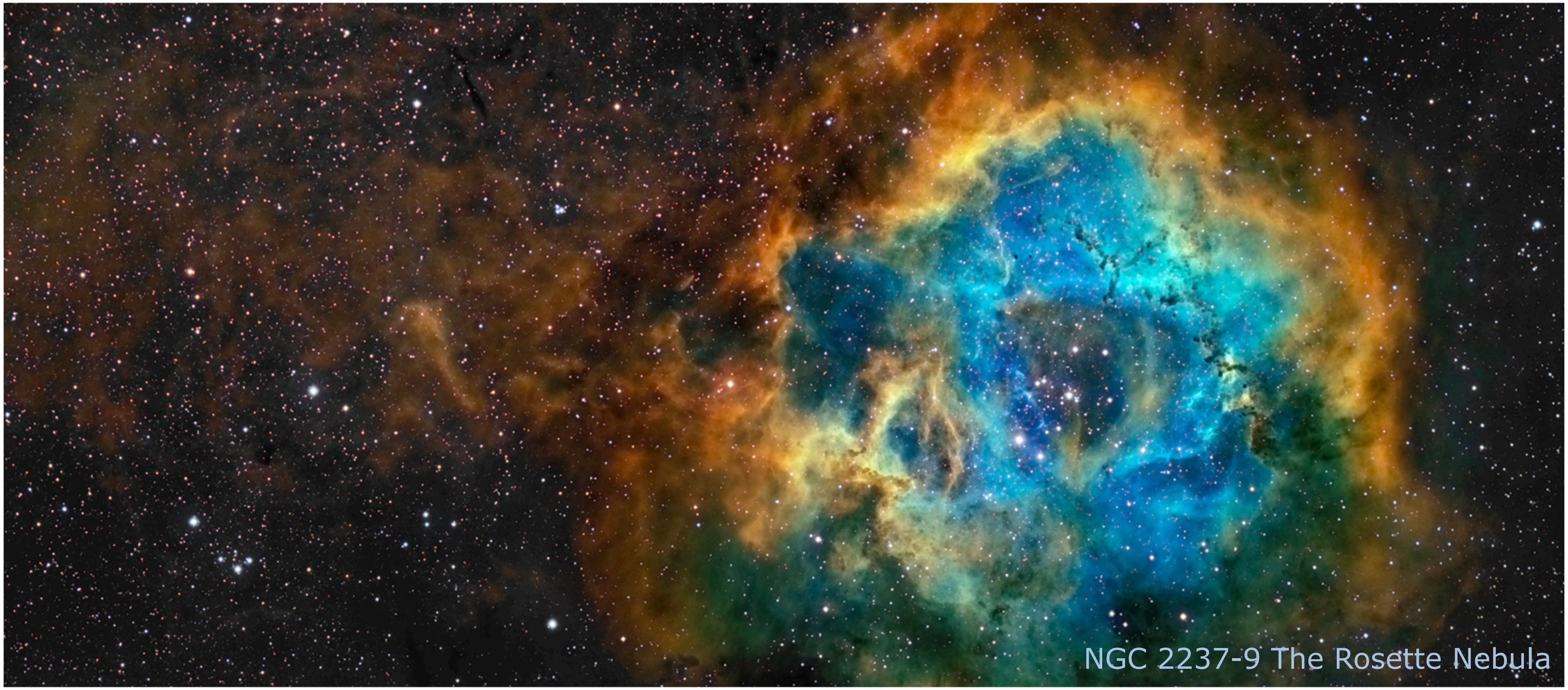

NGC 2237-9 The Rosette Nebula

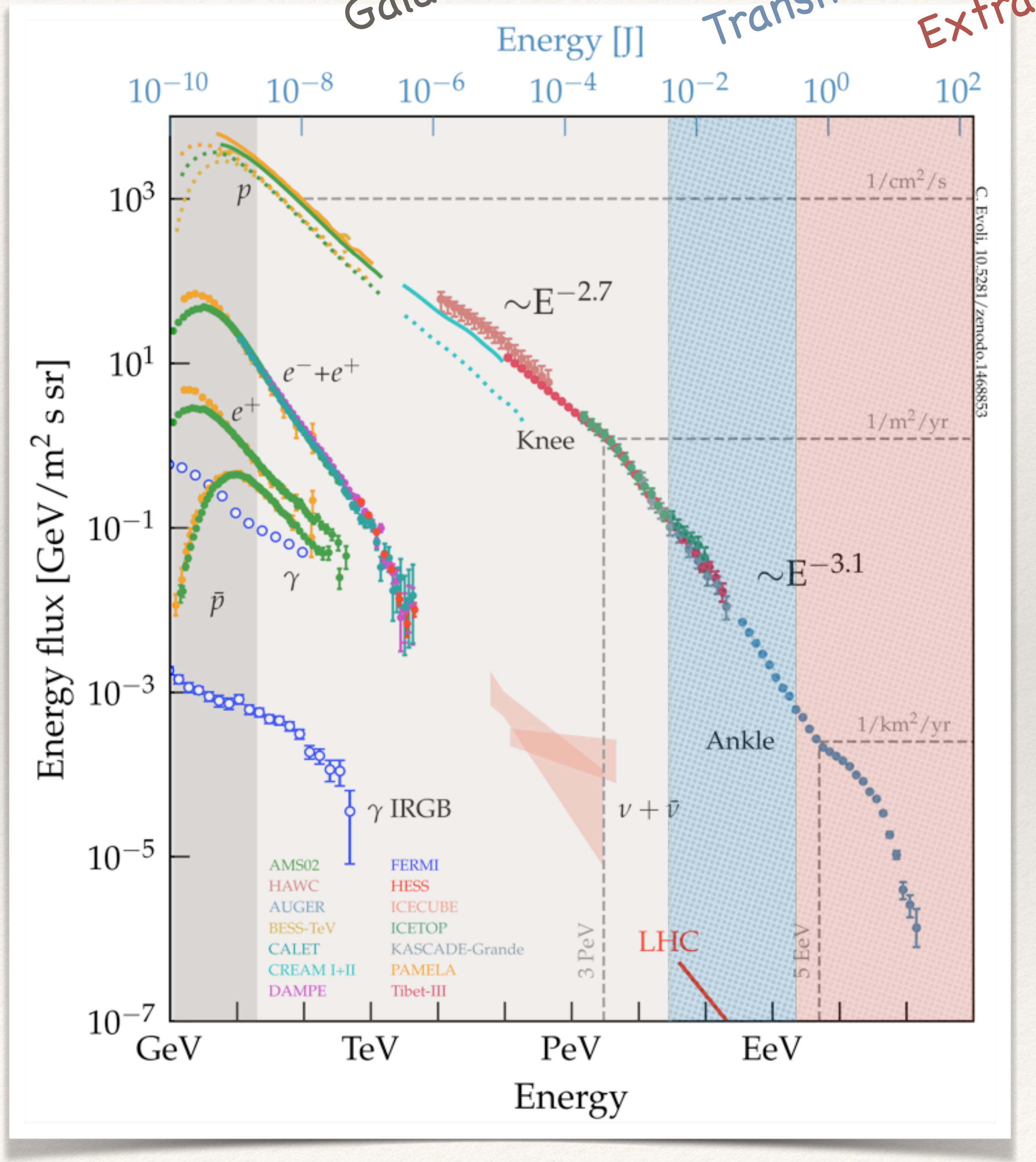
From star clusters to field populations: survived, destroyed and migrated clusters

Firenze — 20-23 November, 2023

Young Stellar Clusters as gamma-ray sources

Giovanni Morlino
INAF/Oss. Astrofisico di Arcetri
Firenze
ITALY

How to explain the origin of Galactic CRs



Requirements for sources to explain the CR flux

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

The most popular scenario: acceleration at SNR shocks

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
- Spectral anomalies (p, He, CNO have different slopes)
- etc…

Looking for alternative sources

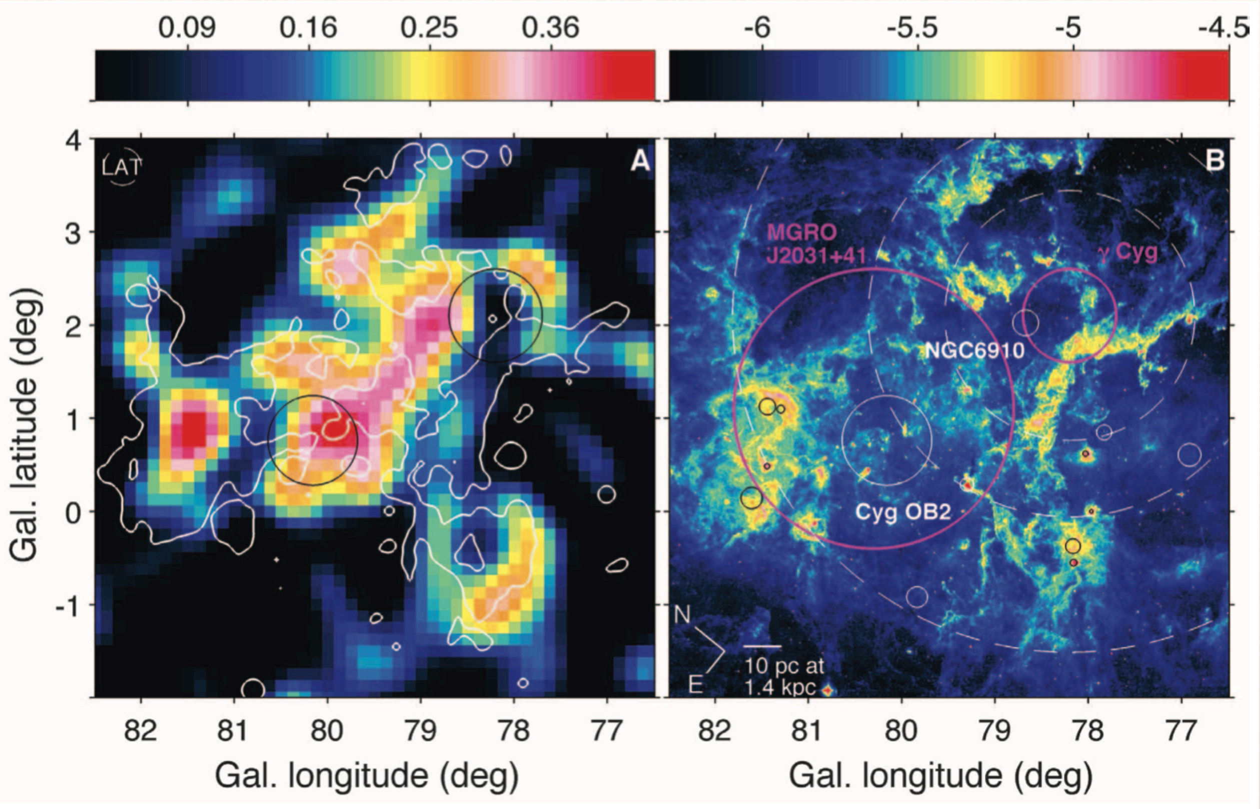
YSCs detected in gamma-rays

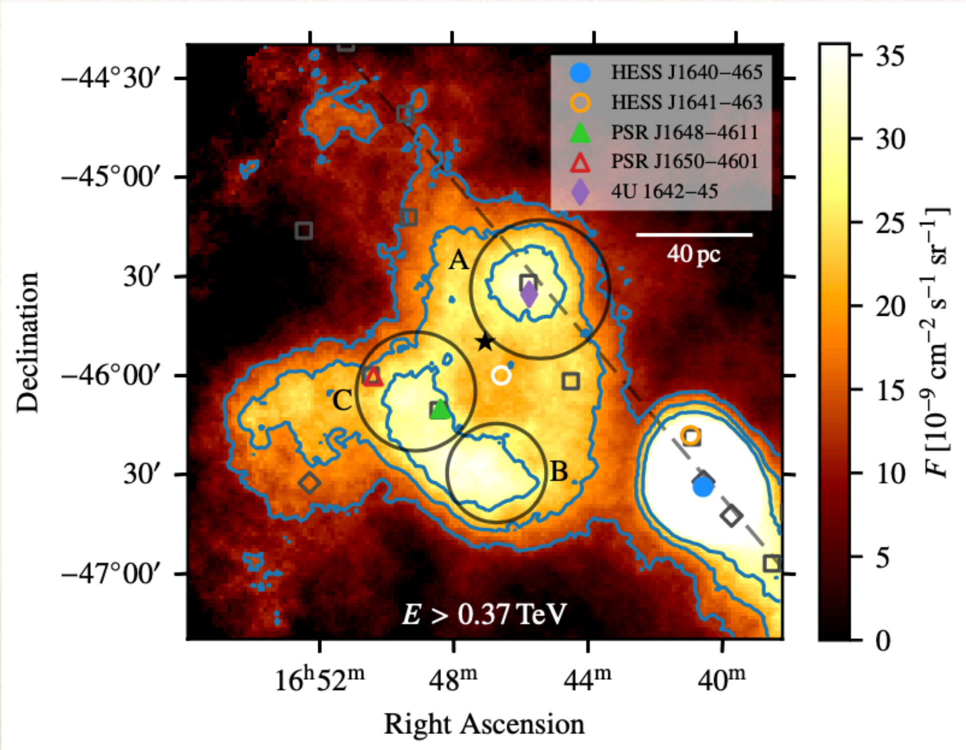
Recently several massive star clusters have been associated with gamma-ray sources

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,
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)
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	~ 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

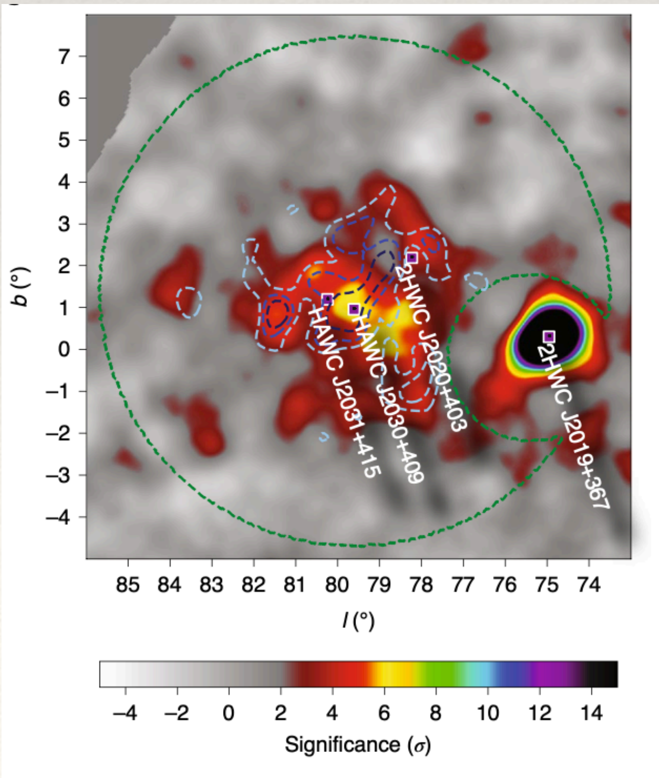
YSCs detected in gamma-rays

Cygnus Cocoon FermiLAT - Ackermann et al. (2011)



