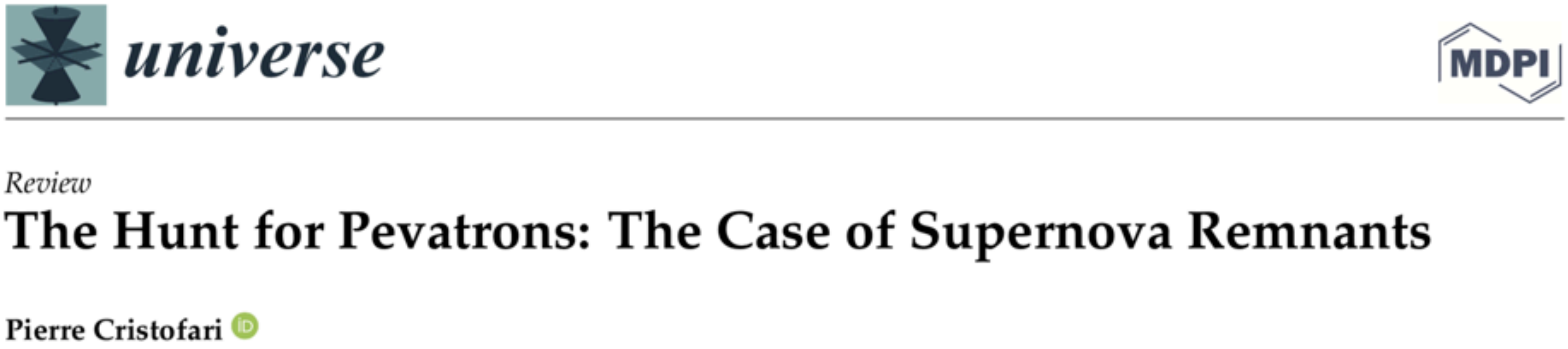
Theory and phenomenology of PeVatrons

Stefano Gabici
APC, Paris



universe

MDPI

Review

The Hunt for Pevatrons: The Case of Supernova Remnants

Pierre Cristofari

cta cherenkov telescope array

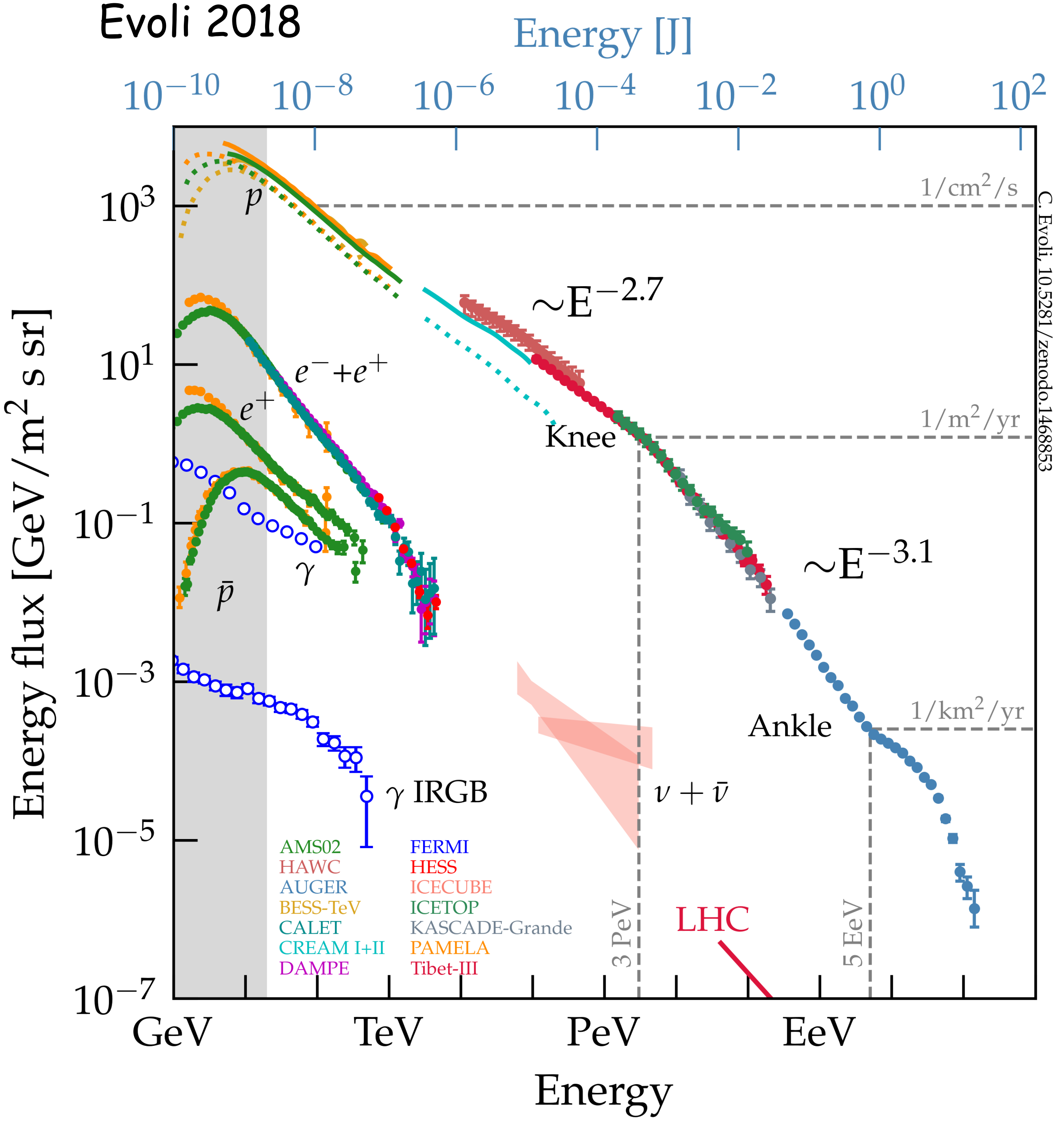
Science with the Cherenkov Telescope Array

arXiv:1709.07997v2 [astro-ph.IM] 22 Jan 2018

search for PeVatrons
—> Key Science
Programme of CTA

Why are PeV cosmic rays important?

Evoli 2018



see Gabici et al. 2019 for a review on Galactic CRs

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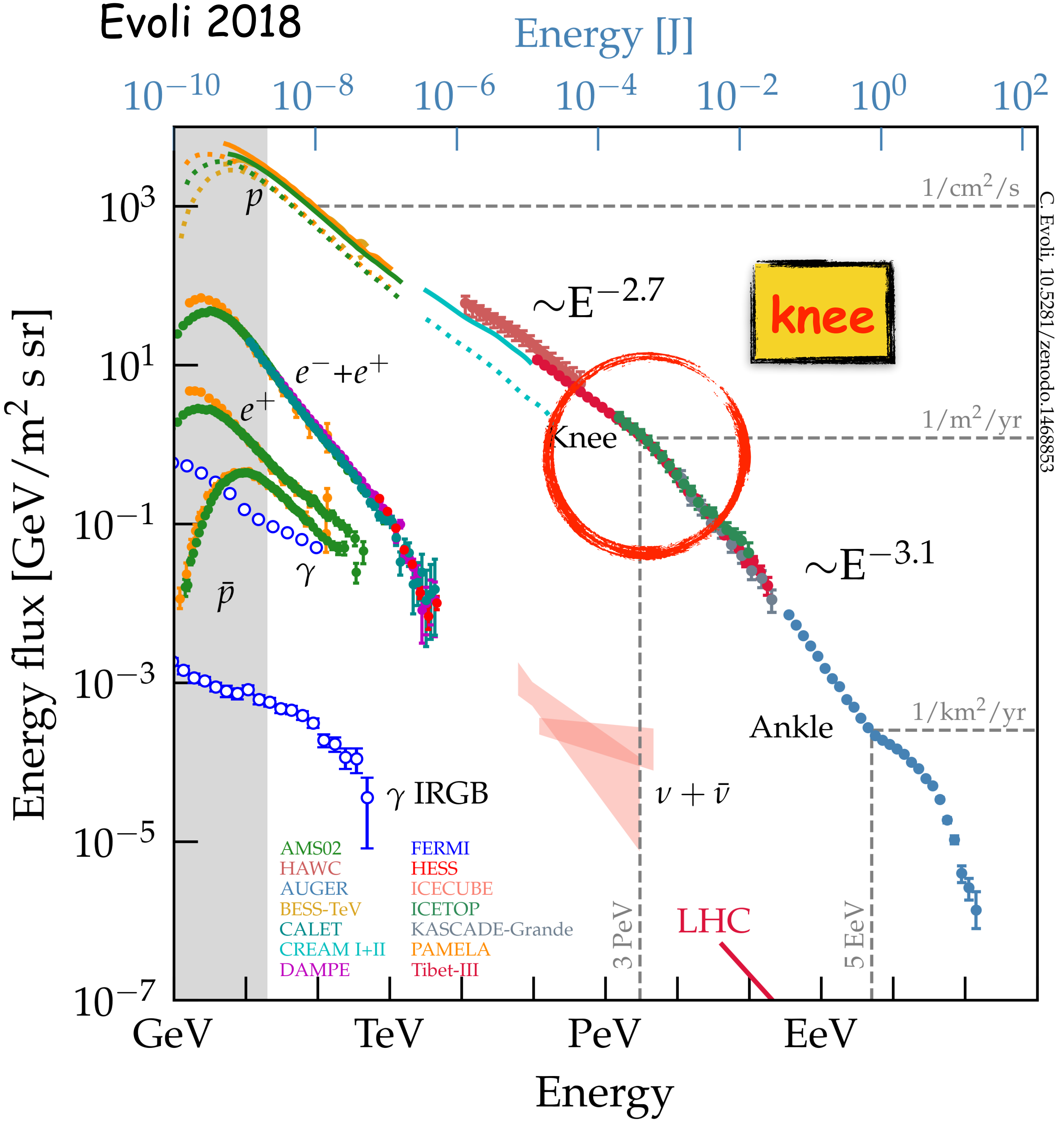

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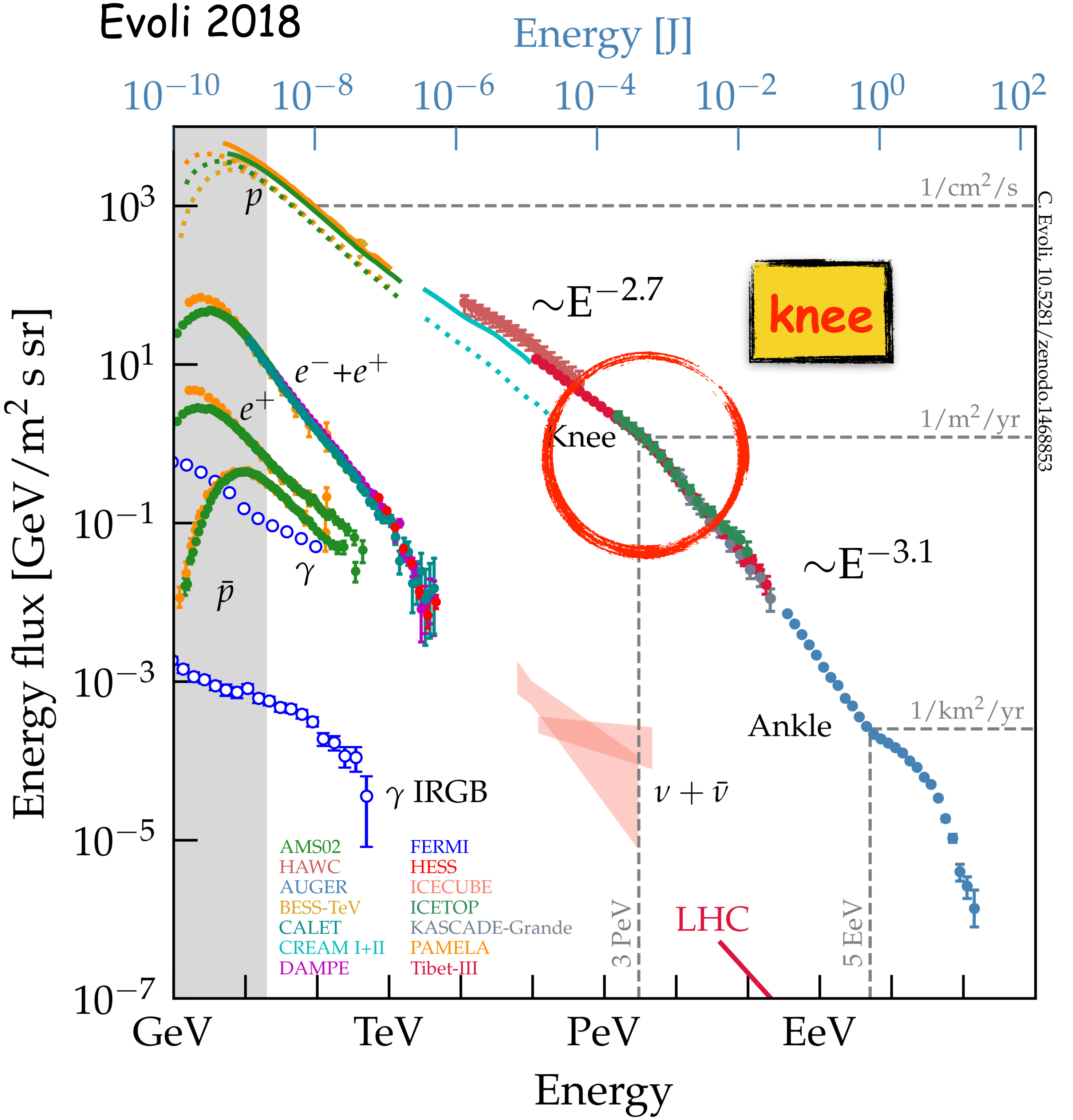
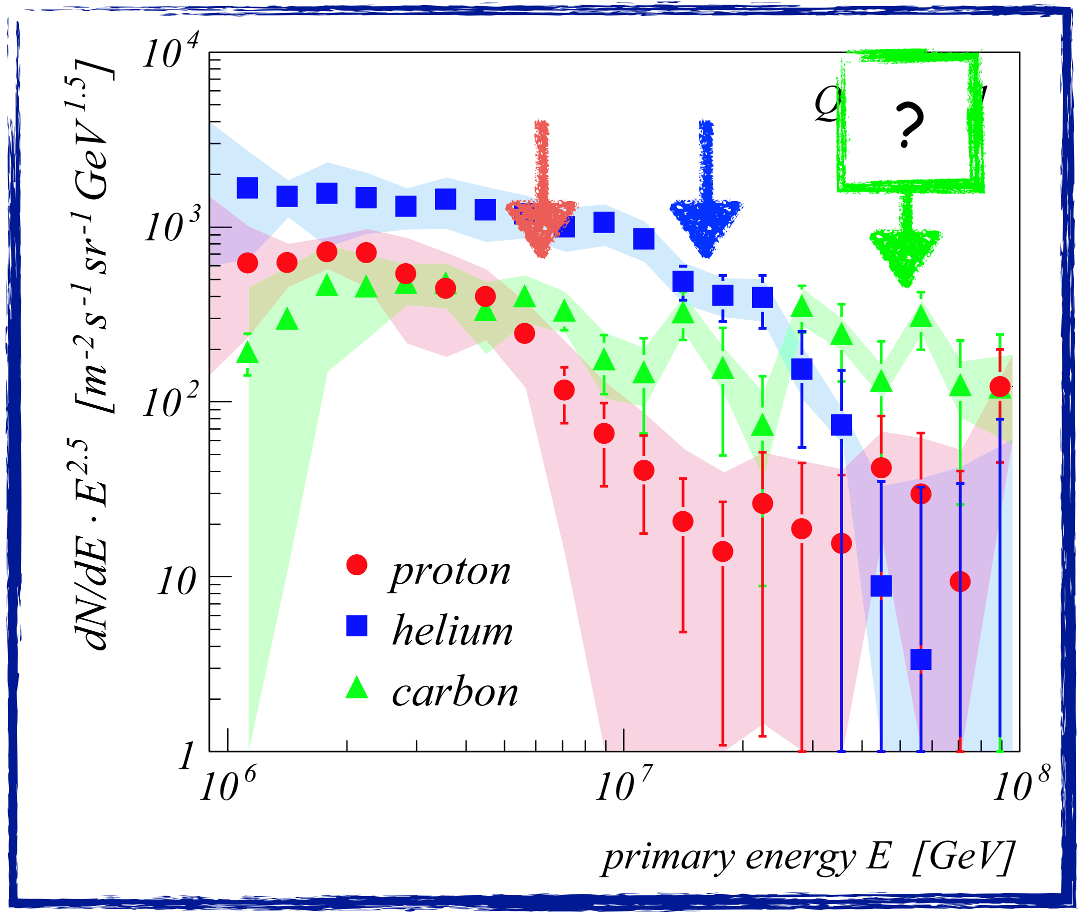
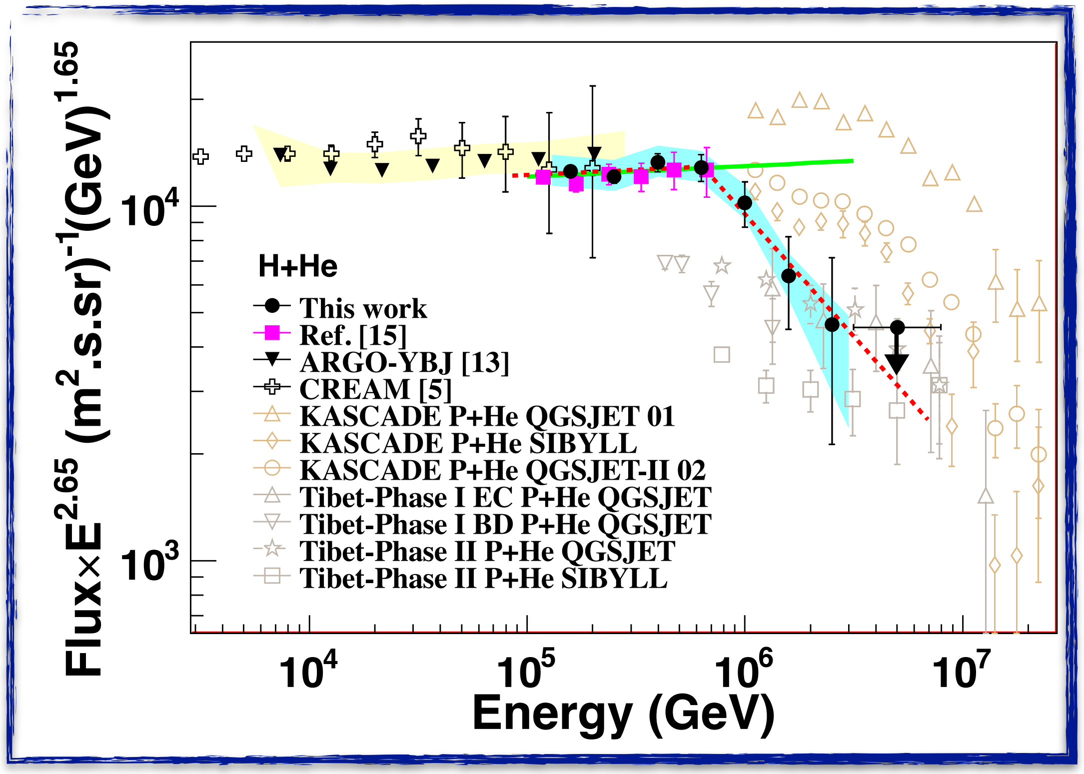




KASCADE coll. 2005



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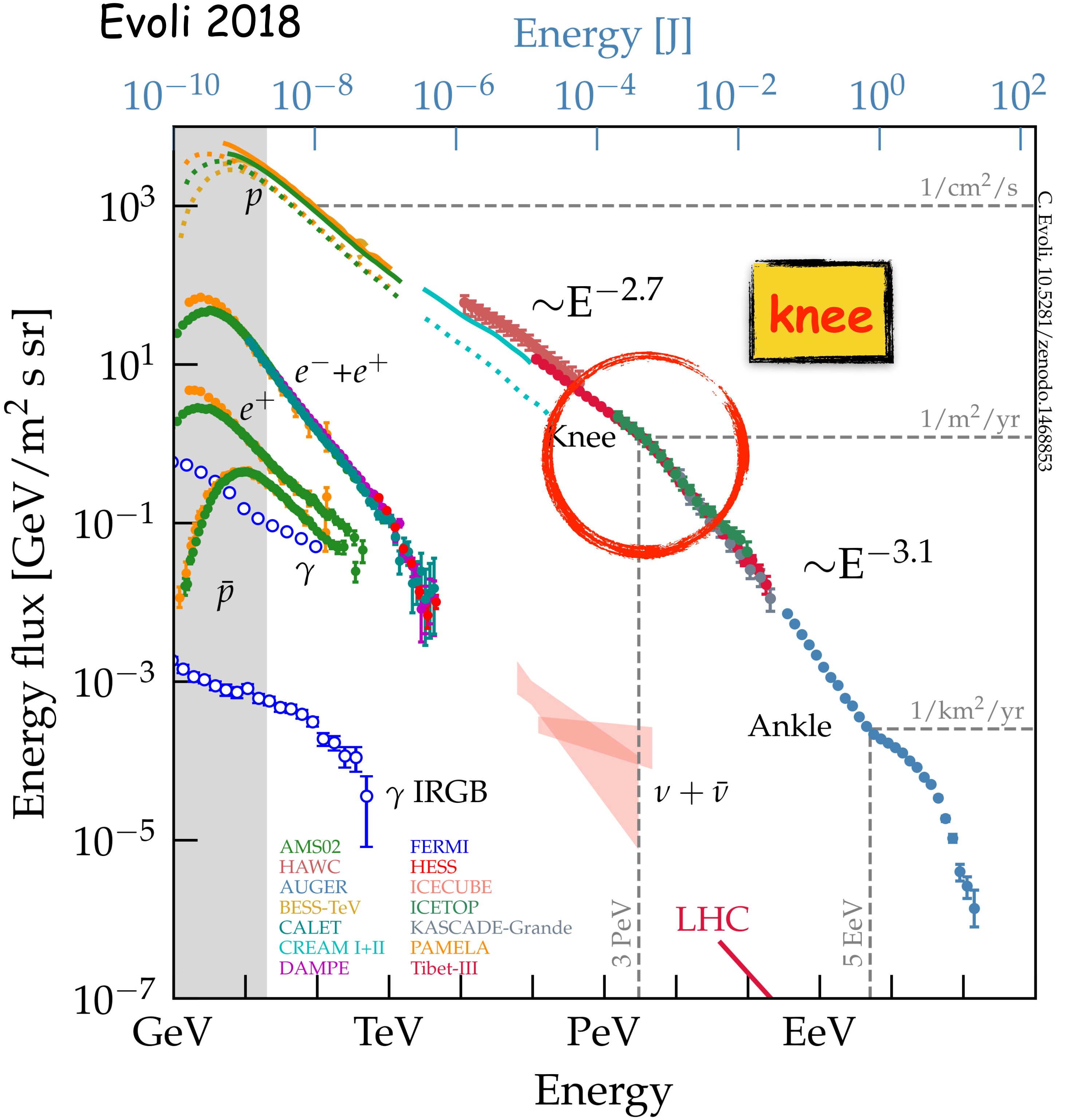

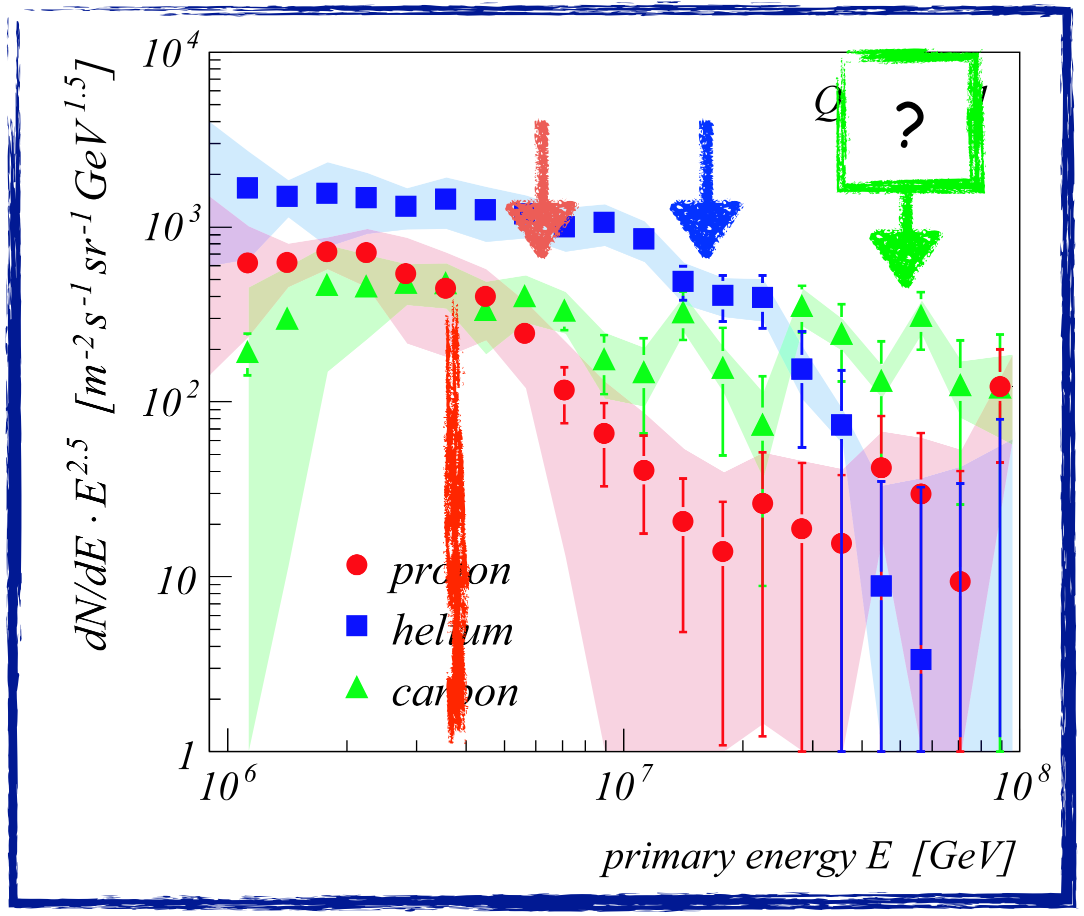

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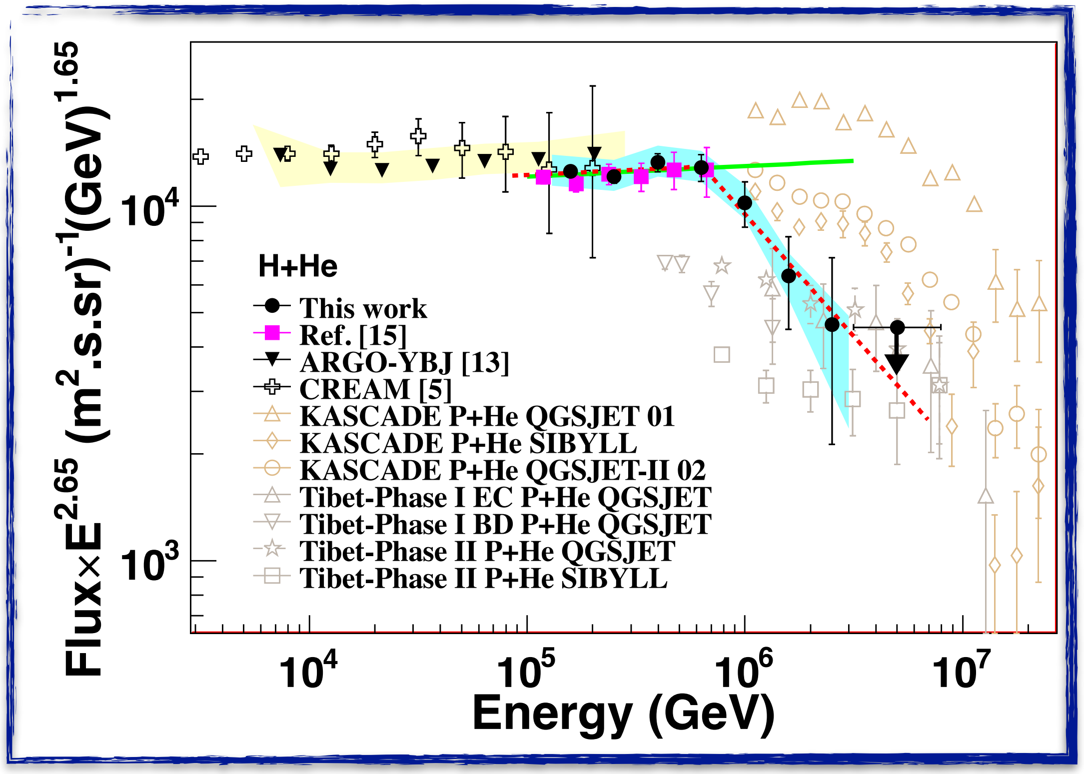

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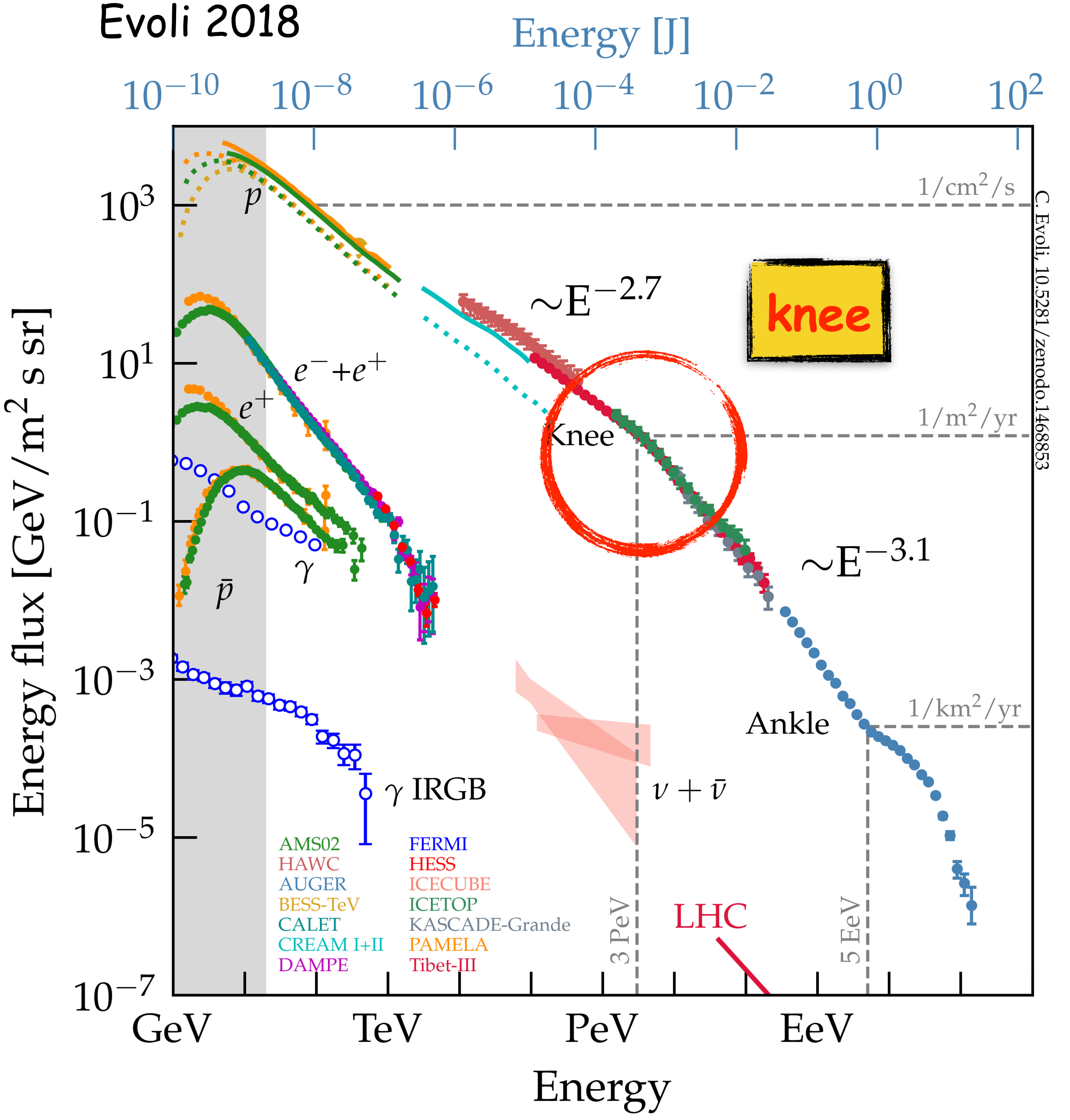

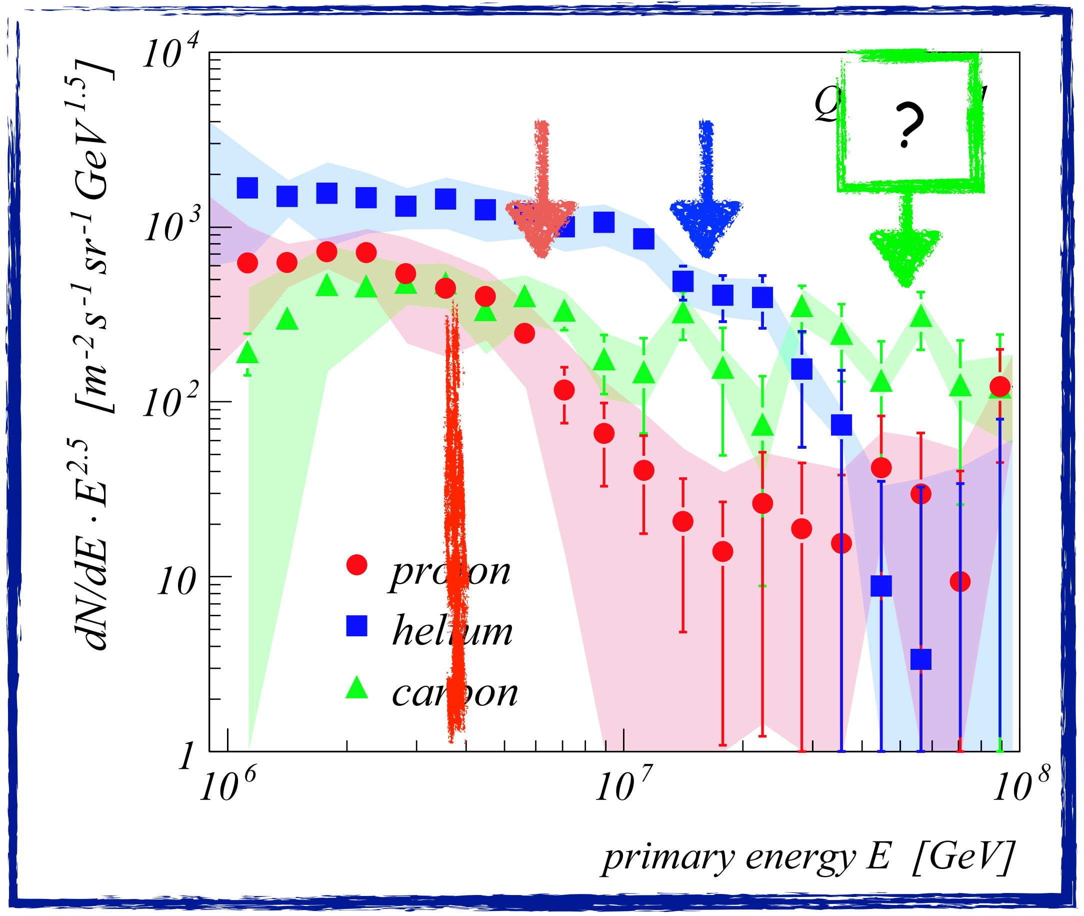

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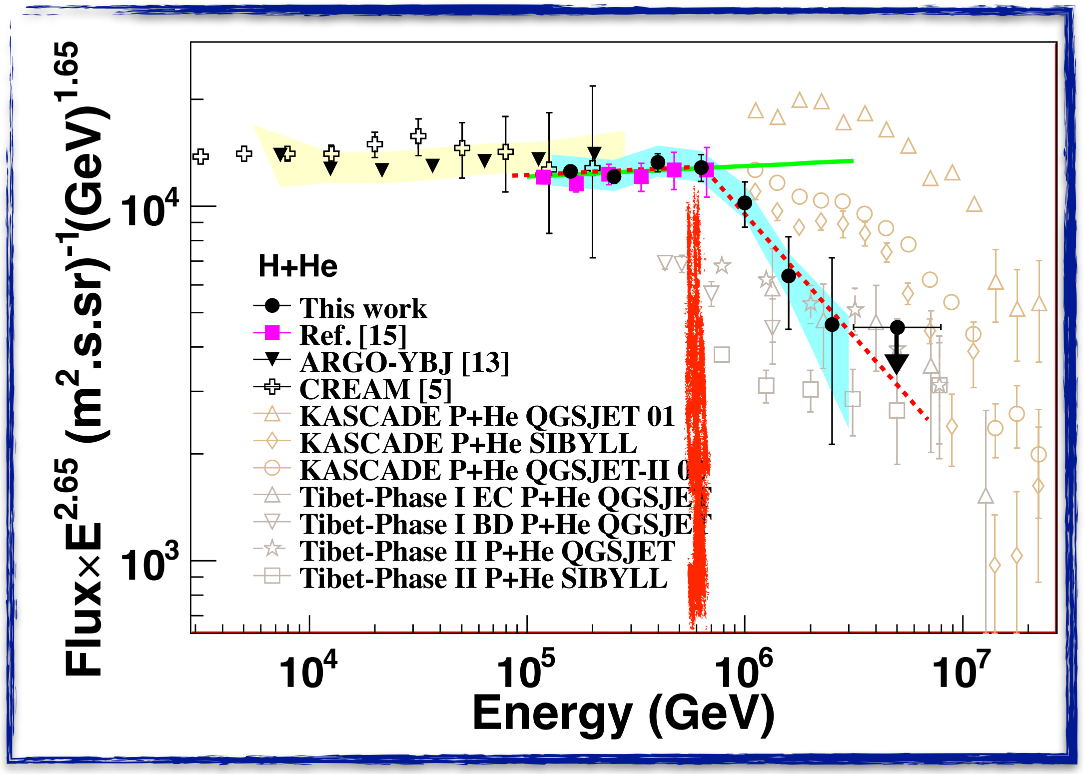

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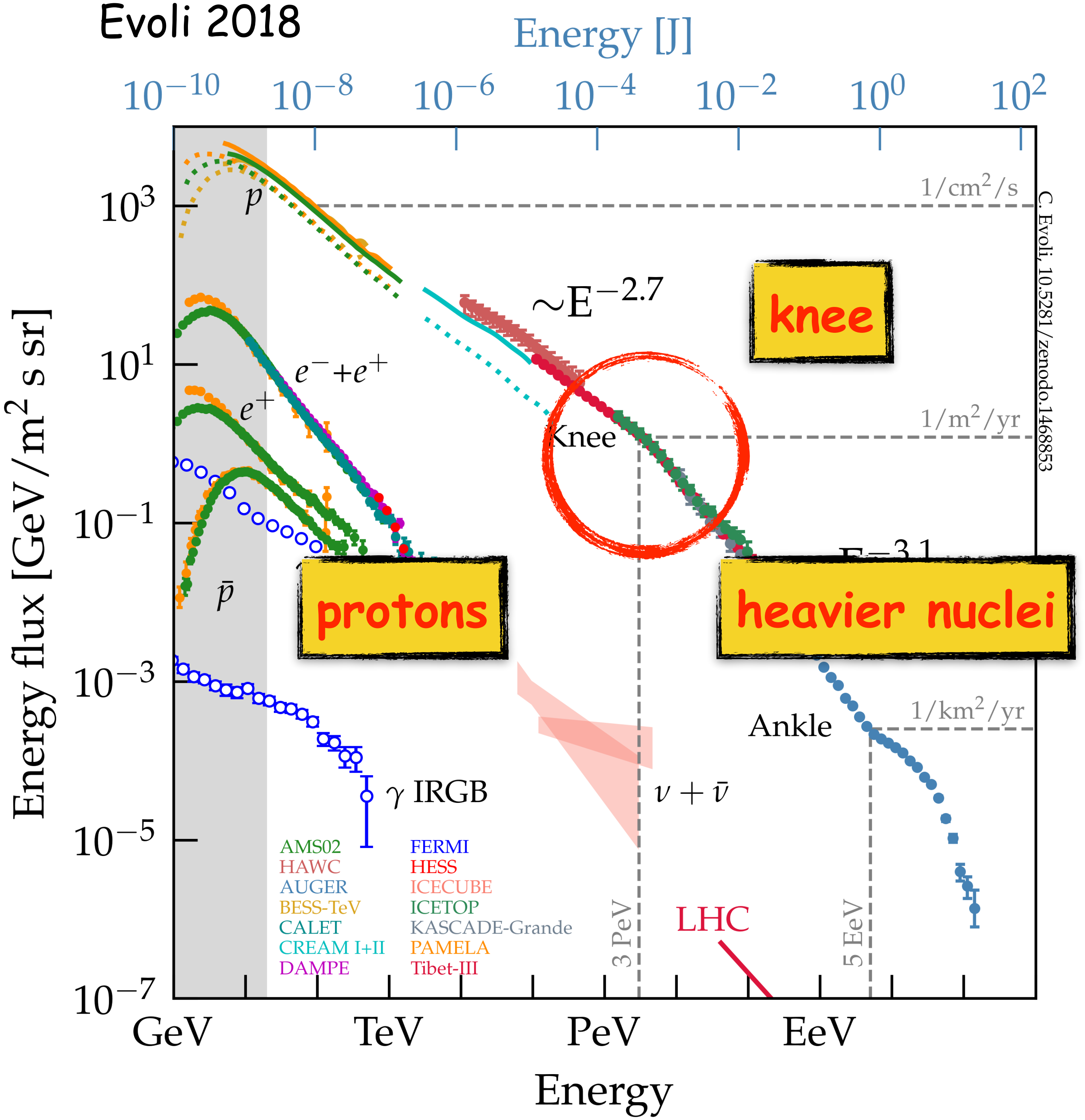
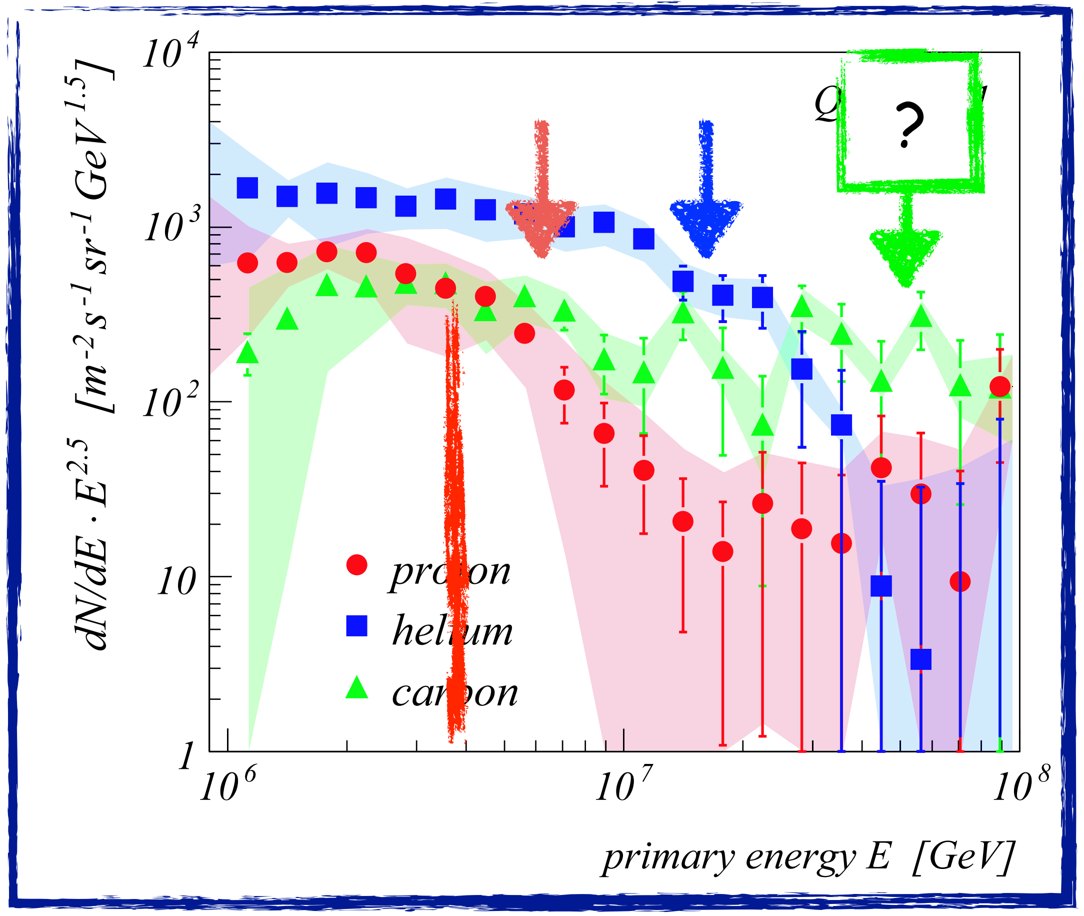


knee

protons

heavier nuclei



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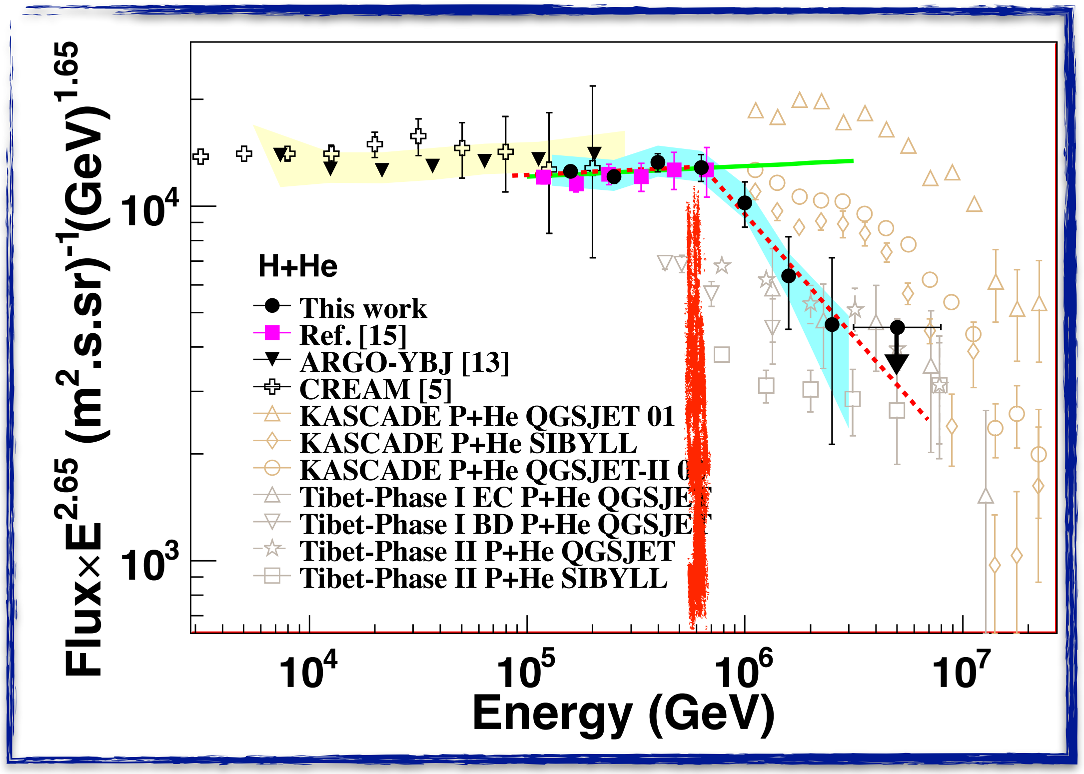

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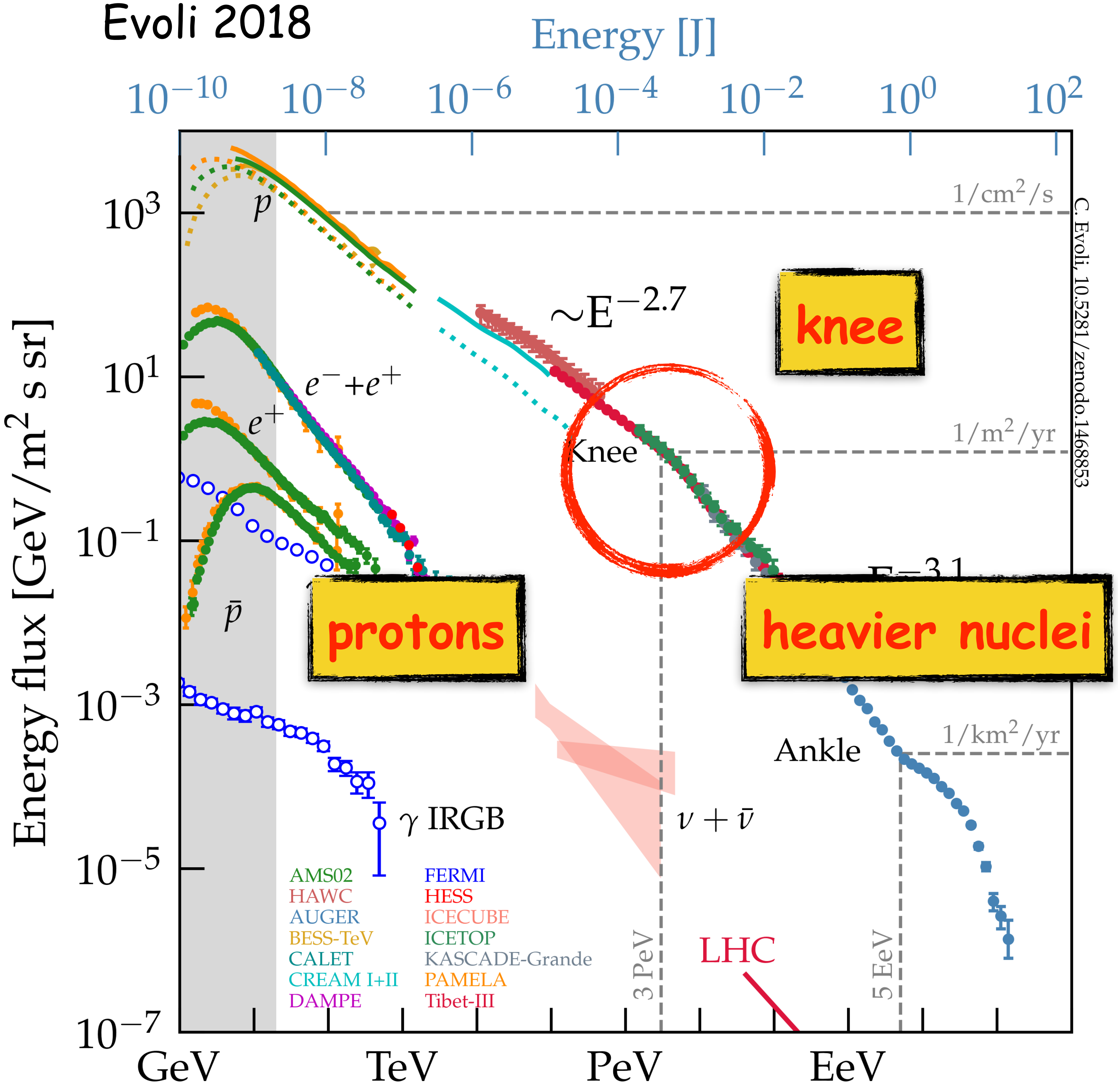

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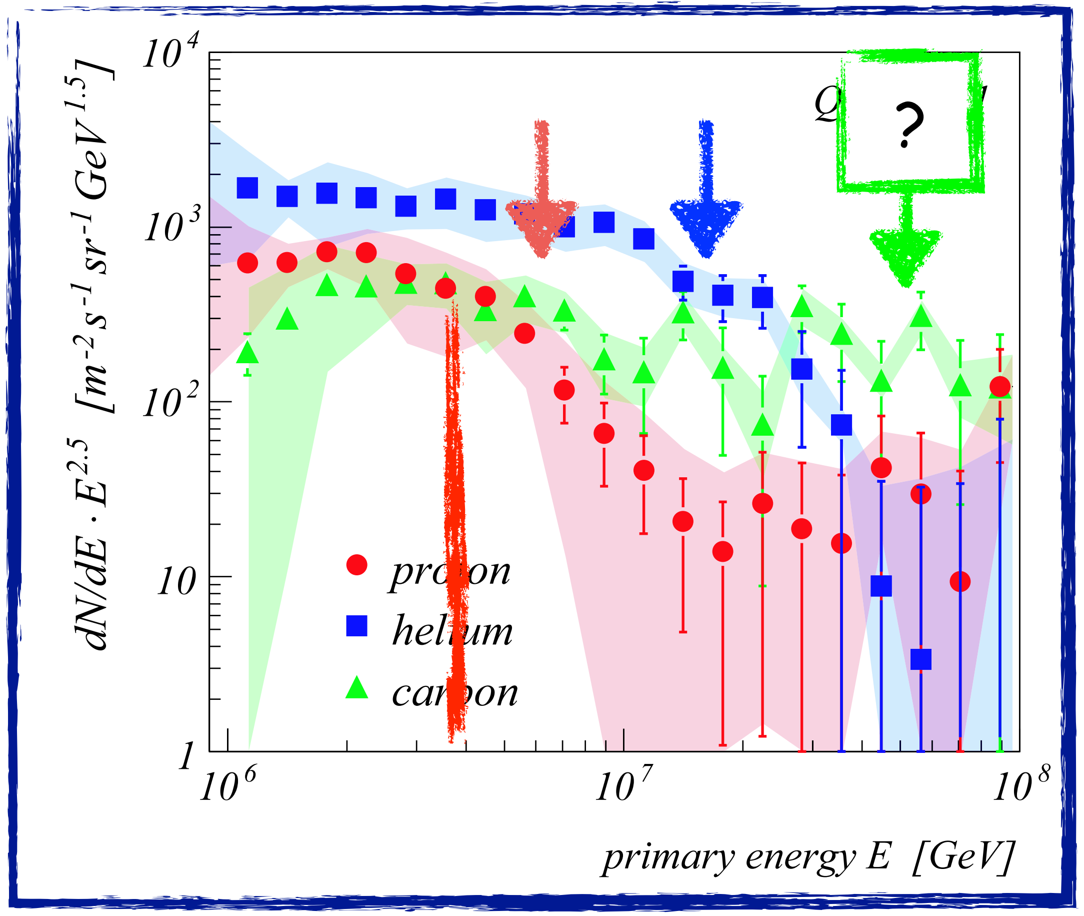

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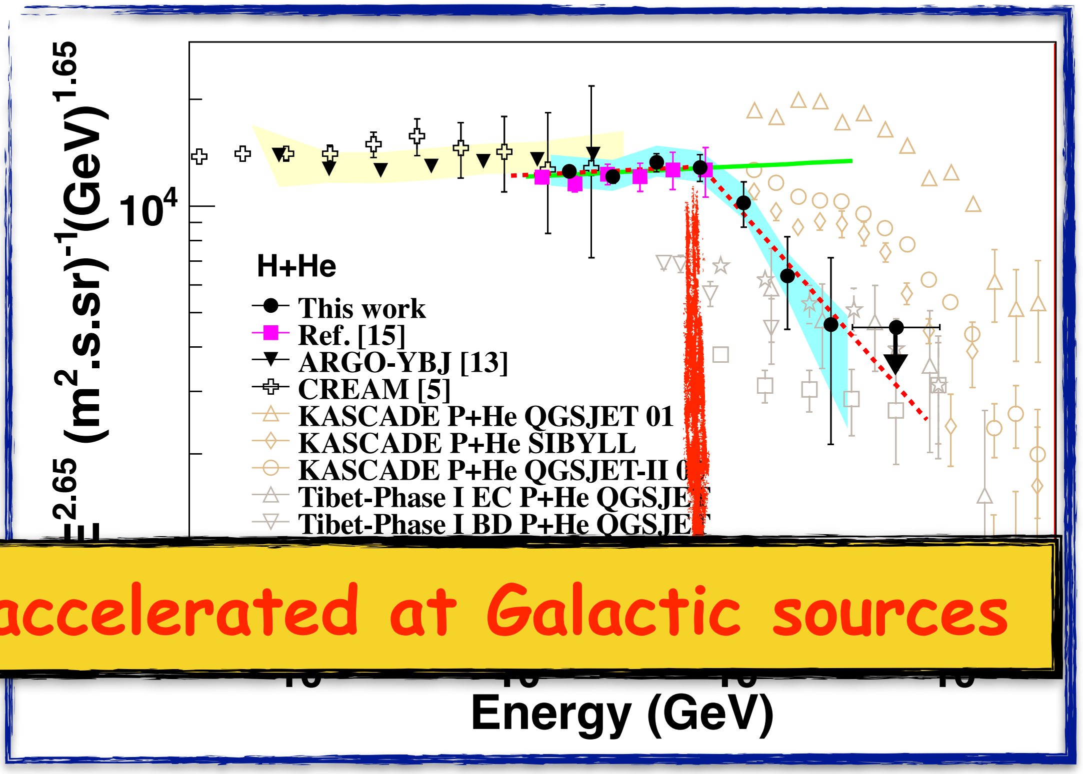
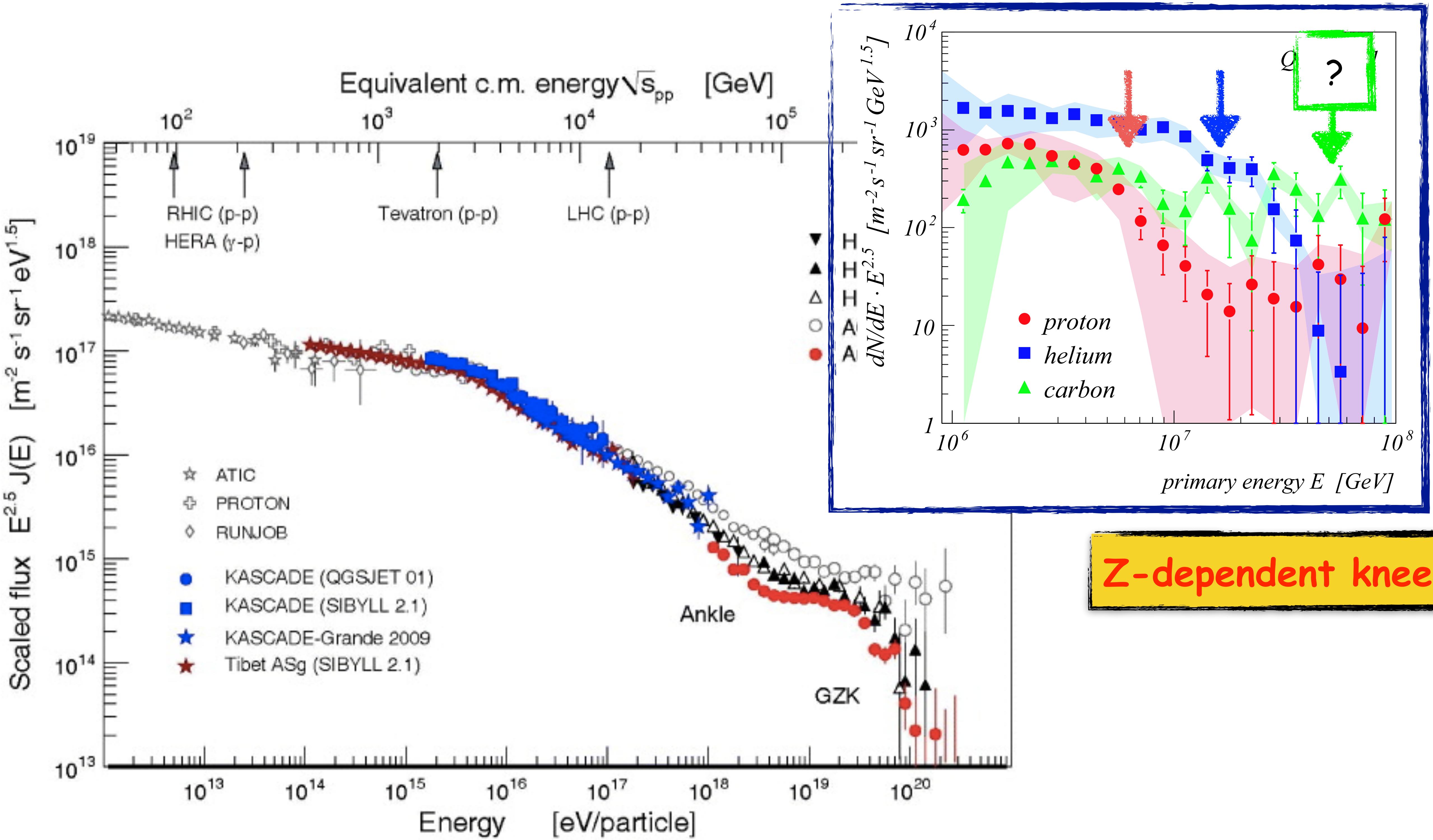


the knee —> maximum(?) energy of protons accelerated at Galactic sources

see Gabici et al. 2019 for a review on Galactic CRs

In fact, we need to go BEYOND the PeV



KASCADE coll. 2005

Z-dependent knee

see Parizot 2014 for a review on the Gal/ExGal transition

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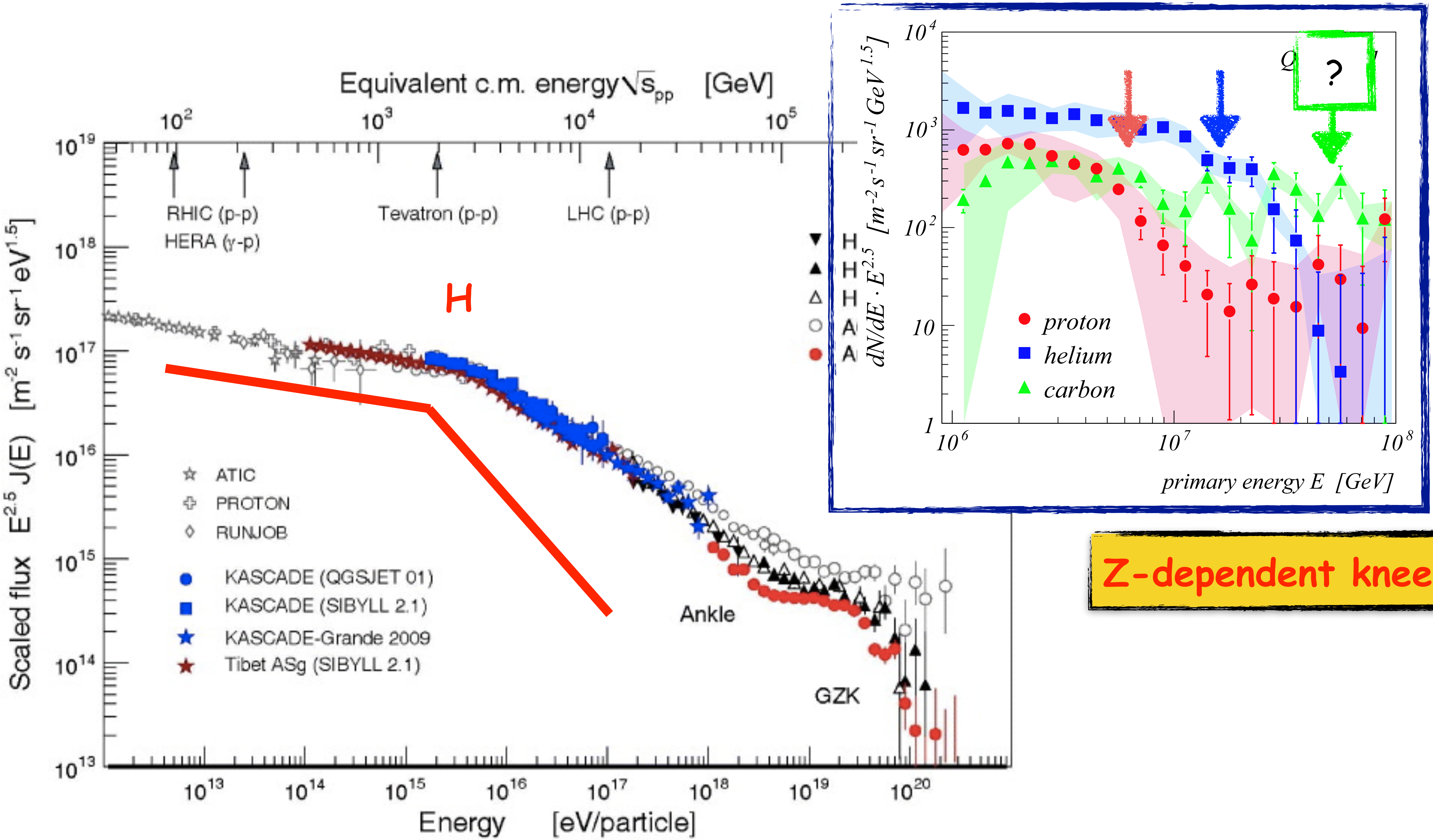

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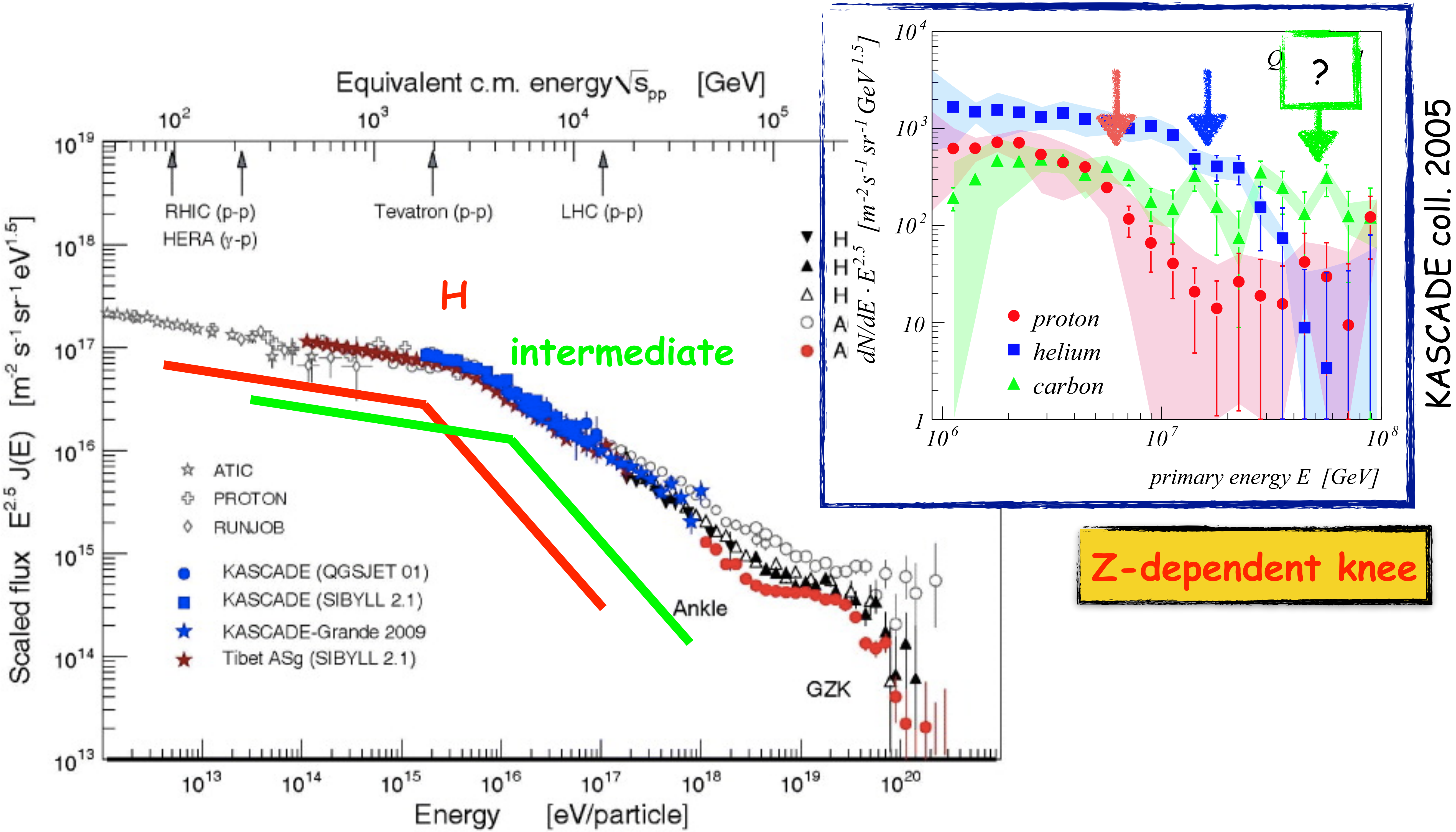

