Gamma rays and the sources of galactic Cosmic Rays

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The SNR paradigm for the origin of CRs

SN explosions-> enough power to explain CRs

Baade & Zwicky 1934 (see also Ter Haar 1950)

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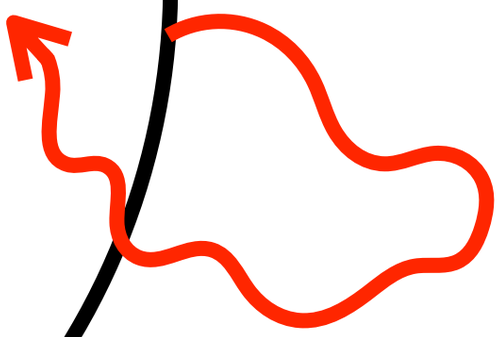

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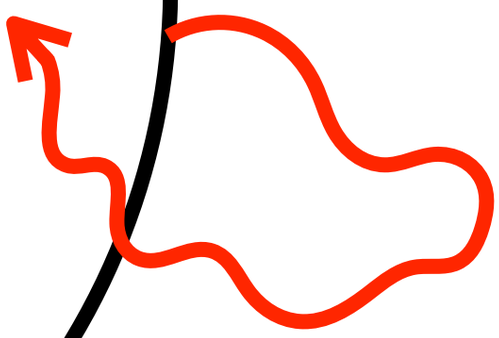

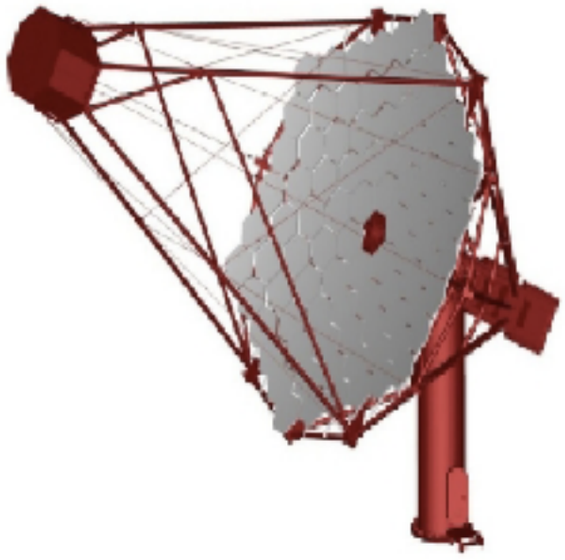

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<- Cherenkov telescope

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Gamma-ray emission from SNRs: hadronic or leptonic?

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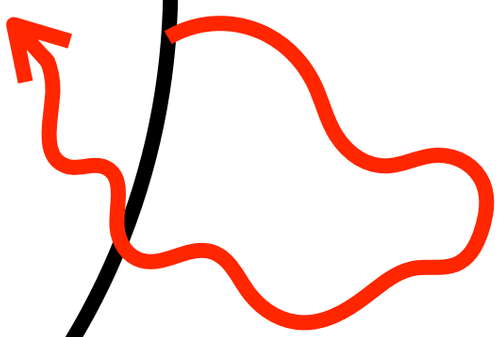

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π^0 bump -> SNRs accelerate GeV protons

Fermi

Fermi, Agile (2013)

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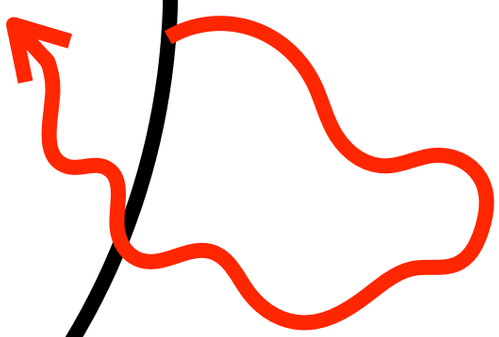

very popular but not proven yet!

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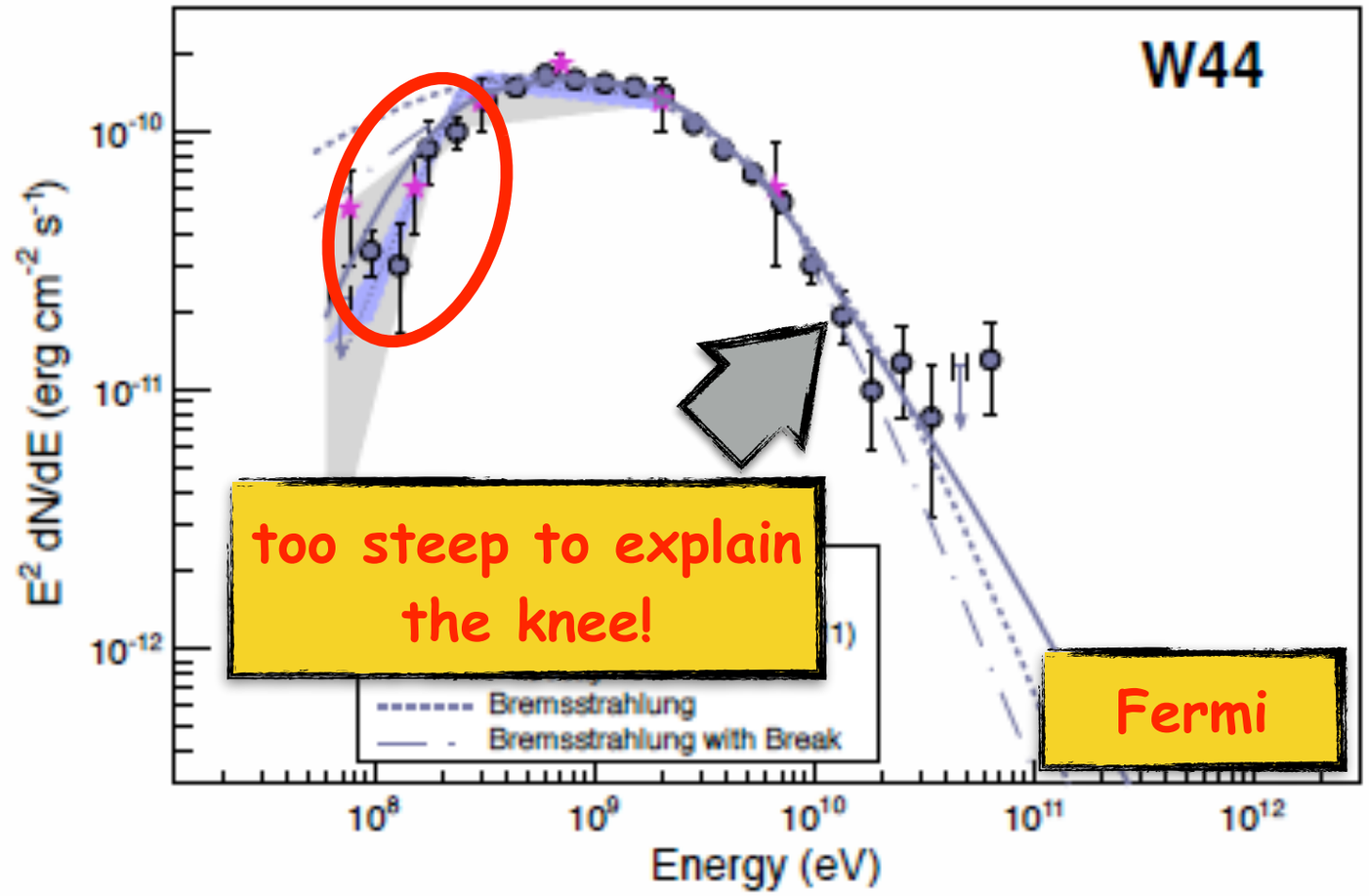

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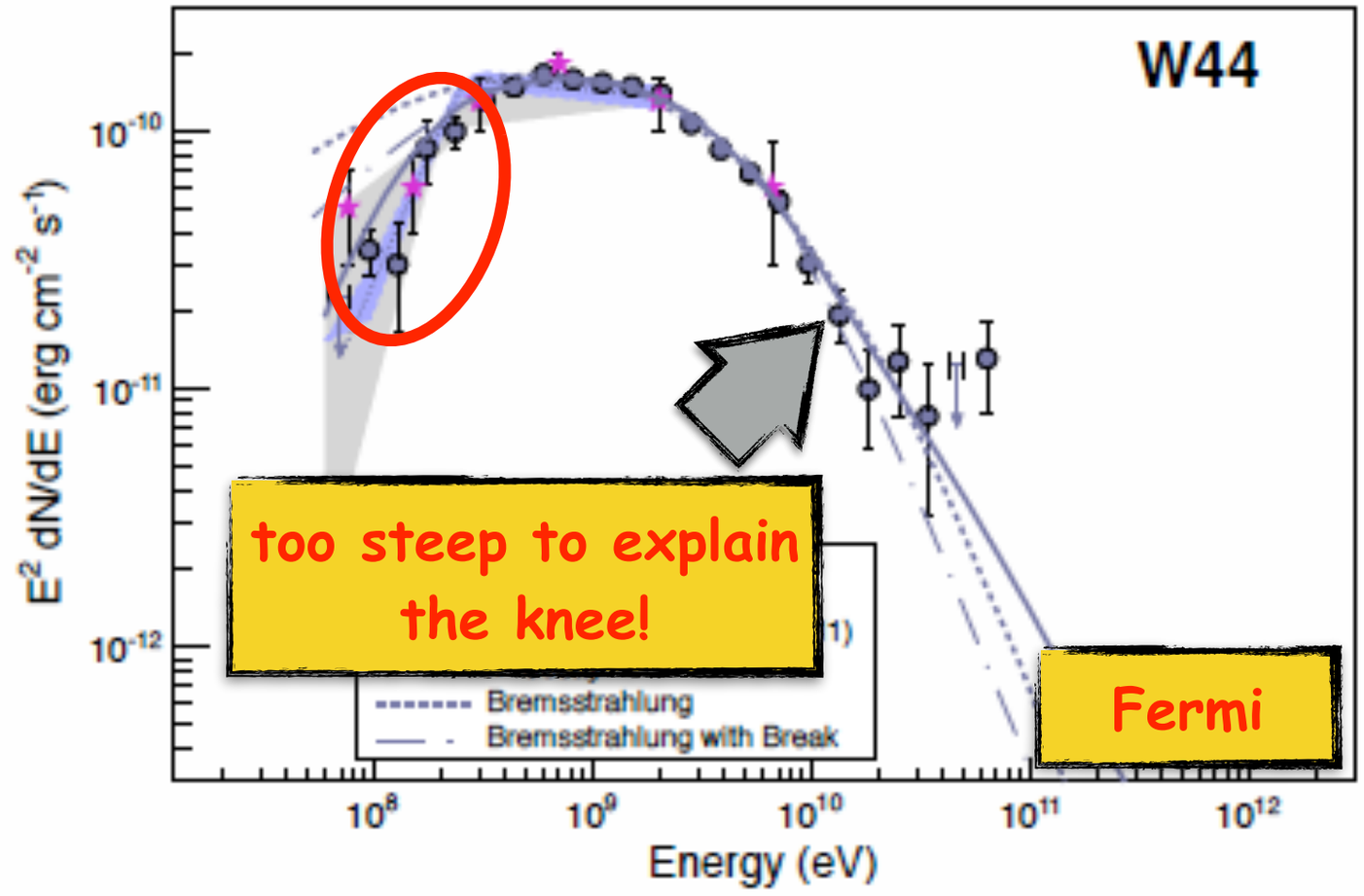

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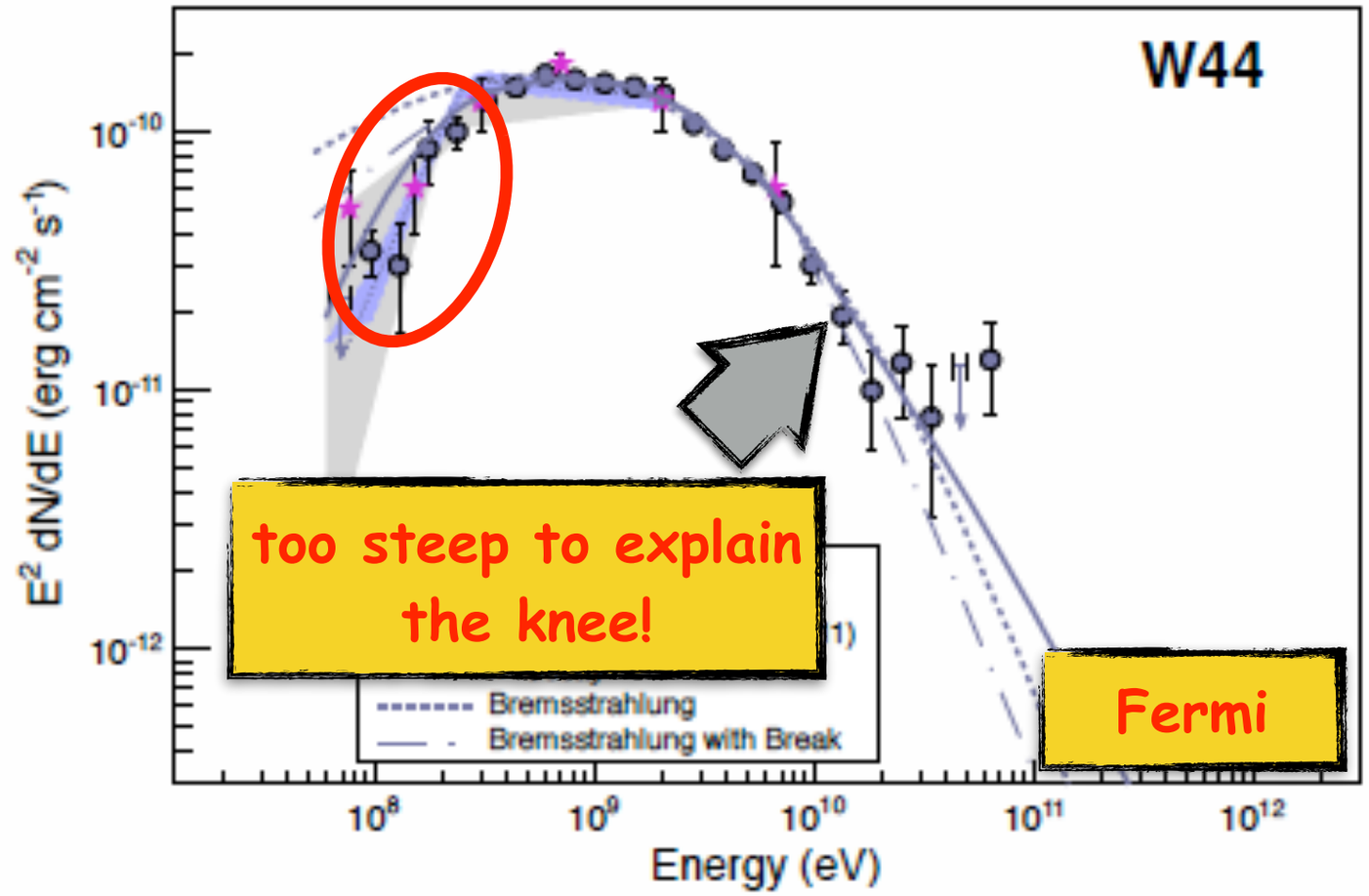

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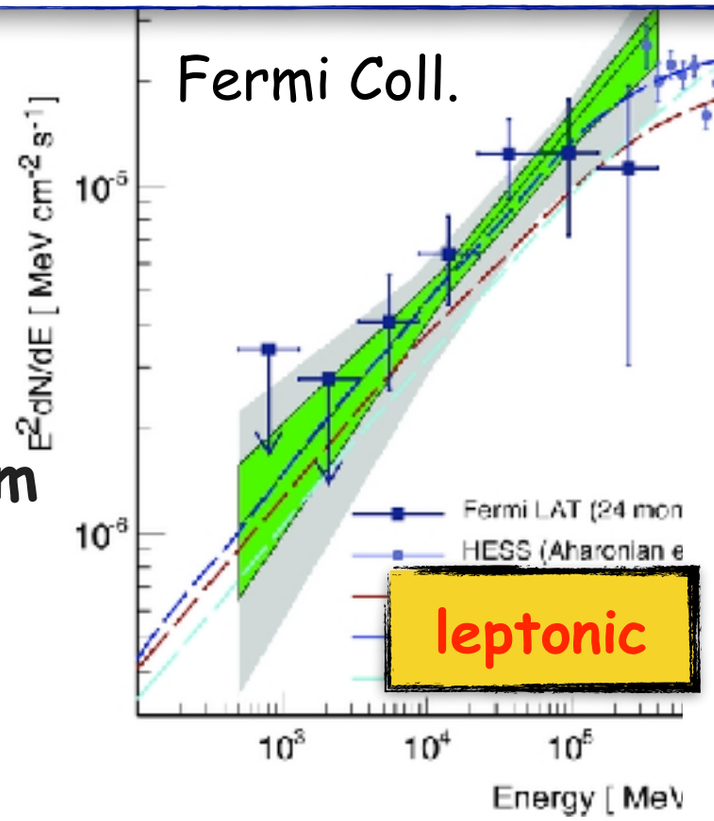

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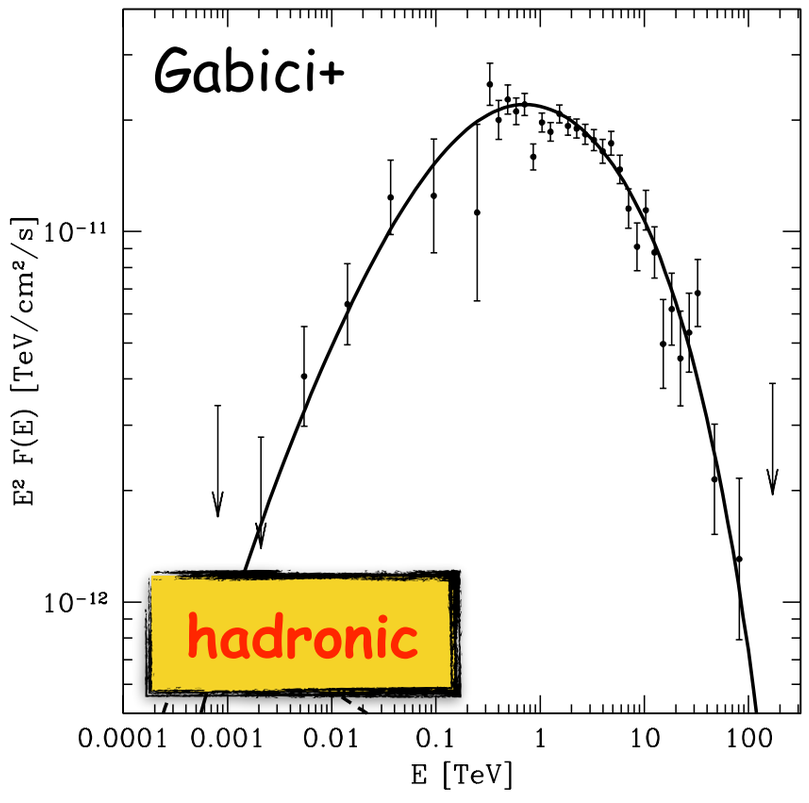

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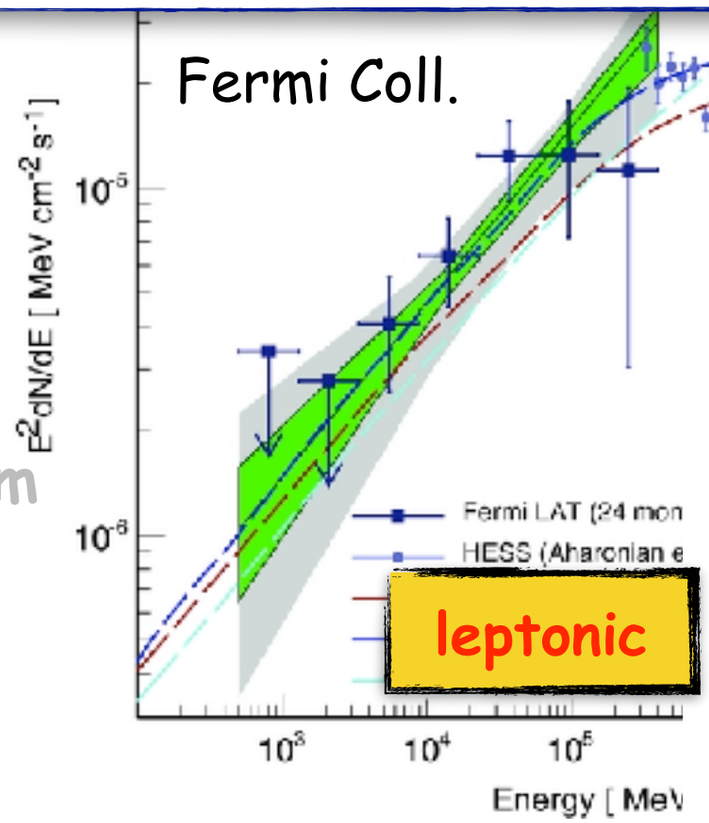
- can't explain the spectrum up to the knee
- **younger SNRs -> several cases are still controversial**



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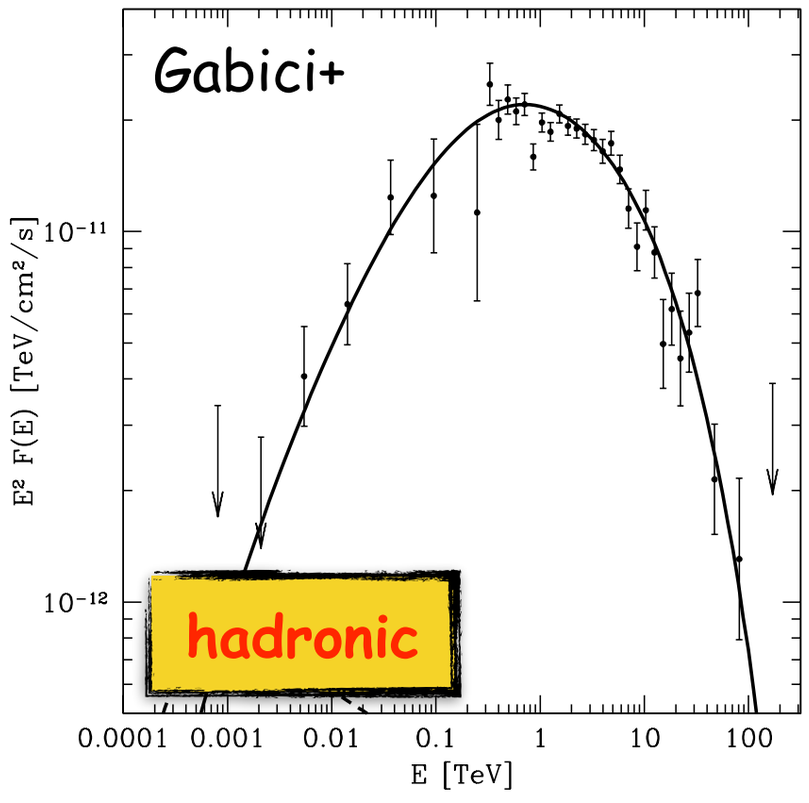

SNRs & MCs:interaction or runaway CRs?

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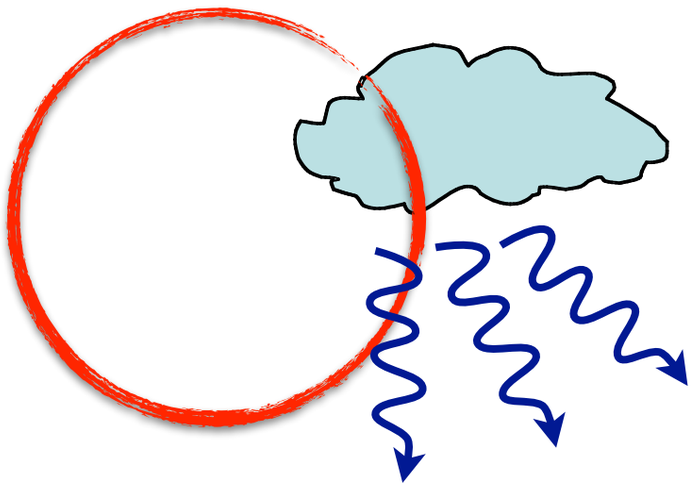
shock/MC interaction



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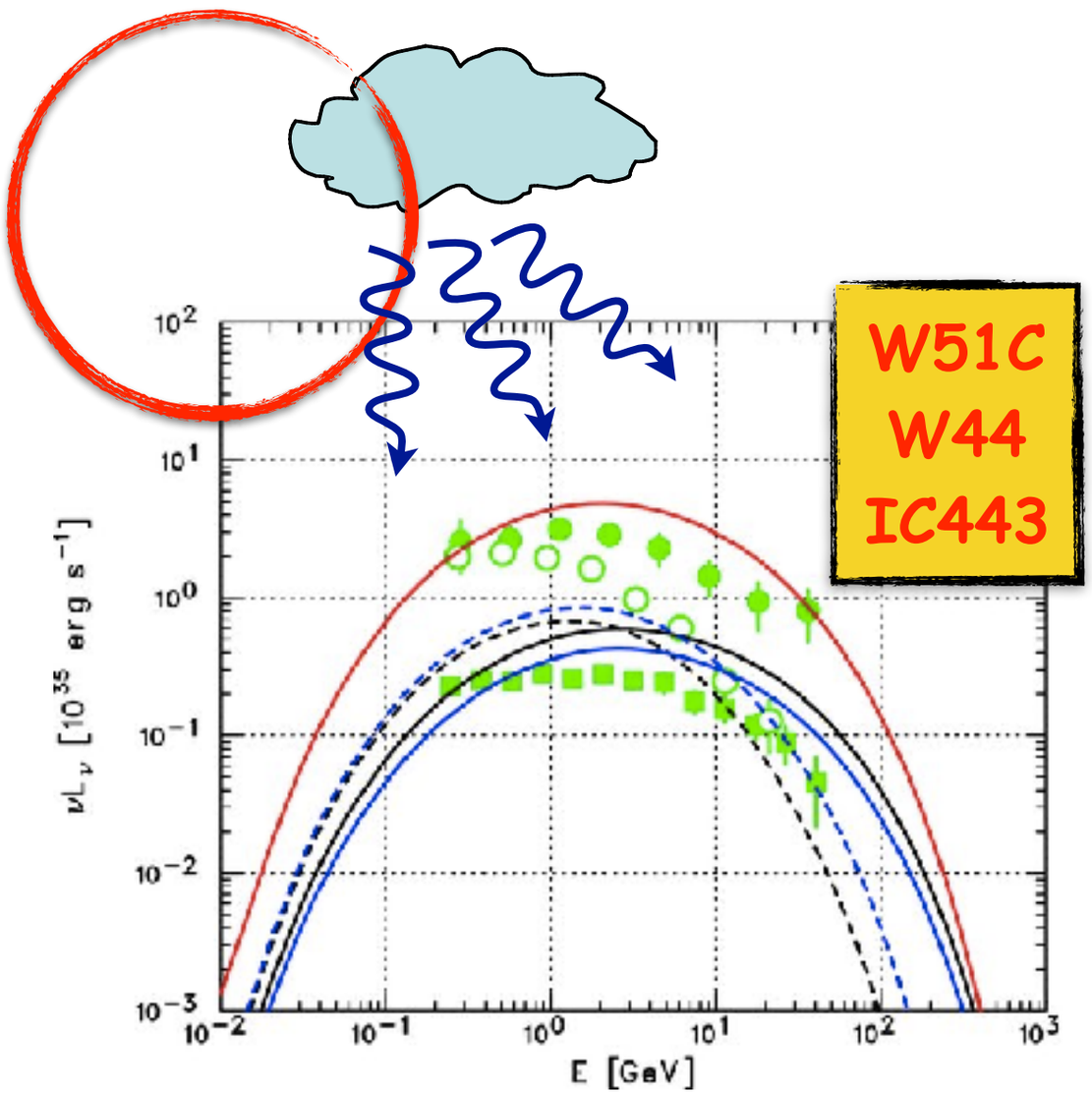

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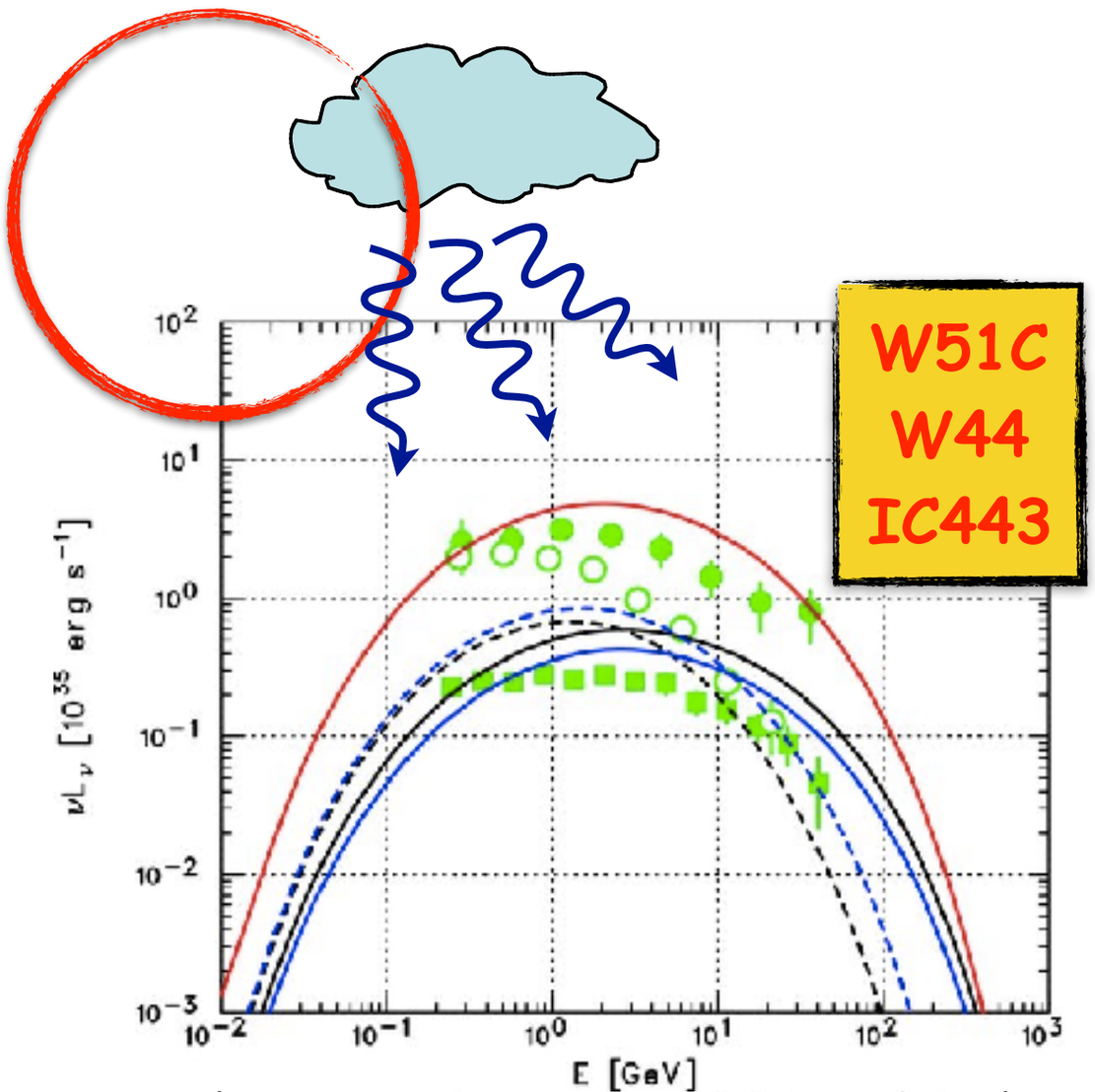
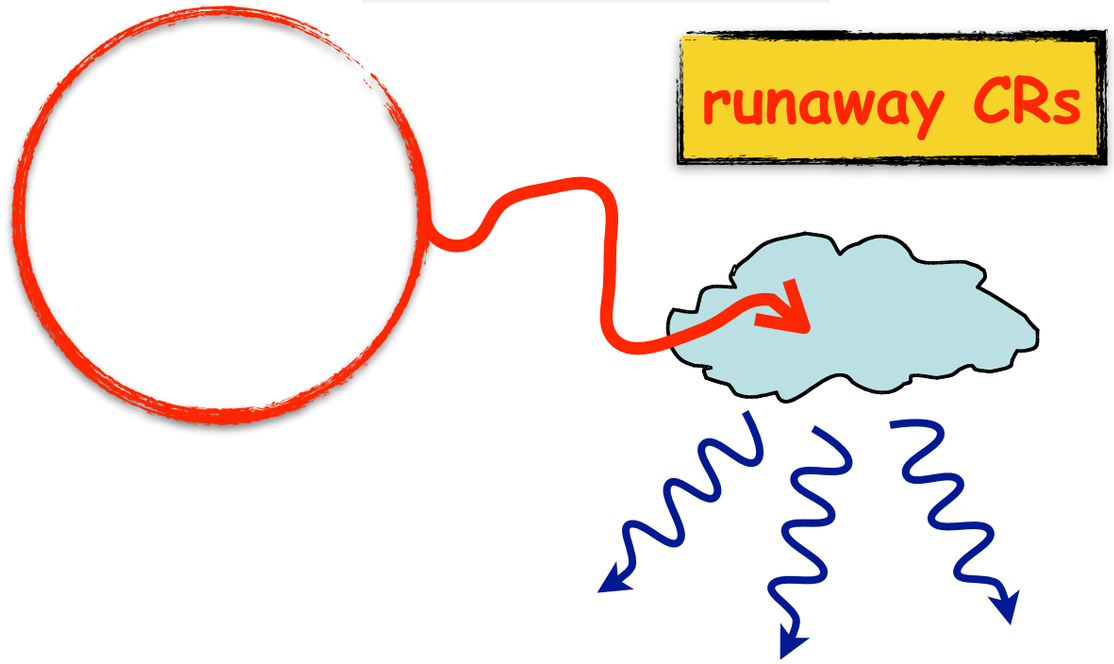


runaway CRs



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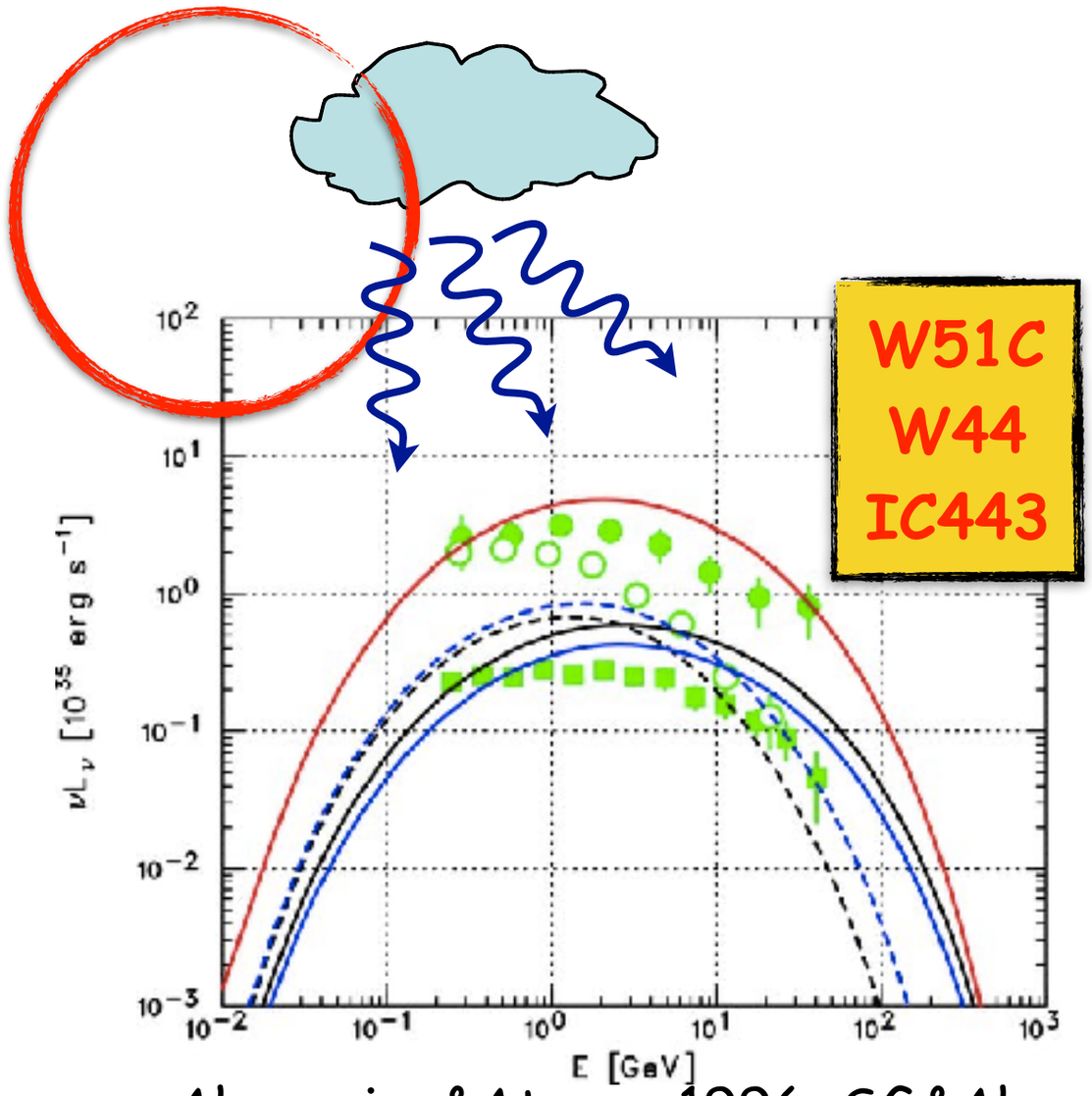

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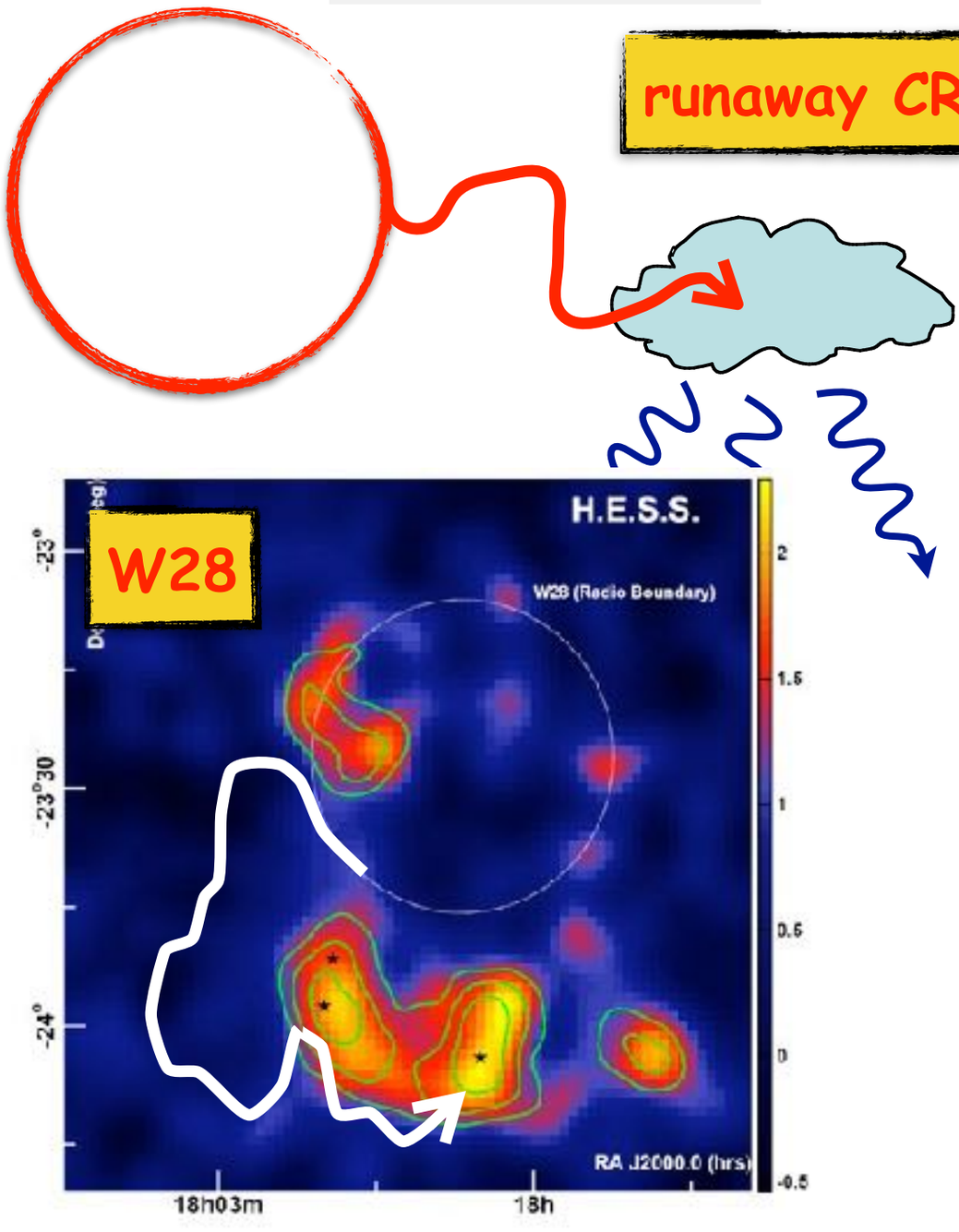

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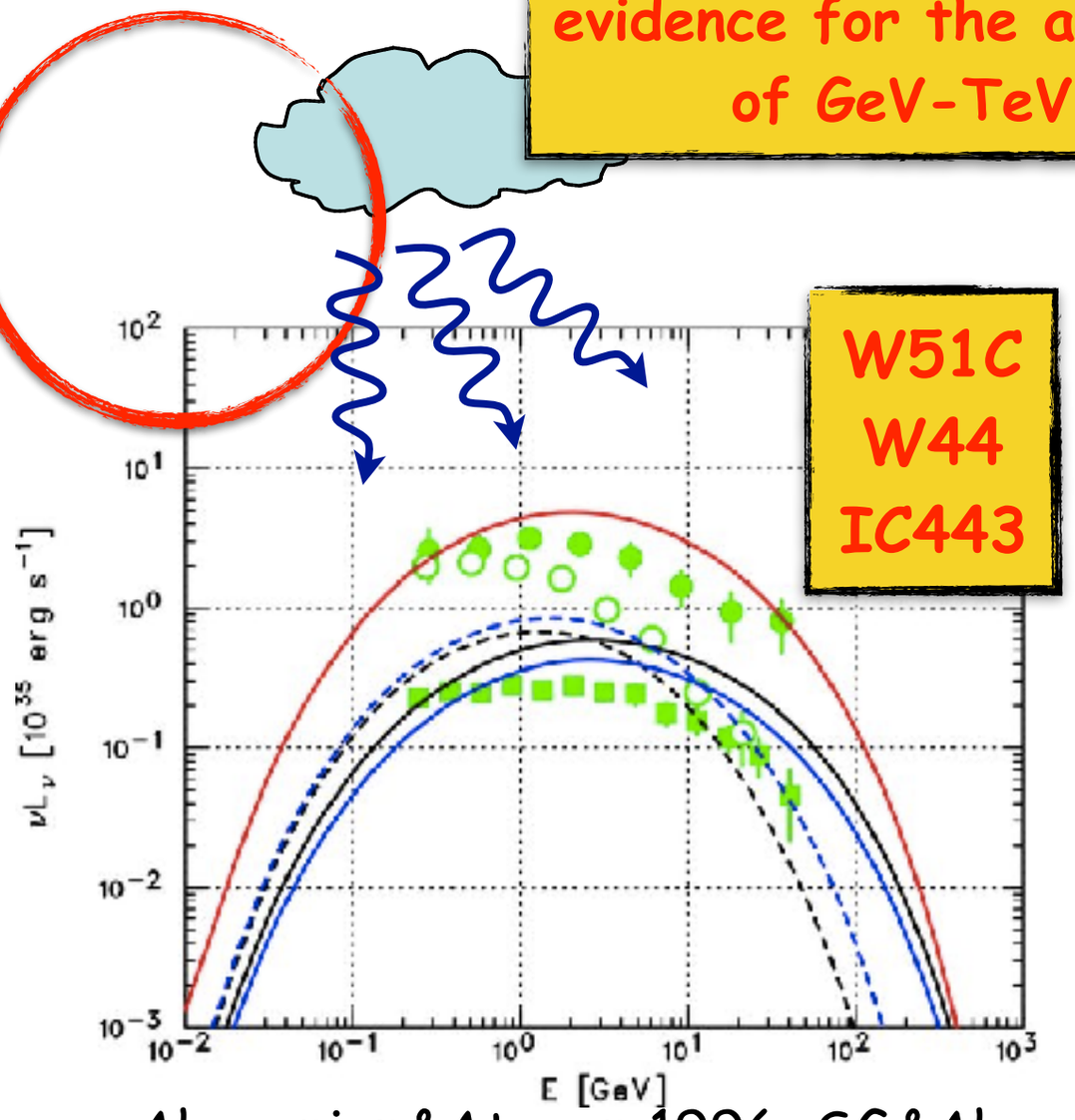
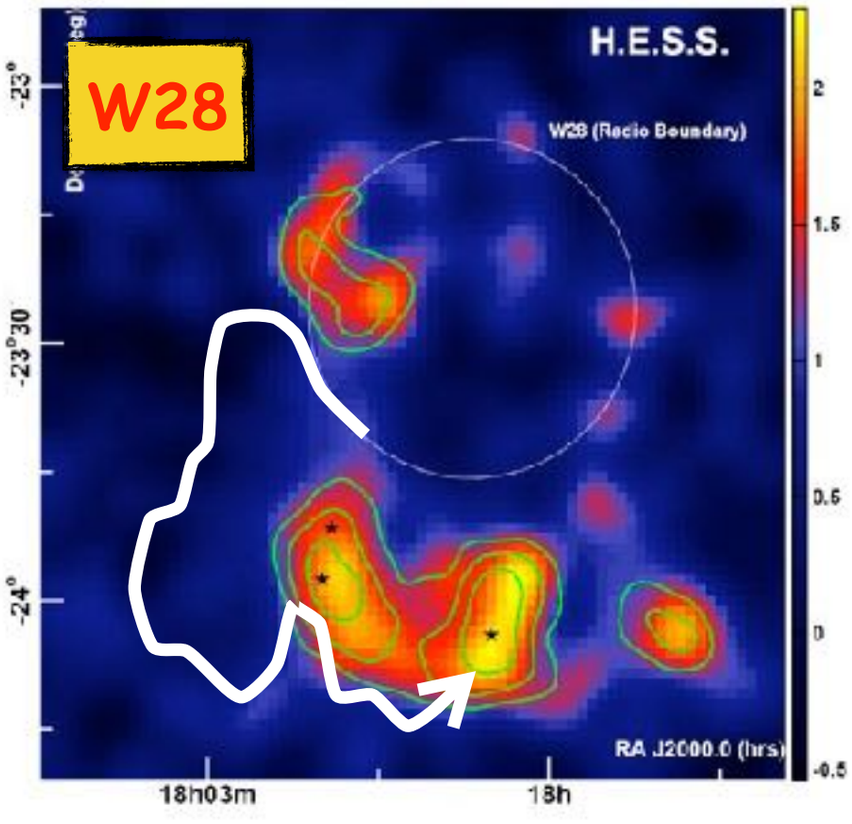
evidence for the acceleration of GeV-TeV CRs





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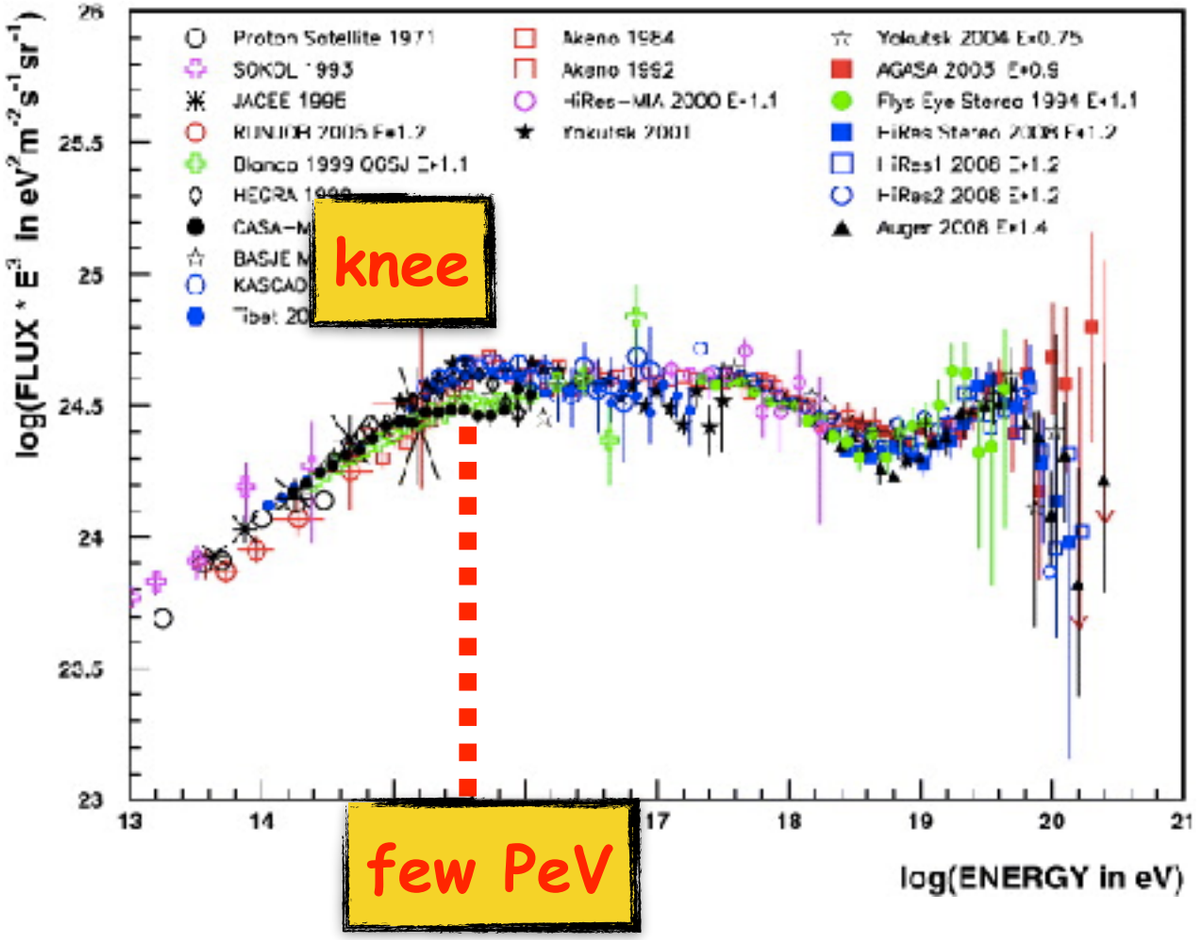
When and how do cosmic rays escape from SNRs?

Are SNRs proton PeVatrons?