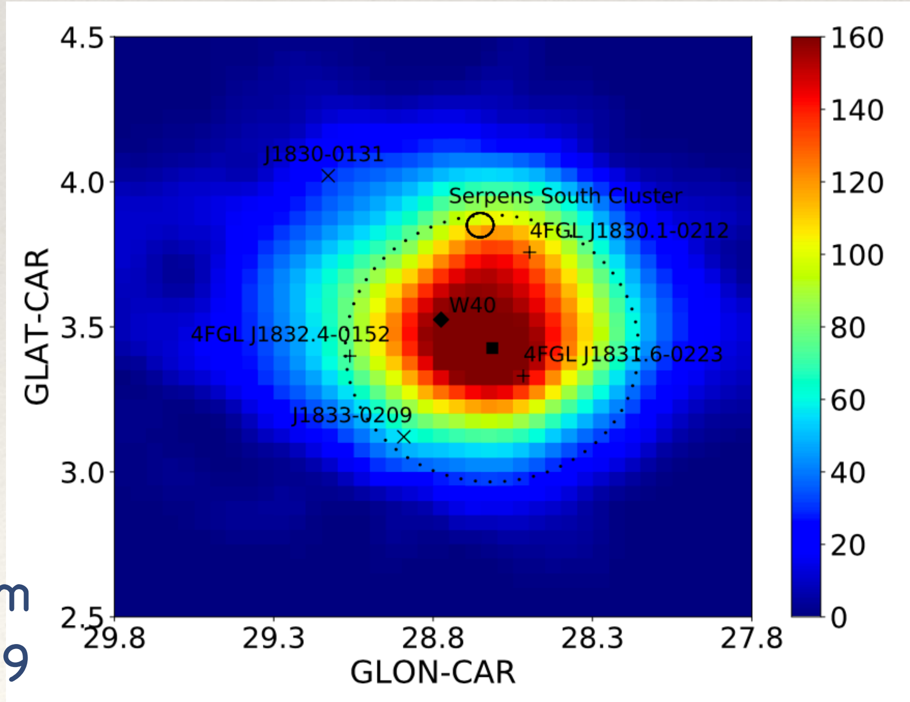


Westerlund 1
HESS coll. A&A (2022)



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

W40 - FermiLAT data from
Sun et al. (2020) arxiv:2006.00879

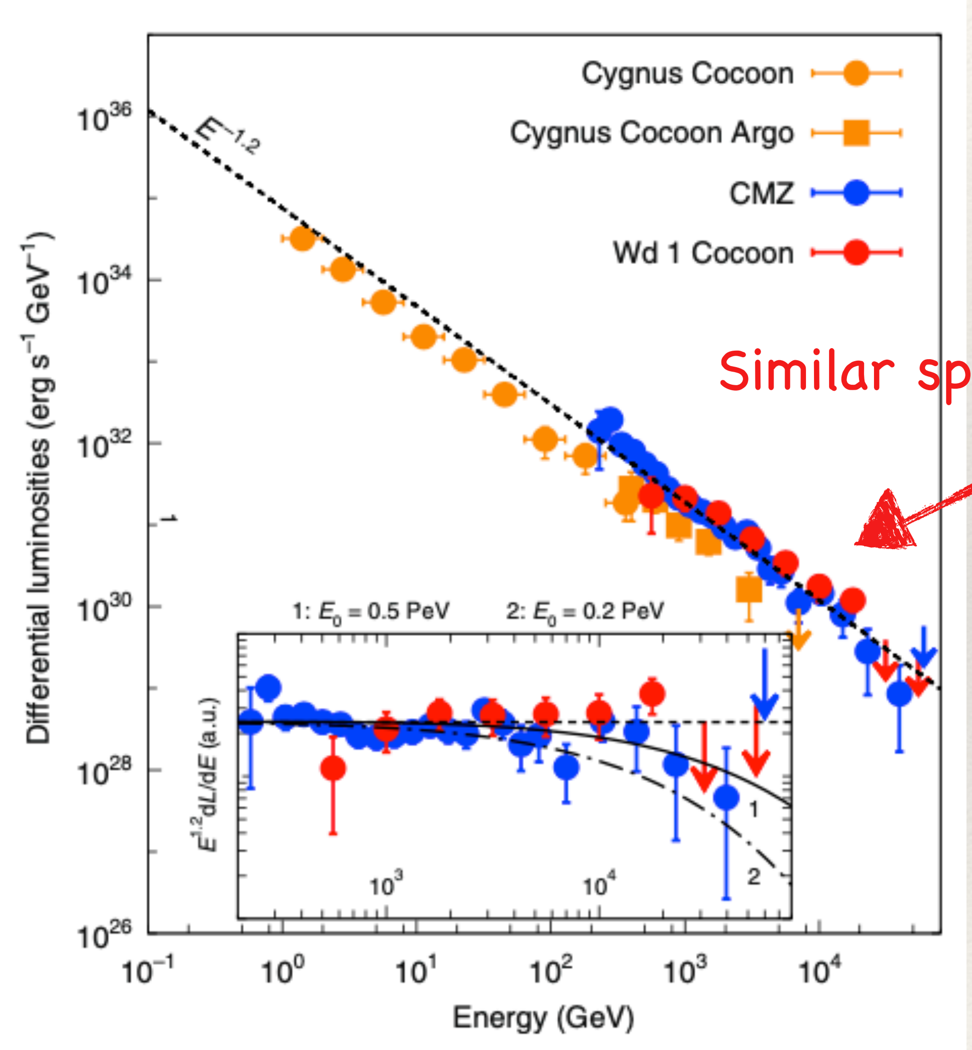


YSCs detected in gamma-rays

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

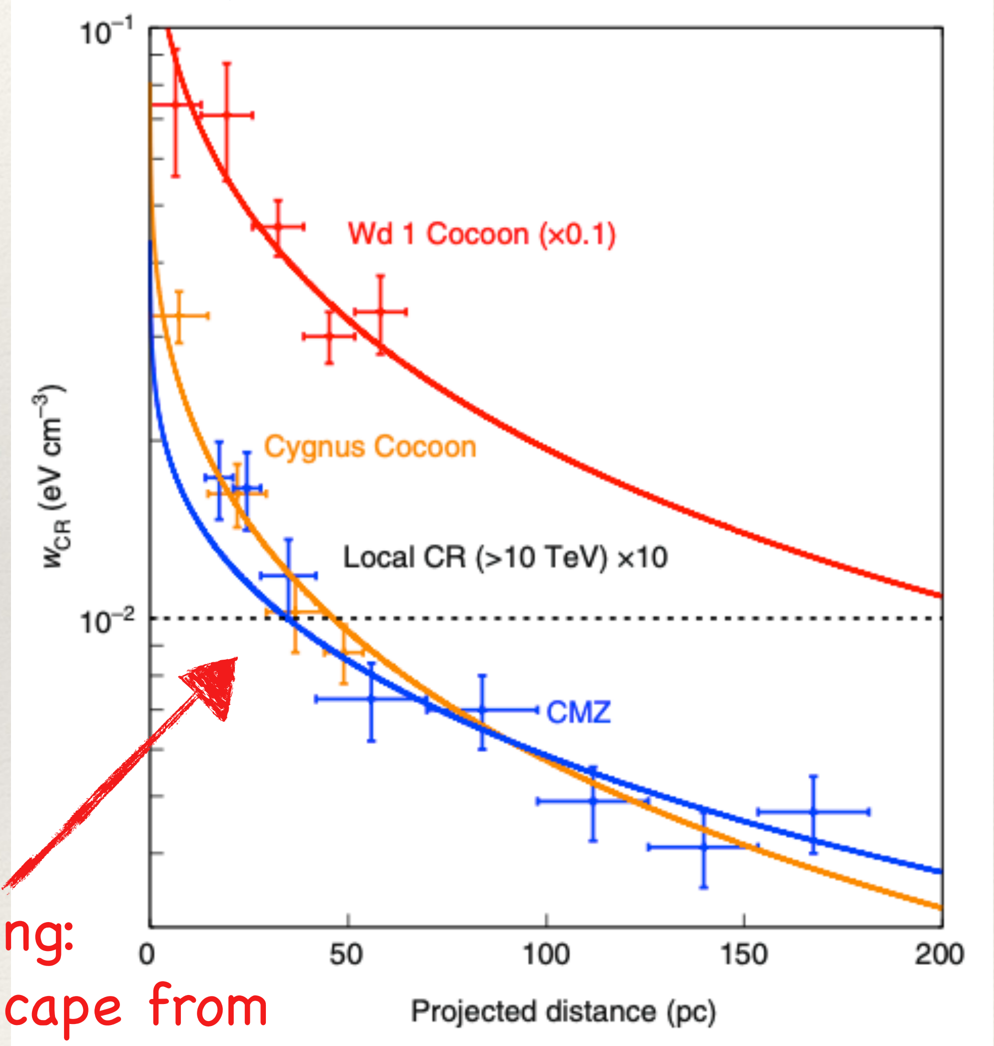
Some clusters show similar spectra and radial profile

Spectrum



Similar spectra $\sim E^{-2.2}$

Radial CR profile

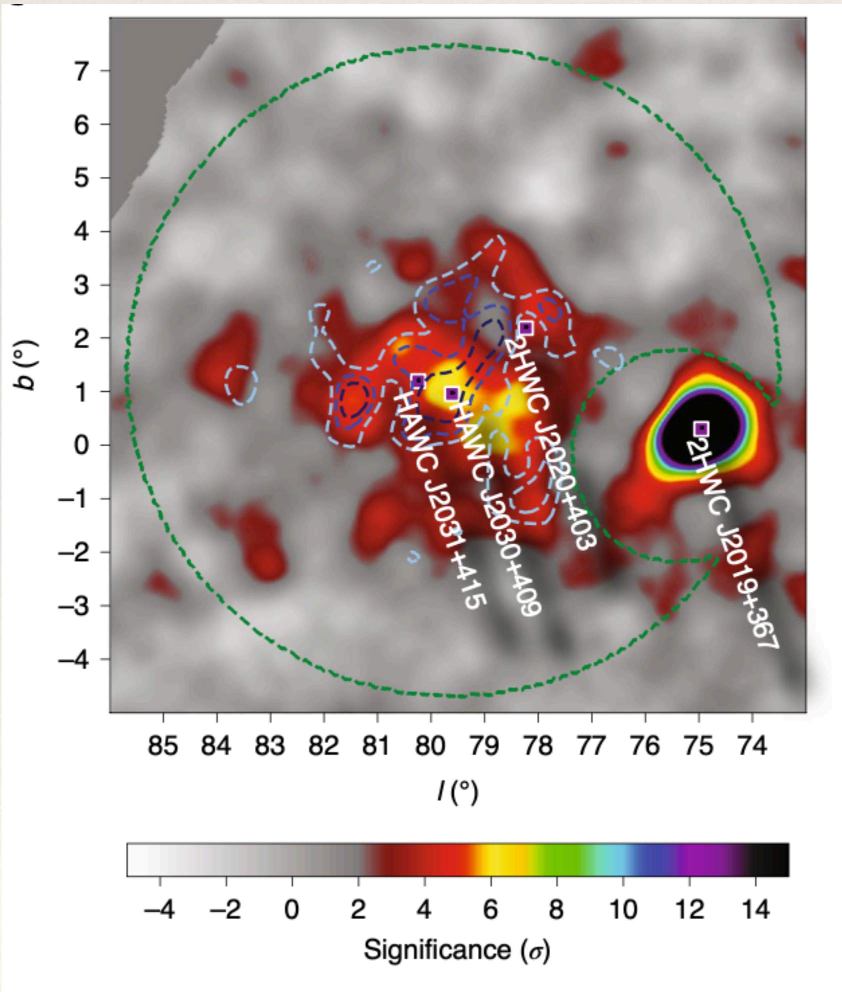


1/r scaling:
CR diffusive escape from
continuous point source?

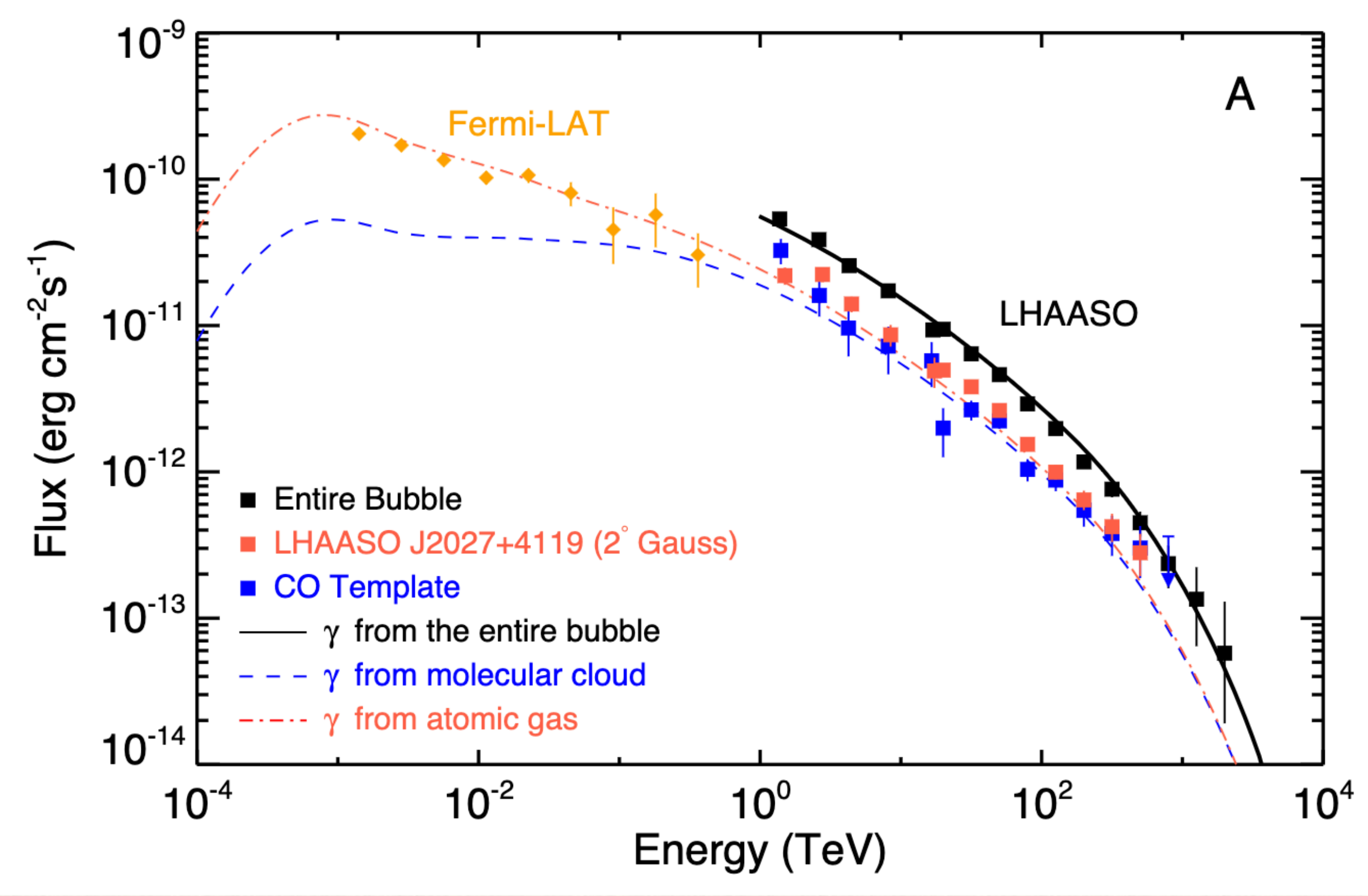
The case of Cygnus Cocoon

- Extended emission up to more than 50 pc for HAWC and Fermi-LAT up to 150 pc for LHAASO
- Hard spectrum in GeV band — Softening in TeV band
- γ-rays detected beyond 1 PeV!

