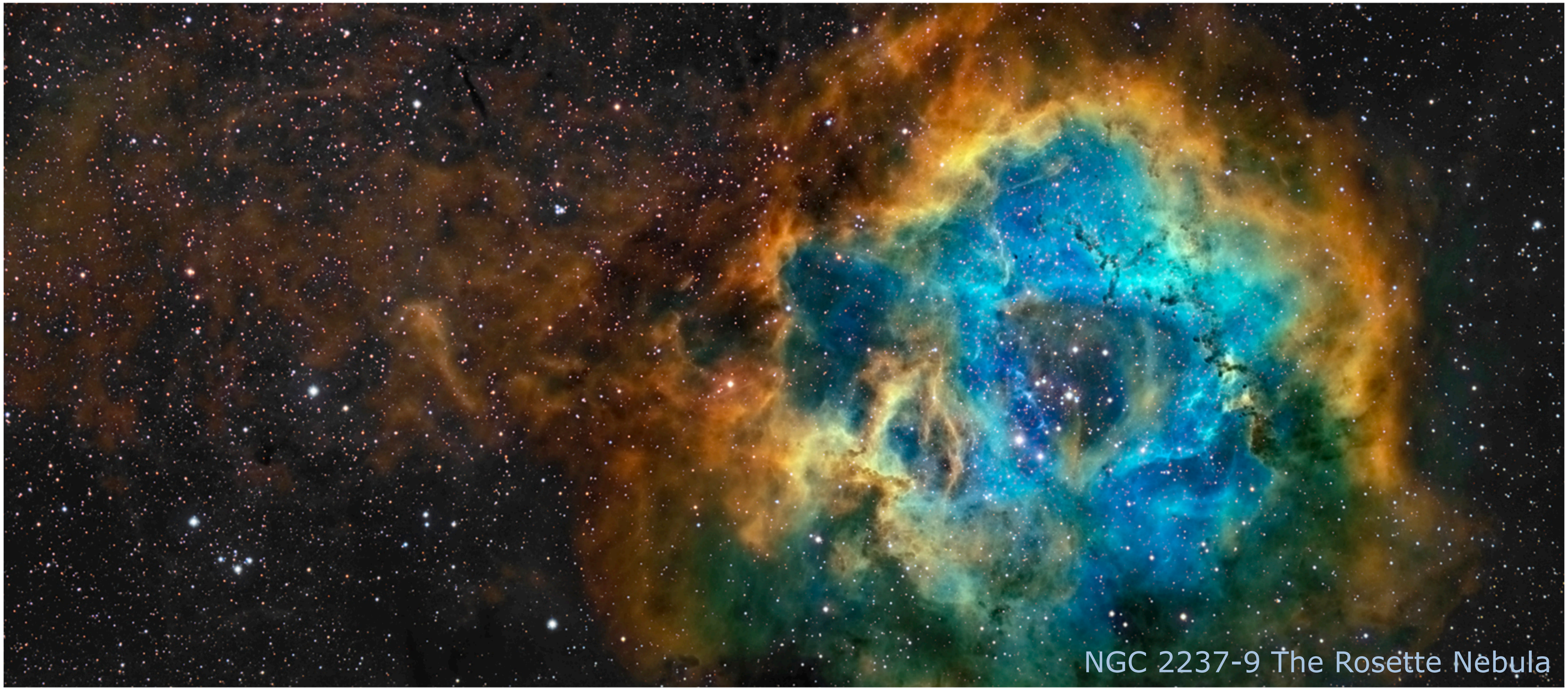

Rome International Conference on Astroparticle Physics — 8 Septembre, 2022 — Rome

Particle acceleration and high energy emission in stellar clusters

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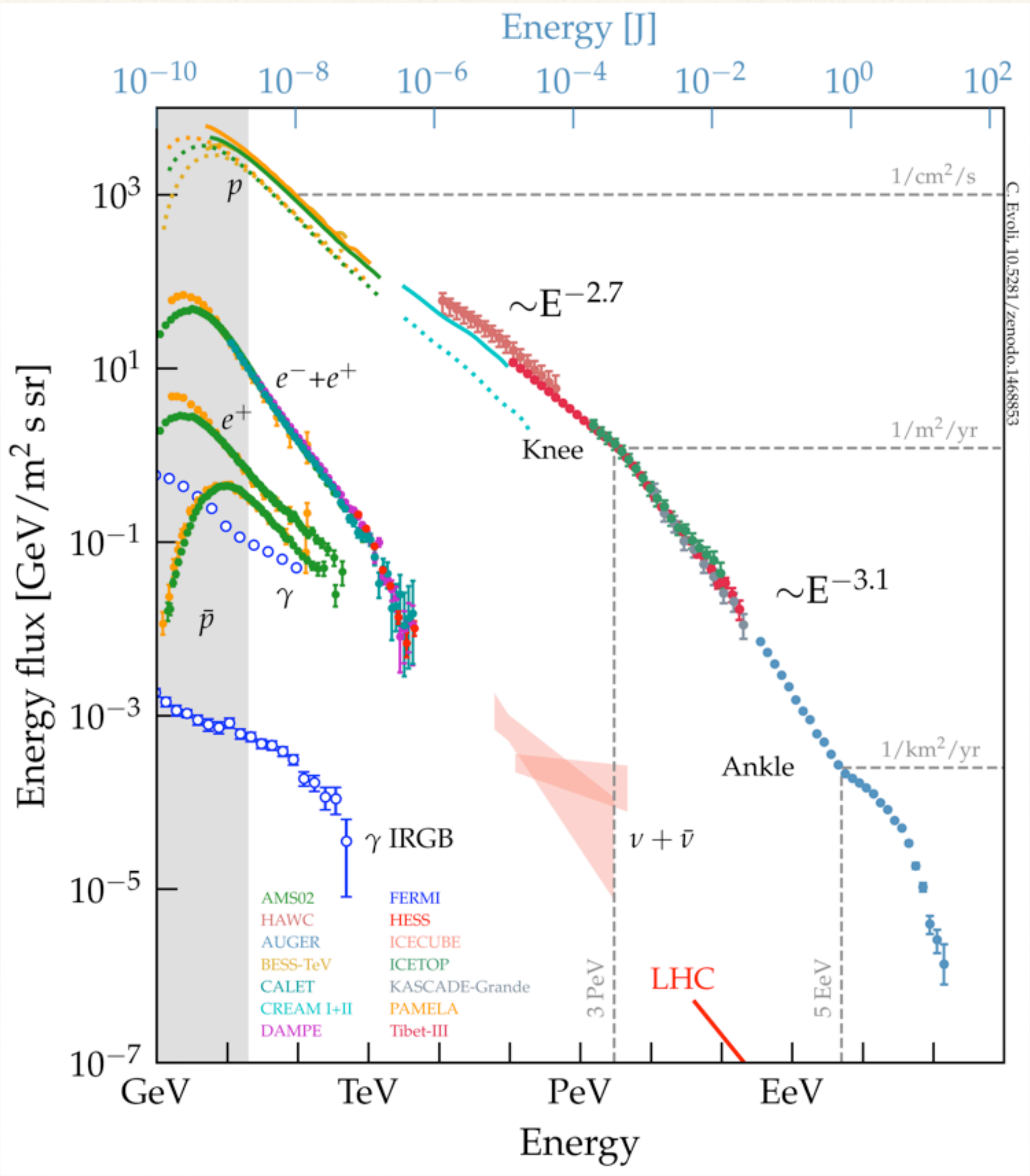
NATIONAL INSTITUTE FOR ASTROPHYSICS

How to explain the origin of Galactic CRs



Requirements for sources

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

The most popular scenario: DSA@SNR shocks

- **Why supernova remnant are so popular?**
  1. Enough power to sustain the CR flux:

$$P_{\rm CR} \sim \frac{U_{\rm CR} V_{\rm CR}}{\tau_{\rm esc}(1\,{\rm GeV})} \sim 10^{40}\,{\rm erg}$$

$$P_{\rm SN} \sim R_{\rm SN} E_{\rm SN} \sim 3 \times 10^{41} \frac{R_{\rm SN}}{(100\,{\rm yr})^{-1}} \frac{E_{SN}}{10^{51}{\rm erg}}\ {\rm erg/s}$$

→ $P_{\rm CR} \simeq 1 - 10\,\%\, P_{\rm SN}$

  2. Enough sources to explain anisotropy:

$$N(<d, E) \sim {\rm R_{SN}}\, (d/R_d)^2\, \tau_{\rm esc}(E) = \frac{1}{100yr} \left(\frac{5{\rm kpc}}{15{\rm kpc}}\right)^2 2\,{\rm Myr} \simeq 7000$$

  4. A well developed theory for particle acceleration: DSA
  5. Observations show the presence of non thermal particles

- **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…

See talk by S. Gabici

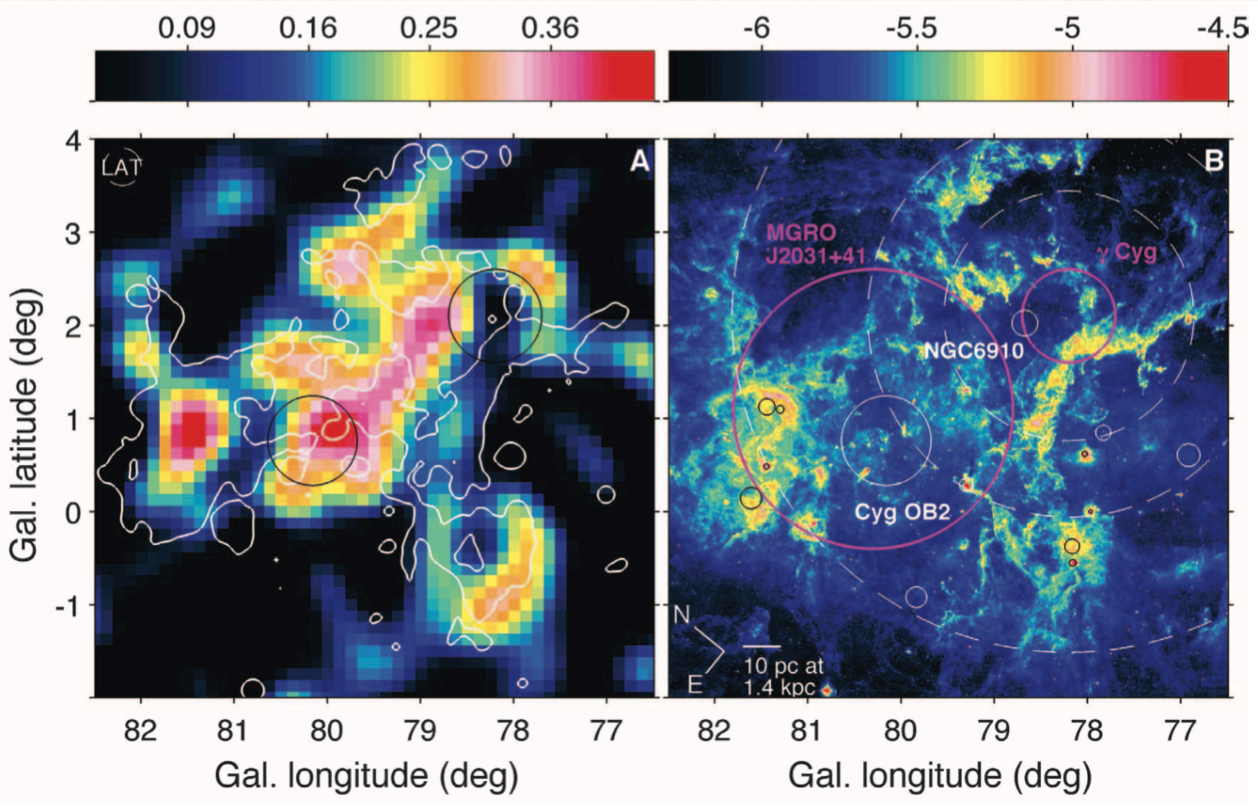
YSCs detected in gamma-rays

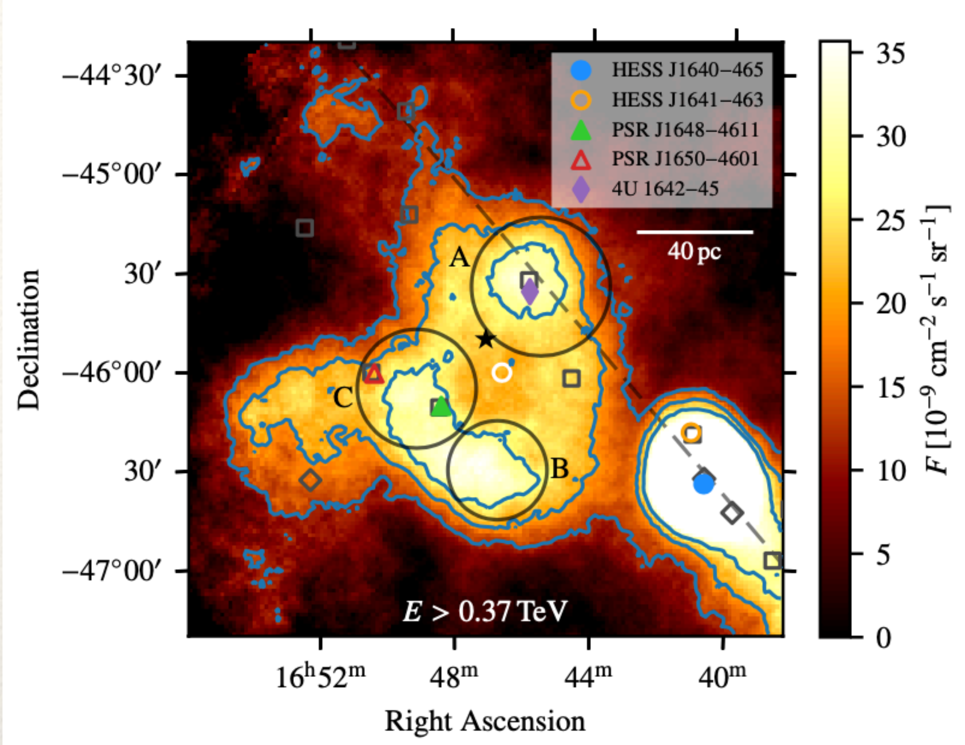
Recently several massive star clusters have been associated with gamma-ray sources

Name	log M/M_{sun}	r_c/pc	D/kpc	age/Myr	L_w/ 10^{38} erg s^{-1}	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,
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, arXiv:2012.15275
W40	2.5	0.44	0.44	1.5	?	Sun, X.-N. et al. 2020, A&A 639
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. 2021, A&A 659
NGC 6618		3.3	~2	< 3	?	Liu et al. 2022, MNRAS 513
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 et al., 2015, Science, 347, 406

