Star Clusters as Cosmic Ray accelerators

Giovanni Morlino

INAF/Osservatorio astrofisico di Arcetri - Firenze - ITALY

2nd LHAASO symposium — 20-25 March 2025, Hong Kong (China)

The role of star clusters in the SNR paradigm

SNR types:
- ~20% type Ia
- ~80% core collapse:
  - (60-80)% explode inside the parent star cluster
  - (20-40)% explode outside the cluster (runaway massive stars)

Massive stars born in OB associations

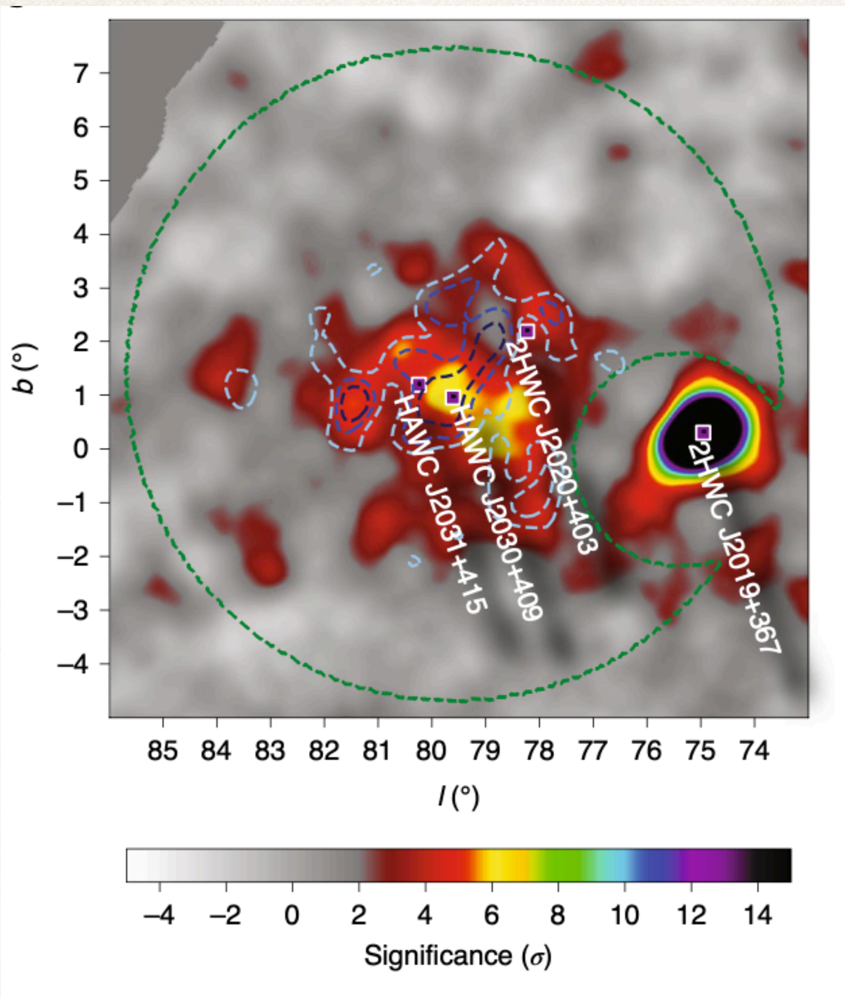
The role of star clusters in the SNR paradigm

Massive stars born in OB associations

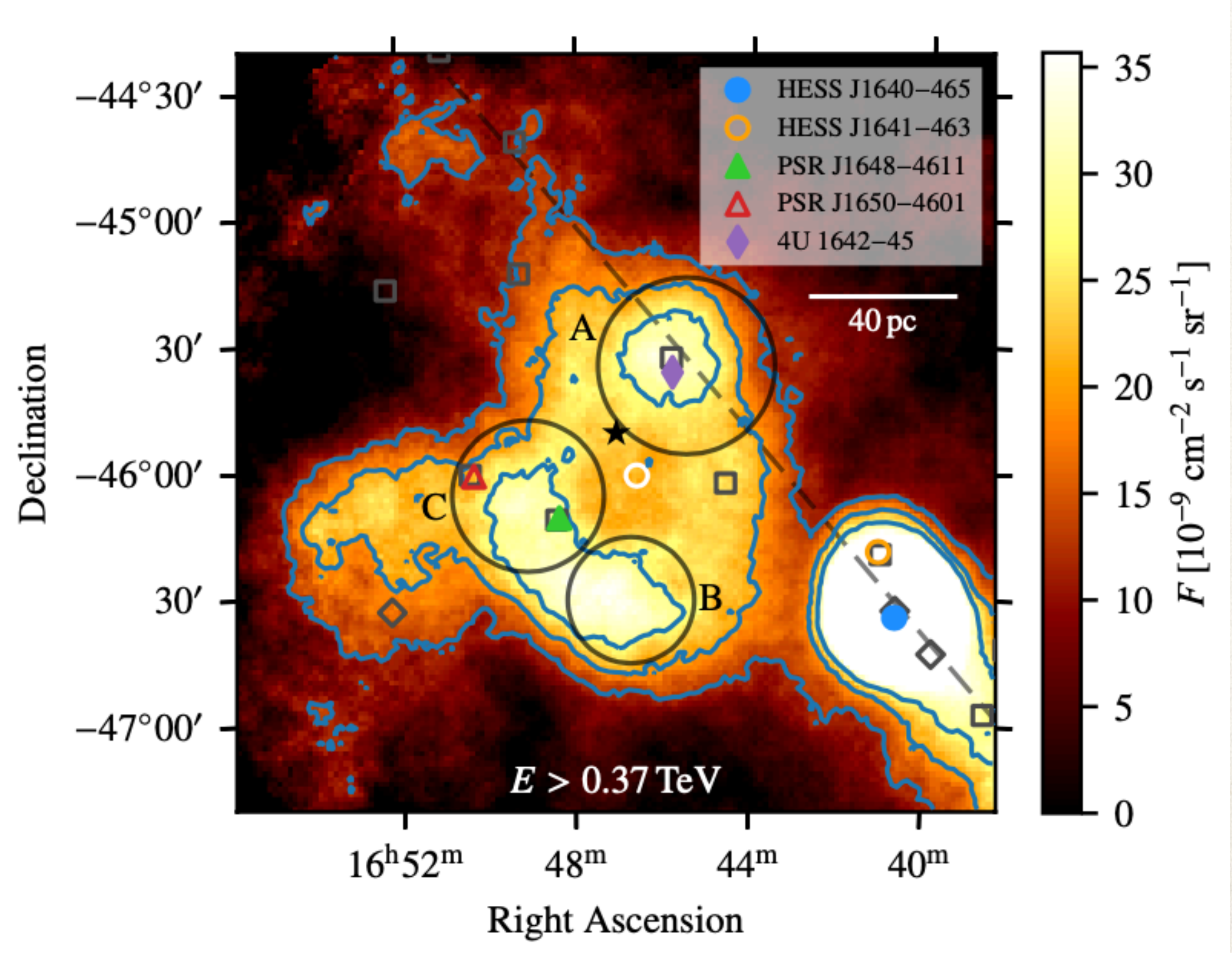
SNR types:
- ~20% type Ia
- ~80% core collapse:
  - (60-80)% explode inside the parent star cluster
  - (20-40)% explode outside the cluster (runaway massive stars)

Recently several massive star clusters have been associated with gamma-ray sources

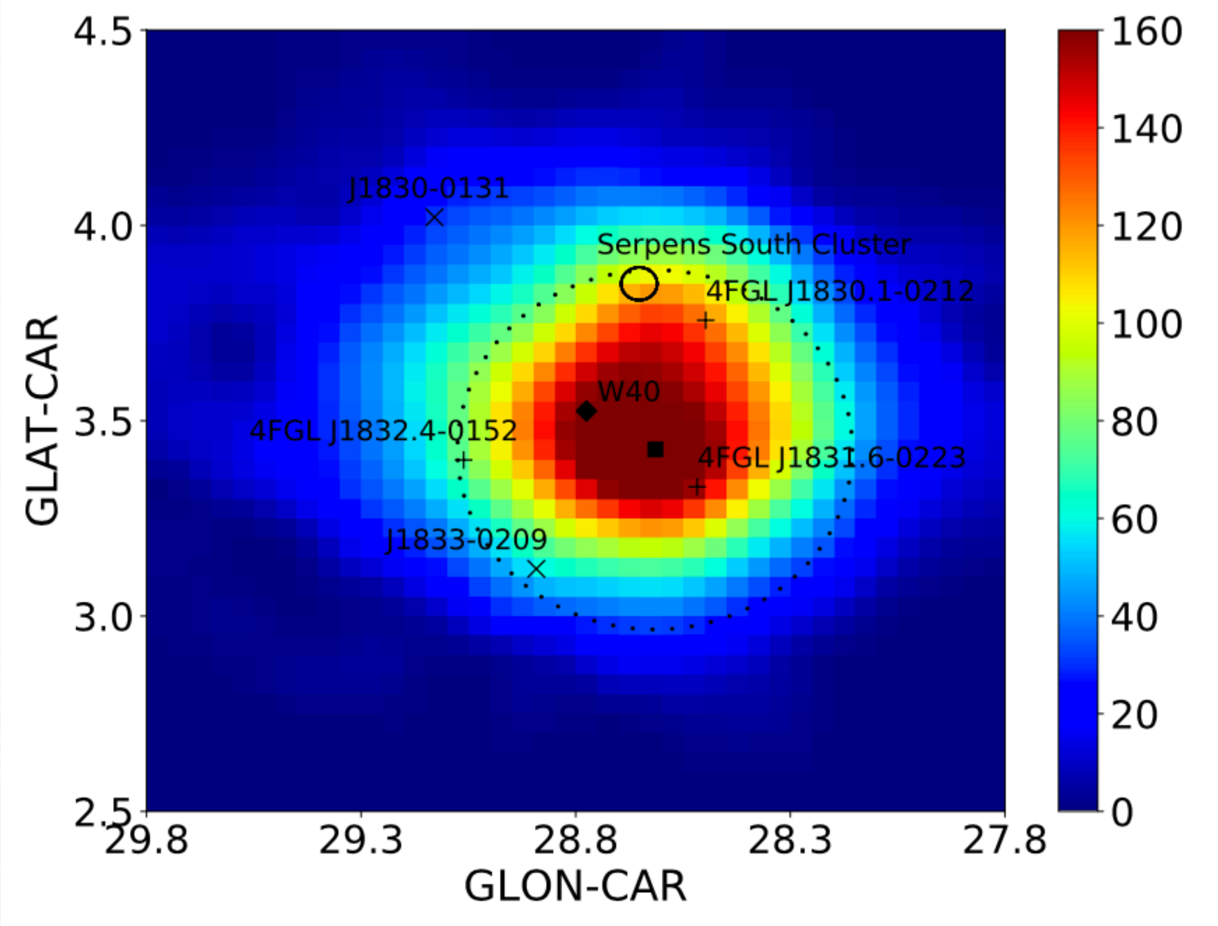
Cygnus Cocoon HAWC coll. Nat. Astr.(2020)



Westerlund 1; HESS coll. A&A (2022)

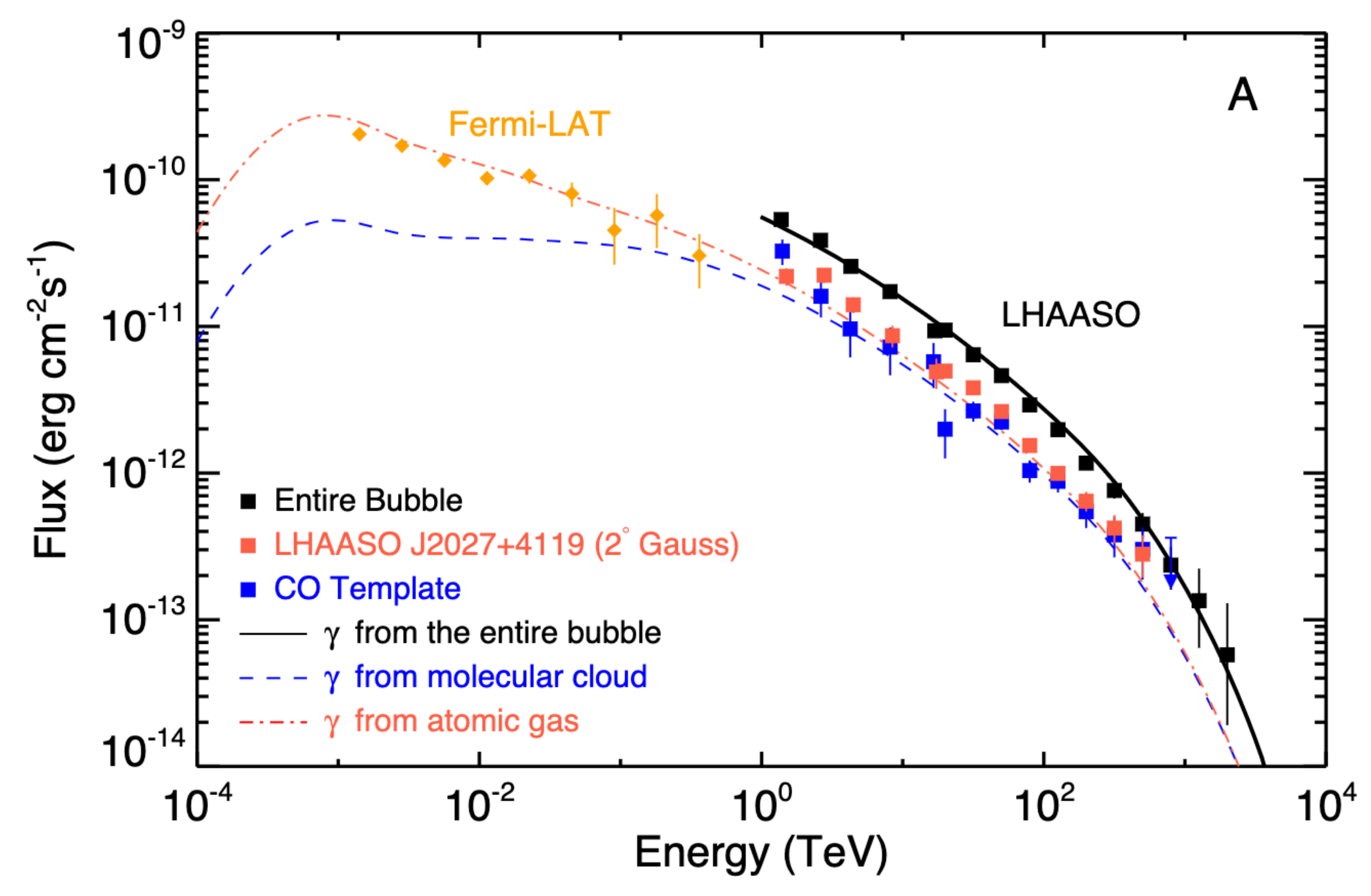


W40 - FermiLAT Sun et al. (2020)

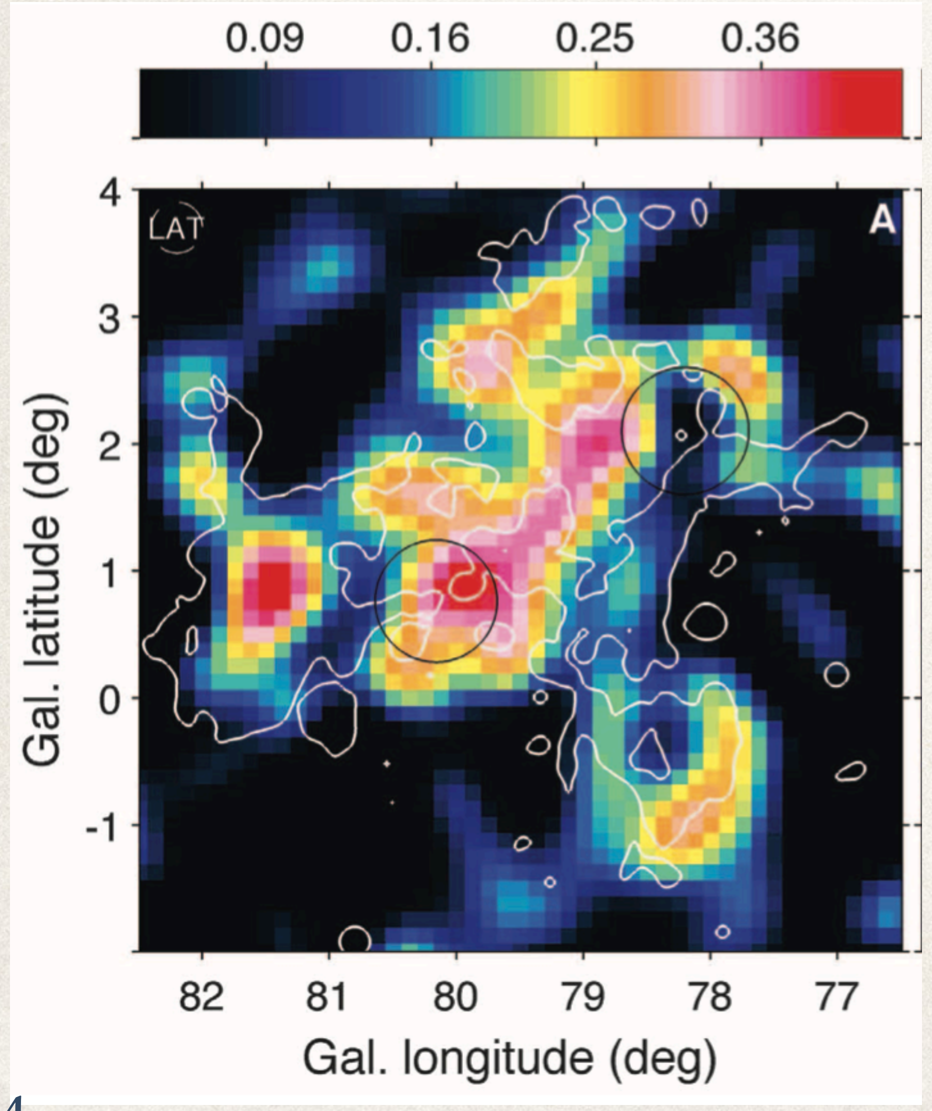


Cygnus cocoon

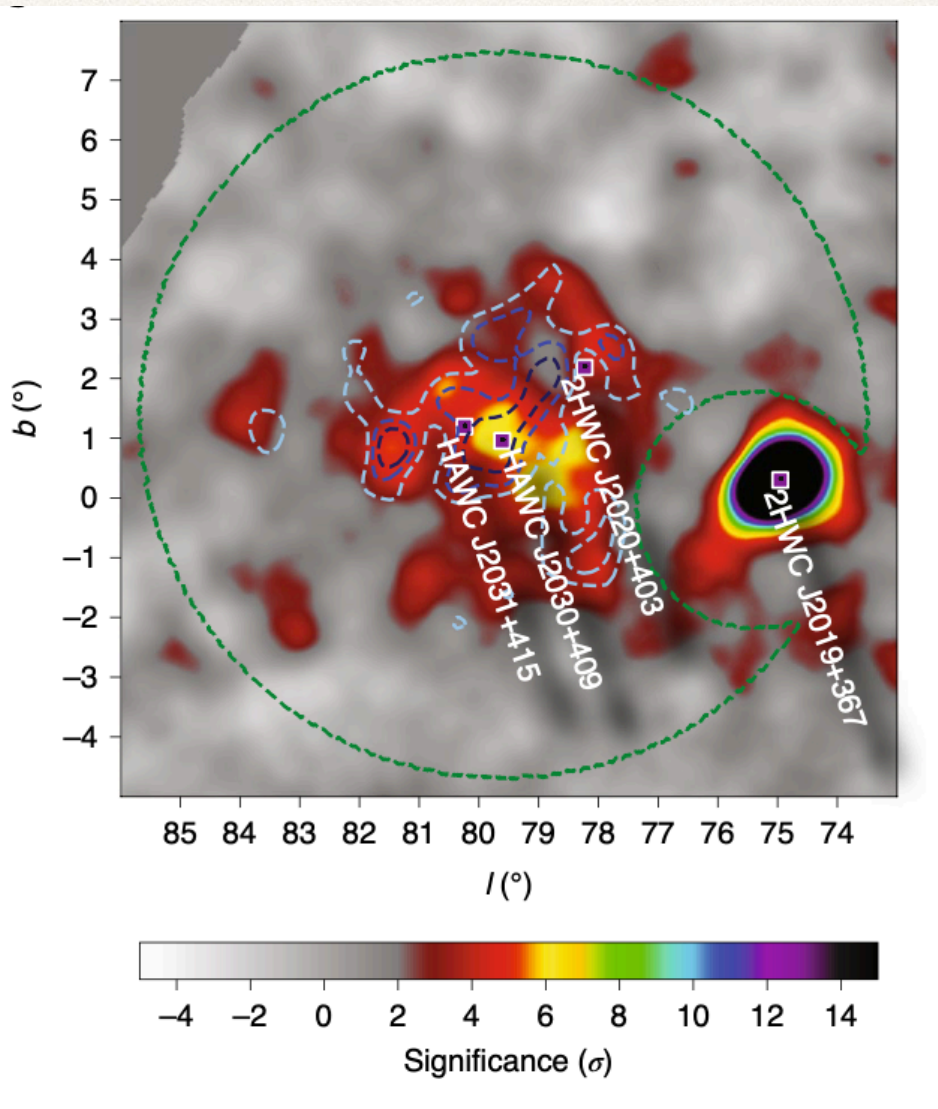
- Extended emission:
  - beyond 50 pc for HAWC and Fermi-LAT
  - and up to ~150 pc for LHAASO
- Hard spectrum in GeV band
- Softening in TeV band
- Photons detected by LHAASO with $E > \mathrm{PeV}$



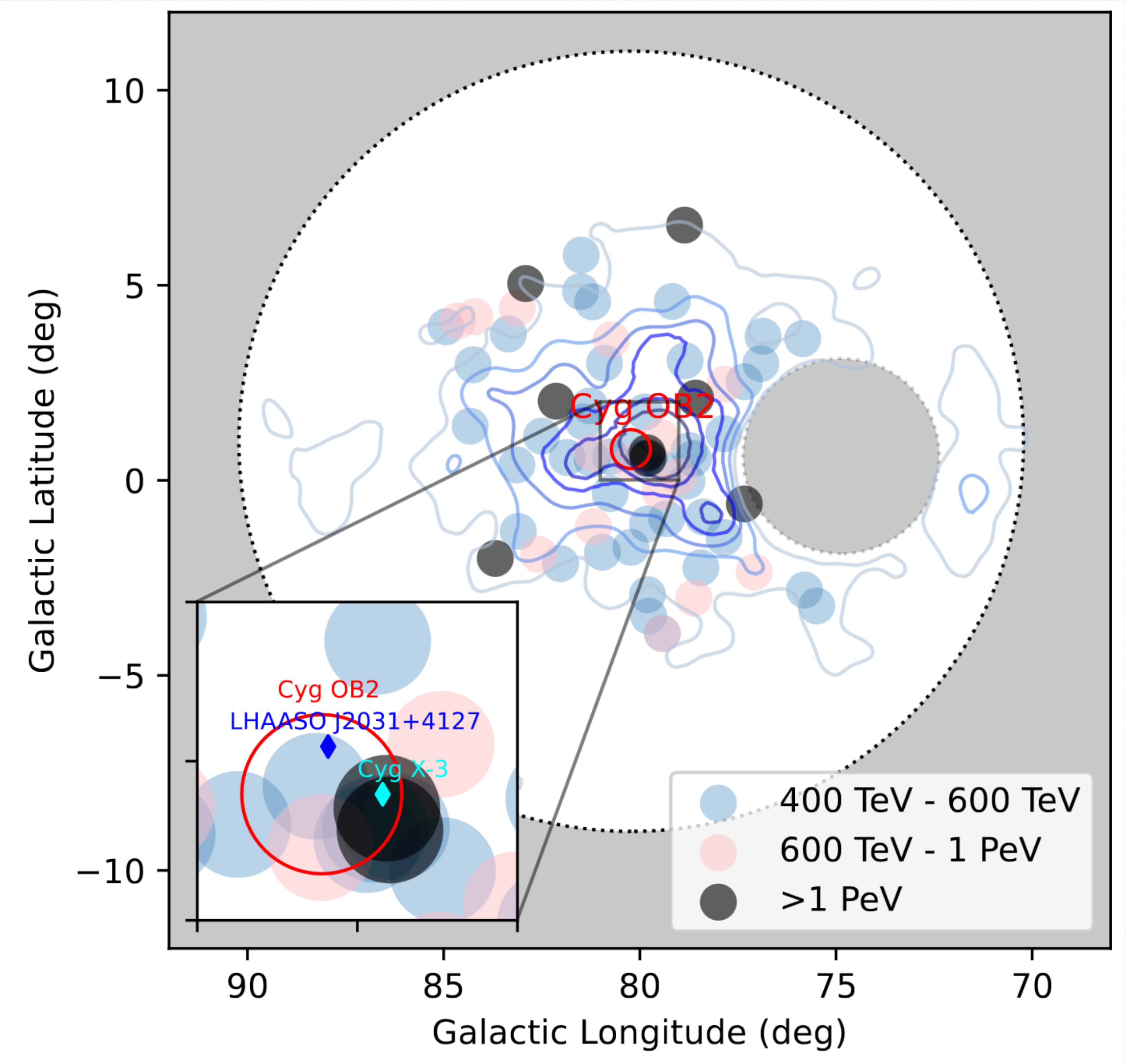
Cygnus Cocoon FermiLAT - Ackermann et al. (2011)



HAWC coll. (2020)



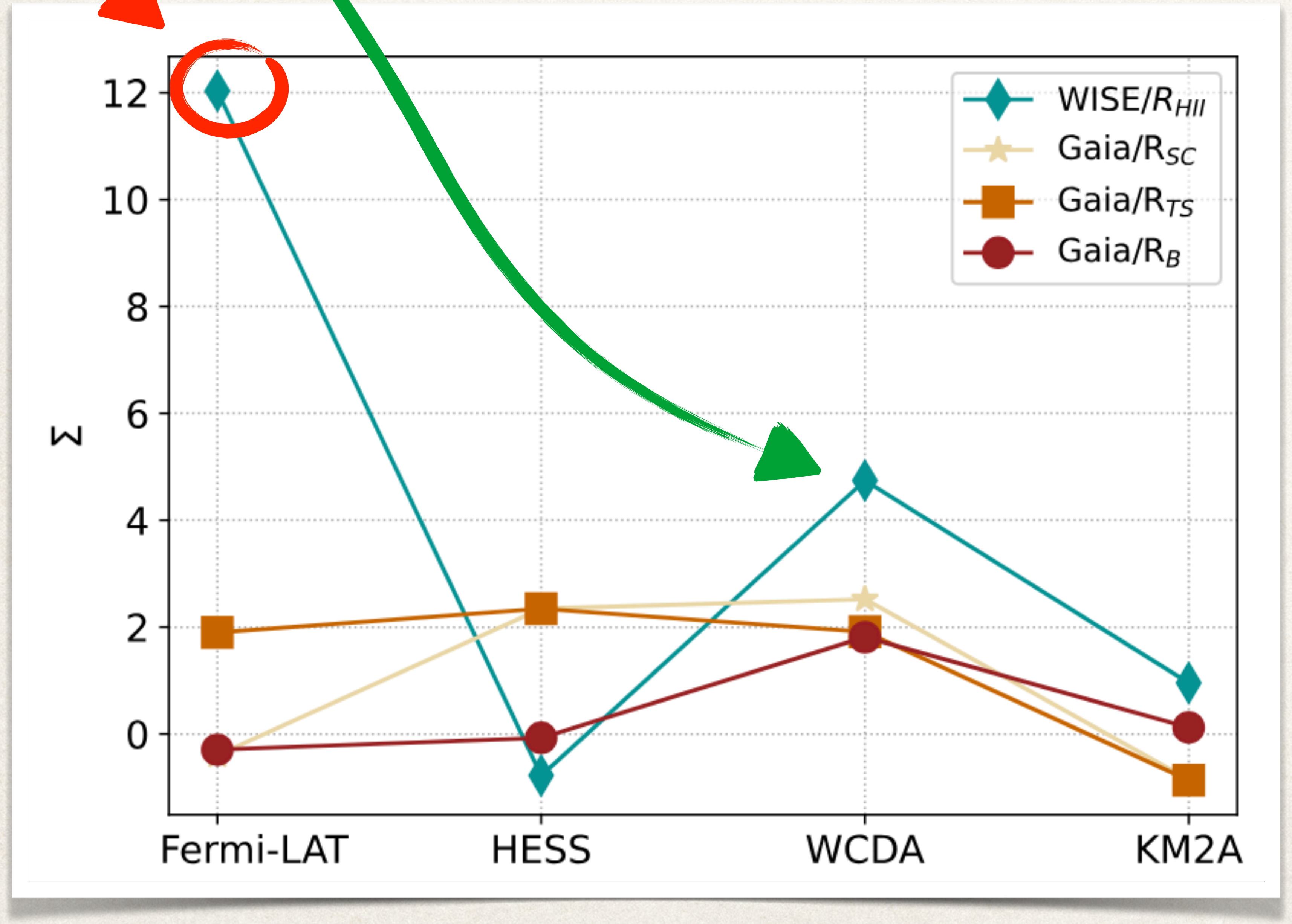
LHAASO coll. (2023)



