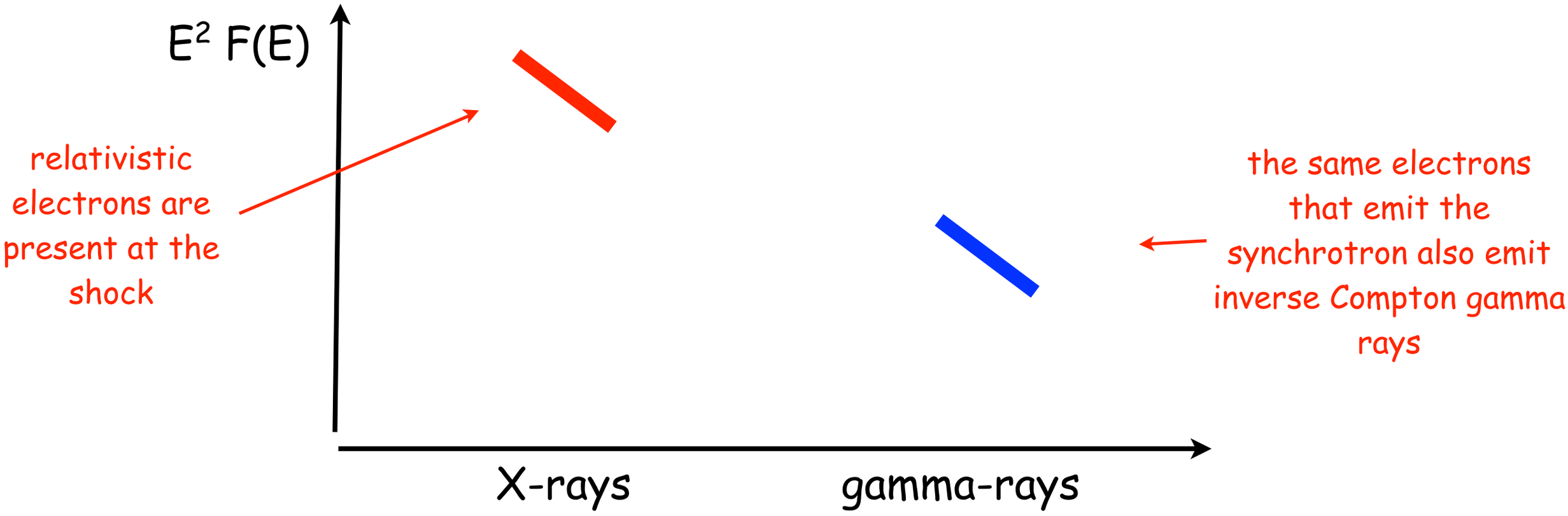
X-ray synchrotron emission is observed from some TeV SNRs
(RXJ1713, Vela Junior...)



very often, the value of the magnetic field is largely unknown

Hadronic or leptonic?

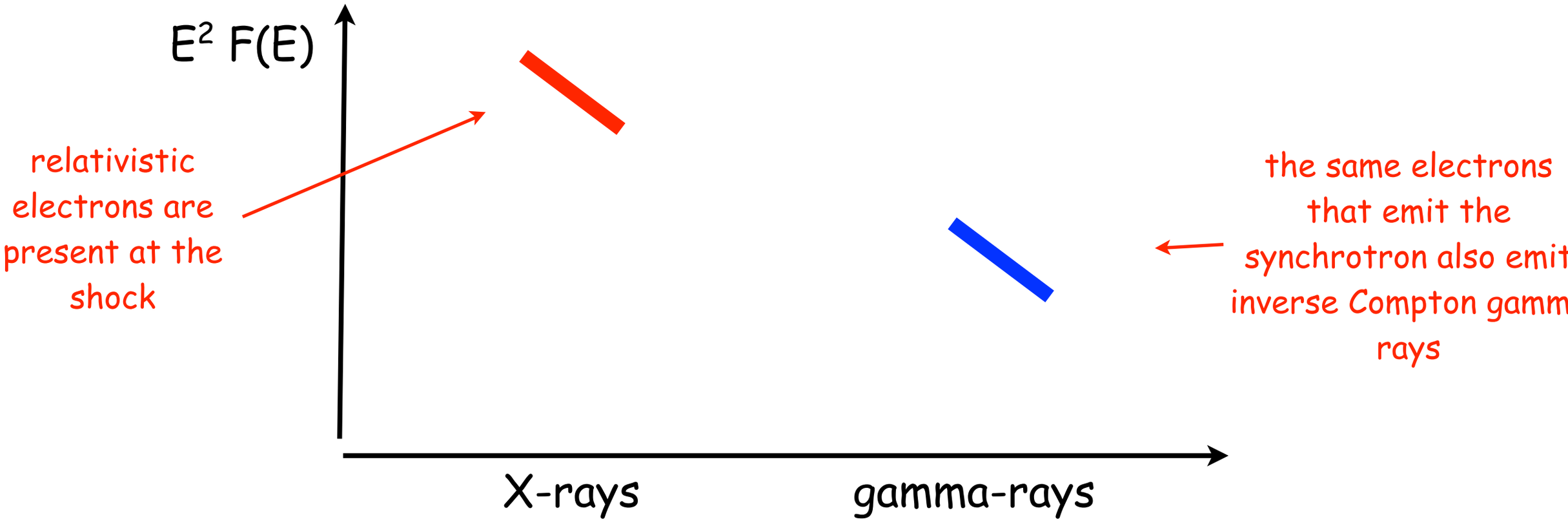
X-ray synchrotron emission is observed from some TeV SNRs
(RXJ1713, Vela Junior...)



very often, the value of the magnetic field is largely unknown

Hadronic or leptonic?

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



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

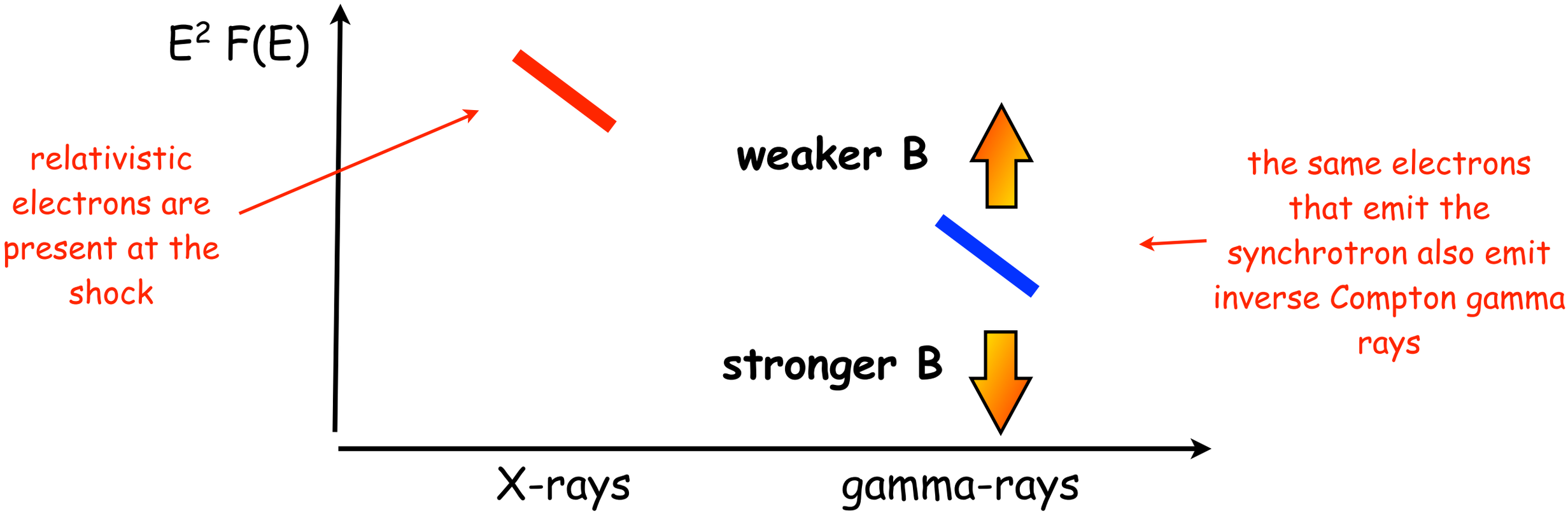
this product is fixed by X-ray obs.

we know this

very often, the value of the magnetic field is largely unknown

Hadronic or leptonic?

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



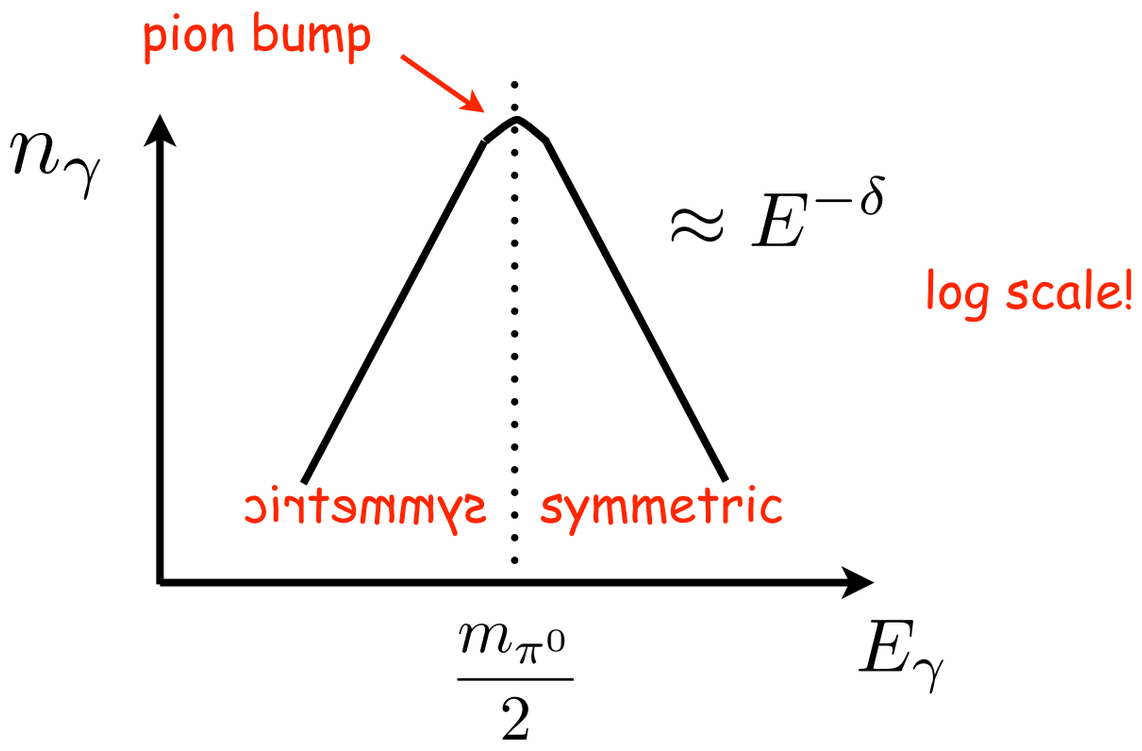
synchrotron -> $F_s \propto n_e B^{\beta}$ inverse Compton -> $F_{IC} \propto n_e w_{soft}$

this product is fixed by X-ray obs.

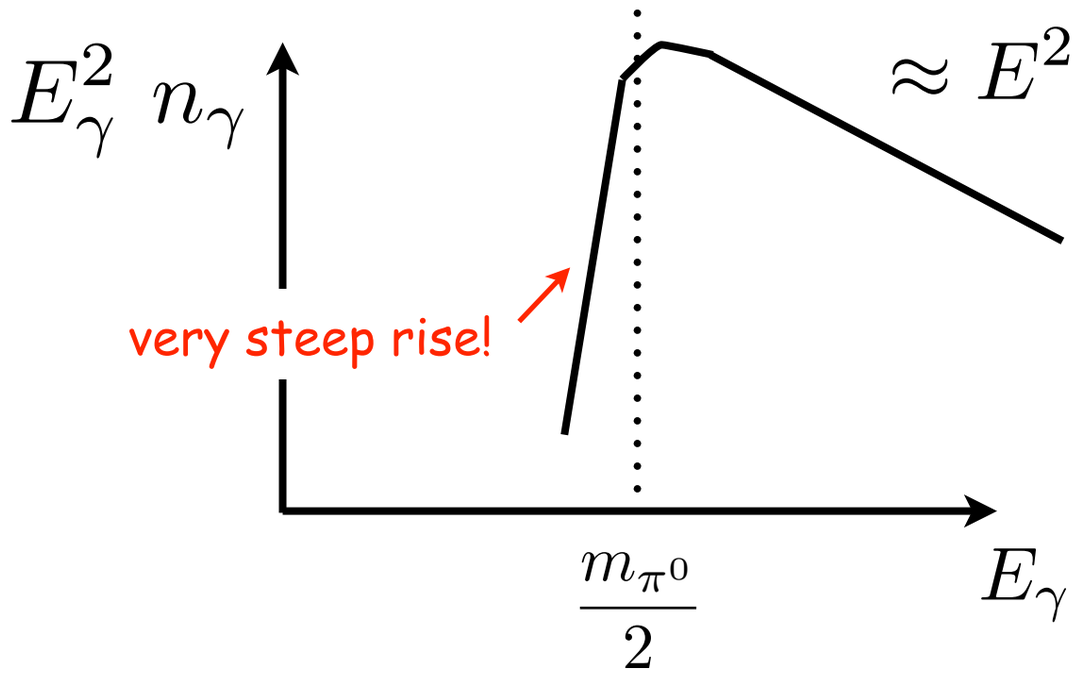
we know this

very often, the value of the magnetic field is largely unknown

Do SNRs accelerate protons?



log scale!

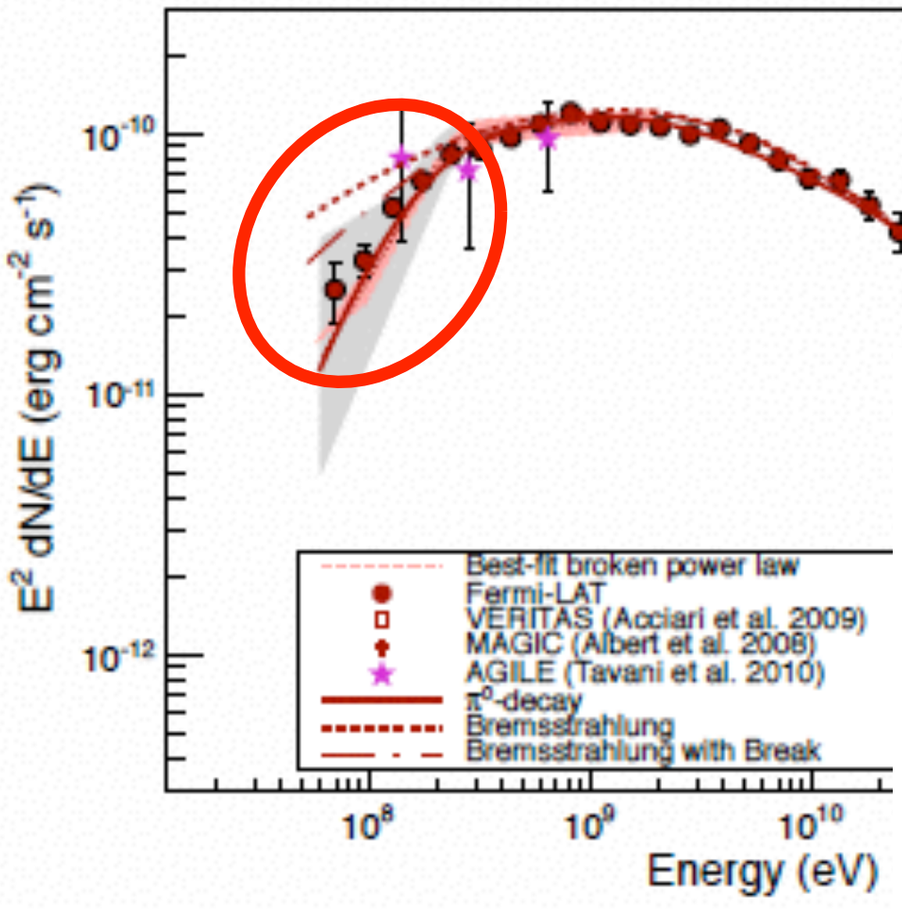


Do SNRs accelerate protons?

(Ackermann et al 2013)

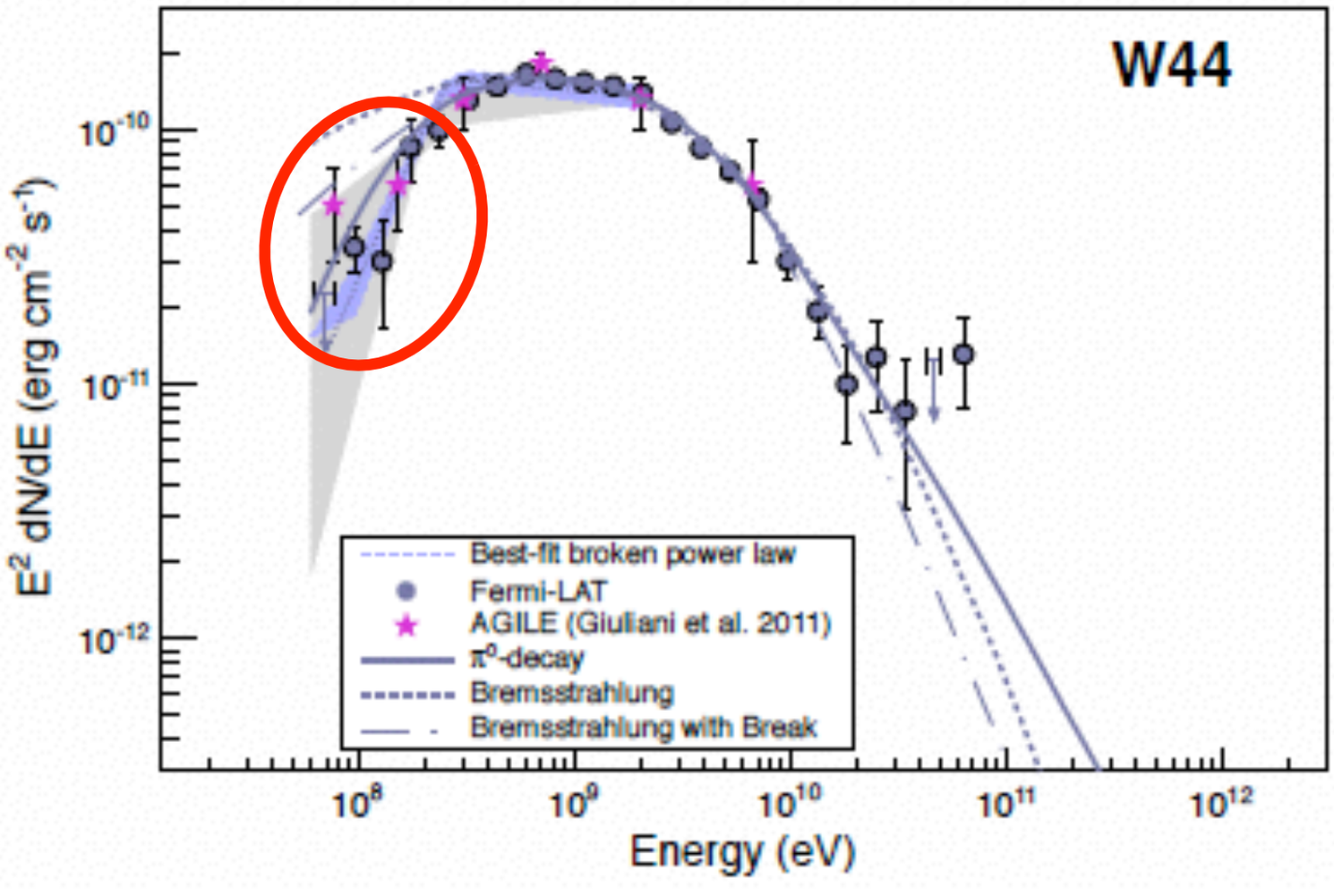
FERMI (and AGILE)

(Giuliani+, Cardillo+)



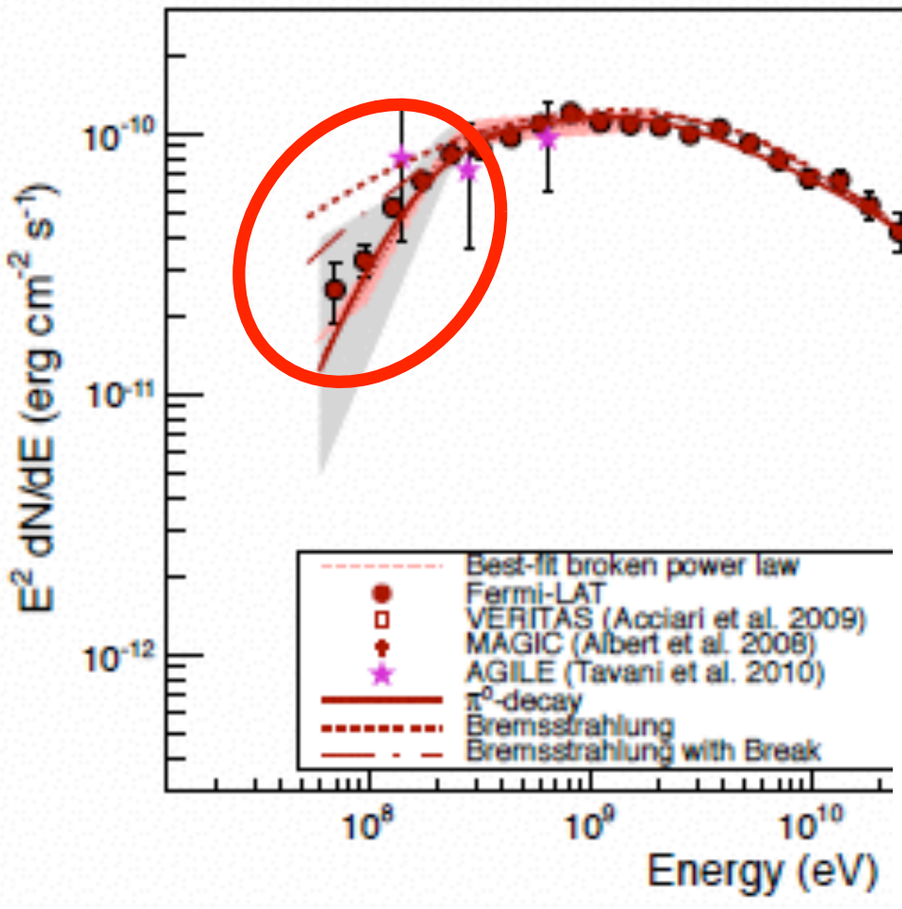
n_γ

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



Do SNRs accelerate protons?

(Ackermann et al 2013)

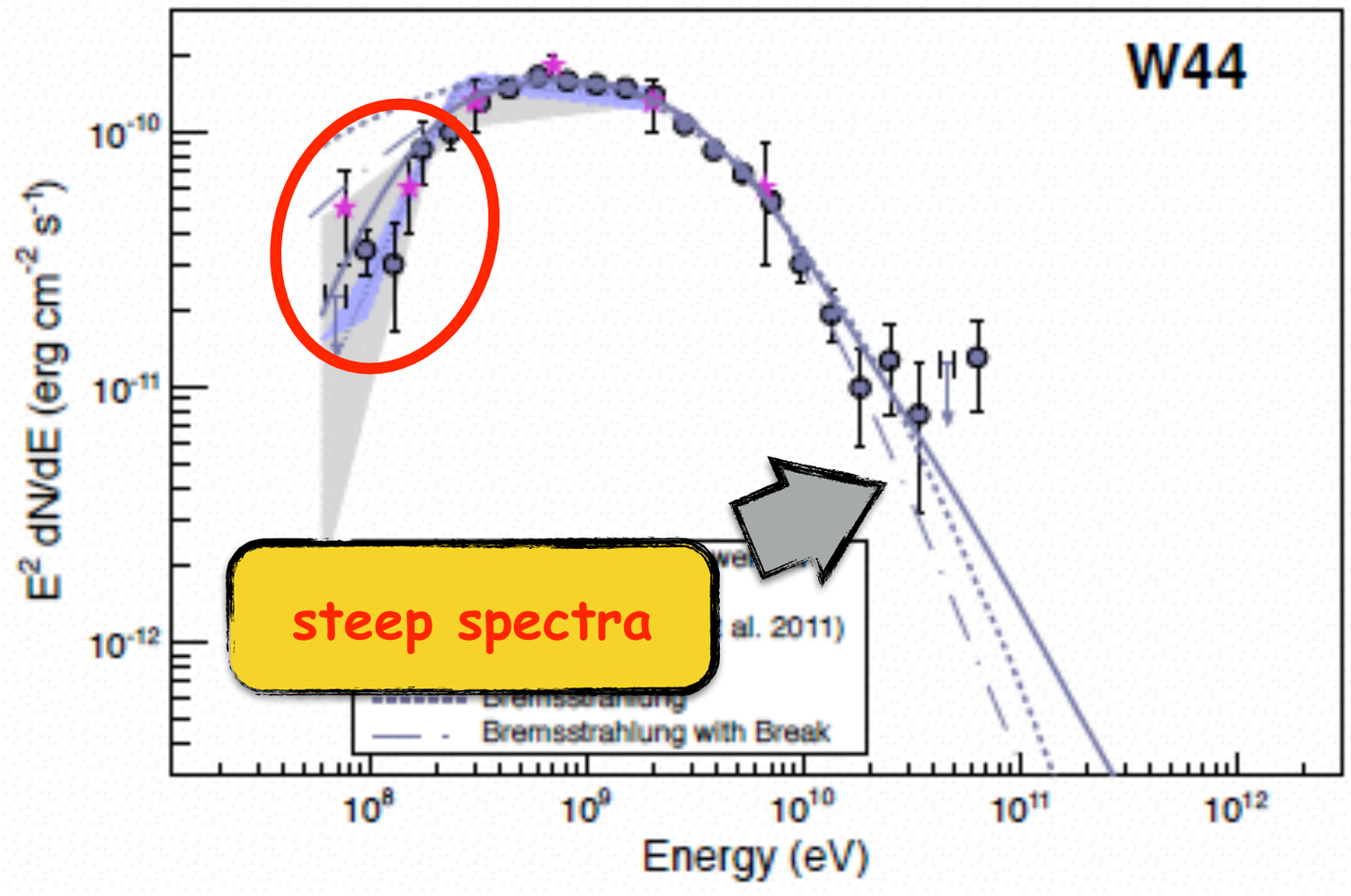


FERMI (and AGILE)

(Giuliani+, Cardillo+)

n_γ ↑

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



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

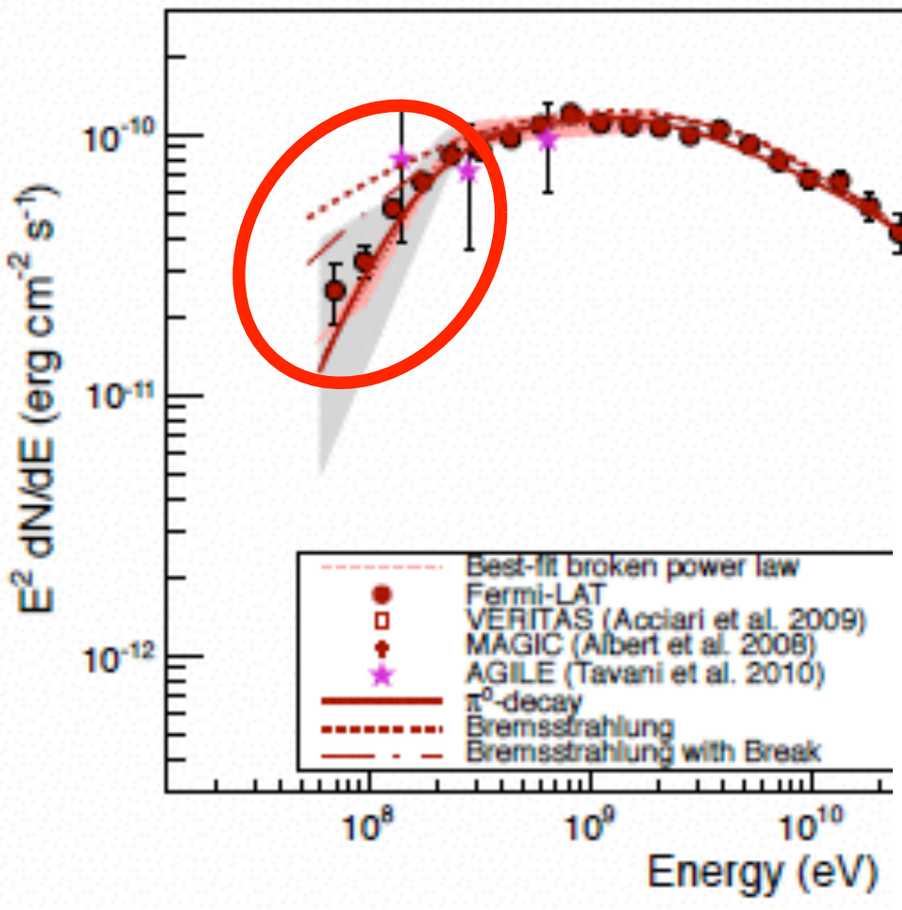
Do SNRs accelerate protons?

YES!