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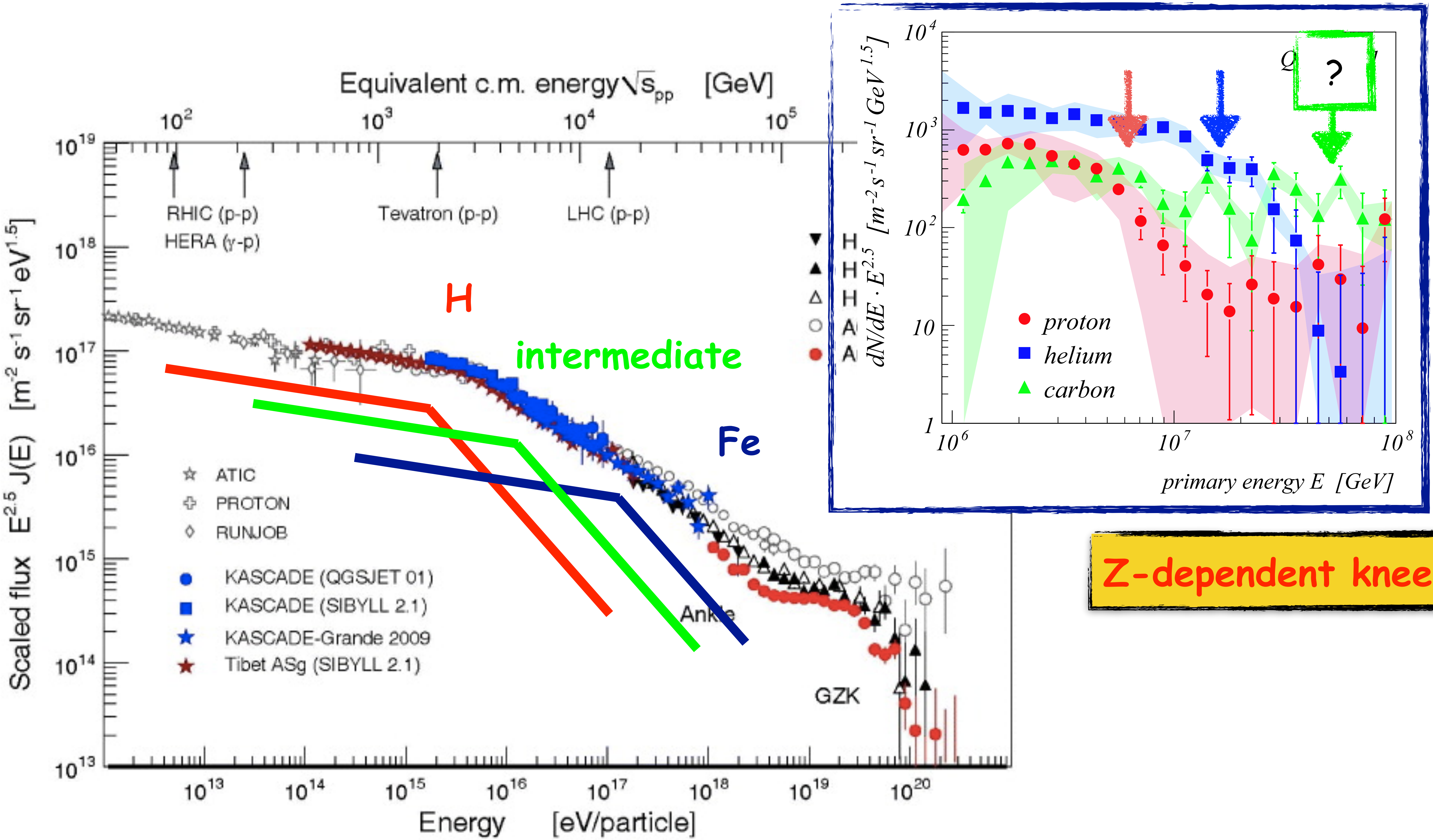

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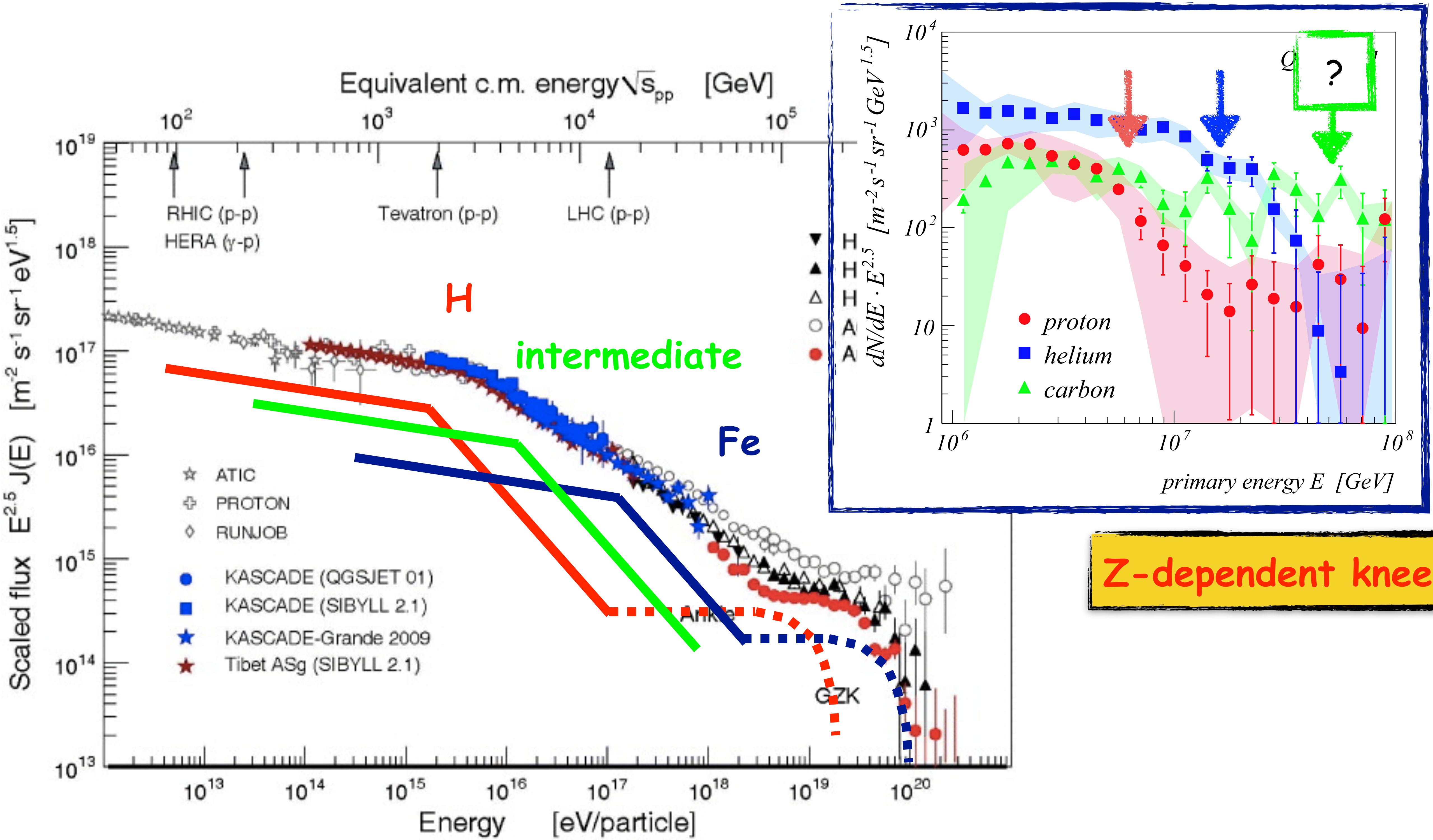

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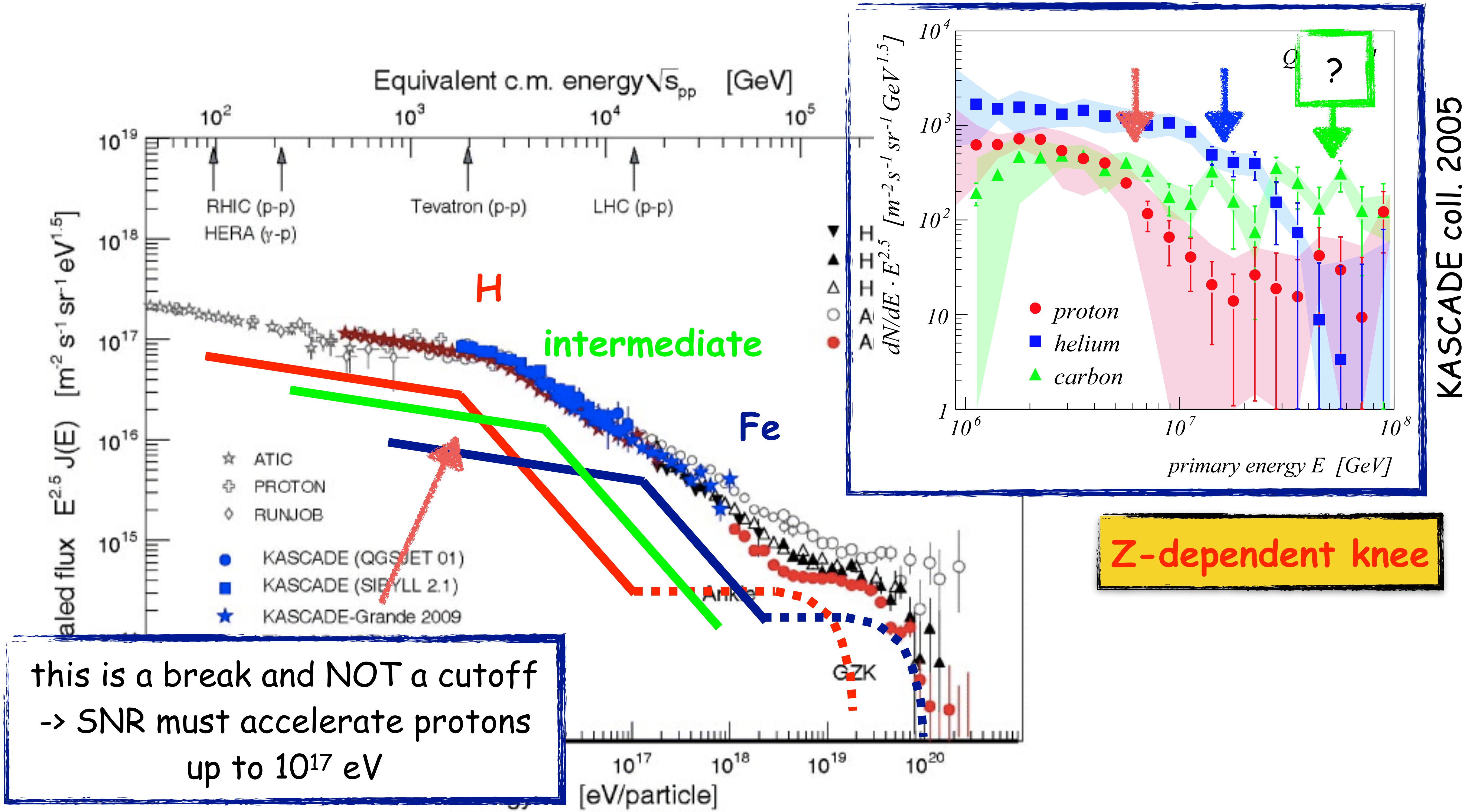

this is a break and NOT a cutoff
-> SNR must accelerate protons
up to 10^{17} eV

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see Parizot 2014 for a review on the Gal/ExGal transition

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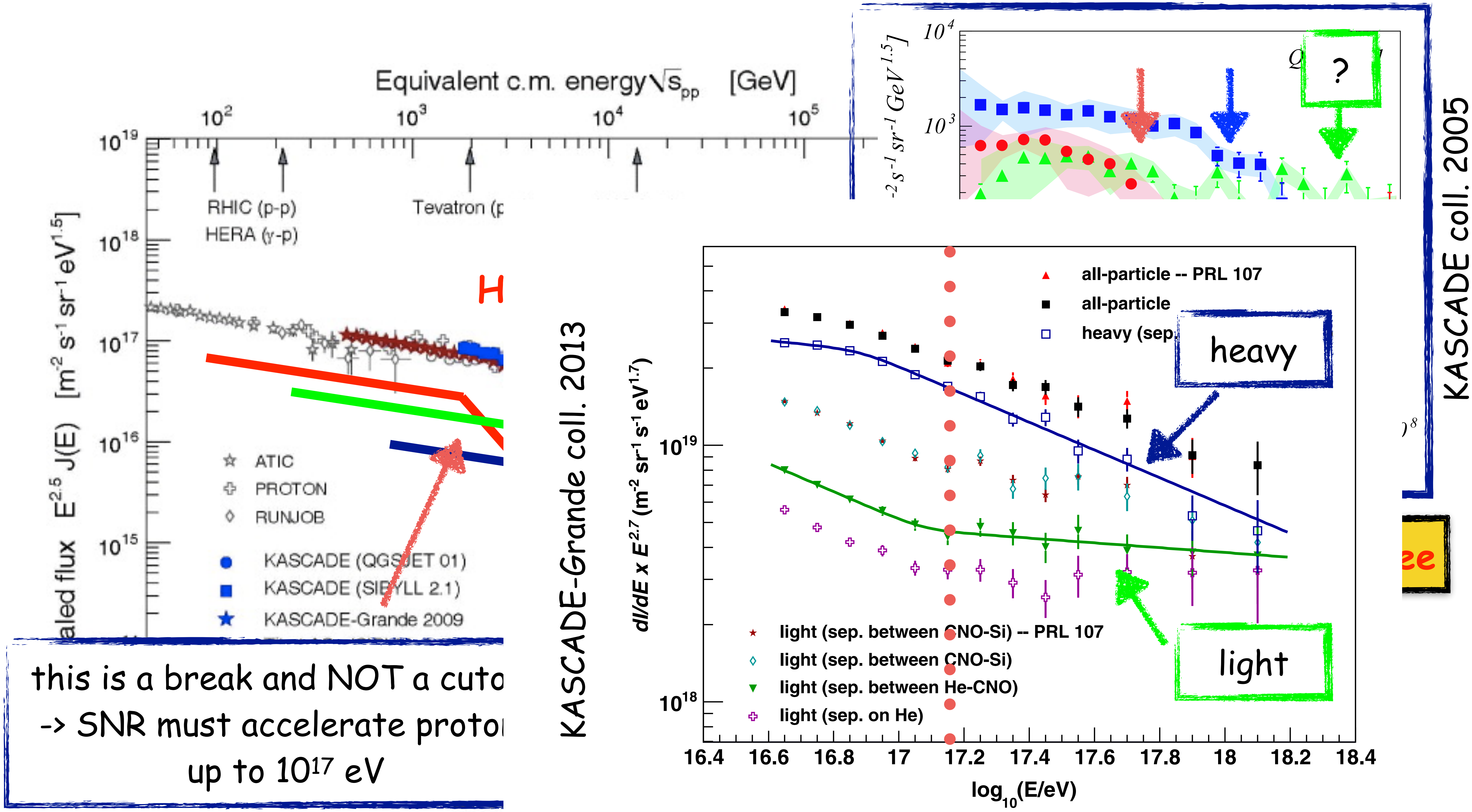

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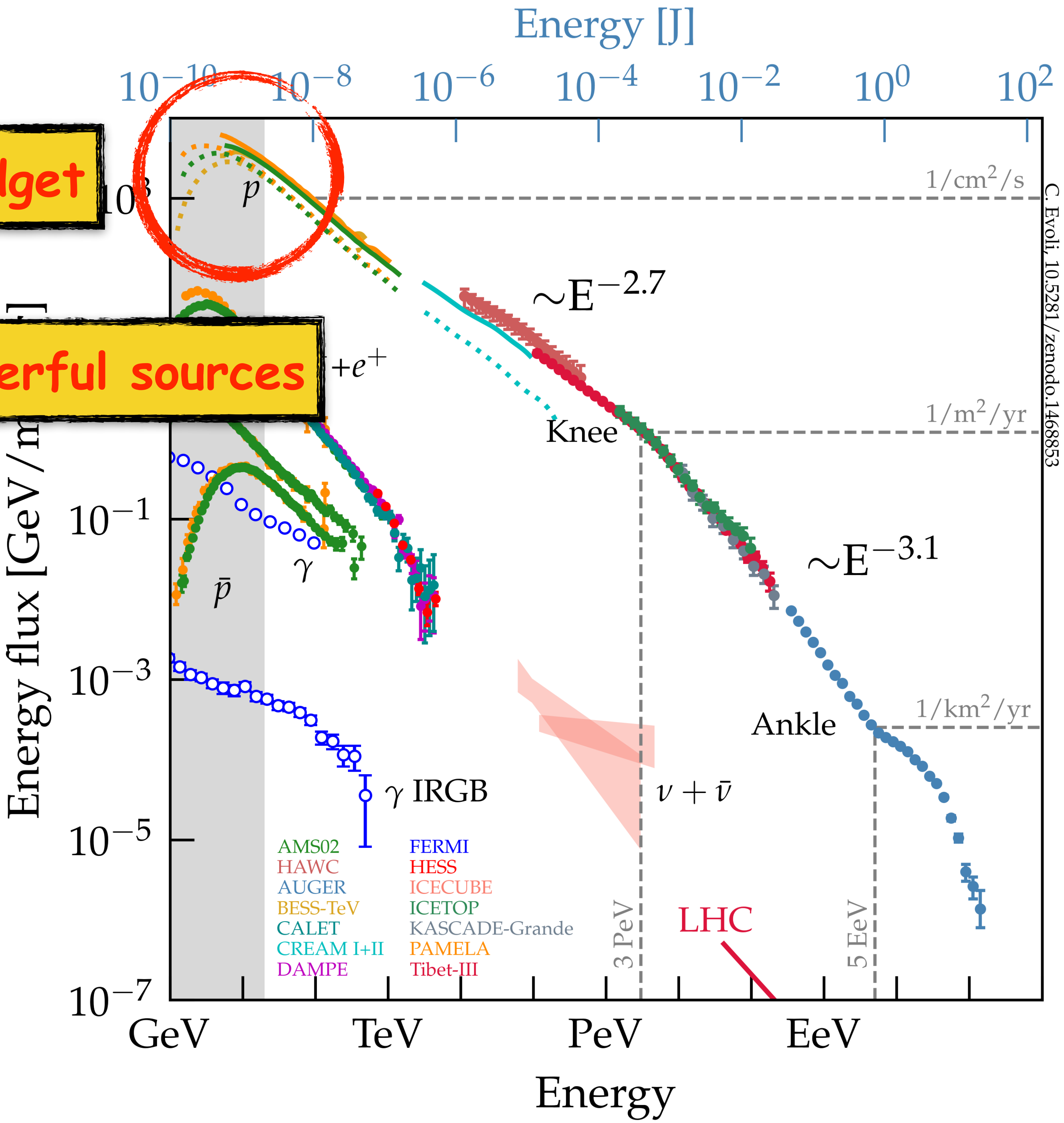
KASCADE-Grande coll. 2013

KASCADE coll. 2005

see Parizot 2014 for a review on the Gal/ExGal transition

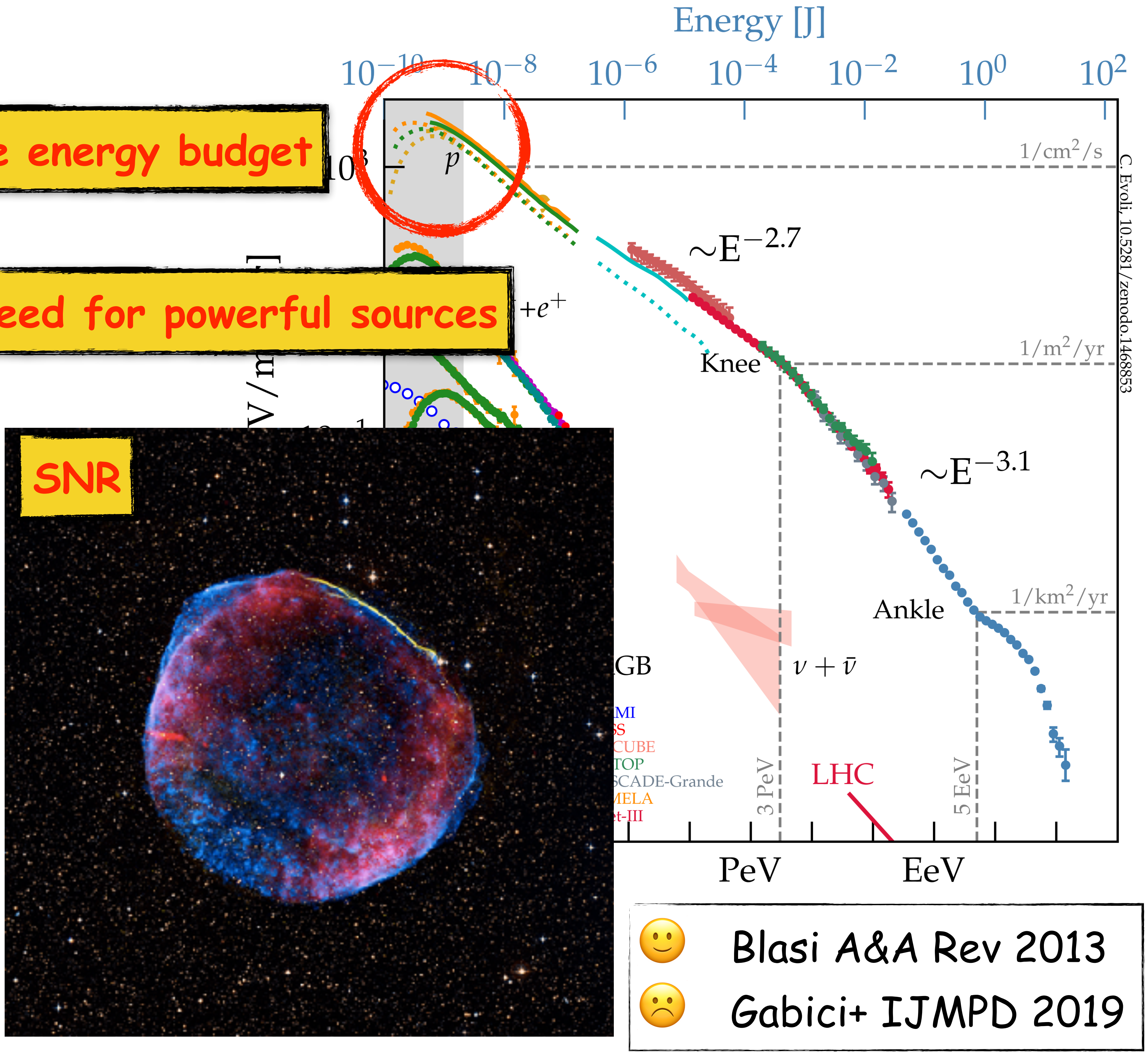
Popular scenario: DSA @ SNR shocks



large energy budget

need for powerful sources

Popular scenario: DSA @ SNR shocks



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🙂 Blasi A&A Rev 2013

☹️ Gabici+ IJMPD 2019

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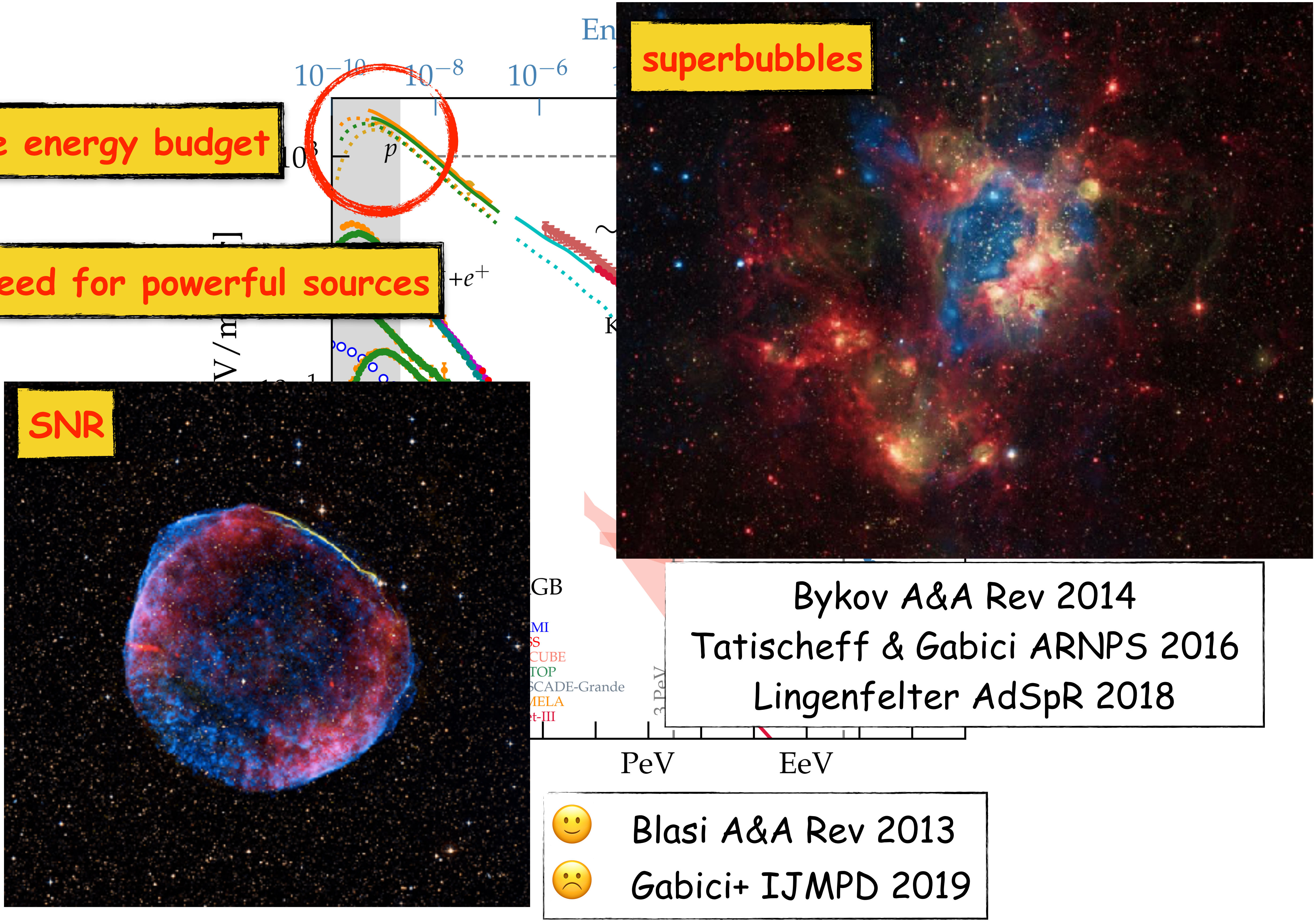

large energy budget

need for powerful sources

superbubbles

SNR

Bykov A&A Rev 2014
Tatischeff & Gabici ARNPS 2016
Lingenfelter AdSpR 2018

🙂 Blasi A&A Rev 2013
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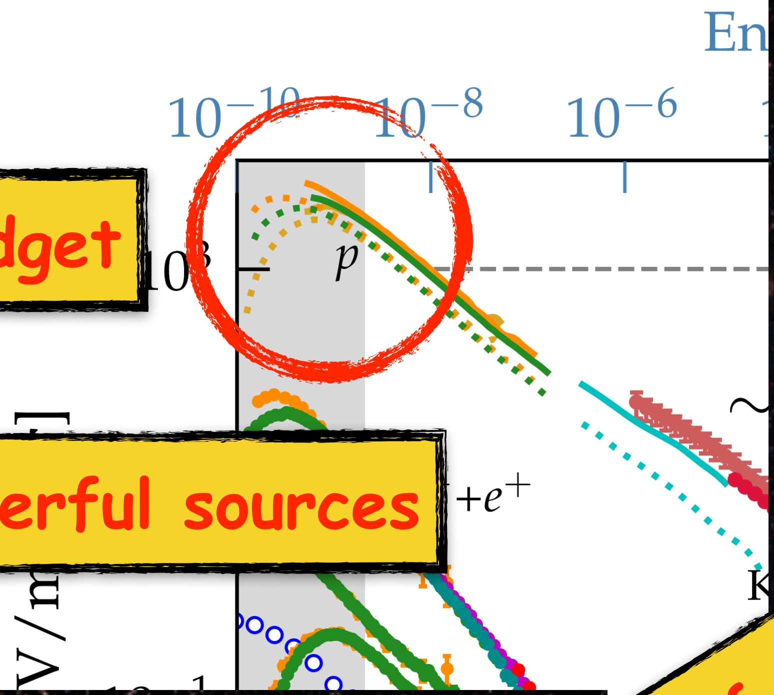
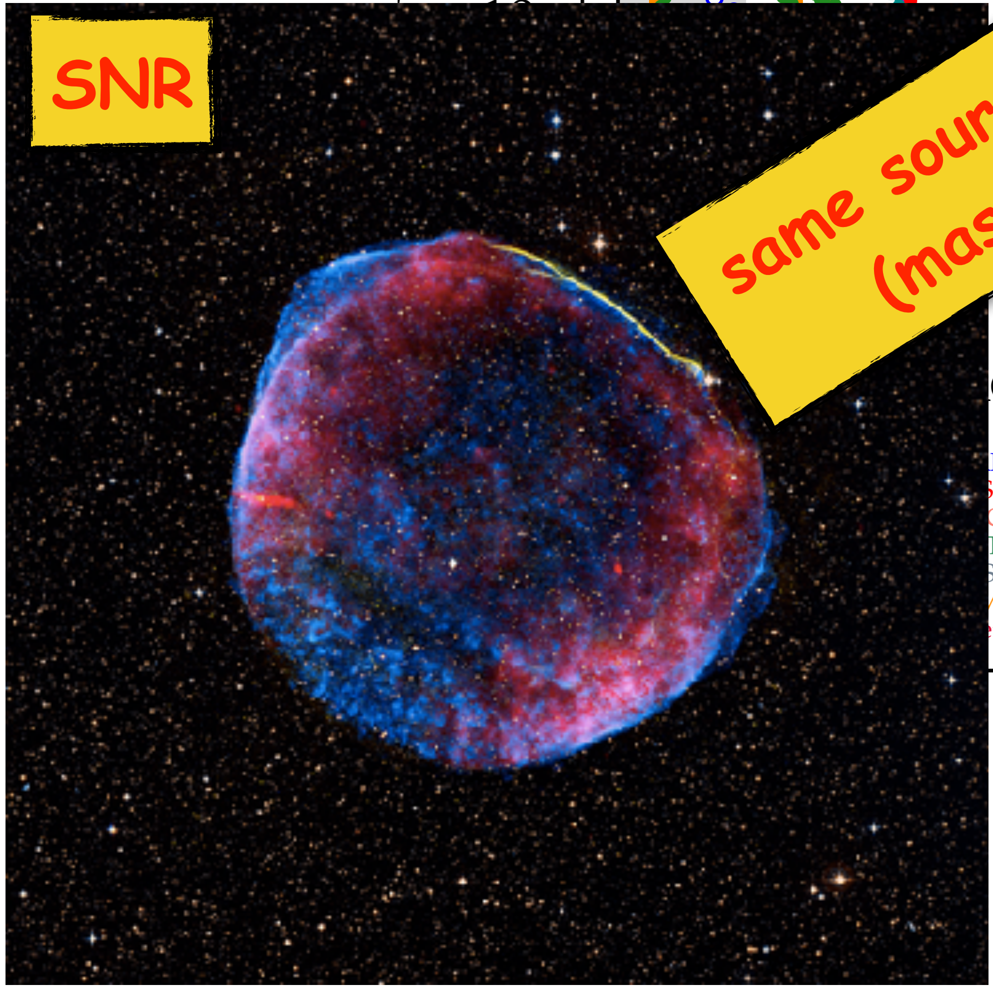


same source of energy (massive stars)

Bykov A&A Rev 2014
Tatischeff & Gabici ARNPS 2016
Lingenfelter AdSpR 2018



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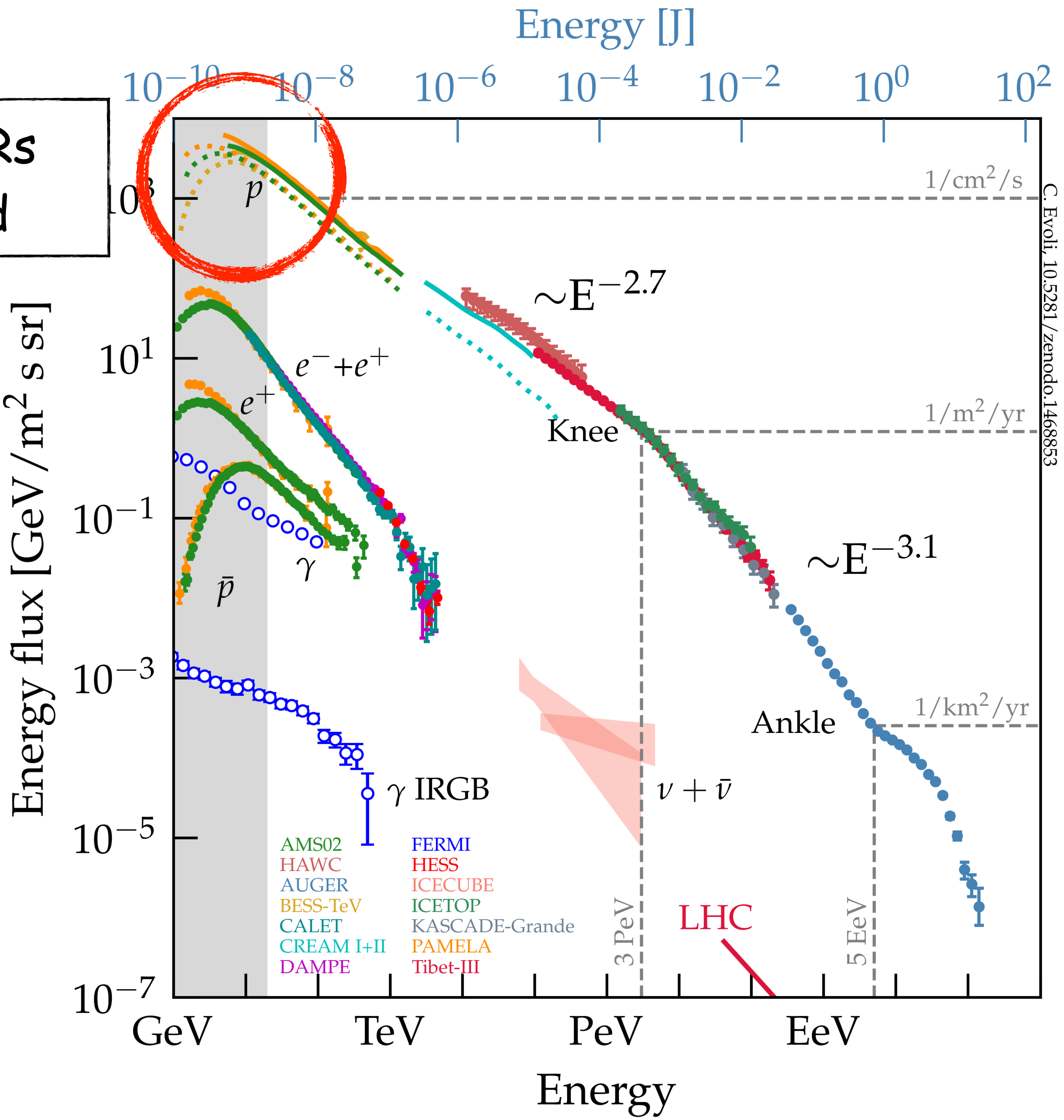
Popular scenario: DSA @ SNR shocks

what about PeV SNR?

this is why SNRs were proposed



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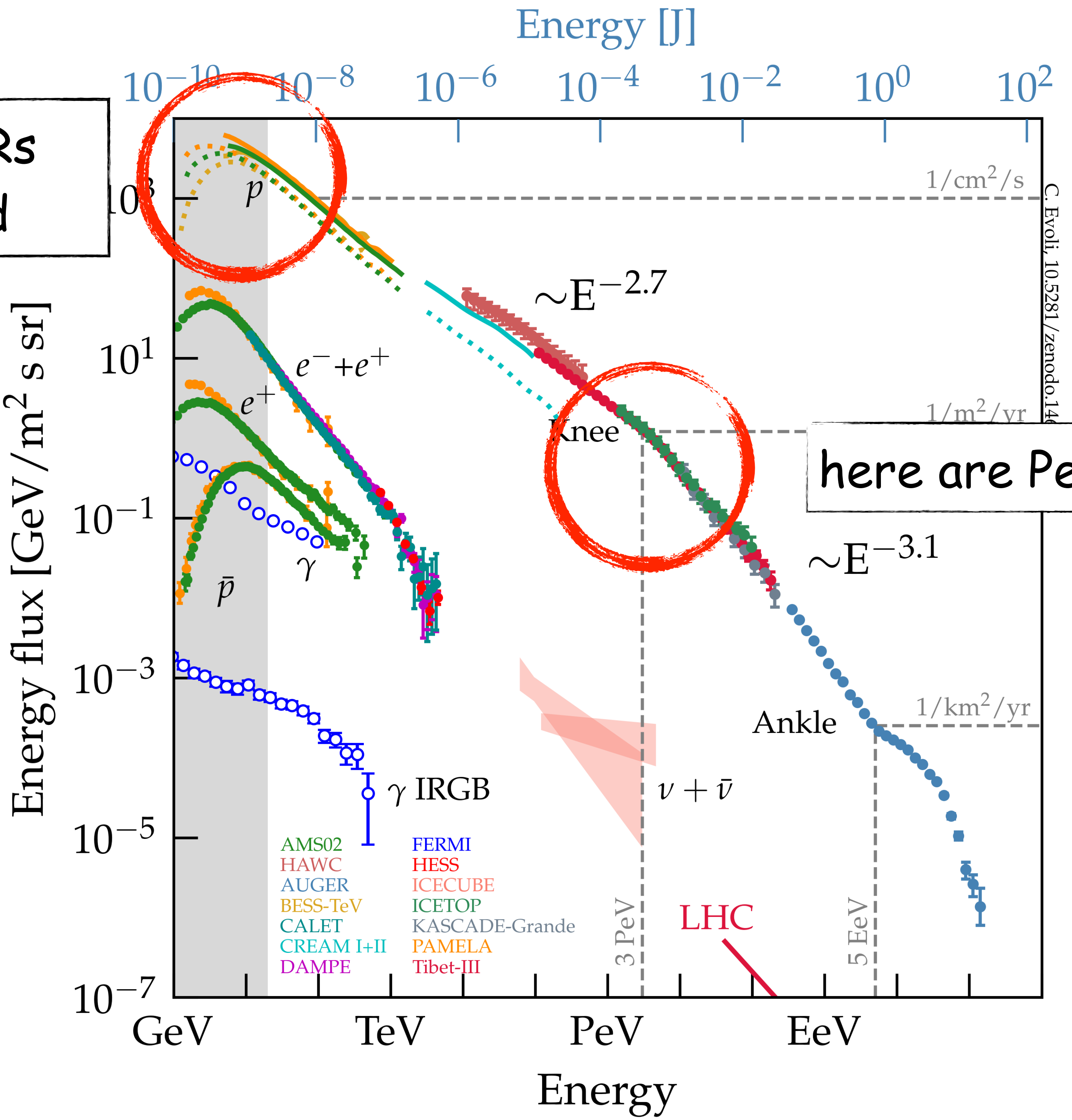

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here are PeV particles

Popular scenario: DSA @ SNR shocks

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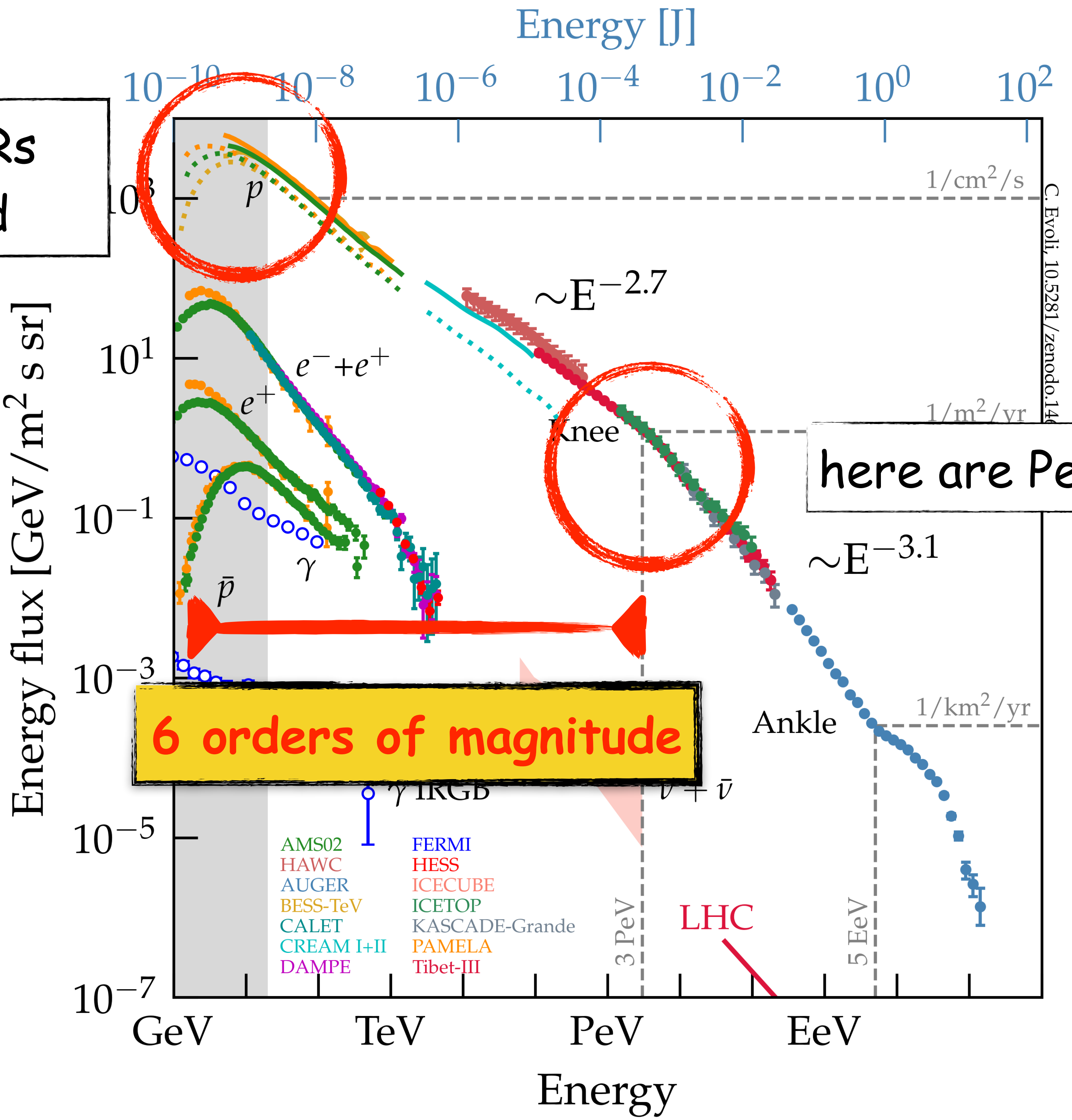
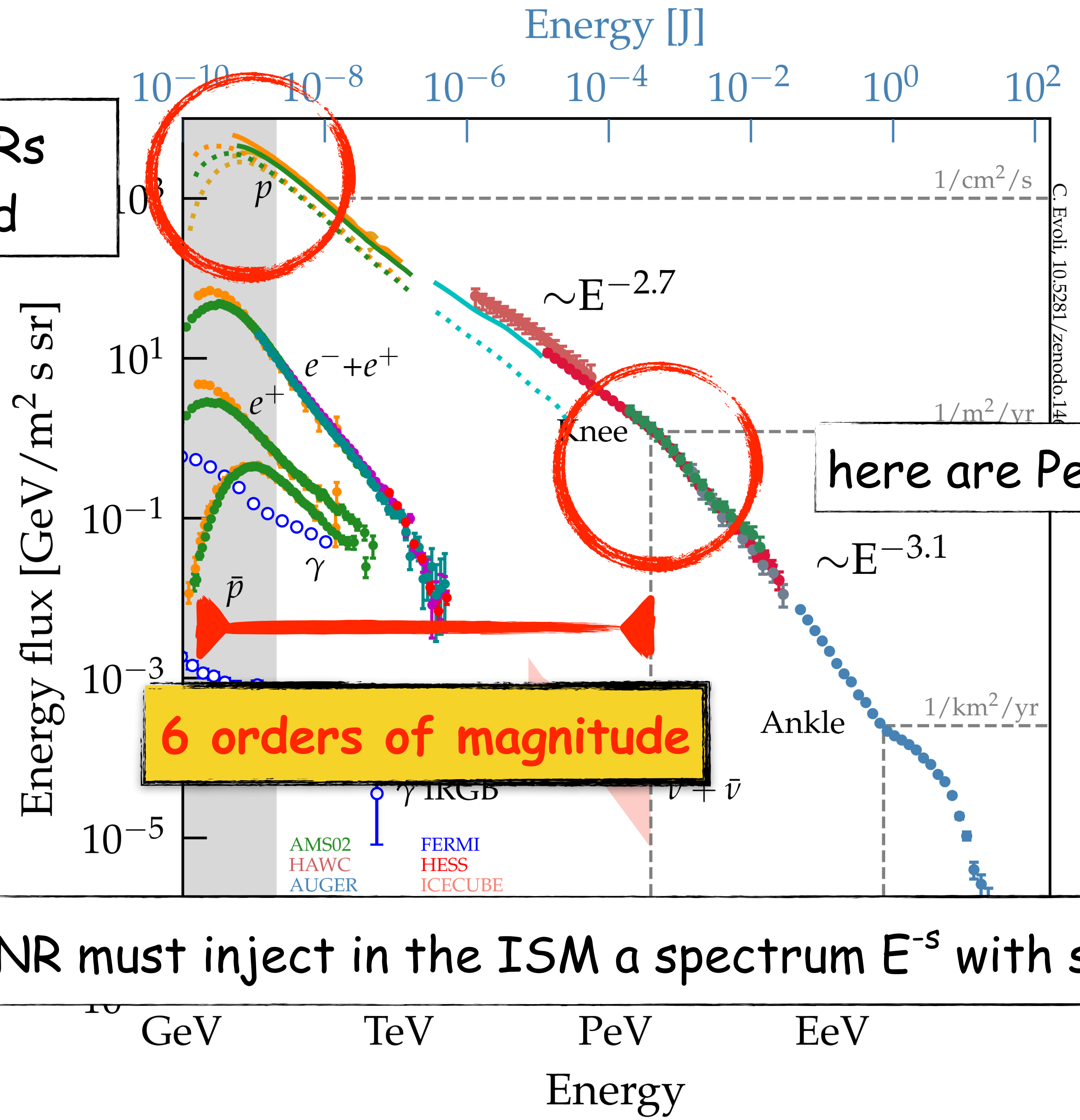


here are PeV particles

6 orders of magnitude

Popular scenario: DSA @ SNR shocks

what about PeV SNR?



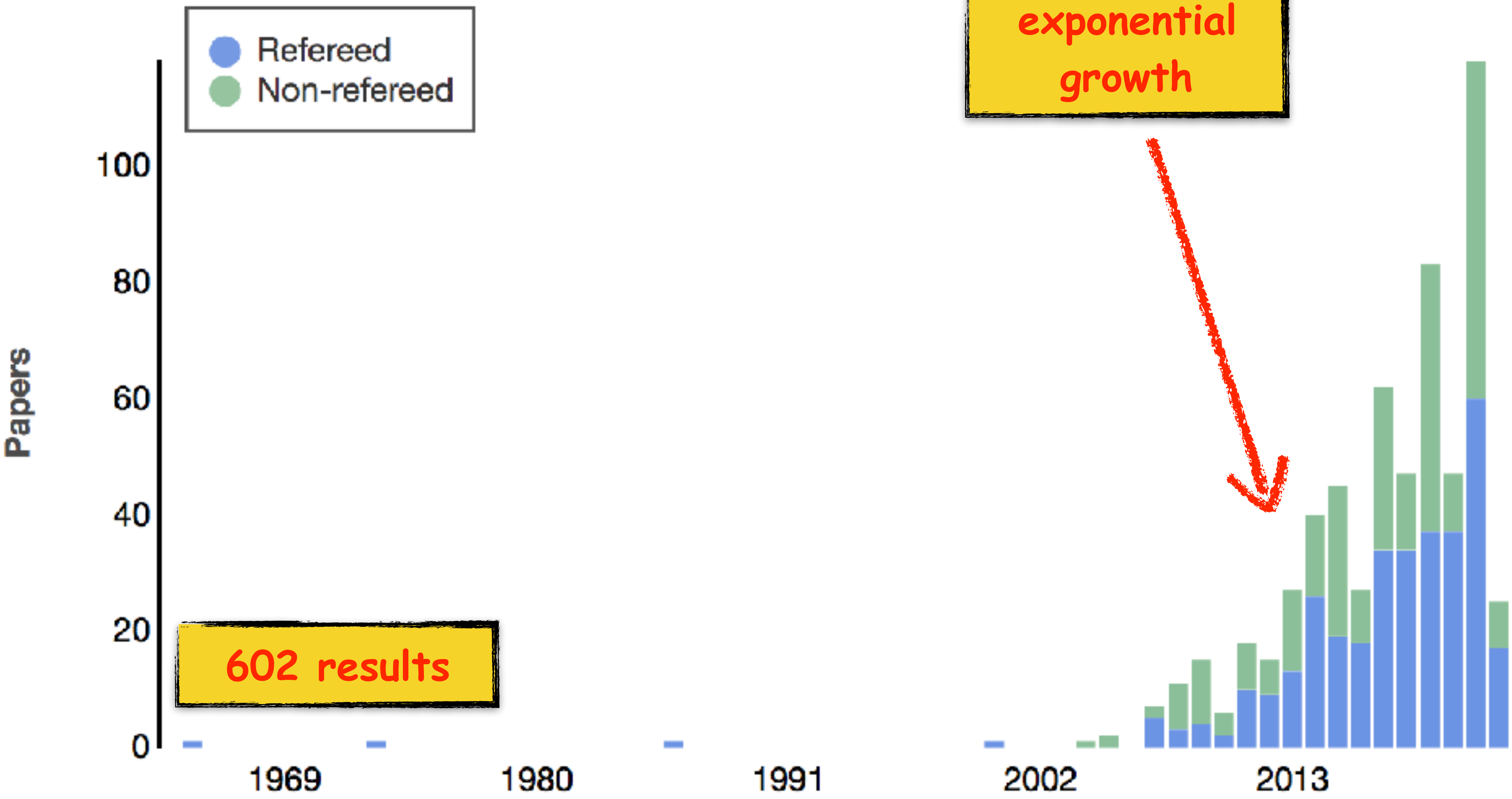
this is why SNRs were proposed

here are PeV particles

6 orders of magnitude

SNR must inject in the ISM a spectrum E^{-s} with $s \gtrsim 2$

When did the word PeVatron appeared?

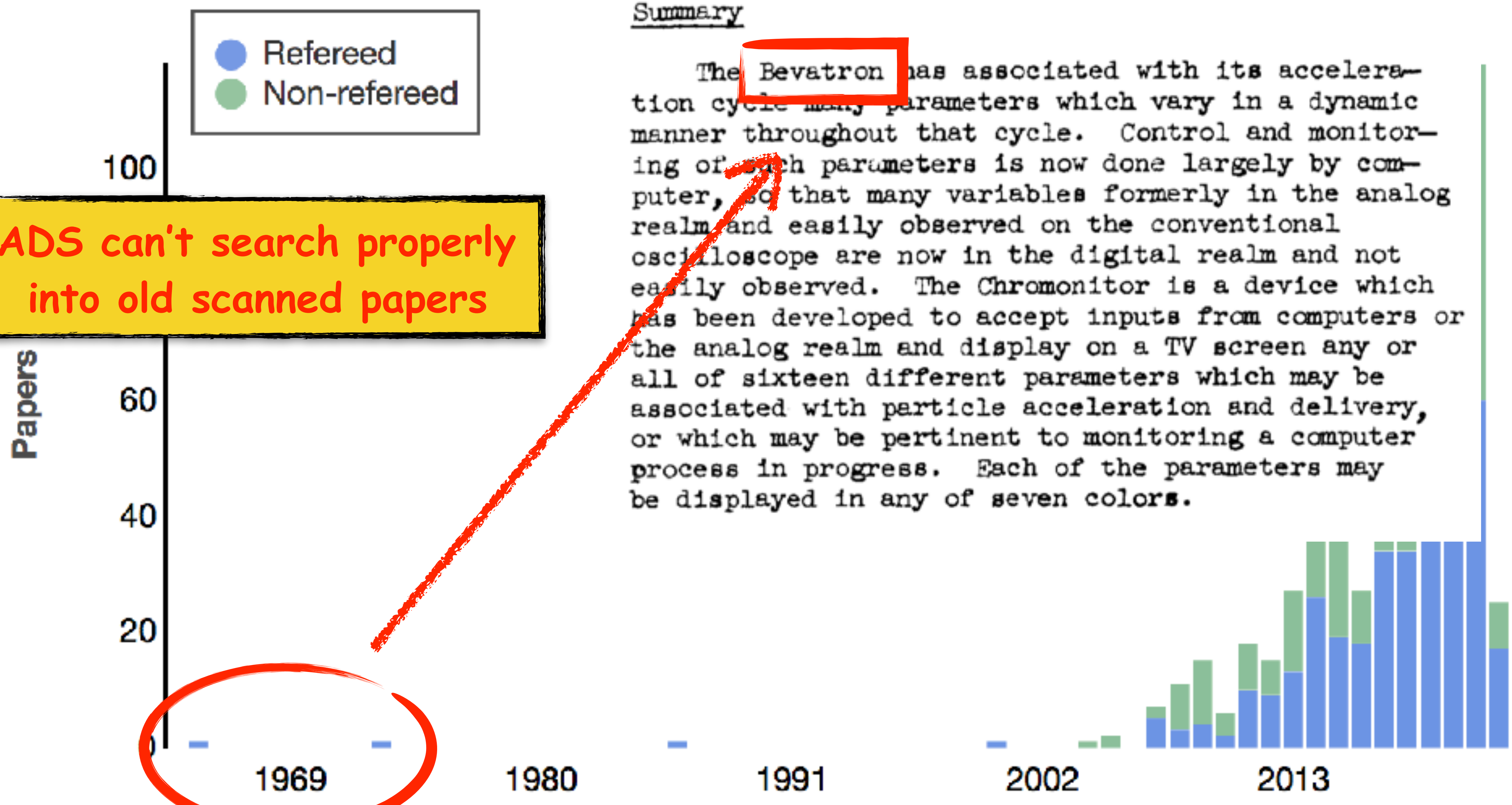


exponential growth

602 results

ADS search for “pevatron” or “pevatrons” (full text)

When did the word PeVatron appeared?

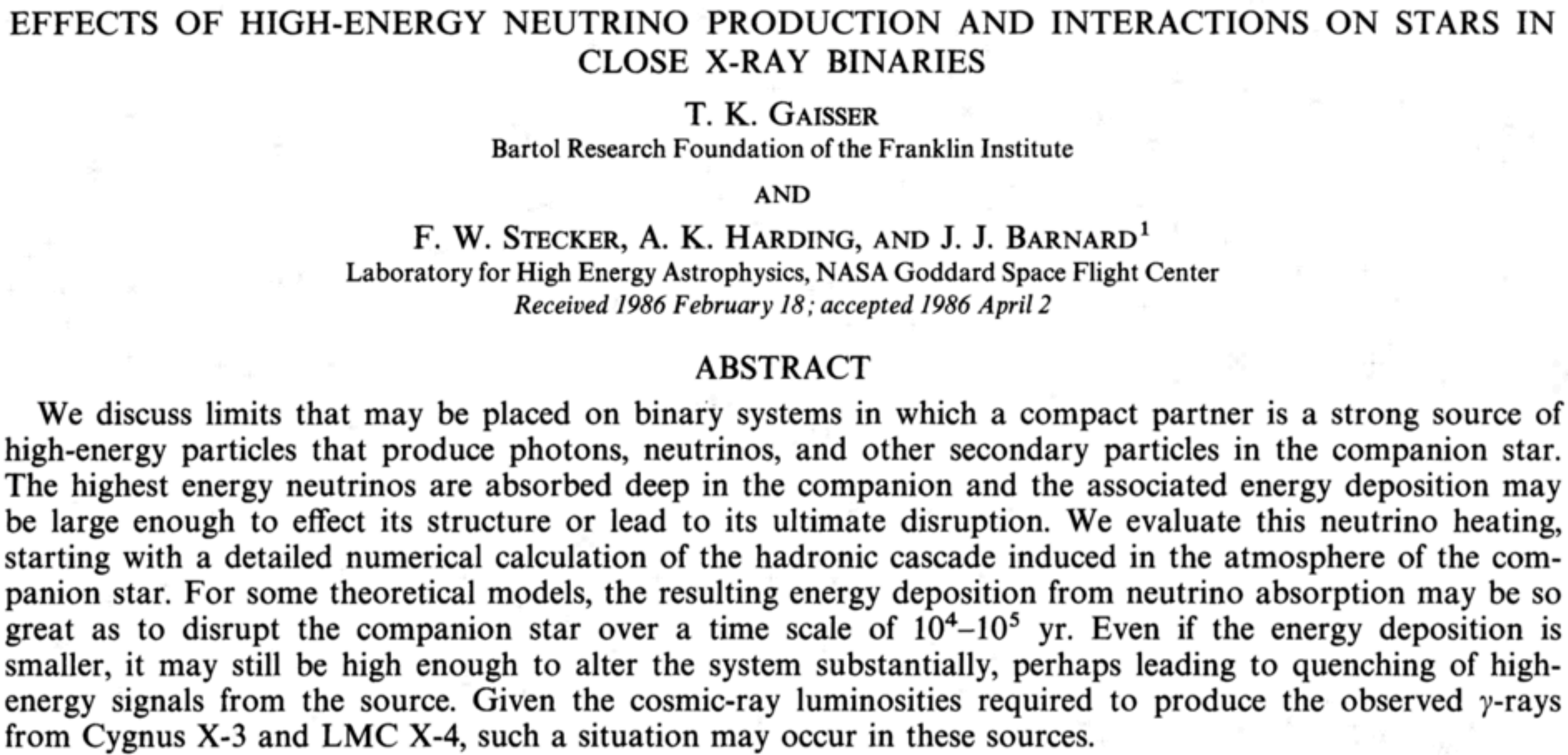


Summary

The Bevatron has associated with its acceleration cycle many parameters which vary in a dynamic manner throughout that cycle. Control and monitoring of such parameters is now done largely by computer, so that many variables formerly in the analog realm and easily observed on the conventional oscilloscope are now in the digital realm and not easily observed. The Chromonitor is a device which has been developed to accept inputs from computers or the analog realm and display on a TV screen any or all of sixteen different parameters which may be associated with particle acceleration and delivery, or which may be pertinent to monitoring a computer process in progress. Each of the parameters may be displayed in any of seven colors.

ADS can't search properly into old scanned papers

ADS search for “pevatron” or “pevatrons” (full text)



EFFECTS OF HIGH-ENERGY NEUTRINO PRODUCTION AND INTERACTIONS ON STARS IN CLOSE X-RAY BINARIES

T. K. Gaisser
Bartol Research Foundation of the Franklin Institute

AND

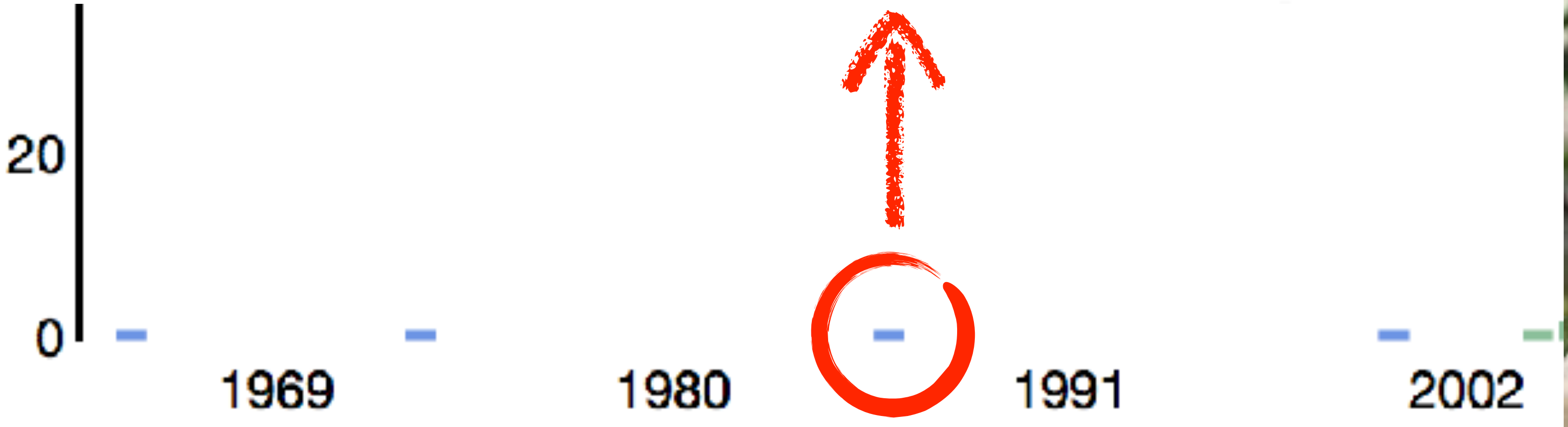
F. W. Stecker, A. K. Harding, and J. J. Barnard[1]
Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center

Received 1986 February 18; accepted 1986 April 2

ABSTRACT

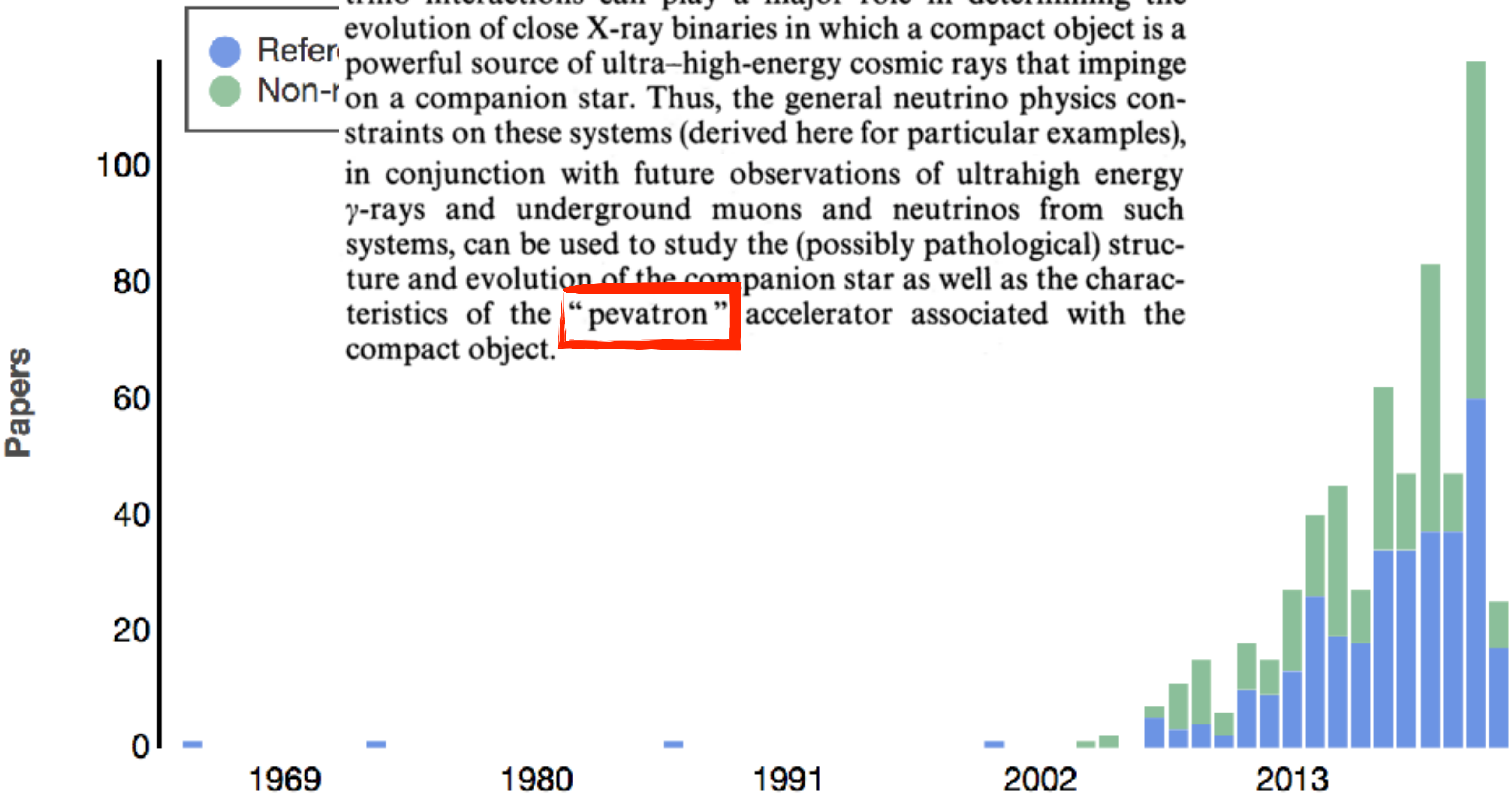
We discuss limits that may be placed on binary systems in which a compact partner is a strong source of high-energy particles that produce photons, neutrinos, and other secondary particles in the companion star. The highest energy neutrinos are absorbed deep in the companion and the associated energy deposition may be large enough to effect its structure or lead to its ultimate disruption. We evaluate this neutrino heating, starting with a detailed numerical calculation of the hadronic cascade induced in the atmosphere of the companion star. For some theoretical models, the resulting energy deposition from neutrino absorption may be so great as to disrupt the companion star over a time scale of 10^4–10^5 yr. Even if the energy deposition is smaller, it may still be high enough to alter the system substantially, perhaps leading to quenching of high-energy signals from the source. Given the cosmic-ray luminosities required to produce the observed γ-rays from Cygnus X-3 and LMC X-4, such a situation may occur in these sources.

Subject headings: cosmic rays: general — neutrinos — stars: interiors — X-rays:



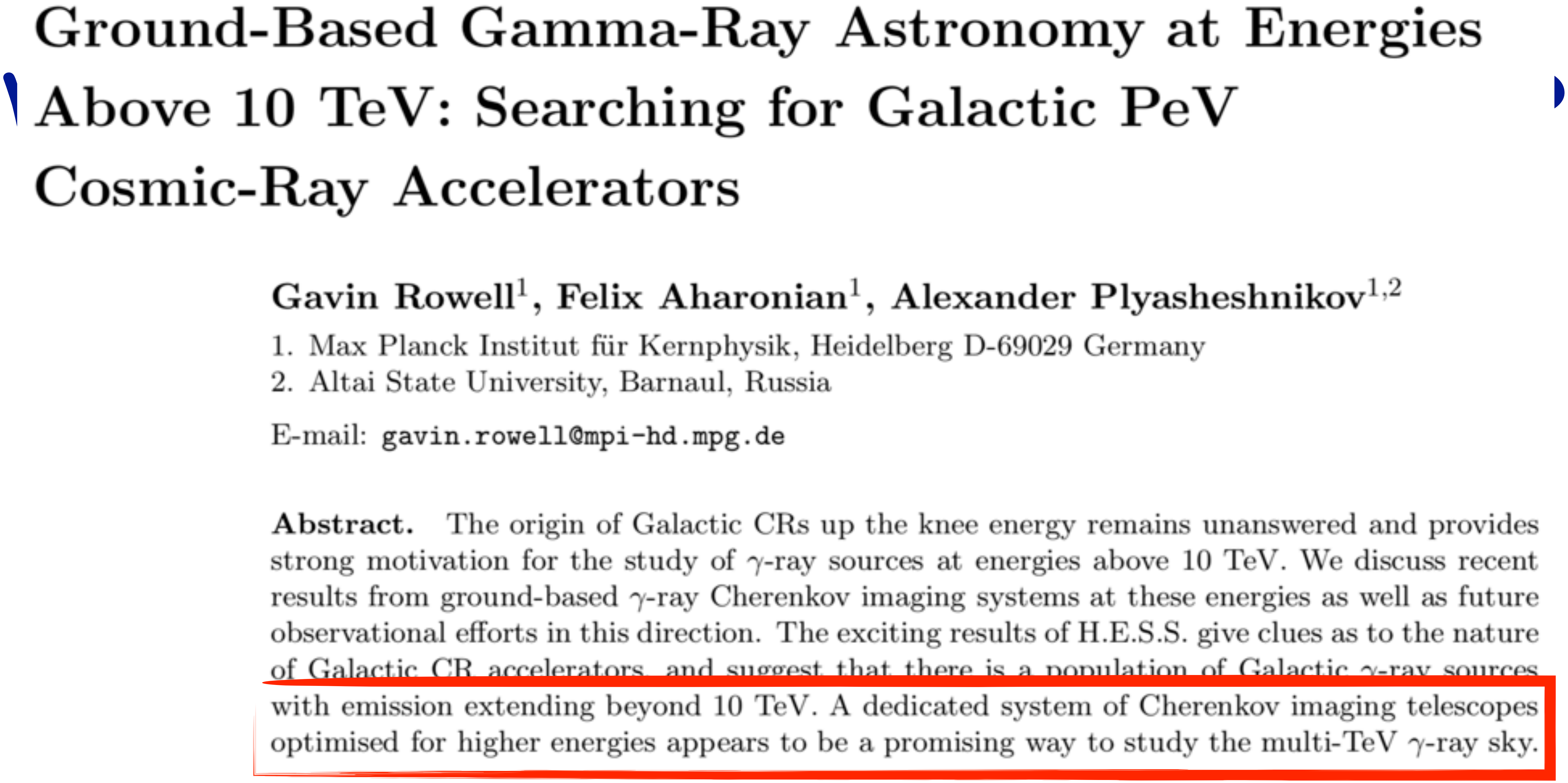
Tom Gaisser (1940-2022)

When did the word PeVatron appeared?



