Who accelerates Galactic cosmic rays?

Stefano Gabici
APC, Paris

Disclaimer

This talk will be (intendedly) quite **critical** towards the **supernova remnant paradigm for the origin of Galactic cosmic rays** (the orthodoxy). Most of the stuff that will follow has been discussed in these review articles (where you'll find plenty of references):

- SG, Low energy cosmic rays, A&A Rev (2022) -> **Low energy CRs (< GeV)**
- SG, Evoli, Gaggero, Lipari, Mertsch, Orlando, Strong, Vittino, The origin of Galactic cosmic rays: Challenges to the standard paradigm, Int. J. Mod. Phys. D (2019) -> **high energy CRs (> GeV)**
- Tatischeff & SG, Particle Acceleration by Supernova Shocks and Spallogenic Nucleosynthesis of Light Elements, Ann. Rev. Nucl. Part. Sci. (2018) -> **LiBeB**

A classic set of questions on Galactic cosmic rays

[1] **Which classes of sources** contribute to the CR flux in different energy ranges? How many types of sources provide a significant contribution to the overall CR flux?

[2] Are CR **nuclei and electrons** accelerated by the same sources?

[3] Which sources are capable of reaching the **highest particle energies** and how?

[4] Which are the processes responsible for **CR confinement in the Galaxy**?

[5] Where is the **transition between Galactic and extra-Galactic CRs** and how can we explain the well-known features such as knee, second knee, ankle?

[6] What is the origin of the difference between the **chemical composition of CRs** and the solar one?

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I will not discuss a (growing) number of issues emerging from recent observations

- breaks in the spectrum
- H and He spectra are different!
- small spatial gradient of CRs
- spectral hardening towards the Gal centre
- very low level of anisotropy, phase points away from GC(<100 TeV)
- origin of small scale anisotropies
- etc etc etc…

explaining all these things is problematic for ANY scenario

The orthodoxy (1)

- The bulk of the energy of cosmic rays originates from supernova explosions in the Galactic disk

The orthodoxy (1)

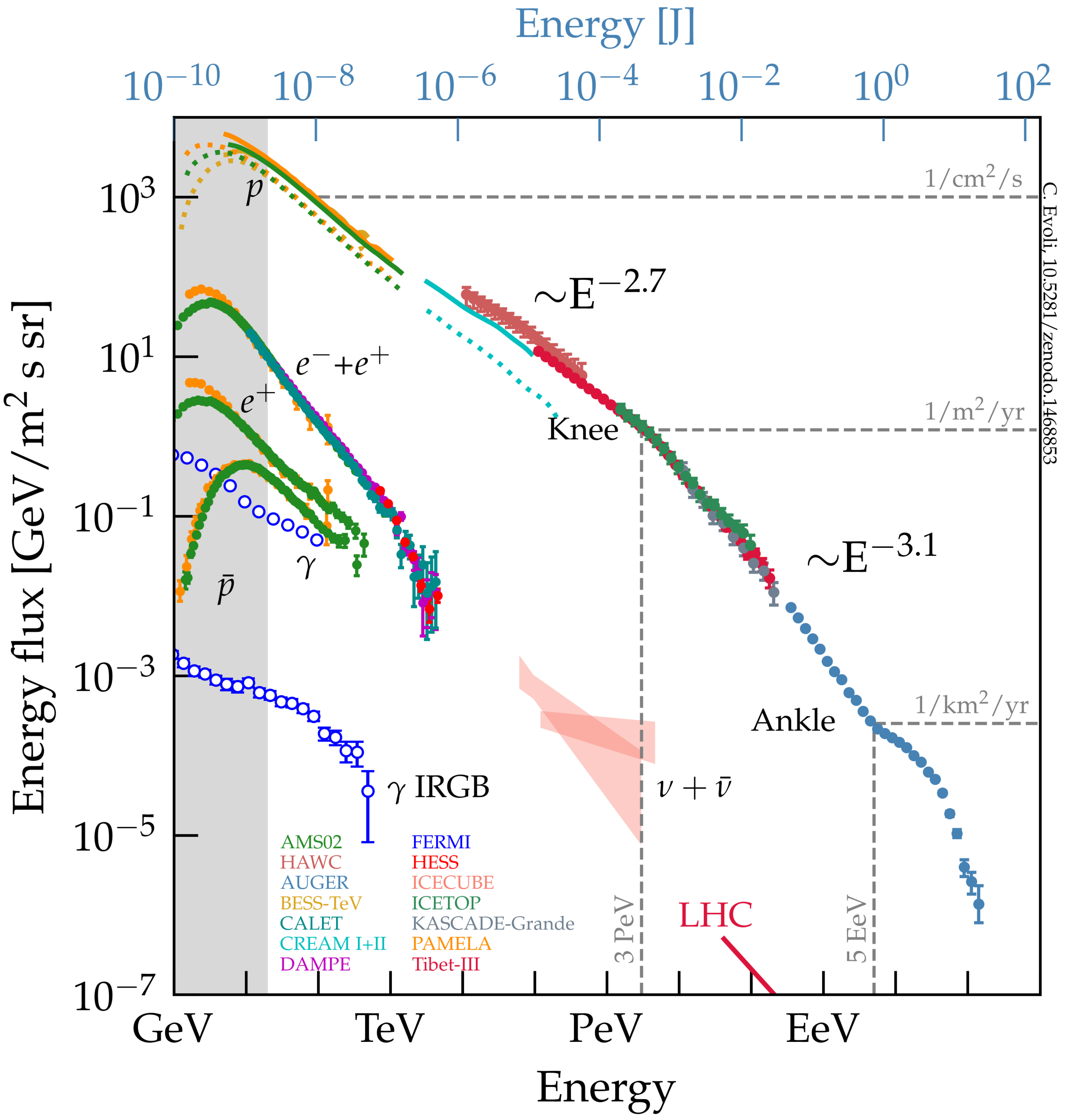
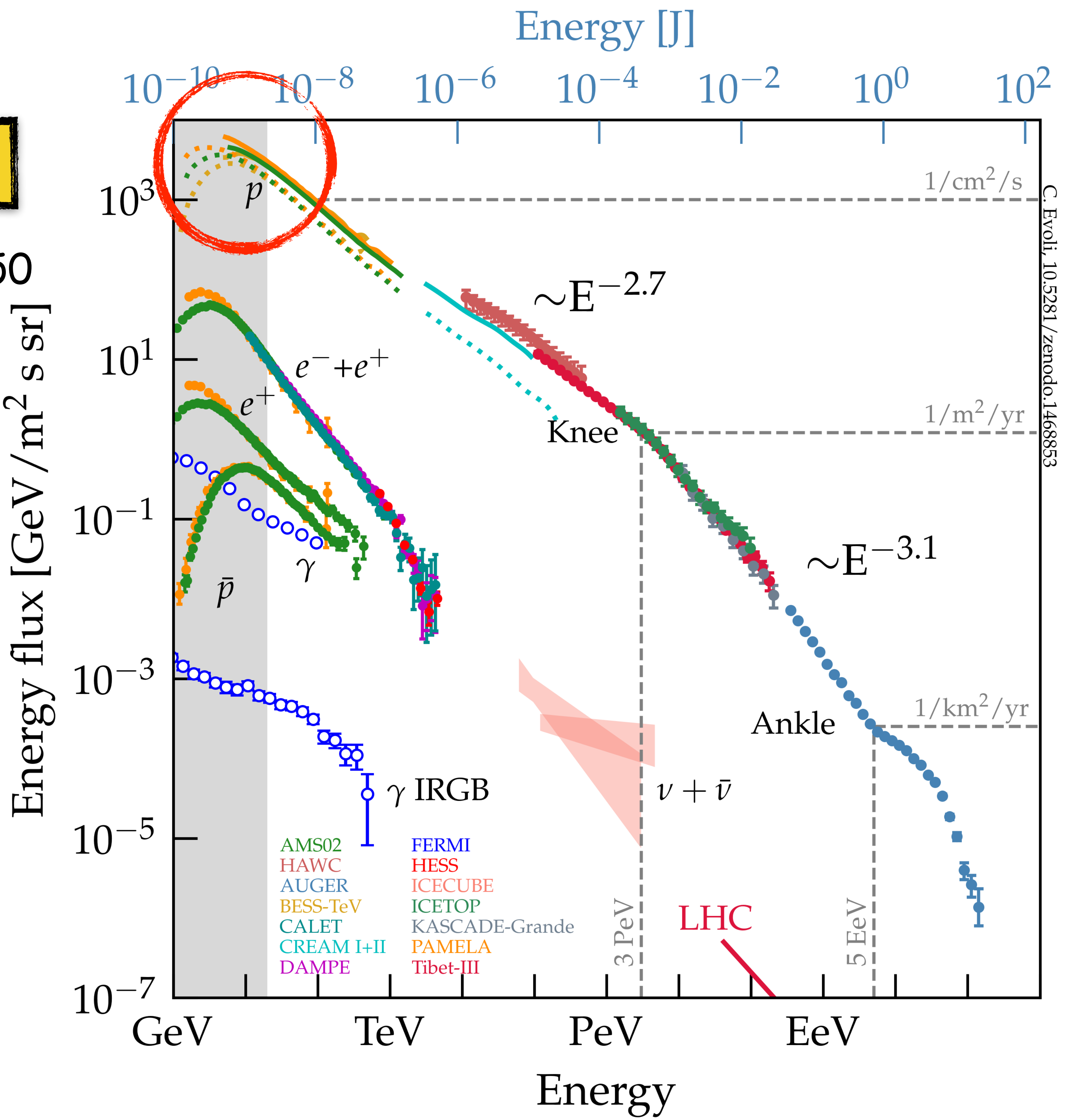


Fig. from Evoli 2018

The orthodoxy (1)

energetics

ter Haar 1950



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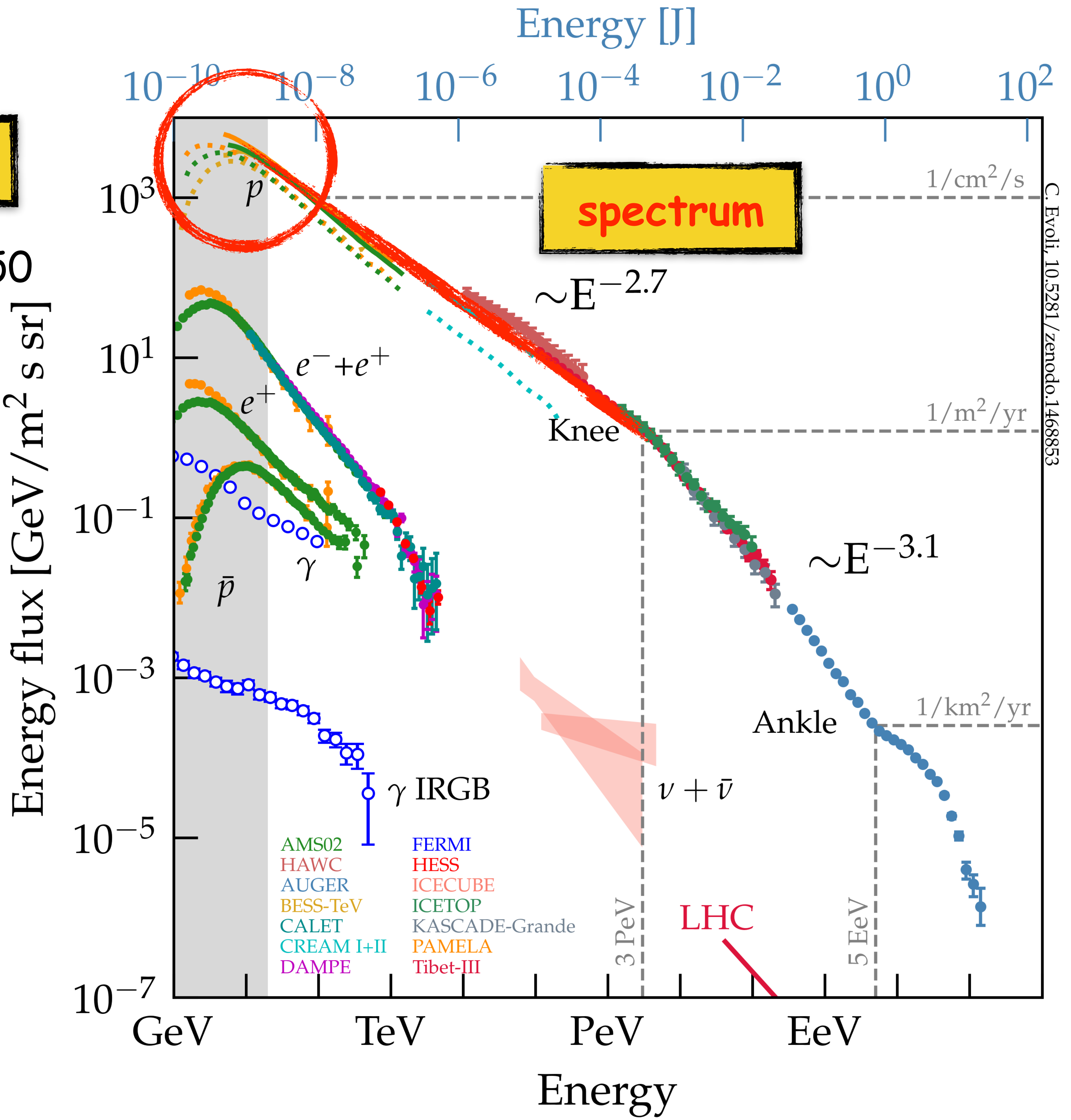

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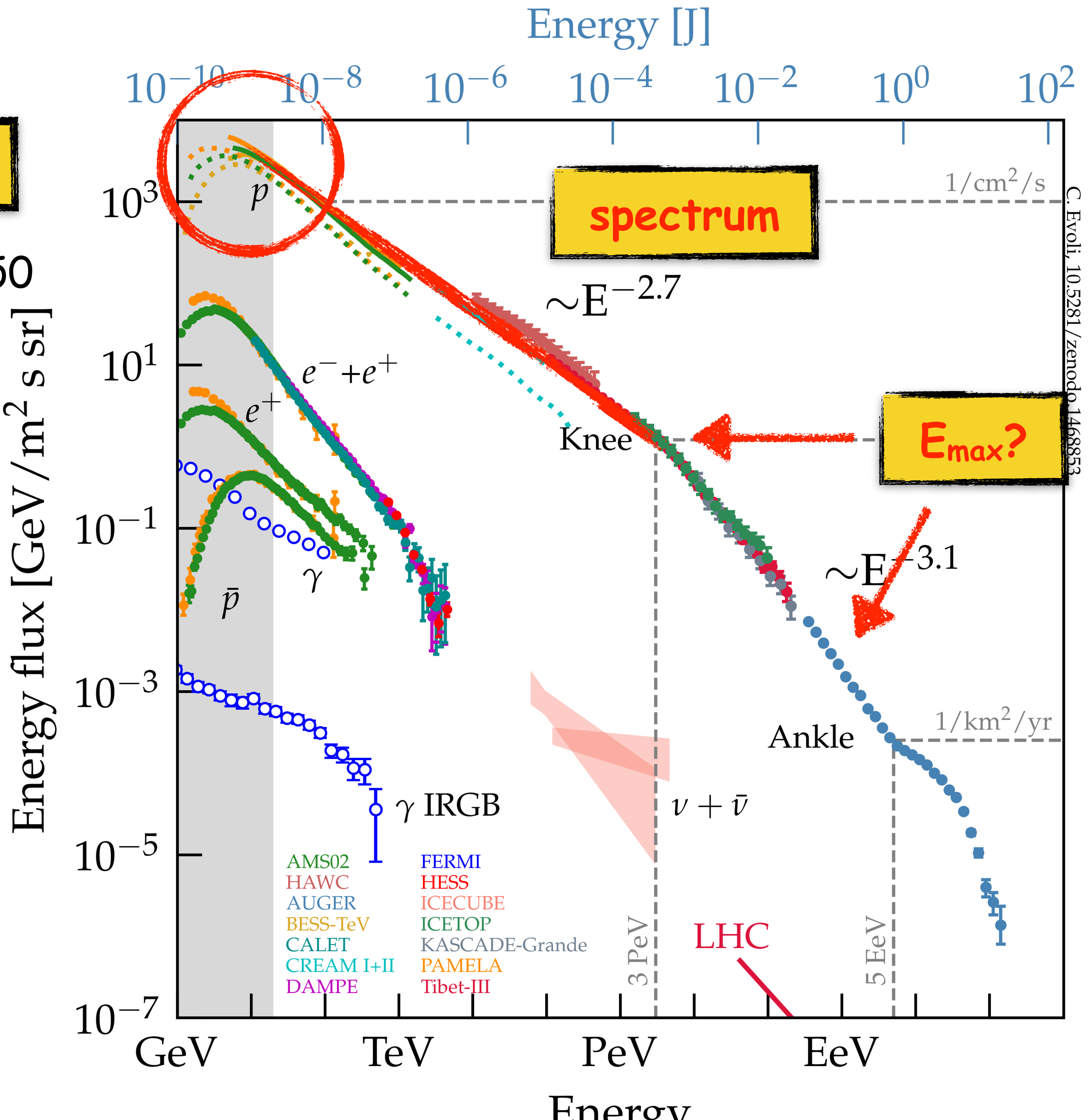

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E_{max}?

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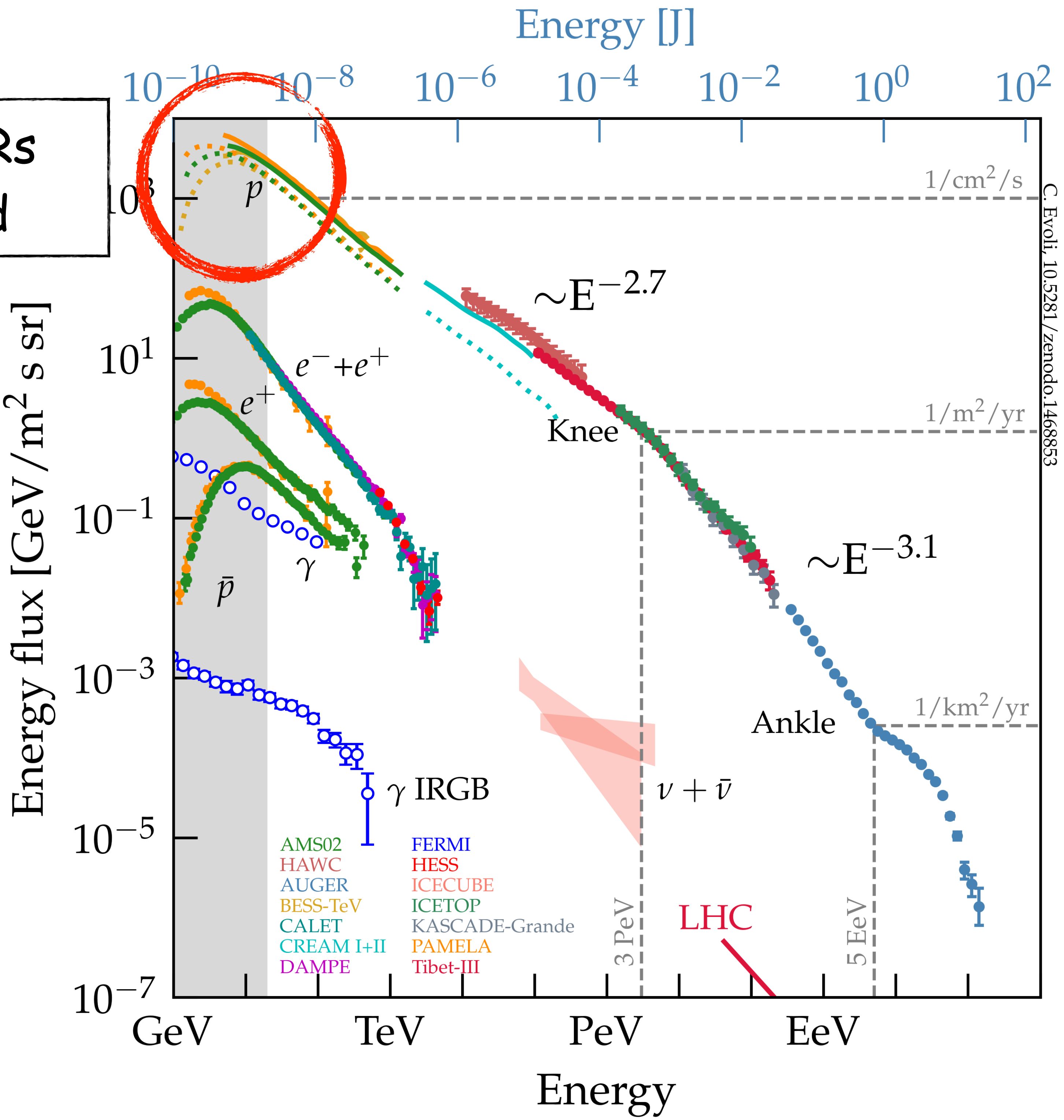
Note on energetic

what about PeV SNR?

this is why SNRs were proposed



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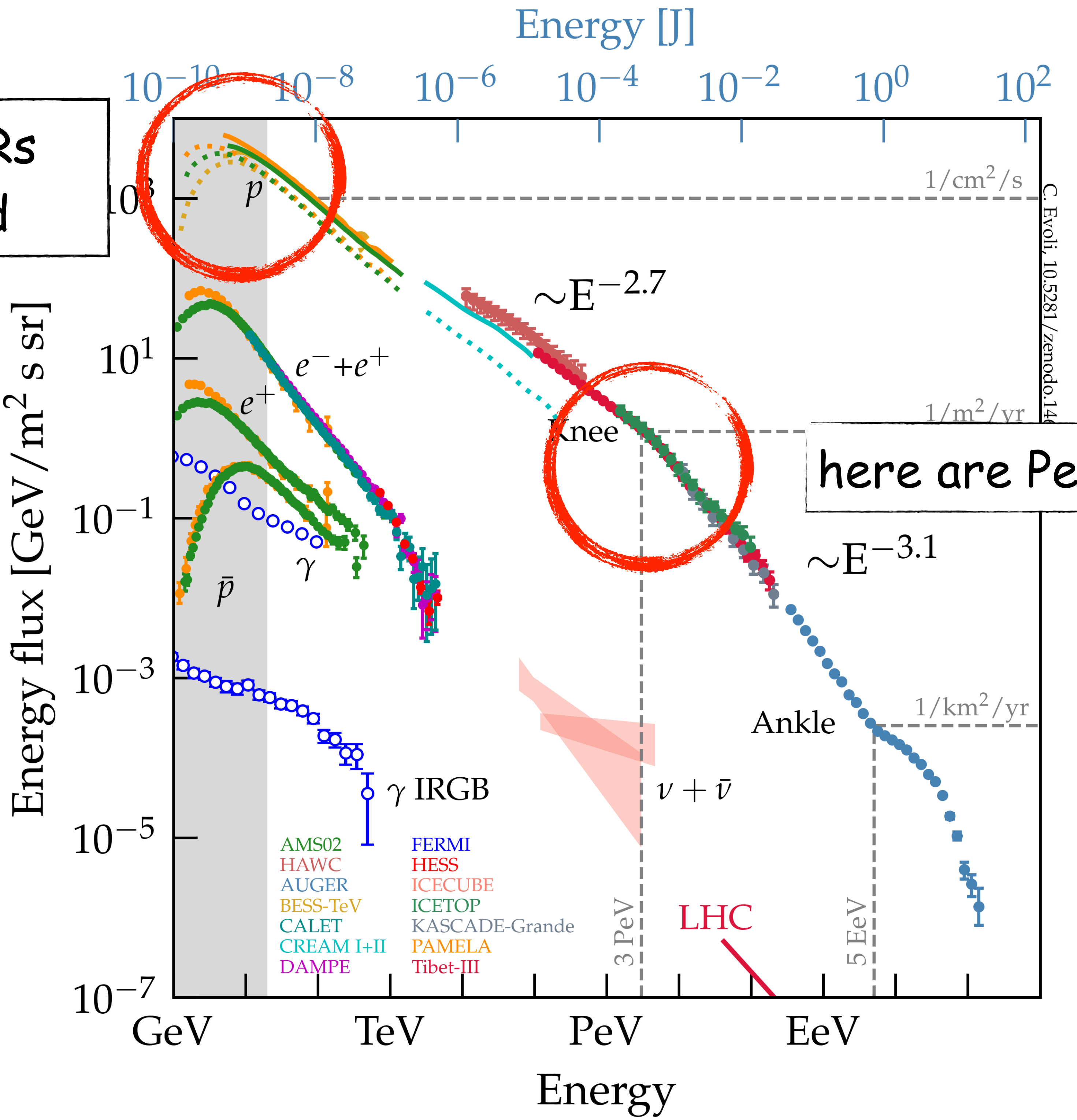

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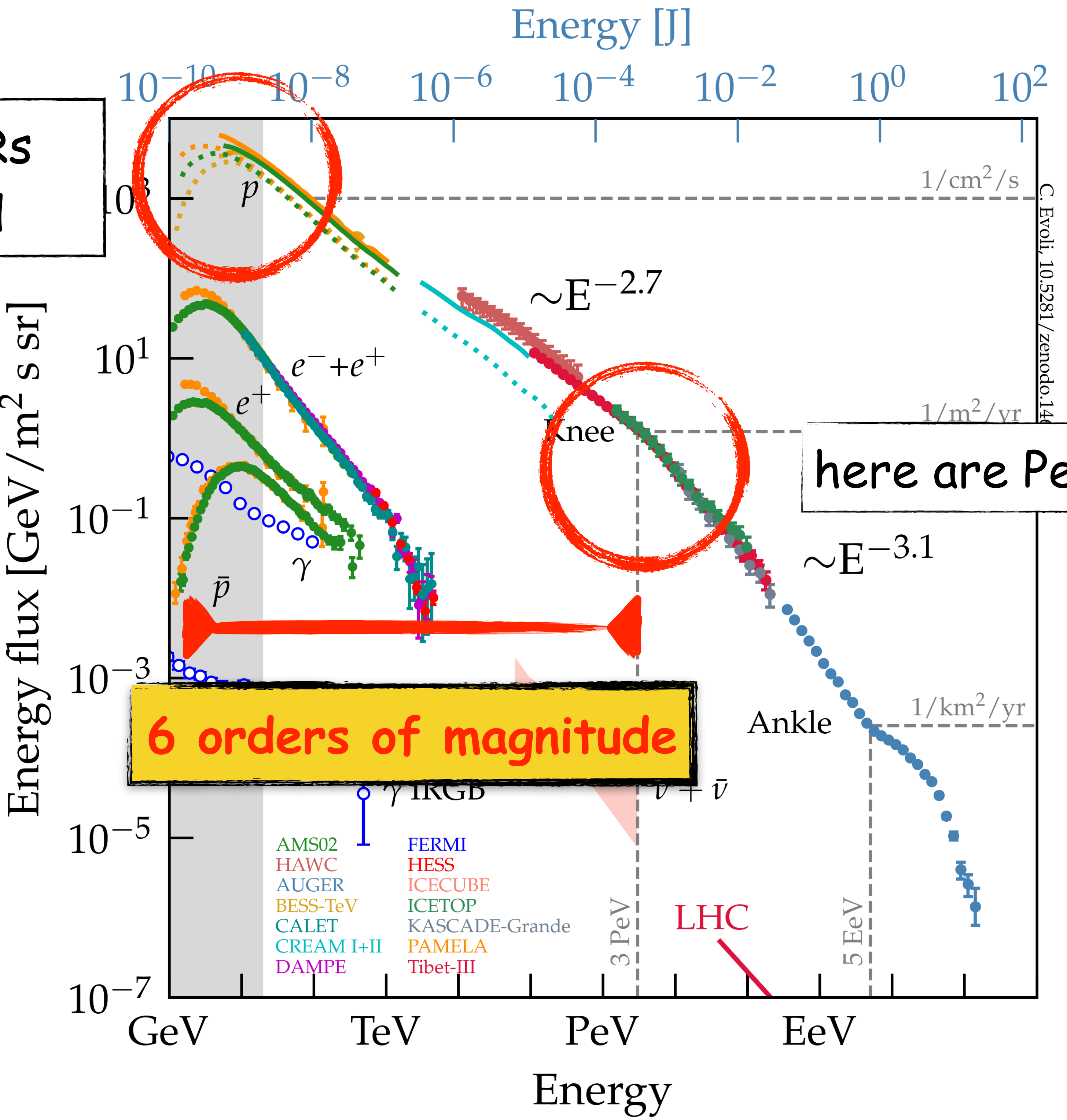

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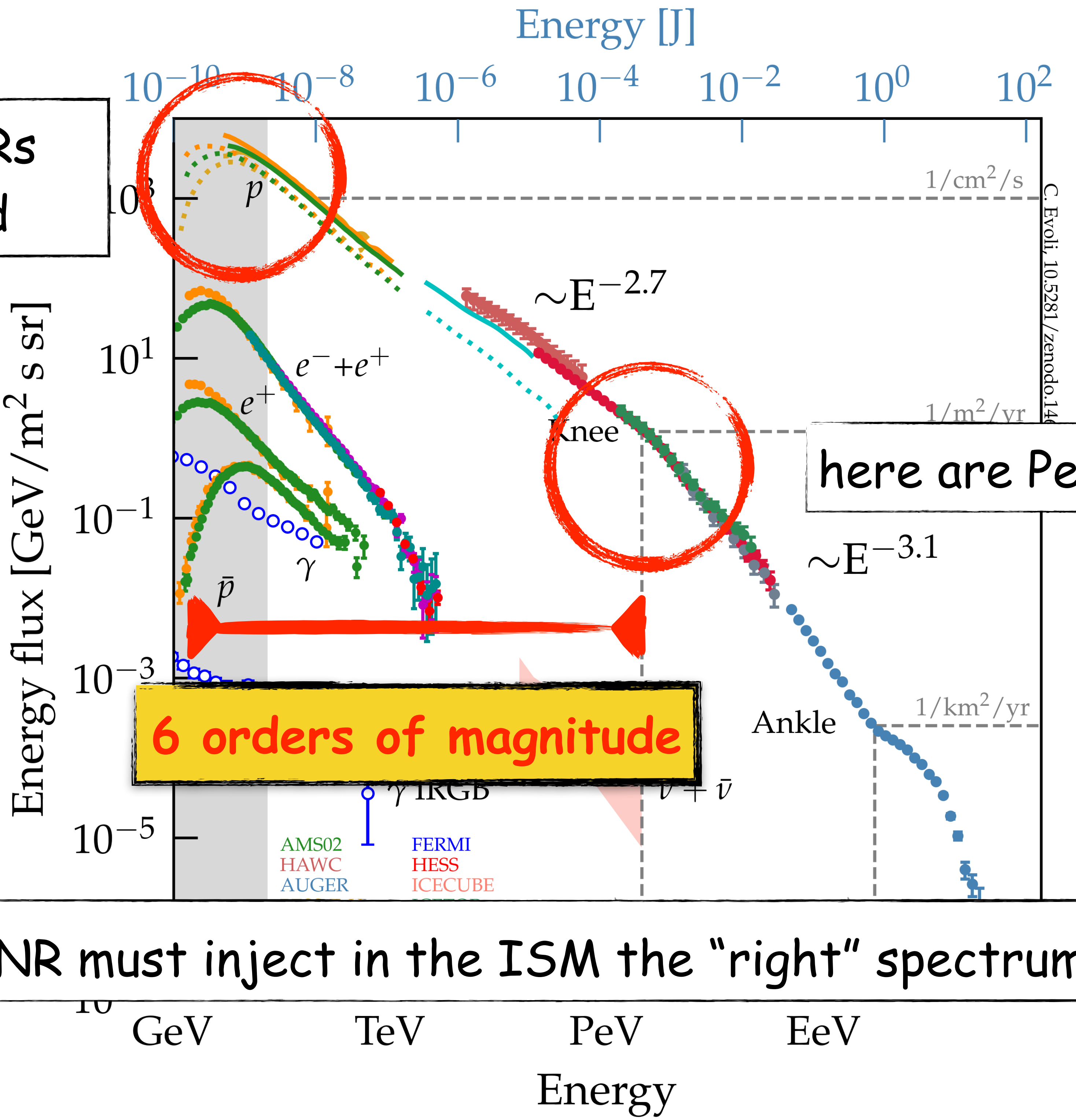

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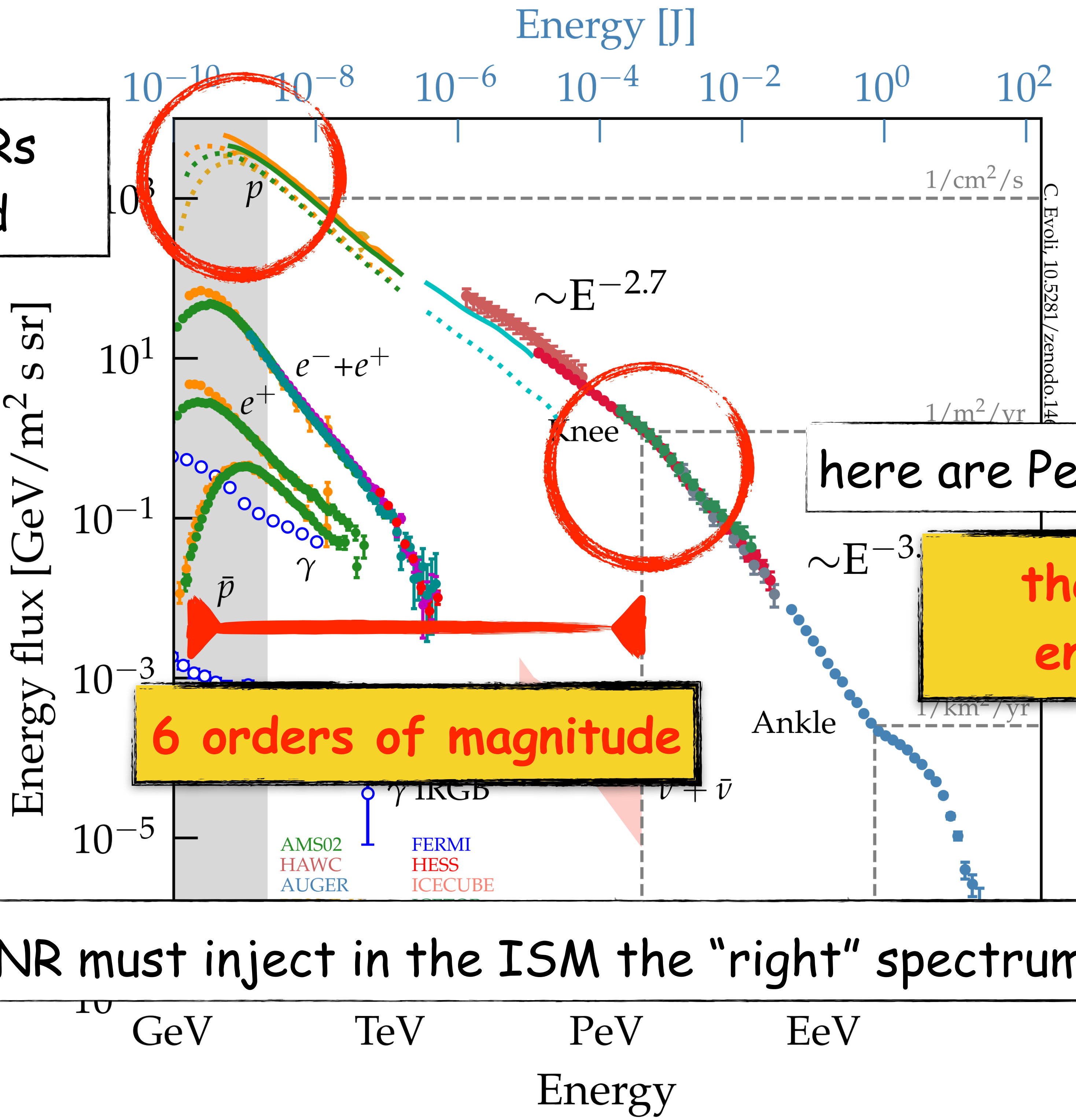

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here are PeV particles

there is little energy here!

