Young Stellar Clusters as Cosmic Ray sources

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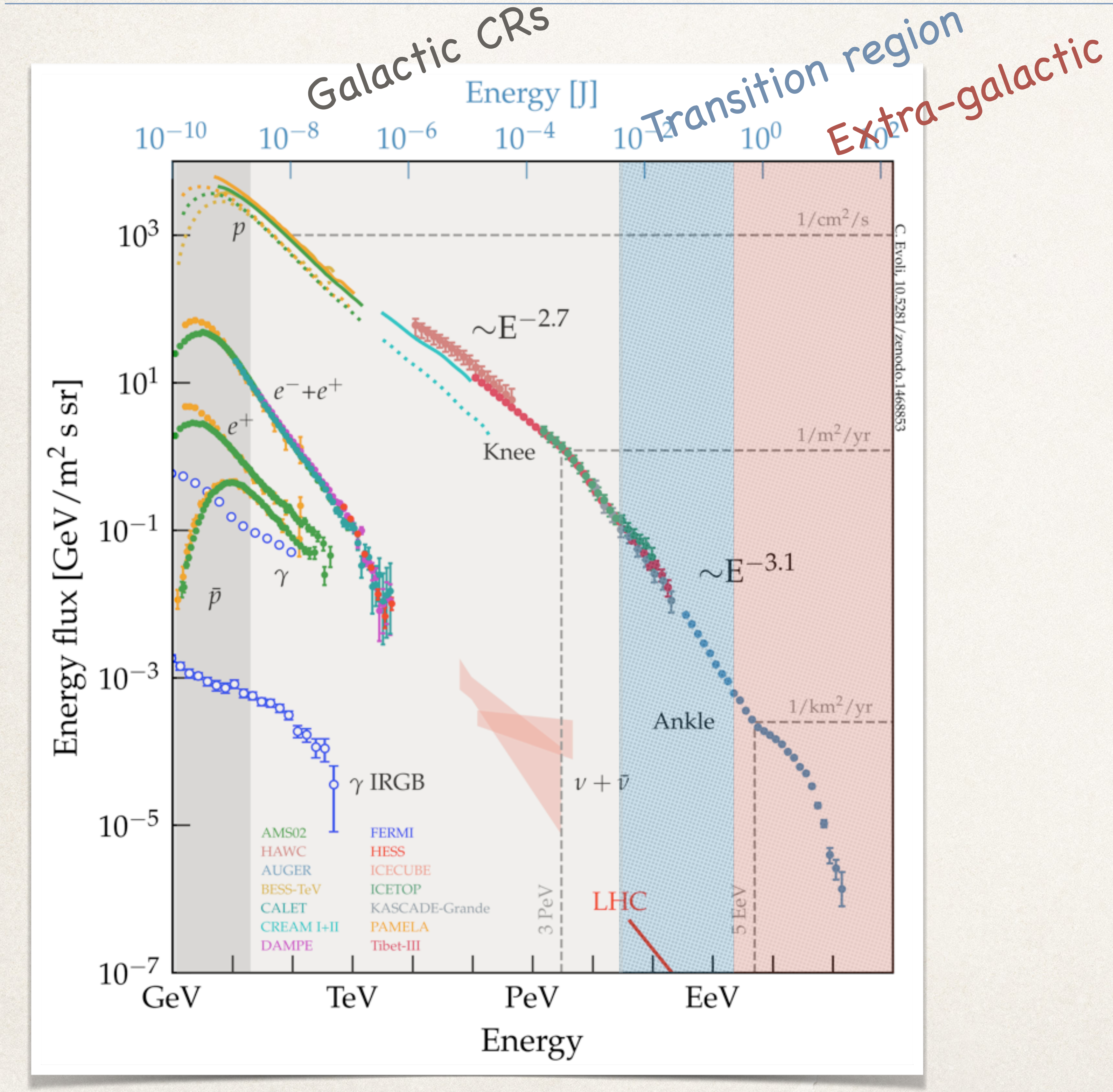
Summary

- Motivation: the *unsatisfactory* SNR paradigm for the CR origin
- Observational evidences of young stellar clusters (YSC) as cosmic ray sources
- The wind-bubble structure
- Possible acceleration mechanisms:
  - The wind termination shock model
  - Wind termination shock + supernovae
- Contribution of YSCs to diffuse γ-ray emission

How to explain the origin of Galactic CRs



Requirements for sources to explain the CR flux

- Energetics: $\sim 10^{40}\,\text{erg/s}$
- Injected spectrum < PeV: $\propto E^{-2.3}$
- Maximum energy (*p*): $\gtrsim 10^{15}\,\text{eV}$
- Anisotropy: $\sim 10^{-3}\,@\,10\,\text{TeV}$
- Composition: few anomalies w.r.t. Solar

The SNR paradigm for the origin of CRs

The *Supernova Remnant paradigm*: why supernova remnant are so popular?

- Enough power to sustain the CR flux (~10% of kinetic energy)
- Spatial distribution of SNRs compatible with CR distribution
- Enough sources to explain anisotropy
- Observations show the presence of non thermal particles
- A well developed theory for particle acceleration (DSA)

However:

- No evidence of acceleration beyond ~ 100 TeV even in very young SNRs
- From theory only very powerful and rare SNRs can reach PeV
- Anomalous CR composition cannot be easily explained (eg. ^{22}Ne/^{20}Ne)
- Spectral anomalies: p, He, CNO have different slopes at injection

Looking for additional sources

The role of star clusters

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

Massive stars born in OB associations

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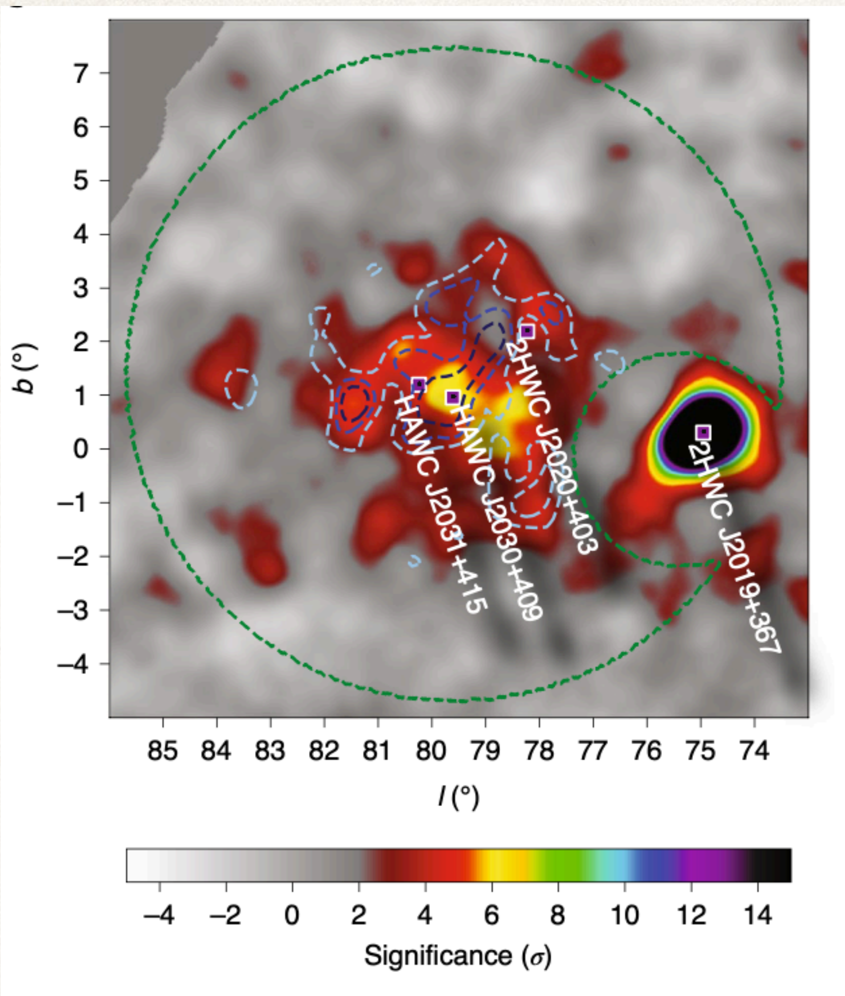
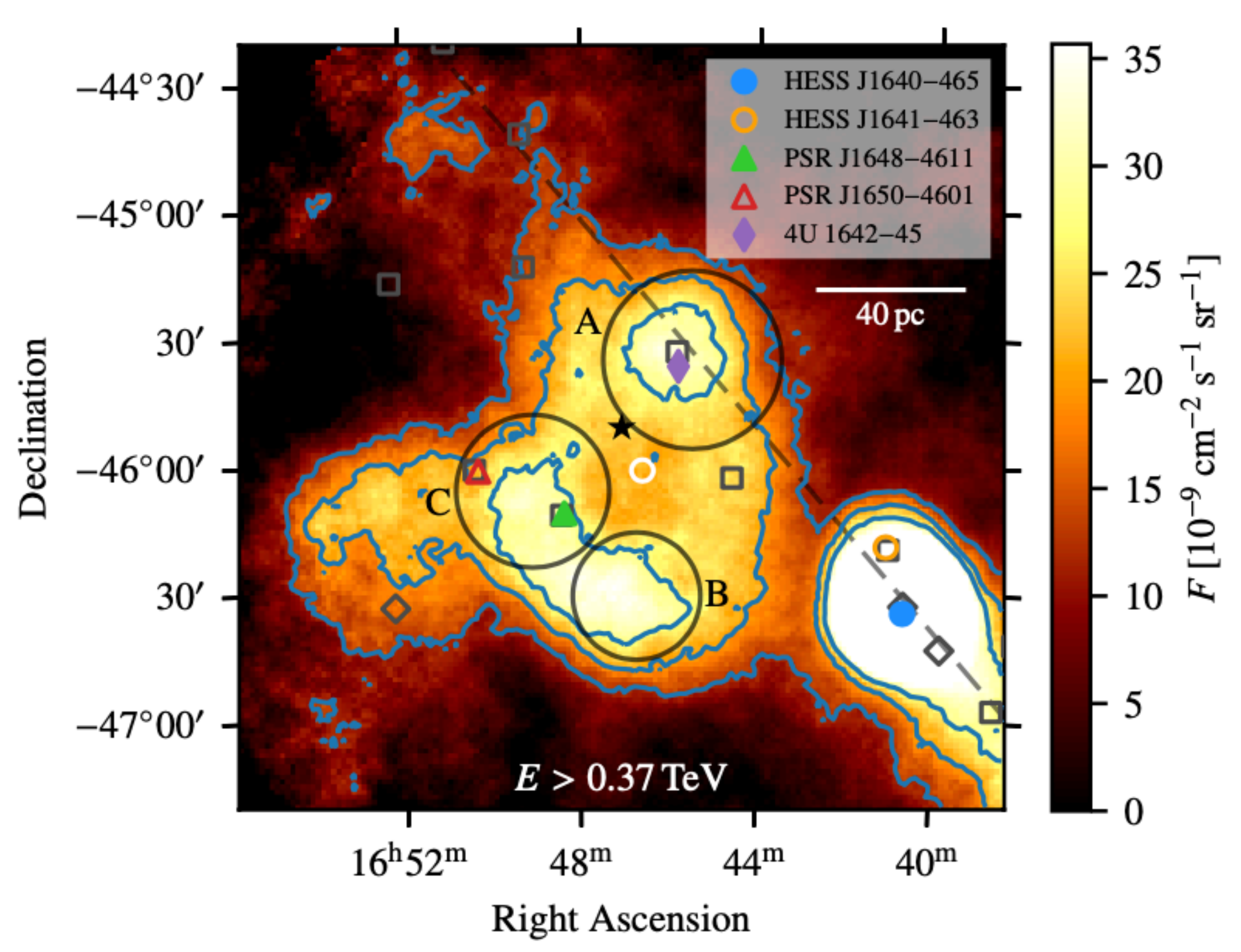
Recently several massive star clusters have been associated with gamma-ray sources

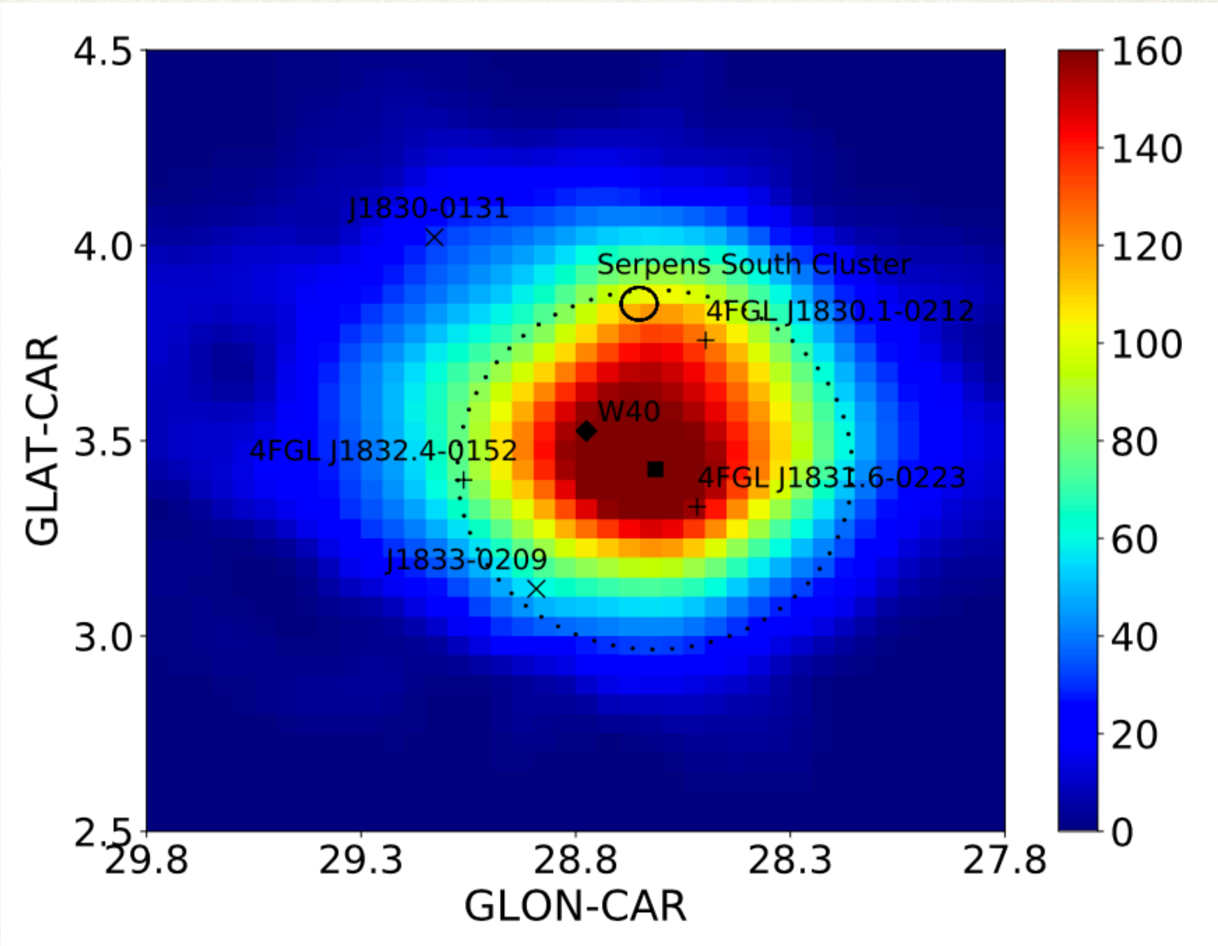
Cygnus Cocoon HAWC coll. Nat. Astr.(2020)



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



W40 - FermiLAT Sun et al. (2020)



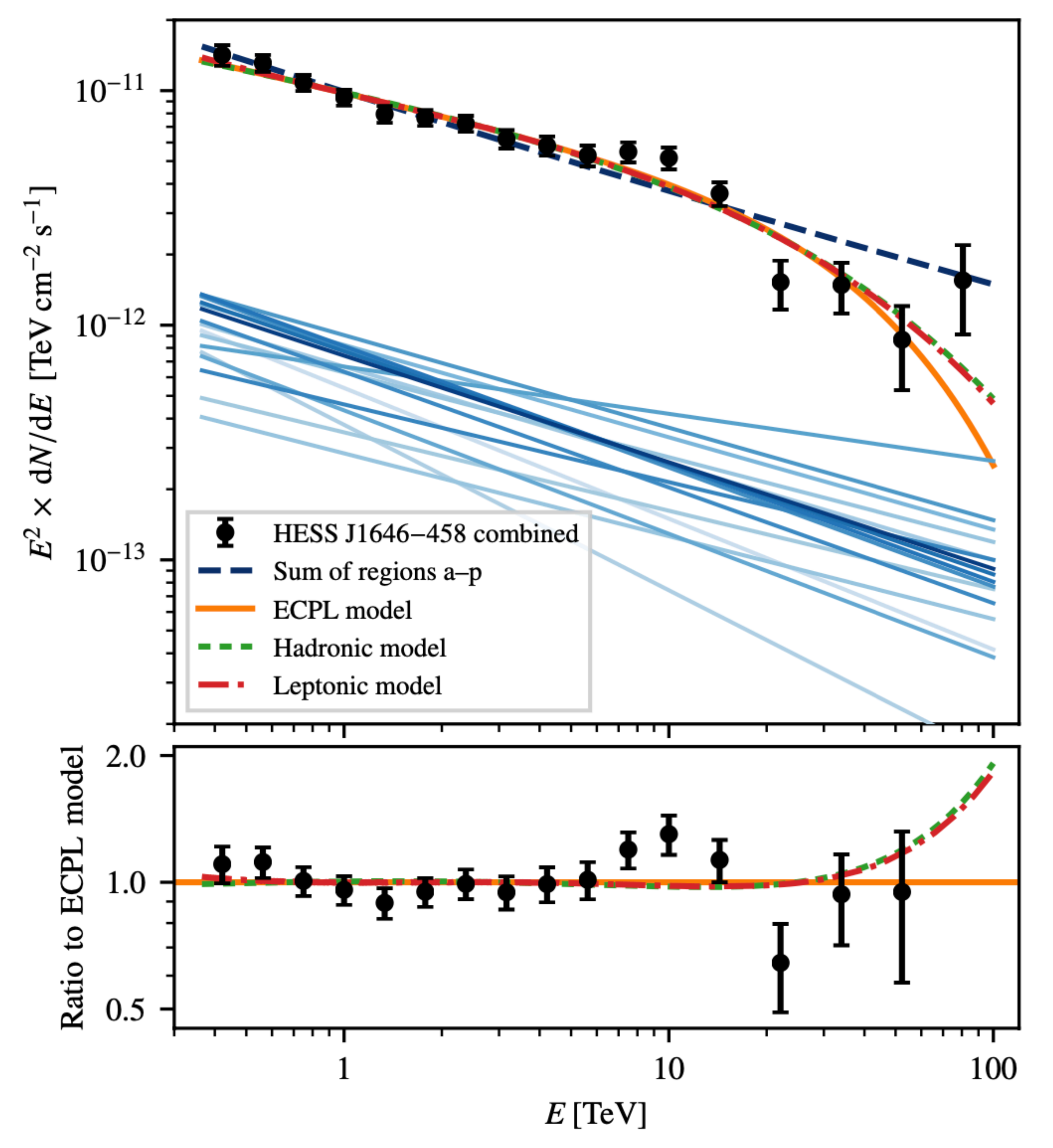
Young Star Clusters detected in γ-rays so far

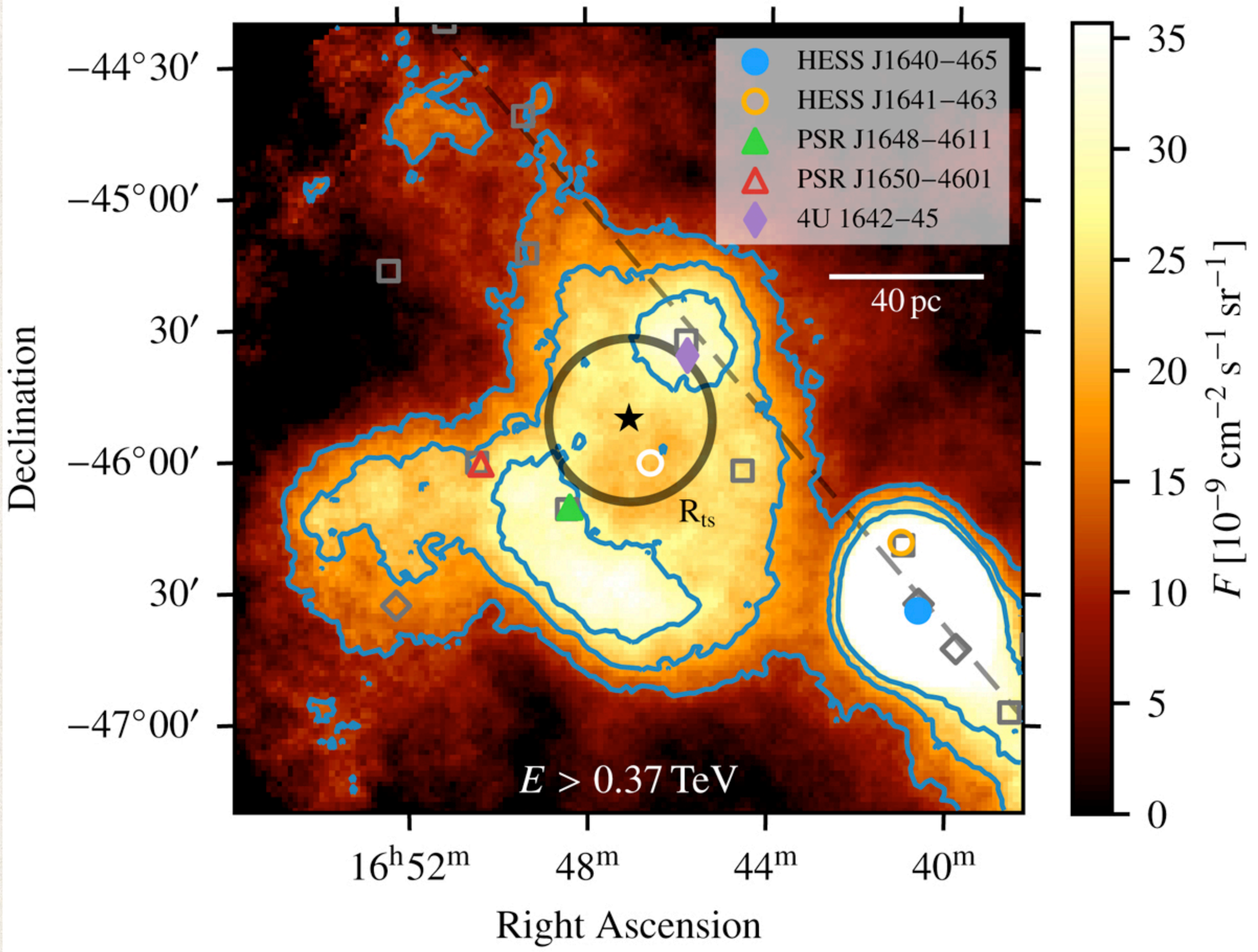
Name	log M/M_{sun}	r_c/pc	D/kpc	age/Myr	L_w/ 10^{38} erg s^{-1}	GeV	TeV	Reference
Westerlund 1	4.6 ± 0.045	1.5	4	4-6	10	●	●	Abramowski A., et al., 2012, A&A, 537, A114
Westerlund 2	4.56 ±0.035	1.1	2.8 ± 0.4	1.5 - 2.5	2	●	●	Yang, de Oña Wilhelmi, Aharonian, 2018, A&A, 611, A77
Cyg. OB2	4.7±0.3	5.2	1.4	3 - 6	2	●	●	Ackermann M., et al. 2011, Science, 334, 1103
NGC 3603	4.1 ± 0.10	1.1	6.9	2 - 3	?	●		Saha, L. et al 2020, ApJ, 897, 131
BDS 2003	4.39	0.2	4	1	?		●	Albert A., et al., 2020, ApJL 907
W 40	2.5	0.44	0.44	1.5	?	●		Sun, X.-N. et al. 2020, A&A 639
W 43					?	●	●	Young et al. (2020), LHAASO coll.(2024)
Carina Nebula	Several clusters		2.3	1-10		●		Ge at al. (2022)
RSGC 1	4.48	1.5	6.6	10 - 14	?	●	?	Sun et al. 2020, MNRAS 494
MC 20	~ 3	1.3	3.8 - 5.1	3 - 8	~4	●	?	Sun et al. 2022, A&A 659
NGC 6618		3.3	~2	< 3	?	●		Liu et al. 2022, MNRAS 513
Vela region (RCW 32, 36, 38, IRS 31)	~ 3	~0.5	1.6	< 2	0.6	●		Peron, Casanova et al. (2023) [submitted]
30 Dor (LMC) NGC 2070/RCM 136	4.8-5.7 4.34-5	multiple sub-clusters	50	1 5	?	●	●	H.E.S.S. Collaboration, 2015, Science, 347, 406
Rosette nebula						●		Liu et al. 2023

Westerlund 1

- Observed byt H.E.S.S. up to ~150 pc
- Hard emission up to ~100 TeV
- No significant spatial variation of spectral index
- Leptonic origin? [Härer et al., 2023]

Westerlund 1 γ-ray spectrum

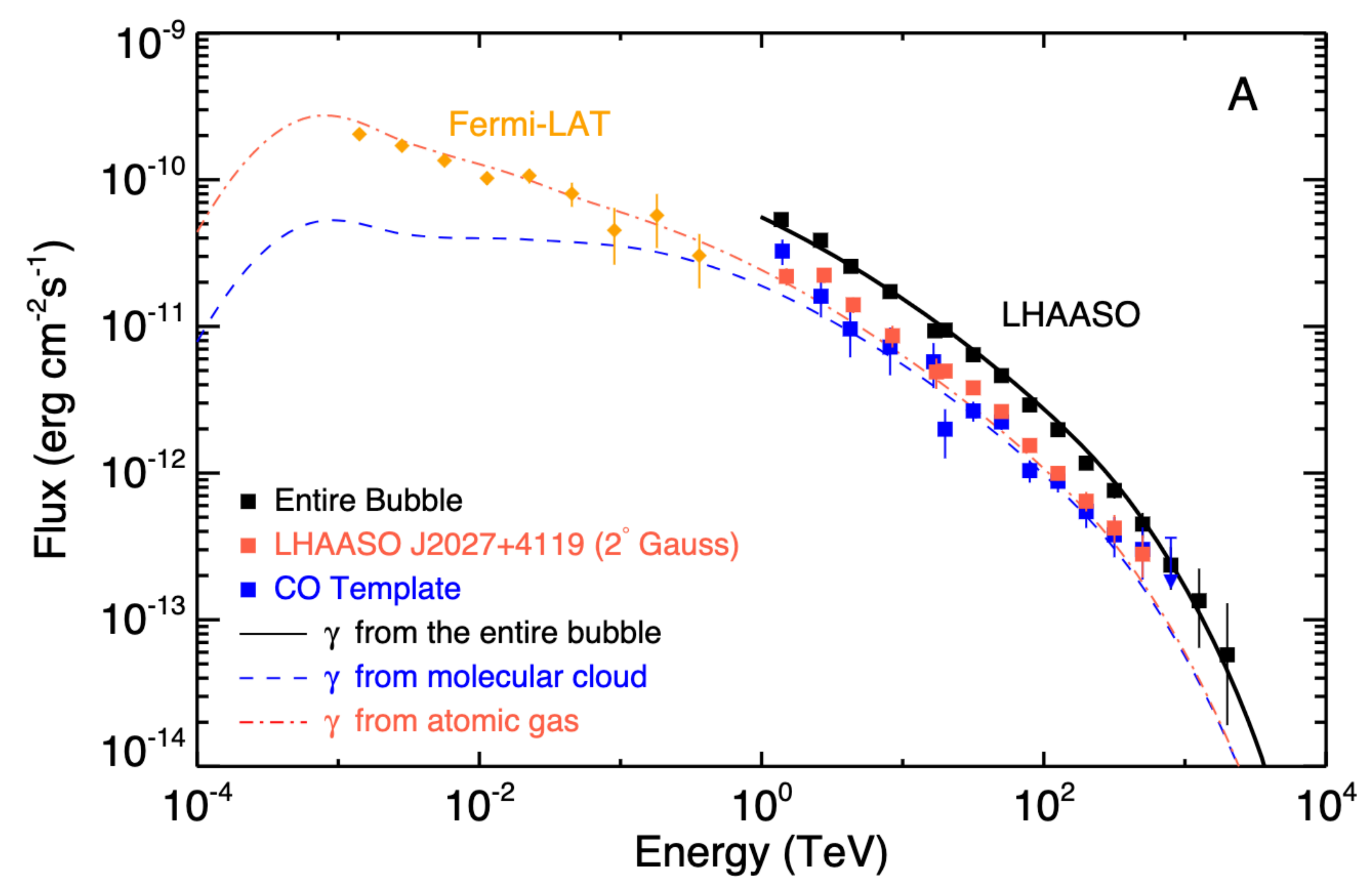




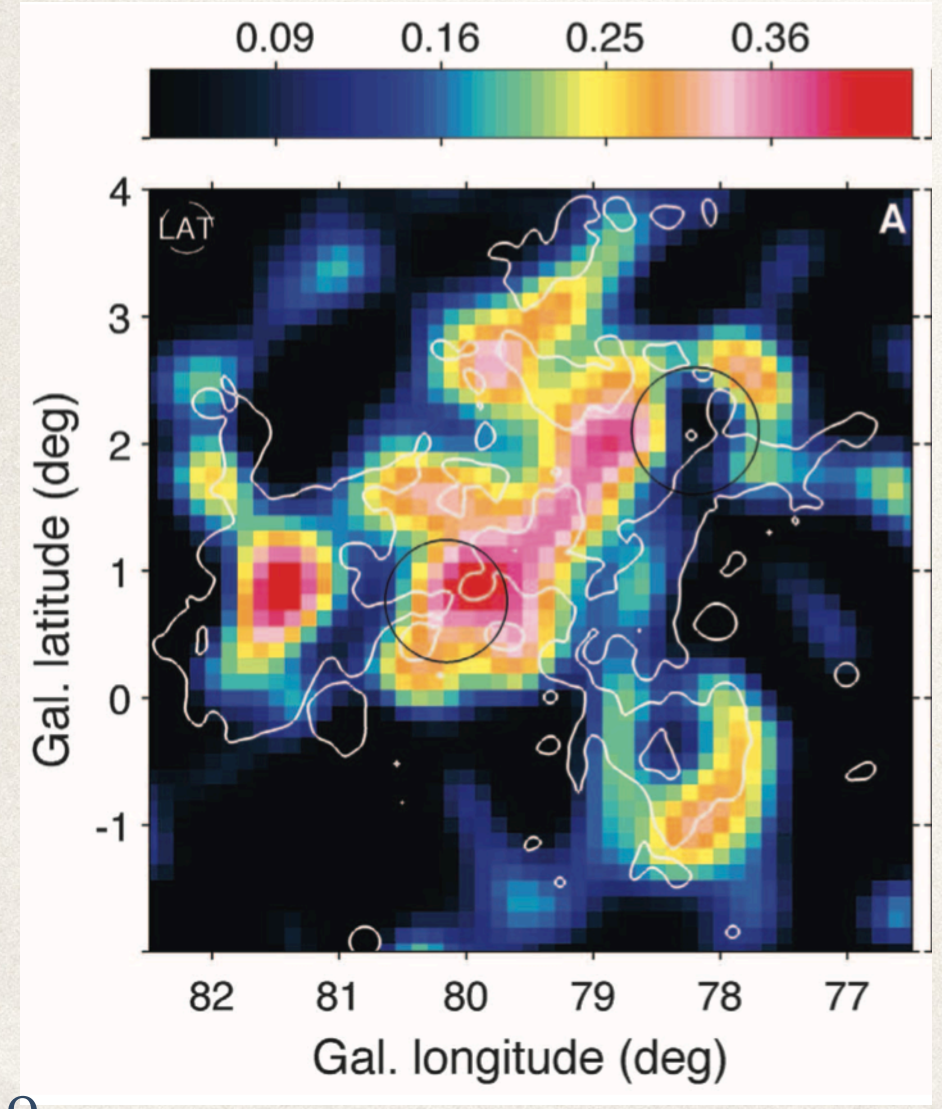
H.E.S.S. γ-ray map [Aharonian et al. (2022), A&A 666, 124]

Cygnus cocoon

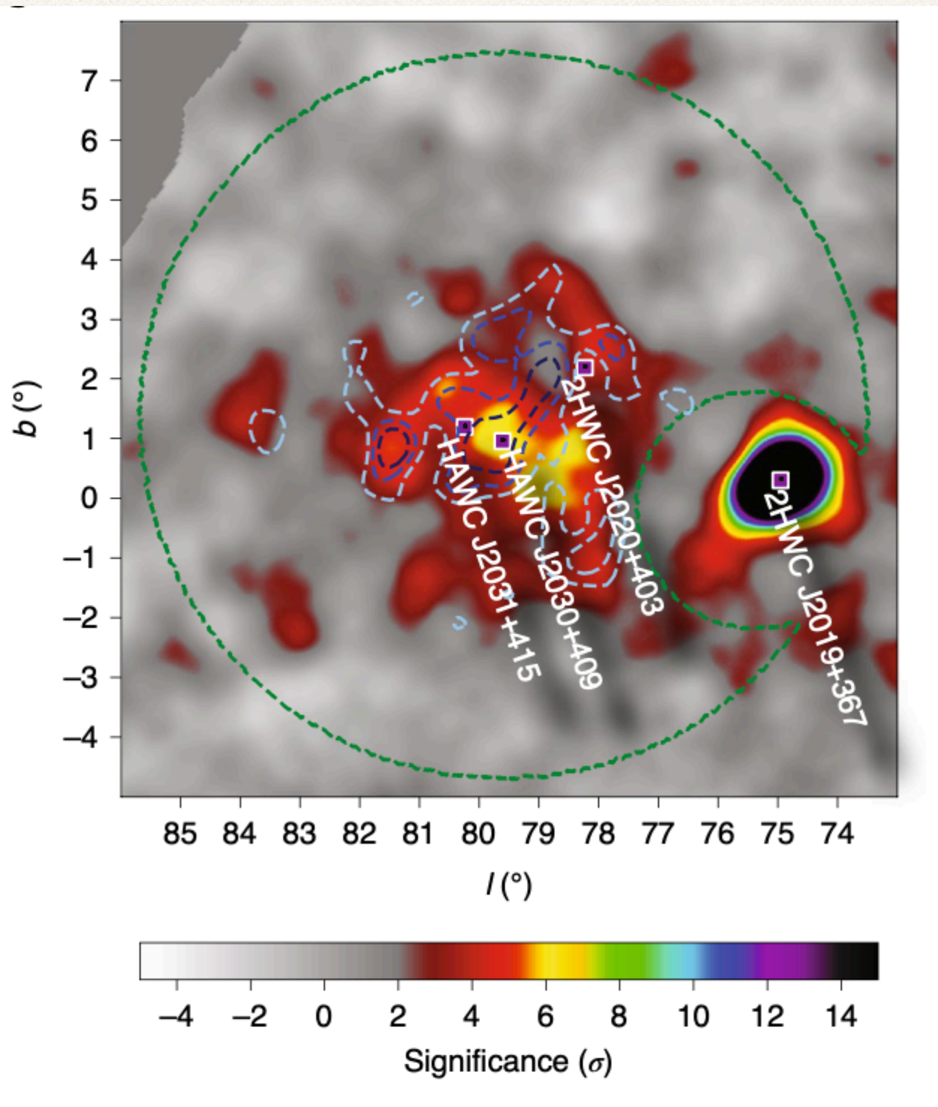
- Extended emission:
    - ➡ beyond 50 pc for HAWC and Fermi-LAT
    - ➡ and up to ~150 pc for LHAASO
- Hard spectrum in GeV band
- Softening in TeV band
- Photons detected by LHAASO with $E >$ PeV