In accordance with SHB, we conclude that high-energy neutrino interactions can play a major role in determining the evolution of close X-ray binaries in which a compact object is a powerful source of ultra–high-energy cosmic rays that impinge on a companion star. Thus, the general neutrino physics constraints on these systems (derived here for particular examples), in conjunction with future observations of ultrahigh energy γ-rays and underground muons and neutrinos from such systems, can be used to study the (possibly pathological) structure and evolution of the companion star as well as the characteristics of the "pevatron" accelerator associated with the compact object.

ADS search for "pevatron" or "pevatrons" (full text)

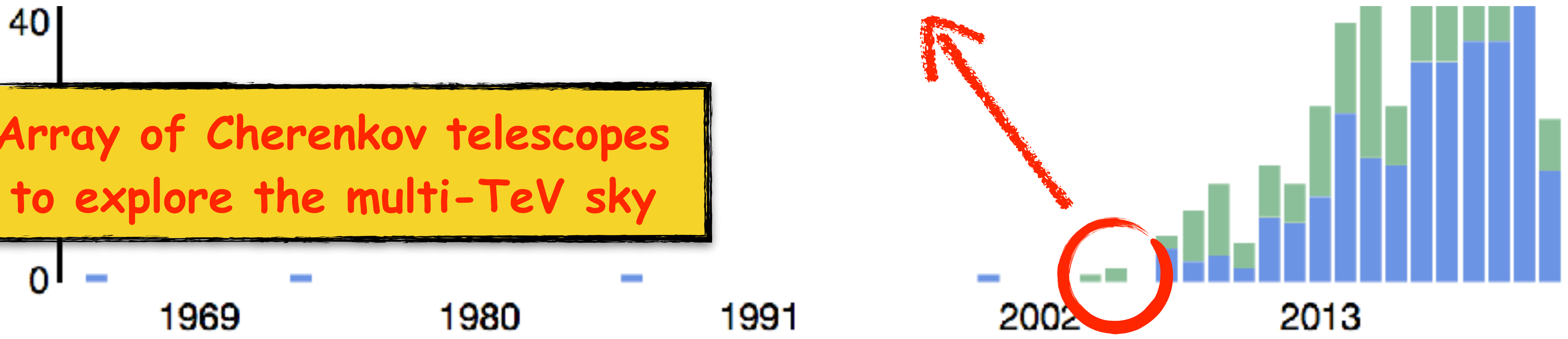


Ground-Based Gamma-Ray Astronomy at Energies Above 10 TeV: Searching for Galactic PeV Cosmic-Ray Accelerators

Gavin Rowell[1], **Felix Aharonian**[1], **Alexander Plyasheshnikov**[1,2]
1. Max Planck Institut für Kernphysik, Heidelberg D-69029 Germany
2. Altai State University, Barnaul, Russia

E-mail: `gavin.rowell@mpi-hd.mpg.de`

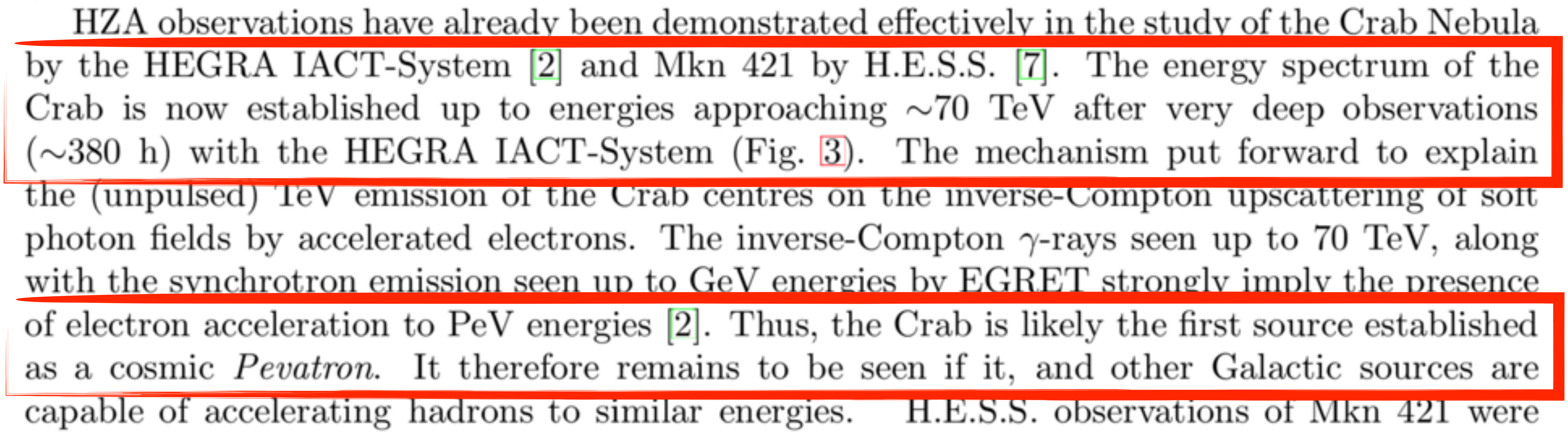
Abstract. The origin of Galactic CRs up the knee energy remains unanswered and provides strong motivation for the study of γ-ray sources at energies above 10 TeV. We discuss recent results from ground-based γ-ray Cherenkov imaging systems at these energies as well as future observational efforts in this direction. The exciting results of H.E.S.S. give clues as to the nature of Galactic CR accelerators, and suggest that there is a population of Galactic γ-ray sources with emission extending beyond 10 TeV. A dedicated system of Cherenkov imaging telescopes optimised for higher energies appears to be a promising way to study the multi-TeV γ-ray sky.



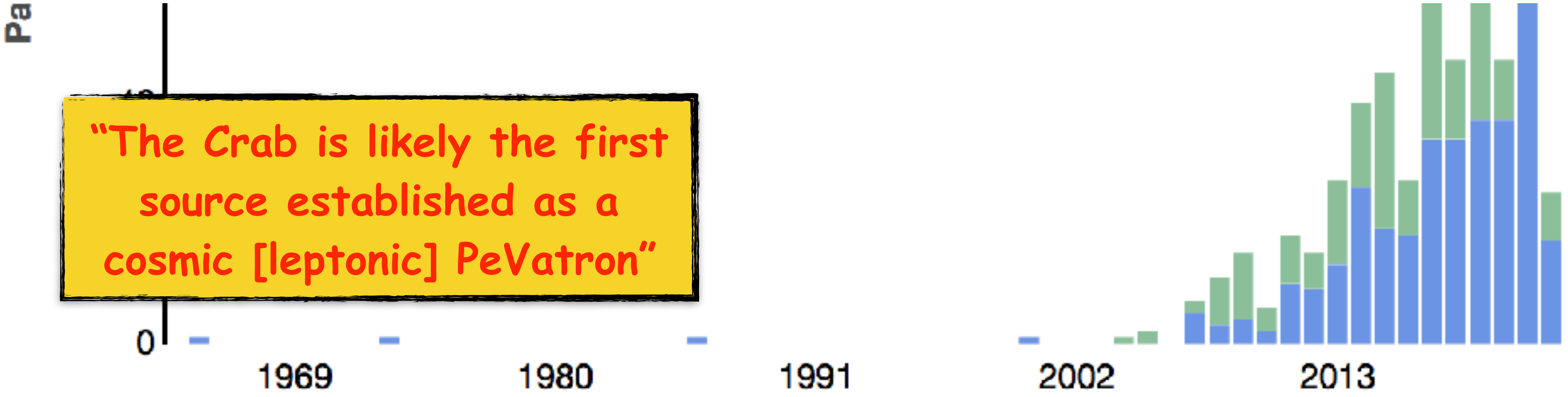
Array of Cherenkov telescopes to explore the multi-TeV sky

ADS search for "pevatron" or "pevatrons" (full text)

The Crab is a PeVatron



HZA observations have already been demonstrated effectively in the study of the Crab Nebula by the HEGRA IACT-System [2] and Mkn 421 by H.E.S.S. [7]. The energy spectrum of the Crab is now established up to energies approaching ~70 TeV after very deep observations (~380 h) with the HEGRA IACT-System (Fig. 3). The mechanism put forward to explain the (unpulsed) TeV emission of the Crab centres on the inverse-Compton upscattering of soft photon fields by accelerated electrons. The inverse-Compton γ-rays seen up to 70 TeV, along with the synchrotron emission seen up to GeV energies by EGRET strongly imply the presence of electron acceleration to PeV energies [2]. Thus, the Crab is likely the first source established as a cosmic *Pevatron*. It therefore remains to be seen if it, and other Galactic sources are capable of accelerating hadrons to similar energies. H.E.S.S. observations of Mkn 421 were



“The Crab is likely the first source established as a cosmic [leptonic] PeVatron”

ADS search for “pevatron” or “pevatrons” (full text)

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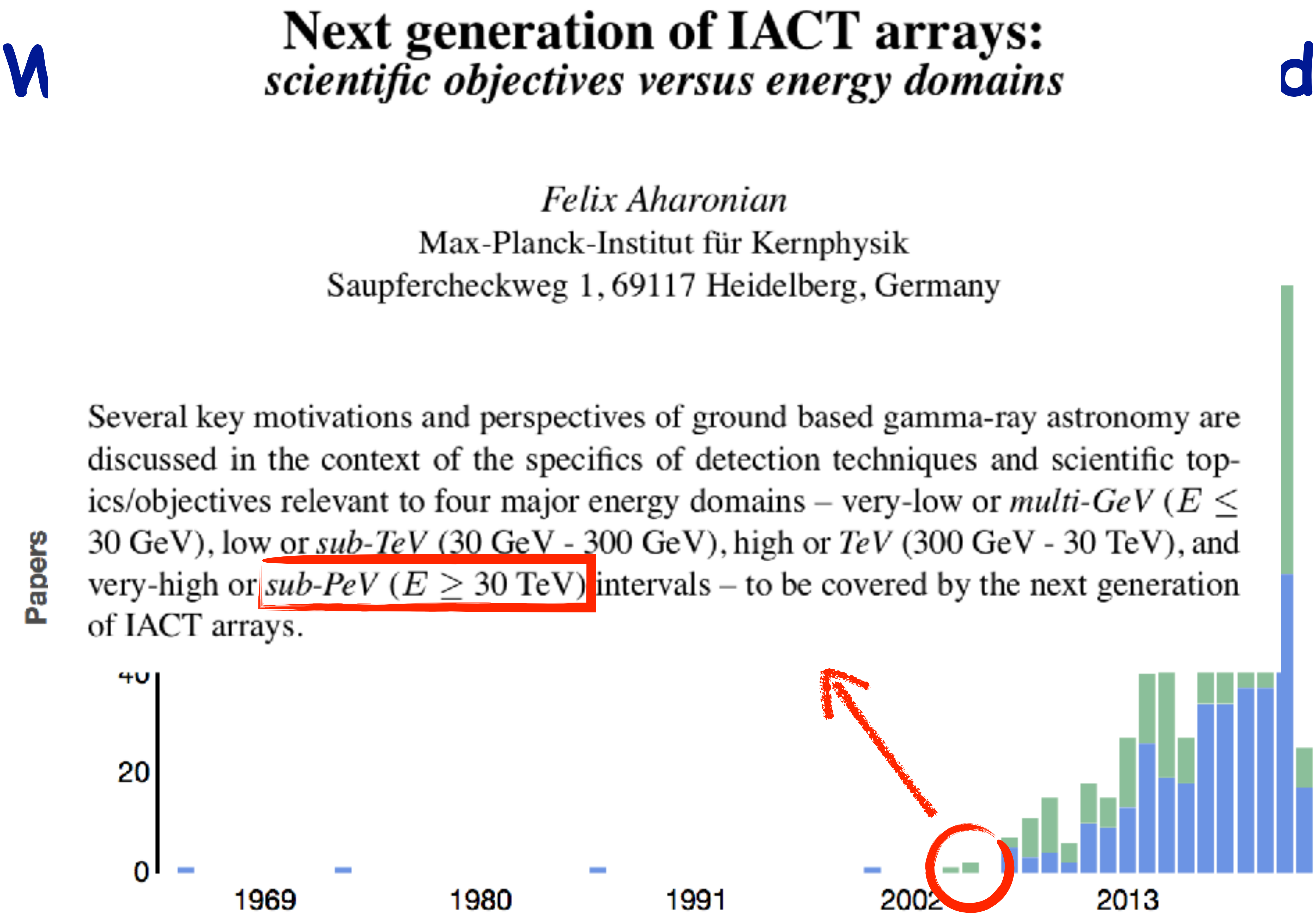


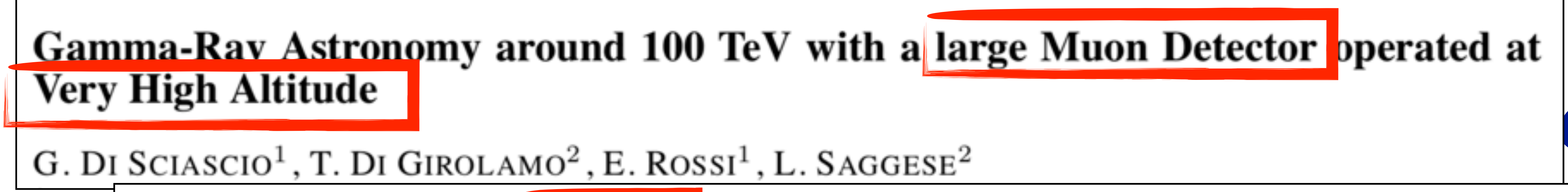
Next generation of IACT arrays:
scientific objectives versus energy domains

Felix Aharonian
Max-Planck-Institut für Kernphysik
Saupfercheckweg 1, 69117 Heidelberg, Germany

Several key motivations and perspectives of ground based gamma-ray astronomy are discussed in the context of the specifics of detection techniques and scientific topics/objectives relevant to four major energy domains – very-low or *multi-GeV* ($E \leq$ 30 GeV), low or *sub-TeV* (30 GeV - 300 GeV), high or *TeV* (300 GeV - 30 TeV), and very-high or *sub-PeV* ($E \geq$ 30 TeV) intervals – to be covered by the next generation of IACT arrays.

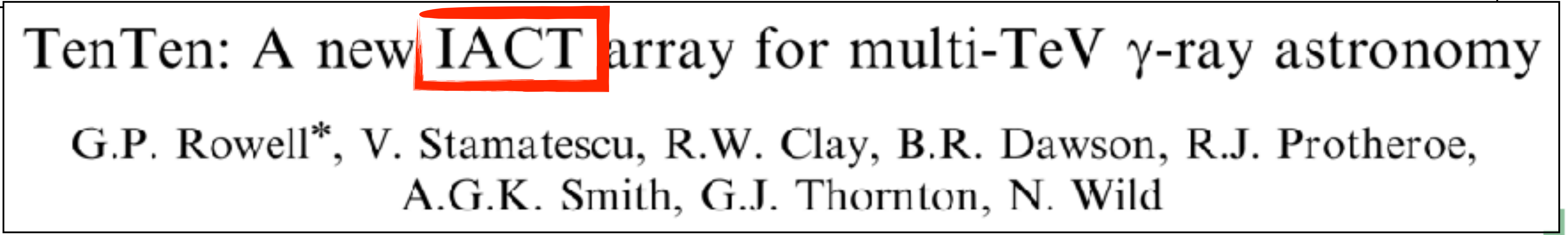
ADS search for “pevatron” or “pevatrons” (full text)

ed?



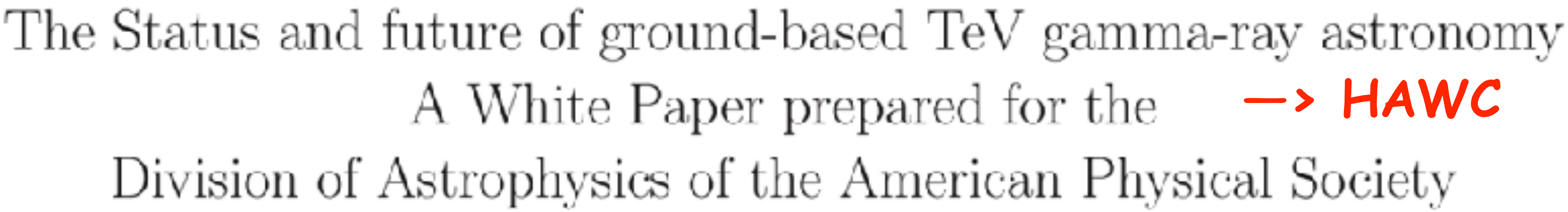
Gamma-Ray Astronomy around 100 TeV with a large Muon Detector operated at Very High Altitude

G. Di Sciascio[1], T. Di Girolamo[2], E. Rossi[1], L. Saggese[2]



TenTen: A new IACT array for multi-TeV γ-ray astronomy

G.P. Rowell*, V. Stamatescu, R.W. Clay, B.R. Dawson, R.J. Protheroe, A.G.K. Smith, G.J. Thornton, N. Wild

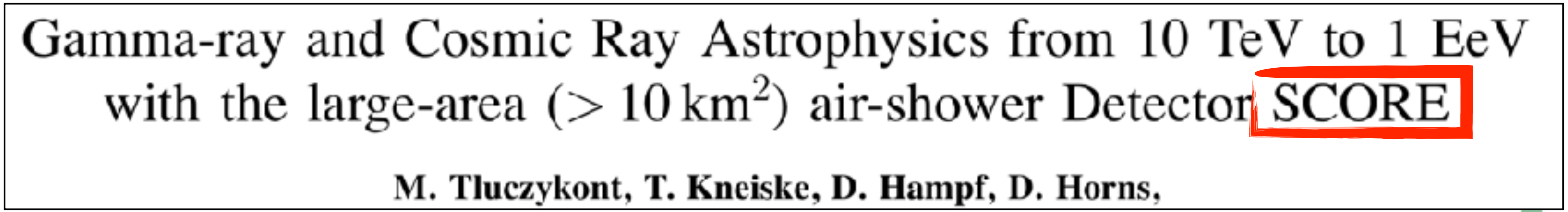


The Status and future of ground-based TeV gamma-ray astronomy

A White Paper prepared for the

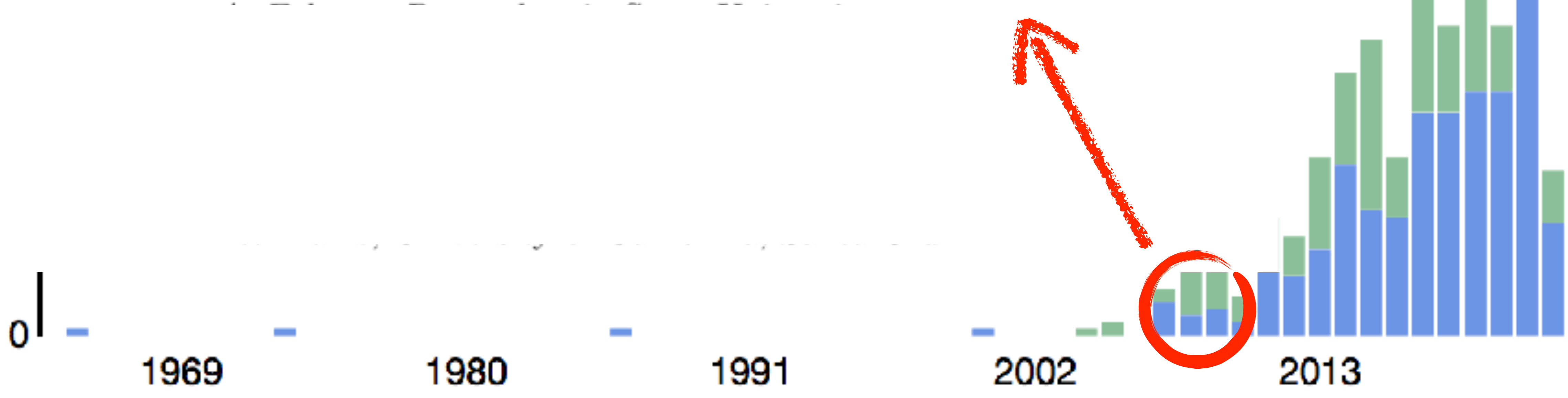
Division of Astrophysics of the American Physical Society

—> HAWC

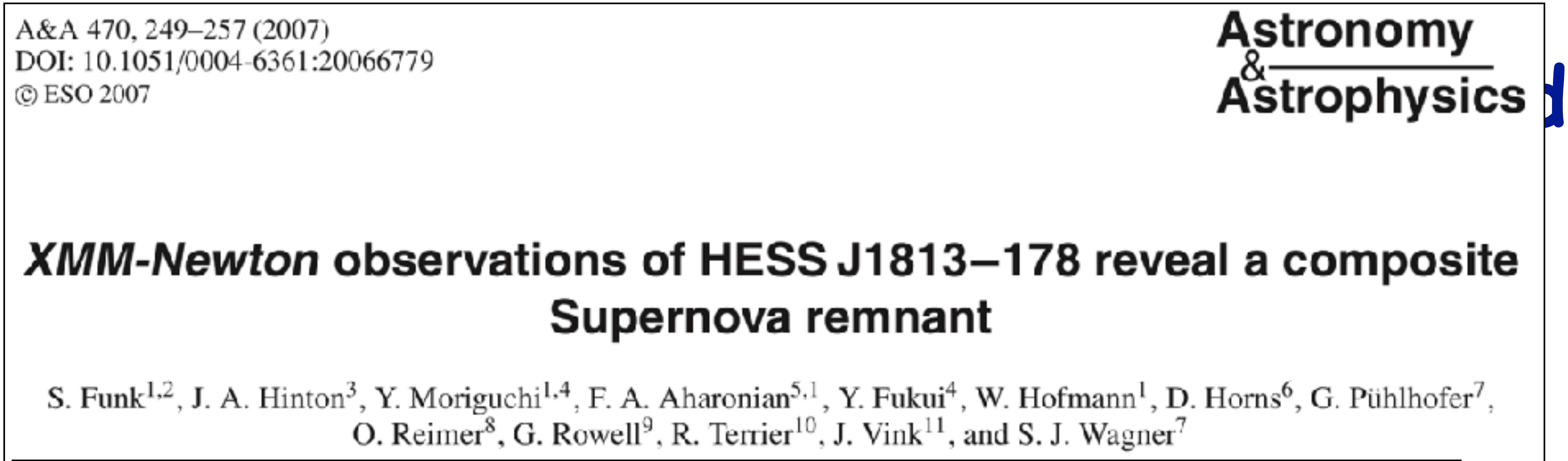


Gamma-ray and Cosmic Ray Astrophysics from 10 TeV to 1 EeV with the large-area ($> 10\,\mathrm{km}^2$) air-shower Detector SCORE

M. Tluczykont, T. Kneiske, D. Hampf, D. Horns,



several proposals for future multi-TeV instruments d?



A&A 470, 249–257 (2007)
DOI: 10.1051/0004-6361:20066779
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Astronomy & Astrophysics

XMM-Newton observations of HESS J1813–178 reveal a composite Supernova remnant

S. Funk[1,2], J. A. Hinton[3], Y. Moriguchi[1,4], F. A. Aharonian[5,1], Y. Fukui[4], W. Hofmann[1], D. Horns[6], G. Pühlhofer[7], O. Reimer[8], G. Rowell[9], R. Terrier[10], J. Vink[11], and S. J. Wagner[7]

A&A 469, L17–L21 (2007)
DOI: 10.1051/0004-6361:20066836
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Astronomy & Astrophysics

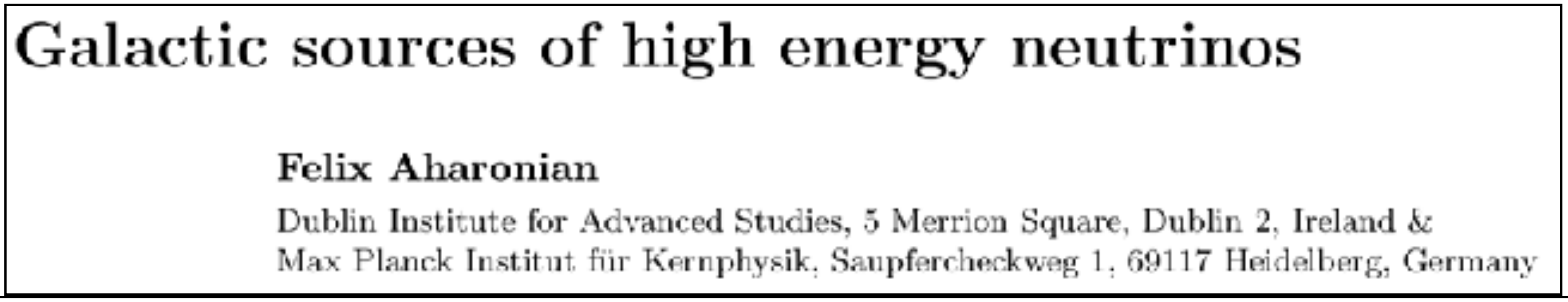
LETTER TO THE EDITOR

XMM-Newton observations of the first unidentified TeV gamma-ray source TeV J2032+4130*

D. Horns[1], A. I. D. Hoffmann[1], A. Santangelo[1], F. A. Aharonian[2], and G. P. Rowell[3]

Early attempts to identify PeVatrons (photons)

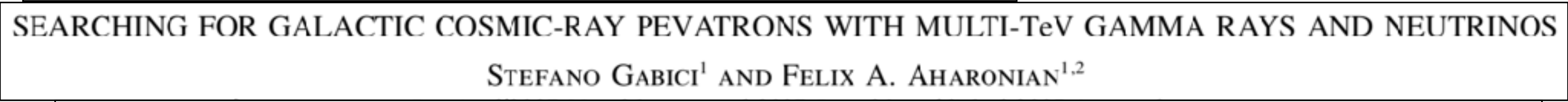
Neutrinos!



Galactic sources of high energy neutrinos

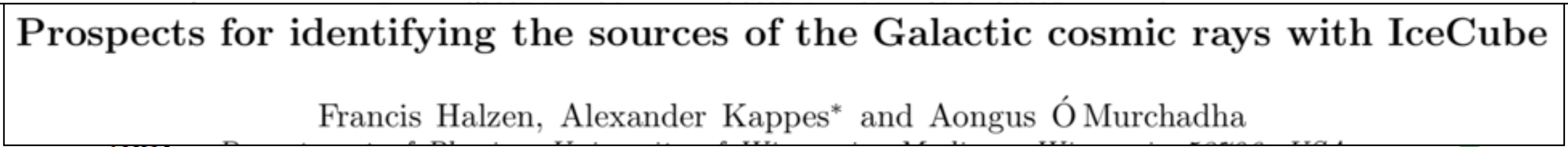
Felix Aharonian

Dublin Institute for Advanced Studies, 5 Merrion Square, Dublin 2, Ireland &
Max Planck Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany



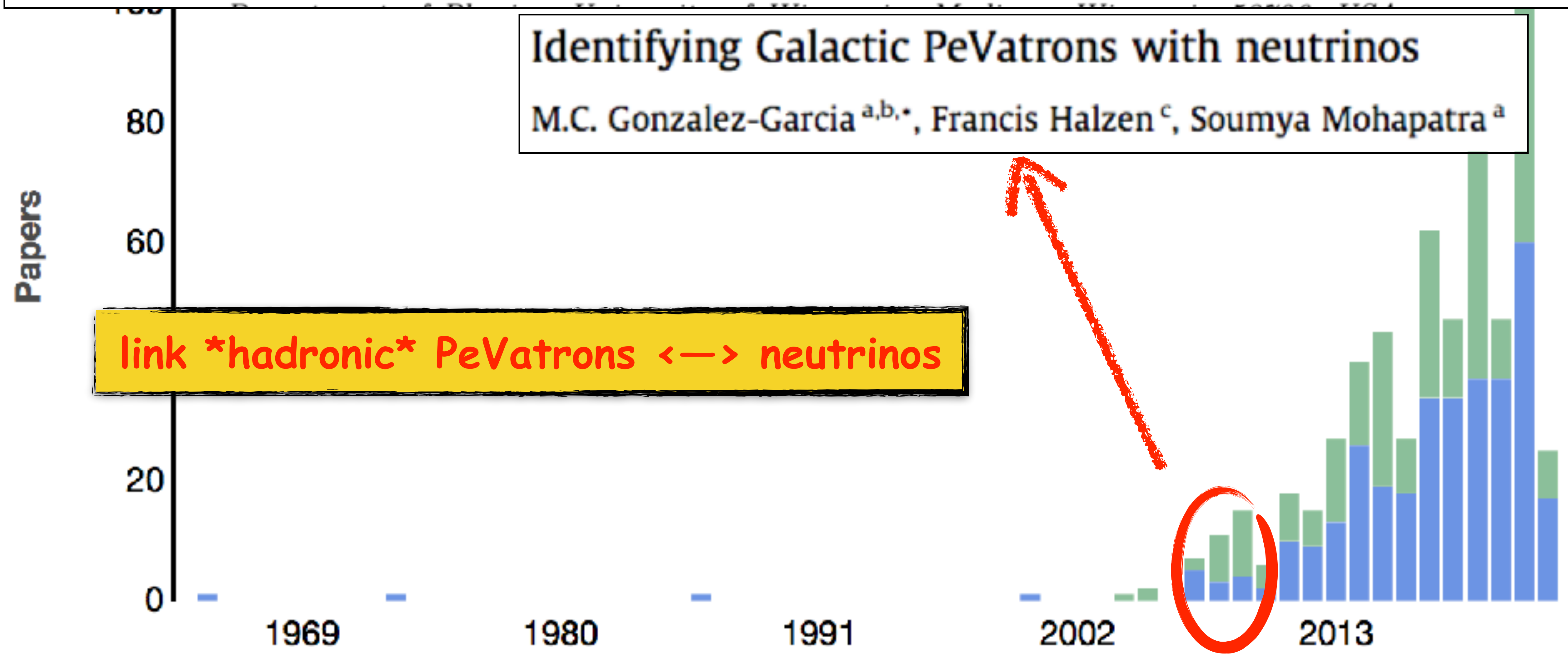
SEARCHING FOR GALACTIC COSMIC-RAY PEVATRONS WITH MULTI-TeV GAMMA RAYS AND NEUTRINOS

STEFANO GABICI[1] AND FELIX A. AHARONIAN[1,2]



Prospects for identifying the sources of the Galactic cosmic rays with IceCube

Francis Halzen, Alexander Kappes* and Aongus Ó Murchadha



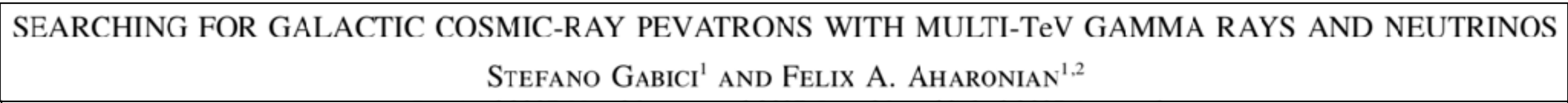
Identifying Galactic PeVatrons with neutrinos

M.C. Gonzalez-Garcia[a,b,•], Francis Halzen[c], Soumya Mohapatra[a]

link *hadronic* PeVatrons <—> neutrinos

ADS search for "pevatron" or "pevatrons" (full text)

The importance of escaping particles



SEARCHING FOR GALACTIC COSMIC-RAY PEVATRONS WITH MULTI-TeV GAMMA RAYS AND NEUTRINOS

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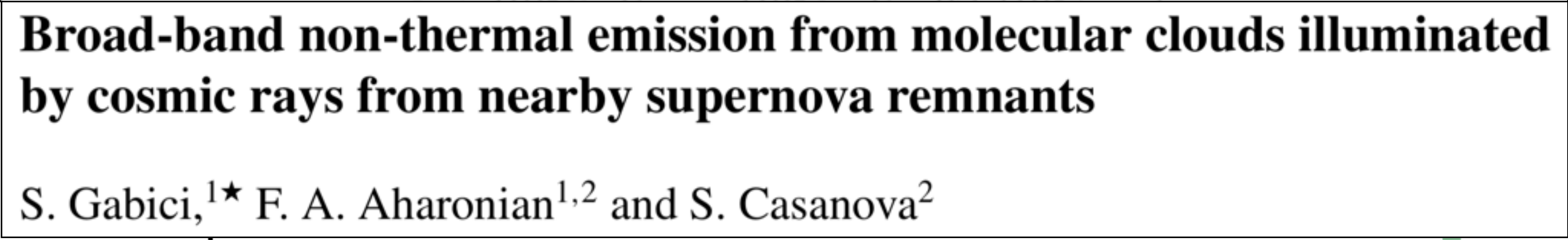
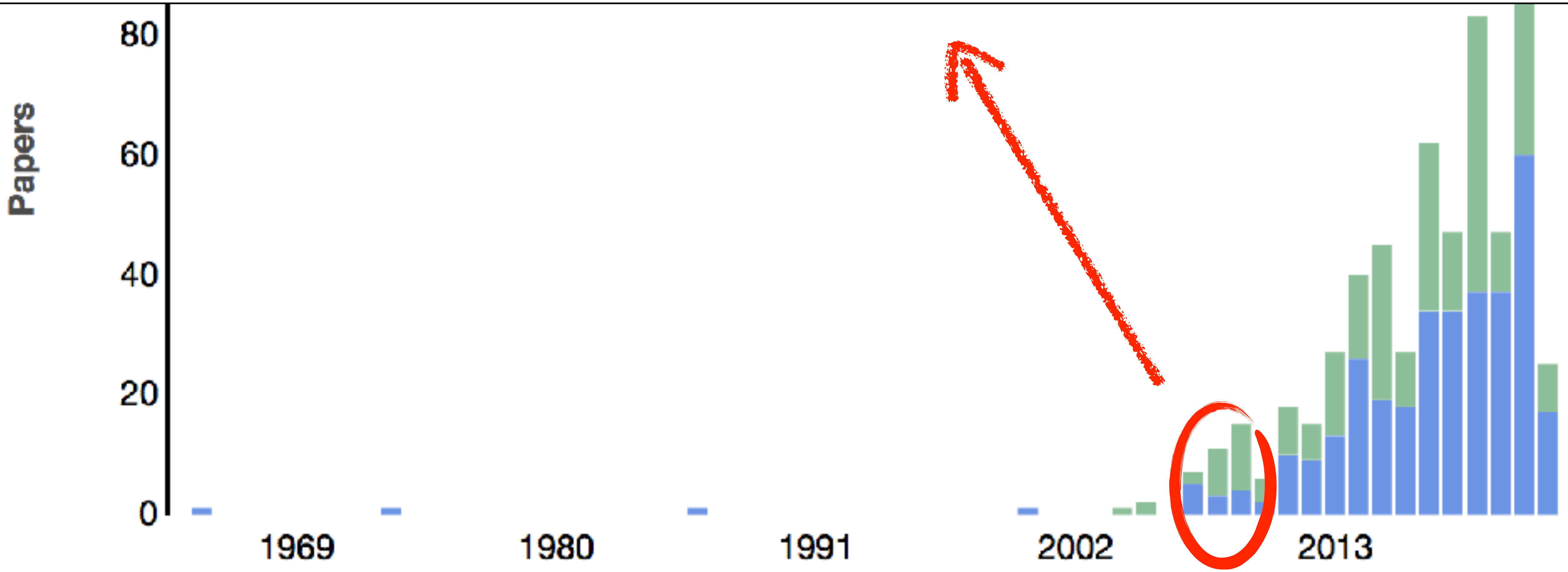


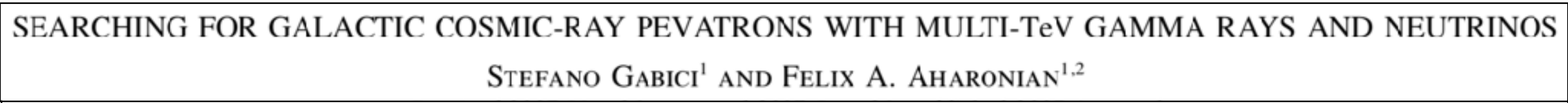
Broad-band non-thermal emission from molecular clouds illuminated by cosmic rays from nearby supernova remnants

S. Gabici,[1★] F. A. Aharonian[1,2] and S. Casanova[2]



the importance of escaping particles: 1) detection of delayed emission

The importance of escaping particles



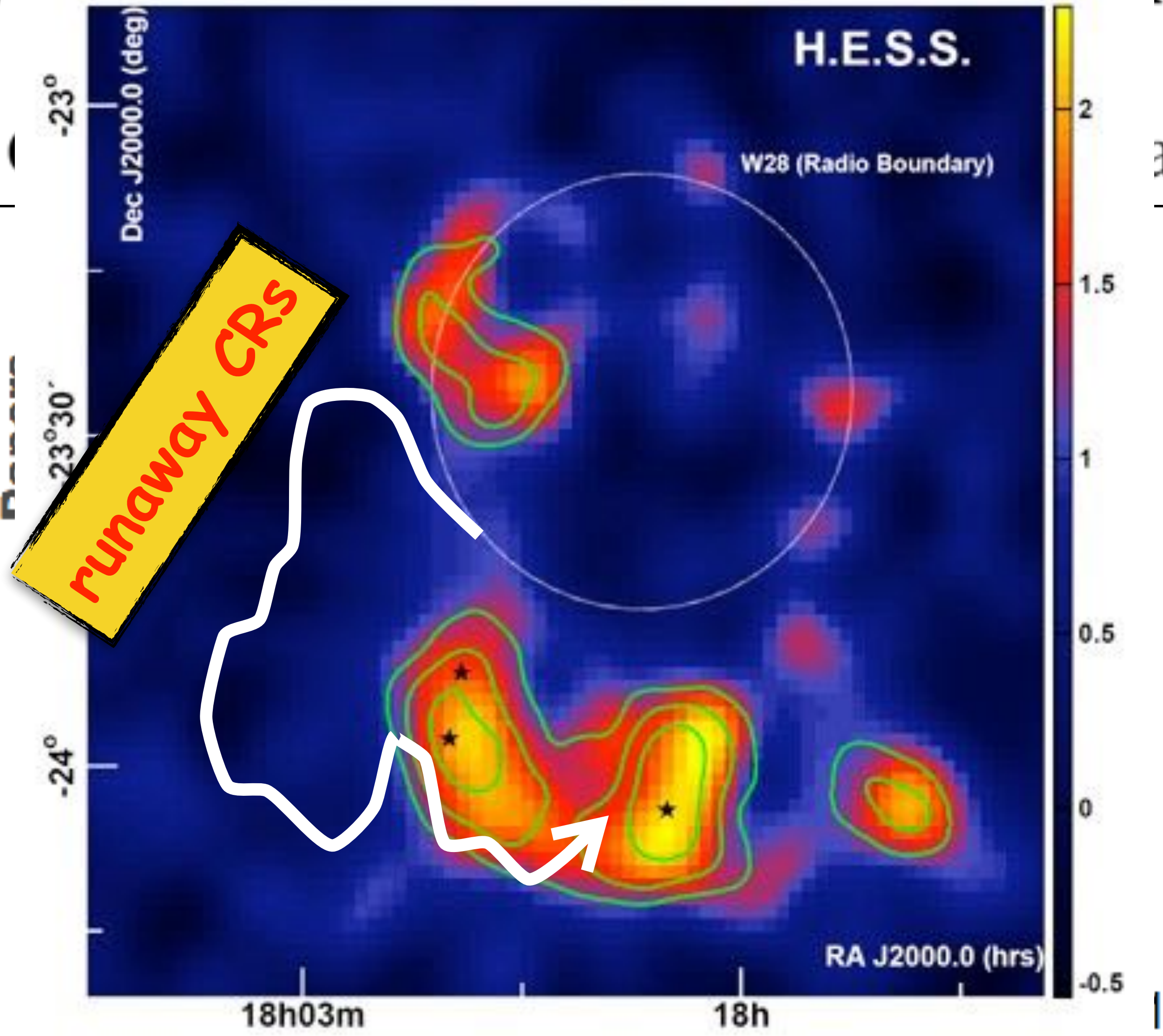
SEARCHING FOR GALACTIC COSMIC-RAY PEVATRONS WITH MULTI-TeV GAMMA RAYS AND NEUTRINOS

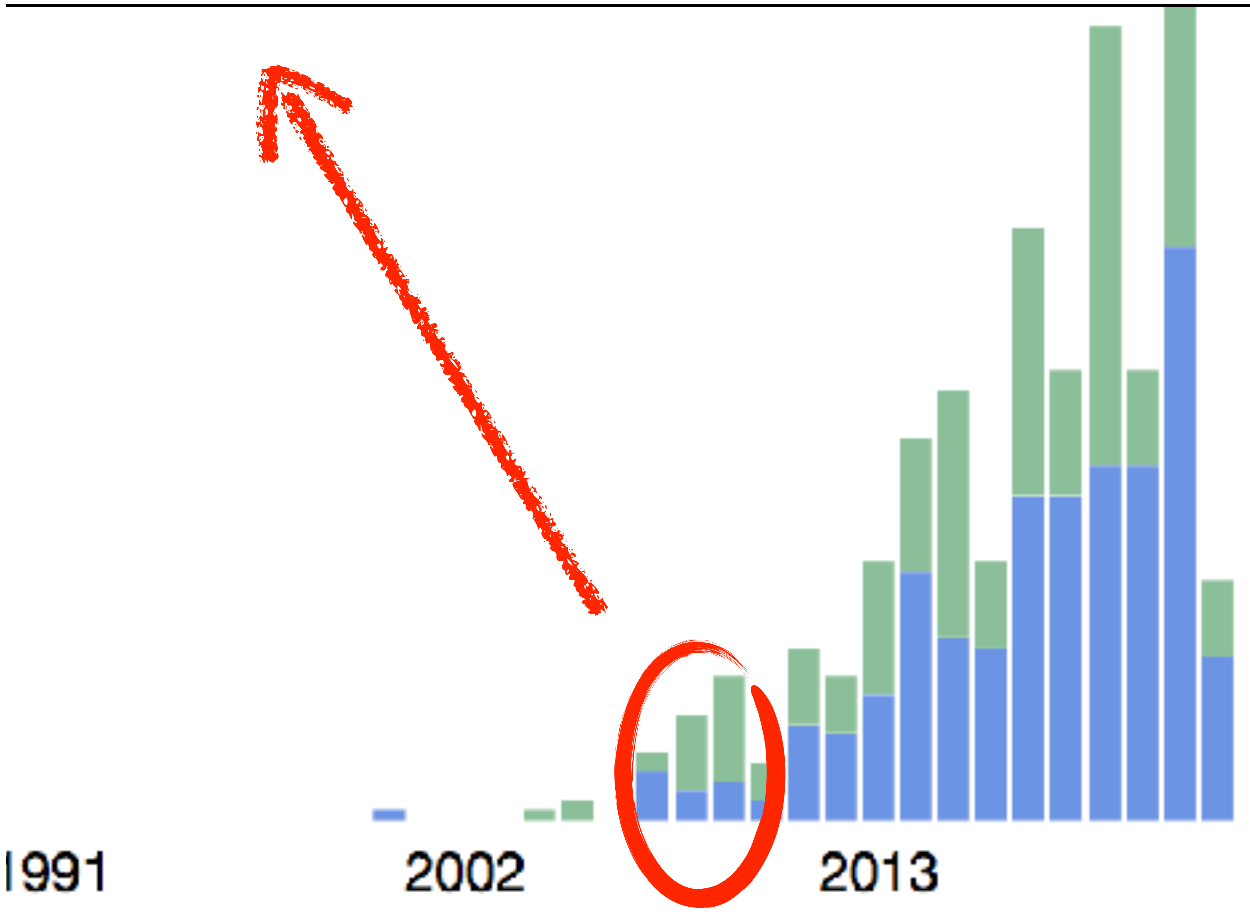
STEFANO GABICI[1] AND FELIX A. AHARONIAN[1,2]

Broad-band non-thermal emission from molecular clouds illuminated by cosmic rays from nearby supernova remnants

S.

asanova[2]





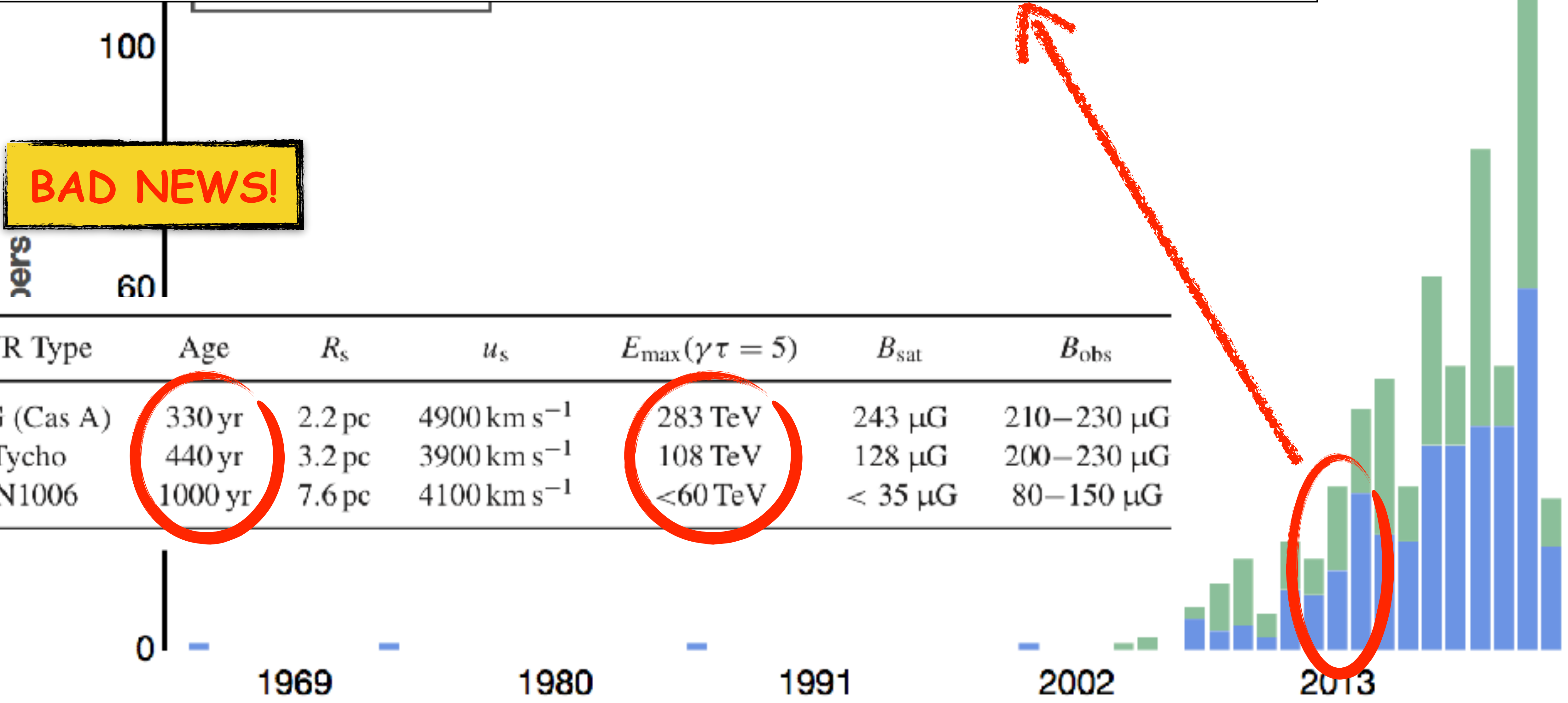
the importance of escaping particles: 1) detection of delayed emission

ticles

MNRAS **435,** 1174–1185 (2013)
Advance Access publication 2013 August 20

Cosmic ray acceleration in young supernova remnants

K. M. Schure[★] and A. R. Bell
Department of Physics, University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK

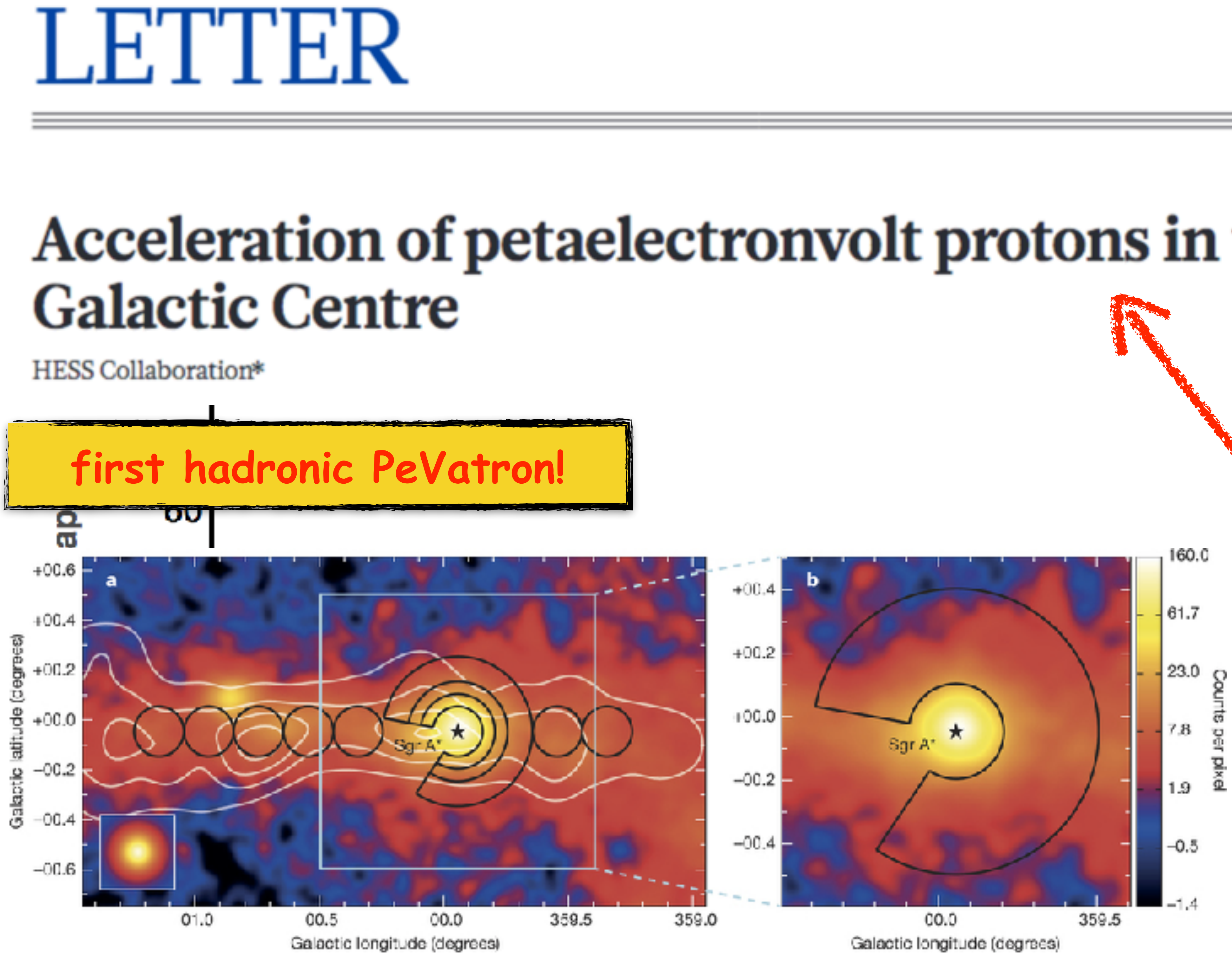


BAD NEWS!

SNR Type	Age	R_s	u_s	$E_{max}(\gamma\tau = 5)$	B_{sat}	B_{obs}
RSG (Cas A)	330 yr	2.2 pc	4900 km s^{-1}	283 TeV	243 μG	210–230 μG
Tycho	440 yr	3.2 pc	3900 km s^{-1}	108 TeV	128 μG	200–230 μG
SN1006	1000 yr	7.6 pc	4100 km s^{-1}	<60 TeV	< 35 μG	80–150 μG

the importance of escaping particles: 2) magnetic field amplification

The 1st hadronic PeVatron is not a SNR



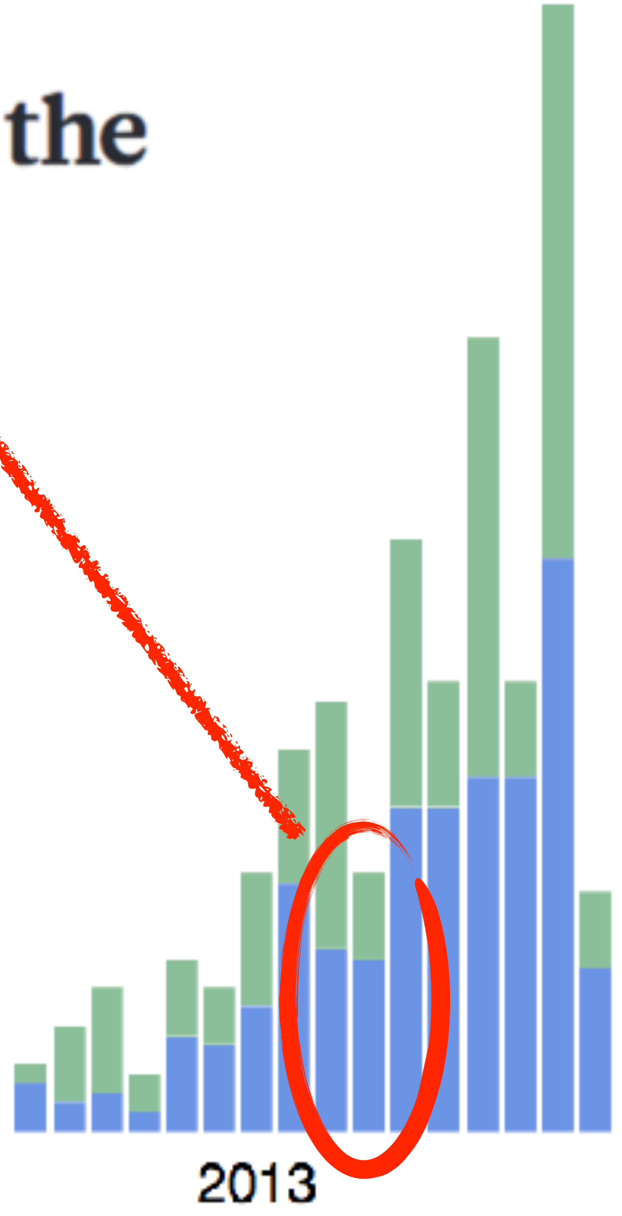
LETTER

doi:10.1038/nature17147

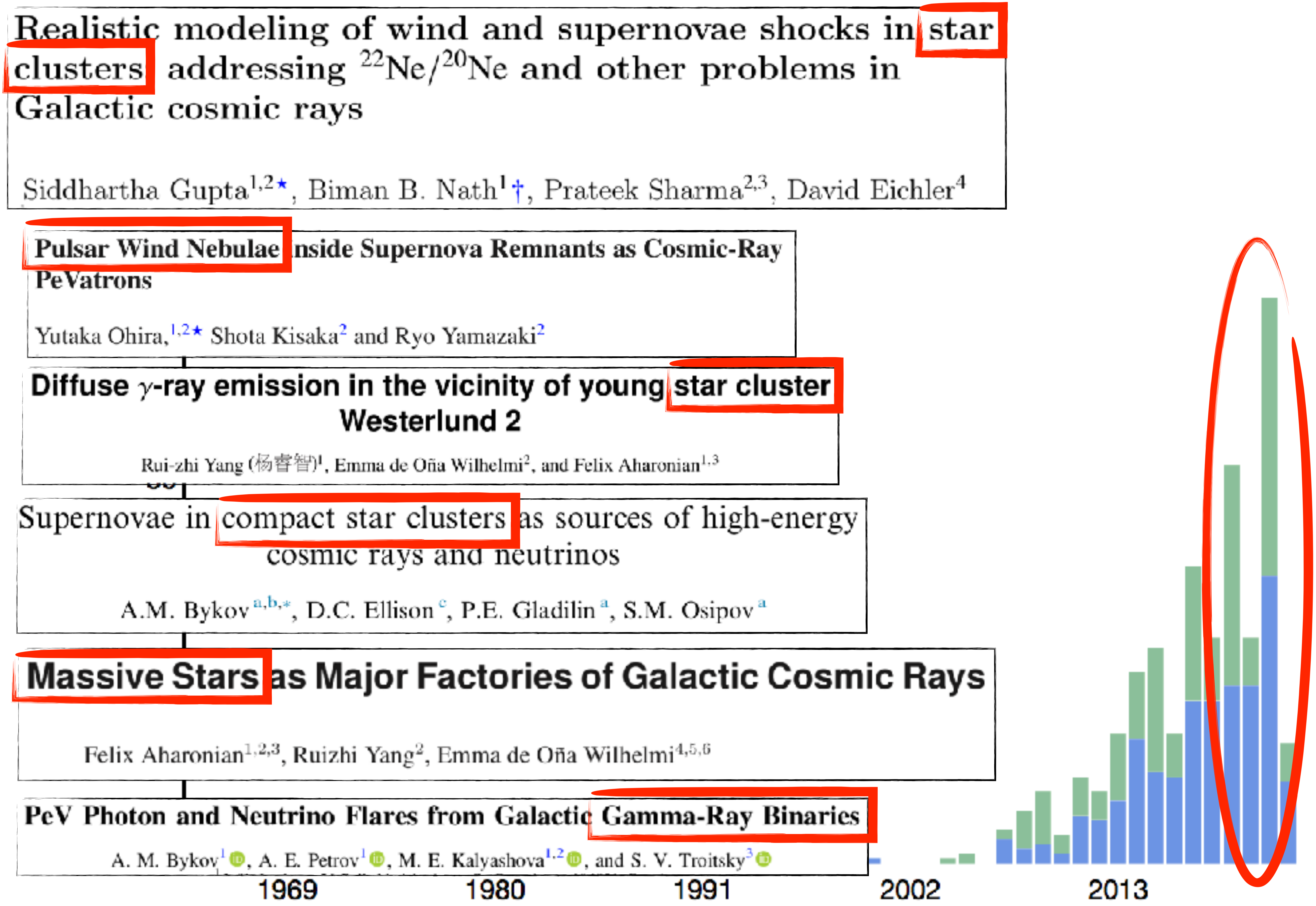
Acceleration of petaelectronvolt protons in the Galactic Centre

HESS Collaboration*

first hadronic PeVatron!



identified thanks to the gamma-ray emission of escaping CRs



Realistic modeling of wind and supernovae shocks in star clusters addressing ^{22}Ne/^{20}Ne and other problems in Galactic cosmic rays

Siddhartha Gupta[1,2]★, Biman B. Nath[1]†, Prateek Sharma[2,3], David Eichler[4]

Pulsar Wind Nebulae inside Supernova Remnants as Cosmic-Ray PeVatrons

Yutaka Ohira,[1,2]★ Shota Kisaka[2] and Ryo Yamazaki[2]

Diffuse γ-ray emission in the vicinity of young star cluster Westerlund 2

Rui-zhi Yang (杨睿智)[1], Emma de Oña Wilhelmi[2], and Felix Aharonian[1,3]

Supernovae in compact star clusters as sources of high-energy cosmic rays and neutrinos

A.M. Bykov[a,b,*], D.C. Ellison[c], P.E. Gladilin[a], S.M. Osipov[a]

Massive Stars as Major Factories of Galactic Cosmic Rays

Felix Aharonian[1,2,3], Ruizhi Yang[2], Emma de Oña Wilhelmi[4,5,6]

PeV Photon and Neutrino Flares from Galactic Gamma-Ray Binaries

A. M. Bykov[1], A. E. Petrov[1], M. E. Kalyashova[1,2], and S. V. Troitsky[3]

many alternatives to SNRs! (star clusters got a lot of attention)

First Detection of sub-PeV Diffuse Gamma Rays from the Galactic Disk: Evidence for Ubiquitous Galactic Cosmic Rays beyond PeV Energies

Potential PeVatron supernova remnant G106.3+2.7 seen in the highest-energy gamma rays

Tibet

Article

Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

ASTROPARTICLE PHYSICS

Peta–electron volt gamma-ray emission from the Crab Nebula

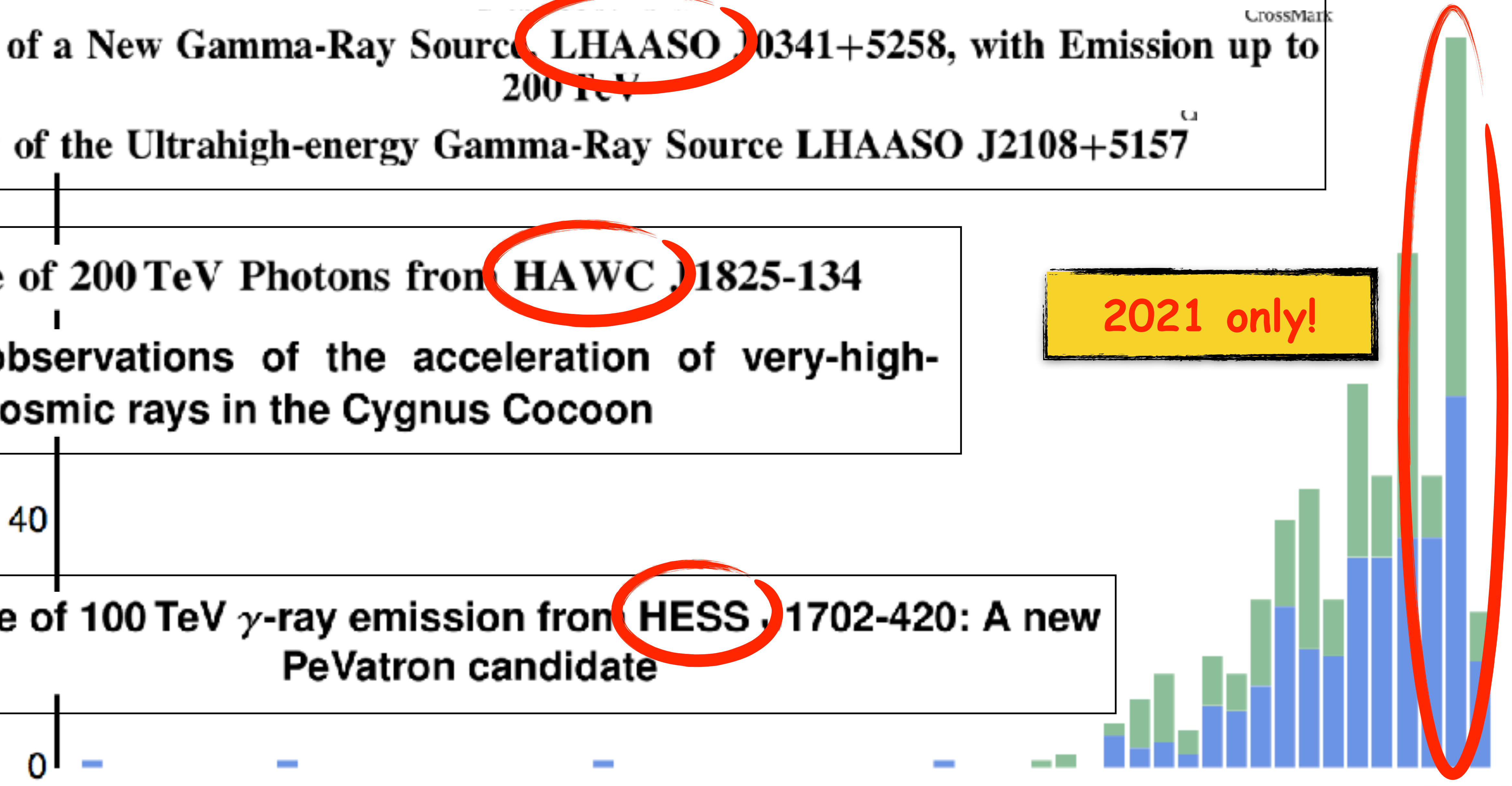
Discovery of a New Gamma-Ray Source, LHAASO J0341+5258, with Emission up to 200 TeV

Discovery of the Ultrahigh-energy Gamma-Ray Source LHAASO J2108+5157

Evidence of 200 TeV Photons from HAWC J1825-134

HAWC observations of the acceleration of very-high-energy cosmic rays in the Cygnus Cocoon

Evidence of 100 TeV γ-ray emission from HESS J1702-420: A new PeVatron candidate



2021 only!

many recent exciting observational results in the multi-TeV domain
—> PeV studies are data driven

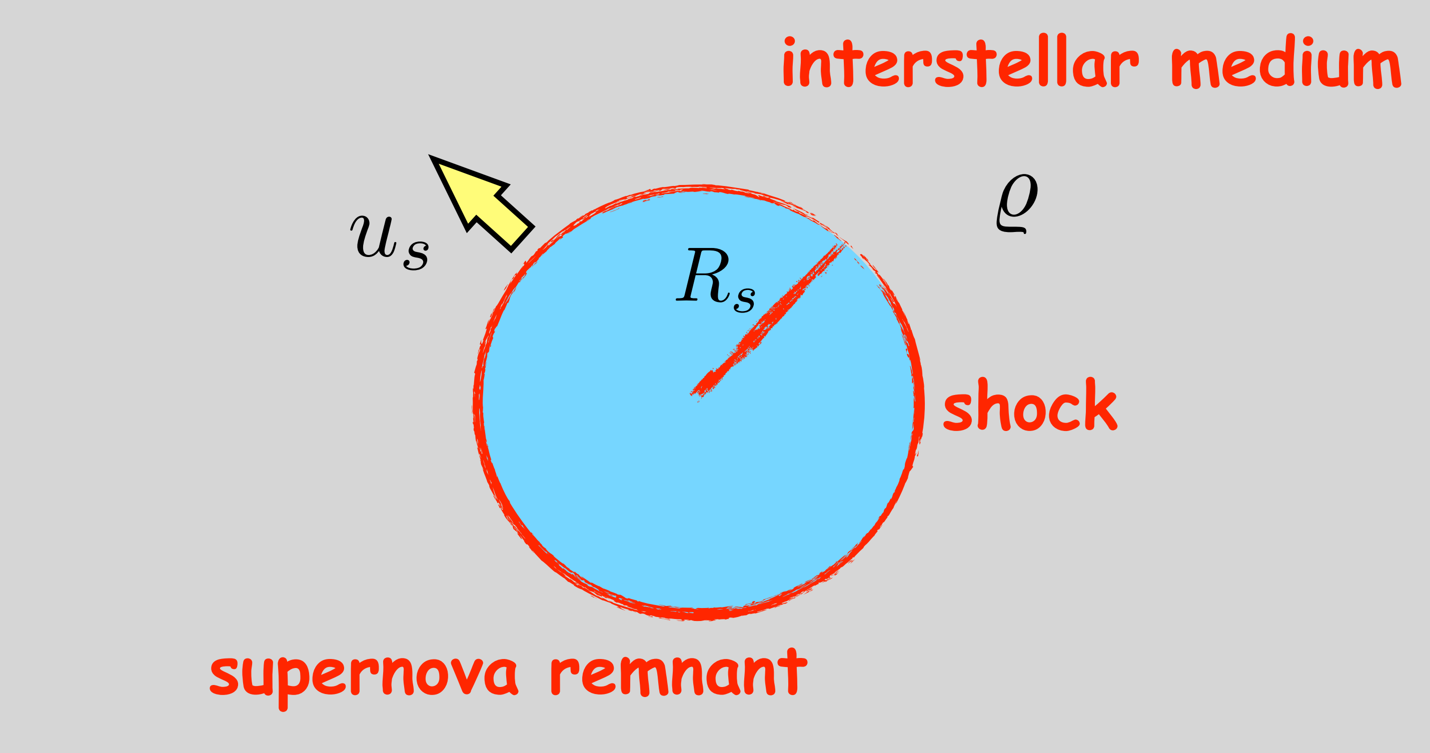
Hadronic PeVatrons: the importance of the escape of particles from supernova remnant