6 orders of magnitude

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The orthodoxy (2)

- Cosmic rays are diffusively confined within an extended and magnetised Galactic halo

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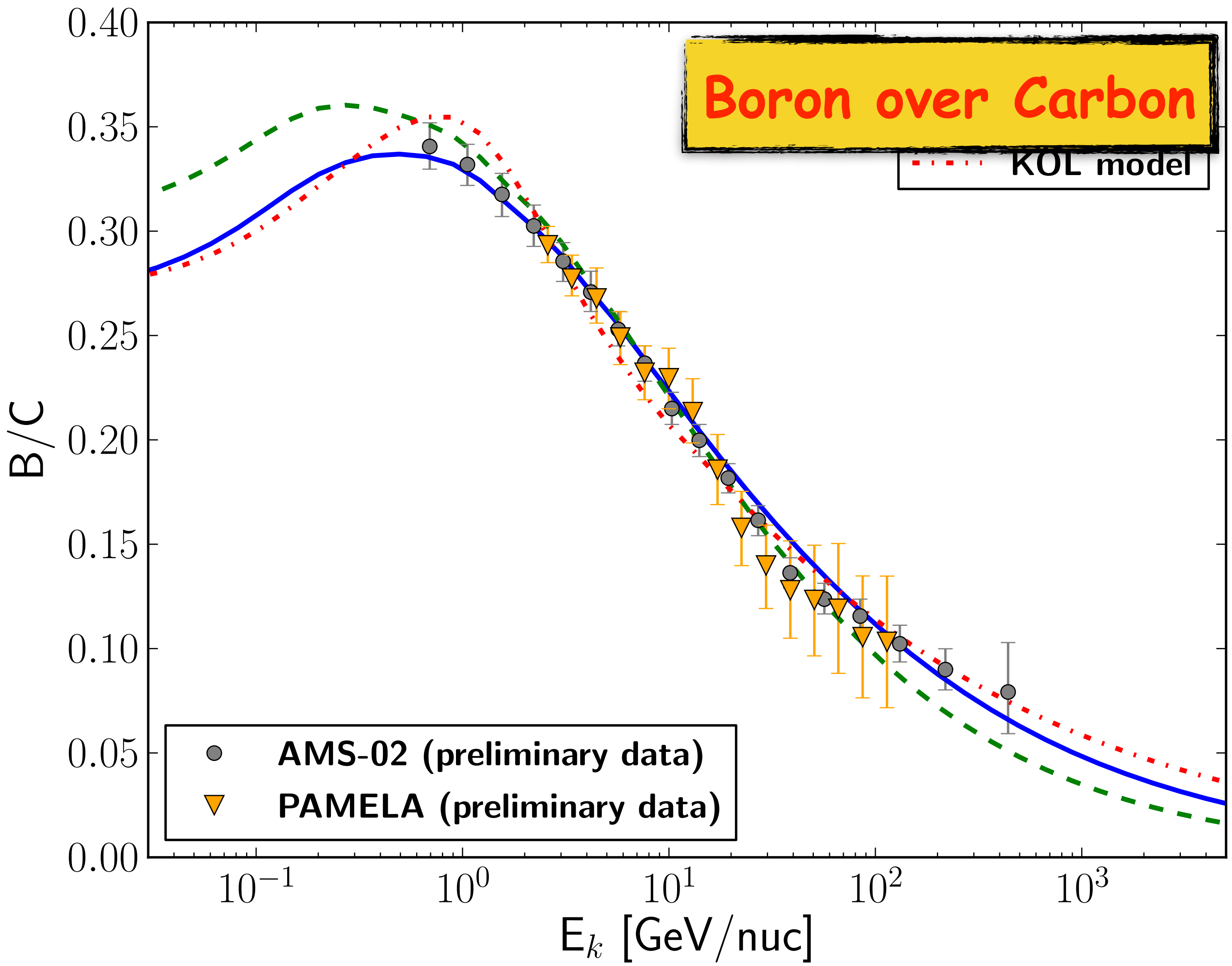

Boron over Carbon

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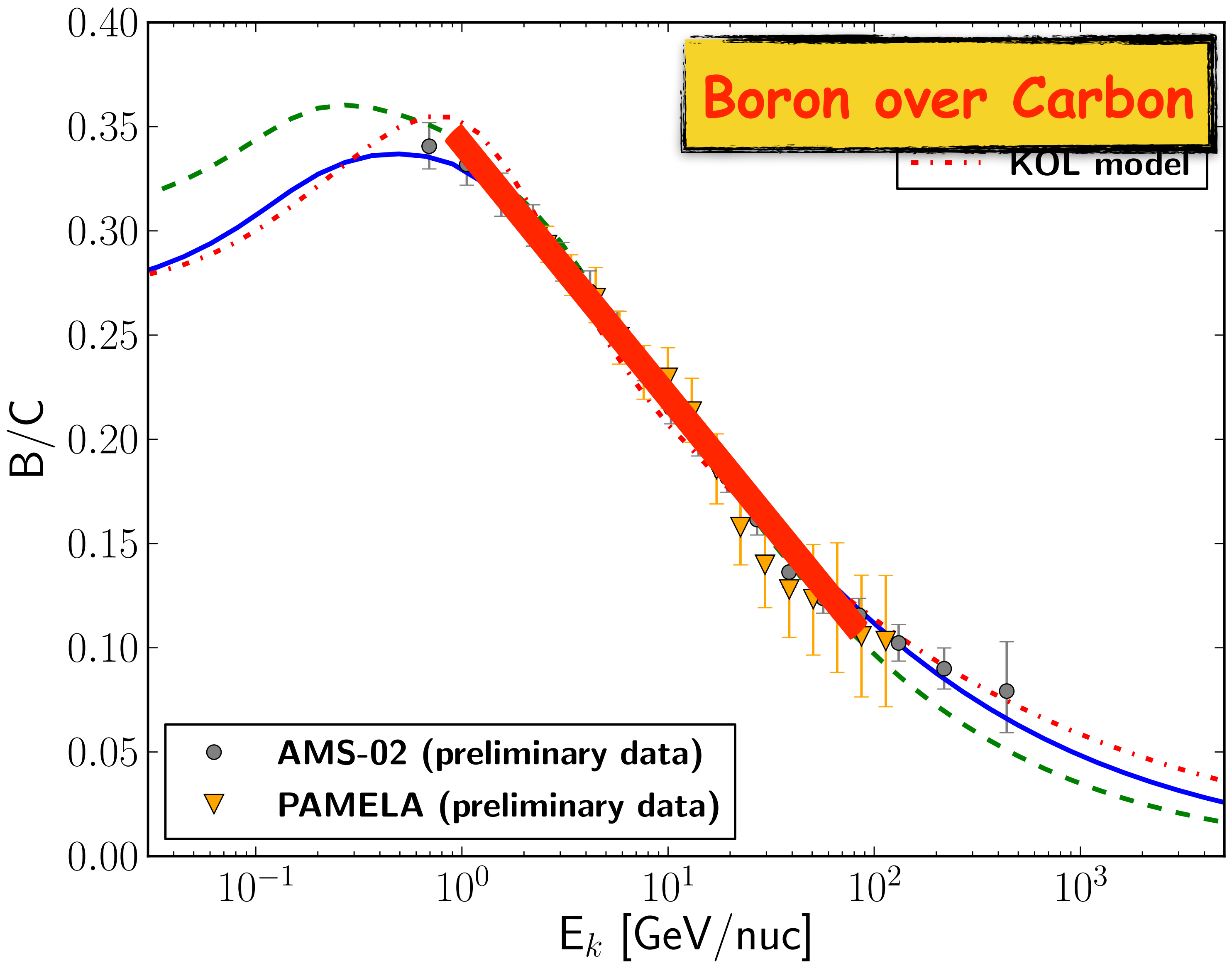

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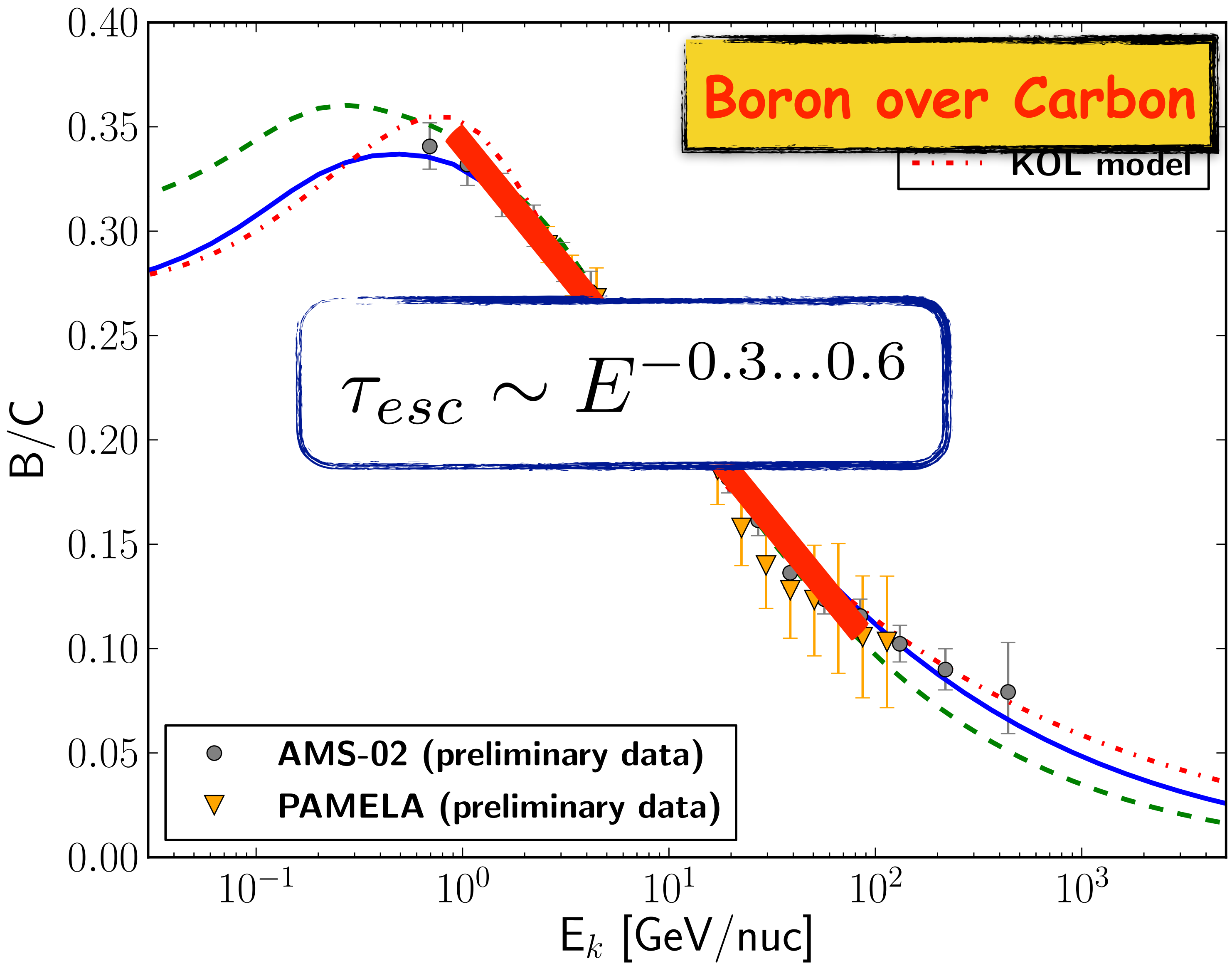

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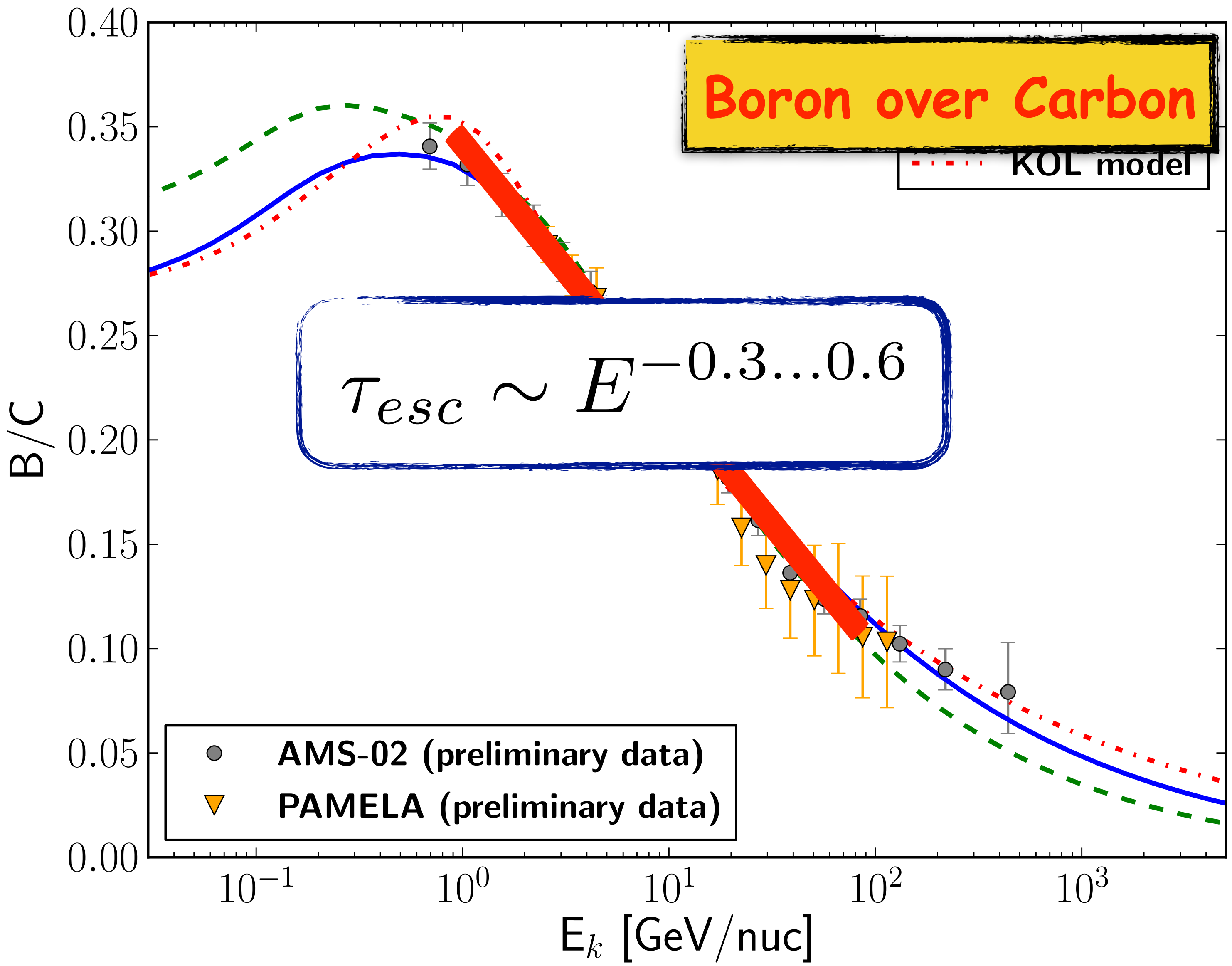

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observed spectrum

injected spectrum

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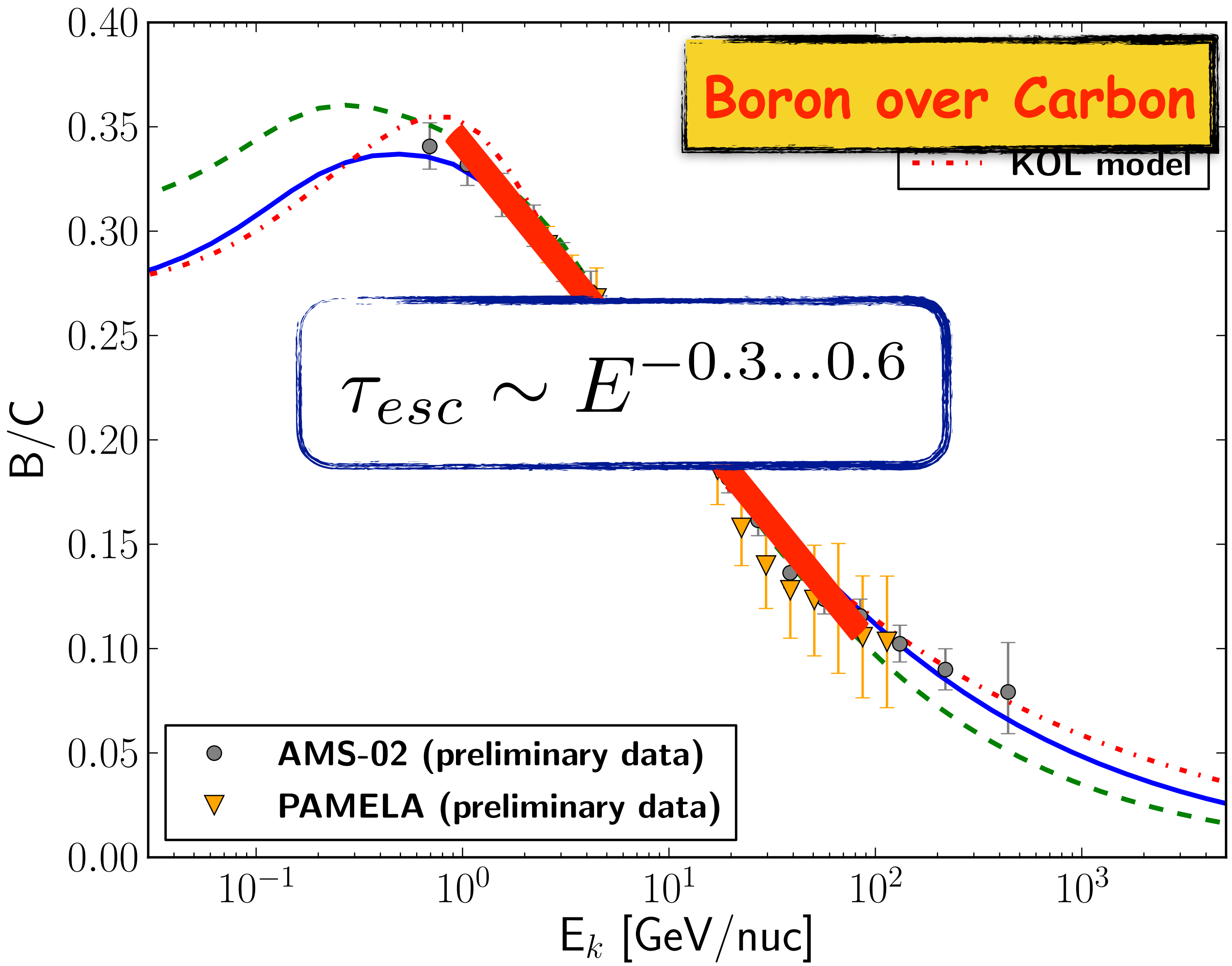

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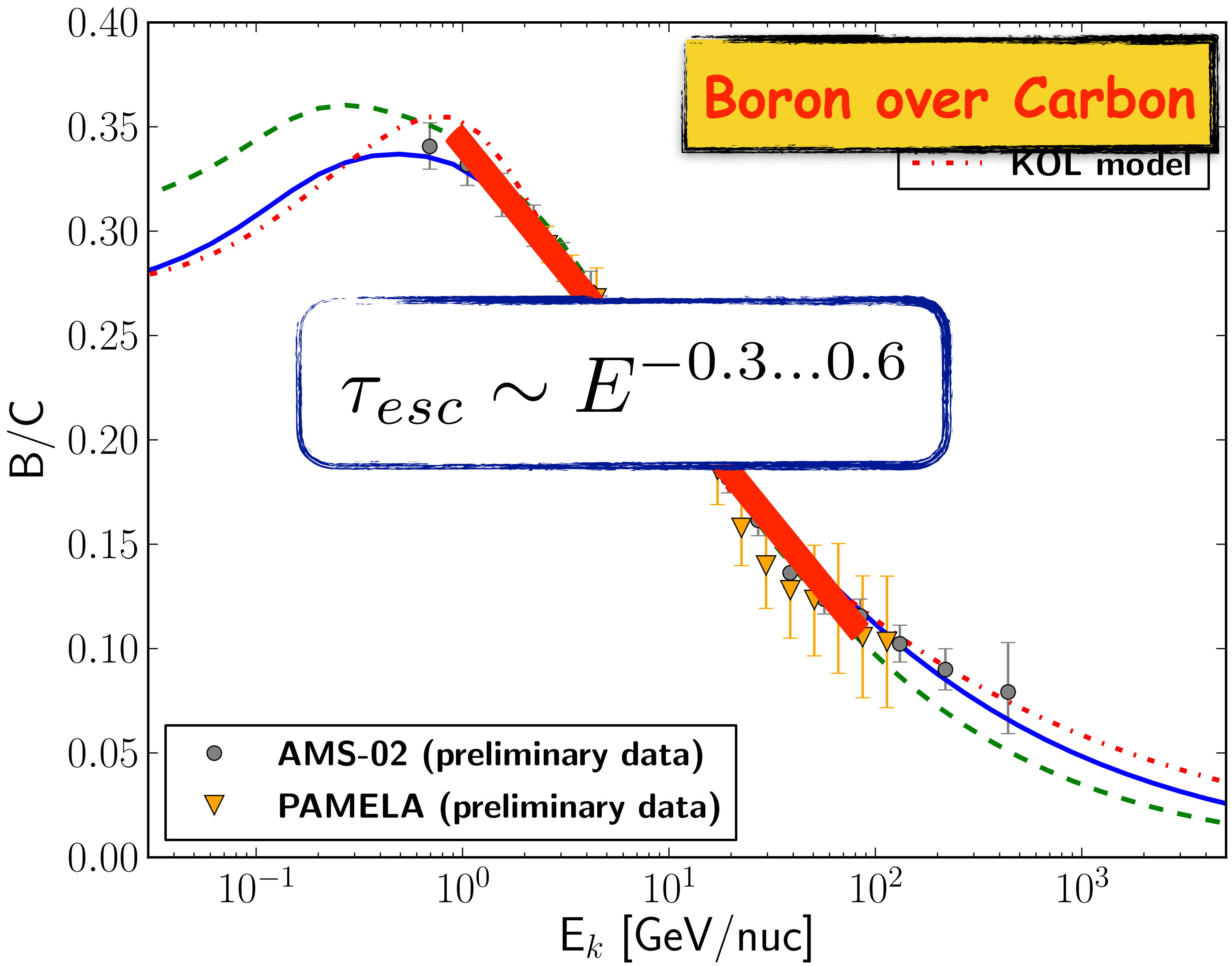

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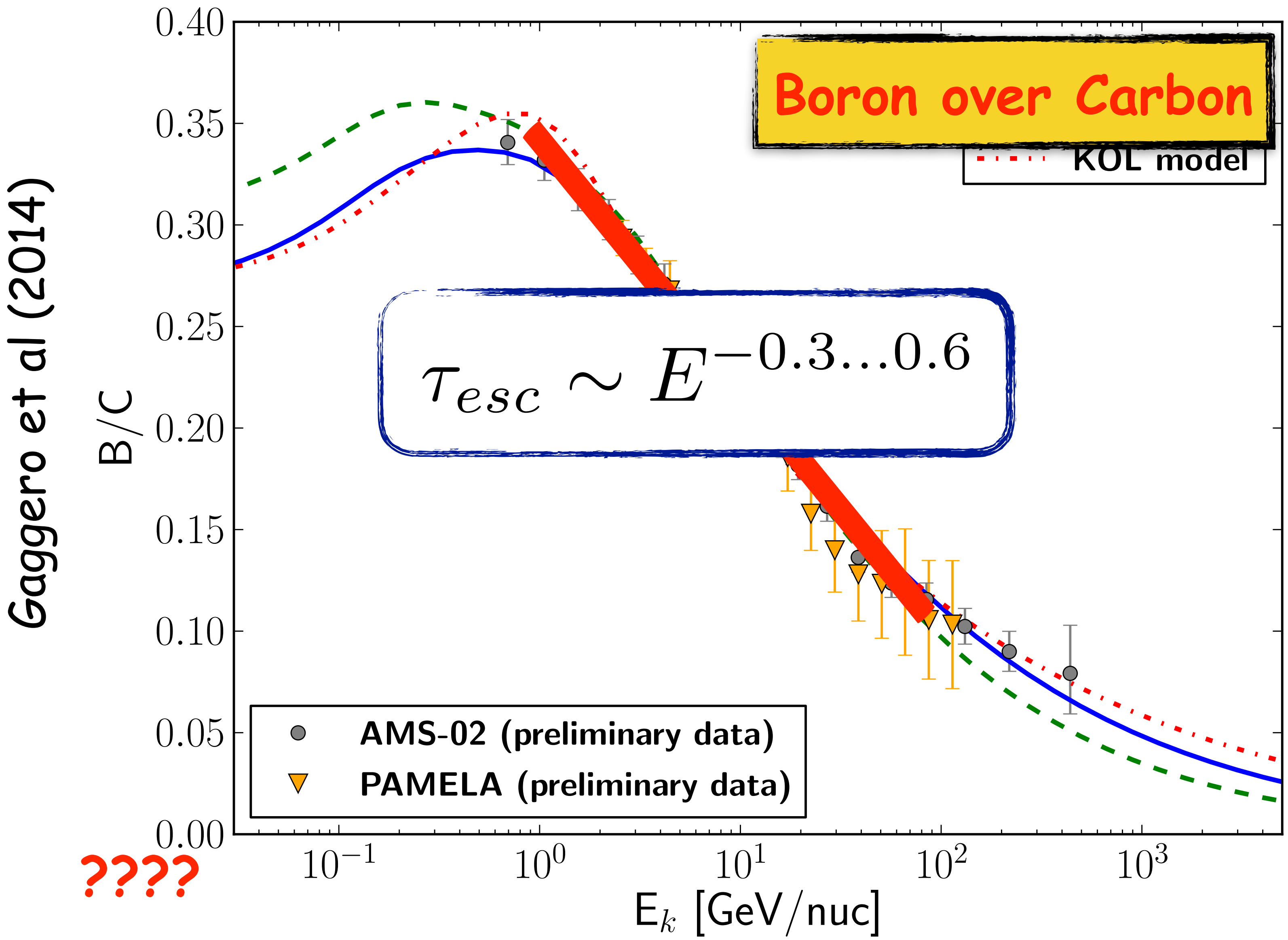

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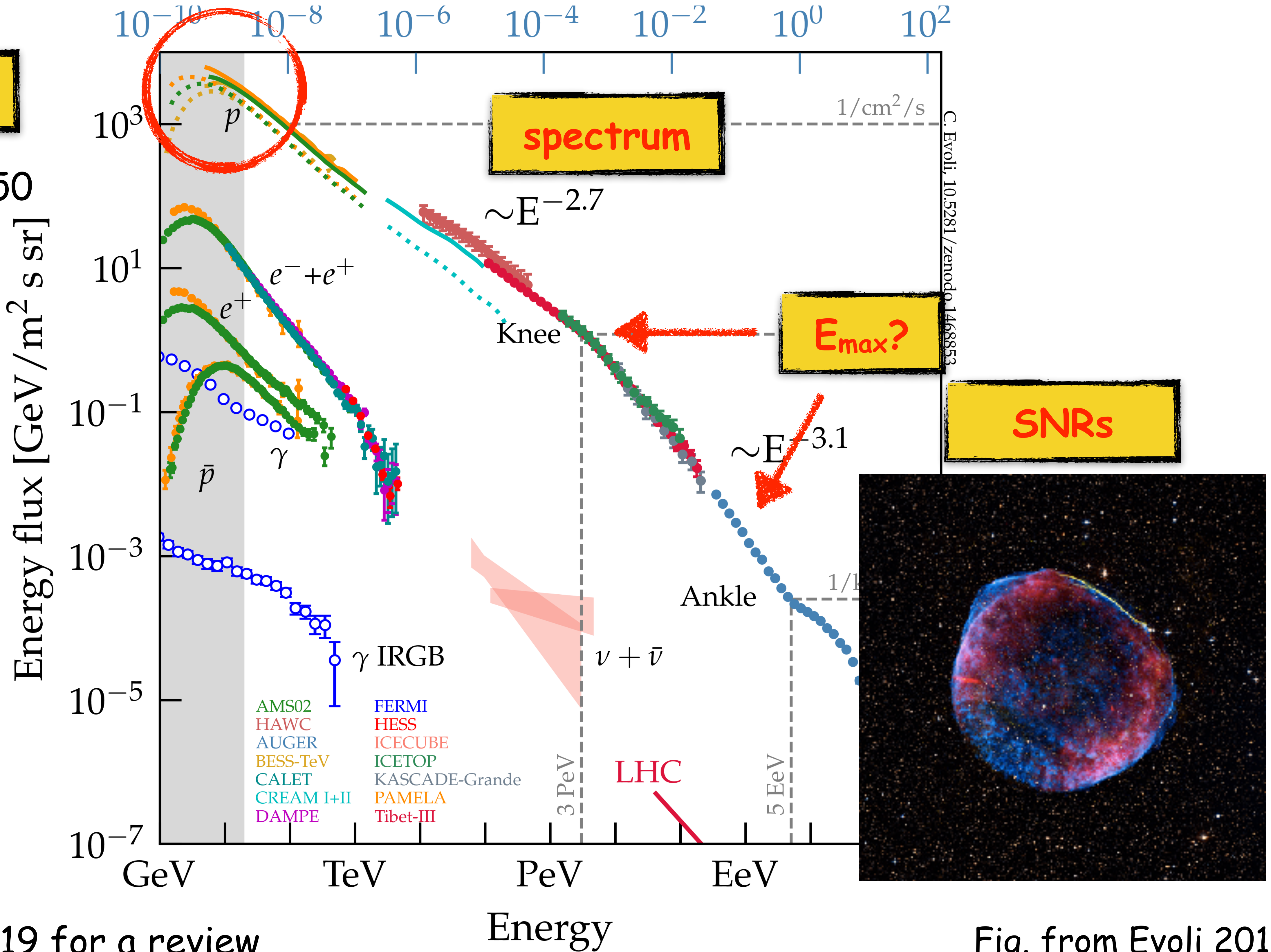
Diffusive shock acceleration at strong SNR shocks

energetics

ter Haar 1950



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E$_{max}$?

SNRs

see Gabici+ 2019 for a review

Fig. from Evoli 2018

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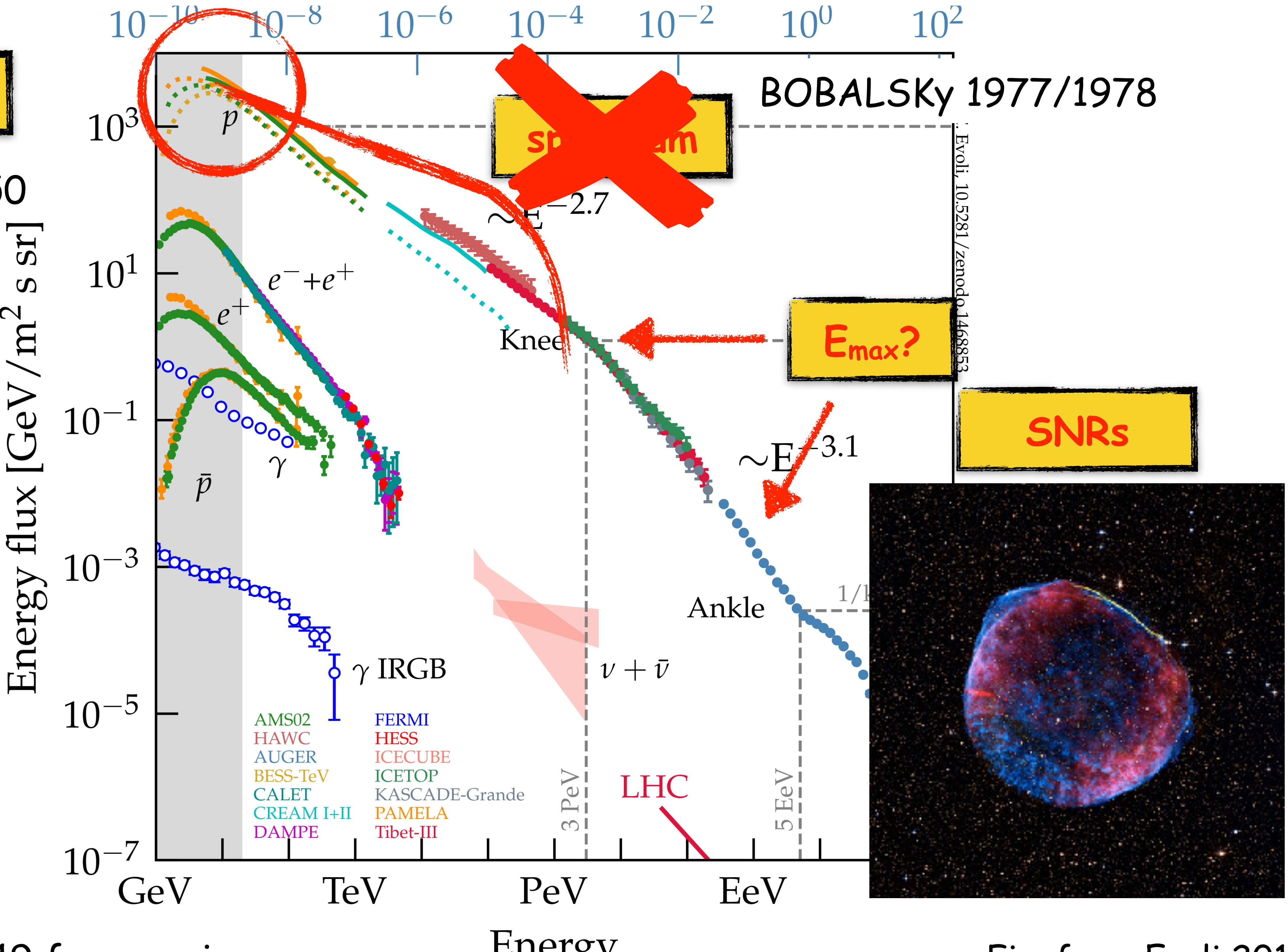

BOBALSKy 1977/1978

~~sp um~~

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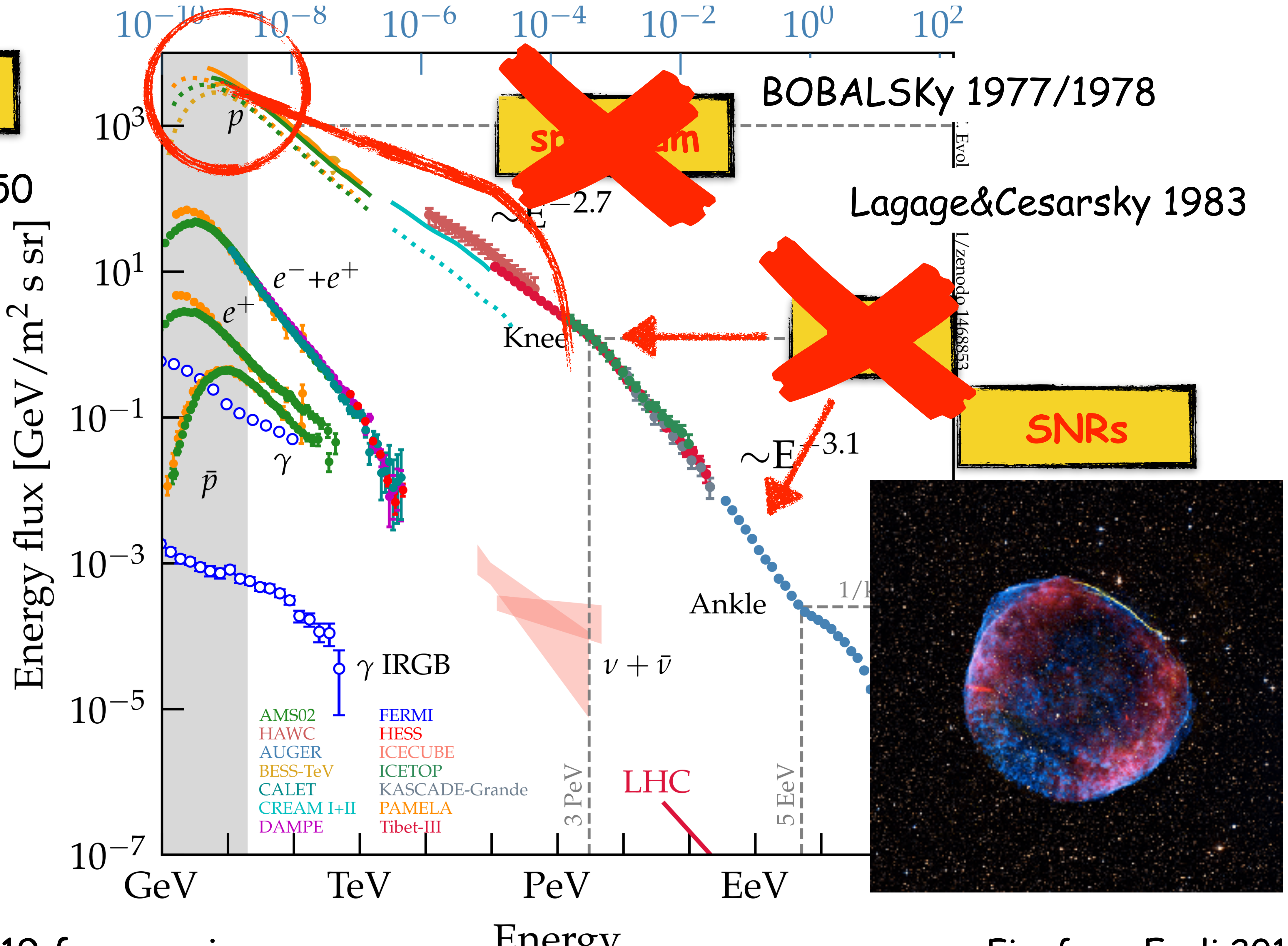

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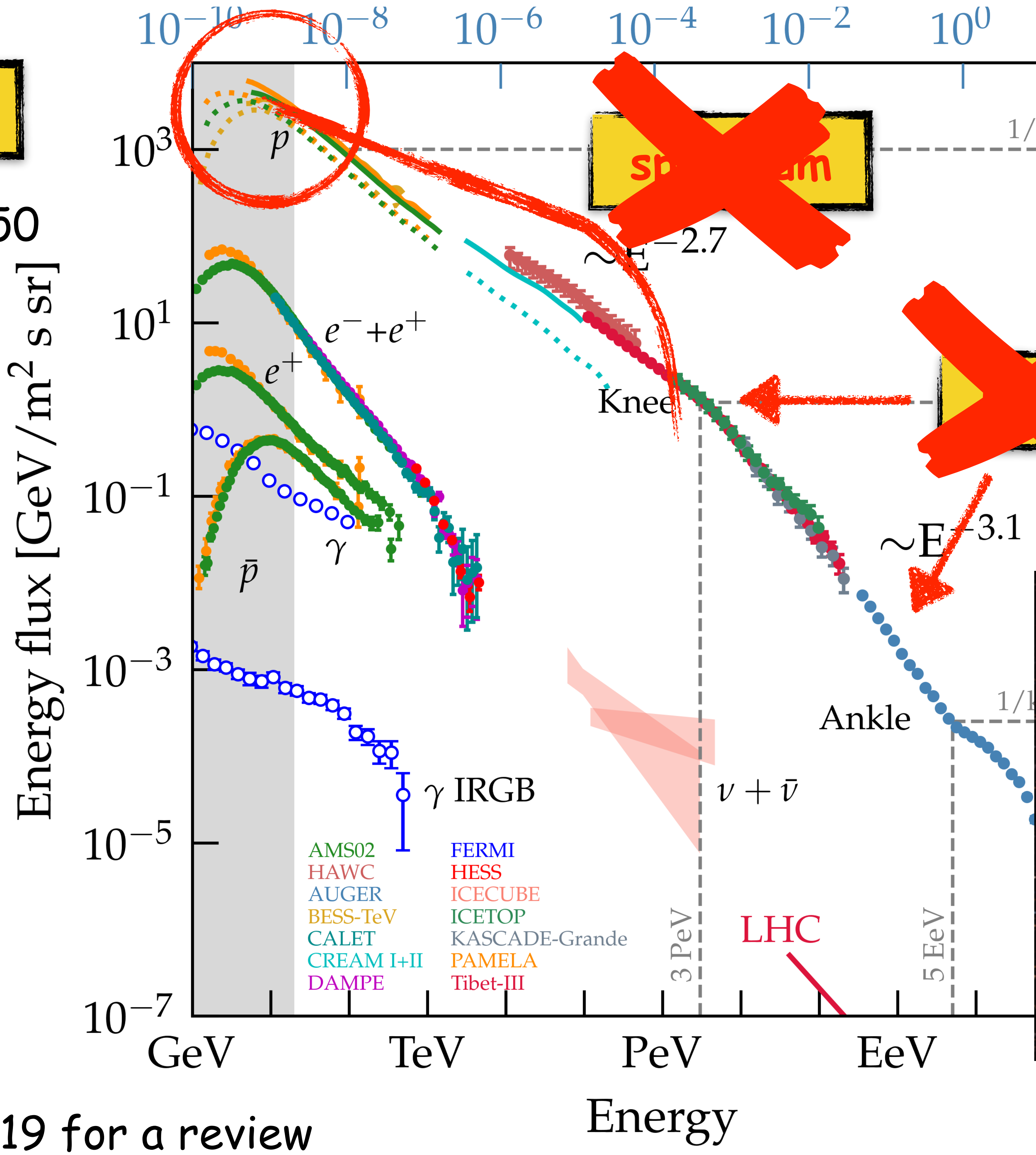

