Sources of Galactic CRs

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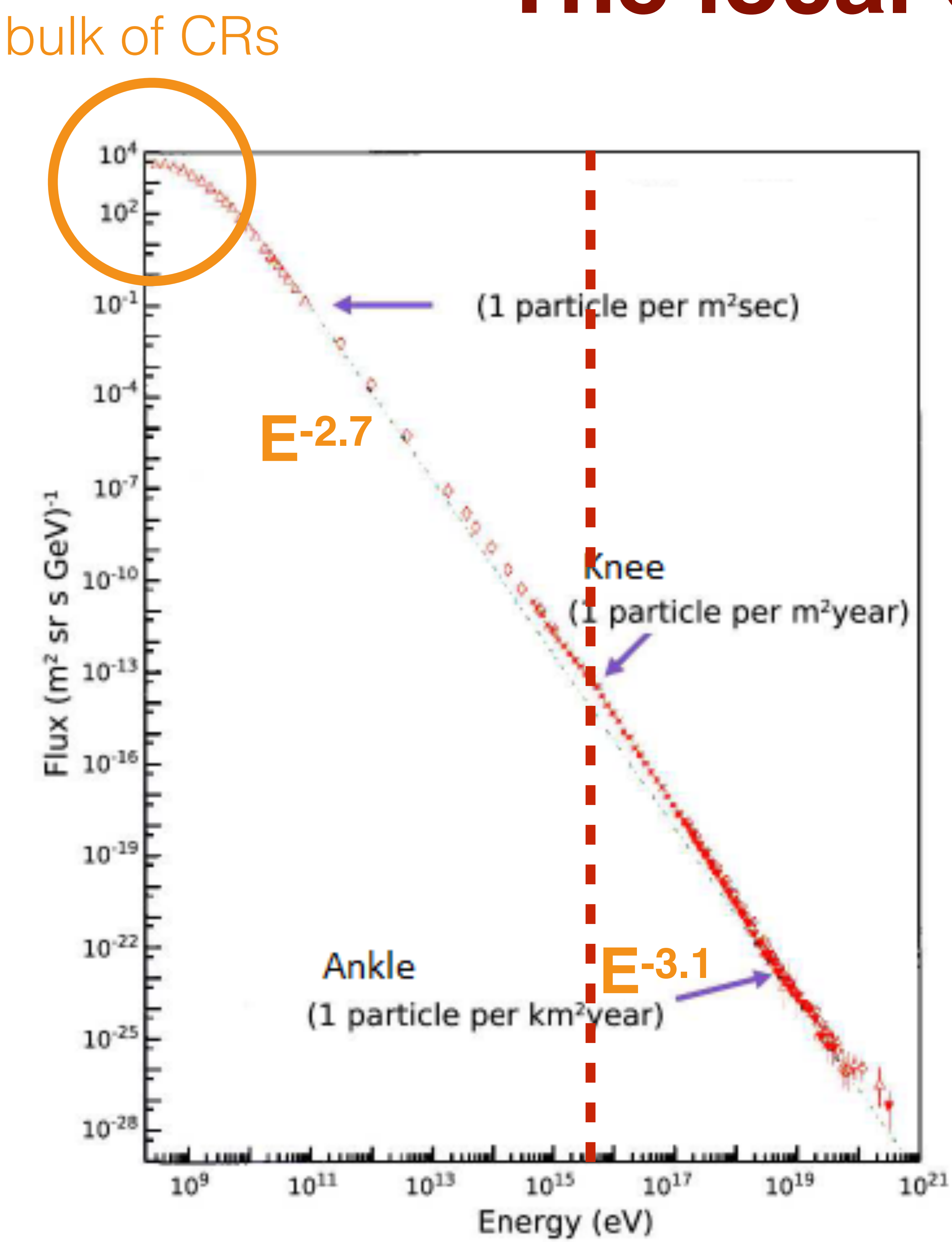
19th Rencontres du Vietnam - January 10th 2023

The local CR spectrum



- **Energy density**
  - which are the CR sources?
  - how can we identify them?

  ⟶ **photon and ν astronomy**

- **Spectral shape**
  - which acceleration mechanism?
  - what are the effects of the CR propagation?

- **Other observables**
  - Chemical composition
  - Sky distribution

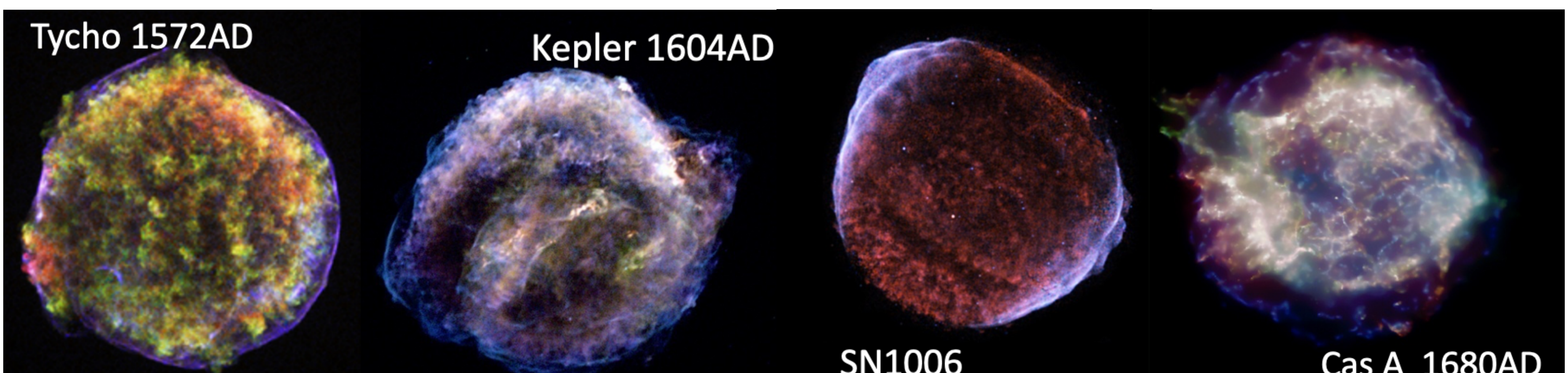
Accelerators that can produce particles up to the knee (~1 PeV) with no cut-off are PeVatrons!

Outline of the talk

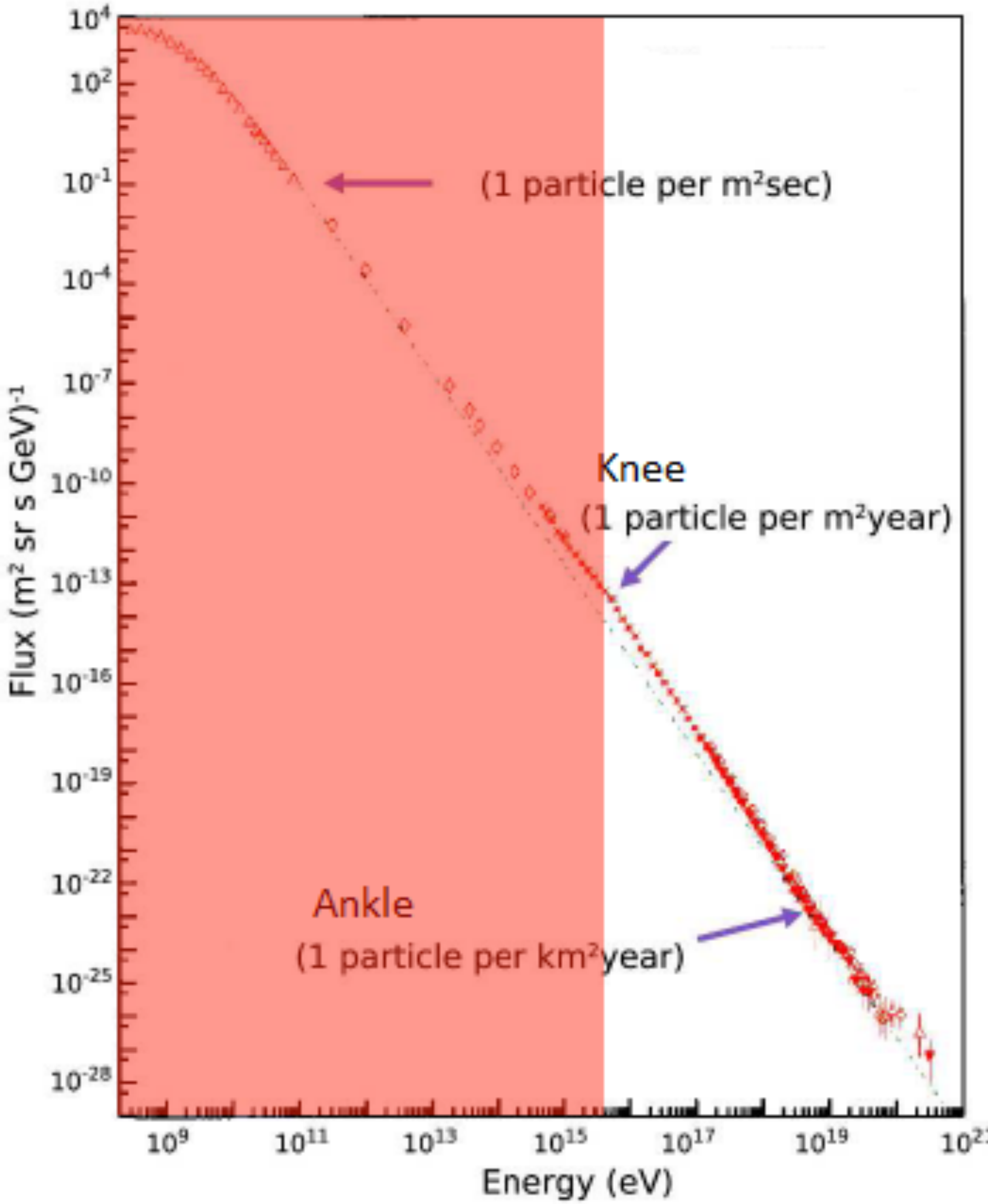
- The **Supernova Remnant (SNR)** paradigm for the **origin of Galactic cosmic rays**:
  - the issue with maximum energy;
  - radiative signatures of SNR PeV activity.

- Alternative hadronic PeVatron candidate sources:
  - Young massive stellar clusters (YMSCs).

- Opening the **ultra-high-energy gamma-ray** domain: recent detections by LHAASO.



The SNR paradigm for the origin of Galactic CRs



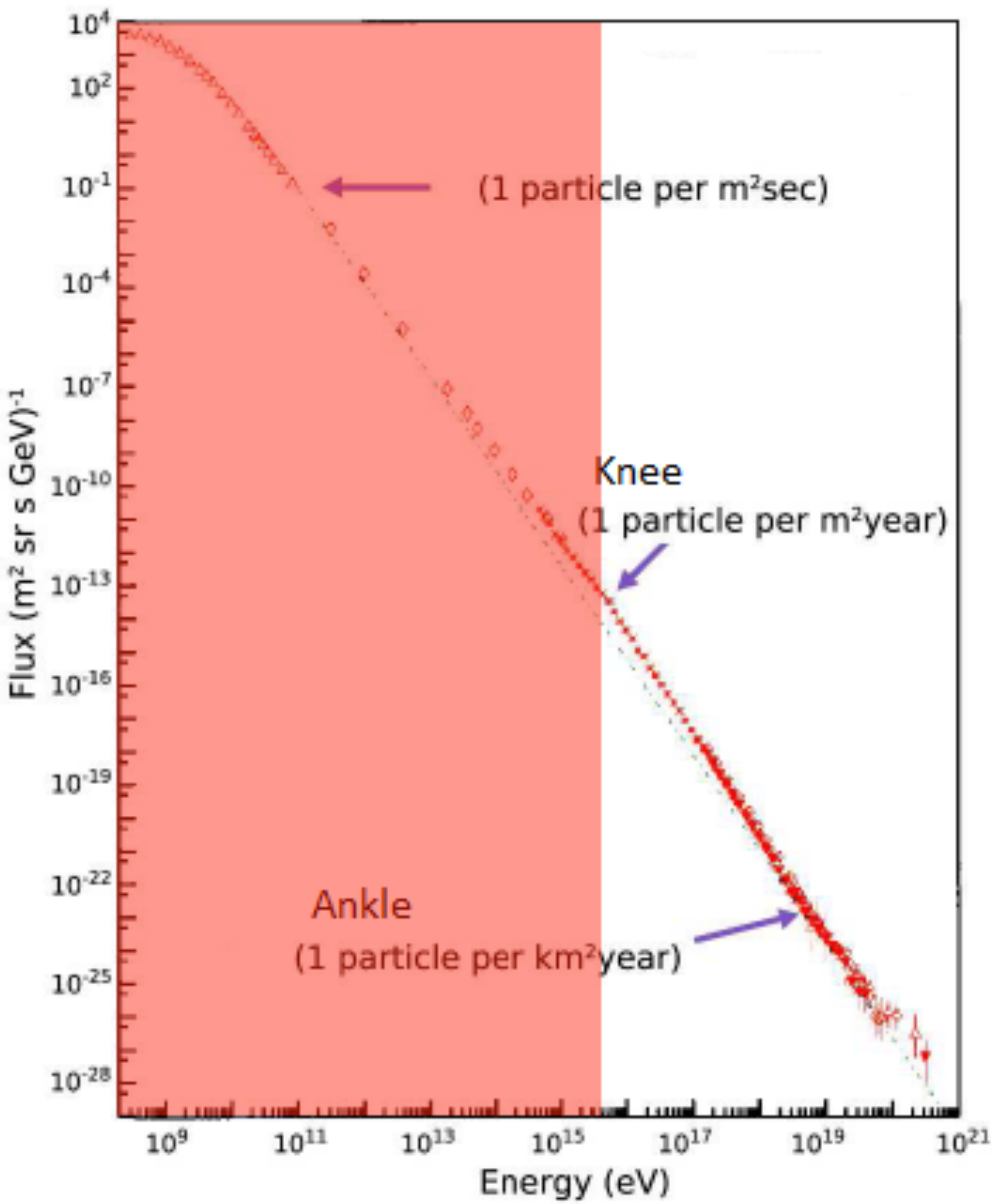
$$U_{\rm CR} = 0.5\,{\rm eV/cm^3}$$

$$V = 4000\,{\rm kpc^3}$$

$$\tau_{\rm res} = 15 \times 10^6\,{\rm yr}$$

$$P_{\rm CR} = \frac{U_{\rm CR} V}{\tau_{\rm res}} \sim 3 \times 10^{40}\,{\rm erg/s}$$