(Ackermann et al 2013)

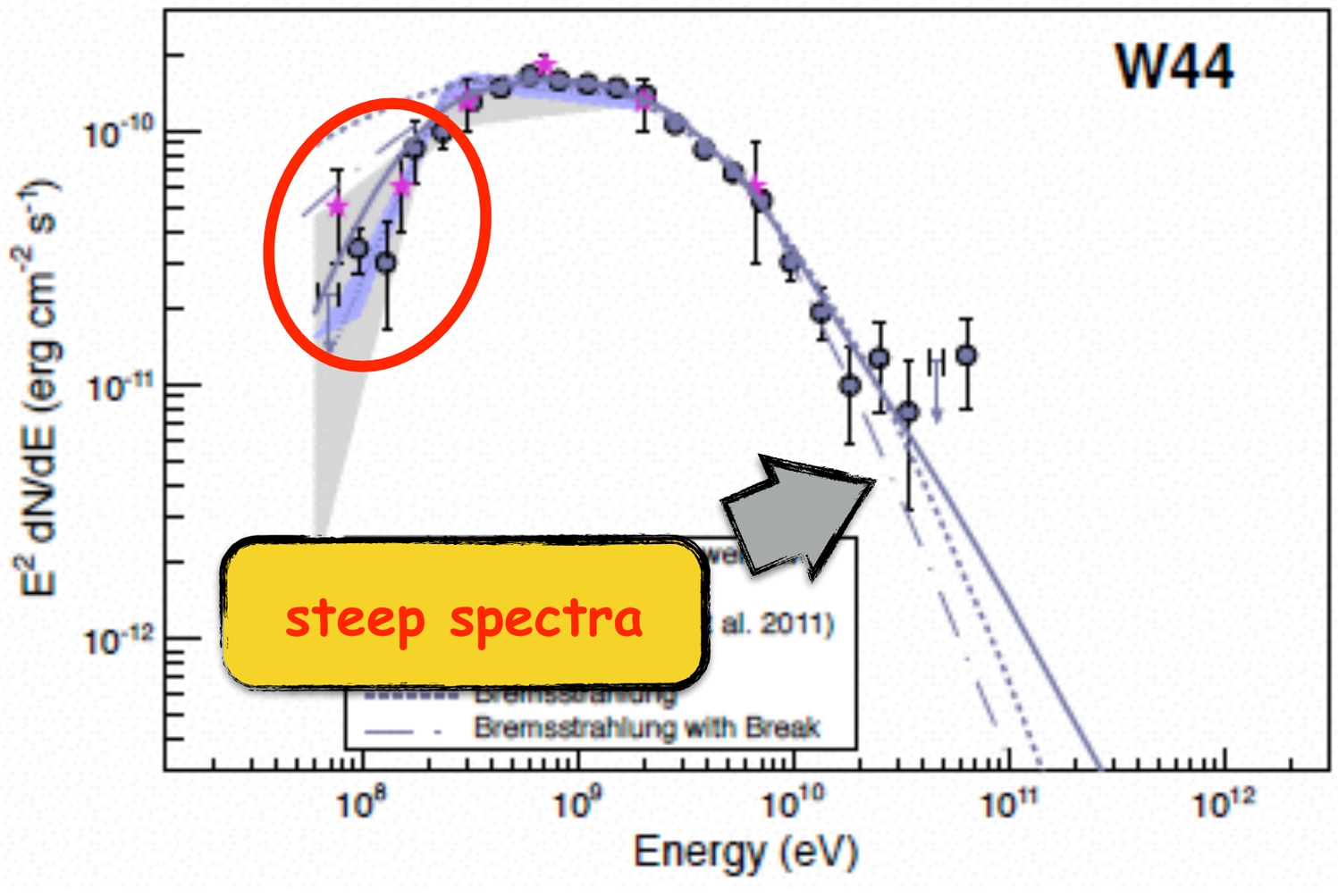
FERMI (and AGILE)

(Giuliani+, Cardillo+)



$n_\gamma \uparrow$

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



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

How to detect PeVatrons w. gamma rays

Observations Let's assume SNRs do accelerate up to the knee

p-p interactions -> $E^{p}_{max} \sim 1 \text{ PeV} \longrightarrow E^{\gamma}_{max} \sim 100 \text{ TeV}$

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

How to detect PeVatrons w. gamma rays

Observations

Let's assume SNRs do accelerate up to the k

p-p interactions -> $E^p_{max} \sim 1$ P $_{max} \sim 100$ TeV

inverse Compt above several tens of TeV (Klein-Nishina effect)

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

How to detect PeVatrons w. gamma rays

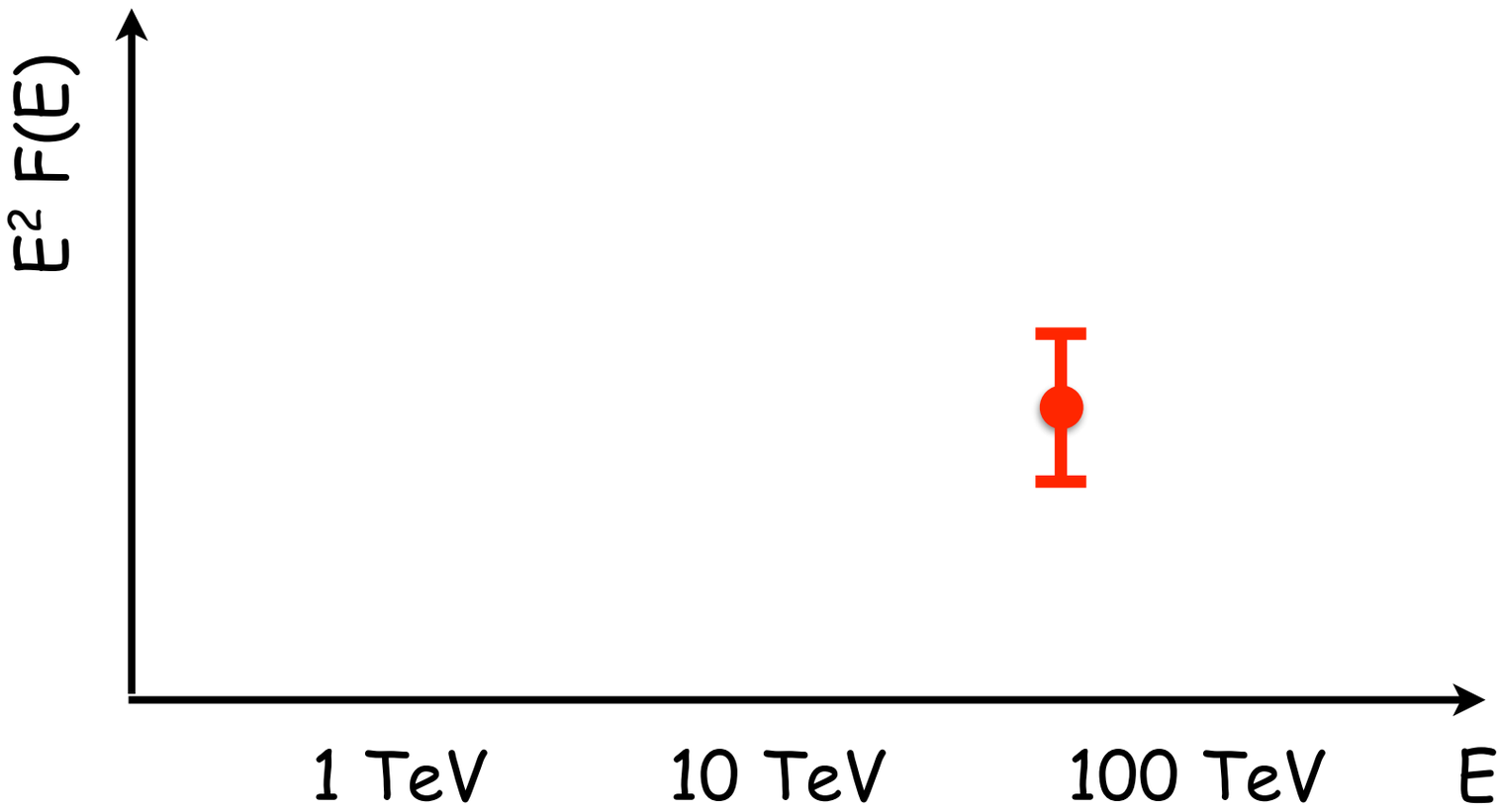
Observations

Let's assume SNRs do accelerate up to the k

p-p interactions -> $E^p_{max} \sim 1$ P $\qquad E^{\gamma}_{max} \sim 100$ TeV

inverse Compt… above several tens of TeV (Klein-Nishina effect)

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



How to detect PeVatrons w. gamma rays

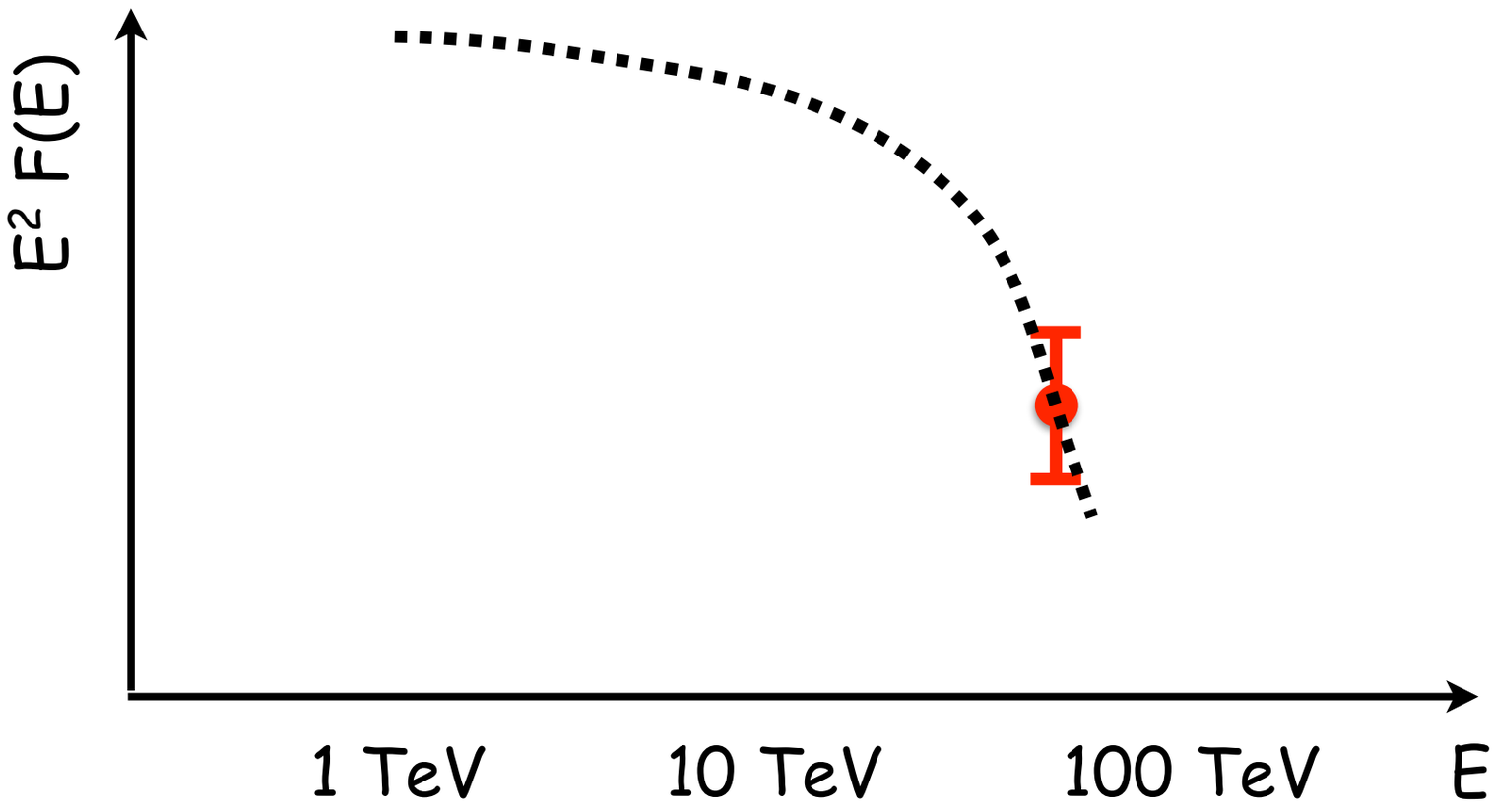
Observations

Let's assume SNRs do accelerate up to the k

p-p interactions -> $E^p_{max} \sim 1$ P $\qquad E^{\gamma}_{max} \sim 100$ TeV

inverse Compt above several tens of TeV (Klein-Nishina effect)

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



It is not enough to detect something at >>1 TeV

How to detect PeVatrons w. gamma rays

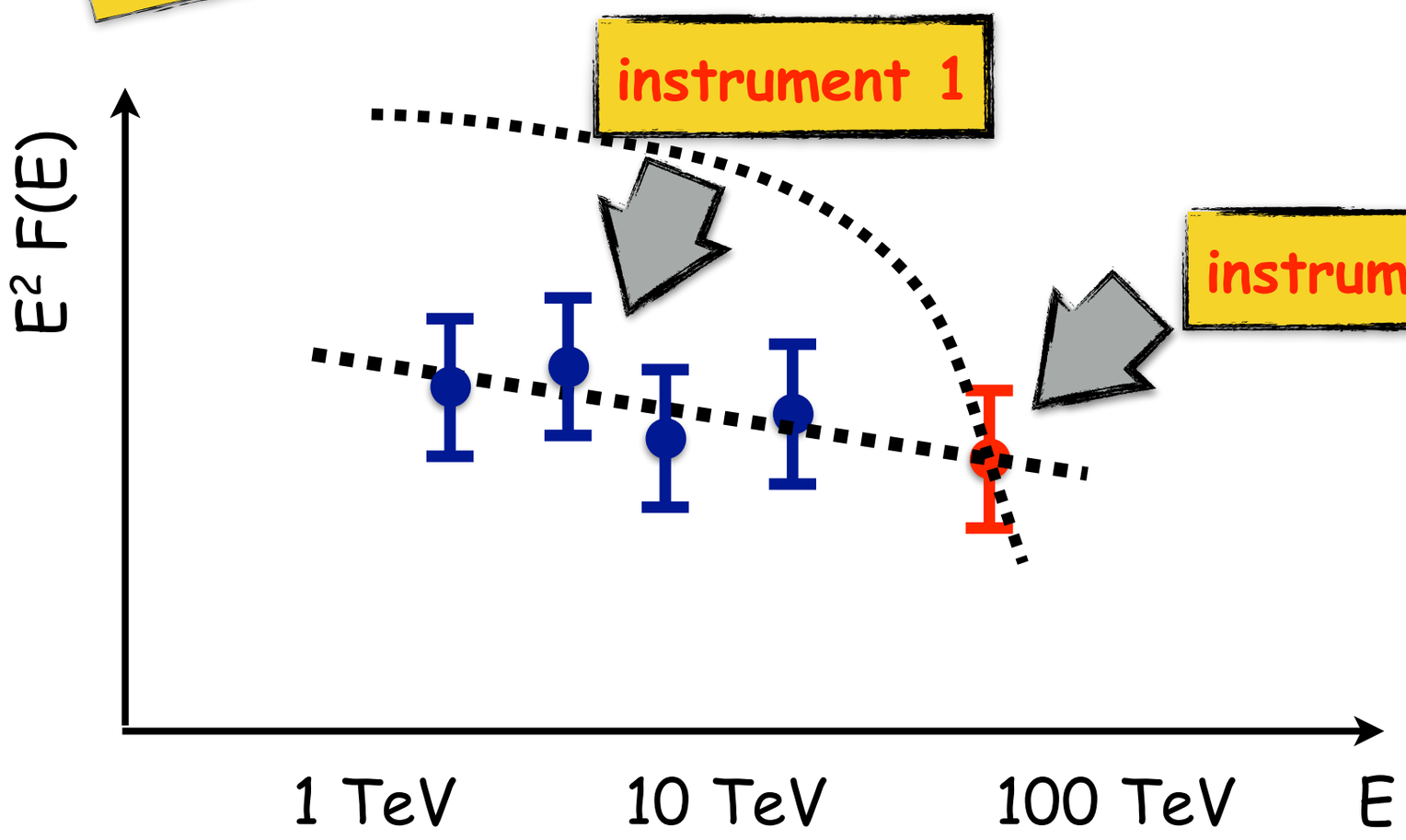
Observations

Let's assume SNRs do accelerate up to the k

p-p interactions -> $E^p_{max} \sim 1$ P $_{max} \sim 100$ TeV

inverse Compt above several tens of TeV (Klein-Nishina effect)

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



It is not enough to detect something at >>1 TeV

How to detect PeVatrons w. gamma rays

Observations

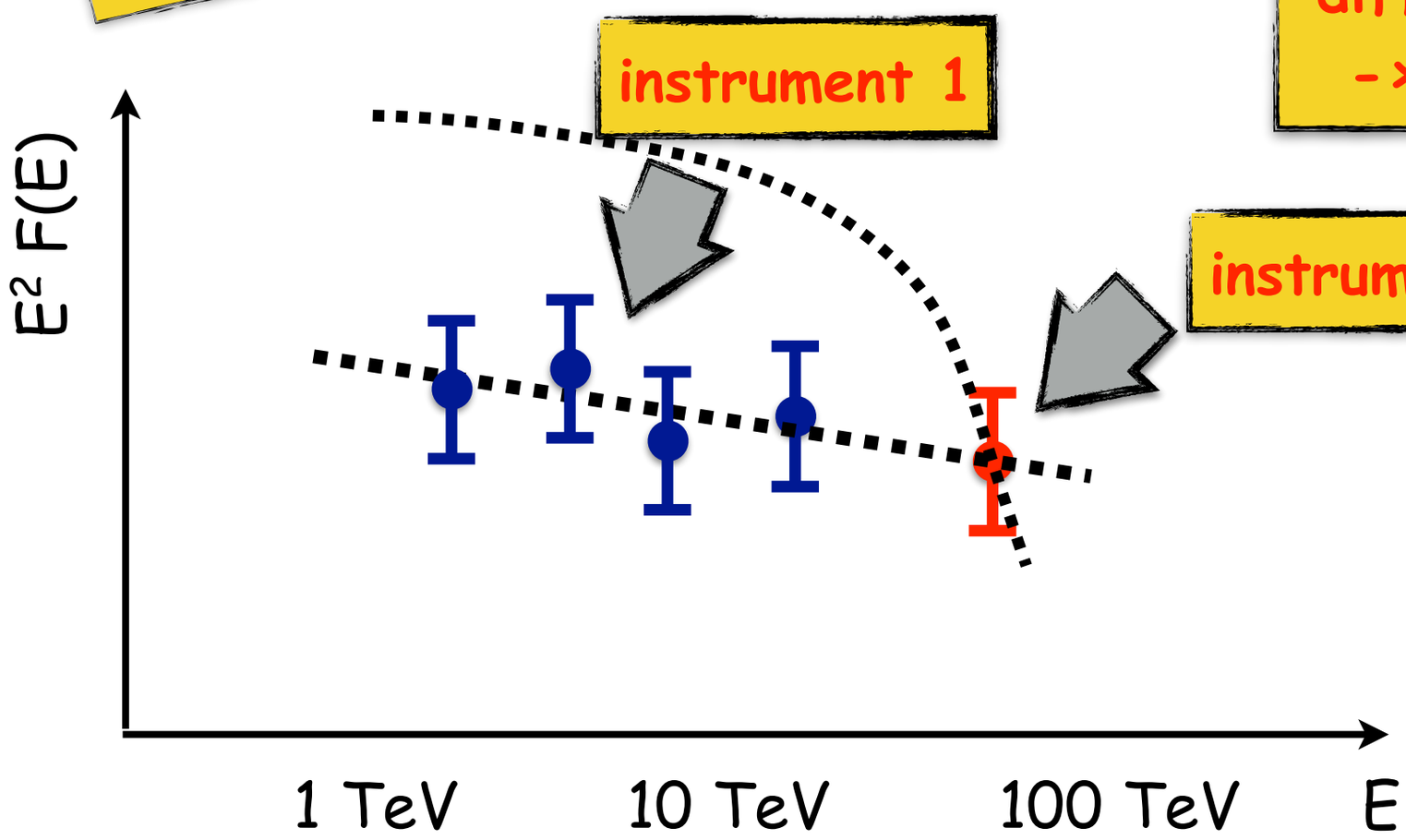
Let's assume SNRs do accelerate up to the k

p-p interactions -> $E^p_{max} \sim 1$ P $\qquad E^{\gamma}_{max} \sim 100$ TeV

inverse Compt above several tens of TeV (Klein-Nishina effect)

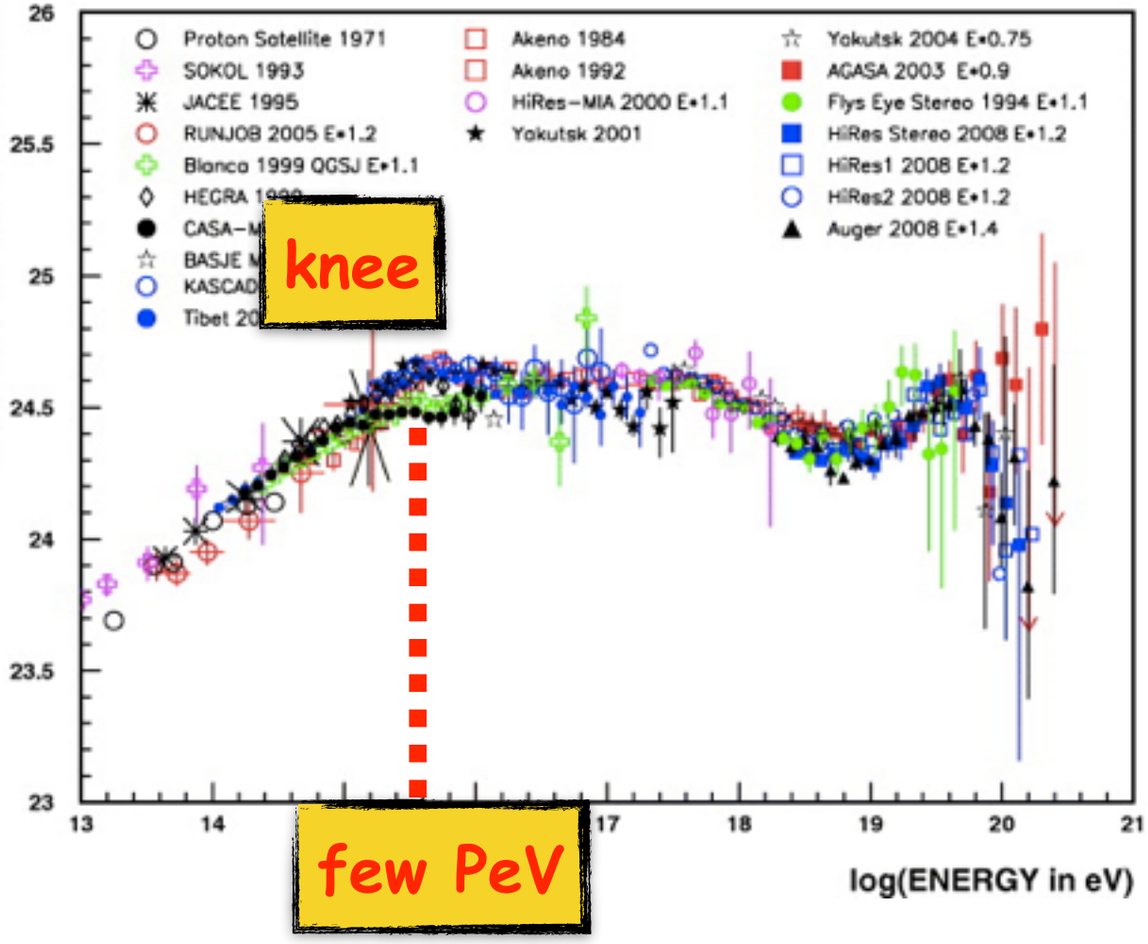
testable with future gamma ray facilities: CTA, HAWC, HiSCORE, LHAASO

difficult w. current instruments
-> H.E.S.S. saw 1 PeVatron!

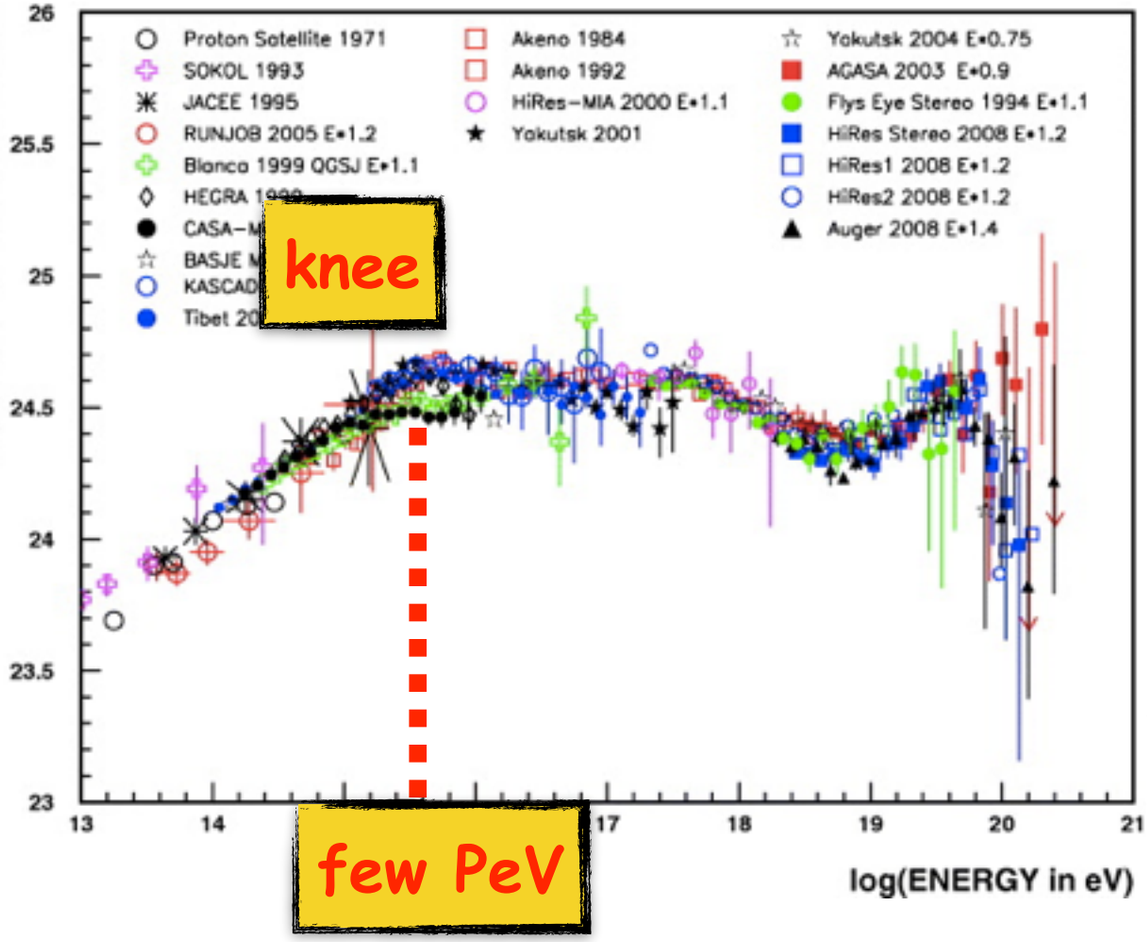


It is not enough to detect something at >>1 TeV

Are SNRs proton PeVatrons?



Are SNRs proton PeVatrons?



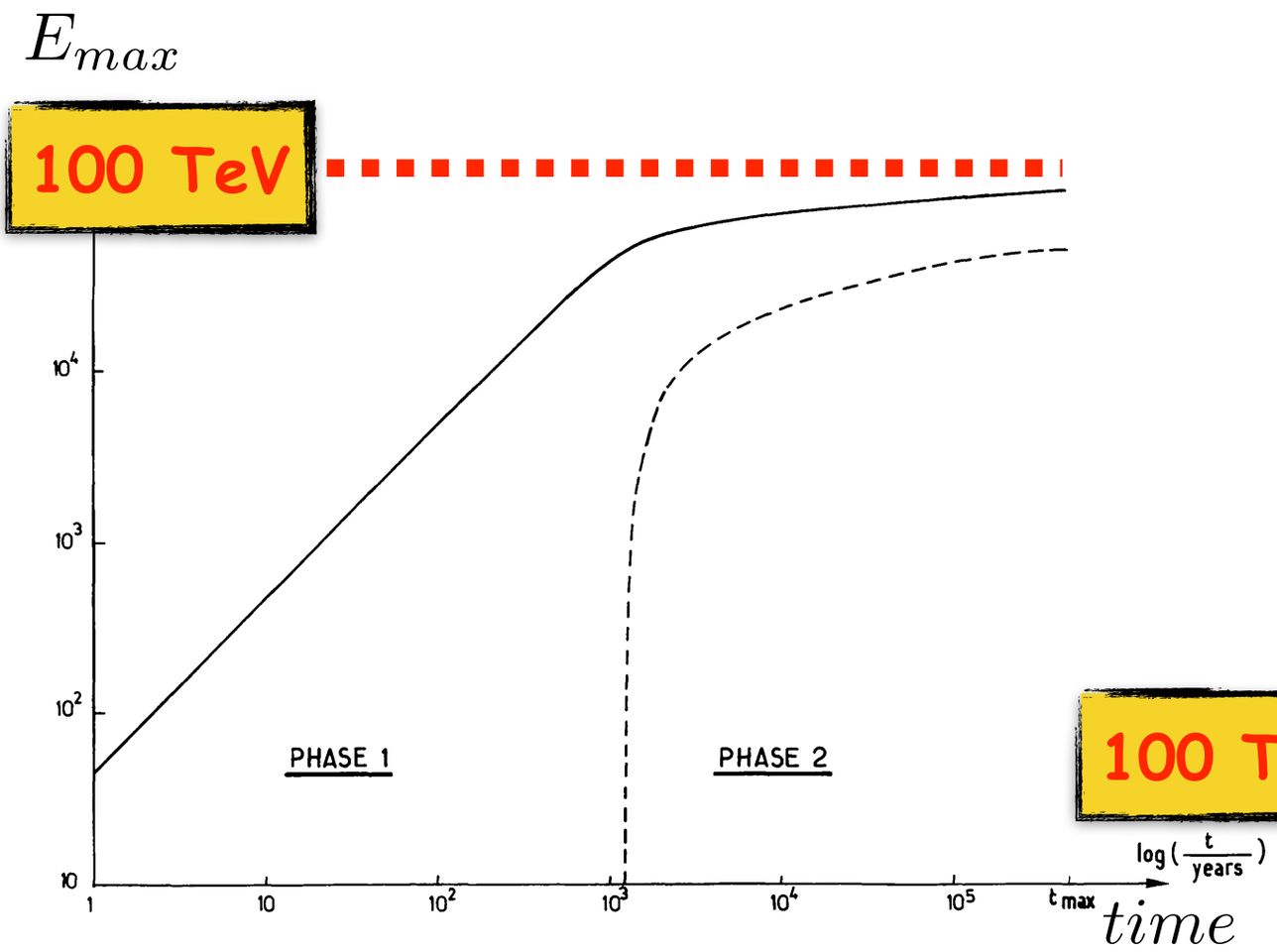
Hillas criterium

$$E_{max} \approx u\, R\, B$$

velocity · size · magnetic field

$$E_{max} \approx 1 \left(\frac{u}{10^3\ \mathrm{km/s}}\right) \left(\frac{R}{\mathrm{pc}}\right) \left(\frac{B}{\mu\mathrm{G}}\right) \mathrm{TeV}$$

Are SNRs proton PeVatrons?