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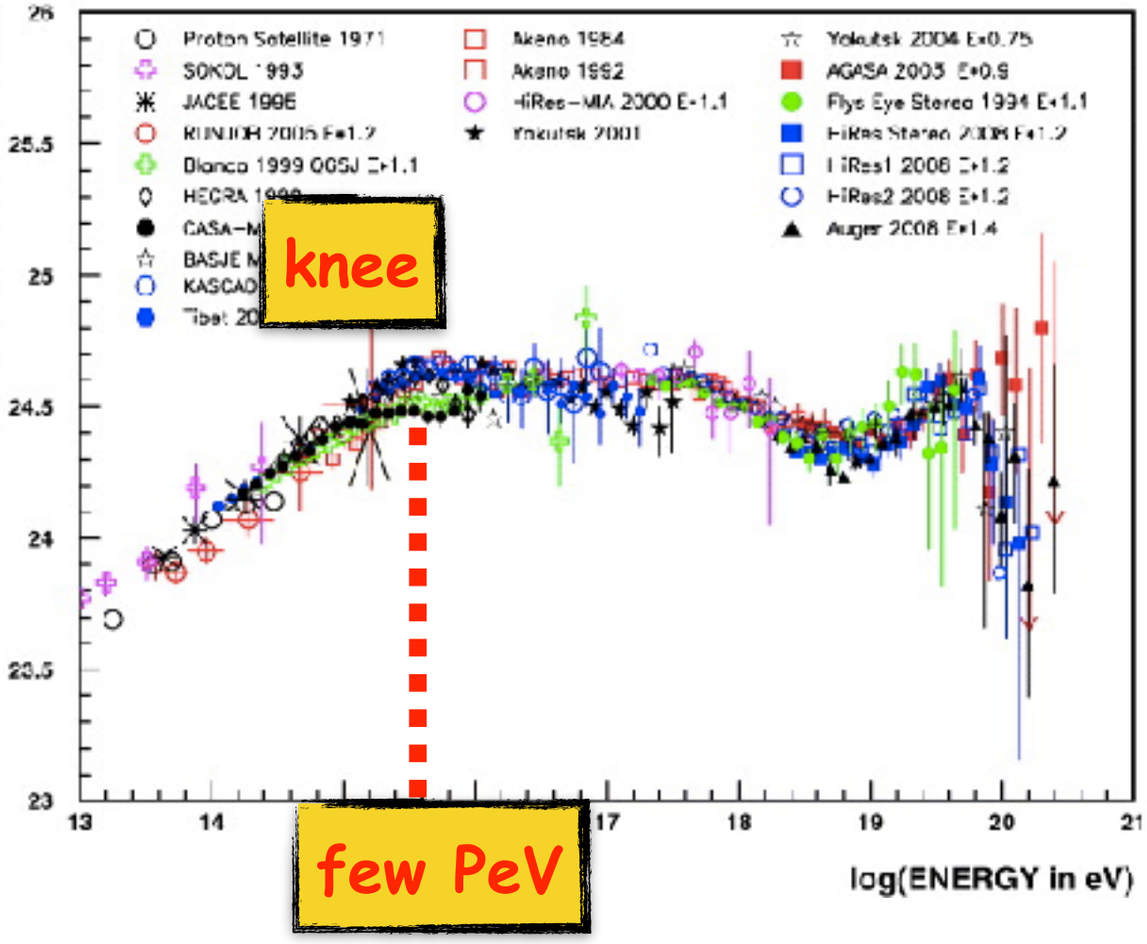

Hillas criterium

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

velocity · size · magnetic field

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

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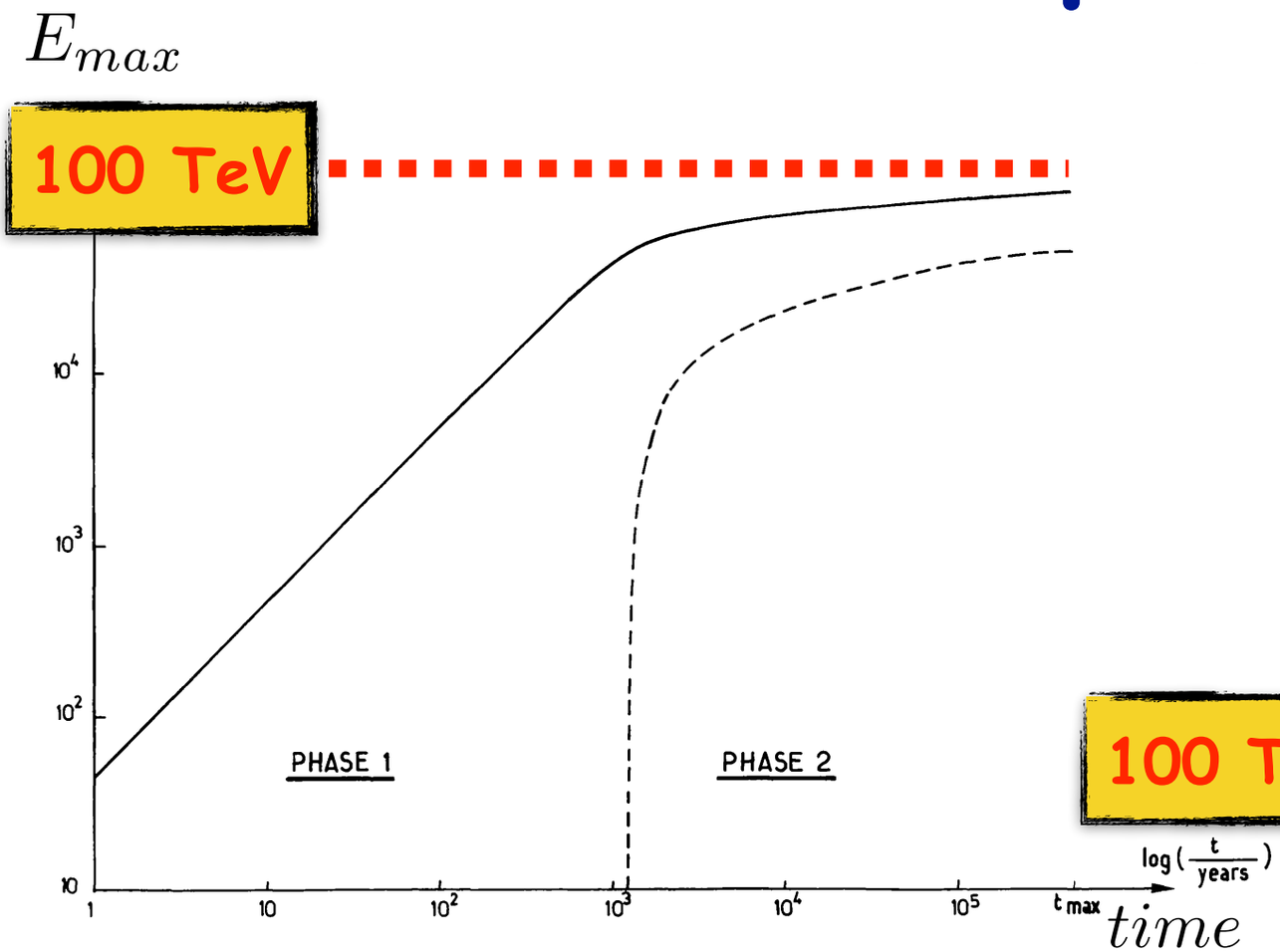

Lagage & Cesarsky 1983

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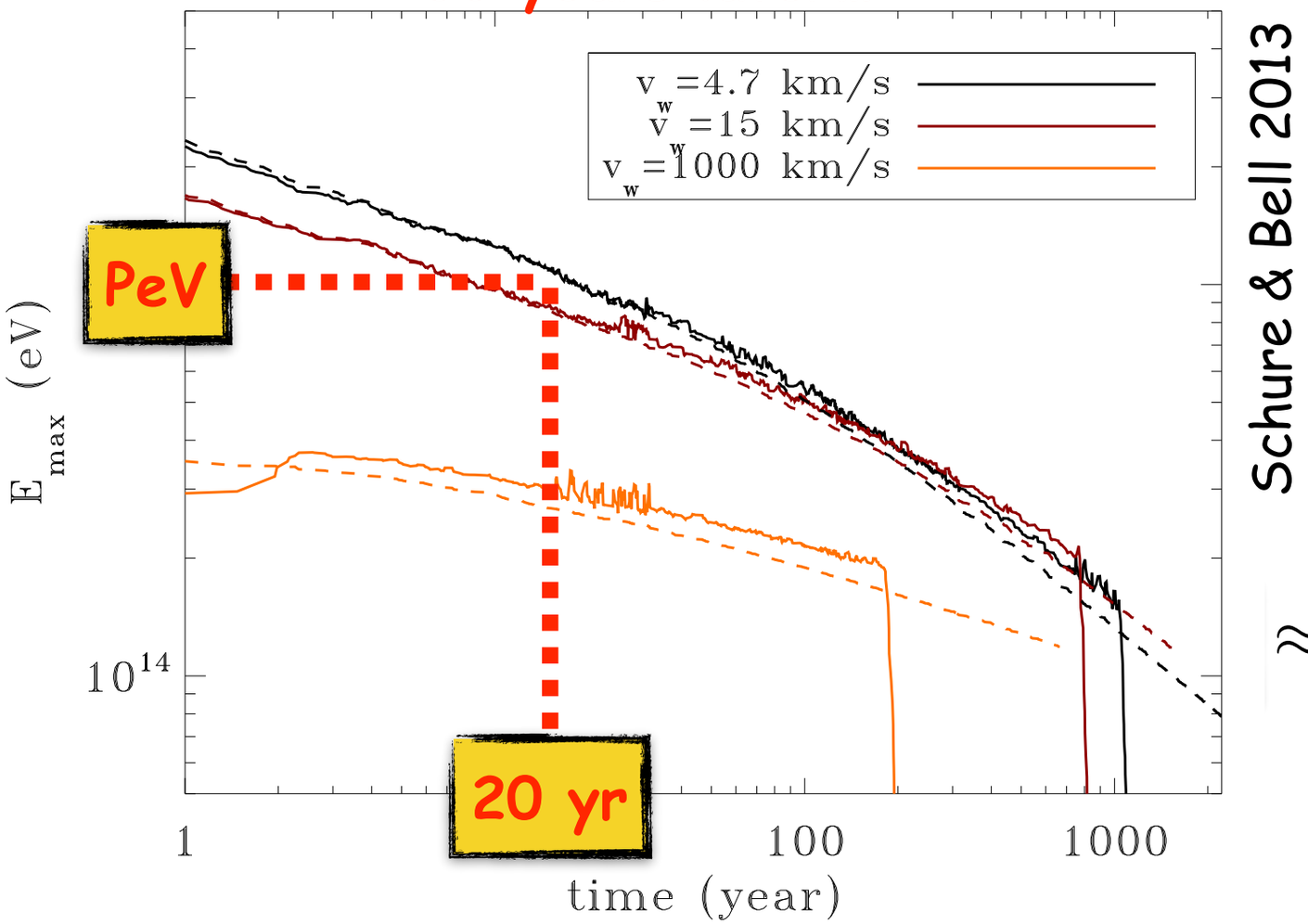
100 TeV $\approx 1 \left(\frac{u}{10^3\ \text{km/s}}\right) \left(\frac{R}{\text{pc}}\right) \left(\frac{B}{\mu\text{G}}\right) \text{TeV}$

~10 ~3 ~3

Are SNRs proton PeVatrons?

30 years later…



Schure & Bell 2013

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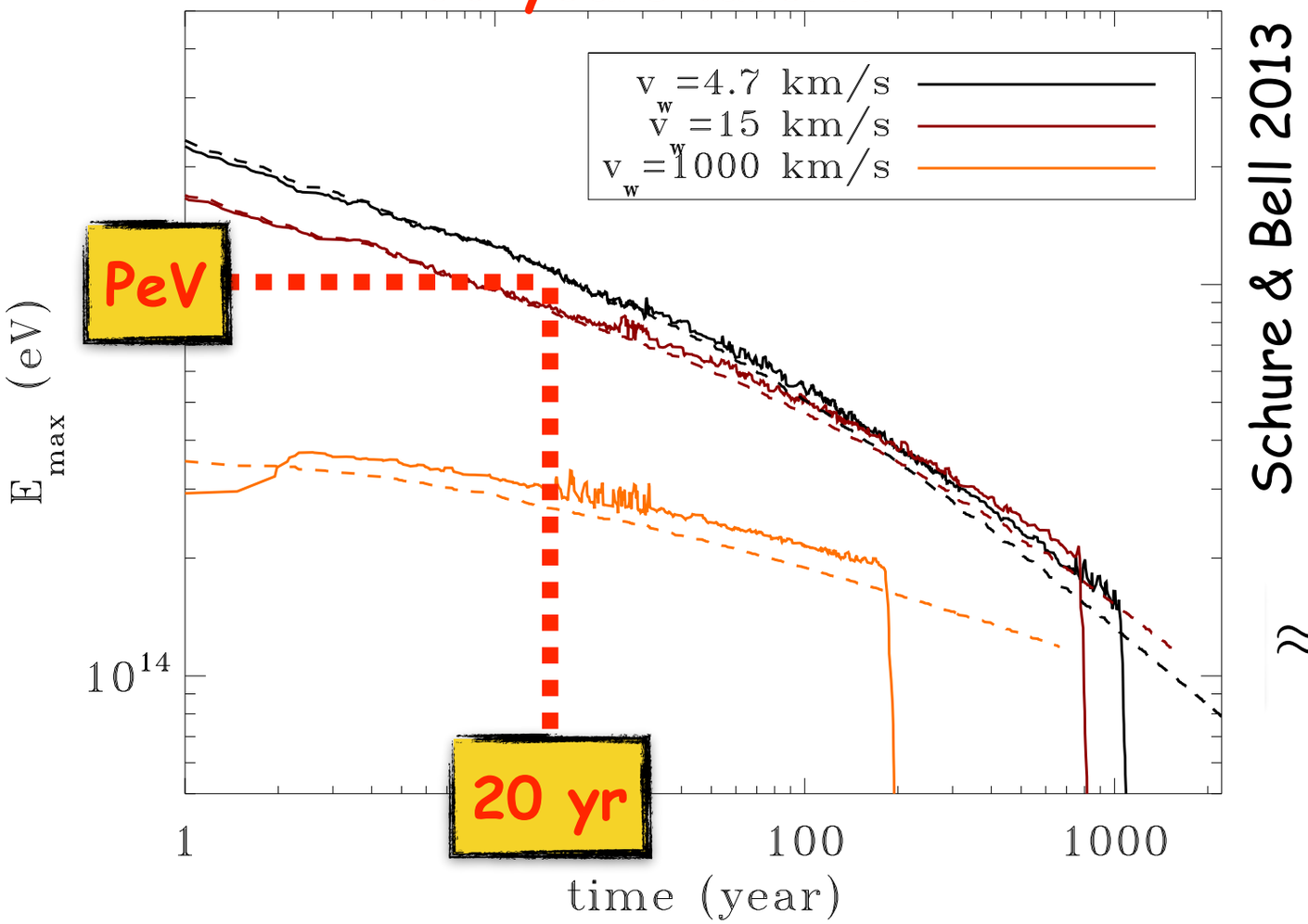

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current driven, non-resonant instability (Bell 2004, 2013) -> PeV particle acceleration possible in the very early (tens of years) stage of a SNR evolution -> ejecta dominated phase -> is there enough power to feed the PeV CR population?

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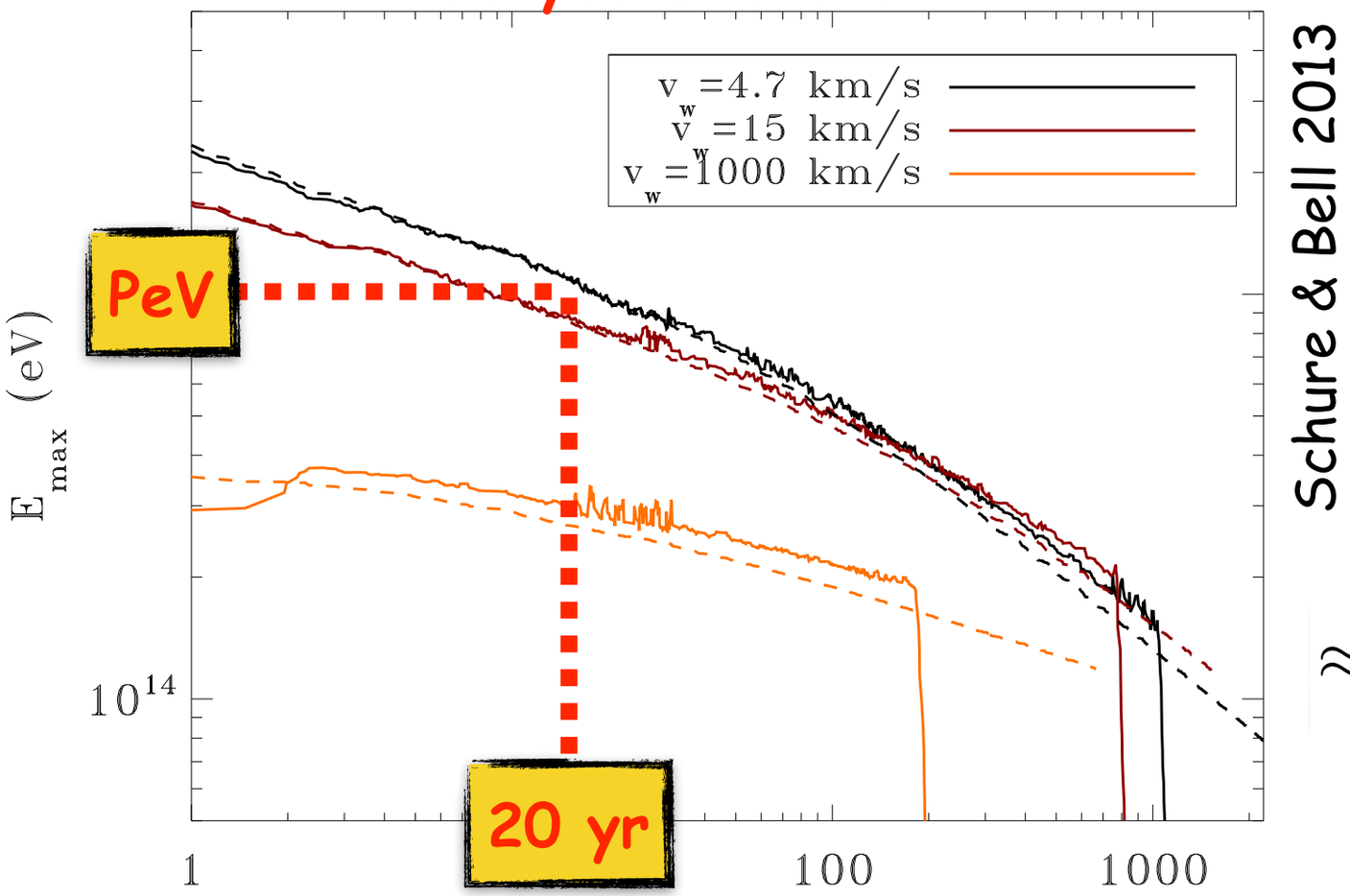

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velocity · size · magnetic field

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

B-field amplification

~10 ~3 ~3

Drury instability might be more effective -> Drury,Downes 2012,2014

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Question #2

When and how do cosmic rays escape from SNRs?

- highest energies released first (<< 100 yrs)
- lower energies released gradually as the shock speed decreases
- the details of the escape mechanism are still largely unknown
- we still don't know whether SNRs are PeVatrons or not

The galactic centre as a CR PeVatron

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)

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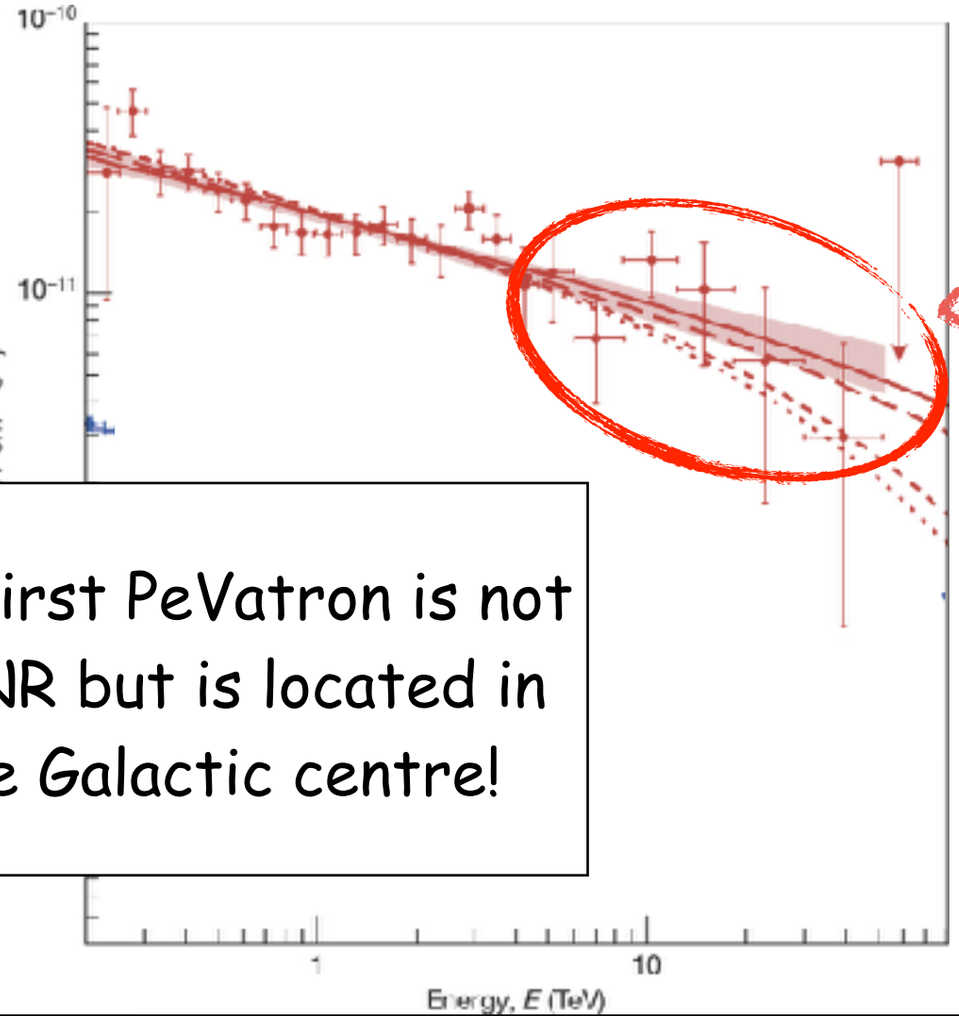
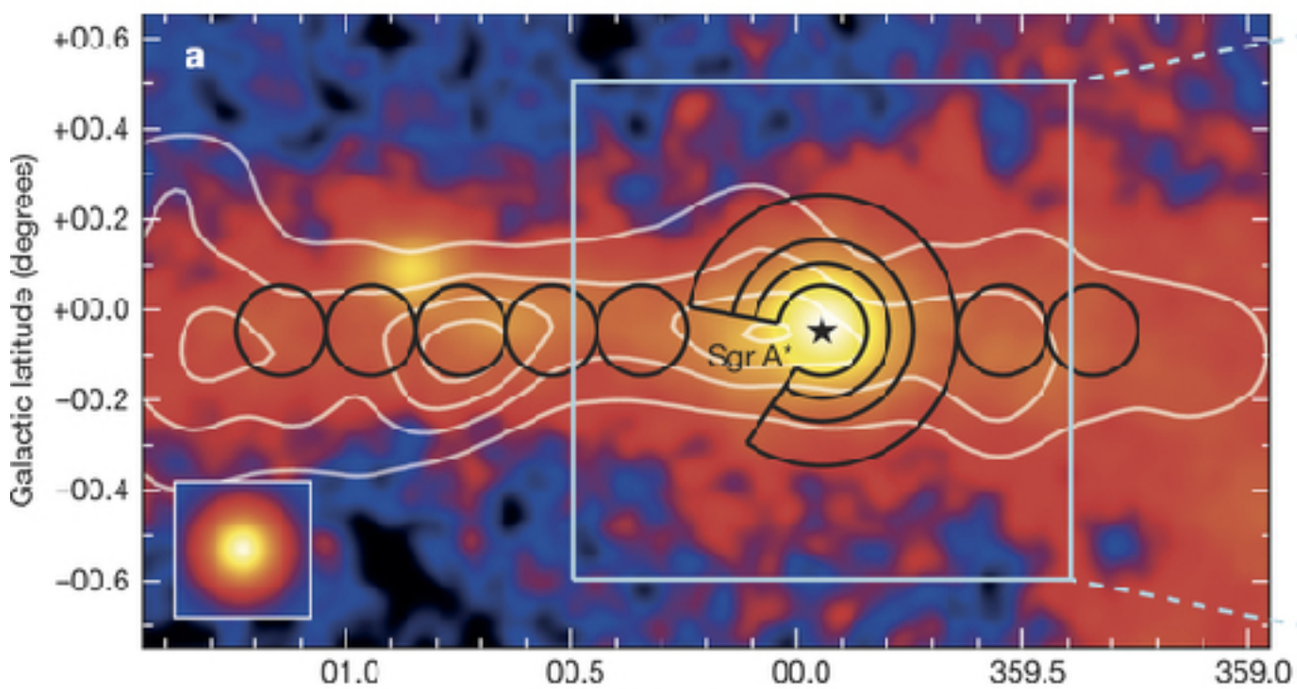


the first PeVatron is not a SNR but is located in the Galactic centre!

diffuse emission from the GC

no cutoff!

H.E.S.S. Coll. 2016



Questions #3 and #4

Where (and who) are PeVatrons?

Are SNRs the best candidates to explain the origin of cosmic rays?

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Where (and who) are PeVatrons?

Are SNRs the best candidates to explain the origin of cosmic rays?

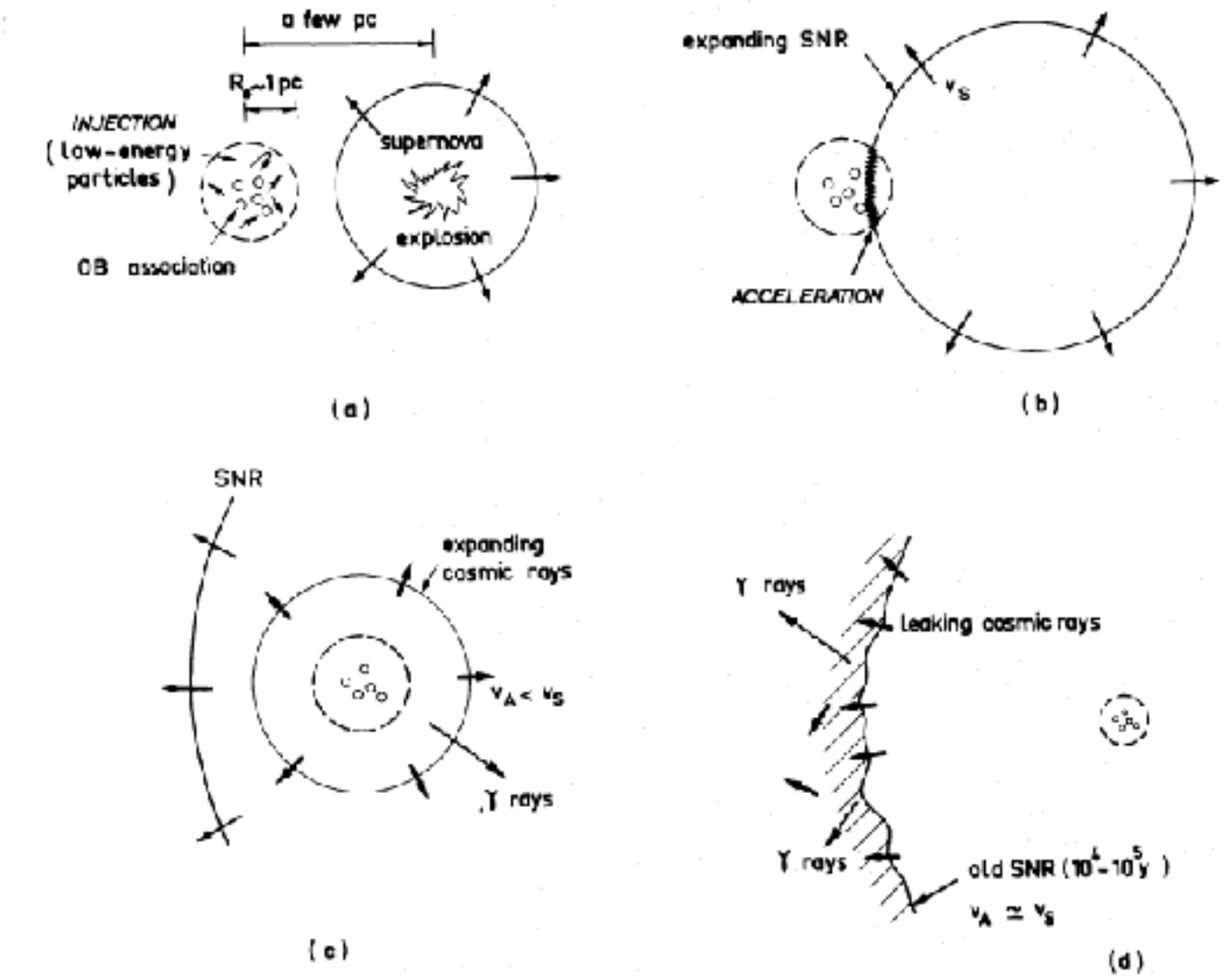
- gamma-ray based tests for the SNR paradigm
- PeV particle acceleration at SNRs: the role of CTA
- search for competing sources

The importance of being a SNOB

Montmerle 1979

SuperNovae OB associations

tentative spatial association between SNOBs and COS B hot spots



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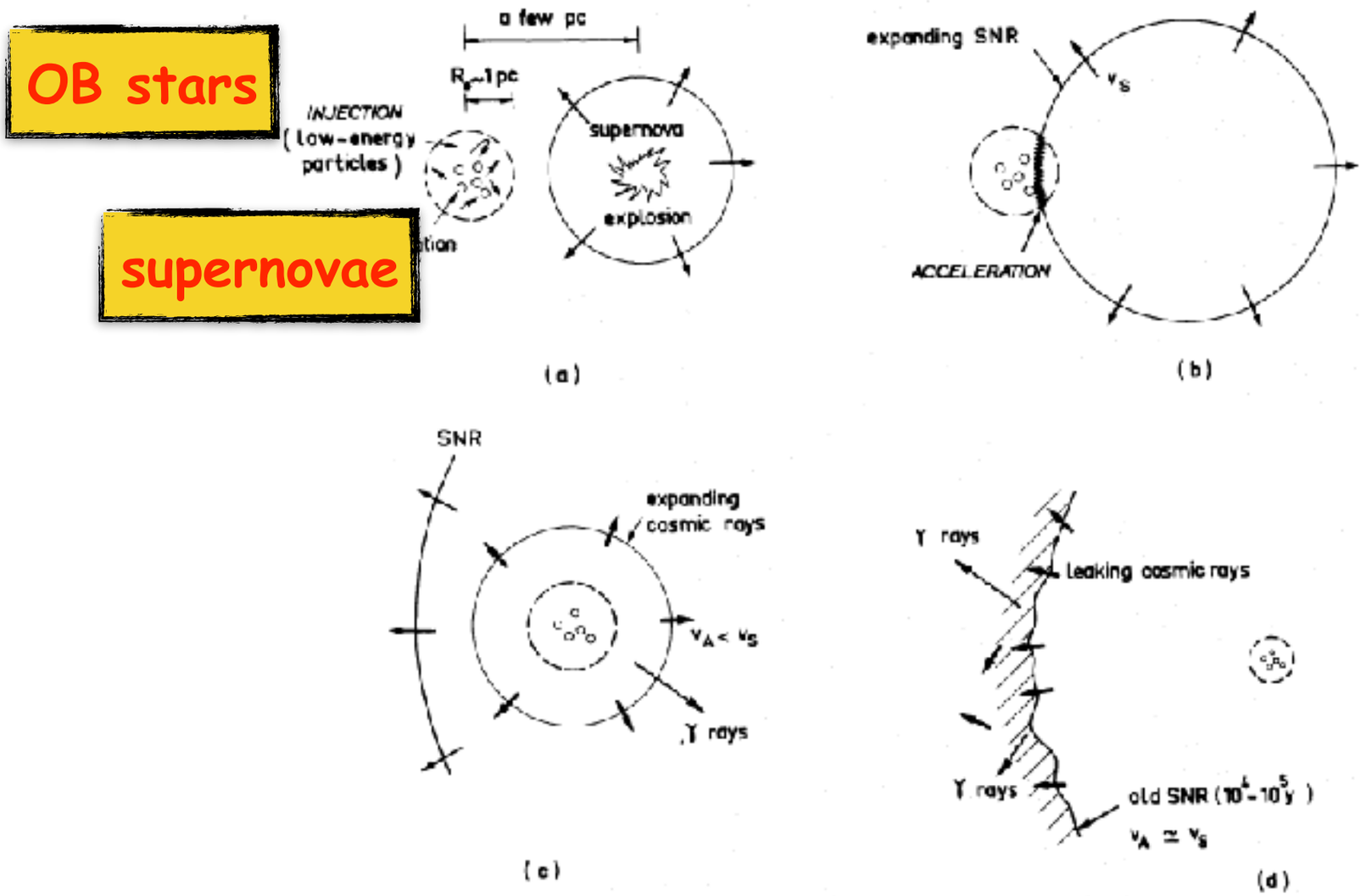
OB stars

supernovae



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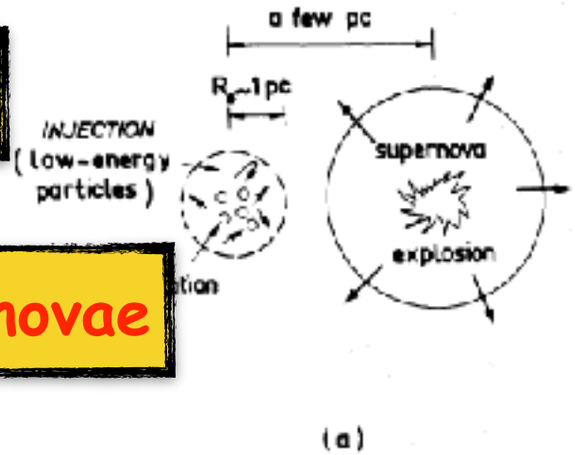
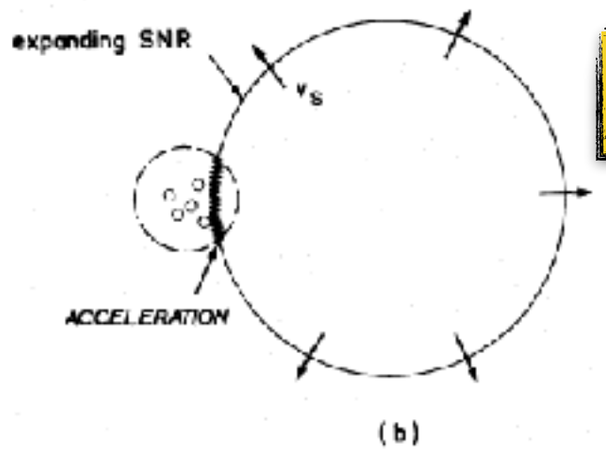
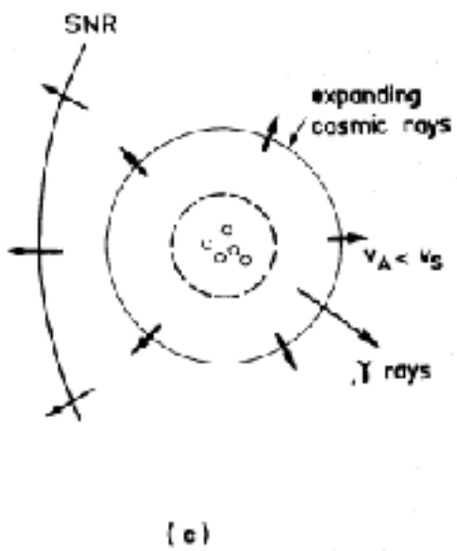
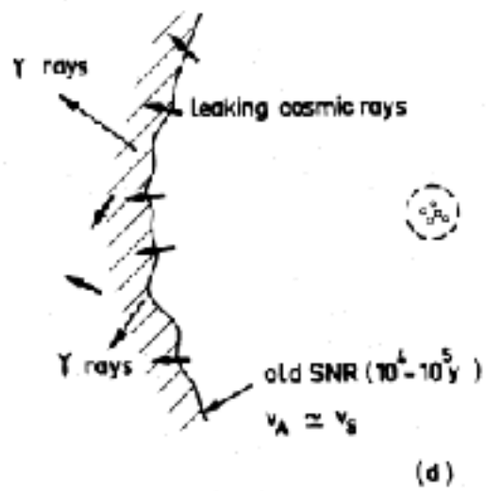


SNRs

CR acceleration







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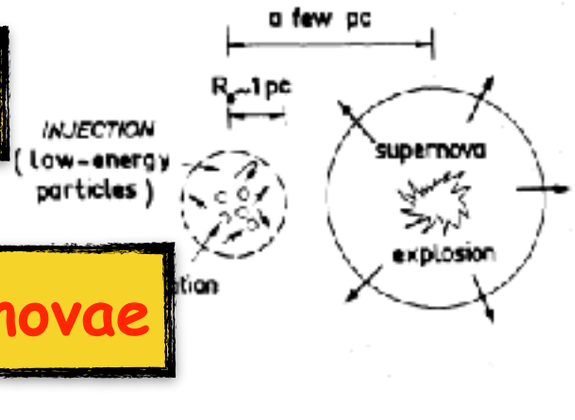

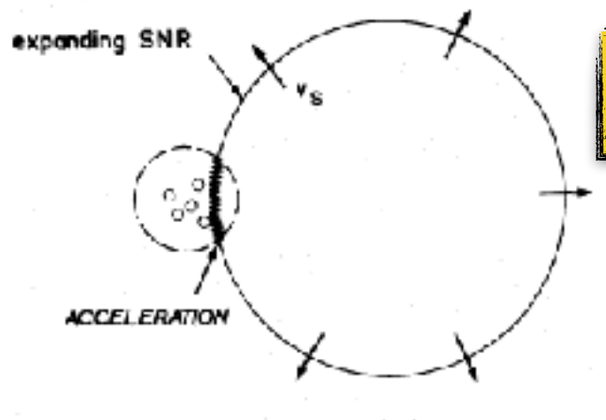

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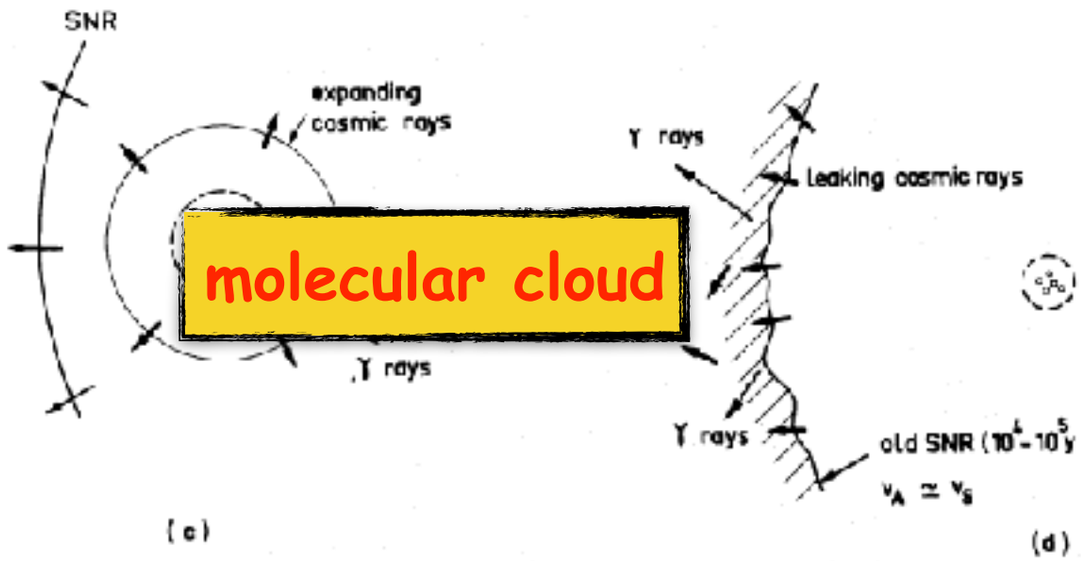


γ-rays

Black & Fazio 1973

The importance of being a SNOB

Montmerle 1979

SuperNovae ... ions

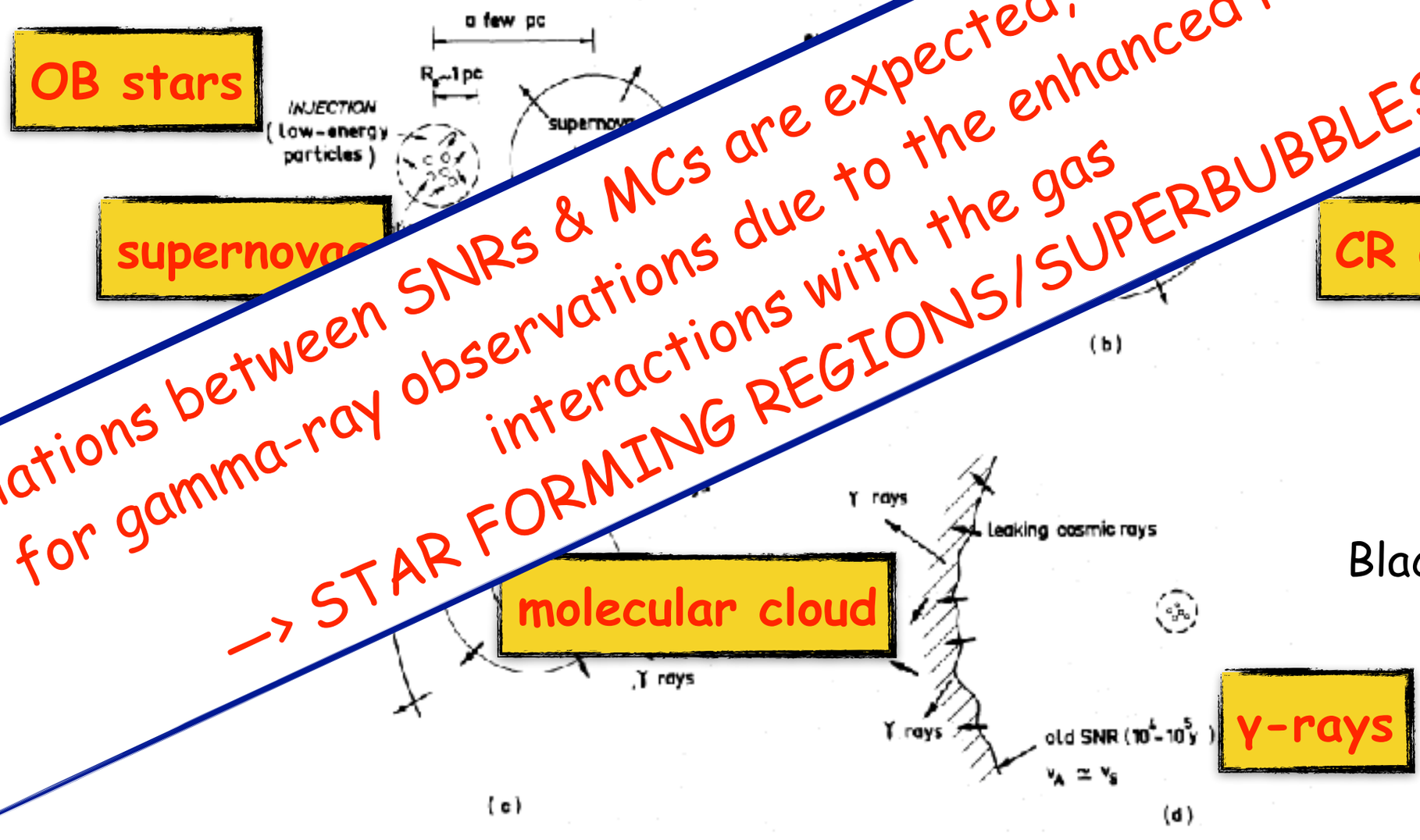
tentative spatial association between SNOBs ...

OB stars

supernovae

CR acceleration

associations between SNRs & MCs are expected, and are ideal targets for gamma-ray observations due to the enhanced rate of CR interactions with the gas —> STAR FORMING REGIONS/SUPERBUBBLES



Black & Fazio 1973

molecular cloud

γ-rays

Questions #5

Has the clustering (in both space & time) of supernova explosions any effect on the acceleration mechanism?

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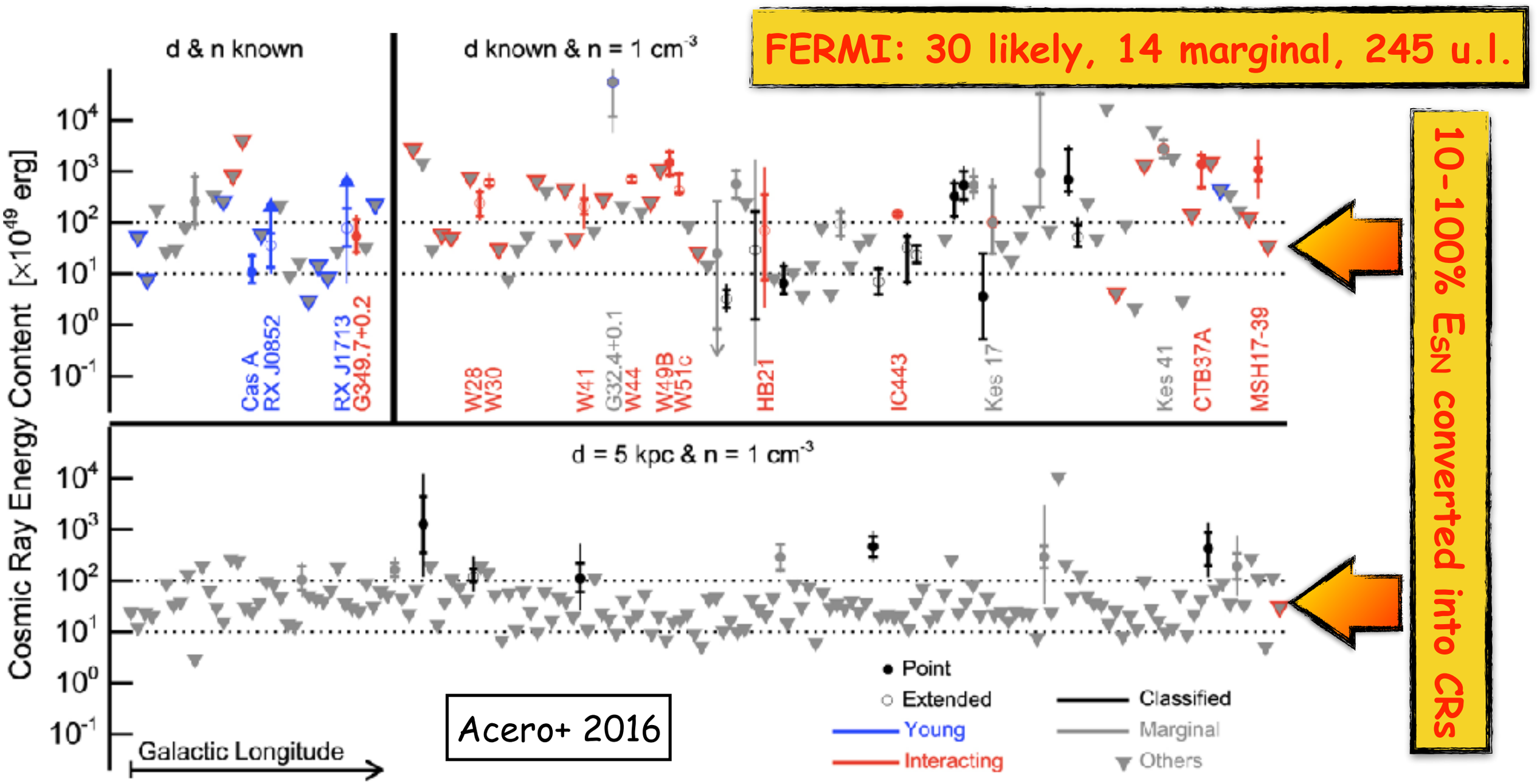
- minimal variation of the SNR paradigm? sum of the acceleration from many individual SNRs (Higdon, Lingenfelter, Ramaty…)
- superbubbles -> radically different acceleration mechanisms (Bykov, Parizot…)

The SNR paradigm for the origin of CRs: gamma-ray based tests

GeV domain

Is the SNR paradigm consistent with γ-ray data? Tests for CR origin

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



Acero+ 2016

10-100% E_{SN} converted into CRs

TeV domain

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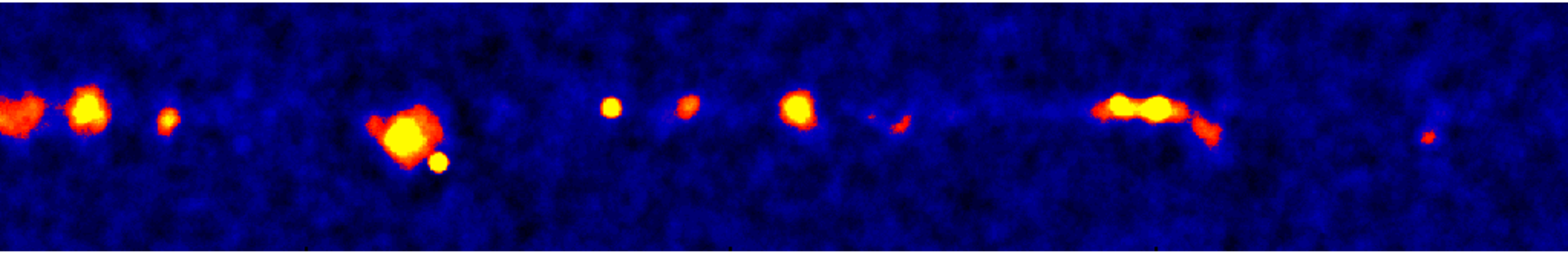
How many SNRs should we detect in the HESS galactic plane survey?