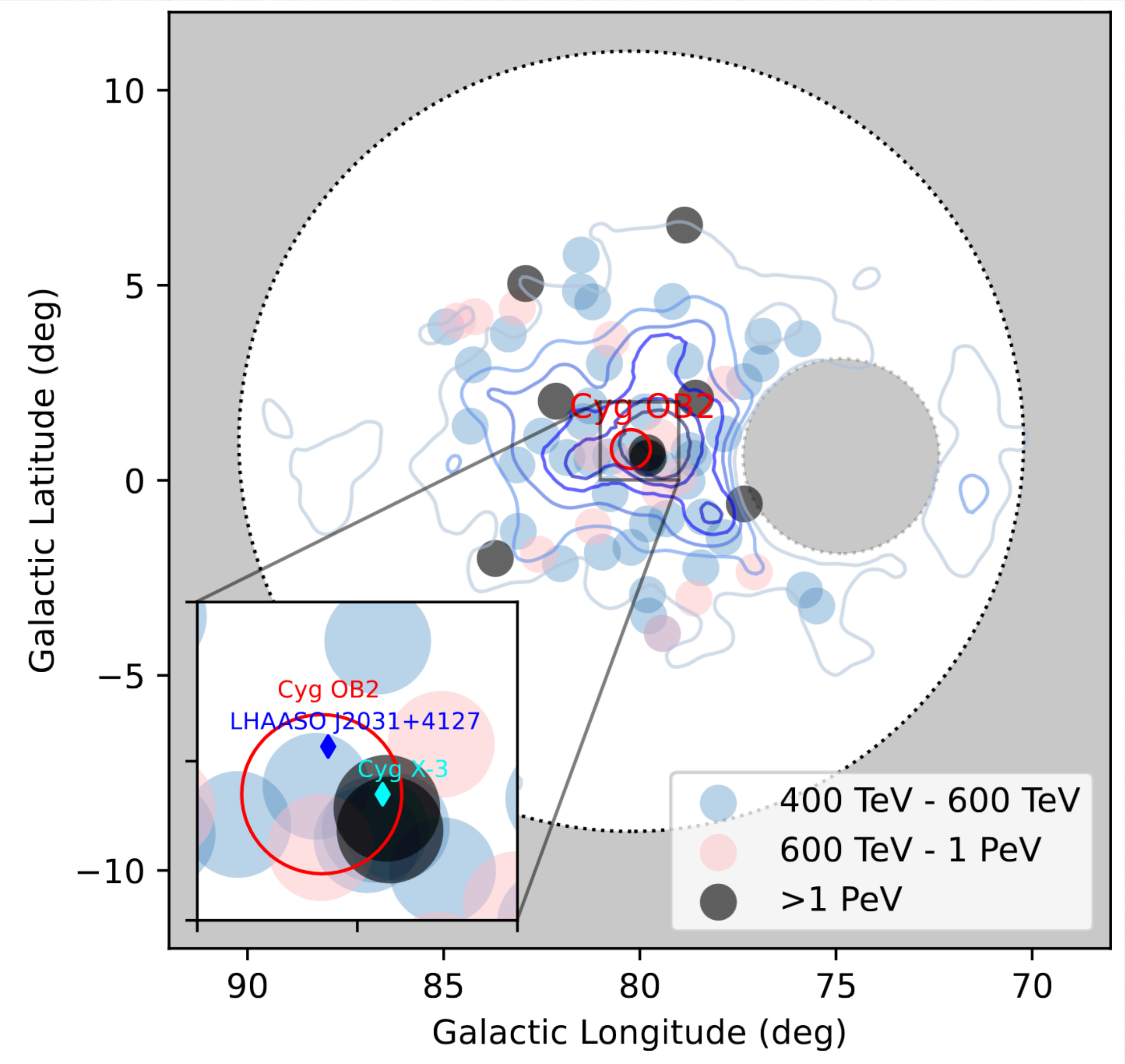
Cygnus Cocoon FermiLAT - Ackermann et al. (2011)



HAWC coll. (2020)



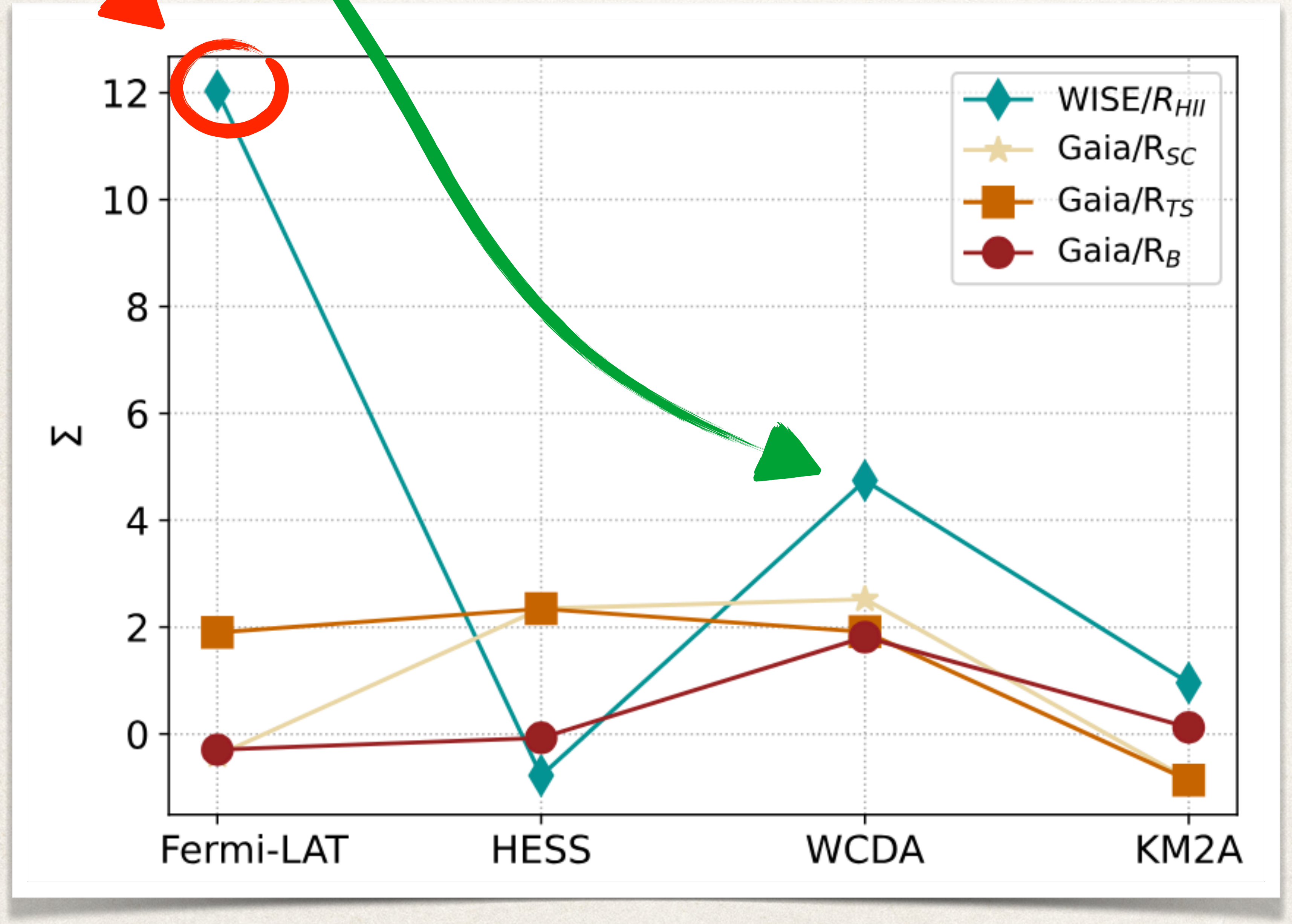
LHAASO coll. (2023)



Correlation between YMSC and Fermi-LAT unassociated sources

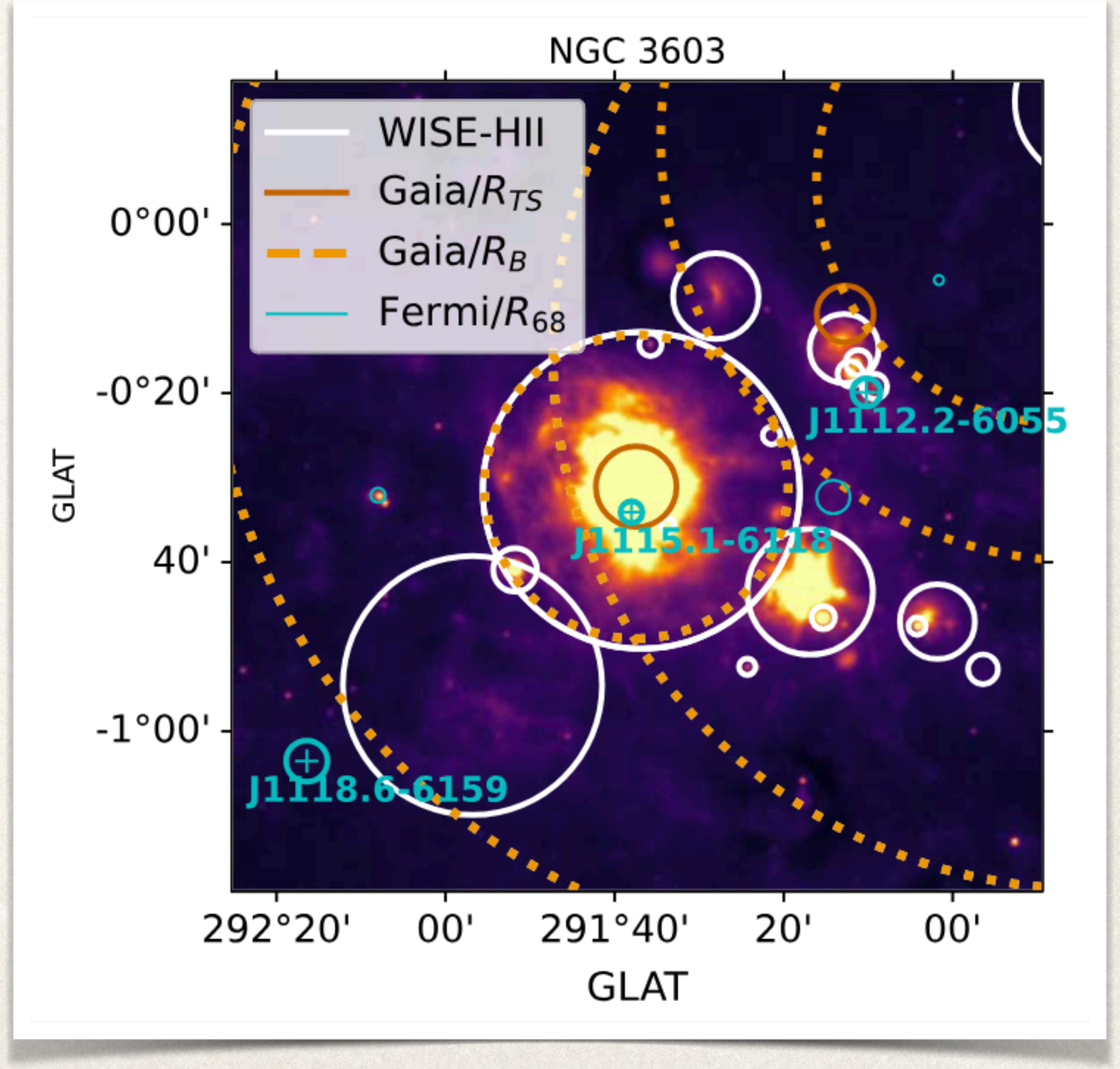
G. Peron et al. ApJL 972 (2024)

- 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

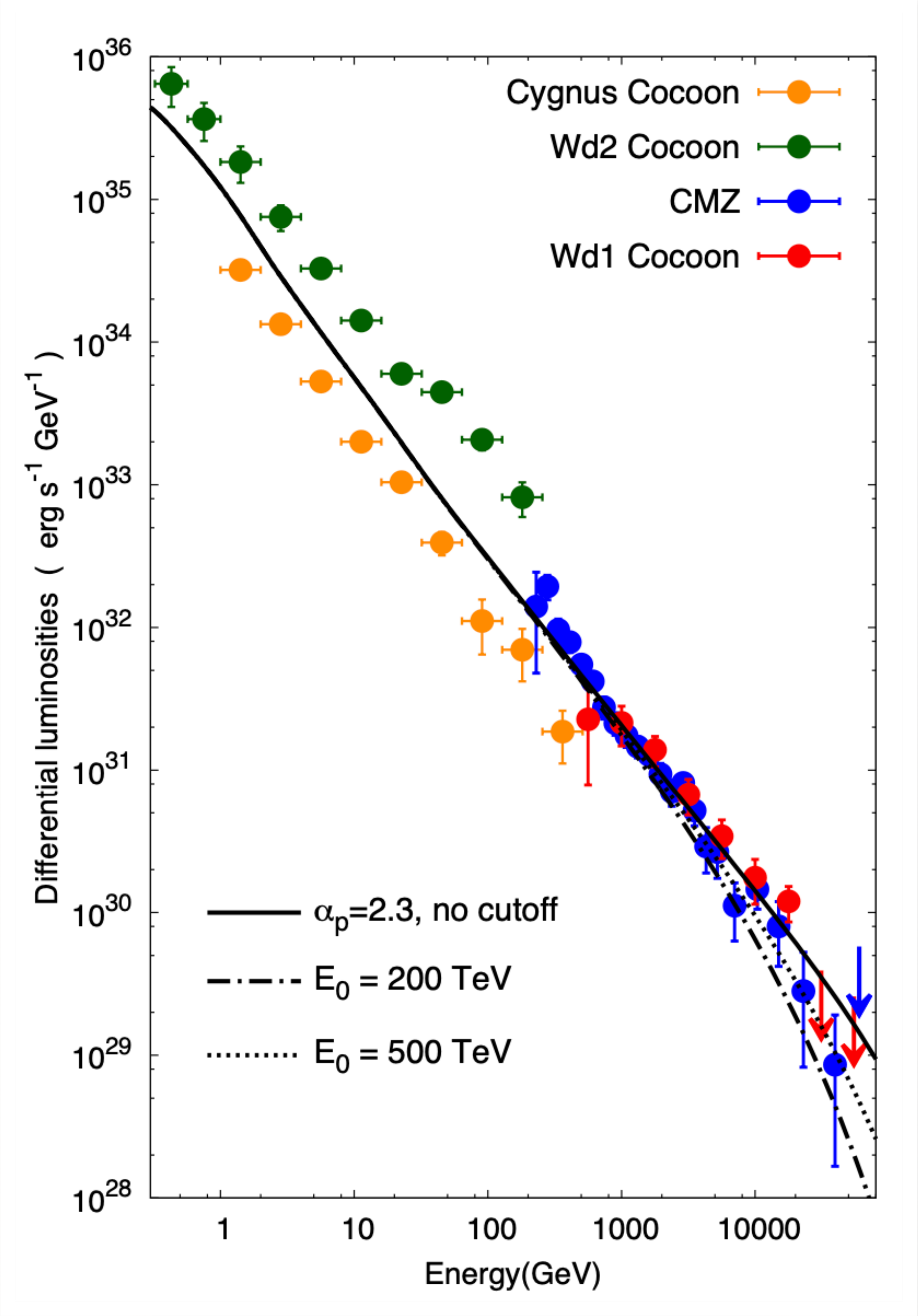
The case of NGC 3606:
the HII region well overlap with
the predicted bubble size



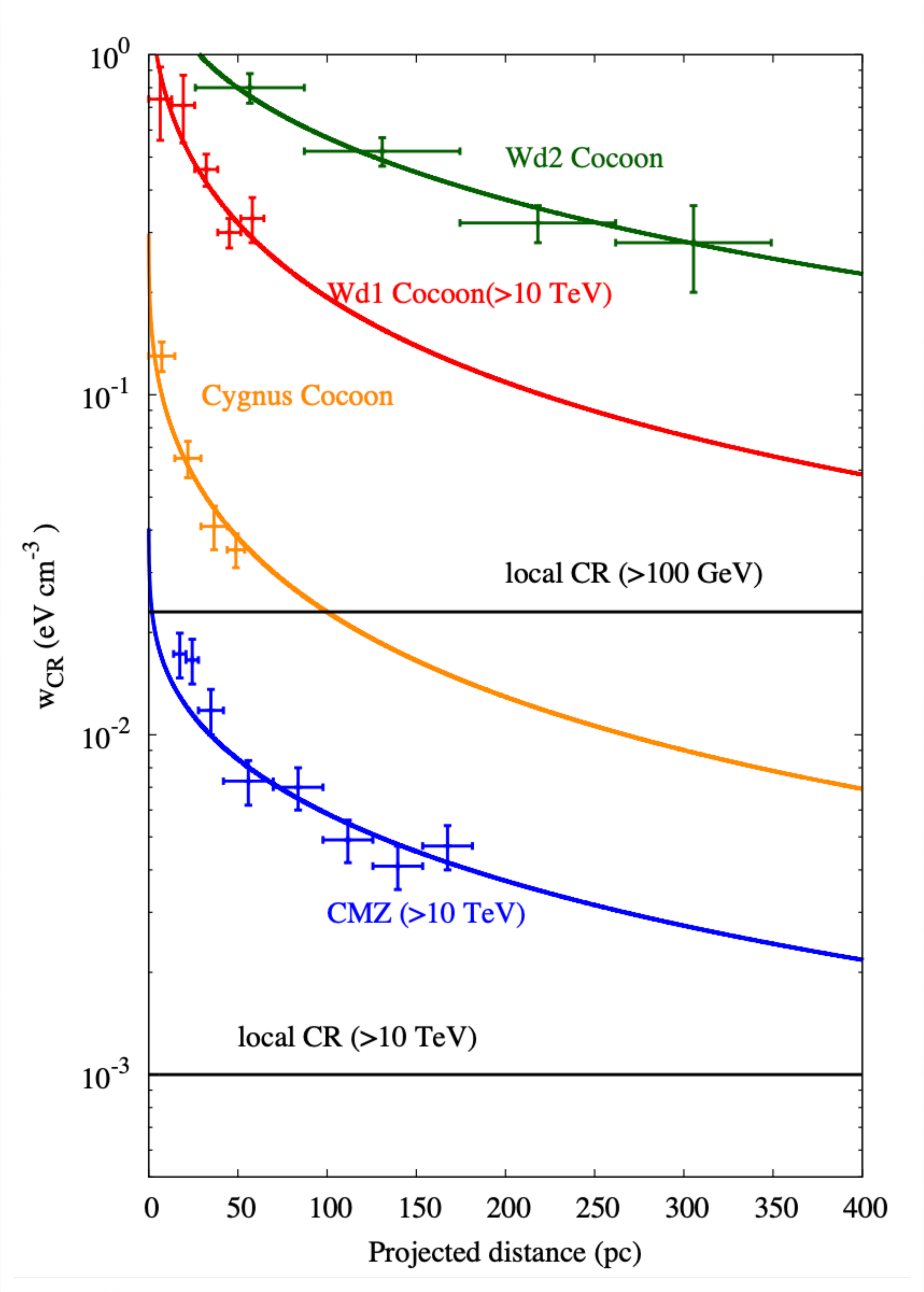
Spectra and radial profiles

[Aharonian, Yang & Wilhelmi, Nat. Astr. (2019)]

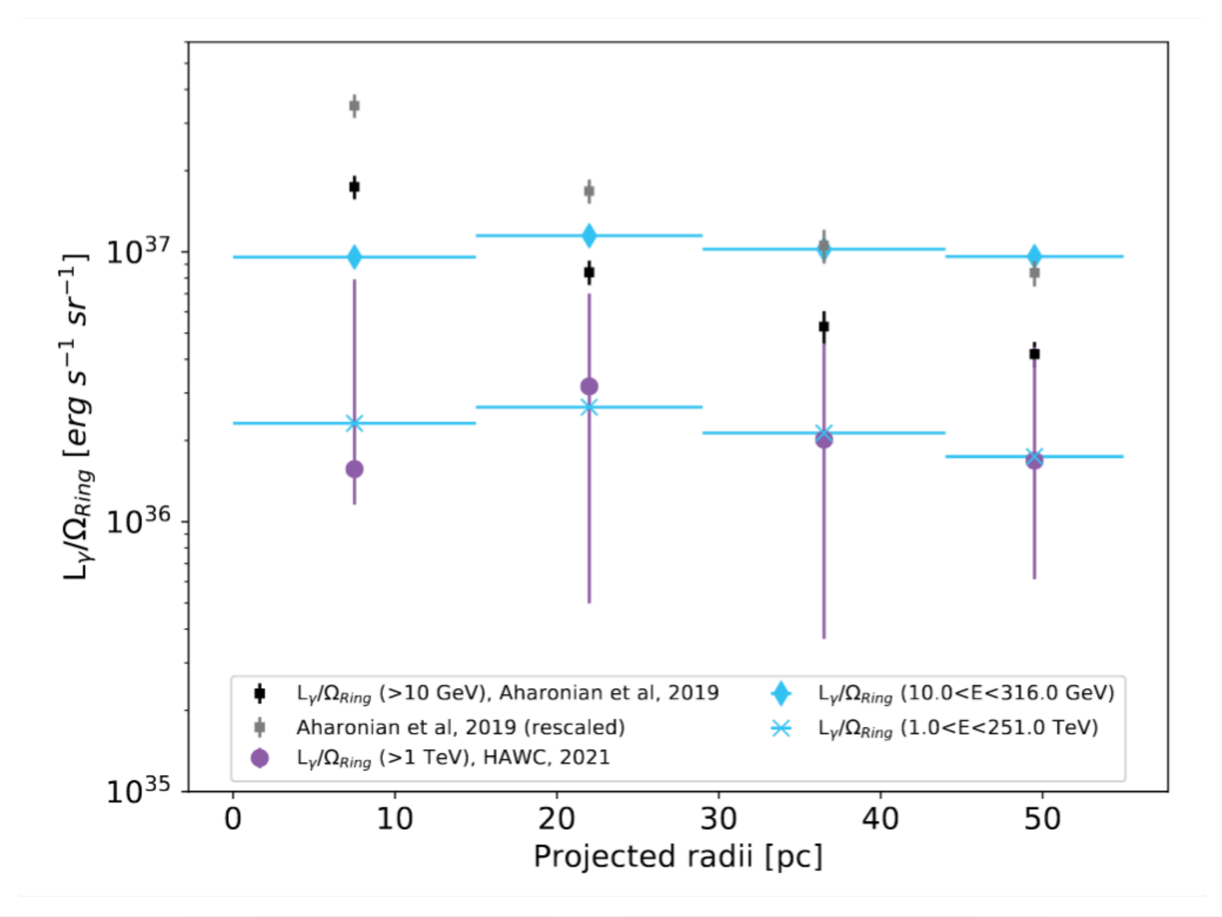
1) Hard spectrum $\propto E^{-(2.2 \div 2.3)}$

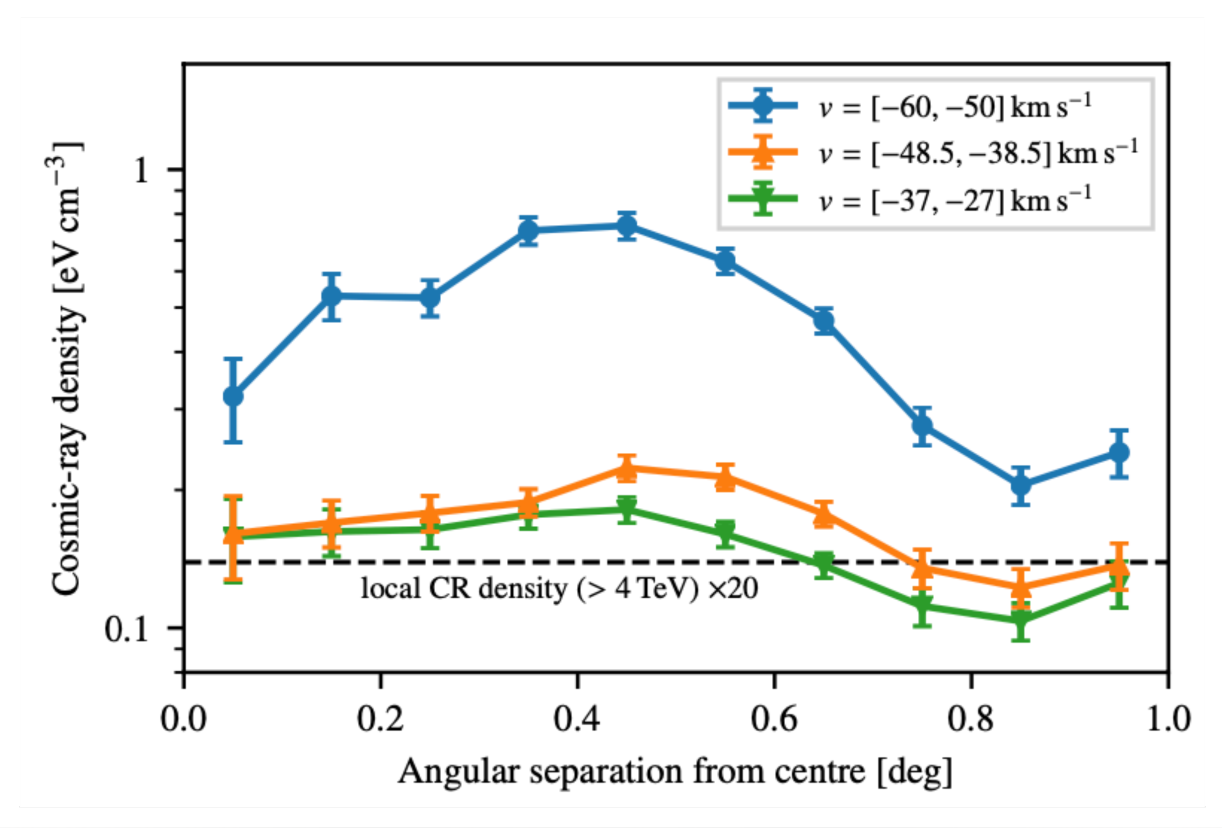


2) 4 sources seems to show a 1/r radial profile in the FermiLAT band



3) Not always true in TeV emission (Cygnus - HAWC; Wd1 - HESS)

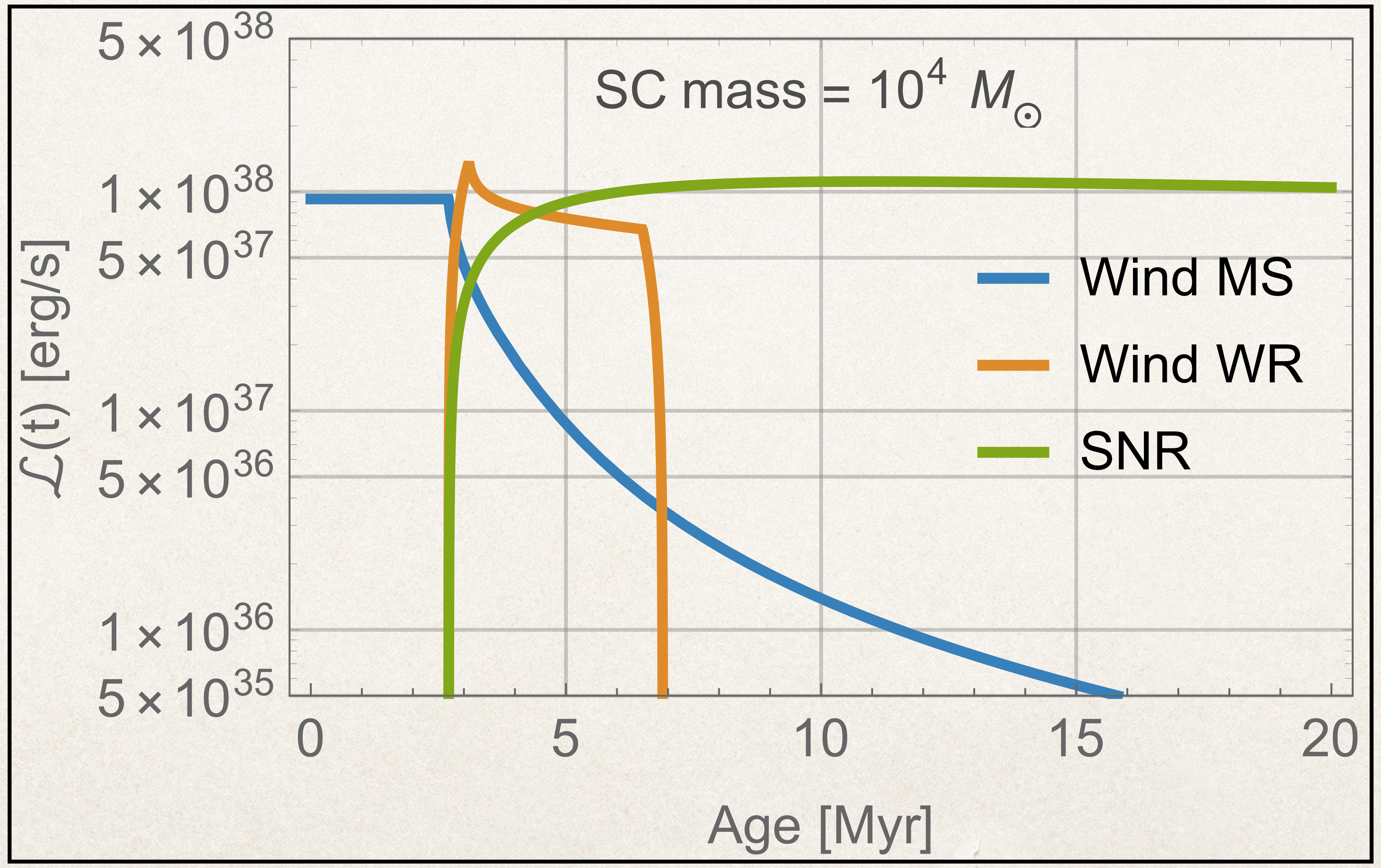




What power Stellar Clusters?