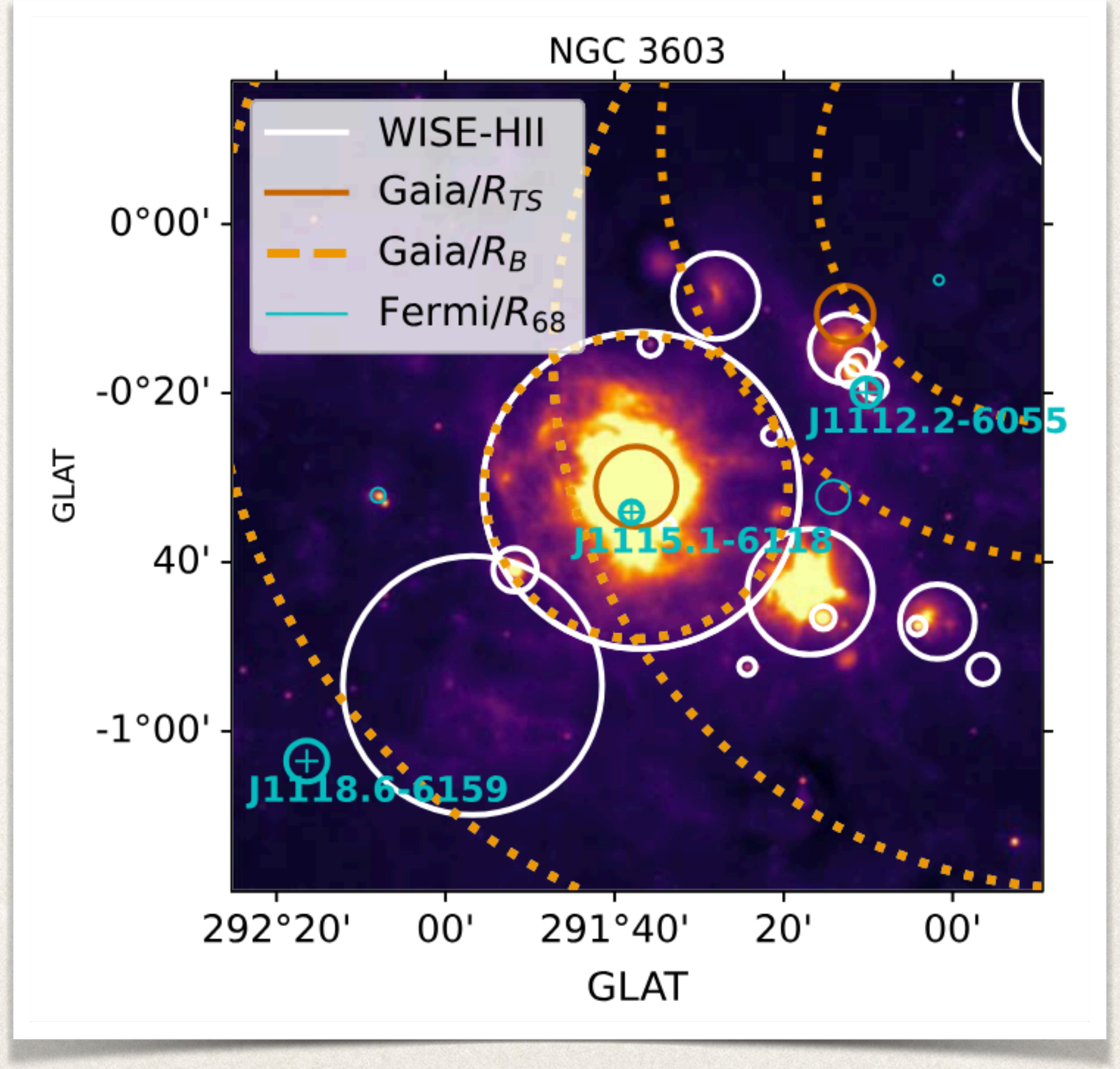
Correlation between YMSCs and Fermi-LAT unassociated sources

G. Peron et al. ApJL 972 (2024)

- Very significant correlation between SCs from the WISE catalog and unassociated Fermi-LAT sources
  - WISE HII region detected in IR:
    - ➡ Very young clusters embedded in the parent molecular cloud
    - ➡ high gas density
    - ➡ small bubble size
- Significant correlation between the Gaia catalog and LHAASO-WCDA sources



Significance of the correlation

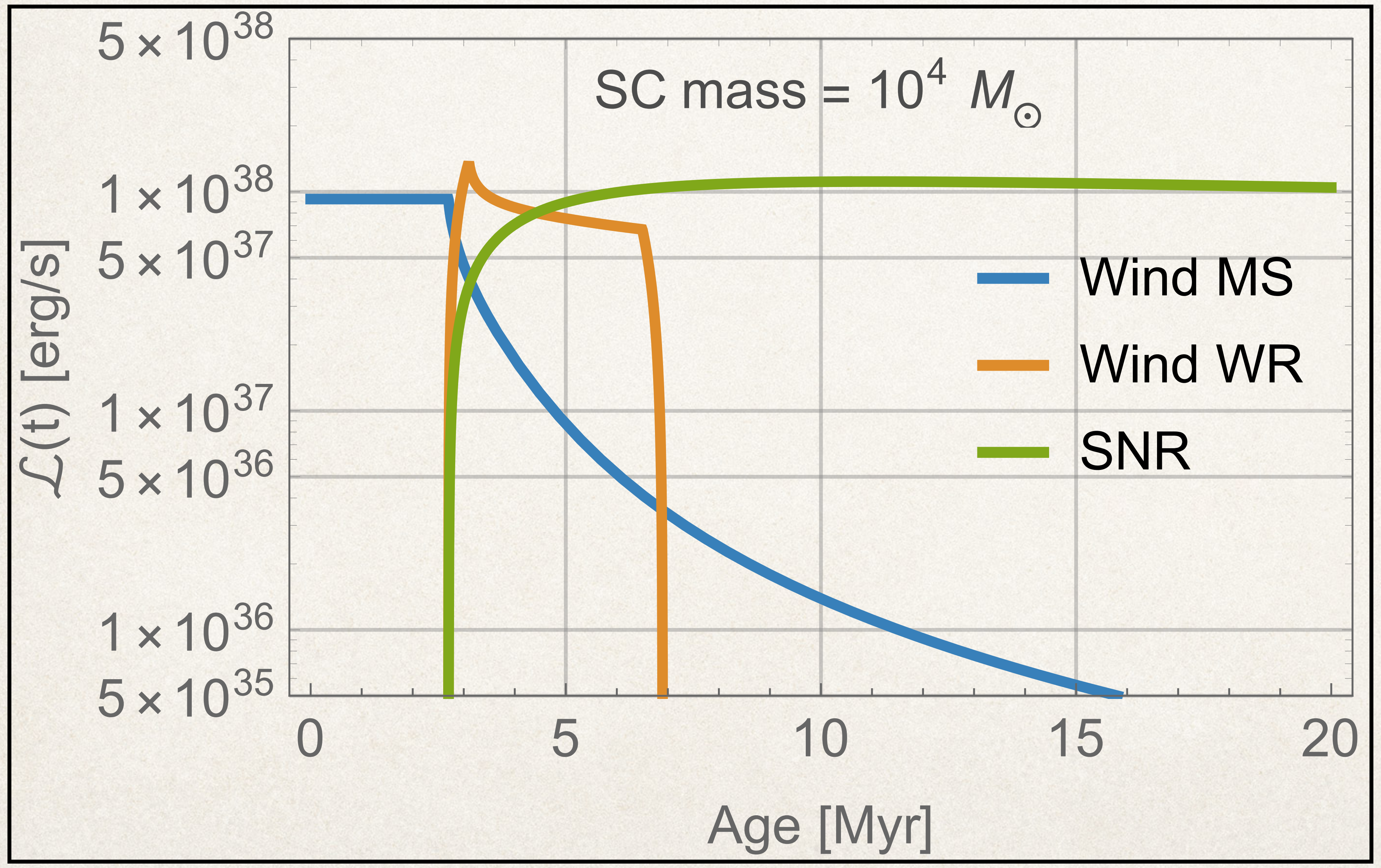


The case of NGC 3606:
the HII region well overlap with
the predicted bubble size

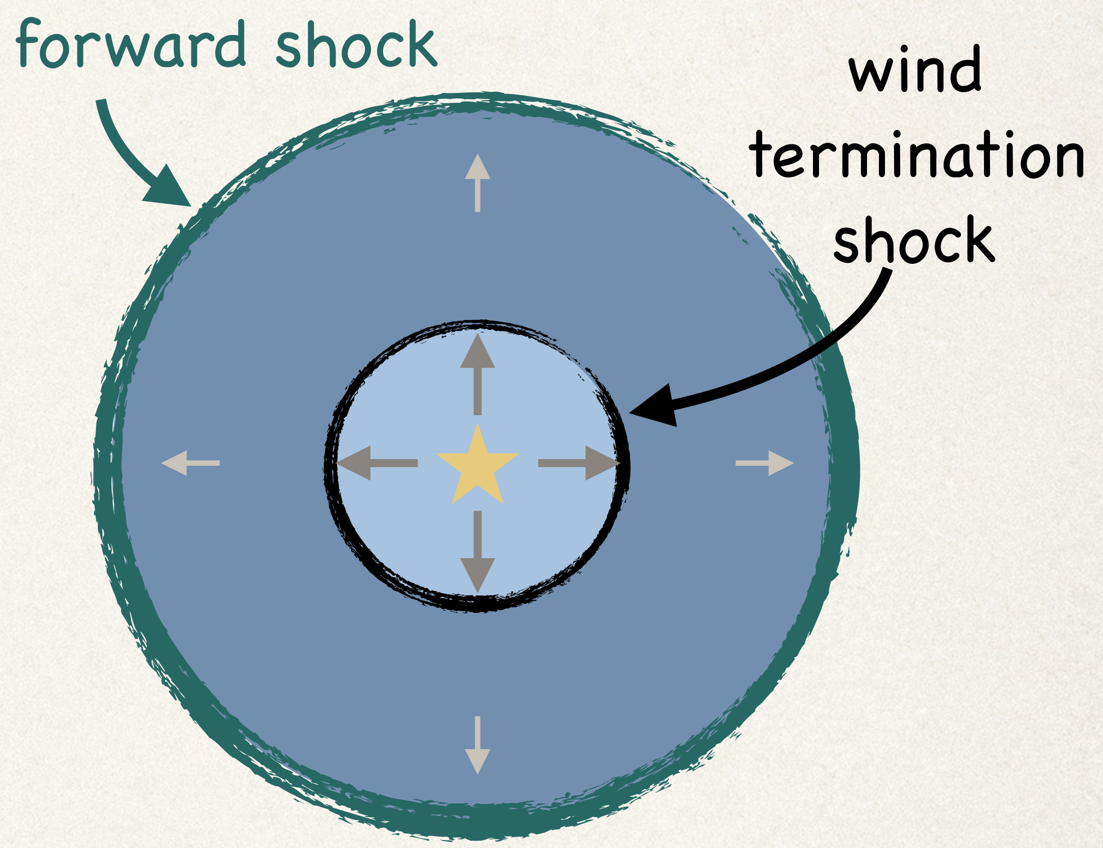
What power Stellar Clusters?

Phase	Source	Time-scale	Model
$t \lesssim 3\,\mathrm{Myr}$	MS stellar winds	$t \gtrsim$ Myr	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

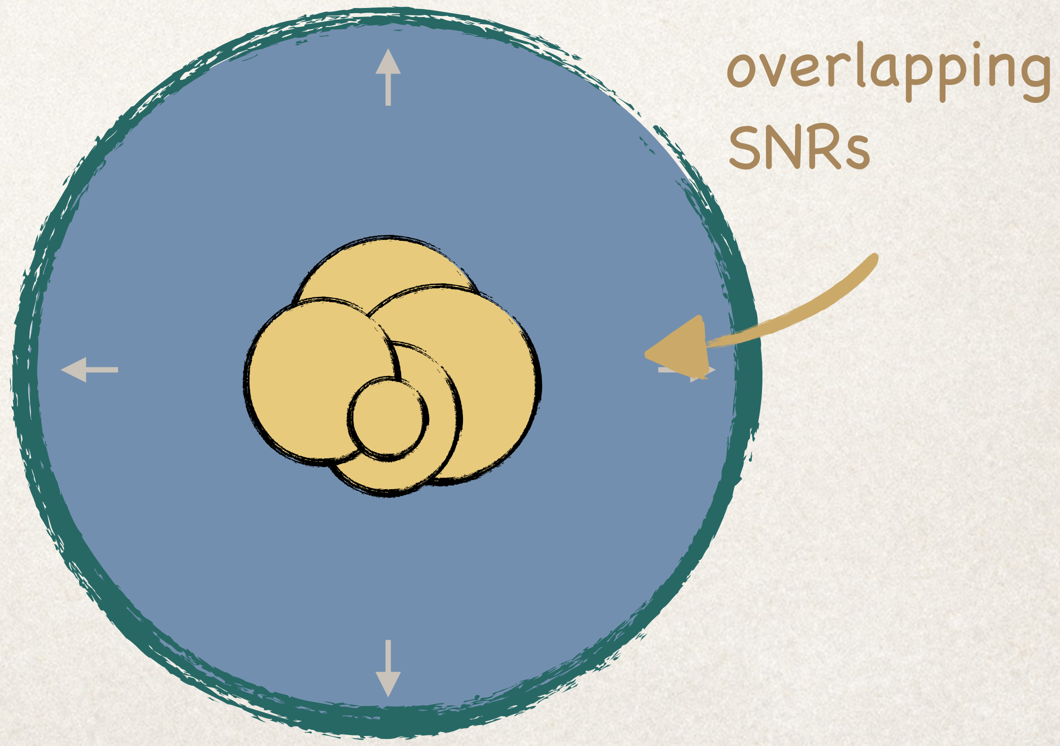
Stellar cluster kinetic luminosity



$t \lesssim 3$ Myr: only stellar winds



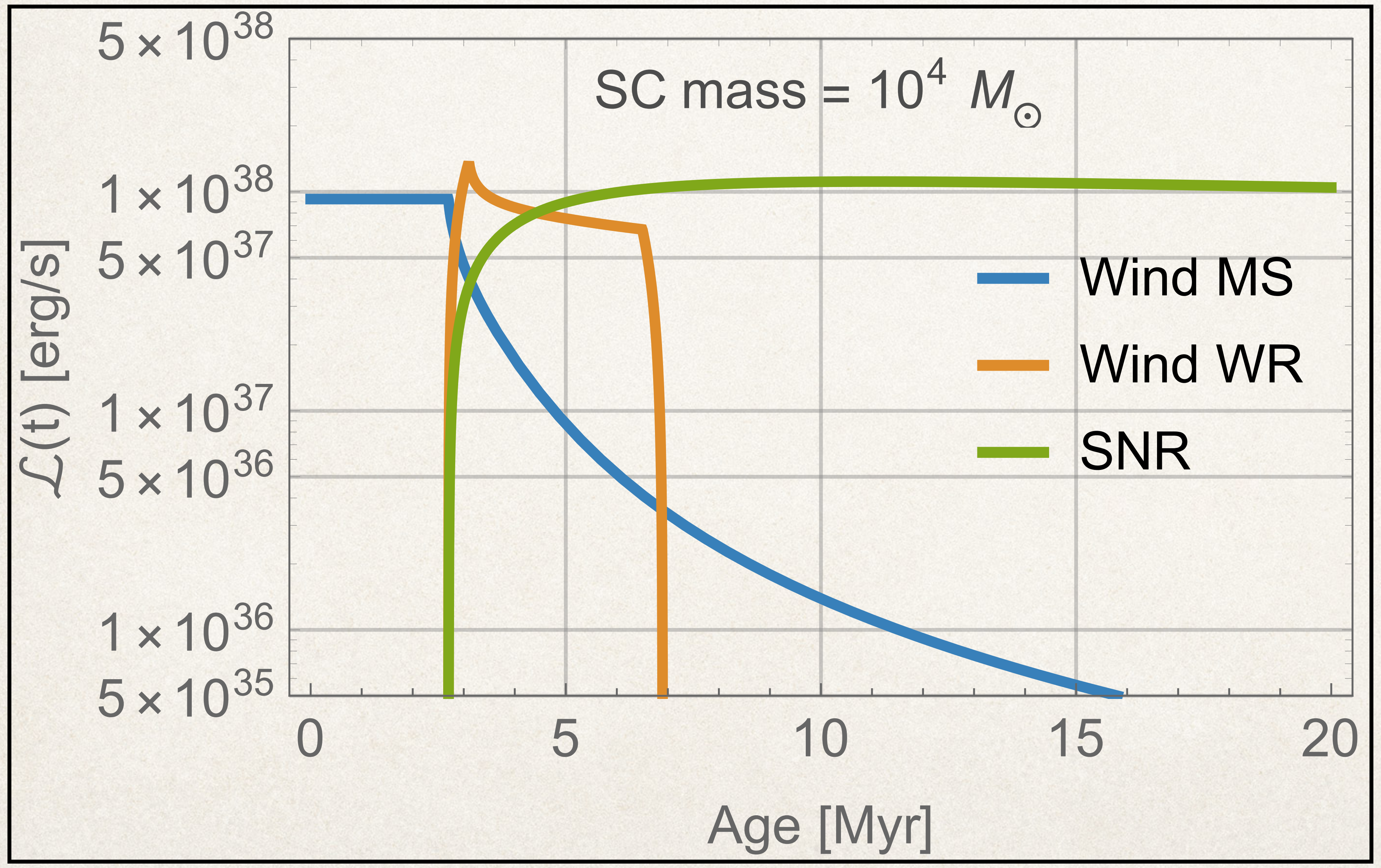
$3\,\mathrm{Myr} \lesssim t \lesssim 30\,\mathrm{Myr}$: stellar winds + SNe



What power Stellar Clusters?

Phase	Source	Time-scale	Model
$t \lesssim 3\,\mathrm{Myr}$	MS stellar winds	$t \gtrsim \mathrm{Myr}$	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

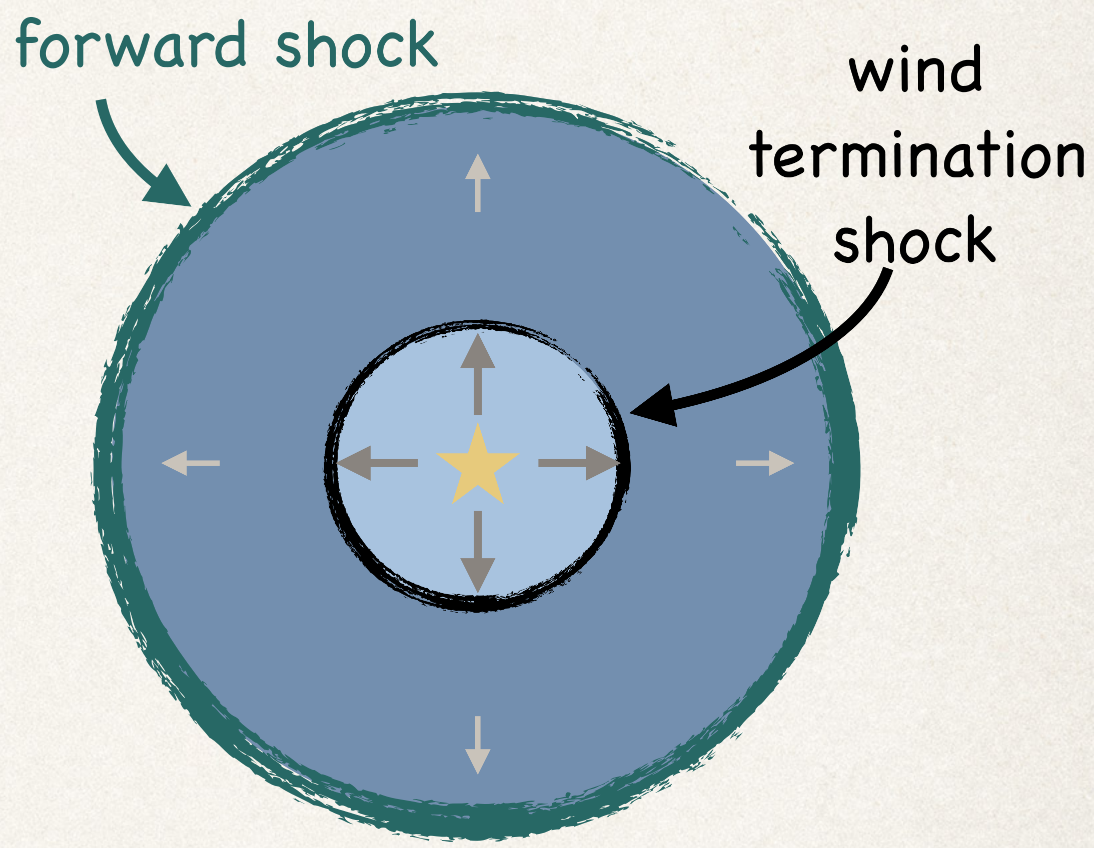
Stellar cluster kinetic luminosity



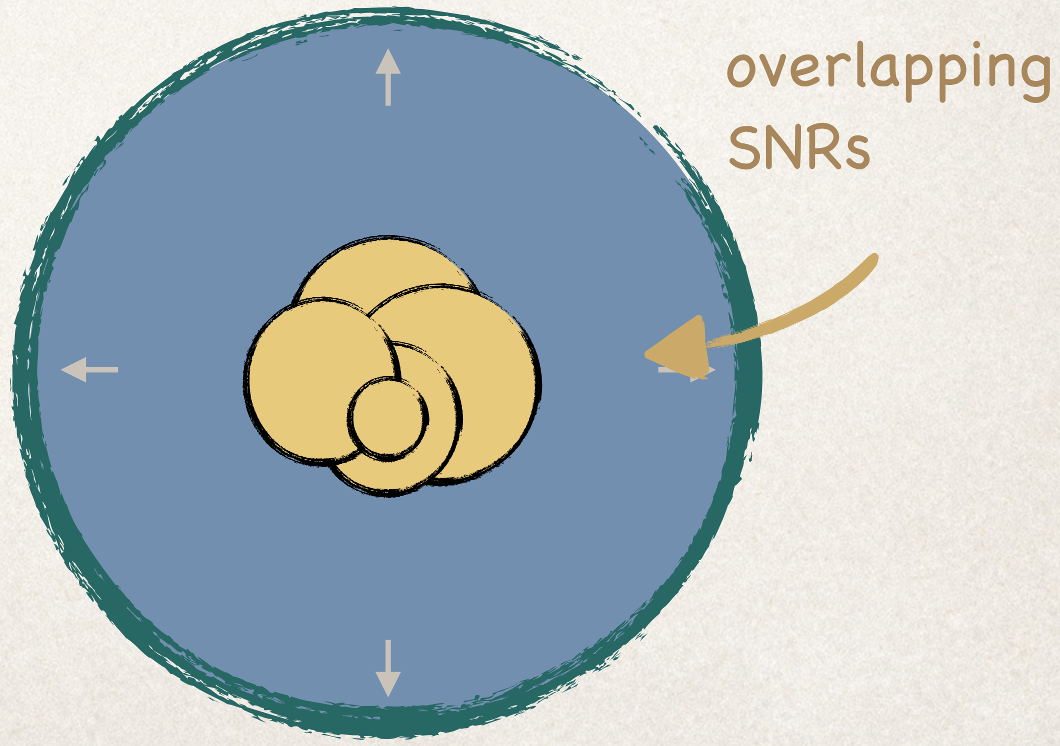
$$\frac{P_{\rm wind}}{P_{\rm SNe}} \simeq 0.1 \div 0.5$$

main uncertainty due to mass loss rate of the winds

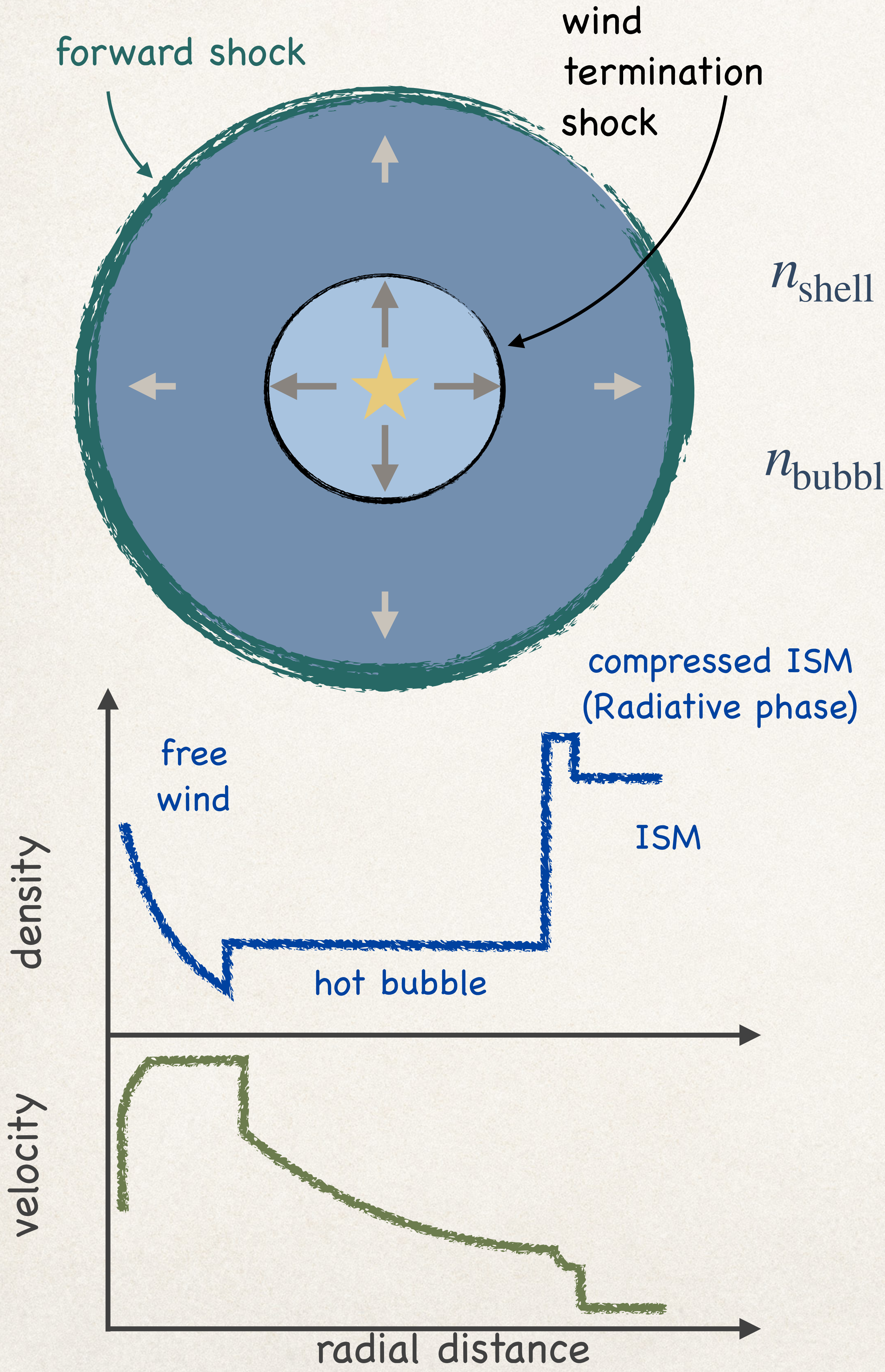
$t \lesssim 3\,\mathrm{Myr}$: only stellar winds



$3\,\mathrm{Myr} \lesssim t \lesssim 30\,\mathrm{Myr}$: stellar winds + SNe



Cluster wind physics



$n_{\rm shell} \simeq 10^3\,{\rm cm}^{-3}$

$n_{\rm bubble} \simeq 10^{-3}\,{\rm cm}^{-3}$

$t \lesssim 3\,$Myr: only stellar winds

- **Wind-blown bubble**: adiabatic model from Weaver & McCray (1977)

  Constant injection of energy in time in a spherical symmetry

$R_{\rm cluster} \simeq 1-2\,{\rm pc}$ Observation of star distribution

$$R_{\rm TS} \simeq 20\ {\rm pc} \left(\frac{\dot{M}}{10^{-4} M_\odot/yr}\right)^{3/10} \left(\frac{v_w}{1000\,{\rm km/s}}\right)^{1/10} \left(\frac{\rho_0/m_p}{{\rm cm}^{-3}}\right)^{-3/10} \left(\frac{t_{\rm age}}{\rm Myr}\right)^{2/5}$$

