Star clusters: to the knee and beyond?

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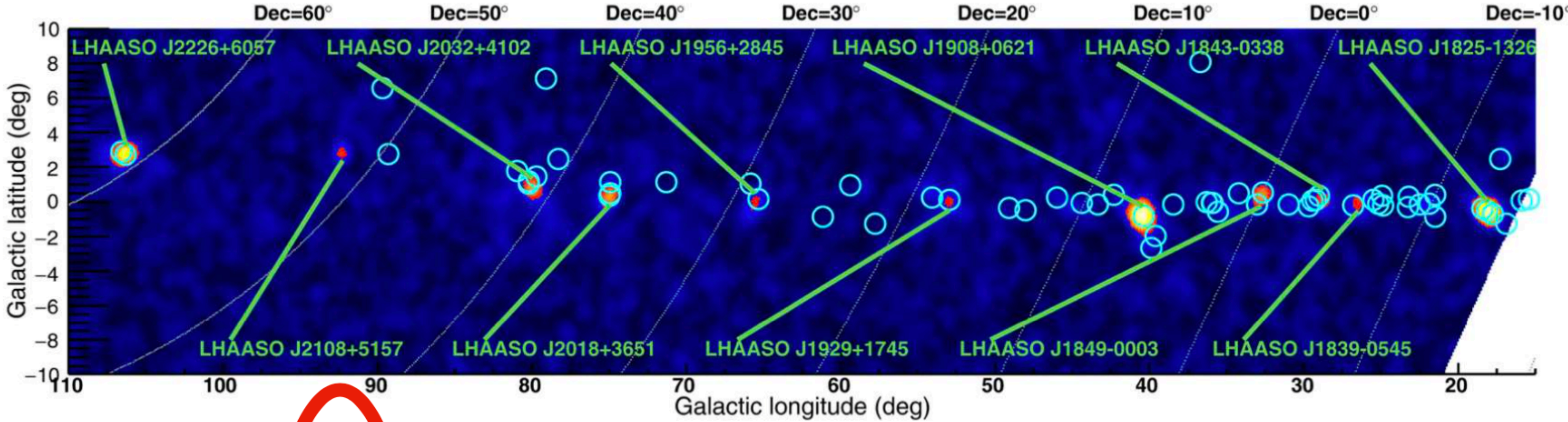
Feb 21st 2024 - The New Era of Multi-messenger Astroparticle Physics

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



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

LHAASO Coll., Nature 594 (2021) 33

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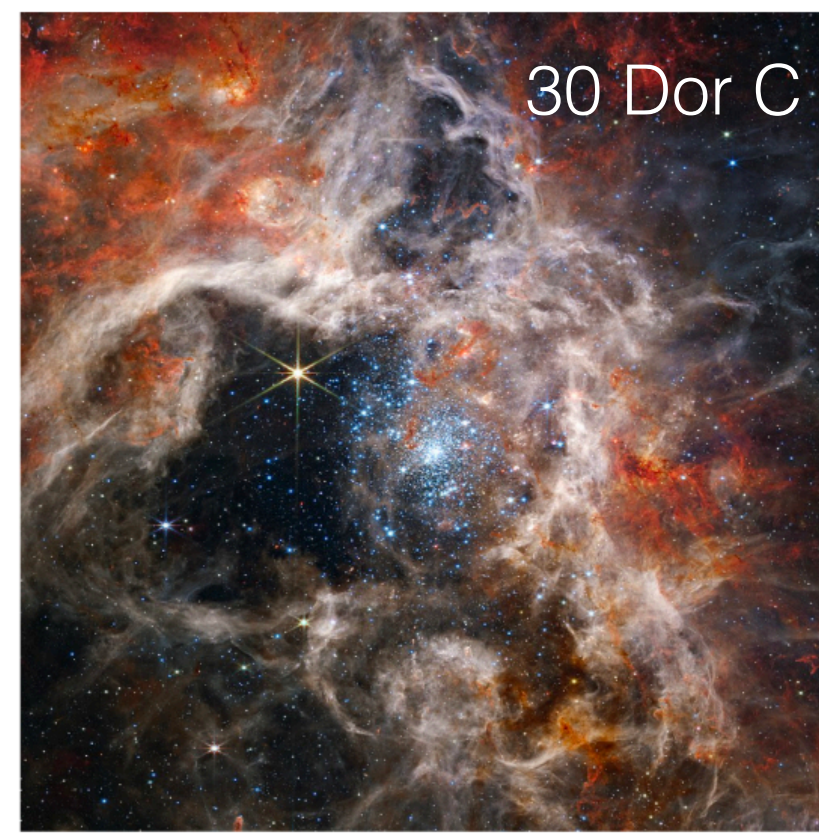
Young Star Clusters

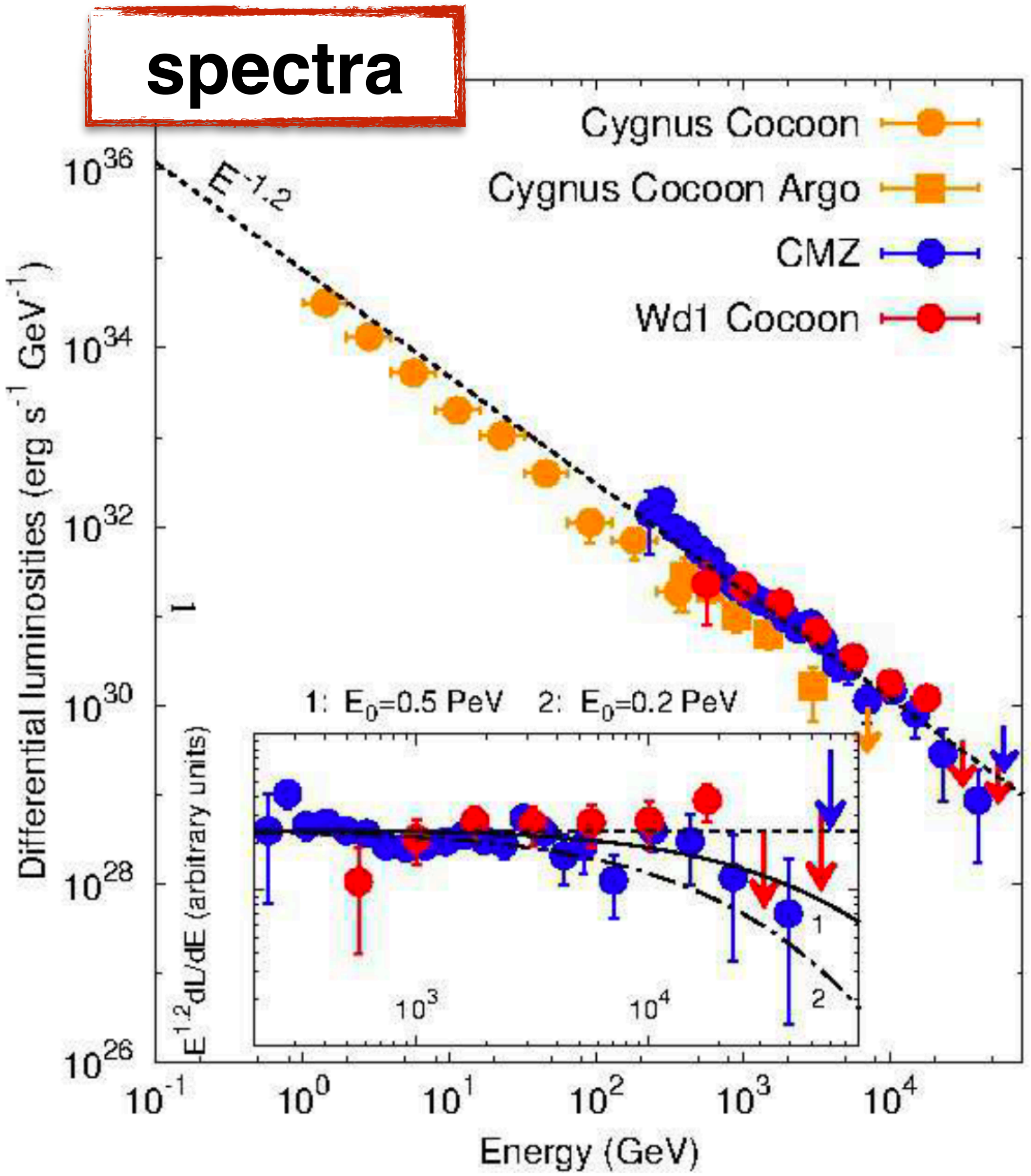
- Open clusters of the Milky Way with **age < few Myr** may contain stellar populations with **thousands of stars** and several tens of OB associations, for a total mass up to ~6×10^4 M_{sun}: as such, they also host a **high density of supernovae;**

- Their **powerful stellar winds** strongly affect the circumstellar medium, hence they are relevant to star formation and galaxy evolution (chemistry, energy input, etc.);

- **Continuous energy release by winds across Myr timescale is comparable to impulsive injection by SNe**.



Very high energy gamma rays from massive stellar clusters



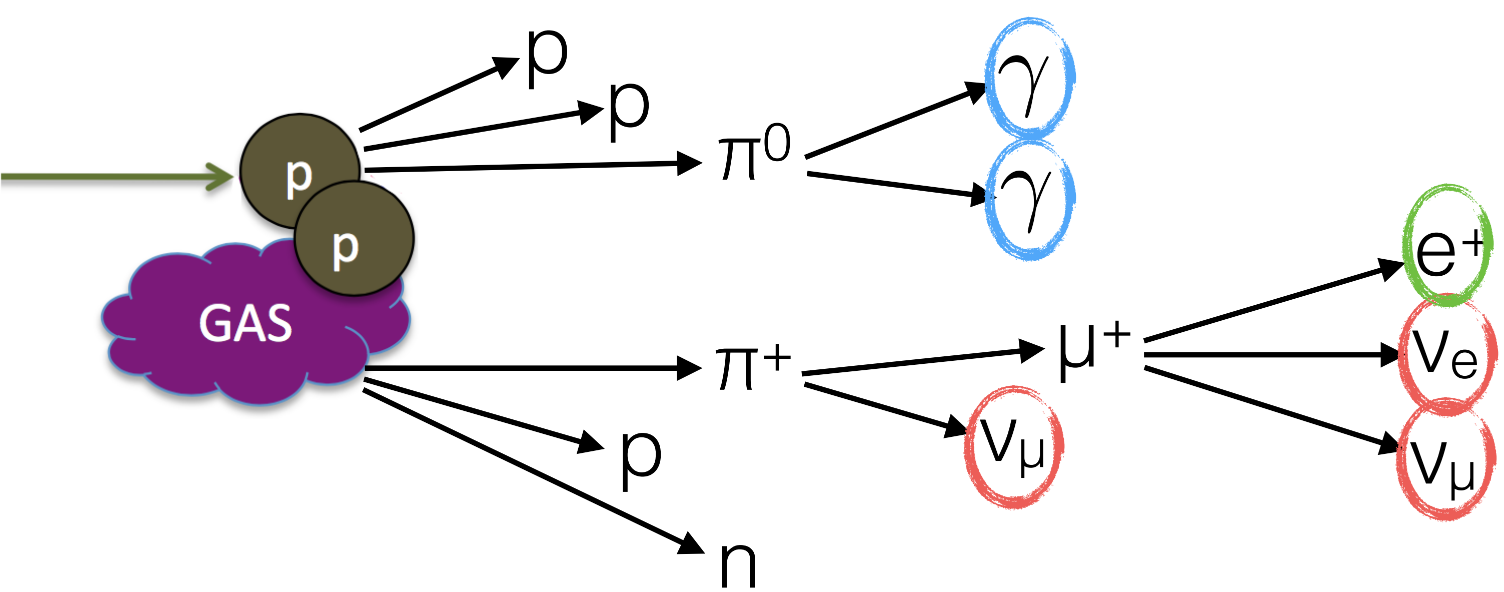
Source	Cyg Cocoon	CMZ	Wd 1 Cocoon
Extension (pc)	50	175	60
Age of cluster (Myr)[28]	3–6	2–7	4–6
L_{kin} of cluster (erg/s)	2×10^{38} [37]	1×10^{39} [29]	1×10^{39} [30]
Distance (kpc)	1.4	8.5	4
$\omega_o(> 10\text{TeV})$ (eV/cm^3)	0.05	0.07	1.2

