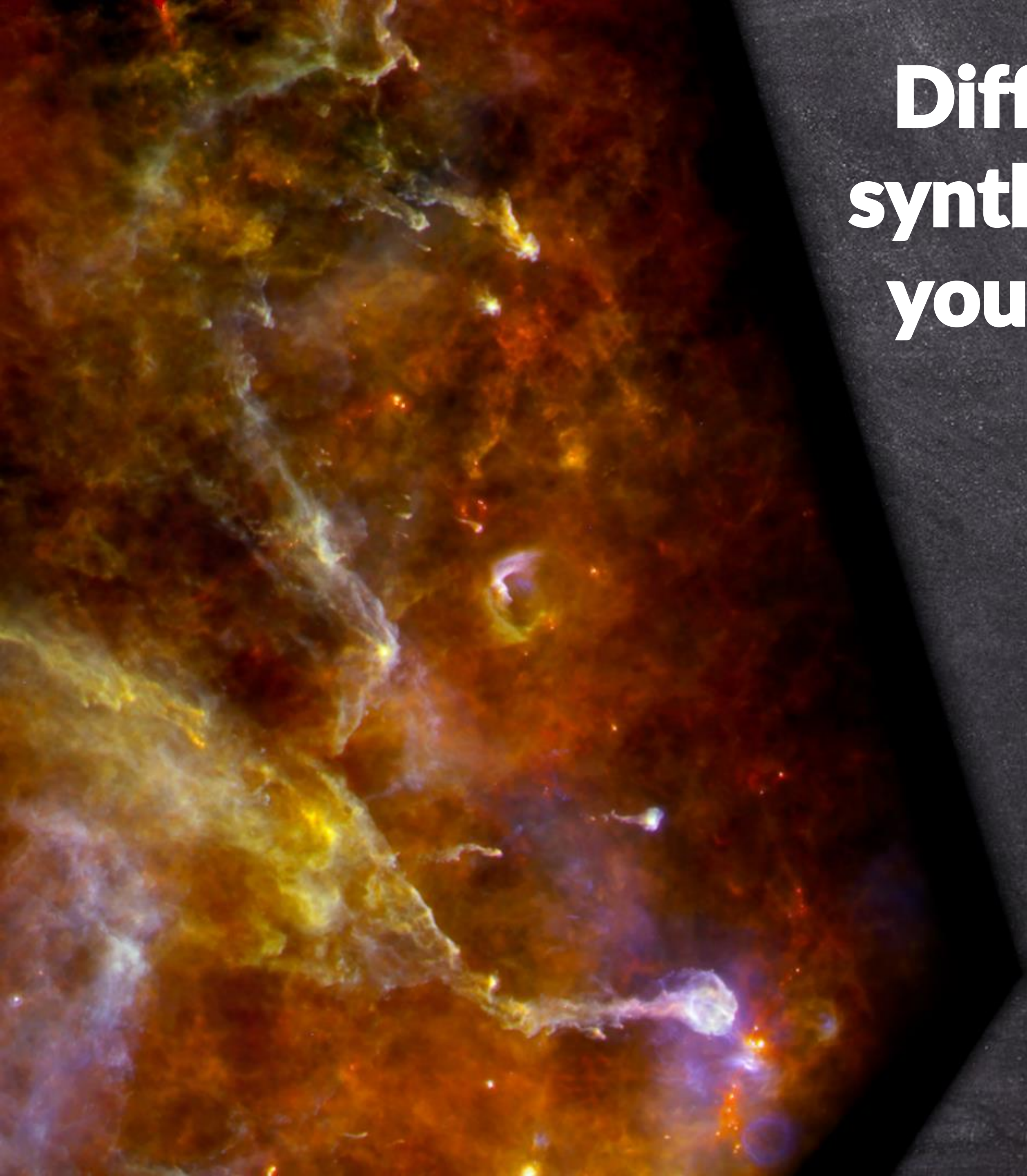

Diffuse γ-ray emission from a synthetic Galactic population of young massive stellar clusters

Stefano Menchiari (INAF-OAA)
Giovanni Morlino (INAF-OAA)
Elena Amato (INAF-OAA)
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[GRA] – 5:30-5:45 PM

TeVPA 2023 – Napoli – 11/09/2023

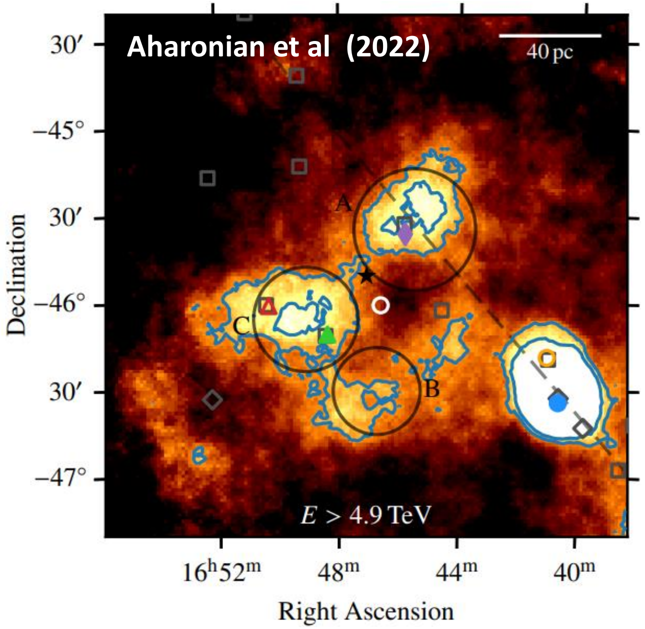
Young massive star clusters (YMSC): Cosmic rays and γ-ray sources

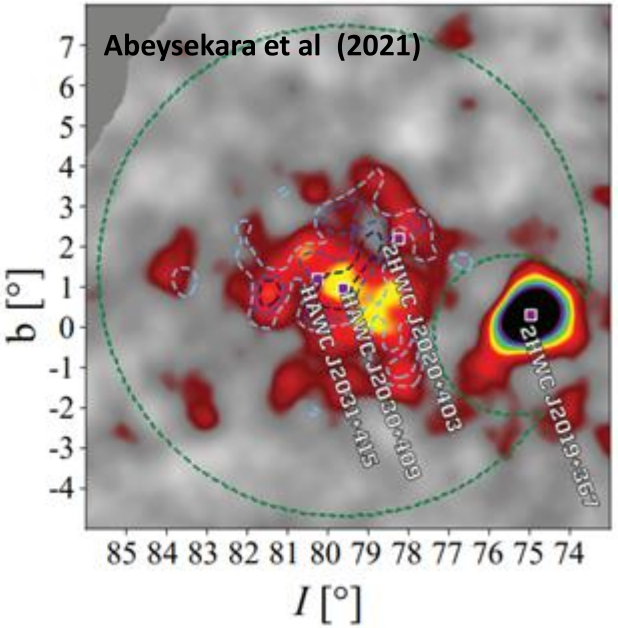
YMSCs: **Clusters of hundreds OB-type** ($M_{☆}$>3 $M_{\odot}$) **stars** packed in few pc.
Young: Age <10 Myr
Massive: M_{SC}>10^3 $M_{\odot}$

Several cosmic ray (CR) acceleration mechanisms proposed in YMSCs.
A few examples:

- Acceleration in massive stars winds (Casse & Paul, 1980)
- Acceleration in cluster wind termination shock (TS) (Morlino et al., 2021)
- Acceleration in cluster wind TS + SNRs (Vieu et al. 2022)

γ-ray emission detected in coincidence with **12 YMSC!**





Name	log $M/M_{\odot}$	r_c [pc]	D [kpc]	Age [Myr]	L_w [erg s^{-1}]
Westerlund 1	4.6 ± 0.045	1.5	4	$4-6$	10
Westerlund 2	4.56 ± 0.035	1.1	2.8 ± 0.4	$1.5-2.5$	2
Cygnus OB2	4.7 ± 0.3	5.2	1.4	$2-7$	2
NGC 3603	4.1 ± 0.1	1.1	6.9	$2-3$	-
BDS 2003	4.39	0.2	4	1	-
W40	2.5	0.44	0.44	1.5	-
RSGC 1	4.48	1.5	6.6	$10-14$	-
MC 20	~ 3	1.3	$3.8-5.1$	$3-8$	~ 4
NGC 6618	-	3.3	~ 2	< 3	-
30 Dor (LMC)	$4.8-5.7$	multiple	50	1	-
NGC 2070 / RCM 136	$4.34-5$	subcluster		5	