The SNR paradigm for the origin of Galactic CRs



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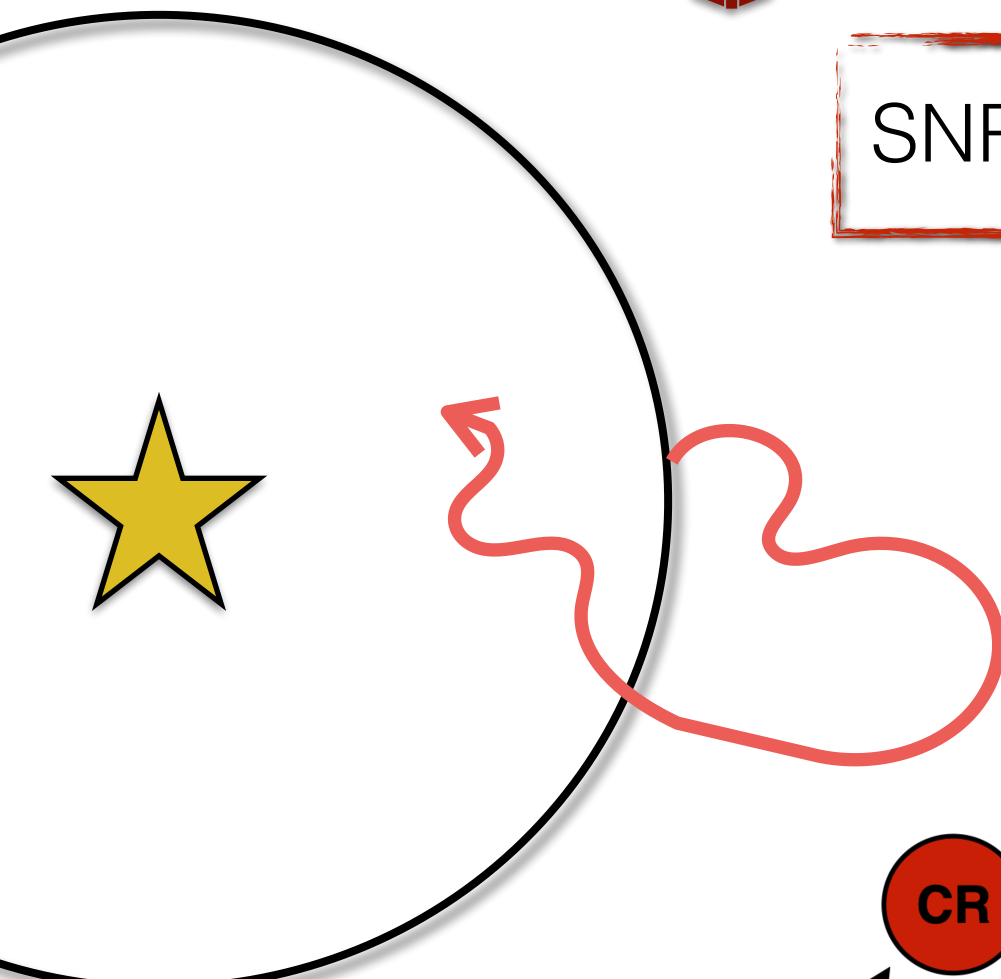
$$E_{\rm SN} = 10^{51}\,{\rm erg}$$
$$R_{\rm SN} = 0.03\,{\rm yr^{-1}}$$
$$P_{\rm SN} = R_{\rm SN} E_{\rm SN} \simeq 3 \times 10^{41}\,{\rm erg/s}$$
$$\longrightarrow \xi_{\rm CR} \simeq 10\%$$

The SNR paradigm for the origin of Galactic CRs

Enough power in SN explosions to explain CRs

Baade & Zwicky, PNAS 20 (1934) 259   Ginzburg & Syrovatsky, PTPS 20 (1961) 1



SNR shocks ⟶ acceleration sites

Diffusive Shock Acceleration

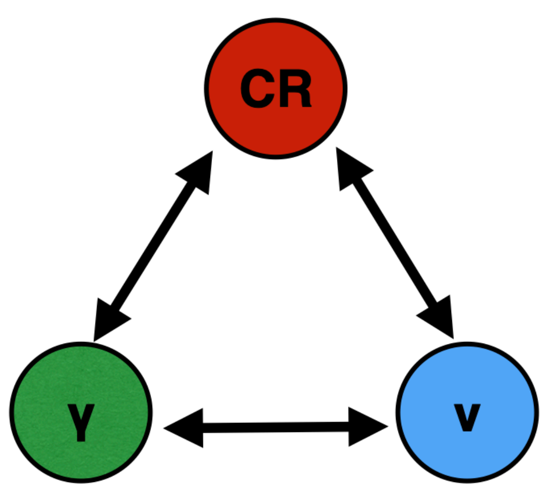
Axford et al., ICRC1977, 11 132

Krymskii, AKSSRD 234 (1977) 1306

Bell, MNRAS 182 (1978) 147

Blandford & Ostriker, ApJ 221 (1978)

$$\longrightarrow f_0(p) \propto p^{-4}$$



pp interaction ⟶ γ rays and ν

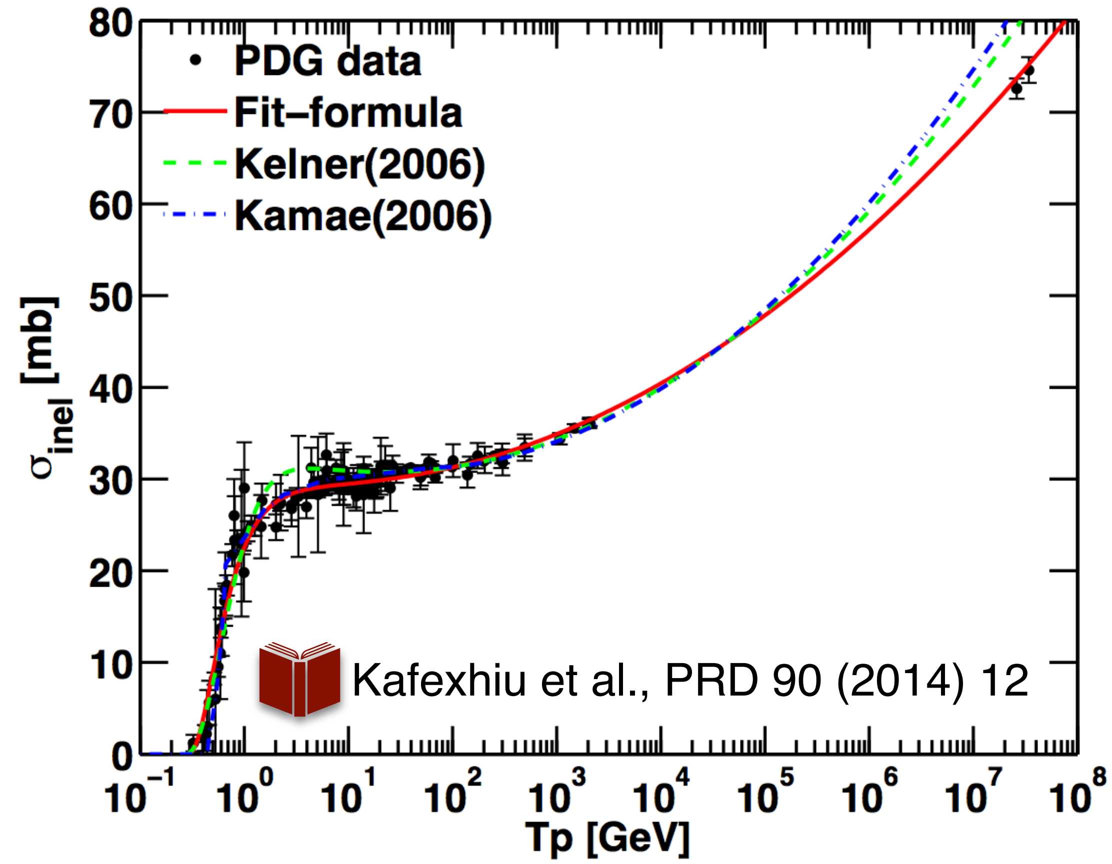
Aharonian et al., A&A 285 (1994) 645A

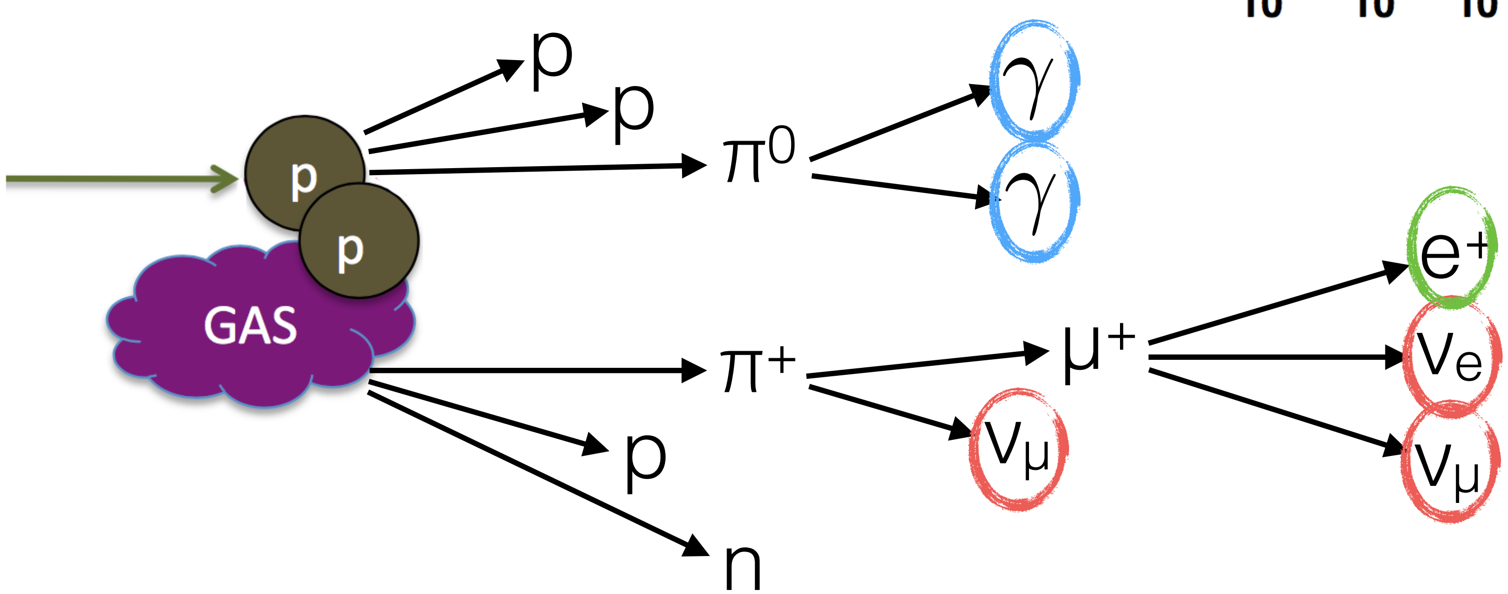
$$\longrightarrow \frac{dN}{dE} \propto E^{-2}$$