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

Very high energy gamma rays from massive stellar clusters

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

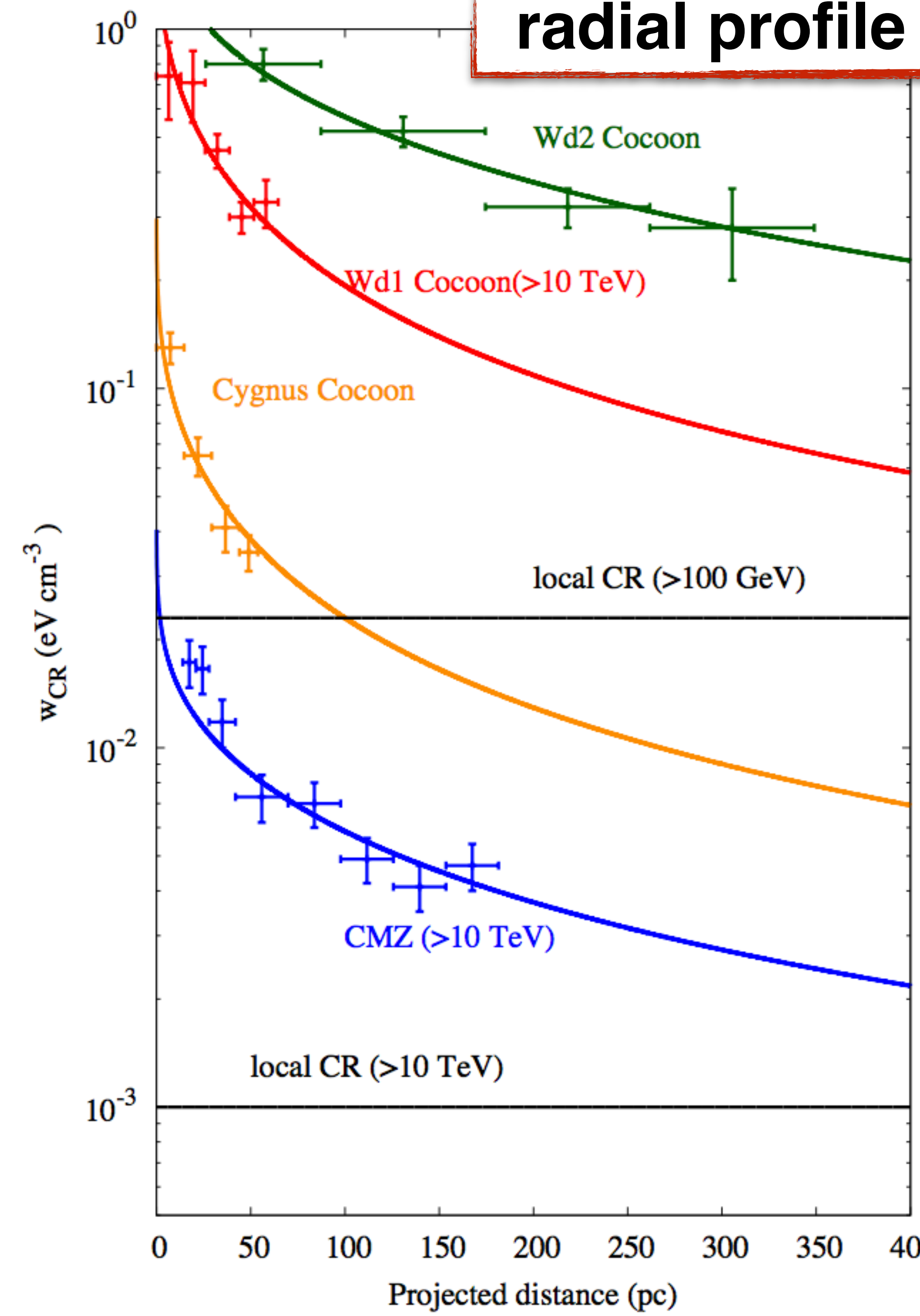
accelerated proton — target gas



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

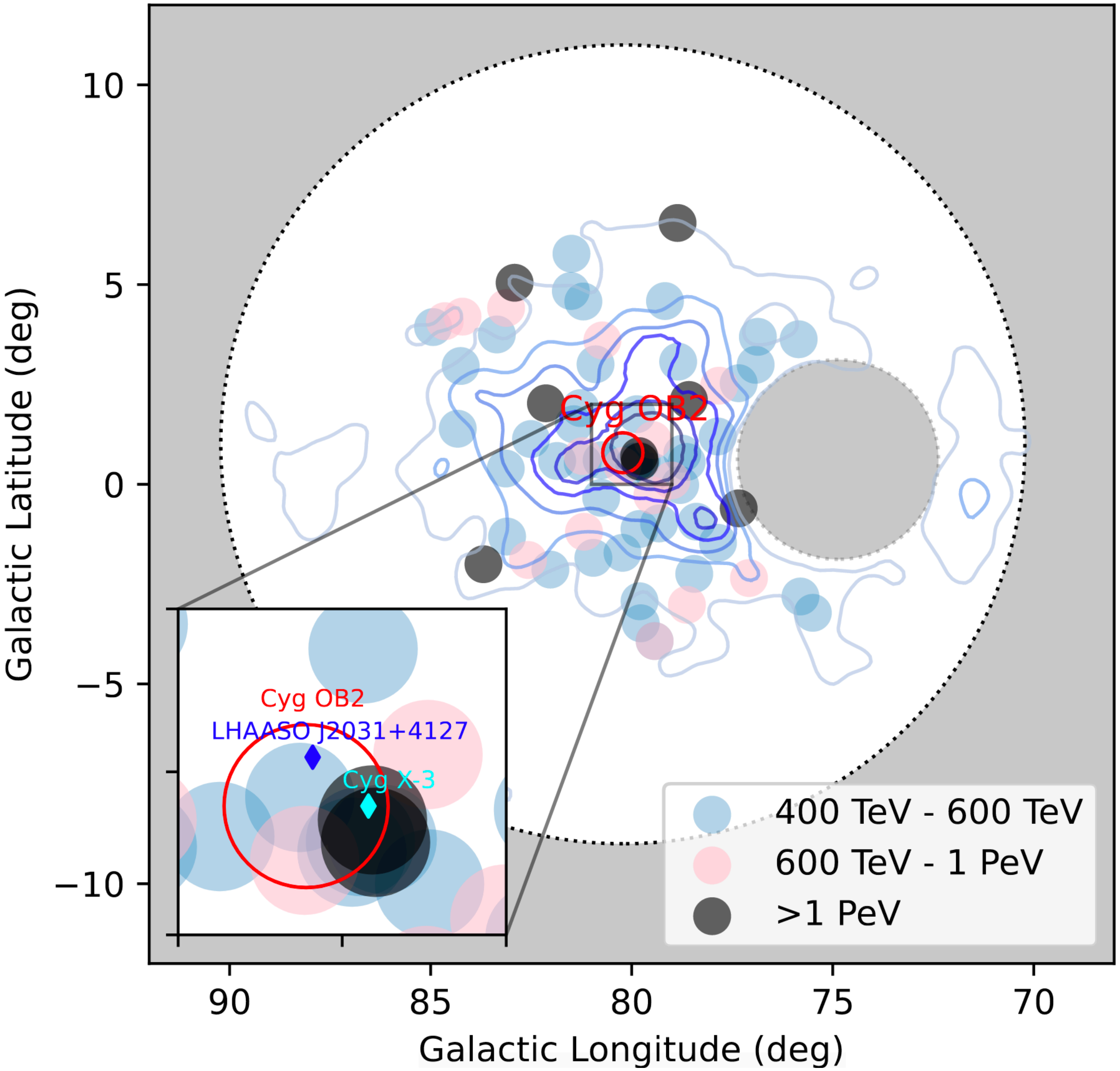
$$E_\nu \simeq E_\mathrm{e} \simeq E_\mathrm{p}/20$$

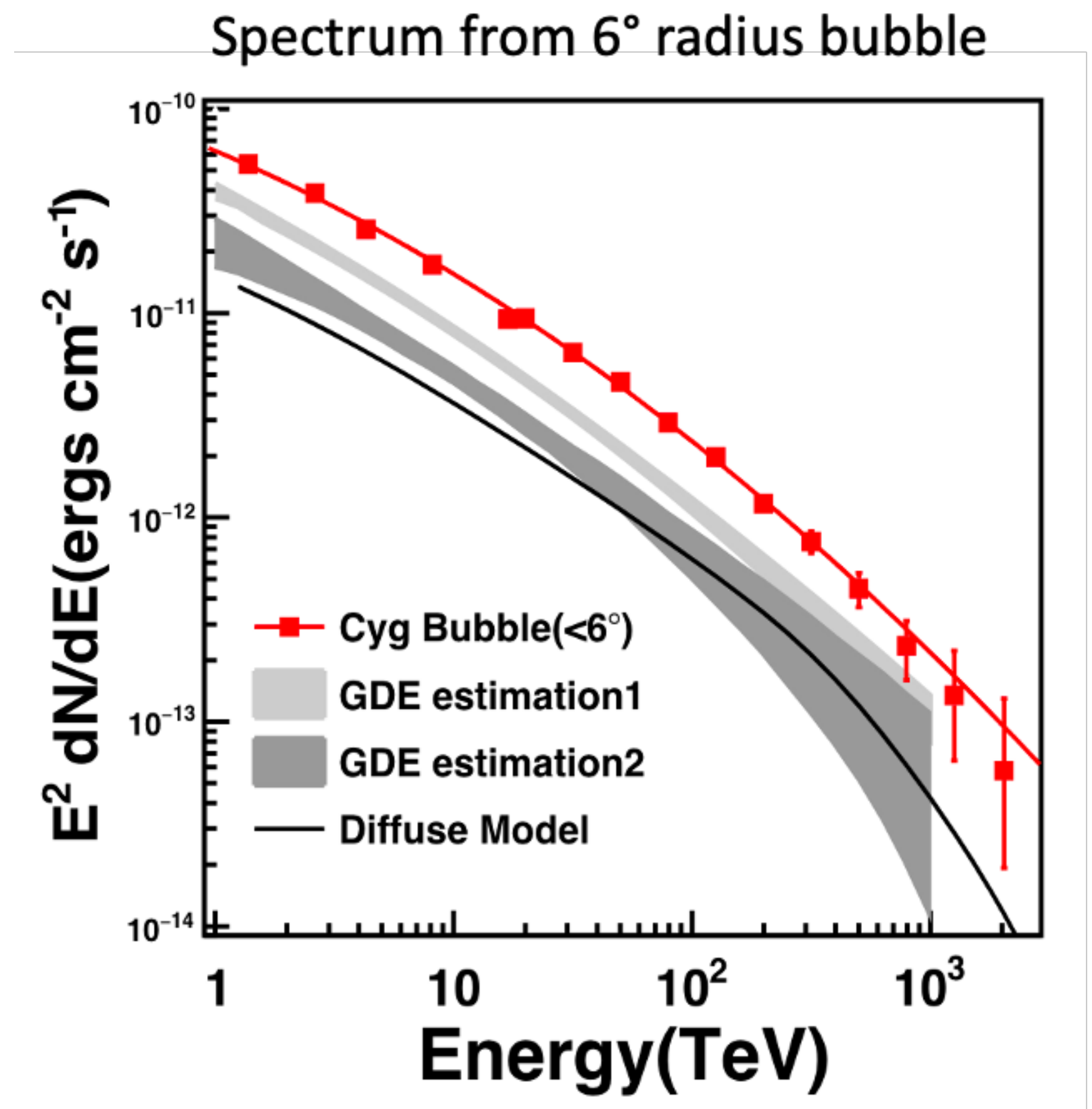
radial profile



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

Ultra high energy gamma rays from massive stellar clusters



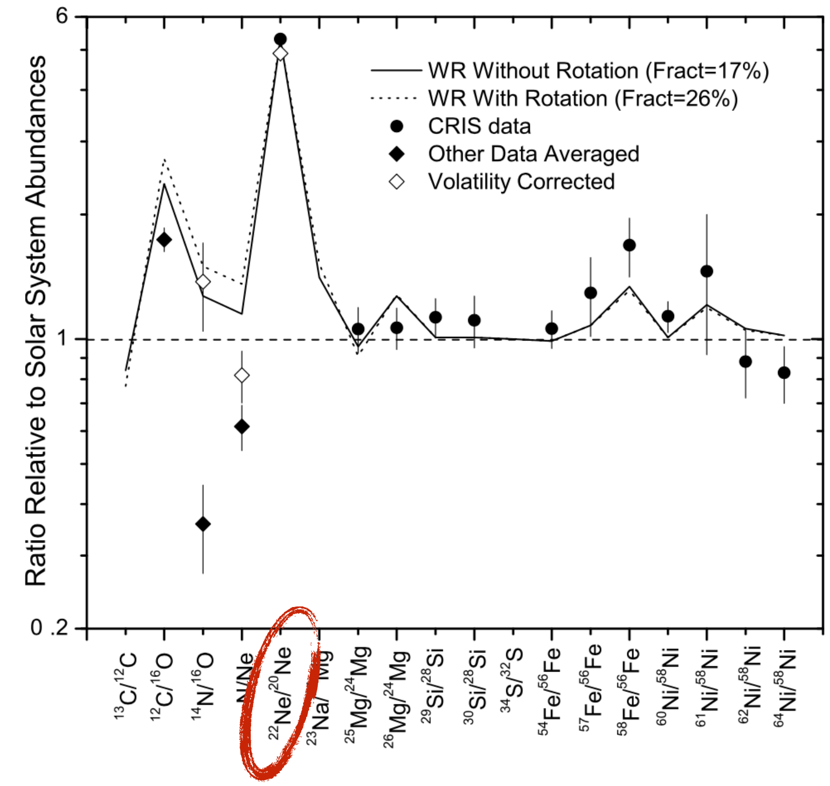


Z. Cao et al. [LHAASO Coll.], arXiv:2310.10100

Particle acceleration in wind-blown bubbles?