TeV domain

Is the SNR paradigm consistent with γ-ray data? Tests for CR origin

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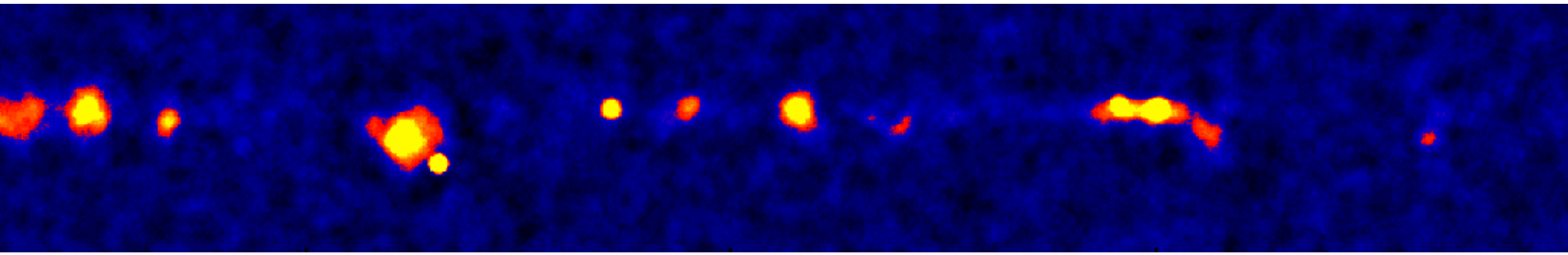

Donath+ 2017

- 78 sources
- 31 identified
- 8 SNRs
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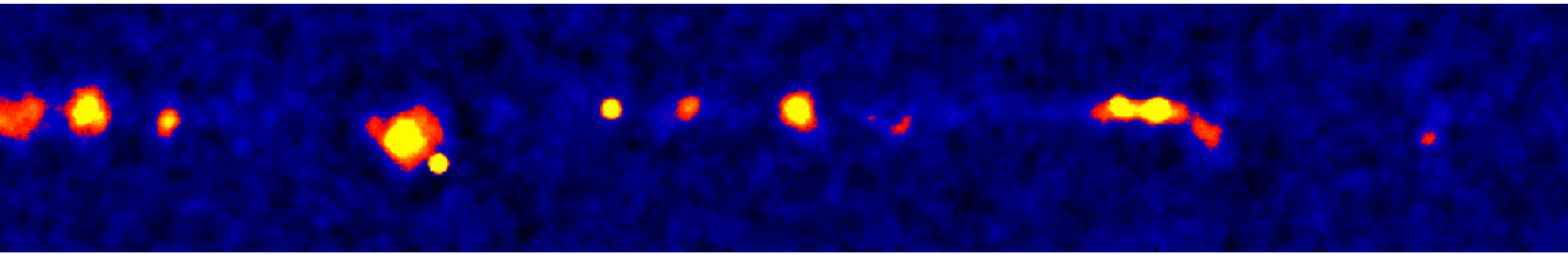

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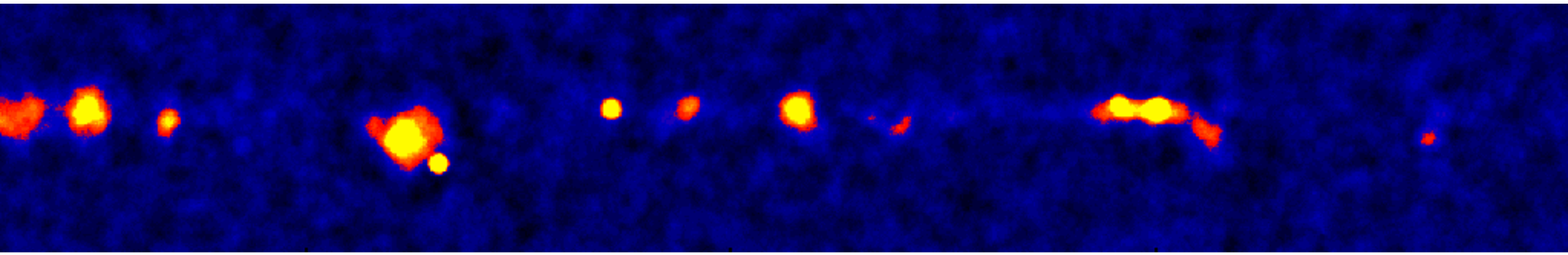

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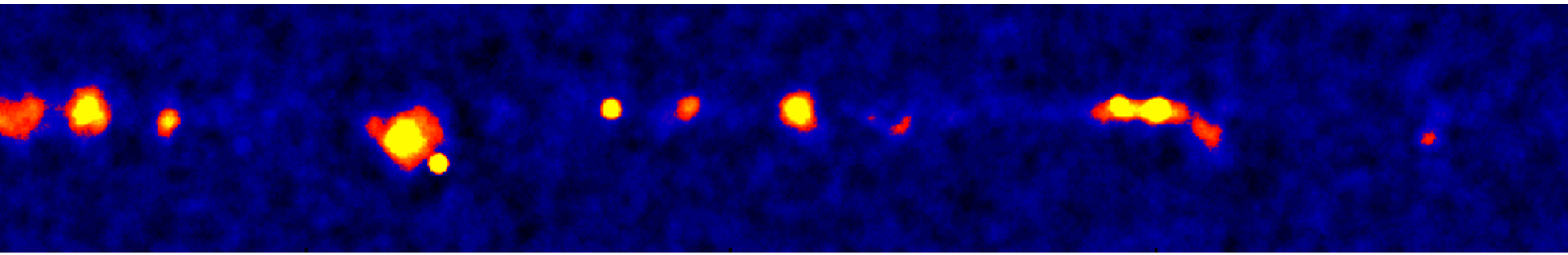

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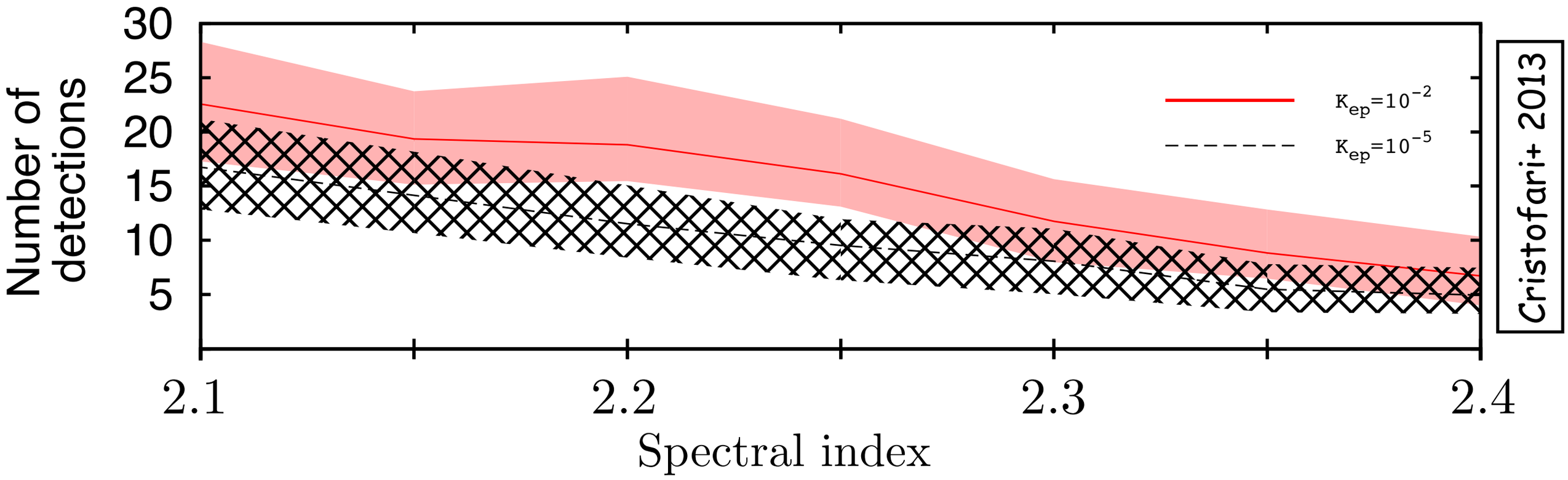

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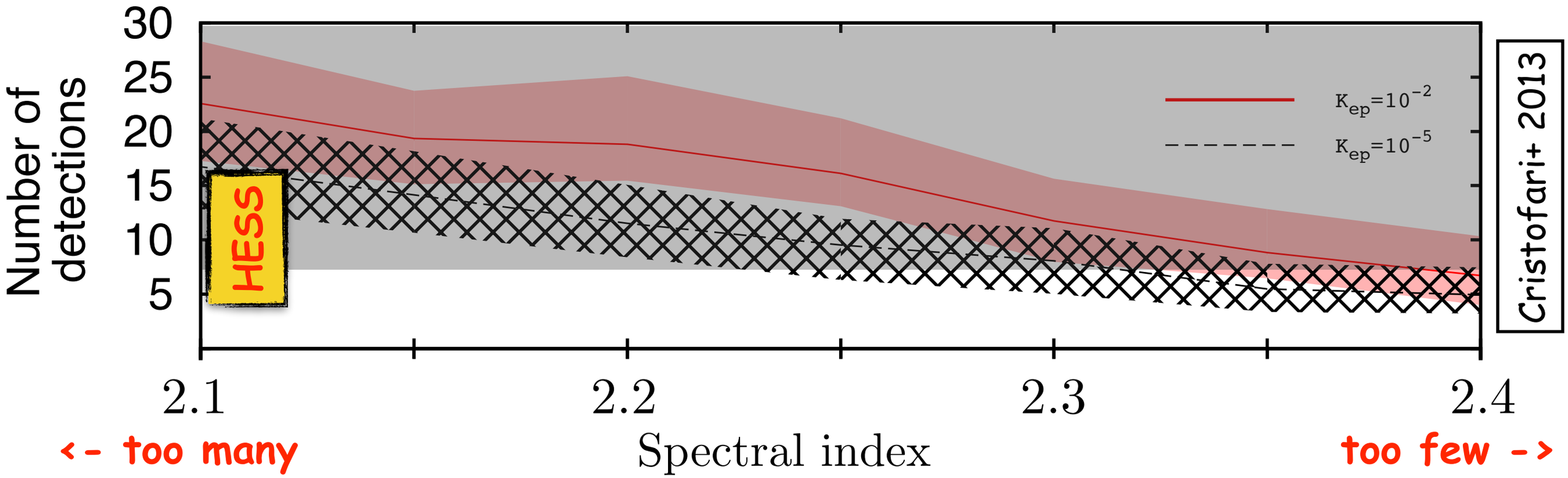
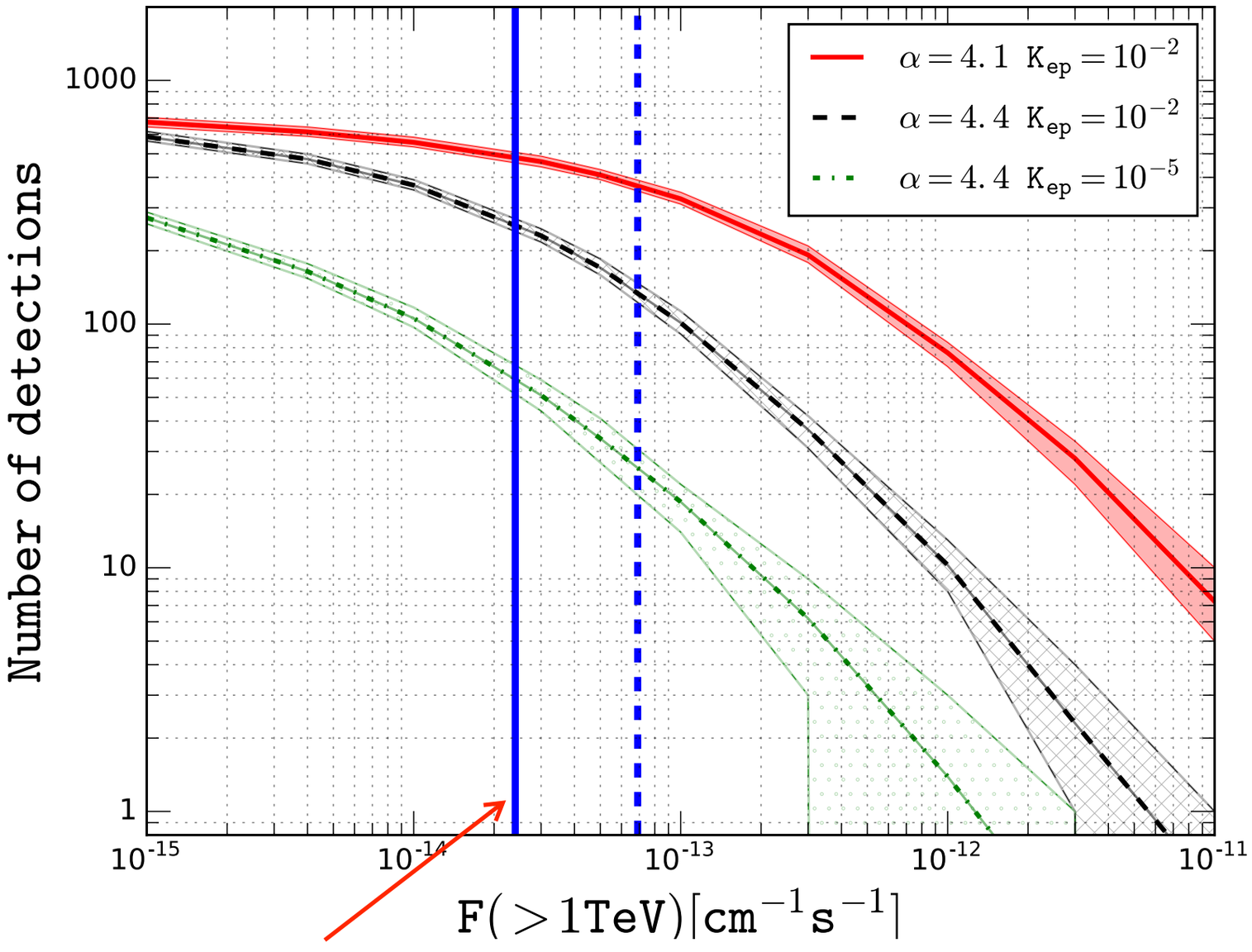


TeV domain

Future tests: the Cherenkov Telescope Array



← optimistic

← pessimistic

CTA sensitivity (point sources)

Cristofari+ 2017

TeV domain

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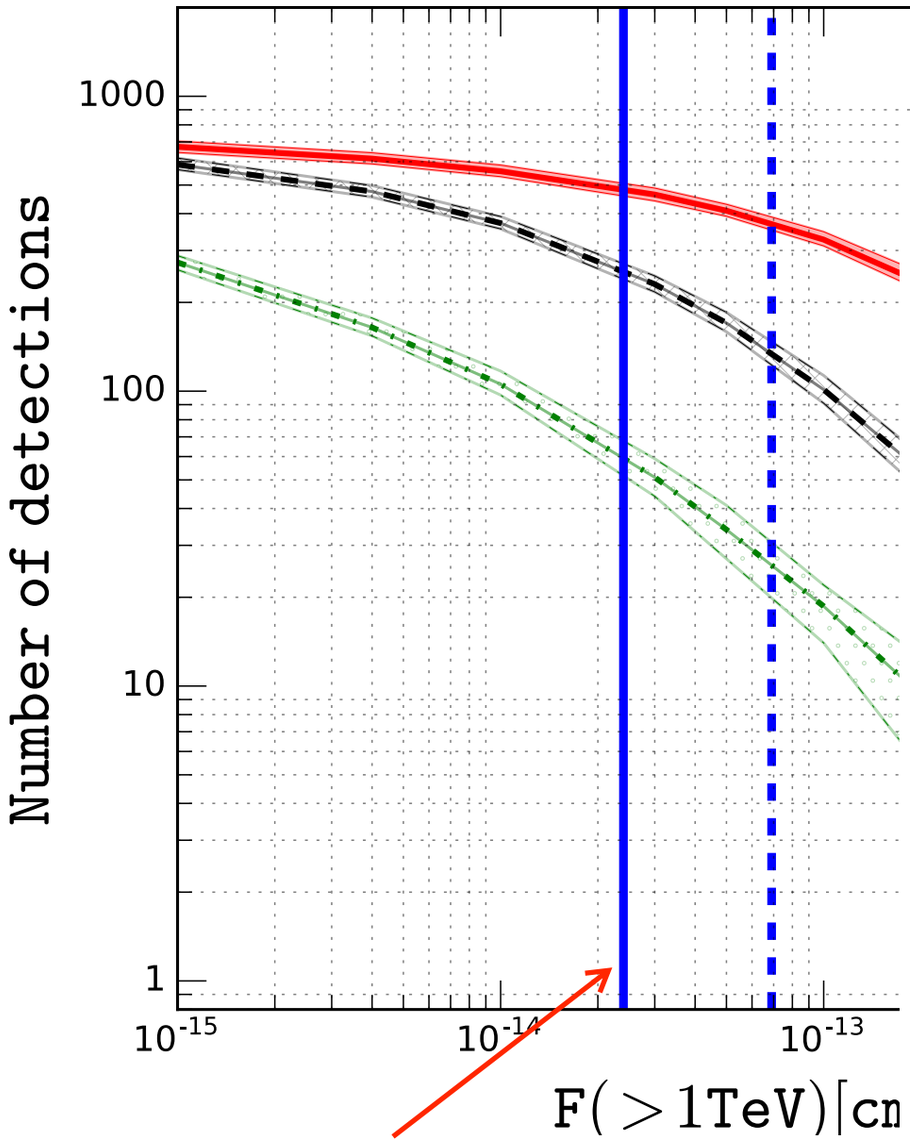

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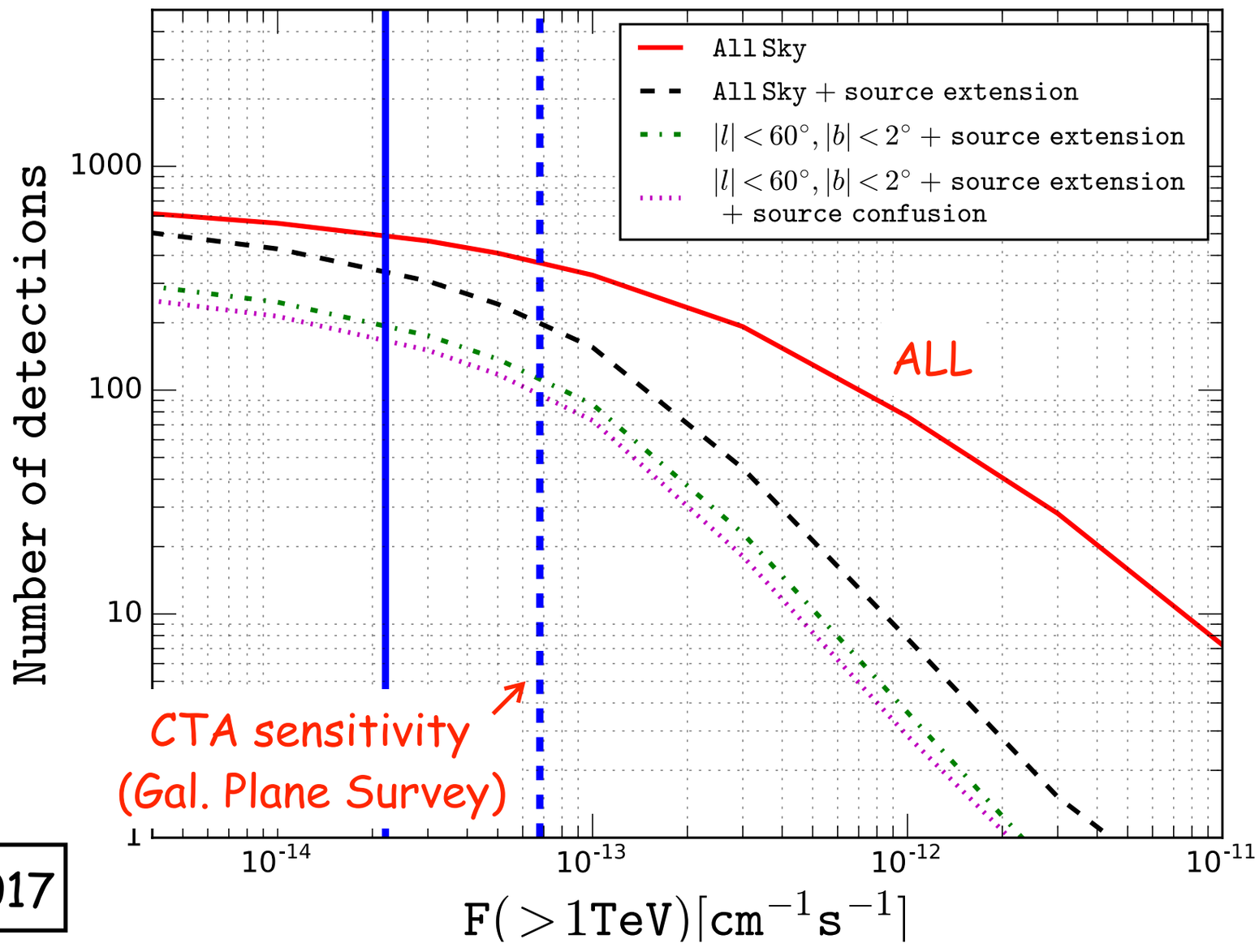

CTA sensitivity (Gal. Plane Survey)

TeV domain

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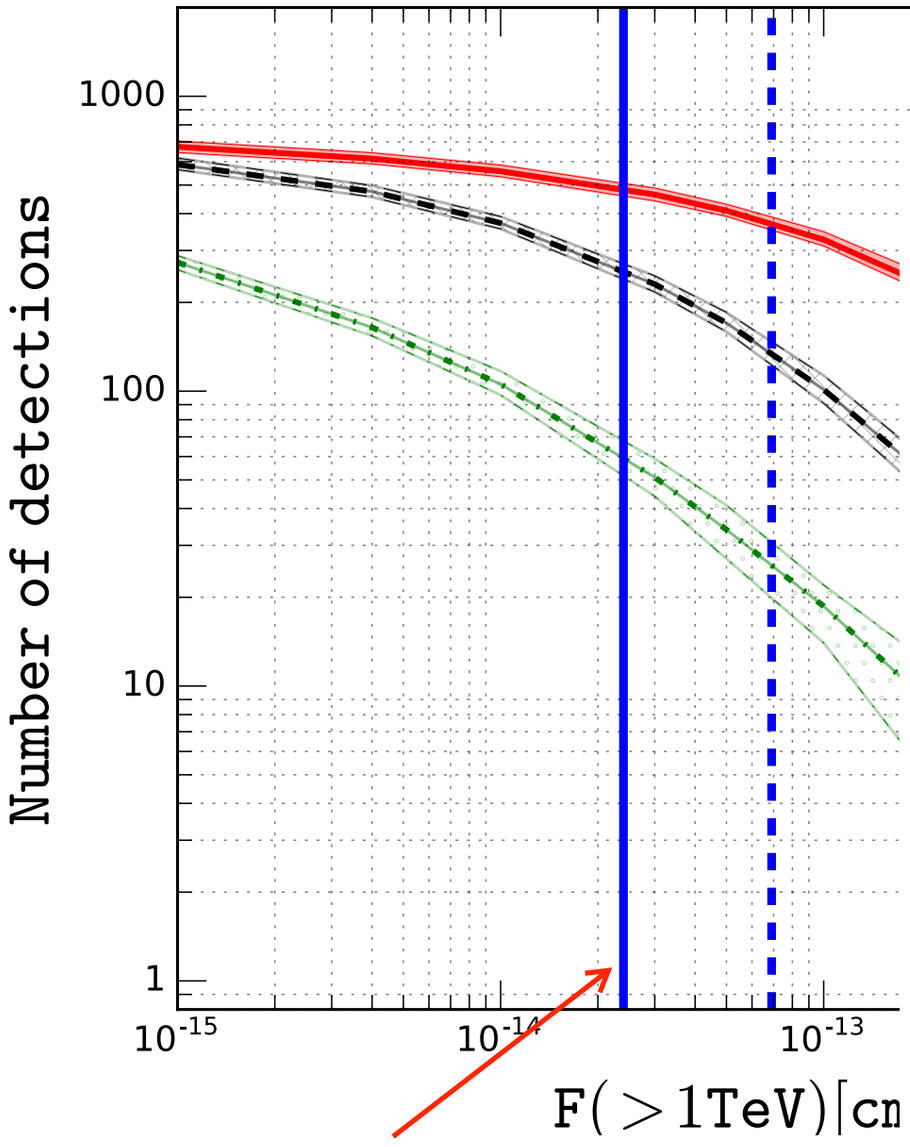

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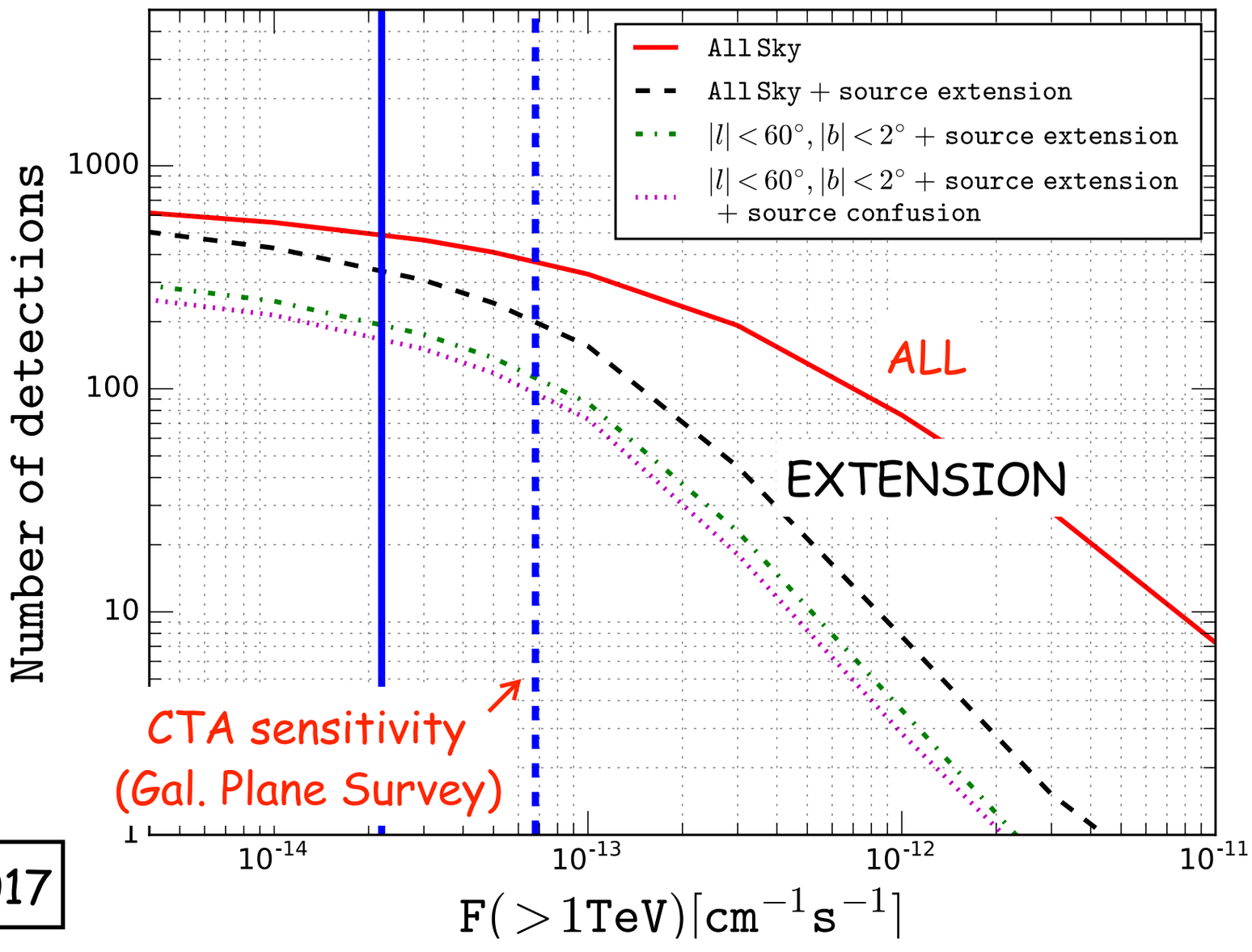

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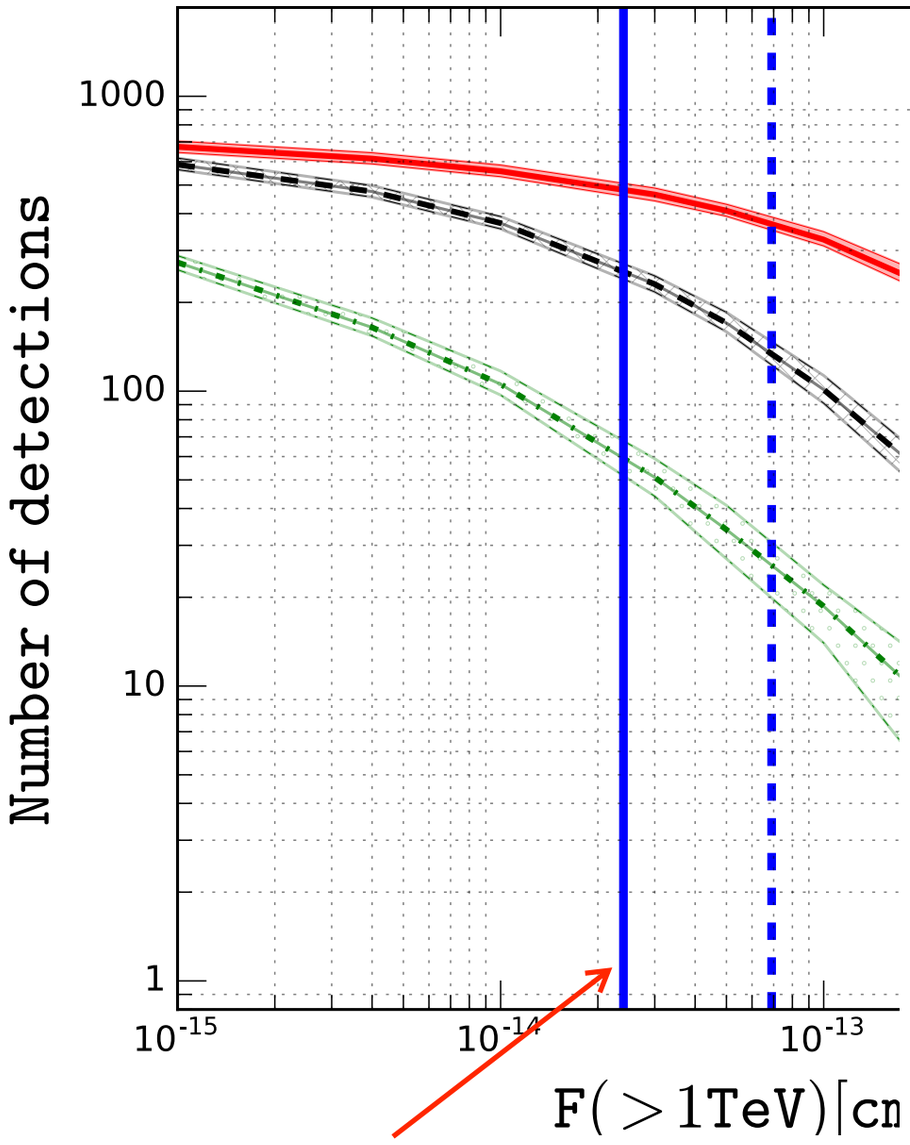

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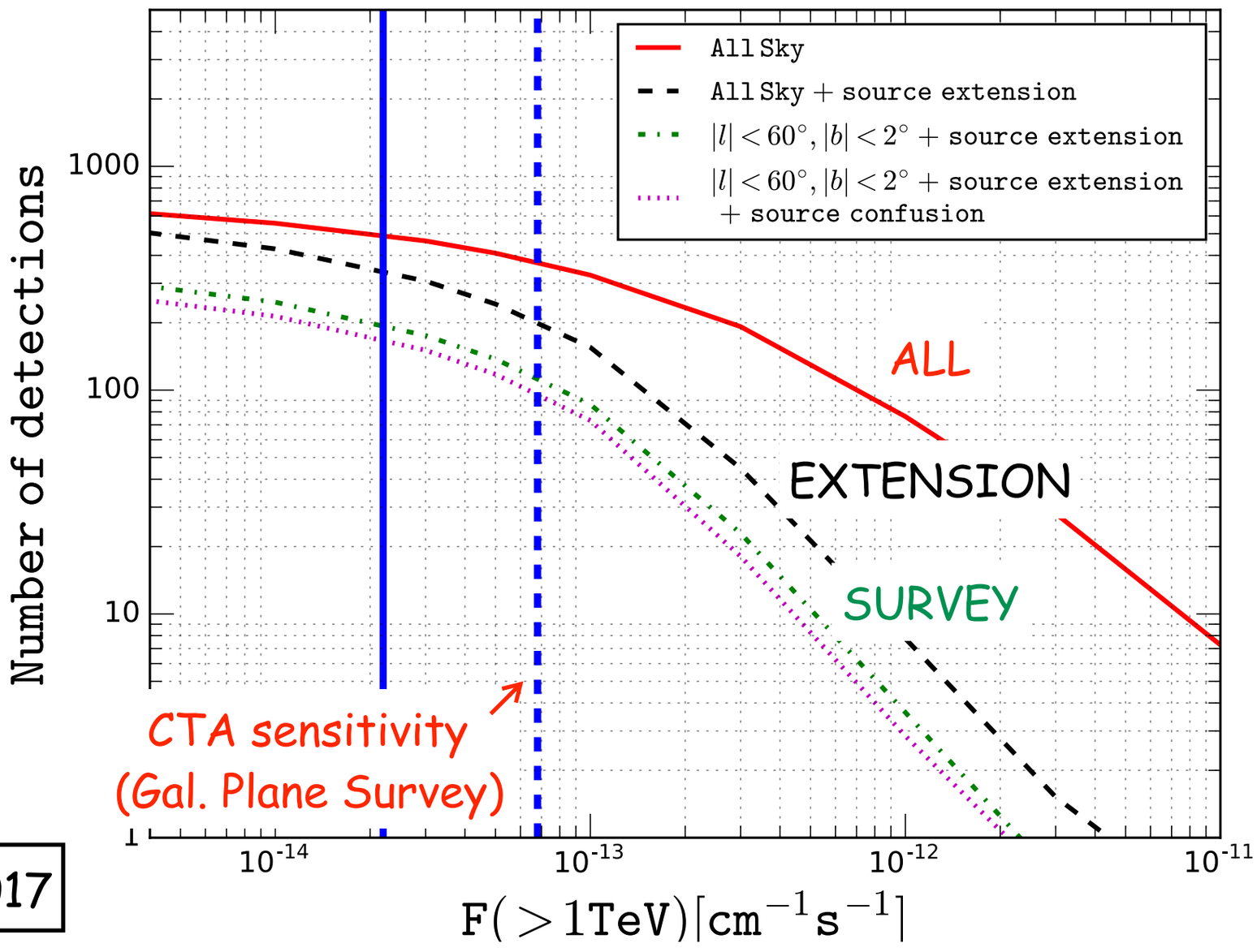

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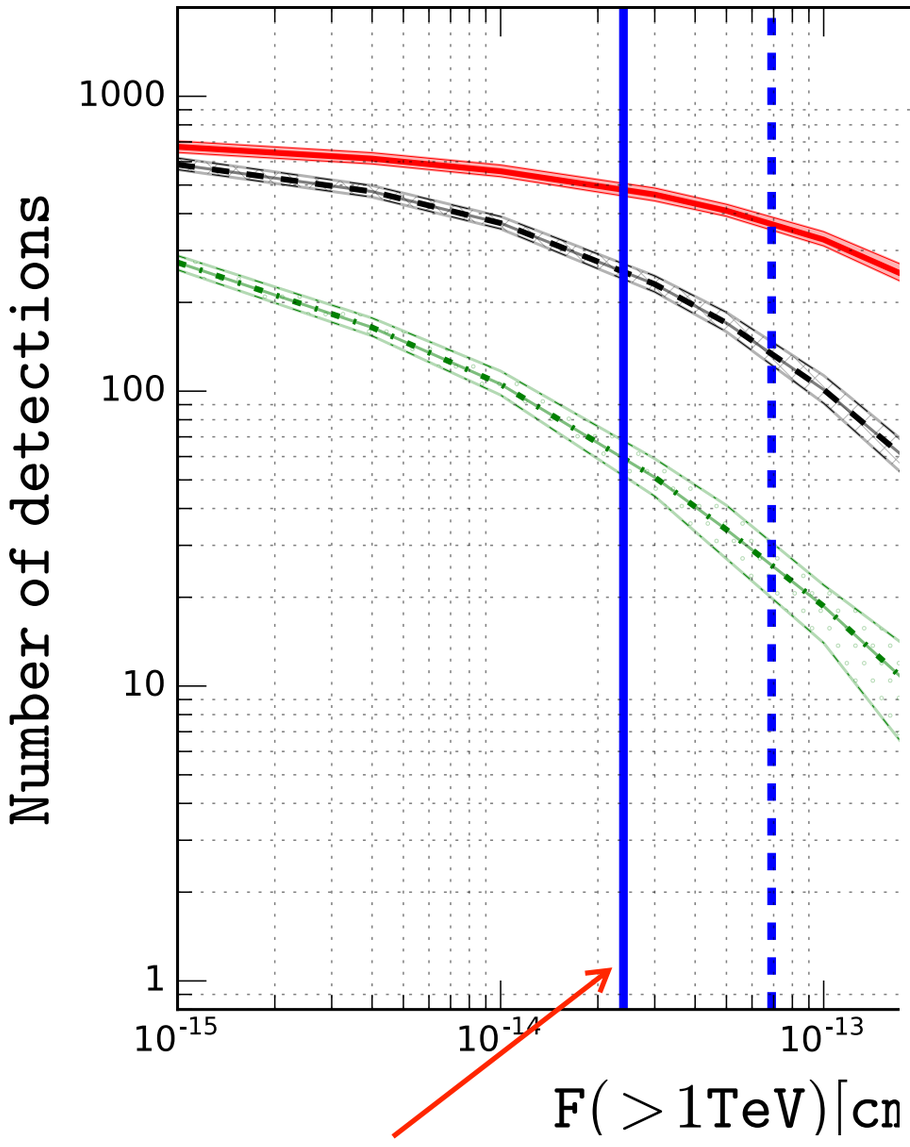

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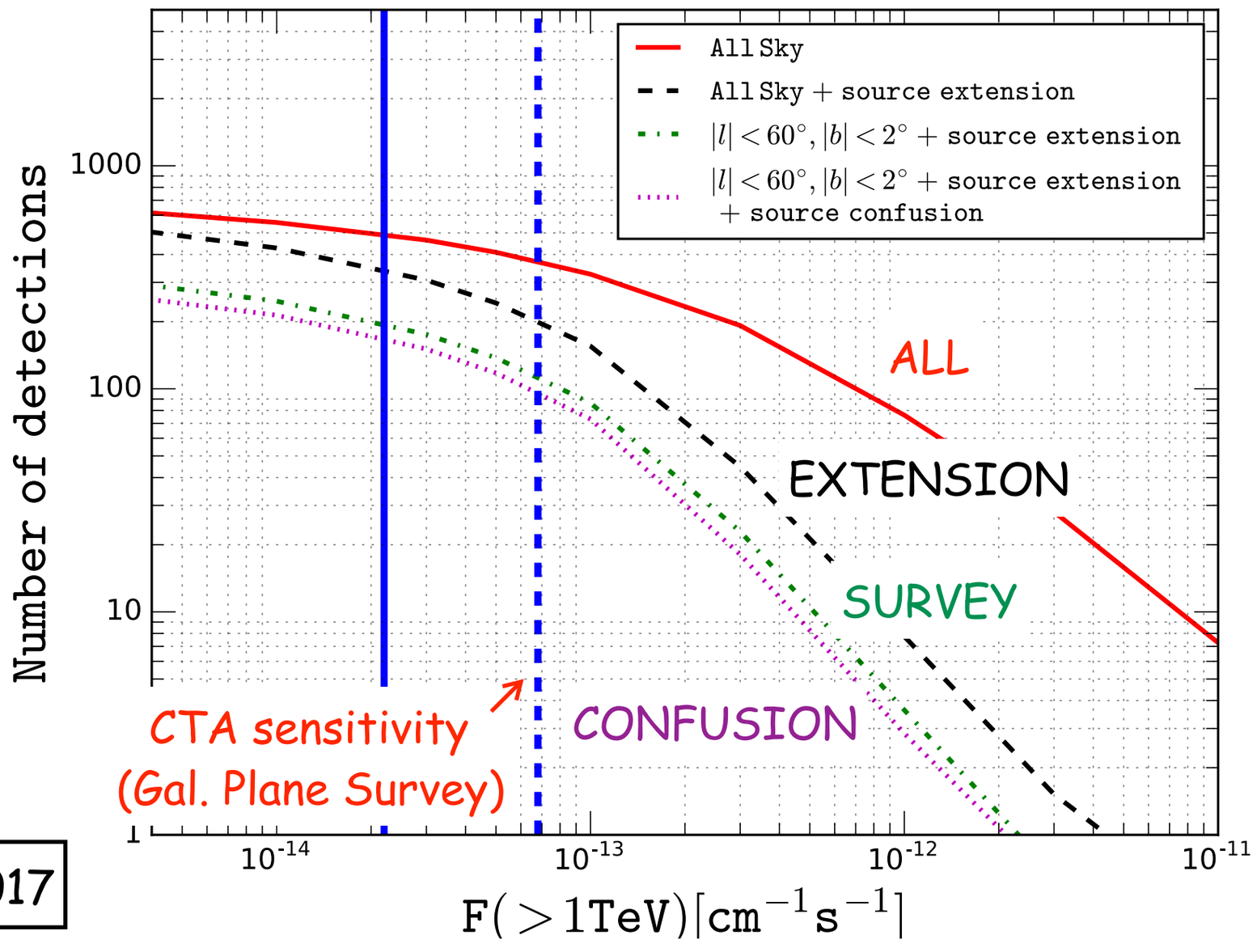

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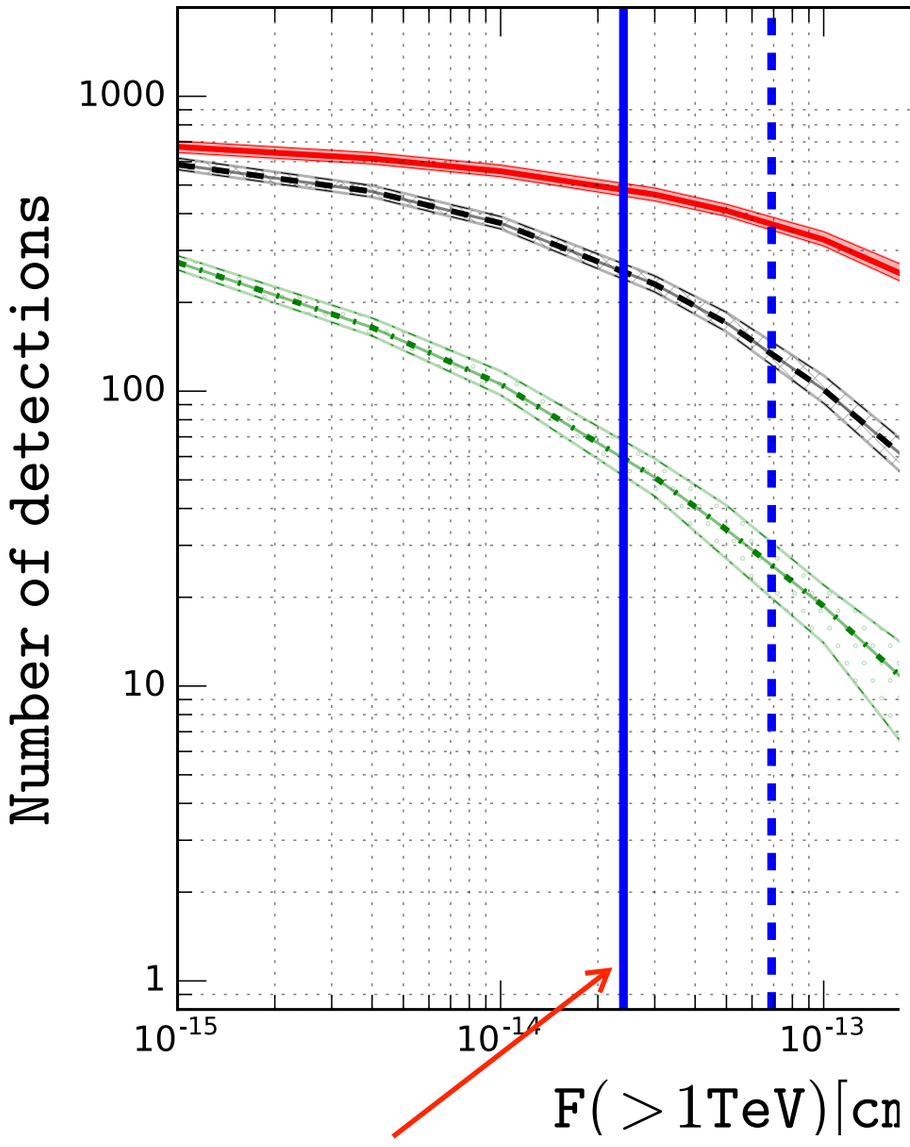

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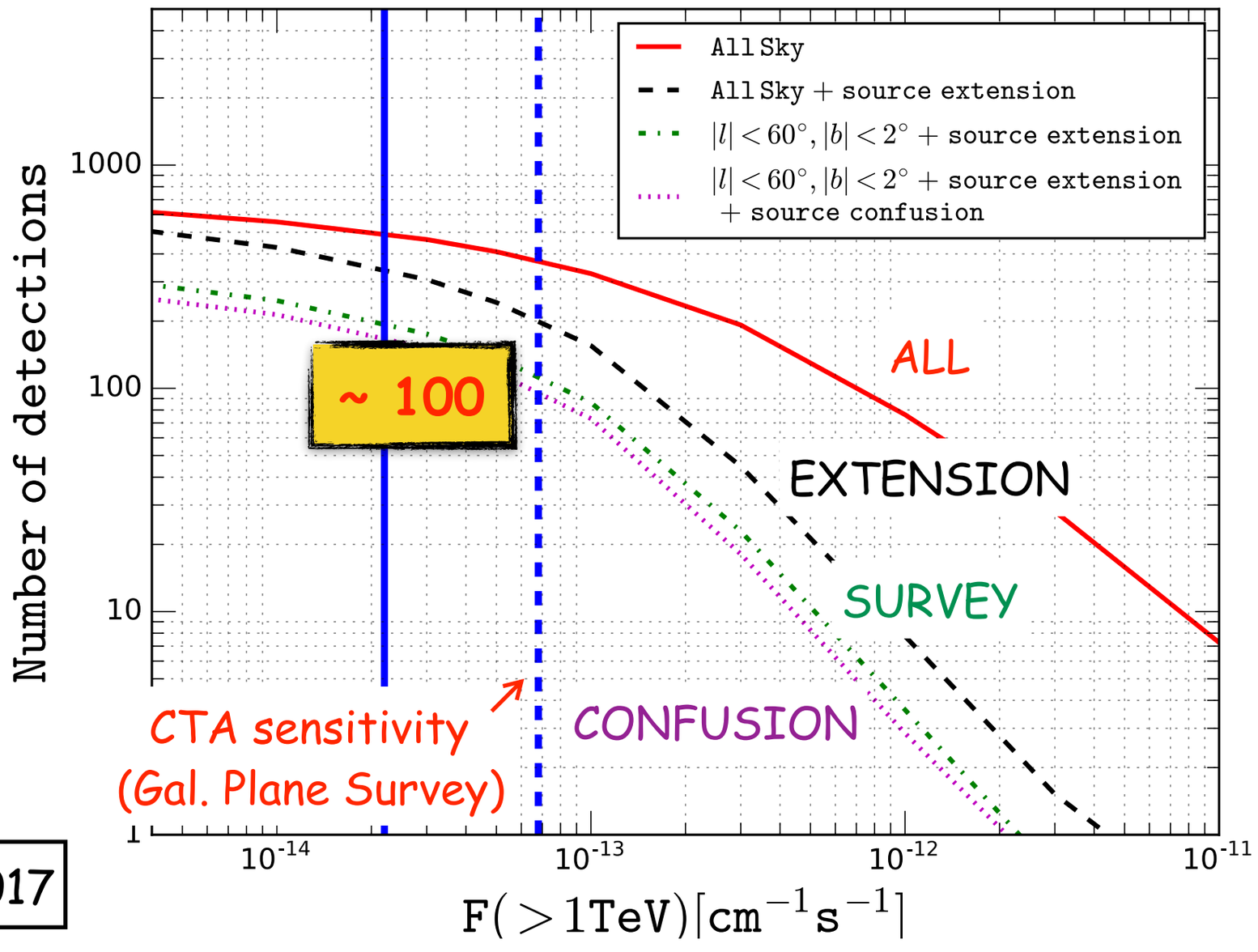

TeV domain

The Cherenkov Telescope Array and the search for PeVatrons

very rough estimate

—> N_{SNR} ~ 100 SNRs

TeV domain

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provided that theoreticians are right

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Question: will we be able to recognise them as PeVatrons?
(i.e. bright enough to be observable up to the multi-TeV domain)

The galactic centre as a cosmic ray PeVatron

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)

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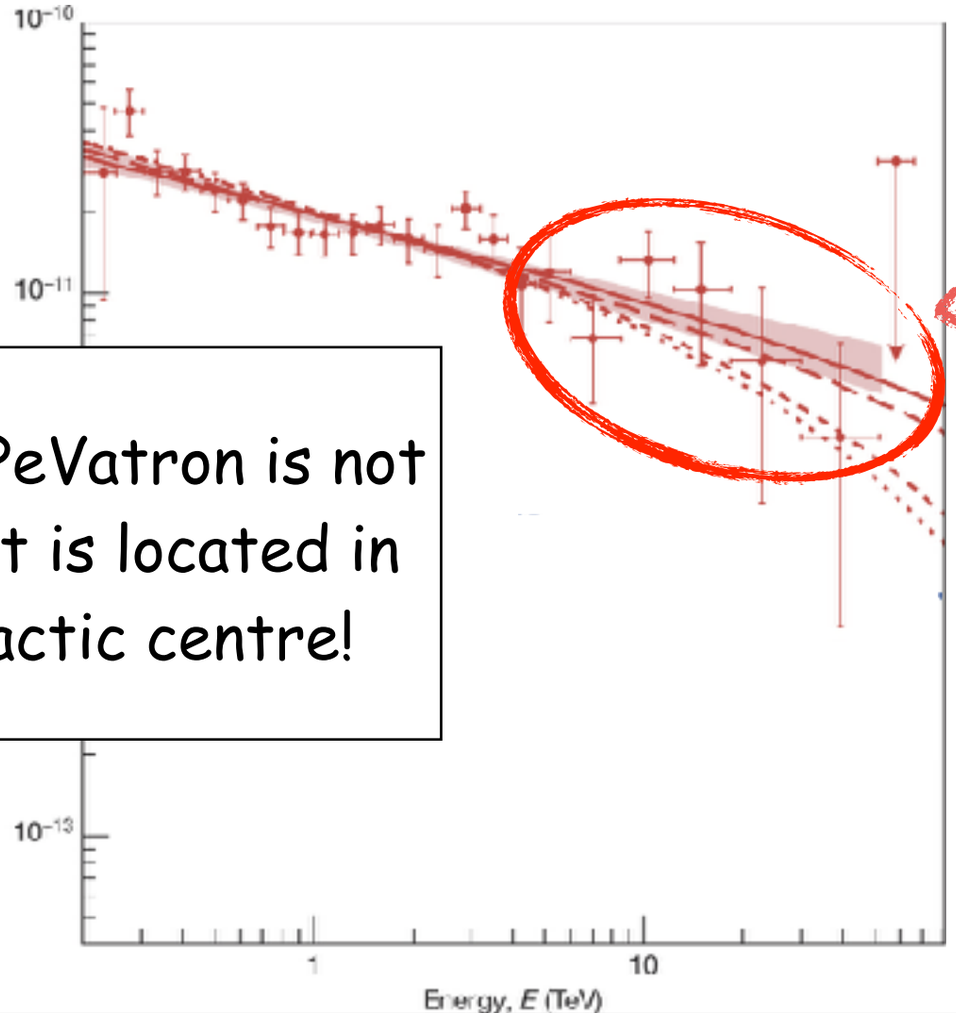

diffuse emission from the GC

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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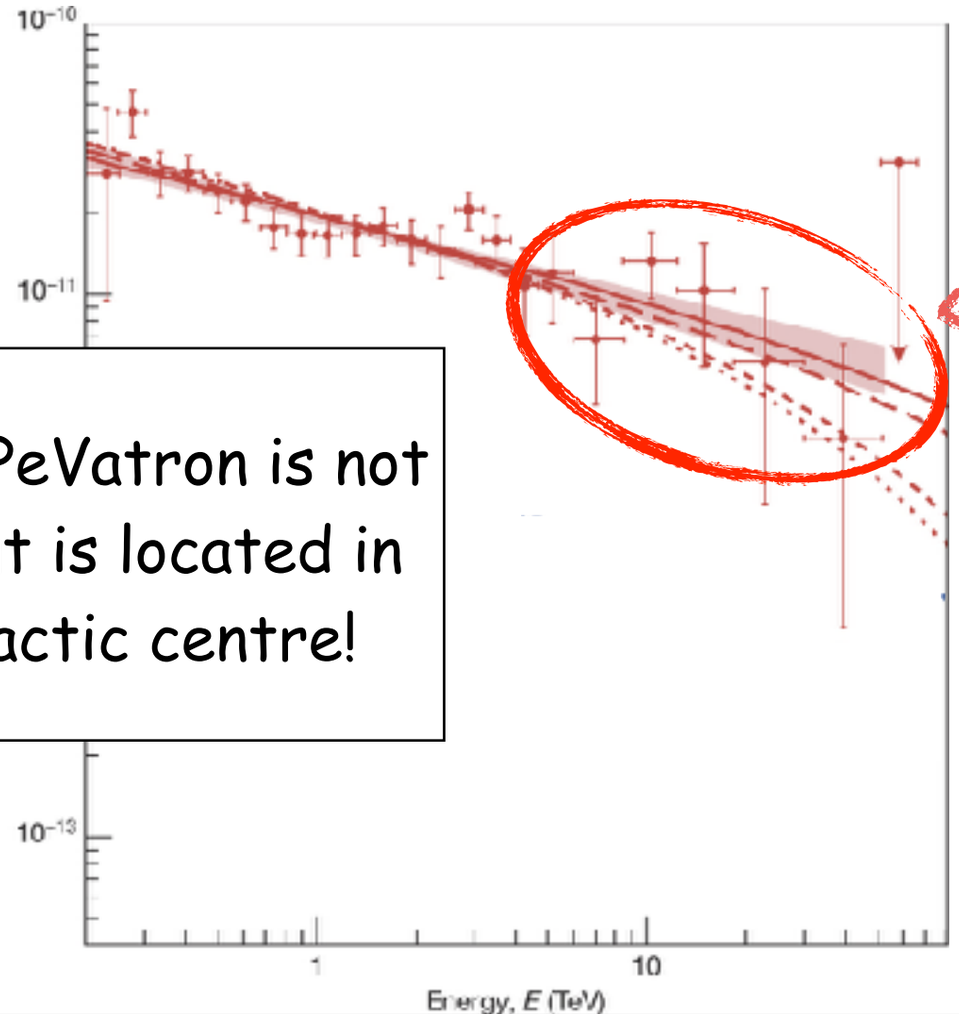

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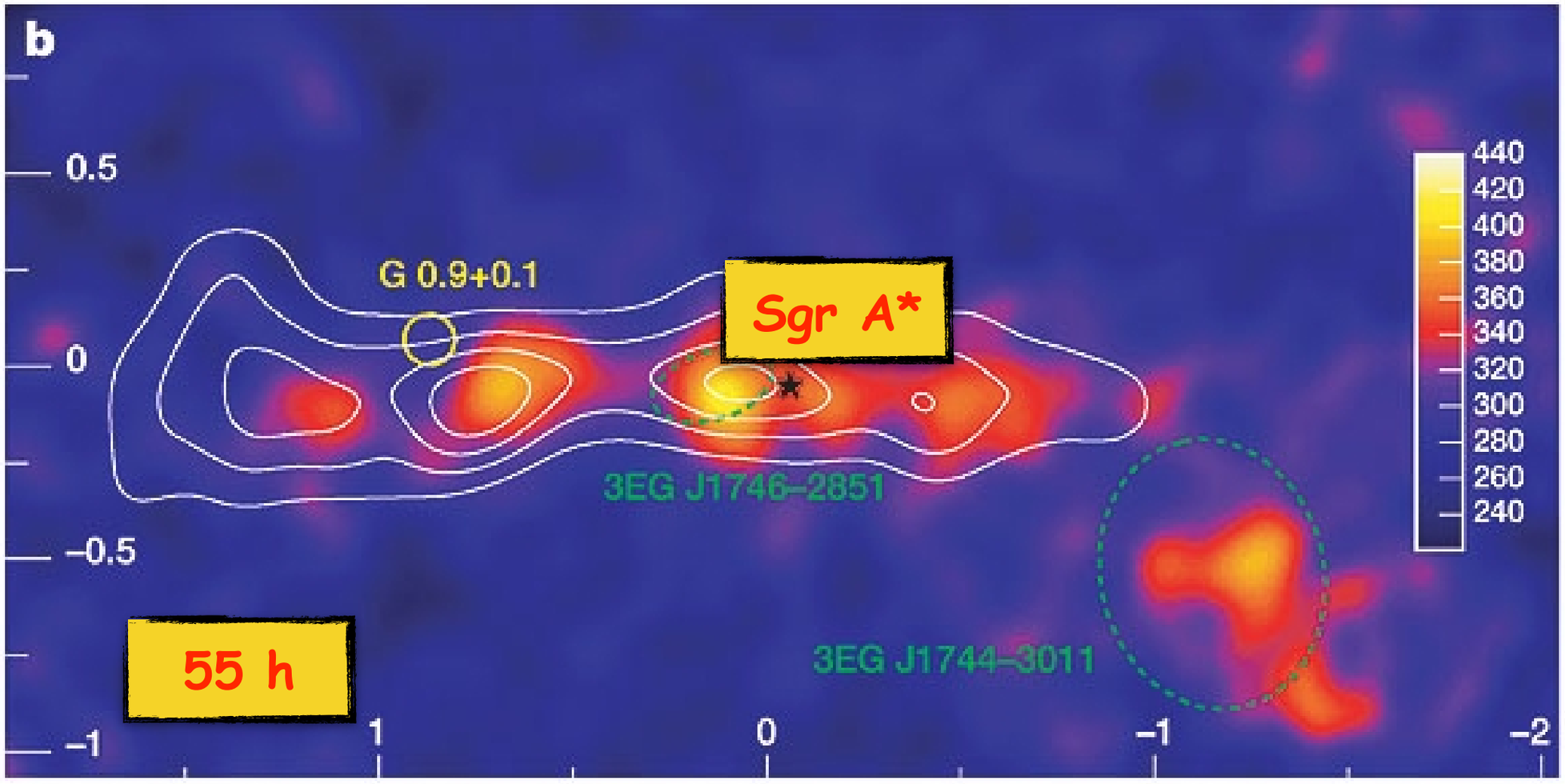
a cutoff @ …	deviates from data @
2.9 PeV	68%
0.6 PeV	90%
0.4 PeV	95%

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)