Hillas criterium

$$E_{max} \approx u\ R\ B$$

velocity — size — magnetic field

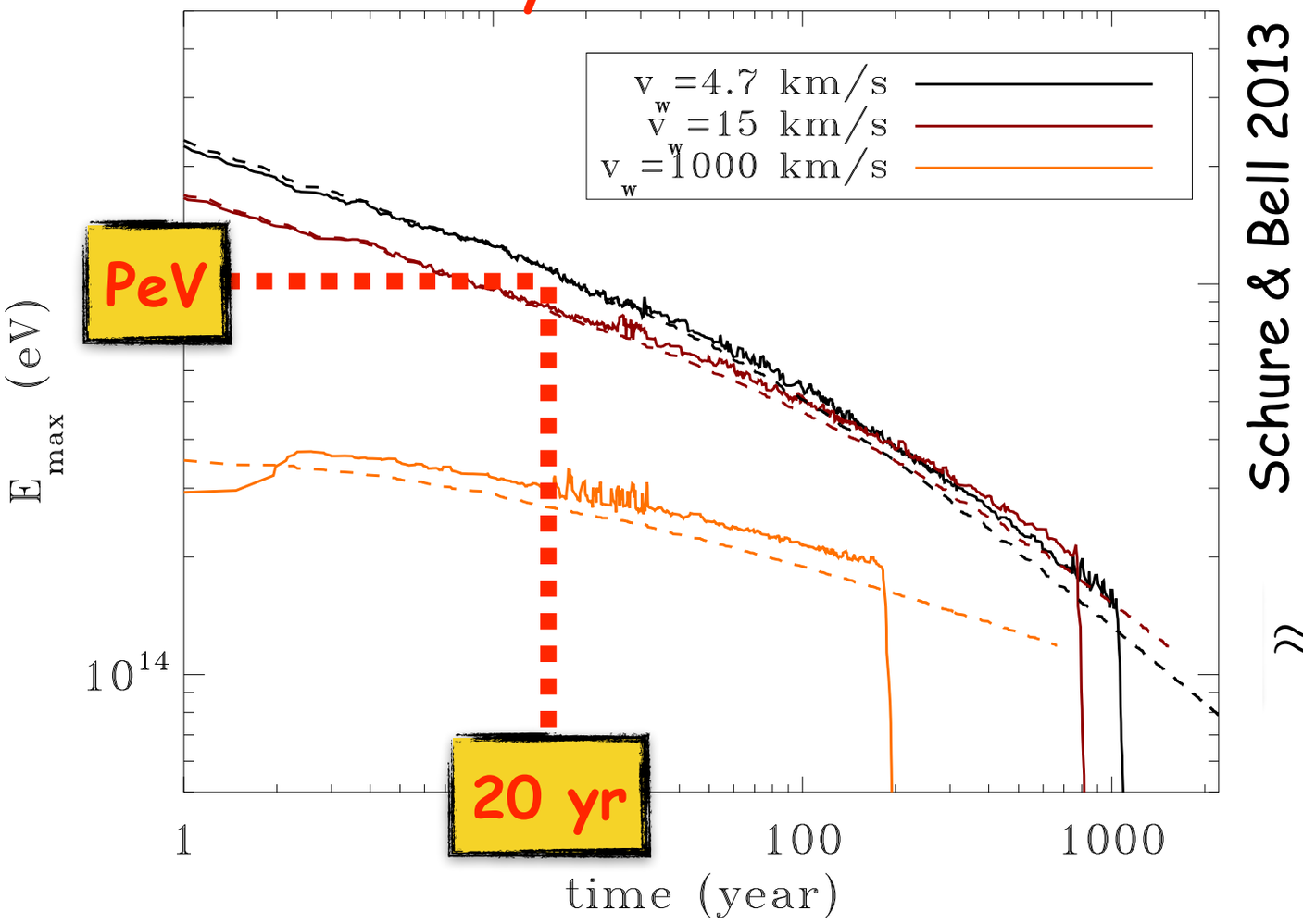
100 TeV $\approx 1 \left(\frac{u}{10^3\ \text{km/s}}\right) \left(\frac{R}{\text{pc}}\right) \left(\frac{B}{\mu\text{G}}\right) \text{TeV}$

~10 ~3 ~3

Lagage & Cesarsky 1983

Are SNRs proton PeVatrons?

30 years later…



Hillas criterium

$$E_{max} \approx u\, R\, B$$

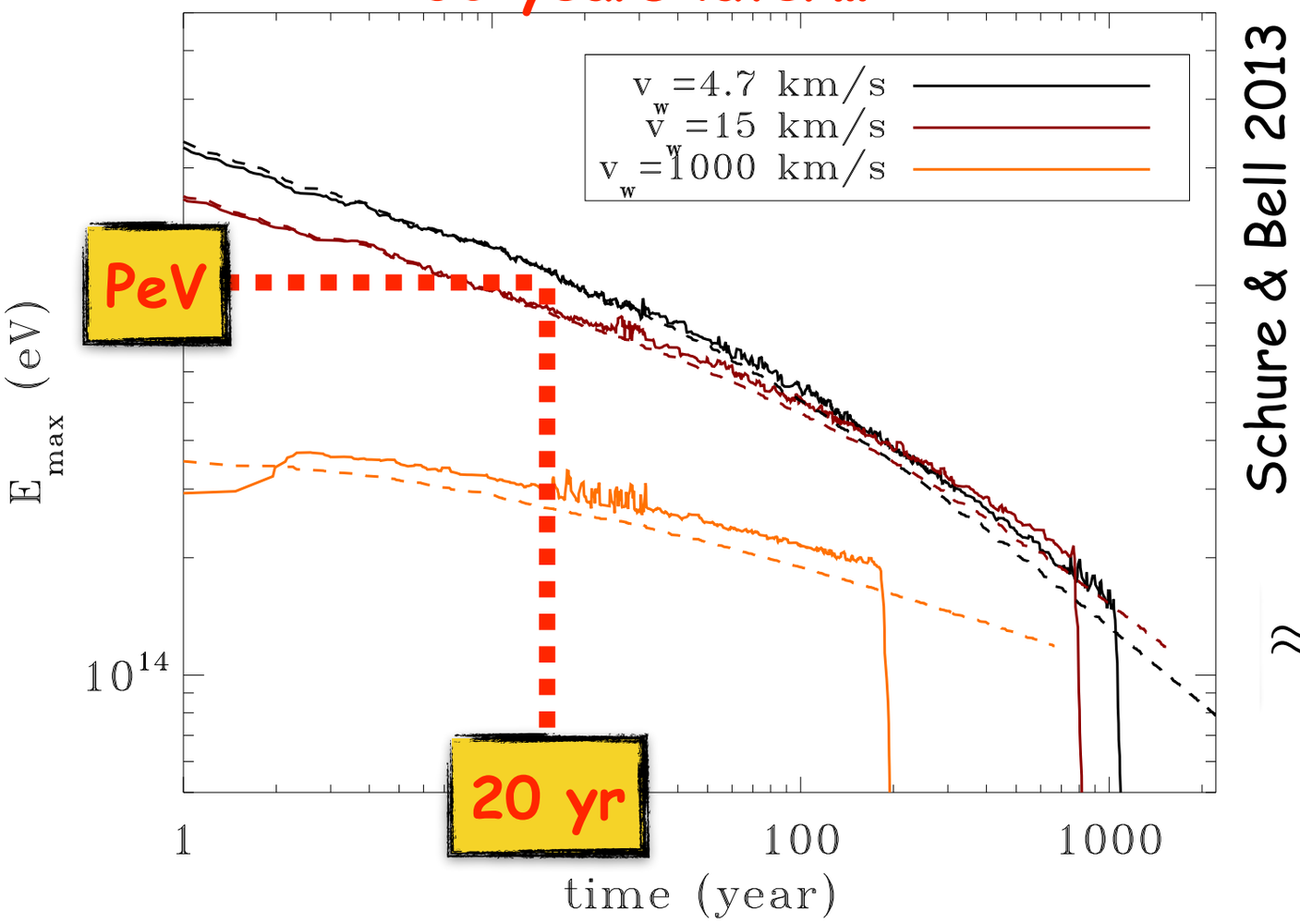
velocity · size · magnetic field

$$\approx \underbrace{\quad}_{\sim 10}\ \underbrace{\quad}_{\sim 3}\ \underbrace{\left(\frac{B}{\mu\mathrm{G}}\right)}_{\sim 3}\ \mathrm{TeV}$$

B-field amplification

Are SNRs proton PeVatrons?

30 years later...



Schure & Bell 2013

Hillas criterium

$$E_{max} \approx u\, R\, B$$

velocity · size · magnetic field

$$\approx \left(\text{B-field amplification}\right)\left(\frac{B}{\mu\text{G}}\right)\text{TeV}$$

~10 · ~3 · ~3

current driven, non-resonant instability (Bell 2004, 2013) -> PeV particle acceleration possible in the very early (tens of years) stage of a SNR evolution -> ejecta dominated phase -> is there enough power to feed the PeV CR population?

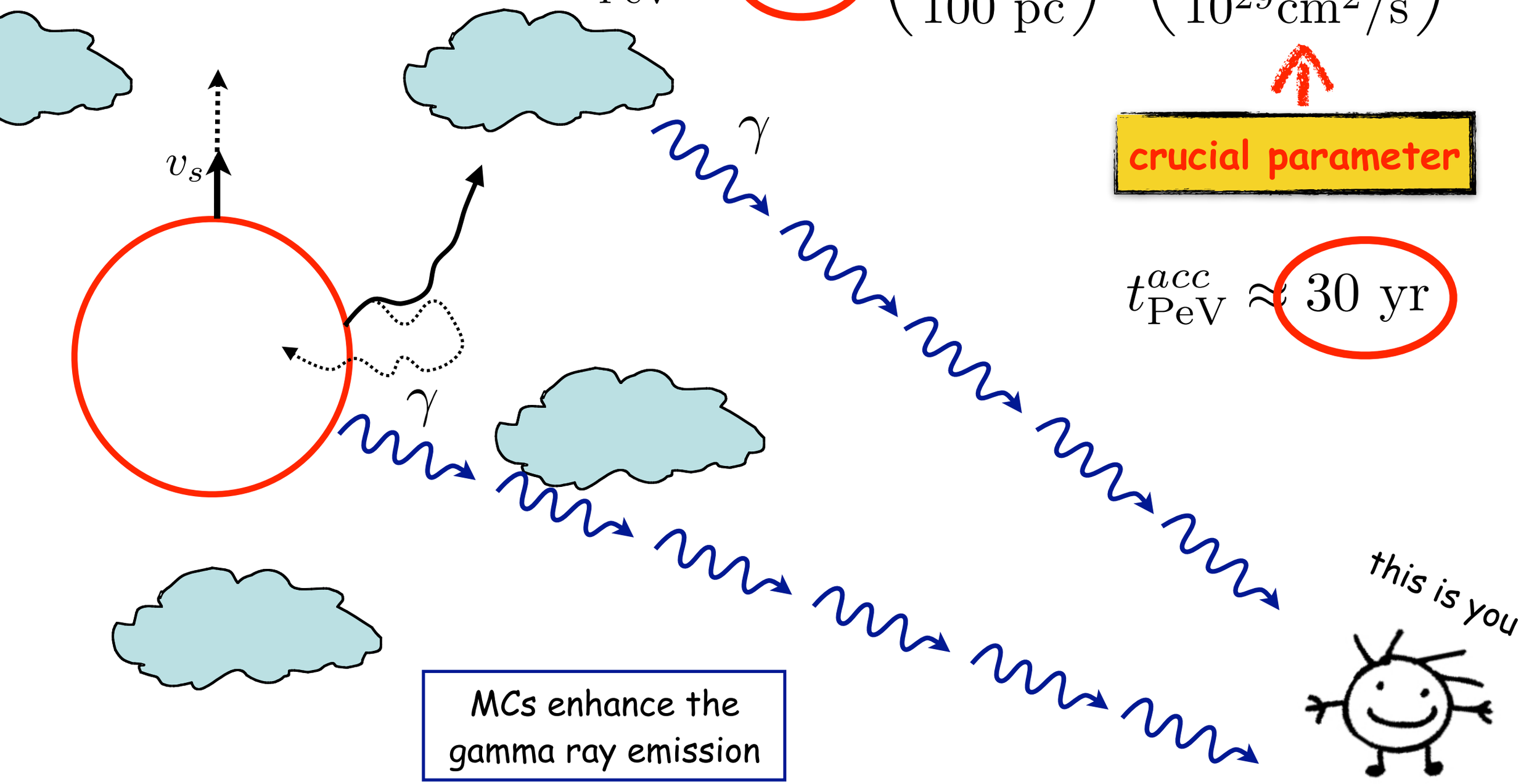
Indirect detection of PeVatrons?

CRs escape the SNR

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

crucial parameter

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



MCs enhance the gamma ray emission

SG & Aharonian 2007

A proton PeVatron in the galactic centre

Observational signature

unattenuated γ-ray spectrum extending to the multi-TeV domain

p-p interactions -> $E^p_{max} \approx 1\ \mathrm{PeV} \longrightarrow E^\gamma_{max} \approx 100\ \mathrm{TeV}$

inverse Compton-> suppressed in the multi-TeV domain (Klein-Nishina effect)

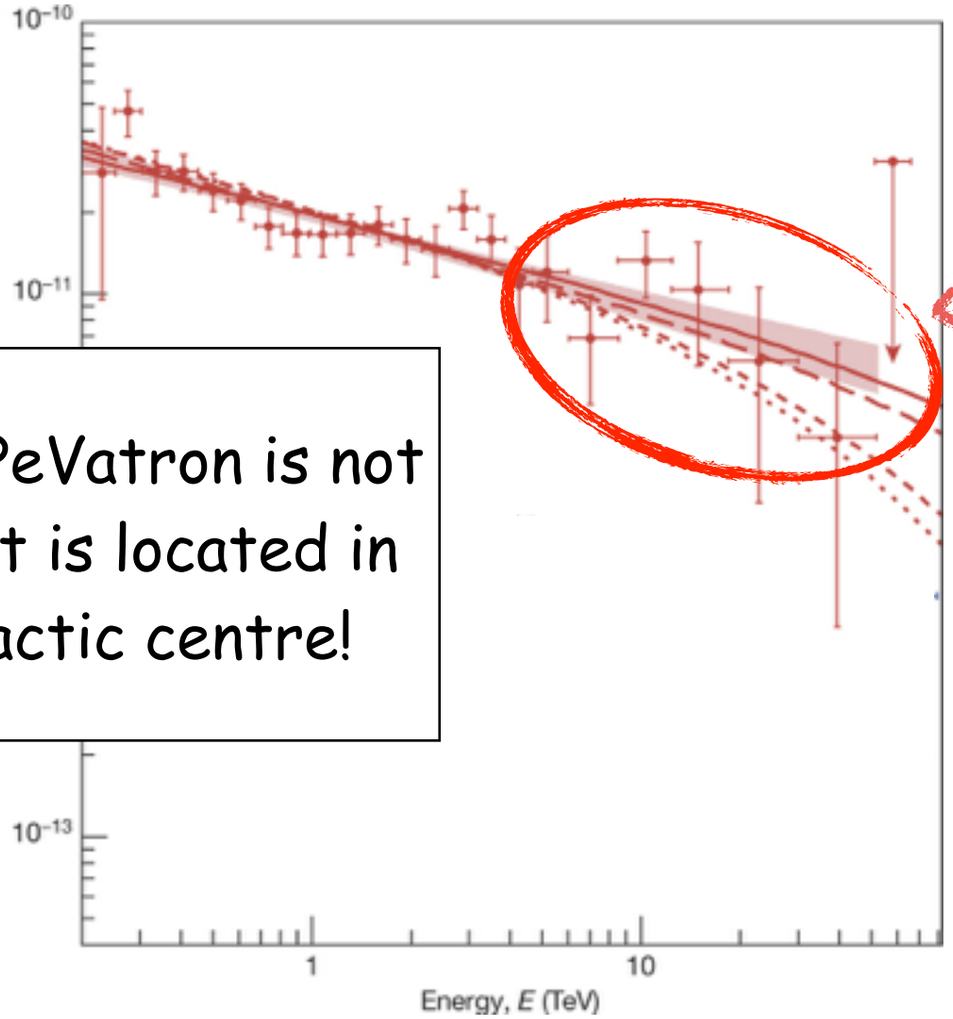
A proton PeVatron in the galactic centre

Observational signature

unattenuated γ-ray spectrum extending to the multi-TeV domain

p-p interactions -> $E^p_{max} \approx 1 \text{ PeV} \longrightarrow E^\gamma_{max} \approx 100 \text{ TeV}$

inverse Compton-> suppressed in the multi-TeV domain (Klein-Nishina effect)



diffuse emission from the GC

no cutoff!

the first PeVatron is not a SNR but is located in the Galactic centre!

H.E.S.S. Coll. 2016

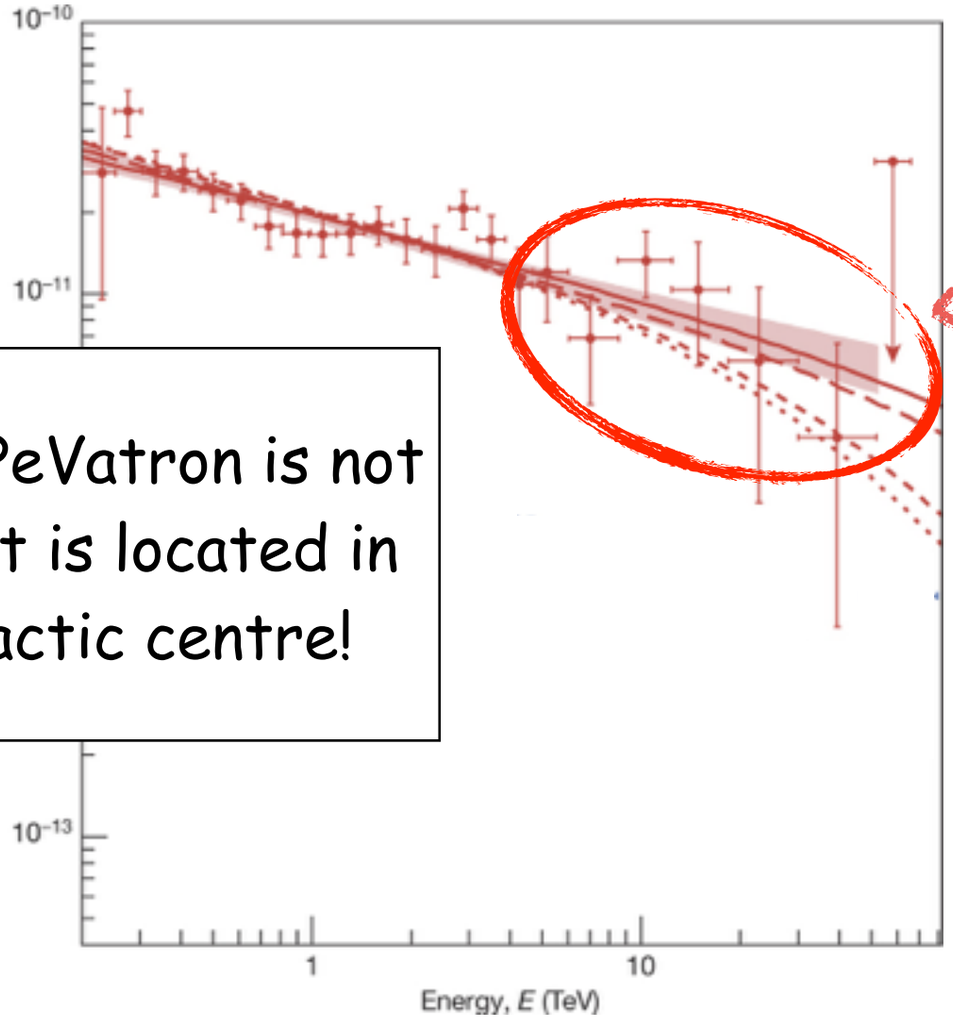
A proton PeVatron in the galactic centre

Observational signature

unattenuated γ-ray spectrum extending to the multi-TeV domain

p-p interactions -> $E^p_{max} \approx 1 \text{ PeV} \longrightarrow E^\gamma_{max} \approx 100 \text{ TeV}$

inverse Compton-> suppressed in the multi-TeV domain (Klein-Nishina effect)



the first PeVatron is not a SNR but is located in the Galactic centre!

diffuse emission from the GC

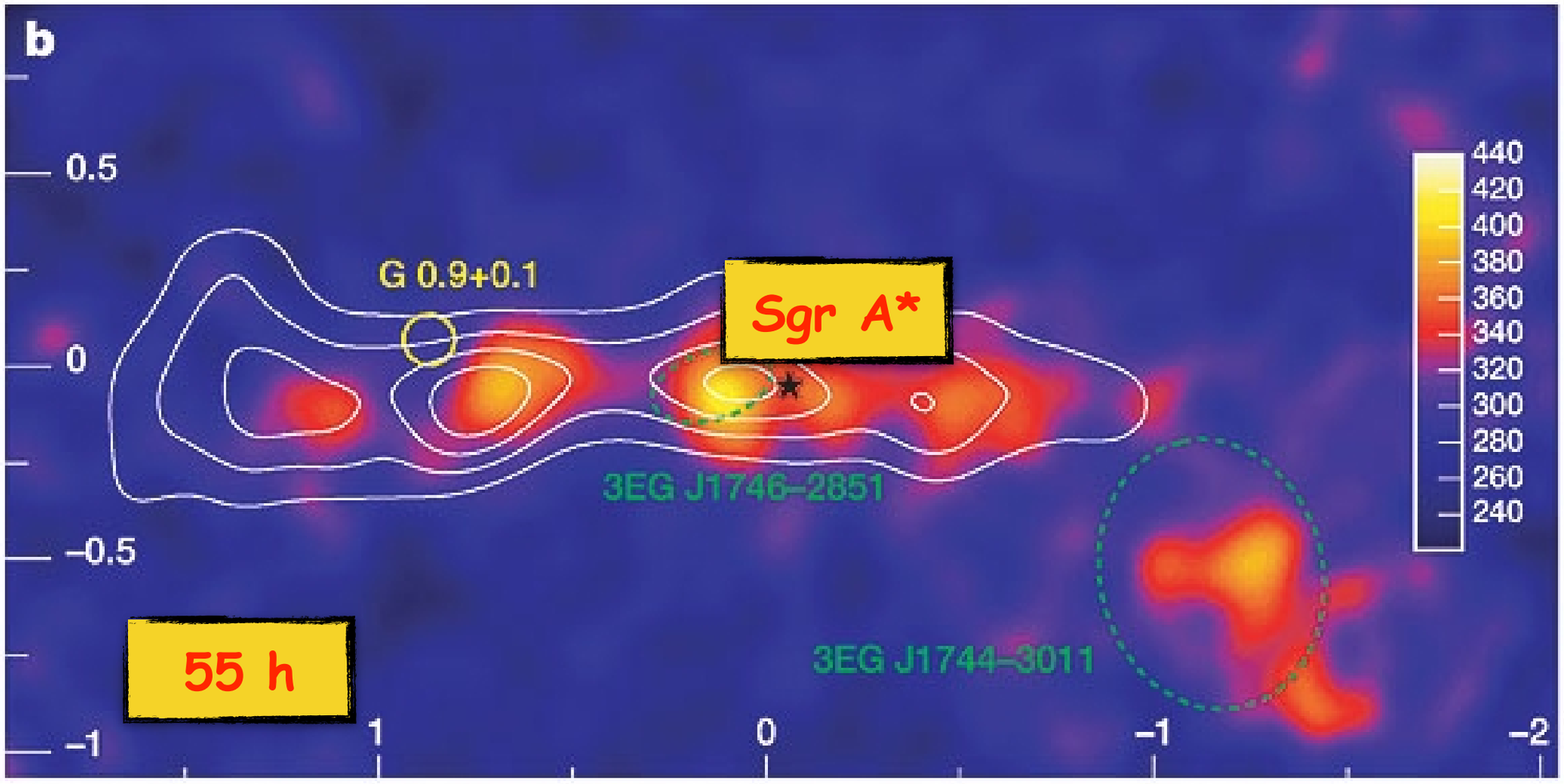
no cutoff!

a cutoff @ …	deviates from data @
2.9 PeV	68%
0.6 PeV	90%
0.4 PeV	95%

H.E.S.S. Coll. 2016

The GC ridge as seen 10 years ago

H.E.S.S. Coll. 2006

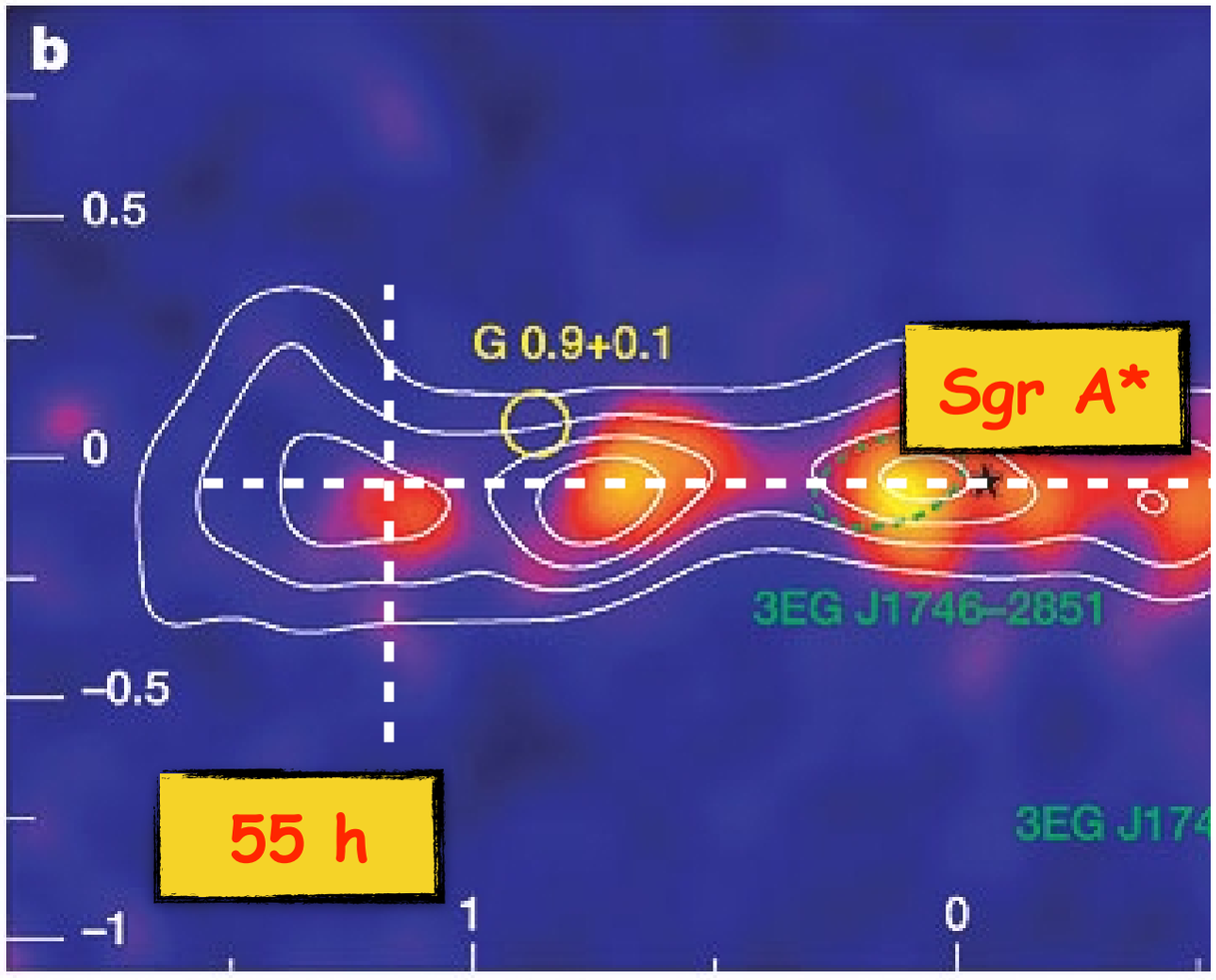


color scale -> γ-rays

contours -> gas (CS)

