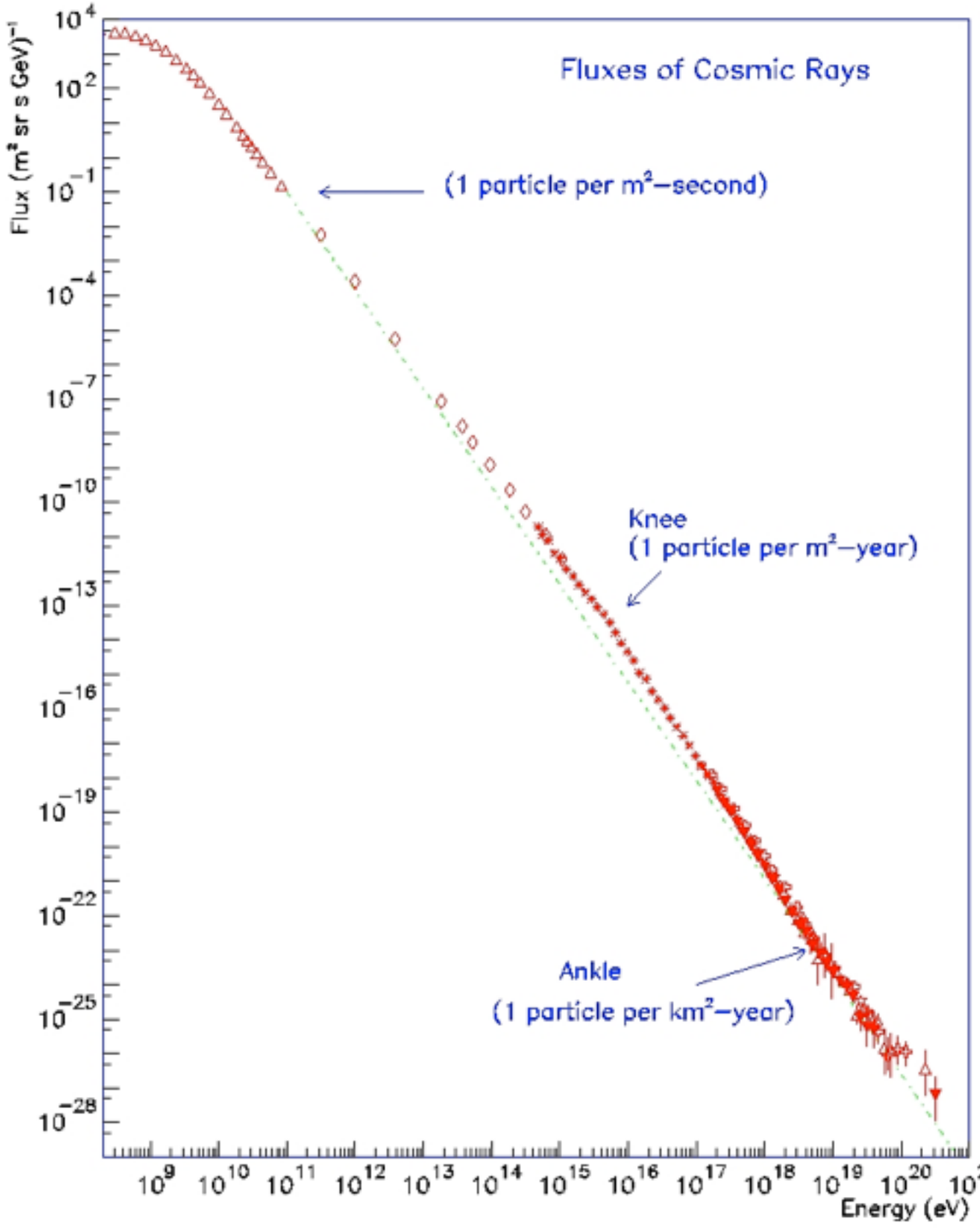
The origin of Cosmic Rays*

Stefano Gabici
APC, Paris

* biased view of a gamma-ray astronomer

The Cosmic Ray spectrum



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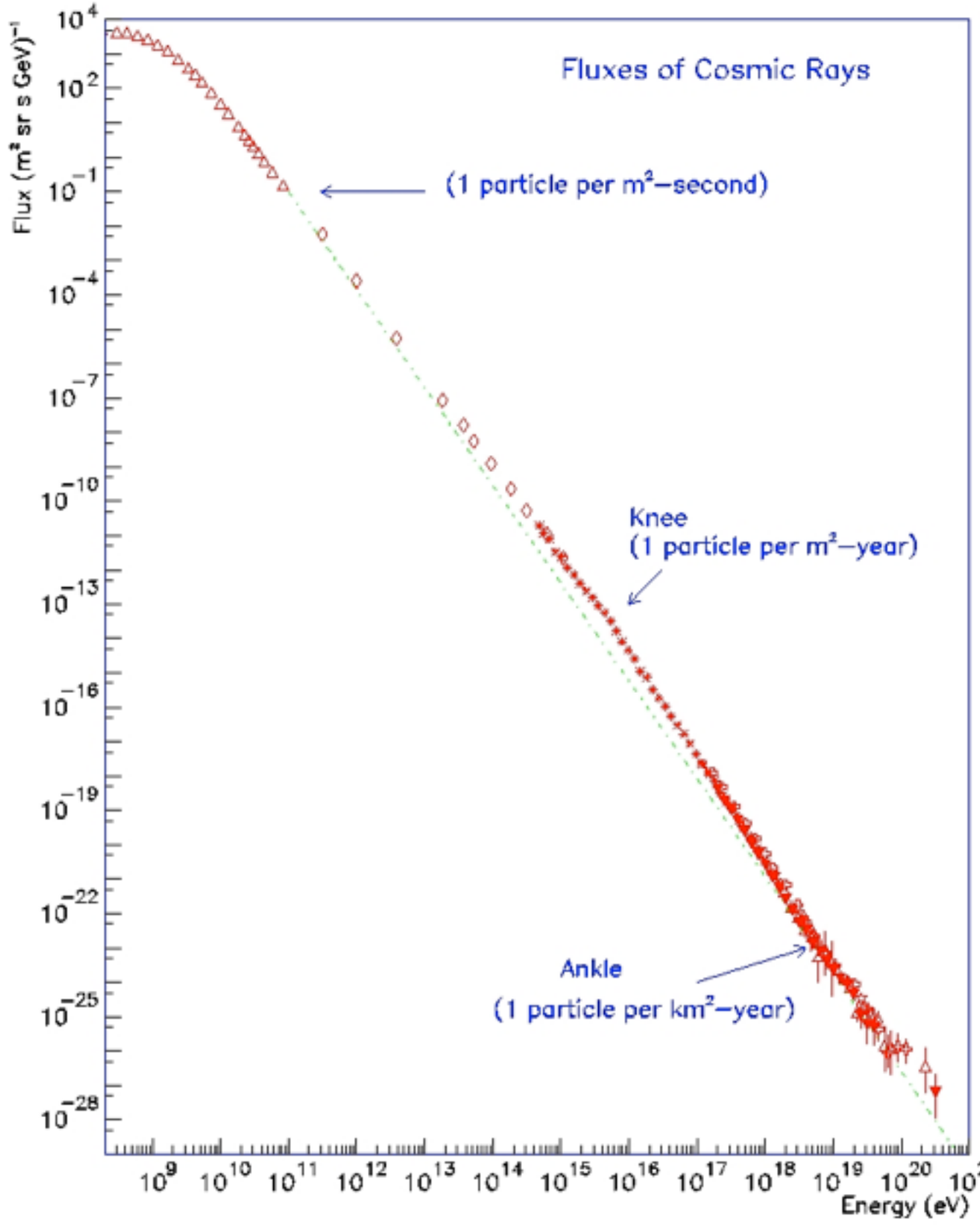
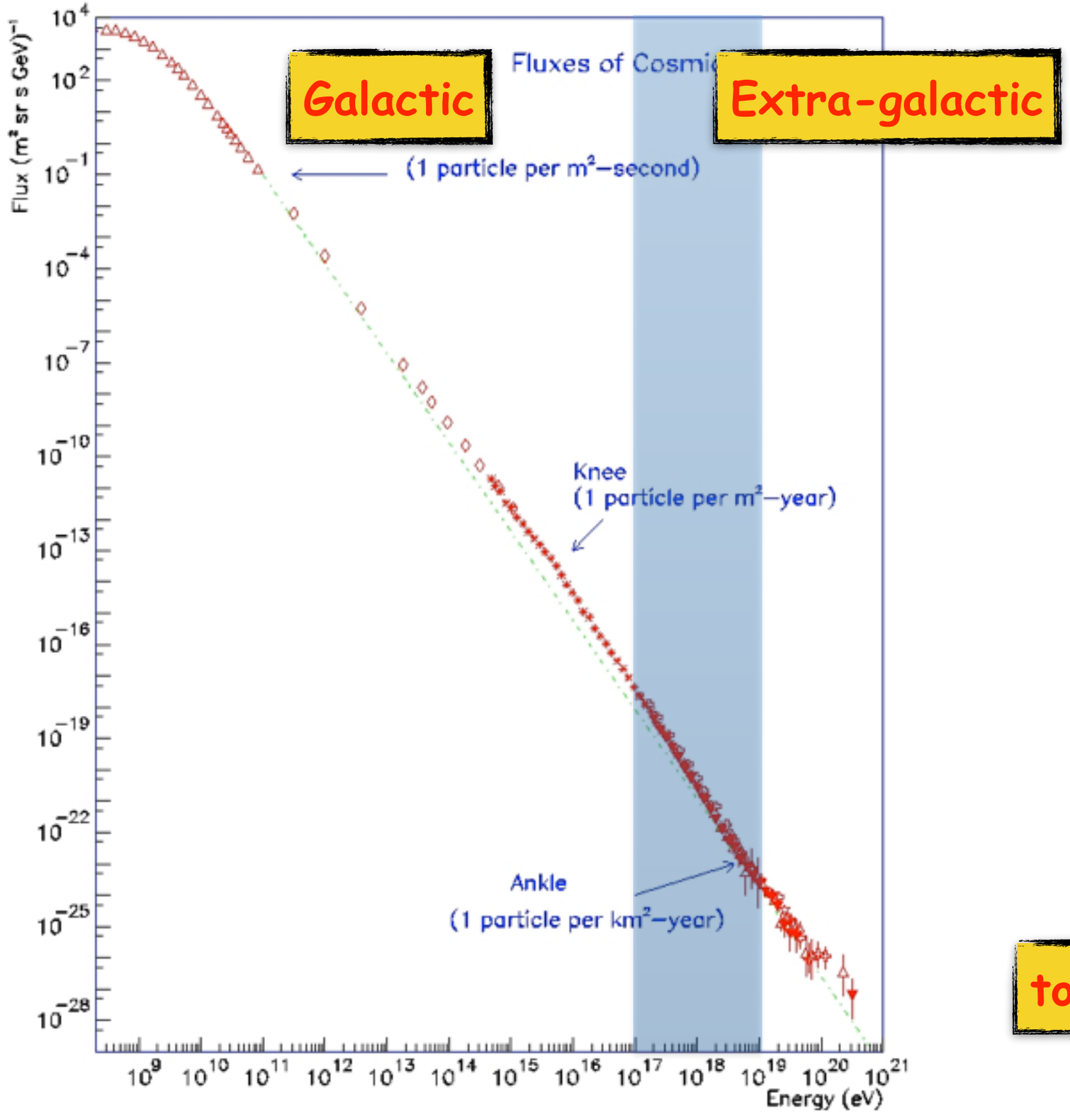


from sub-GeV

to ~EeV

The Cosmic Ray spectrum



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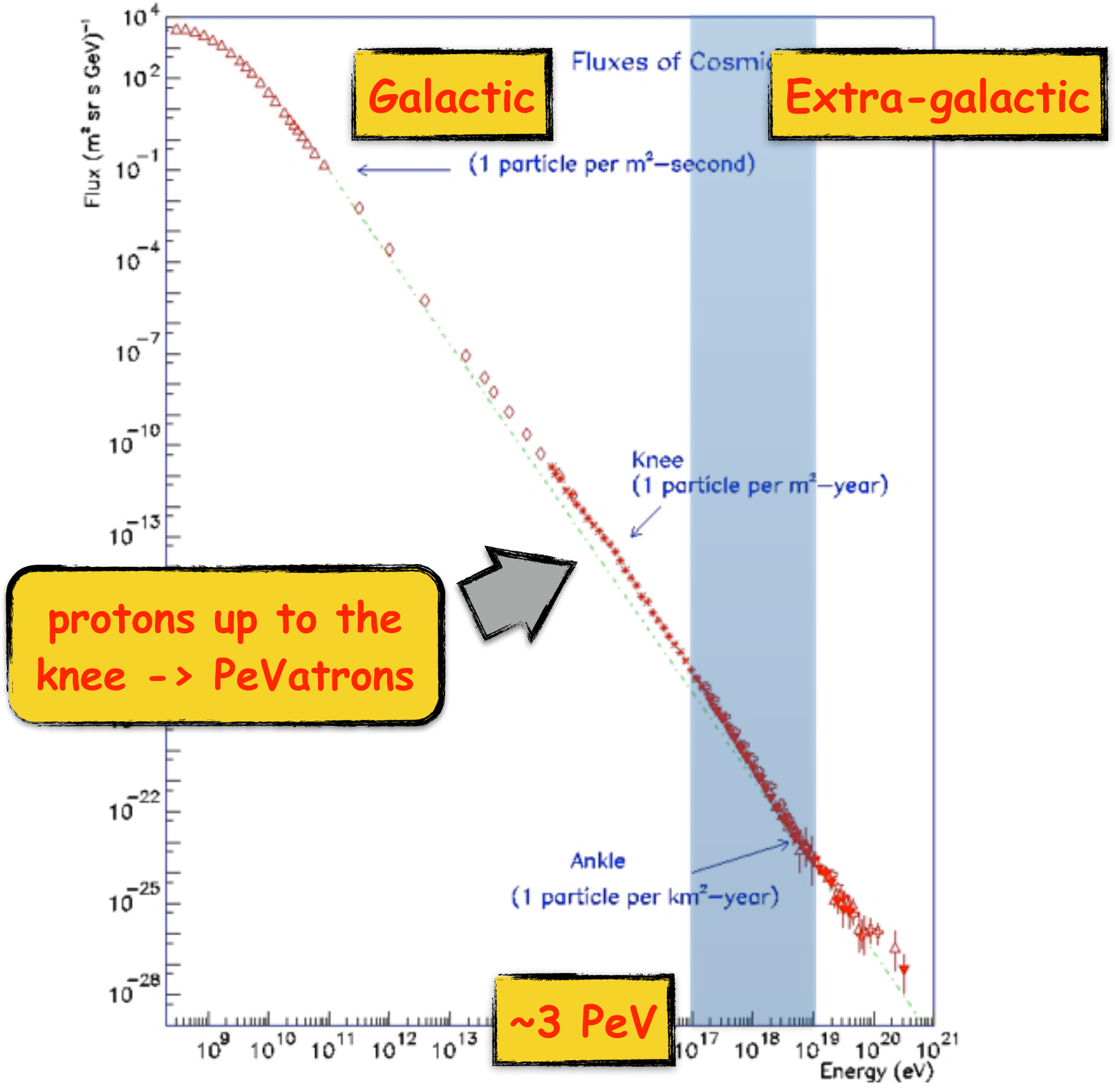

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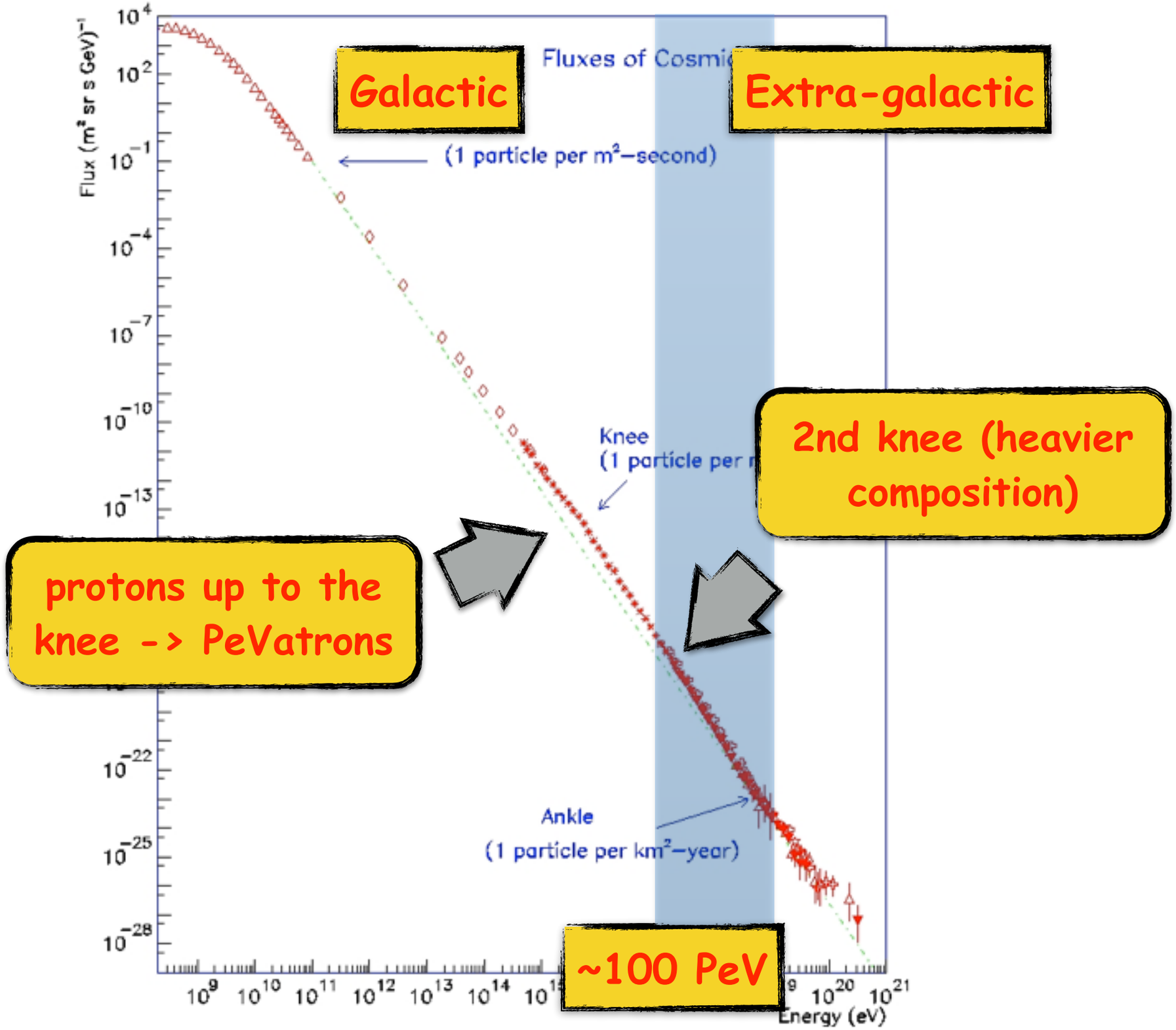

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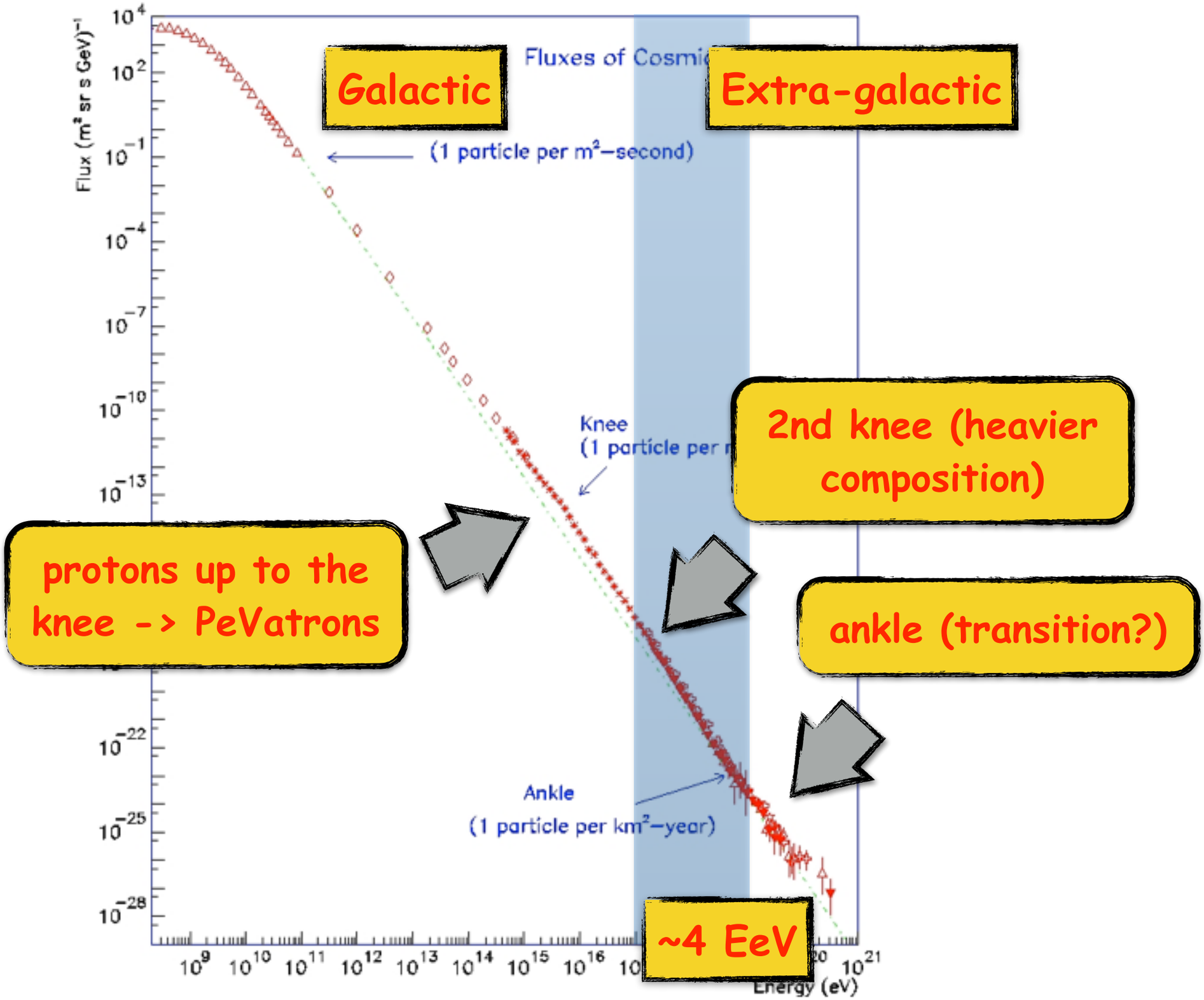

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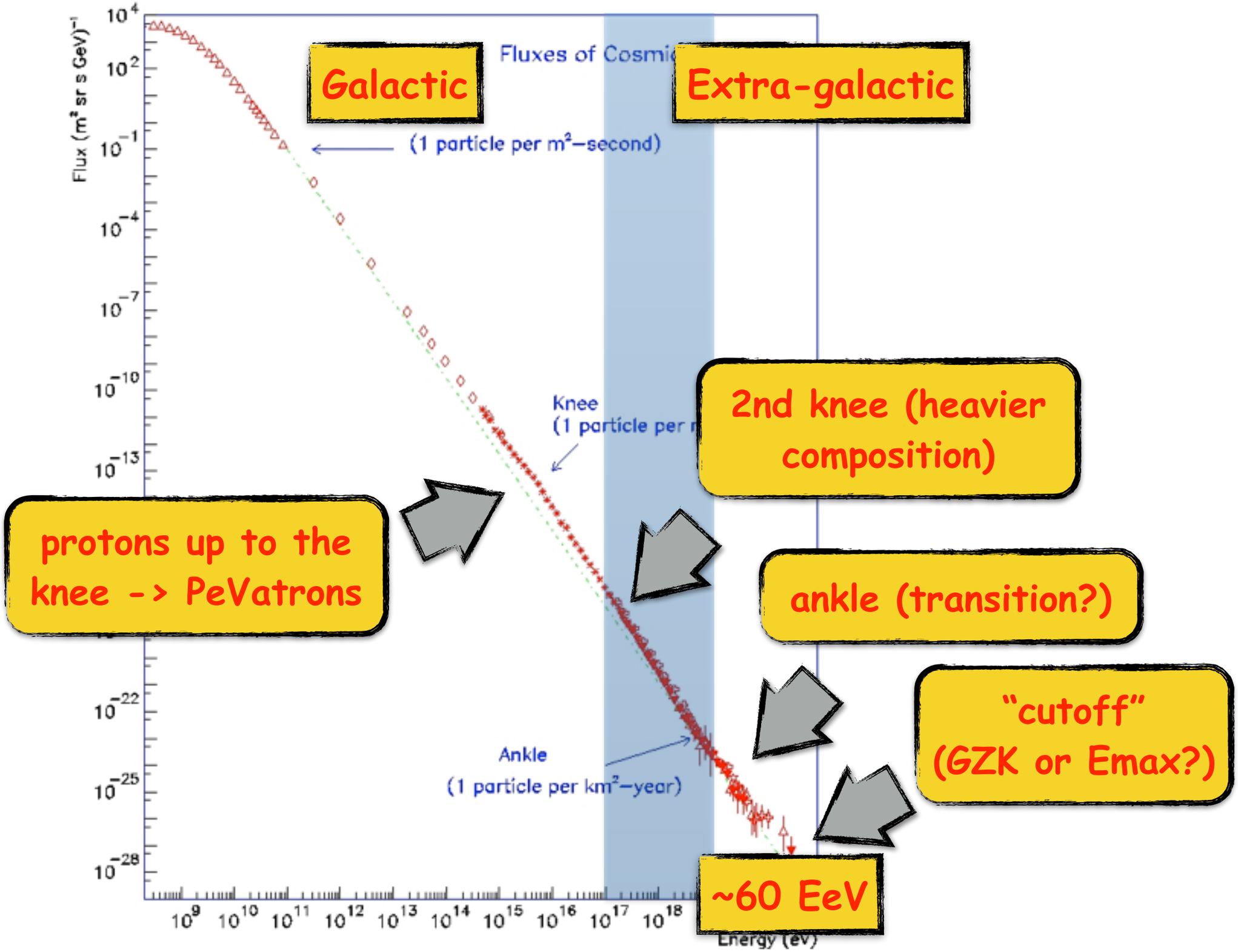

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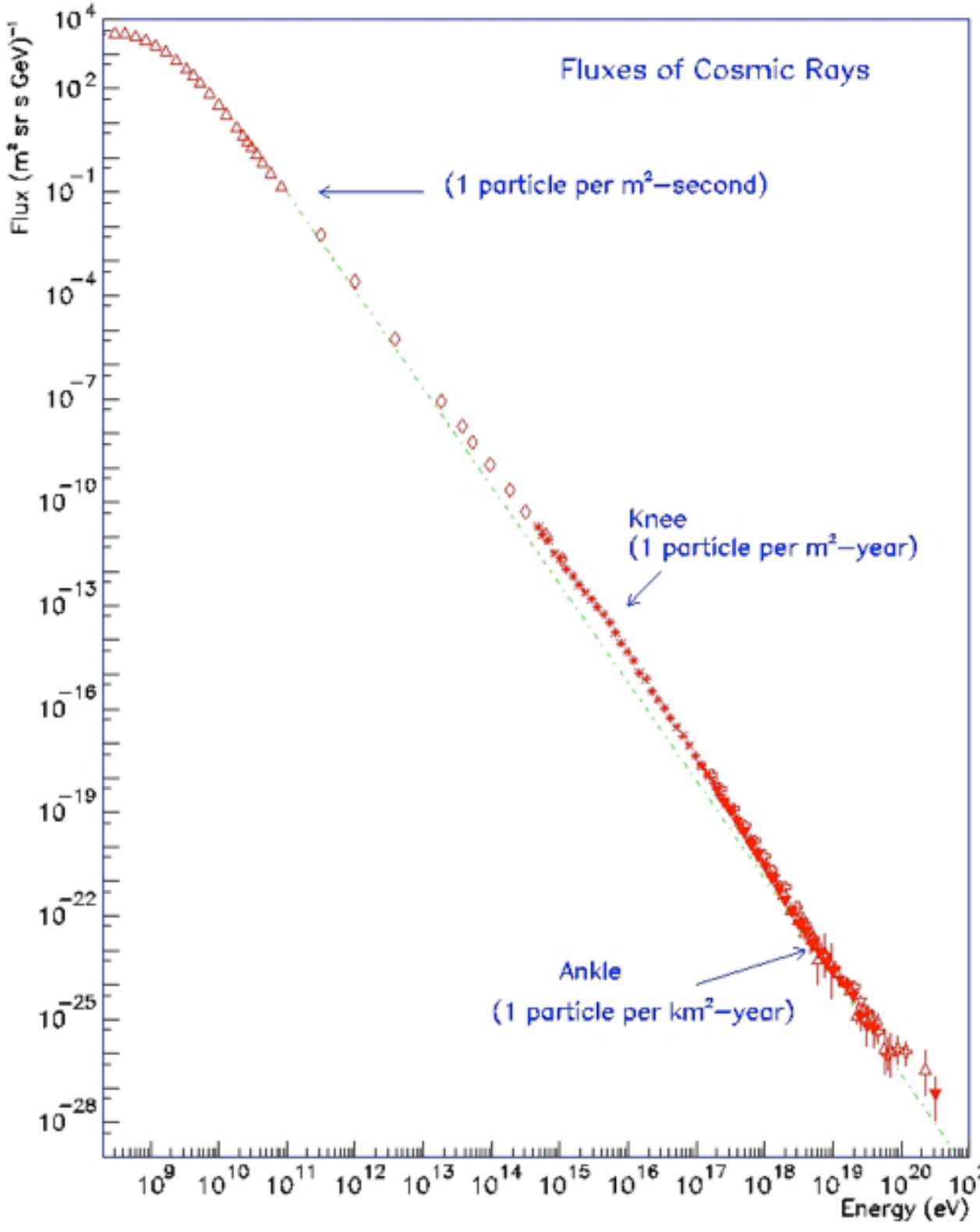

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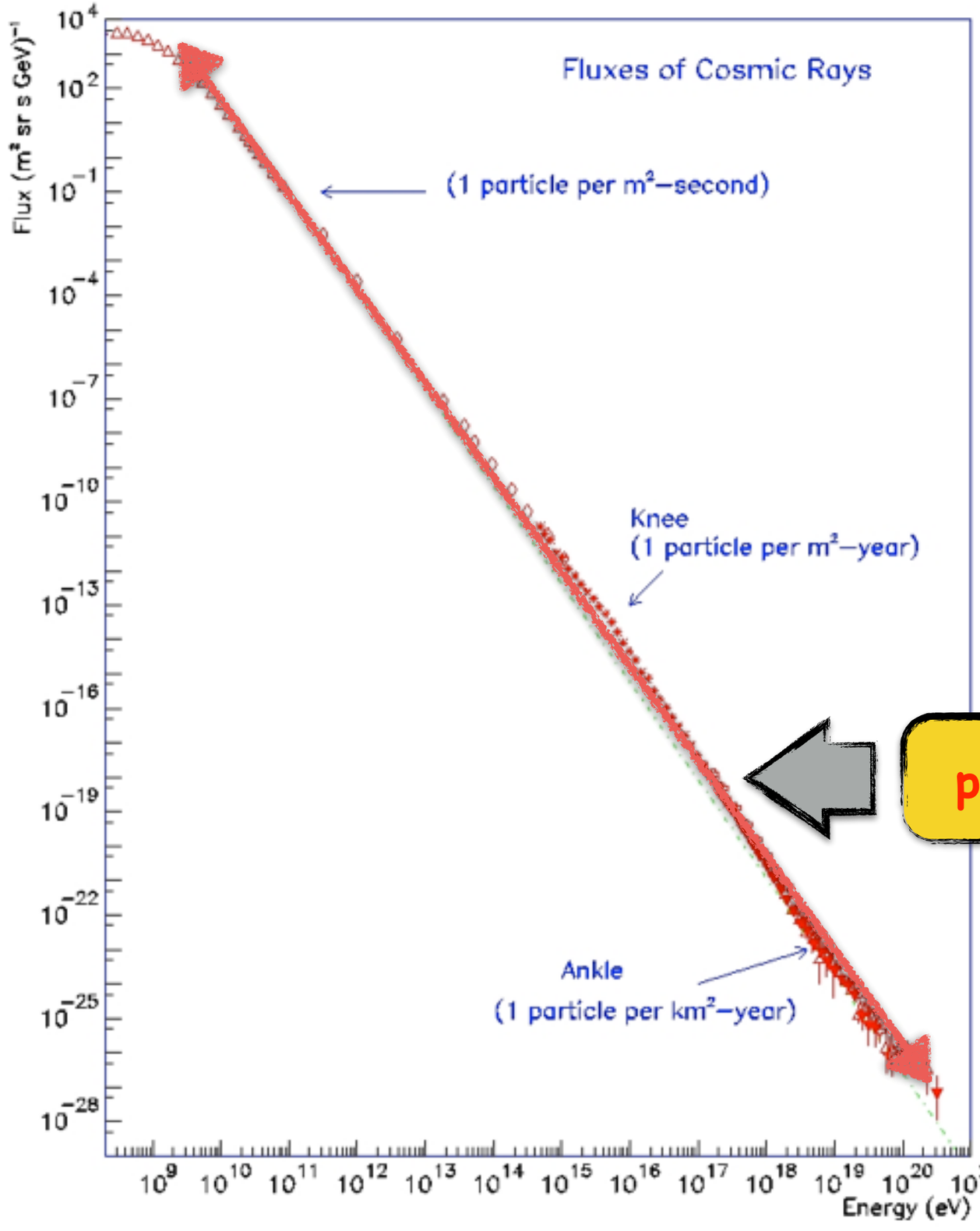

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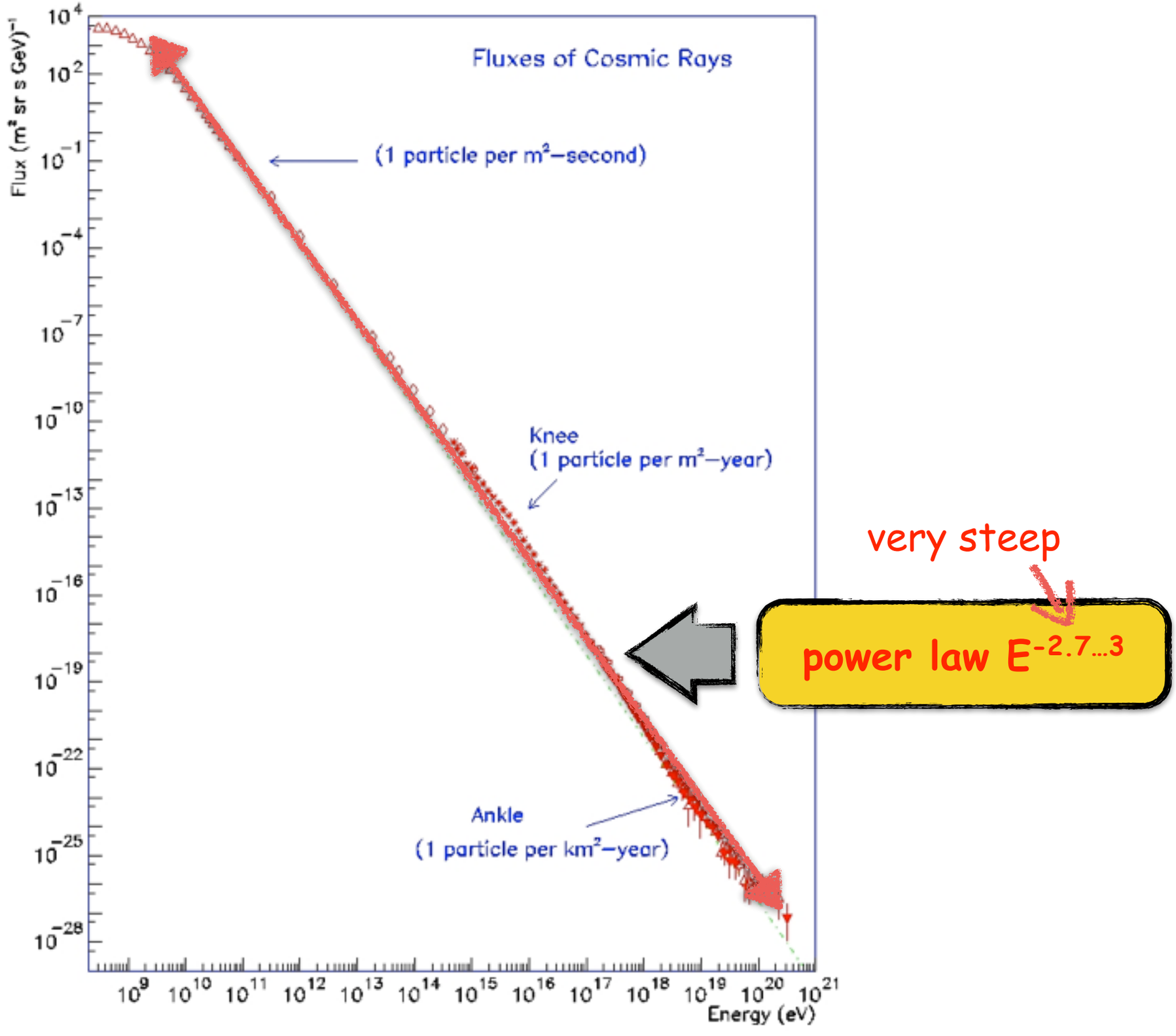
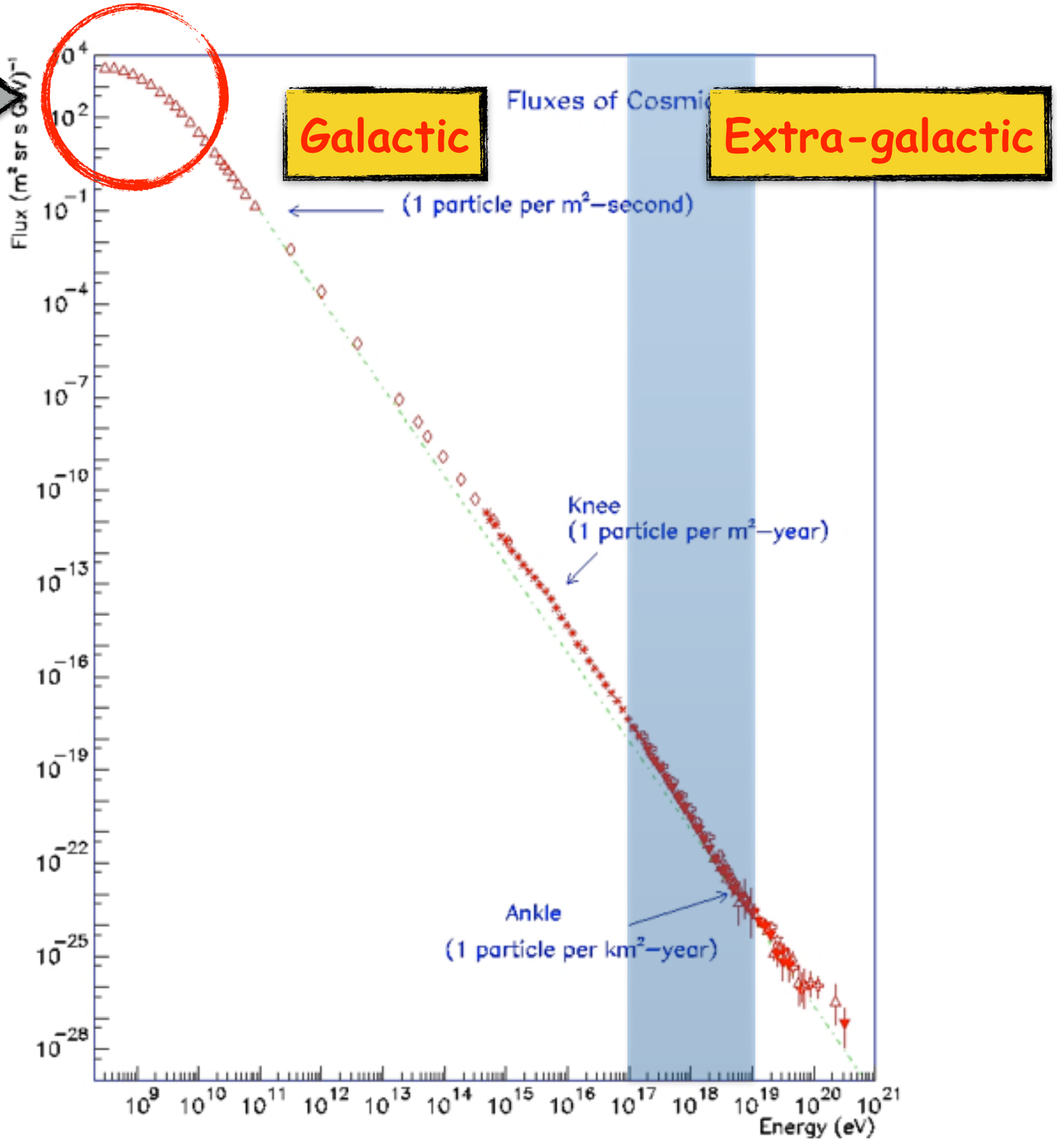


The origin of CRs: energy requirement

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



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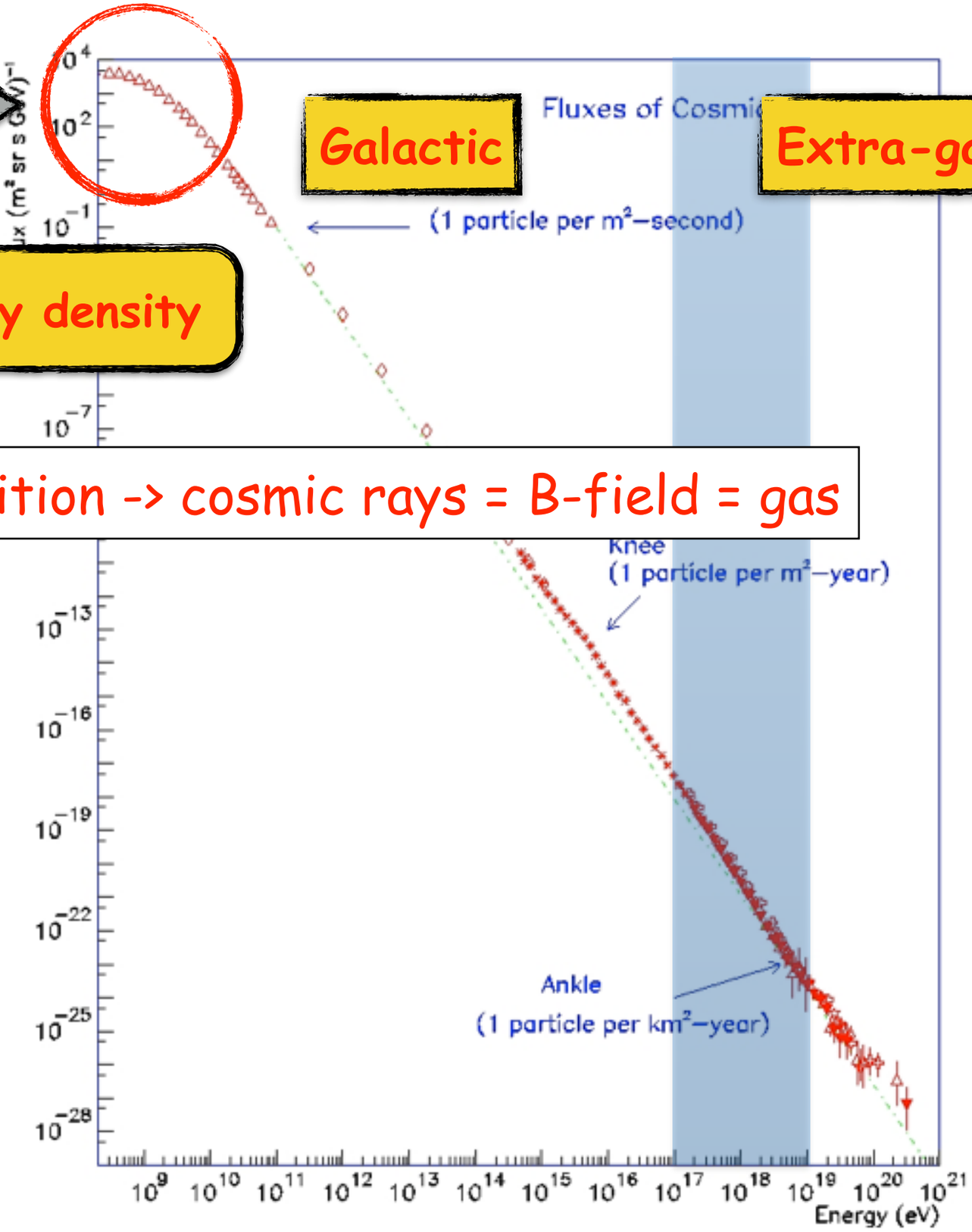
Quite large energy density



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

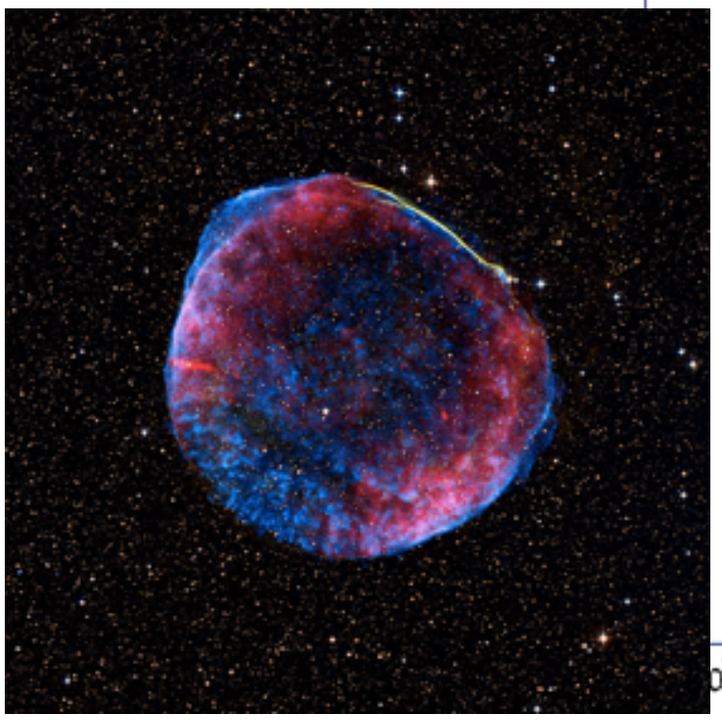
The origin of CRs: Galactic sources

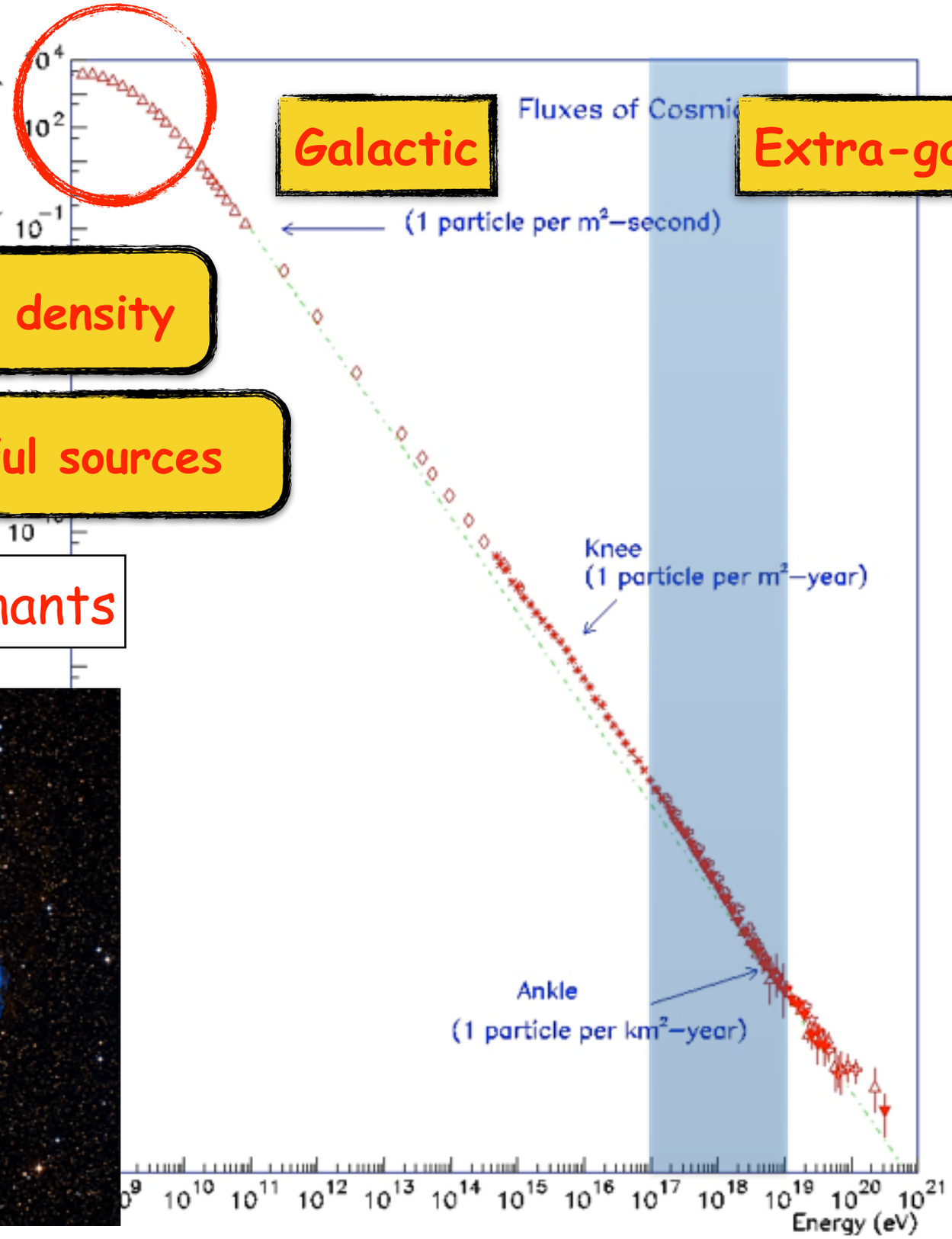
$1\ \mathrm{eV/cm^3}$

Quite large energy density

Powerful sources

SuperNova Remnants





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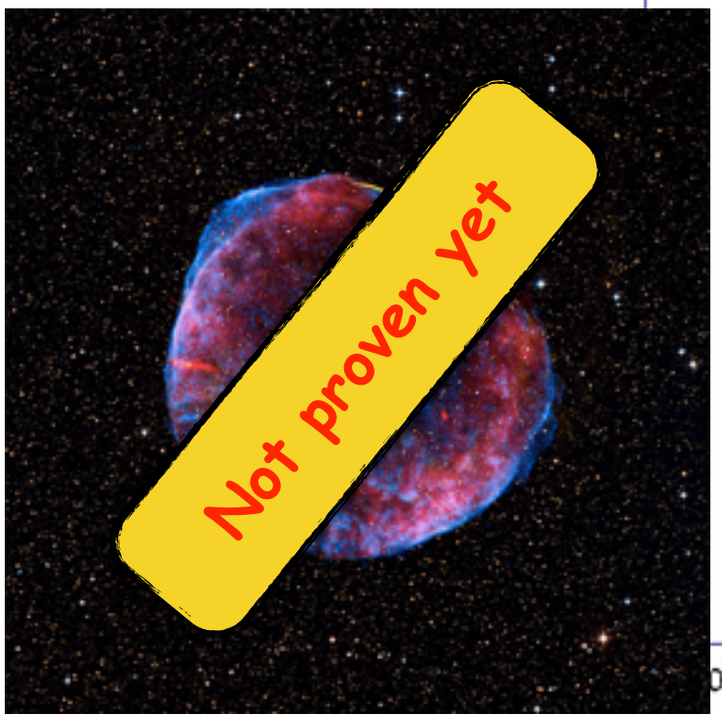

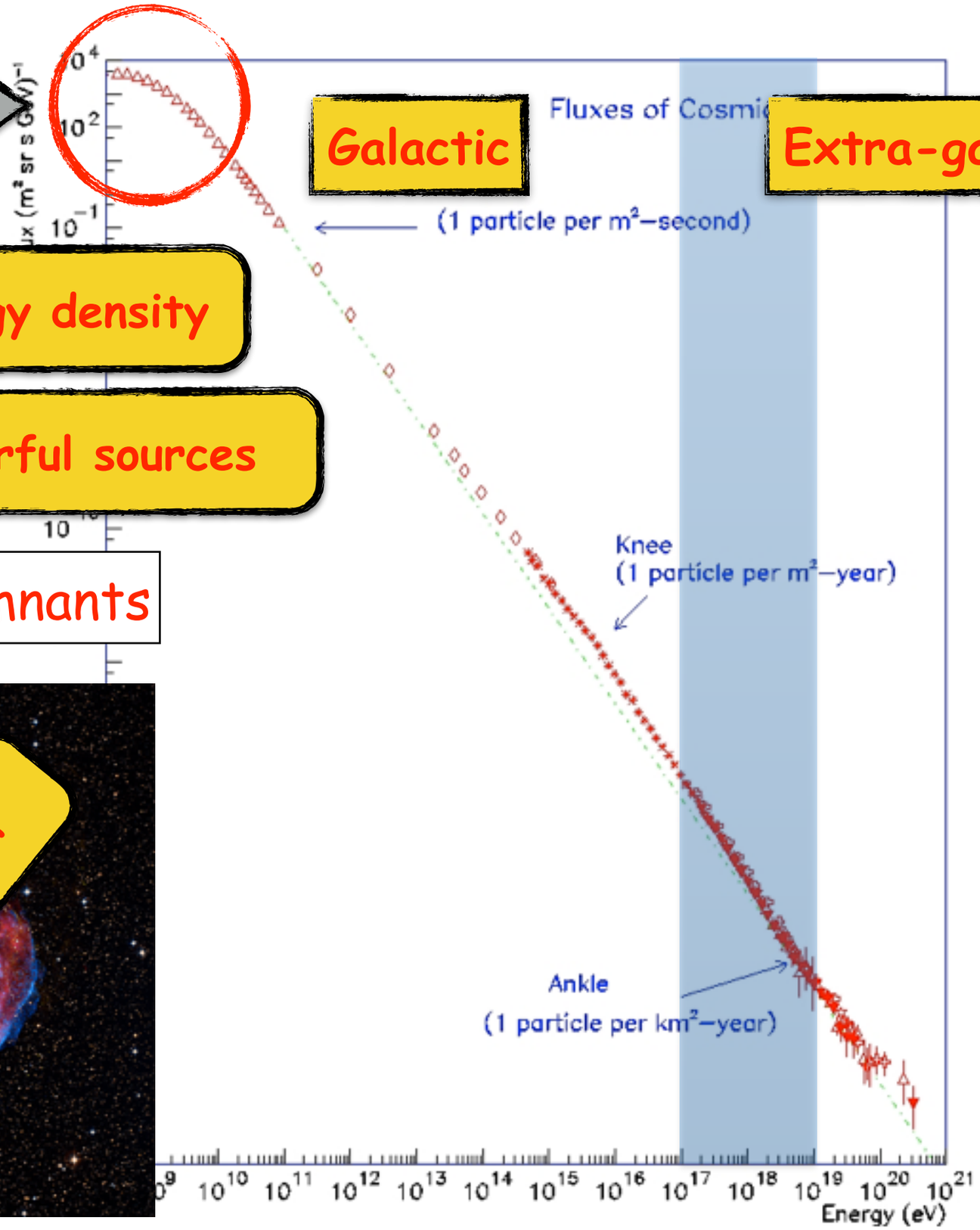

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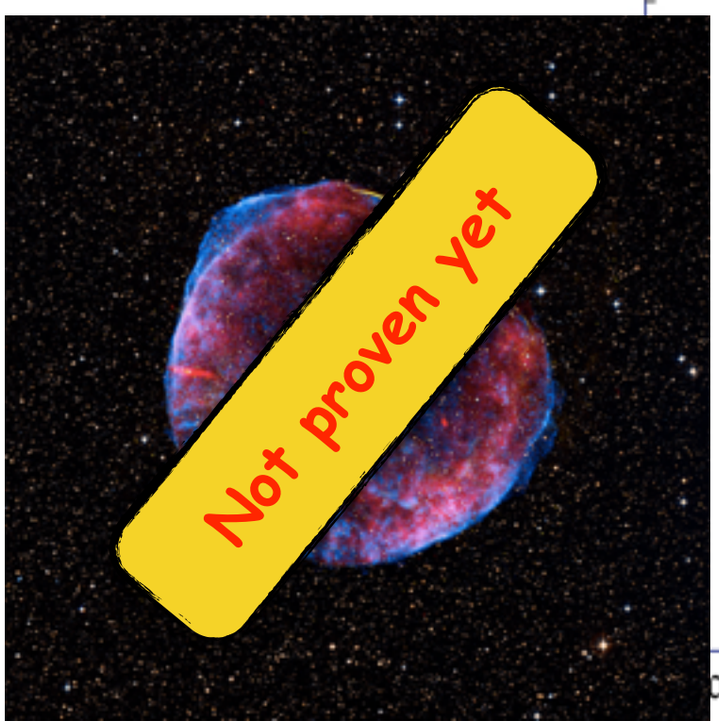
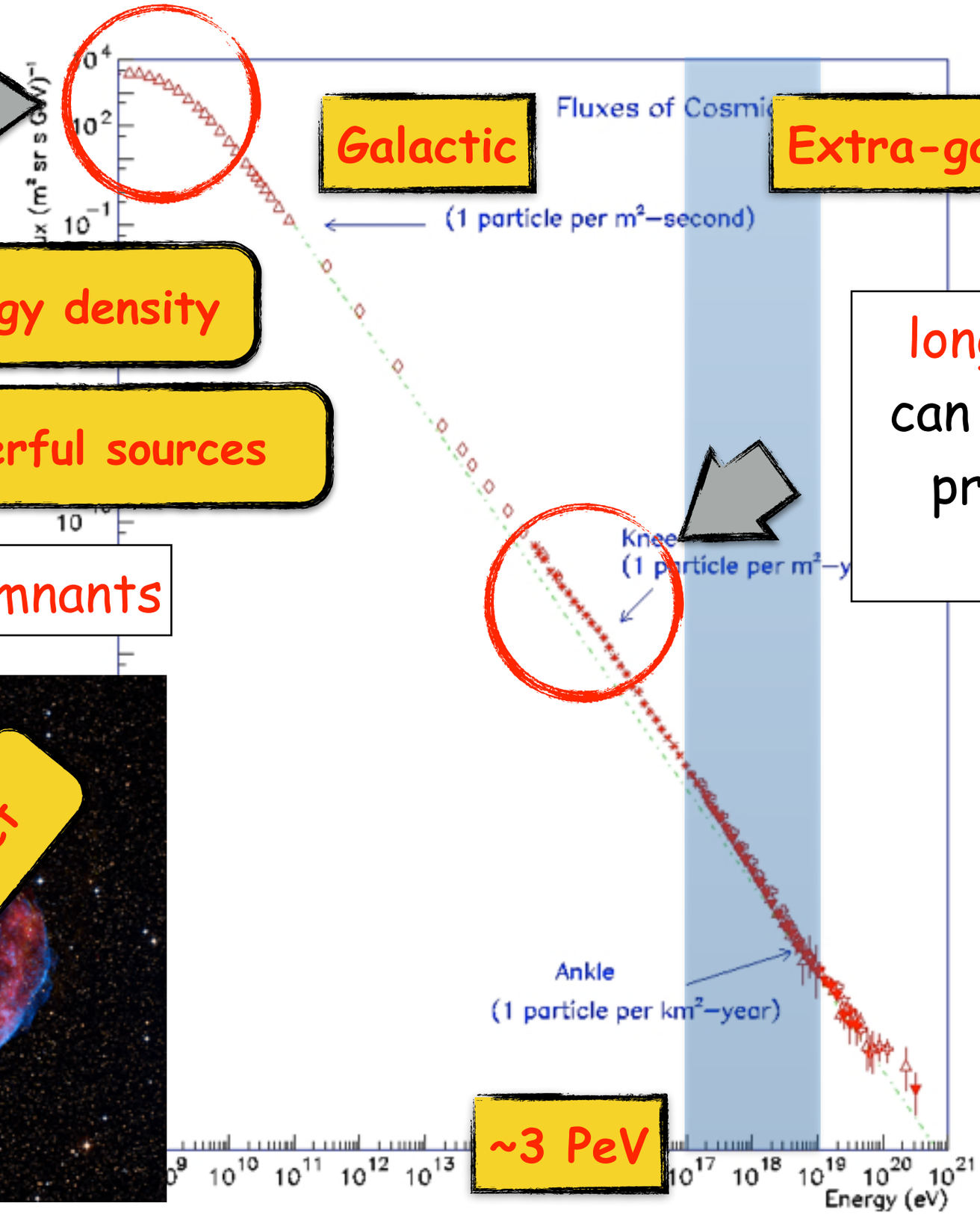
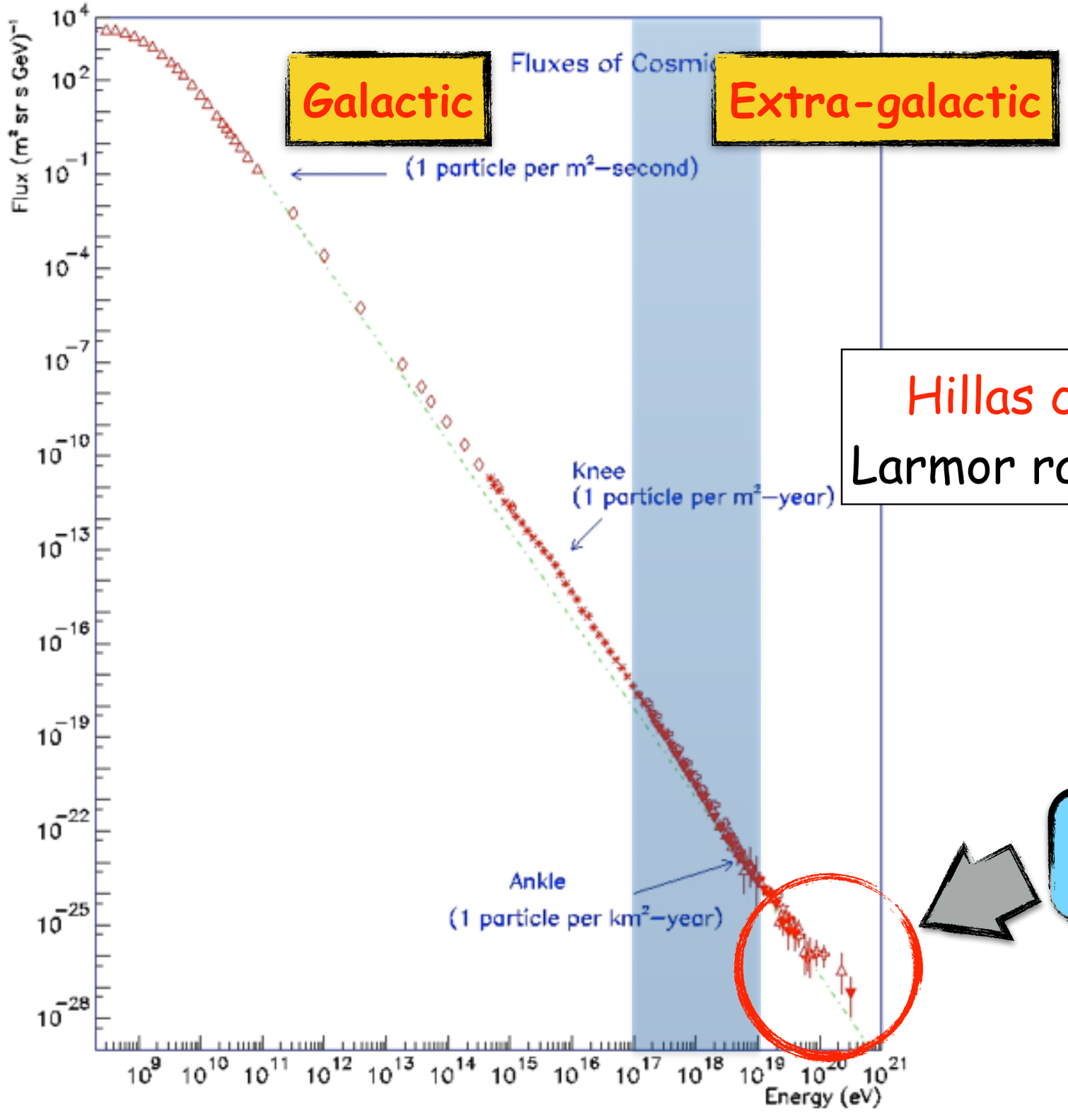




long standing issue:
can SNRs accelerate protons up to the knee?