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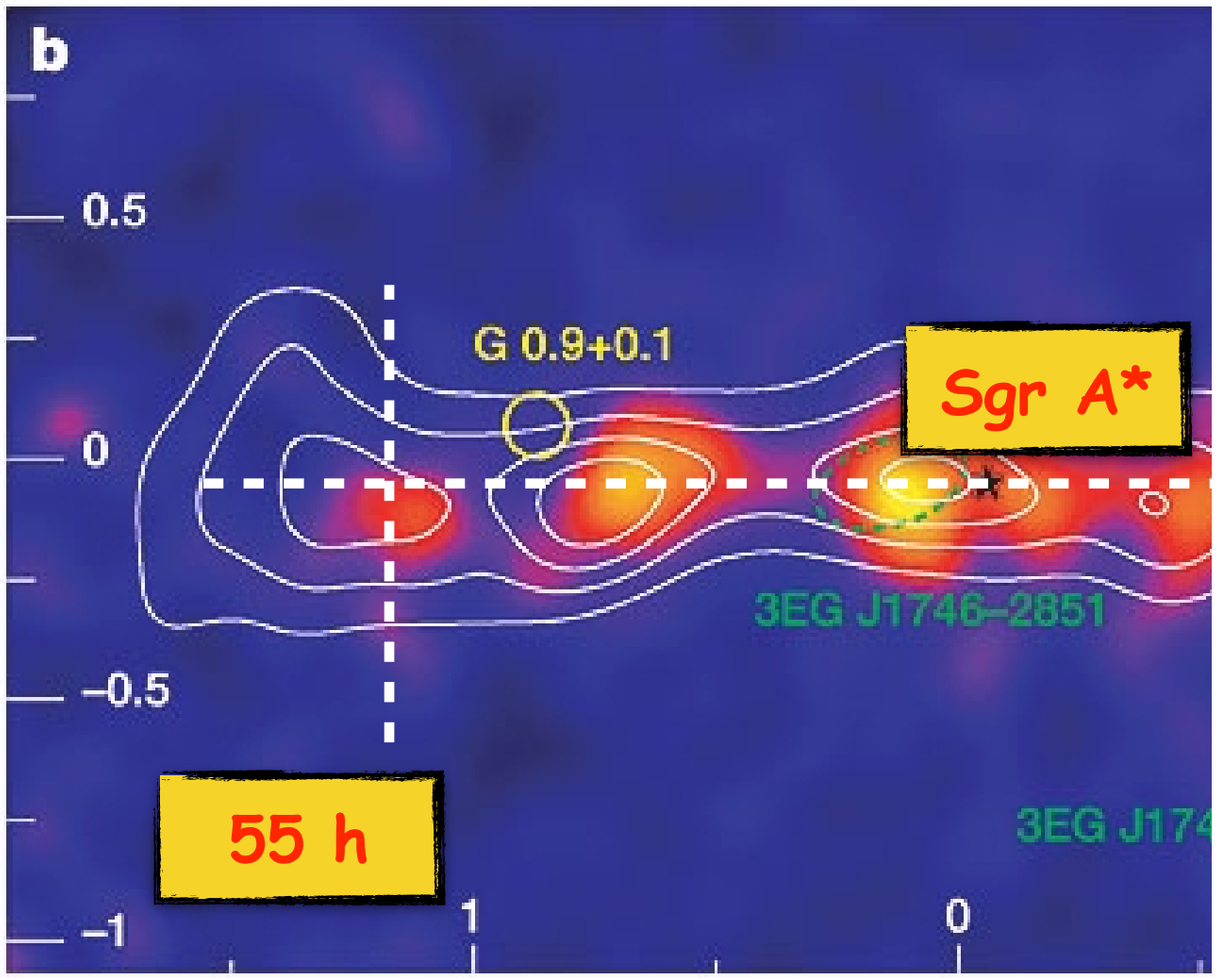

histogram -> γ-rays

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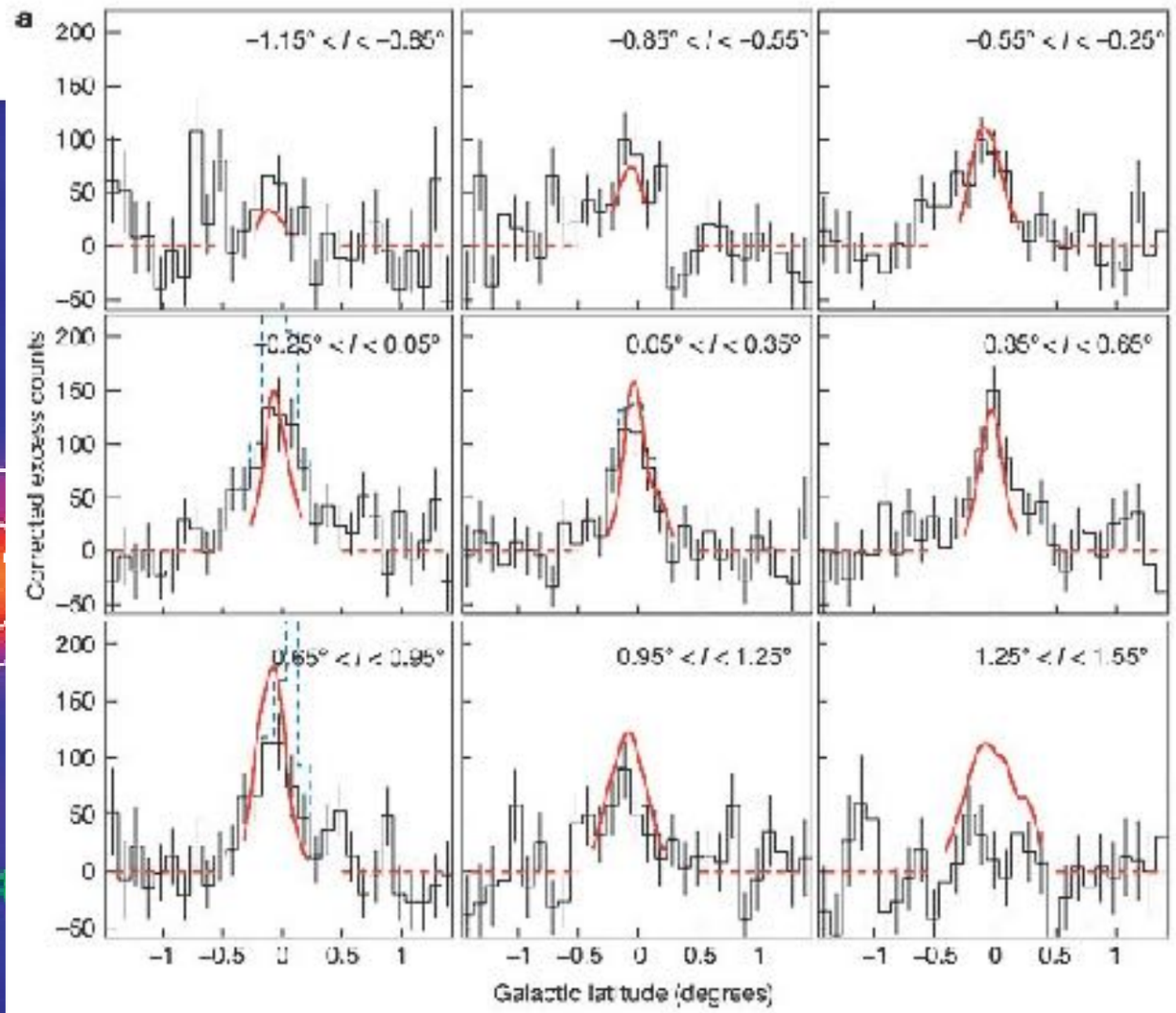

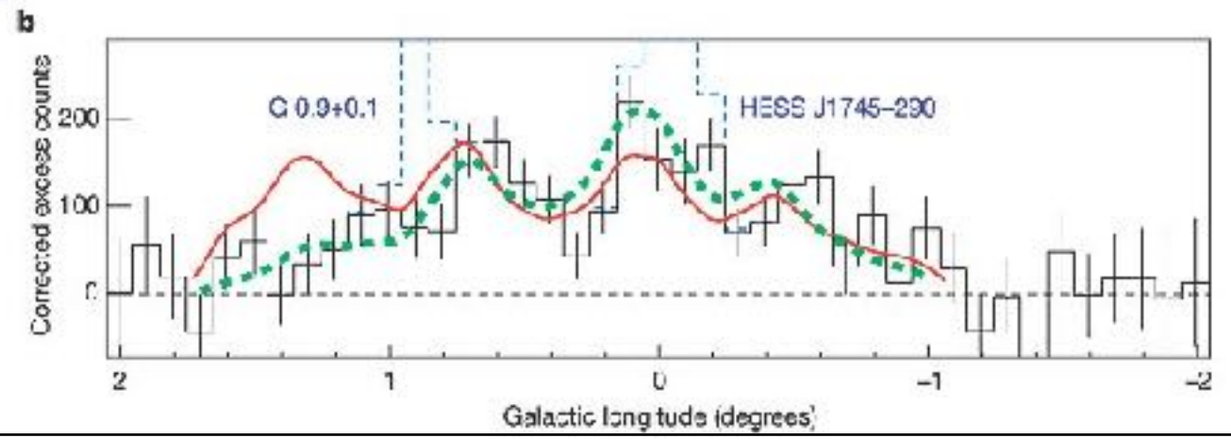

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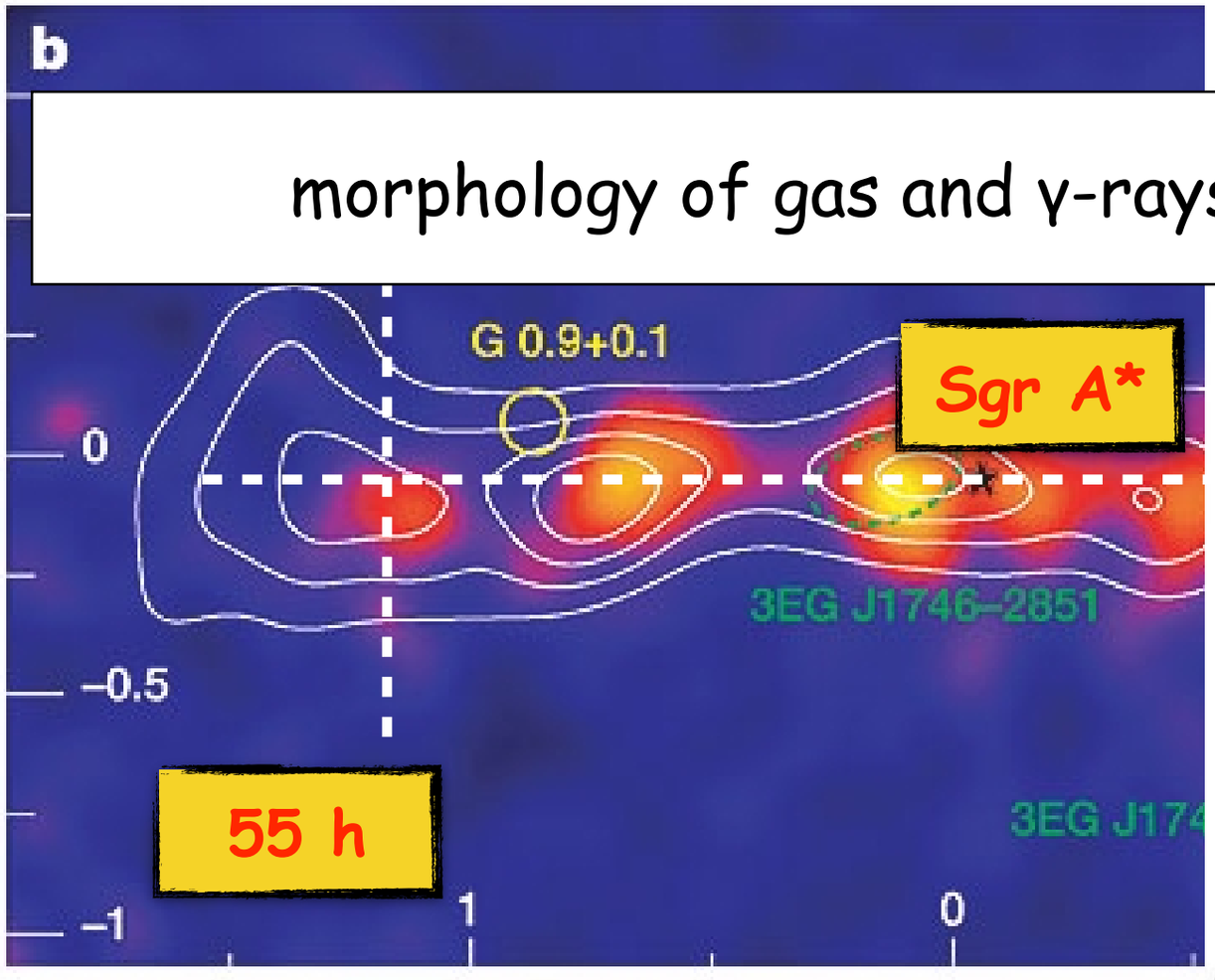
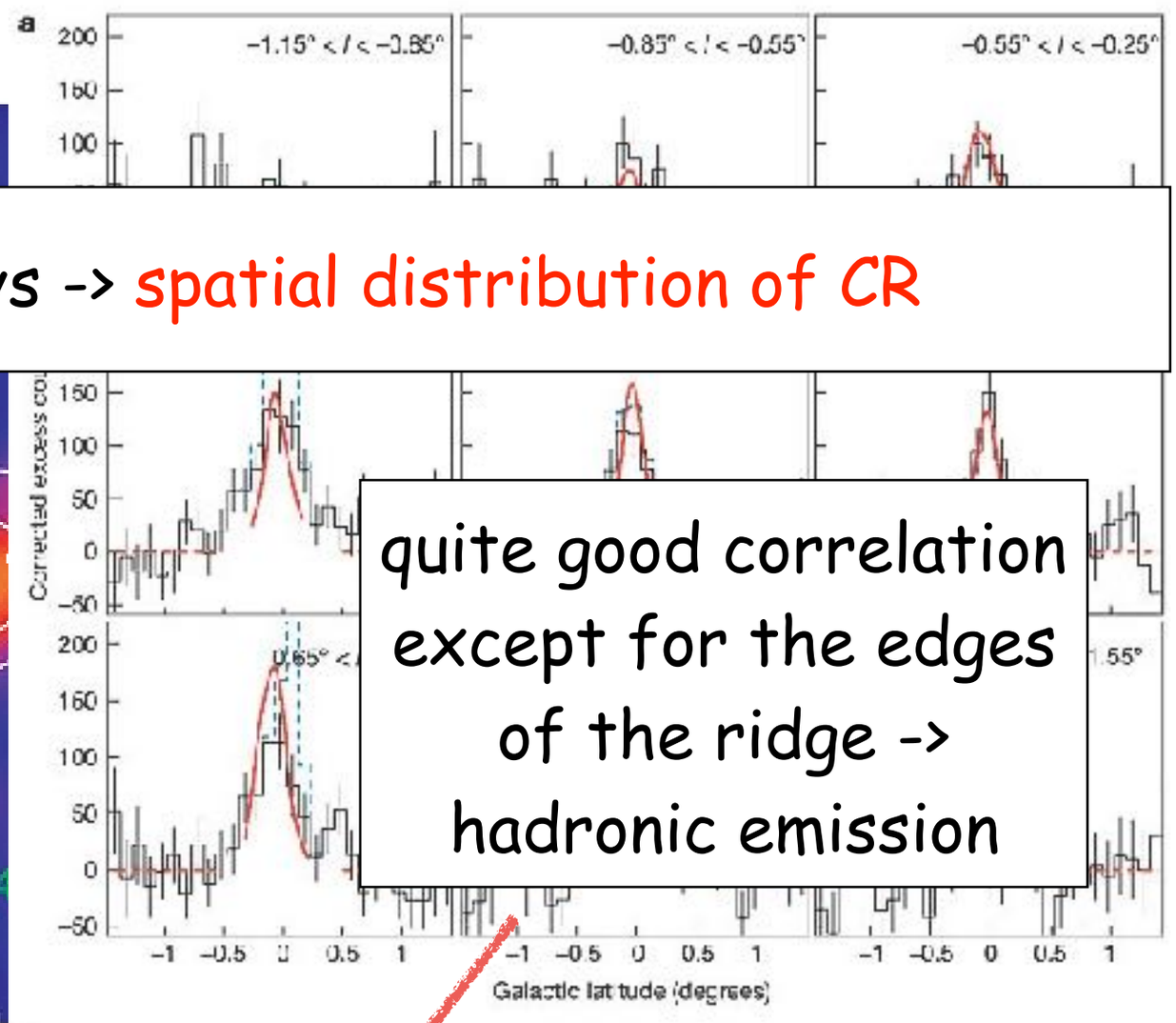


morphology of gas and γ-rays -> spatial distribution of CR



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

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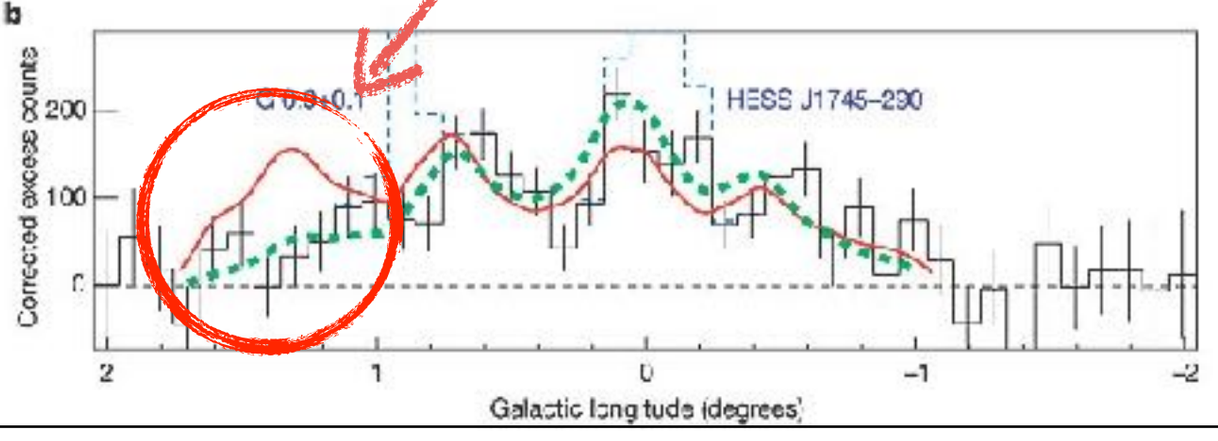

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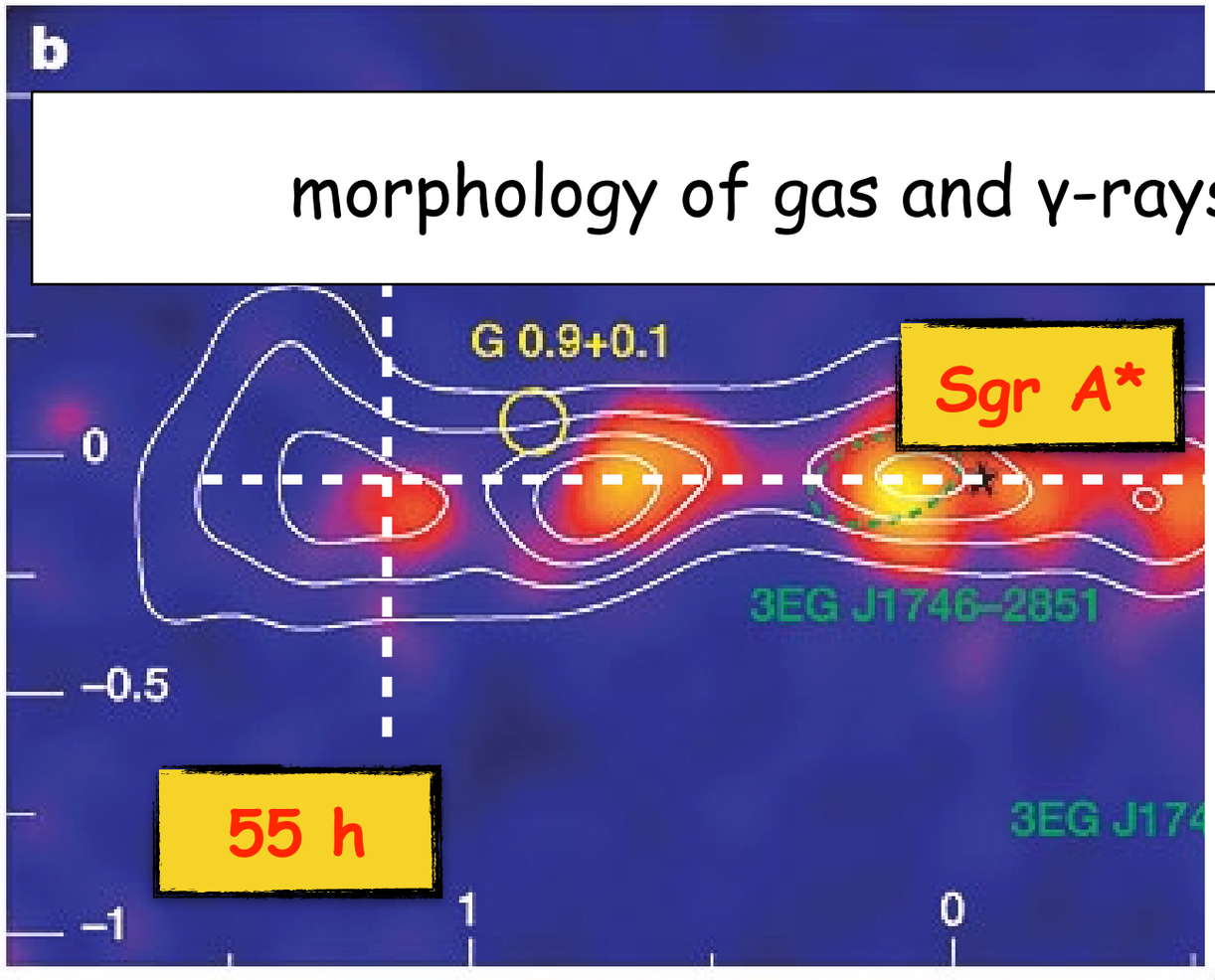

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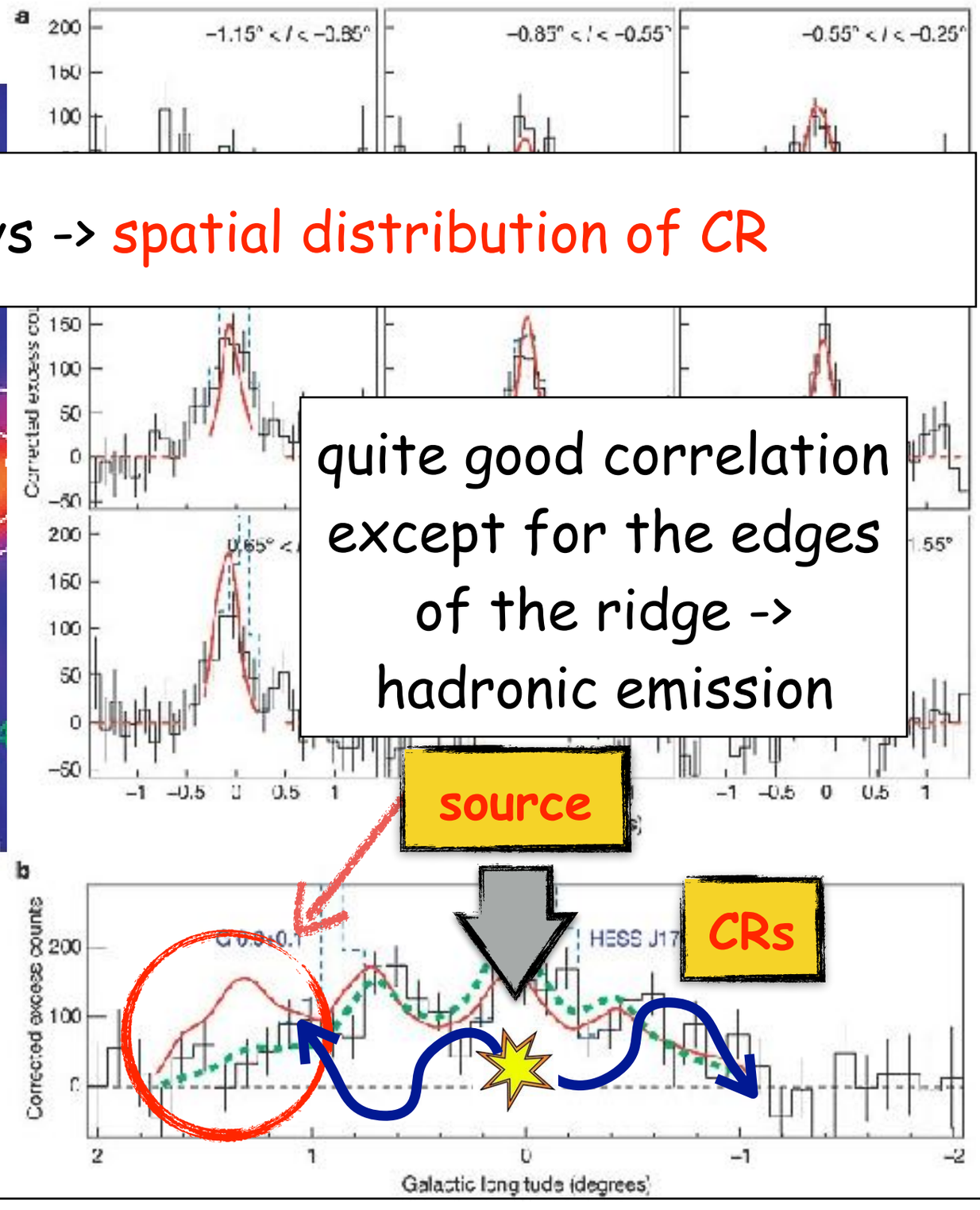

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source

CRs

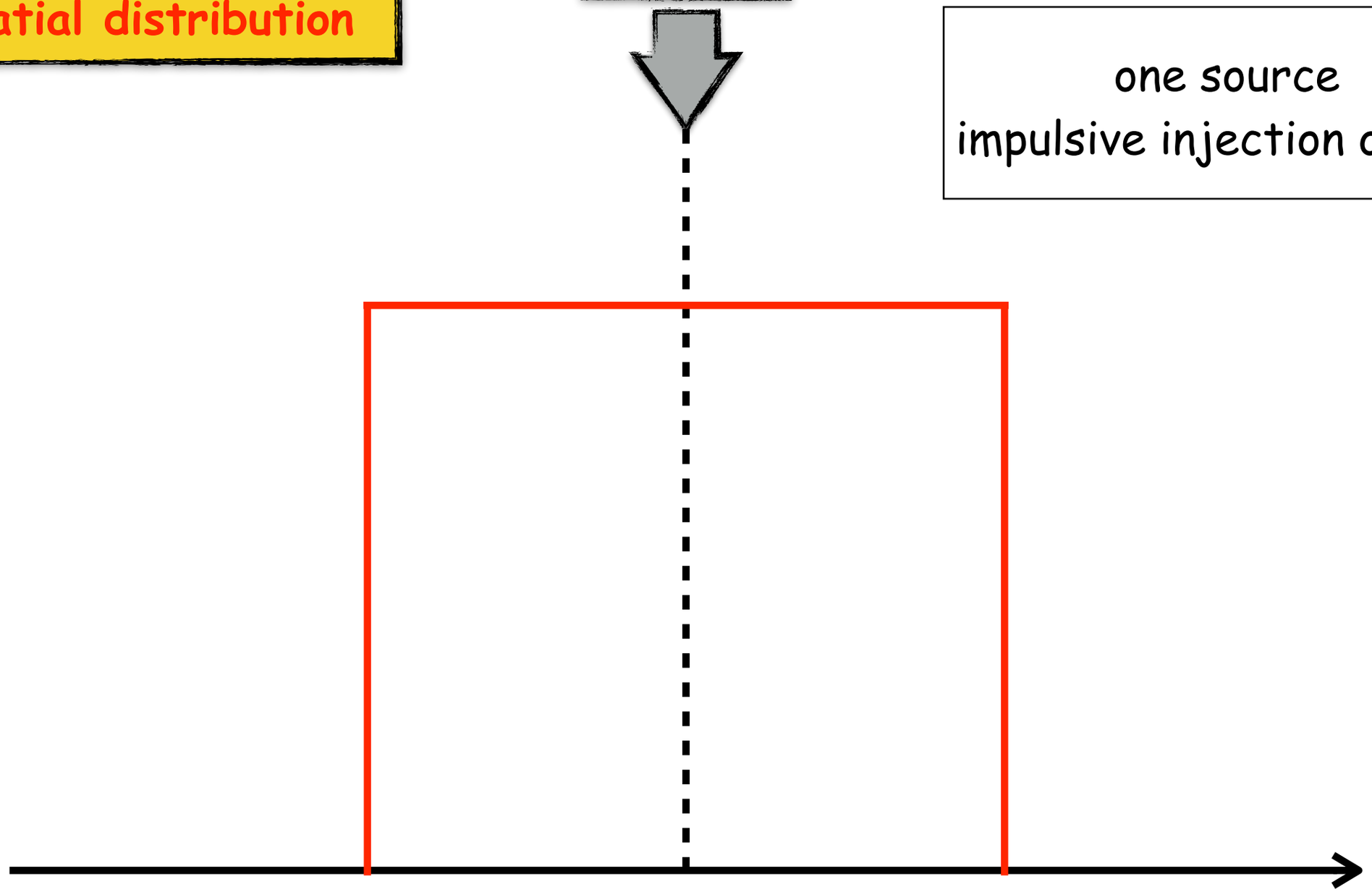
histogram -> γ-rays

red -> gas (CS)

Where is the source?

CR spatial distribution

Sgr A*



one source
impulsive injection of CRs

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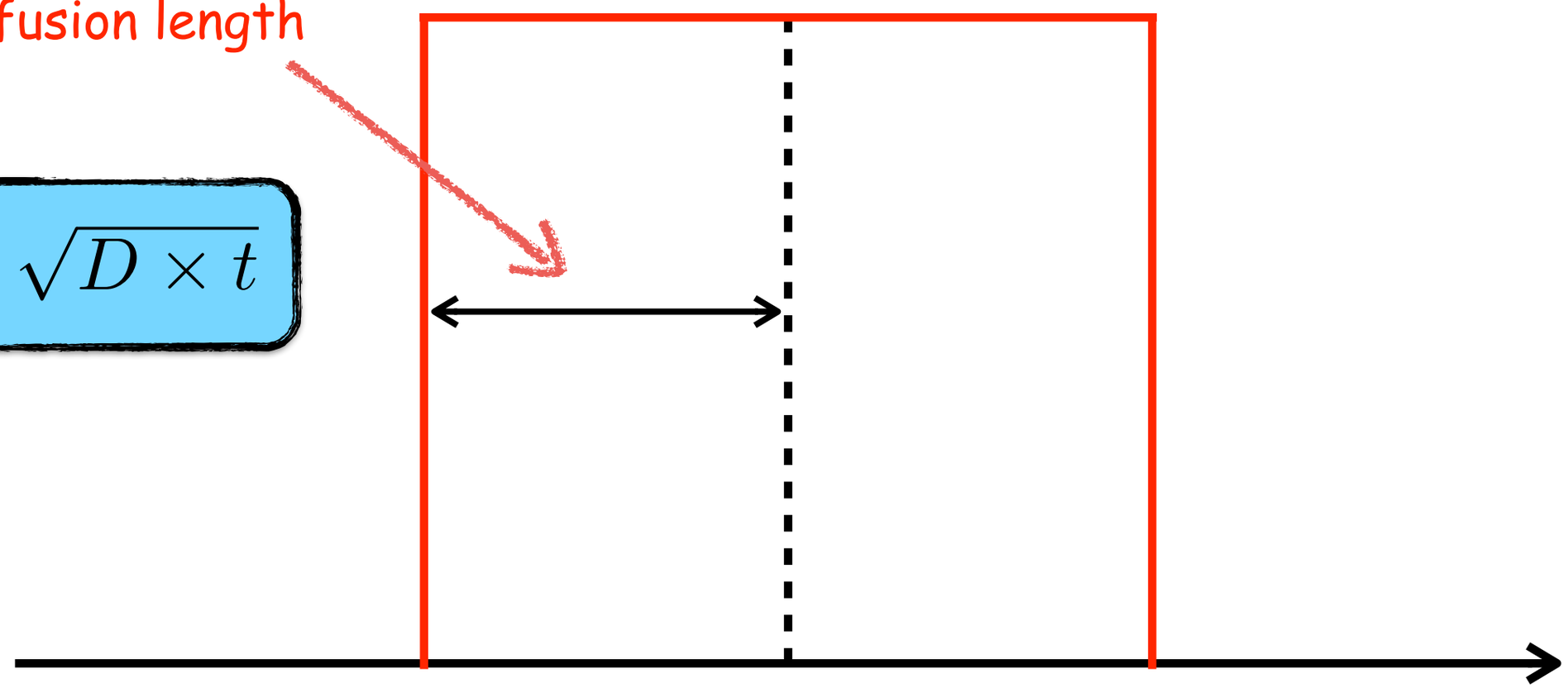
diffusion length

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



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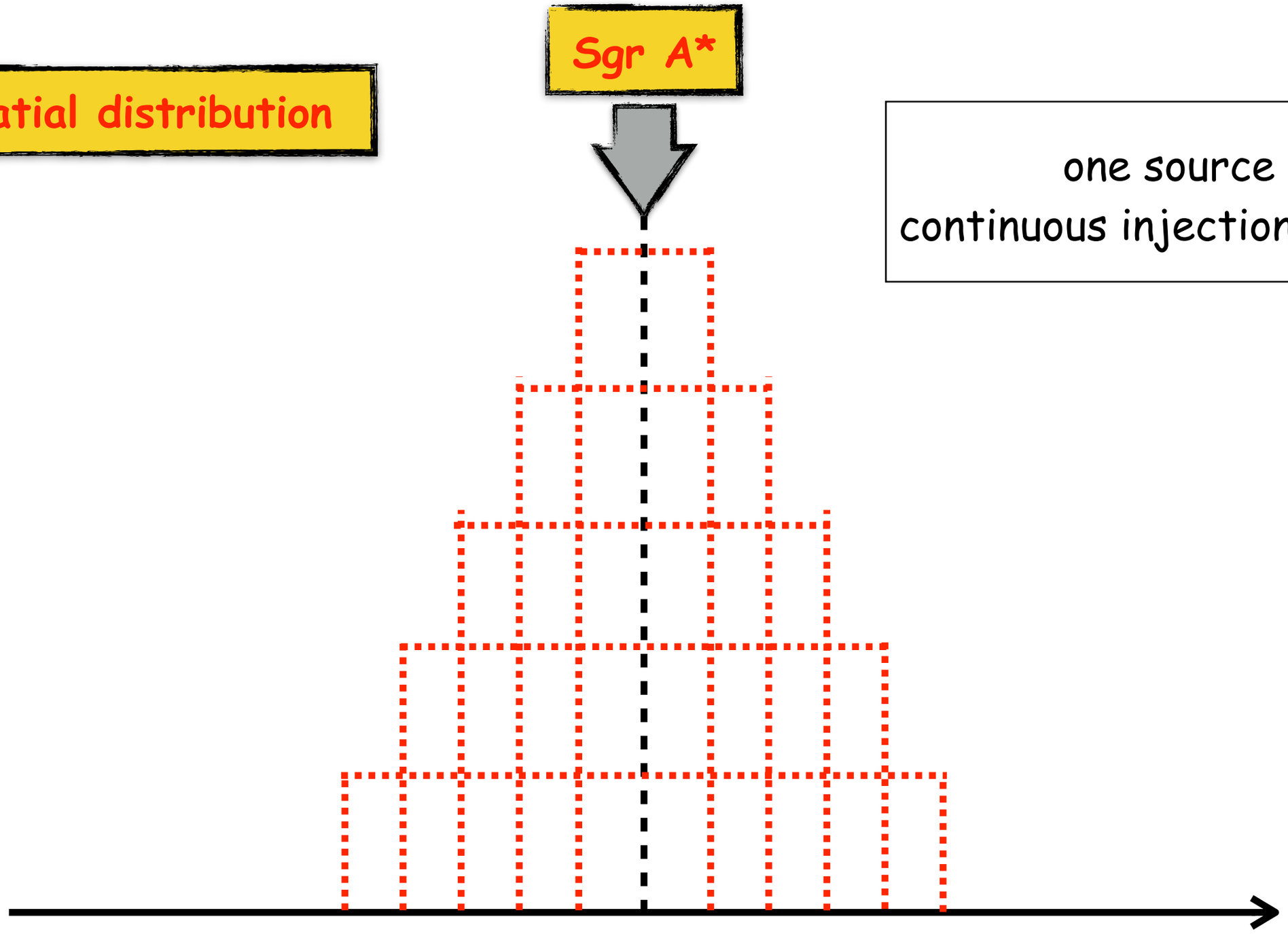

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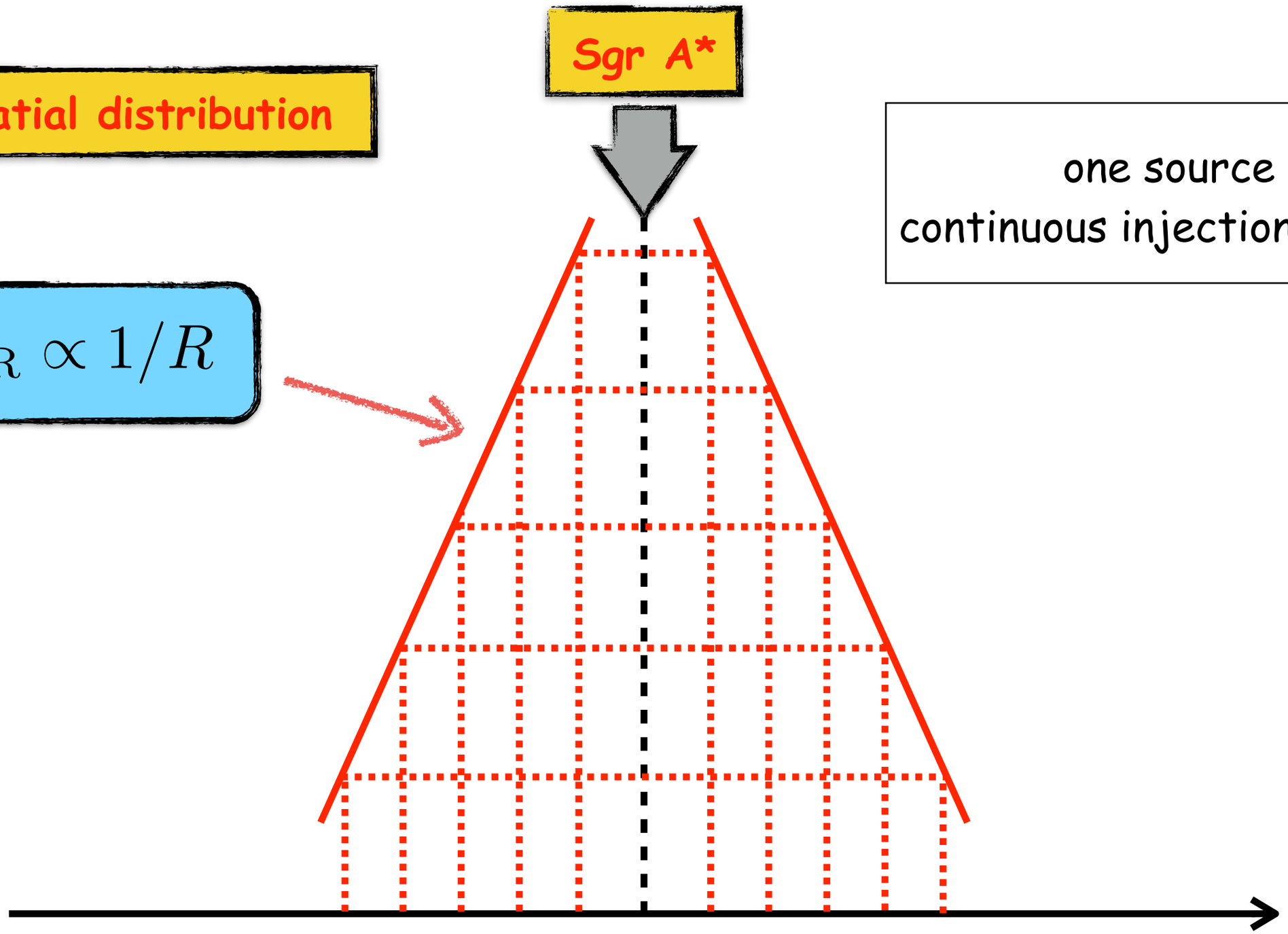
$n_{\rm CR} \propto 1/R$



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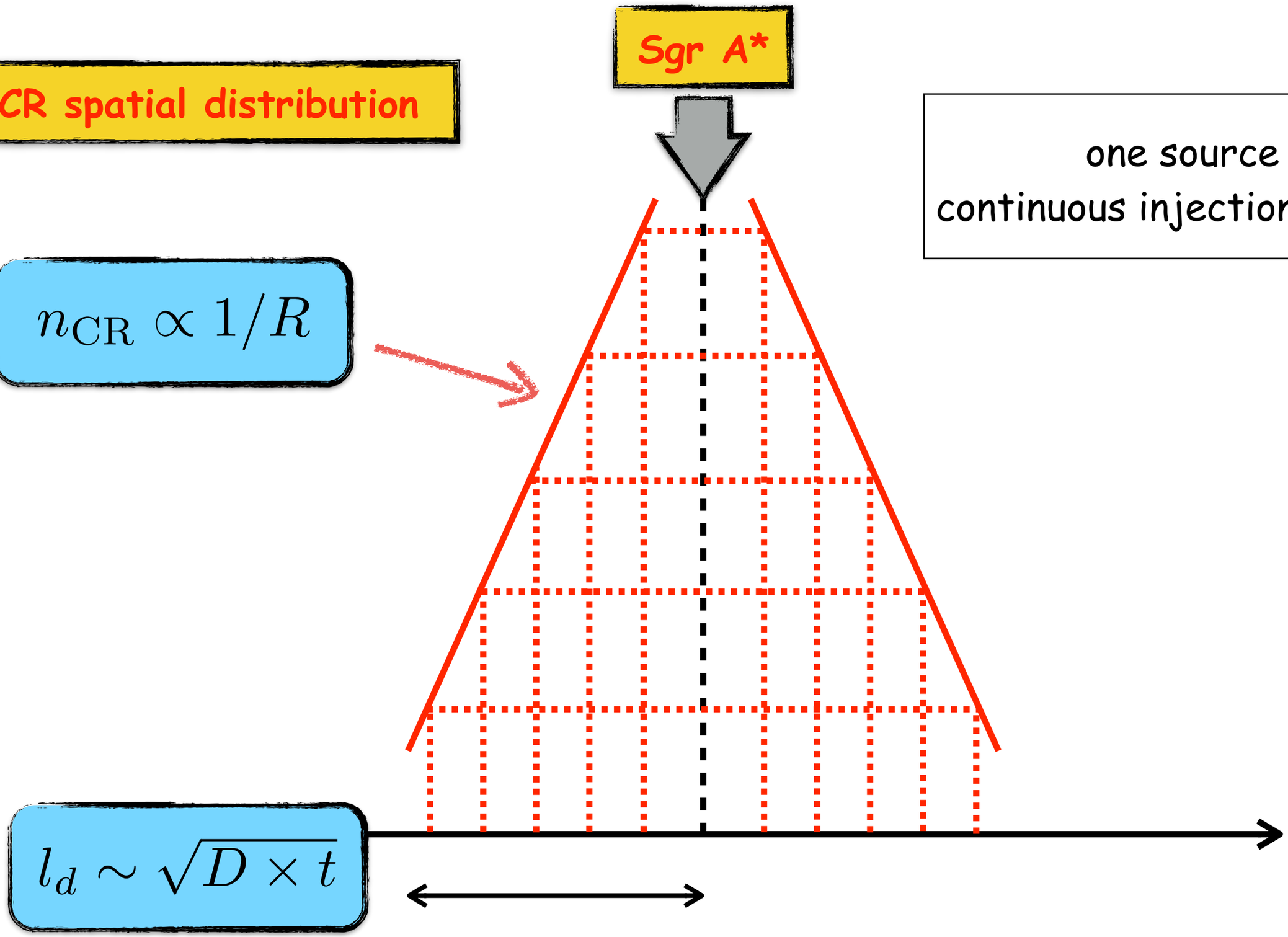

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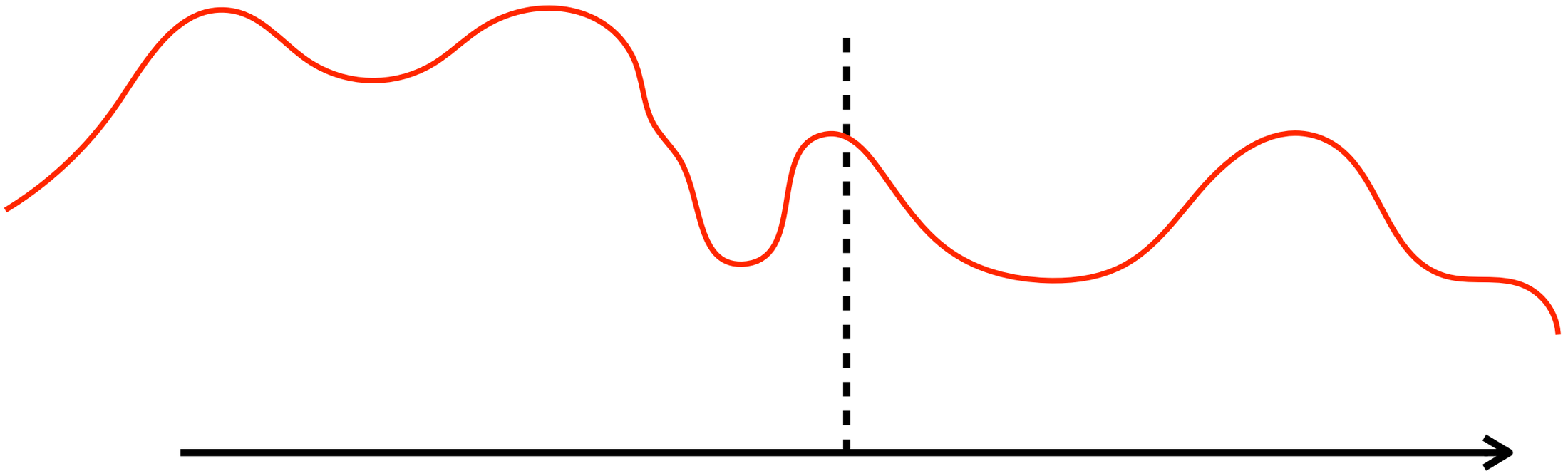
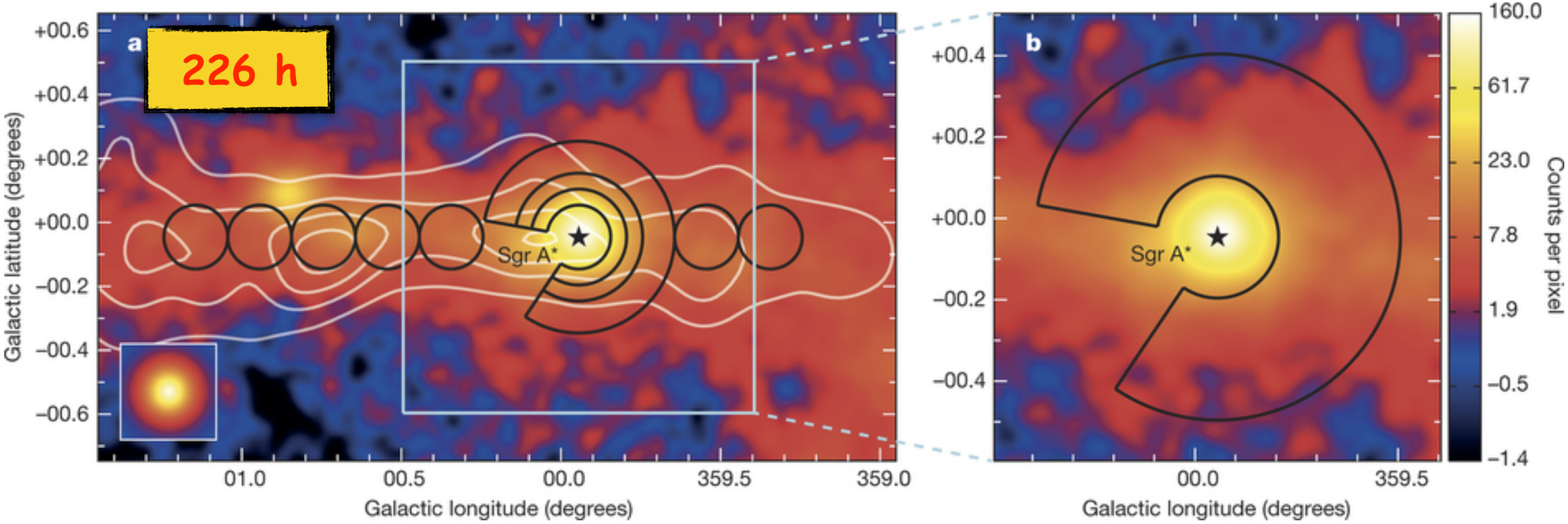
Sgr A*

many sources
-> any distribution



The source is at the GC

H.E.S.S. Coll. 2016



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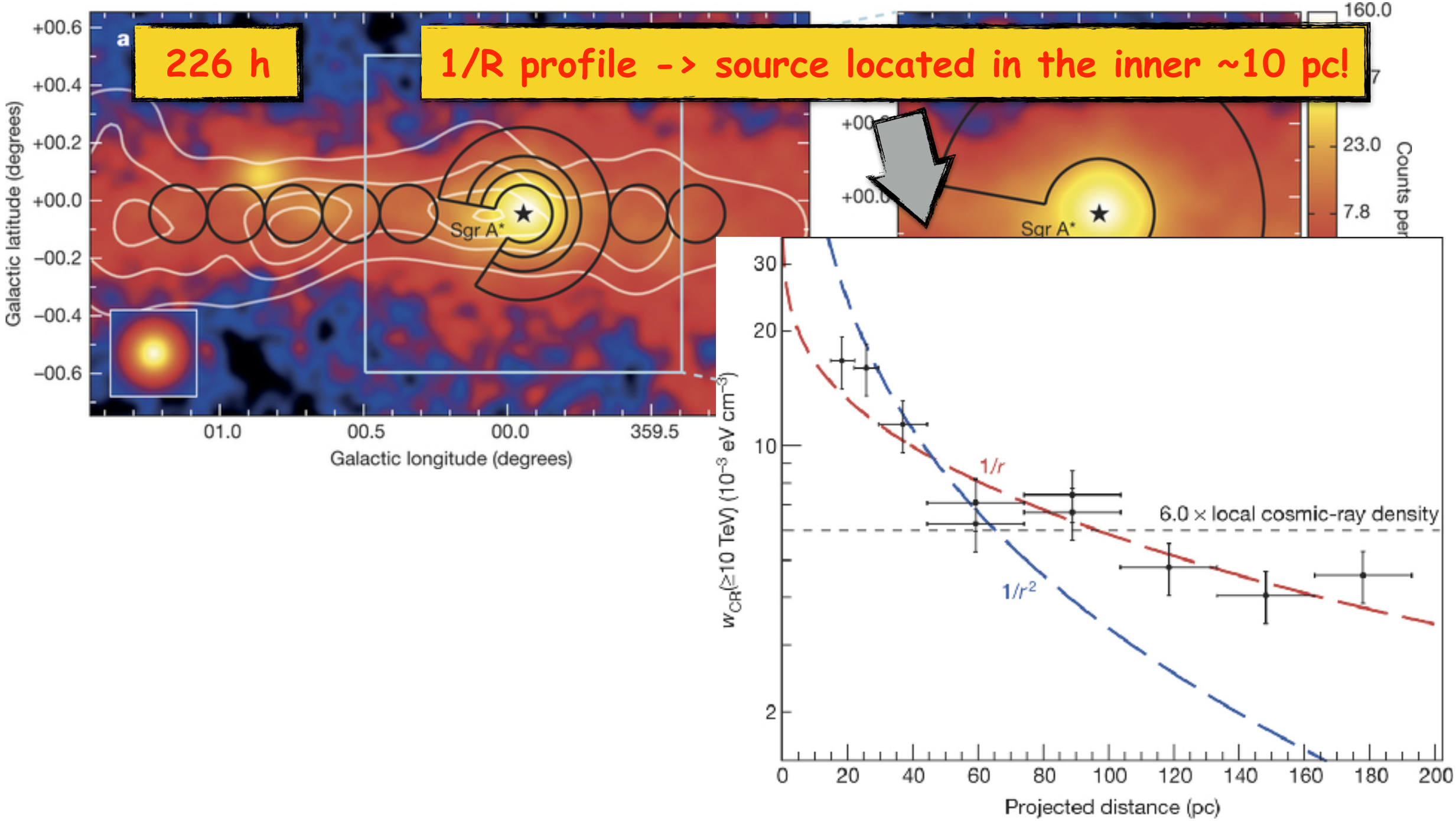

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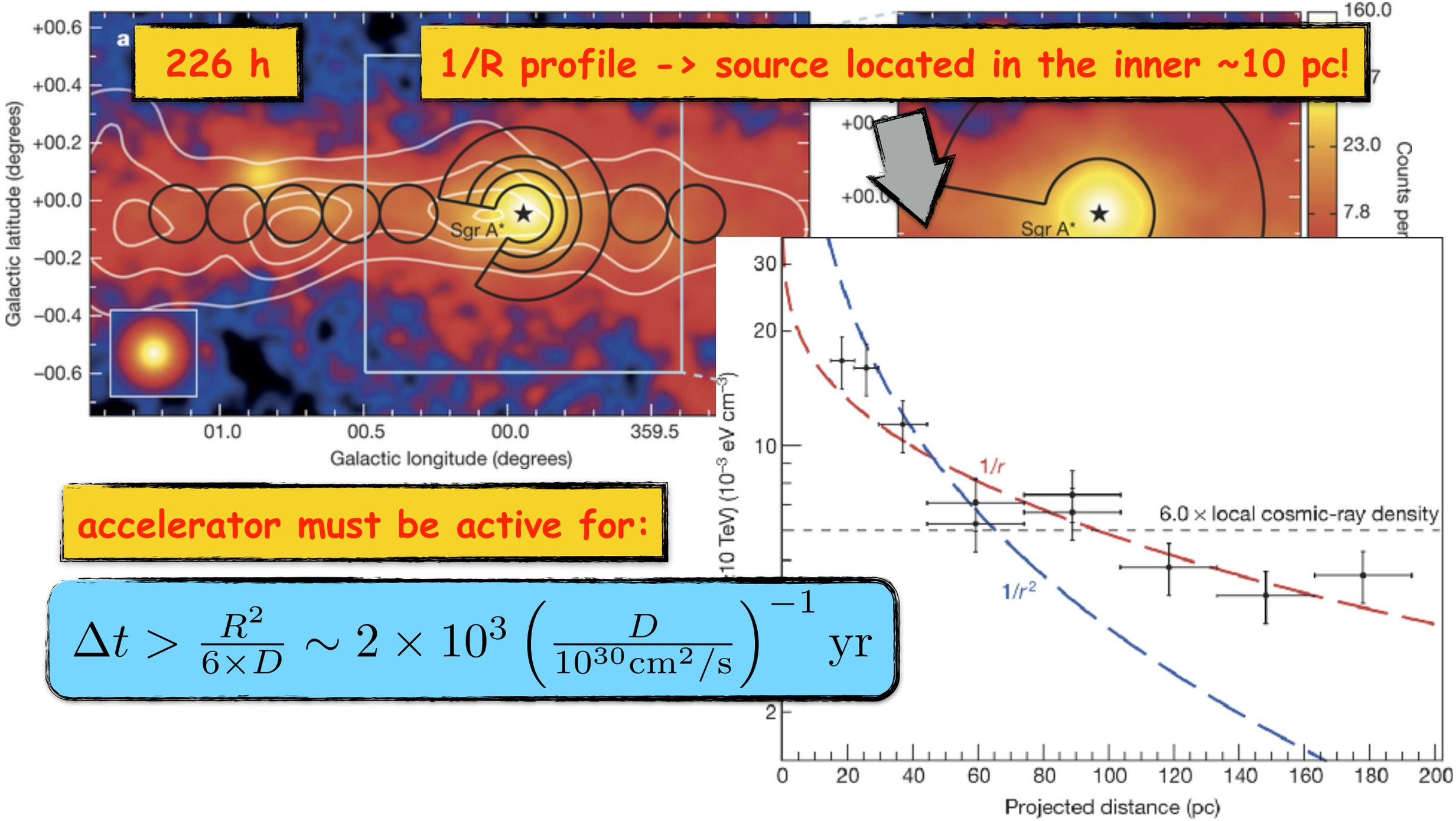

accelerator must be active for:

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

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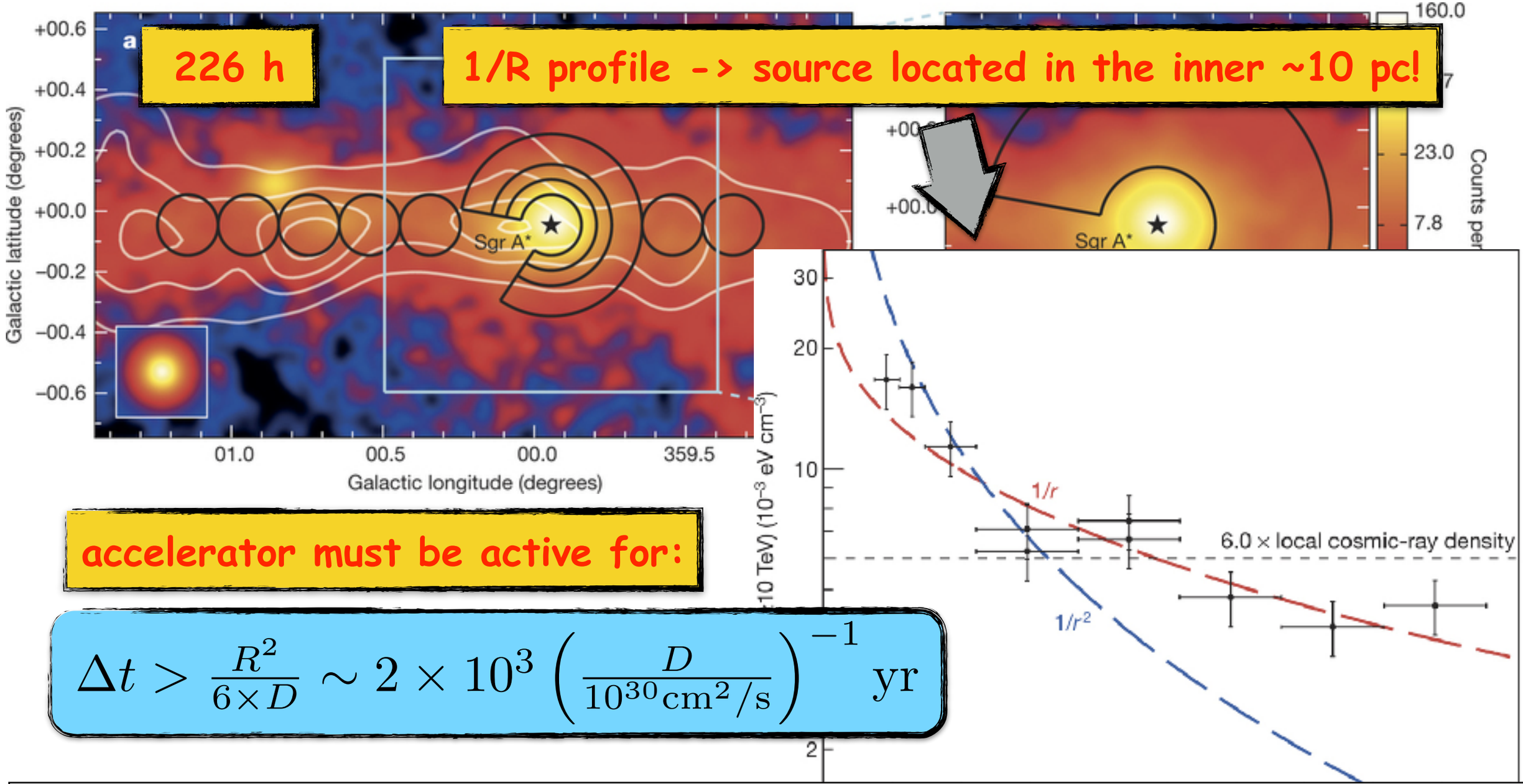

226 h

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

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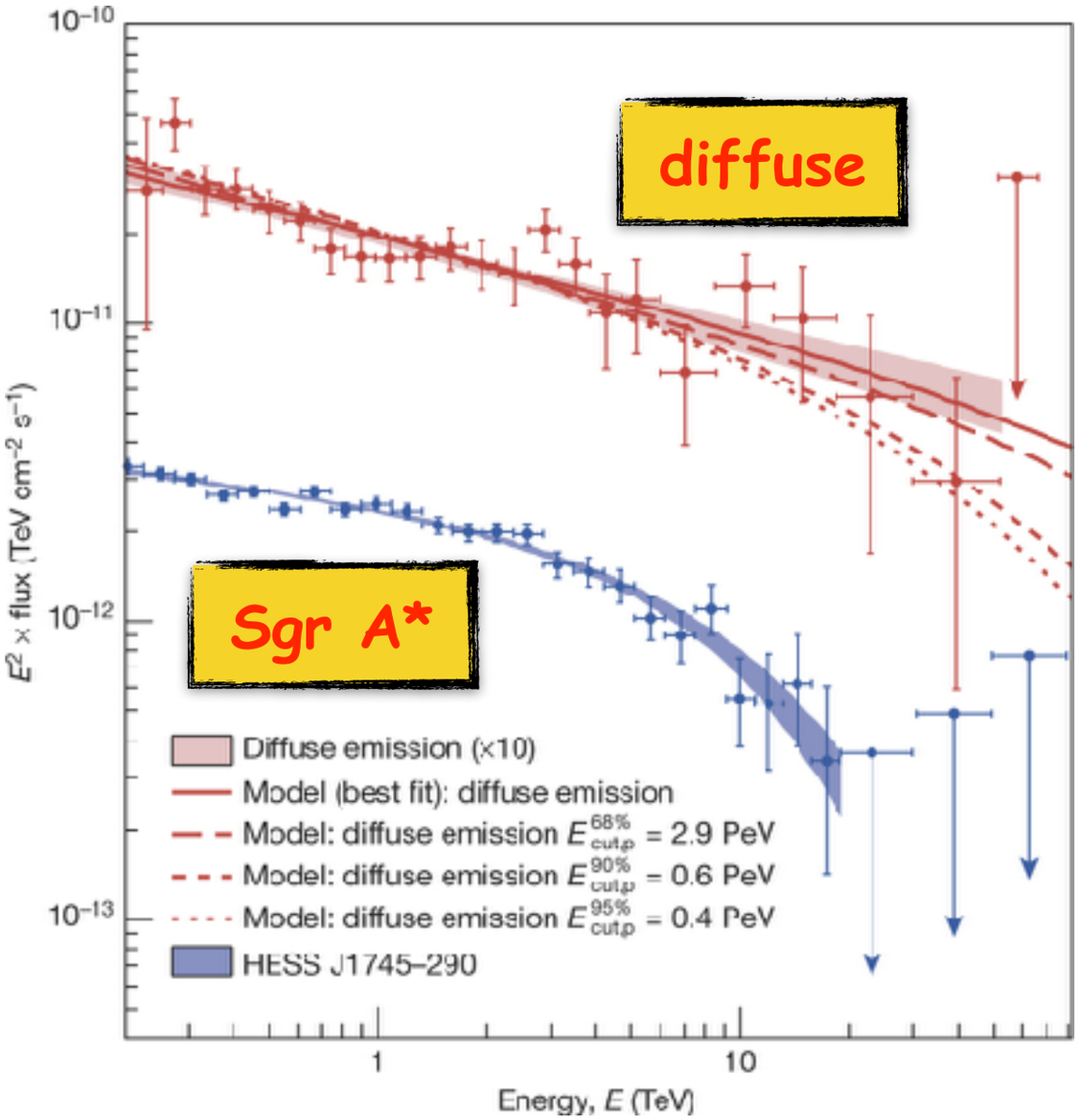
multi-source scenarios require excessive fine-tuning/unrealistic number of sources

Supermassive black hole as a PeVatron

is Sgr A* as the source of PeV cosmic rays?



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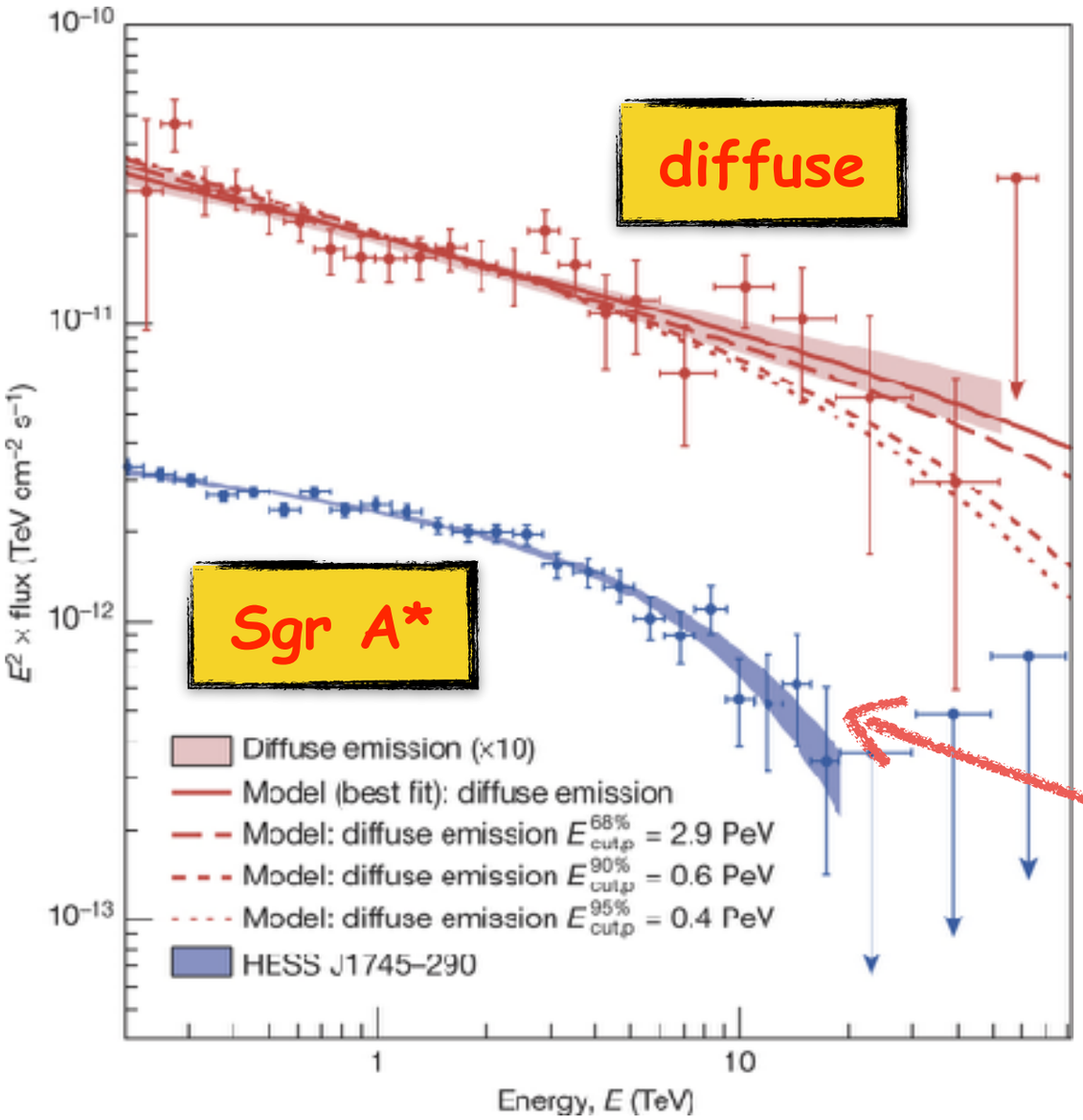

~10 TeV cutoff -> inconsistency? no...

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

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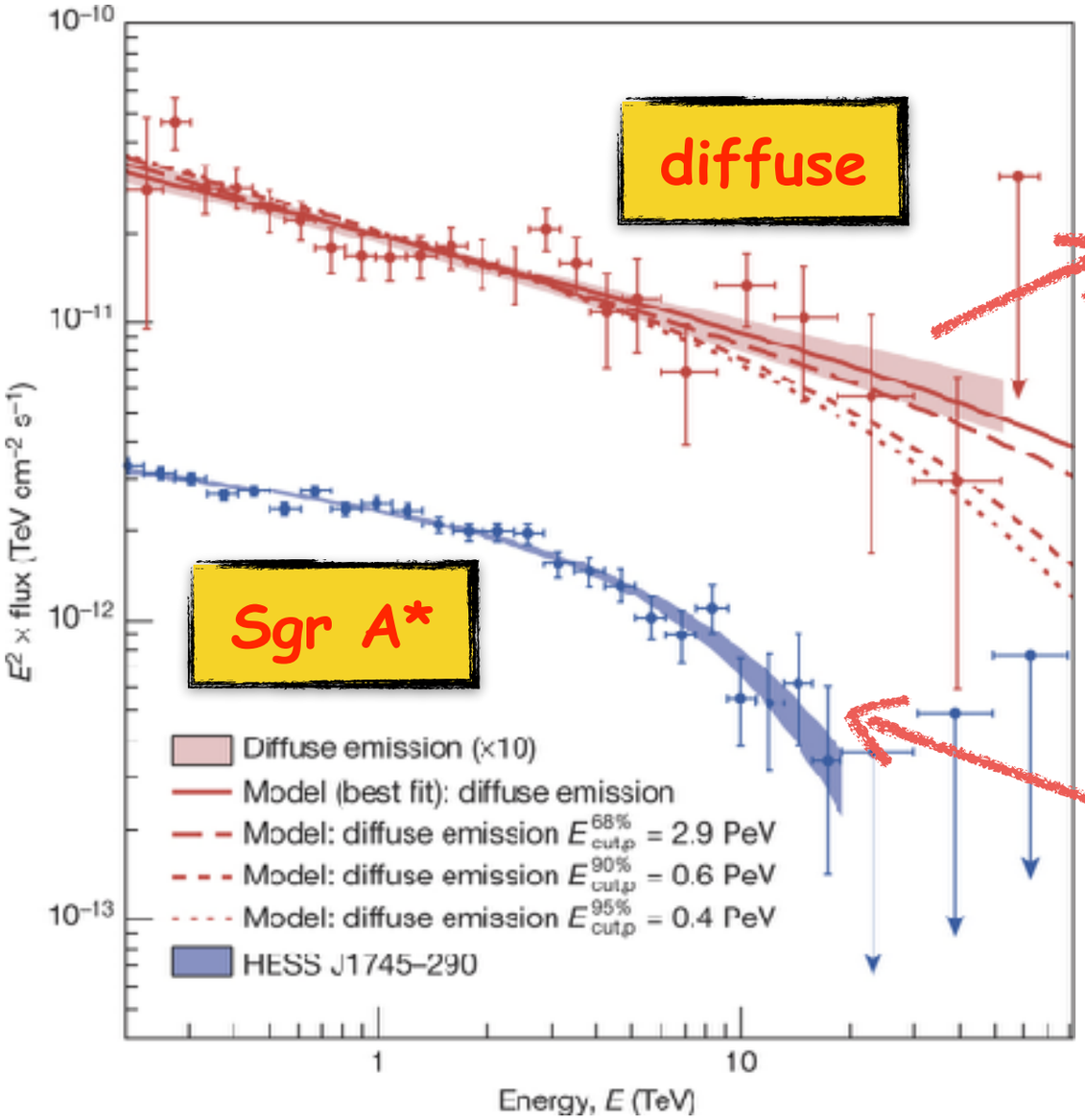

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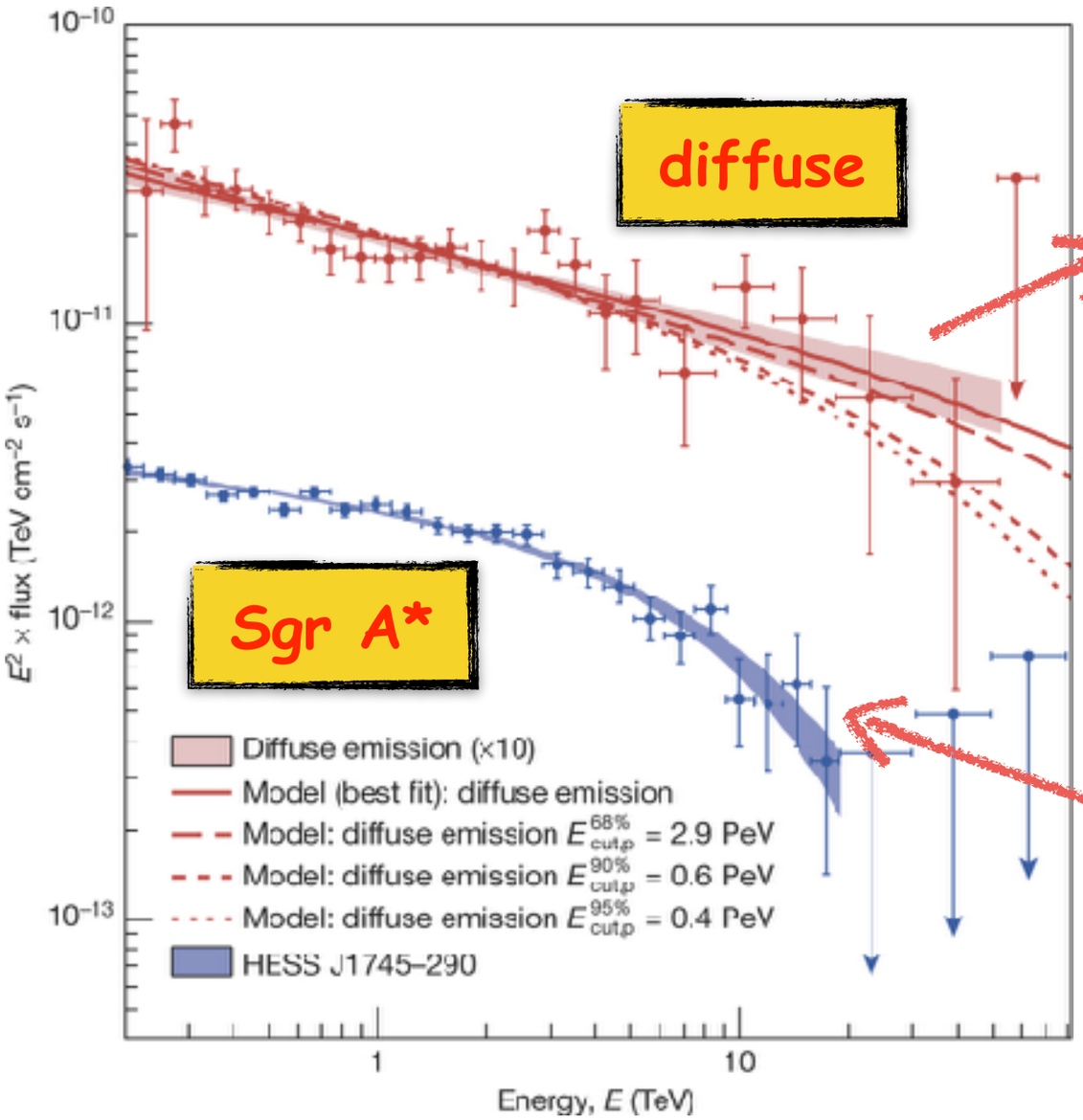

gas mass → $W_p \sim 10^{49}\mathrm{erg}$

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)

SNOBs, superbubbles, star forming regions…

Another scenario: SNOBs,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)
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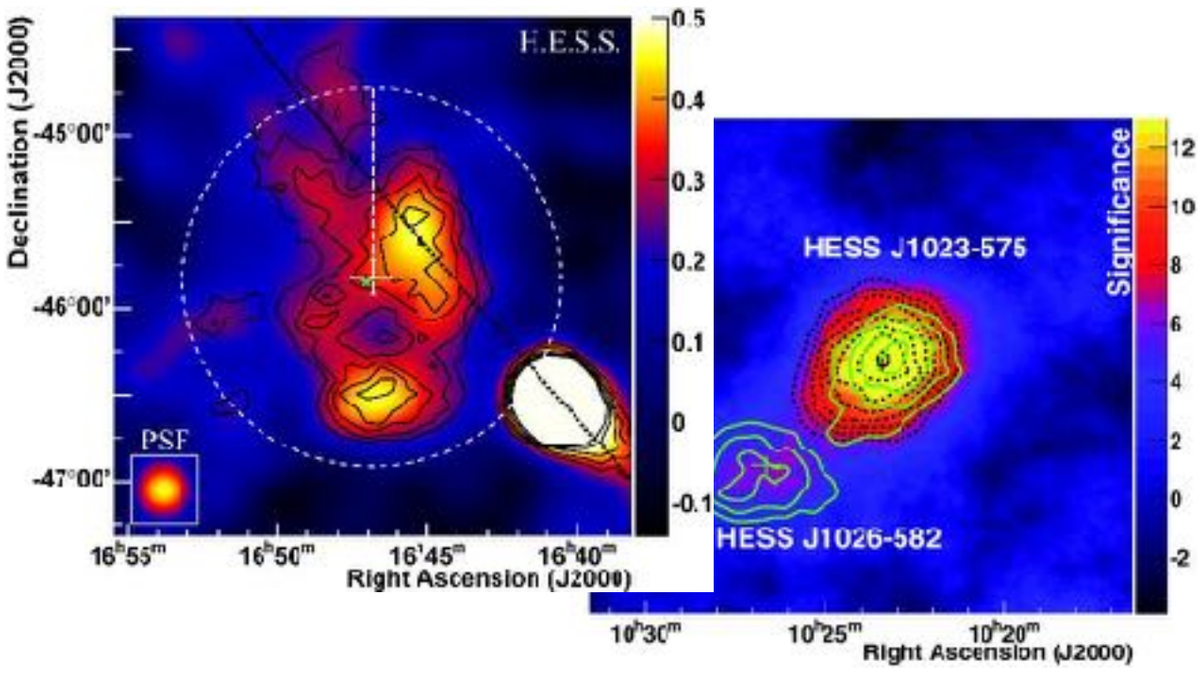
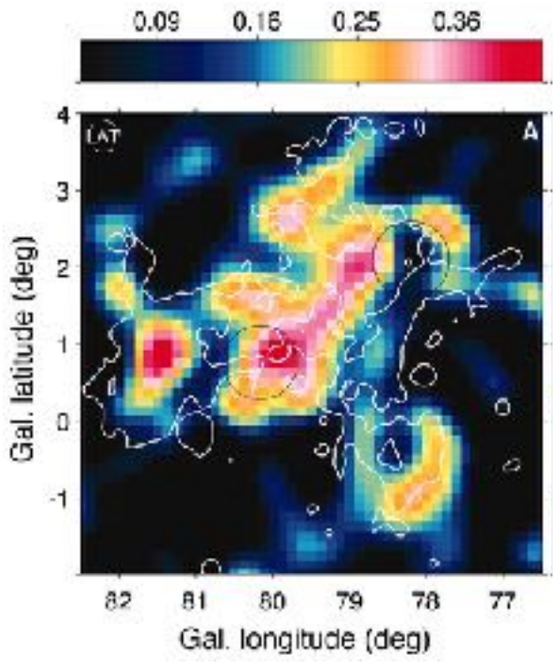
star clusters in γ-rays

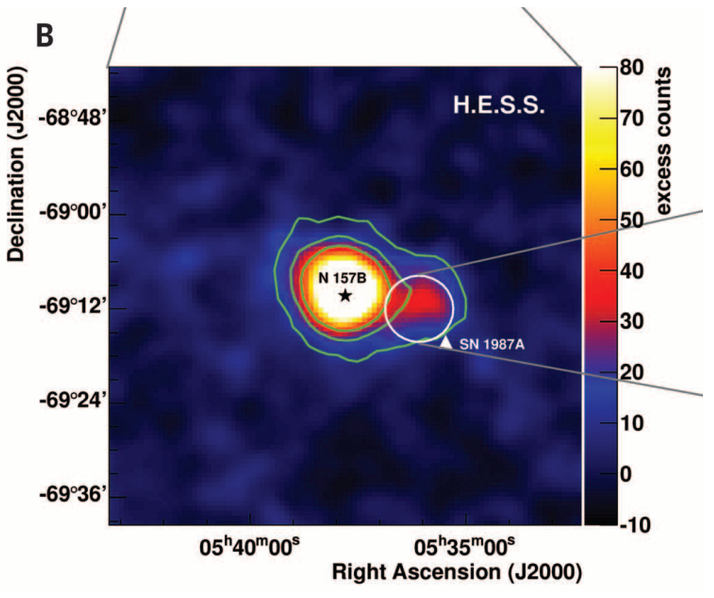


westerlund 1 and 2, HESS

superbubbles in γ-rays



Cygnus, Fermi



30 Dor C, LMC, HESS

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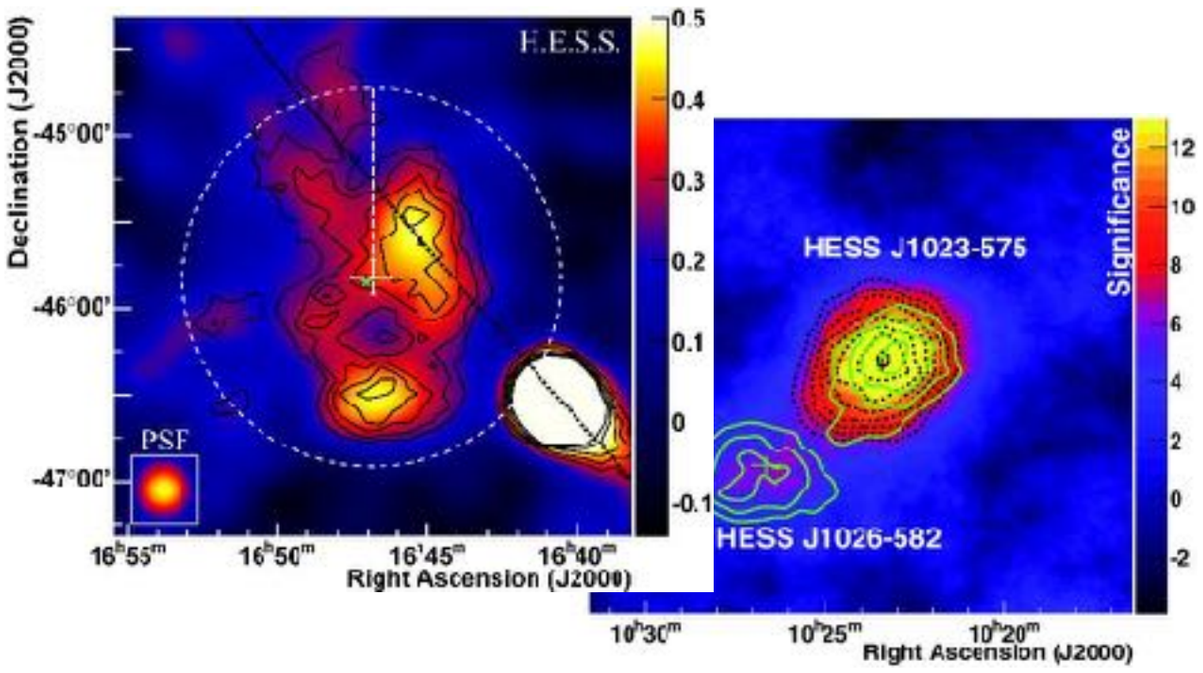

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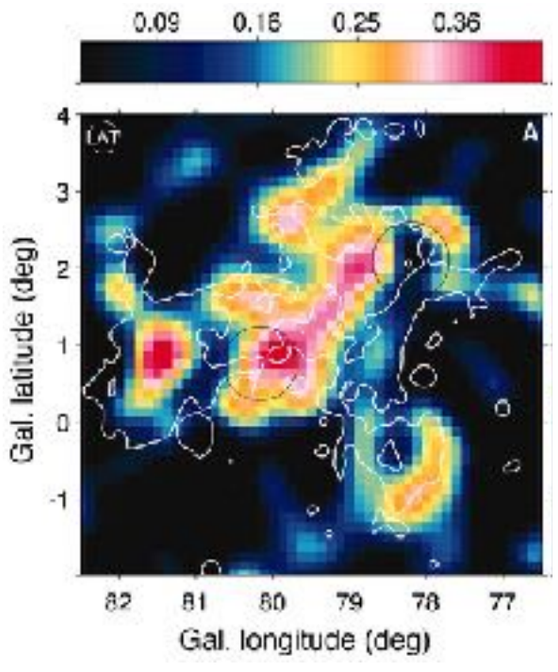

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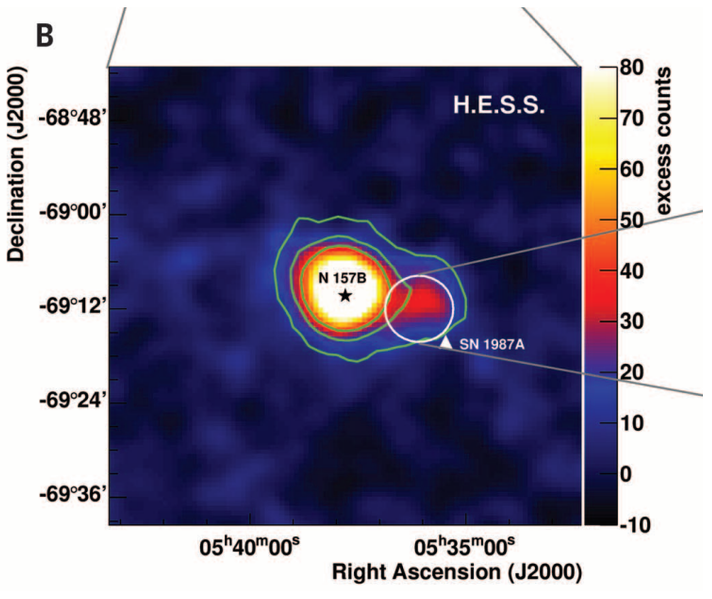


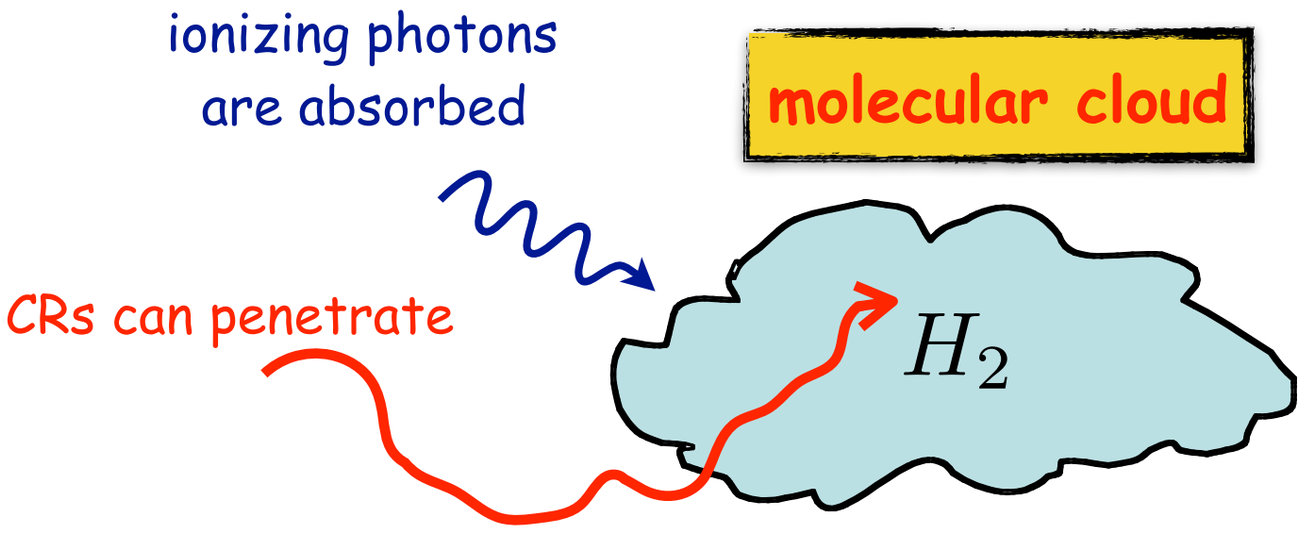
30 Dor C, LMC, HESS

- the acceleration mechanism might be completely different (Bykov&Fleishman92)
- particle spectrum not universal, large E_{max} (large size!)

Selected non-gamma-ray observations
-> ionisation rate of clouds
-> Li Be B abundances

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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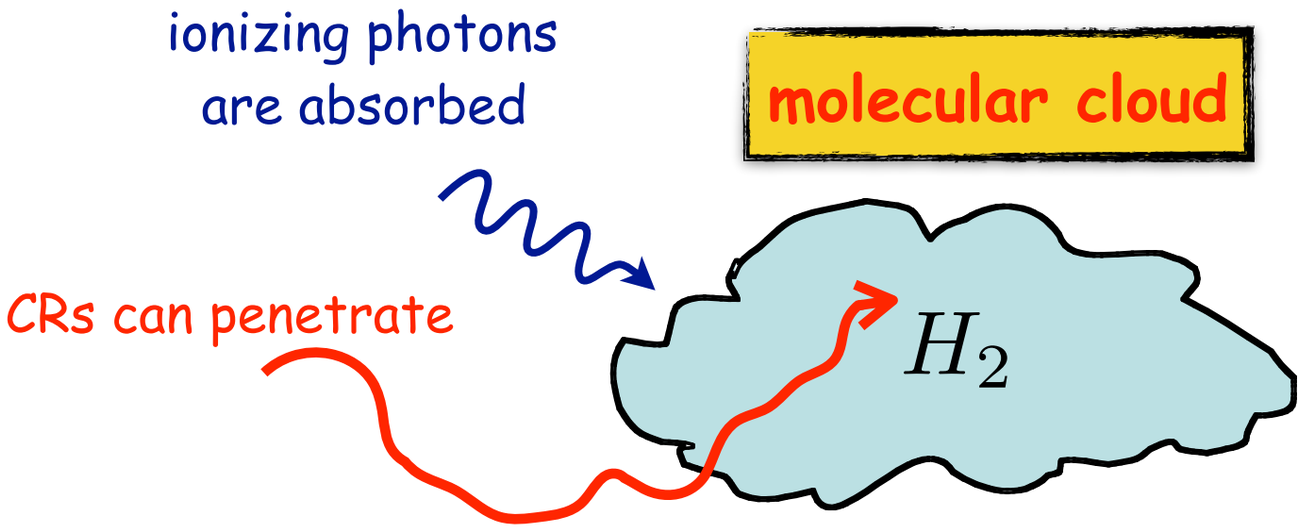

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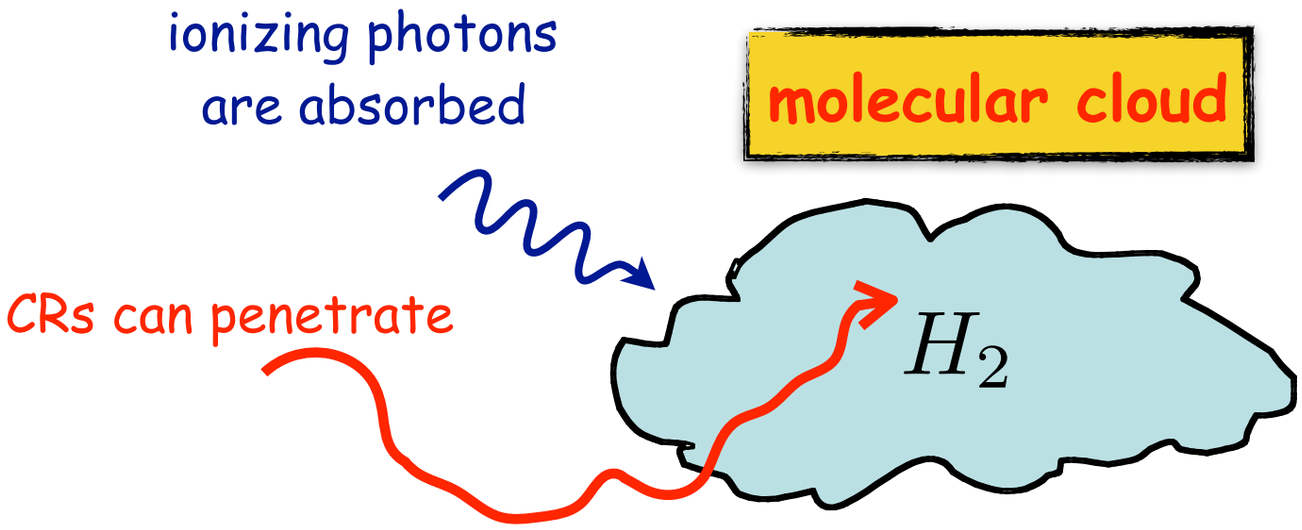

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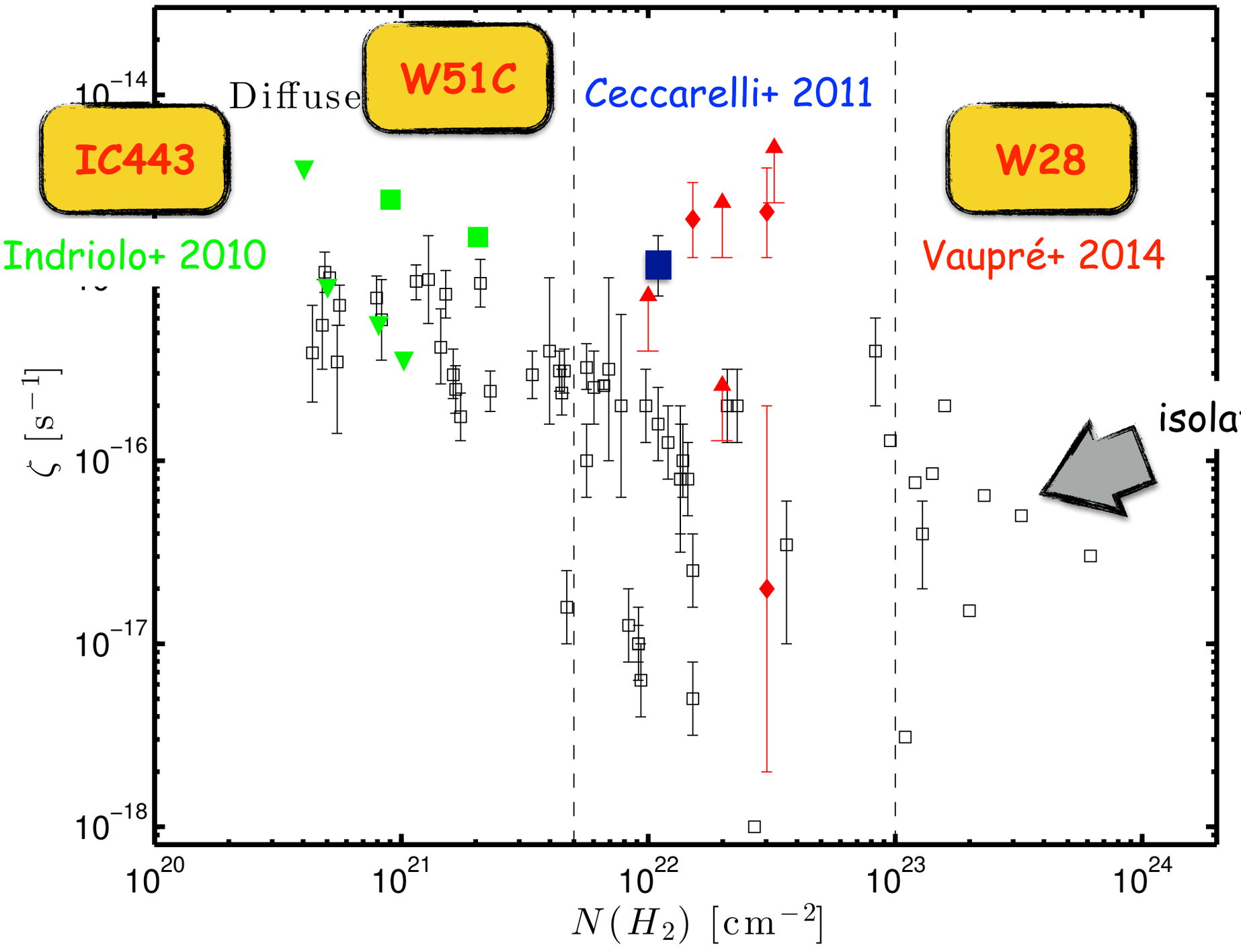
chemistry

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

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

SuperNova Remnants & MeV cosmic rays

(for a review see SG & Montmerle 2015)



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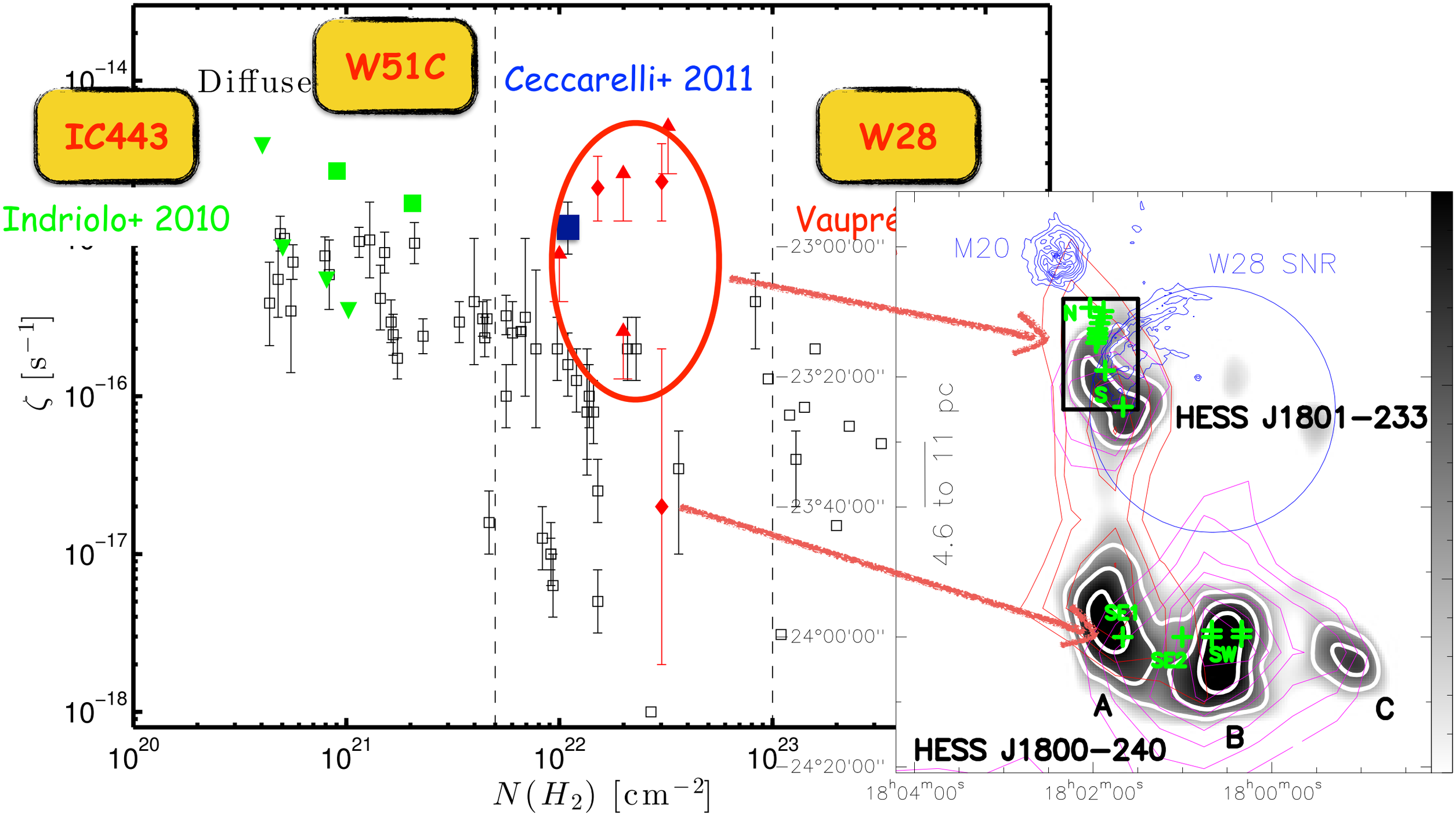

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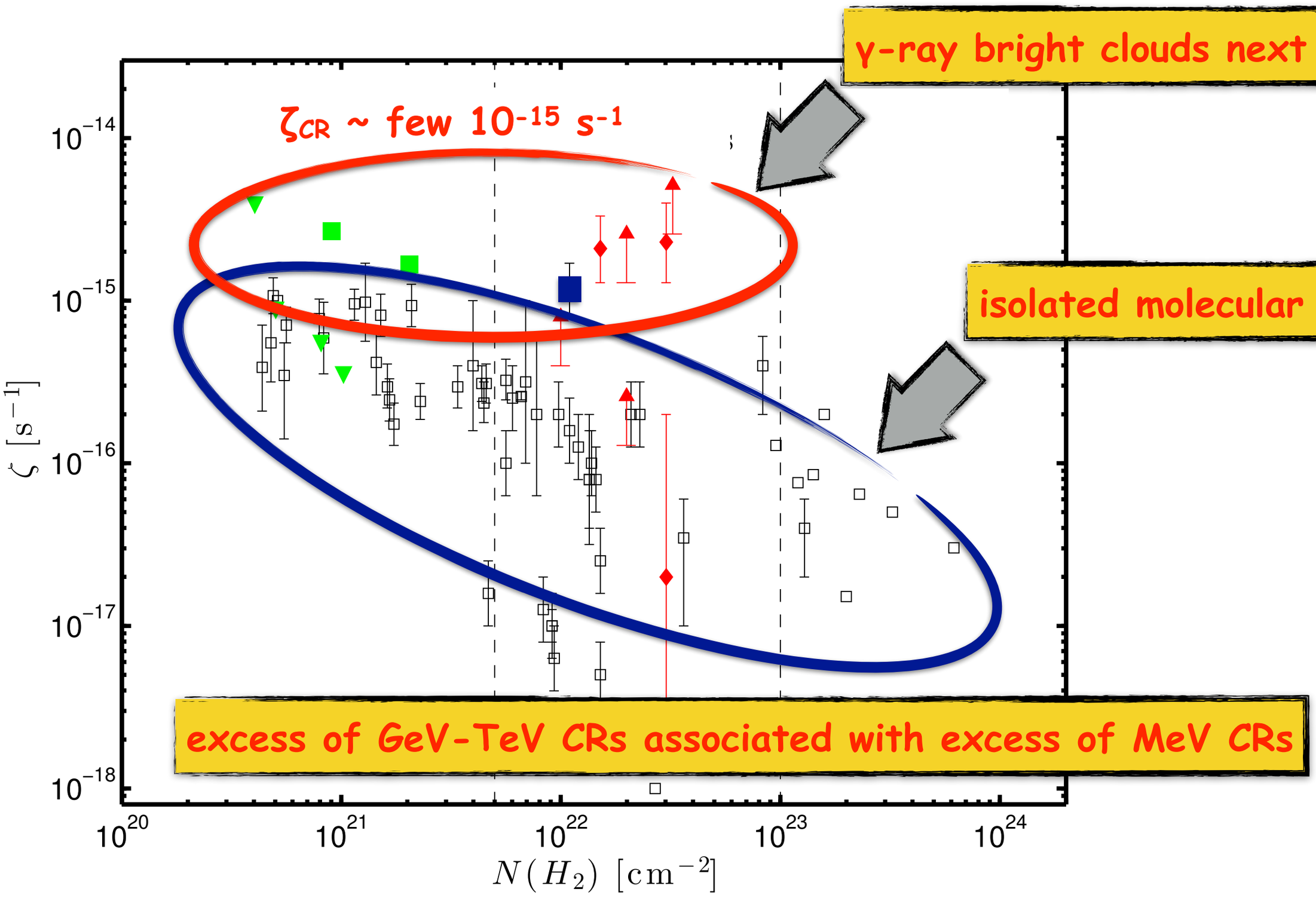
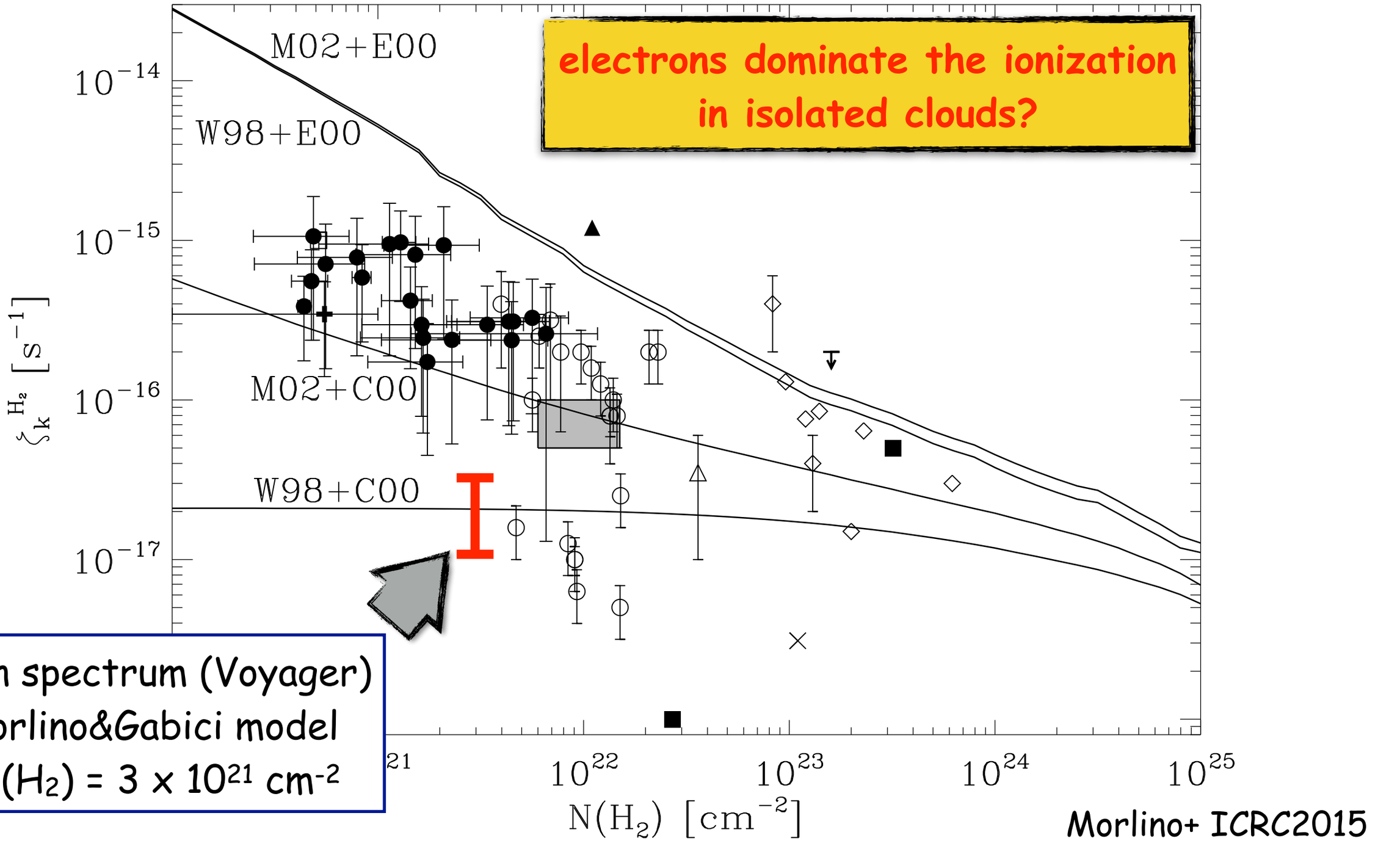


Isolated clouds

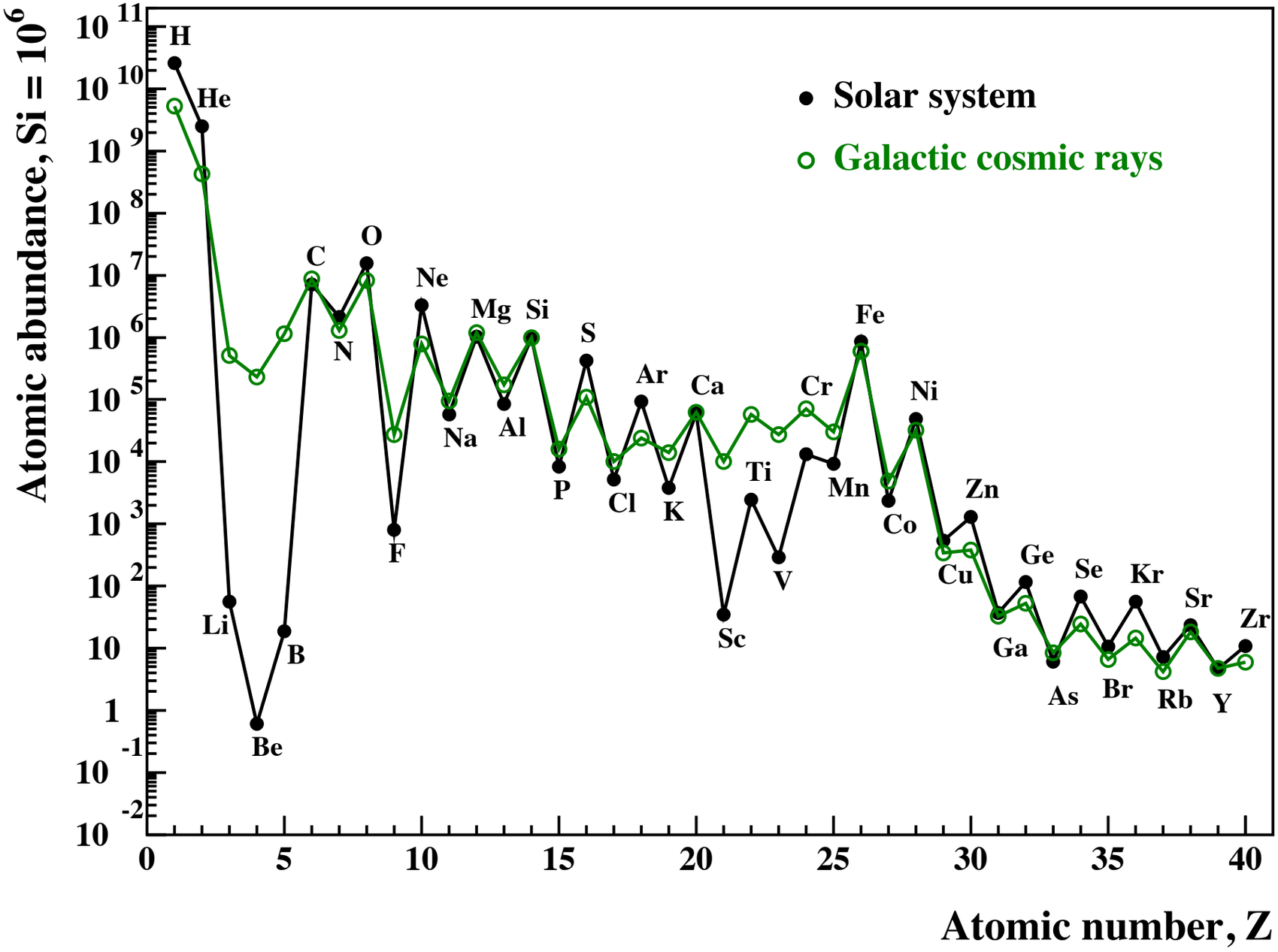


electrons dominate the ionization in isolated clouds?