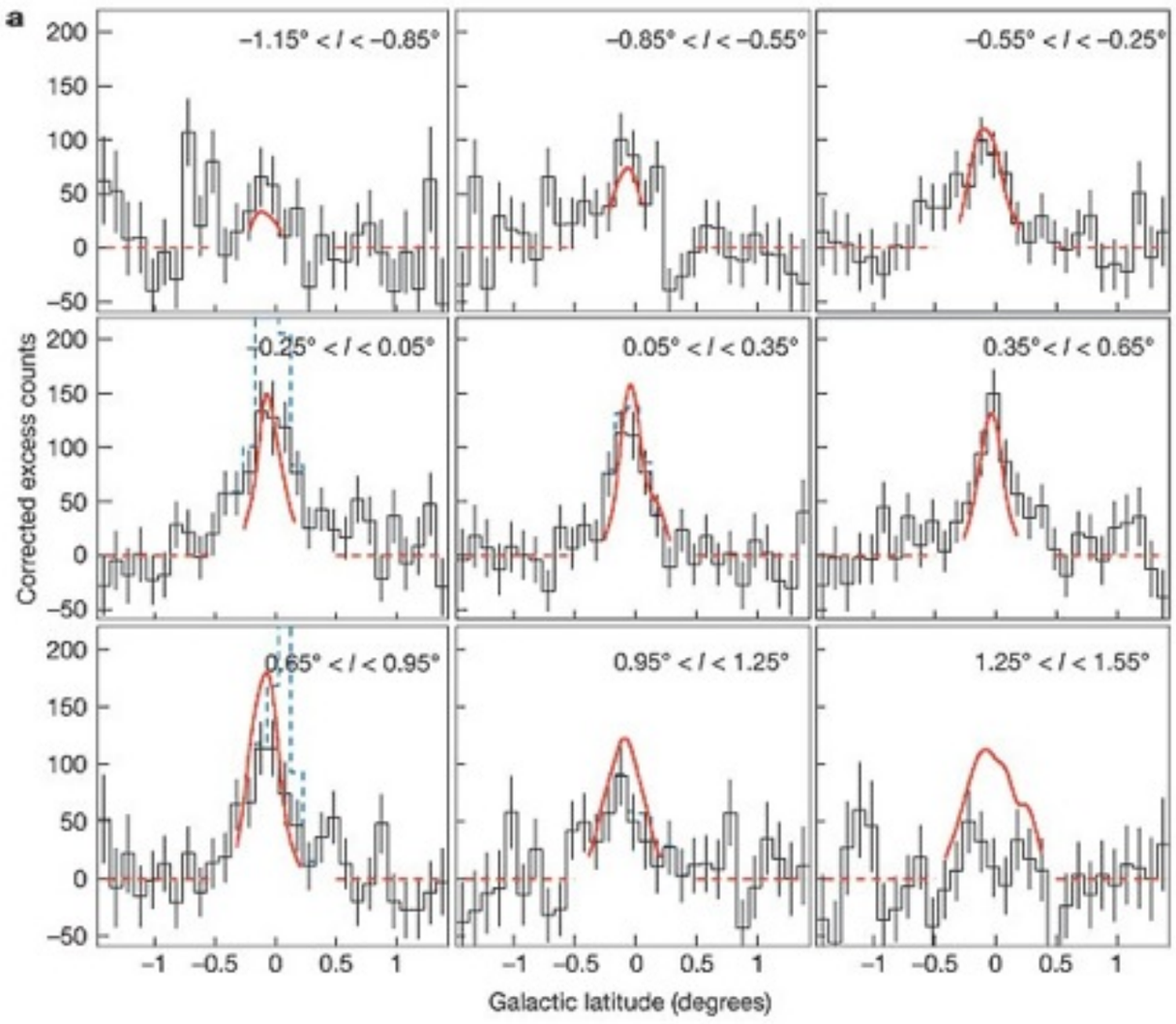
The GC ridge as seen 10 years ago

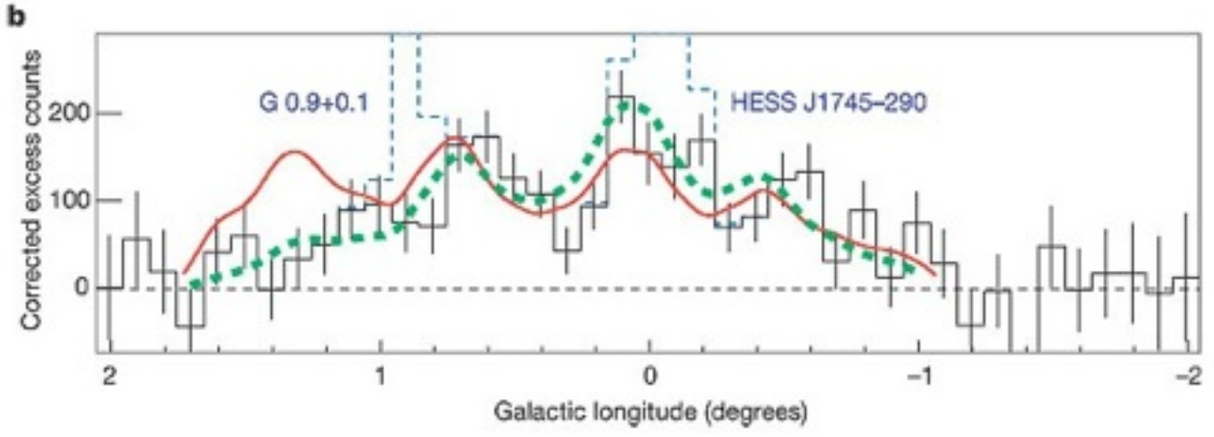
H.E.S.S. Coll. 2006



histogram -> γ-rays

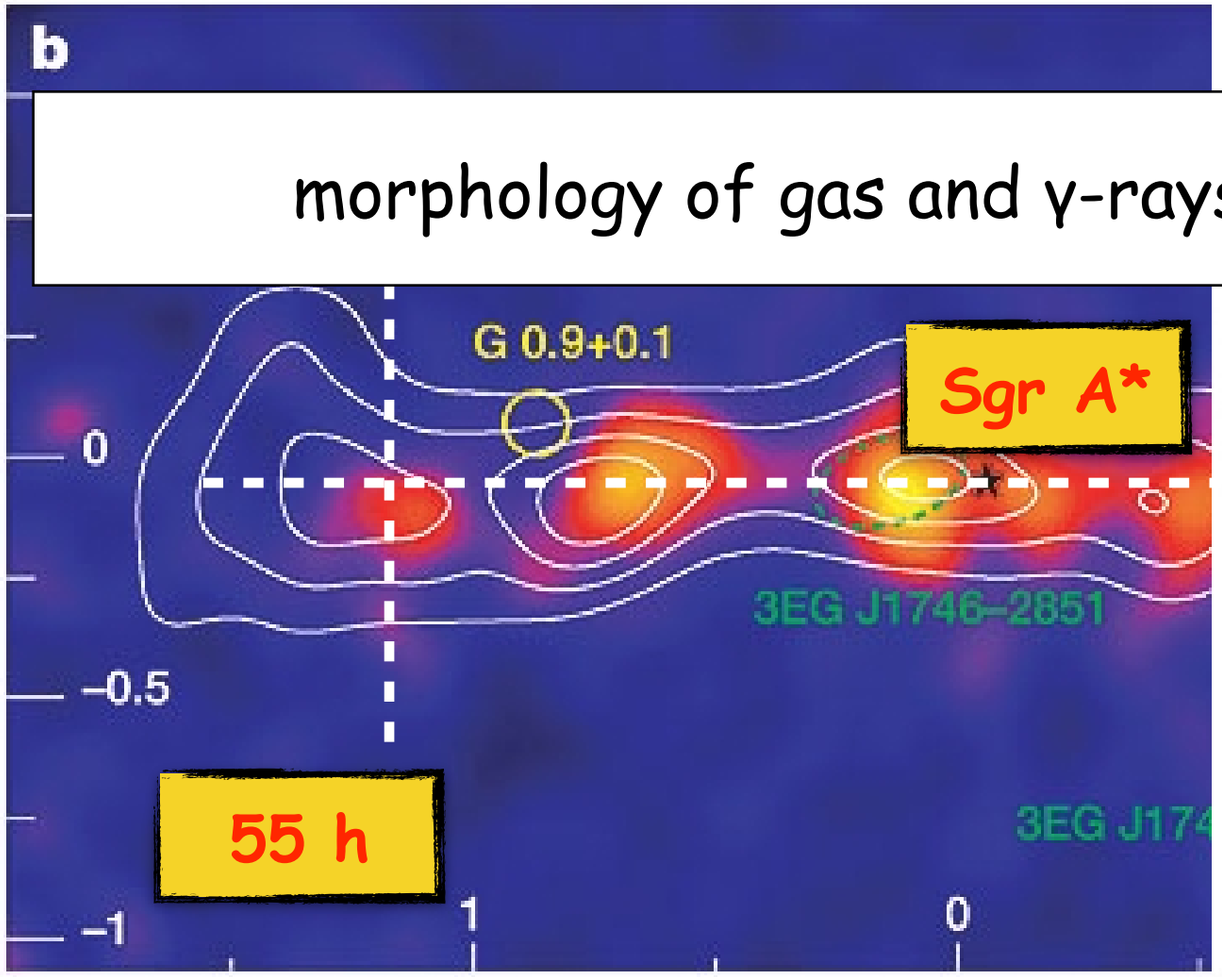
red -> gas (CS)



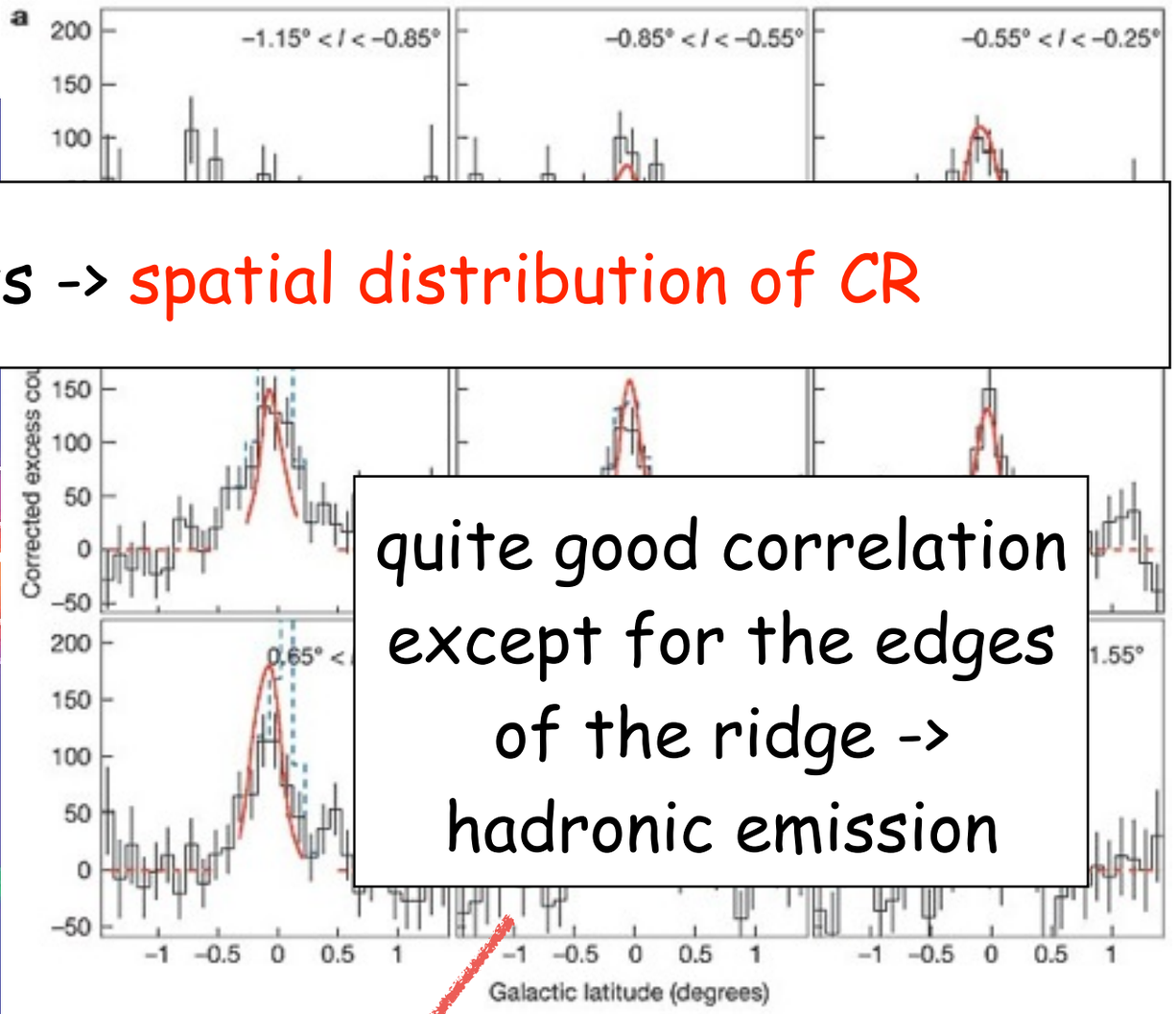


The GC ridge as seen 10 years ago

H.E.S.S. Coll. 2006



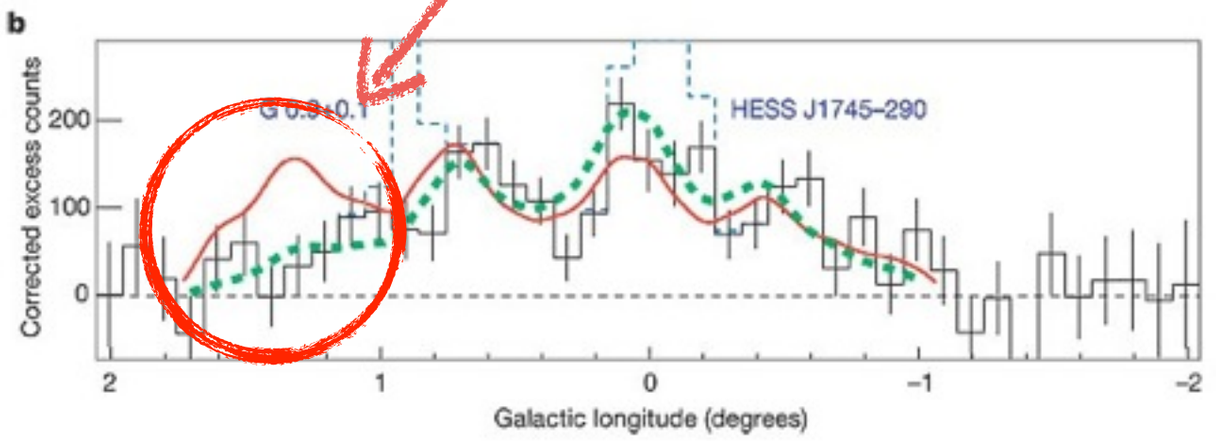
morphology of gas and γ-rays -> spatial distribution of CR



quite good correlation except for the edges of the ridge -> hadronic emission

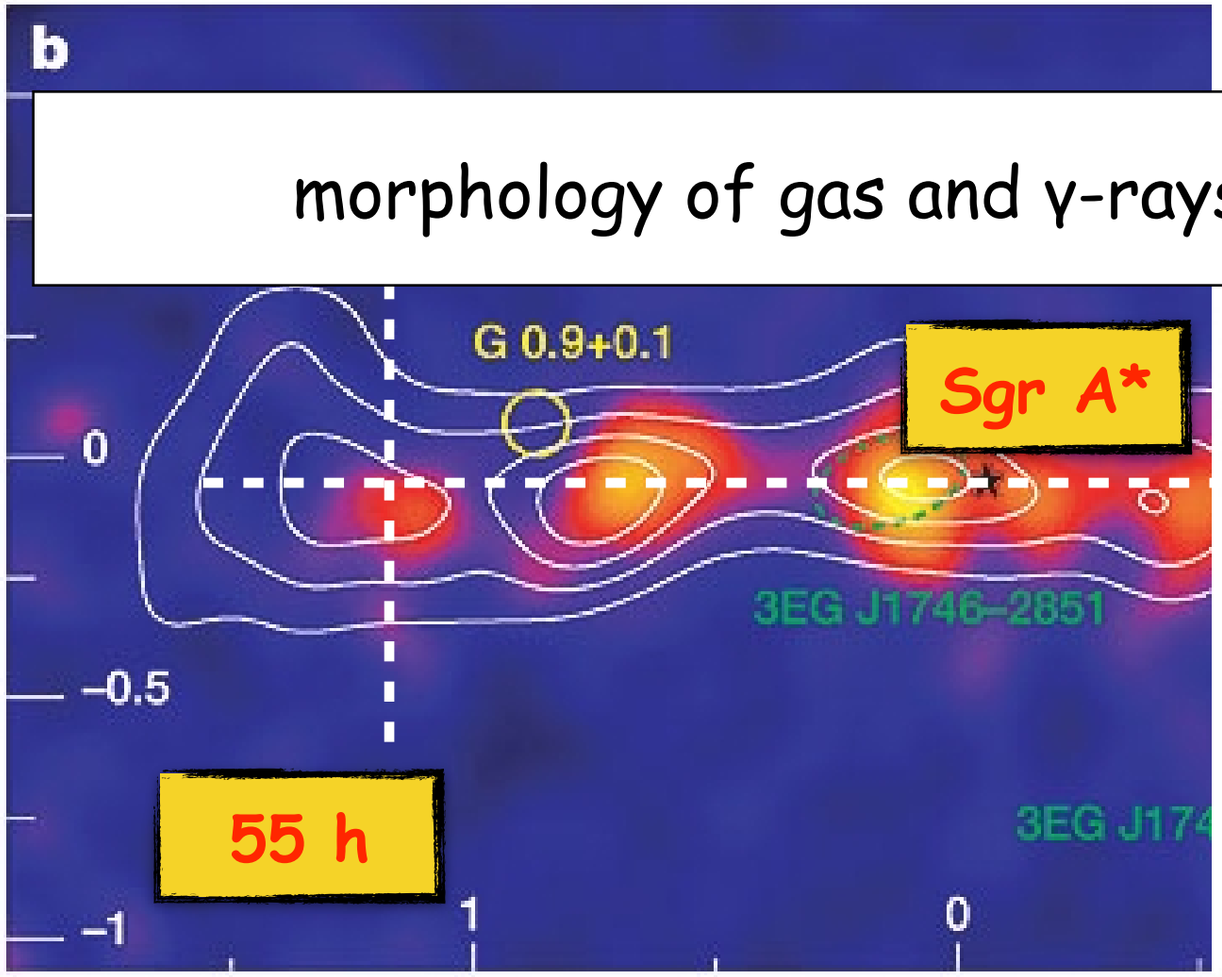
histogram -> γ-rays

red -> gas (CS)

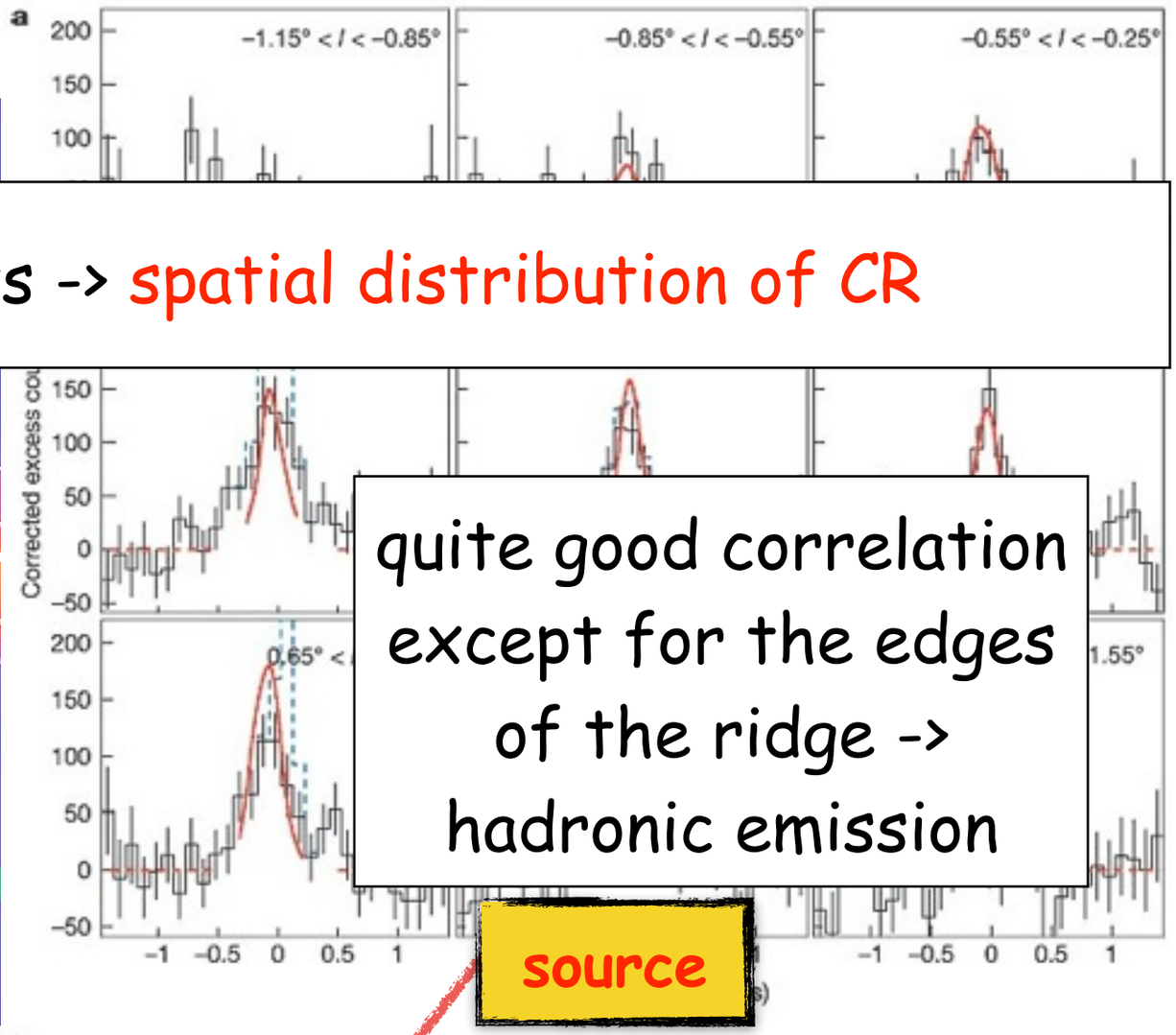


The GC ridge as seen 10 years ago

H.E.S.S. Coll. 2006



morphology of gas and γ-rays -> spatial distribution of CR



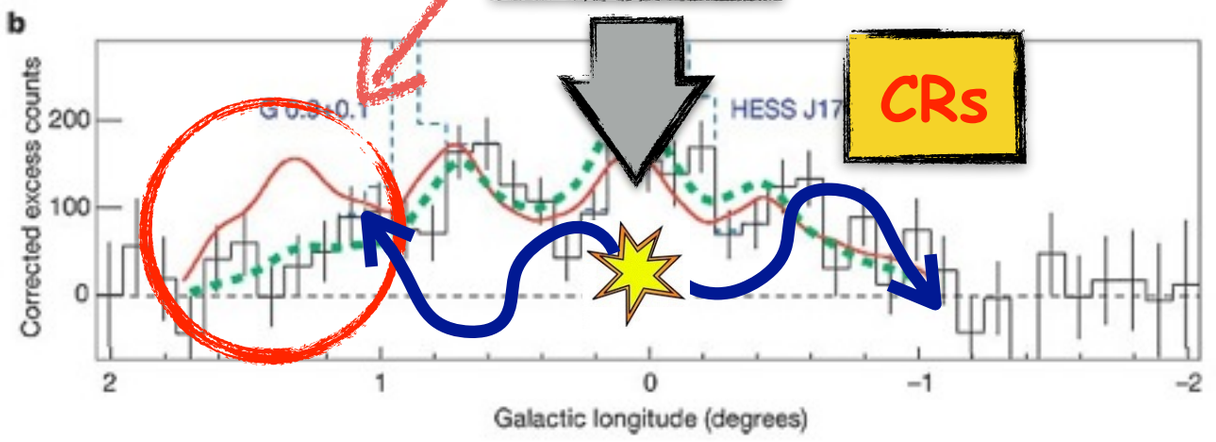
quite good correlation except for the edges of the ridge -> hadronic emission

source

CRs

histogram -> γ-rays

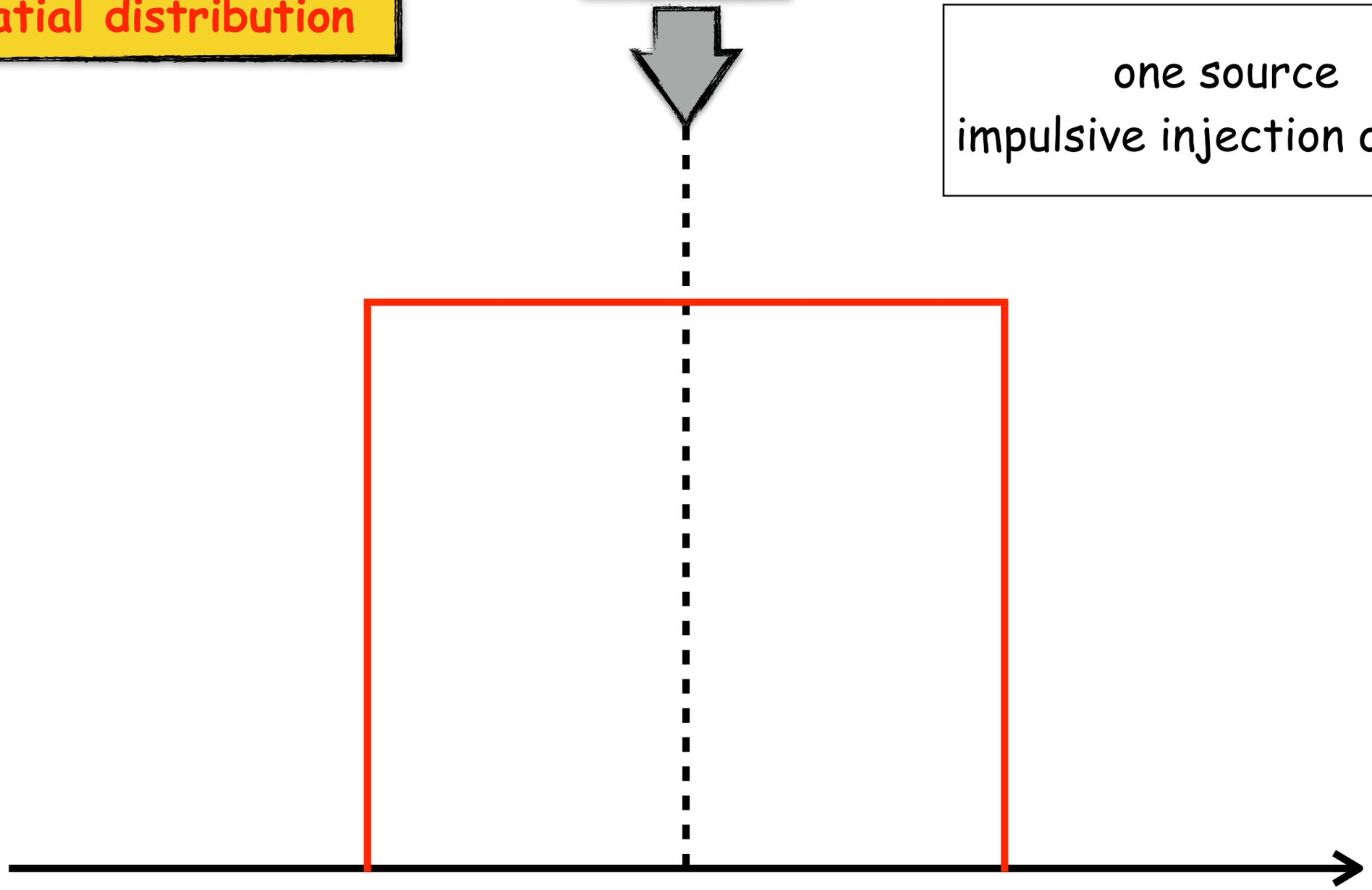
red -> gas (CS)



Where is the source?

CR spatial distribution

Sgr A*



one source
impulsive injection of CRs

Where is the source?

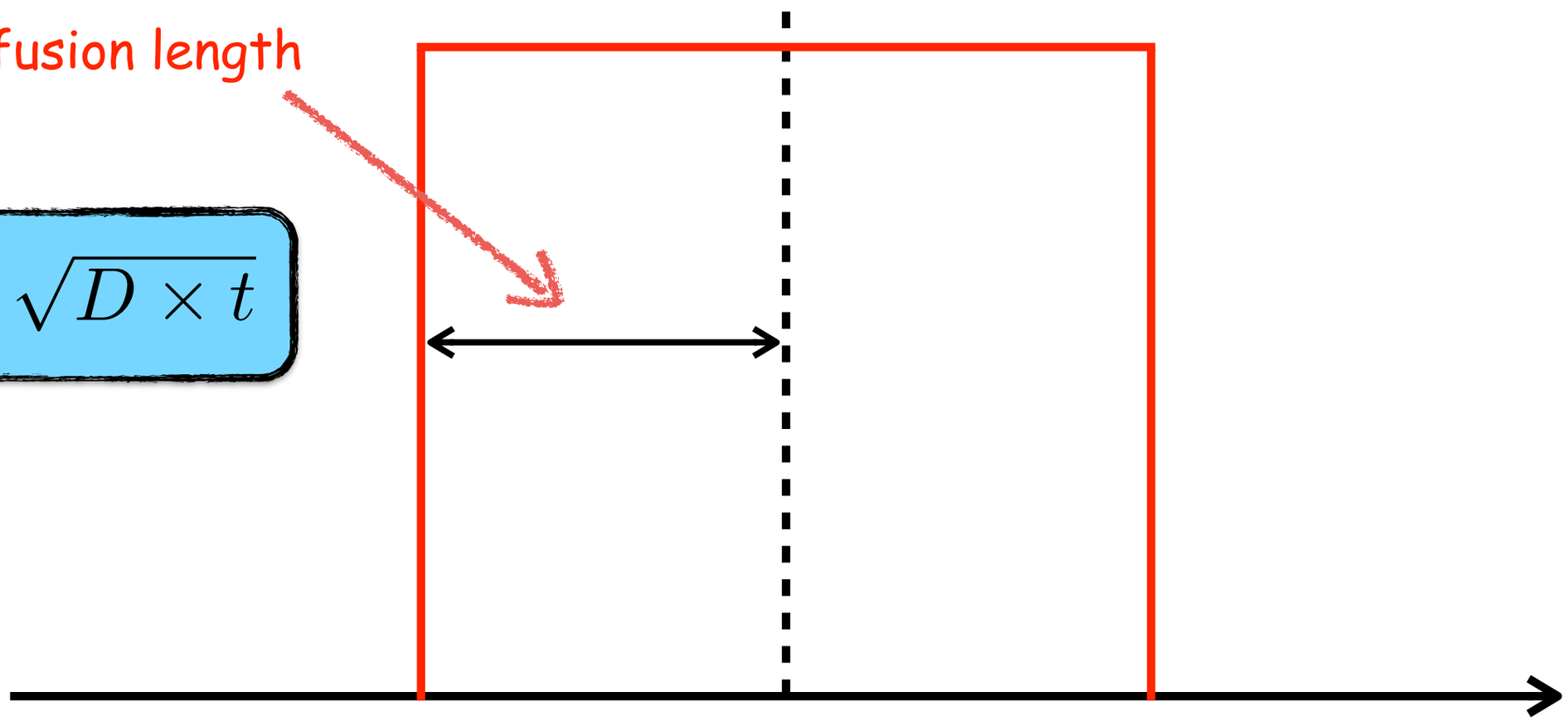
CR spatial distribution

Sgr A*

one source
impulsive injection of CRs

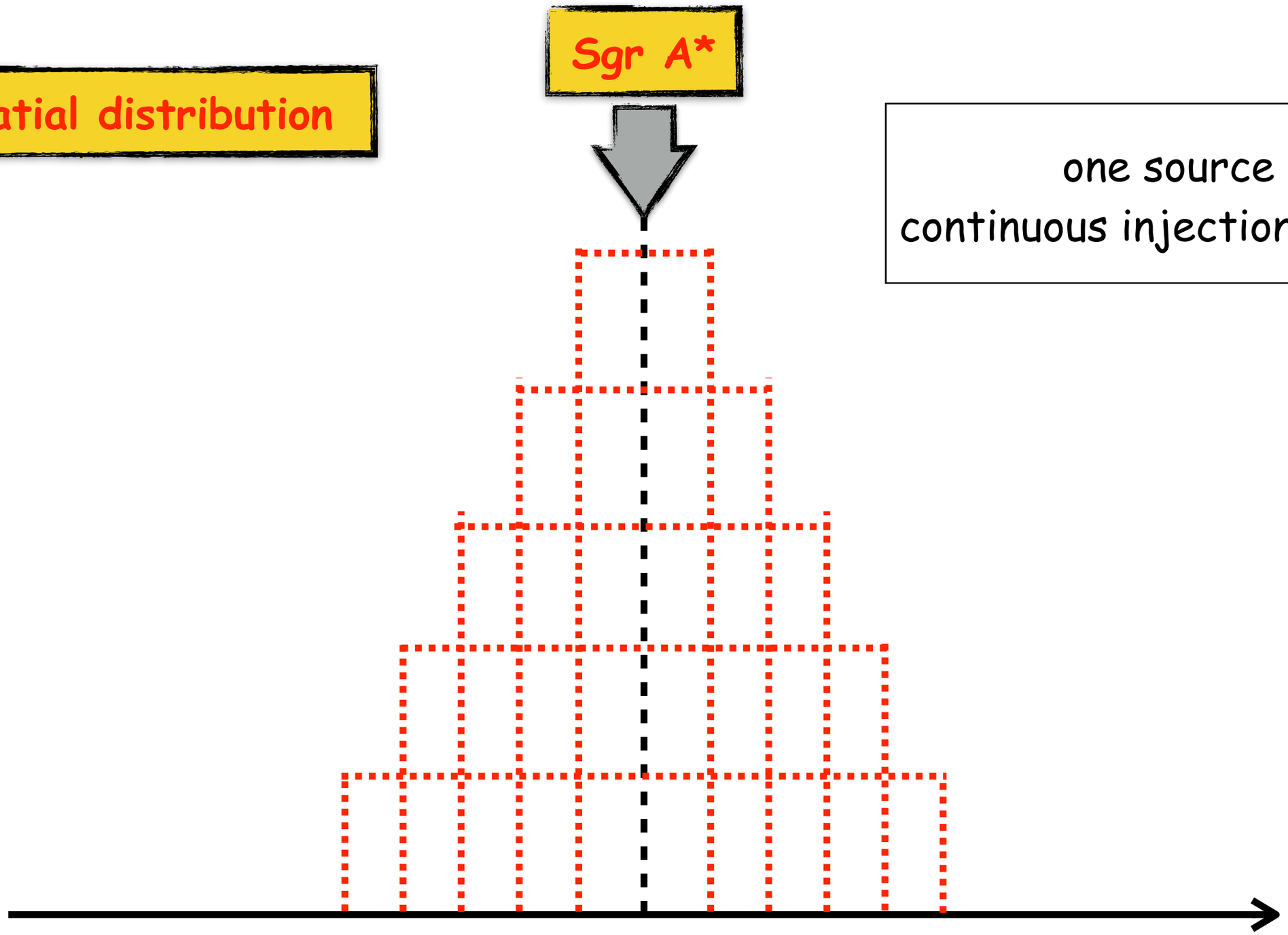
diffusion length

$$l_d \sim \sqrt{D \times t}$$



Where is the source?

