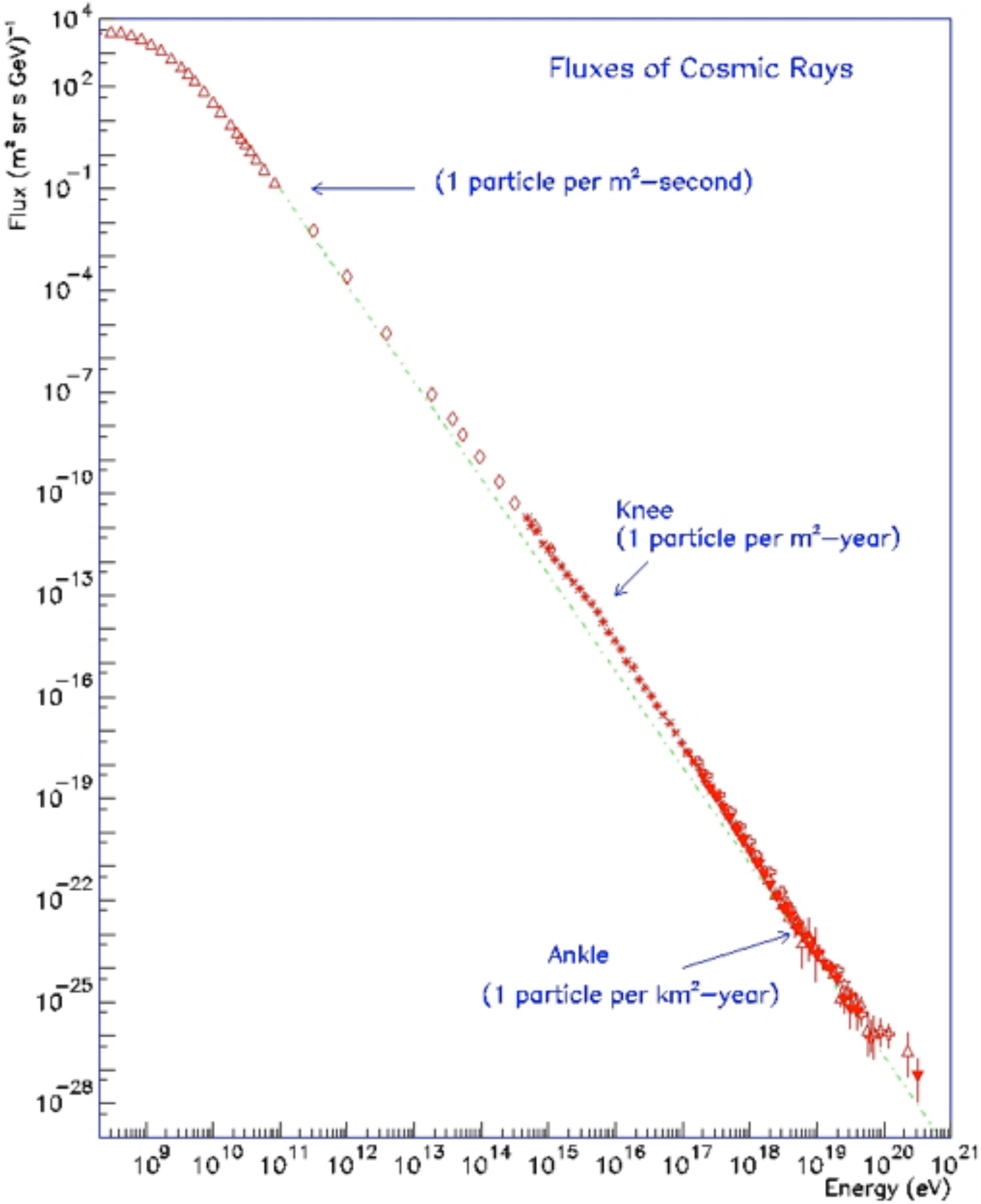
Acceleration of particles up to PeV energies at the Galactic Centre

Stefano Gabici (APC, Paris)
Felix Aharonian, Emmanuel Moulin, Aion Viana
on behalf of the HESS collaboration

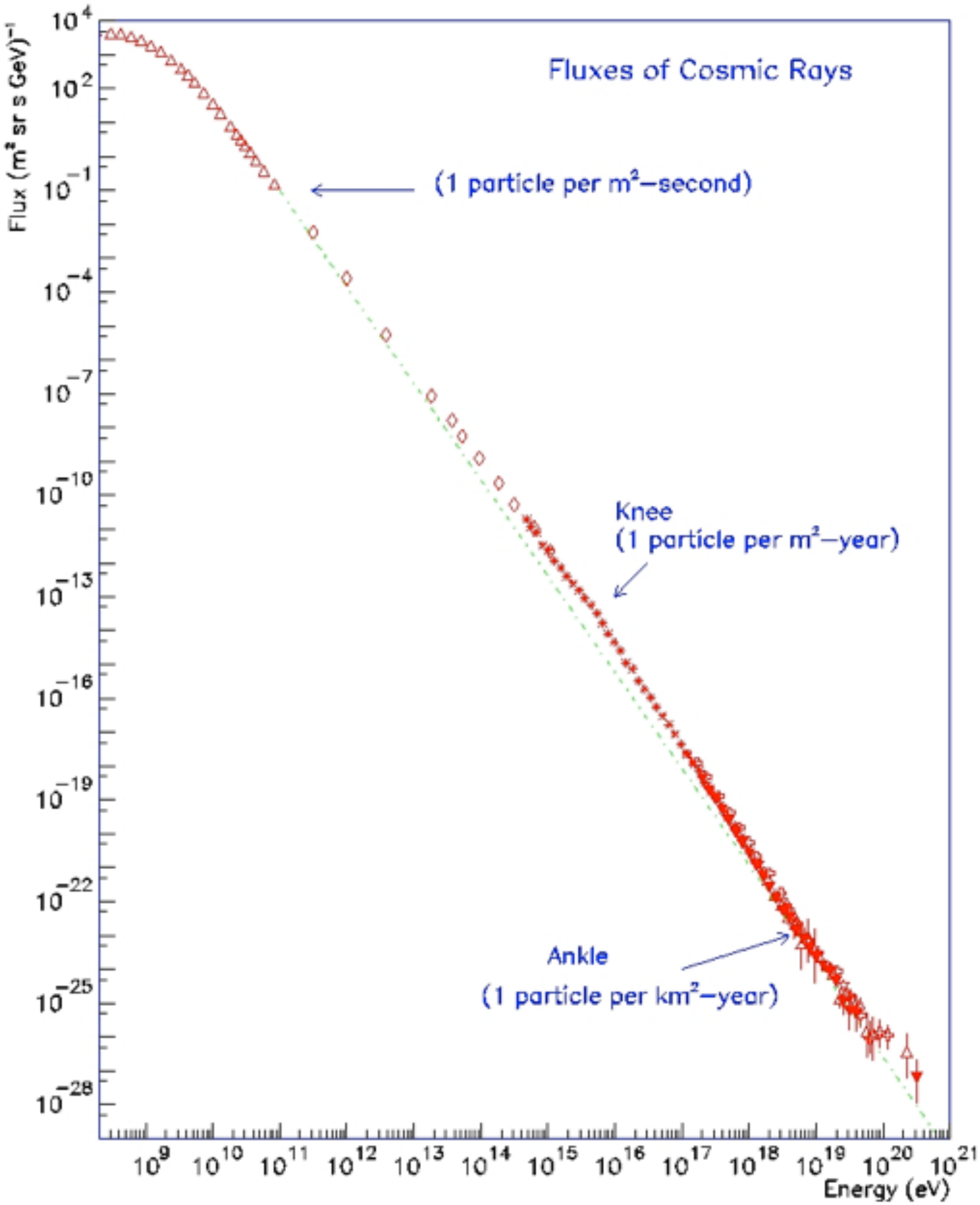
Outline of the talk

- brief introduction to galactic Cosmic Rays
- the link with gamma-ray astronomy
- the HESS array of Cherenkov telescopes
- the Galactic Centre as an accelerator of cosmic rays up to PeV energies
- Conclusions

The Cosmic Ray spectrum



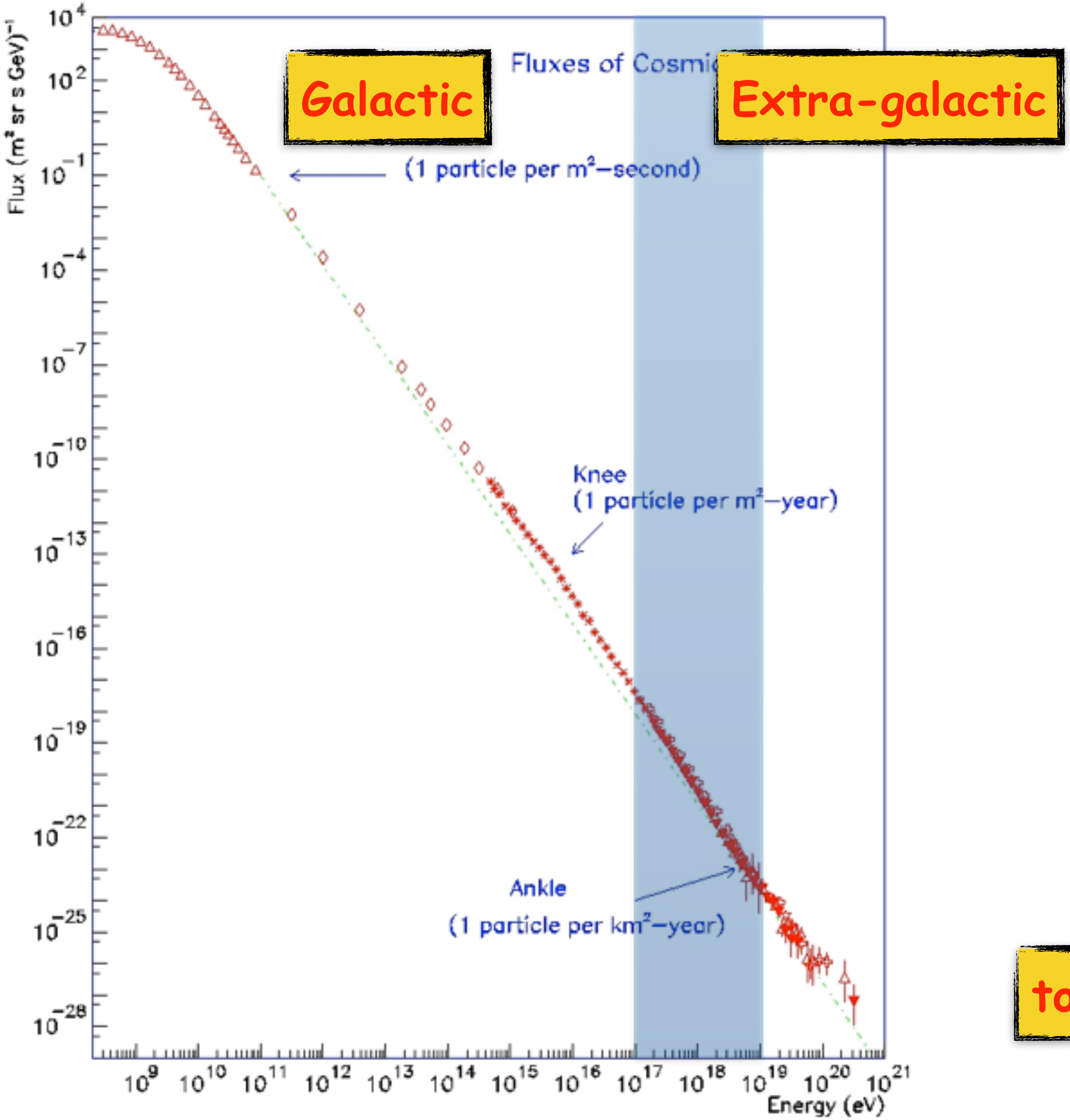
The Cosmic Ray spectrum



from sub-GeV

to ~ZeV

The Cosmic Ray spectrum



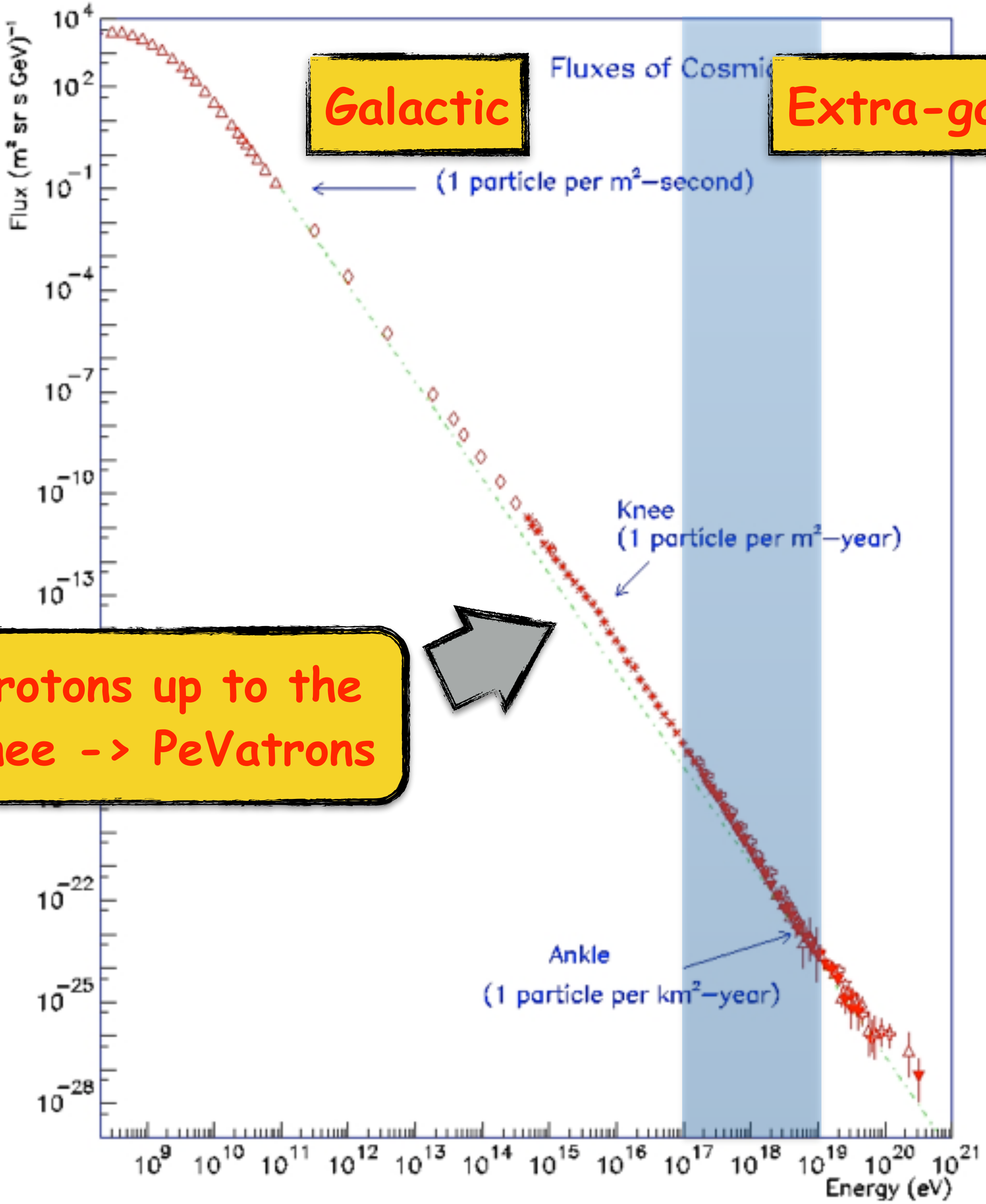
Galactic

Extra-galactic

from sub-GeV

to ~ZeV

The Cosmic Ray spectrum

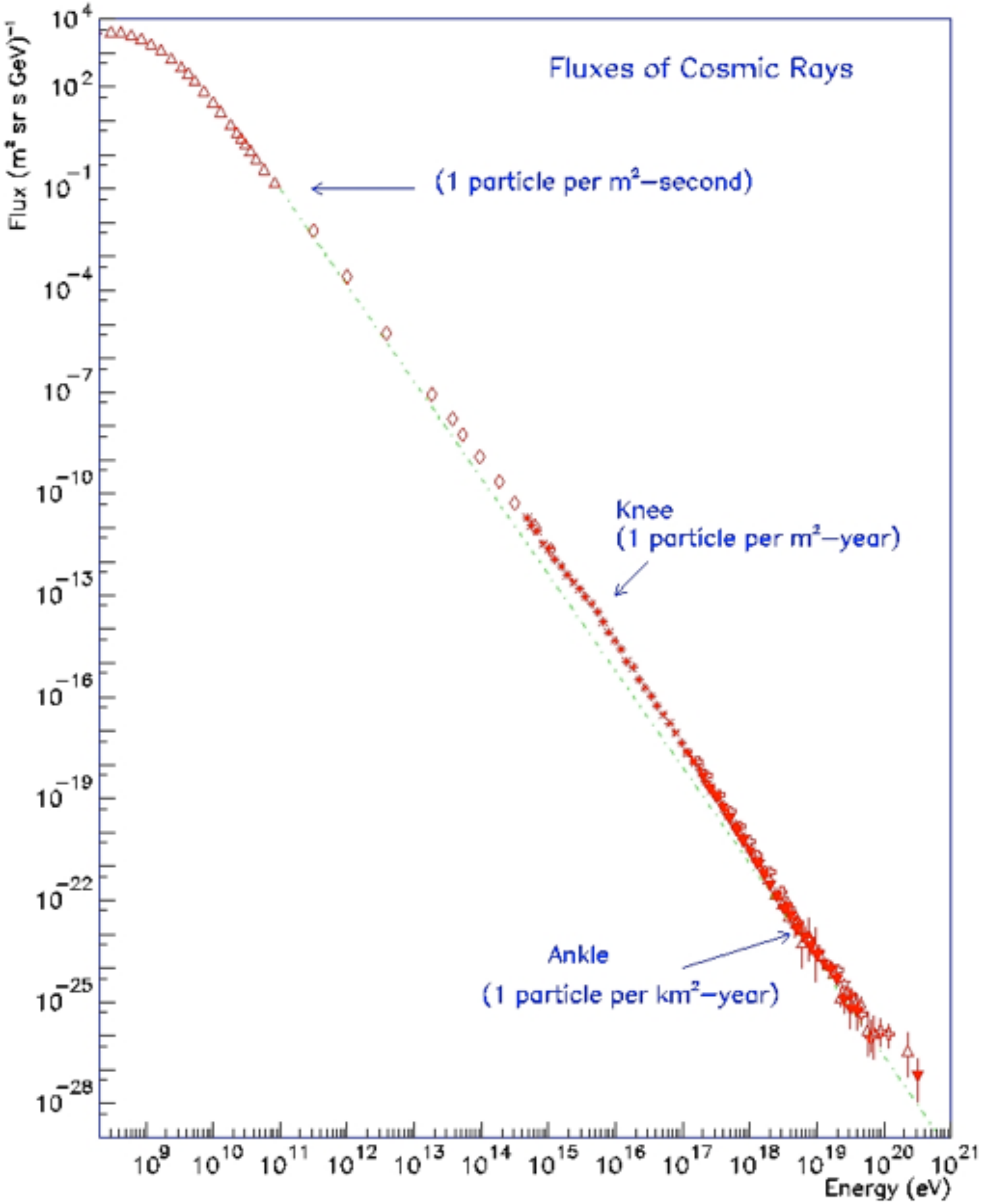


Galactic

Extra-galactic

protons up to the knee -> PeVatrons

The Cosmic Ray spectrum



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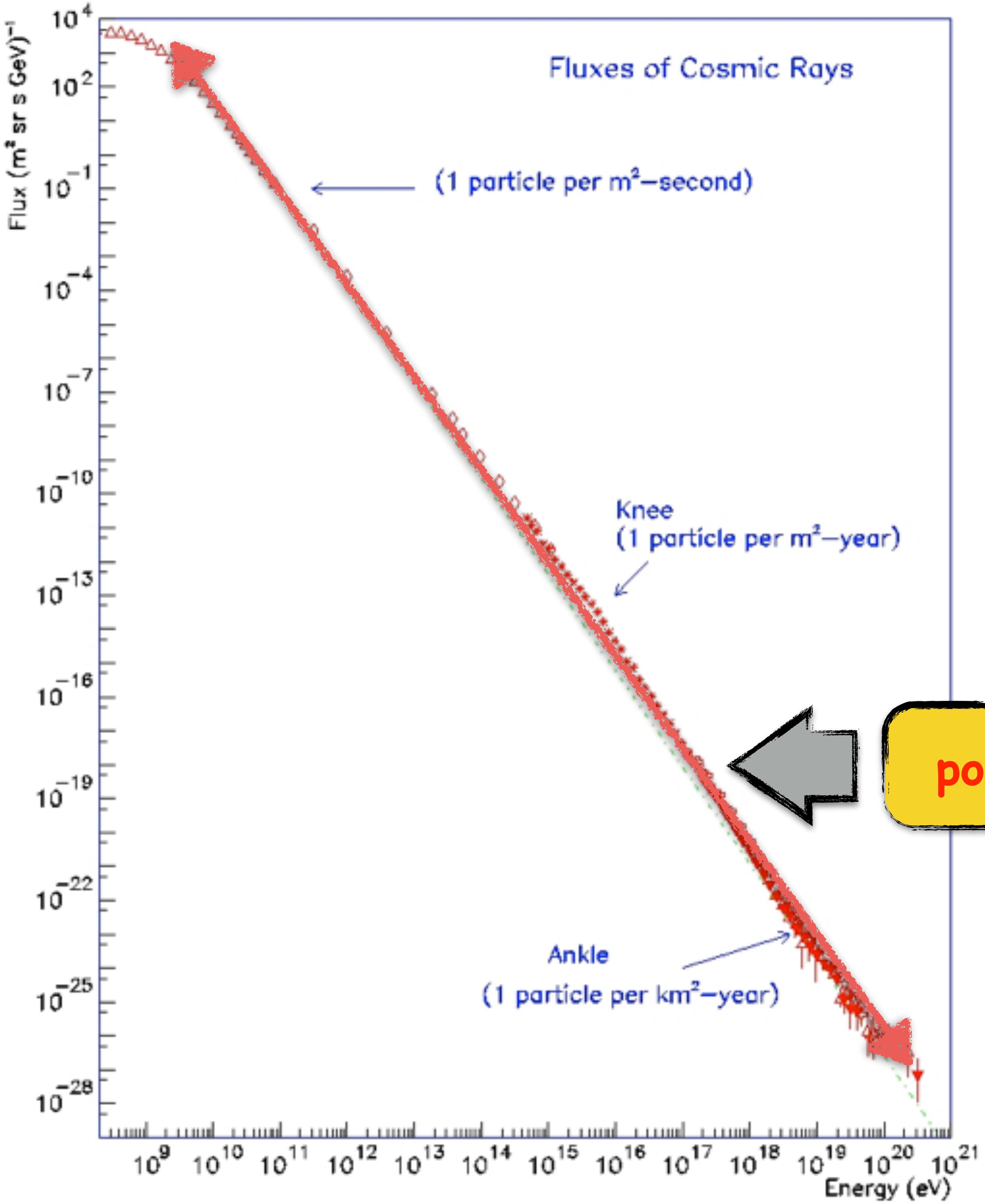
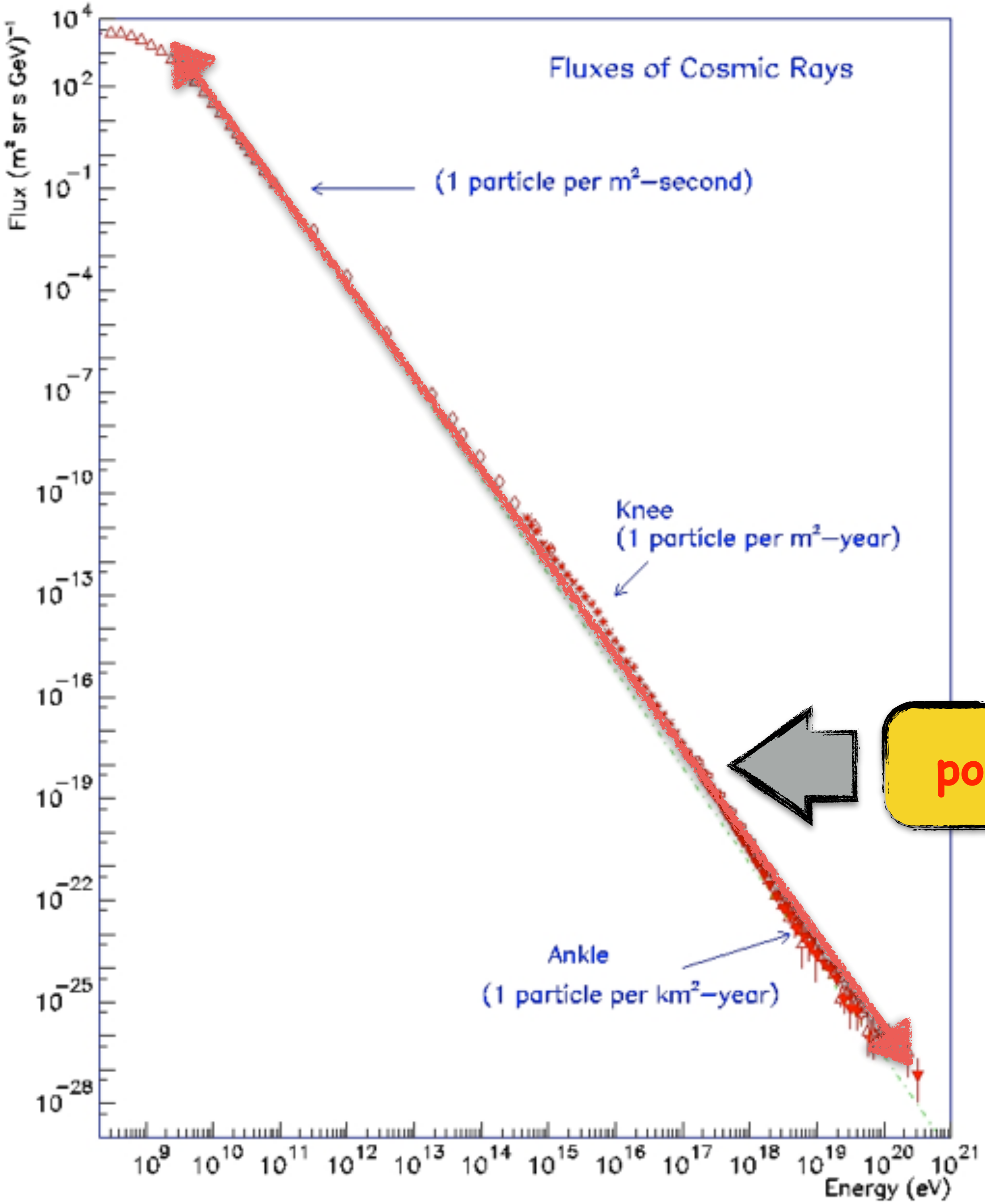