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



Spectrum from LHAASO, arXiv:2310.10100

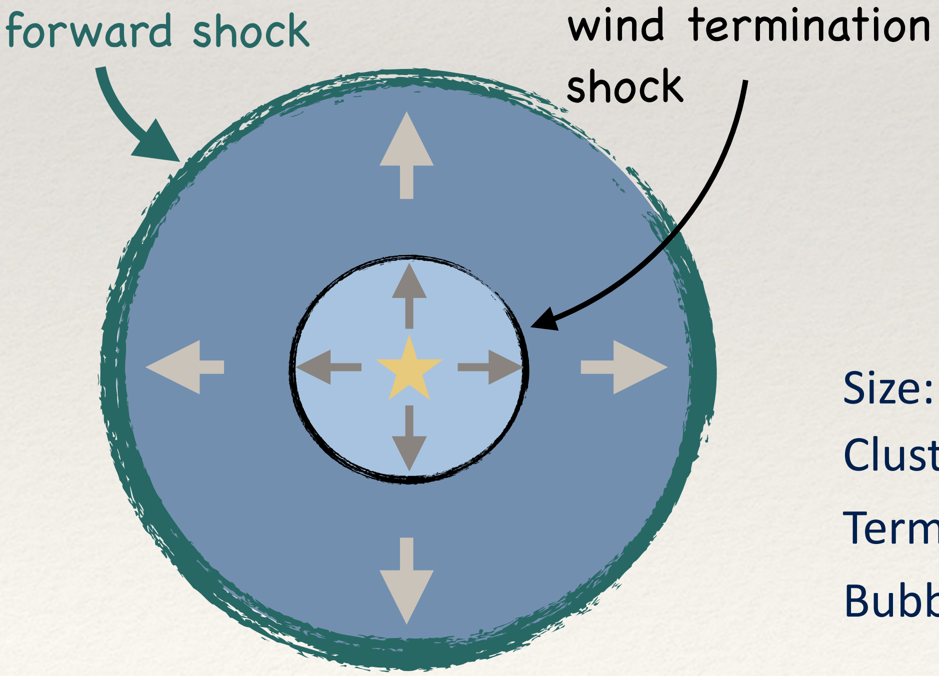


What power Stellar Clusters?

Multiple sources of power

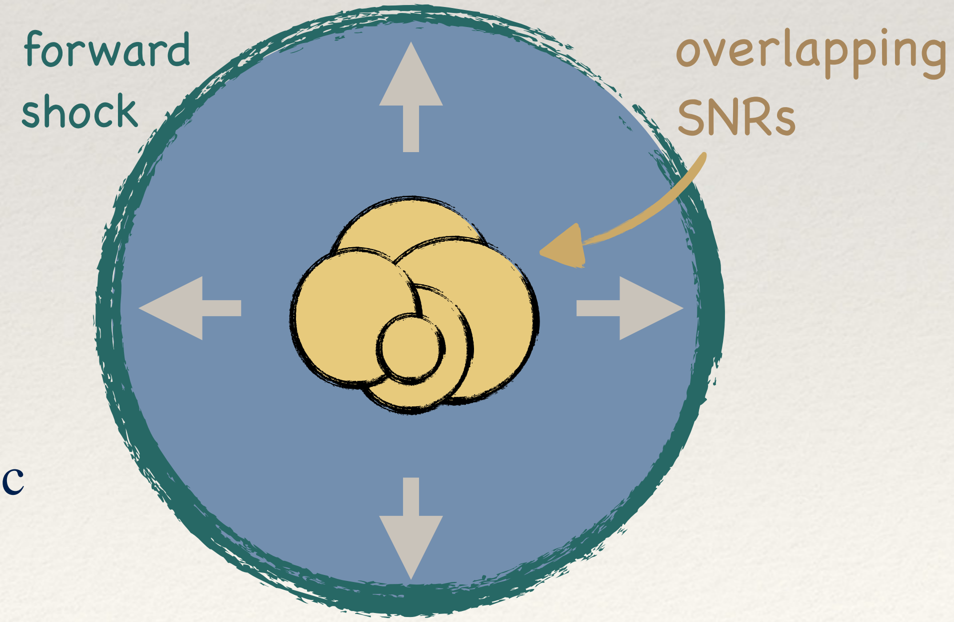
Phase	Source	Single episode	Model
$t \lesssim 3\,\mathrm{Myr}$	MS stellar winds	$t \gtrsim\ \mathrm{Myr}$	quasi-stationary
$3\,\mathrm{Myr} \lesssim t \lesssim 7\,\mathrm{Myr}$	WR stellar winds	$t \sim 10^5\,\mathrm{yr}$	semi-stationary
$3\,\mathrm{Myr} \lesssim t \lesssim 30\,\mathrm{Myr}$	SNe	$t \sim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

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



Size:
Cluster core $\sim 1\,\mathrm{pc}$
Termination shock $\sim 5 - 10\,\mathrm{pc}$
Bubble $\sim 50 - 100\,\mathrm{pc}$

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



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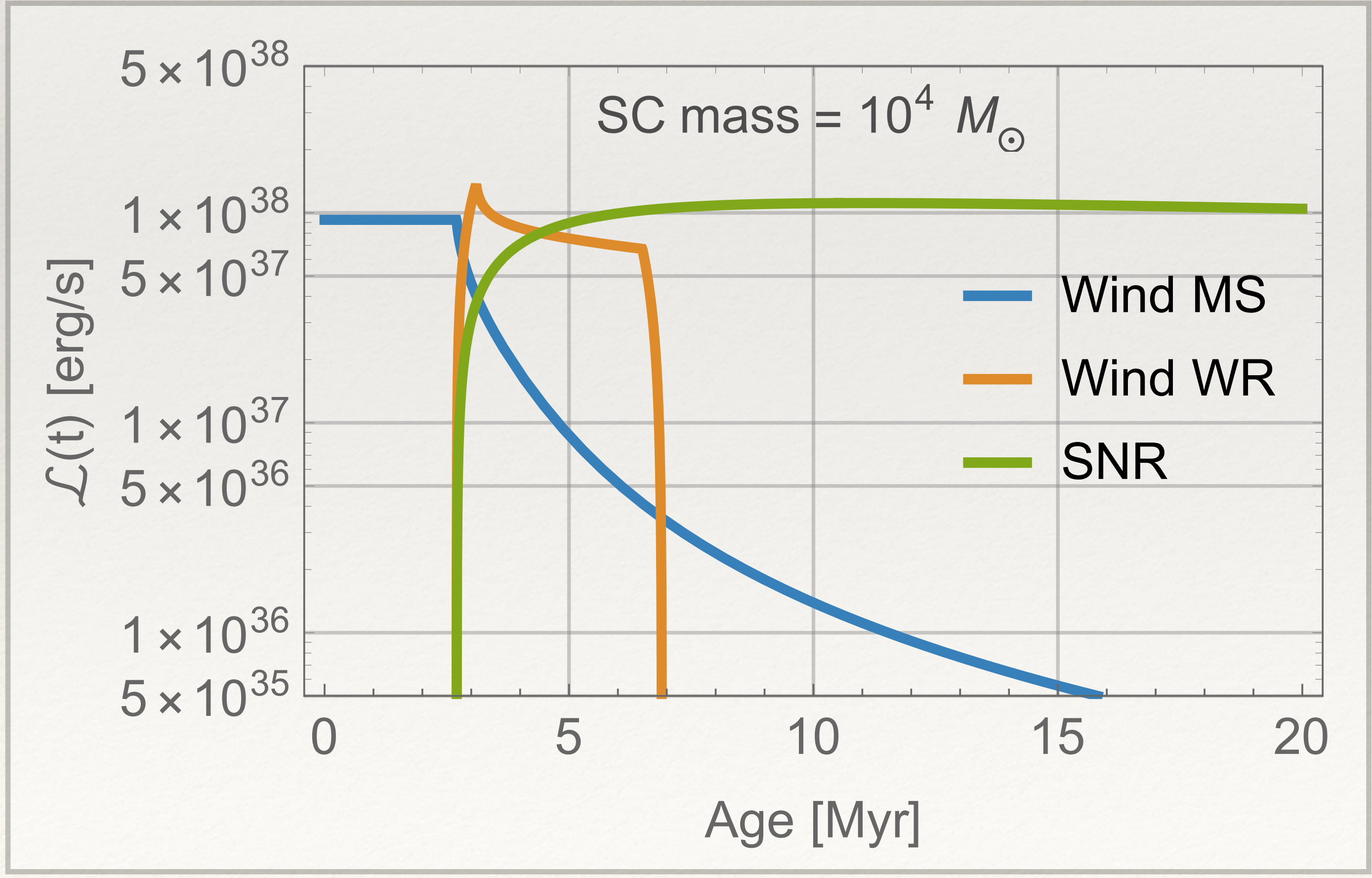
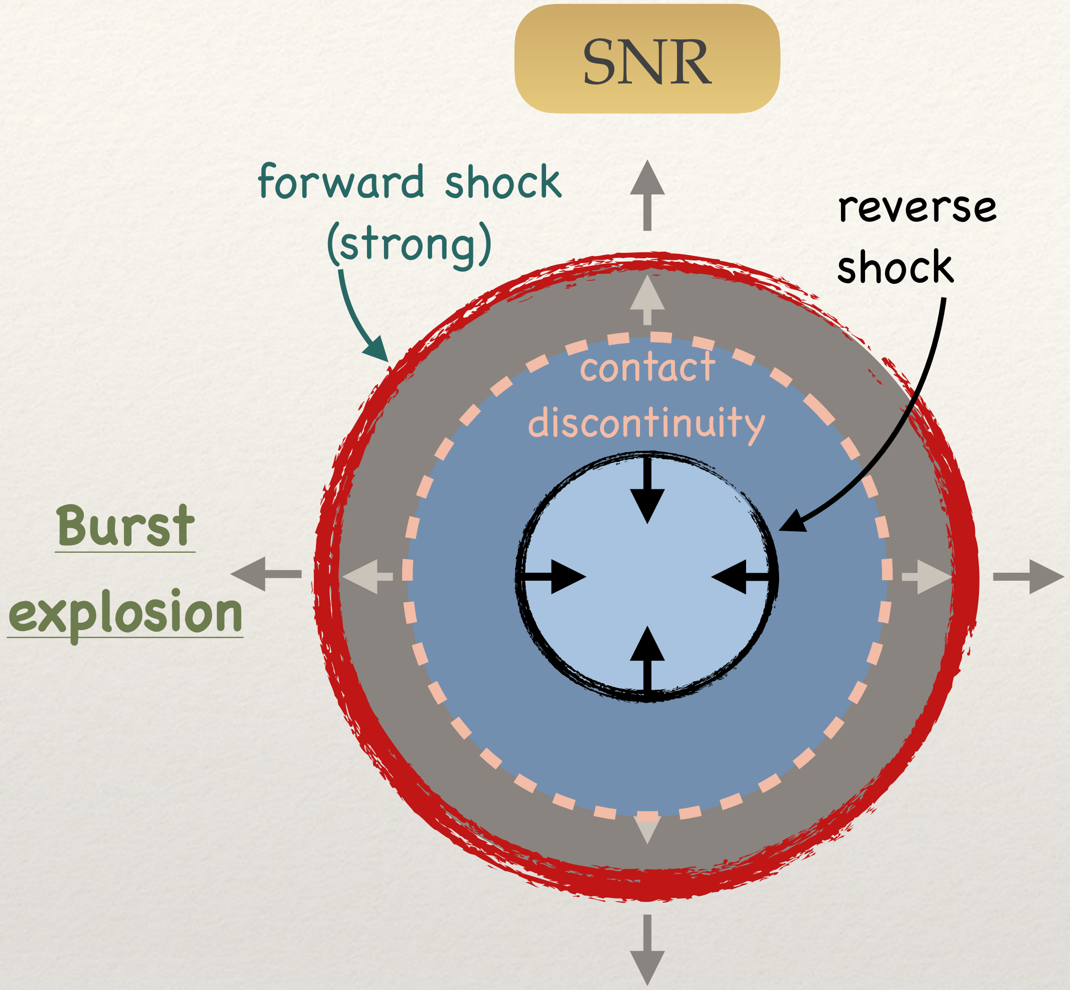
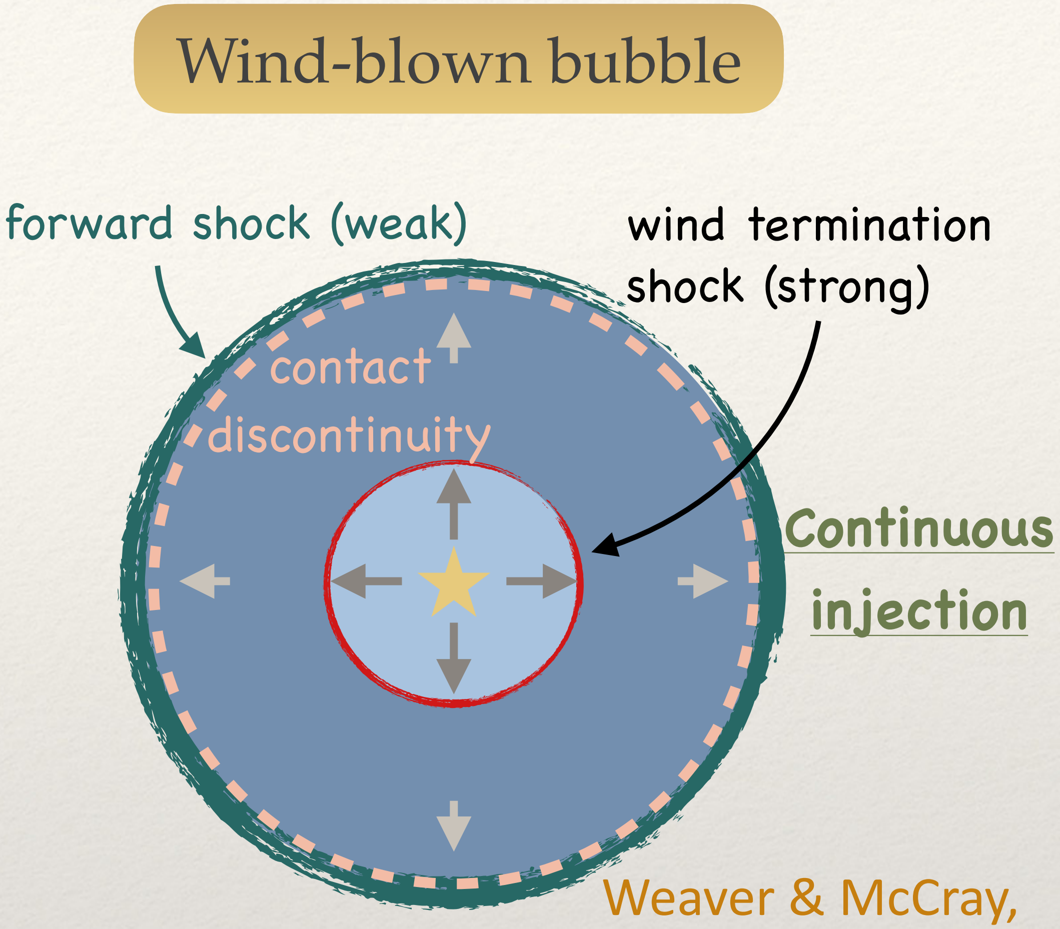
Kinetic luminosity of a massive SC, $M_c = 10^4\,\mathrm{M}_\odot$