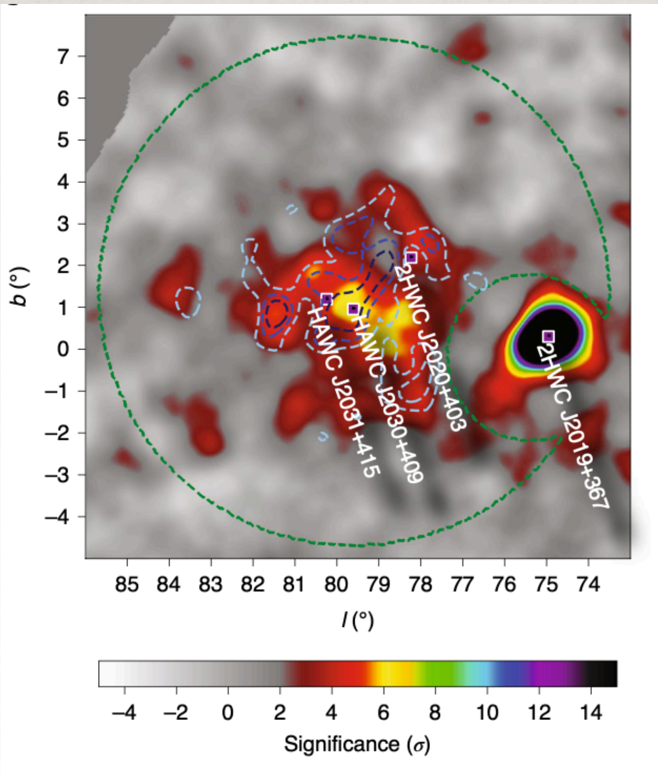
YSCs detected in gamma-rays

Cygnus Cocoon FermiLAT - Ackermann et al. (2011)



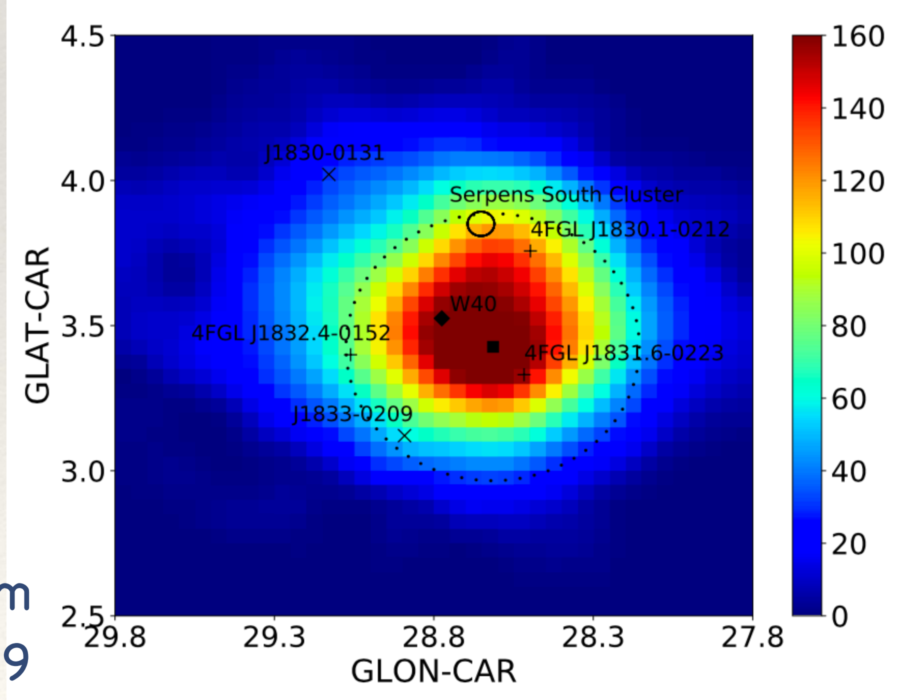


Westerlund 1
HESS coll. A&A (2022)



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

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

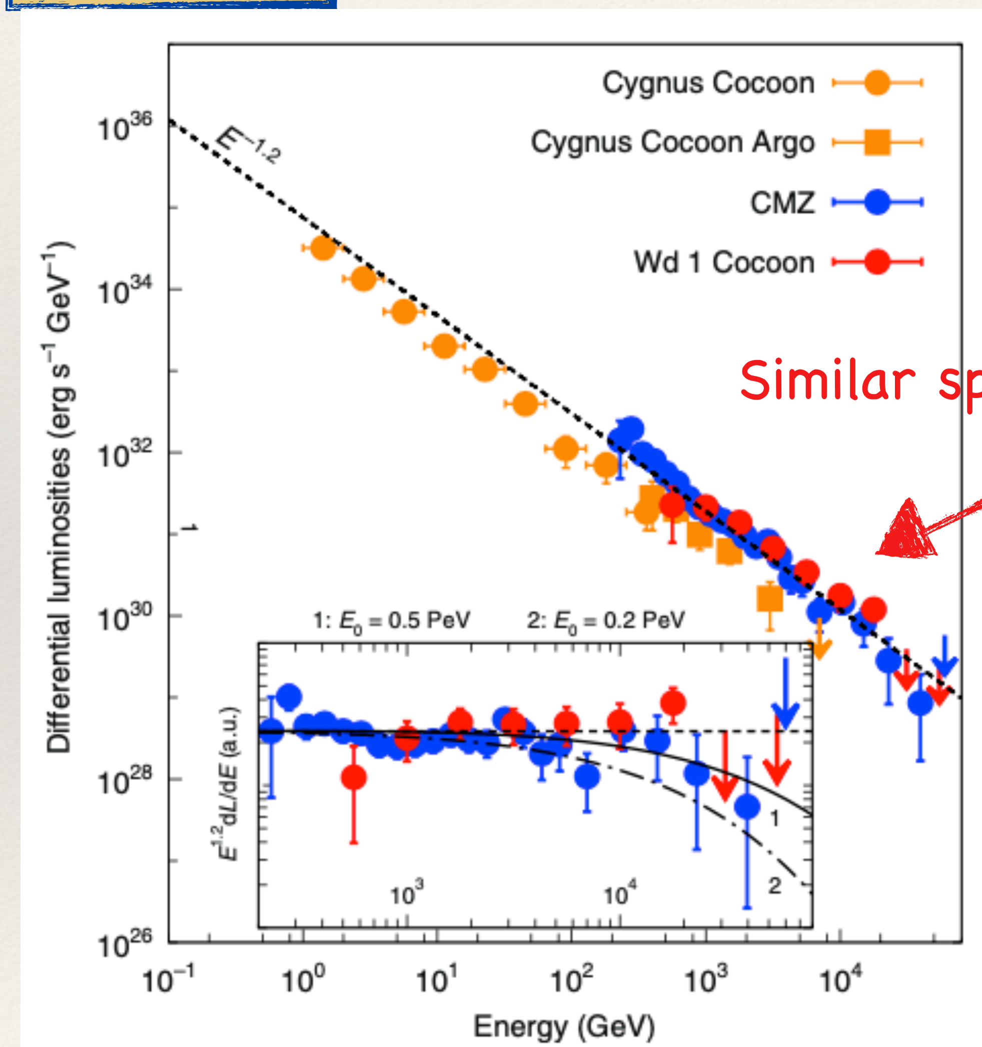


YSCs detected in gamma-rays

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

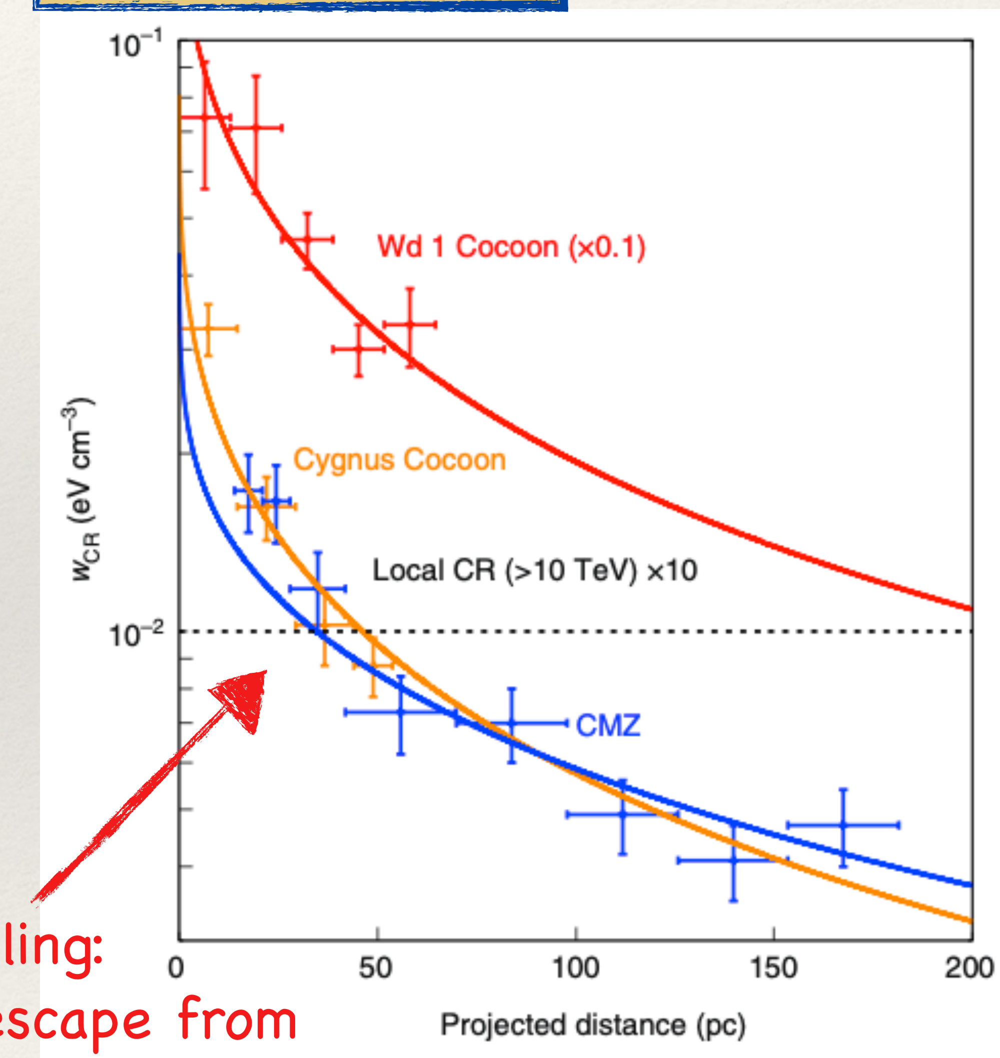
Some clusters show similar spectra and radial profile

Spectrum



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

Radial CR profile



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

See talk by F. Aharonian

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

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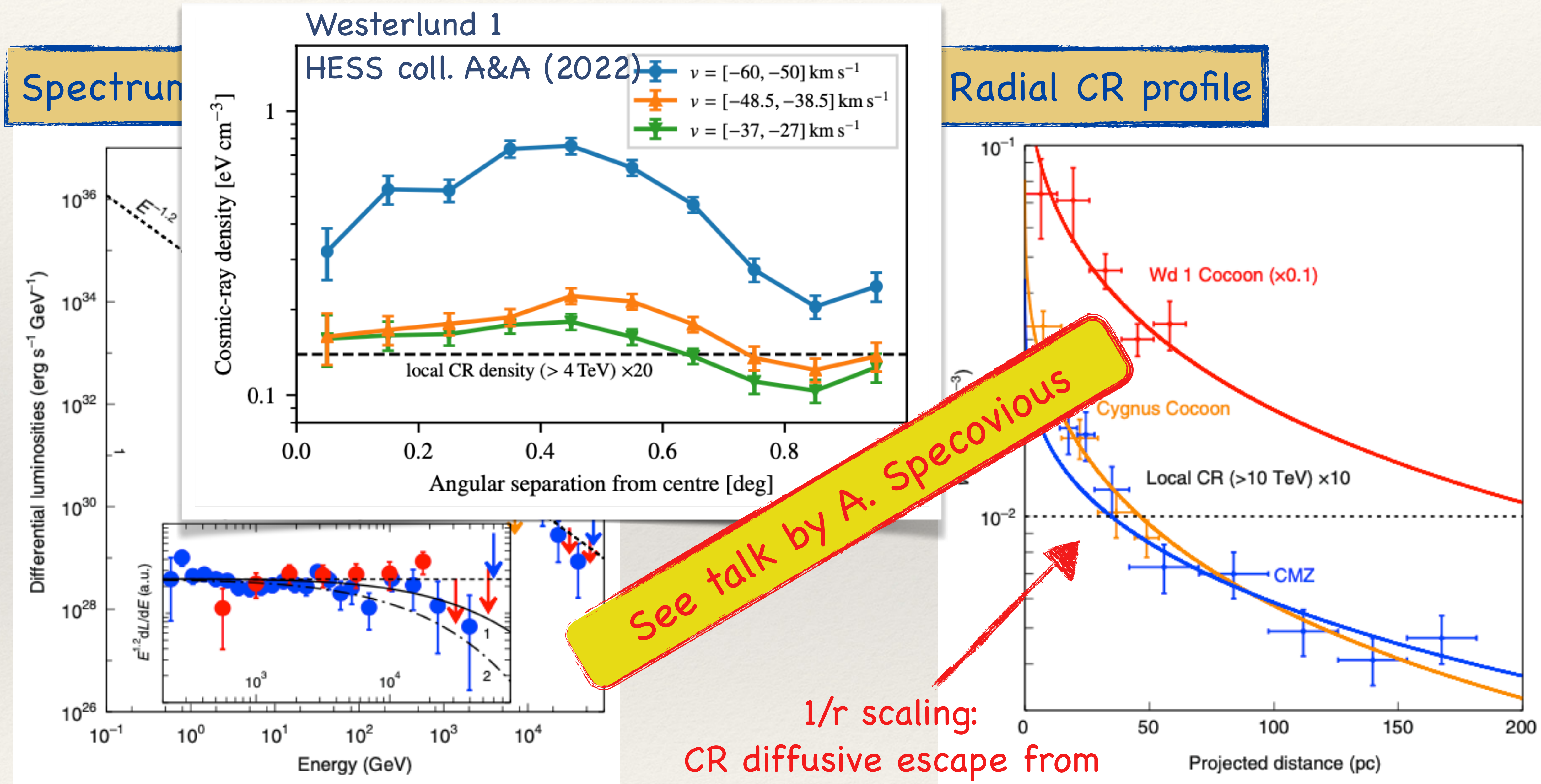


1/r scaling:
CR diffusive escape from
continuous point source?