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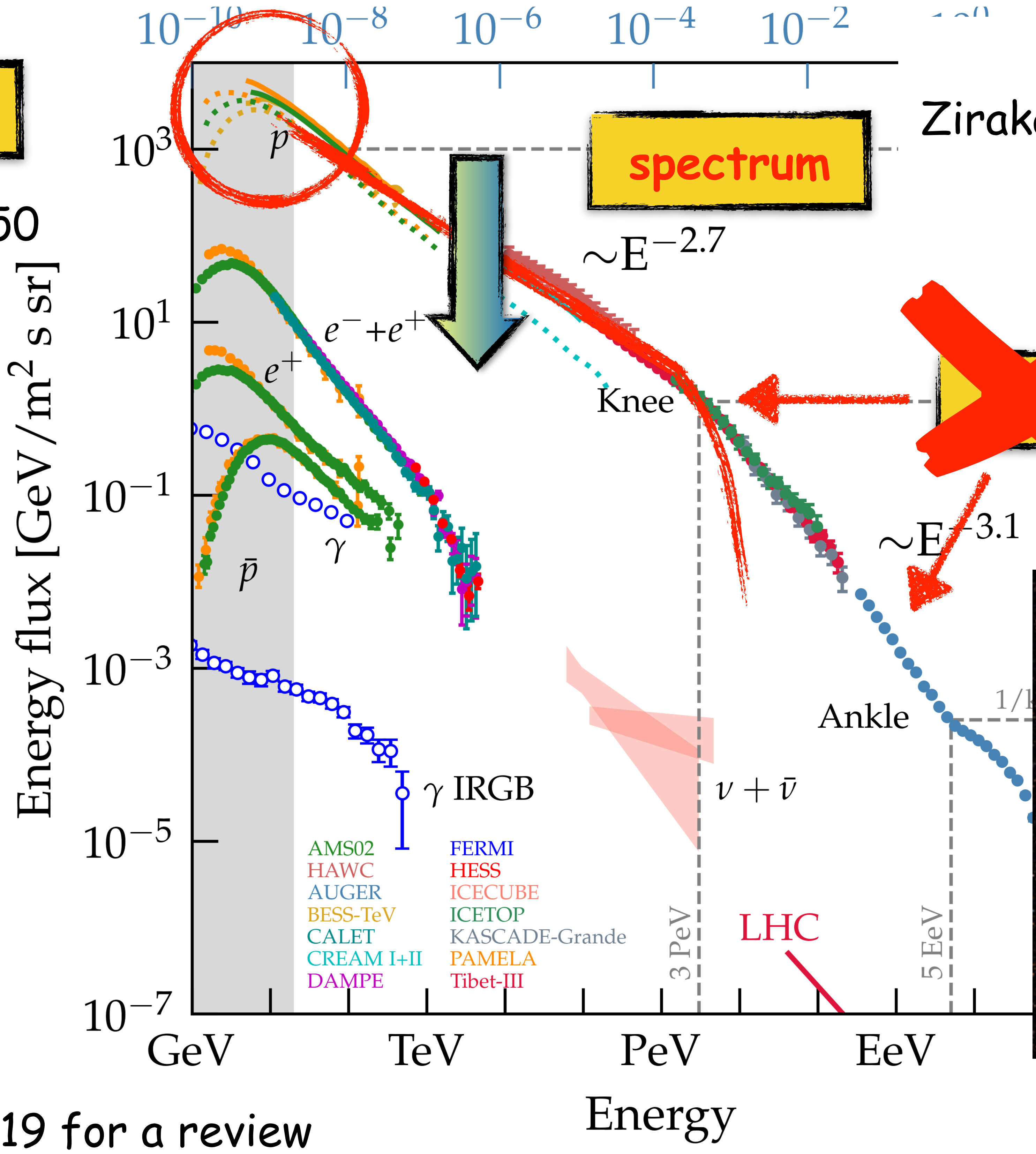

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Non-linear DSA

Zirakashvili&Ptuskin, Caprioli…

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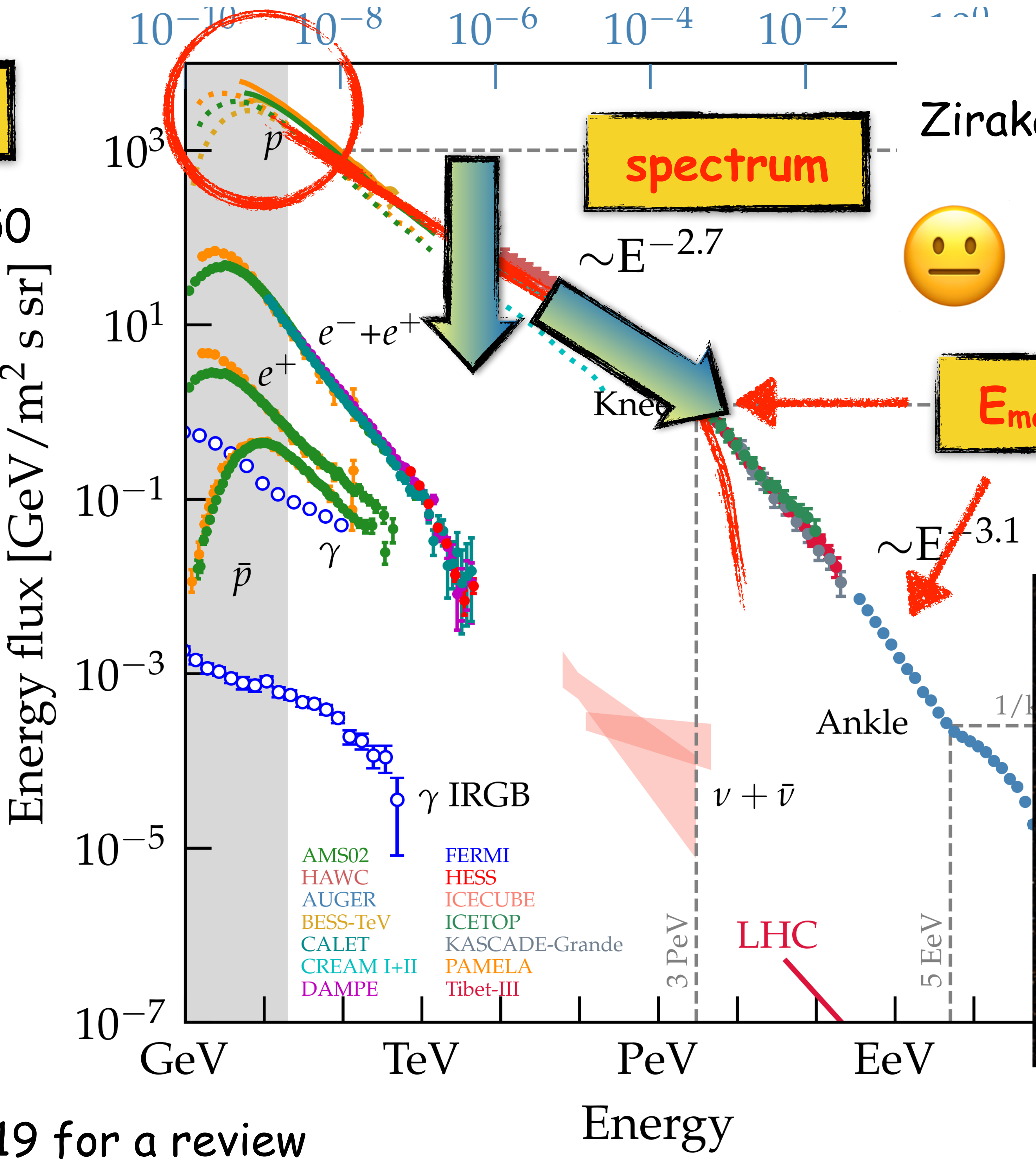

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B-field amplification

Bell 2004

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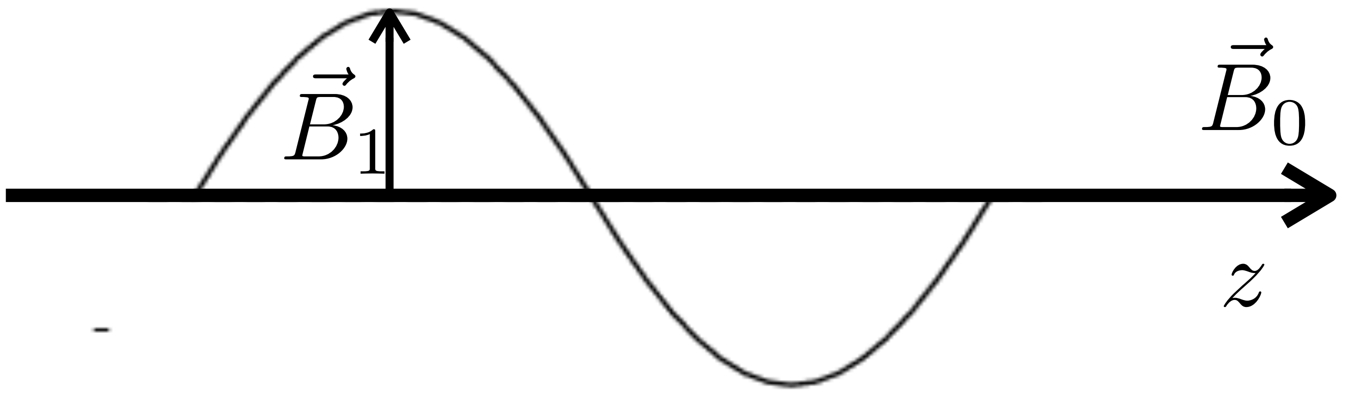
Non-resonant "Bell" instability

circularly polarised



wavelength << Larmor radius

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

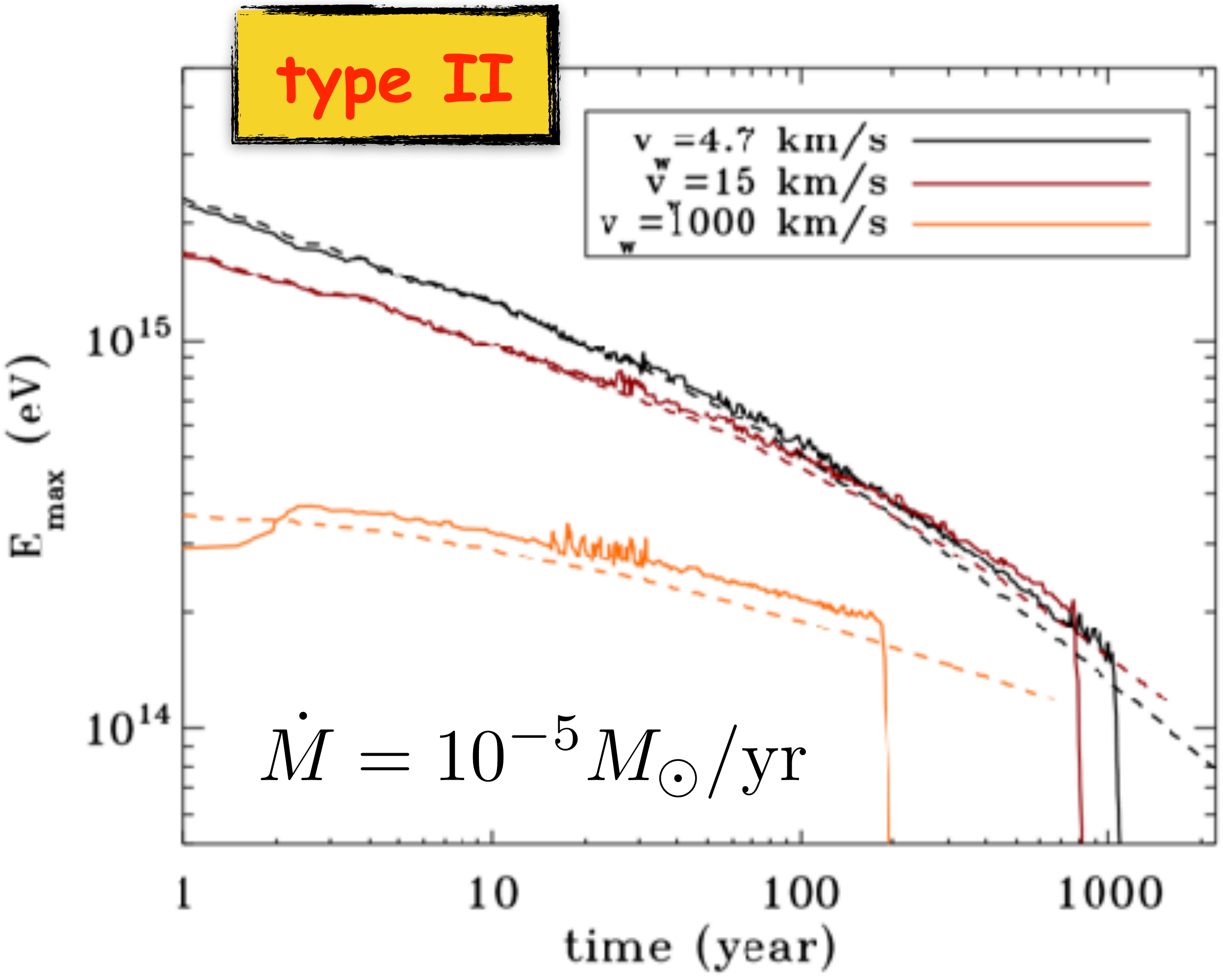
$-\vec{j} \times \vec{B}_1$ **force acting on the plasma —> expands the helical perturbation of B**

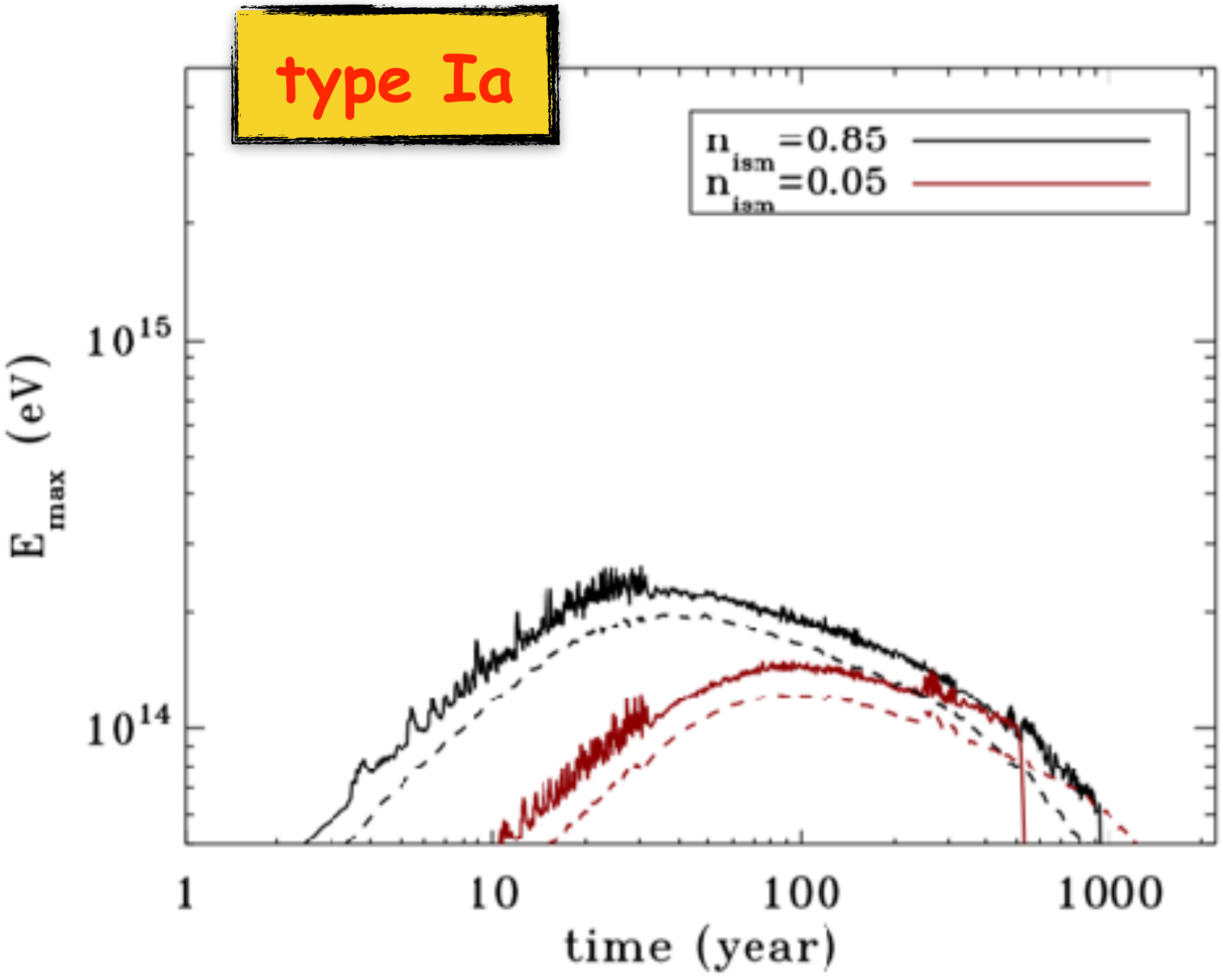
(until the size of the perturbation is of the order of the Larmor radius or magnetic tension balances it)

Bell 2004 … Bell et al 2013

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

Only very young SNRs accelerate to PeV





Schure & Bell 2013

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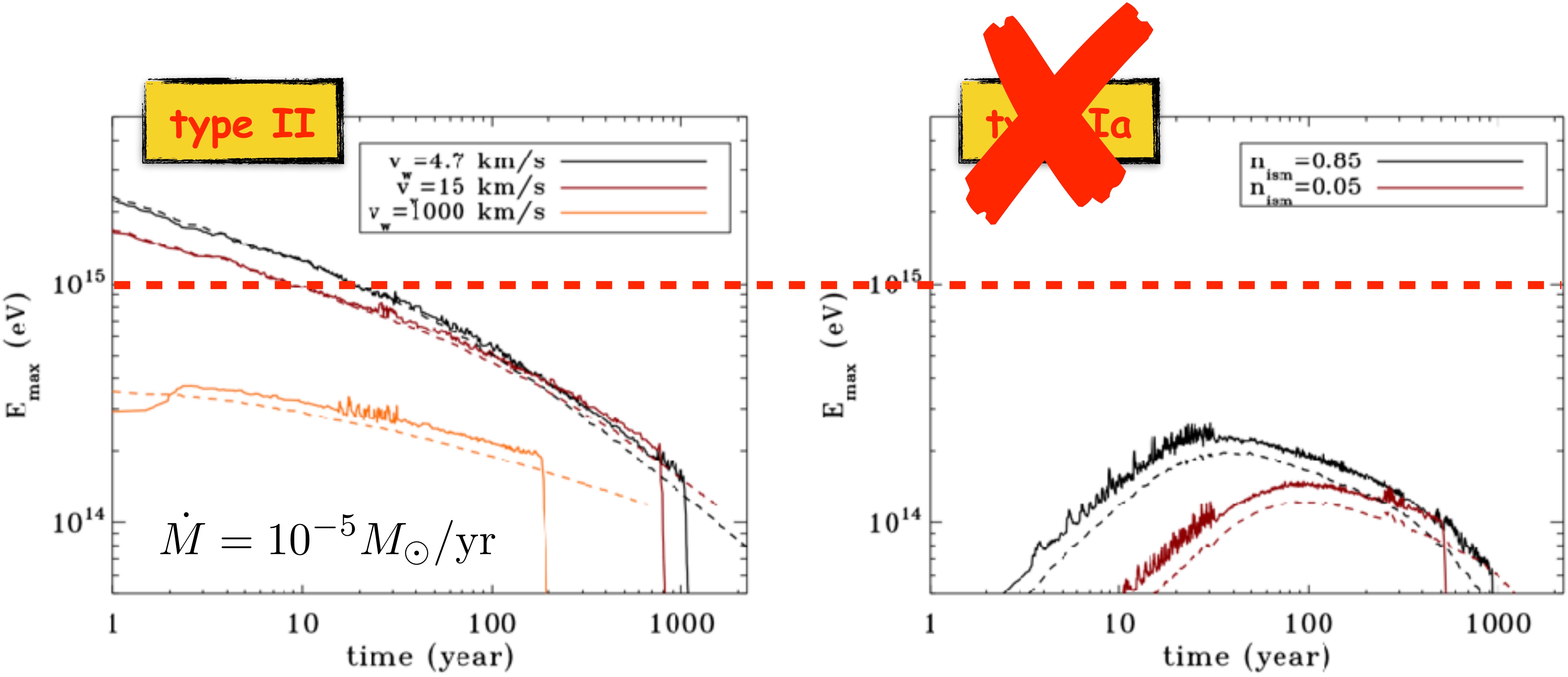

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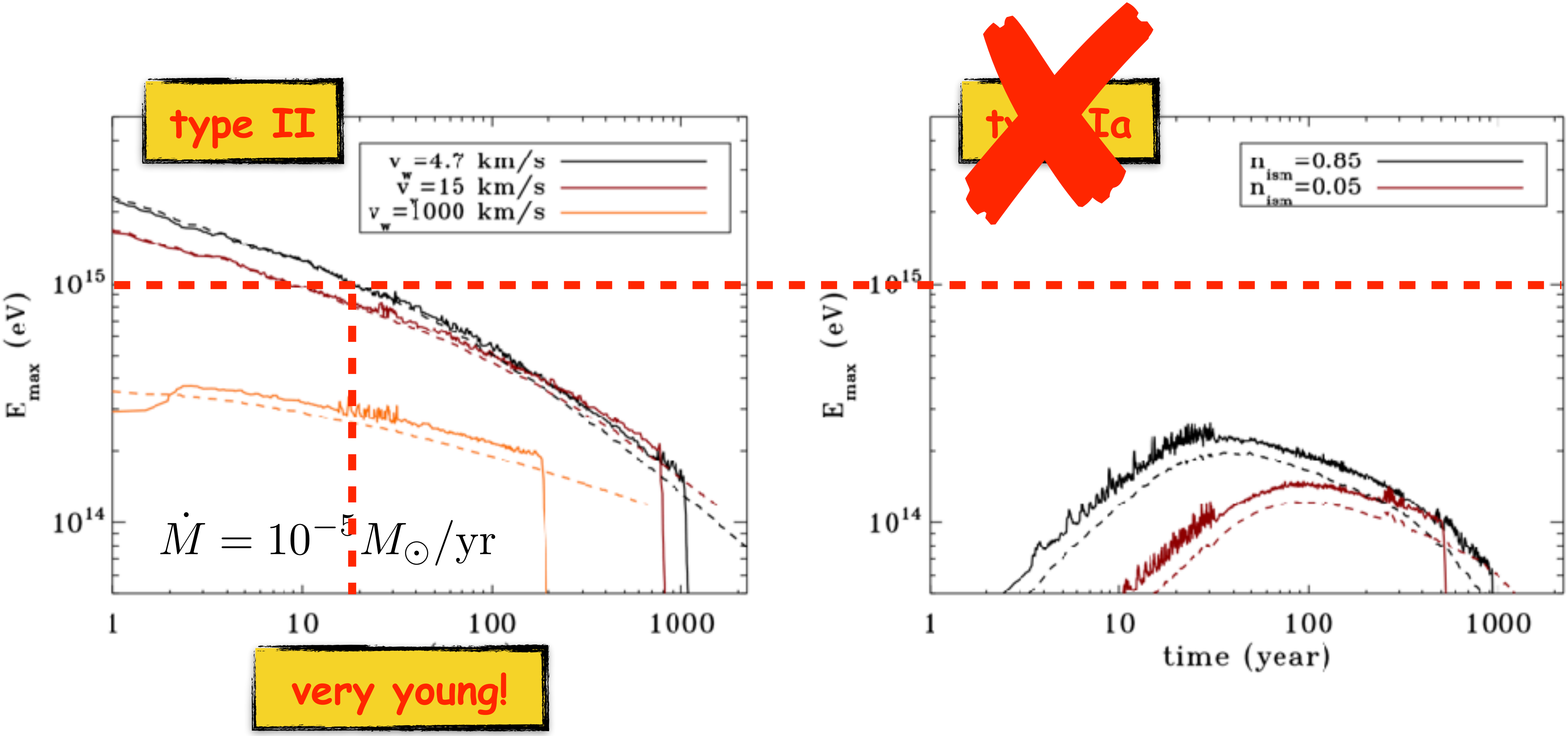

type II

ty Ia

very young!

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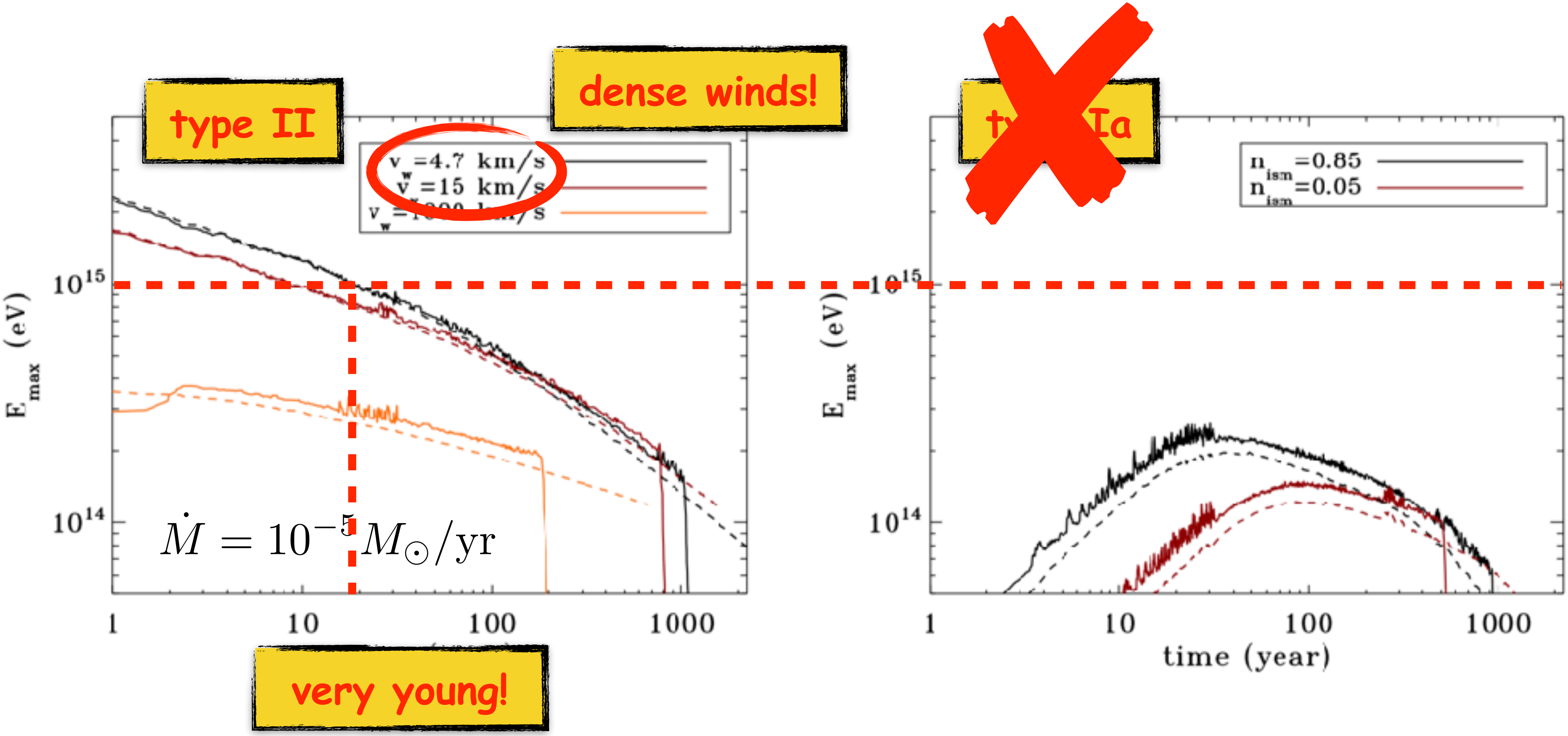

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dense winds!

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$\dot{M} = 10^{-5} M_\odot/\mathrm{yr}$

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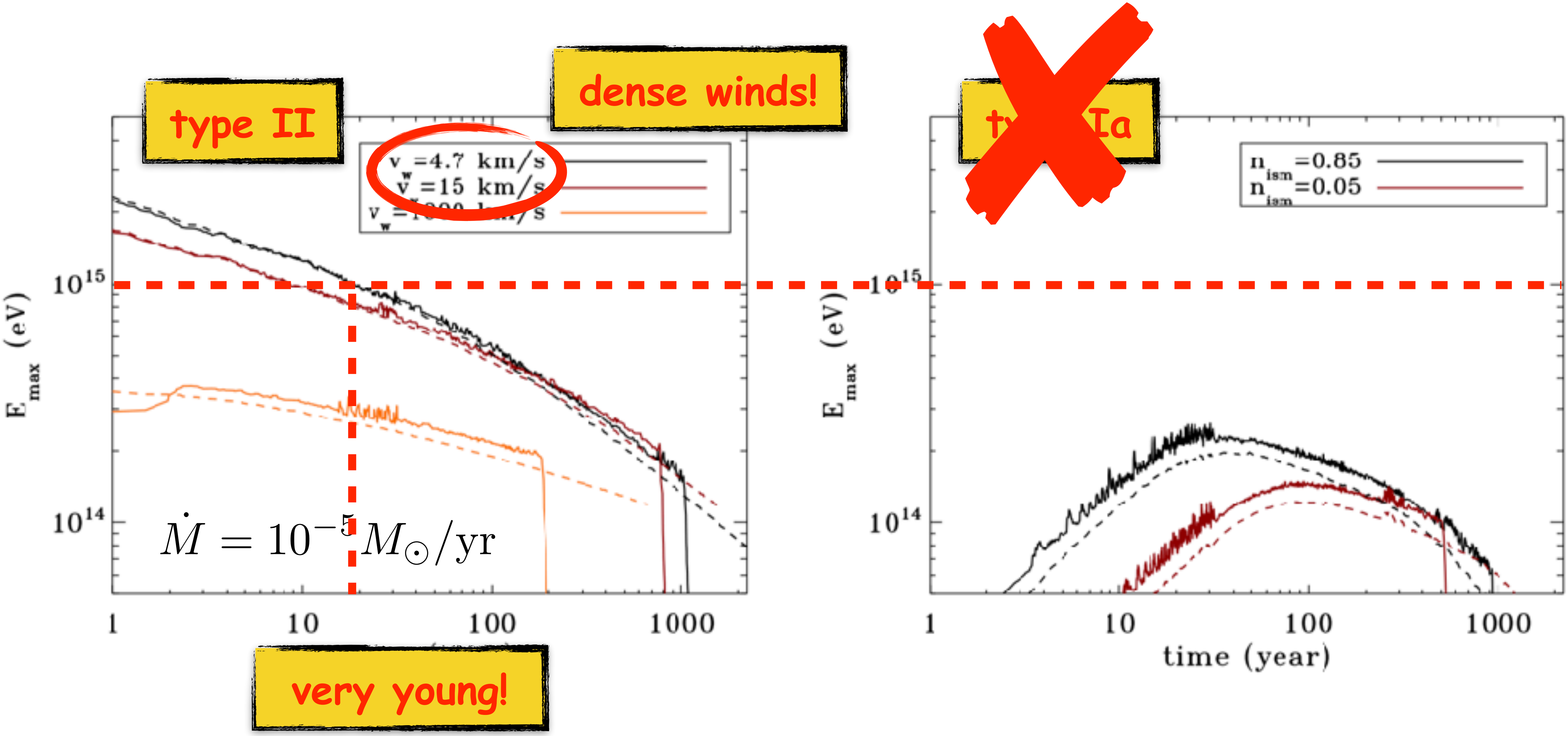
Schure & Bell 2013



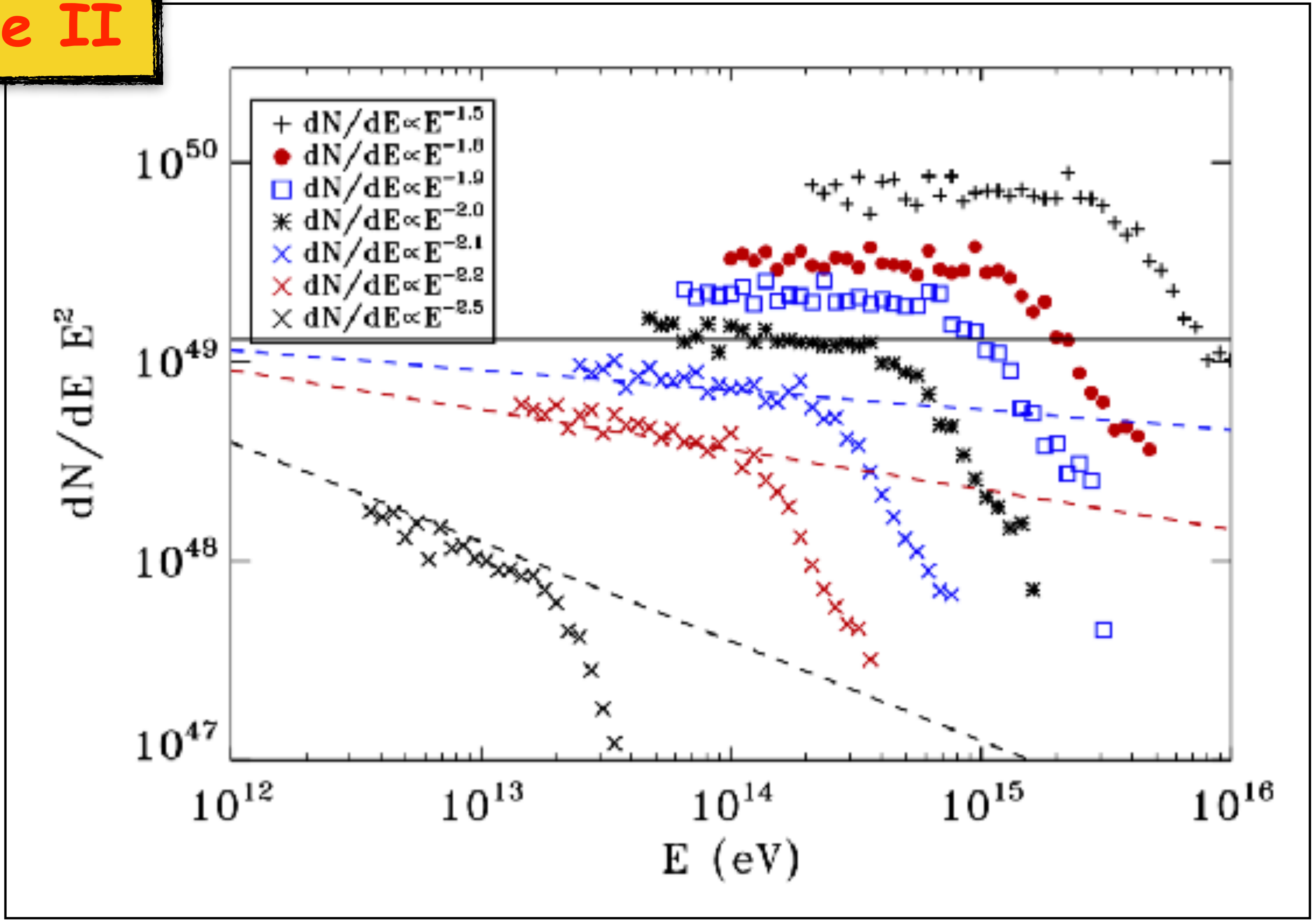
3 consequences:

- ☐ 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)

Spectrum or Emax?