Stellar winds vs. SNRs

Cassé & Paul (1980, 1982) — Cesarsky & Montmerle (1983)





Weaver & McCray, ApJ 218 (1977)

		Forward shock		Reverse shock	
	age	V_{FS} [km/s]	R_{FS} [pc]	V_{RS} [km/s]	R_{RS} [pc]
SNR	kyr	> 5000	< 1	< 3000	< 1
Wind bubble	Myr	10 - 20	50-100	< 3000	1-10

G. Morlino, 21th Nov. 2023

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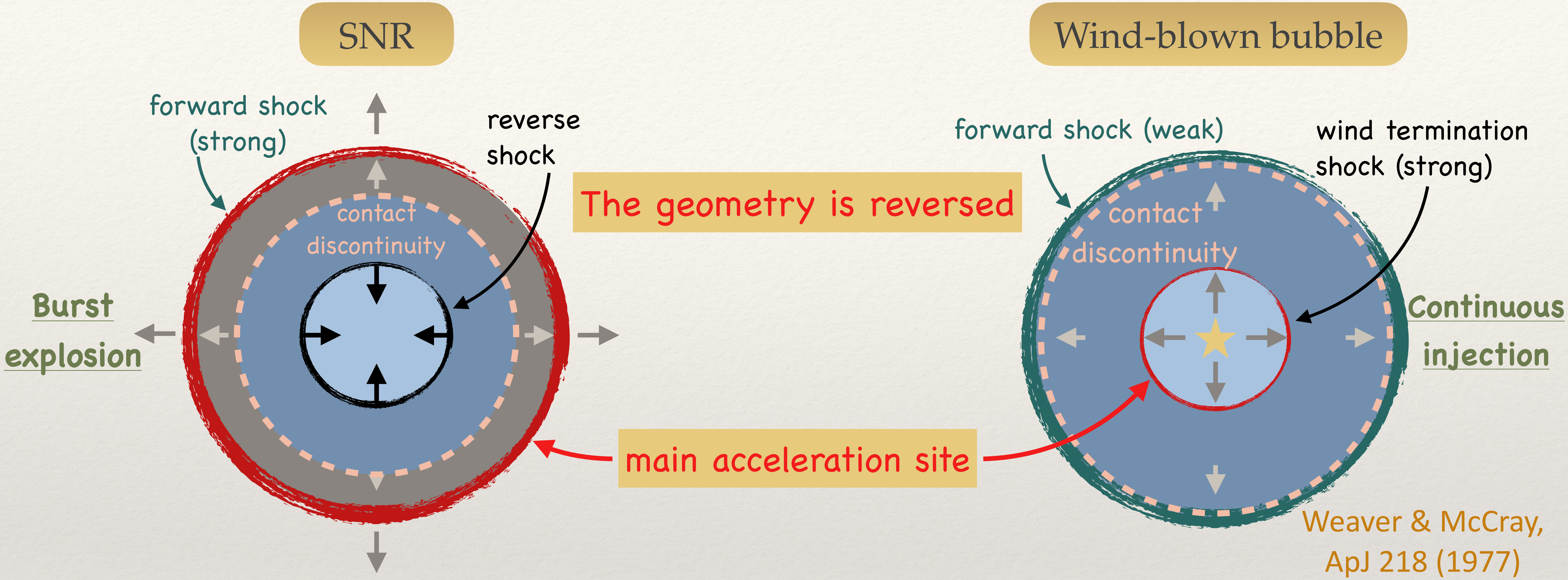

SNR

Wind-blown bubble

forward shock (strong)

reverse shock

Burst explosion

contact discontinuity

The geometry is reversed

main acceleration site

forward shock (weak)

wind termination shock (strong)

Continuous injection

Weaver & McCray, ApJ 218 (1977)

		Forward shock		Reverse shock	
	age	V_{FS} [km/s]	R_{FS} [pc]	V_{RS} [km/s]	R_{RS} [pc]
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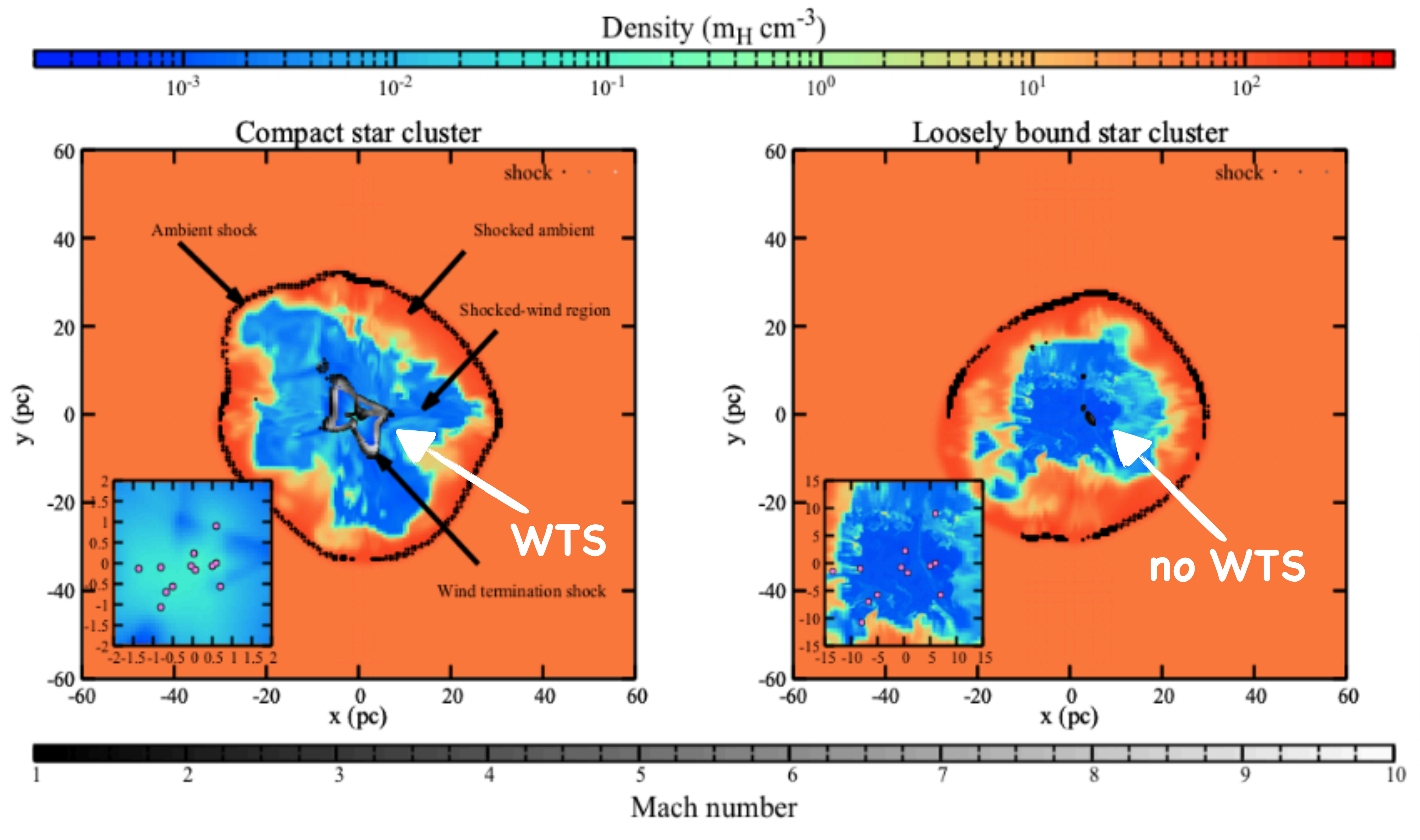
Cluster compactness

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

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



Compact cluster

Loose cluster

Cluster compactness

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

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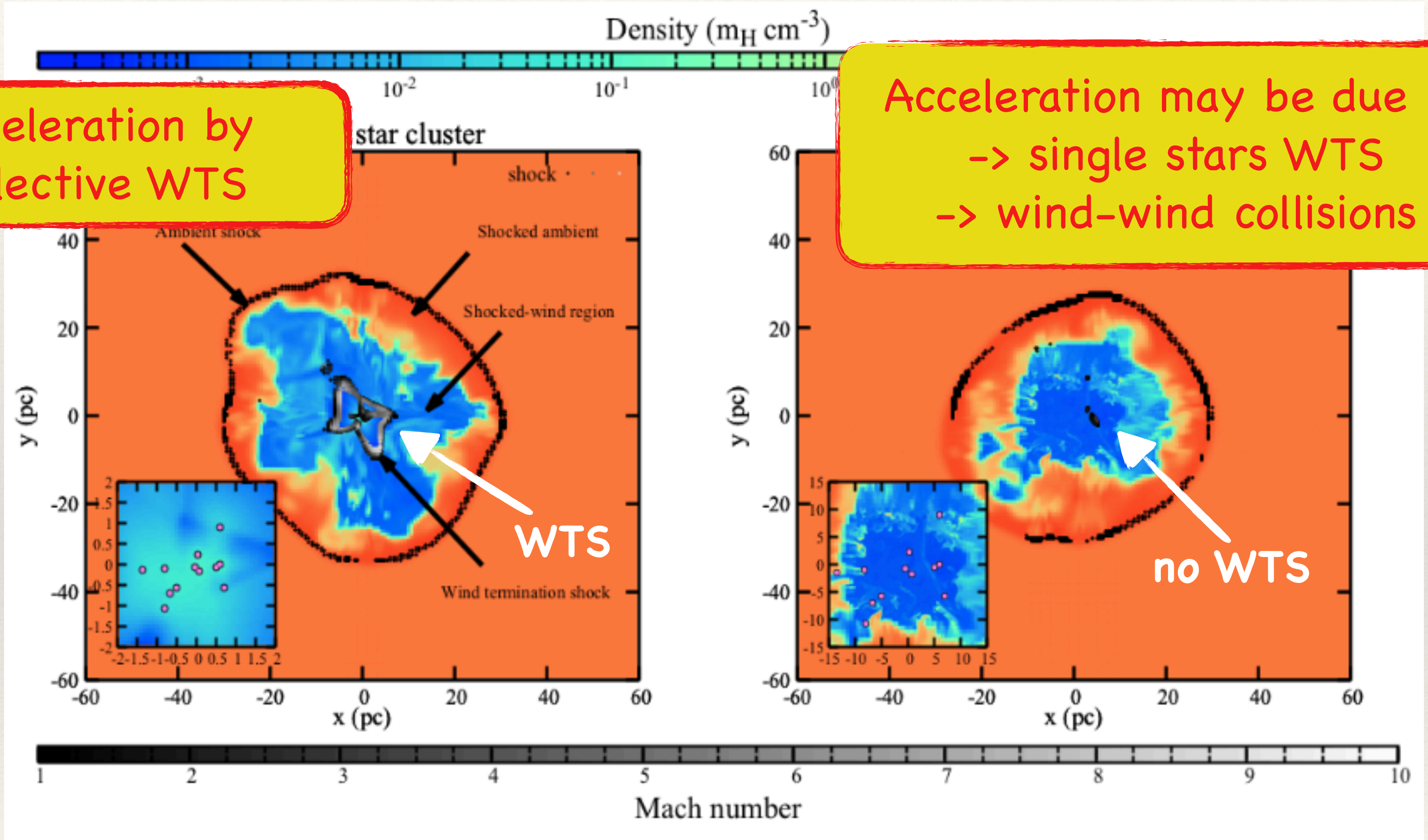


Acceleration by collective WTS

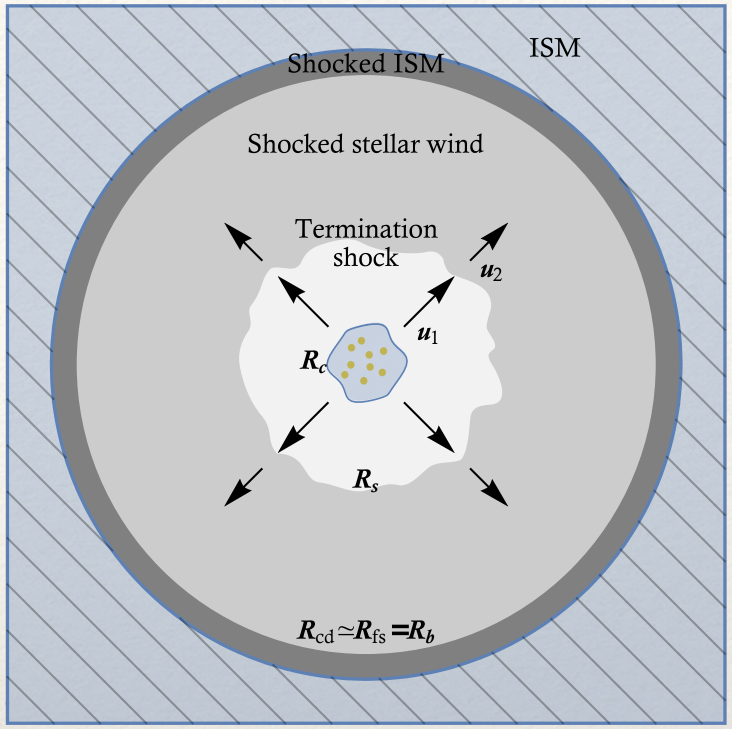
Acceleration may be due to
-> single stars WTS
-> wind-wind collisions

Compact cluster

Loose cluster

Particle acceleration at the wind TS

GM, Blasi, Peretti & Cristofari (2019)



Acceleration at the collective wind termination shock

[GM et al. (2019)]

Badmaev et al. (2022)

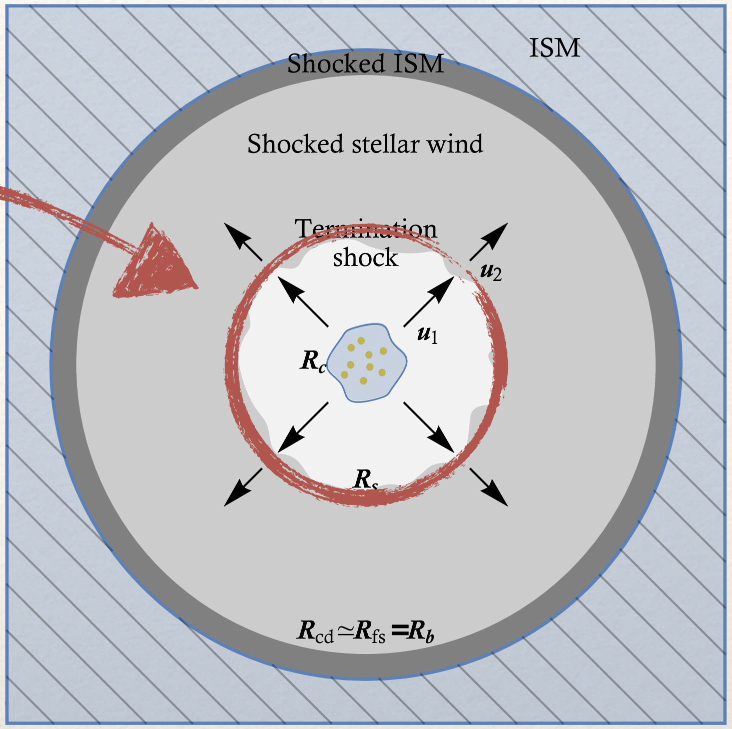
Particle acceleration at the wind TS

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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Acceleration at the collective wind termination shock