See talk by F. Aharonian

Energetics: stellar winds vs. SNe

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

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

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

$v_w = 2.5\sqrt{2G_N M/R}$ for line-driven winds;

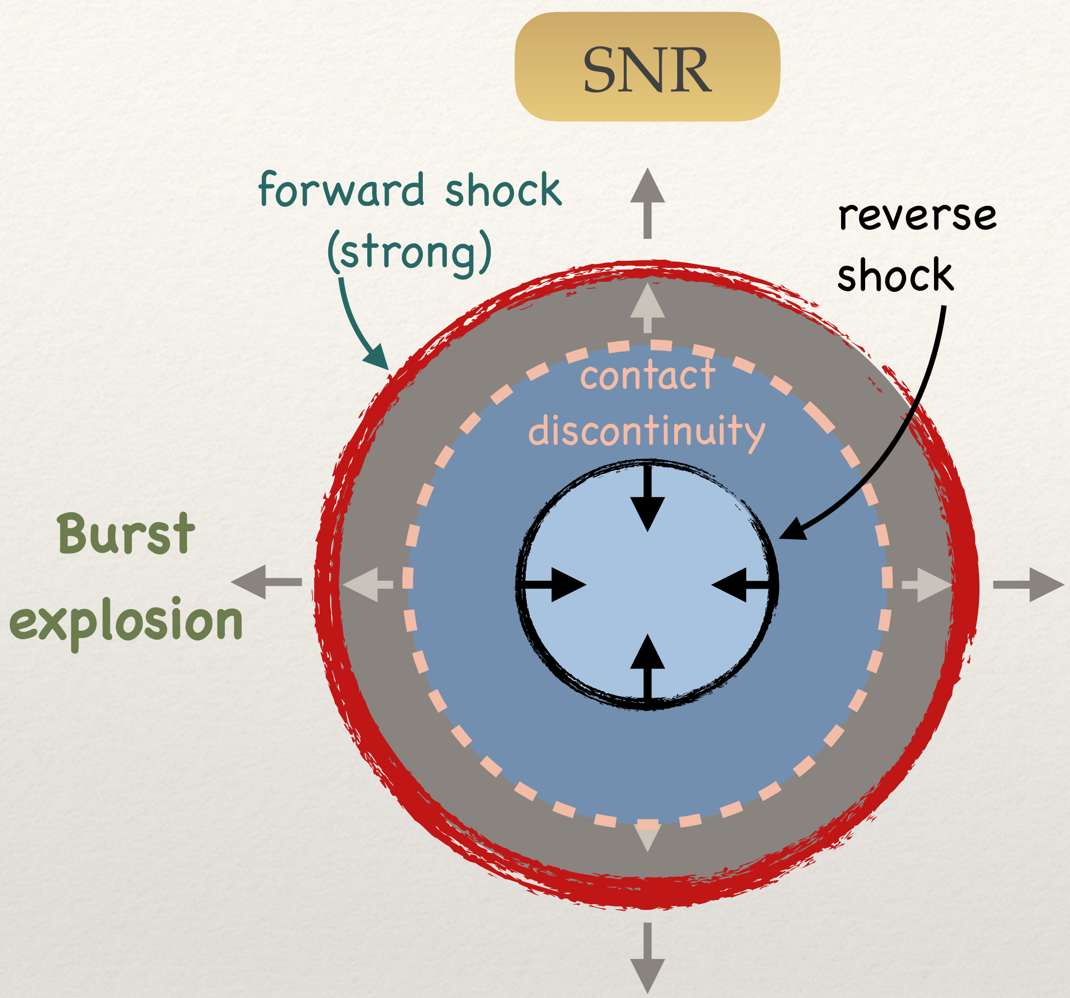
$\dot{M}$ from analytical (approximated) models [Nieuwenhuijzen & de Jager(1990)]

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

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

Stellar winds vs. SNRs

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



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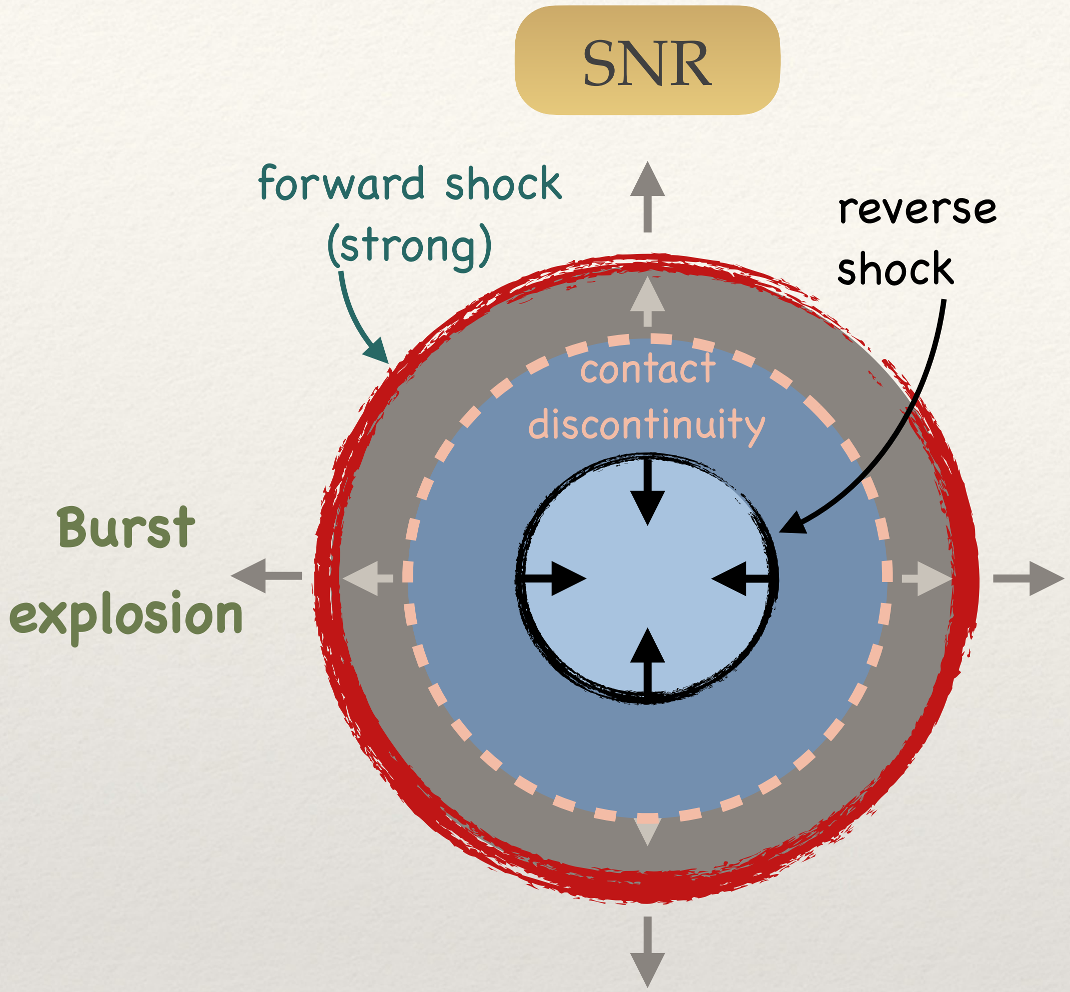

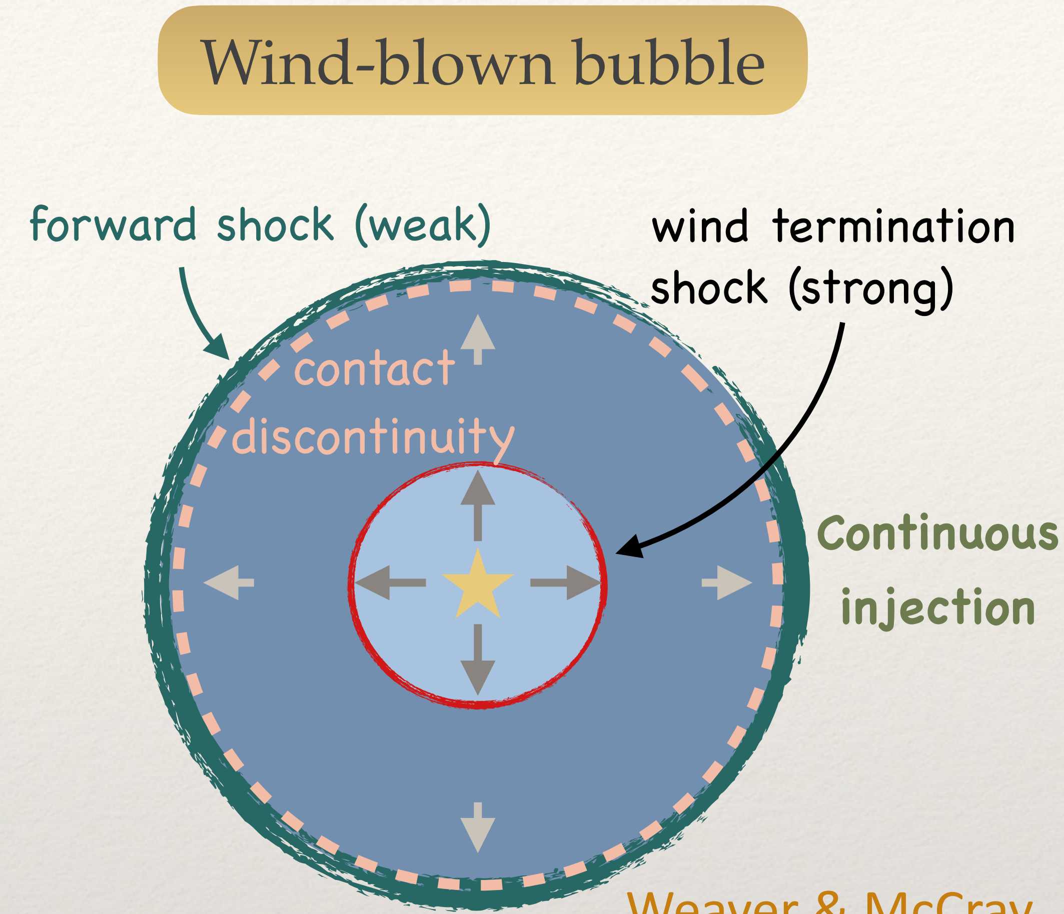

Weaver & McCray, ApJ 218 (1977)

Stellar winds vs. SNRs

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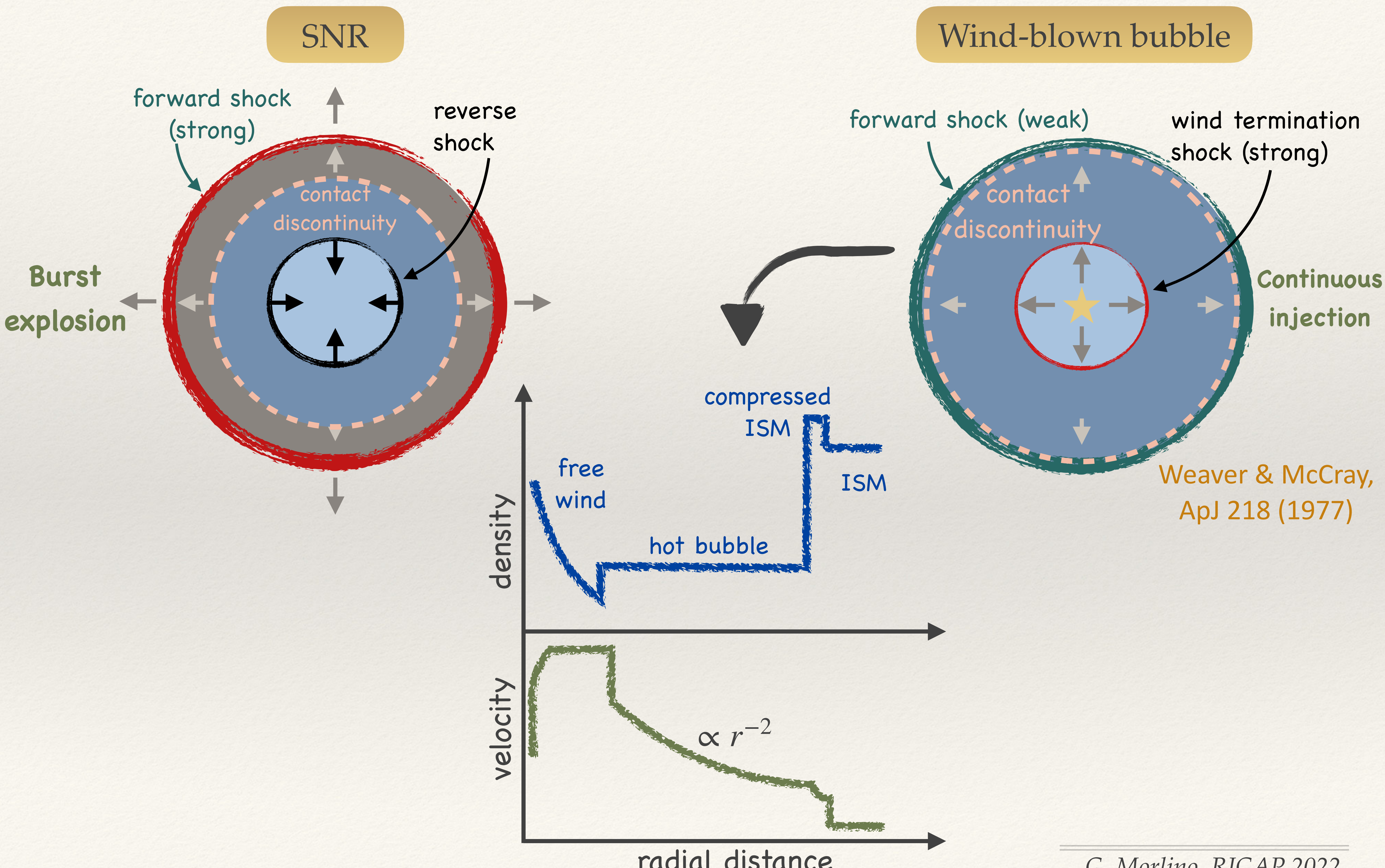

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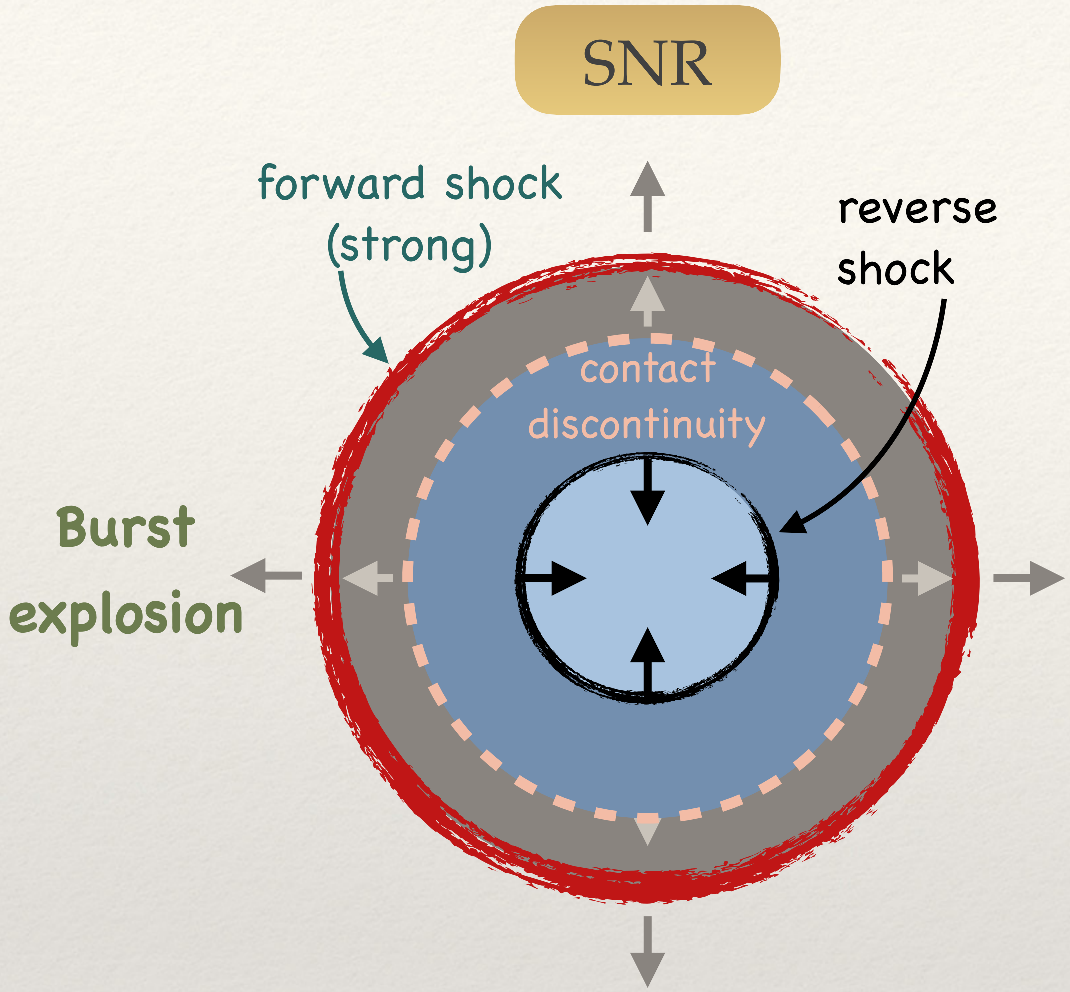