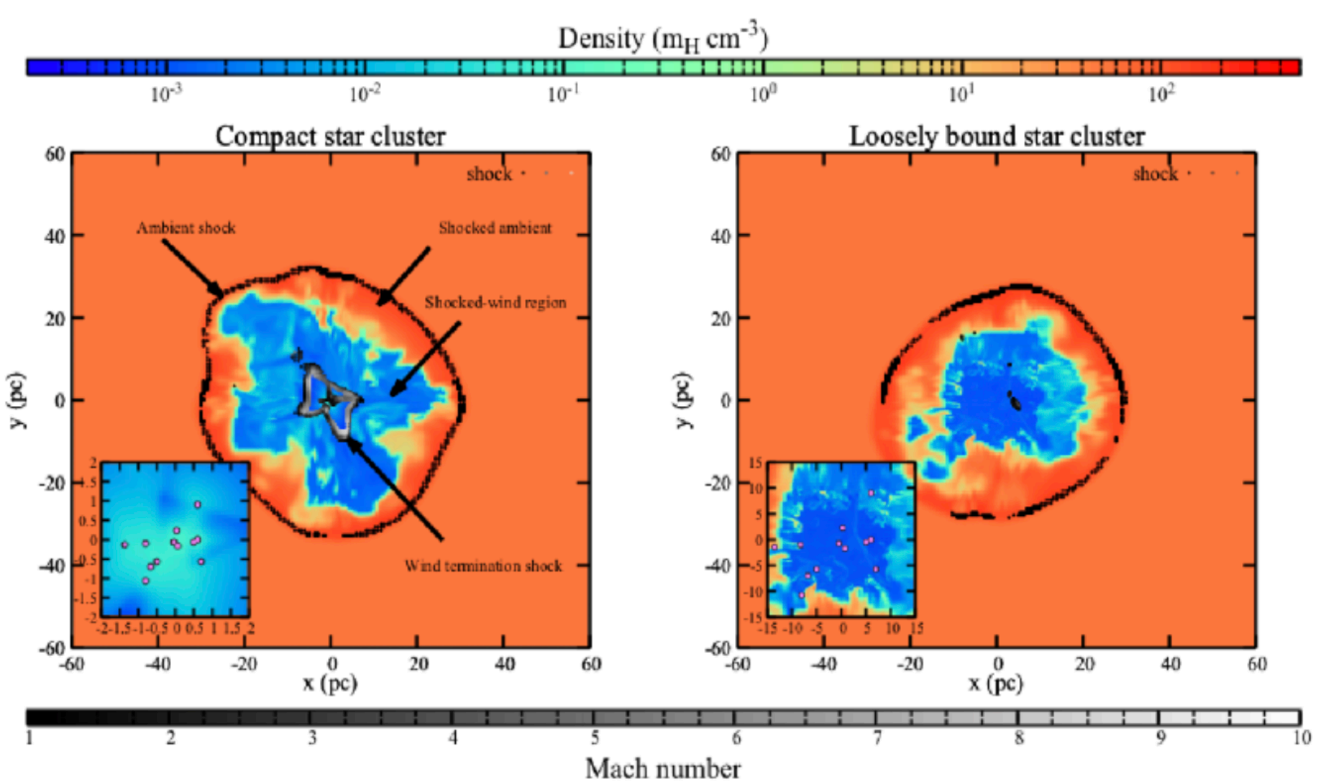
- Anomalous CR composition can't be easily accommodated in the SNR scenario for the origin of GCRs

- In particular, the **^{22}Ne/^{20}Ne** appears 5 times larger in CRs than in solar wind
  ⟶ Heavy ejecta required



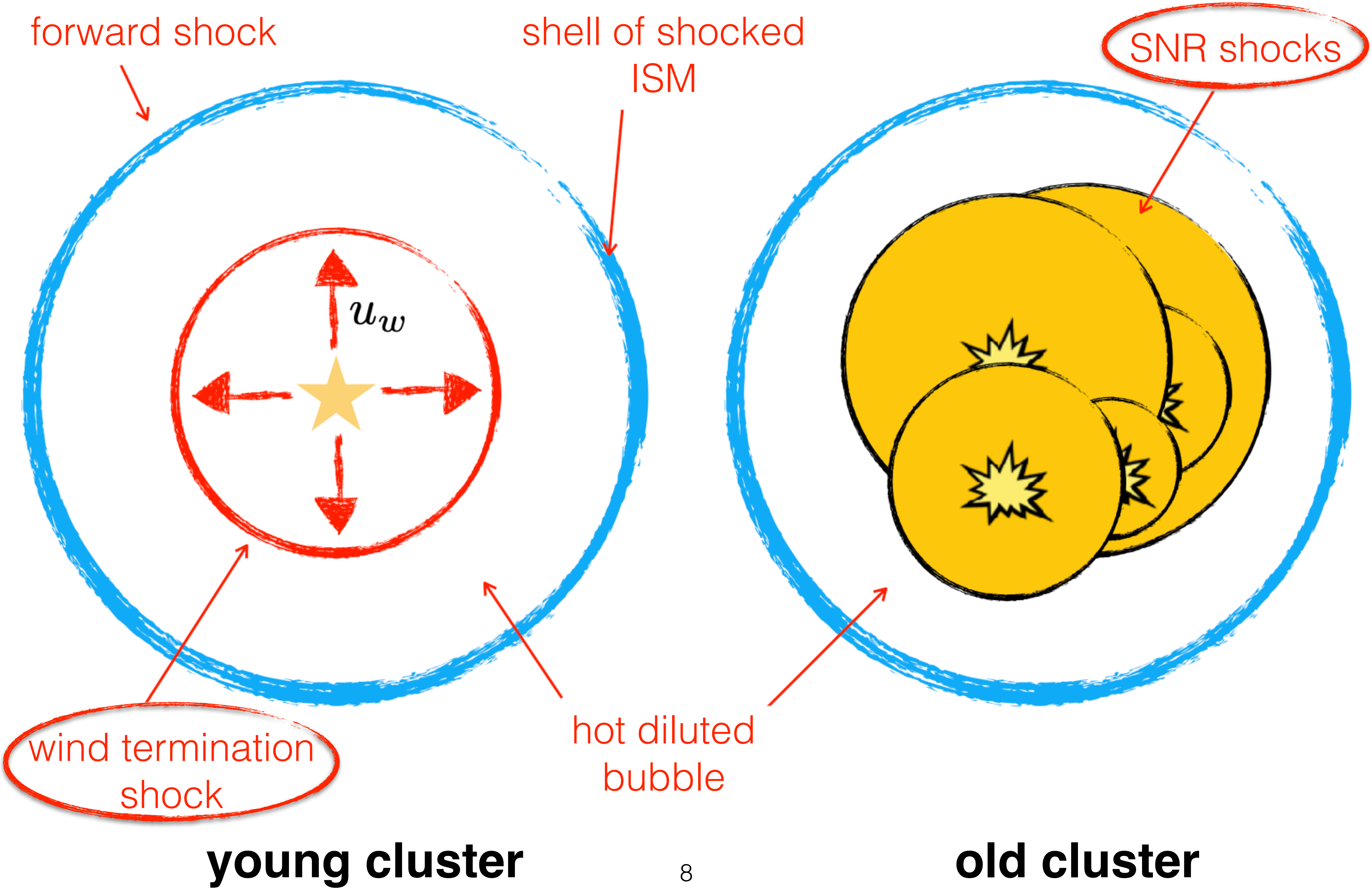
Cassè & Paul, ApJ 258 (1982) 860

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



- Compact clusters can blow **strong WTSs**, where **CR acceleration** can occur with an efficiency of few % of the wind mechanical power;

Stellar winds vs SNRs



Stellar winds vs SNRs: energetics

- **Energy injected by SNe:** $E_{\rm SNe} = 10^{51}\,{\rm erg} \int_{8\,M_\odot}^{M_{\rm max}} \xi(M) dM$

- **Energy injected by winds:** $E_{\rm wind} = \int_{M_{\rm min}}^{M_{\rm max}} \frac{1}{2} \dot{M}_s(M) v_{\rm w,s}^2(M) \tau_{\rm s}(M) \xi(M) dM$

$$\dot{M}_{\rm s}(M) \simeq 9.63 \times 10^{-15} \left(\frac{L_{\rm s}(M)}{L_\odot}\right)^{1.42} \left(\frac{M}{M_\odot}\right)^{0.16} \left(\frac{R_{\rm s}(M)}{R_\odot}\right)^{0.81} \frac{{\rm M}_\odot}{\rm yr}$$

Nieuwenhuijzen & de Jager, A&A 231 (1990) 134

$$R_{\rm s}(M) = 0.85 R_\odot (M/M_\odot)^{0.67}$$

Demircan & Kahraman, Ap&SS 181 (1991) 313

$$v_{\rm w,s}(M) = C(T_{\rm eff}) \sqrt{2 G_{\rm N} \frac{M}{R_{\rm s}(M)} \left(1 - \frac{L_{\rm s}(M)}{L_{\rm edd}(M)}\right)}$$

$$C(T_{\rm eff}) = \begin{cases} 1.0 & T_{\rm eff}/{\rm K} < 10^4 \\ 1.4 & 10^4 \le T_{\rm eff}/{\rm K} < 2.1 \times 10^4 \\ 2.65 & T_{\rm eff}/{\rm K} \ge 2.1 \times 10^4 \,. \end{cases}$$

Kudritzki & Pulz, ARA&A 38 (2000) 613

$$L_{\rm s}(M) = \begin{cases} L_{b1} \left(\frac{M}{M_{b1}}\right)^{\gamma_1} \left[\frac{1}{2} + \frac{1}{2}\left(\frac{M}{M_{b1}}\right)^{1/\Delta_1}\right]^{\Delta_1(-\gamma_1+\gamma_2)} & M/M_\odot < 12 \\ \epsilon L_{b2} \left(\frac{M}{M_{b2}}\right)^{\gamma_2} \left[\frac{1}{2} + \frac{1}{2}\left(\frac{M}{M_{b2}}\right)^{1/\Delta_2}\right]^{\Delta_2(-\gamma_2+\gamma_3)} & M/M_\odot \ge 12 \end{cases}$$

where $L_{b1} = 3191\,L_\odot$, $L_{b2} = 368874\,L_\odot$, $M_{b1} = 7 M_\odot$, $M_{b2} = 36.089 M_\odot$, $\gamma_1 = 3.97$, $\gamma_2 = 2.86$, $\gamma_3 = 1.34$, $\Delta_1 = 0.01$, $\Delta_2 = 0.15$, and $\epsilon = 0.817$

Menchiari, PhD thesis (2023)

$$\longrightarrow \frac{E^*_{\rm wind}}{E_{\rm SNe}} \simeq 0.5$$

*neglecting WR contribution

What do we need to describe the star cluster gamma-ray emission?

Stellar wind physics

Stellar population inside star clusters

Cluster dynamics:
- → the wind-blown bubble
- → SNR shock evolution
- → HD & MHD turbulence

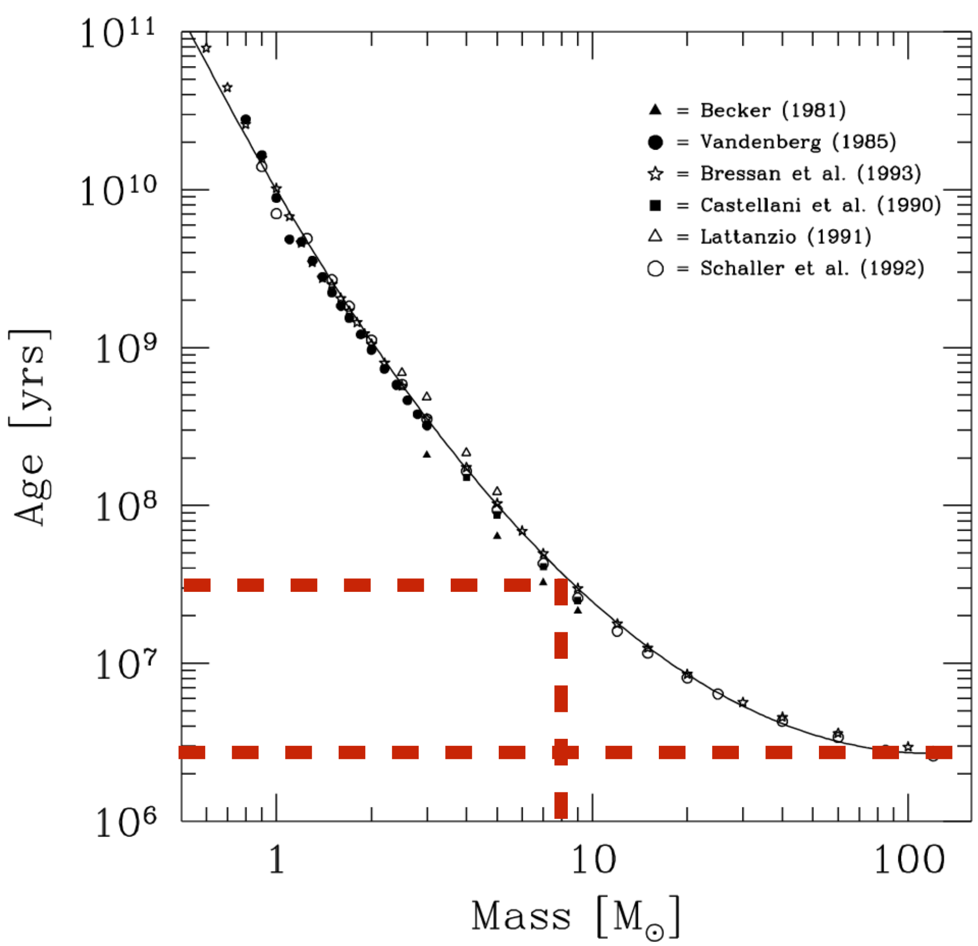
Target gas distribution:
- → wind ejecta + shell
- → uniform? clumpy?

Particle acceleration model:
- → Wind Termination Shock (WTS)
- → SNR Shocks
- → Wind-wind collisions
- → Turbulent Acceleration

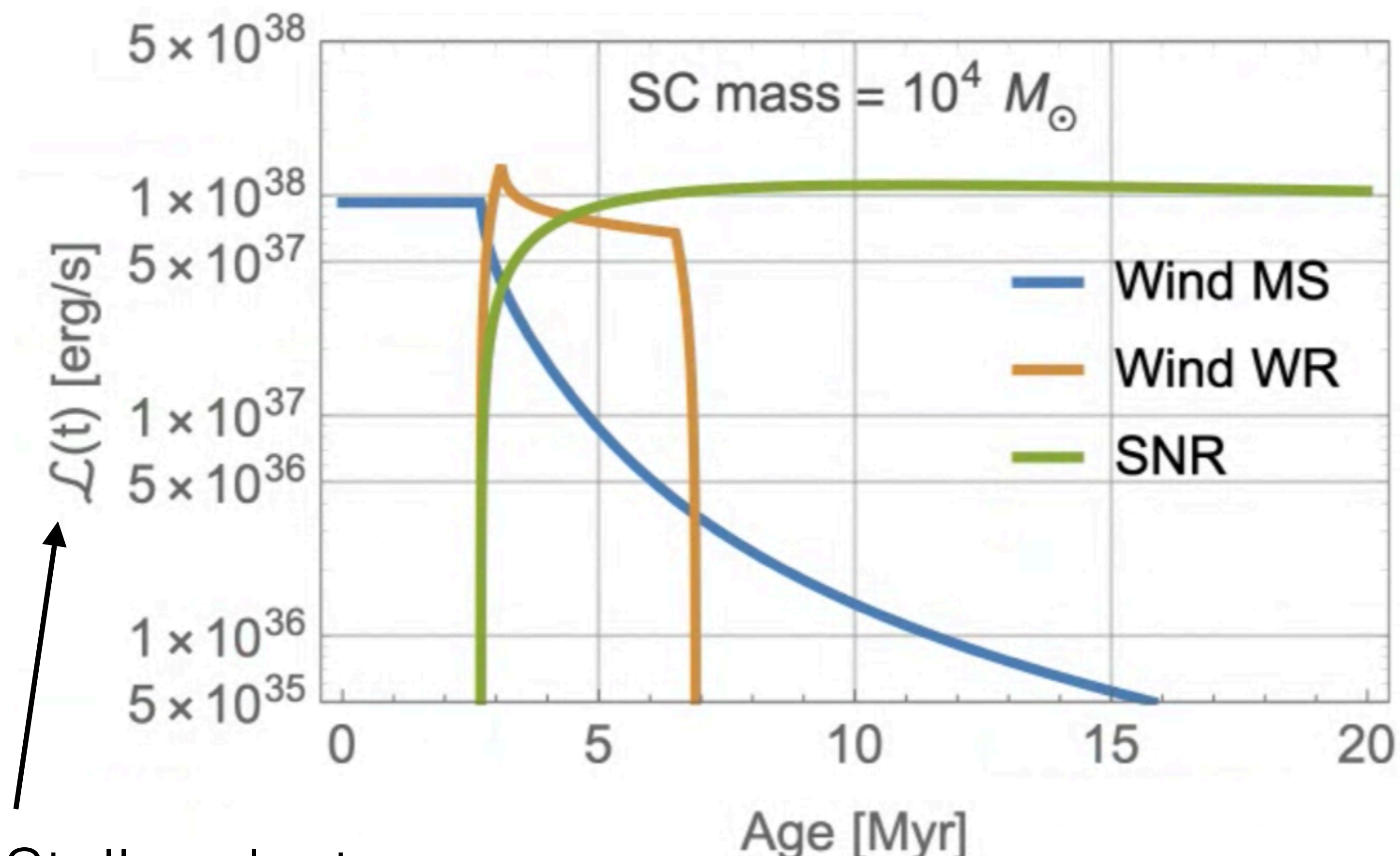
What powers stellar clusters?

