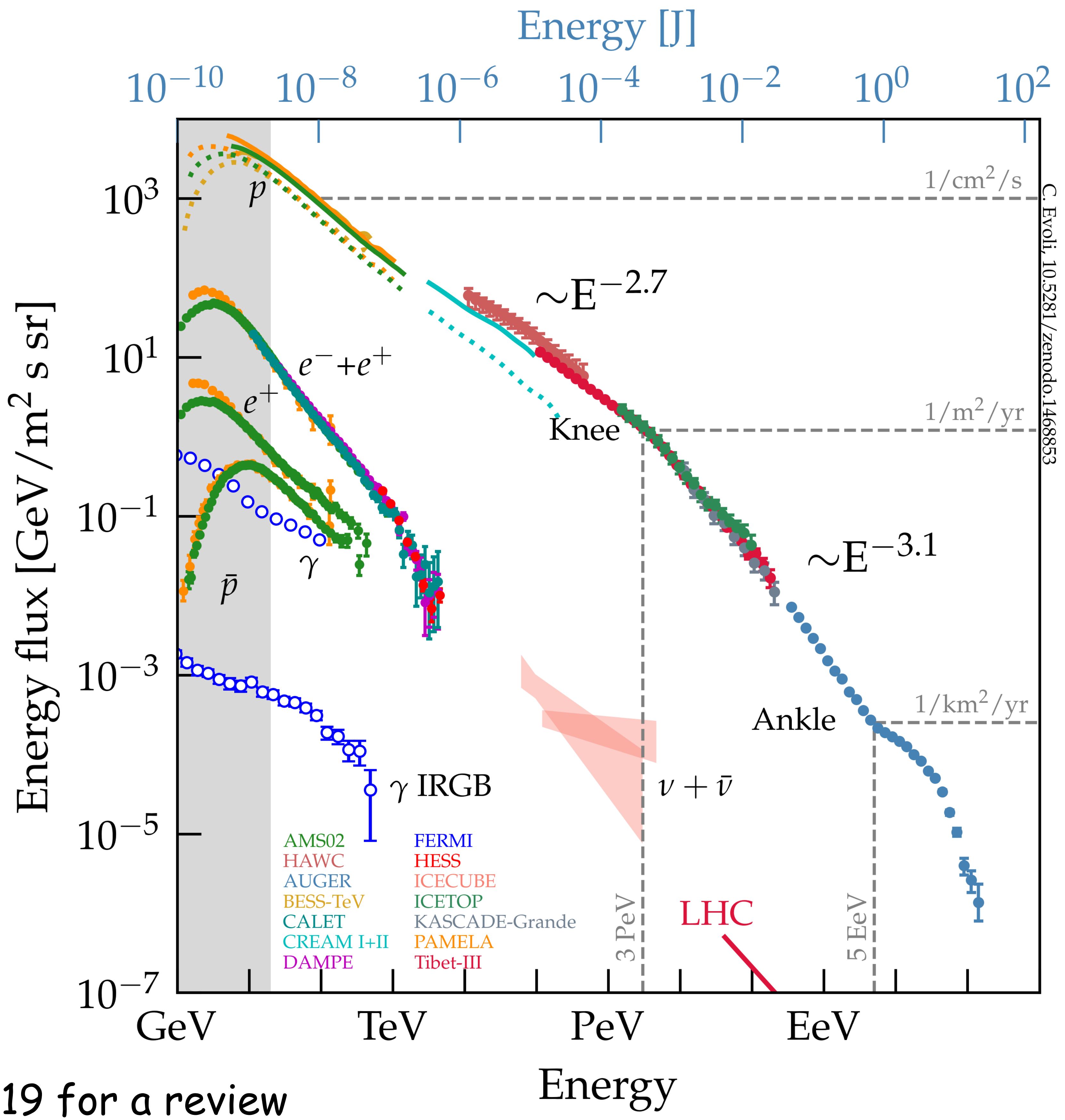
Star clusters as cosmic ray accelerators

Stefano Gabici
APC, Paris

How to explain the origin of galactic CRs

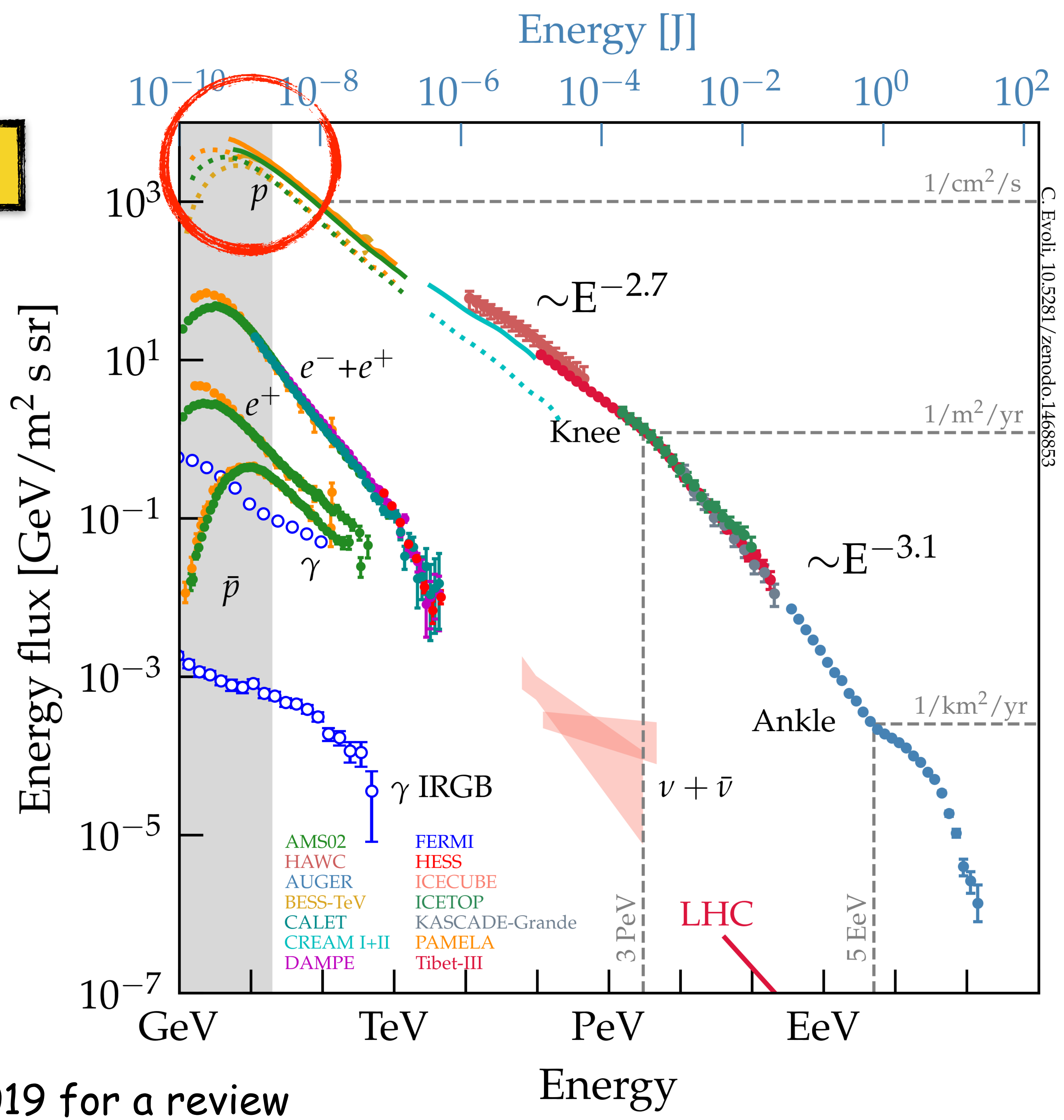


see Gabici+ 2019 for a review

Fig. from Evoli 2018

How to explain the origin of galactic CRs

energetics



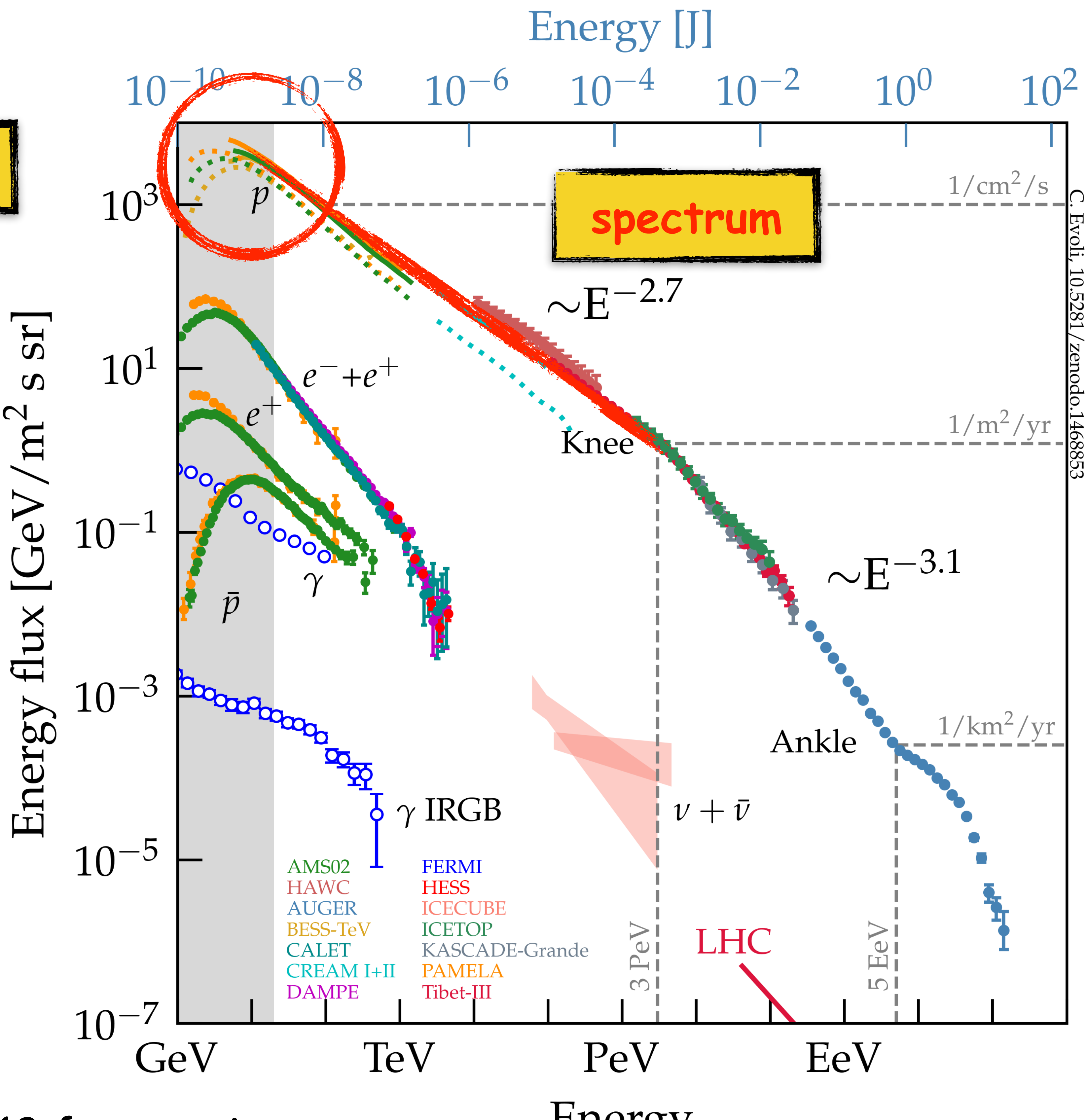
see Gabici+ 2019 for a review

Fig. from Evoli 2018

How to explain the origin of galactic CRs

energetics

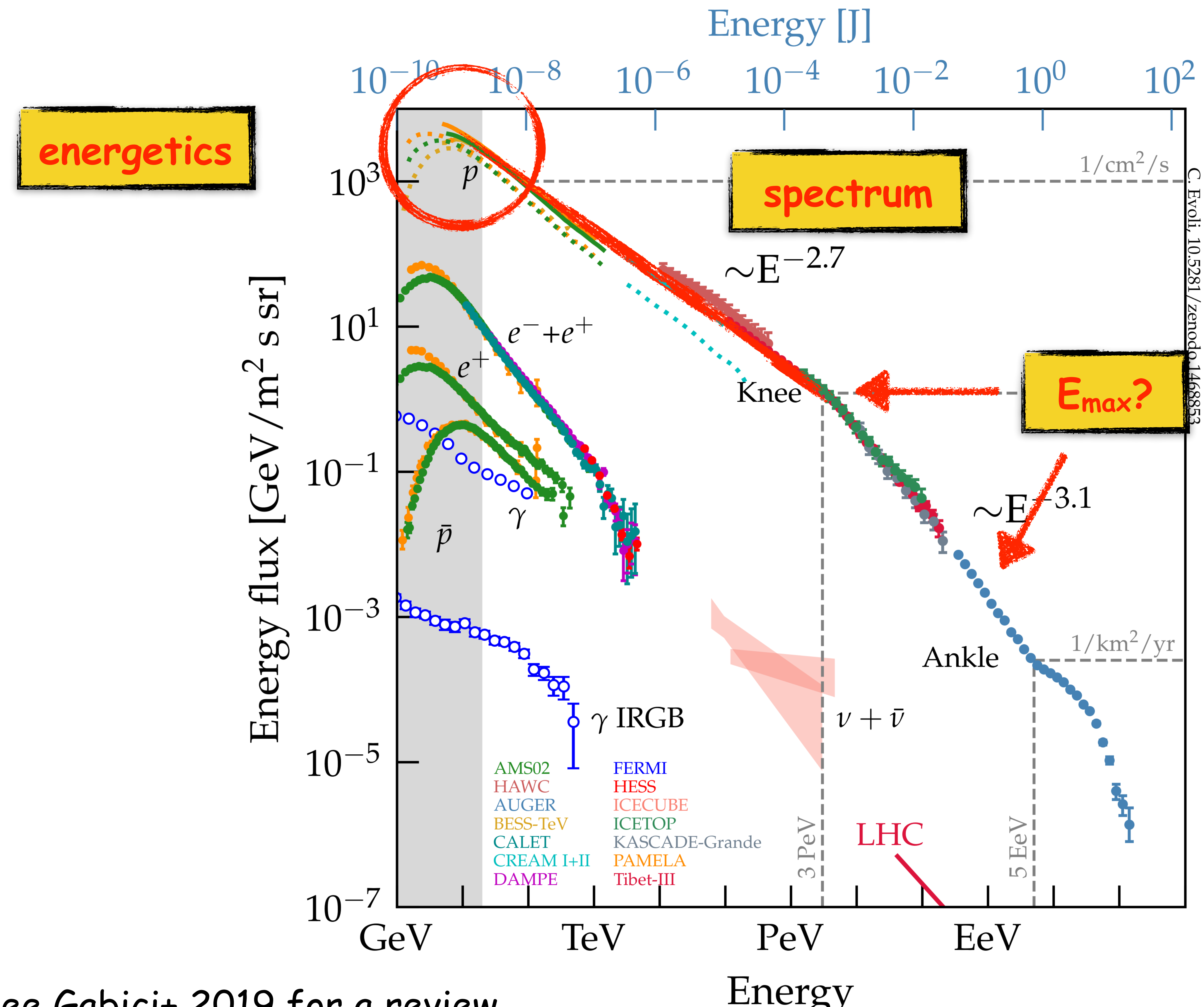
spectrum



see Gabici+ 2019 for a review

Fig. from Evoli 2018

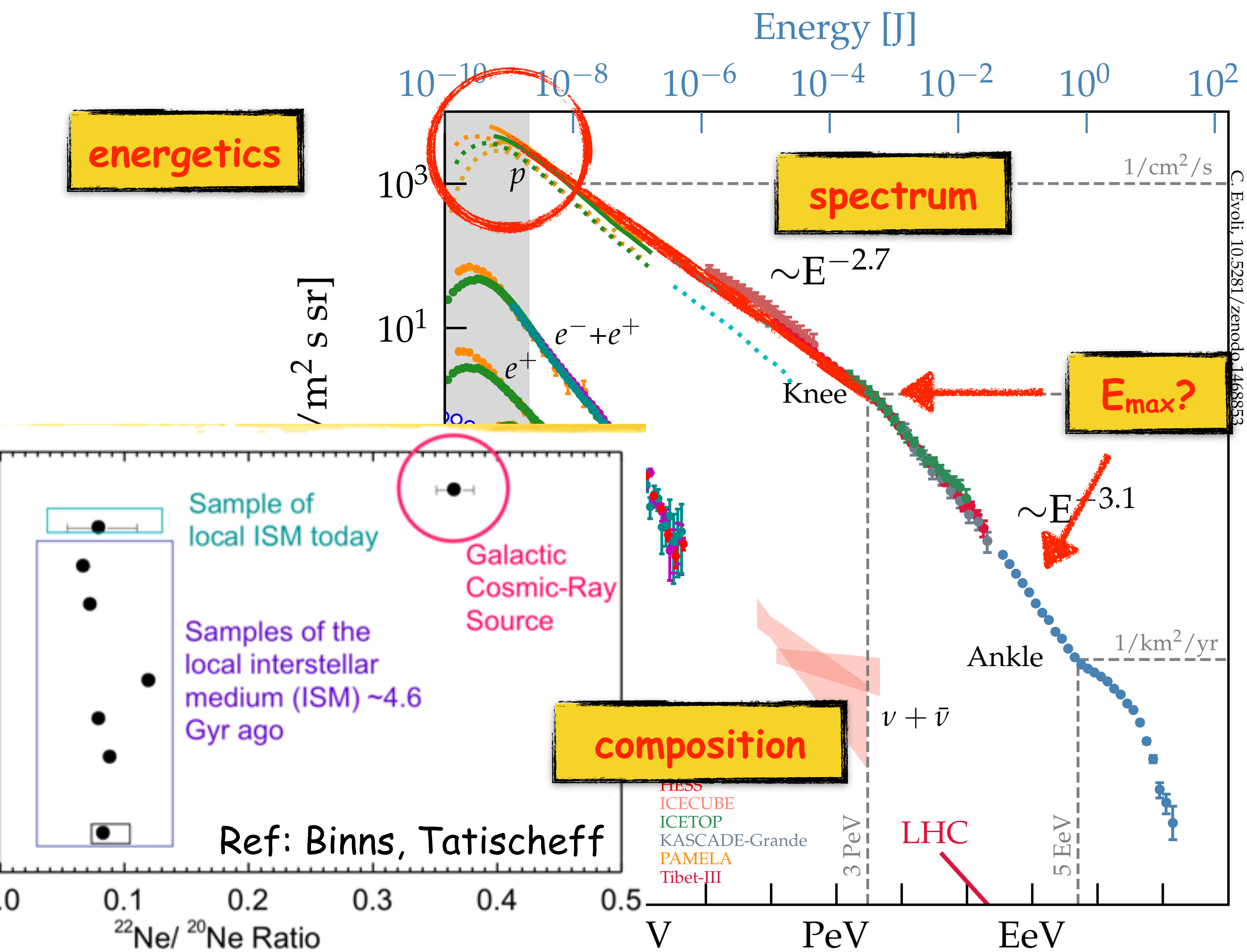
How to explain the origin of galactic CRs



see Gabici+ 2019 for a review

Fig. from Evoli 2018

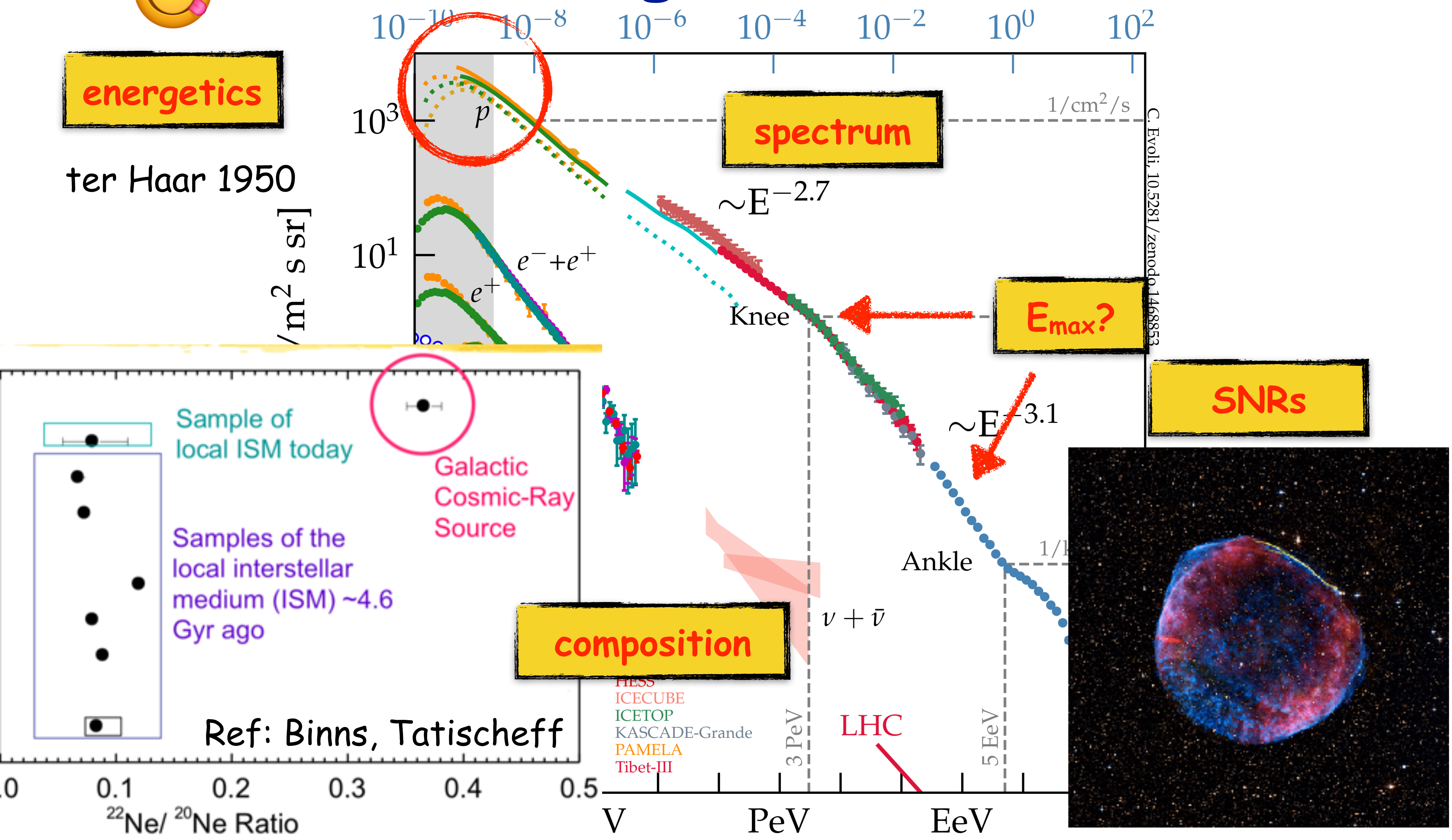
How to explain the origin of galactic CRs