Proton-proton collisions

$$p + p \longrightarrow N\pi + X$$

accelerated proton — target gas



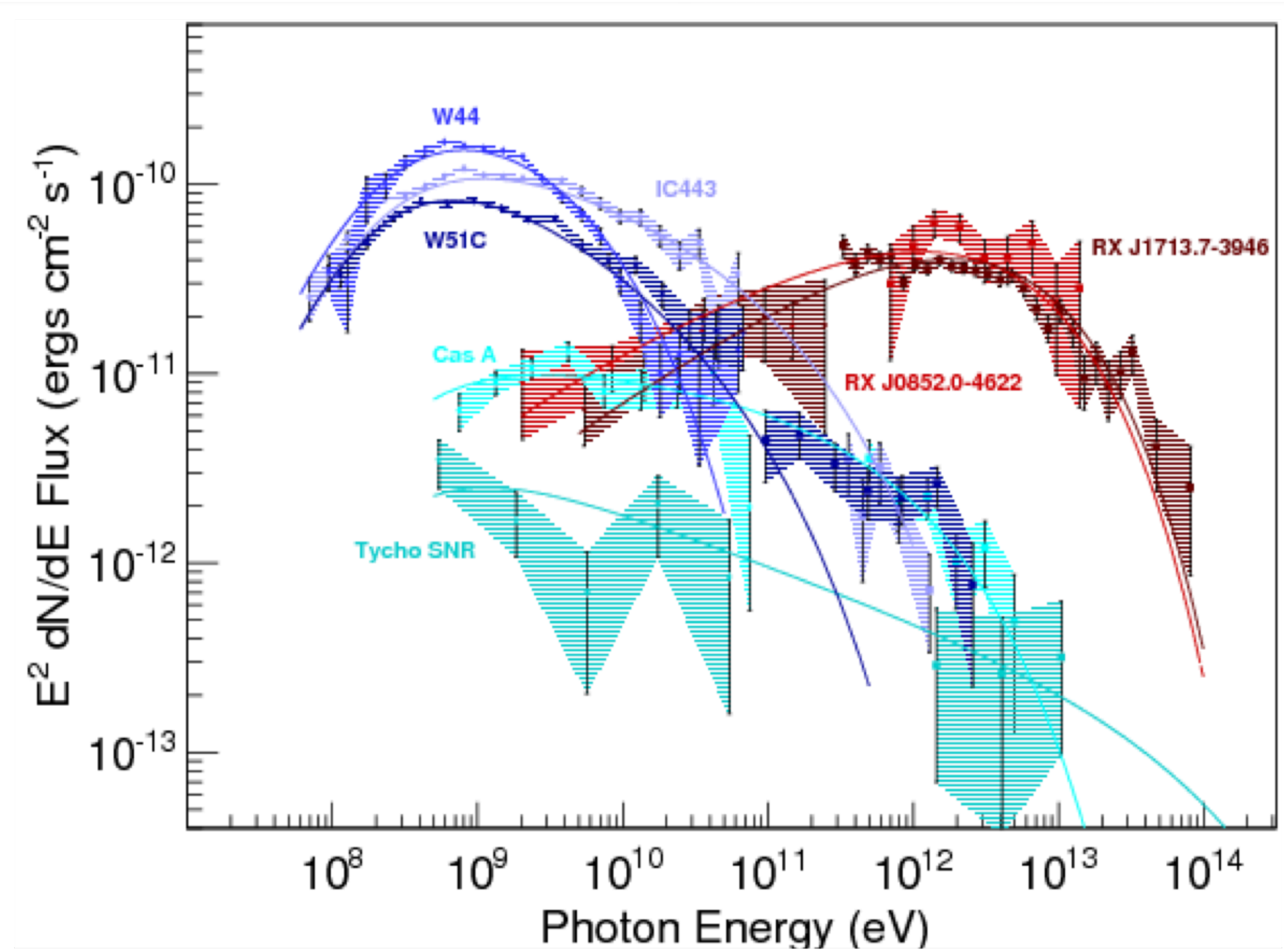


$$E_\gamma \simeq E_\mathrm{p}/10$$

$$E_\nu \simeq E_\mathrm{e} \simeq E_\mathrm{p}/20$$

<u>1 PeV proton ⟶ ~100 TeV gamma rays, ~50 TeV neutrinos/electrons</u>

Gamma rays from SNRs



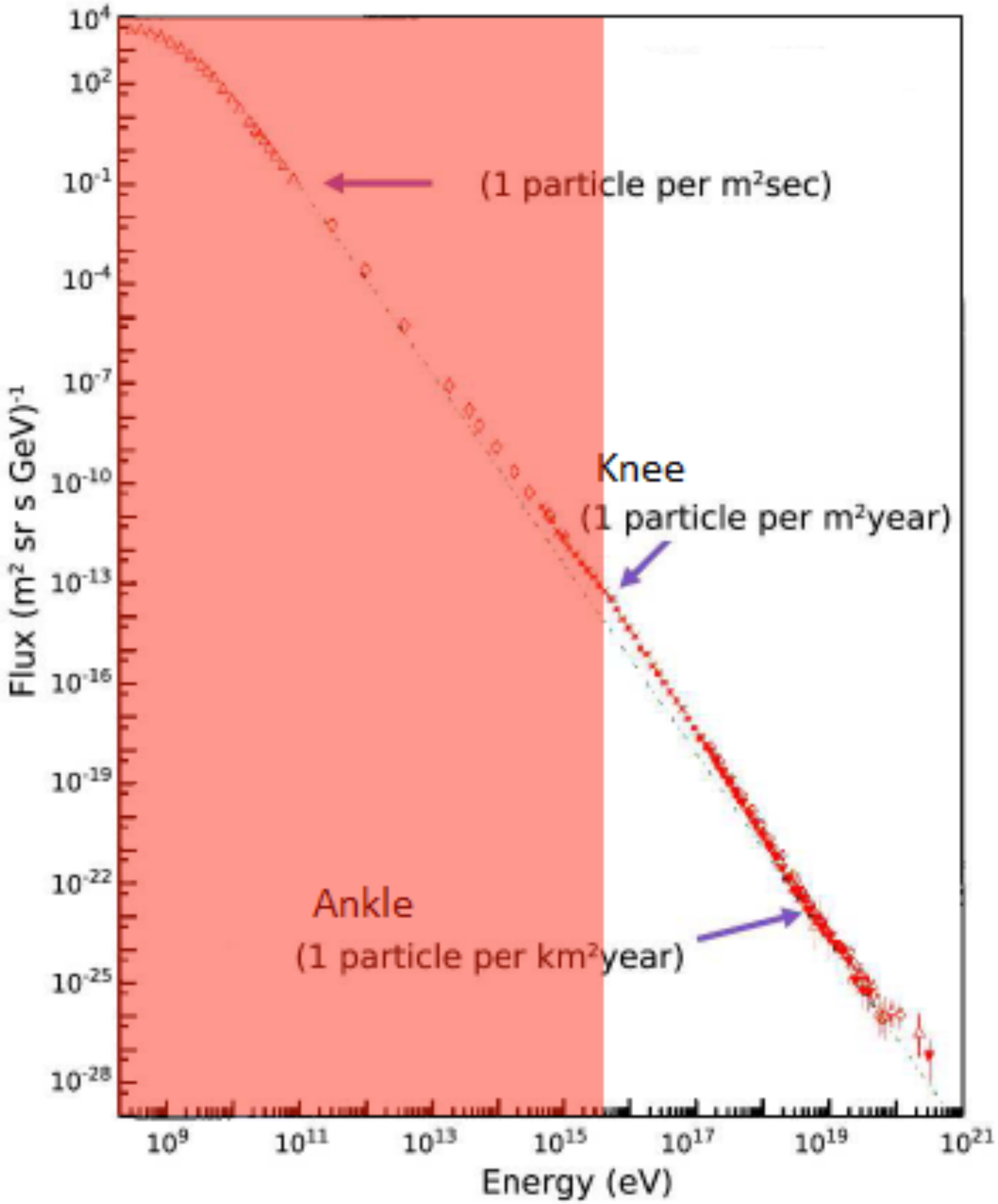
- Drury et al., A&A 287 (1994) 959
- Tsuguya & Fumio, J. Phys. G 20 (1994) 477
- Funk et al., ARNPS 65 (2015) 245F

Middle-aged SNRs (20000 yrs)
- hadronic emission
- steep spectra
- E_{max} < 1 TeV

Young SNRs (2000 yrs)
- hadronic/leptonic ?
- hard spectra
- E_{max} = 10 - 100 TeV

Very young SNRs (300 yrs)
- hadronic ?
- steep spectra $E^{-2.3}$
- E_{max} = 10 - 100 TeV

Are SNRs proton PeVatrons?



Hillas criterion

$$E_{max} \simeq v_s R B$$

shock speed — radius — magnetic field

$$E_{max} \simeq 1 \left(\frac{v_s}{10^3 Km/s}\right) \left(\frac{R}{pc}\right) \left(\frac{B}{\mu G}\right) TeV$$

3 **3** **10**

$$E_{max} \simeq 100\,\mathrm{TeV}$$

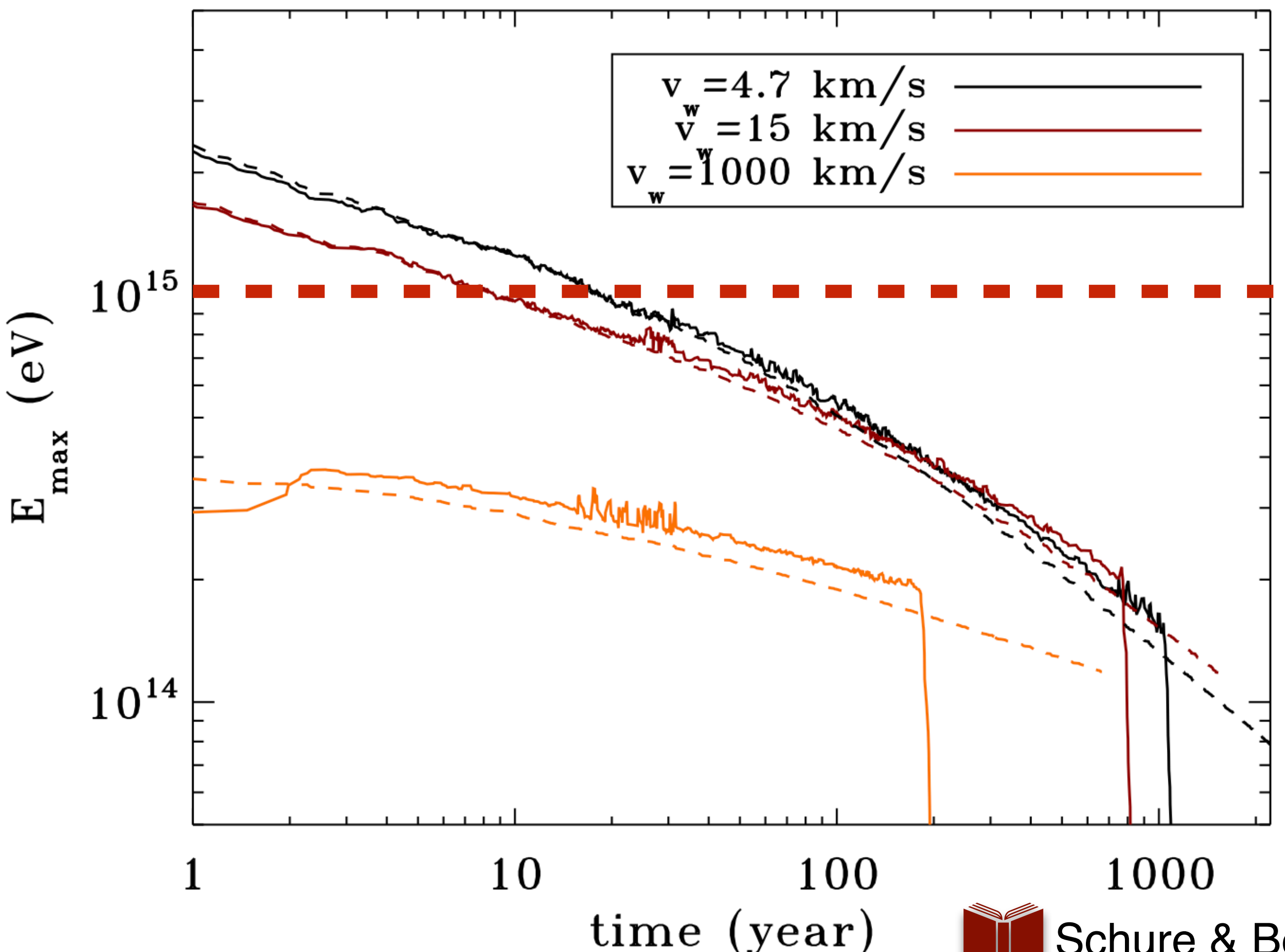
B-field amplification is required to achieve PeV energies

Cesarsky et al., SSRev 36 (1983) 173C

The problem of maximum energy in young SNRs

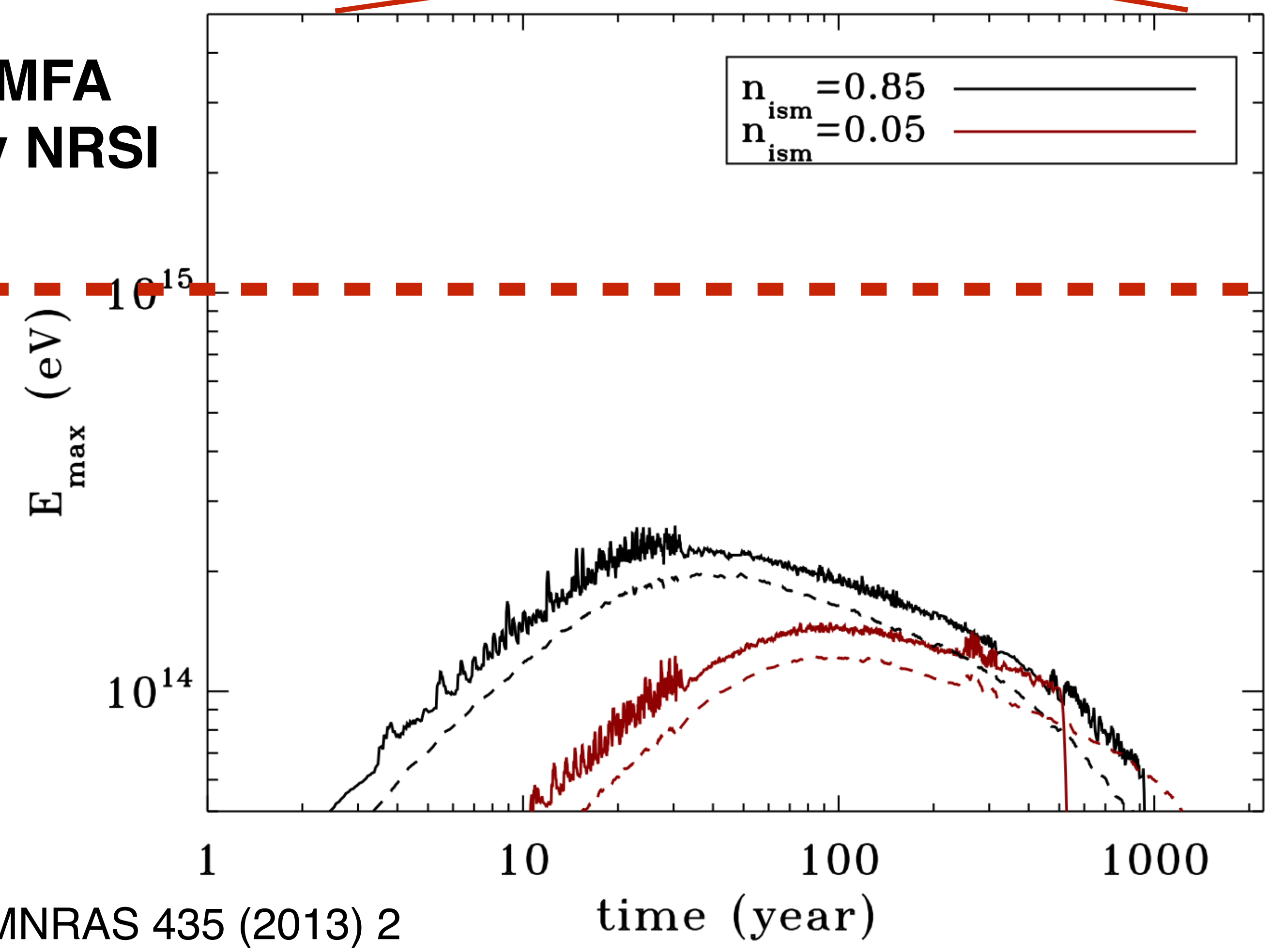
- Type Ia (e.g. Tycho) ⟶ expanding in constant density medium
- Core Collapse (e.g. CasA, RXJ1713.7-3946) ⟶ expanding in the dense slow wind of the progenitor star

Remnants of type II



MFA by NRSI

~~Remnants of type Ia~~



Schure & Bell, MNRAS 435 (2013) 2

With NRSI, only special explosions can achieve the knee

Cardillo et al., Astropart. Phys. 69 (2015) 1

Cristofari et al., Astropart. Phys. 69 (2020) 102492

The role of particle escape or how do accelerated particles become CRs?