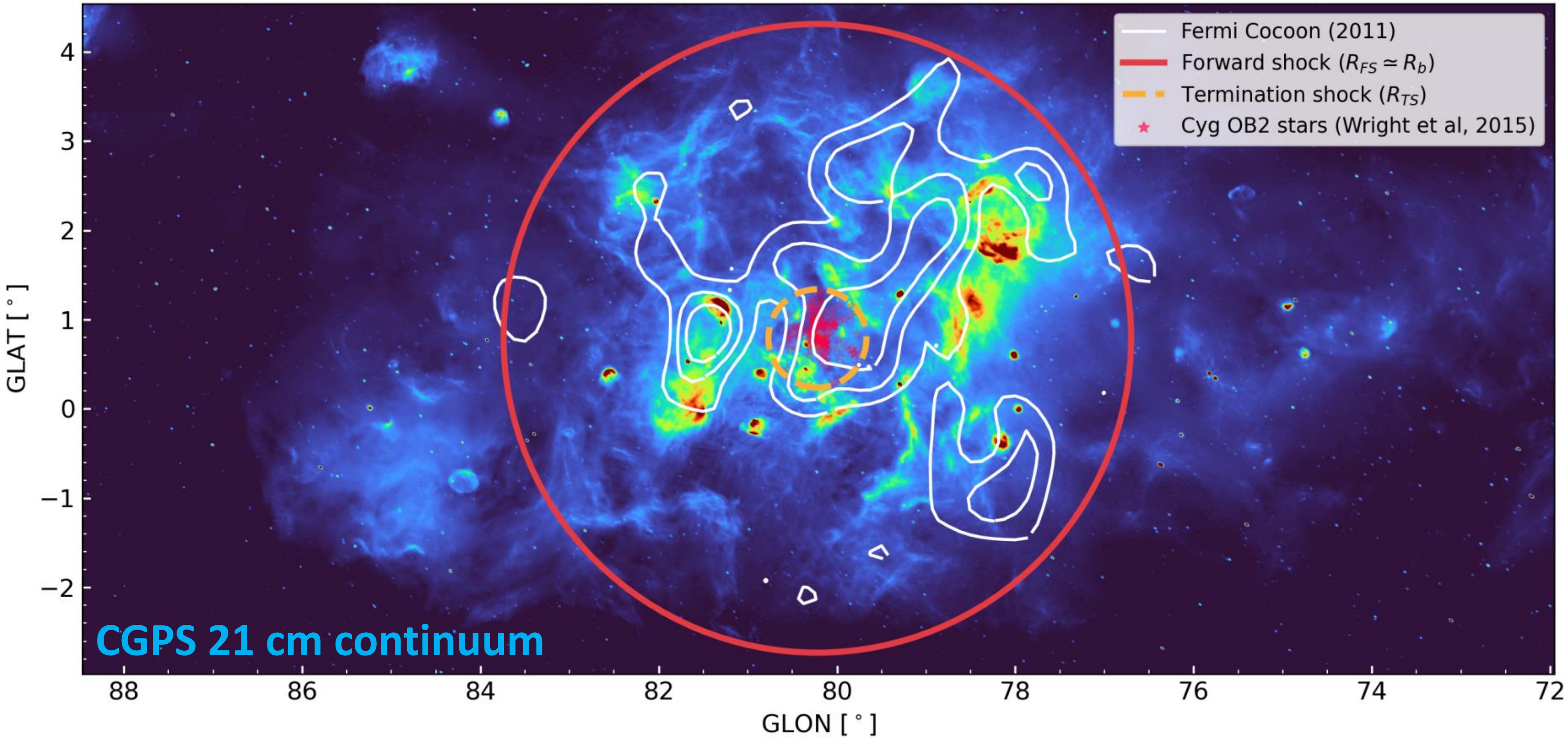
Diffuse emission

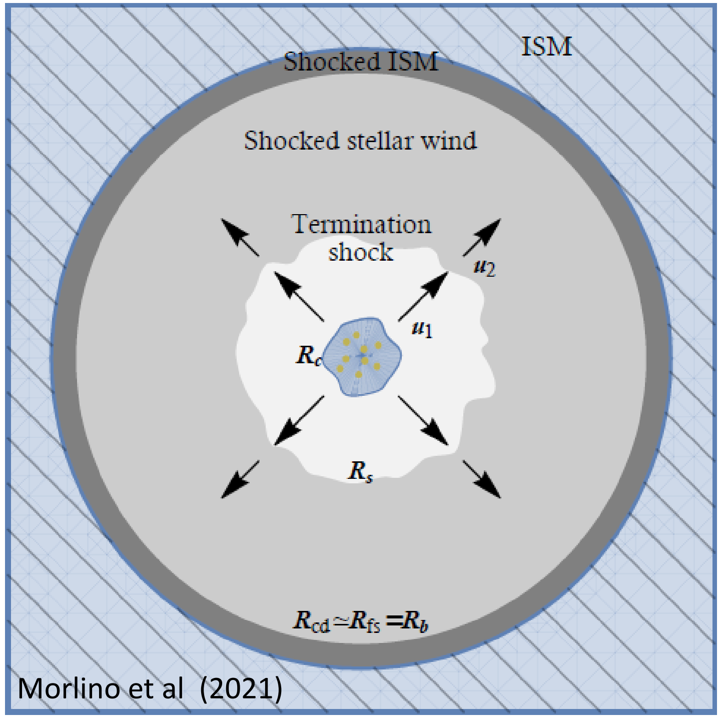
The γ-ray emission is diffuse and extended (1°-3°)!

Emission size consistent with projected dimension of wind-blown bubble

Detecting and analyzing diffuse γ-ray emission is a challenging task!

Detection bias for low surface brightness sources





Work objective

OBJECTIVES:

1) Estimate contribution to Galactic diffuse emission from YMSCs

2) Comparison with observations

$100^\circ < l < 25^\circ$, $|b| < 5^\circ$ (ROI1)

$125^\circ < l < 15^\circ$, $|b| < 5^\circ$ (ROI2)

Nota bene:

Population of YMSCs in Milky Way is not known!

Use a synthetic population of YMSC

Work objective

Required ingredients

OBJECTIVES:

1) Estimate contribution to Galactic diffuse emission from YMSCs

2) Comparison with observations

100°<l<25°, |b|<5° (ROI1)

125°<l<15°, |b|<5° (ROI2)

Nota bene: Population of YMSCs in Milky Way is not known!

Use a synthetic population of YMSC

1

a) Cosmic ray acceleration mechanism:

Acceleration at the cluster wind termination shock (TS) (Morlino et al. 2021)

b) Modeling γ-ray emission:

Pure hadronic emission

Work objective

OBJECTIVES:

1) Estimate contribution to Galactic diffuse emission from YMSCs

2) Comparison with observations

100°<l<25°, |b|<5° (ROI1)

125°<l<15°, |b|<5° (ROI2)

Nota bene:
Population of YMSCs in Milky Way is not known!
Use a synthetic population of YMSC

Required ingredients

1

a) Cosmic ray acceleration mechanism:
Acceleration at the cluster wind termination shock (TS) (Morlino et al. 2021)

b) Modeling γ-ray emission:
Pure hadronic emission

2

a) Modeling stellar population in a YMSC

b) Modeling stellar wind physics:
Use pure empirical approach

Work objective

OBJECTIVES:

1) Estimate contribution to Galactic diffuse emission from YMSCs

2) Comparison with observations

100°<l<25°, |b|<5° (ROI1)

125°<l<15°, |b|<5° (ROI2)

Nota bene: Population of YMSCs in Milky Way is not known!

Use a synthetic population of YMSC

Required ingredients

1

a) Cosmic ray acceleration mechanism: Acceleration at the cluster wind termination shock (TS) (Morlino et al. 2021)

b) Modeling γ-ray emission: Pure hadronic emission

2

a) Modeling stellar population in a YMSC

b) Modeling stellar wind physics: Use pure empirical approach

3

Modeling galactic population of YMSCs: Use info from local population of YMSCs

CR distribution in YMSCs

Morlino et al (2021)

CR accelerated at cluster wind TS + Propagation in the turbulent bubble

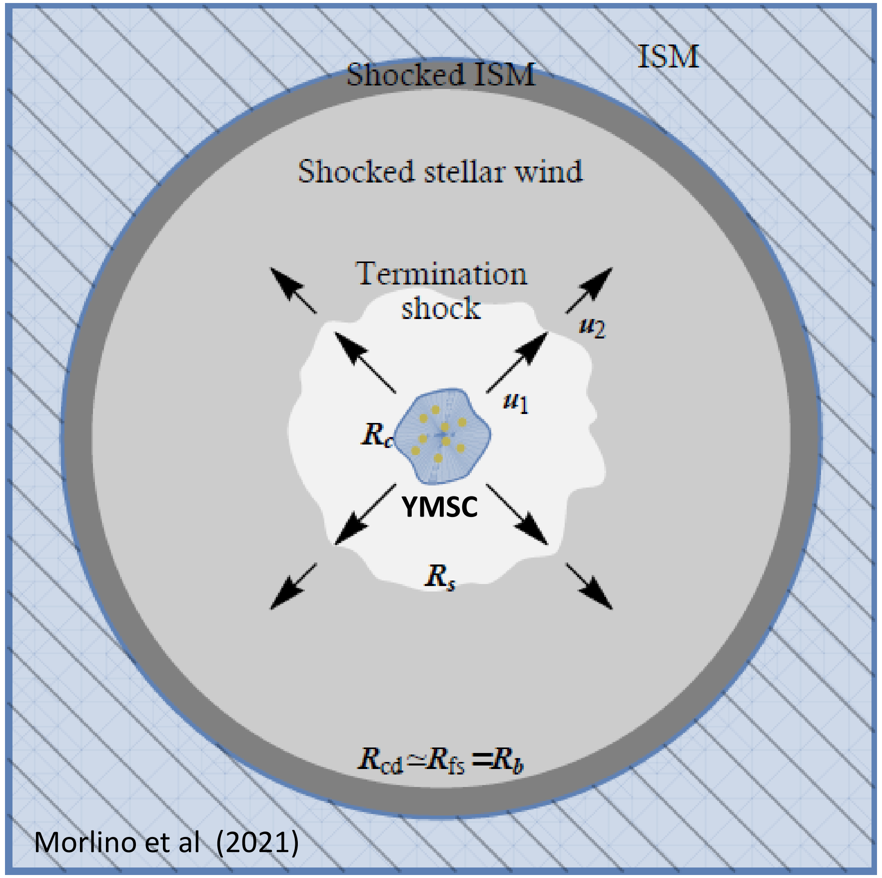
1) Spectral slope: $\propto p^{-4}$

2) Normalization: 10% of wind power spent to accelerate CRs

Cutoff spectral shape and maximum energy depend on diffusion coefficient!

TWO CASES CONSIDERED:

$$D_{\rm Kra} \propto r_L^{1/2} \qquad D_{\rm B} \propto r_L$$



Maximum energy:

NB: $\boldsymbol{E_{max}}$ depends on $\boldsymbol{L_w}$, $\boldsymbol{\dot{M}}$, **age**

$$\frac{D_1(E_{\rm max})}{v_w} = R_{\rm TS} \Rightarrow E^{Kra}_{max} \propto \eta_B^{1/2} \dot{M}^{-5/10} L_w^{13/10} \rho_{ism}^{-3/10} t^{2/5} \qquad E^{Bohm}_{max} \propto \eta_B^{1/2} \dot{M}^{-1/4} L_w^{3/4}$$

Stellar population in YMSC

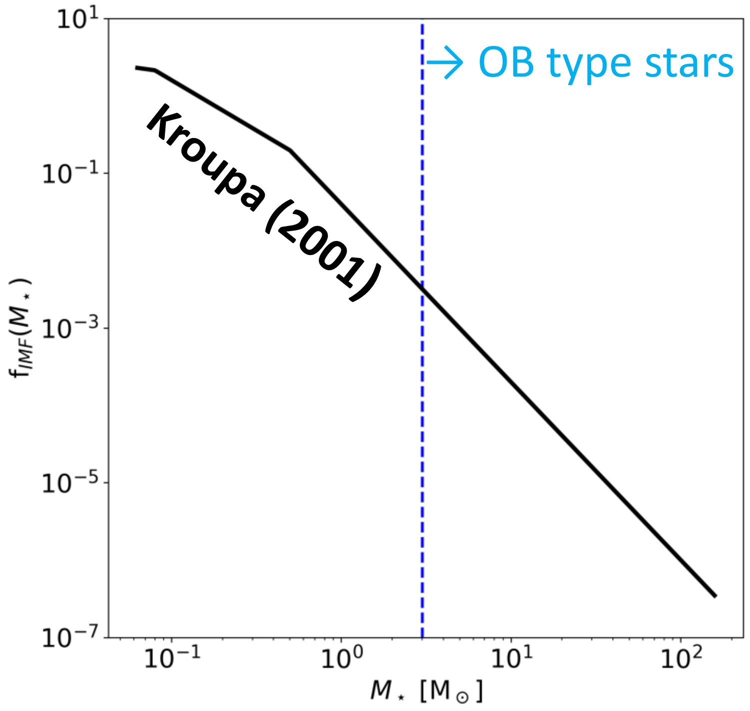
- Total number of stars:

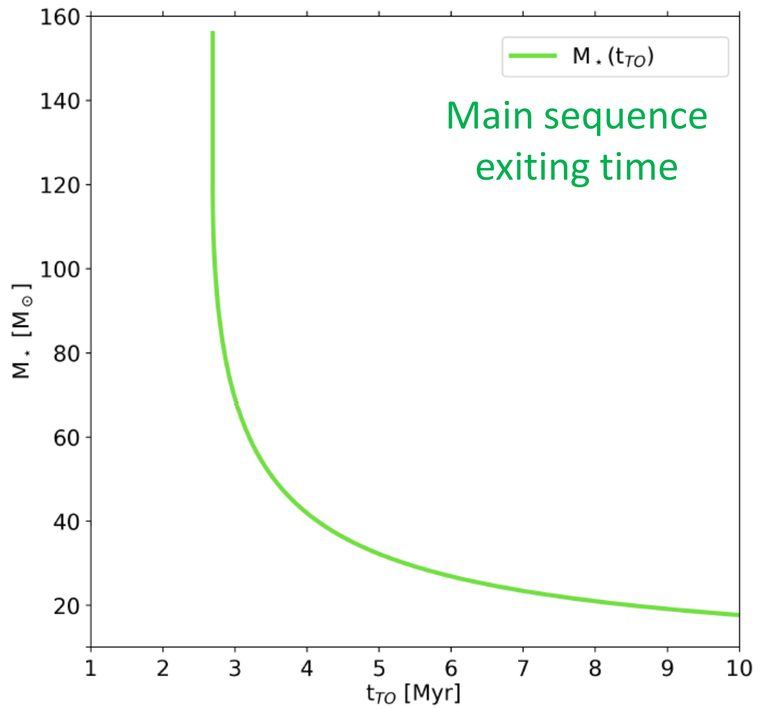
$$N_\star(M_{SC}) = M_{SC} \frac{\int_{M_{\star,min}}^{M_{\star,max}} f_\star(M_\star) dM_\star}{\int_{M_{\star,min}}^{M_{\star,max}} M_\star f_\star(M_\star) dM_\star}$$

- Stellar initial mass function (IMF) according to Kroupa (2001)
- Maximum stellar mass is 150 $M_\odot$
- *<u>All stars that have left the main sequence at a time equal to the age of the cluster are removed (Buzzoni 2002)</u>*

WE DO NOT ACCOUNT FOR THE ENERGY INJECTED BY SUPERNOVE!

CR (and γ-ray) normalization and maximum energy must be interpreted as lower limits!





Stellar wind physics

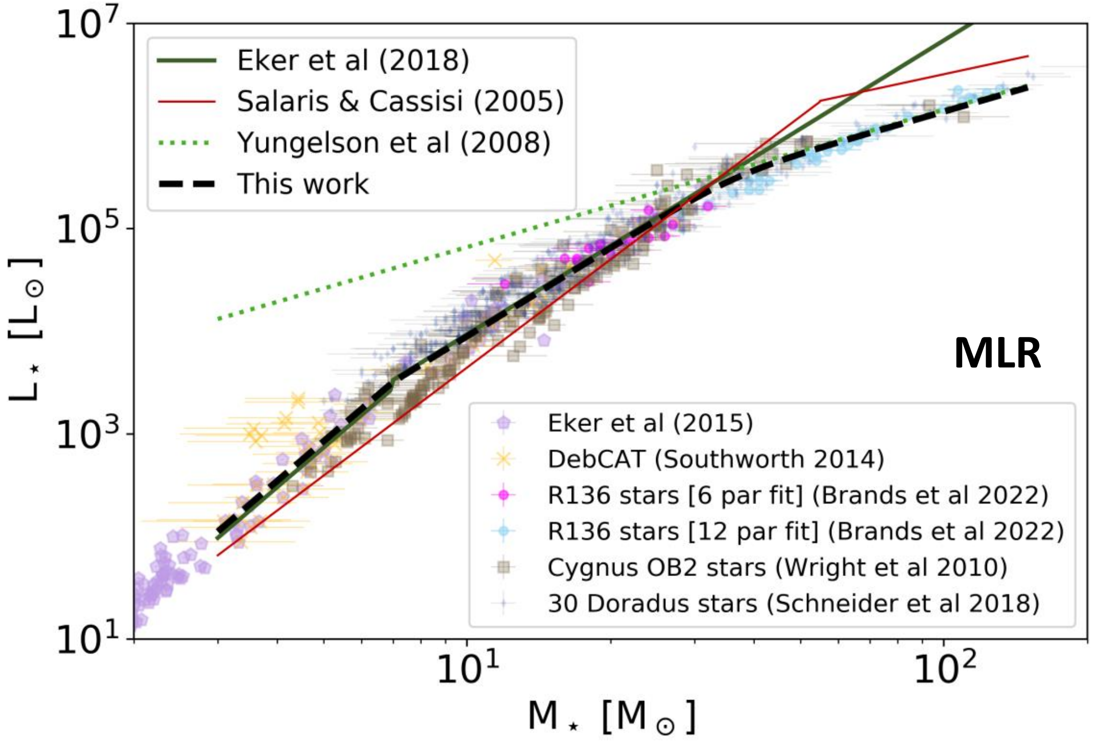
Stellar properties calculated using empirical relations

- Mass-luminosity relation (MLR) (Menchiari 2023)
- Mass-radius relation (MRR) (Demicran 1991)
- Mass-temperature relation (MTR) (Boltzmann-law)

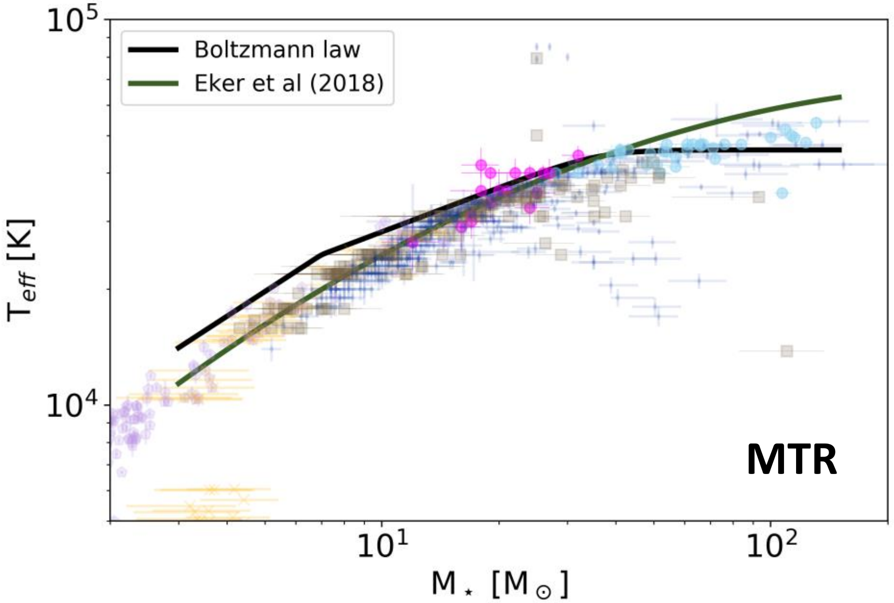
$$\log\left(\frac{\dot{M}_\star}{\mathrm{M_\odot yr^{-1}}}\right) = -14.02 + 1.24\log\left(\frac{L_\star}{\mathrm{L_\odot}}\right) + 0.16\log\left(\frac{M_\star}{\mathrm{M_\odot}}\right) + 0.81\left(\frac{R_\star}{\mathrm{R_\odot}}\right)$$

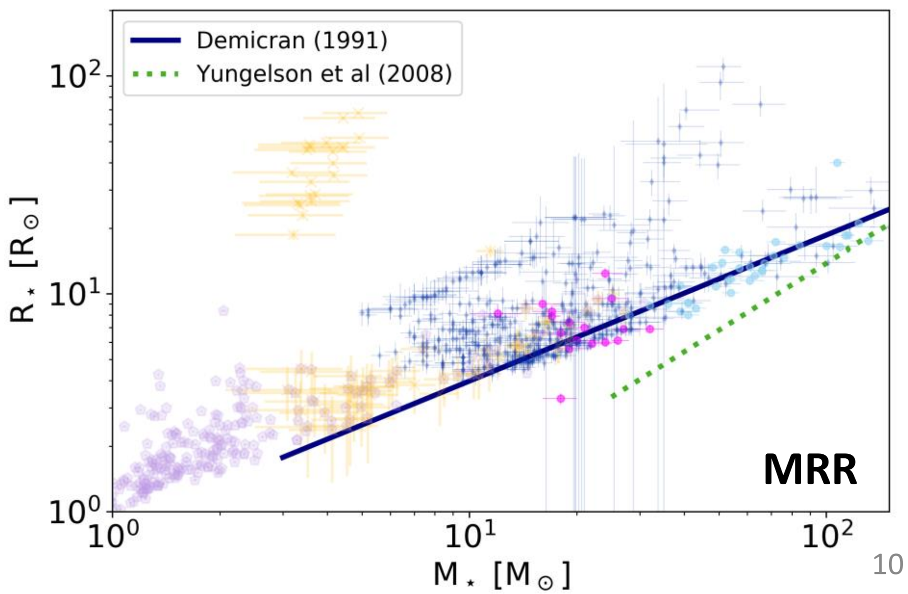
$$L_{\star,w} = \frac{1}{2}\dot{M}_\star\underbrace{\left\{C(T_{\mathrm{eff}})^2\left[\frac{2GM_\star(1-L_\star/L_{\mathrm{Edd}})}{R_\star}\right]\right\}}_{v_{\star,w}^{\,2}}$$

$\dot{M}_\star$: Nieuwenhuijzen et al. (1990)
$v_{\star,w}$: Kudritzki & Puls (2000)



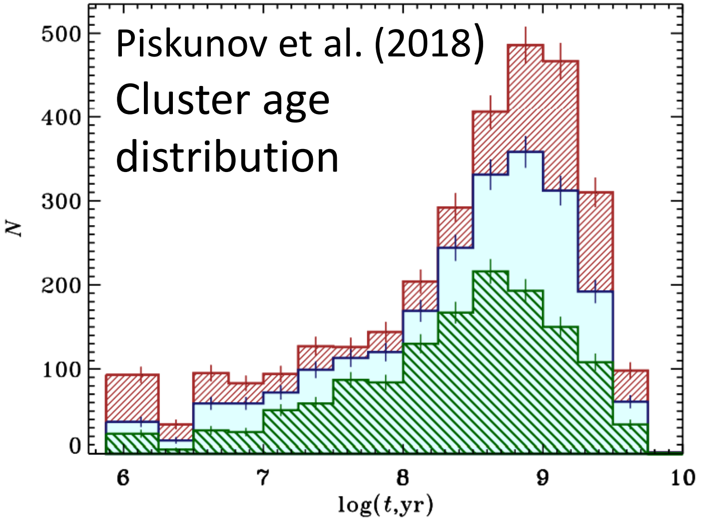
Cluster wind luminosity and mass loss rate calculating by summing all $L_{\star,w}$ and $\dot{M}_\star$