see Gabici+ 2019 for a review

Fig. from Evoli 2018

Diffusive shock acceleration at strong SNR shocks



see Gabici+ 2019 for a review

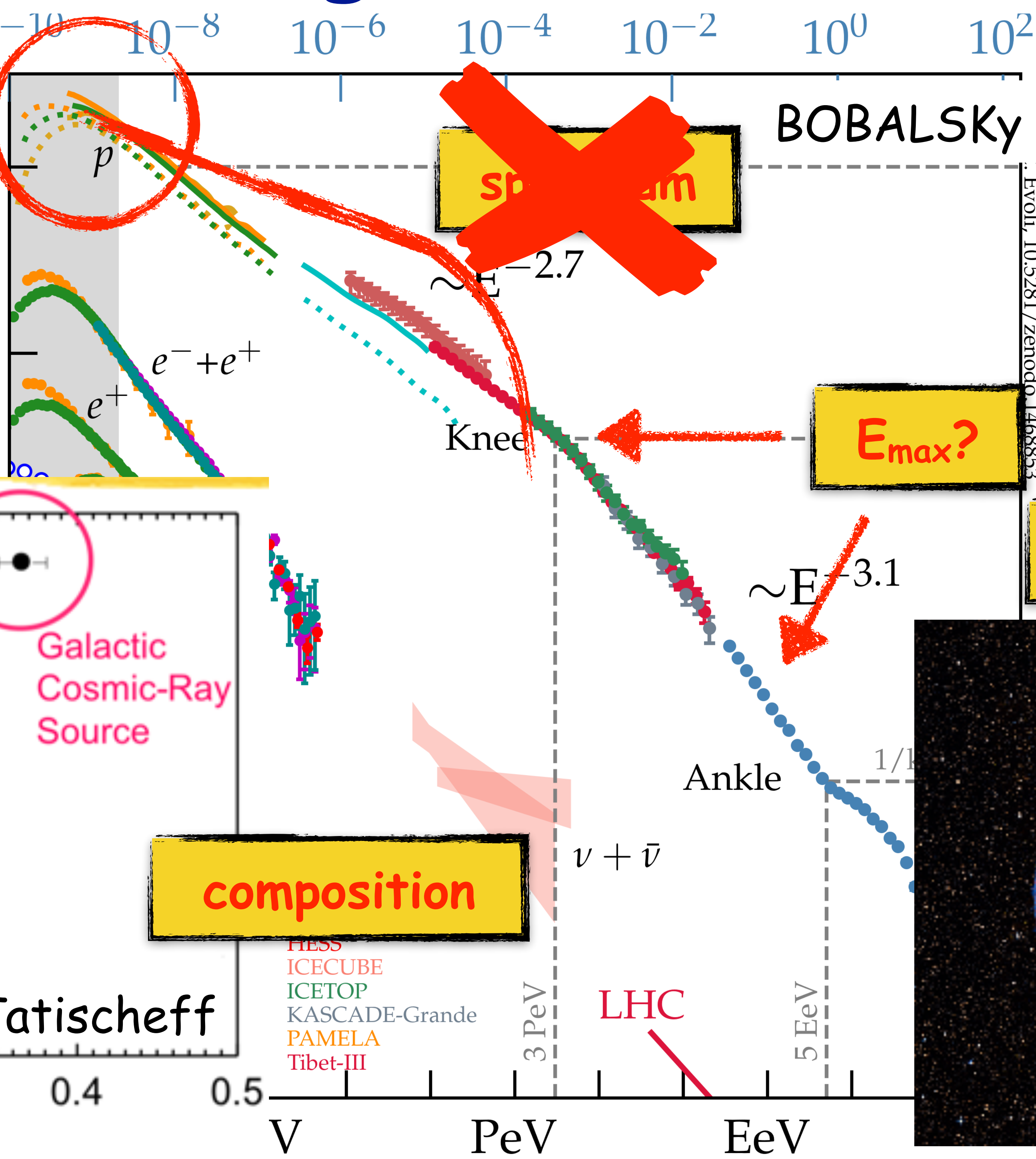
Fig. from Evoli 2018

Diffusive shock acceleration at strong SNR shocks

energetics

ter Haar 1950

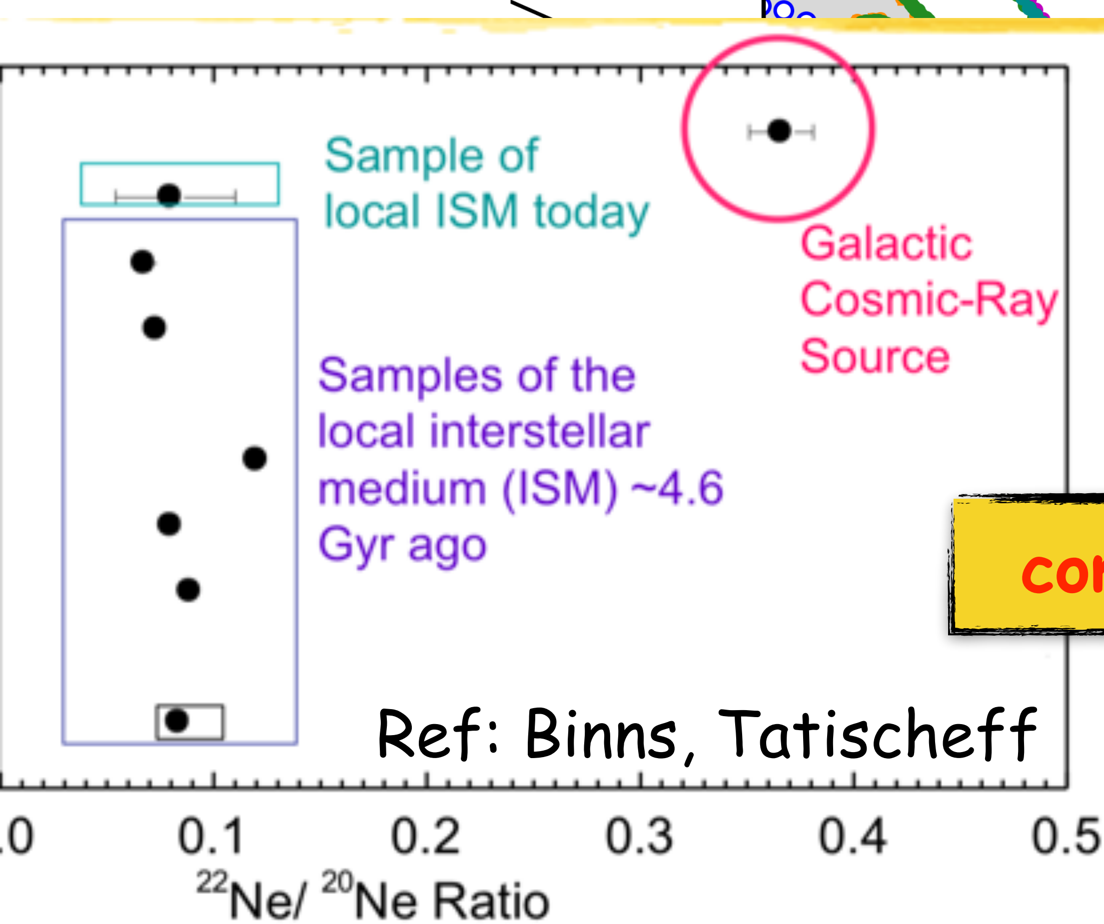
BOBALSKy 1977/1978

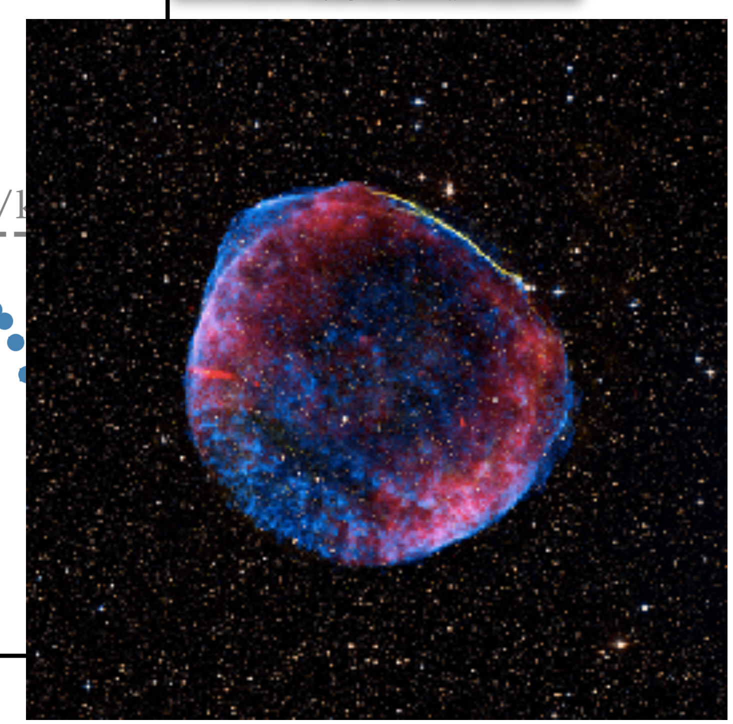


E_{max}?

SNRs

composition





see Gabici+ 2019 for a review

Fig. from Evoli 2018

Diffusive shock acceleration at strong SNR shocks

energetics

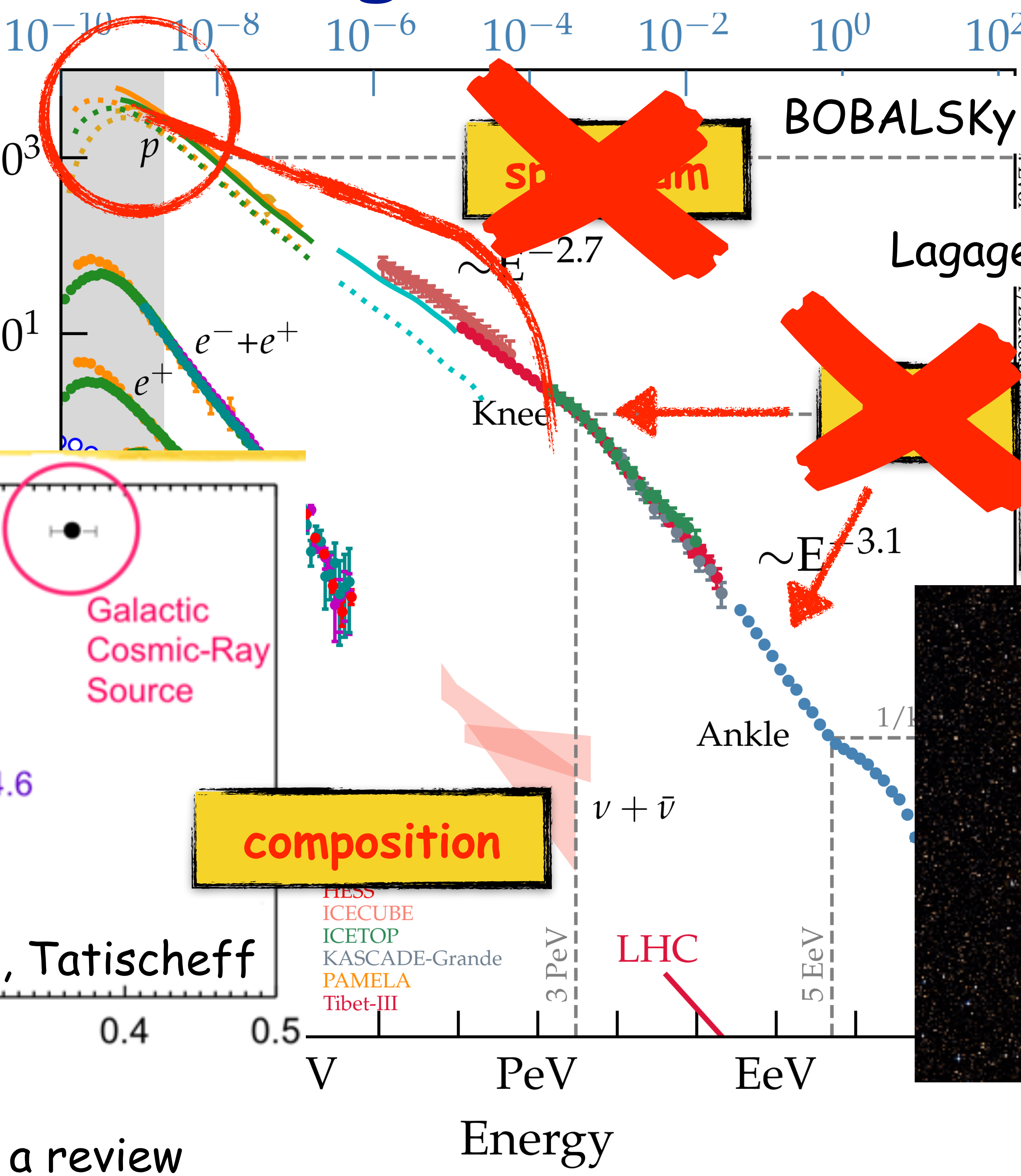
ter Haar 1950

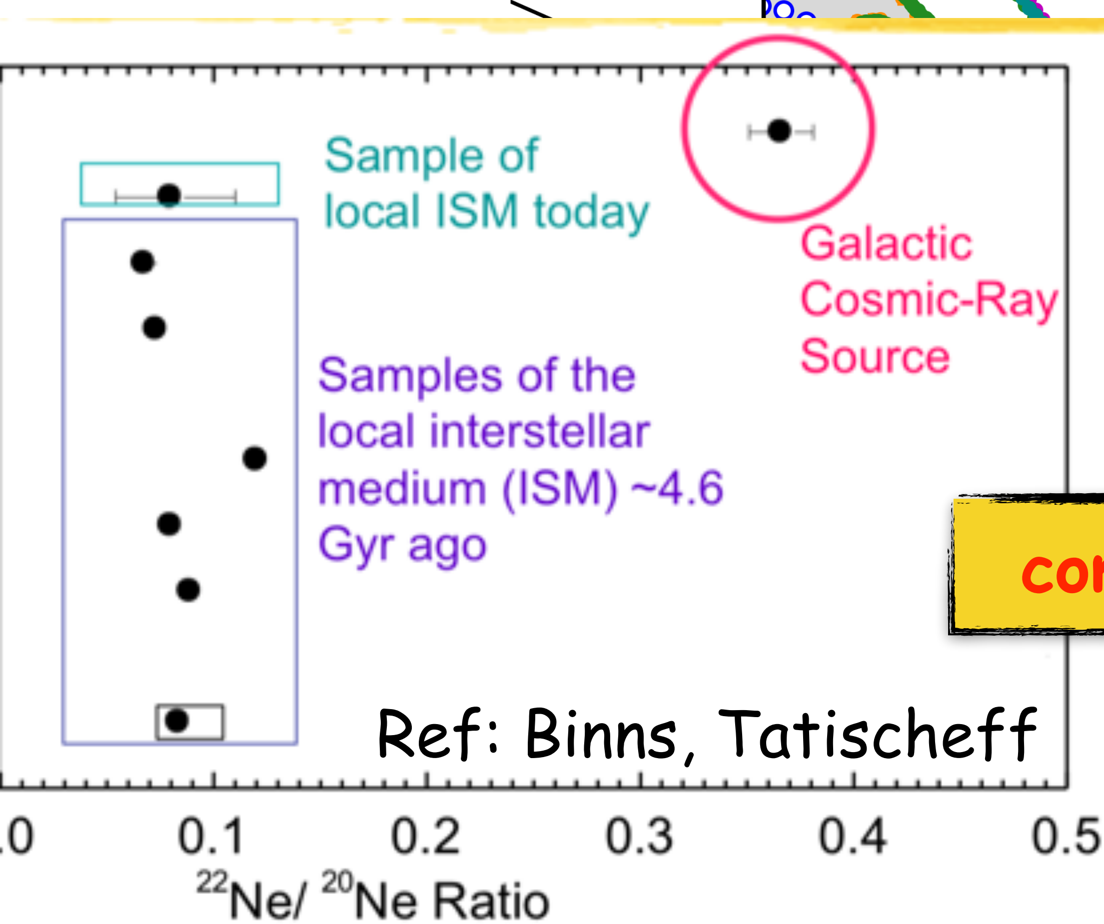
BOBALSKy 1977/1978

Lagage&Cesarsky 1983

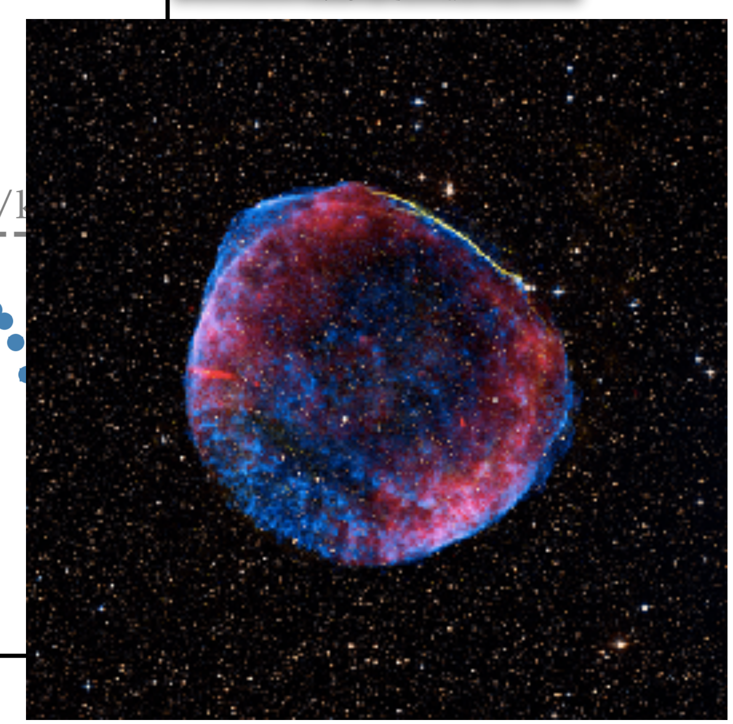
SNRs

composition





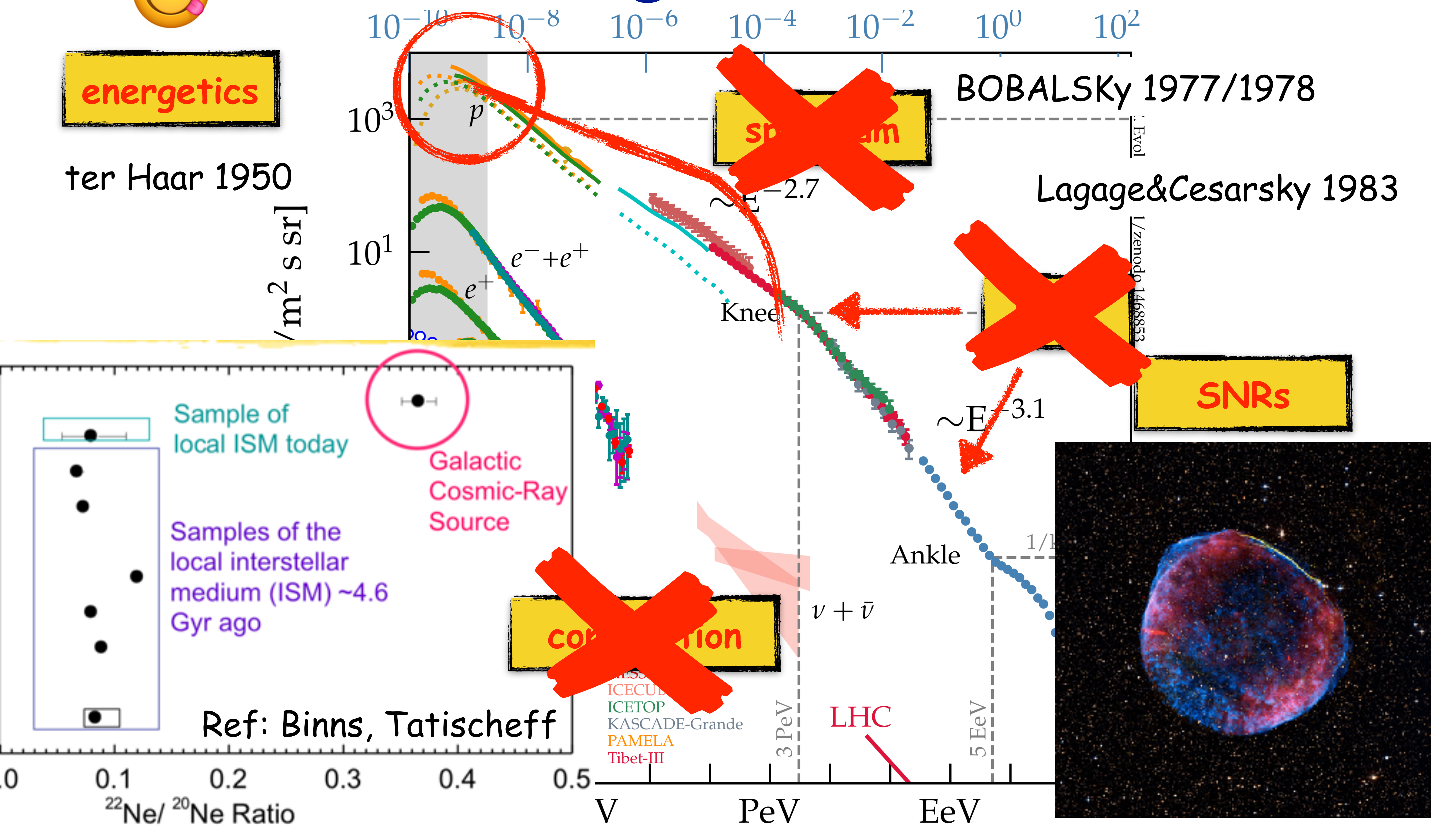
Ref: Binns, Tatischeff



see Gabici+ 2019 for a review

Fig. from Evoli 2018

Diffusive shock acceleration at strong SNR shocks



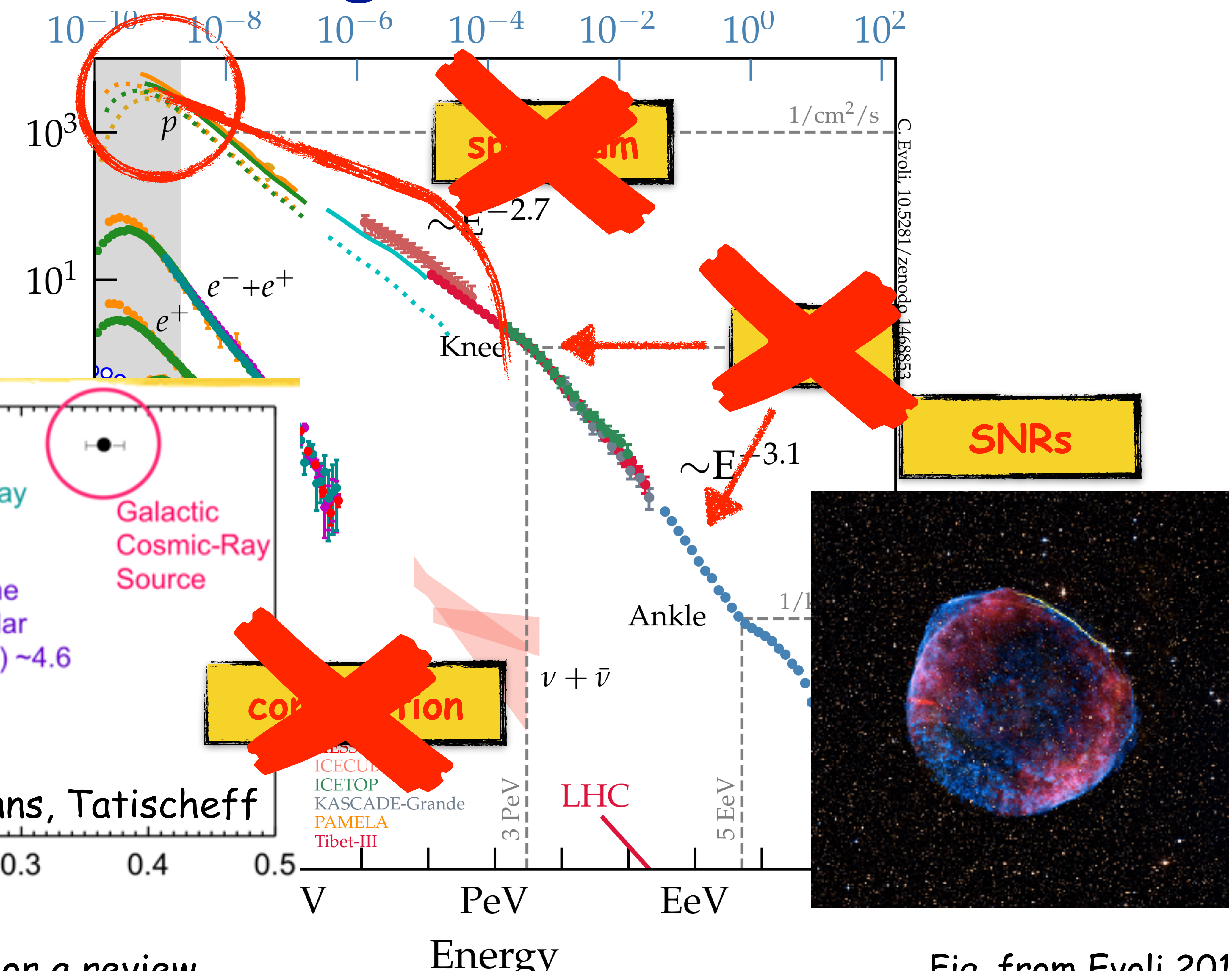
see Gabici+ 2019 for a review

Fig. from Evoli 2018

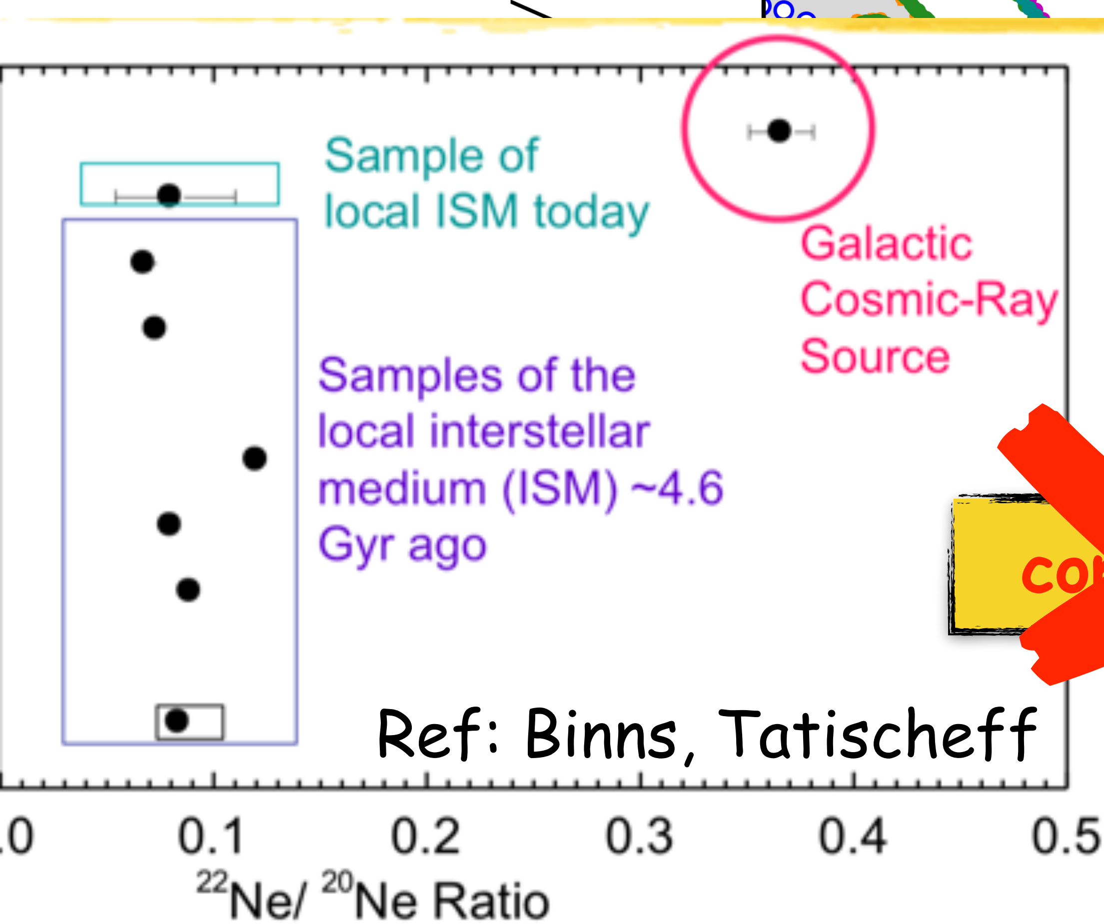
Diffusive shock acceleration at strong SNR shocks