The origin of CRs: Galactic sources

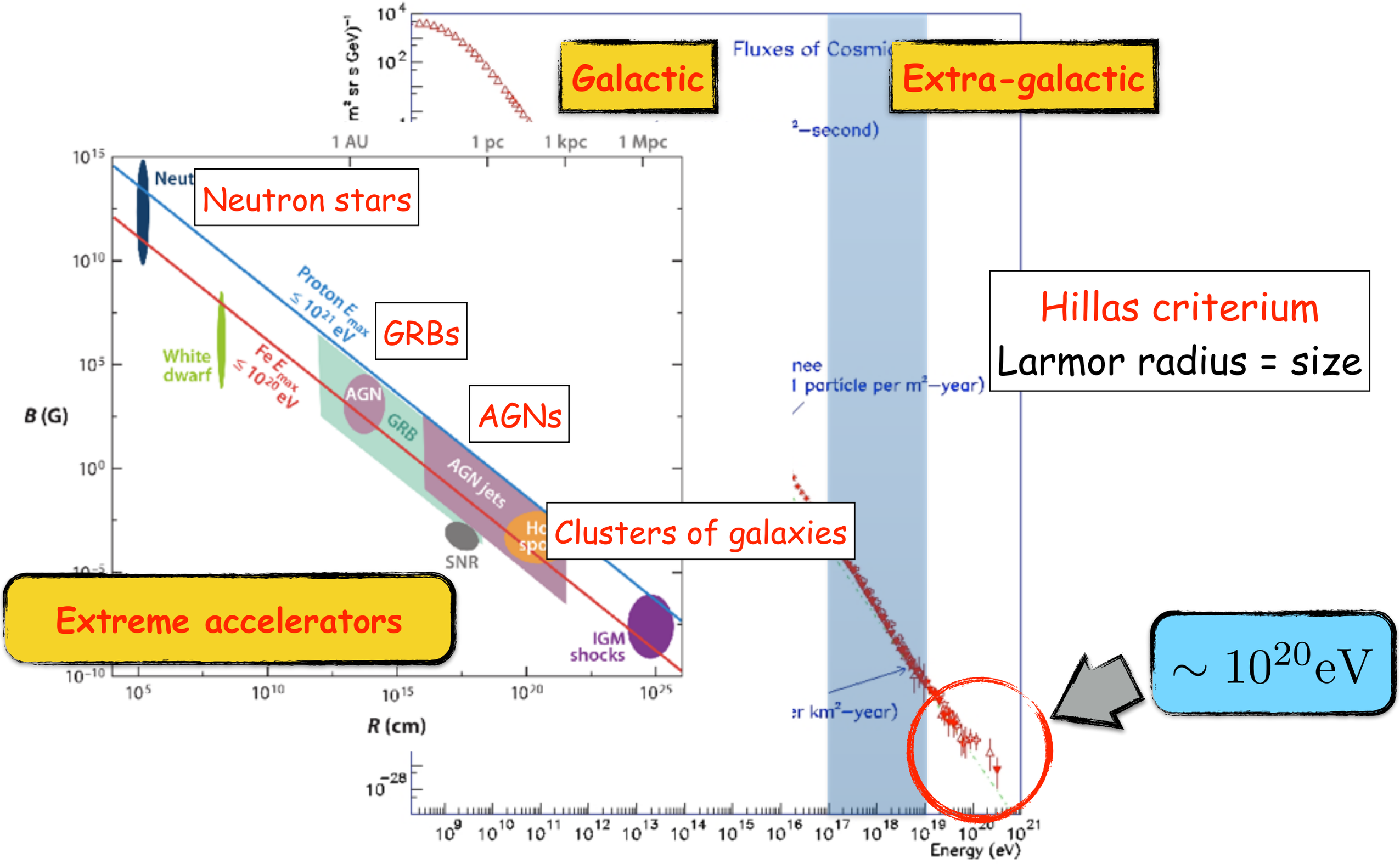


Hillas criterium

Larmor radius = size

$\sim 10^{20}$eV

The origin of CRs: Galactic sources



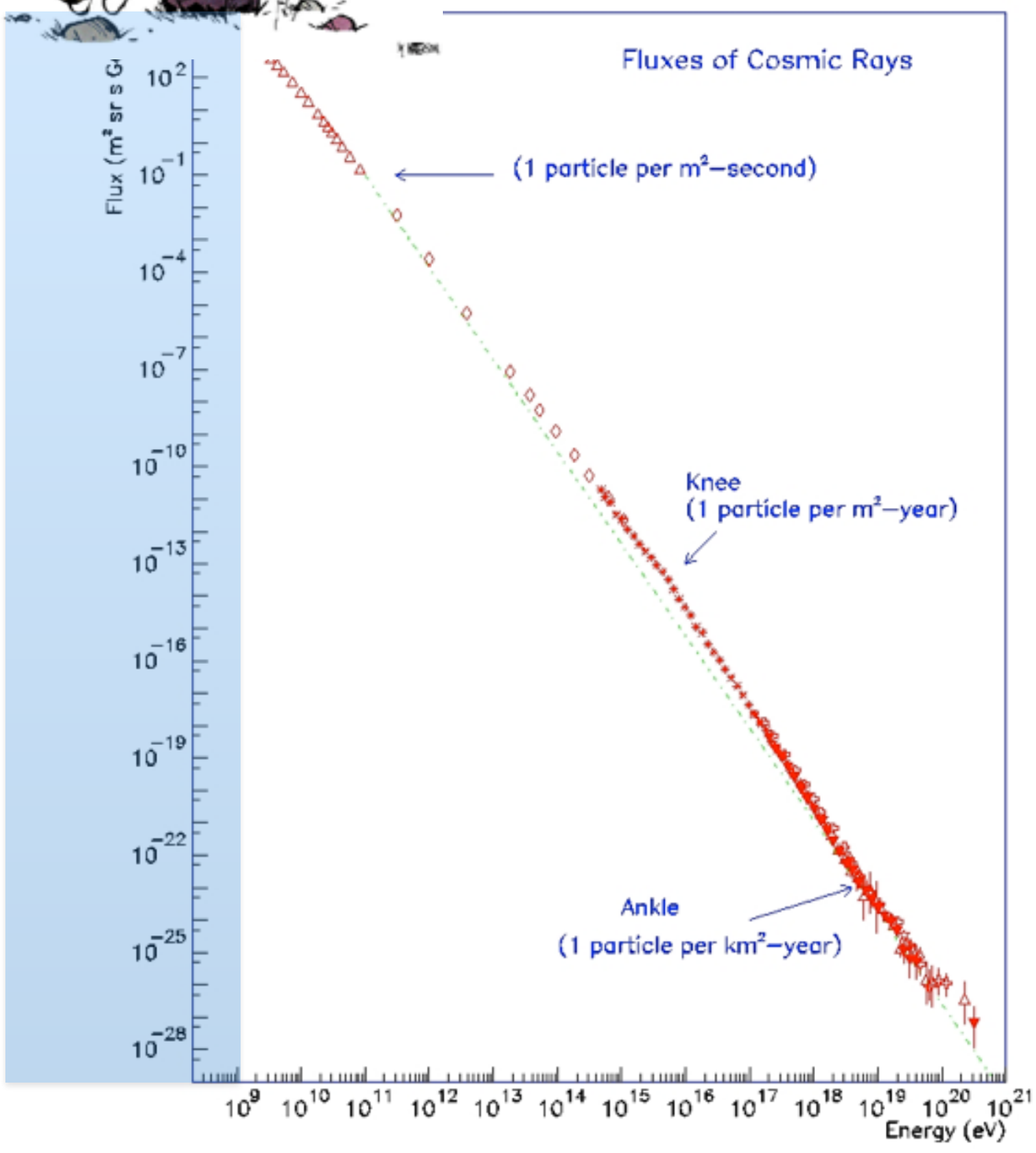
Extreme accelerators

Hillas criterium

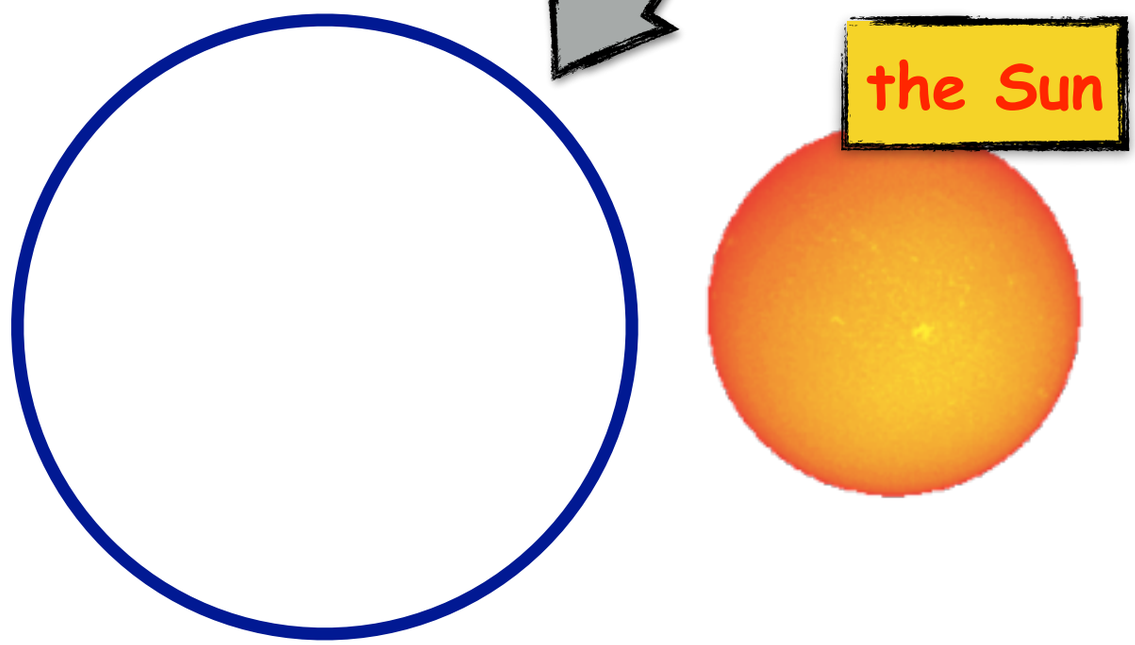
Larmor radius = size

$\sim 10^{20}$eV

The MeV domain (MeV…~1 GeV)



$$R_L(1\ \mathrm{MeV}) \sim 5 \times 10^{10}\ \mathrm{cm}$$



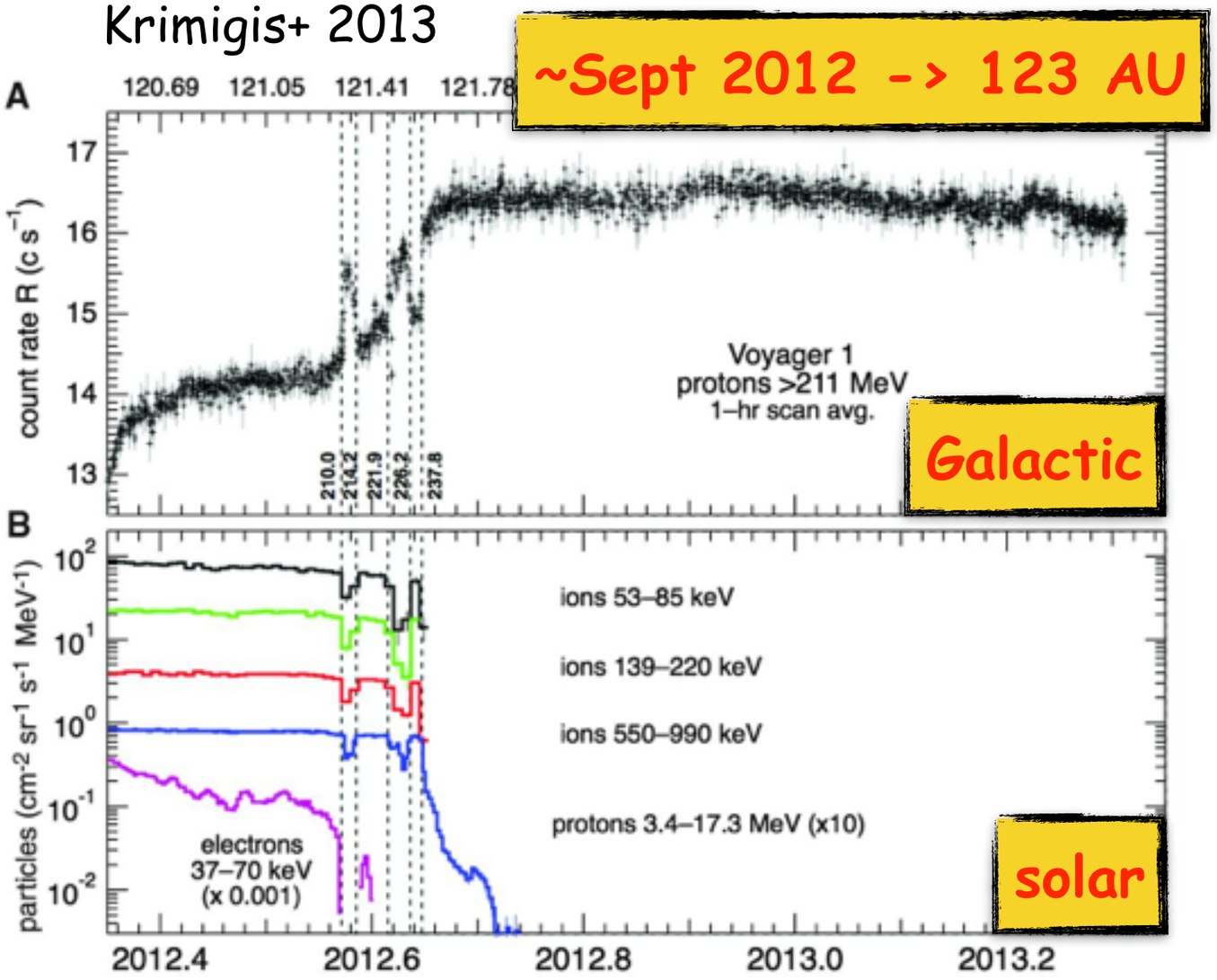
Solar modulation

CR spectrum known with very large uncertainties in the MeV range
-> but see recent Voyager results

MeV GeV TeV PeV EeV ZeV

Voyager 1 at Heliosphere's border

Krimigis+ 2013

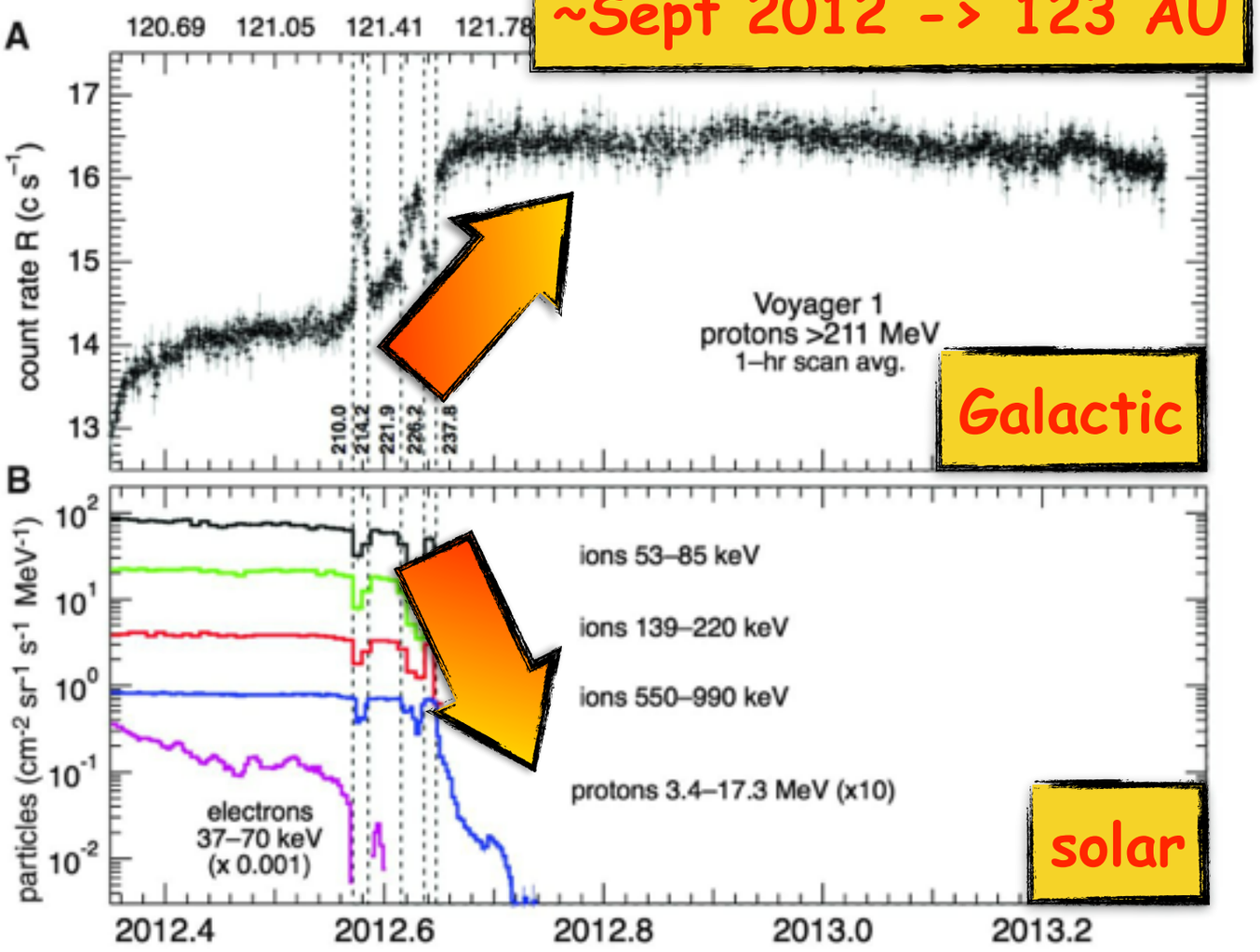


MeV GeV TeV PeV EeV ZeV

Voyager 1 at Heliosphere's border

Krimigis+ 2013

~Sept 2012 -> 123 AU



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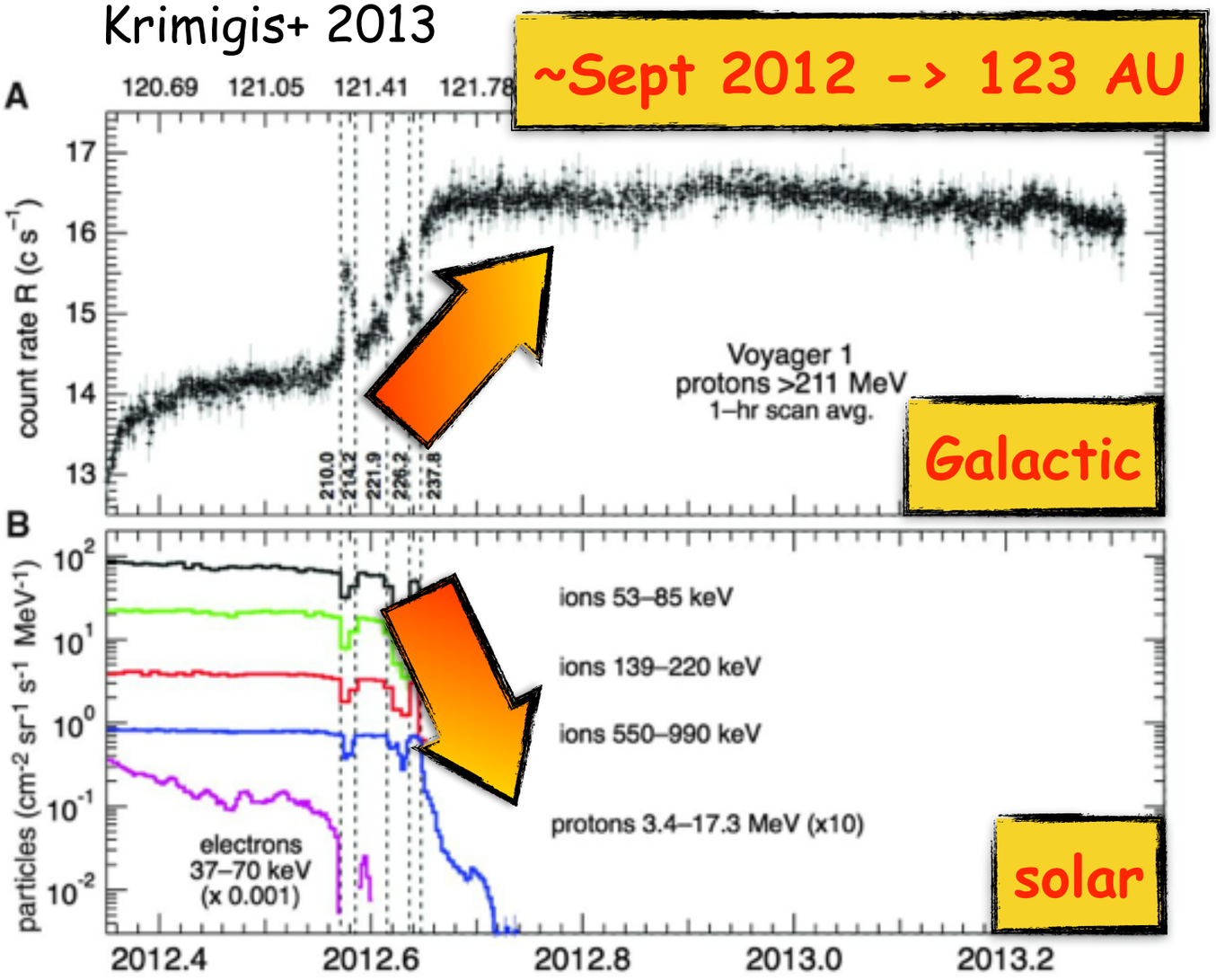
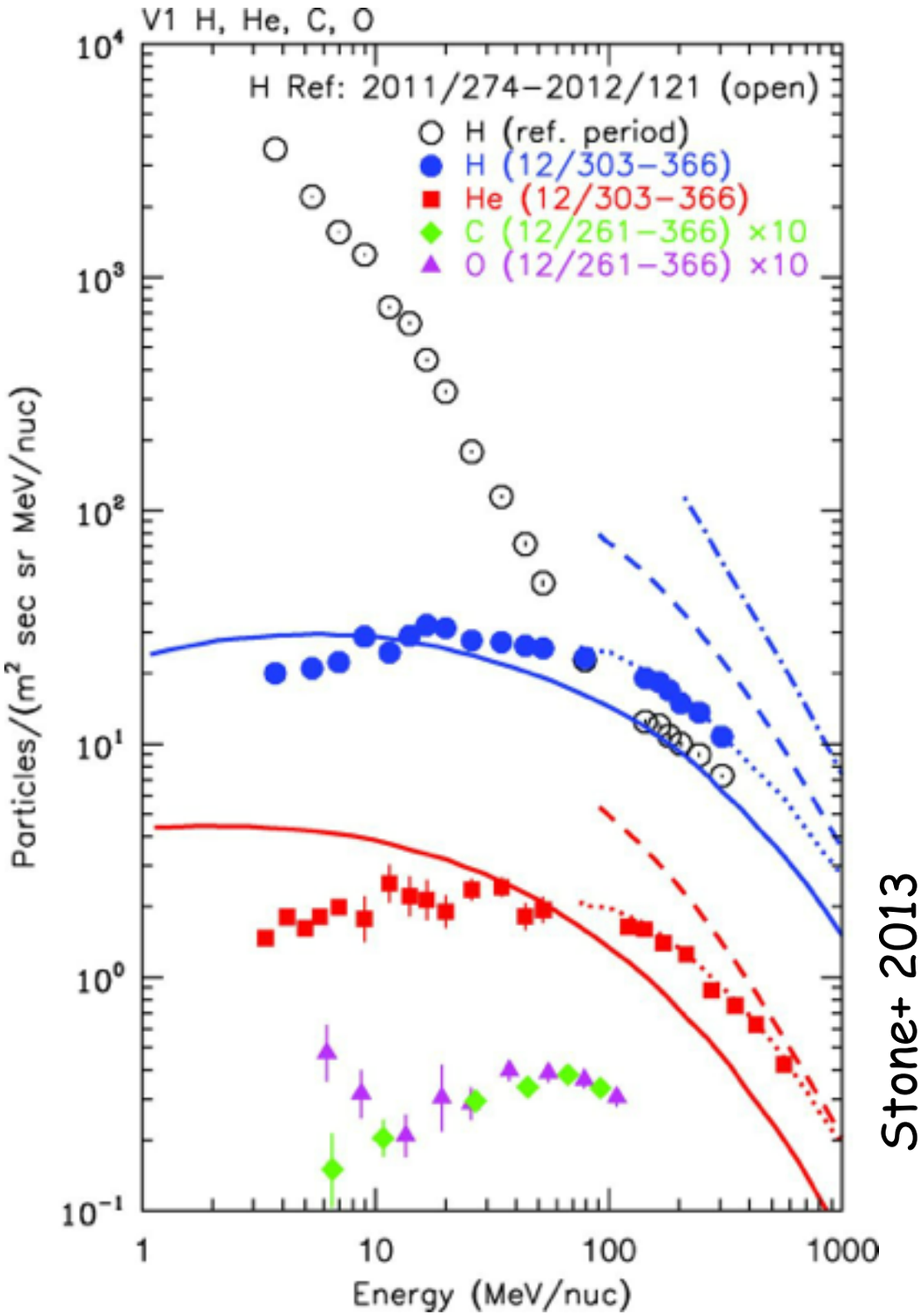
Krimigis+ 2013



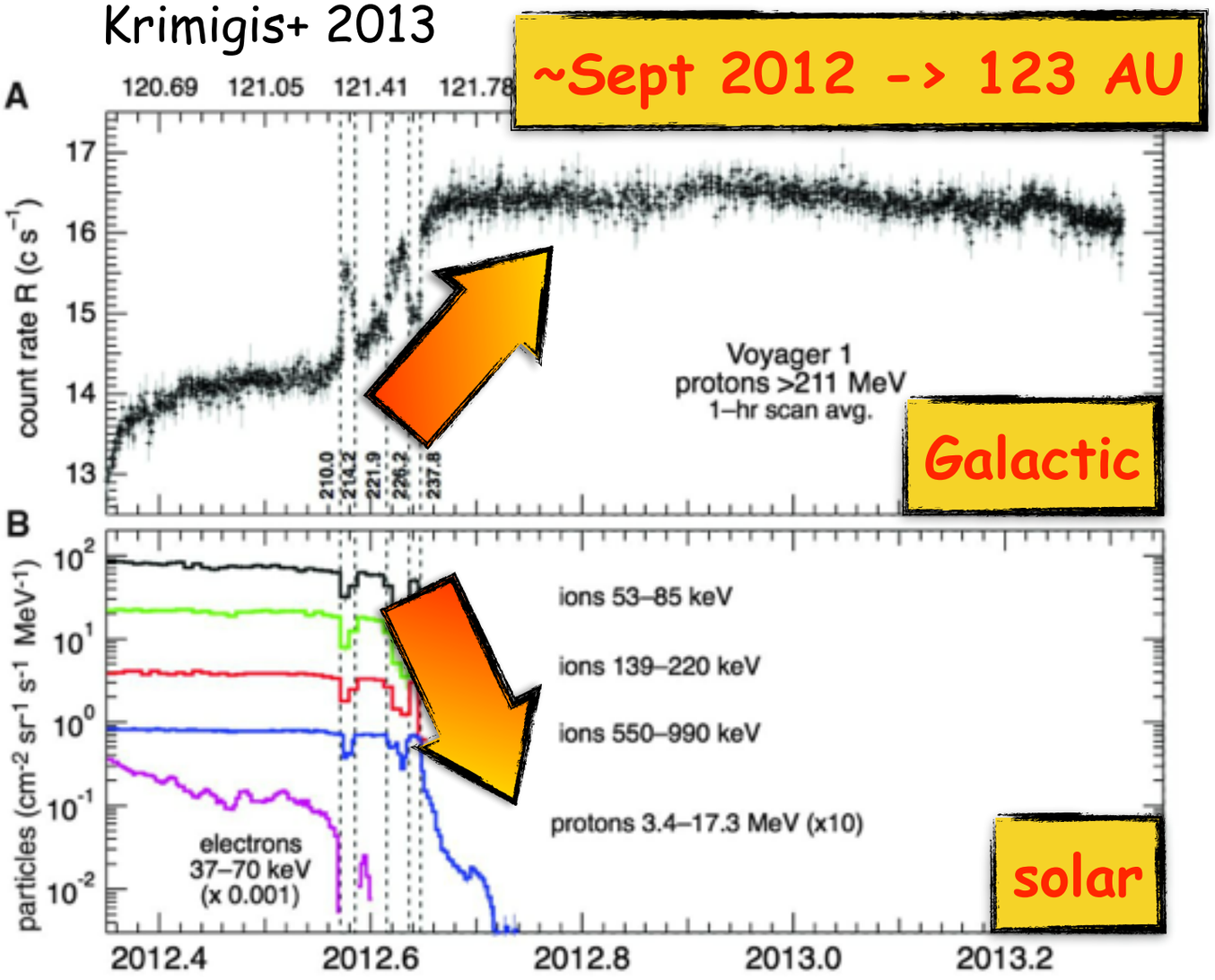


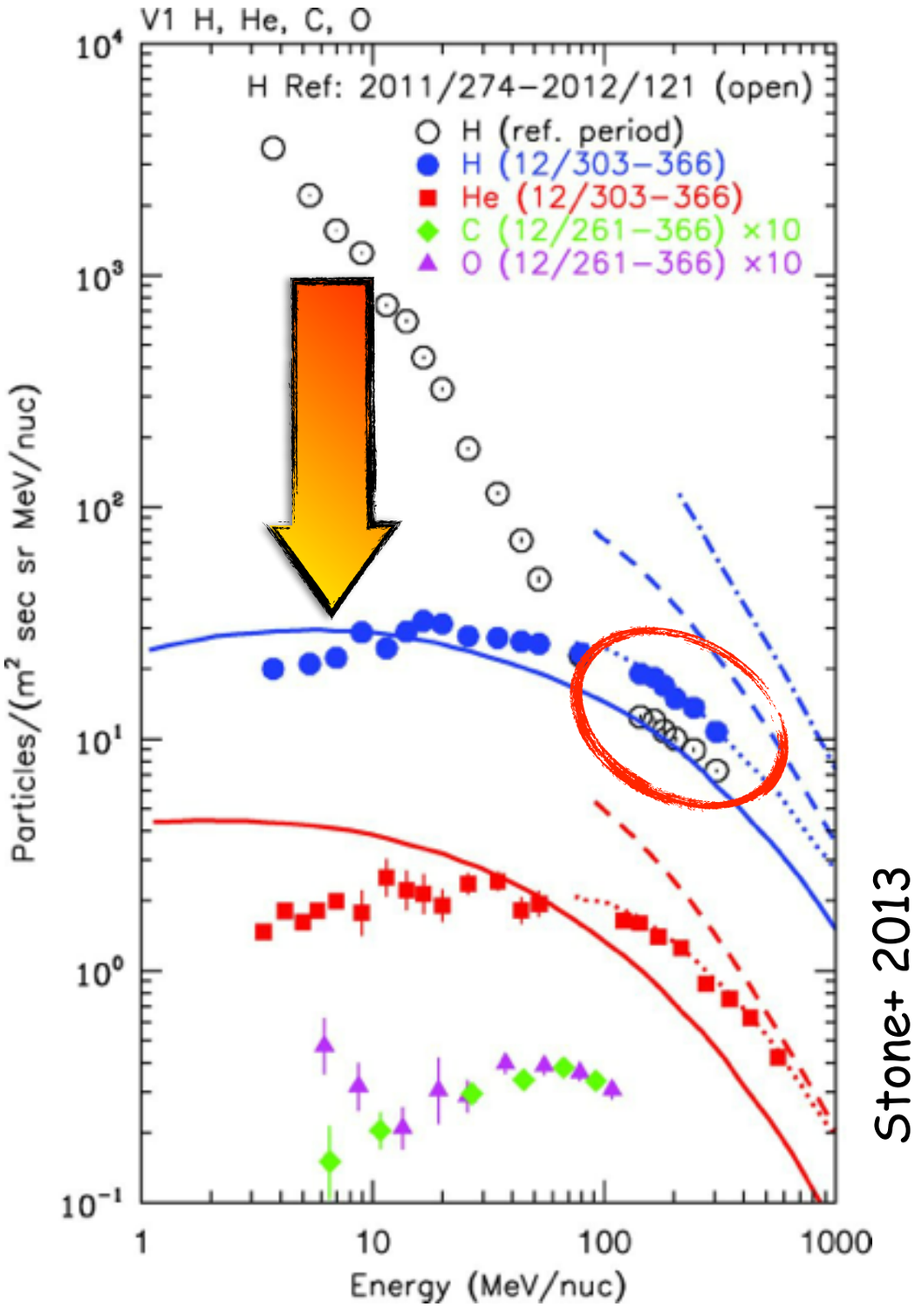
Stone+ 2013

MeV GeV TeV PeV EeV ZeV

Voyager 1 at Heliosphere's border

Krimigis+ 2013





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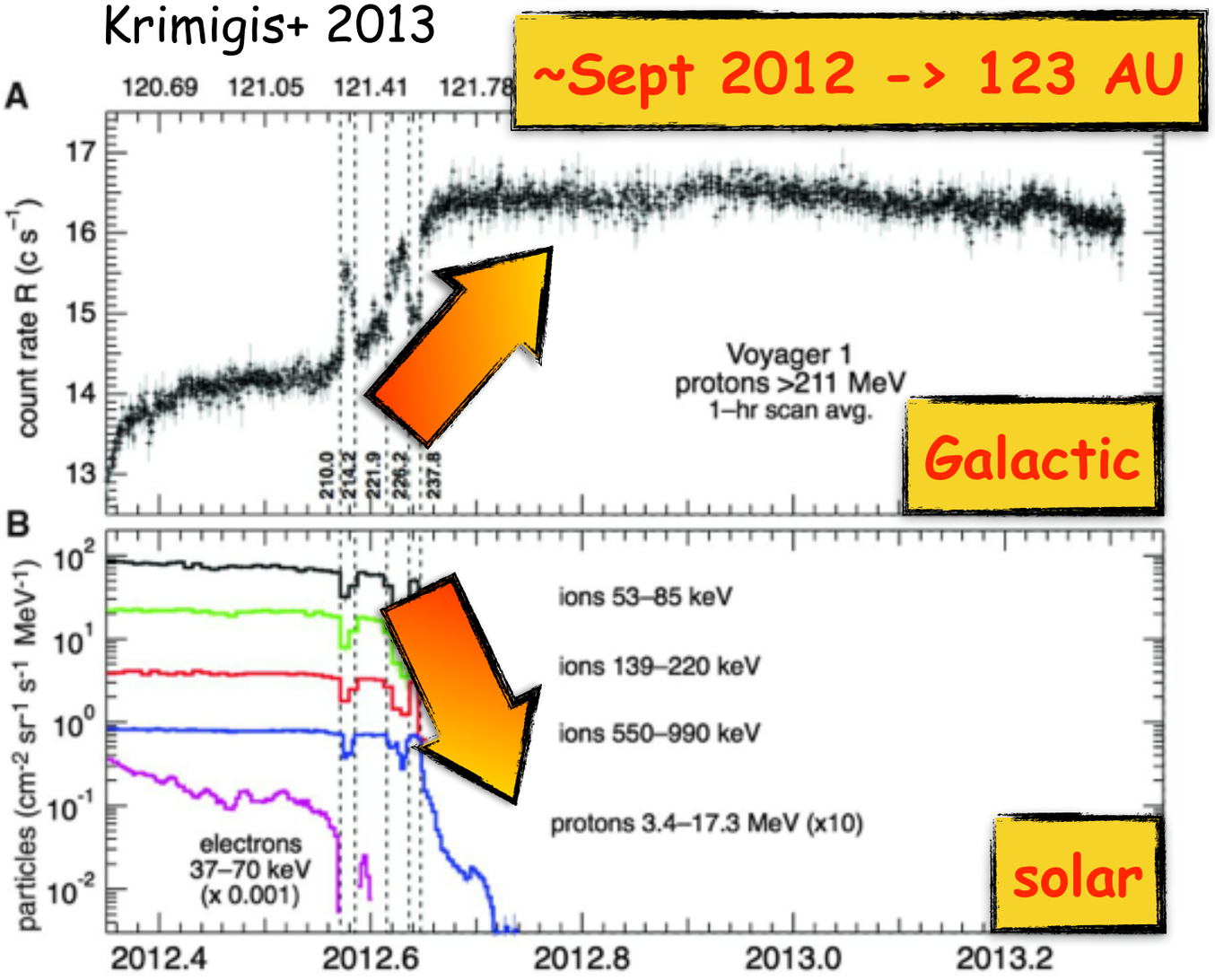
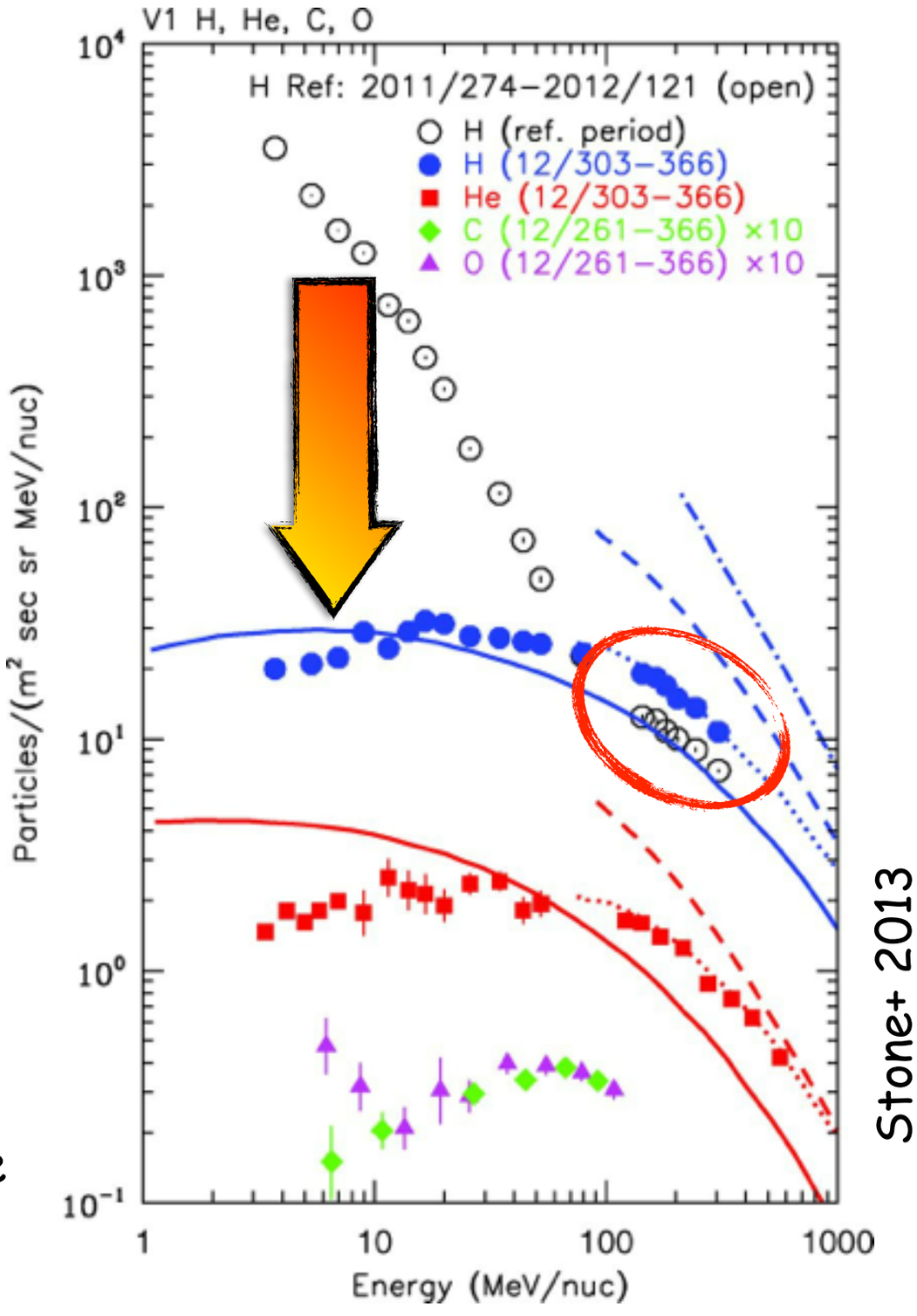




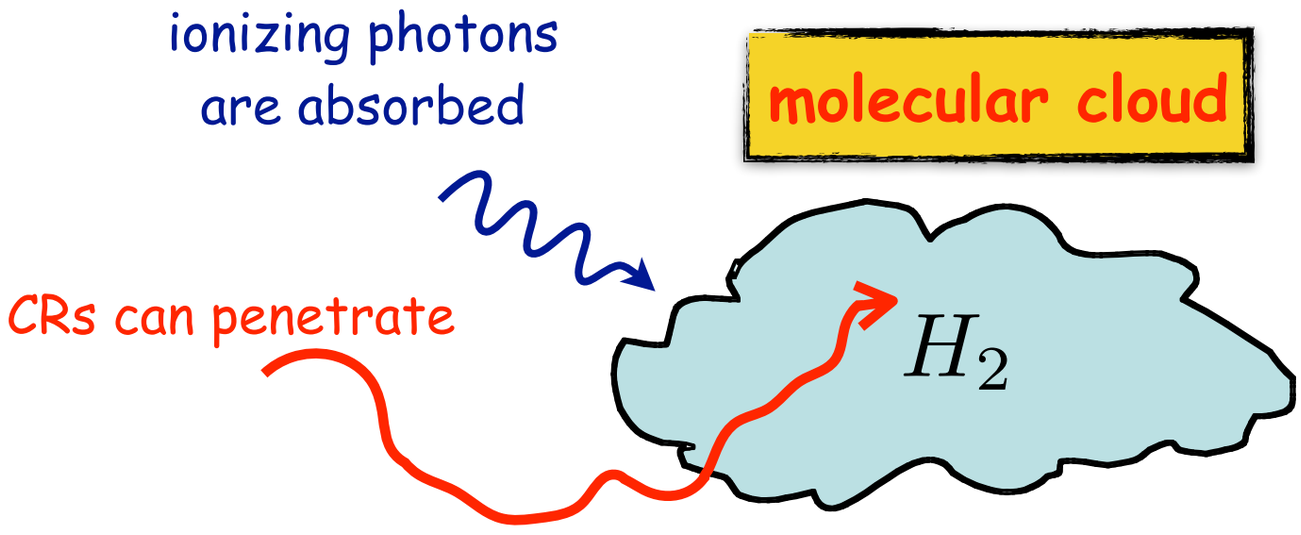
Stone+ 2013

- test propagation models <GeV energies
- is the spectrum representative of the whole Galaxy?

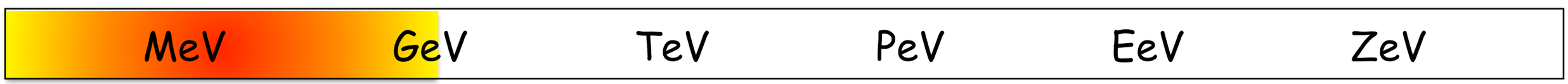
MeV GeV TeV PeV EeV ZeV

The MeV domain: CR ionization

(see SG & Montmerle 2015, Padovani+ 2009 for recent reviews)



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



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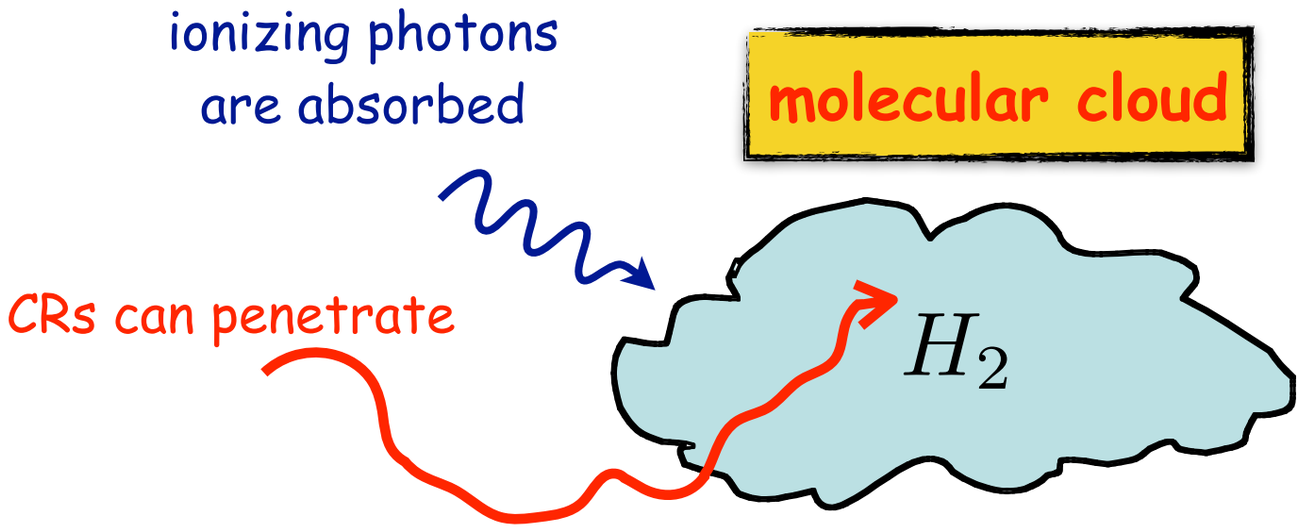

$$H_2 + CR \longrightarrow H_2^+ + e^-$$

chemistry

$$H_3^+, HCO^+, DCO^+ ...$$

MeV GeV TeV PeV EeV ZeV

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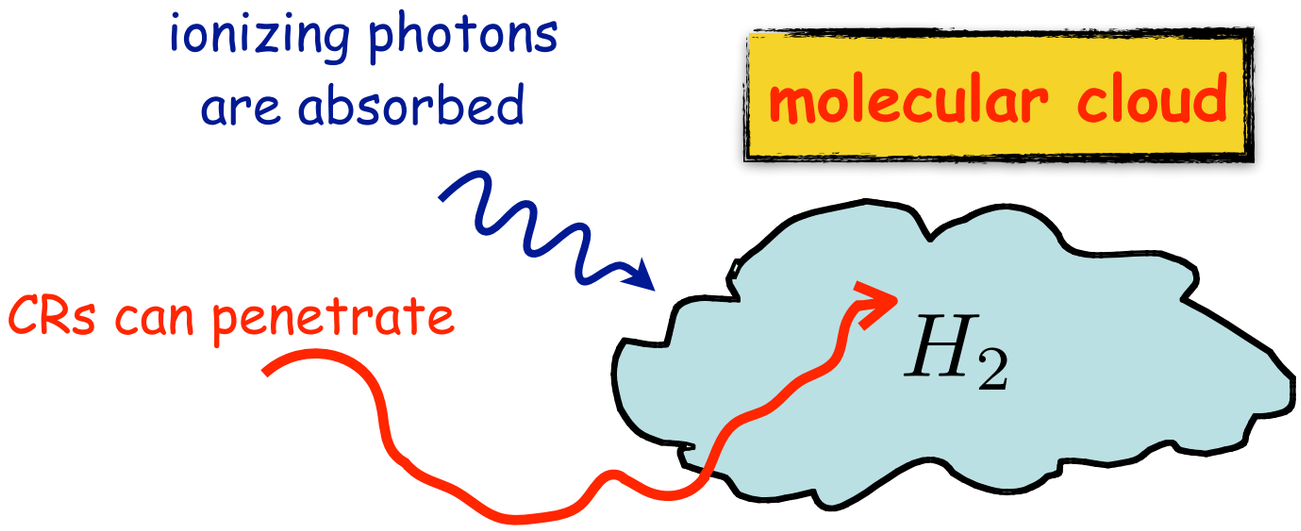

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see e.g. McCall+, Indriolo+, Ceccarelli+, Vaupré+ ...