CR spatial distribution

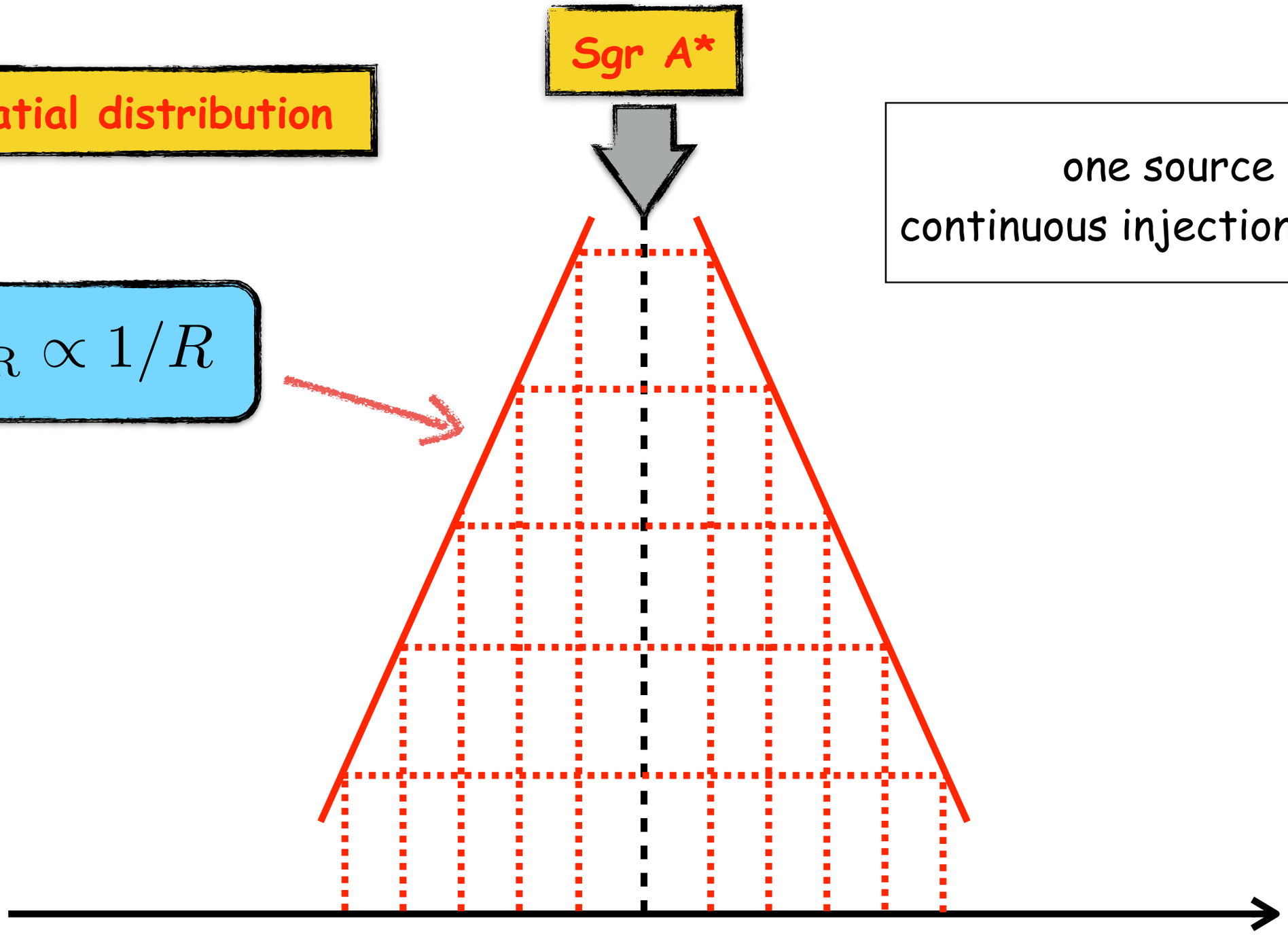


one source
continuous injection of CRs

Where is the source?

CR spatial distribution

$n_{\rm CR} \propto 1/R$

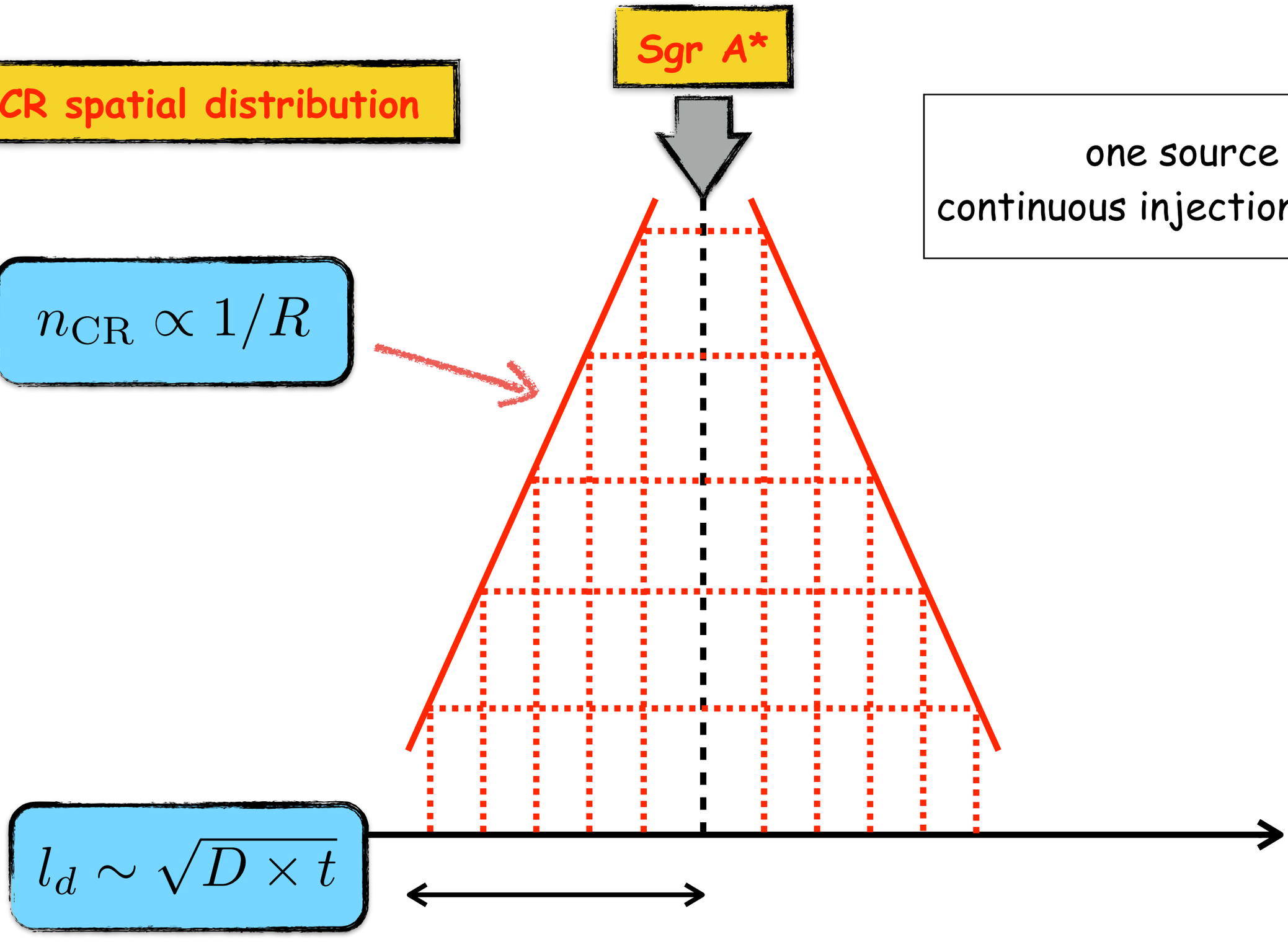


one source
continuous injection of CRs

Where is the source?

CR spatial distribution

$n_{\rm CR} \propto 1/R$



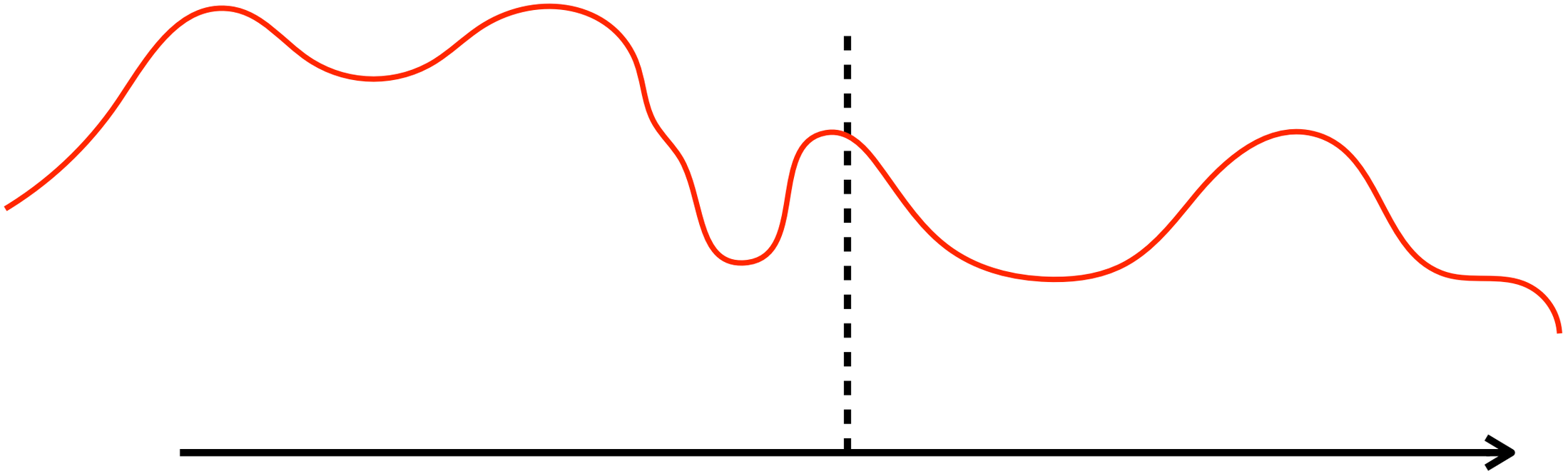
one source
continuous injection of CRs

Where is the source?

CR spatial distribution

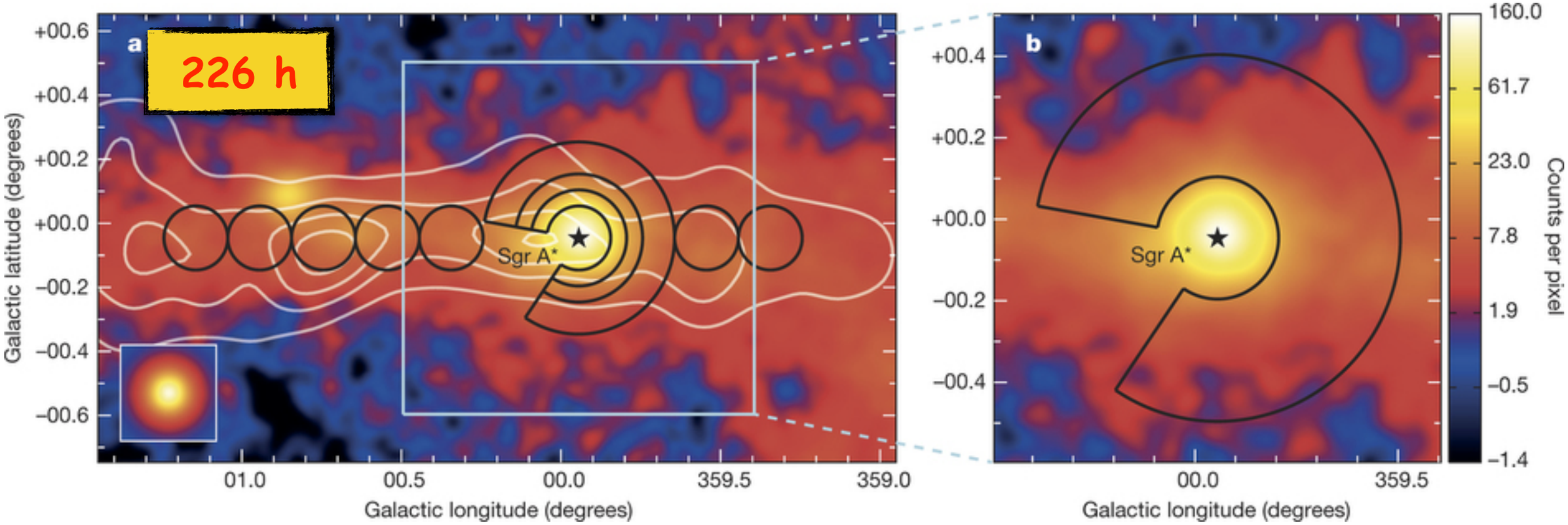
Sgr A*

many sources
-> any distribution



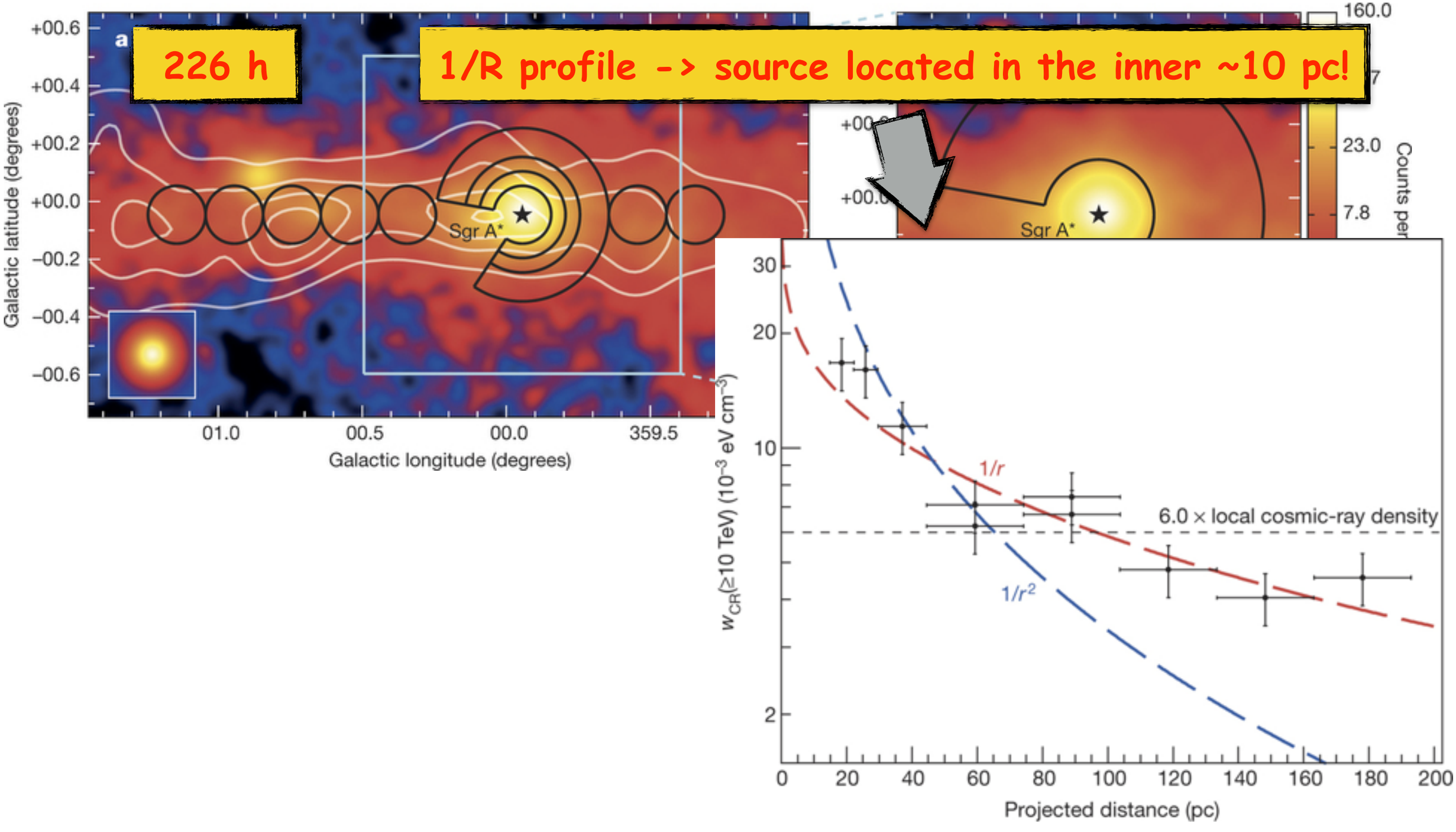
The source is at the GC

H.E.S.S. Coll. 2016



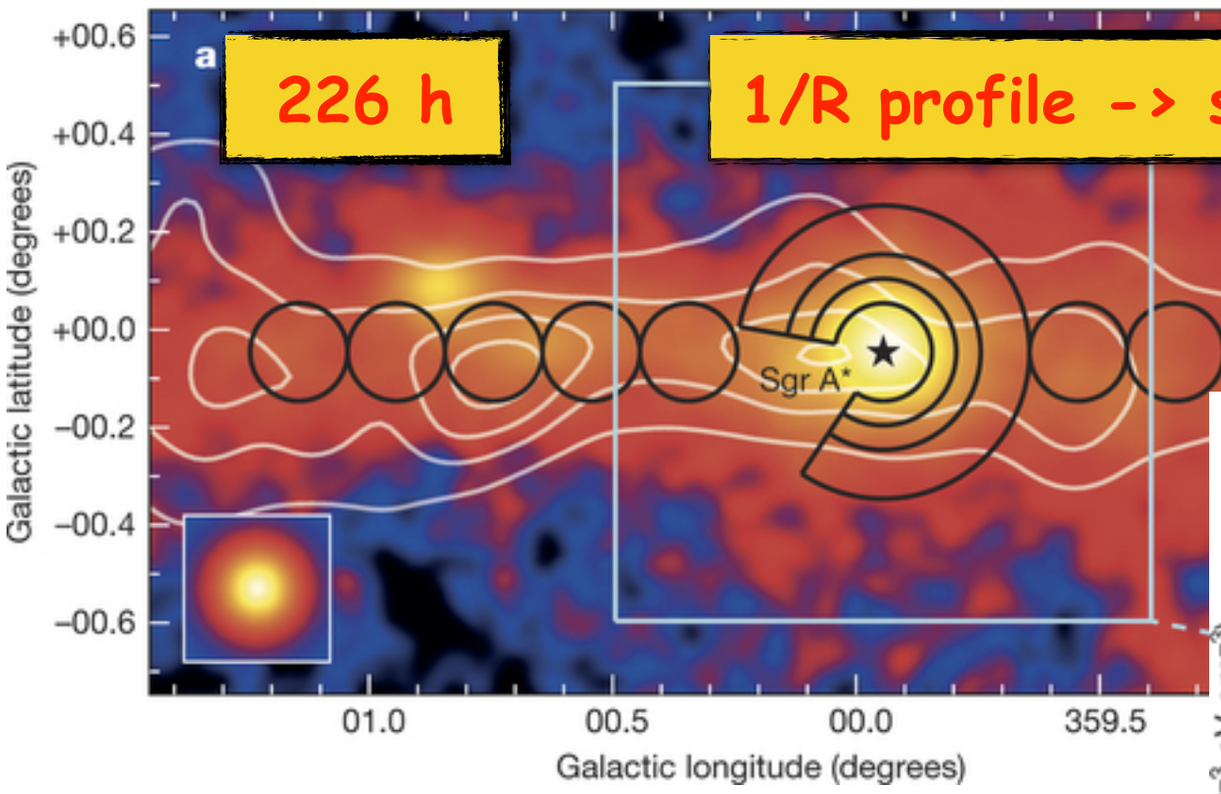
The source is at the GC

H.E.S.S. Coll. 2016



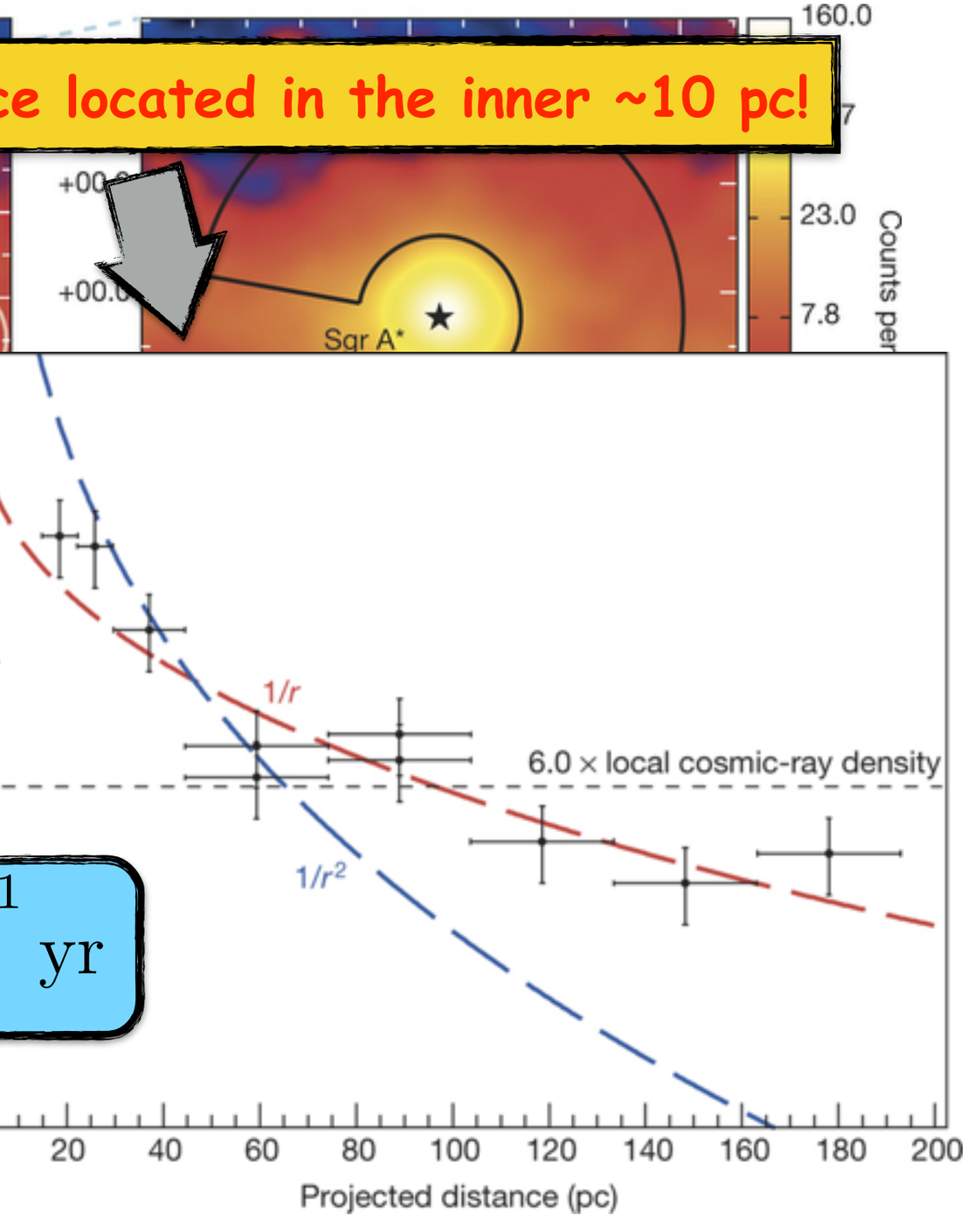
The source is at the GC

H.E.S.S. Coll. 2016



226 h

1/R profile -> source located in the inner ~10 pc!

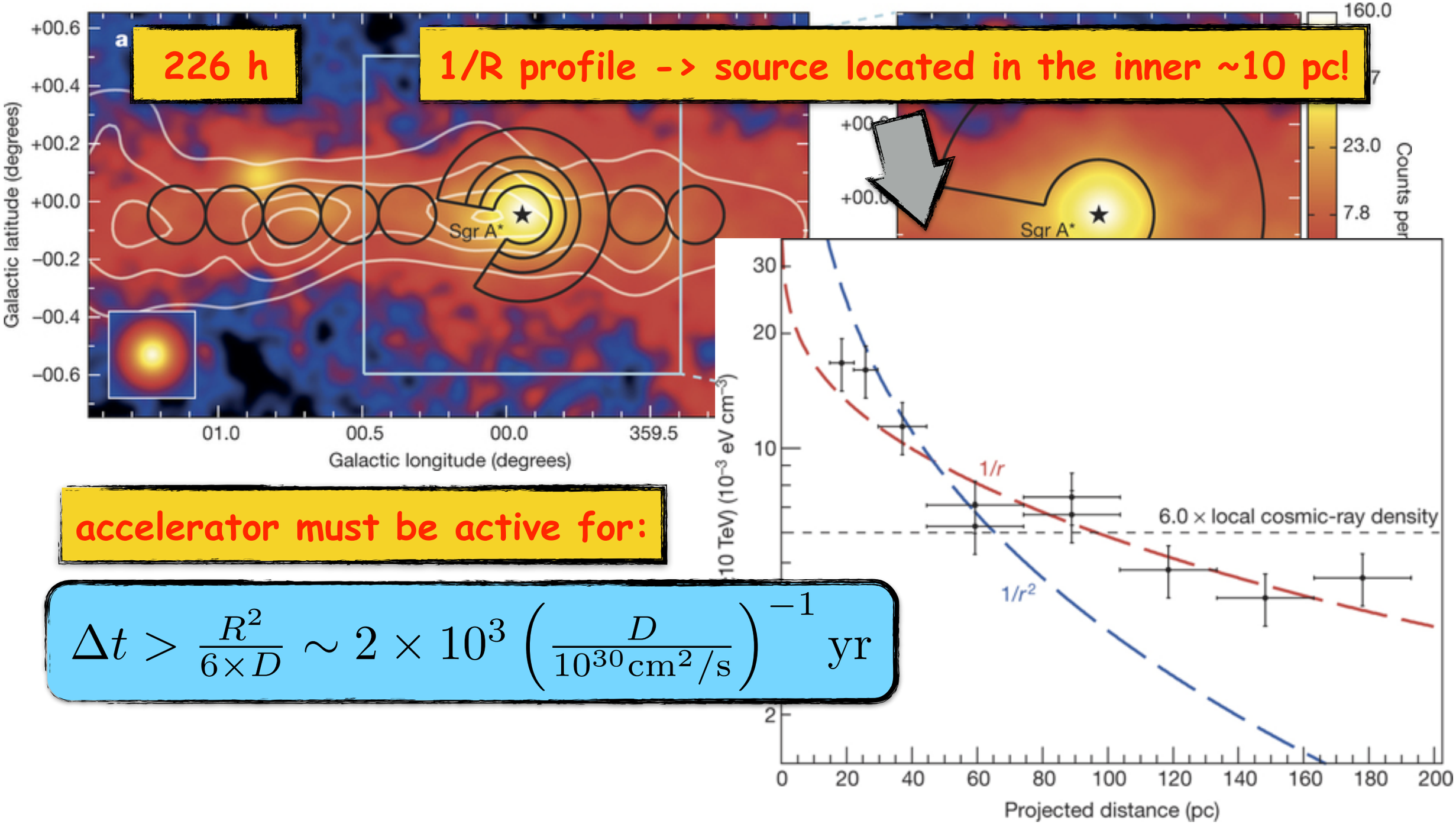


accelerator must be active for:

$$\Delta t > \frac{R^2}{6 \times D} \sim 2 \times 10^3 \left(\frac{D}{10^{30} \mathrm{cm}^2/\mathrm{s}} \right)^{-1} \mathrm{yr}$$

The source is at the GC

H.E.S.S. Coll. 2016



226 h

1/R profile -> source located in the inner ~10 pc!