energetics

ter Haar 1950



SNRs

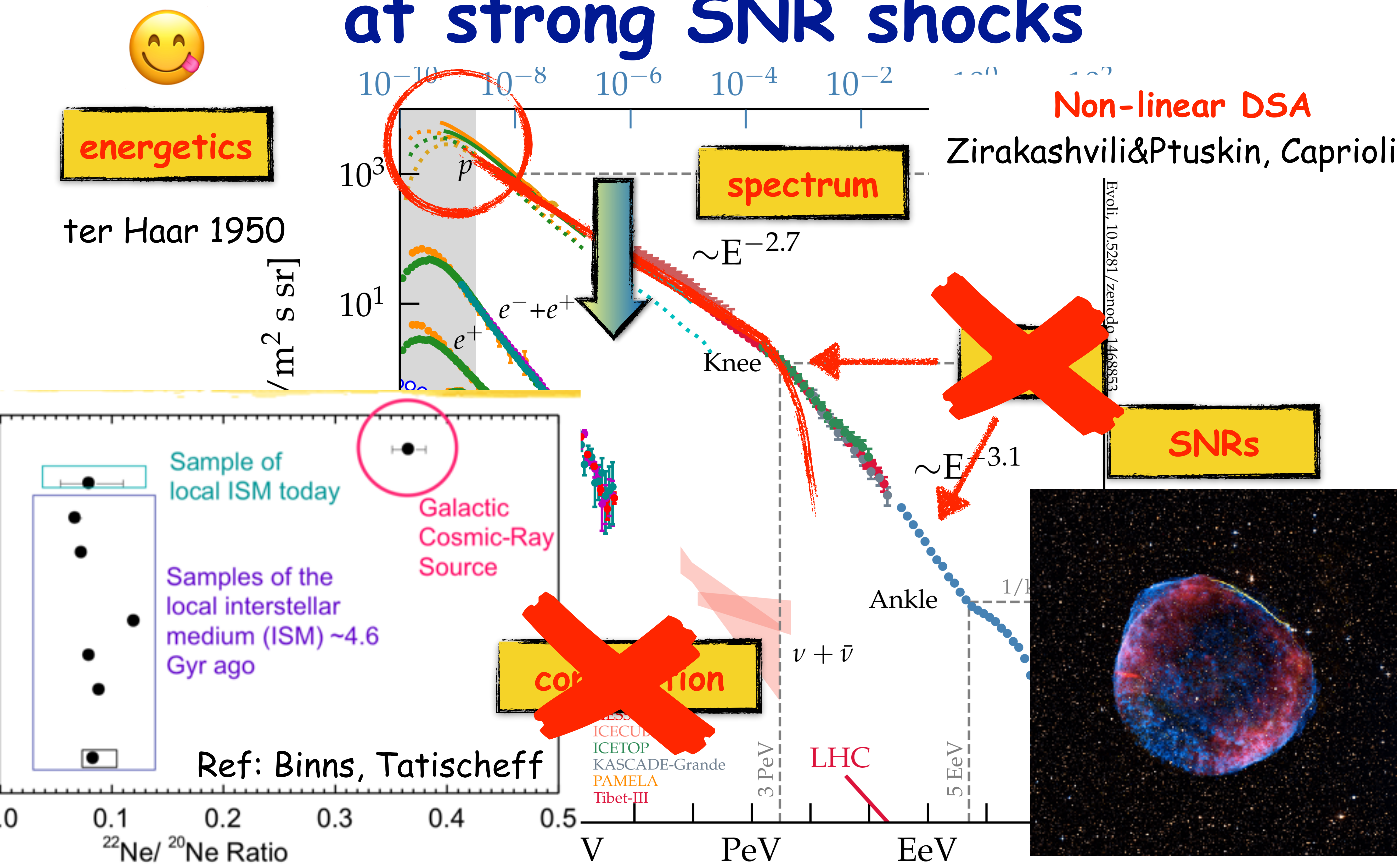


Ref: Binns, Tatischeff

see Gabici+ 2019 for a review

Fig. from Evoli 2018

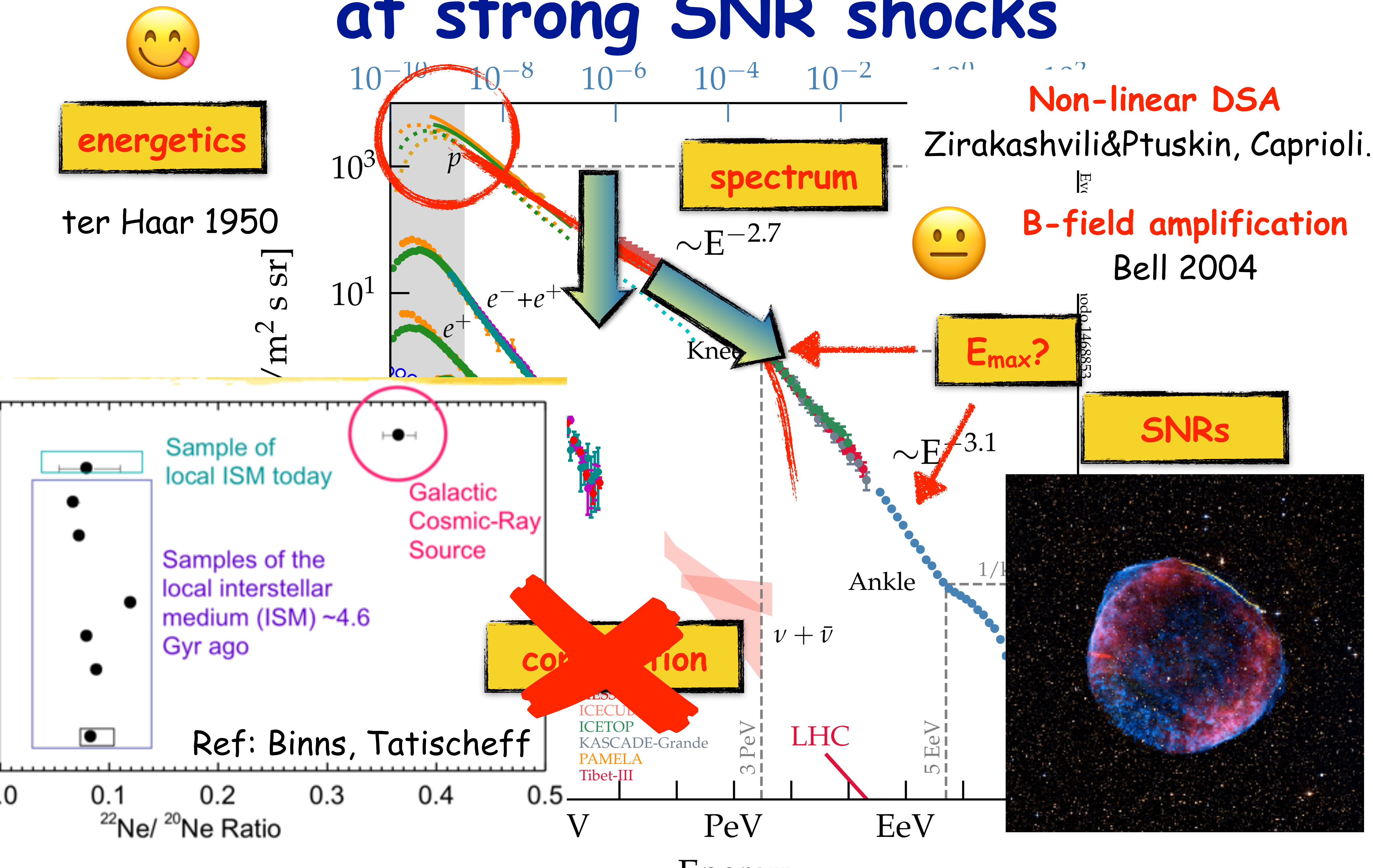
Diffusive shock acceleration at strong SNR shocks



see Gabici+ 2019 for a review

Fig. from Evoli 2018

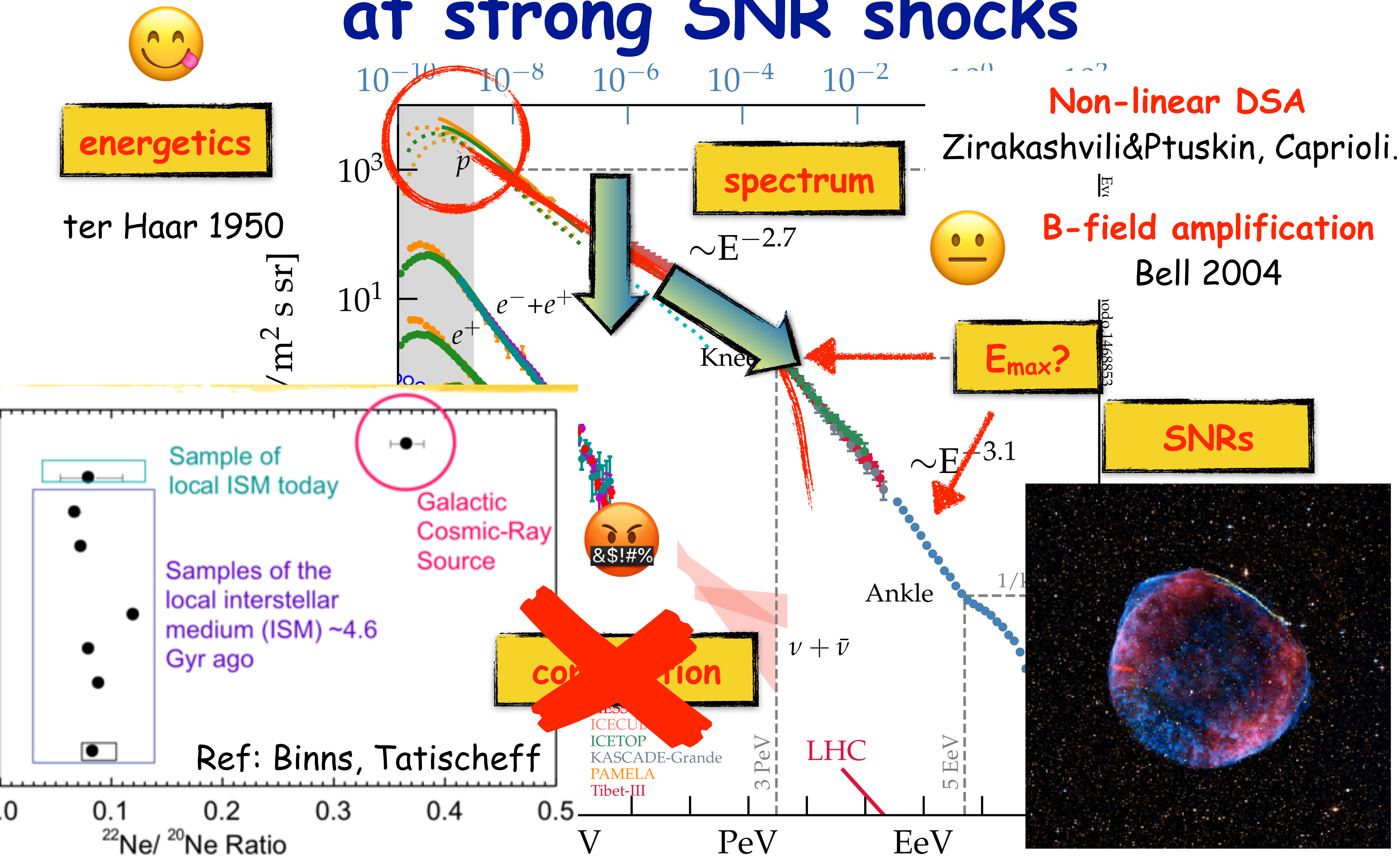
Diffusive shock acceleration at strong SNR shocks



see Gabici+ 2019 for a review

Fig. from Evoli 2018

Diffusive shock acceleration at strong SNR shocks

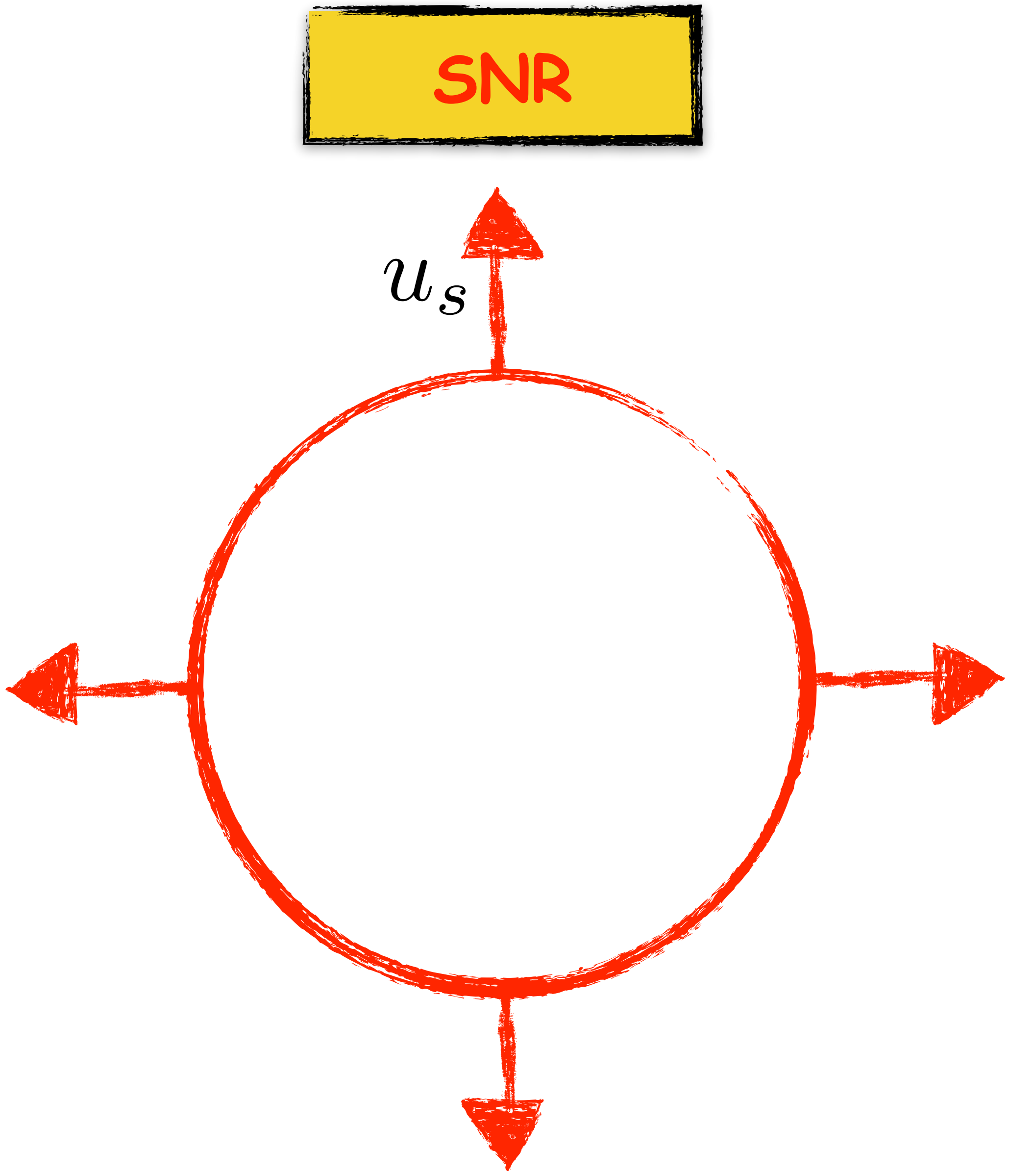


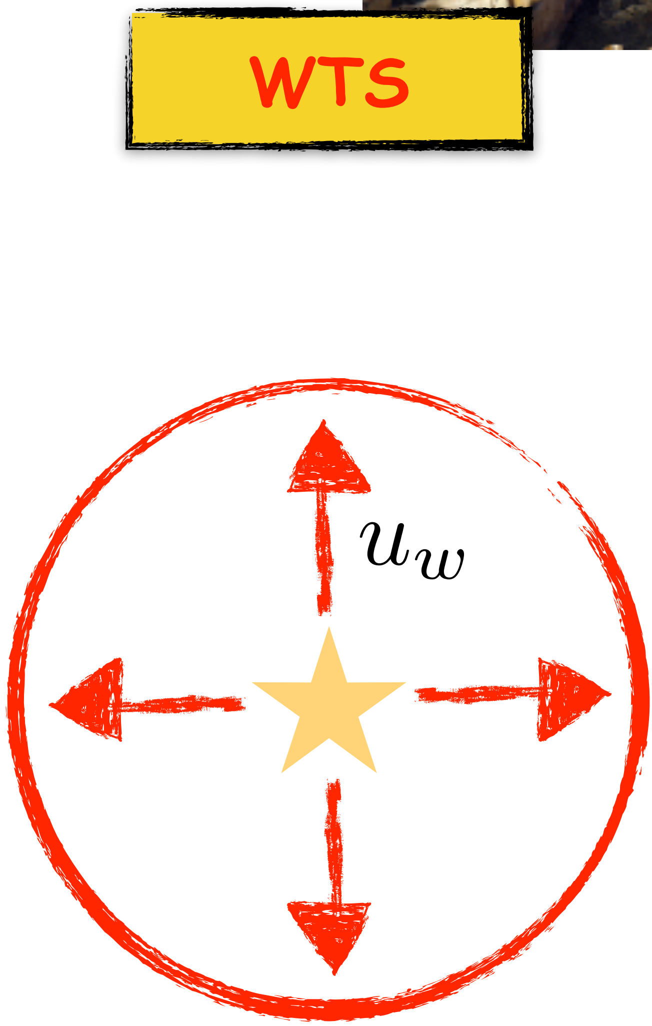
see Gabici+ 2019 for a review

Fig. from Evoli 2018

Stellar wind termination shocks

Cassé & Paul 1980, 1982 — Cesarsky & Montmerle 1983

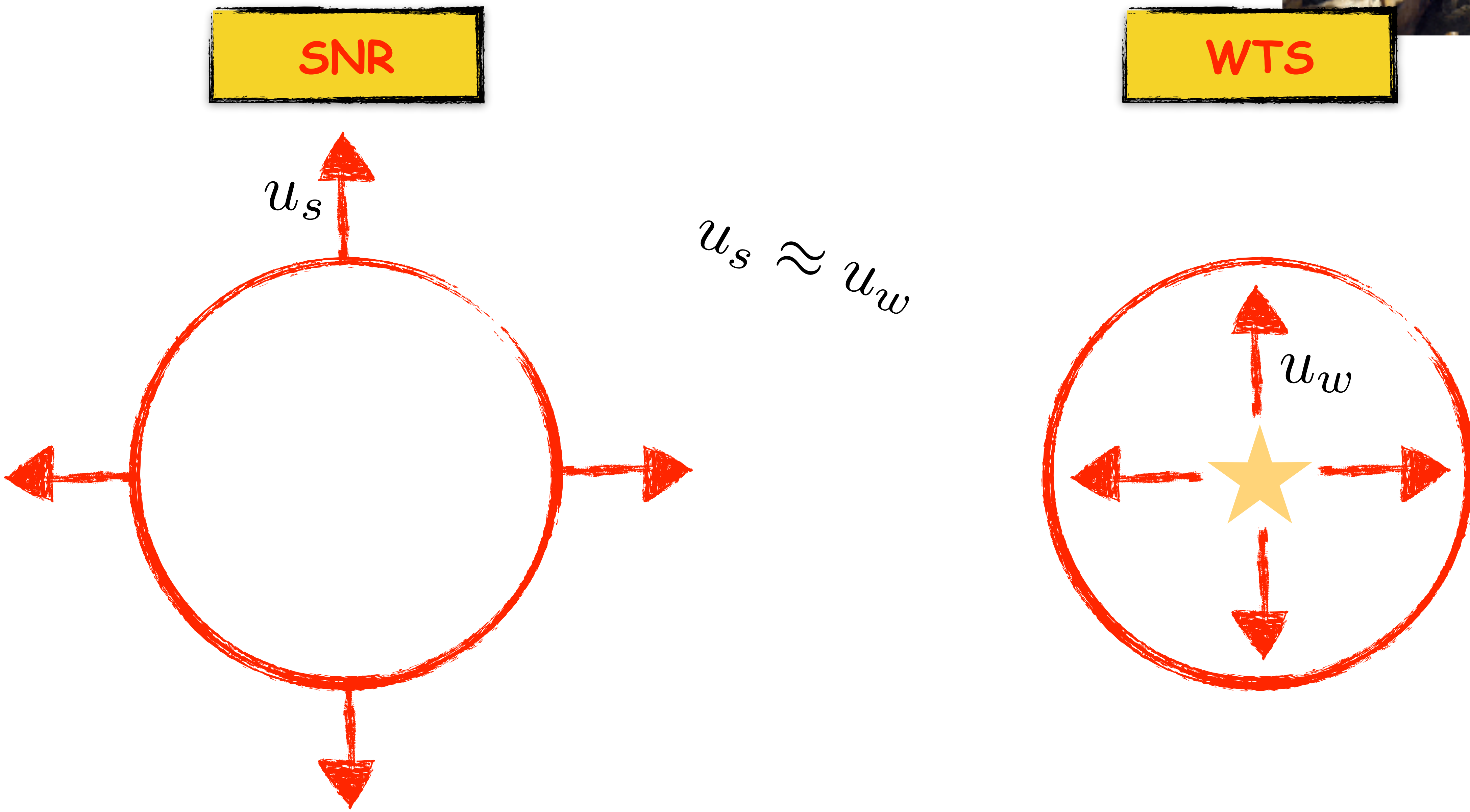




analogy with solar WTS (Parker, Jokipii…) + DSA (BOBALSKy…)

Stellar wind termination shocks

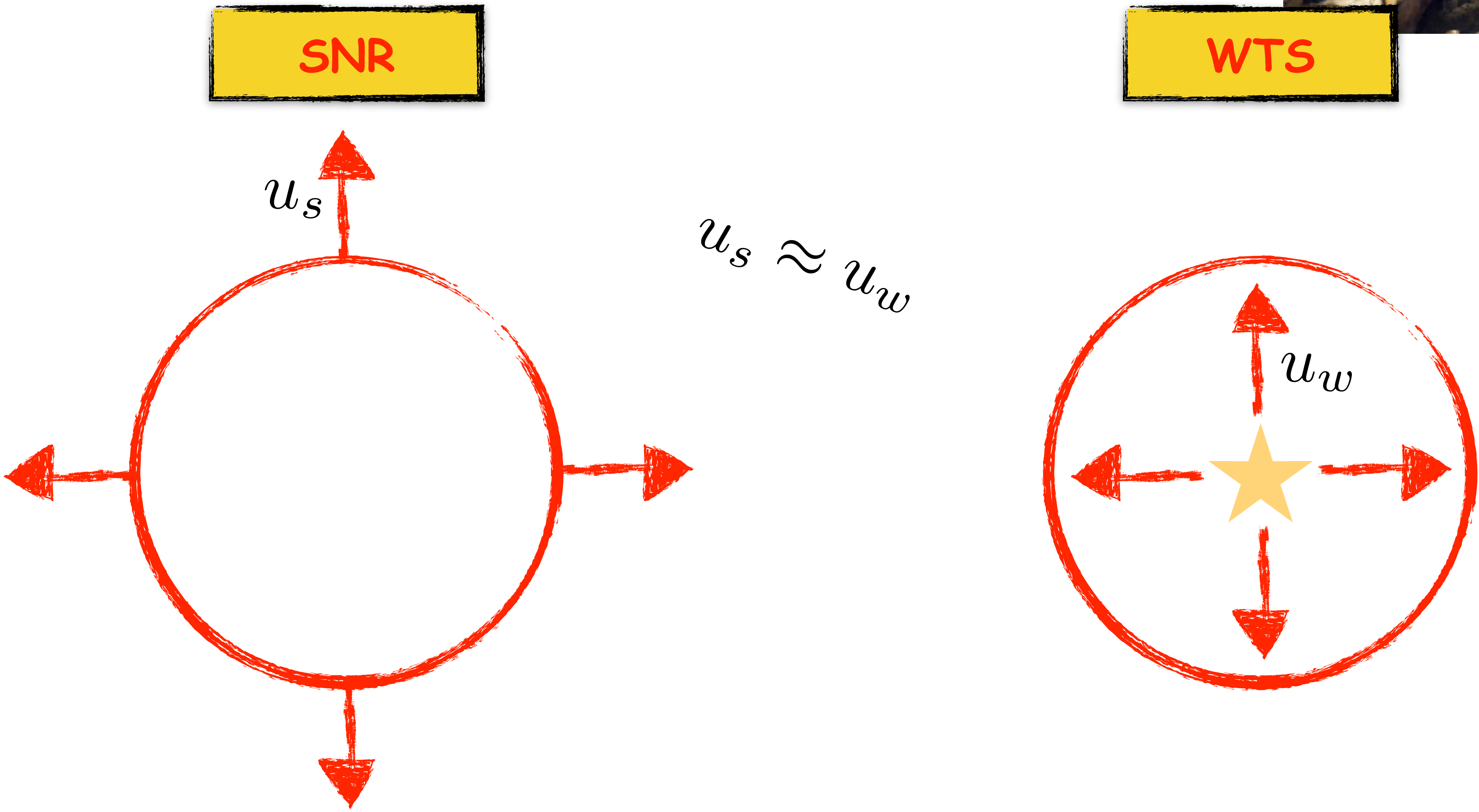
Cassé & Paul 1980, 1982 — Cesarsky & Montmerle 1983



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

Stellar wind termination shocks

Cassé & Paul 1980, 1982 — Cesarsky & Montmerle 1983



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 ($\dot{M}_w u_w$)

momentum carried by stellar photons (L_*/c)

Energy problem

Cassé & Paul 1980, 1982 — Cesarsky & Montmerle 1983

stellar winds are radiation driven

$$\dot{M}_w u_w \approx \eta \frac{L_*}{c} \propto M_*^3$$

momentum carried by the wind

momentum carried by stellar photons

total wind power dominated by the most massive stars

very steep mass-luminosity scaling

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

Energy problem

Cassé & Paul 1980, 1982 — Cesarsky & Montmerle 1983

stellar winds are radiation driven

$$\dot{M}_w u_w \approx \eta \frac{L_*}{c} \propto M_*^3$$

momentum carried by the wind

momentum carried by stellar photons

total wind power dominated by the most massive stars

very steep mass-luminosity scaling

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

for the most massive stars:

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

Energy problem

Cassé & Paul 1980, 1982 — Cesarsky & Montmerle 1983

stellar winds are radiation driven

$$\dot{M}_w u_w \approx \eta \frac{L_*}{c} \propto M_*^3$$

momentum carried by the wind

momentum carried by stellar photons

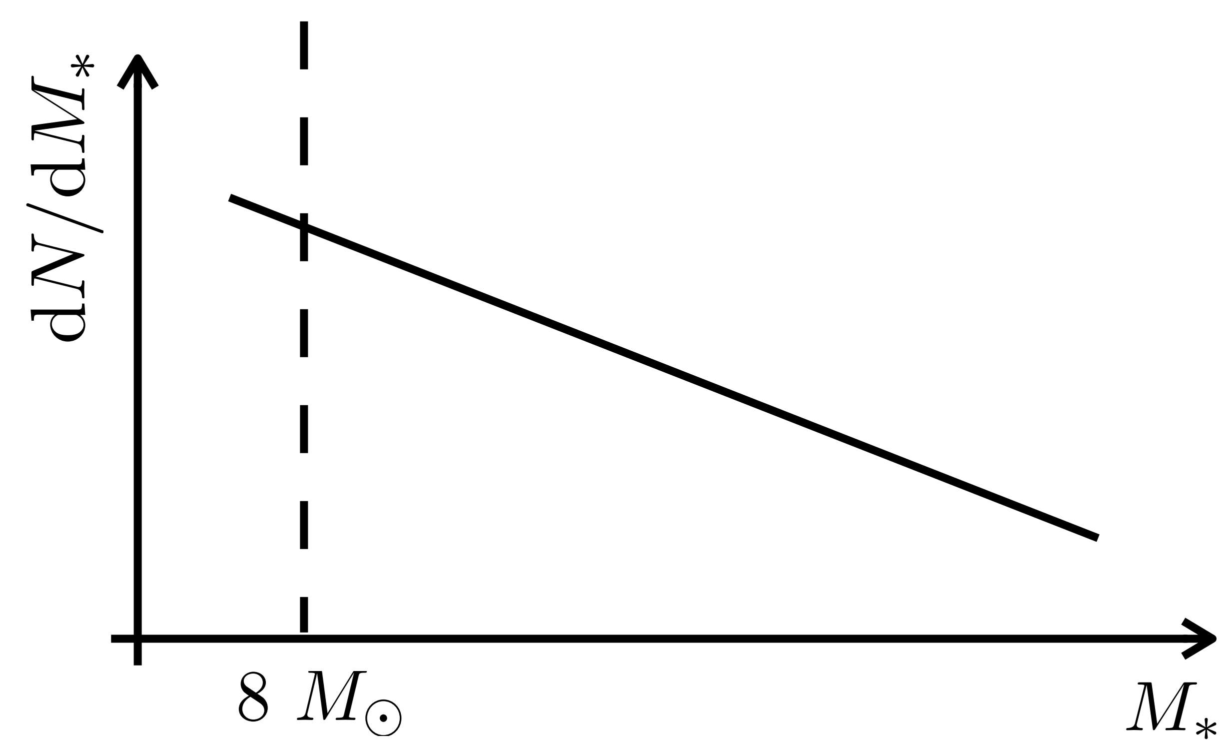
total wind power dominated by the most massive stars

very steep mass-luminosity scaling

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

for the most massive stars:

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



Energy problem

Cassé & Paul 1980, 1982 — Cesarsky & Montmerle 1983

stellar winds are radiation driven

$$\dot{M}_w u_w \approx \eta \frac{L_*}{c} \propto M_*^3$$

momentum carried by the wind

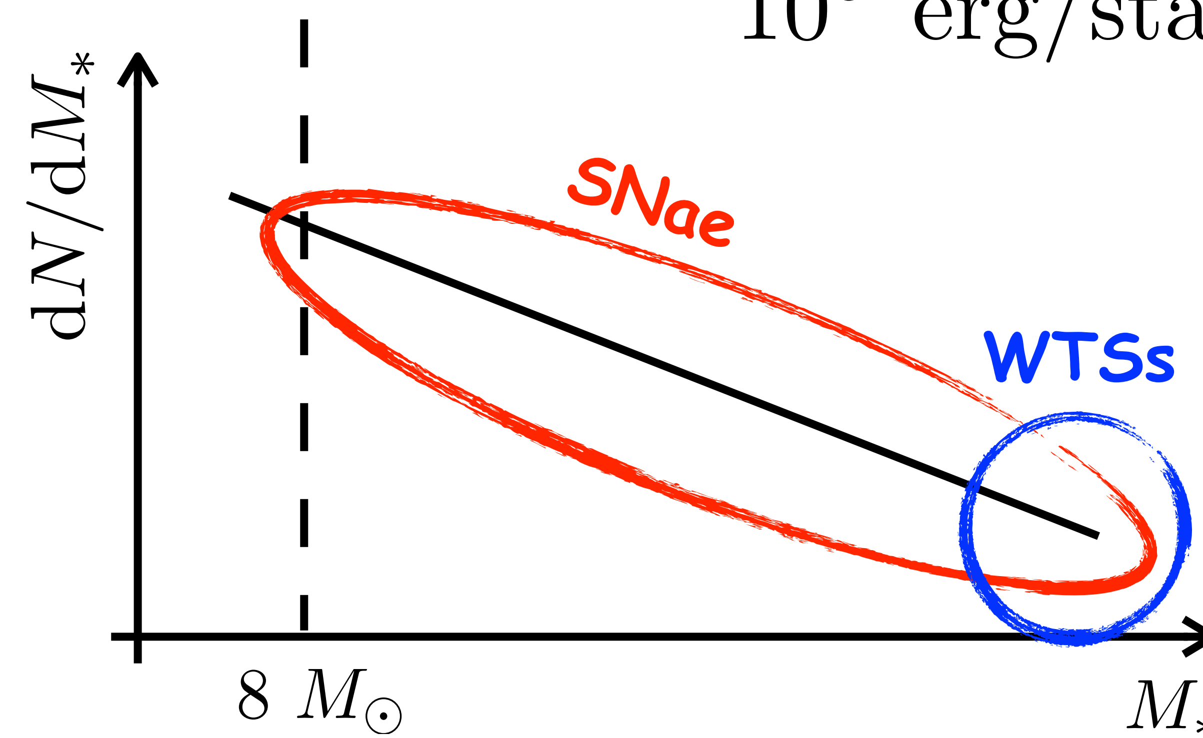
momentum carried by stellar photons

total wind power dominated by the most massive stars

very steep mass-luminosity scaling

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

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



for the most massive stars:

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

Energy problem

Cassé & Paul 1980, 1982 — Cesarsky & Montmerle 1983

stellar winds are radiation driven

$$\dot{M}_w u_w \approx \eta \frac{L_*}{c} \propto M_*^3$$

momentum carried by the wind

momentu...
by ...

very steep
mass-lum...