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- Particle injected and accelerated at the termination shock
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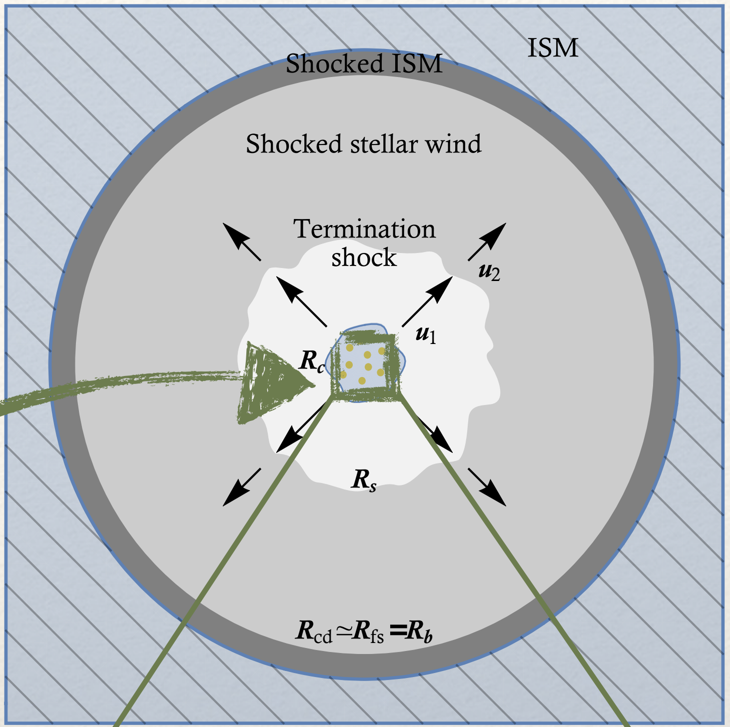
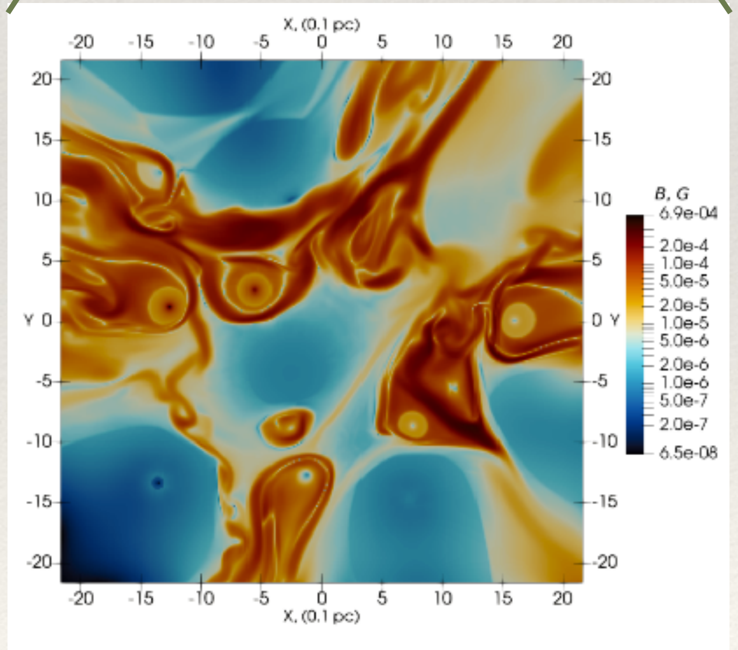
- Magnetic turbulence produced by MHD instabilities
  - ➡ Diffusion coefficient depends on the type of turbulence cascade: Kolmogorov, Kraichnan, Bohm



If we assume that a fraction η_B of kinetic energy is converted into magnetic field at the termination shock

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

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



Badmaev et al. (2022)

Particle acceleration at the wind TS

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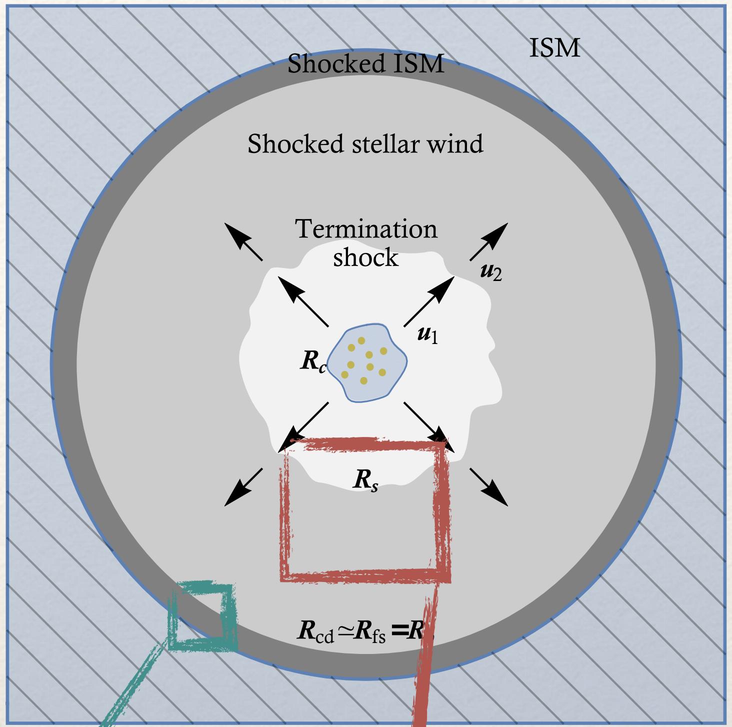

Acceleration at the collective wind termination shock

[GM et al. (2019)]

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  - ➡ 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 $p_{\rm cr} + p_{\rm gas} \to p + p + \pi^\pm + \pi^0$

$\pi^0 \to \gamma\,\gamma$

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

Badmaev et al. (2022)

Maximum energy: a more detailed analysis

GM, Blasi, Peretti & Cristofari (2019)

Solution of diffusive shock acceleration in spherical geometry

Standard power-law for plane shocks

$$s = \frac{3u_1}{u_1 - u_2}$$

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

Maximum energy

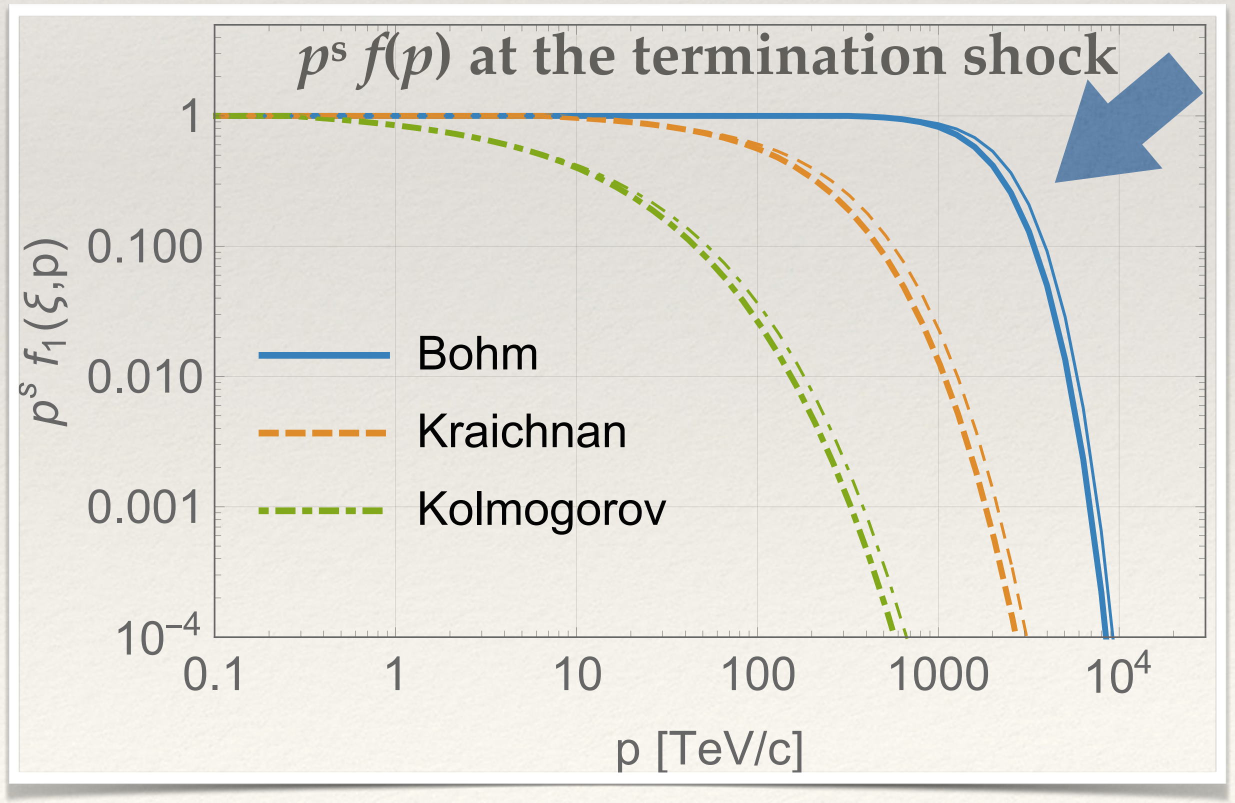
Due to:

- Size of TS
- Size of the bubble

The diffusion coefficient has a strong impact on the cutoff shape and effective maximum energy

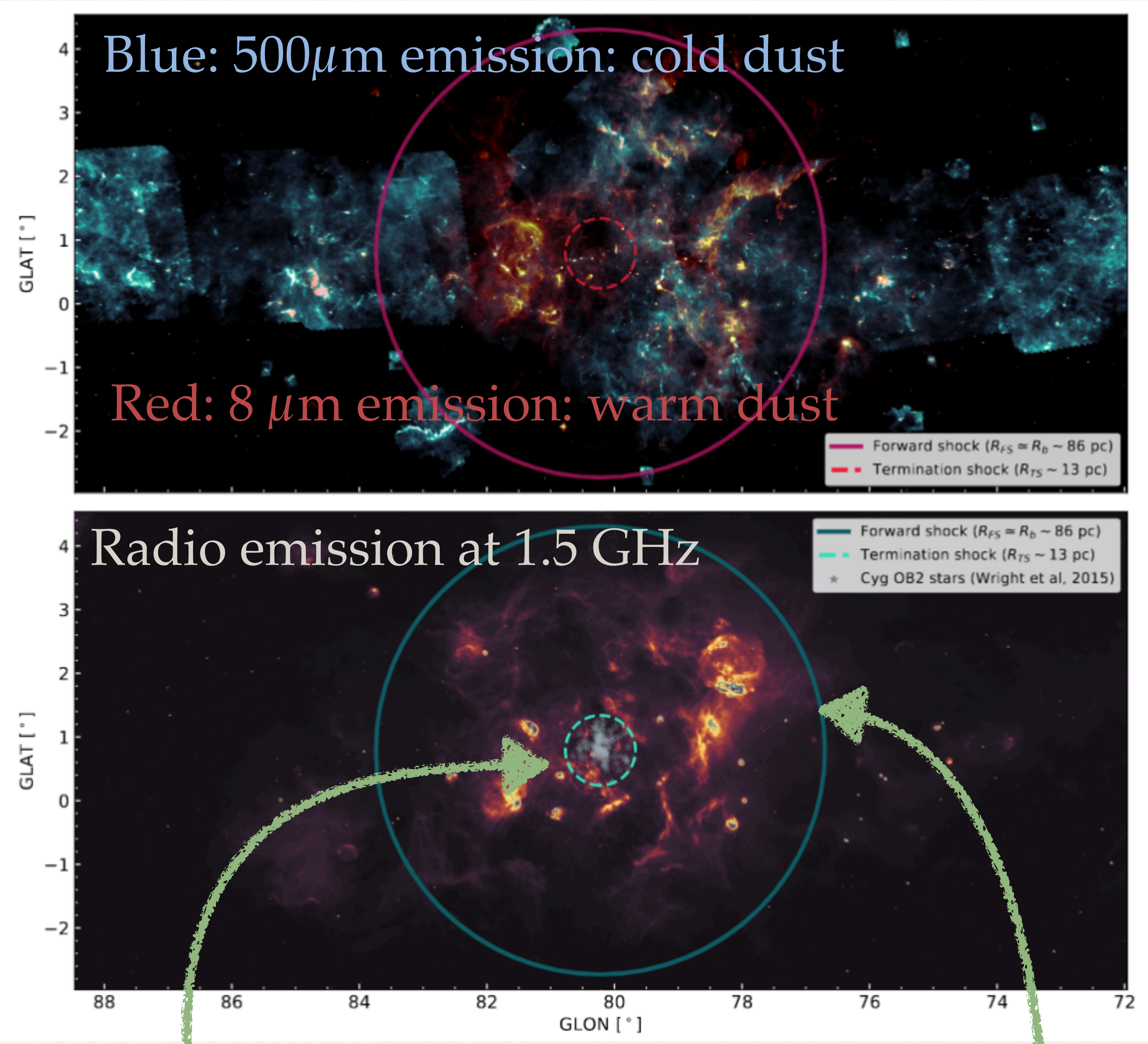
Typical values for massive stellar clusters

$$\begin{cases} \dot{M} = 10^{-4}\, M_\odot\, {\rm yr}^{-1} \\ v_w = 3000\ {\rm km/s} \\ L_{\rm CR} = 0.1\, L_w \\ \eta_B = 0.01 \end{cases}$$



The case of Cygnus Cocoon

[S. Menchiari et al. in preparation]