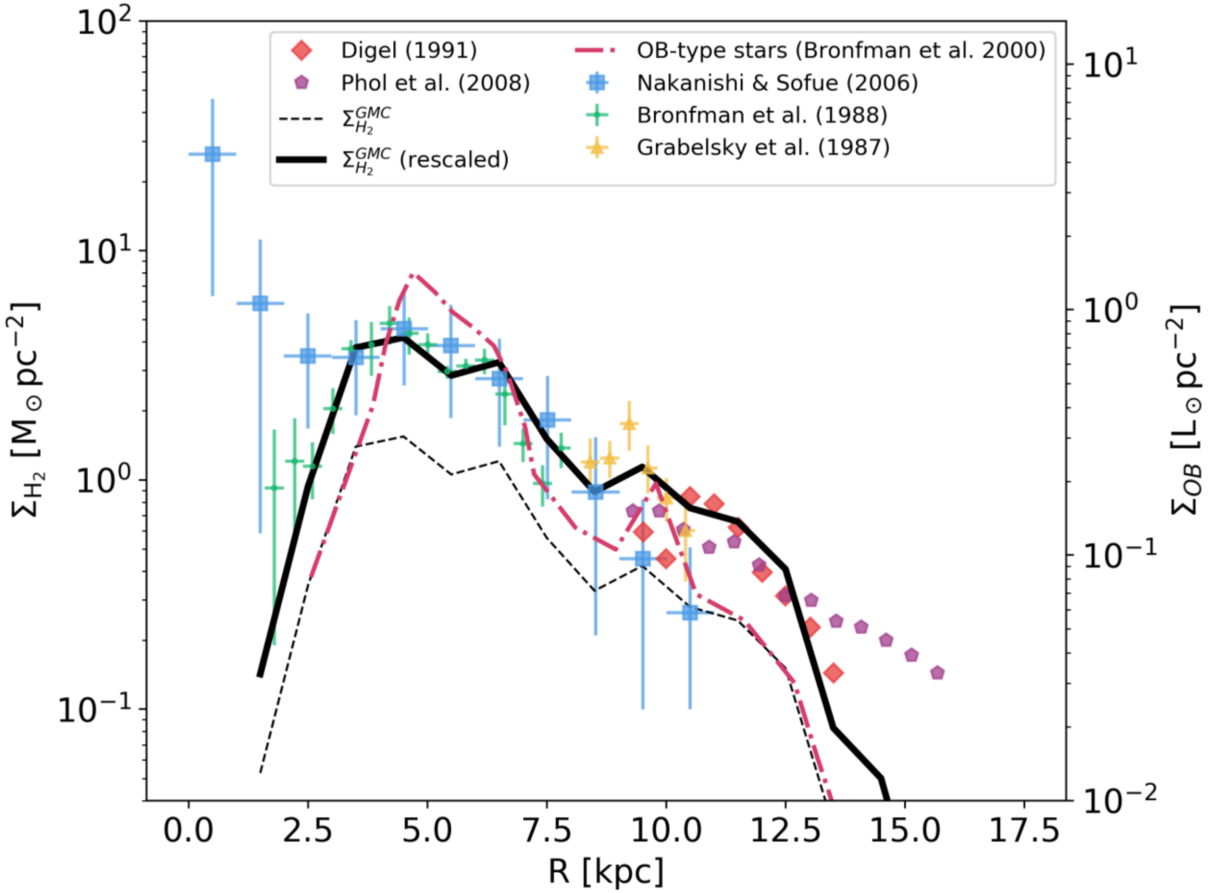


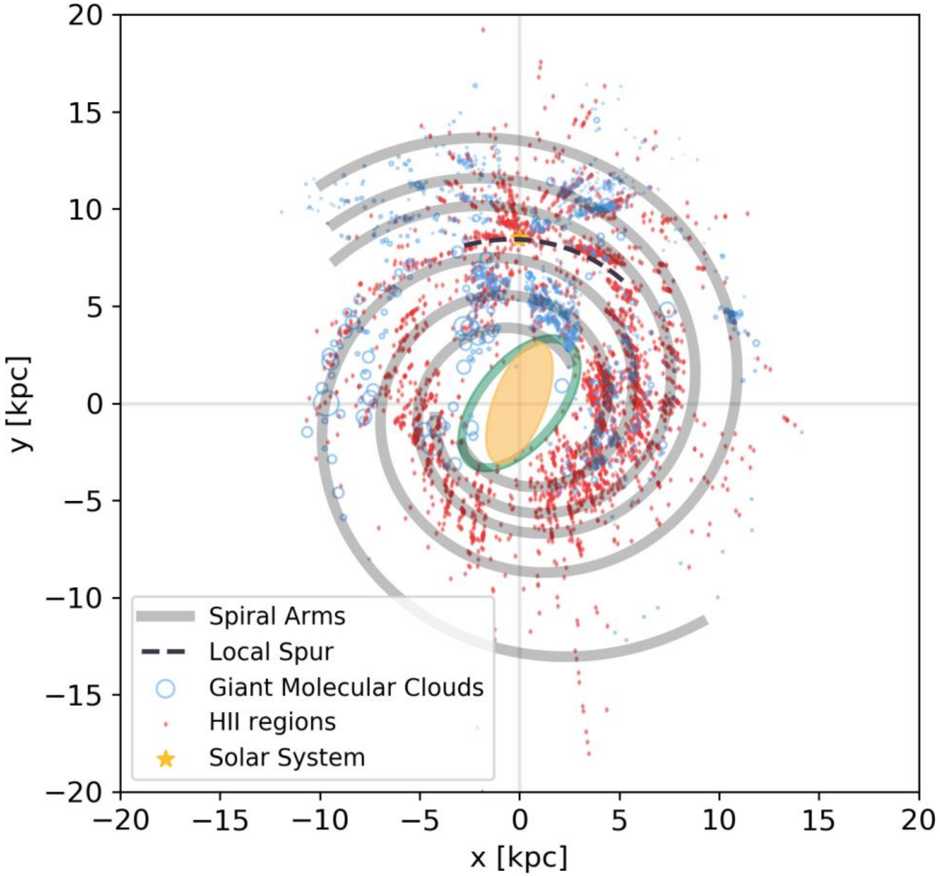
Synthetic YMSCs population (I)

YMSC distribution function: $\xi_{SC}(M_{SC},t,r,\theta) = \frac{dN_{SC}}{dM_{SC}dtdrd\theta} = f(M_{SC})\psi(t)\rho(r,\theta)$



- Cluster IMF: $f(M_{SC}) \propto M_{SC}^{-1.54}$ [2.5 – 6.3x10^4 M$_\odot$] (Piskunov et al, 2018)
- Cluster formation rate: $\overline{\psi} = 1.8$ Myr^{-1} kpc^{-2} (Bonatto et al 2011)
- Cluster radial distribution follow giant molecular cloud (Hou & Han 2014)



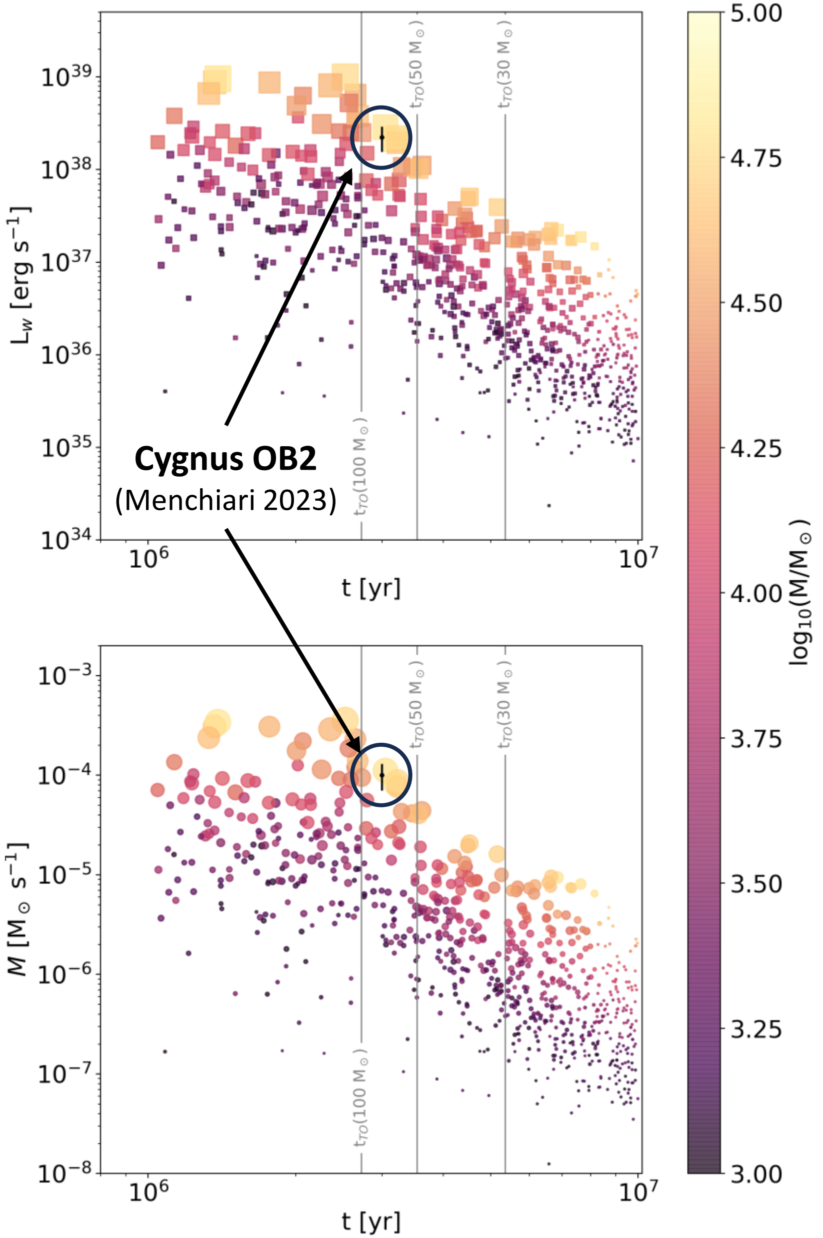


Synthetic YMSCs population (II)