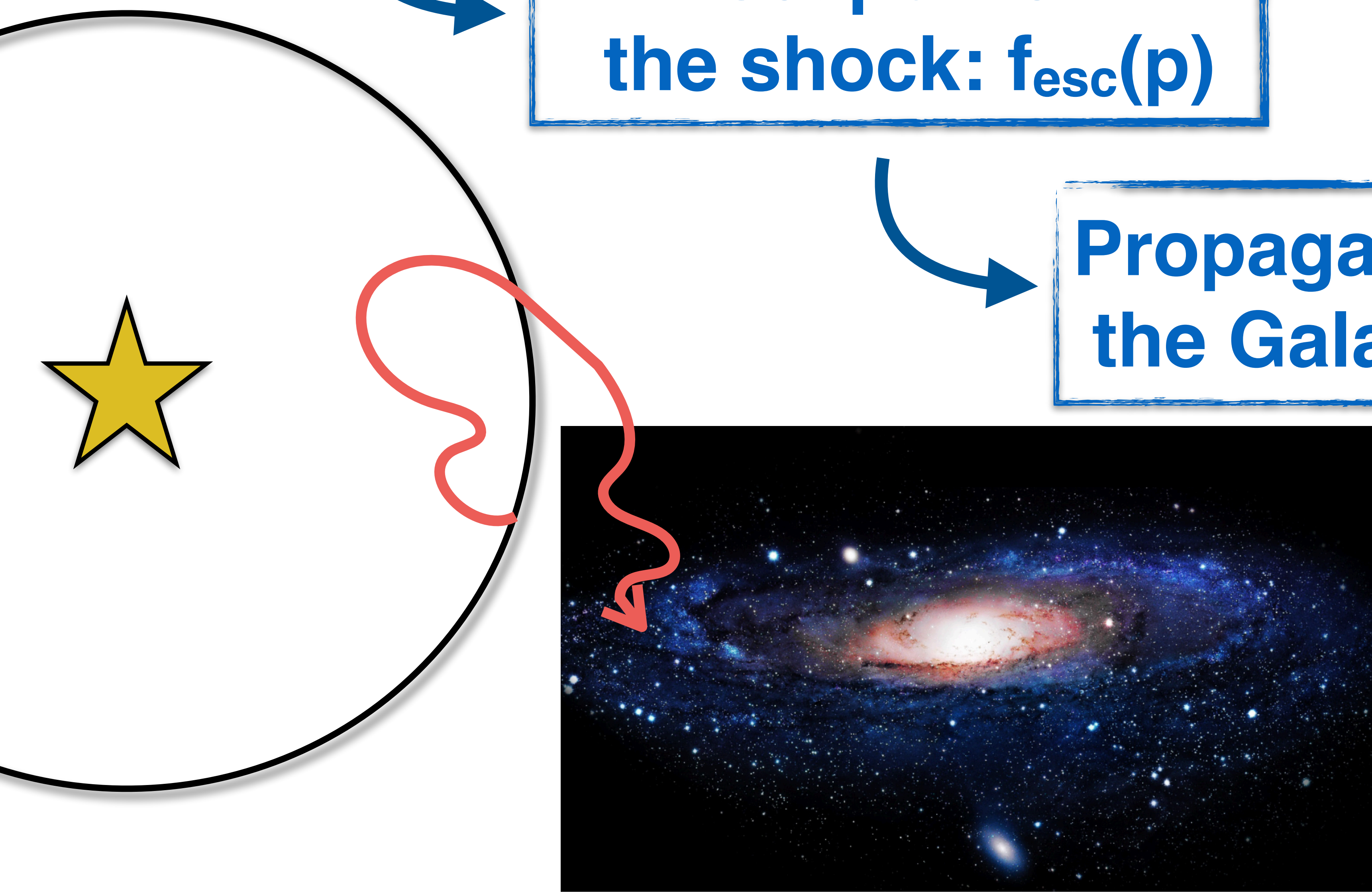
Acceleration at the shock: $f_0(p)$

$$f_0(p) \neq f_{\rm esc}(p) \neq f_{\rm prop}(p)$$

Escape from the shock: $f_{esc}(p)$

Propagation inside the Galaxy: $f_{prop}(p)$

Observation



The role of particle escape or how do accelerated particles become CRs?

Acceleration at the shock: $f_0(p)$

Escape from the shock: $f_{esc}(p)$

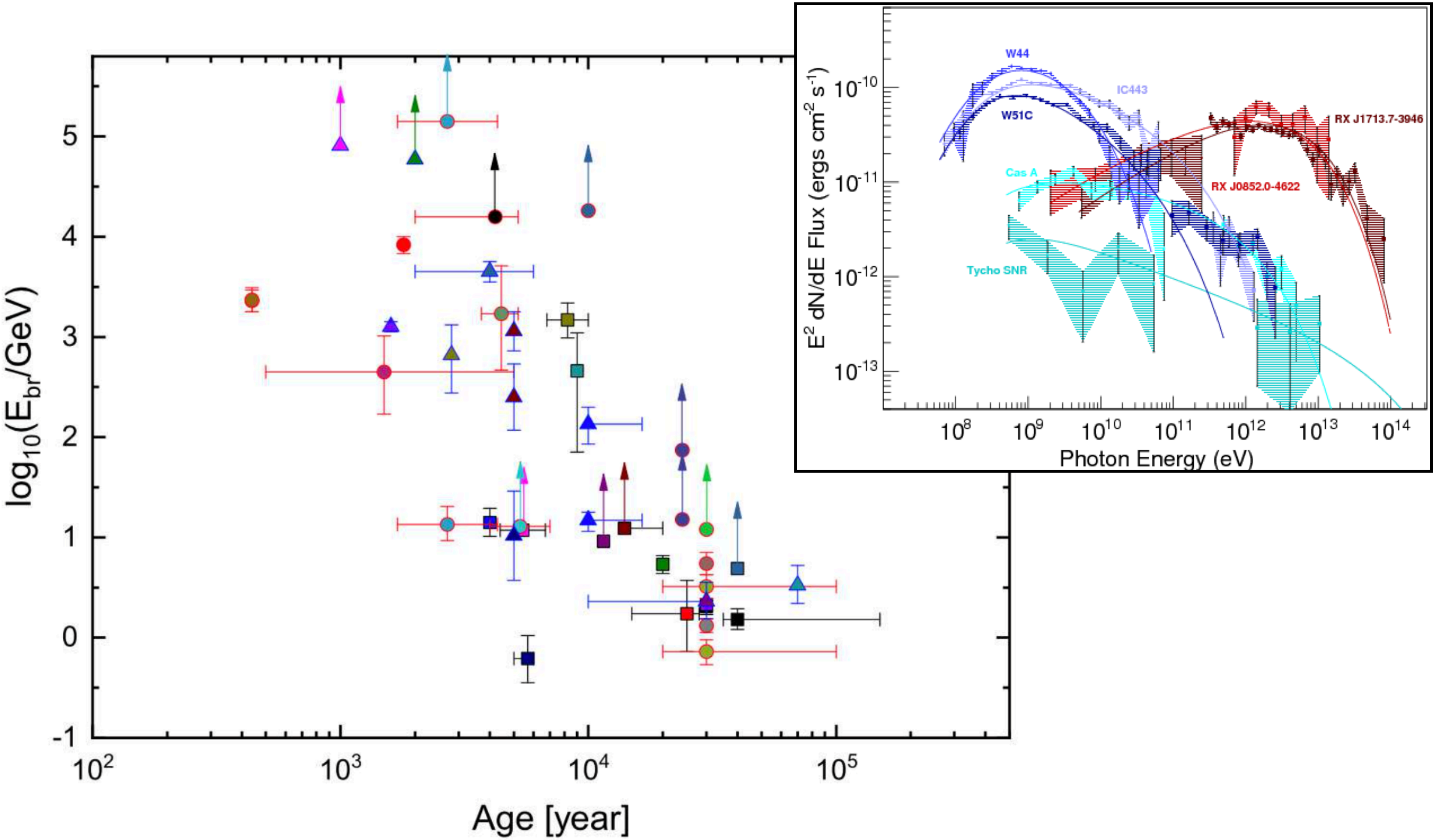
- Ptuskin & Zirakashvili, A&A 429 (2005) 755
- Gabici, Aharonian & Casanova, MNRAS (2009)
- Ohira, Murase & Yamakazi, A&A (2010) 513
- Bell & Shure, MNRAS 437 (2014) 2802
- Cardillo, Amato & Blasi, APh 69 (2015) 1

Defines $\mathbf{E_{max}}$ and **spectral slope** of both **particles** and **radiation**

A **phenomenological** model to investigate the particle **escape** through spectral and morphological features of evolved SNRs in the HE and VHE domain.