Blue: 500μm emission: cold dust

Red: 8 μm emission: warm dust

Radio emission at 1.5 GHz

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

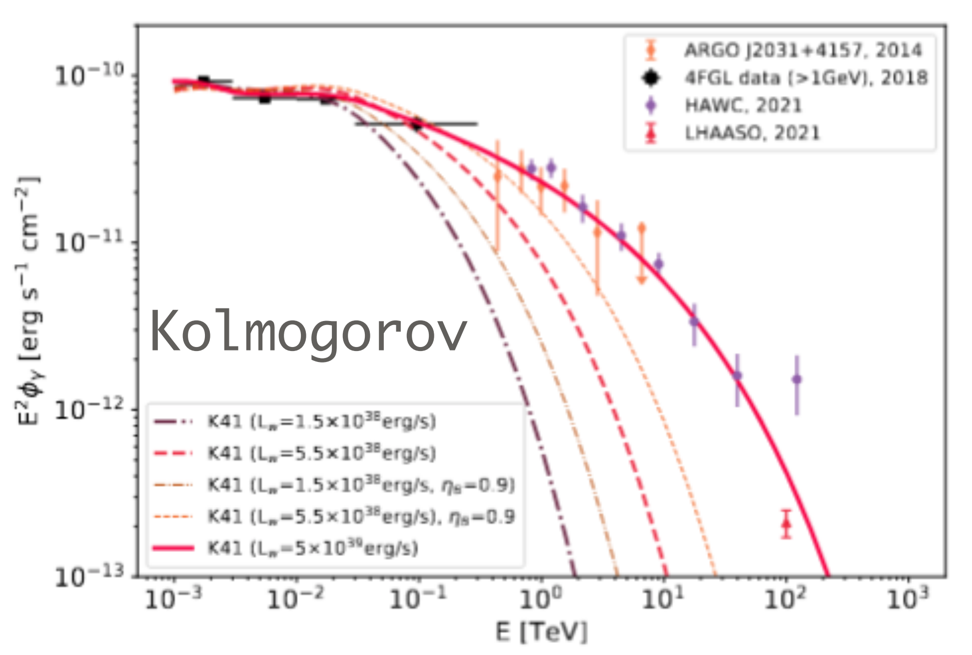
The case of Cygnus Cocoon

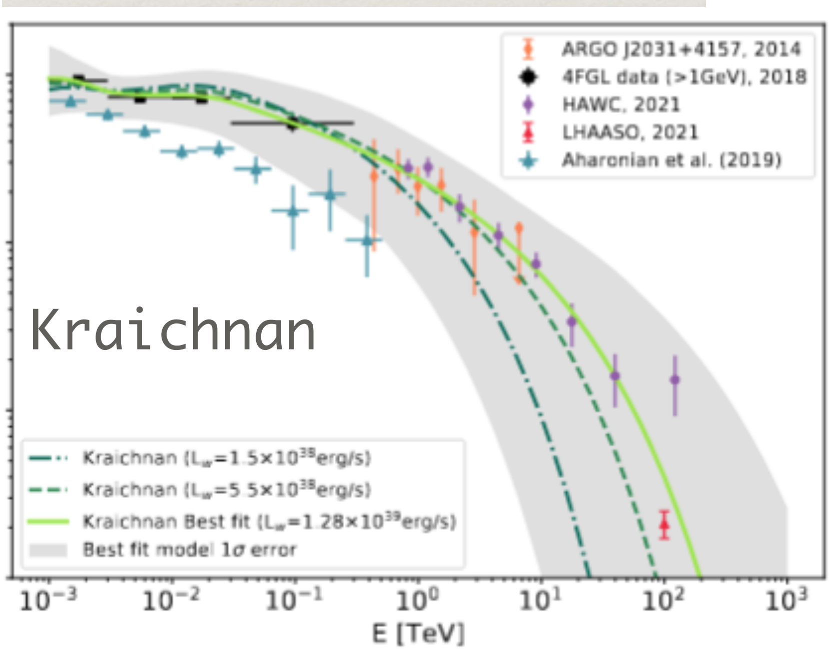
[S. Menchiari et al. in preparation]

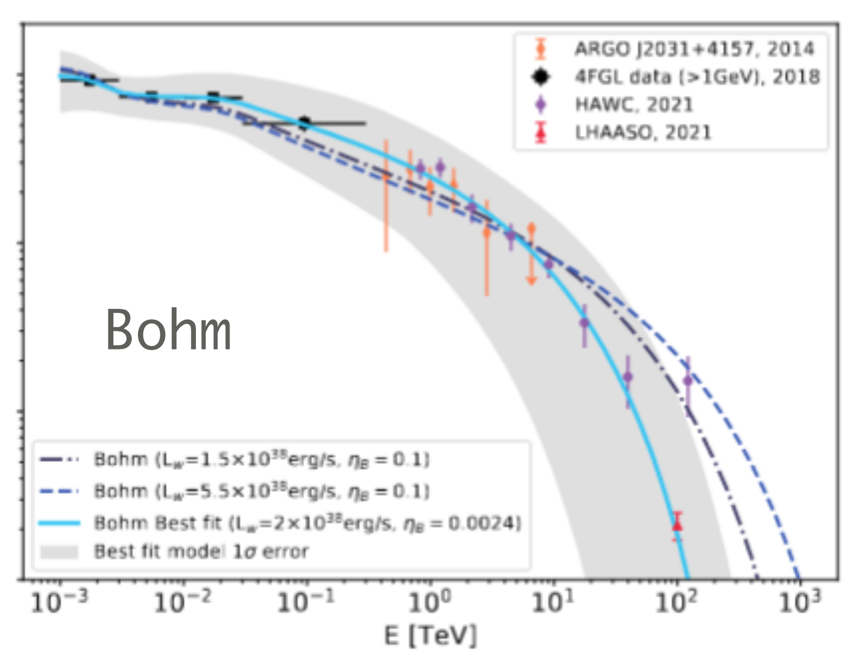
Model	Kolmogorov	Kraichnan	Bohm
Wind luminosity	5x10^{39} erg s^{-1}	1.3x10^{39} erg s^{-1}	2x10^{37} erg s^{-1}
Magnetic field	35 μG	20 μG	5 μG
Acc. efficiency	0.4%	0.7%	13%
Slope	4.17	4.23	4.27
E_{max}	23 PeV	4 PeV	0.5 PeV

Unrealistically high

The most realistic scenario is something in between Bohm and Kraichnan







Evaluating γ-ray emission from all SCs

The questions we want to answer:

- How many CRs are produced by SCs in the entire Galaxy?
- Mow many SCs emit significant flux of γ-rays?

Two possible strategies:

Study detected clusters

Pros:

- Physical quantities are measured
- Position is known

Cons:

- Distribution known only locally
- Unclear if the sample is complete

Generating synthetic populations

Pros:

- Covers the entire Galaxy

Cons:

- Affected by uncertainties in the parameters that depend on the spatial position

See talk by S. Menchiari

Evaluating γ-ray emission from Gaia clusters (DR2)

[S. Celli, A. Specovious, A. Mitchel, S. Menchiari, GM (2023) submitted arXiv:2311.09089]

We selected young clusters from Cantat-Gaudin et al. (2020) with Age $<$ 30 Myr $\Rightarrow$ 390 clusters

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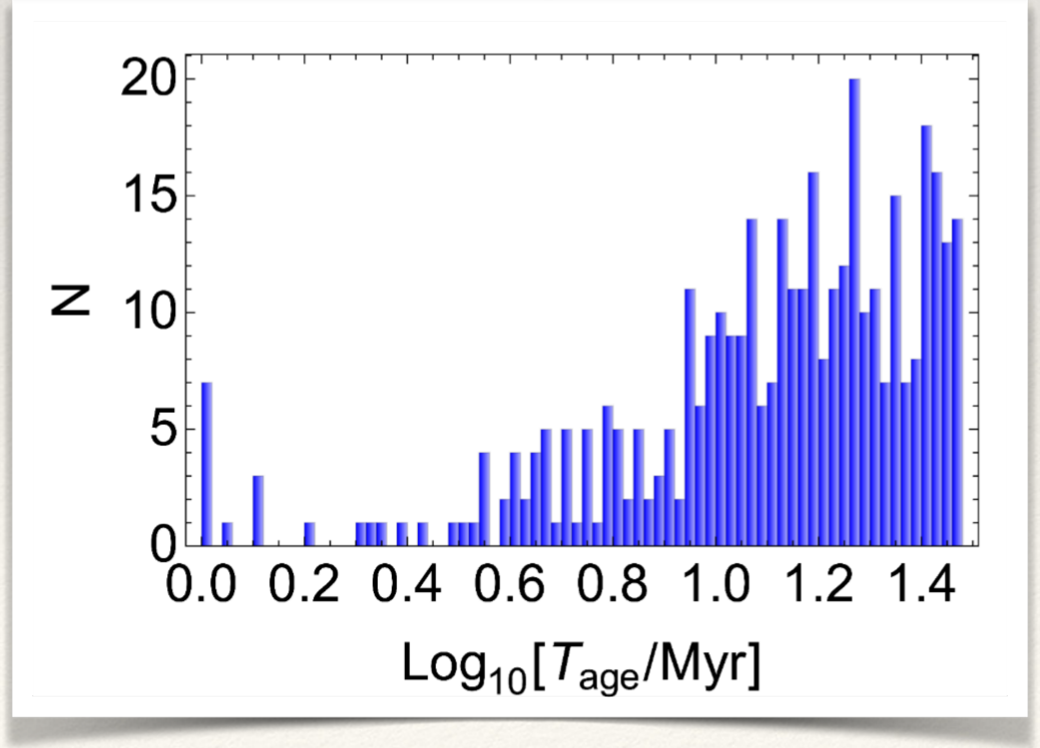
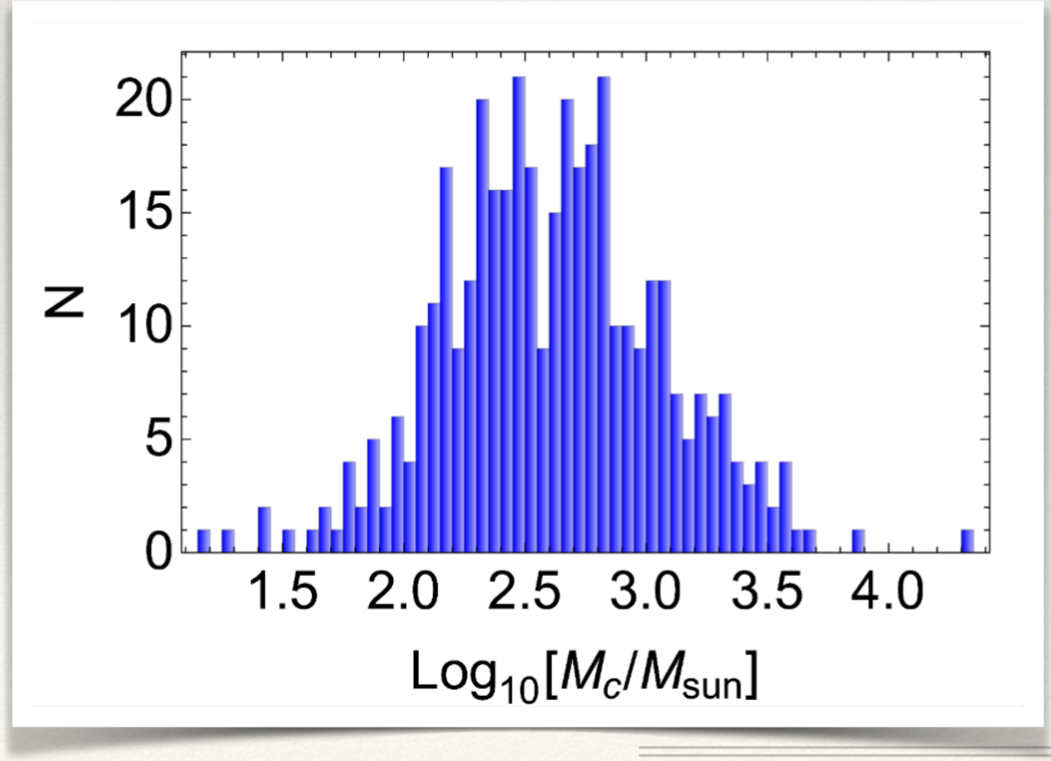
For each cluster:

- Extract the number of detected stars
- Estimate the number of actual stars assuming IMF from Weidner & Kroupa (2004)
    - Assuming maximum stellar mass depending of the SC mass [Weidner & Kroupa (2006)]


SC age distribution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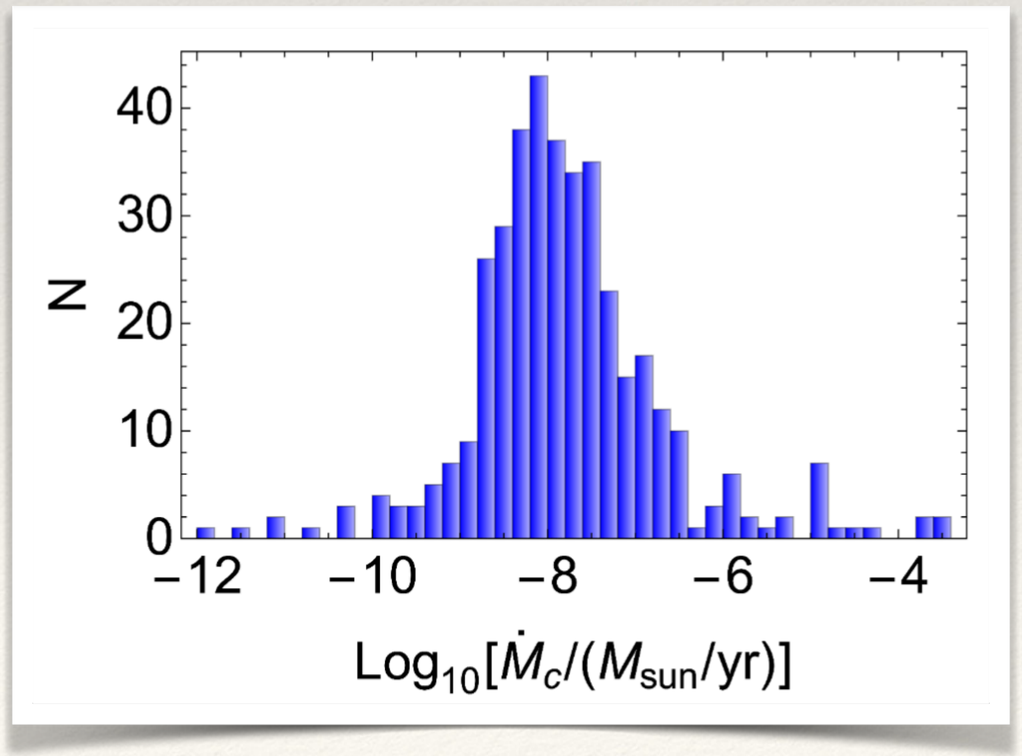
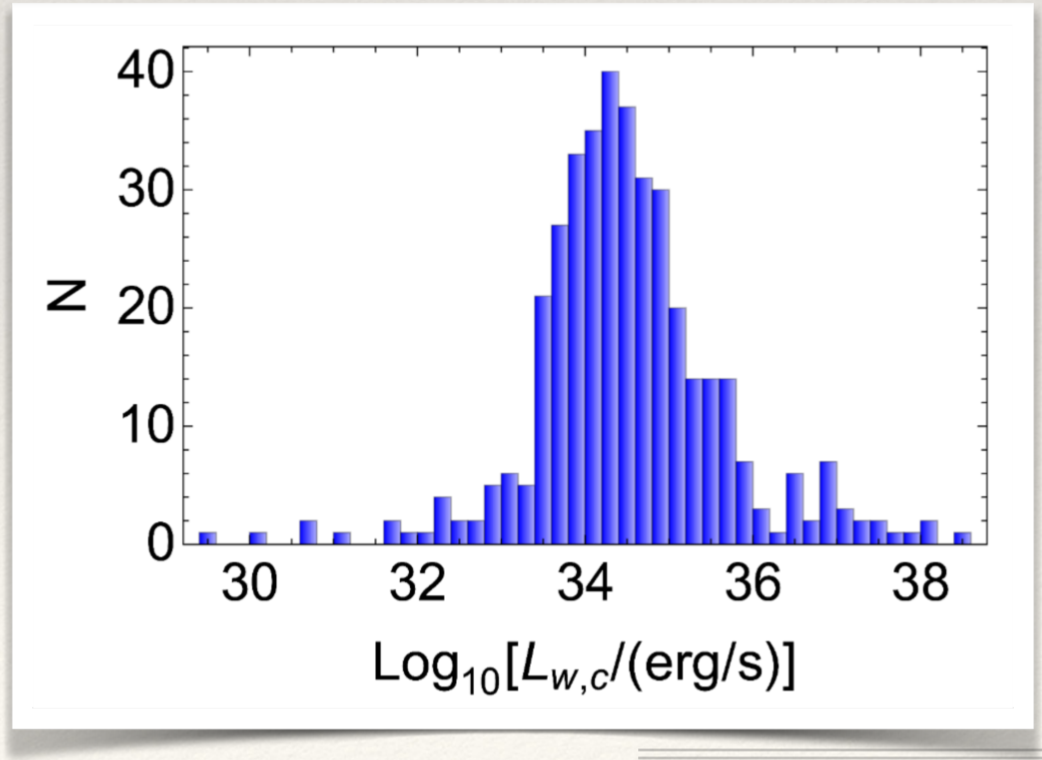
- Estimate $\dot{M}$ and v_w of stellar winds