power law $E^{-2.7…3}$

The Cosmic Ray spectrum

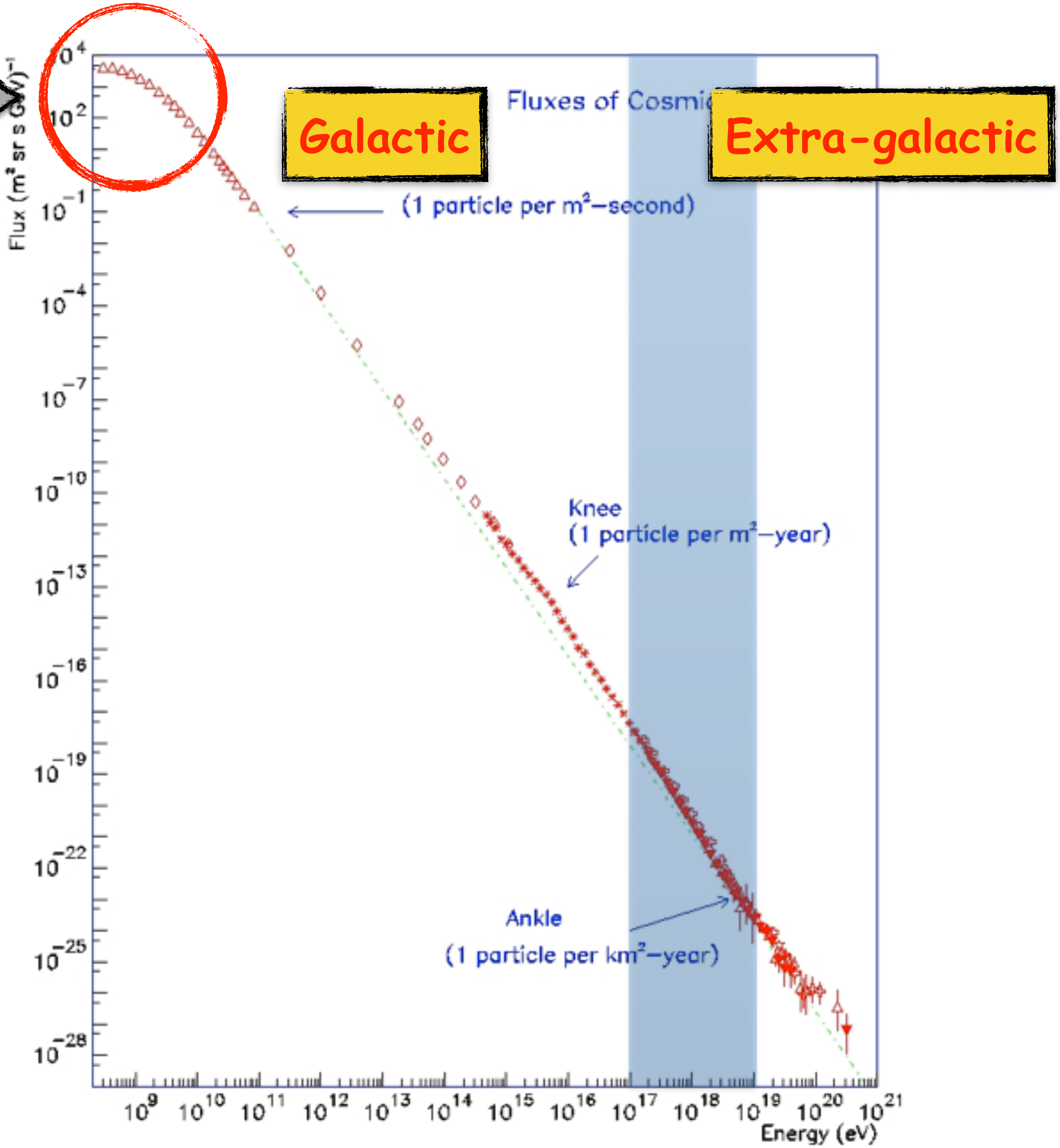


very steep

power law $E^{-2.7...3}$

The origin of CRs: energy requirement

$1\ \mathrm{eV/cm^3}$



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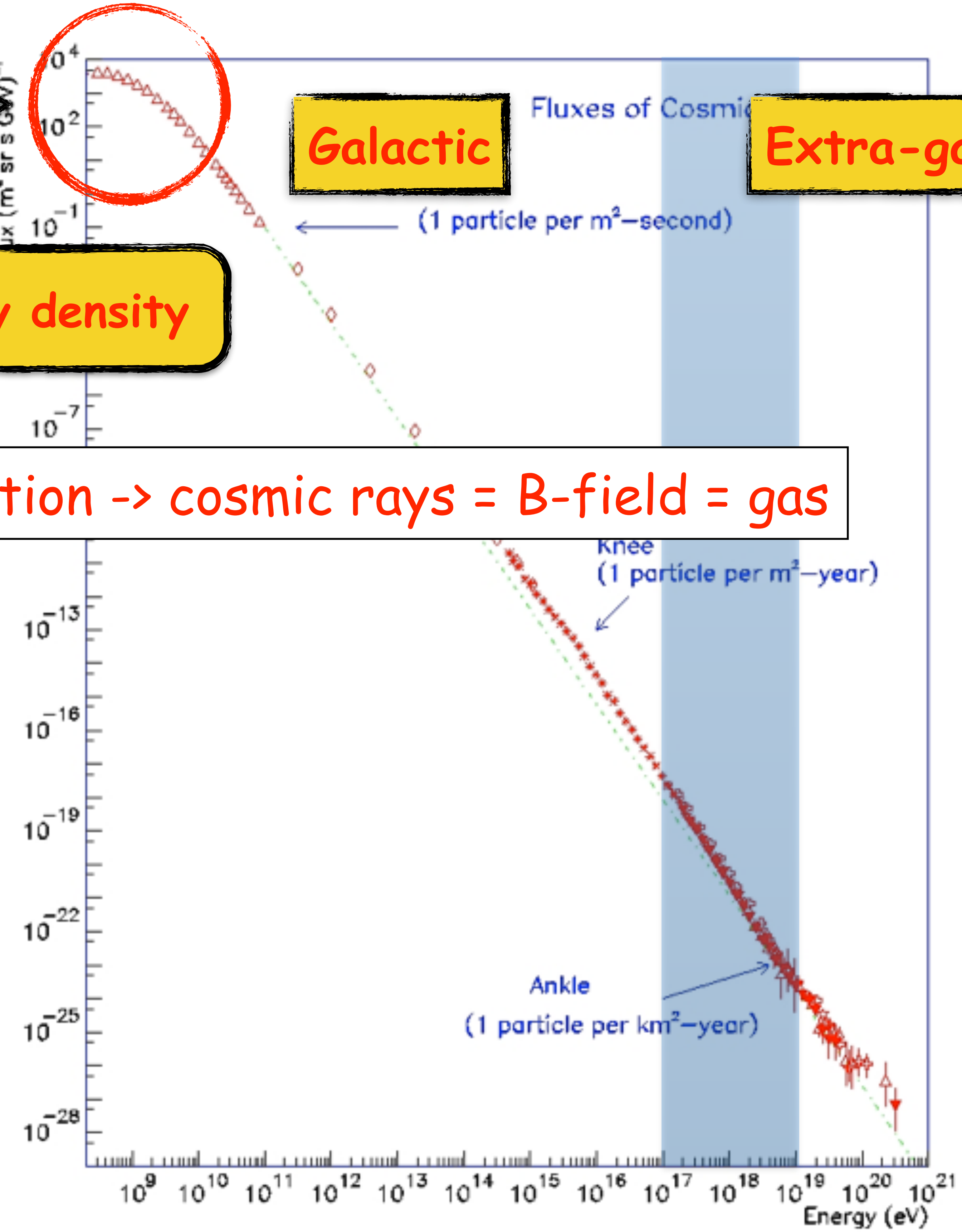


Galactic

Extra-galactic

Quite large energy density

Energy equipartition -> cosmic rays = B-field = gas

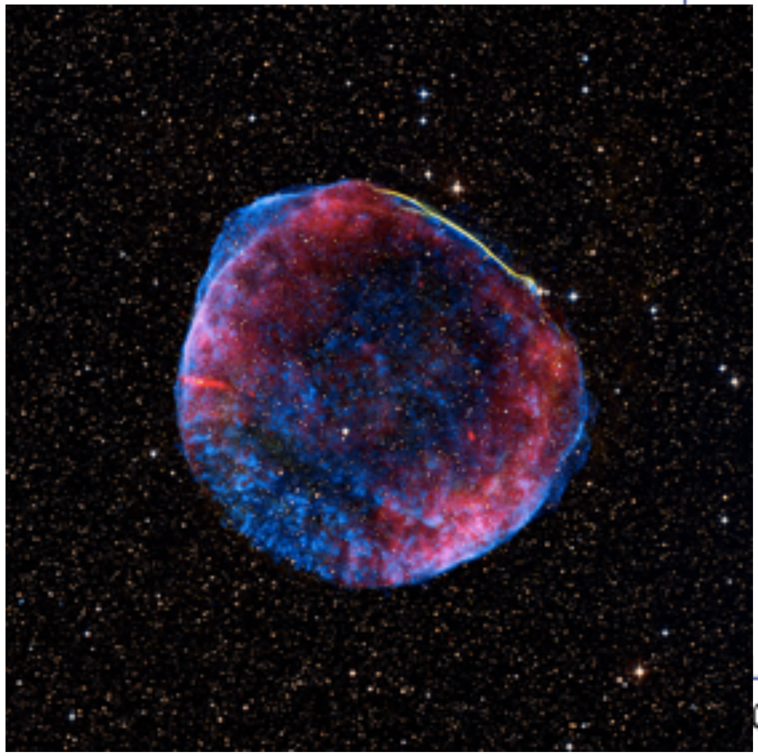
The origin of CRs: Galactic sources

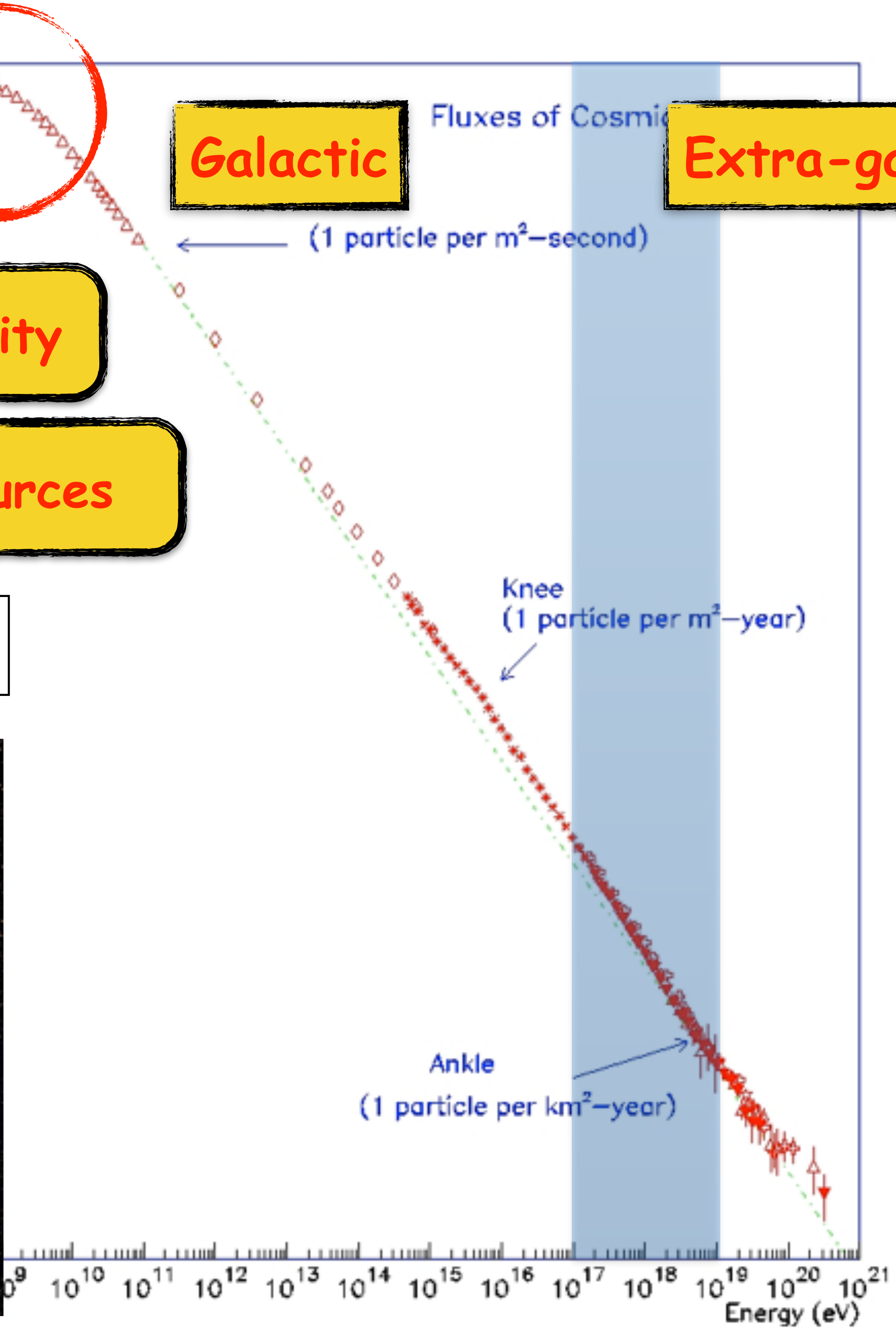
$1\ \mathrm{eV/cm^3}$

Quite large energy density

Powerful sources

SuperNova Remnants





Galactic

Extra-galactic

The origin of CRs: Galactic sources

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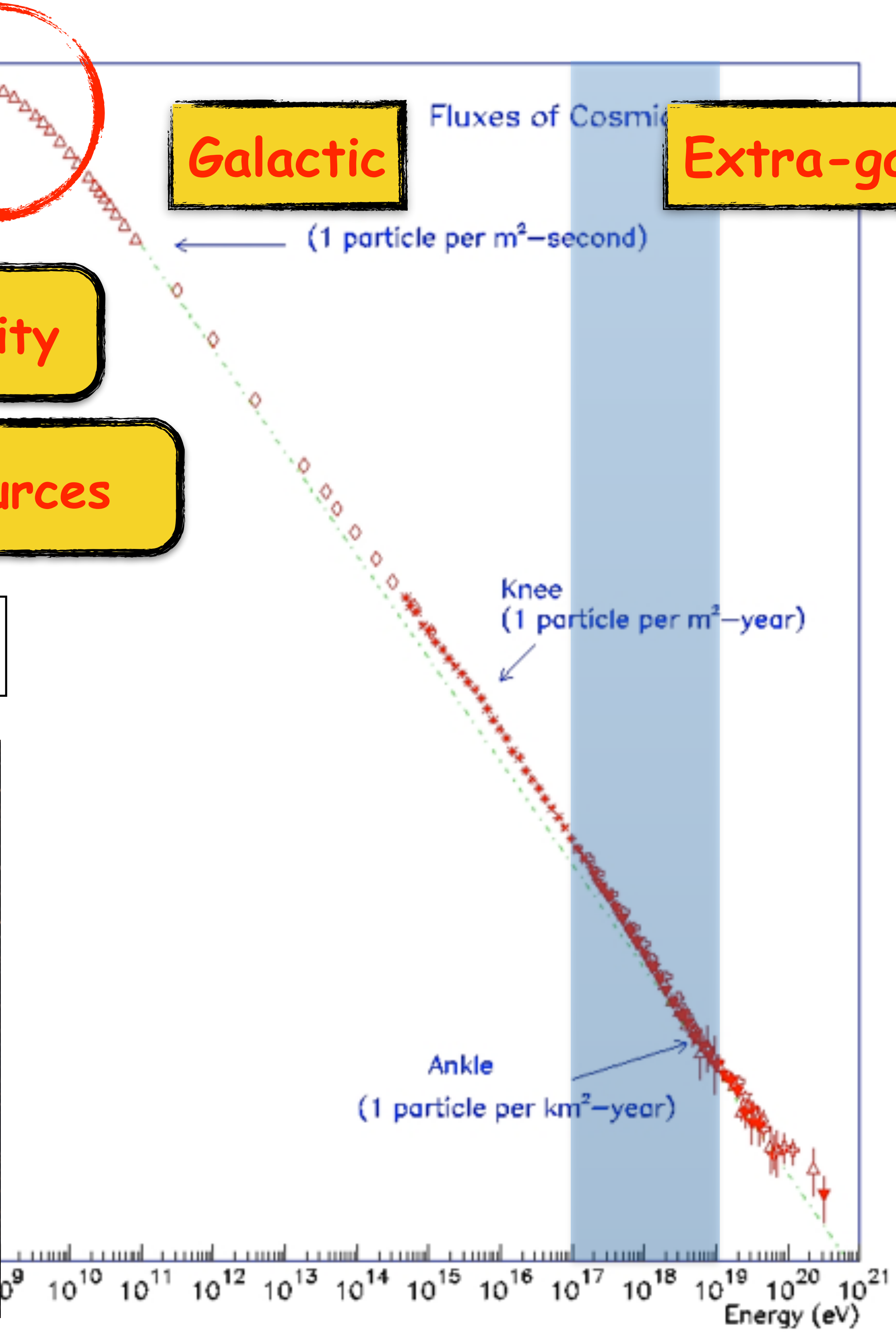

Galactic

Extra-galactic

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SuperNova Remnants

Not proven yet

The origin of CRs: Galactic sources

$1\ \mathrm{eV/cm^3}$

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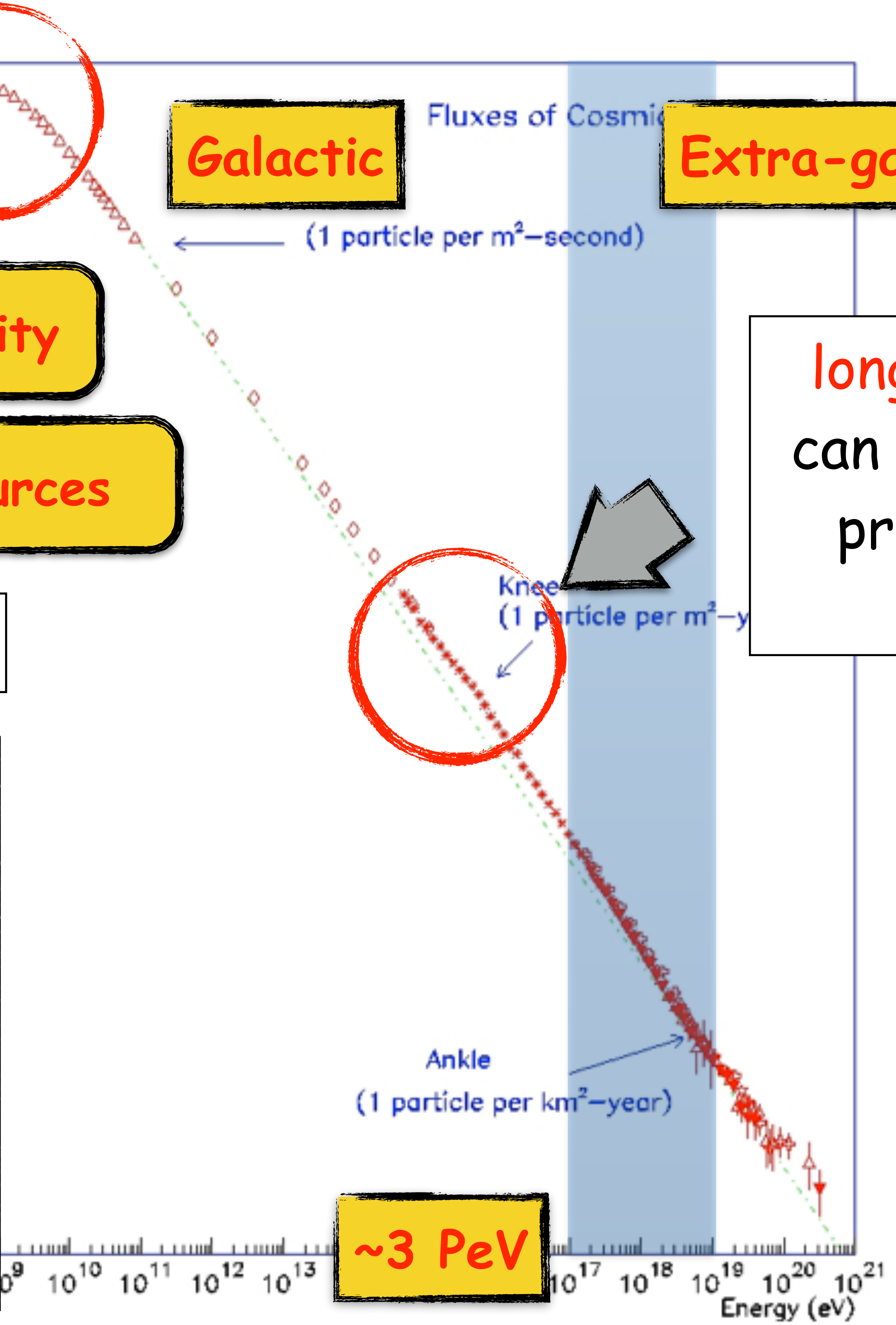
Powerful sources

SuperNova Remnants



Galactic

Extra-galactic

~3 PeV

long standing issue:
can SNRs accelerate protons up to the knee?