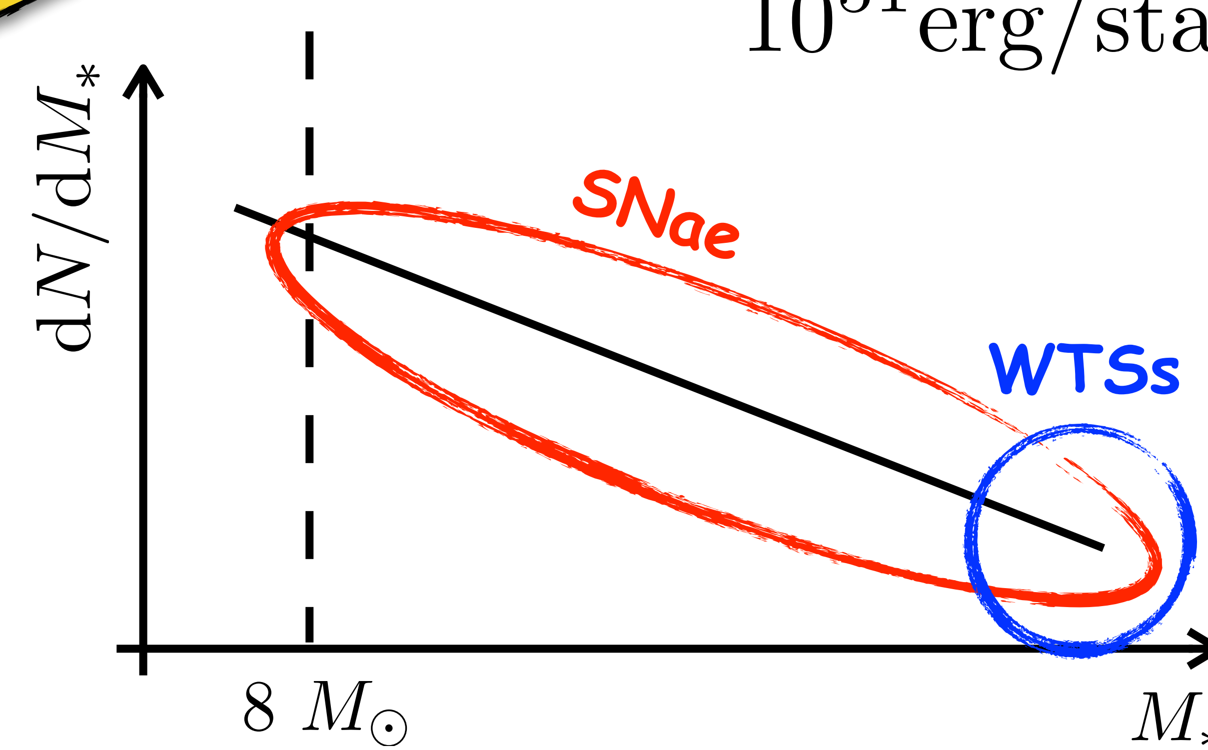
M_*^3

--> supernovae win by about a factor of 10 (caveat: failed SNae?)
--> WTS could explain LOCAL CRs (conflict w. diffuse gamma rays from the disk)

... stars:

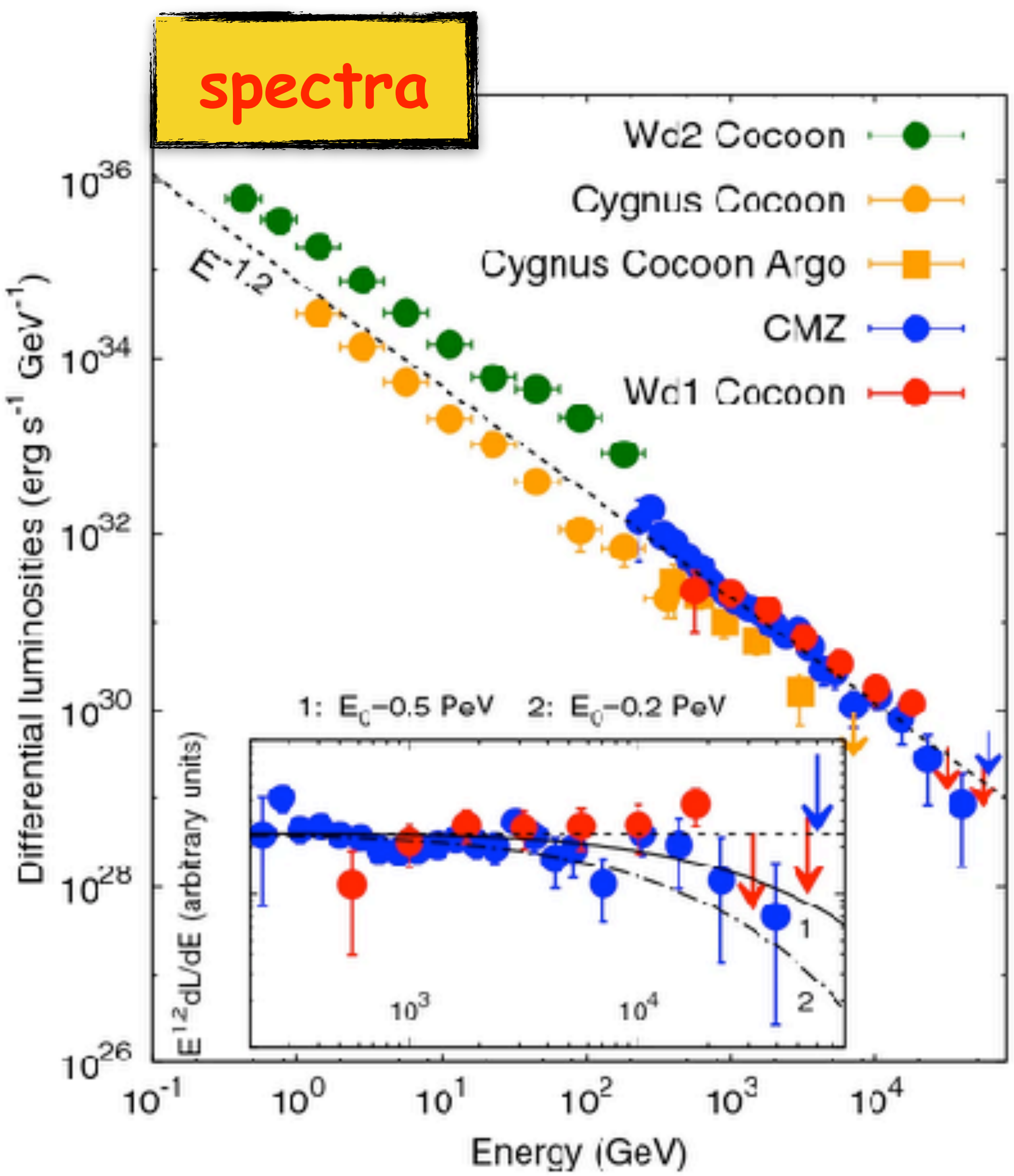
$\int \ldots_w \approx 10^{51}\mathrm{erg} \sim \mathrm{E_{SN}}$

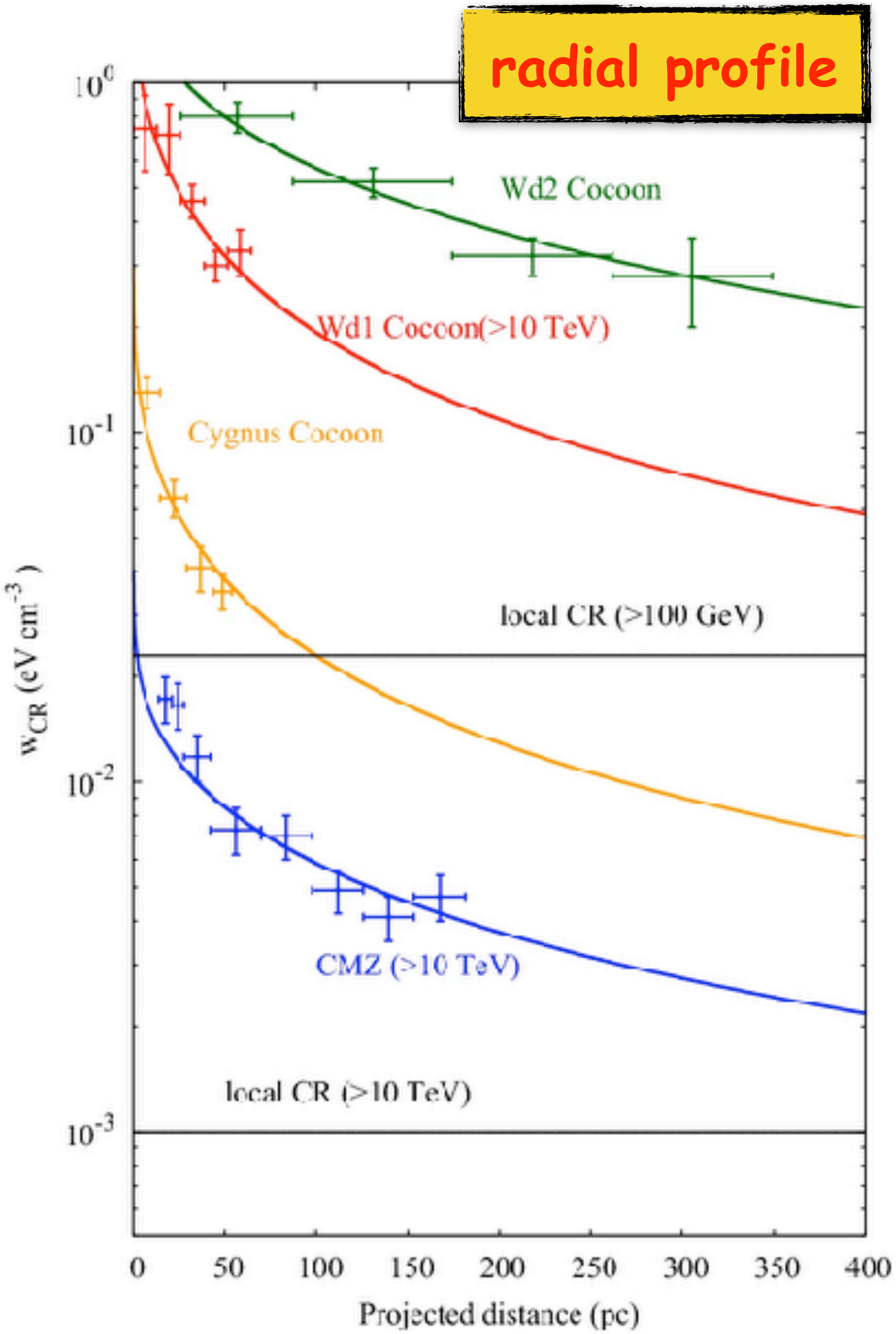
$10^{51}\mathrm{erg/star}$



Gamma rays around young star clusters

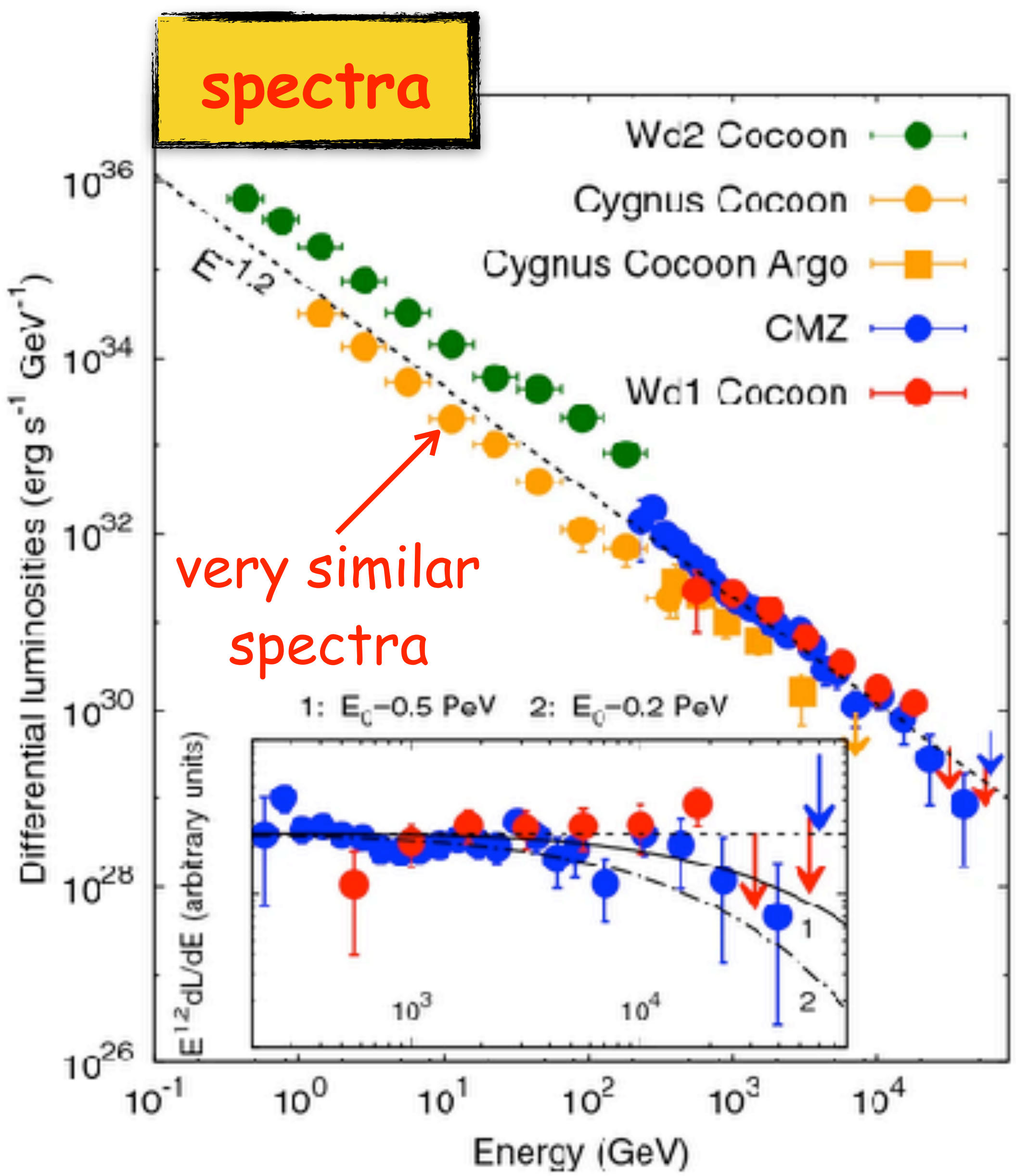
Aharonian+ 2019, plus several papers especially by Yang and collaborators

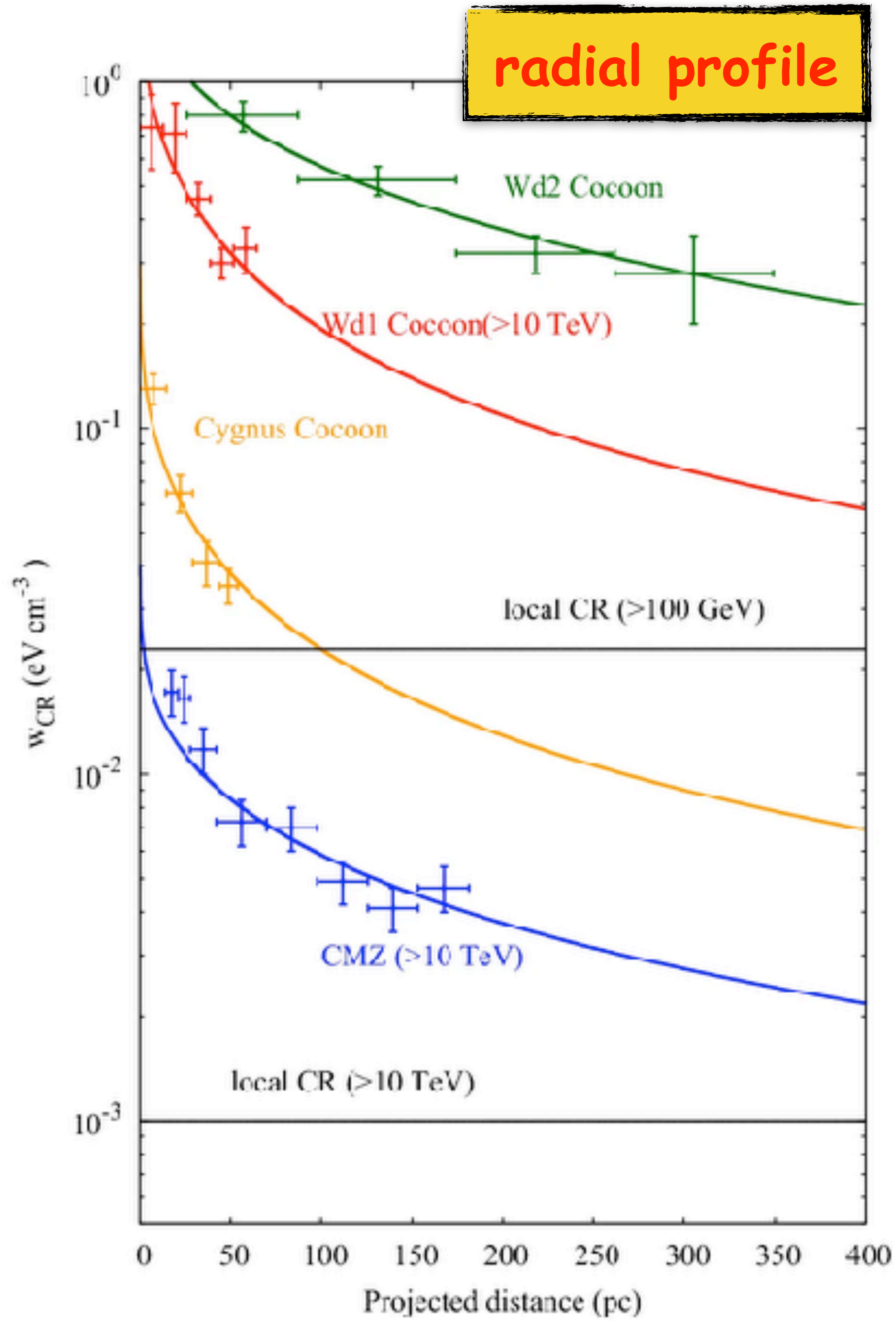




Gamma rays around young star clusters

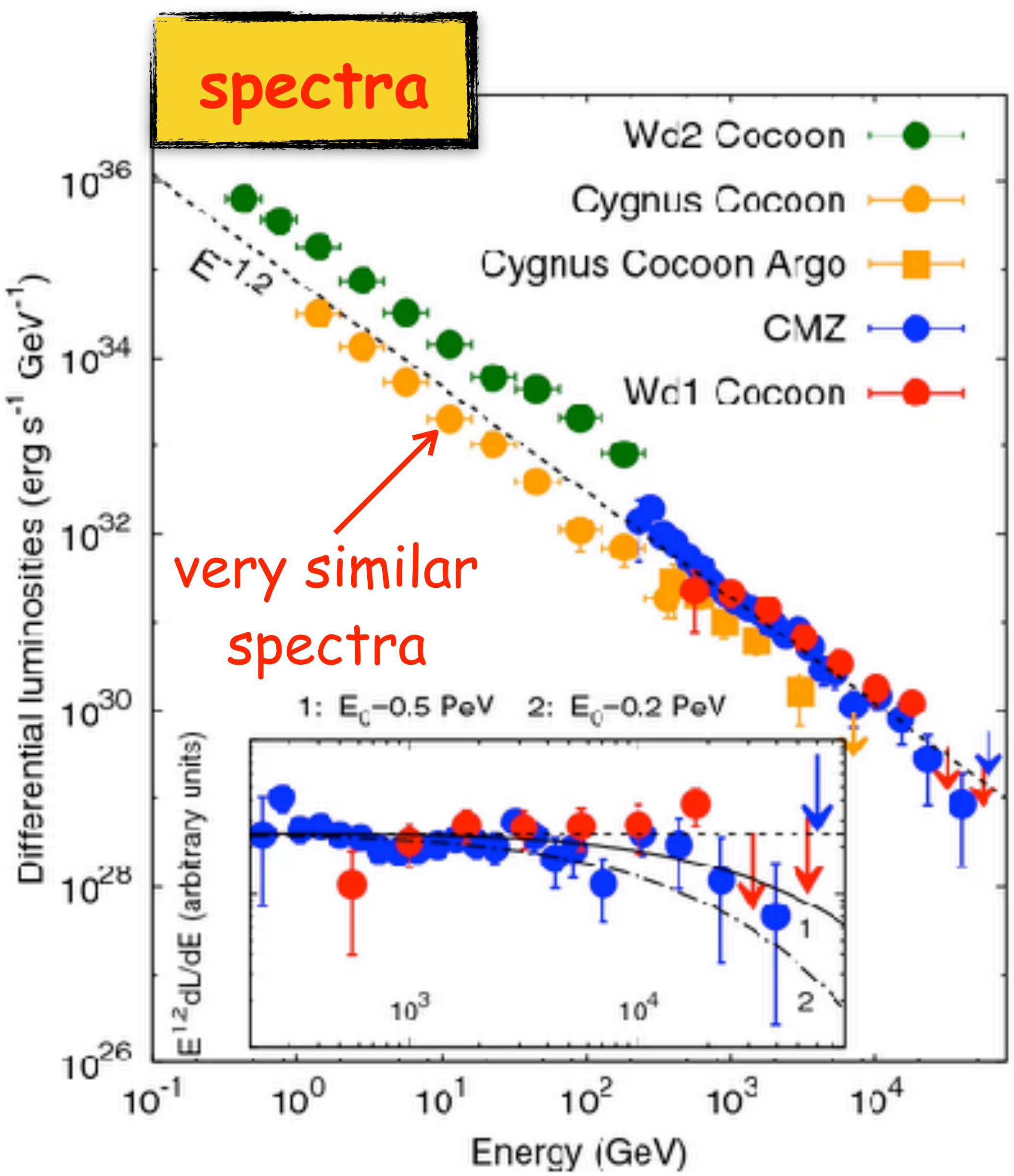
Aharonian+ 2019, plus several papers especially by Yang and collaborators