See talk by S. Menchiari for details

Mass loss rate



Kinetic wind luminosity



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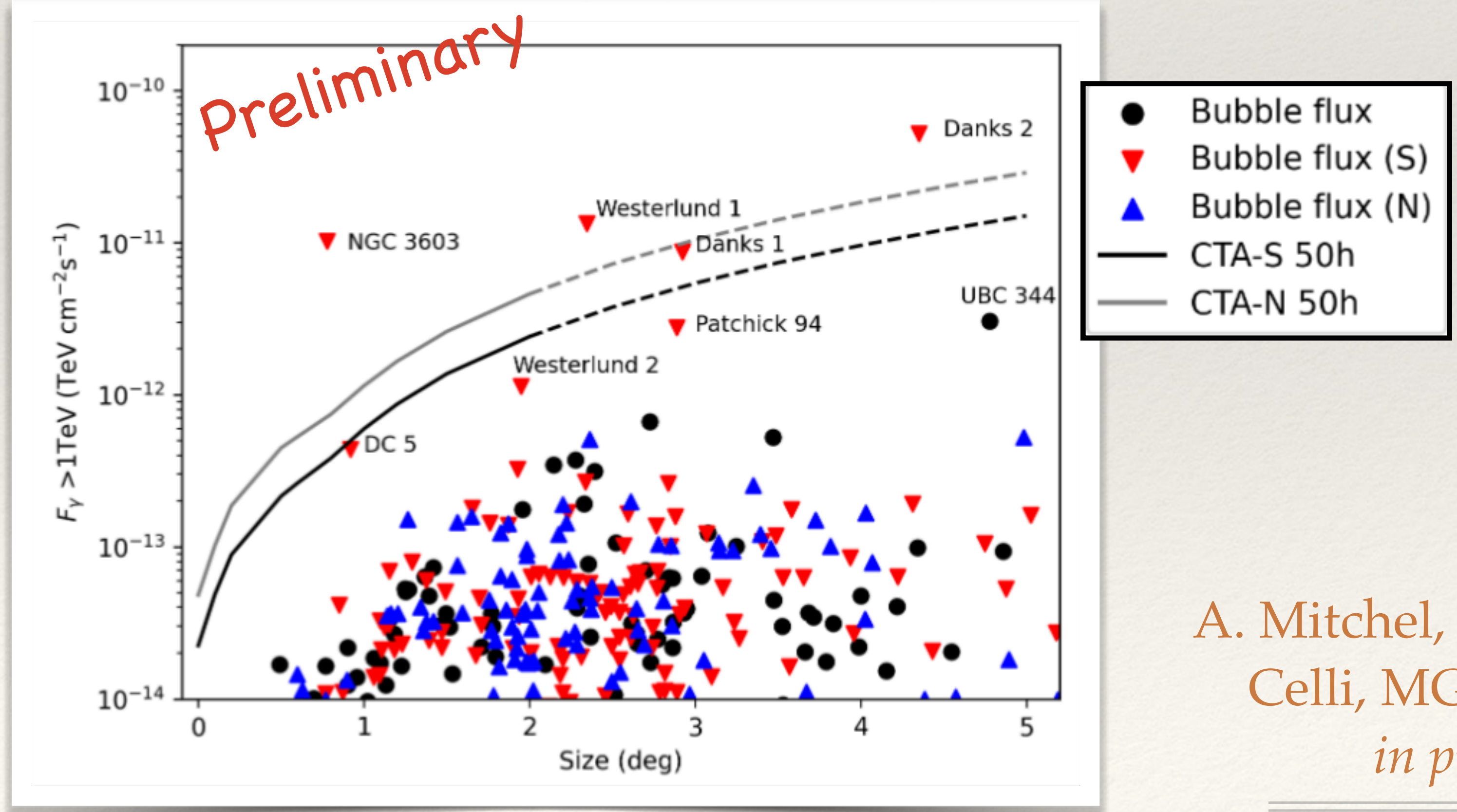
- Estimate $\dot{M}$ and v_w of stellar winds ➡ See talk by S. Menchiari for details
- **Apply the particle acceleration model to get the gamma-ray luminosity**

γ-ray luminosity above 1 TeV



A. Mitchel, A. Specovious, S. Celli, MG, S. Menchiari, *in preparation*

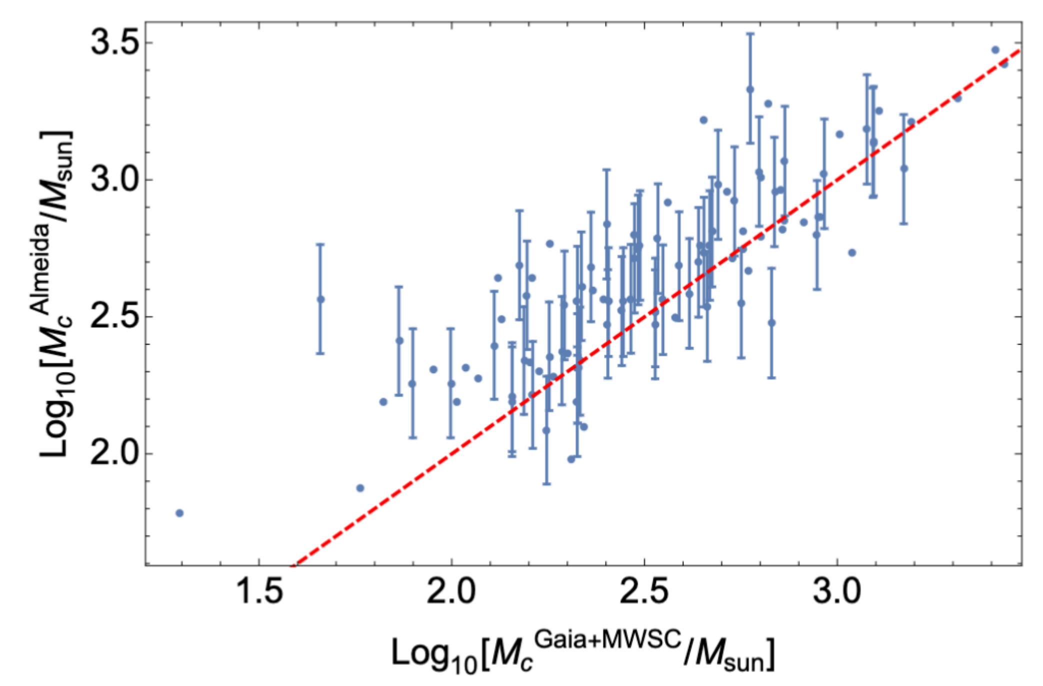
Uncertainty in the mass determination

[S. Celli, A. Specovious, A. Mitchel, S. Menchiari, GM (2023) submitted arXiv:2311.09089]

The mass estimate affect the predicted gamma-ray luminosity. Double check needed.

Mass comparison with Almeida et al. (2022)

- 149 SC in common with our sample
- Almeida et al. estimated masses are ~40% larger
- We do not account for binaries



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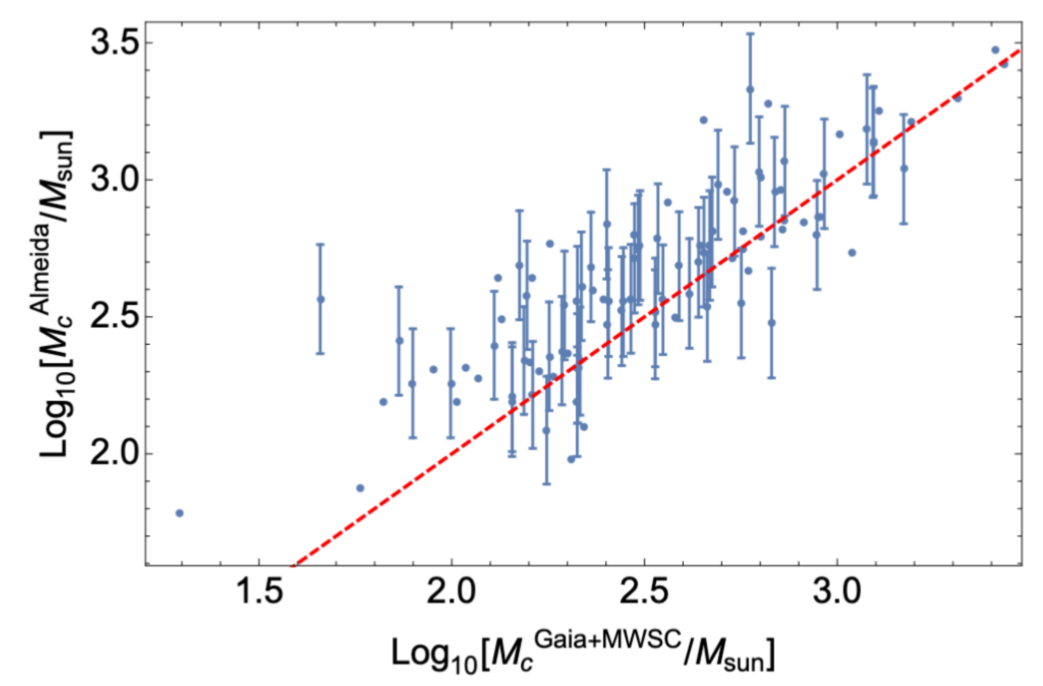
- Almeida et al. estimated masses are ~40% larger
- We do not account for binaries



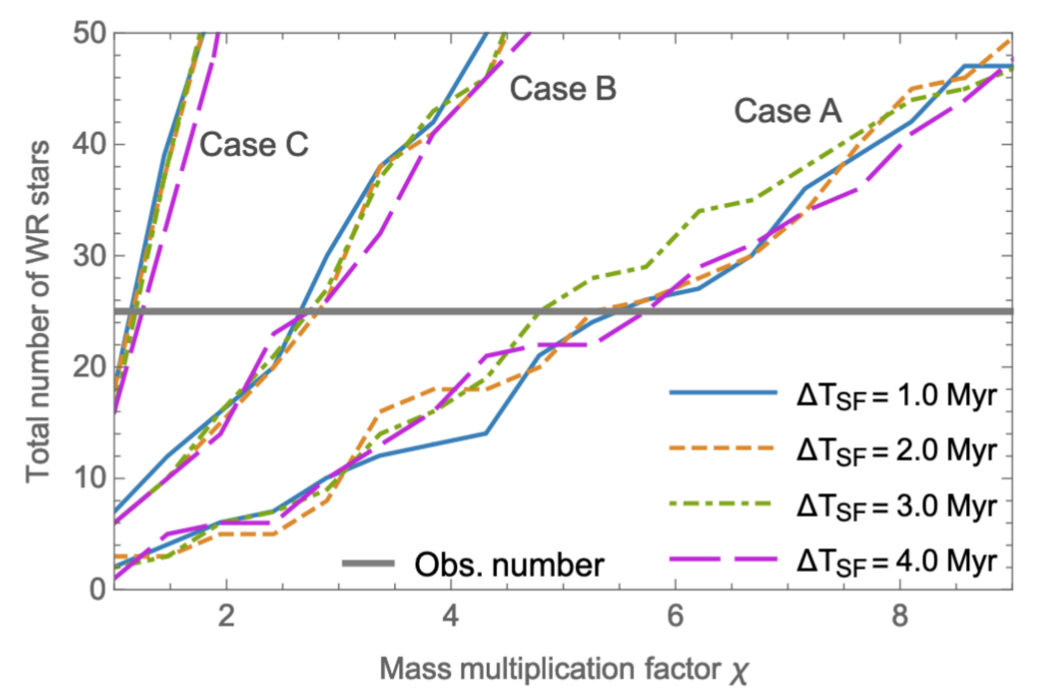
The Wolf-Rayet technique

Mass uncertainty derived comparing the observed number of WR stars with the predicted ones based on mass and age of SC from Cantat-Gaudin et al.(2020).

Assumed parameters for WR stars:

- $M_{\min,\mathrm{WR}} \in [20{,}25]\,\mathrm{M}_\odot$
- $\Delta t_{\mathrm{WR}} \in [0.25{,}0.40]\,\mathrm{Myr}$

➡ **Masses underestimated by at least a factor ~2**



Conclusions

- Young stellar clusters are promising CR factories
- Particle acceleration can be tested through gamma-rays
- Next generation of Atmospheric Cherenkov Telescope will probably detect many new stellar clusters in gamma-rays (but extended sources with low surface brightness)
- Correct predictions require a detailed description of the young SC population
  - Spatial distribution in the Galaxy
  - Stellar IMF (including maximum stellar masses)
  - Spatial distribution of stars (compactness)
  - Properties of stellar winds (including metallicity)
  - More? (Star formation history, cluster dynamics, etc…)

Backup slides

What power Stellar Clusters?