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

type II



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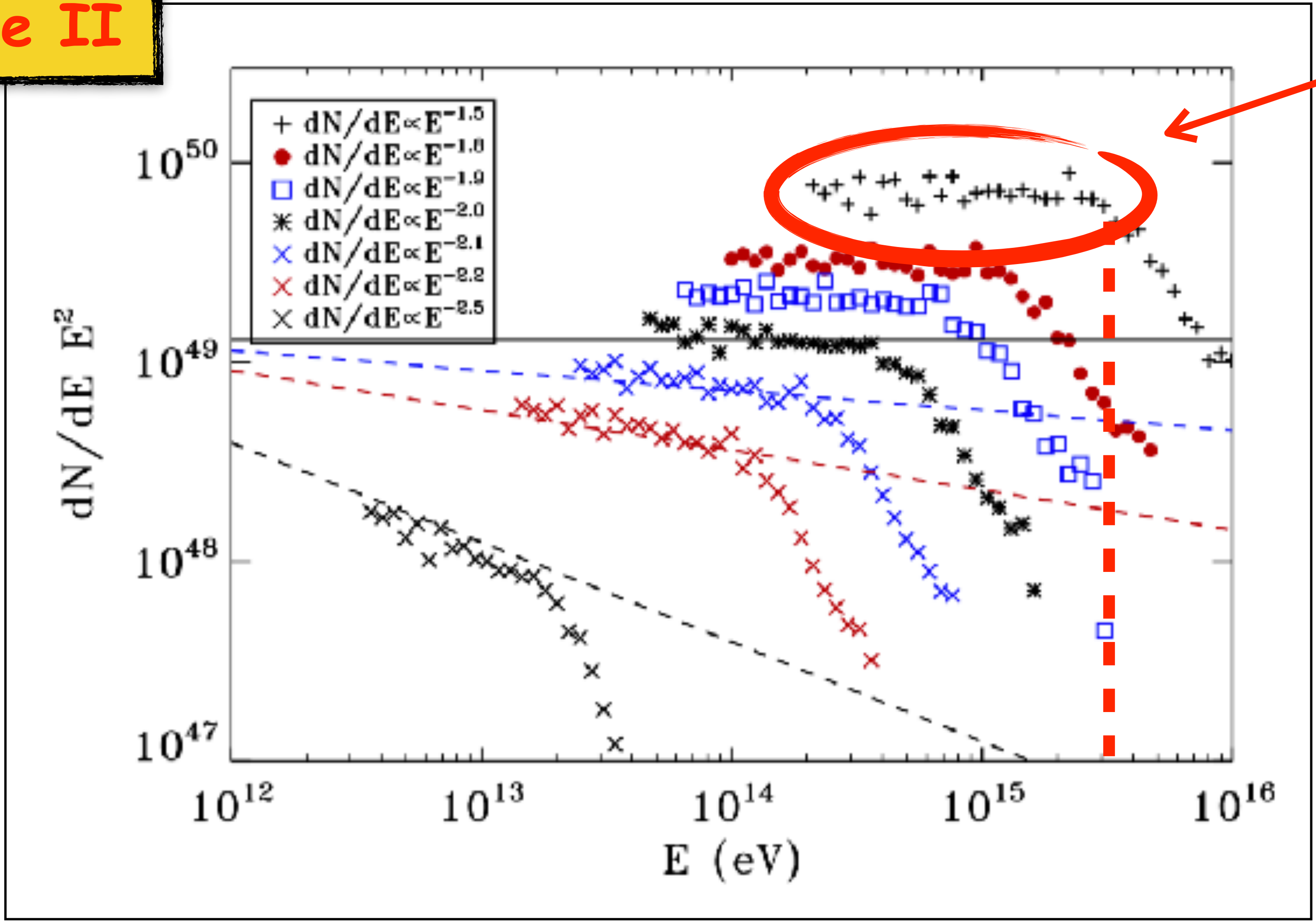

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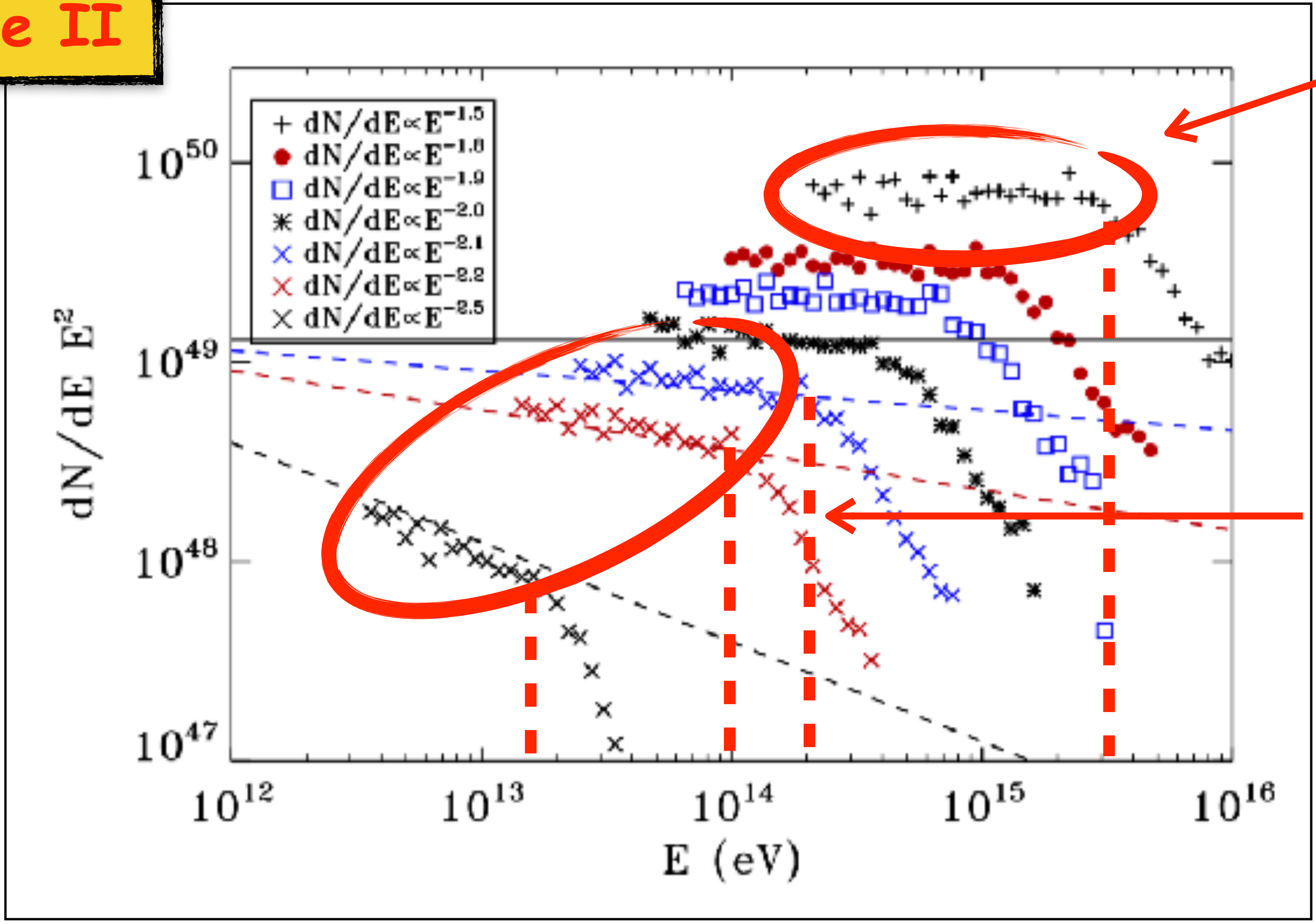

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—> not enough to reach the knee

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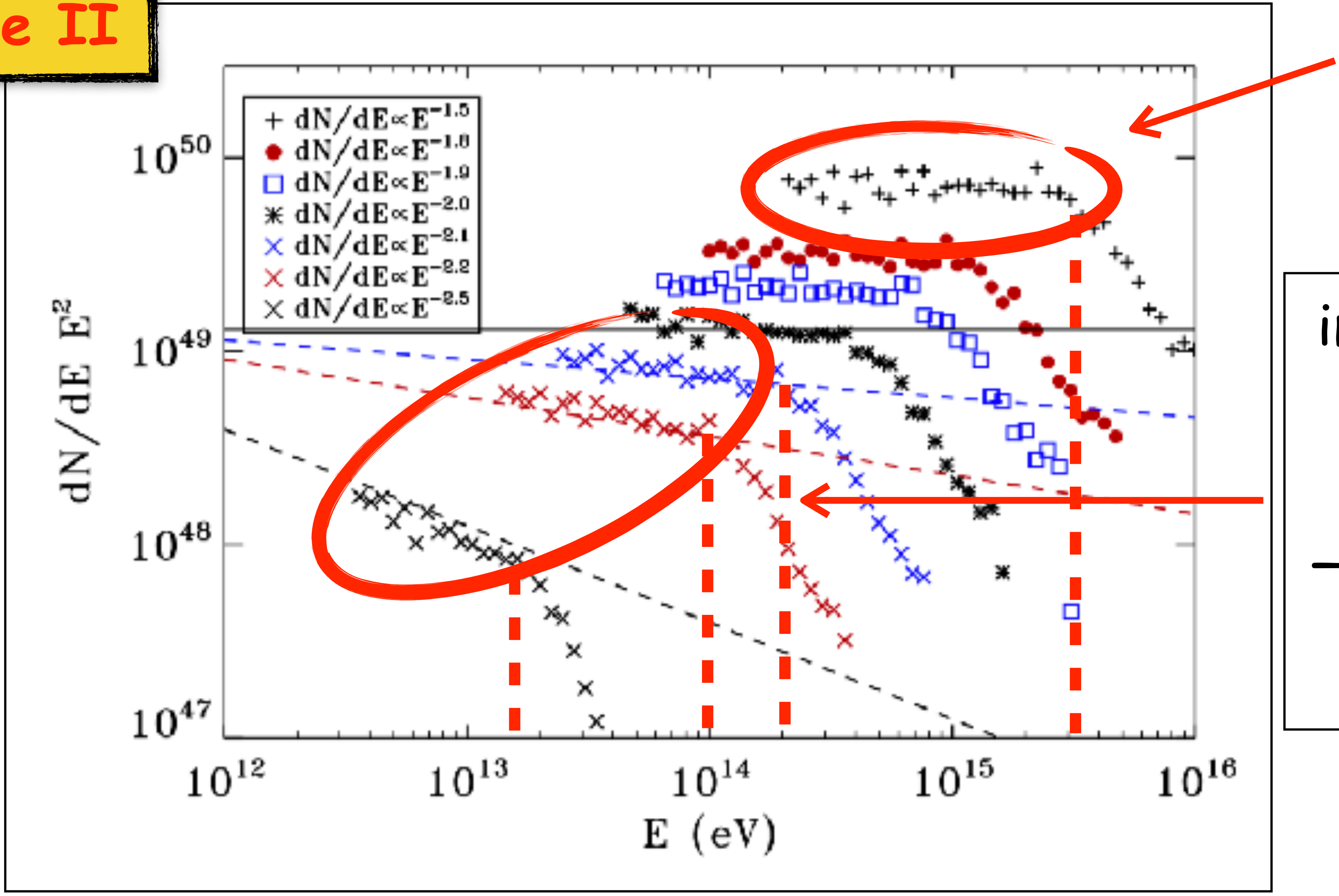

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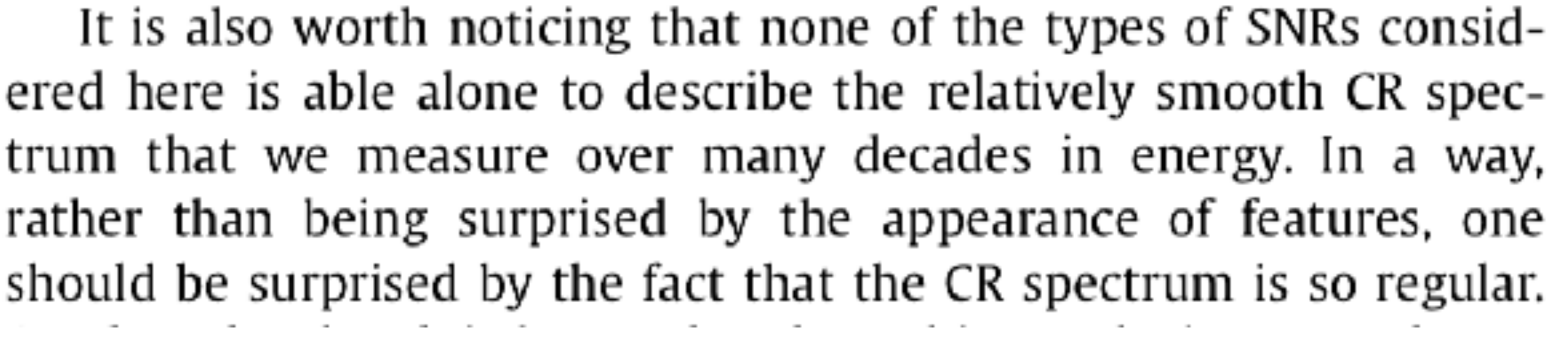
can we tune it?



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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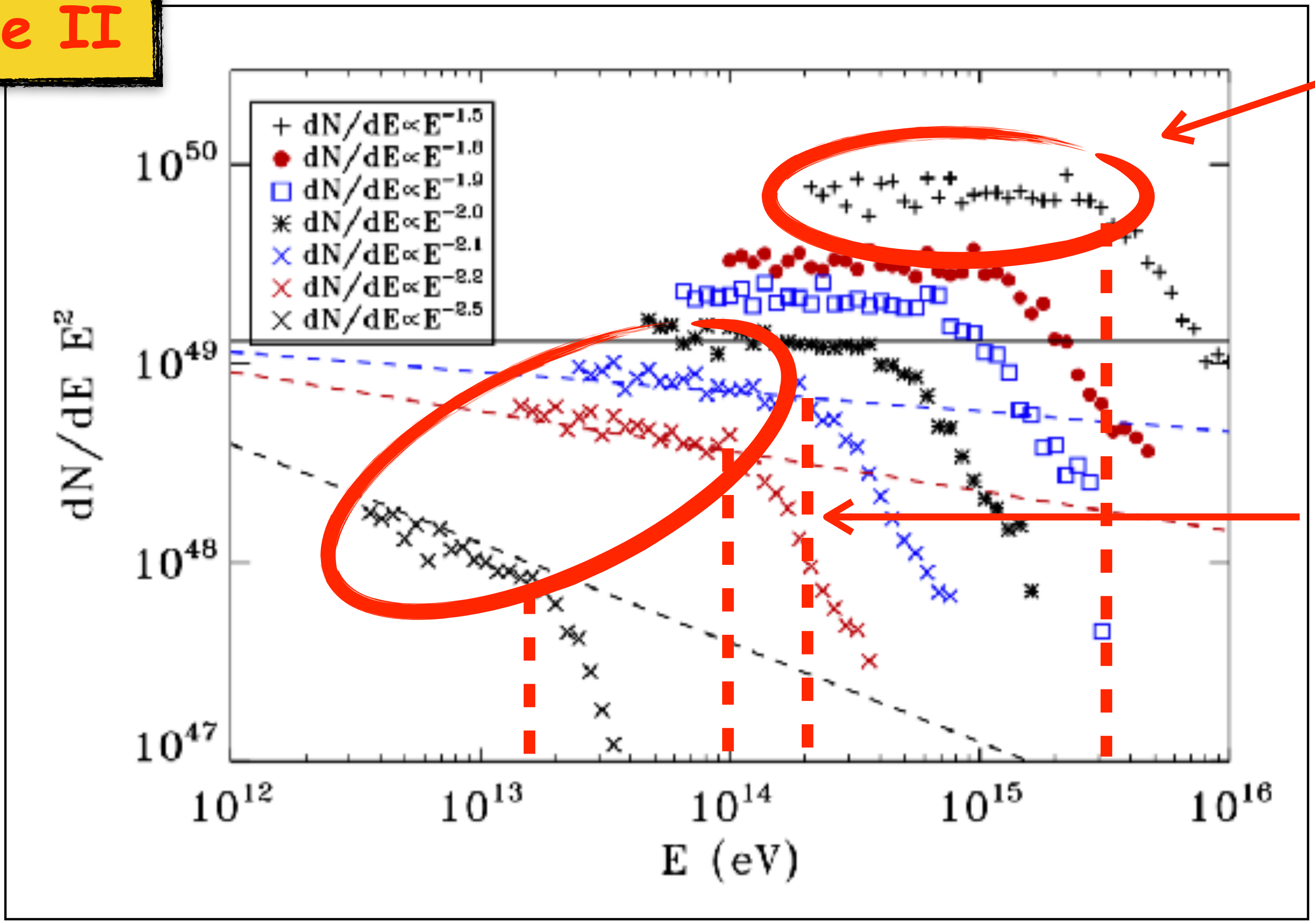

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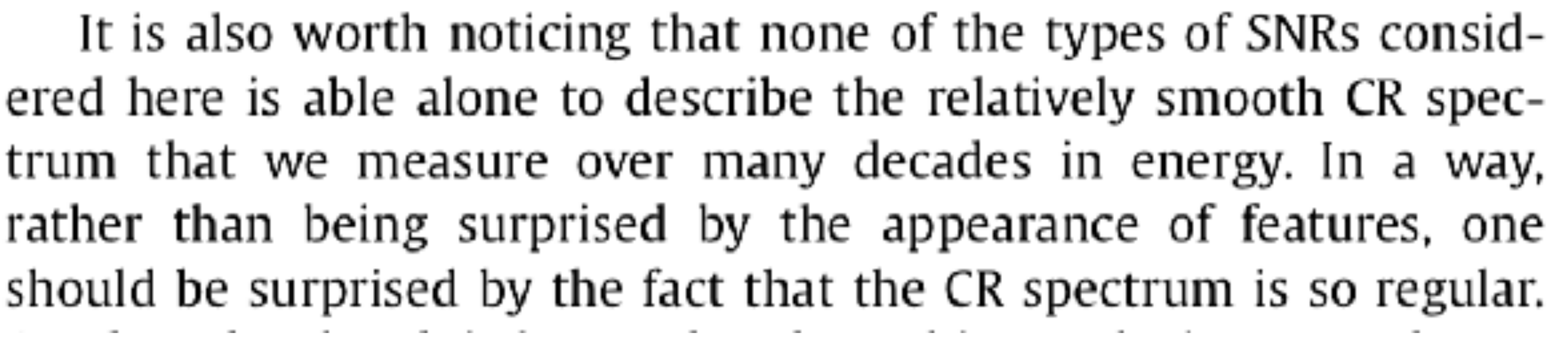
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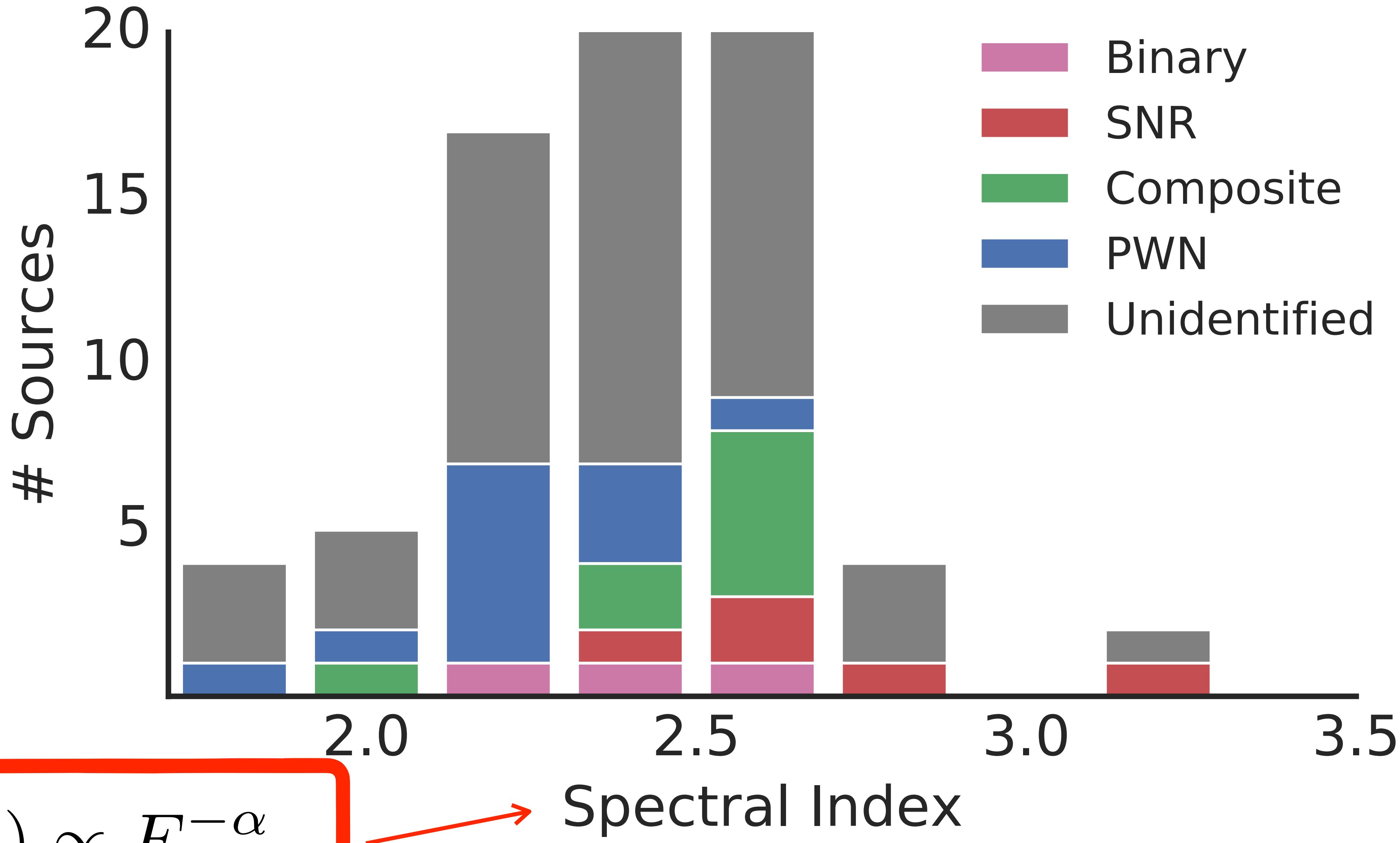
Gamma-ray spectra are steep!

Galactic plane survey performed by HESS above ~100 GeV



$$F_\gamma(E_\gamma) \propto E_\gamma^{-\alpha}$$

HESS Collaboration 2018

Possible wayouts

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

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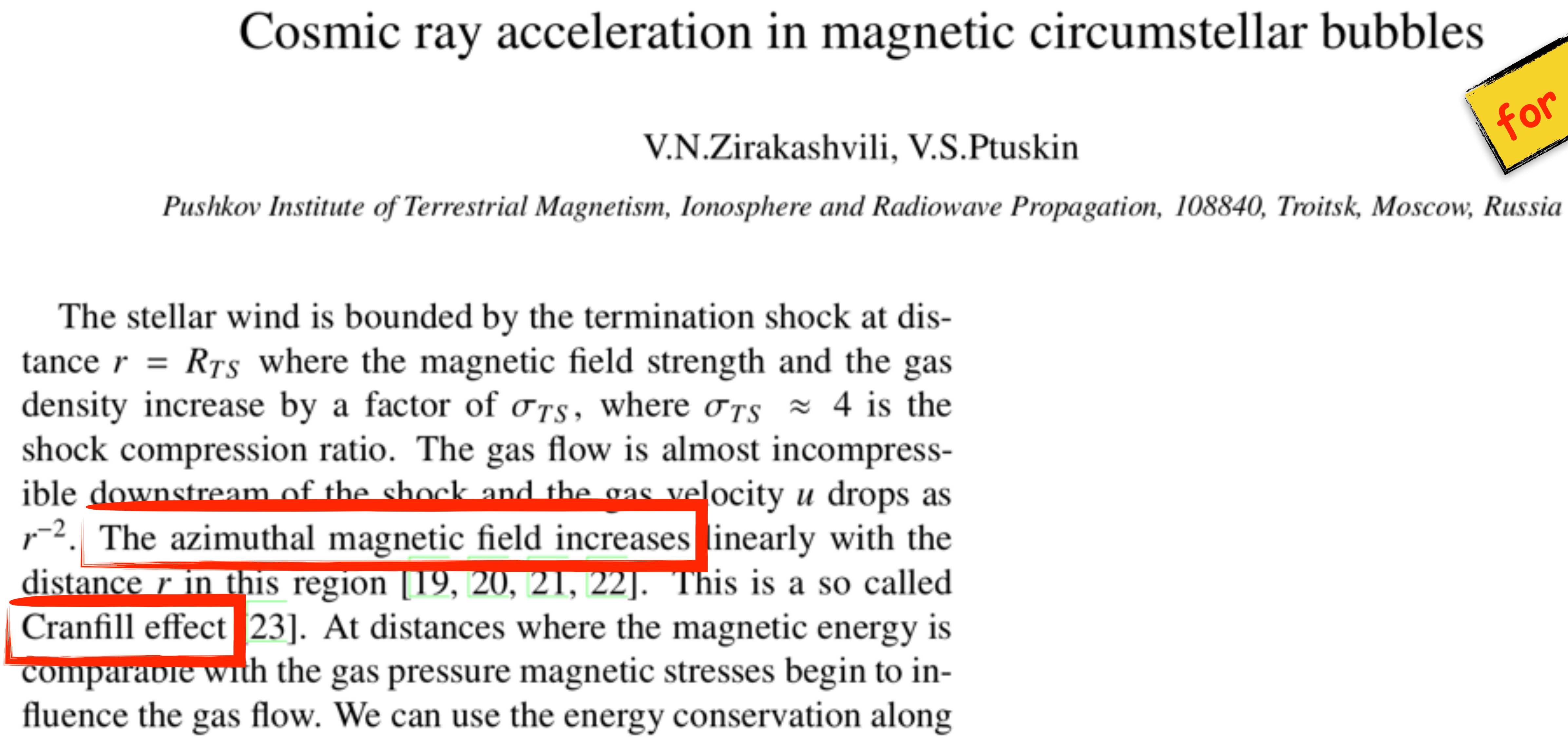

Cosmic ray acceleration in magnetic circumstellar bubbles

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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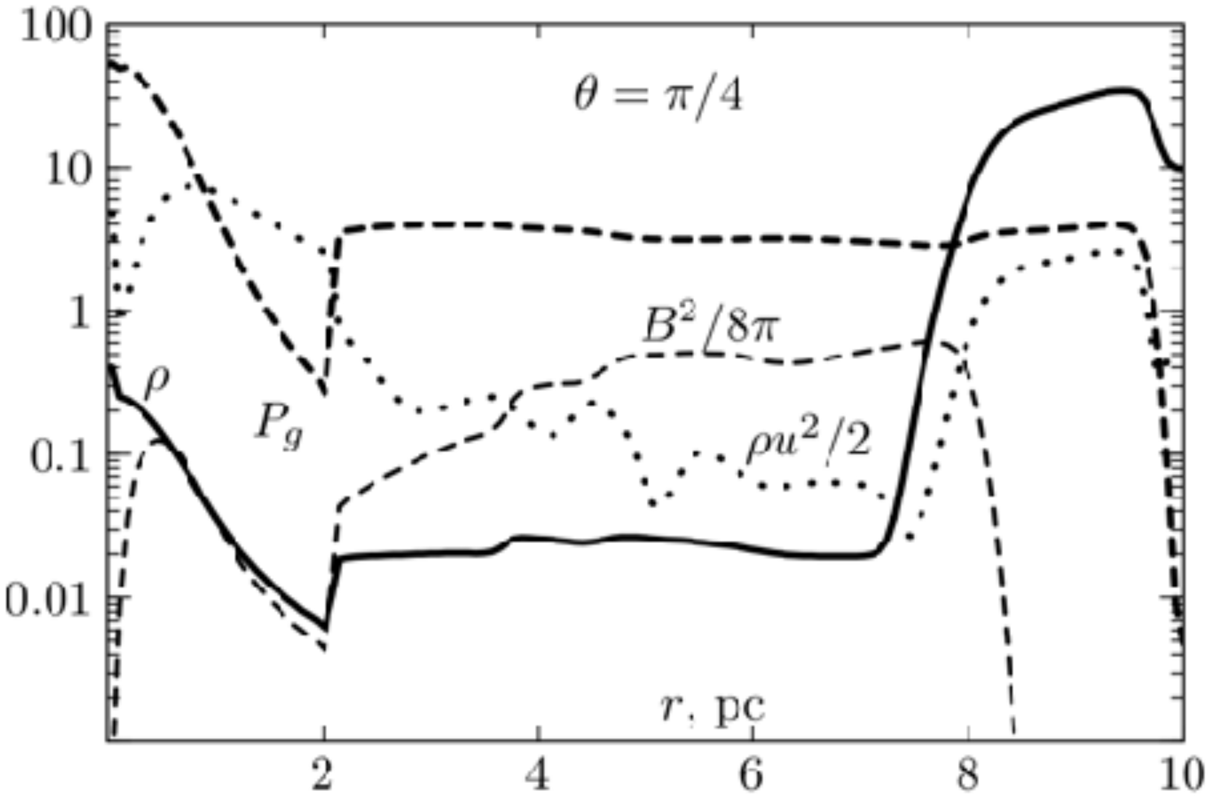

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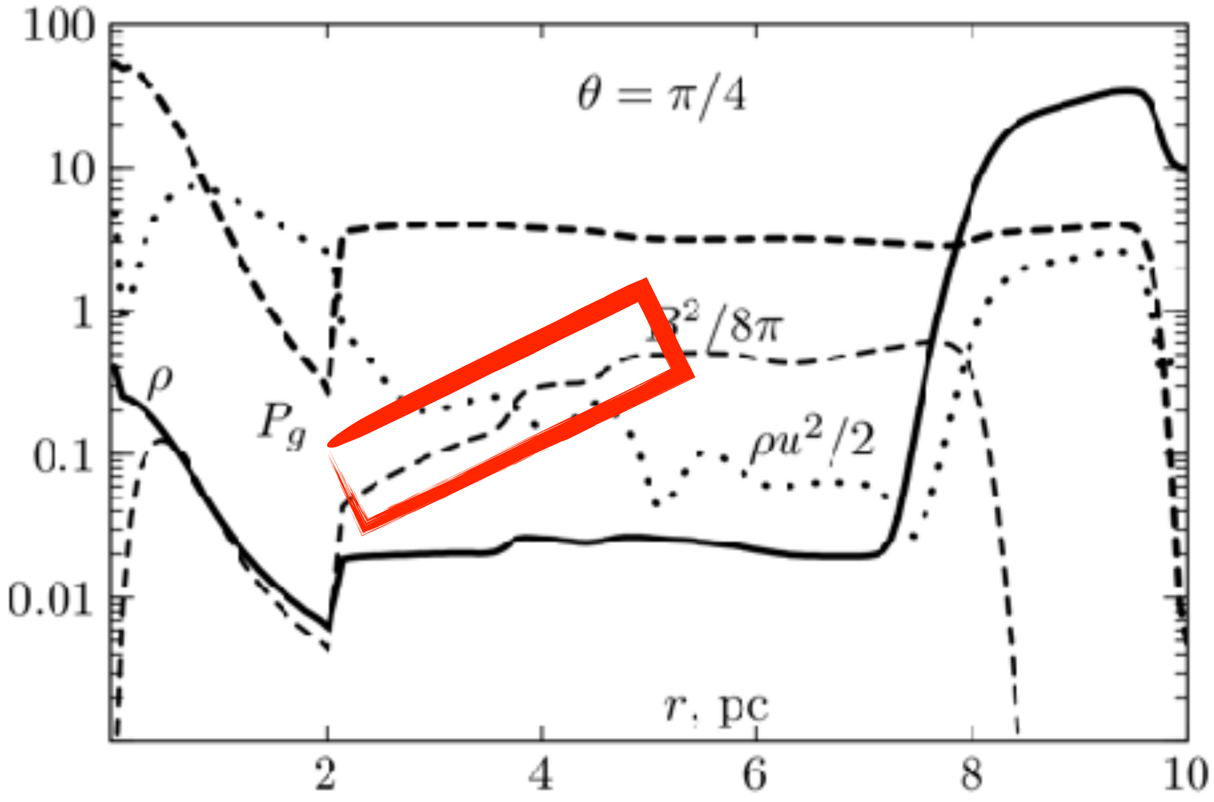
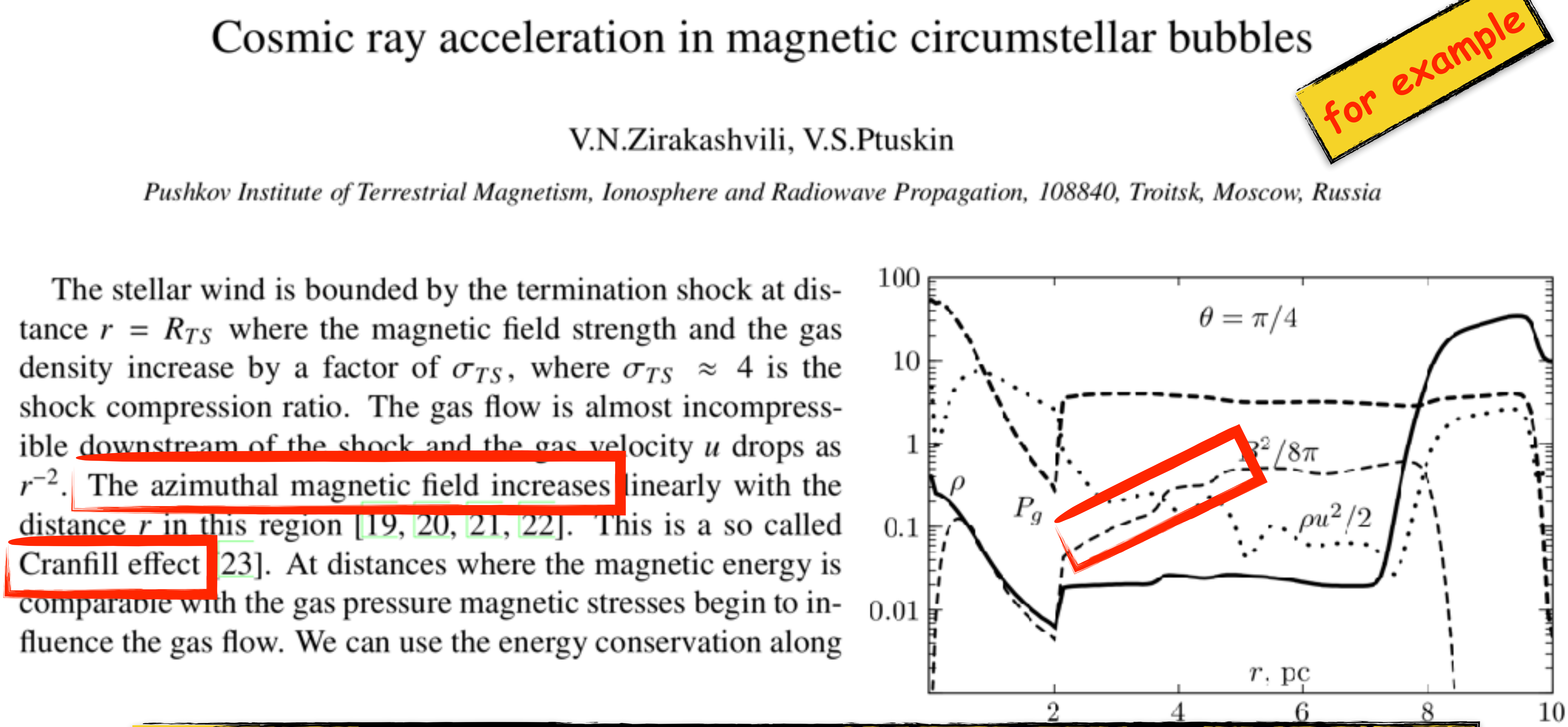


Possible wayouts

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



Cosmic ray acceleration in magnetic circumstellar bubbles

for example

V.N.Zirakashvili, V.S.Ptuskin

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

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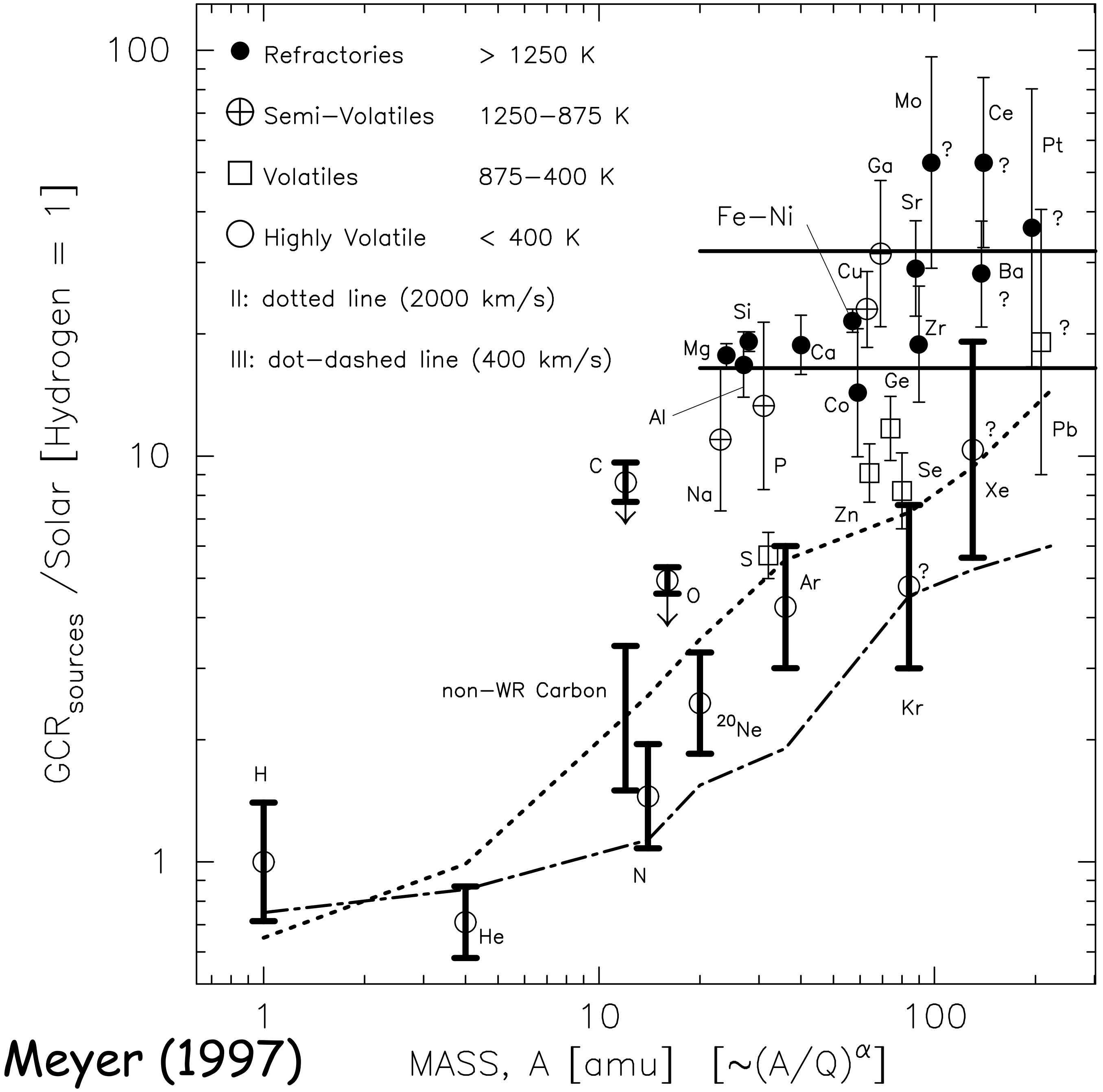
…or allow for a different/modified acceleration mechanism (see later)

The orthodoxy (3)

- Cosmic rays are accelerated out of the (dusty) interstellar medium through diffusive shock acceleration in supernova remnants

The orthodoxy (3)

CRs are accelerated out of the (dusty) ISM through DSA in SNRs



why dusty?