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



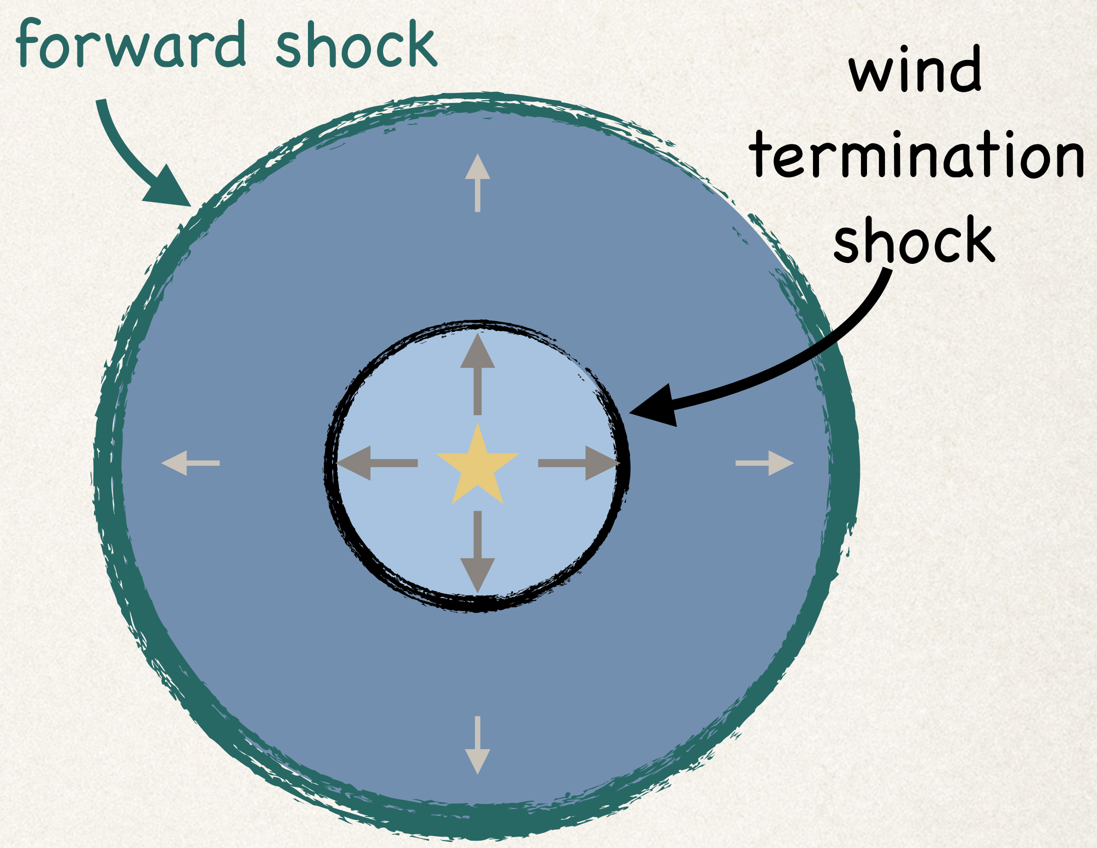
Size:

Cluster core ~ 1 pc

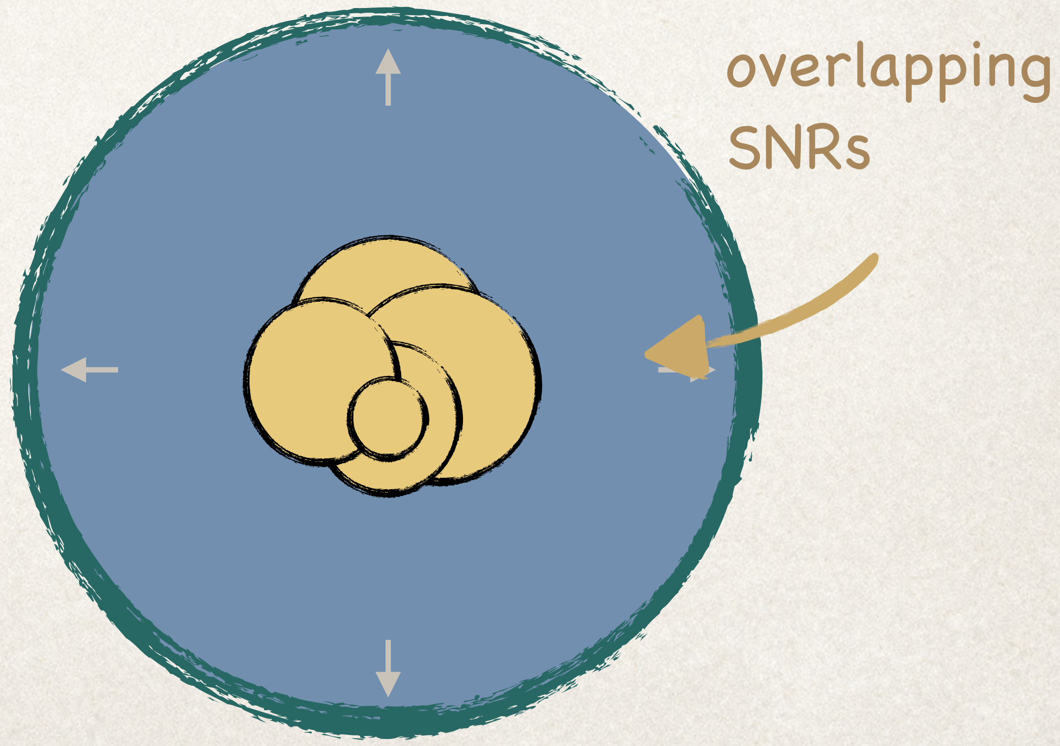
Termination shock $\sim 5 - 10$ pc

Bubble $\sim 50 - 100$ pc

$t \lesssim 3$ Myr: only stellar winds



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



Energetics: SNe *vs* Stellar Winds

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

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

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

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

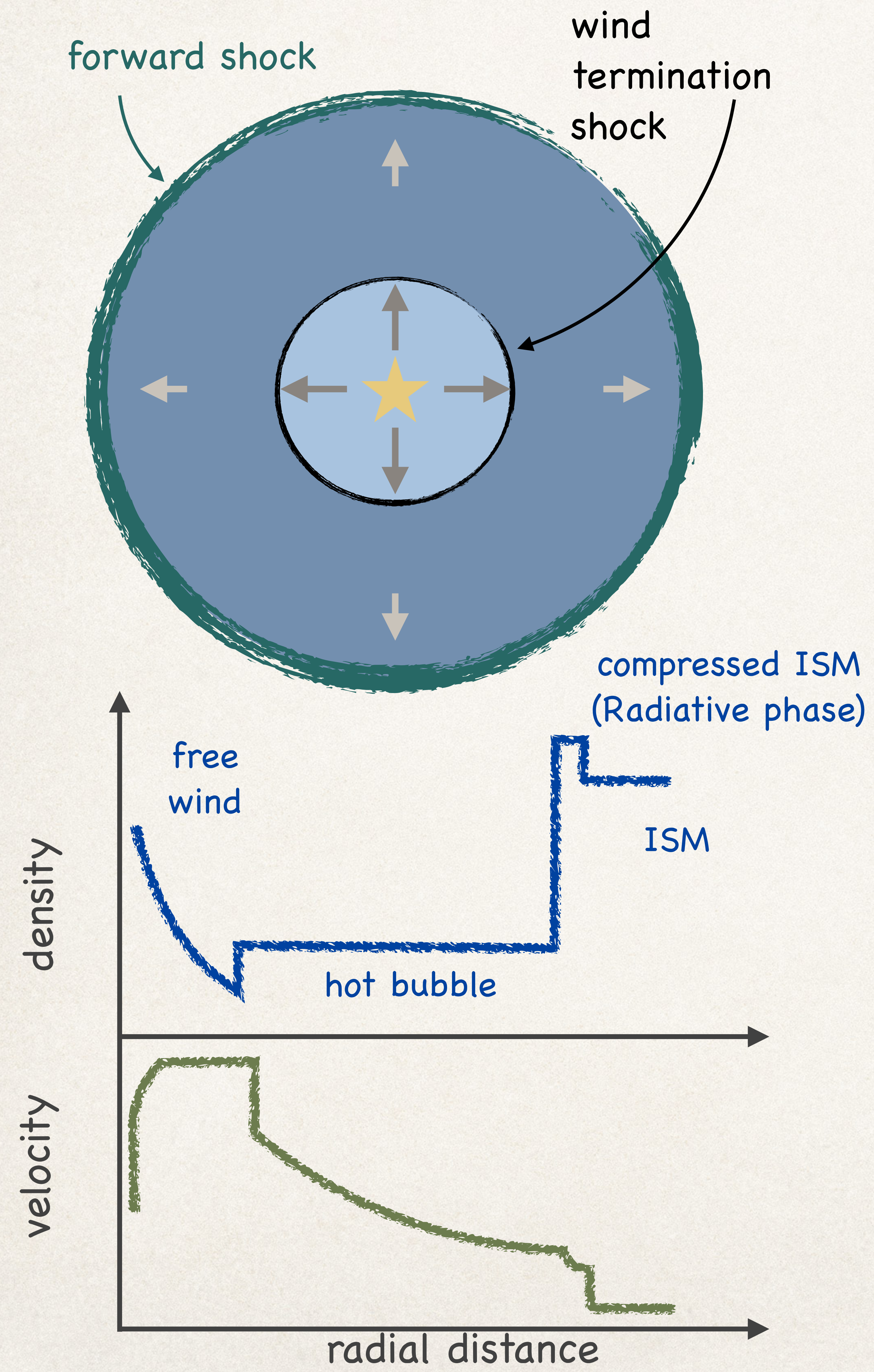
[Nieuwenhuijzen & de Jager(1990)]

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

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)]

Cluster wind physics



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

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

  Constant injection of energy in time in a spherical symmetry

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

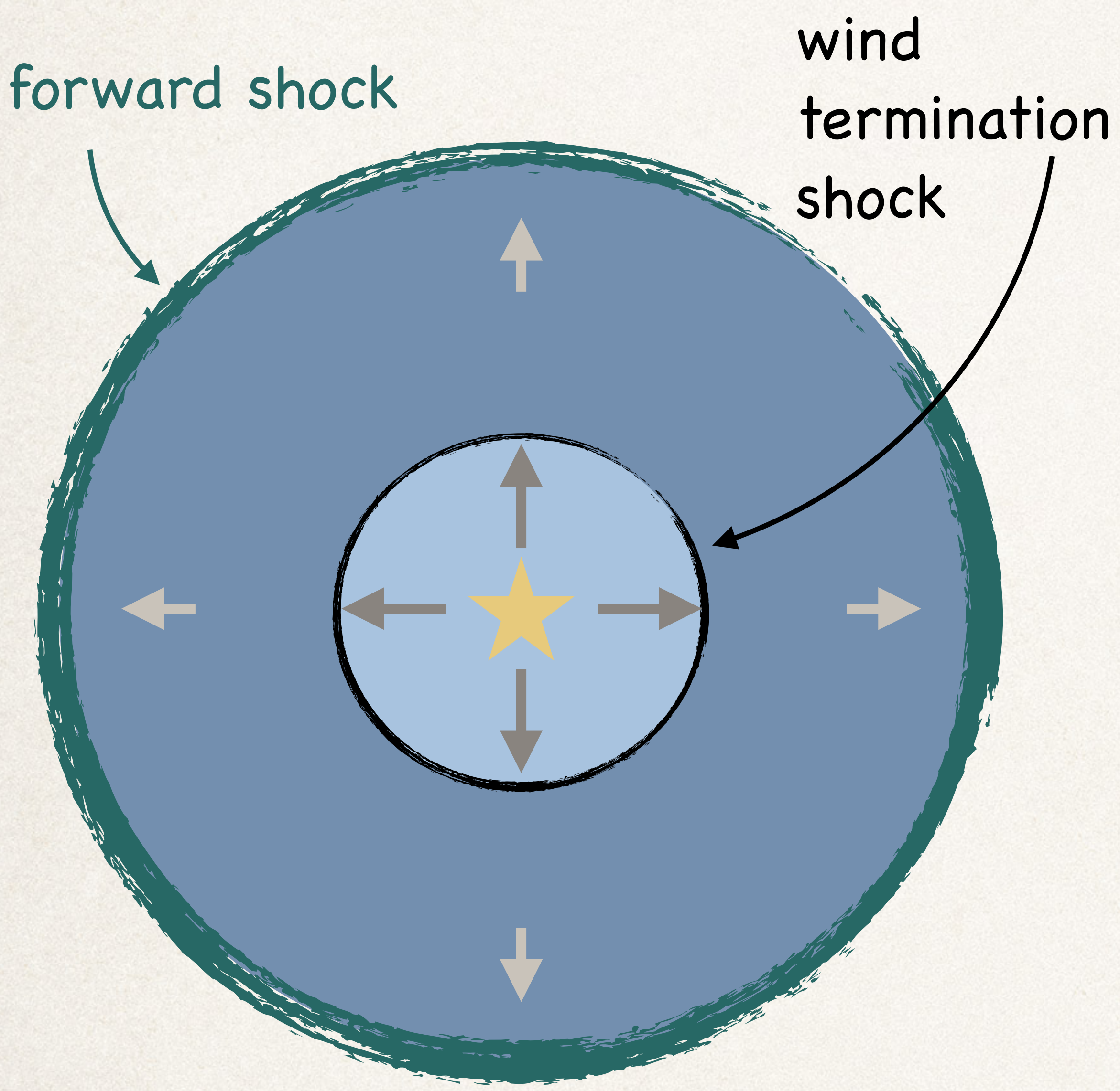
$$R_{\rm TS} \simeq 20\ \mathrm{pc}\left(\frac{\dot M}{10^{-4}M_\odot/yr}\right)^{3/10}\left(\frac{v_w}{1000\,\mathrm{km/s}}\right)^{1/10}\left(\frac{\rho_0/m_p}{\mathrm{cm}^{-3}}\right)^{-3/10}\left(\frac{t_{\rm age}}{\mathrm{Myr}}\right)^{2/5}$$

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

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

Caveat 1: non spherical evolution

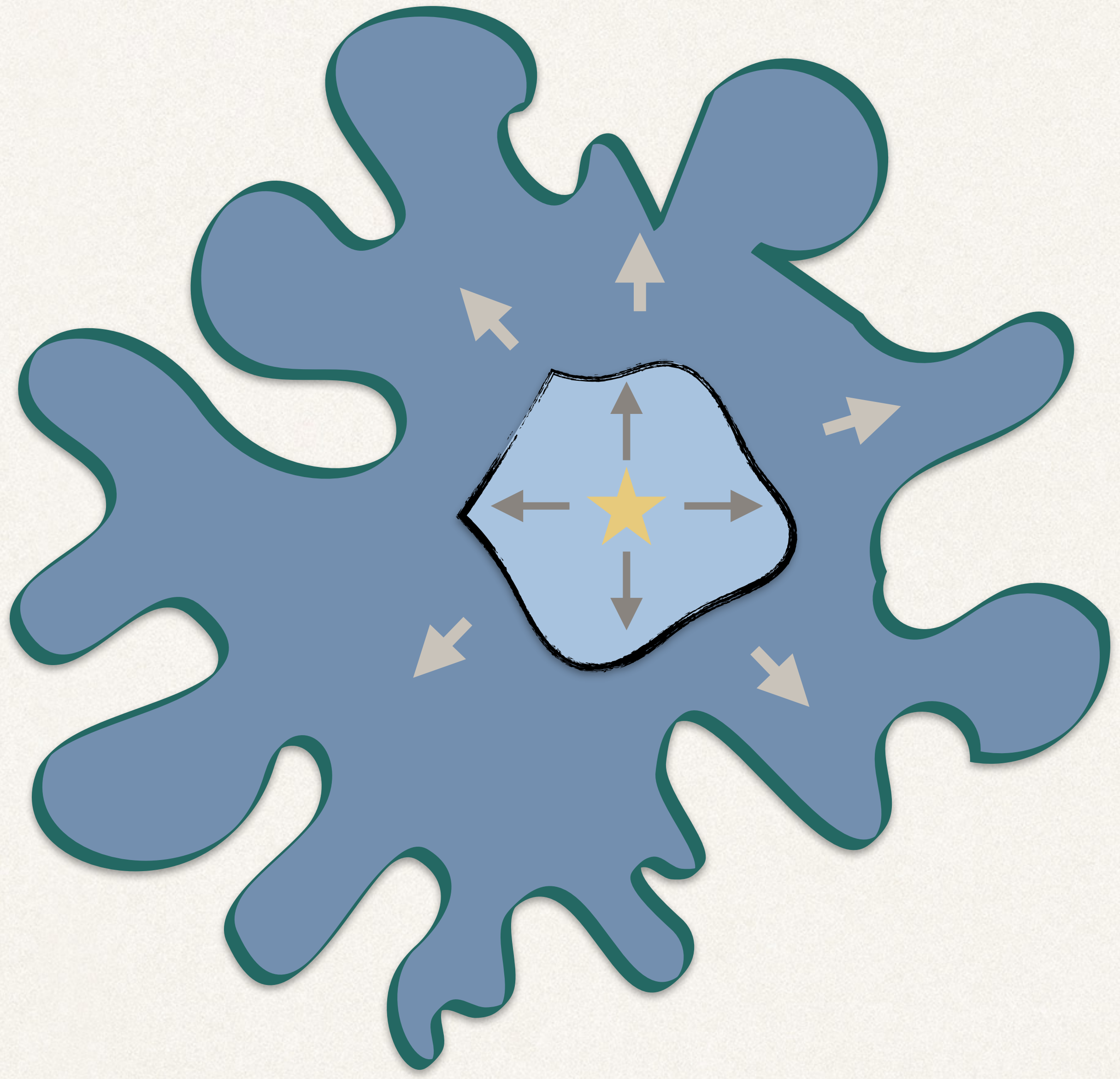
Idealised spherical model



Pure adiabatic model

[Weaver & McCray (1977)]

Realistic fractal structure



Effects that produce HD instabilities:

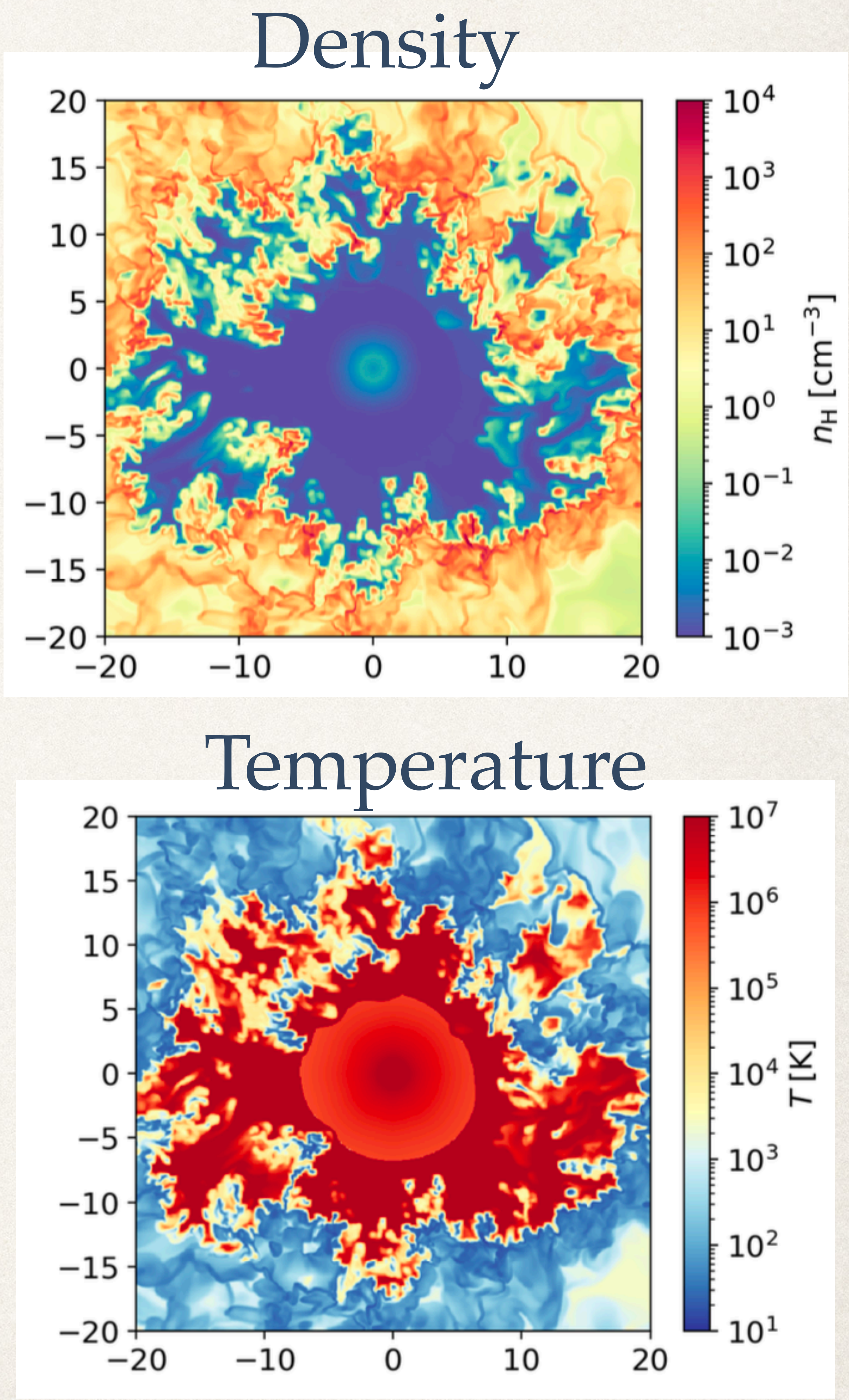
- ISM inhomogeneities
- Wind clumpiness (WR)
- Cooling

Effects that damp HD instabilities:

- Magnetic field pressure

Important for:

- Particle transport
- Emission processes



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

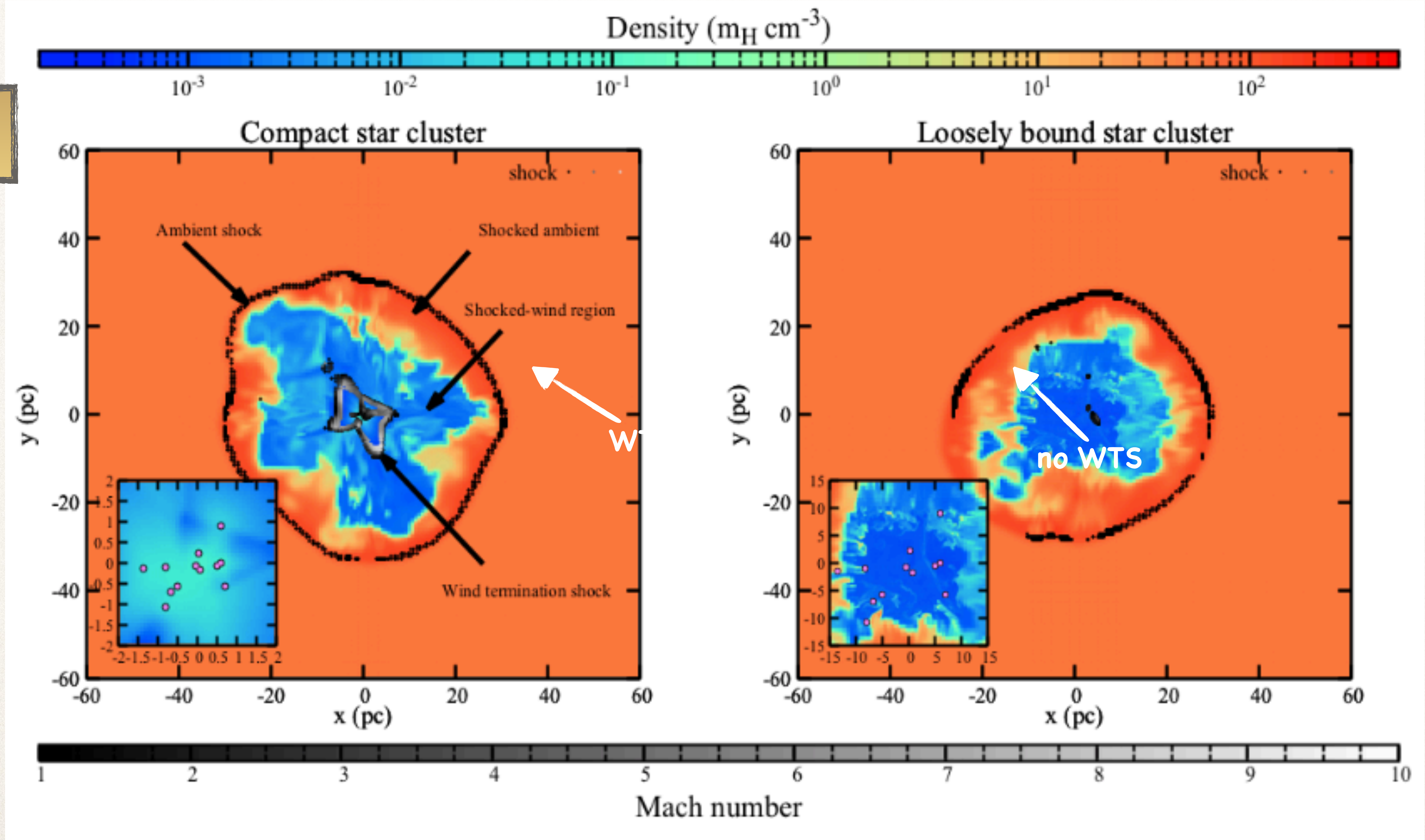
Caveat 2: compactness

[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

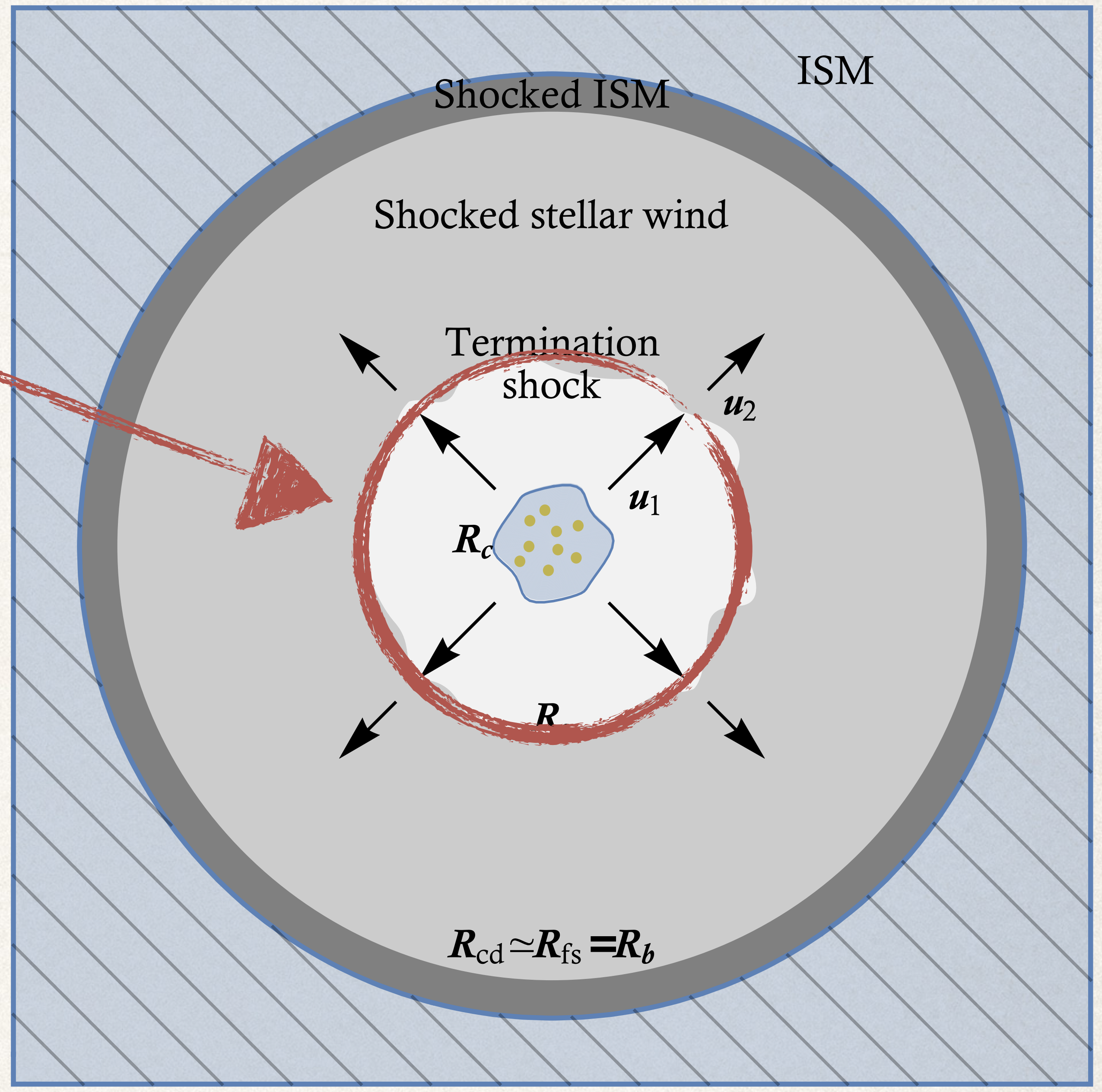
Particle acceleration at the wind termination shock

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 %



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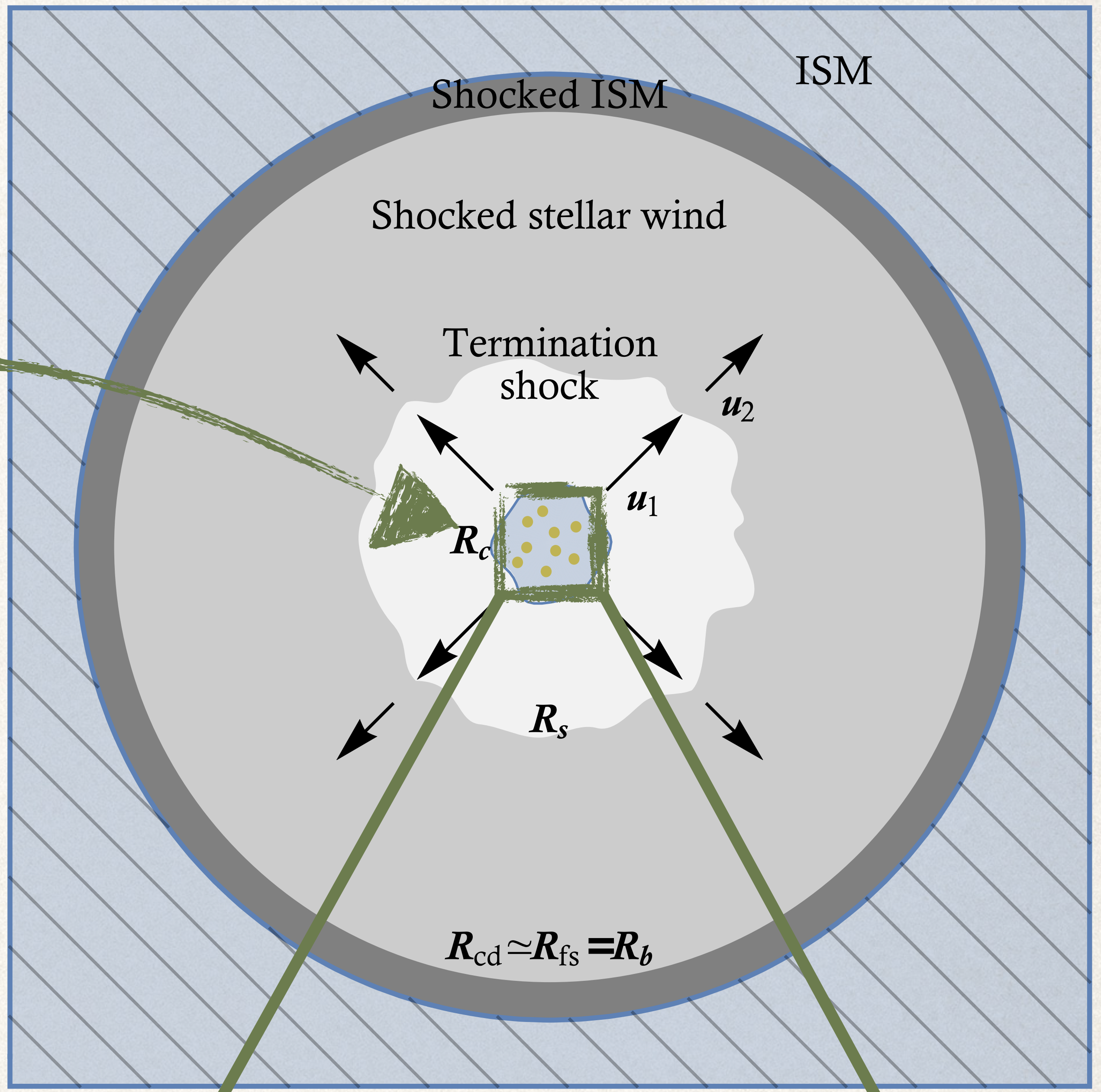
- Magnetic turbulence produced by MHD instabilities
  - ➡ Diffusion coefficient depends on the type of turbulence cascade:

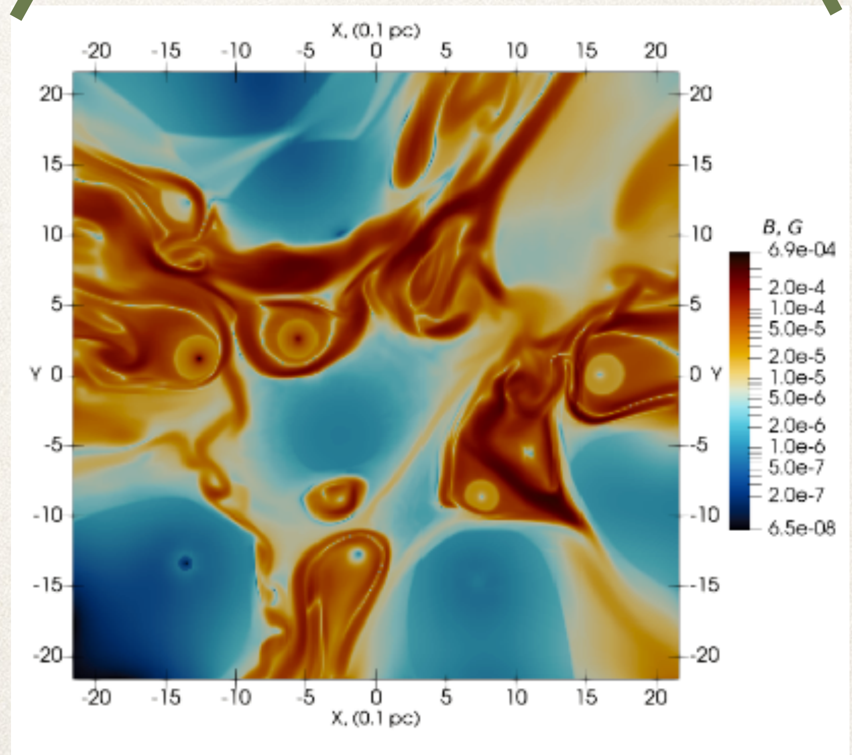
    Kolmogorov, Kraichnan, Bohm



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)



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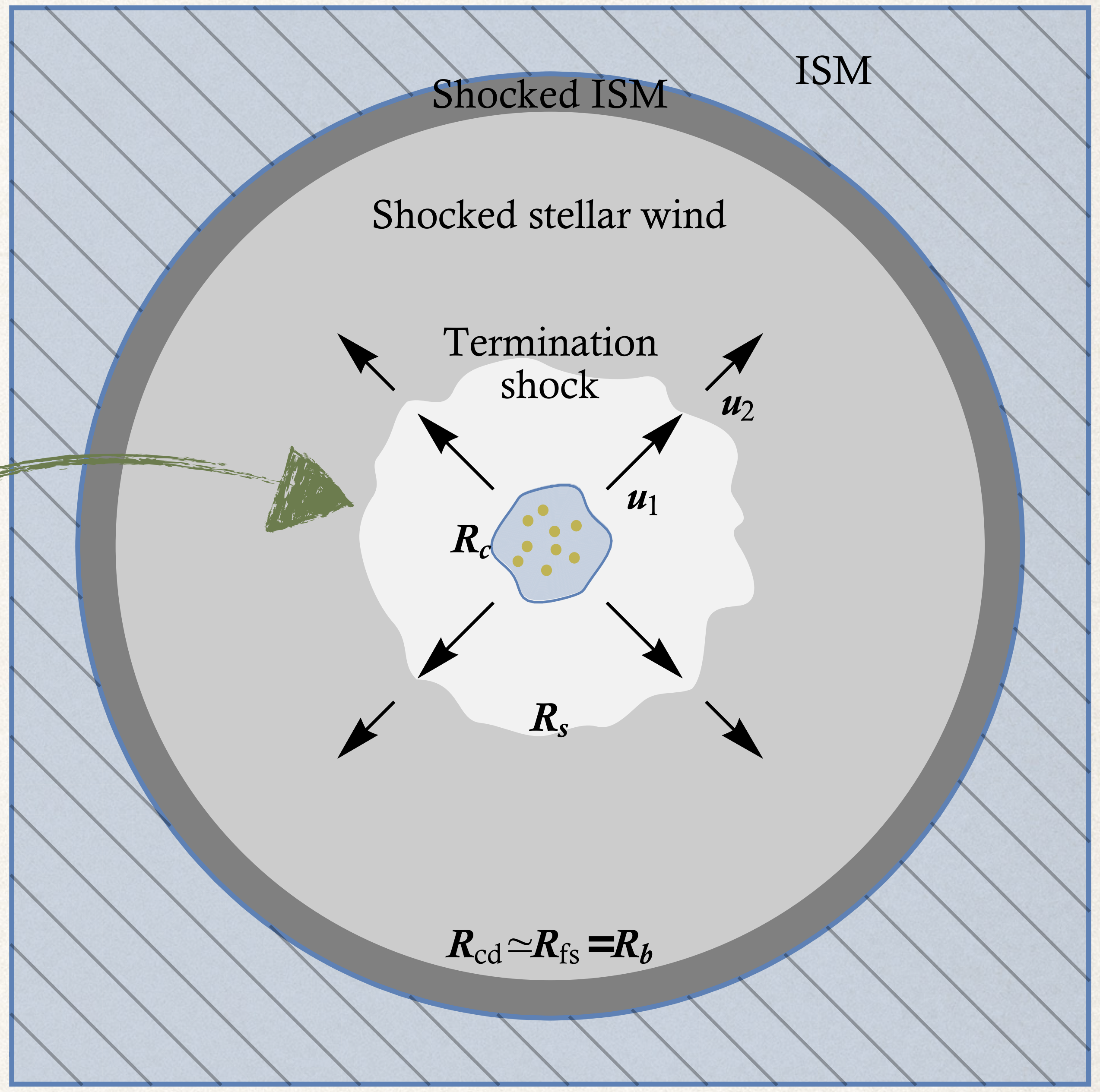