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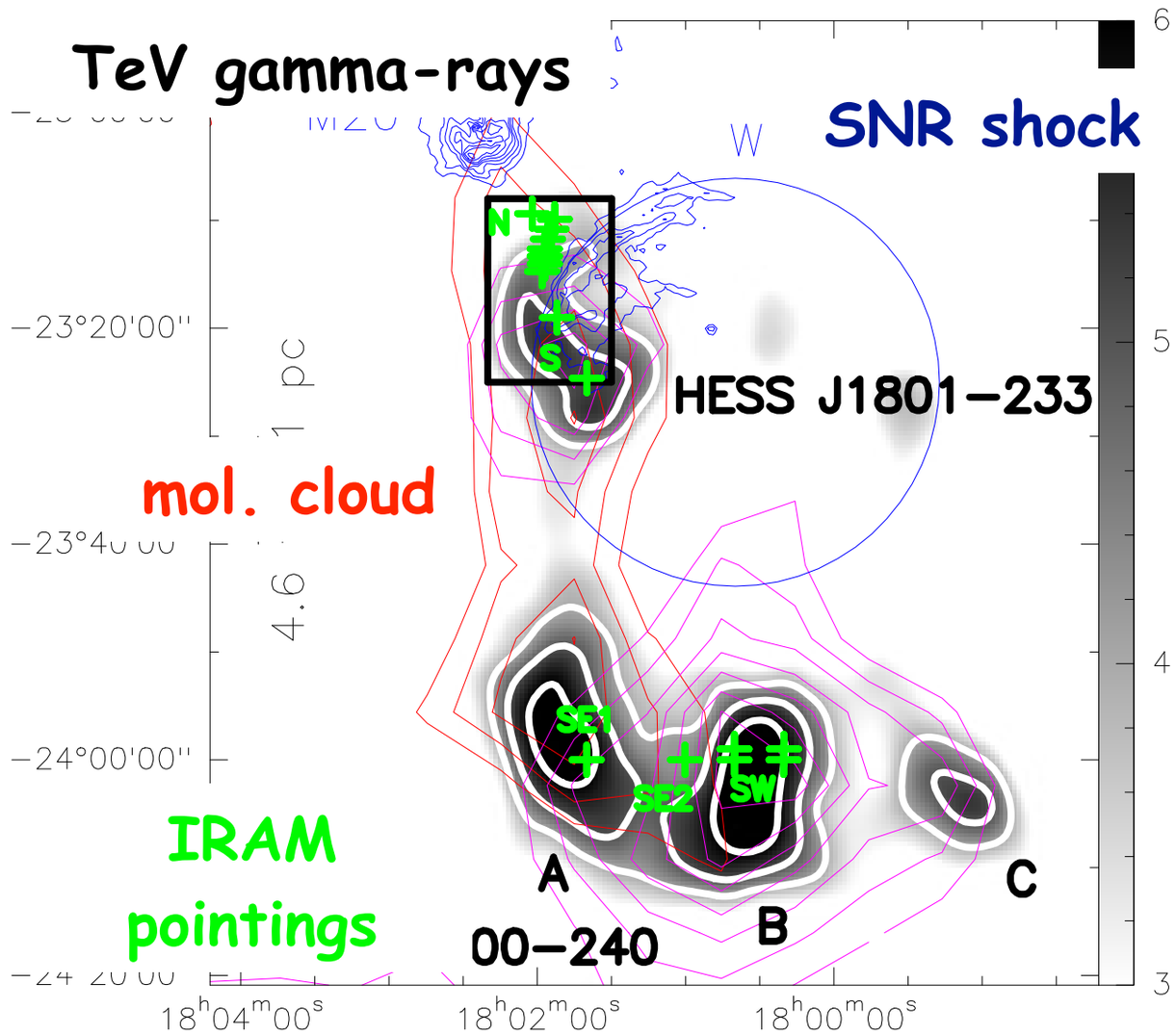
The SuperNova Remnant W28

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



TeV + gas -> multi-TeV CR protons

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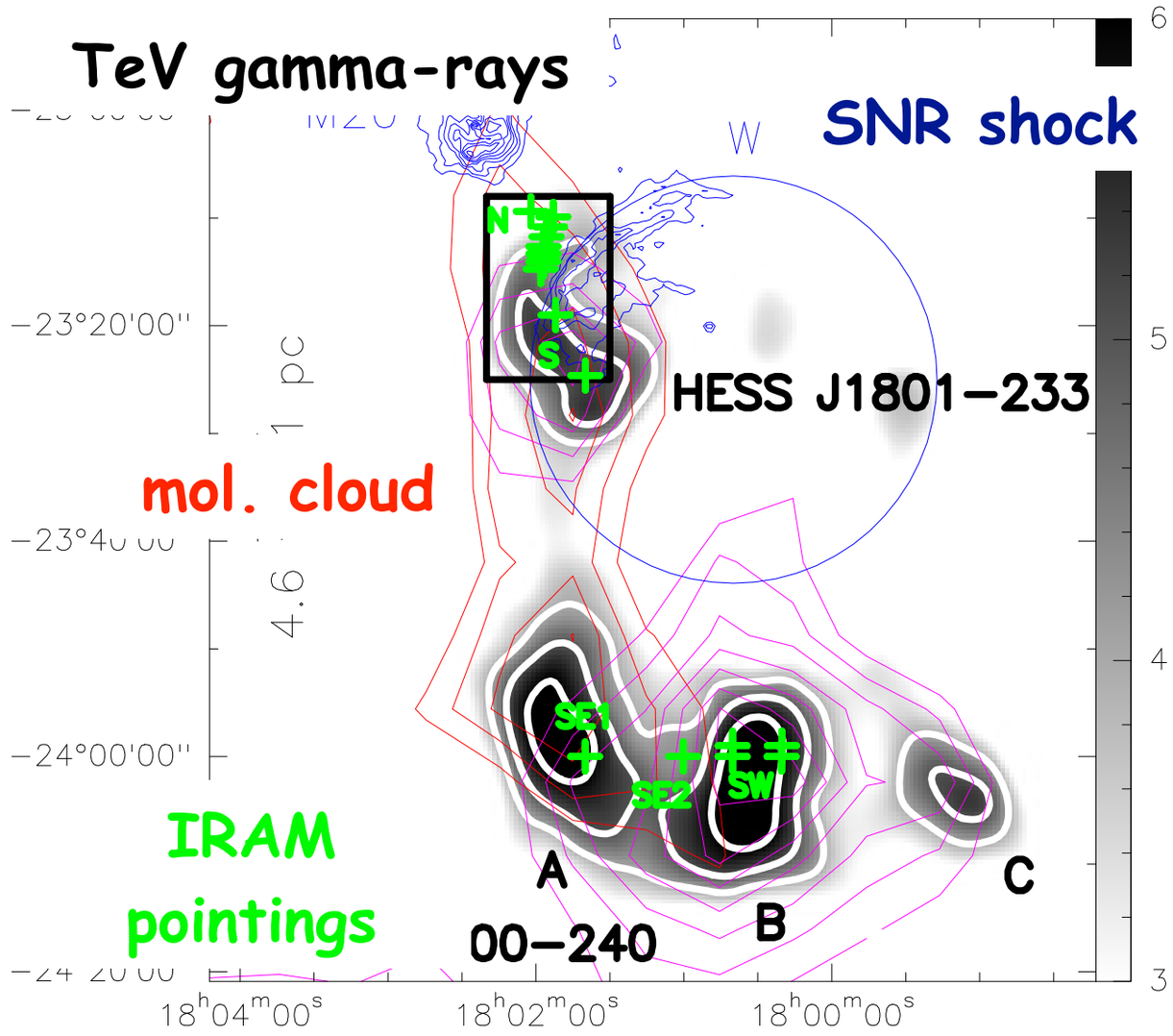
TeV gamma-rays



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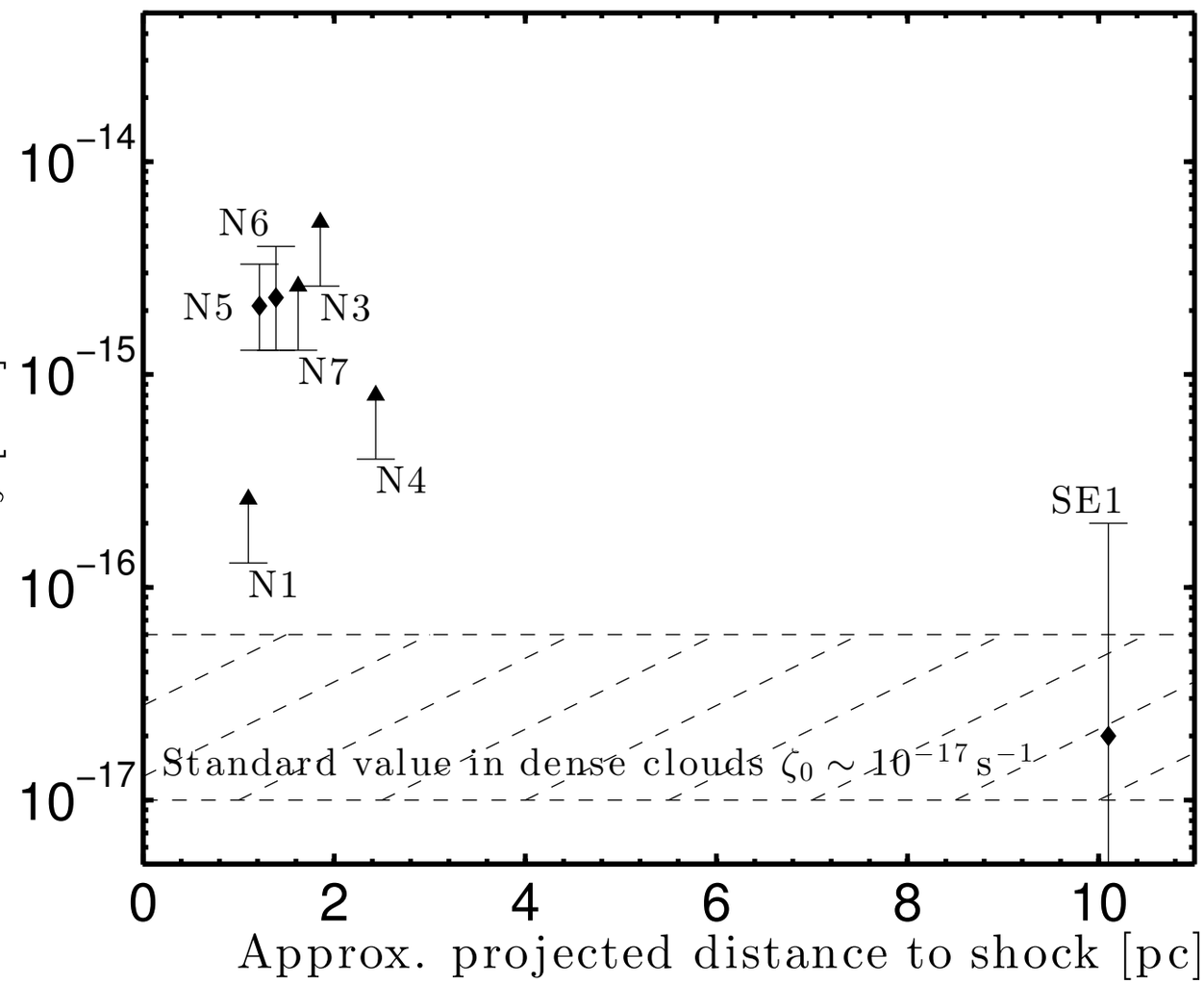

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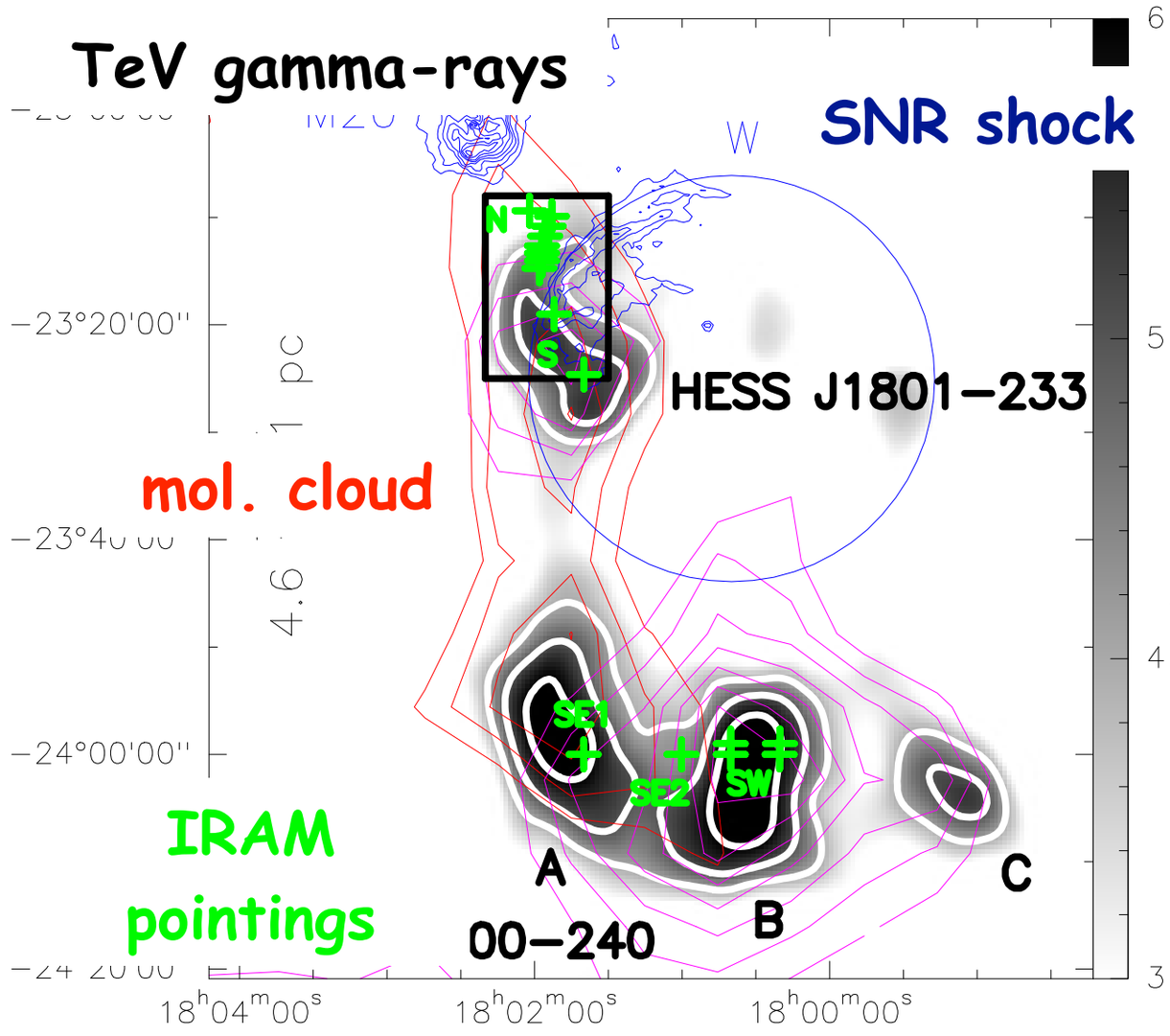

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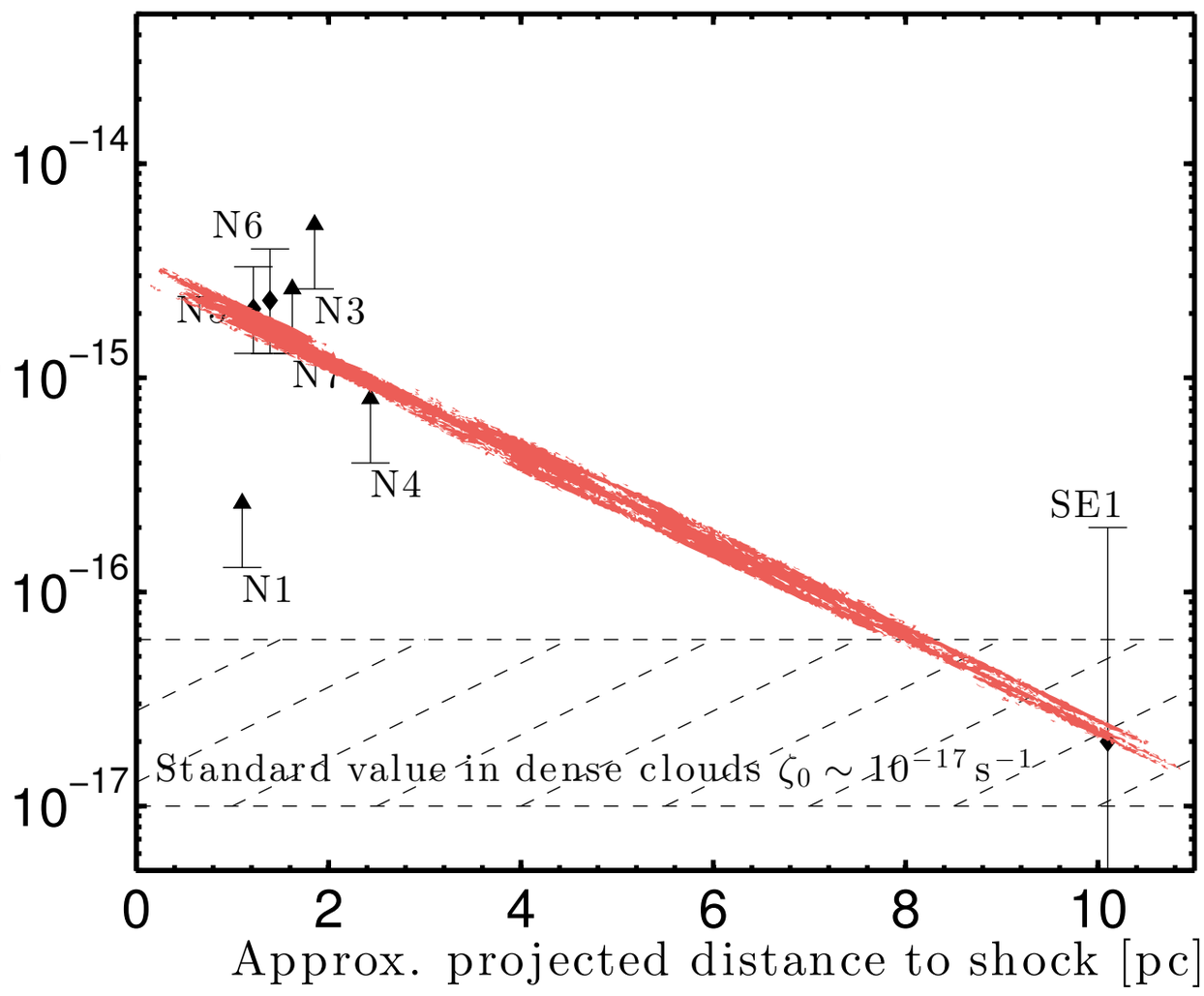

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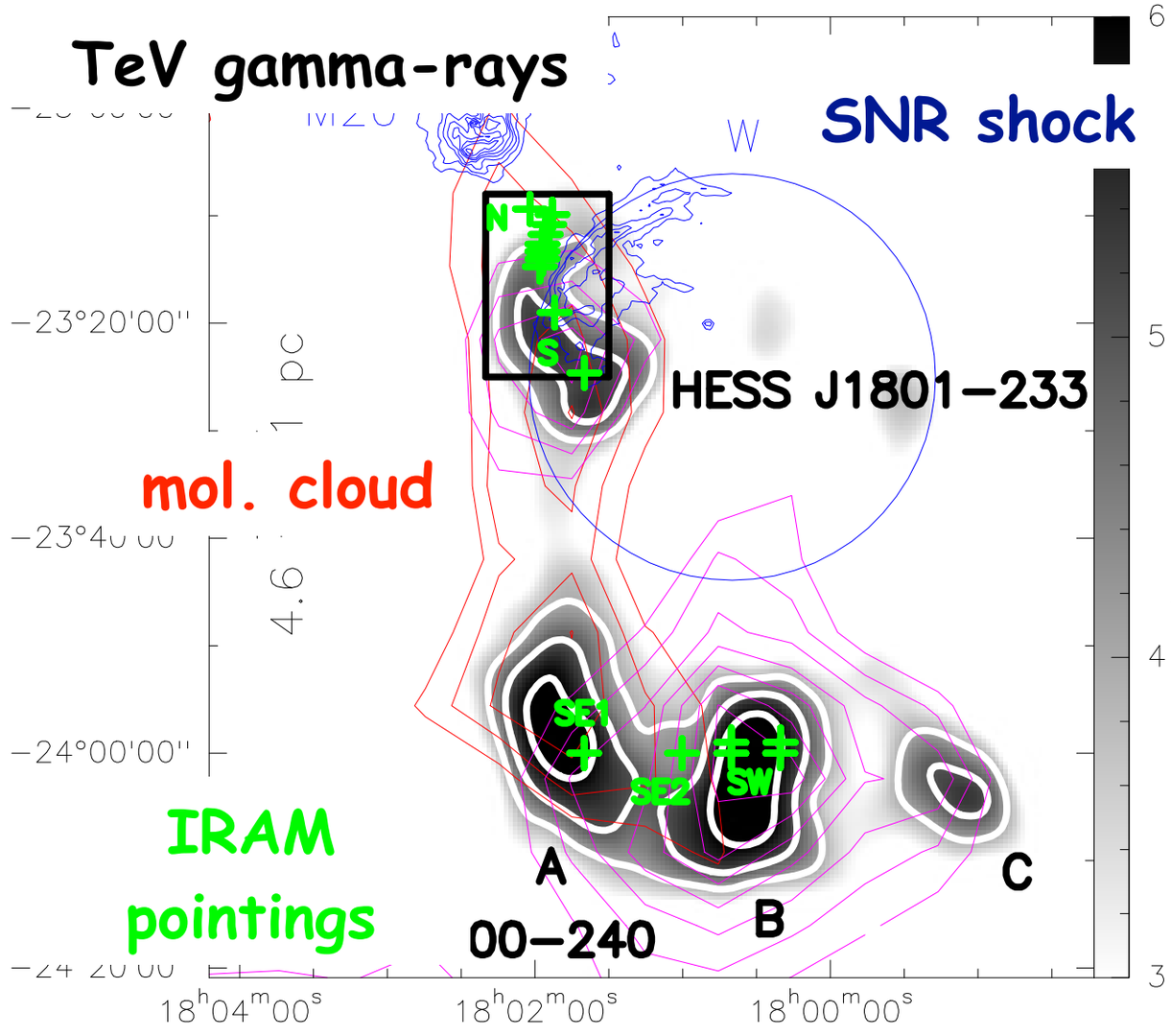

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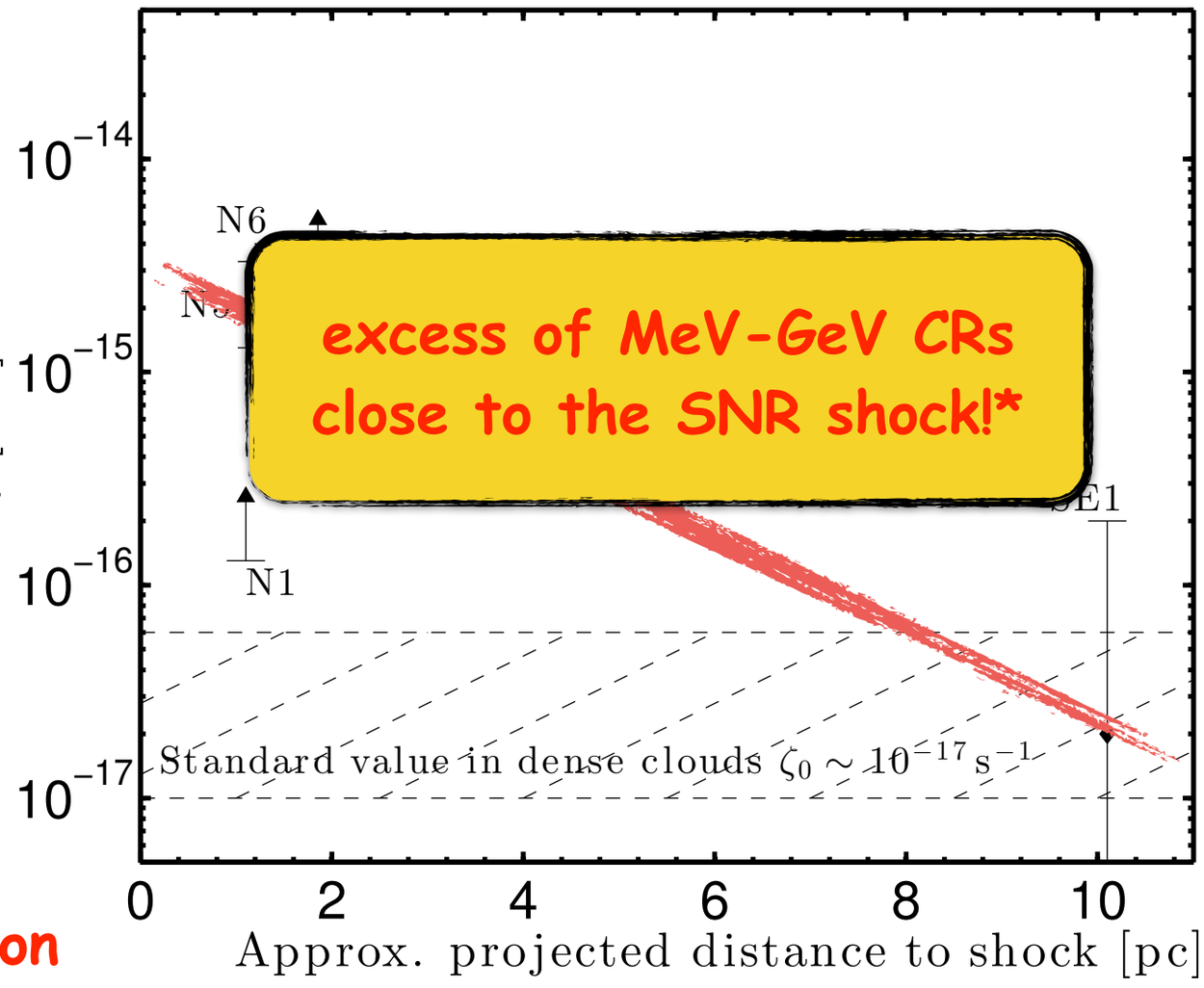
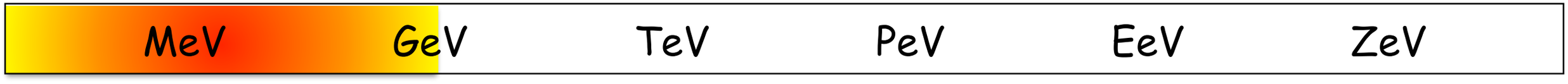


* also CR electrons contribute to ionization



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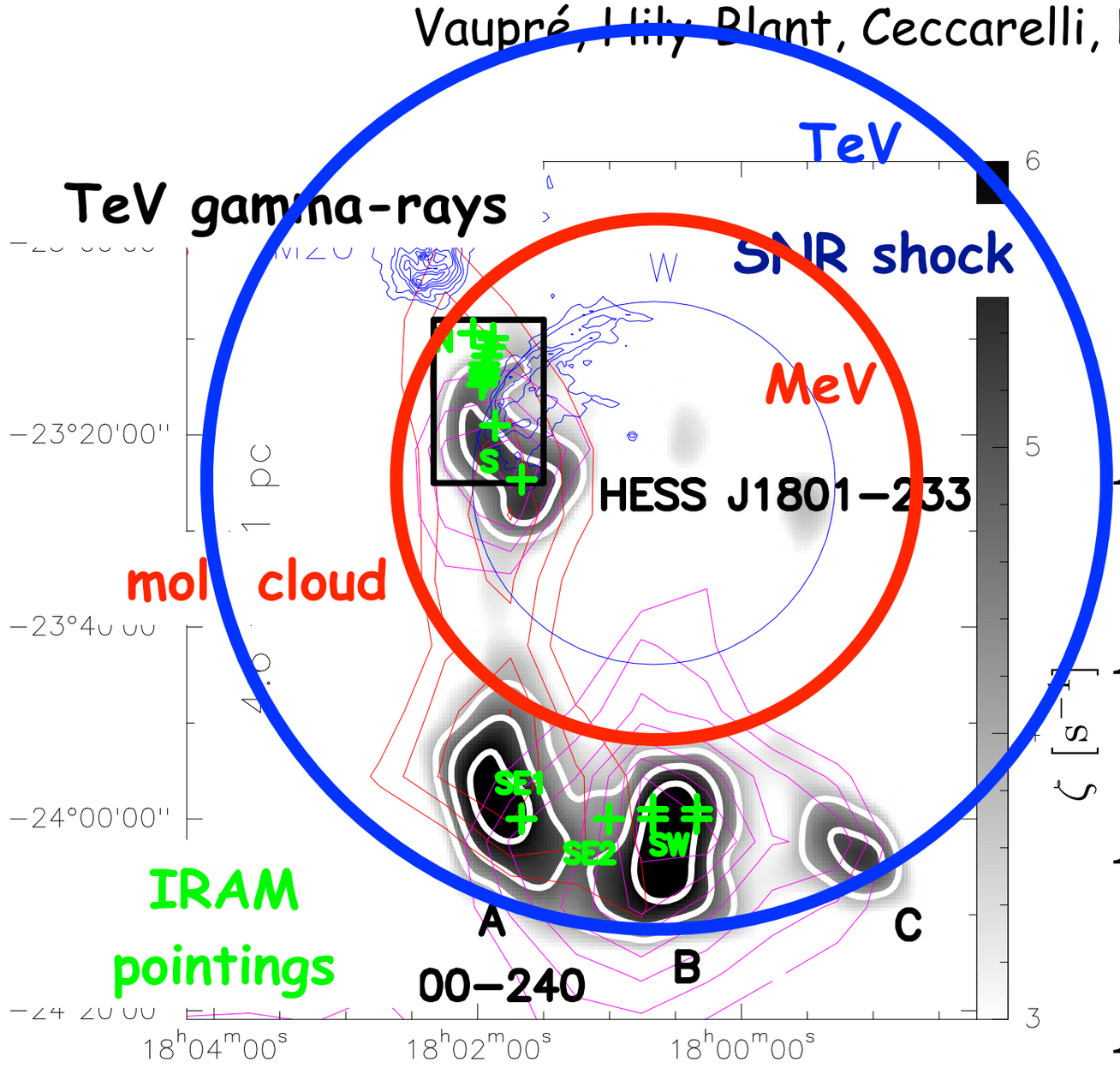

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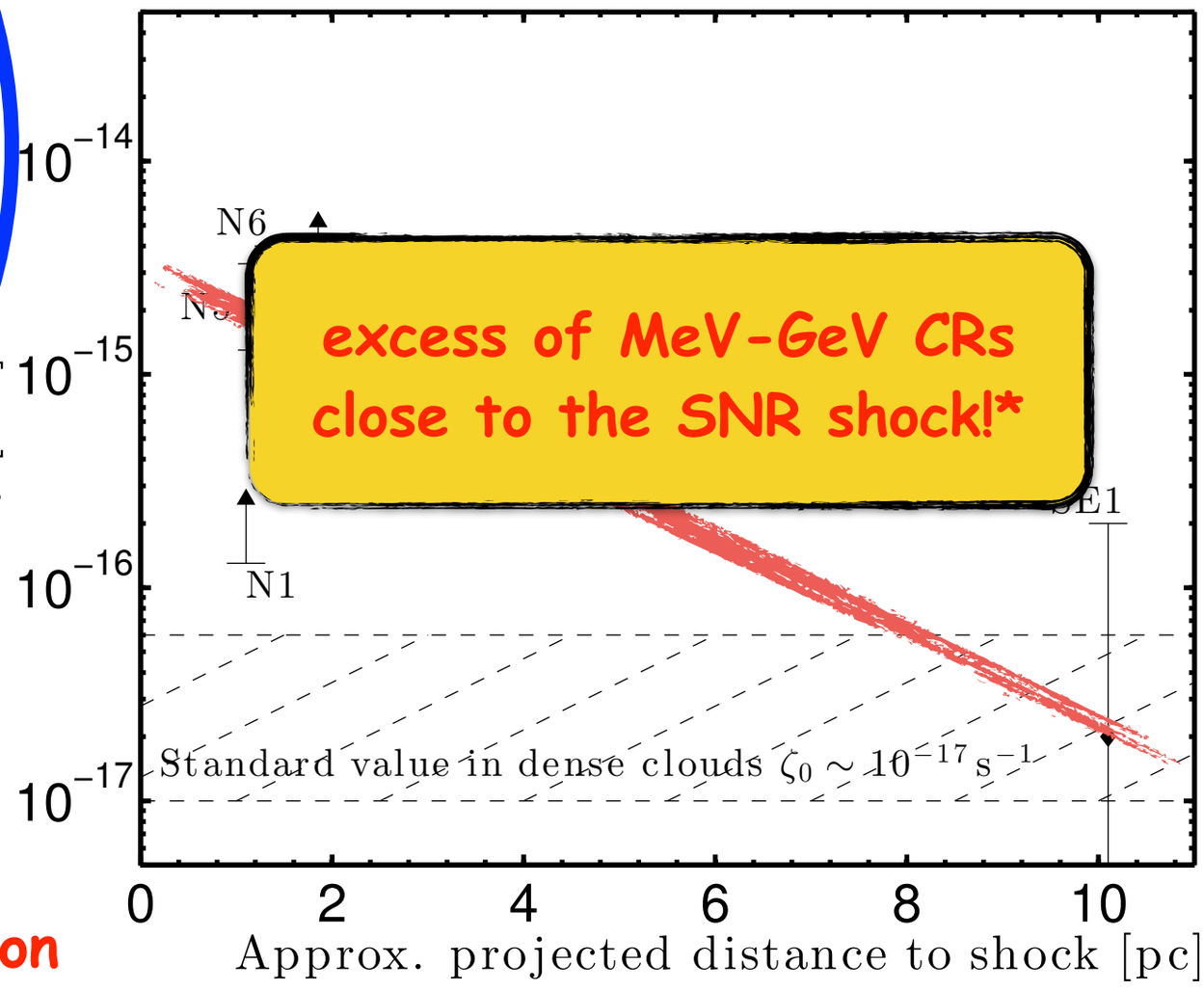

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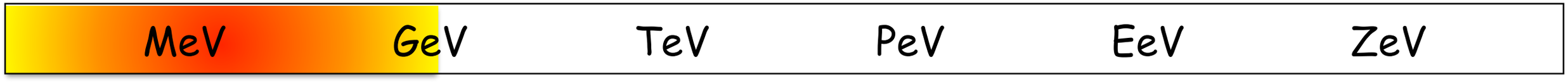
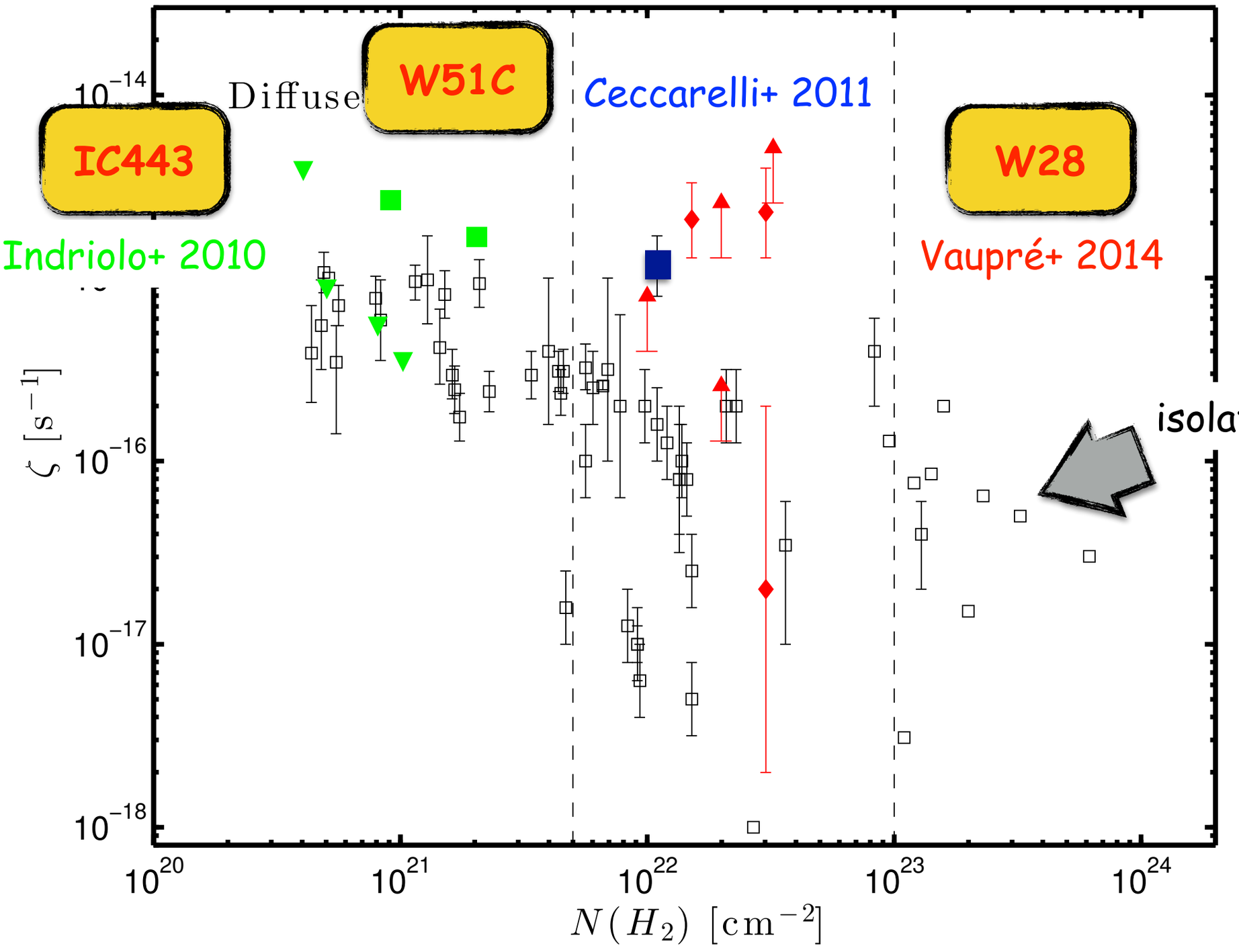


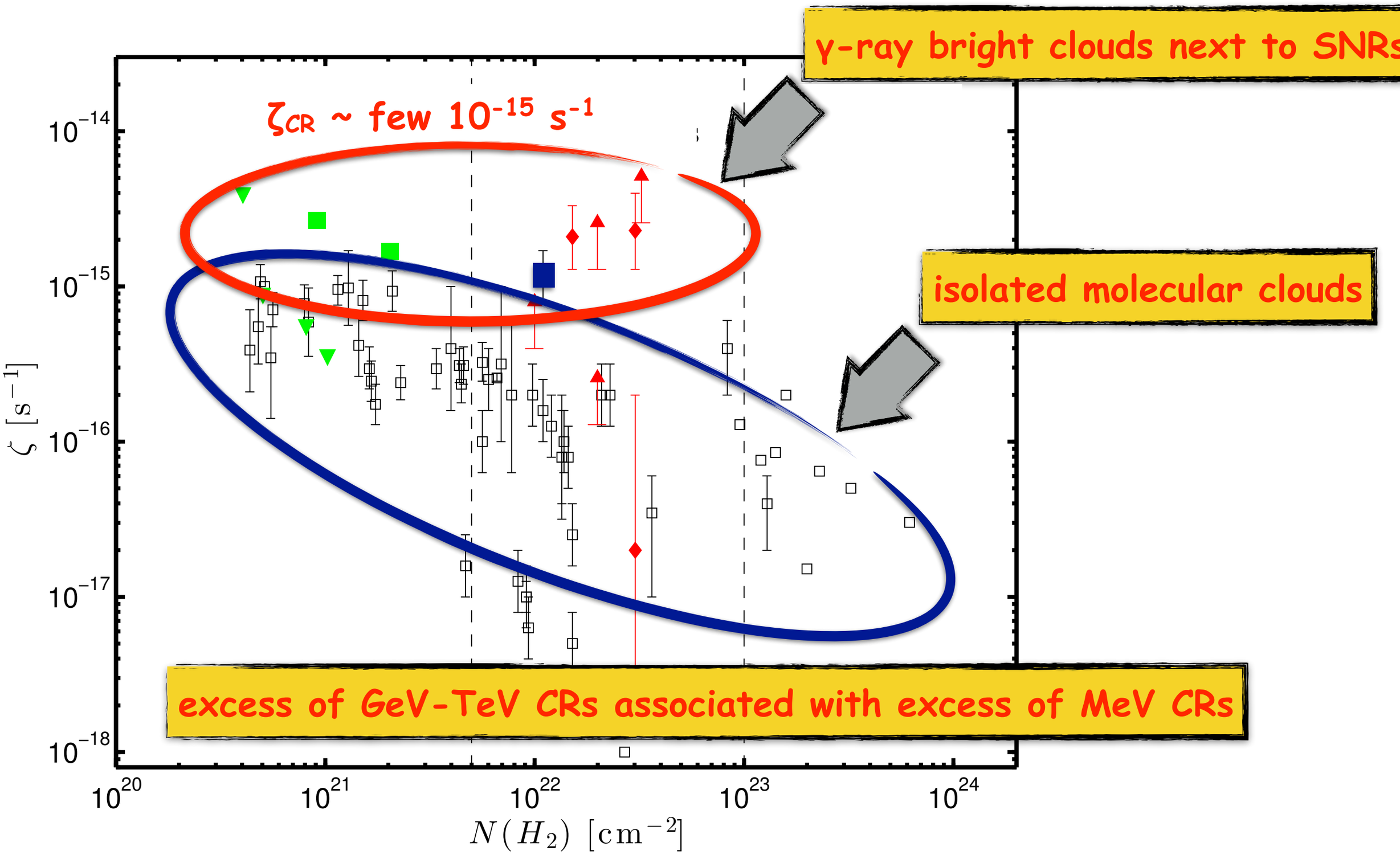
SuperNova Remnants & MeV cosmic rays

(for a review see SG & Montmerle 2015)



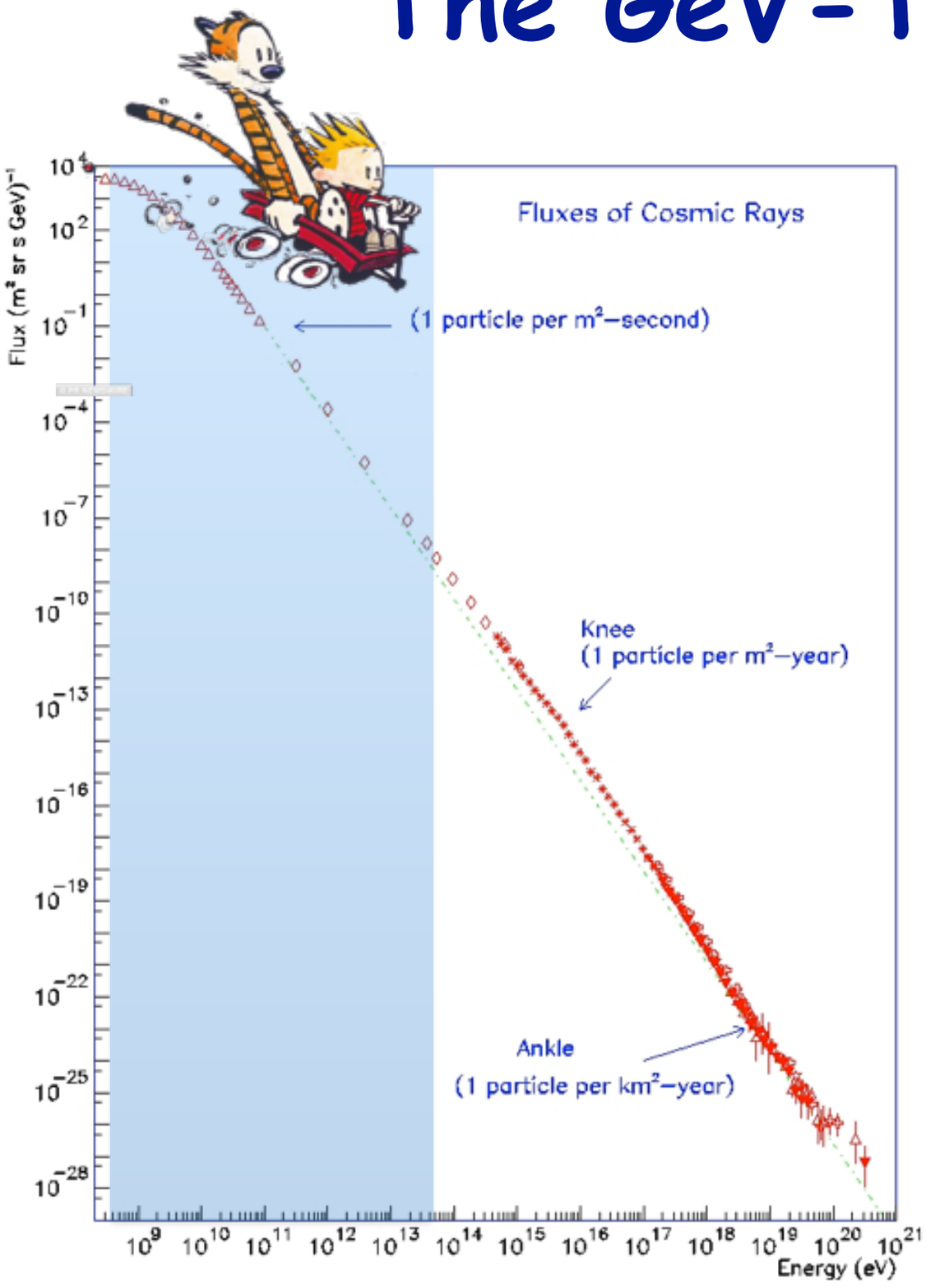
MeV GeV TeV PeV EeV ZeV

SuperNova Remnants & MeV cosmic rays



MeV GeV TeV PeV EeV ZeV

The GeV-TeV domain



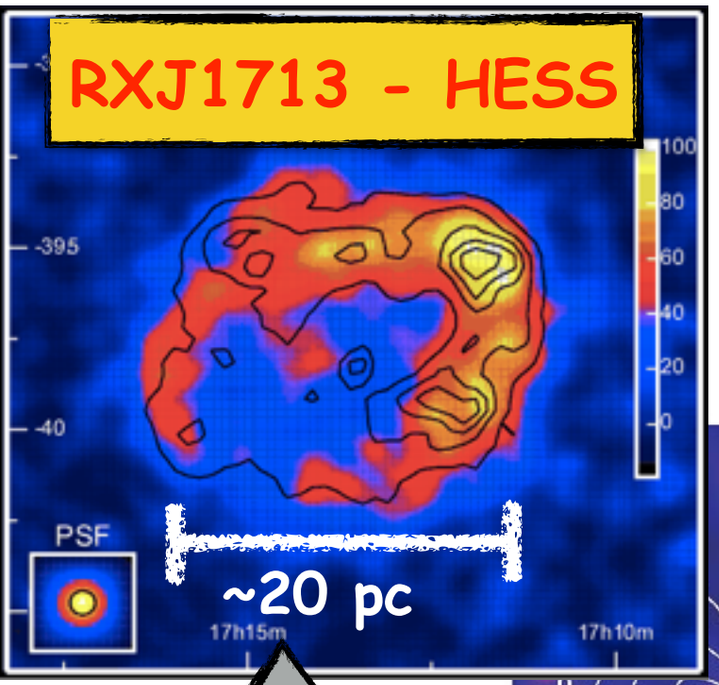
$$R_L(10\ \mathrm{GeV}) \sim 1.2 \times 10^{13}\mathrm{cm}$$

Galactic cosmic rays

bulk of the energy

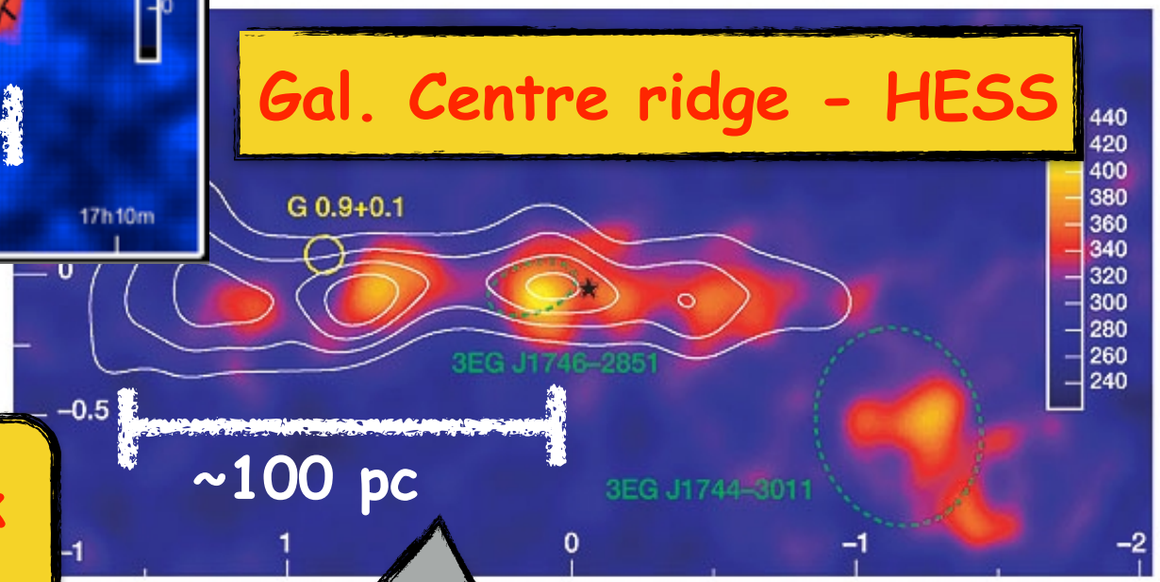
MeV	GeV	TeV	PeV	EeV	ZeV

The GeV-TeV domain: gamma rays



CR + ISM

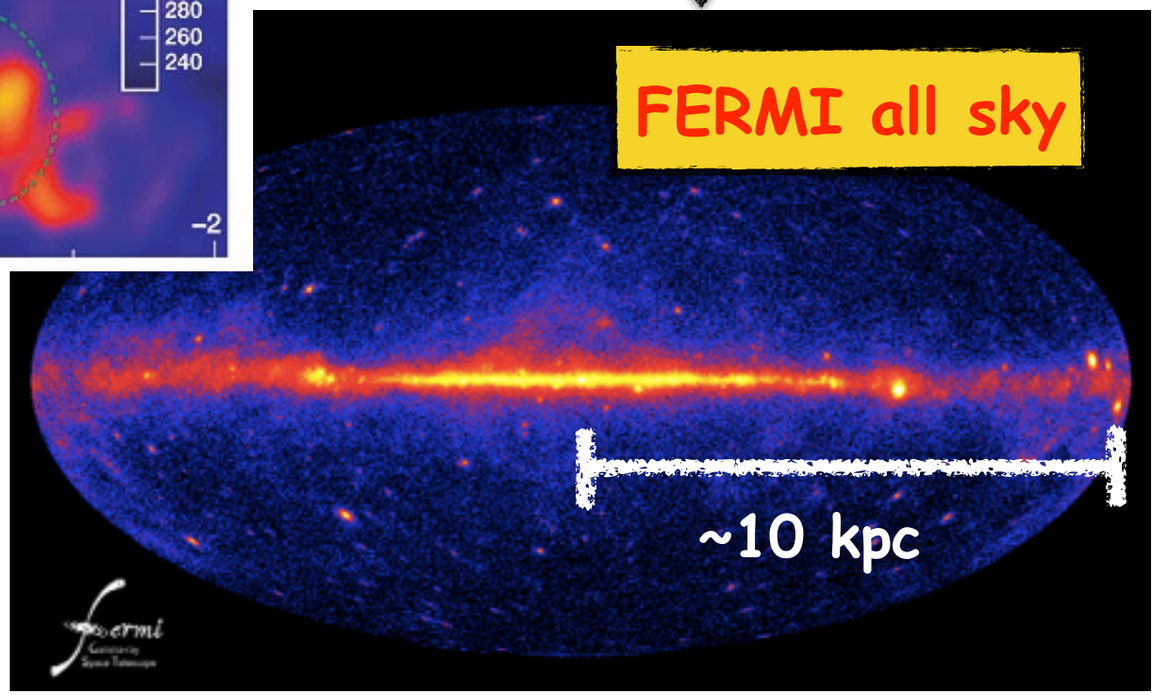
$$p + p \rightarrow p + p + \pi^0 \qquad \pi^0 \rightarrow \gamma + \gamma$$



diffusive shock acceleration

CR transport close to sources

CR transport on Galactic scale

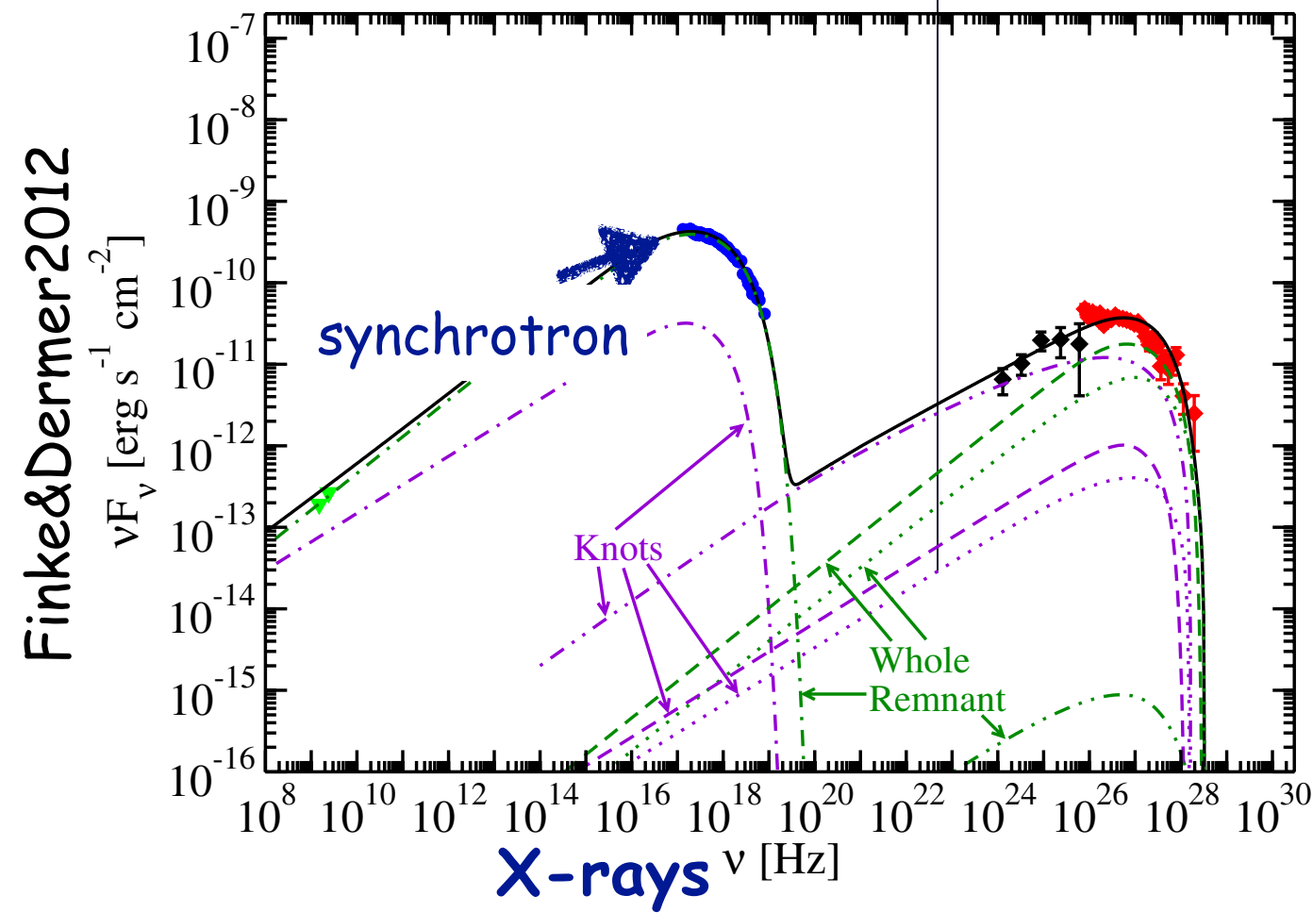


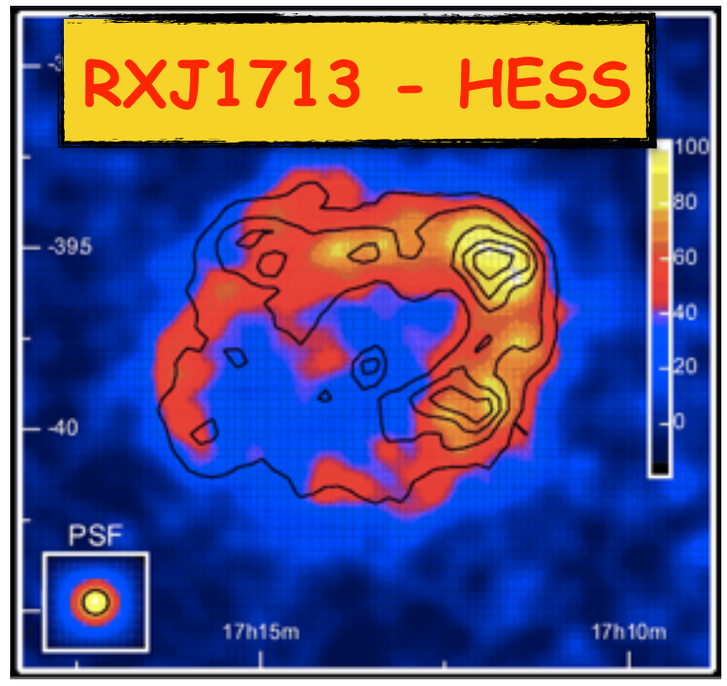
MeV | GeV | TeV | PeV | EeV | ZeV

γ-rays: leptonic or hadronic?