Ellison, Drury, Meyer (1997)

see also Caprioli+ 2017

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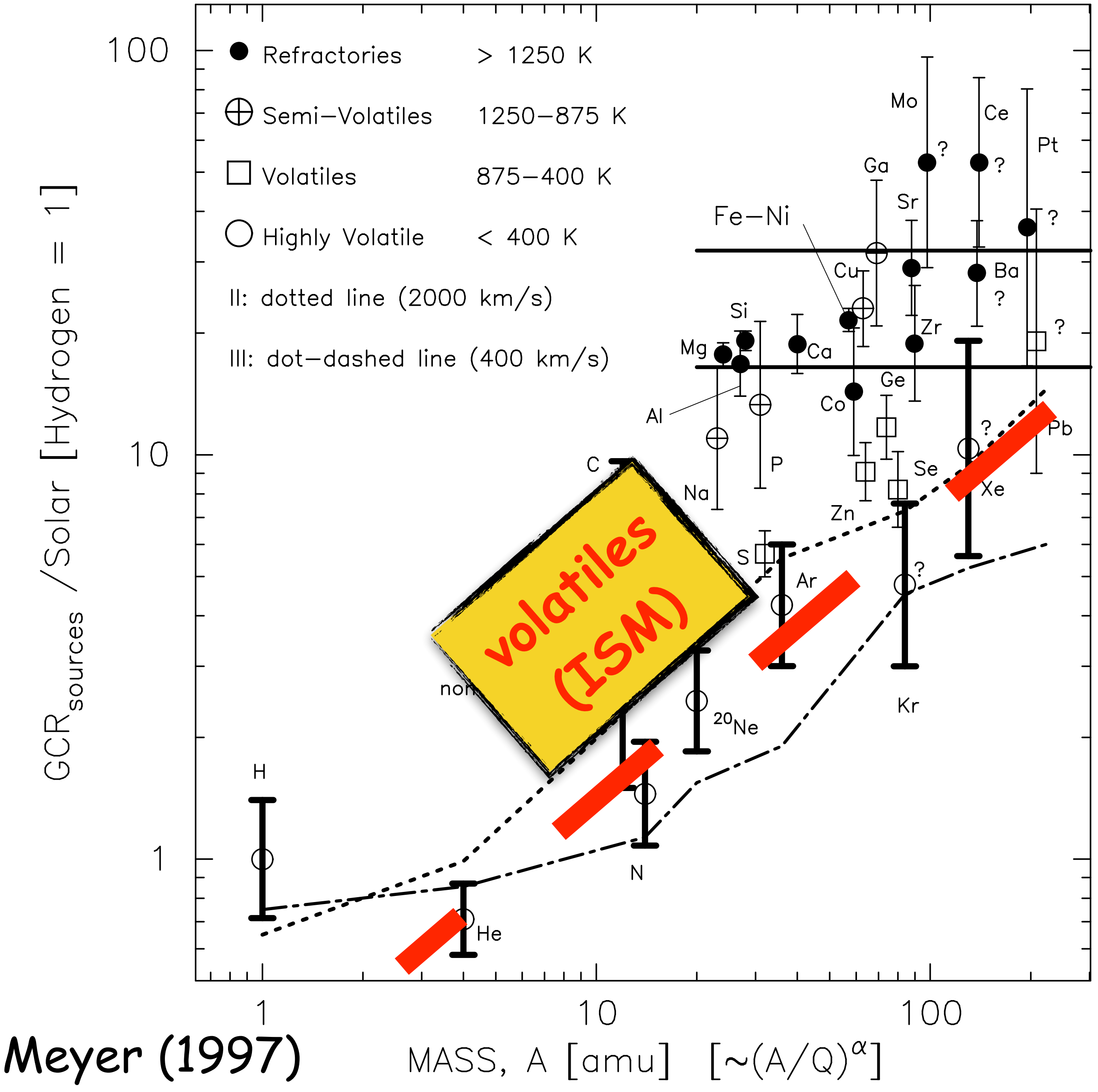

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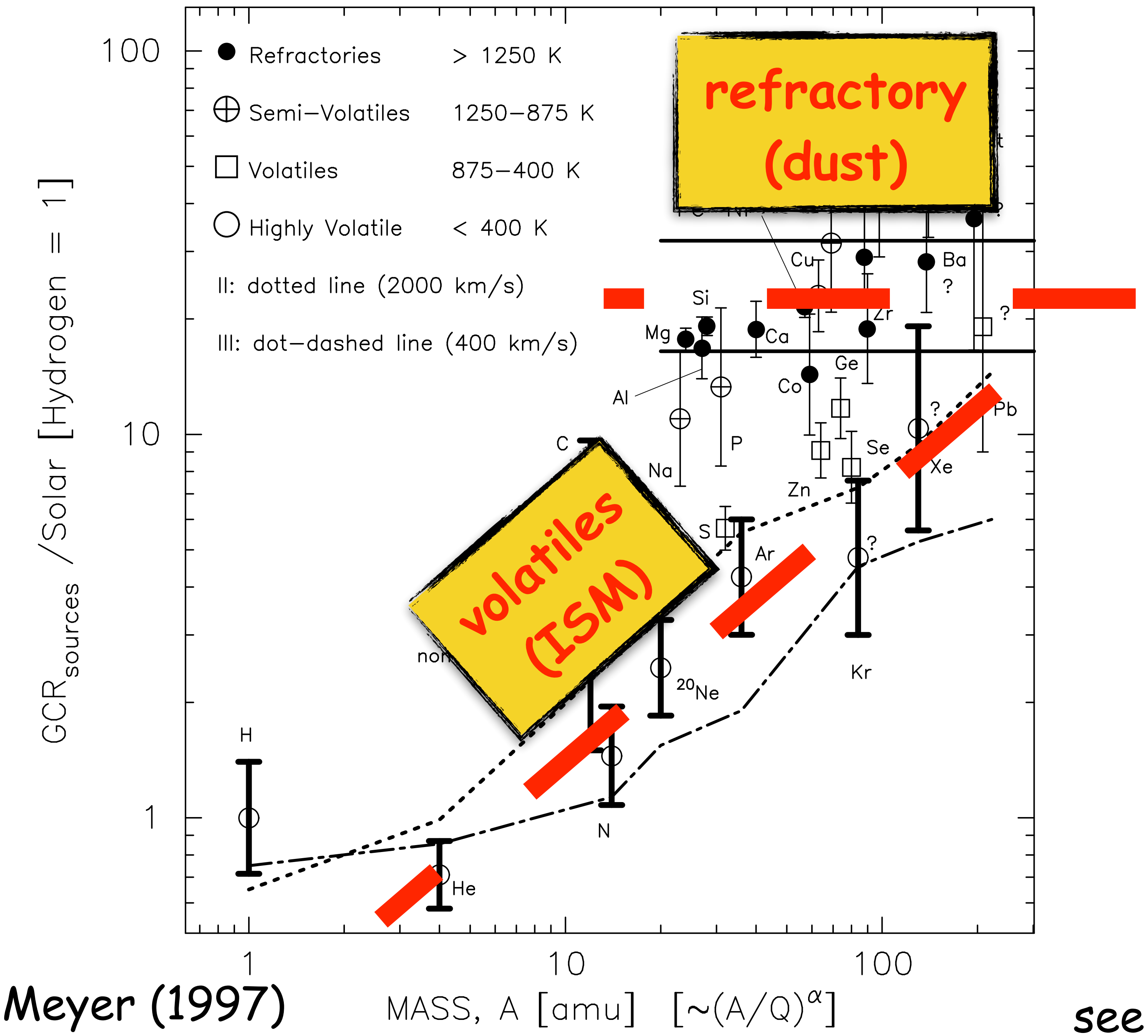


refractory (dust)

volatiles (ISM)

why dusty?

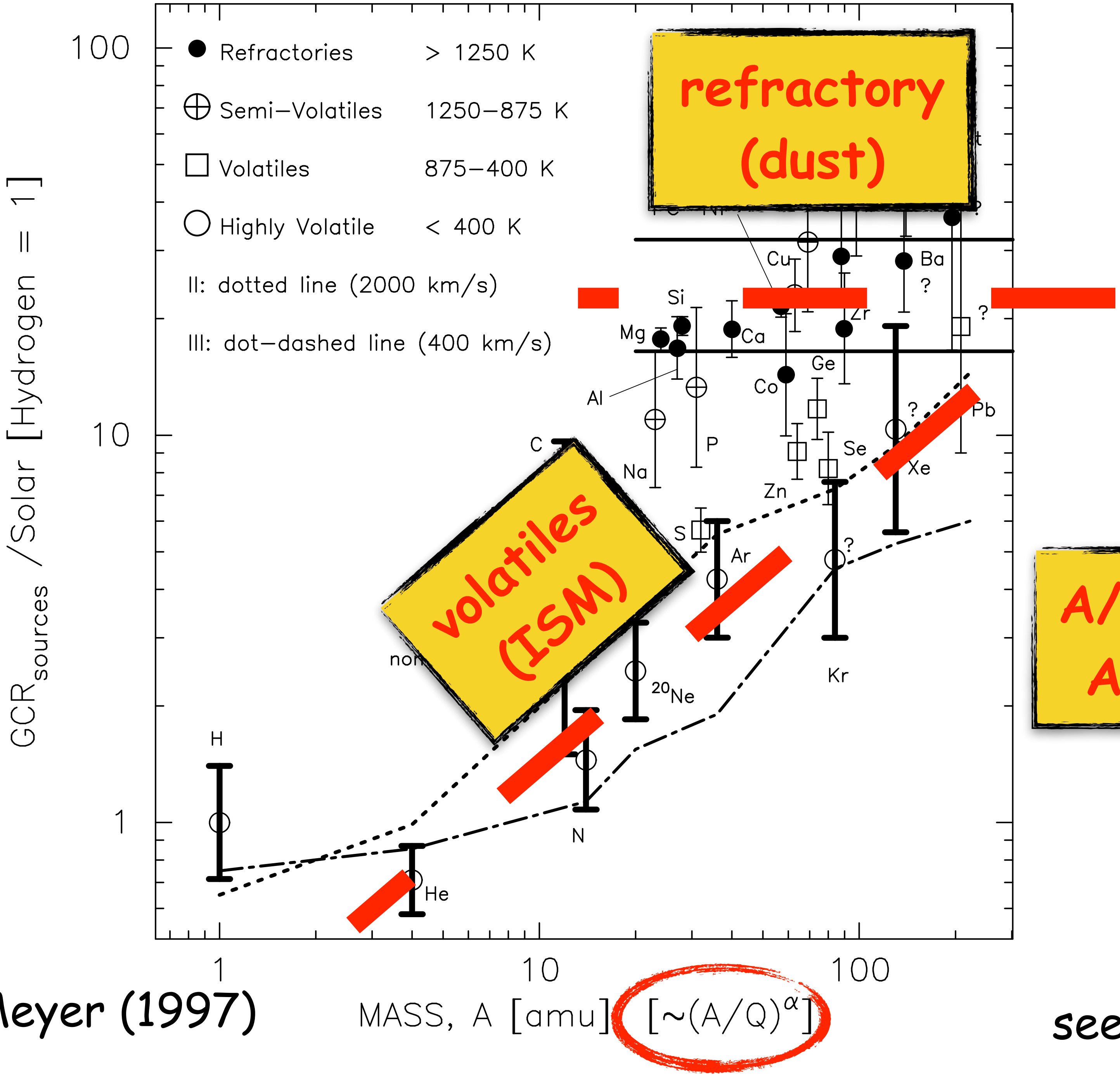
Ellison, Drury, Meyer (1997)

see also Caprioli+ 2017

The orthodoxy (3)

▷ CRs are accelerated out of the (dusty) ISM through DSA in SNRs

Data are best explained if refractory CRs are injected at shocks through sputtering of pre-accelerated dust grains



refractory (dust)

volatiles (ISM)

why dusty?

A/Q ~ A —> warm ISM

A/Q ~ 2 —> hot ISM

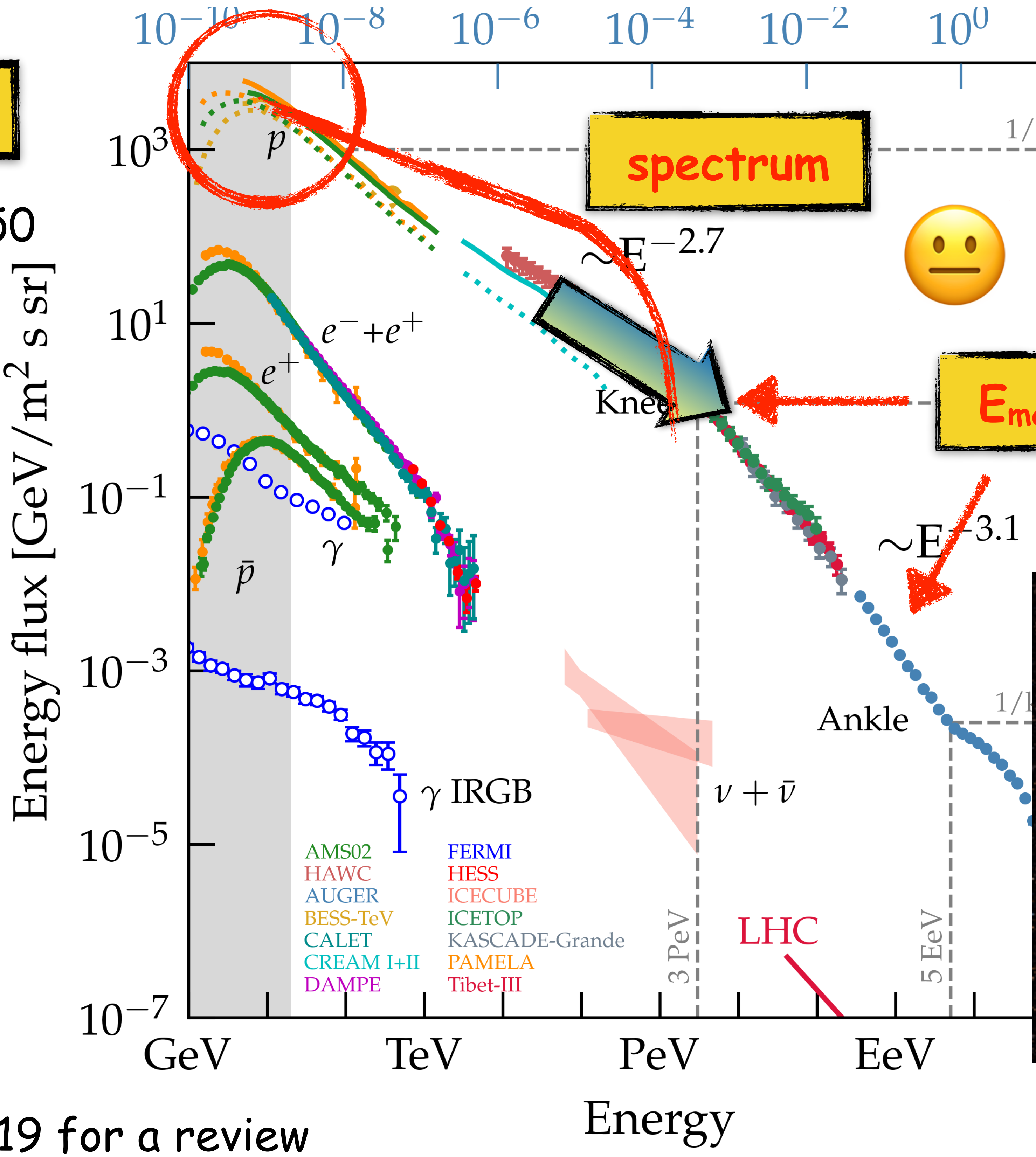
Ellison, Drury, Meyer (1997)

see also Caprioli+ 2017

Diffusive shock acceleration at strong SNR shocks

energetics

ter Haar 1950



spectrum

B-field amplification

Bell 2004

E$_{max}$?

SNRs

see Gabici+ 2019 for a review

Fig. from Evoli 2018

Diffusive shock acceleration at strong SNR shocks

😋

energetics

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Non-linear DSA

Zirakashvili&Ptuskin, Caprioli…

😐

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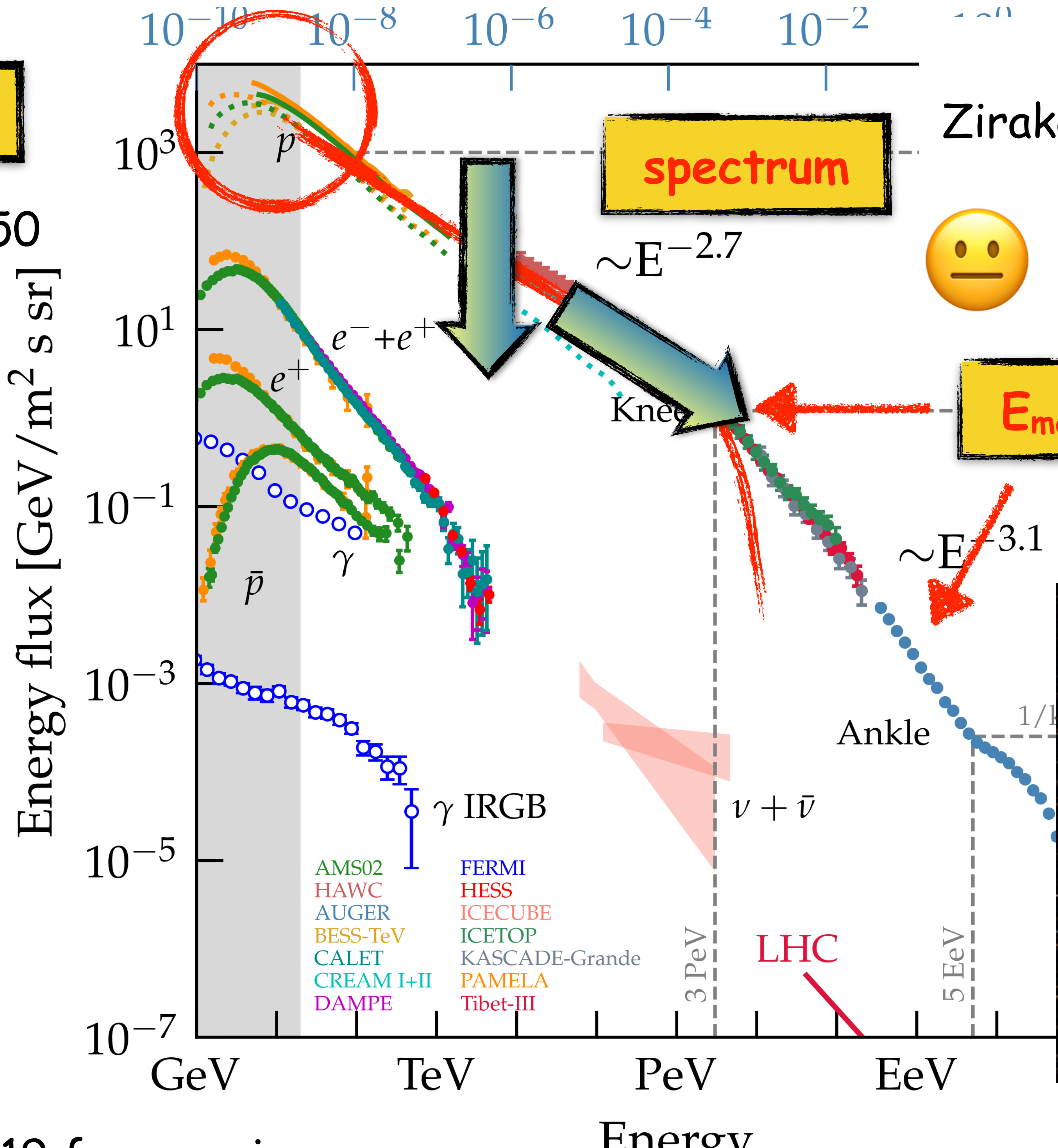

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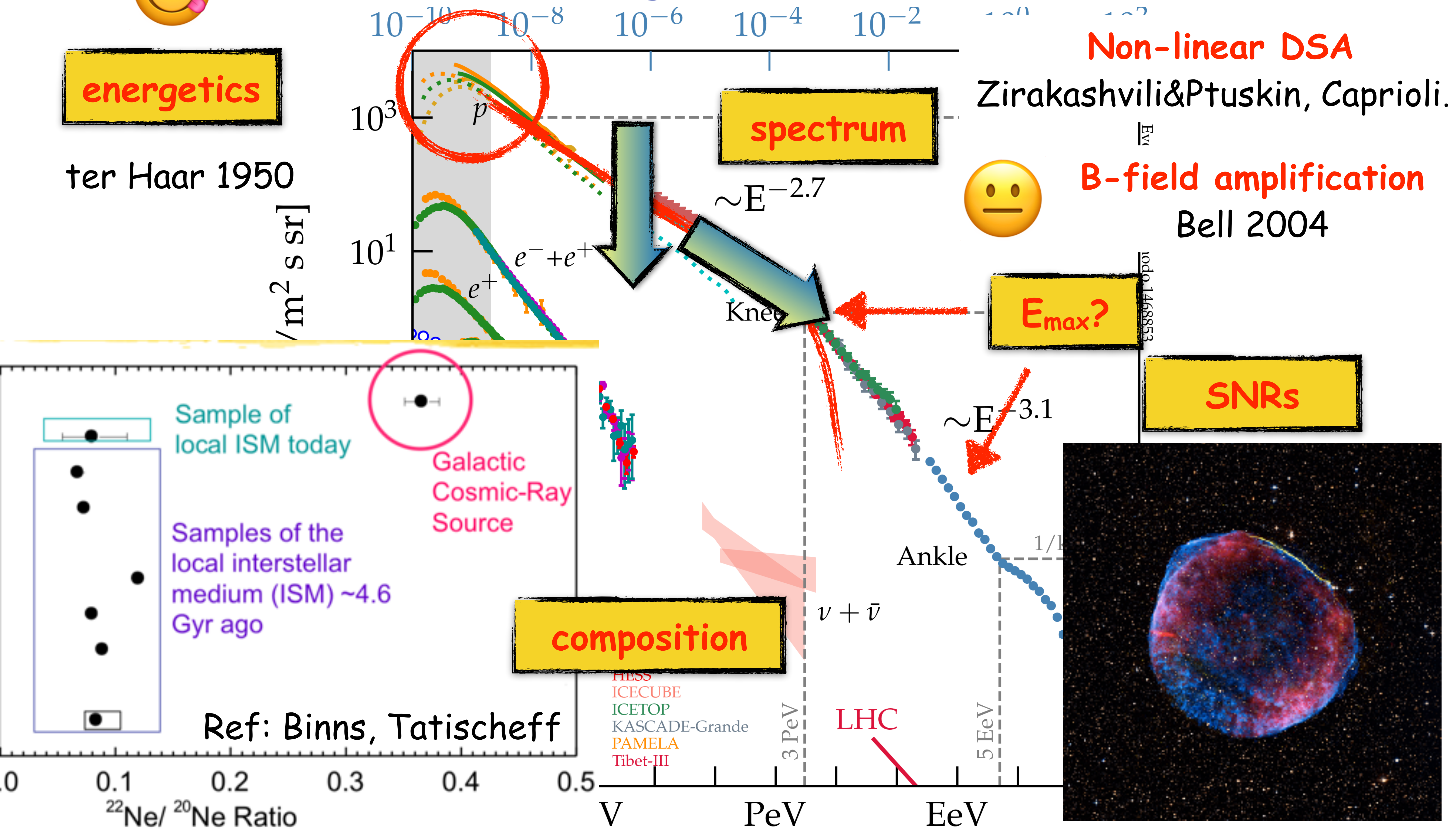

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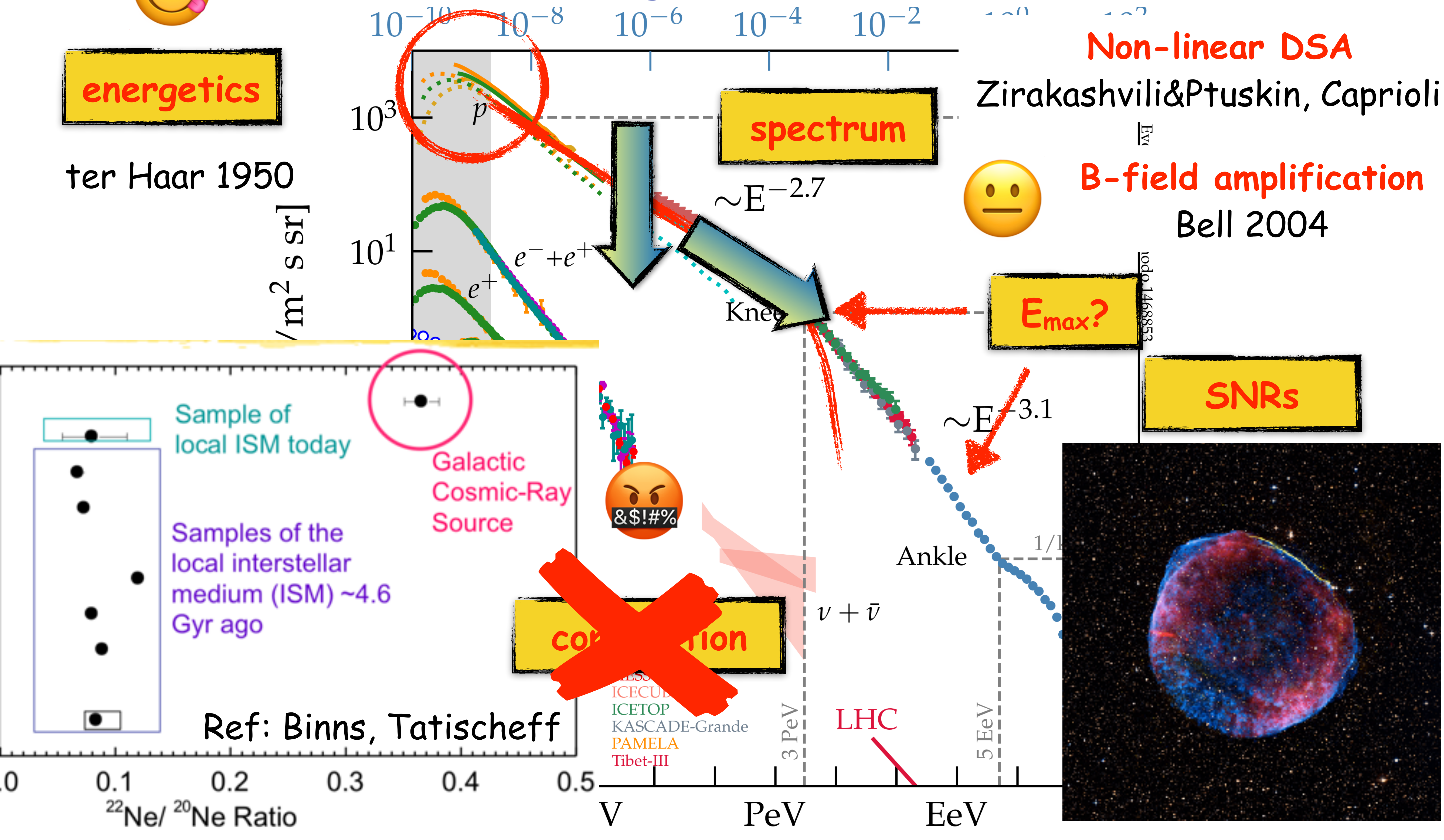

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~~co ion~~

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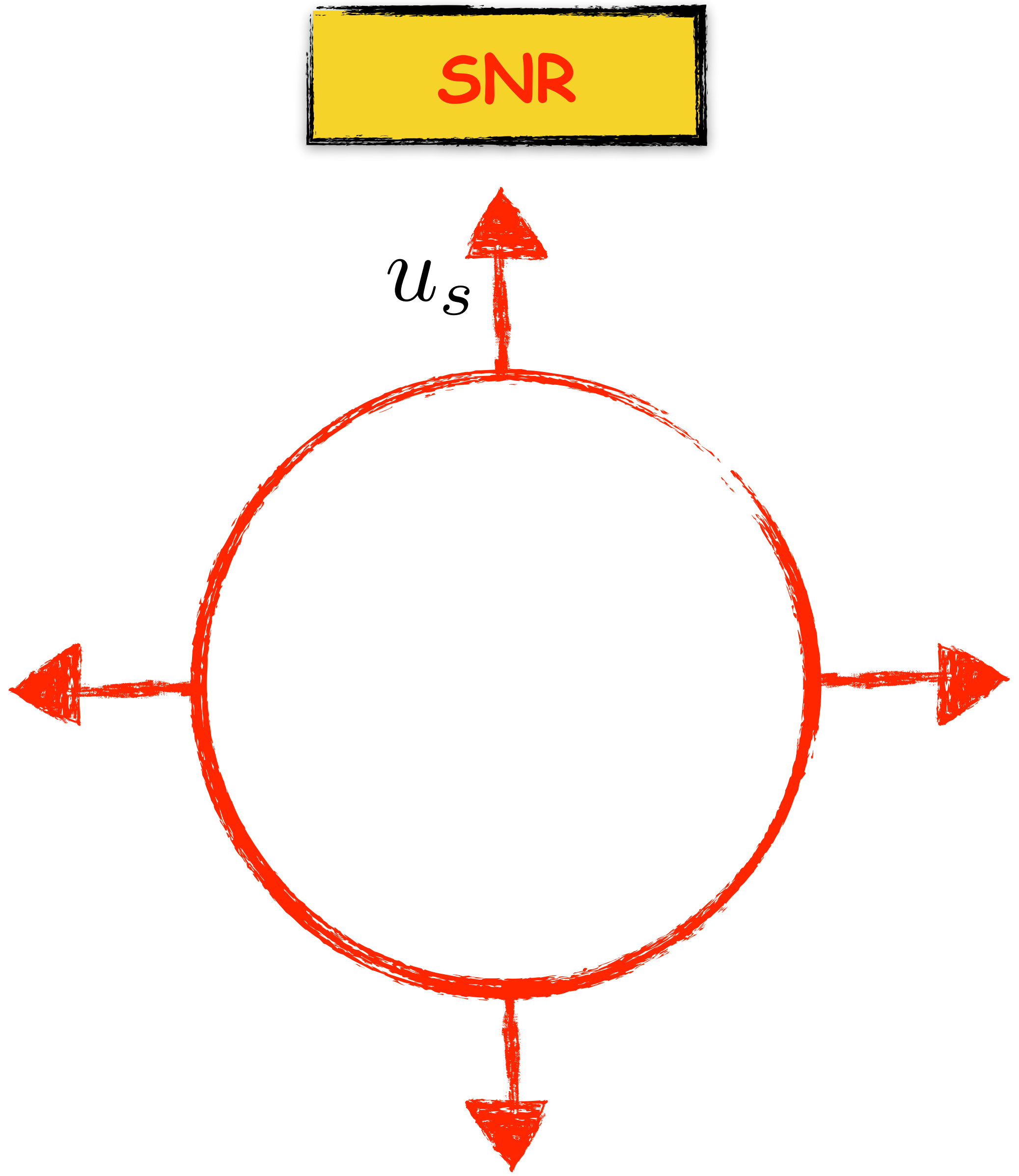
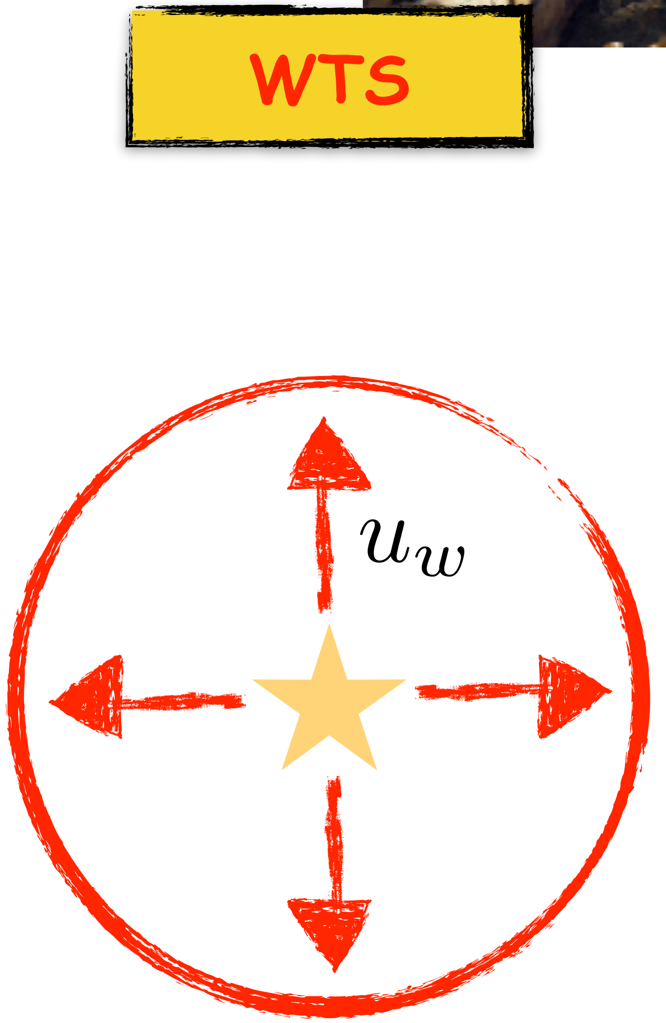
Stellar wind termination shocks

Cassé & Paul 1980, 1982 — Cesarsky & Montmerle 1983



SNR



WTS

analogy with solar WTS (Parker, Jokipii...) + DSA (BOBALSKy...)

Stellar wind termination shocks

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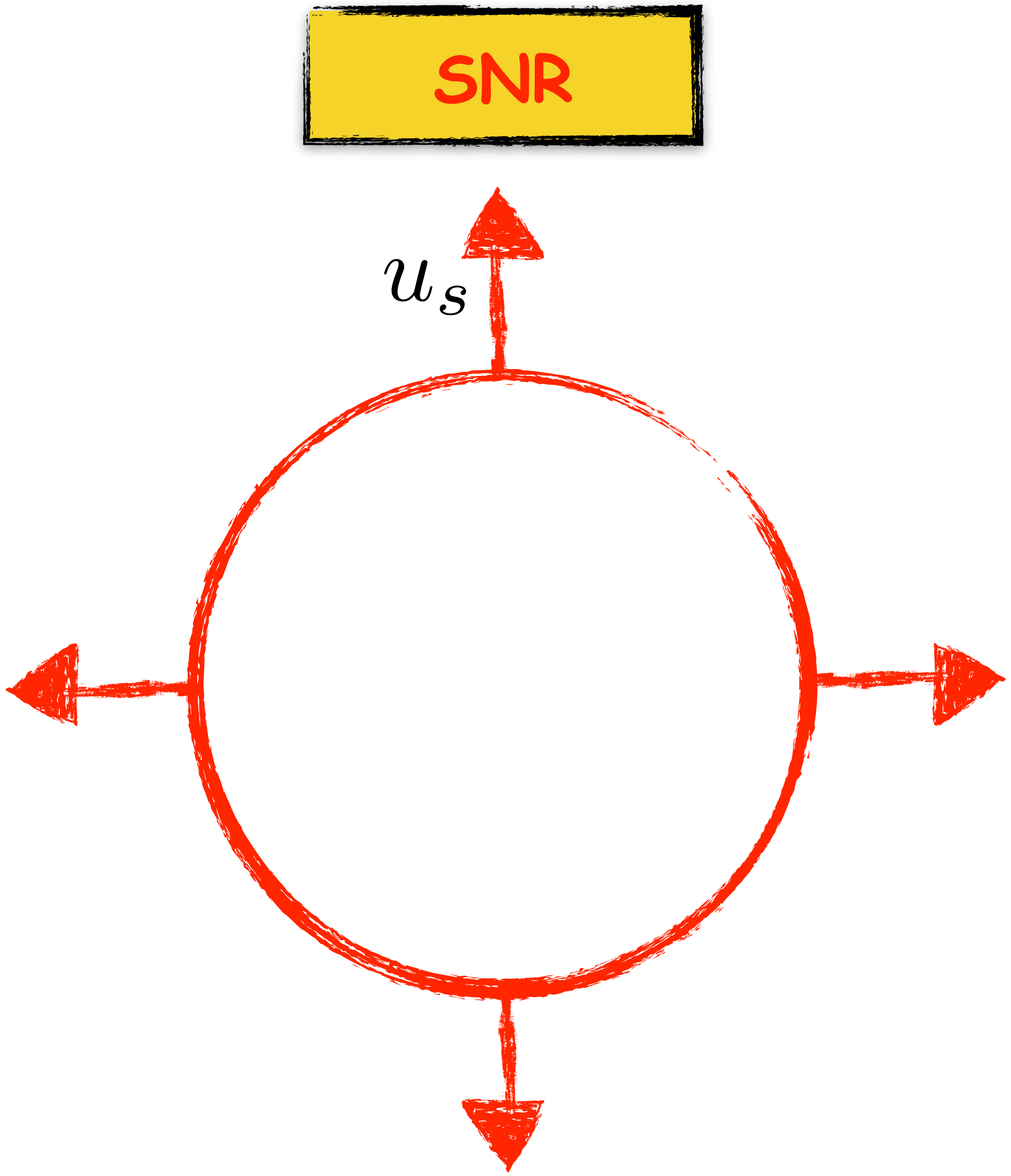
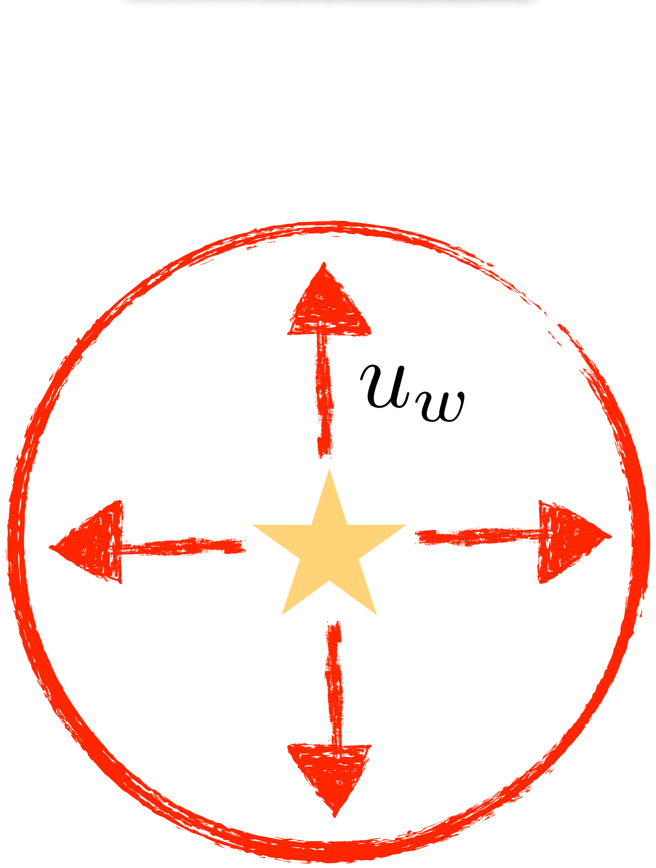


$$u_s \approx u_w$$

WTS



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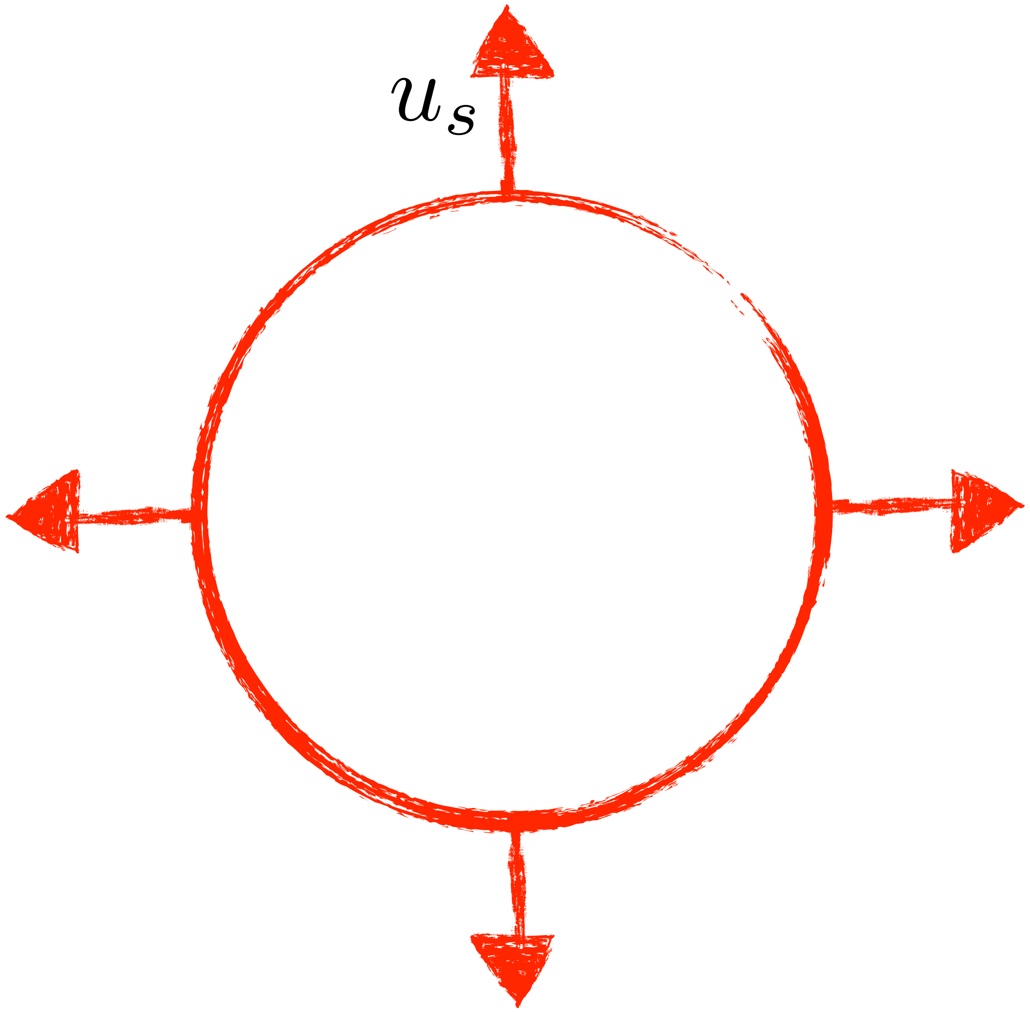