2) Self-generated magnetic turbulence
Applying resonant instability:

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

Self-amplification may be relevant al low energies

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

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Acceleration at the collective wind termination shock

[GM et al. (2019)]

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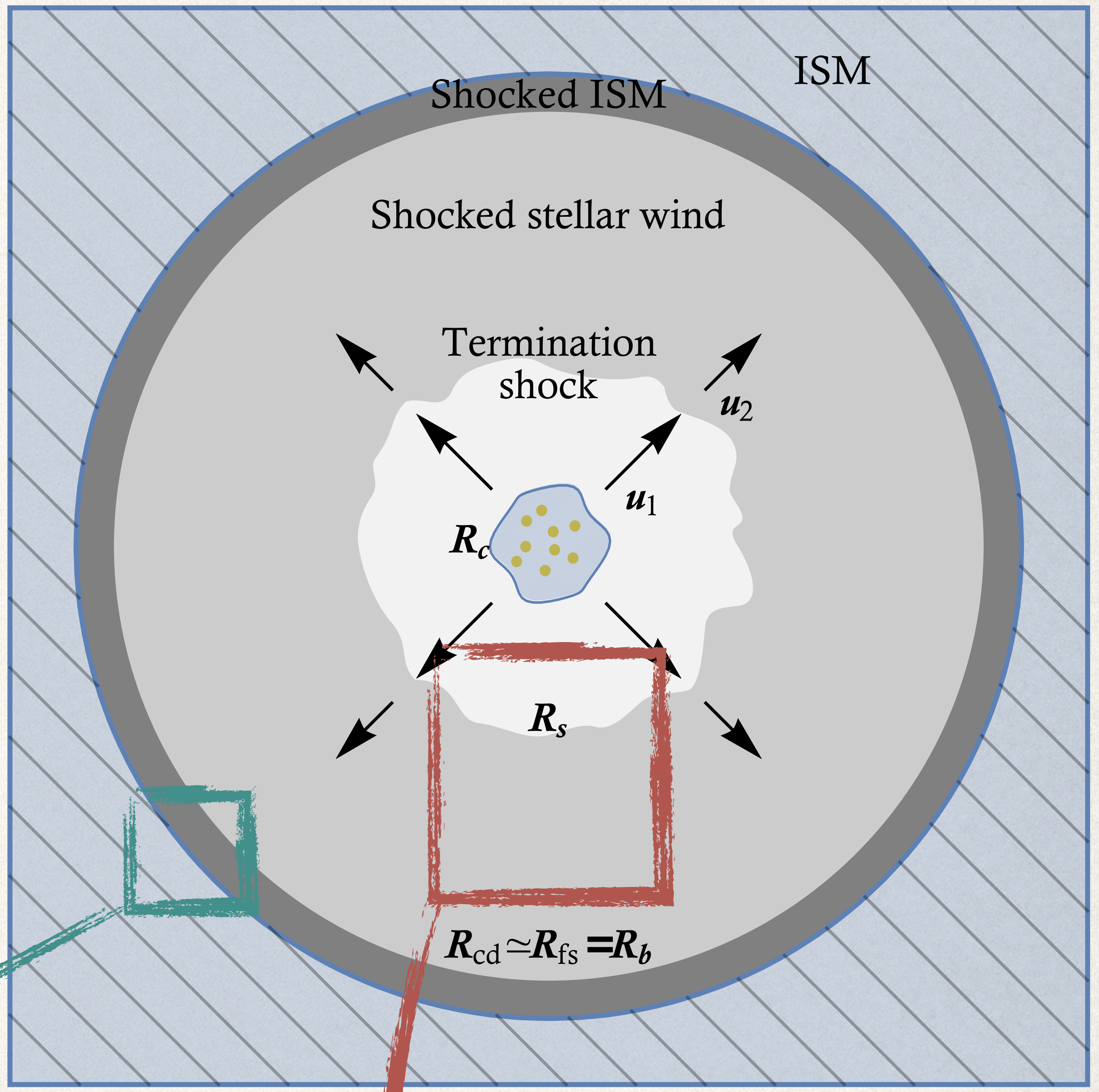
- Particle diffuse and interact in the bubble



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

$\pi^0 \rightarrow \gamma\,\gamma$

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

Particle acceleration at the wind termination shock

GM, Blasi, Peretti & Cristofari (2019)

Solution at the shock

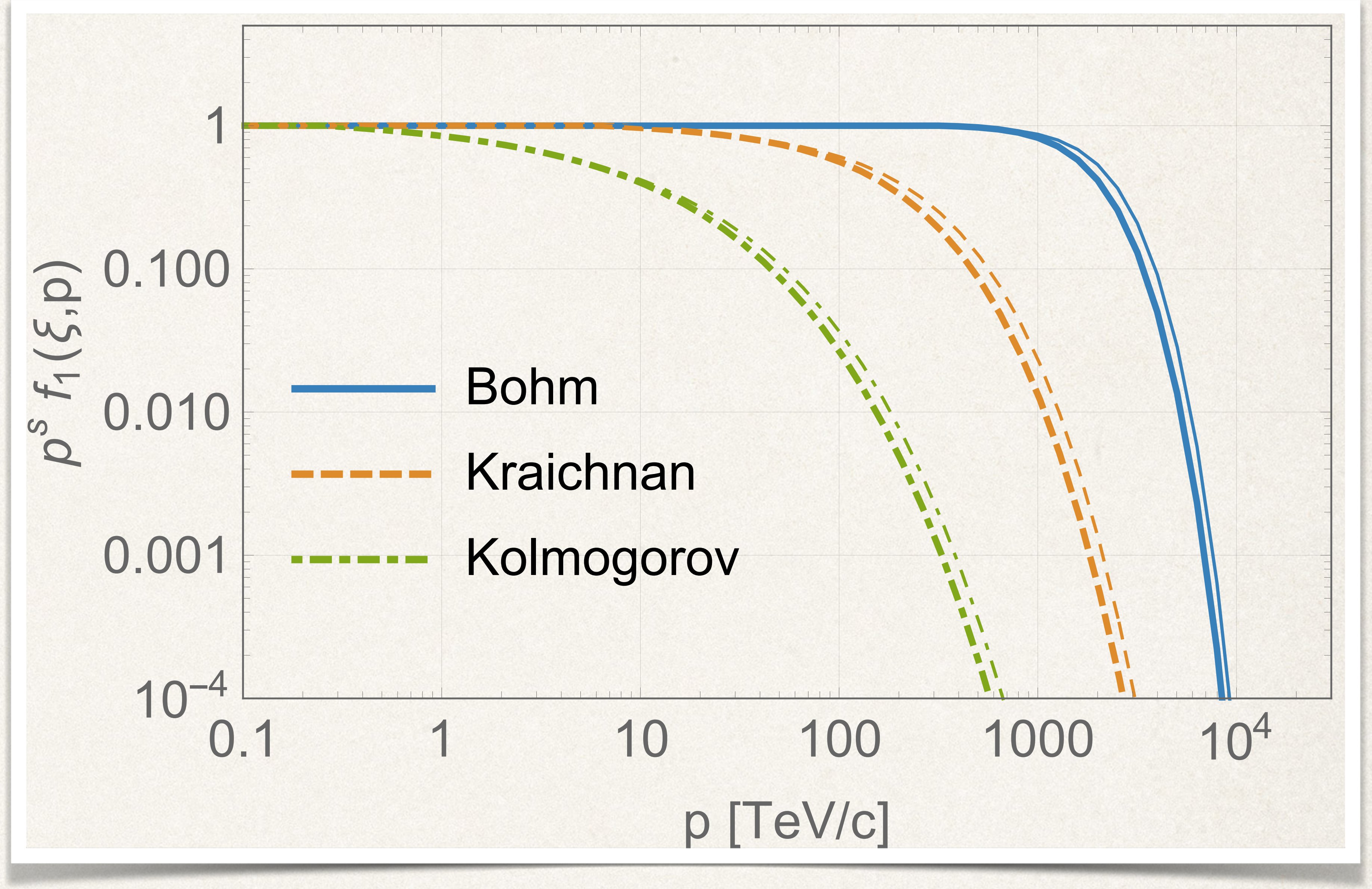
$$f_s(p) = s \frac{\eta_{\rm inj}\, n_1}{4\pi\, p_{\rm inj}^3} \left(\frac{p}{p_{\rm inj}}\right)^{-s} e^{-\Gamma_1(p)}\; e^{-\Gamma_2(p)}$$

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



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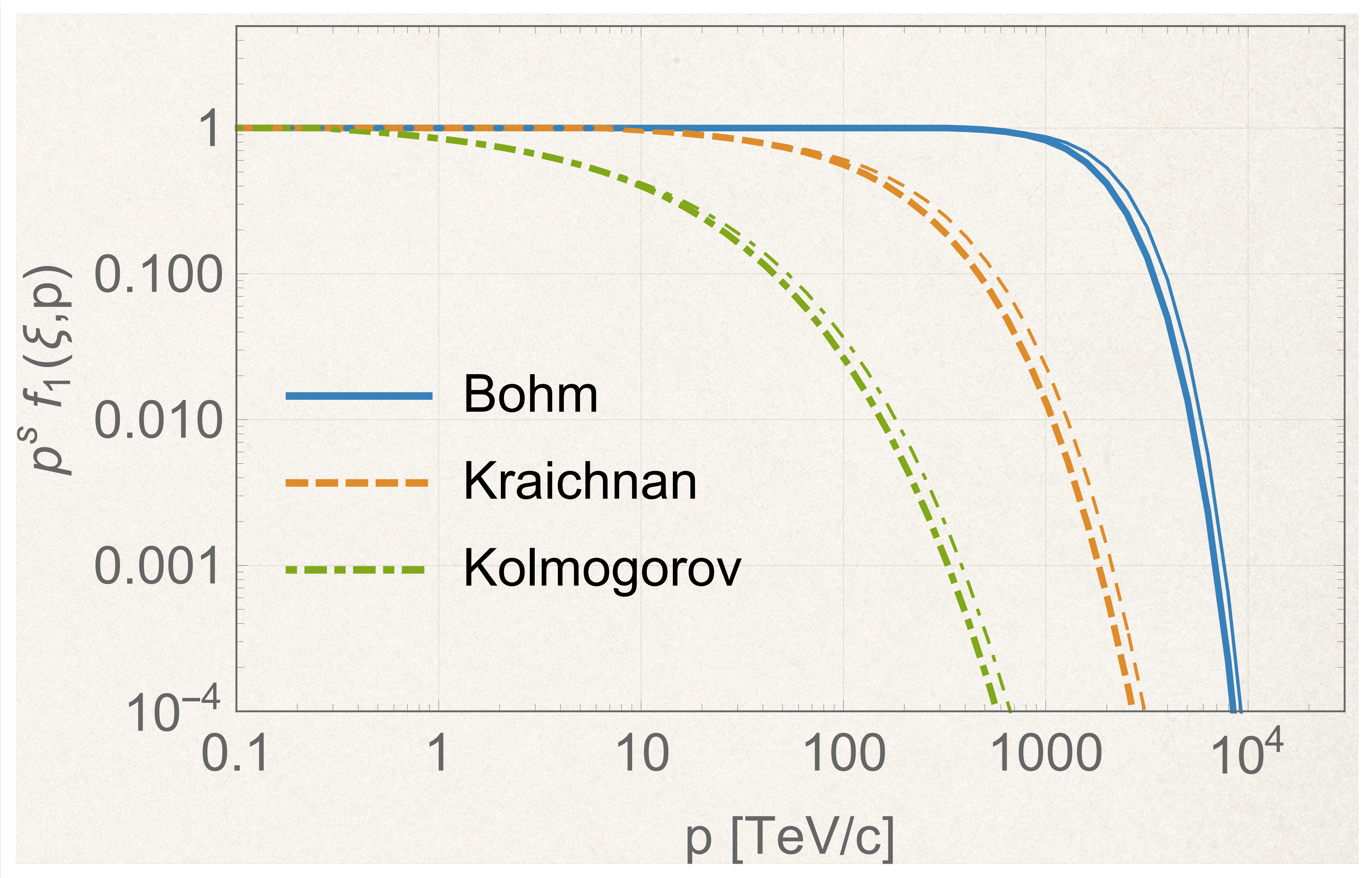
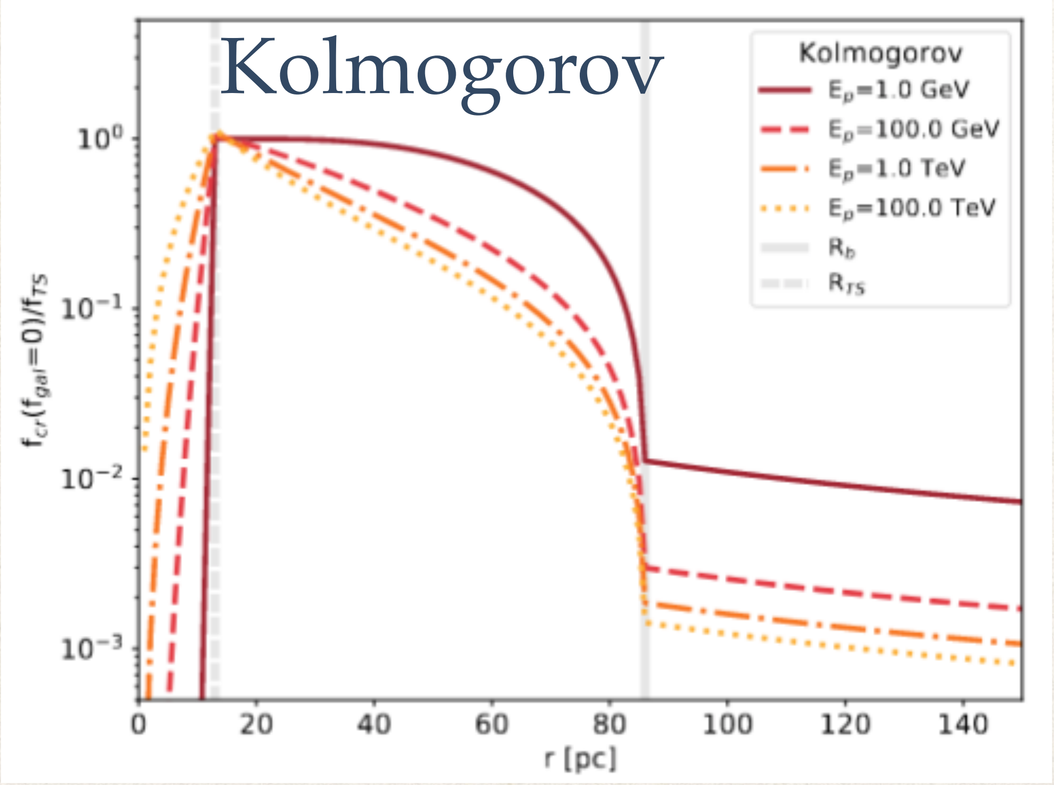
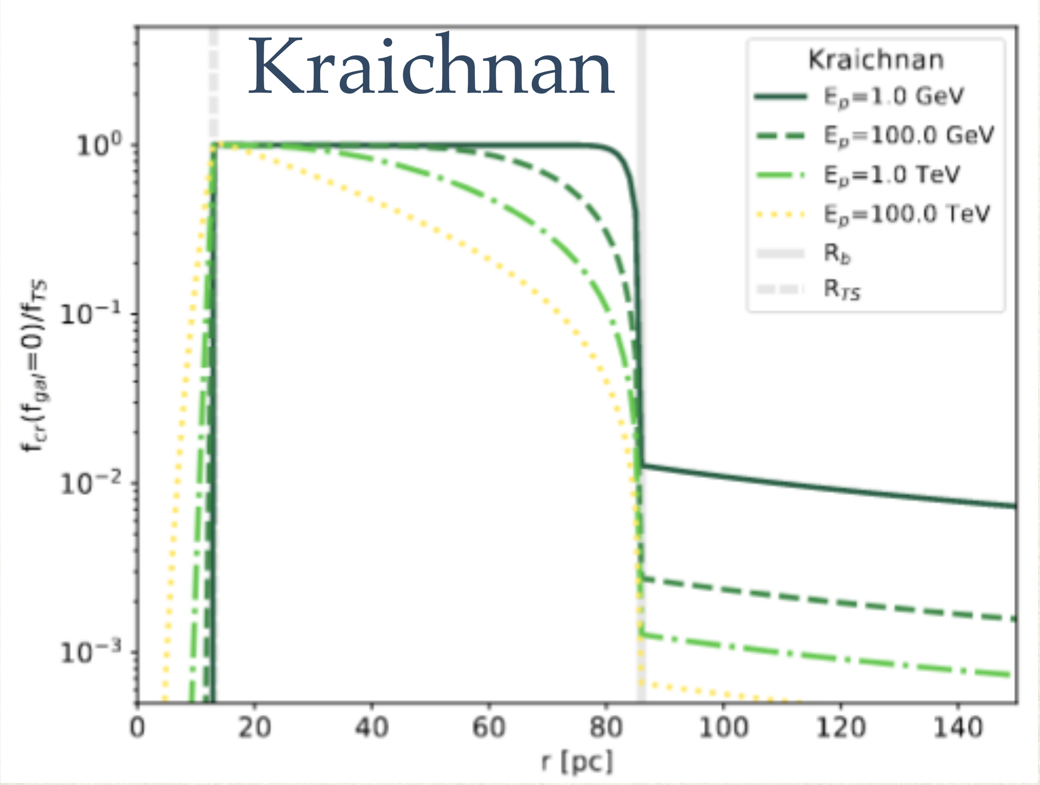
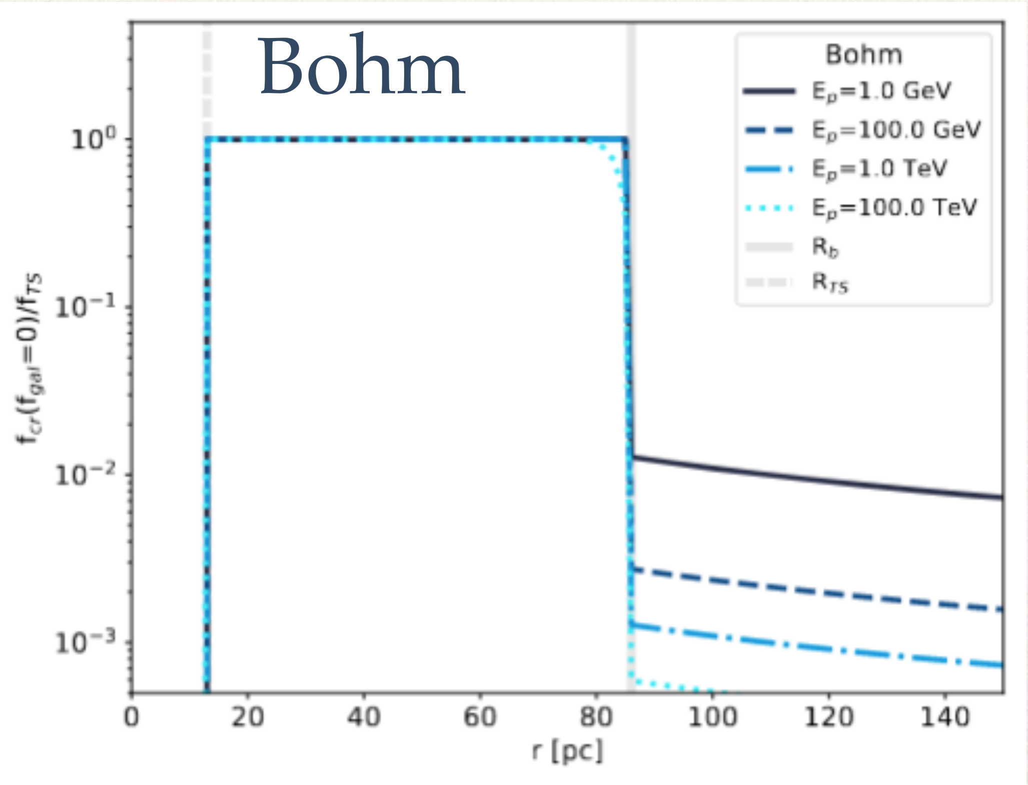




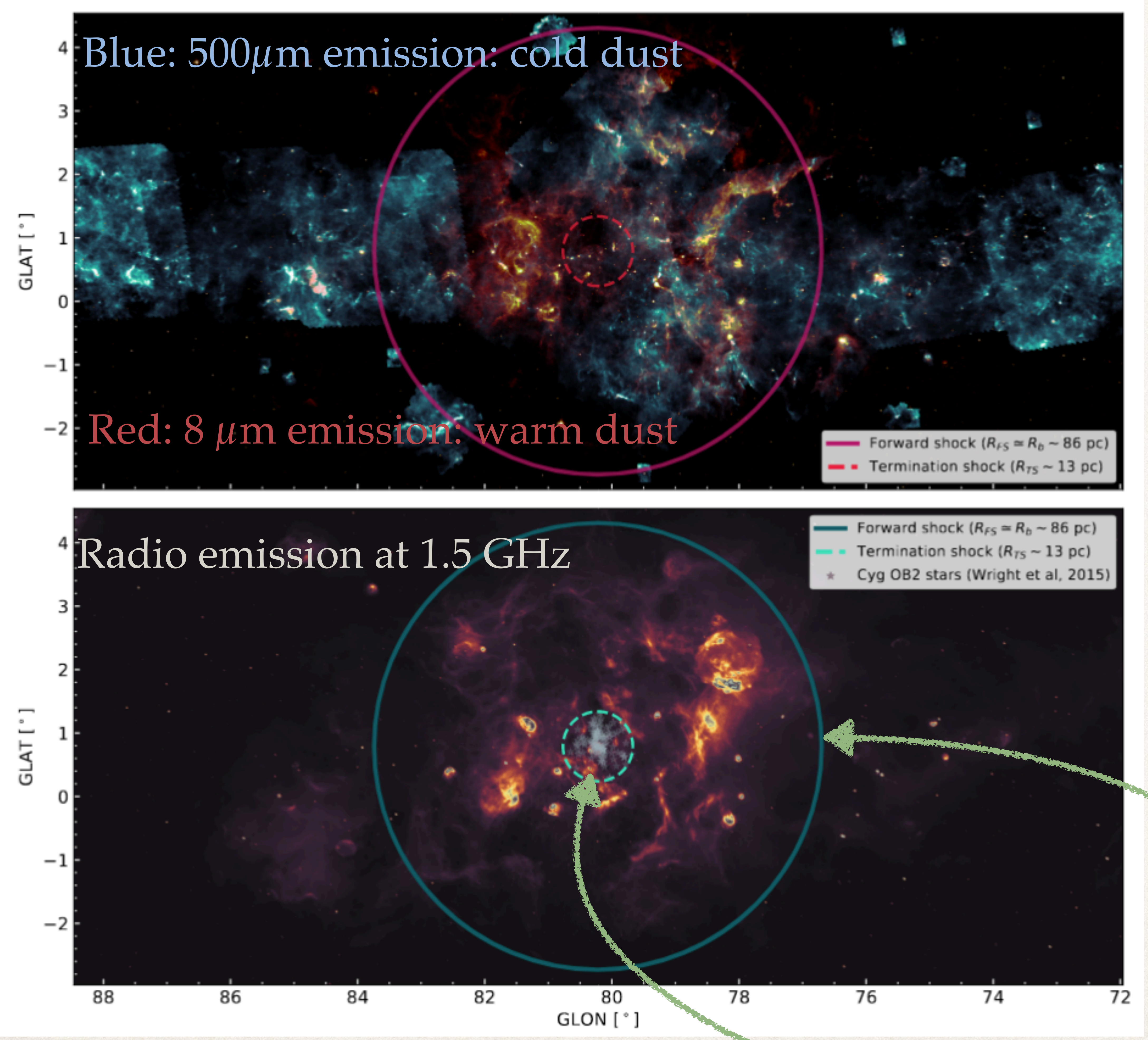




Spatial profile: the harder is the diffusion coefficient the flatter is the CR distribution

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 $v_w \simeq 2300\,\mathrm{km s^{-1}}$
- 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

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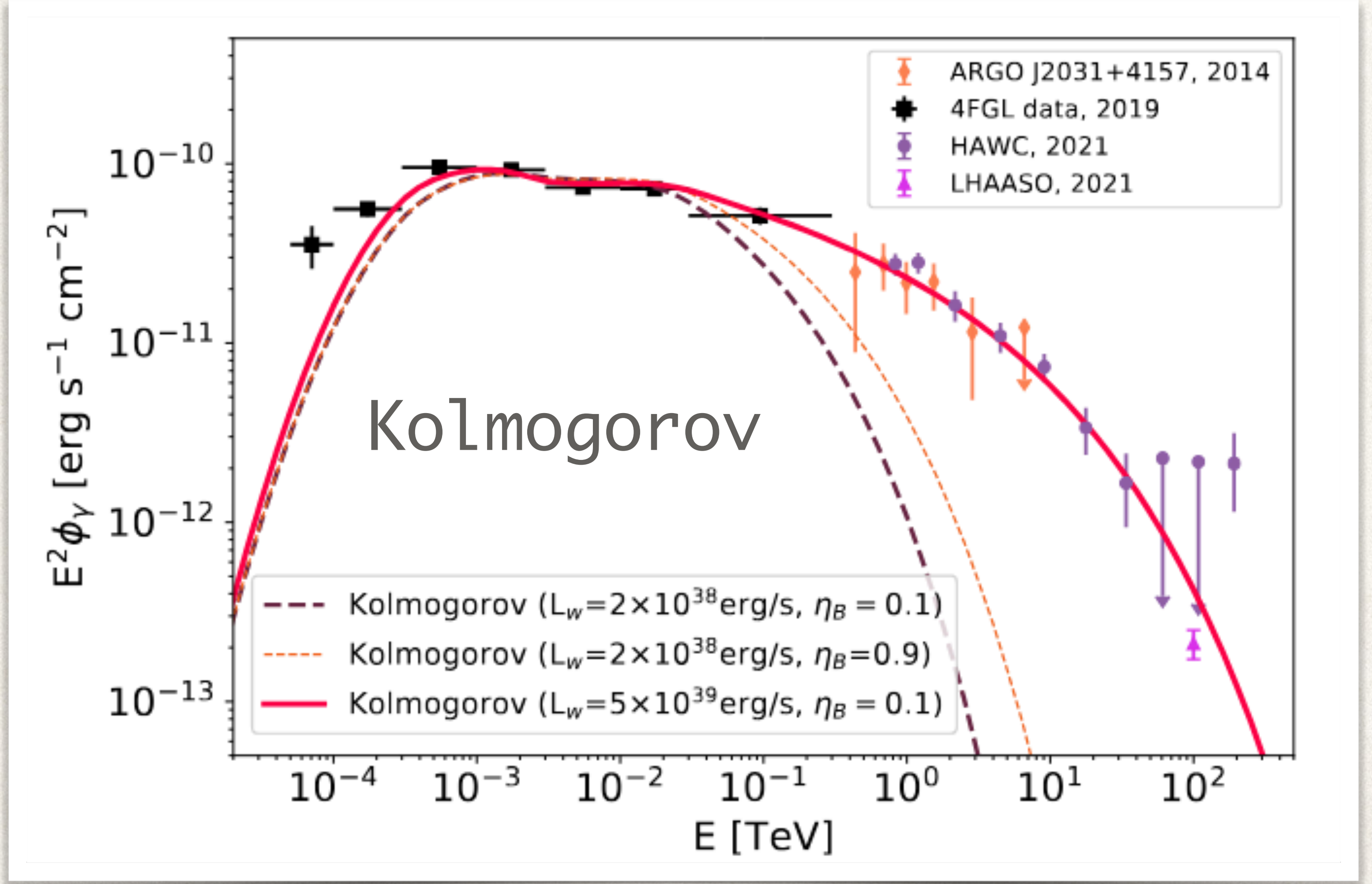
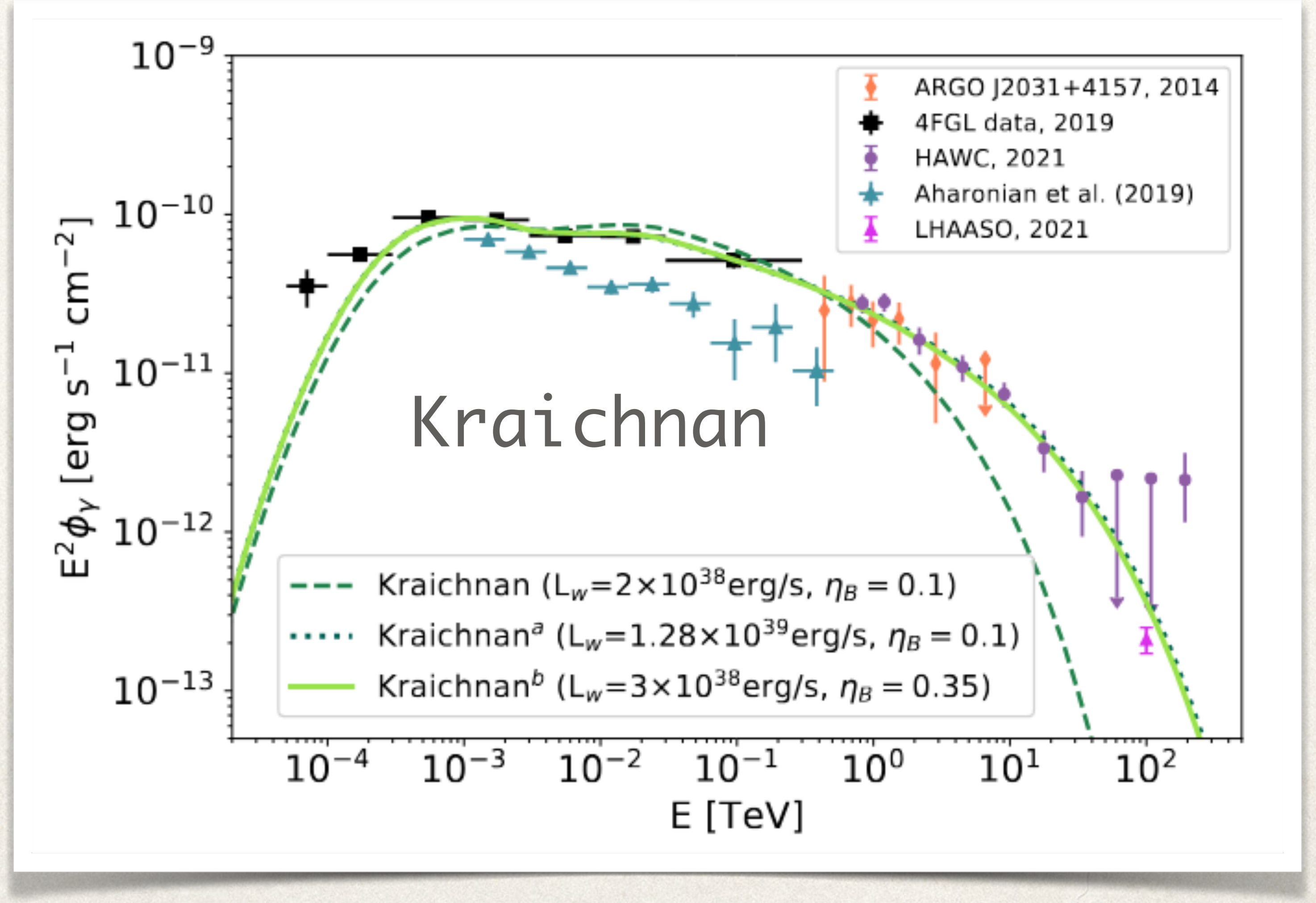
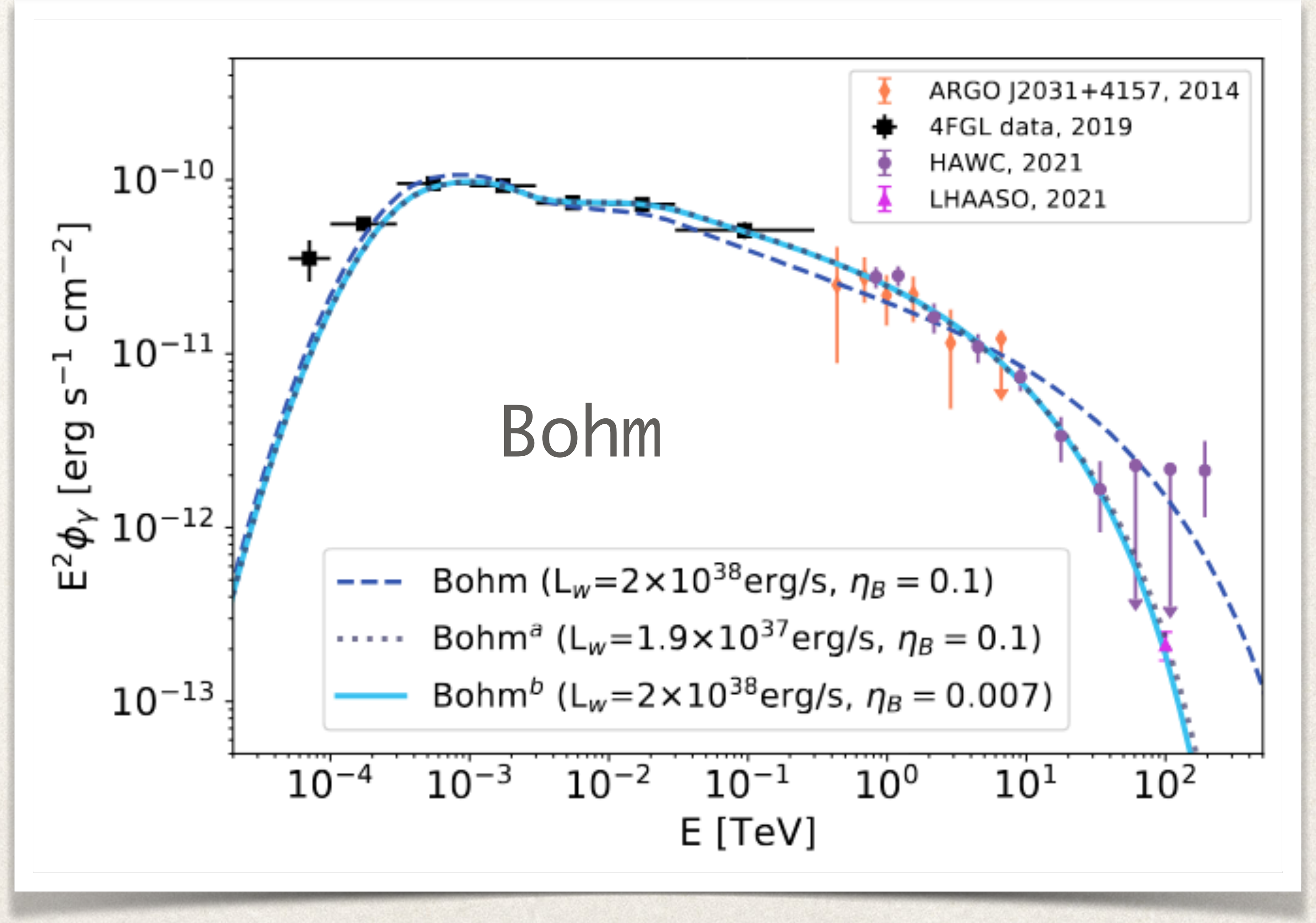
Model	Kolmogorov	Kraichnan	Bohm
Wind luminosity	5x10^{39} erg s^{-1}	1.3x10^{39} erg s^{-1}	2x10^{37} erg s^{-1}
Magnetic field	35 μG	20 μG	5 μG
Acc. efficiency	0.4%	0.7%	13%
Slope	4.17	4.23	4.27
E$_{max}$	23 PeV	4 PeV	0.5 PeV