Different sources of power:

Phase	Source	Single episode	Model
$t \lesssim 3\,\mathrm{Myr}$	MS stellar winds	$t \gtrsim \mathrm{Myr}$	quasi-stationary
$3\,\mathrm{Myr} \lesssim t \lesssim 7\,\mathrm{Myr}$	WR stellar winds	$t \sim 10^5\,\mathrm{yr}$	semi-stationary
$3\,\mathrm{Myr} \lesssim t \lesssim 30\,\mathrm{Myr}$	SNe	$t \sim 10^3 - 10^4\,\mathrm{yr}$	impulsive

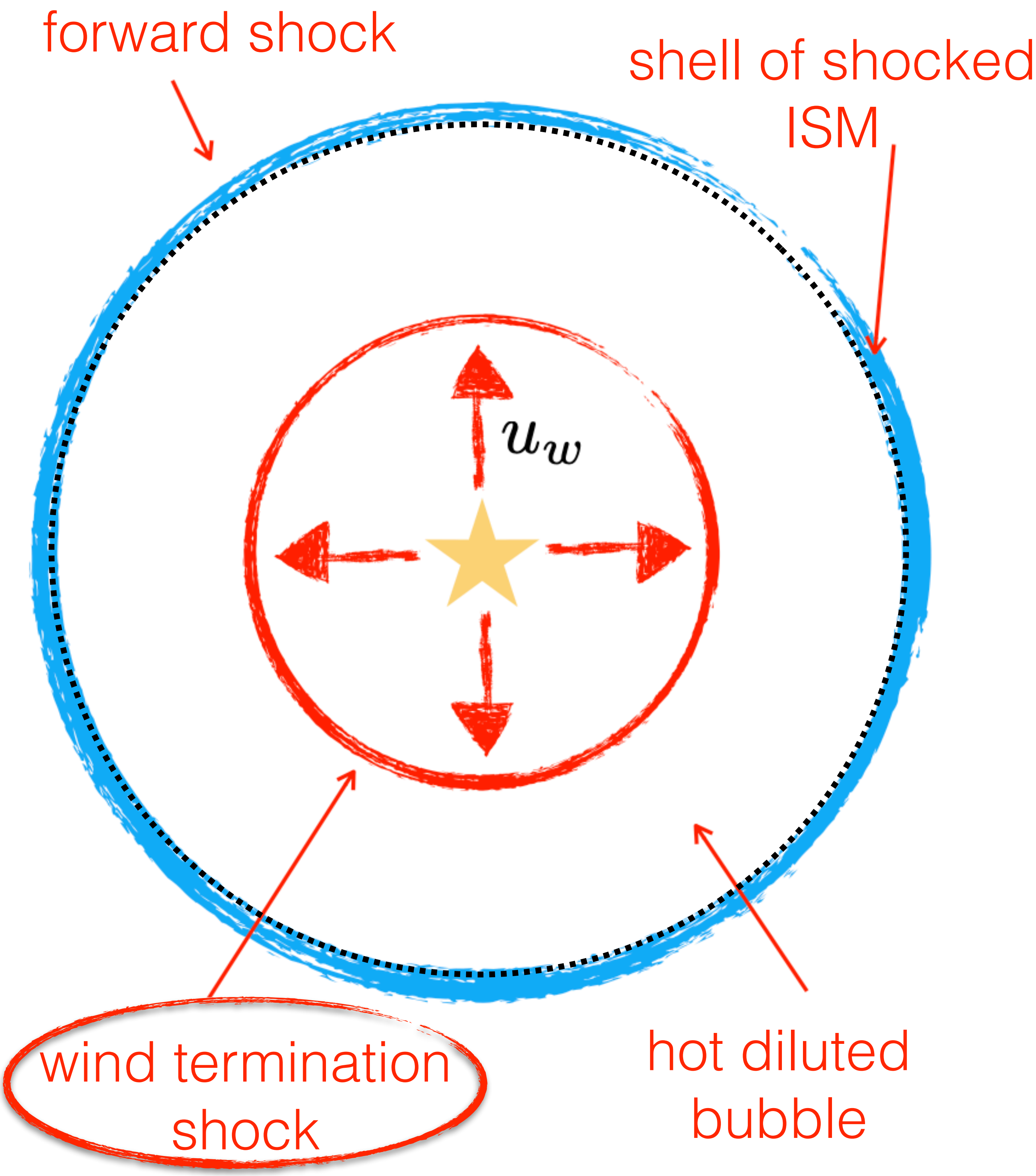


Buzzoni, ApJ 123 (2002) 1188



Stellar cluster luminosity

The geometry of YSCs



T_{age} < 3 Myr: only stellar winds

Constant injection of energy in spherical symmetry:

- **Stellar Cluster core:**

~ few pc radius

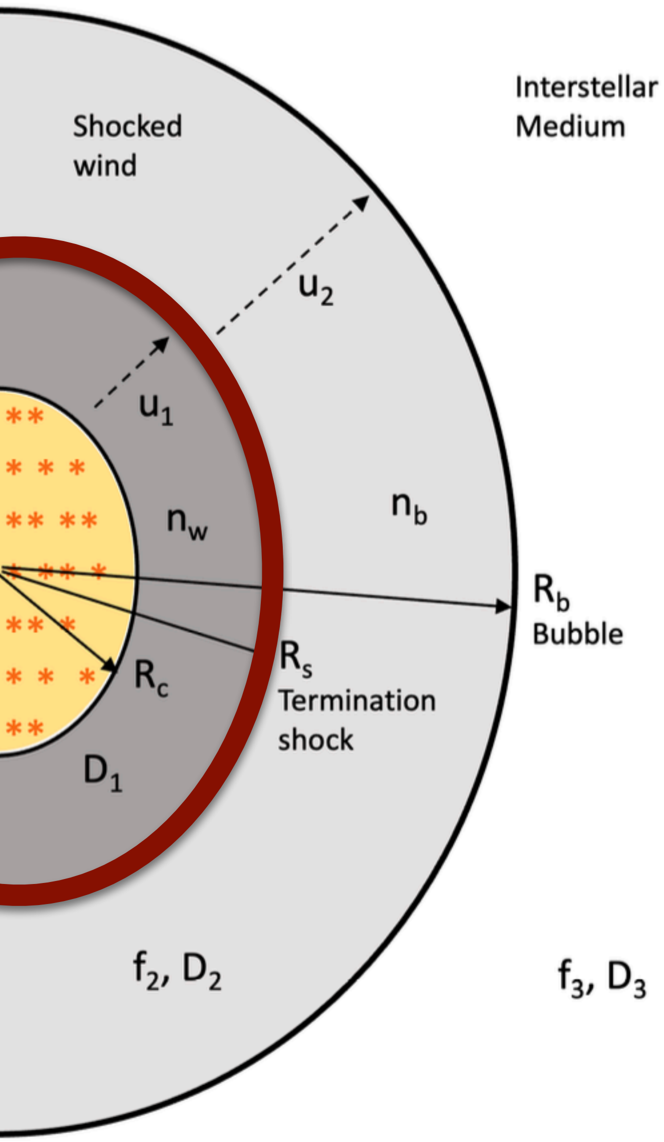
- **Collective Wind Termination Shock (WTS):**

$$R_s(t) = 48.6 \left(\frac{n}{\mathrm{cm}^{-3}}\right)^{-0.3} \left(\frac{\dot{M}_c}{10^{-4} M_\odot \mathrm{yr}^{-1}}\right)^{0.3} \left(\frac{v_{w,c}}{1000\,\mathrm{km\,s}^{-1}}\right)^{0.1} \left(\frac{t}{10\,\mathrm{Myr}}\right)^{0.4} \mathrm{pc}$$

- **Bubble:**

$$R_b(t) = 174 \left(\frac{n}{\mathrm{cm}^{-3}}\right)^{-0.2} \left(\frac{L_{w,c}}{10^{37}\,\mathrm{erg\,s}^{-1}}\right)^{0.2} \left(\frac{t}{10\,\mathrm{Myr}}\right)^{0.6} \mathrm{pc}$$

Particle acceleration @ WTS of YSCs



Time-stationary transport equation in spherical geometry:

$$\frac{\partial}{\partial r}\left[r^2 D(r,p)\frac{\partial f}{\partial r}\right] - r^2 u(r)\frac{\partial f}{\partial r} + \frac{d\left[r^2 u\right]}{dr}\frac{p}{3}\frac{\partial f}{\partial p} + r^2 Q(r,p) = 0$$

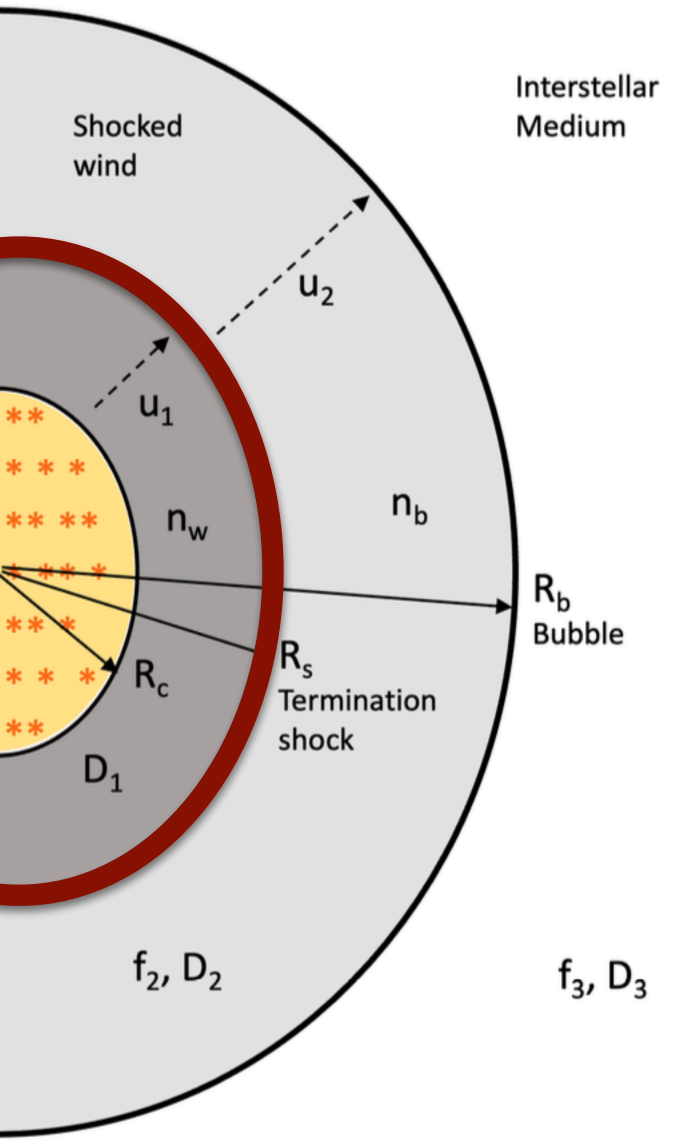
- Arbitrary diffusion coefficient D(r,p)
- Injection only at the termination shock $Q(r,p) \propto \delta(p - p_{\rm inj})\,\delta(r - R_s)$
- Wind velocity profile: $u(r) = \begin{cases} u_1 = v_w & \text{for } r < R_s\,, \\ \frac{u_1}{\sigma}\left(\frac{R_s}{r}\right)^2 & \text{for } R_s < r < R_b\,, \\ 0 & \text{for } r > R_b\,; \end{cases}$

Boundary conditions:

1. No net flux at the cluster center: $r^2[D\partial_r f - uf]_{r=R_c} = 0$
2. Matching the Galactic distribution: $f(r \to \infty, p) = f_{\rm gal}(p)$

“Reversed” geometry wrt supernova remnants

Particle acceleration @ WTS of YSCs



Acceleration at the collective WTS is calculated under the following assumptions:

- **CR acceleration efficiency** is a few % of the wind kinetic luminosity:

  $$L_{cr} = \epsilon_{cr} L_w,$$

- **Magnetic turbulence** is produced by wind non-stationarity and inhomogeneities

  $$4\pi r^2 v_w \frac{\delta B_w^2}{4\pi} = \eta_B \frac{1}{2} \dot{M} v_w^2$$

  —> few % of wind kinetic energy converted into magnetic energy;