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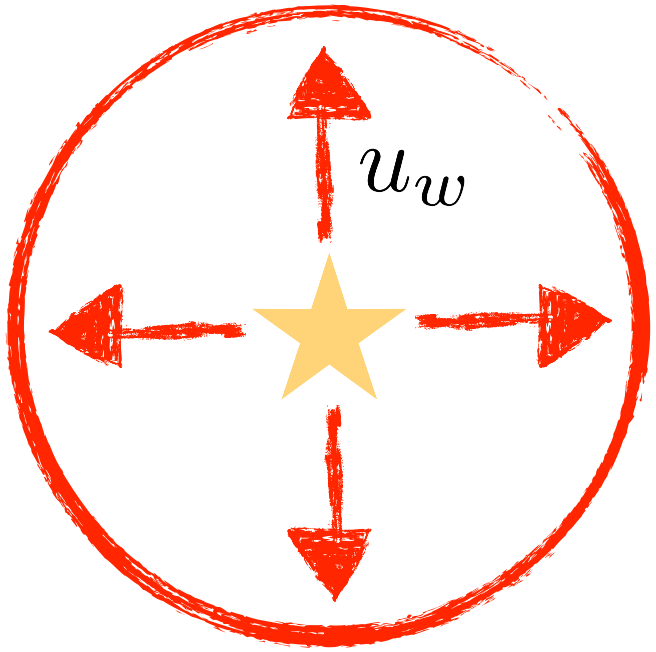

analogy with solar WTS (Parker, Jokipii…) + DSA (BOBALSKy…)

Bonus: Wolf-Rayet WTR are enriched in ^{22}Ne —> composition 😎(with dilution)

Energy problem

Cassé & Paul 1980, 1982 — Cesarsky & Montmerle 1983

stellar winds are radiation driven

$$\dot{M}_w u_w \approx \eta \frac{L_*}{c}$$

momentum carried by the wind

momentum carried by stellar photons

Energy problem

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total wind power dominated by the most massive stars

very steep mass-luminosity scaling

$$L_* \approx M_*^3$$

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$$\int \mathrm{d}t \; P_w \approx 10^{51} \mathrm{erg} \sim \mathrm{E_{SN}}$$

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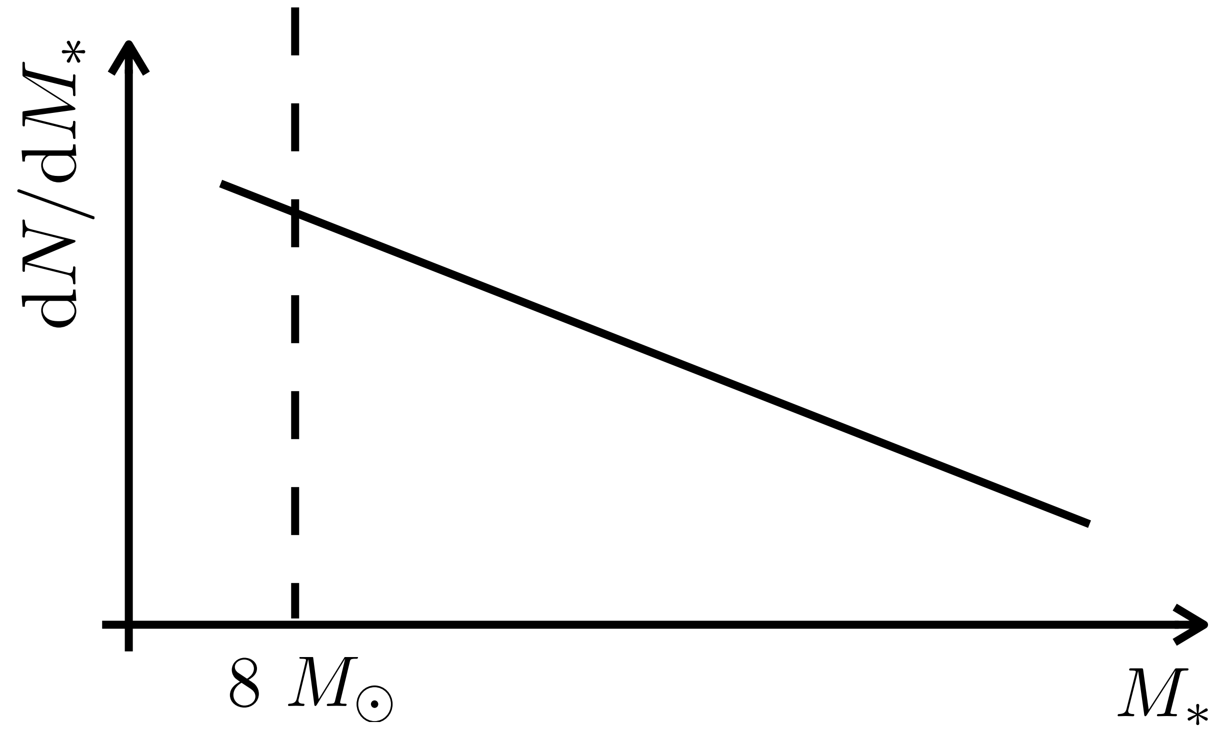

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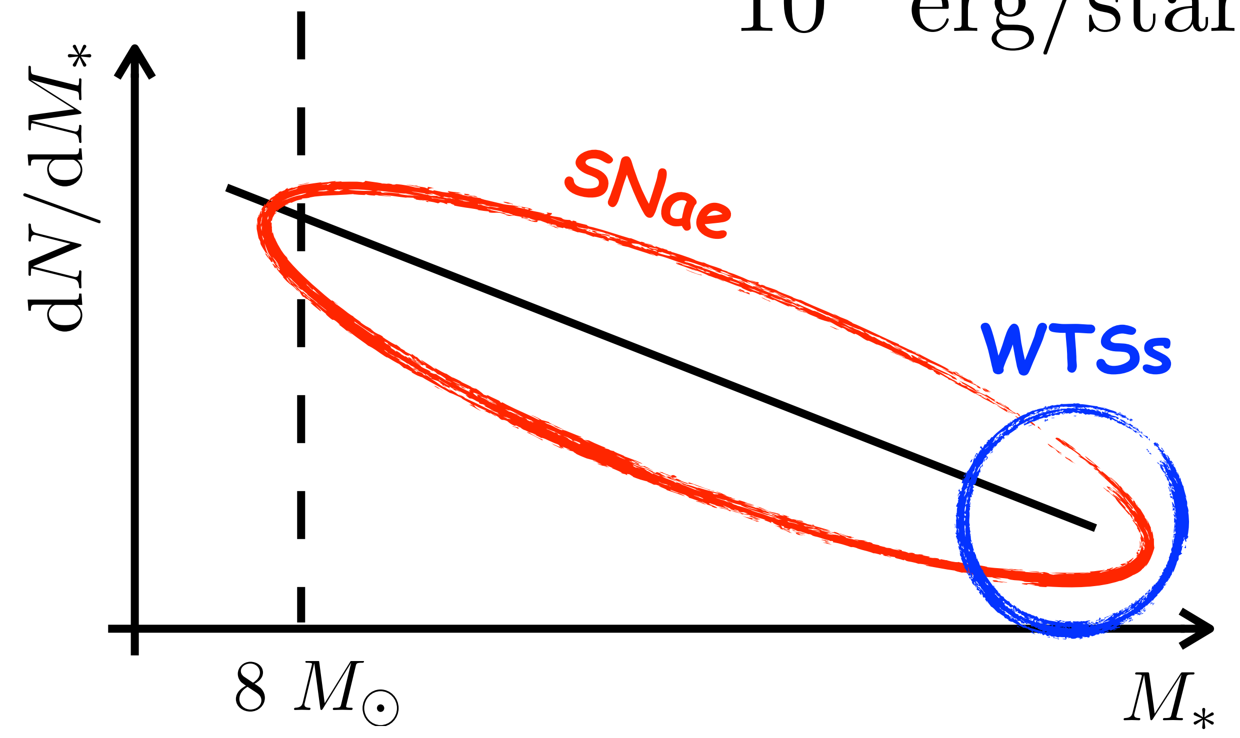
$10^{51}\mathrm{erg/star}$



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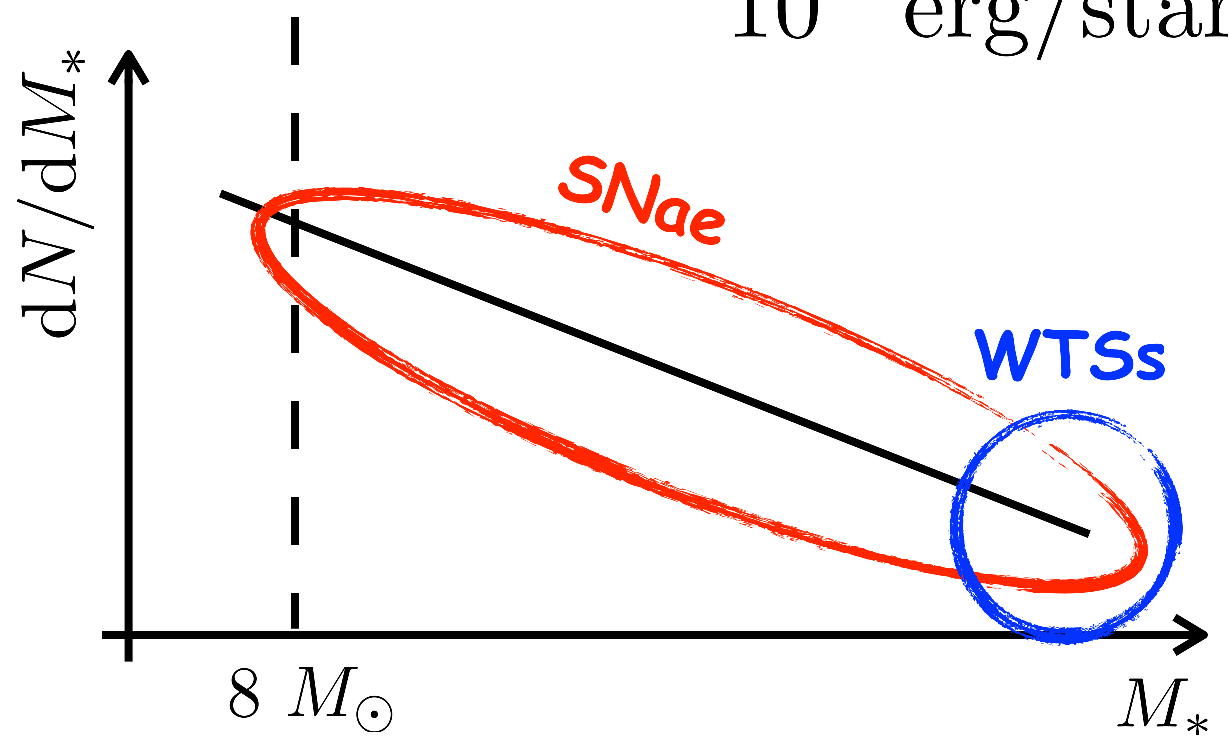
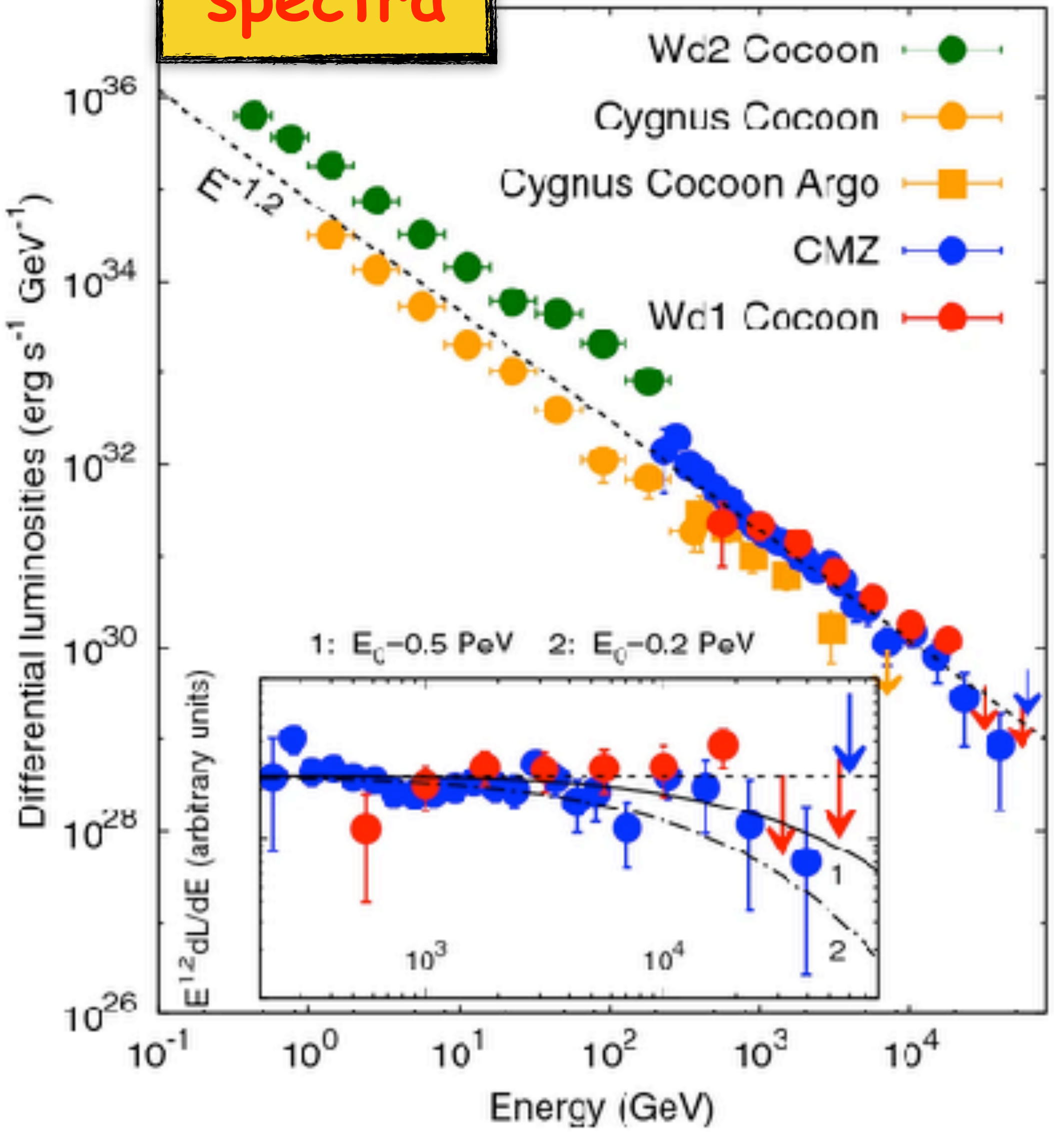
10^{51}erg/star



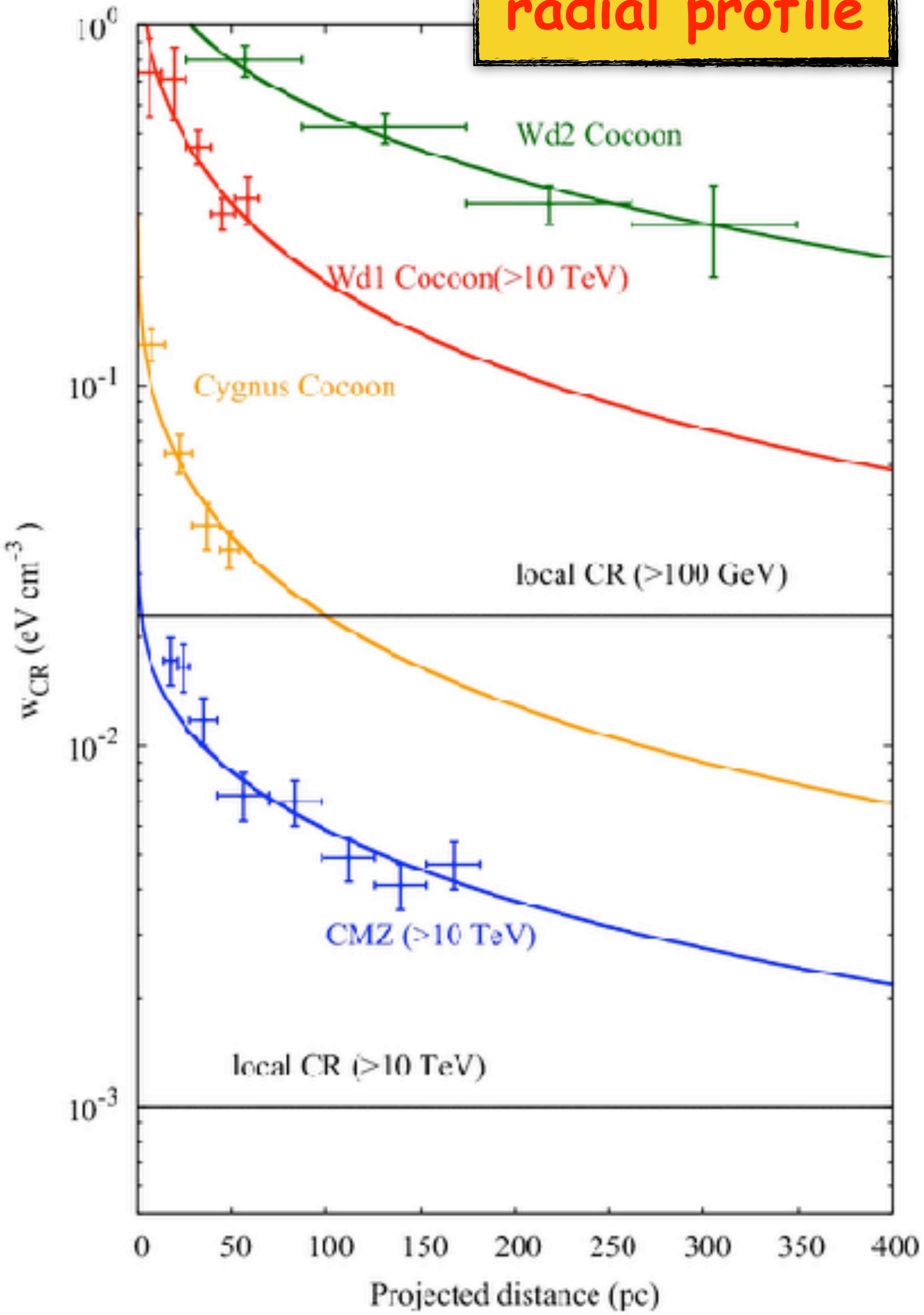
—> supernovae win by about a factor of 10 (caveat: failed SNae?)

Gamma rays around young star clusters

Aharonian+ 2019, plus several papers especially by Yang and collaborators



spectra



radial profile

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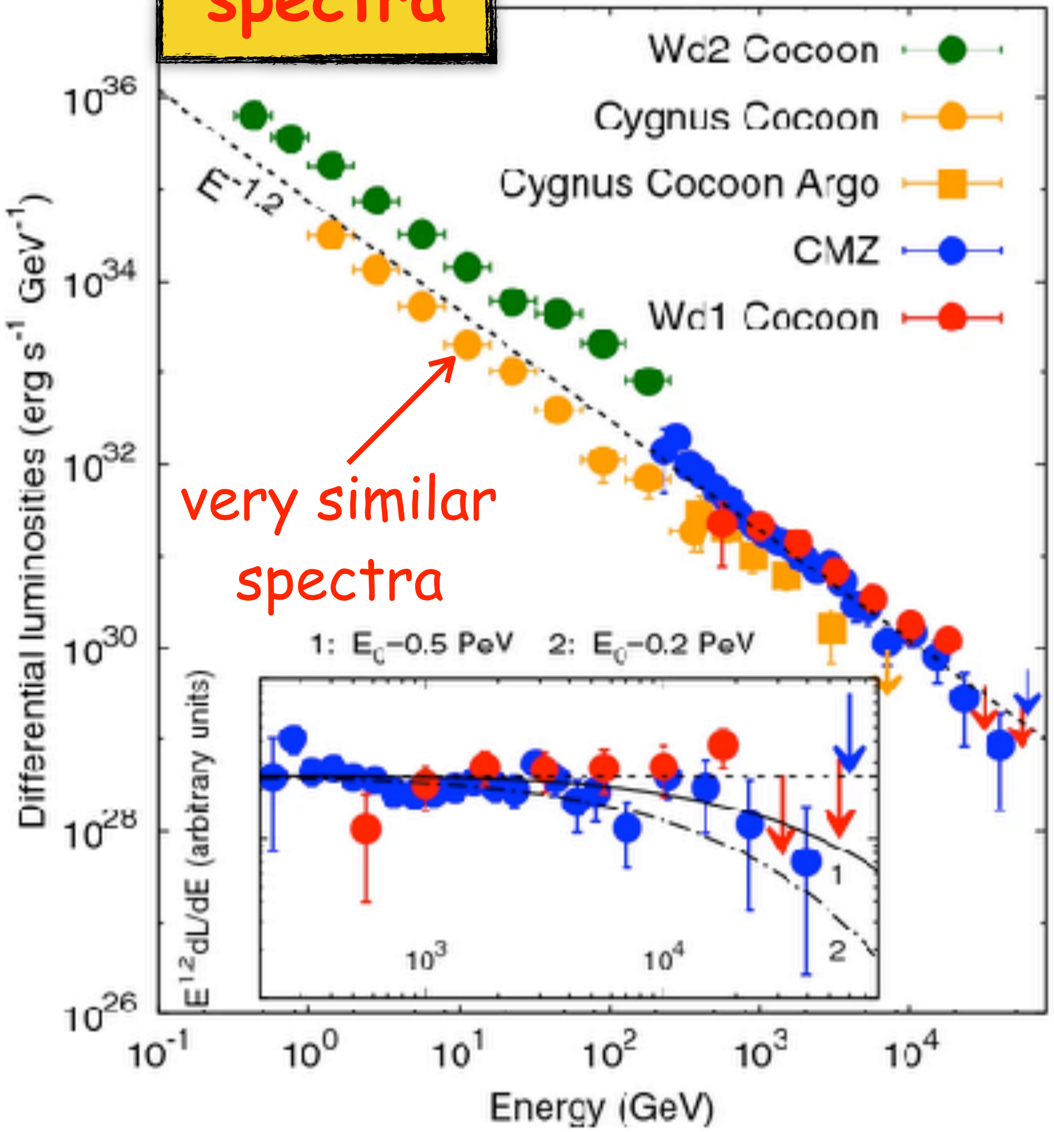
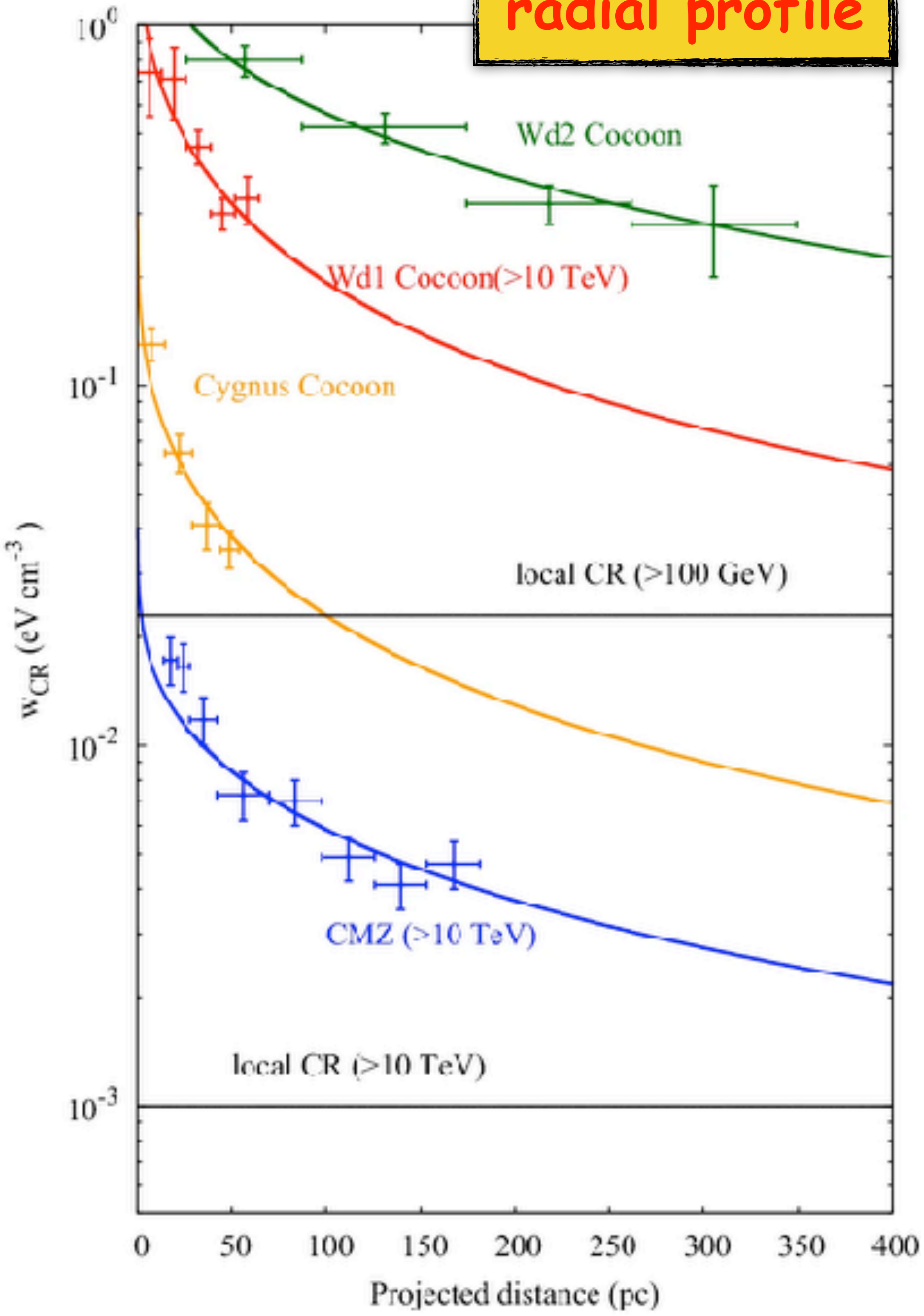


spectra

very similar spectra



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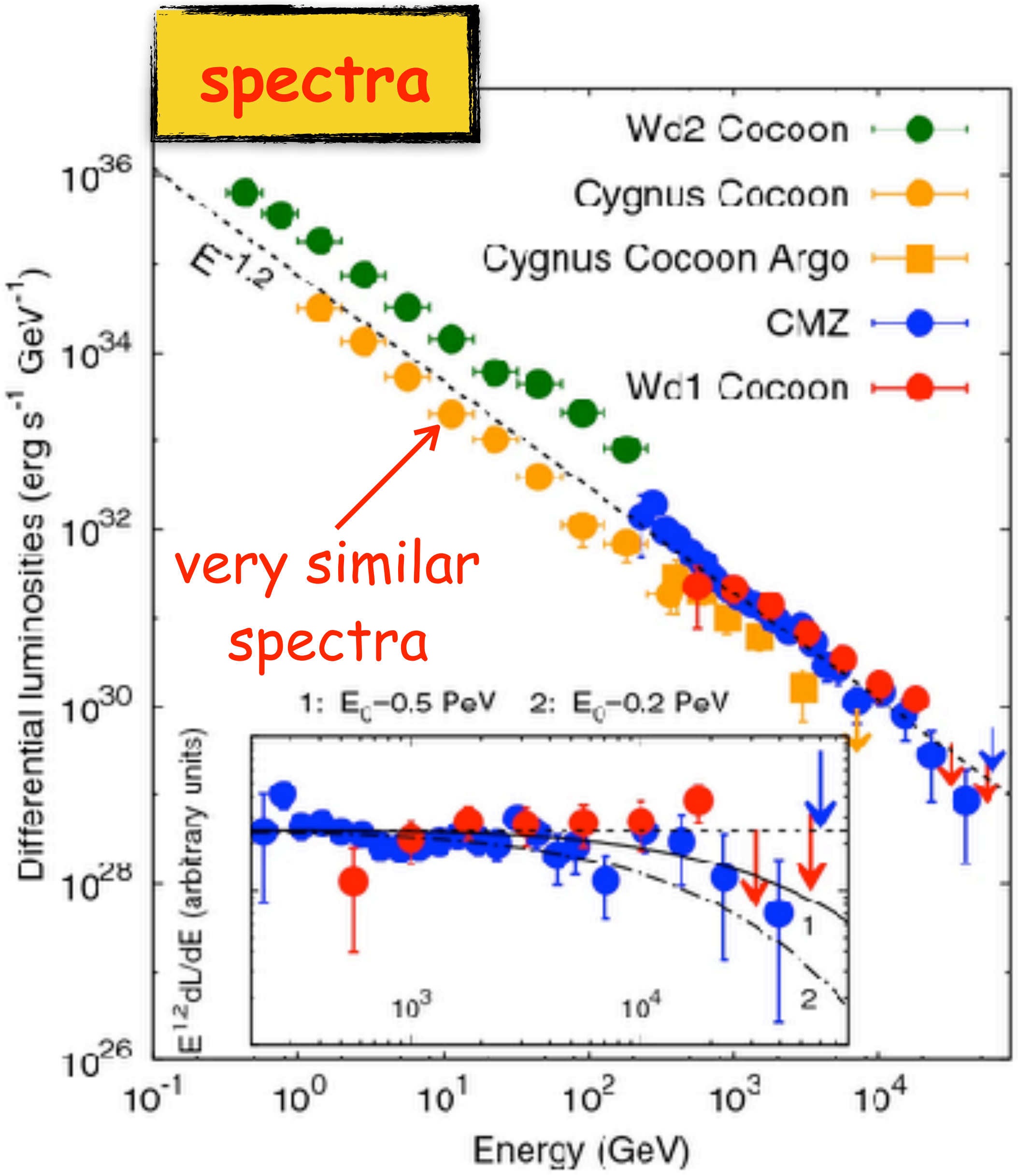

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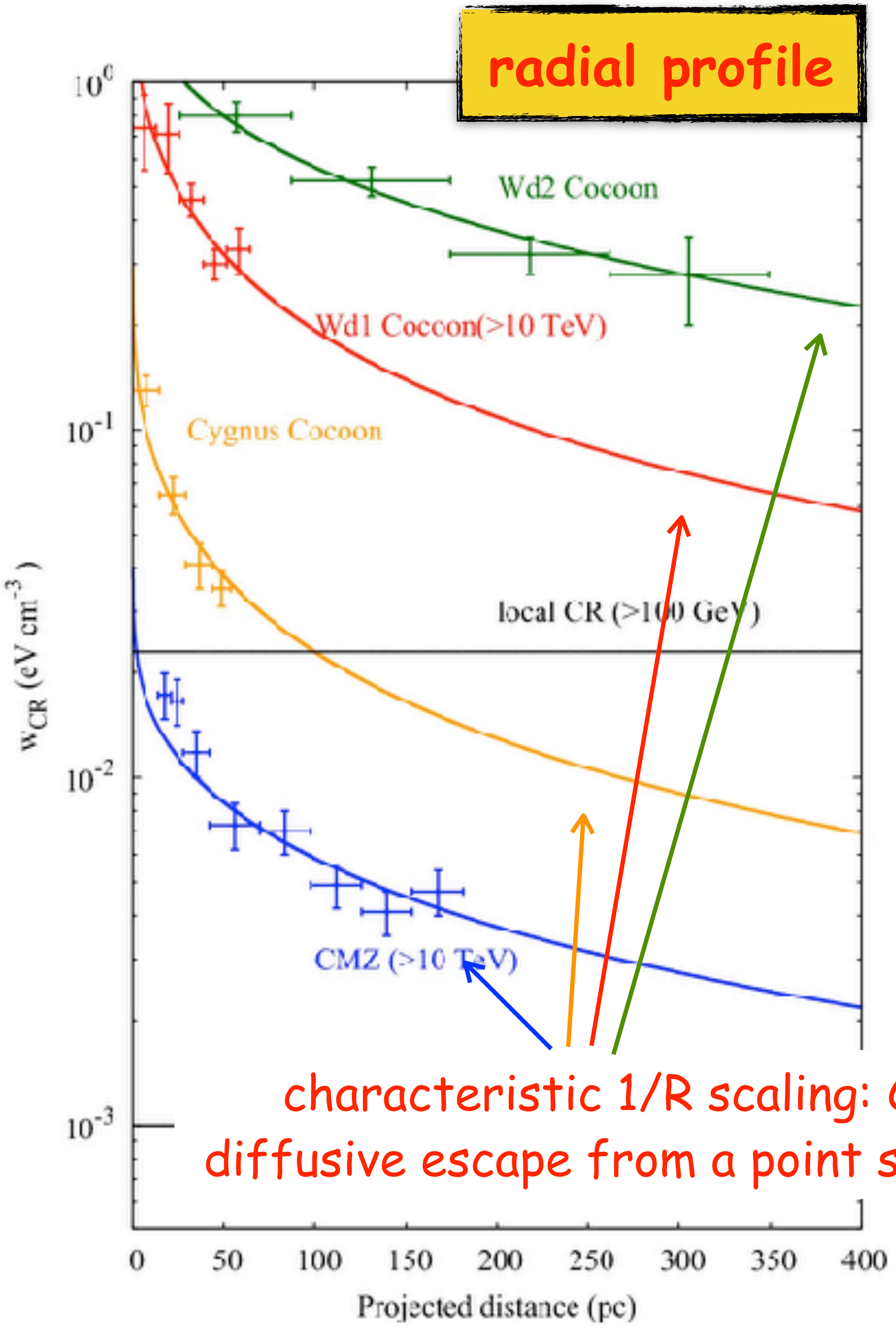

characteristic 1/R scaling: CR diffusive escape from a point source

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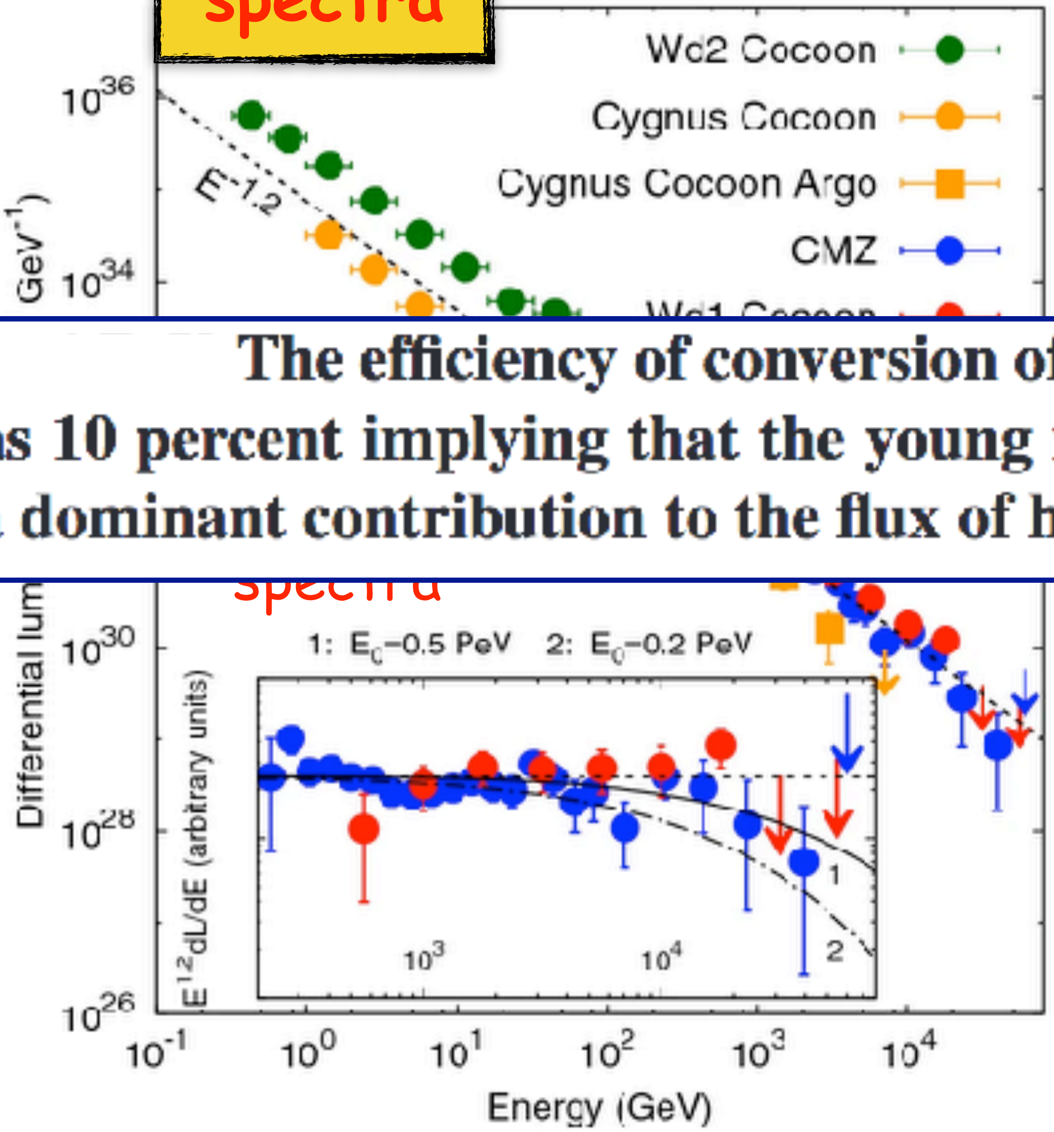
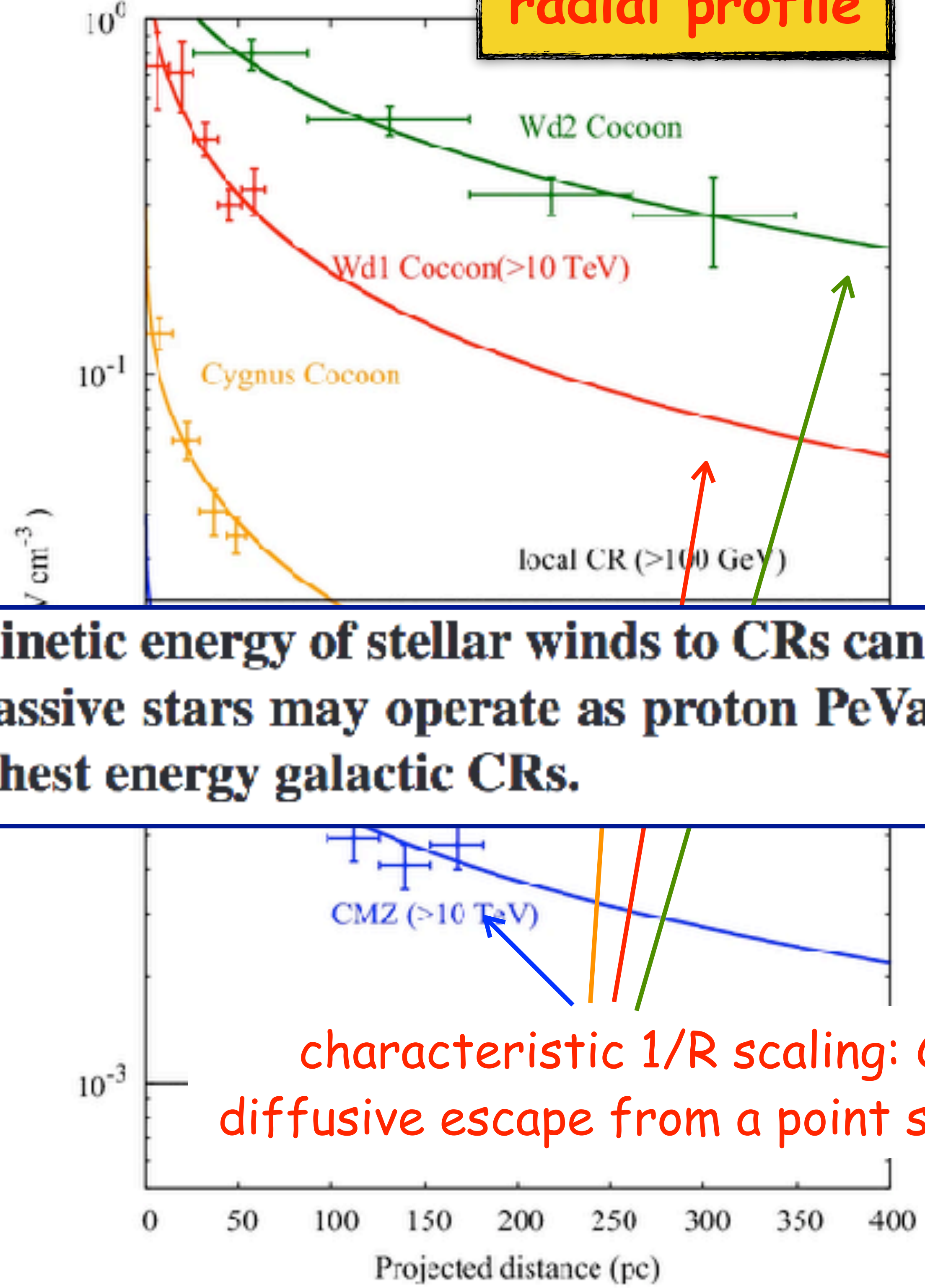


radial profile



> **The efficiency of conversion of kinetic energy of stellar winds to CRs can be as high as 10 percent implying that the young massive stars may operate as proton PeVatrons with a dominant contribution to the flux of highest energy galactic CRs.**