Leptonic…

RXJ 1713



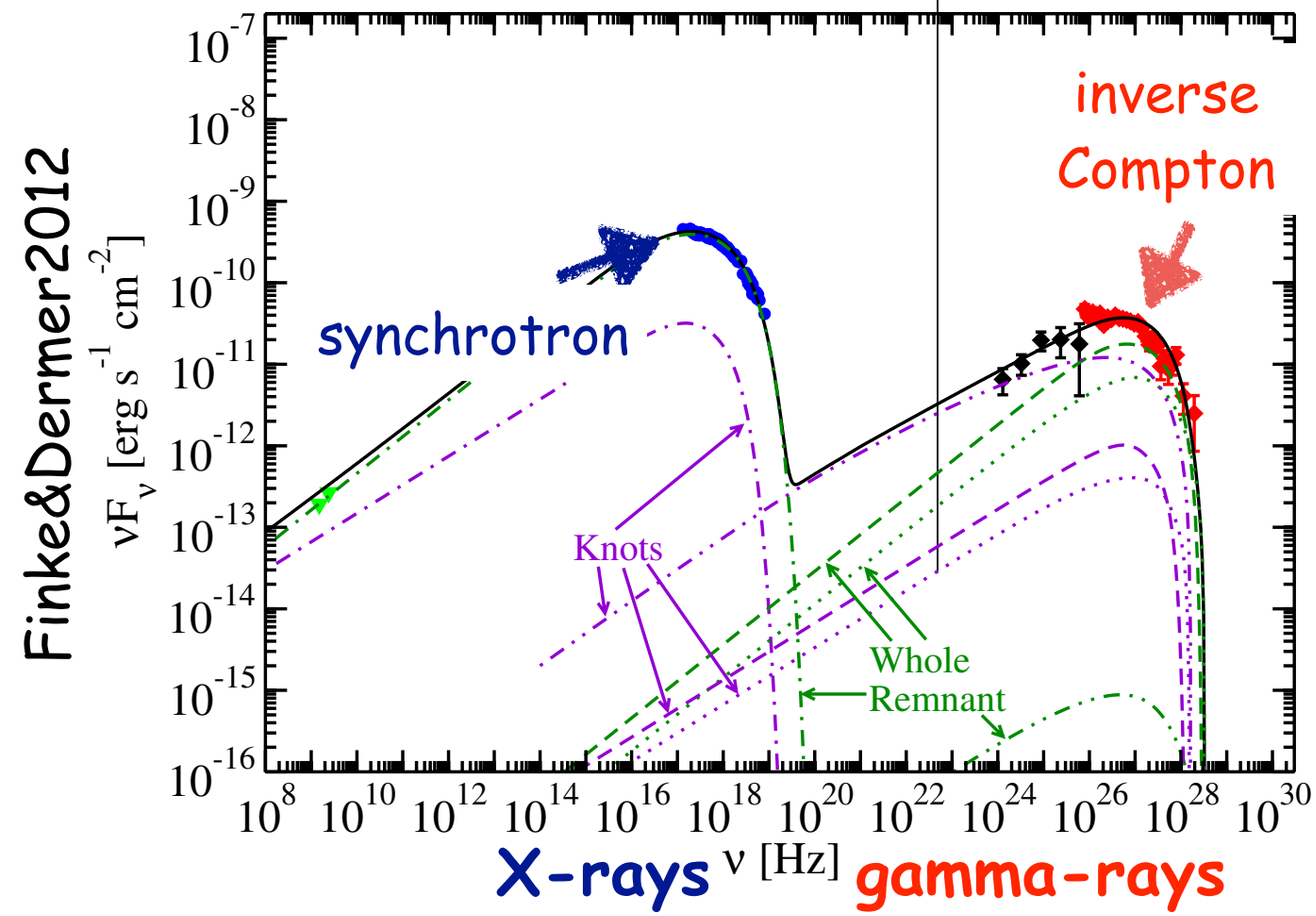


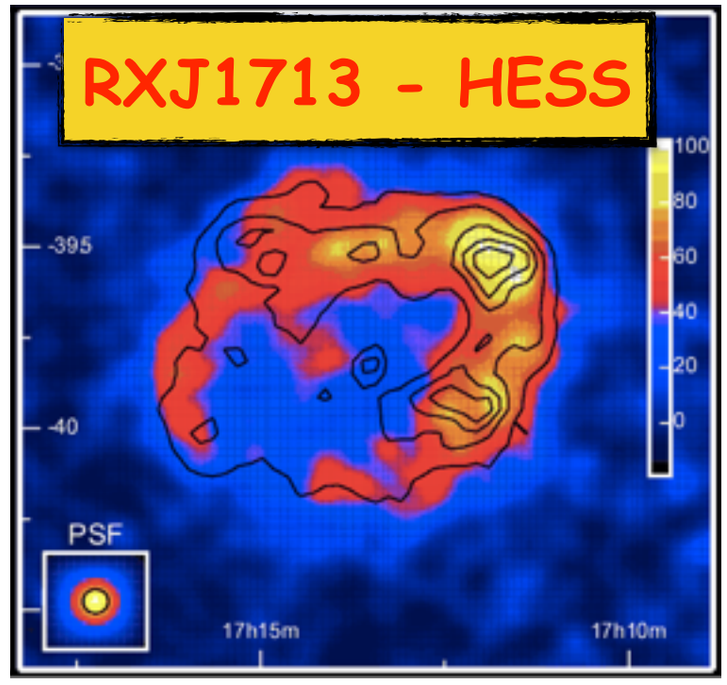
MeV	GeV	TeV	PeV	EeV	ZeV

γ-rays: leptonic or hadronic?

Leptonic…

RXJ 1713





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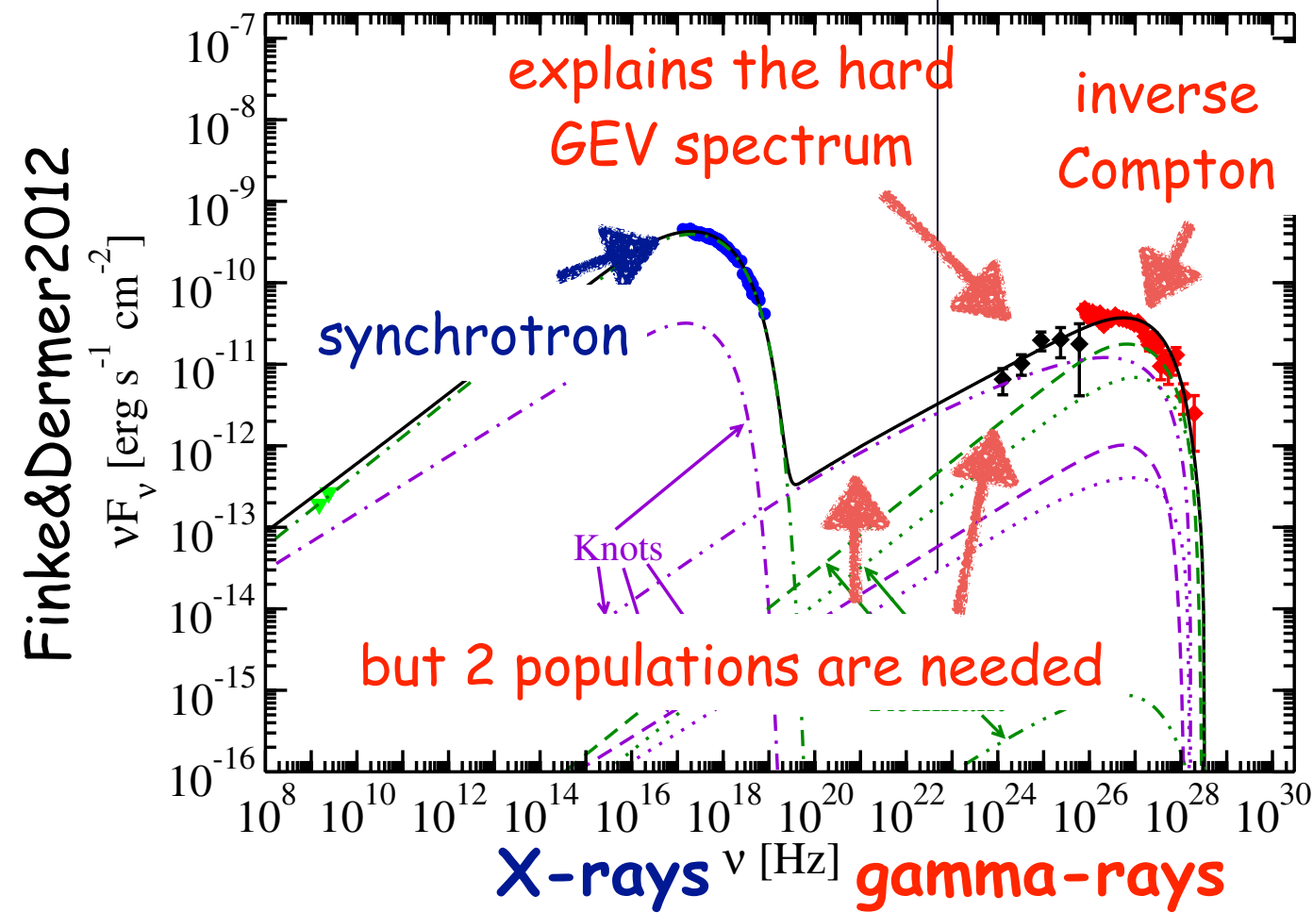

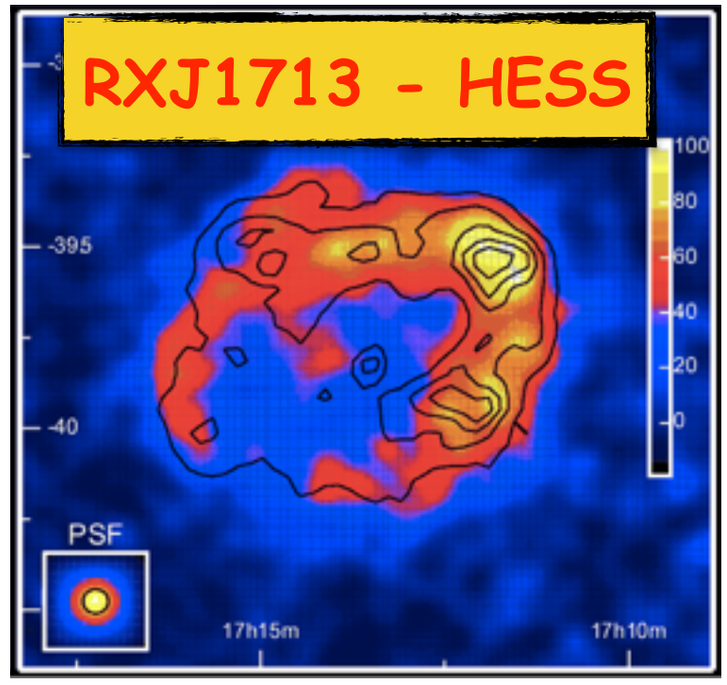

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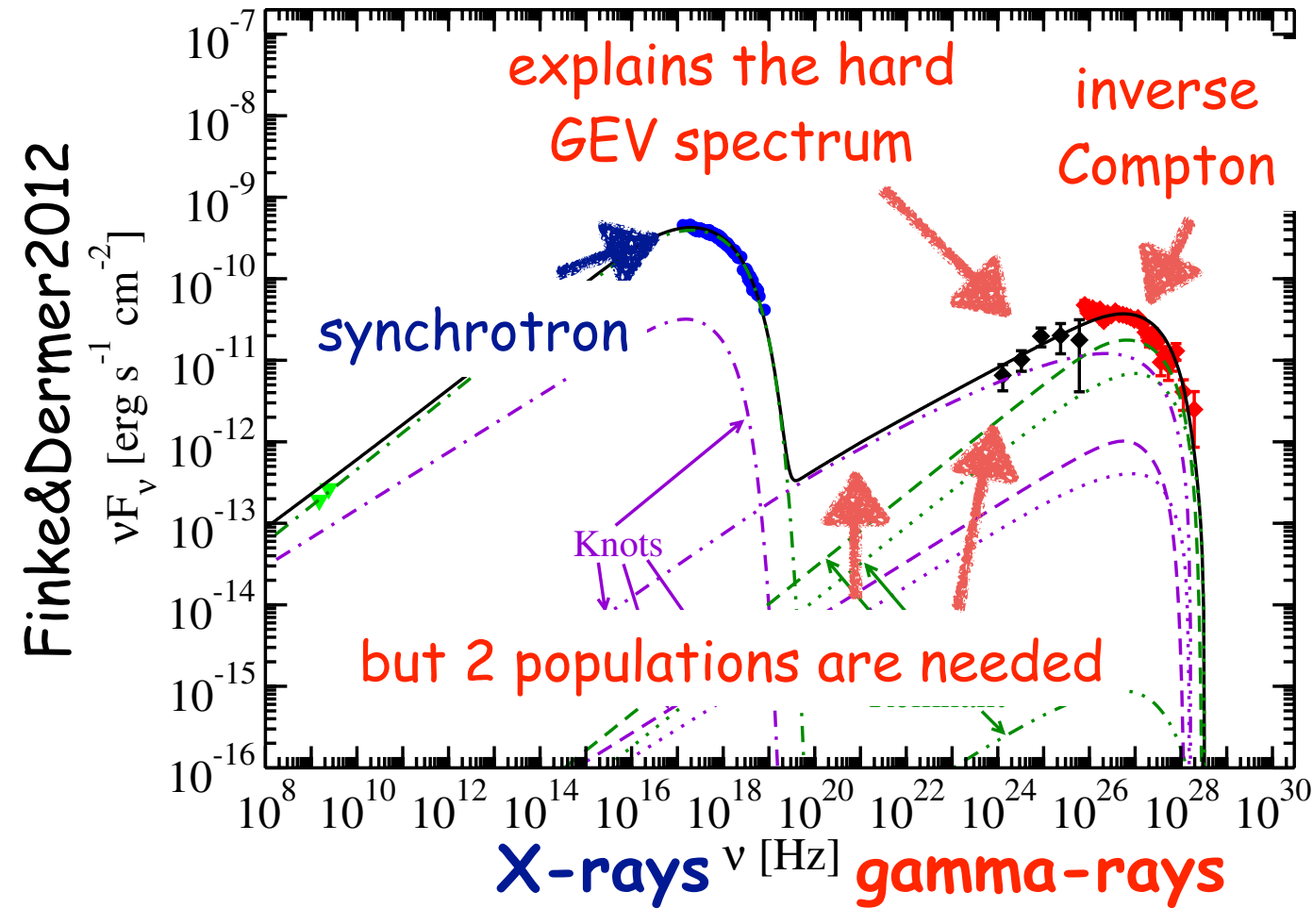

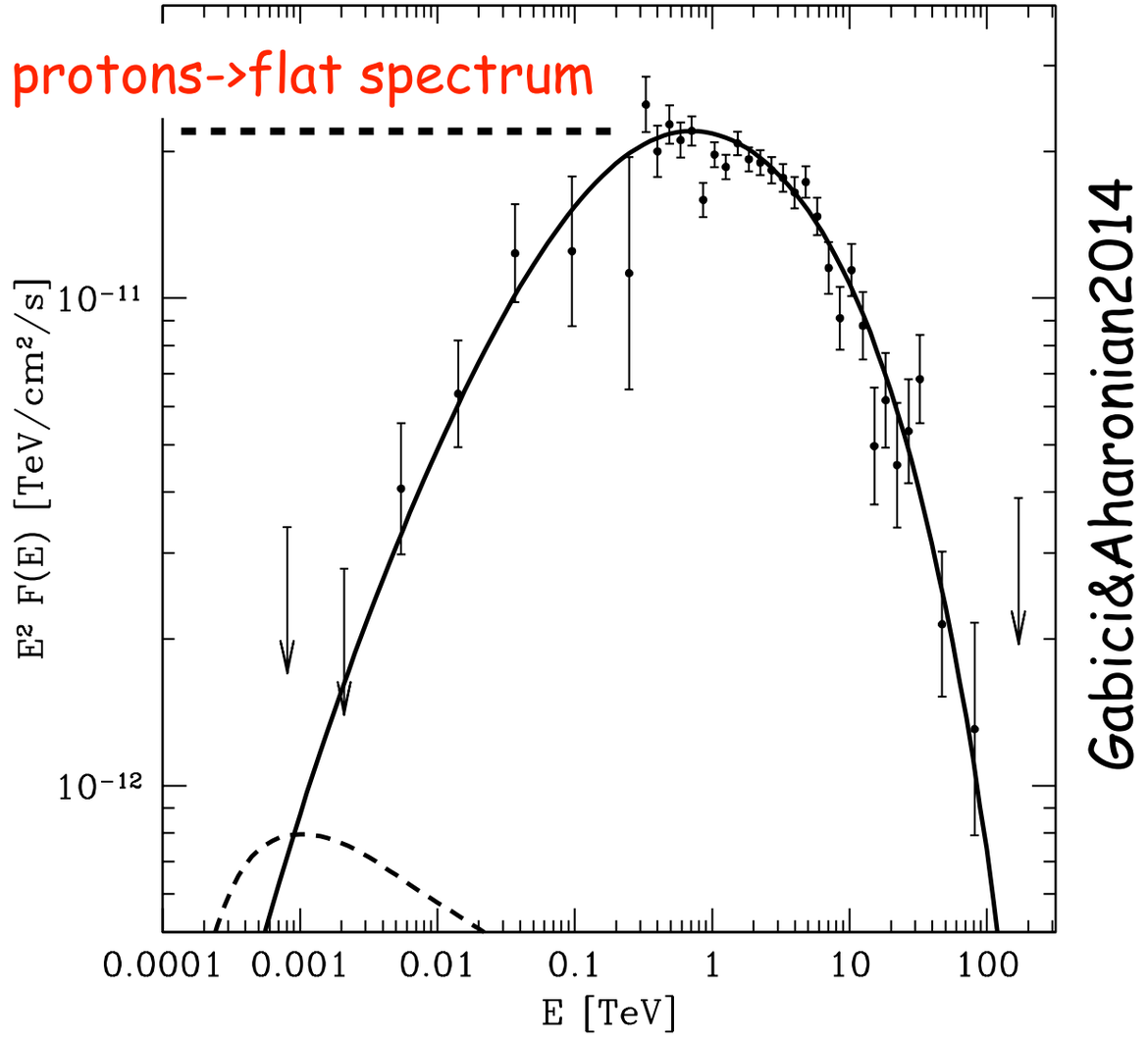

MeV | GeV | TeV | PeV | EeV | ZeV

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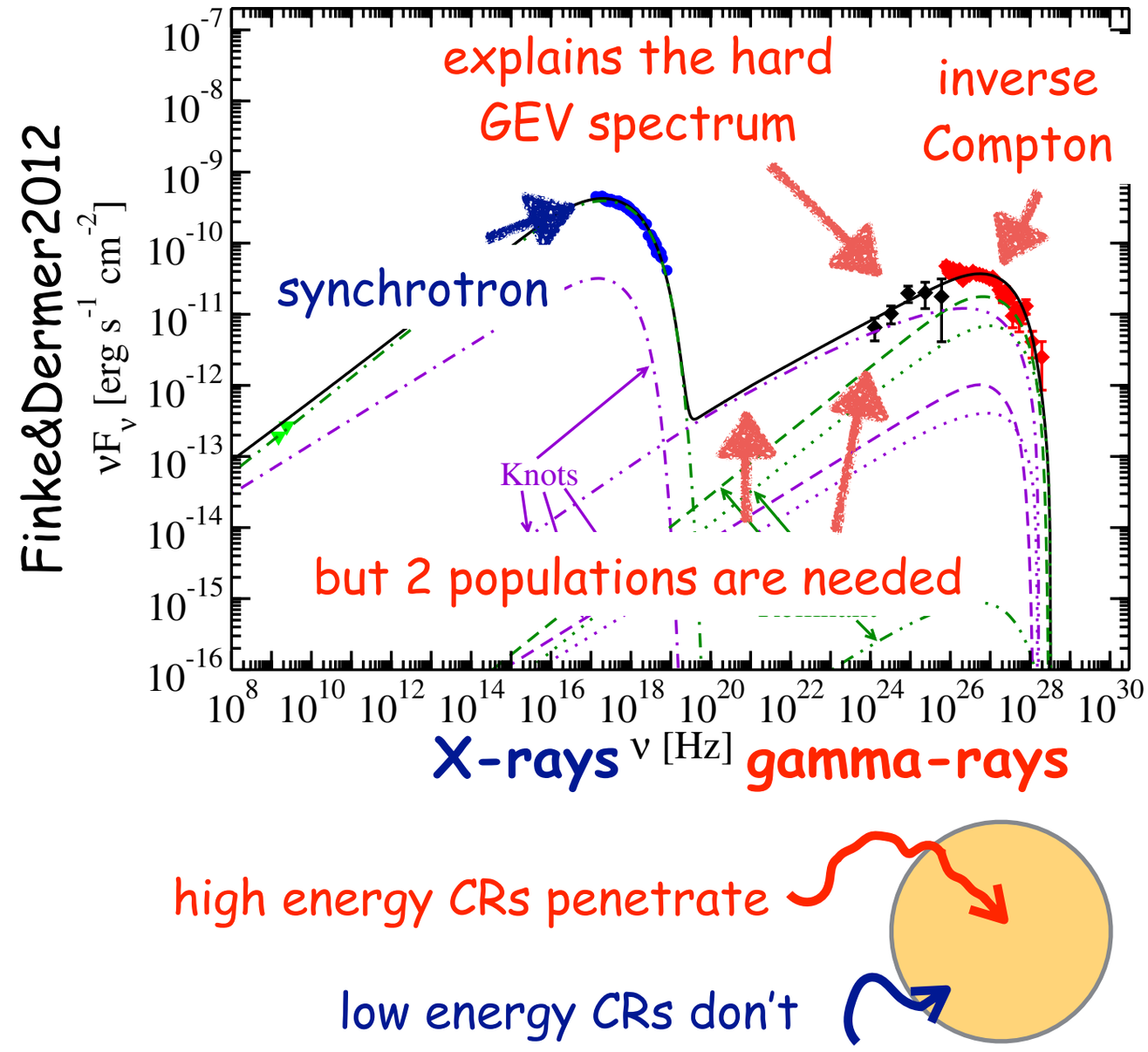
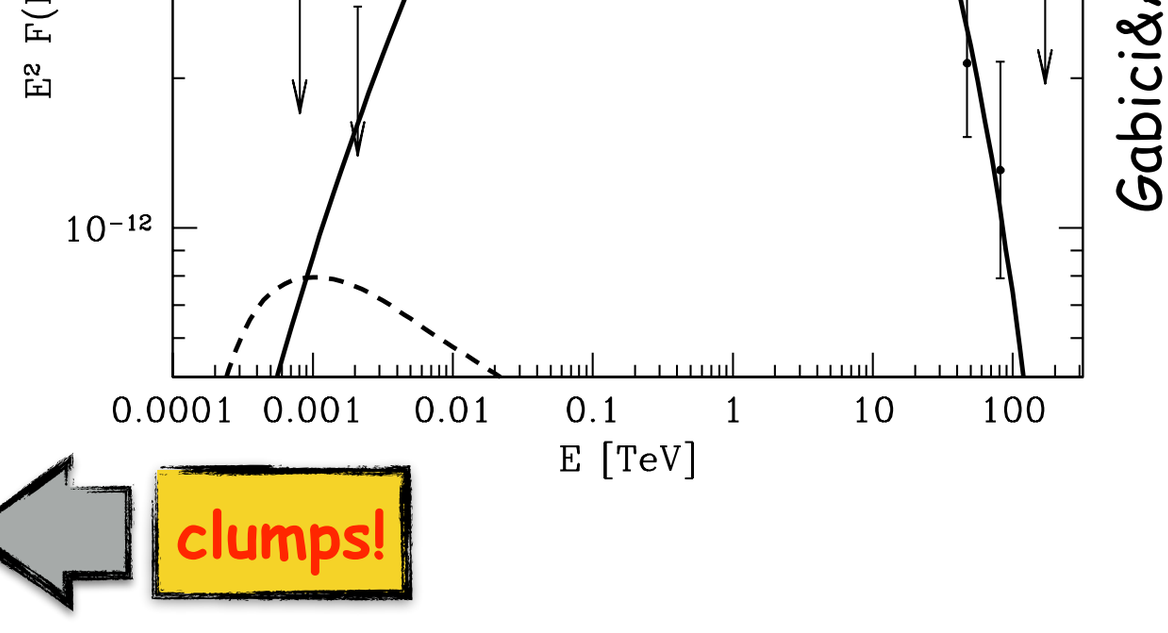


high energy CRs penetrate

low energy CRs don't

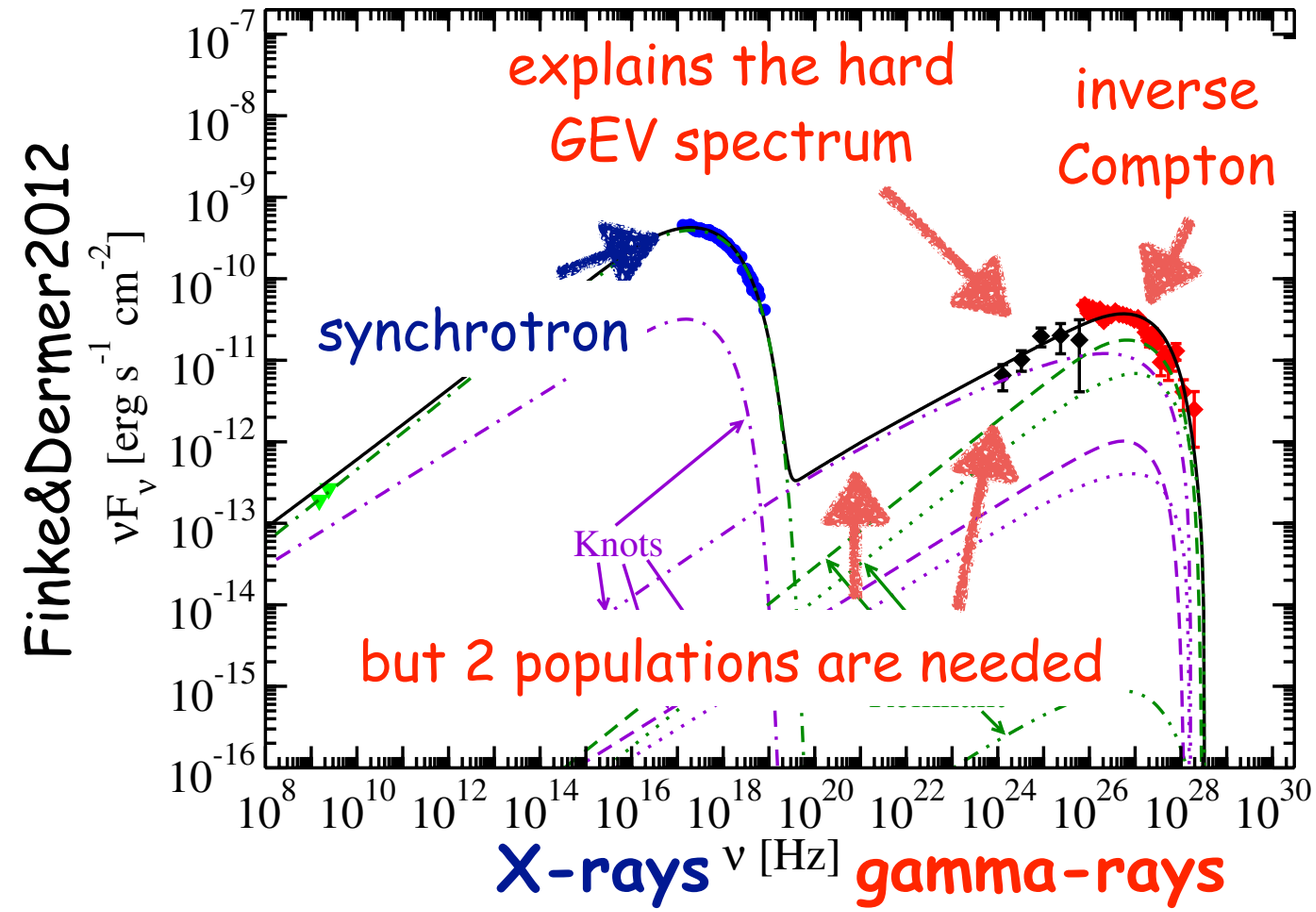


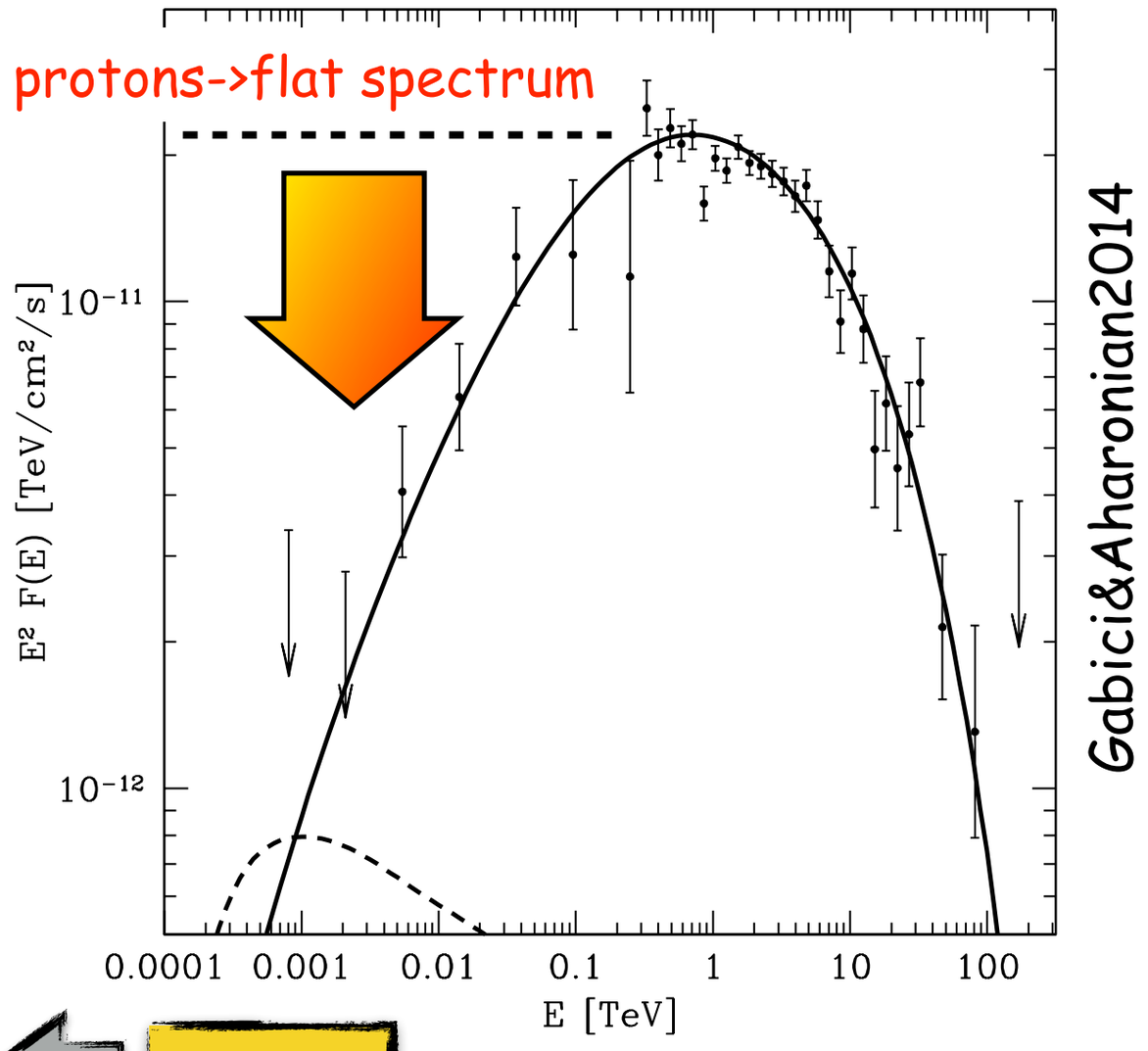
clumps!

MeV	GeV	TeV	PeV	EeV	ZeV

γ-rays: leptonic or hadronic?

Leptonic… **RXJ 1713** **…or hadronic?**





high energy CRs penetrate

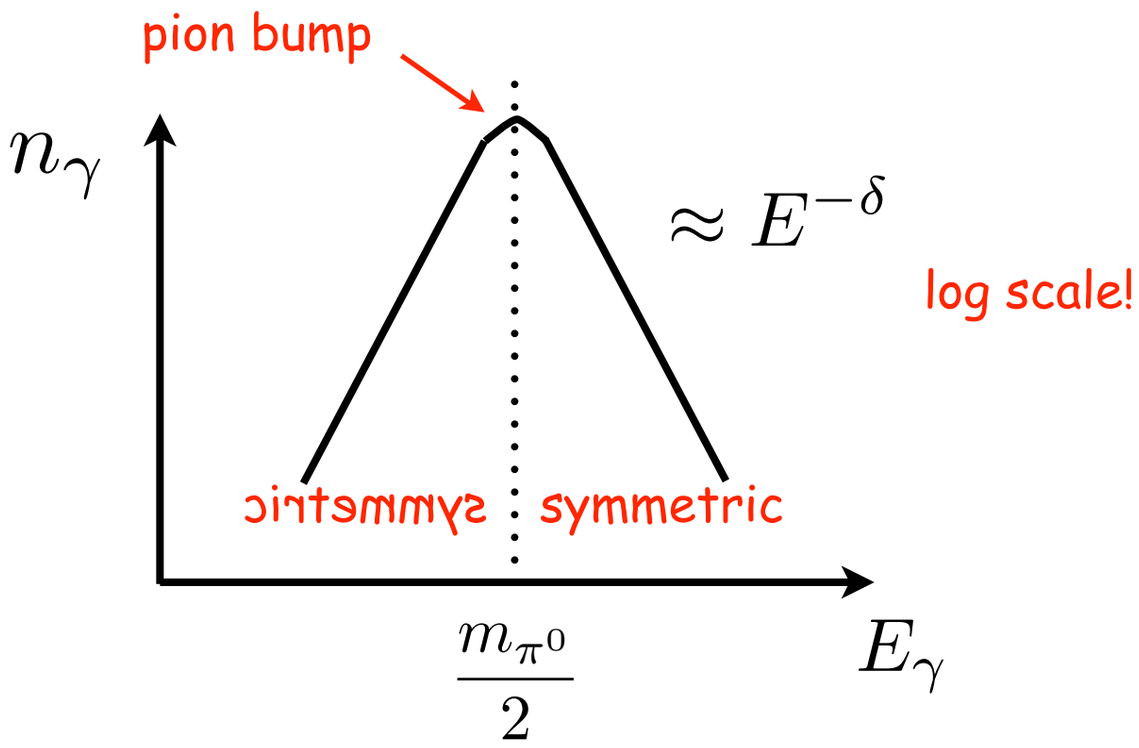
low energy CRs don't

clumps!

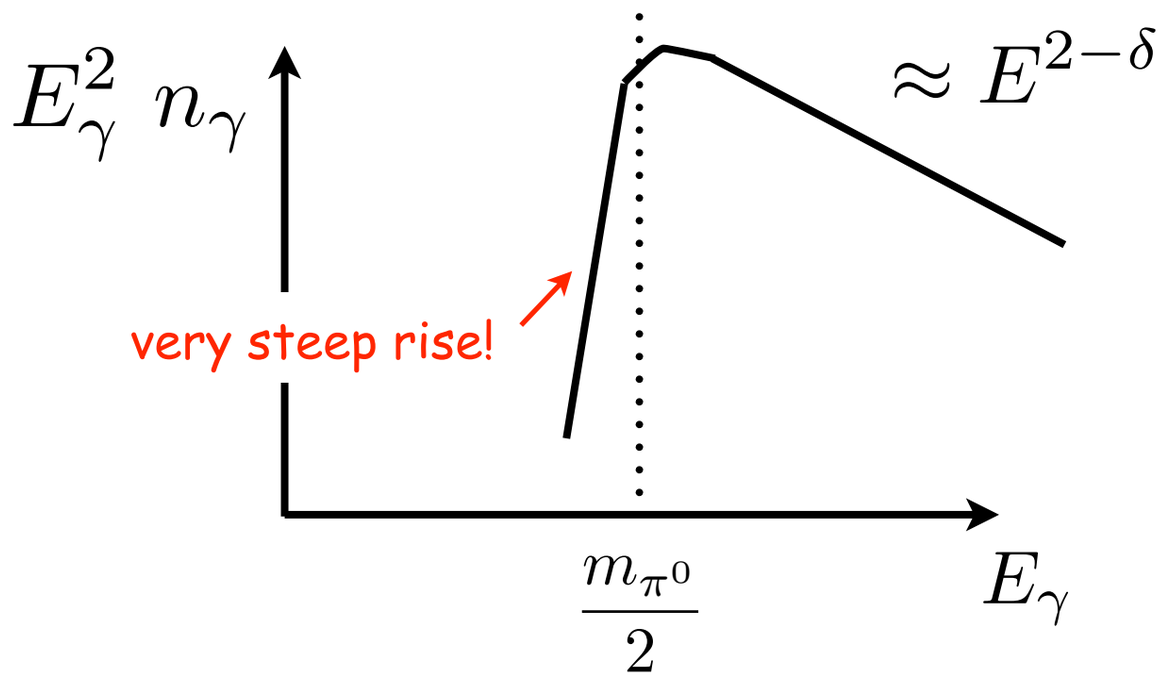
see also Ellison+ 2010 for leptonic, Zirakashvili+ 2010,Fukui+2012 for hadronic

MeV	GeV	TeV	PeV	EeV	ZeV

Do SNRs accelerate protons?



log scale!

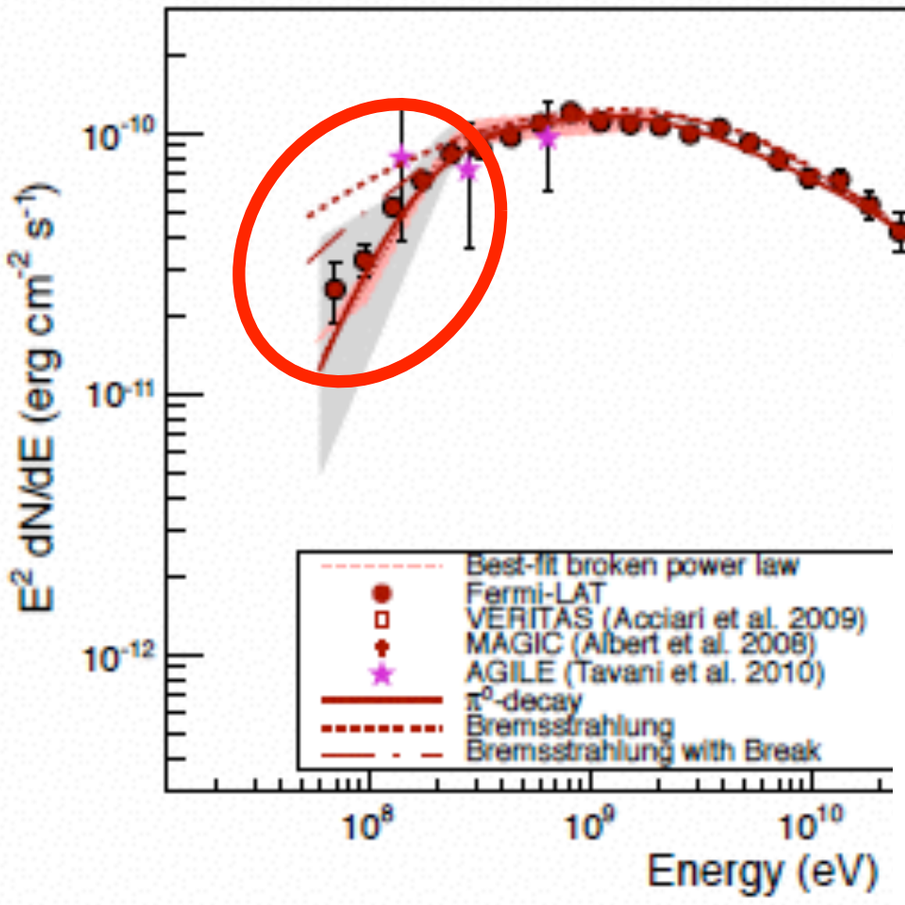


Do SNRs accelerate protons?

(Ackermann et al 2013)

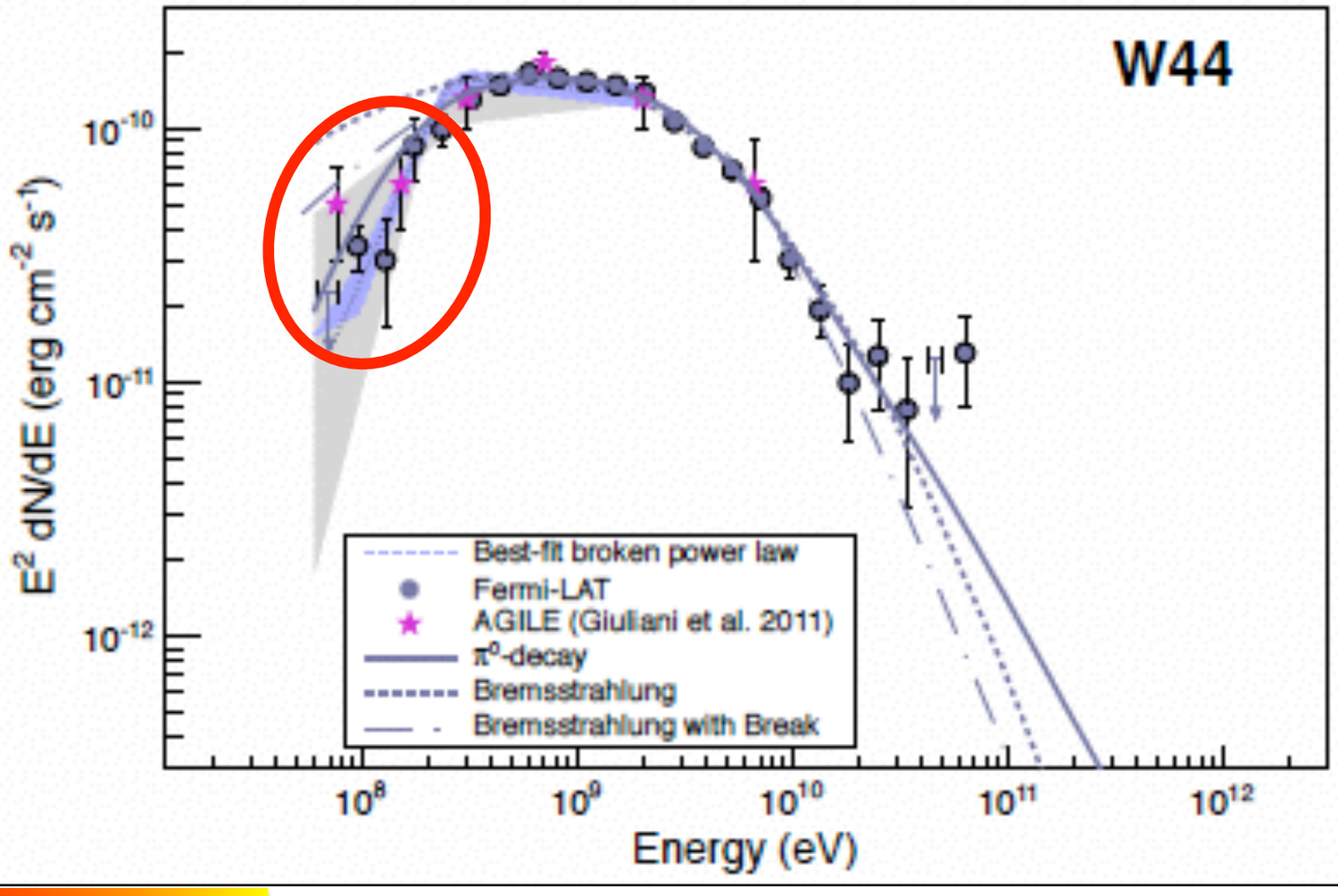
FERMI (and AGILE)

(Giuliani+, Cardillo+)



n_γ ↑

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



MeV | GeV TeV | PeV | EeV | ZeV

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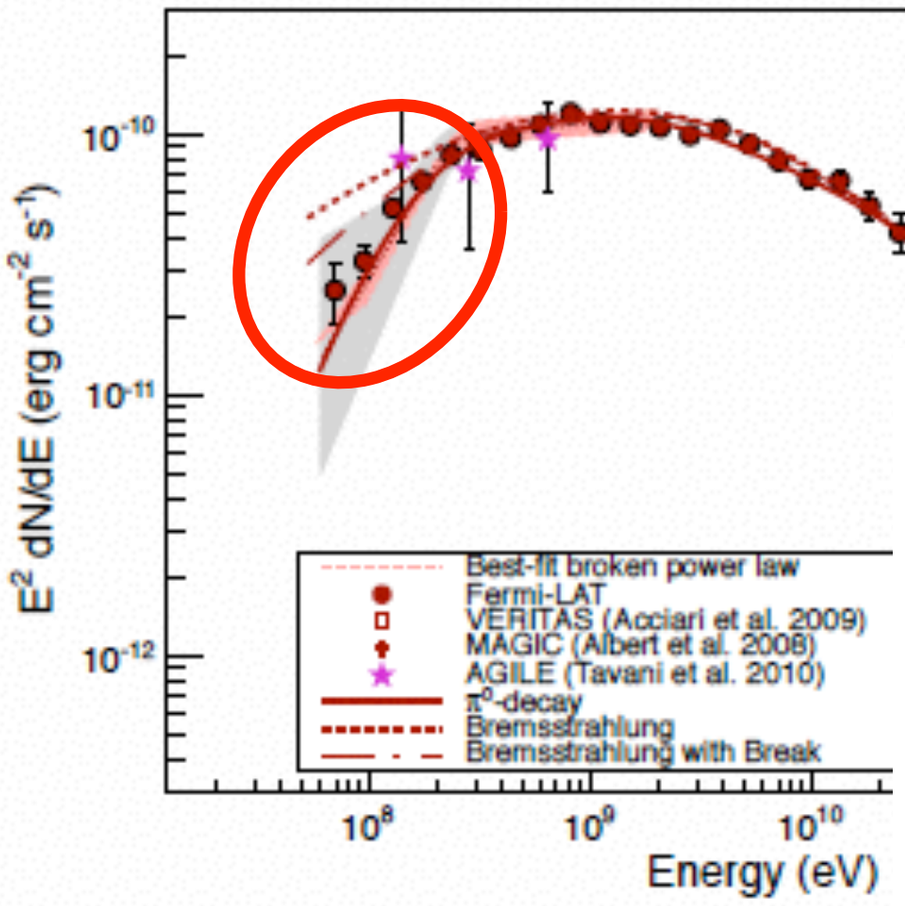
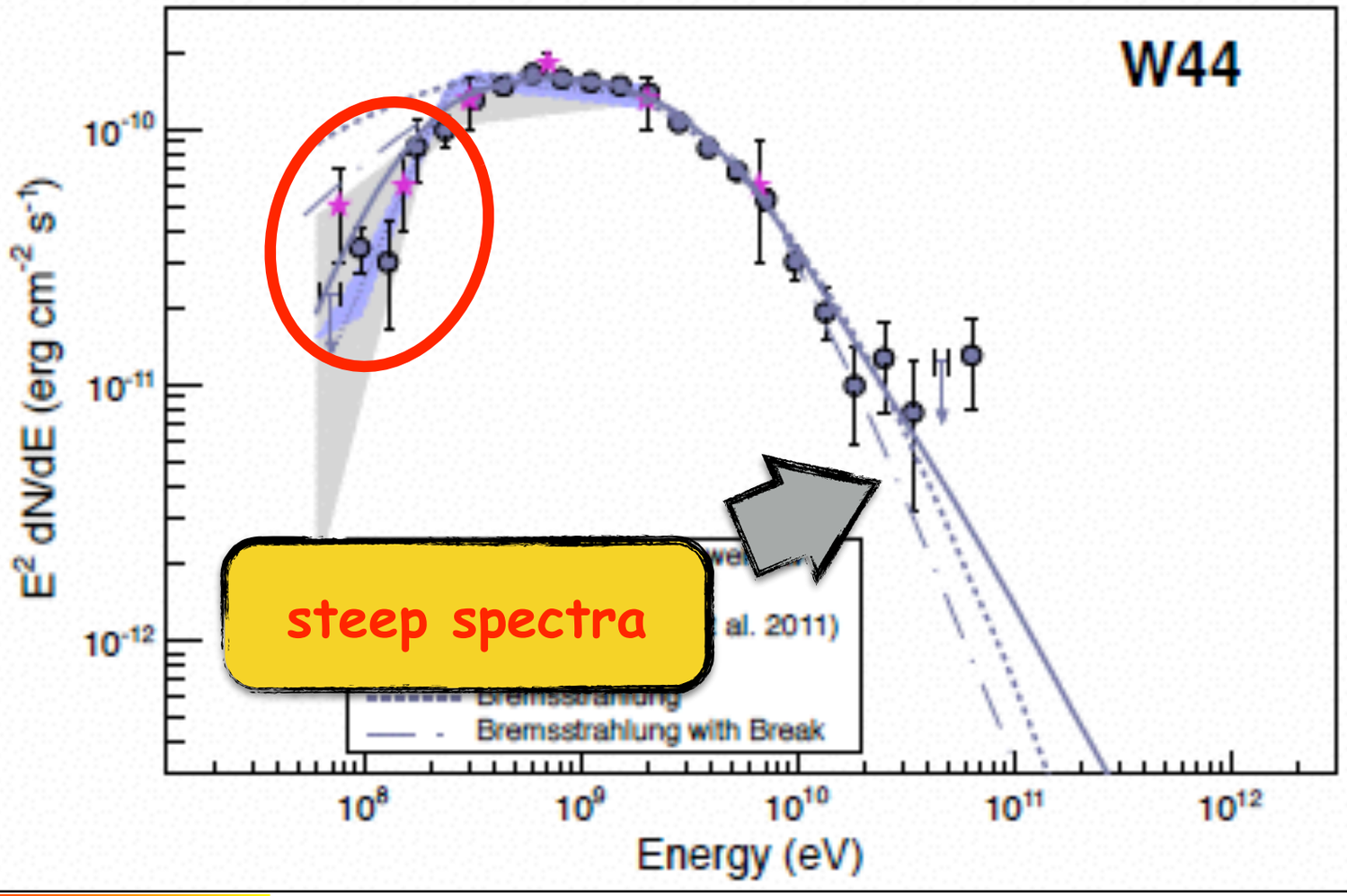


FERMI (and **AGILE**)

(Giuliani+, Cardillo+)

$n_\gamma \uparrow$

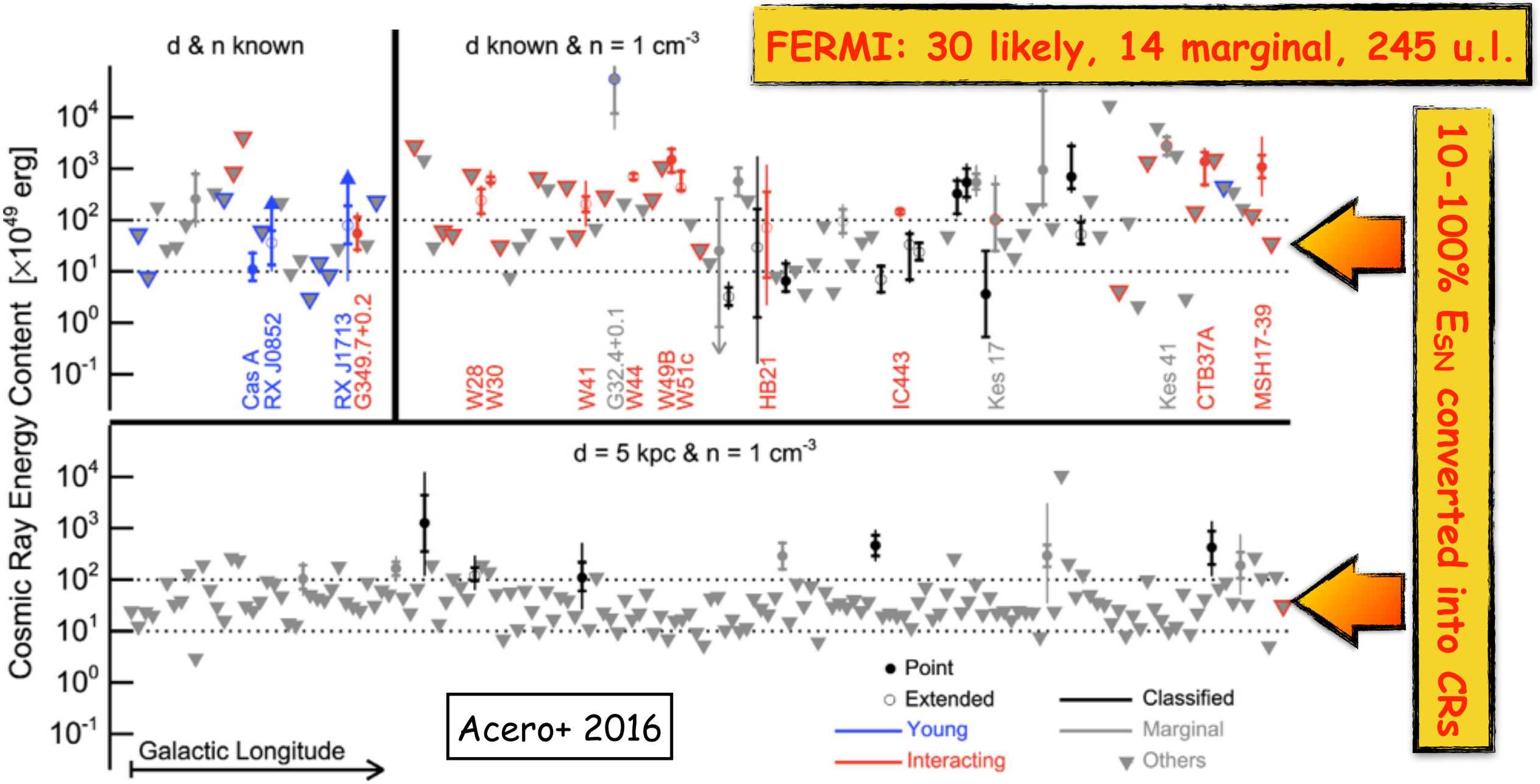
$\approx E^{2-\delta}$



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

MeV	GeV	TeV	PeV	EeV	ZeV

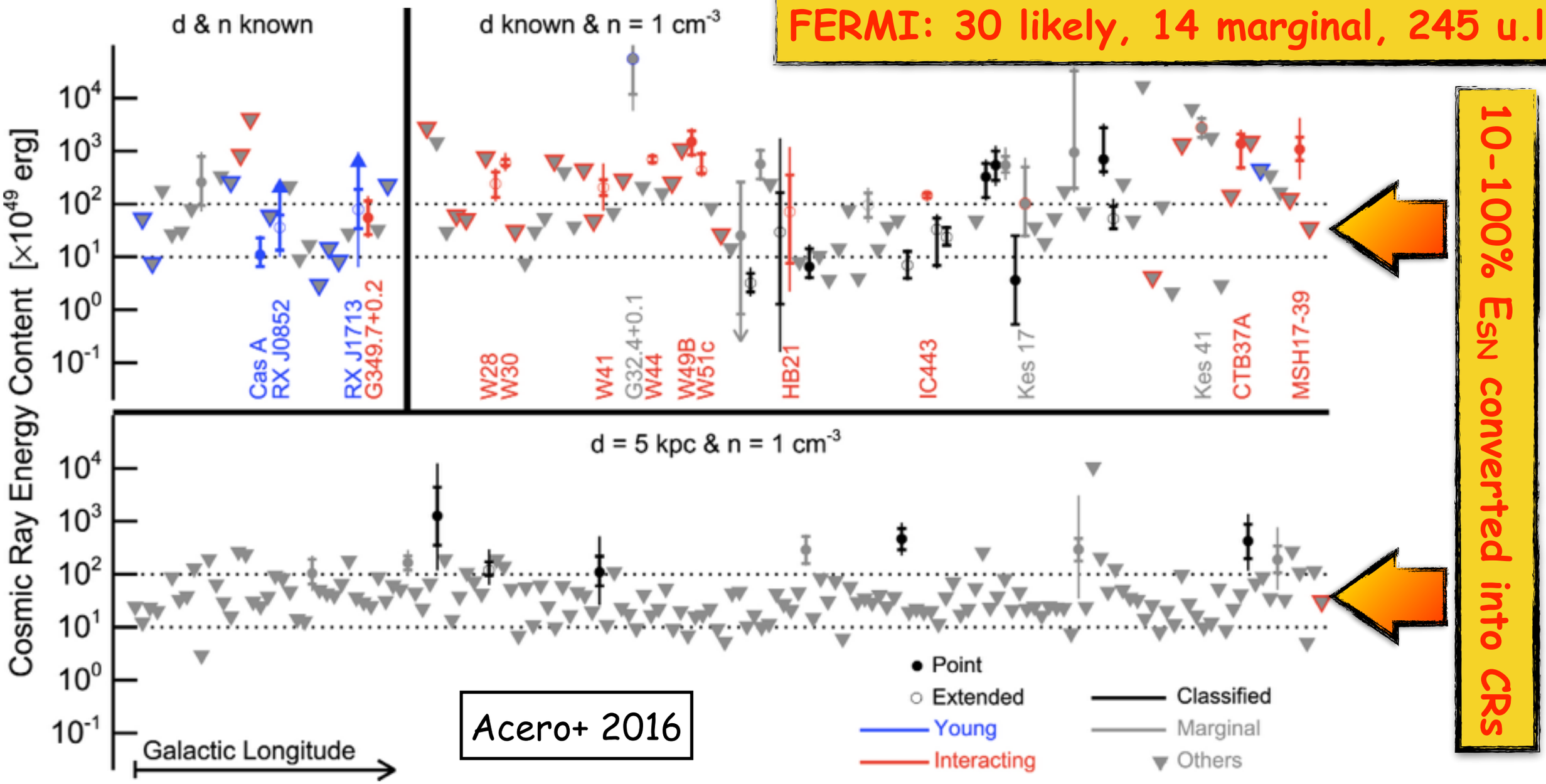
FERMI SNR catalogue and HESS survey



MeV | GeV | TeV | PeV | EeV | ZeV

FERMI SNR catalogue and HESS survey

FERMI: 30 likely, 14 marginal, 245 u.l.