Are SNRs proton PeVatrons?

Theory

Hillas criterium ->

velocity

size

magnetic field

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

Are SNRs proton PeVatrons?

Theory

Hillas criterium -> $E_{max} \approx \overset{\text{velocity}}{u} \; \overset{\text{size}}{R} \; \overset{\text{magnetic field}}{B}$

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

Are SNRs proton PeVatrons?

Theory

Hillas criterium ->

$$E_{max} \approx \overset{\text{velocity}}{u}\ \overset{\text{size}}{R}\ \overset{\text{magnetic field}}{B}$$

$$E_{max} \approx 1 \underbrace{\left(\frac{u}{1000\ \mathrm{km/s}}\right)}_{\sim 10} \underbrace{\left(\frac{R}{\mathrm{pc}}\right)}_{\sim 3} \underbrace{\left(\frac{B}{\mu\mathrm{G}}\right)}_{\sim 3} \mathrm{TeV} \Rightarrow \boxed{100\ \mathrm{TeV}}$$

Are SNRs proton PeVatrons?

Theory

velocity

size

magnetic field

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

B is the only parameter we can play with

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

~10 ~3 ~3

100 TeV

Are SNRs proton PeVatrons?

Theory

velocity

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magnetic field

Hillas criterium ->

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

$$\left(\frac{u}{\quad} \right) \left(\frac{R}{\quad} \right) \boxed{\left(\frac{B}{\mu \mathrm{G}} \right)} \mathrm{TeV} \Rightarrow \boxed{100 \text{ TeV}}$$

B is the only parameter we can play with

~10

~3

~3

B-field amplification

CR escape from SNRs
-> current driven (and self regulating!) plasma instability

$$\varrho u_s^2 \longrightarrow \frac{B^2}{8\pi}$$

B field

ram pressure

Bell+ 2004...2013

Are SNRs proton PeVatrons?

Theory

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

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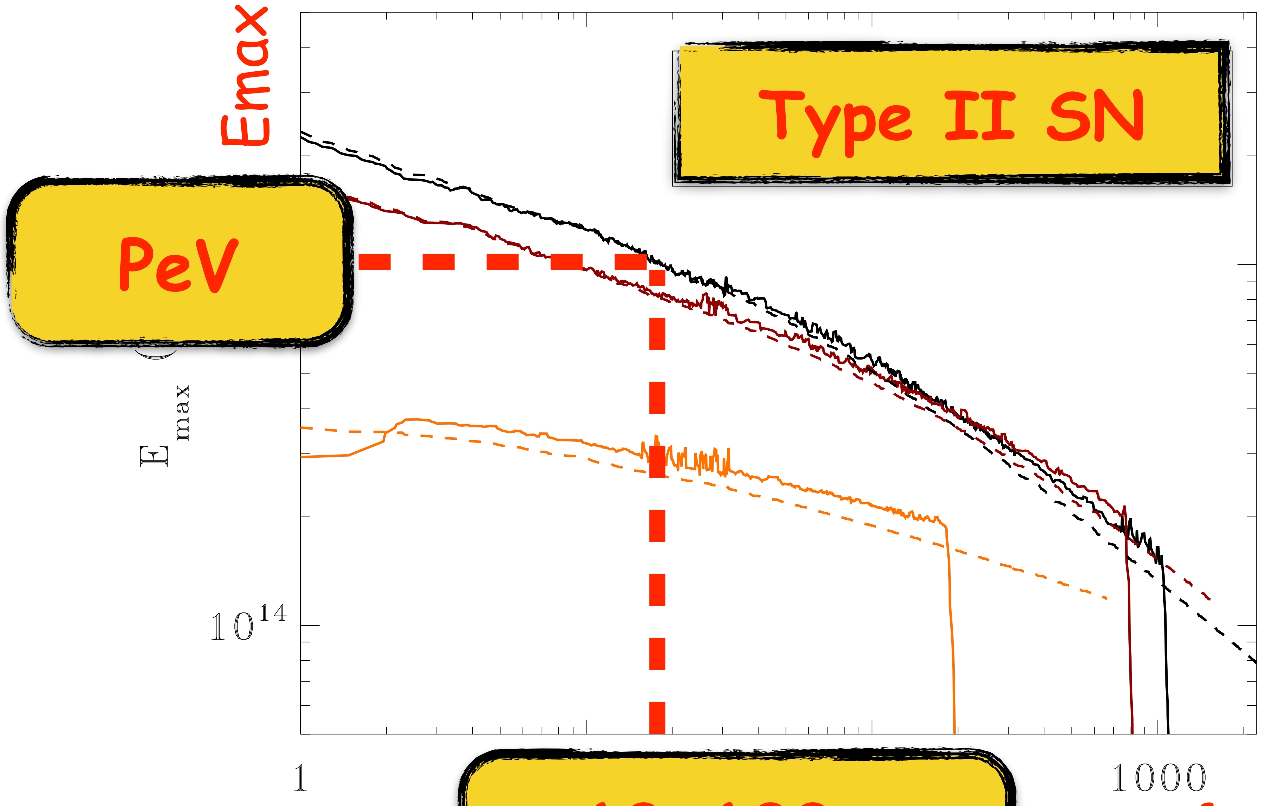

~10-100 yr

age of the SNR

Schure & Bell 2013/2014

Are SNRs proton PeVatrons?

Theory

velocity size magnetic field

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

$$\left(\frac{u}{\quad}\right)\left(\frac{R}{\quad}\right)\boxed{\left(\frac{B}{\mu\mathrm{G}}\right)}\ \mathrm{TeV}$$

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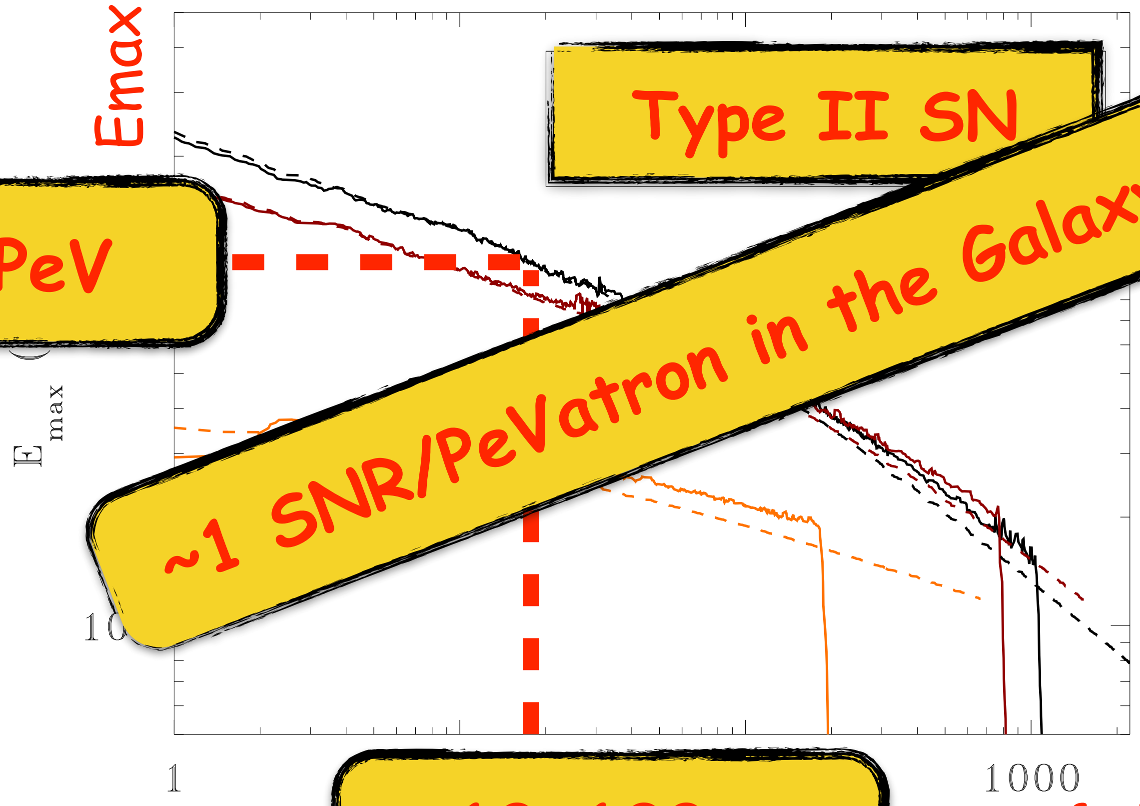


Emax

PeV

Type II SN

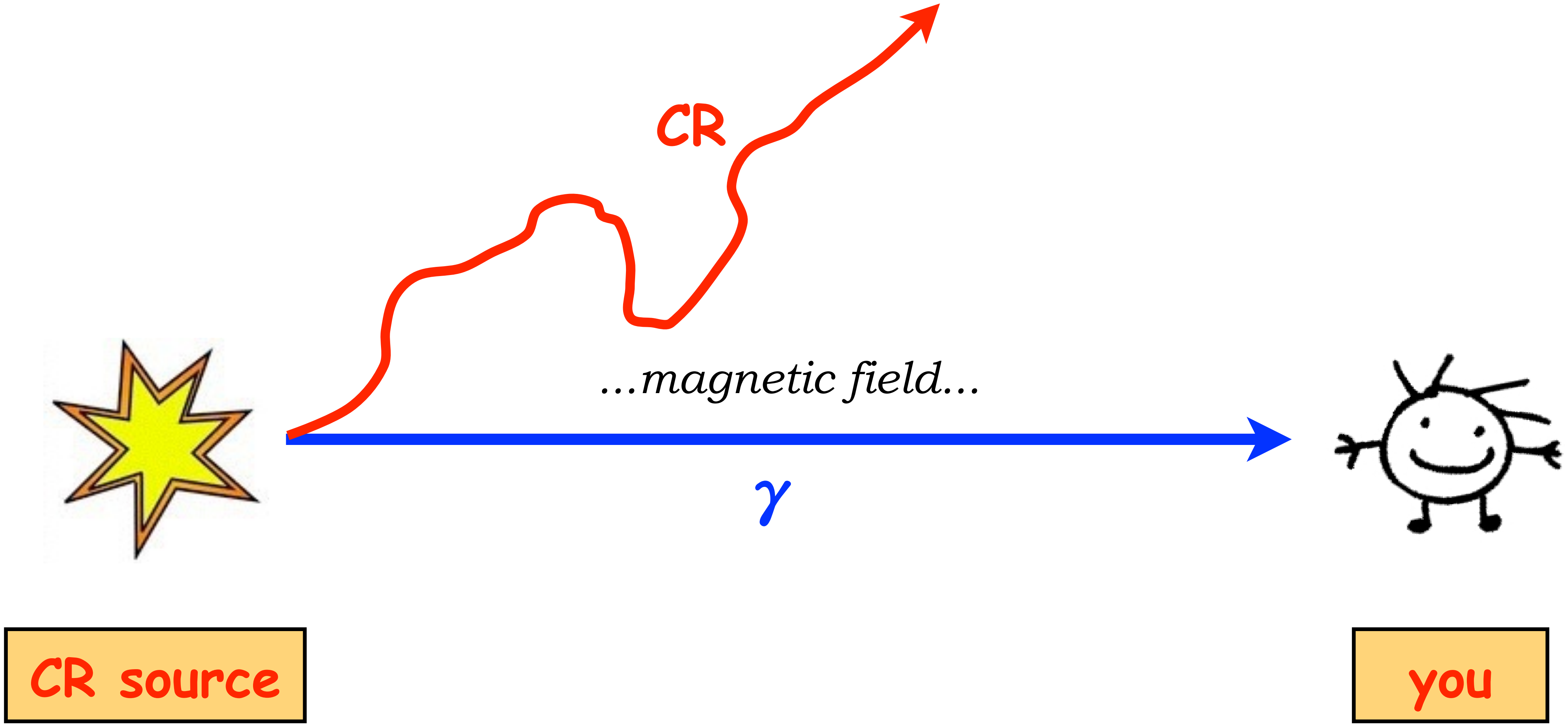
~1 SNR/PeVatron in the Galaxy!

~10-100 yr

age of the SNR

Schure & Bell 2013/2014

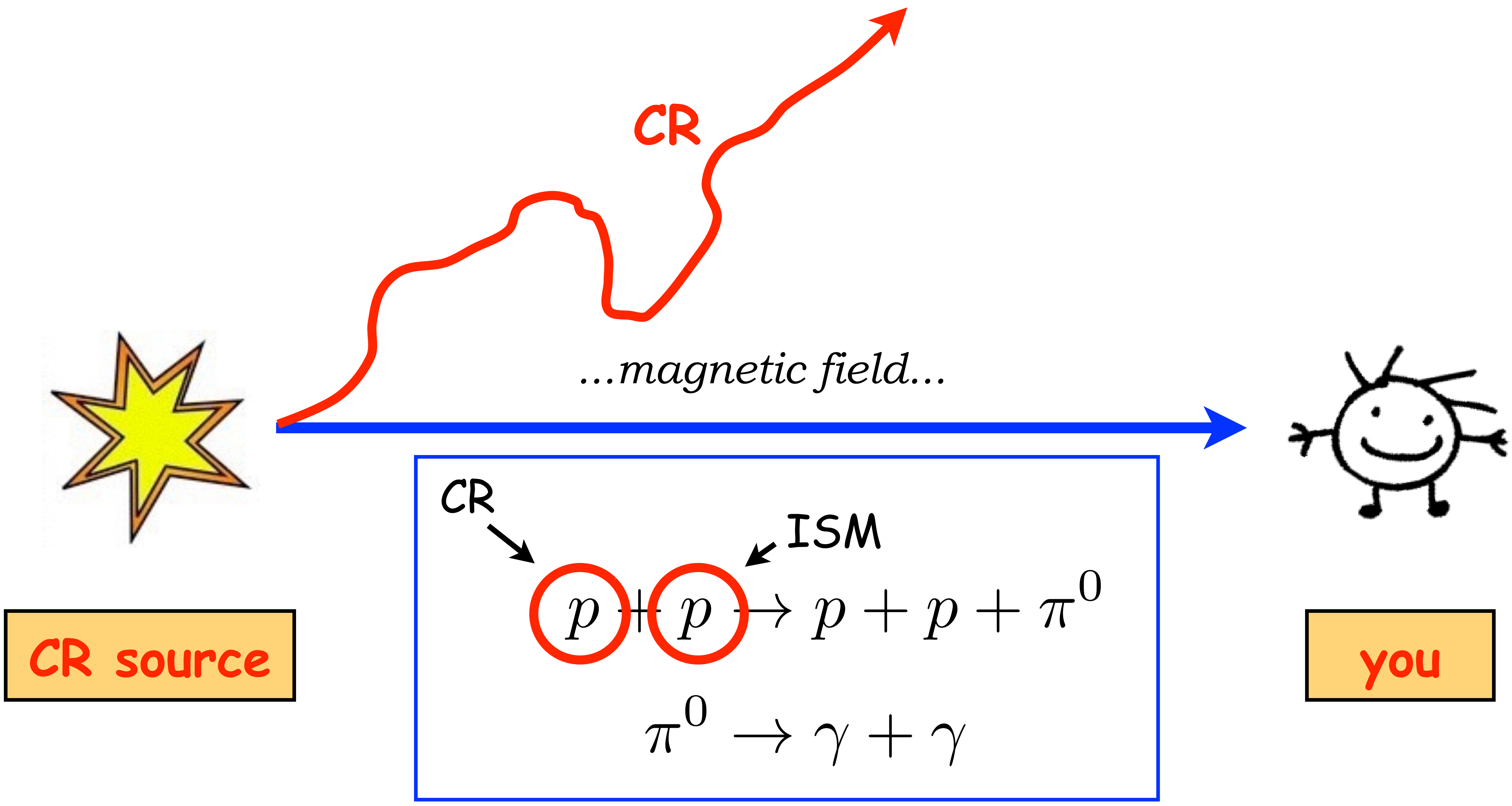
Cosmic ray sources: why is it so difficult?



We cannot do CR Astronomy.

Need for indirect identification of CR sources.

Cosmic ray sources: why is it so difficult?



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

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

We cannot do CR Astronomy.

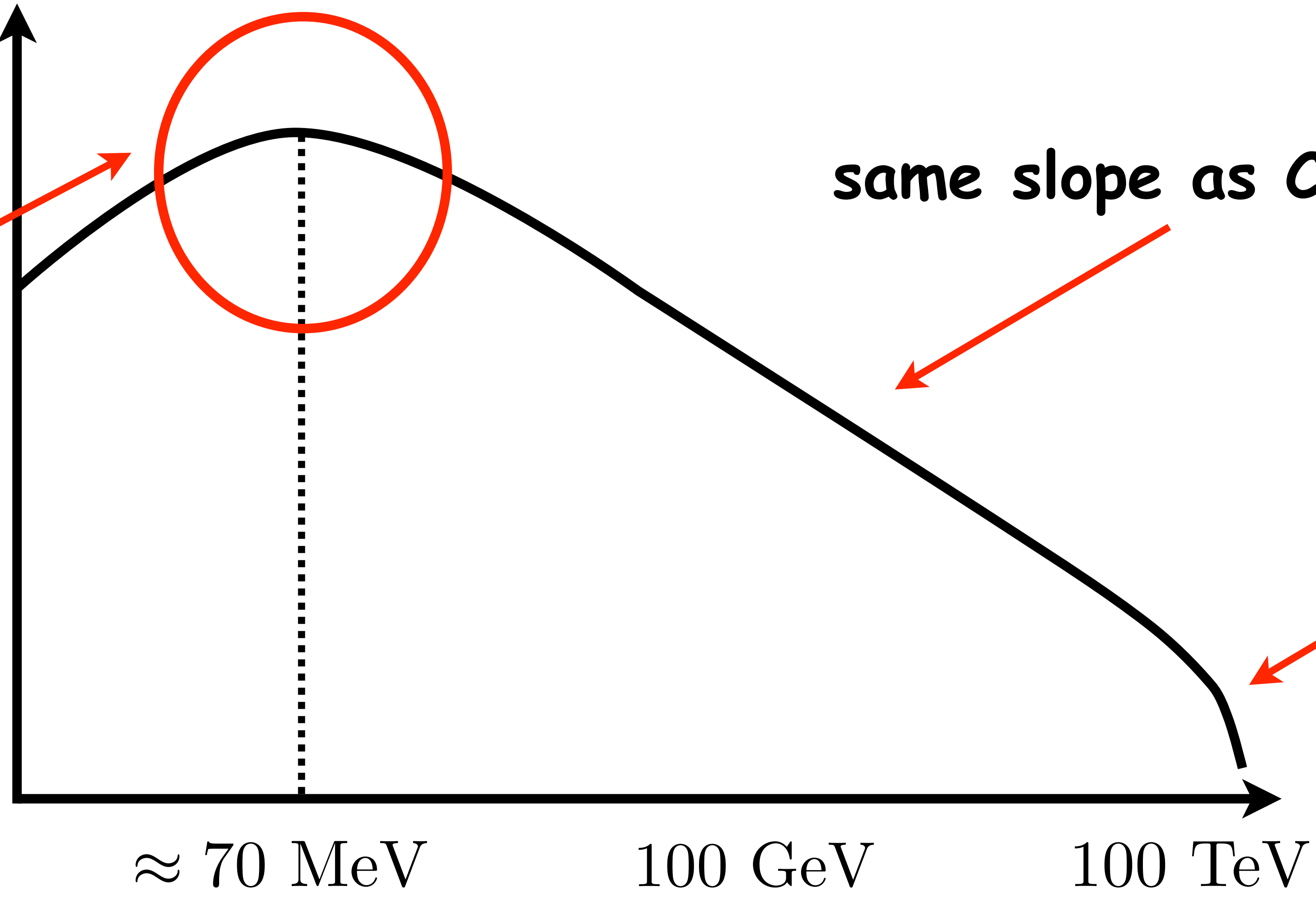
Need for indirect identification of CR sources.

Gamma-ray astronomy

$$\underset{\substack{\uparrow \\ \text{CR}}}{p} + \underset{\substack{\uparrow \\ \text{ISM}}}{p} \to p + p + \pi^0$$

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

$$\boxed{\langle E_\gamma \rangle \approx E_{CR}/10}$$



$$E_{peak} = \frac{m_{\pi^0}}{2}$$

same slope as CR spectrum

knee?