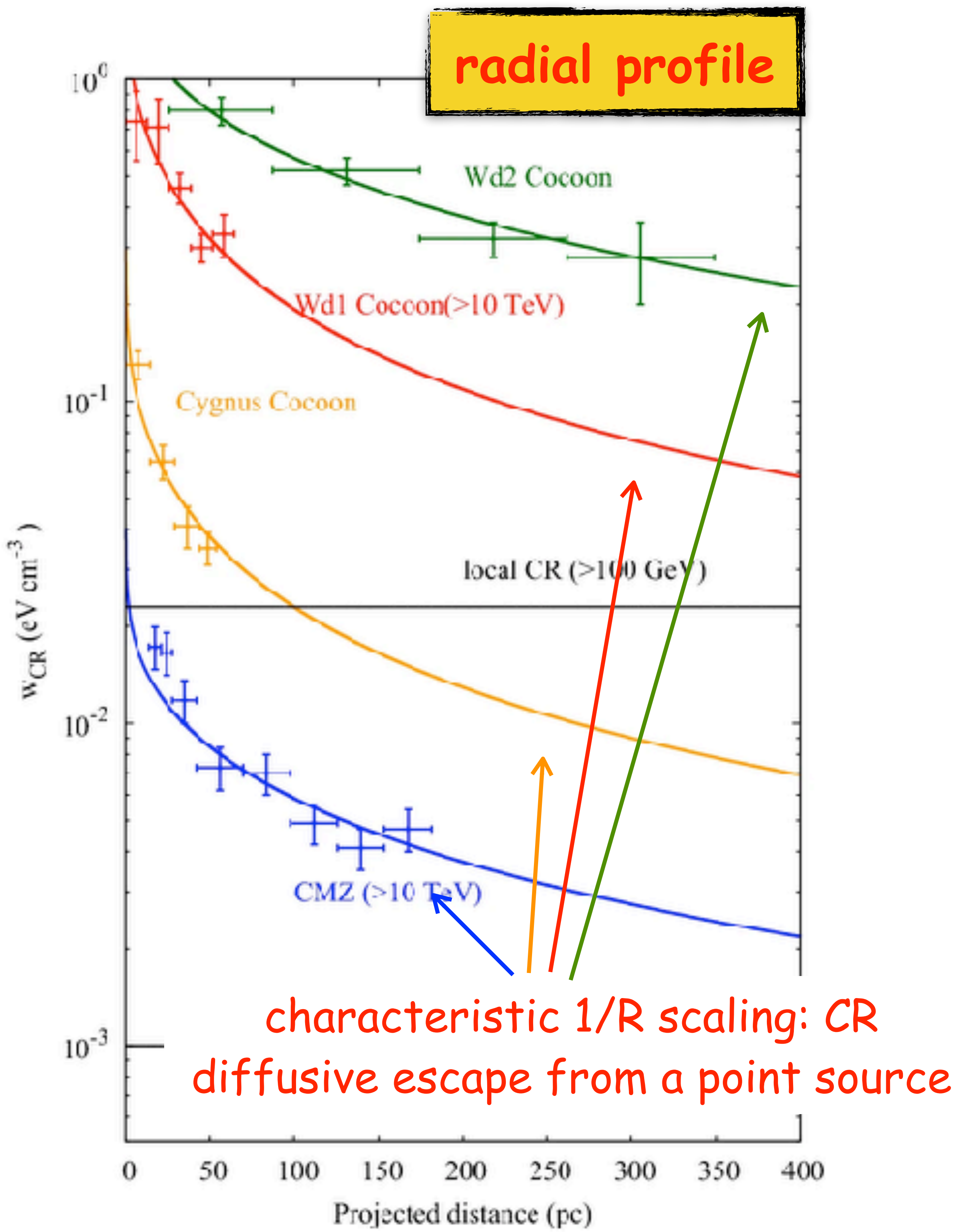




Gamma rays around young star clusters

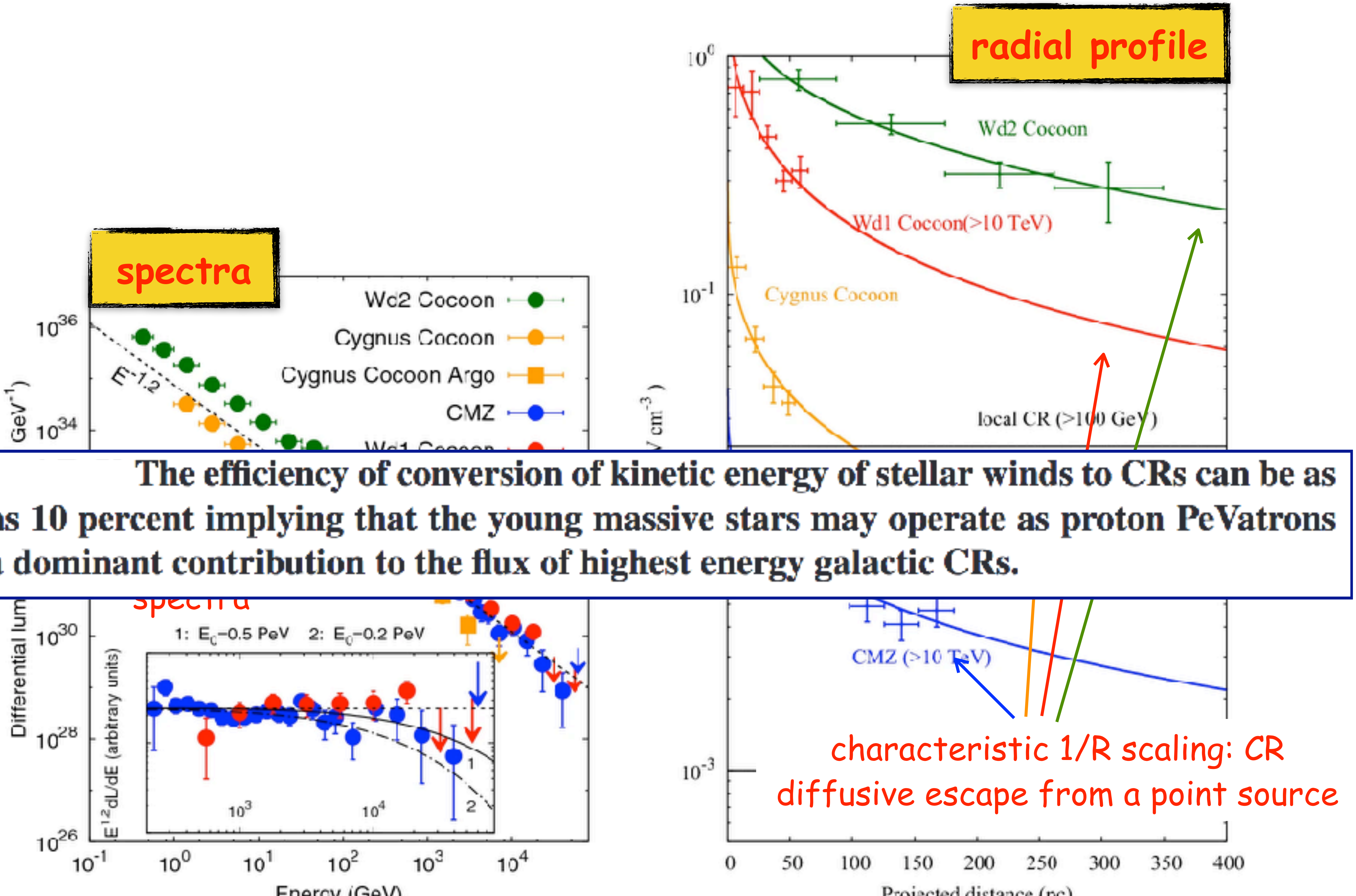
Aharonian+ 2019, plus several papers especially by Yang and collaborators





Gamma rays around young star clusters

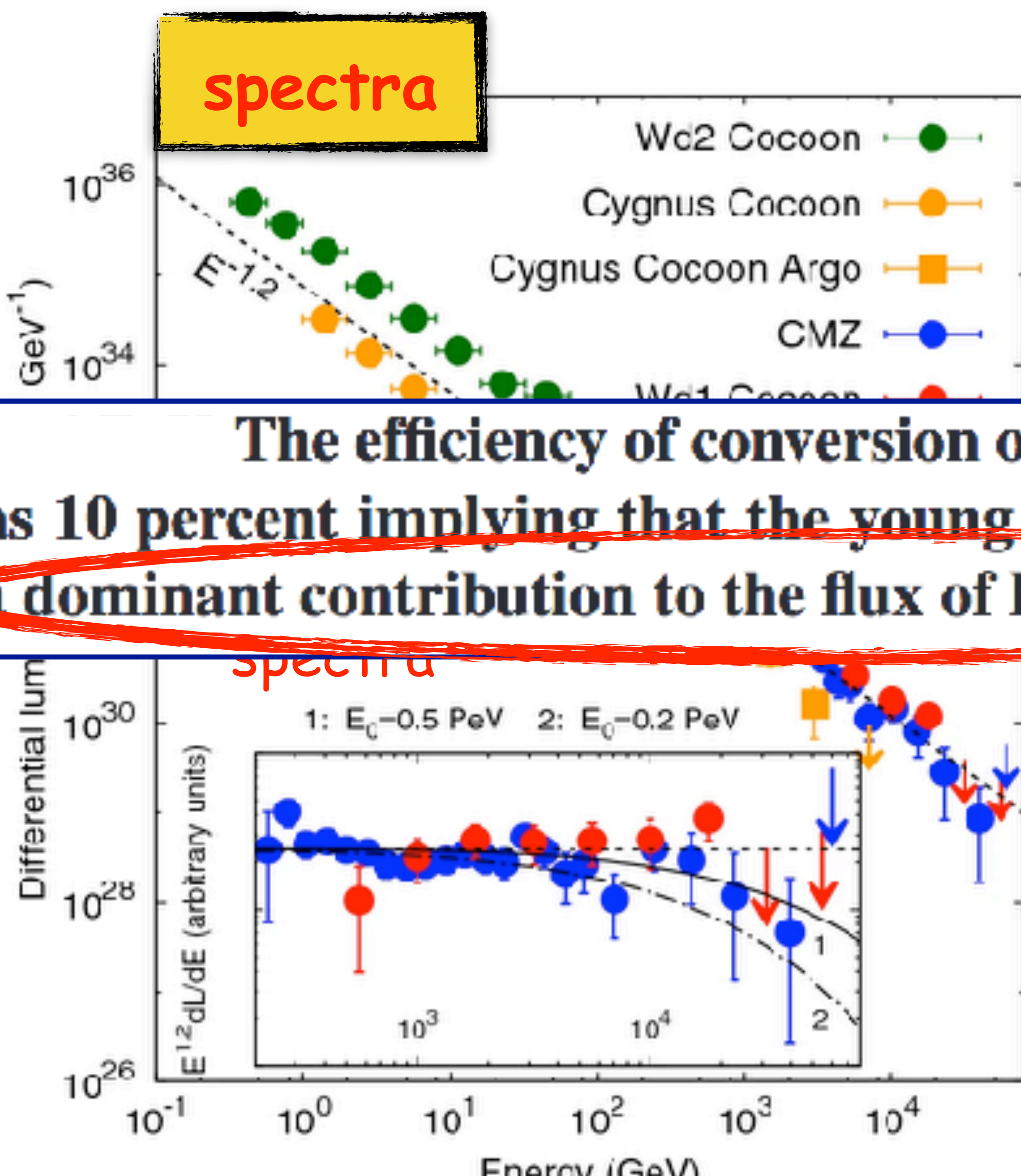
Aharonian+ 2019, plus several papers especially by Yang and collaborators

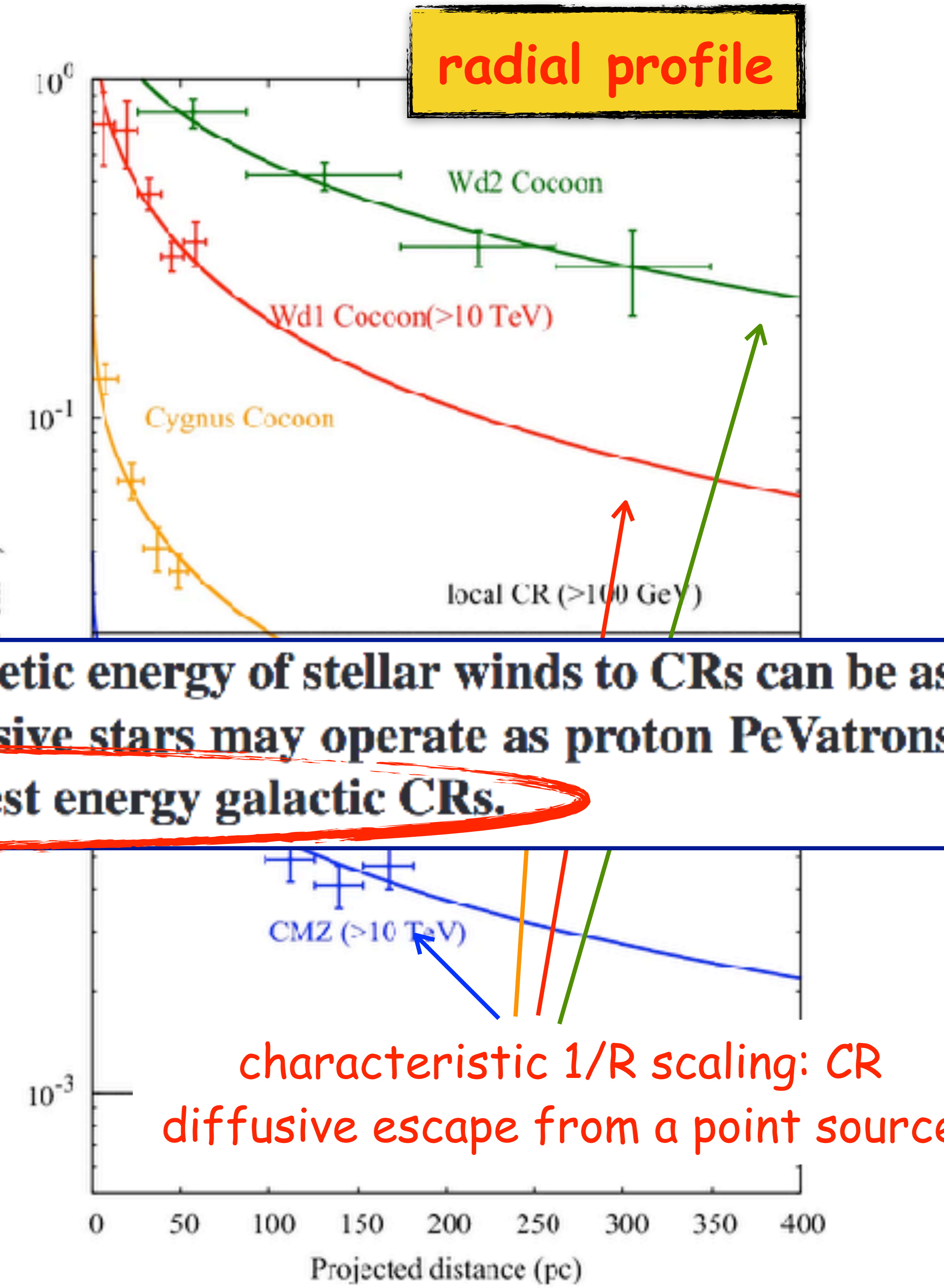


The efficiency of conversion of kinetic energy of stellar winds to CRs can be as high as 10 percent implying that the young massive stars may operate as proton PeVatrons with a dominant contribution to the flux of highest energy galactic CRs.

Gamma rays around young star clusters

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

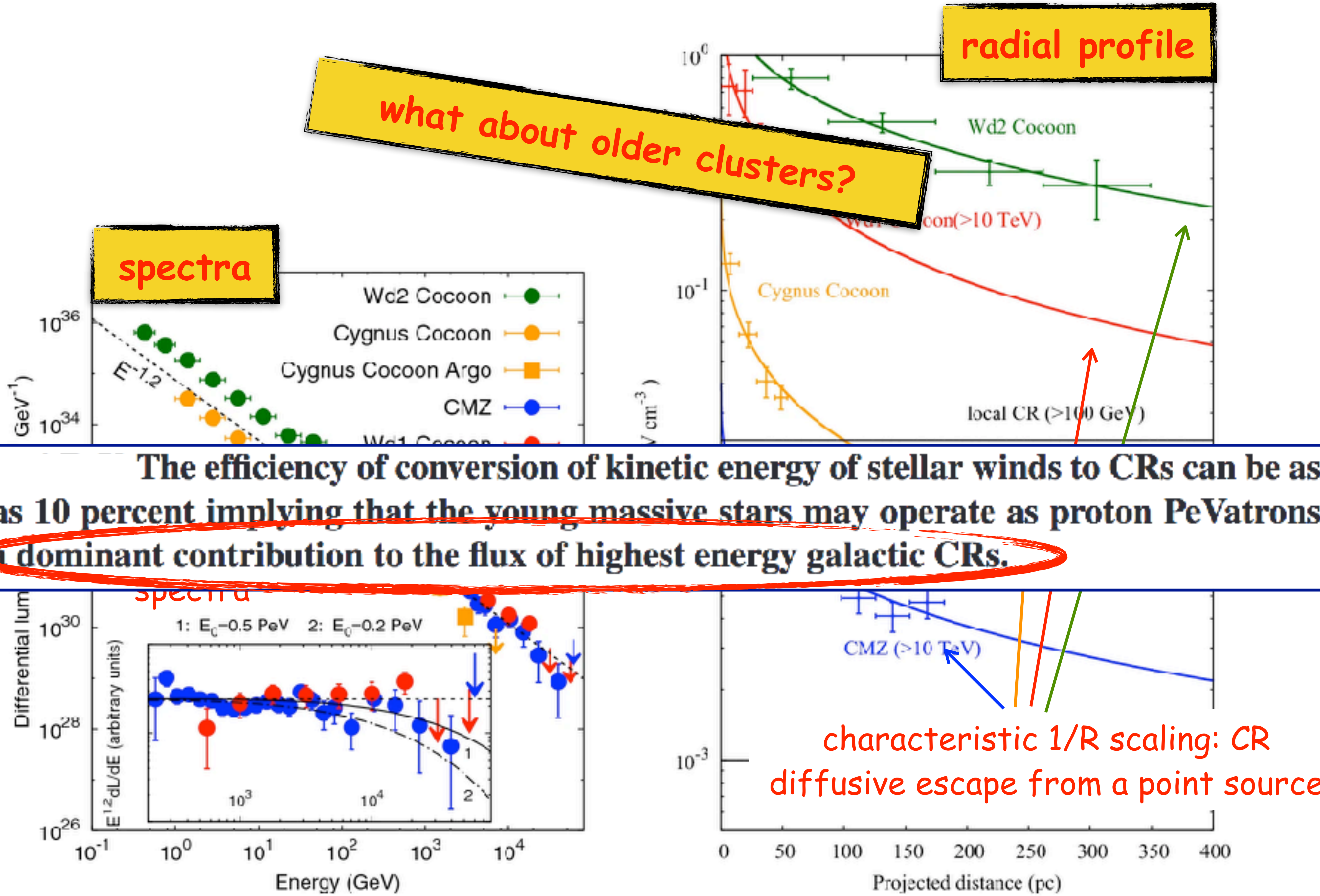




> The efficiency of conversion of kinetic energy of stellar winds to CRs can be as high as 10 percent implying that the young massive stars may operate as proton PeVatrons with a dominant contribution to the flux of highest energy galactic CRs.

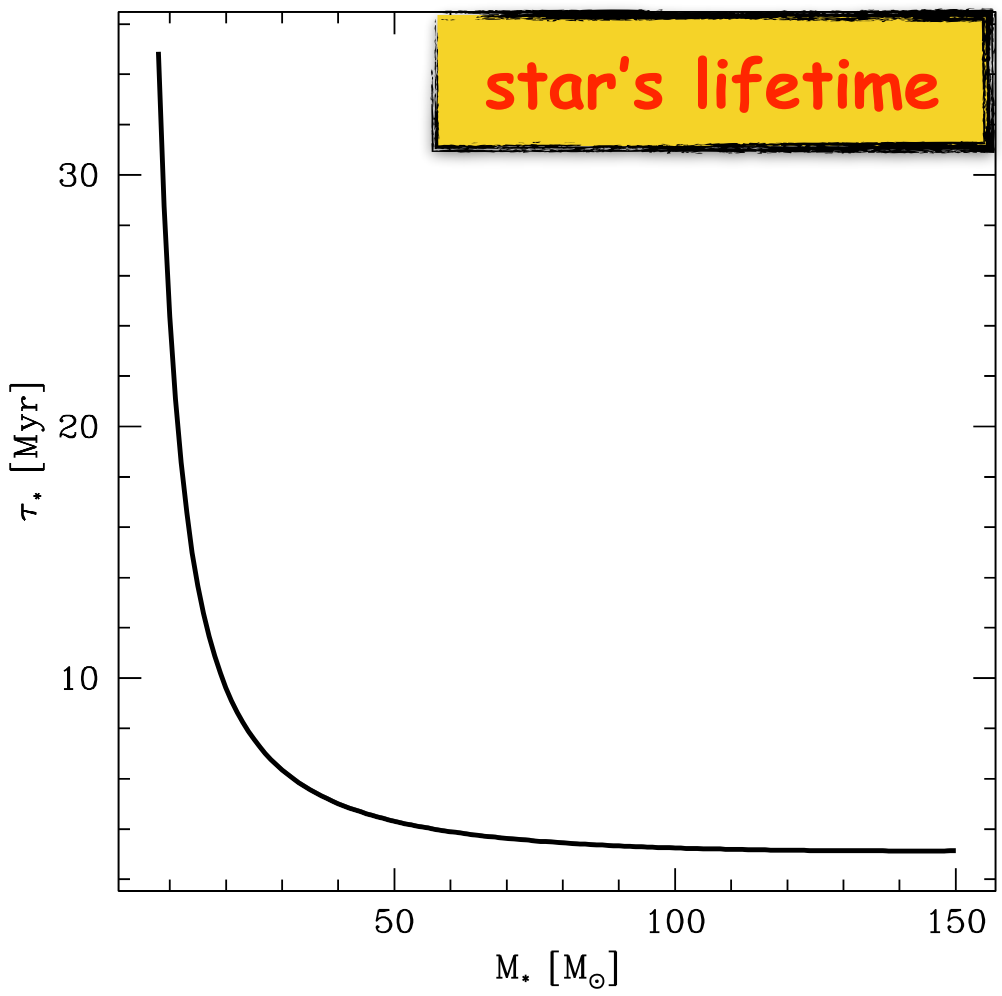
Gamma rays around young star clusters

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

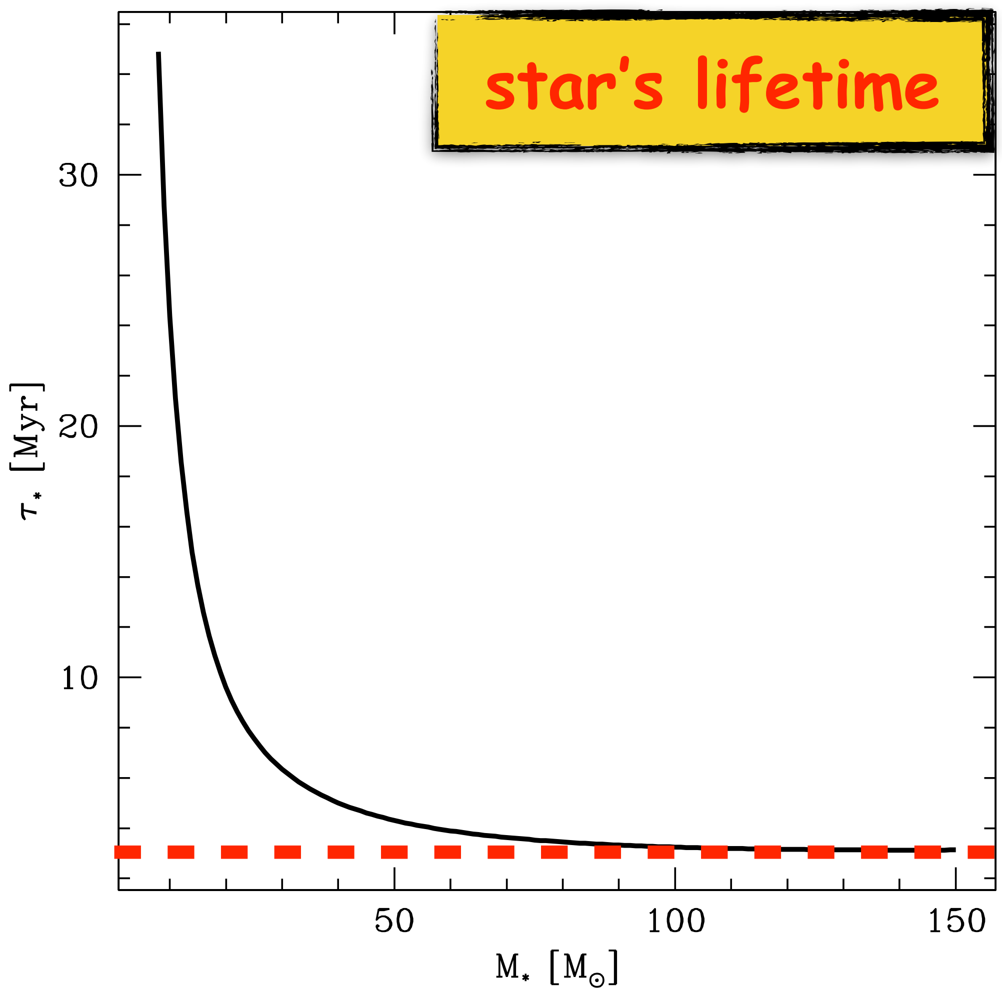


The efficiency of conversion of kinetic energy of stellar winds to CRs can be as high as 10 percent implying that the young massive stars may operate as proton PeVatrons with a dominant contribution to the flux of highest energy galactic CRs.