$R_{\rm CD} \simeq R_{\rm bubble}$ Rapid cooling of shocked ejecta

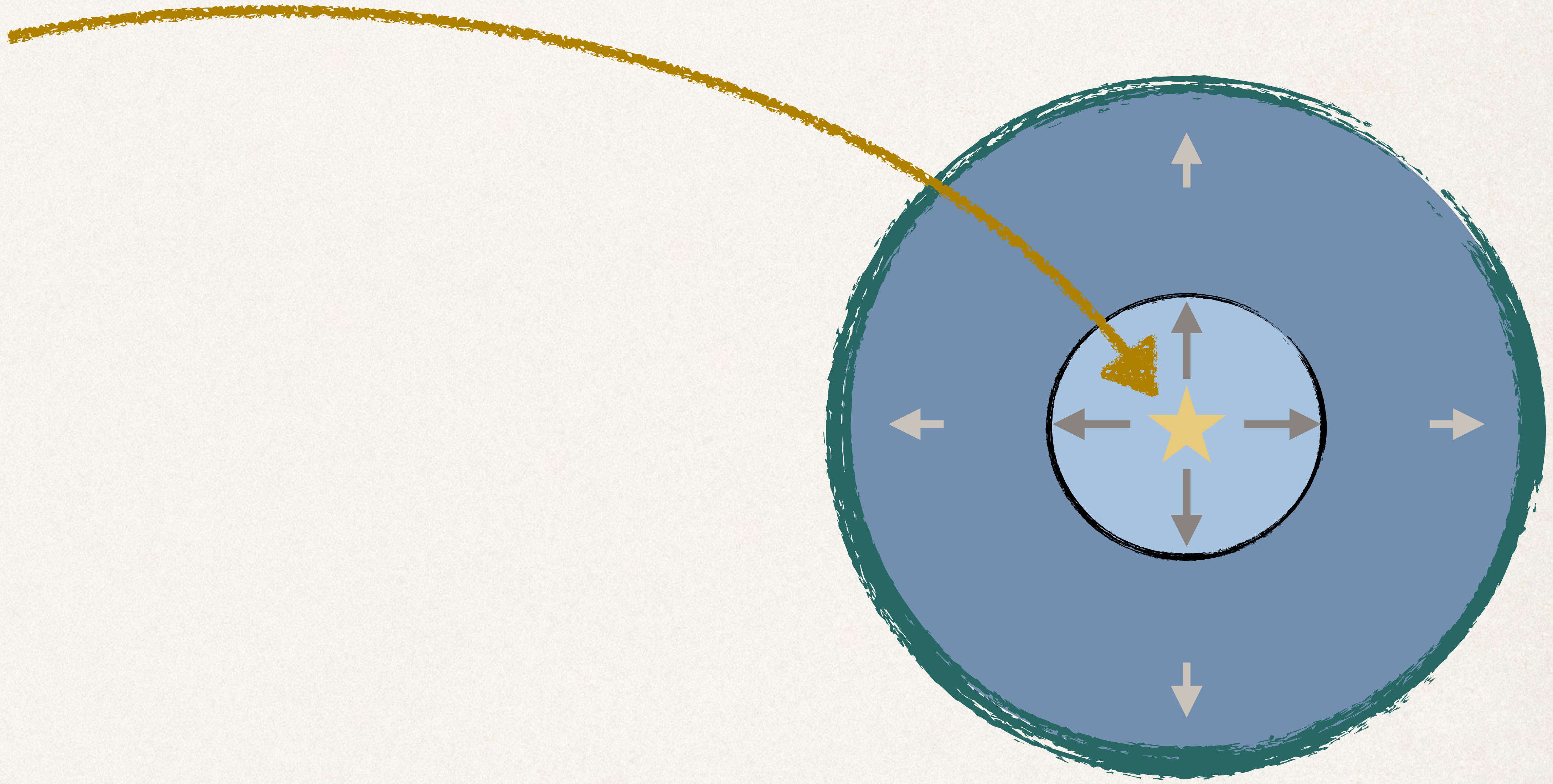
$$R_{\rm bubble} \simeq 55\ {\rm pc} \left(\frac{\dot{M}}{10^{-4} M_\odot/yr}\right)^{1/5} \left(\frac{v_w}{1000\,{\rm km/s}}\right)^{2/5} \left(\frac{\rho_0/m_p}{{\rm cm}^{-3}}\right)^{-1/5} \left(\frac{t_{\rm age}}{\rm Myr}\right)^{3/5}$$

Possible acceleration mechanisms

Inside the SC core:

- Colliding winds from binary stars
  (fraction of massive stars in binary systems ~50%-100%)
- Single stellar wind termination shocks

Relevant adiabatic losses for particle escaping the bubble



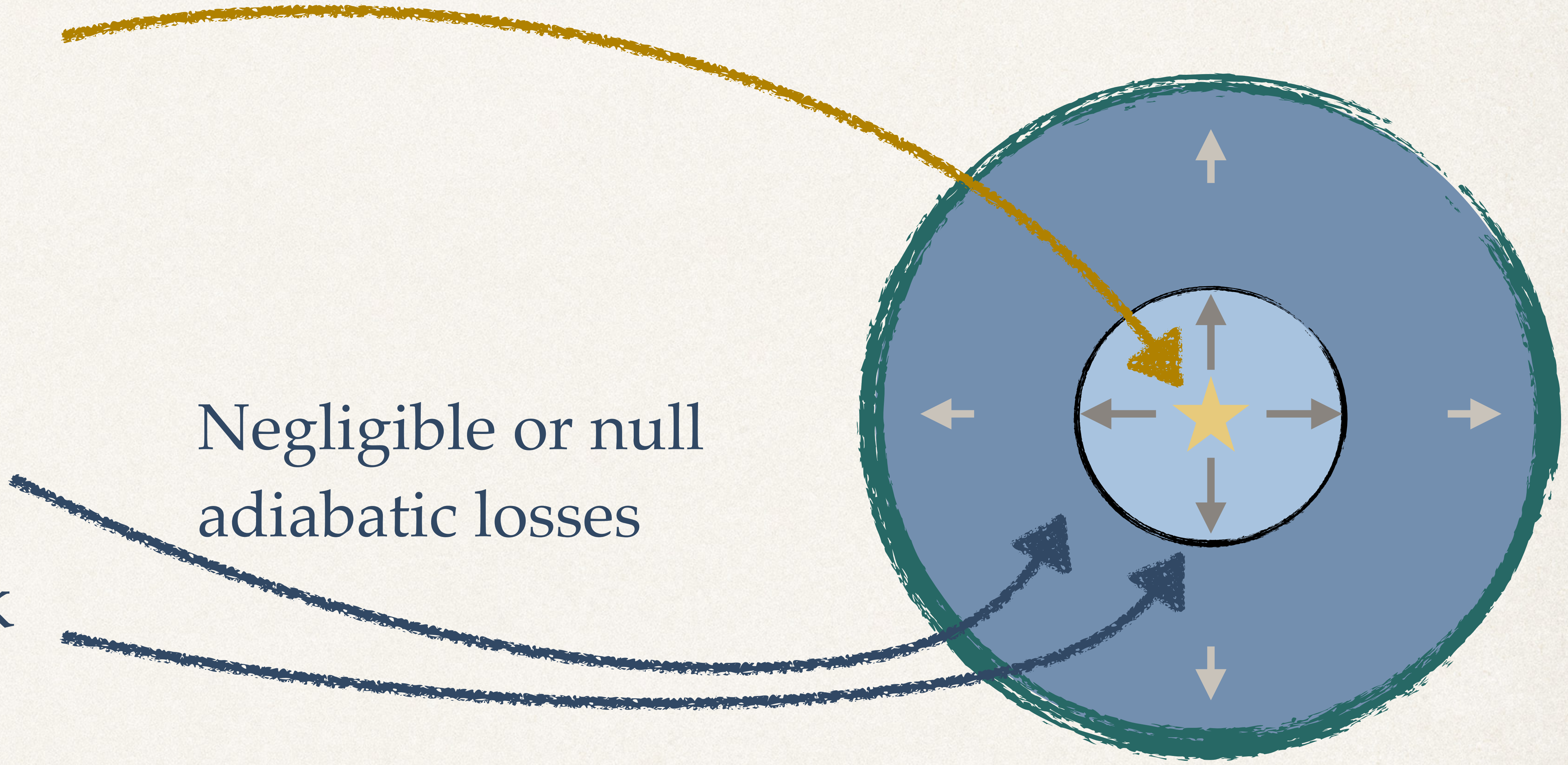
Possible acceleration mechanisms

<u>Inside the SC core:</u>

- Colliding winds from binary stars
  (fraction of massive stars in binary systems ~50%-100%)
- Single stellar wind termination shocks

<u>Inside the hot bubble:</u>

- Acceleration due to turbulence (II order)
- Collective cluster wind termination shock



Relevant adiabatic losses for particle escaping the bubble

Negligible or null adiabatic losses

Possible acceleration mechanisms

Inside the SC core:

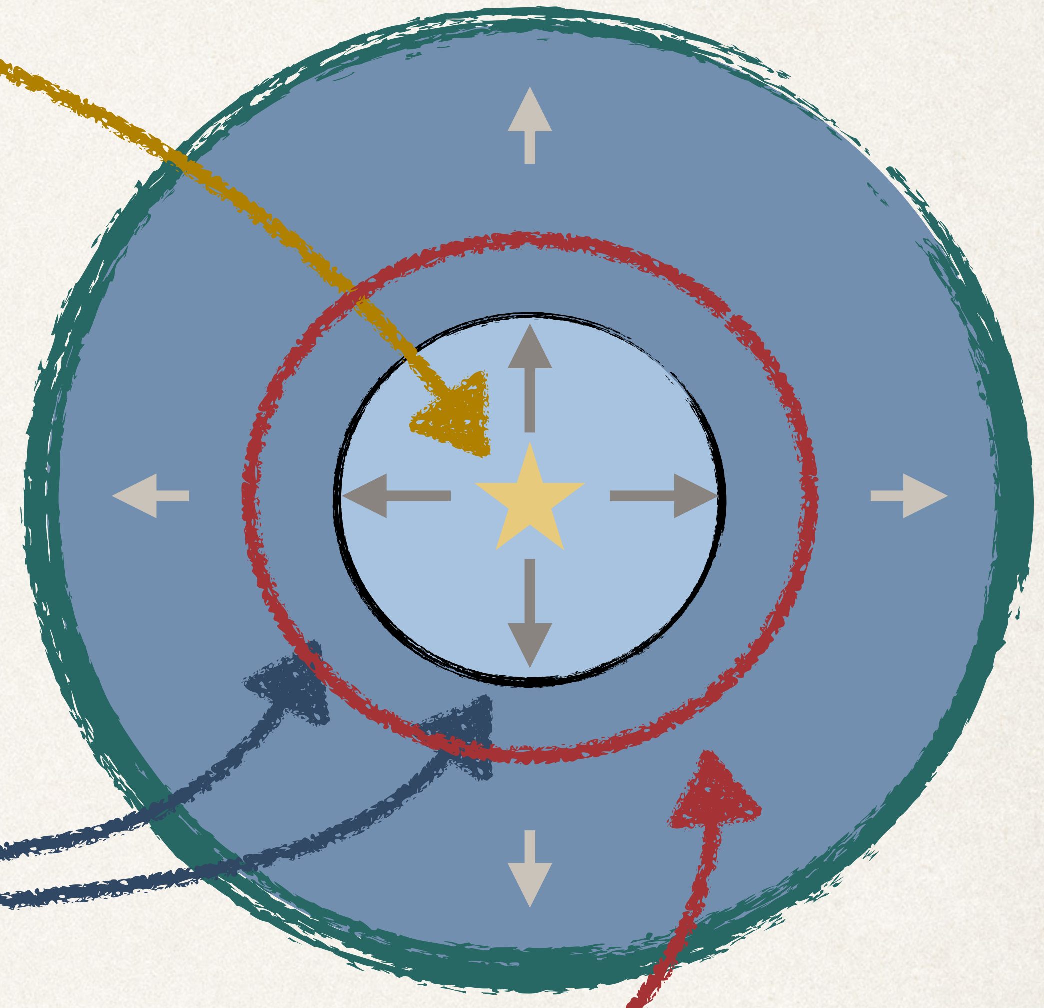
- Colliding winds from binary stars
  (fraction of massive stars in binary systems ~50%-100%)
- Single stellar wind termination shocks

Inside the hot bubble:

- Acceleration due to turbulence (II order)
- Collective cluster wind termination shock

Entire bubble:

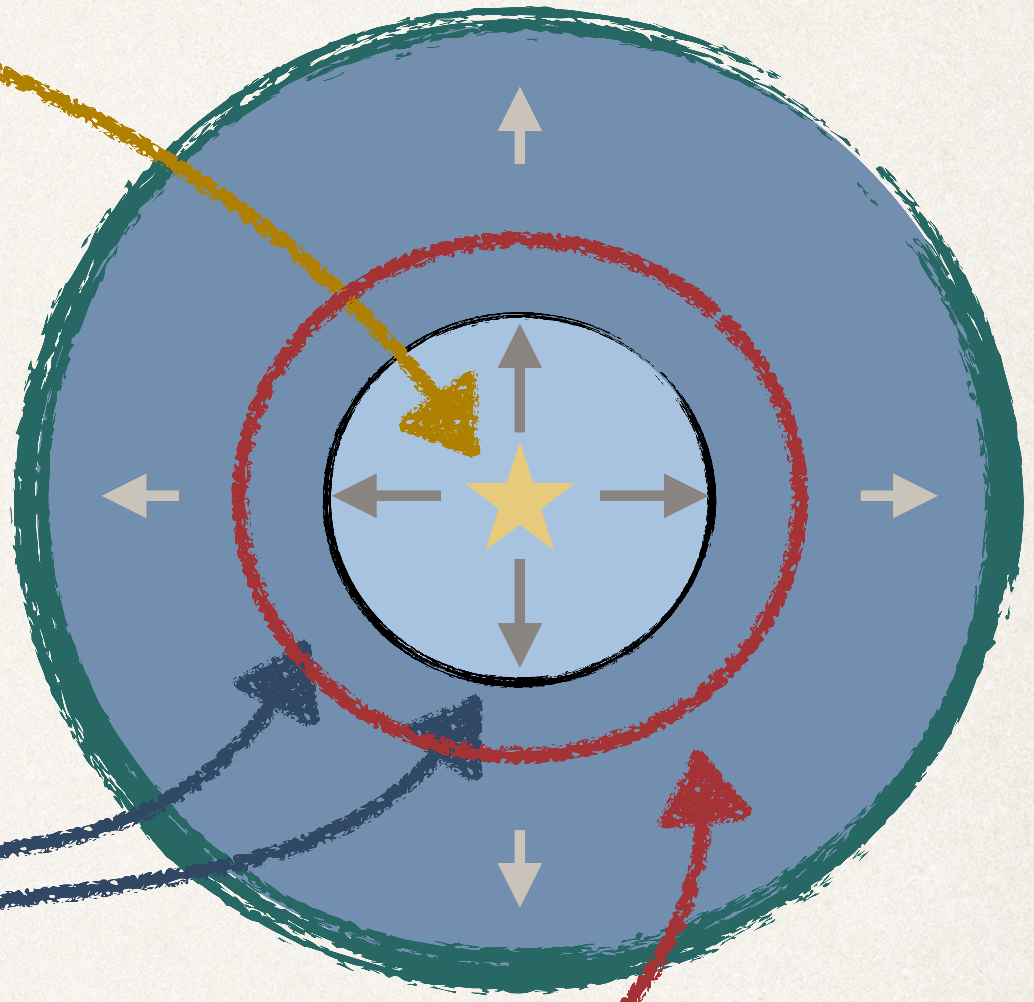
- SNR shocks



Relevant adiabatic losses for particle escaping the bubble

Negligible or null adiabatic losses

Possible acceleration mechanisms



Inside the SC core:

- Colliding winds from binary stars
  (fraction of massive stars in binary systems ~50%-100%)
- Single stellar wind termination shocks

Inside the hot bubble:

- Acceleration due to turbulence (II order)
- Collective cluster wind termination shock

Entire bubble:

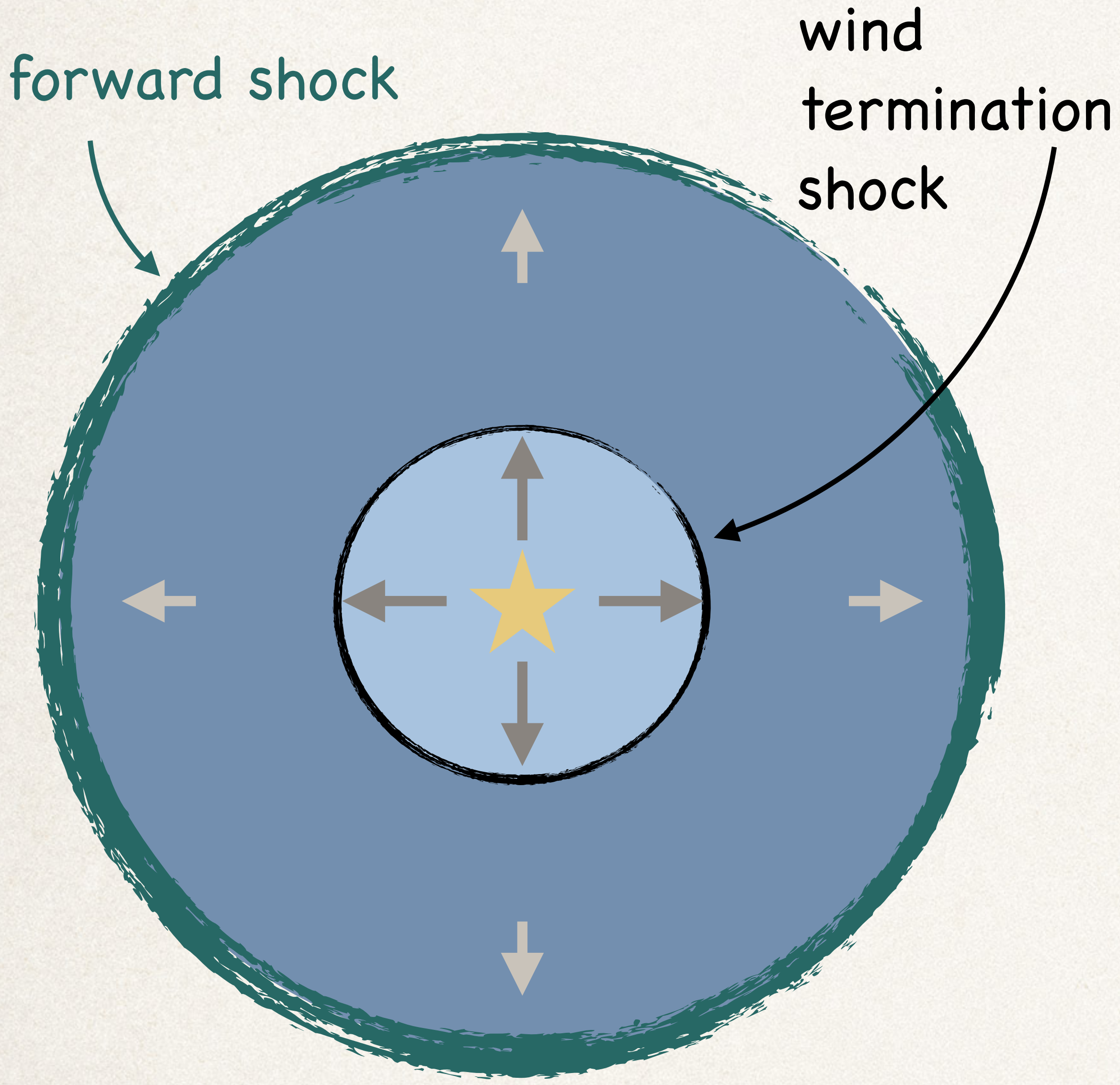
- SNR shocks

Relevant adiabatic losses for particle escaping the bubble

Negligible or null adiabatic losses

Caveat 1: non spherical evolution

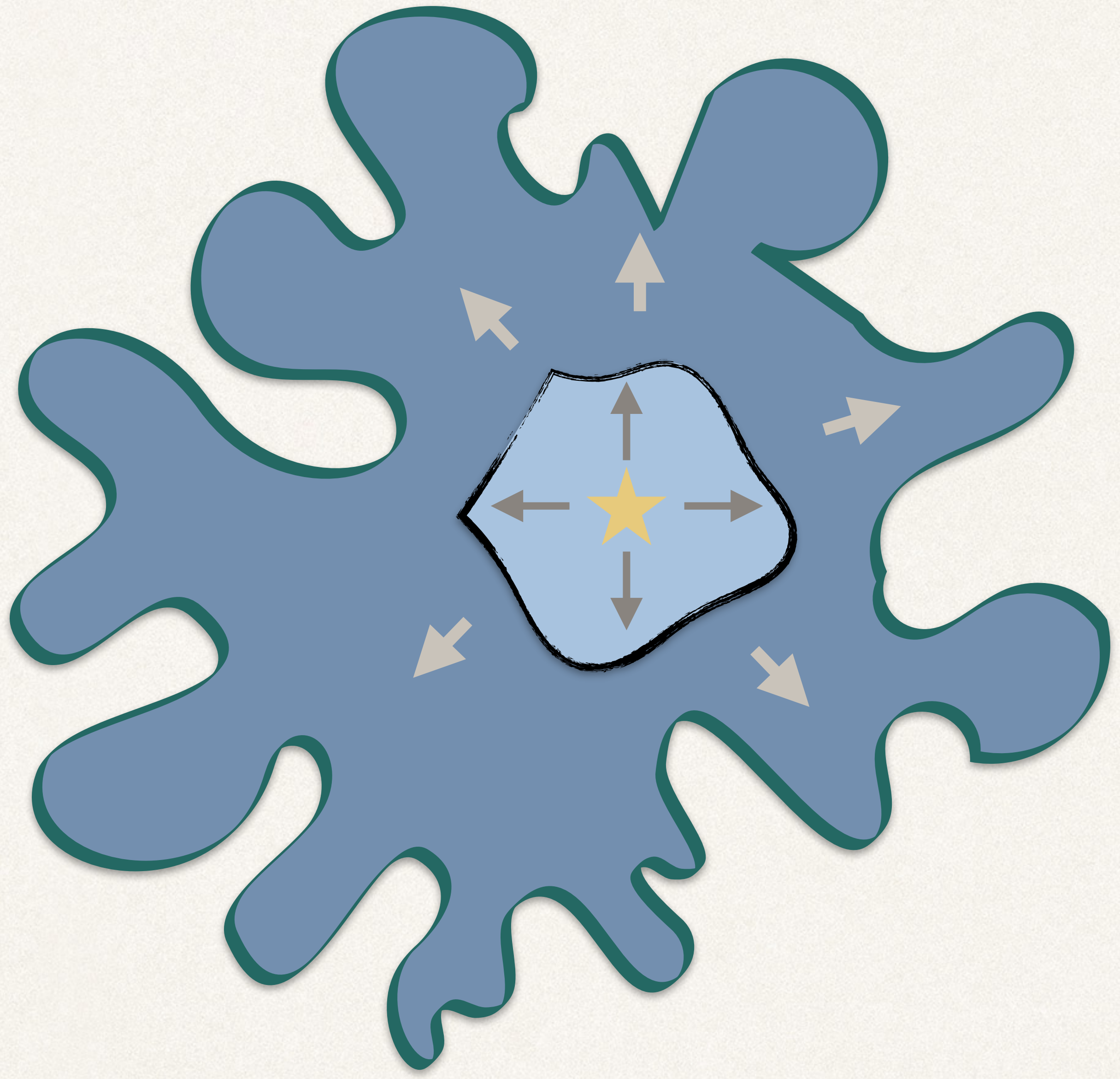
Idealised spherical model



Pure adiabatic model

[Weaver & McCray (1977)]

Realistic fractal structure



Effects that produce HD instabilities:

- ISM inhomogeneities
- Wind clumpiness (WR)
- Cooling

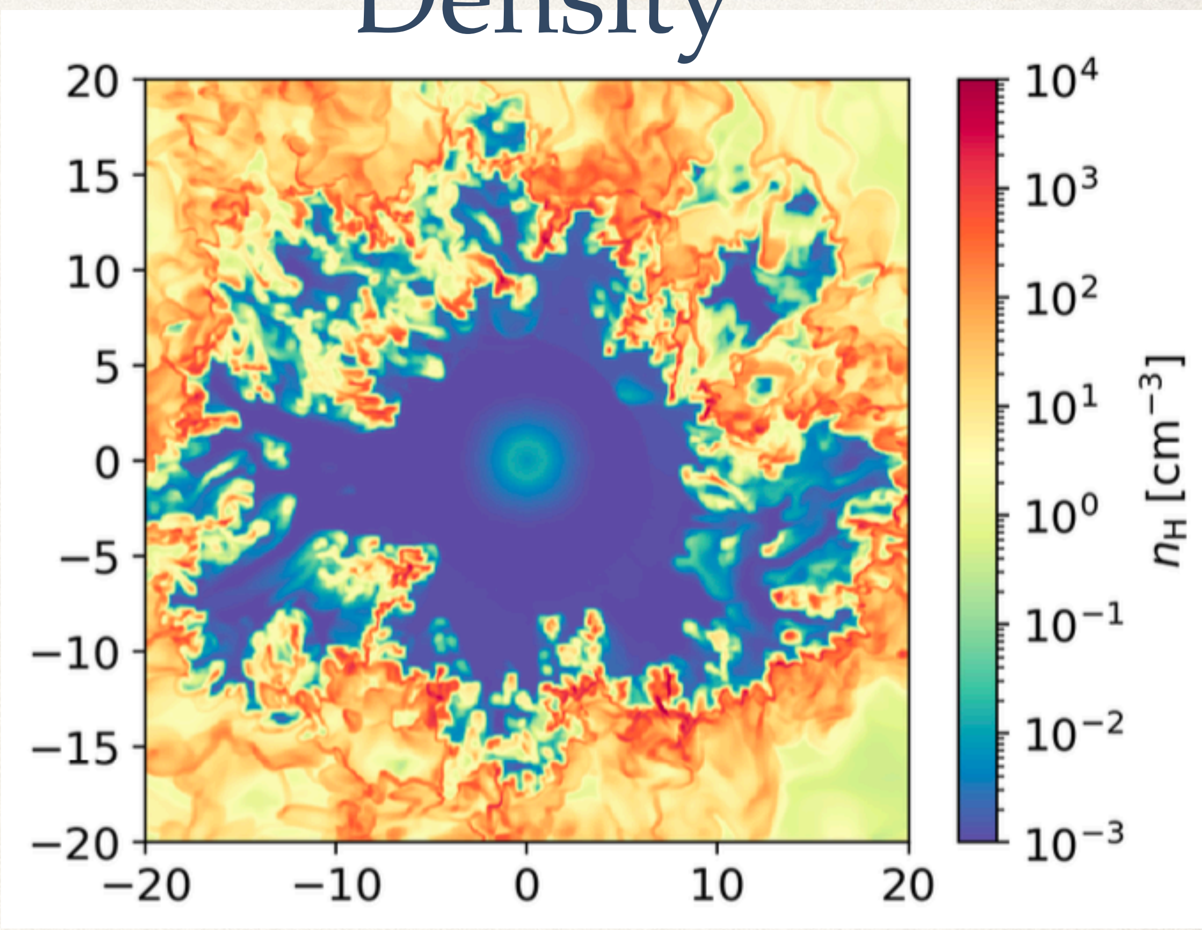
Effects that damp HD instabilities:

- Magnetic field pressure

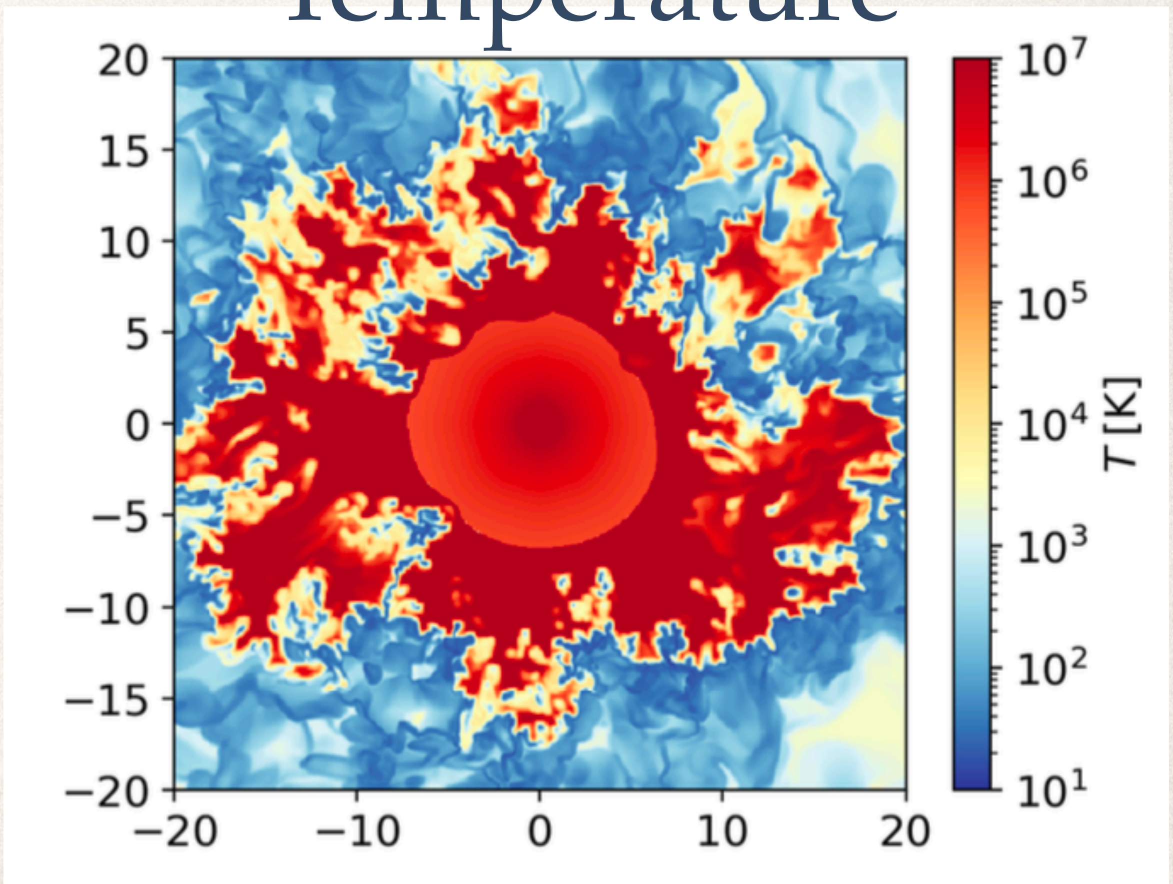
Important for:

- Particle transport
- Emission processes

Density



Temperature



[see e.g., L. Lancaster et al. (2021)]

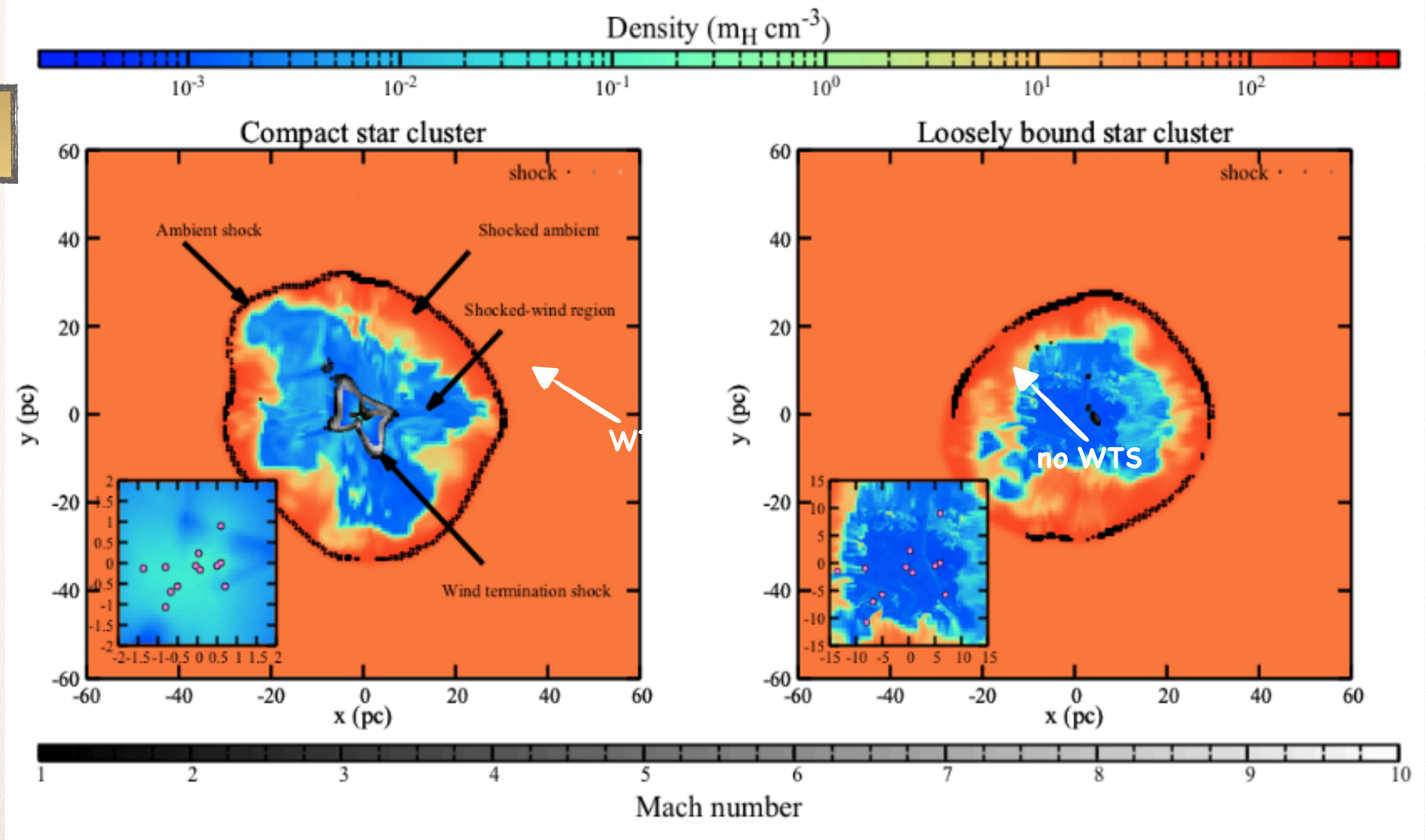
Caveat 2: compactness

[Gupta, Nath, Sharma & Eichler, MNRAS 2020]

A WTS is generated if the cluster is compact enough, such that $R_{\text{cluster}} \ll R_{\text{ts}}$

Compact cluster

Collective WTS is generated



Loose cluster

No collective WTS

Acceleration may be due to:

- Single star WTS
- Wind wind collision
- Magnetic turbulence

II order Fermi acceleration due to turbulence

The hot bubble is expected to be highly turbulent

Space-diffusion and momentum-diffusion connected by $D_{xx} D_{pp} = \frac{1}{9} p^2 V_A^2$ (Thornbury & Drury 2014)

- 1st order Fermi acceleration timescale $\tau_{\rm acc} \approx 8\, D/V_{\rm sh}^2$
- 2nd order Fermi acceleration timescale $\tau_{\rm acc} \approx 3\, D/V_{\rm A}^2$

1st and 2nd order may have similar timescales if $V_A \sim V_{\rm sh}$

$$V_A = \frac{B}{\sqrt{4\pi\rho}} \simeq 200 \left(\frac{B}{10\mu G}\right) \left(\frac{n}{0.01}\right)^{-1} \mathrm{km\,s^{-1}}$$

Maximum energy taking into account escape:

- Escaping time from the bubble $\tau_{\rm esc} \simeq \frac{R_{\rm bubble}^2}{6D}; \quad D = \eta\, B_{\rm Bohm}$
- $\tau_{\rm acc,} \approx \tau_{\rm esc} \;\Rightarrow\; E_{\max} \approx 36\, \eta^{-1} \left(\frac{B}{10\mu{\rm G}}\right) \left(\frac{R_{\rm bubble}}{50\,{\rm pc}}\right) \left(\frac{V_A}{100\,{\rm km/s}}\right)$ TeV

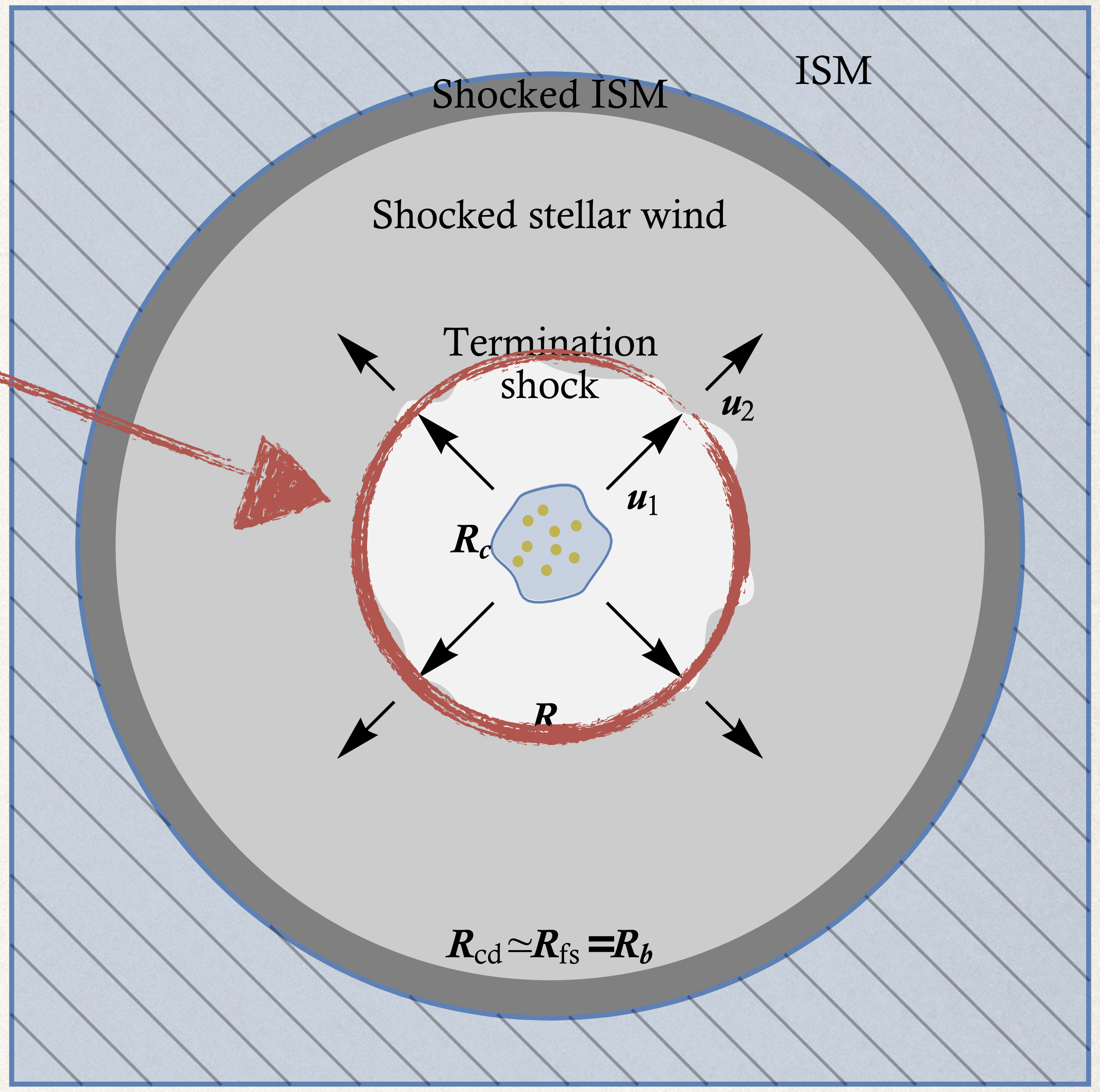
Particle acceleration at the wind termination shock

GM, Blasi, Peretti & Cristofari (2019)

Acceleration at the collective wind termination shock

[GM et al. (2019)]

- Particle injected and accelerated at the termination shock
  - ➡ Acceleration efficiency ~1-10 %



Particle acceleration at the wind termination shock

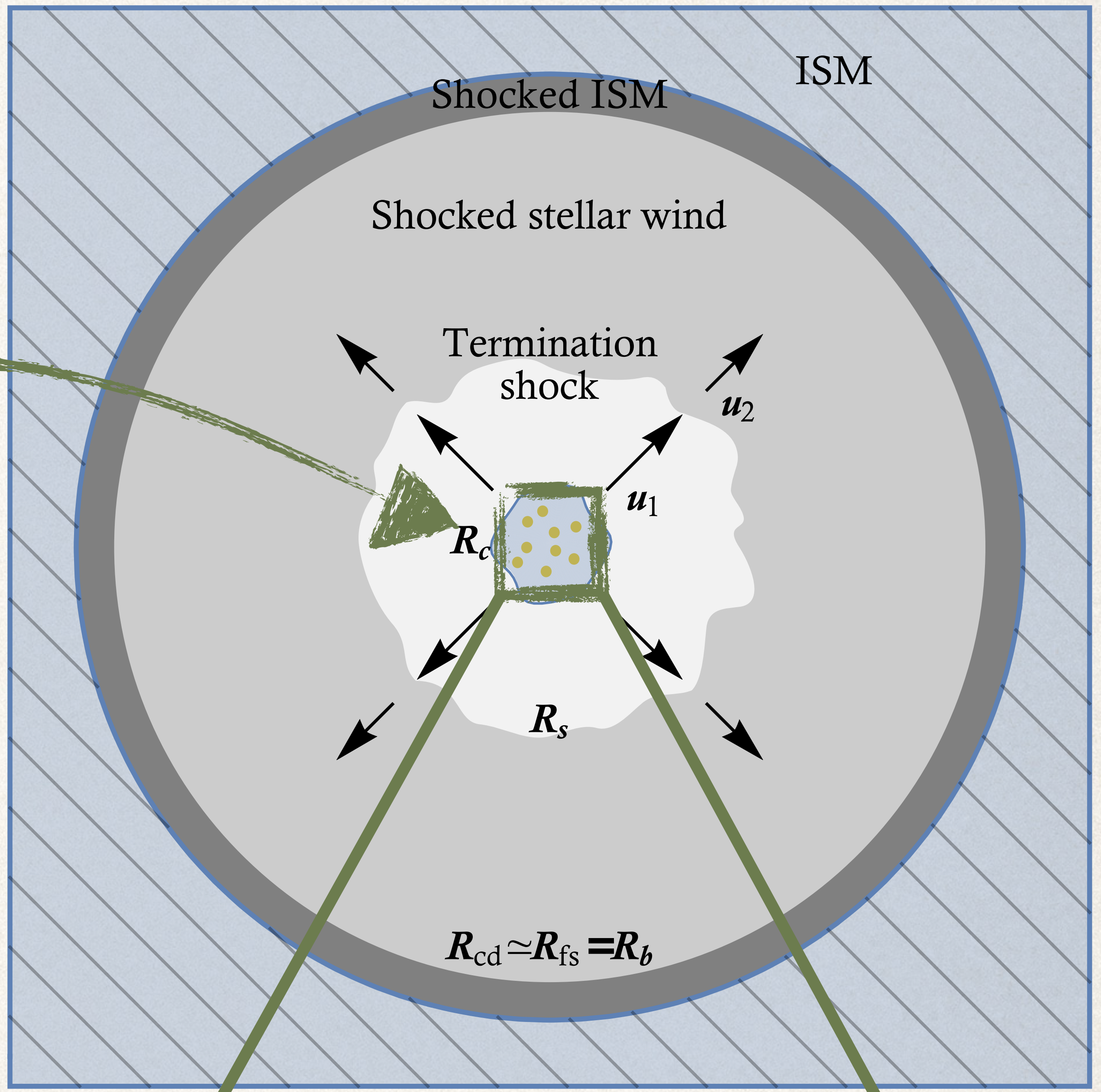
GM, Blasi, Peretti & Cristofari (2019)

Acceleration at the collective wind termination shock

[GM et al. (2019)]

- Particle injected and accelerated at the termination shock
  - ➡ Acceleration efficiency ~1-10 %
- Magnetic turbulence produced by MHD instabilities
  - ➡ Diffusion coefficient depends on the type of turbulence cascade:

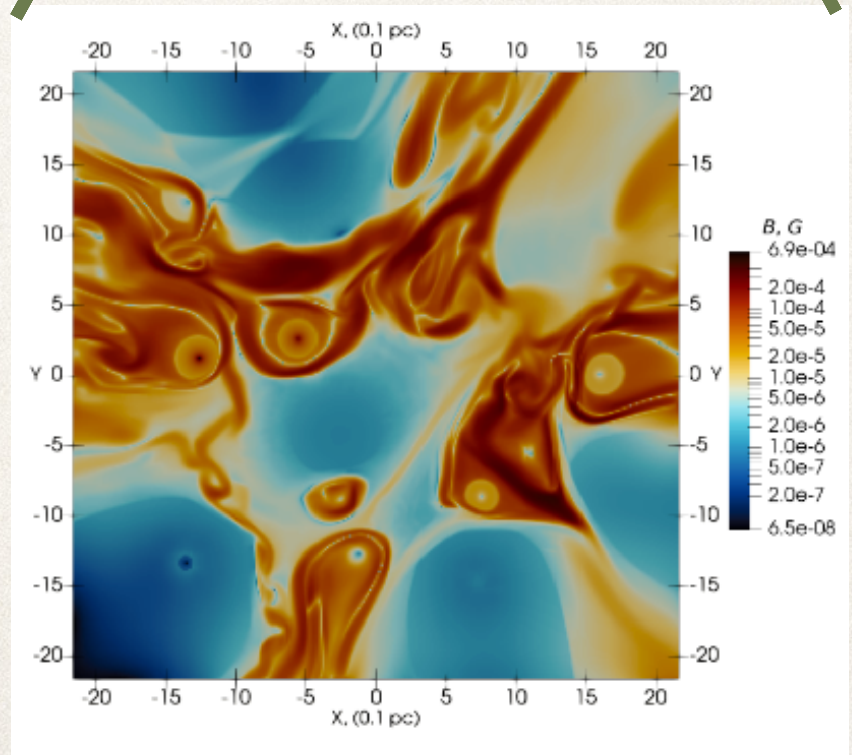
    Kolmogorov, Kraichnan, Bohm



1) MHD turbulence:
Assuming a fraction η_B of kinetic energy converted into magnetic field

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

Badmaev et al. (2022)



Particle acceleration at the wind termination shock

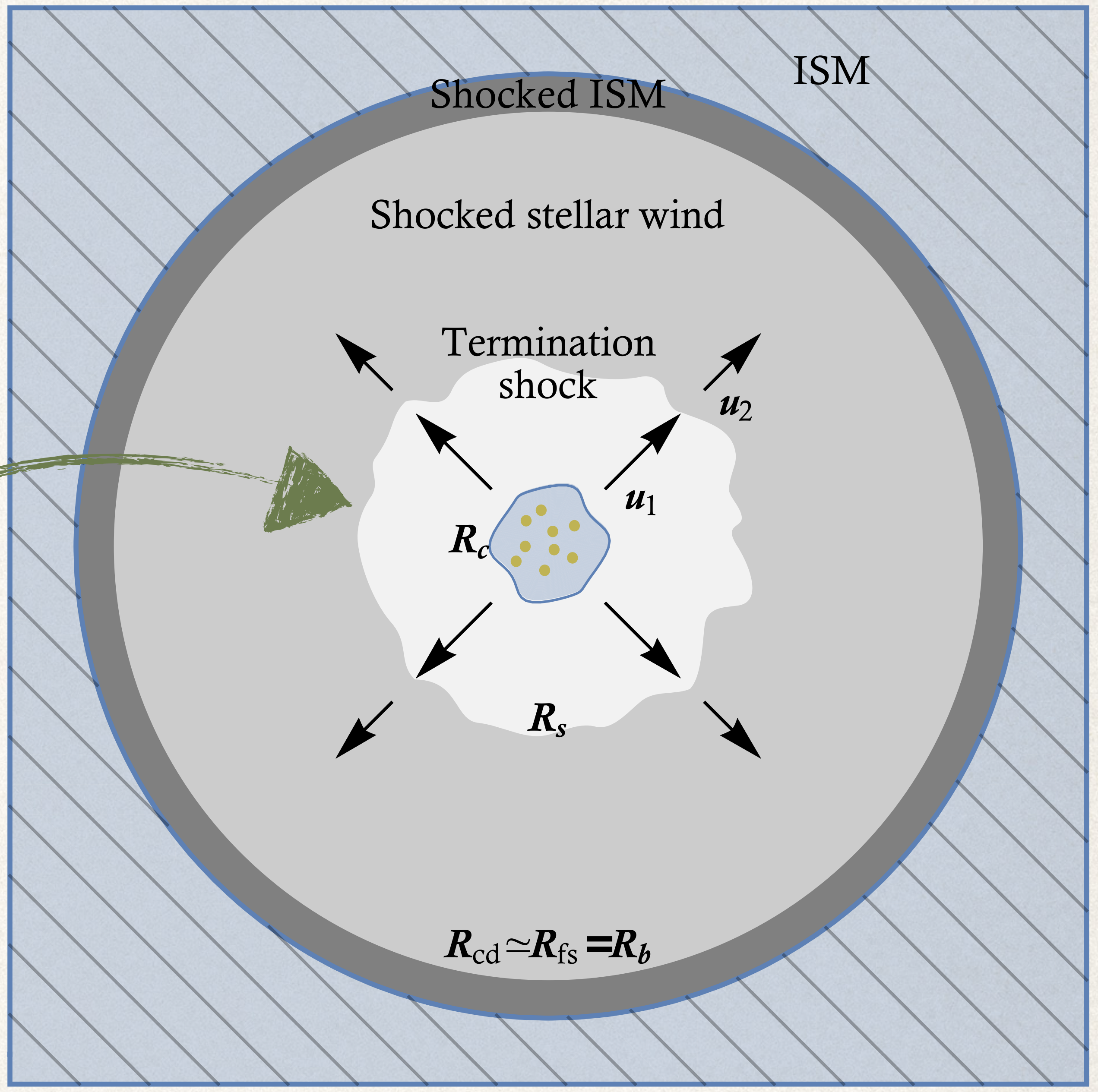
GM, Blasi, Peretti & Cristofari (2019)

Acceleration at the collective wind termination shock

[GM et al. (2019)]

- Particle injected and accelerated at the termination shock
  - ➡ Acceleration efficiency ~1-10 %
- Magnetic turbulence produced by MHD instabilities
  - ➡ Diffusion coefficient depends on the type of turbulence cascade:

Kolmogorov, Kraichnan, Bohm



2) Self-generated magnetic turbulence
Applying resonant instability:

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

Self-amplification may be relevant al low energies but not at high energies

3) Non-resonant instability is suppressed (too small current)

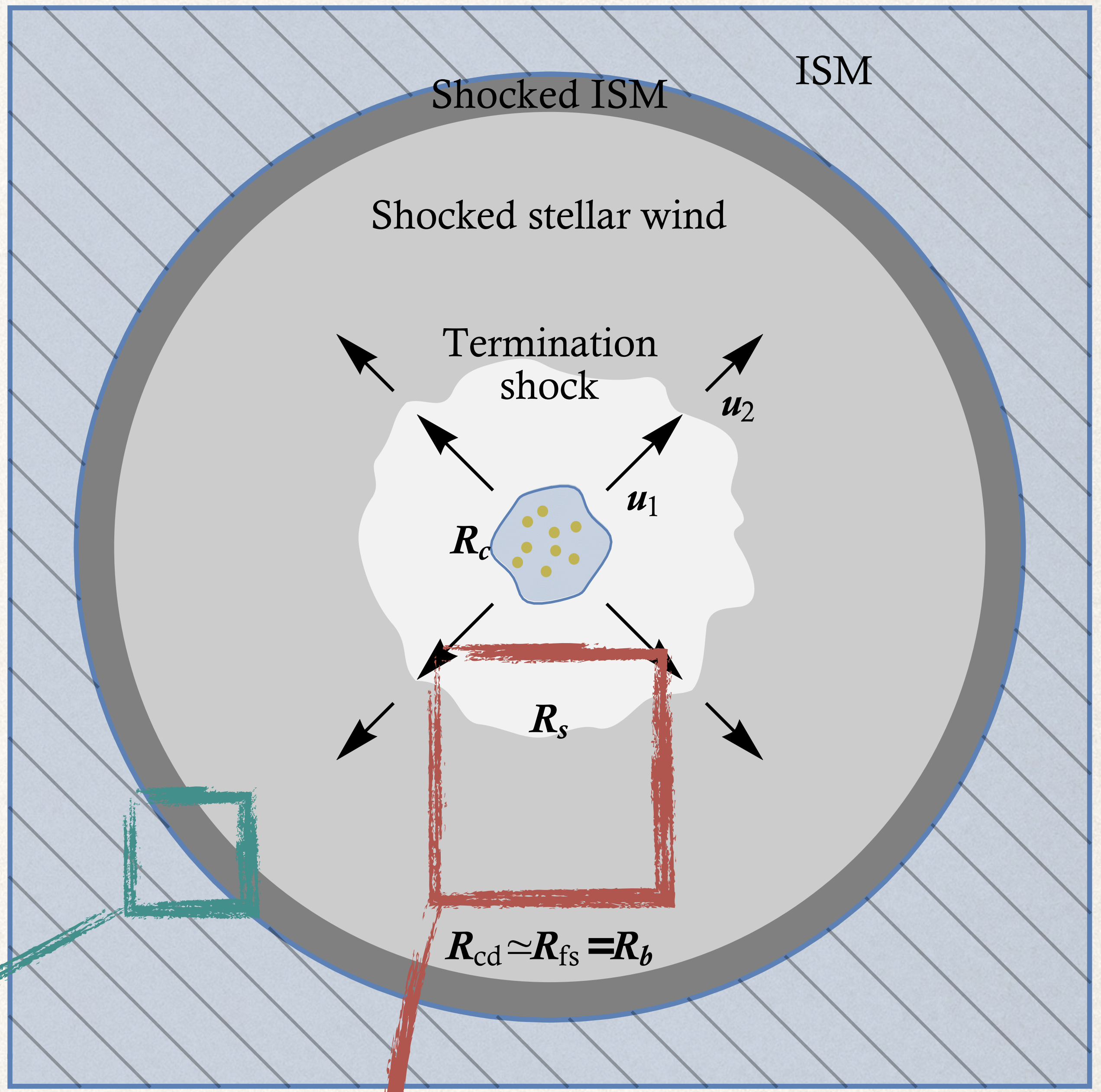
Particle acceleration at the wind termination shock

GM, Blasi, Peretti & Cristofari (2019)

Acceleration at the collective wind termination shock

[GM et al. (2019)]

- Particle injected and accelerated at the termination shock
  - ➡ Acceleration efficiency ~1-10 %
- Magnetic turbulence produced by MHD instabilities
  - ➡ Diffusion coefficient depends on the type of turbulence cascade: Kolmogorov, Kraichnan, Bohm
- Particle diffuse and interact in the bubble



Hadronic $p_{cr} + p_{gas} \rightarrow p + p + \pi^{\pm} + \pi^{0}$

$$\boxed{\pi^0 \rightarrow \gamma\,\gamma}$$

Leptonic IC : $e_{cr} + \gamma_{CMB,IR,opt} \rightarrow \boxed{e_{cr} + \gamma_{HE}}$

Particle acceleration at the wind termination shock

GM, Blasi, Peretti & Cristofari (2019)

Solution at the shock

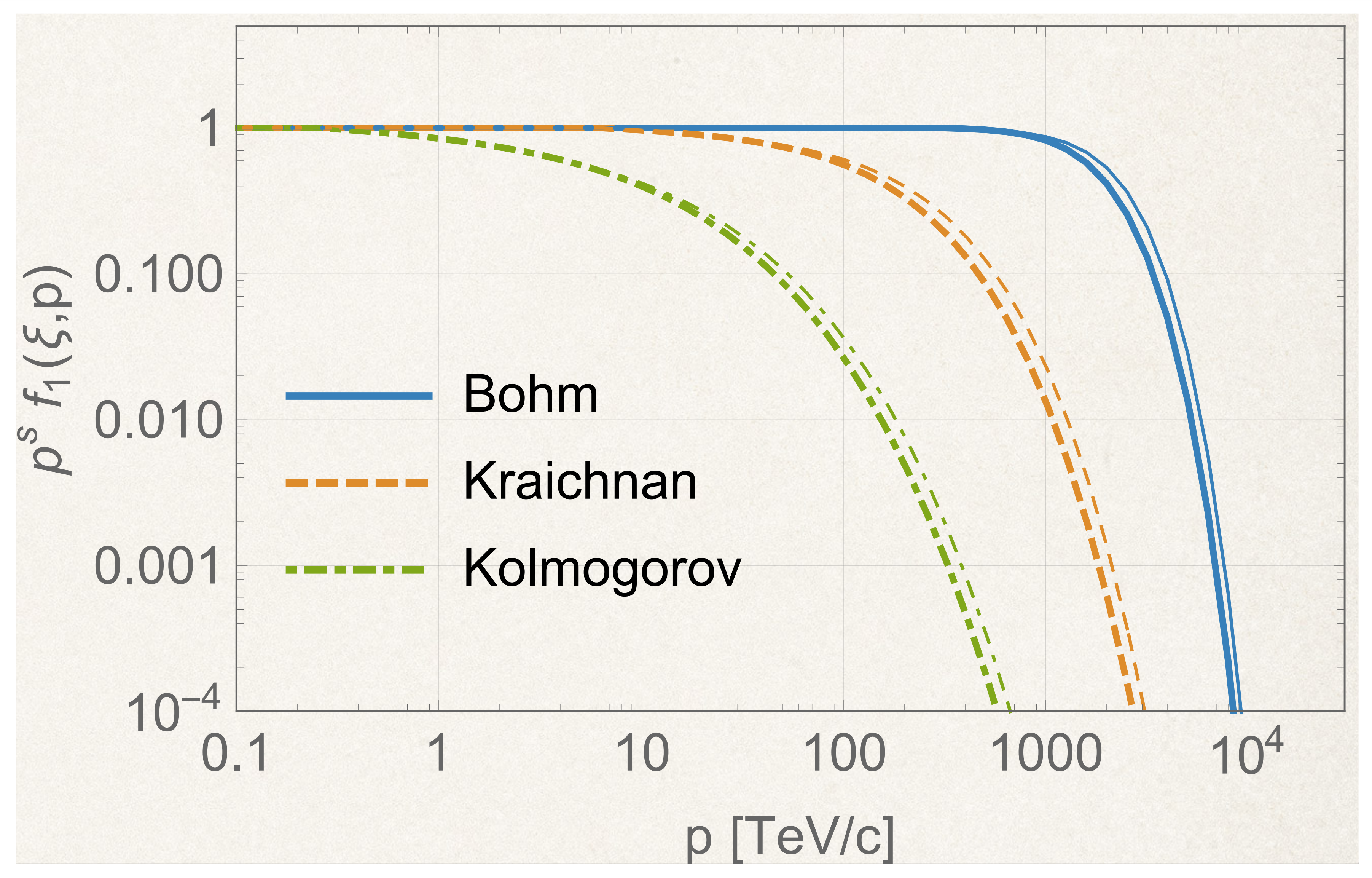
$$f_s(p) = s\frac{\eta_{\rm inj}\, n_1}{4\pi\, p_{\rm inj}^3}\left(\frac{p}{p_{\rm inj}}\right)^{-s} e^{-\Gamma_1(p)}\ e^{-\Gamma_2(p)}$$