SuperNova Remnant evolution

mass of the ejecta M_{ej}

explosion energy E_{SN}

swept-up mass $M_{sw} = \frac{4\pi}{3} R_s^3 \varrho$



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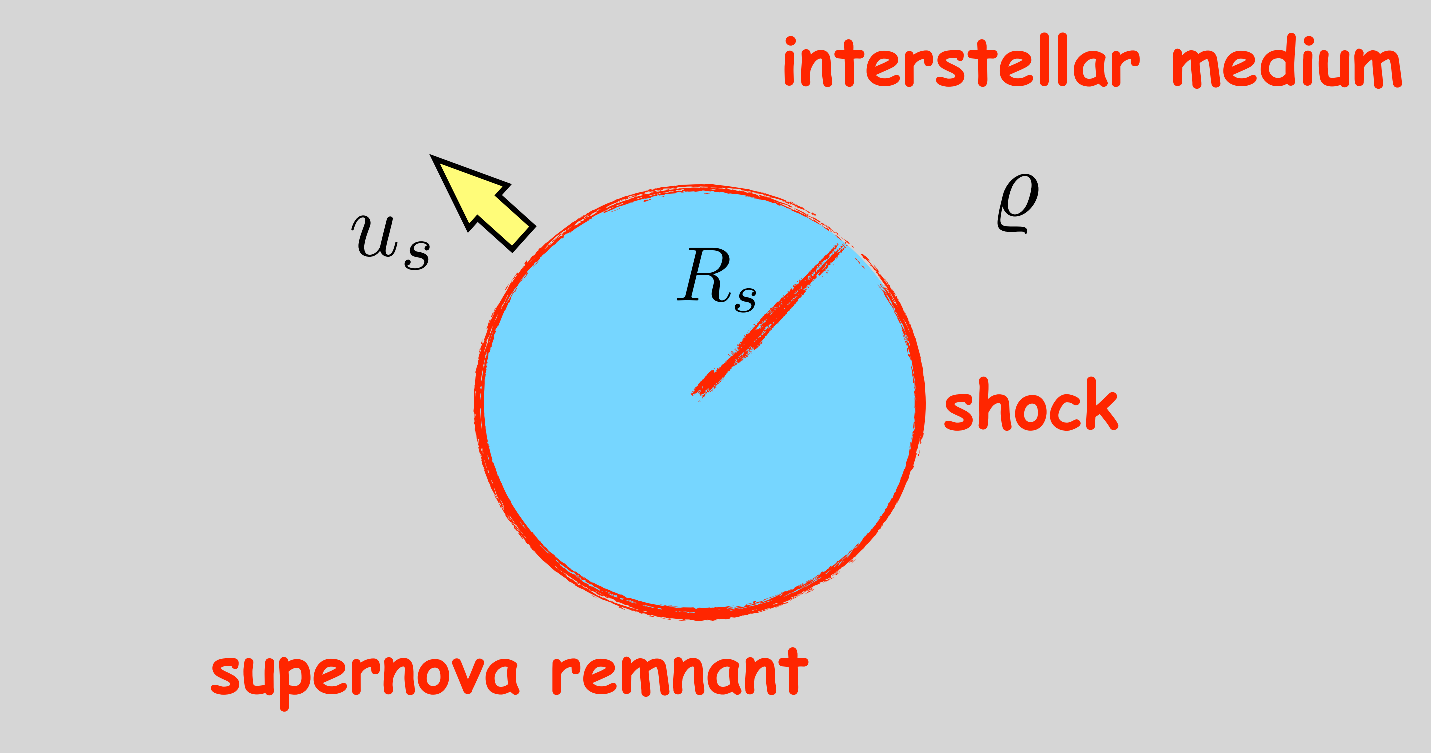


$M_{ej} \gg M_{sw}$ **free expansion** $R_s \sim u_s t$

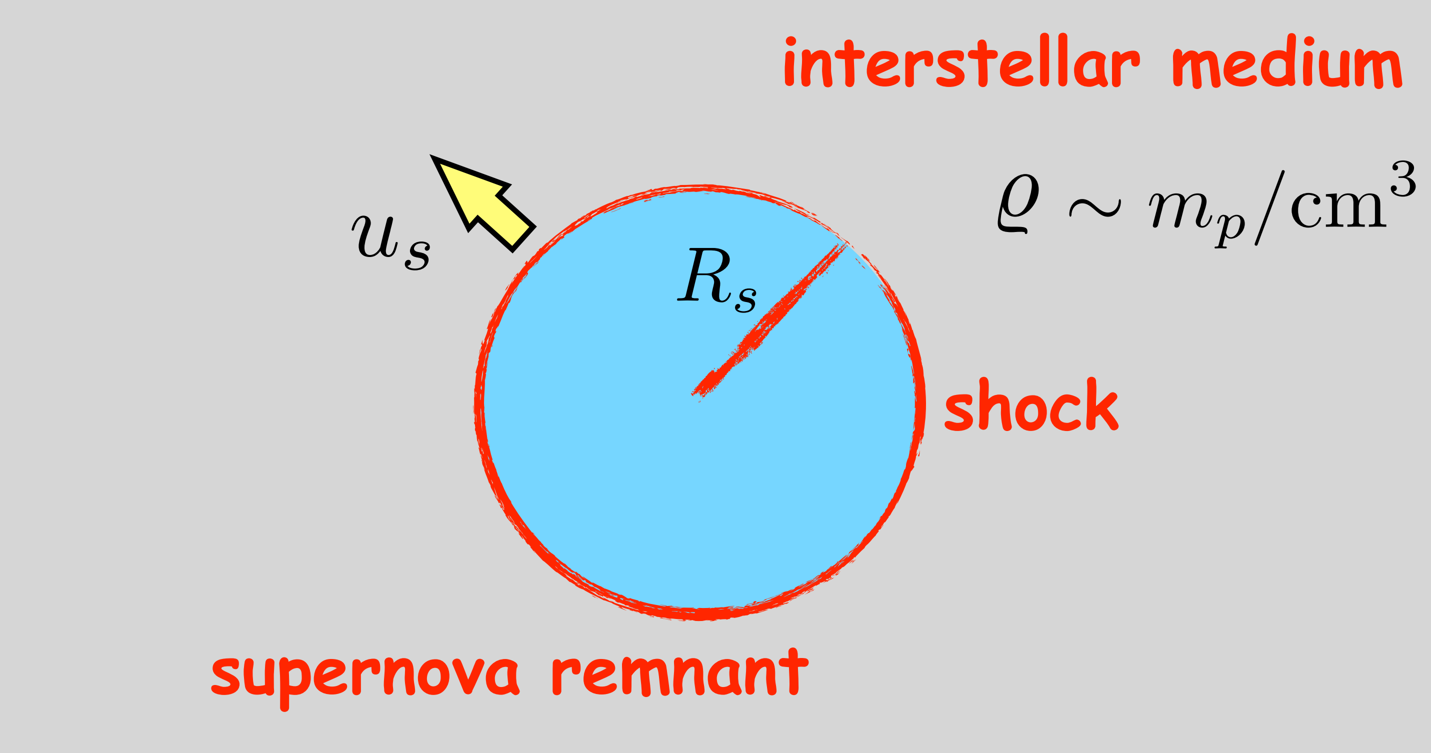
$M_{ej} \ll M_{sw}$ **Sedov** $R_s \sim \left(\frac{E_{SN}}{\varrho}\right)^{1/5} t^{2/5}$

SuperNova Remnant evolution

mass of the ejecta $M_{ej} \sim 1 \ M_\odot$

explosion energy $E_{SN} \sim 10^{51} \mathrm{erg}$

swept-up mass $M_{sw} = \dfrac{4\pi}{3} R_s^3 \varrho$



$M_{ej} \gg M_{sw}$ **free expansion** $R_s \sim u_s t$

$M_{ej} \ll M_{sw}$ **Sedov** $R_s \sim \left(\dfrac{E_{SN}}{\varrho} \right)^{1/5} t^{2/5}$

$M_{ej} \sim M_{sw}$

$\Downarrow$

$R_* \sim 2 \ \mathrm{pc}$

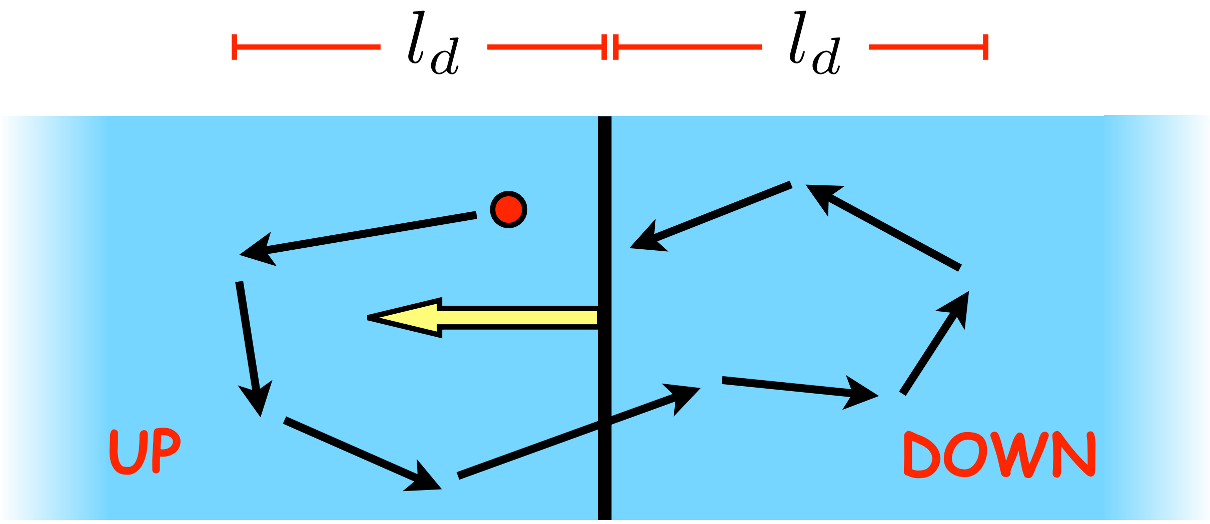
$t_* \sim 200 \ \mathrm{yr}$

BOBALSKY: diffusive shock acceleration

Blandford & **O**striker 1978, **B**ell 1978, **A**xford, **L**eer & **S**kadron 1977, **K**rimsky 1977

shock speed

u_s



CR diffusion coefficient

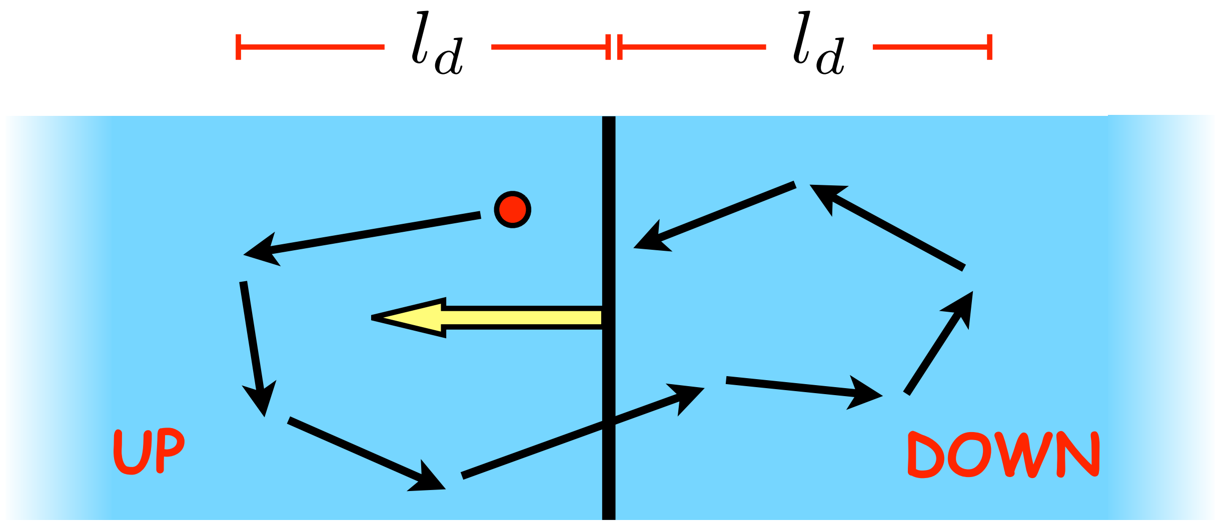
$D(E)$

BOBALSKY: diffusive shock acceleration

Blandford & **O**striker 1978, **B**ell 1978, **A**xford, **L**eer & **S**kadron 1977, **K**rimsky 1977

shock speed

u_s



CR diffusion coefficient

$D(E)$

infinite plane shock moving at constant speed —> characteristic length & time scales

acceleration time —>

$$\tau_{acc} \sim \frac{D(E)}{u_s^2}$$

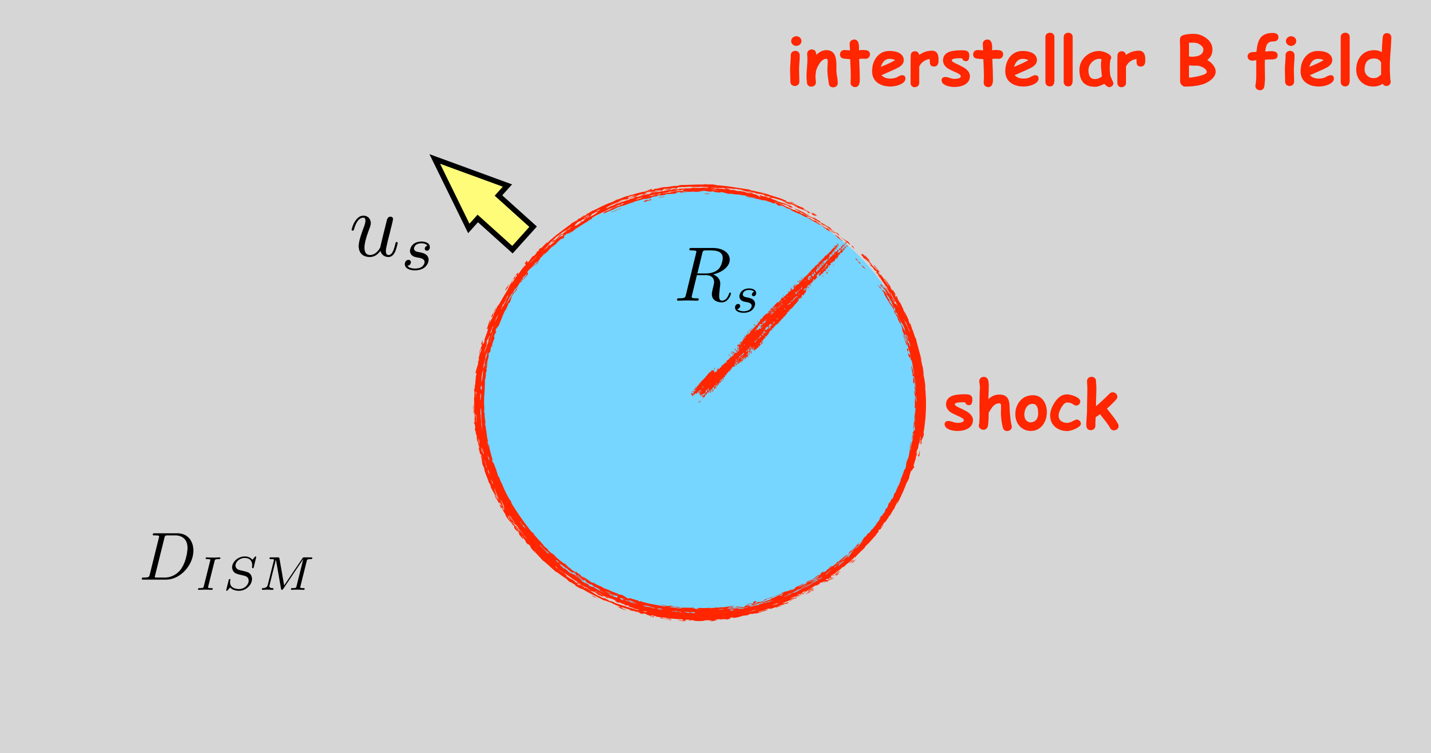
diffusion length —>

$$l_d \sim \frac{D(E)}{u_s}$$

Diffusive shock acceleration: E_{max}

"typical" Galactic diffusion

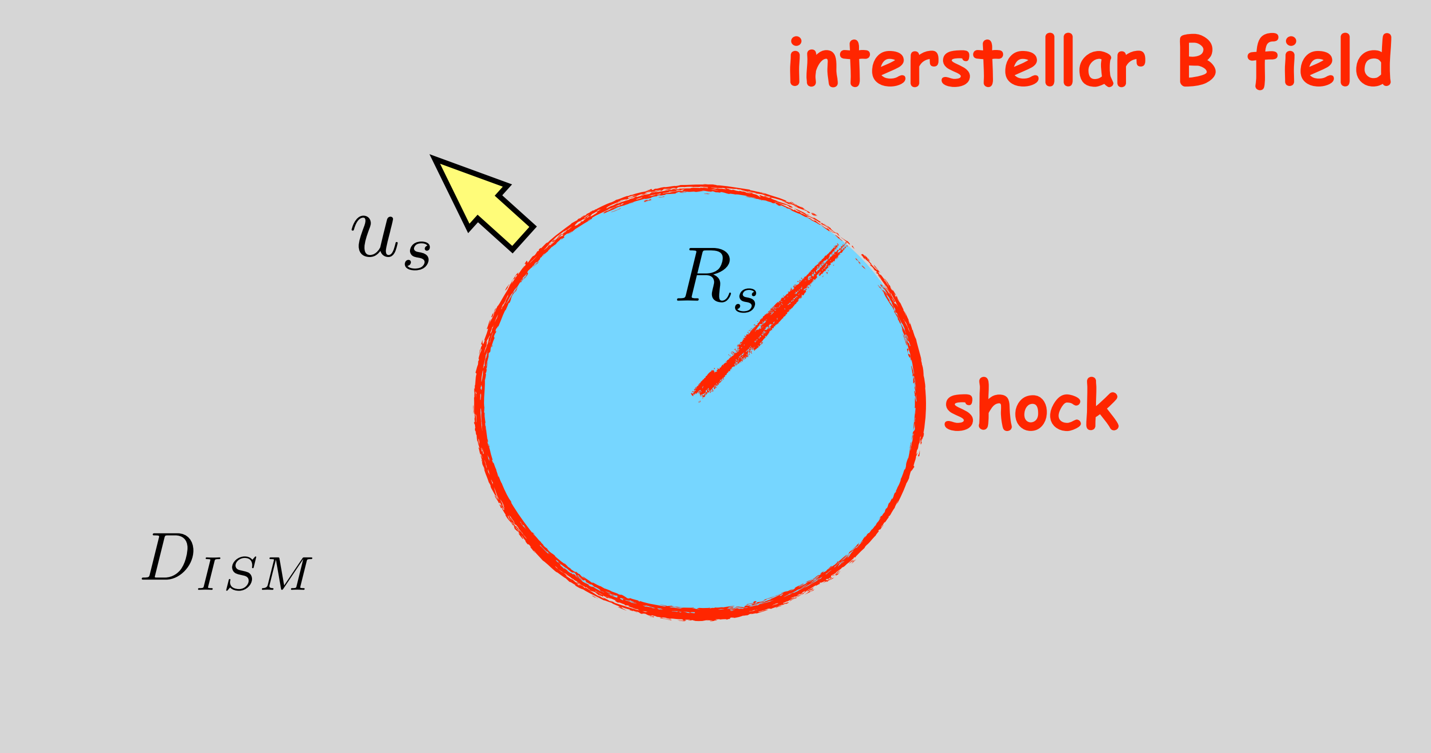
$$D_{ISM} \approx 10^{28} \left(\frac{E}{\mathrm{GeV}} \right)^{0.5} \mathrm{cm^2/s}$$



Diffusive shock acceleration: E_{max}

“typical” Galactic diffusion

$$D_{ISM} \approx 10^{28} \left(\frac{E}{\text{GeV}} \right)^{0.5} \text{cm}^2/\text{s}$$



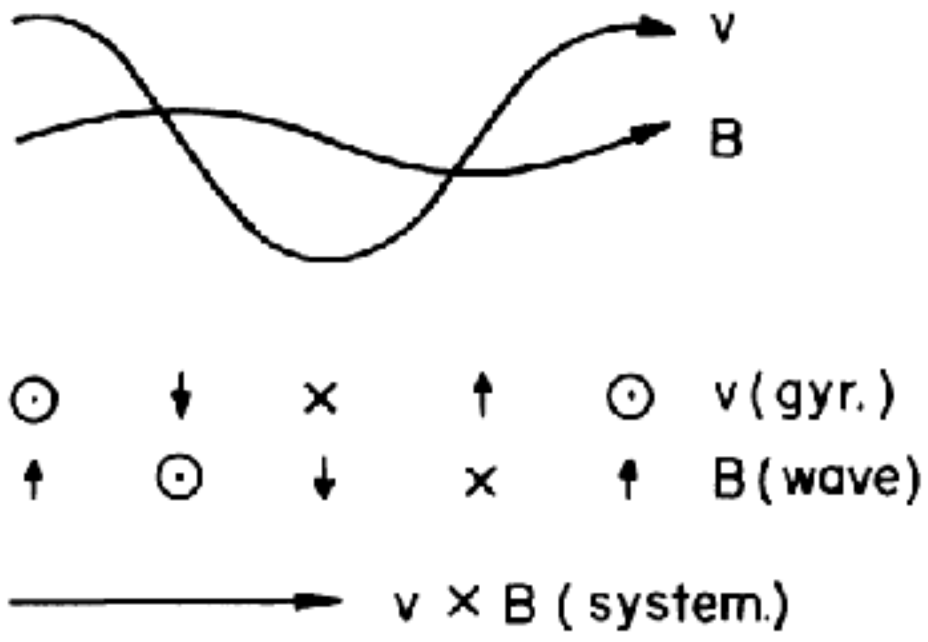
maximum energy (free expansion/Sedov transition)

$$\tau_{acc}(E_{max}) \equiv \frac{D_{ISM}(E_{max})}{u_s^2} \sim t_* \longrightarrow E_{max} < 1 \text{ GeV}$$

very small!

Resonant streaming instability

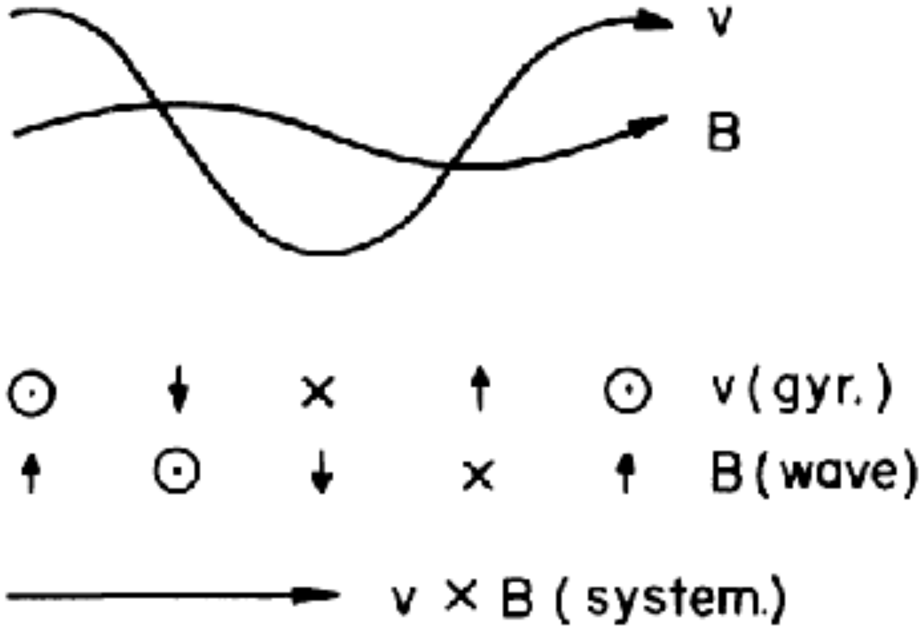
e.g. Wentzel 1972



RESONANCE—> $k_{res} \approx \frac{1}{R_L} \propto \frac{1}{E}$

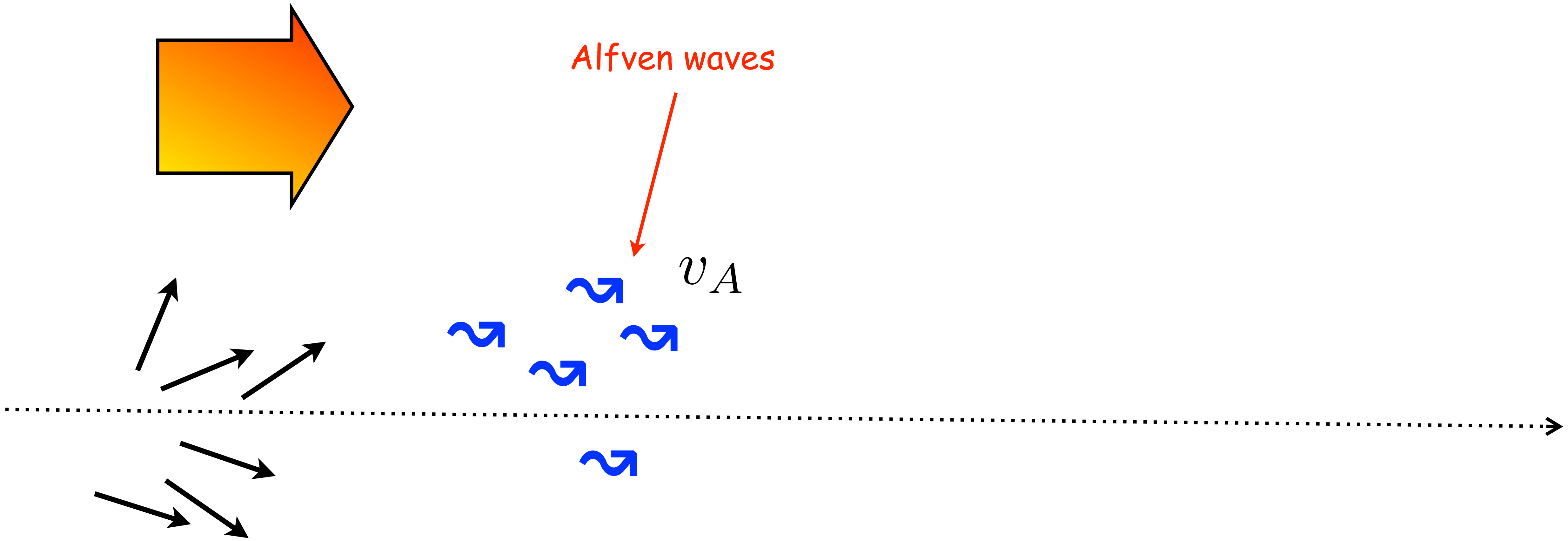
Resonant streaming instability

e.g. Wentzel 1972



RESONANCE—> $k_{res} \approx \frac{1}{R_L} \propto \frac{1}{E}$

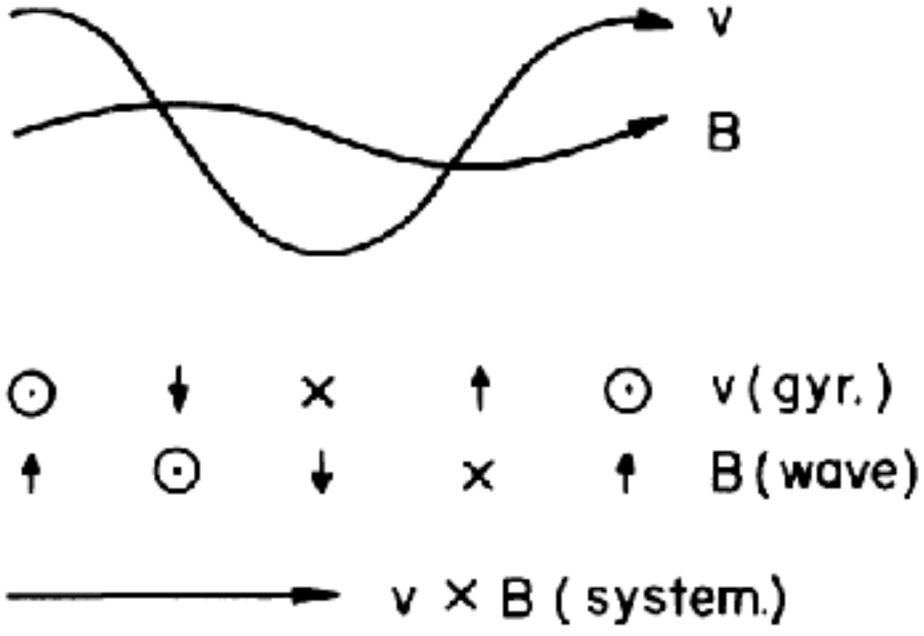
CR streaming velocity v_D



Kulsrud's book

Resonant streaming instability

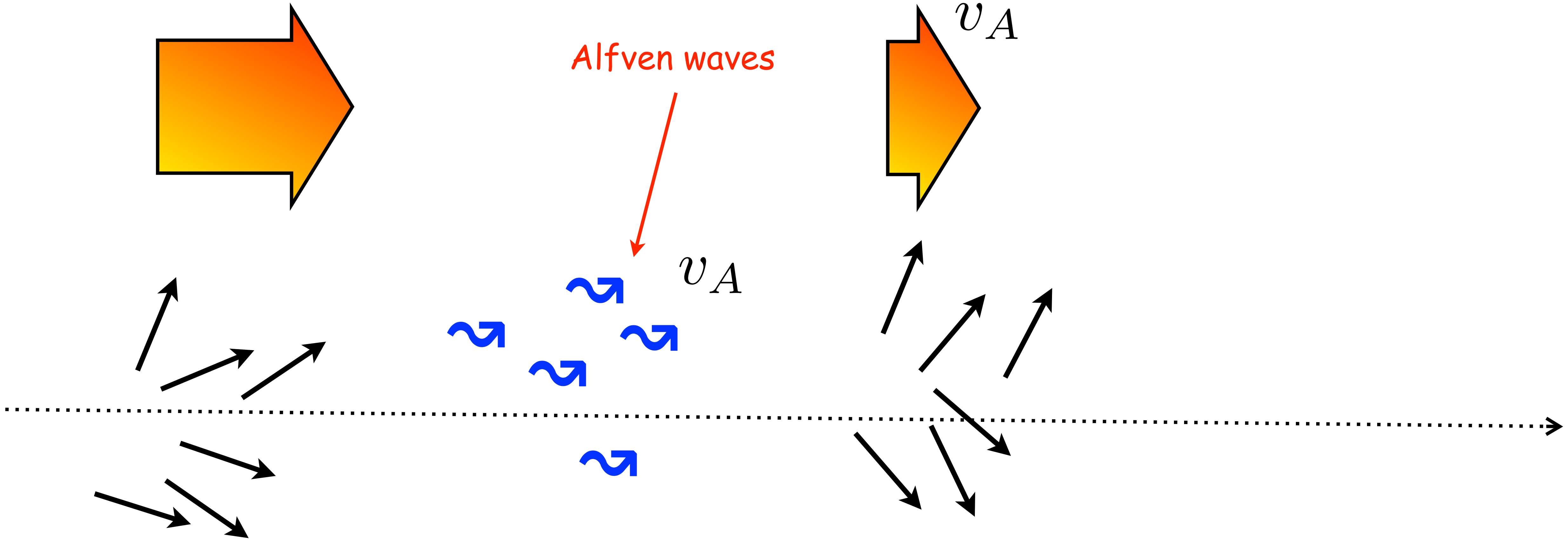
e.g. Wentzel 1972



RESONANCE—> $k_{res} \approx \frac{1}{R_L} \propto \frac{1}{E}$

CR streaming velocity v_D

momentum -> waves



Kulsrud's book

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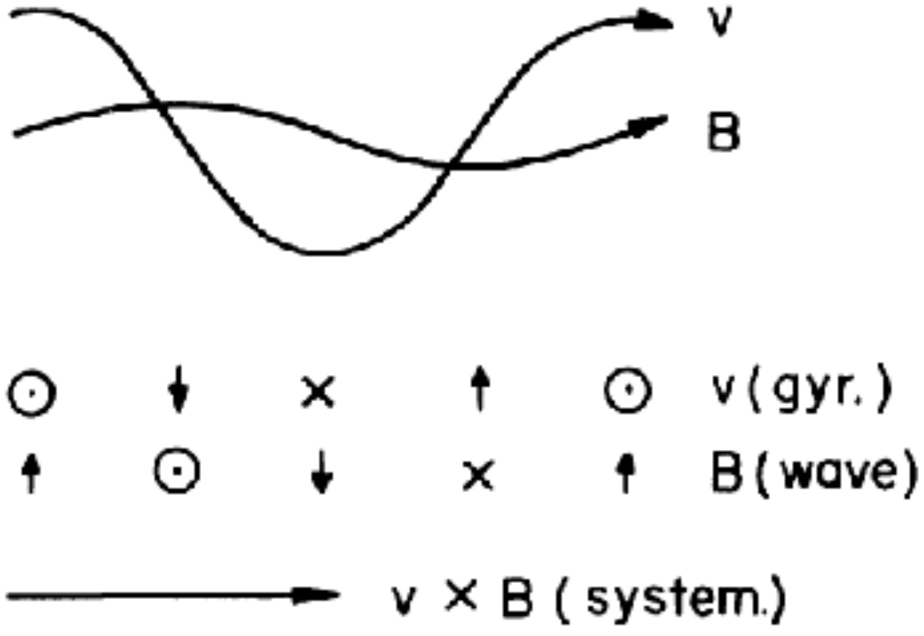

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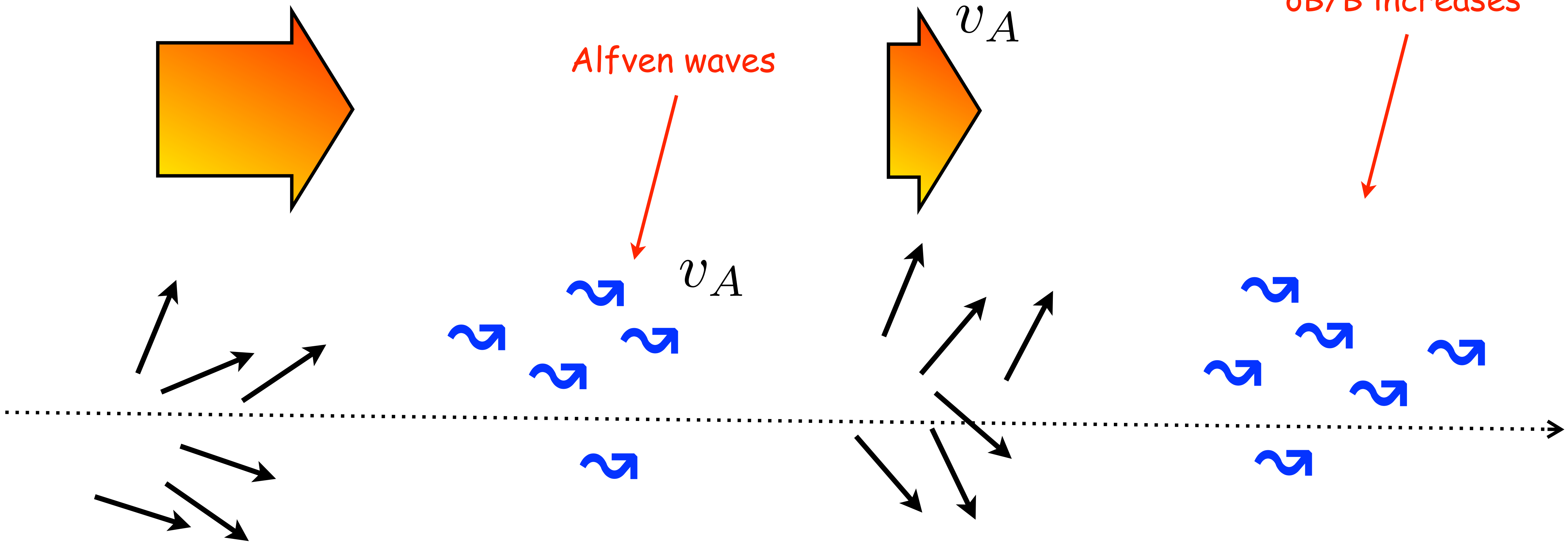
CR streaming velocity v_D

momentum -> waves

δB/B increases

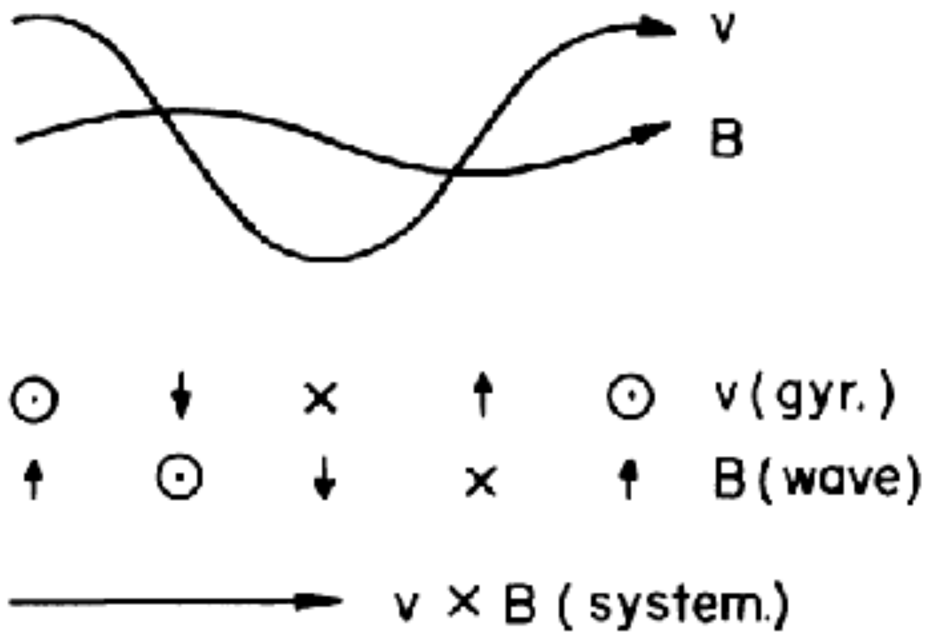
Alfven waves



Kulsrud's book

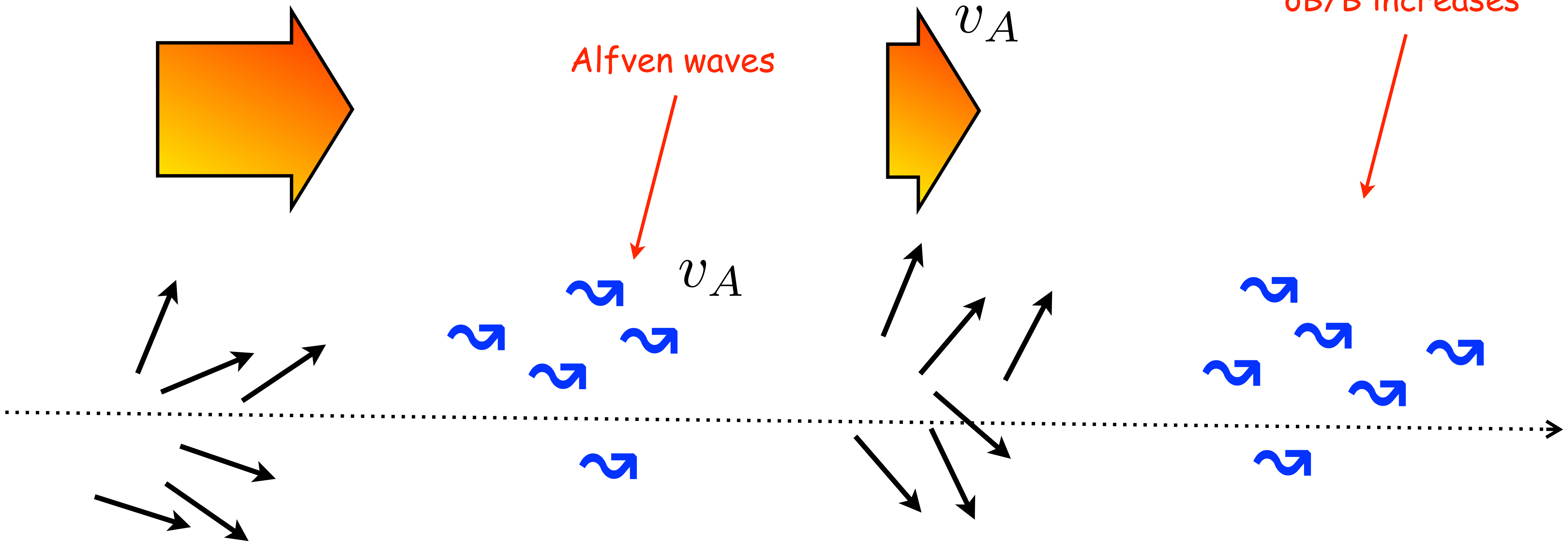
Resonant streaming instability

e.g. Wentzel 1972



RESONANCE—> $k_{res} \approx \frac{1}{R_L} \propto \frac{1}{E}$

saturates @ $\frac{\delta B}{B} \sim 1$



CR streaming velocity v_D

momentum -> waves

Alfven waves

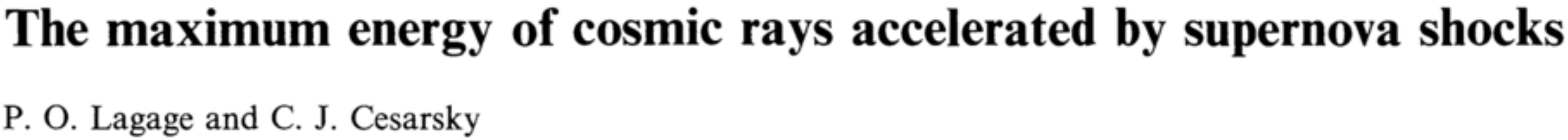
v_A

v_A

δB/B increases

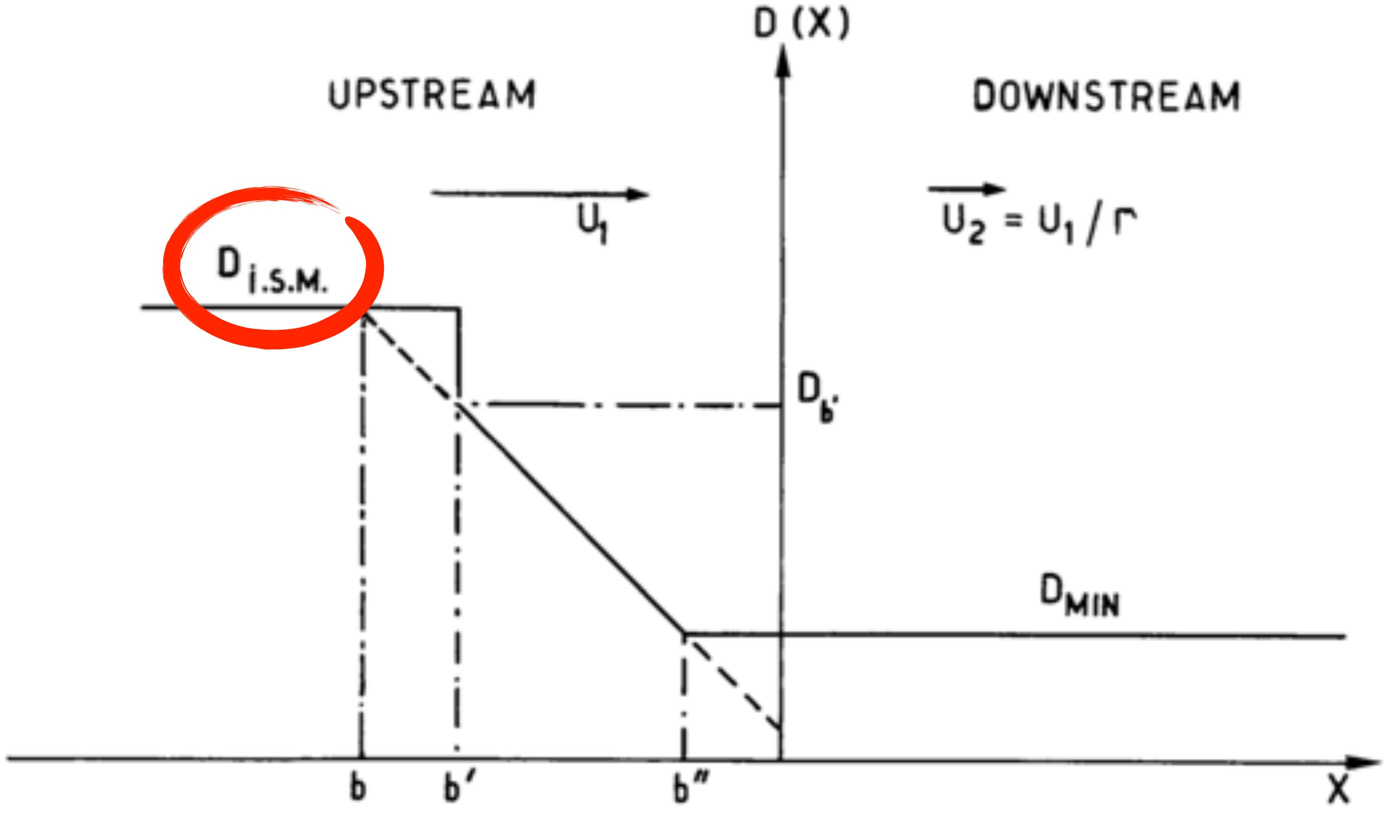
Kulsrud's book

Lagage & Cesarsky 1983



The maximum energy of cosmic rays accelerated by supernova shocks

P. O. Lagage and C. J. Cesarsky



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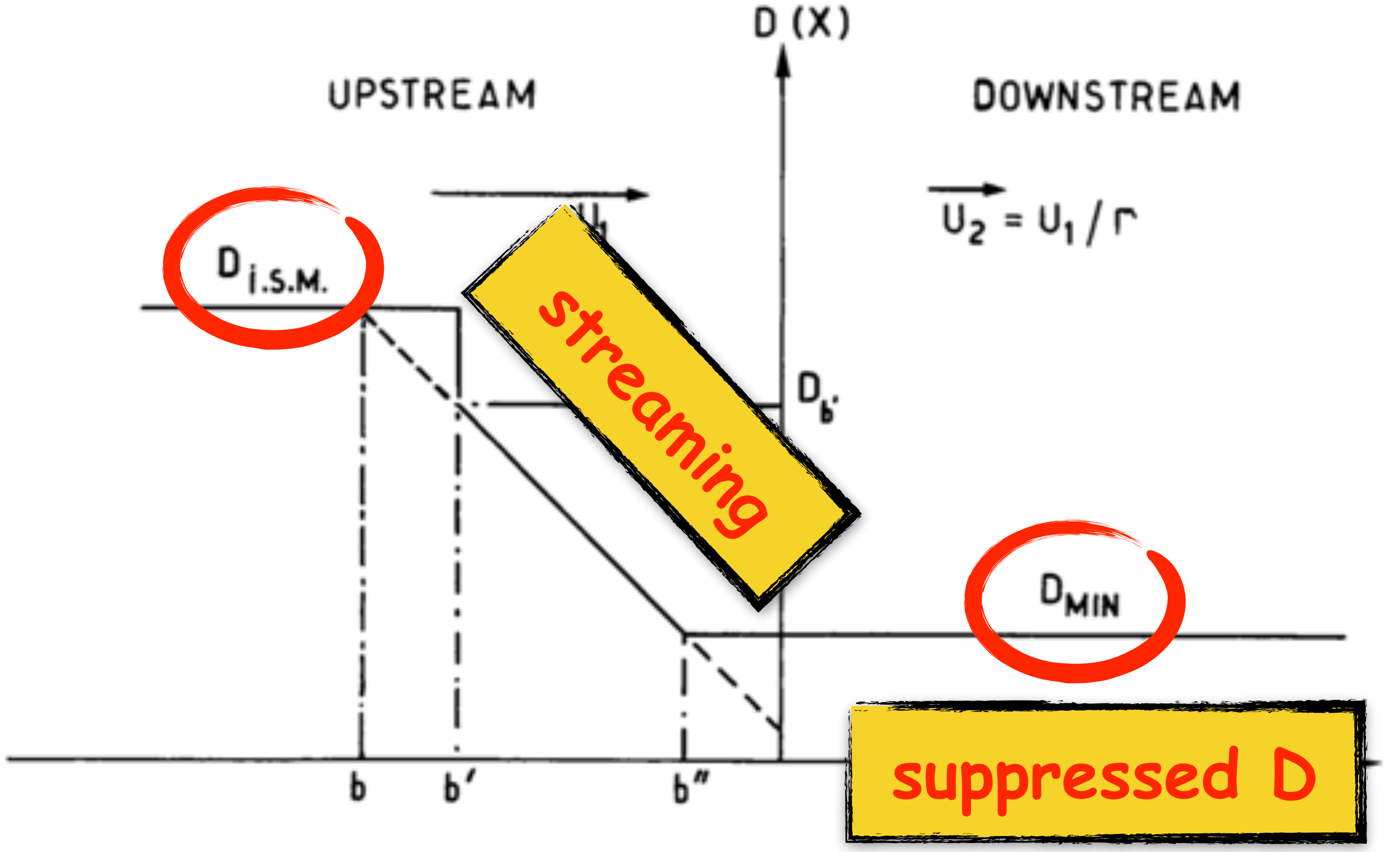

streaming

suppressed D

Lagage & Cesarsky 1983

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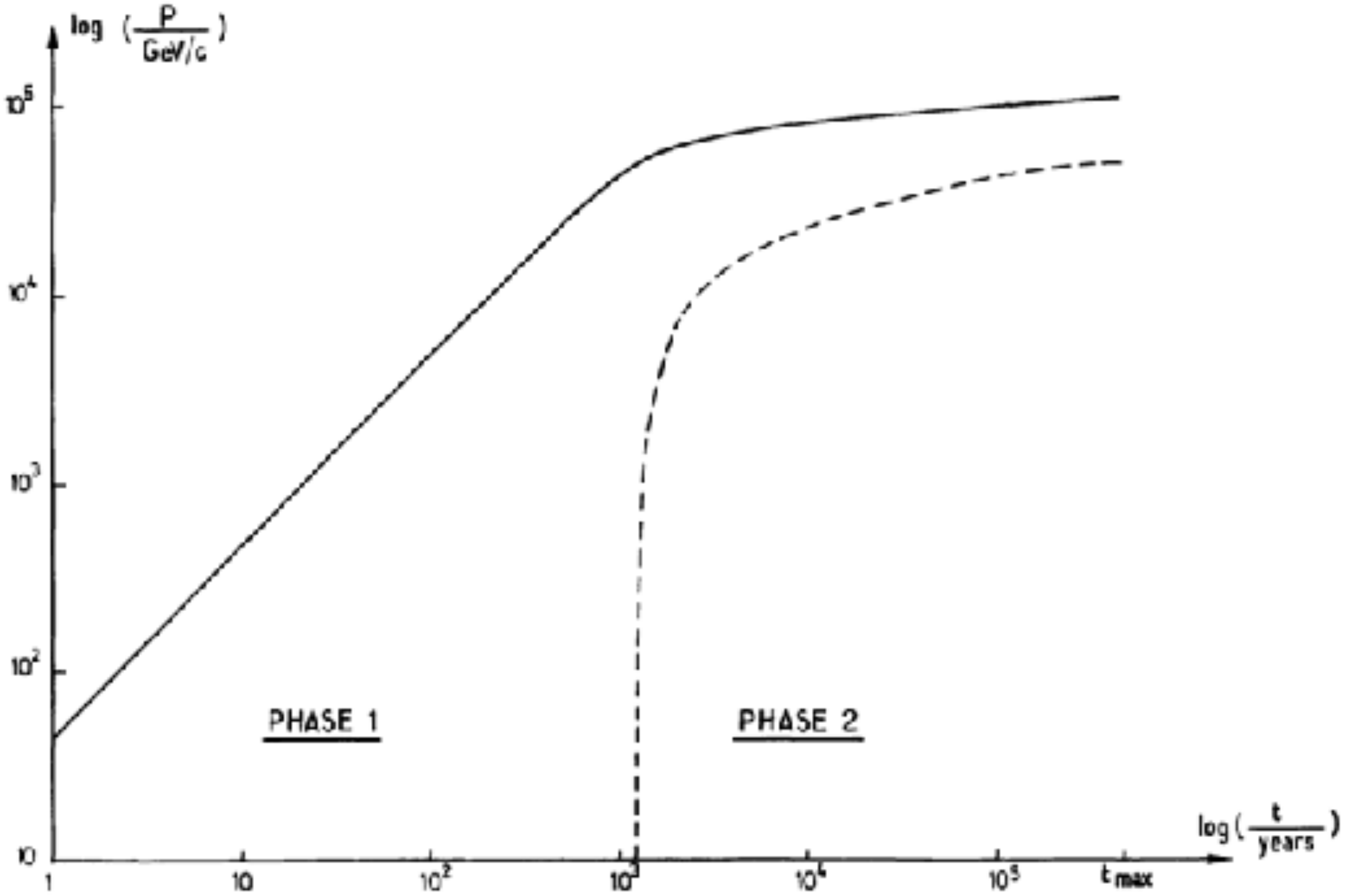

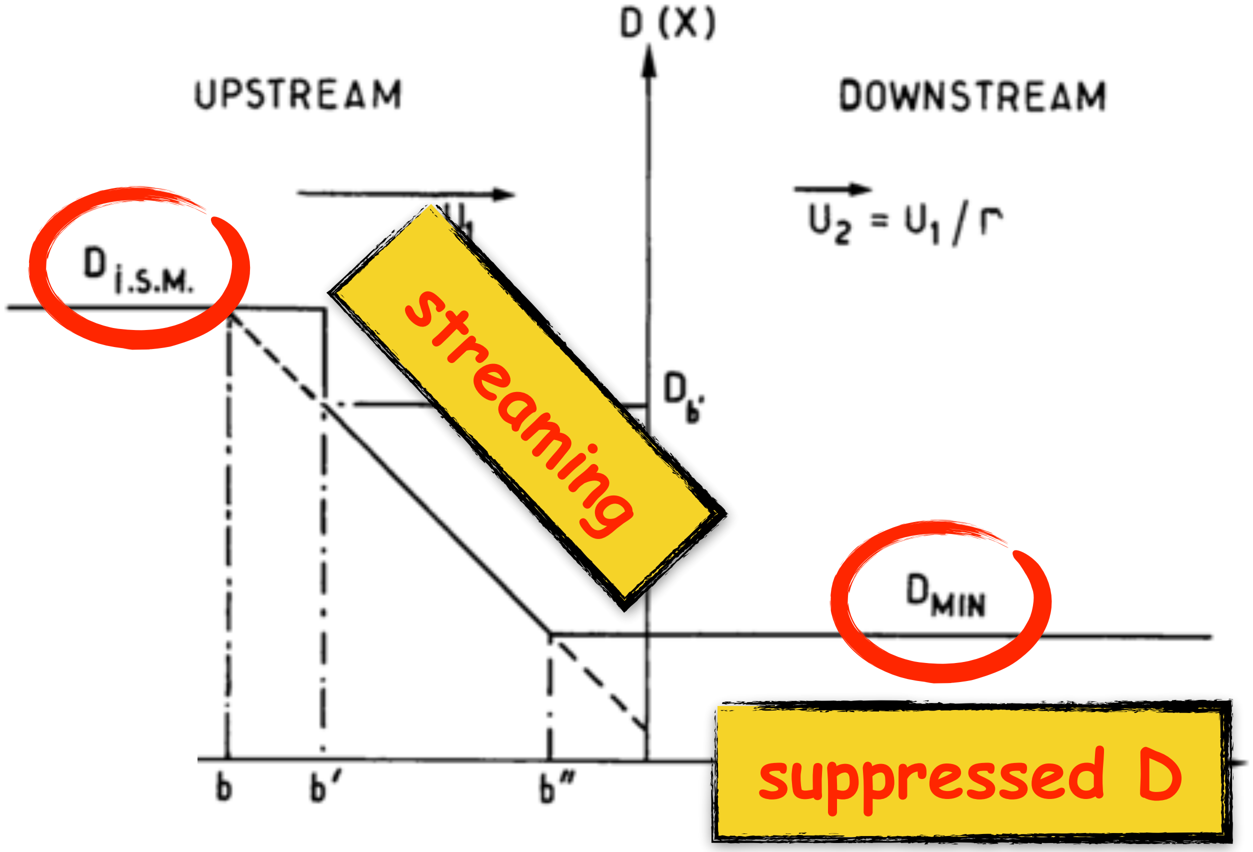

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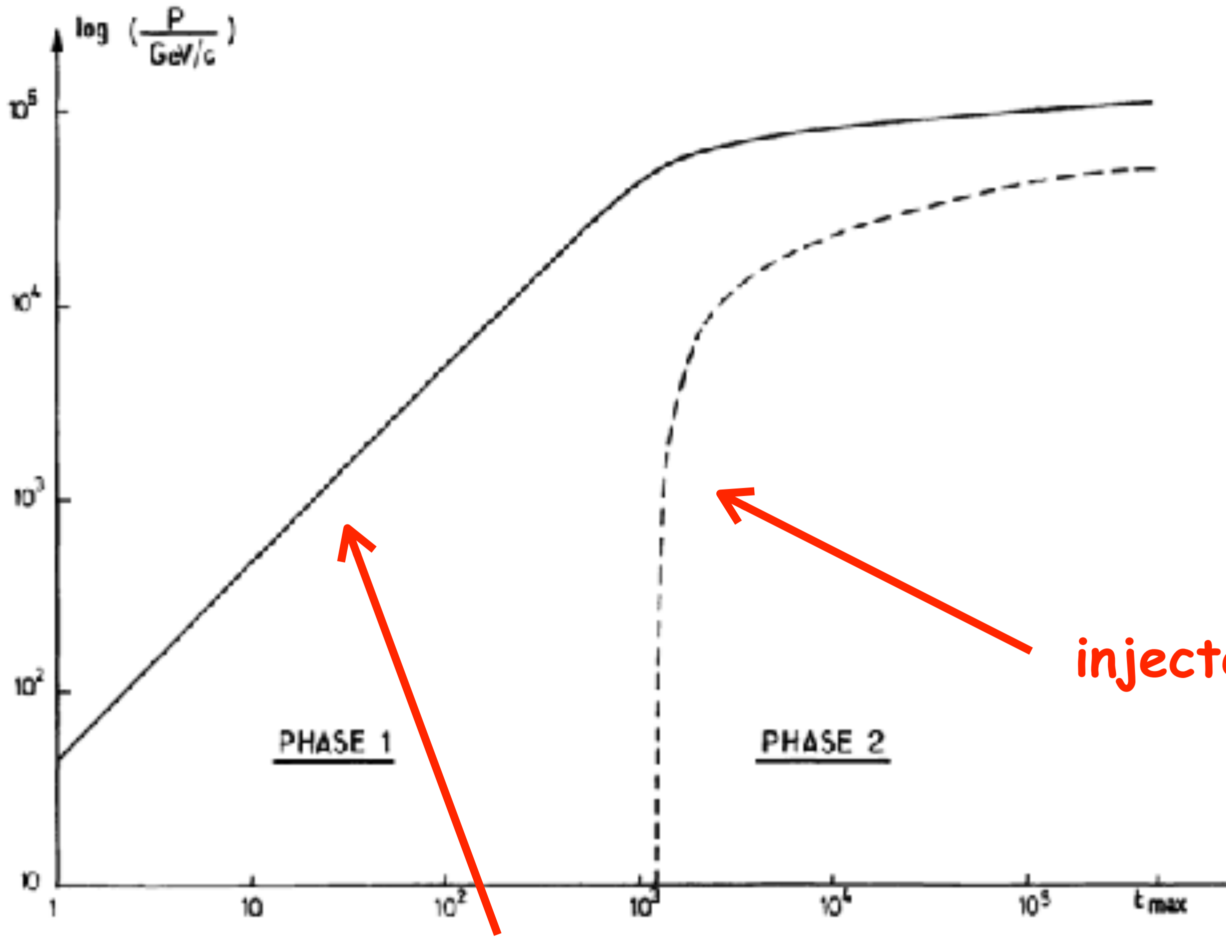
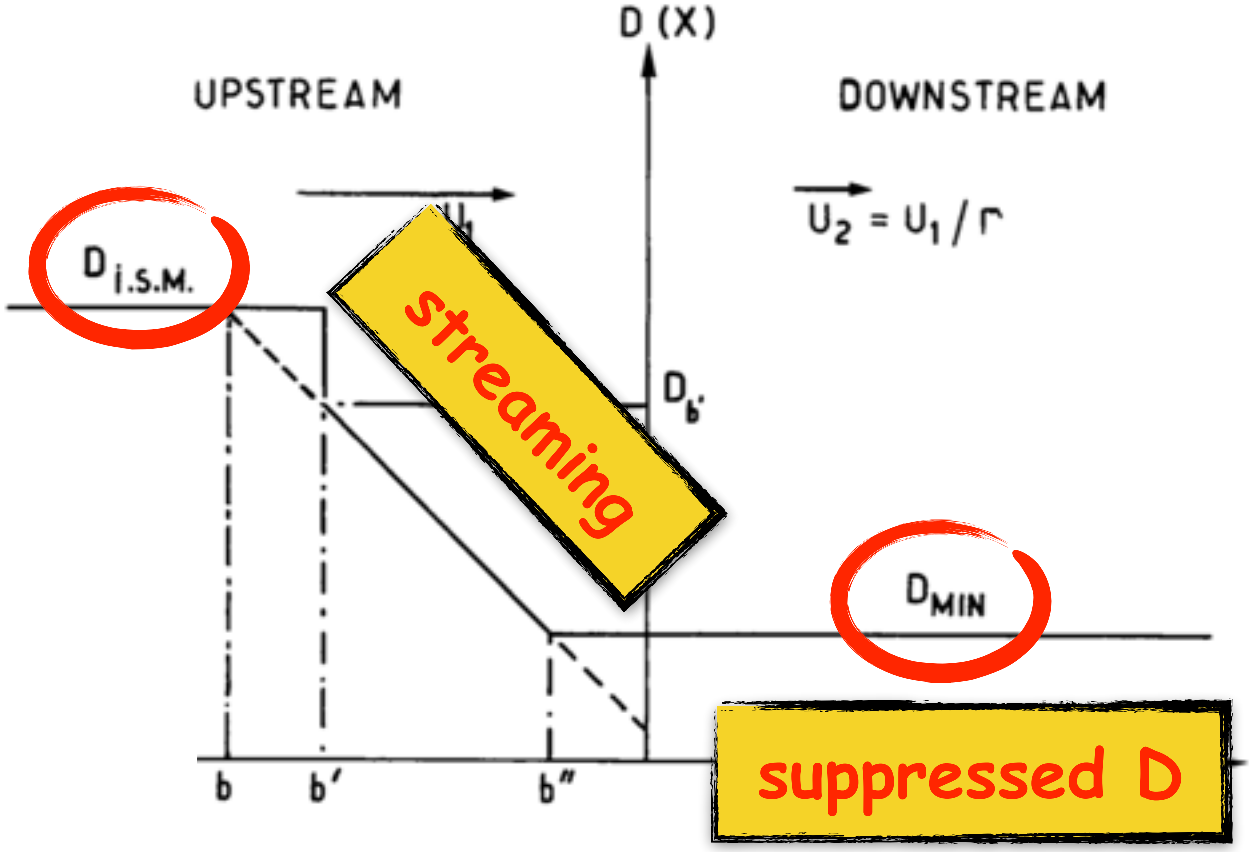


injected at $t = t_*$

injected at $t = 0$



streaming

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Lagage & Cesarsky 1983

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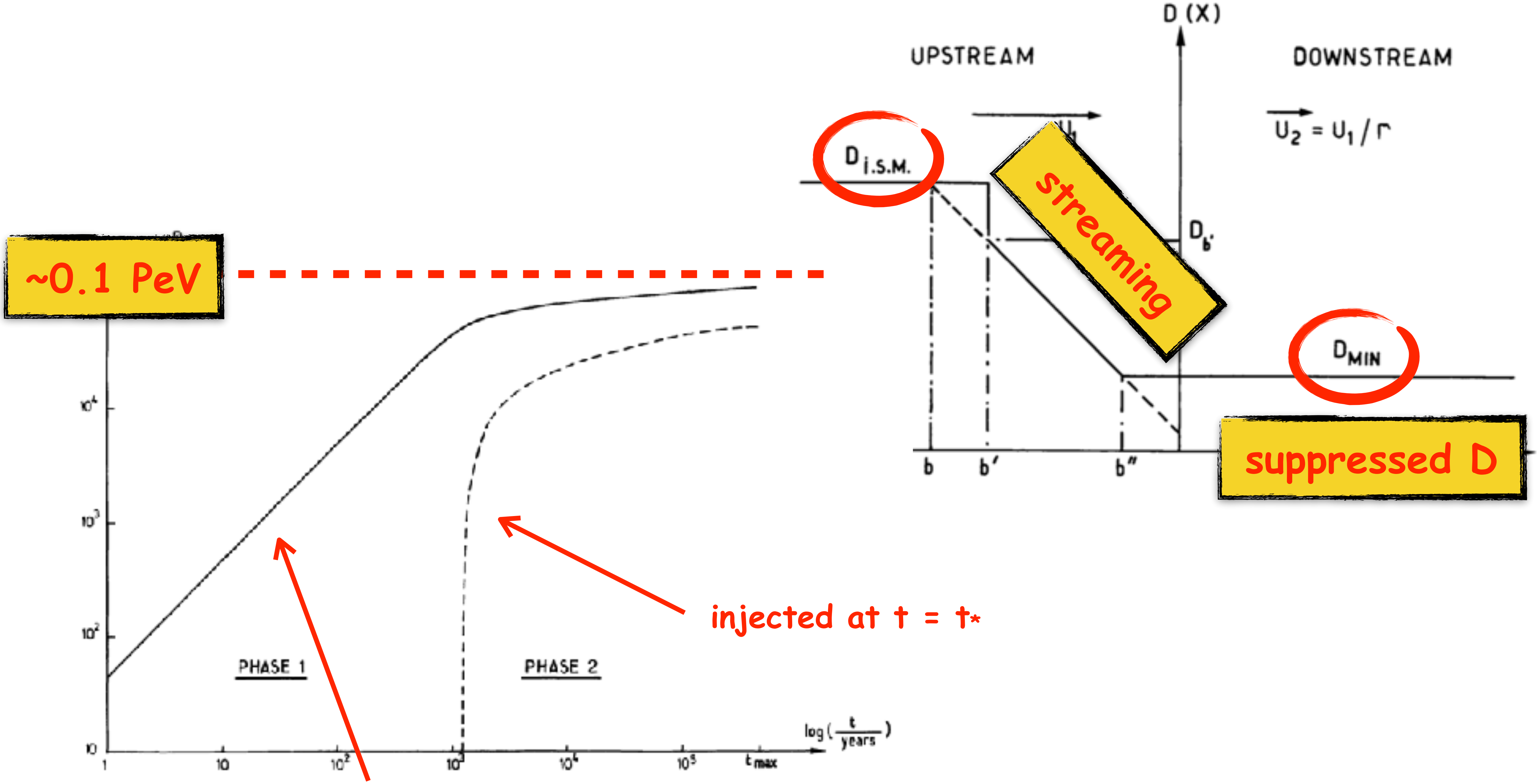