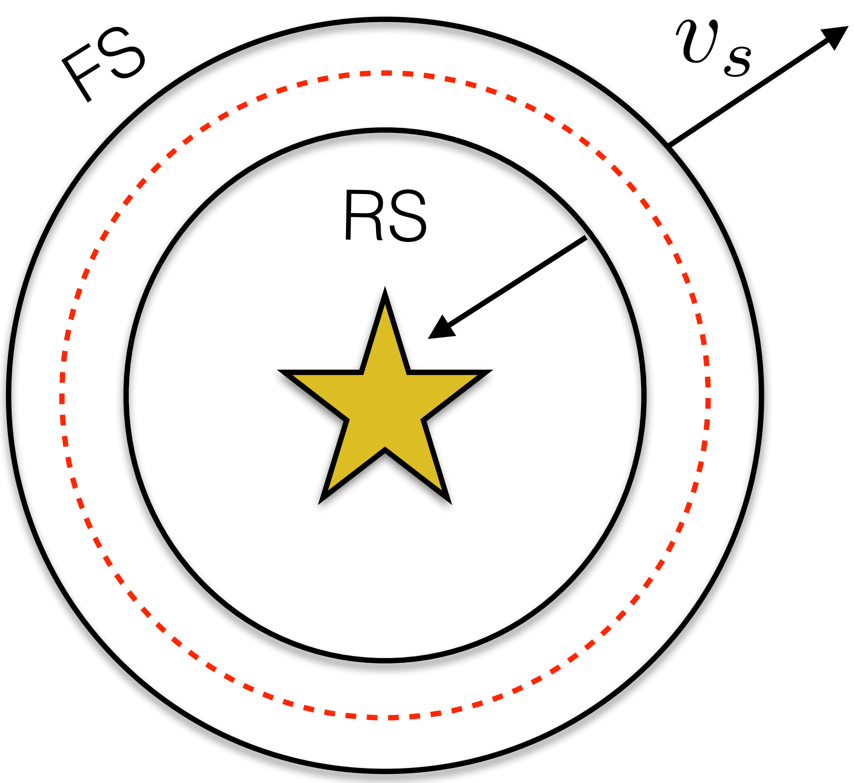
Celli et al., MNRAS 490 (2019) 3

A population study of evolved SNRs



Zeng et al., ApJ 874 (2019) 50Z

The hydrodinamical evolution of an SNR



Vink, A&A Rev 20 (2012) 1

I. Ejecta-dominated (ED) stage

$$M_{\rm ej} \gg \frac{4}{3}\pi\rho R_s^3(t)$$

⟶ free expansion

II. Sedov-Taylor (ST) stage

$$M_{\rm ej} \sim \frac{4}{3}\pi\rho R_s^3(t)$$

⟶ energy conservation

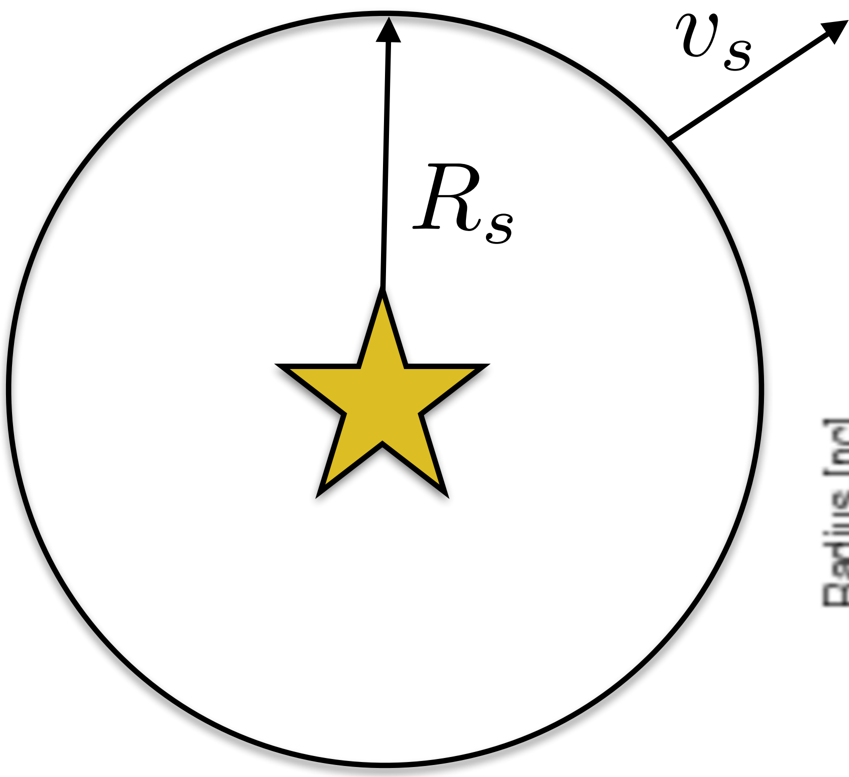
III. Radiative stage

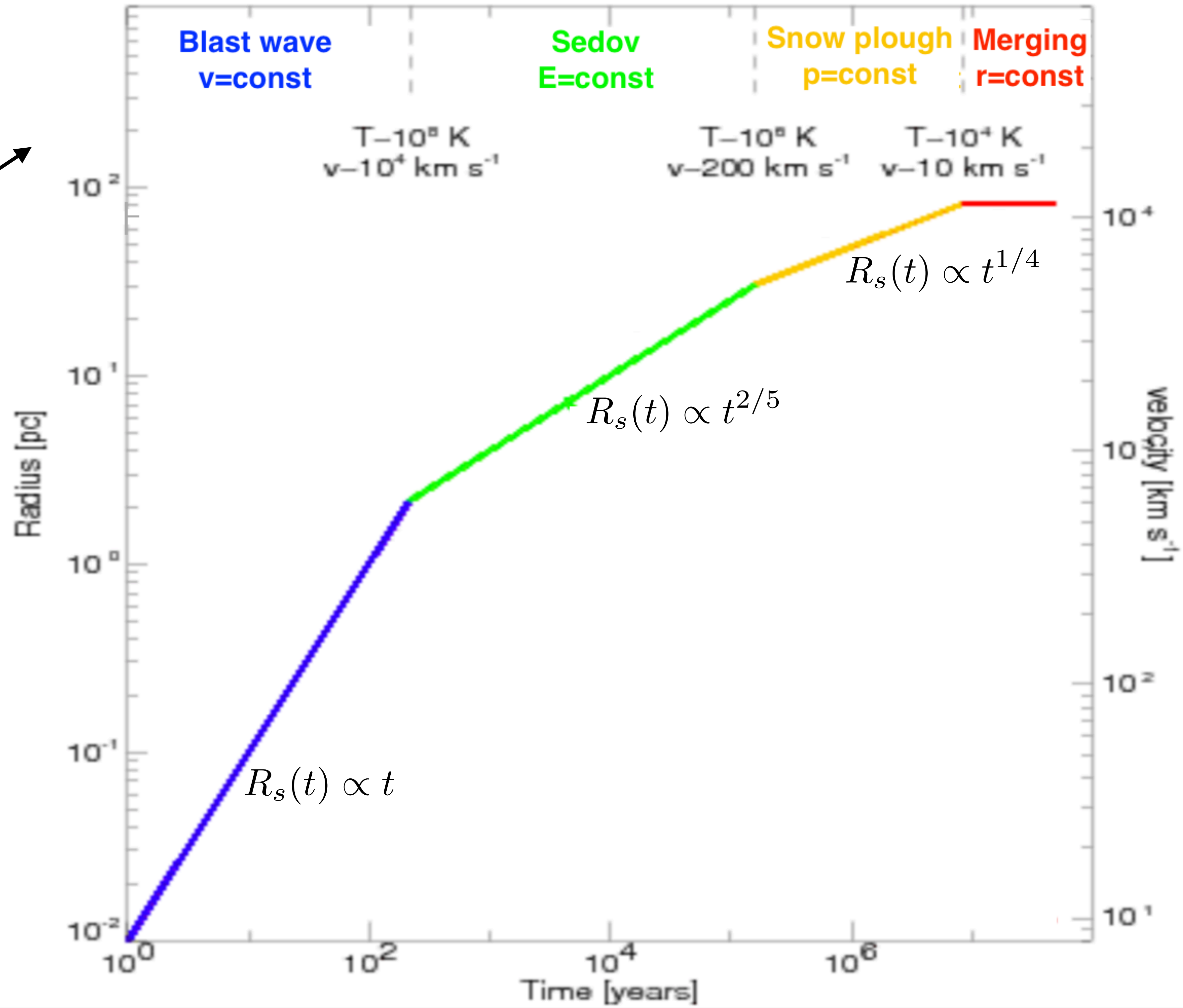
⟶ momentum conservation

IV. Merging phase

⟶ pressure comparable to ISM

The hydrodinamical evolution of an SNR

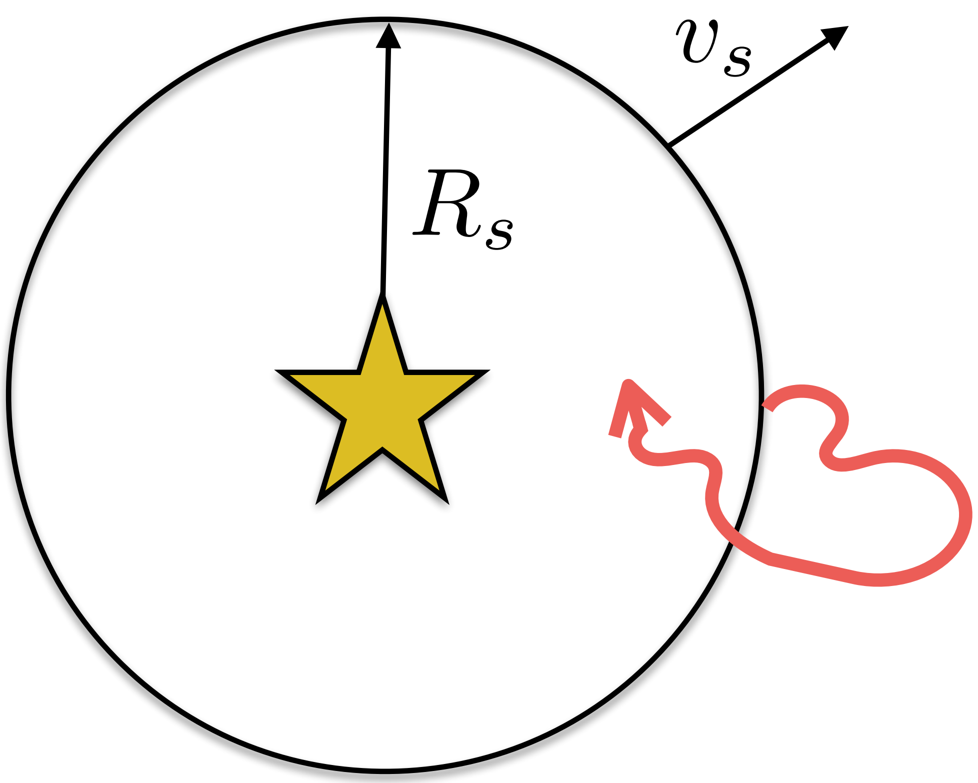




Vink, A&A Rev 20 (2012) 1

$$t_{\rm Sed} \simeq 1.6 \times 10^3\,{\rm yr} \left(\frac{E_{\rm SN}}{10^{51}\,{\rm erg}}\right)^{-1/2} \left(\frac{M_{\rm ej}}{10\,M\odot}\right)^{5/6} \left(\frac{\rho_0}{1\,m_{\rm p}/{\rm cm}^3}\right)^{-1/3}$$

Maximum energy in SNRs



- At Sedov time, particles at maximum energy E_M are still confined:

$$\lambda_{\rm d}(E_{\rm M}, t_{\rm Sed}) \simeq R_{\rm s}(t_{\rm Sed})$$

- Later in the evolution, particles diffusion length increases faster than SNR shock size:

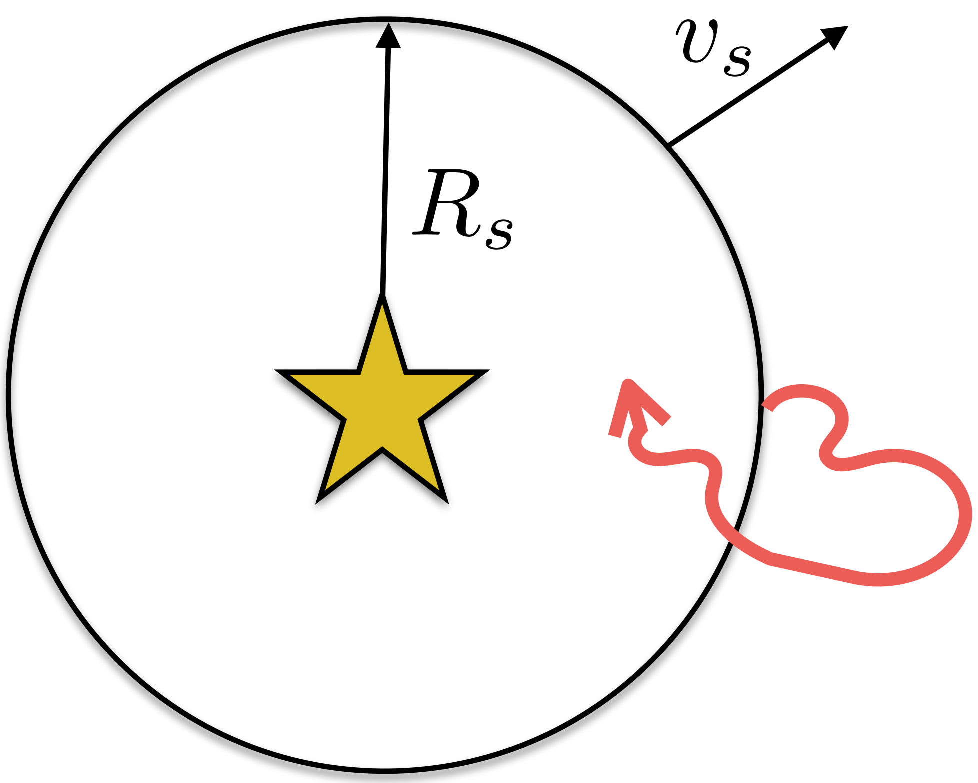
$$\lambda_{\rm d} \simeq D(E_{\rm M})/v_{\rm s} \propto t^{3/5}$$

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

Particles previously confined will now violate Hillas criterion

⟶ **escape is expected to occur on shorter timescales for the highest energy particles, but it is not an instantaneous process**

Maximum energy in SNRs



$$t_{\rm acc} = t_{\rm age}$$

acceleration limited by remnant age

$$\frac{D(p_{\max})}{v_s^2(t)} = t$$

$$\frac{p_{\max}}{B_0\,\mathcal{F}(t)} = v_s^2(t)\,t$$

$$\left(\frac{\delta B(\mathbf{x},t)}{B_0}\right)^2 = \int \mathcal{F}(k,\mathbf{x},t)d\ln k$$

$$p_{\max,0} \propto \mathcal{F}(t)\,v_s^2(t)\,t$$

ED stage:

$$v_s(t) \simeq \text{const}$$

$$p_{\max,0}(t) \propto \mathcal{F}(t)\,t$$

ST stage:

$$v_s(t) \simeq t^{-3/5}$$

$$p_{\max,0}(t) \propto \mathcal{F}(t)\,t^{-1/5} \propto t^{-\delta}$$

Celli et al., MNRAS 490 (2019) 3

Maximum energy in SNRs

In the scenario where the maximum momentum of particles confined by the shock is a decreasing function of time, i.e.

$$p_{\mathrm{max},0}(t) = p_{\mathrm{M}} \left(\frac{t}{t_{\mathrm{Sed}}} \right)^{-\delta} \longrightarrow t_{\mathrm{esc}}(p) = t_{\mathrm{Sed}} \left(\frac{p}{p_{\mathrm{M}}} \right)^{-1/\delta}$$

Ptuskin & Zirakashvili, A&A 429 (2005) 755

$\delta > 0$: high-energy particles escape earlier

- Magnetic field not amplified

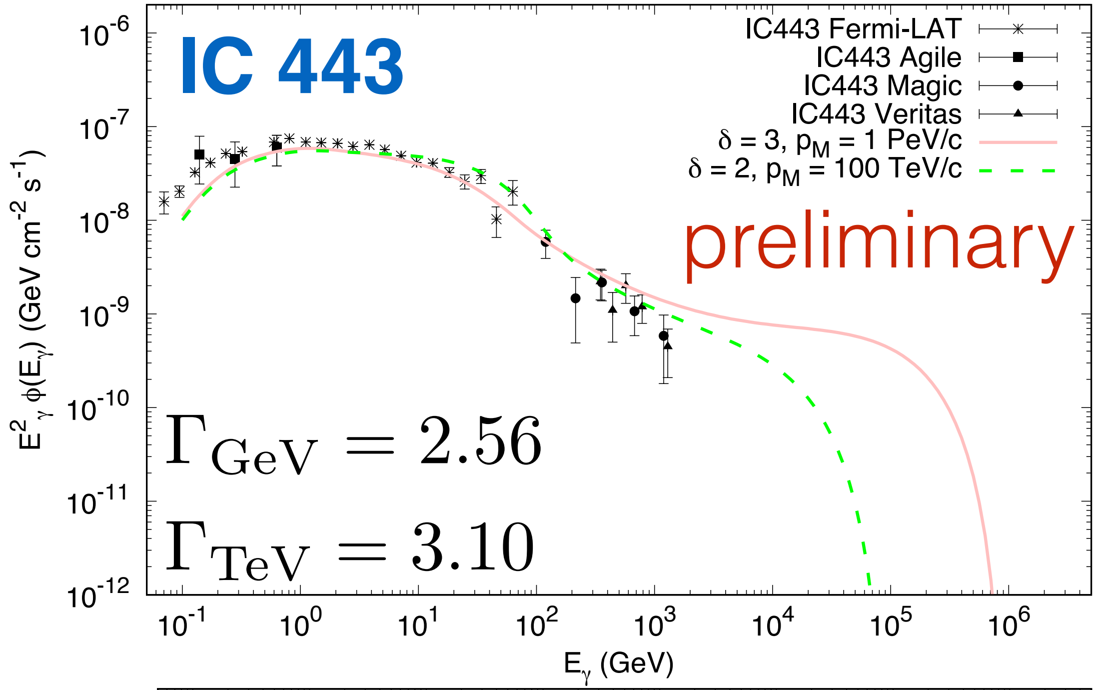
  $p_{\mathrm{max},0}(t) \propto t^{-1/5}$