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

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

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)]

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

Uncertainty mainly due to wind mass loss rate

- Not accounting for WR stars

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

Maximum energy: first order estimate

Hillas criterium

$$E_{\rm max} \sim \left(\frac{q}{c}\right) B_{\rm sh} u_{\rm sh} R_{\rm sh}$$

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

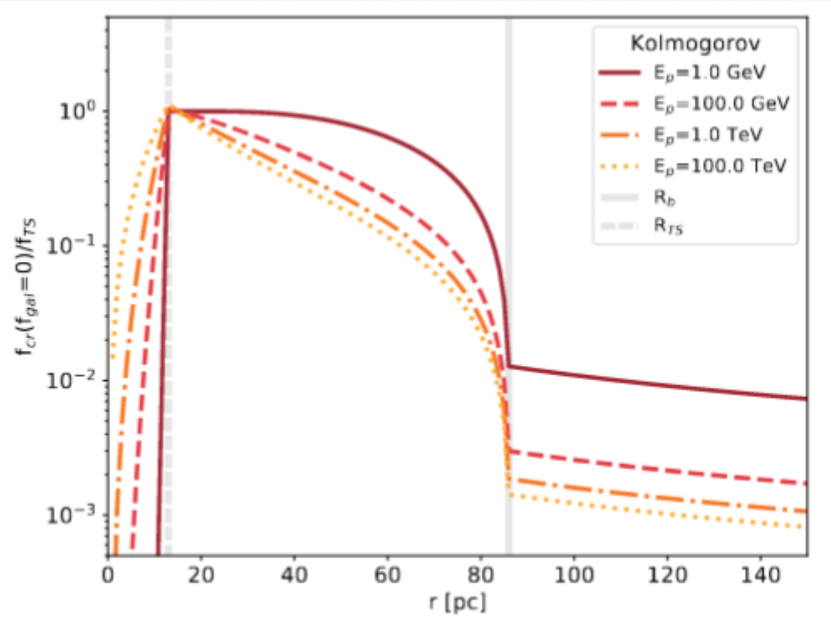
For massive star cluster ($\gtrsim 10^4\, M_\odot$) PeV energies can be reached

CR radial profile

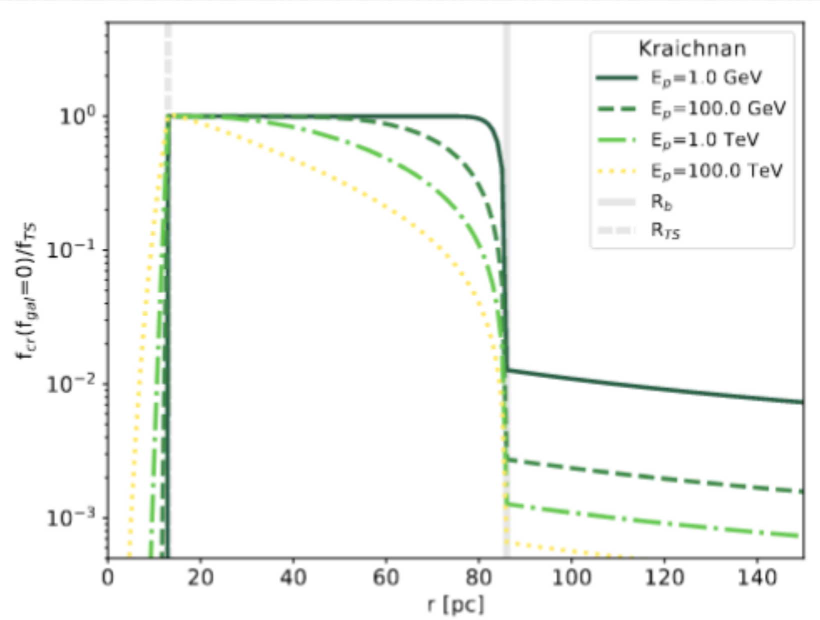
[S. Menchiari et al. in preparation]

The harder is the diffusion coefficient the flatter is the CR distribution

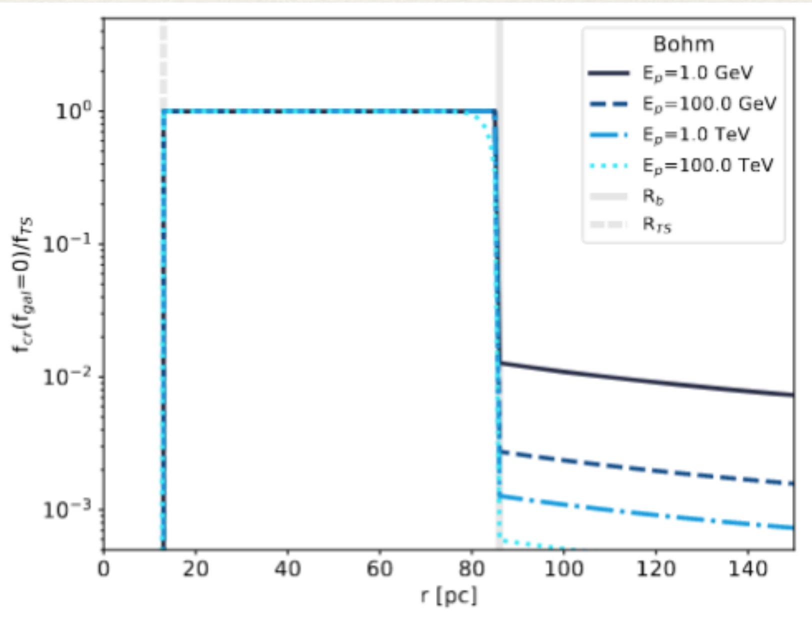
Kolmogorov



Kraichnan



Bohm

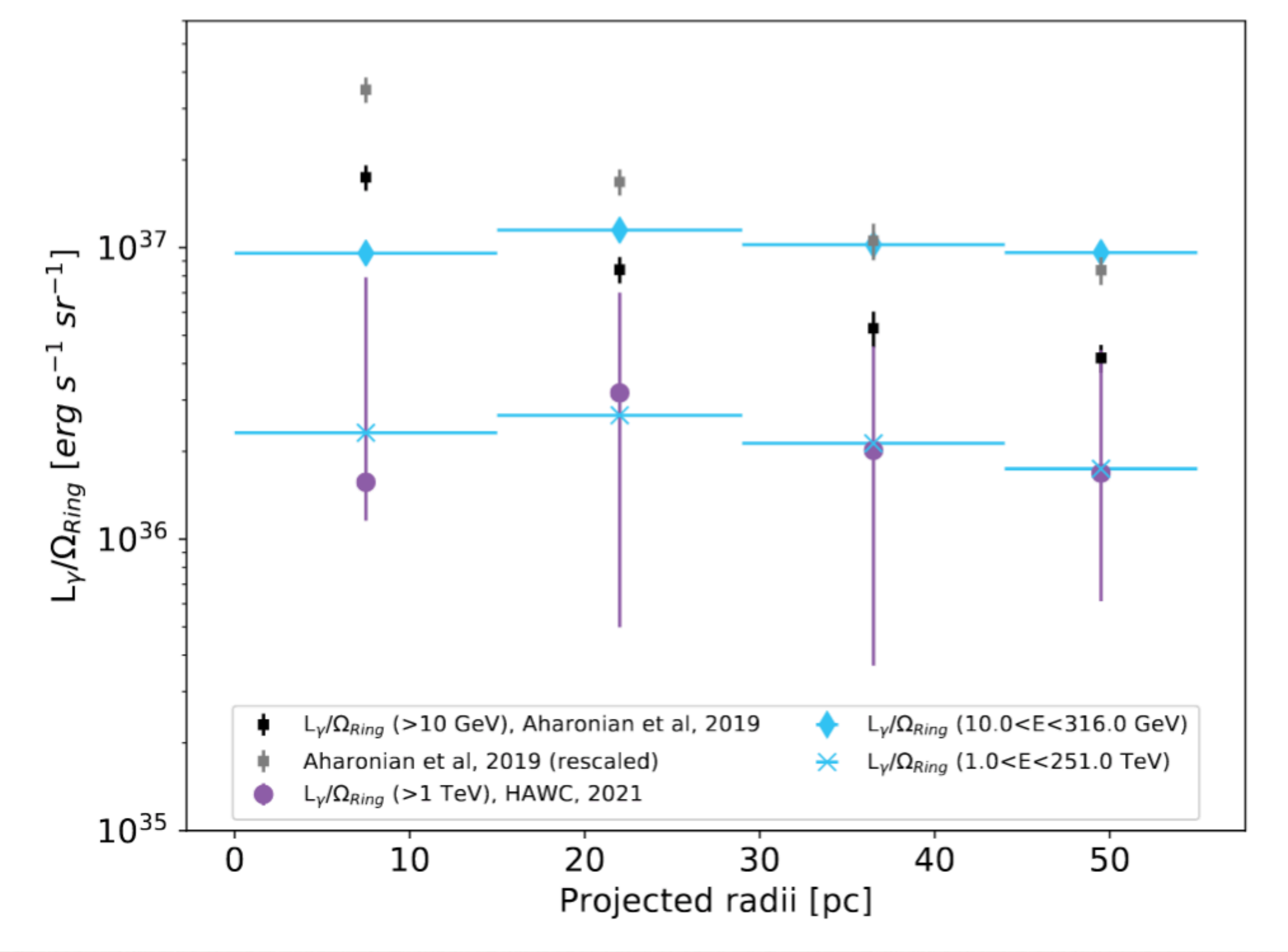


CR radial profile

[S. Menchiari et al. in preparation]

The line-of-sight integrated gamma-ray emission

Kraichnan
case



- ■ GeV (Fermi-LAT)
- ■ Fermi-LAT rescaled
- ● TeV (HAWC)

- Not compatible with $1/r^2$ inferred from FermiLAT data
- Compatible with HAWC data in TeV

Possible role of YSC in the Galactic Center

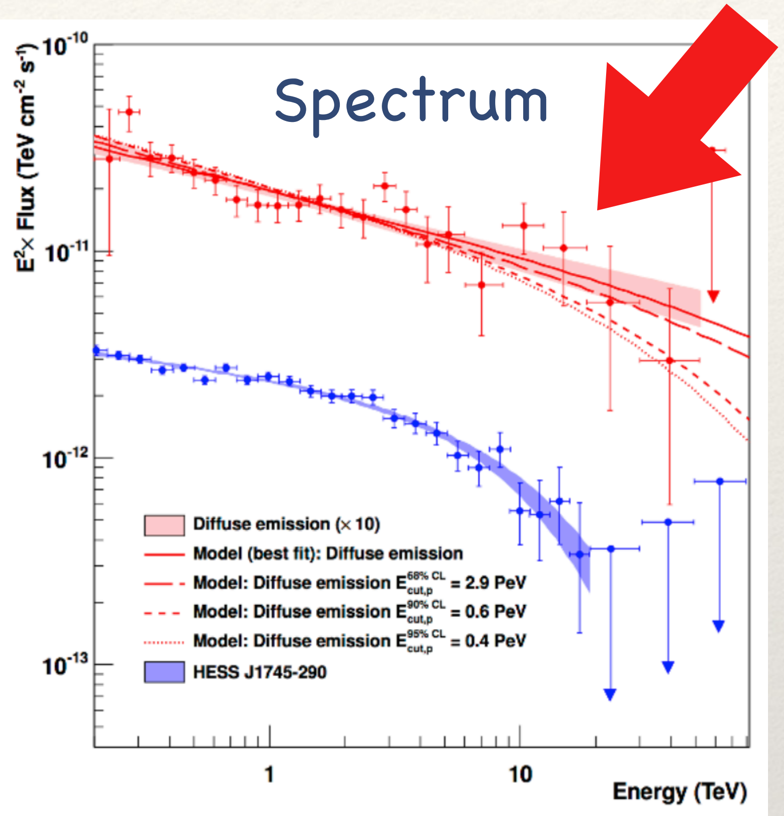
[H.E.S.S. coll., Abramowski et al. Nat. 531 (2016)]

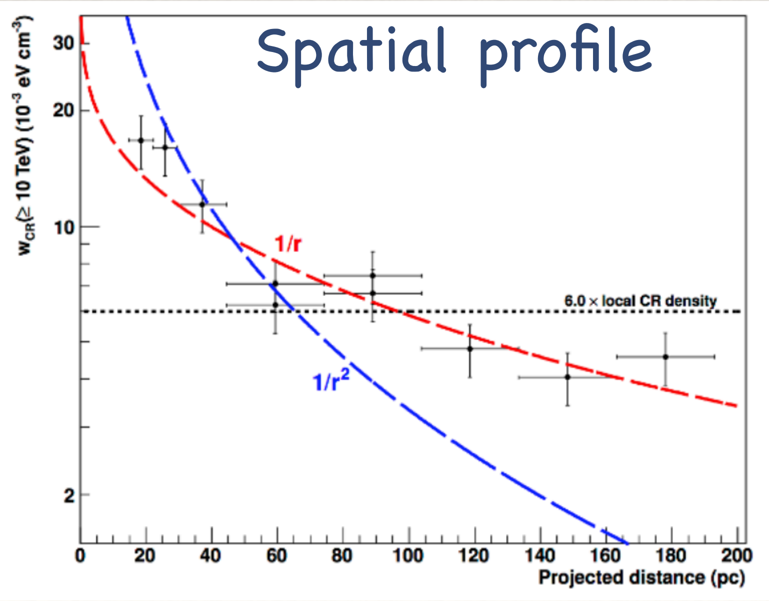
The Galactic Centre has been recognised as a PeVatron

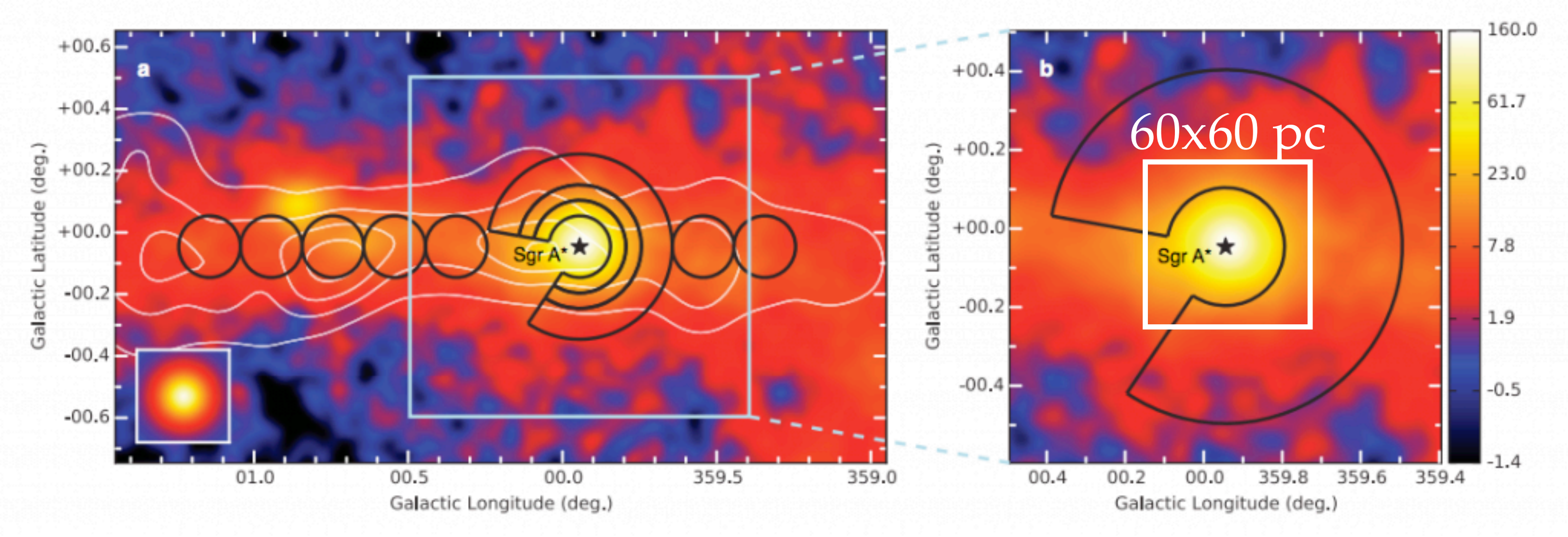
- Minimum proton energy > 0.4 PeV
- Spatial profile compatible with continuous emission

  ➡ SNR disfavoured

- CR luminosity: $L_{\mathrm{CR}}(>10\,\mathrm{TeV}) = 4\times10^{37}\left(\mathrm{D}/10^{30}\,\mathrm{cm^2s^{-1}}\right)\,\mathrm{erg/s}$
  (could be supplied by a powerful cluster wind if diffusion is suppressed)
- Stellar clusters in the GC region:
  - Arches (~30 pc from Sgr A*, Mass~$10^4 M_\odot$, age ~ 2.5 Myr)
  - Quintuplet (~30 pc from Sgr A*, Mass~$10^4 M_\odot$, age ~ 4 Myr)
  - Central cluster (~200 young stars at $r \lesssim 1$ pc from Sgr A* including ~30 WR stars) [e.g. von Fellenberg et al. (2022) and Poumard T. (2008)]







Gas and photons distribution

[S. Menchiari et al. in preparation]

Gas distribution from CO map

Photon background is dominated by IR radiation Star-light form Cyg. OB2 is negligible