~0.1 PeV

streaming

suppressed D

injected at t = t*

injected at t = 0

Lagage & Cesarsky 1983

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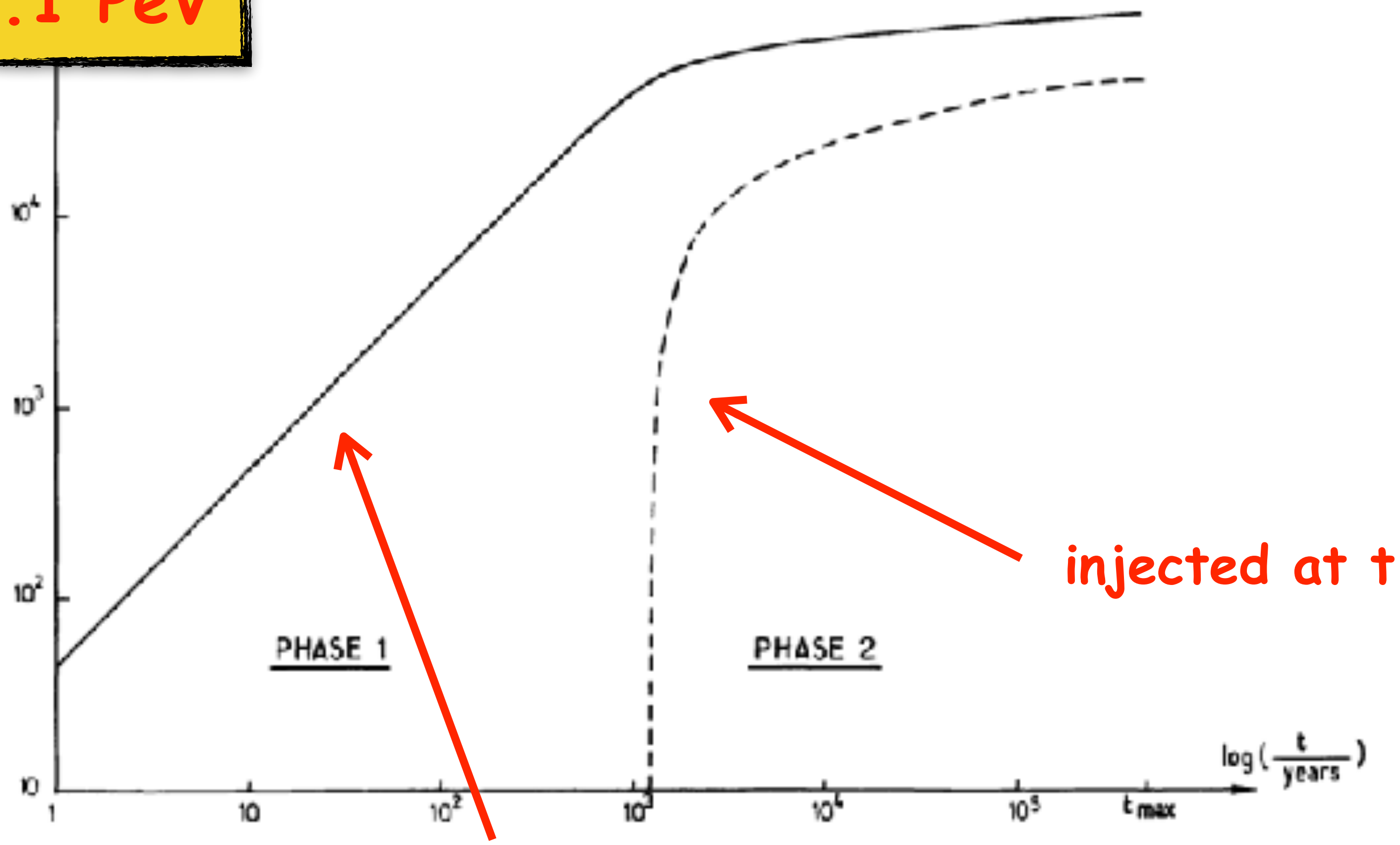
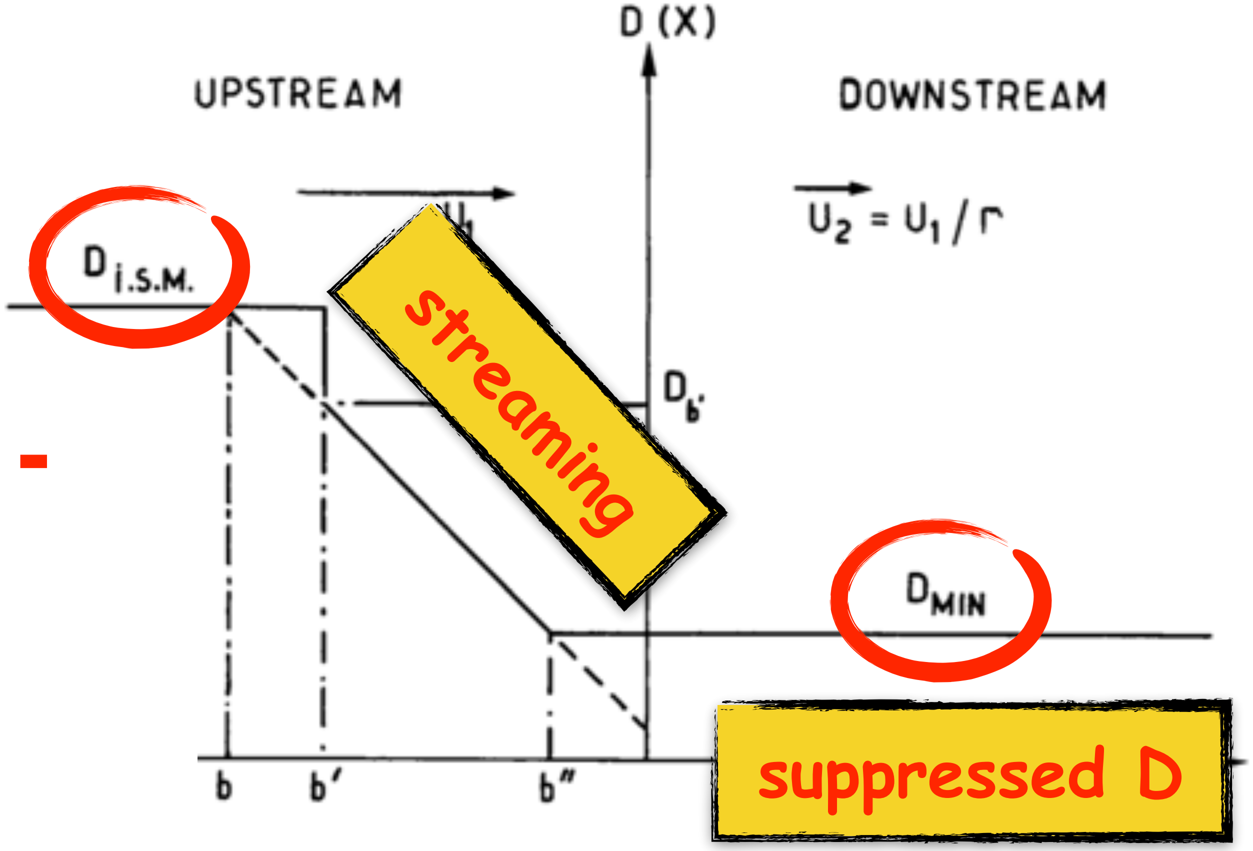
~0.1 PeV



injected at t = t*

injected at t = 0

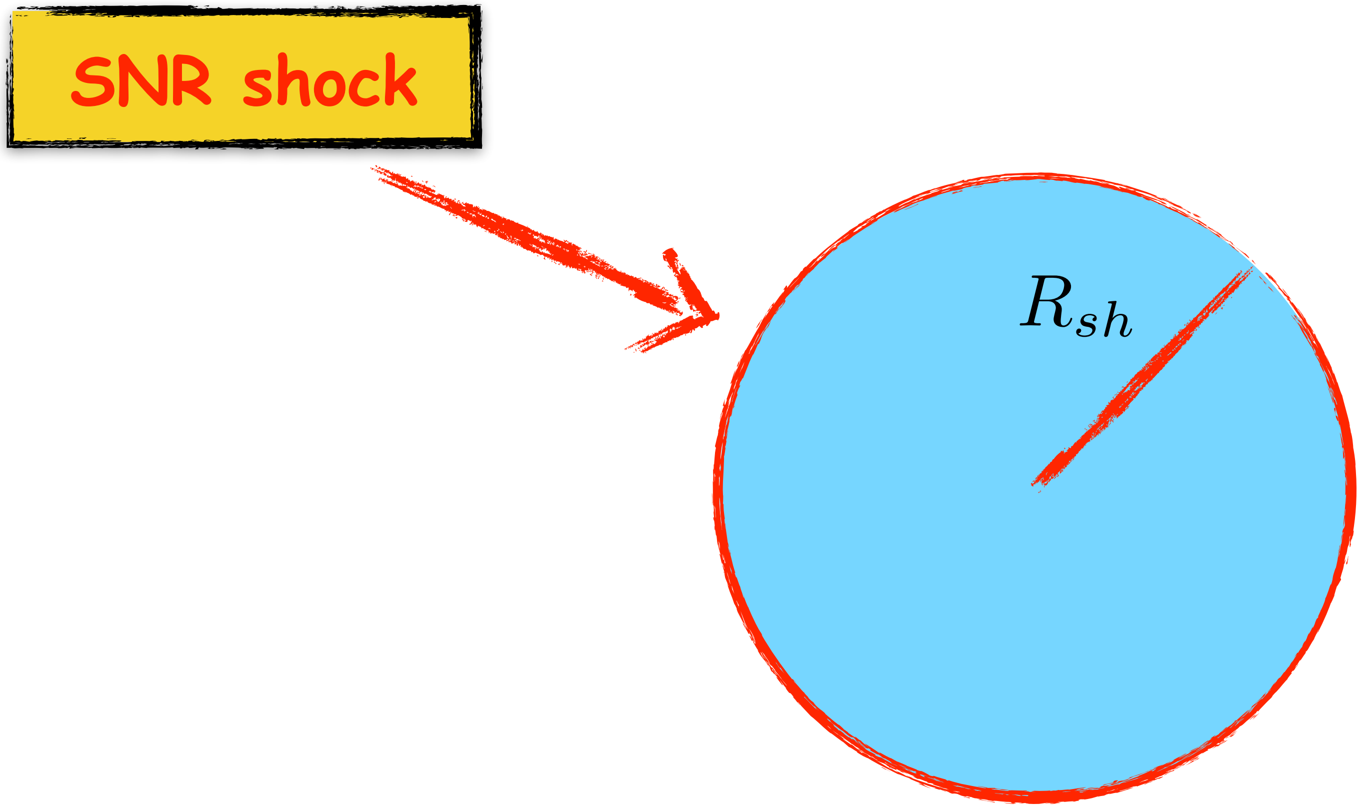


streaming

suppressed D

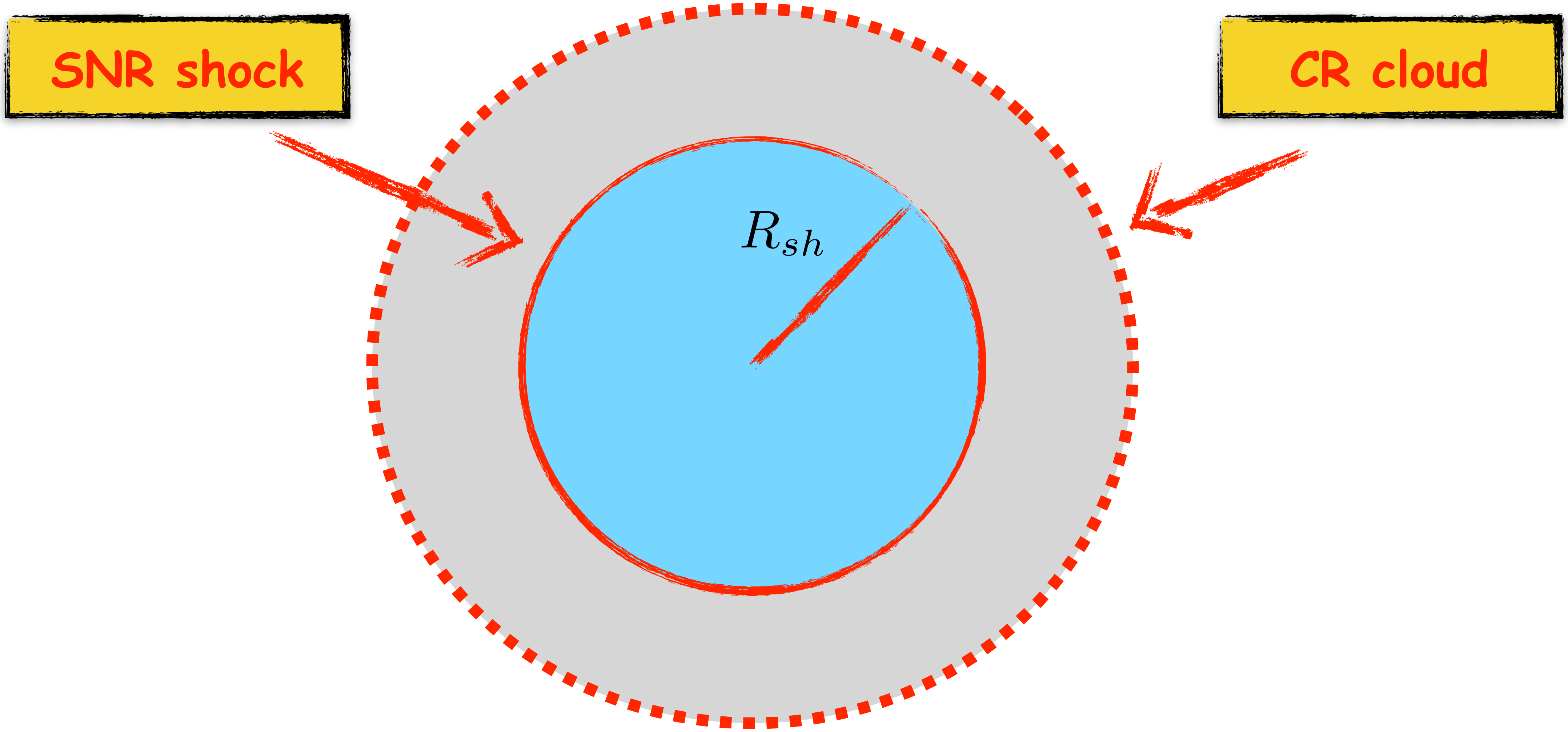
NO ESCAPE!

SNRs are spherical —> CR escape!



e.g. Drury 2011

SNRs are spherical —> CR escape!



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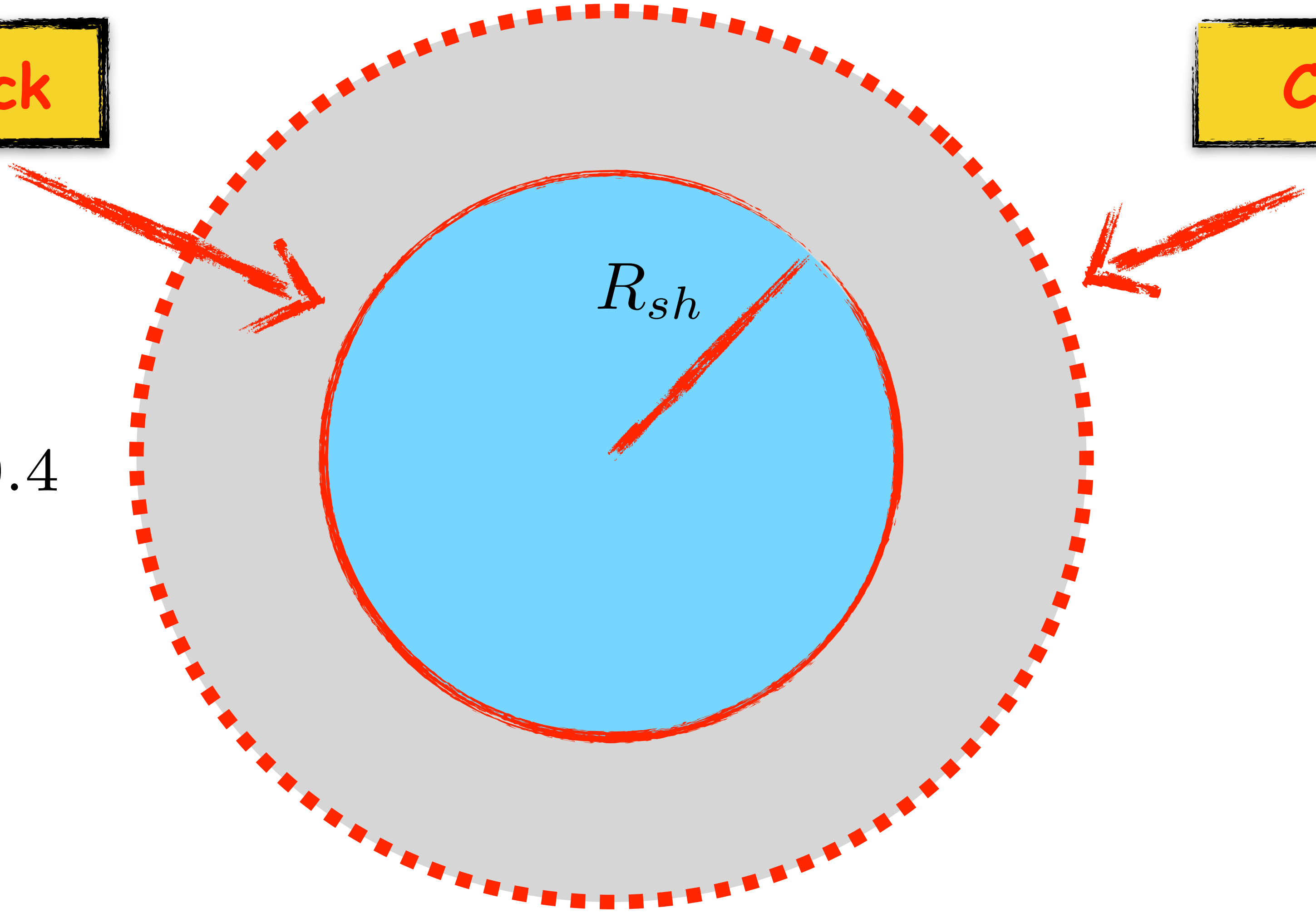
SNRs are spherical —> CR escape!



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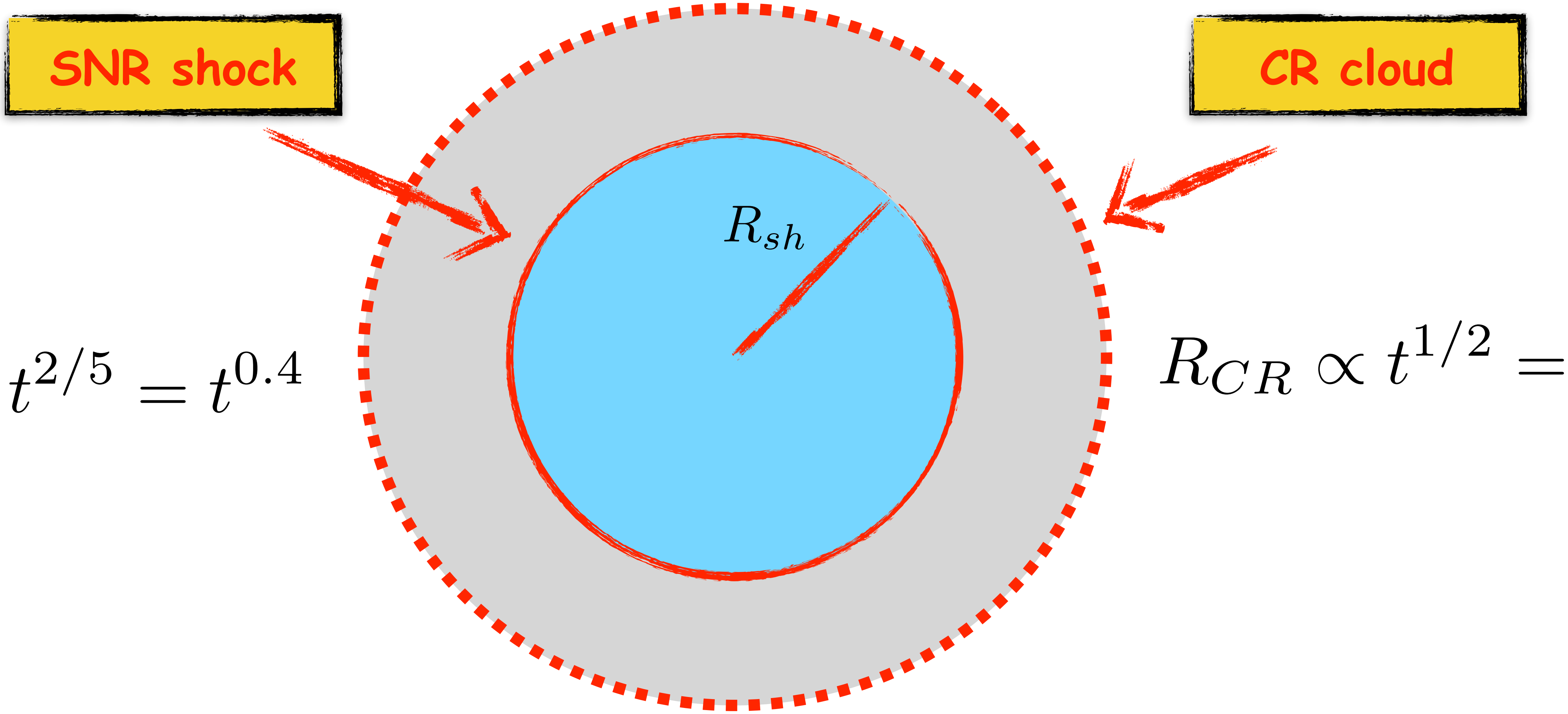

SNR shock

CR cloud

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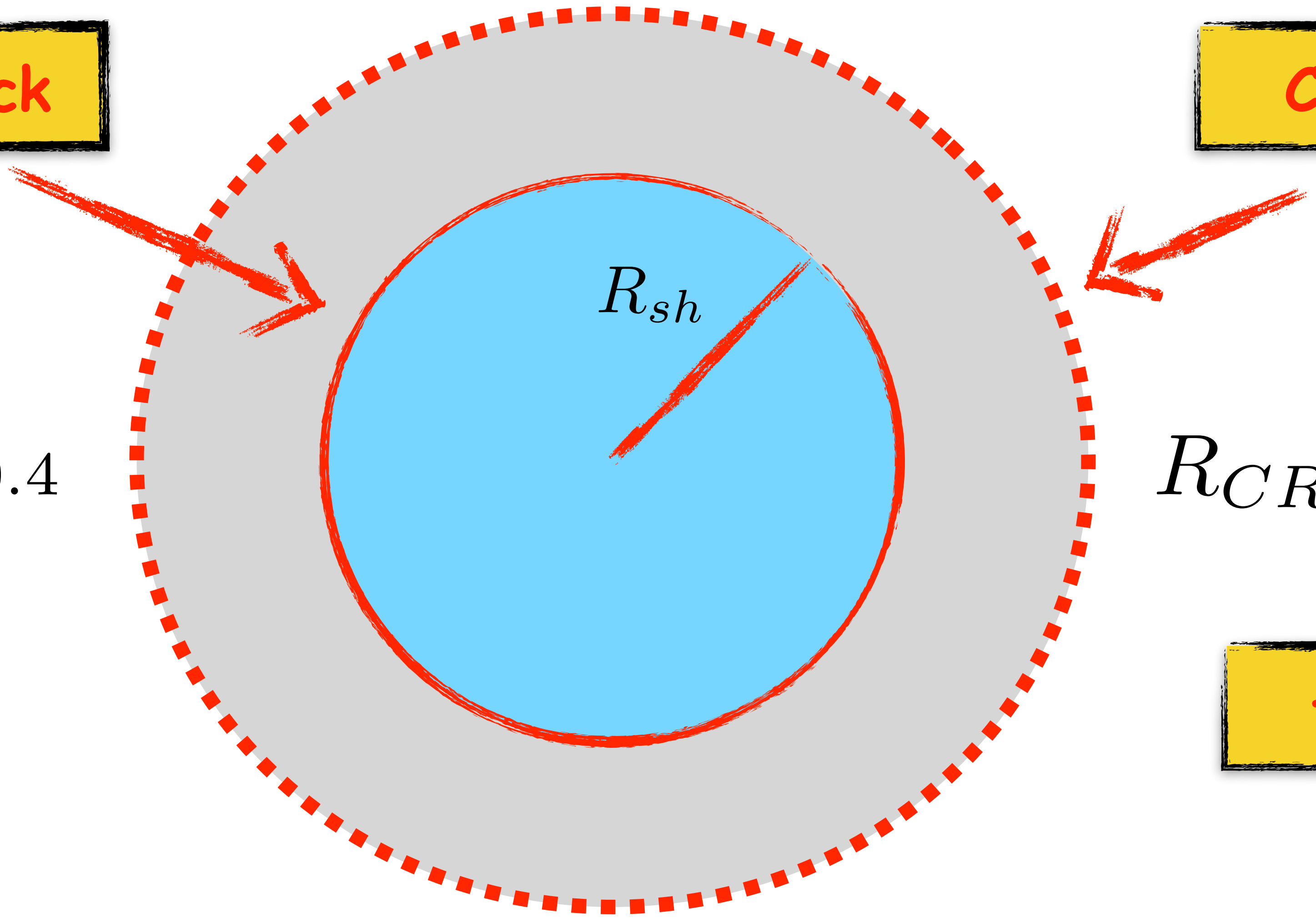

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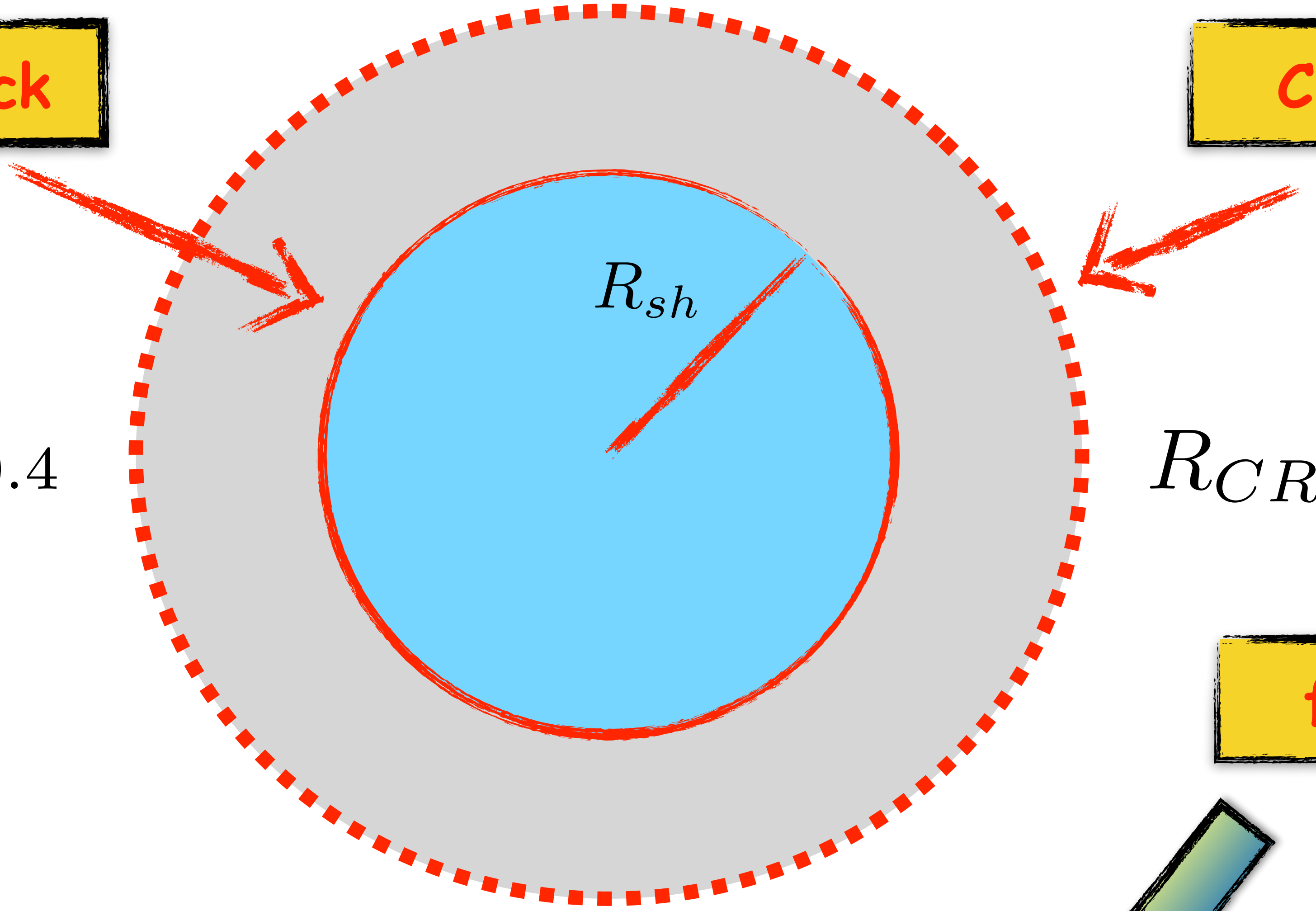

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particle escape from SNRs?

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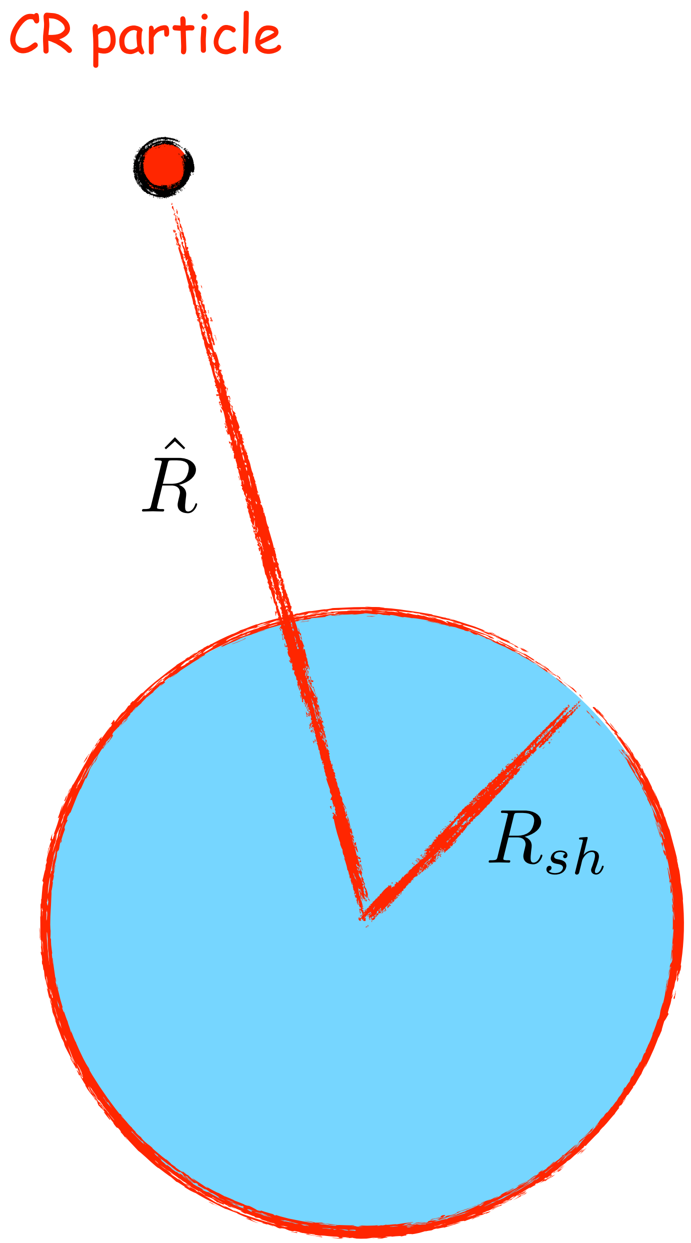
return probability to the shock for a particle located upstream

for simplicity let's take the shock to be at rest



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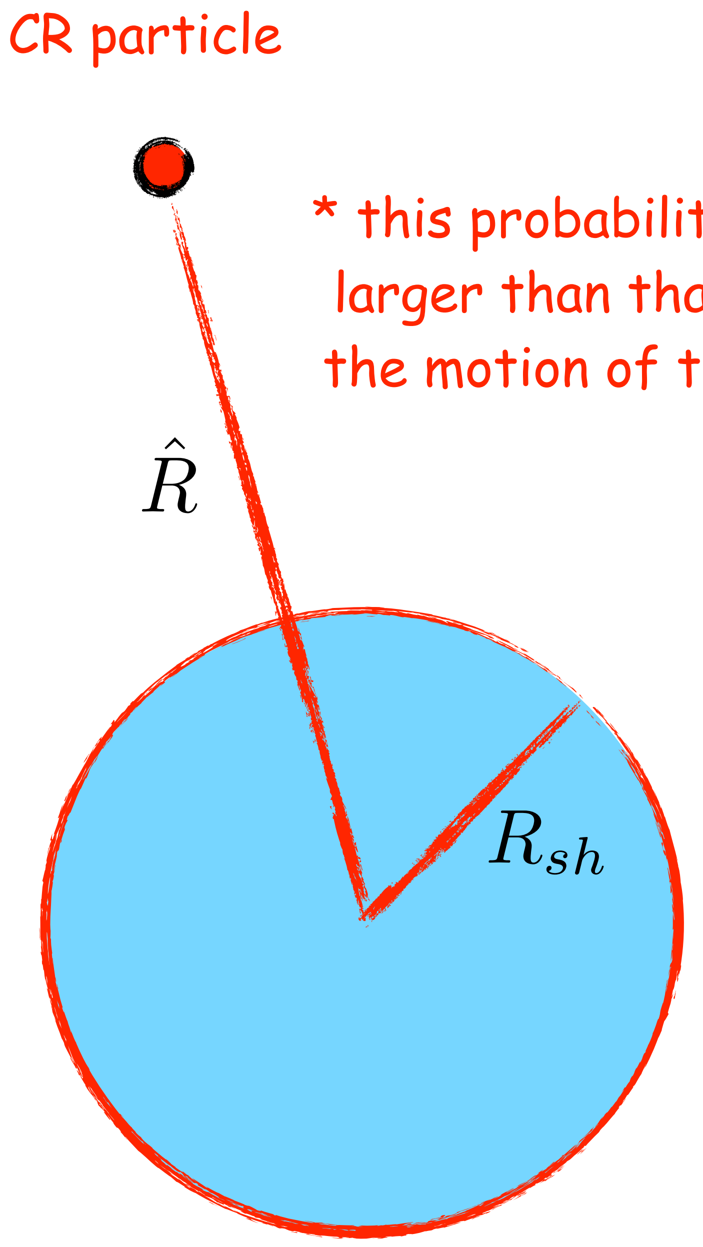

* this probability is a bit larger than that due to the motion of the shock

return probability*

$$P_{ret} = \frac{R_{sh}}{\hat{R}}$$

escape probability

$$P_{\infty} = 1 - \frac{R_{sh}}{\hat{R}}$$

particles have a non-vanishing probability to return to the shock even if they are quite far from it

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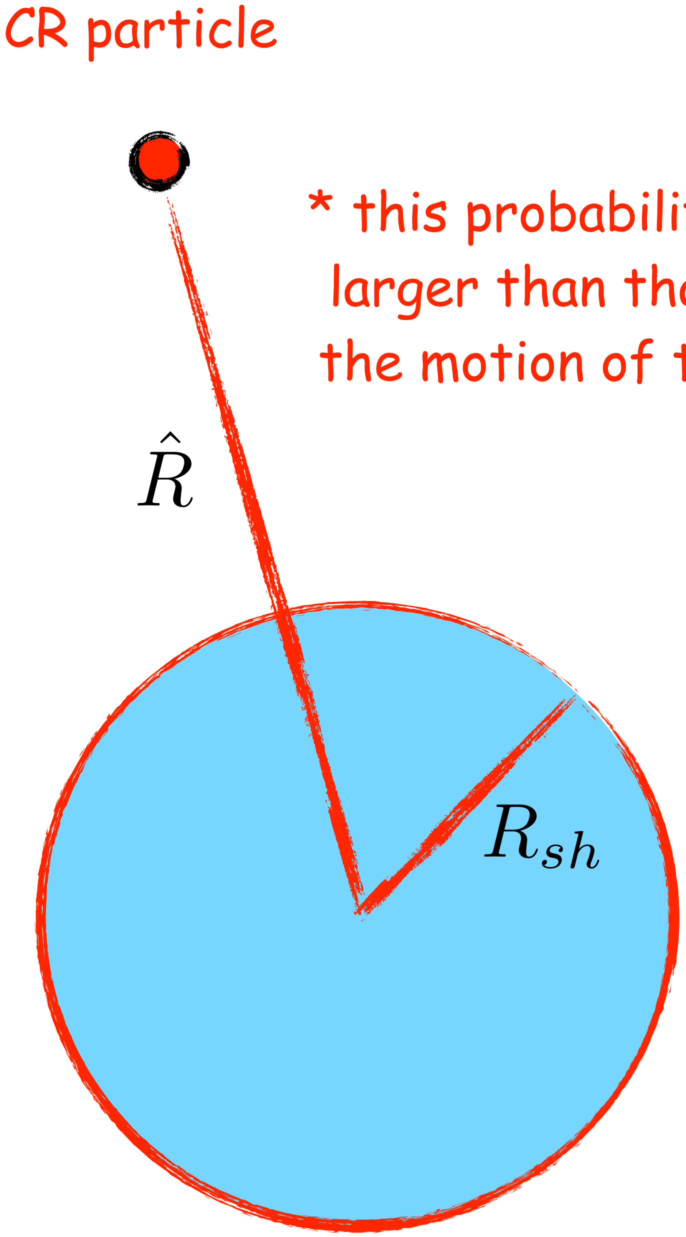

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in order to maintain an effective acceleration, such probability should be very close to 1

$$P_{ret} = 1 - \frac{u_{sh}}{c} \gtrsim 0.97$$

← free expansion

Drury 2011

Bell 1978

SNRs are spherical —> CR escape!

escape condition

$$l_d \equiv \frac{D}{u_s} \gtrsim \xi R_s$$

~5%

$R_s \sim t^{2/5}$

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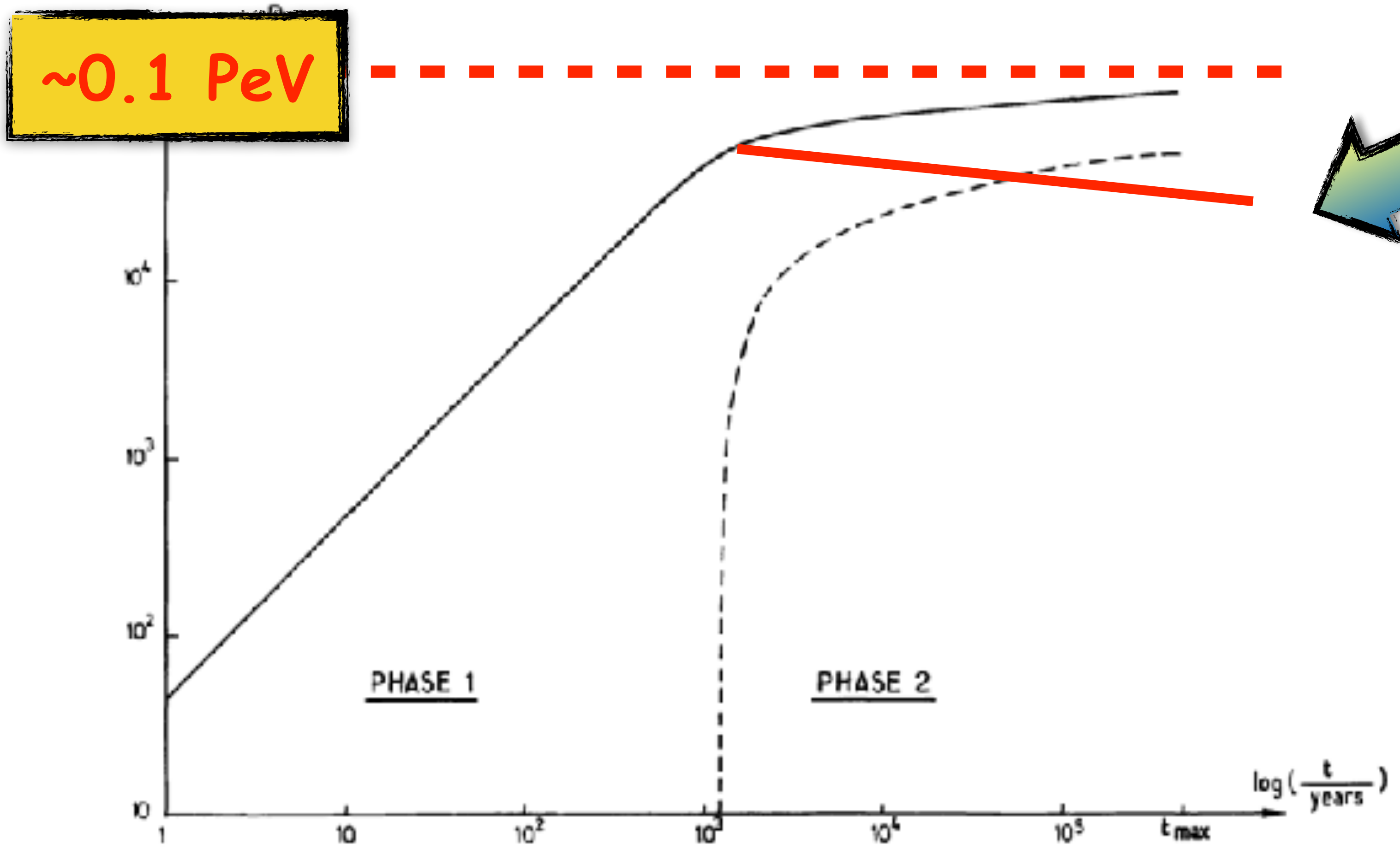

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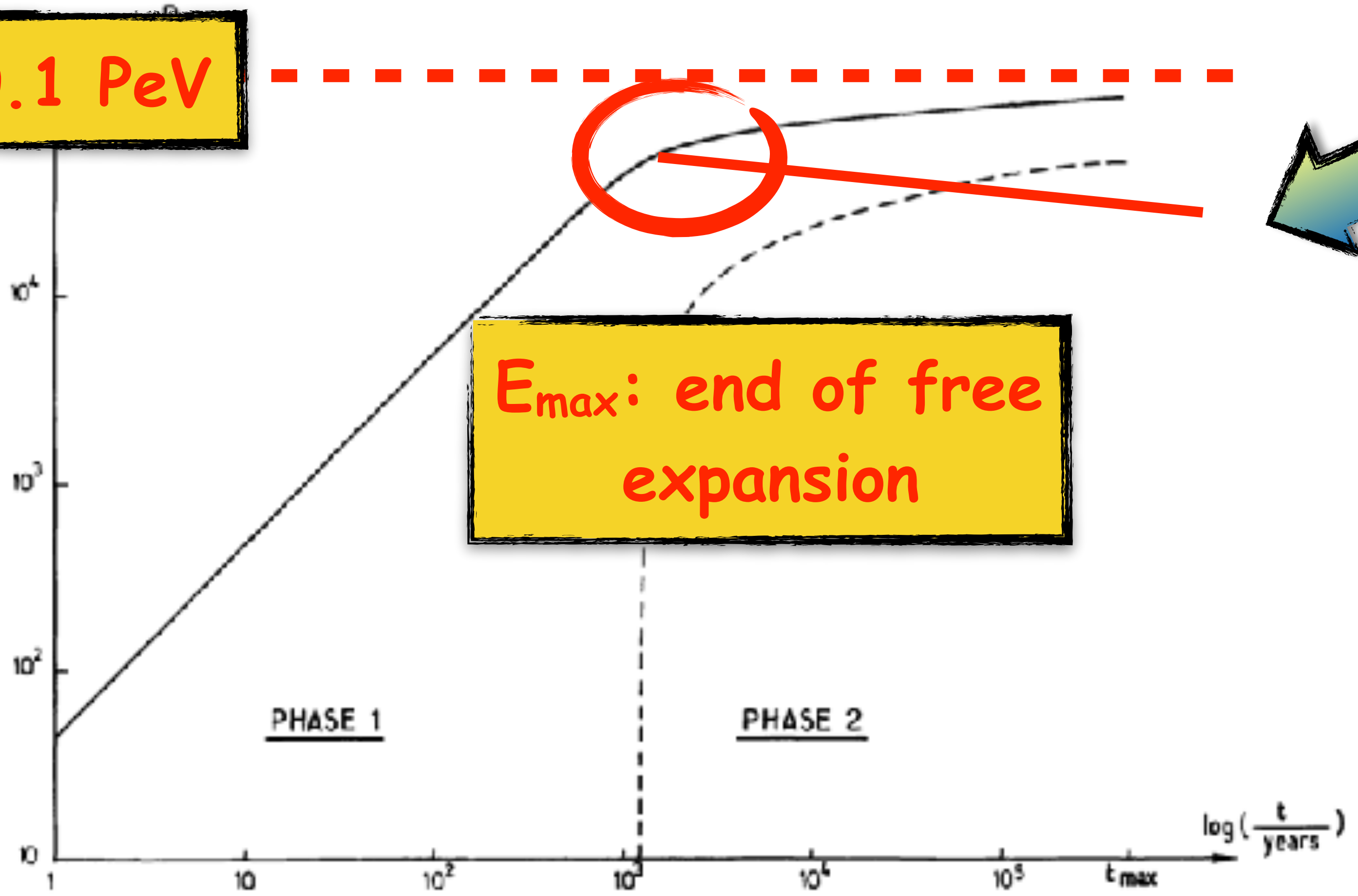

~0.1 PeV

E_{max}: end of free expansion

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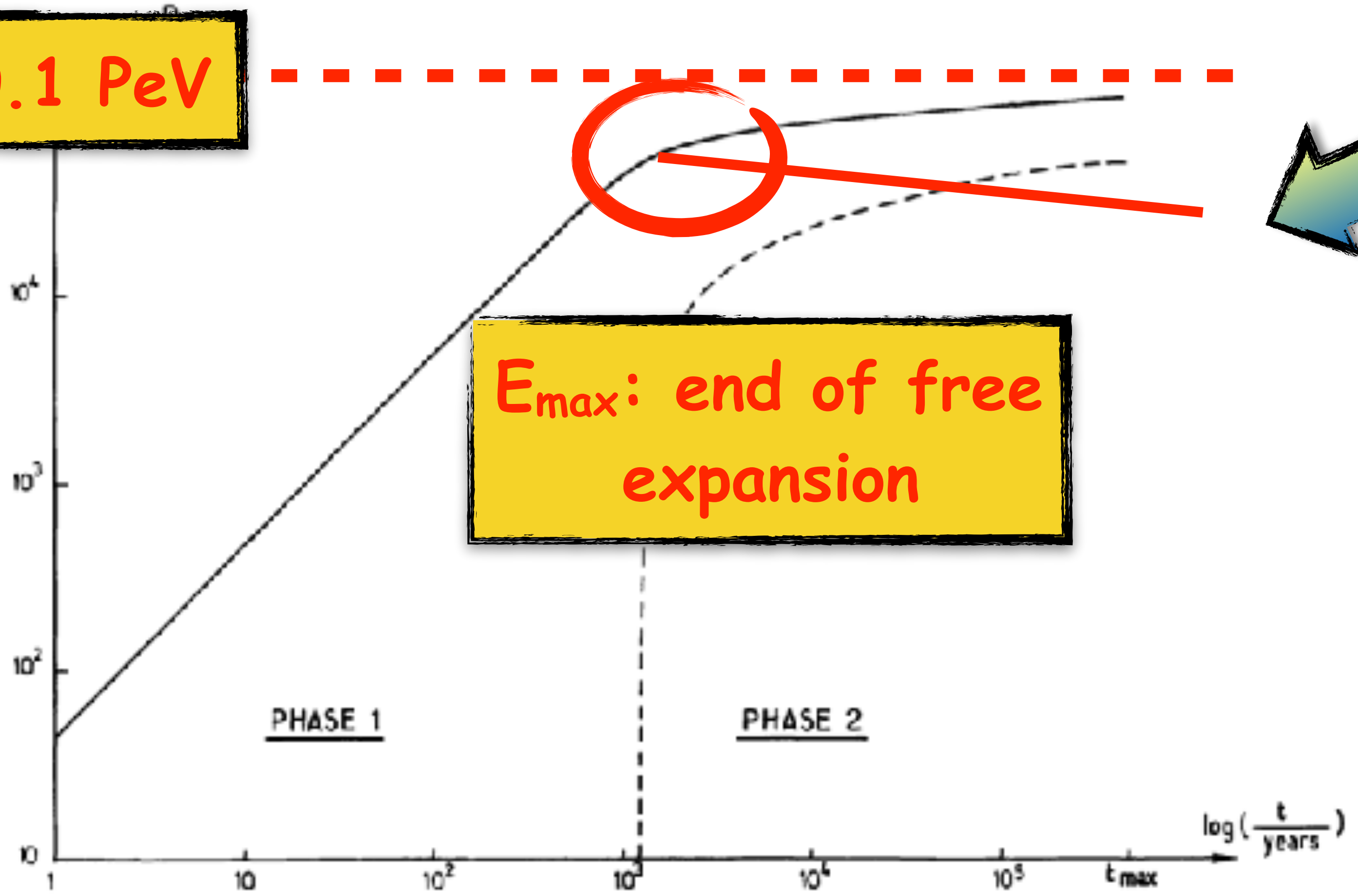

E_{max}: end of free expansion

wayout: increase B!

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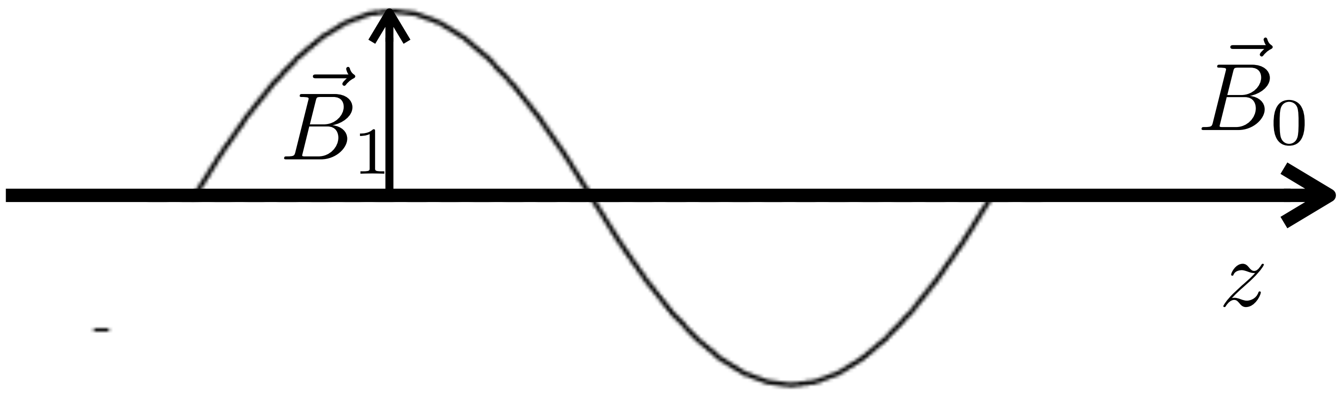
Non-resonant "Bell" instability



circularly polarised

wavelength << Larmor radius

escaping CRs barely deflected
—> CR current j along B_0
—> return current in the opposite direction

$-\vec{j} \times \vec{B}_1$ **force acting on the plasma —> expands the helical perturbation of B**

(until the size of the perturbation is of the order of the Larmor radius)

Bell 2004 … Bell et al 2013

see also earlier works (space plasma community): Sentman+ 81, Winske & Leroy 84, Gary 93

Non-resonant "Bell" instability

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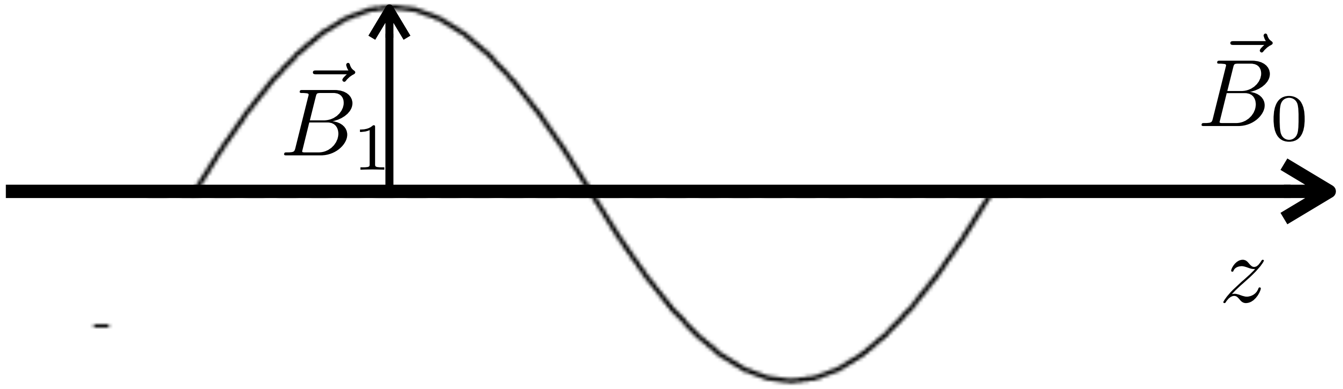

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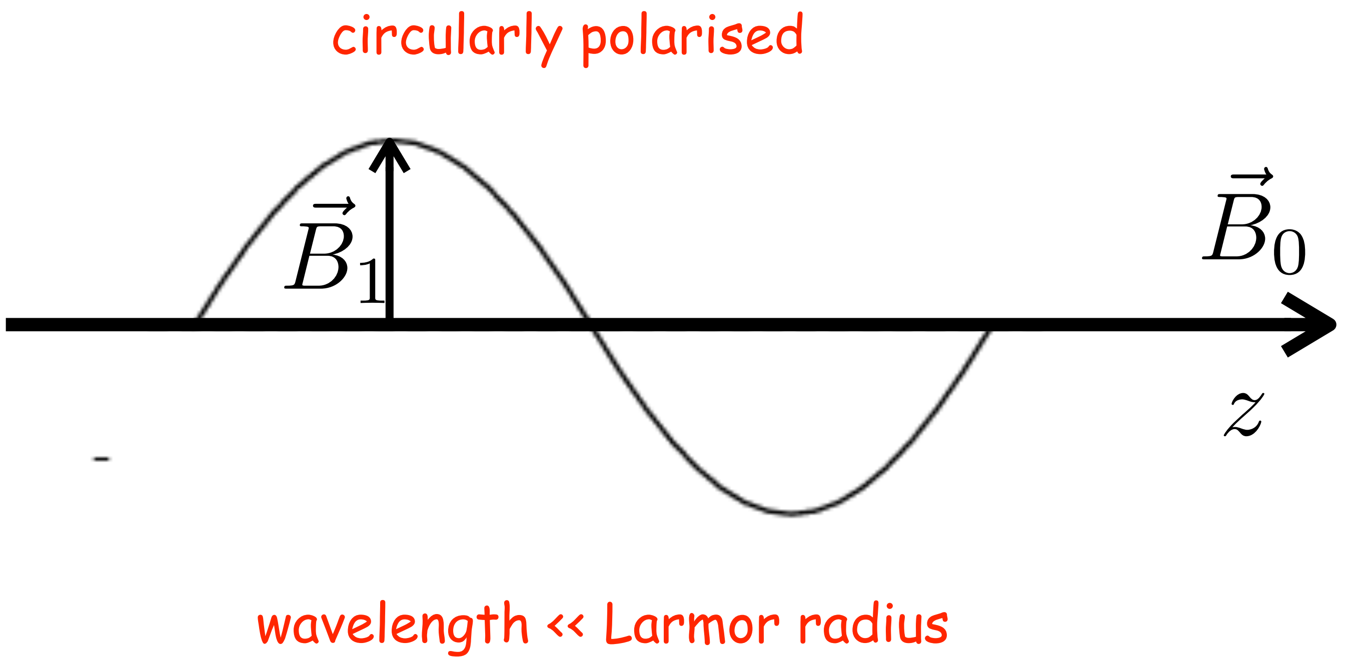
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$$\Rightarrow \quad \gamma_{grow} \approx \left(\frac{k\ j\ B_0}{2\pi\ c\varrho}\right)^{1/2}$$

Bell 2004 … Bell et al 2013

Non-resonant "Bell" instability

1) wavelength << Larmor radius

2) magnetic tension << j x B force

⇒

$$\frac{1}{R_L} < \frac{k}{2\pi} < \frac{4\pi j}{cB_0}$$

Bell 2004 … Bell et al 2013 …
Reville 2008, Zweibel 2010 …

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saturation of the instability

$$\frac{\vec{j}}{c} \times \vec{B} > \frac{1}{4\pi}(\nabla \times \vec{B}) \times \vec{B}$$

$$j > Bc/4\pi L$$

$$\left(\frac{B_{sat}}{B_0}\right)^2 \sim \left(\frac{U_{CR}}{U_B^0}\right)\frac{u_d}{c}$$

can be >> 1!!!

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Escape and maximum energy

assumption: pareticles with E < Emax are diffusively confined within the shock, while particles with E > Emax can freely escape

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CR data ~4

spectrum at the shock —> $f_0(p) = Ap^{-q}$

unknown

diffusive shock acceleration theory —> acceleration rate at p_{max} —> $j(p_{max})$!!!

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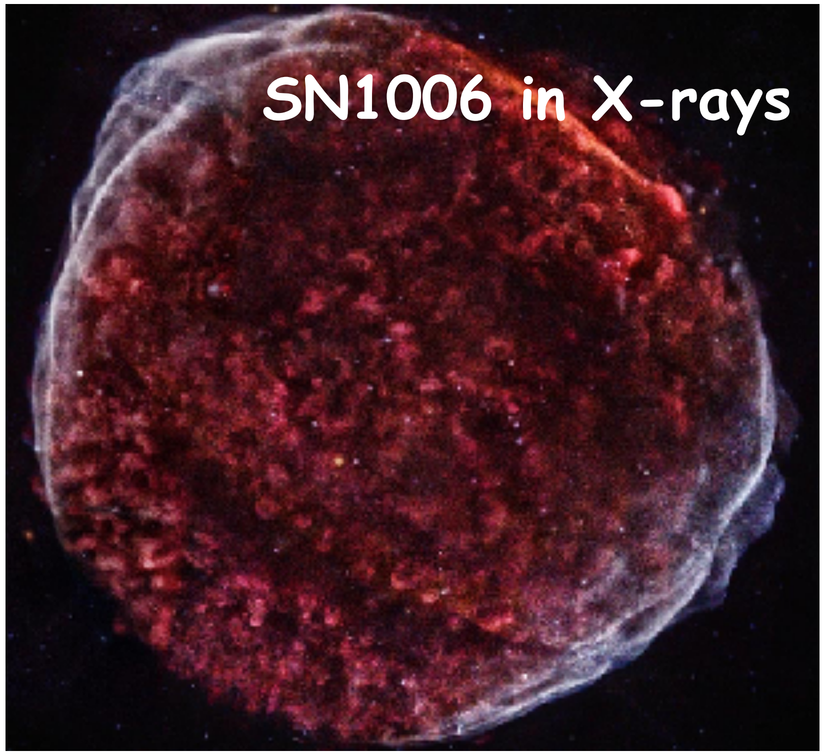
the field at the shock is amplified by a factor of exp(a)



See e.g. review by J. Vink

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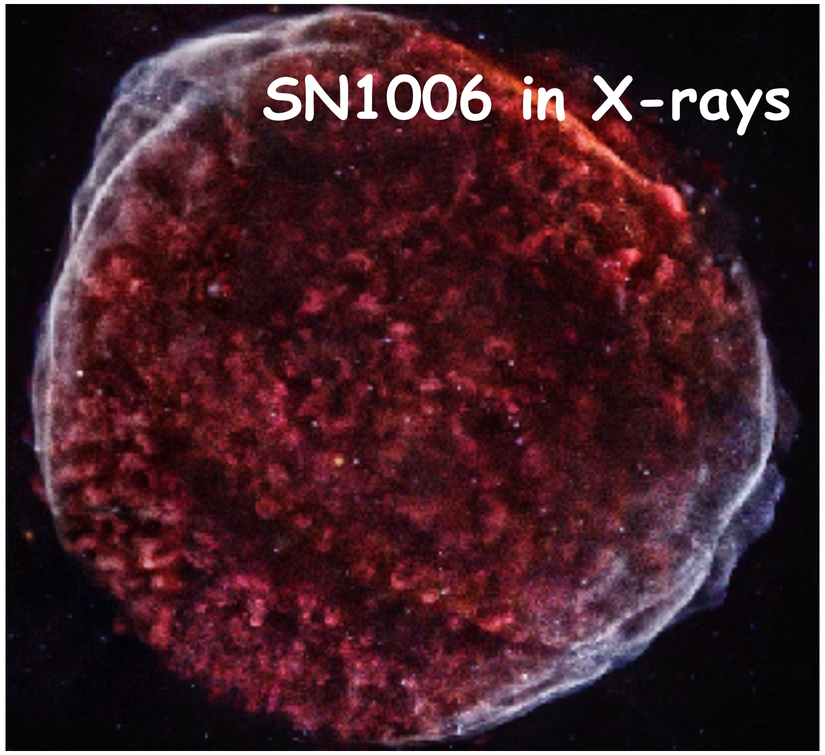
$$a = \int \mathrm{dt}\ \gamma_{max}(j(p_{max}))$$

—> we can estimate Emax!!!



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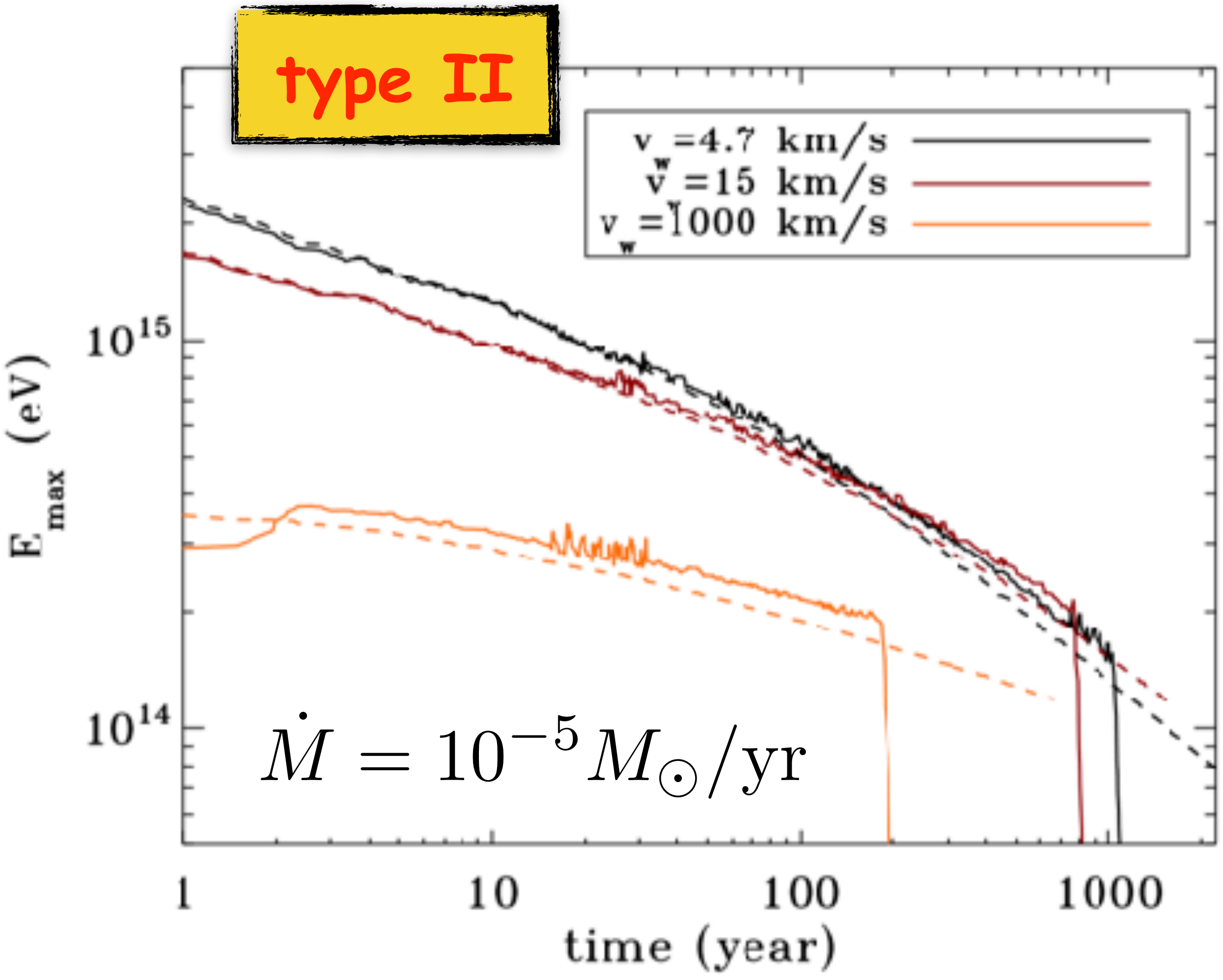
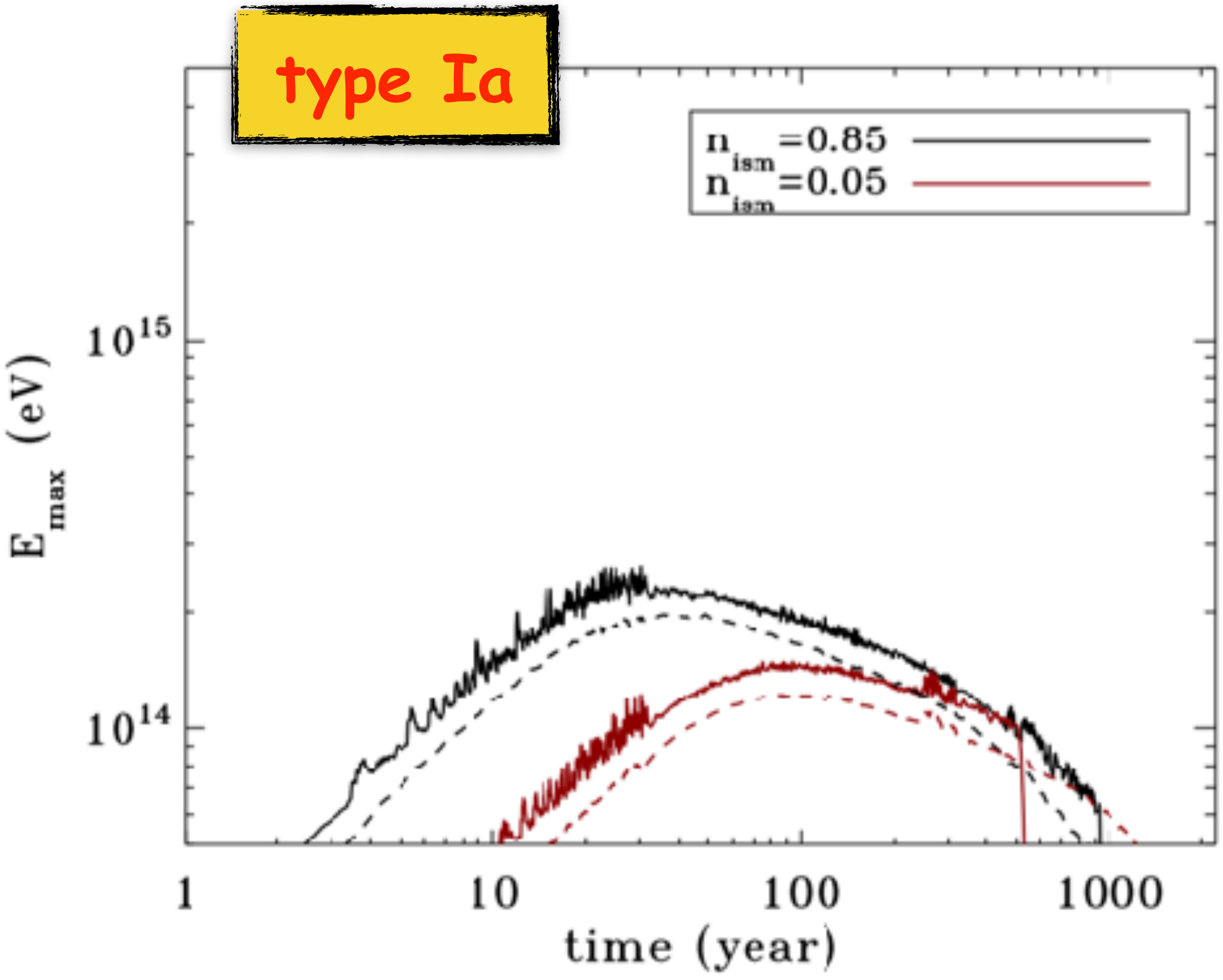
Only very young SNRs accelerate to PeV

Schure & Bell 2013





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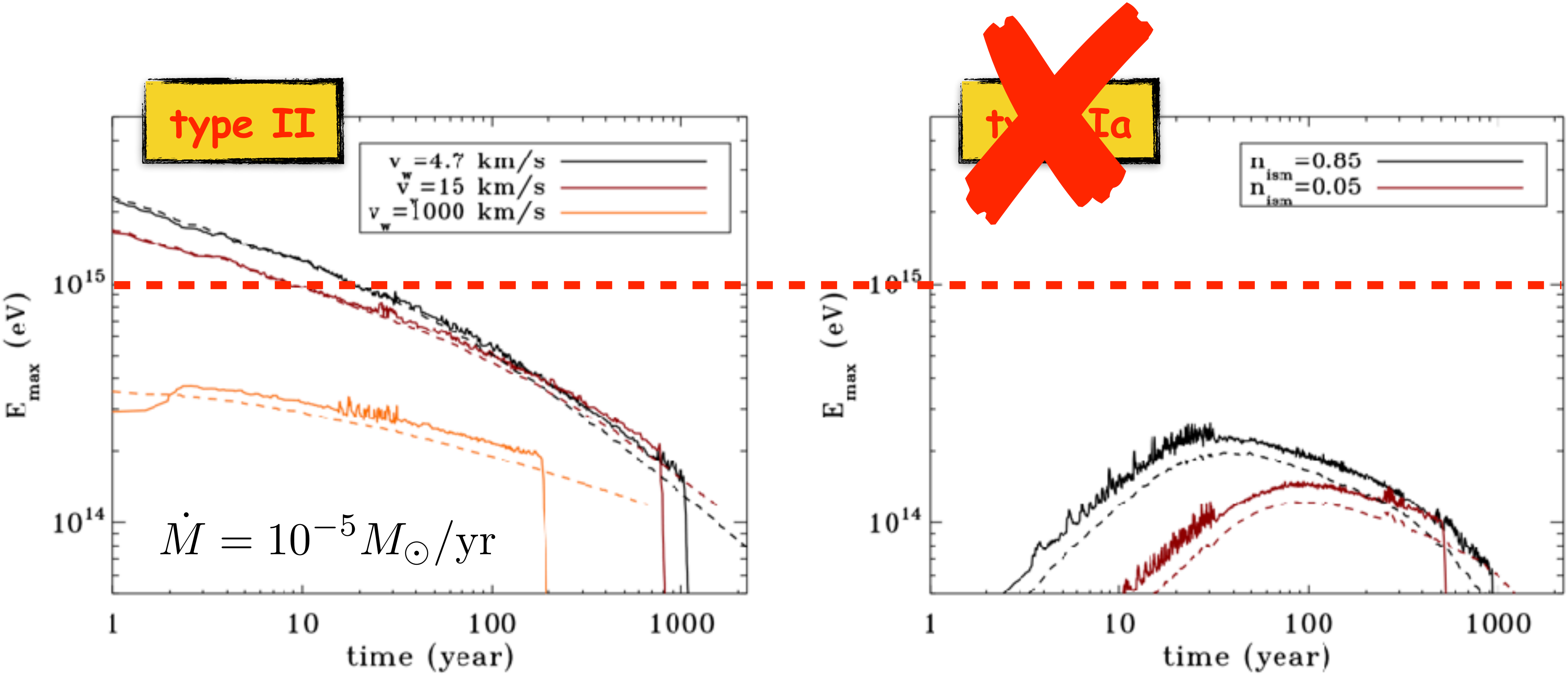

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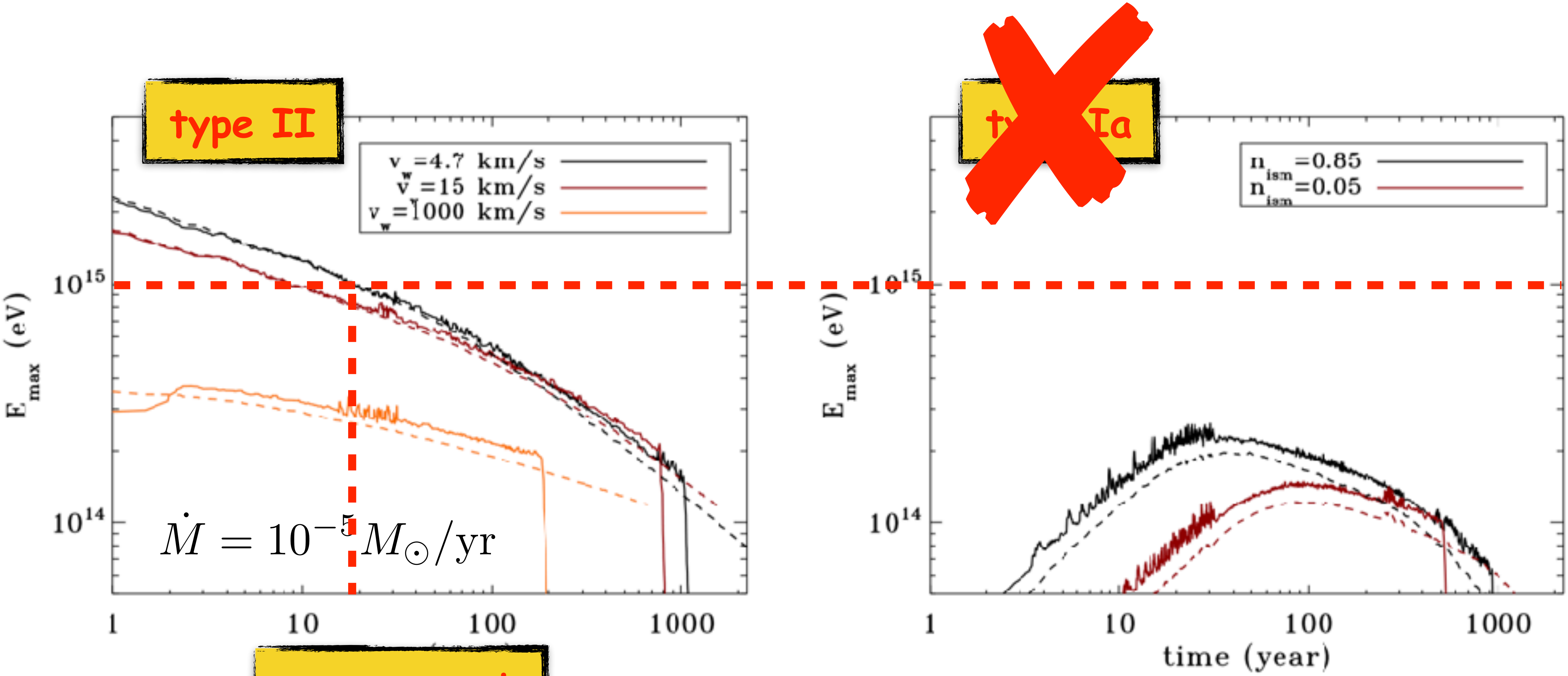
type II

ty Ia



very young!