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



Particle acceleration at the wind termination shock

GM, Blasi, Peretti & Cristofari (2019)

Solution at the shock

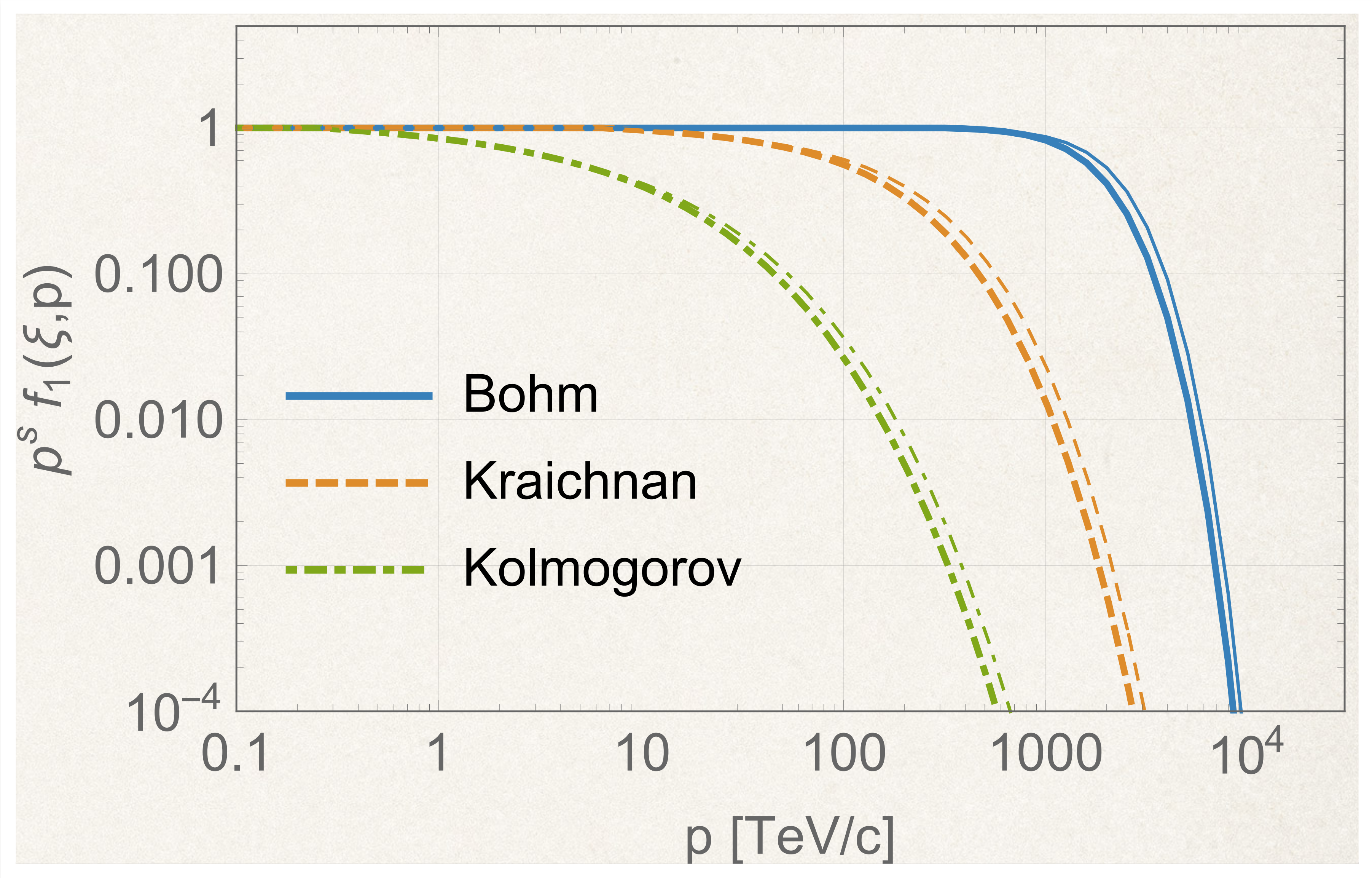
$$f_s(p) = s\frac{\eta_{\rm inj}\, n_1}{4\pi\, p_{\rm inj}^3}\left(\frac{p}{p_{\rm inj}}\right)^{-s} e^{-\Gamma_1(p)}\ e^{-\Gamma_2(p)}$$

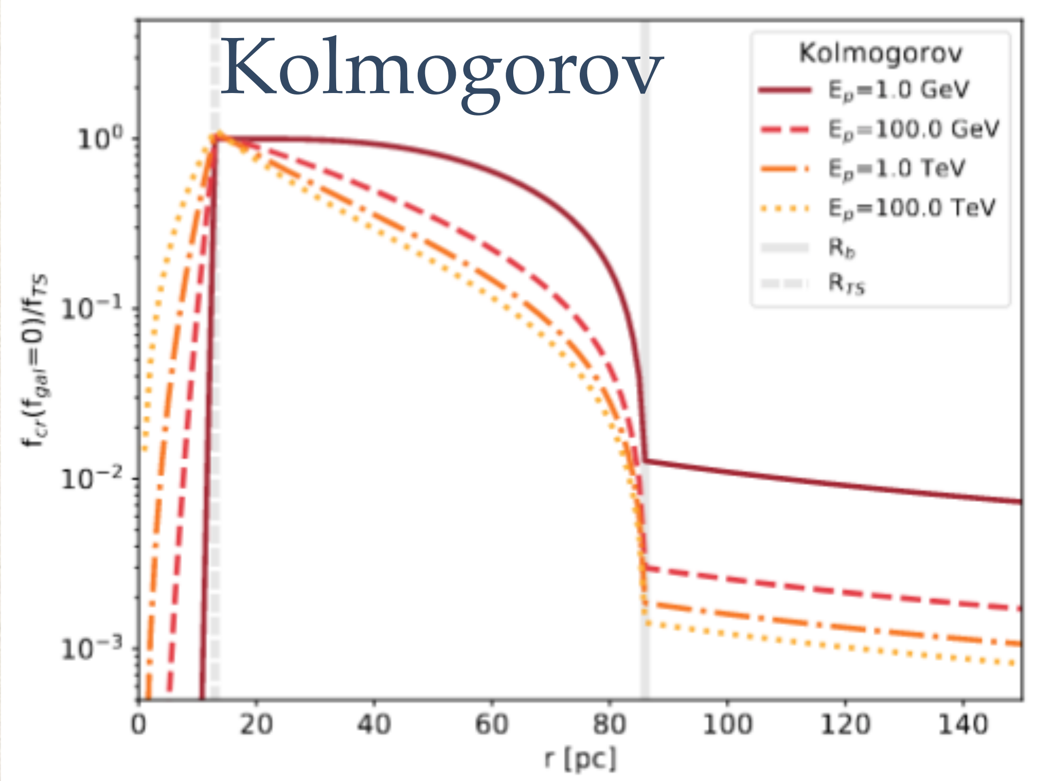
Standard power-law for plane shocks

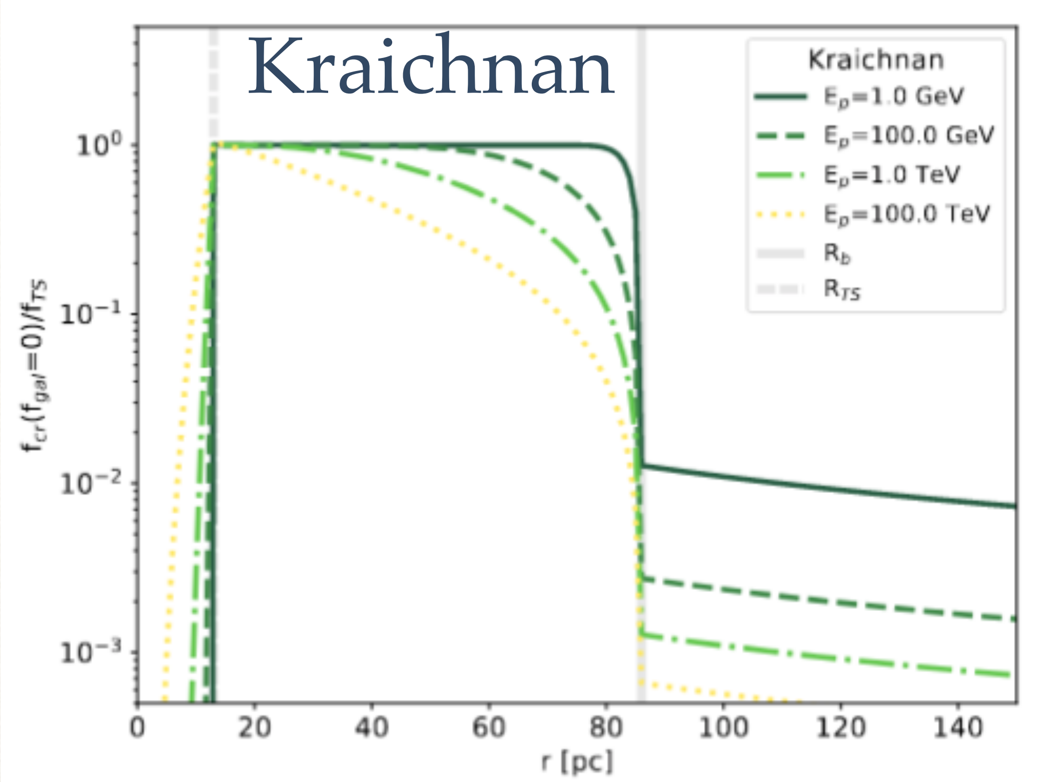
$$s = \frac{3\sigma}{\sigma - 1}$$

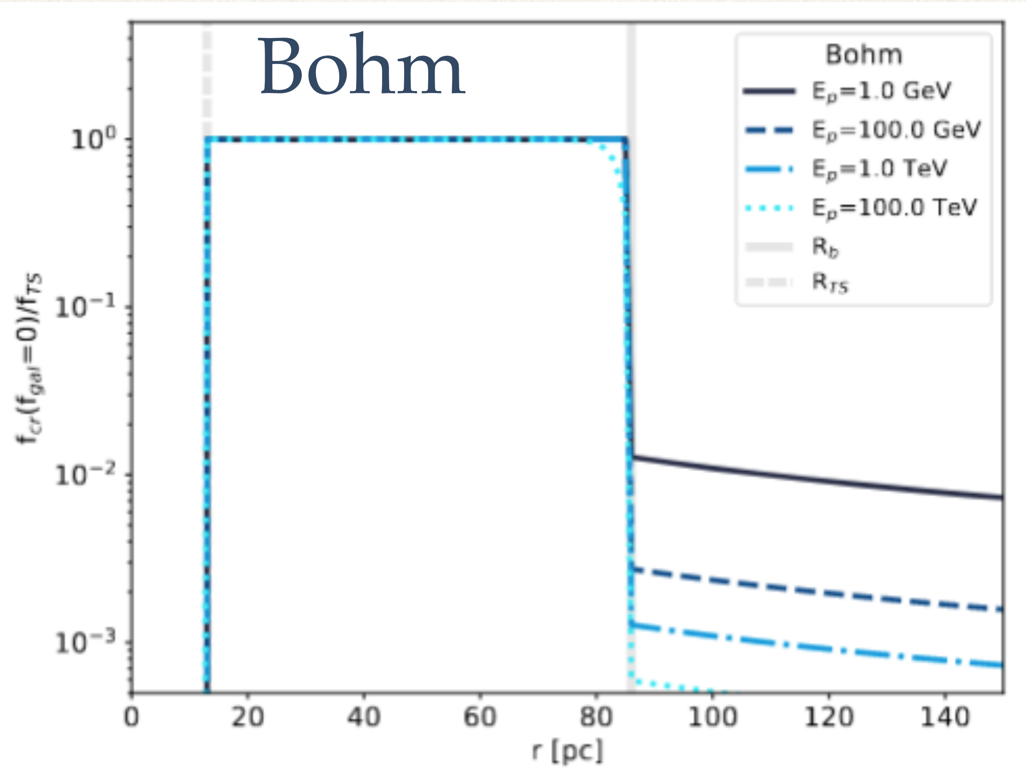
Cutoff due to particle confinement upstream in a spherical geometry

Cutoff due to particle escaping from the bubble





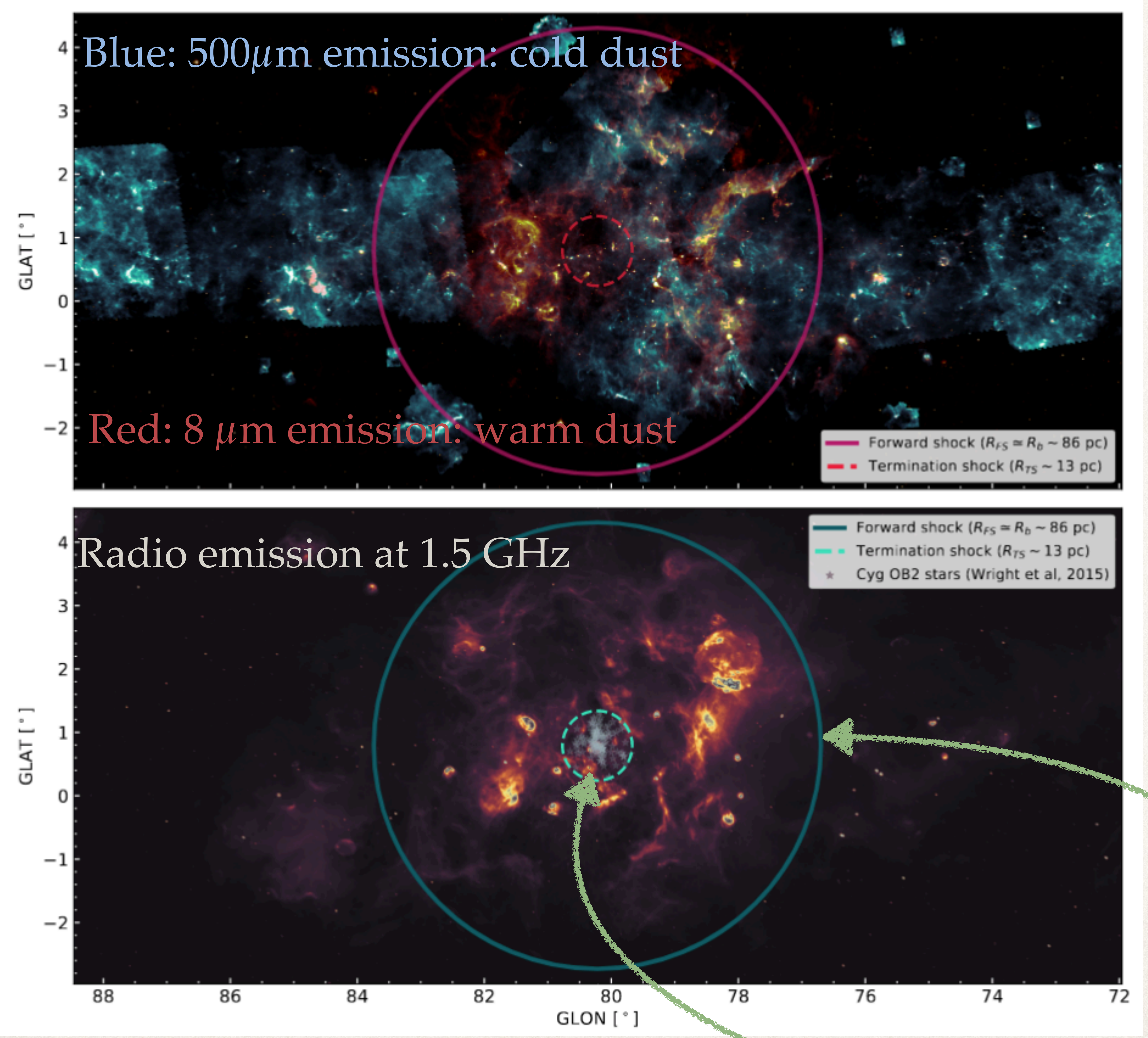




Spatial profile: the harder is the diffusion coefficient the flatter is the CR distribution

The case of Cygnus Cocoon

Menchiari, GM, Amato, Bucciantini & Beltran (2024)
Blasi & GM (2023)



Assumed properties

- Wind luminosity $\simeq 2 \times 10^{38}\,\mathrm{erg\,s^{-1}}$
- Ejecta mass $\dot{M} \simeq 10^{-4} M_{\odot}\,\mathrm{yr}^{-1}$;
- wind speed $v_w \simeq 2300\,\mathrm{kms}^{-1}$
- Cluster age $\simeq 3\,\mathrm{Myr}$
- Average ISM density $\simeq 10\,\mathrm{cm}^{-3}$

Wind luminosity inferred from stellar population as reported by Wright et al. (2015) MNRAS, 449, 741

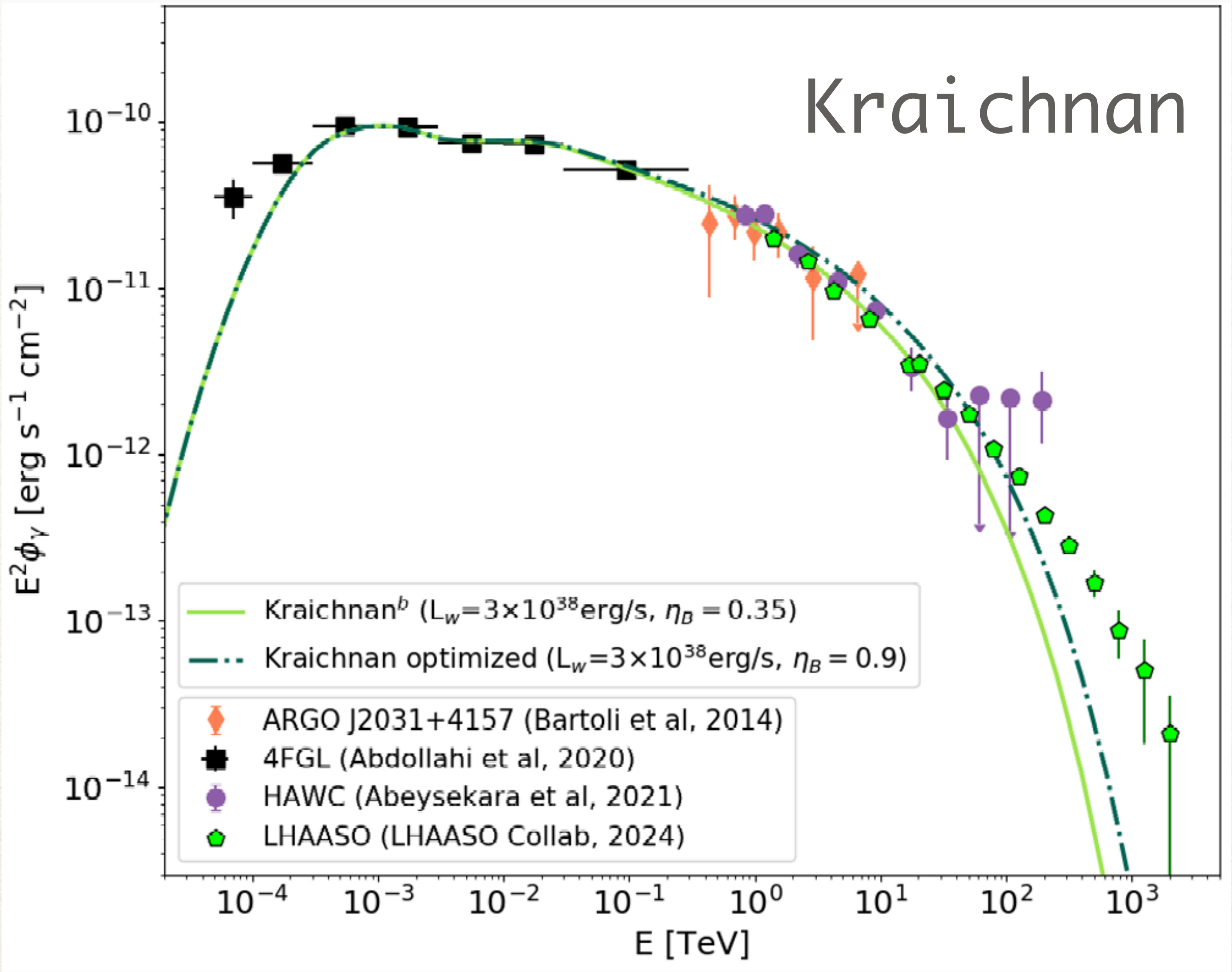
Estimated size of the bubble $\simeq$ 90 pc

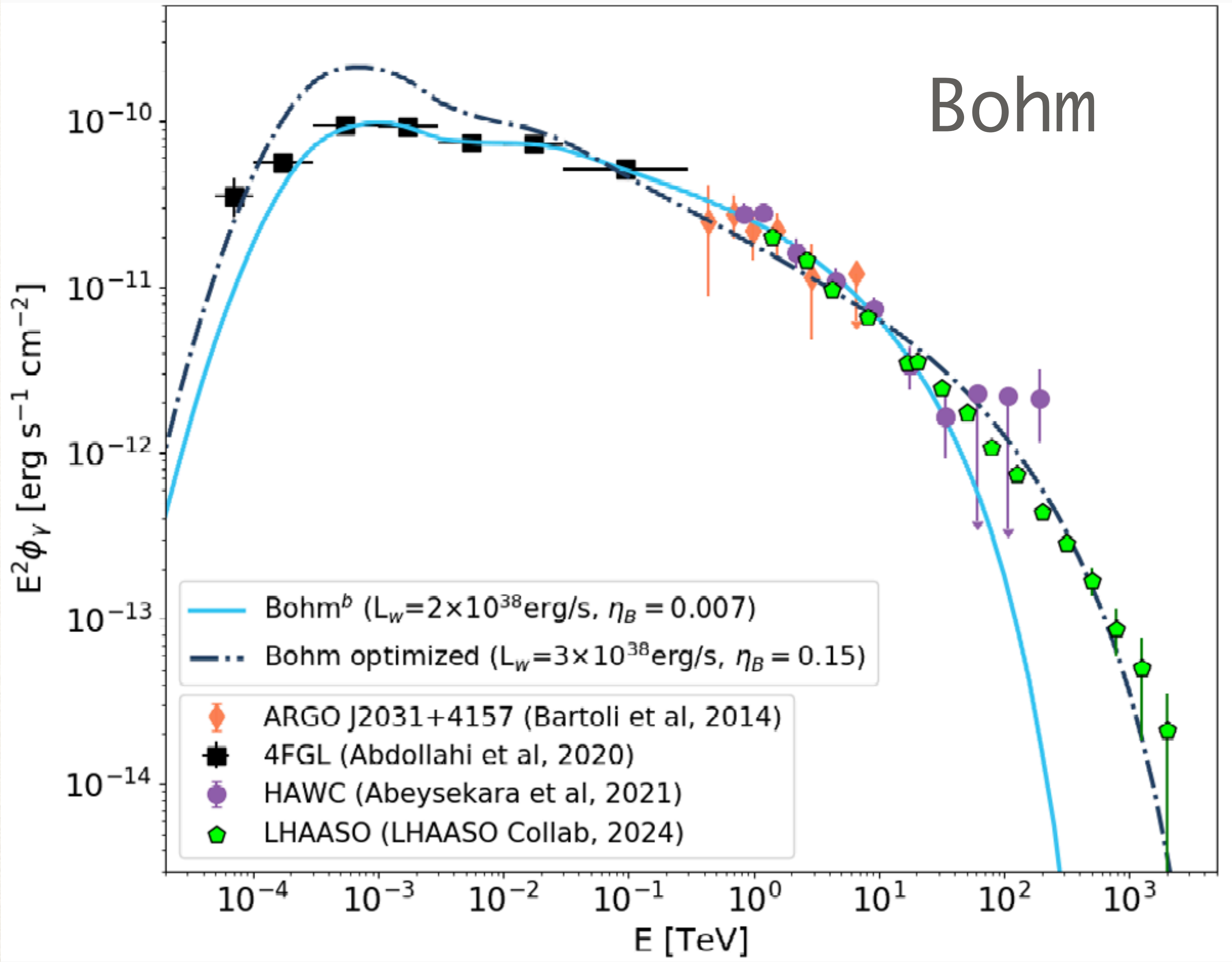
Termination shock radius $\simeq$ 13 pc

The case of Cygnus Cocoon

Menchiari, GM, Amato, Bucciantini & Beltran (2024)
Blasi & GM (2023)

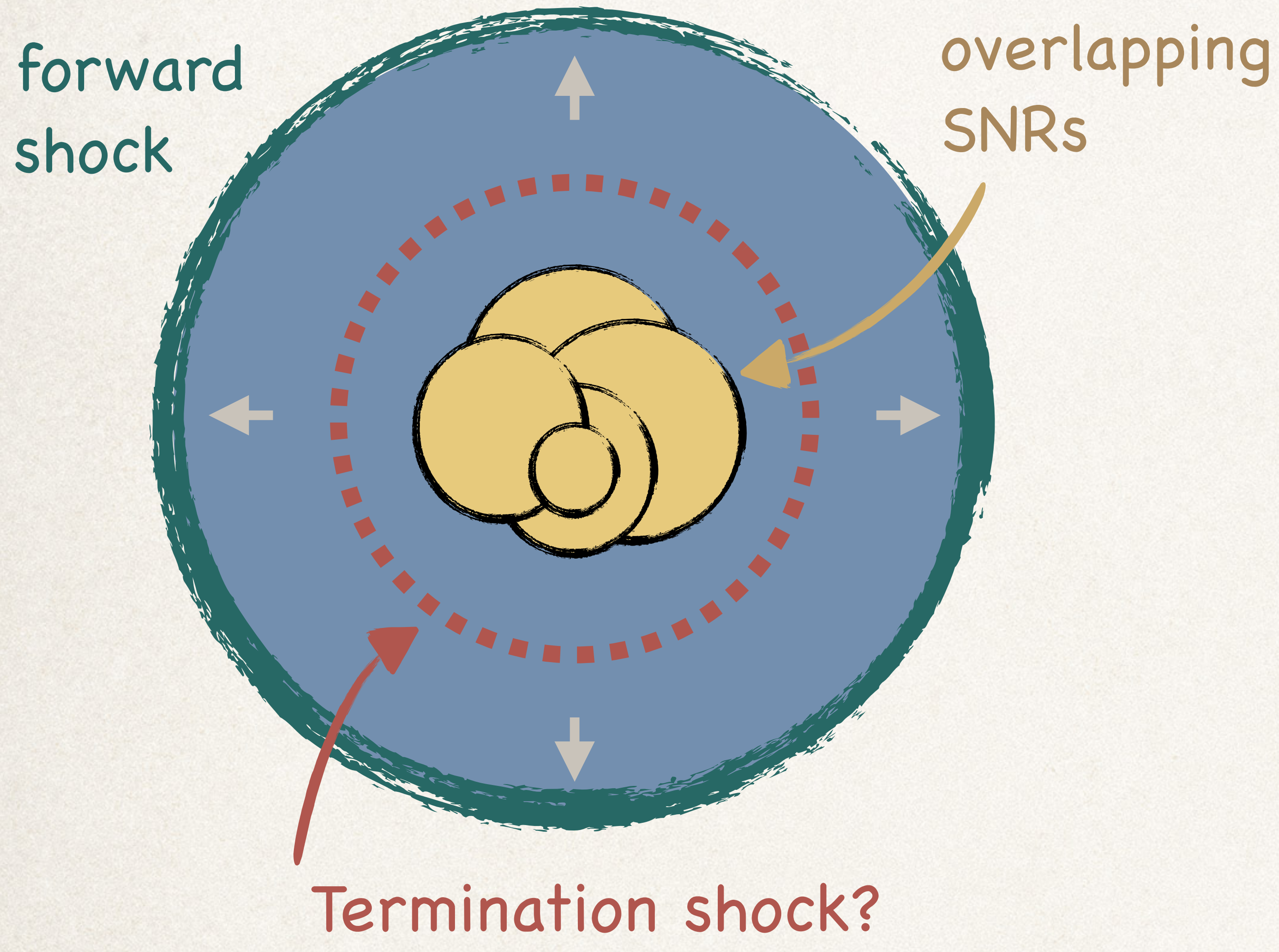
- Large magnetic field required ($\eta_B \gtrsim 20\,\%$)
- Kolmogorov diffusion excluded (requires too much wind power)
- Kraichnan is not sufficient at highest energies
- Bohm may explain high energy data but Fermi-LAT data are not well fitted
- Difficult to reproduce the extension of ~150 pc