Unrealistically high

The most realistic scenario is something in between Bohm and Kraichnan





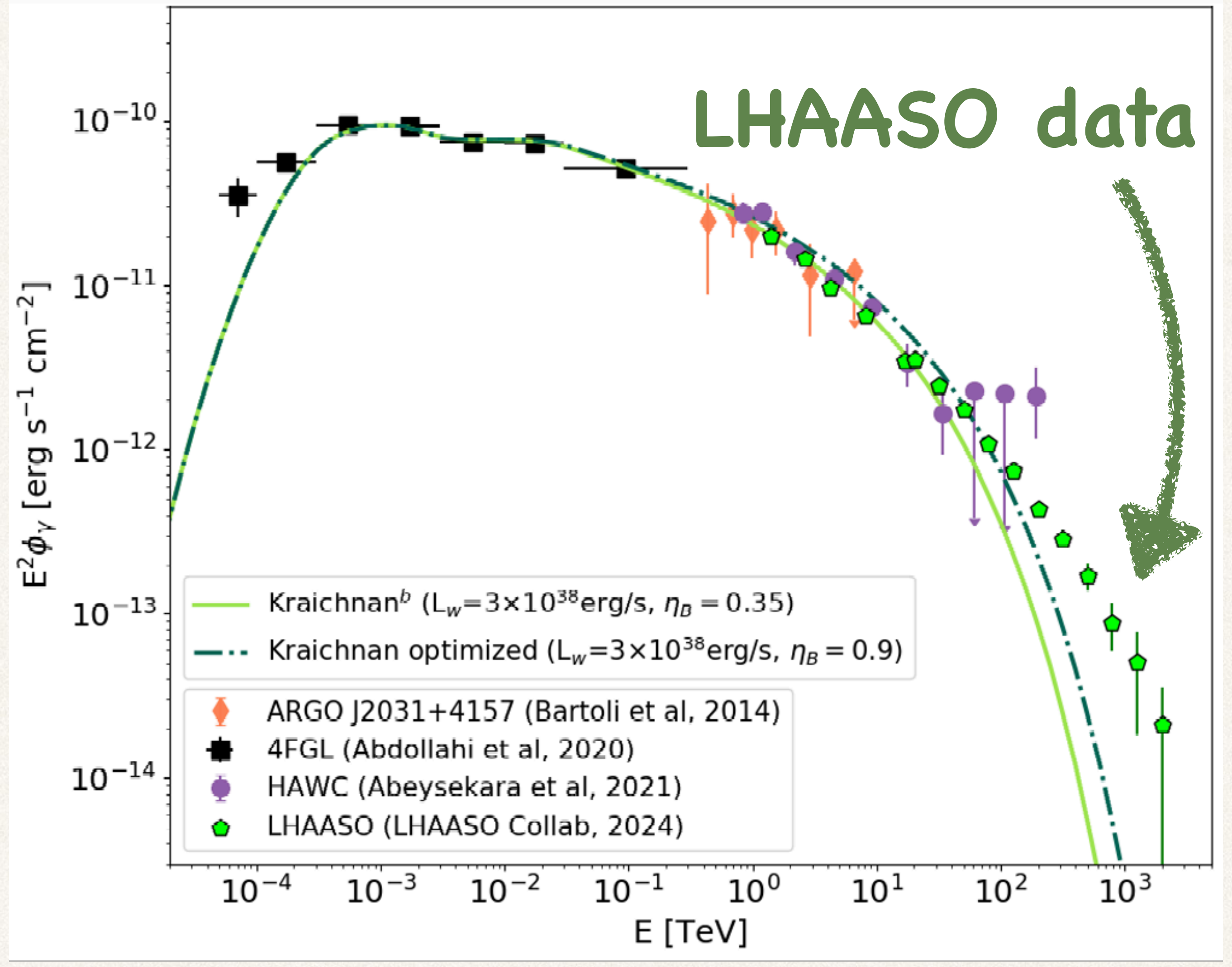


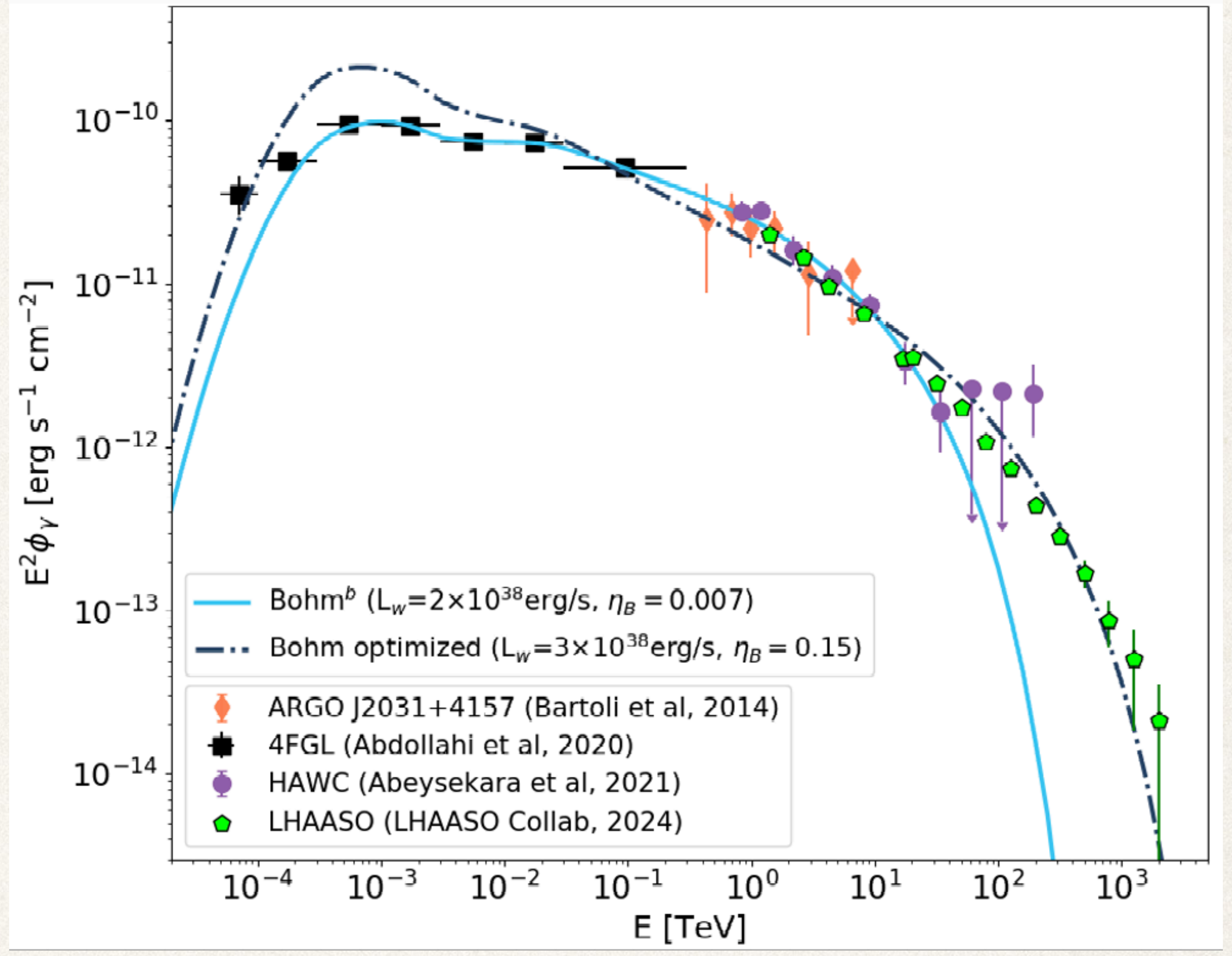
The case of Cygnus Cocoon

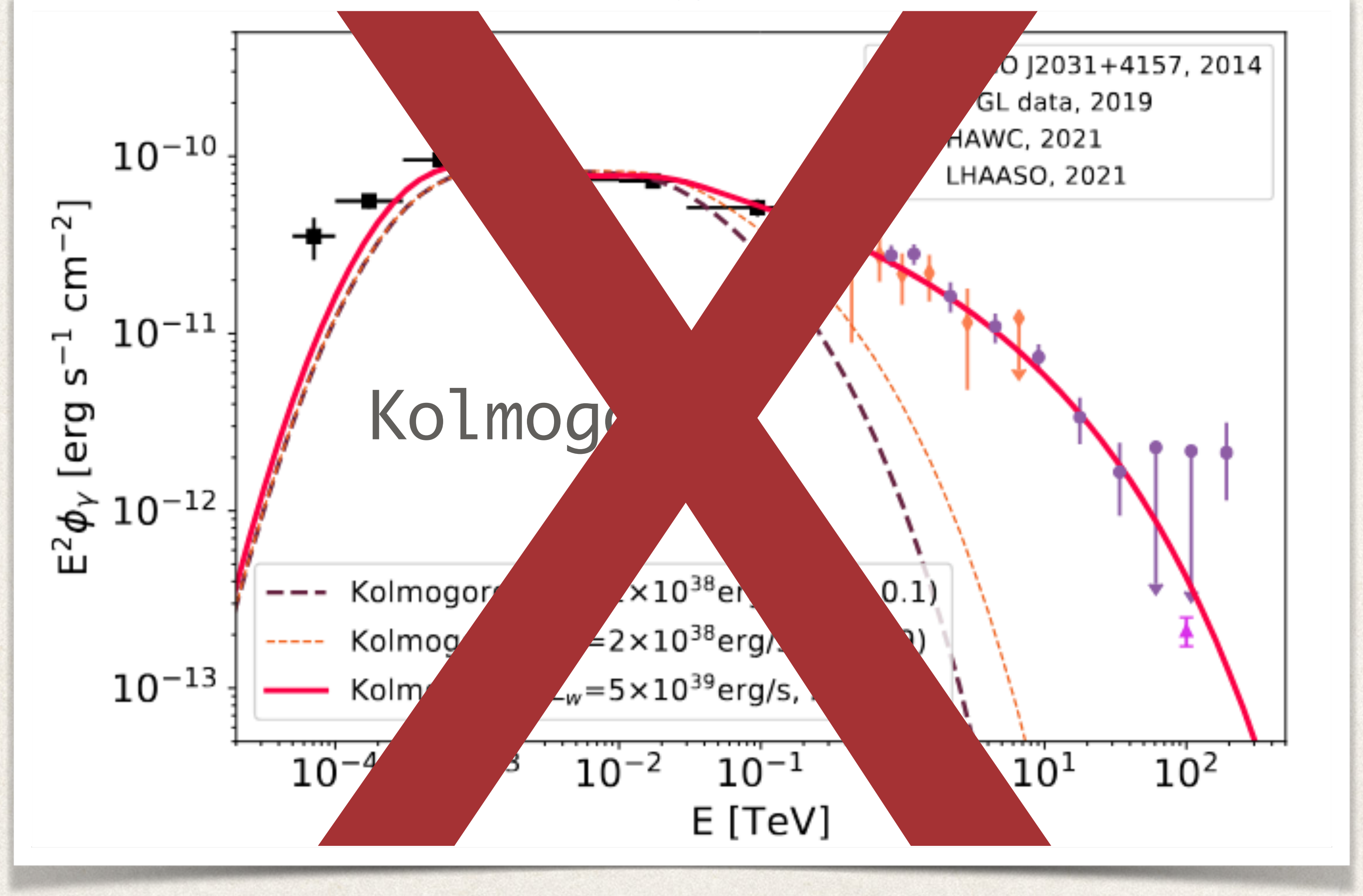
Menchiari, GM, Amato, Bucciantini & Beltran (2024)
Blasi & GM (2023)

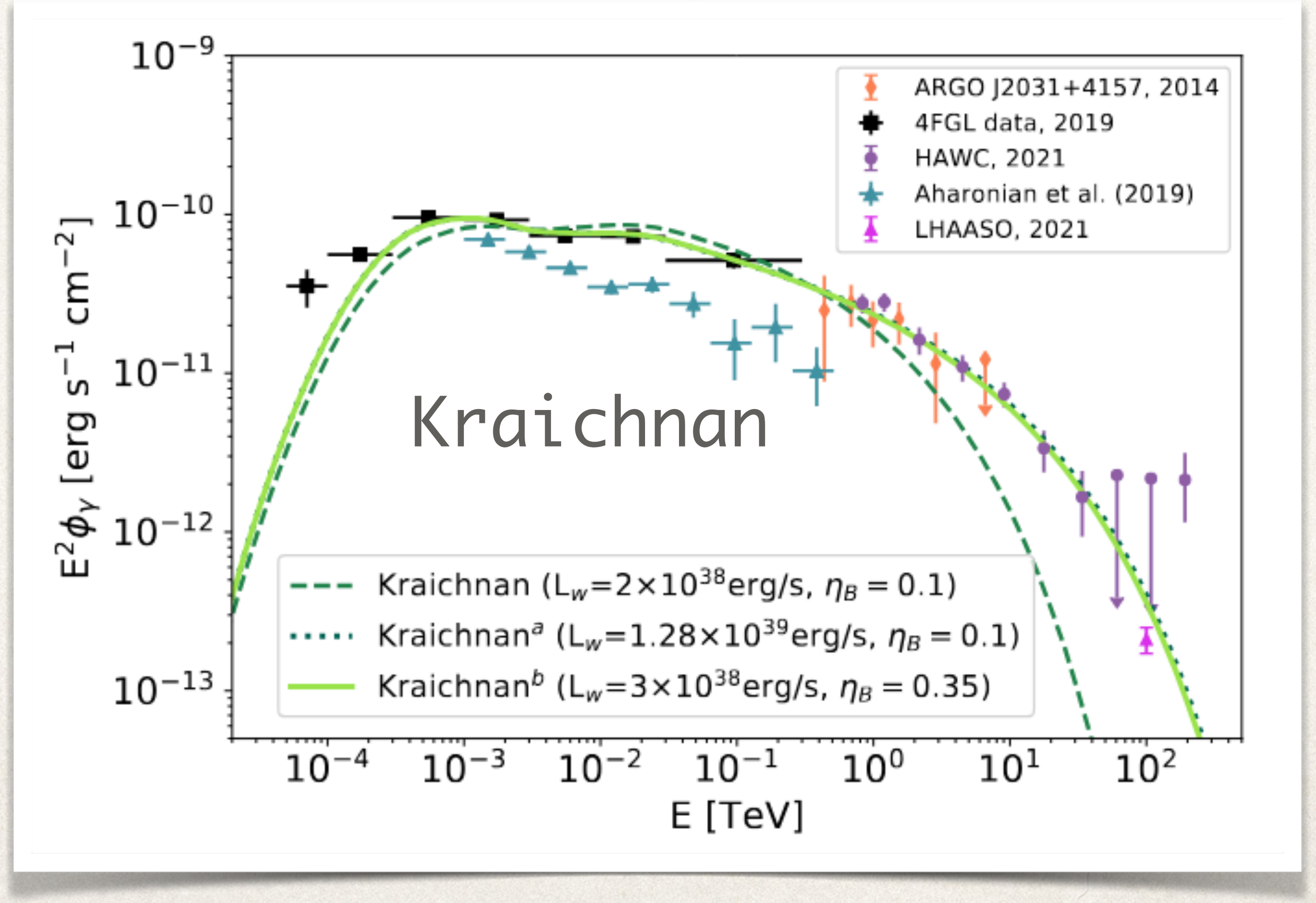
When LHAASO data are considered:

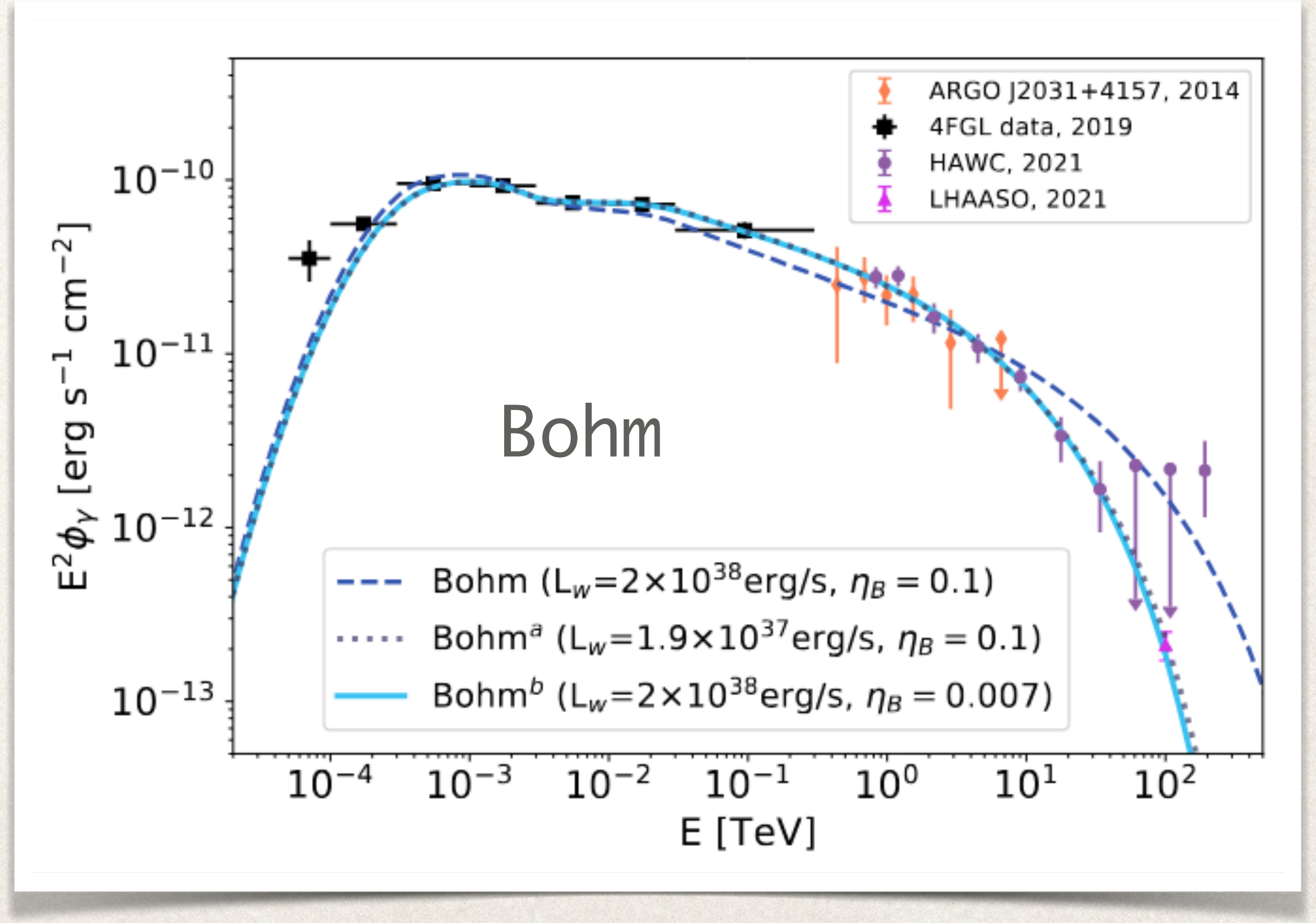
- Large magnetic field required ($\eta_B \gtrsim 20\,\%$)
- Kraichnan is not sufficient
- Bohm may explain the data but Fermi-LAT data are not well fitted
- Difficult to reproduce the extension of ~150 pc









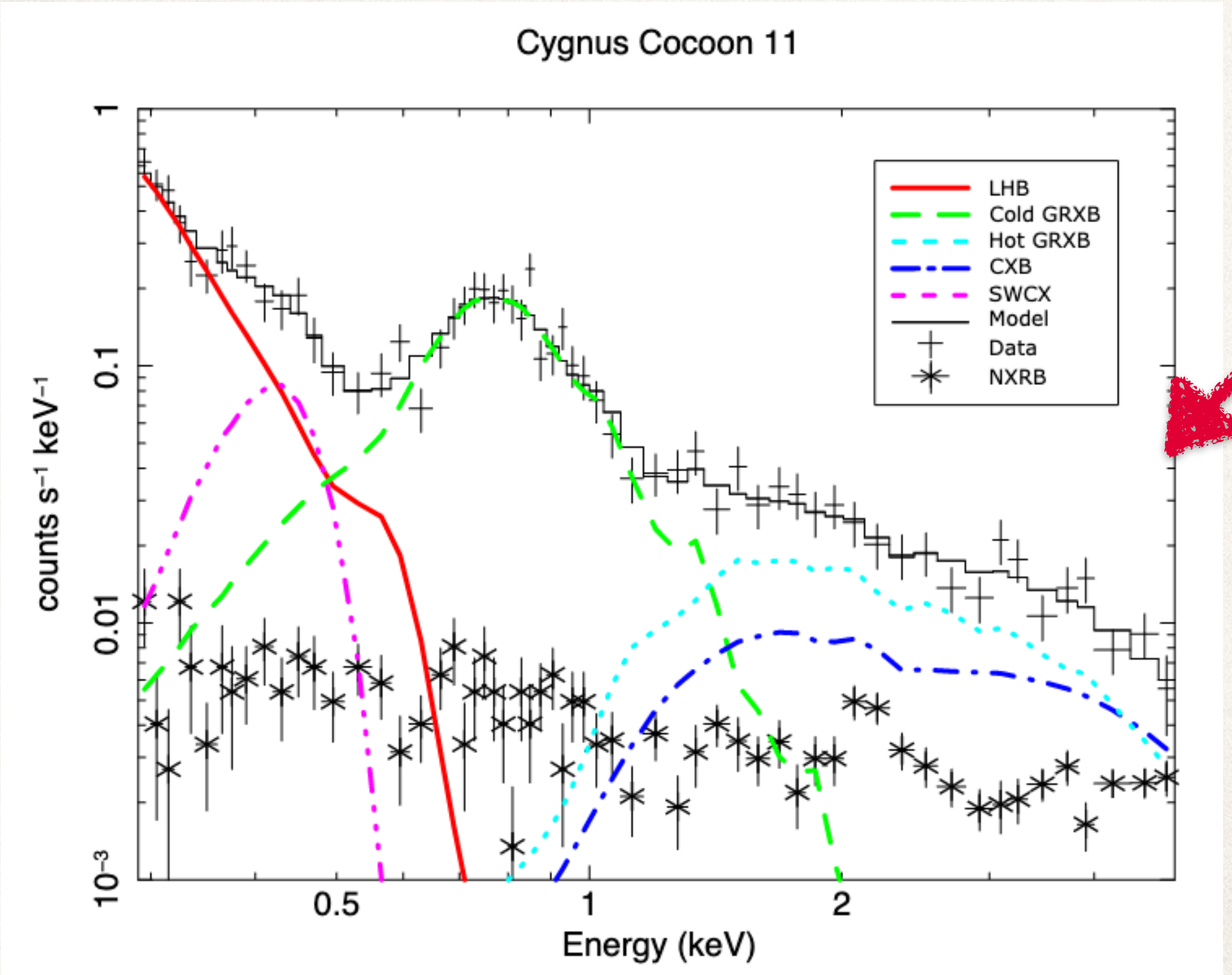


Leptonic contribution to the Cygnus Cocoon

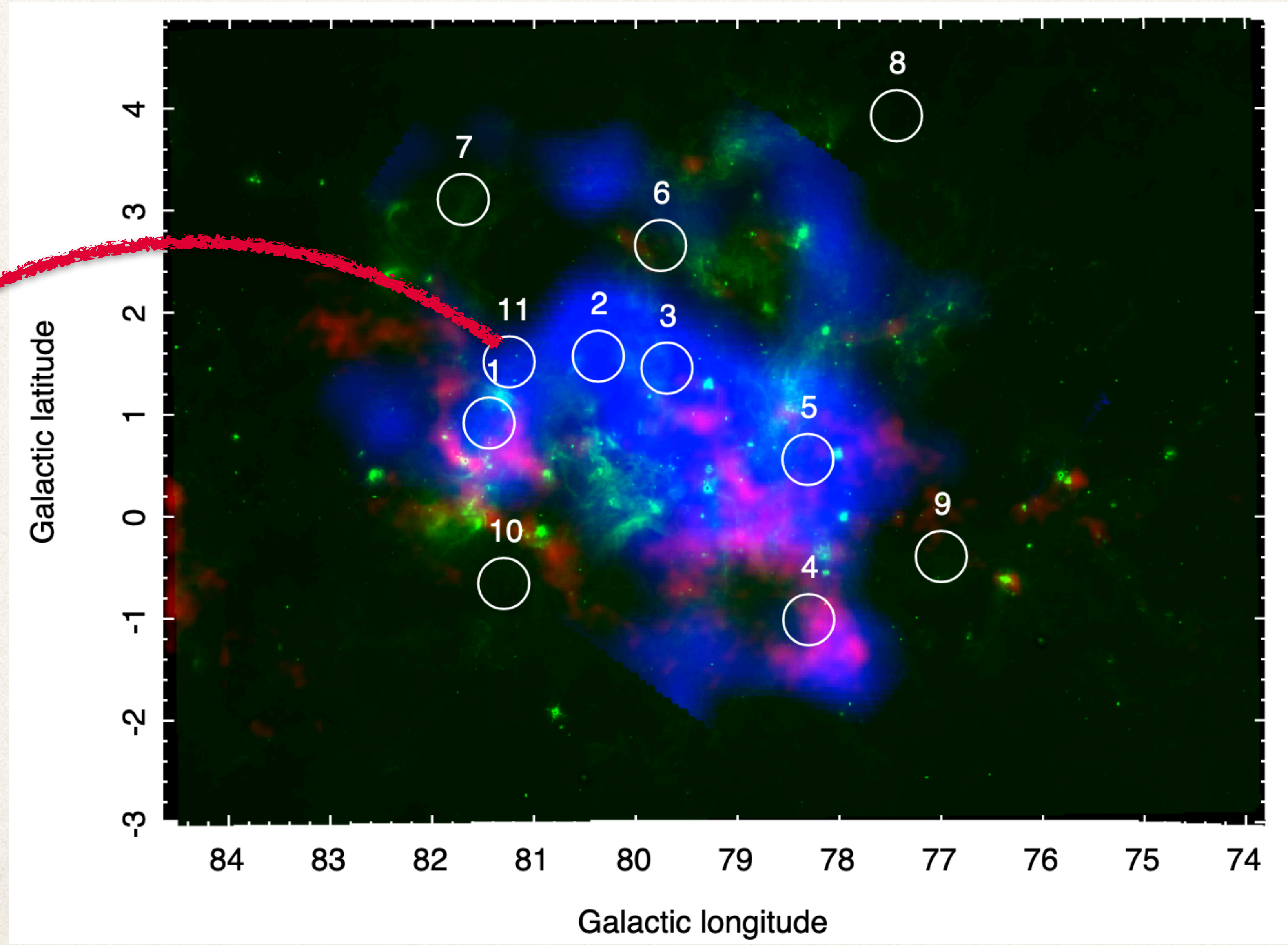
Guevel et al. (2022) estimated un upper limit to the leptonic contribution from the Cygnus Cocoon region looking at the X-ray emission with Swift-XRT telescope.

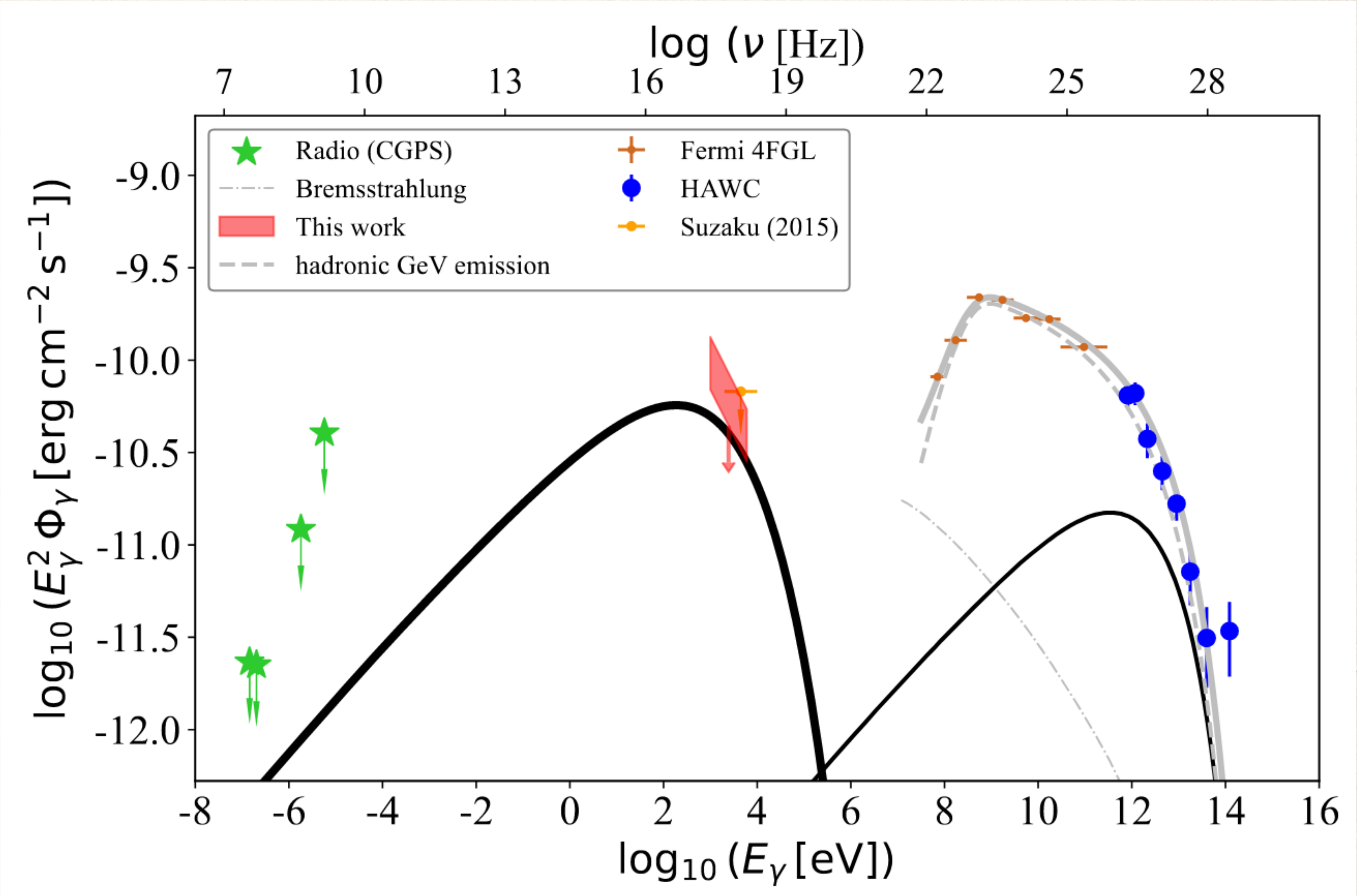
F_X (2-10 keV) < (5-8) x 10^{-11} erg cm^{-2} s^{-1}