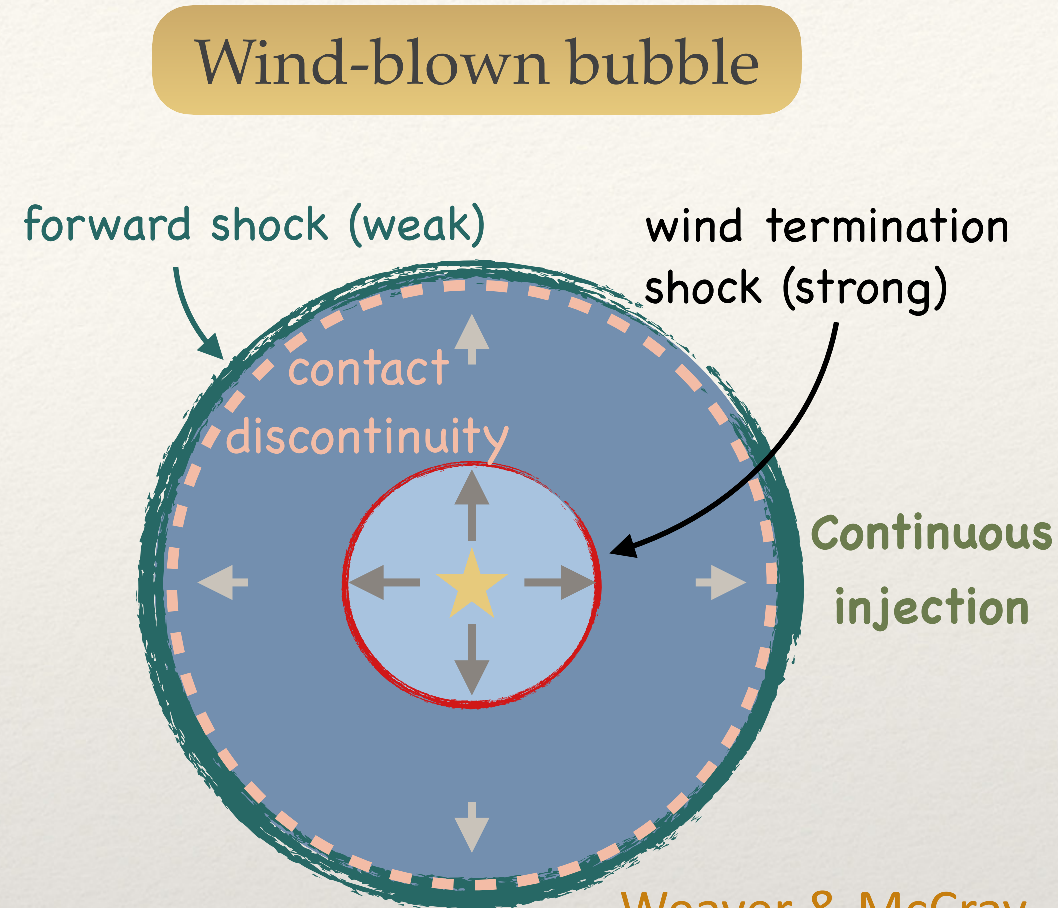

Weaver & McCray, ApJ 218 (1977)

		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

Stellar winds vs. SNRs

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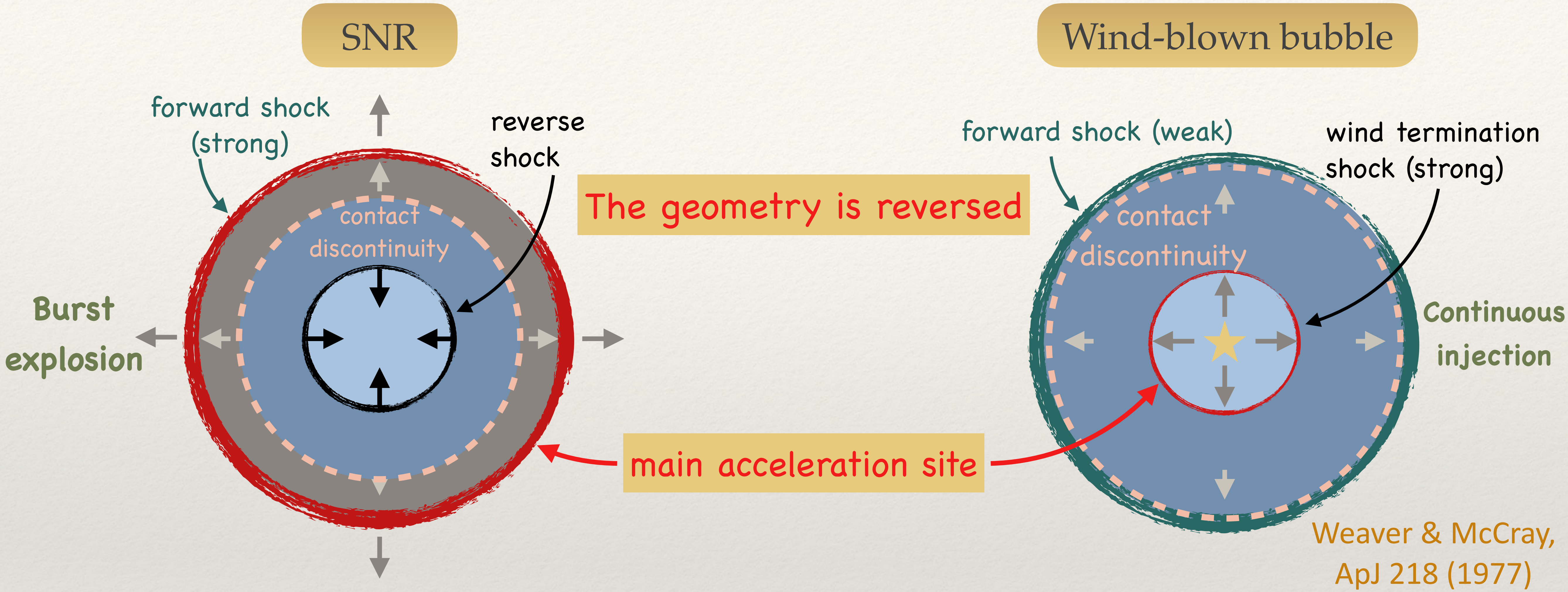

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Stellar winds vs. SNRs

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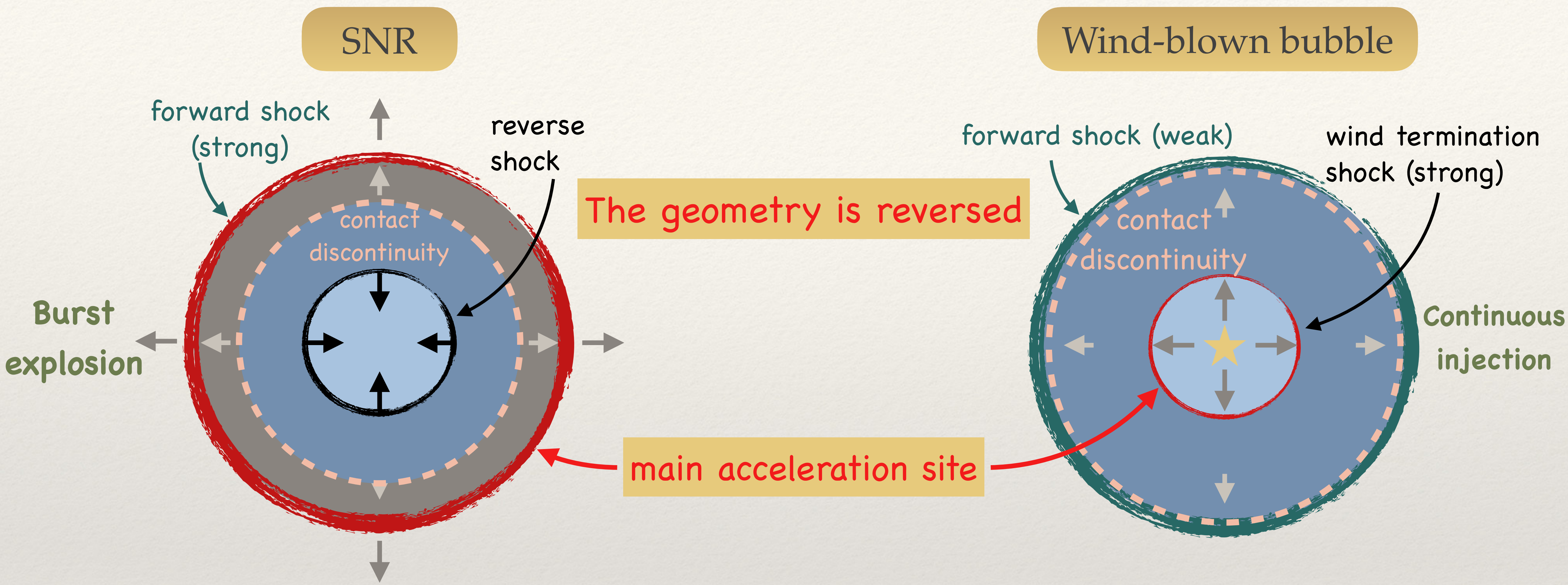


Self-generated by accelerated particles	MAGNETIC FIELD	Amplified by MHD turbulence in the wind

Maximum energy: first order estimate

Hillas criterium

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

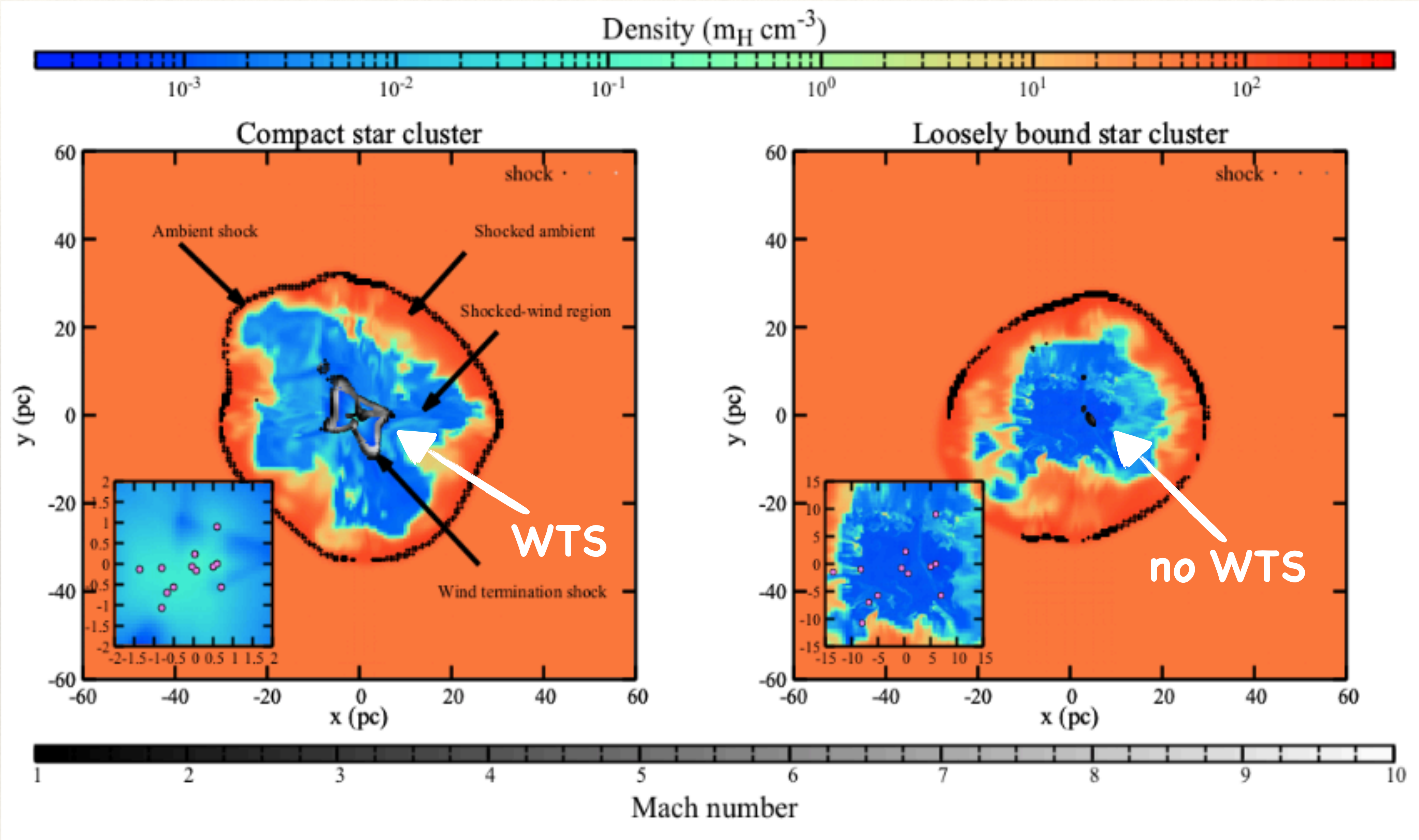
	dM/dt M_{sol}/yr	u_{sh} km/s	R_{sh} pc	B μG	*age* yr	lim E_{max}	E_{max} TeV
SNR	—	> 5000	< 1	~100 self-amplification	~10^3	time limited	~10-100
WTS (single star)	10^{-6}	< 3000	~ 1	~ 1 MHD turbulence	~10^6	space limited	~ 10
WTS (massive cluster)	10^{-4}	< 3000	> 10	> 10 MHD turbulence	~10^6	space limited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