10-100% E_{SN} converted into CRs

Acero+ 2016

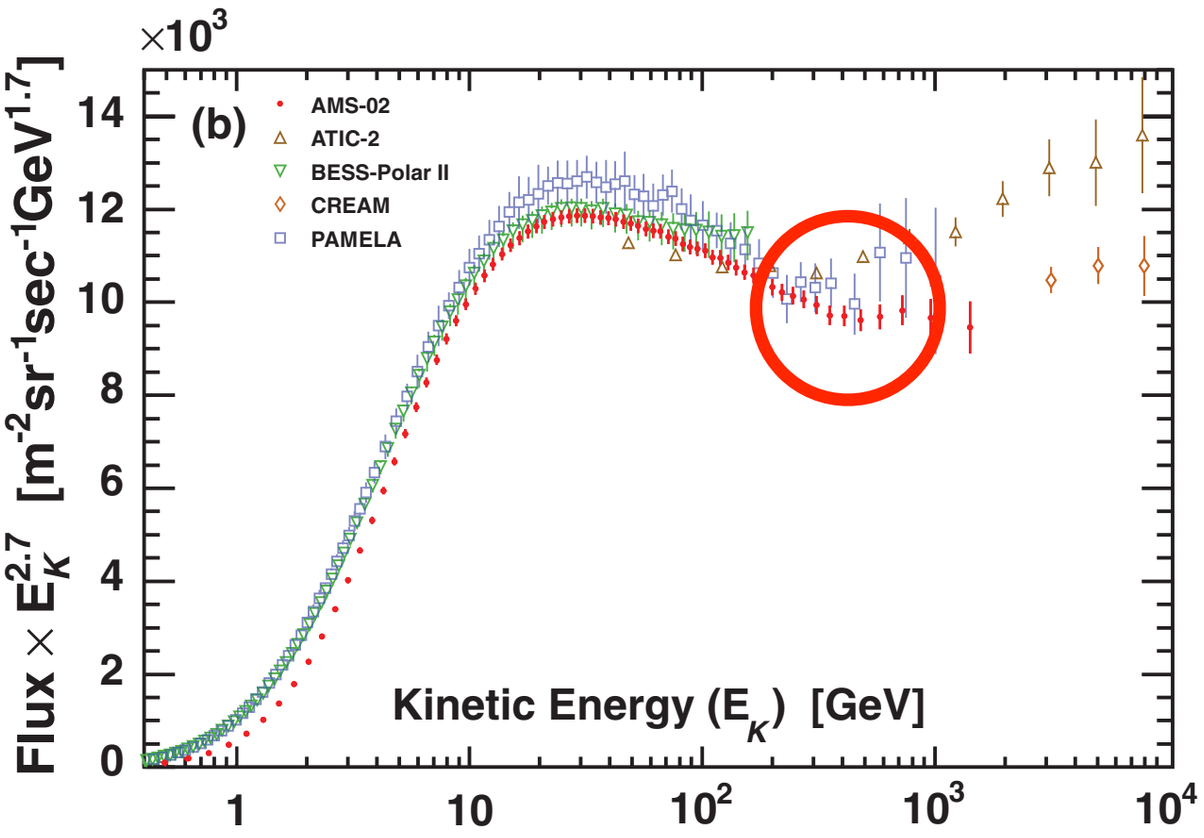
HESS: # of SNRs in Gal. plane survey is OK with expectations

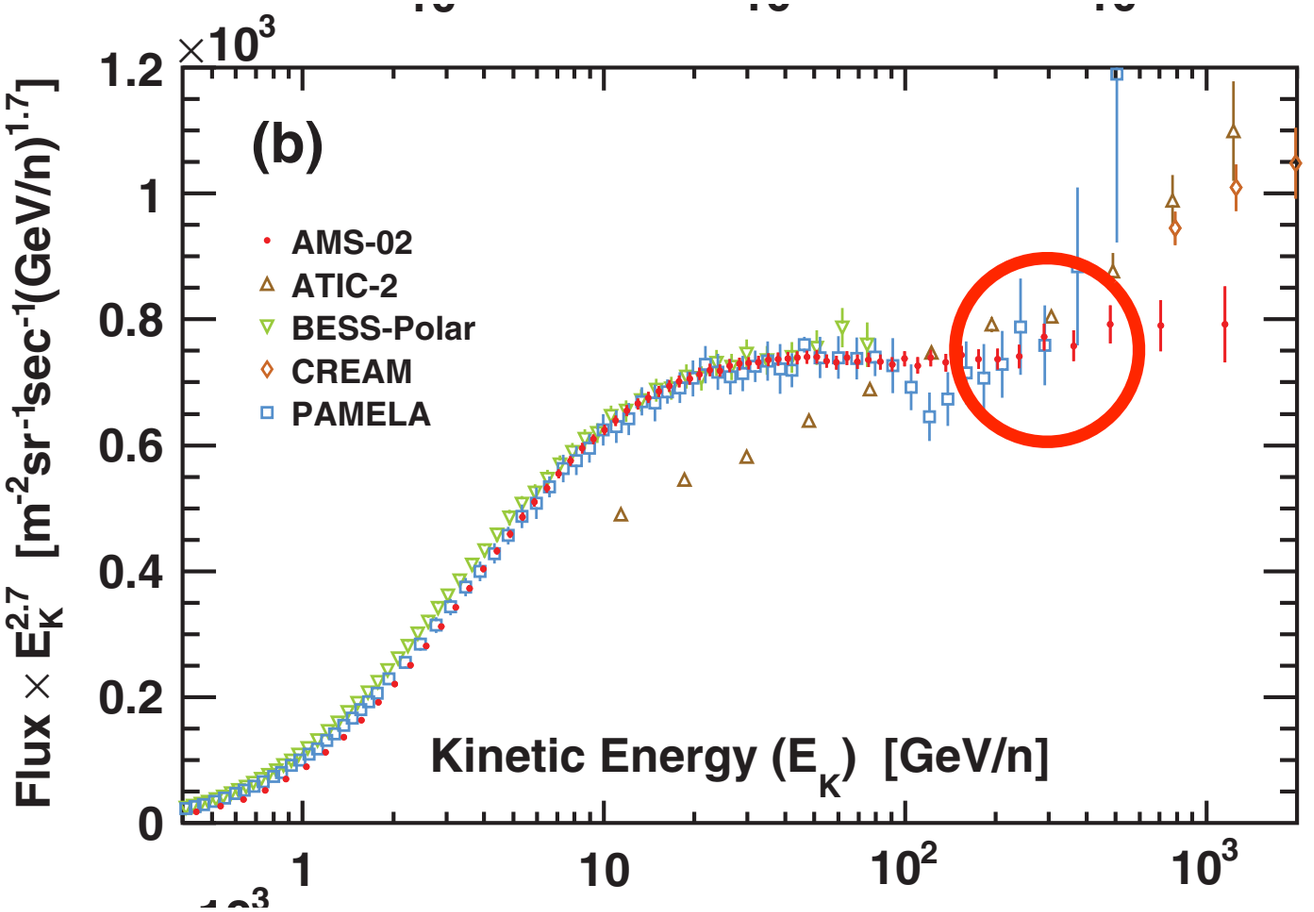
Cristofari+ 2013

MeV | GeV | TeV | PeV | EeV | ZeV

PAMELA, AMS 02

breaks in H and He spectra pf CRs



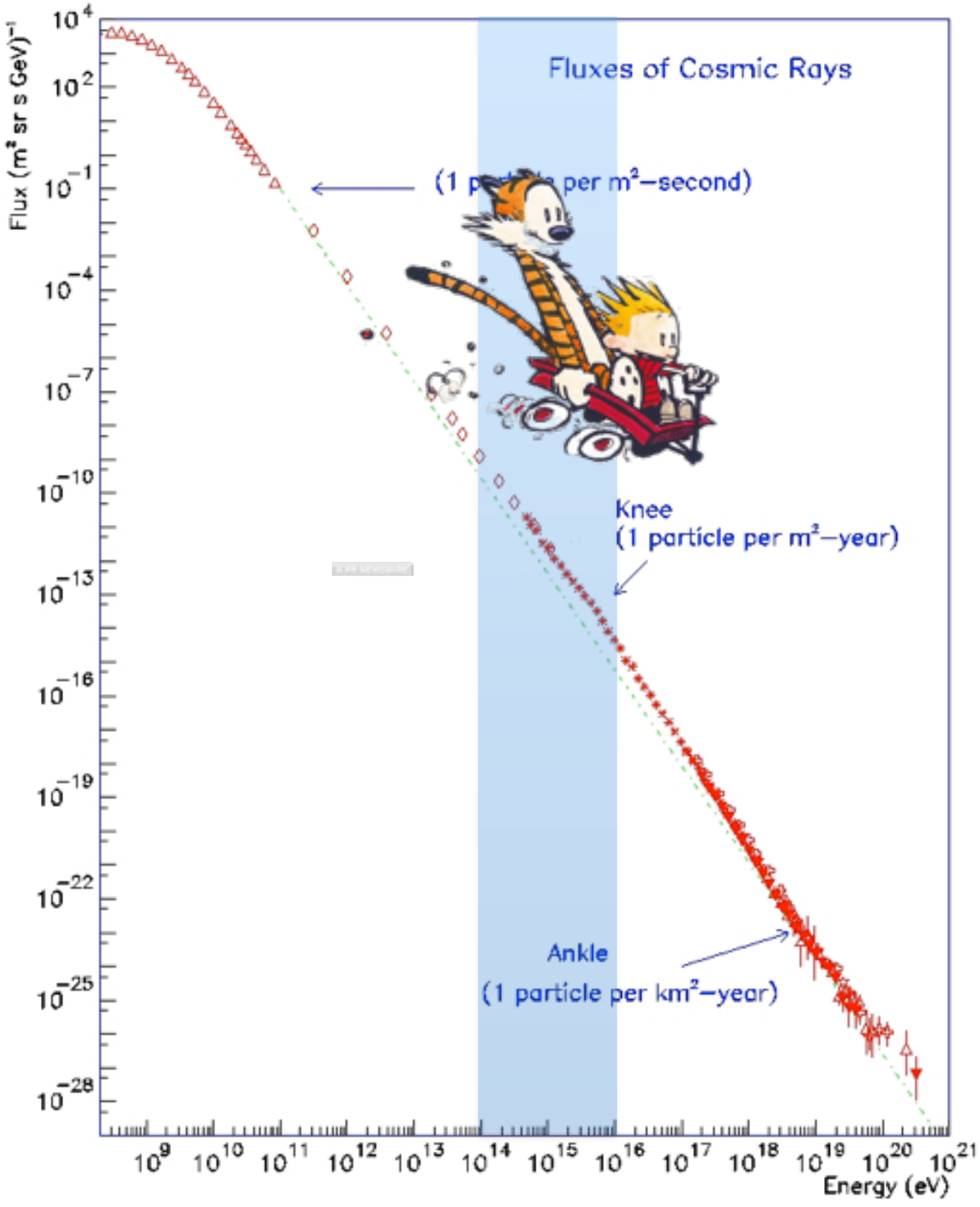


the breaks, unexpected, tell us something about the acceleration and/or propagation of CRs

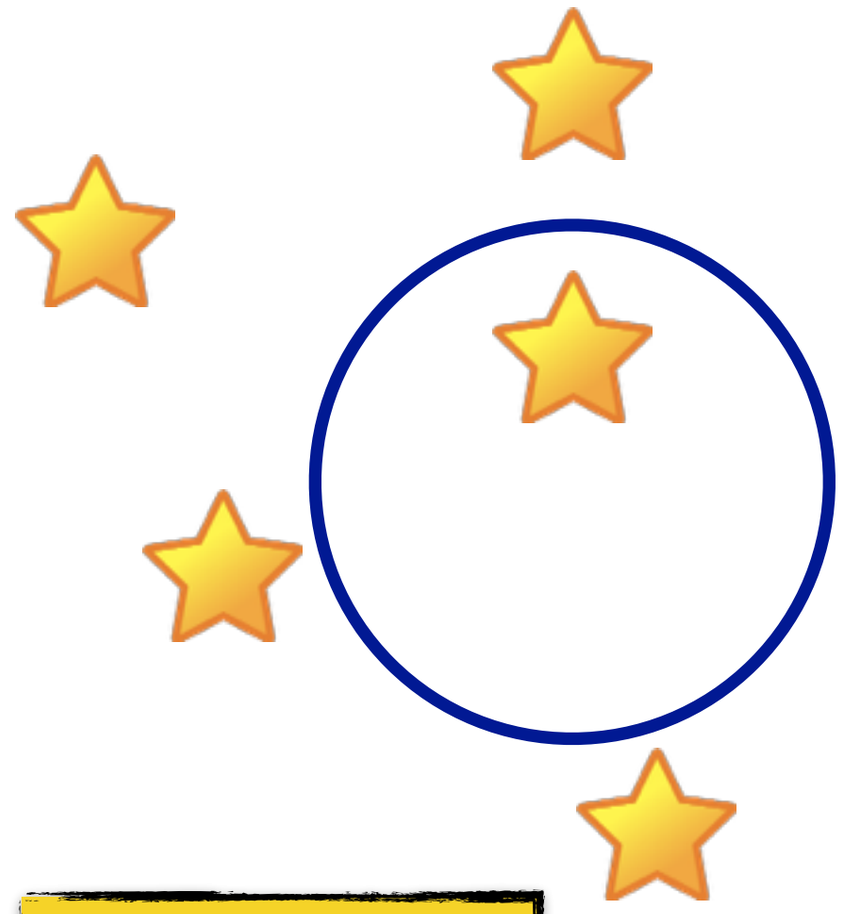
PAMELA -> Adriani+ 2011, 2013 ::: AMS 02 -> Aguilar+ 2015

MeV | GeV TeV | PeV | EeV | ZeV

The PeV domain (100 TeV-10 PeV)



$$R_L(1\ \mathrm{PeV}) \sim 0.36\ \mathrm{pc}$$



still Galactic...

MeV	GeV	TeV	PeV	EeV	ZeV

Are SNRs proton PeVatrons?

Theory

Hillas criterium ->

velocity

size

magnetic field

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

Are SNRs proton PeVatrons?

Theory

Hillas criterium ->

velocity

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magnetic field

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

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

MeV GeV TeV **PeV** EeV ZeV

Are SNRs proton PeVatrons?

Theory

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

velocity — size — magnetic field

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

~10 ~3 ~3

100 TeV

Are SNRs proton PeVatrons?

Theory

Hillas criterium ->

velocity size magnetic field

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

B is the only parameter we can play with

$$\left(\frac{u}{0.1c}\right)\left(\frac{R}{1\,\mathrm{pc}}\right)\left(\frac{B}{\mu\mathrm{G}}\right)\mathrm{TeV}$$

~10 ~3 ~3

100 TeV

MeV GeV TeV **PeV** EeV ZeV

Are SNRs proton PeVatrons?

Theory

Hillas criterium ->

velocity, size, magnetic field

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

$$\left(\frac{u}{10^{-2}}\right)\left(\frac{R}{1\,\mathrm{pc}}\right)\left(\frac{B}{\mu\mathrm{G}}\right)\mathrm{TeV}$$

~10 ~3 ~3

B is the only parameter we can play with

100 TeV

B-field amplification

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

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

ram pressure — B field

Bell+ 2004…2013

MeV GeV TeV **PeV** EeV ZeV

Are SNRs proton PeVatrons?

Theory

Hillas criterium ->

velocity · size · magnetic field

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

$$\left(\frac{u}{10^4\ \mathrm{km\,s^{-1}}}\right)\left(\frac{R}{1\ \mathrm{pc}}\right)\left(\frac{B}{\mu\mathrm{G}}\right)\ \mathrm{TeV}$$

~10 · ~3 · ~3

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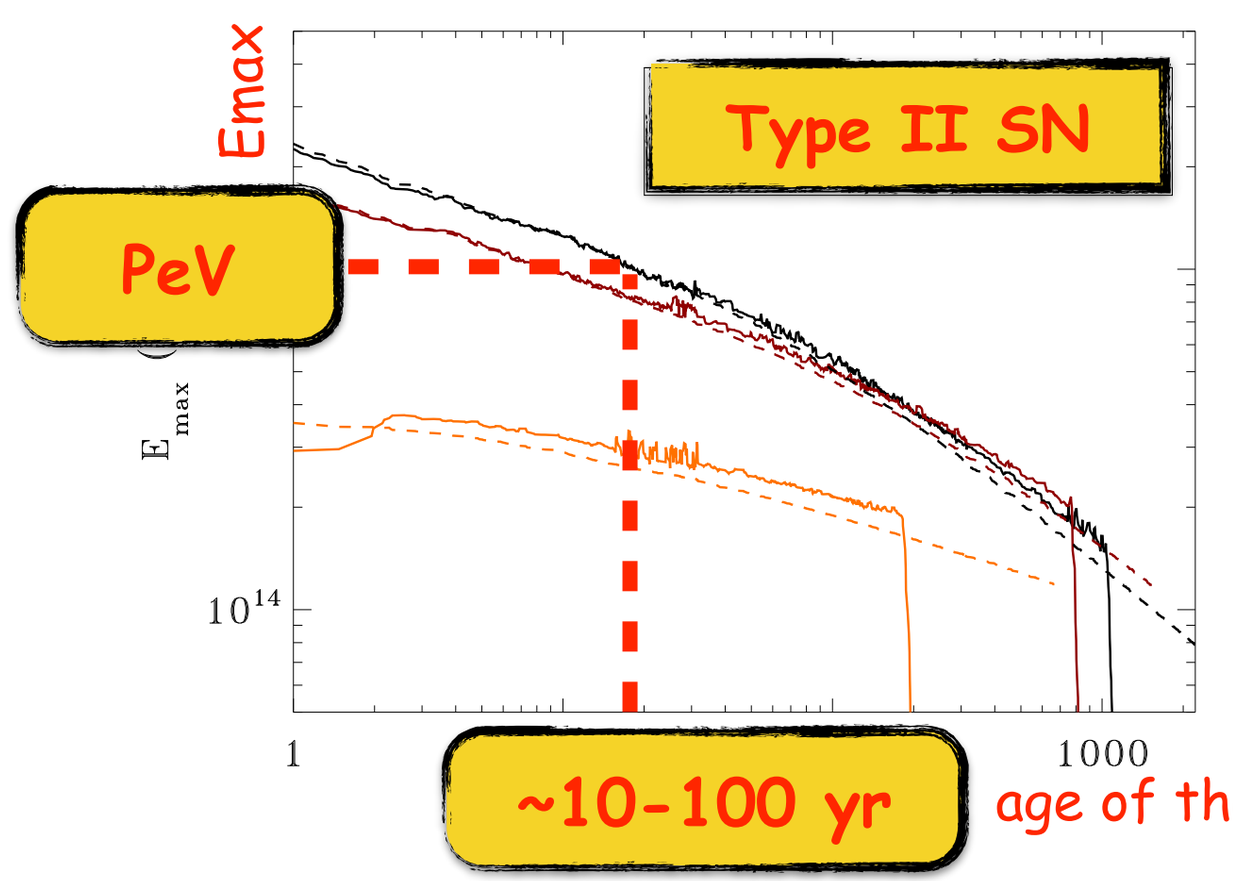

Schure & Bell 2013/2014

MeV · GeV · TeV · **PeV** · EeV · ZeV

Are SNRs proton PeVatrons?

Theory

Hillas criterium ->

velocity, size, magnetic field

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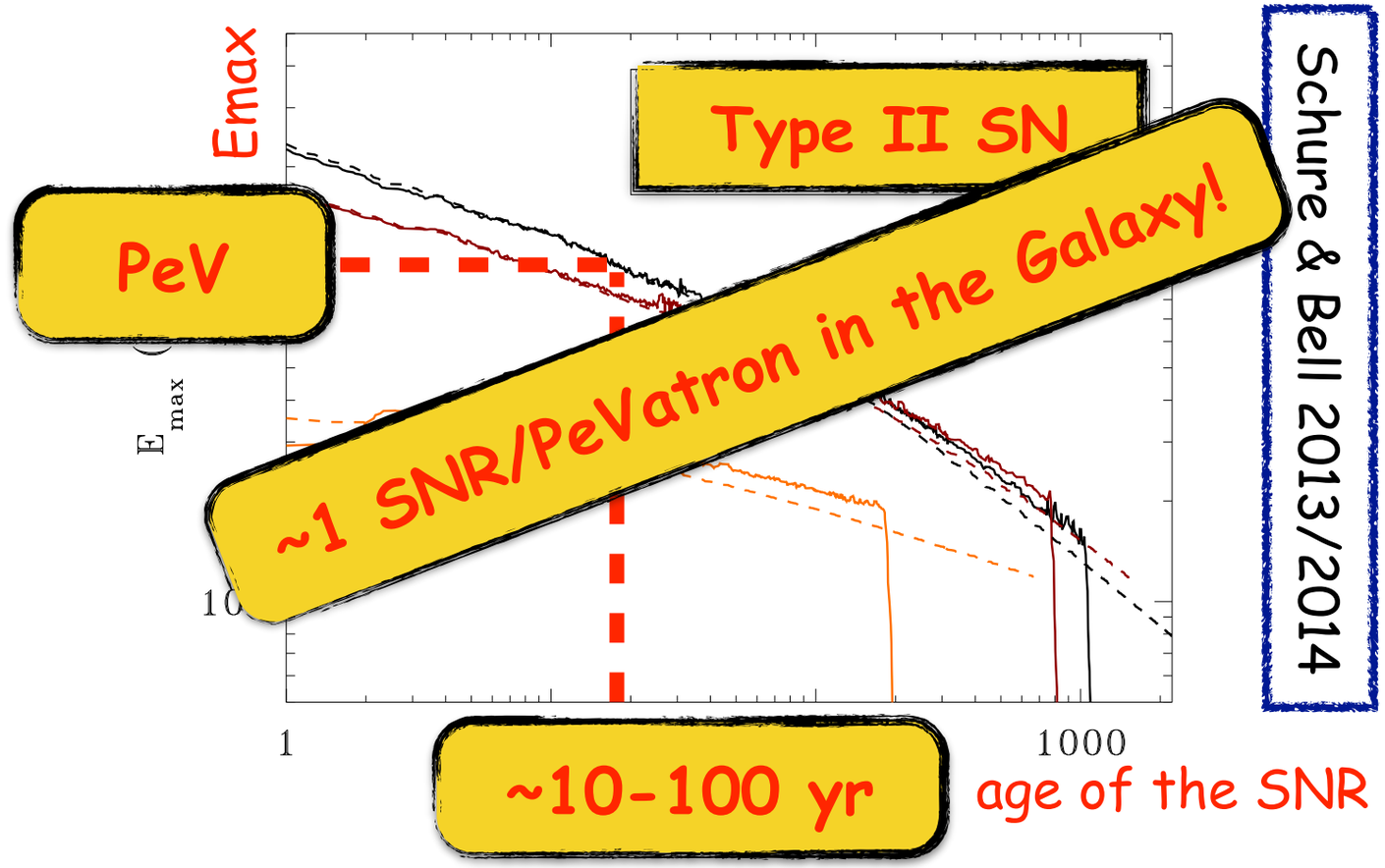

MeV GeV TeV **PeV** EeV ZeV

A proton PeVatron in the galactic centre

Observational signature

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)

A proton PeVatron in the galactic centre

Observational signature

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

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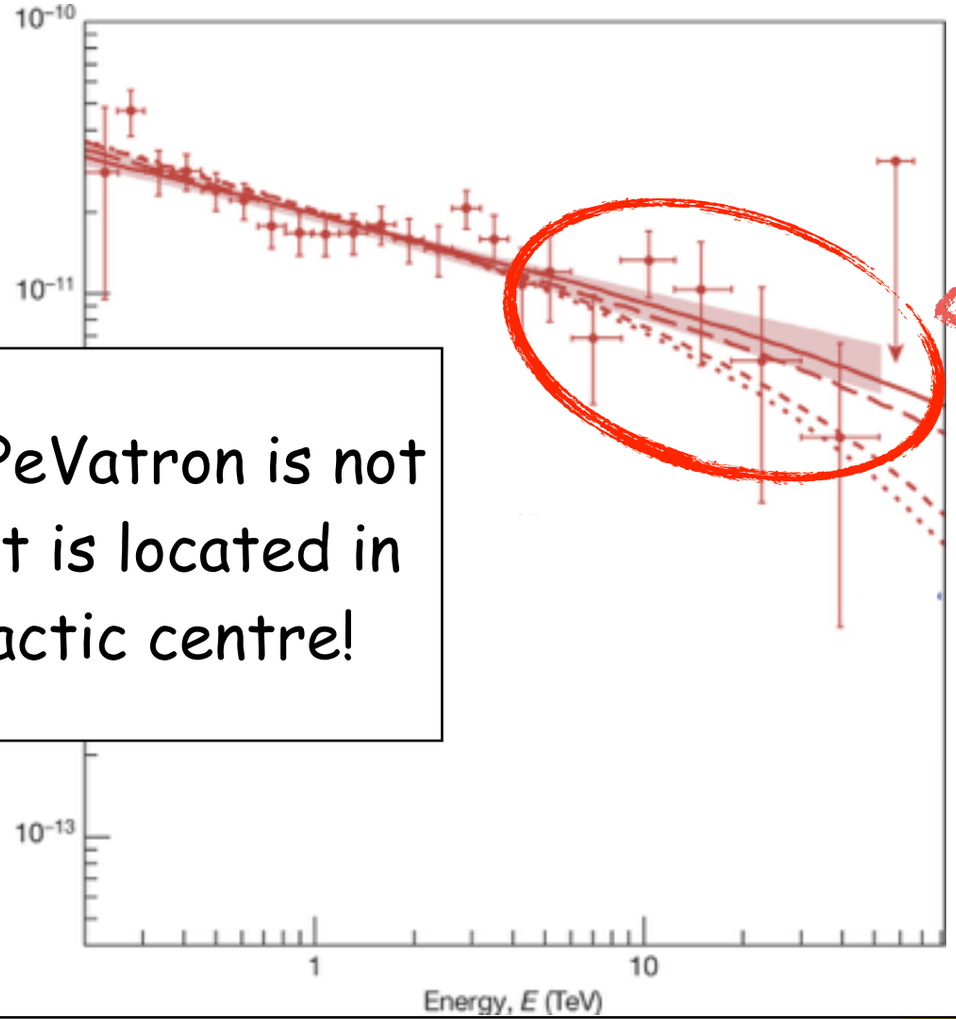

diffuse emission from the GC

no cutoff!

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

H.E.S.S. Coll. 2016

MeV | GeV | TeV | **PeV** | EeV | ZeV

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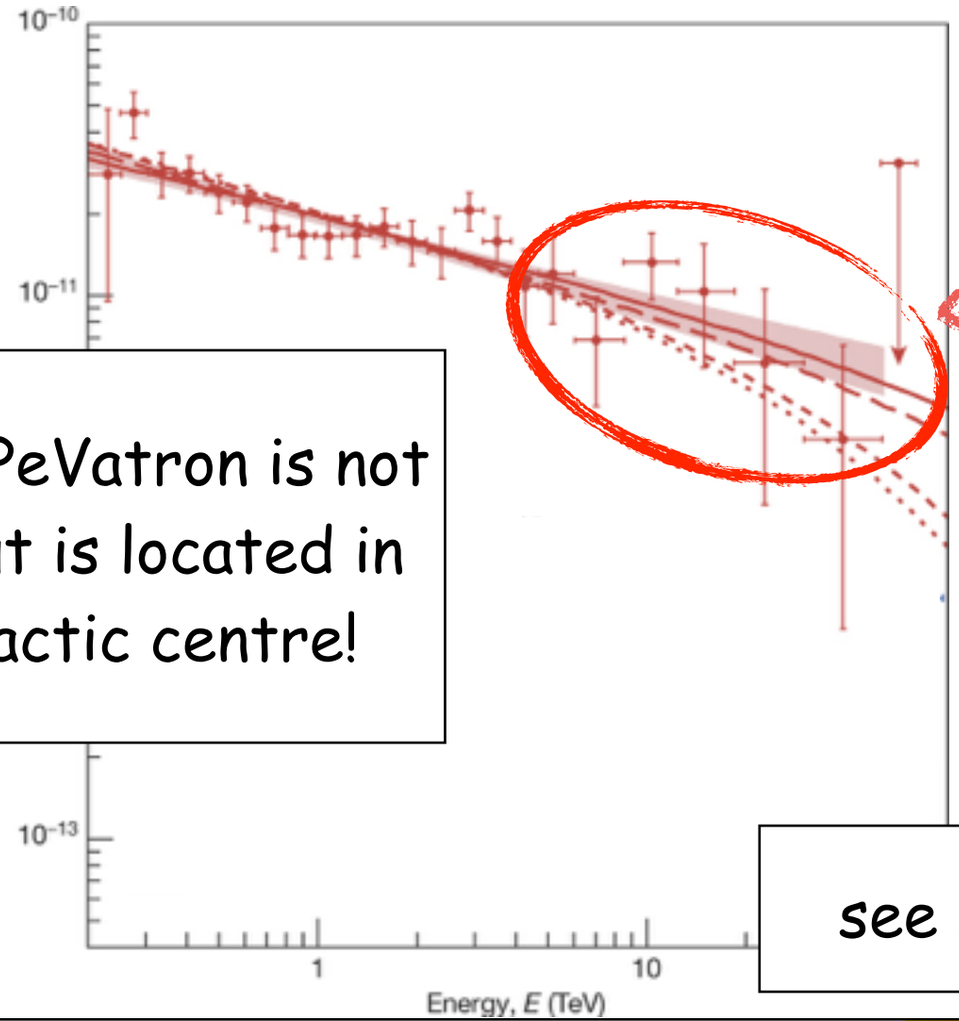

diffuse emission from the GC

no cutoff!

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

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

see Aion Viana's talk

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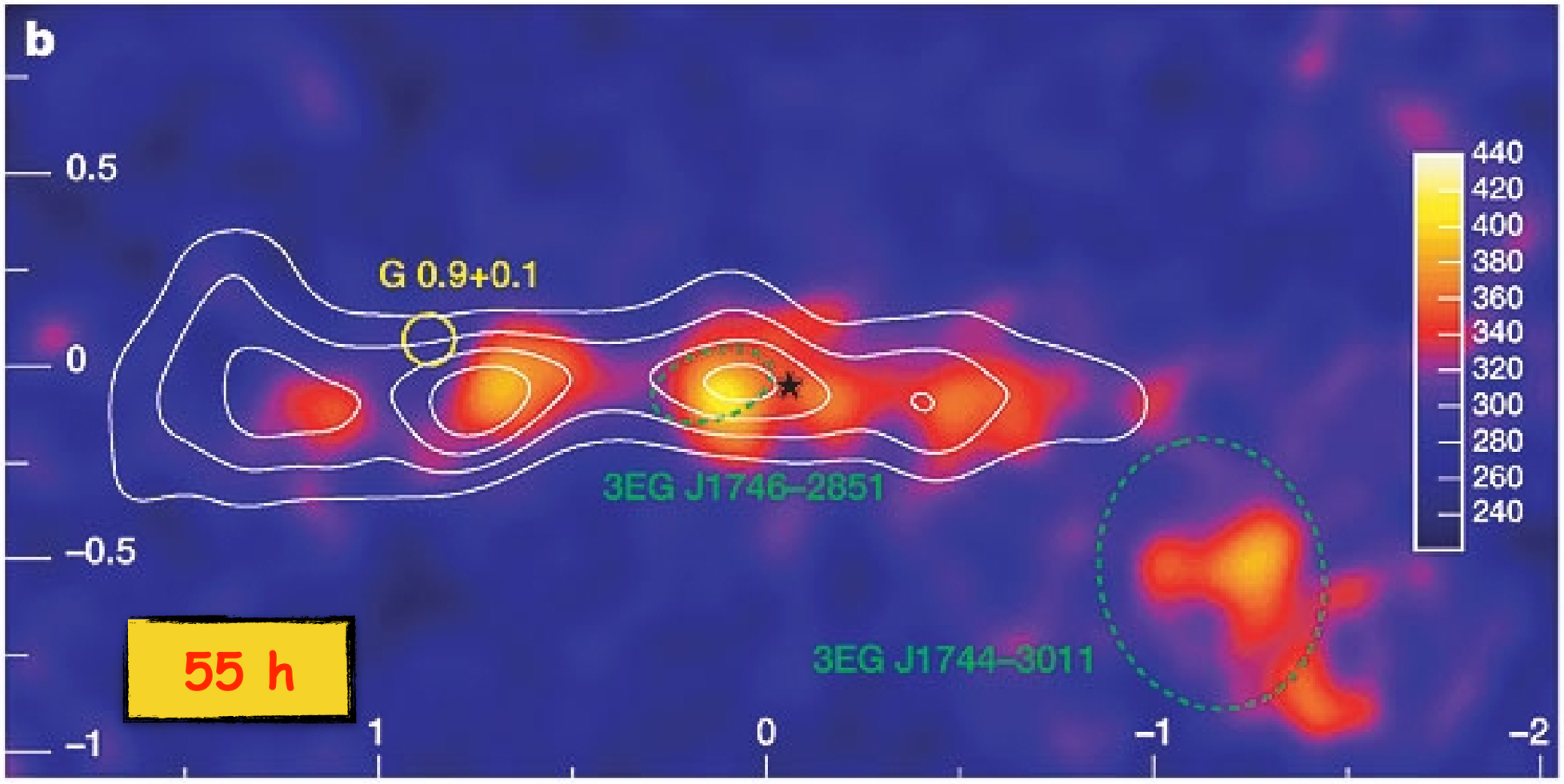
MeV GeV TeV **PeV** EeV ZeV

The GC ridge as seen 10 years ago

H.E.S.S. Coll. 2006



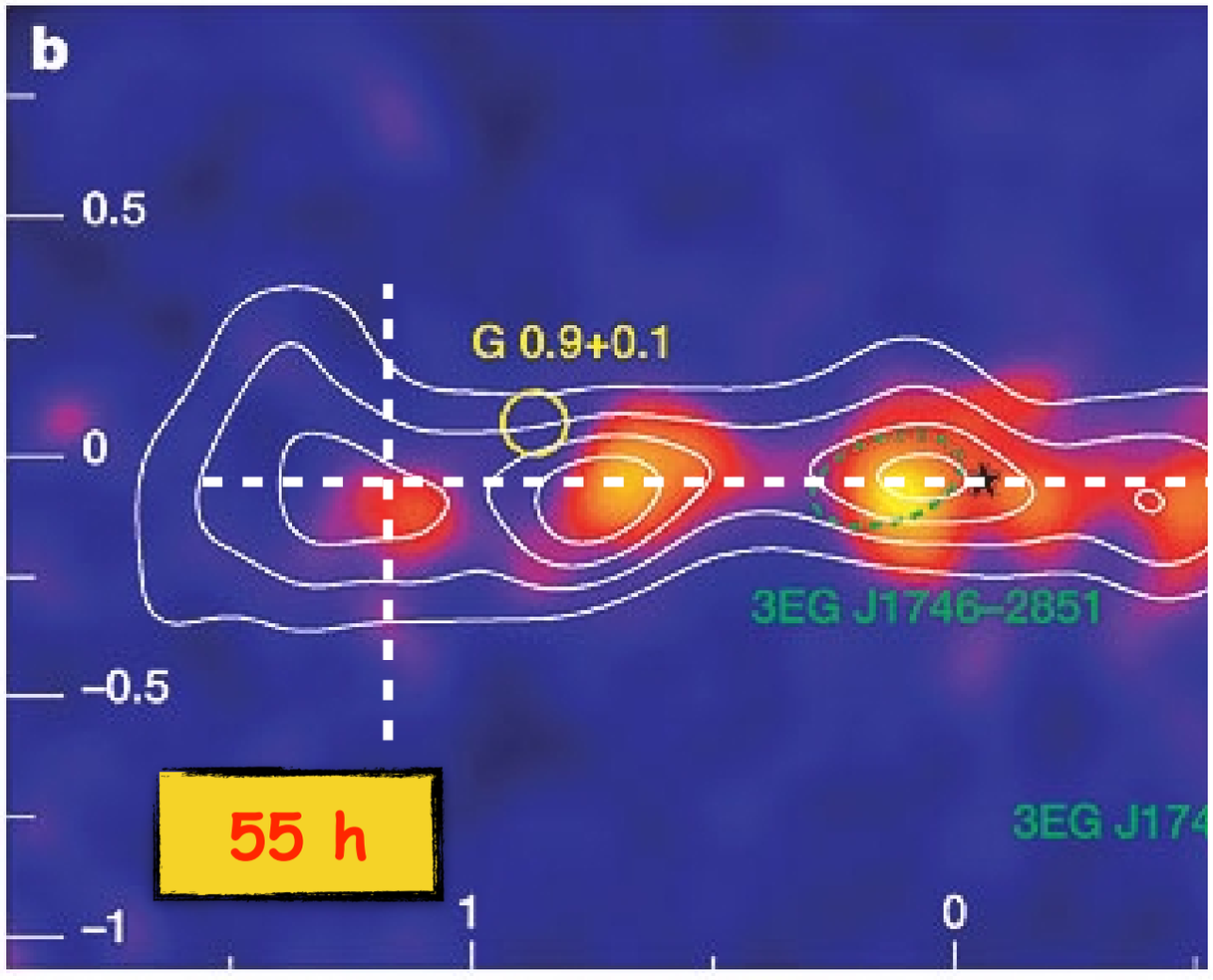
color scale -> γ-rays

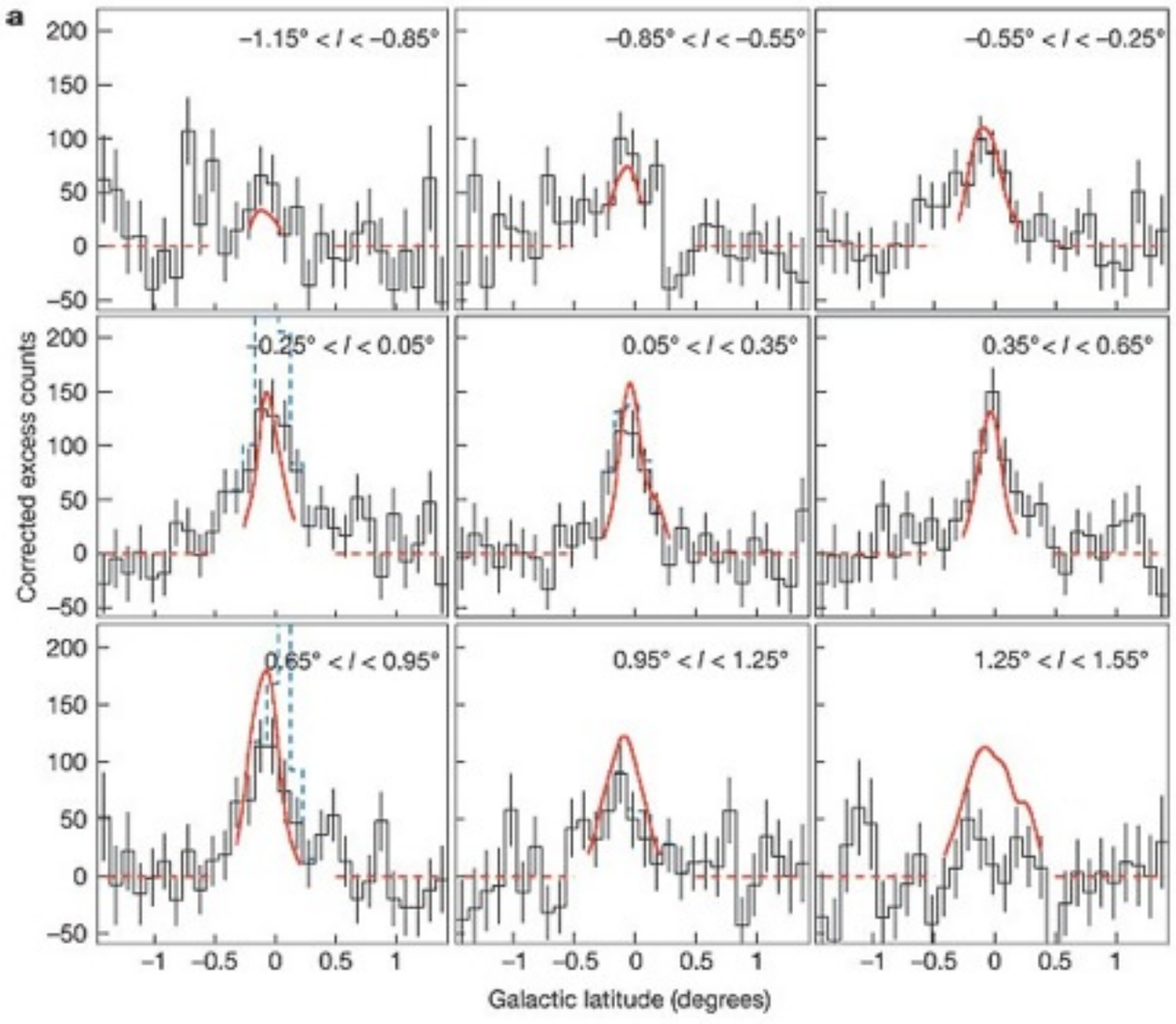
contours -> gas (CS)

MeV	GeV	TeV	PeV	EeV	ZeV

The GC ridge as seen 10 years ago

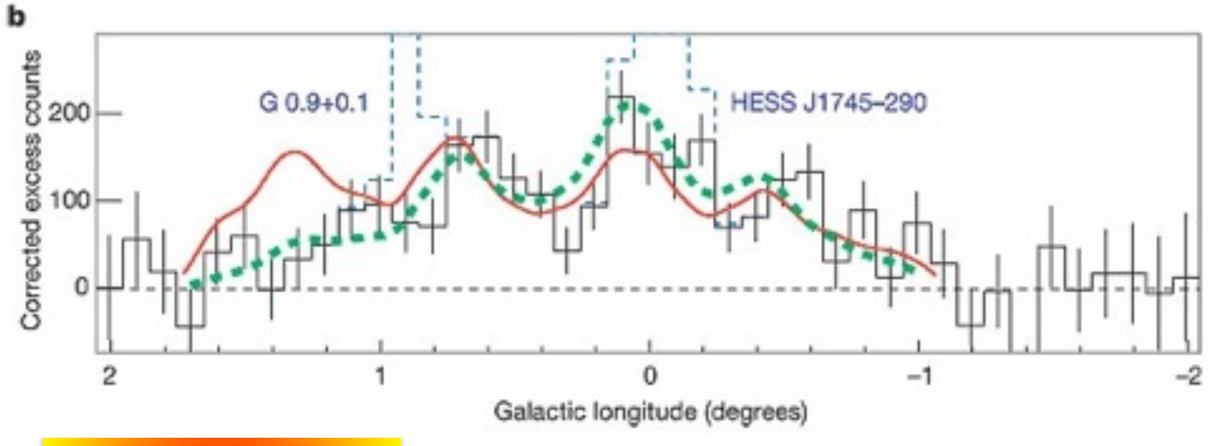
H.E.S.S. Coll. 2006





histogram -> γ-rays

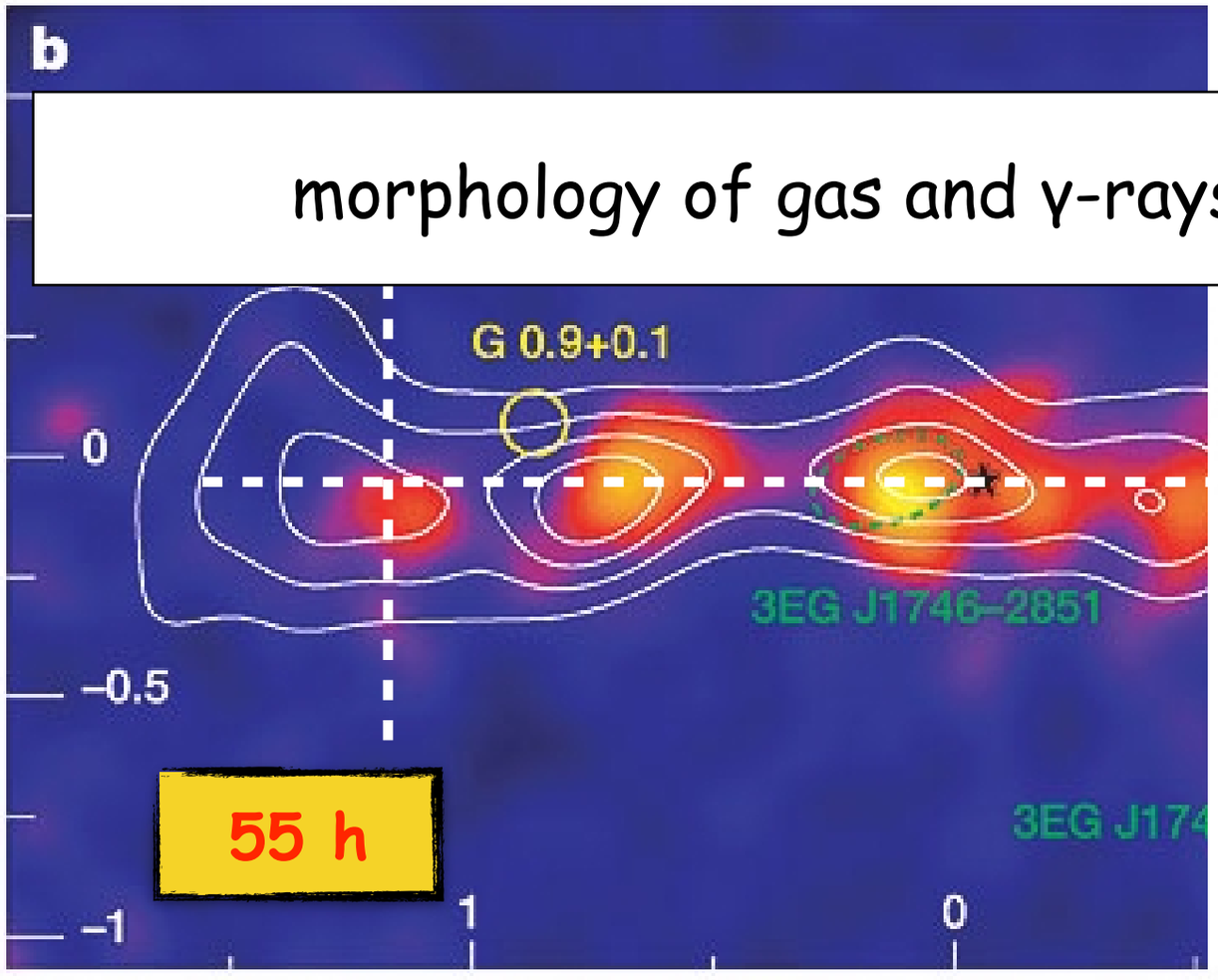
red -> gas (CS)



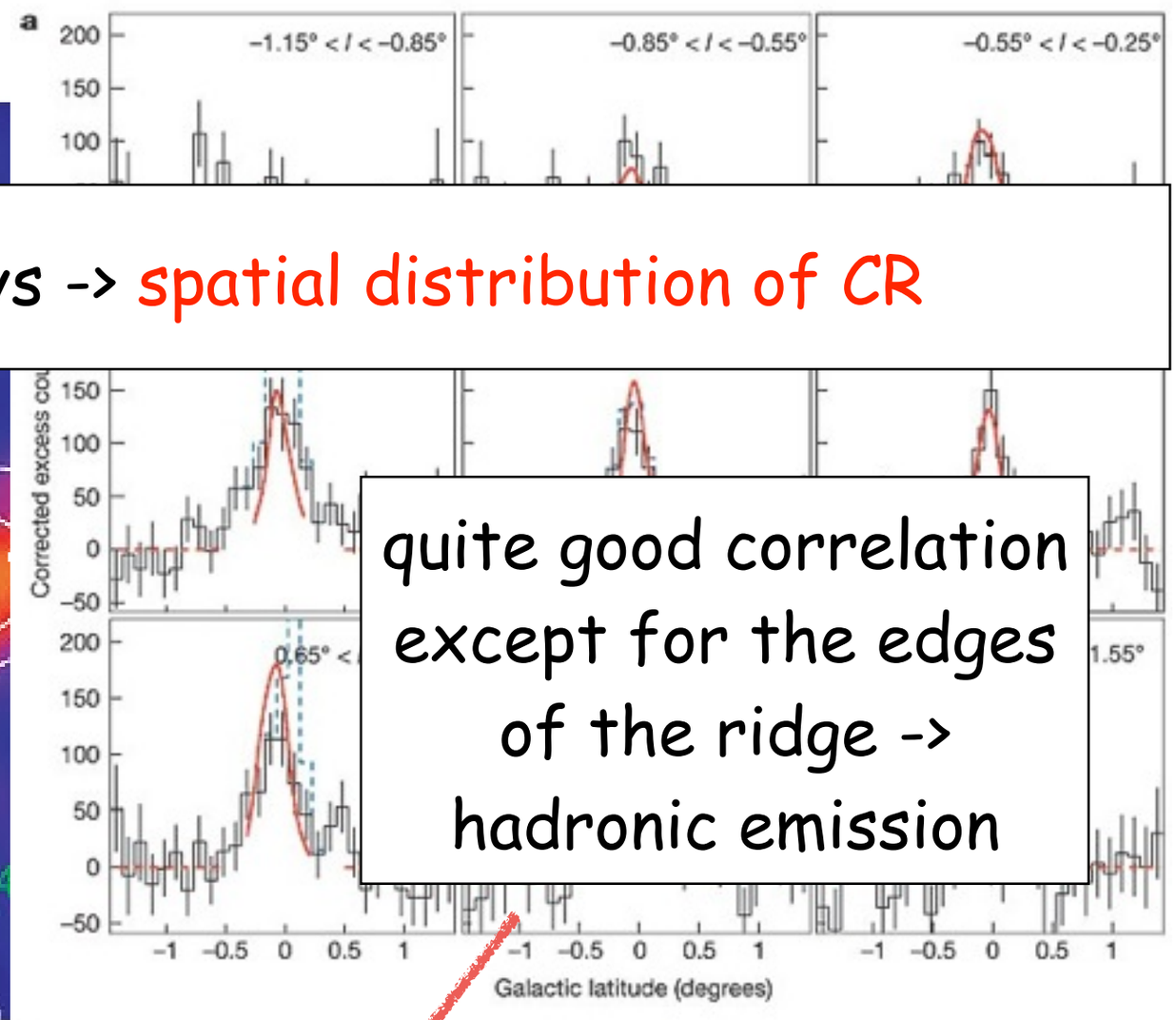
MeV GeV TeV **PeV** EeV ZeV

The GC ridge as seen 10 years ago

H.E.S.S. Coll. 2006



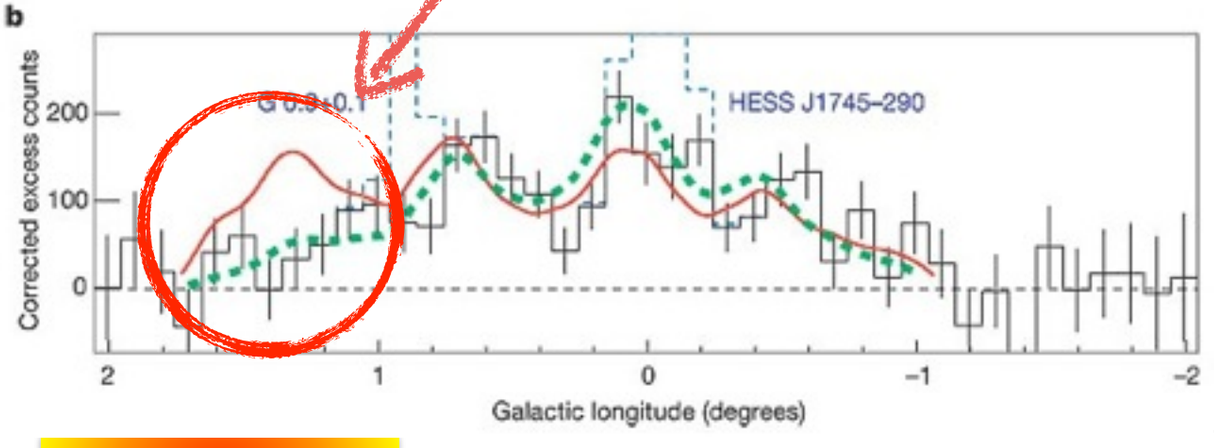
morphology of gas and γ-rays -> spatial distribution of CR