IC contribution at 1 TeV
< 25% of the observed one



Cygnus Cocoon region in X-rays

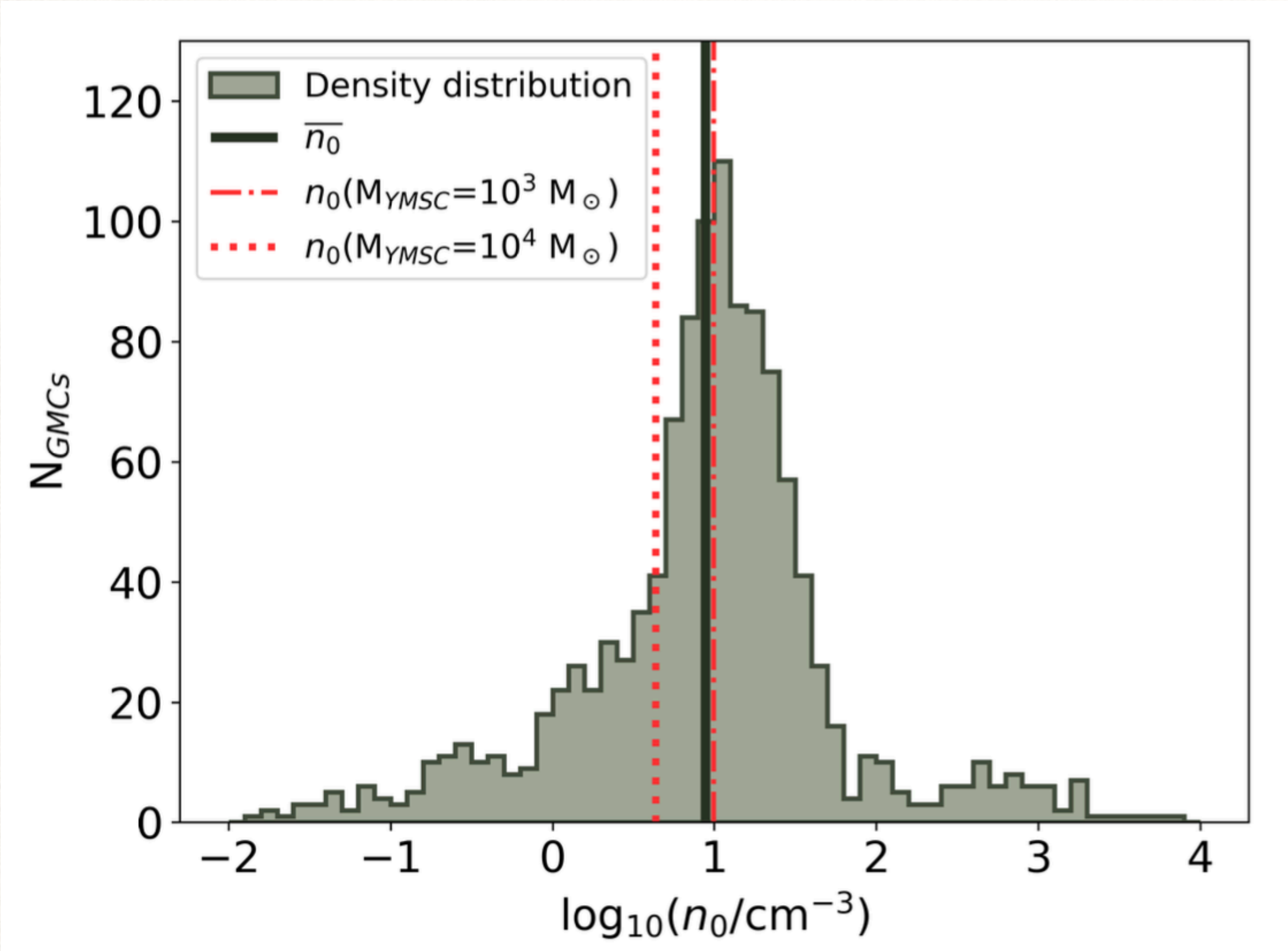




Gas density and the question of grammage

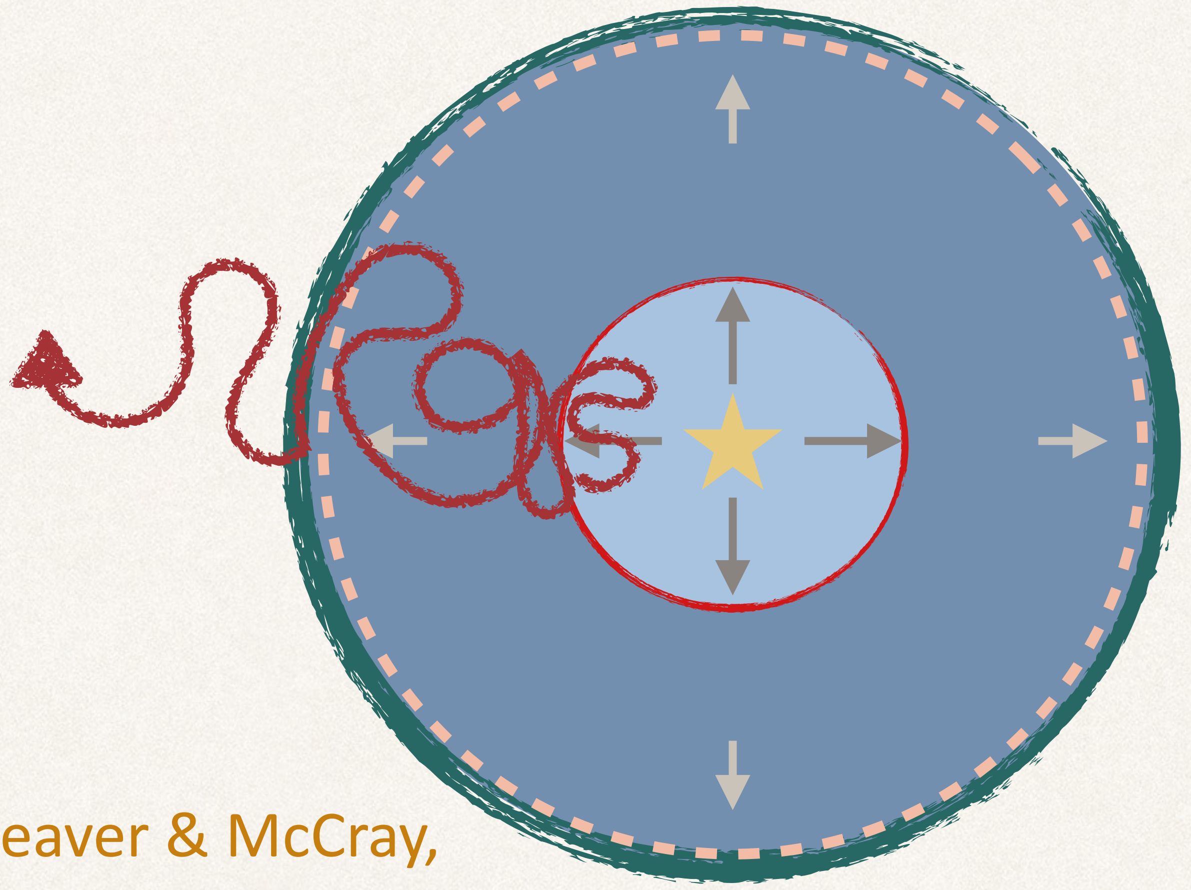
Giant molecular clouds

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



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

Idealised wind-blown bubble



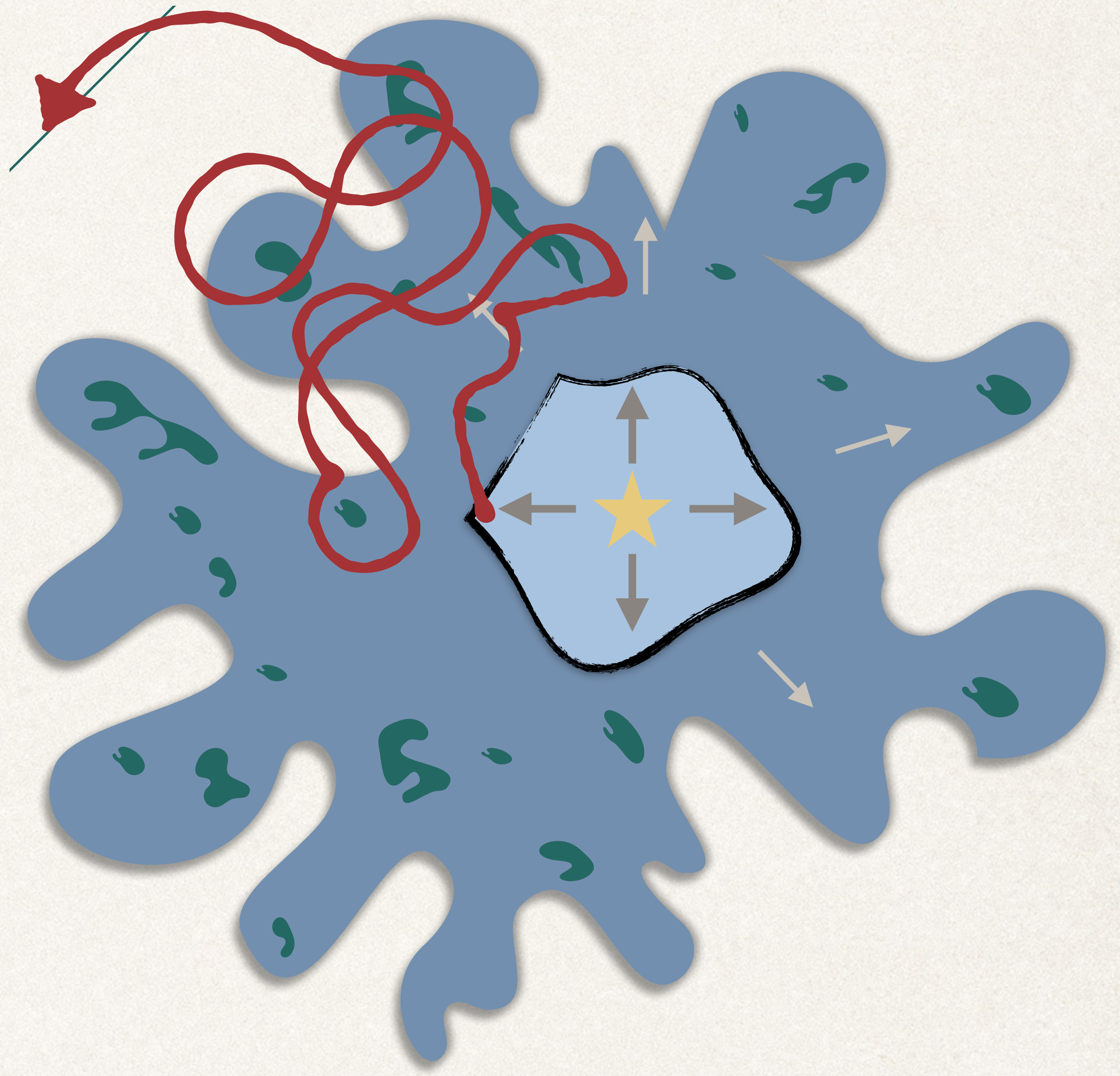
Weaver & McCray, ApJ 218 (1977)

Average density small if diffusion outside the bubble is fast

$\langle n \rangle \simeq 10^{-2} \text{ cm}^{-3}$

Grammage is negligible

Fragmented wind bubble



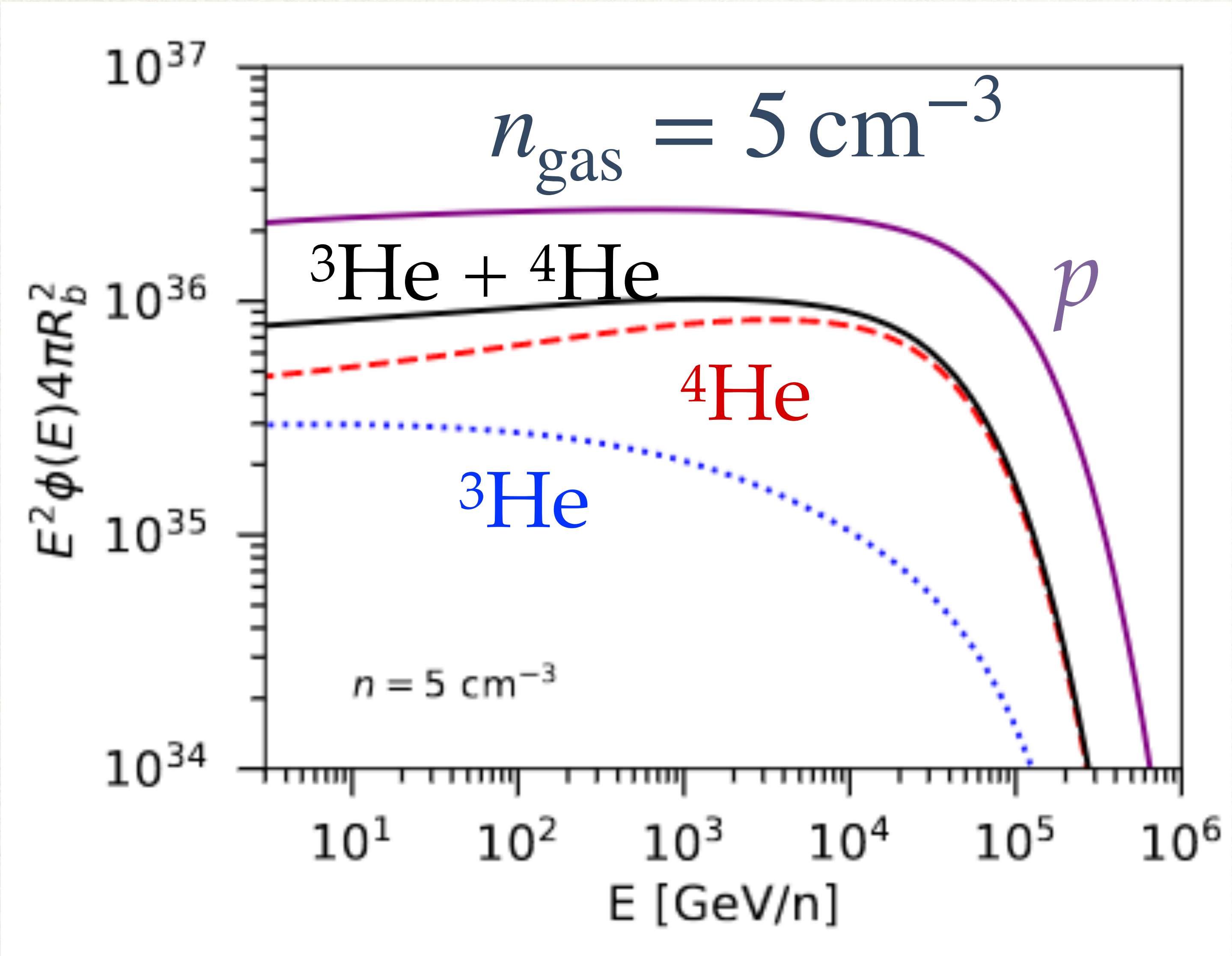
Average density felt by diffusing particles
→ depends on the clump distribution and by diffusion around each clump

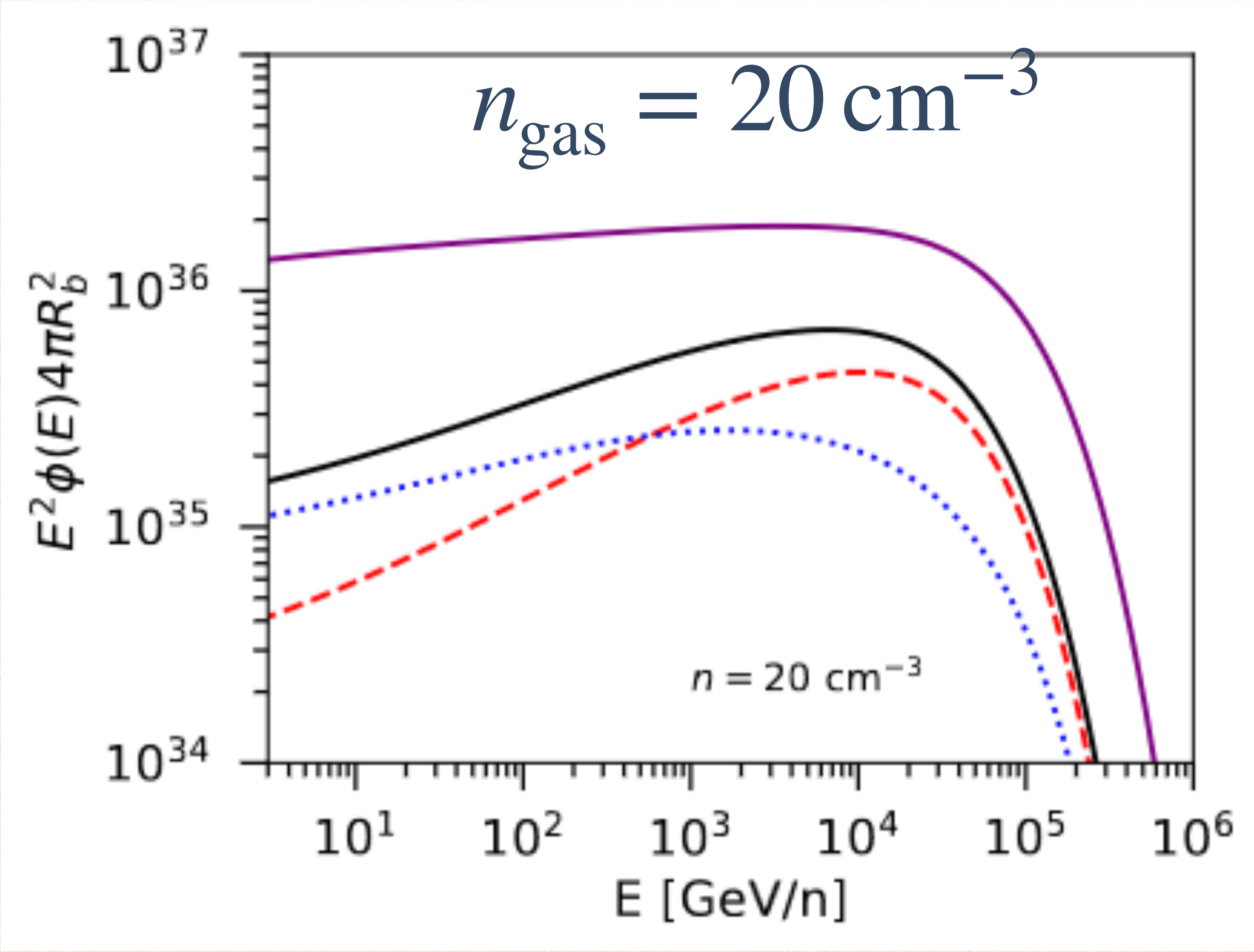
$\langle n \rangle \simeq 10 \text{ cm}^{-3}$

Grammage can be relevant

H and He spectra escaping from the bubble

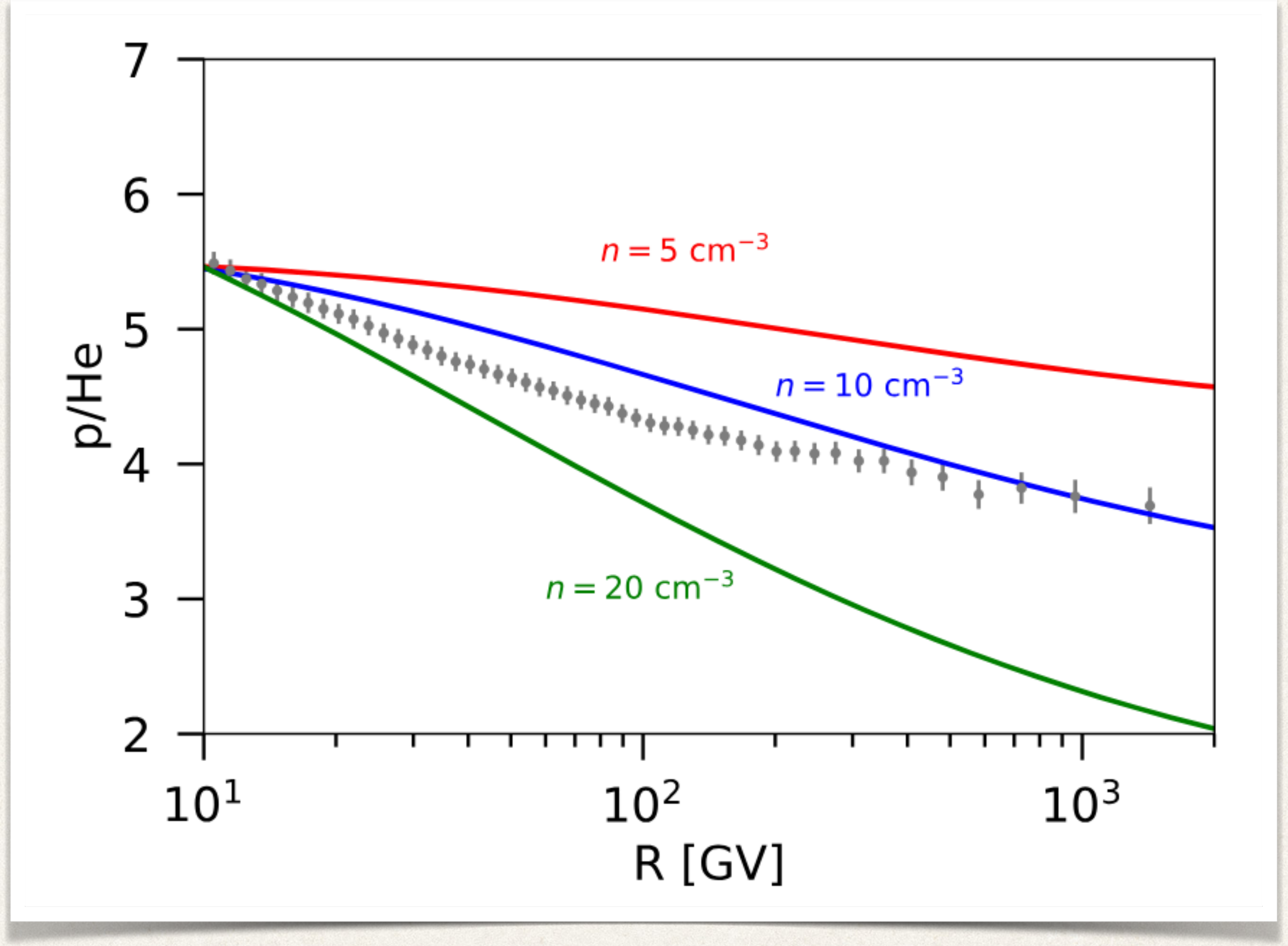
[P. Blasi, GM (2024) MNRAS 533, 561]





Predicted ratio p/He at the source from a single powerful SC (lines) compared to p/He measured by AMS-02 [AMS coll. PRL 115 (2015)]

Assumed parameters: $L_{\rm wind} \simeq 10^{38}\,{\rm erg/s}\,;\;\; {\rm age} \simeq 3\,{\rm Myr}$



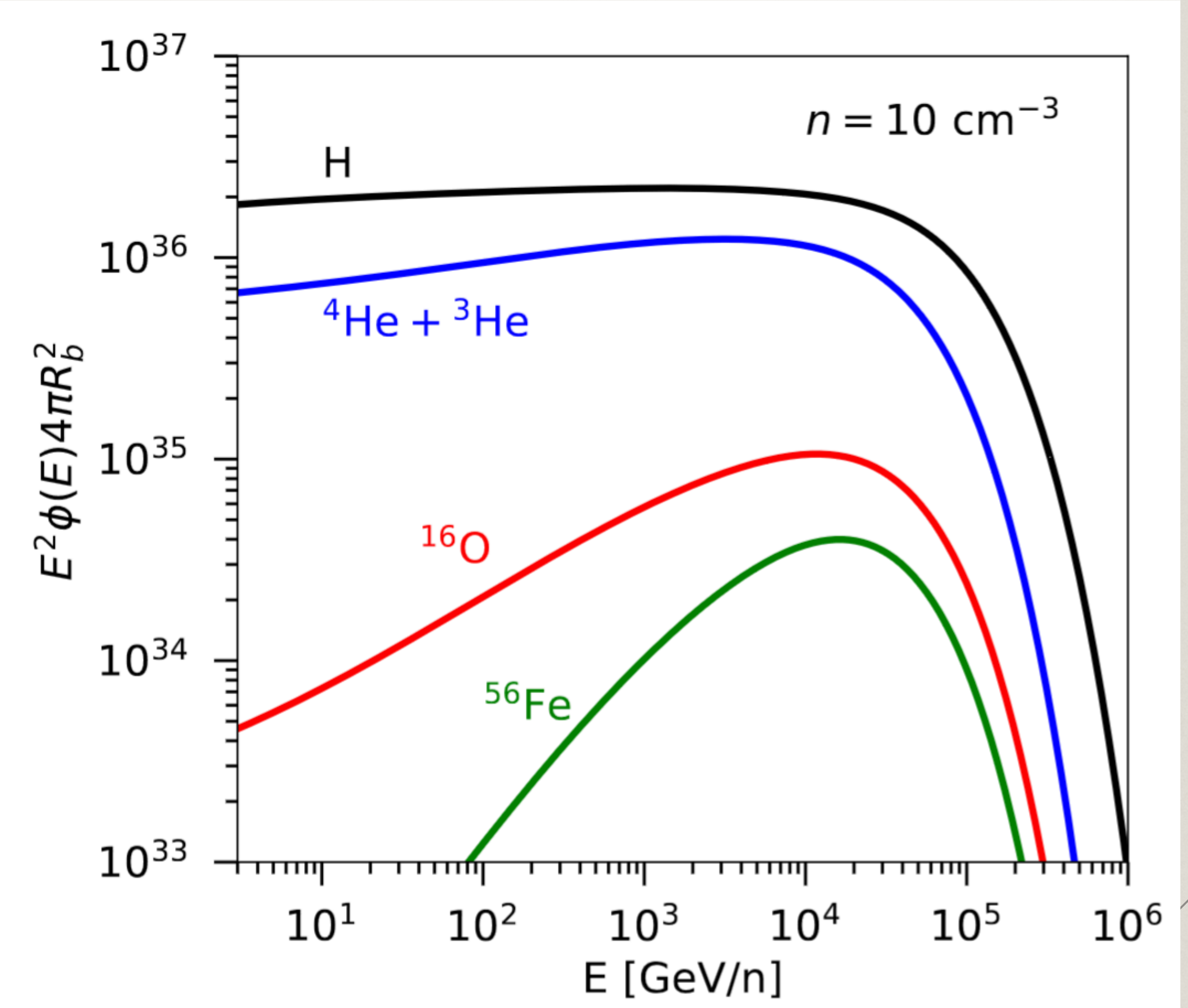
Note: a fair comparison requires to account for the entire population of SCs with different luminosities

Heavier nuclei

[P. Blasi, GM (2024) arXiv:2307.11663]

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

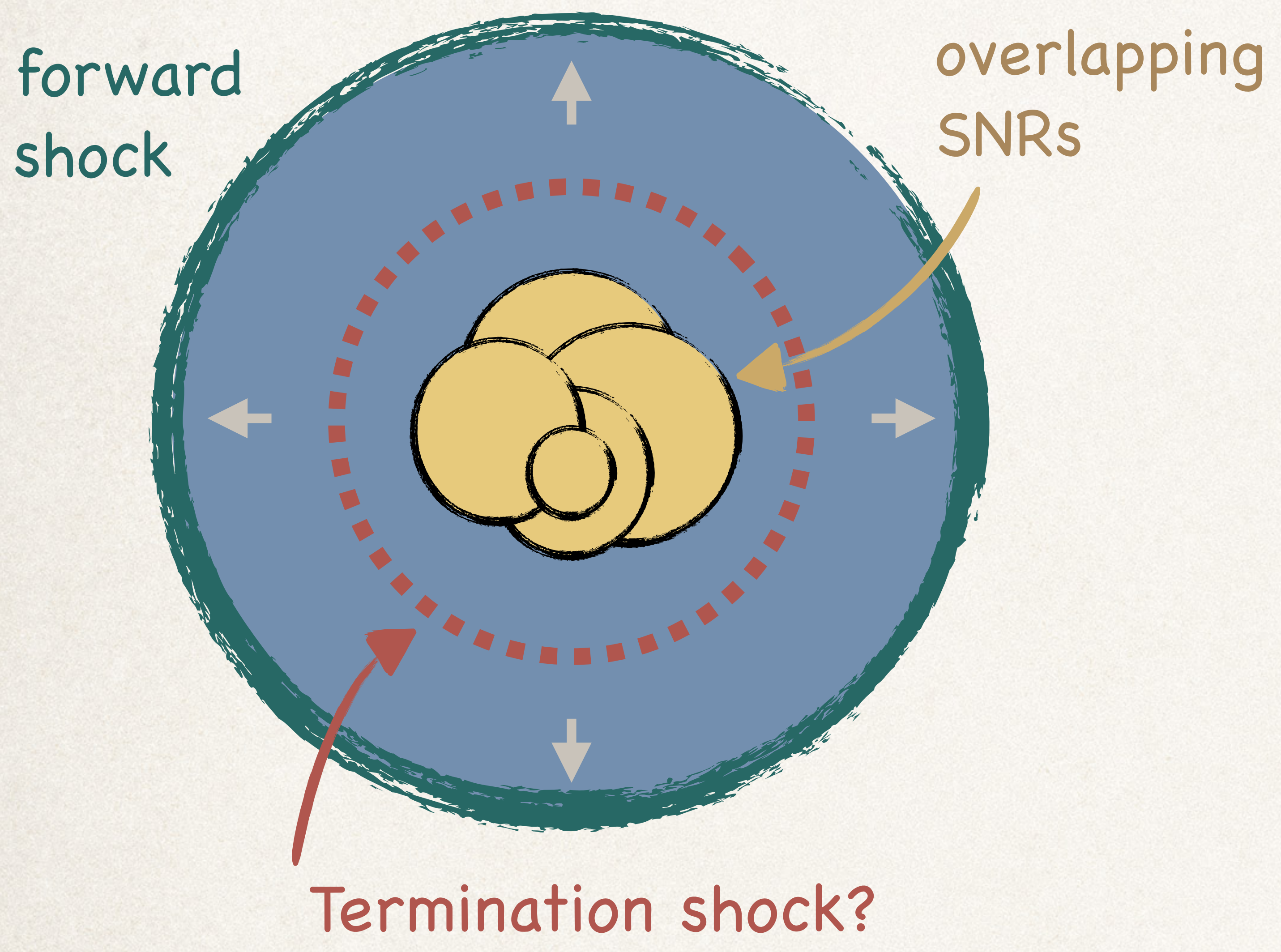


Possible caveats:

- Heavier nuclei may be mainly produced by 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

Old clusters → super-bubbles

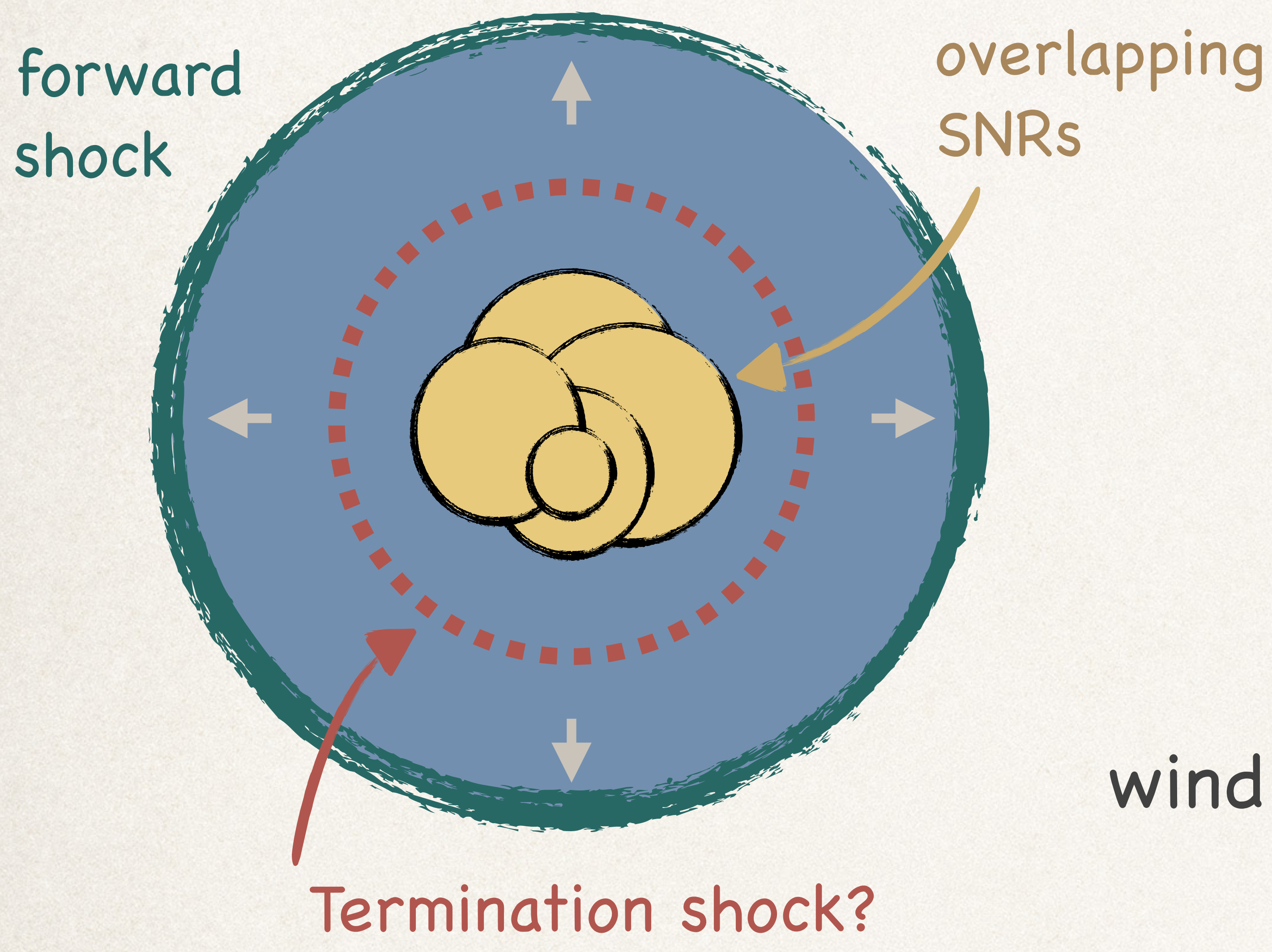
$t \gtrsim 3\,\mathrm{Myr}$ stellar wind + SNe



- Does the TS still exist?
- The turbulence in the bubble remains high due to wind and SN explosions
  → Efficient particles confinement in the bubble
- Maximum energy probably similar to the WTS case