- **Diffusion coefficient** depends on the turbulence inside the bubble **(unknown)**: most likely, it is generated by wind itself (MHD instabilities, flow non stationarity) as

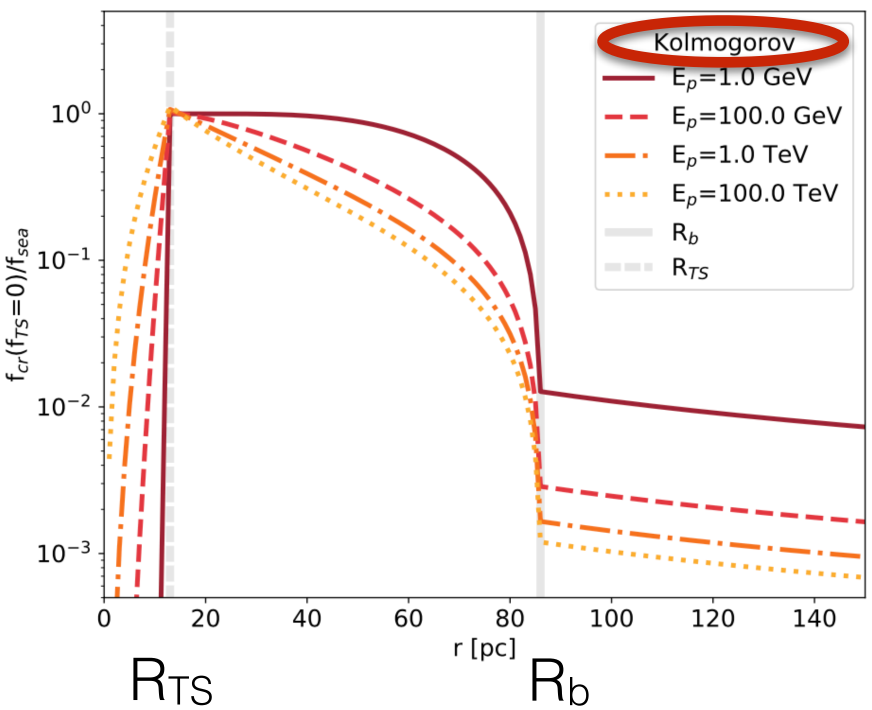
$$\begin{cases} D_{\rm Kol}(E) = \frac{v}{3} r_L (\delta B)^{1/3} L_c^{2/3} \\ D_{\rm Kra}(E) = \frac{v}{3} r_L (\delta B)^{1/2} L_c^{1/2} \\ D_{\rm Bohm}(E) = \frac{v}{3} r_L (\delta B) \end{cases}$$

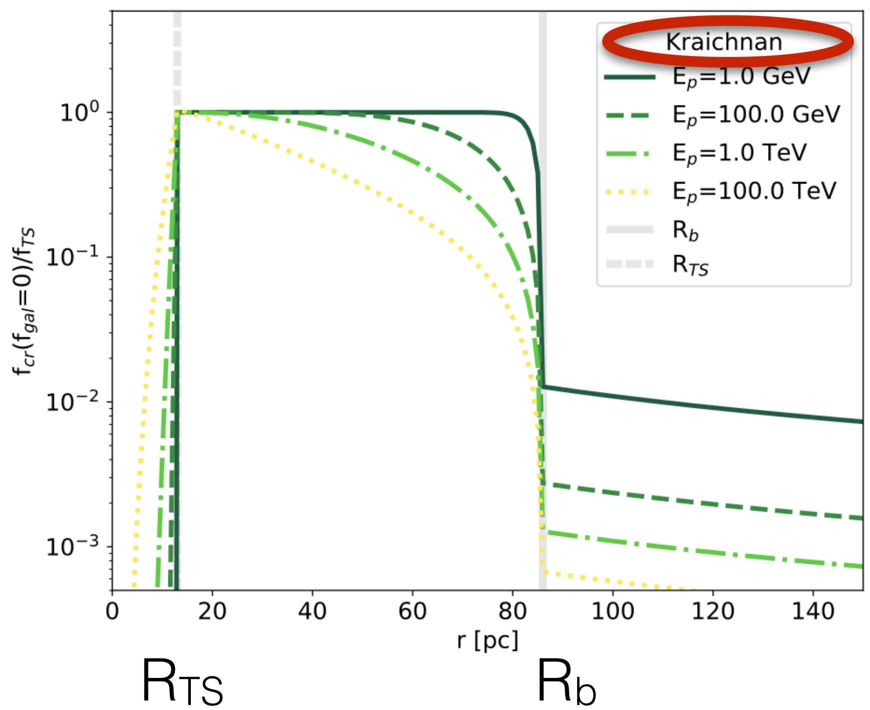
The injection scale of the turbulence L_c is assumed to be of the order of the cluster core size

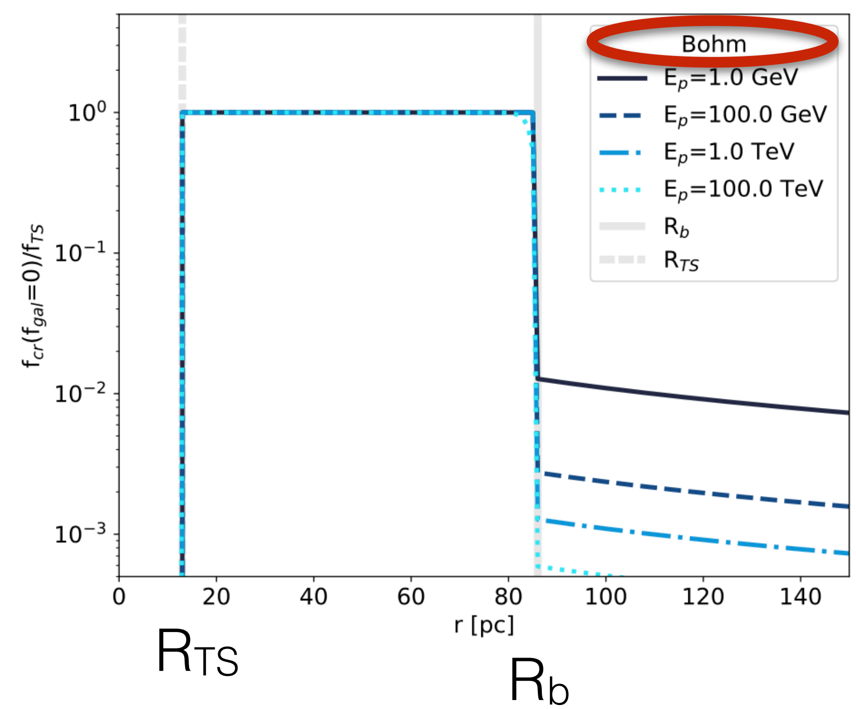
Morlino et al., MNRAS 504 (2021) 4

Diffusion effects on particle transport

The **diffusion coefficient** determines both transport (i.e. CR spatial profile) and E_{max}:







decreasing profile at $r>R_{TS}$

flat profile below 10 GeV at $R_{TS}<r<R_b$: high-energy particle transport is diffusion driven

flat profile at $R_{TS}<r<R_b$: advection dominates over diffusion

Menchiari et al., arXiv:2402.07784

Possible origin of the turbulence

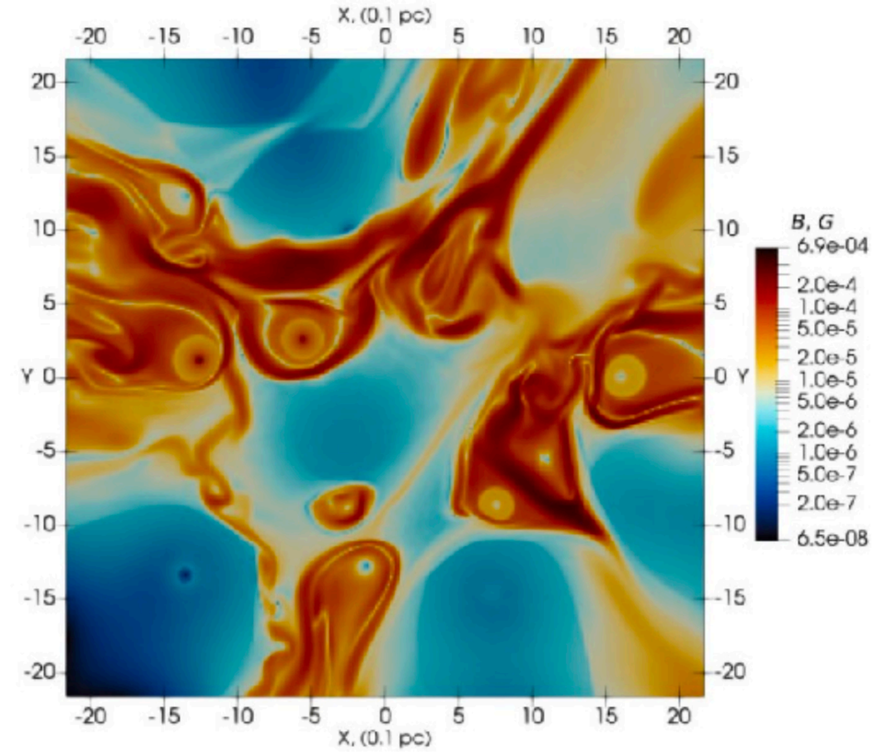
- **Magnetic turbulence**
  is produced by wind non-stationarity and inhomogeneities, possible efficiency conversion of few % of wind kinetic energy.

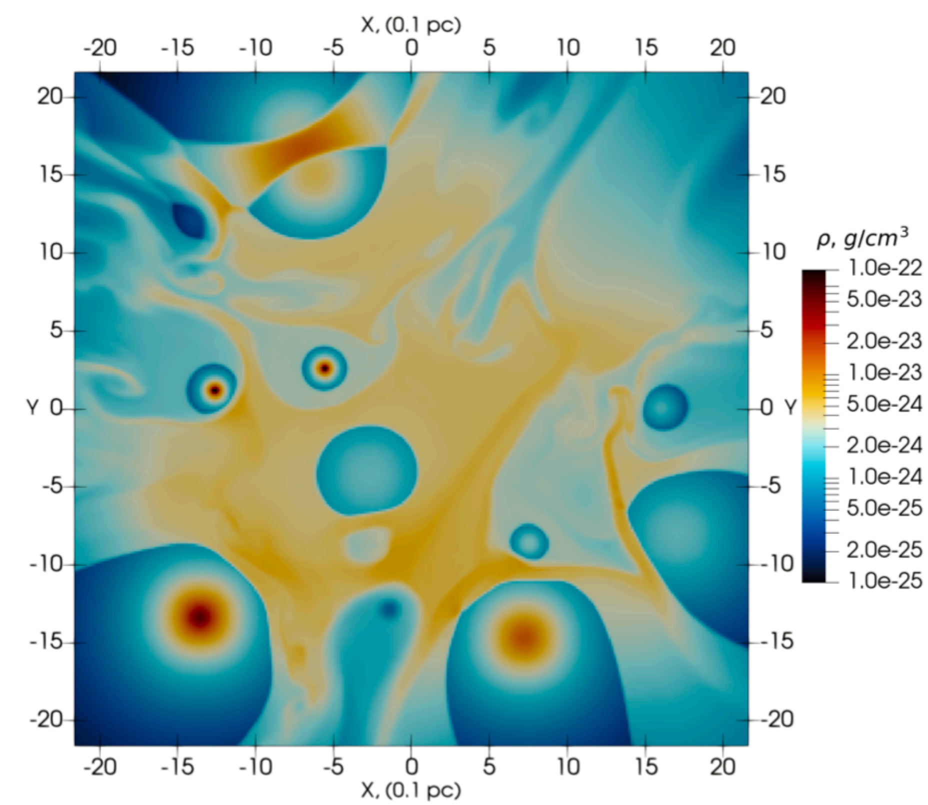
- **MHD amplification**:
  - Wind-wind interaction results into MHD turbulence (inside the SC core, ~100 μG may be achieved);
  - Wind clumpiness might trigger shear instability;
  - Assuming that a fraction η_B of kinetic energy is converted into magnetic field at the WTS

$$\delta B(R_s) \simeq 4\,\mu G \left(\frac{\eta_B}{0.05}\right)^{\frac{1}{2}} \left(\frac{\dot{M}}{10^{-4} M_\odot/\mathrm{yr}}\right)^{\frac{3}{10}} \left(\frac{v_w}{2500\,\mathrm{km/s}}\right)^{\frac{1}{10}}$$

- **CR self-amplification** (may be relevant at low energies): in the linear regime

$$\mathcal{F}_0(k) = \frac{\pi}{2}\frac{\xi_{\rm CR}}{\Lambda_p}\frac{v_{\rm sh}}{v_A} = \frac{\pi}{2}\frac{\xi_{\rm CR}}{\Lambda_p}\eta_b^{-1/2} \simeq 0.06\,\frac{\xi_{\rm CR}}{0.1}\left(\frac{\eta_B}{0.05}\right)^{-1/2}$$





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

Diffusion effects on E_{max}

The maximum particle energy results from the combination of three effects:

- upstream confinement time;
- downstream confinement time;
- effective jump condition at the shock.