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

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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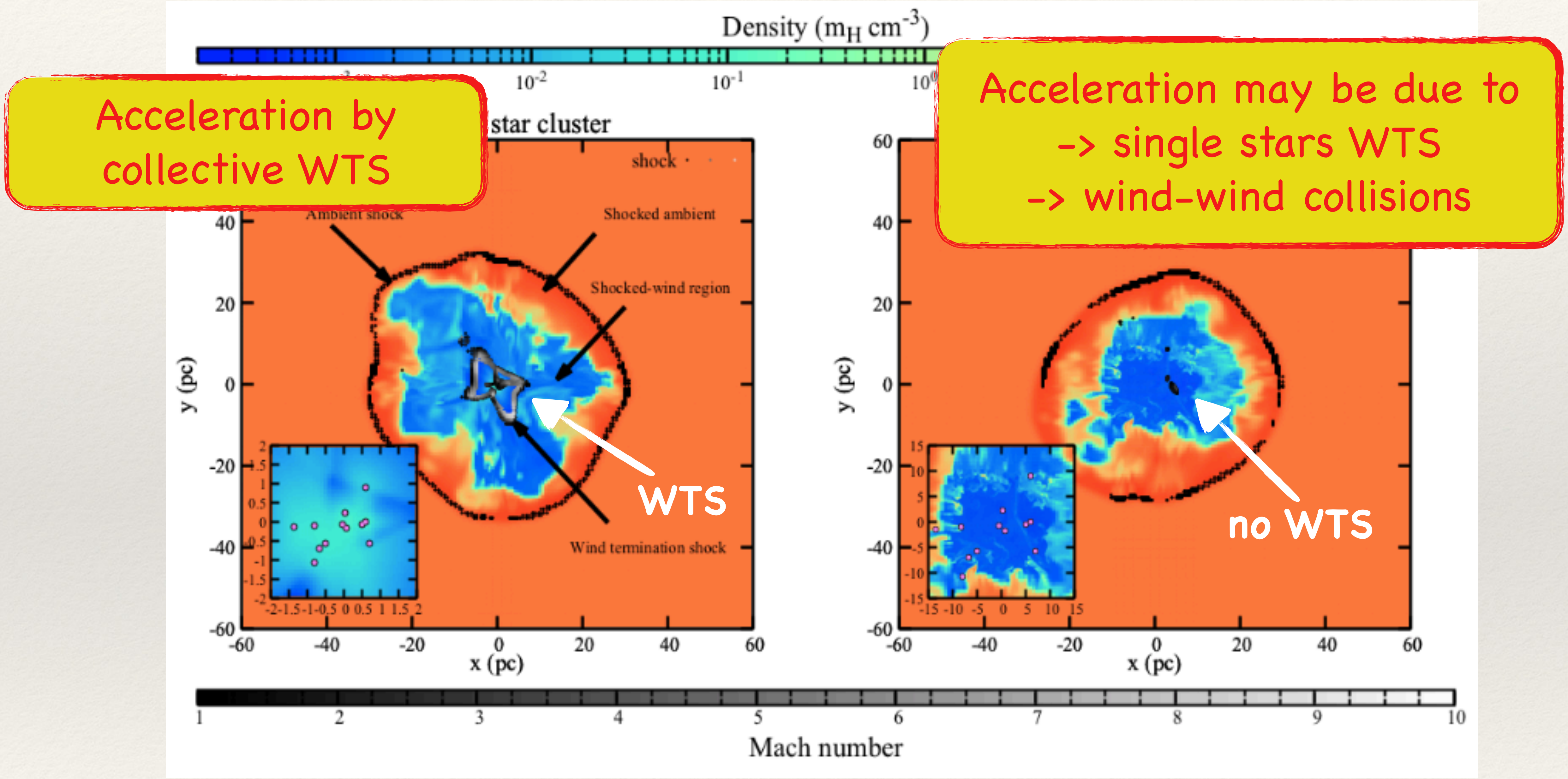


Compact cluster

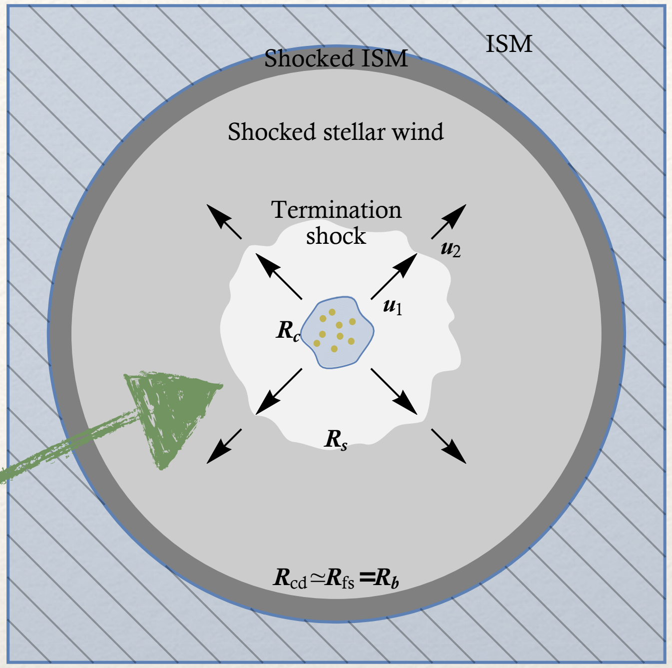
Loose cluster

Particle acceleration at the wind TS

GM, Blasi, Peretti & Cristofari (2019)

Time-stationary transport equation in spherical geometry:

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



- **Injection only at the termination shock:** $Q(r,p) \propto \delta(p - p_{\rm inj})\, \delta(r - R_s)$

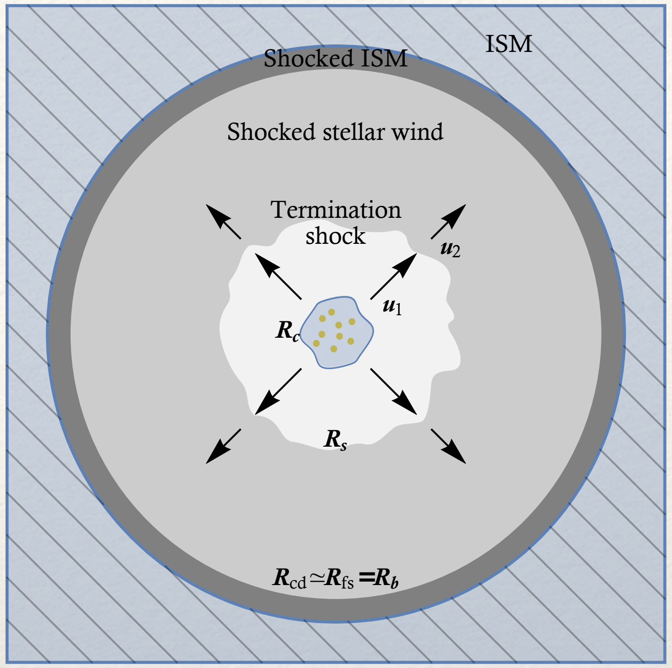
- **Wind velocity profile:** $$u(r) = \begin{cases} u_1 = v_w & \text{for } r < R_s\,, \\ \frac{u_1}{\sigma}\left(\frac{R_s}{r}\right)^2 & \text{for } R_s < r < R_b\,, \\ 0 & \text{for } r > R_b\,; \end{cases}$$

- **Boundary conditions:**

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

Particle acceleration at the wind TS

GM, Blasi, Peretti & Cristofari (2019)



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- **Arbitrary diffusion coefficient: *D*(r,*p*)**

Wind-wind collision and non-stationarity can produce high level of HD turbulence

Assuming that a fraction $\eta_B \gtrsim 1\,\%$ of kinetic wind energy is converted into magnetic energy

$$\frac{\delta B}{4\pi} 4\pi r^2 v_w = \frac{1}{2}\eta_B \dot{M} v_w^2 \Rightarrow \delta B(R_s) \gtrsim \mu G$$

The type of turbulent cascade can result into different diffusion coefficients

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

L_c ~pc is the injection scale of turbulence

Maximum energy: a more detailed analysis

GM, Blasi, Peretti & Cristofari (2019)

Solution of diffusive shock acceleration in spherical geometry

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

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Solution of diffusive shock acceleration in spherical geometry

Standard power-law for plane shocks

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

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Maximum energy due to confinement in the upstream: the effective plasma speed decreased reducing the energy gain

Maximum energy: a more detailed analysis

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Maximum energy due to escaping from the downstream

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Maximum energy: a more detailed analysis

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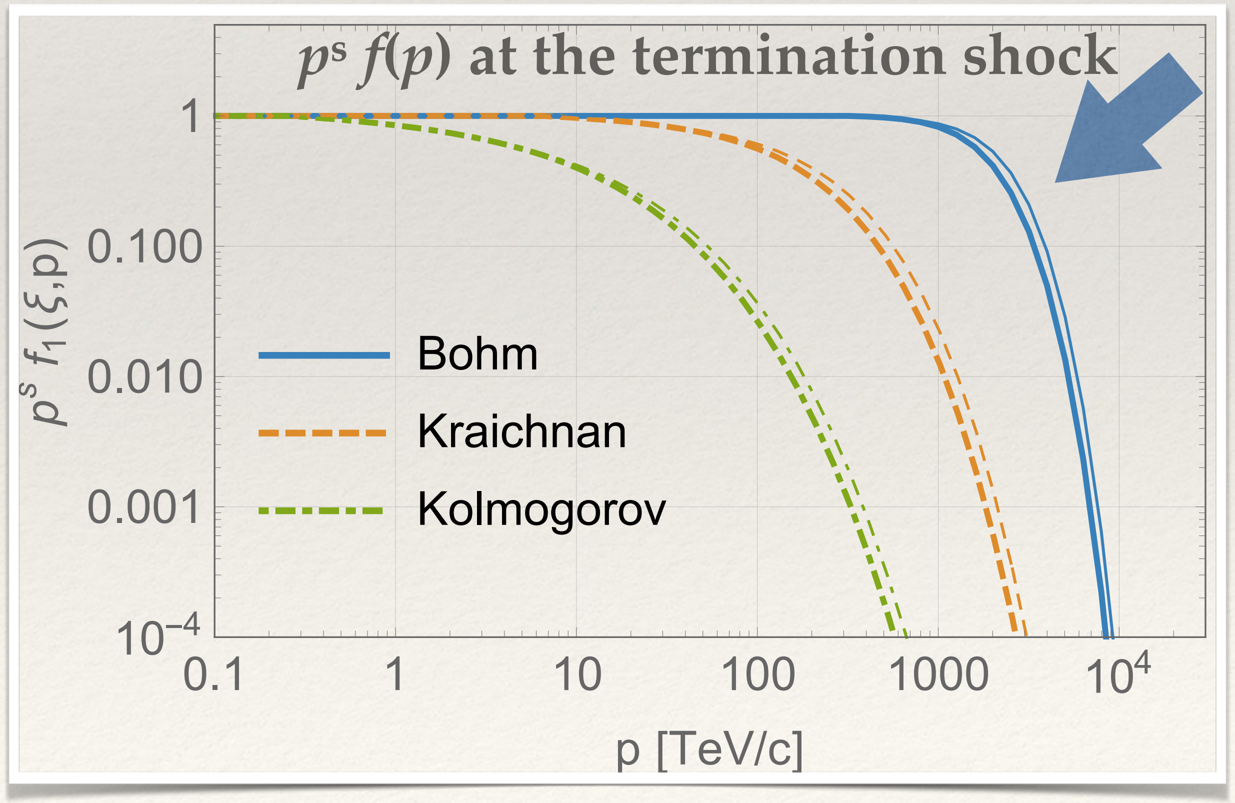
Maximum energy due to escaping from the downstream

Maximum energy due to confinement in the upstream: the effective plasma speed decreased reducing the energy gain

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

Typical values for massive stellar clusters

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



Maximum energy: a more detailed analysis

GM, Blasi, Peretti & Cristofari (2019)

Solution of diffusive shock acceleration in spherical geometry

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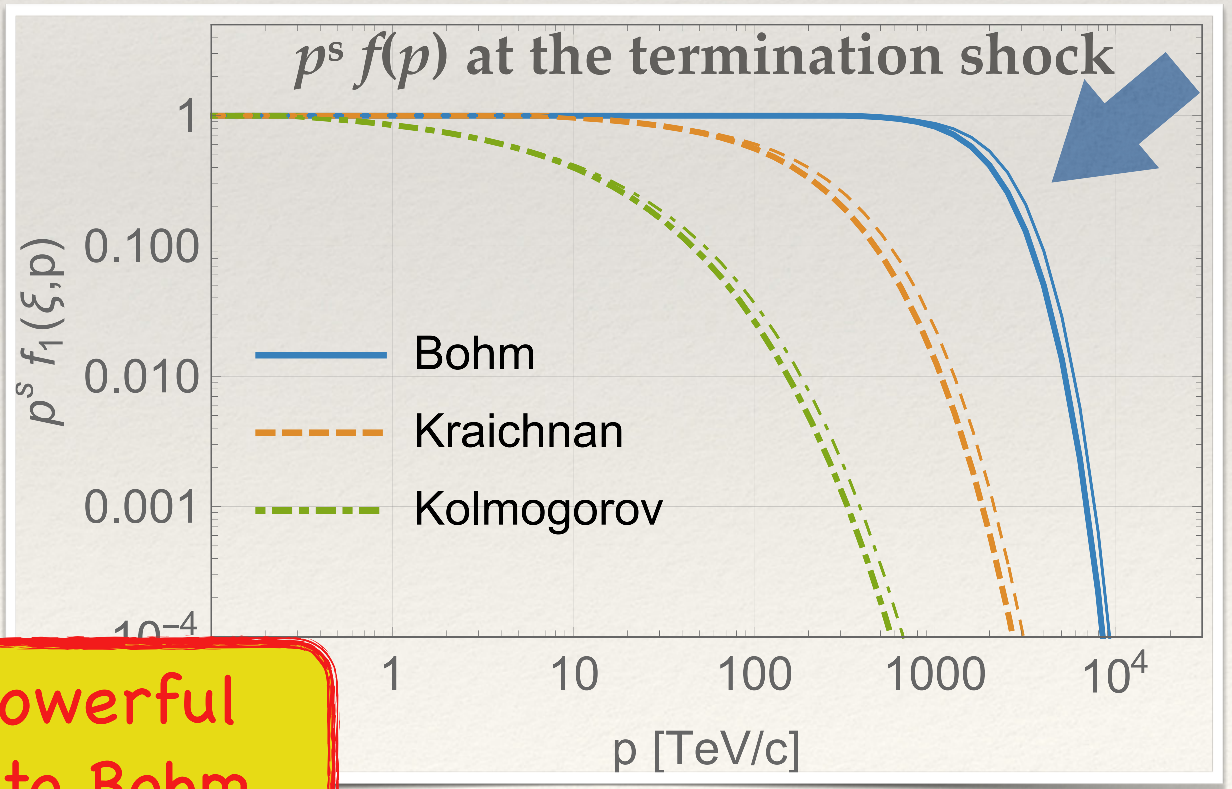
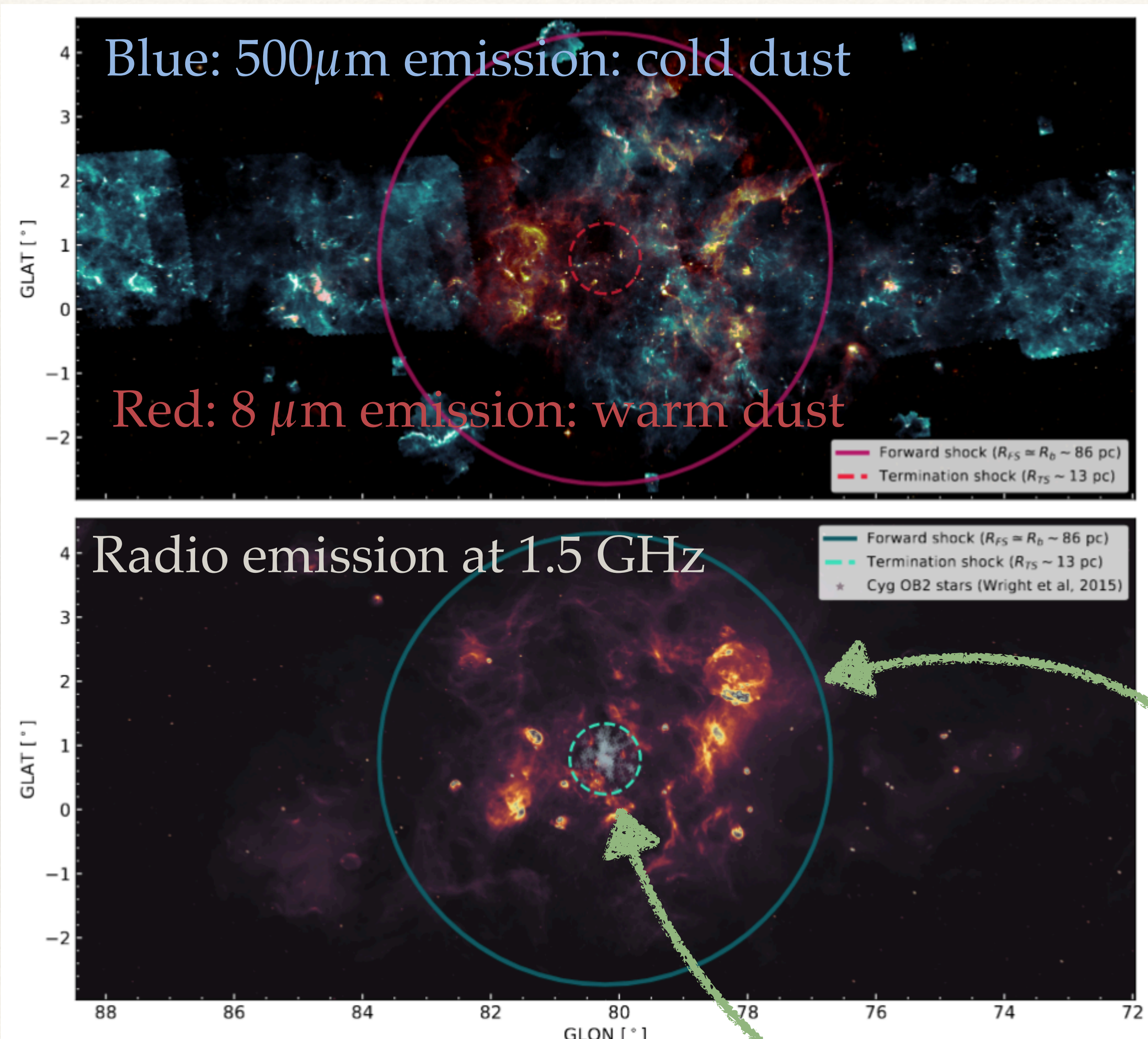