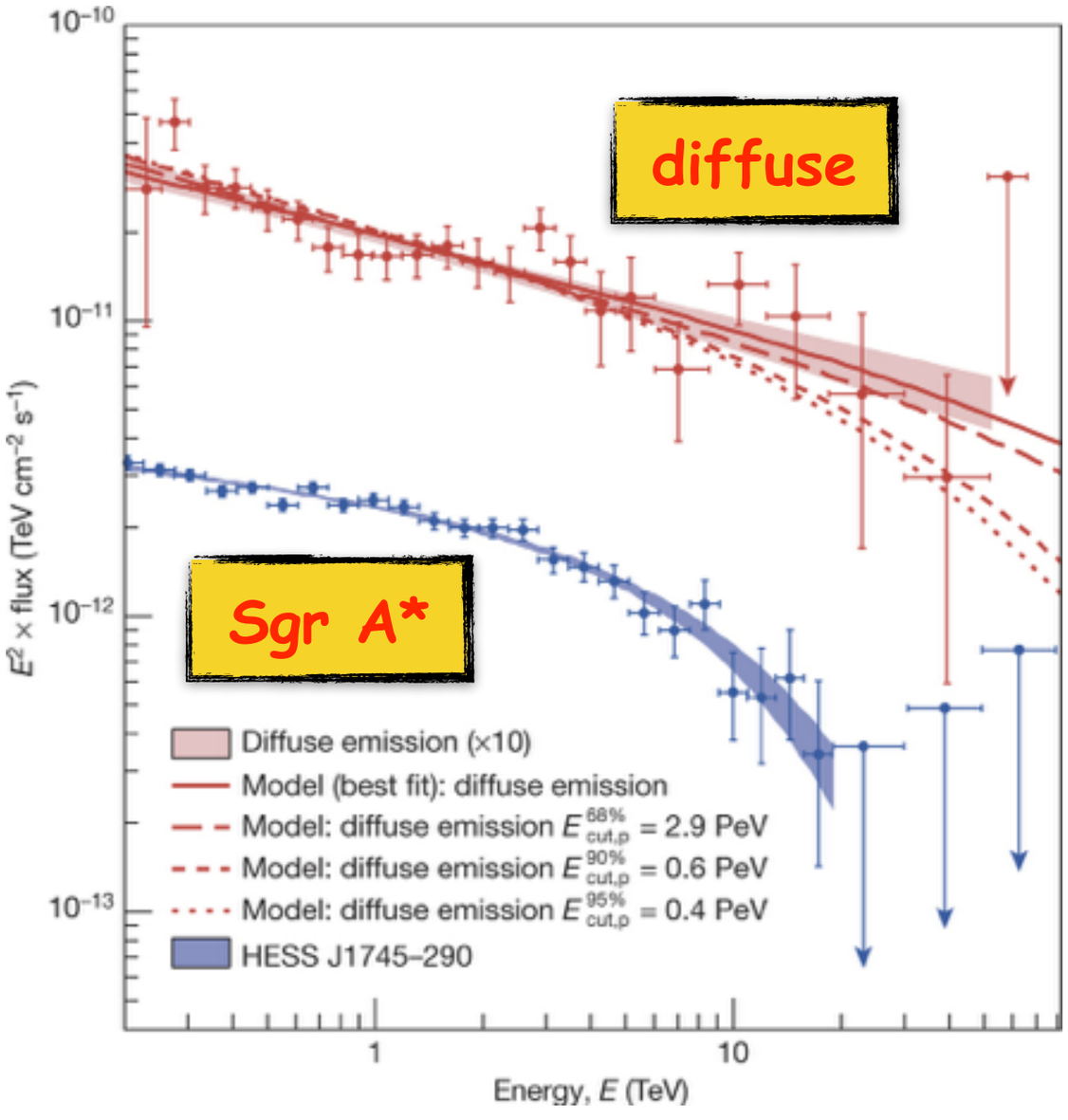
accelerator must be active for:

$$\Delta t > \frac{R^2}{6 \times D} \sim 2 \times 10^3 \left(\frac{D}{10^{30} \mathrm{cm}^2/\mathrm{s}} \right)^{-1} \mathrm{yr}$$

multi-source scenarios require excessive fine-tuning/unrealistic number of sources

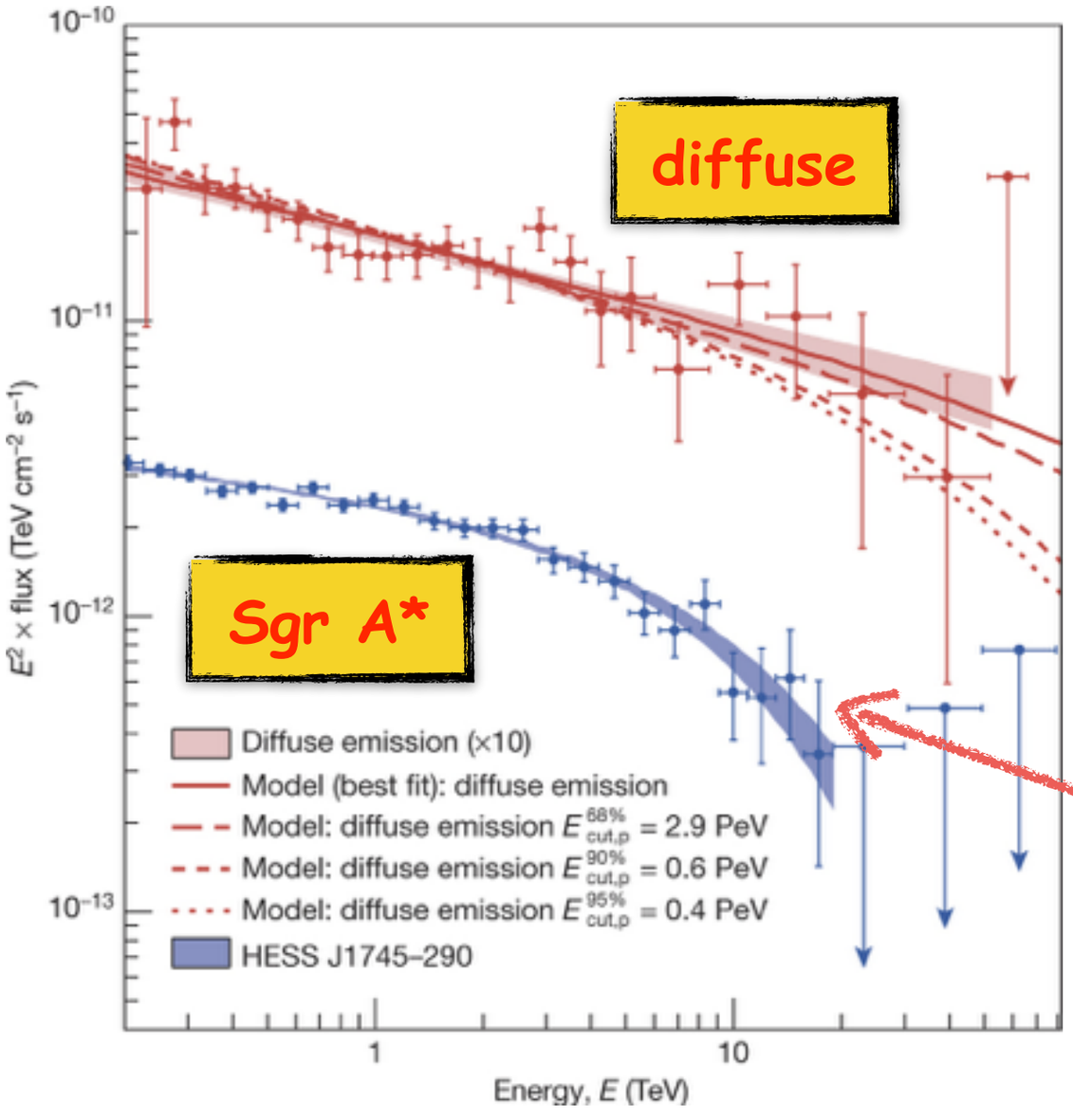
Supermassive black hole as a PeVatron

Sgr A* is the best bet candidate source of PeV cosmic rays



Supermassive black hole as a PeVatron

Sgr A* is the best bet candidate source of PeV cosmic rays

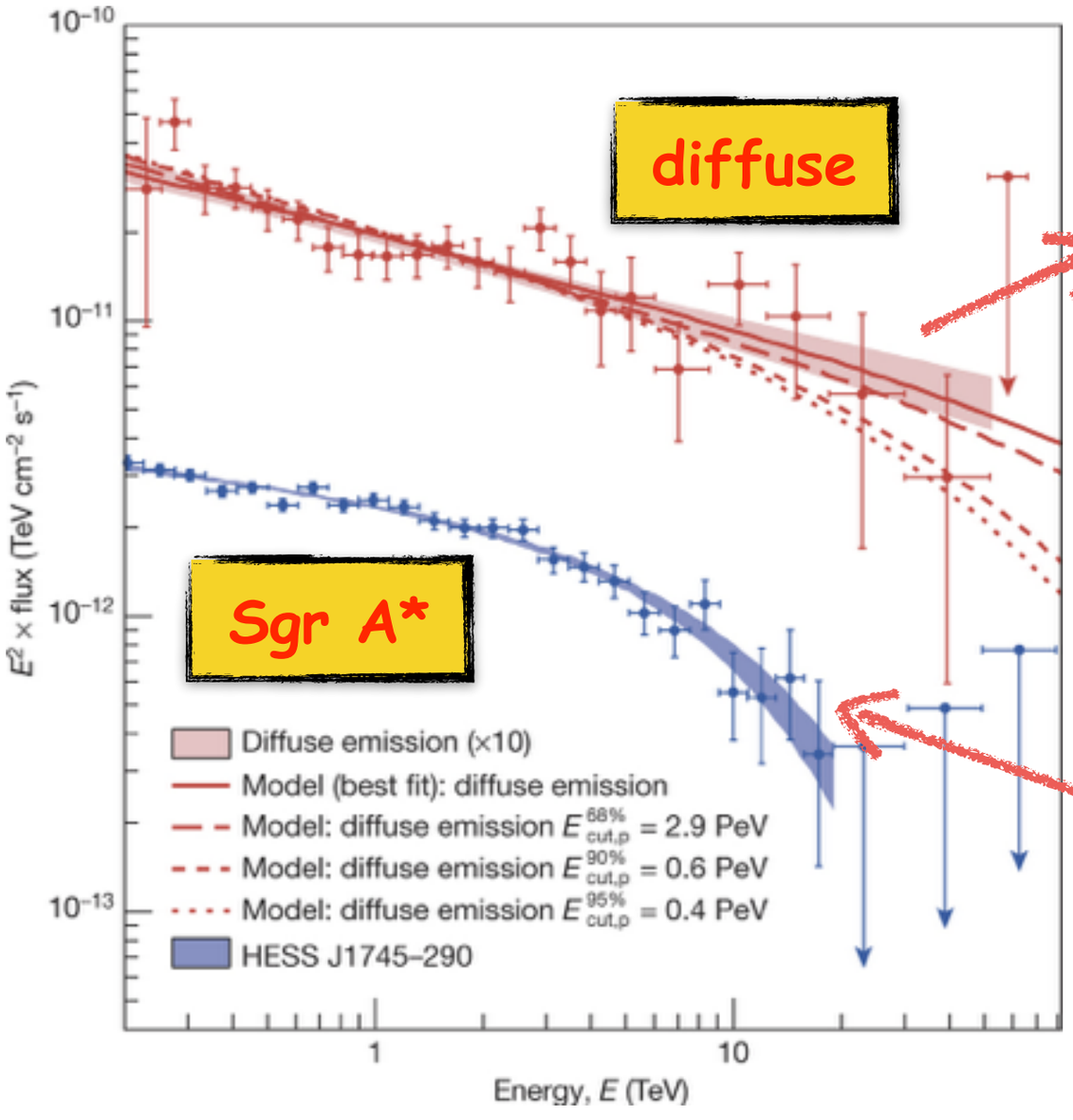


~10 TeV cutoff -> inconsistency? no...

- emission could be unrelated
- time dependent effect
- γγ-absorption w. IR photons? (Celli+ 2016)

Supermassive black hole as a PeVatron

Sgr A* is the best bet candidate source of PeV cosmic rays



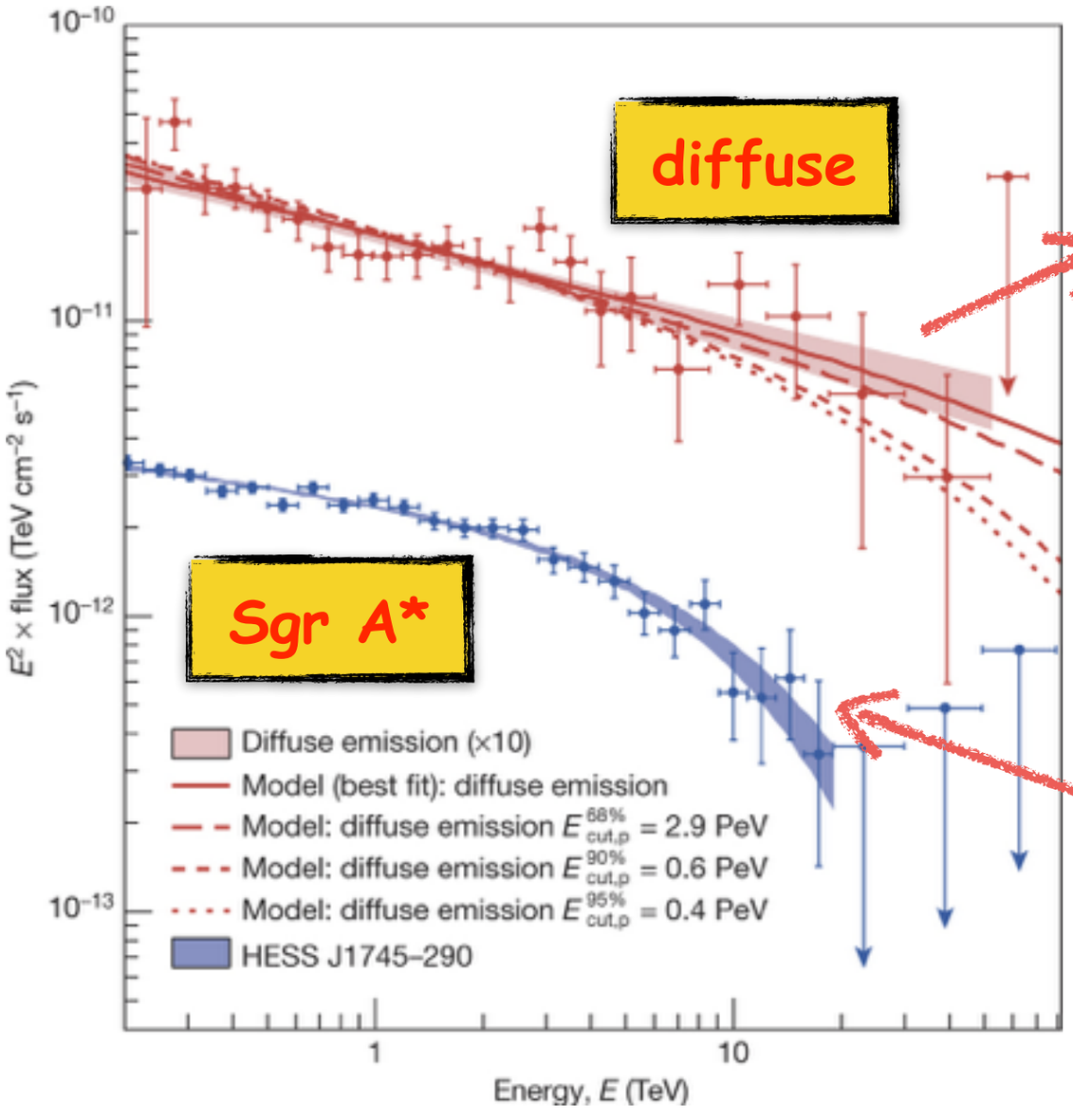
gas mass → $W_p \sim 10^{49}\mathrm{erg}$

~10 TeV cutoff -> inconsistency? no...

- emission could be unrelated
- time dependent effect
- γγ-absorption w. IR photons? (Celli+ 2016)

Supermassive black hole as a PeVatron

Sgr A* is the best bet candidate source of PeV cosmic rays



gas mass → $W_p \sim 10^{49}\mathrm{erg}$

1/R profile → $\dot{Q}_p \sim 4 \times 10^{37} \left(\frac{D}{10^{30}\mathrm{cm}^2/\mathrm{s}} \right) \mathrm{erg/s}$

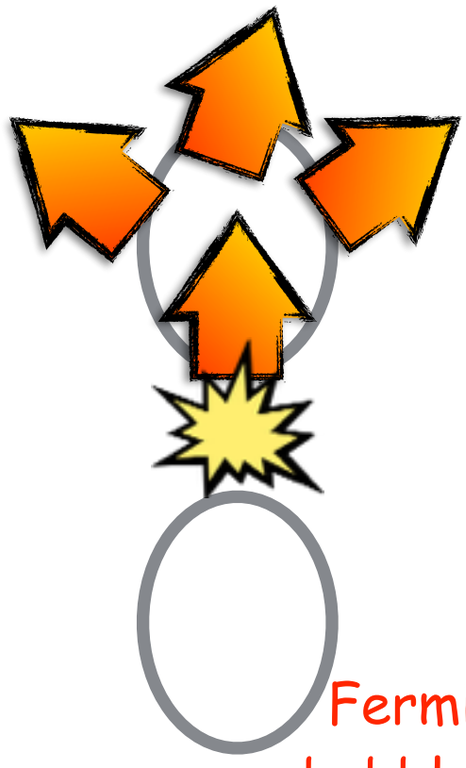
~10 TeV cutoff -> inconsistency? no...

- emission could be unrelated
- time dependent effect
- γγ-absorption w. IR photons? (Celli+ 2016)

speculations

BH activity, cosmic rays, neutrinos

the GC activity highly variable (Ponti+2013) -> what if the CR acceleration efficiency was larger in the past?



Fermi bubbles

speculations

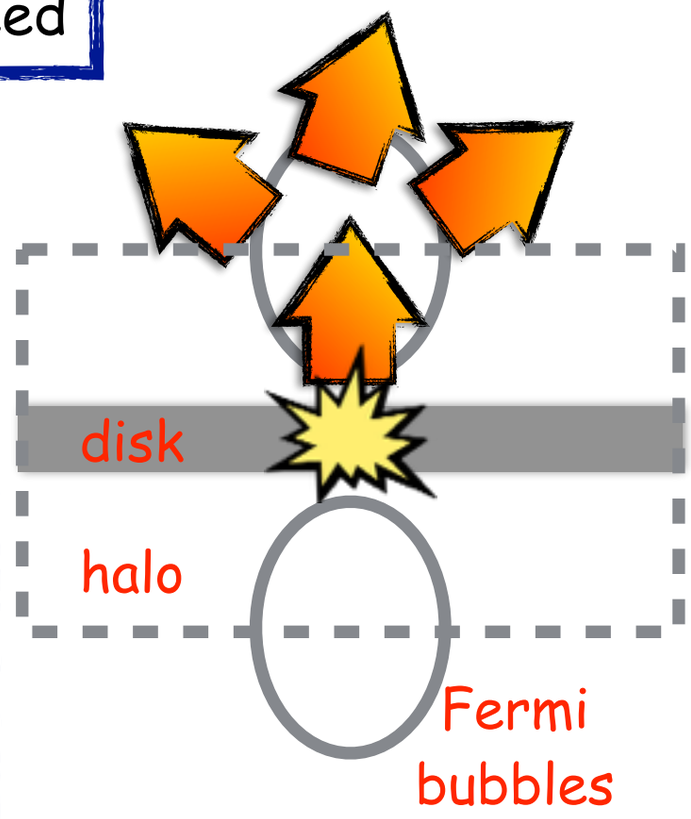
BH activity, cosmic rays, neutrinos

to explain **all** CRs >10 TeV we need

$$L_{CR} \approx 10^{39}\ \mathrm{erg/s}$$

for ~10^6-10^7 yrs

the GC activity highly variable (Ponti+2013) -> what if the CR acceleration efficiency was larger in the past?



speculations

BH activity, cosmic rays, neutrinos

~200 kpc

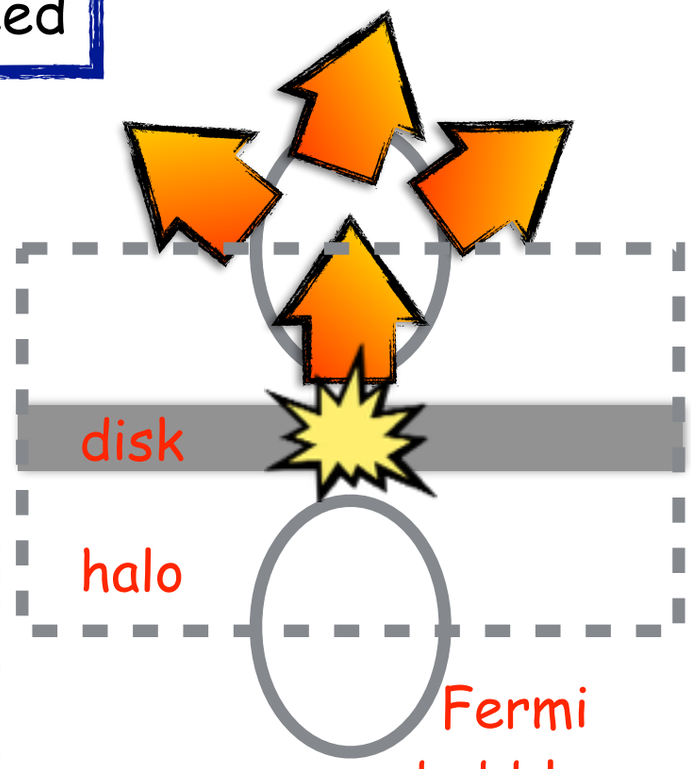
to explain **all** CRs >10 TeV we need

$L_{CR} \approx 10^{39}$ erg/s

for ~10^6-10^7 yrs

the GC activity highly variable (Ponti+2013) -> what if the CR acceleration efficiency was larger in the past?

evidence for a huge reservoir of ionized gas (> 10^{10} M_{sun}) in the halo from X-ray observations (Gupta+ 2012)



speculations

BH activity, cosmic rays, neutrinos

~200 kpc

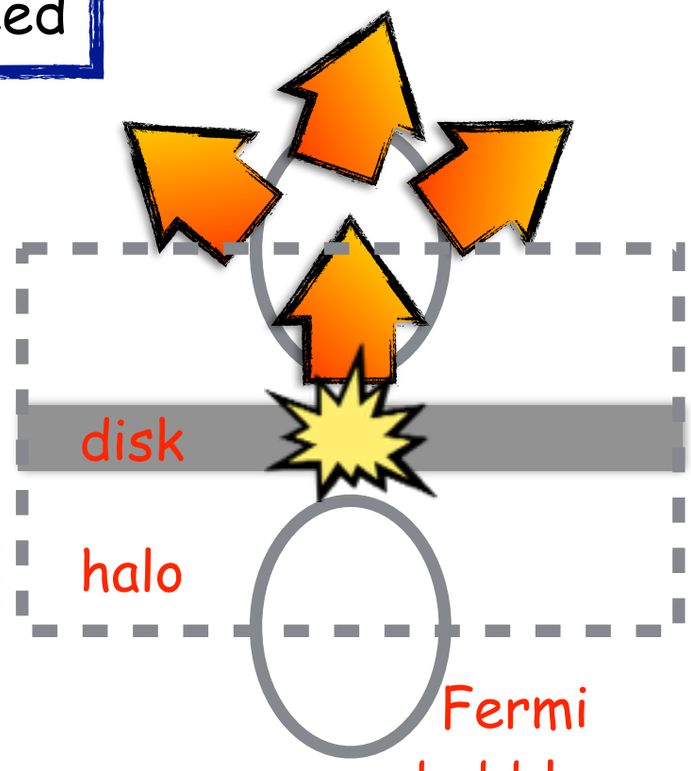
to explain **all** CRs >10 TeV we need

$L_{CR} \approx 10^{39}$ erg/s

for ~10^6-10^7 yrs

the GC activity highly variable (Ponti+2013) -> what if the CR acceleration efficiency was larger in the past?

evidence for a huge reservoir of ionized gas (> 10^{10} M_{sun}) in the halo from X-ray observations (Gupta+ 2012)



IceCube neutrinos

Taylor, SG, Aharonian 2014

speculations

BH activity, cosmic rays, neutrinos

~200 kpc

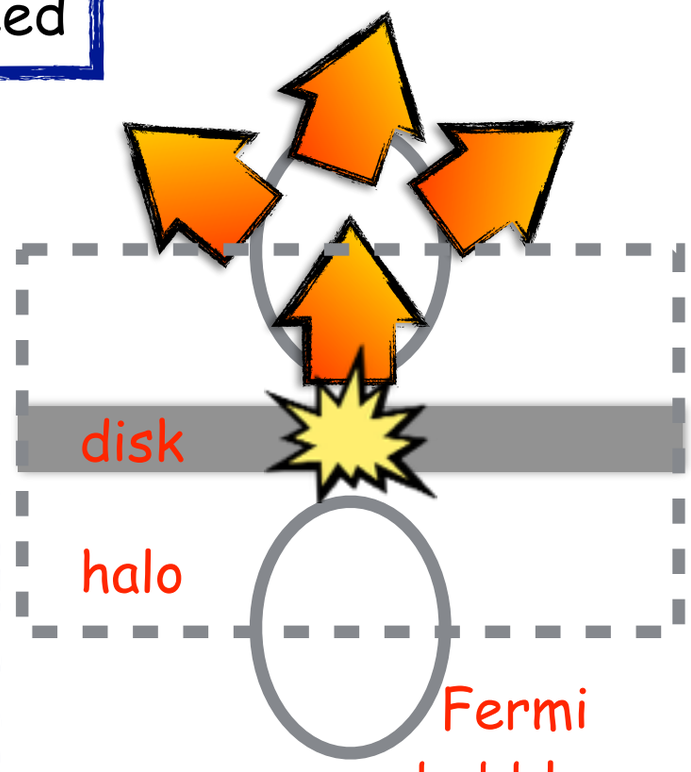
to explain **all** CRs >10 TeV we need

$$L_{CR} \approx 10^{39}\ \mathrm{erg/s}$$

for ~10^6-10^7 yrs

the GC activity highly variable (Ponti+2013) -> what if the CR acceleration efficiency was larger in the past?

evidence for a huge reservoir of ionized gas (> 10^{10} M_{sun}) in the halo from X-ray observations (Gupta+ 2012)



CR bursts from GC
Ptuskin & Khazan (1981)
see also Fujita+ 2016
CR in Gal. breeze
Taylor & Giacinti 2016

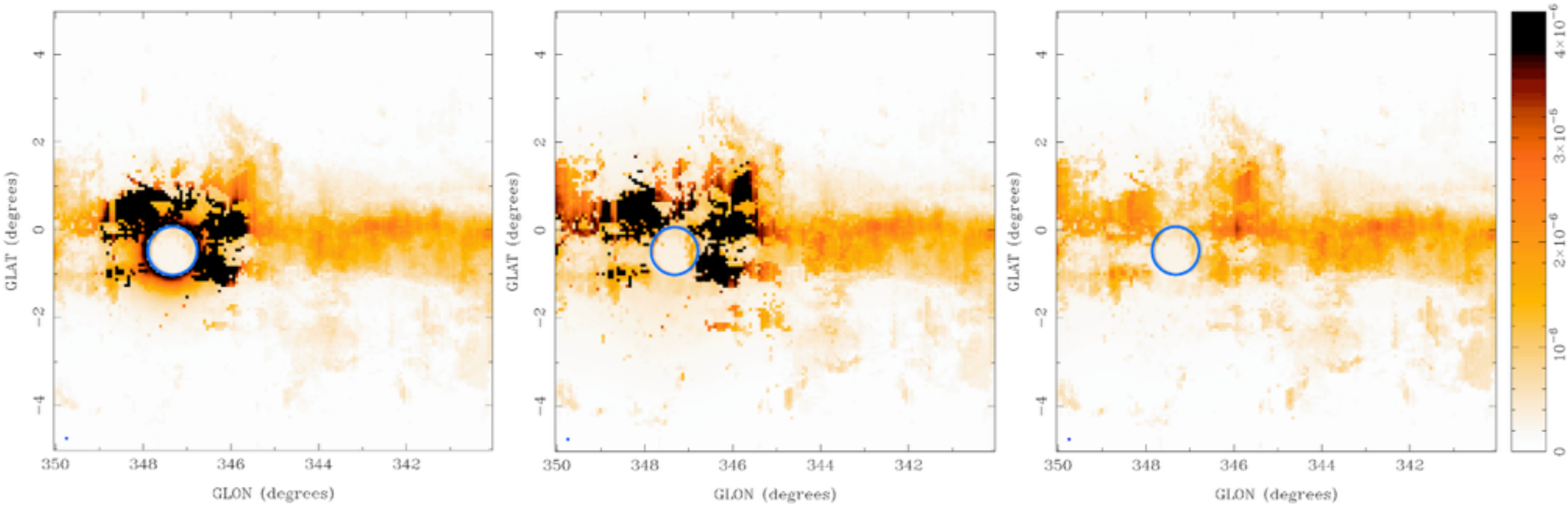
IceCube neutrinos

Taylor, SG, Aharonian 2014

What if the PeVatron is nearby?

particle escape from RXJ1713

CR spatial distribution + HI and H_2 spatial distribution = gamma ray maps @ 1 TeV



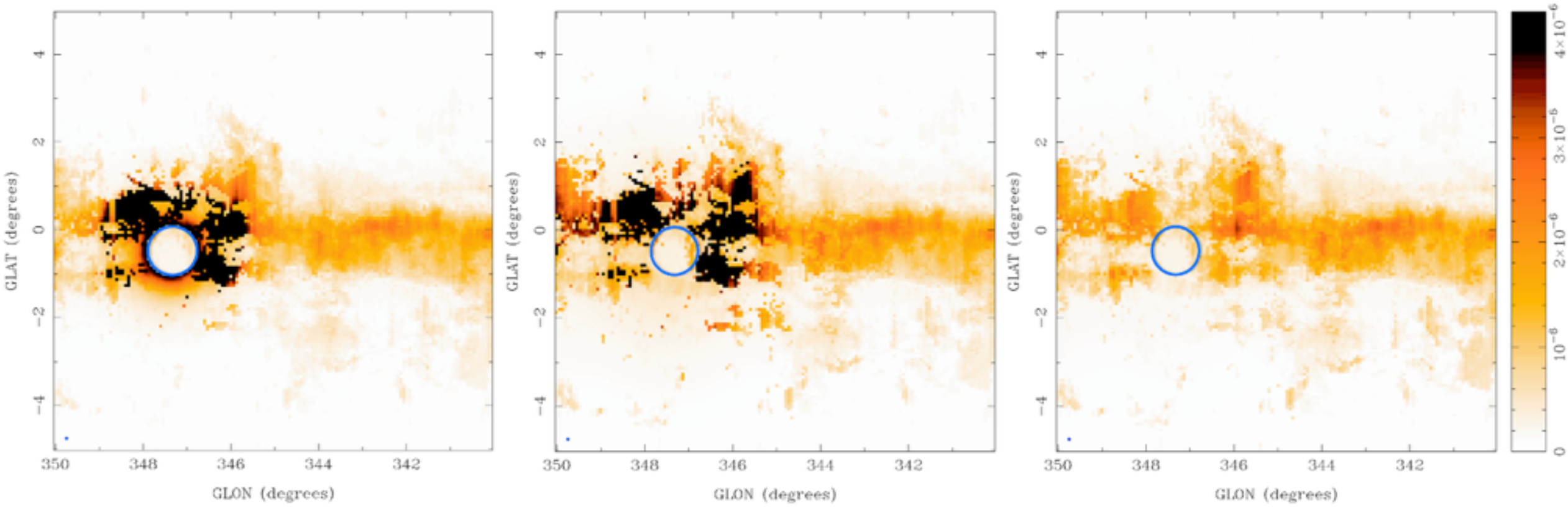
$$D = 10^{26} \left(\frac{E}{10\mathrm{GeV}}\right)^{0.5} \mathrm{cm}^2/\mathrm{s} \qquad D = 10^{27} \left(\frac{E}{10\mathrm{GeV}}\right)^{0.5} \mathrm{cm}^2/\mathrm{s} \qquad D = 10^{28} \left(\frac{E}{10\mathrm{GeV}}\right)^{0.5} \mathrm{cm}^2/\mathrm{s}$$

average diffusion coefficient in the Galaxy
from spallation measurements

What if the PeVatron is nearby?