E.g., the upstream condition in Kolmogorov turbulence reads as:

$$E_{\rm max}^{\rm Kol} \simeq 1.2 \left(\frac{\eta_{\rm B}}{0.1}\right)^{1/2} \left(\frac{\dot{M}}{10^{-4} {\rm M_\odot yr^{-1}}}\right)^{-3/4} \left(\frac{L_{\rm w}}{10^{39}\ {\rm erg\ s^{-1}}}\right)^{37/20} \left(\frac{\rho_0}{20\ m_p\ {\rm cm^{-3}}}\right)^{-3/5} \left(\frac{t_{\rm age}}{3\ {\rm Myr}}\right)^{4/5} \left(\frac{L_c}{2\ {\rm pc}}\right)^{-2} {\rm PeV}\,;$$

while in Kraichnan it is

$$E_{\rm max}^{\rm Kra} \simeq 2.84 \left(\frac{\eta_{\rm B}}{0.1}\right)^{1/2} \left(\frac{\dot{M}}{10^{-4} {\rm M_\odot yr^{-1}}}\right)^{-5/10} \left(\frac{L_{\rm w}}{10^{39}\ {\rm erg\ s^{-1}}}\right)^{13/10} \left(\frac{\rho_0}{20\, m_p\ {\rm cm^{-3}}}\right)^{-3/10} \left(\frac{t_{\rm age}}{3\ {\rm Myr}}\right)^{2/5} \left(\frac{L_c}{2\ {\rm pc}}\right)^{-1} {\rm PeV}\,;$$

and finally for Bohm

$$E_{\rm max}^{\rm Bohm} \simeq 10 \left(\frac{\eta_{\rm B}}{0.1}\right)^{1/2} \left(\frac{\dot{M}}{10^{-4} {\rm M_\odot yr^{-1}}}\right)^{-1/4} \left(\frac{L_{\rm w}}{10^{39}\ {\rm erg\ s^{-1}}}\right)^{3/4} {\rm PeV}$$

Menchiari et al., arXiv:2402.07784

WTS particle acceleration: spectrum & E_{max}

$$f_s(p) = s\frac{\eta_{inj}\, n_1}{4\pi\, p_{inj}^3}\left(\frac{p}{p_{inj}}\right)^{-s} e^{-\Gamma_1(p)}\; e^{-\Gamma_2(p)}$$

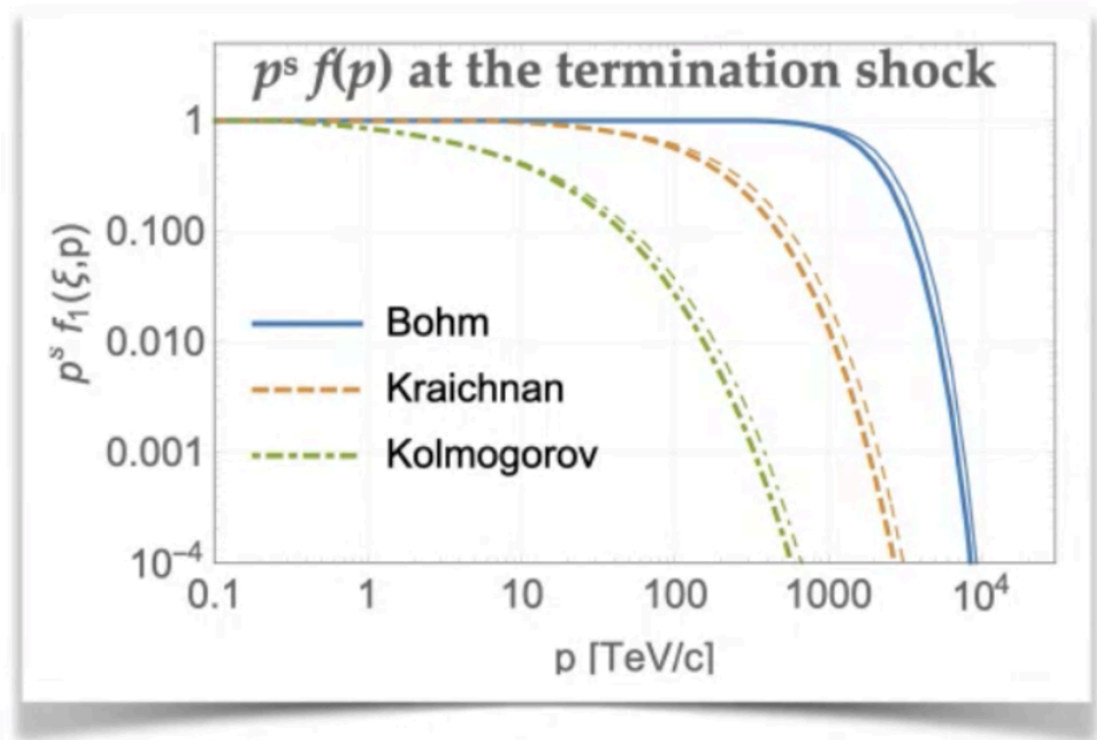
Standard power-law for plane shocks

$$s = \frac{3\sigma}{\sigma - 1}$$

Cutoff due to particle confinement upstream in a spherical geometry

Cutoff due to particle escaping from the bubble

Morlino et al., MNRAS 504 (2021) 4



Hillas criterion

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

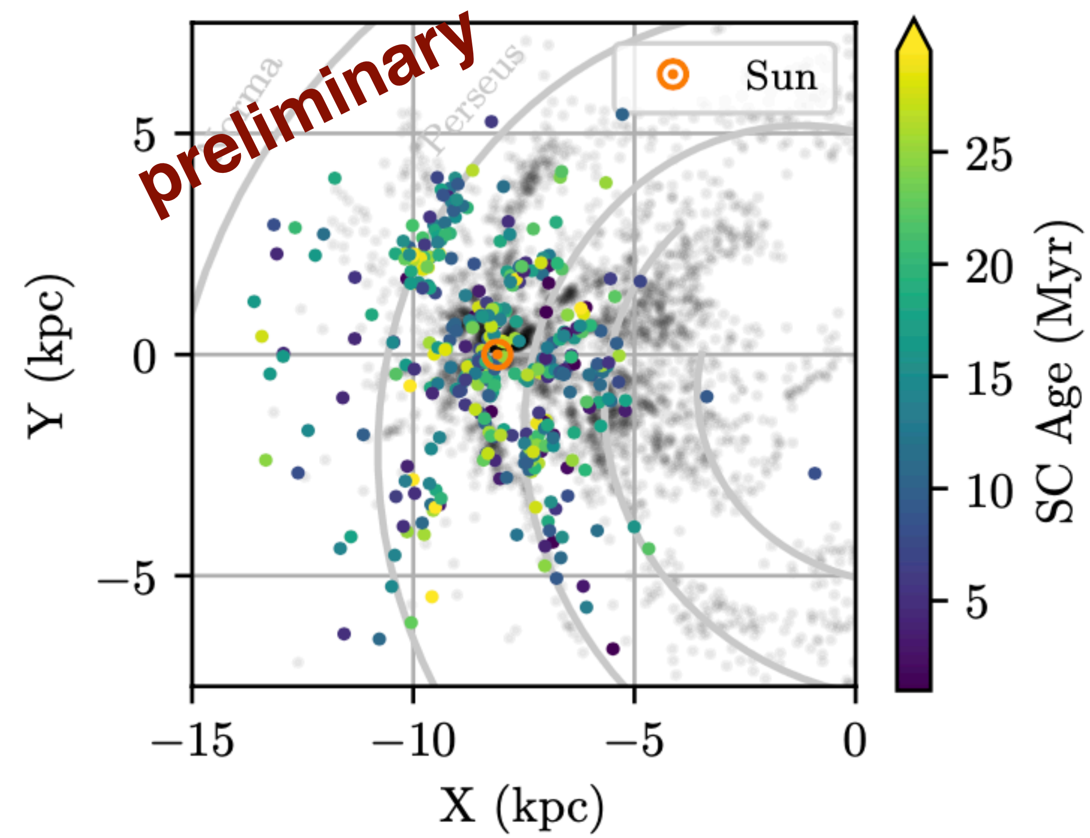
	dM/dt M_{sol}/yr	u_{sh} km/s	R_{sh} pc	B μG	age yr	lim E_{max}	E_{max} TeV
Isolated SNR	—	> 5000	< 1	~100 self-amplification	~10^3	time limited	~100-1000
WTS (massive cluster)	10^{-4}	< 3000	> 10	> 10 MHD turbulence	~10^6	space limited	~> 1000

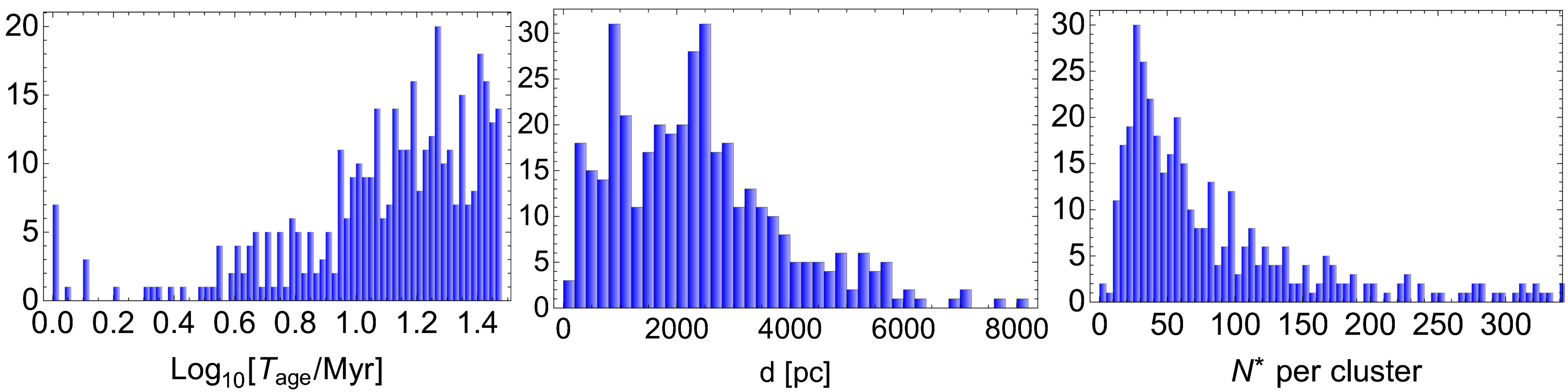
Vieu & Reville, MNRAS 519 (2023) 136V

The Gaia DR2 cluster sample

- 2017 **open clusters** detected on Galactic Plane with precise astrometry (3D positions available) and optical photometry;
- 390 of these are younger than **30 Myr;**
- For Cygnus OB2, see dedicated work by

Menchiari et al., arXiv:2402.07784





Cantat-Gaudin et al. [GAIA Coll.], A&A 640 (2020) A1

Mass and wind luminosity of YSCs

Cluster wind luminosities are not provided in catalogs. We hence developed a method aiming to characterize the stellar content of each cluster, as to reproduce the observed number of stars per cluster:

- by assuming a **stellar Mass Function** (MF):

$$\xi(M) = k \times \begin{cases} \left(\frac{M}{M_{\min}}\right)^{-\beta_1} & M_H \leq M < M_0 \\ \left(\frac{M_0}{M_H}\right)^{-\beta_1} \left(\frac{M}{M_0}\right)^{-\beta_2} & M_0 \leq M < M_1 \\ \left(\frac{M_0}{M_H}\right)^{-\beta_1} \left(\frac{M_1}{M_0}\right)^{-\beta_2} \left(\frac{M}{M_1}\right)^{-\beta_3} & M_1 \leq M < M_{\max} \end{cases}$$

with $\beta_1 = 1.30$, $\beta_2 = 2.30$, $\beta_3 = 2.35$, $M_{\min} = 0.08\, M_\odot$, $M_0 = 0.50\, M_\odot$, and $M_1 = 1.00\, M_\odot$

Weidner & Kroupa, MNARS 384 (2004) 187

- we derive the intrinsic luminosity of each star thanks to its magnitude and optical extinction from cluster direction;

$$\mathcal{M}_{\rm bol} = \mathcal{M}_G + BC_G \longrightarrow L_s = L_\odot 10^{0.4(\mathcal{M}_{\odot,\rm bol} - \mathcal{M}_{\rm bol} + A_G)}$$

- the absolute luminosity of stars is then converted into mass through L(M) of MS stars;

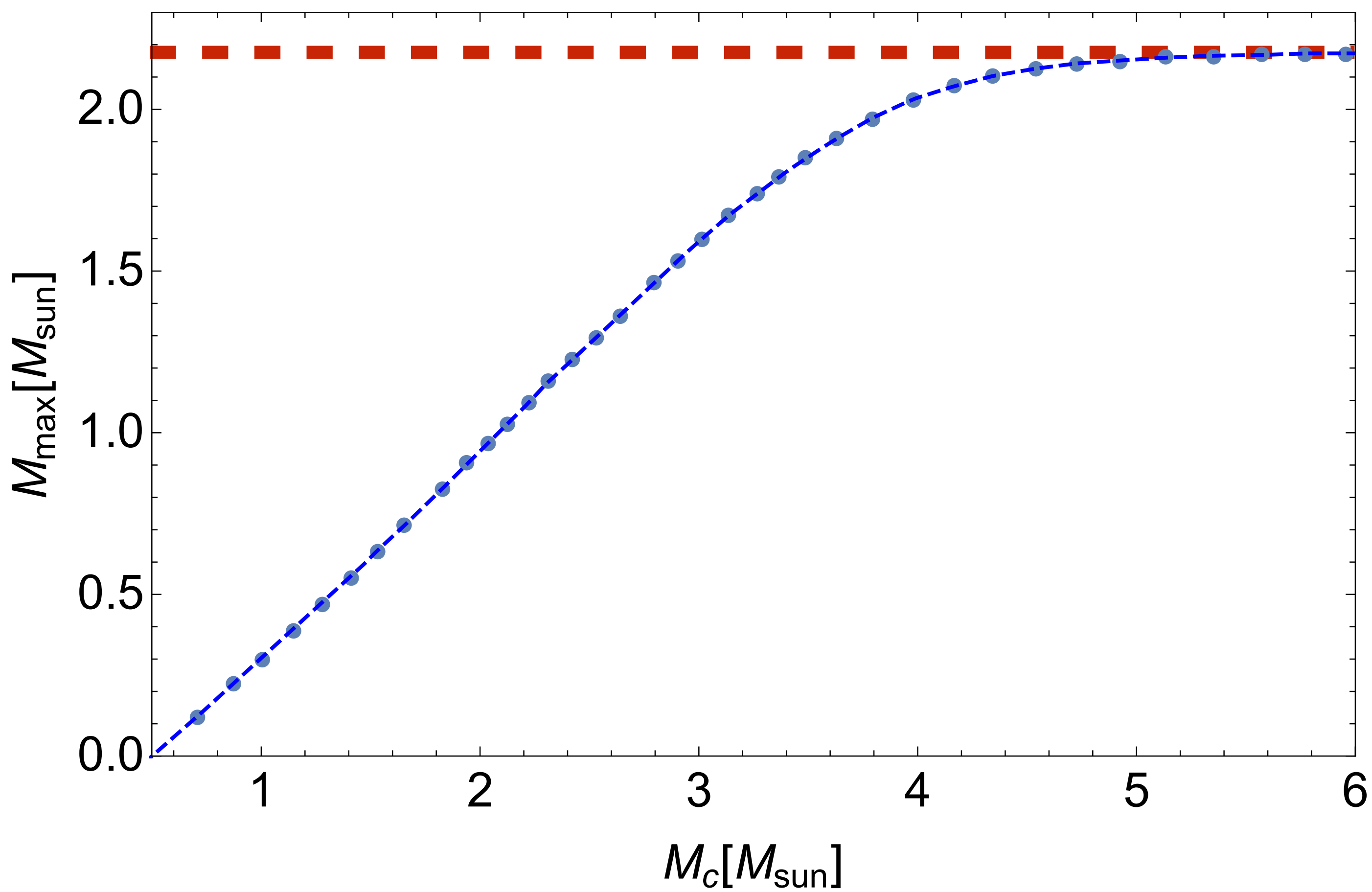
- finally the magnitude distribution of all stars in cluster is used to infer the stellar mass range of observations ⟶ k.