PeV energies can be reached in very powerful stellar clusters if the diffusion is close to Bohm

The case of Cygnus Cocoon

[S. Menchiari et al. in preparation]



Assumed properties

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

Estimated size of the bubble $\simeq$ 90 pc

Termination shock radius $\simeq$ 13 pc

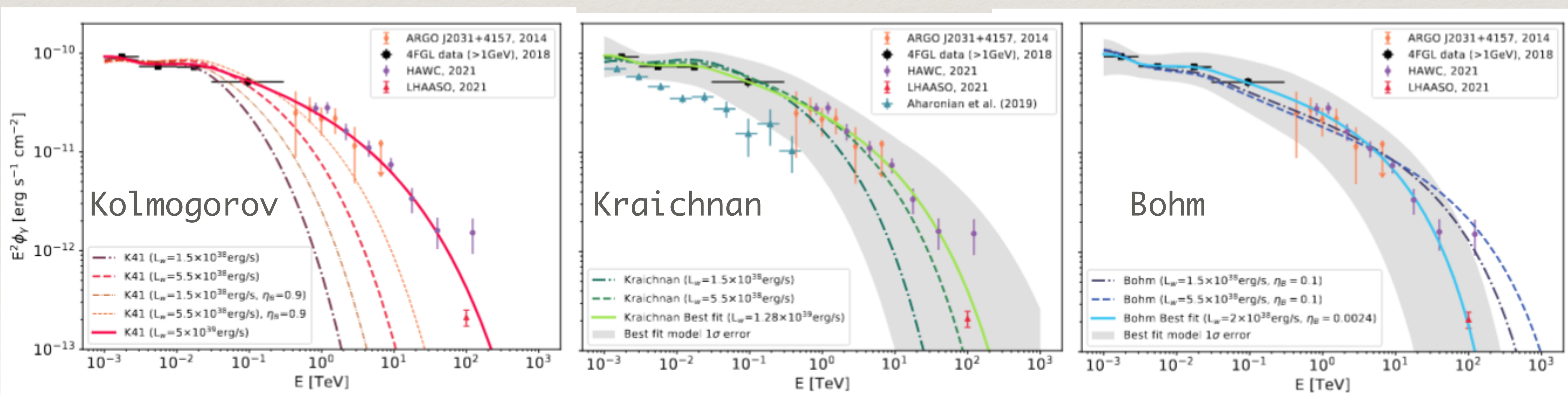
The case of Cygnus Cocoon

[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}
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



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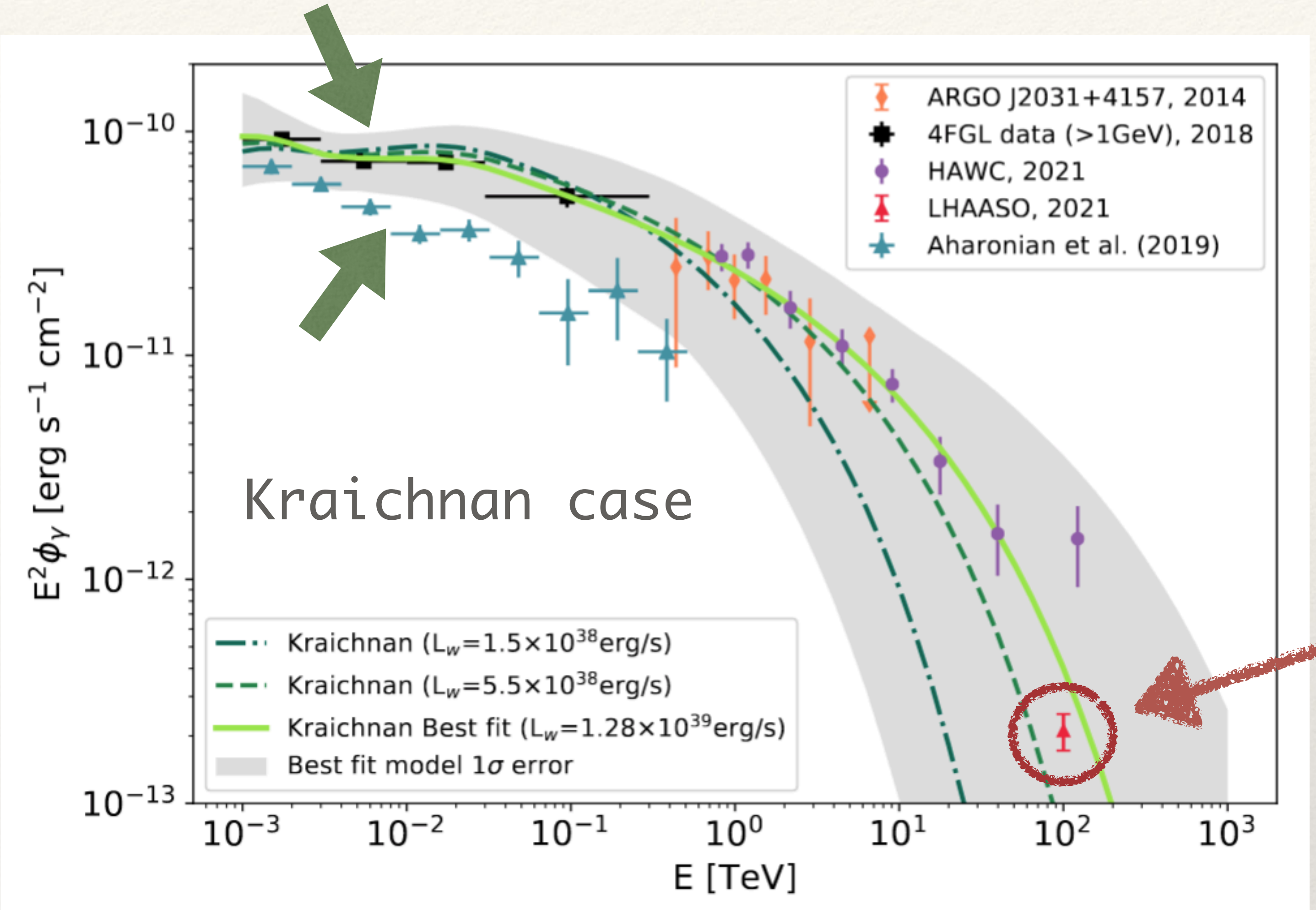


Some caveats:

❖ Different analysis of Fermi-LAT data gives different results

❖ In comparing different experiments we need to correctly account for the different extraction area

❖ LHAASO data-point is not used for the fit because the extraction area is not specified

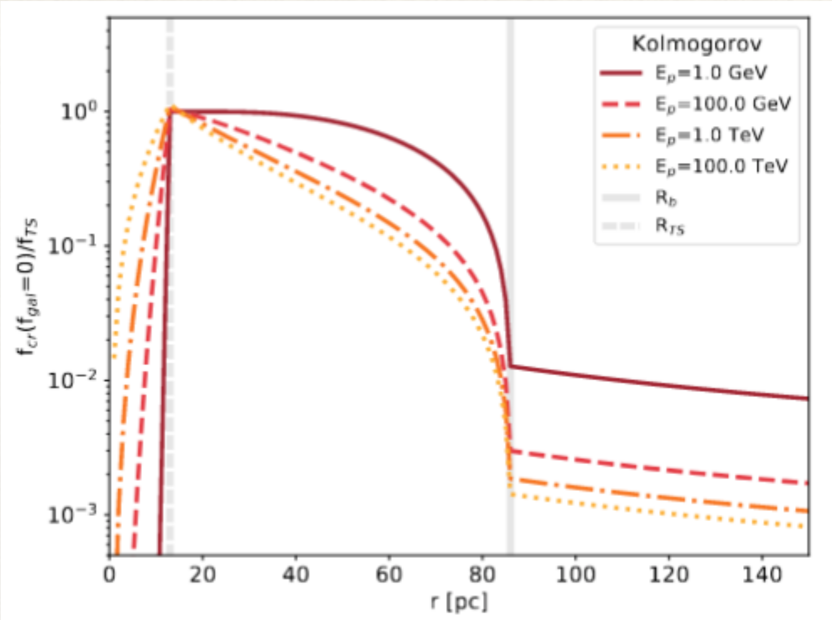
Better constraints requires a careful combined analysis of different experiments

CR radial profile

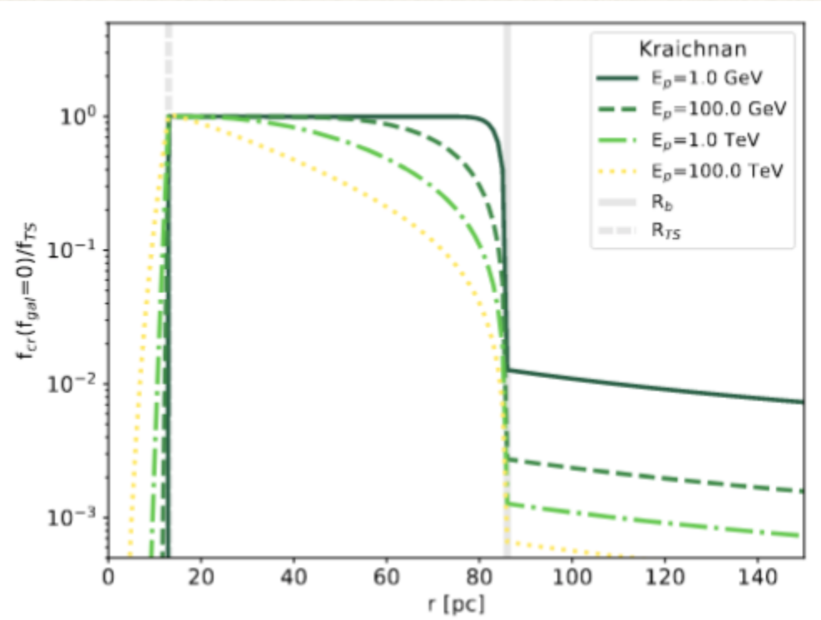
[S. Menchiari et al. in preparation]