Gamma-ray astronomy

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

CR

ISM

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

$$\boxed{\langle E_\gamma \rangle \approx E_{CR}/10}$$

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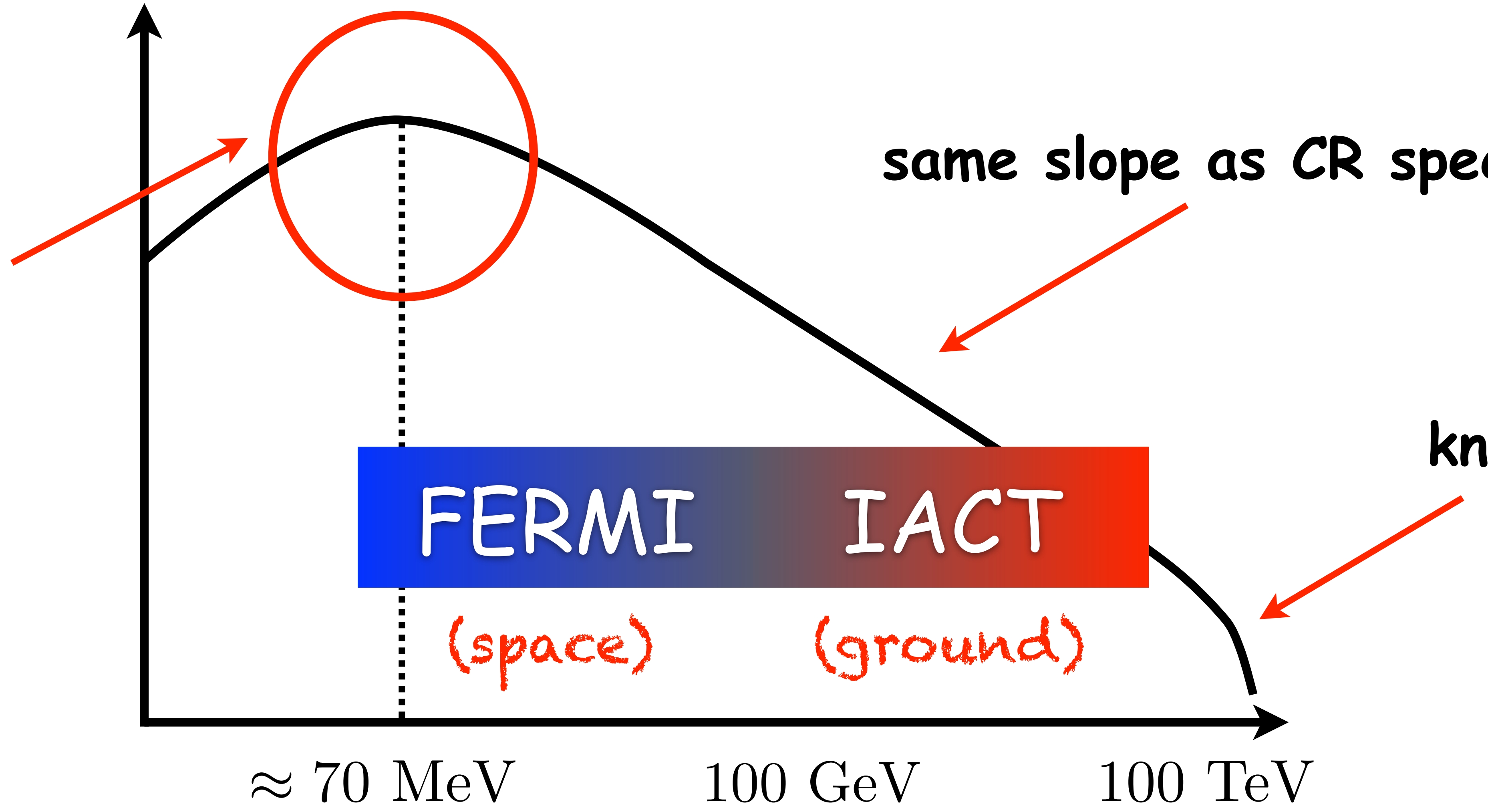
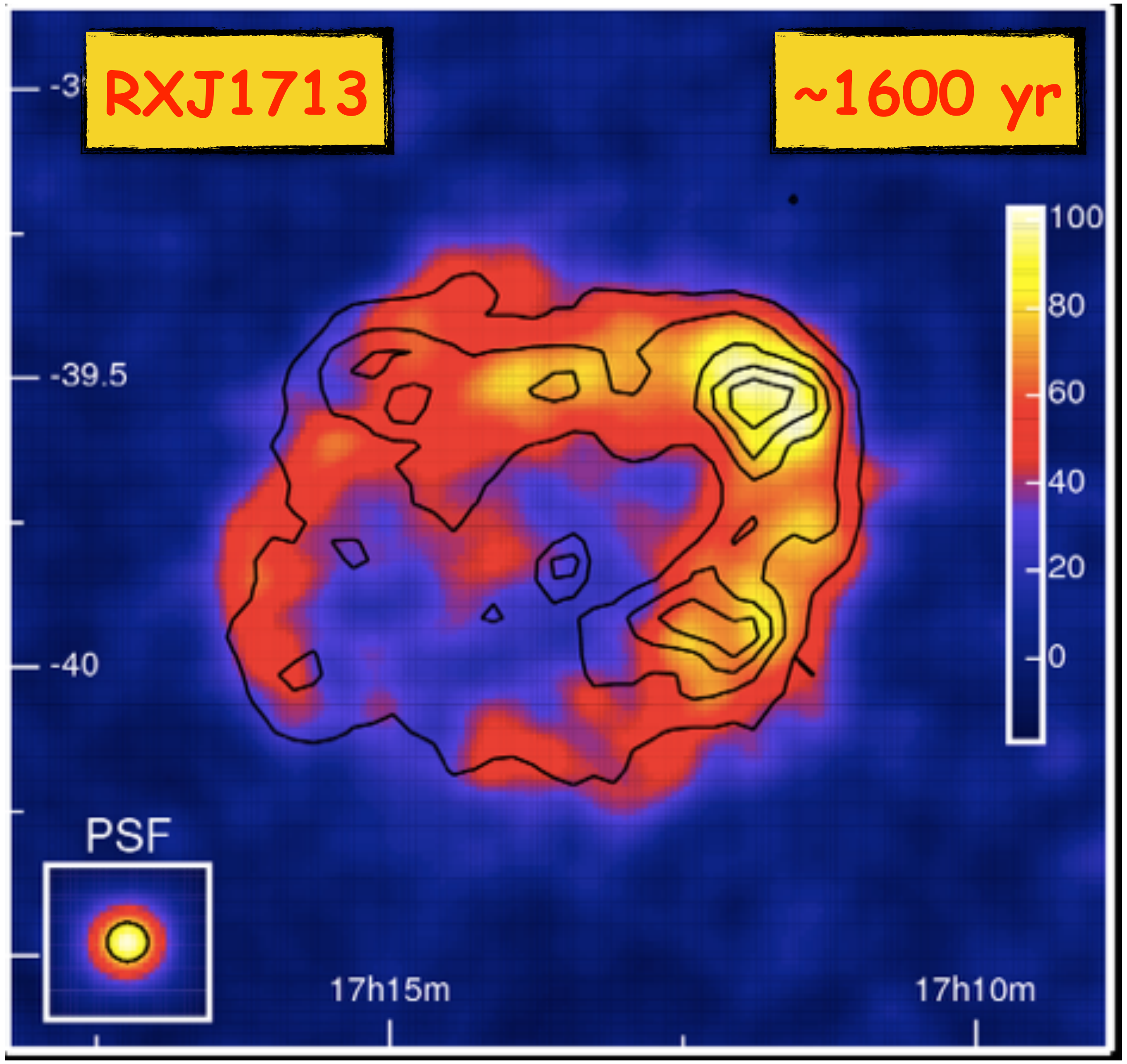


same slope as CR spectrum

knee?

SNRs in γ-rays: hadronc or leptonic?

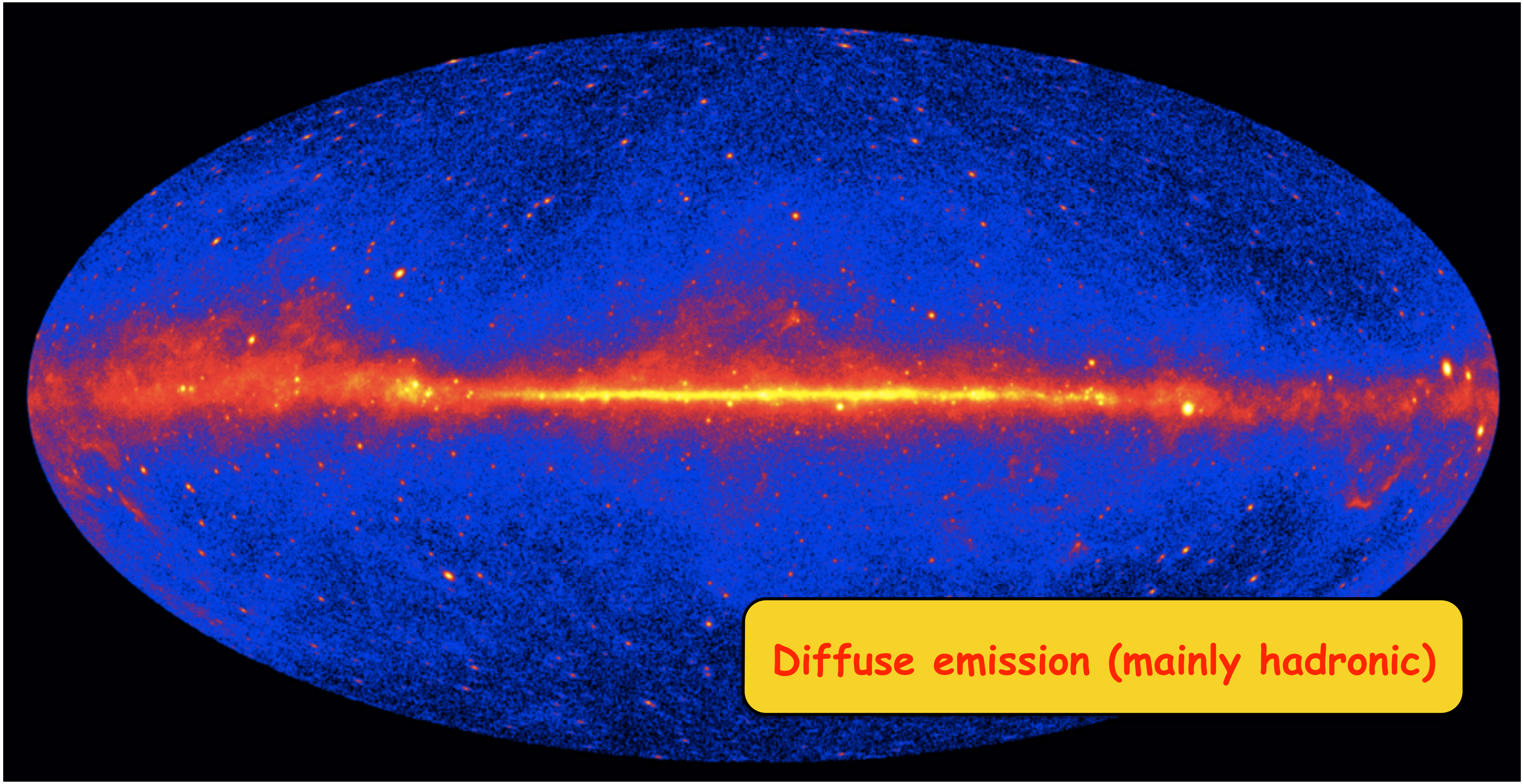


possible interpretations:

- **inverse Compton scattering** off CMB (Ellison+, Fermi Coll., ...)
- **proton-proton interactions** (Zirakashvili&Aharonian, Inoue+, SG & Aharonian, ...)

The gamma-ray sky: GeV domain

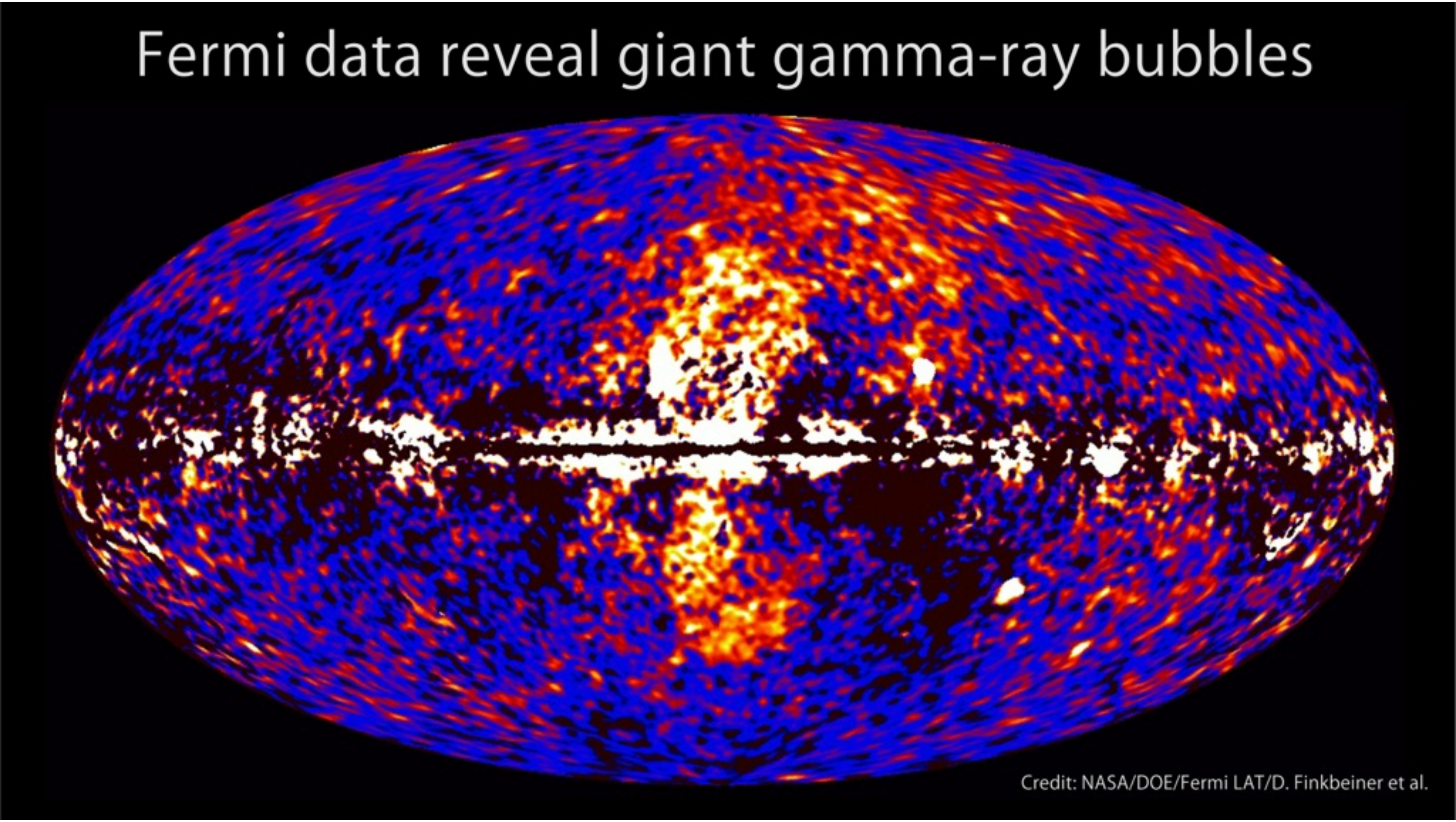
The FERMI sky



Diffuse emission (mainly hadronic)

Fermi bubbles

Signature of past activity of the SMBH



Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

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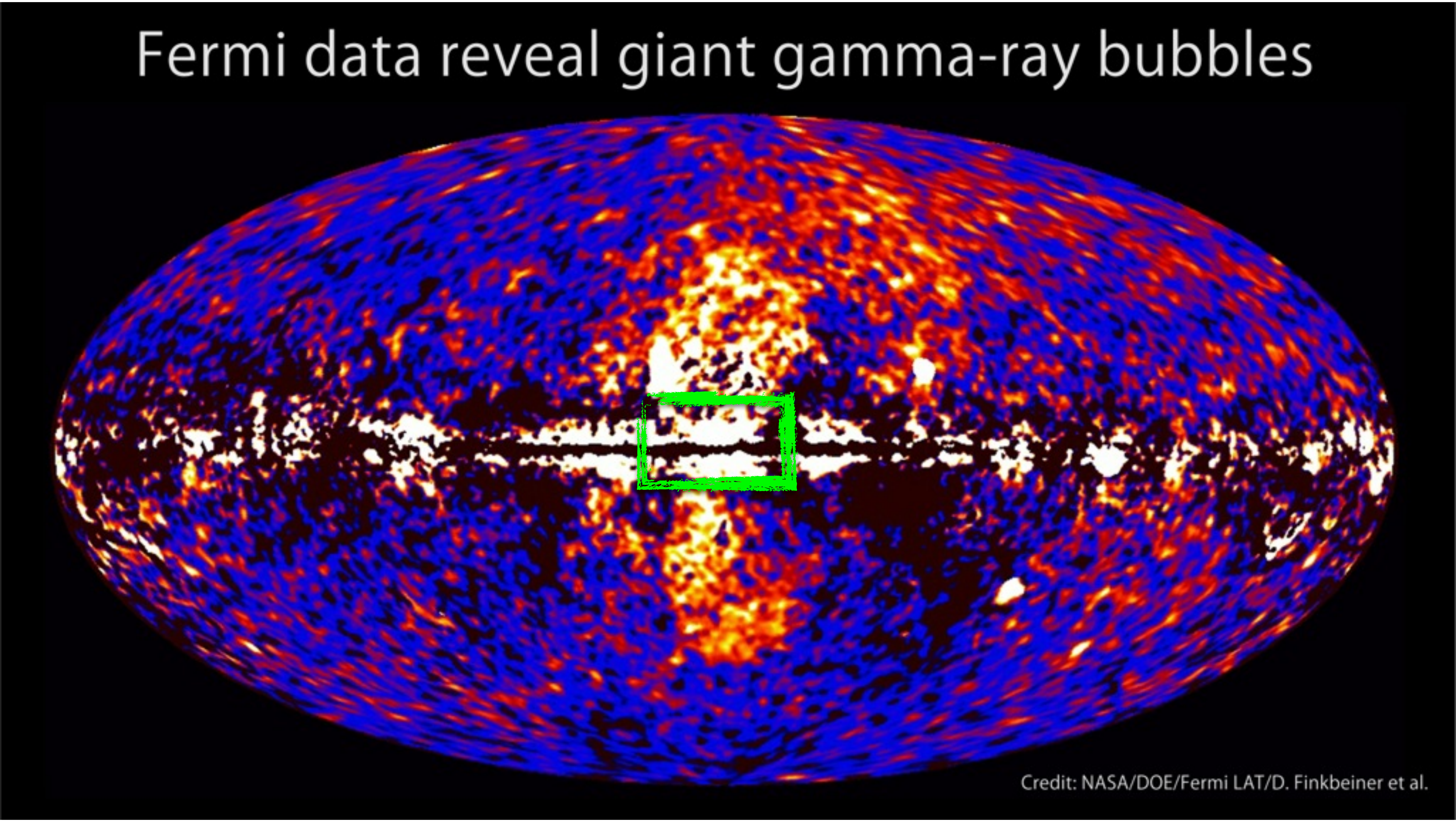

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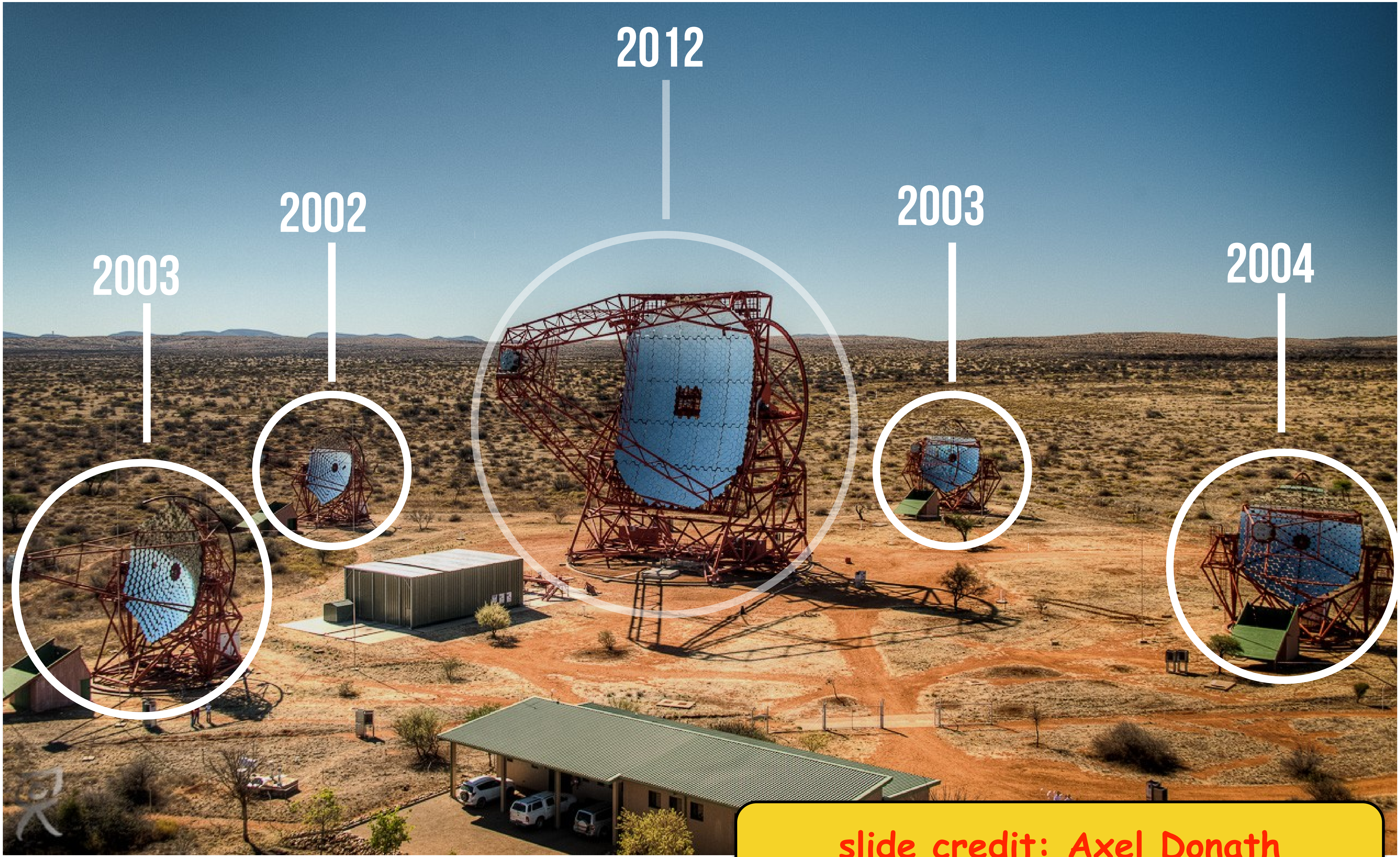
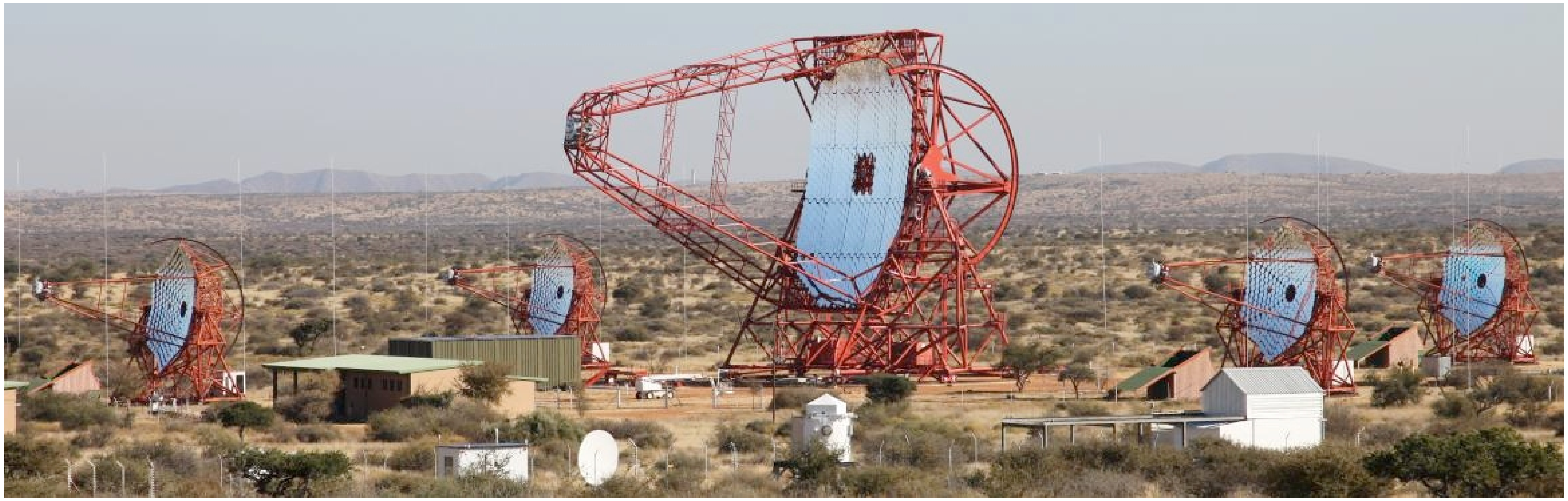


slide credit: Axel Donath



The H.E.S.S. II telescope array

- Phase I
  - 4 telescopes (Ø 12 m, 107 m^2)
  - 5° FoV
  - 960 PMTs / camera
  - E_{min}(zenith) ~ 100 GeV
  - Sterescopic reconstruction
  - Observations ~1000 h / year
  - Source position: ~10 arcsec

- **Phase II**
  - + 5th telescope (Ø **28** m, 600 m^2)
  - **3.5°** FoV
  - **2048** PMTs
  - E_{min}(zenith) ~ **20** GeV

H.E.S.S.

slide credit: Ryan Chaves

A proton PeVatron in the galactic centre

Observational signature

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

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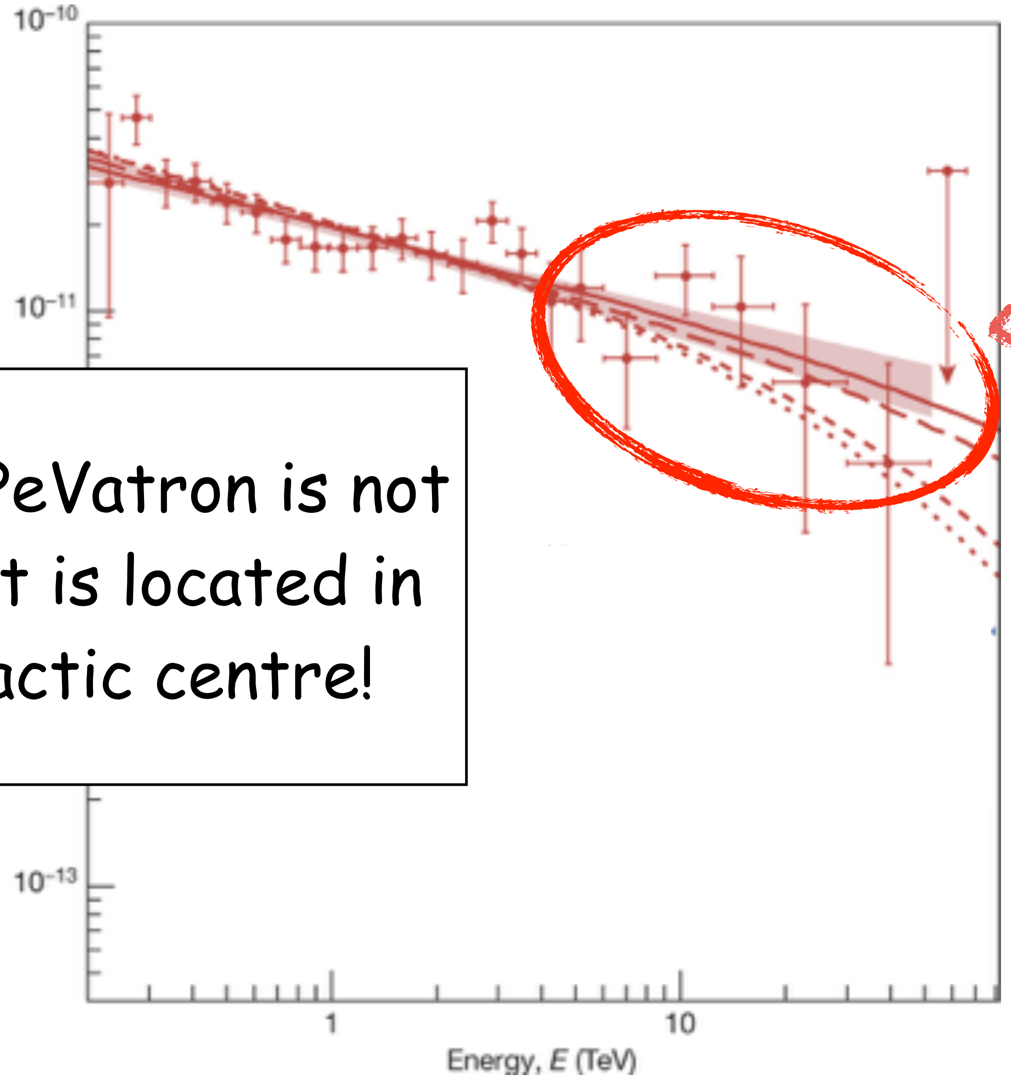

diffuse emission from the GC

no cutoff!