proton spectrum (Voyager)
+ Morlino&Gabici model
@ $N(H_2) = 3 \times 10^{21}$ cm^{-2}

Morlino+ ICRC2015

Spallogenic nucleosynthesis of Li-Be-B



e.g. Parizot 2000, for a review see Tatischeff&Gabici 2018

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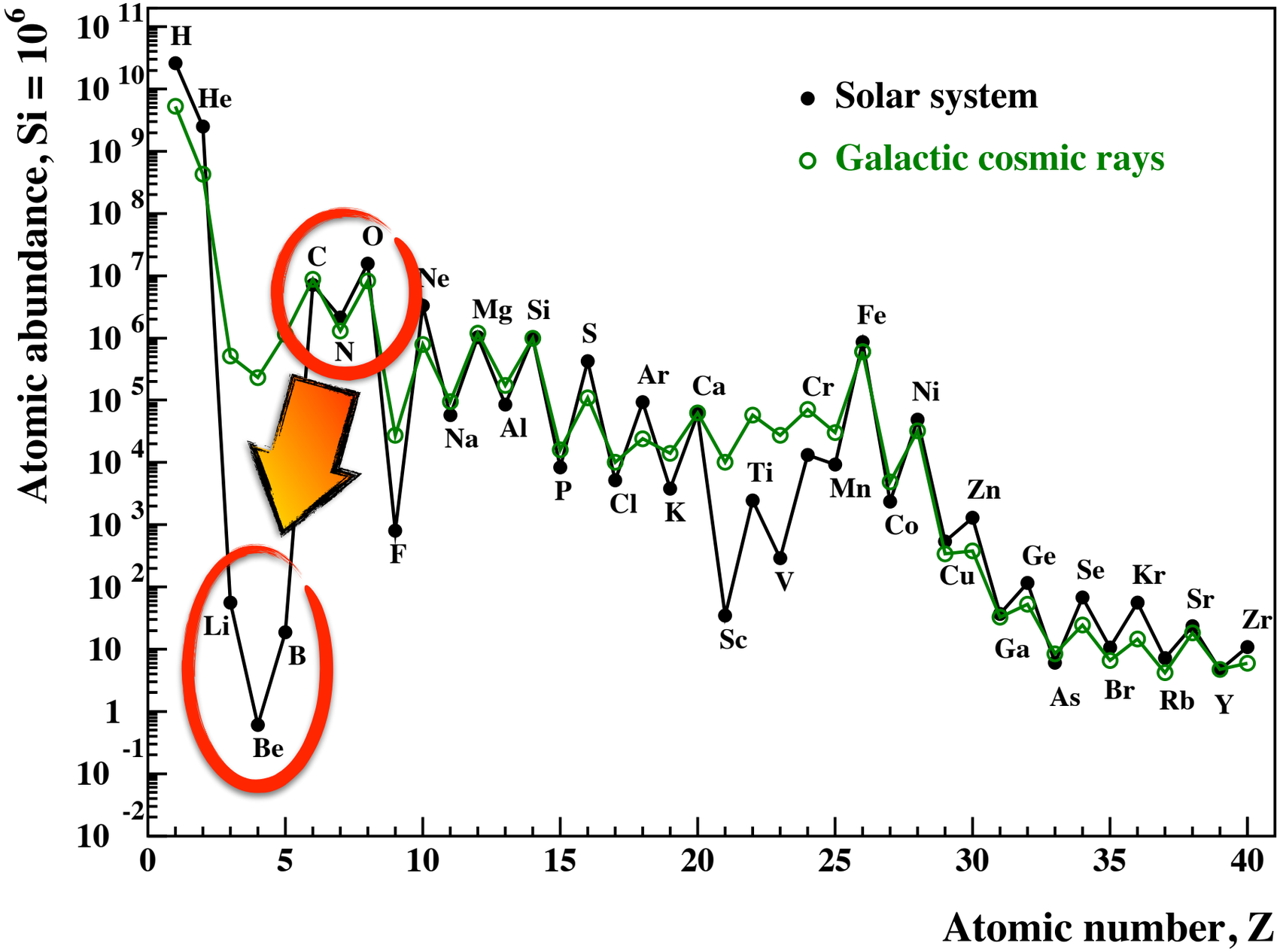

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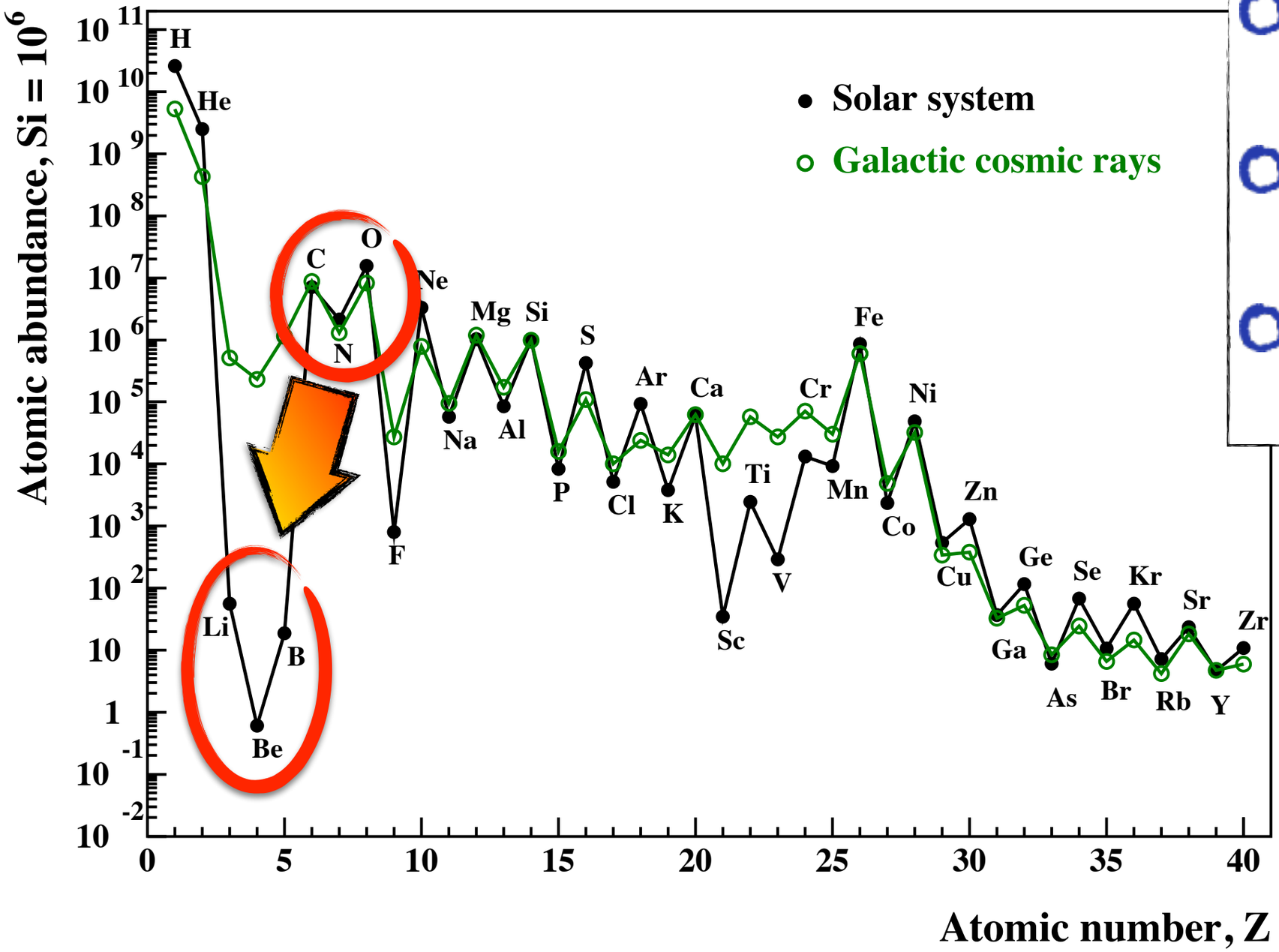
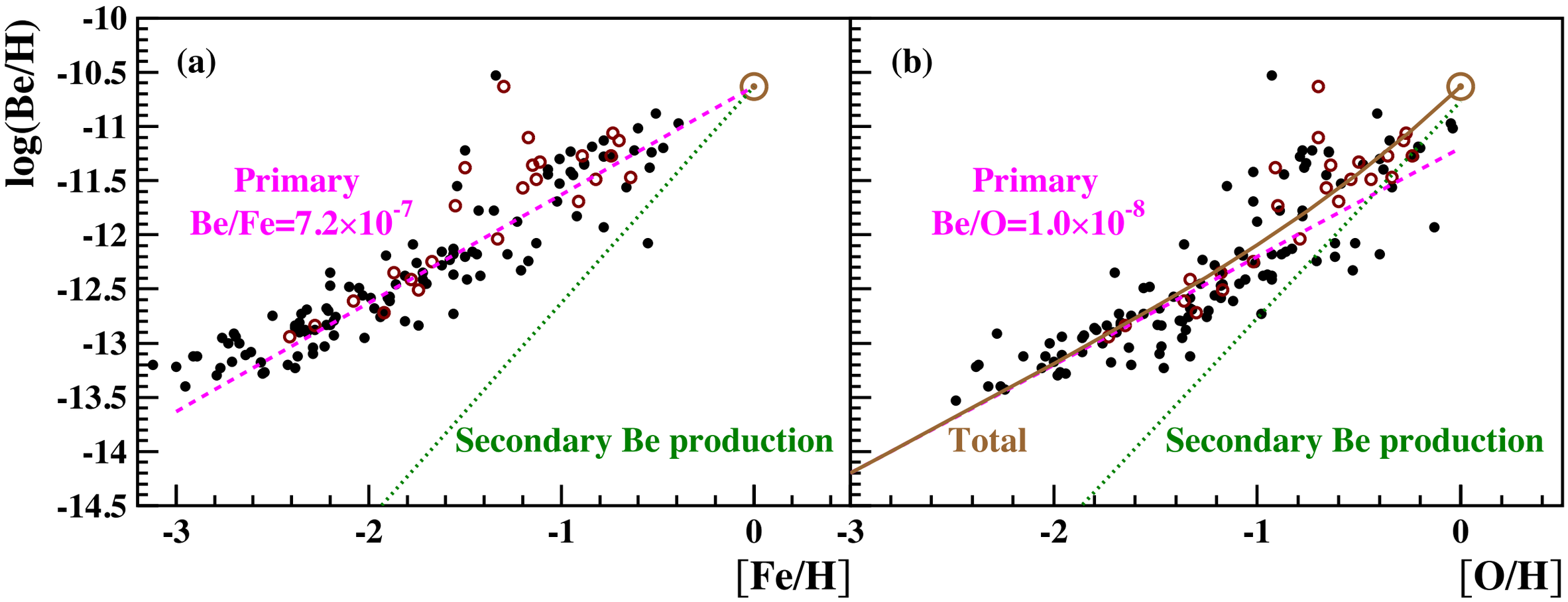


- metallicity X_{ISM} of the ISM increases with time
- CRs are accelerated from the ISM
- LiBeB abundance should scale as X_{ISM}^2

e.g. Parizot 2000, for a review see Tatischeff&Gabici 2018

Spallogenic nucleosynthesis of Li-Be-B



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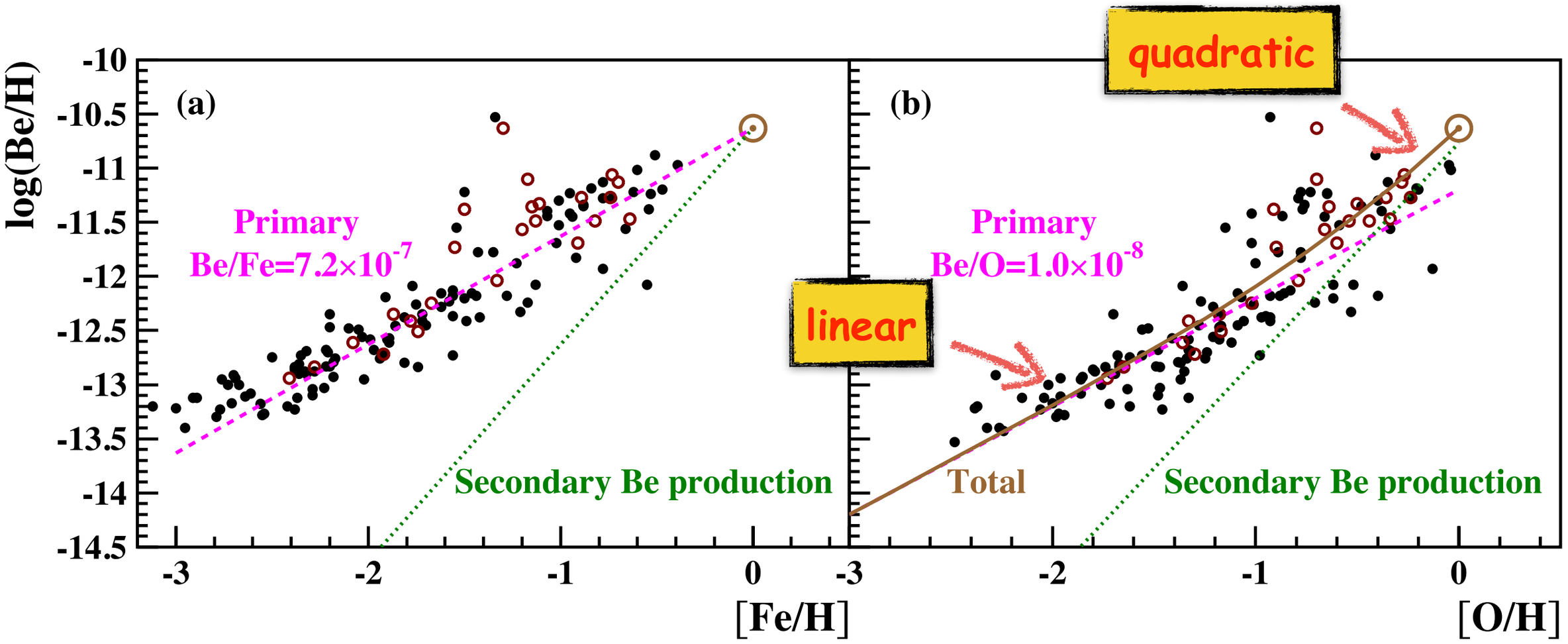

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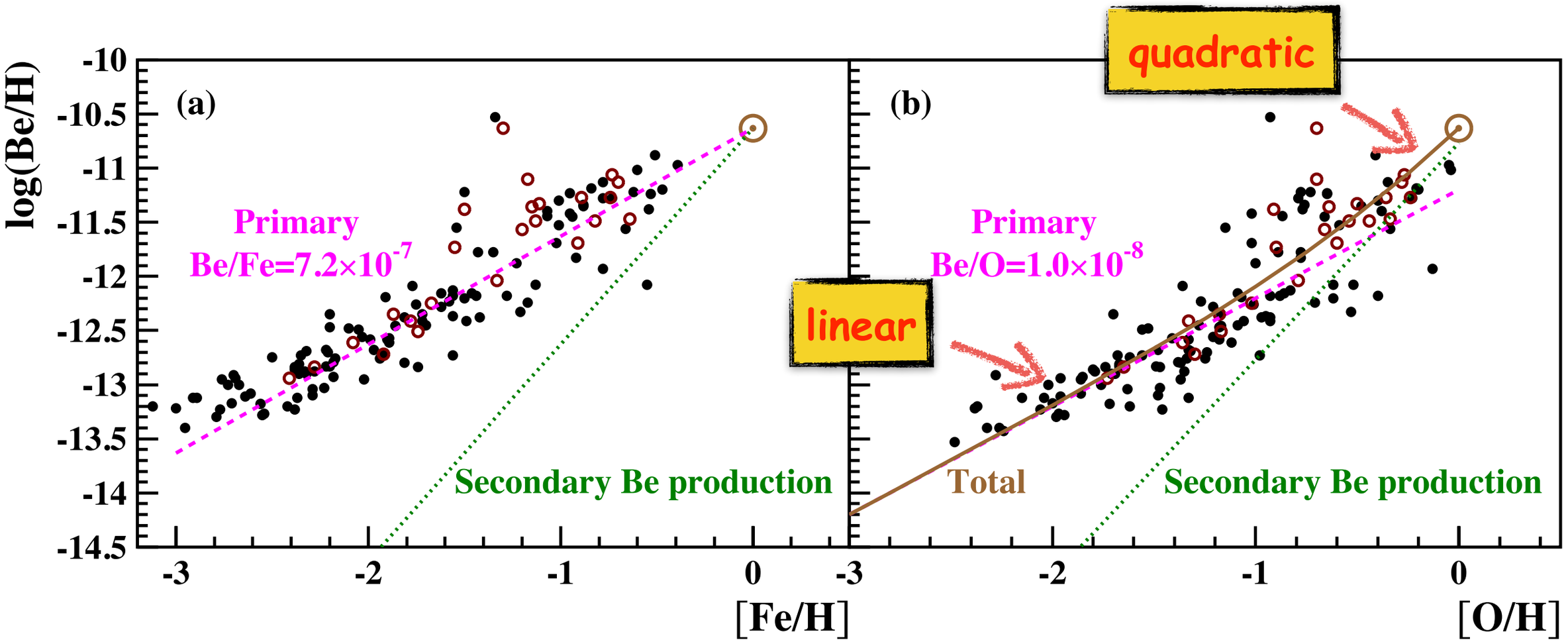


superbubbles -> CRs are accelerated from an enriched ISM
(X_{CR} closer to constant rather than X_{ISM})

e.g. Parizot 2000, for a review see Tatischeff&Gabici 2018

Conclusions

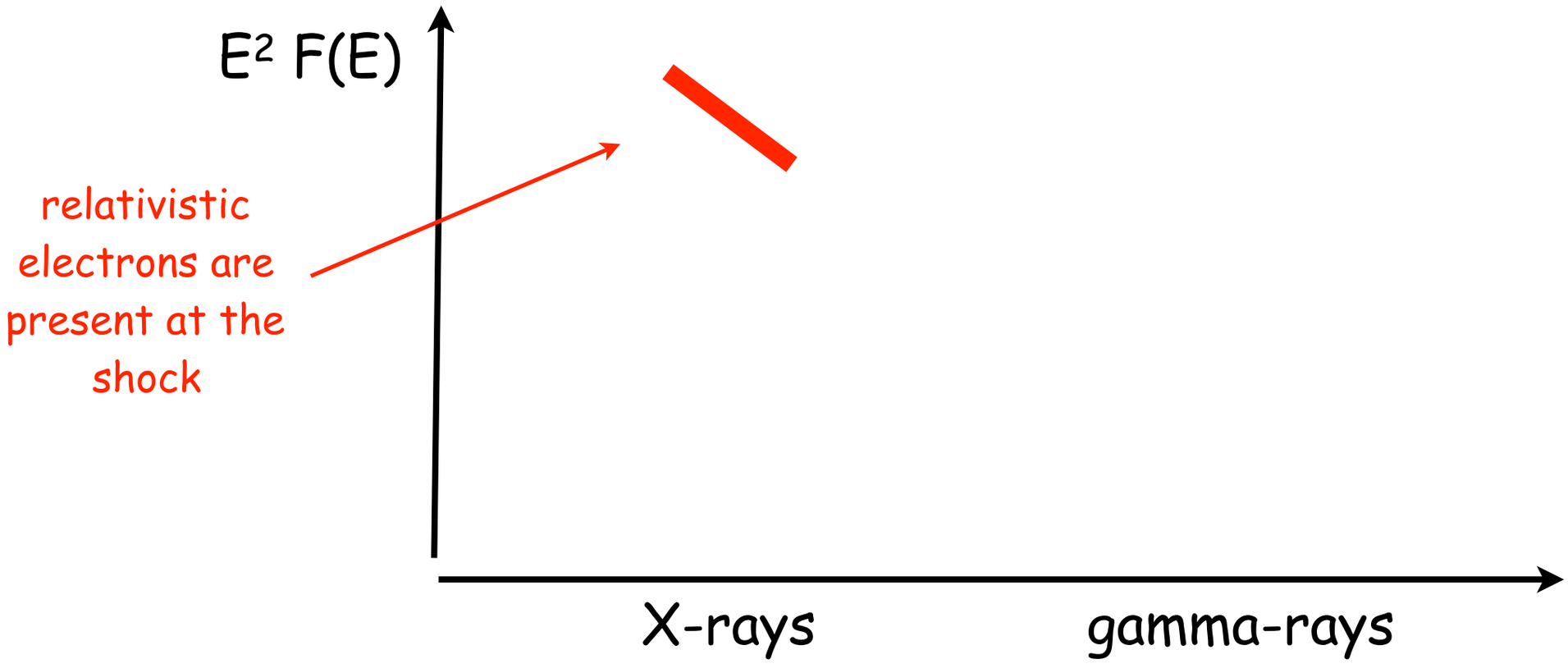
- the SNR paradigm for the origin of cosmic rays is not in contradiction with GeV and TeV gamma-ray observations, but:
  - where are SNR PeVatrons?
  - isolated SNRs or SNRs in SNOBs, super bubbles, stellar clusters?
    - is the acceleration mechanism "pure" diffusive shock acceleration?
- evidence for the acceleration of PeV particles at the Galactic Centre
  - competing sources?
- multiwavelength/multimessenger…
- look at low energies, also!

Backup slides

Gamma-ray emission from SNRs: hadronic or leptonic?

Hadronic versus leptonic emission: the role of the magnetic field

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



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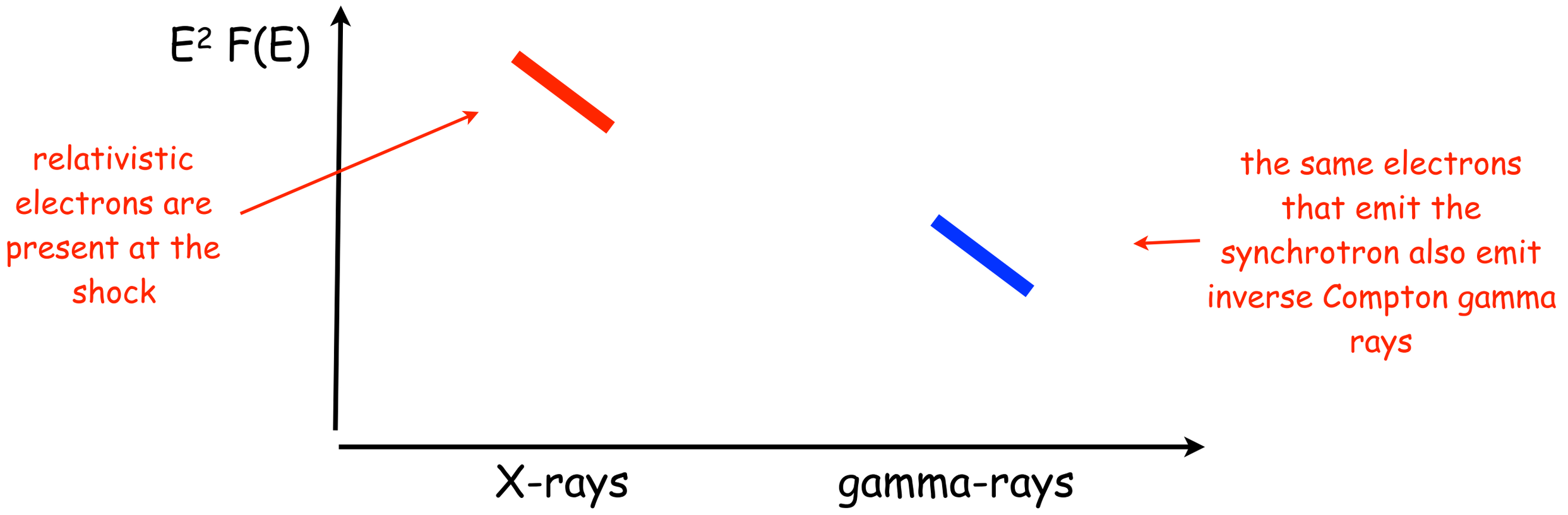

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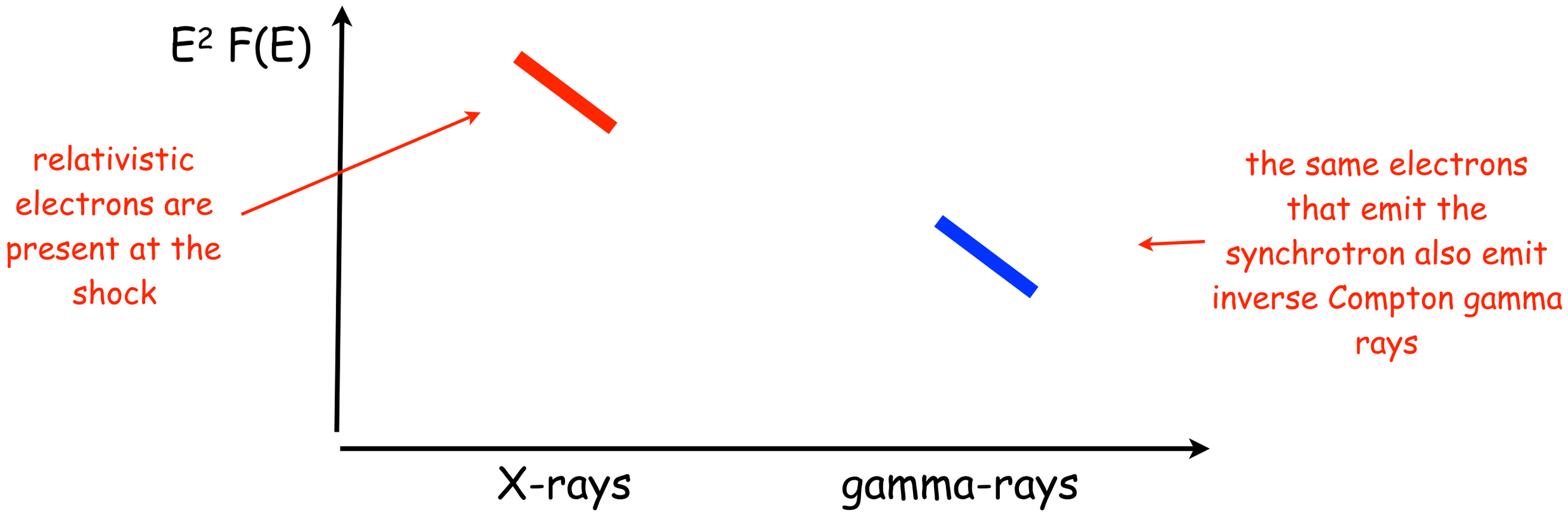

synchrotron -> $F_s \propto n_e B^{\beta}$ this product is fixed by X-ray obs.

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

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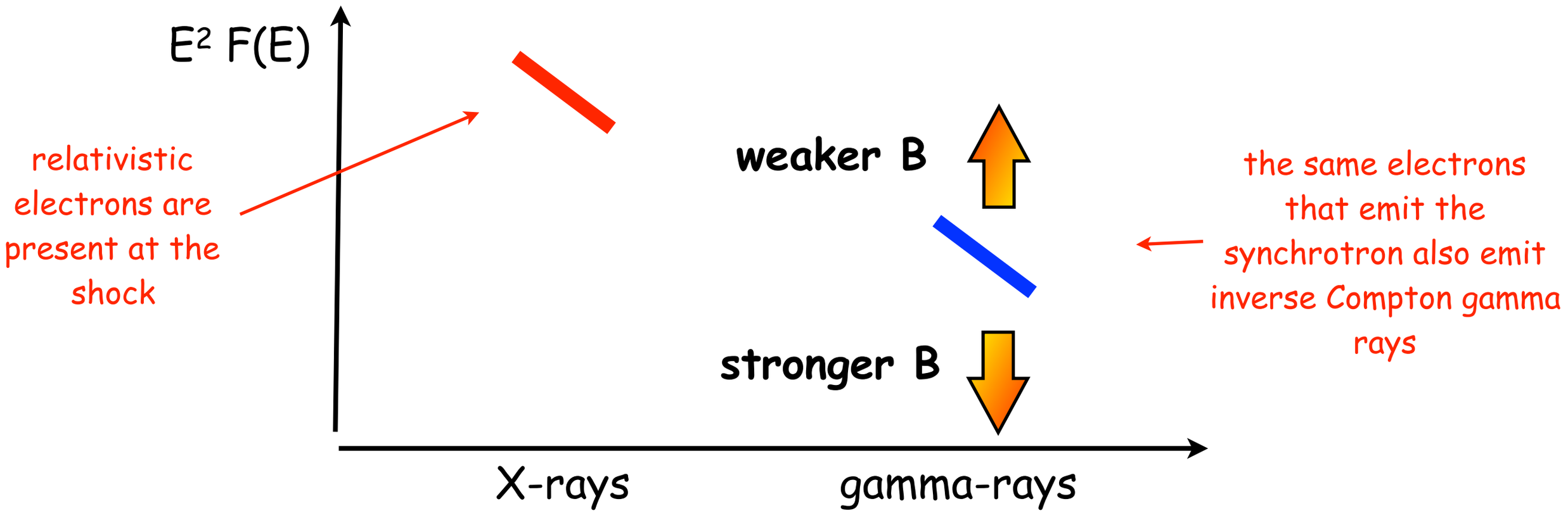

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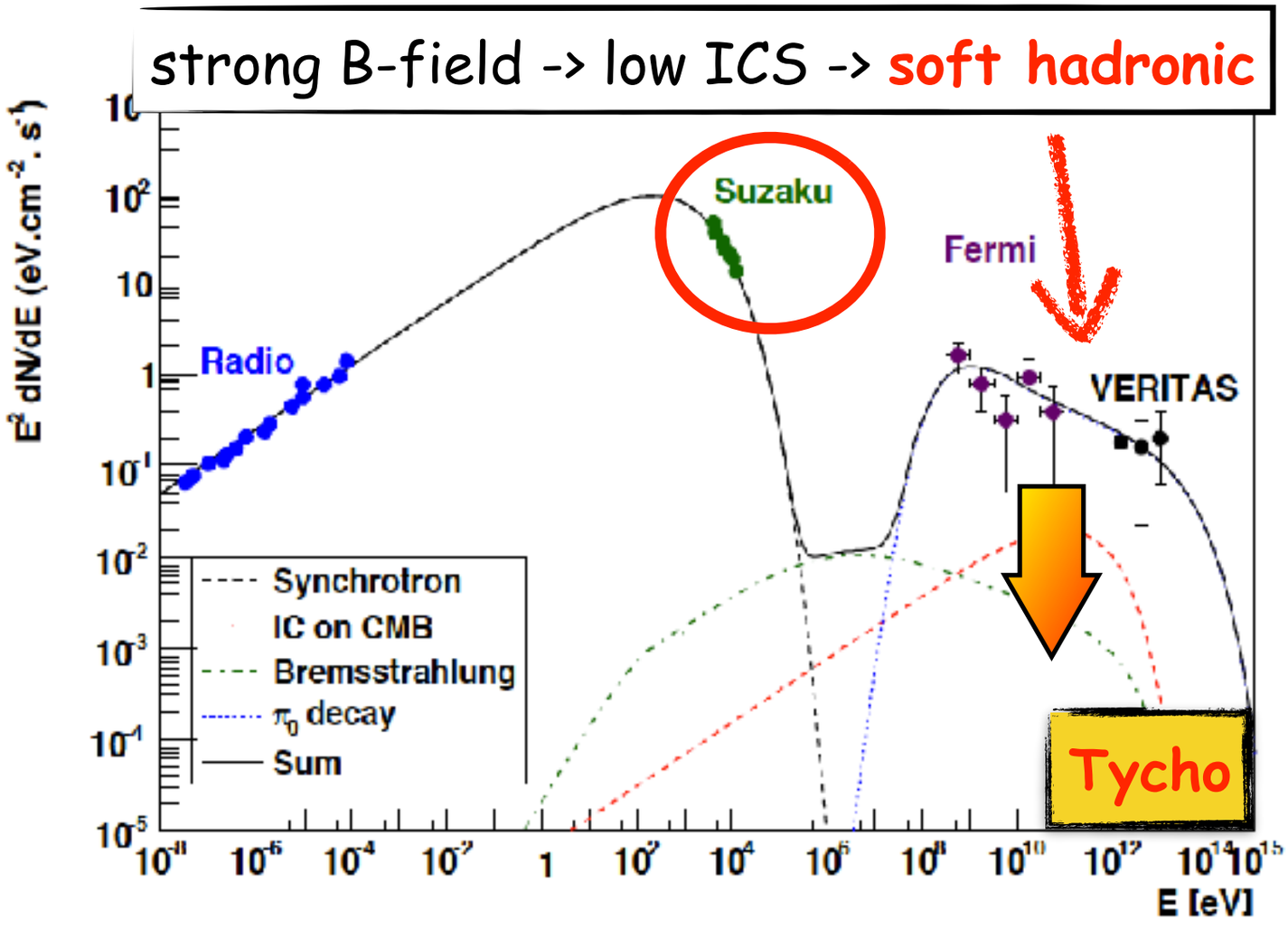
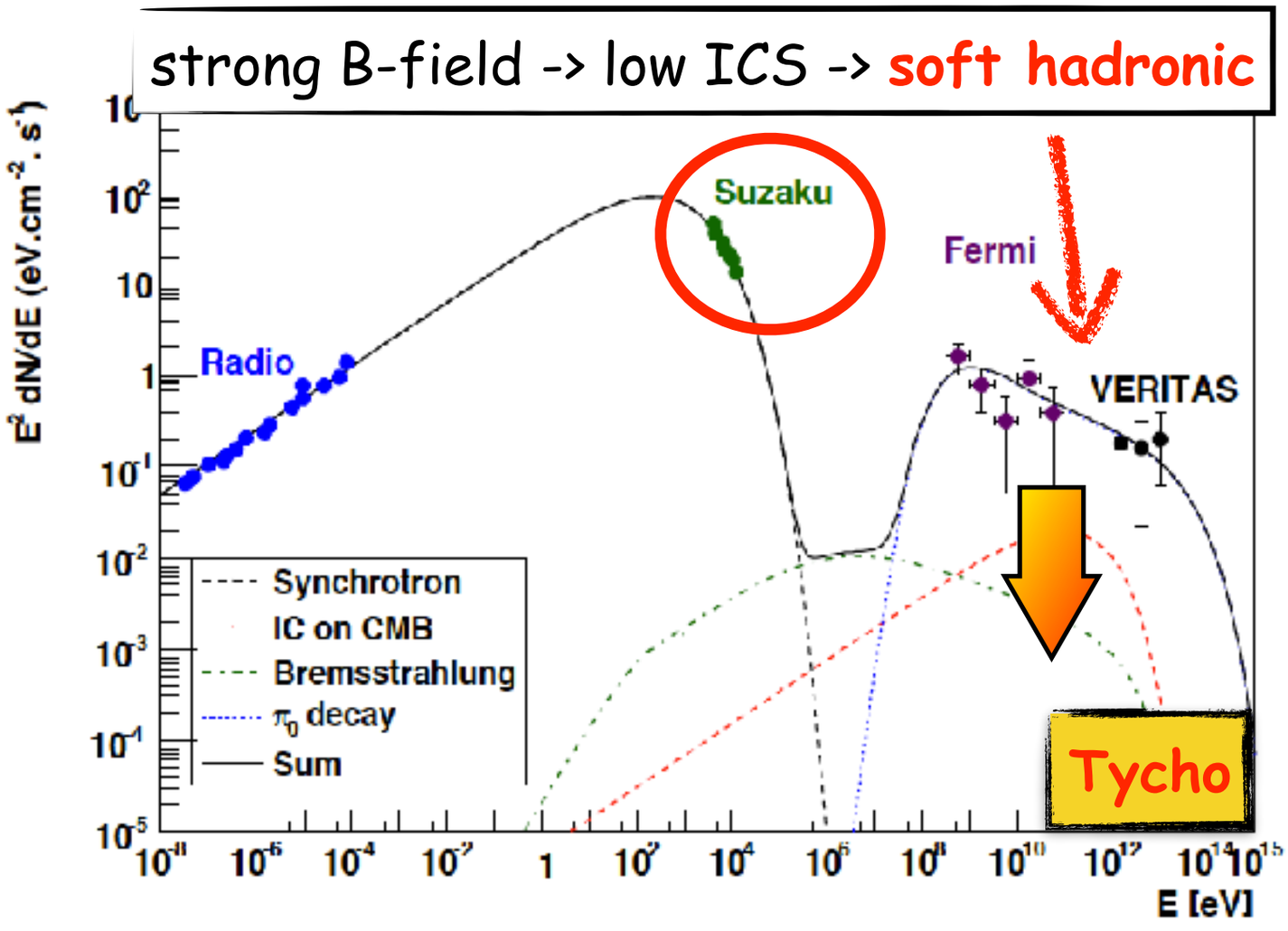
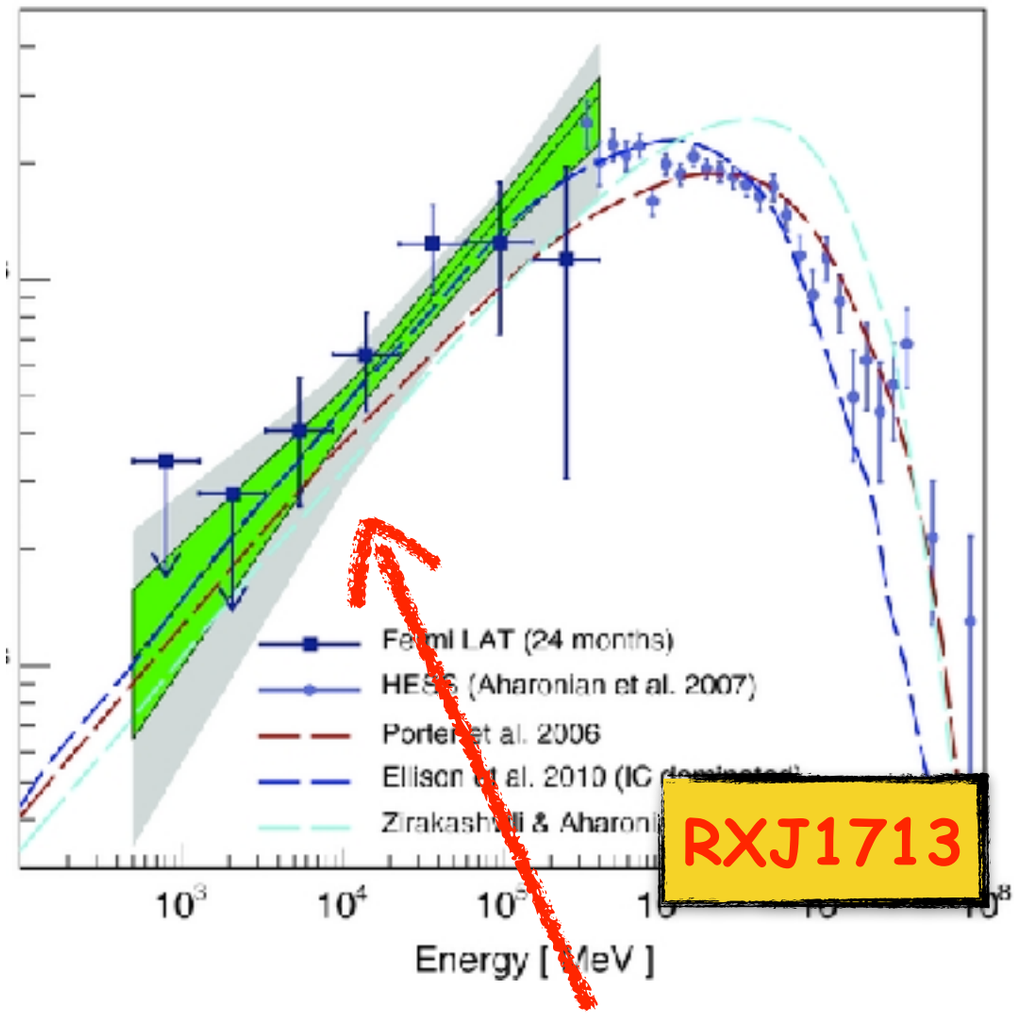


Hadronic or leptonic?

strong B-field -> low ICS -> **soft hadronic**





weak B-field -> uncooled e^- spectrum -> **hard leptonic***

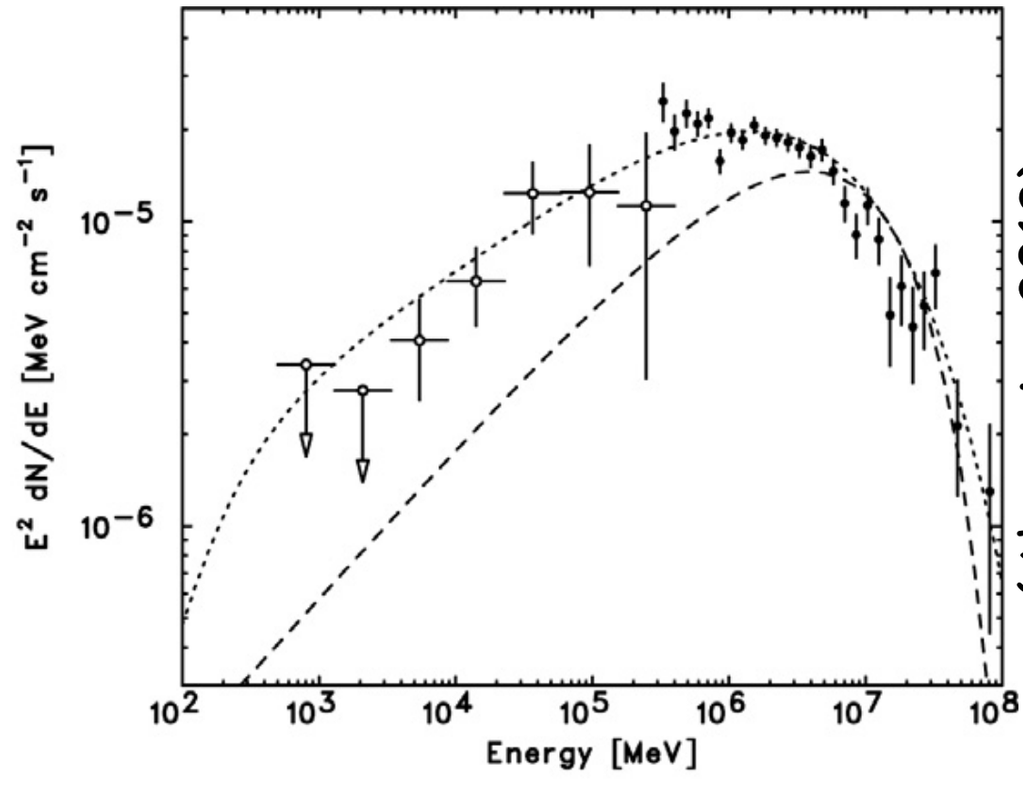
*** very low level of thermal X-rays from RXJ1713 -> leptonic? (Ellison+ 2010)**

RXJ1713: difficulties of one-zone leptonic models

two features in the electron spectrum:

acceleration time = synchrotron loss time -> acceleration cutoff at E_{max}

SNR age = synchrotron loss time -> cooling break at E_{cool}



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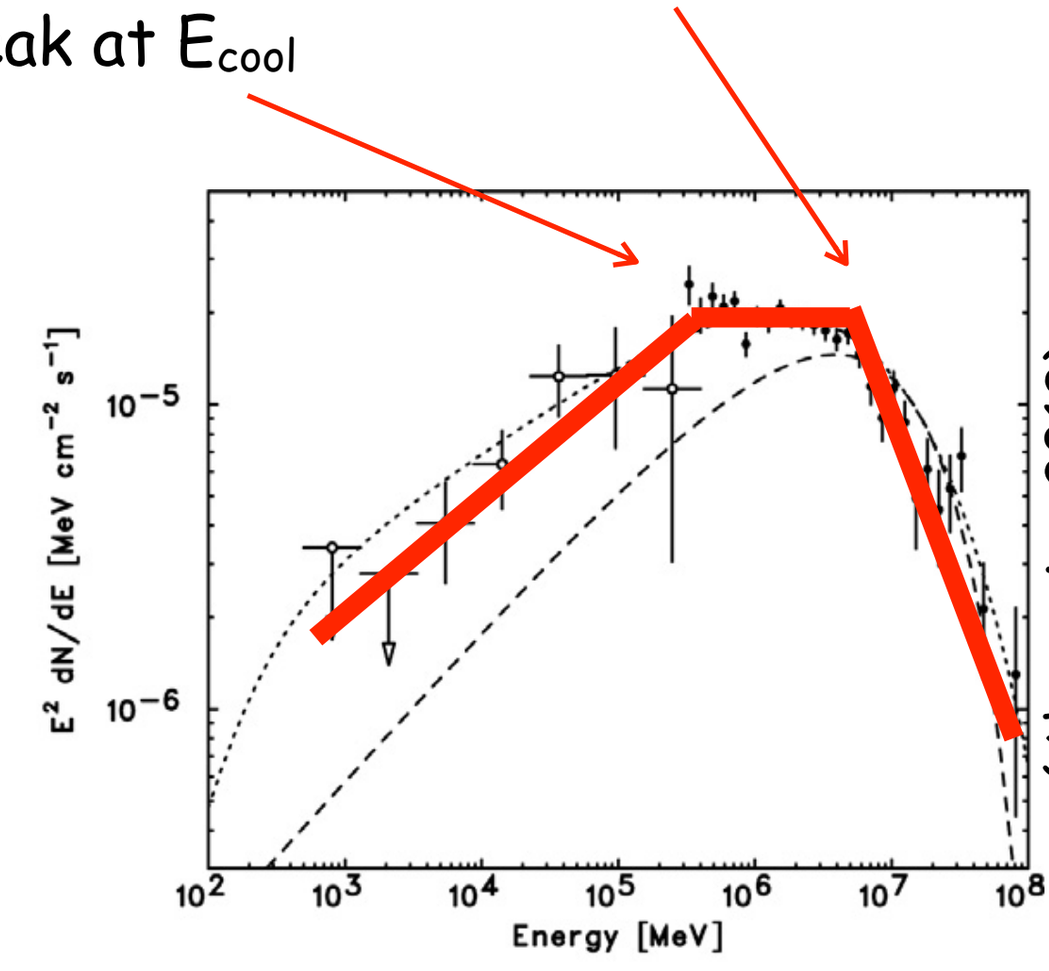

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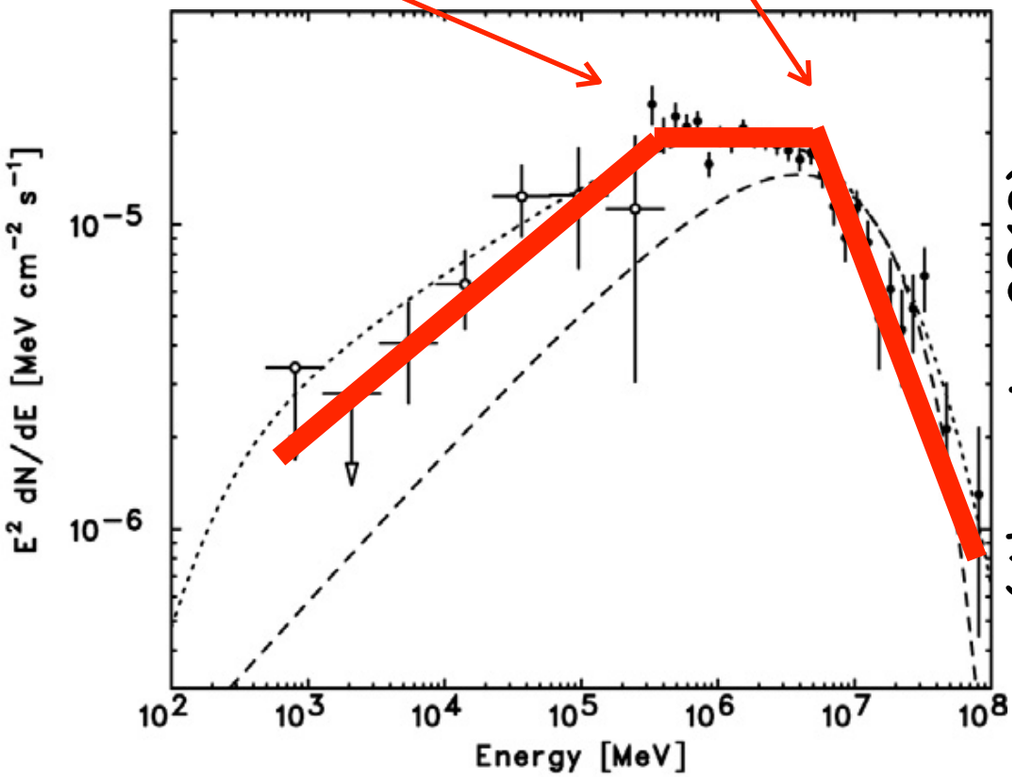

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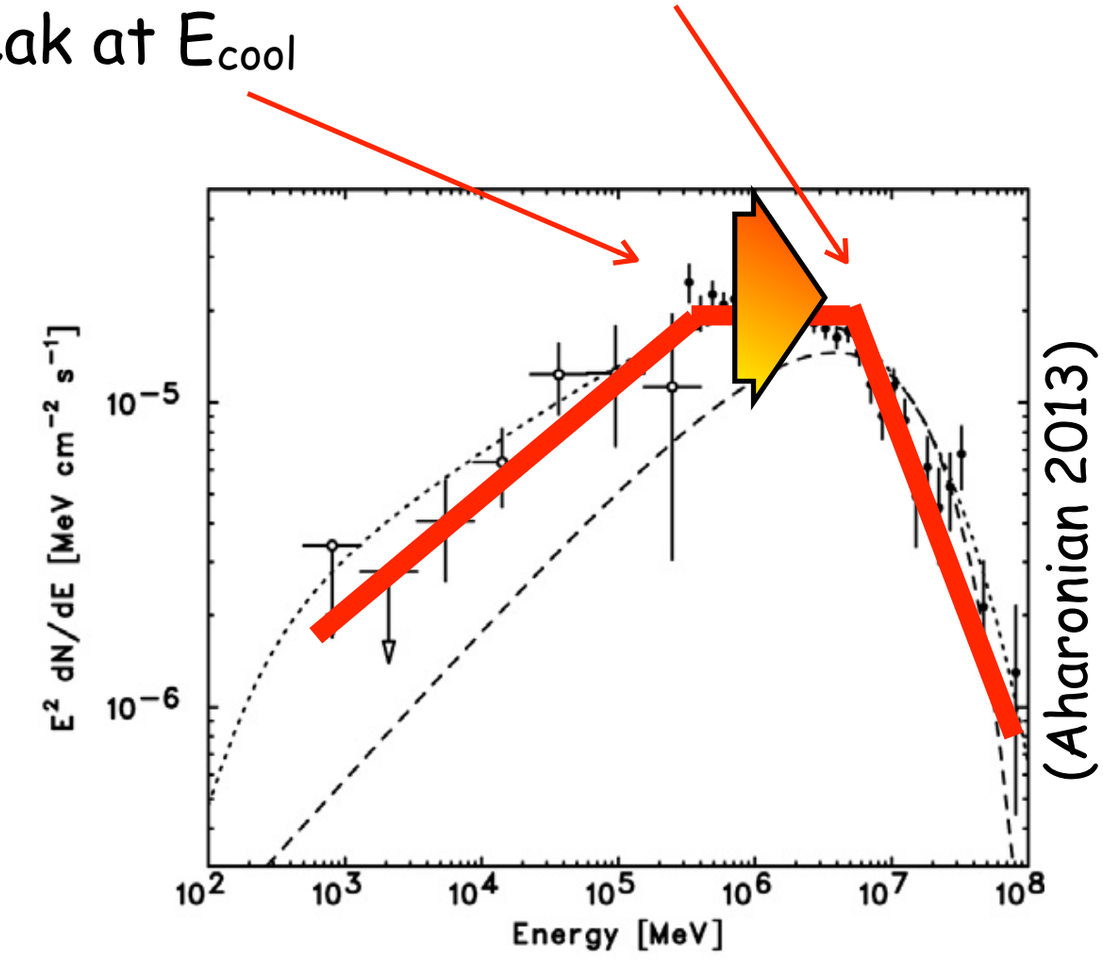