Onset of SN explosion → super-bubbles

$t \gtrsim 3\,\mathrm{Myr}$ stellar wind + SNe

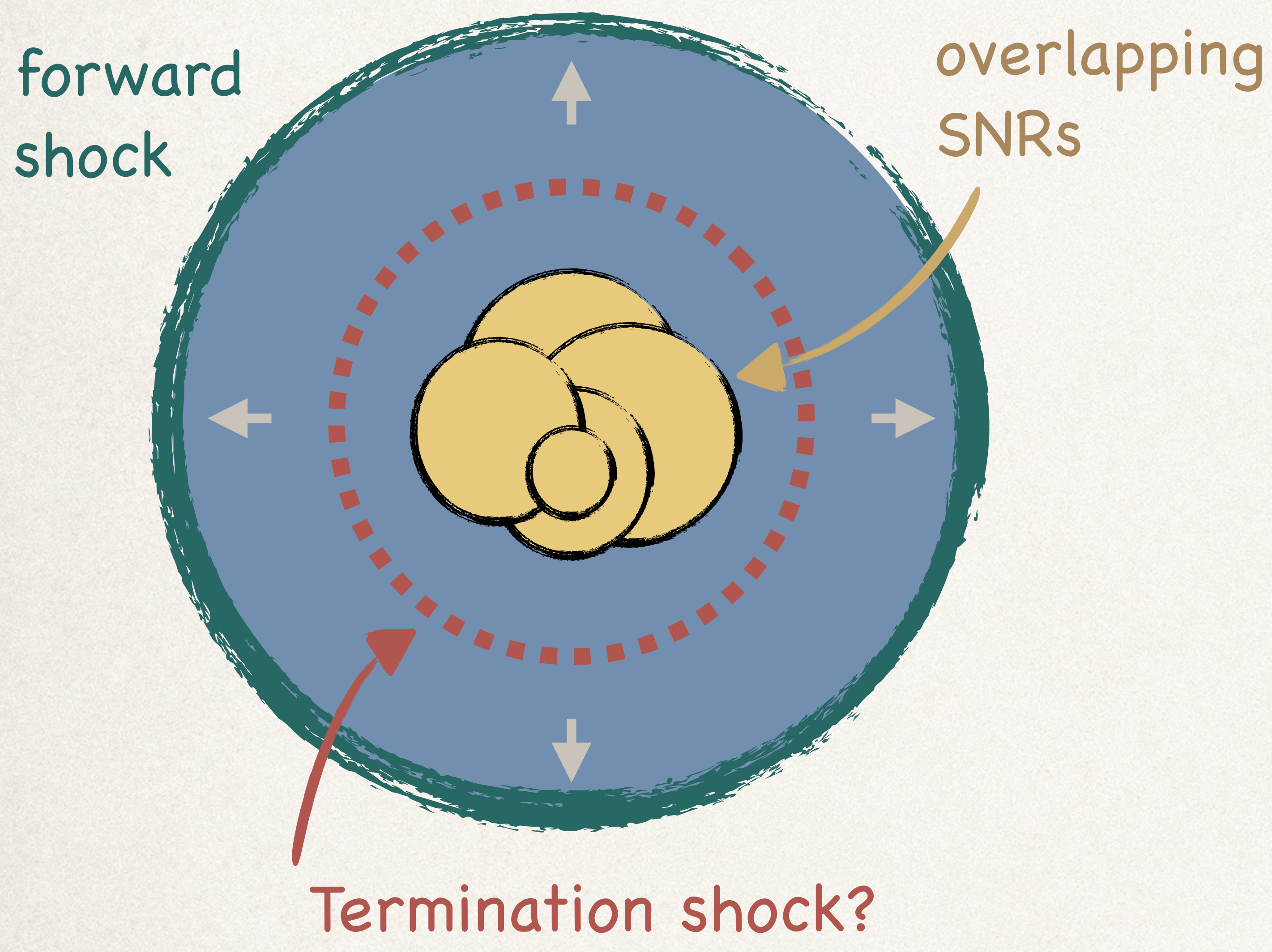


Main effects on the SNR evolution

1. High temperature ⇒ low Mach number
    - The SNR dies inside the bubble in a timescale shorter than isolated SNR: ($v_{\rm sh} = c_{\rm s}$ @ $\sim 10^4$ yr)
2. High turbulence ⇒ high magnetic field
    - low Alfvénic Mach number
    - faster acceleration time

Onset of SN explosion → super-bubbles

$t \gtrsim 3$ Myr   stellar wind + SNe

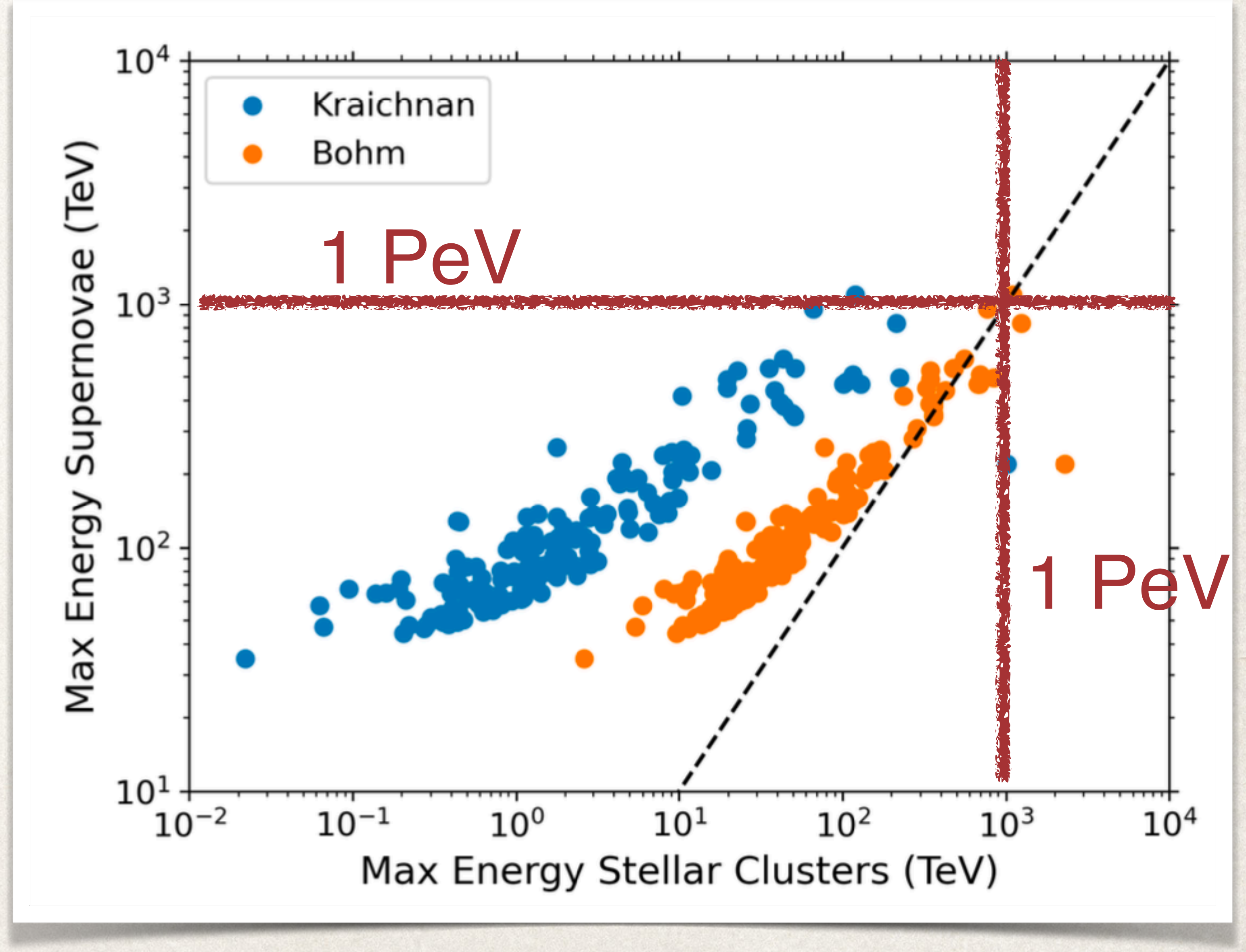


Main effects on the SNR evolution

1. High temperature ⇒ low Mach number
    - The SNR dies inside the bubble in a timescale shorter than isolated SNR: ($v_{sh} = c_s$ @ ~ 10^4 yr)
2. High turbulence ⇒ high magnetic field
    - low Alfvénic Mach number
    - faster acceleration time

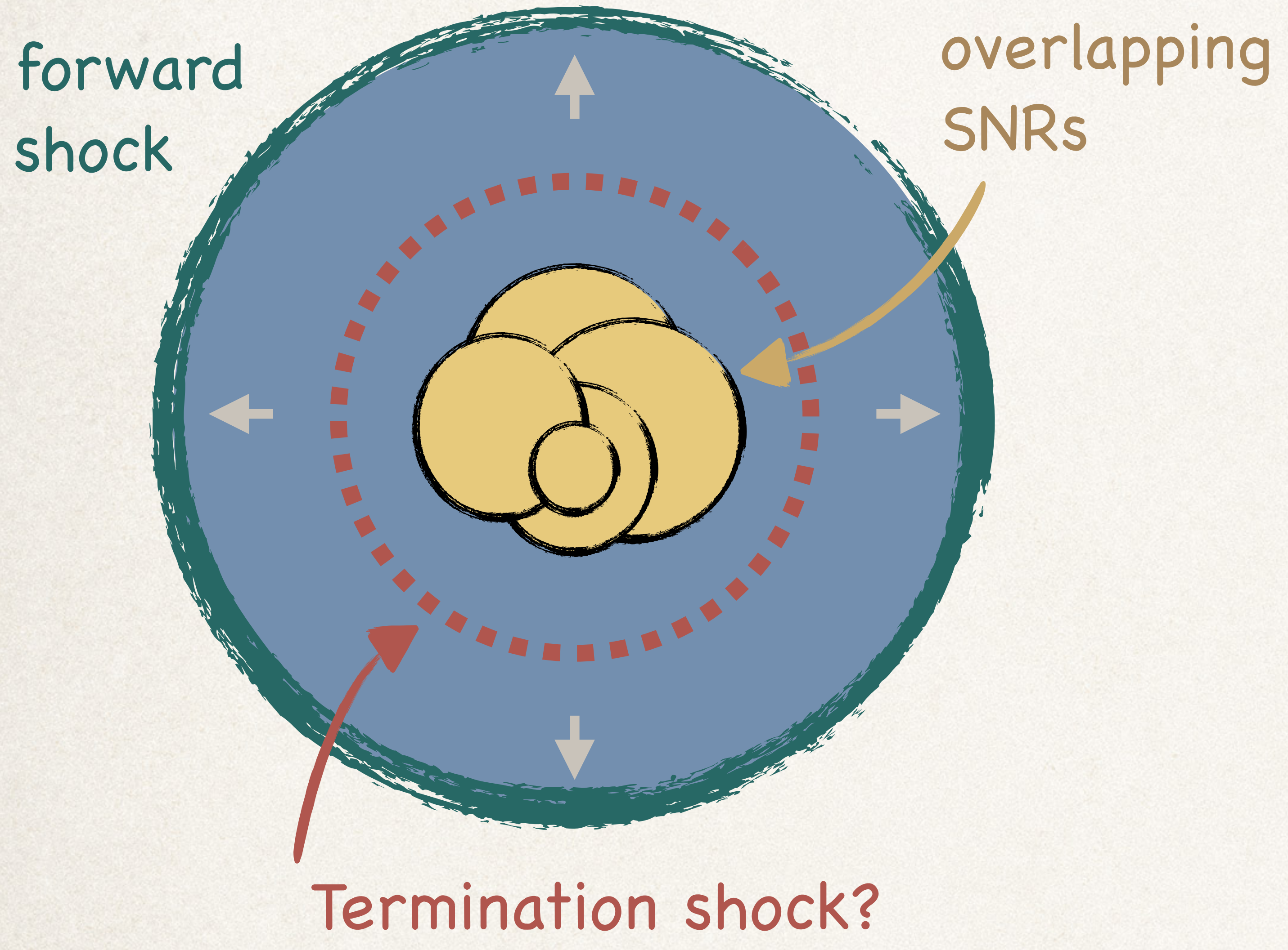
Mitchell et al. arXiv: 2403.16650

Maximum energy of SNR vs WTS for the Gaia clusters



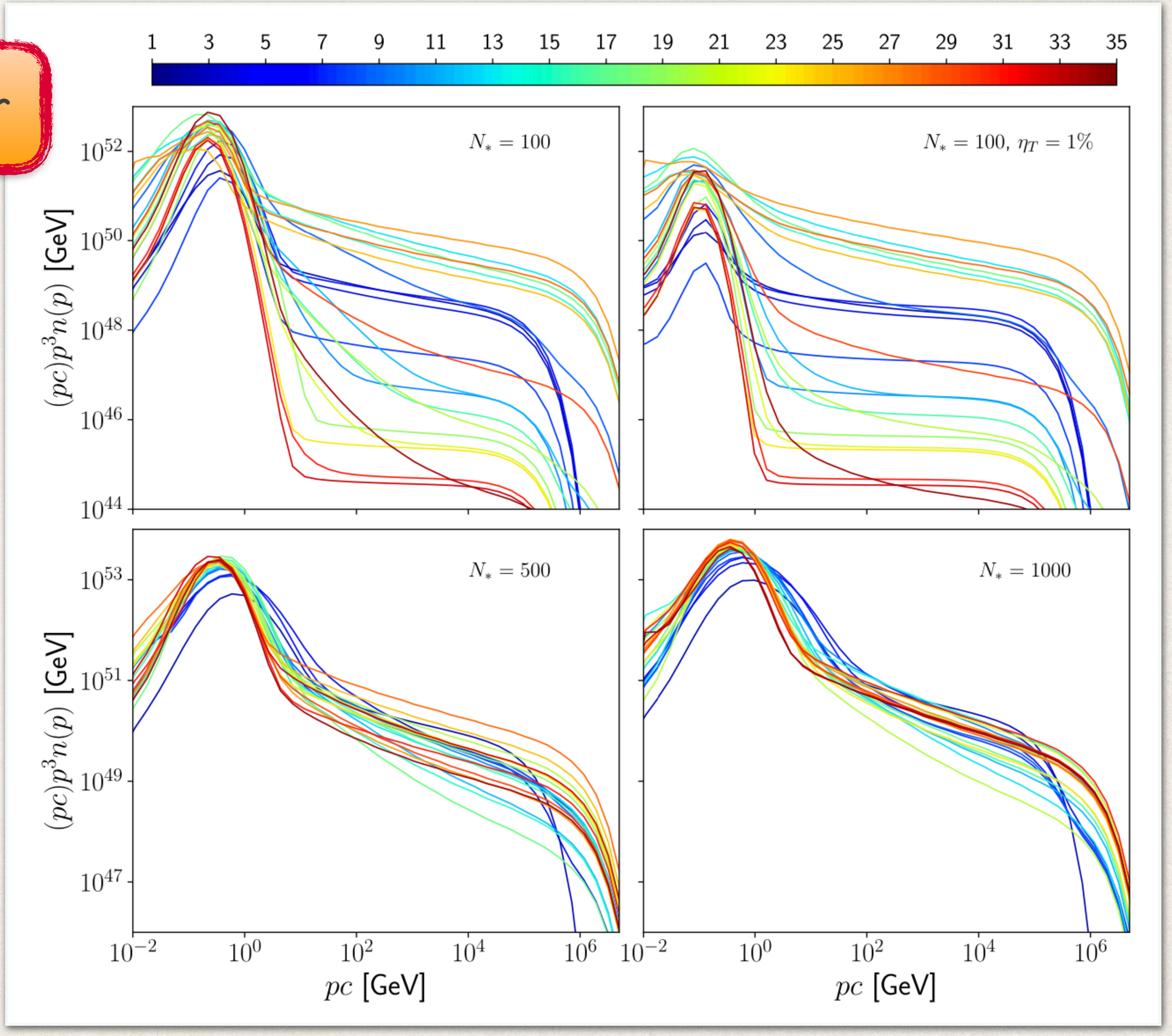
Super-bubbles: intermittency

$t \gtrsim 3\,\mathrm{Myr}$ stellar wind + SNe



<u>Vieu et al. (2022)</u>:

consider acceleration at WTS + SNR forward shock + turbulent acceleration



Time in Myr

- Energetically Super-bubbles may produce the bulk of CRs
- Maximum energy can reach ~PeV
- The spectrum is not universal -> strong intermittency

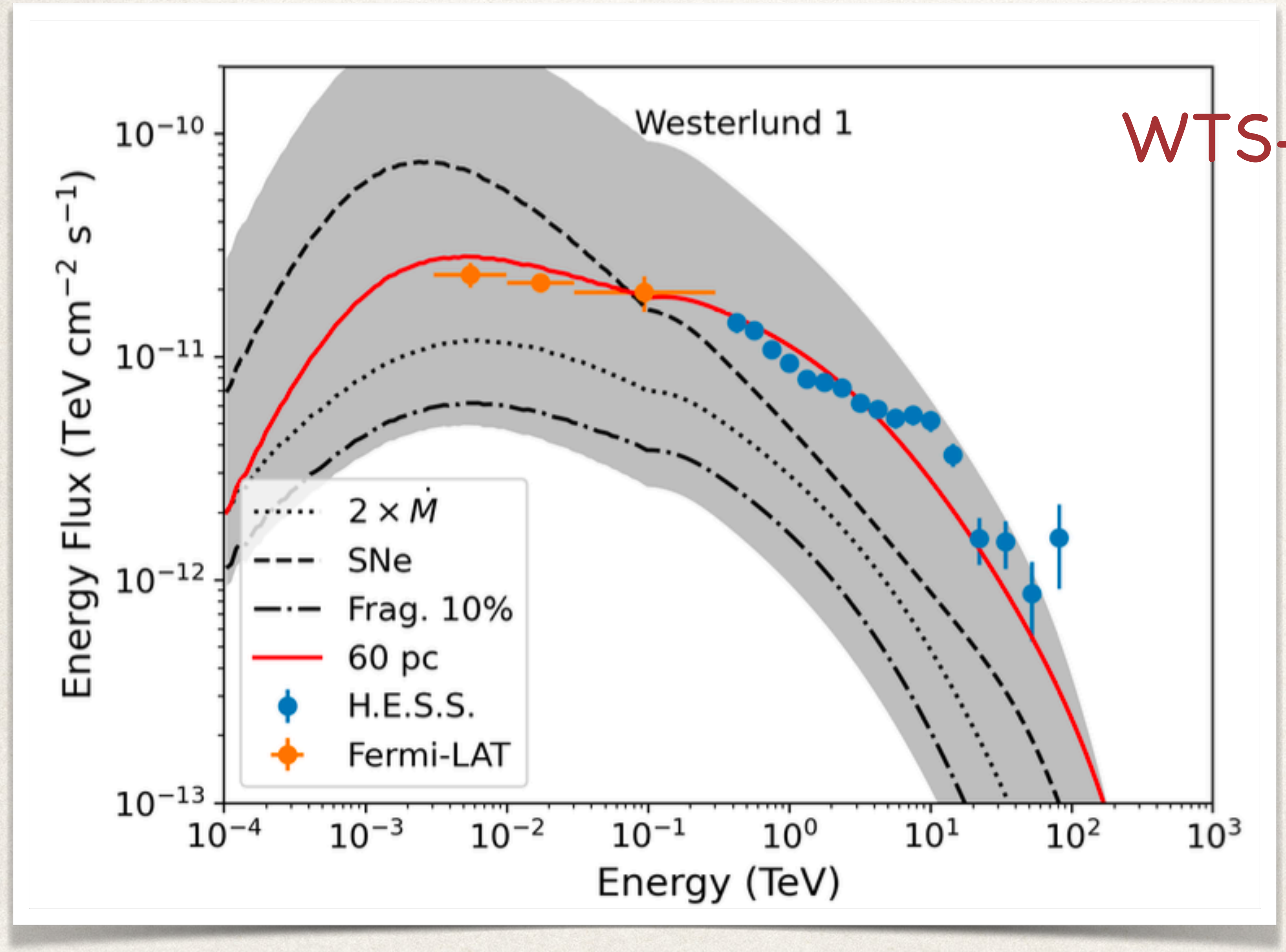
WTS+SNRs: application to some known SCs

[Mitchel, GM, Celli, Menchiari, Specovious (2024) arXiv:2403.16650]

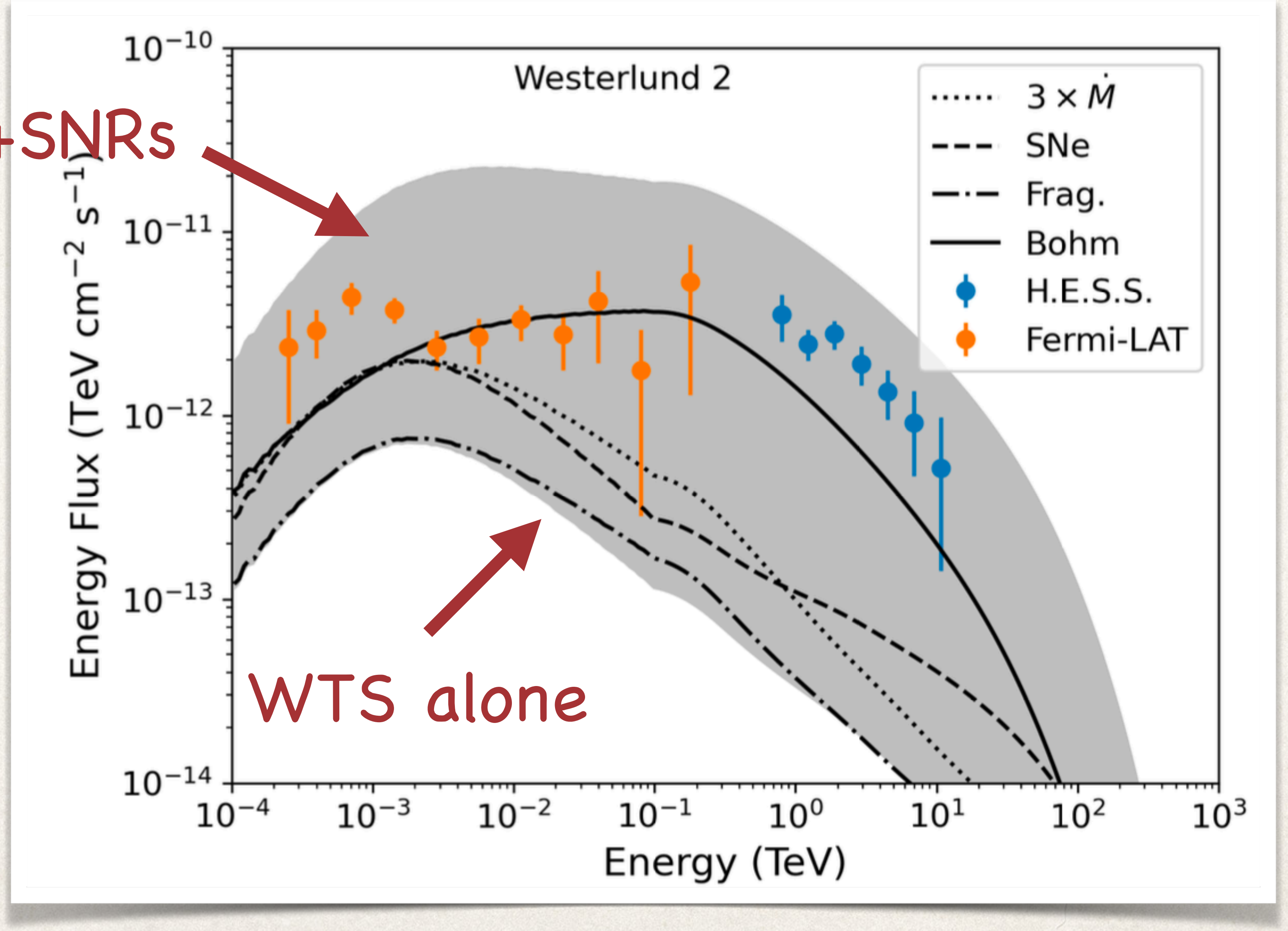
Applying the model of WTS+SNR for three SCs detected in gamma-rays:

- Uncertainty due to SC masses and wind models
- WTS alone is not sufficient to explain the gamma-ray flux (assuming 10% efficiency)
- SNR are needed (#SNe estimated according to SC age and mass)
- Flat spectra (Wd2 & NGC 3603) require Bohm like diffusion in the bubble

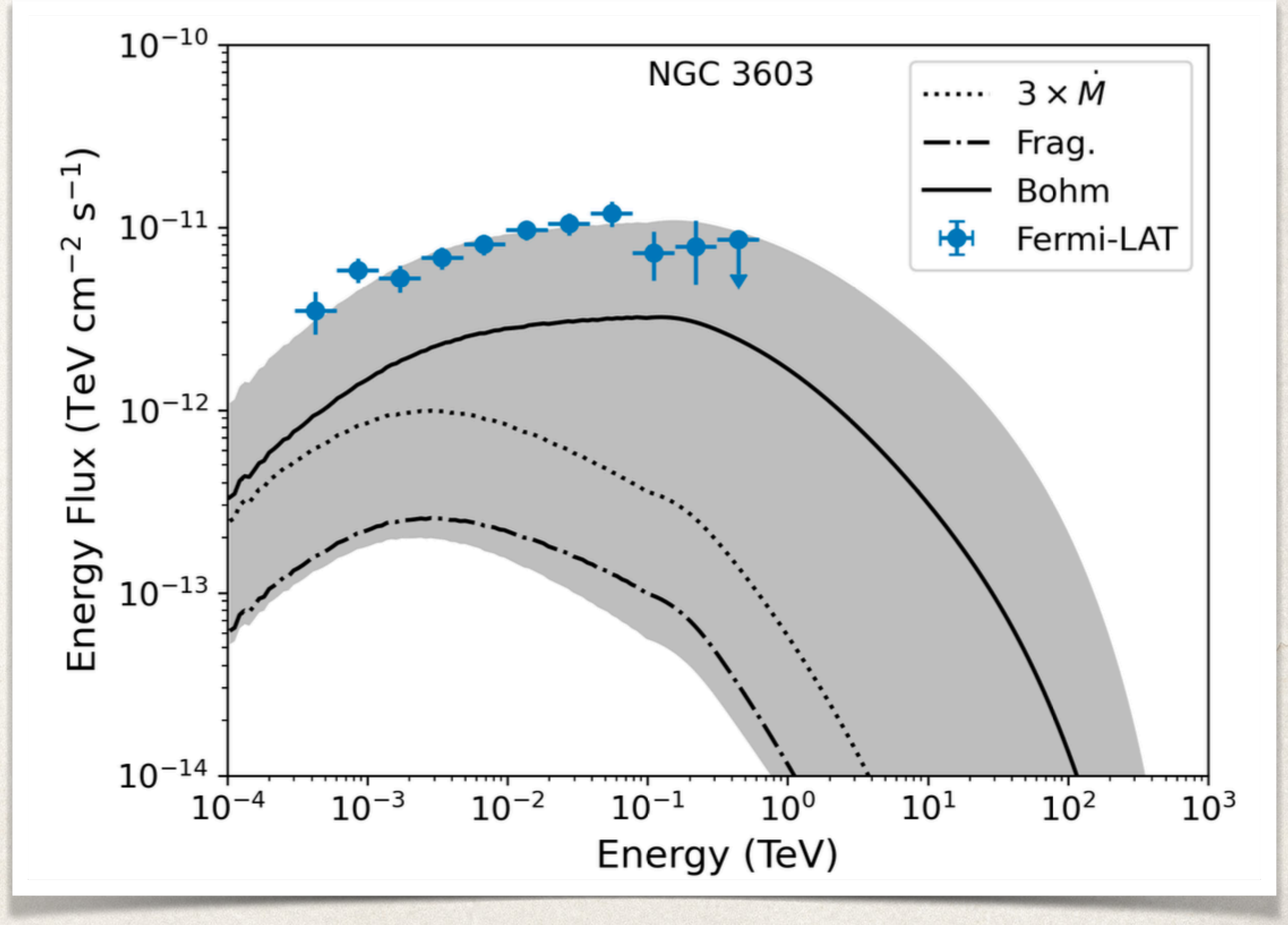
Westerlund 1



Westerlund 2



NGC 3603



The unresolved clusters

SC bubbles are very large ⇒ diffuse sources with low surface brightness ⇒ difficult to detect

$$R_{bubble} \simeq 2.9^{\circ} \left(\frac{L_w}{2\times 10^{38}\,\mathrm{erg/s}}\right)^{1/5} \left(\frac{n_{\rm ism}}{10\,\mathrm{cm}^{-3}}\right)^{-1/5} \left(\frac{t_{\rm age}}{1\,\mathrm{Myr}}\right)^{3/5} \left(\frac{d}{2\,\mathrm{kpc}}\right)$$

May SC contribute to diffuse γ-ray emission?