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

H.E.S.S. Coll. 2016

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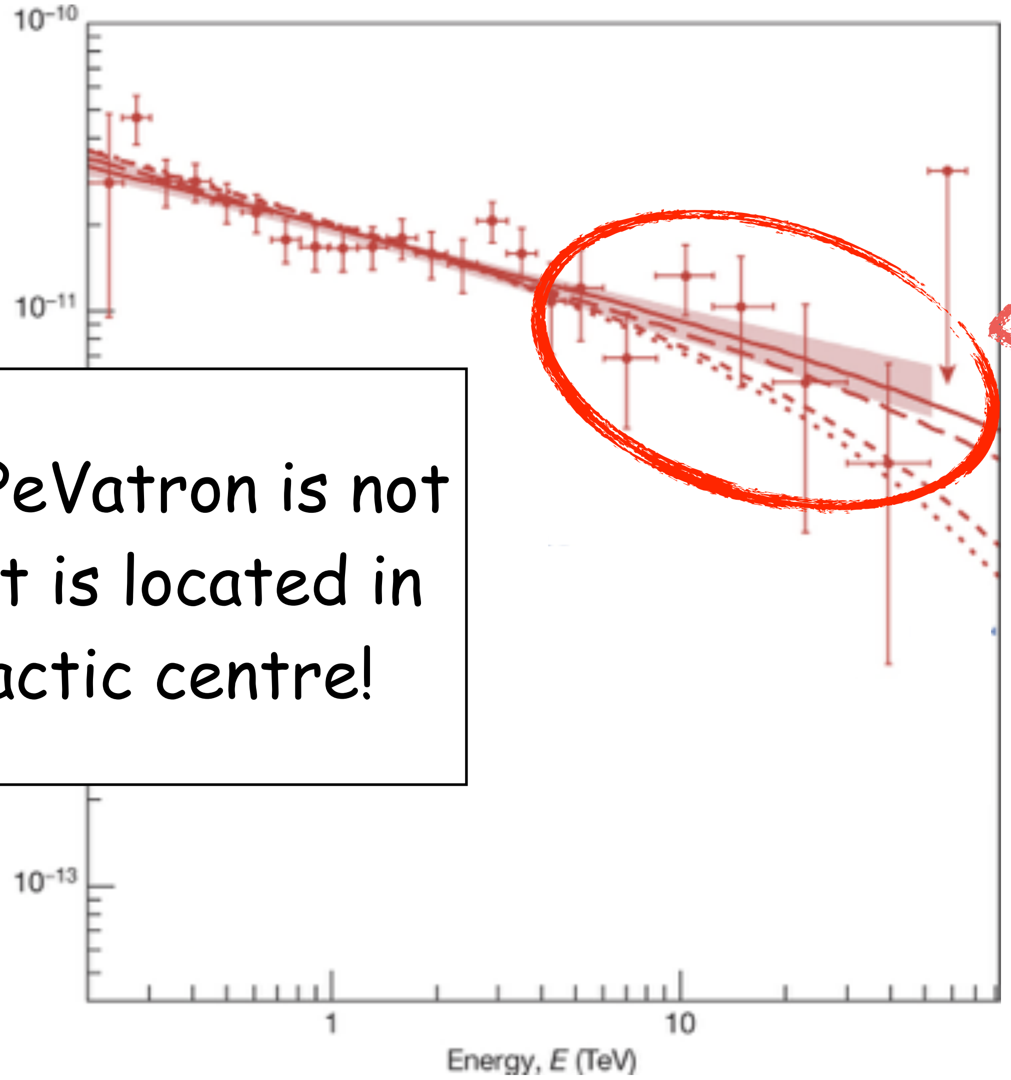

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a cutoff @ …	deviates from data @
2.9 PeV	68%
0.6 PeV	90%
0.4 PeV	95%

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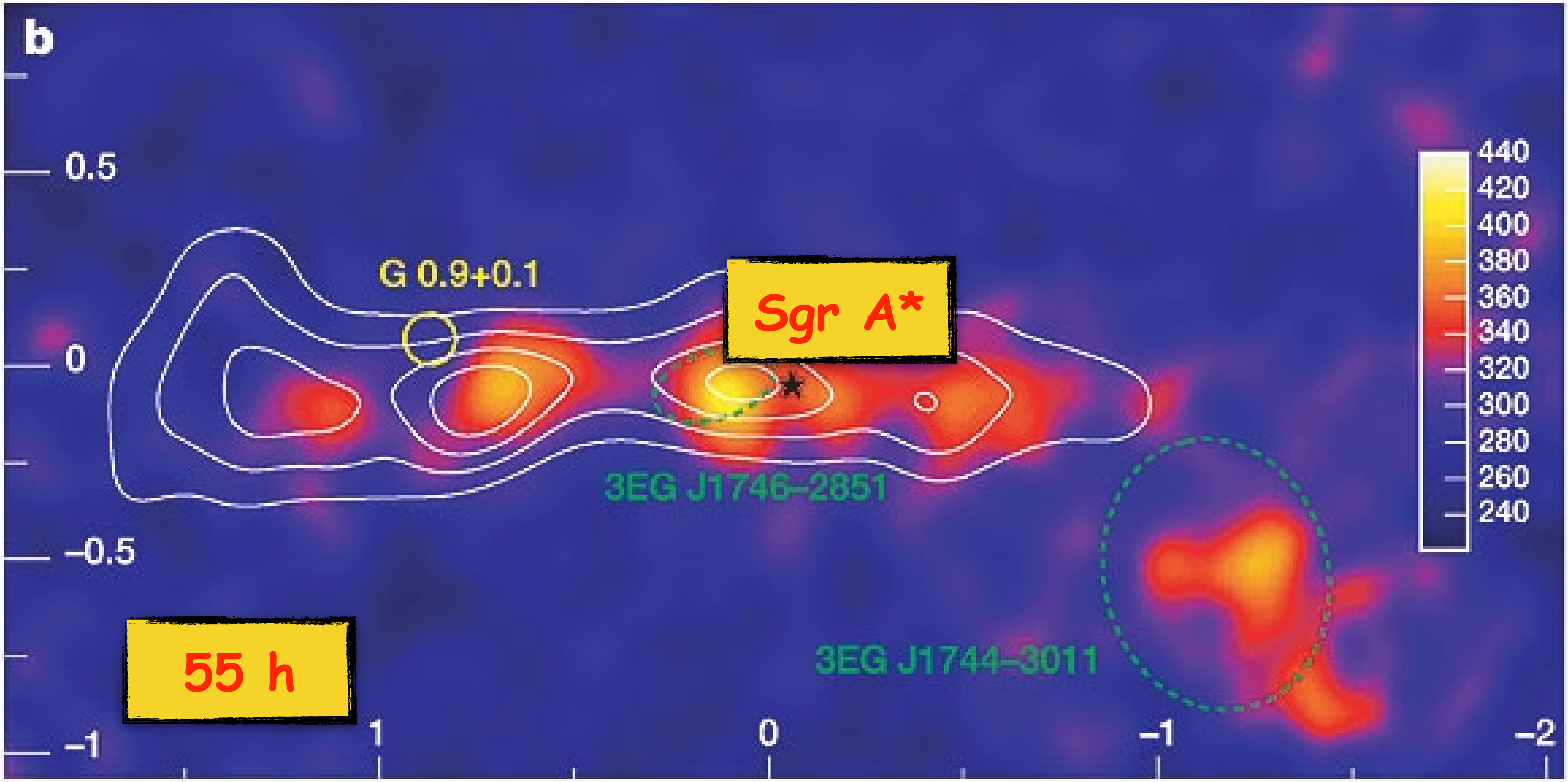
The GC ridge as seen 10 years ago

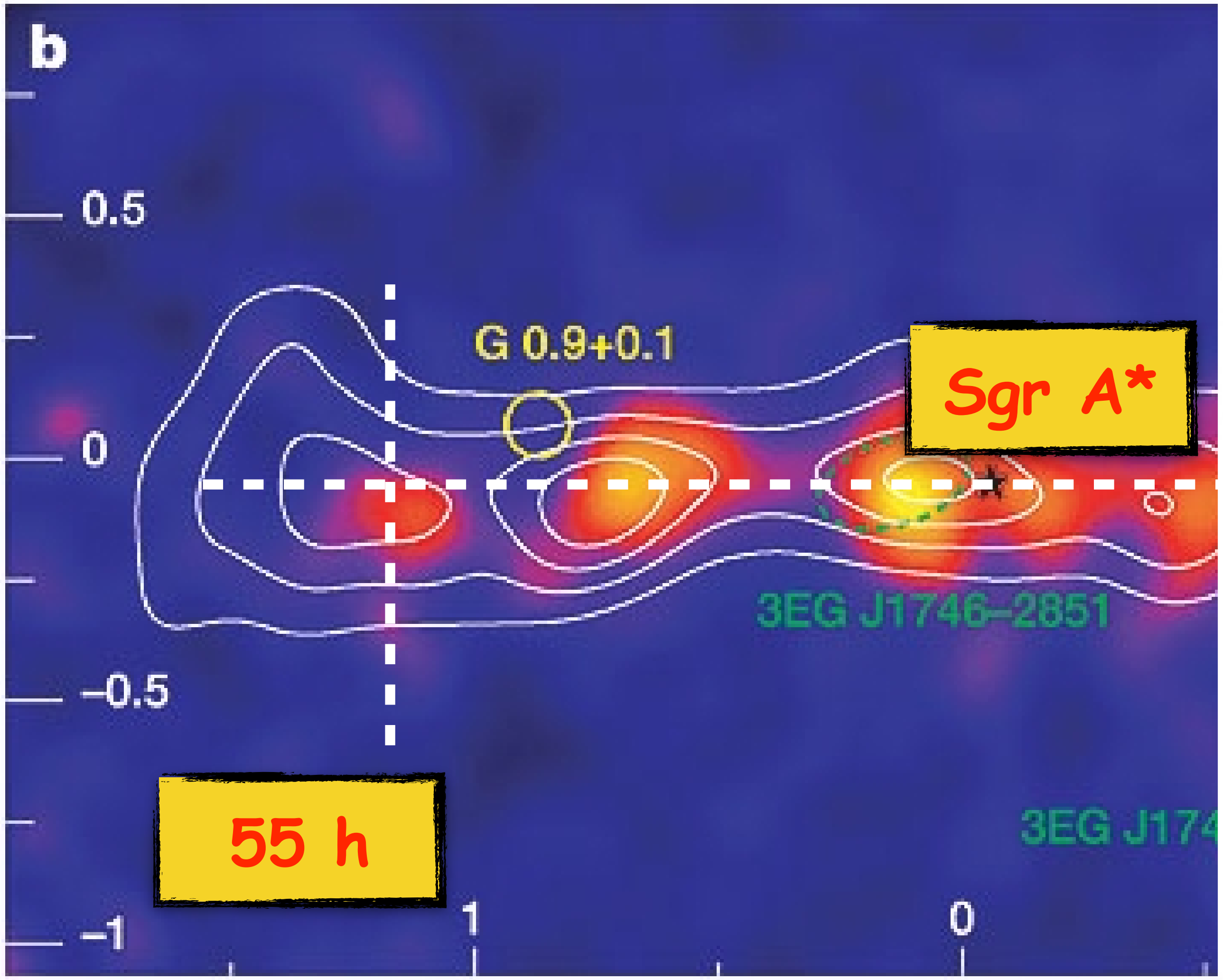
H.E.S.S. Coll. 2006



color scale -> γ-rays
contours -> gas (CS)

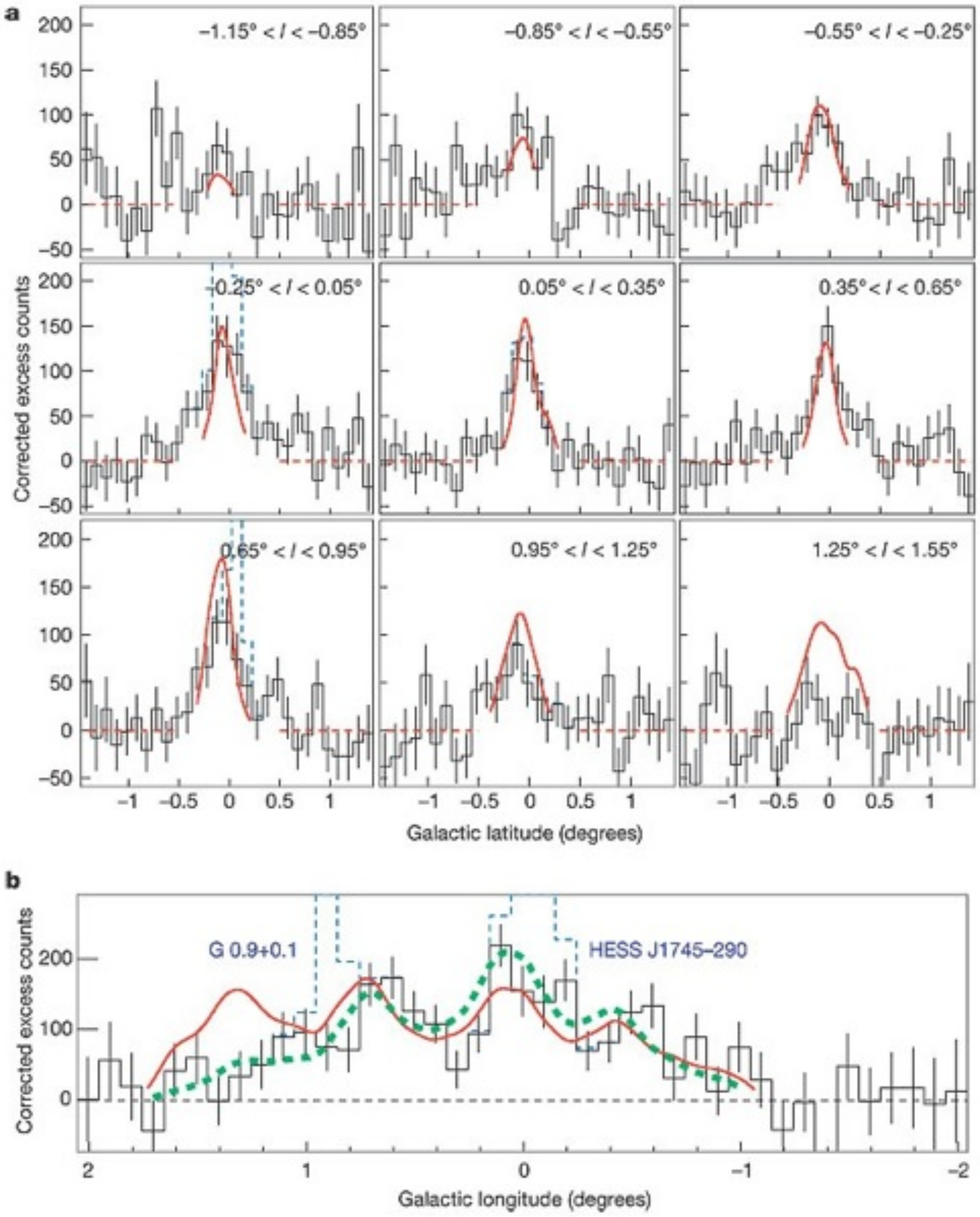
The GC ridge as seen 10 years ago

H.E.S.S. Coll. 2006



histogram -> γ-rays

red -> gas (CS)



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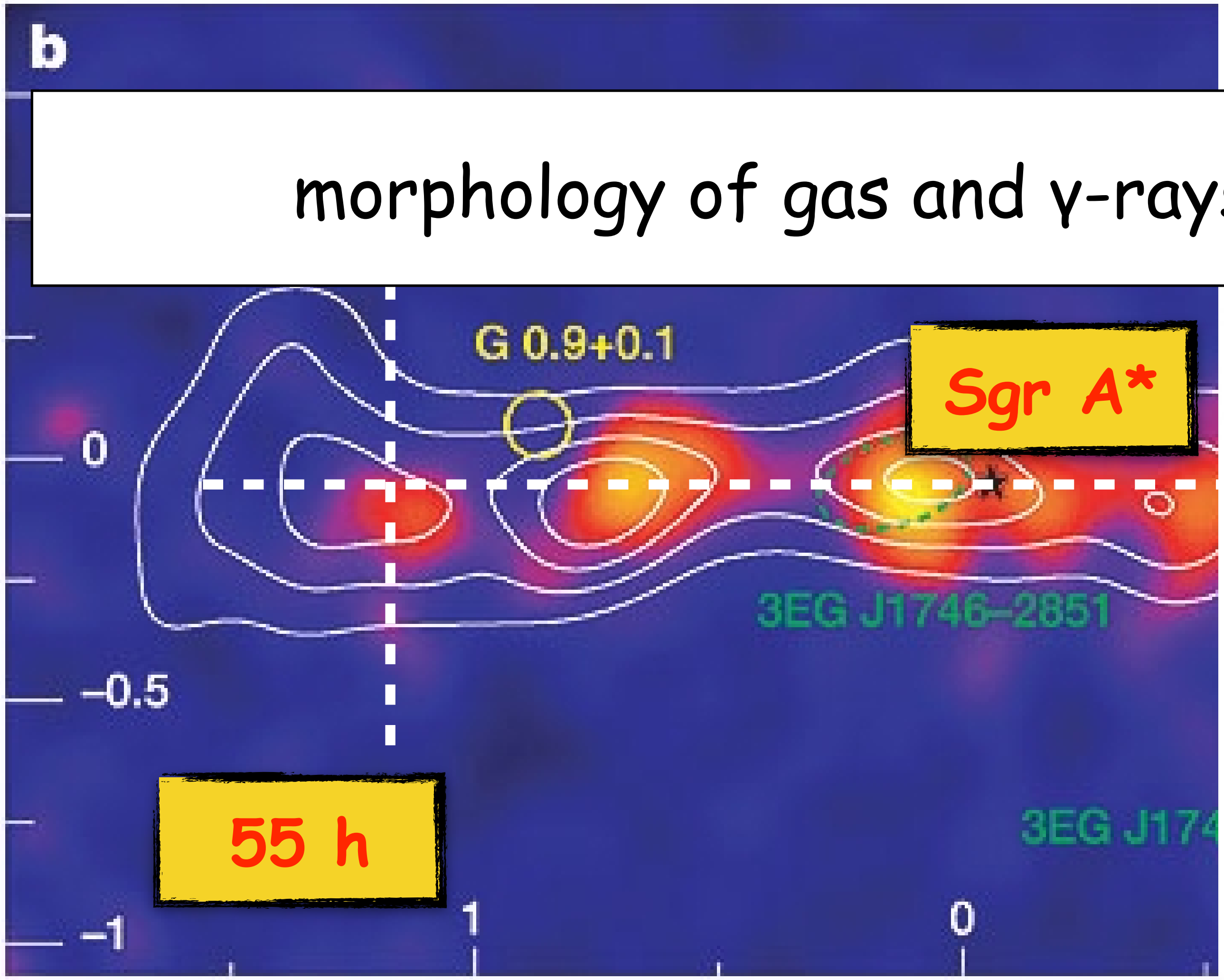
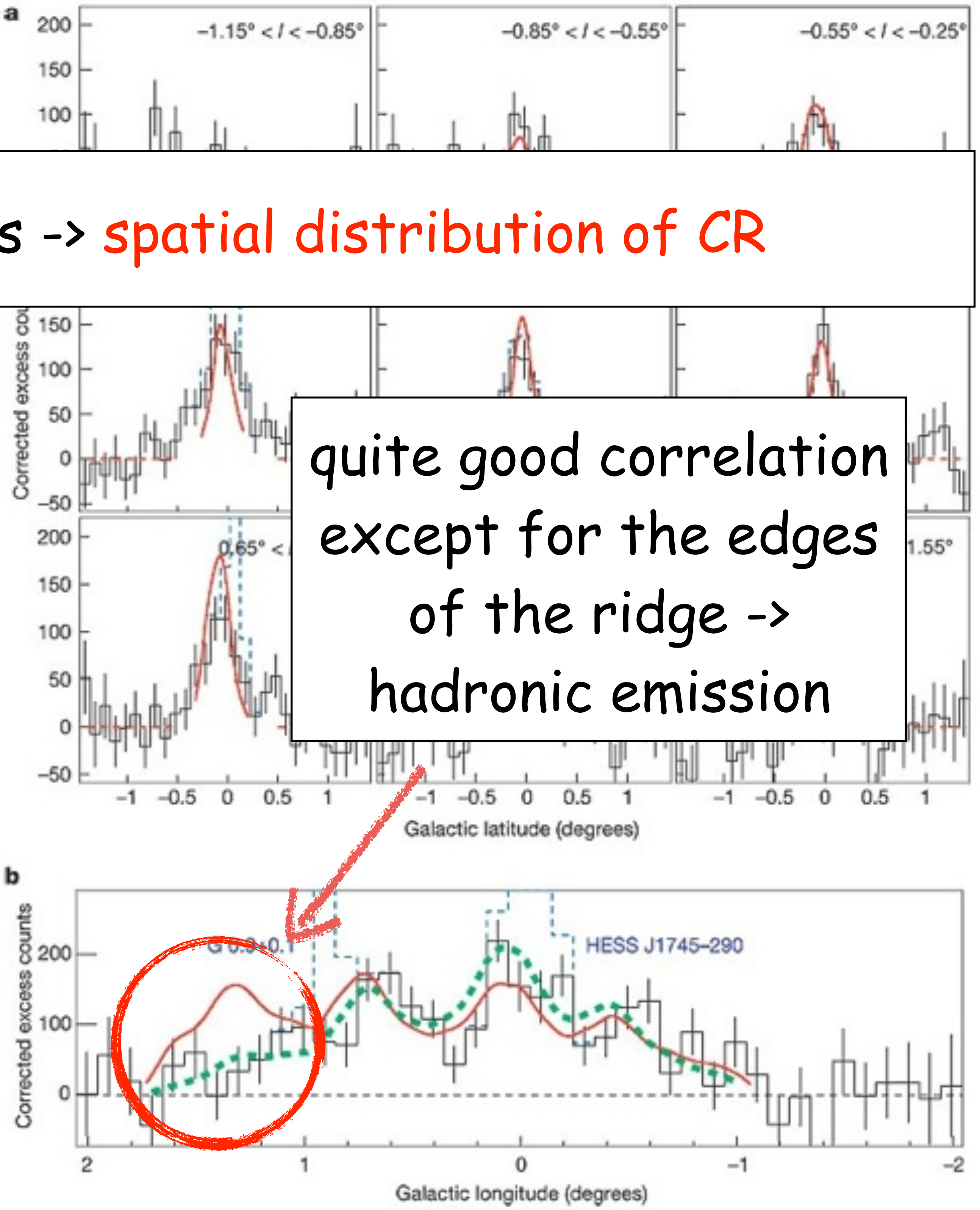
H.E.S.S. Coll. 2006