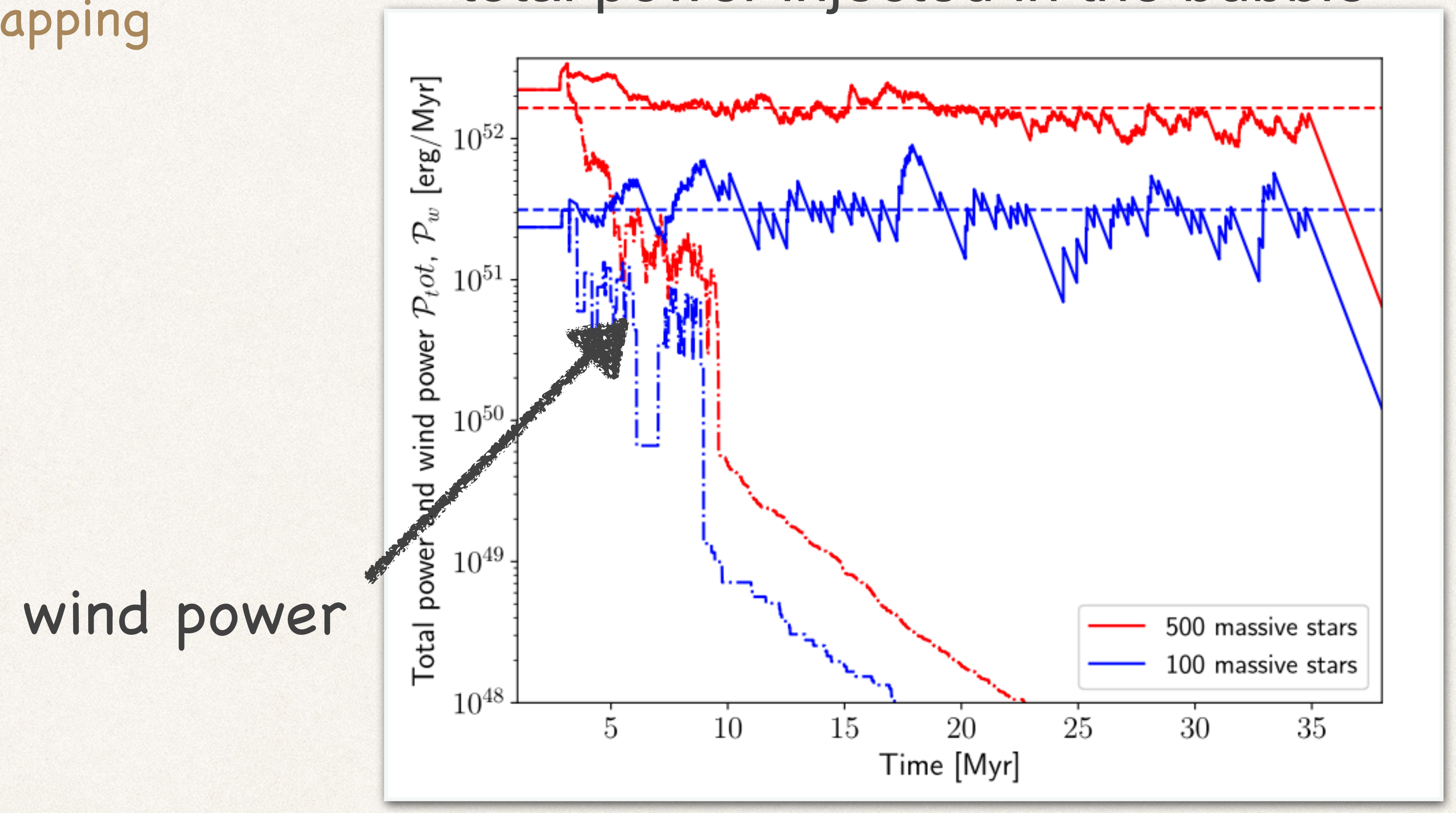
Old clusters → super-bubbles

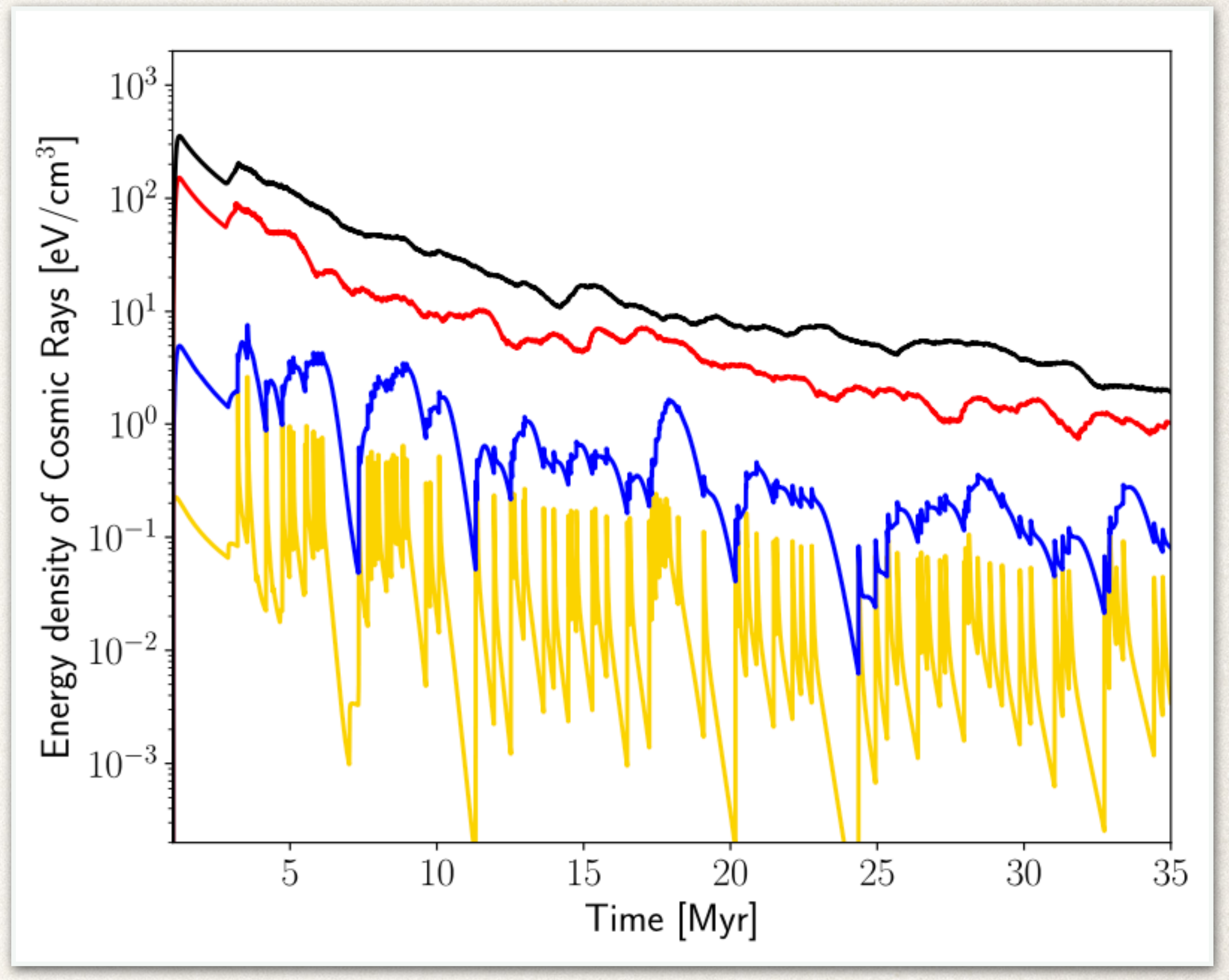
$t \gtrsim 3\,\mathrm{Myr}$ stellar wind + SNe



Vieu et al. (2022):
consider acceleration at WTS + SNR forward shock + turbulent acceleration

total power injected in the bubble





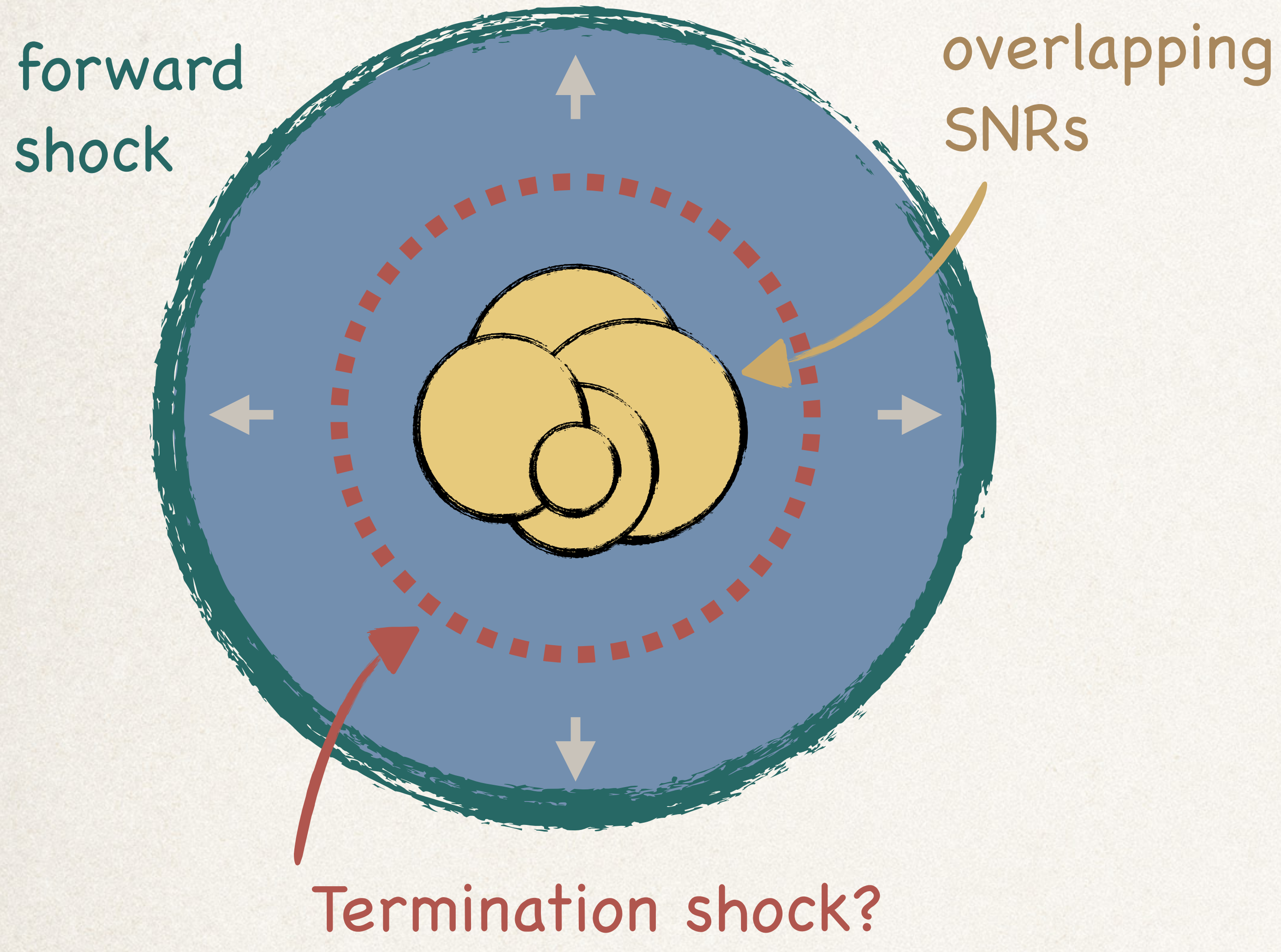
$N_\star = 1000$ $N_\star = 100$

$N_\star = 500$ $N_\star = 100$ $\eta_T = 1\,\%$

- Does the TS still exist?
- The turbulence in the bubble remains high due to wind and SN explosions
  → Efficient particles confinement in the bubble
- Maximum energy maybe enhanced if MF is amplified by stellar winds

Old clusters → super-bubbles: intermittency

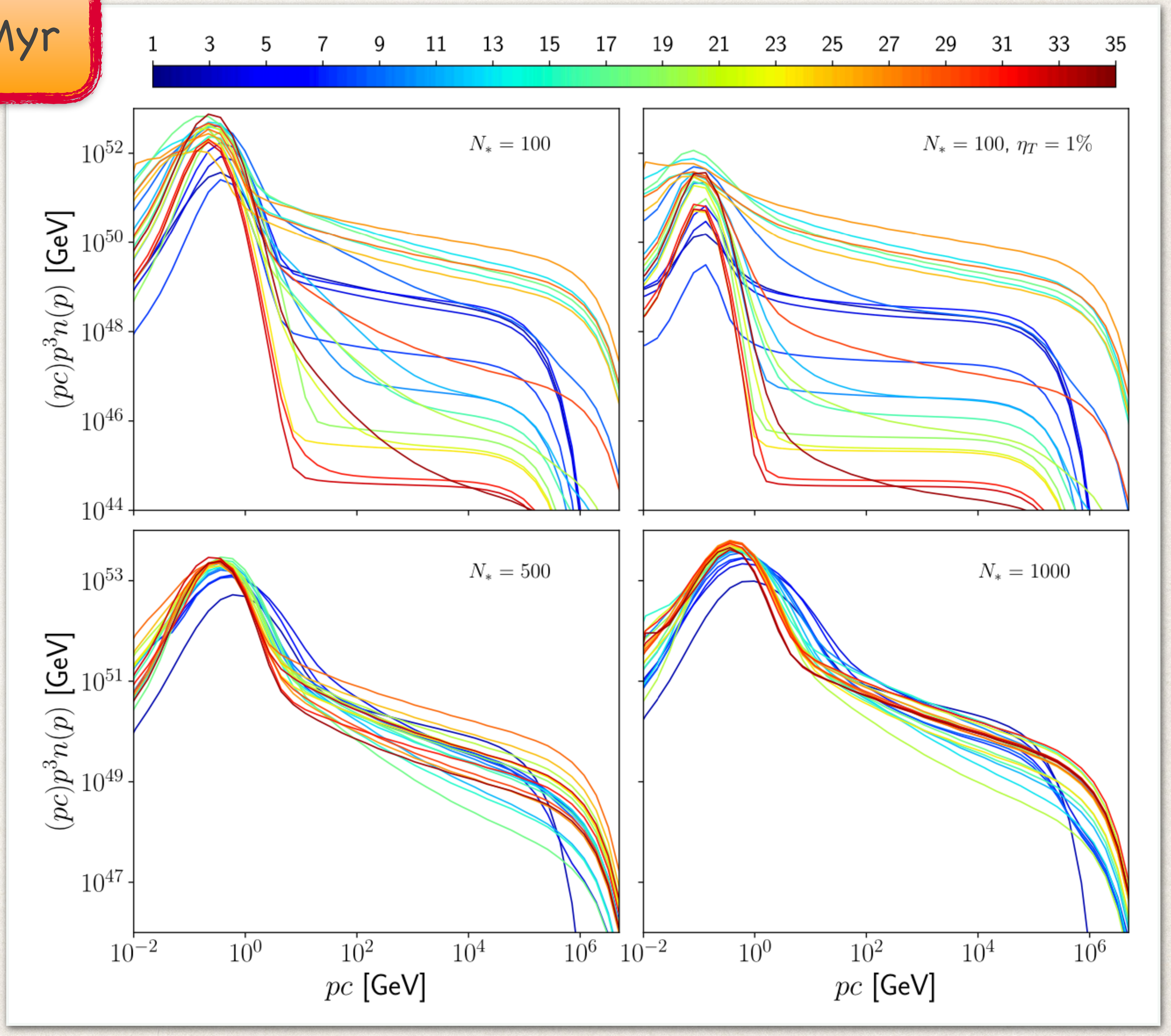
$t \gtrsim 3\,\mathrm{Myr}$ stellar wind + SNe



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

Time in Myr

Vieu et al. (2022)



SNR expanding into super-bubbles

Main effects on the SNR evolution

1. High temperature ⇒ low Mach number

Example: first SN expanding into the shocked wind

Shocked wind temperature: $k_B T_b = \frac{3}{16} m_p v_w$

Sound speed: $c_{\rm sound} = \sqrt{\gamma k_B T_b / m_p}$

$$\Rightarrow M = \frac{v_{sh}}{c_s} = 3.6 \left(\frac{v_{sh}}{5000\,\mathrm{km/s}} \right) \left(\frac{v_w}{2500\,\mathrm{km/s}} \right)^{-1}$$

CAVEAT:
Temperature may decrease due to radiative losses/heat conduction

$$\tau_{\rm cool} \simeq 6 \left(\frac{T}{10^6\,K} \right)^{1.7} \left(\frac{n}{0.01\,\mathrm{cm^{-3}}} \right)^{-1} \mathrm{Myr}$$

SNR expanding into super-bubbles

Main effects on the SNR evolution

1. High temperature ⇒ low Mach number
2. High turbulence ⇒ high magnetic field
    - low Alfvénic Mach number

Example: first SN expanding into the shocked wind

If the magnetic field is produced by wind turbulence:

$$\frac{B^2}{4\pi} v_w = \eta_B L_w \;\Rightarrow\; B_b \simeq 10\,\mu\mathrm{G}$$

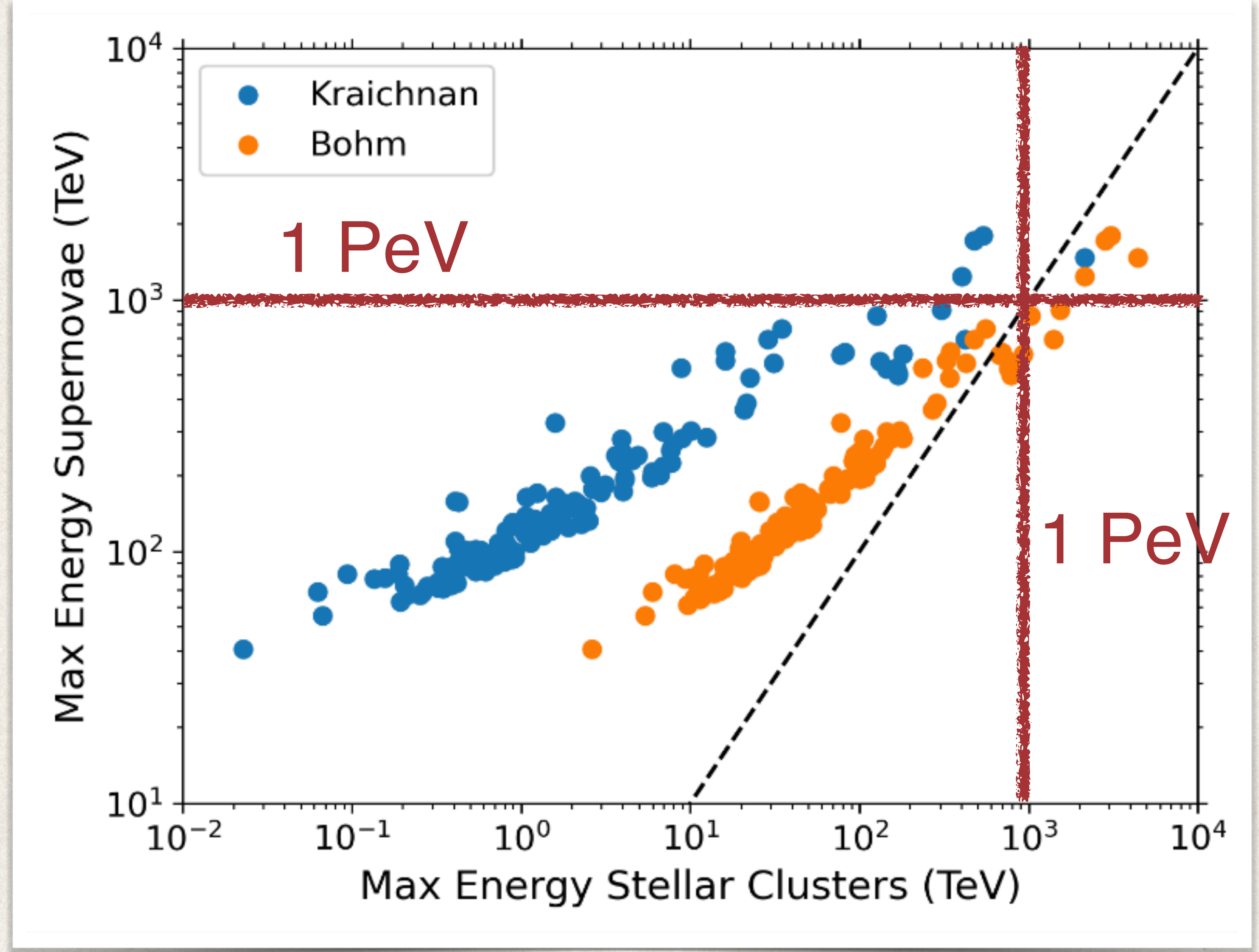
Than the Alfvénic Mach number is

$$M_A = \frac{v_{\mathrm{sh}}}{v_{\mathrm{A}}} = \sqrt{\frac{4}{11\eta_B}\frac{v_{\mathrm{sh}}}{v_w}} \gtrsim 4$$

SNR expanding into super-bubbles

Main effects on the SNR evolution

1. High temperature ⇒ low Mach number
2. High turbulence ⇒ high magnetic field
    - low Alfvénic Mach number
    - faster acceleration time



Mitchell et al. arXiv: 2403.16650

Example: first SN expanding into the shocked wind

If the magnetic field is produced by wind turbulence:

$$\frac{B^2}{4\pi} v_w = \eta_B L_w \;\Rightarrow\; B_b \simeq 10\,\mu\mathrm{G}$$

Than the Alfvénic Mach number is

$$M_A = \frac{v_{\rm sh}}{v_{\rm A}} = \sqrt{\frac{4}{11\eta_B}\frac{v_{\rm sh}}{v_w}} \gtrsim 4$$

The maximum energy increases:

$$E^p_{\rm max} \simeq 2\,\mathcal{F}\left(\frac{B_0}{10\mu G}\right)\left(\frac{M_{\rm ej}}{M_\odot}\right)^{-\frac{1}{6}}\left(\frac{E_{\rm SN}}{10^{51}{\rm erg}}\right)^{\frac{1}{2}}\left(\frac{n_0}{0.01{\rm cm}^{-3}}\right)^{-\frac{1}{3}}\,\mathrm{PeV}$$

Diffusion needs to be Bohm-like

SNR expanding into super-bubbles

Main effects on the SNR evolution

1. High temperature ⇒ low Mach number
2. High turbulence ⇒ high magnetic field
    - low Alfvénic Mach number
    - faster acceleration time
    - enhanced syn. losses

Synchrotron loss time: $\tau_{\rm syn} = \frac{9 m_e^2}{4 r_0^2 c\, B^2} E^{-1}$

Advection time: $\tau_{\rm adv} = \frac{4 R_b}{3 v_w} \left(\frac{R_b}{R_s} \right)^2$

$$\tau_{adv} = \tau_{\rm syn} \;\Rightarrow\; E_{\rm esc} \lesssim 200 \left(\frac{B}{10\,\mu G} \right)^{-2} \text{GeV}$$

⬇

High energy electrons cannot escape from the bubble

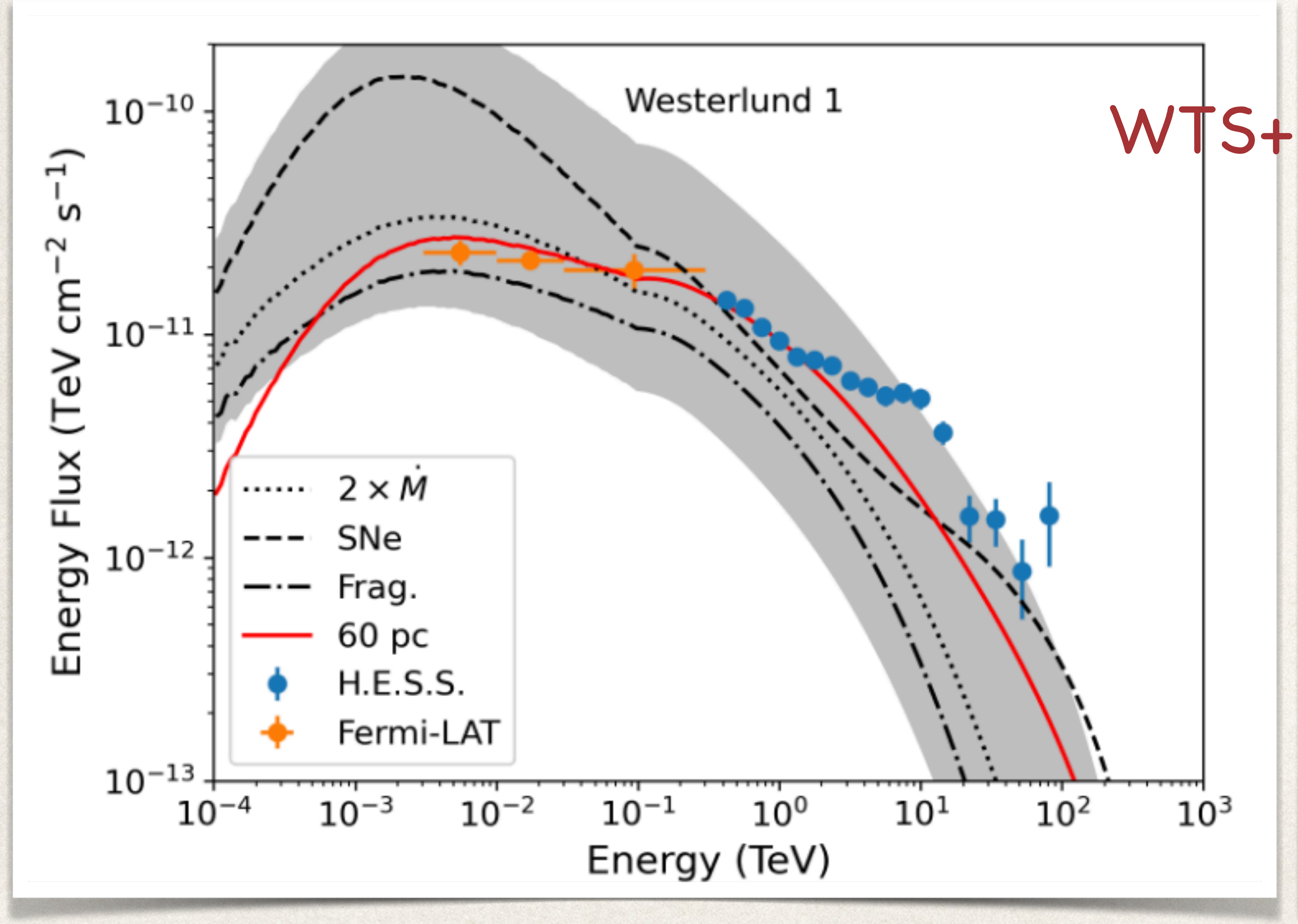
WTS+SNRs: application to some known SCs

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

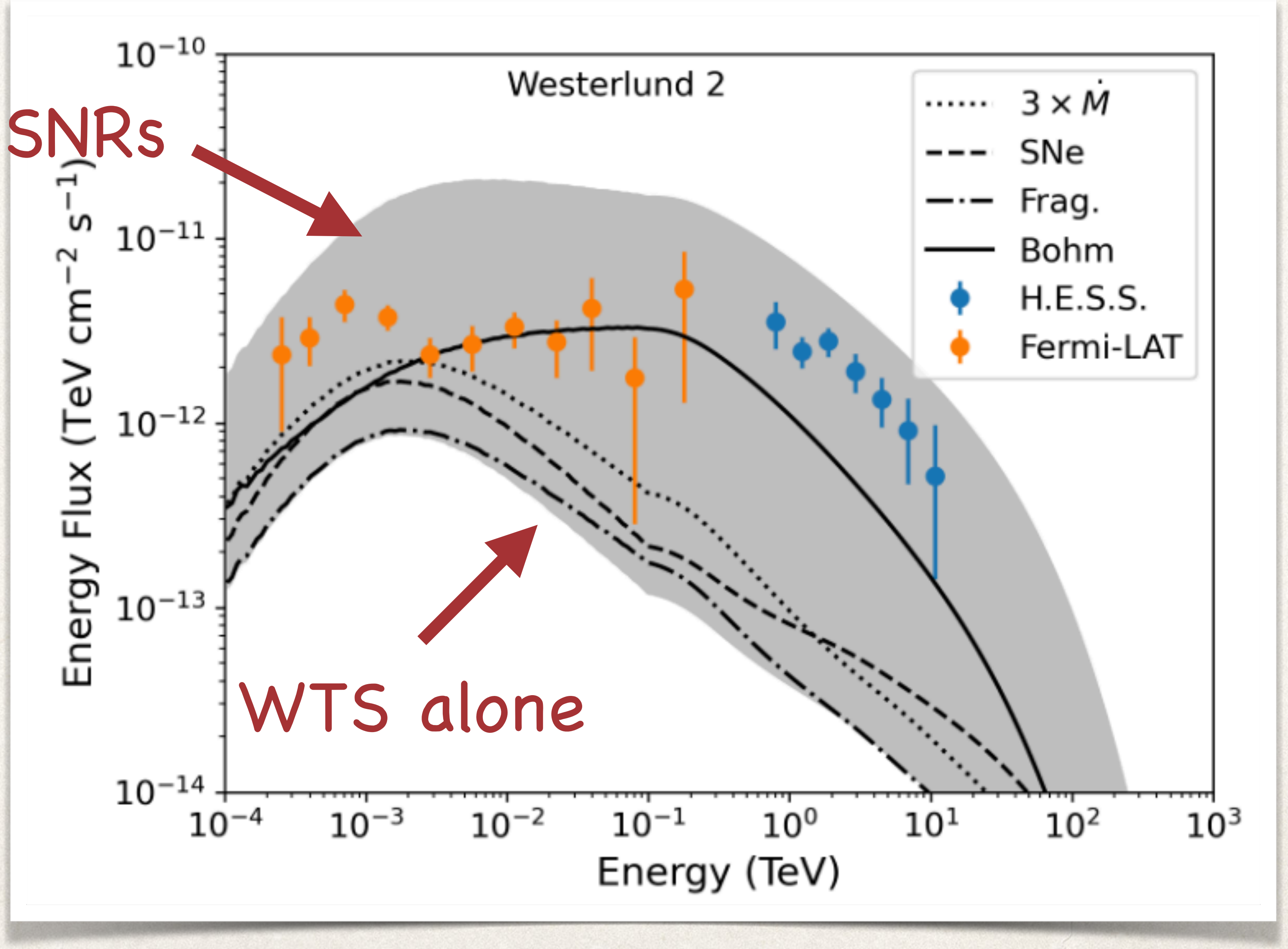
Applying the model of WTS+SNR for three SC detected in gamma-rays:

- 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

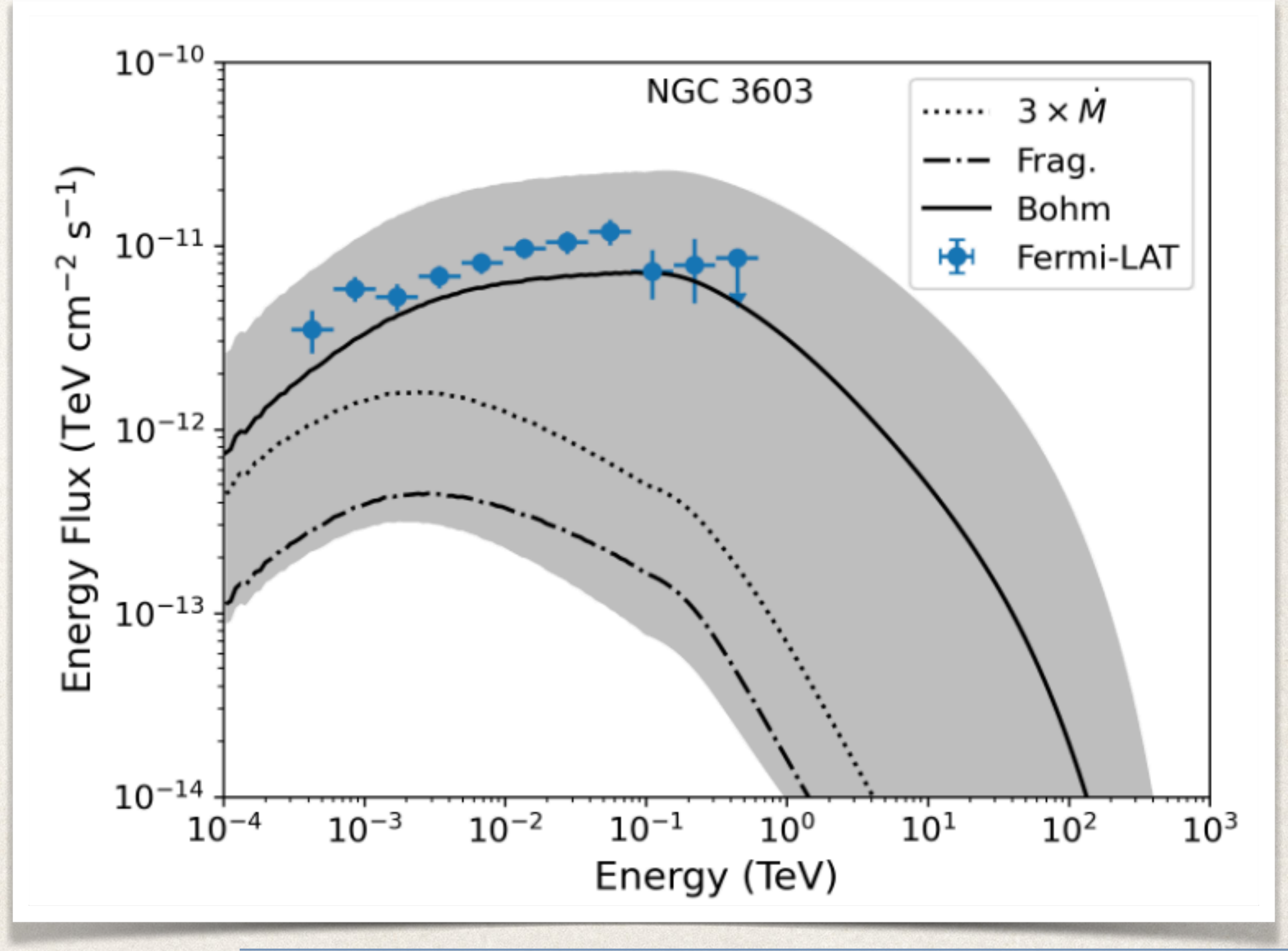
Westerlund 1



Westerlund 2



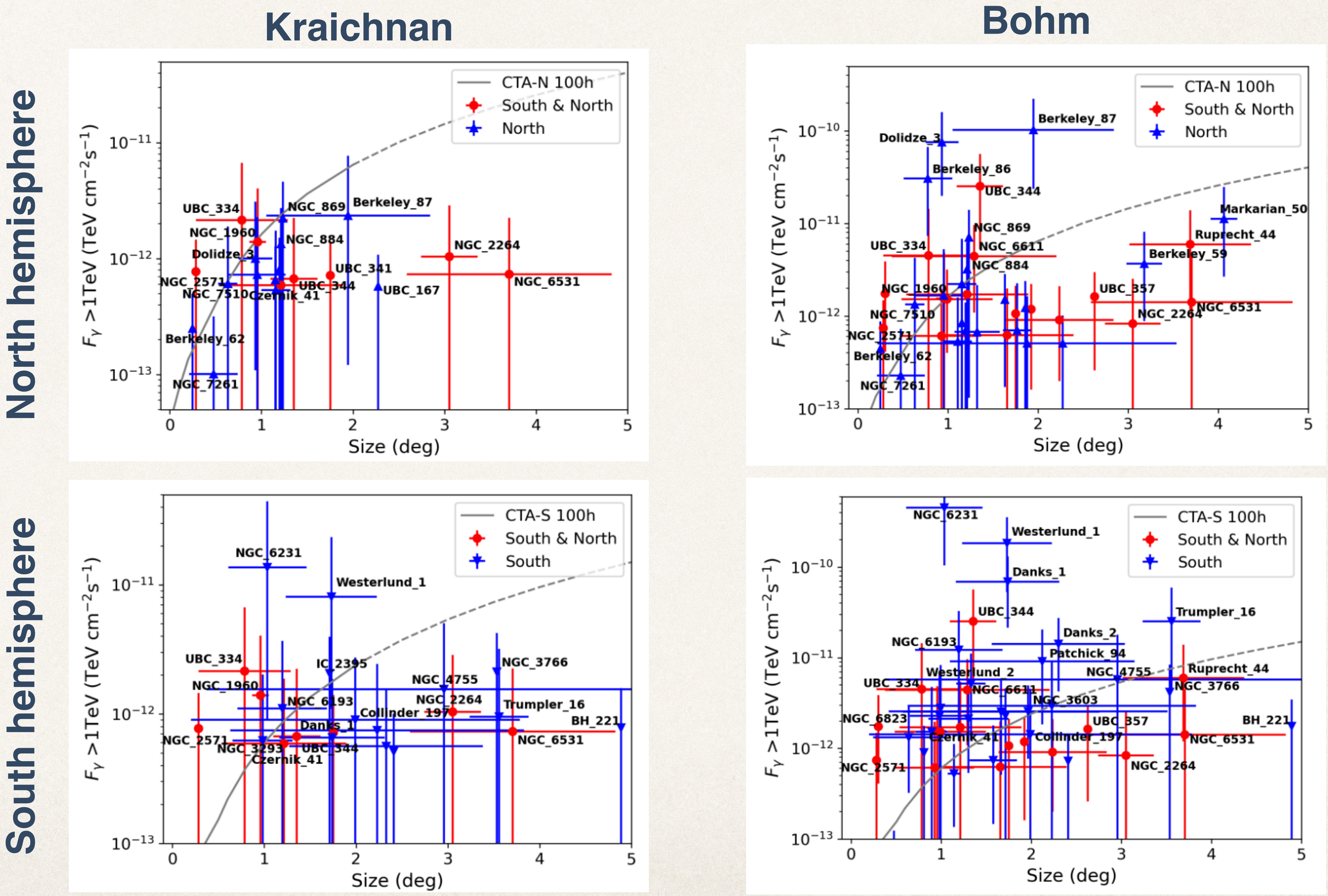
NGC 3603



WTS+SNRs: application to Gaia SCs

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

Integral γ-ray flux above 1 TeV from the cluster bubble, plotted as a function of the bubble size
Compared to CTA sensitivity for extended sources



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?