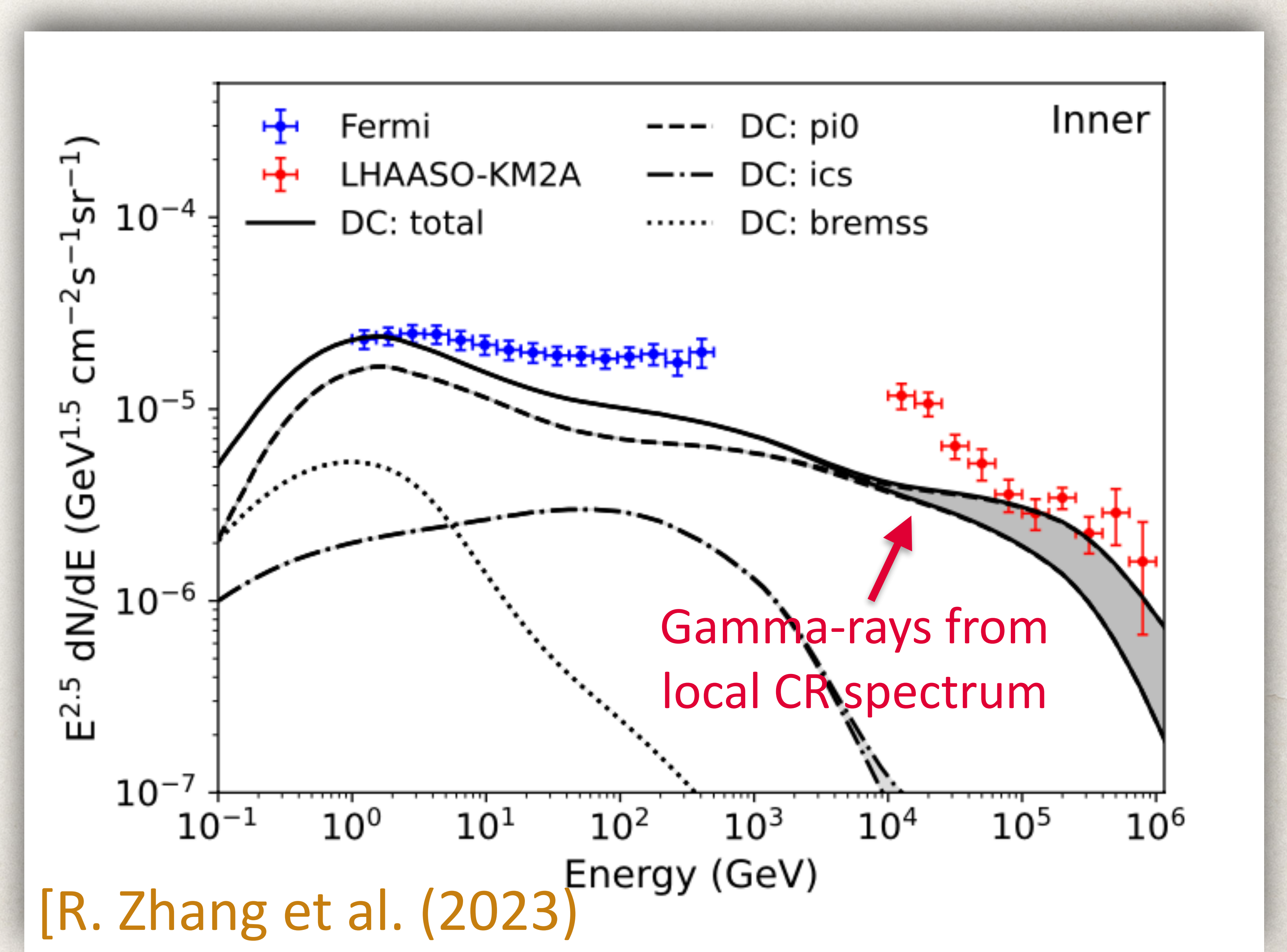
- How many SC there are in the Galaxy
- How are they distributed?

Gaia satellite has observed thousand of SCs but:

- Not clear if Gaia catalogue is complete (maybe only for $d \lesssim 2\,\mathrm{kpc}$)
- Difficult to detect young clusters ($t \lesssim 1-2\,\mathrm{Myr}$) embedded in the parent molecular cloud due to stellar light extinction
- Difficult to resolve the most inner stars: core very dense (mass segregation)

⇒The problem may be handled with synthetic population

Claimed discrepancy between diffuse emission due to CR and observations



Gamma-rays from local CR spectrum

[R. Zhang et al. (2023)]

Building a synthetic SC population

[Menchiari, GM et al. (2024) arXiv:2406.04087]

- The Galactic cluster population is only known within ~2 kpc from the Sun
- We can build a synthetic SC population.

Several physical ingredients are needed:

- Clusters population (local population extrapolated to the entire Galaxy following the gas density)
- Stellar population inside clusters
- Stellar wind physics
- Bubble dynamics (depends on local density)
- Gas density from cloud distributions
- Particle acceleration model (WTS; WTS + SNRs)

Gamma-ray emission

Example of a synthetic SC population

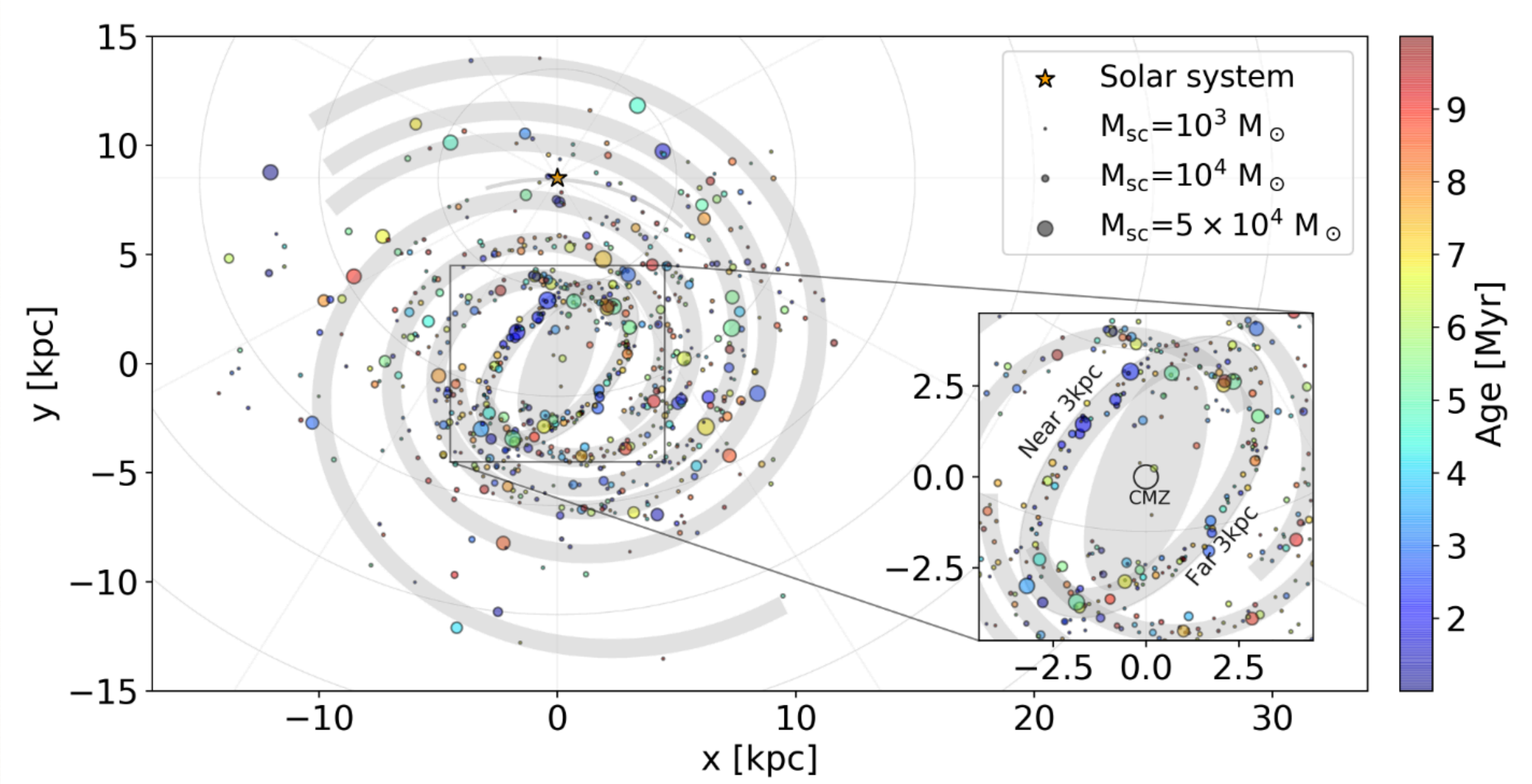
[Menchiari, GM et al. (2024) arXiv:2406.04087]

Single realisation of stellar cluster population with:

- Age < 10 Myr
- $100\,M_\odot <$ Mass $< 6.3 \times 10^4\,M_\odot$

→ total number of SC $\simeq 750$

Compatible with Gaia results



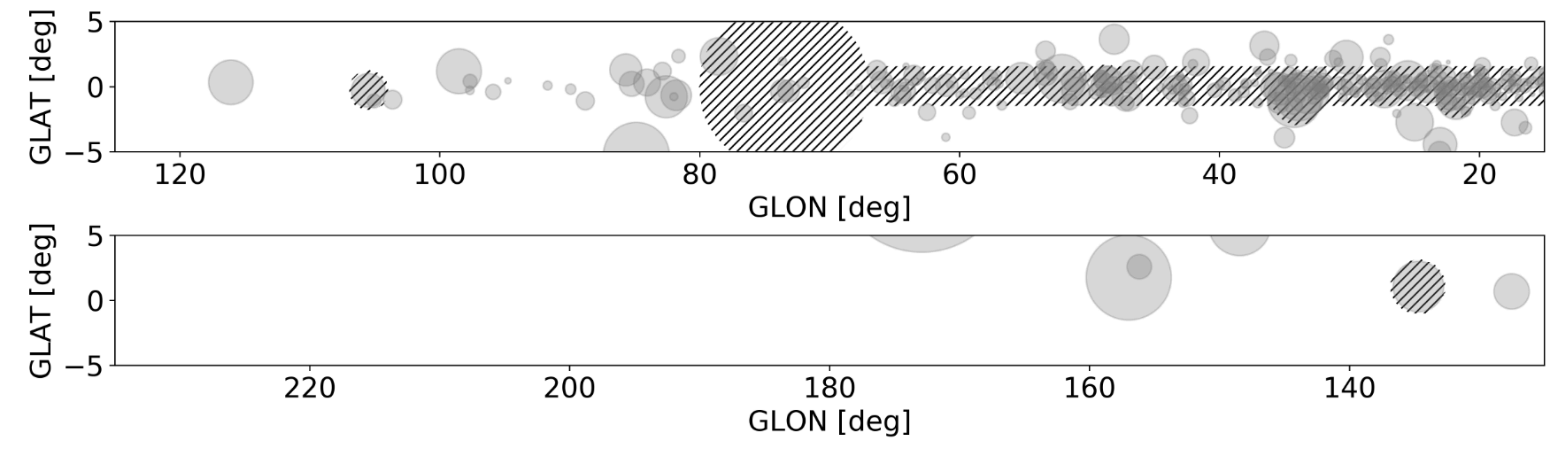
Applied masks

[Menchiari, GM et al. (2024) arXiv:2406.04087]

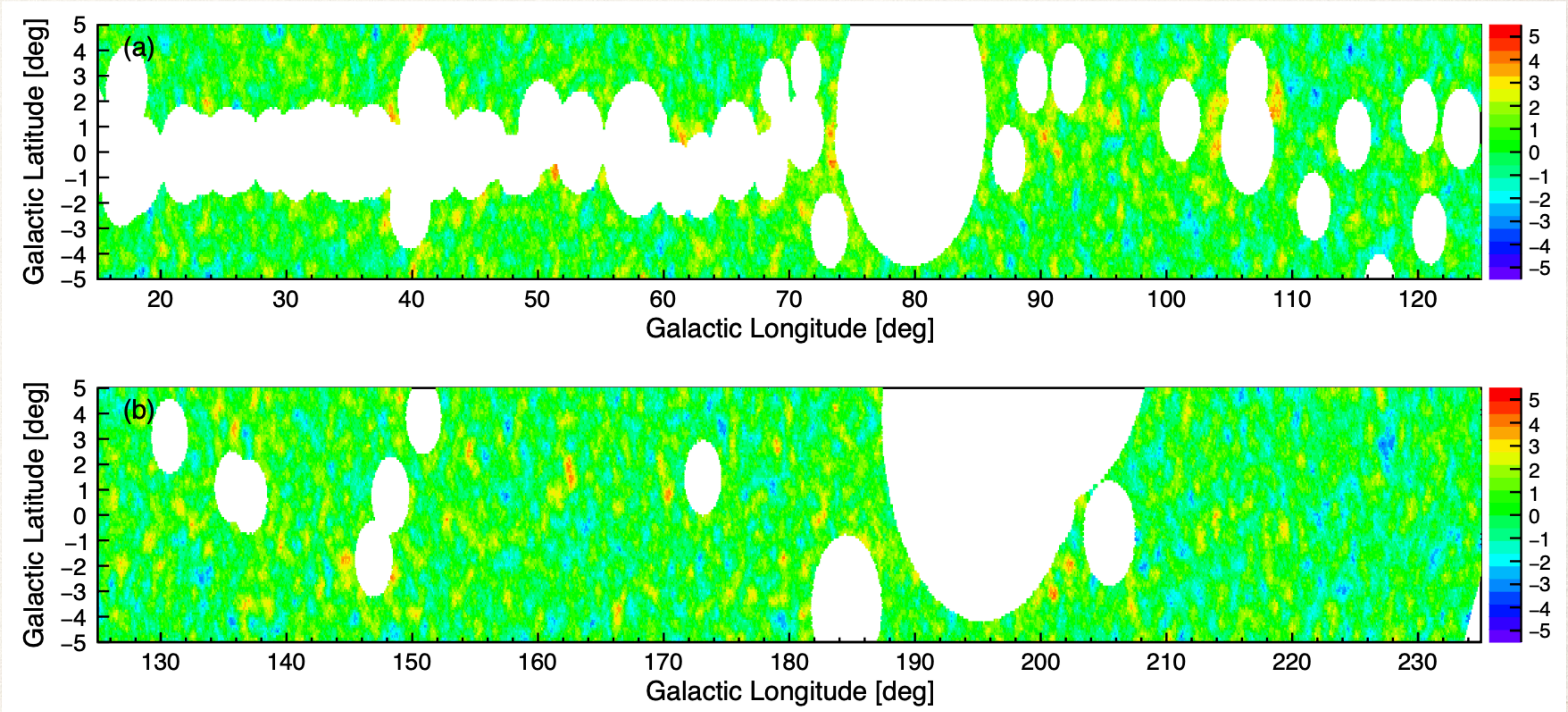
The SC gamma-ray bubble are masked to be consistent with the method used by the LHAASO coll.

Masks:

1) Galactic plane ($l \leq 70^\circ, |b| \leq 1.5^\circ$) and local arm ($l = 73.5^\circ, b = 0$)
2) All SCs having surface brightness at 100 TeV > 5 times the average diffuse emission

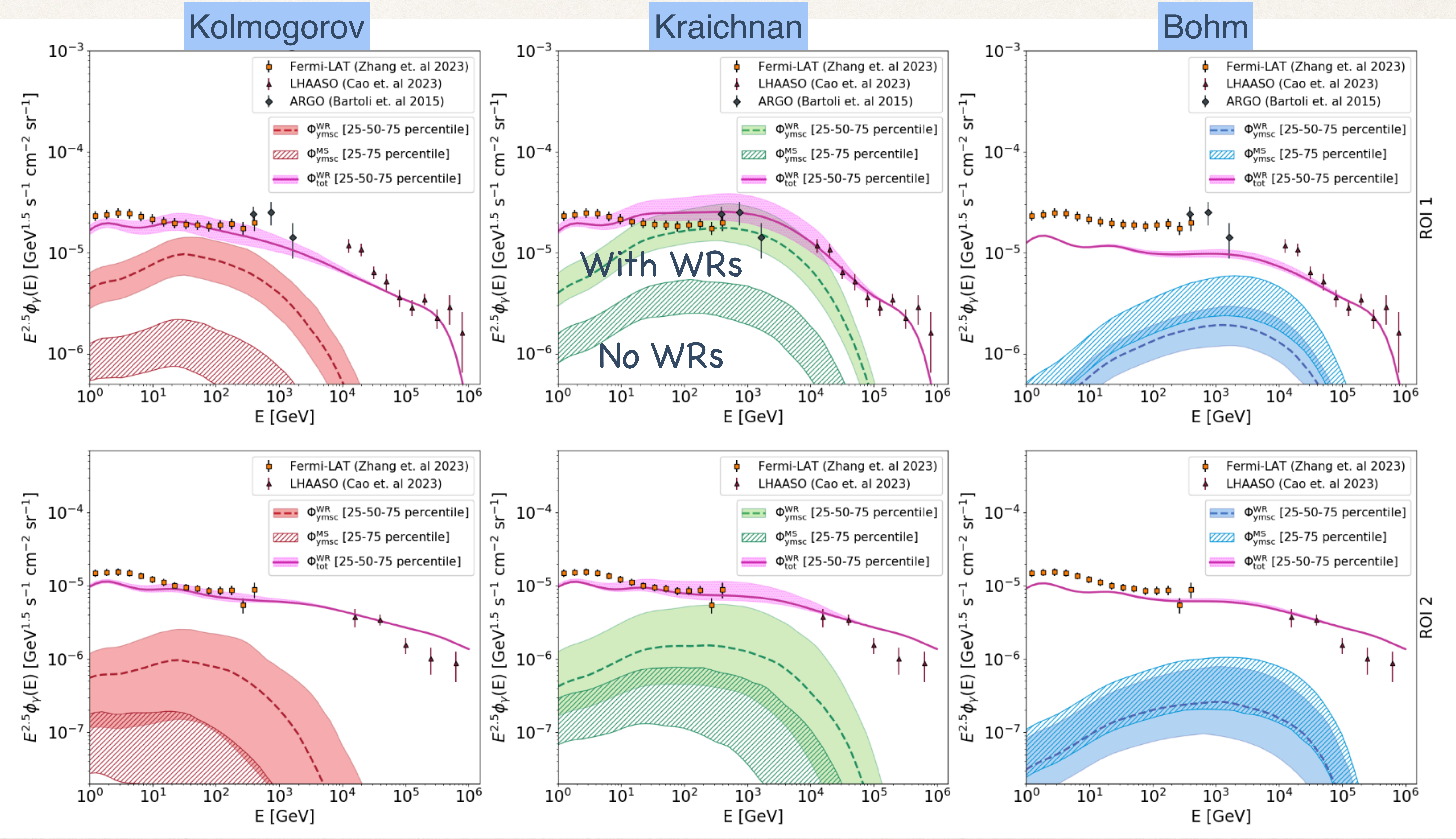


LHAASO mask



Contribution of SCs to the diffuse Galactic γ-ray emission

[Menchiari, GM et al. (2024) arXiv:2406.04087]



Inner Galaxy

Outer Galaxy

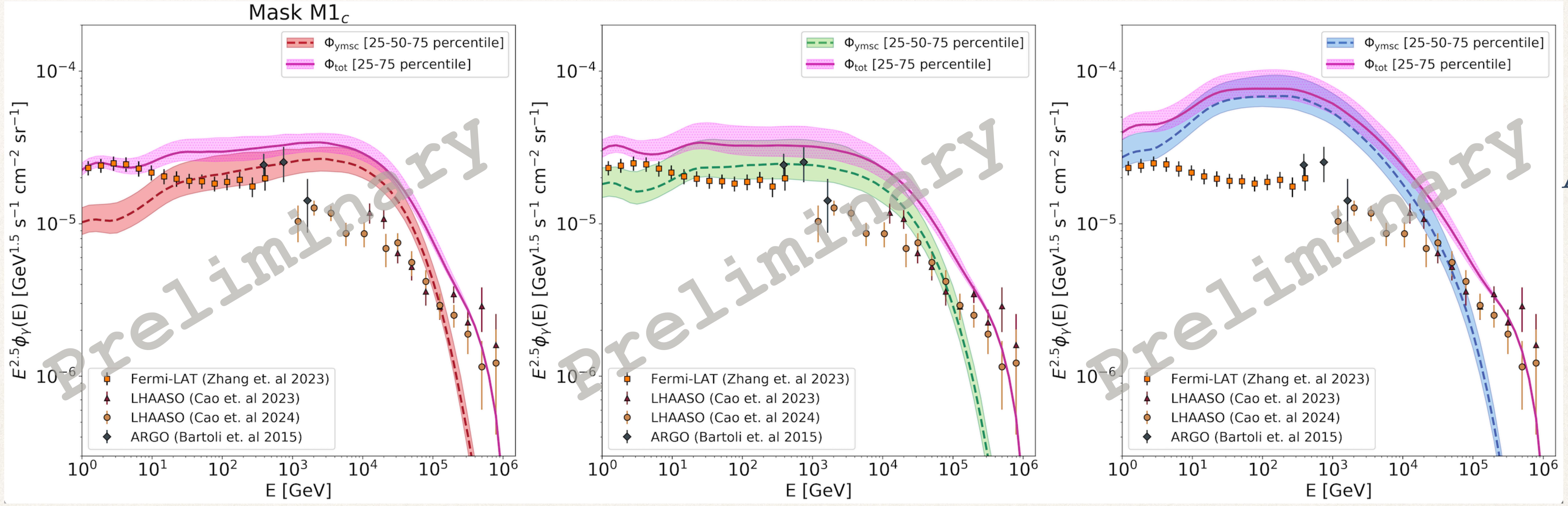
Acceleration efficiency $\simeq 10\,\%$

Contribution of SCs + SNRS in clusters

[Menchiari, GM et al. (2024) arXiv:2406.04087]

Kolmogorov Kraichnan Bohm

Inner Galaxy



Acceleration efficiency $\simeq 10\,\%$

The inclusion of SNR tends to over-predict the diffuse gamma-ray flux:

- Smaller density around clusters?
- More significant role of energy losses?

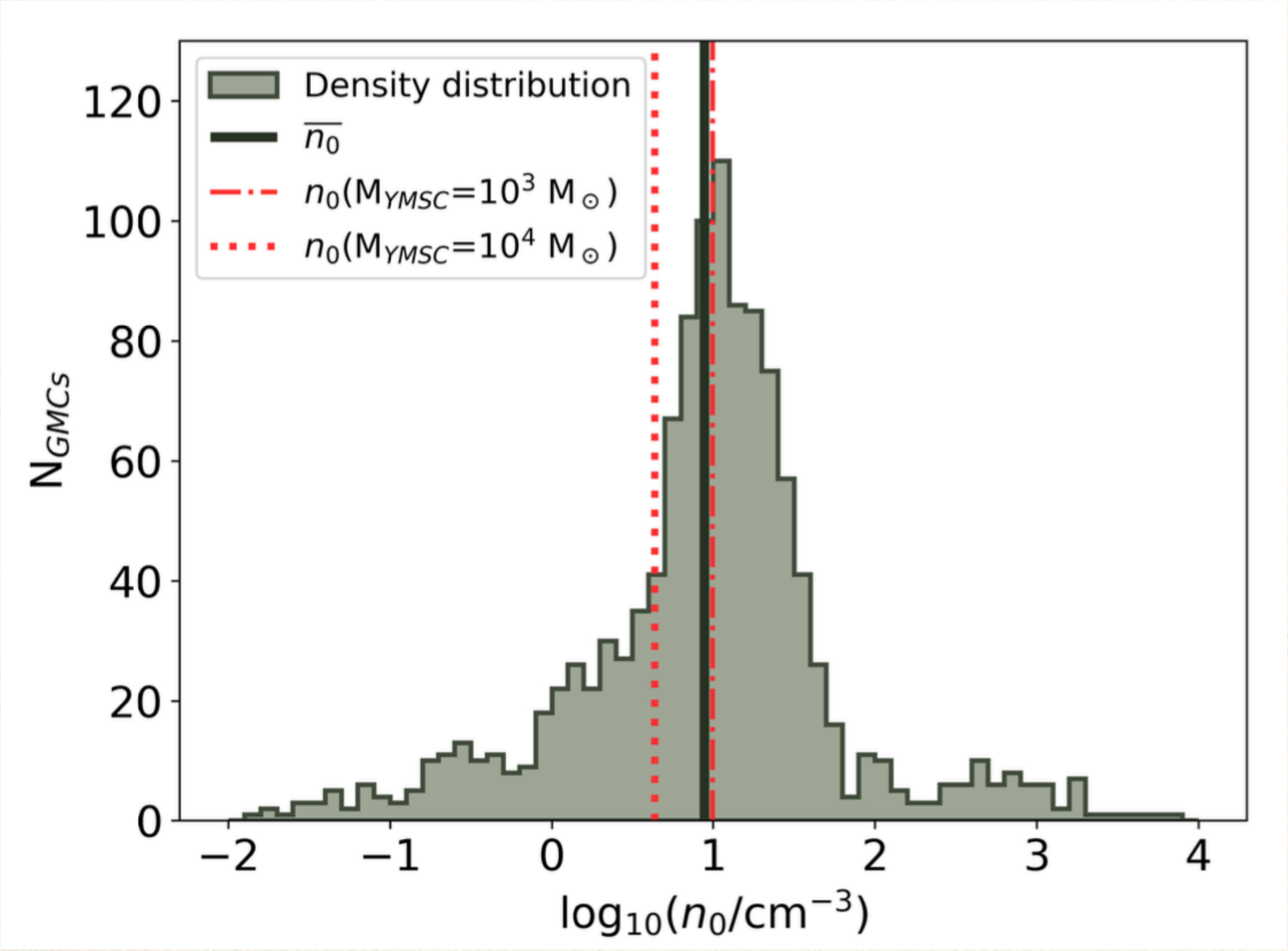
Gas density and the question of grammage