Energy injection at star clusters

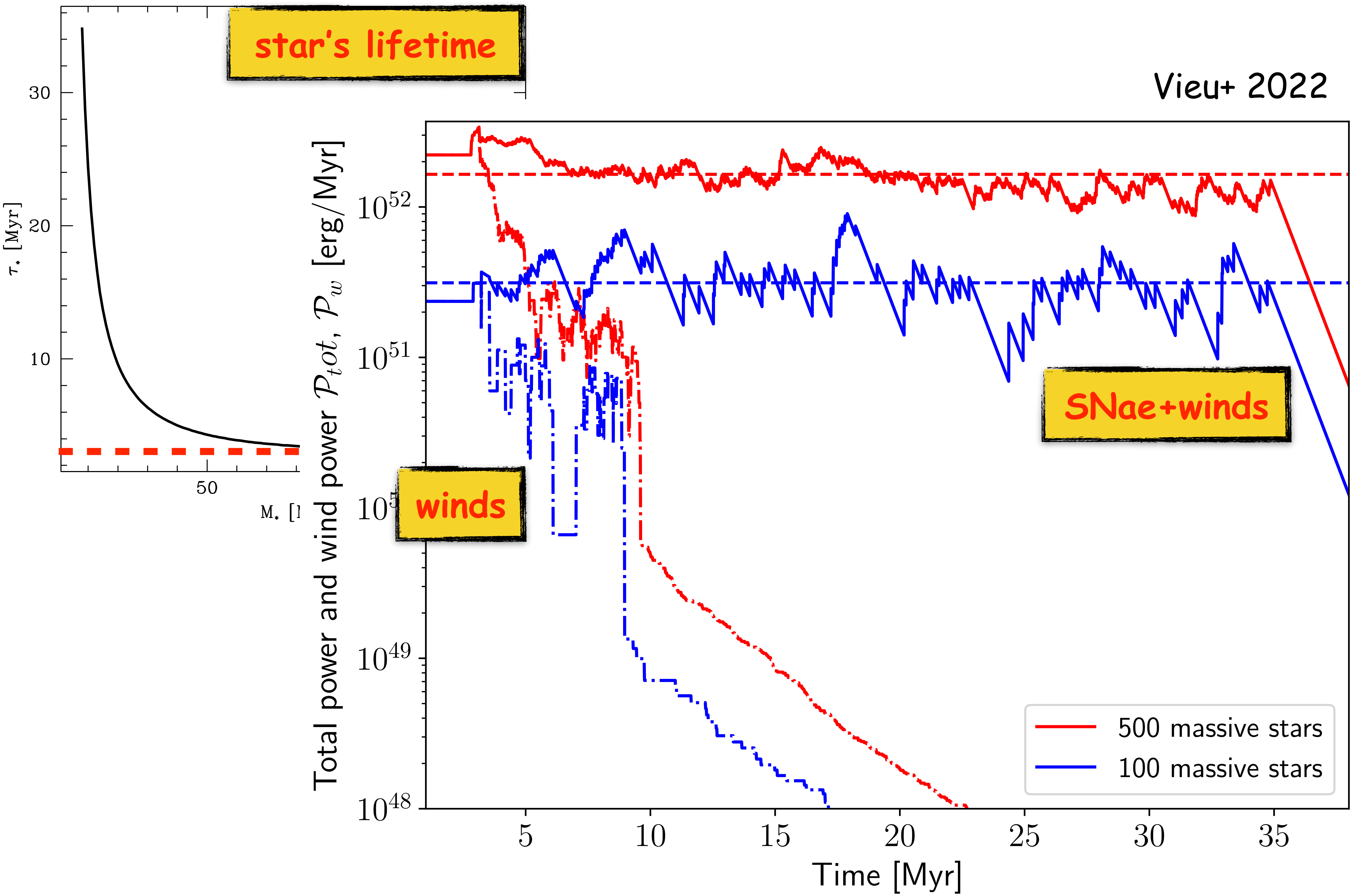


Energy injection at star clusters

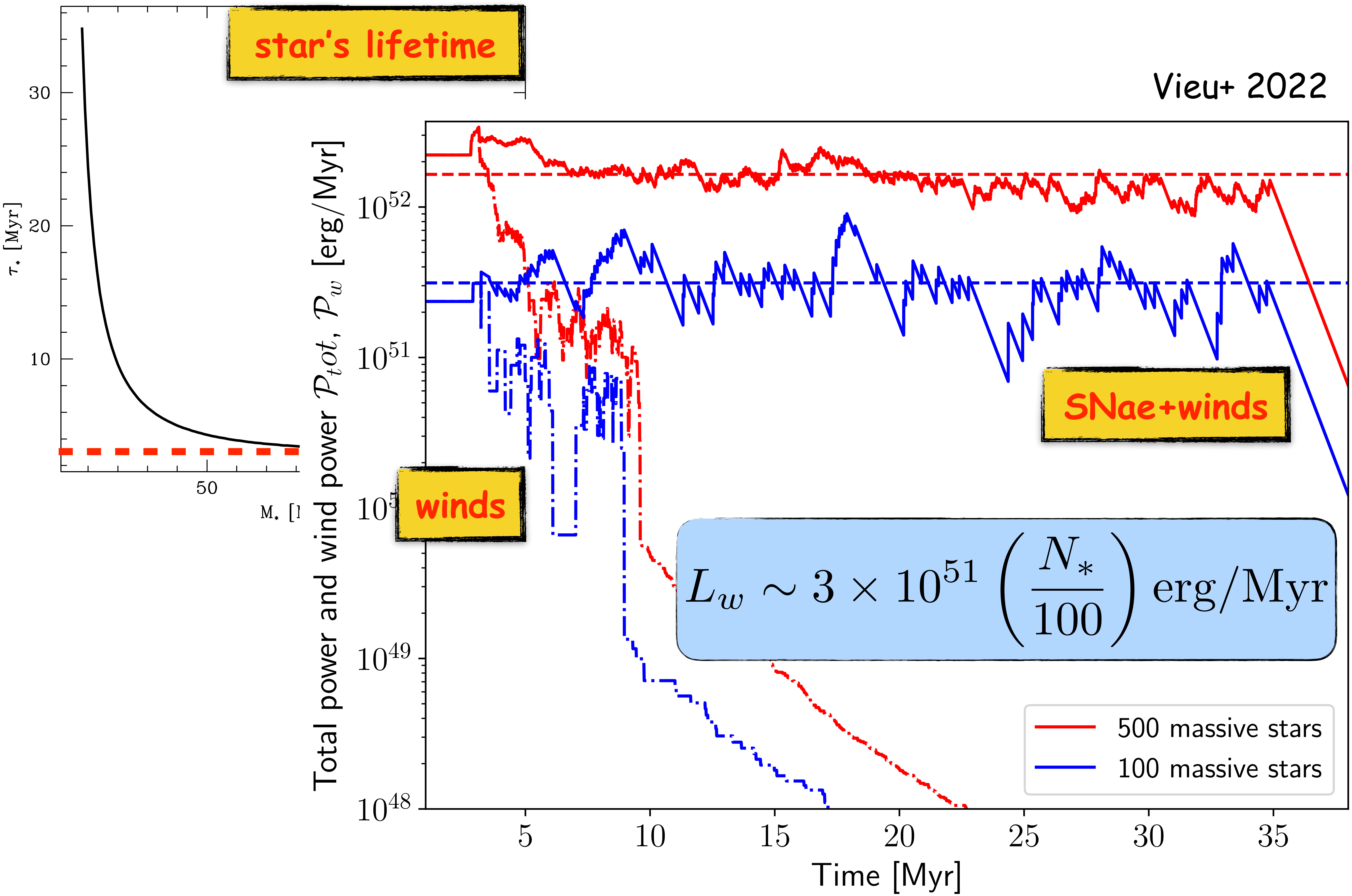


t < 3 Myr —> only stellar winds

Energy injection at star clusters

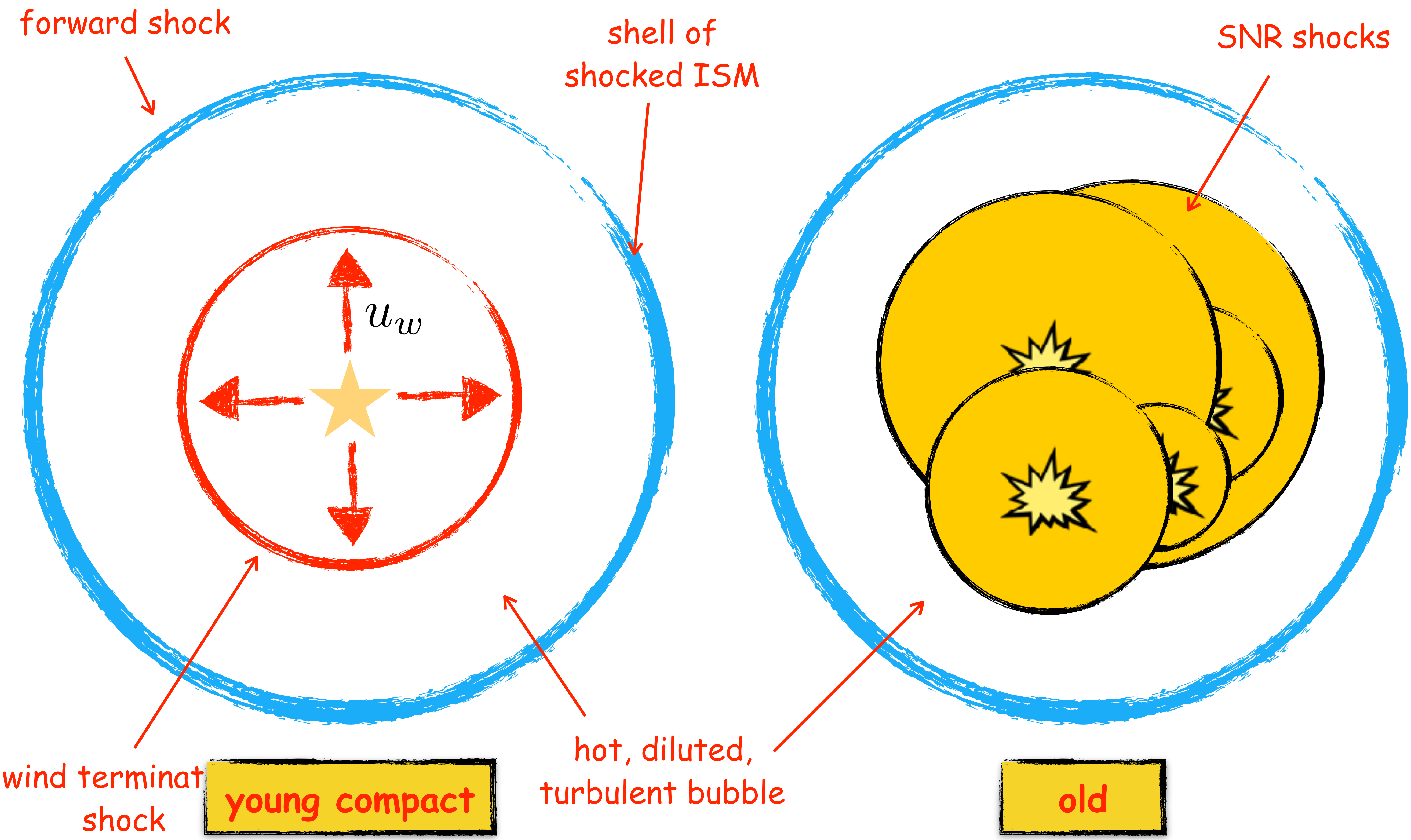


Energy injection at star clusters



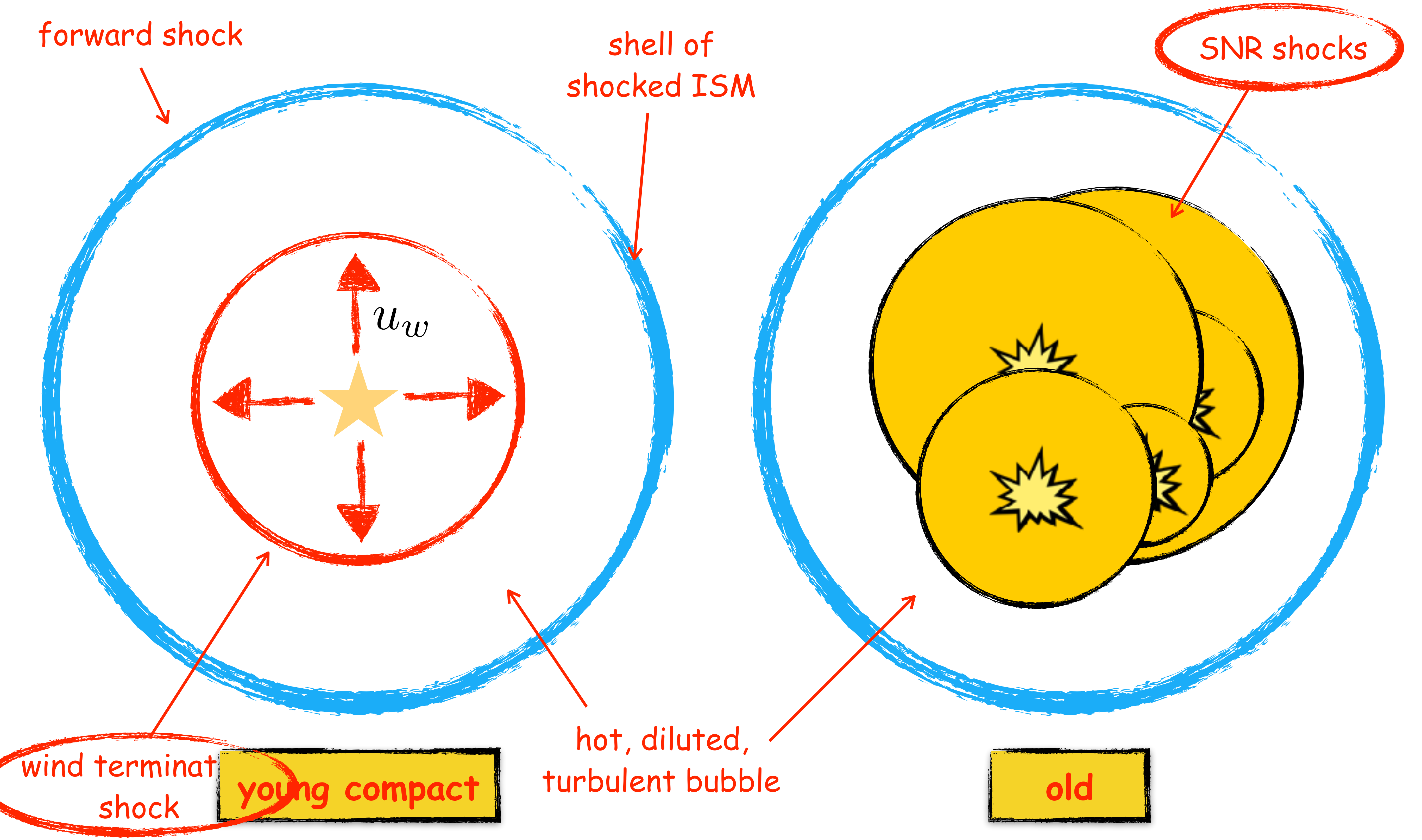
Interstellar bubbles around star clusters

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



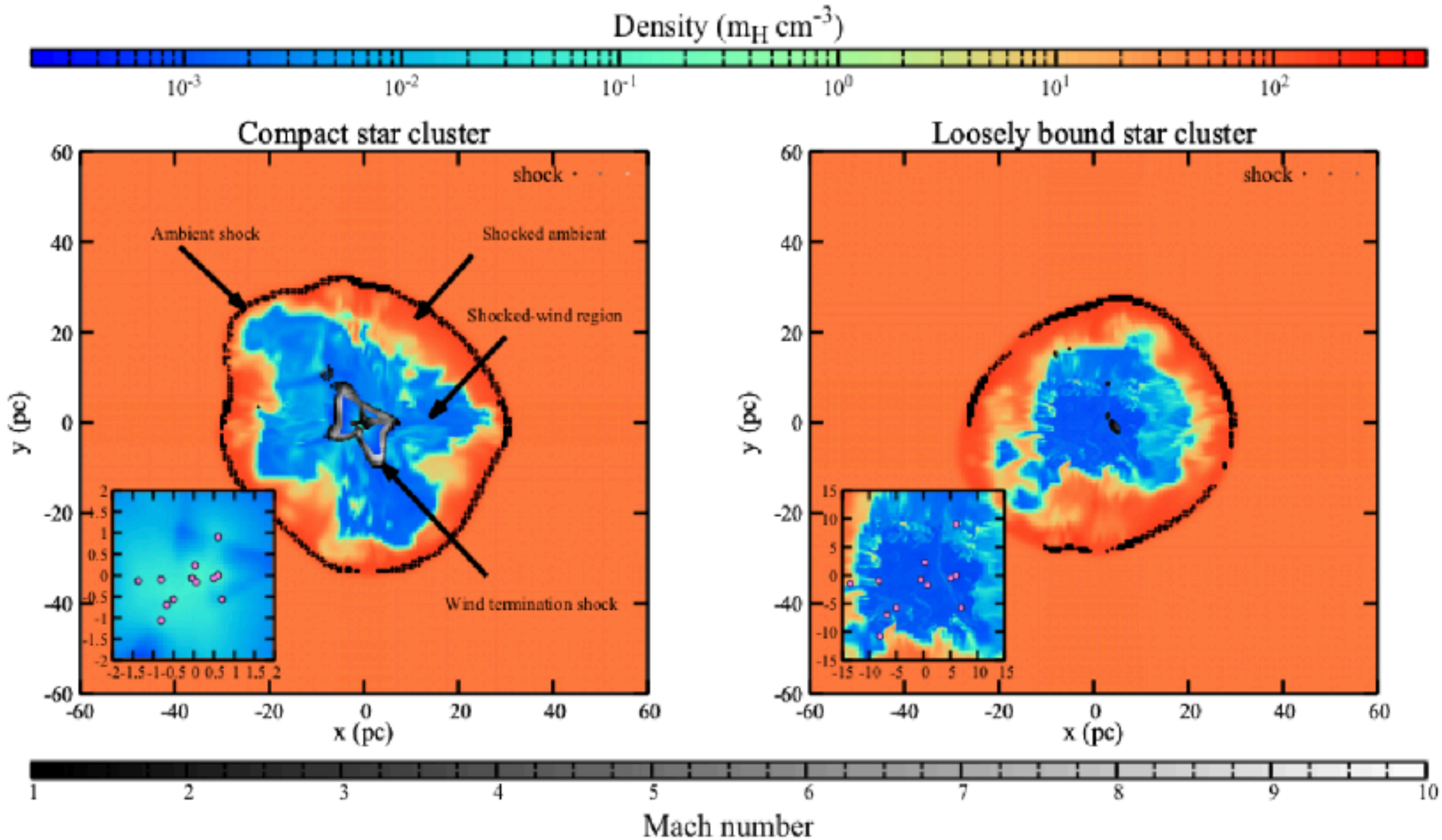
Interstellar bubbles around star clusters

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



Particle acceleration at WTSs: spectrum

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



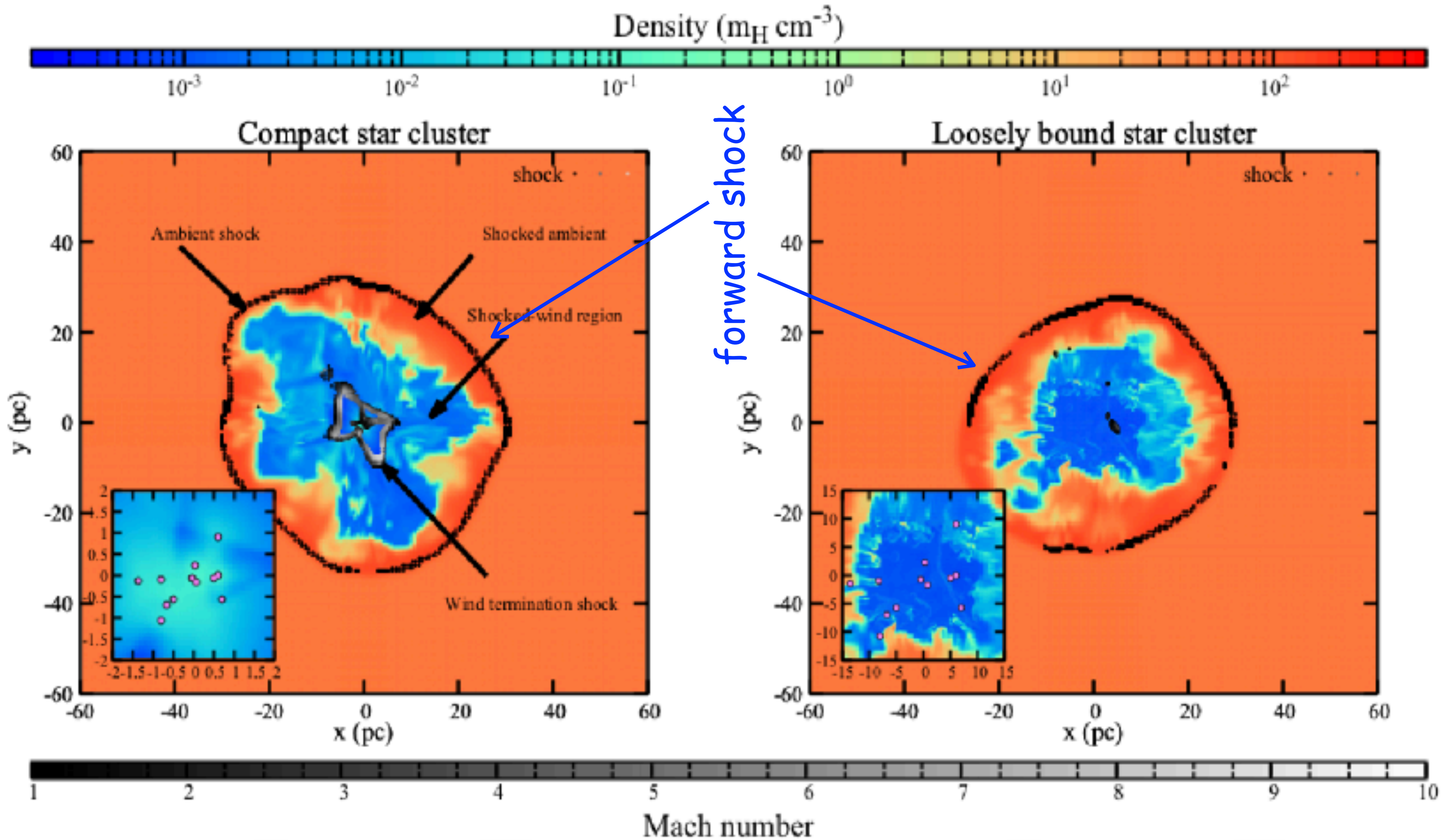
compact cluster

loose cluster

Gupta+ 2020

Particle acceleration at WTSs: spectrum

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



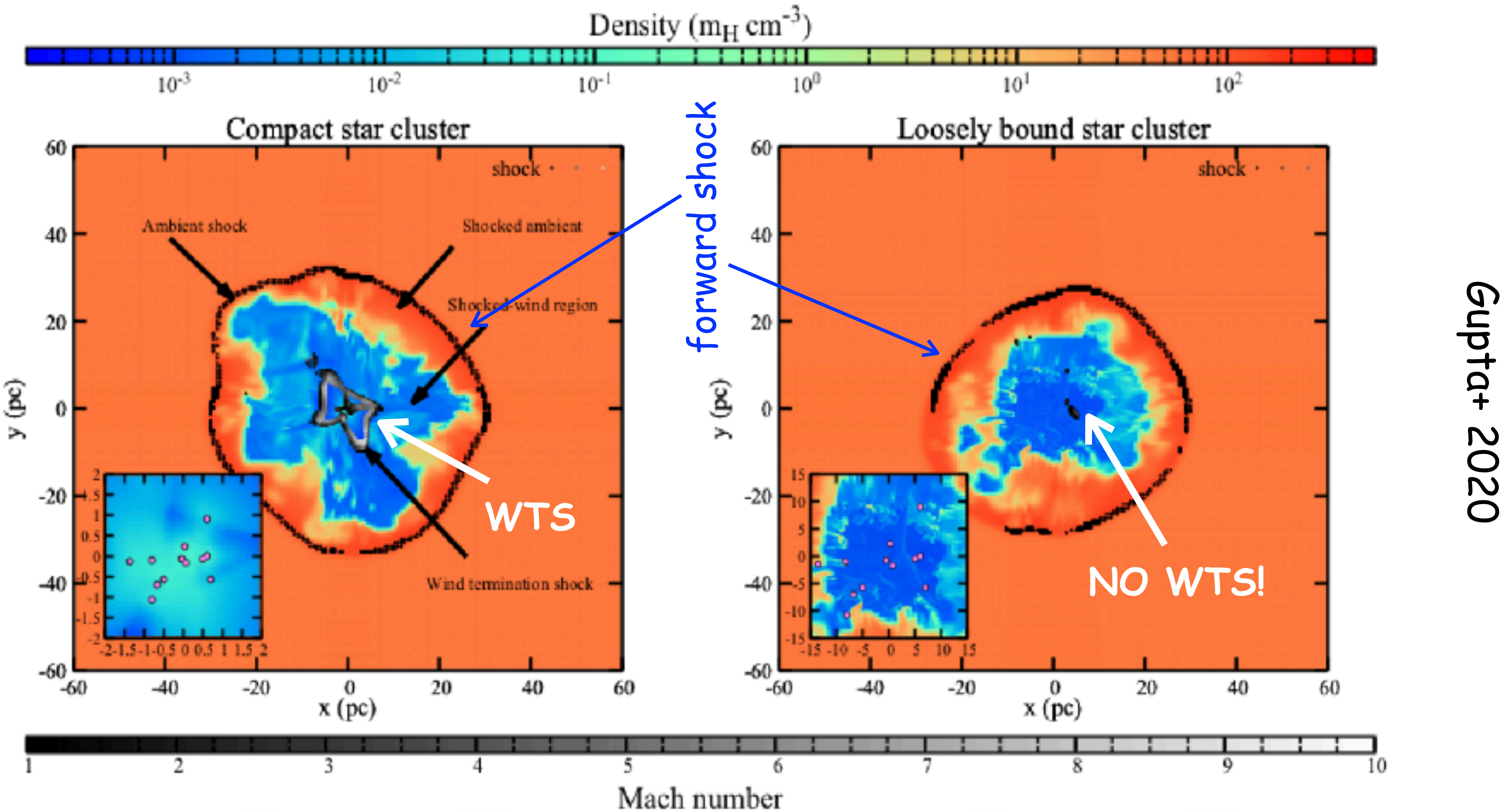
compact cluster

loose cluster

Gupta+ 2020

Particle acceleration at WTSs: spectrum

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

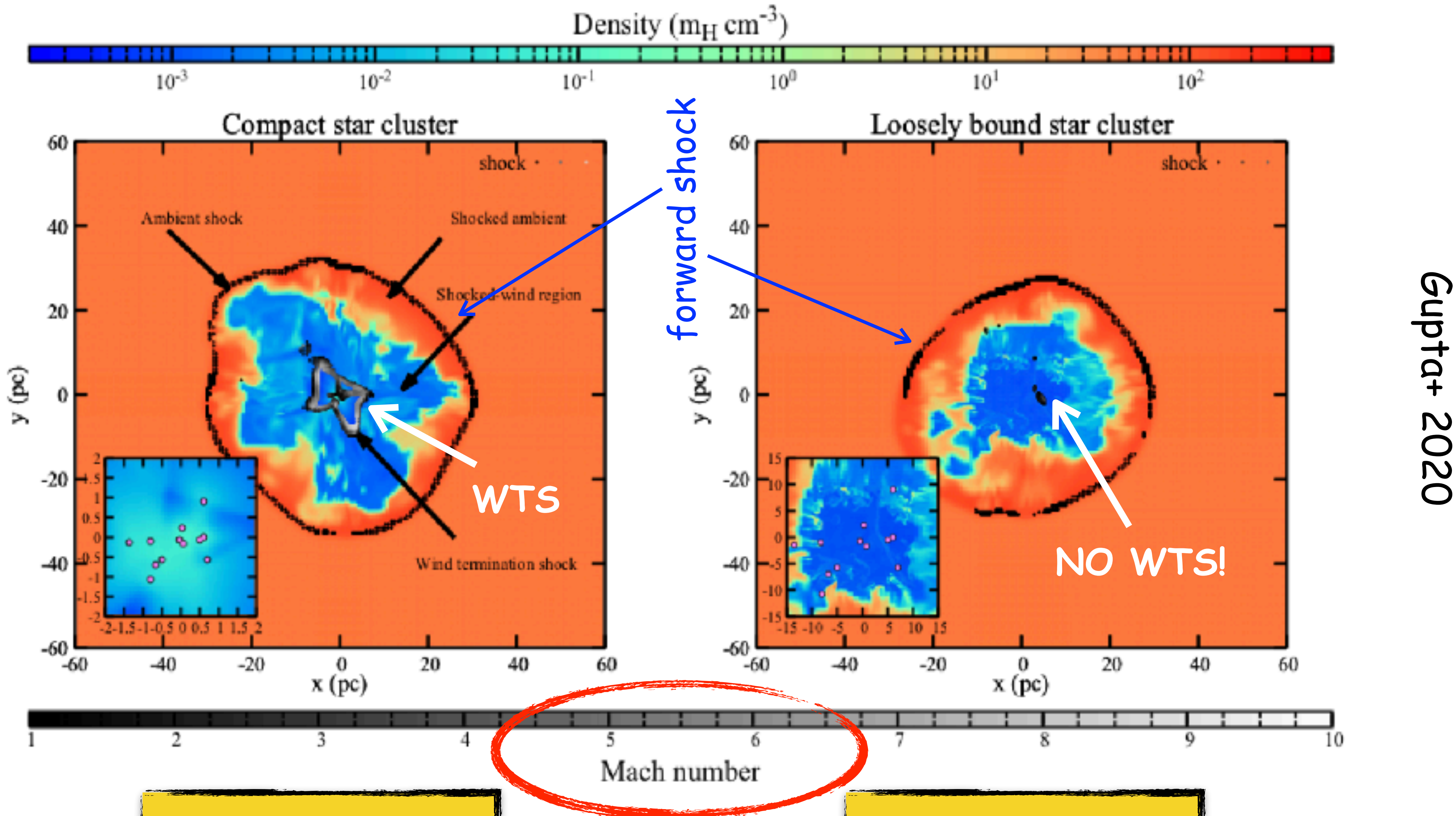


compact cluster

loose cluster

Particle acceleration at WTSs: spectrum

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



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}

Hillas criterium —>

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

Morlino+ 2021

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

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

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

$$\eta_B = 0.1$$

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

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

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

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

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

$$\eta_B = 0.1$$

quite small

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

possible for powerful clusters

Particle acceleration in superbubbles

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

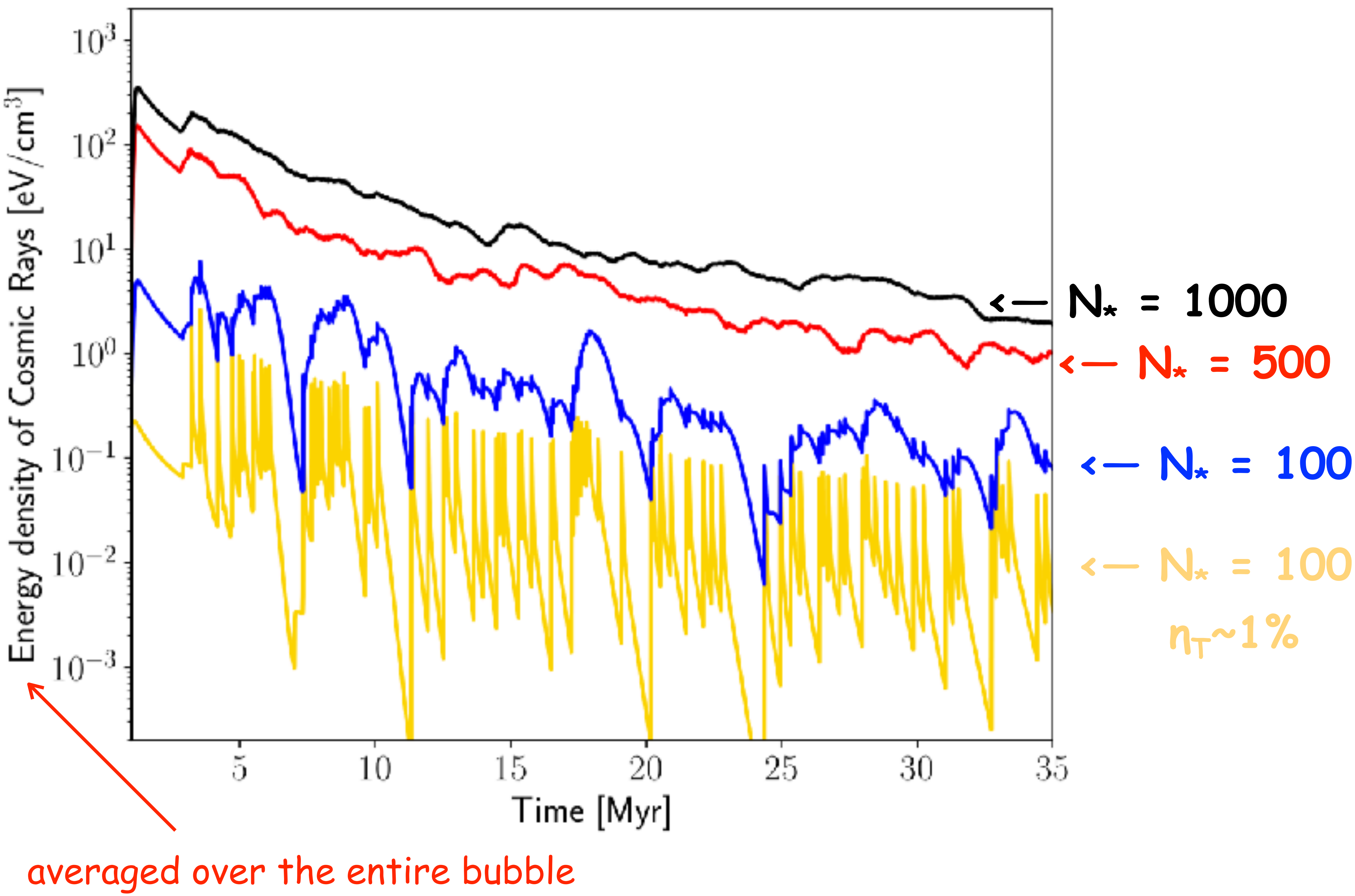
Vieu+ 2022

- cluster of N_* massive stars following a standard (e.g. Salpeter...) IMF
- stars blow winds and eventually explode
- CRs injected by wind termination shocks (η ~ 10% efficiency)
- CRs accelerated/reaccelerated by SNR shocks (η ~ 10% efficiency)
- generation of magnetic turbulence (MHD waves), (η_T~30% efficiency)
- CR turbulent reacceleration (Fermi II), energy transferred waves —> CRs
- CR escape from the bubble (diffusion coefficient in the bubble & in the shell)
- energy losses (ionization/Coulomb)

A universal spectrum is not expected...