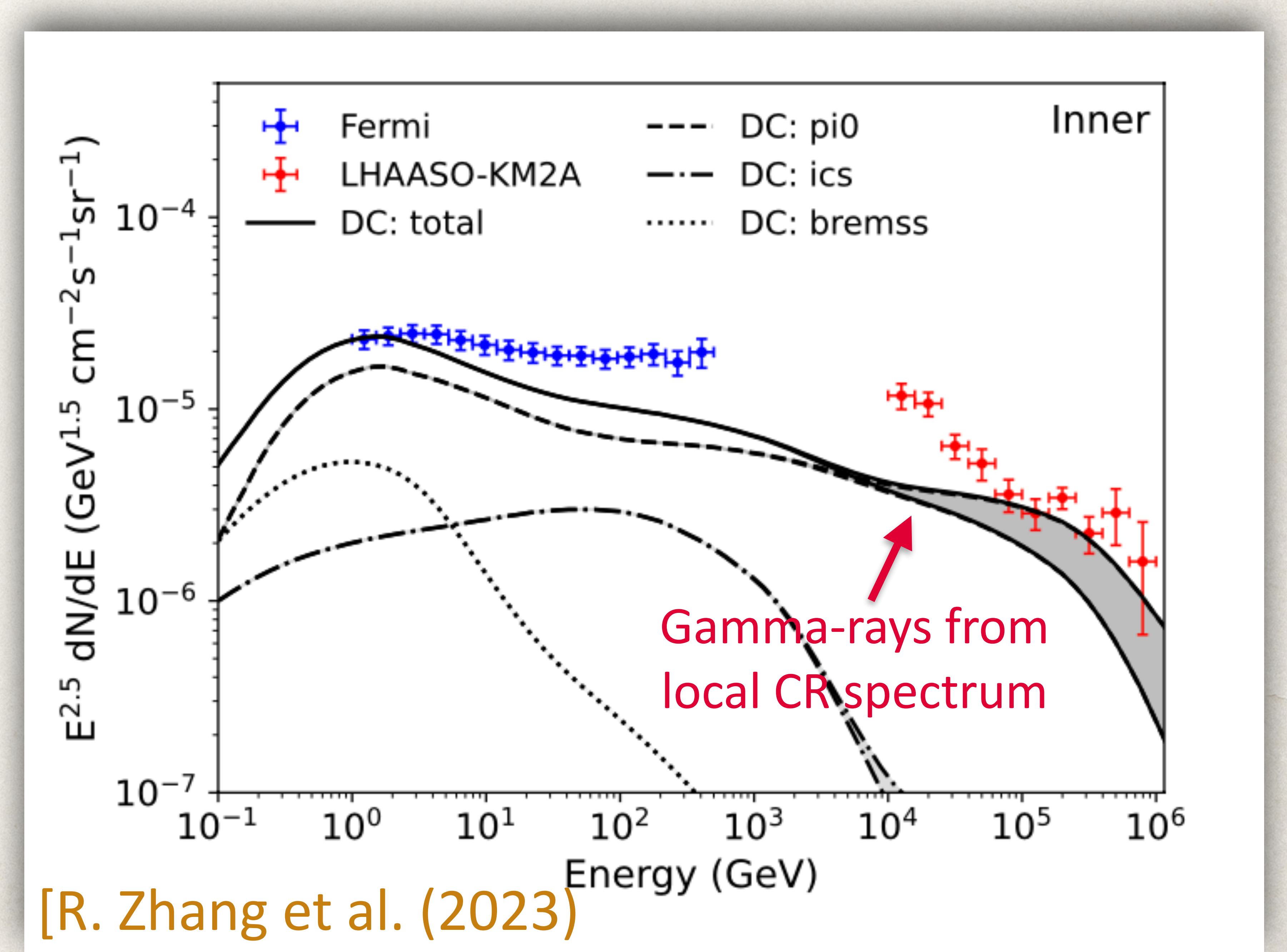
- How many SC there are in the Galaxy
- How are they distributed?

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]

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:

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

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

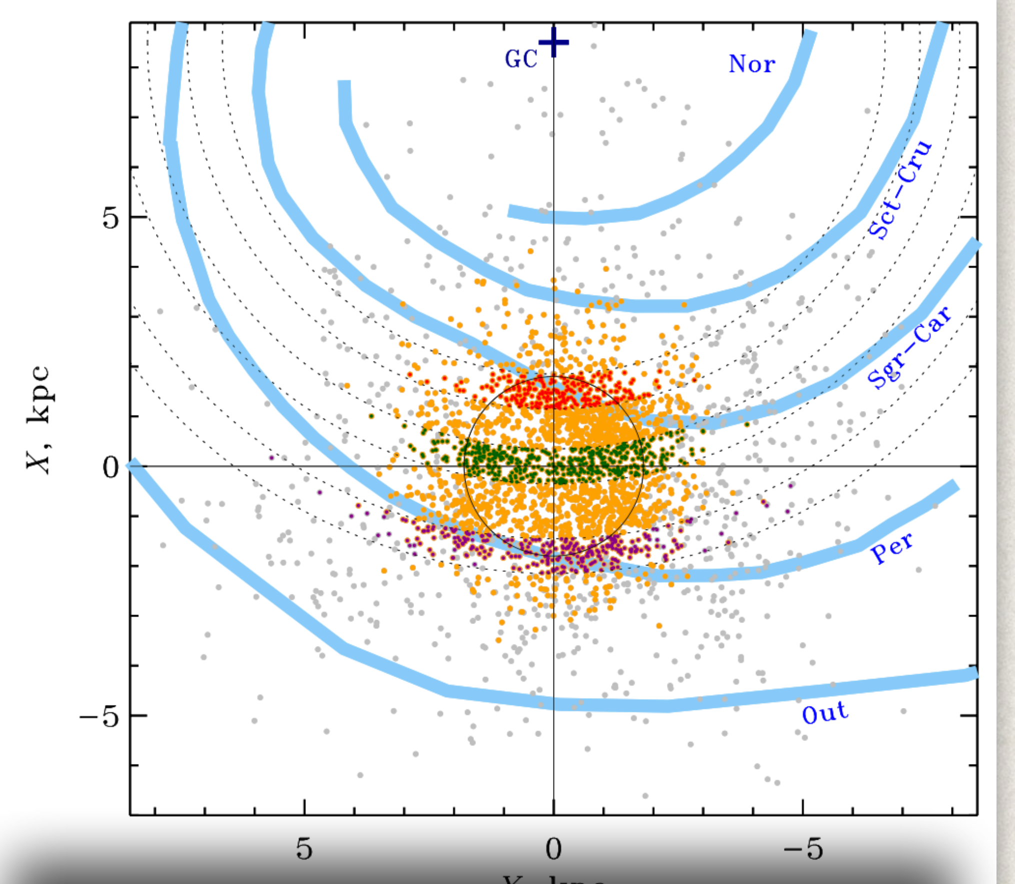
Gamma-ray emission

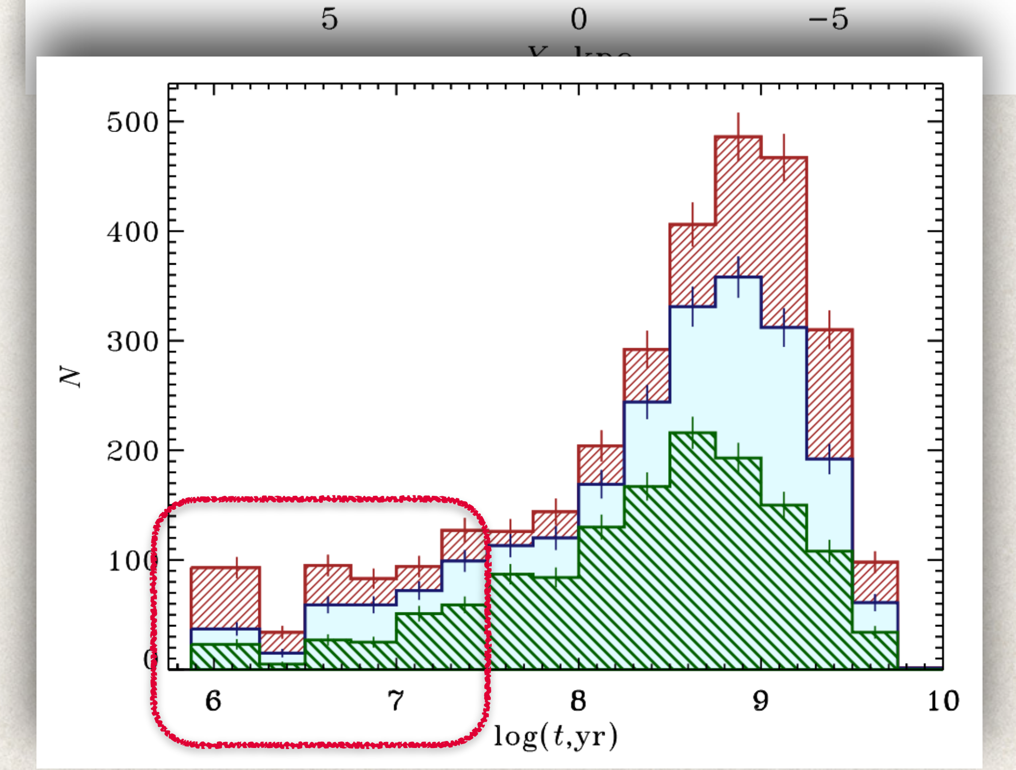
- Mass distribution based on observation of local clusters ($d \lesssim 2\,\mathrm{kpc}$) **Milky Way Stellar Cluster Survey** [Piskunov et al. (2018)]

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

- 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

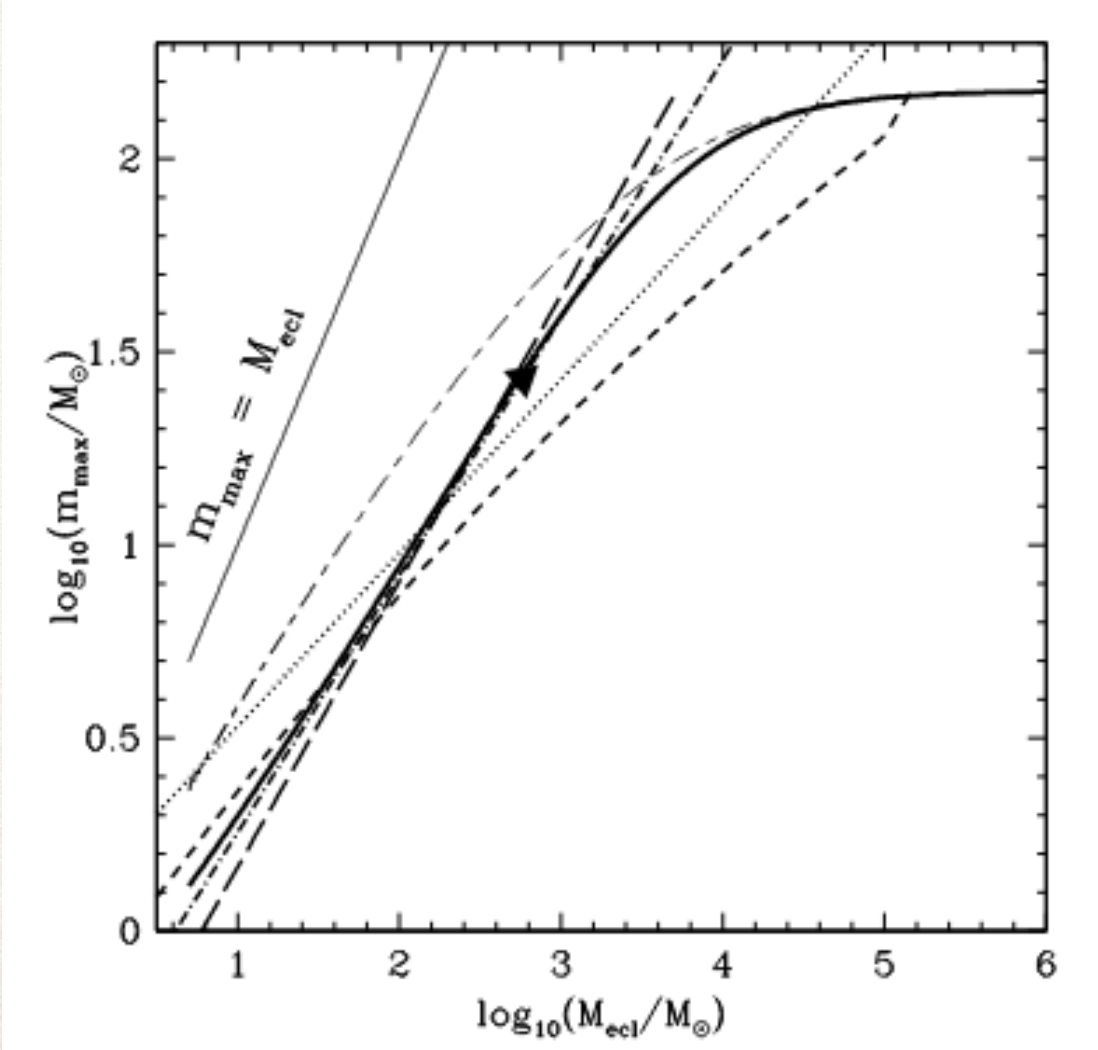
- Stellar mass distribution according to Kroupa (2001)

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

- 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

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

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

$$C_{\rm eff} = \begin{cases} 1.0 & T < 10^4\mathrm{K} \\ 1.4 & 10^4\mathrm{K} < T < 2.1\times10^4\mathrm{K} \\ 2.65 & T > 2.1\times10^4\mathrm{K} \end{cases}$$

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

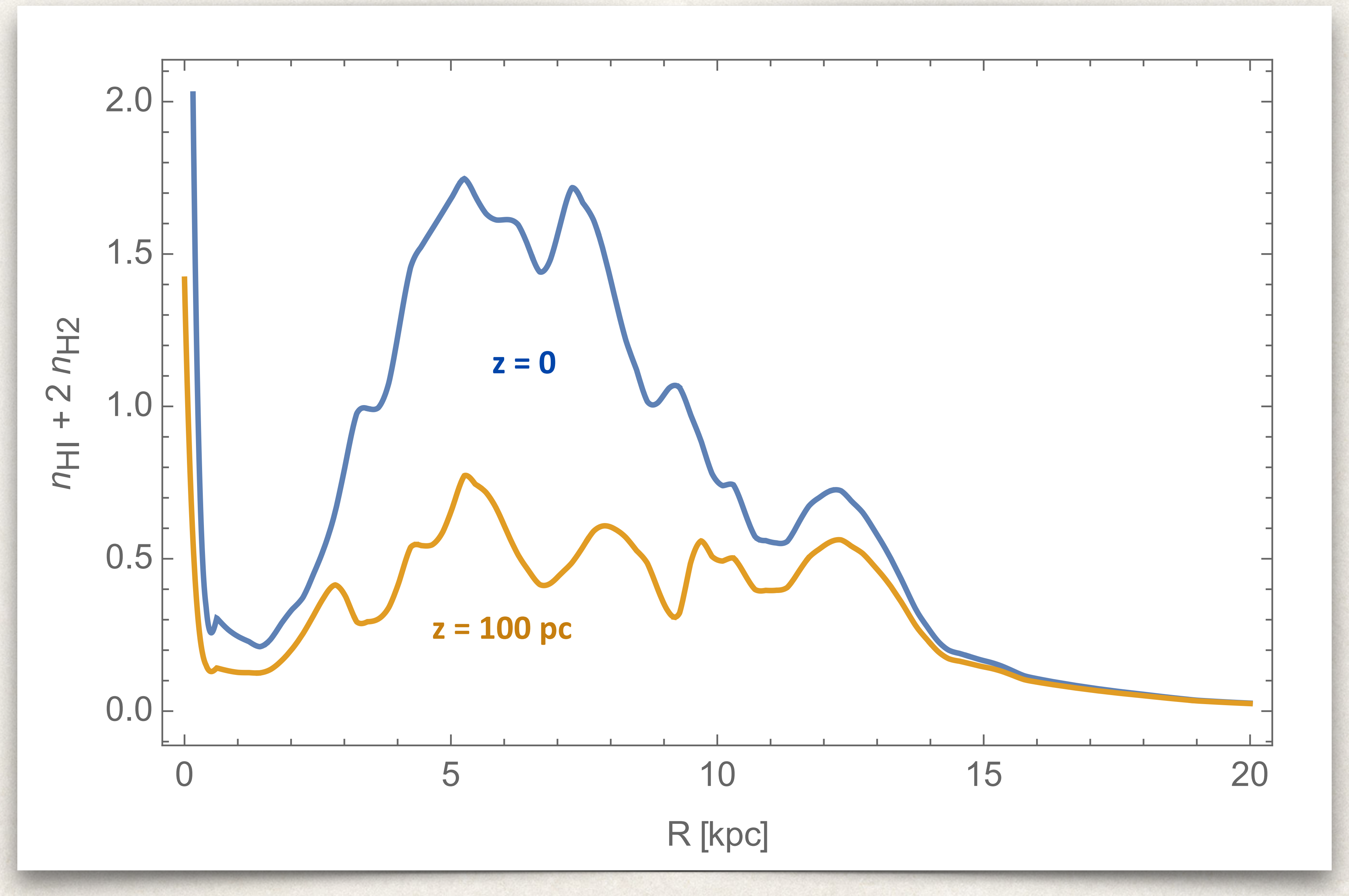
[Menchiari, GM et al. (2024) arXiv:2406.04087]

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



Example of a synthetic SC population

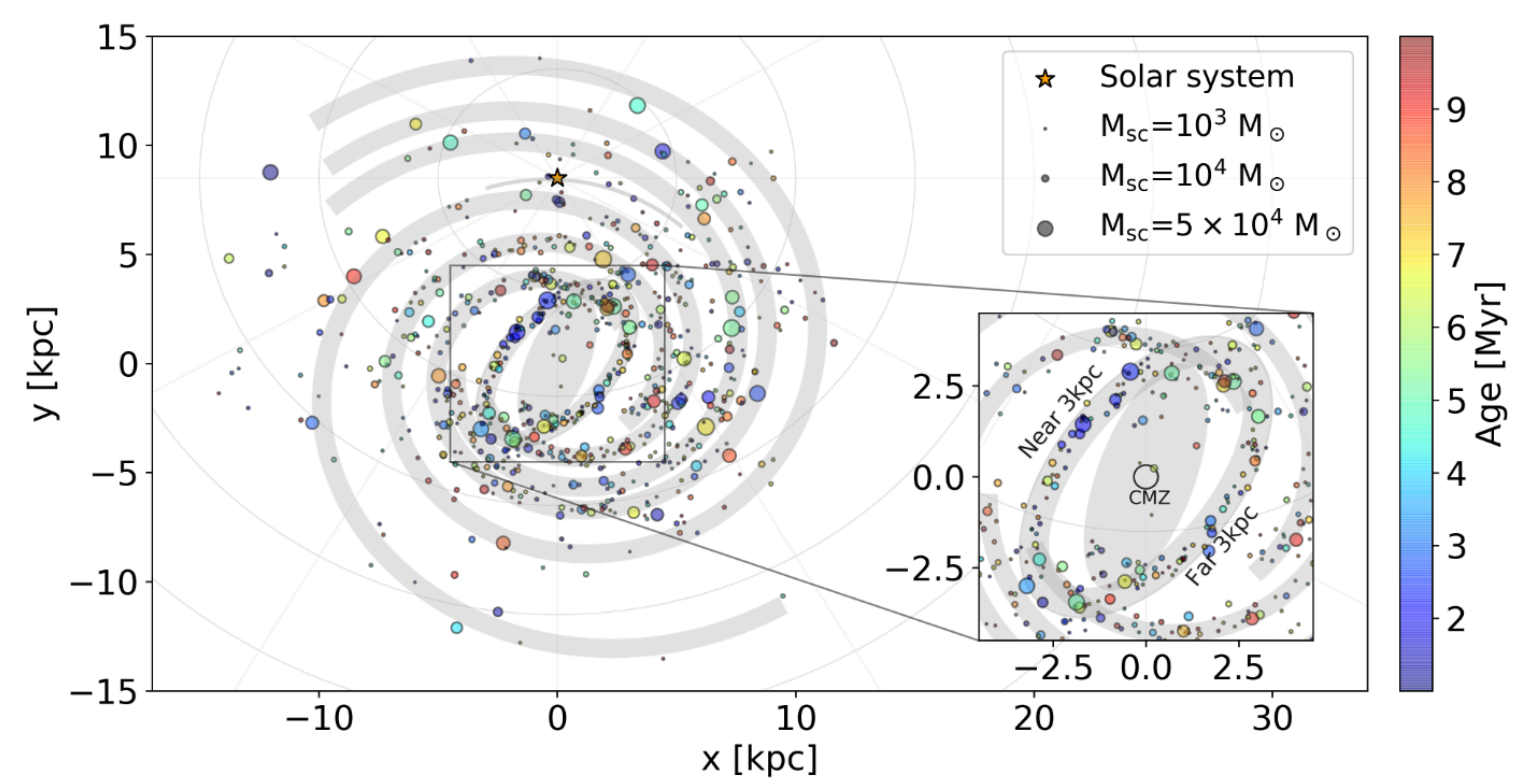
[Menchiari, GM et al. (2024) arXiv:2406.04087]

Single realisation of stellar cluster population with:

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

→ total number of SC $\simeq 750$

Compatible with Gaia results



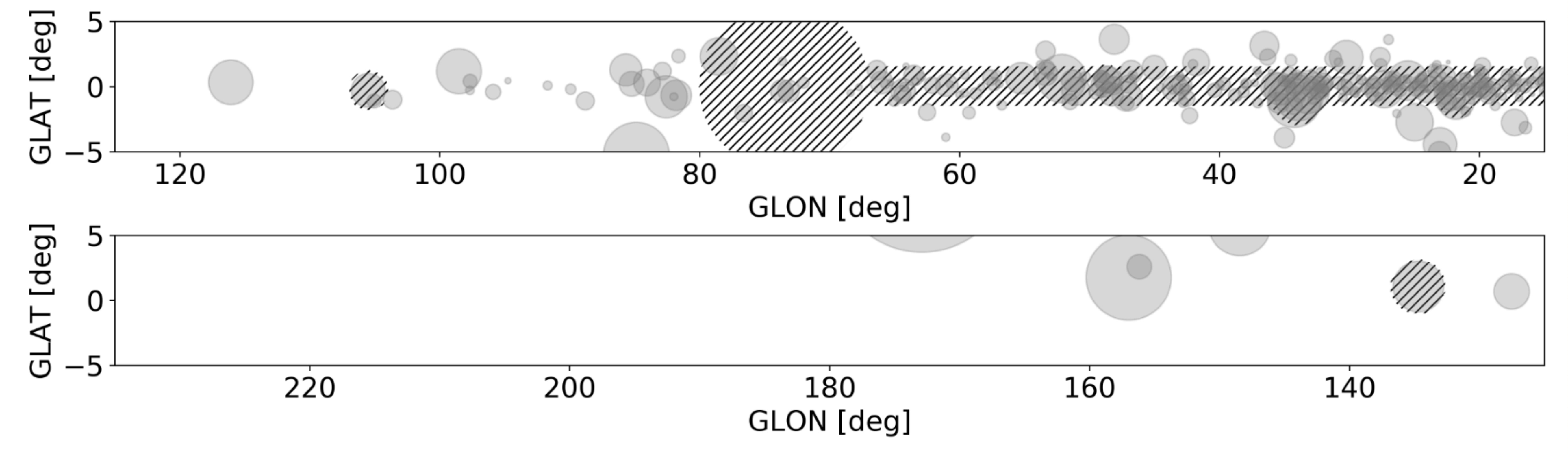
Applied masks

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

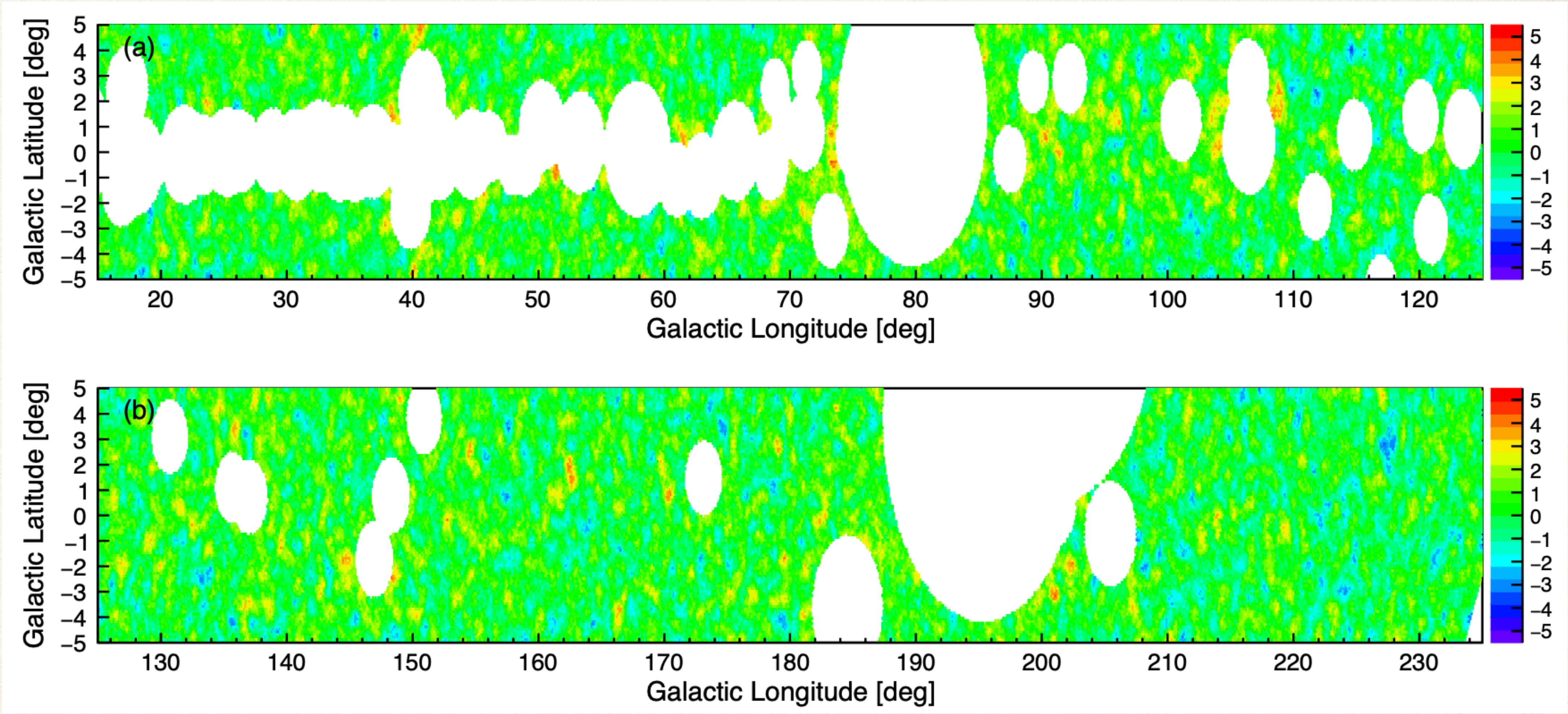
The SC gamma-ray bubble are masked to be consistent with the method used by the LHAASO coll.

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

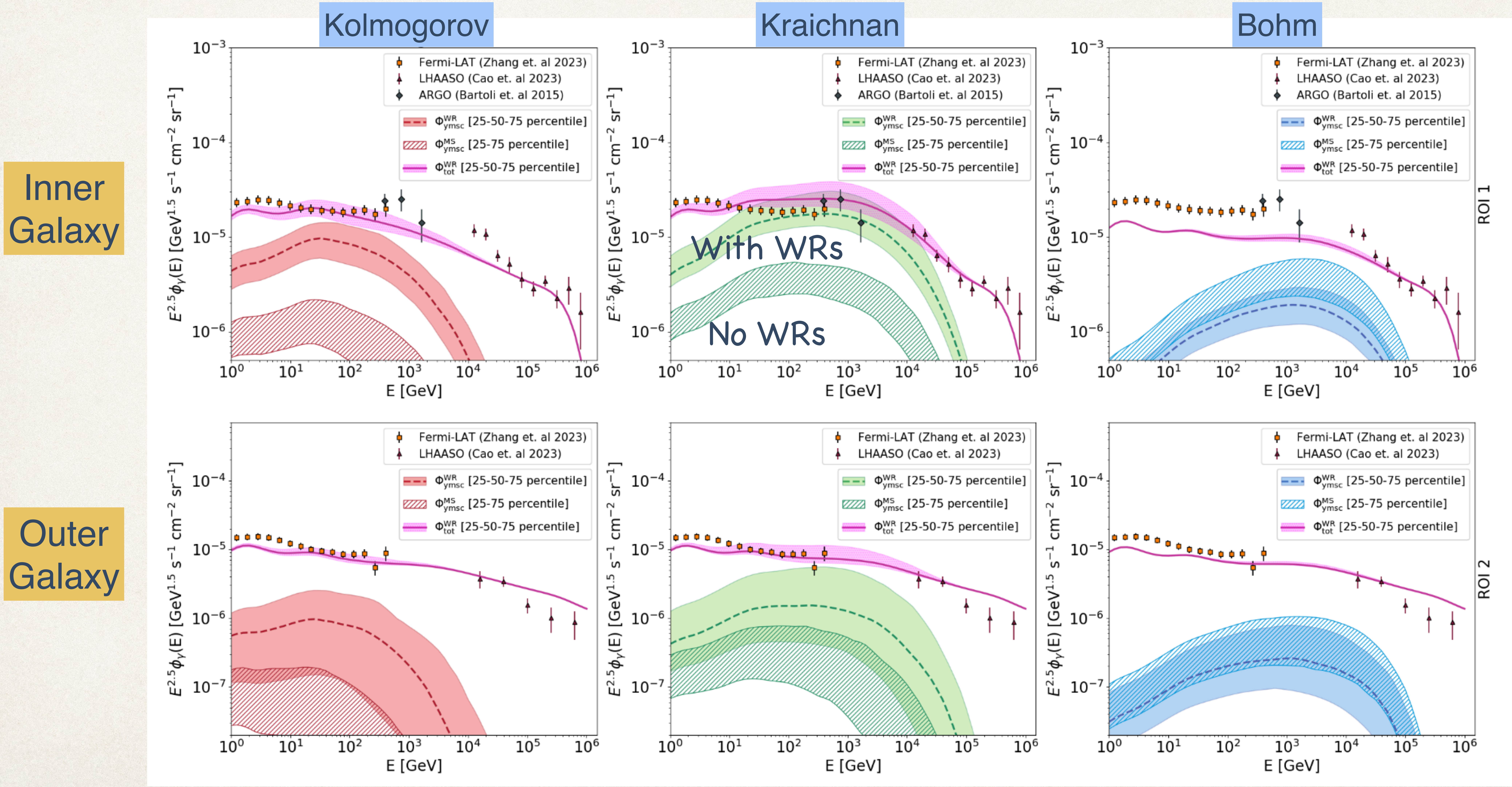


LHAASO mask



Contribution of SCs to the diffuse Galactic γ-ray emission

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



Acceleration efficiency $\simeq 10\,\%$

A composite scenario for the CR spectrum

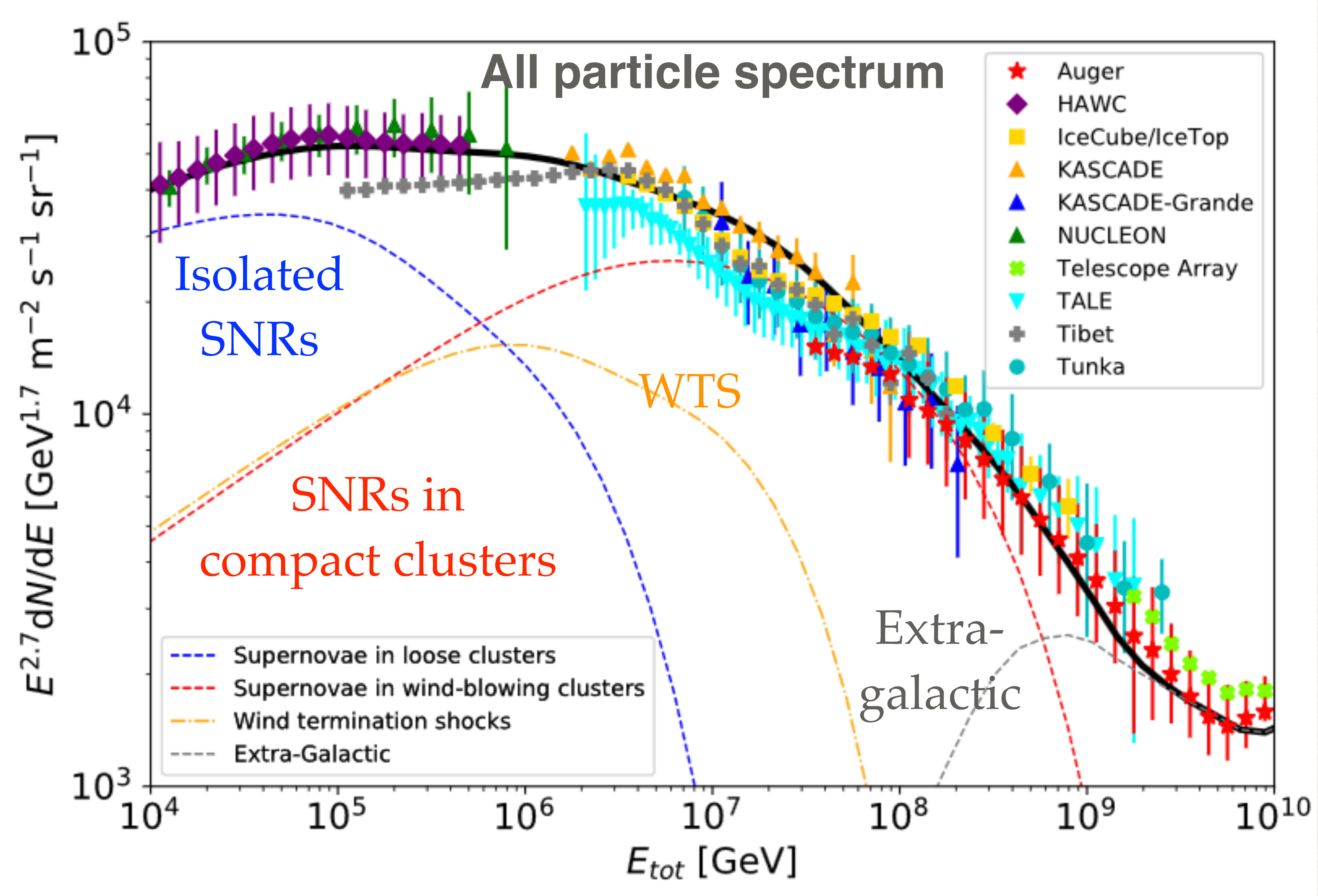
[Vieu & Reville, MNRAS 2023]

Attempt to explain the all-particle spectrum with a combination of isolated SNRs + wind termination shock + SNR in compact clusters

Caveats:

- Diffusion in the bubble not understood yet
- Evolution of SNR inside bubble unclear
- Effect of grammage increase not included

Slope and maximum energy not very well determined



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