Cluster wind luminosity vs cluster age

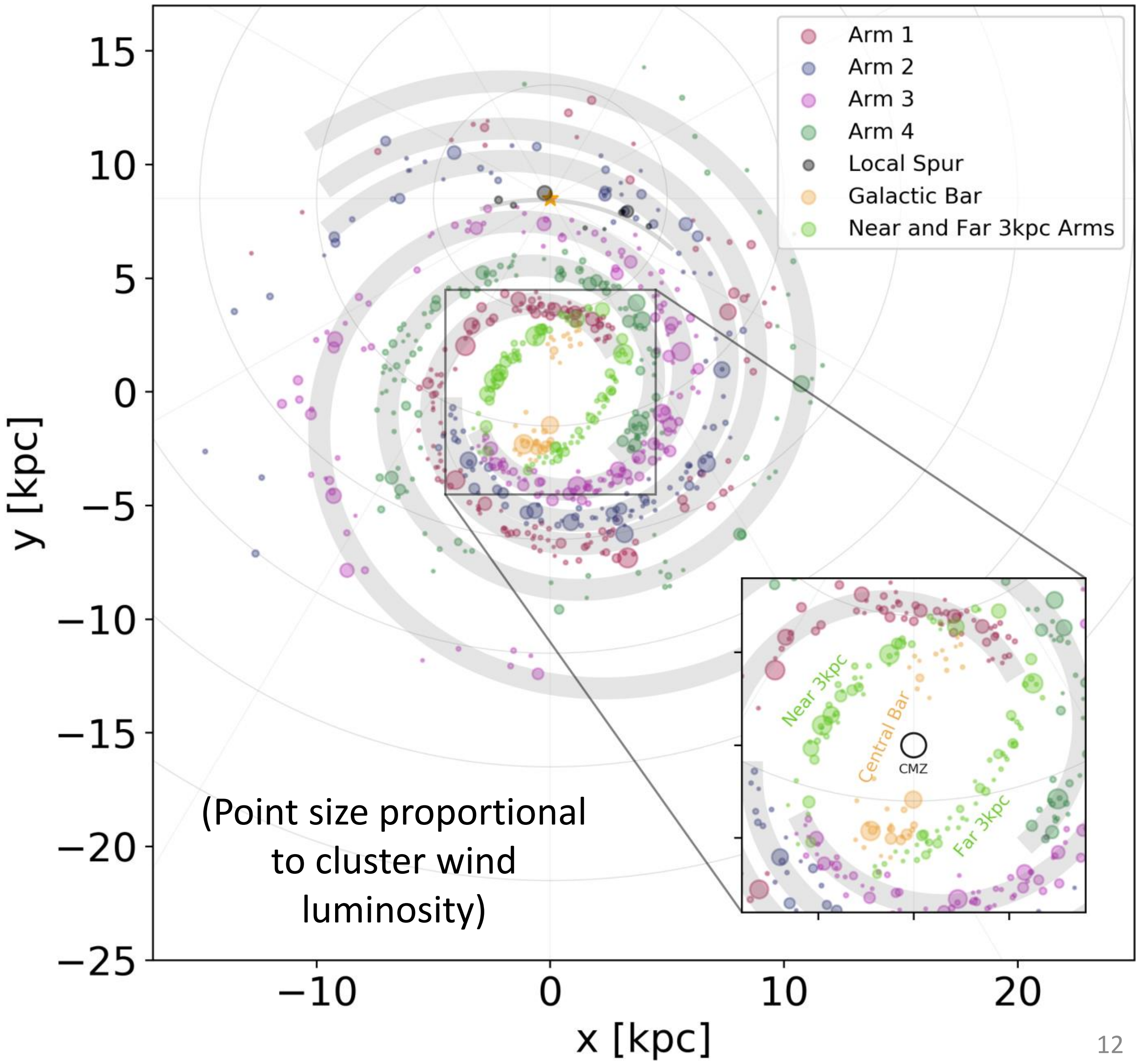
(Point size proportional to number of O-type stars)

Cluster wind mass loss rate vs cluster age



Total number of YMSCs: 747

(Age <10 Myr, M_{SC} >10^3 $M_\odot$)



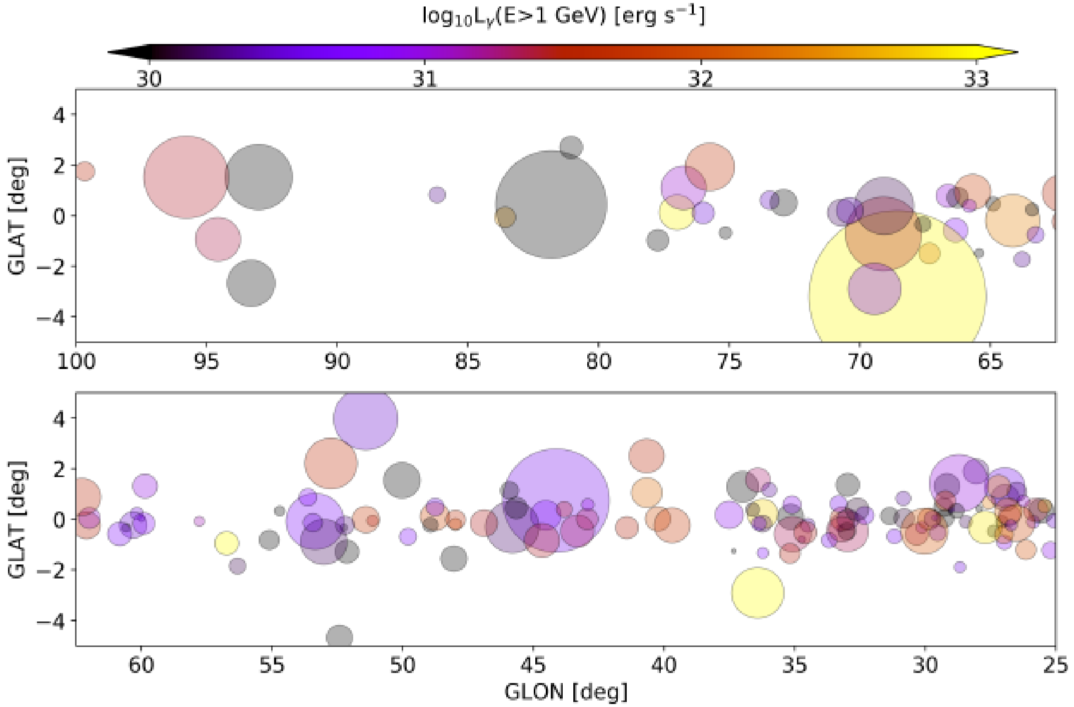
(Point size proportional to cluster wind luminosity)

Diffuse γ-ray emission (ROI1)

Hadronic γ-ray emission for single YMSC
(cross section: by Kafexhiu et al 2014)

$$\phi_\gamma(E_\gamma) = \frac{cn_0}{d^2} \int \int_{R_{TS}}^{R_b} r^2 f(r, E_p) \frac{d\sigma(E_p, E_\gamma)}{dE_p} dr dE_p$$

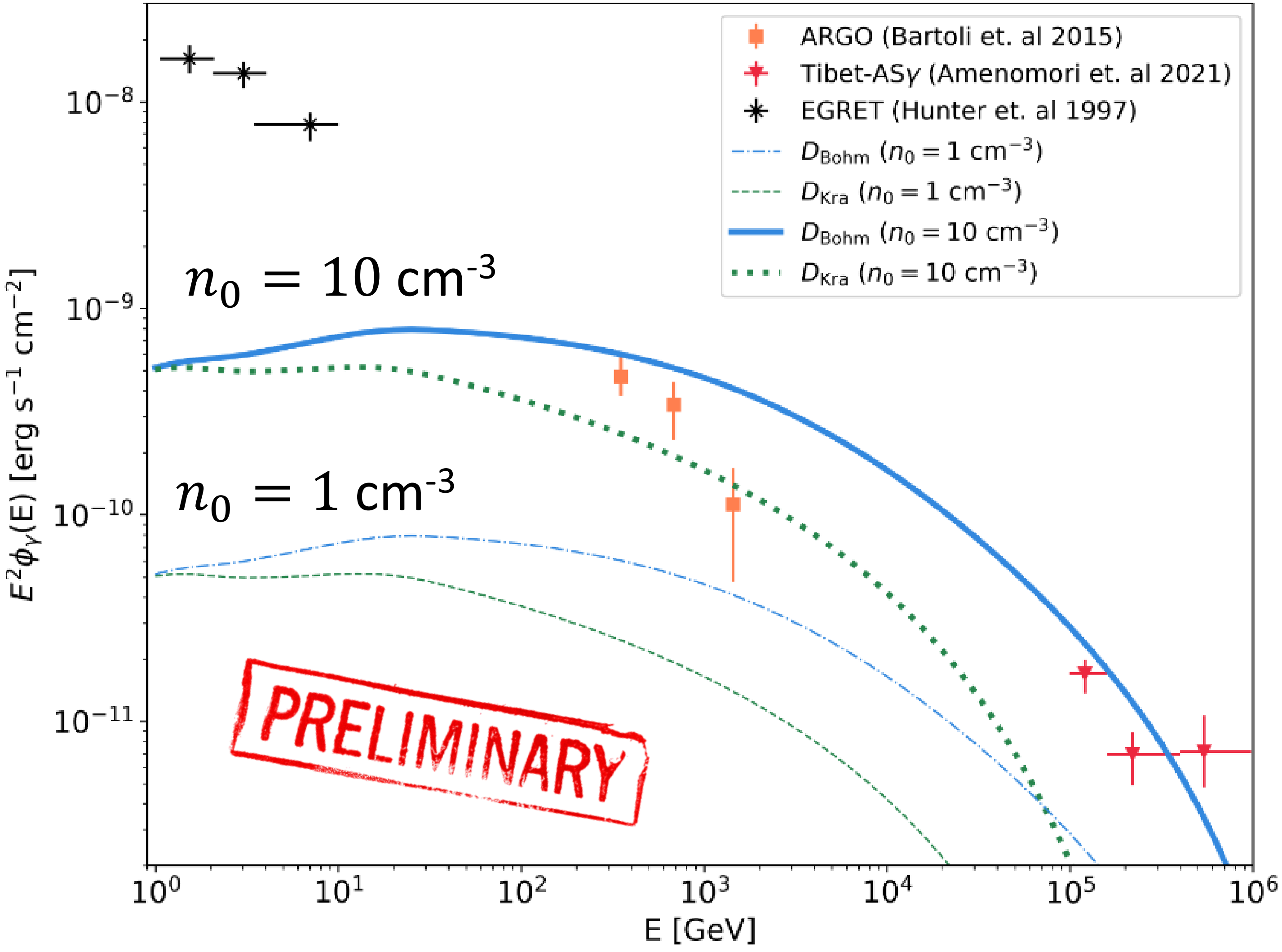
SIGNIFICANT EMISSION AT E>100 GeV!