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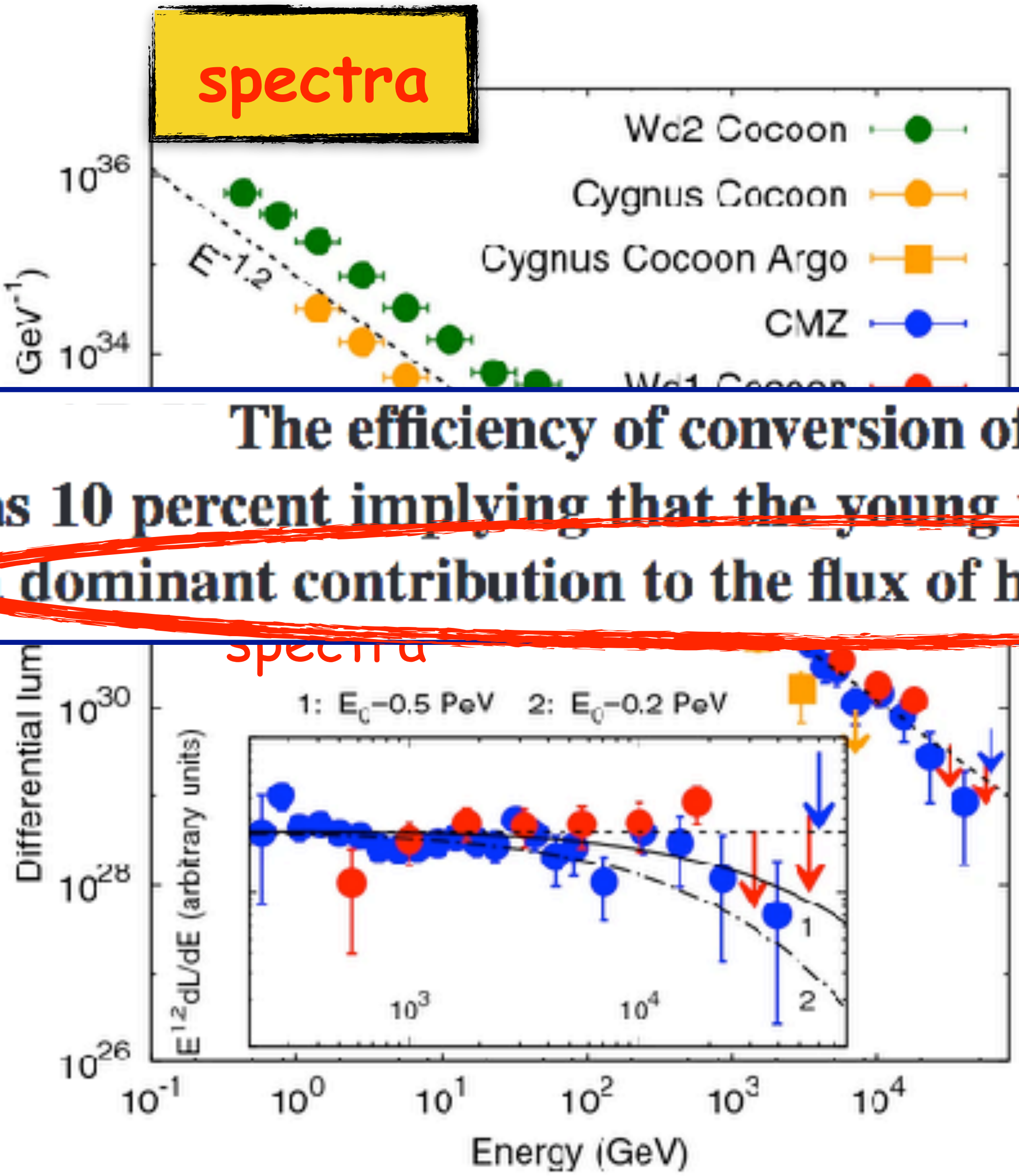

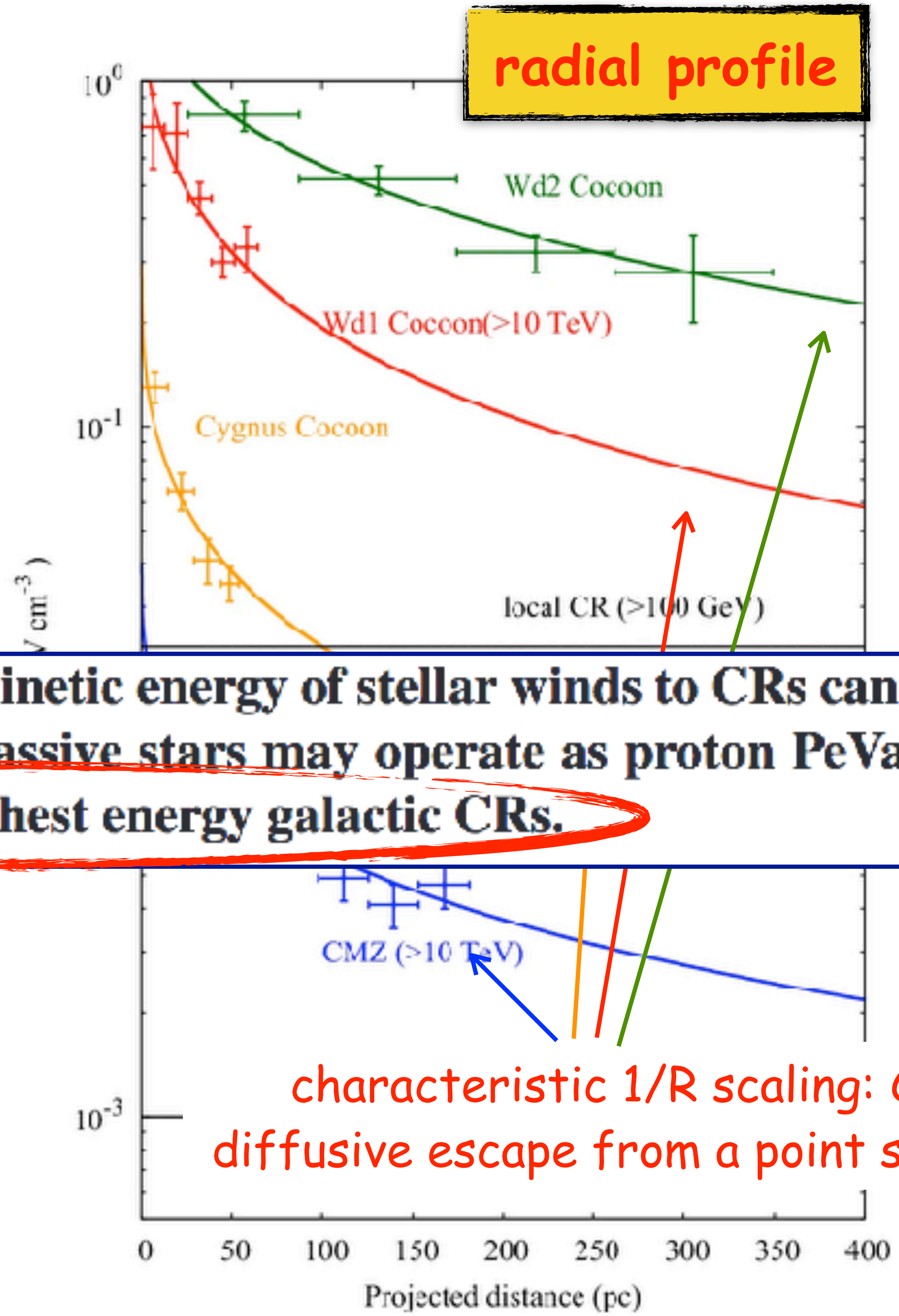

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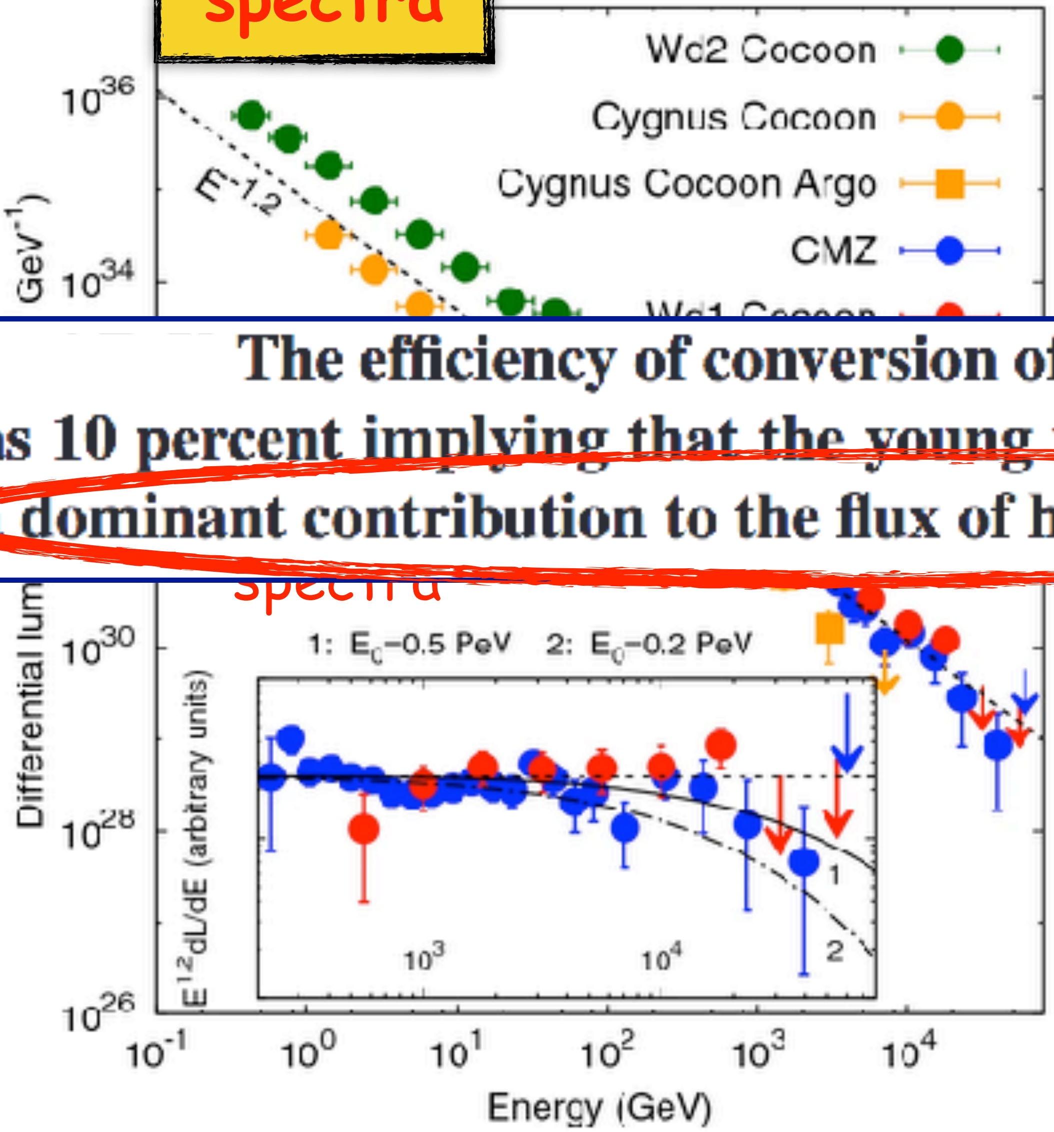
characteristic 1/R scaling: CR diffusive escape from a point source

Gamma rays around young star clusters

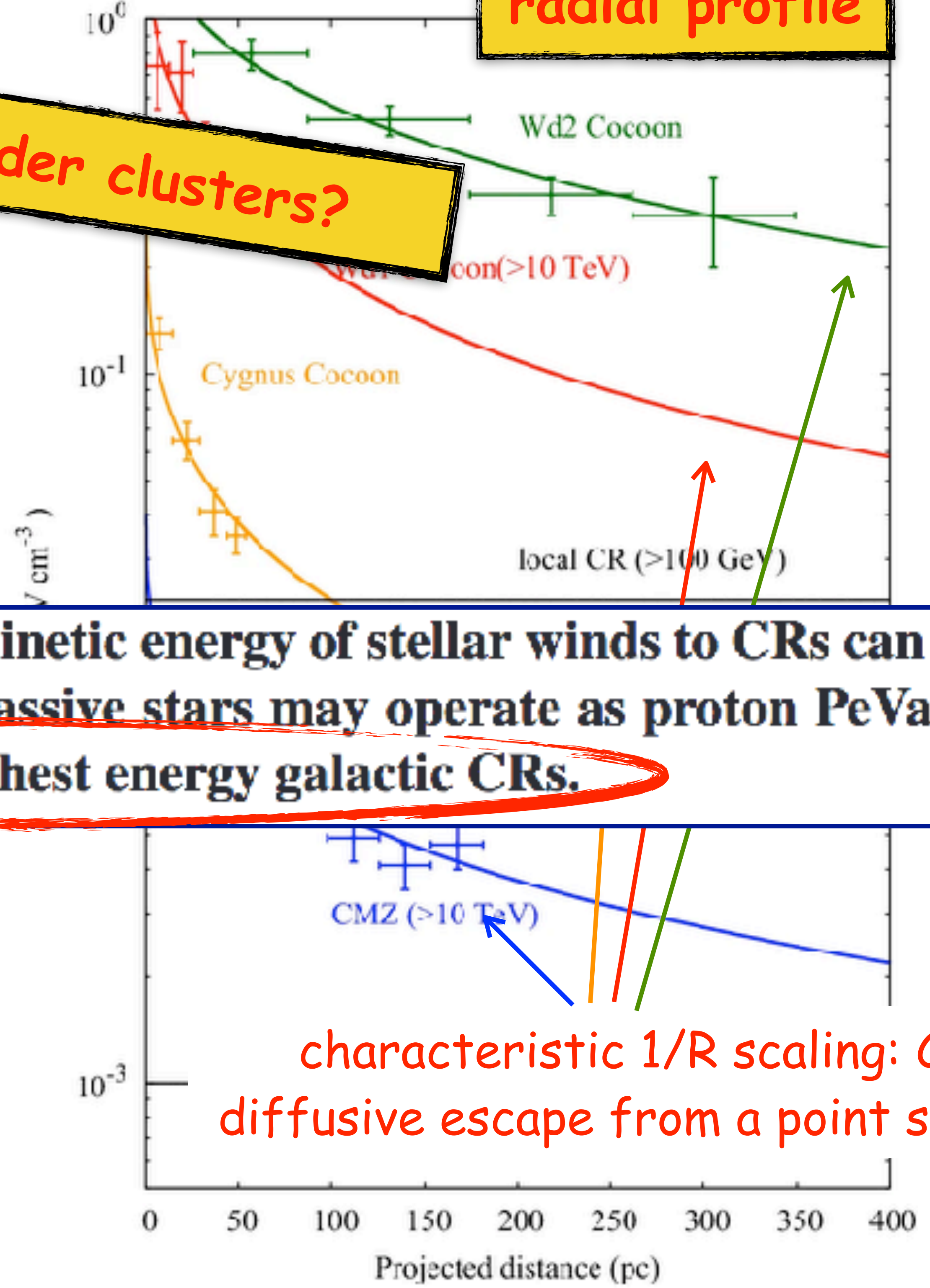
Aharonian+ 2019, plus several papers especially by Yang and collaborators

what about older clusters?

spectra



radial profile



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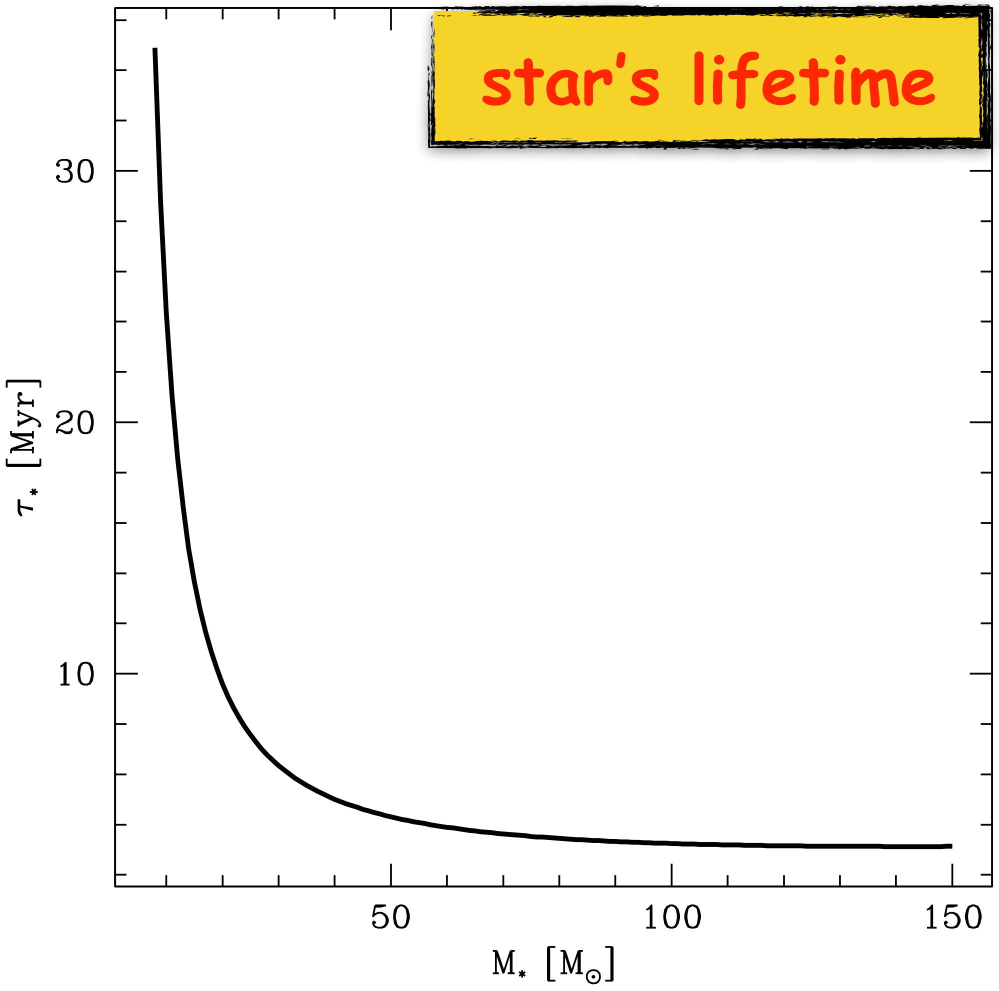
characteristic 1/R scaling: CR diffusive escape from a point source

Energy injection at star clusters



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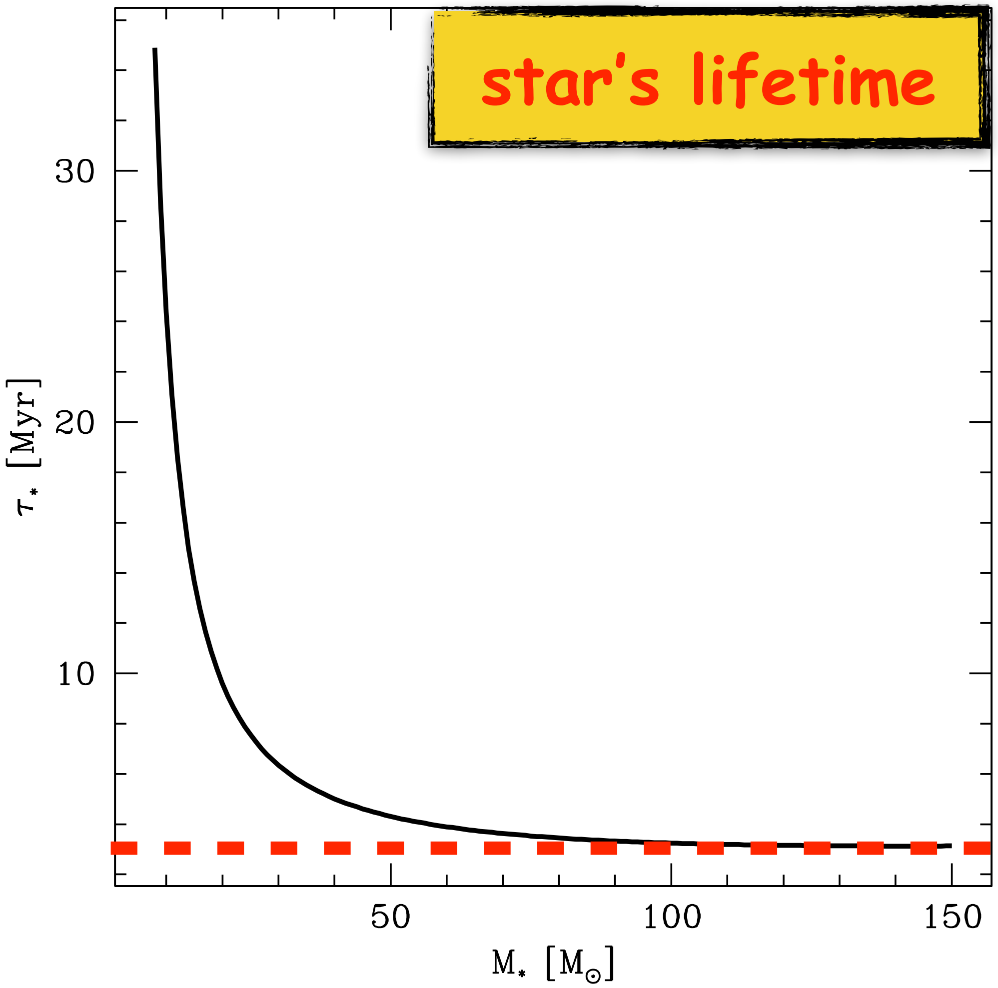
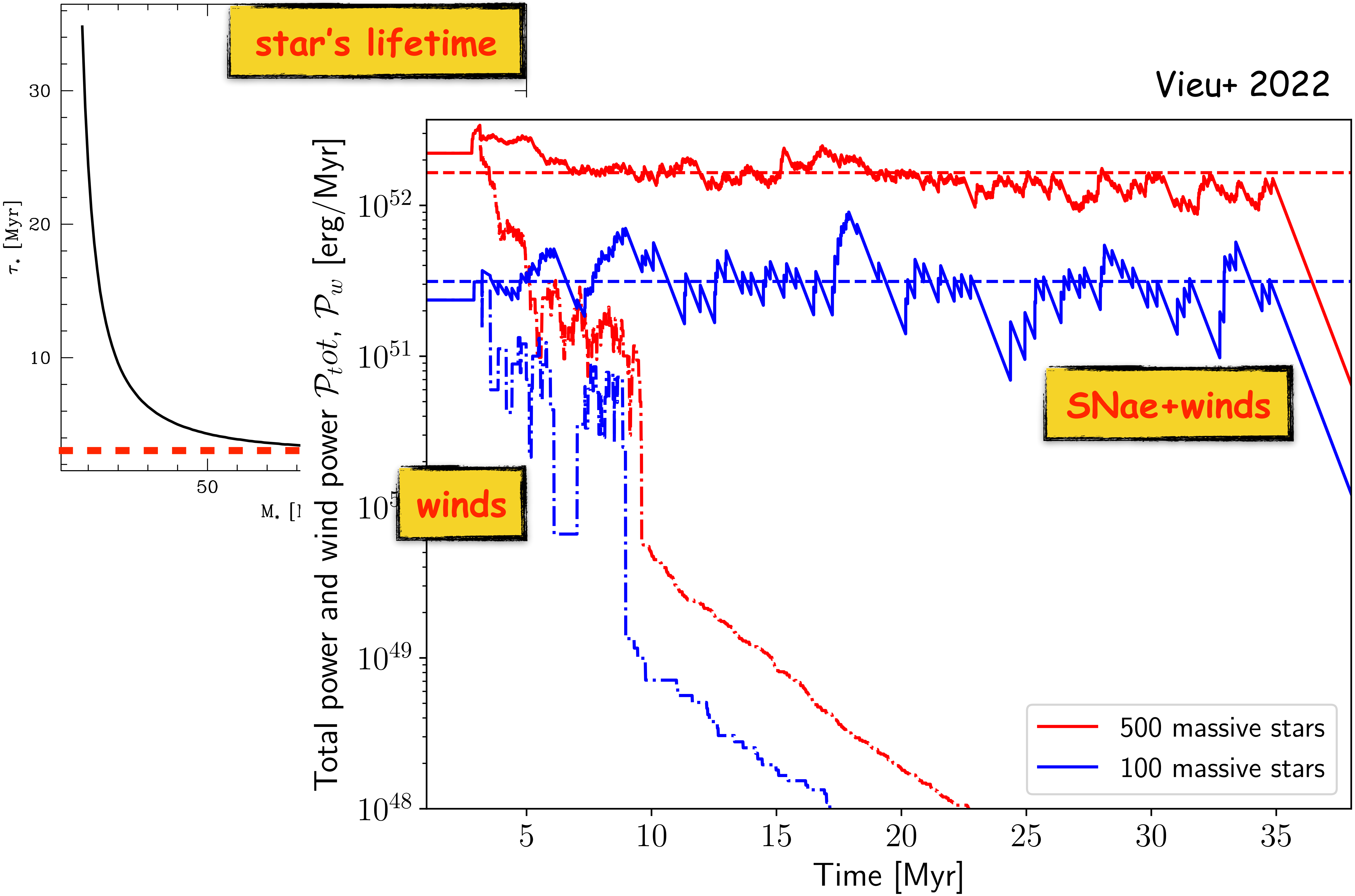


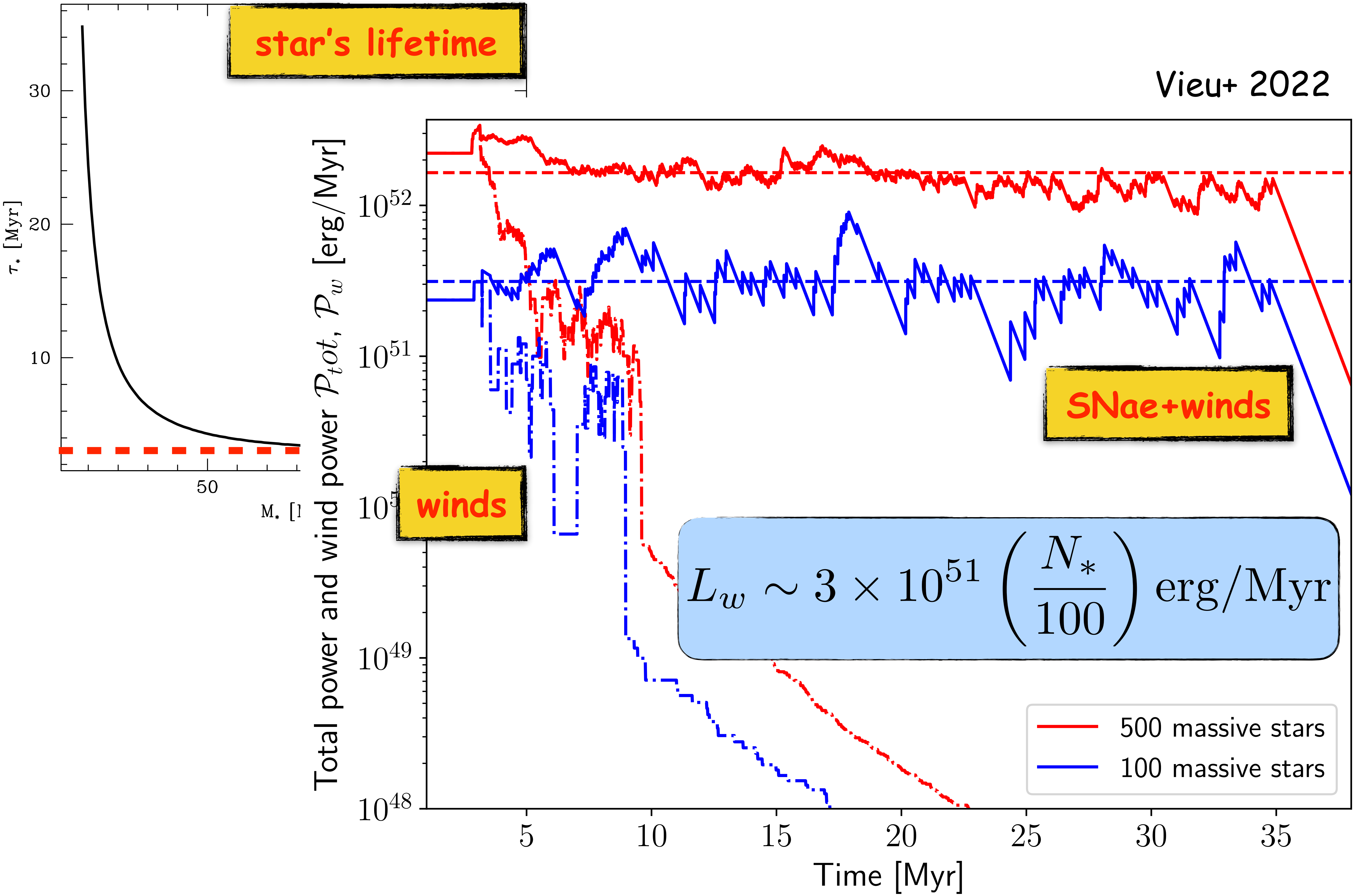
t < 3 Myr —> only stellar winds

Energy injection at star clusters



Vieu+ 2022

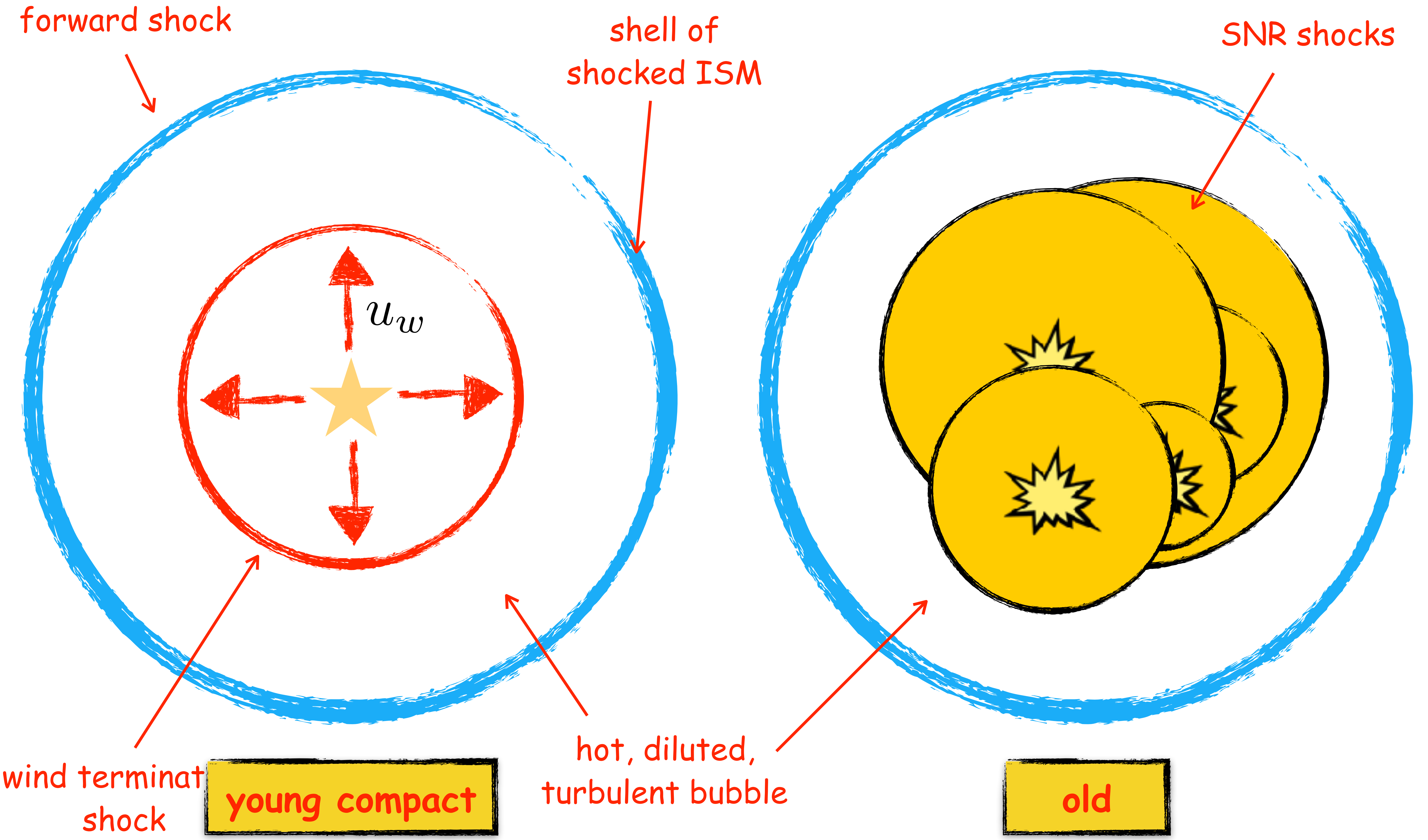
Energy injection at star clusters



$$L_w \sim 3 \times 10^{51} \left(\frac{N_*}{100} \right) \mathrm{erg/Myr}$$

Interstellar bubbles around star clusters

Castor+ 75, Weaver+ 77, McCray&Kafatos 87, Mac Low&McCray 88, Koo&McKee 92...



forward shock

shell of shocked ISM

SNR shocks

wind terminat shock

young compact

hot, diluted, turbulent bubble

old

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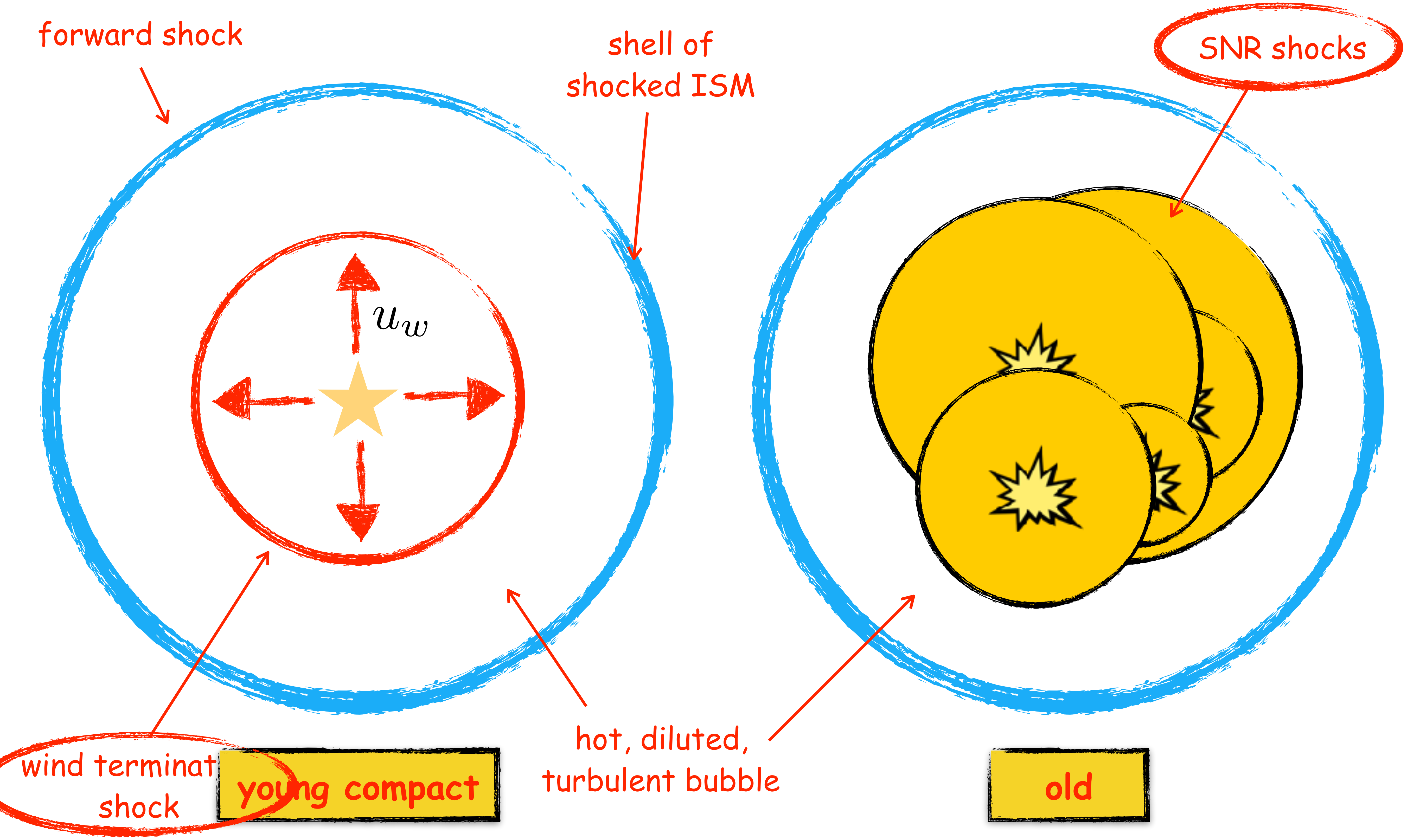