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



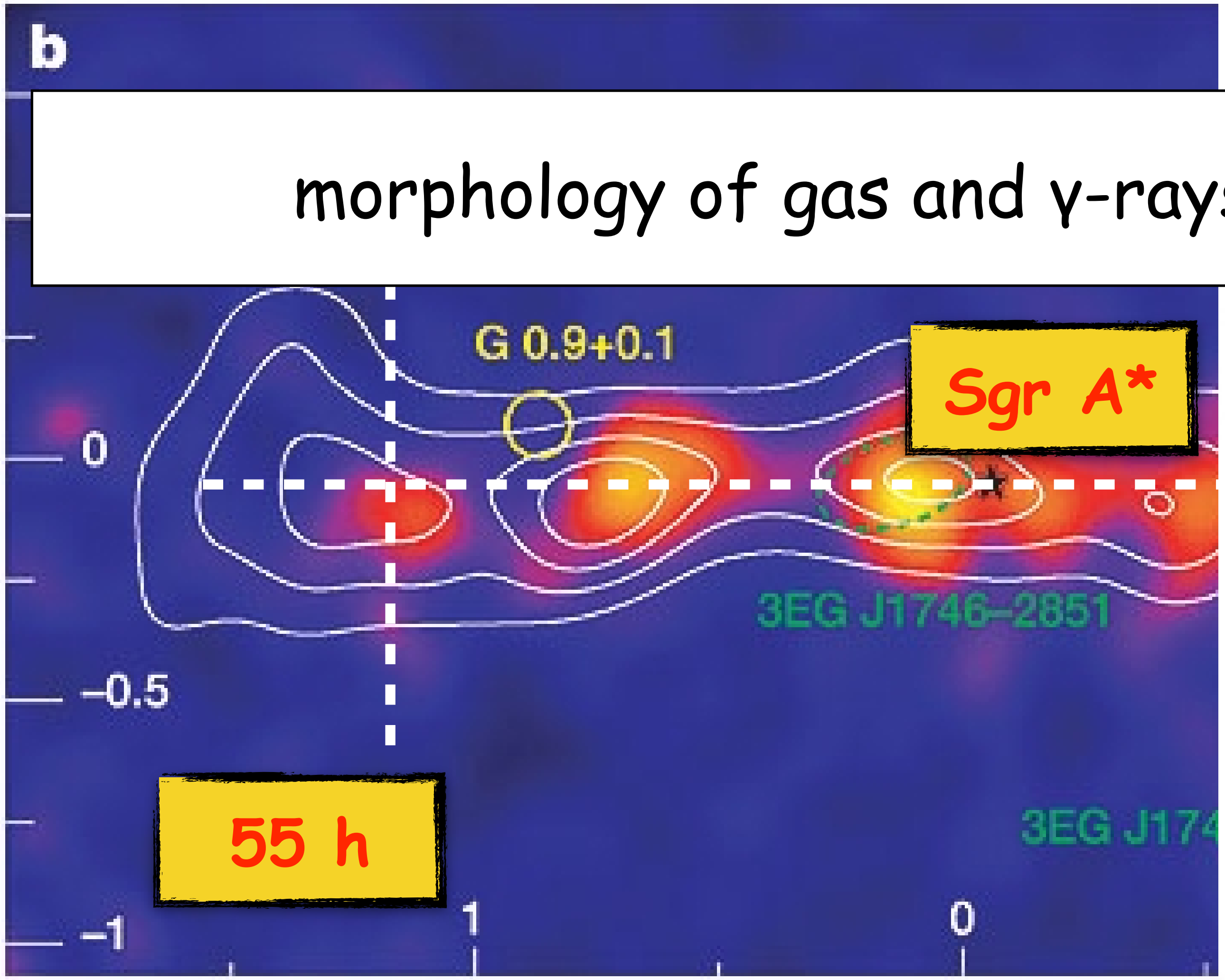
quite good correlation except for the edges of the ridge -> hadronic emission

histogram -> γ-rays
red -> gas (CS)

The GC ridge as seen 10 years ago

H.E.S.S. Coll. 2006

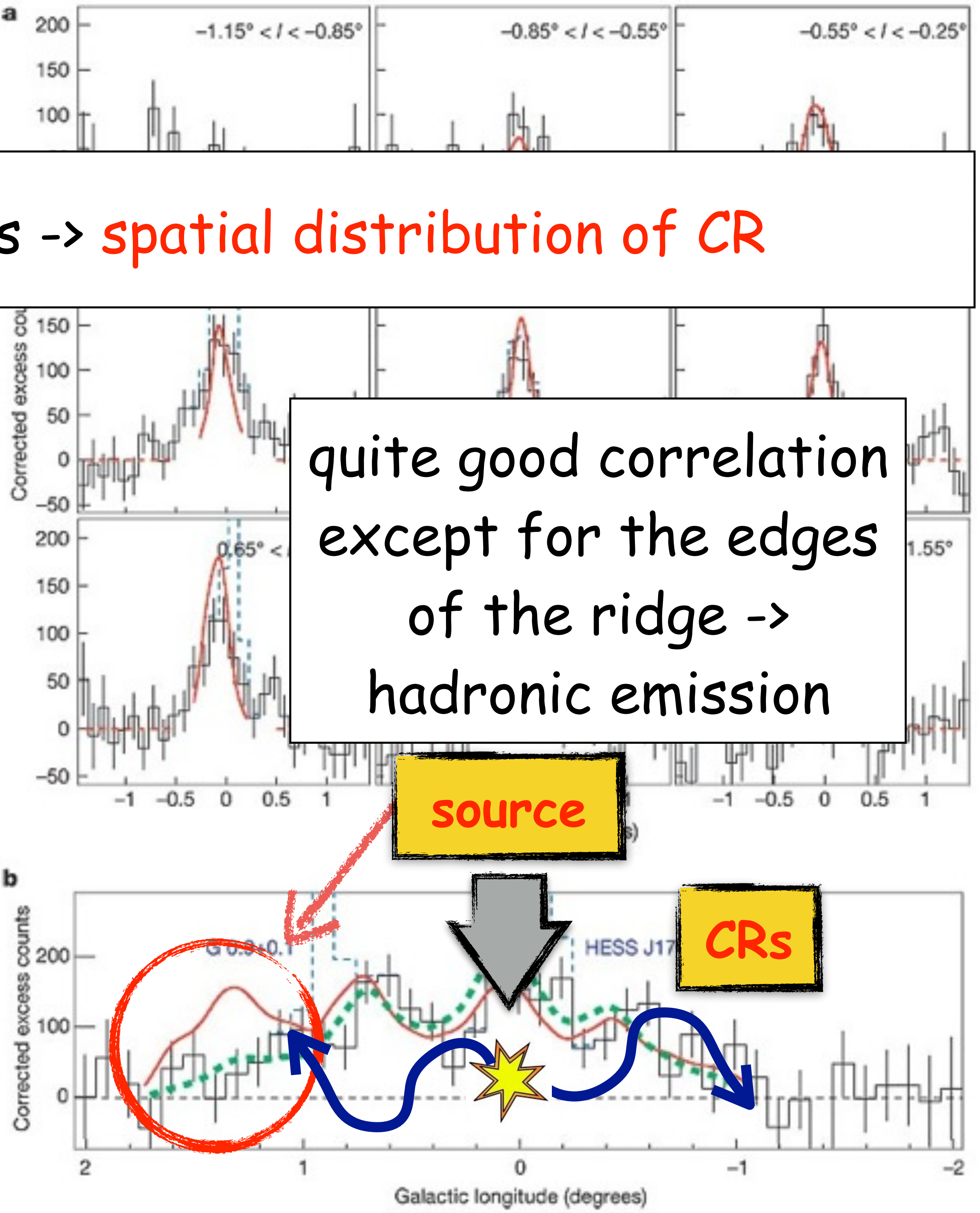
morphology of gas and γ-rays -> spatial distribution of CR



Sgr A*

55 h

histogram -> γ-rays
red -> gas (CS)



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

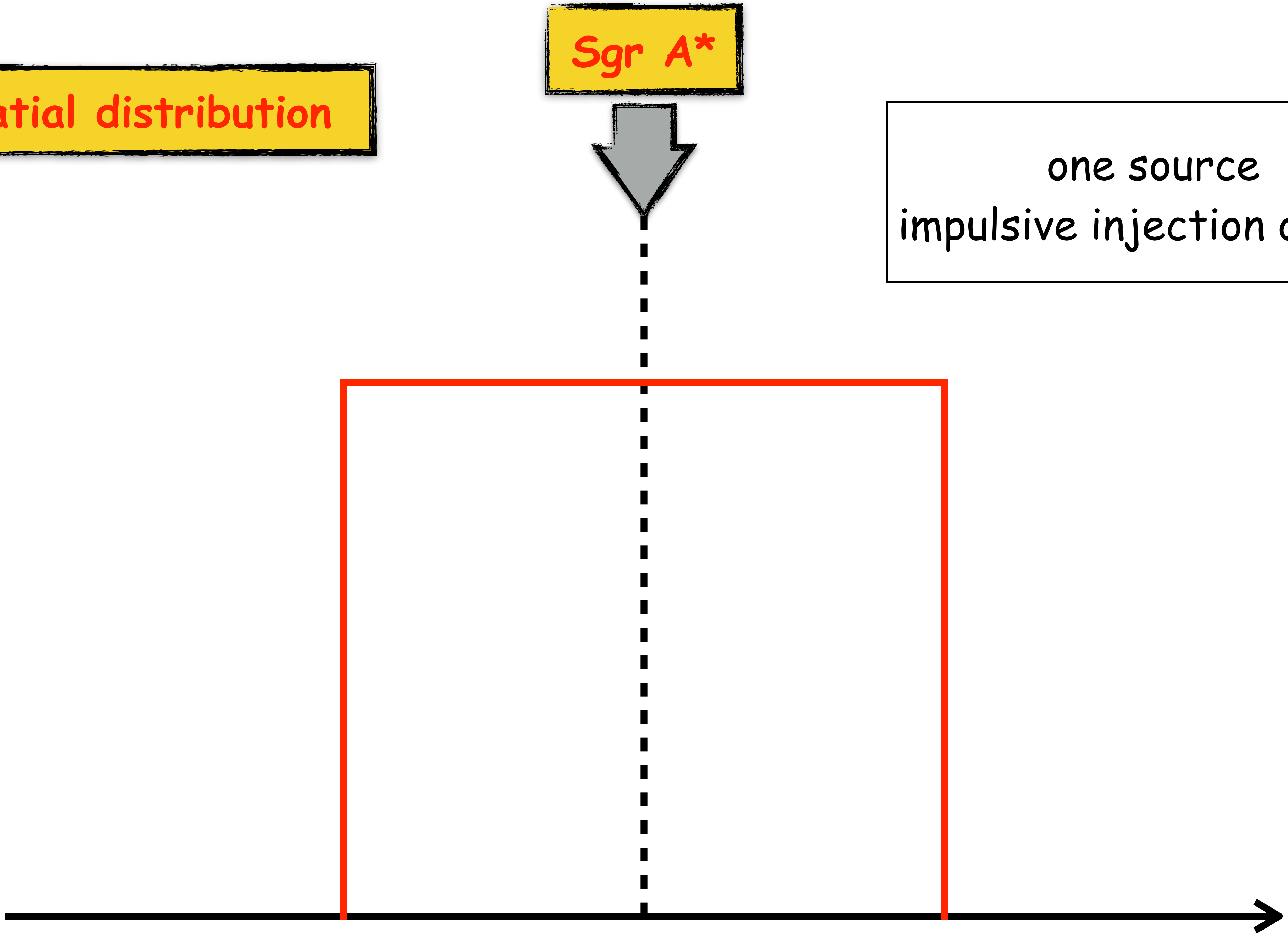
source

CRs

Where is the source?

CR spatial distribution

one source
impulsive injection of CRs



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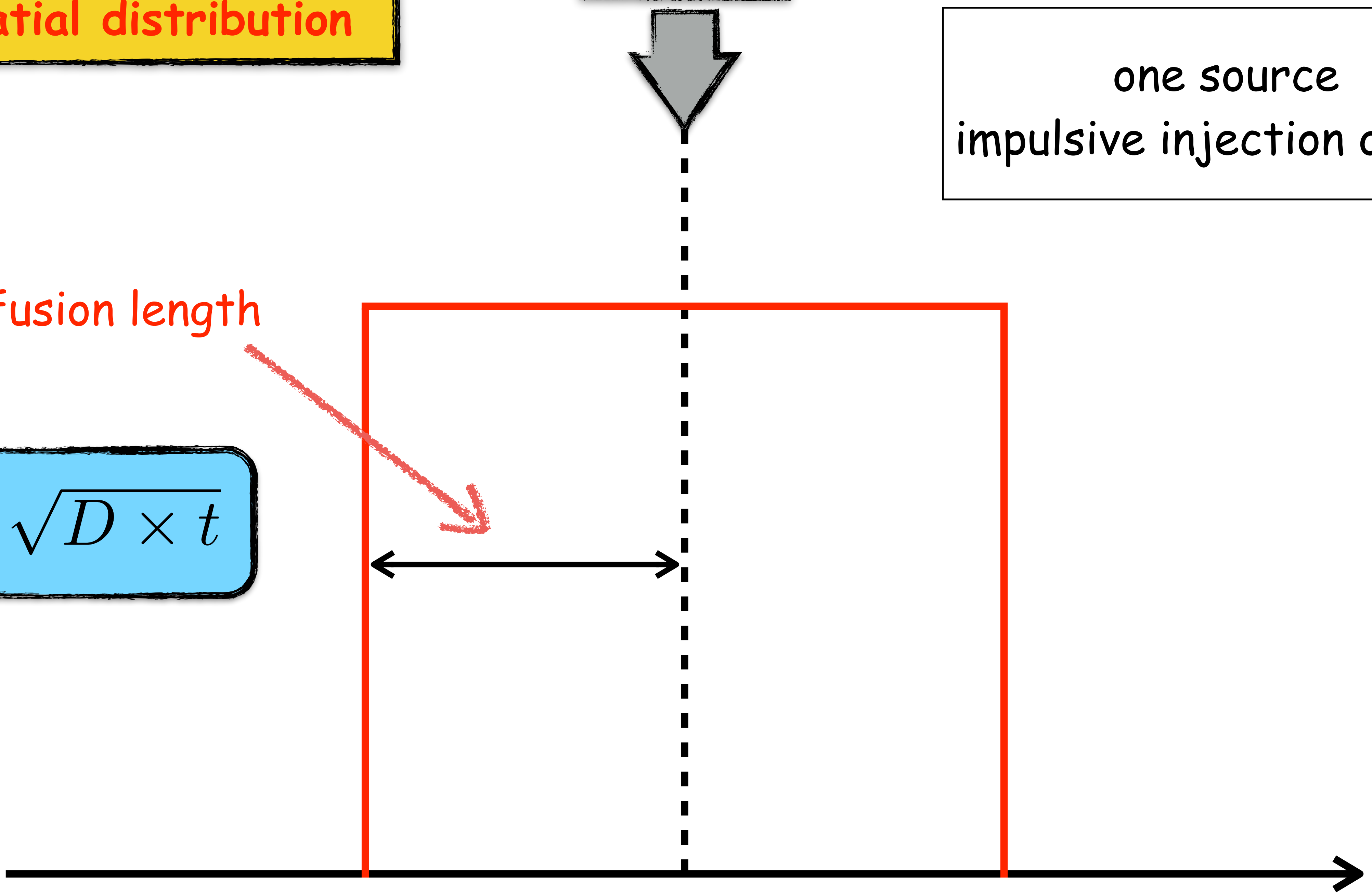
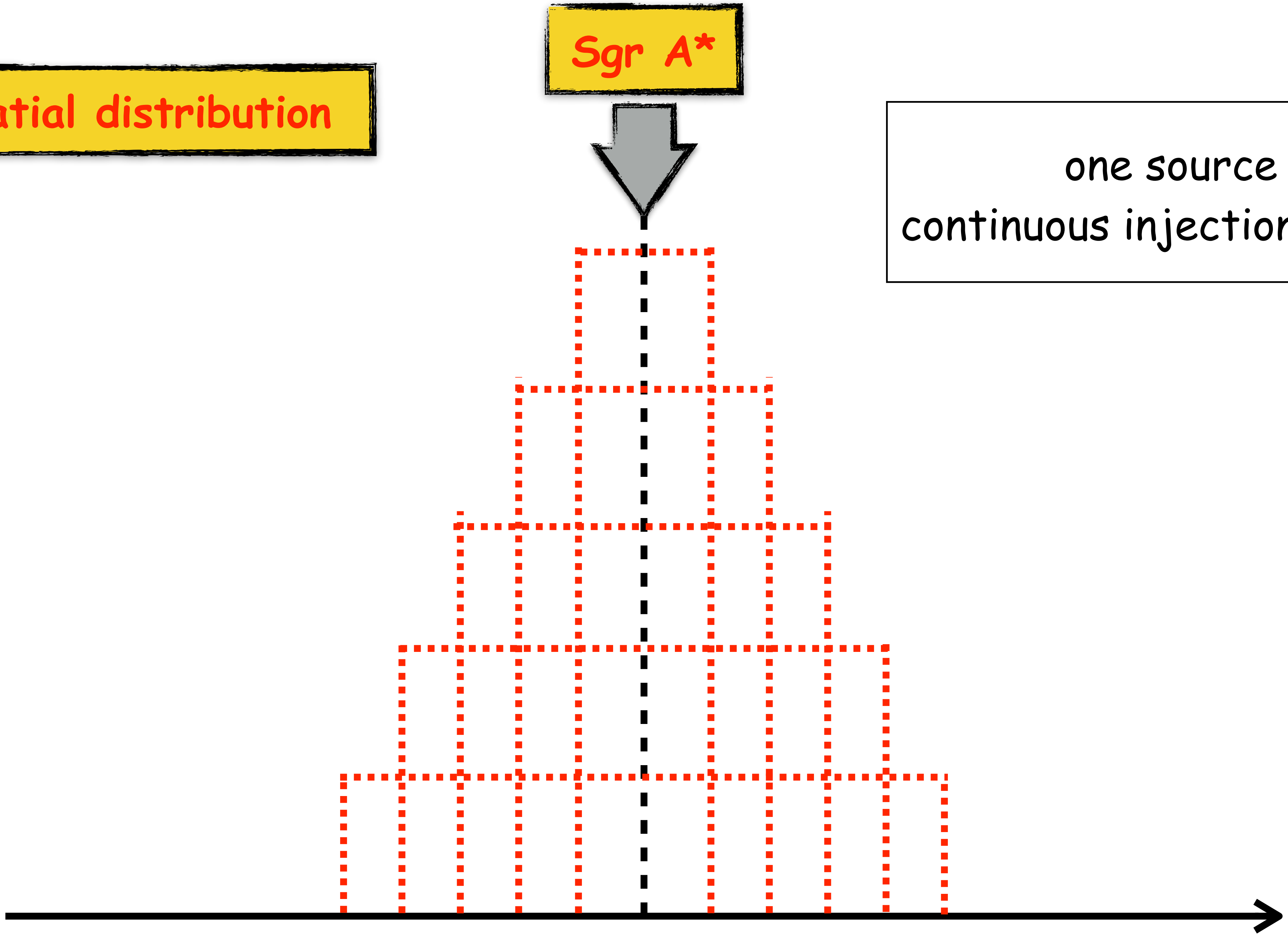


diffusion length

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

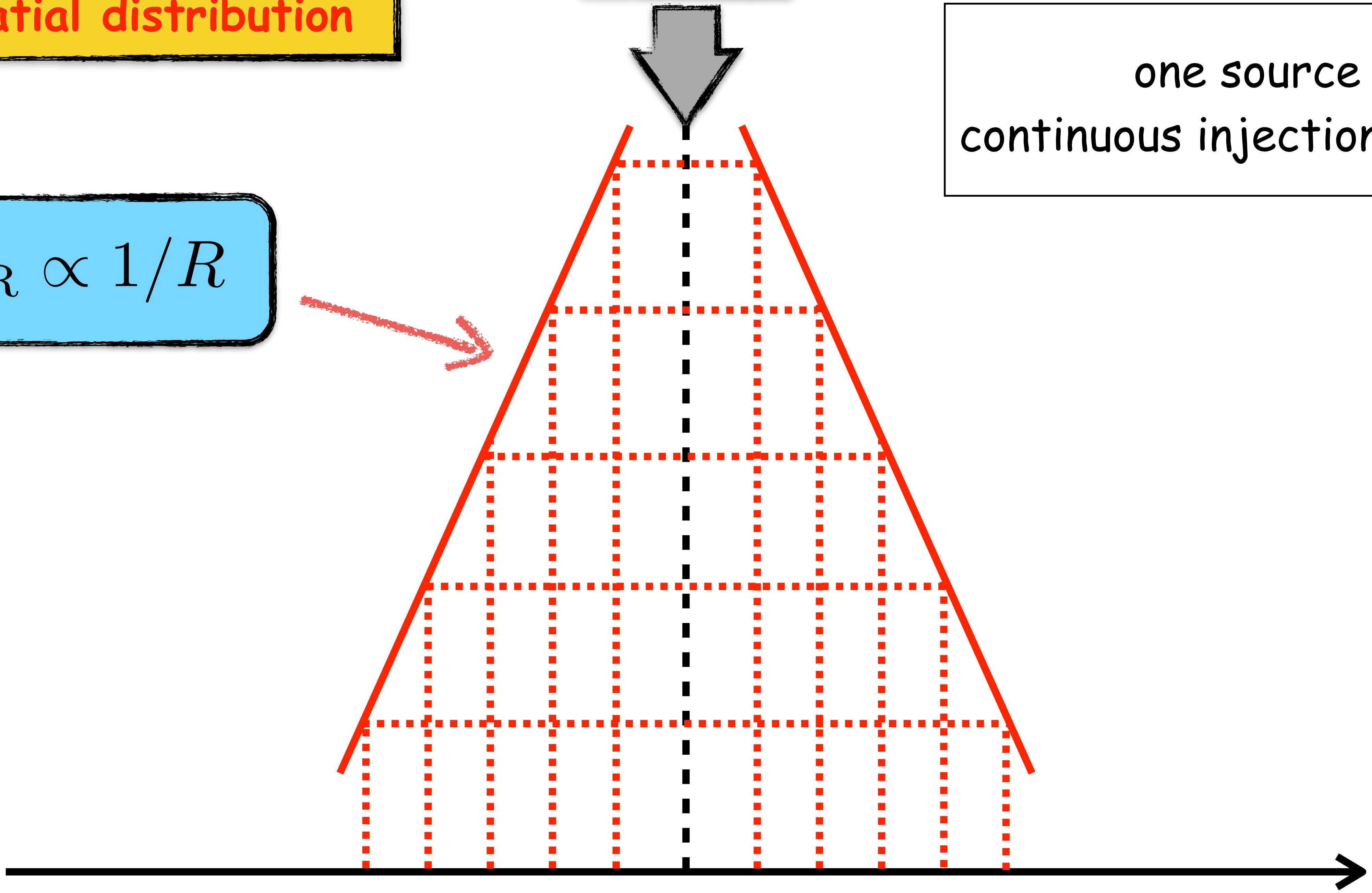
Where is the source?