Comparison with EGRET, ARGO and Tibet-ASγ data

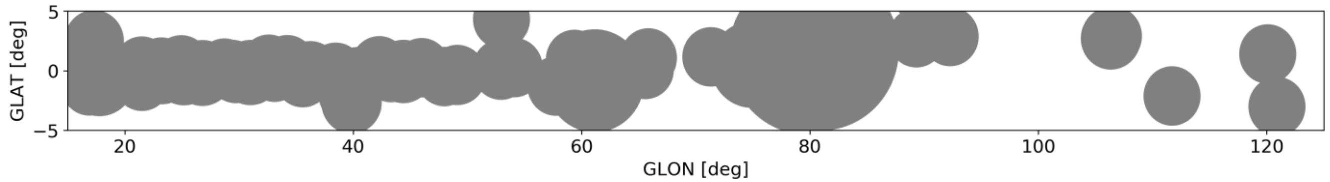
(Hunter et al 1997, Bartoli et al 2015, Amenomori et al 2021)

Region investigated: 100°<l<25° and -5°<b<5°



Diffuse γ-ray emission (ROI2)

γ-ray emission extracted after masking known sources



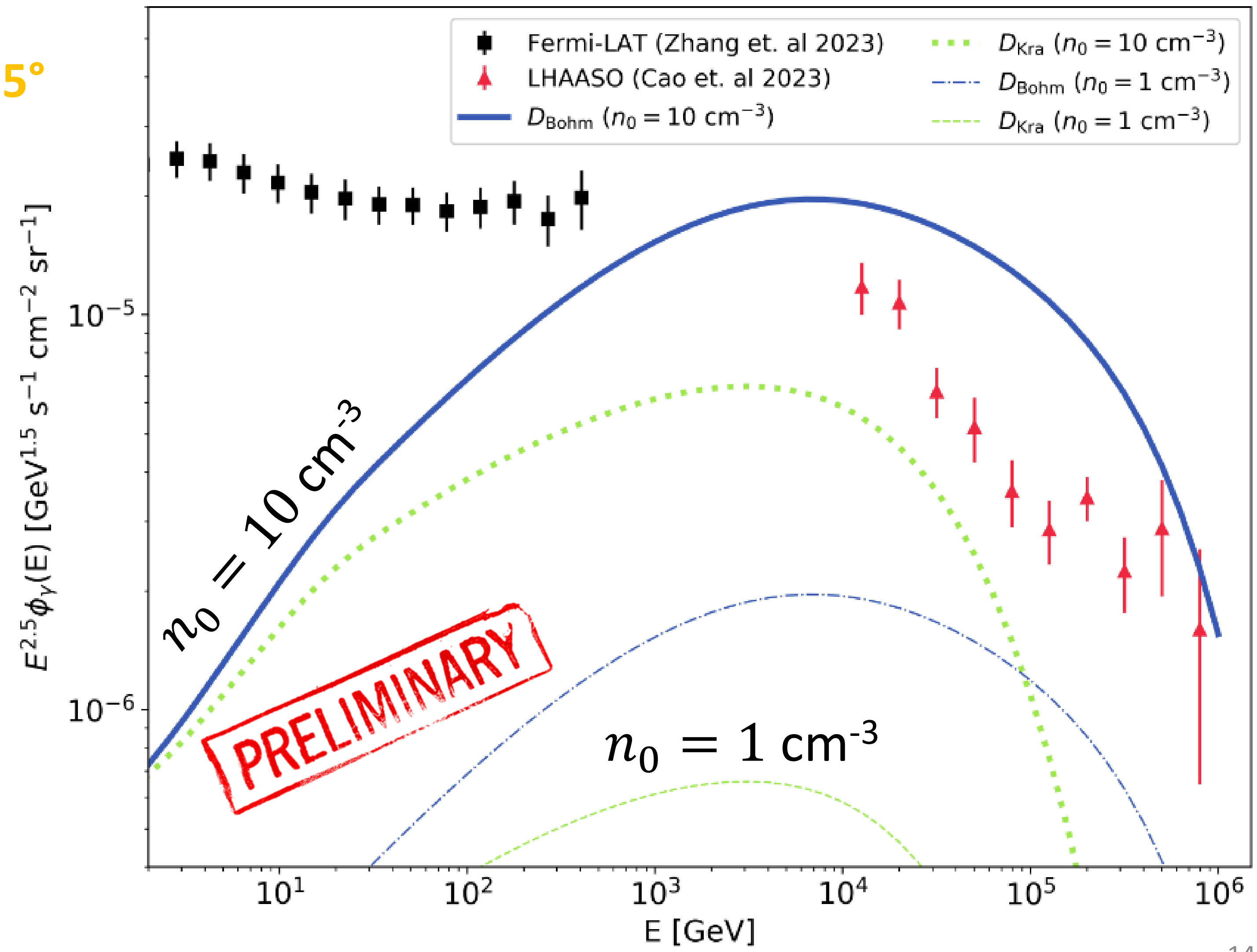
Comparison with Fermi-LAT, and LHAASO data (Zhang et al 2023, Cao et al 2023)

Region investigated: 125°<l<15° and -5°<b<5°

In Bohm regime γ-ray emission can be significant in the range 10 < E < 100 TeV

Statistical fluctuation must be taken into account!

Average emission from multiple realizations of the galactic population is necessary to obtain a robust flux estimation



Conclusions

❖ Importance of YMSCs as high energy sources has constantly growing in the last decades

❖ **First comprehensive study of Galactic population of YMSCs**

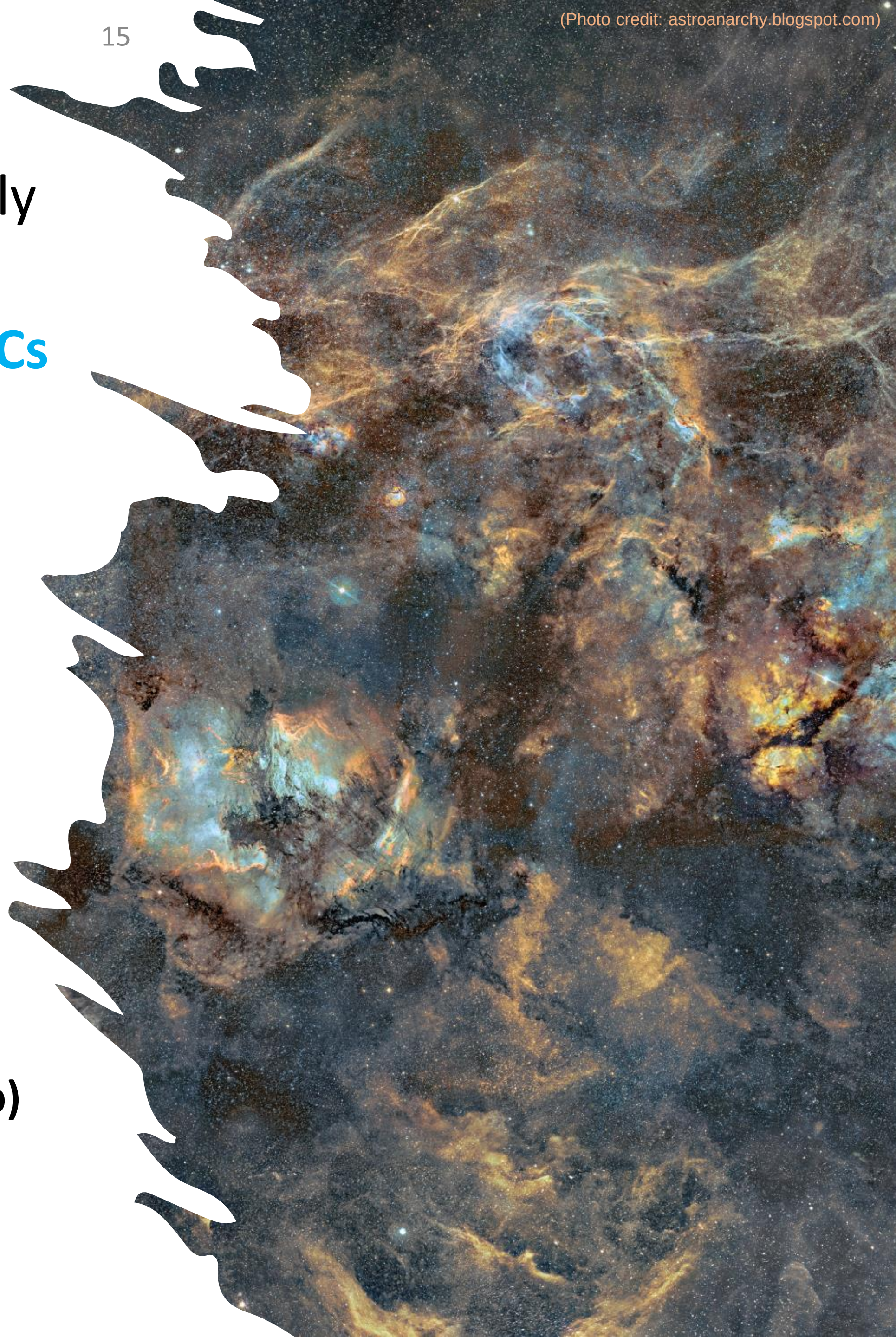
❖ **Contribution to the diffuse emission likely not negligible from hundreds of GeV to hundreds of TeV.**

Future prospects

- Evaluate contribution to neutrino flux
- Population study cross check with Milky-Way like galaxies