- Magnetic field amplification driven by resonant waves

  $p_{\mathrm{max},0}(t) \propto t^{-7/5}$

- Magnetic field amplification driven by non-resonant waves

  $p_{\mathrm{max},0}(t) \propto t^{-2}$

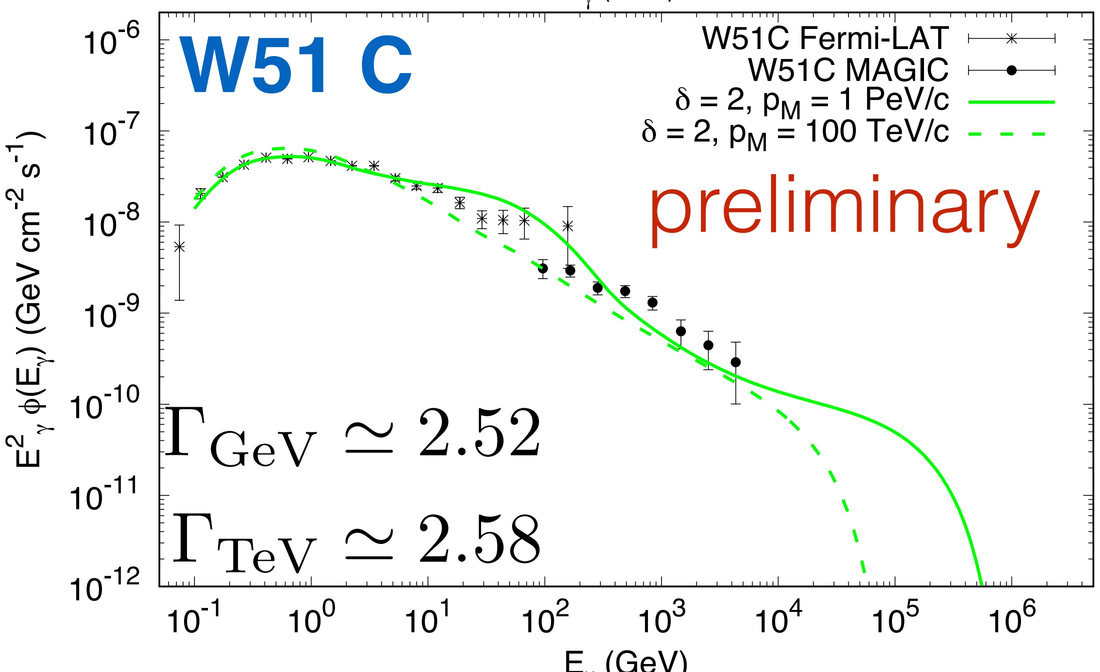


$$f_0(p) \propto p^{-4}$$

$$T_{\rm SNR} = 1.5 \times 10^4\,{\rm yr}, n_{\rm up} = 10\ {\rm cm}^{-3}$$

$$d = 1.5\ {\rm kpc}, \xi_{\rm CR} = 2\%$$

$$D(10\ {\rm GeV}/c) = 10^{27}\ {\rm cm}^2{\rm s}^{-1}$$

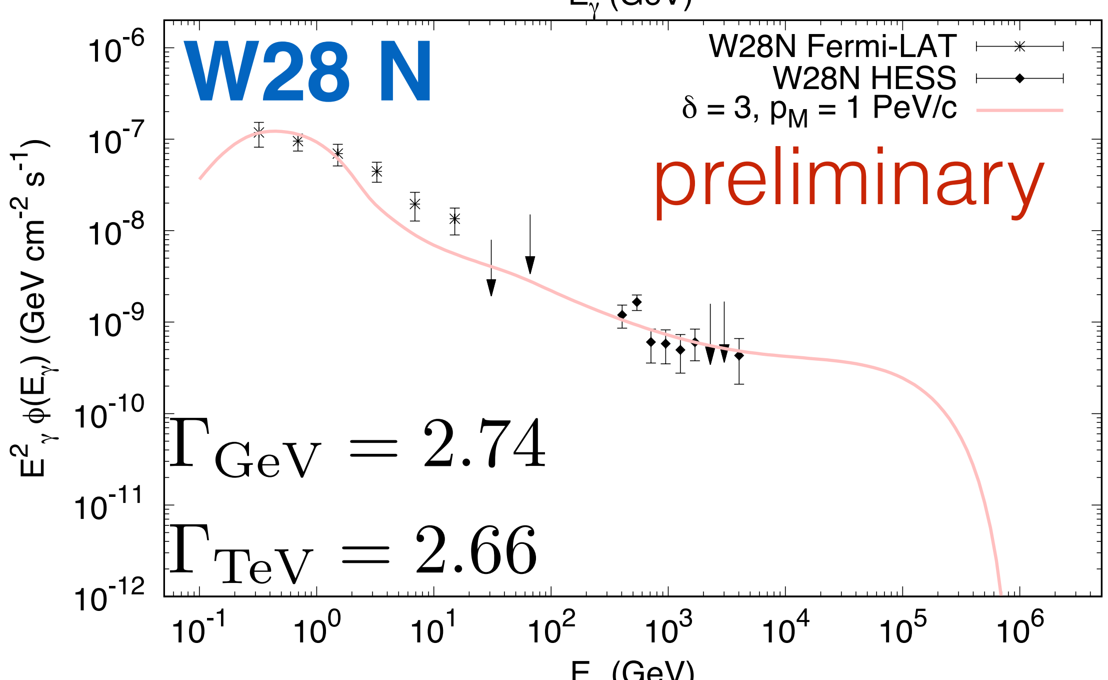


$$f_0(p) \propto p^{-(4+1/3)}$$

$$T_{\rm SNR} = 3 \times 10^4\,{\rm yr}, n_{\rm up} = 10\ {\rm cm}^{-3}$$

$$d = 5.4\ {\rm kpc}, \xi_{\rm CR} = 12\% - 15\%$$

$$D(10\ {\rm GeV}/c) = 3 \times 10^{26}\ {\rm cm}^2{\rm s}^{-1}$$



$$f_0(p) \propto p^{-4}$$

$$T_{\rm SNR} = 4 \times 10^4\,{\rm yr}, n_{\rm up} = 10\ {\rm cm}^{-3}$$

$$d = 2.0\ {\rm kpc}, \xi_{\rm CR} = 15\%$$

$$D(10\ {\rm GeV}/c) = 3 \times 10^{27}\ {\rm cm}^2{\rm s}^{-1}$$

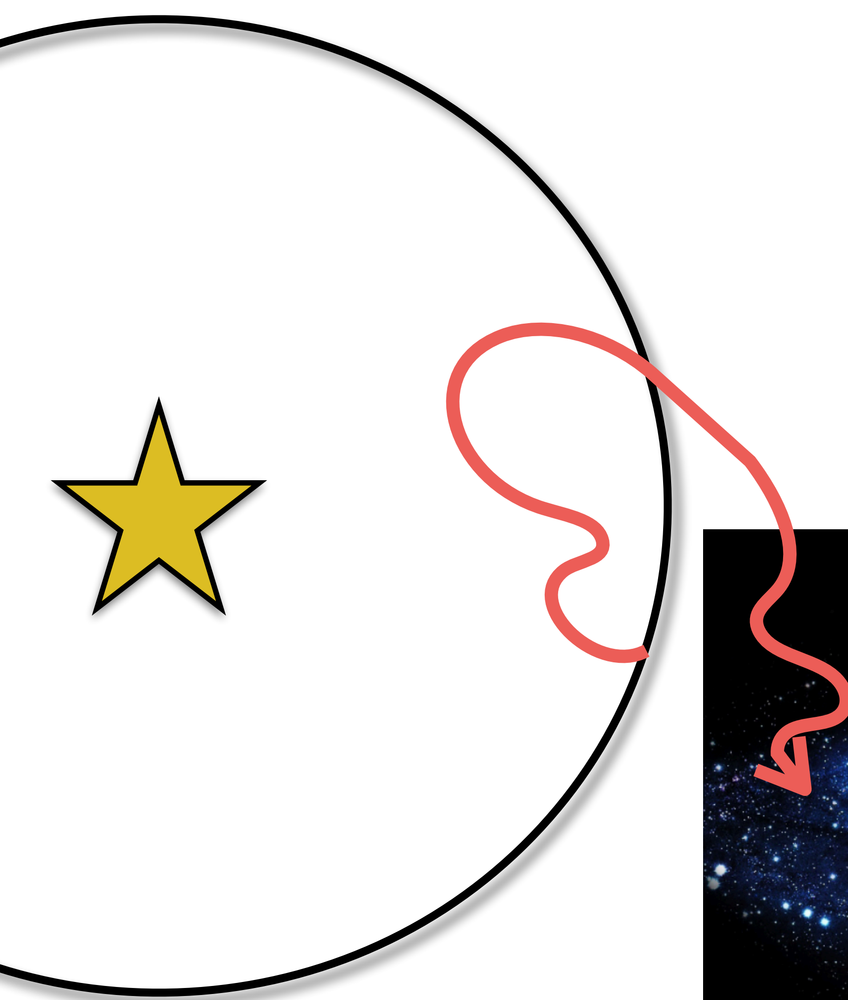
The CR spectrum injected into the Galaxy

$$f_{\rm inj}(p) = 4\pi \int_0^{R_{\rm esc}(p)} r^2 f_{\rm conf}\left(t_{\rm esc}(p), r, p\right) dr$$

$$\longrightarrow f_{\rm inj}(p) \propto v_{\rm esc}^2(p) R_{\rm esc}^3(p) \frac{p^{-\alpha}}{\Lambda(p)}$$

$$\longrightarrow f_{\rm inj}(p) \propto \frac{p^{-\alpha}}{\Lambda(p)}$$

Exact balance between v^2_{esc} and R^3_{esc} during the ST phase



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$$\longrightarrow f_{\rm inj}(p) \propto \frac{p^{-\alpha}}{\Lambda(p)}$$

during the ST phase

- Ultra-relativistic limit ($p \gg m_p c$):

$$f_{\rm inj}(p) \propto \begin{cases} p^{-\alpha} & \alpha > 4 \\ p^{-4} & \alpha < 4 \end{cases}$$

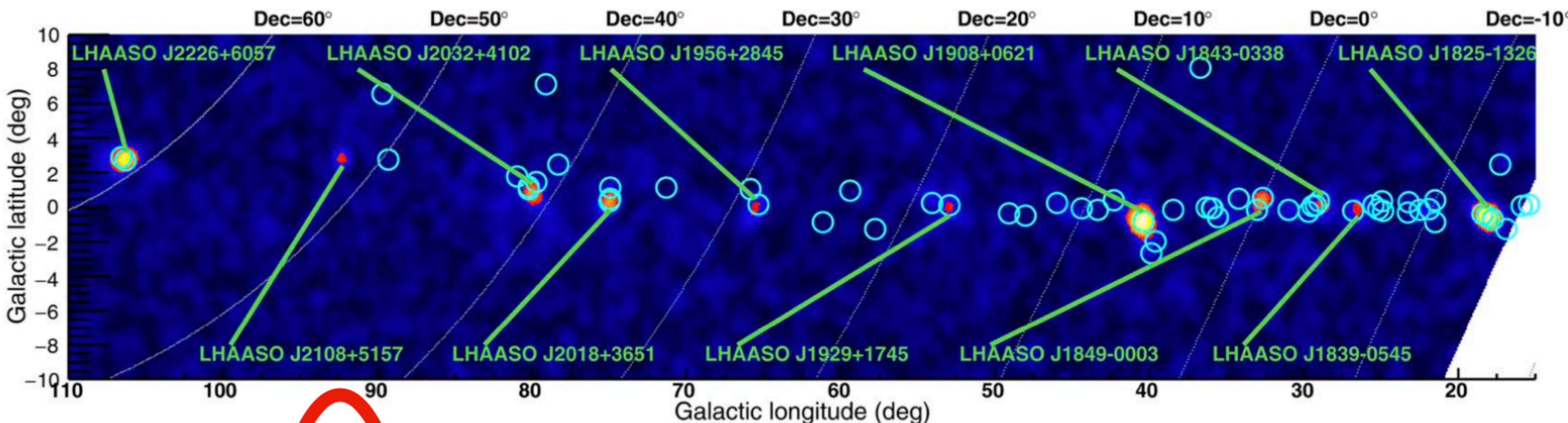
Bell & Shure, MNRAS 437 (2014) 2802

Cardillo, Amato & Blasi, APh 69 (2015) 1

Celli et al., MNRAS 490 (2019) 4317C

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

LHAASO Coll., Nature 594 (2021) 33

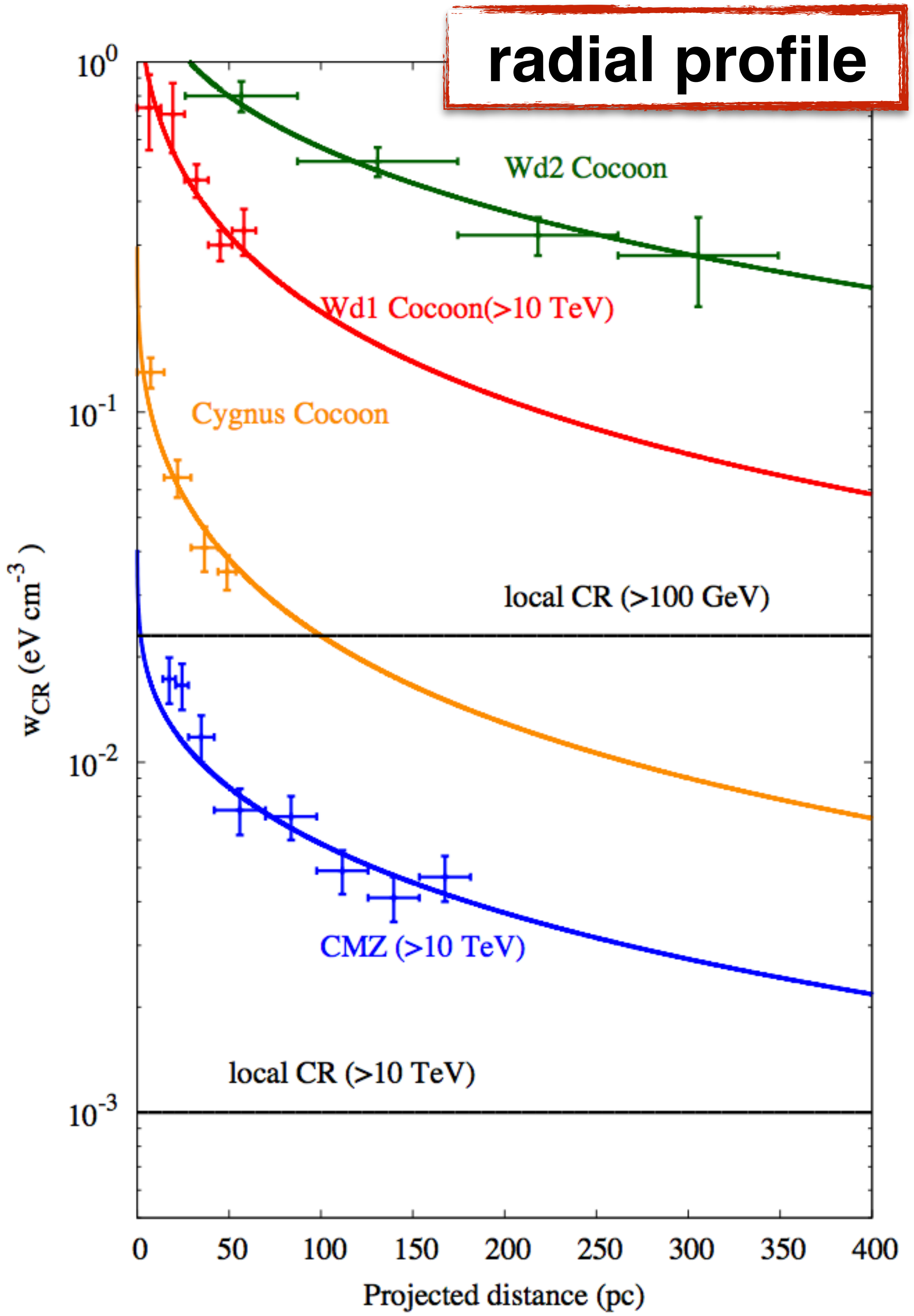


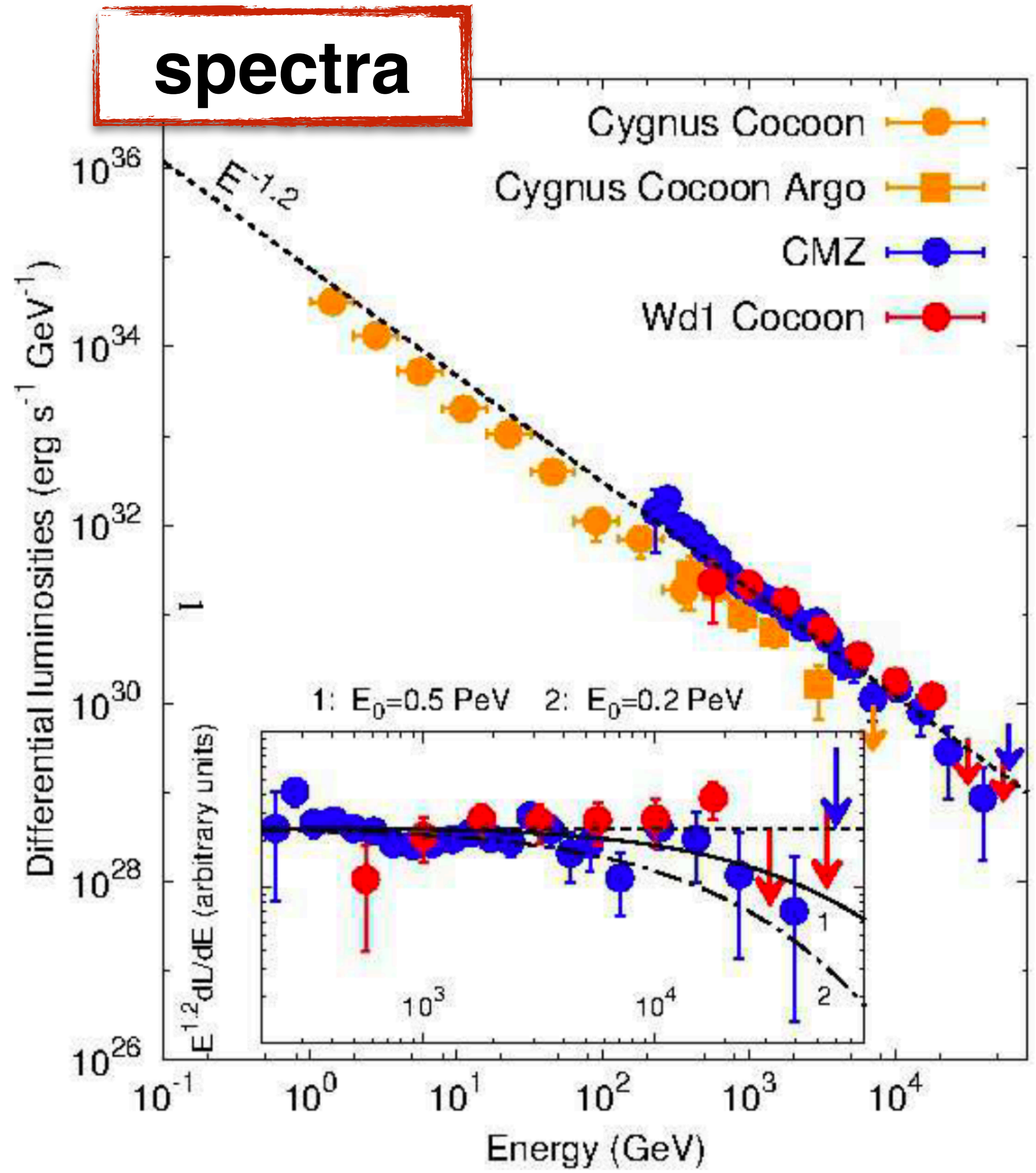
LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)[a]	L_s (erg/s)[b]	Potential TeV Counterpart[c]
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2^d	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	2HWC J1825-134
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}	2HWC J1837-065, HESS J1837-069,
	PSR J1838-0537	PSR	1.3^e	4.9	6.0×10^{36}	HESS J1841-055
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3^f	$< 2^f$	—	HESS J1843-033, HESS J1844-030, 2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001	PSR	7^g	43.1	9.8×10^{36}	HESS J1849-000, 2HWC J1849+001
	W43	YMC	5.5^h	—	—	
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4^i	$\sim 10 - 20^j$	—	MGRO J1908+06, HESS J1908+063,
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	ARGO J1907+0627, VER J1907+062,
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}	2HWC 1908+063
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}	2HWC J1928+177, 2HWC J1930+188,
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}	HESS J1930+188, VER J1930+188
	SNR G54.1+0.3	SNR	$6.3^{+0.8}_{-0.7}{}^d$	$1.8 - 3.3^k$	—	
LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}	2HWC J1955+285
	SNR G66.0-0.0	SNR	2.3 ± 0.2^d	—	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7}_{-1.4}{}^l$	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
	Sh 2-104	H II/YMC	$.3 \pm 0.3^m/4.0 \pm 0.5^n$	—	—	VER J2016+371
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08^o	—	—	TeV J2032+4130, ARGO J2031+4157,
	PSR 2032+4127	PSR	1.40 ± 0.08^o	201	1.5×10^{35}	MGRO J2031+41, 2HWC J2031+415,
	SNR G79.8+1.2	NR candidate	—	—	—	VER J2032+414
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8^p	$\sim 10^p$	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8^p	$\sim 10^p$	2.2×10^{37}	