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

histogram -> γ-rays

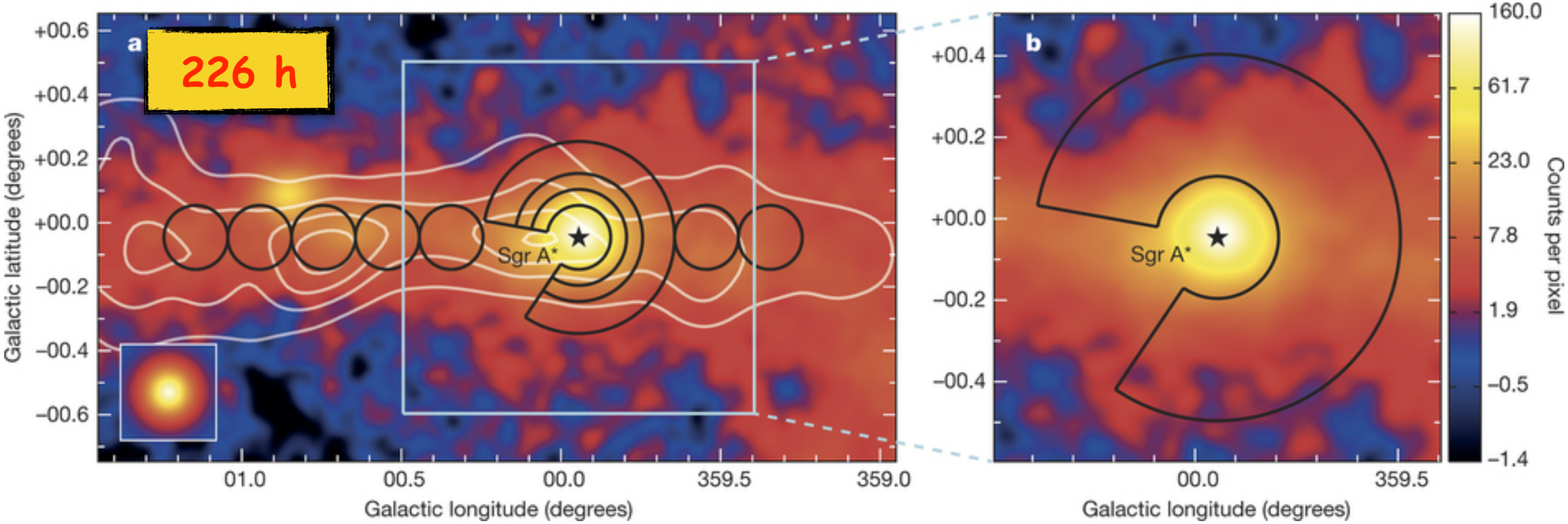
red -> gas (CS)



MeV GeV TeV **PeV** EeV ZeV

The source is at the GC

H.E.S.S. Coll. 2016



MeV | GeV | TeV | **PeV** | EeV | ZeV

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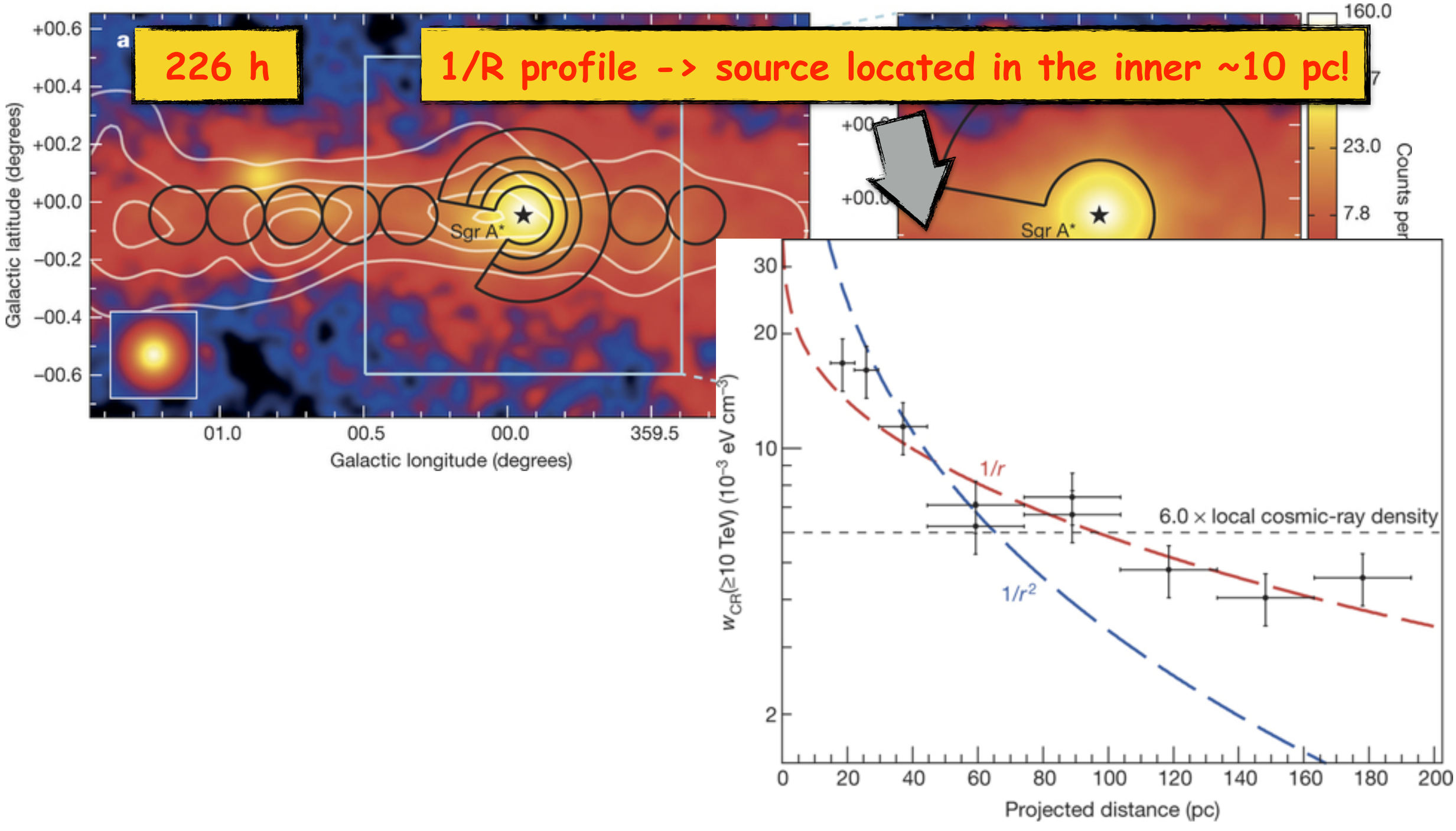

MeV	GeV	TeV	PeV	EeV	ZeV

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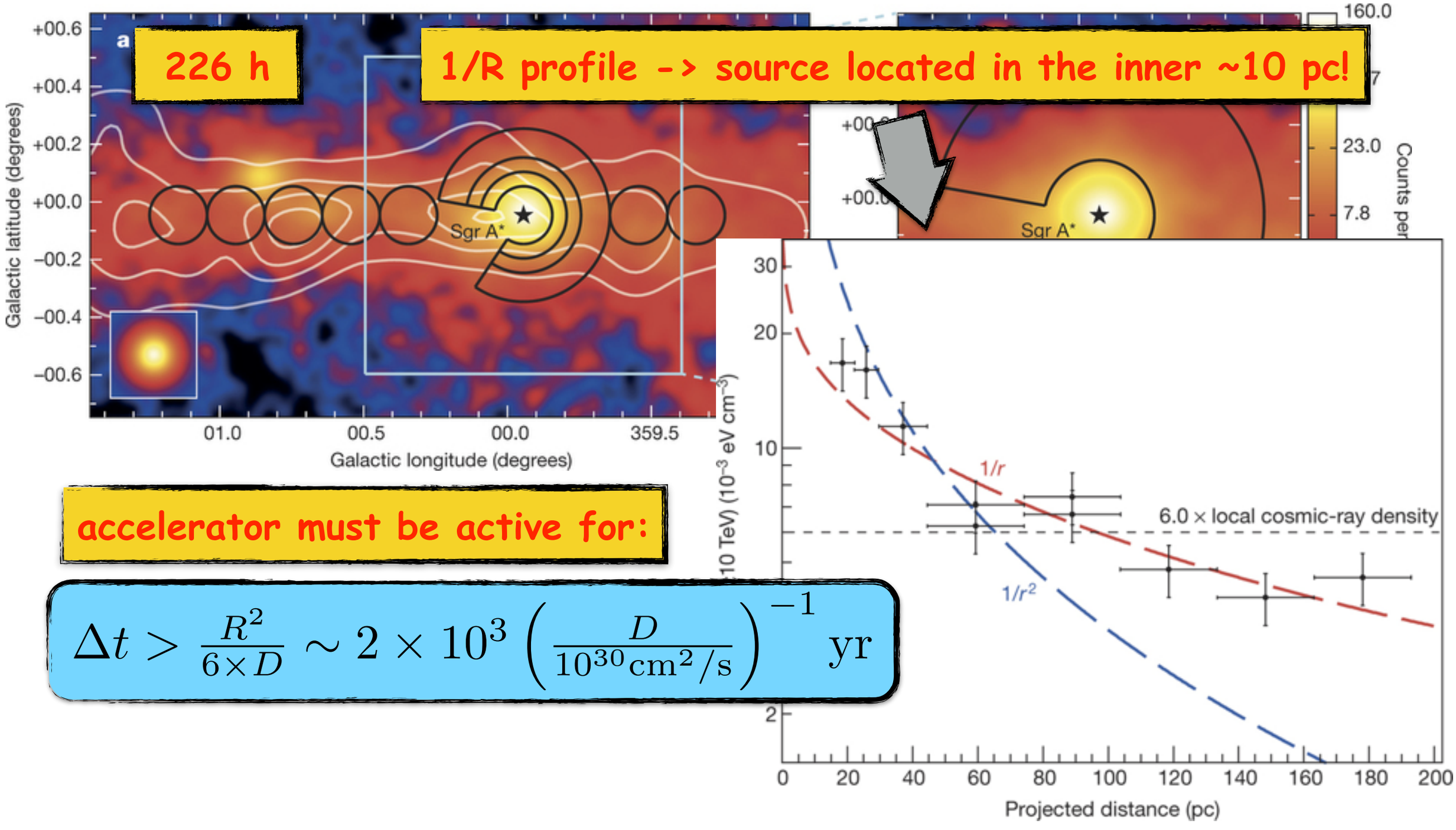

226 h

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

accelerator must be active for:

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

MeV	GeV	TeV	PeV	EeV	ZeV

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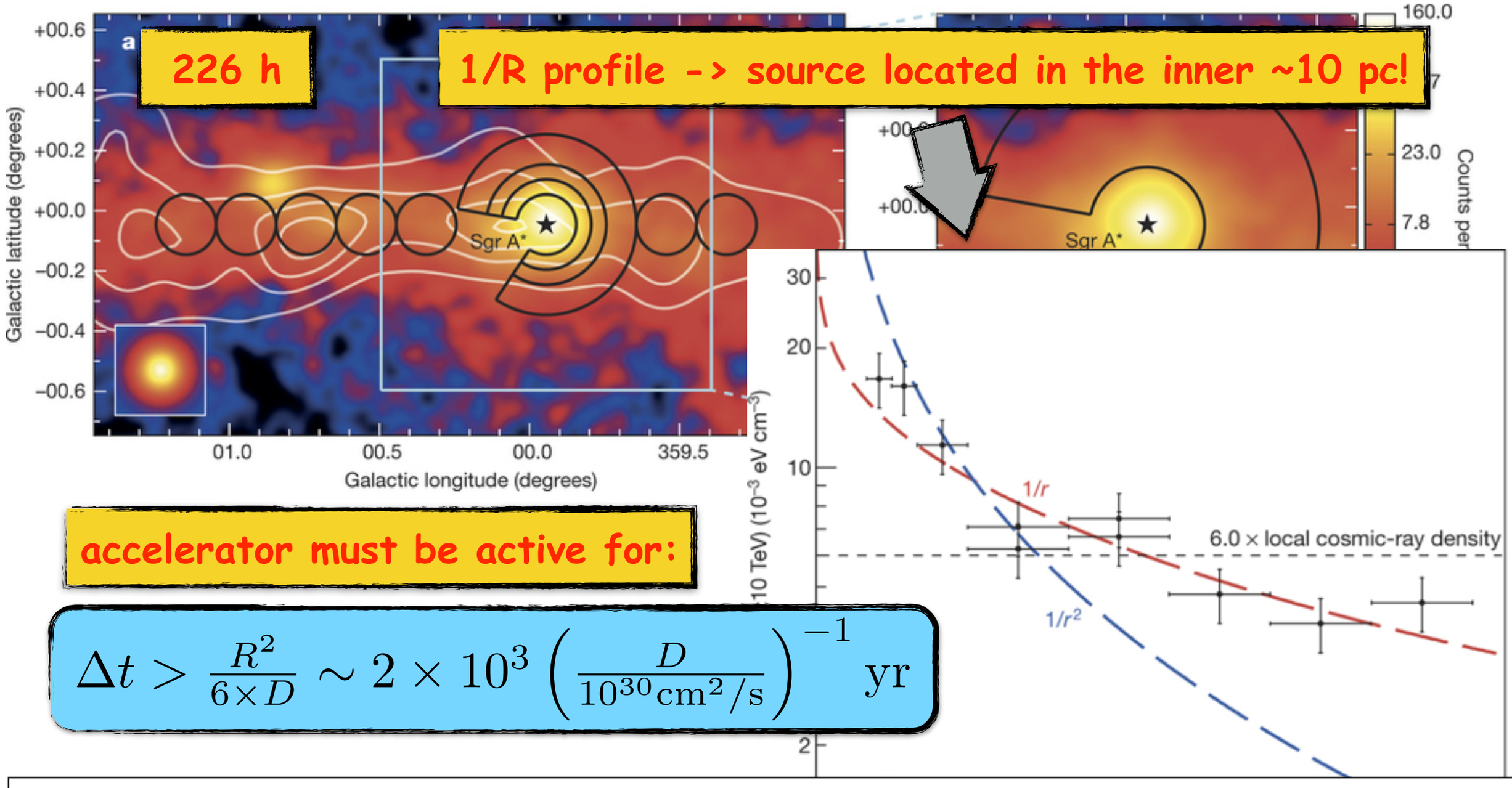
H.E.S.S. Coll. 2016



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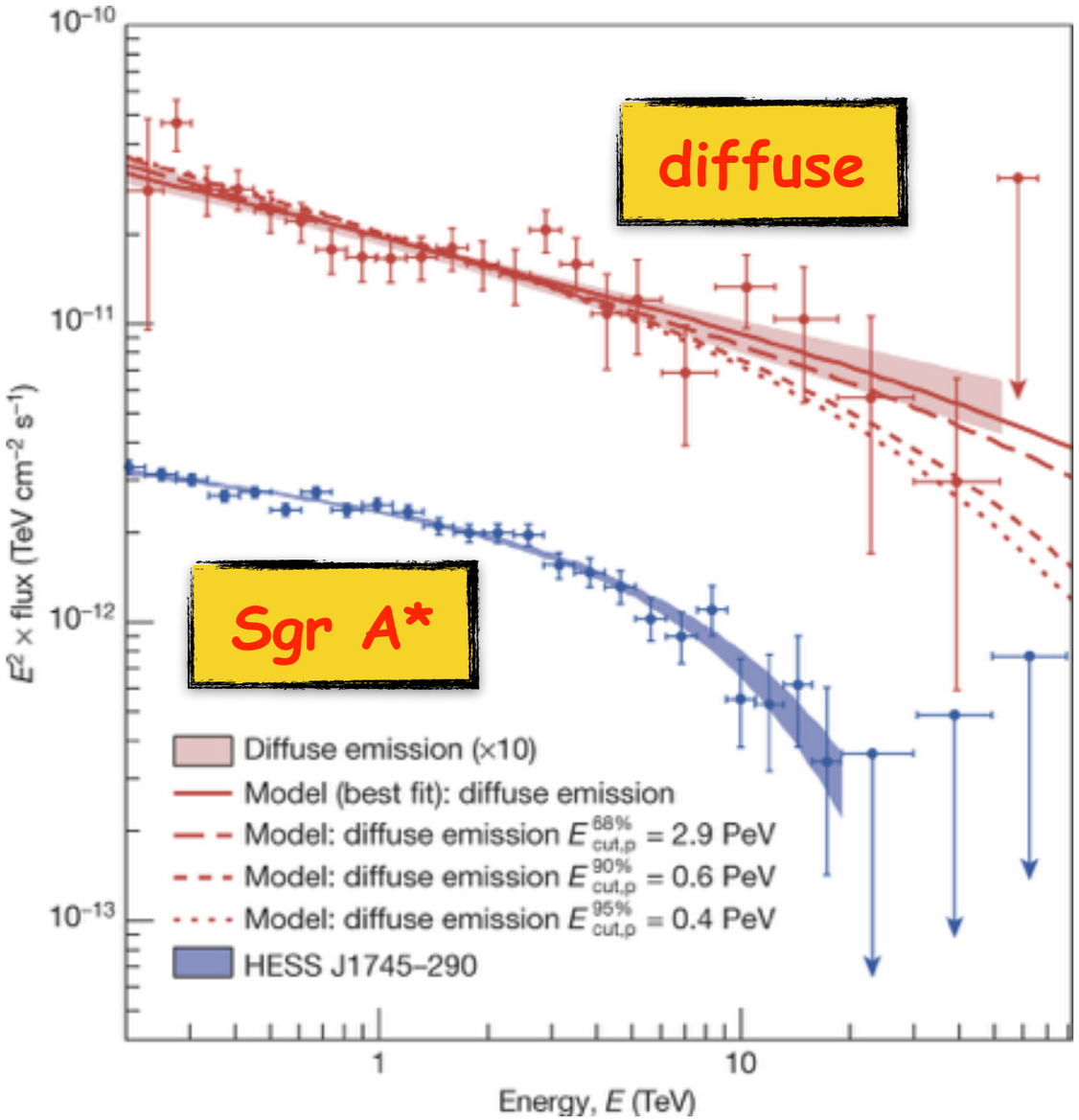
multi-source scenarios require excessive fine-tuning/unrealistic number of sources

MeV	GeV	TeV	PeV	EeV	ZeV

Supermassive black hole as a PeVatron

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



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Supermassive black hole as a PeVatron

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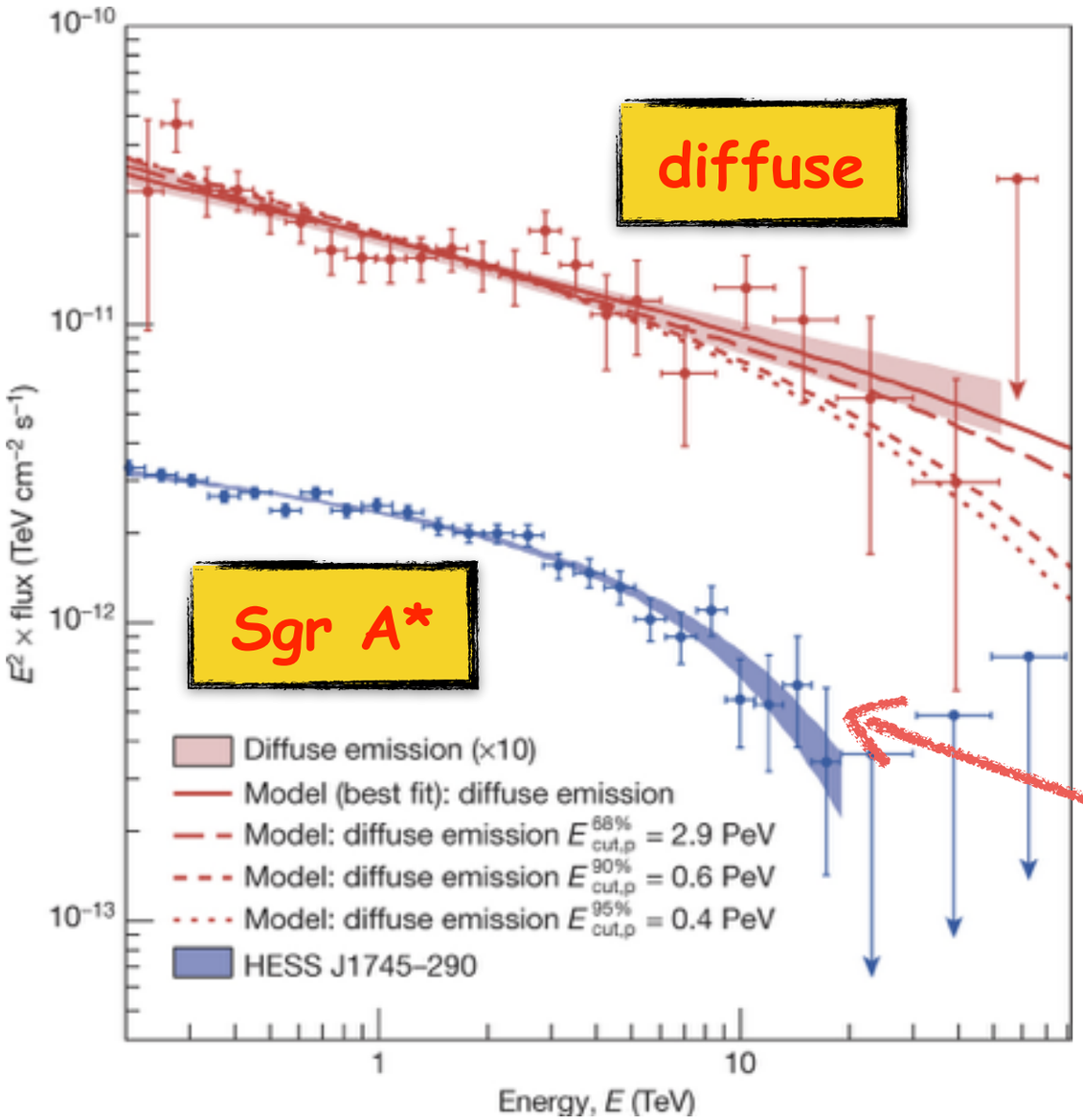

~10 TeV cutoff -> inconsistency? no...

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

MeV	GeV	TeV	**PeV**	EeV	ZeV

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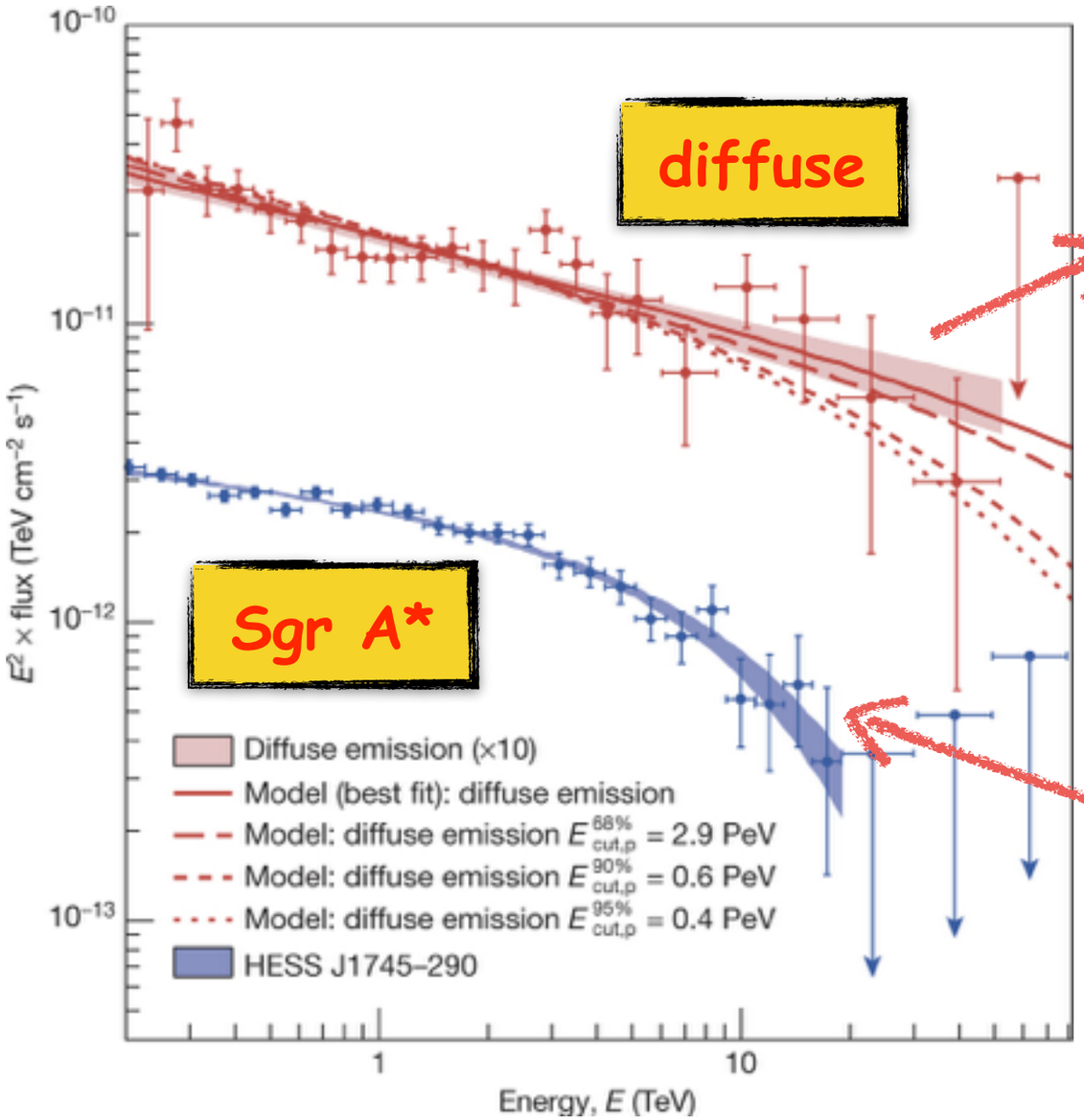

gas mass → $W_p \sim 10^{49}\mathrm{erg}$

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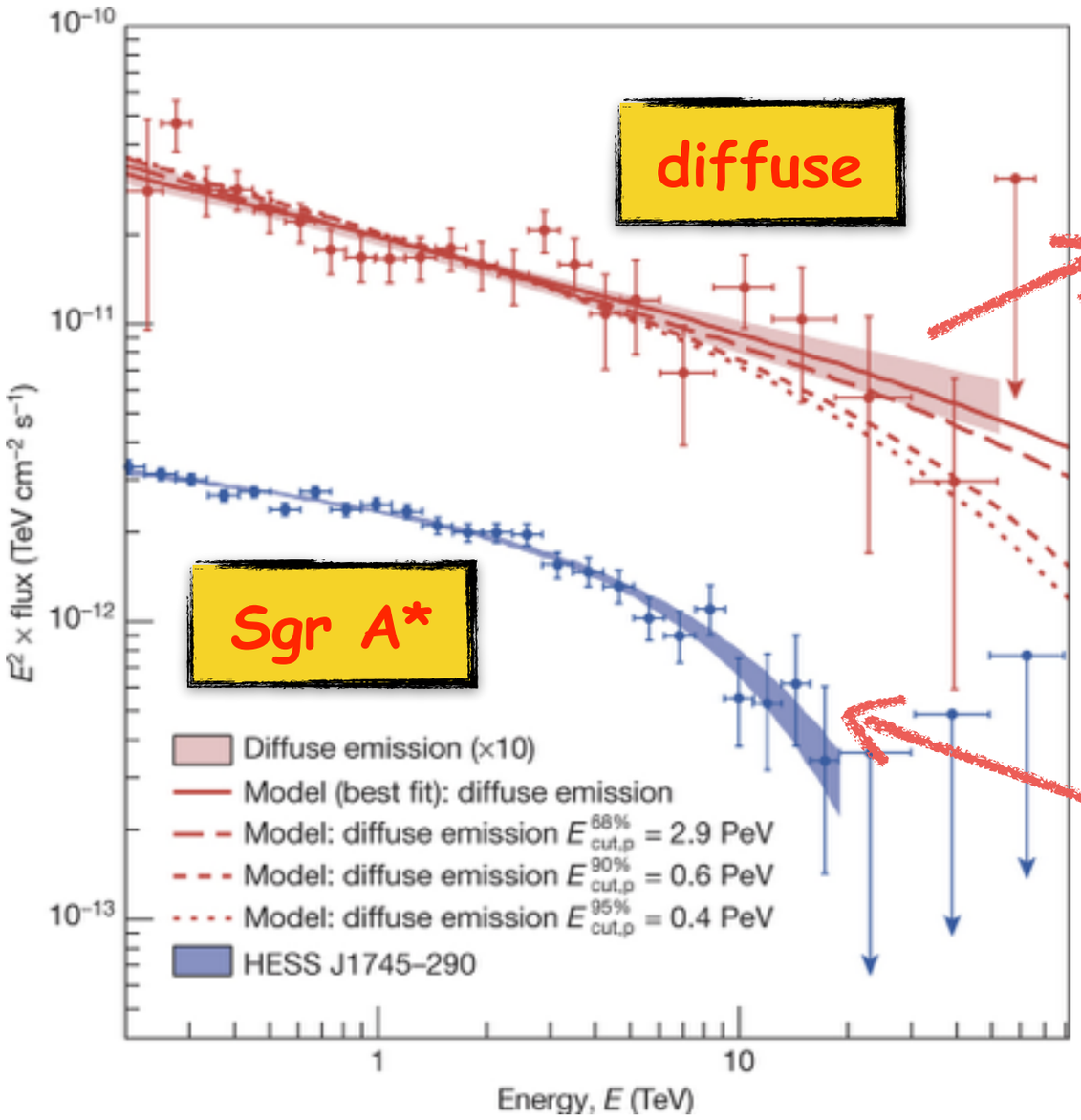

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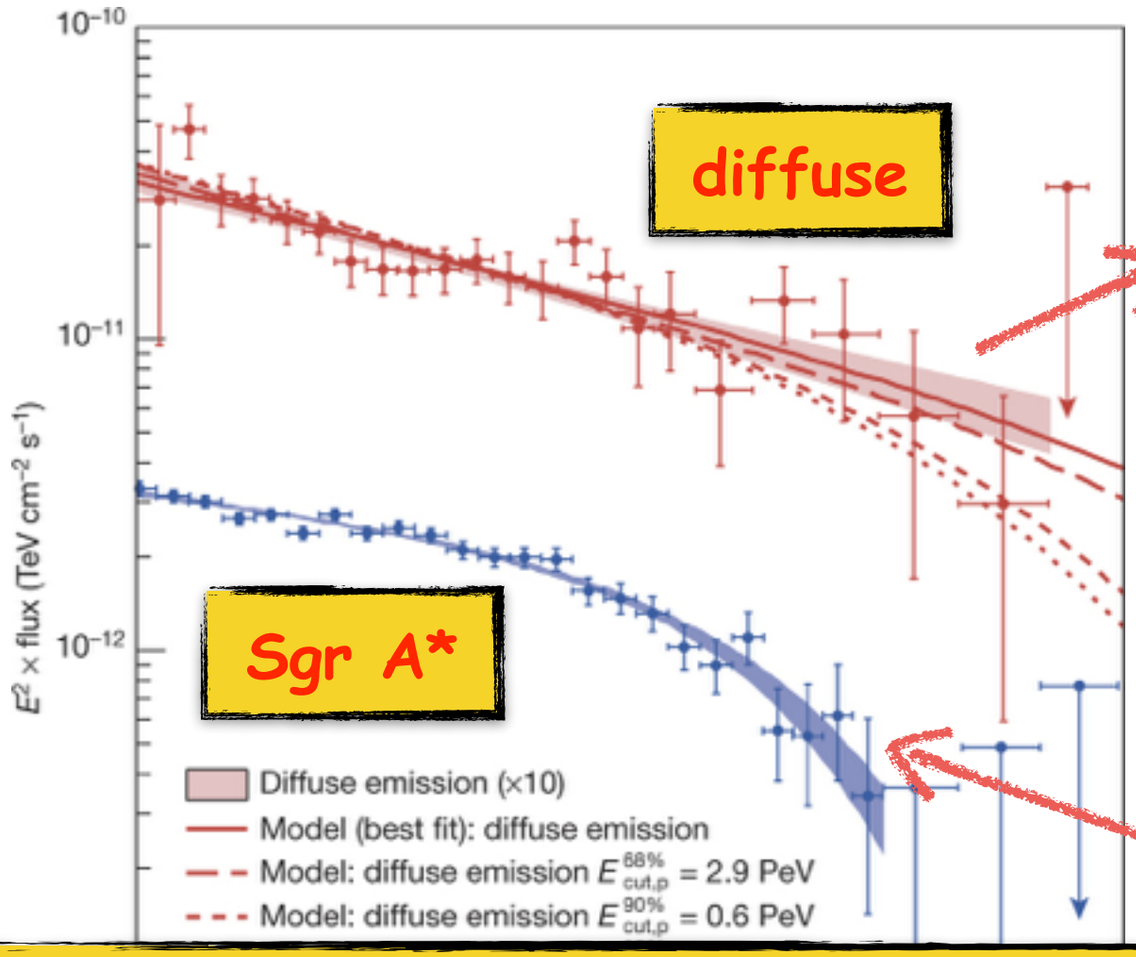

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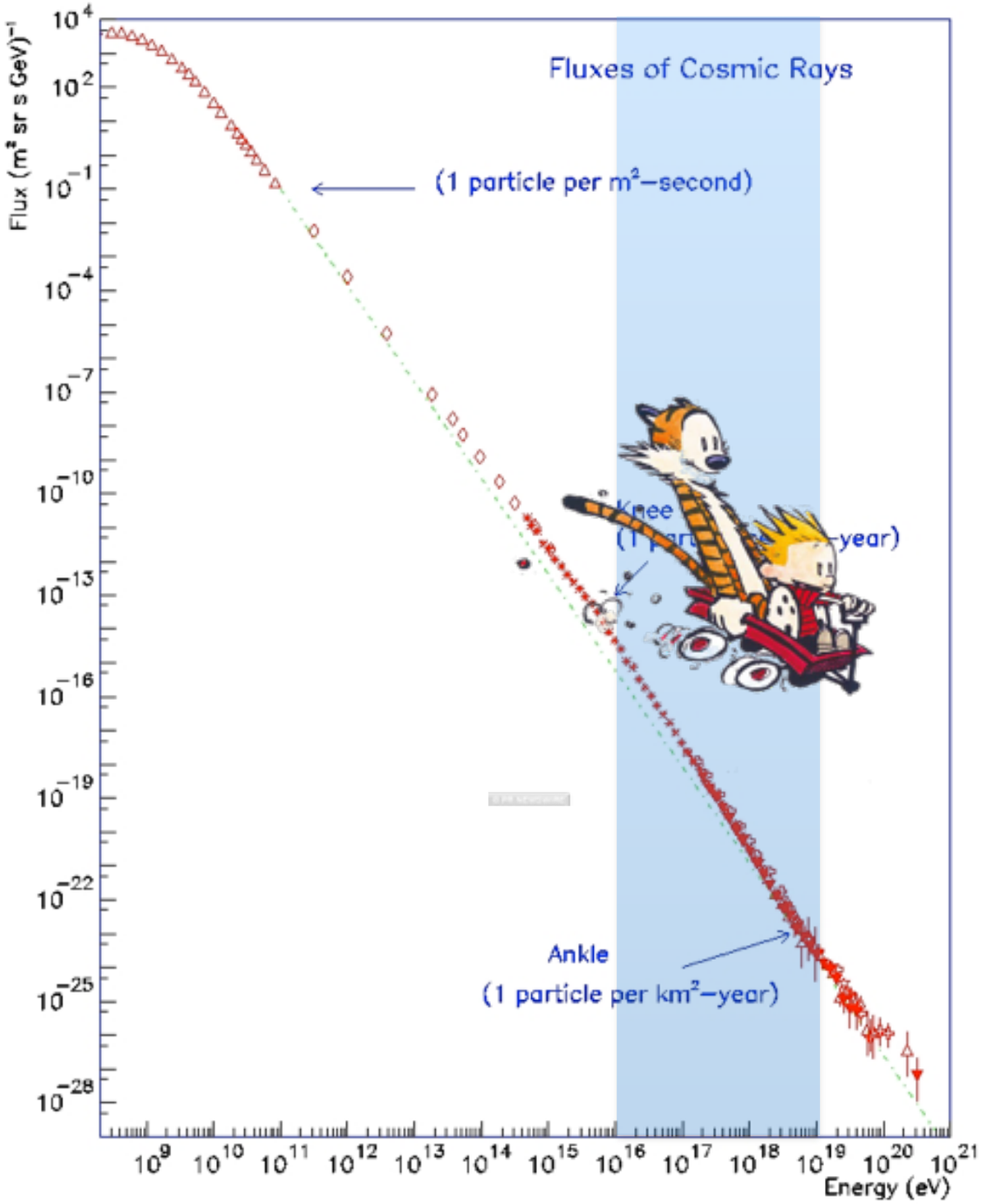
~10 TeV cutoff -> inconsistency? no...

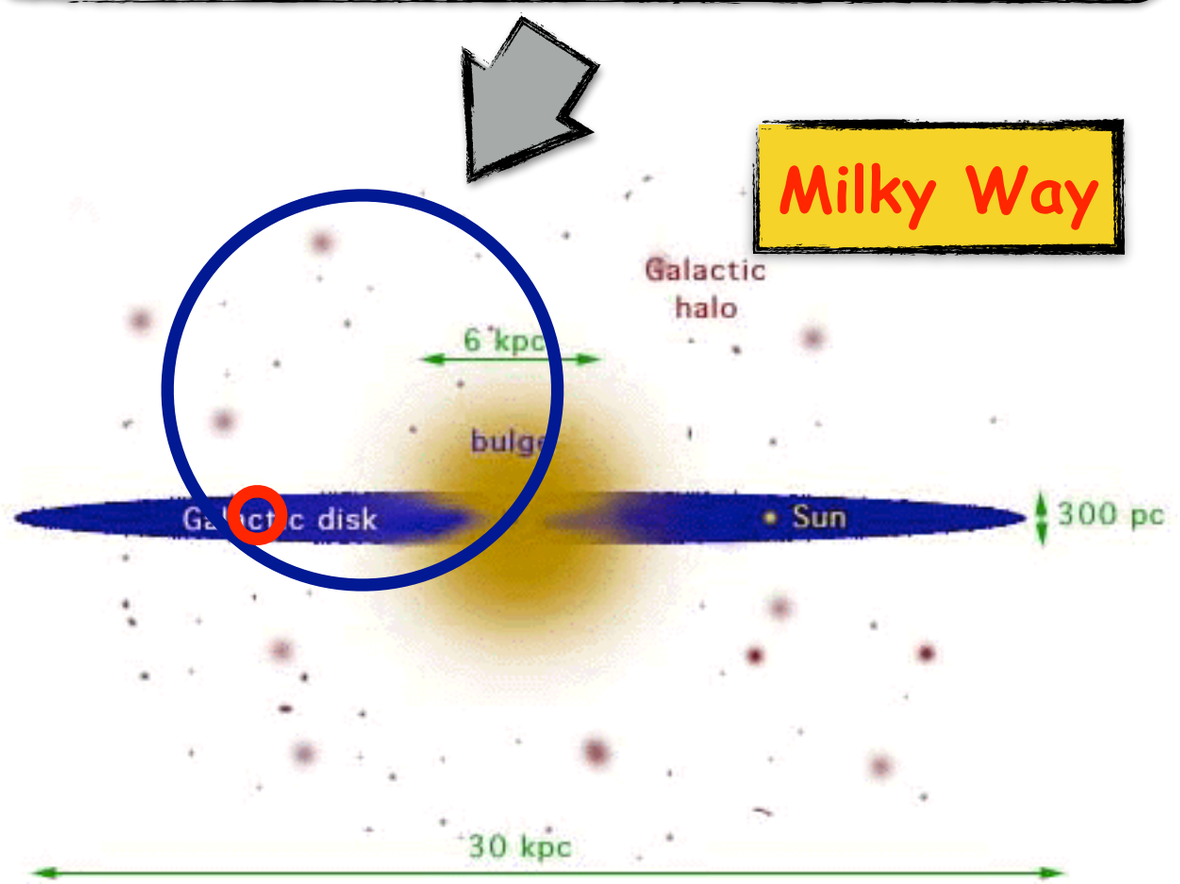
speculation: if Sgr A* was more active in the past (and we know it was!), at the level ~10^{39} erg/s -> could in principle explain all galactic CRs >10 TeV and IceCube neutrinos produced in a very large (few 100 kpc) galactic halo

MeV | GeV | TeV | **PeV** | EeV | ZeV

The EeV domain (10^{16} eV-10^{19} eV)



$$R_L(10^{19}\ \text{eV}) \sim 3.6\ \text{kpc}$$



Transition from Galactic to extra-galactic Cosmic Rays

MeV	GeV	TeV	PeV	EeV	ZeV

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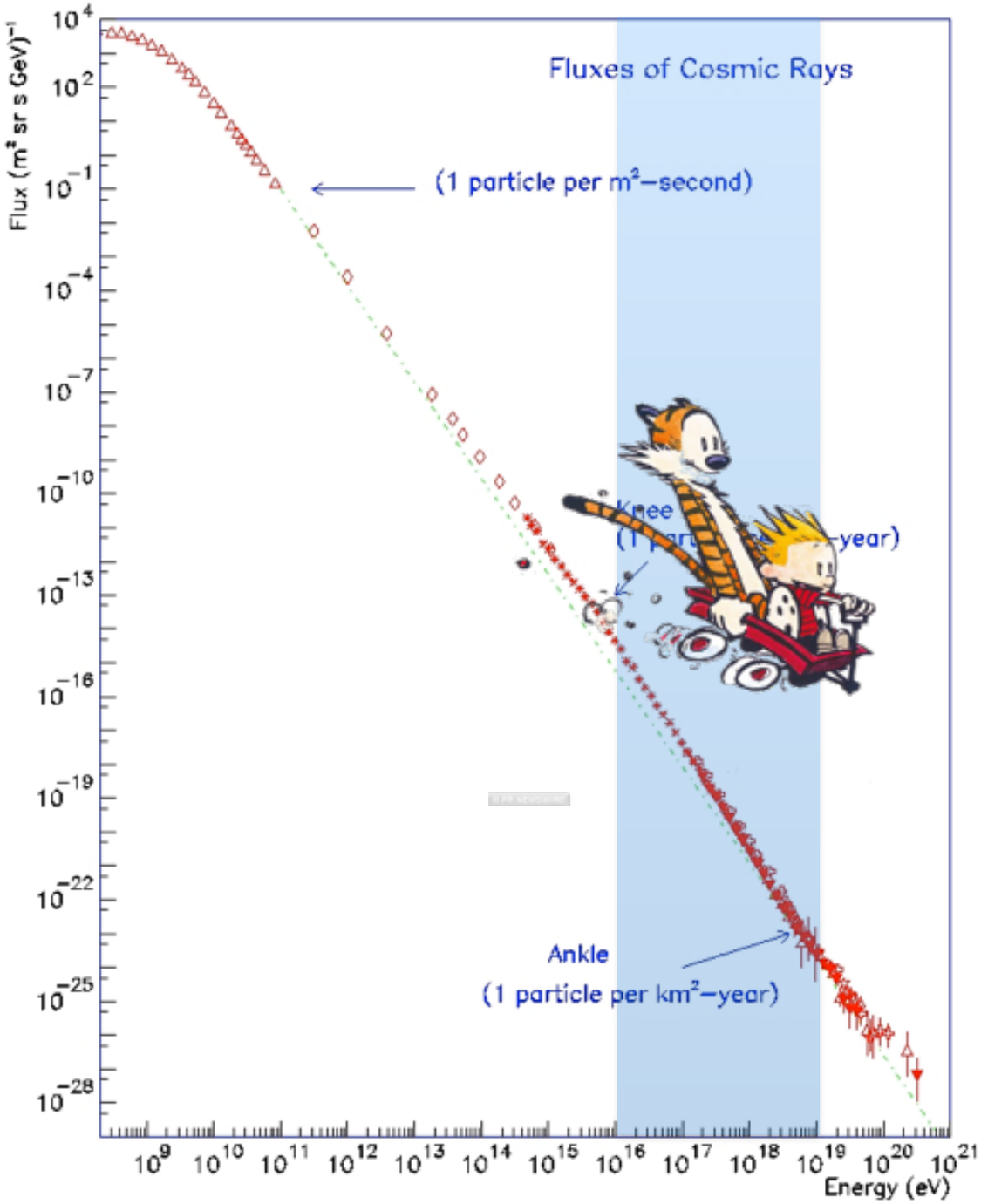

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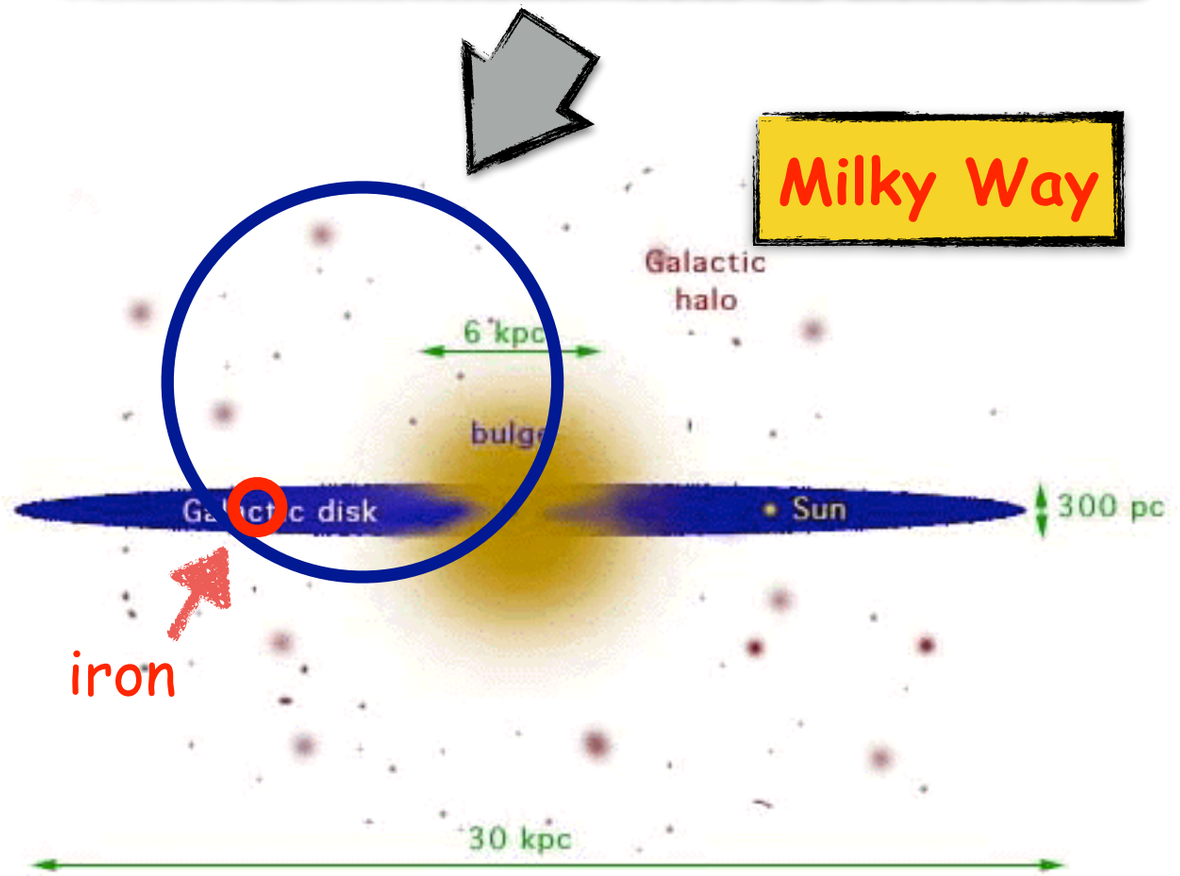
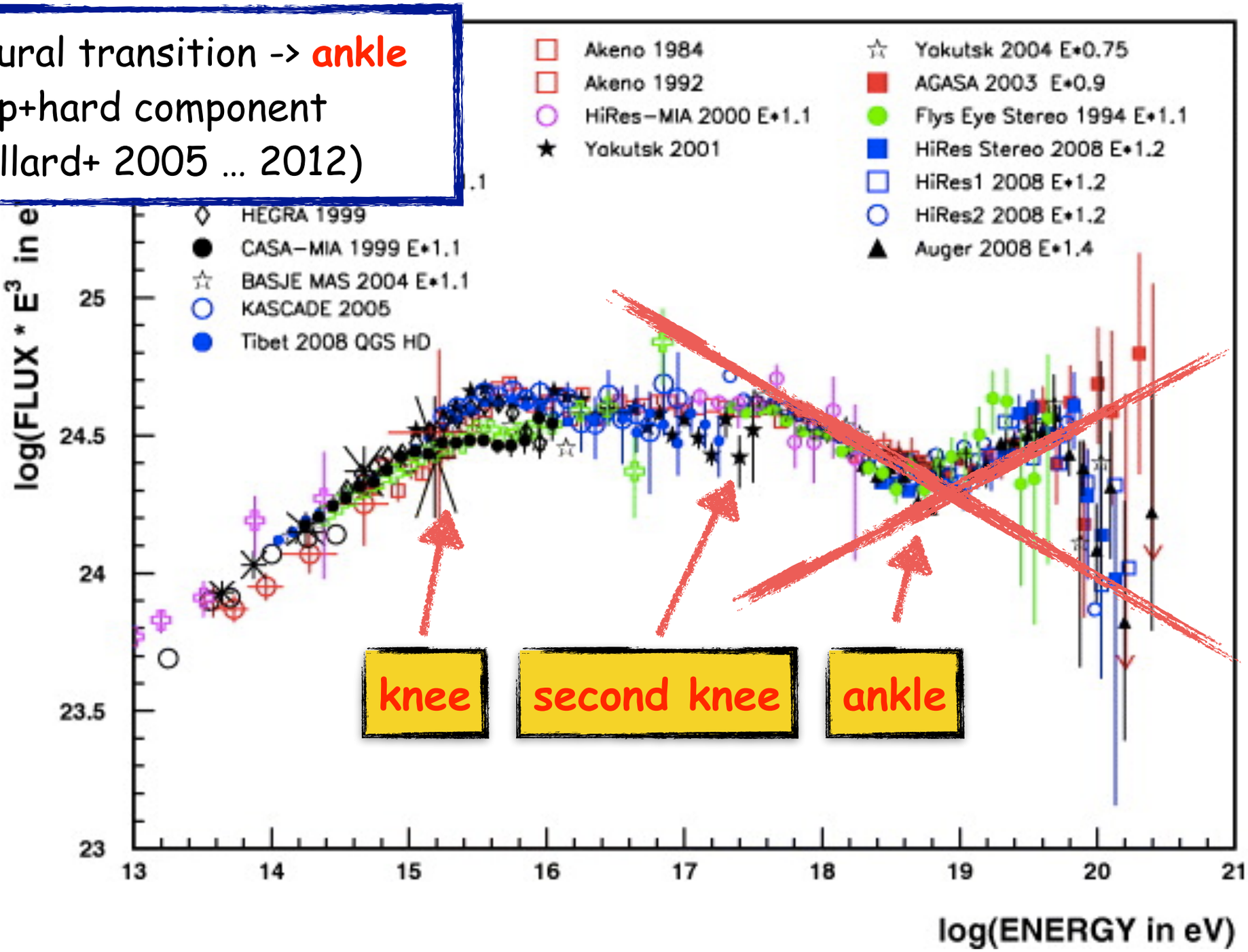


Transition from Galactic to extra-galactic Cosmic Rays

MeV	GeV	TeV	PeV	EeV	ZeV

The EeV domain: Galactic-Extragalactic

most natural transition -> **ankle**
steep+hard component
(e.g. Allard+ 2005 … 2012)



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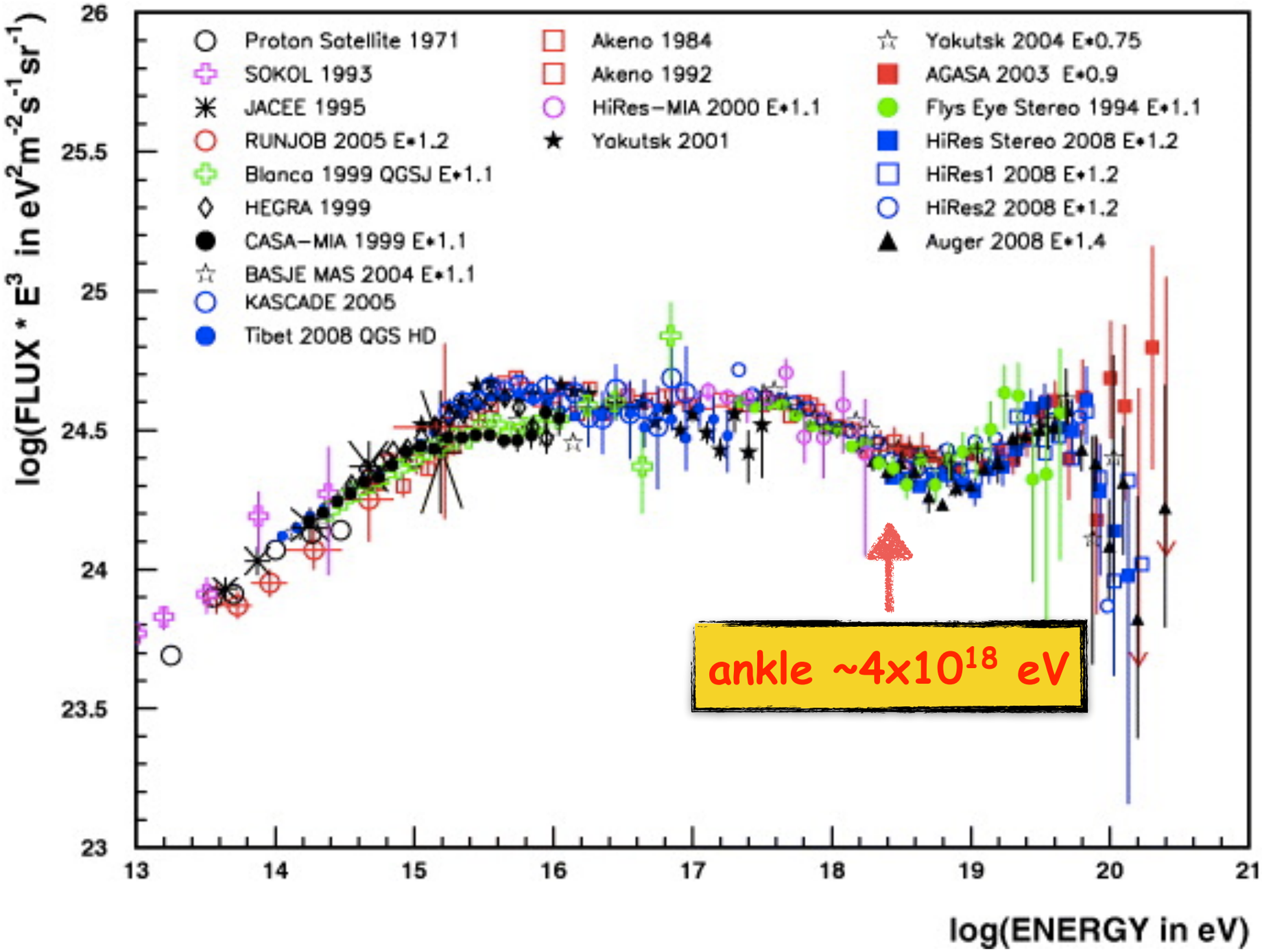
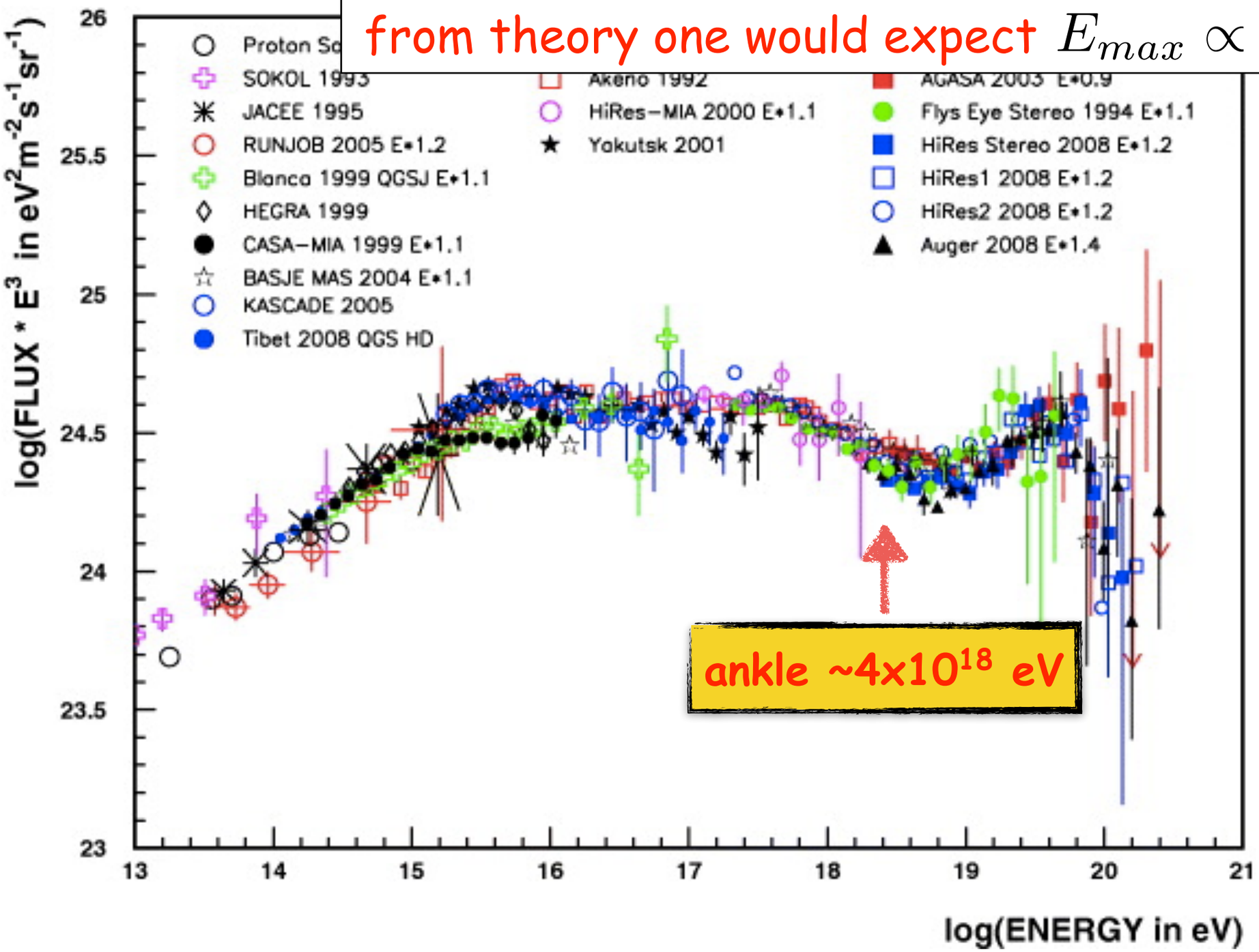