Giant molecular clouds

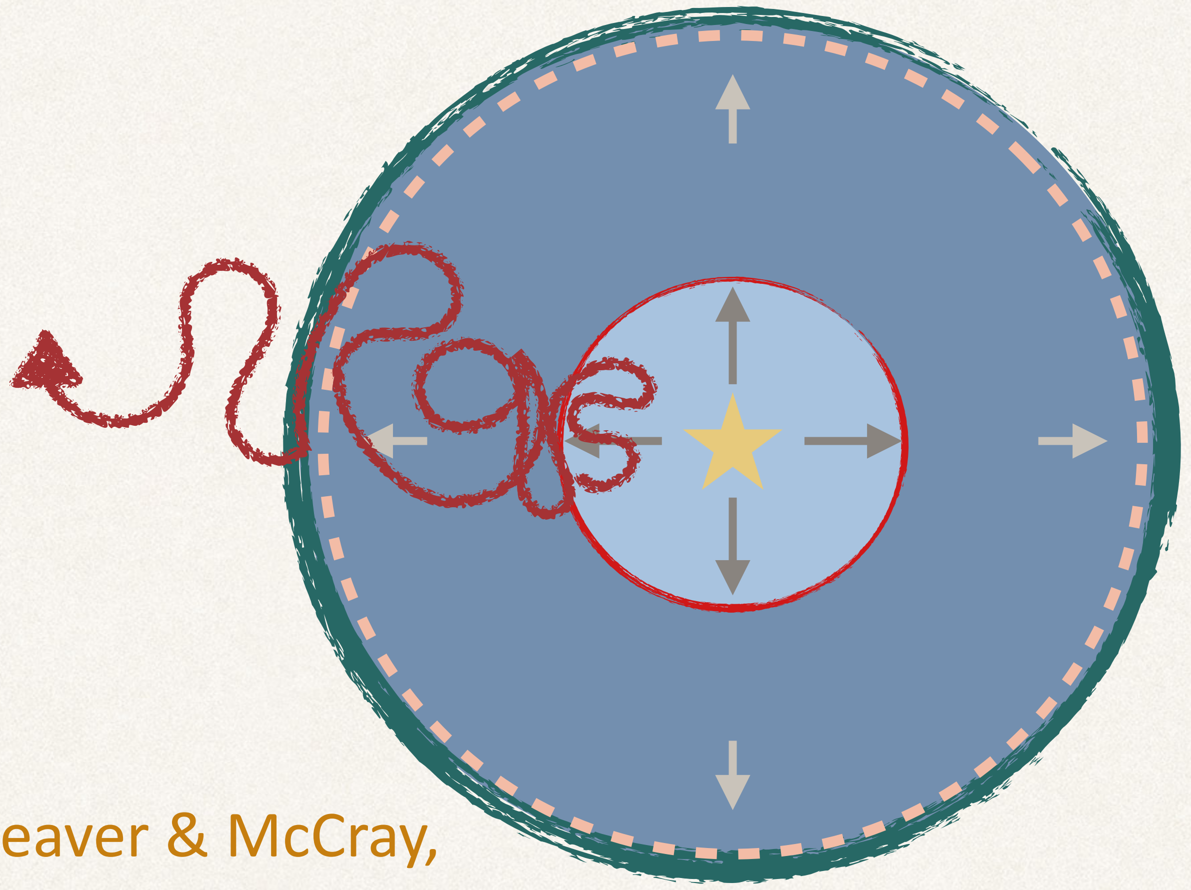
Idealised wind-blown bubble

Fragmented wind bubble

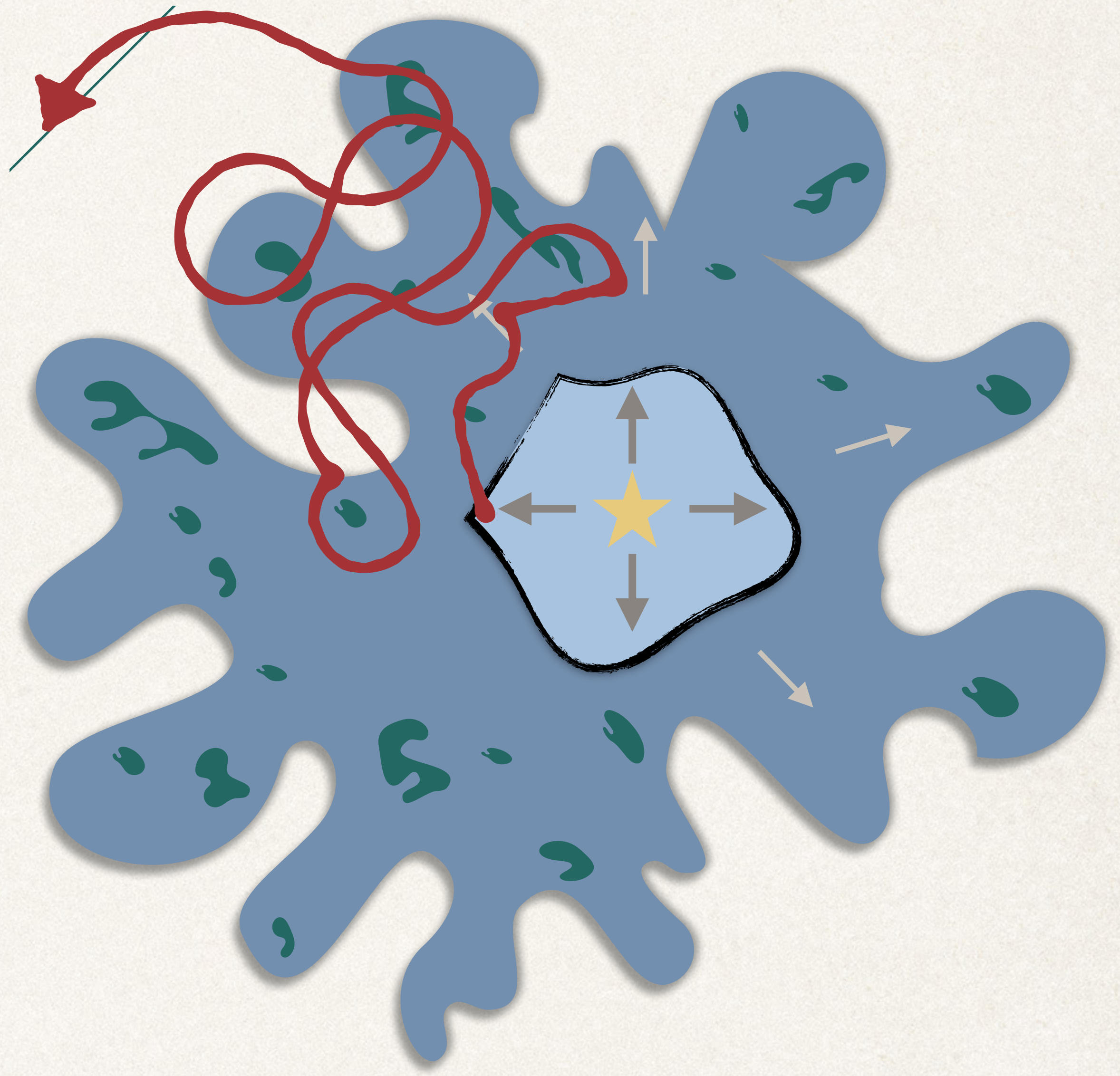
$\bar{n} \simeq 10\ \text{cm}^{-3}$



Particle density distribution in Giant Molecular Clouds [Hou & Han, 2014]



Weaver & McCray, ApJ 218 (1977)



Average density small if diffusion outside the bubble is fast
$\langle n \rangle \simeq 10^{-2}\ \text{cm}^{-3}$

Average density felt by diffusing particles
→ depends on the clump distribution
and by diffusion around each clump
$\langle n \rangle \simeq 10\ \text{cm}^{-3}$

Grammage is negligible

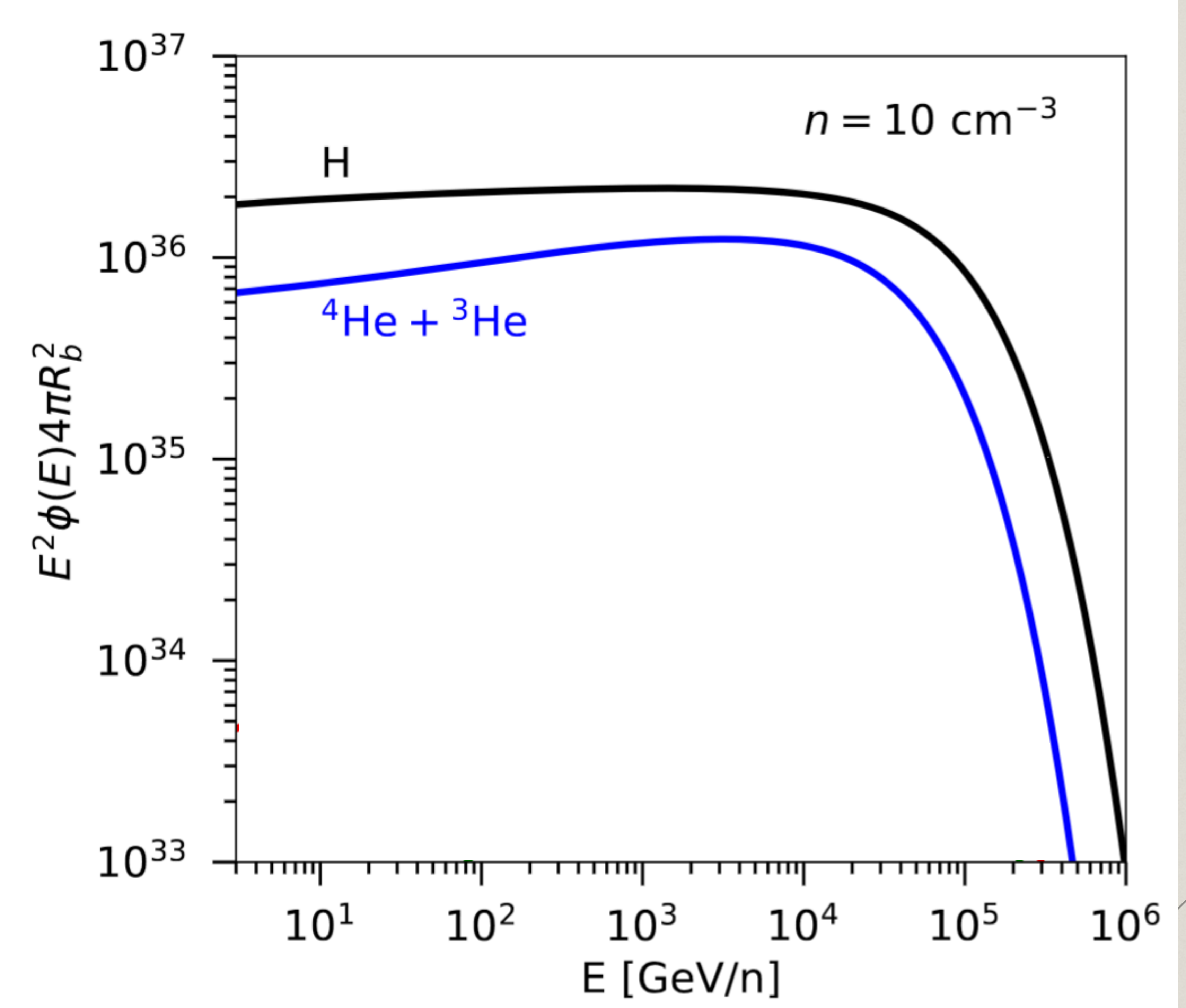
Grammage can be relevant

Spectrum of H and heavier nuclei escaping from the bubble

[P. Blasi, GM (2024) MNRAS 533, 561]

Spectrum of different species escaping the bubble for a young MSC (like Cygnus OB2 $L_{\rm wind} \gtrsim 10^{38}$ erg/s)

- H and He can escape the bubble suffering only a little energy losses

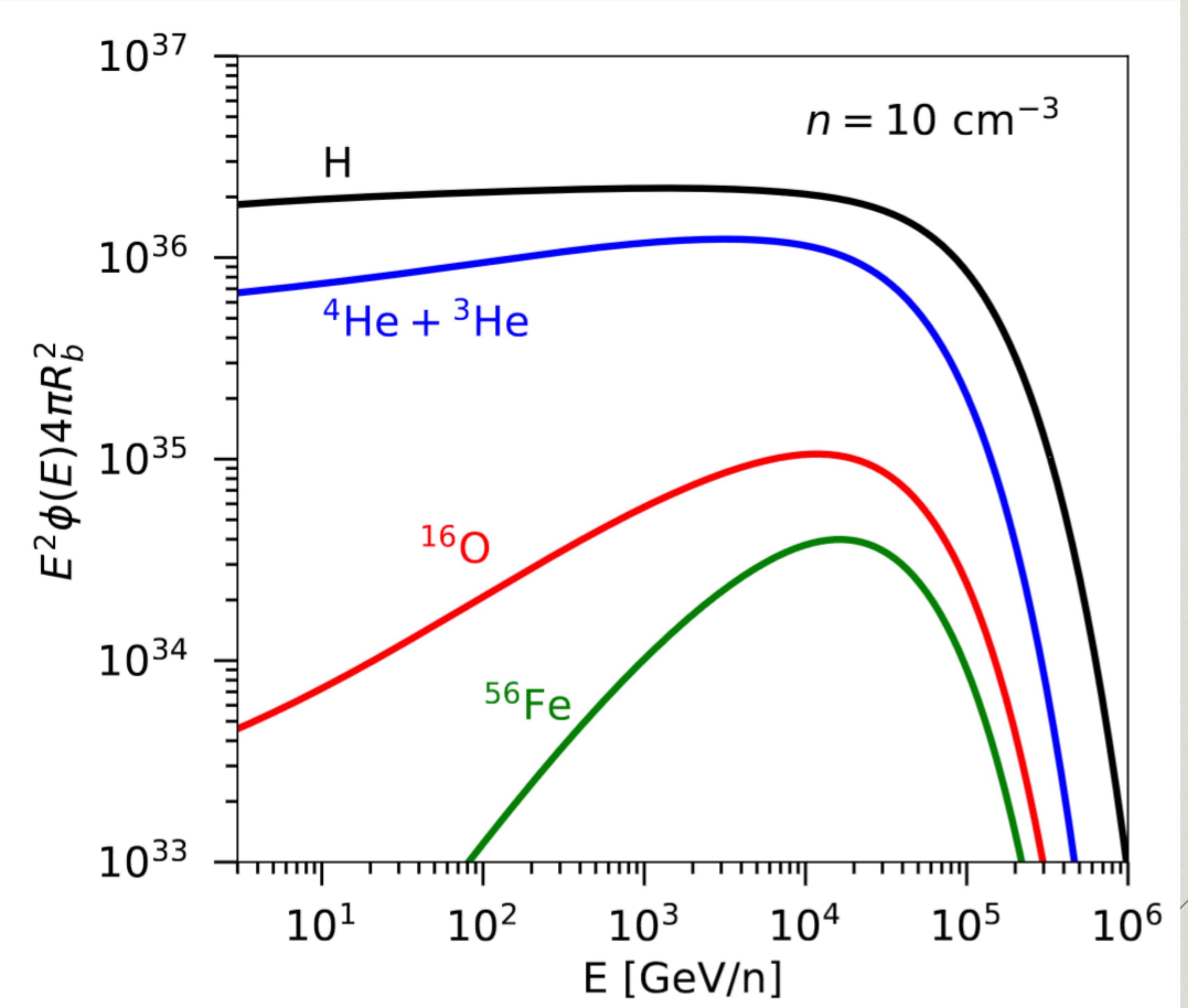


Spectrum of H and heavier nuclei escaping from the bubble

[P. Blasi, GM (2024) MNRAS 533, 561]

Spectrum of different species escaping the bubble for a young MSC (like Cygnus OB2 $L_{\rm wind} \gtrsim 10^{38}$ erg/s)

- H and He can escape the bubble suffering only a little energy losses
- Spallation for heavier nuclei is much stronger ($\sigma_{\rm sp} \propto A^{0.7}$)
    - Nuclear have a harder spectrum
    - The flux normalisation is suppressed



Possible caveats:

- Heavier nuclei may be mainly produced by isolated SNRs?
- SNR acceleration may be modified in wind-bubbles
- Heavier nuclei may be mainly produced at later phase of the bubble, when the diffusion is not suppresses any more

Conclusions

- Stellar clusters play a crucial role in the origin of cosmic rays
  - They host the majority of core-collapse SNe
  - They shape the environment where SNRs expand
  - Powerful stellar winds may accelerate CRs in addition to SNR shocks
- SCs may help to resolve several issues:
  - Significant contribution to diffuse γ-ray Galactic emission
  - Maximum energy of CRs (most promising are SNR expanding into wind bubbles)
  - Anomalous chemical composition (acceleration of wind material)
  - Spectral anomalies
    - The accumulated grammage produce harder spectra for heavier species
    - Good for p/He ratio, not for heavier elements
- It is crucial to better understand the time evolution of both wind bubbles and SNR inside them

Backup slides

Energetics: SNe *vs* Stellar Winds

Salpeter (1955) initial mass function of stars inside a cluster: $f(M) = \dfrac{dN_{\rm star}}{dM} \propto M^{-2.35}$

Power injected by SNe $P_{\rm SNe} = \boxed{10^{51}{\rm erg}} \displaystyle\int_{8M_\odot}^{M_1} f(M)\, dM$ Stars with $M \gtrsim 8M_\odot$ explode as SNe

Power injected by winds $P_{\rm wind} = \displaystyle\int_{M_{\rm min}}^{M_{\rm max}} \boxed{\frac{1}{2}\dot{M}_w(M)\, v_w(M)^2\, \tau_{\rm life}(M)}\, f(M)\, dM$

- $v_w = 2.5\sqrt{2G_N M/R}$ for line-driven winds;
- $\dot{M}$ from analytical (approximated) models

[Nieuwenhuijzen & de Jager(1990)]

$$\frac{P_{\rm wind}}{P_{\rm SNe}} \simeq 0.1 \div 0.5$$

main uncertainty due to mass loss rate

- Not accounting for WR stars
- Not accounting for failed supernovae ~10% of the total [Adams et al. (2017, MNRAS 469)]

Building a synthetic SC population

[Menchiari, GM et al. (2024) arXiv:2406.04087]

Several physical ingredients are needed to describe a realistic population of SCs:

- Clusters population
- Stellar population inside clusters
- Stellar wind physics
- Cluster wind physics
- Particle acceleration model
- Gas distribution (target)

Gamma-ray emission

Building a synthetic SC population

[Menchiari, GM et al. (2024) arXiv:2406.04087]

Several physical ingredients are needed to describe a realistic population of SCs:

- **Clusters population**
- Stellar population inside clusters
- Stellar wind physics
- Cluster wind physics
- Particle acceleration model
- Gas distribution (target)

Gamma-ray emission

$$f_c(M,t,R,z) = \frac{dN_c}{dM\,dt\,dR\,dz} = \xi_c(M)\,\psi_c(t)\,\rho_c(R,\theta_{\rm arm})\,g(z)$$

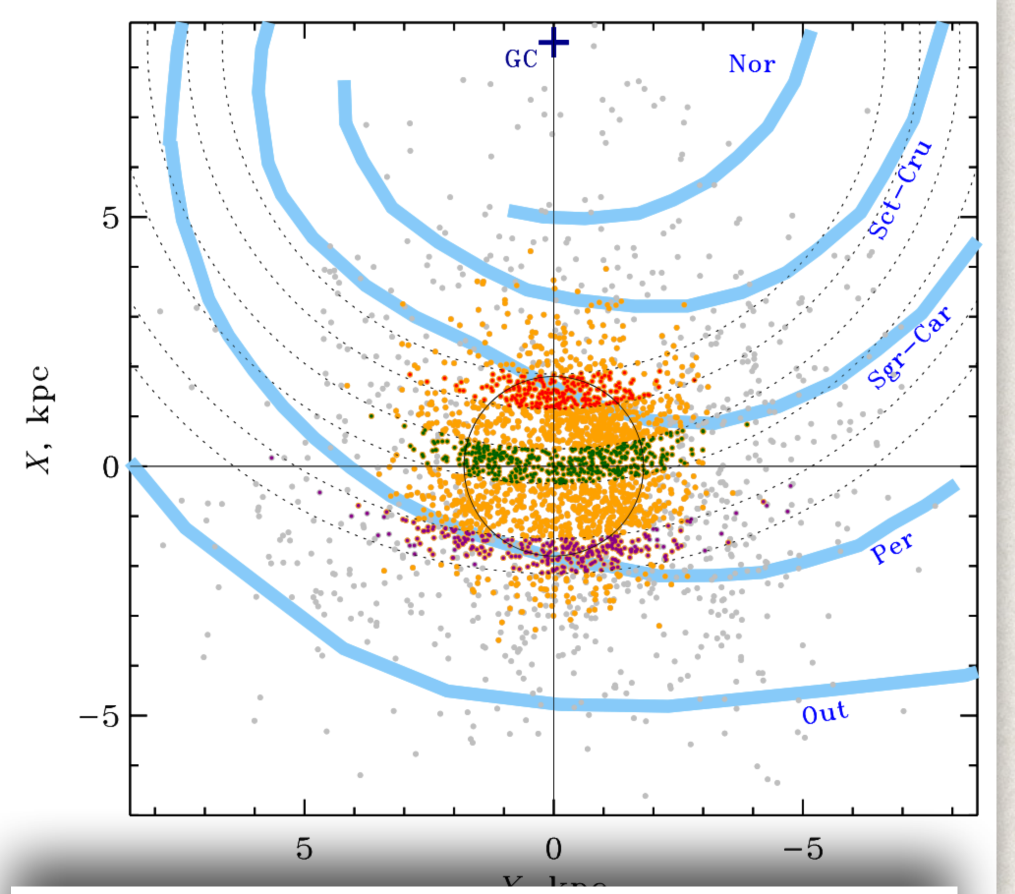
- Mass distribution based on observation of local clusters ($d \lesssim 2\,$kpc) **Milky Way Stellar Cluster Survey** [Piskunov et al. (2018)]

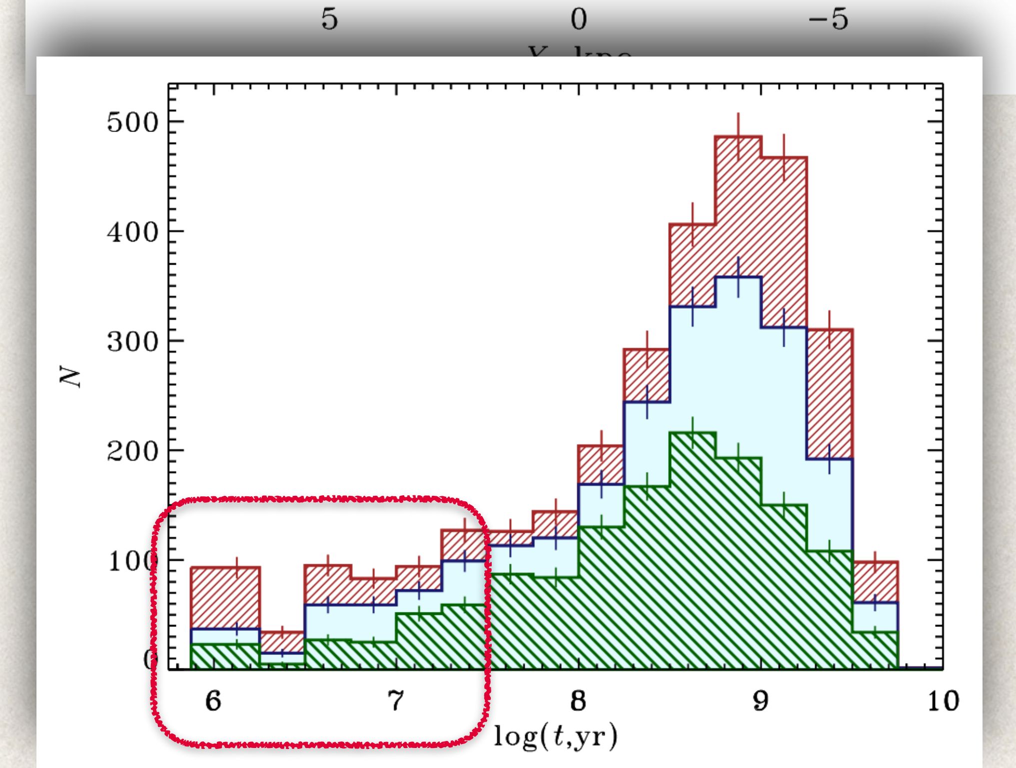
$$\xi_c(M) \propto M^{-\alpha} \text{ with } 1.1 < \alpha < 1.6$$

- Radial distribution: rescaled with the molecular cloud spatial distribution

- Age distribution ~ constant in the last ~100 Myr with a surface star formation rate in the solar neighbourhood given by [Lamers & Gieles (2006)]

$$\langle\psi_c\rangle_{SN} \simeq 350\,M_\odot\,\mathrm{Myr}^{-1}\,\mathrm{kpc}^{-1}$$





Building a synthetic SC population

[Menchiari, GM et al. (2024) arXiv:2406.04087]

Several physical ingredients are needed to describe a realistic population of SCs:

- Clusters population
- **Stellar population inside clusters**
- Stellar wind physics
- Cluster wind physics
- Particle acceleration model
- Gas distribution (target)

Gamma-ray emission

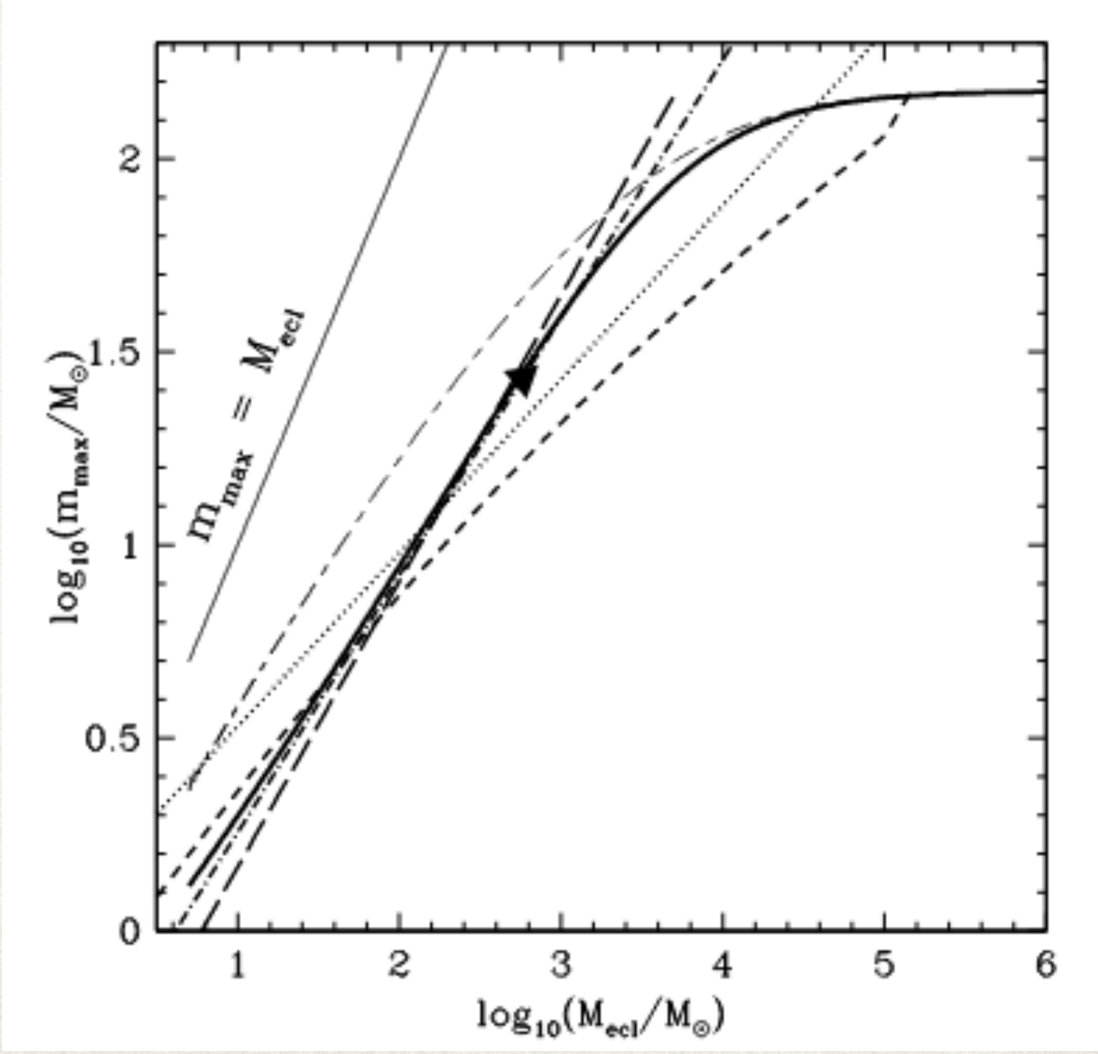
- Stellar mass distribution according to Kroupa (2001)

$$\xi_s(M) = \frac{dN}{dM} \propto \begin{cases} M^{-1.3} & 0.08 \le M/M_\odot \le 0.5 \\ M^{-2.3} & 0.5 \le M/M_\odot \le M^*_{\max} \end{cases}$$

- Maximum stellar mass according to Weidner & Kroupa (2004)

The maximum stellar mass play a crucial role because the wind power is mainly determined by the most massive stars

$$M_{\star,\,\max} \propto M_{\rm SC}$$



Maximum stellar mas as a function of the cluster mass for different models [Fig. 1 from Weidner & Kroupa, 2004]

Building a synthetic SC population

[Menchiari, GM et al. (2024) arXiv:2406.04087]

Several physical ingredients are needed to describe a realistic population of SCs:

- Clusters population
- Stellar population inside clusters
- **Stellar wind physics**
- Cluster wind physics
- Particle acceleration model
- Gas distribution (target)

Gamma-ray emission

- Analytical approximation for the **mass loss rate** [Nieuwenhuijzen & de Jager (1990)]

$$\dot{M}_s \simeq 10^{-14} \left(\frac{L_s}{L_\odot}\right)^{1.42} \left(\frac{M_s}{M_\odot}\right)^{0.16} \left(\frac{R_s}{R_\odot}\right)^{0.81} \frac{M_\odot}{\mathrm{yr}}$$

- **Wind speed** from line-driven wind models [Kudritzki & Puls (2000)]

The wind velocity is generally larger than the escape speed due to the radiation pressure from the star

$$V_{w,s} = C(T_{\mathrm{eff}})\, v_{\mathrm{esc}}$$

$$v_{\mathrm{esc}} = \sqrt{2G_N M_s/R_s\,(1 - L/L_{\mathrm{Edd}})}$$

$$C_{\mathrm{eff}} = \begin{cases} 1.0 & T < 10^4\mathrm{K} \\ 1.4 & 10^4\mathrm{K} < T < 2.1 \times 10^4\mathrm{K} \\ 2.65 & T > 2.1 \times 10^4\mathrm{K} \end{cases}$$

Building a synthetic SC population

[Menchiari, GM et al. (2024) arXiv:2406.04087]

Several physical ingredients are needed to describe a realistic population of SCs:

- Clusters population
- Stellar population inside clusters
- Stellar wind physics
- **Cluster wind physics**
- Particle acceleration model
- Gas distribution (target)

Gamma-ray emission

- Wind-blown bubble model of Weaver & McCray (1977)
  Constant injection of energy in time in a spherical symmetry

- Correction due to cooling at the contact discontinuity: using a phenomenological recipe based on simulation from Lancaster L. et al.(ApJ 914, 2021)

$$R_{\rm bubble} = f_{\rm cool}(t)\, R_{\rm bubble}^{\rm WM}$$

Building a synthetic SC population

[Menchiari, GM et al. (2024) arXiv:2406.04087]

Several physical ingredients are needed to describe a realistic population of SCs:

- Clusters population
- Stellar population inside clusters
- Stellar wind physics
- Cluster wind physics
- **Particle acceleration model**
- Gas distribution (target)

- Acceleration at the wind termination shock [GM, Blasi, Peretti, Cristofari (2019)]

Gamma-ray emission

Building a synthetic SC population

[Menchiari, GM et al. (2024) arXiv:2406.04087]

Several physical ingredients are needed to describe a realistic population of SCs:

- Clusters population
- Stellar population inside clusters
- Stellar wind physics
- Cluster wind physics
- Particle acceleration model
- **Gas distribution (target)**

Gamma-ray emission

Gas distribution in the Galactic plane according to the one implemented in the GALPROP code including atomic and molecular Hydrogen