CR spatial distribution



one source
continuous injection of CRs

Where is the source?



Sgr A*

CR spatial distribution

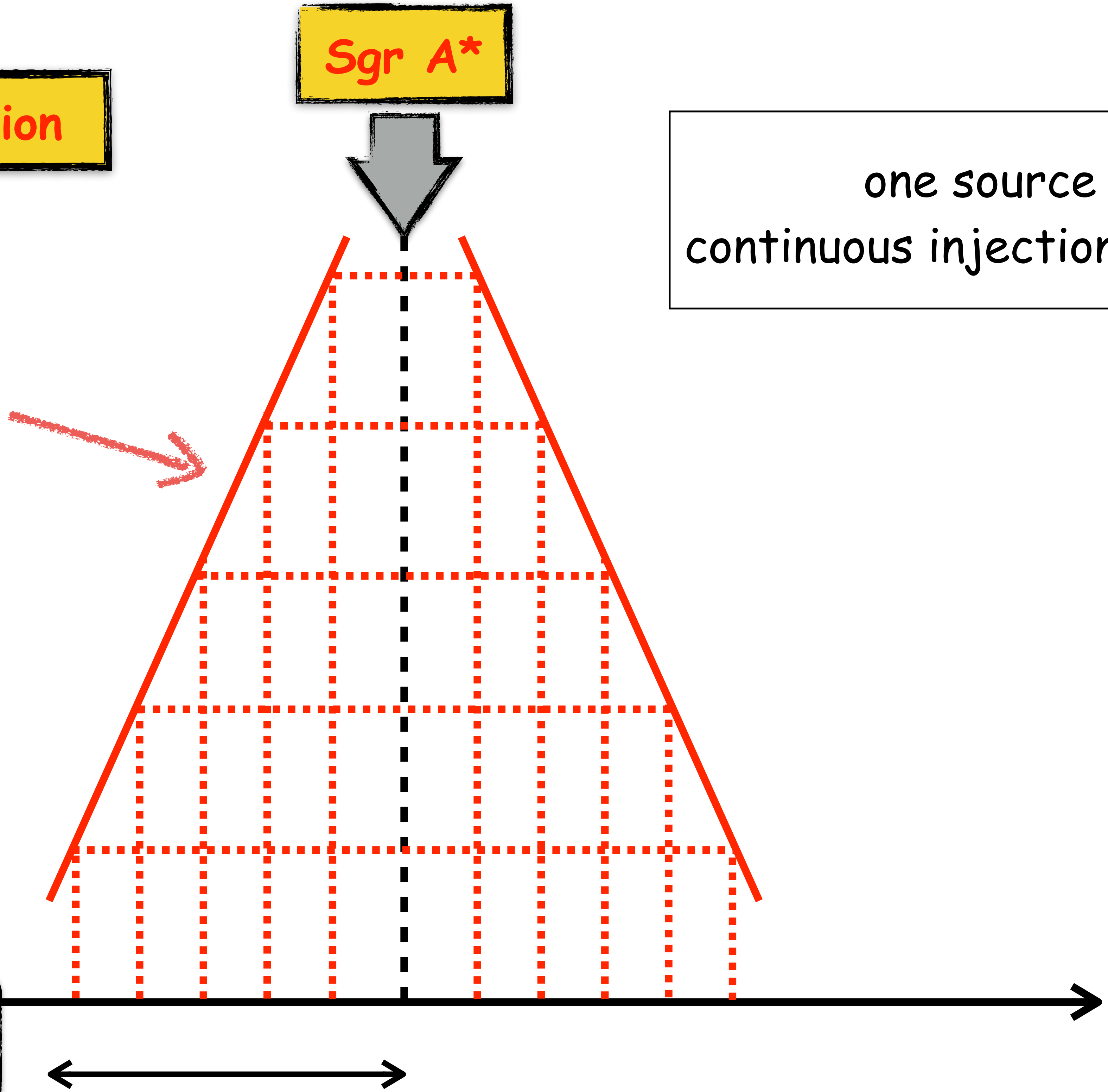
$$n_{\rm CR} \propto 1/R$$

one source

continuous injection of CRs

Where is the source?

CR spatial distribution

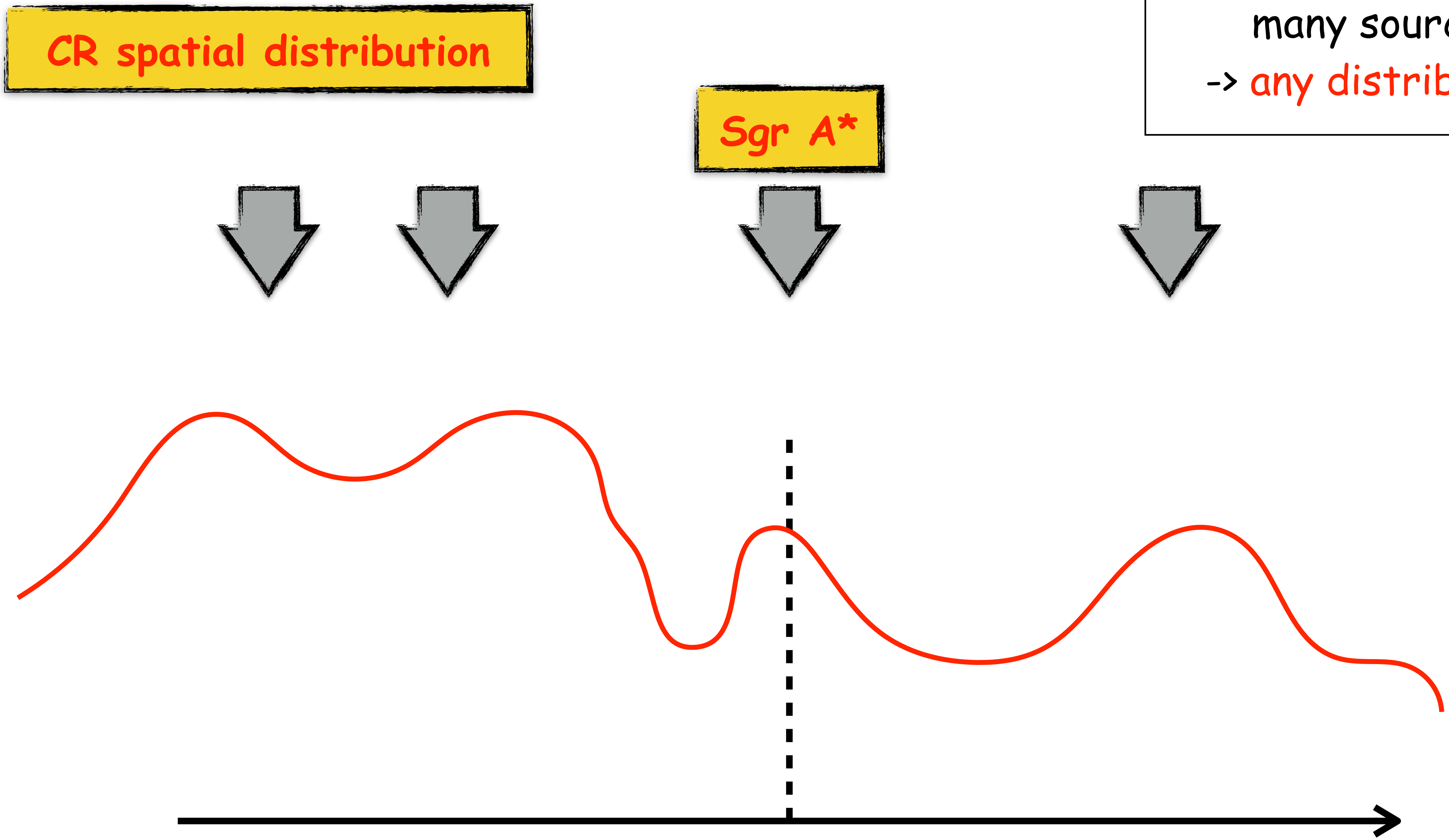


one source
continuous injection of CRs

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

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

Where is the source?



CR spatial distribution

Sgr A*

many sources
-> any distribution

The source is at the GC

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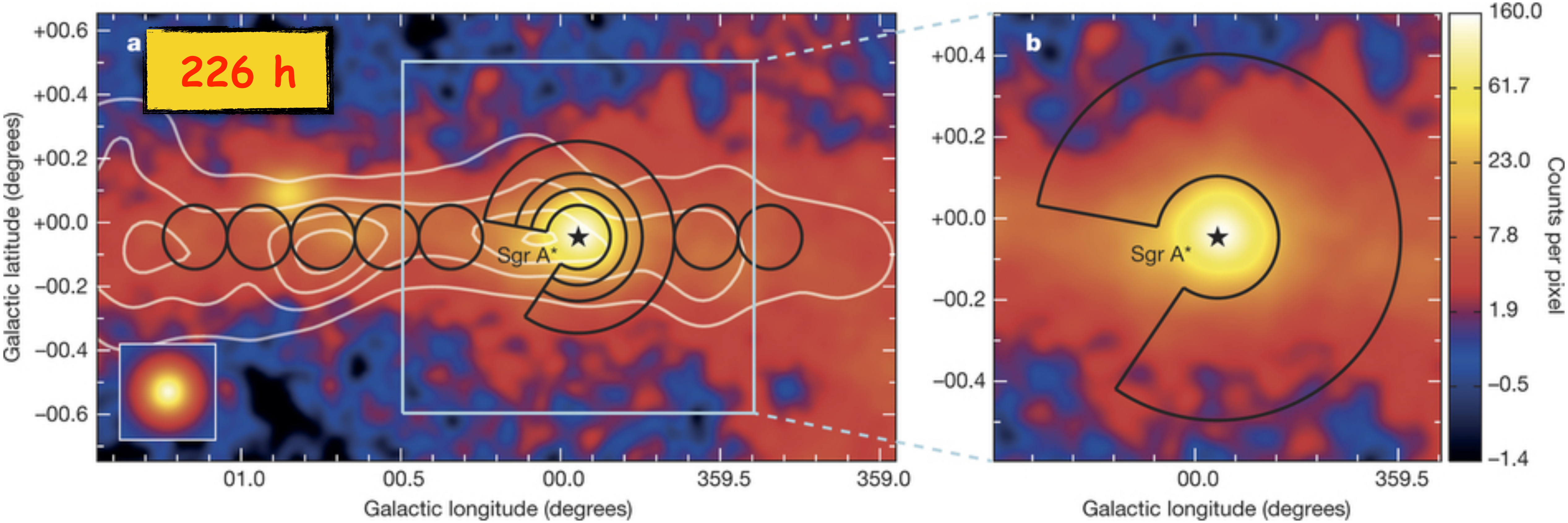

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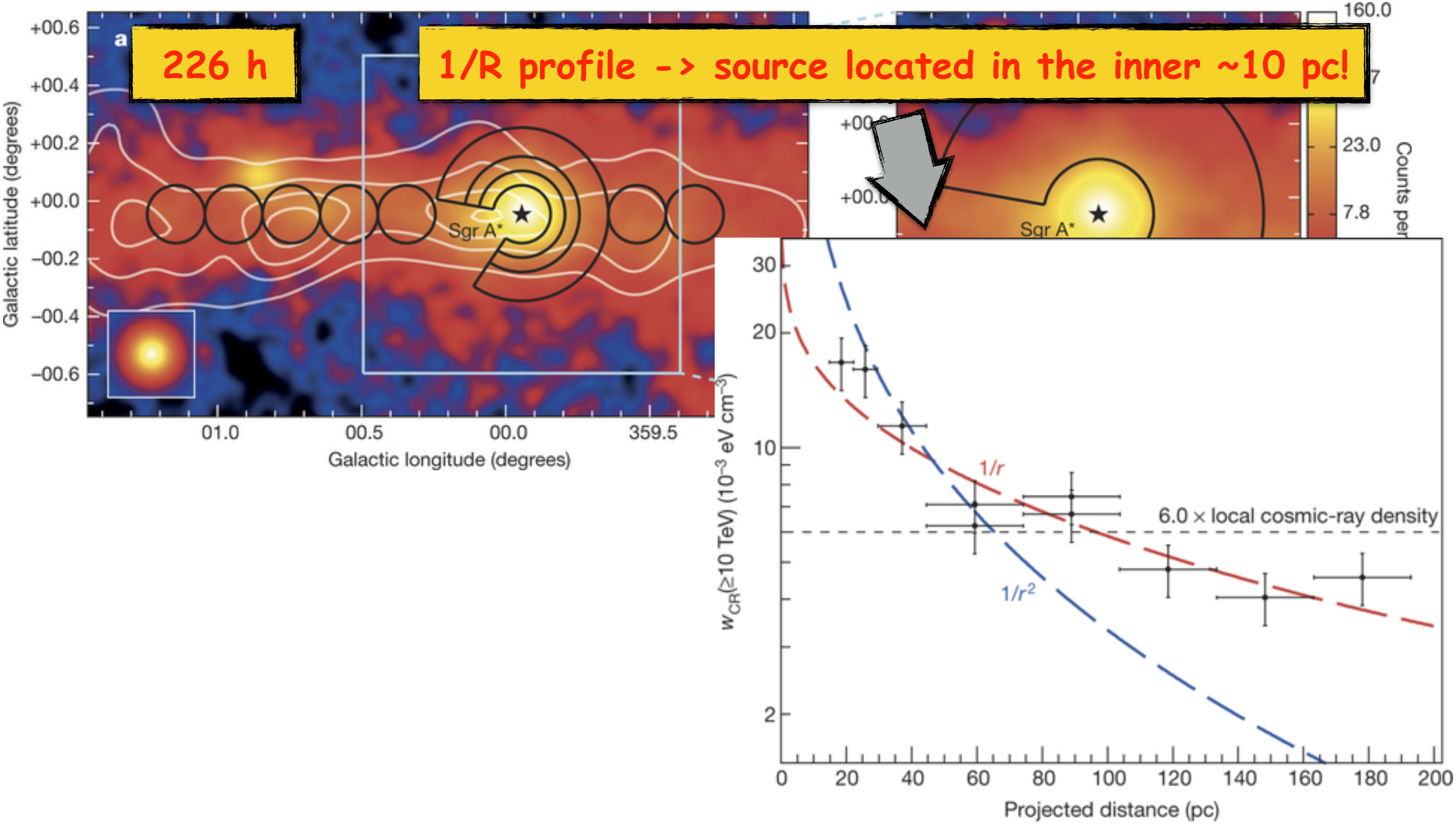
H.E.S.S. Coll. 2016



226 h

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

The source is at the GC

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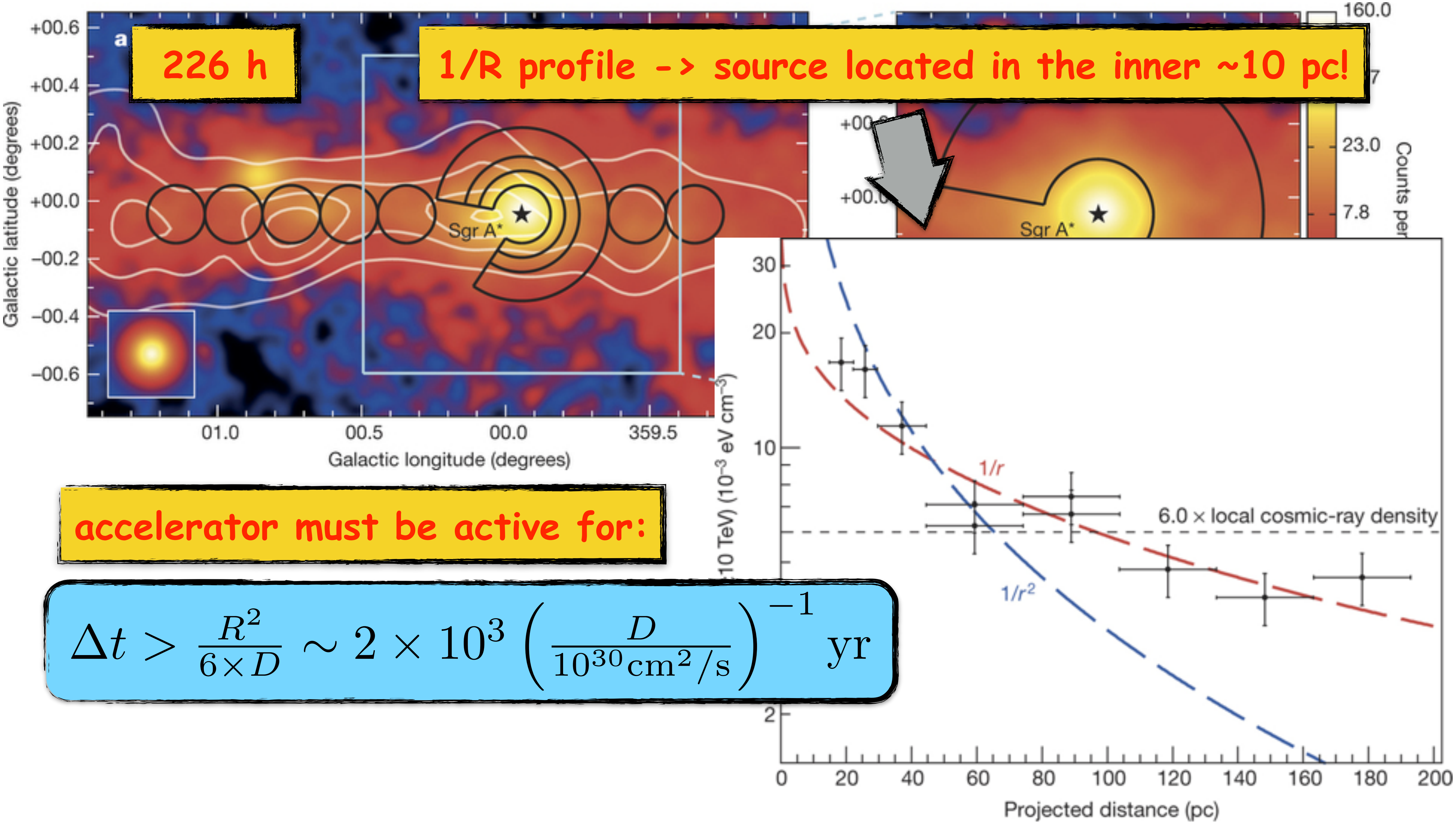


226 h

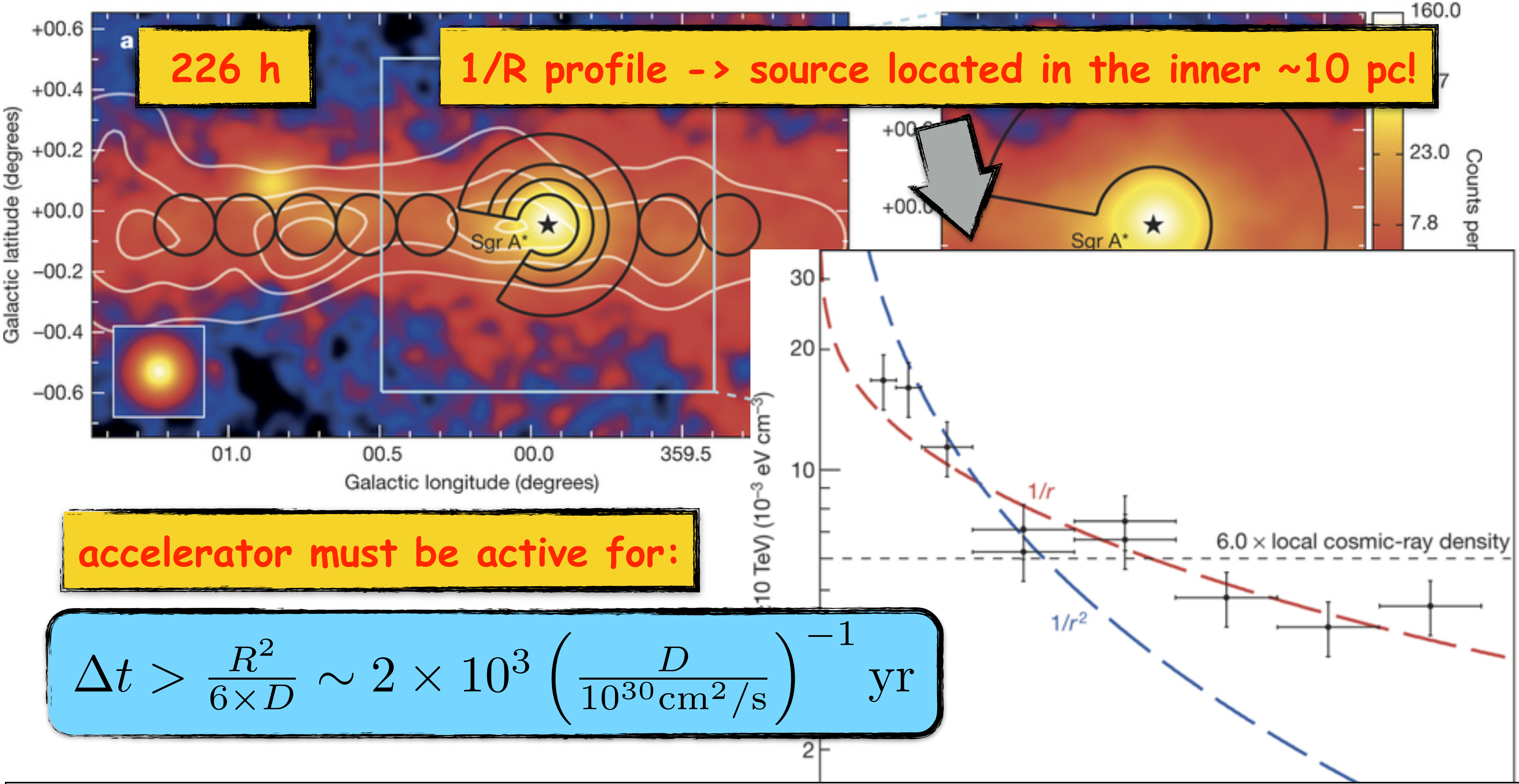
1/R profile -> source located in the inner ~10 pc!