MeV	GeV	TeV	PeV	EeV	ZeV

The EeV domain: Galactic-Extragalactic

from theory one would expect $E_{max} \propto Z$



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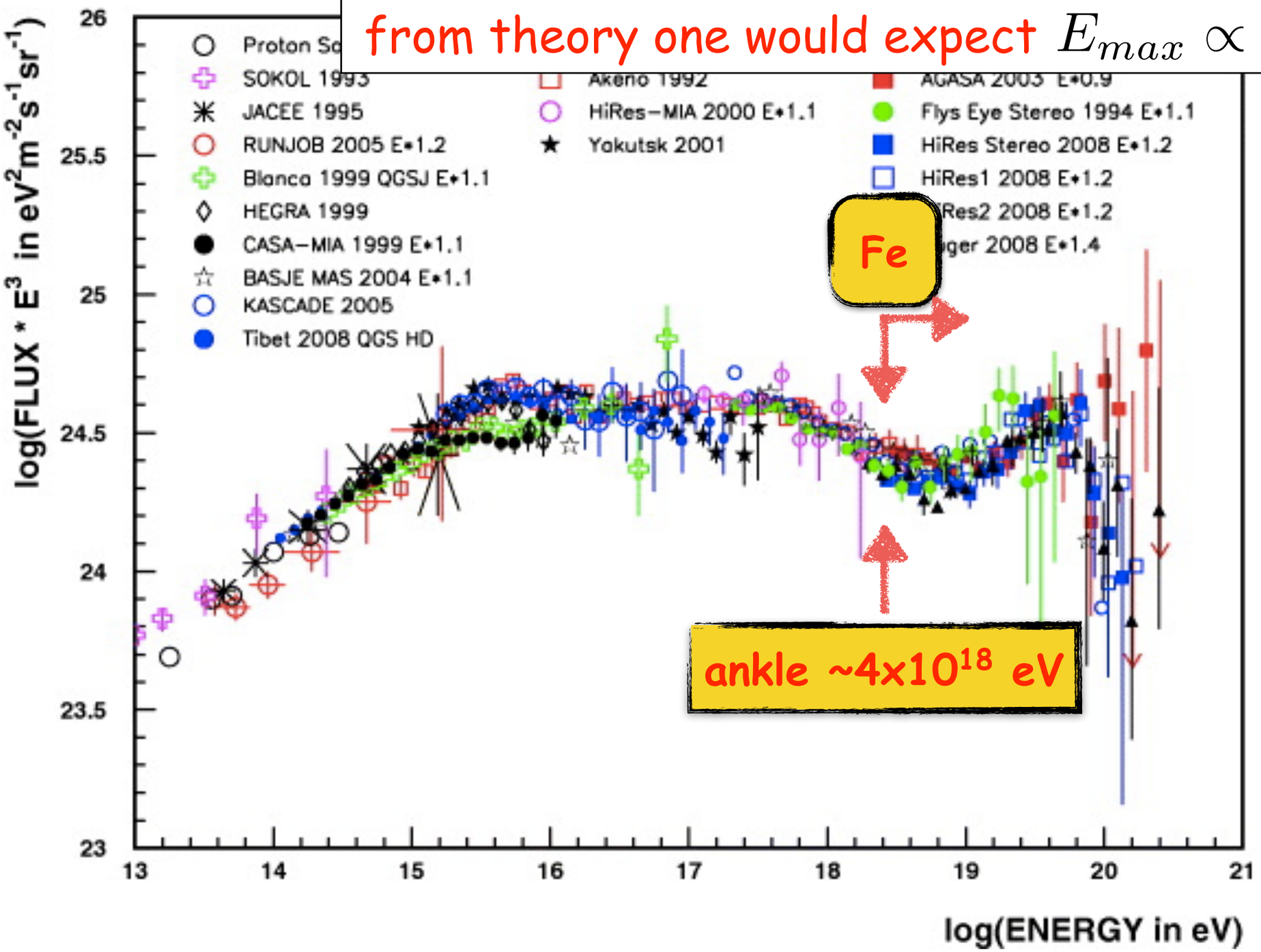

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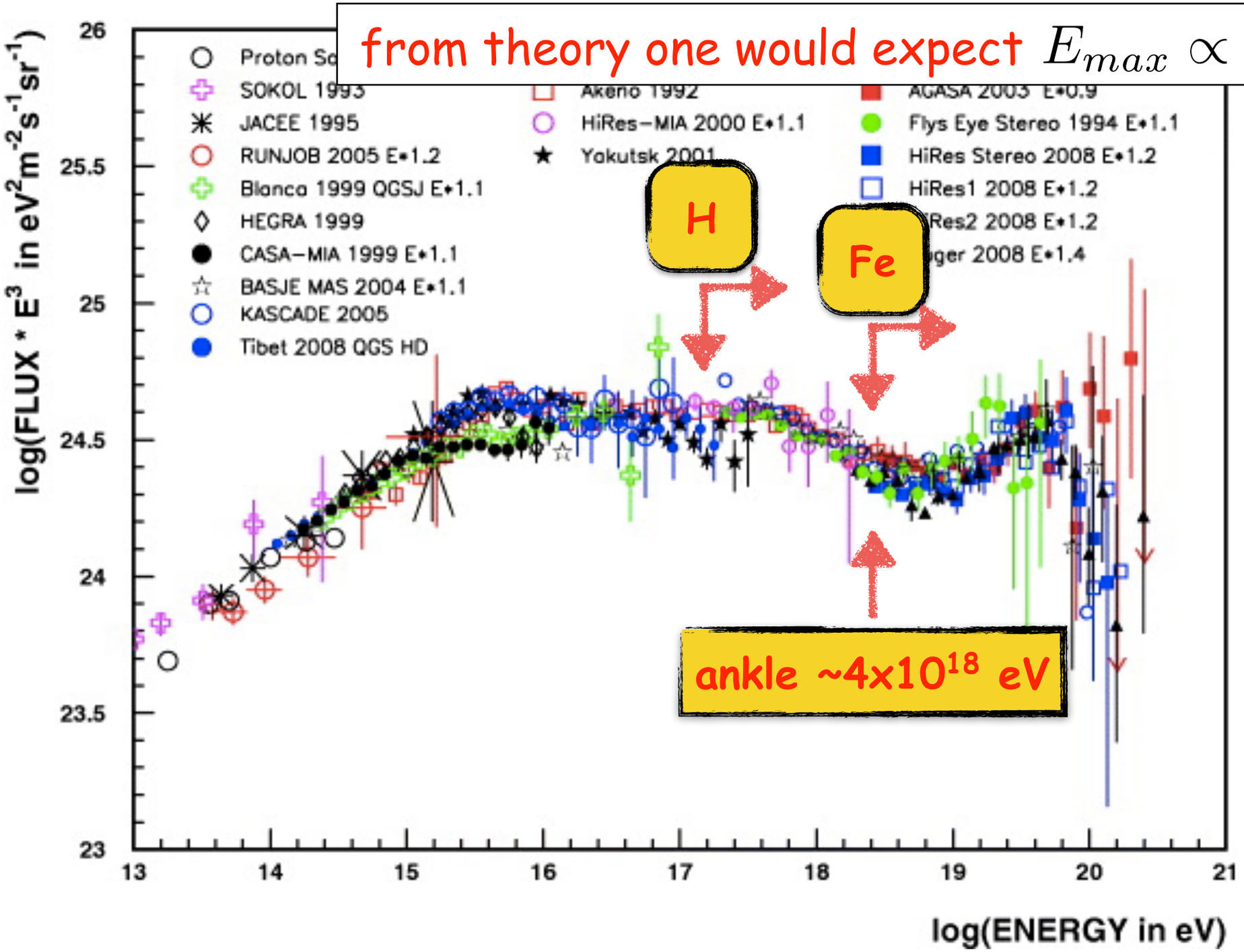

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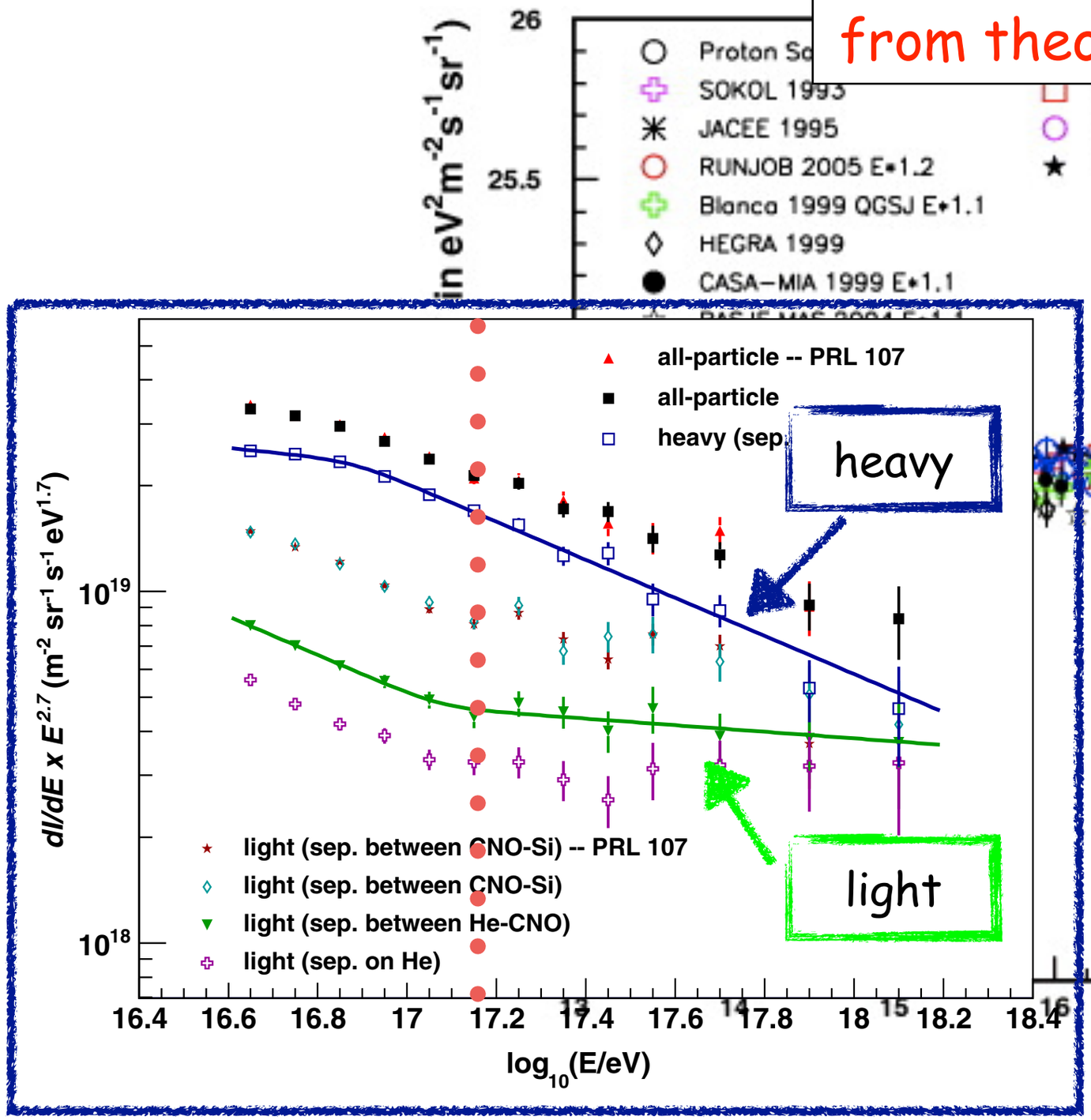

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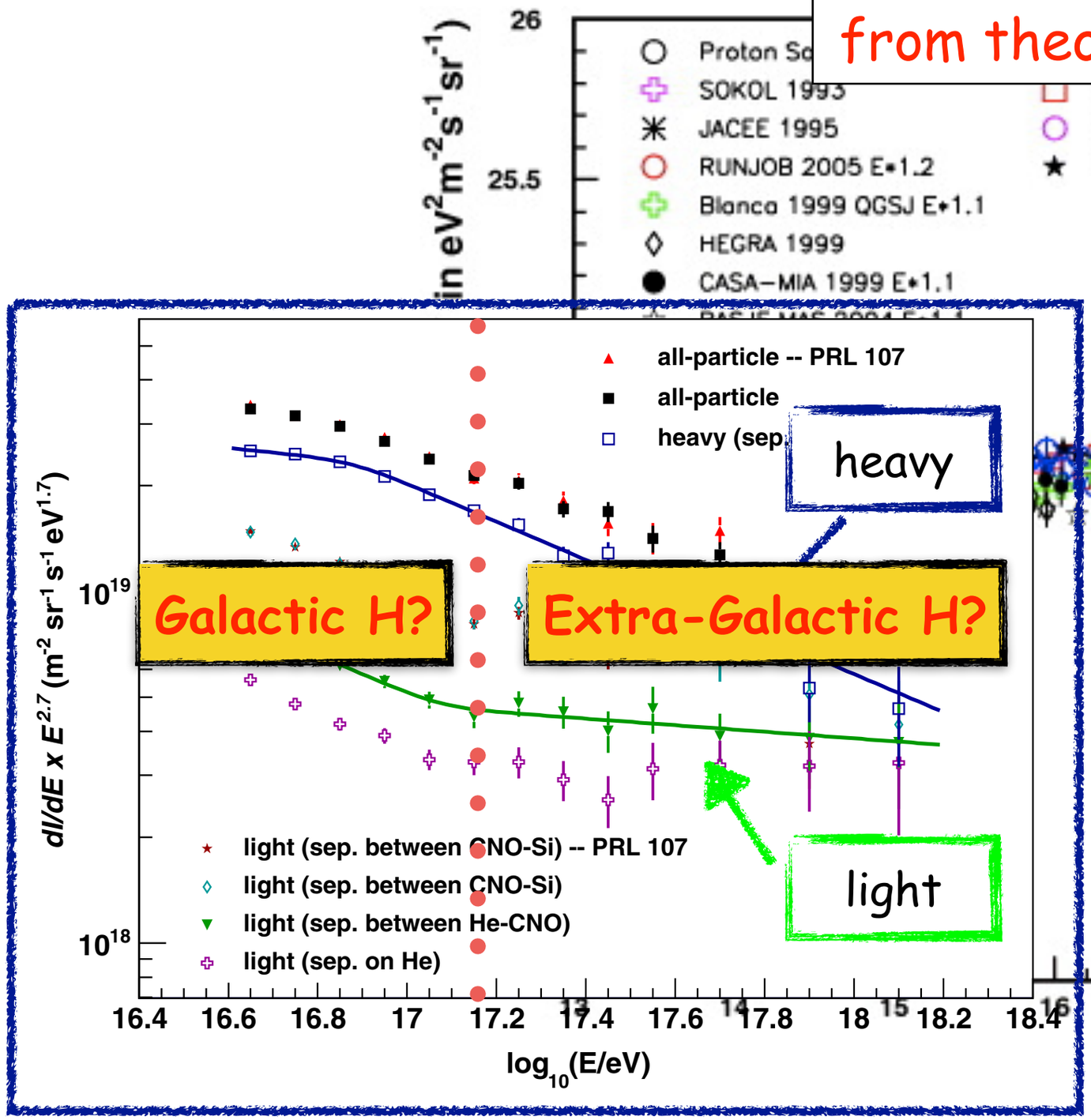

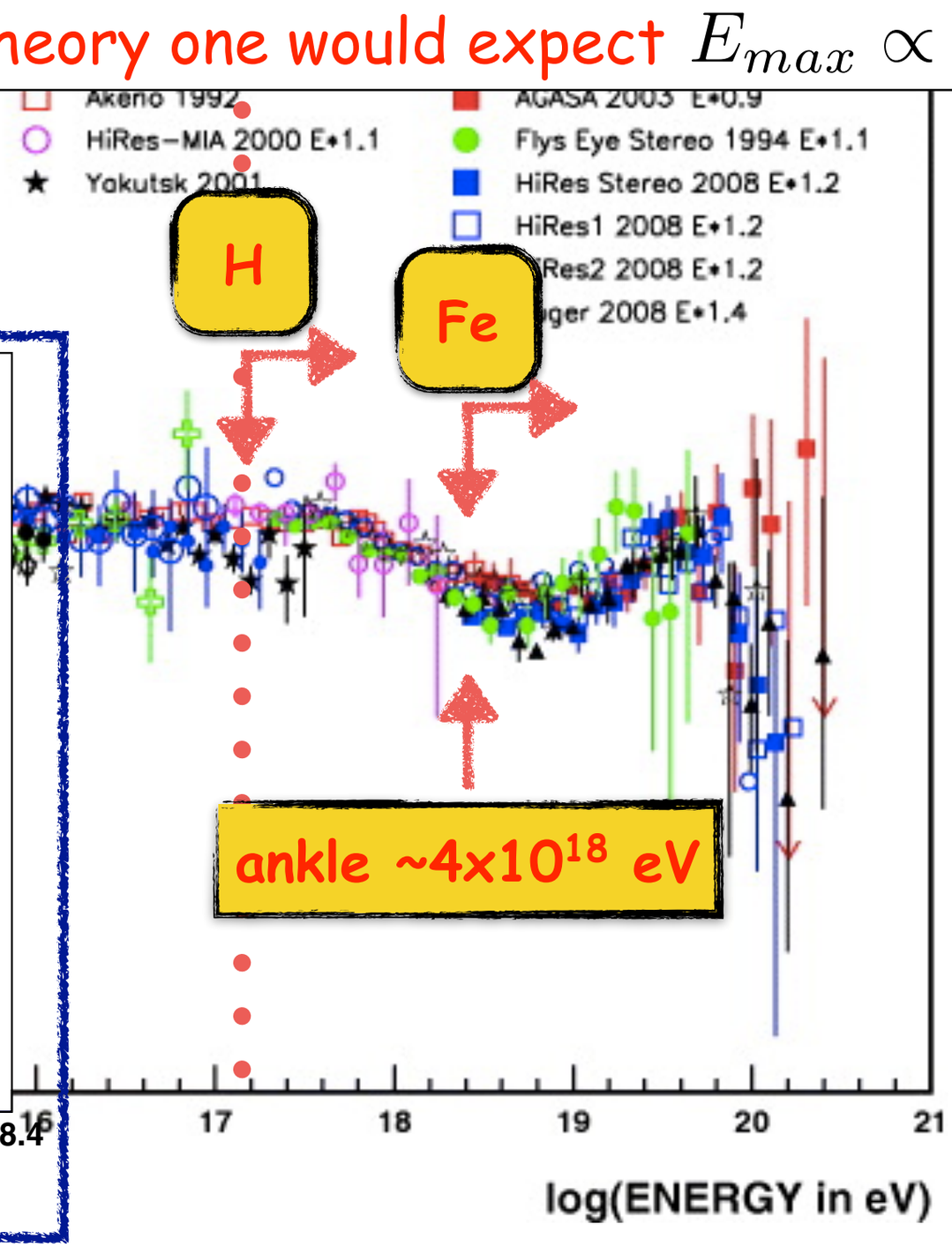

MeV GeV TeV PeV **EeV** ZeV

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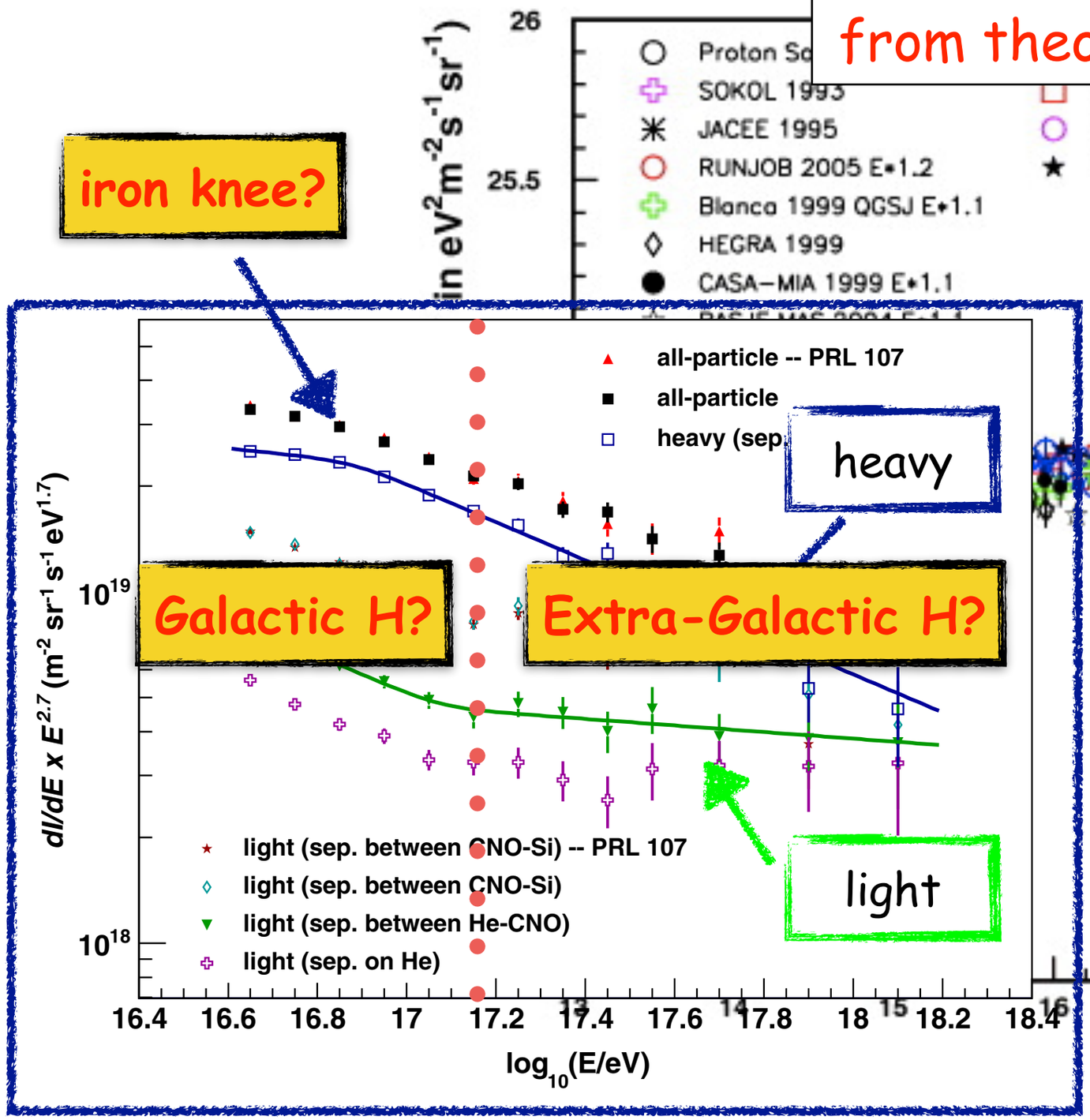

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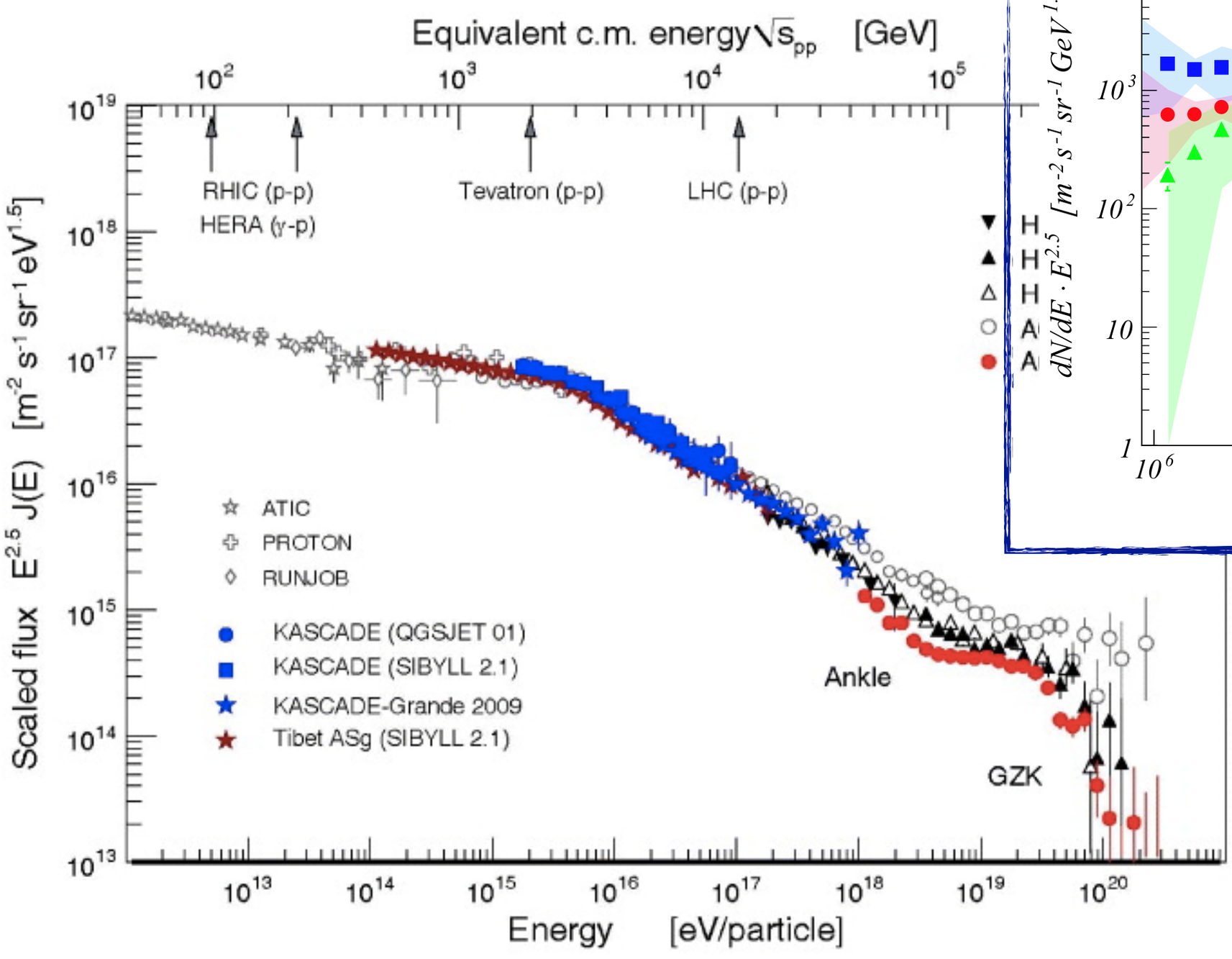
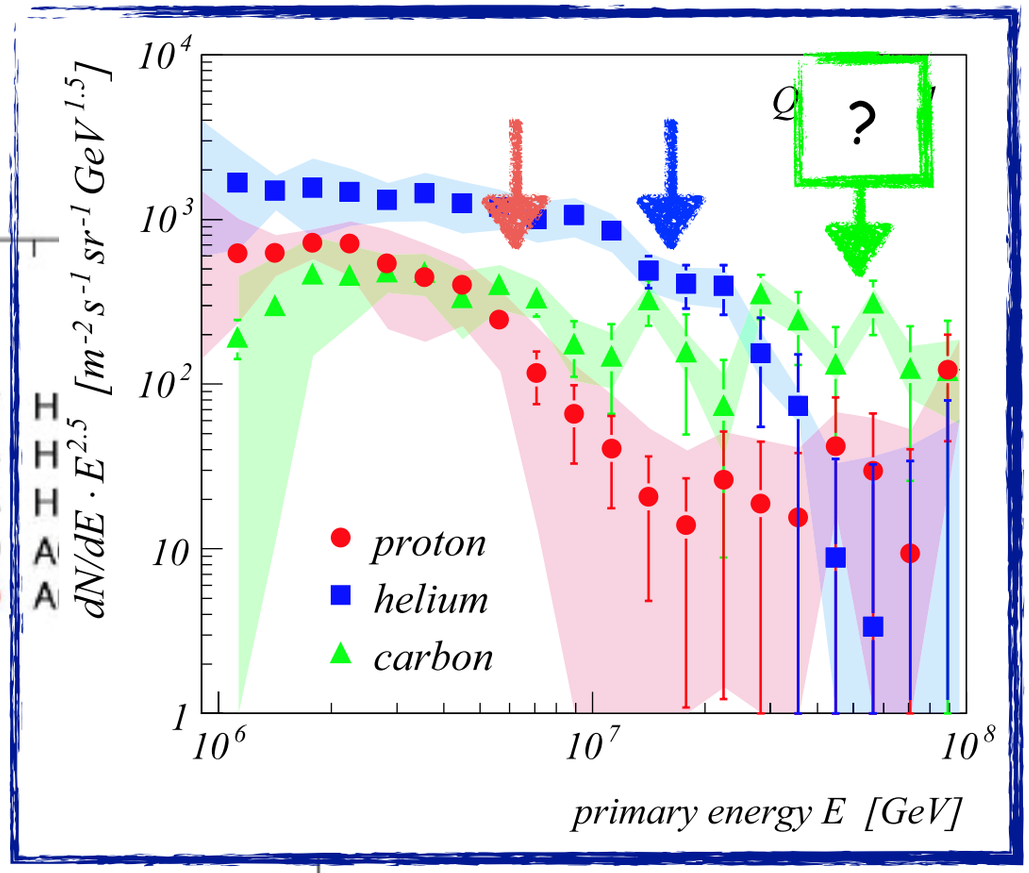


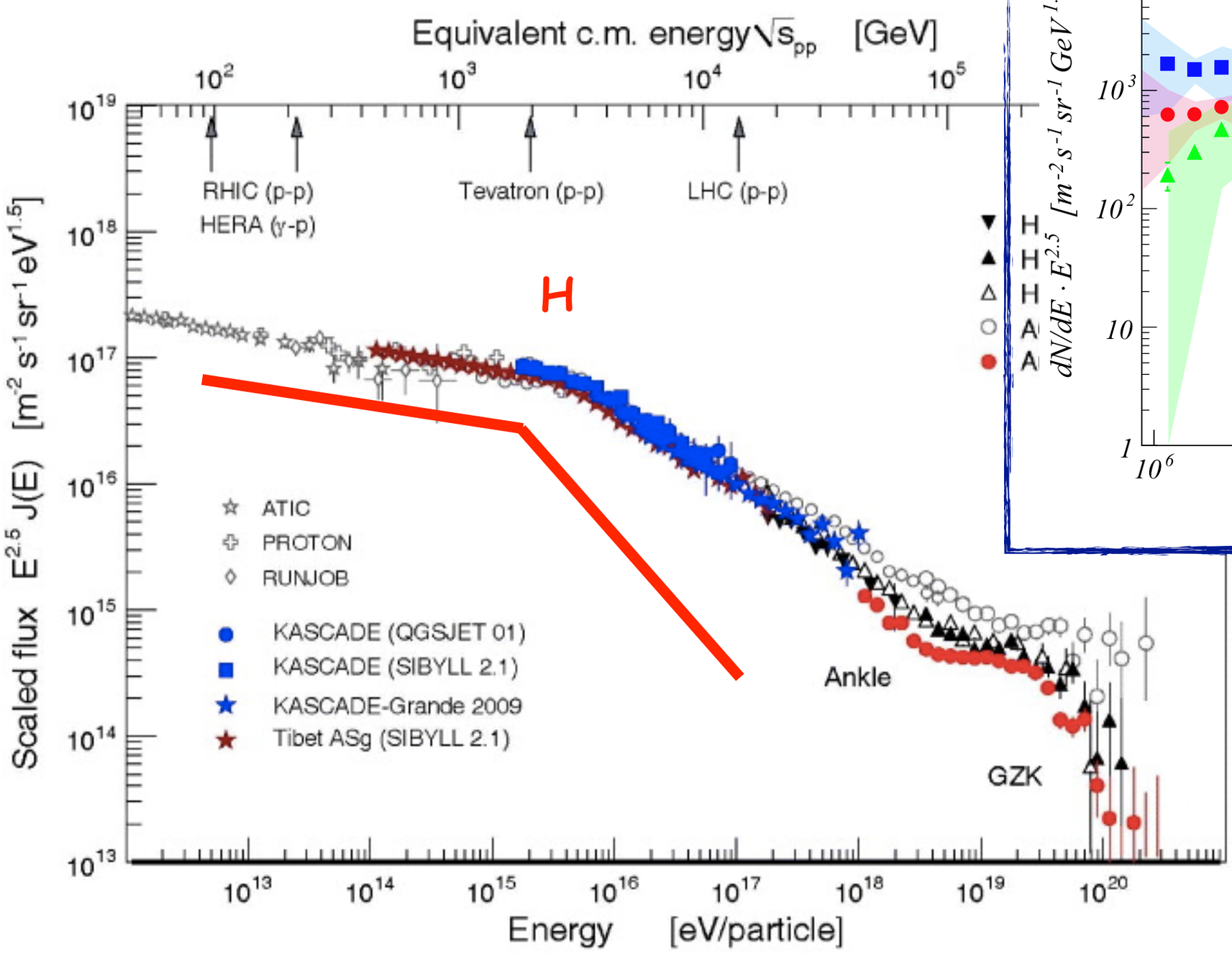


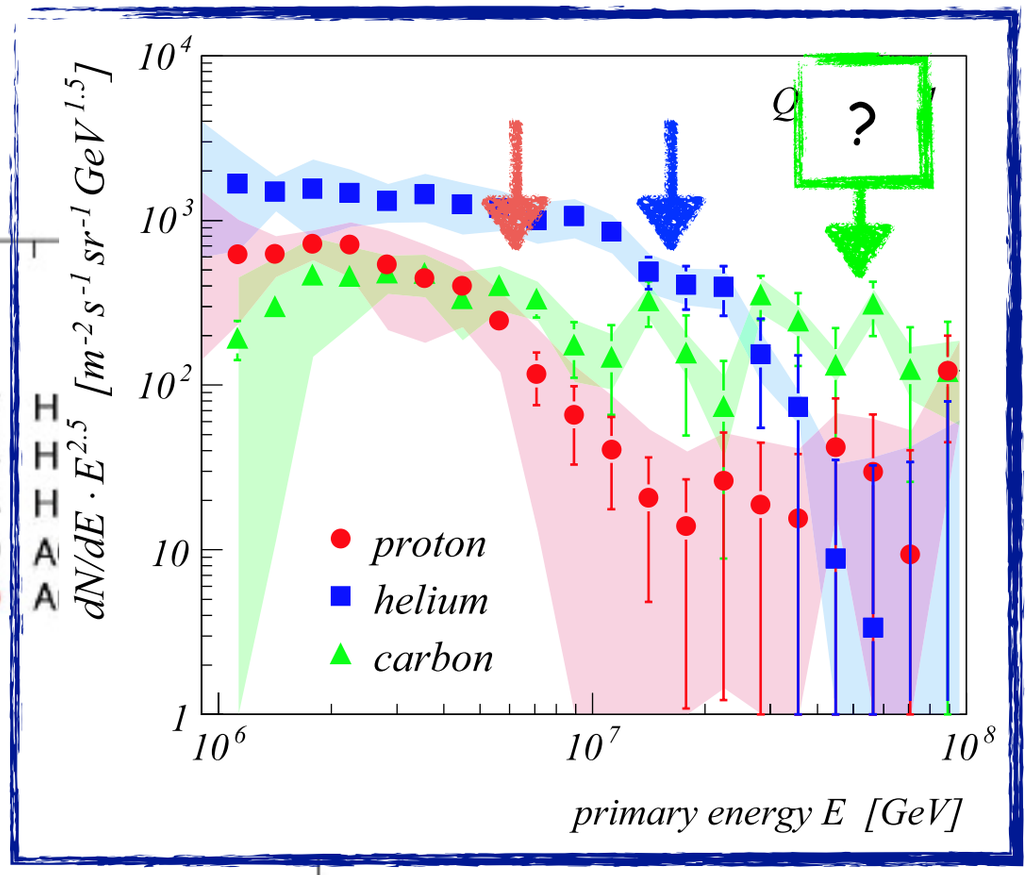
KASCADE coll. 2005

Z-dependent knee

MeV	GeV	TeV	PeV	EeV	ZeV

The EeV domain: Galactic-Extragalactic





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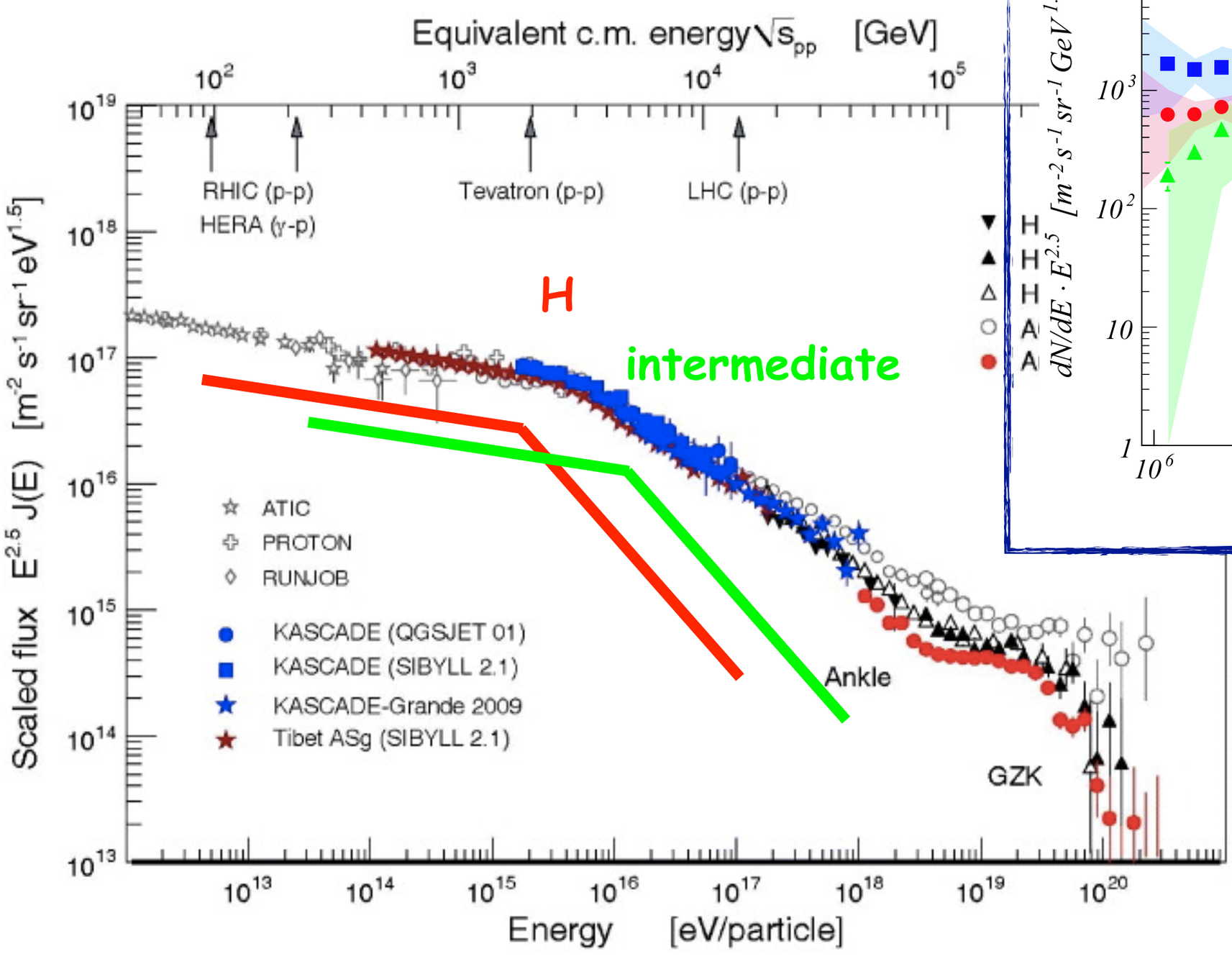

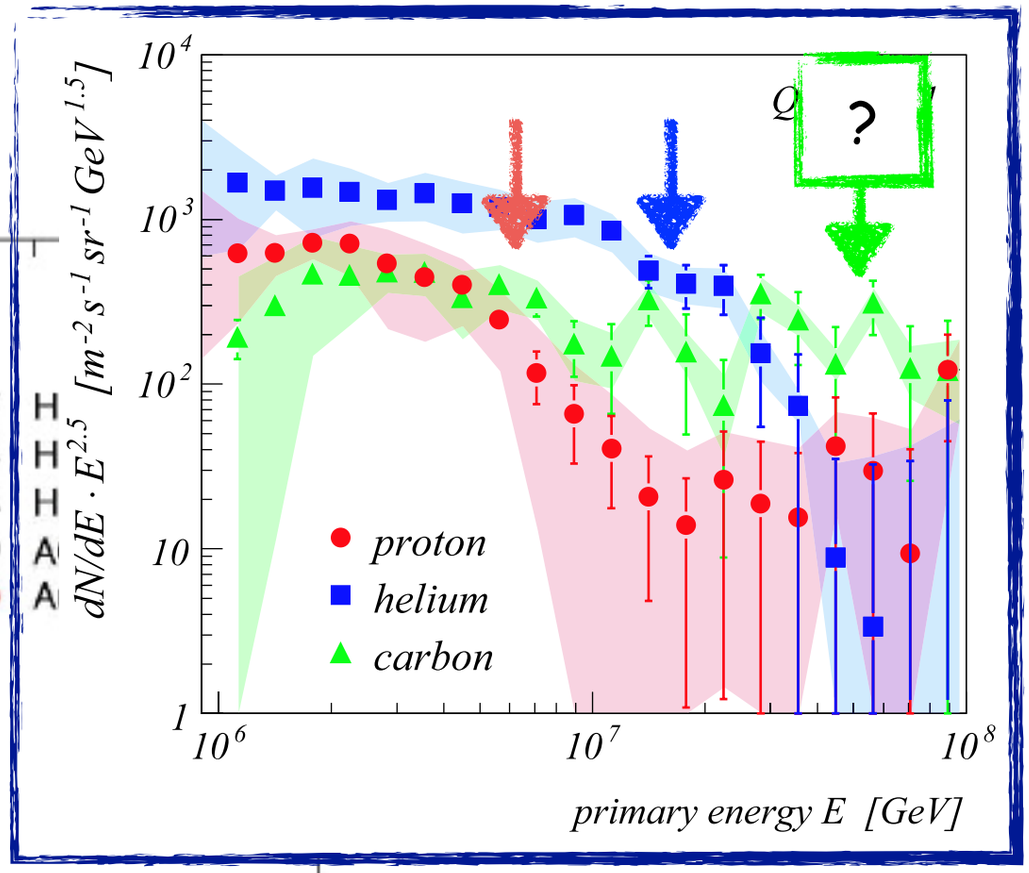

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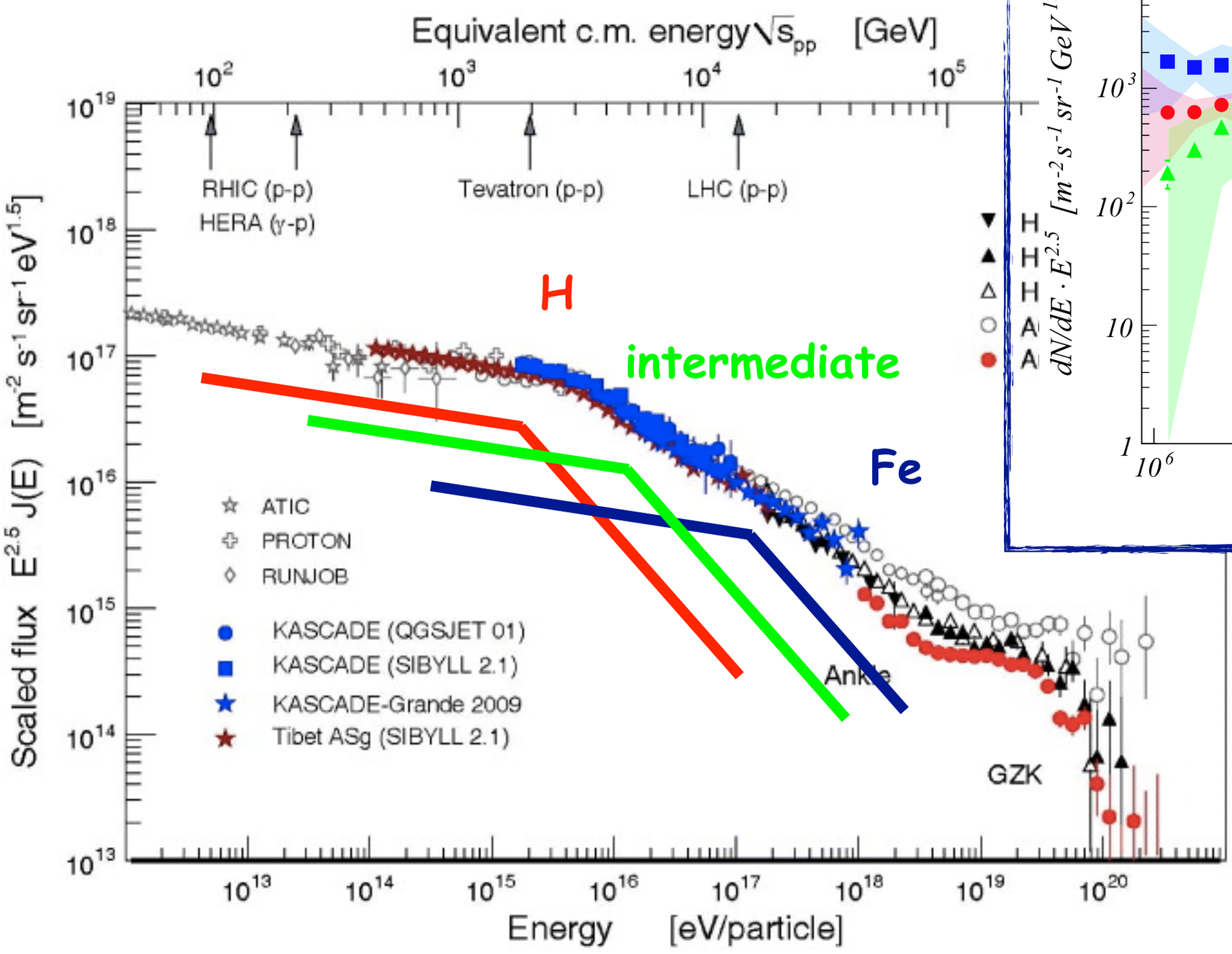

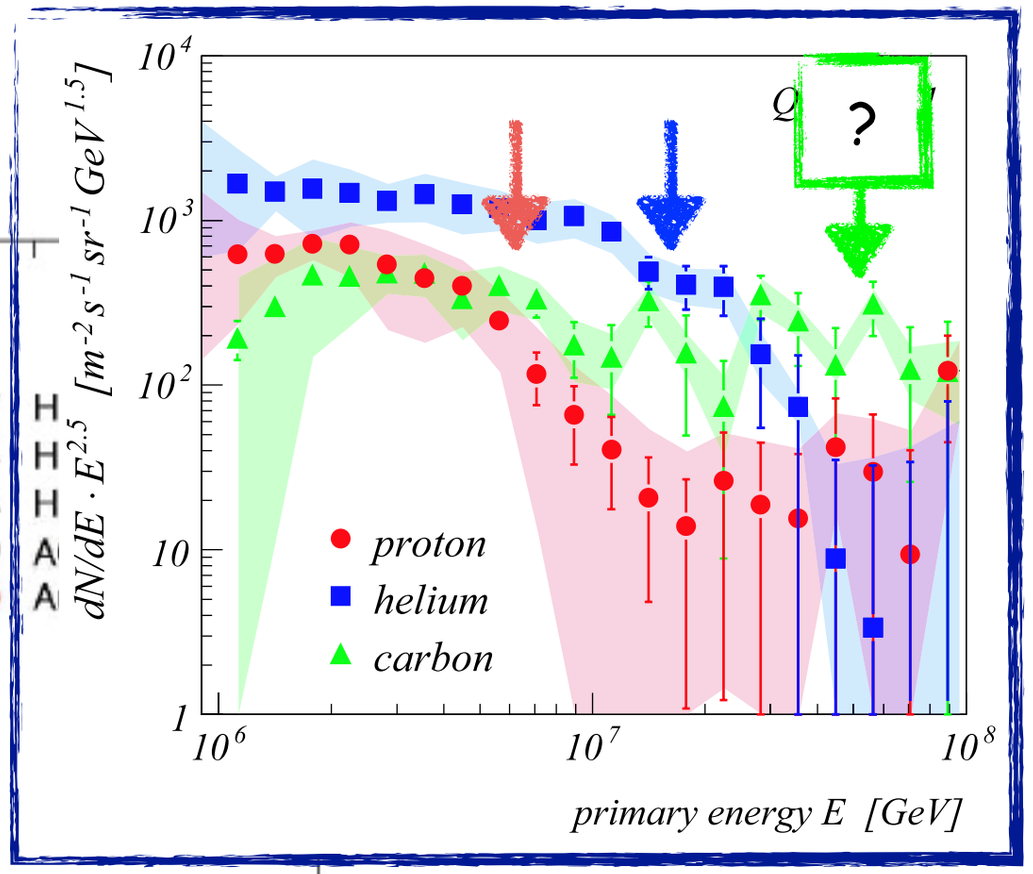

KASCADE coll. 2005

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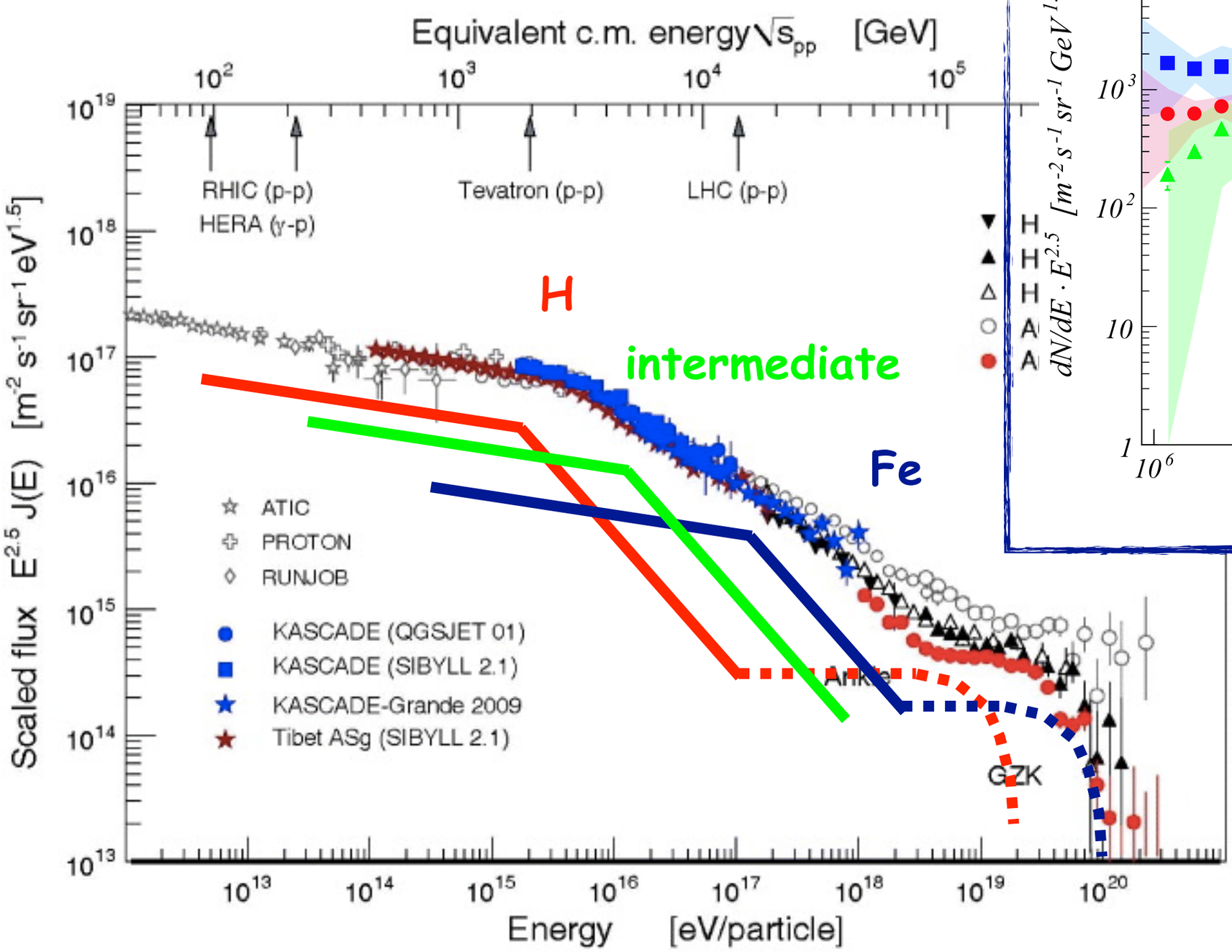