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

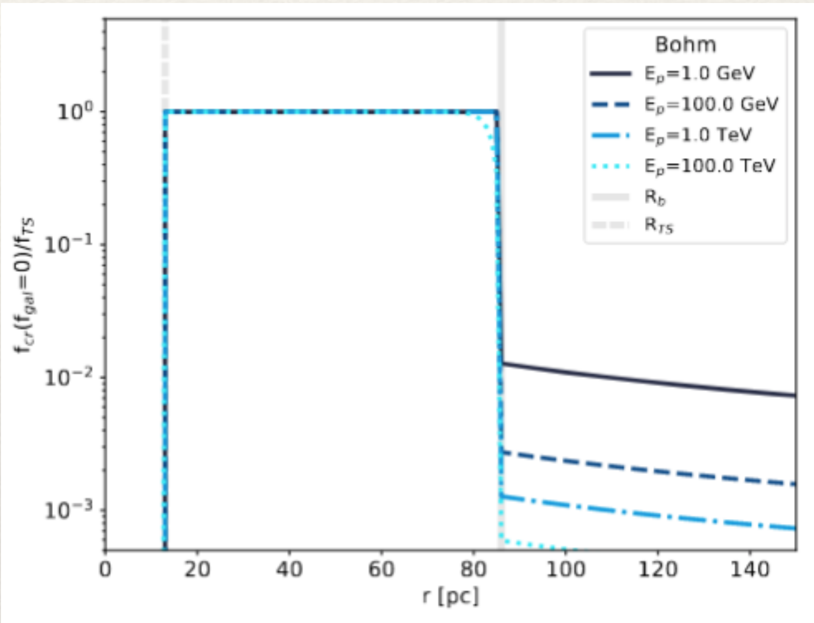
Kolmogorov



Kraichnan



Bohm

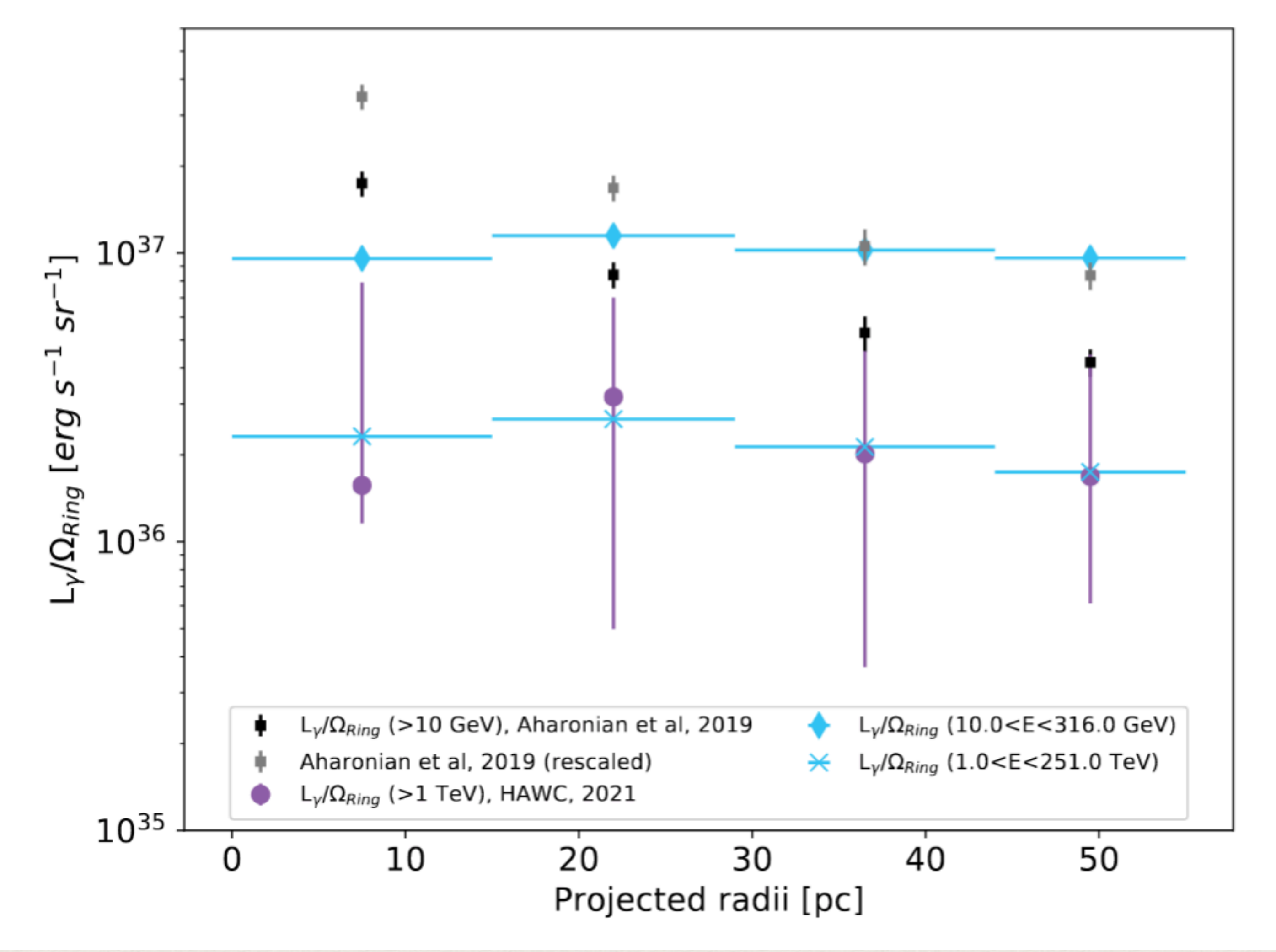


CR radial profile

[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

Radial profile: advection vs. diffusion

What should be the CR spatial profile in stellar clusters?

1. Pure diffusion model from a stationary central source

$$f_{\rm CR} = Q(E)\frac{4Dt}{\sqrt{\pi}\, r}\, e^{-\frac{r^2}{4Dt}} \propto \frac{1}{r} \qquad \text{for } r < 4\,D\,t$$

2. Transport in a wind-blown bubble from a stationary central source

Diffusion time: $t_{\rm diff} \sim R^2/4D(E)$ Advection time: $t_{\rm adv} \sim R/v_w$

Upper limit on the diffusion coefficient
can be estimated from gamma-ray luminosity

$$L_\gamma^{pp} \propto \xi_{\rm CR} L_w\, n_{\rm bubble}\, V_{\rm bubble} \lesssim L_\gamma^{\rm obs}$$

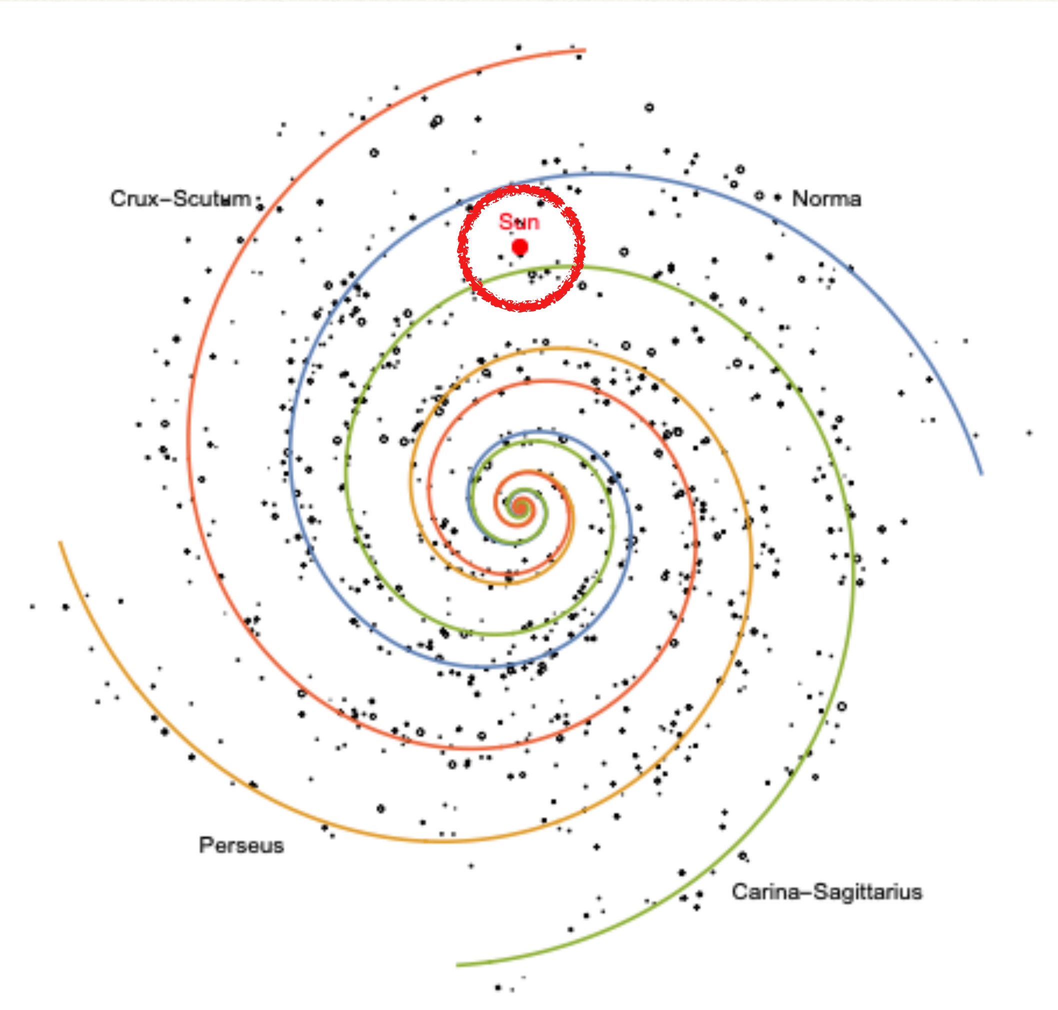
for Cygnus cocoon $\Rightarrow D \lesssim 100\, D_{\rm gal}$

⇒ $t_{\rm diff}(E) > t_{\rm adv}$ for $E \lesssim 100\ GeV$

In the Fermi-LAT energy range we do expect a flat CR profile

How many Star Clusters?

Synthetic realisation of Stellar cluster population



- *Age < 10 Myr*
- $100\,M_\odot < \text{Mass} < 6\times10^4\,M_\odot$

↓

- total number of SC in the Galaxy ≈ 1000
- SCs within 2 kpc from the Sun $\simeq 70$

Present number of clusters detected in gamma-rays ~ 10

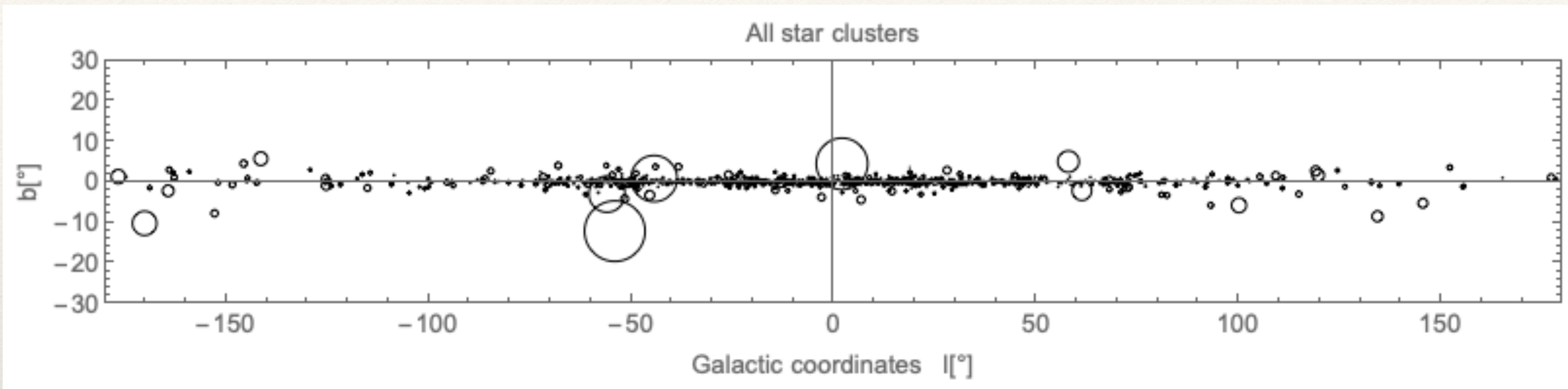
Bubble size ~ degree ⇒ diffuse sources with low surface brightness ⇒ difficult to detect

$$R_{bubble} \simeq 2.9^\circ \left(\frac{L_w}{2\times10^{38}\,\mathrm{erg/s}}\right)^{1/5} \left(\frac{n_0}{10\,\mathrm{cm^{-3}}}\right)^{-1/5} \left(\frac{t_{age}}{1\,\mathrm{Myr}}\right)^{3/5} \left(\frac{d}{2\,\mathrm{kpc}}\right)$$

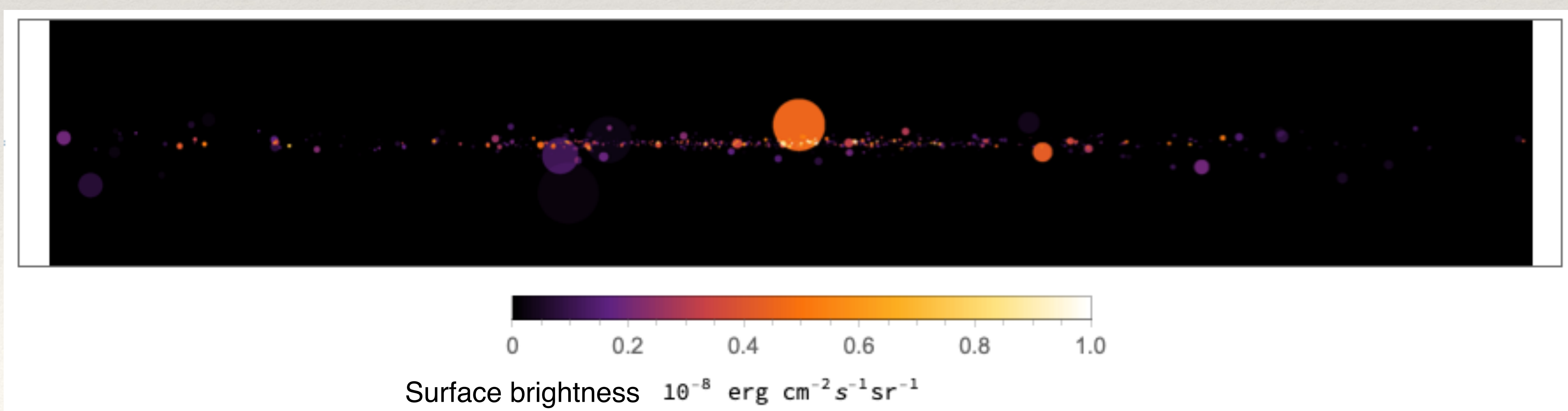
Weaver & McCray, ApJ 218 (1977)

How many Star Clusters?

Bubble size in the sky from the entire population of SC in galactic coordinates:



Some bubbles disappear when plotted against their surface brightness



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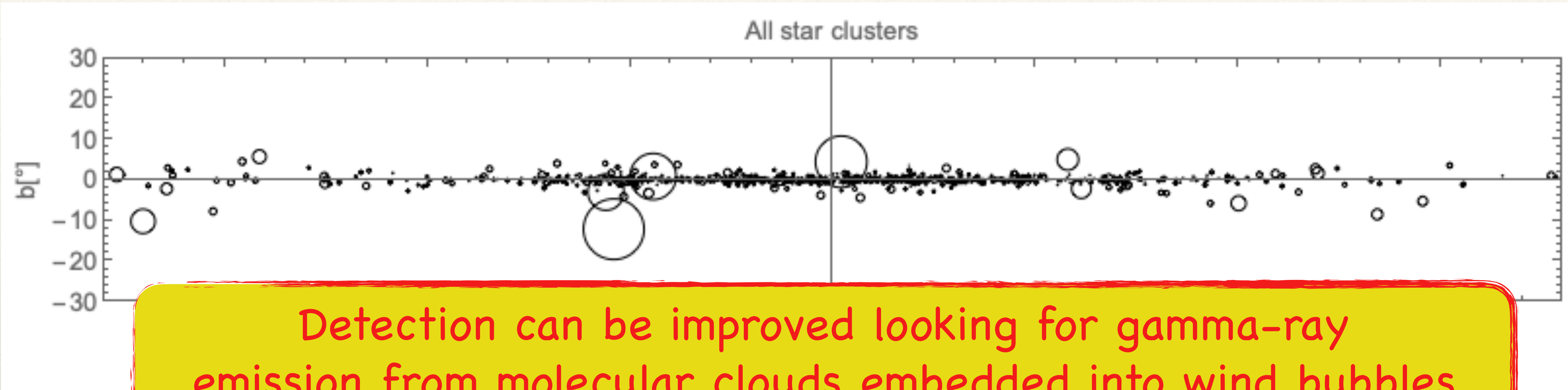
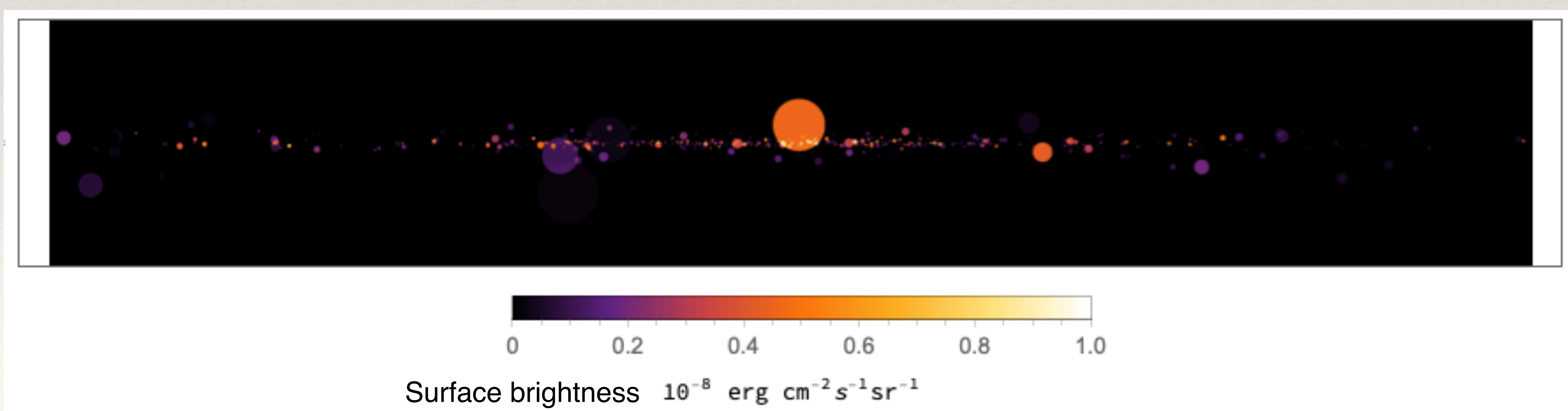