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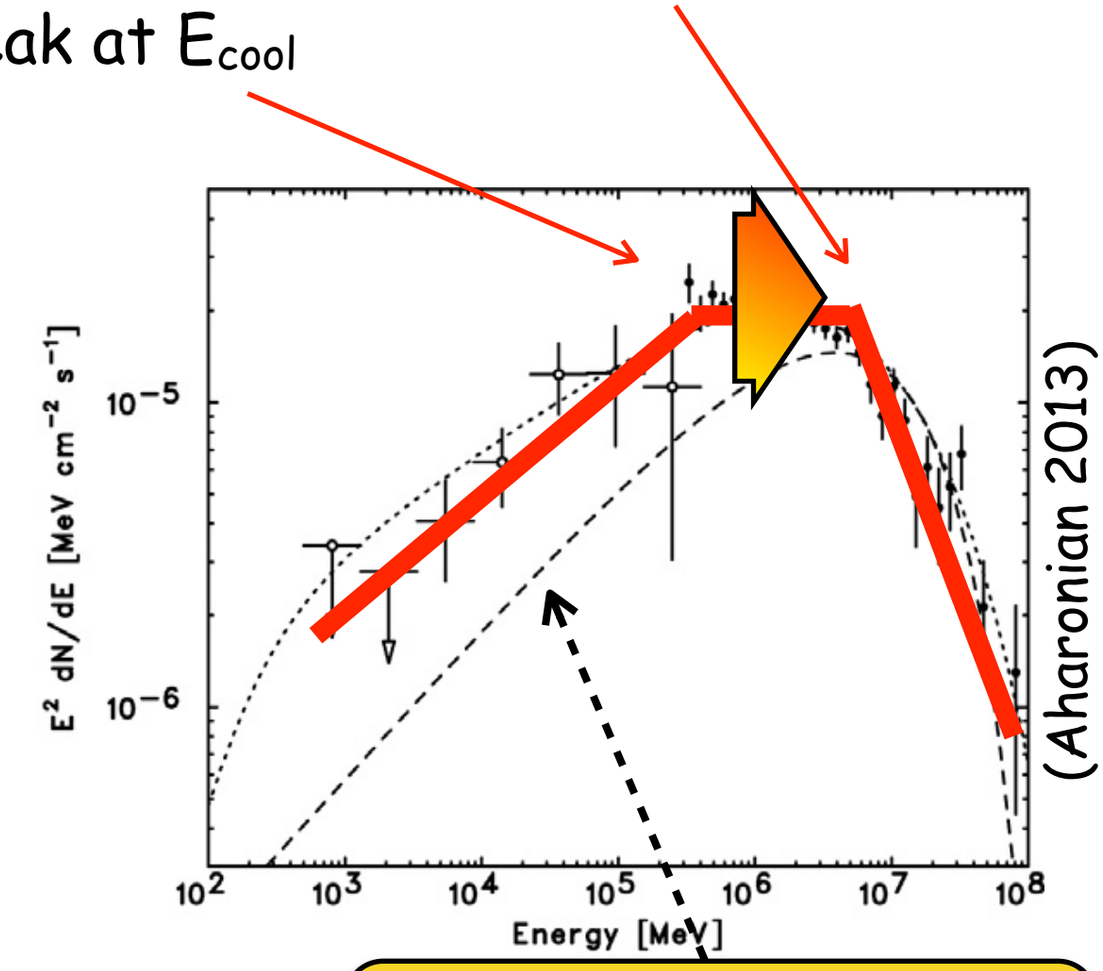


one-zone IC model

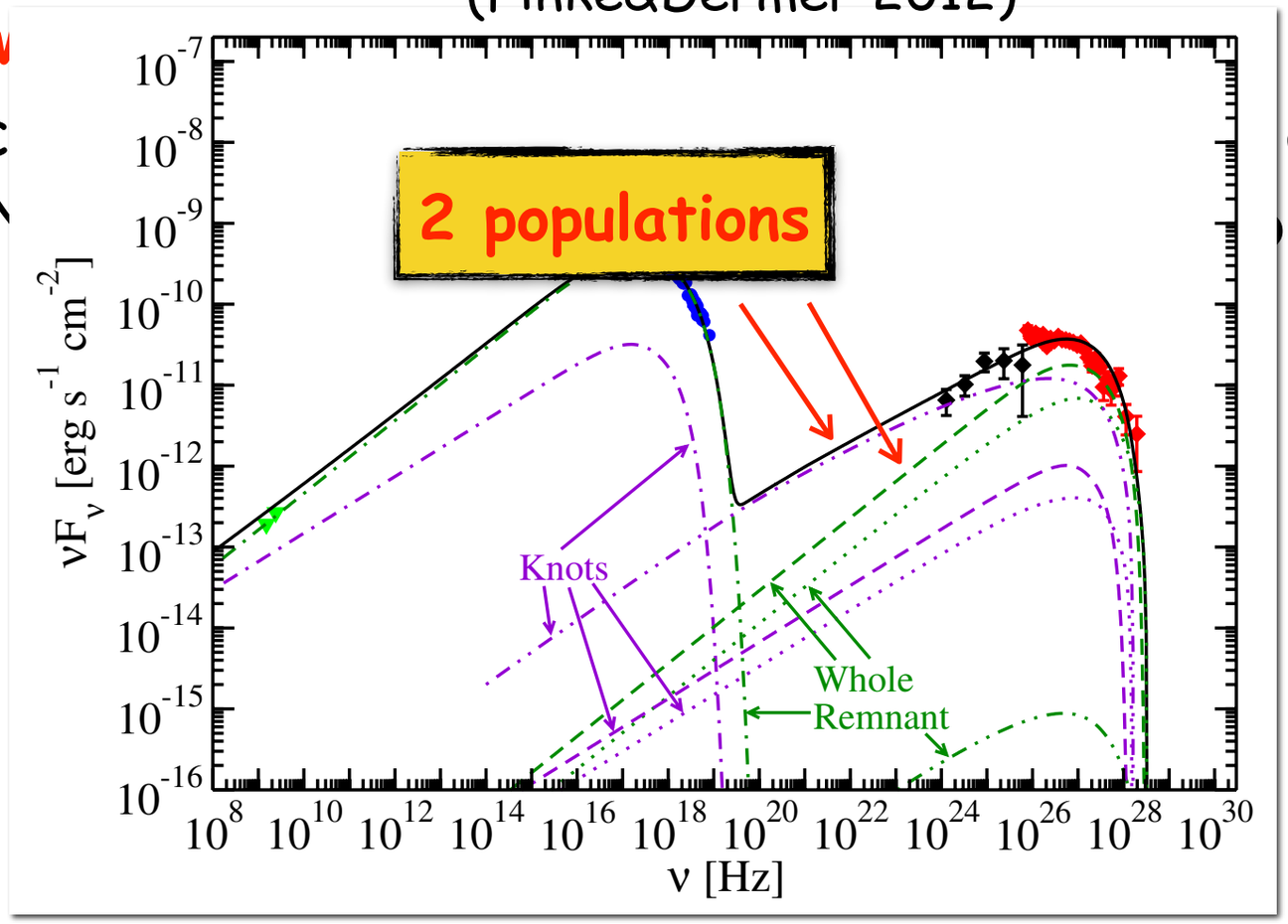
RXJ1713: difficulties of one-zone leptonic models

(Finke&Dermer 2012)

tw

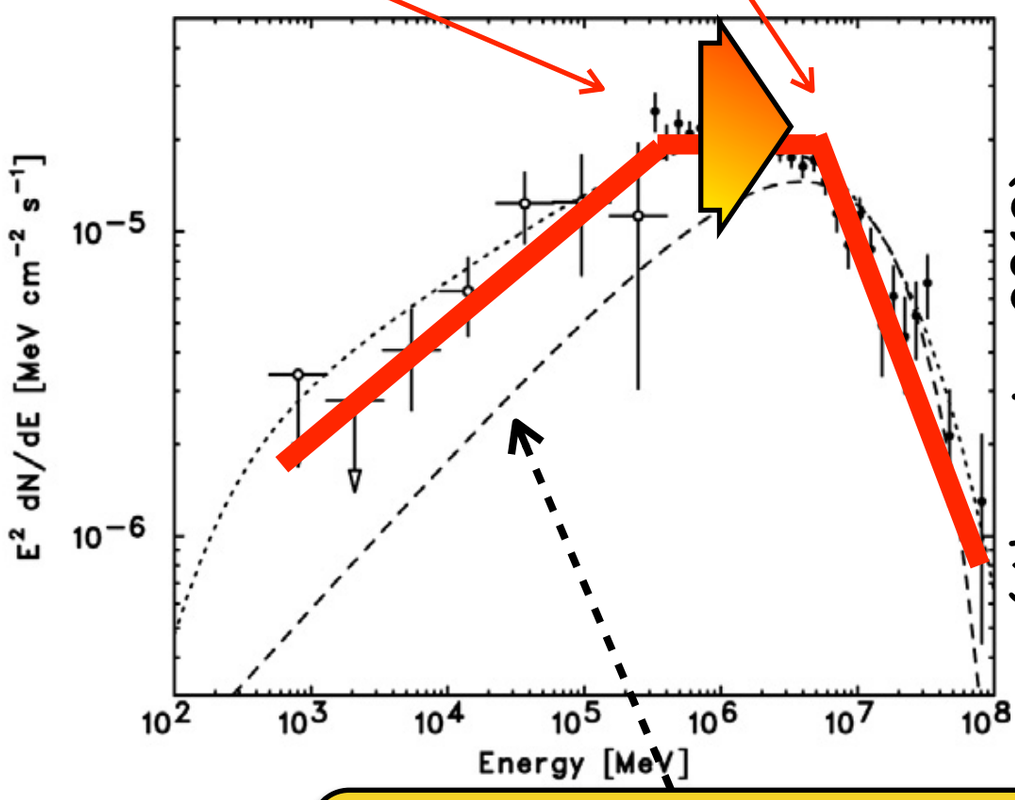
ac

SN



acceleration cutoff at E_{max}

break at E_{cool}



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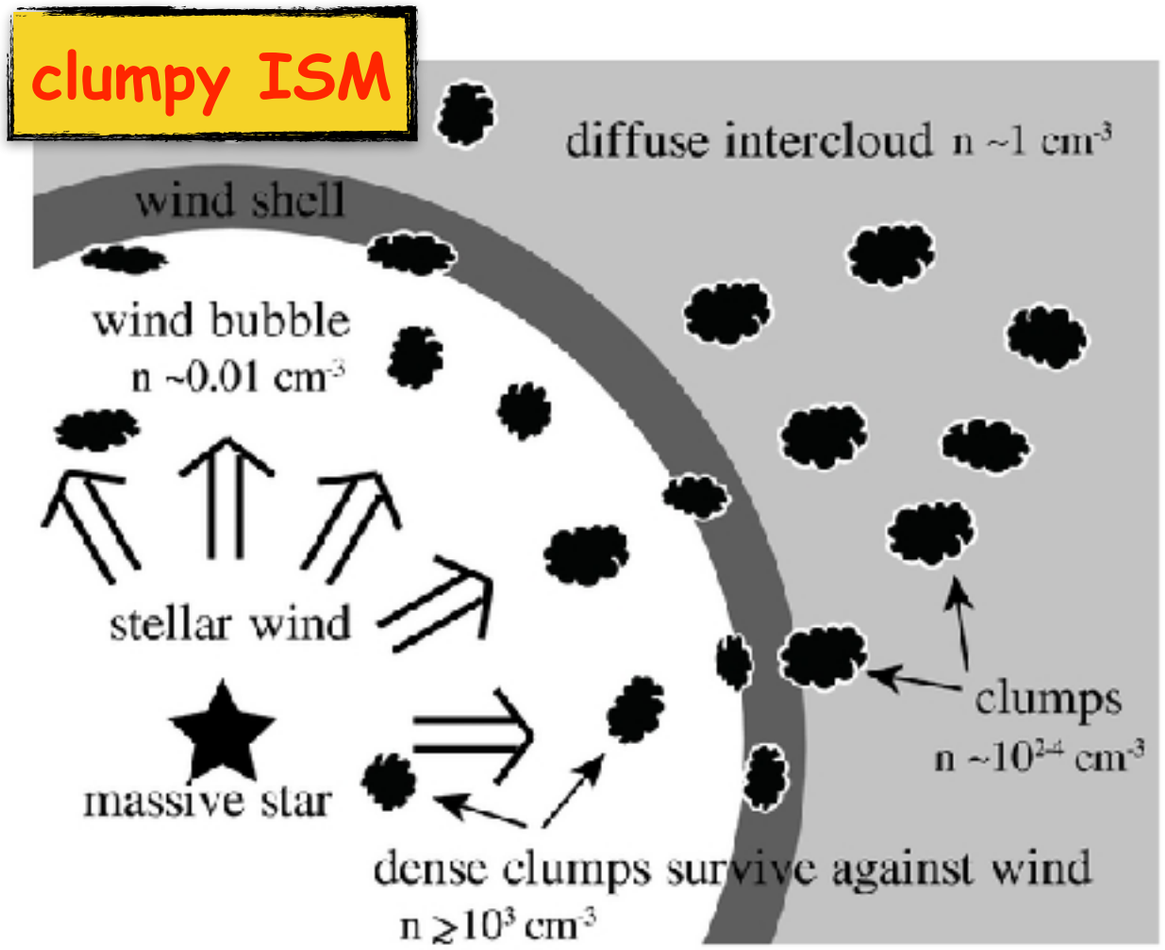
Hadronic RXJ1713: a SNR inside a MC?

Zirakashvili & Aharonian 2010, Fukui+ 2012, Inoue+ 2012, Gabici & Aharonian 2014



stellar wind sweeps the gas and creates a cavity

dense clumps survive (unshocked) both the stellar wind and the SNR shock

no thermal X-rays!

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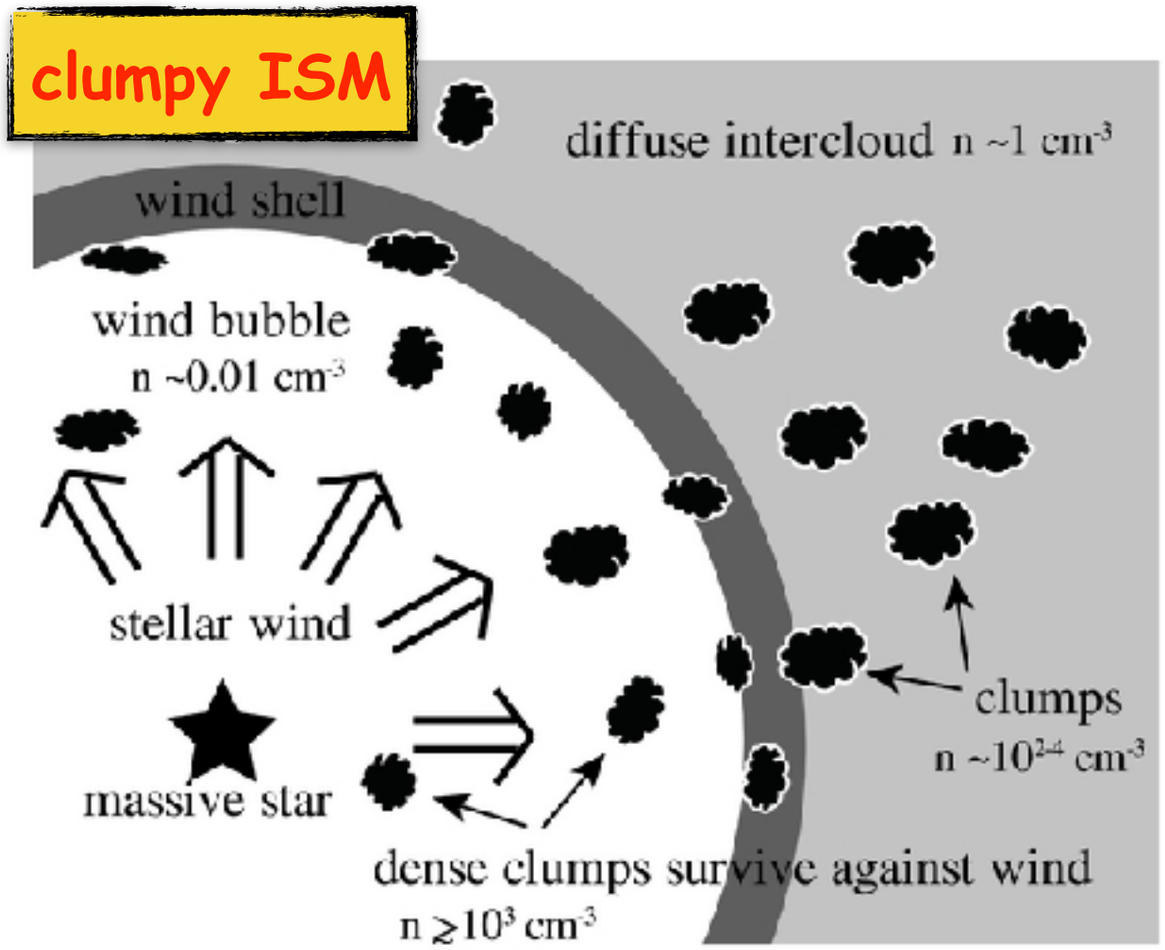

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dense clumps survive (unshocked) both the stellar wind and the SNR shock

no thermal X-rays!

high energy CRs penetrate

low energy CRs don't

clumps!

sub-parsec

Hadronic RXJ1713: a SNR inside a MC?

Zirakas

aronian 2014

clumpy IS

wind shel

wind bubbl

n ~0.01 cm

stellar win

massive star

s the gas and

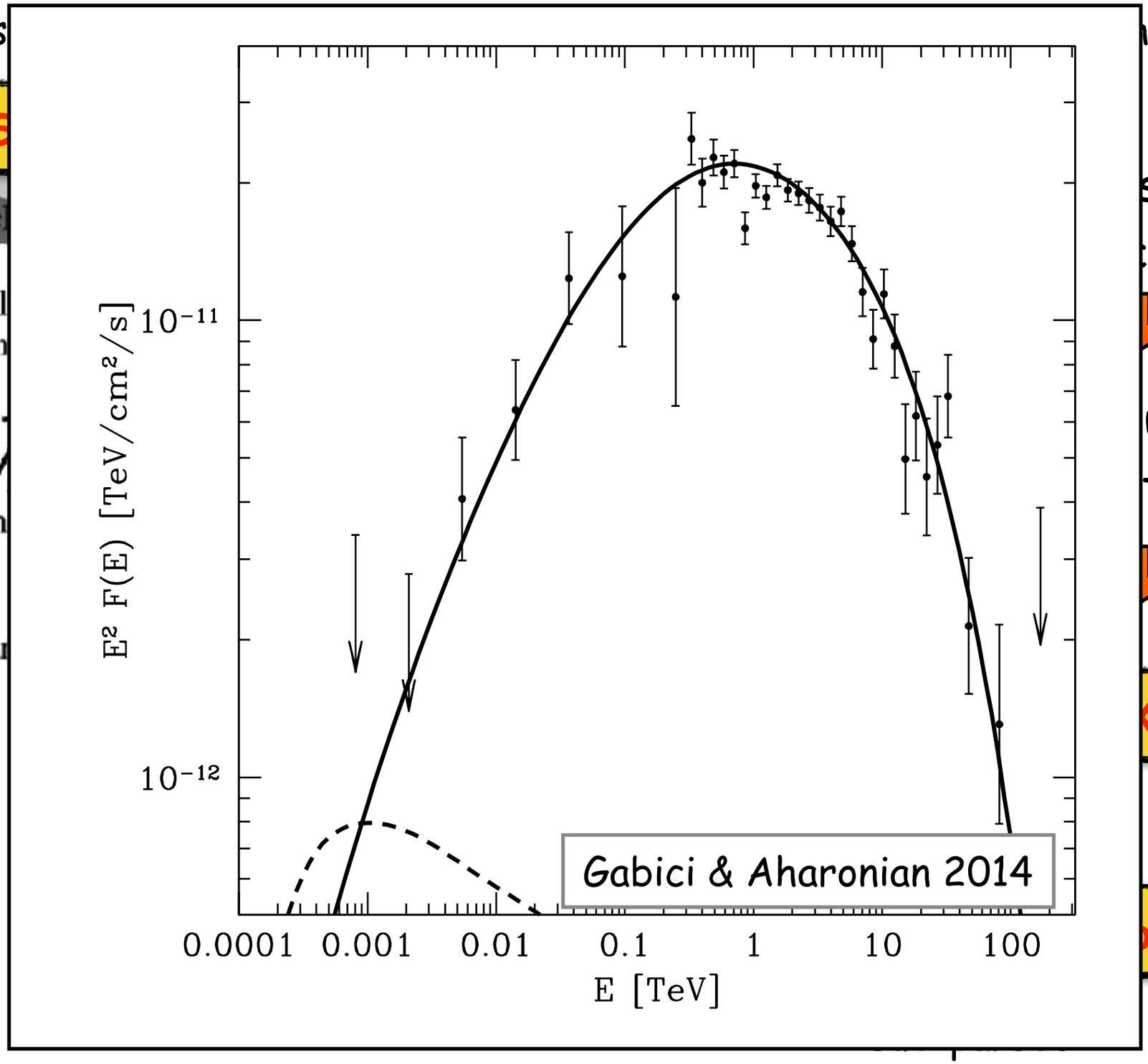
avity

unshocked) both

the SNR shock

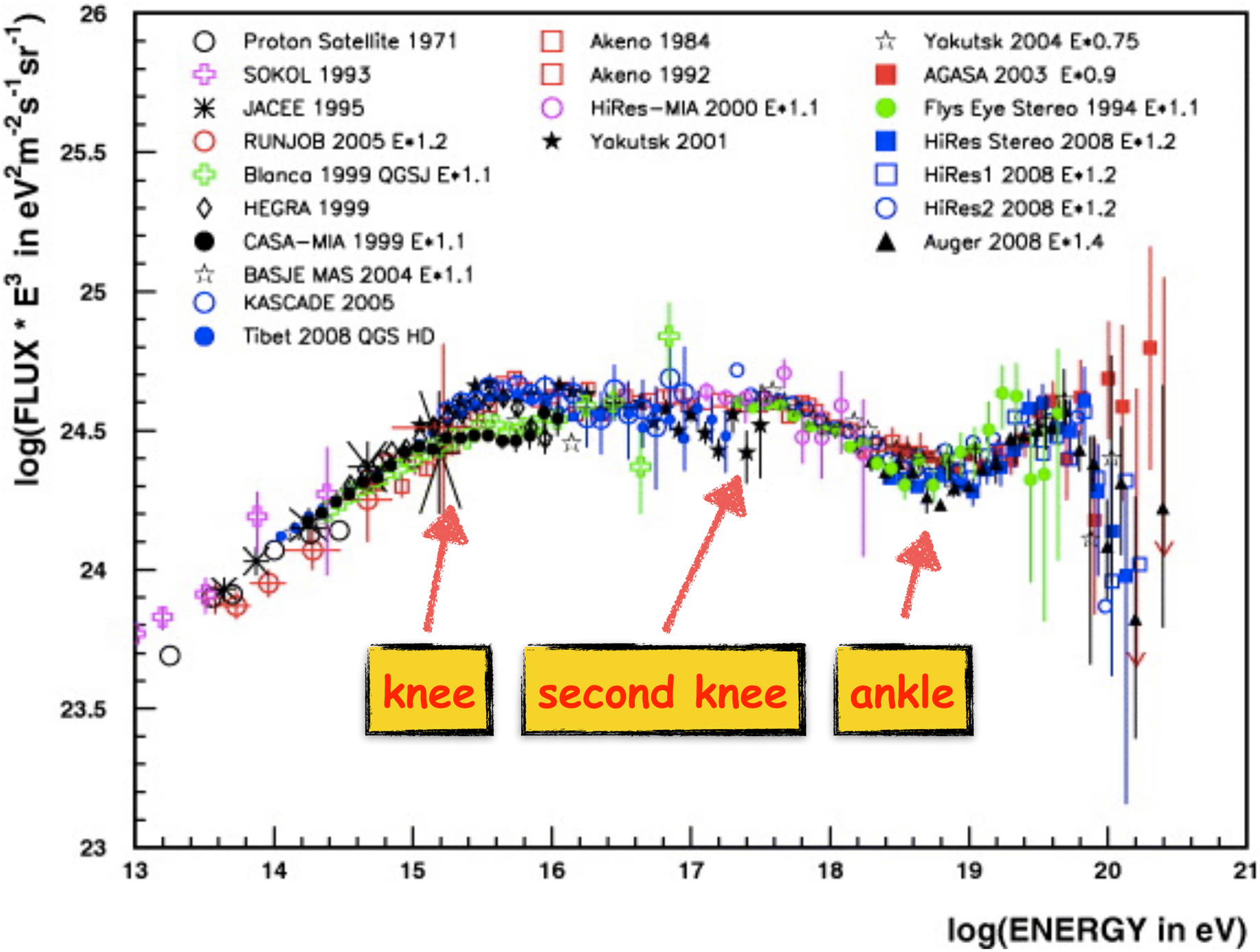
K-rays!

os!



Galactic to extragalactic transition in the CR spectrum

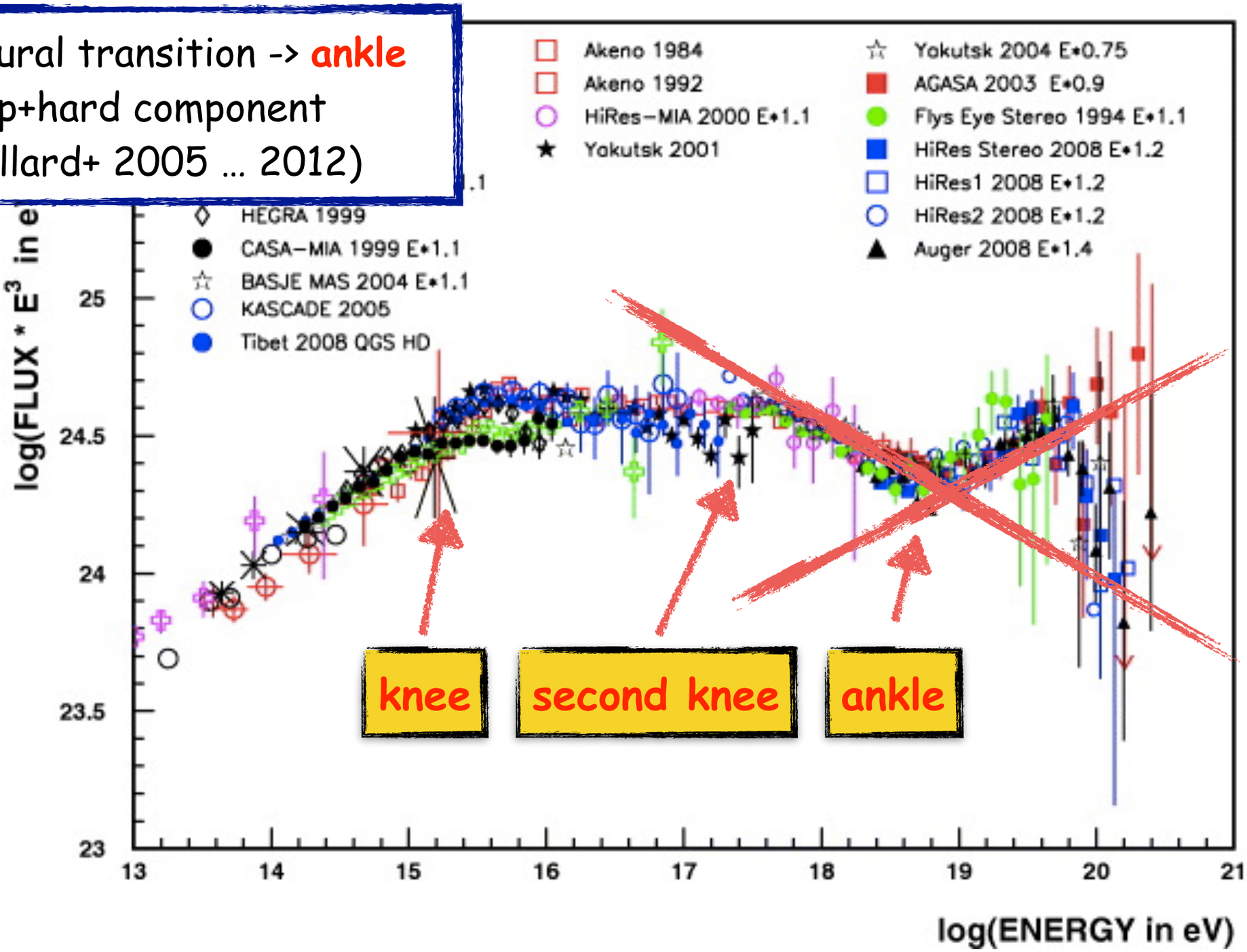
The EeV domain: Galactic-Extragalactic



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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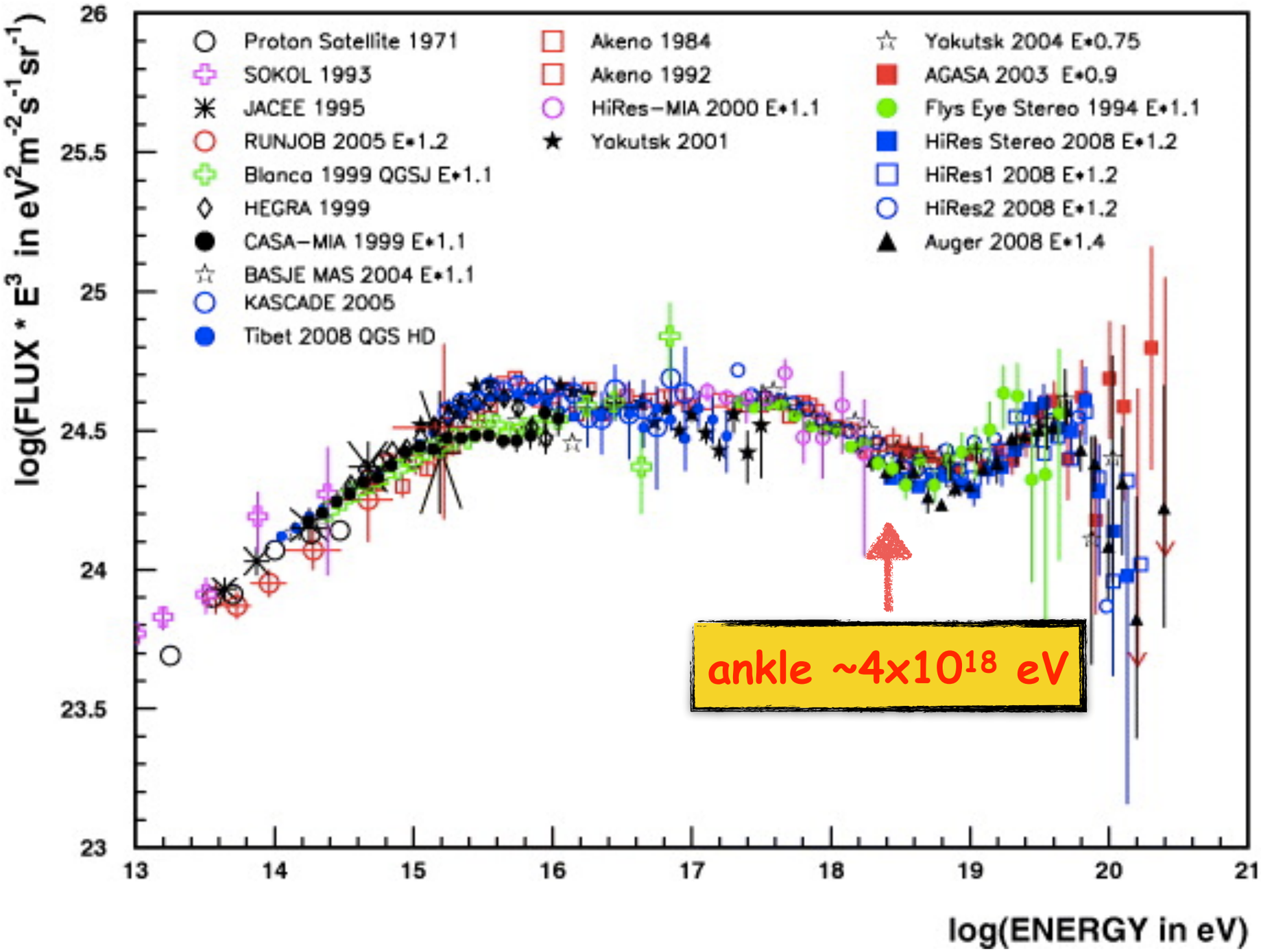
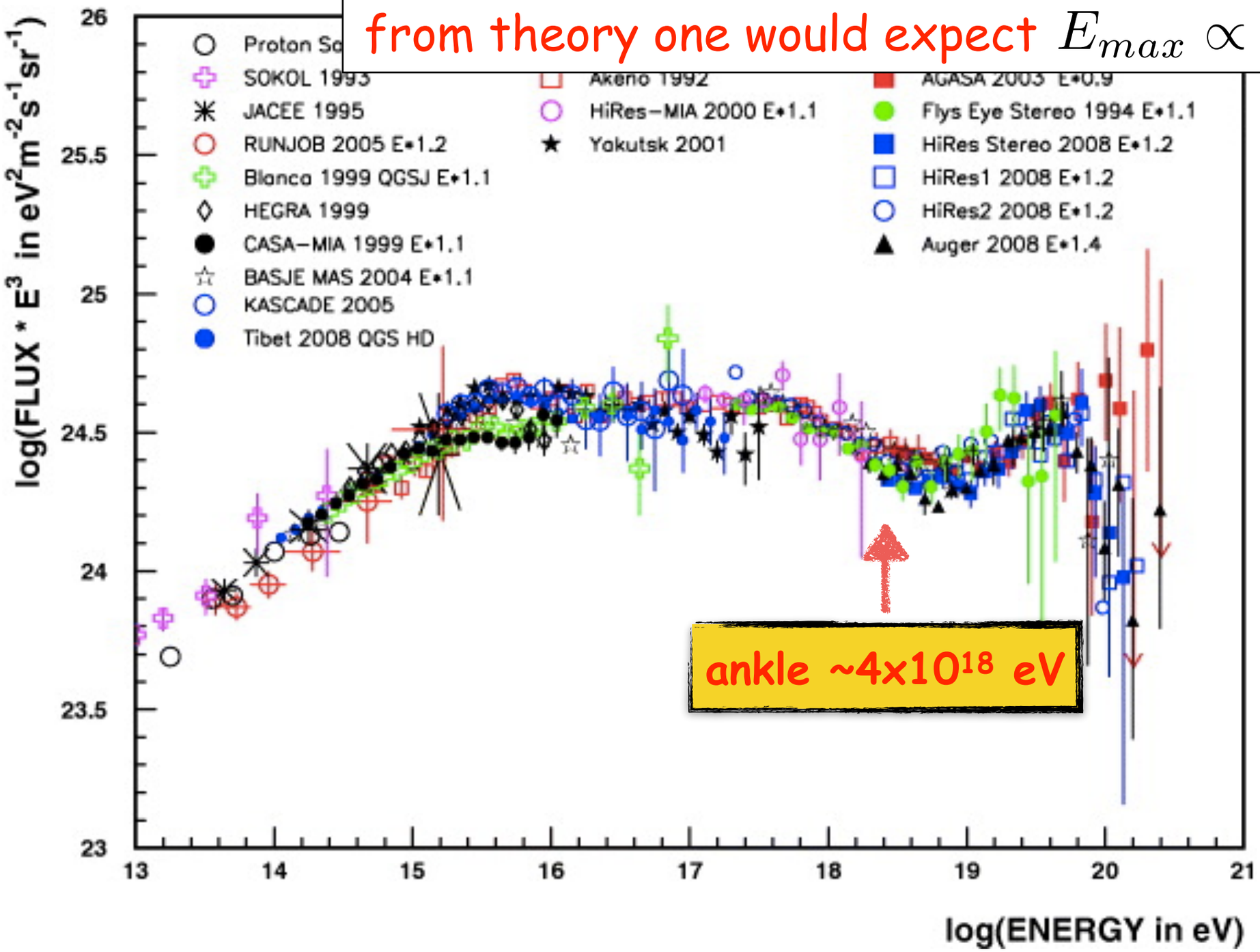


MeV	GeV	TeV	PeV	EeV	ZeV

The EeV domain: Galactic-Extragalactic

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



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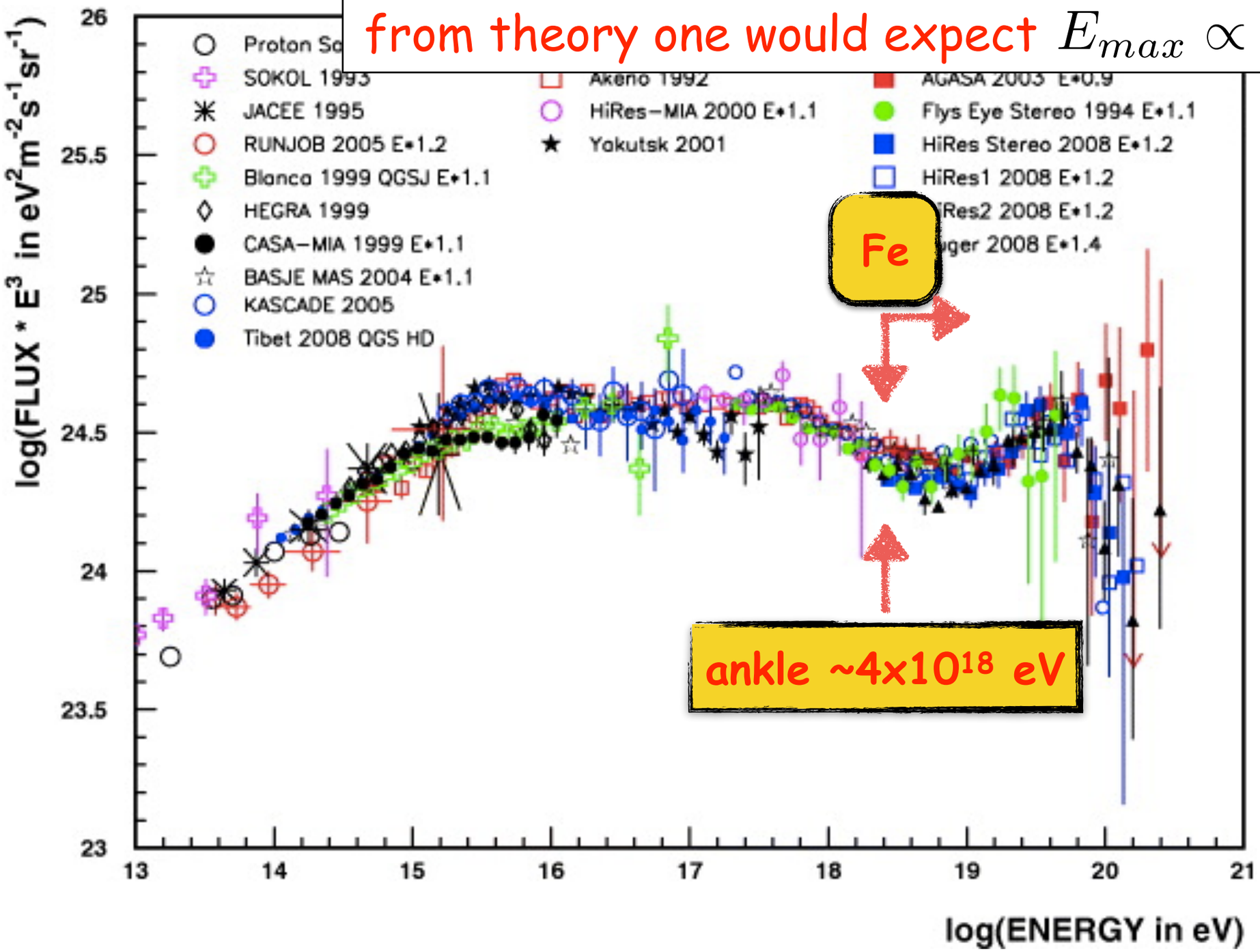

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The EeV domain: Galactic-Extragalactic

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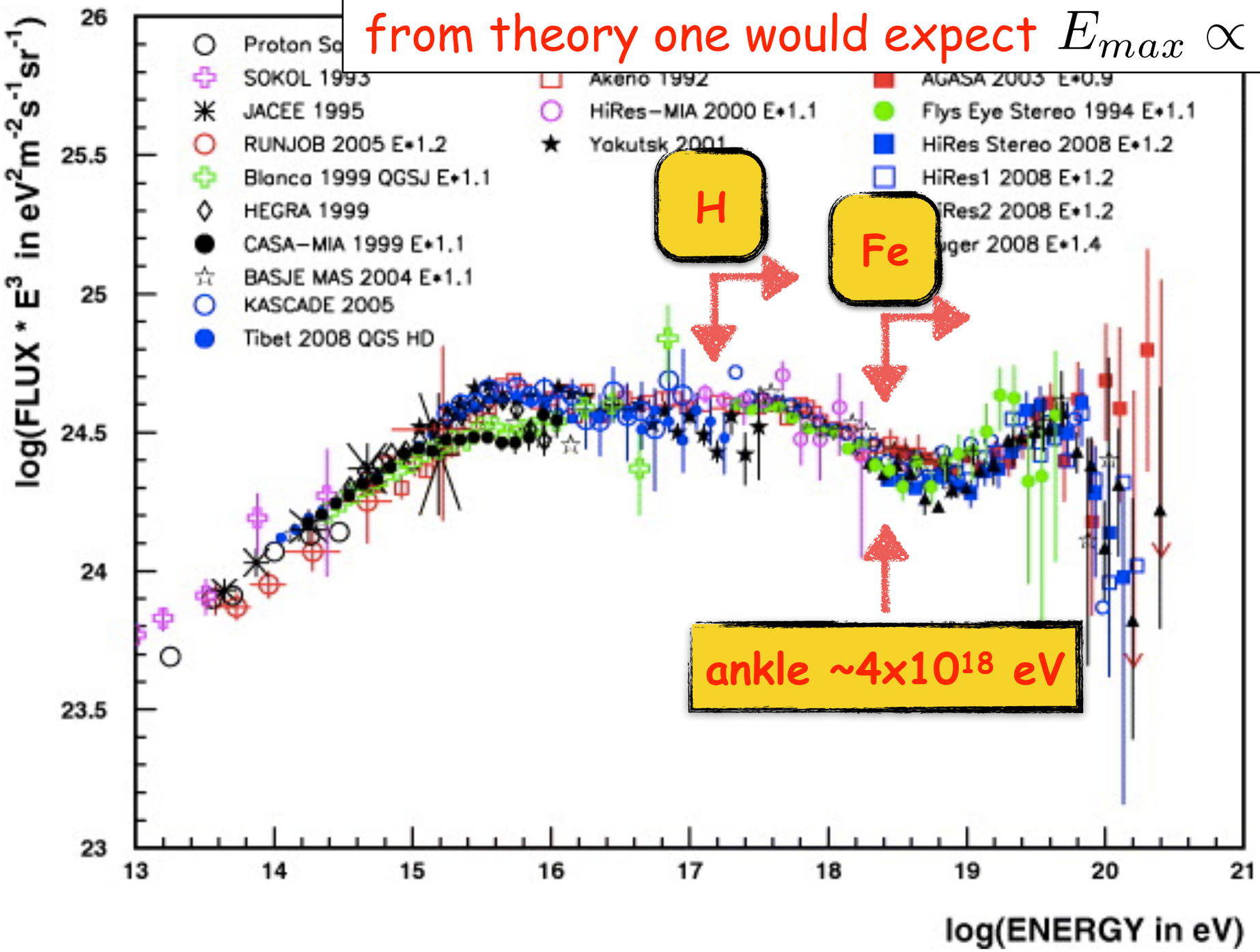

MeV	GeV	TeV	PeV	EeV	ZeV

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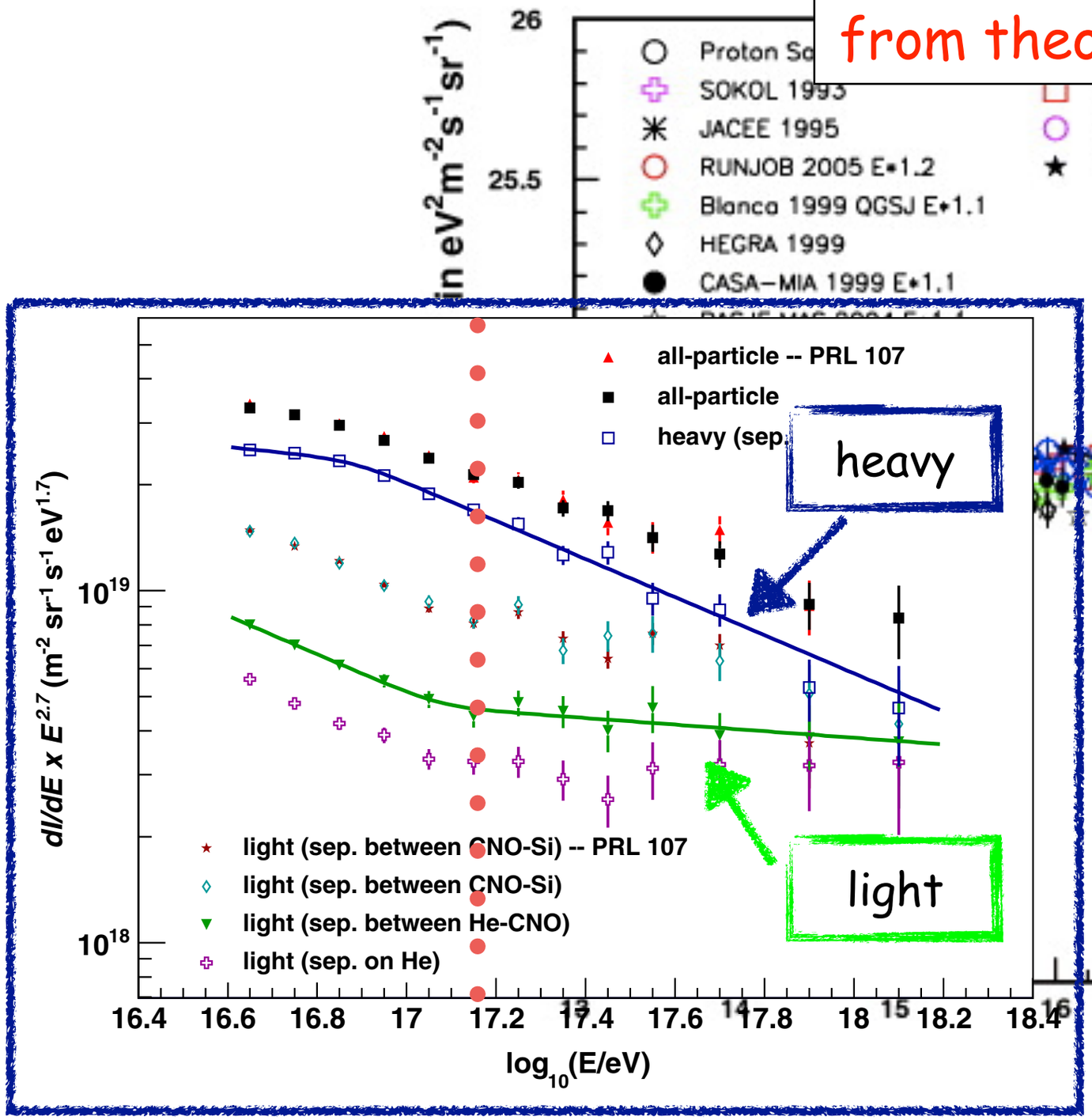

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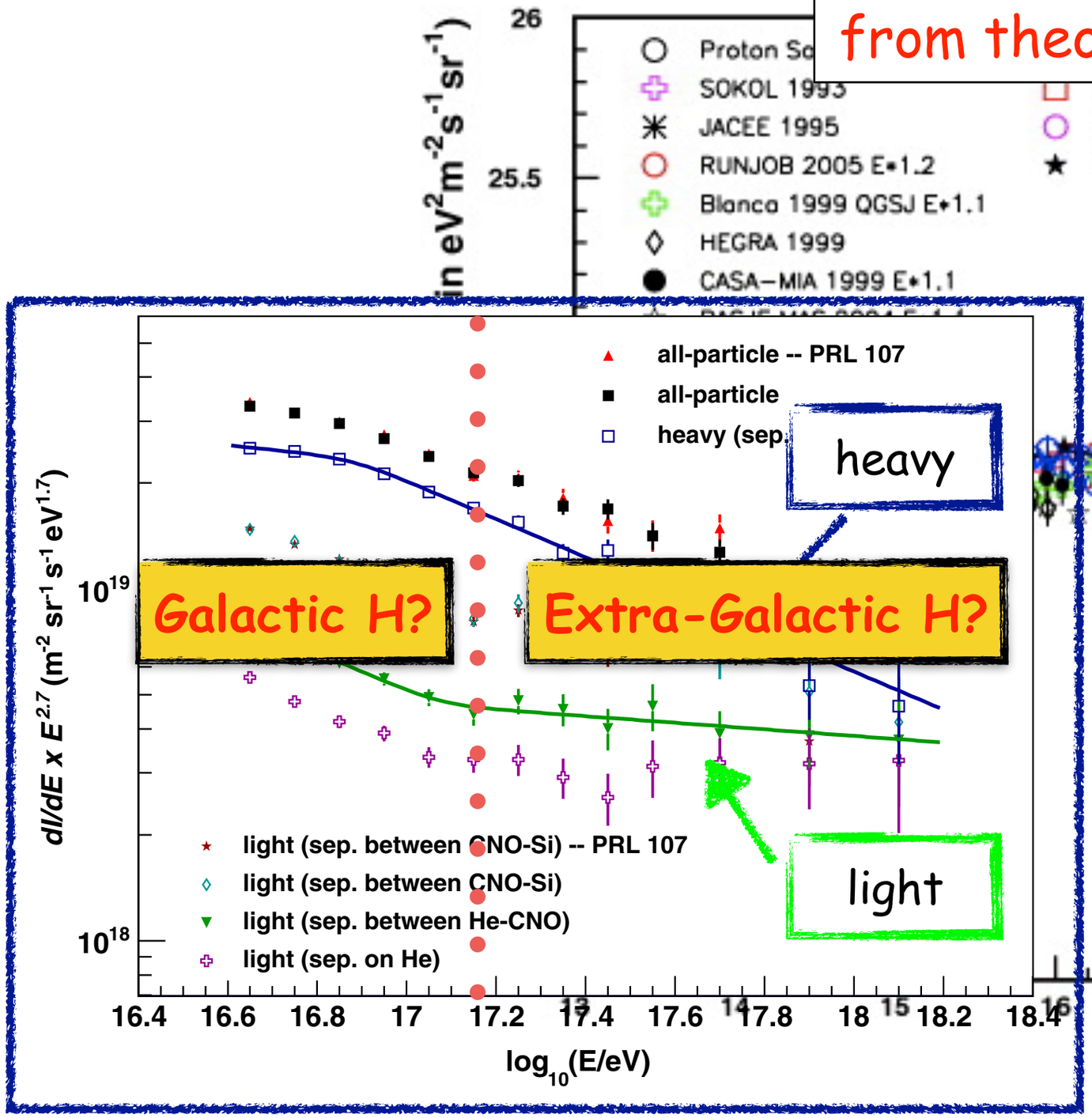