Uncertain nature of sources,
Not many SNRs

https://doi.org/10.1038/s41586-021-03498-z
Received: 21 October 2020
Accepted: 26 March 2021
Published online: 17 May 2021

VHE gamma rays from massive stellar clusters





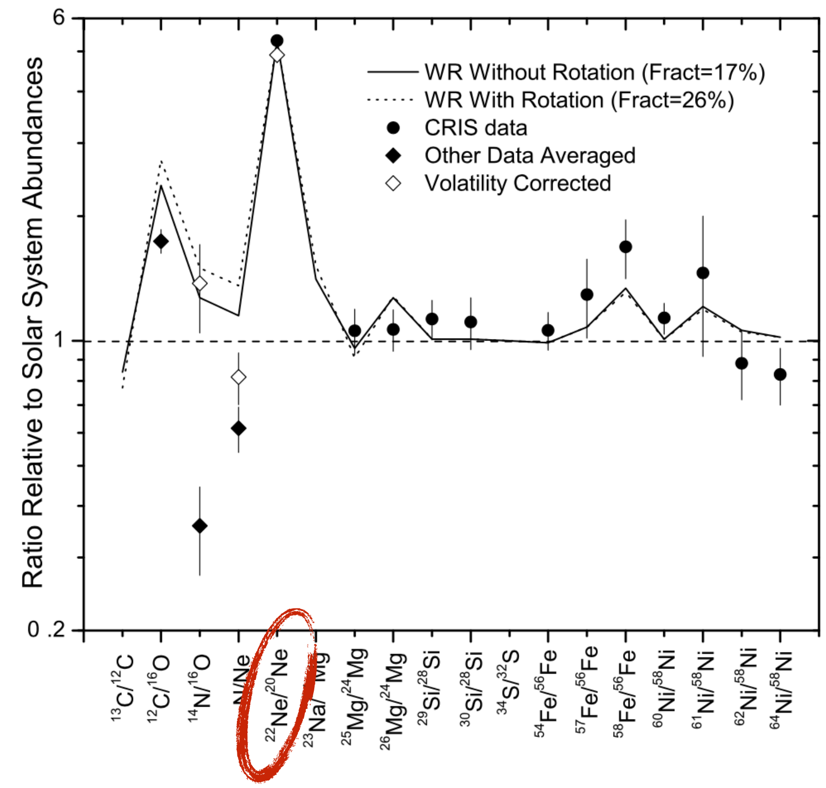
Source	Cyg Cocoon	CMZ	Wd 1 Cocoon
Extension (pc)	50	175	60
Age of cluster (Myr)[28]	3–6	2–7	4–6
L_{kin} of cluster (erg/s)	2×10^{38} [37]	1×10^{39} [29]	1×10^{39} [30]
Distance (kpc)	1.4	8.5	4
$\omega_o(> 10\text{TeV})$ (eV/cm^3)	0.05	0.07	1.2

Aharonian et al., Nature Astr. 3 (2019) 561

Particle acceleration in wind-blown bubbles

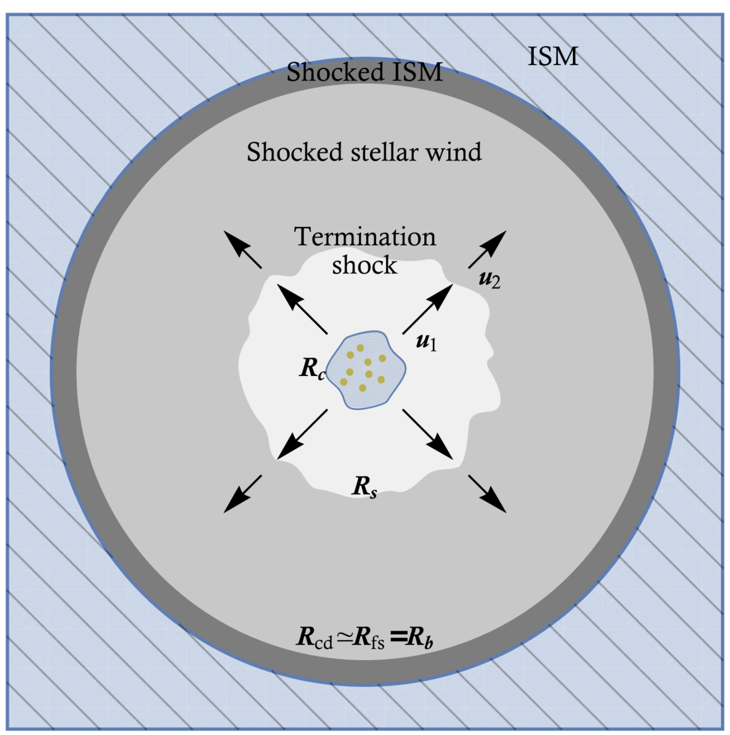
see Peretti's talk

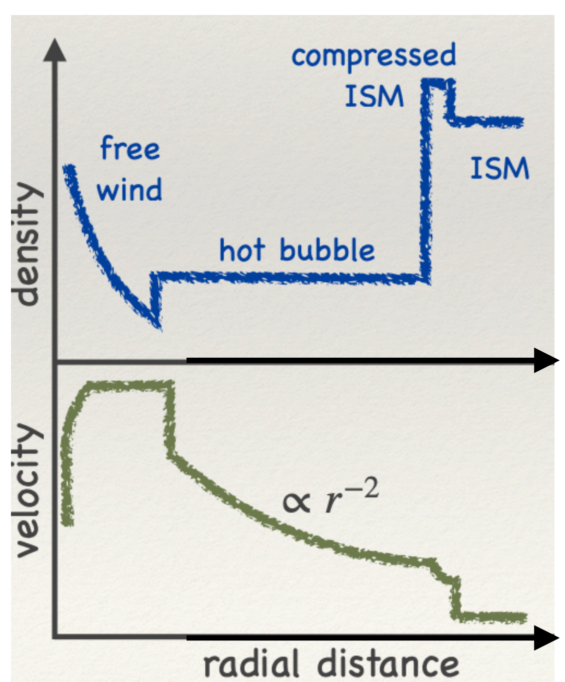
- Anomalous CR composition can't be easily accommodated in the standard SNR scenario for the origin of GCRs
- In particular, the ^{22}**Ne/**^{20}**Ne** appears 5 times larger in CRs than in solar wind
  ⟶ Heavy ejecta required