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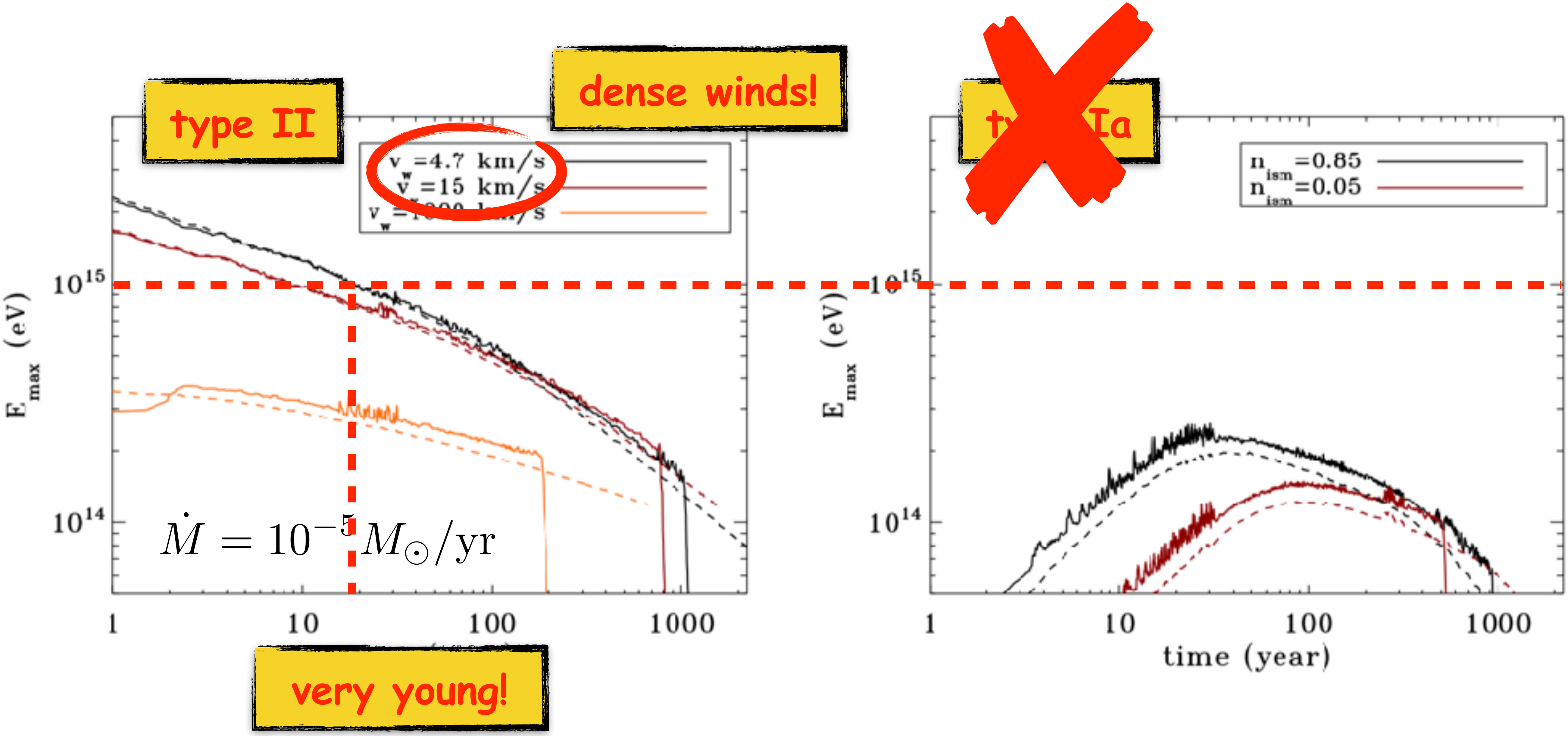

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dense winds!

very young!

ty Ia

Schure & Bell 2013

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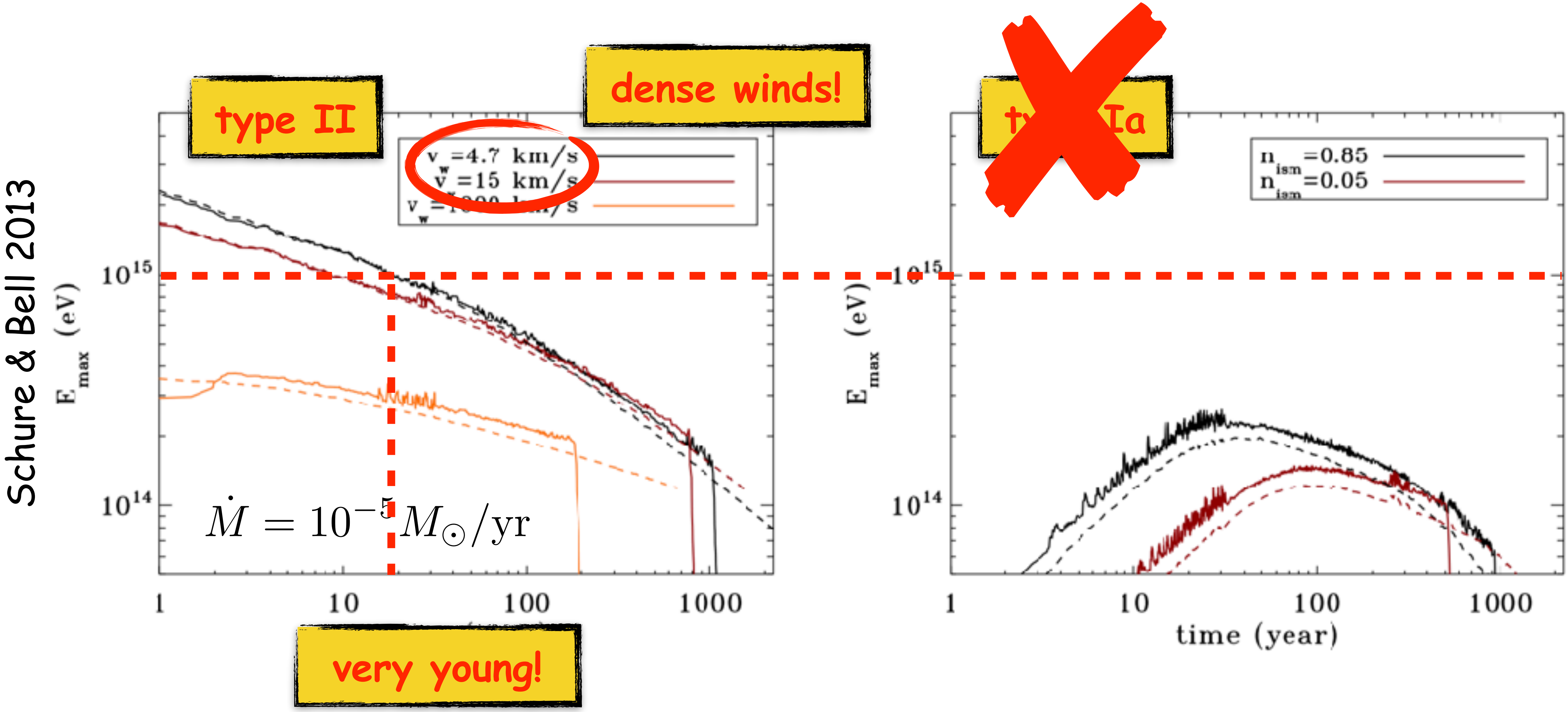

3 consequences:

- ☐ very dense winds (type IIb?) —> go to PeV or beyond! (Ptuskin+ 2010)
- ☐ very rare events —> # of active PeV SNRs = 0 (Cristofari+ 2020)
- ☐ “knee” in the spectrum from one SNR at transition to Sedov (Cardillo+ 2015)

Only very young SNRs accelerate to PeV

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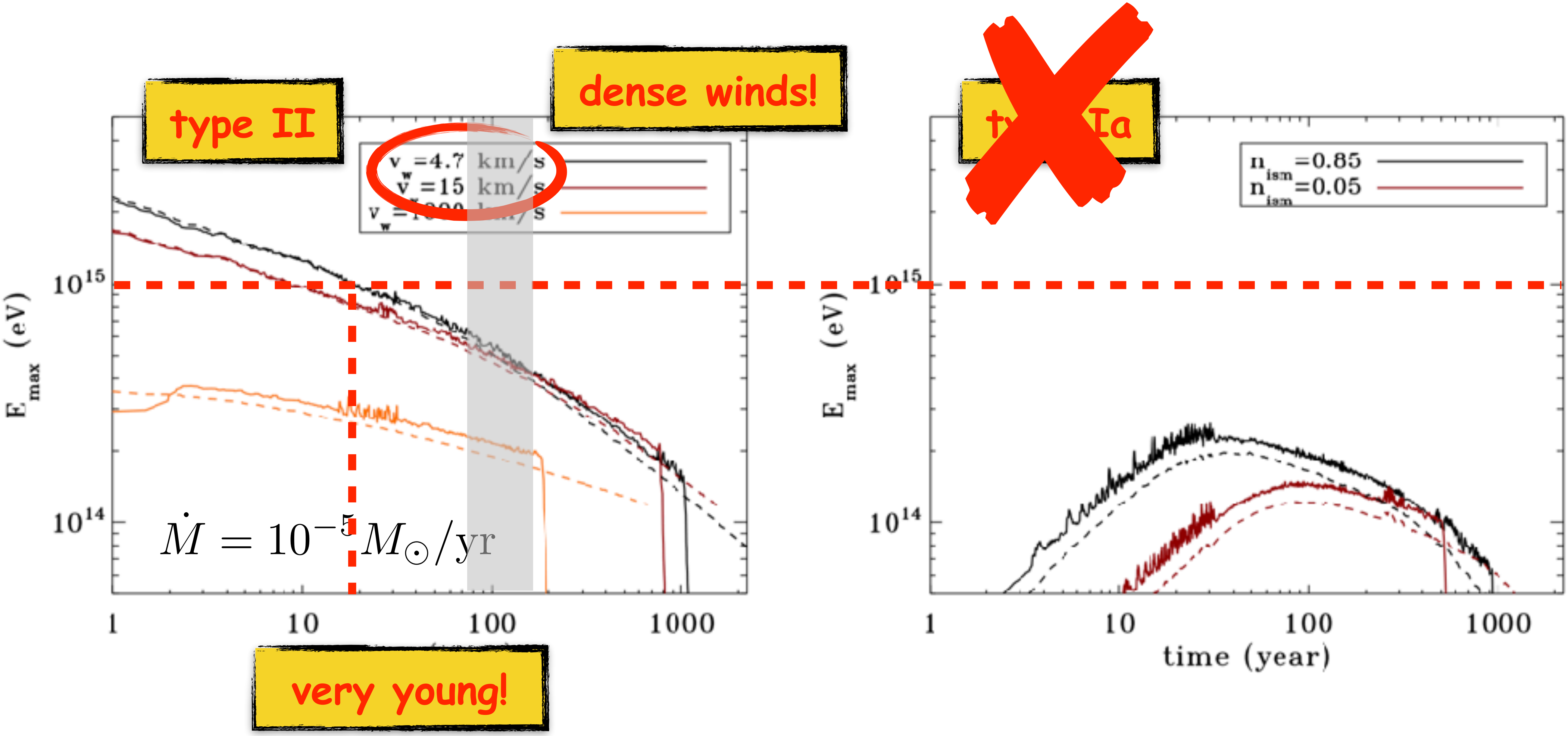

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One can't have everything…

spectrum of CRs released in the ISM during the entire SNR life

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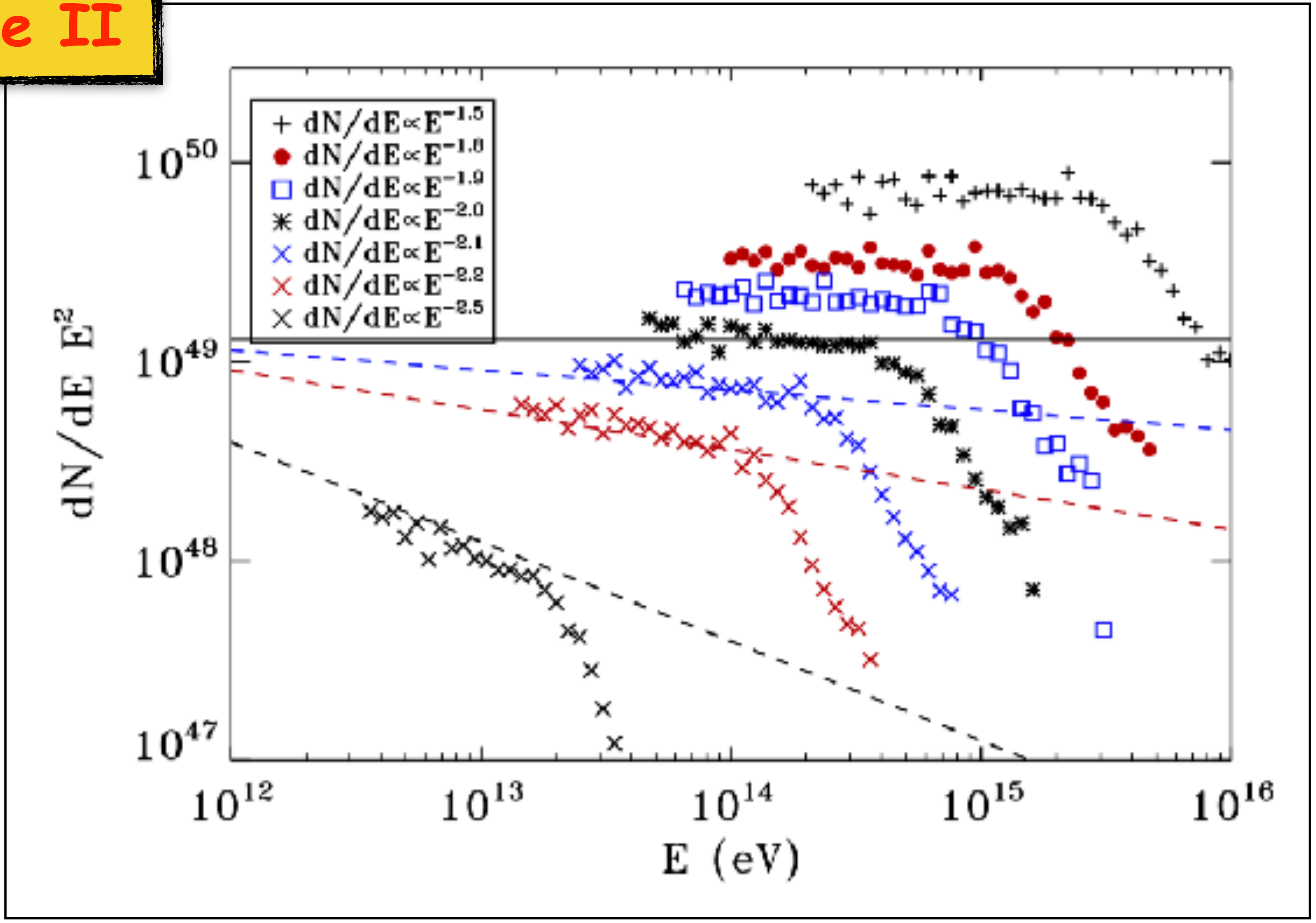

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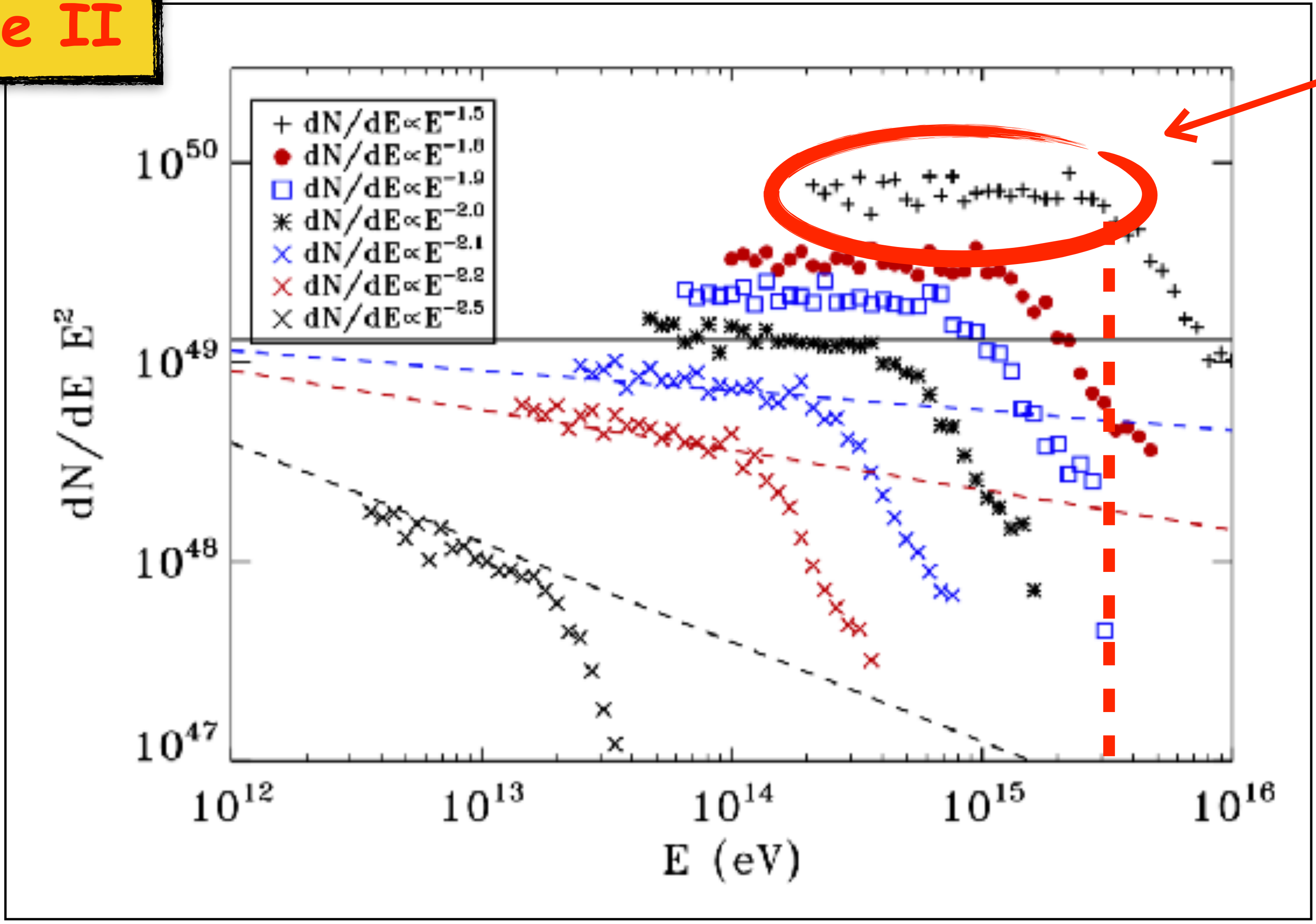

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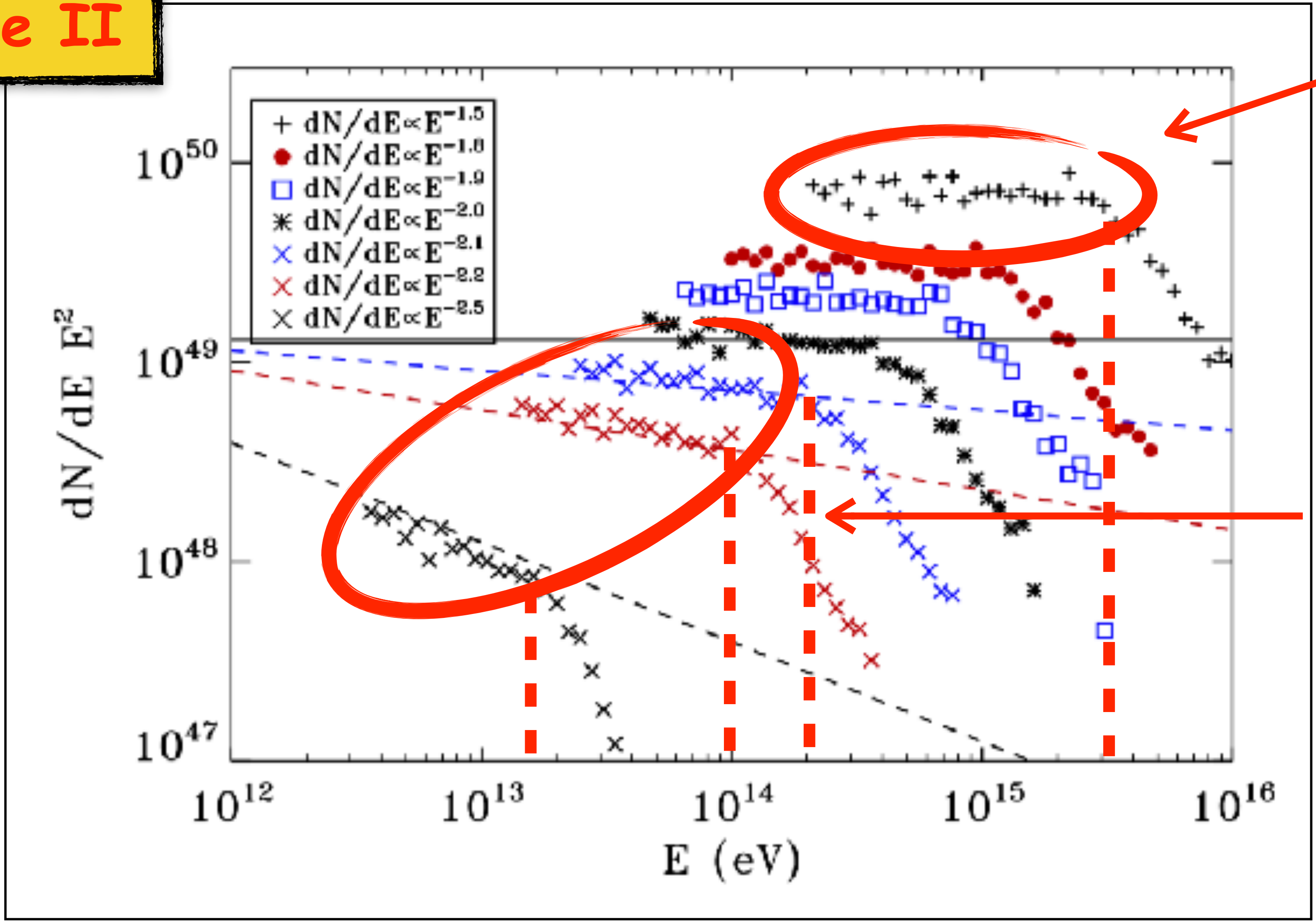

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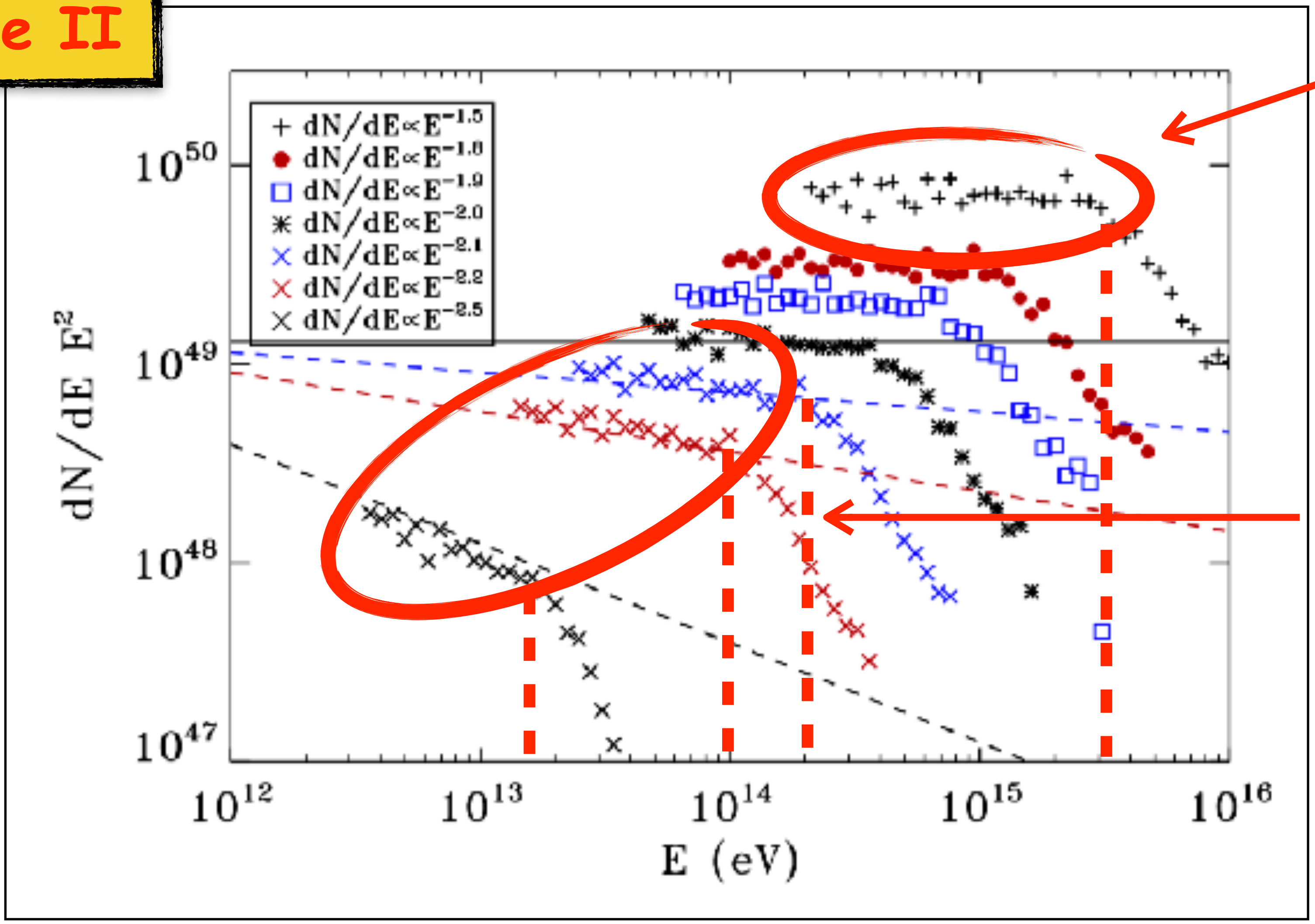

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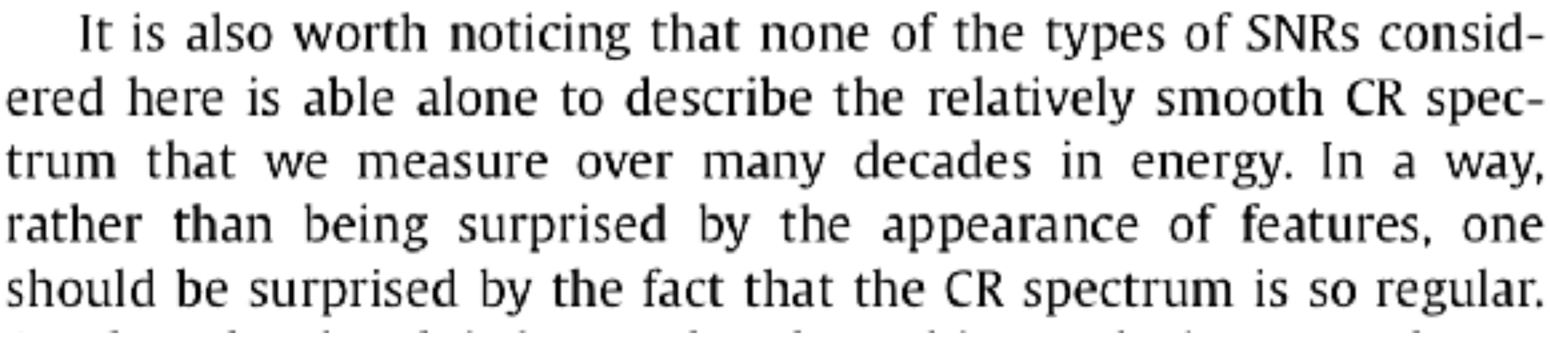

It is also worth noticing that none of the types of SNRs considered here is able alone to describe the relatively smooth CR spectrum that we measure over many decades in energy. In a way, rather than being surprised by the appearance of features, one should be surprised by the fact that the CR spectrum is so regular.

(Cristofari+ 2020)

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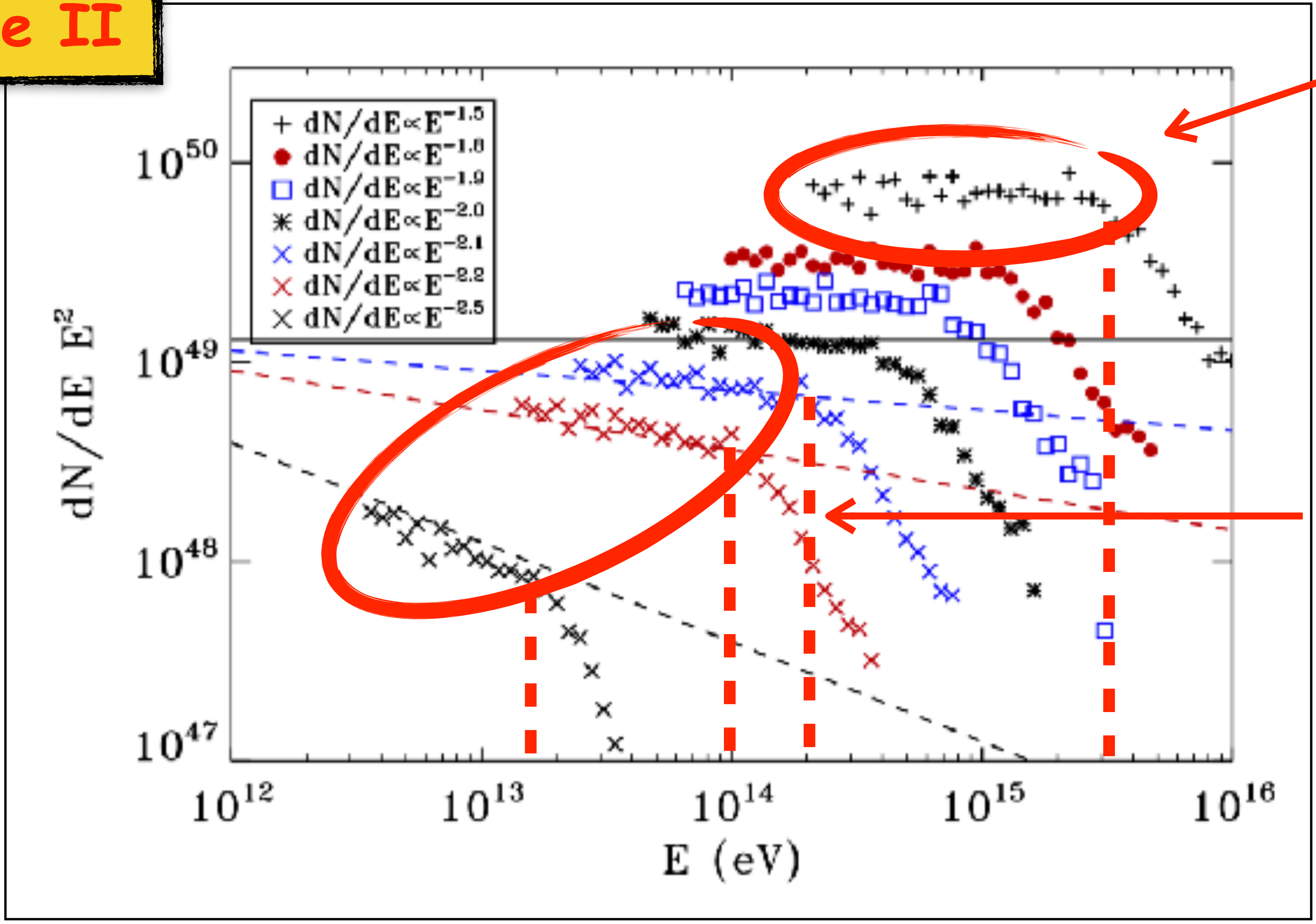

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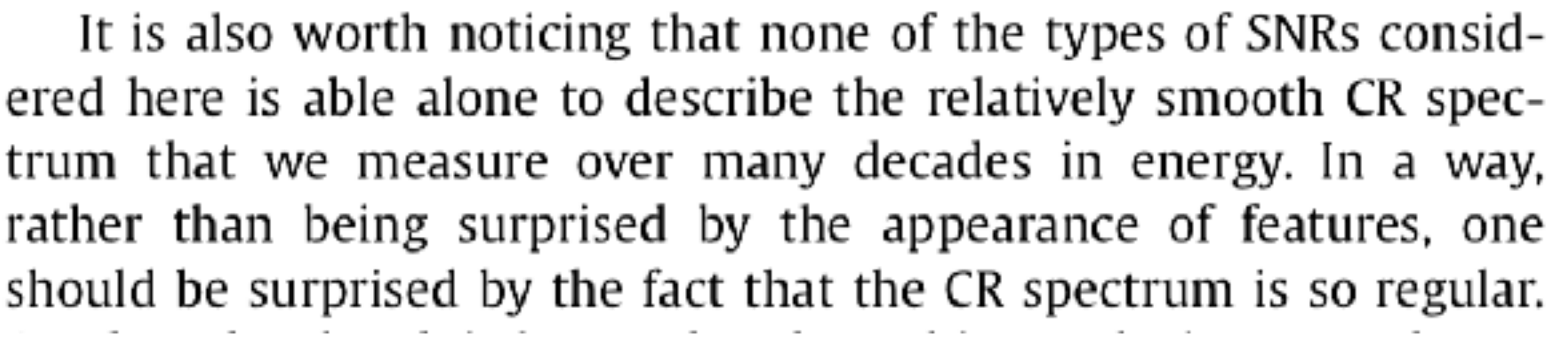

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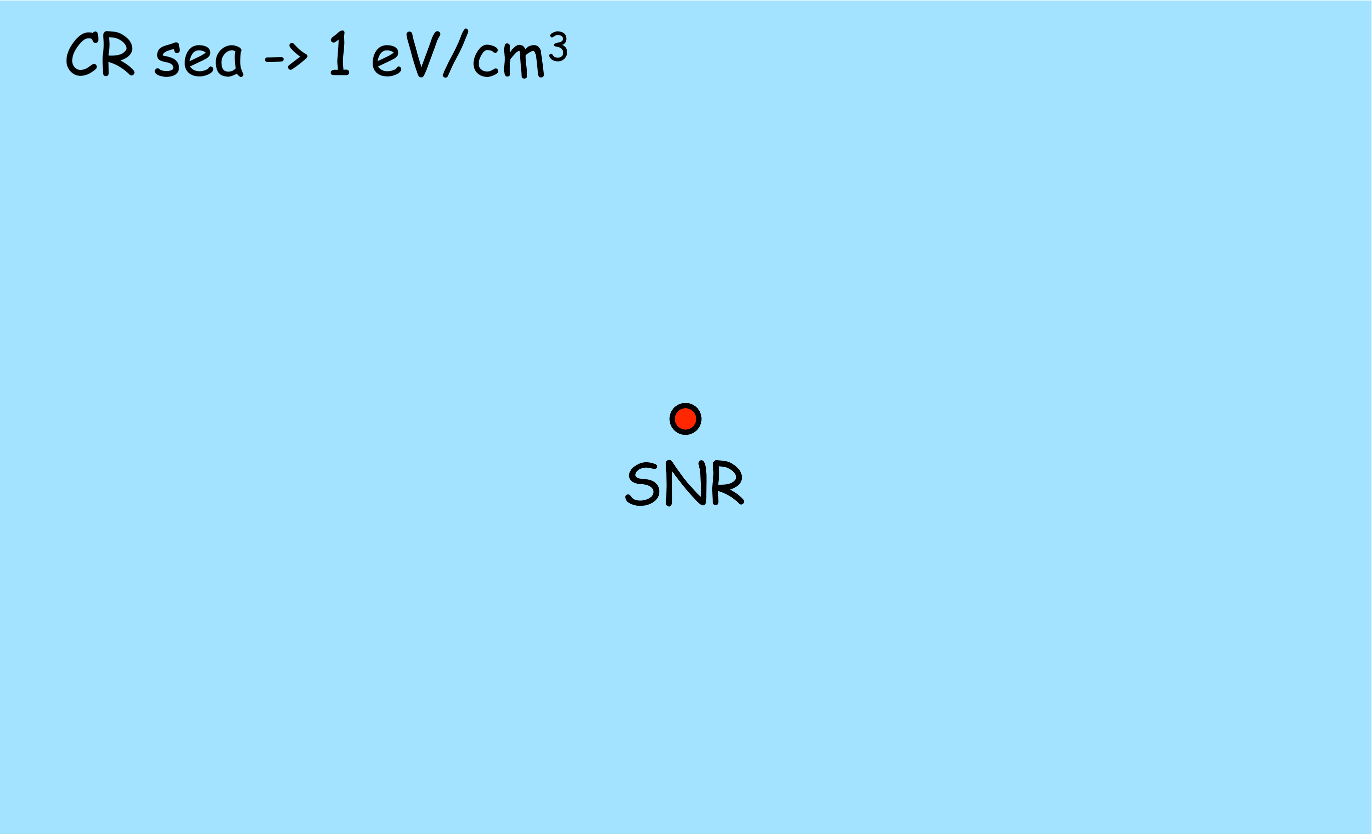

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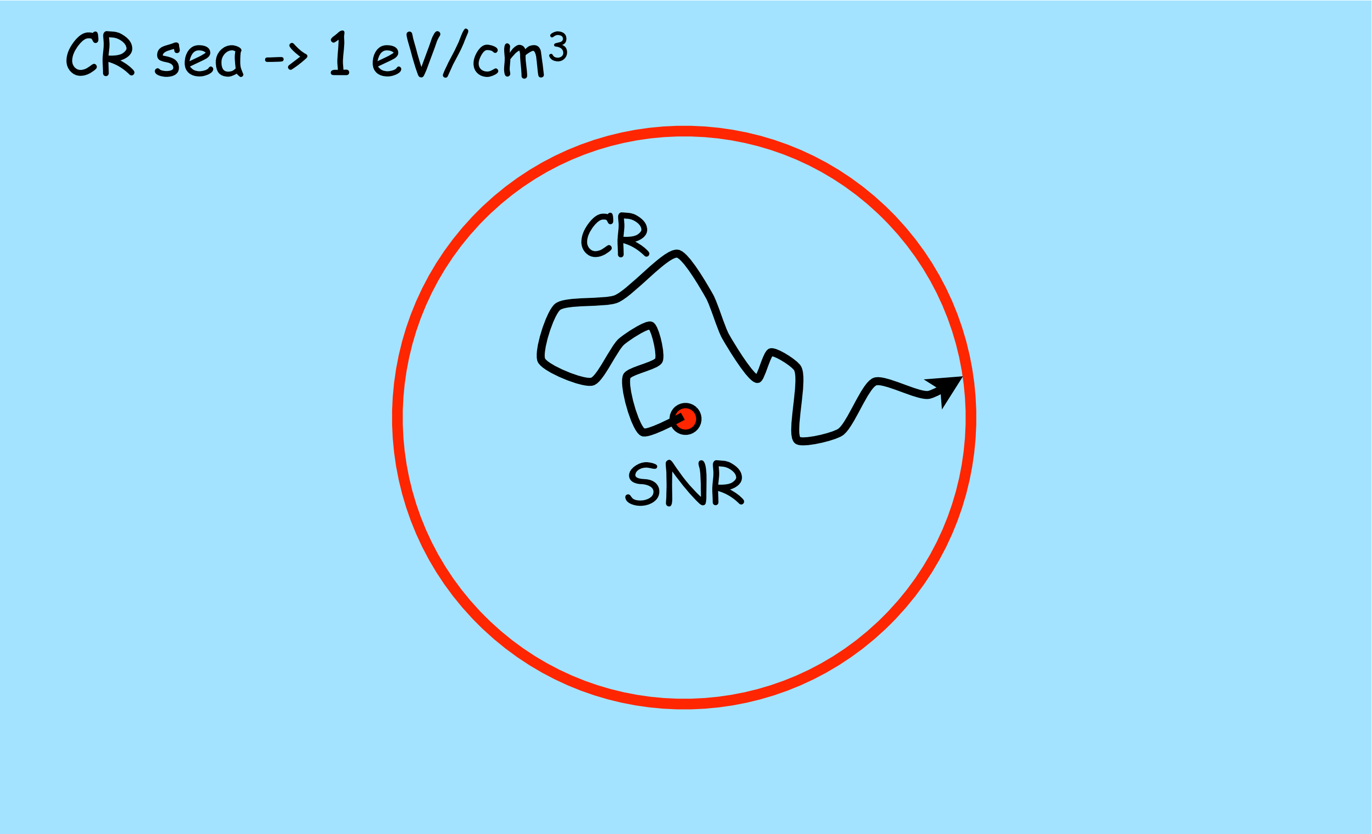

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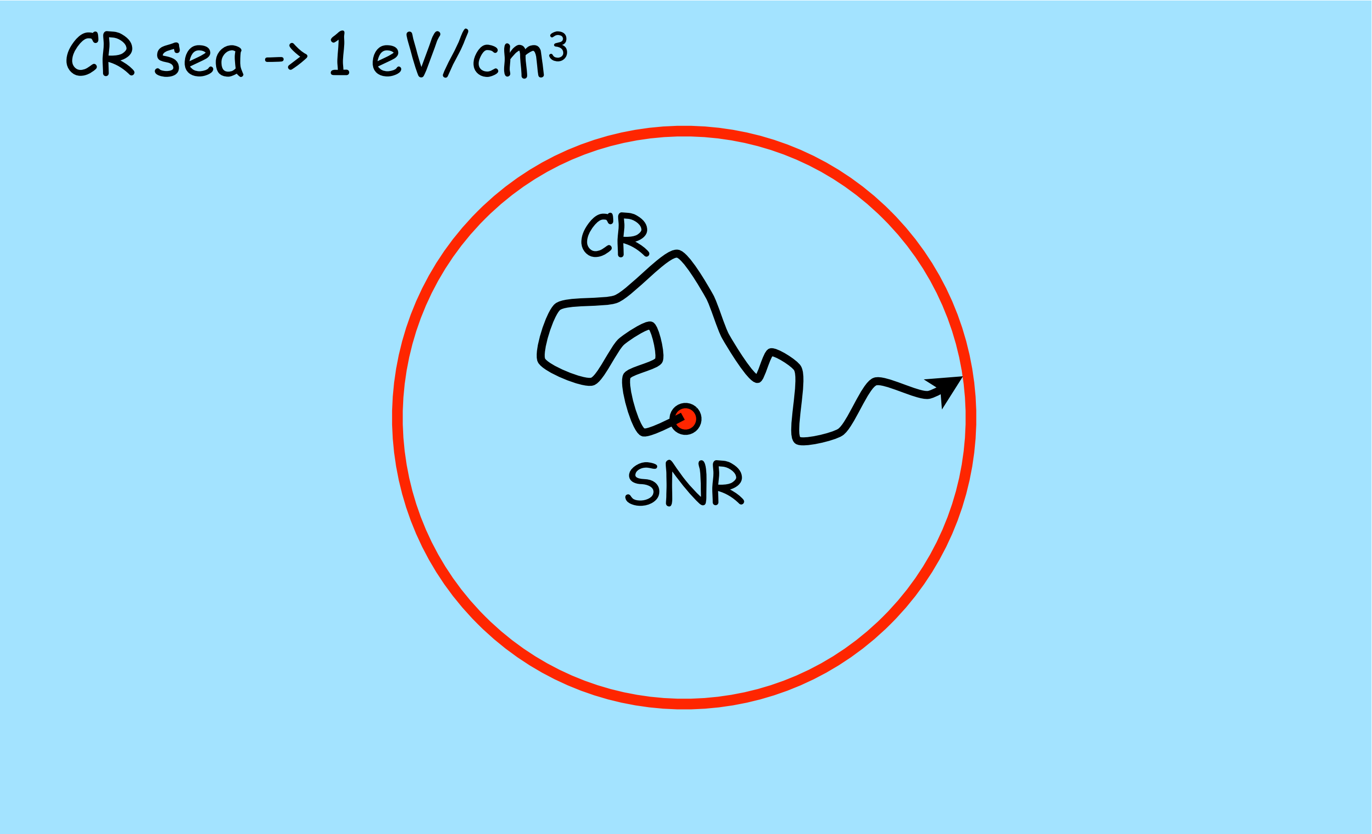

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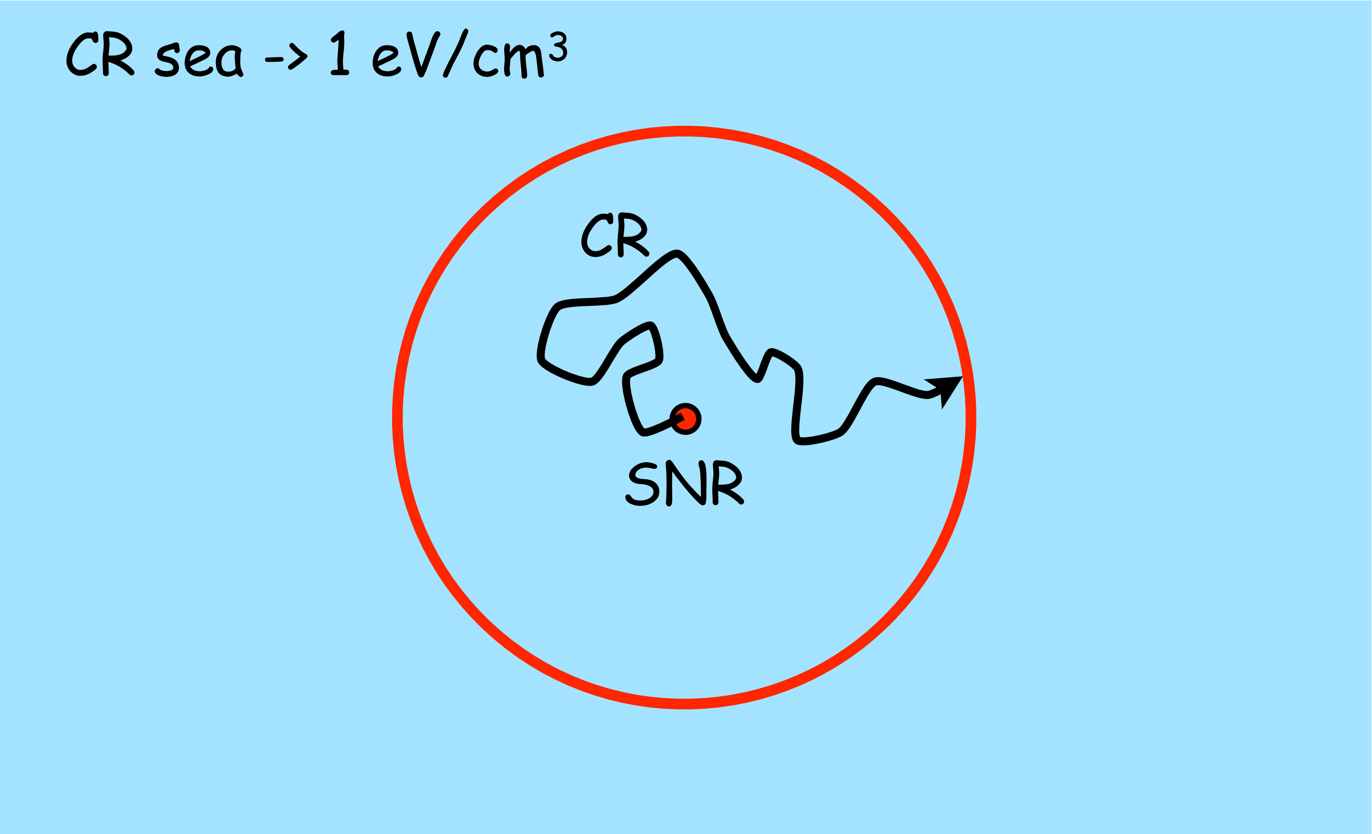

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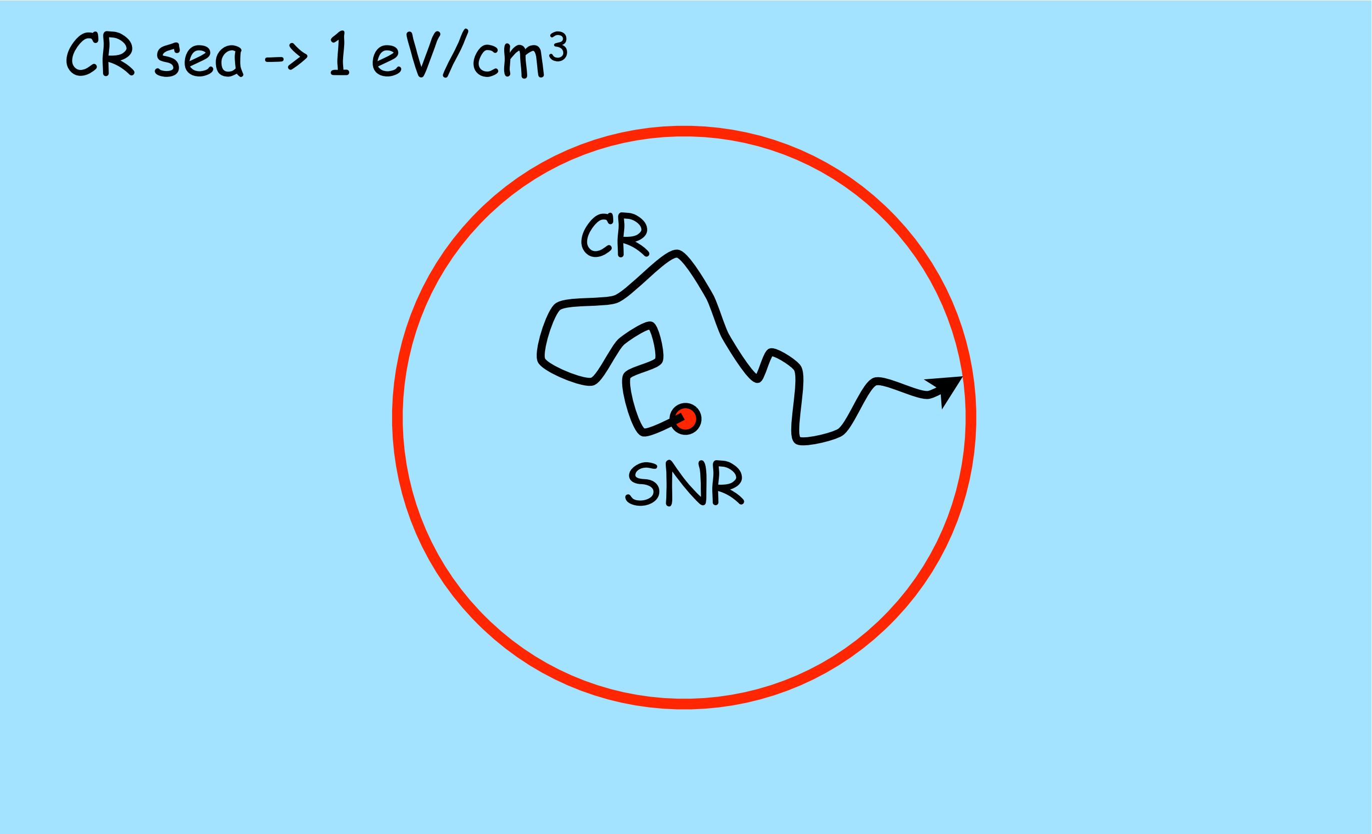

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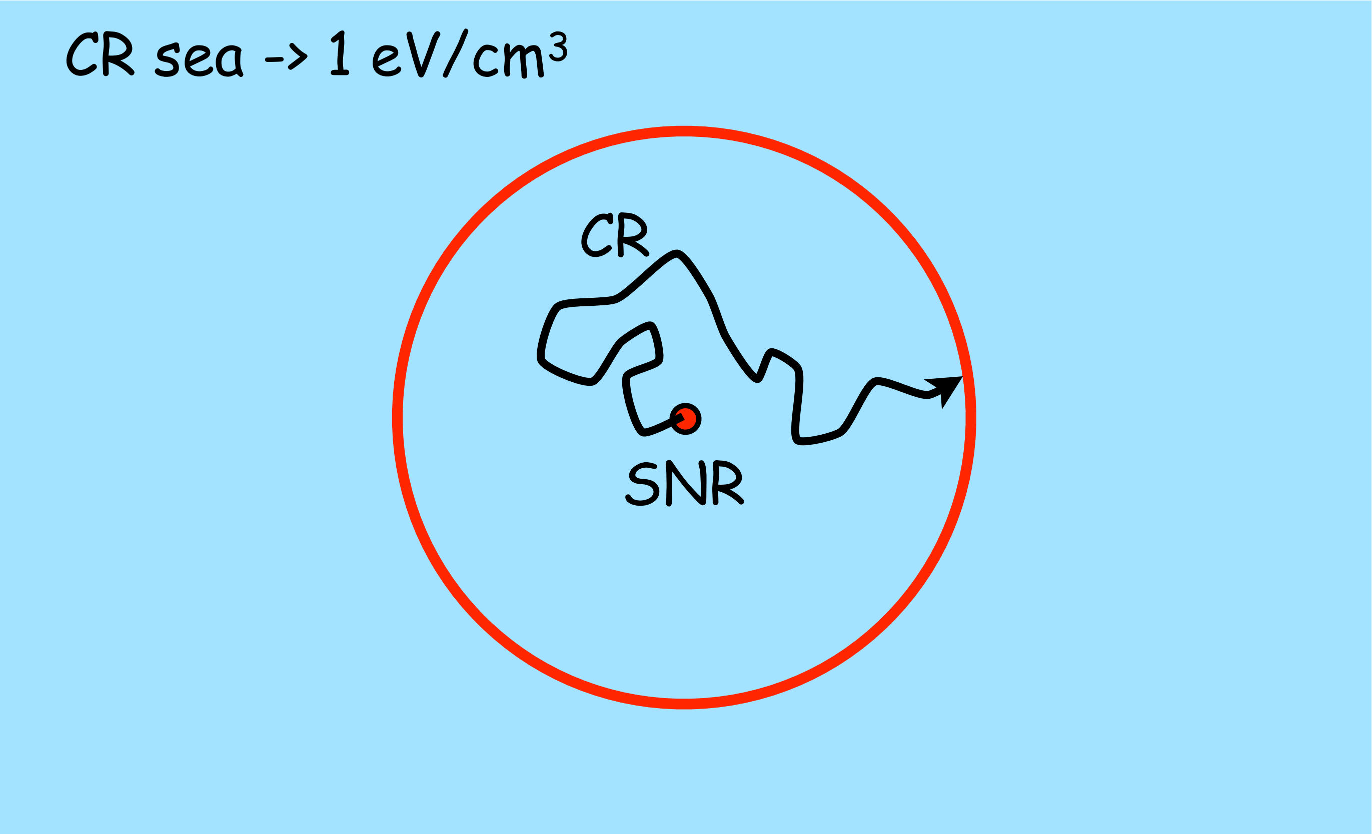
or longer if D suppressed

Escape: isotropic spatial diffusion



$$E_{CR}^{SNR} = 10^{50} \text{erg}$$

volume affected by CRs from the SNR

$$\frac{E_{CR}^{SNR}}{\left(\frac{4\pi}{3} R_{CR}^3\right)} = 1 \text{ eV/cm}^3$$

$$R_{CR} \approx 100 \text{ pc}$$

such a volume is affected for a time:

$$D = 10^{28} \left(\frac{E}{10 \text{ GeV}}\right)^{0.6} \text{cm}^2/\text{s} \qquad D(1 \text{ TeV}) \approx 2 \times 10^{29} \text{ cm}^2/\text{s}$$

$$t \approx \frac{R_{CR}^2}{D} \approx 10^4 \text{ yr}$$

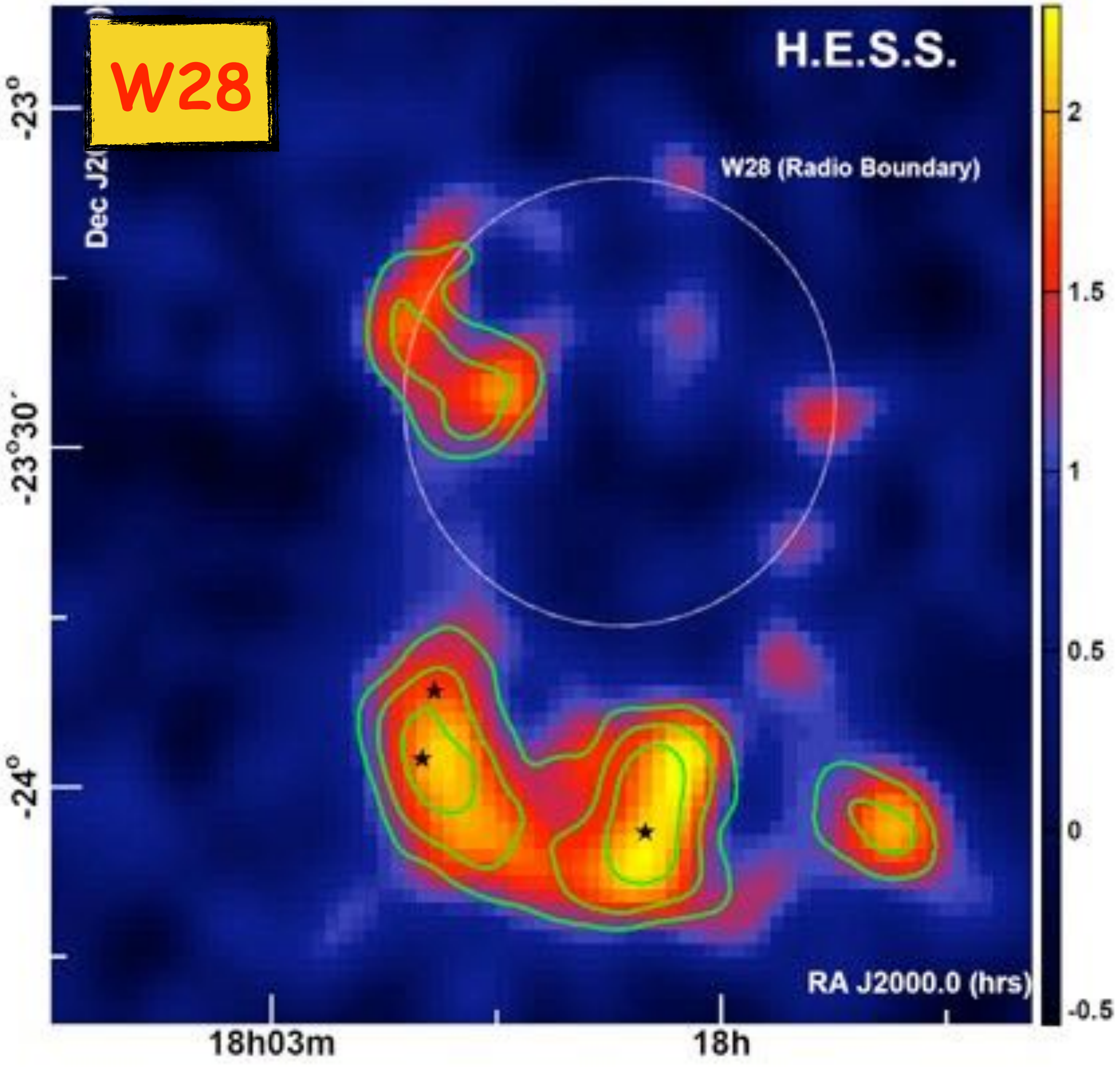
or longer if D suppressed

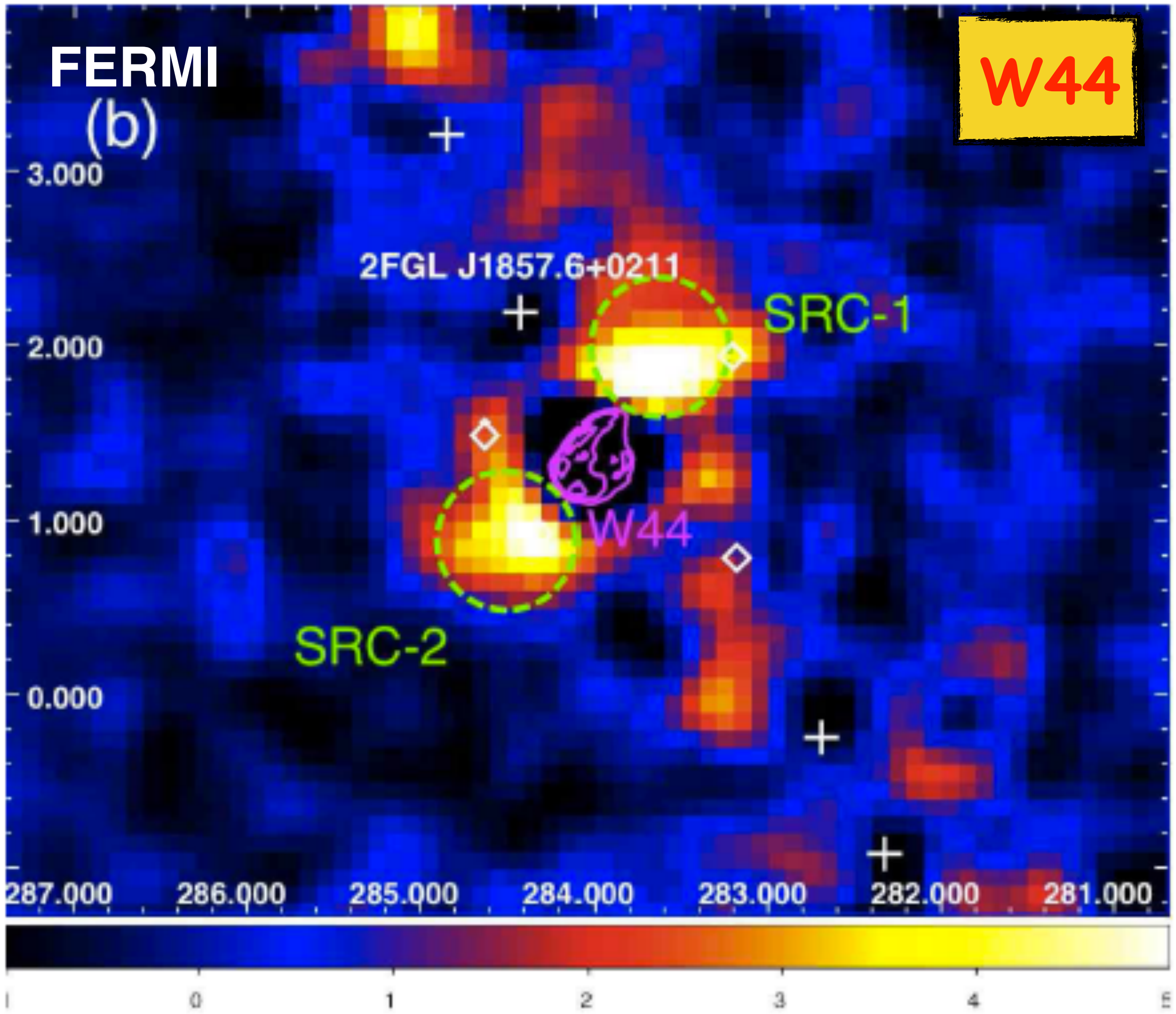
one expects shorter times for PeV particles