On the maximum stellar mass per cluster

To avoid observational biases, we extended the expected mass range of stars populating the cluster, down to mass of 0.08 M_{sun} and up to a maximum given by:

- cluster age T_{age} ⟶ M_{max} by stellar evolution (SN explosions);
- parent cluster mass M_c ⟶ $M_{max,0}$ at cluster formation.

$$M_{max}=\min[M_{max,0}(M_c),M_{max}(T_{age})]$$

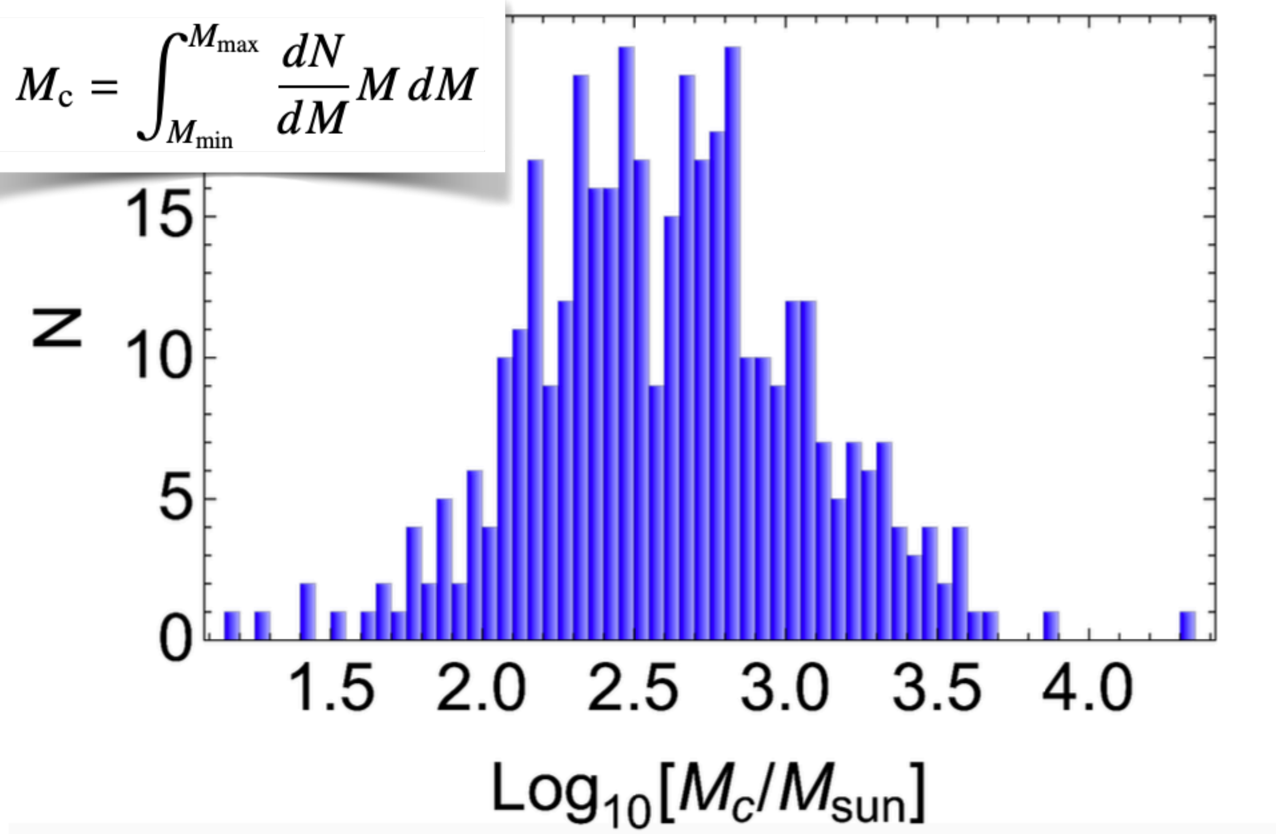


Iterative algorithm implemented as to account for $M_{max,0}(M_c)$.

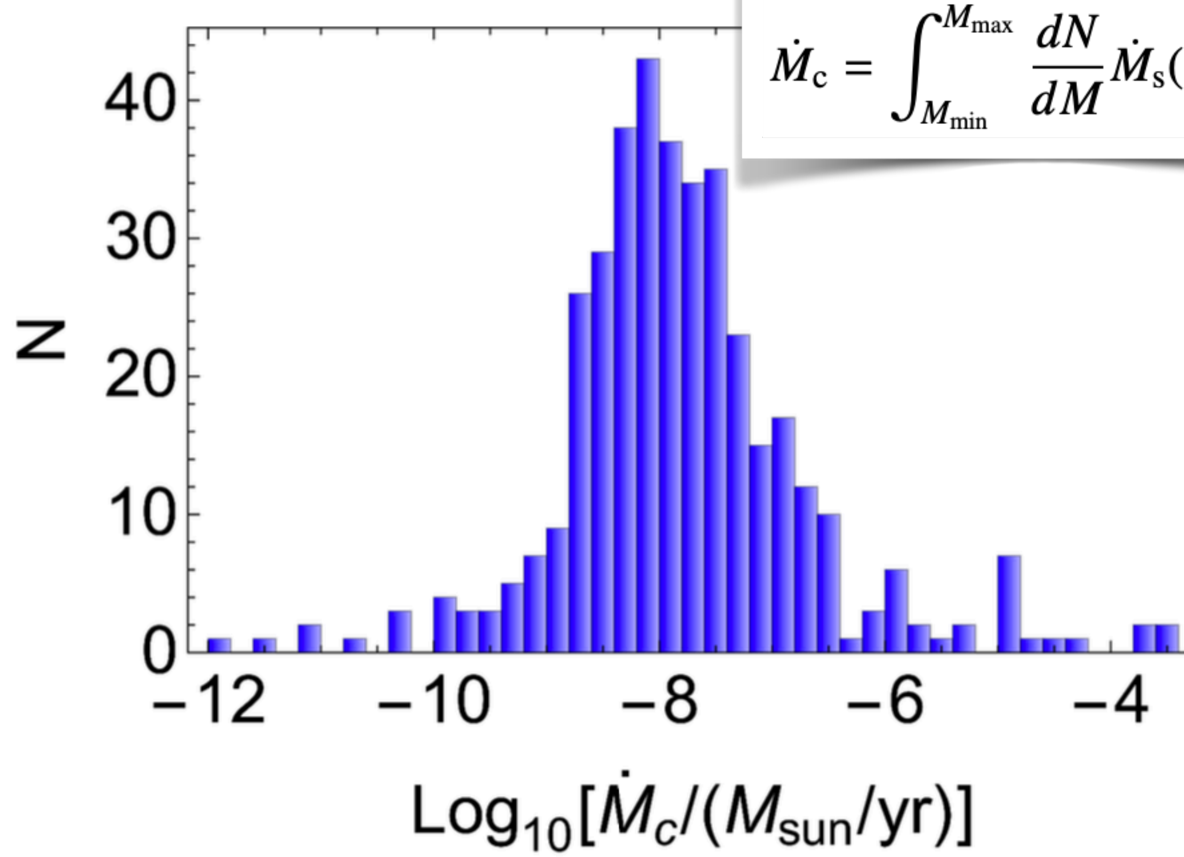
Weidner & Kroupa, MNARS 384 (2004) 187

Mass and wind luminosity of YSCs

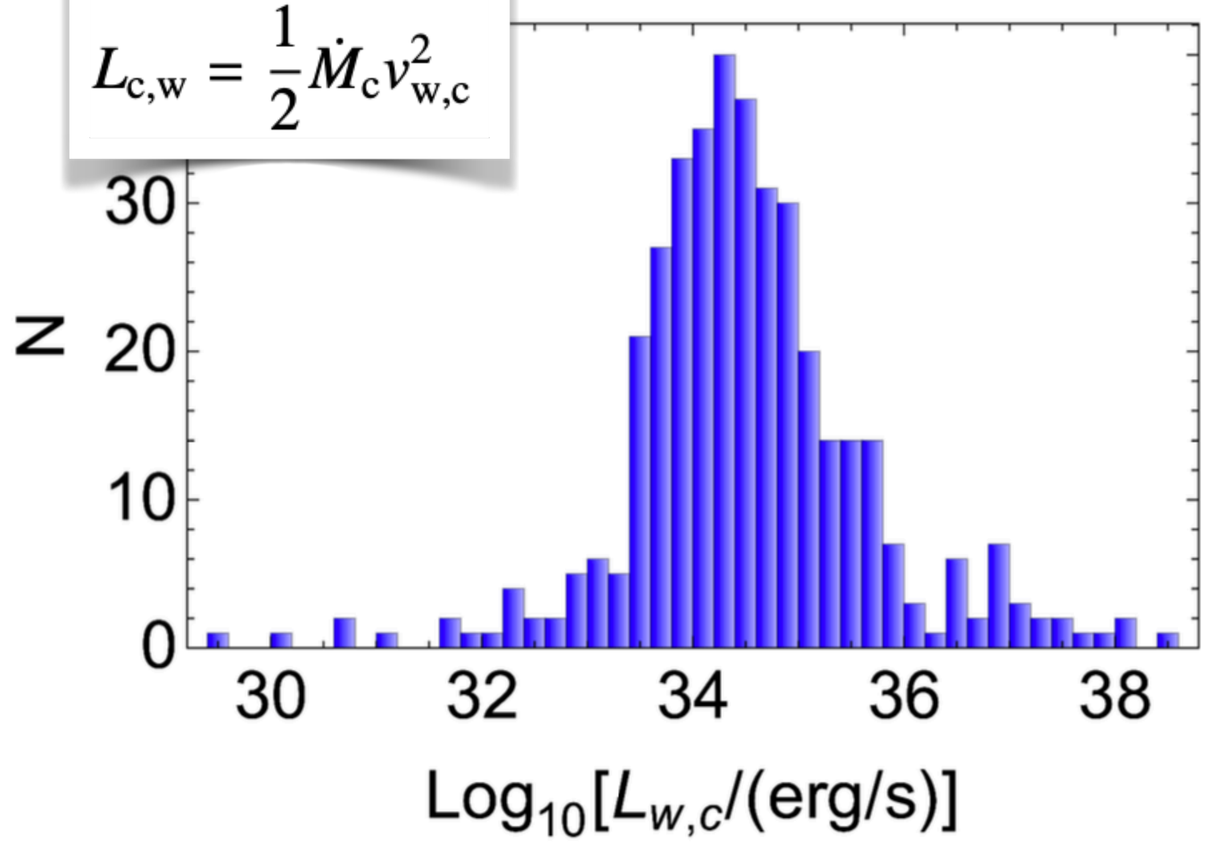
$$M_c = \int_{M_{min}}^{M_{max}} \frac{dN}{dM} M \, dM$$