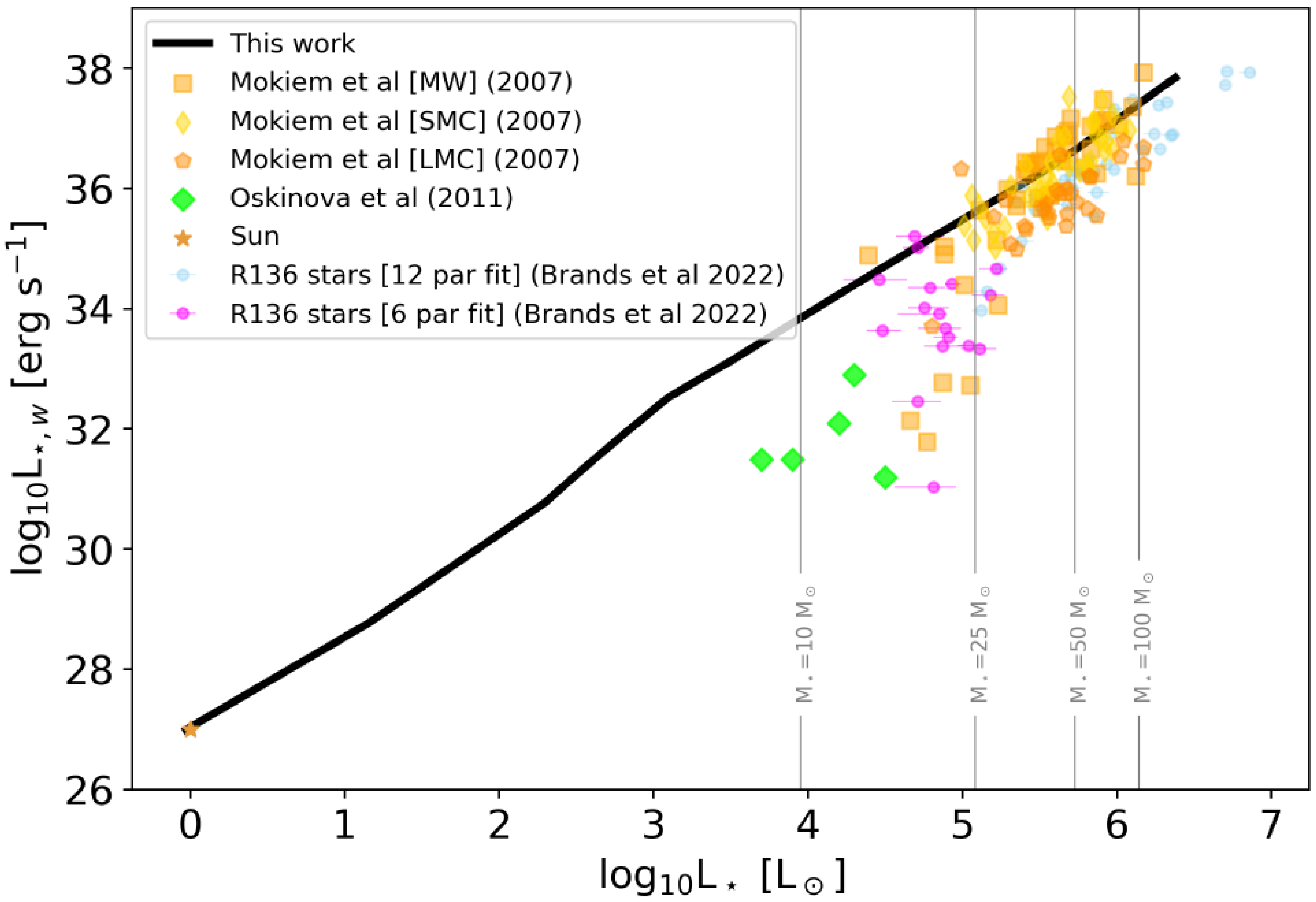
Additional ongoing works

- Contribution to Galactic cosmic rays from young stellar clusters, by **Giovanni Morlino et al. (in prep)**
- Searching for evidence of PeVatron activity from stellar clusters via gamma-ray and neutrino signatures, **Alison M. W. Mitchell et al. (in prep)**
- Gamma-ray emission from molecular clouds illuminated by local young massive stellar clusters and detection prospects with current and next generation instruments, by **Silvia Celli et al. (in prep)**

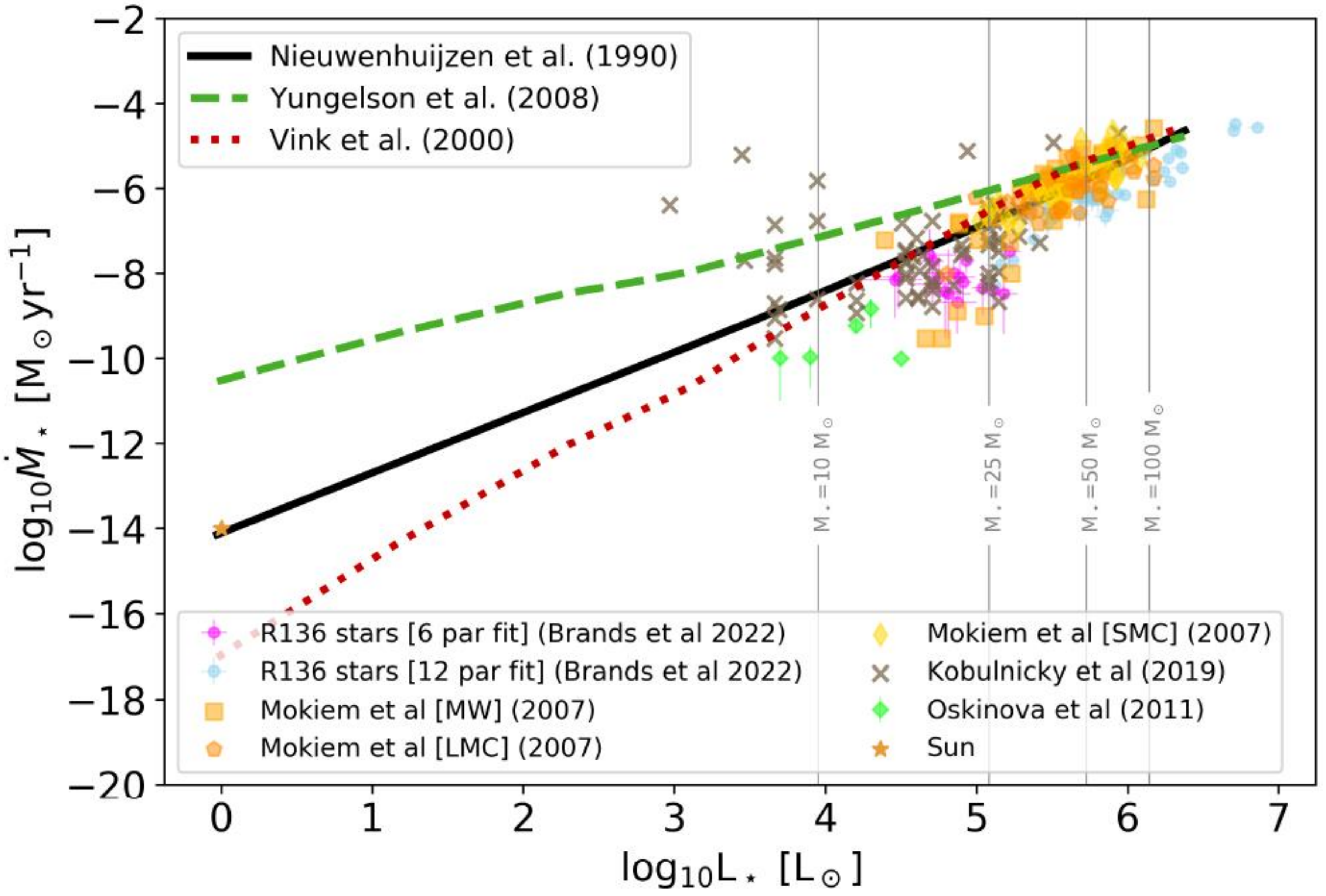


BACKUP SLIDES

Stellar wind power

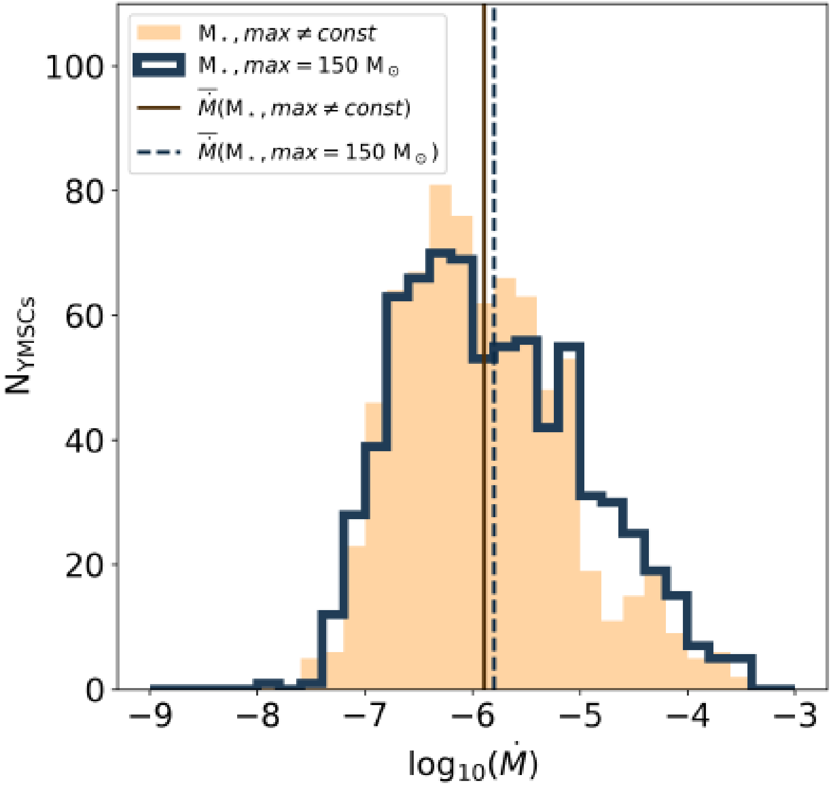


Stellar wind mass loss rate

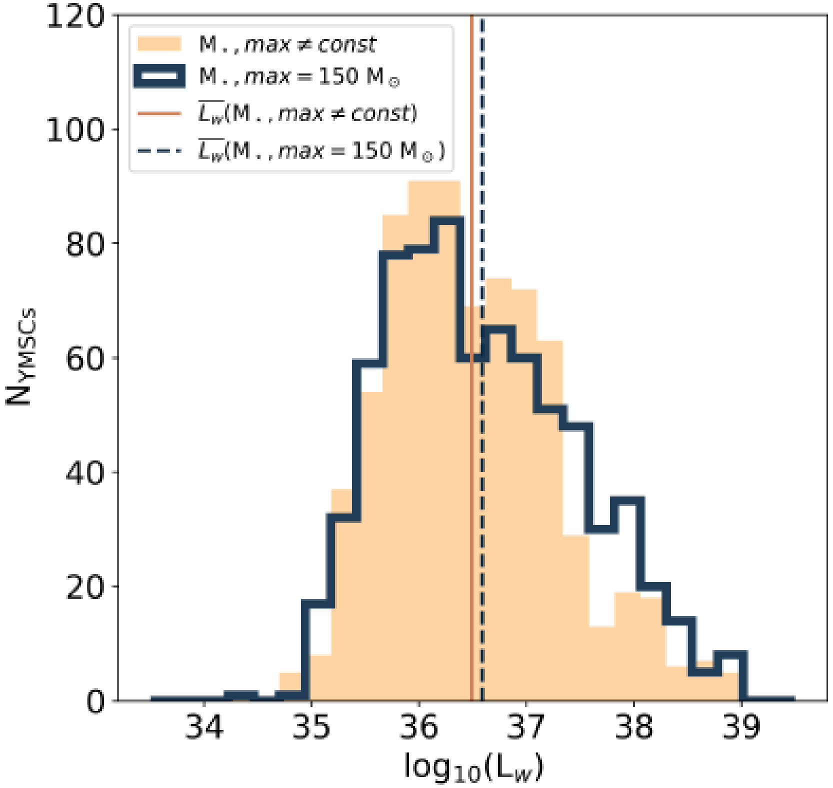


Cluster population study (I)