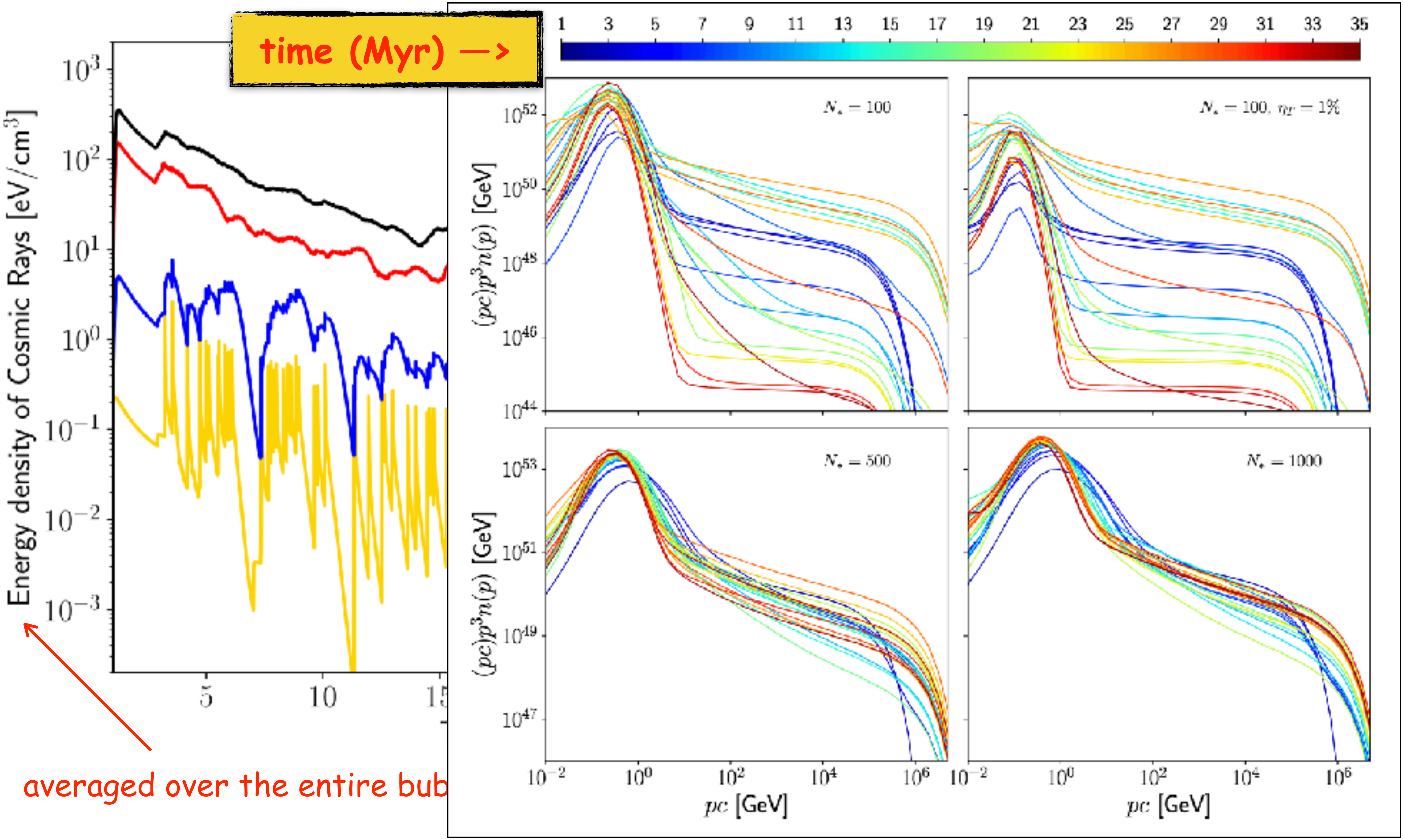
Particle acceleration in superbubbles: intermittency

Vieu+ 2022



Particle acceleration in superbubbles: intermittency

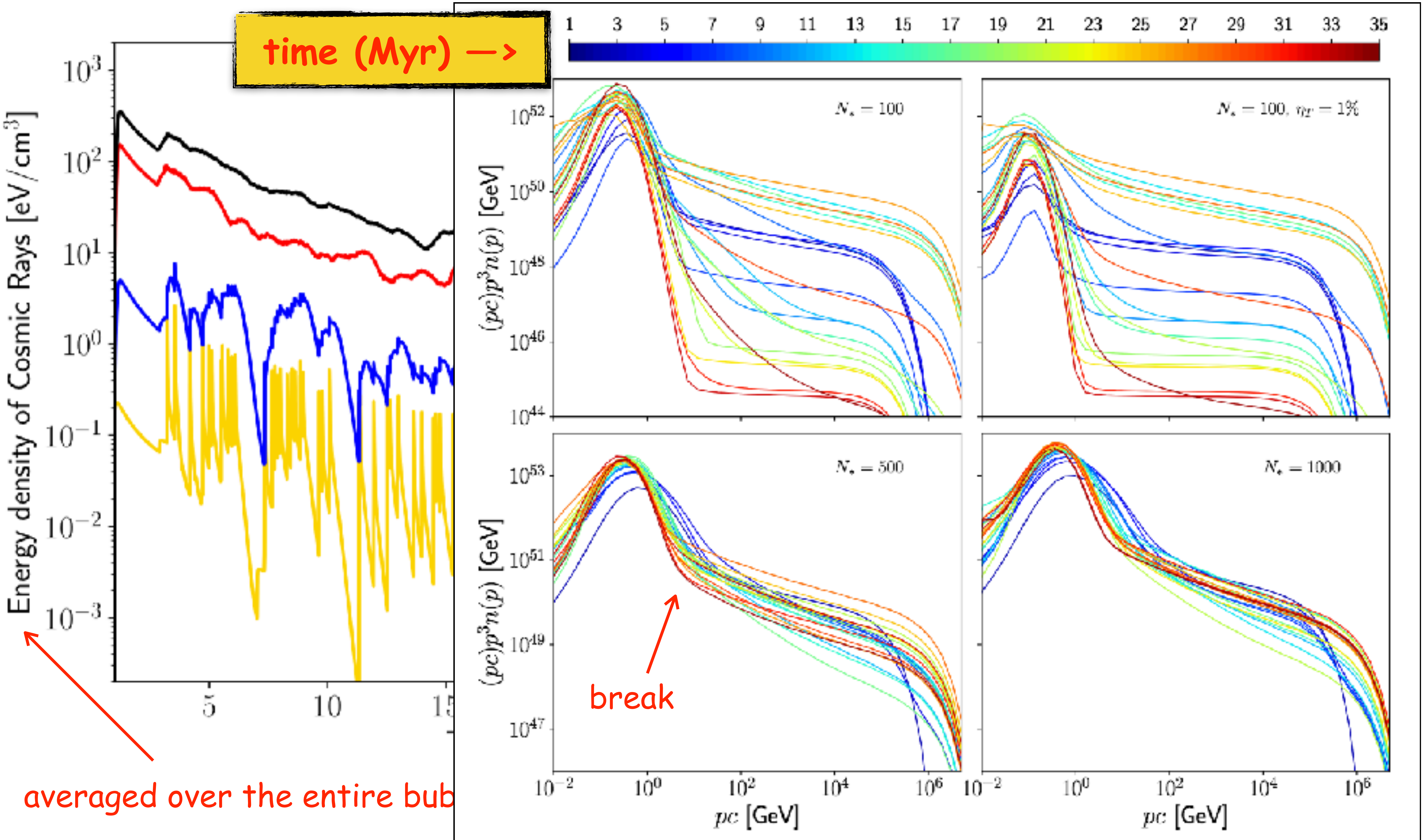
Vieu+ 2022



averaged over the entire bub

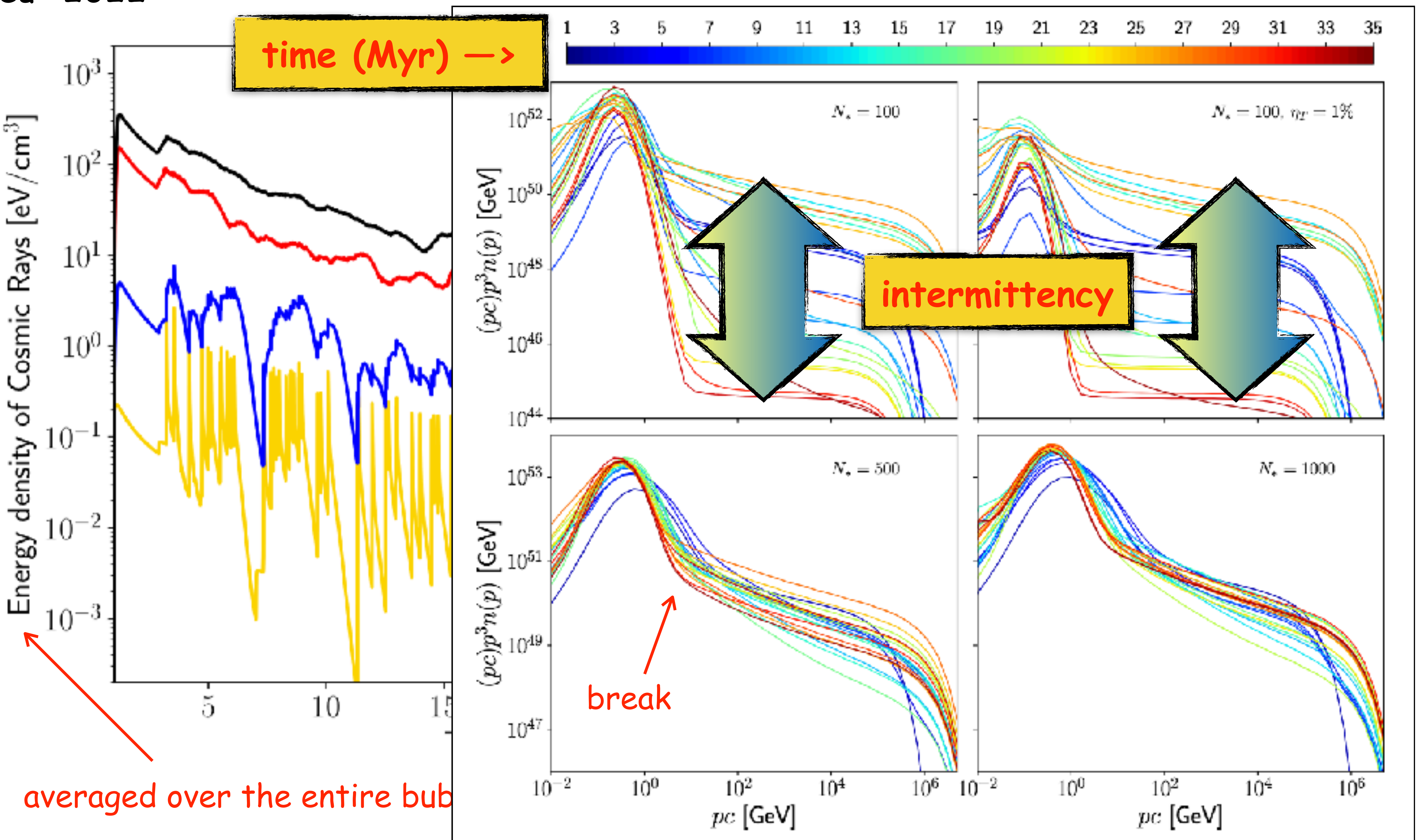
Particle acceleration in superbubbles: intermittency