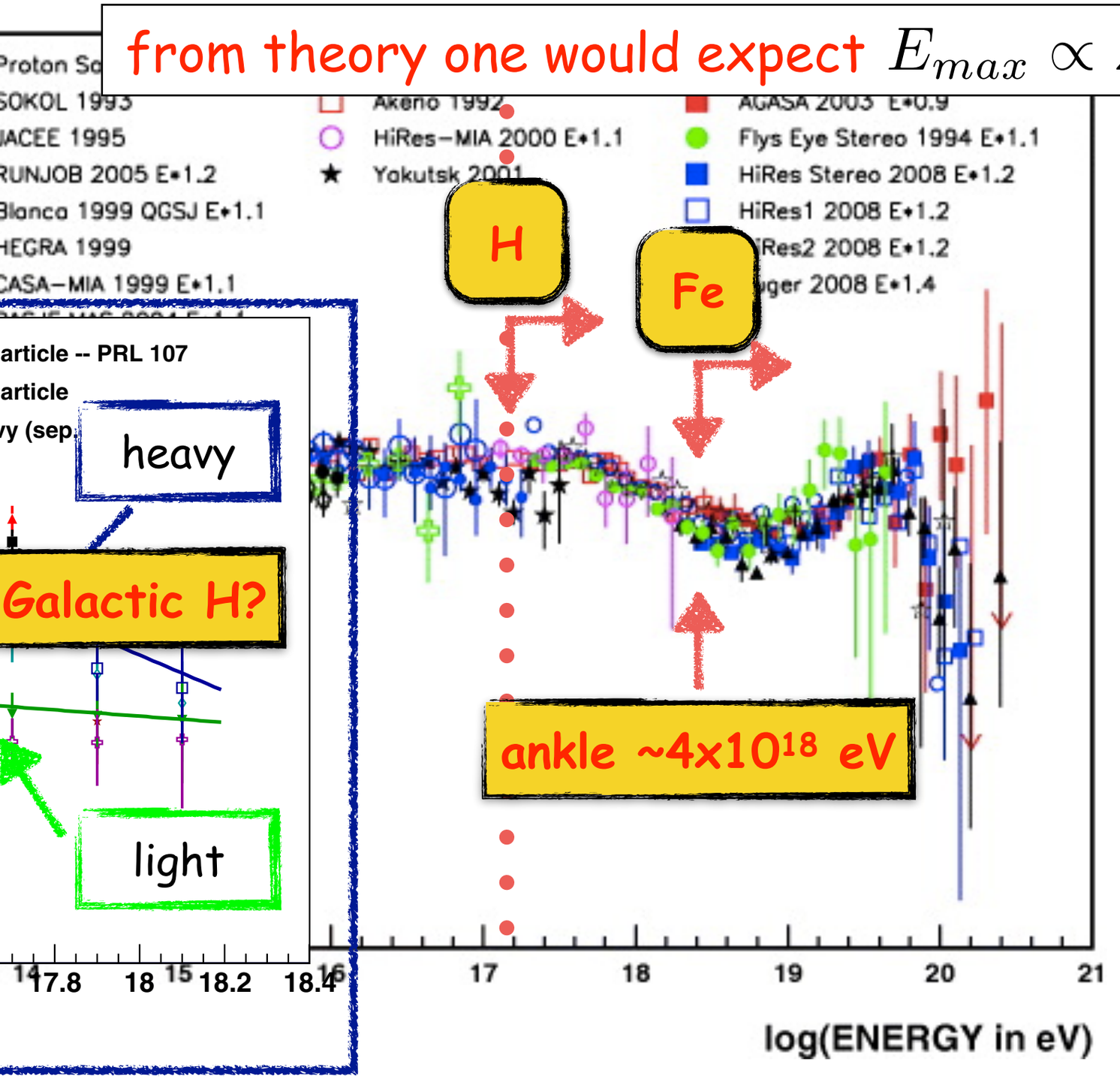

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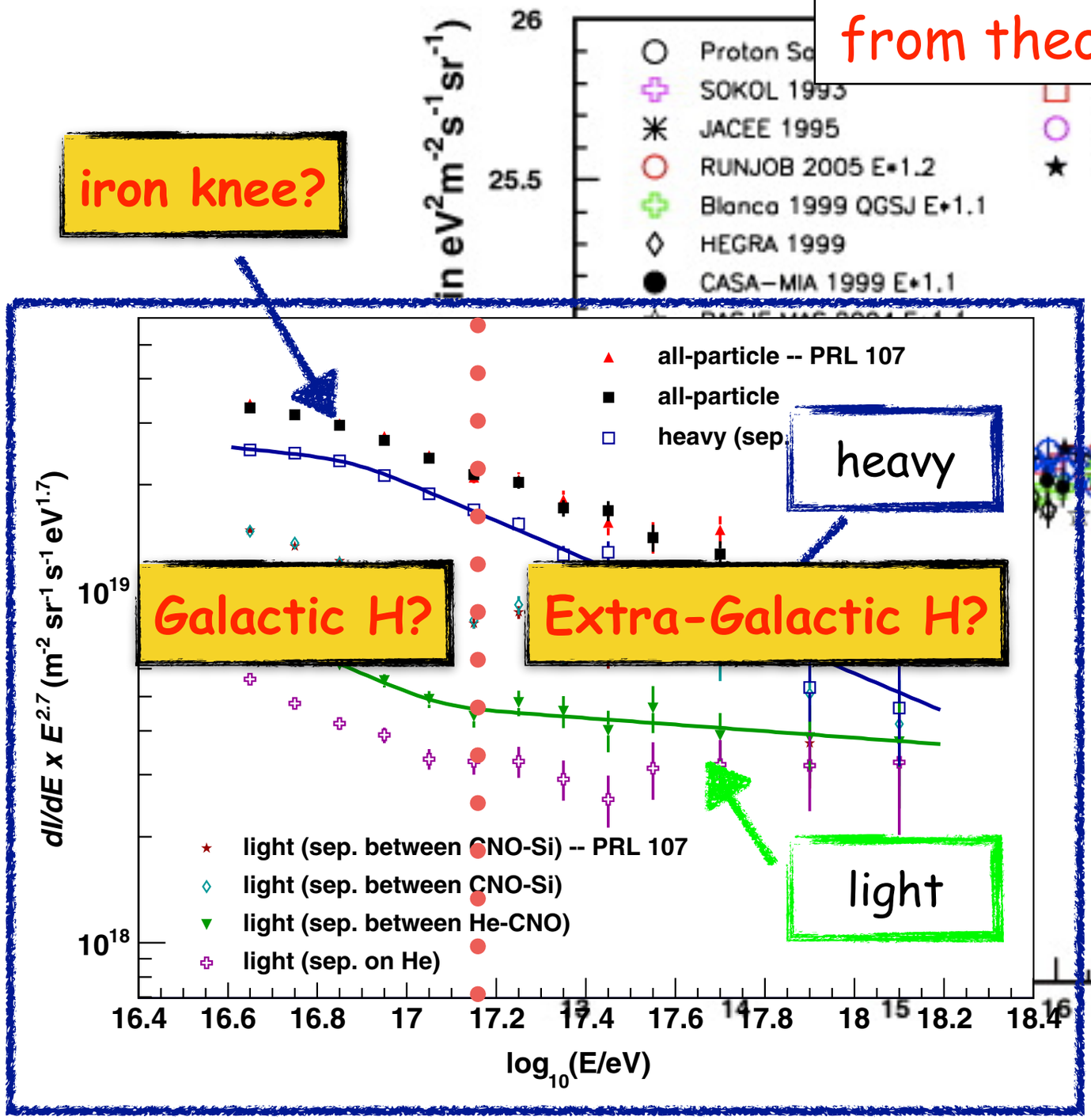
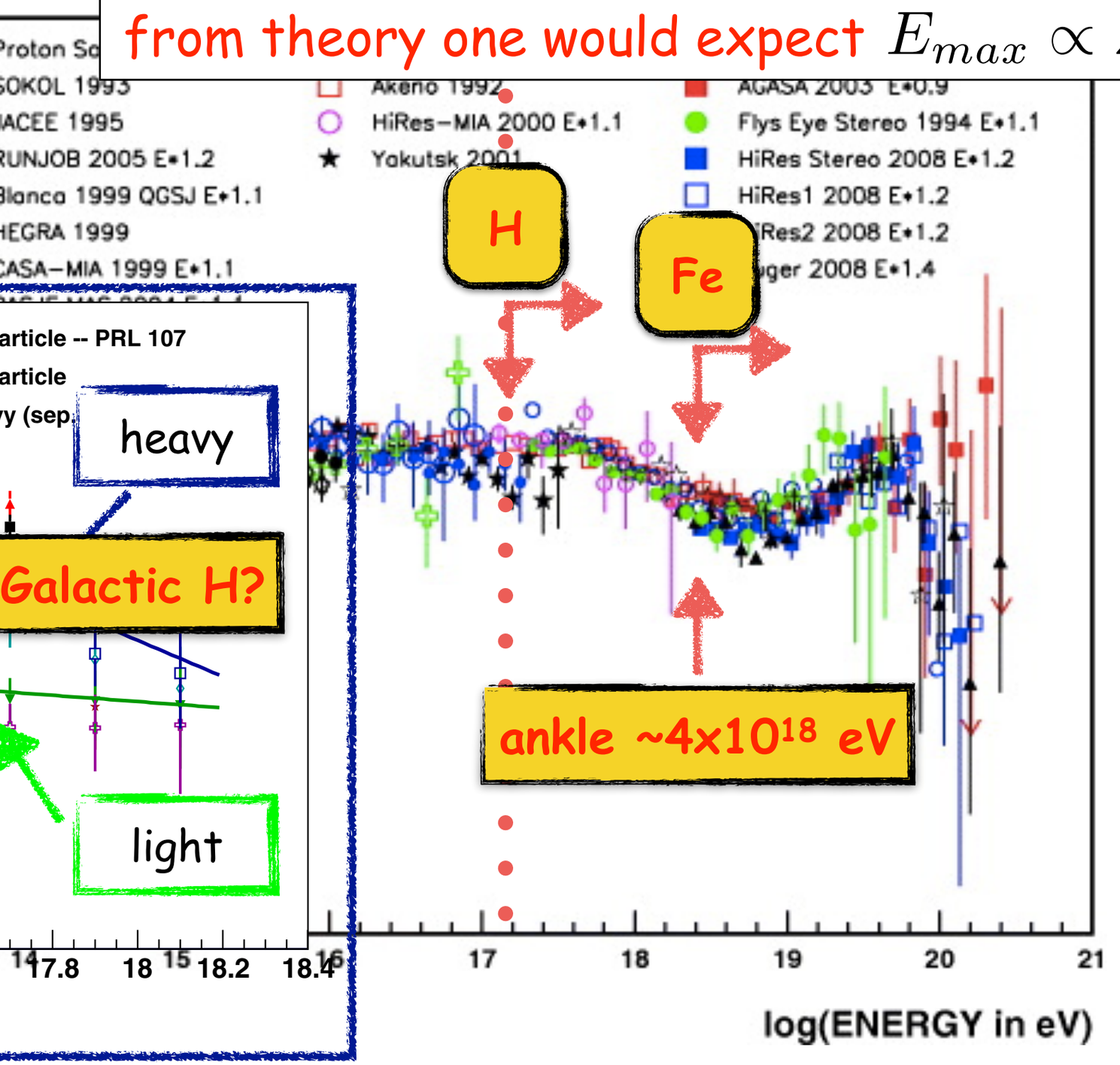
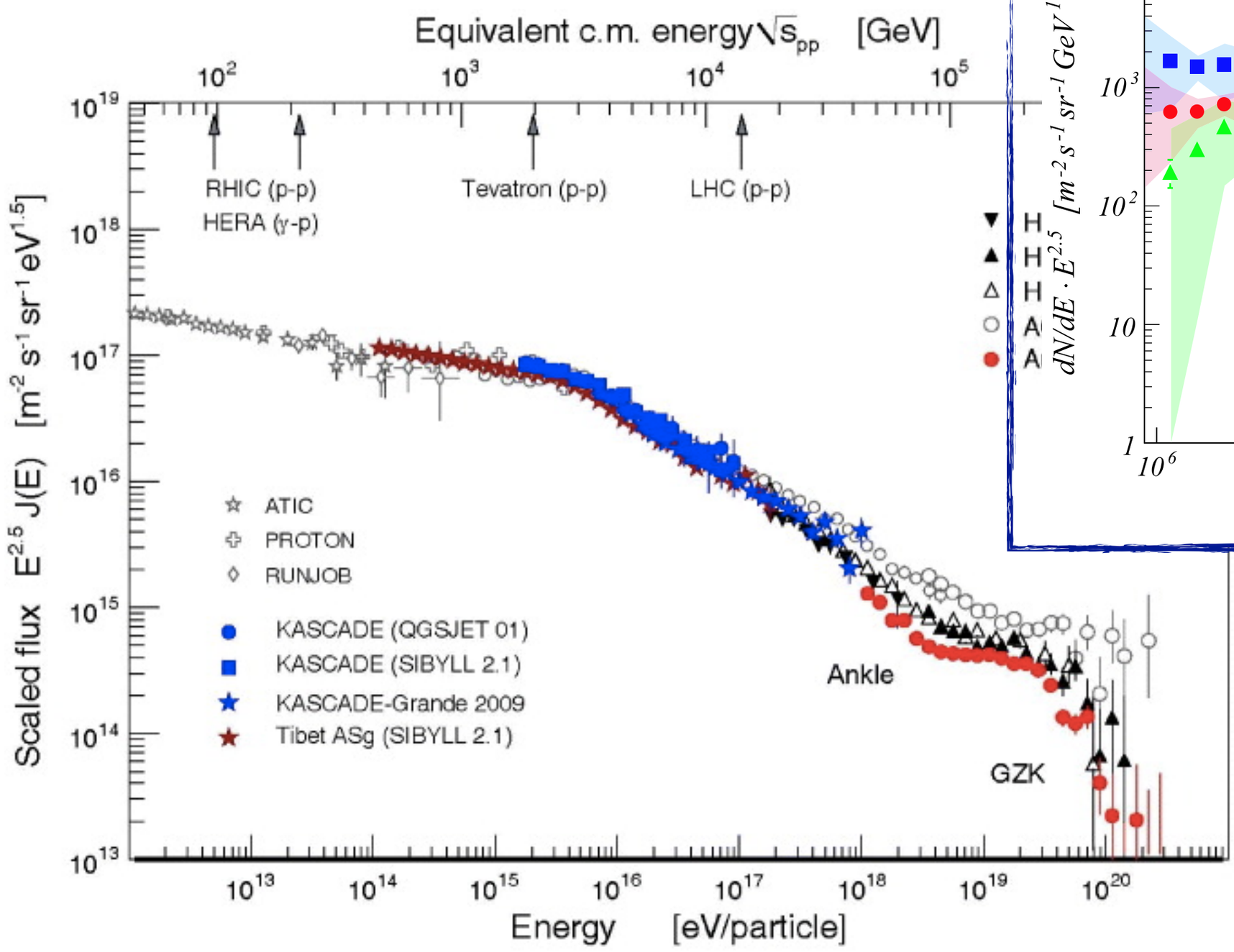
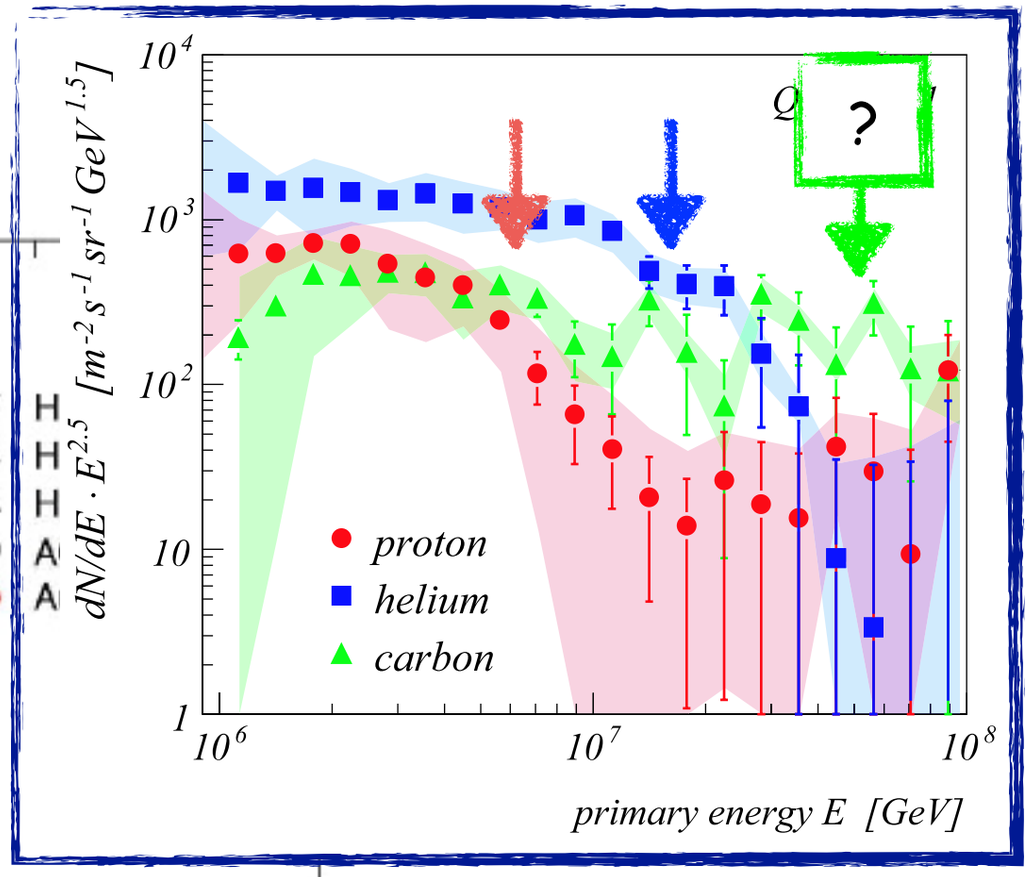




MeV	GeV	TeV	PeV	EeV	ZeV

The EeV domain: Galactic-Extragalactic





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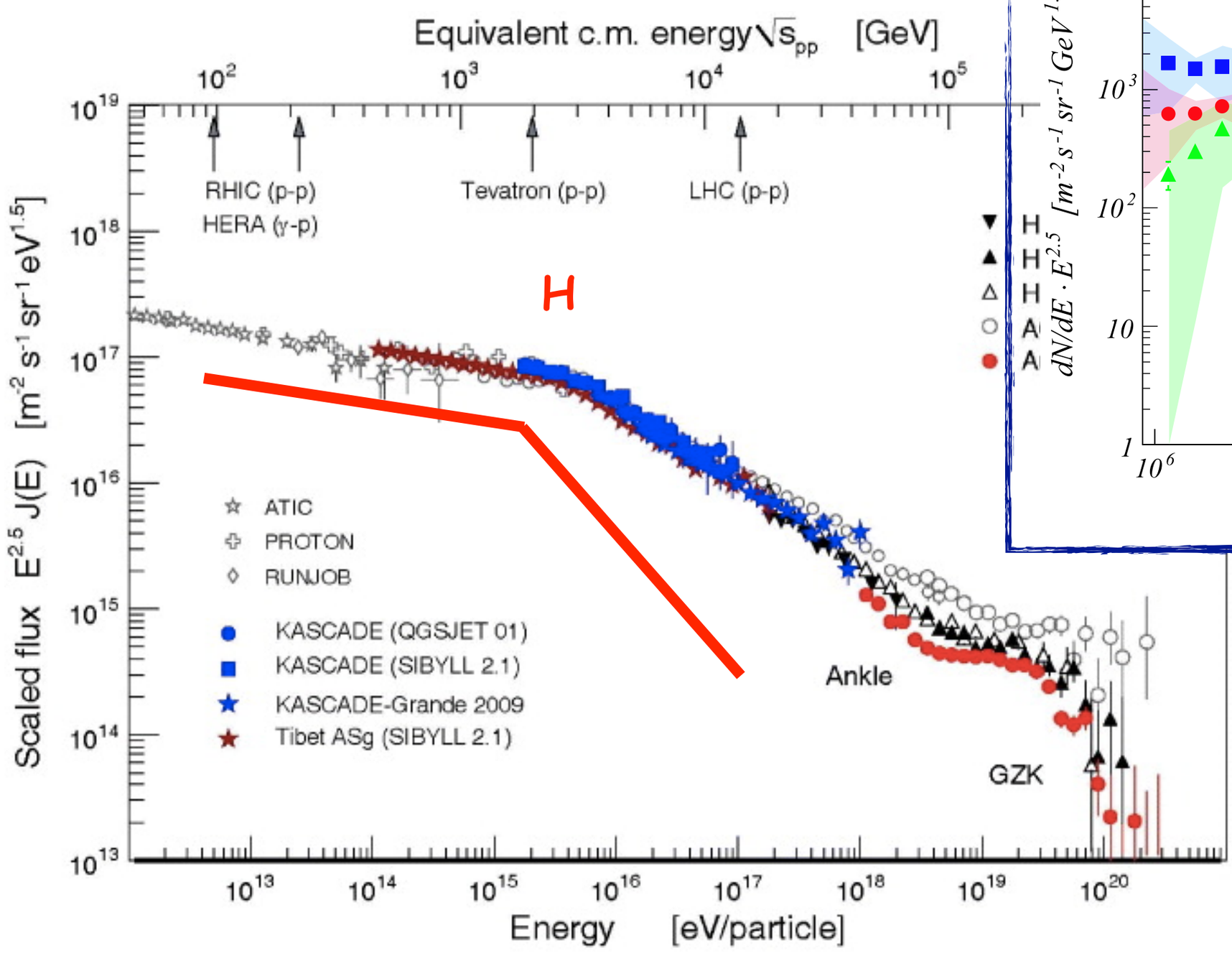
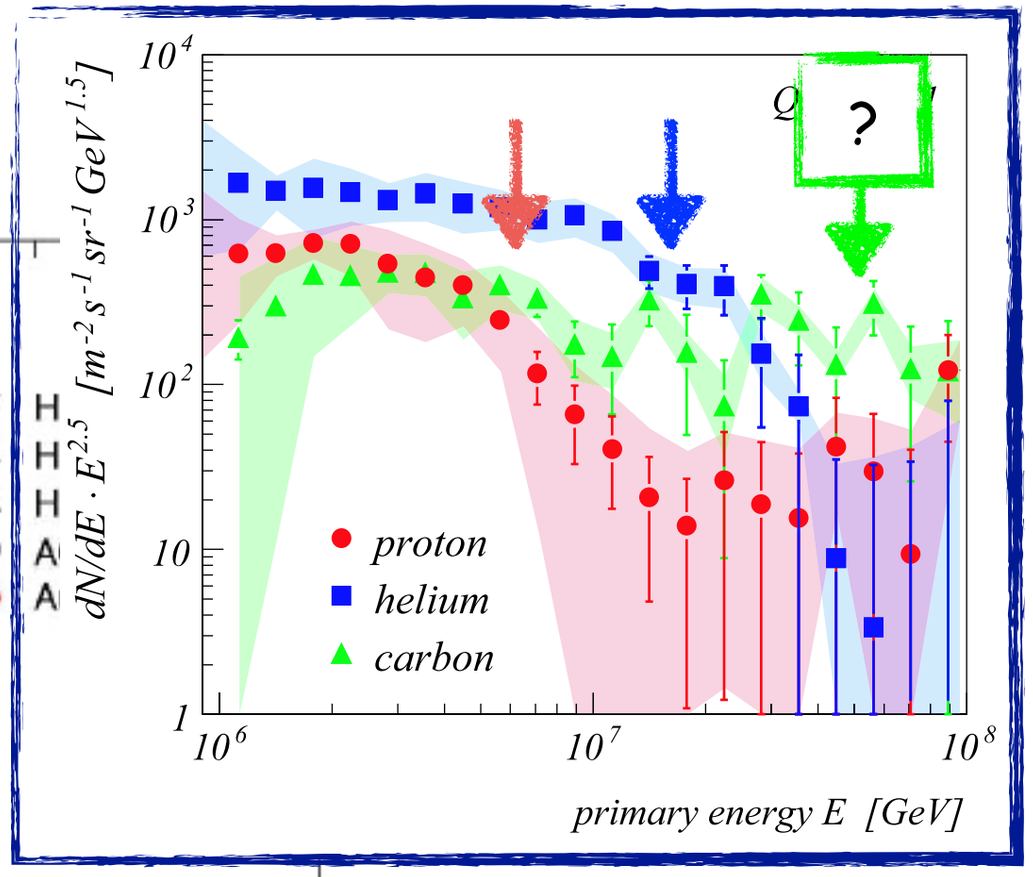
Z-dependent knee

MeV	GeV	TeV	PeV	EeV	ZeV

The EeV domain: Galactic-Extragalactic





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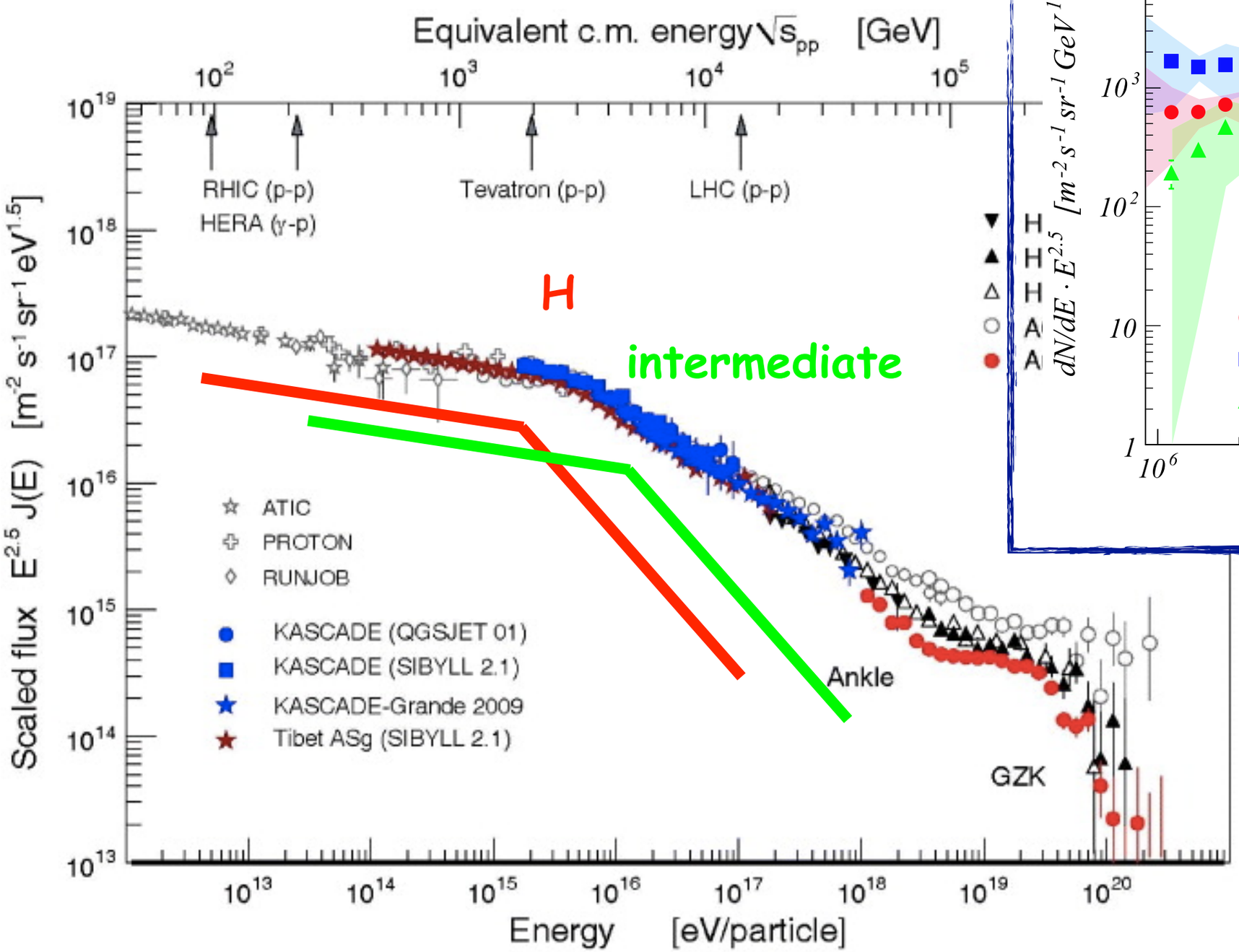
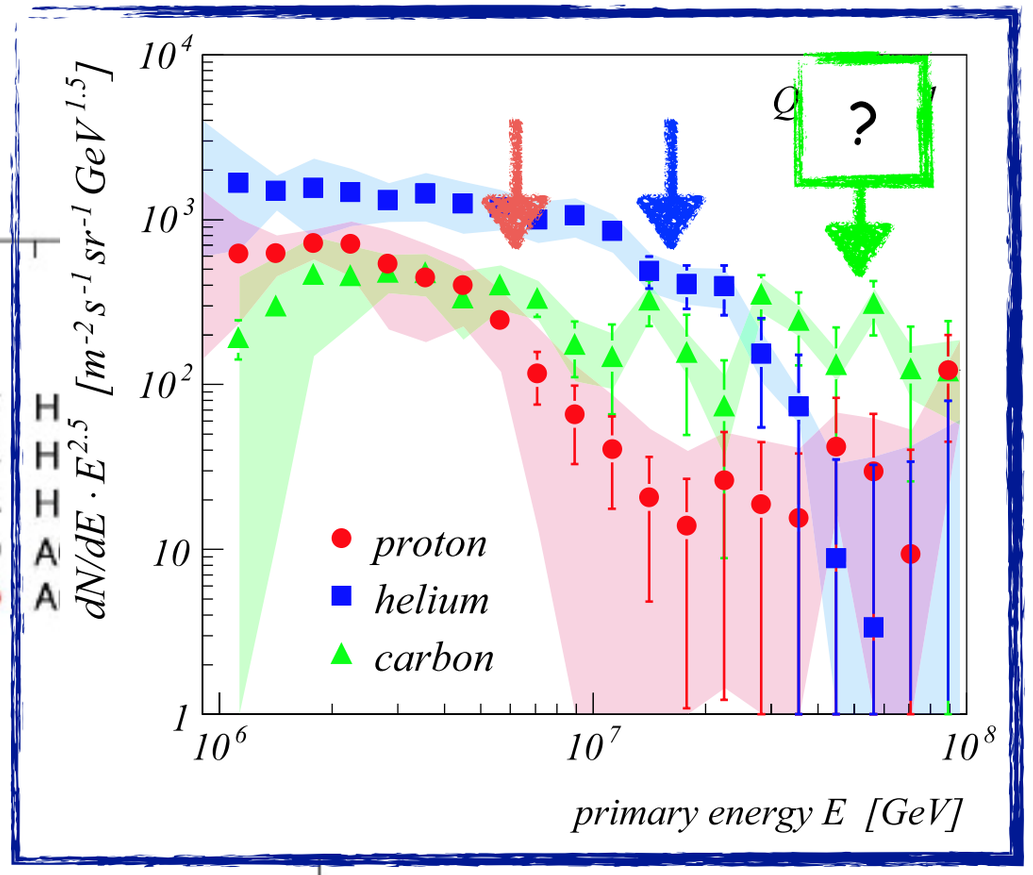
Z-dependent knee

MeV	GeV	TeV	PeV	EeV	ZeV

The EeV domain: Galactic-Extragalactic





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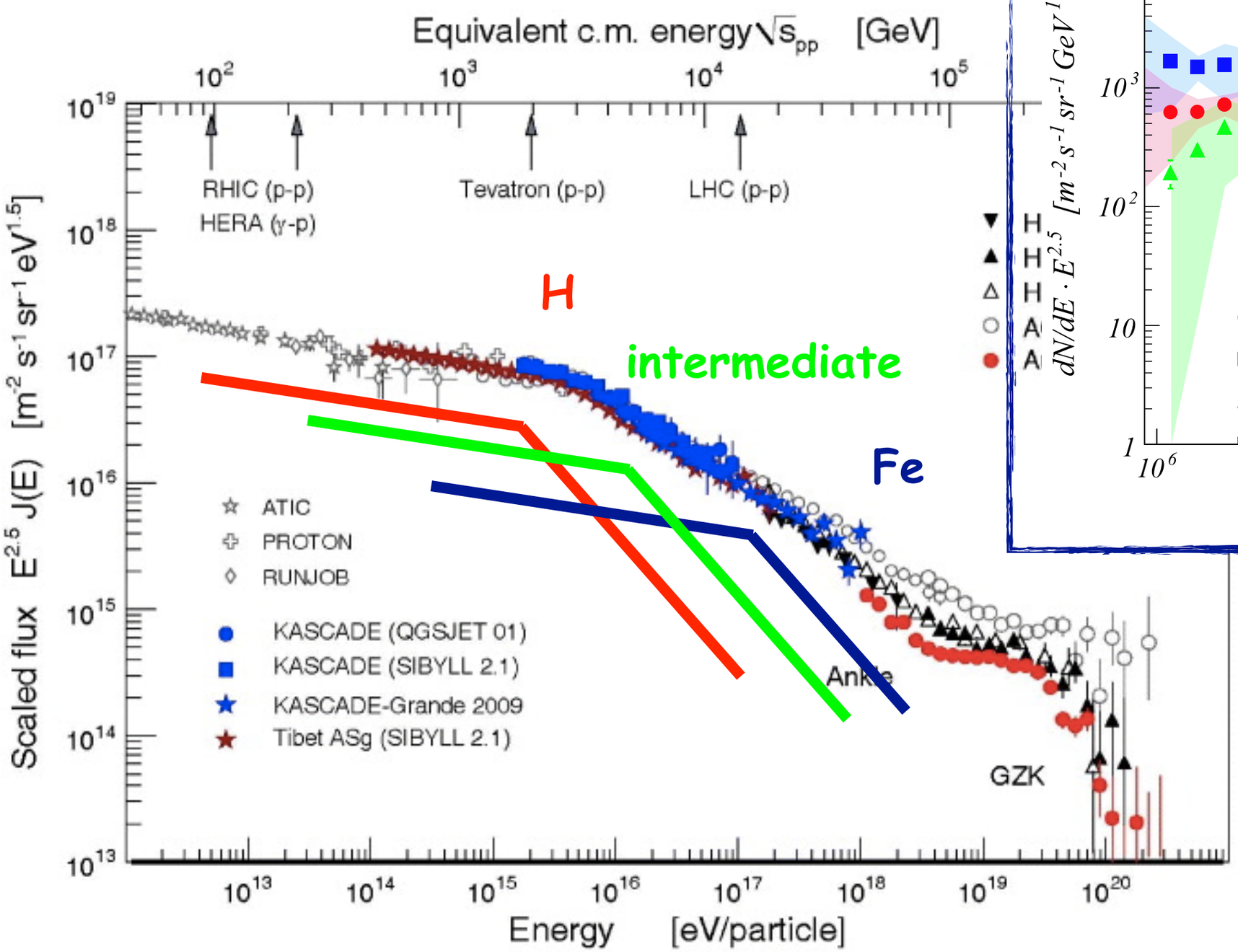
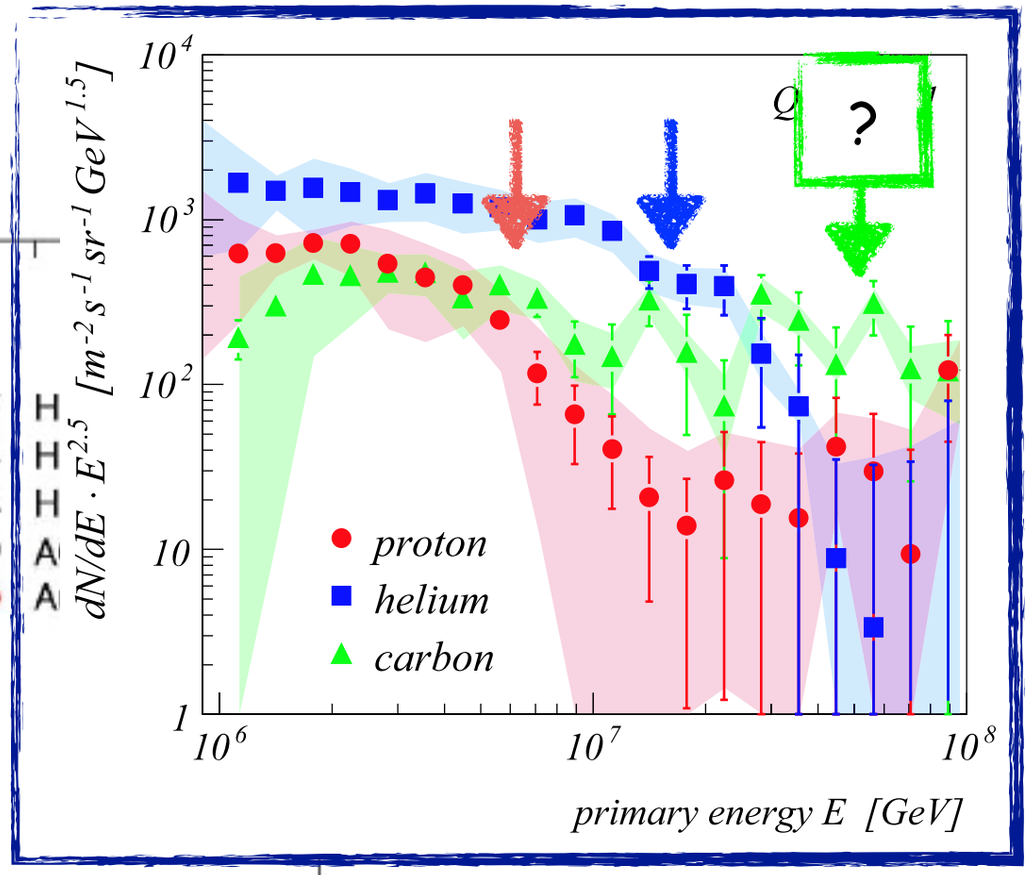
Z-dependent knee

MeV	GeV	TeV	PeV	EeV	ZeV

The EeV domain: Galactic-Extragalactic





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Z-dependent knee

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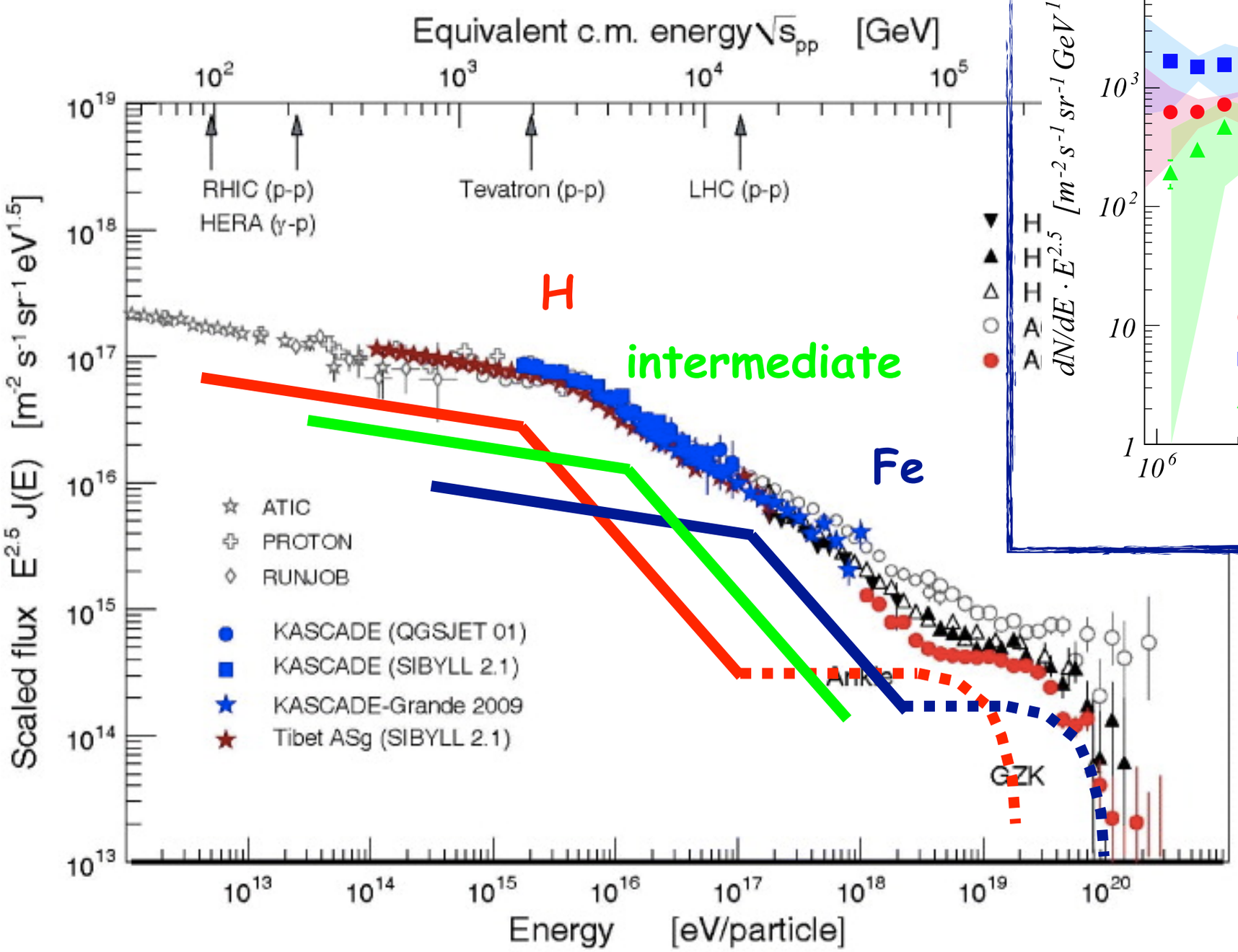

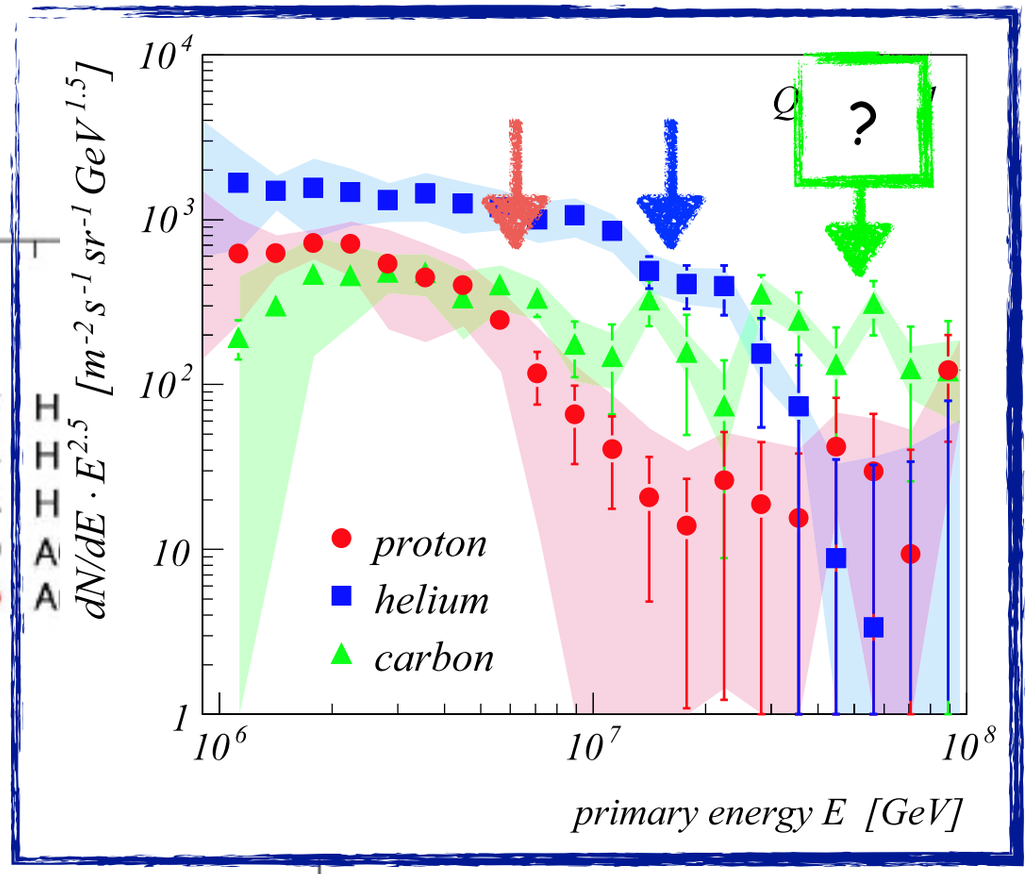

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Z-dependent knee

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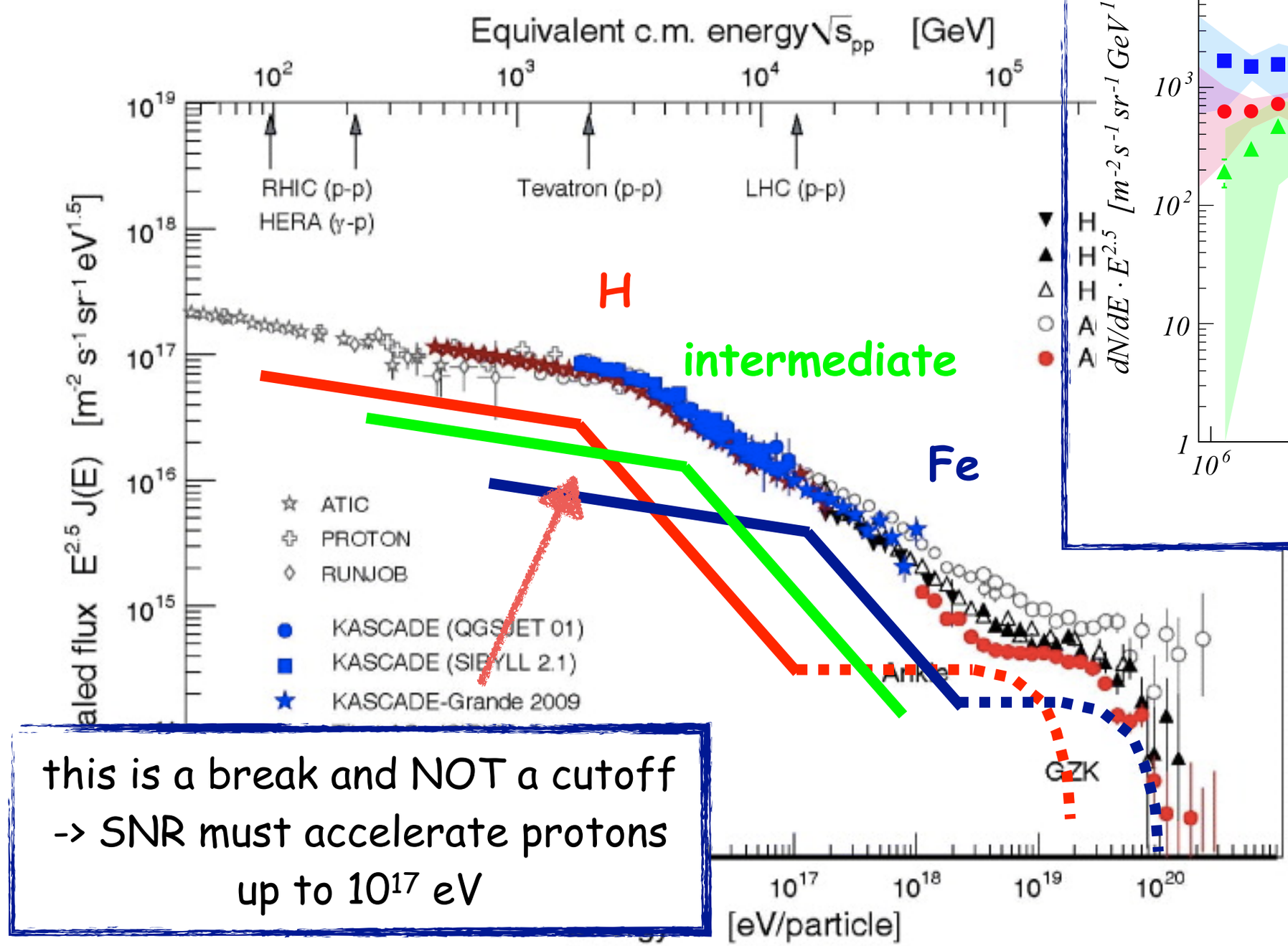
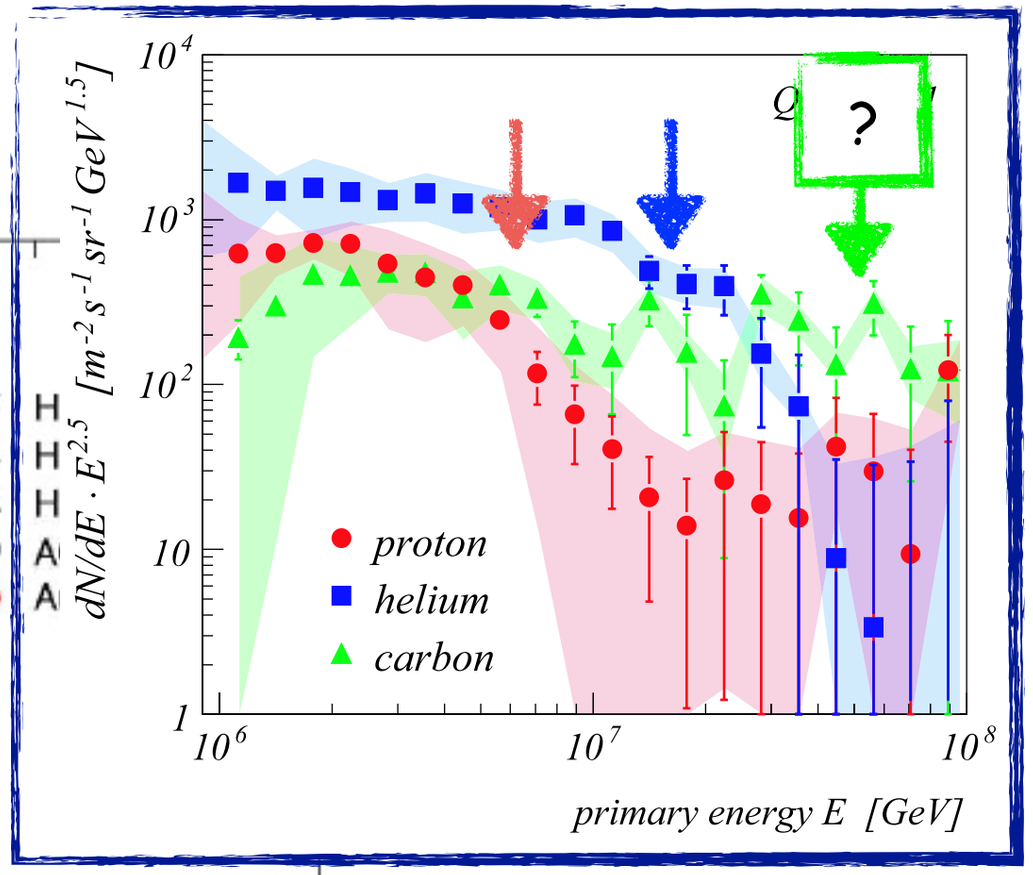


this is a break and NOT a cutoff
-> SNR must accelerate protons
up to 10^{17} eV



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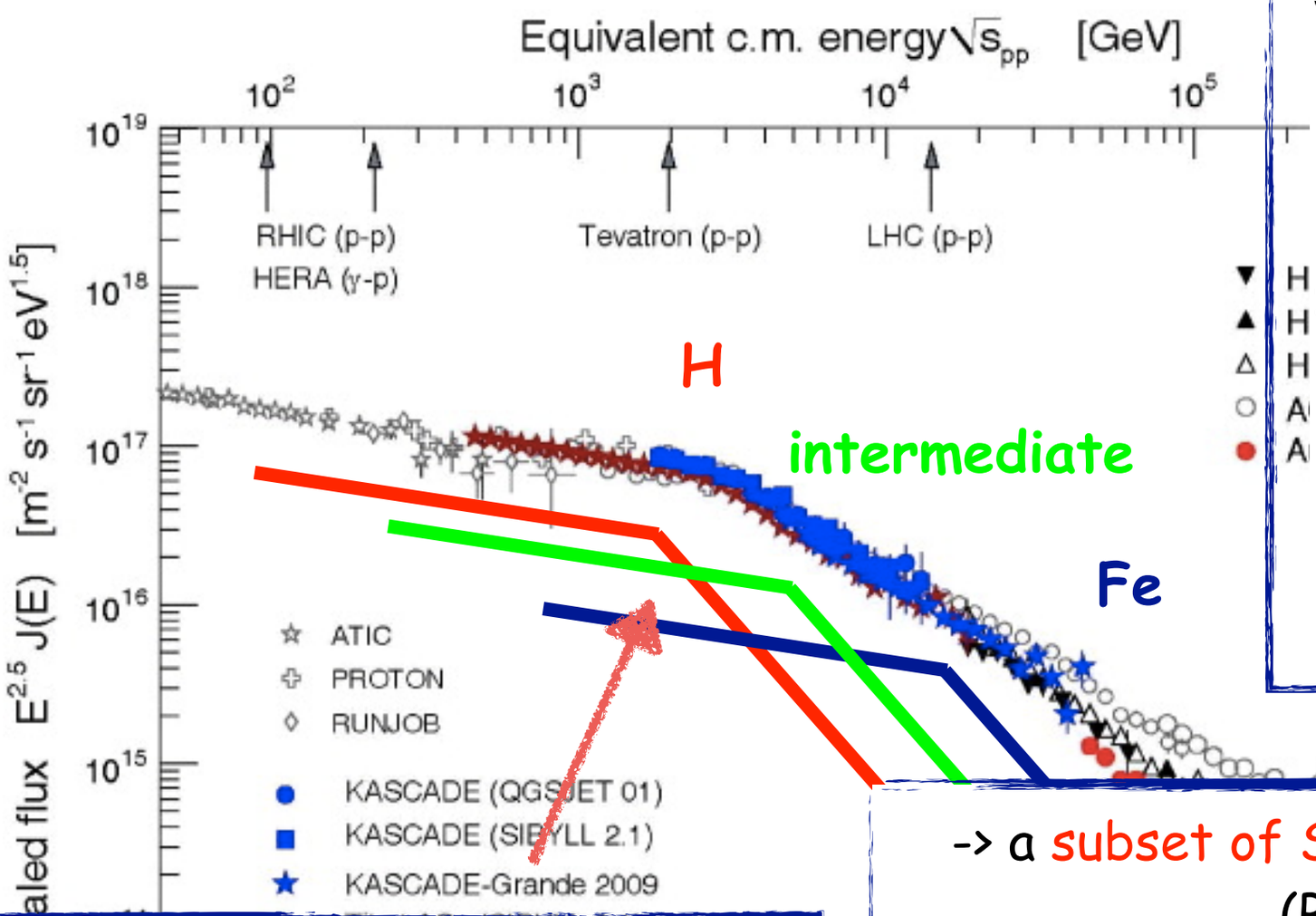
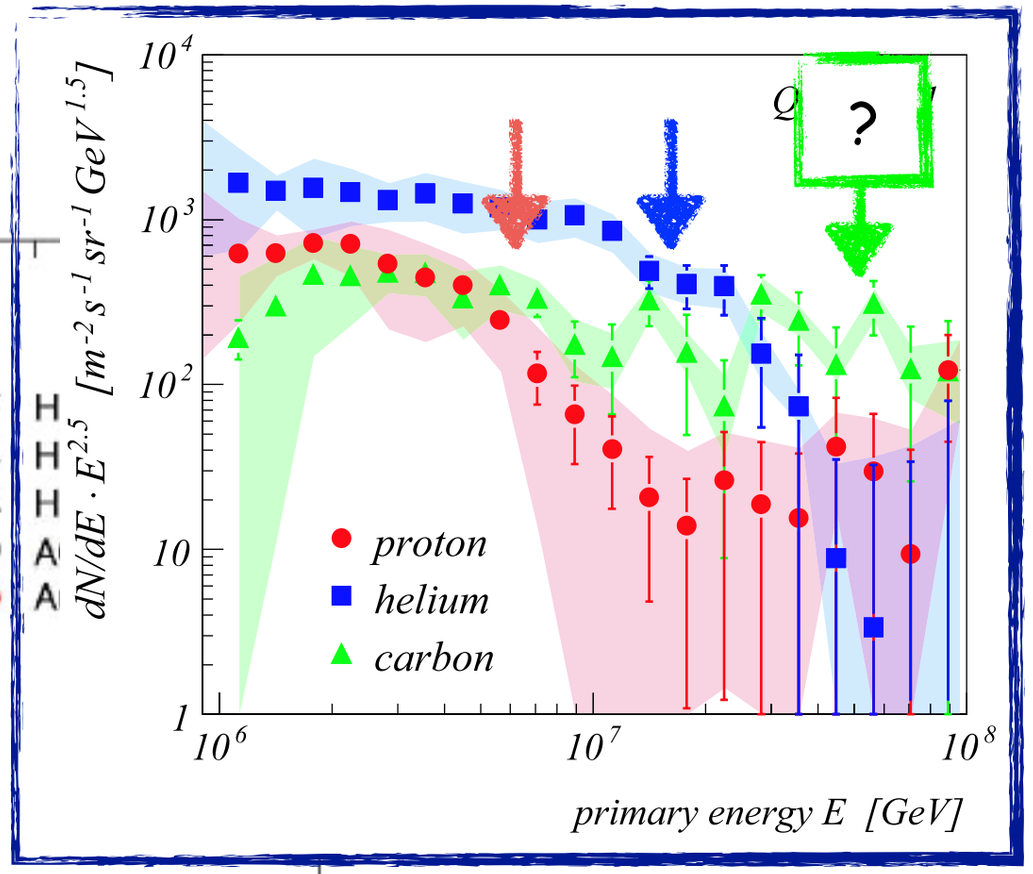
Z-dependent knee

MeV	GeV	TeV	PeV	EeV	ZeV

The EeV domain: Galactic-Extragalactic





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-> 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