$$\dot{M}_c = \int_{M_{min}}^{M_{max}} \frac{dN}{dM} \dot{M}_s(M) \, dM$$

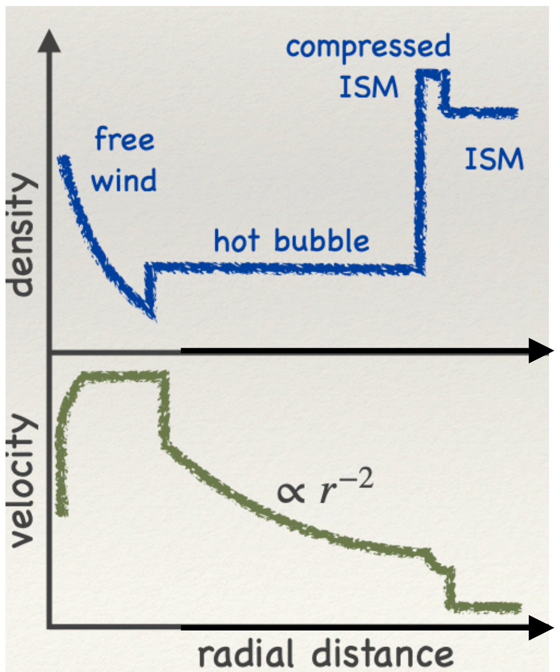


$$L_{c,w} = \frac{1}{2} \dot{M}_c v_{w,c}^2$$



Celli et al., arXiv:2311.09089
A&A (2024) accepted

Target gas distribution in wind bubbles



1. $R_c < r < R_s$ ⟶ free cold wind profile

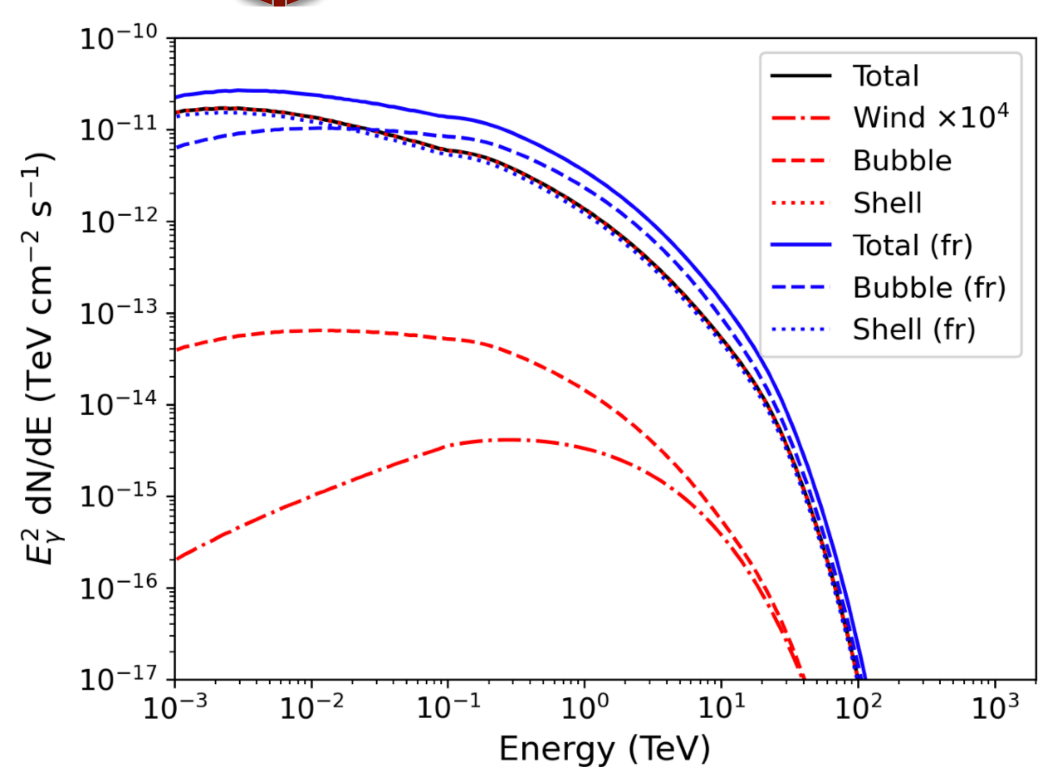
$$n_w(r) = \frac{\dot{M}_c}{4\pi r^2 v_w}$$

2. $R_s < r < R_{cd}$ ⟶ uniform density in the hot bubble

$$n_b = \frac{M_b}{\frac{4}{3}\pi(R_{cd}^3 - R_s^3)}$$

Morlino et al., MNRAS 504 (2021) 4

Mitchell et al. (2024) in prep.



3. $R_{cd} < r < R_b$ ⟶ uniform density in the shell

$$n_{sh} = \frac{n_0}{1 - R_{cd}^3/R_b^3} - \frac{\dot{M}_{sh} T_{age}}{m_p V_{sh}}$$

shell fragmentation:

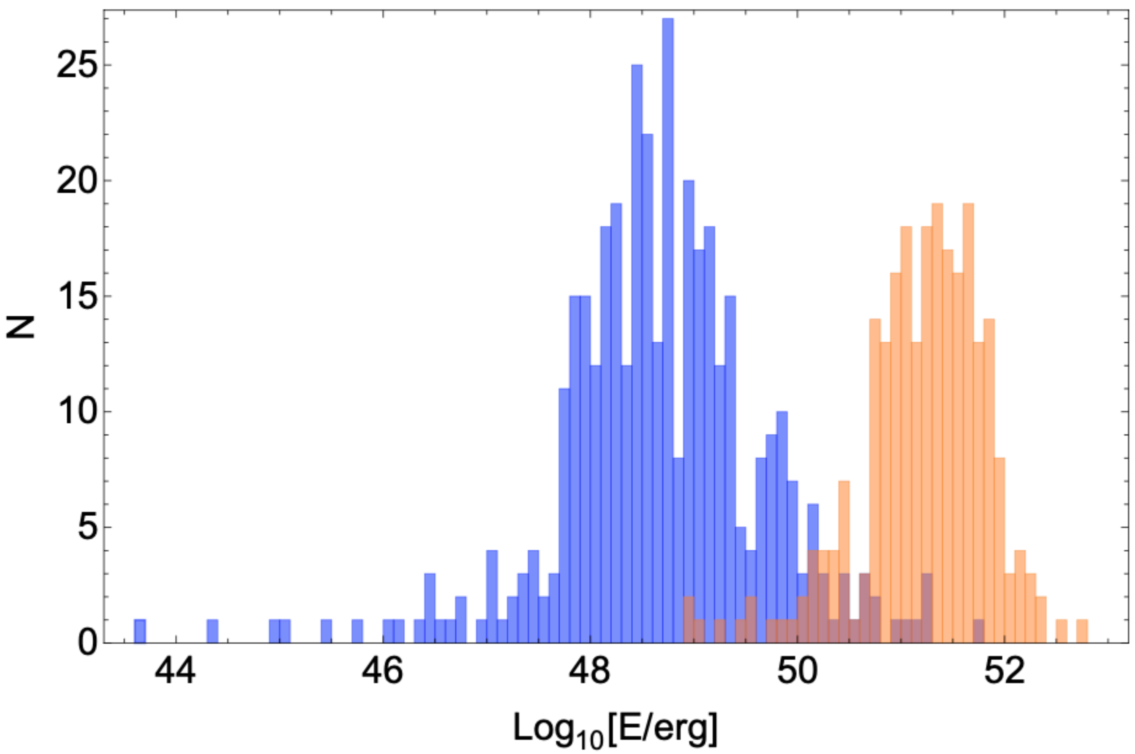
$$\begin{cases} n'_{sh} &= (1 - \eta_{fr})\, n_{sh} \\ n'_b &= n_b + \eta_{fr}\, n_{sh}\, R_b^3/R_{cd}^3 \end{cases}$$

Menchiari et al. (2024) arXiv:2402.07784

Blasi & Morlino, MNRAS 523 (2023) 4015

The contribution from SN explosions

Celli et al., arXiv:2311.09089
A&A (2024) accepted



We can now derive the total energetics injected from winds and SNe over the entire cluster lifetime

$$N_{\rm SN}(t) = \int_{{\rm Max}[8M_\odot, M_{\rm max}(t)]}^{M_{\rm max,0}} \xi(M)dM$$

Note that SNe behave as short transients wrt the cluster lifetime, namely the **average CR distribution inside the bubble is only contributed by explosions occurred within the last escape time** (t_{esc}=t_{adv})

Mitchell et al. (2024) in prep.

OUR PRESCRIPTION TO INCLUDE SNe:

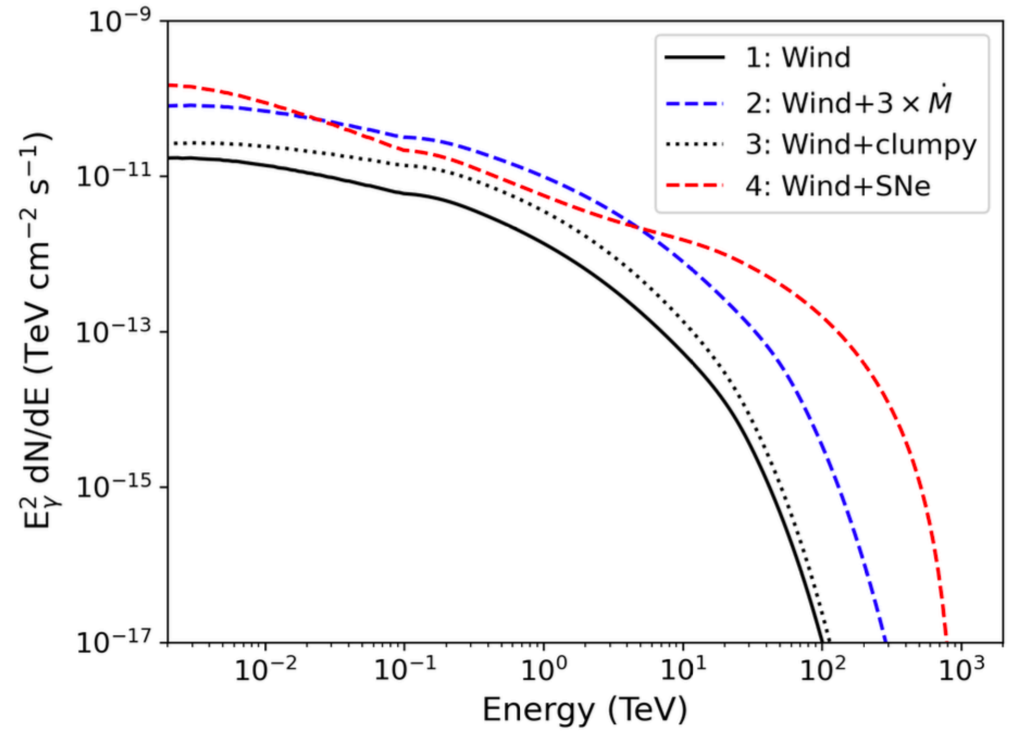
- Same acceleration efficiency at SNR shocks as at WTS;
- Steeper injection slope than WTS, i.e. $dN/dp = kp^{-4.3}$;
- Maximum energy achieved in bkg magnetic field of the cluster, including self-amplification by particles;
- Injection located at the TS, as SNR enter Sedov phase with $R_{SNR} \sim R_{TS}$;
- Same transport as WTS accelerated particles.

SNR maximum energy

With regards to the normalization, since SNR max energy decreases during ST stage, production during the ED stage dominates the overall amount of CRs

$$\mathcal{R} \equiv \left.\frac{\langle f_{\rm snr}\rangle}{f_{\rm ts}}\right|_{p=m_p c} = 1.65\,\frac{N_{\rm sn} E_{\rm sn}}{L_w t_{\rm adv}}$$

$$\Longrightarrow \langle f_{\rm snr}(p)\rangle = \mathcal{R}\, f_{\rm ts}(m_p c)\left(\frac{p}{m_p c}\right)^{-s} e^{-p/p_{\rm max}}$$



Mitchell et al. (2024) in prep.

Time-limited max energy in SNRs:

$$E_{\rm max} = 41\,\mathcal{F} B_{\mu G} E_{51}^{1/2} M_{\rm ej,5}^{-1/6} n_{b,0.1}^{-1/3}\ {\rm TeV}$$

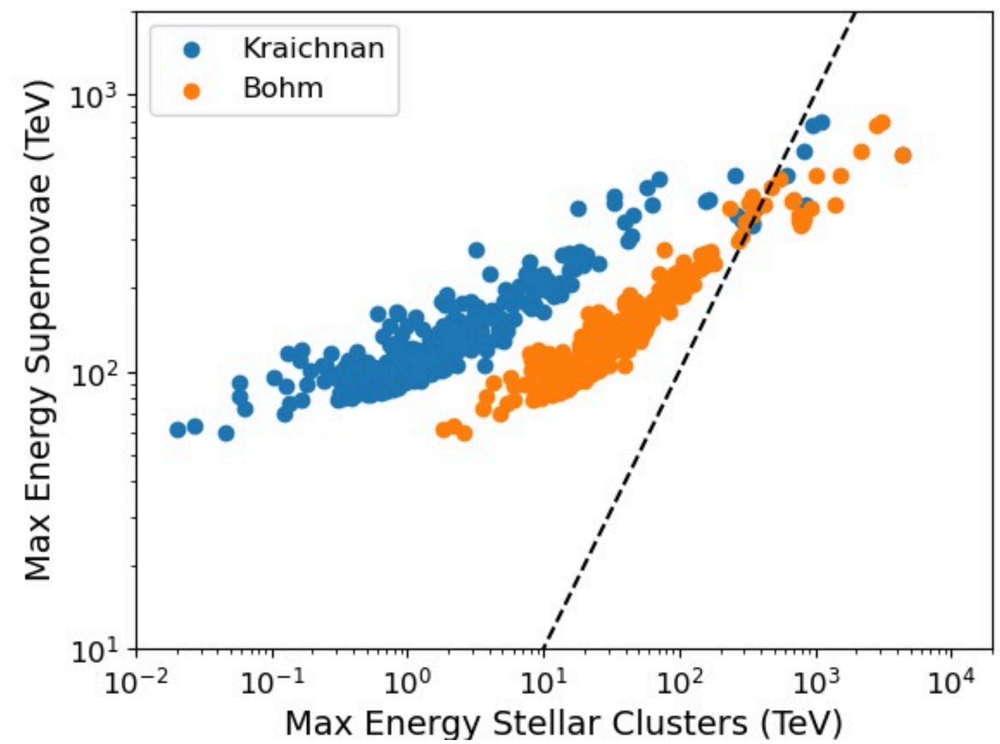
- wind turbulence only

$$E_{\rm max} = 1\, B_{\mu G} E_{51} M_{\rm ej,5}^{-1/3} n_{b,0.1}^{-2/3}\ {\rm TeV}$$

- CR driven turbulence (SI)

$$\mathcal{F}_{\rm res} = \left(\frac{\pi\,\xi_{\rm cr}\, c}{6\,\Lambda\, u_{\rm sh}}\right)^{1/2} = 0.5\left(\frac{\xi_{\rm cr}}{0.1}\right)^{\frac{1}{2}}\left(\frac{E_{\rm sn}}{10^{51}{\rm erg}}\right)^{\frac{1}{4}}\left(\frac{M_{\rm ej}}{5M_\odot}\right)^{-\frac{1}{4}}$$

$$\longrightarrow E_{\rm max} > 100\ {\rm TeV}$$



Open questions

- **What is the dominant acceleration mechanism?**
  - wind-wind collisions
  - turbulent acceleration
  - wind termination shock
- **What is the maximum possible energy of accelerated particles?**
  - strong dependence on magnetic field strength and turbulence power
- **How to study turbulence in YSCs?**
  - need for specific numerical simulations
  - role of realistic environments (fragmentation, cooling)
- **Can stellar winds significantly contribute to GCRs?**

Thanks for your kind attention!