Vieu+ 2022



Particle acceleration in superbubbles: intermittency

Vieu+ 2022

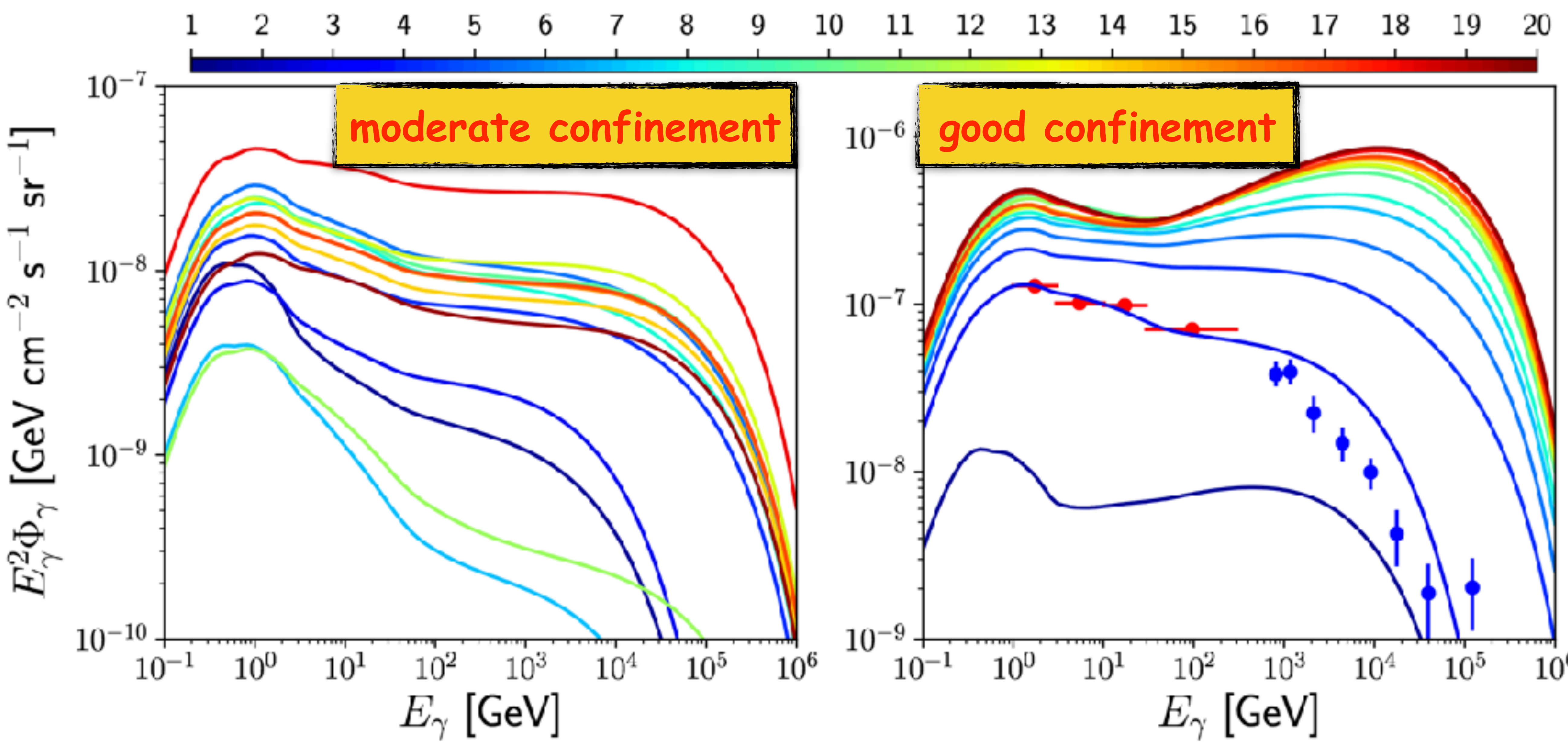


Particle acceleration in superbubbles: implications for observations

Vieu+ 2022

gamma ray observations

N_* = 100 - d = 1,5 kpc

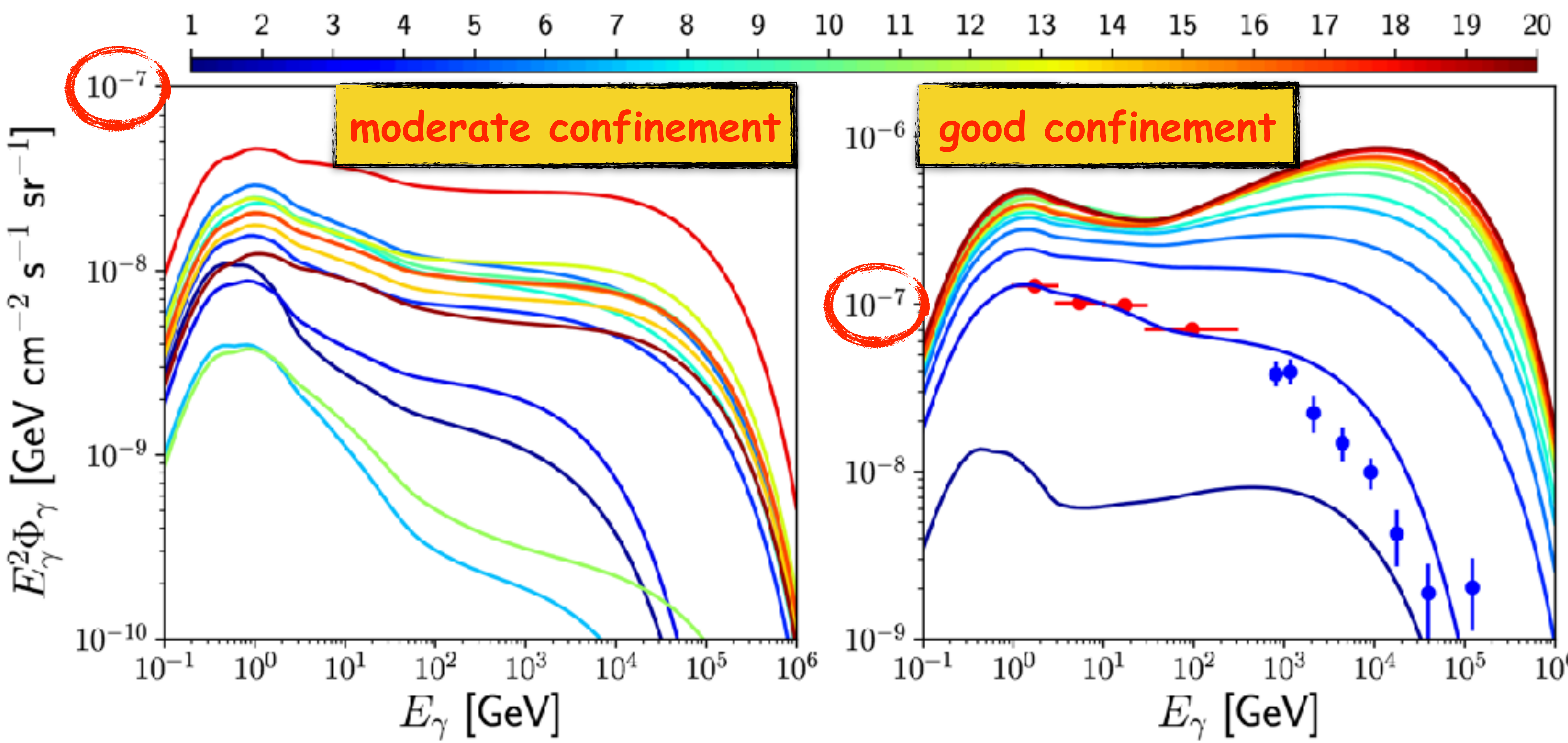


Particle acceleration in superbubbles: implications for observations

Vieu+ 2022

gamma ray observations

N* = 100 - d = 1,5 kpc

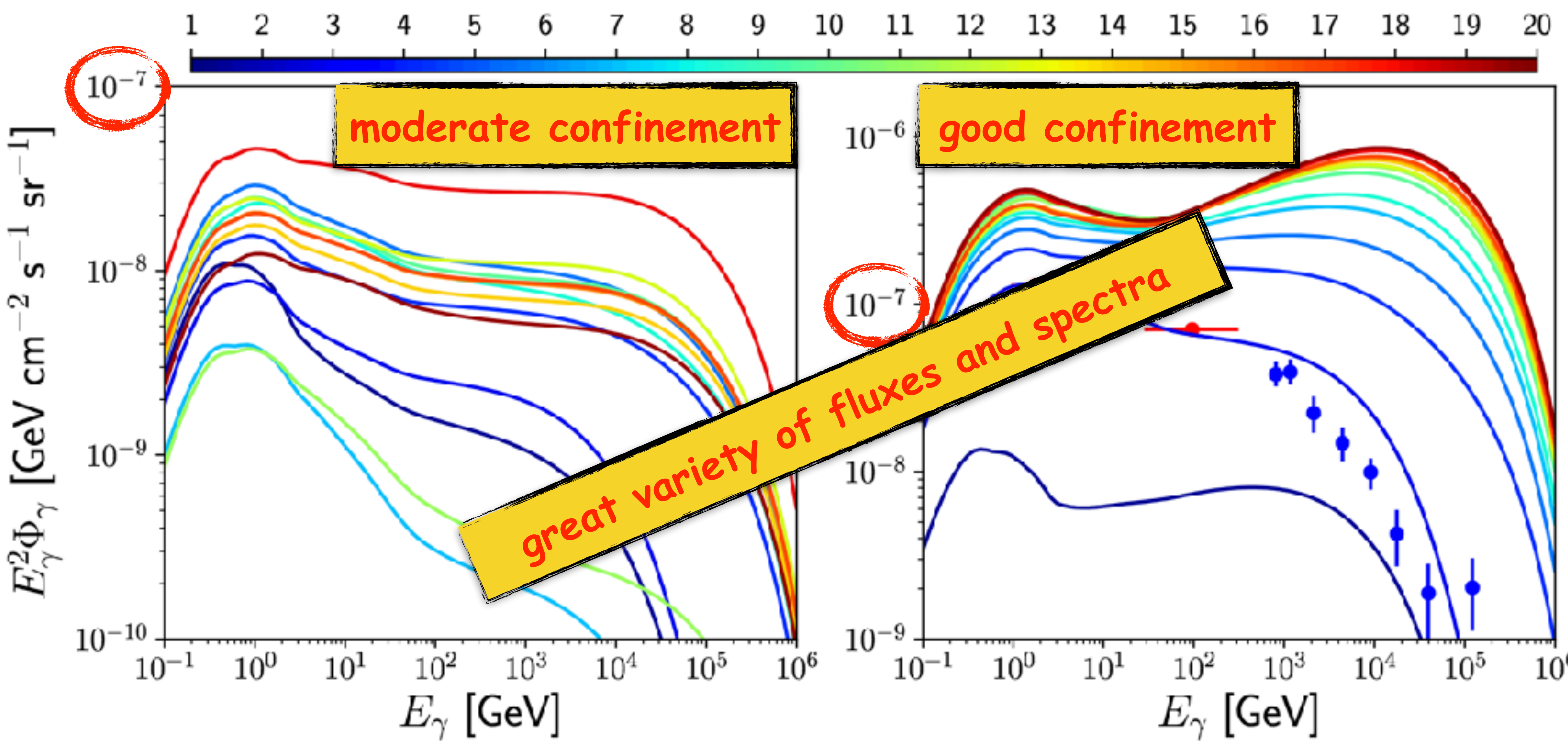


Particle acceleration in superbubbles: implications for observations

Vieu+ 2022

gamma ray observations

N_* = 100 - d = 1,5 kpc

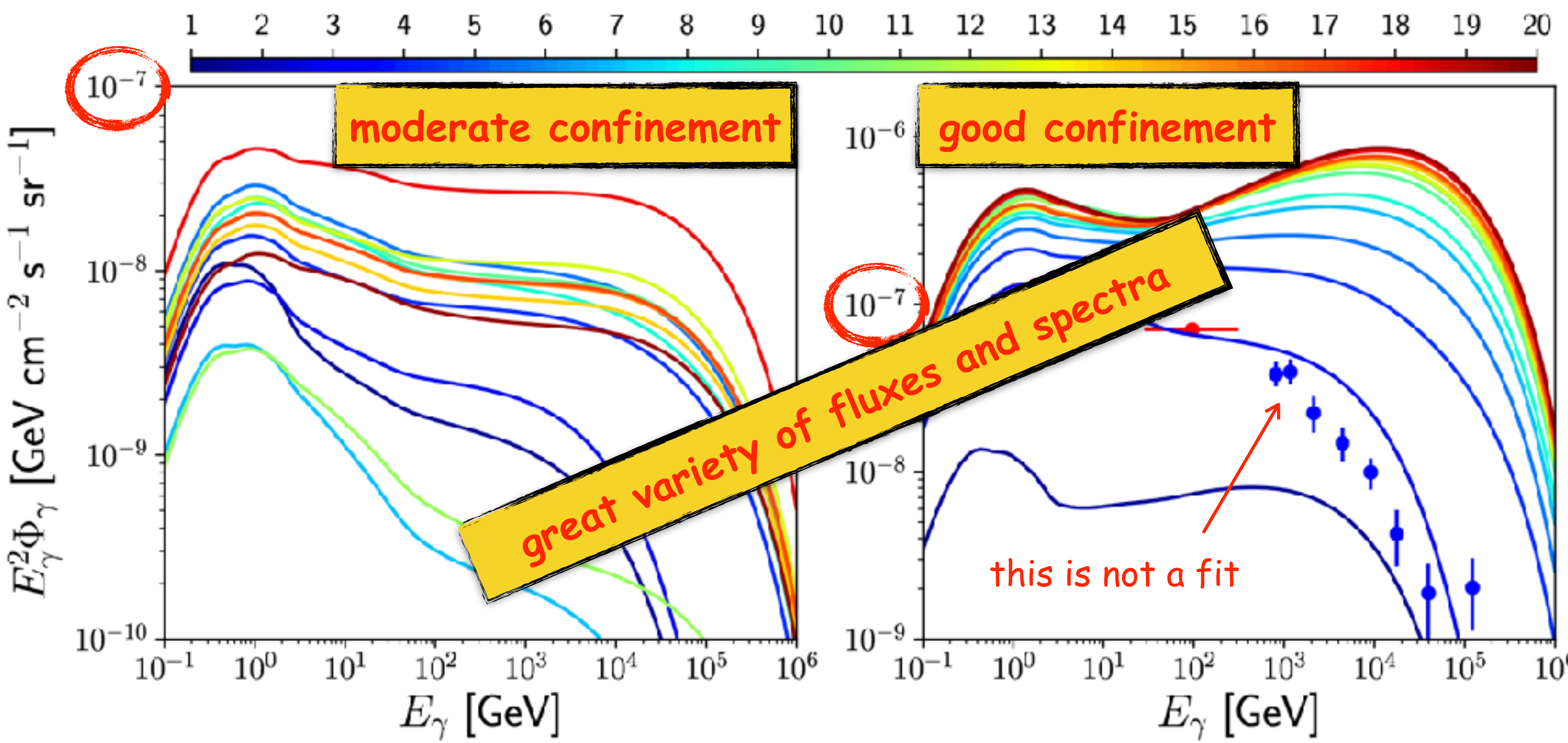


Particle acceleration in superbubbles: implications for observations

Vieu+ 2022

gamma ray observations

N* = 100 - d = 1,5 kpc

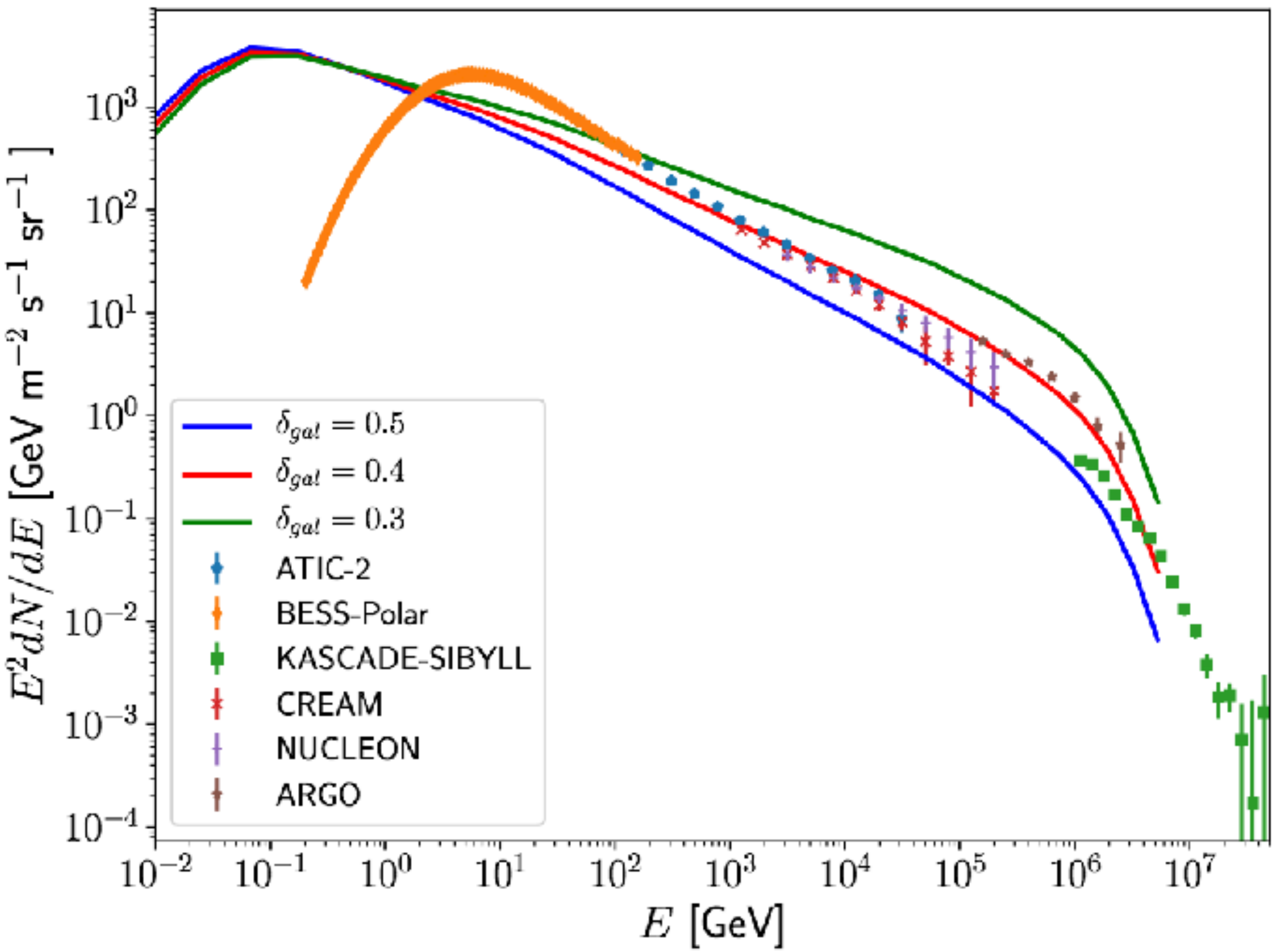


Orion-Eridani —> no gammas, Cygnus region —> gammas

Particle acceleration in superbubbles: implications for observations

Vieu+ 2022

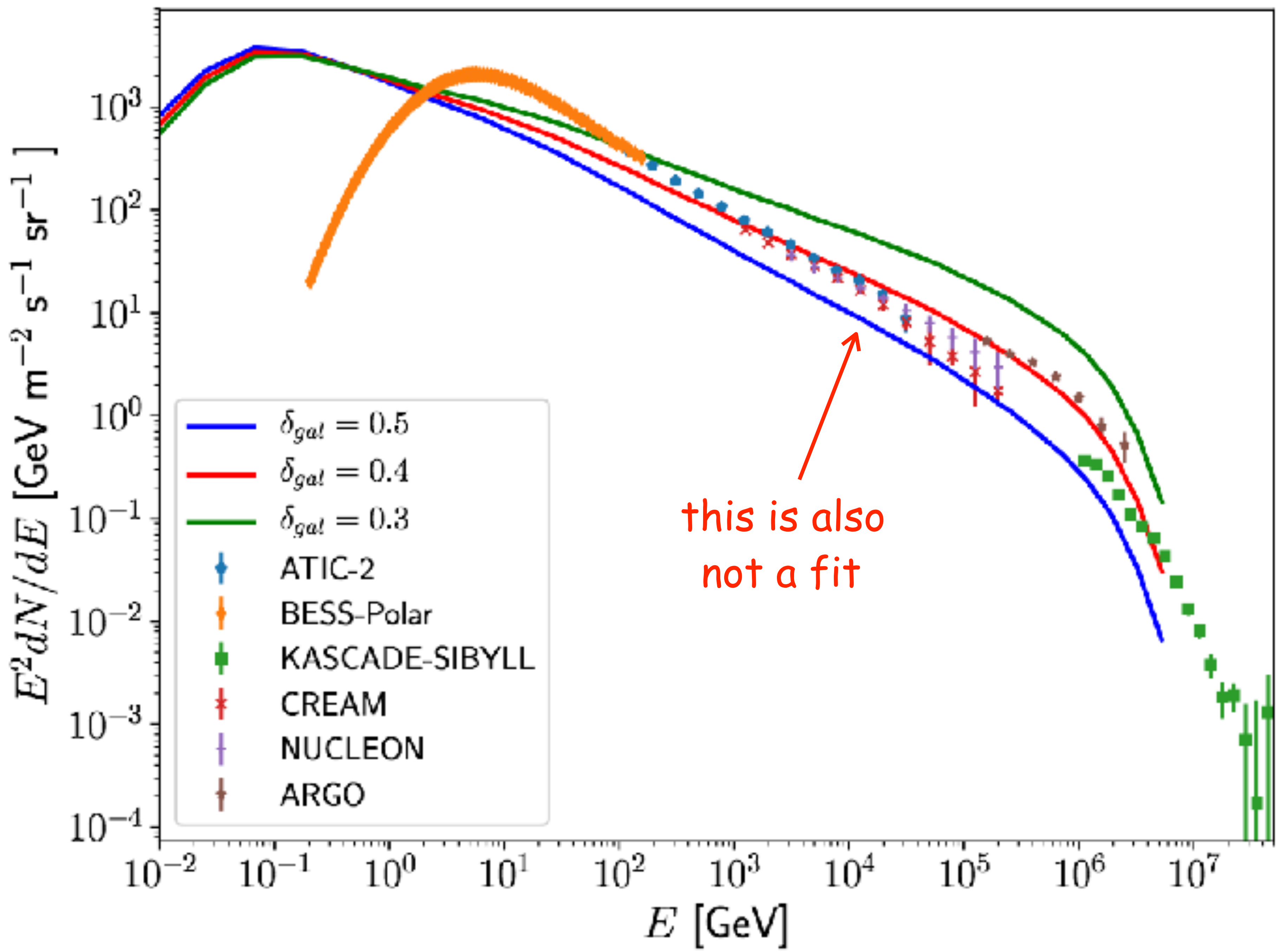
cosmic ray observations



Particle acceleration in superbubbles: implications for observations

Vieu+ 2022

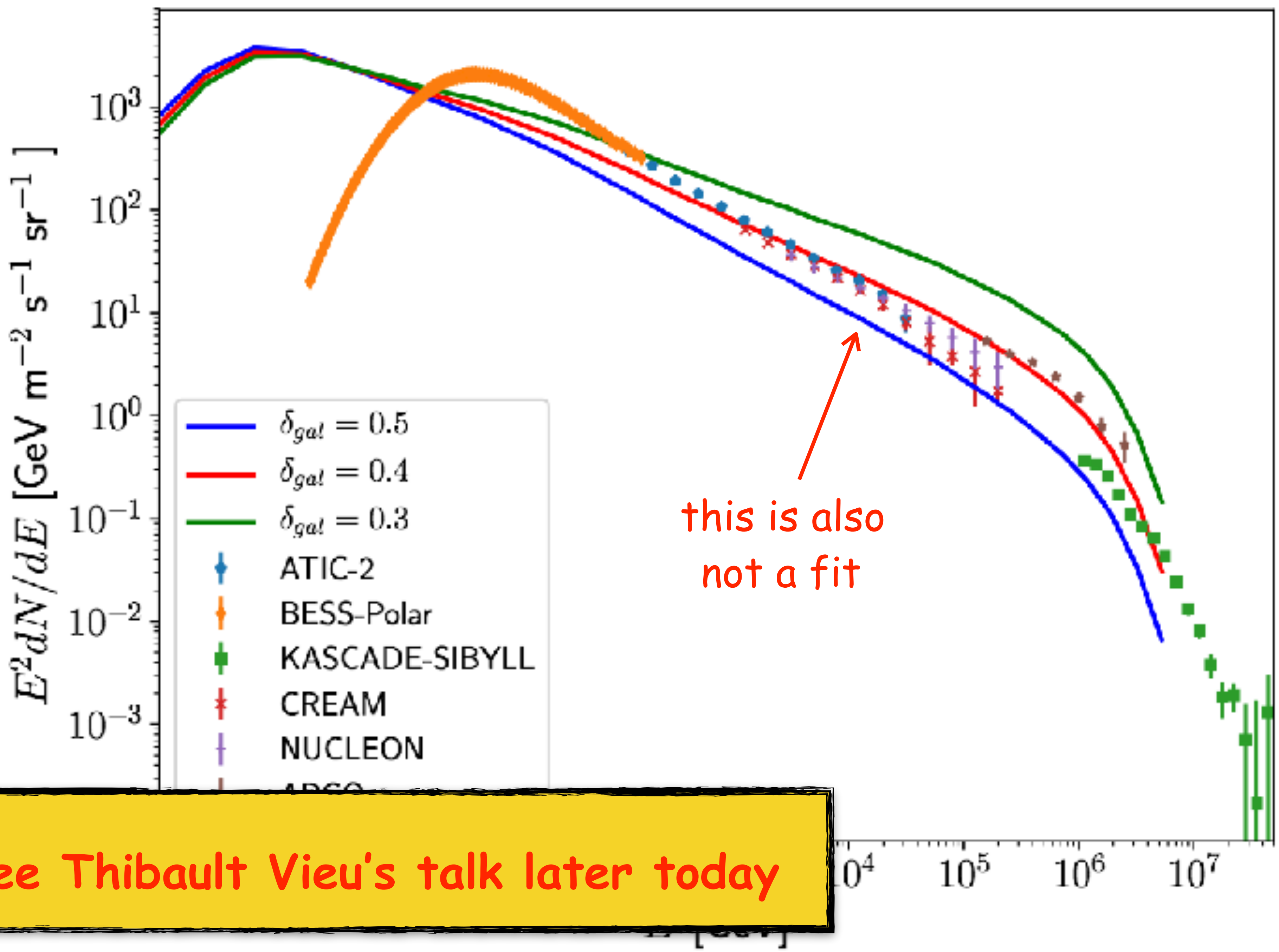
cosmic ray observations



Particle acceleration in superbubbles: implications for observations

Vieu+ 2022

cosmic ray observations



see Thibault Vieu's talk later today

Particle acceleration in superbubbles: maximum energy

Hillas criterium —>

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

Particle acceleration in superbubbles: maximum energy

Hillas criterium —>

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

bubbles are large!

Particle acceleration in superbubbles: maximum energy

efficiency kinetic—> magnetic

Hillas criterium —>

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

bubbles are large!

Particle acceleration in superbubbles: maximum energy

efficiency kinetic—> magnetic

Hillas criterium —>

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

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

bubbles are
large!

Particle acceleration in superbubbles: maximum energy

efficiency kinetic—> magnetic

Hillas criterium —>

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

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

bubbles are large!

see Thibault Vieu's talk later today

Particle acceleration in superbubbles: maximum energy

efficiency kinetic—> magnetic

Hillas criterium —>

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

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

bubbles are large!

🤓 **see Thibault Vieu's talk later today**

possible to go to PeV and possibly beyond

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…

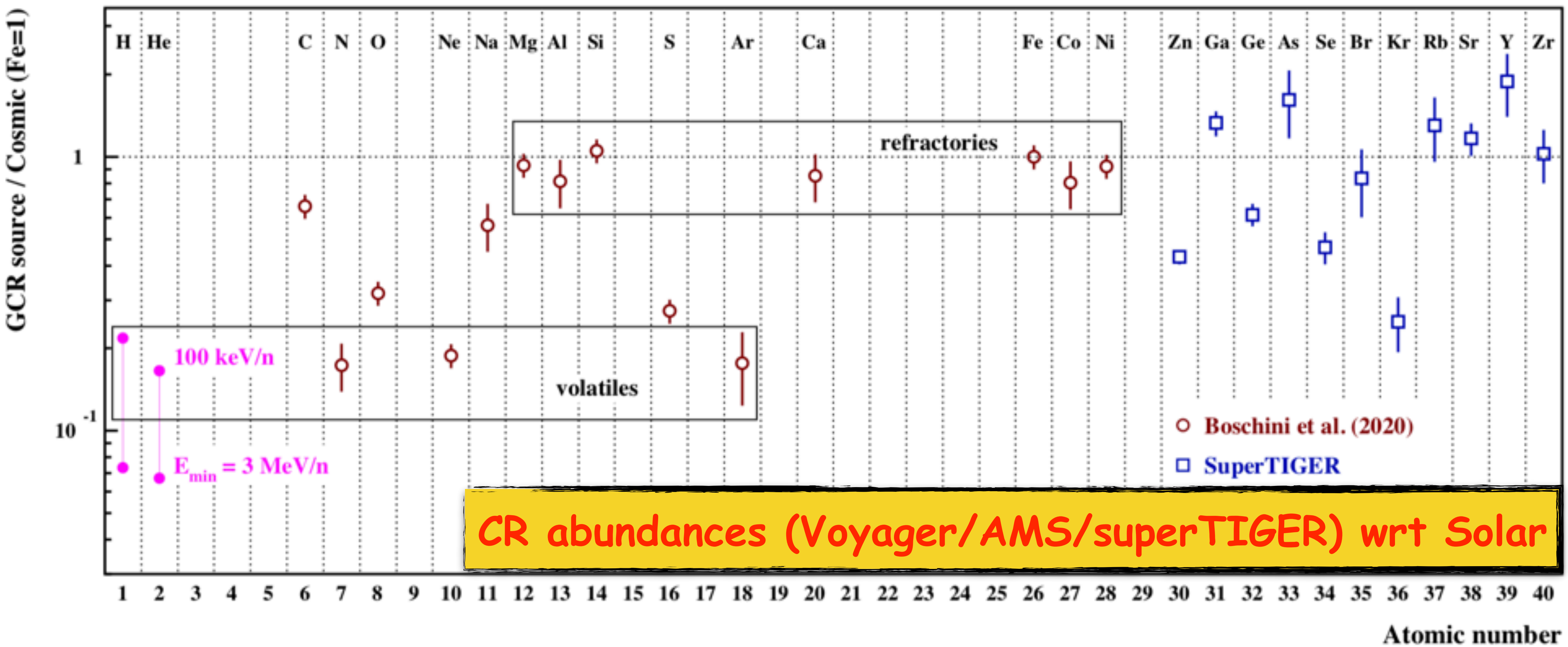
	power	spectrum	E_{max}	$^{22}Ne/^{20}Ne$
SNR	😋	😋	🤔	can SNRs accelerate ENOUGH PeV CRs?
WTS	🤬	😋	🤔	only very luminous star clusters
SB	😋	😋	😋	large, messy and contain many shocks!

You can't always get what you want…

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

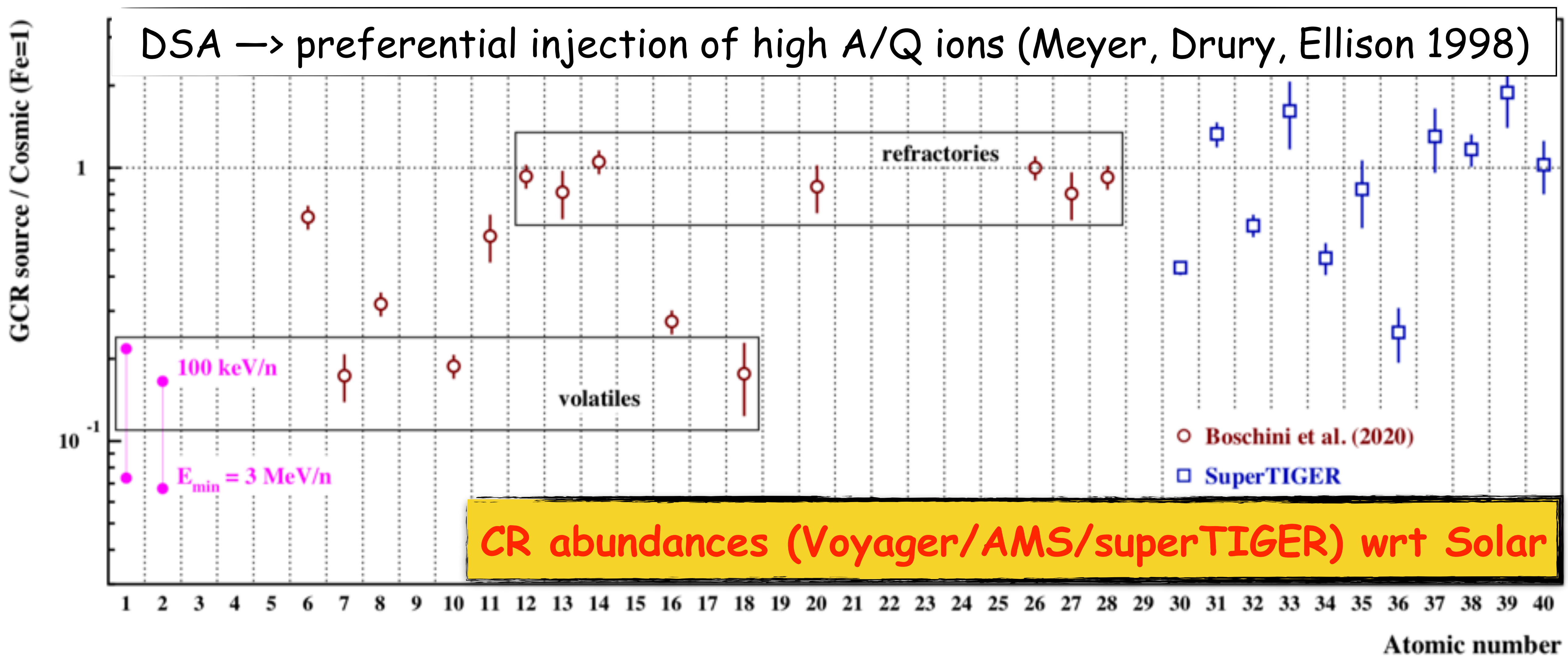
…but if you try sometimes, well, you might find…

Tatischeff+ 2021



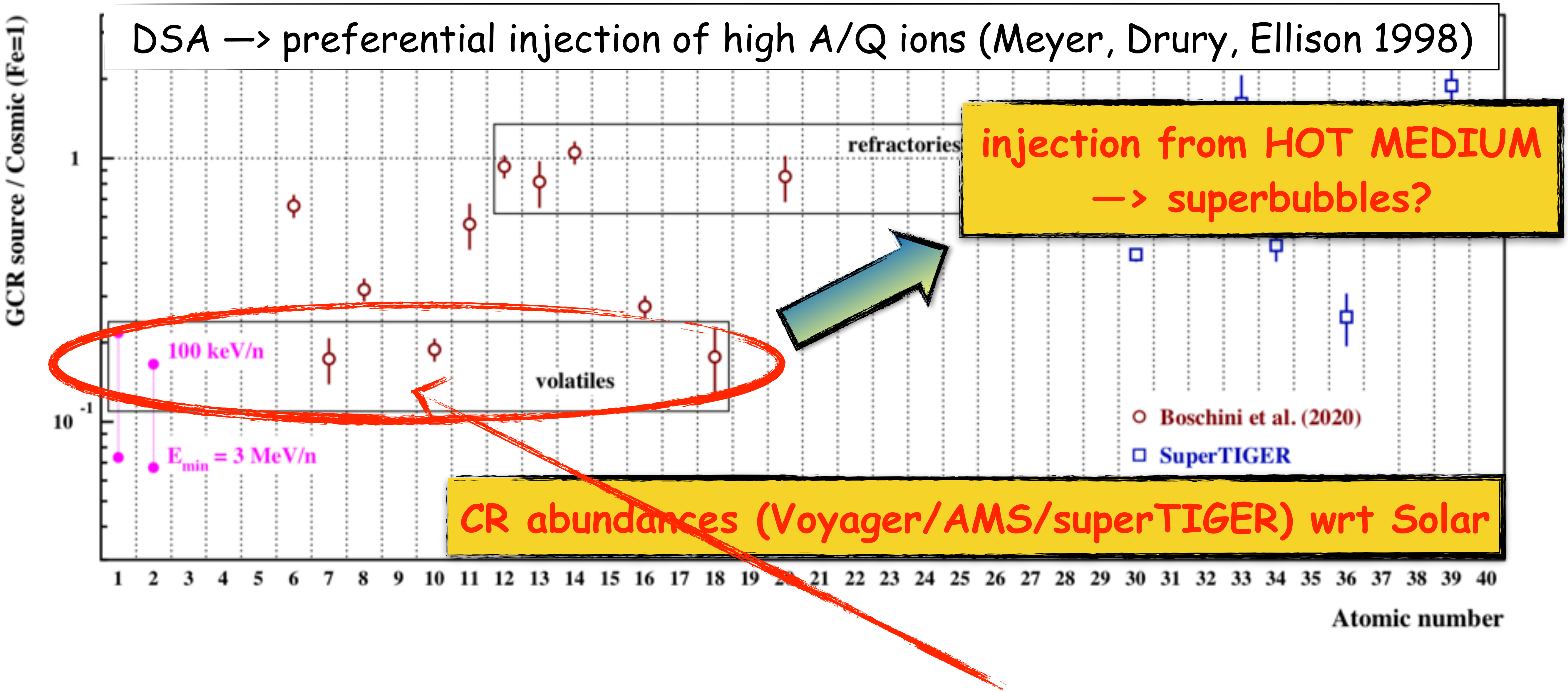
…but if you try sometimes, well, you might find…

Tatischeff+ 2021



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

Tatischeff+ 2021



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 $\log(T_{SB})^a$	–	6.50 ± 0.25	> 6.45	$6.5^{+0.3}_{-0.2}$	> 6.35
Relative eff. $\epsilon = \epsilon_{dust}/\epsilon_{gas}{}^b$	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)%
χ^2_{min}(GCR dust source)^d	24.6	26.9	25.9	26.0	24.8
χ^2_{min}(GCR gas source)^e	24.7	31.1	12.2	31.4	16.7
SB temperature $\log(T_{SB})$	–	6.6 (fixed)	6.6 (fixed)	6.6 (fixed)	6.6 (fixed)
Relative eff. $\epsilon = \epsilon_{dust}/\epsilon_{gas}{}^b$	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%
χ^2_{min}(GCR dust source)^d	24.6	28.0	26.9	26.4	25.0
χ^2_{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)

	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 $\log(T_{SB})^a$	–	6.50 ± 0.25	> 6.45	$6.5^{+0.3}_{-0.2}$	> 6.35
Relative eff. $\epsilon = \epsilon_{dust}/\epsilon_{gas}{}^b$	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)%
χ^2_{min}(GCR dust source)^d	24.6	26.9	25.9	26.0	24.8
χ^2_{min}(GCR gas source)^e	24.7	31.1	12.2	31.4	16.7
SB temperature $\log(T_{SB})$	–	6.6 (fixed)	6.6 (fixed)	6.6 (fixed)	6.6 (fixed)
Relative eff. $\epsilon = \epsilon_{dust}/\epsilon_{gas}{}^b$	33.8 ± 13.4	$23.2 \pm$ [illegible].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%
χ^2_{min}(GCR dust source)^d	24.6	28.0	26.9	26.4	25.0
χ^2_{min}(GCR gas source)^e	24.7	32.3	13.2	32.4	18.3

mixed scenario
most CRs come from SNRs in SBs + ~5% (in number!) of CRs come from stellar cluster WTSs

Conclusions

- 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 (see next talk by Thibault)
- mixed scenarios (acceleration at SNR+WTS) fit both CR spectra and abundances

Conclusions

- 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 (see next talk by Thibault)
- mixed scenarios (acceleration at SNR+WTS) fit both CR spectra and abundances

a warning to those who want to enter this field...

Conclusions

- 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 (see next talk by Thibault)
- mixed scenarios (acceleration at SNR+WTS) fit both CR spectra and abundances

a warning to those who want to enter this field...

DSA @WTS, spherically symmetric, almost stationary, allows (almost) analytic solution, blah blah blah...

Conclusions

- 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 (see next talk by Thibault)
- mixed scenarios (acceleration at SNR+WTS) fit both CR spectra and abundances

a warning to those who want to enter this field...

SUPERBUBBLES

DSA @WTS, spherically symmetric, almost stationary, allows (almost) analytic solut
blah blah blah...