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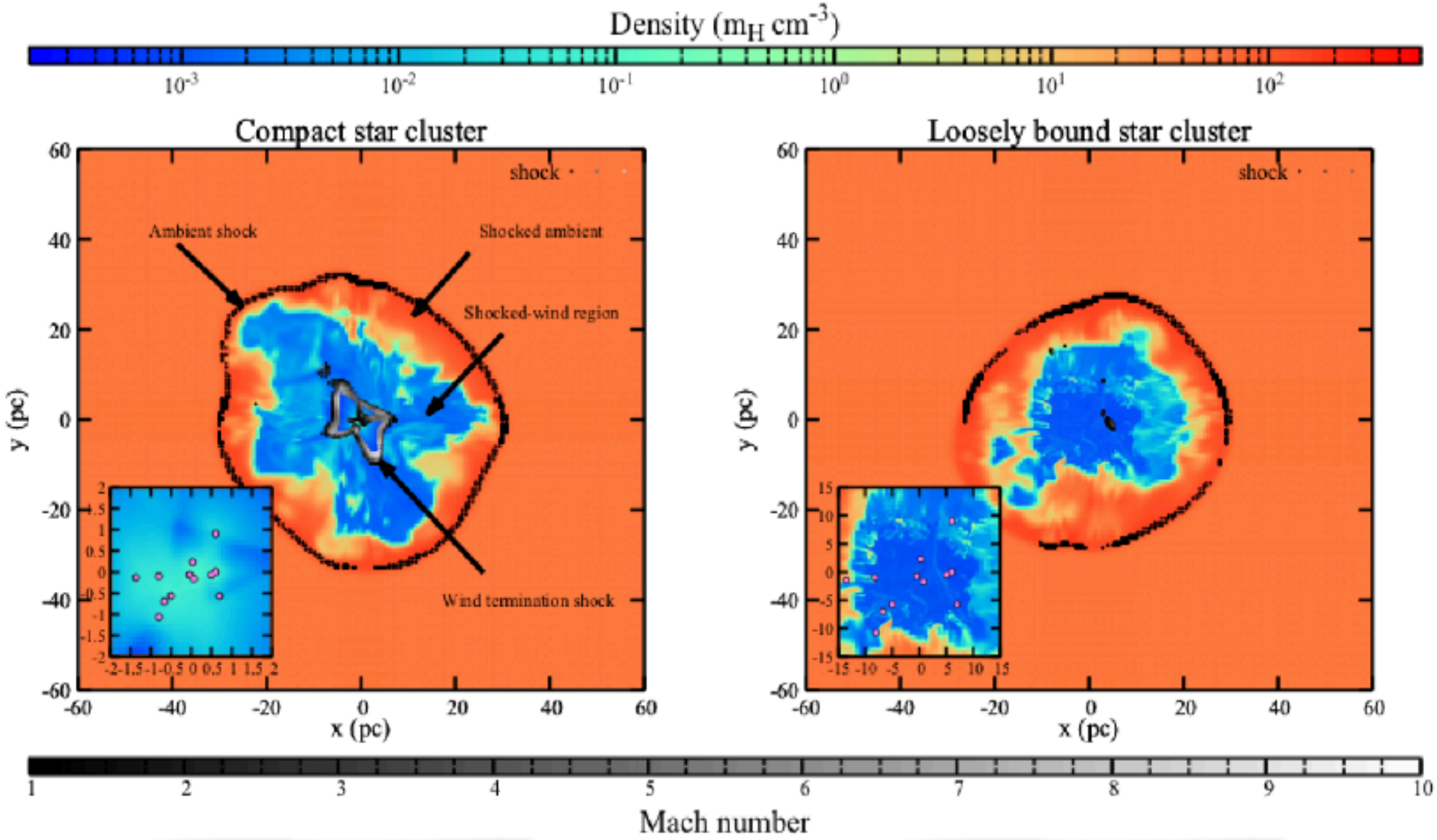
Particle acceleration at WTSs: spectrum

strong WTS: Volk&Forman 82, Webb+ 85, Morlino+ 21



Gupta+ 2020

compact cluster

loose cluster

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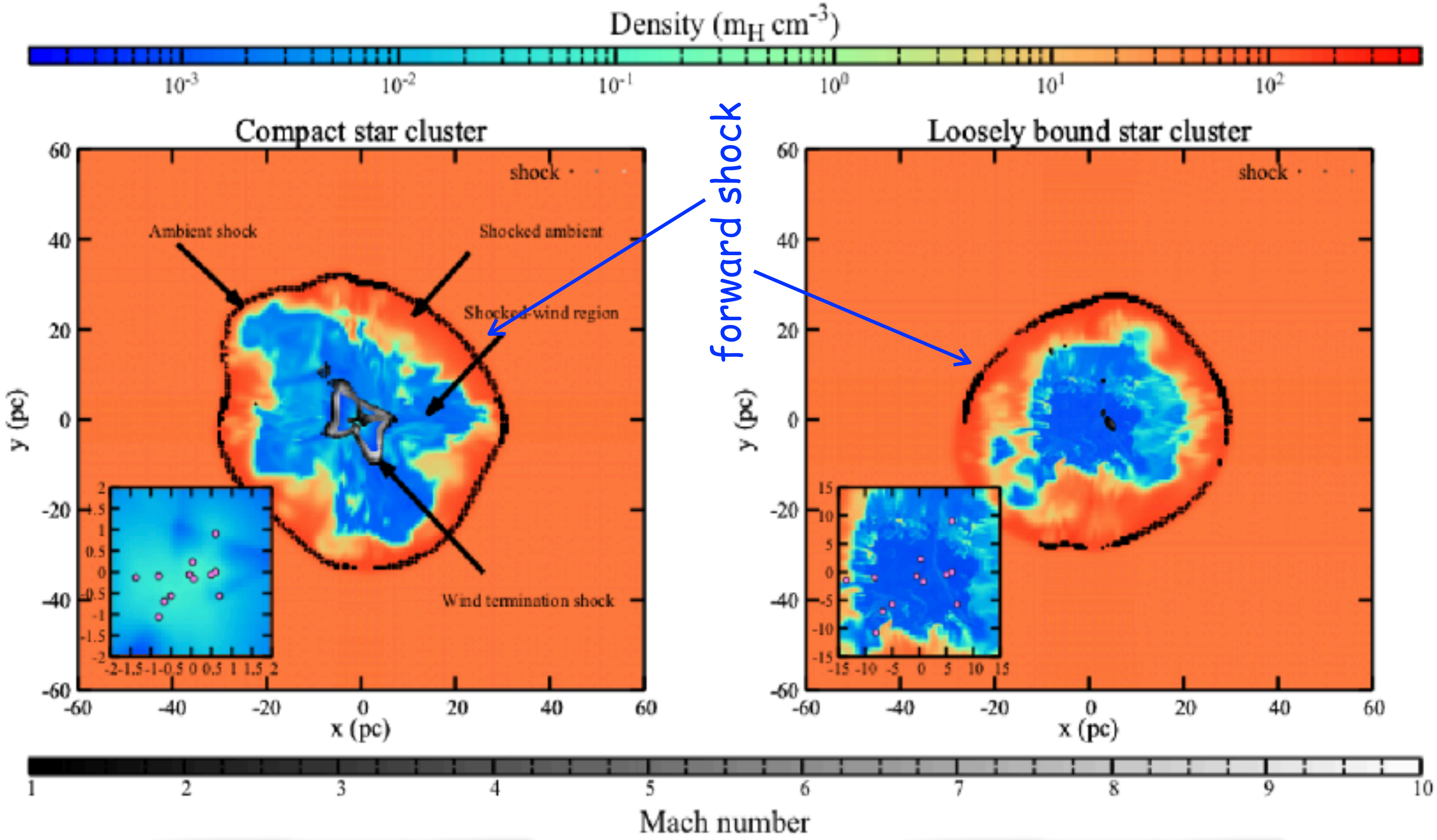

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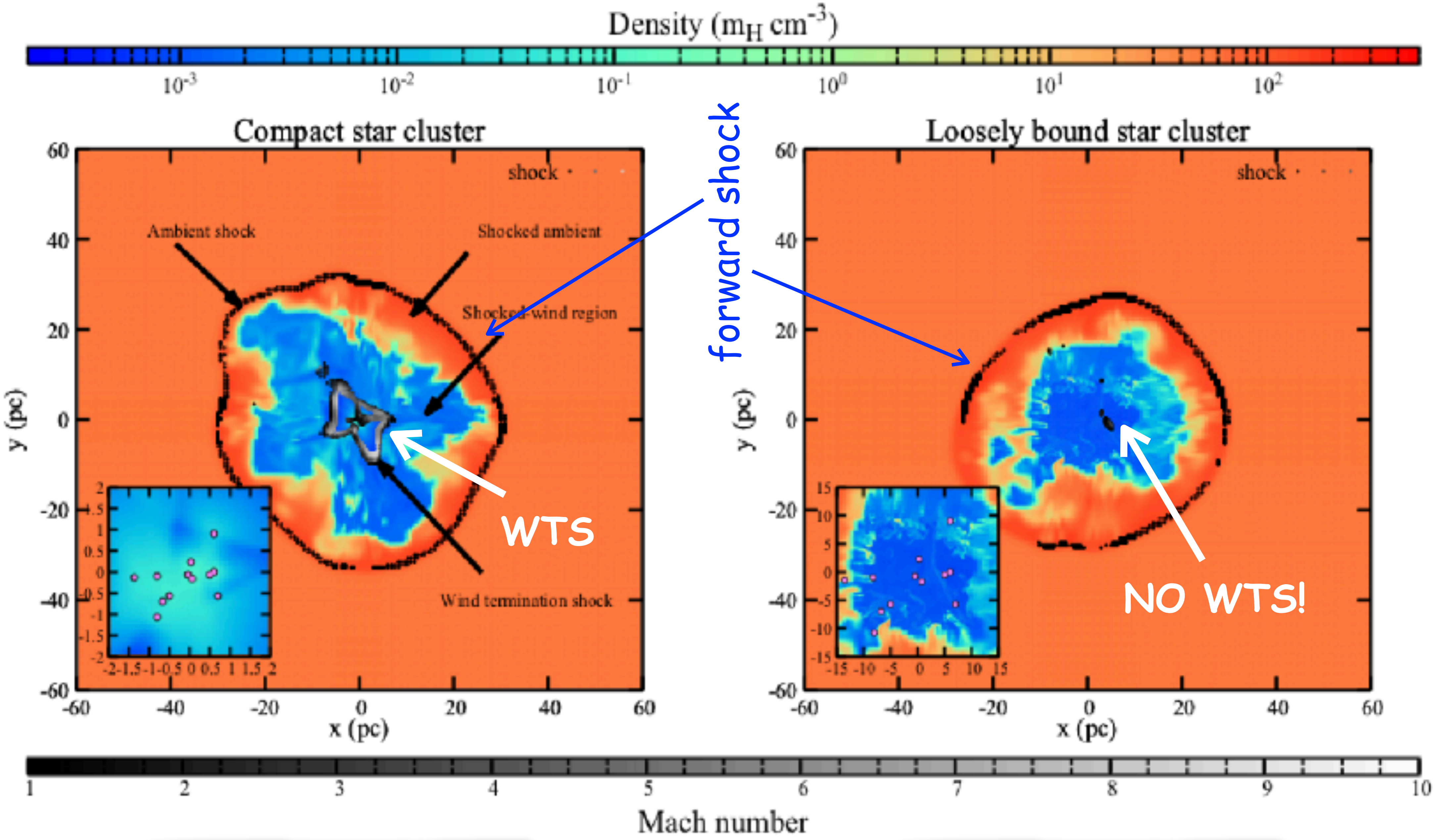

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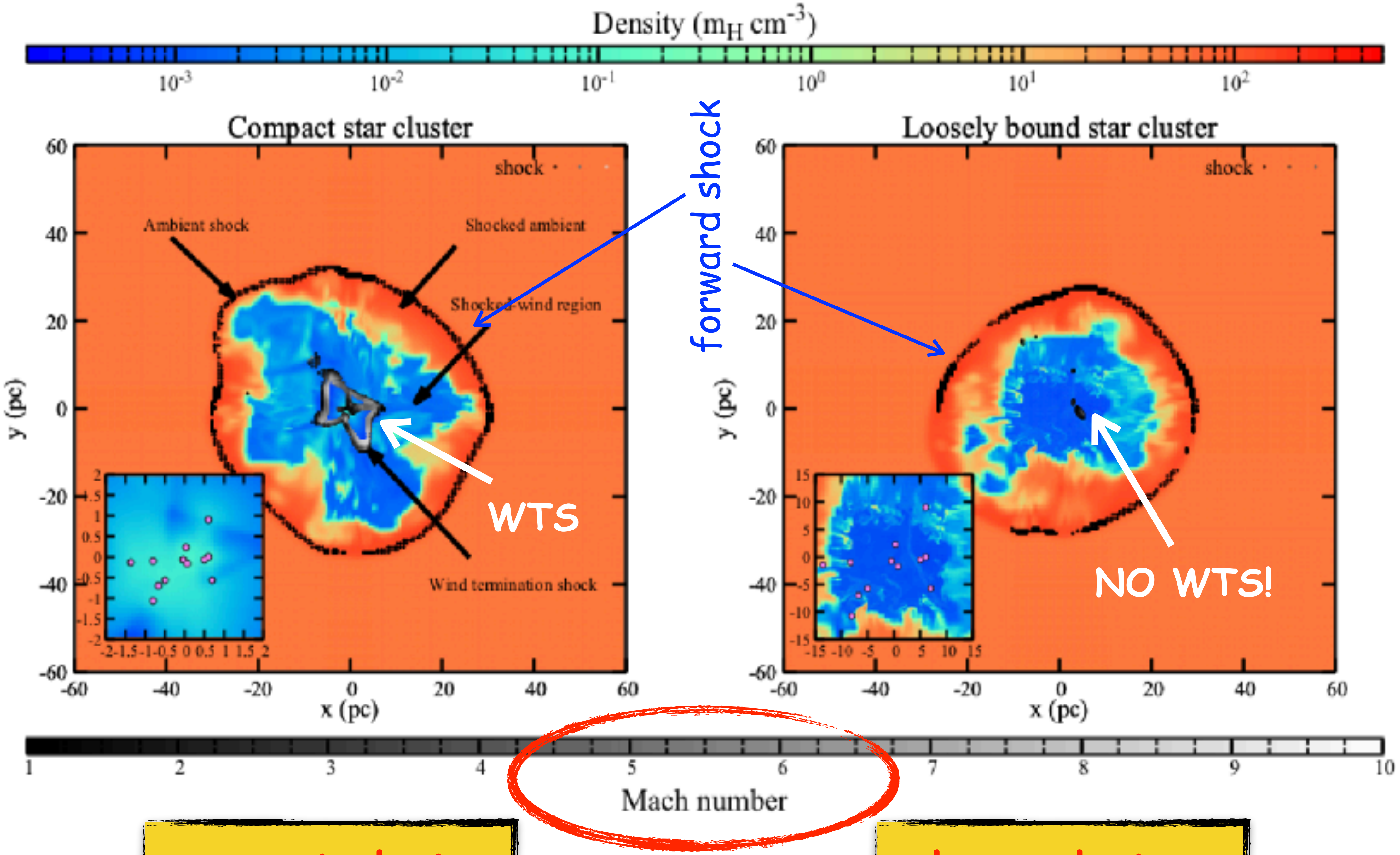

Gupta+ 2020

compact cluster

loose cluster

weak shock —> spectra slightly steeper than E^{-2} —> good to fit CR data

Particle acceleration at WTSs: E_{max}

Hillas criterium —>

$$E_{max} \sim \left(\frac{q}{c}\right) B_s u_s R_s$$

Particle acceleration at WTSs: E_{max}

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$$E_{max} \sim \left(\frac{q}{c}\right) B_s u_s R_s$$

Morlino+ 2021

$$L_w = 3 \times 10^{38} \mathrm{erg/s}$$

$$u_w = 3000 \ \mathrm{km/s}$$

$$n_{ISM} = 1 \ \mathrm{cm}^{-3}$$

$$\eta_B = 0.1$$

$$\Rightarrow$$

$$E_{max} \approx 2 - 3 \ \mathrm{PeV}$$

Particle acceleration at WTSs: E_{max}

Hillas criterium —>

$$E_{max} \sim \left(\frac{q}{c}\right) B_s u_s R_s$$

Morlino+ 2021

quite large

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$$\eta_B = 0.1$$

$$E_{max} \approx 2 - 3 \ \mathrm{PeV}$$

possible for powerful clusters

Particle acceleration in superbubbles

many papers by Bykov+, Parizot+, Ferrand&Marcowith, Vieu…

Vieu+ 2022

A universal spectrum is not expected…

Particle acceleration in superbubbles

many papers by Bykov+, Parizot+, Ferrand&Marcowith, Vieu…

Vieu+ 2022

A universal spectrum is not expected…

efficiency kinetic—> magnetic

Hillas criterium —>

$$E_{max} \sim \left(\frac{q}{c}\right) B_s u_s R_s$$

possible to go to PeV and possibly beyond

which velocity?
—> turbulent motions?
—> forward shock?
—> SN shocks?

bubbles are large!

You can't always get what you want…

	power	spectrum	E_{max}	$^{22}Ne/^{20}Ne$
SNR	😋			
WTS	🤬	—> 10% of SN power		
SB	😋			

You can't always get what you want…

	power	spectrum	E_{max}	$^{22}Ne/^{20}Ne$
SNR	😋	😋	—> non-linear DSA	
WTS	🤬	😋	—> weak WTS	
SB	😋	😋	—> non universal	

You can't always get what you want…

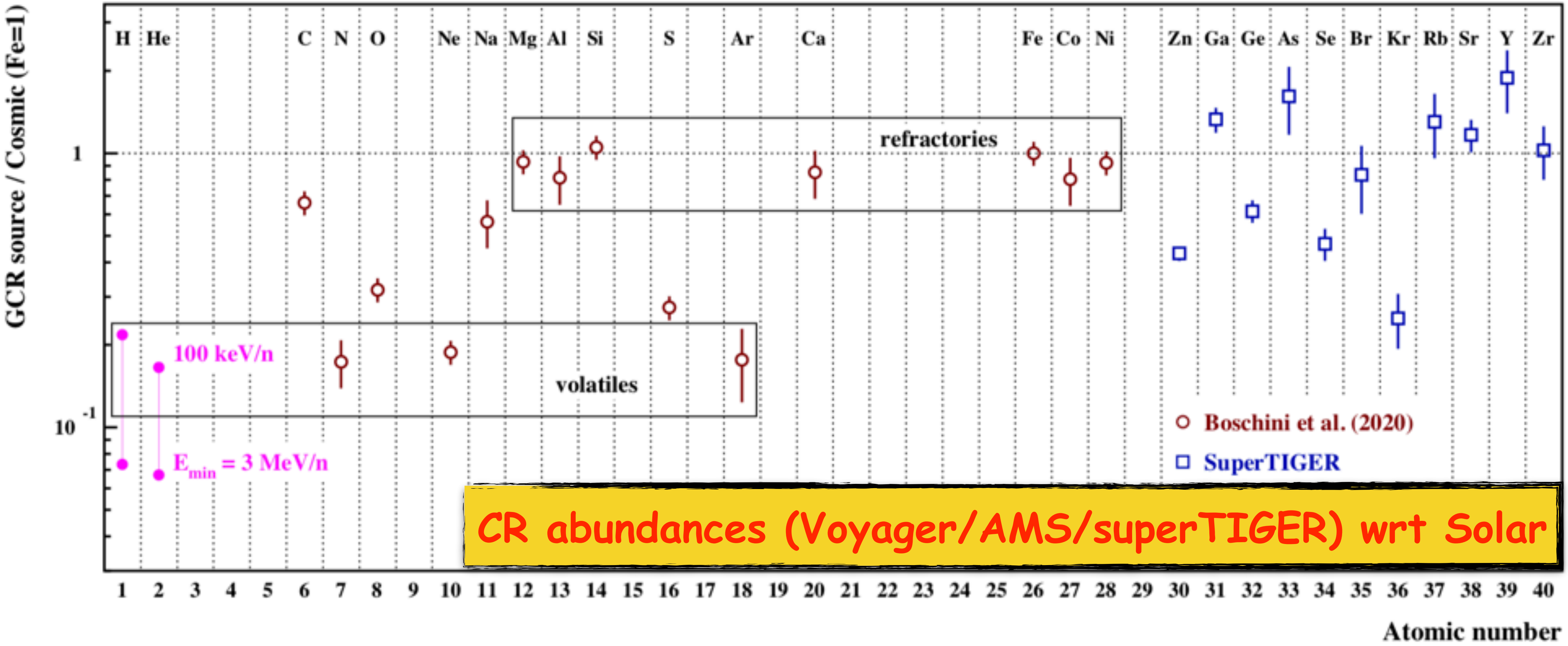
	power	spectrum	E_{max}	^{22}Ne/^{20}Ne
SNR	😋	😋	🤔	can SNRs accelerate ENOUGH PeV CRs?
WTS	🤬	😋	🤔	only very luminous star clusters
SB	😋	😋	😋	large, messy and contain many shocks!

You can't always get what you want…

	power	spectrum	E_{max}	$^{22}\mathrm{Ne}/^{20}\mathrm{Ne}$
SNR	😋	😋	🤔	🤬 not enough
WTS	🤬	😋	🤔	🤬 too much
SB	😋	😋	🤔	🤬 not enough

…but if you try sometimes, well, you might find…

Tatischeff+ 2021

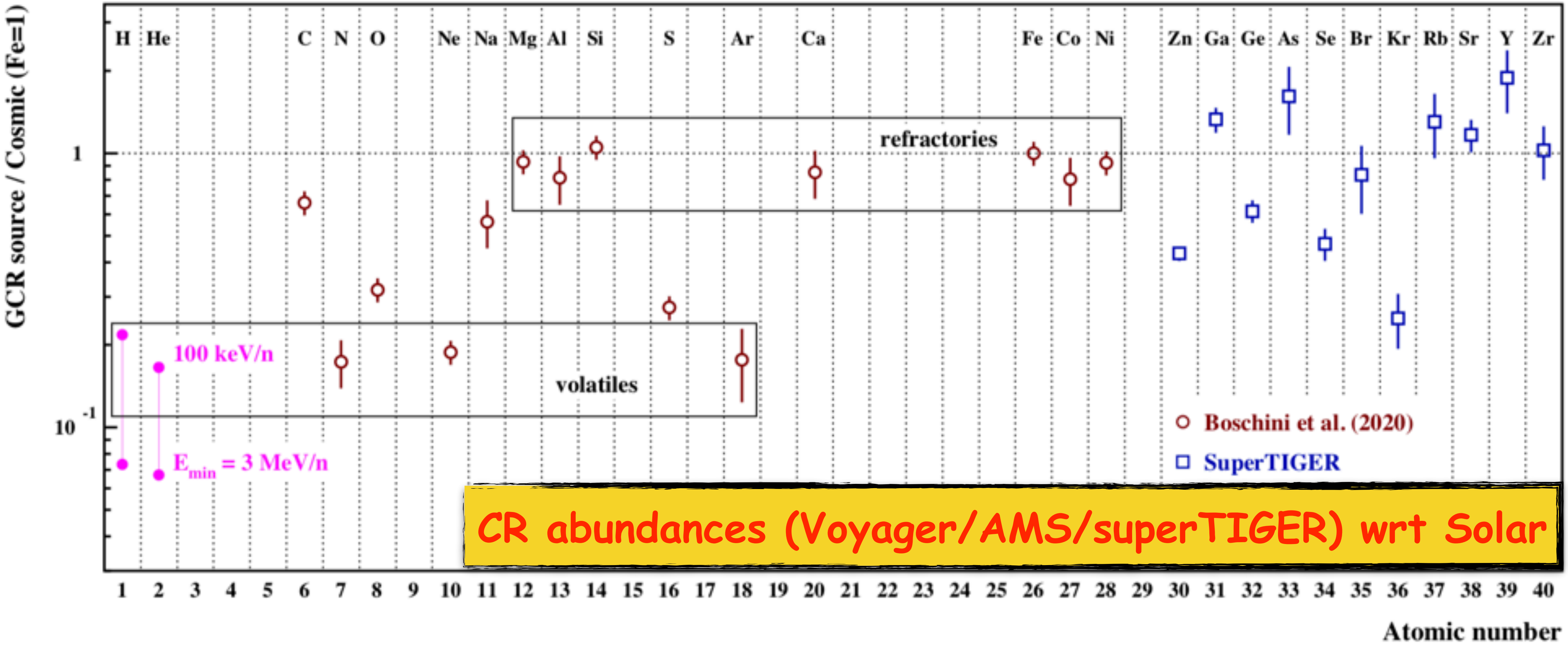


CR abundances (Voyager/AMS/superTIGER) wrt Solar

…but if you try sometimes, well, you might find…

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

Tatischeff+ 2021



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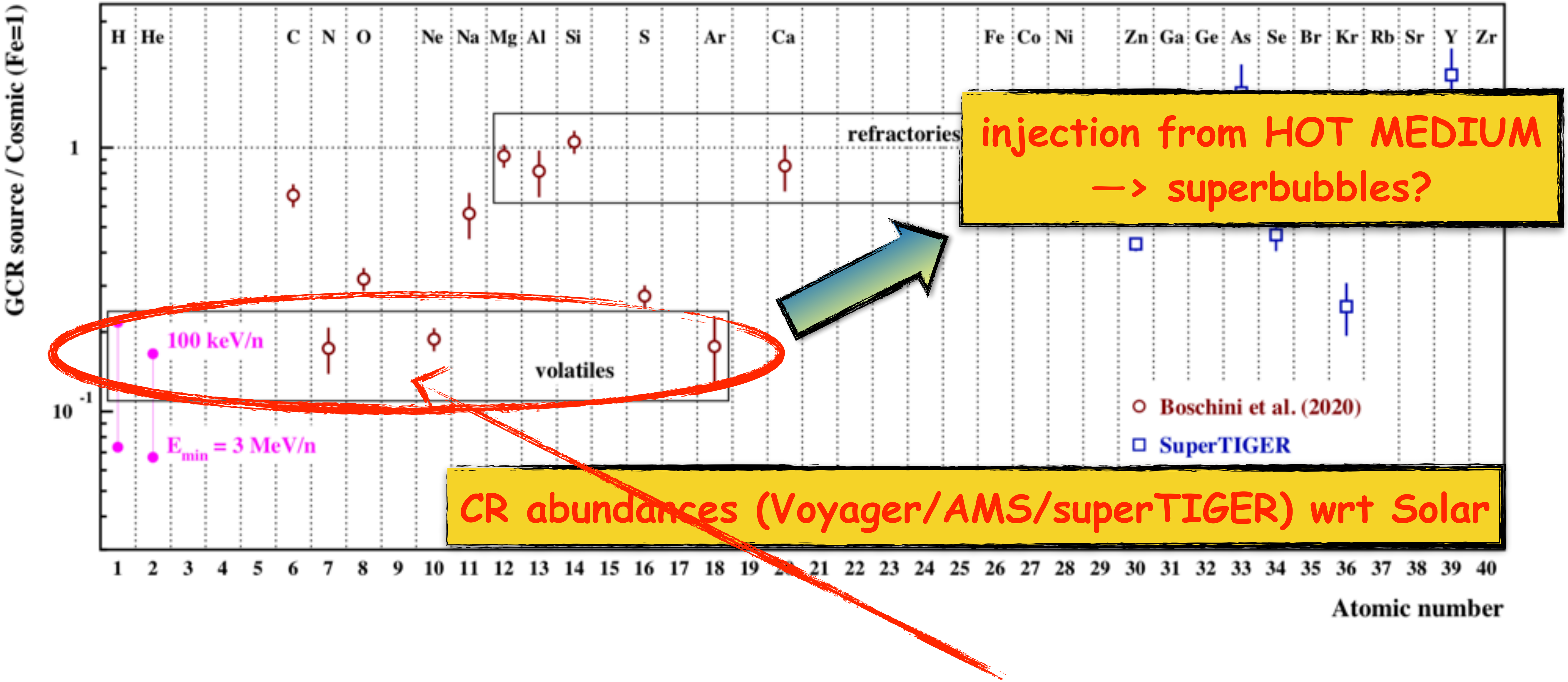


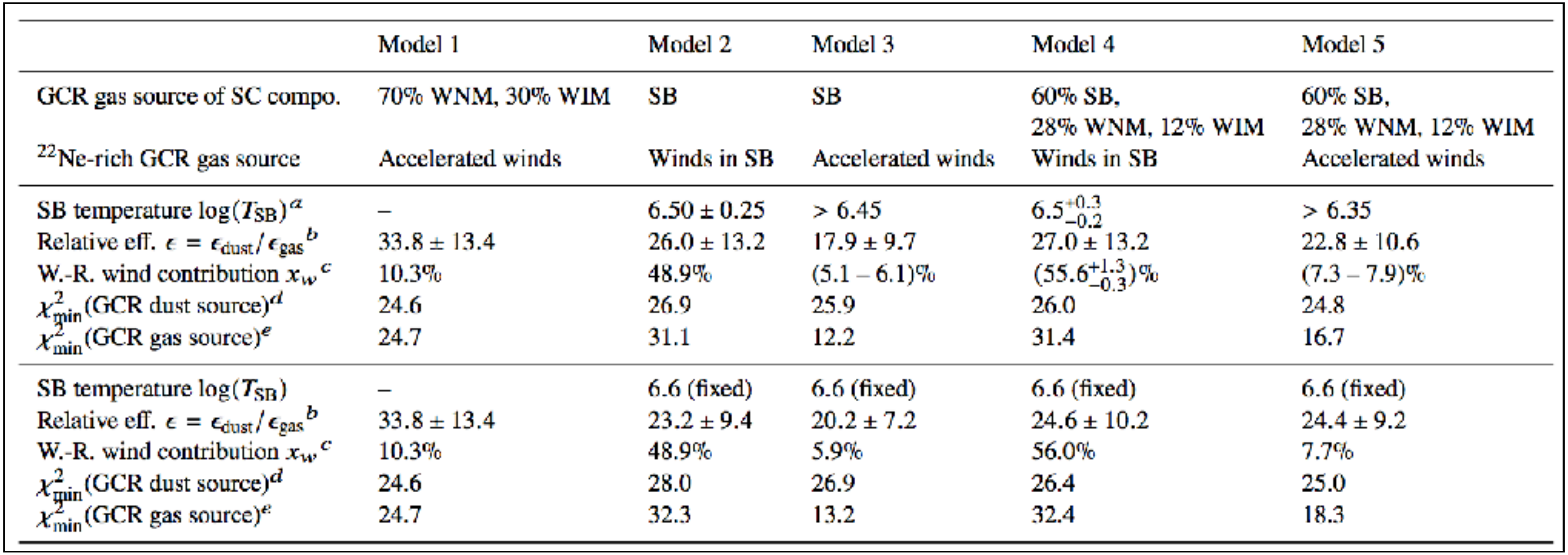
injection from HOT MEDIUM —> superbubbles?

CR abundances (Voyager/AMS/superTIGER) wrt Solar

SBs are hot —> A/Q ~2 for all elements —> **flat abundance/solar ratio**

…you get what you need!

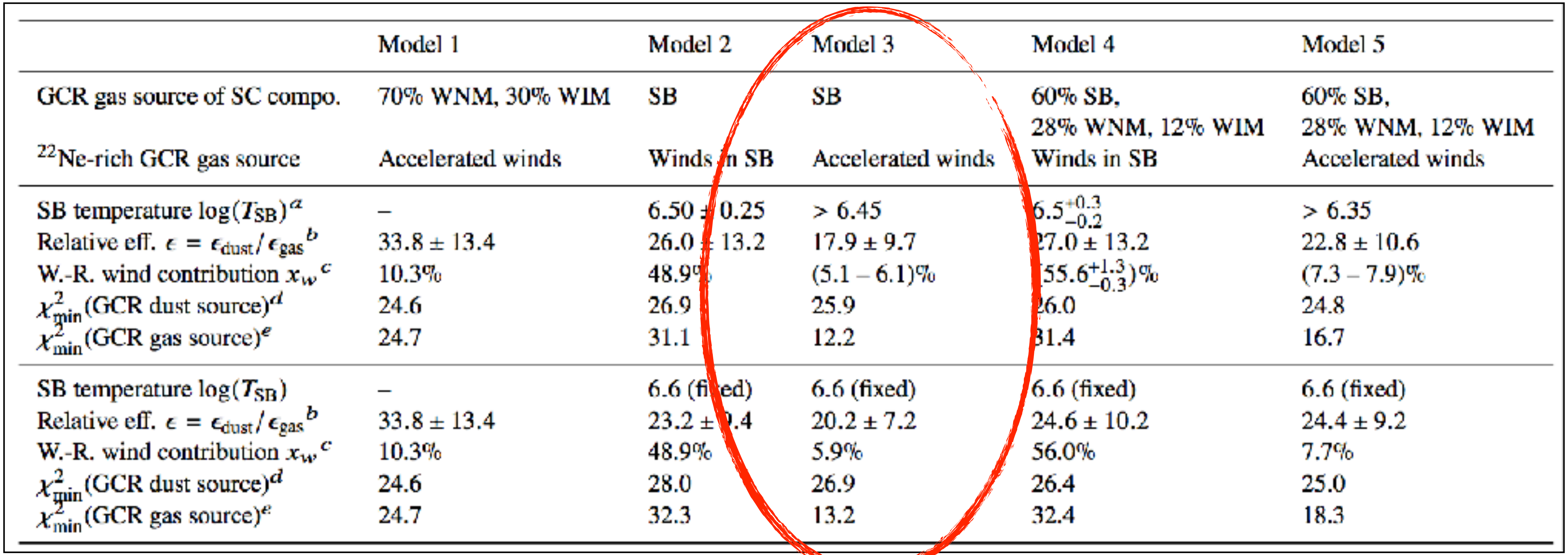
Tatischeff+ 2021 (see also Gupta+ 2020)



	Model 1	Model 2	Model 3	Model 4	Model 5
GCR gas source of SC compo.	70% WNM, 30% WIM	SB	SB	60% SB, 28% WNM, 12% WIM	60% SB, 28% WNM, 12% WIM
^{22}Ne-rich GCR gas source	Accelerated winds	Winds in SB	Accelerated winds	Winds in SB	Accelerated winds
SB temperature $\log(T_{\rm SB})$[a]	–	6.50 ± 0.25	> 6.45	$6.5^{+0.3}_{-0.2}$	> 6.35
Relative eff. $\epsilon = \epsilon_{\rm dust}/\epsilon_{\rm gas}$[b]	33.8 ± 13.4	26.0 ± 13.2	17.9 ± 9.7	27.0 ± 13.2	22.8 ± 10.6
W.-R. wind contribution x_w[c]	10.3%	48.9%	(5.1 – 6.1)%	$(55.6^{+1.3}_{-0.3})$%	(7.3 – 7.9)%
$\chi^2_{\rm min}$(GCR dust source)[d]	24.6	26.9	25.9	26.0	24.8
$\chi^2_{\rm min}$(GCR gas source)[e]	24.7	31.1	12.2	31.4	16.7
SB temperature $\log(T_{\rm SB})$	–	6.6 (fixed)	6.6 (fixed)	6.6 (fixed)	6.6 (fixed)
Relative eff. $\epsilon = \epsilon_{\rm dust}/\epsilon_{\rm gas}$[b]	33.8 ± 13.4	23.2 ± 9.4	20.2 ± 7.2	24.6 ± 10.2	24.4 ± 9.2
W.-R. wind contribution x_w[c]	10.3%	48.9%	5.9%	56.0%	7.7%
$\chi^2_{\rm min}$(GCR dust source)[d]	24.6	28.0	26.9	26.4	25.0
$\chi^2_{\rm min}$(GCR gas source)[e]	24.7	32.3	13.2	32.4	18.3

…you get what you need!

Tatischeff+ 2021 (see also Gupta+ 2020)



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^{22}Ne-rich GCR gas source	Accelerated winds	Winds in SB	Accelerated winds	Winds in SB	Accelerated winds
SB temperature $\log(T_{\mathrm{SB}})^a$	–	6.50 ± 0.25	> 6.45	$6.5^{+0.3}_{-0.2}$	> 6.35
Relative eff. $\epsilon = \epsilon_{\mathrm{dust}}/\epsilon_{\mathrm{gas}}{}^b$	33.8 ± 13.4	26.0 ± 13.2	17.9 ± 9.7	27.0 ± 13.2	22.8 ± 10.6
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χ^2_{min}(GCR gas source)^e	24.7	31.1	12.2	31.4	16.7
SB temperature $\log(T_{\mathrm{SB}})$	–	6.6 (fixed)	6.6 (fixed)	6.6 (fixed)	6.6 (fixed)
Relative eff. $\epsilon = \epsilon_{\mathrm{dust}}/\epsilon_{\mathrm{gas}}{}^b$	33.8 ± 13.4	23.2 ± 9.4	20.2 ± 7.2	24.6 ± 10.2	24.4 ± 9.2
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mixed scenario

most CRs come from SNRs in SBs + ~5% of CRs come from stellar cluster WTSs

Conclusions

- orthodoxy (**DSA @SNR shocks**) faces problems
  - energetic is ok
  - spectra can be fixed (non-linearities)
  - E_{max} problematic (can we go up to the transition, >> PeV?)
  - composition is very problematic (mainly $^{22}Ne/^{20}Ne$ ratio)
- **star clusters** do accelerate CRs (**WTS** or in **superbubbles**)
  - source of energy: WTSs ~10%, SNae ~90%
  - the acceleration proceeds in a different way in young and old clusters
  - PeVatrons? Extreme WTS might do, doable for SBs
- **mixed scenarios** (acceleration at SNR+WTS) fit both CR spectra and abundances