Escape: isotropic spatial diffusion

oldish (several 10^4 yr) SNRs

Aharonian et al. 2008





Uchiyama et al. 2012

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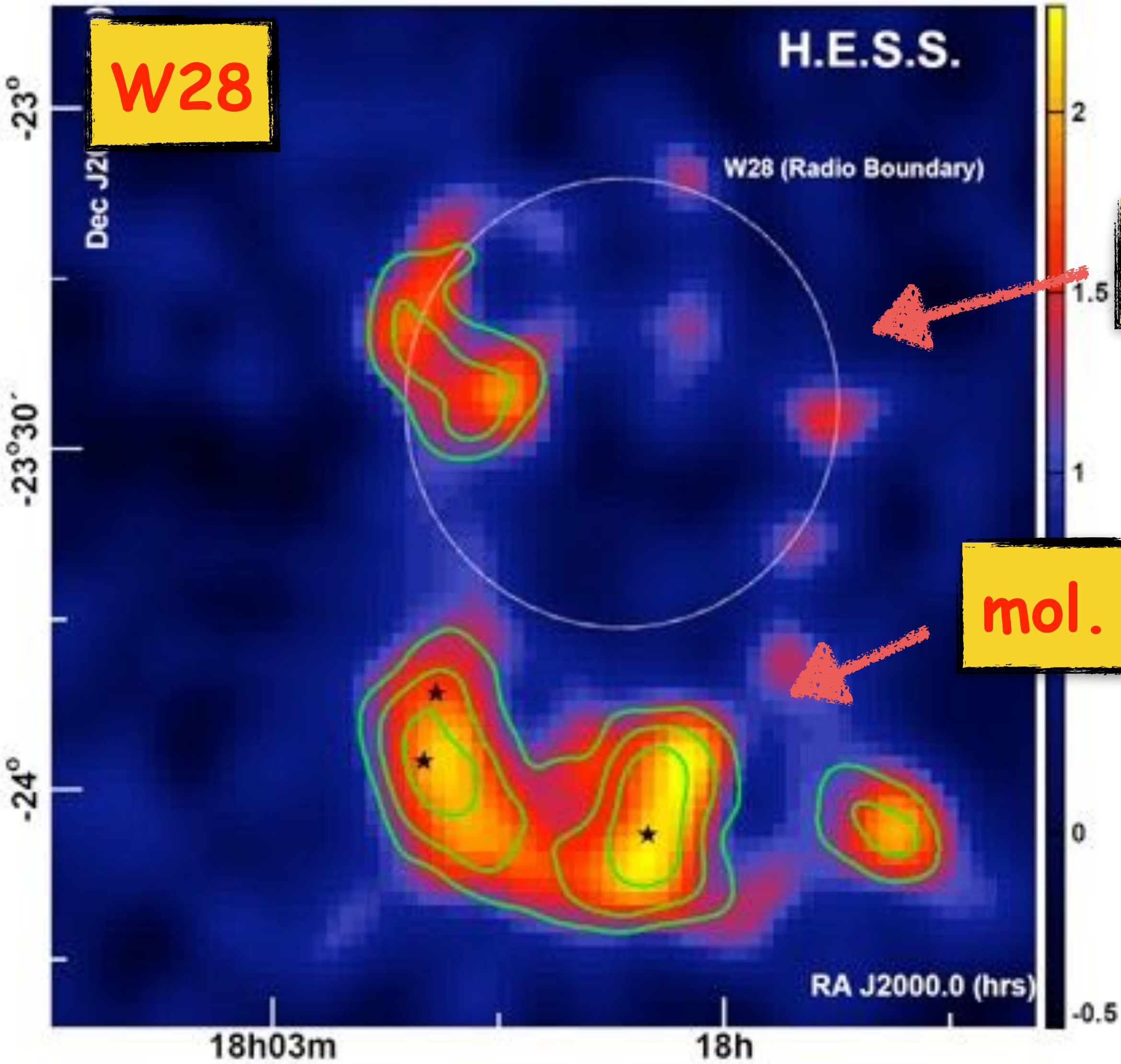
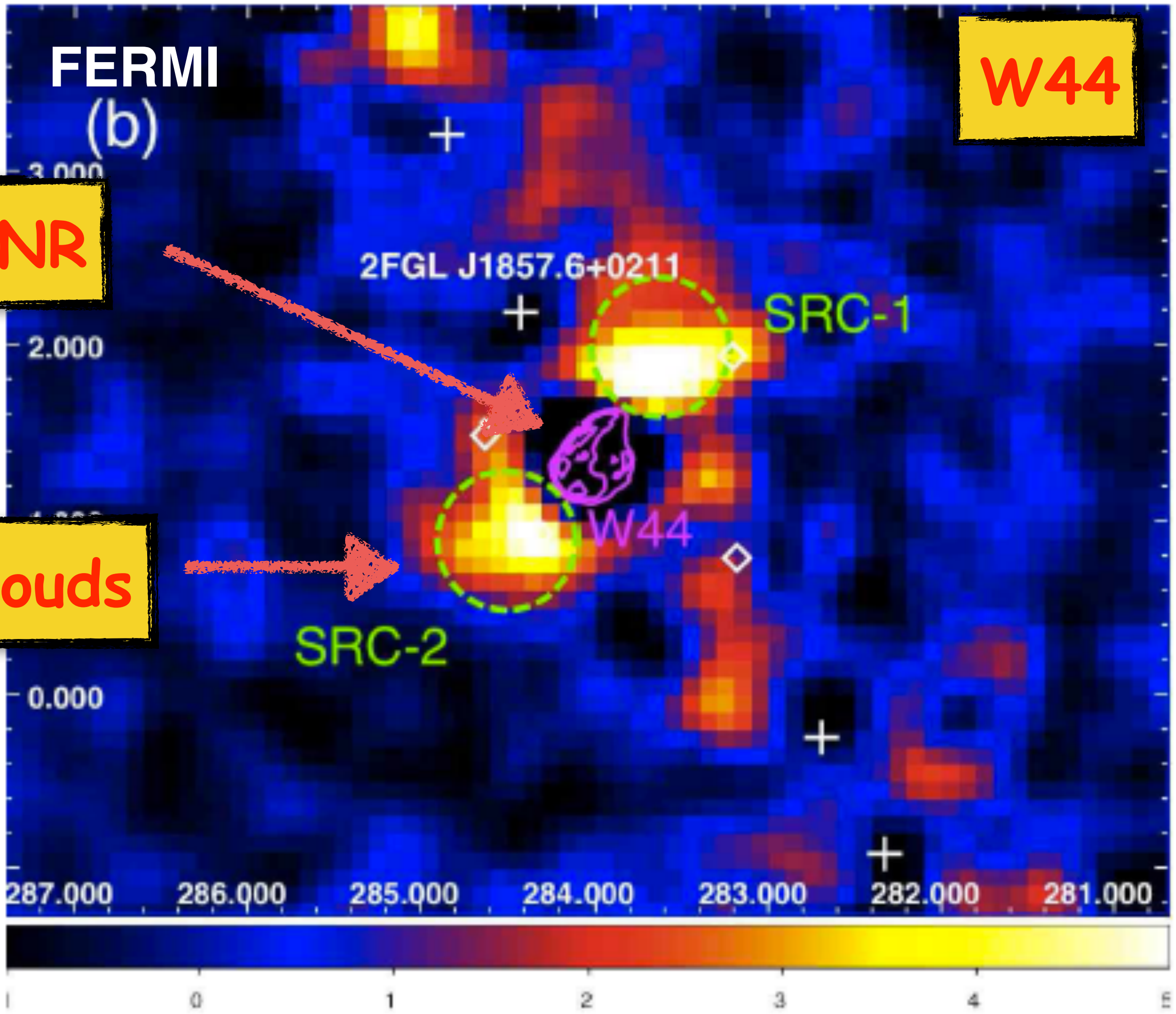


SNR

mol. clouds



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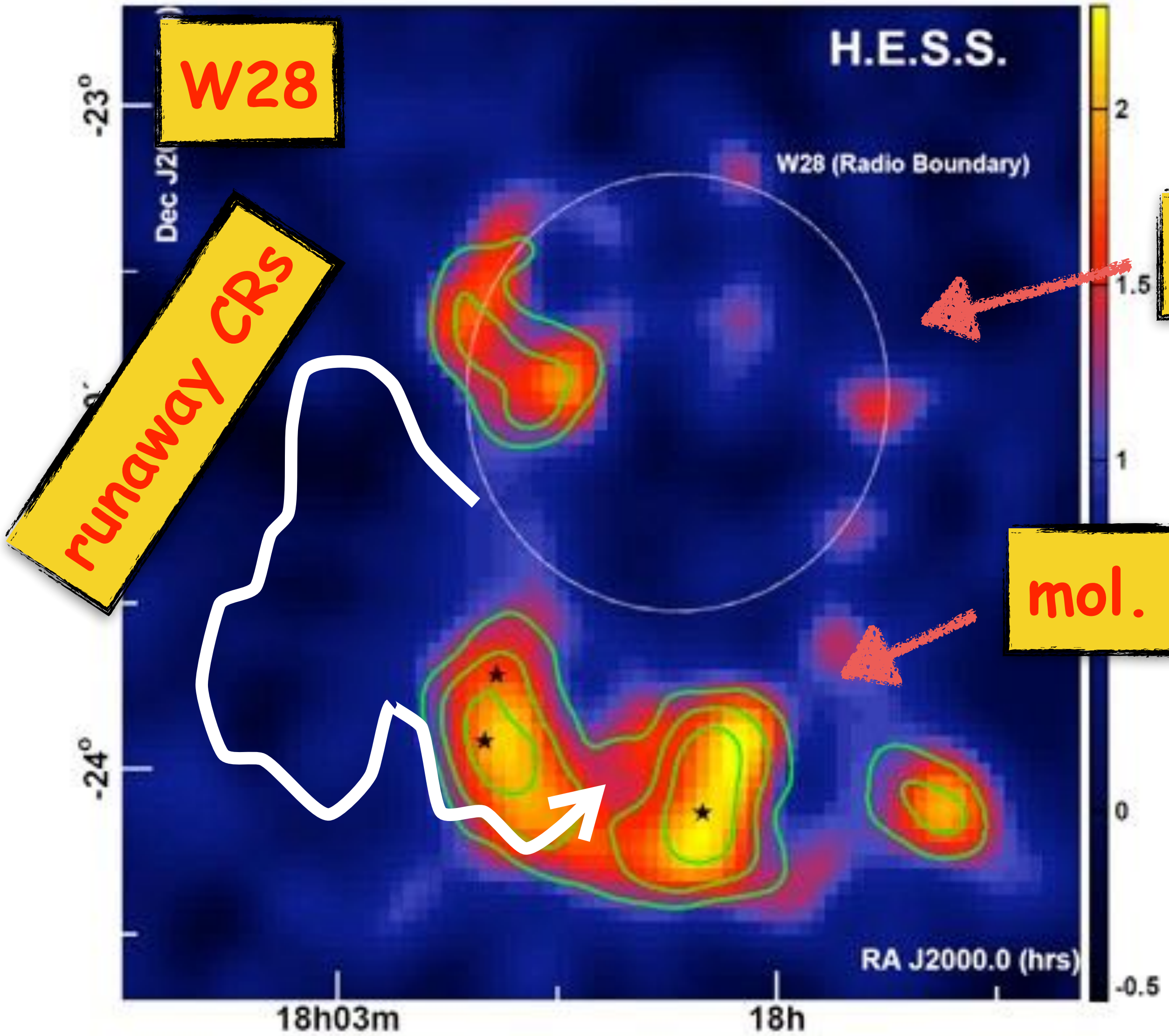

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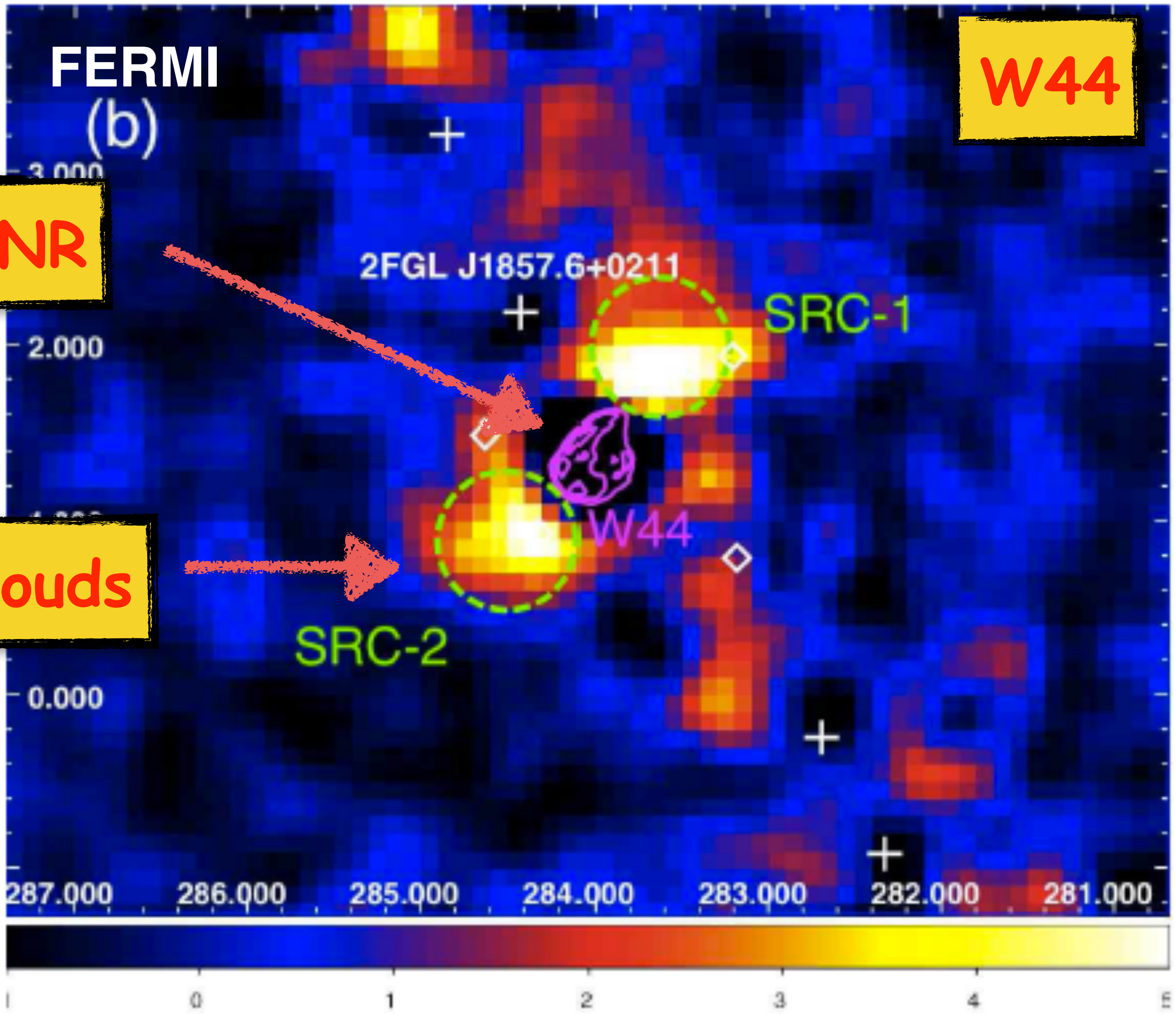

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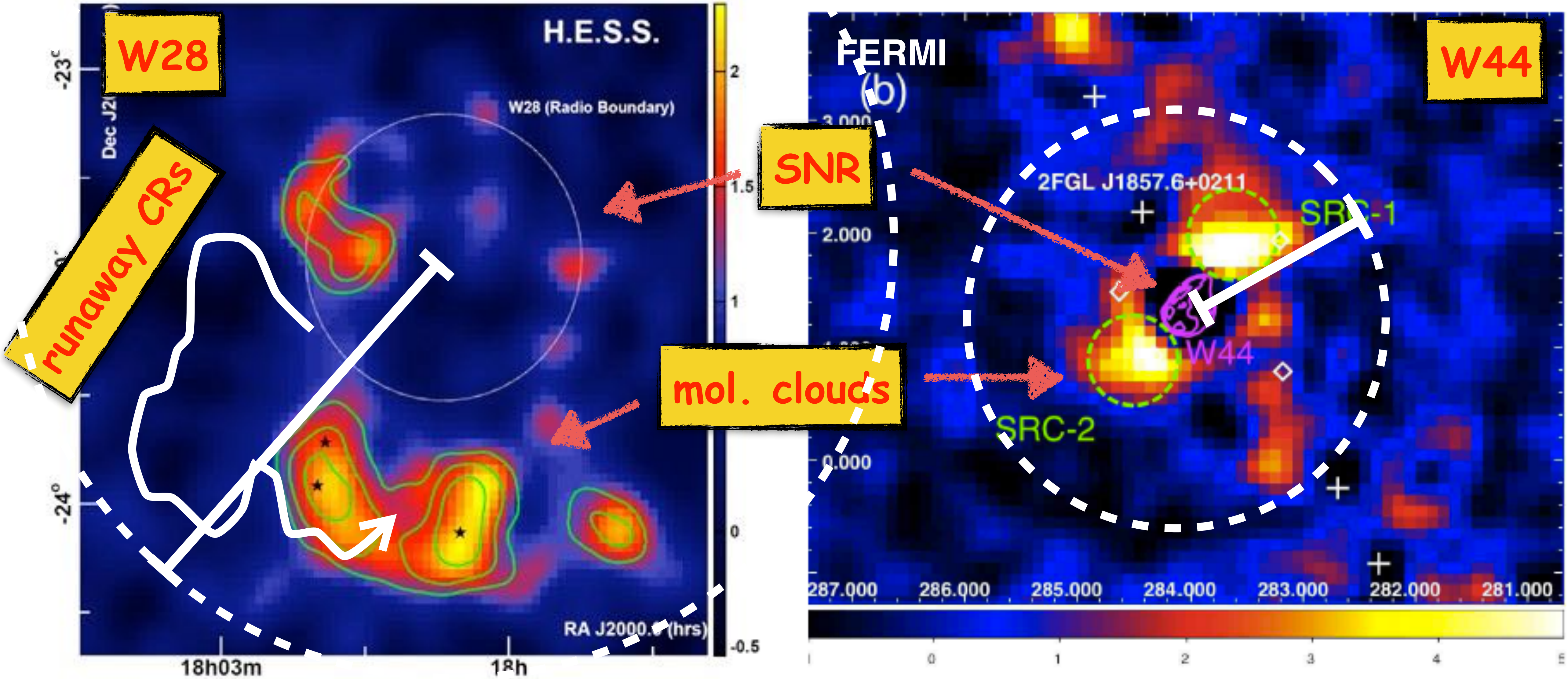

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$$R_{diff} = \sqrt{6\ D\ t}$$

for theoretical modeling see Aharonian & Atoyan, Gabici+, Casanova+, Nava & Gabici, Torres+, Li & Chen, Ohira+, Fujita+, Ellison&Bykov ...

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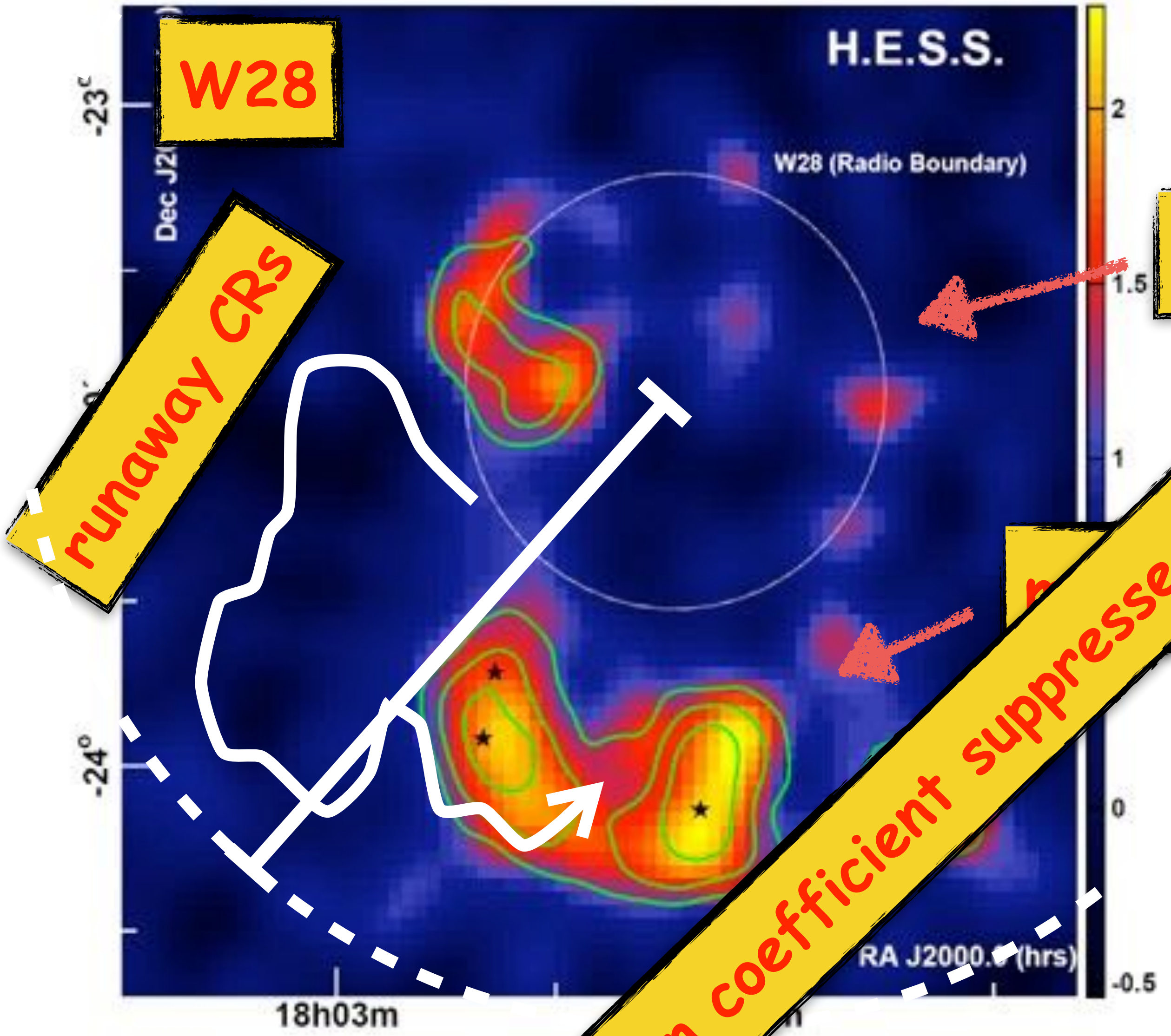
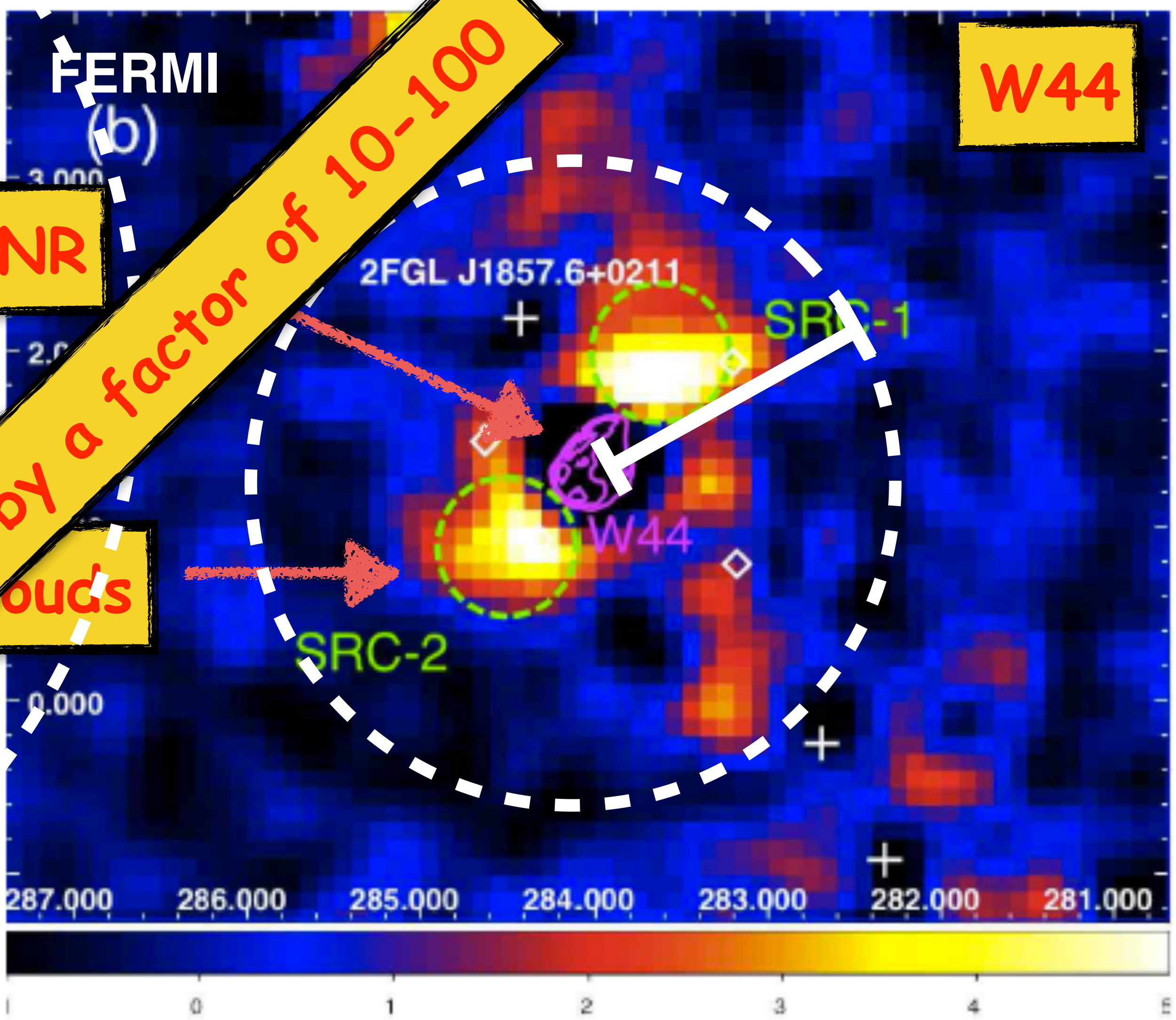


diffusion coefficient suppressed by a factor of 10-100



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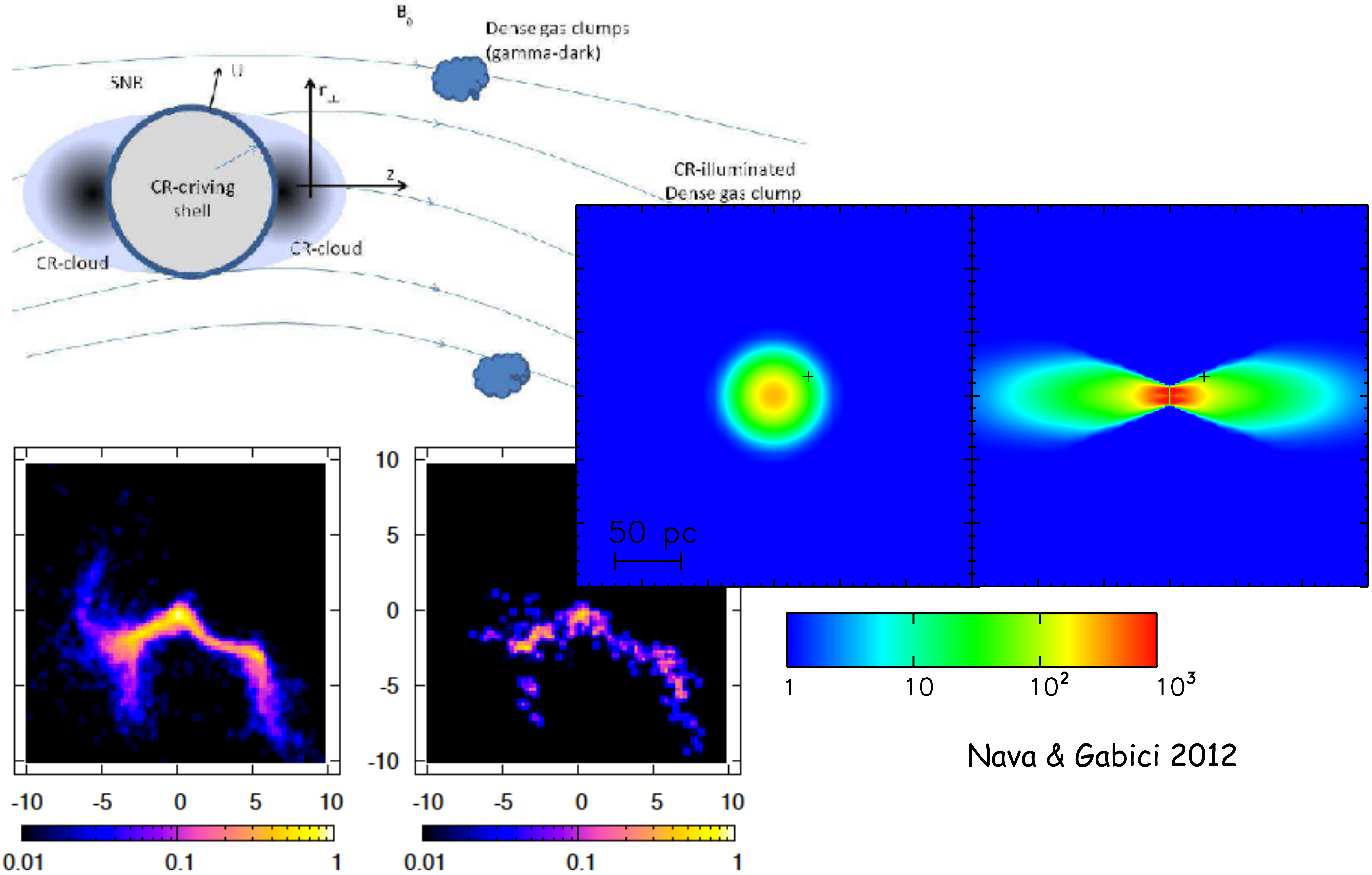
Anisotropic (1D) diffusion

1st paper in this direction is probably Skilling 71, revived by Ptuskin+ 07 -> streaming instability+damping



Malkov et al 2012

Giacinti et al. 2012

Nava & Gabici 2012

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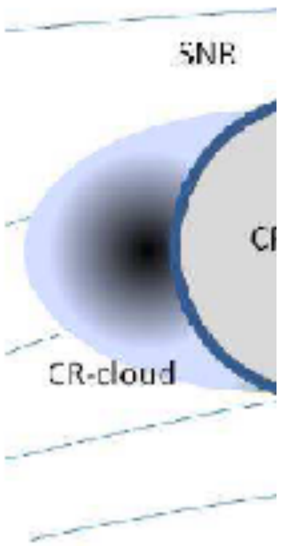

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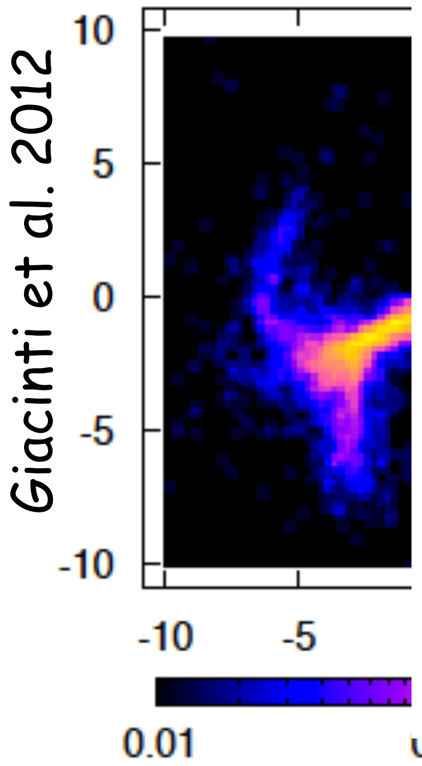

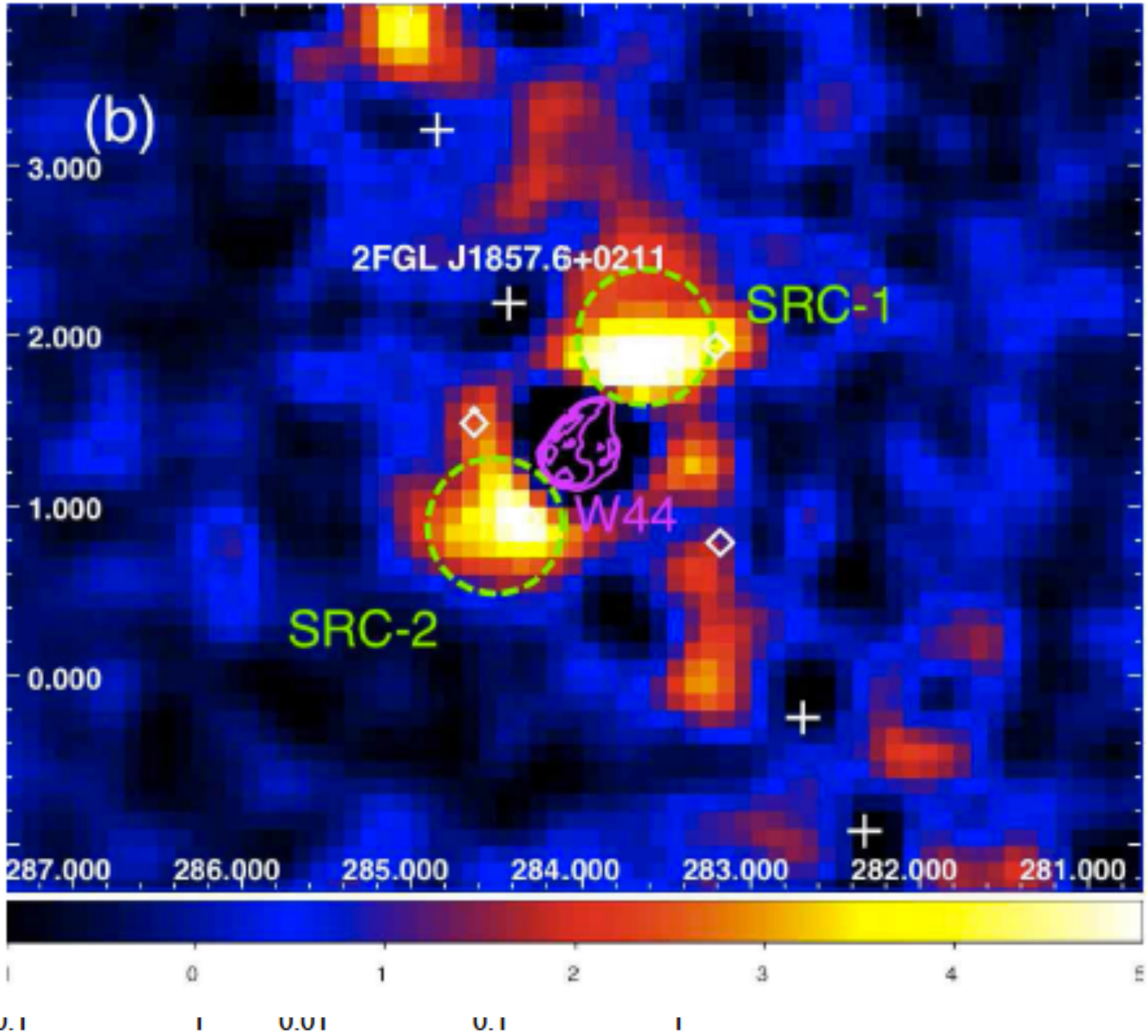

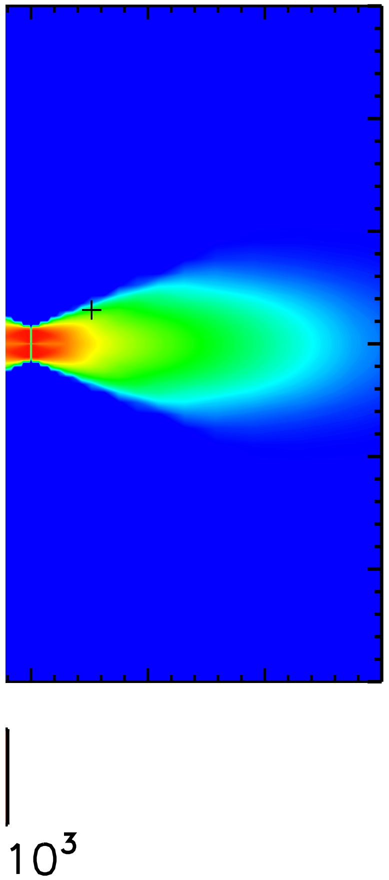

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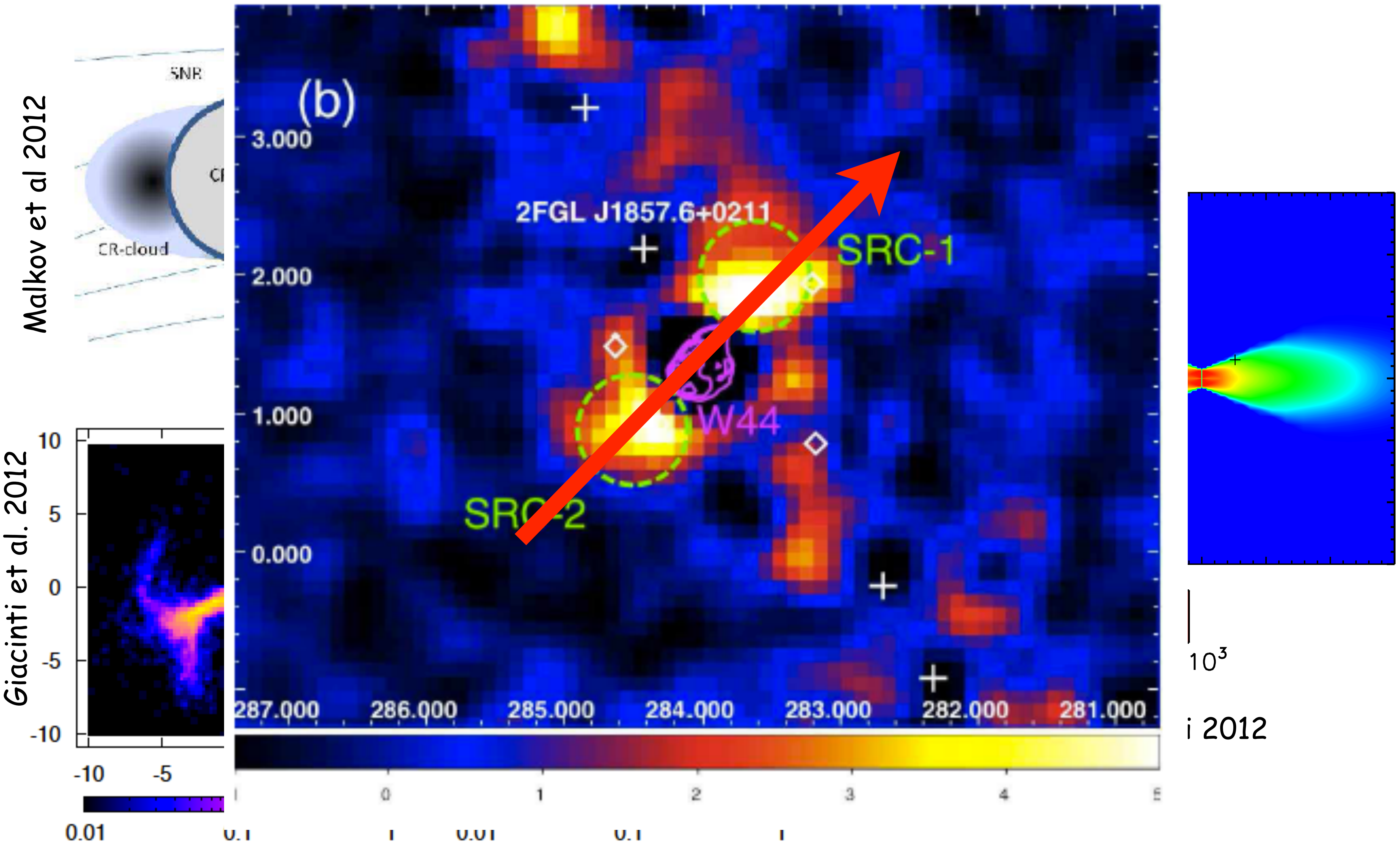


Malkov et al 2012

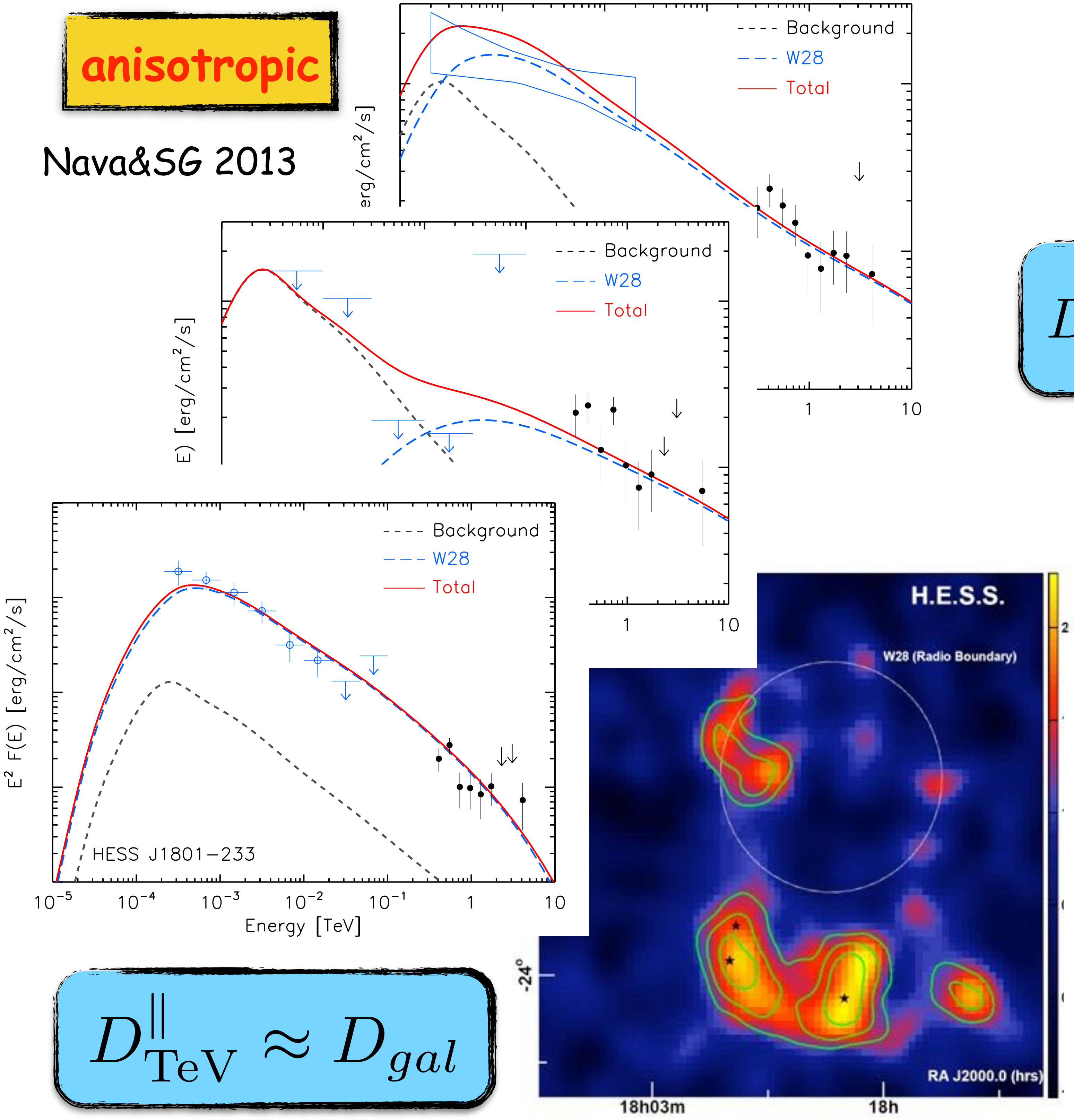
Giacinti et al. 2012

i 2012

An example: W28

anisotropic

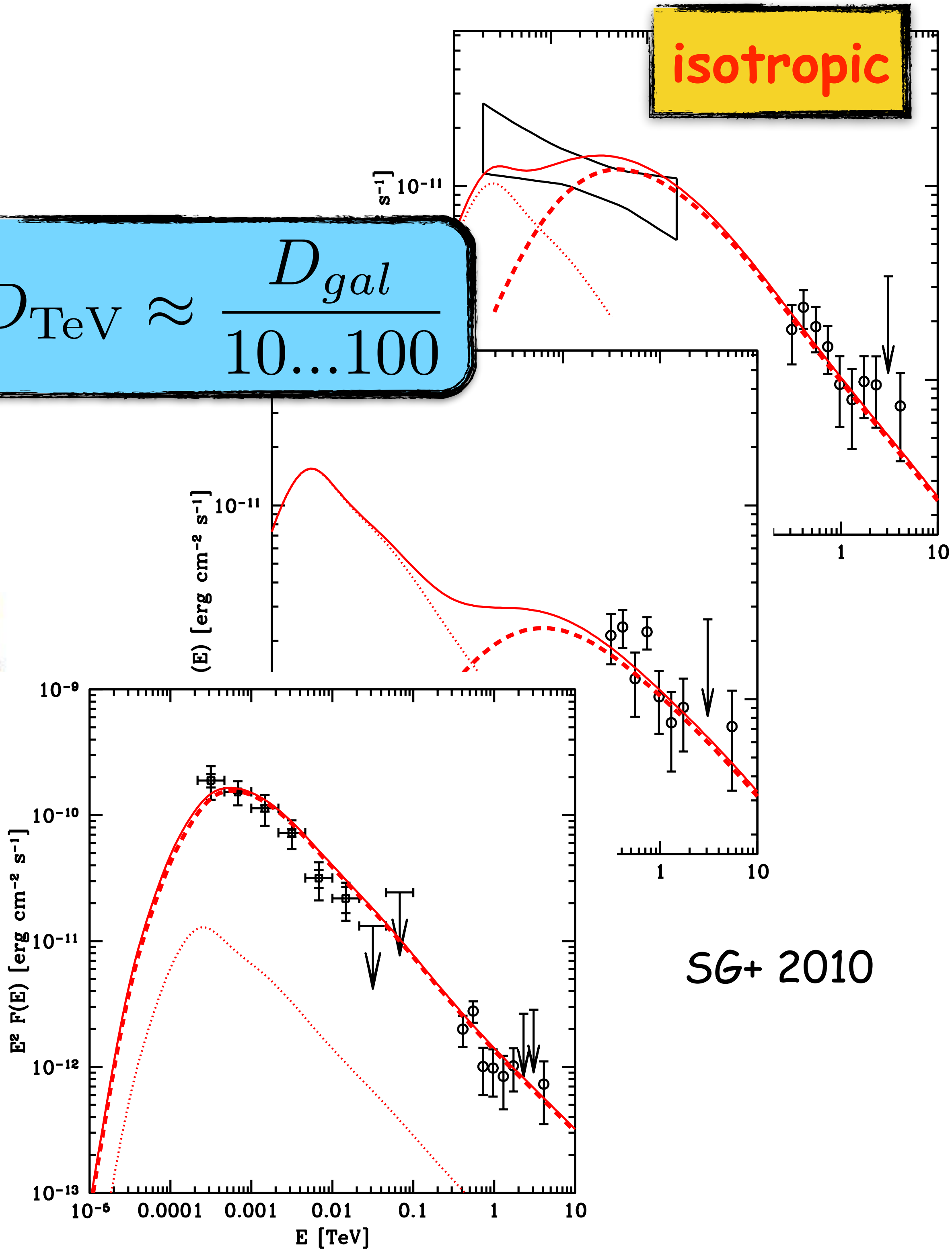
Nava&SG 2013



$$D_{\mathrm{TeV}}^{\parallel} \approx D_{gal}$$

isotropic

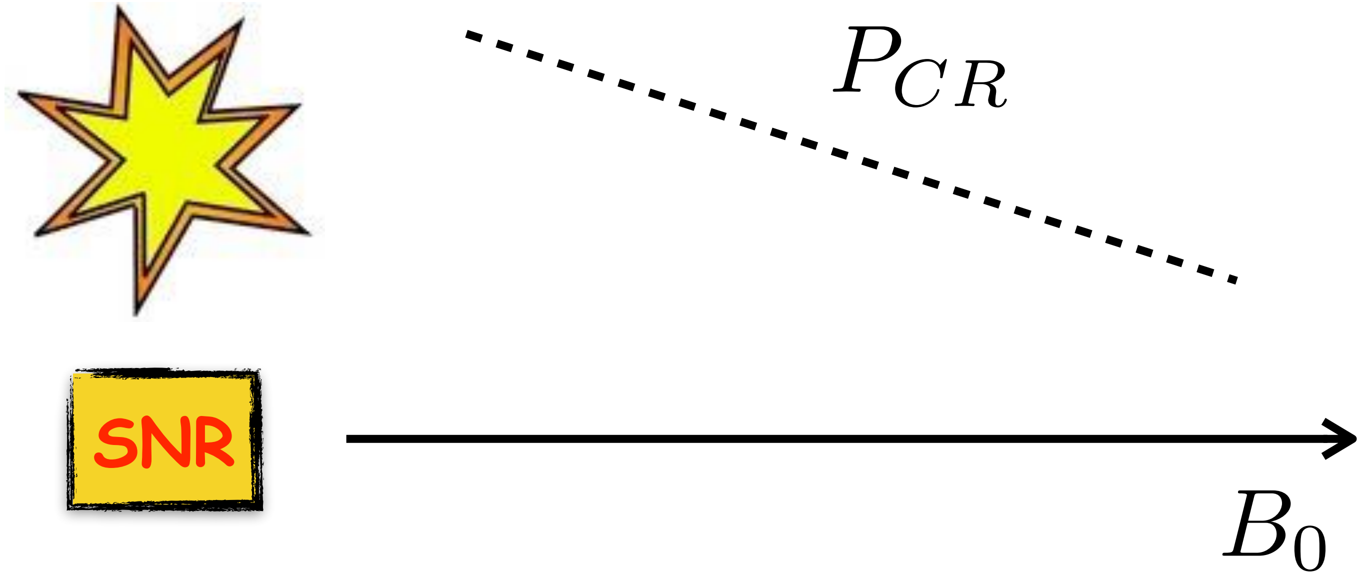
$$D_{\mathrm{TeV}} \approx \frac{D_{gal}}{10 \ldots 100}$$



SG+ 2010

Nonlinear diffusion: streaming instability

Skilling 1971, Ptuskin+ 2007, Malkov+ 2013, Nava+ 2016, D'Angelo+ 2016, Recchia+ 2021



growth of Alfven waves

$$-V_a \frac{\partial P_{CR}}{\partial z}$$

work done by CRs onto waves/time

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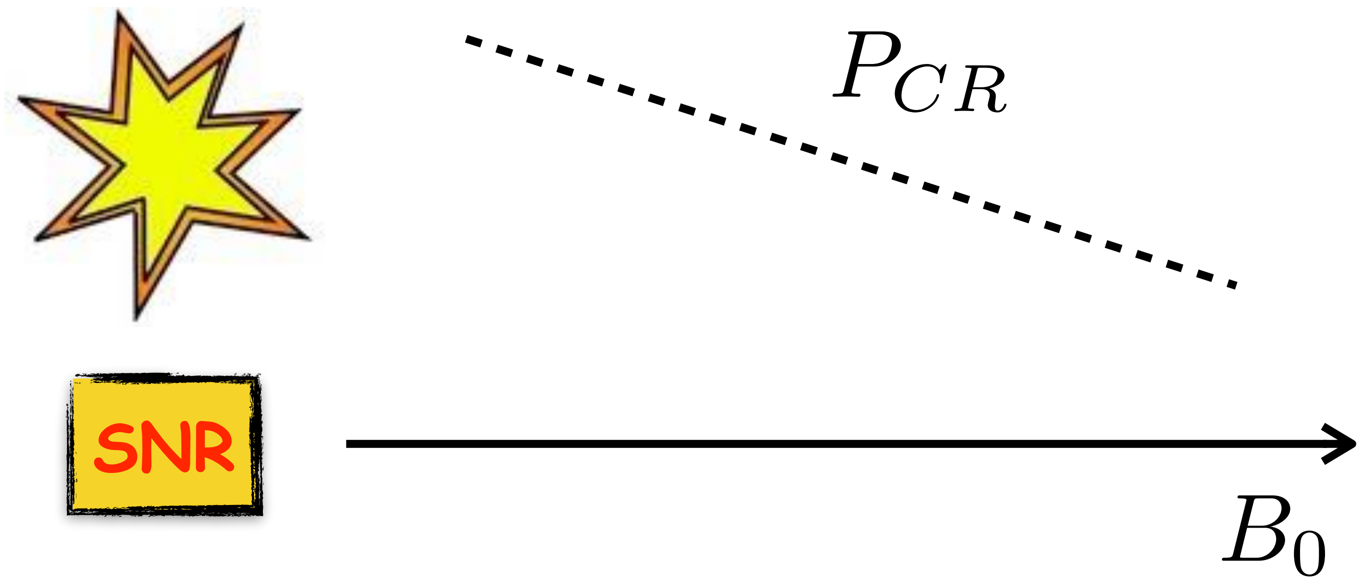

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work done by CRs onto waves/time

to be balanced by: $\Gamma_d W_a$ -> in most of the disk's volume this is ion-neutral friction

Nonlinear diffusion: streaming instability

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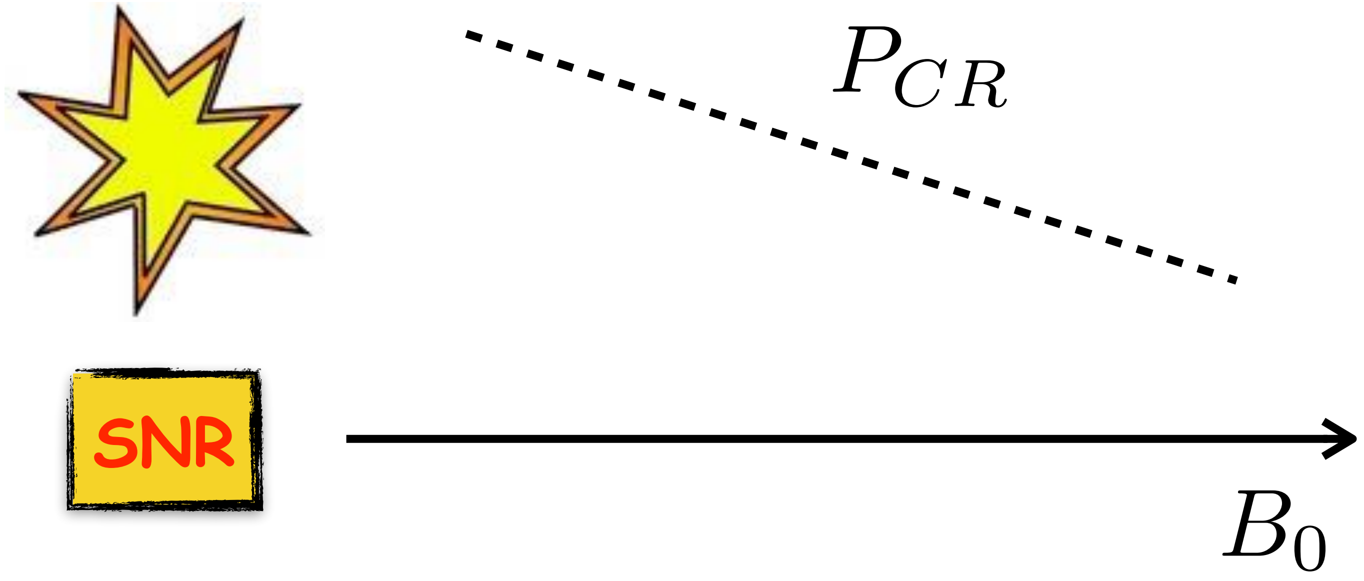

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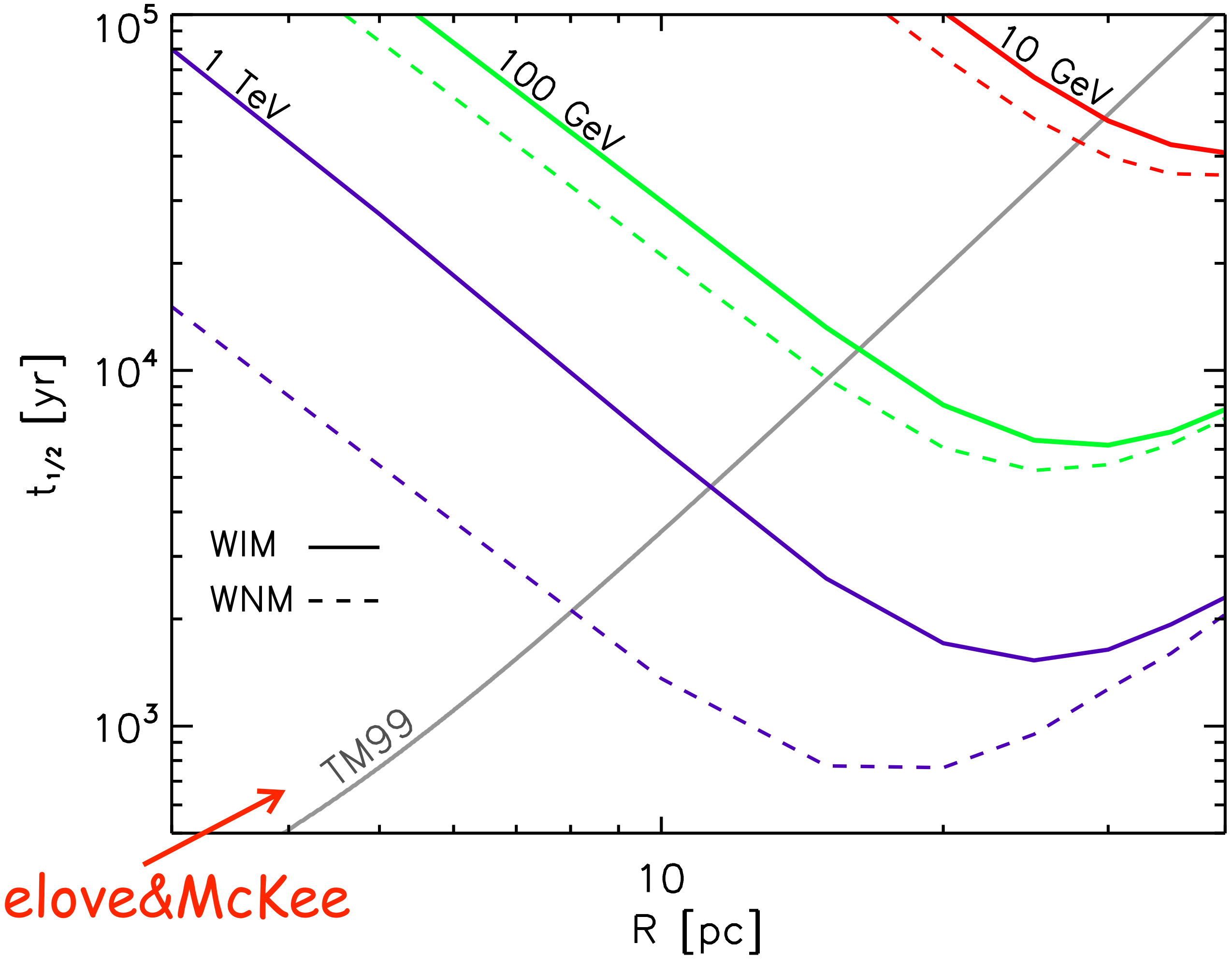

Nava+ 2016

Truelove&McKee

time it takes to have 1/2 of the CRs outside of a initial CR cloud of size R

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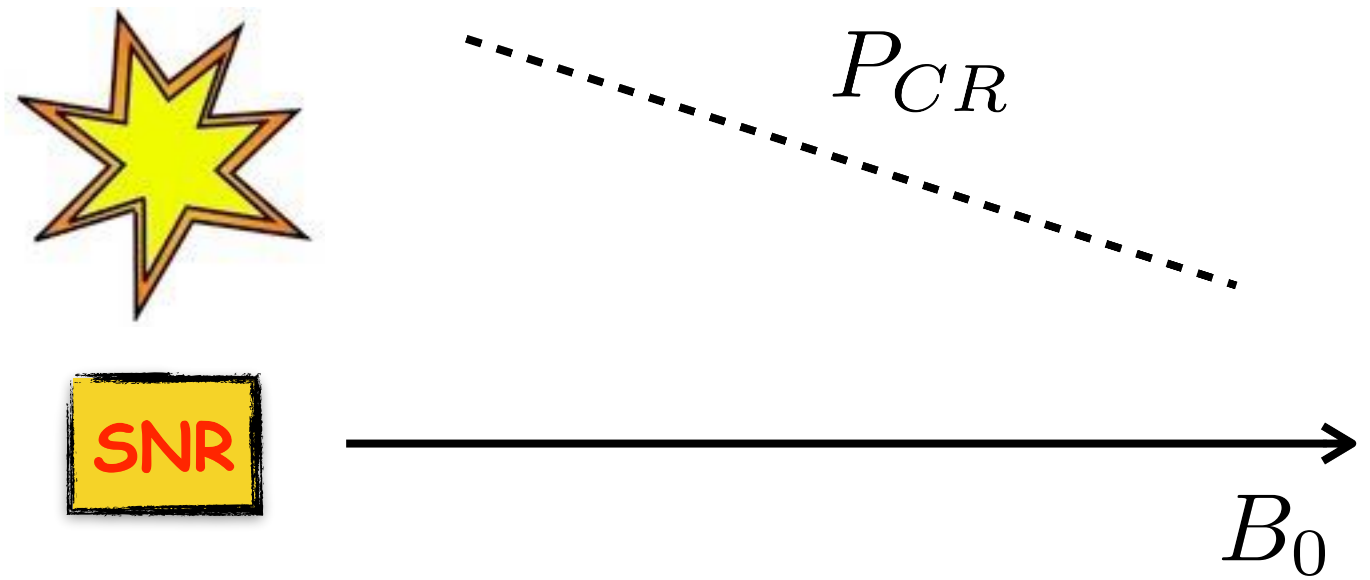

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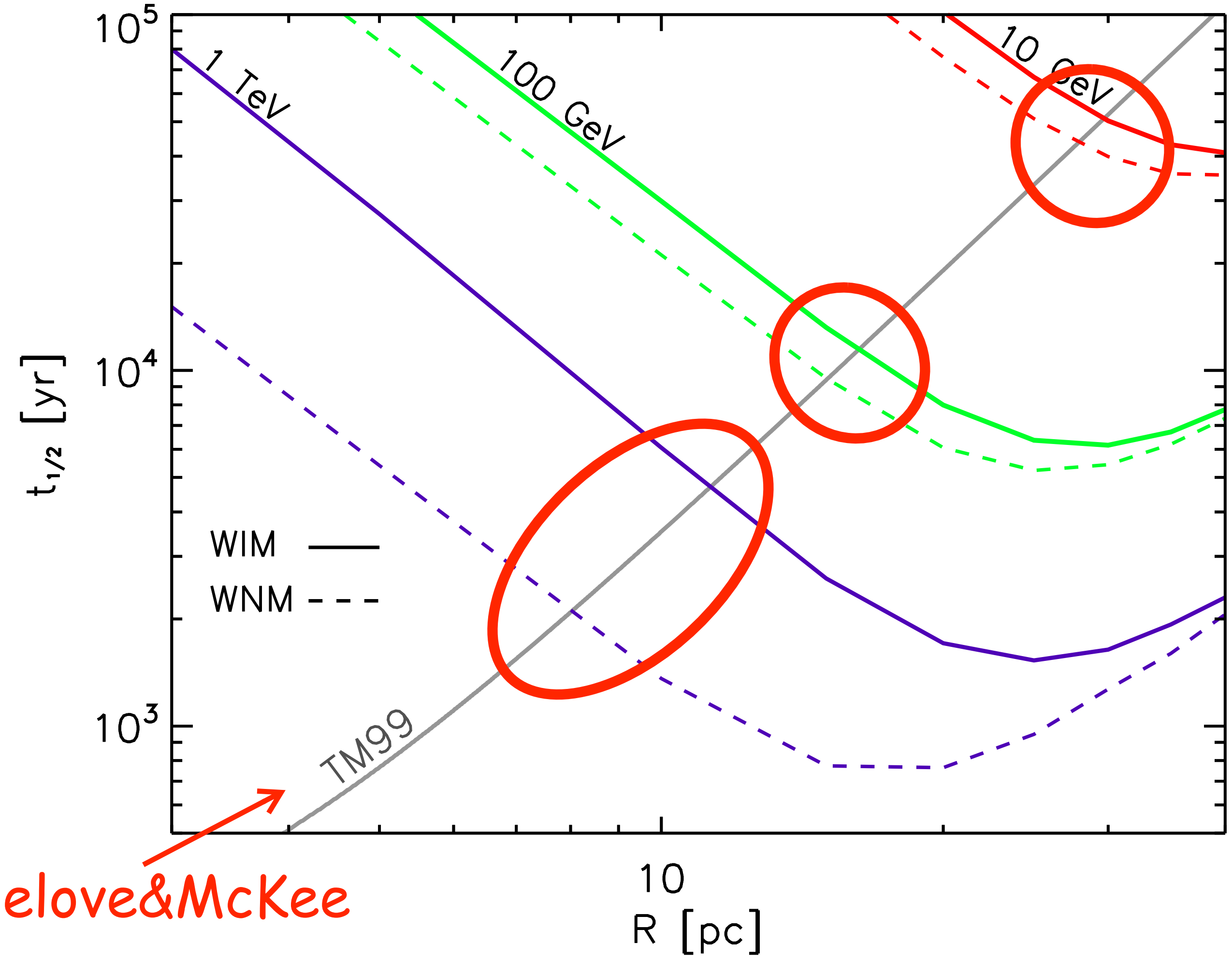

Truelove&McKee

time it takes to have 1/2 of the CRs outside of a initial CR cloud of size R

$$\tau_{esc} \approx \tau_{waves}$$

escape time

time when $W_a \gg W_{gal}$
(D suppressed)

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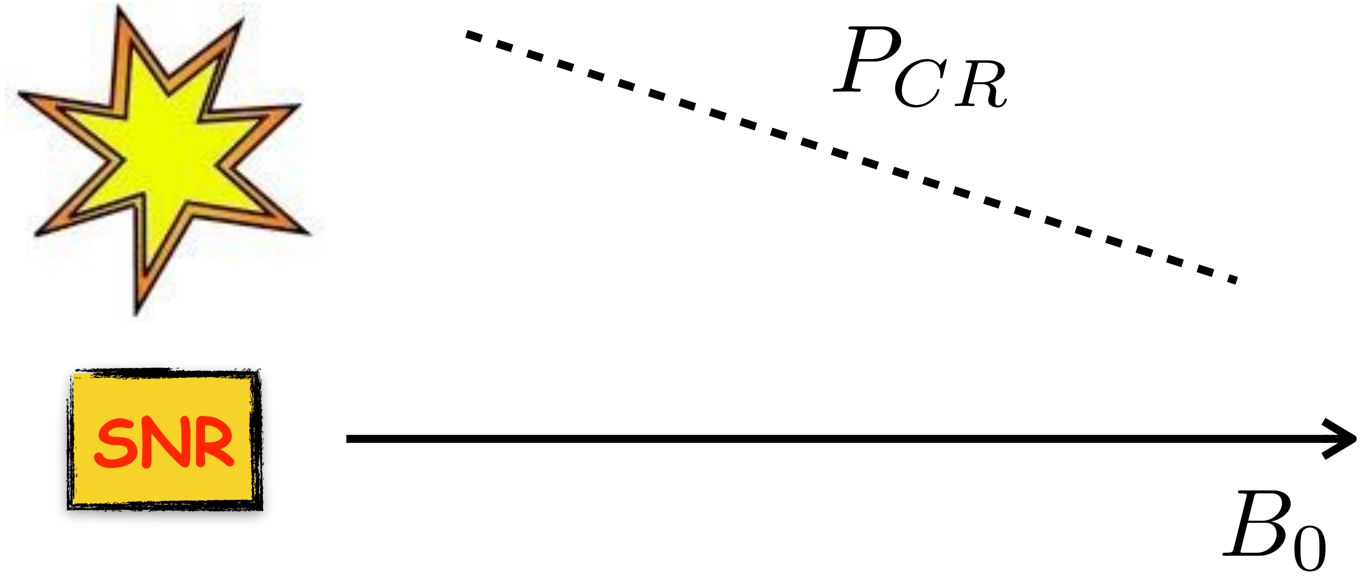

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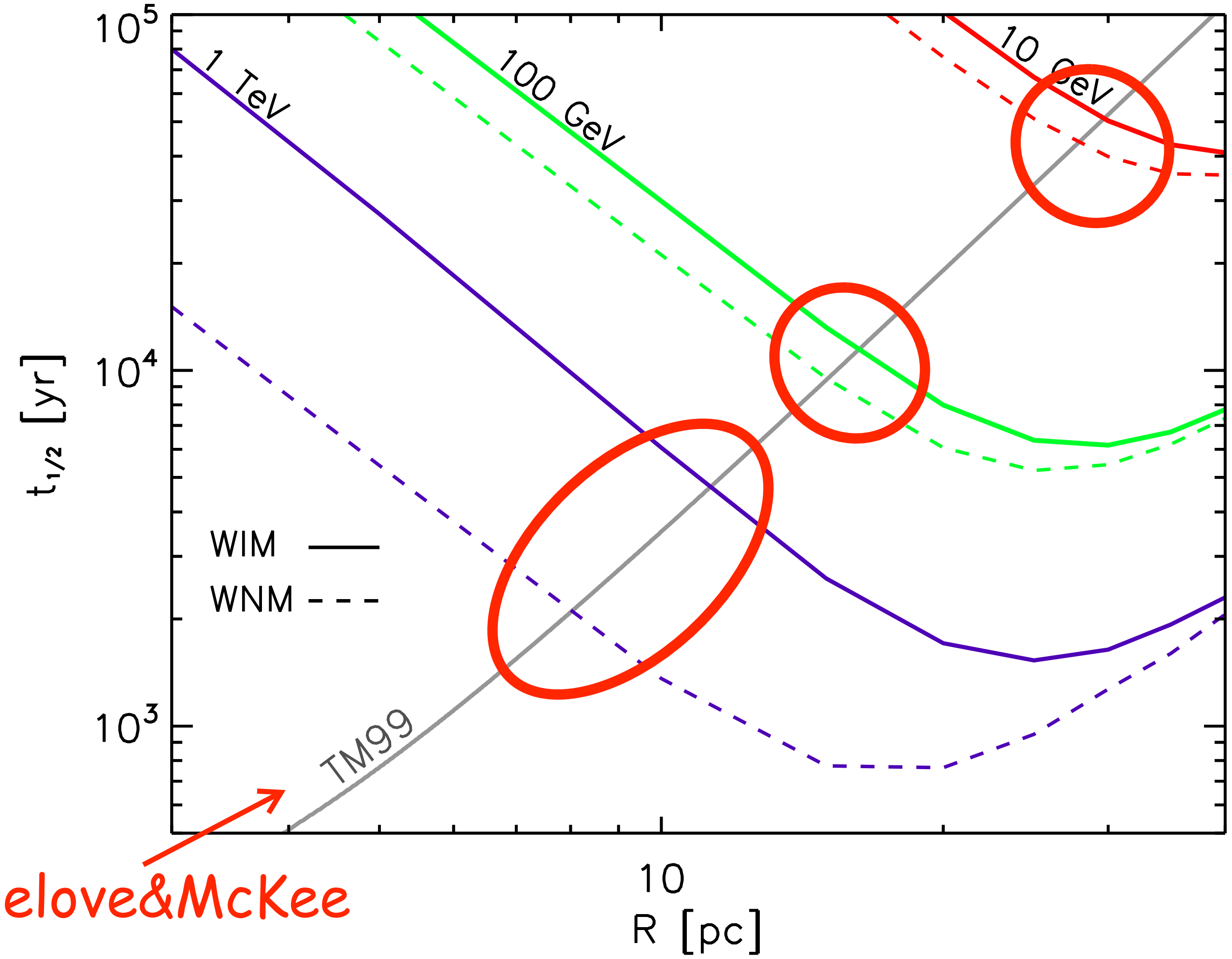

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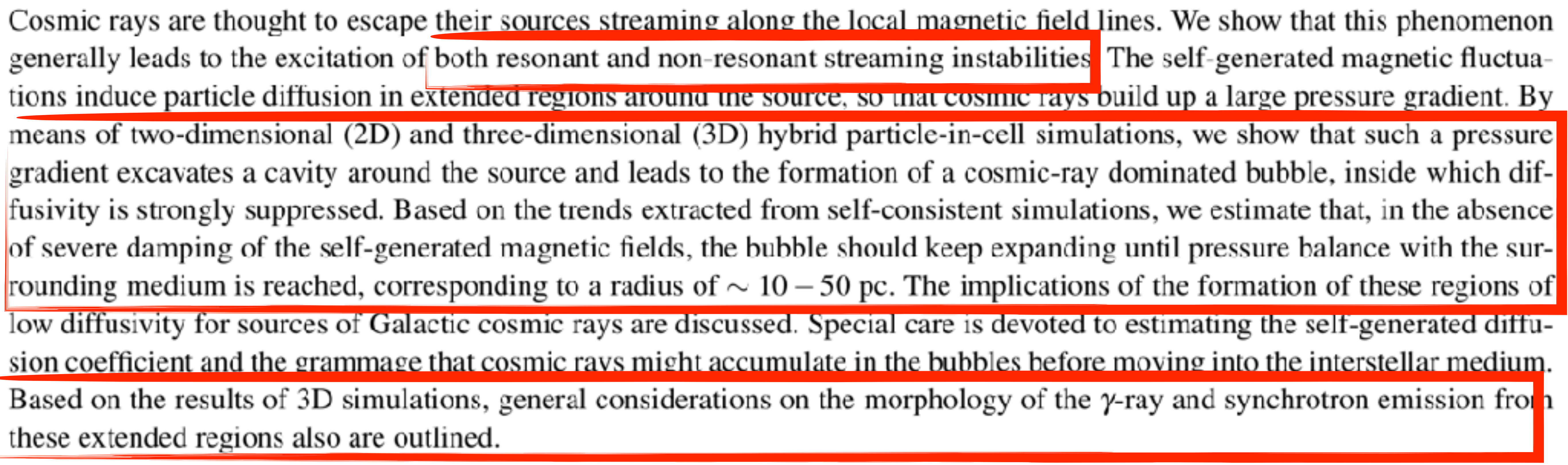
search for delayed emission —> ☹

Non-resonant instability?