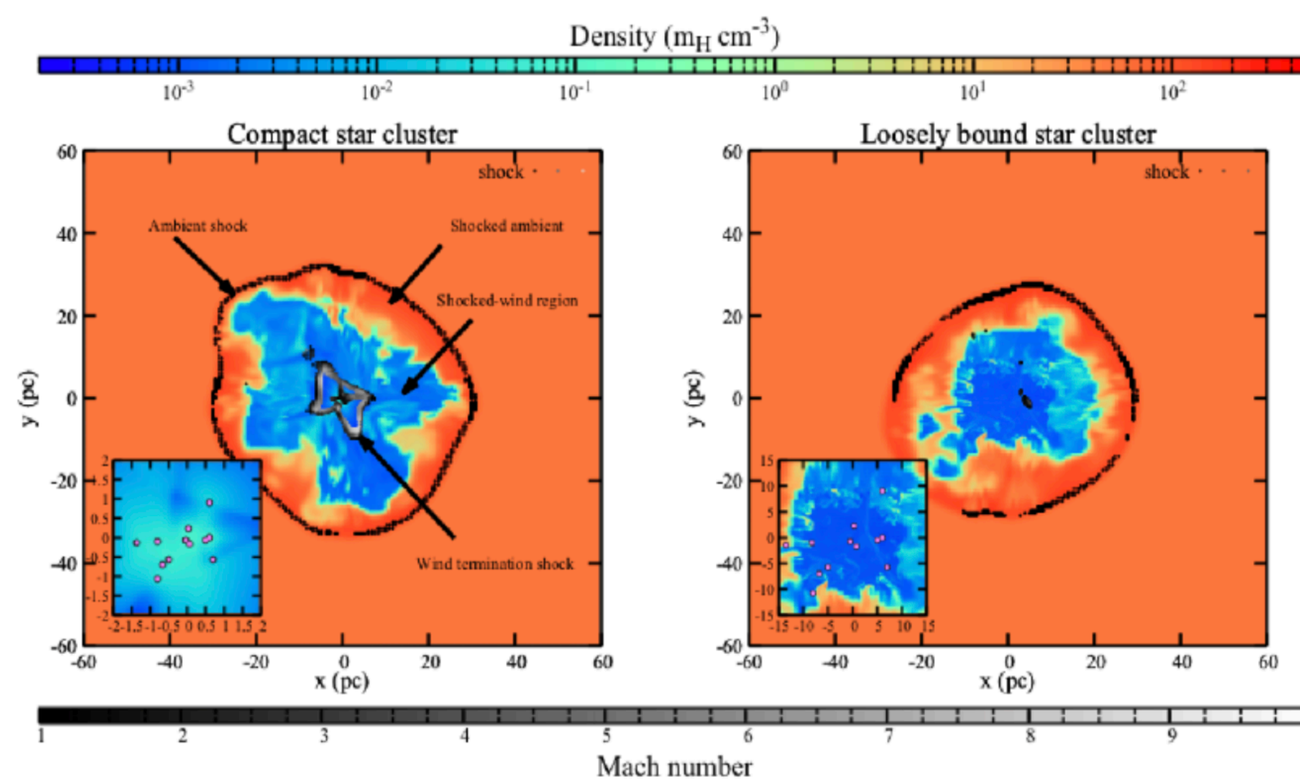


Cassè & Paul , ApJ 258 (1982) 860

Binns et al., New Astr. Rev. 52 (2008) 427





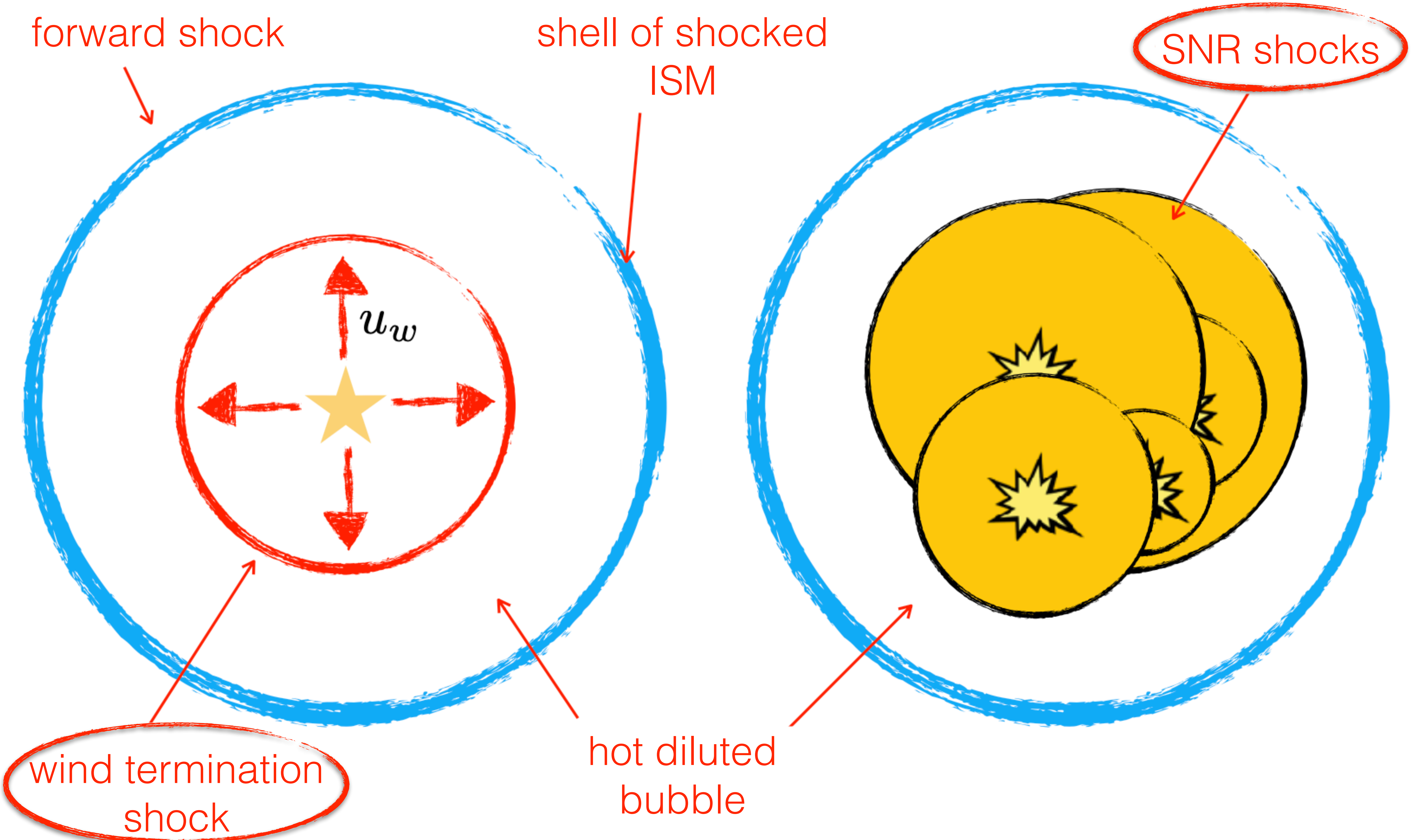


Weaver et al., ApJ 218 (1977) 377

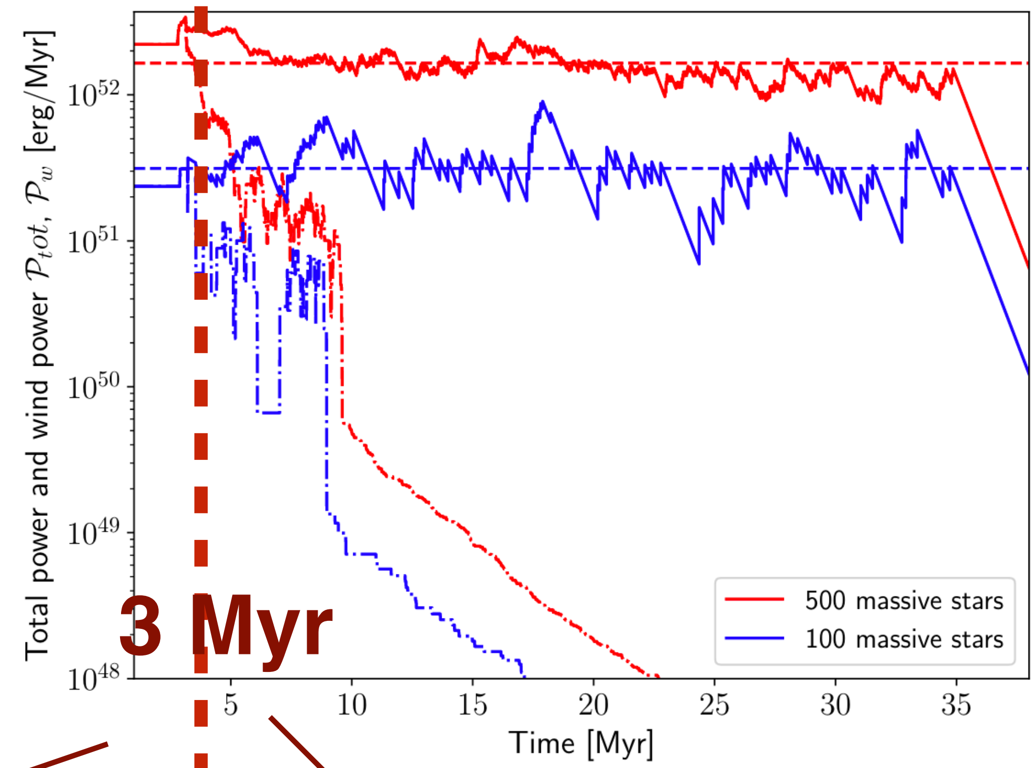
Morlino et al., MNRAS 504 (2021) 4

Gupta et al., MNRAS 493 (2020) 3

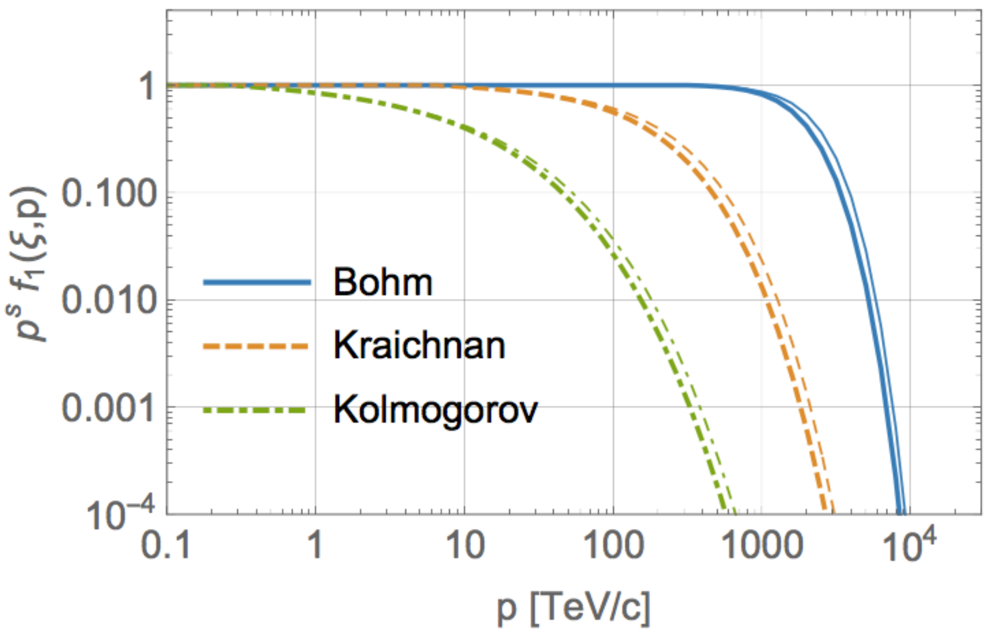
Stellar winds vs SNRs



Particle acceleration in wind-blown bubbles



Acceleration @ WTS

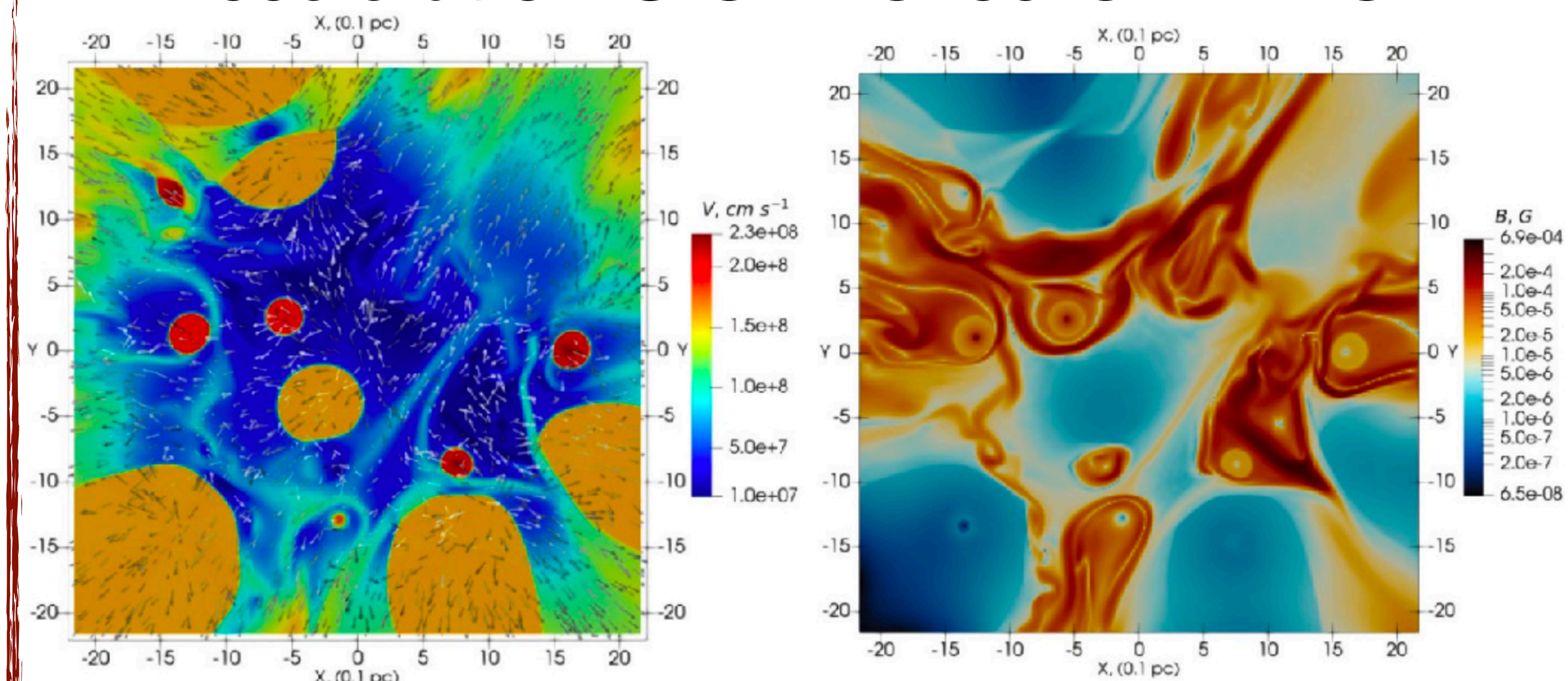


$$\dot{M} = 10^{-4} M_\odot/\mathrm{yr}, v_w = 3000\,\mathrm{km/s},$$
$$L_\mathrm{w} = 3 \times 10^{38}\,\mathrm{erg/s}, \xi_\mathrm{CR} = \eta_\mathrm{B} = 0.1$$

→ **PeV energies** can be reached in powerful compact clusters **only** if diffusion is close to **Bohm**

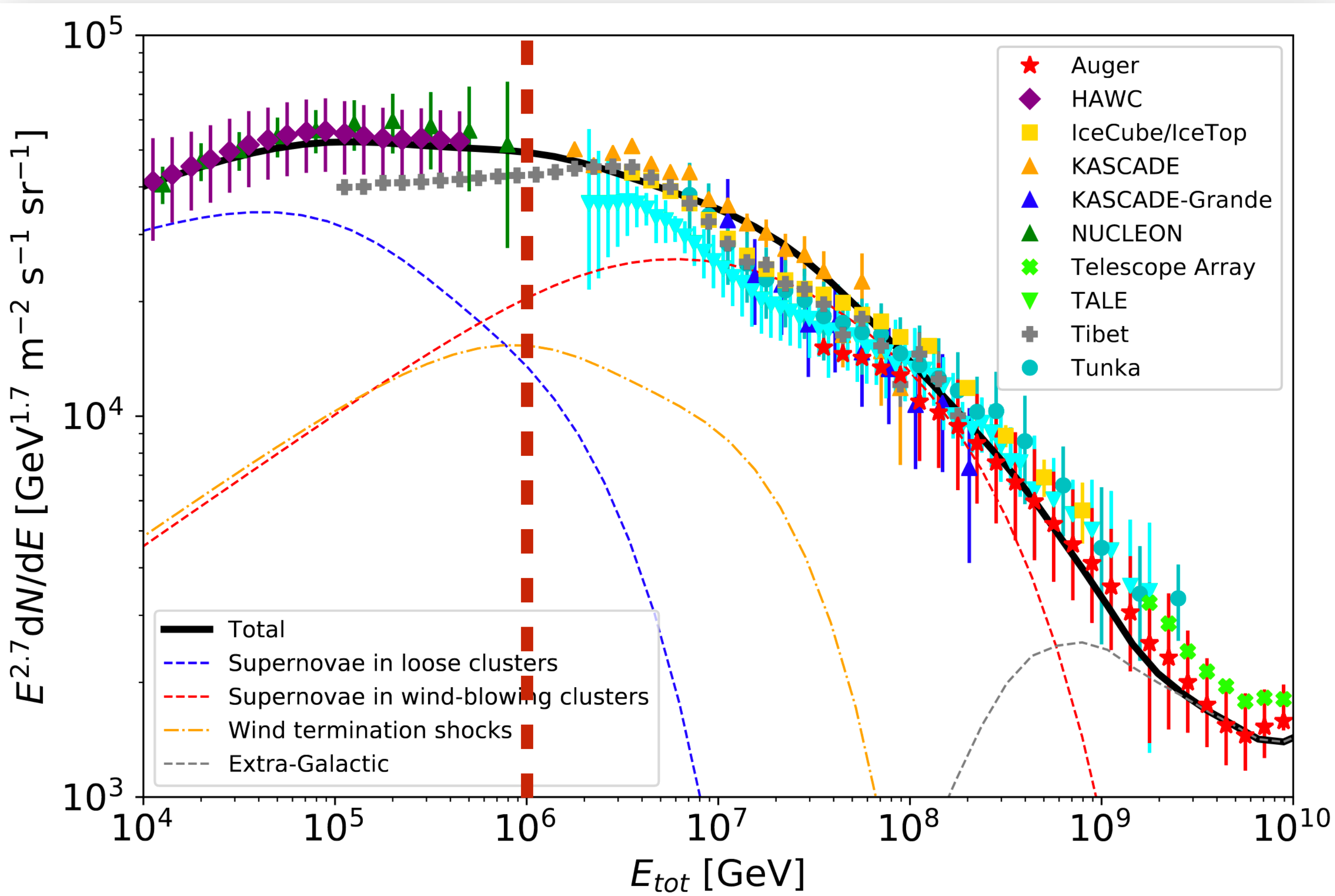
Morlino et al., MNRAS 504 (2021) 4

Acceleration @ SNR shocks in WTS



Badmaev et al., MNRAS 517 (2022) 1818B

What about Galactic SuperPeVatrons?



- Compelling fit to CR data (spectrum & composition)
- Contribution from clustered SNRs in compact MSCs takes over at few hundreds TeV, creating a knee-like feature

Vieu & Reville, MNRAS 515 (2022) 2256

Acceleration mechanism	U (km s^{-1})	B (μG)	R (pc)	E_{max}, canonical (PeV)	E_{max}, optimistic (PeV)
SB forward shock	30	1–10	50–100	0.01	0.1
SNR inside SB	3000	10–50	10–30	1	5
WTS around a compact cluster	2000	10–50	5–30	1	5
SNR embedded in a WTS	5000	10–50	5–30	5	10
HD turbulence	100	1–10	50–100	0.5	1
Collection of individual winds (loose cluster)	10–100	10–50	1–10	0.05	0.5

Conclusions

- LHAASO observations have unveiled **many PeVatrons the Milky Way**:
  - while spectral studies have allowed to locate accelerators, morphological studies are also needed to firmly identify them.

- The role of **SNRs** as PeV-hadron accelerators is not yet established, the main difficulties being the maximum achievable energy and the composition of injected particles:
  - **isolated SNRs appear to be the main contributors of GCRs up to the knee**;
  - none of VHE emitters shows ongoing PeV acceleration, still possibly PeV particles have escaped their shocks within the first 10-100 years;
  - particle **escape** still nowadays poorly understood, mainly because of its dependence on the dynamics of the magnetic turbulence ⟶ MM signatures.

- **Massive stellar clusters** are promising PeVatrons: a rigorous treatment for acceleration in these systems is still lacking, as it works differently in young and old systems:
  - extreme WTSs might produce PeV particles;
  - SNRs occurring in the hot and turbulent medium within WTSs might accelerate up to 100 PeV;
  - most likely, **mixed scenarios at PeV**.

Thanks for your kind attention!