Detection can be improved looking for gamma-ray emission from molecular clouds embedded into wind bubbles

Some bubbles disappear when plotted against their surface brightness



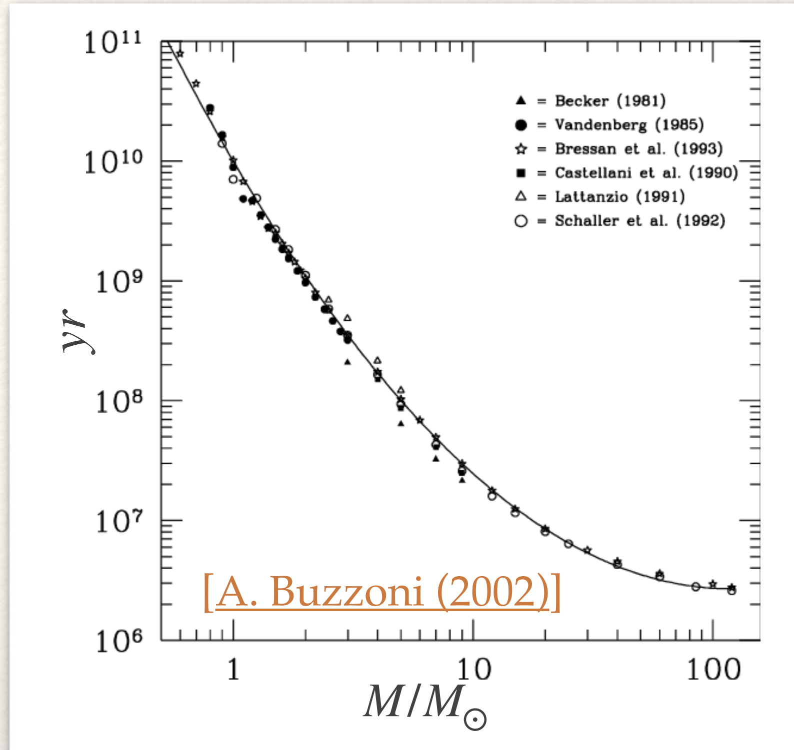
Conclusions

- Young stellar clusters are promising gamma ray sources
- YSC can significantly contribute to Galactic CRs
- Maximum energies can reach ~PeV (but strong dependence on diffusion)
- Super-bubbles (= older SCs with stellar winds+ SNRs) may be the major contributors of Galactic CRs (but theoretical models still incomplete)
- Next generation IACT will probably detect many new stellar clusters (~several tens) (but extended sources with low surface brightness)
- Observational strategy: look for gamma-ray emission from molecular clouds close to stellar clusters

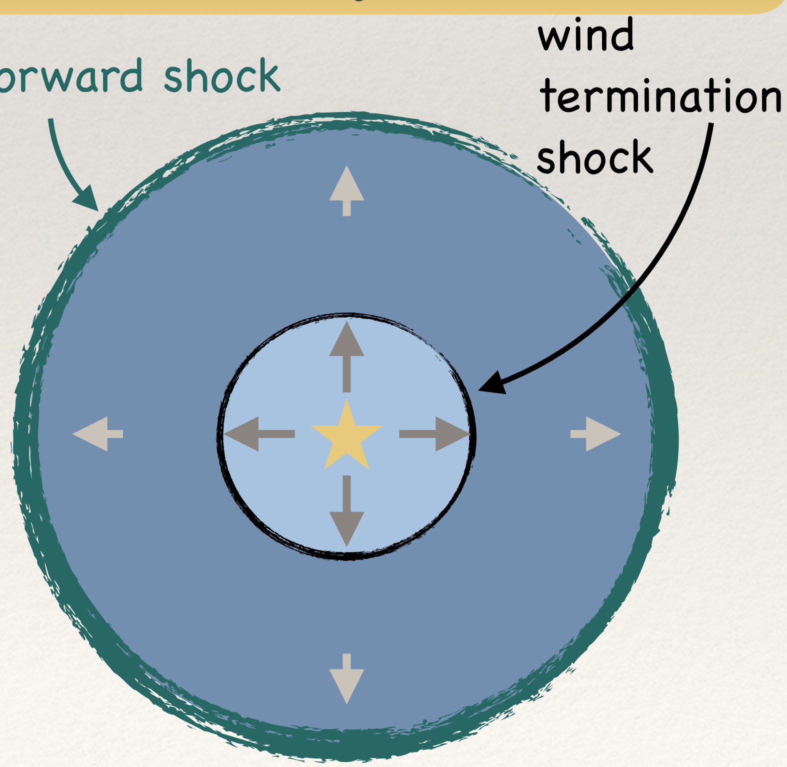
Backup slides

Young vs. old clusters

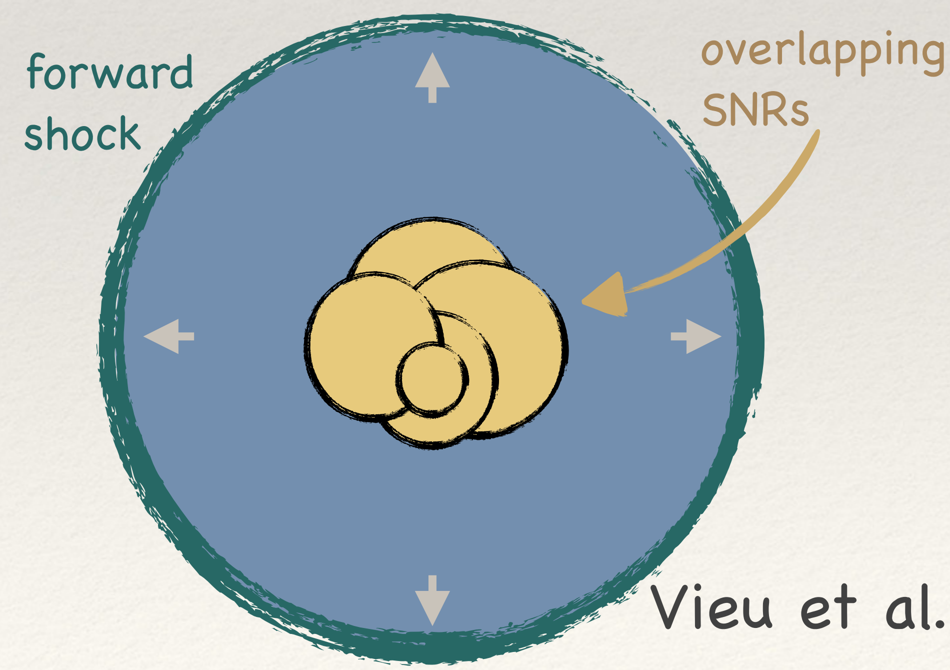
Star's lifetime



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



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



Vieu et al. (2022)

Possible role of YSC in the Galactic Center

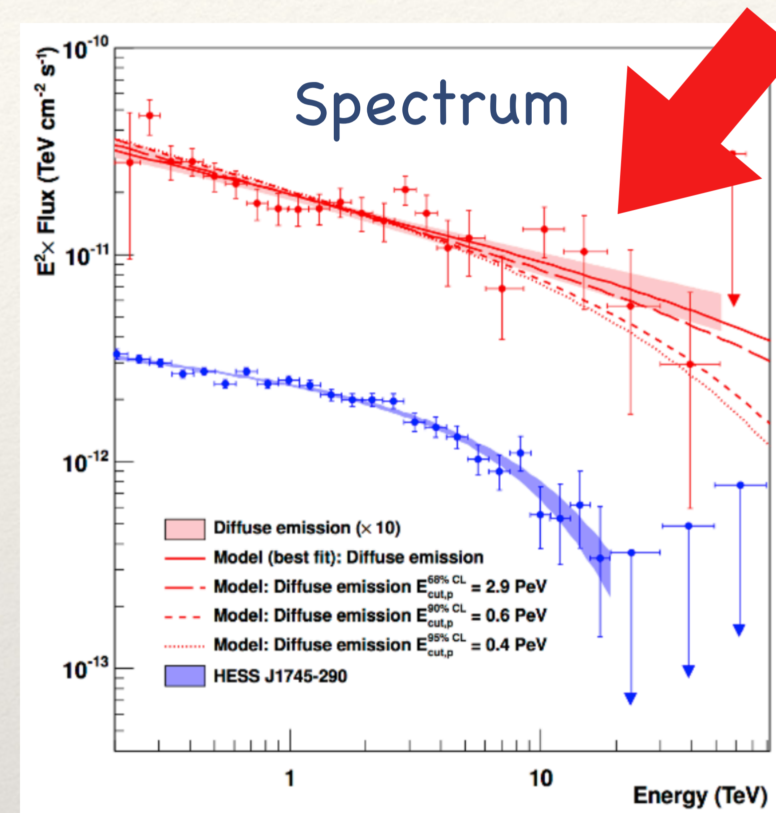
[H.E.S.S. coll., Abramowski et al. Nat. 531 (2016)]

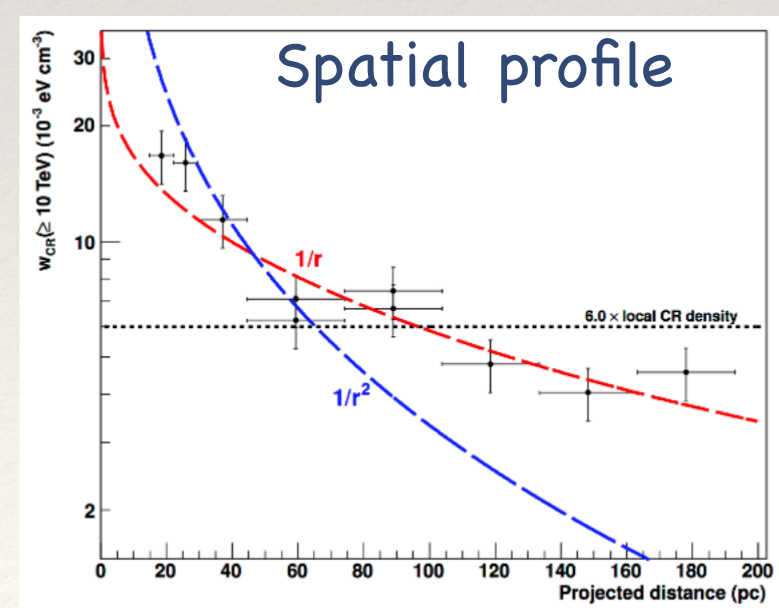
The Galactic Centre has been recognised as a PeVatron

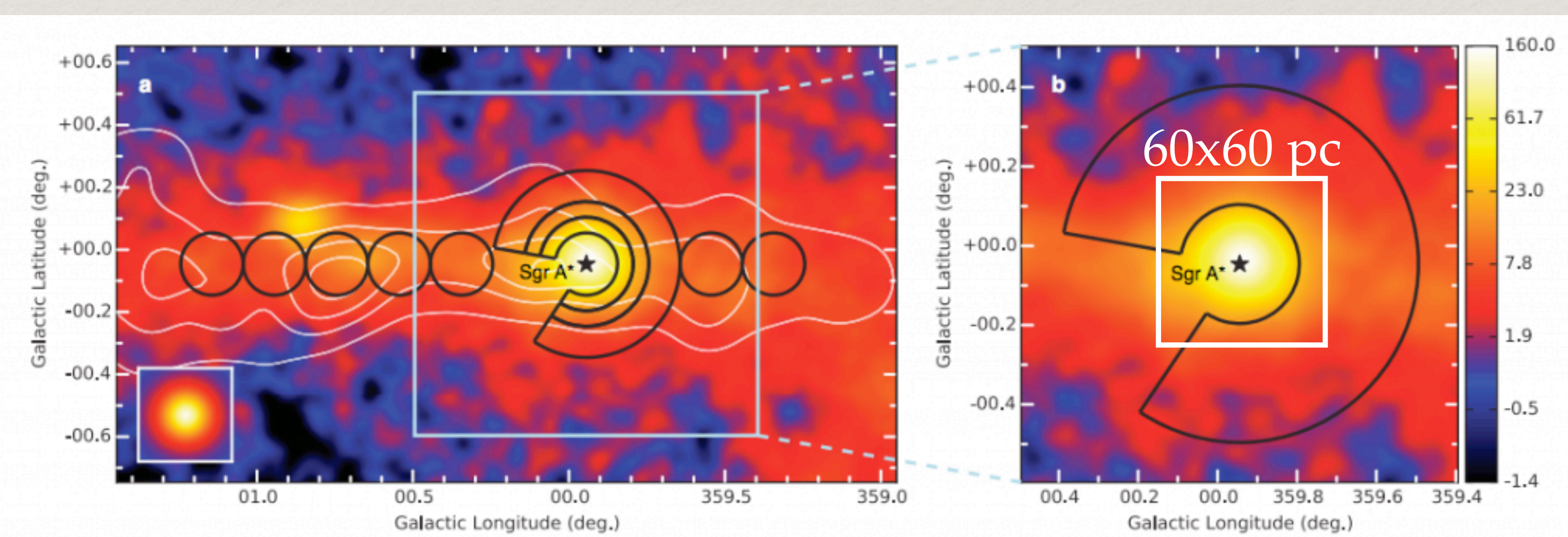
- Minimum proton energy > 0.4 PeV
- Spatial profile compatible with continuous emission

  ➡ SNR disfavoured

- CR luminosity: $L_{CR}(>10\,\mathrm{TeV}) = 4\times10^{37}\left(\mathrm{D}/10^{30}\,\mathrm{cm^2 s^{-1}}\right)$ 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