Schroer+ 2022



Cosmic rays are thought to escape their sources streaming along the local magnetic field lines. We show that this phenomenon generally leads to the excitation of both resonant and non-resonant streaming instabilities. The self-generated magnetic fluctuations induce particle diffusion in extended regions around the source, so that cosmic rays build up a large pressure gradient. By means of two-dimensional (2D) and three-dimensional (3D) hybrid particle-in-cell simulations, we show that such a pressure gradient excavates a cavity around the source and leads to the formation of a cosmic-ray dominated bubble, inside which diffusivity is strongly suppressed. Based on the trends extracted from self-consistent simulations, we estimate that, in the absence of severe damping of the self-generated magnetic fields, the bubble should keep expanding until pressure balance with the surrounding medium is reached, corresponding to a radius of $\sim 10-50$ pc. The implications of the formation of these regions of low diffusivity for sources of Galactic cosmic rays are discussed. Special care is devoted to estimating the self-generated diffusion coefficient and the grammage that cosmic rays might accumulate in the bubbles before moving into the interstellar medium. Based on the results of 3D simulations, general considerations on the morphology of the γ-ray and synchrotron emission from these extended regions also are outlined.

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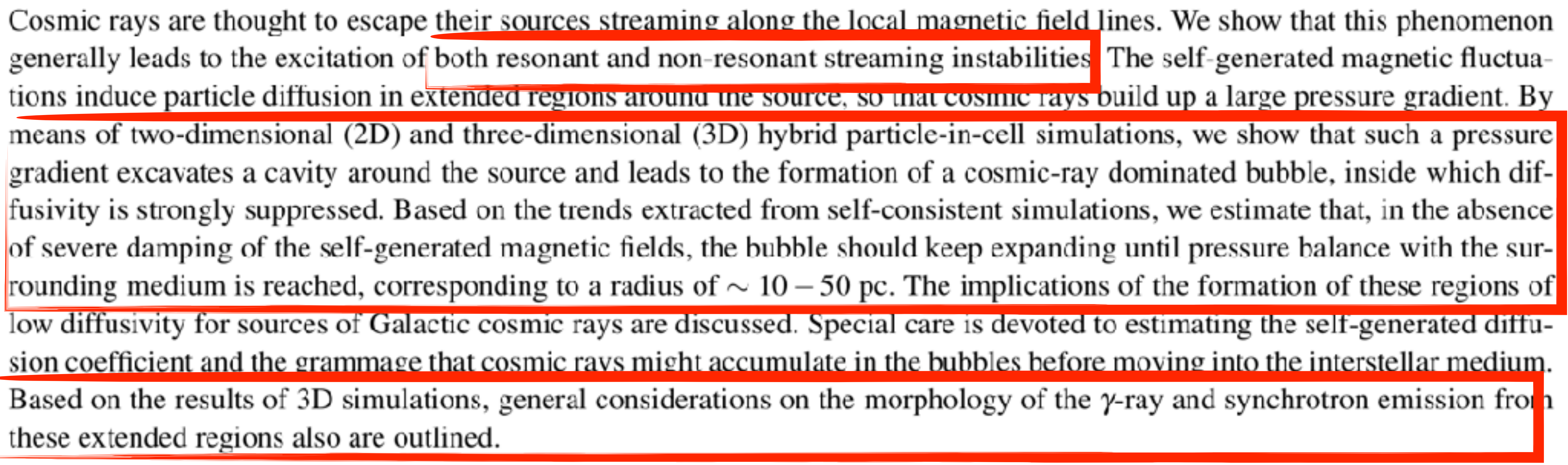

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- Idea for discussion?
  - Non-resonant —> need for escaping particles
  - Escape assumed to happen at the transition to Sedov (shock speed is large)
  - Fast shock + very suppressed diffusion
  - How is escape possible? (Hillas… Emax = u R B …)

SNR crisis? Possible wayouts
1) plasma physics

can we amplify B more than in the non-resonant instability?

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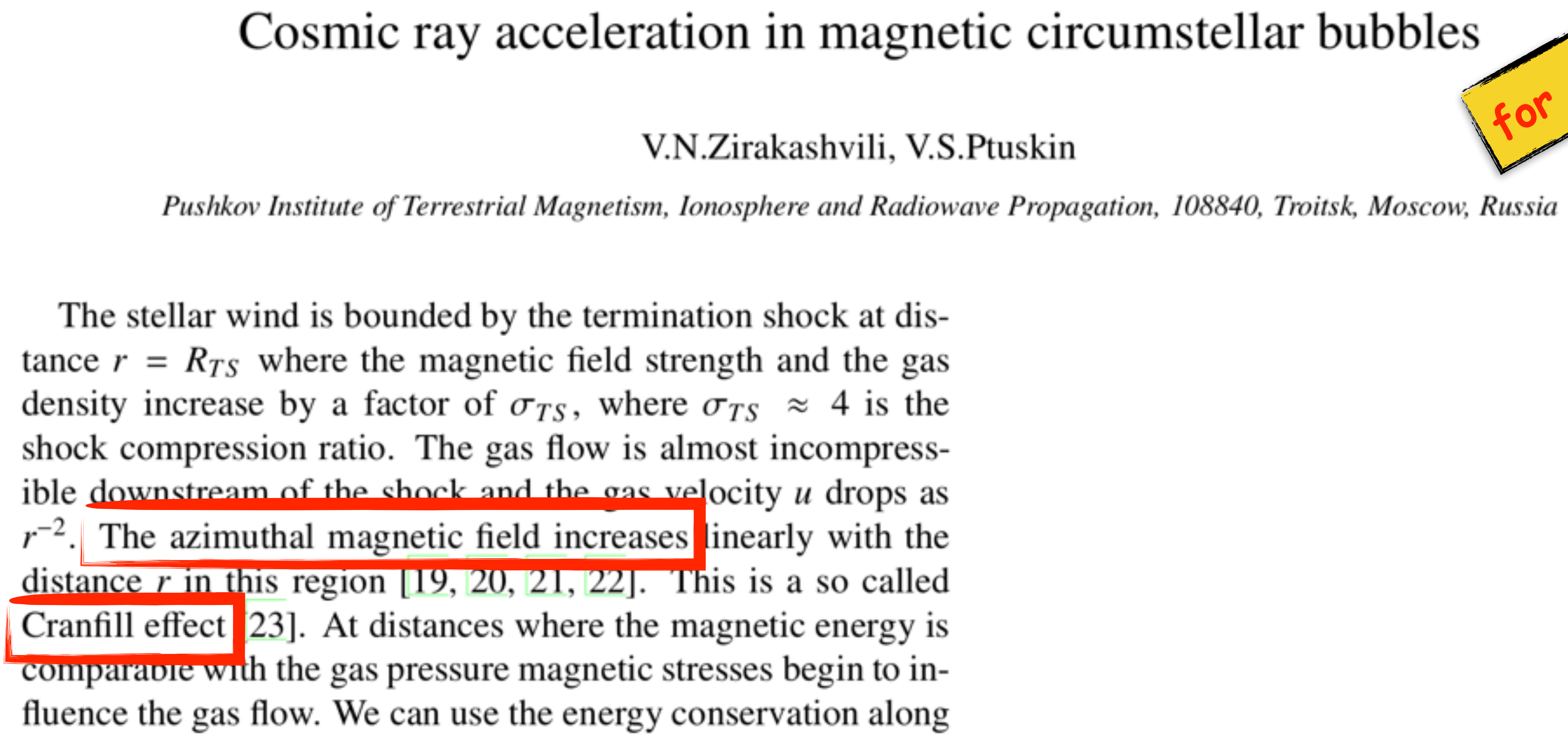
for example



Cosmic ray acceleration in magnetic circumstellar bubbles

V.N.Zirakashvili, V.S.Ptuskin

Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation, 108840, Troitsk, Moscow, Russia

The stellar wind is bounded by the termination shock at distance $r = R_{TS}$ where the magnetic field strength and the gas density increase by a factor of σ_{TS}, where $\sigma_{TS} \approx 4$ is the shock compression ratio. The gas flow is almost incompressible downstream of the shock and the gas velocity u drops as r^{-2}. The azimuthal magnetic field increases linearly with the distance r in this region [19, 20, 21, 22]. This is a so called Cranfill effect [23]. At distances where the magnetic energy is comparable with the gas pressure magnetic stresses begin to influence the gas flow. We can use the energy conservation along

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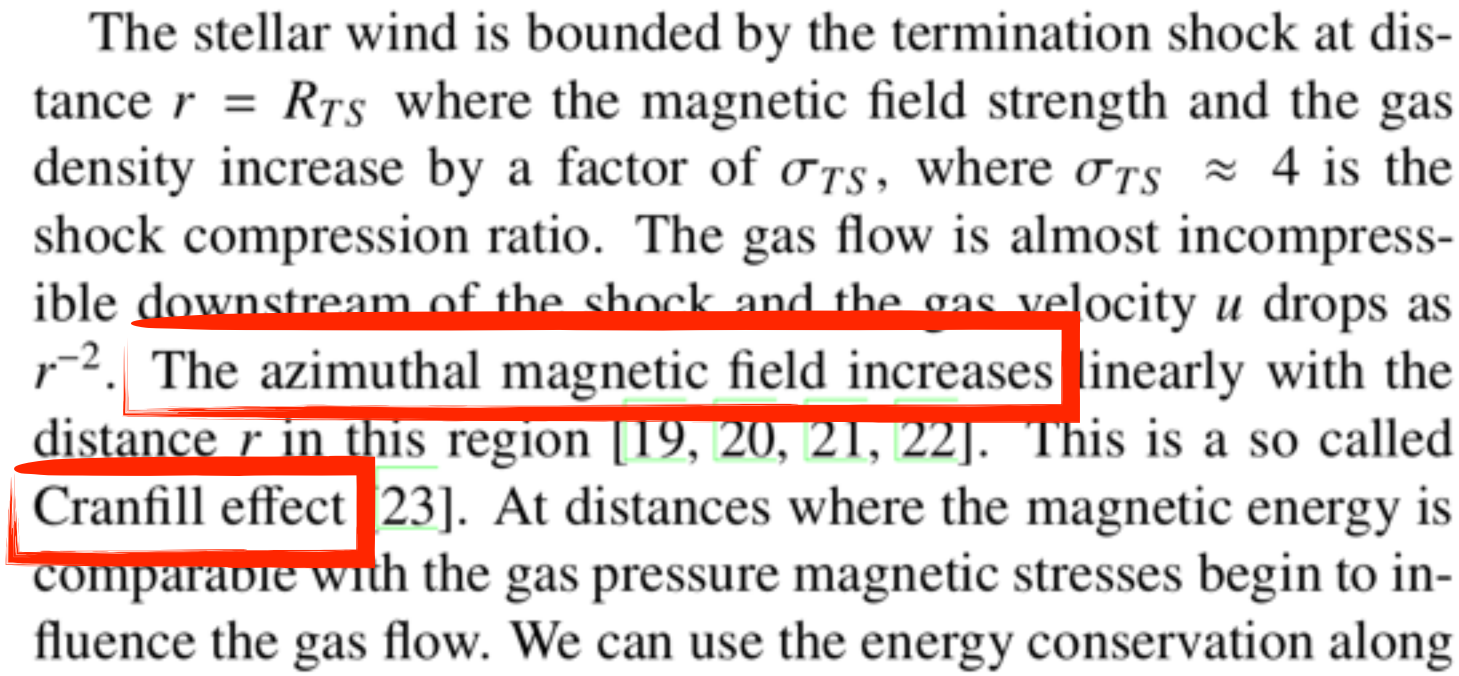

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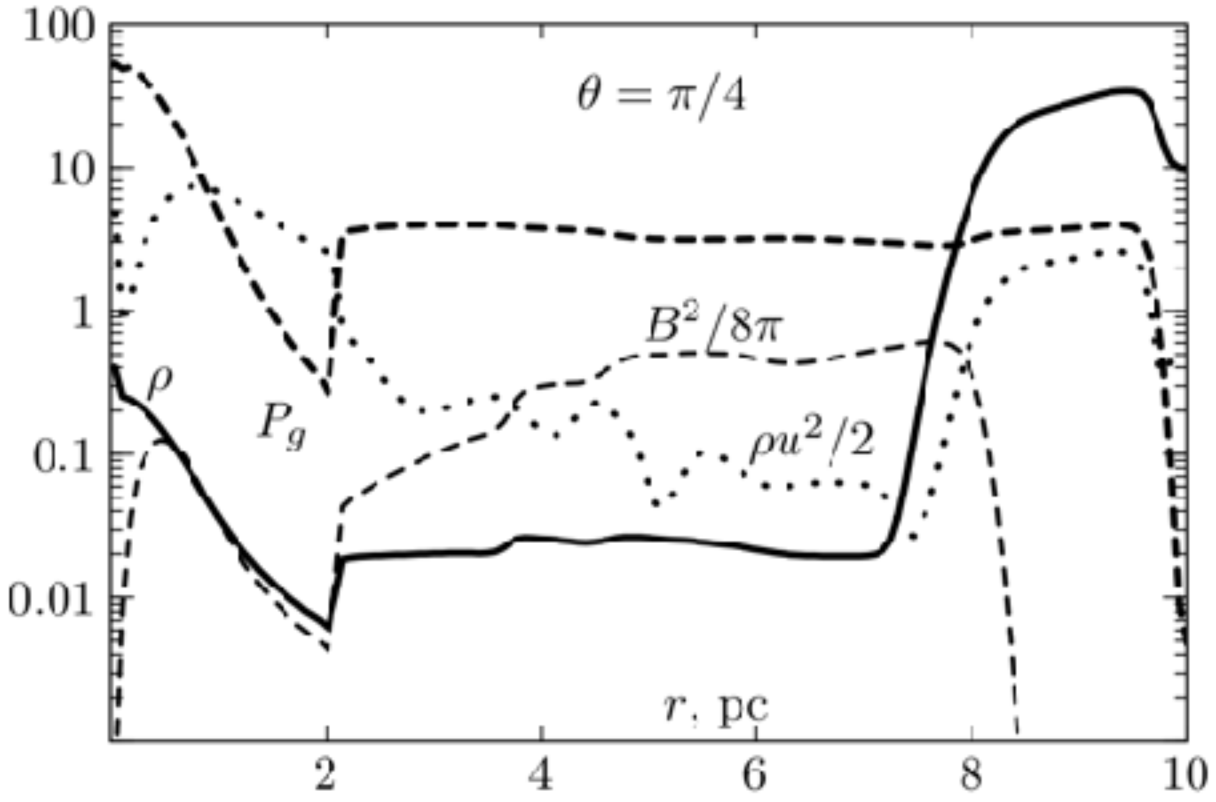

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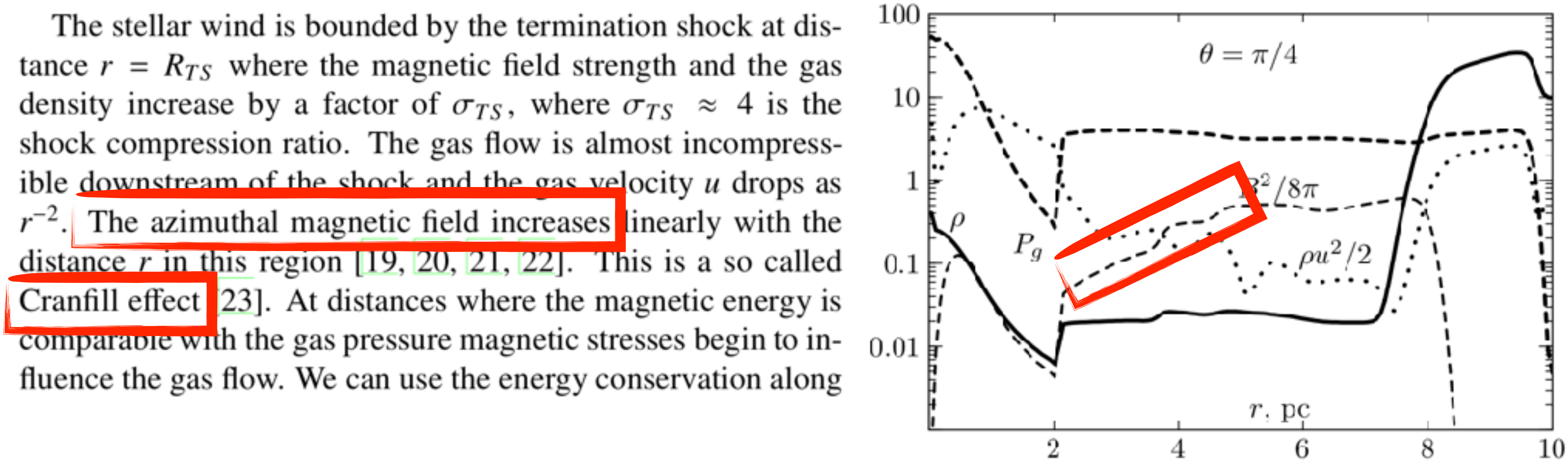

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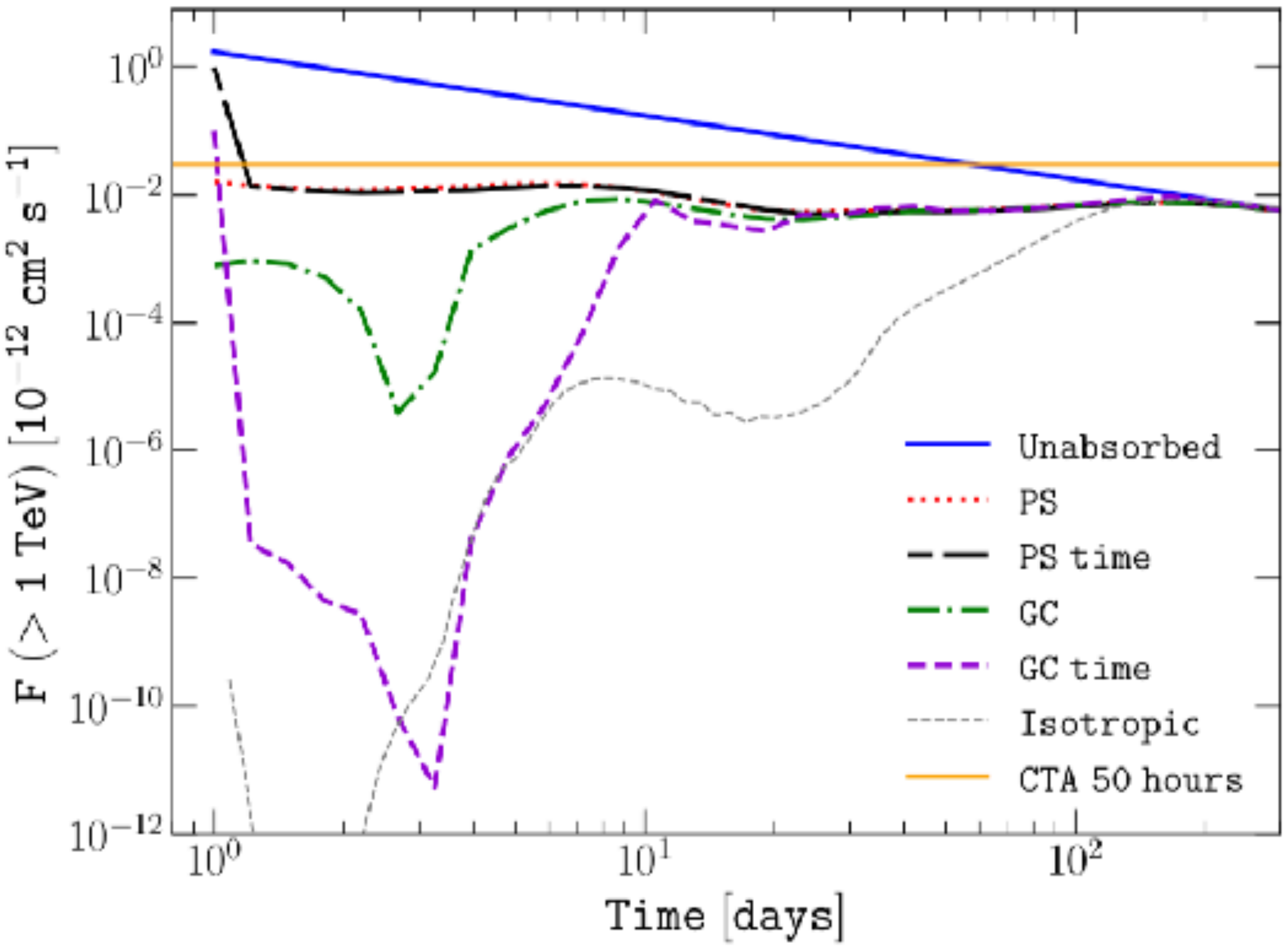
known SNRs are too old to go to PeV —> search for extragalactic SNae!



Cristofari et al 2020

Figure 6. Time evolution of the integrated flux above 1 TeV from SN 1993J. Legend is similar to Fig. 5.

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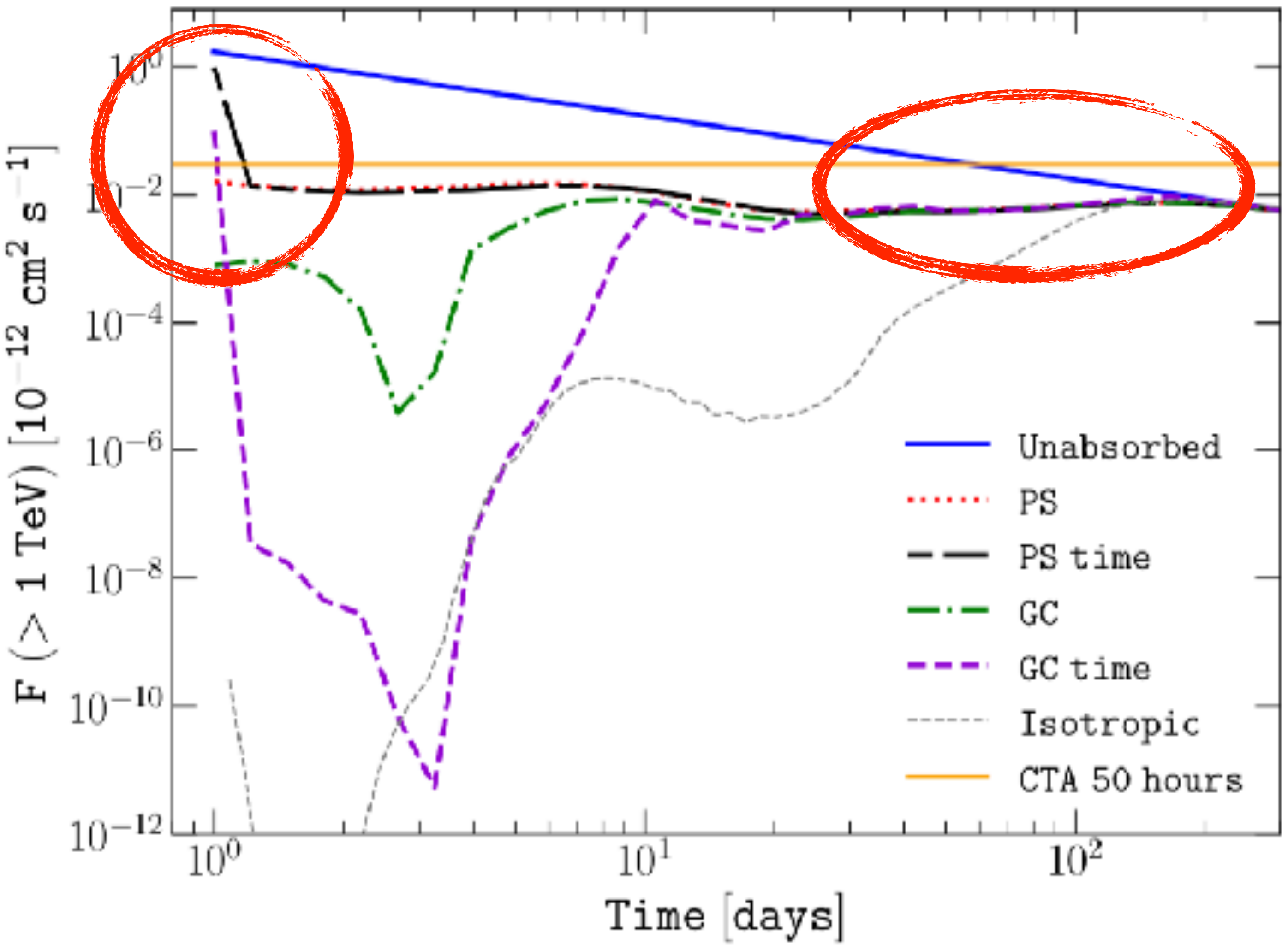

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SNR crisis? Possible wayouts

3) PeV-SNR —> PeV-something-else

superbubbles, star clusters, binaries, colliding shocks, pulsar wind nebulae…

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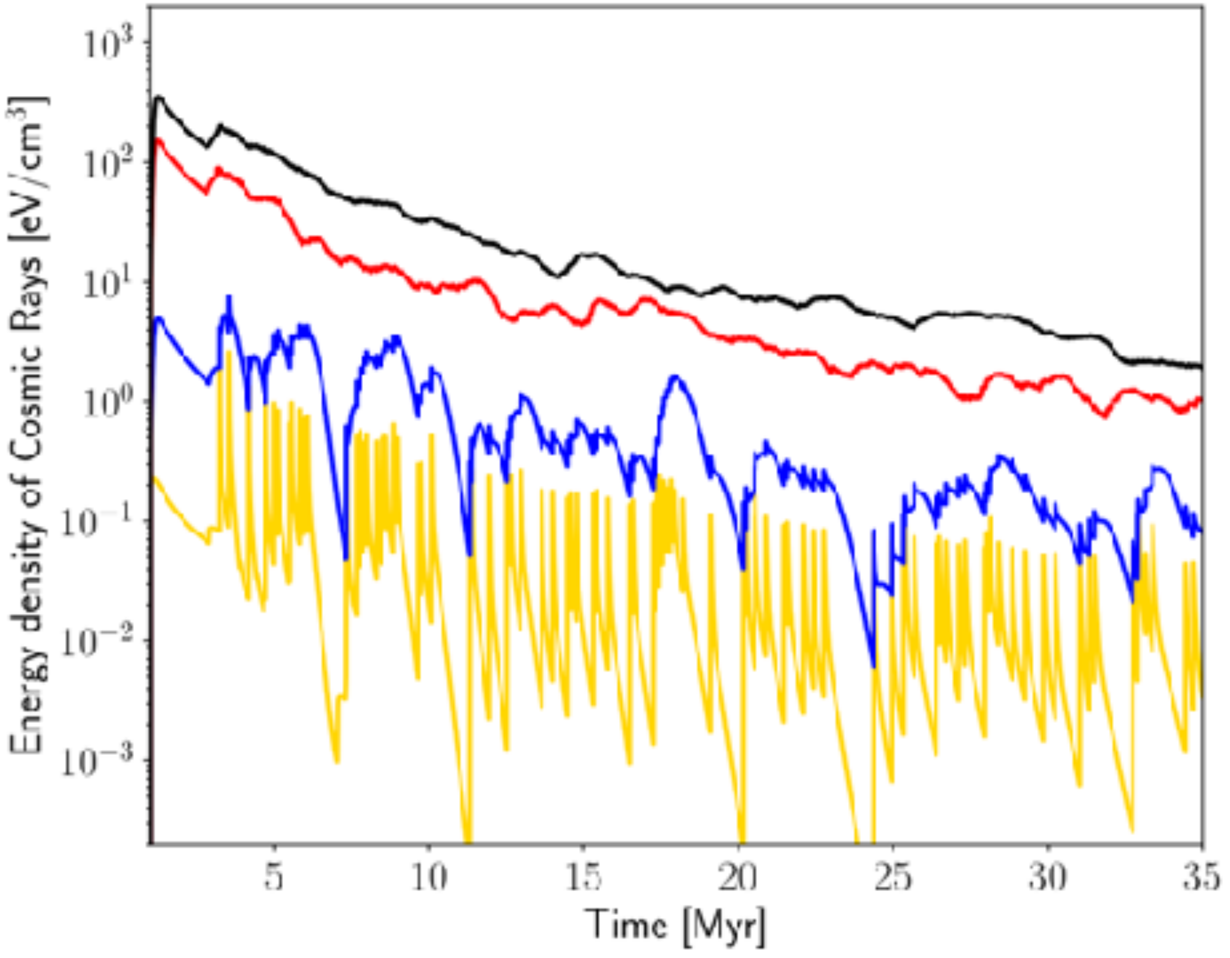


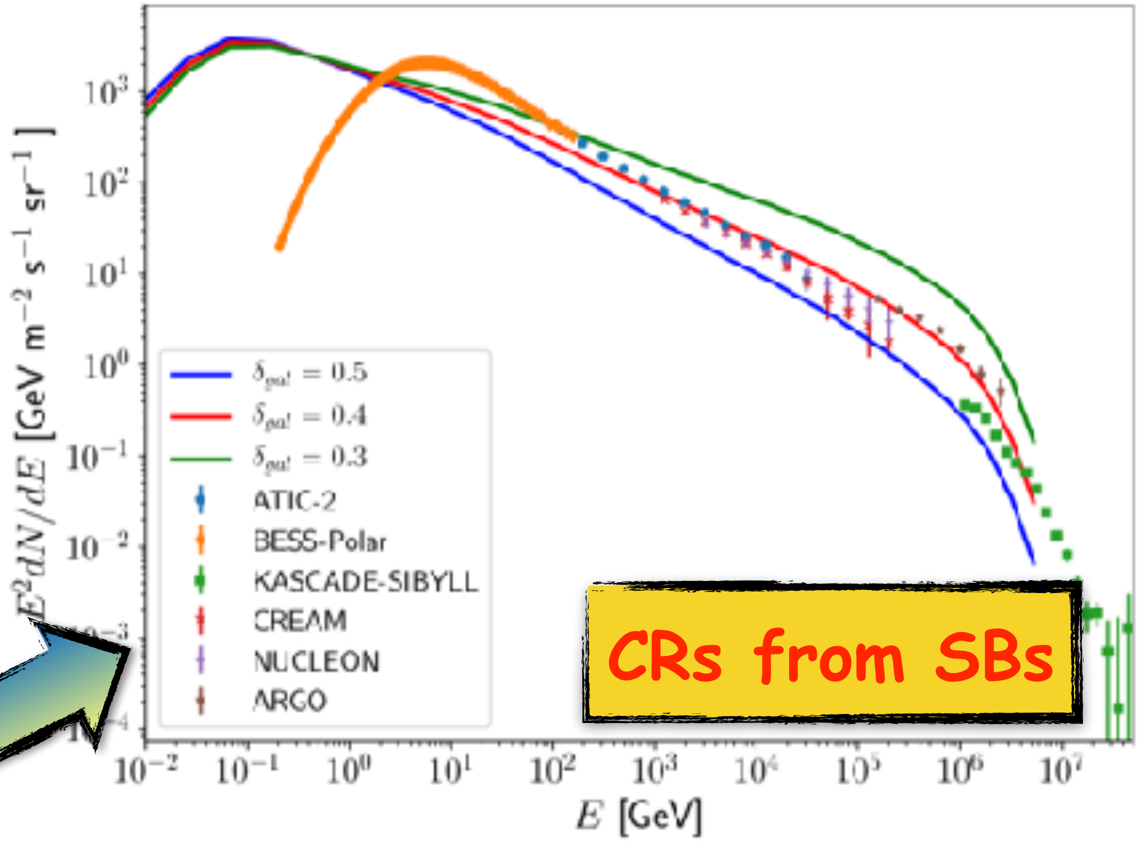
# of stars —>

Vieu+ 2022

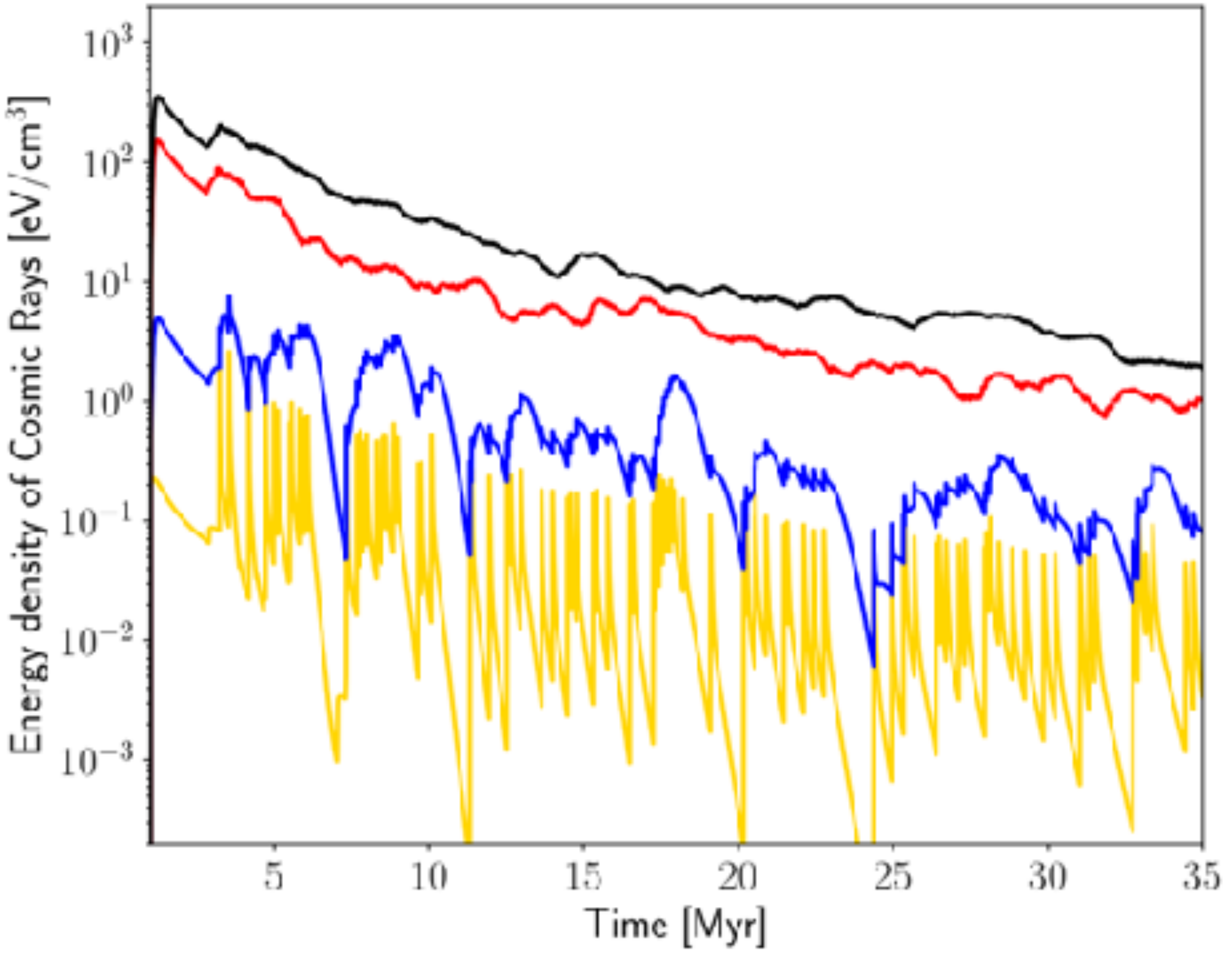
SNR crisis? Pos

3) PeV-SNR —> Pe

superbubbles, star clusters, binaries, co



CRs from SBs



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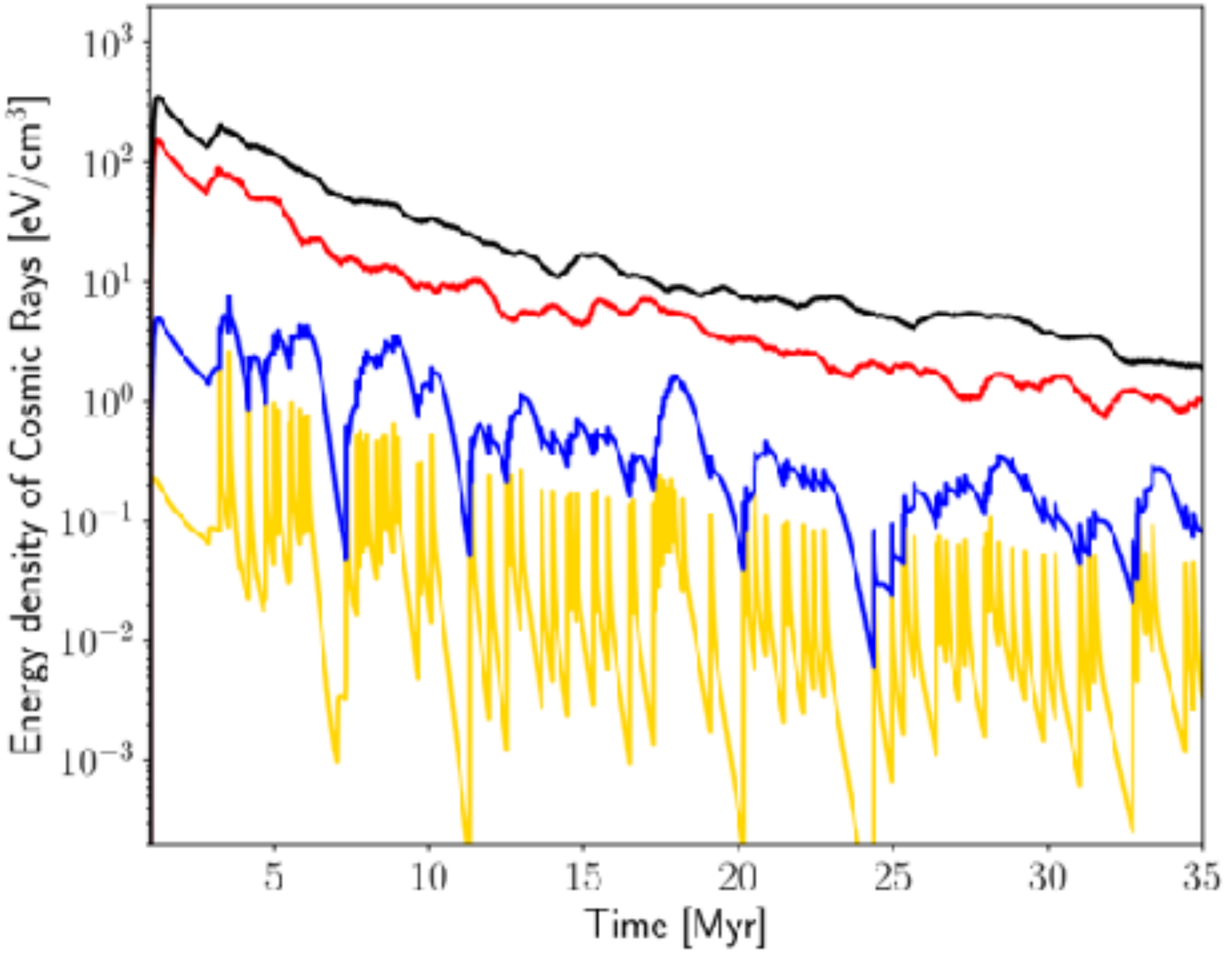

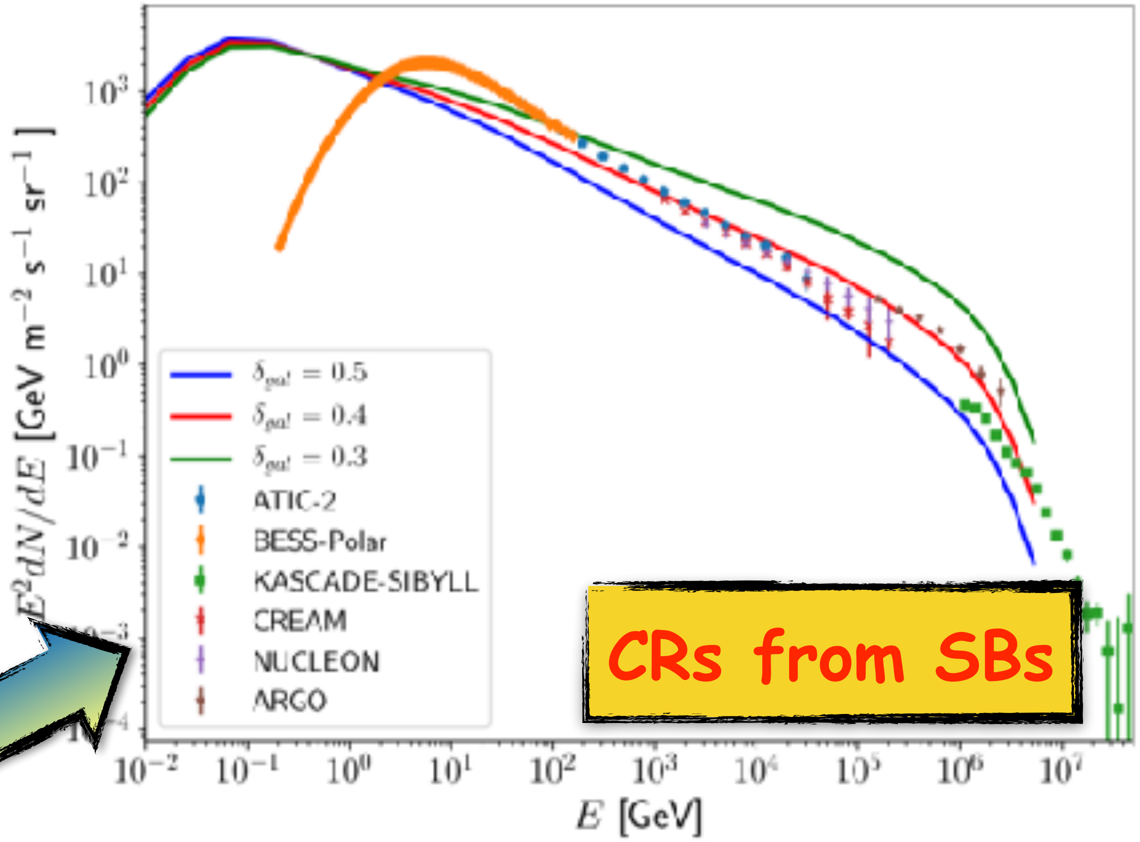

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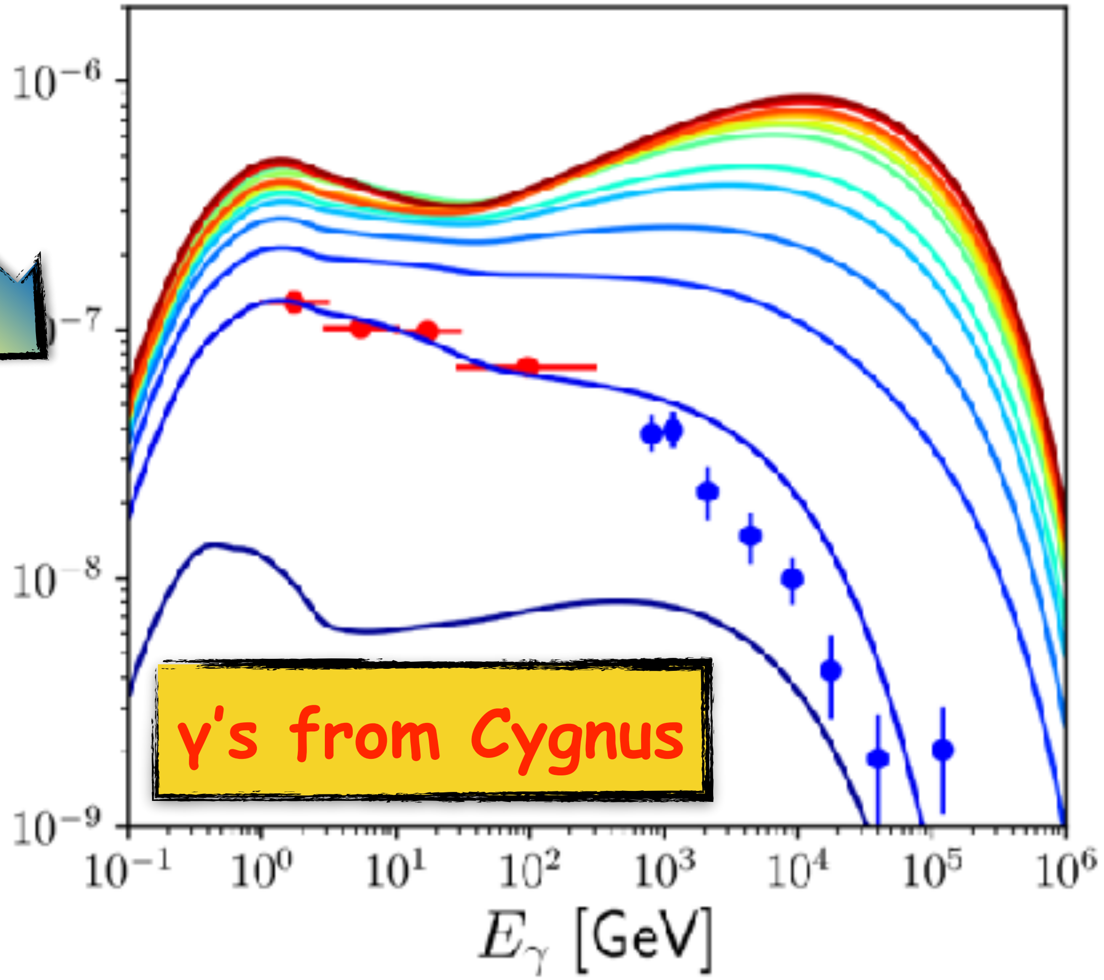
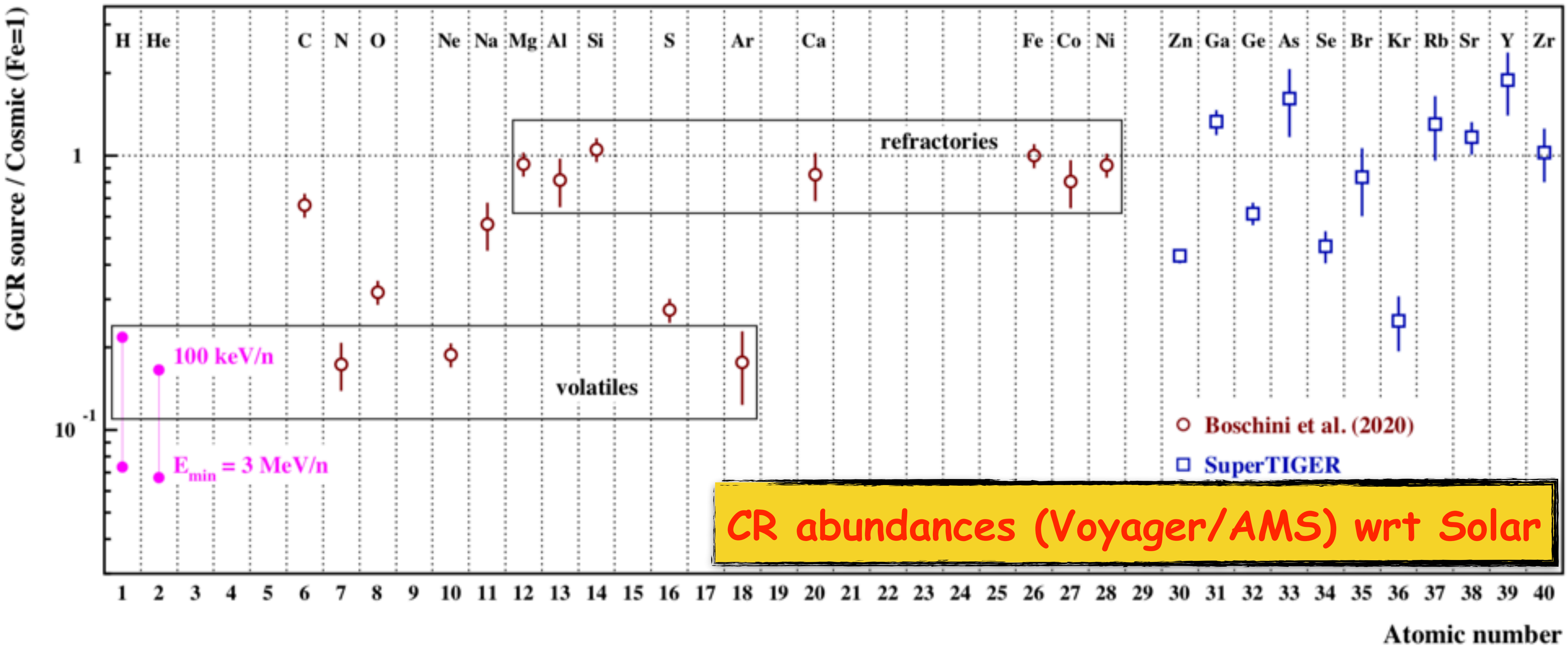


Vieu+ 2022

Low energy CRs: can they help?

yes



CR abundances (Voyager/AMS) wrt Solar

Tatischeff+ 2021

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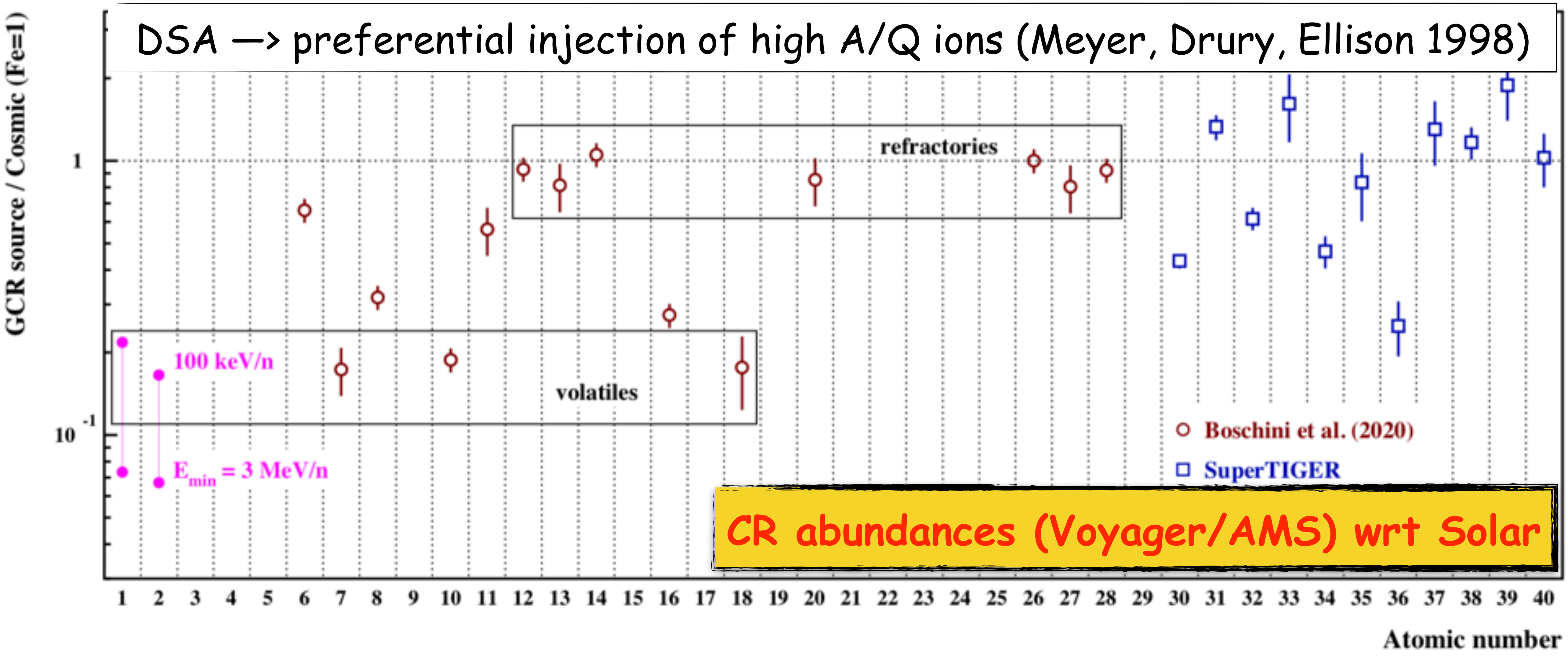

DSA —> preferential injection of high A/Q ions (Meyer, Drury, Ellison 1998)

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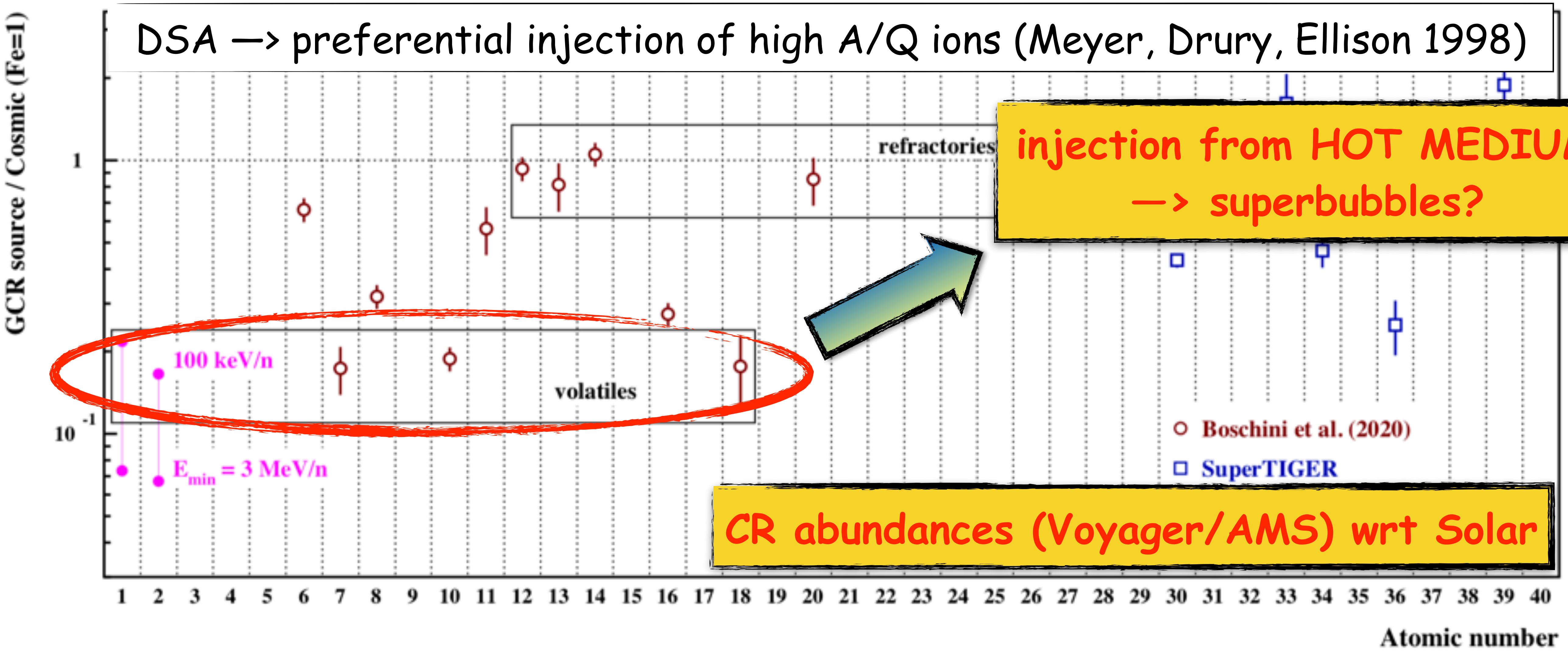

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injection from HOT MEDIUM
—> superbubbles?

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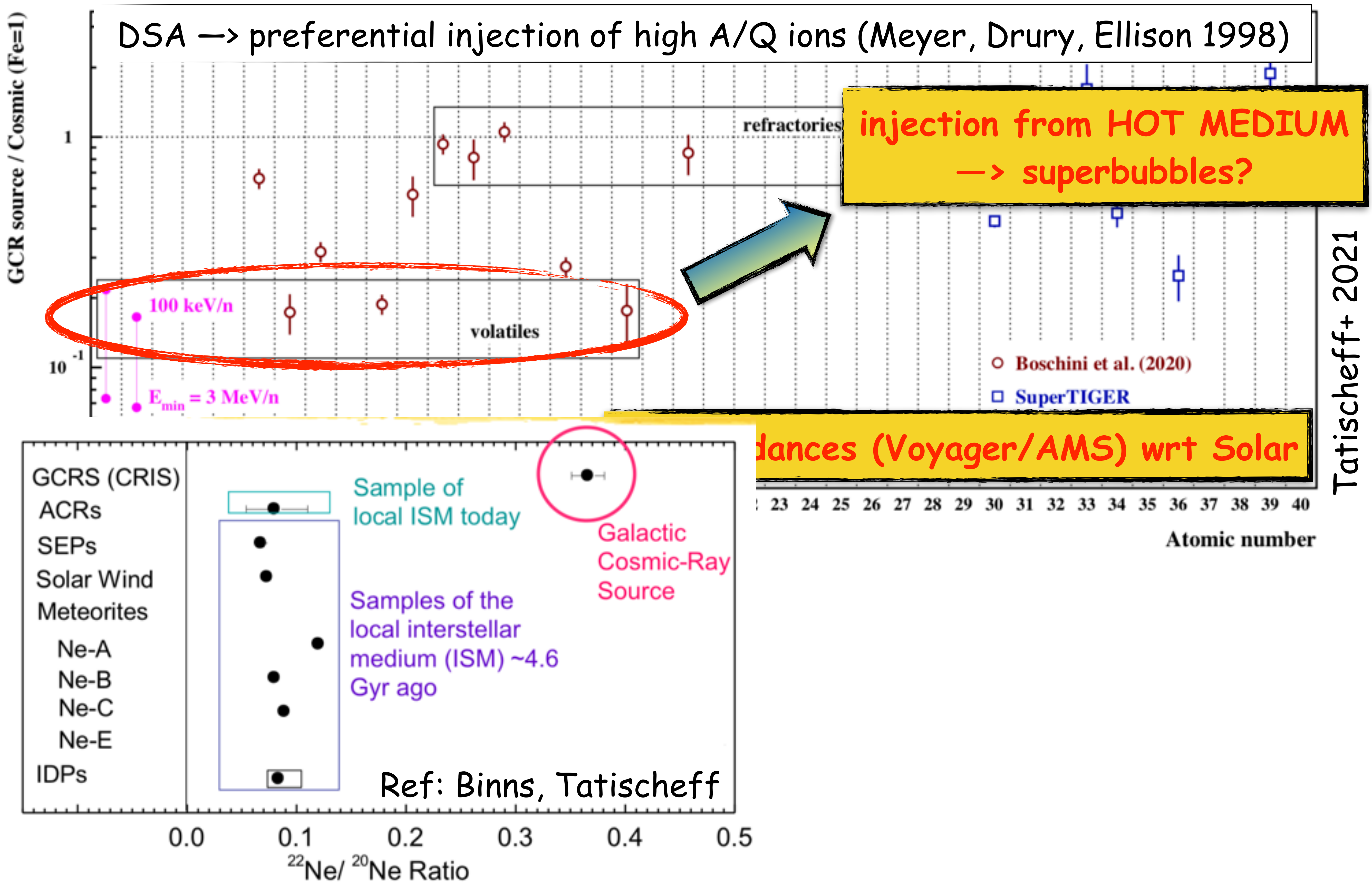

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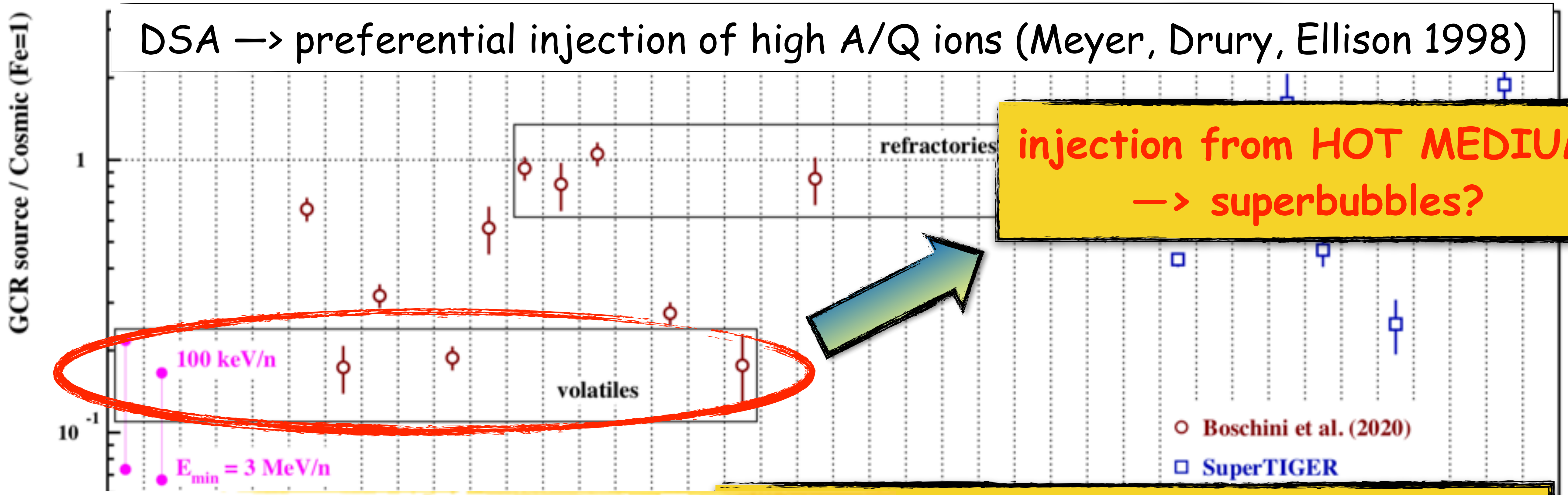
Ref: Binns, Tatischeff

Low energy CRs: can they help?

yes

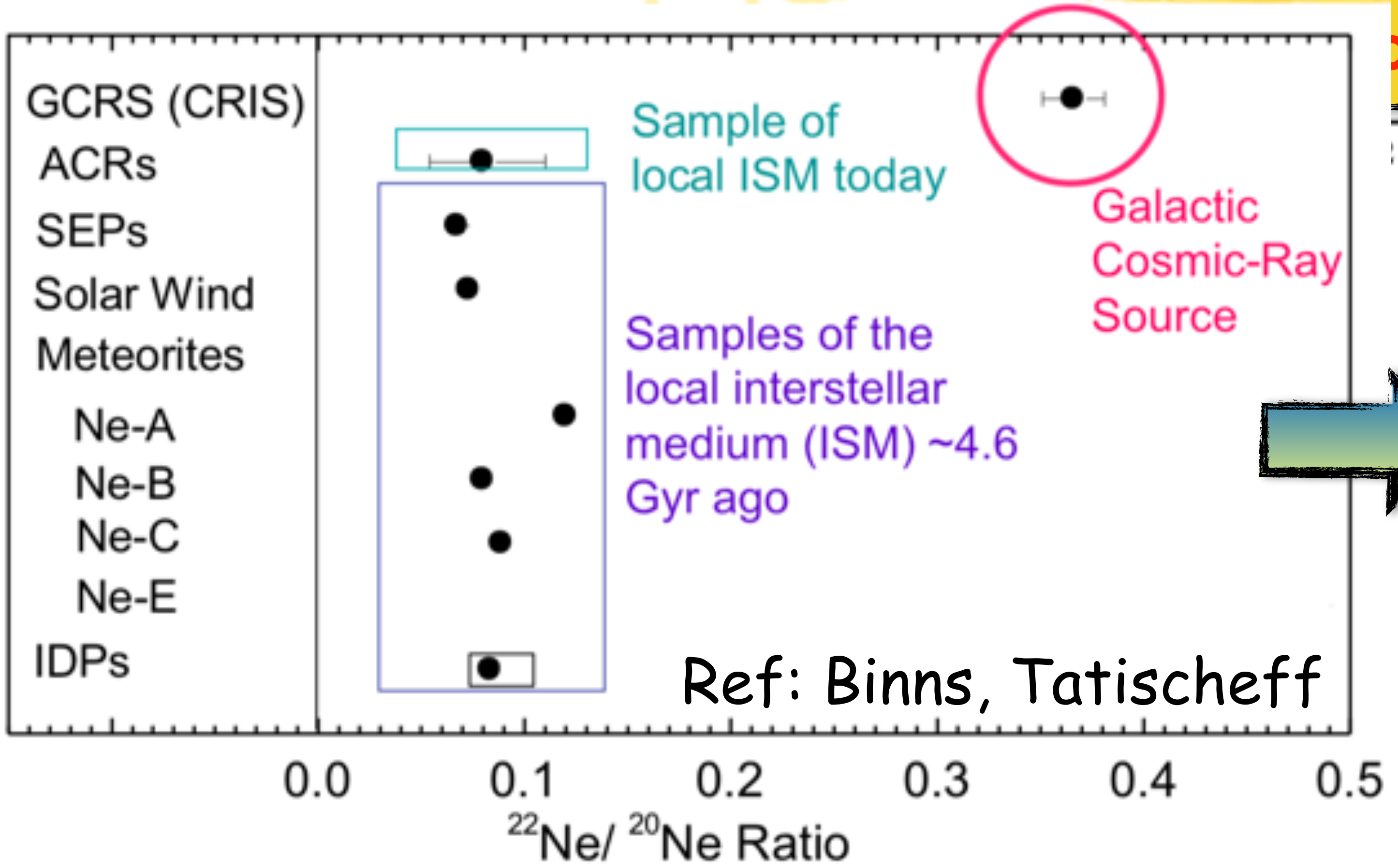
DSA —> preferential injection of high A/Q ions (Meyer, Drury, Ellison 1998)



injection from HOT MEDIUM —> superbubbles?

dances (Voyager/AMS) wrt Solar

Tatischeff+ 2021



Ref: Binns, Tatischeff

~5-10% of CRs from wind termination shocks of WR stars —> star clusters?

Conclusions

- We still don't know where PeV cosmic ray protons are accelerated
- There is a PeVatron in the GC: what is it? Do we observe CRs coming from it?
- Acceleration of PeV protons at SNR shocks is quite problematic
- Observation of PeV protons at (or near) SNR shocks is also problematic
- What should we do?
  - Hunt for VERY YOUNG supernovae (gamma ray astronomy)
  - Boost B-field (plasma physics)
  - Understand better CR escape
  - Explore for alternative scenarios (theoretical/observational astrophysics)
  - Do not ignore hints from low energies (e.g. abundances, isotopic ratios, etc.)