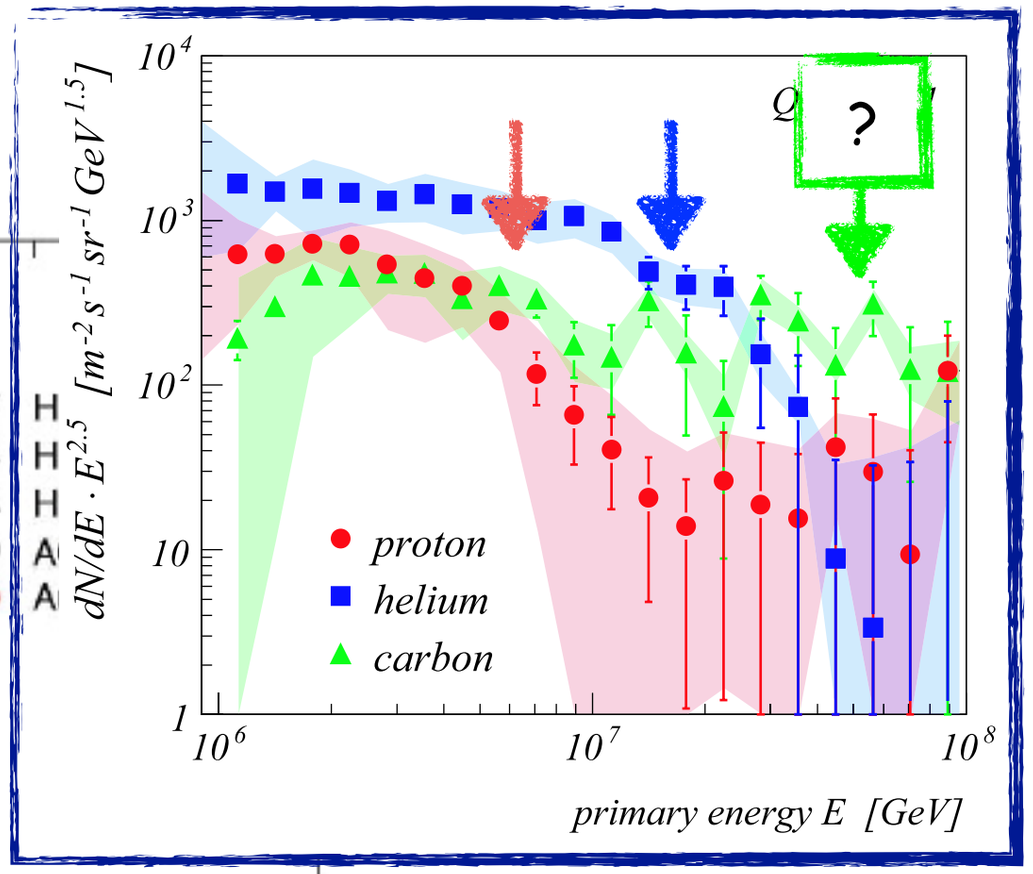

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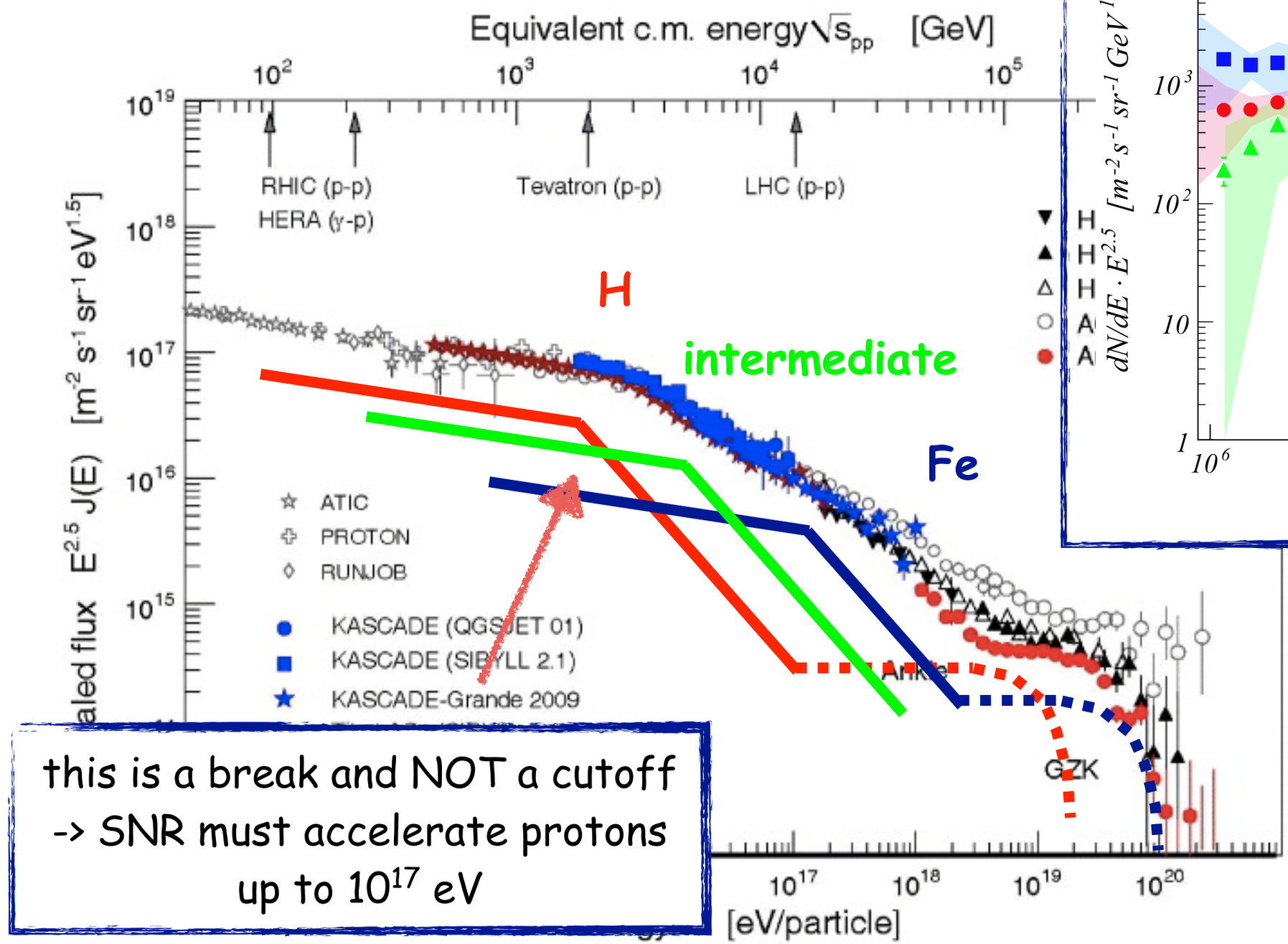
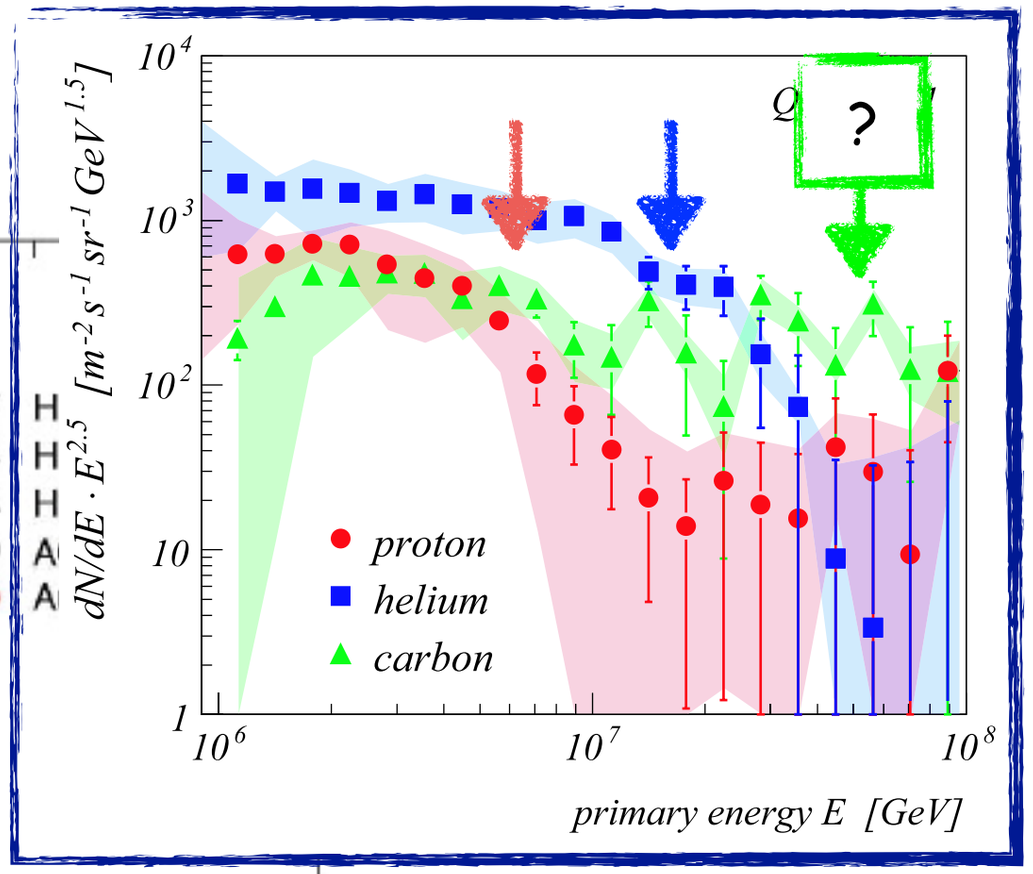




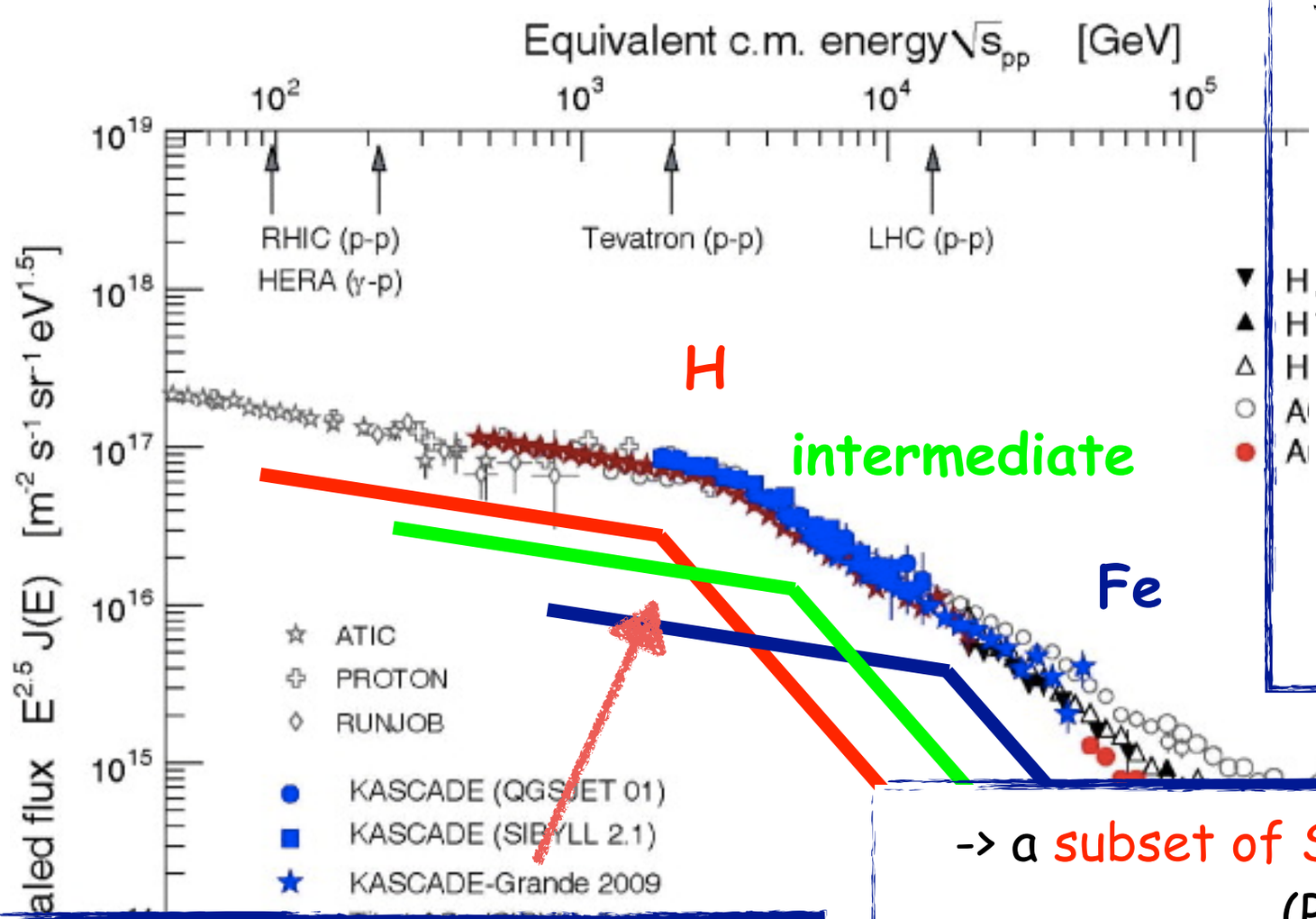
KASCADE coll. 2005

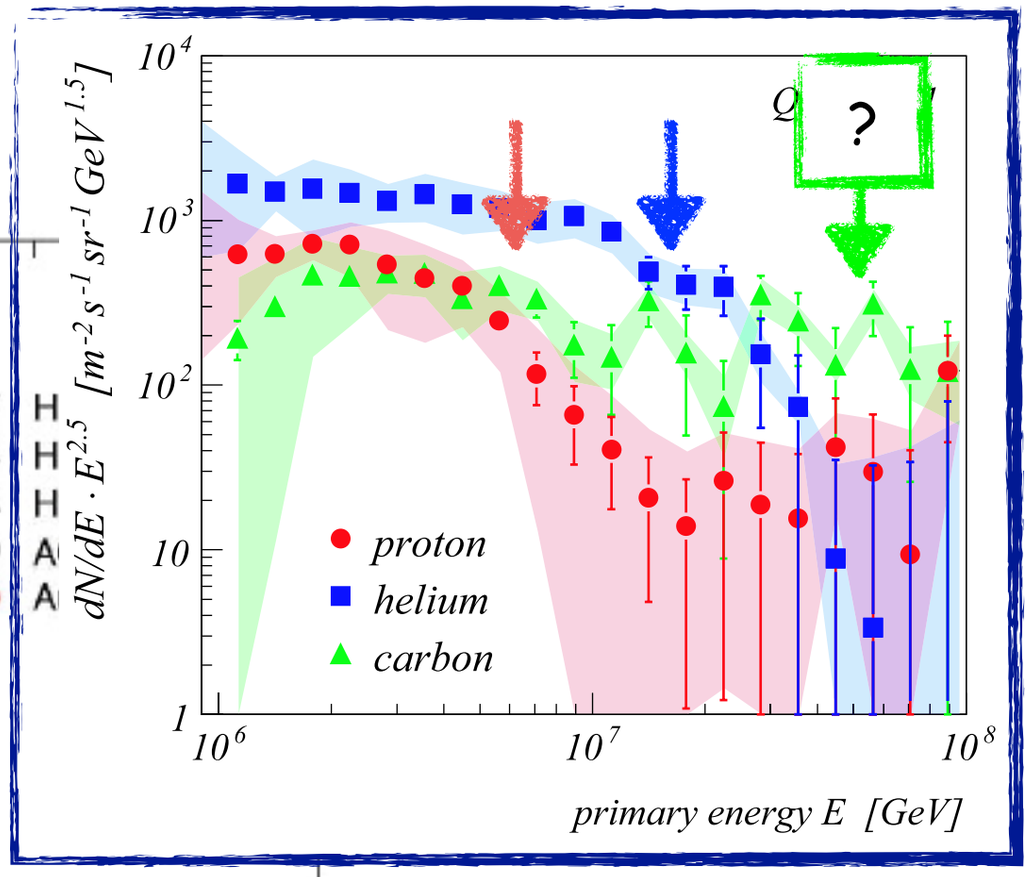
Z-dependent knee

this is a break and NOT a cutoff
-> SNR must accelerate protons
up to 10^{17} eV

MeV | GeV | TeV | PeV | EeV | ZeV

The EeV domain: Galactic-Extragalactic





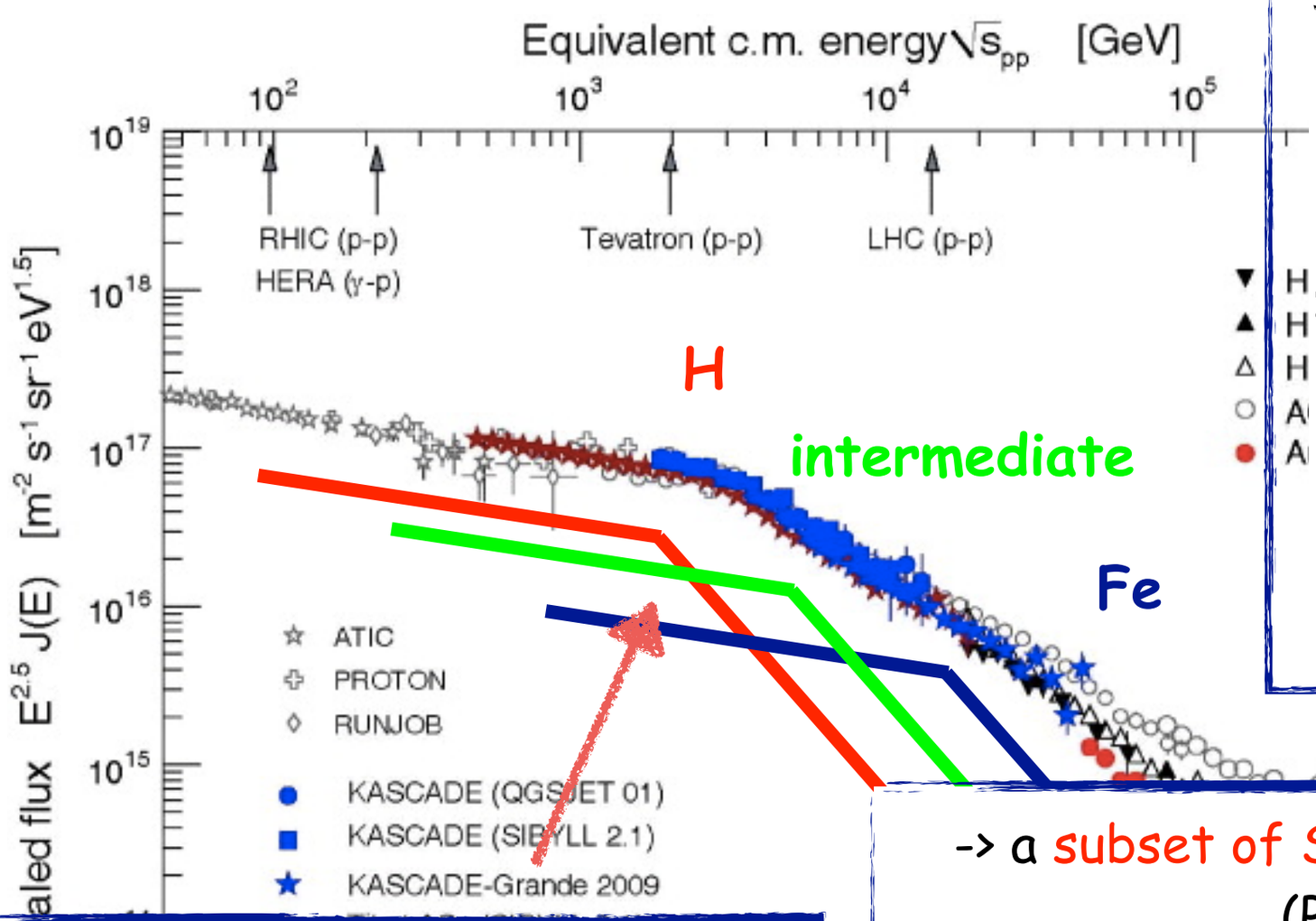
KASCADE coll. 2005

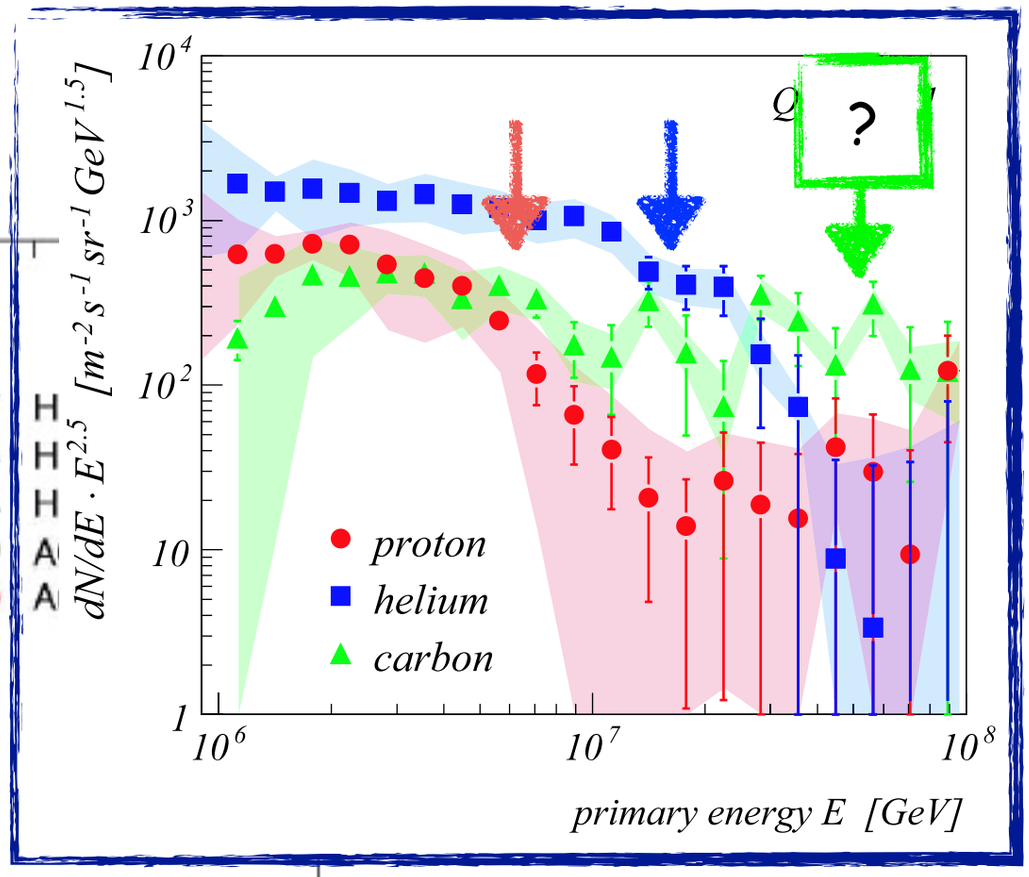
this is a break and NOT a cutoff
-> SNR must accelerate protons up to 10^{17} eV

-> a subset of SNRs accelerate H up to >10^{17} eV? (Ptuskin&Zirakashvili)
-> SNRs are NOT the sources of CRs? (superbubbles? Bykov+, Parizot+)
-> E_{max} = Z only if iron is FULLY ionized. Is that true? (Morlino)

MeV | GeV | TeV | PeV | EeV | ZeV

The EeV domain: Galactic-Extragalactic





KASCADE coll. 2005

this is a break and NOT a cutoff

- up to 10^{17} eV

-> a subset of SNRs accelerate H up to >10^{17} eV? (Ptuskin&Zirakashvili)

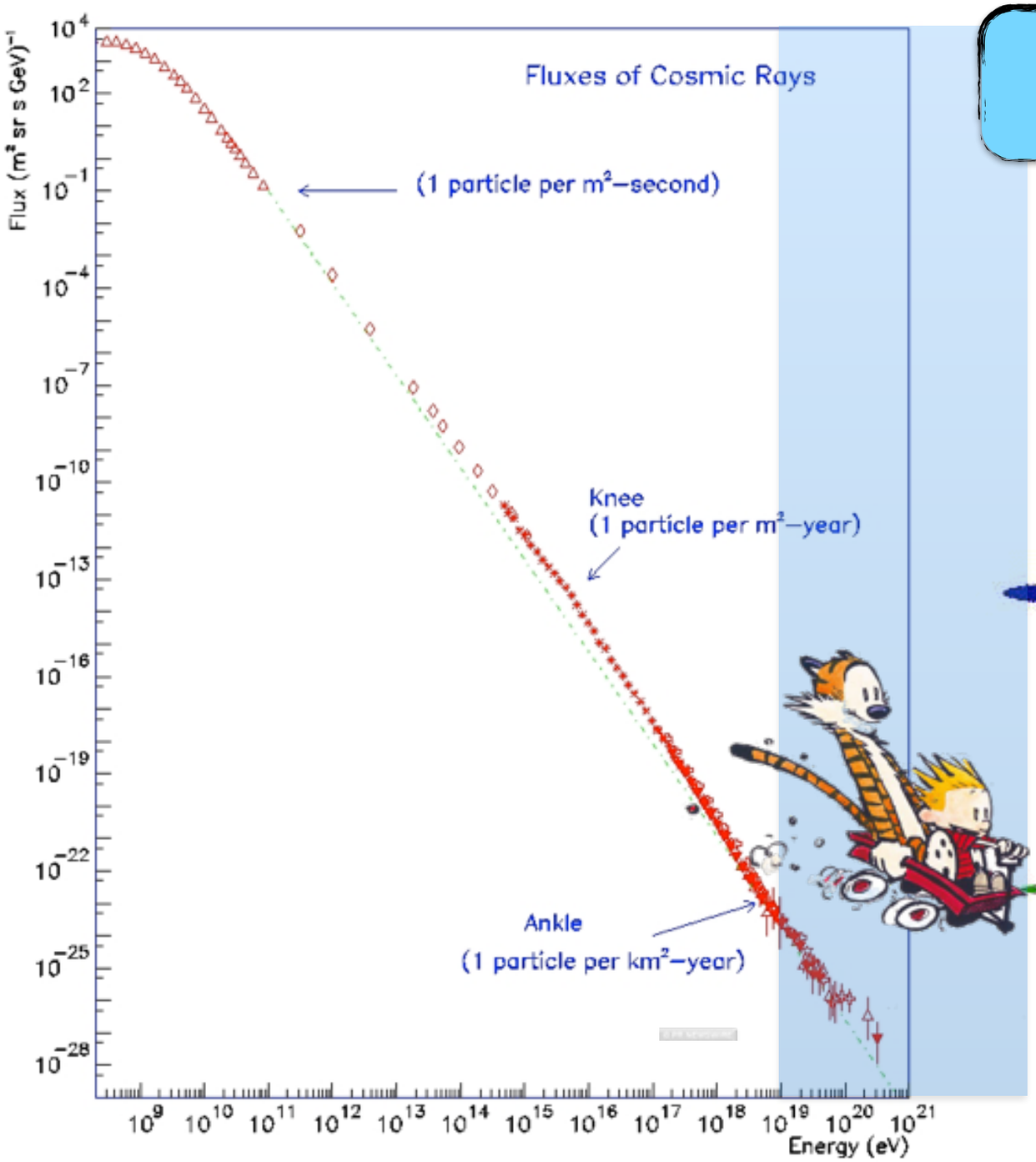
-> SNRs are NOT the sources of CRs? (Morlino)

radio detection of air showers -> mass composition (LOFAR, Buitink+ 2016)

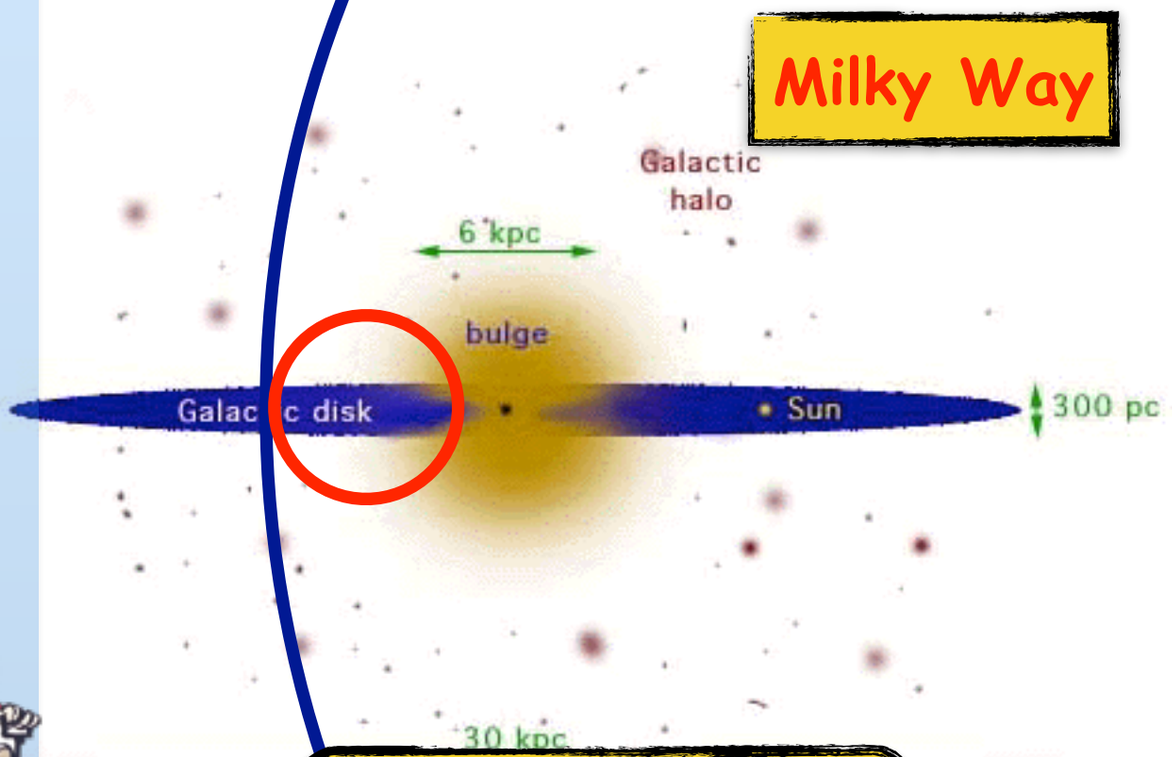
-> E_{max} = Z only if iron is FULLY ionized. Is that true? (Morlino)

MeV | GeV | TeV | PeV | EeV | ZeV

The ZeV domain (> 10^{19} eV)



$$R_L(10^{20}\mathrm{eV}) \sim 36\ \mathrm{kpc}$$



extragalactic CRs

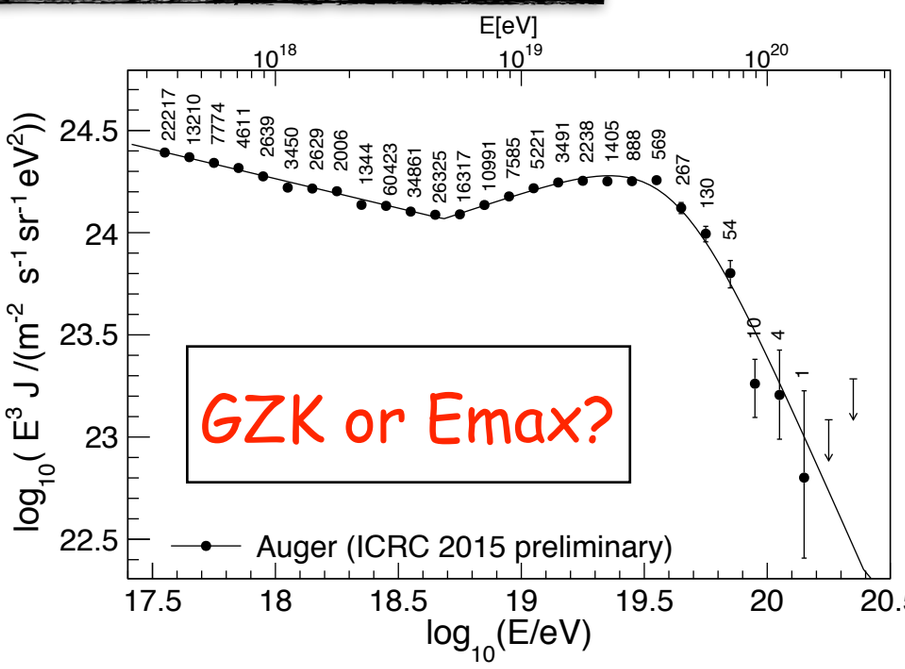
AUGER Obs., Telescope Array

MeV GeV TeV PeV EeV ZeV

The ZeV domain (> 10^{19} eV)

spectral suppression

Valino+ 2015

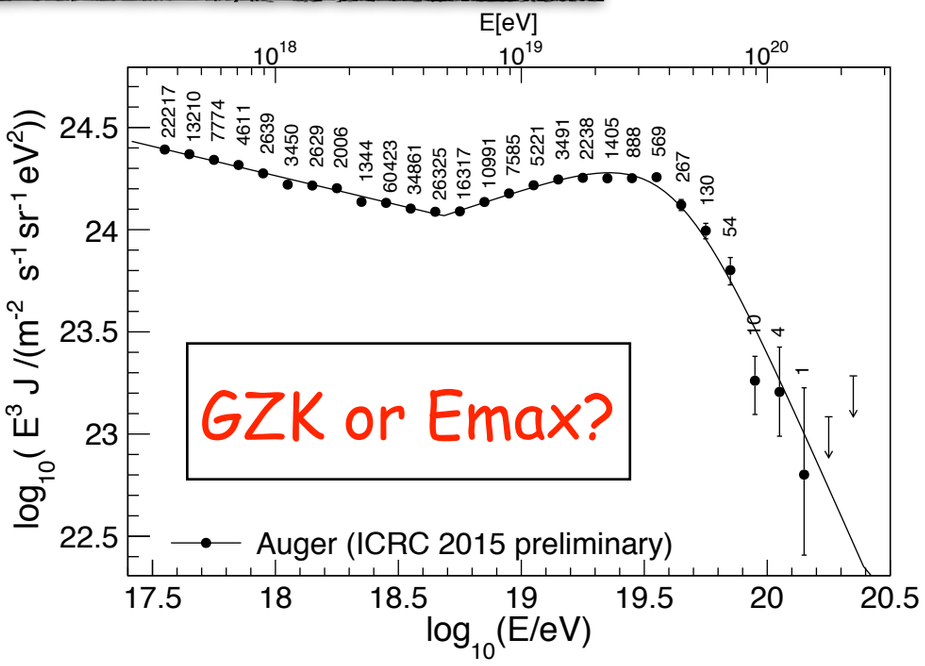


MeV | GeV | TeV | PeV | EeV | ZeV

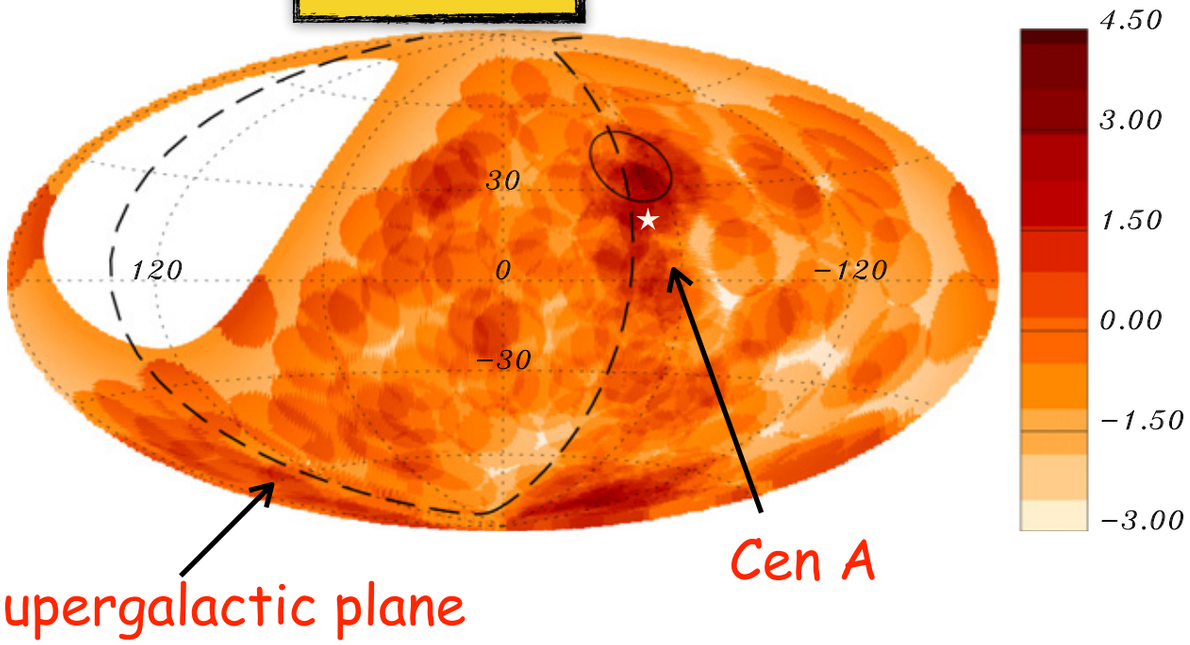
The ZeV domain (> 10^{19} eV)

spectral suppression

Valino+ 2015



isotropy

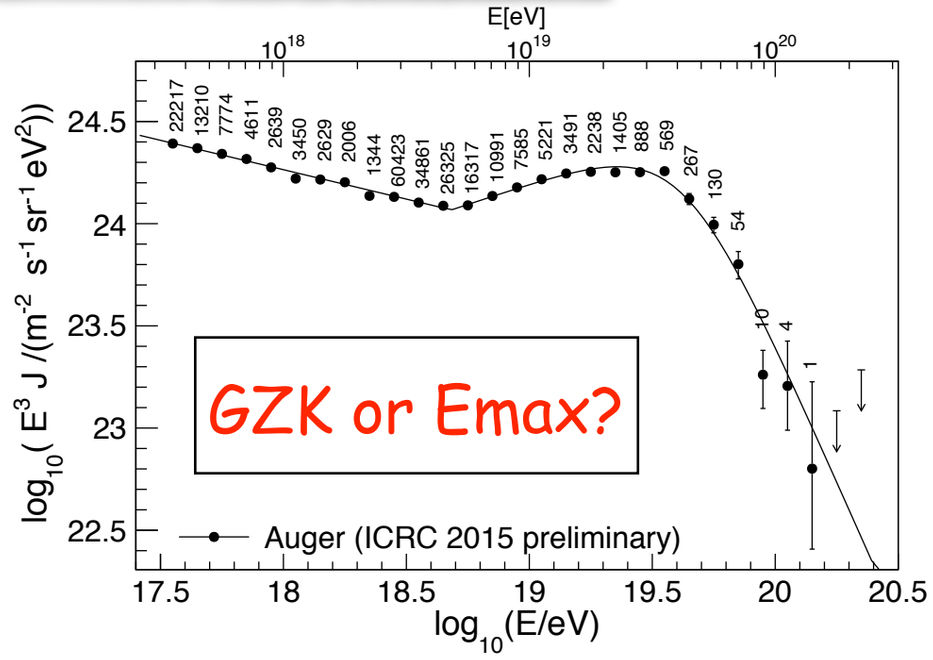


Auger+ 2015

MeV GeV TeV PeV EeV **ZeV**

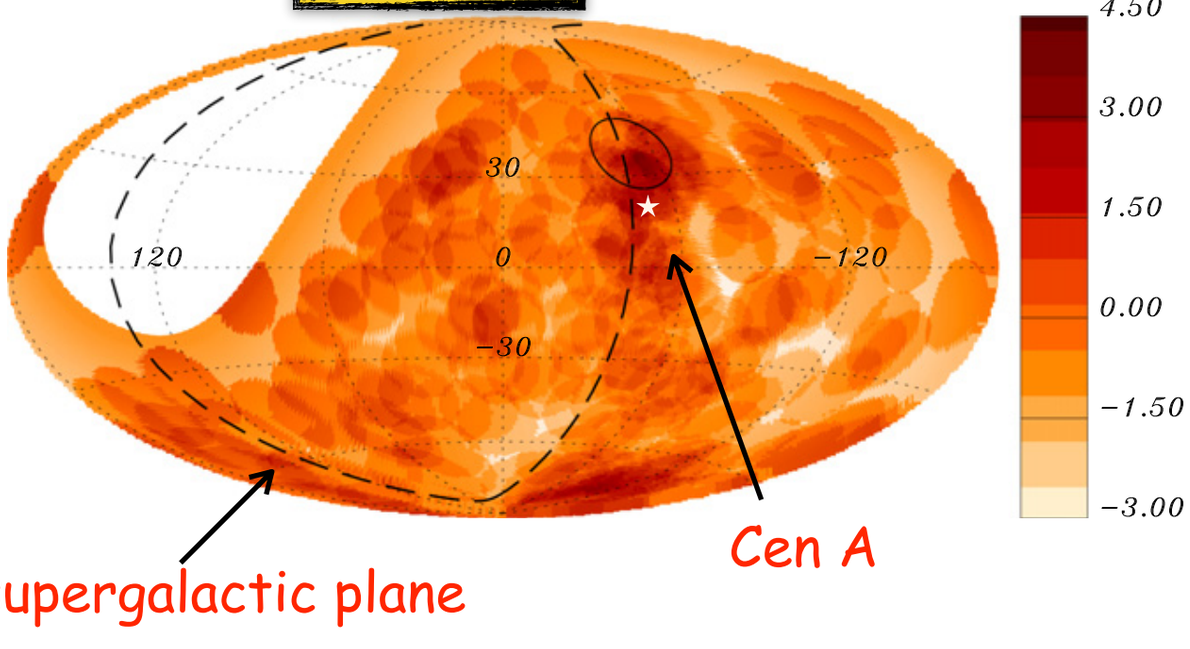
The ZeV domain (> 10^{19} eV)

spectral suppression



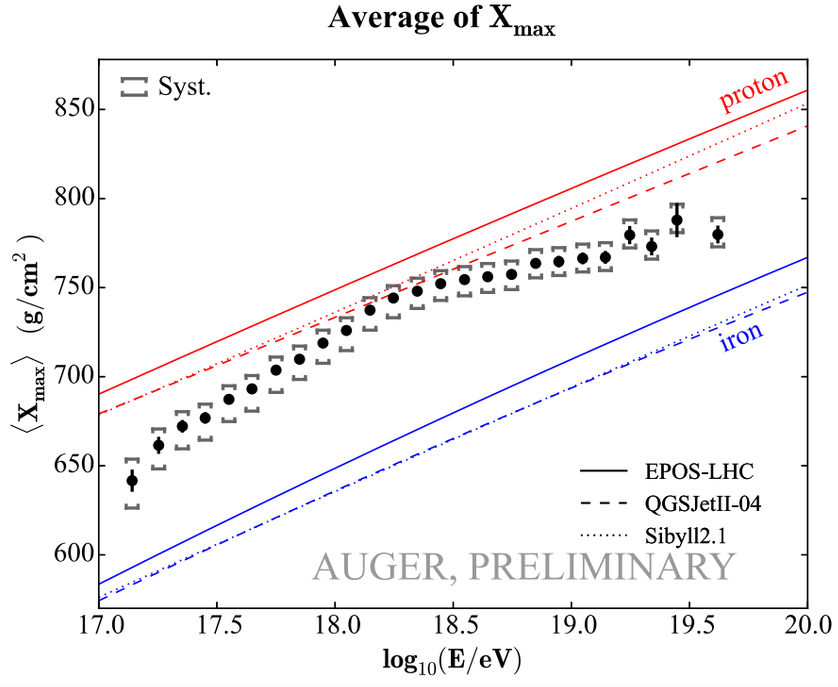
Valino+ 2015

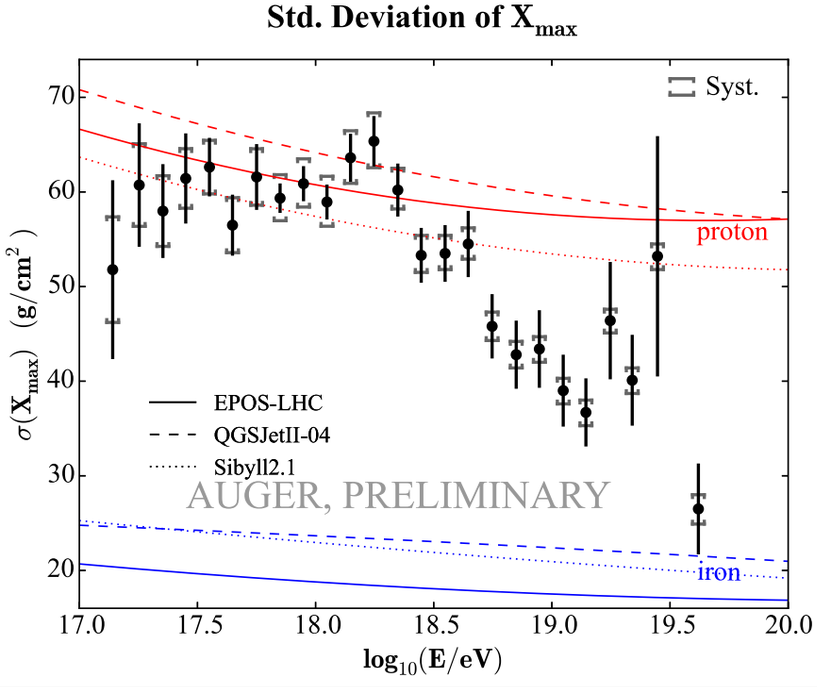
isotropy



Aab+ 2015

mixed composition



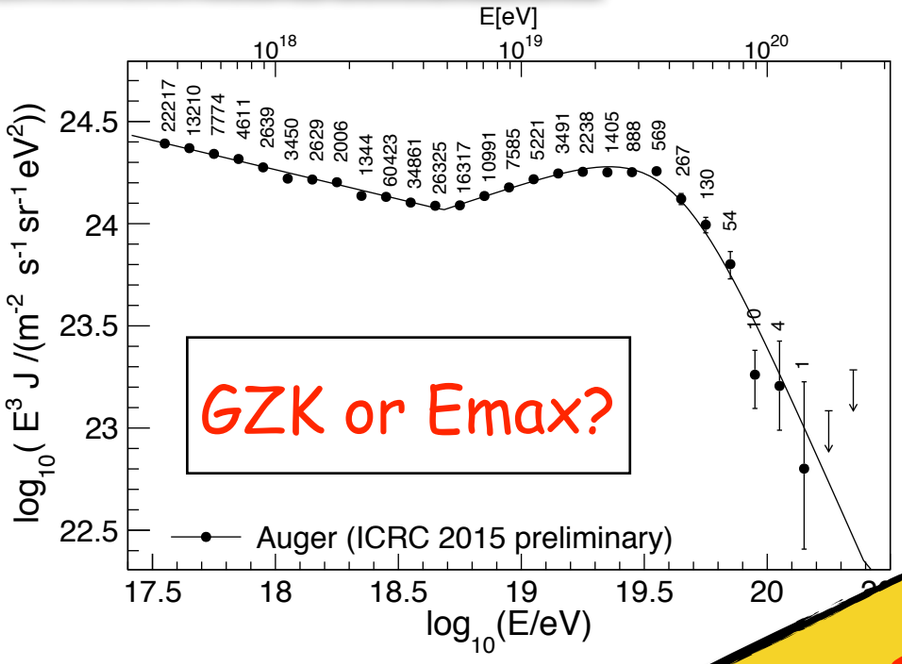


Porcelli+ 2015

MeV GeV TeV PeV EeV ZeV

The ZeV domain (> 10^{19} eV)

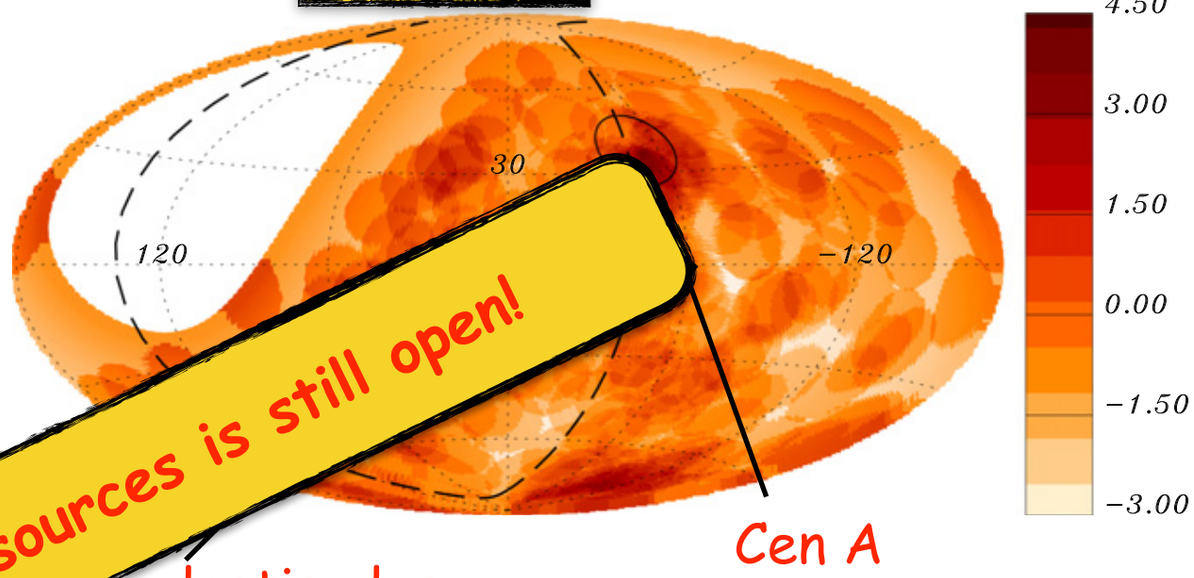
spectral suppression



Valino+ 2015

GZK or Emax?

isotropy



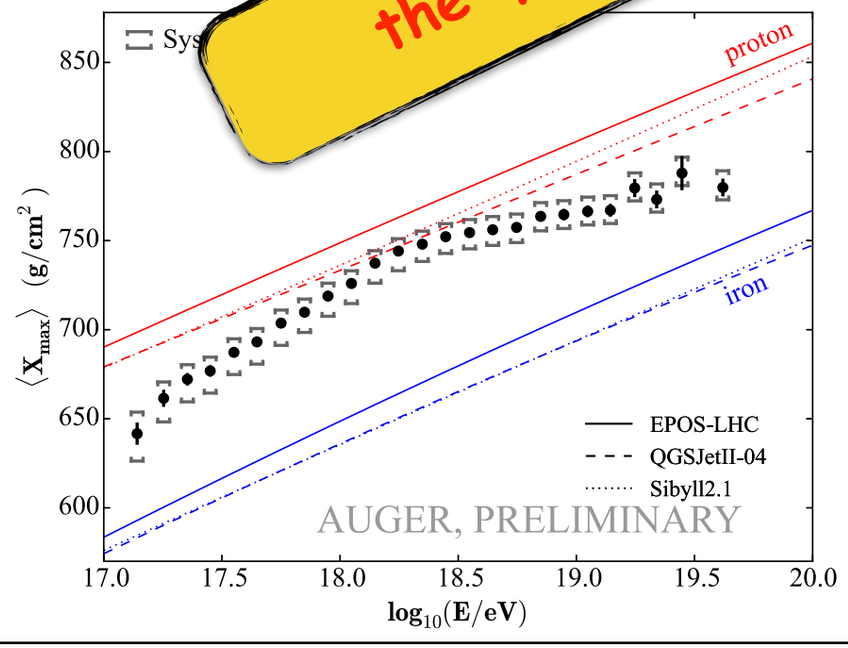
Aab+ 2015

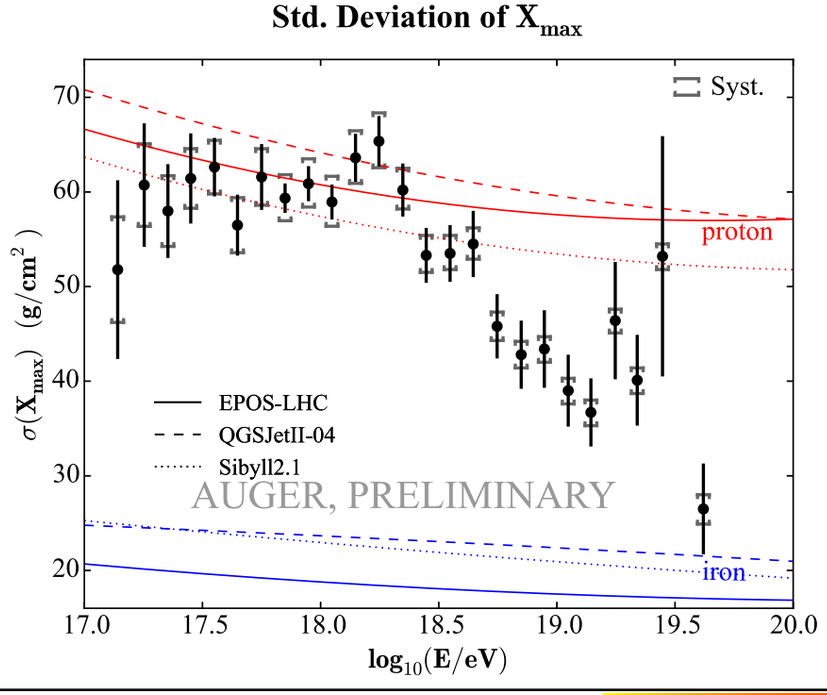
Cen A

Ergalactic plane

the quest for sources is still open!

mixed composition





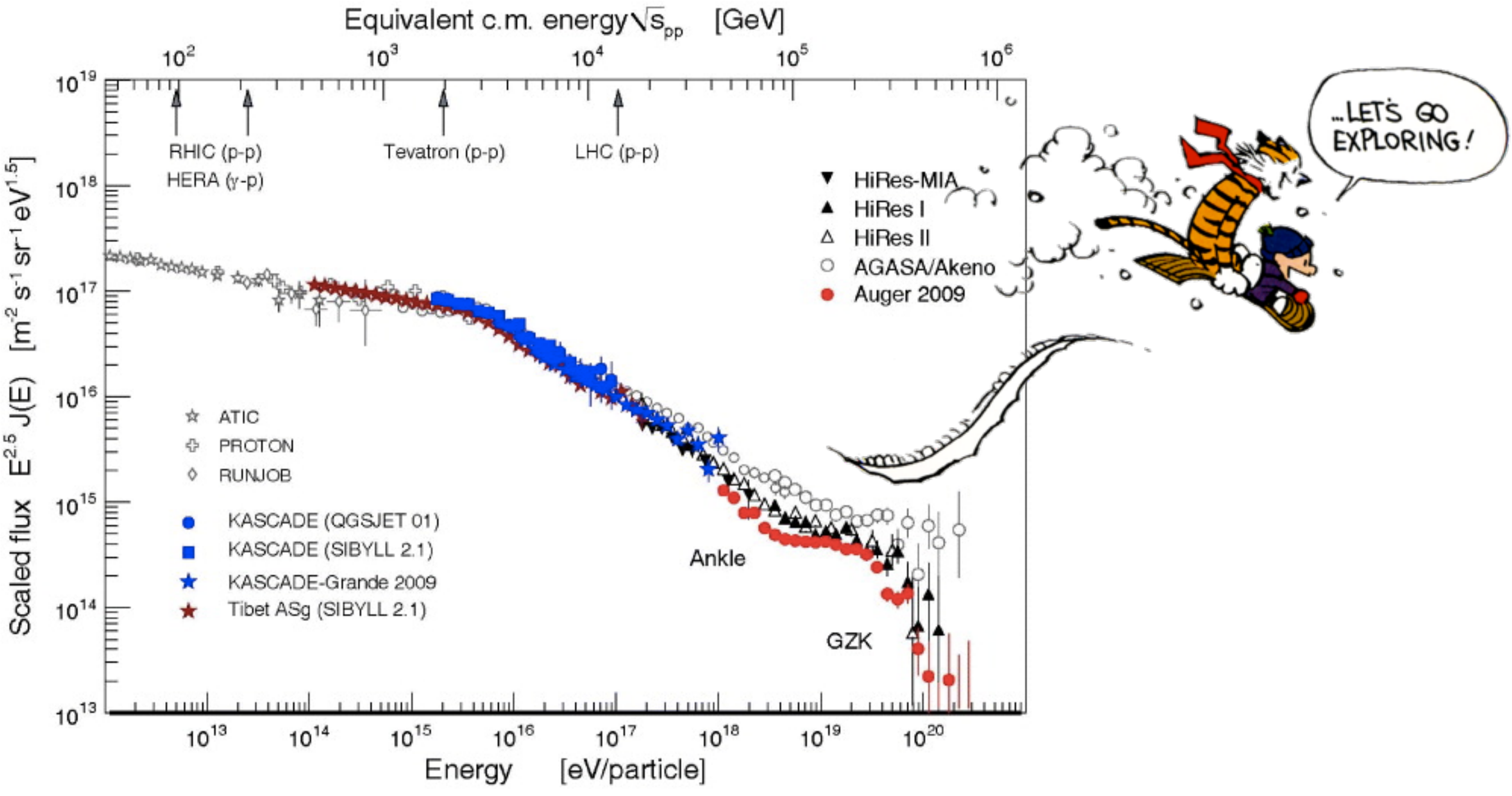
Porcelli+ 2015

MeV GeV TeV PeV EeV ZeV

Conclusions

- new view of the **MeV domain** -> **Voyager 1** in interstellar space! plus indirect estimates from ionization rates in **molecular clouds**
- **GeV-TeV domain** -> **gamma ray astronomy** domain -> test of the **supernova remnant hypothesis** for the origin of galactic cosmic rays. some **puzzling spectral features** in H and He spectra
- the first **PeVatron detected** in our Galaxy is NOT a SNR, but most likely the **supermassive black hole in the galactic centre**
- galactic to extragalactic **transition at the ankle**, possible **scaling of Emax with Z** (same rigidity)
- suppression (**GZK or Emax?**) in the spectrum at 60 EeV, **isotropy** (keep an eye on Cen A), **mixed composition** -> who accelerates UHECRs?

Thank you.


Equivalent c.m. energy $\sqrt{s_{pp}}$ [GeV]
10^2
10^3
10^4
10^5
10^6
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
LHC (p-p)
HiRes-MIA
HiRes I
HiRes II
AGASA/Akeno
Auger 2009
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2009
Tibet ASg (SIBYLL 2.1)
Ankle
GZK
Scaled flux $E^{2.5}$ J(E) [m^{-2} s^{-1} sr^{-1} $eV^{1.5}$]
Energy [eV/particle]
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
...LET'S GO EXPLORING!