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



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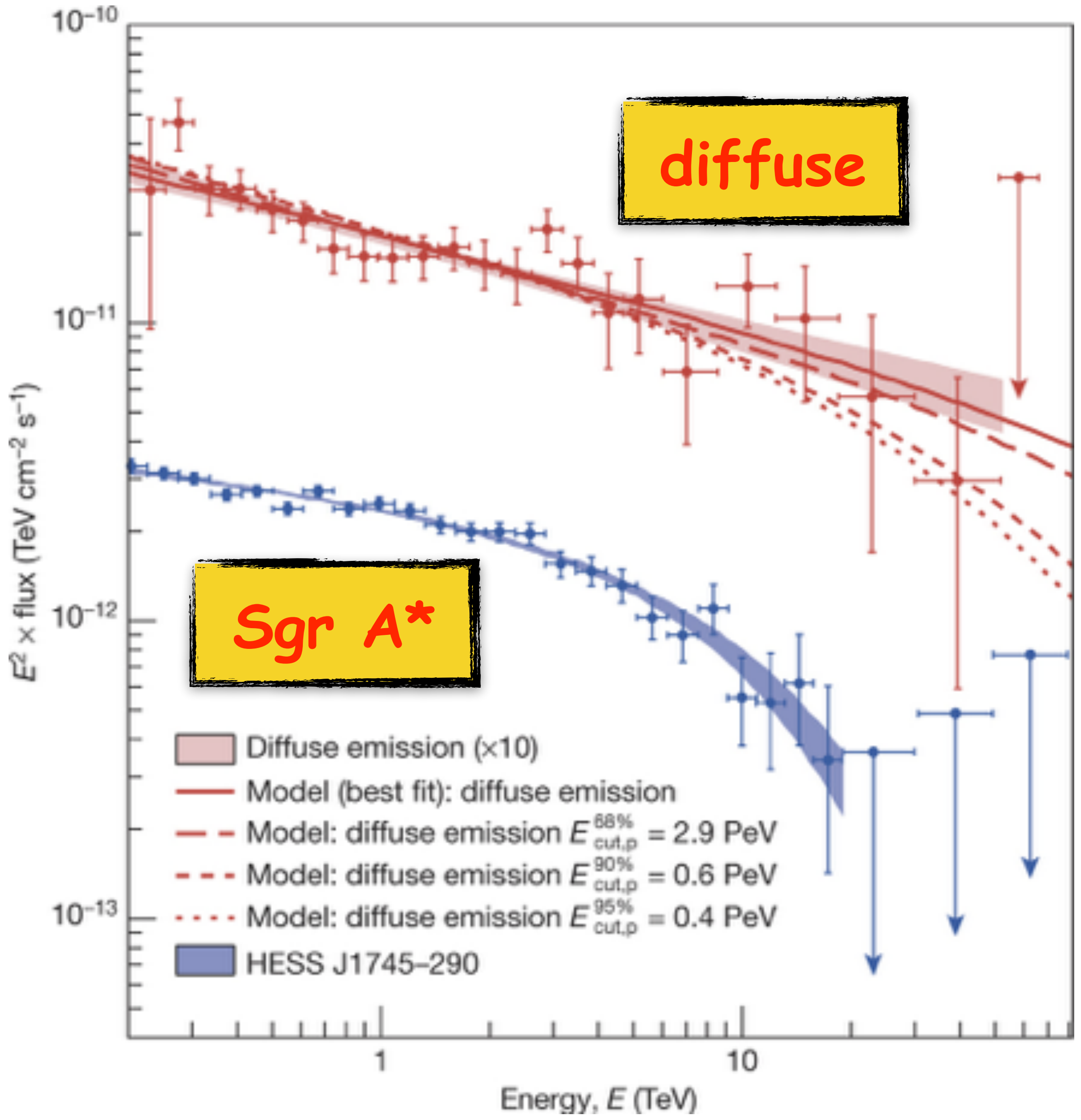
$$\Delta t > \frac{R^2}{6\times D} \sim 2\times 10^3 \left(\frac{D}{10^{30}\mathrm{cm}^2/\mathrm{s}}\right)^{-1} \mathrm{yr}$$

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



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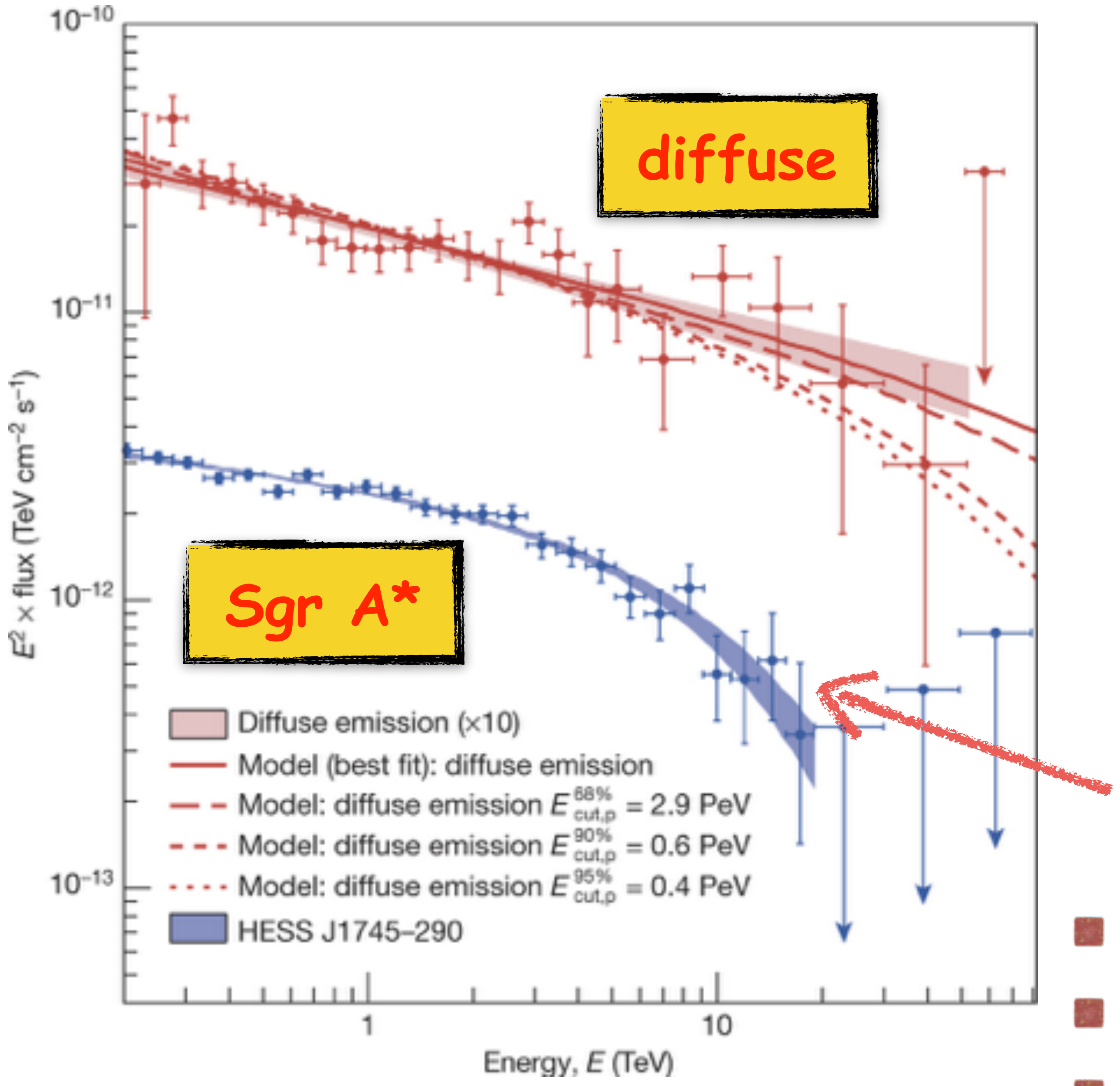

~10 TeV cutoff -> inconsistency? no…

- emission could be unrelated
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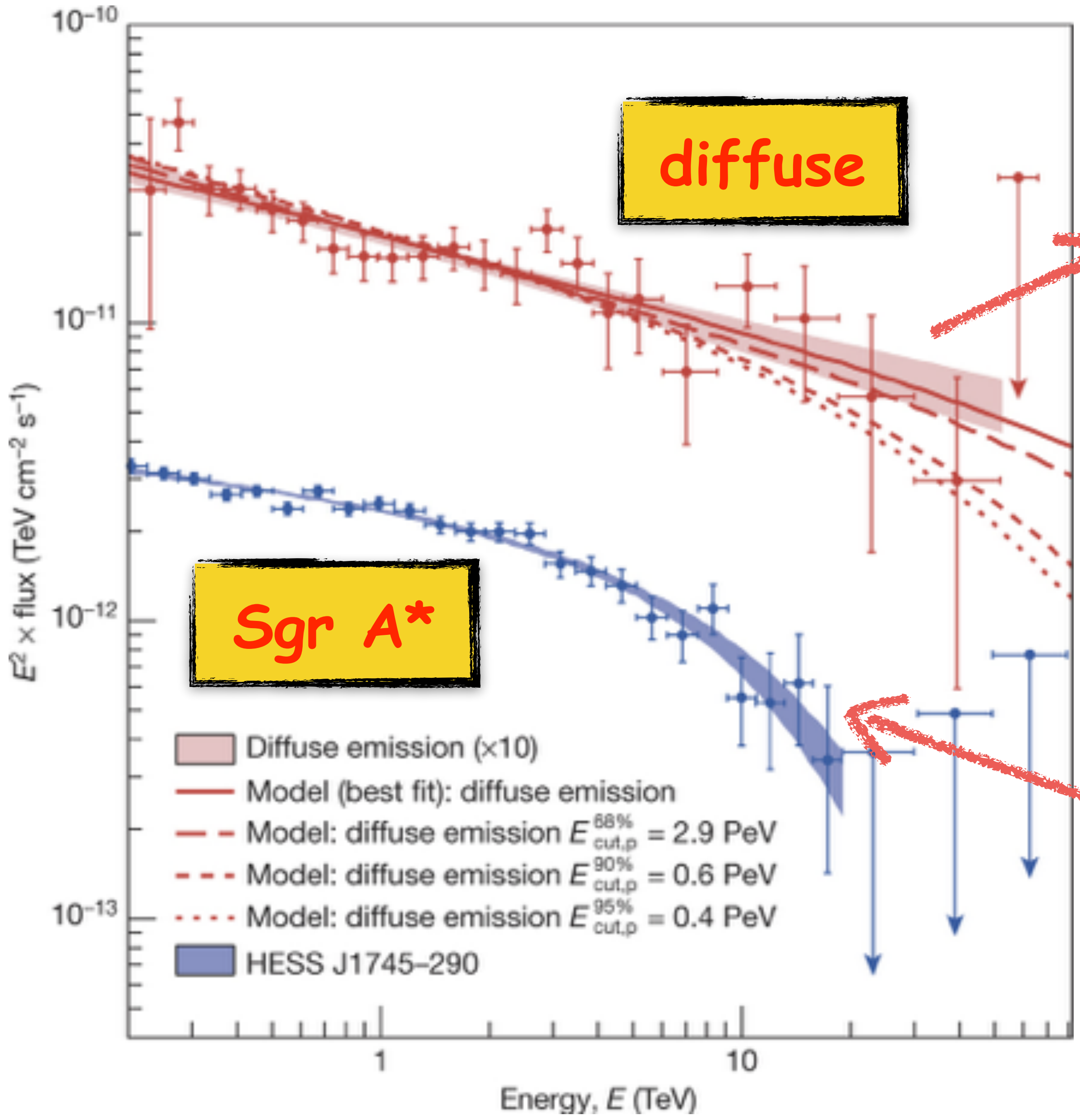

gas mass

$$W_p \sim 10^{49} \mathrm{erg}$$

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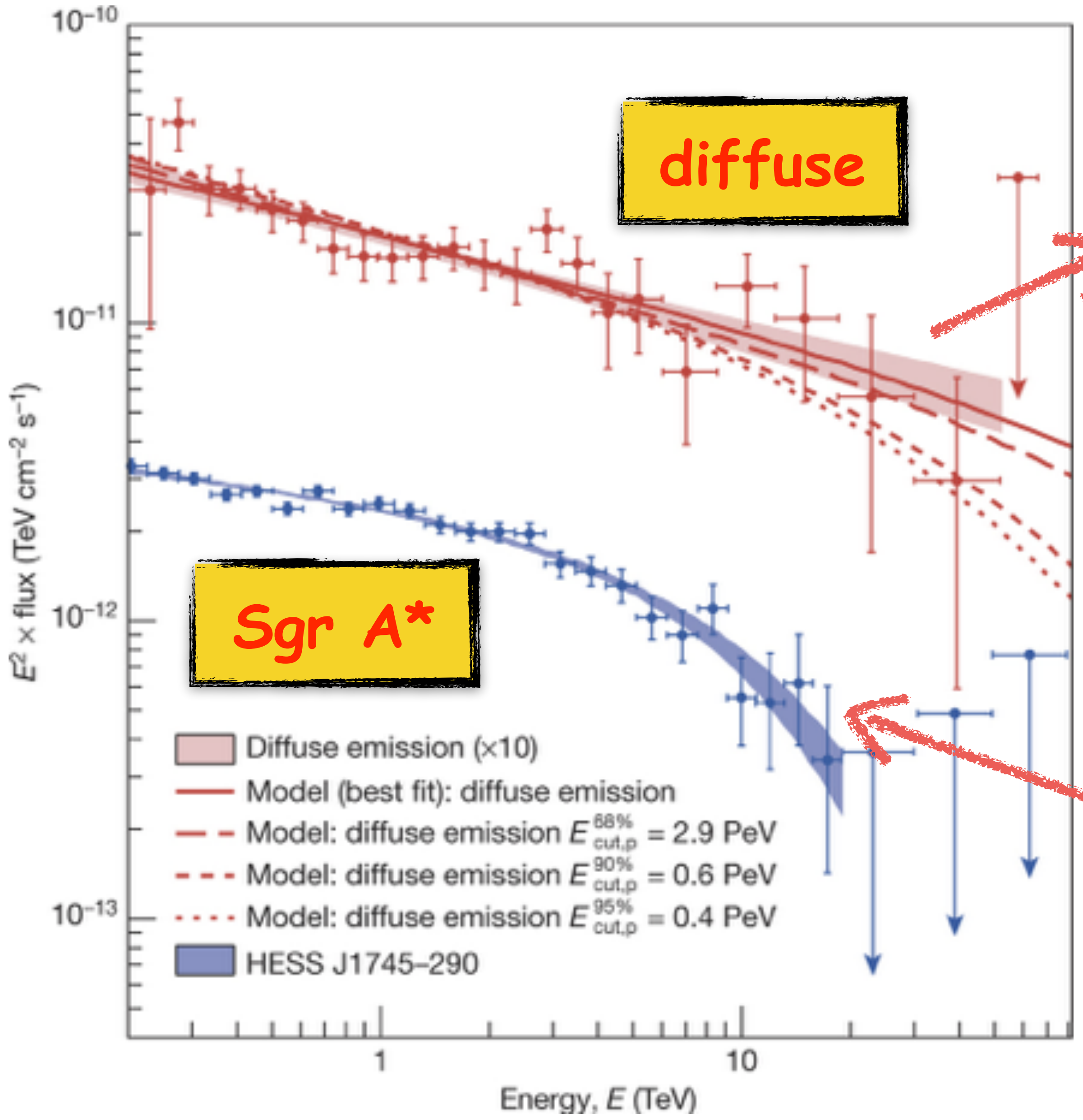

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1/R profile

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

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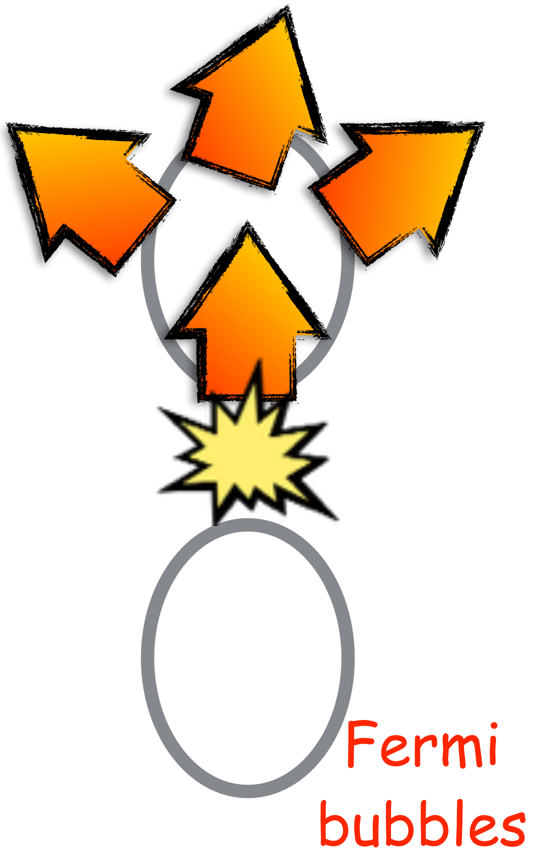
speculations

BH activity, cosmic rays, neutrinos

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



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

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for ~10^6-10^7 yrs

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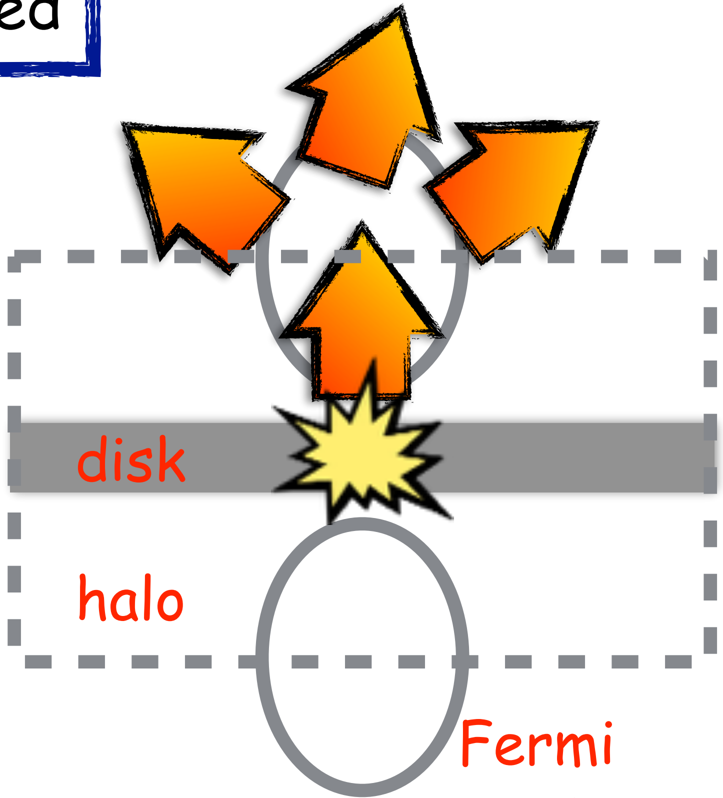

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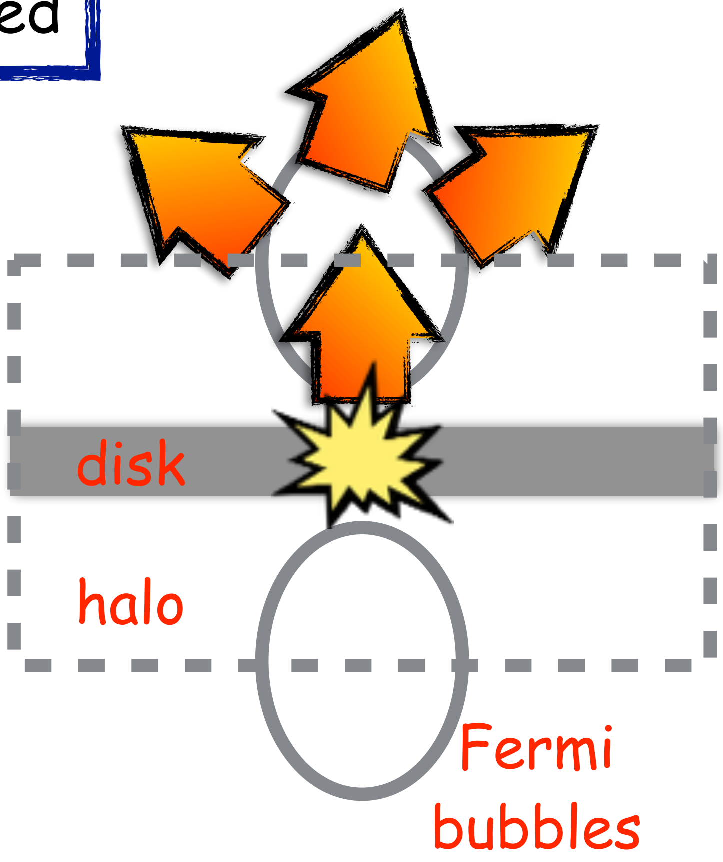

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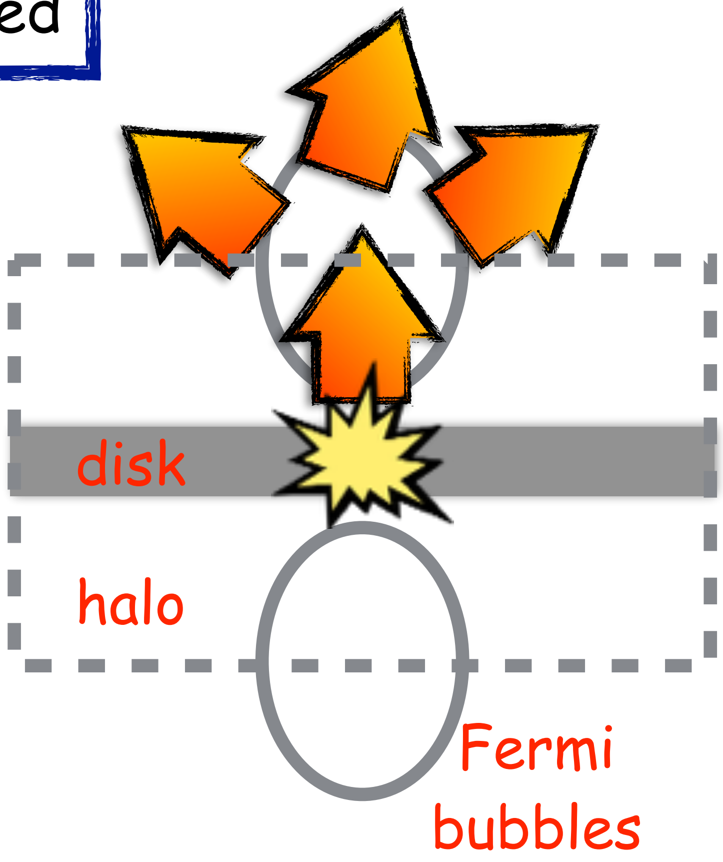

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Taylor, SG, Aharonian 2014

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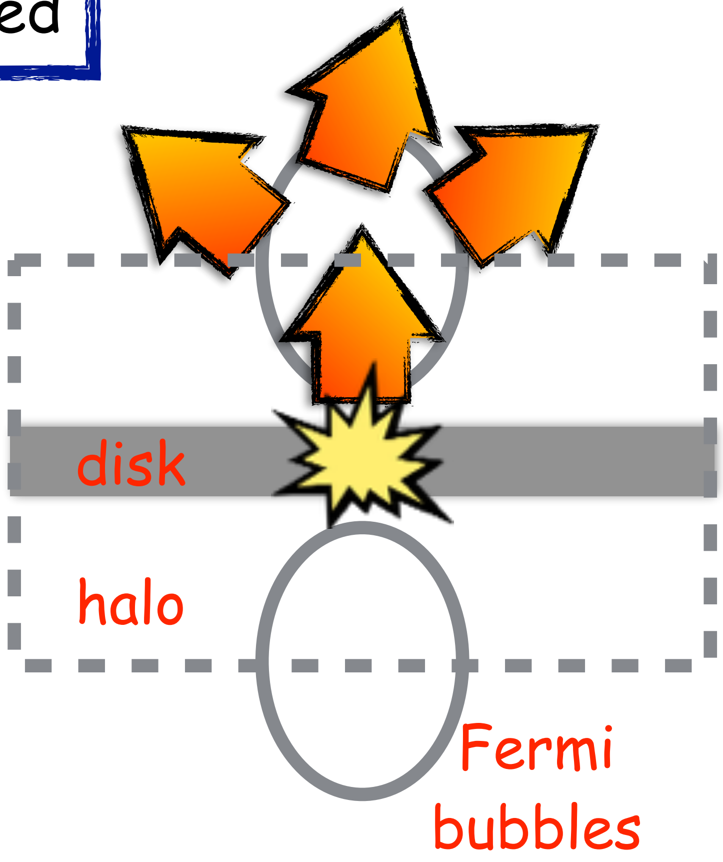

CR bursts from GC
Ptuskin & Khazan (1981)
see also Fujita+ 2016
CR in Gal. breeze
Taylor & Giacinti 2016

IceCube neutrinos

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Conclusions

- first detection of a proton PeVatron in our Galaxy!
- the first PeVatron detected is not, as one might have expected, a SNR, but it is the Galactic Centre
- plausible accelerator: SMBH
- if it was more active in the past, the SMBH might compete with SNRs as a dominant source of galactic CRs
- might also account for the isotropic flux of neutrinos recently detected by IceCube