particle escape from RXJ1713

CR spatial distribution + HI and H_2 spatial distribution = gamma ray maps @ 1 TeV



$$D = 10^{26} \left(\frac{E}{10\mathrm{GeV}}\right)^{0.5} \mathrm{cm}^2/\mathrm{s} \qquad D = 10^{27} \left(\frac{E}{10\mathrm{GeV}}\right)^{0.5} \mathrm{cm}^2/\mathrm{s} \qquad D = 10^{28} \left(\frac{E}{10\mathrm{GeV}}\right)^{0.5} \mathrm{cm}^2/\mathrm{s}$$

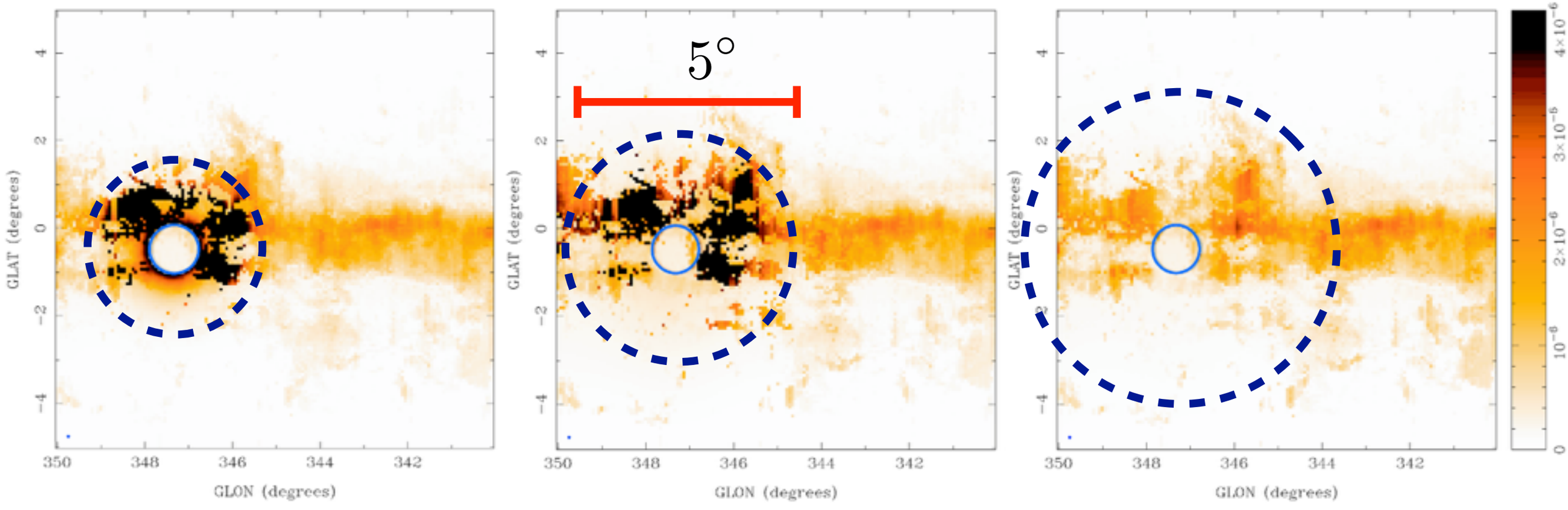
average diffusion coefficient in the Galaxy from spallation measurements

Casanova et al, 2010

What if the PeVatron is nearby?

particle escape from RXJ1713

CR spatial distribution + HI and H_2 spatial distribution = gamma ray maps @ 1 TeV



$$D = 10^{26} \left(\frac{E}{10\mathrm{GeV}}\right)^{0.5} \mathrm{cm}^2/\mathrm{s} \qquad D = 10^{27} \left(\frac{E}{10\mathrm{GeV}}\right)^{0.5} \mathrm{cm}^2/\mathrm{s} \qquad D = 10^{28} \left(\frac{E}{10\mathrm{GeV}}\right)^{0.5} \mathrm{cm}^2/\mathrm{s}$$

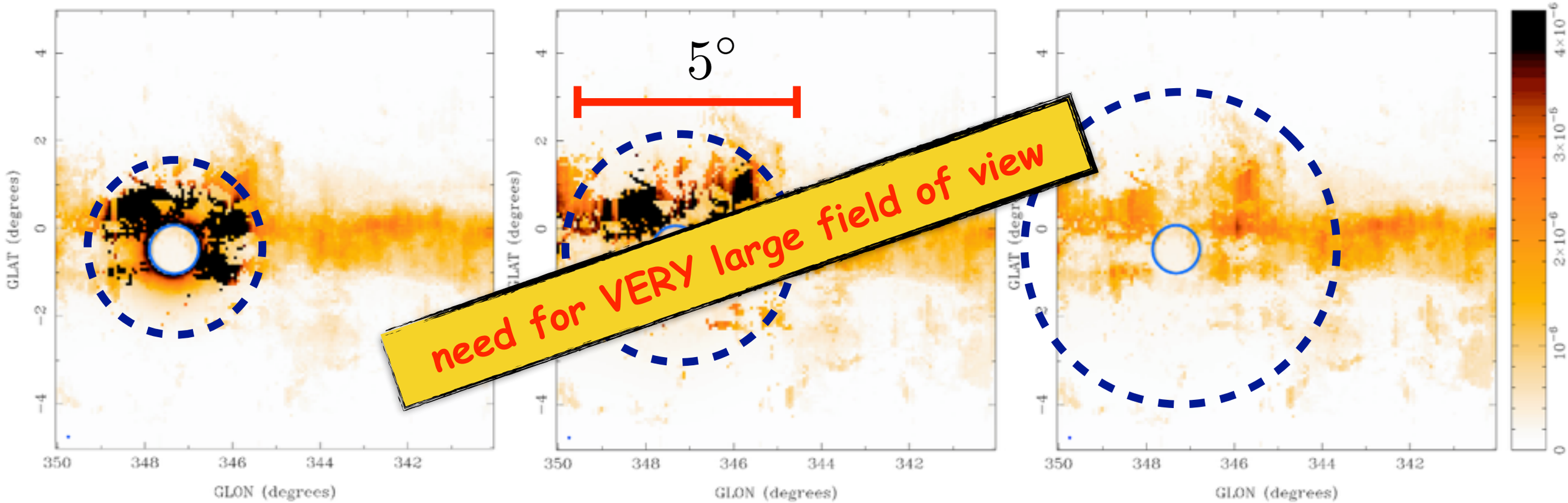
average diffusion coefficient in the Galaxy from spallation measurements

Casanova et al, 2010

What if the PeVatron is nearby?

particle escape from RXJ1713

CR spatial distribution + HI and H_2 spatial distribution = gamma ray maps @ 1 TeV



$$D = 10^{26} \left(\frac{E}{10\mathrm{GeV}}\right)^{0.5} \mathrm{cm}^2/\mathrm{s} \qquad D = 10^{27} \left(\frac{E}{10\mathrm{GeV}}\right)^{0.5} \mathrm{cm}^2/\mathrm{s} \qquad D = 10^{28} \left(\frac{E}{10\mathrm{GeV}}\right)^{0.5} \mathrm{cm}^2/\mathrm{s}$$

average diffusion coefficient in the Galaxy from spallation measurements

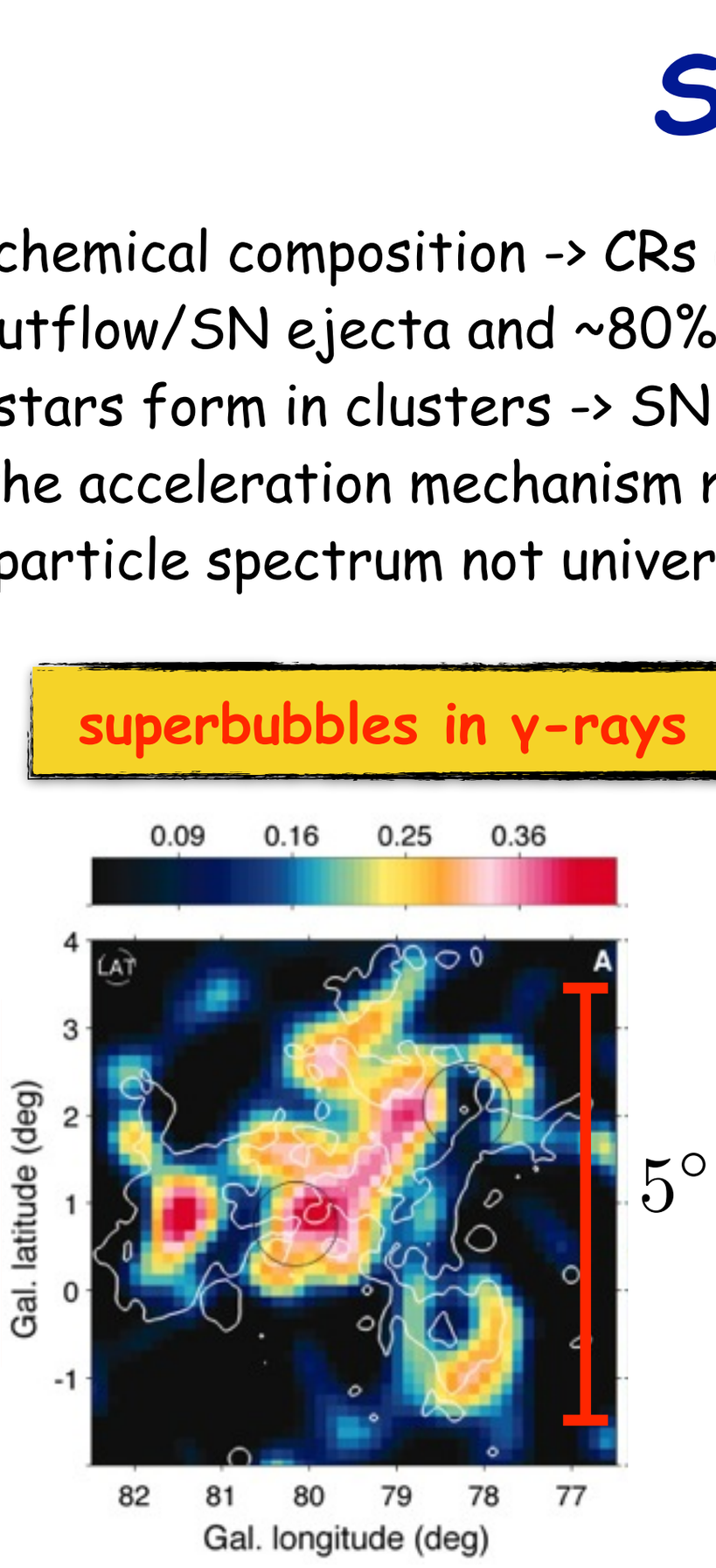
Casanova et al, 2010

Superbubbles

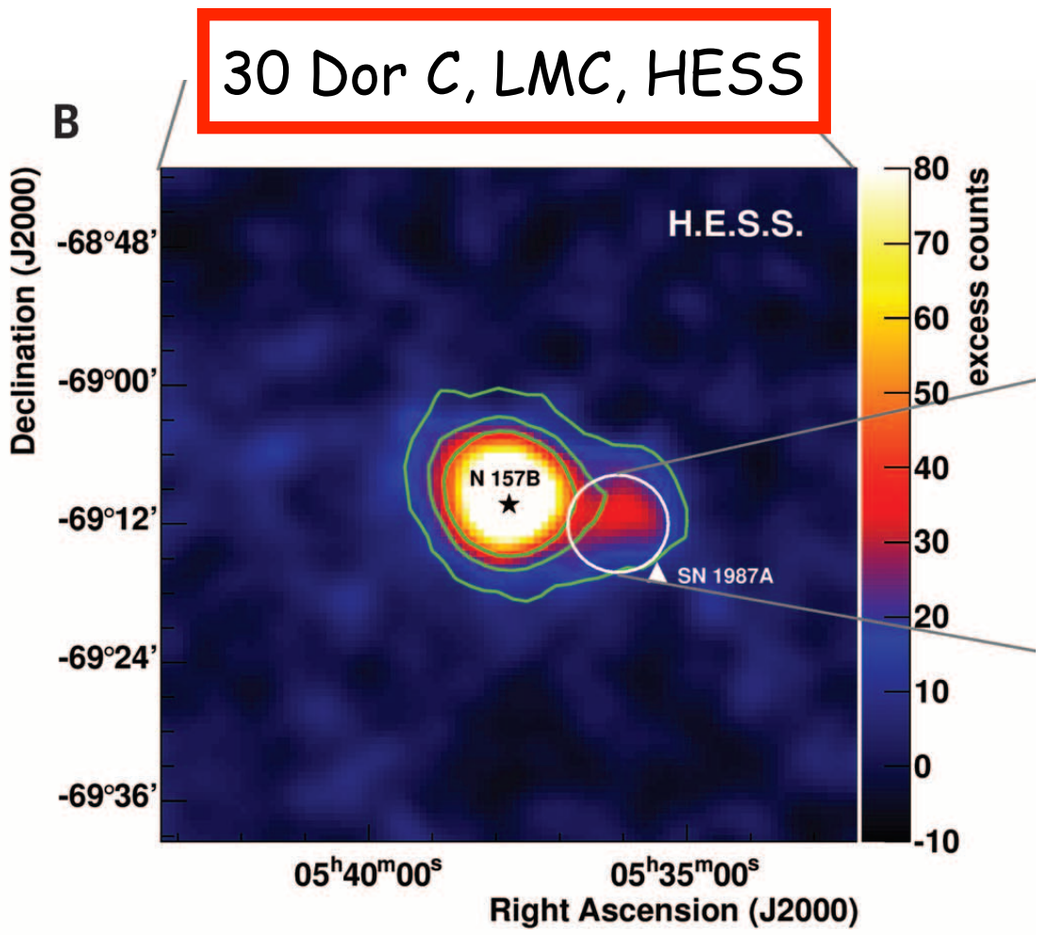
- chemical composition -> CRs originate in a source which is a mixture ~20% stellar outflow/SN ejecta and ~80% interstellar medium (Murphy+ 2016 and references)
- stars form in clusters -> SN explosions -> SNOBs and superbubbles
- the acceleration mechanism might be completely different (Bykov&Fleishman92)
- particle spectrum not universal, large E_{max} (large size!)

superbubbles in γ-rays

Cygnus, Fermi



5°



would be degrees @ 1 kpc

The neutrino-gamma ray connection

Secondary electrons and positrons:

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

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

$$\left\{ \begin{array}{l} \pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu) \\ \mu^{\pm} \rightarrow e^{\pm} + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e) \end{array} \right.$$

Final products of proton-proton interactions are not only **gamma ray photons** but also **neutrinos**, **anti-neutrinos**, **electrons** and **positrons**

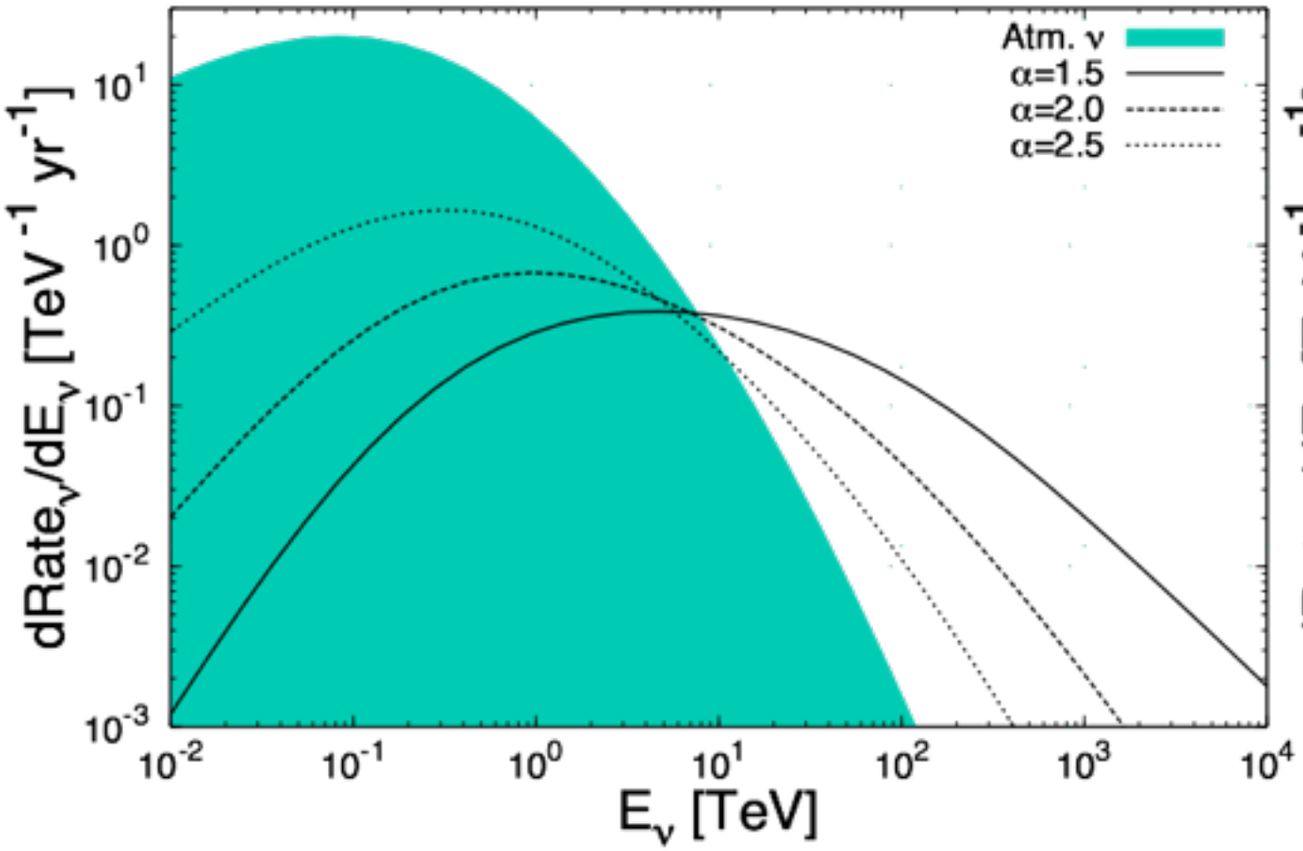
$$E_e \approx E_\nu \approx \frac{E_p}{20}$$

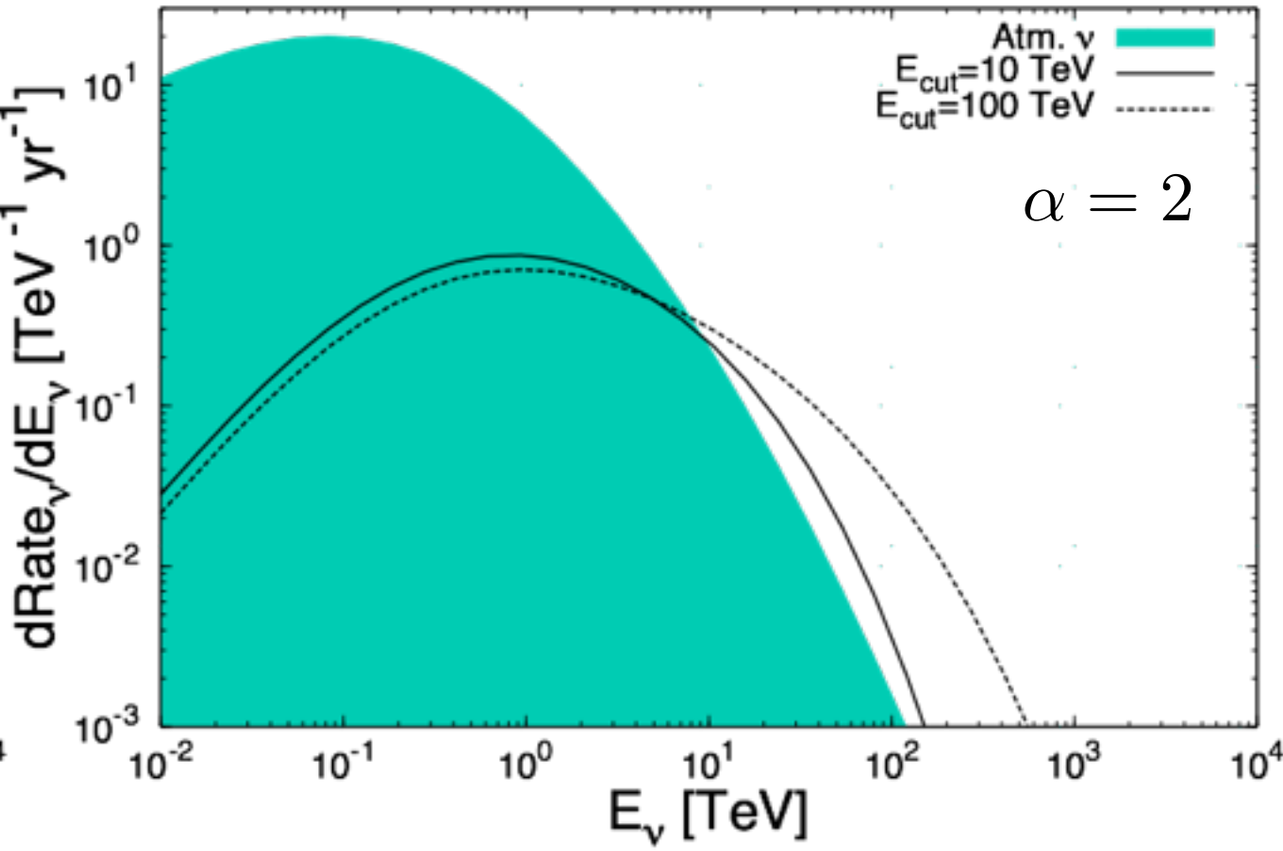
Neutrino sources: fluxes

very roughly, what we need is 1 Crab ->

(with KM3NeT, TDR)

$$F_\nu(> 1\ \mathrm{TeV}) \approx 10^{-11}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$





$$\frac{dF_\nu}{dE} \propto E^{-\alpha} \exp\left[-\frac{E}{E_{cut}}\right]$$

$$E_{cut} >> 1\ \mathrm{PeV}$$

$$E_{cut} = 10\ \mathrm{TeV},\ 100\ \mathrm{TeV}$$

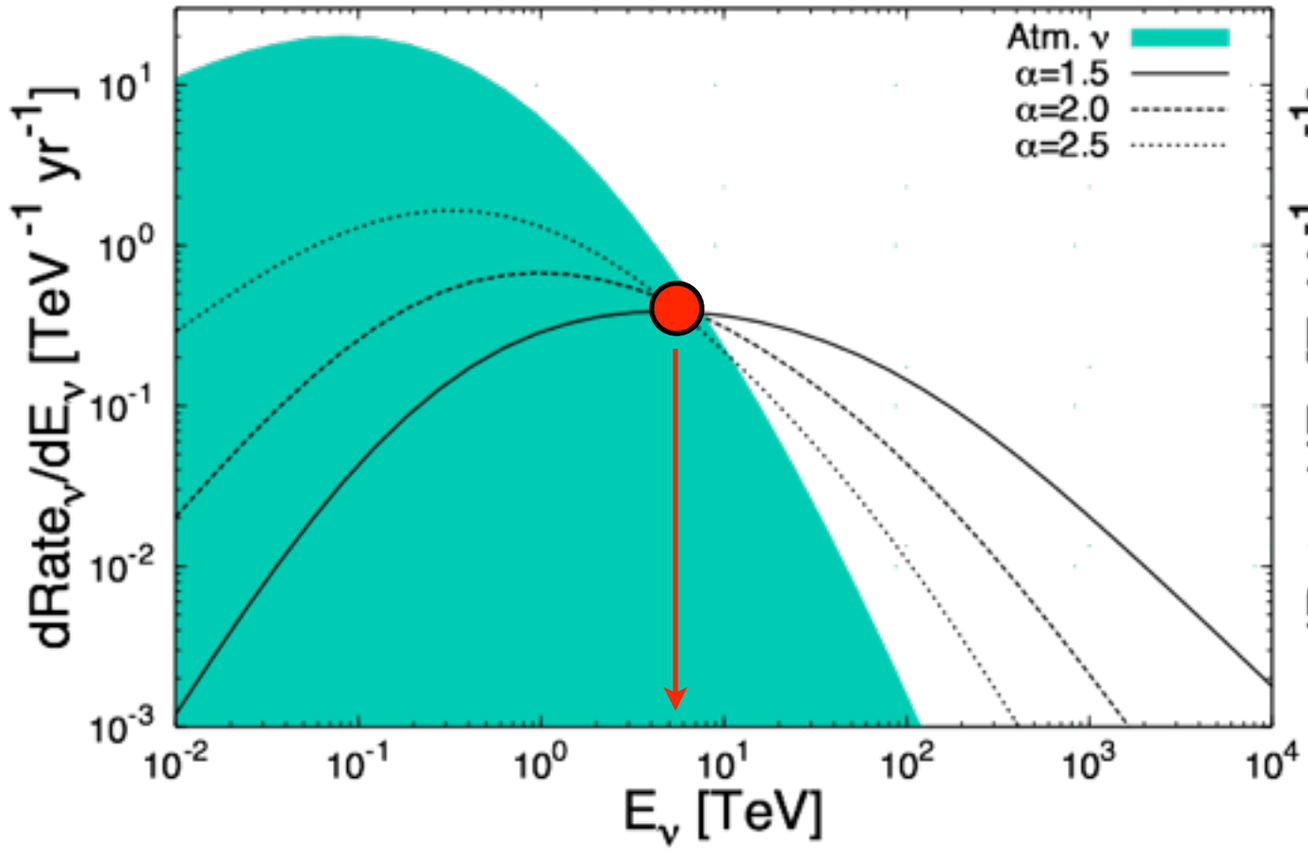
Gabici et al. 2008

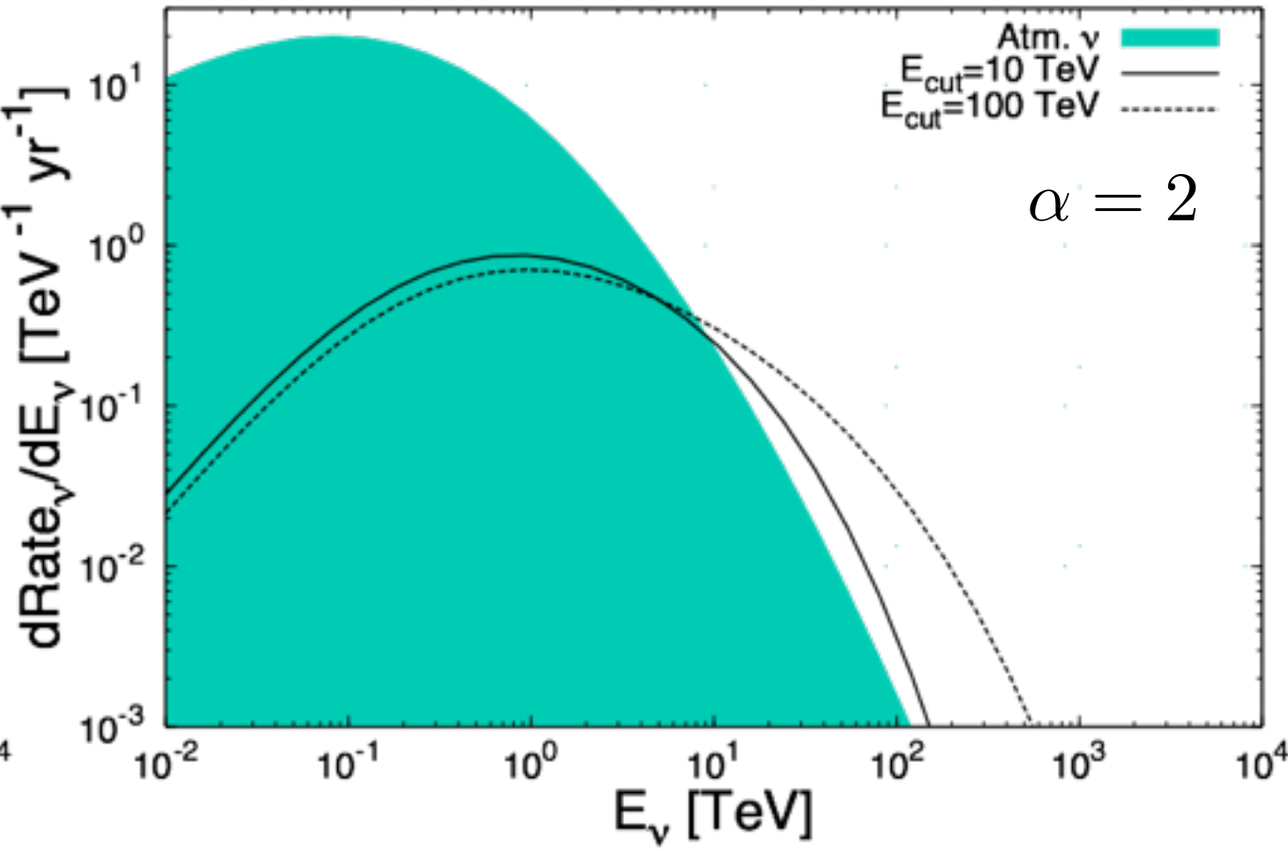
Neutrino sources: fluxes

very roughly, what we need is 1 Crab ->

(with KM3NeT, TDR)

$$F_\nu(> 1\ \mathrm{TeV}) \approx 10^{-11}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$





$$\frac{dF_\nu}{dE} \propto E^{-\alpha} \exp\left[-\frac{E}{E_{cut}}\right]$$

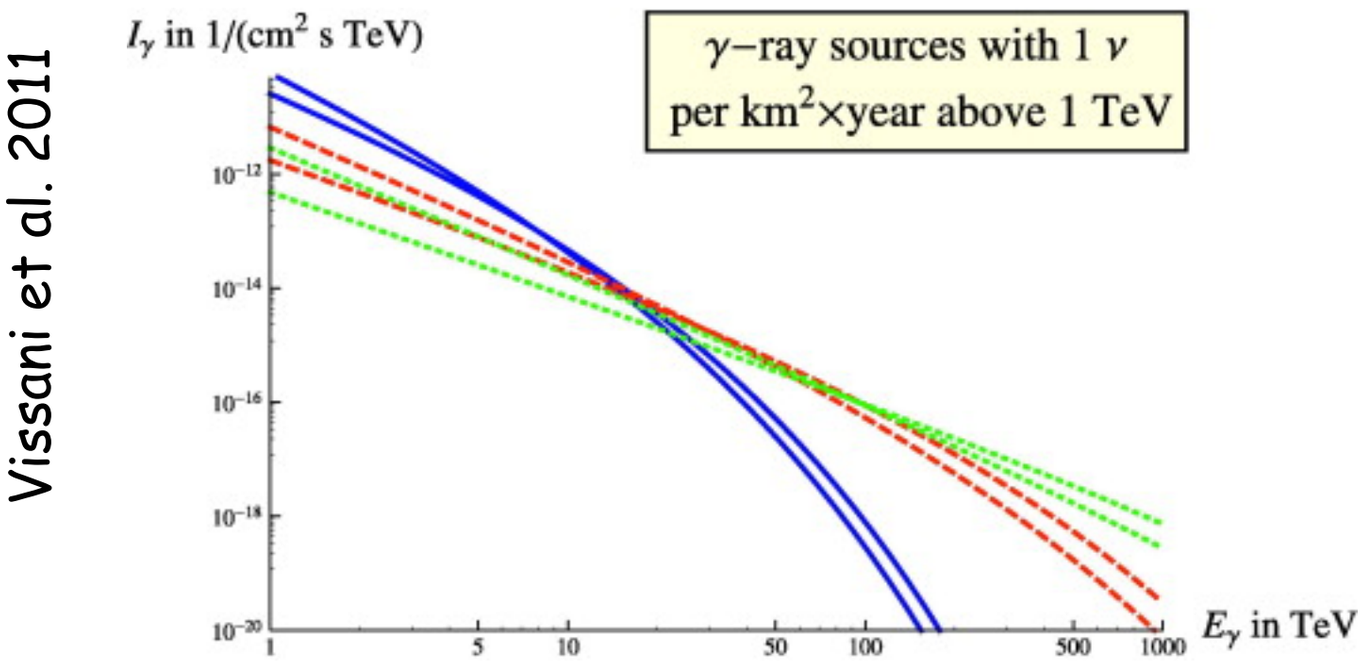
$$E_{cut} >> 1\ \mathrm{PeV}$$

$$E_{cut} = 10\ \mathrm{TeV},\ 100\ \mathrm{TeV}$$

Gabici et al. 2008

The neutrino-gamma ray connection

exercise: convert a minimal detectable flux (1 nu/km^2/yr) into a gamma-ray one above 1 TeV



$$\alpha = 1.8, 2.2$$

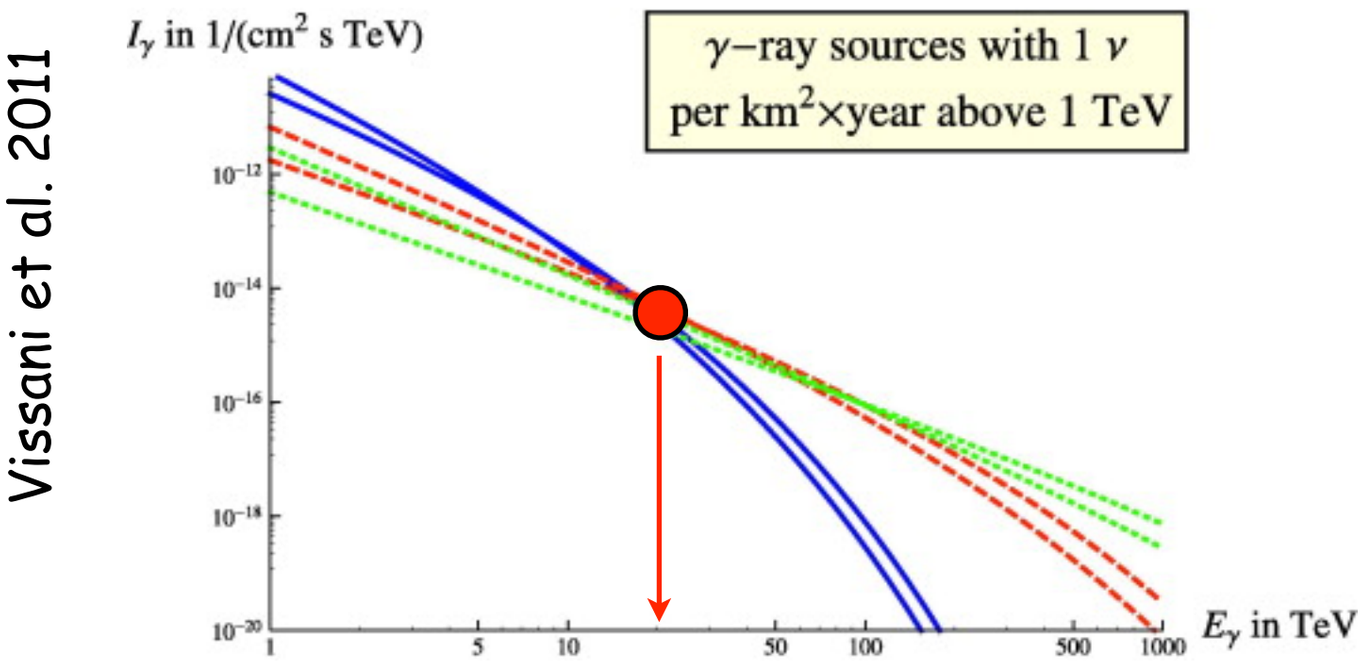
E_{cut} = 1 TeV

E_{cut} = $10^{1.5}$ TeV

E_{cut} = 10^3 TeV

The neutrino-gamma ray connection

exercise: convert a minimal detectable flux (1 nu/km^2/yr) into a gamma-ray one above 1 TeV



$$\alpha = 1.8, 2.2$$

E_{cut} = 1 TeV

E_{cut} = $10^{1.5}$ TeV

E_{cut} = 10^3 TeV

$$F_\gamma(20\ \mathrm{TeV}) = 2 - 6 \times 10^{-15}\ \mathrm{ph/cm^2/s}$$

best performances of atmospheric Cherenkov telescopes **@1TeV**

MILAGRO -> 20 TeV

gamma ray observations at ~20 TeV are the most relevant for neutrinos

Diffuse emission from the Galaxy

rationale: signal: $s_\nu \ \mathrm{sr}^{-1} \longrightarrow S_\nu \propto s_\nu \times \vartheta^2$

noise: $n_\nu \ \mathrm{sr}^{-1} \longrightarrow N_\nu \propto n_\nu \times \vartheta^2$

$$\frac{S_\nu}{\sqrt{N_\nu}} \propto \vartheta$$

tenuous + very extended sources

Diffuse emission from the Galaxy

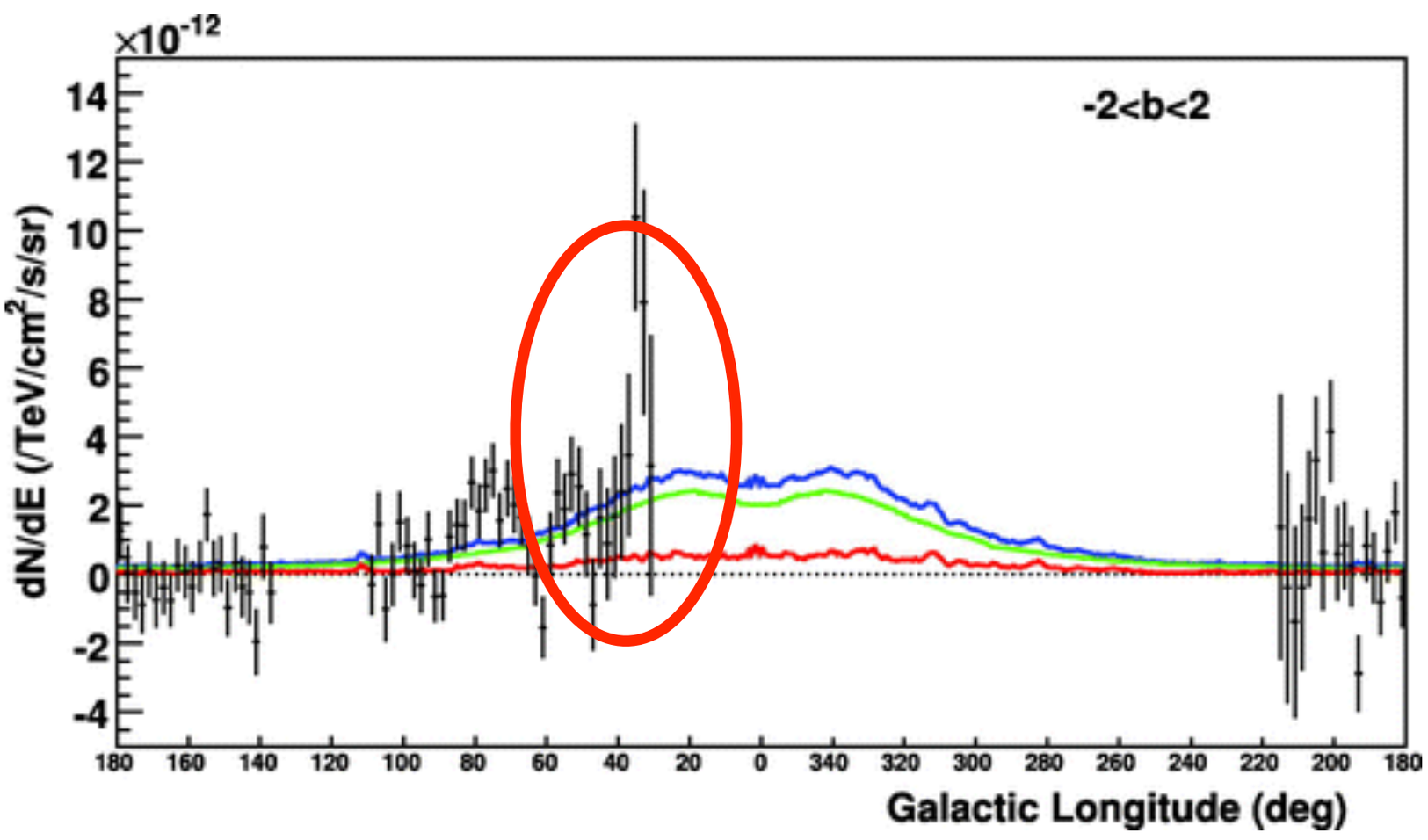
rationale: signal: $s_\nu \ \mathrm{sr}^{-1} \longrightarrow S_\nu \propto s_\nu \times \vartheta^2$

noise: $n_\nu \ \mathrm{sr}^{-1} \longrightarrow N_\nu \propto n_\nu \times \vartheta^2$

$$\frac{S_\nu}{\sqrt{N_\nu}} \propto \vartheta$$

tenuous + very extended sources

ideal gamma-ray observations @20 TeV -> MILAGRO



Abdo et al. 2008

Diffuse emission from the Galaxy

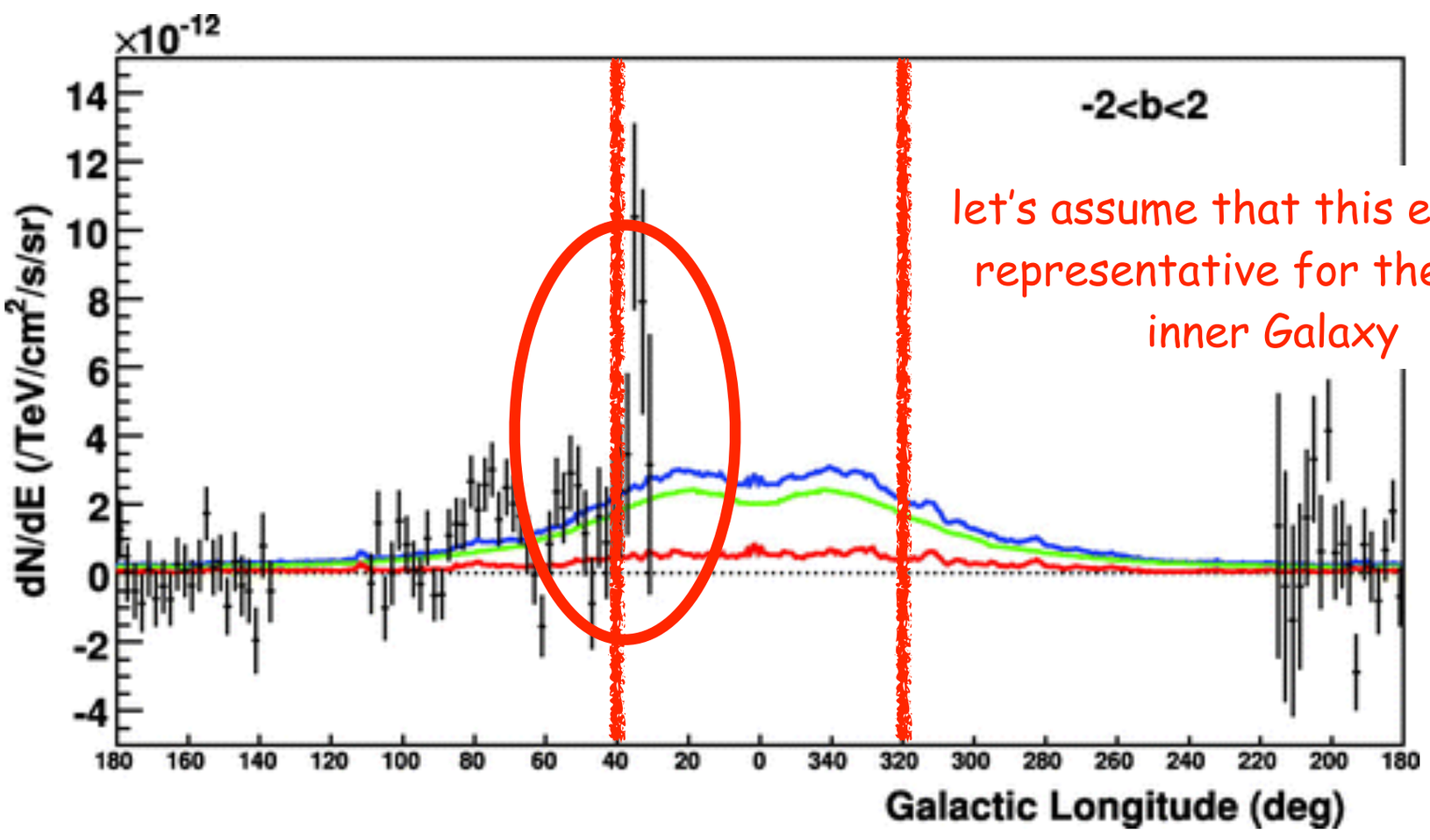
rationale: signal: $s_\nu \ \mathrm{sr}^{-1} \longrightarrow S_\nu \propto s_\nu \times \vartheta^2$

noise: $n_\nu \ \mathrm{sr}^{-1} \longrightarrow N_\nu \propto n_\nu \times \vartheta^2$

$$\frac{S_\nu}{\sqrt{N_\nu}} \propto \vartheta$$

tenuous + very extended sources

ideal gamma-ray observations @20 TeV -> MILAGRO

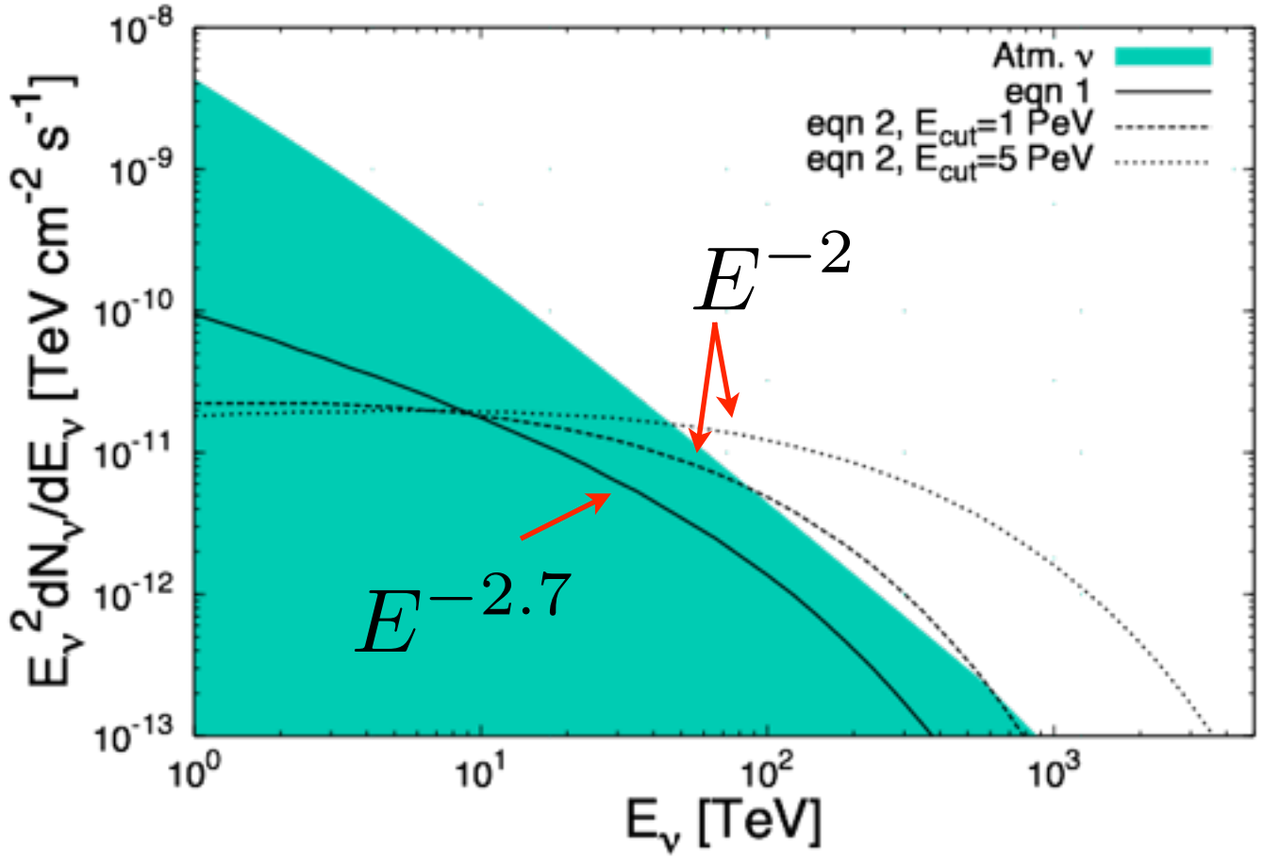


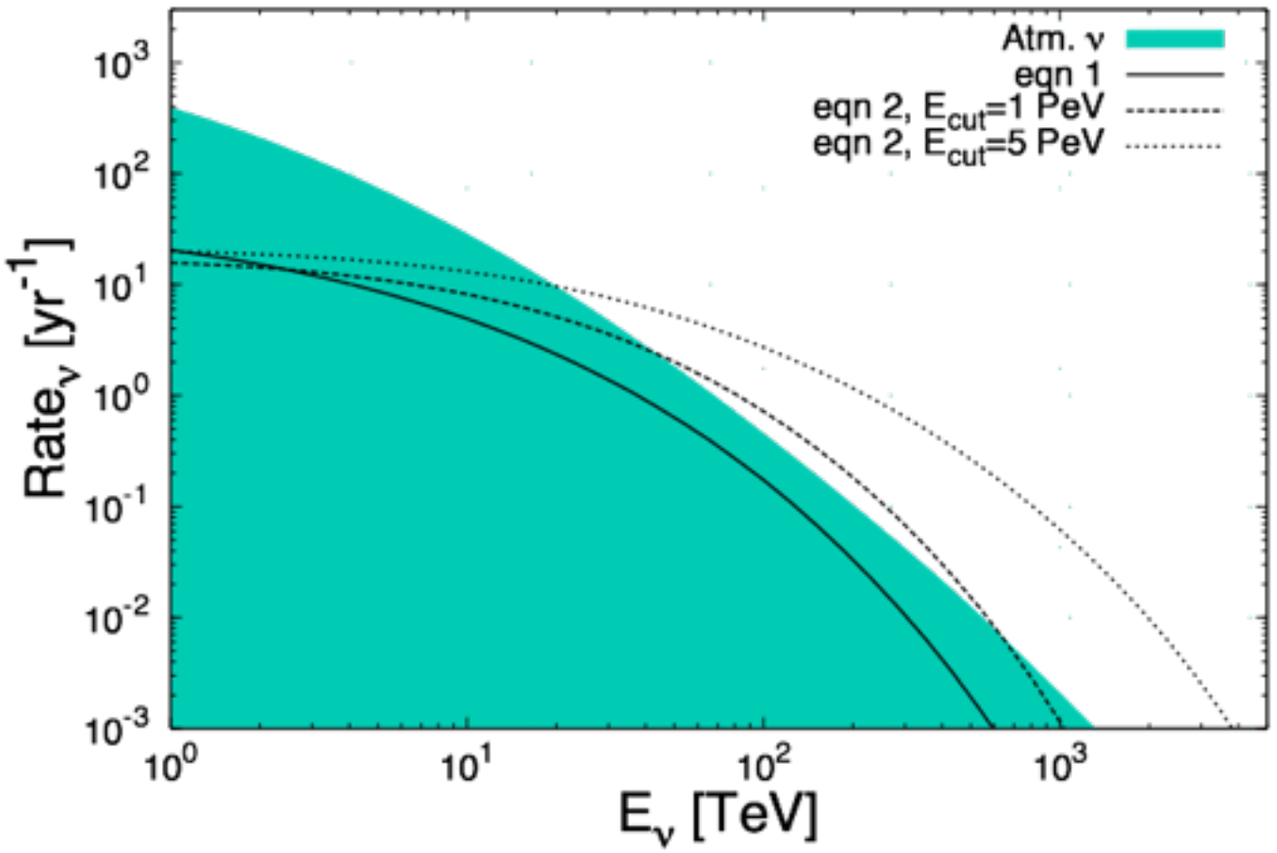
Abdo et al. 2008

Diffuse emission from the Galaxy

Gabici et al. 2008

in the plot below 1 yr = 1.5 yr

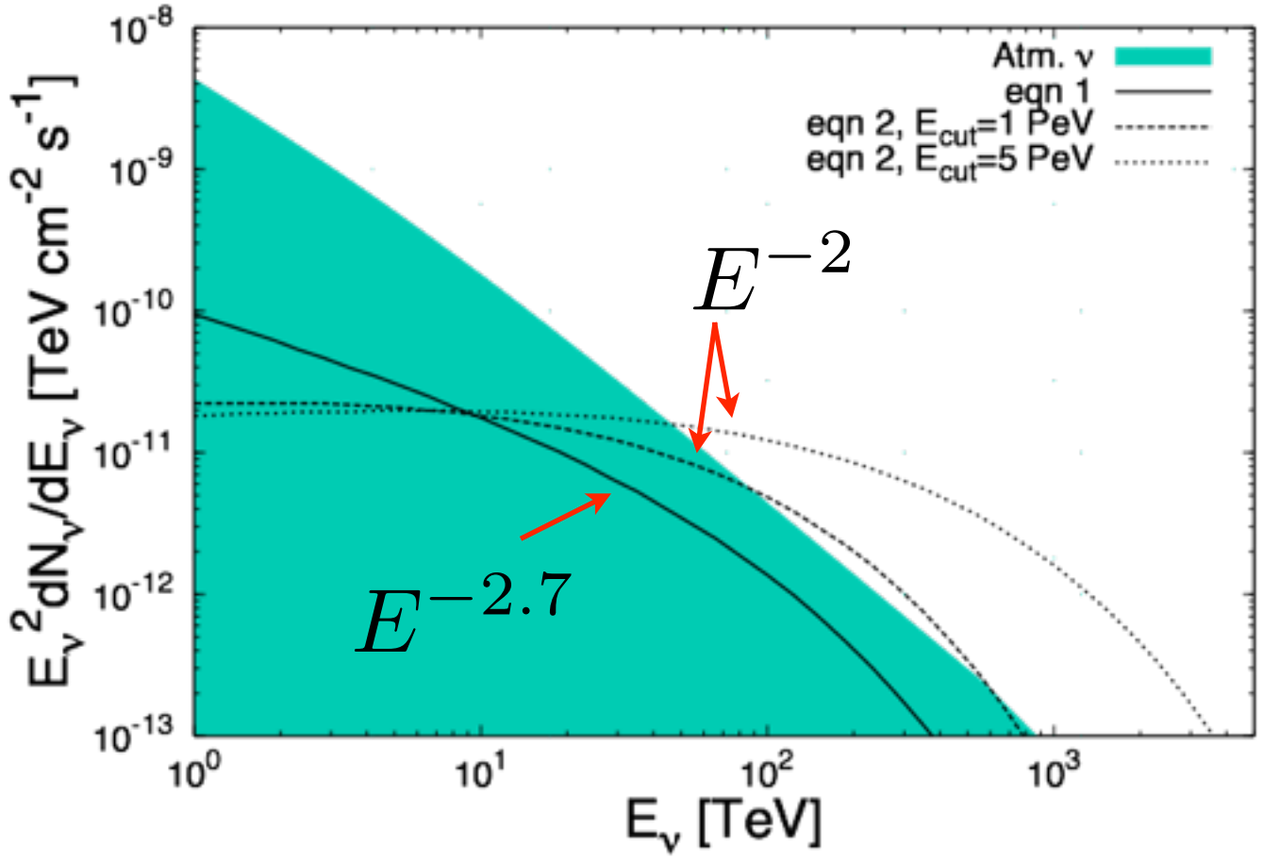


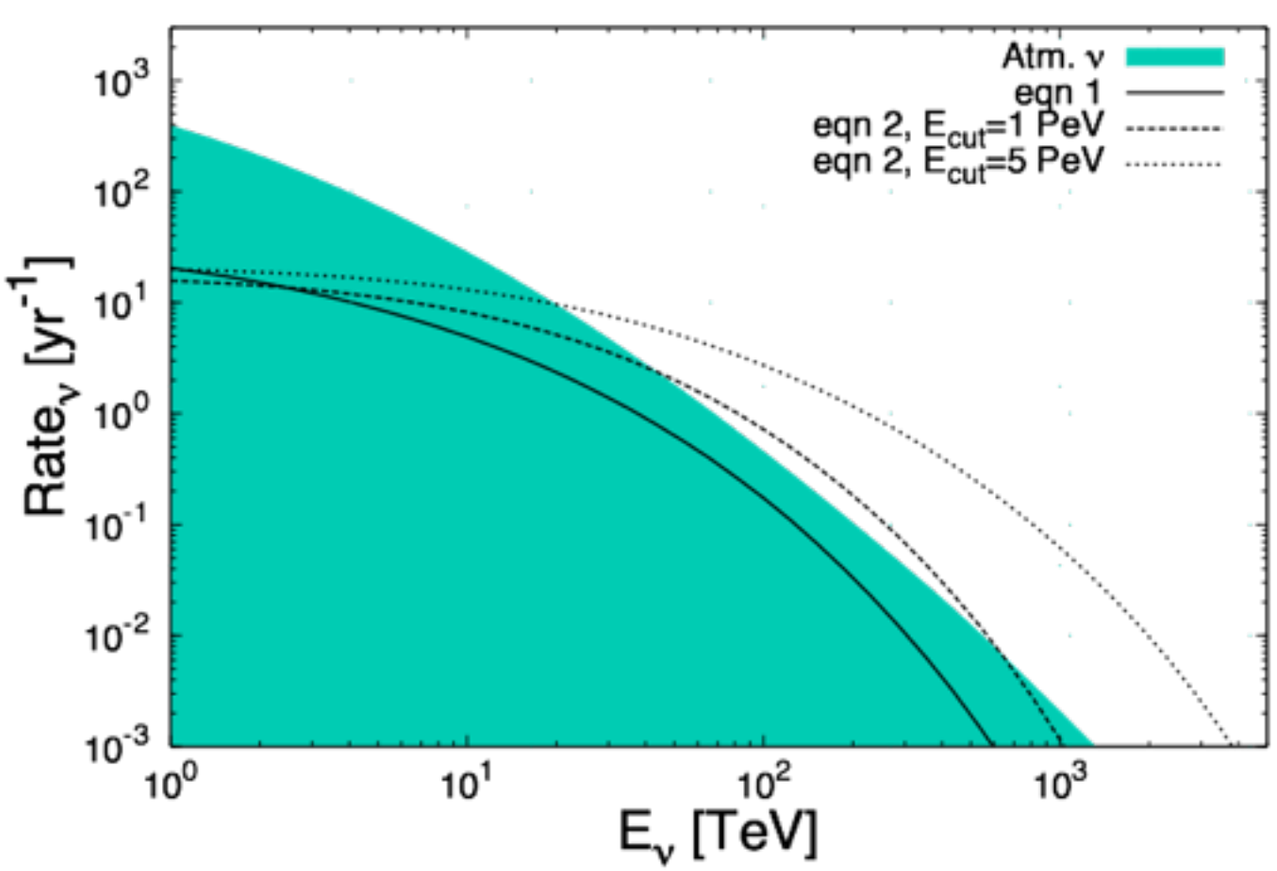


Diffuse emission from the Galaxy

Gabici et al. 2008

in the plot below 1 yr = 1.5 yr





most optimistic case: 15 neutrinos above 10 TeV (versus 28 background counts)

10 neutrinos above 20 TeV (versus 10 background counts)

very similar fluxes obtained more recently (Neronov&Semikoz, DRAGON team…)

Outline ~~of~~ the talk

Conclusions

Bottom line question: why are instruments like MILAGRO & sons so cool?

- Gamma-ray astronomy: present and future facilities
- Gamma-ray astronomy and the origin of cosmic rays
- Where are CR PeVatrons?
- Diffuse emission in the (multi-)TeV energy domain
- The link with neutrino astronomy