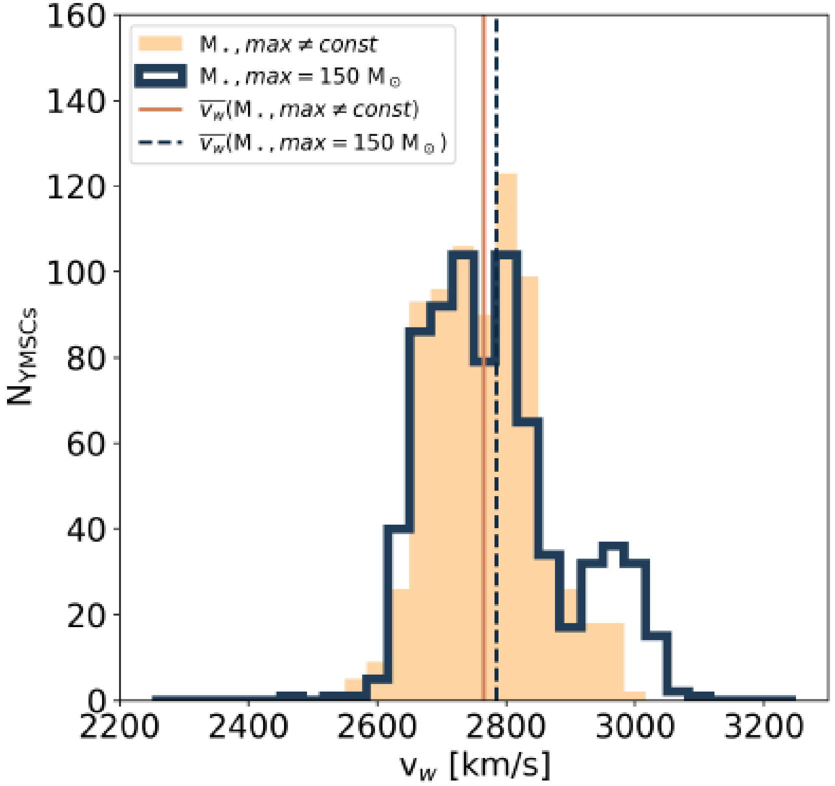
Mass loss rate



Wind luminosity



Wind velocity



CR accelerated by YMSC

Morlino et al. (2022): CRs accelerated at the wind TS

$$① \quad f_1(r,p) \simeq f_{TS}(p) \cdot exp\left[-\int_r^{R_{TS}} \frac{u_1}{D_1(r',p)} dr'\right]$$

$$② \quad f_2(r,p) = f_{TS}(p) e^{\alpha} \frac{1+\beta(e^{\alpha_B - \alpha}-1)}{1+\beta(e^{\alpha_B}-1)} + f_{gal}(p) \frac{\beta(e^{\alpha}-1)}{1+\beta(e^{\alpha_B}-1)}$$

$$③ \quad f_{ism}(r,p) = f_2(R_b,p)\frac{R_b}{r} + f_{gal}(p)\left(1-\frac{R_{TS}}{r}\right)$$

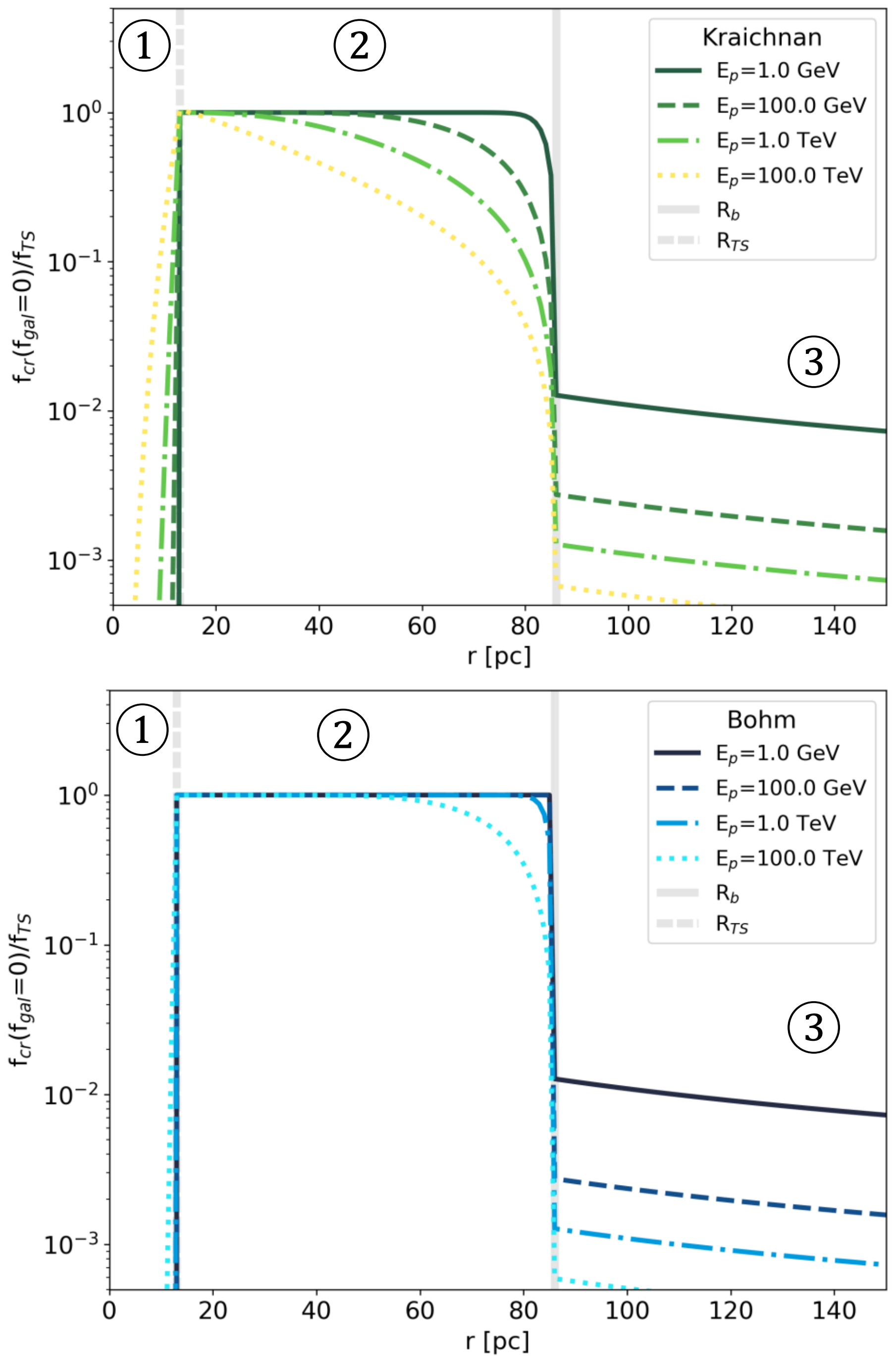
$$f_{TS}(p) \simeq \frac{3 n_1 u_1^2 \epsilon_{CR}}{4\pi \Lambda_p (m_p c)^3 c^2} \left(\frac{p}{m_p c}\right)^{-s} \left[1 + a_1 \left(\frac{p}{p_{max}}\right)^{a_2}\right] e^{-a_3 (p/p_{max})^{a_4}}$$

Models	a_1	a_2	a_3	a_4
Kolmogorov	10	0.308653	22.0241	0.43112
Kraichnan	5	0.448549	12.52	0.642666
Bohm	8.94	1.29597	5.31019	1.13245

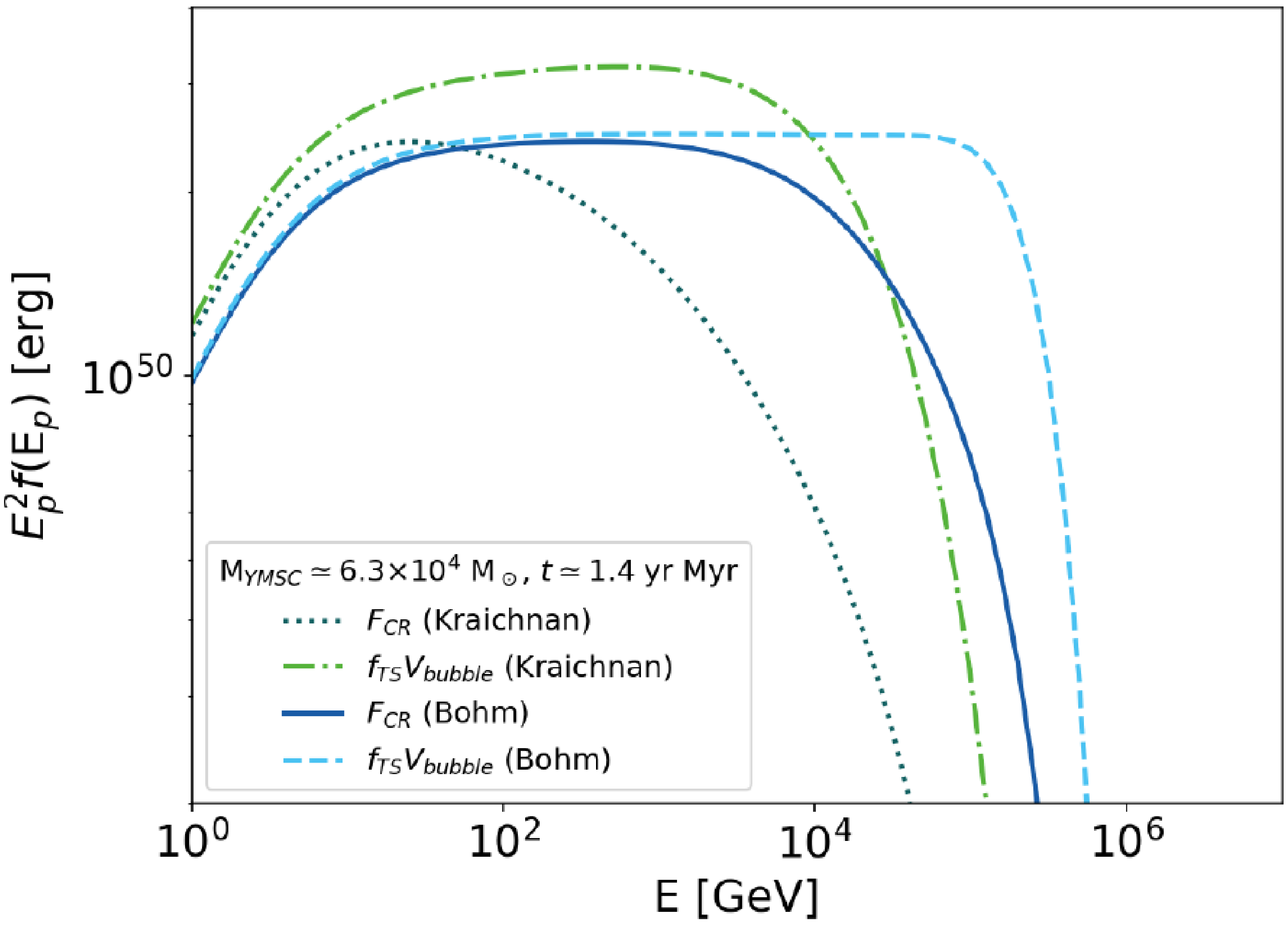
$$\alpha = \alpha(r,p) = \frac{u_2 R_{TS}}{D_2(p)}\left(1-\frac{R_{TS}}{r}\right)$$

$$\alpha_B = \alpha(r=R_b, p)$$

$$\beta = \beta(p) = \frac{D_{ism}(p) R_b}{u_2 R_{TS}^2}$$



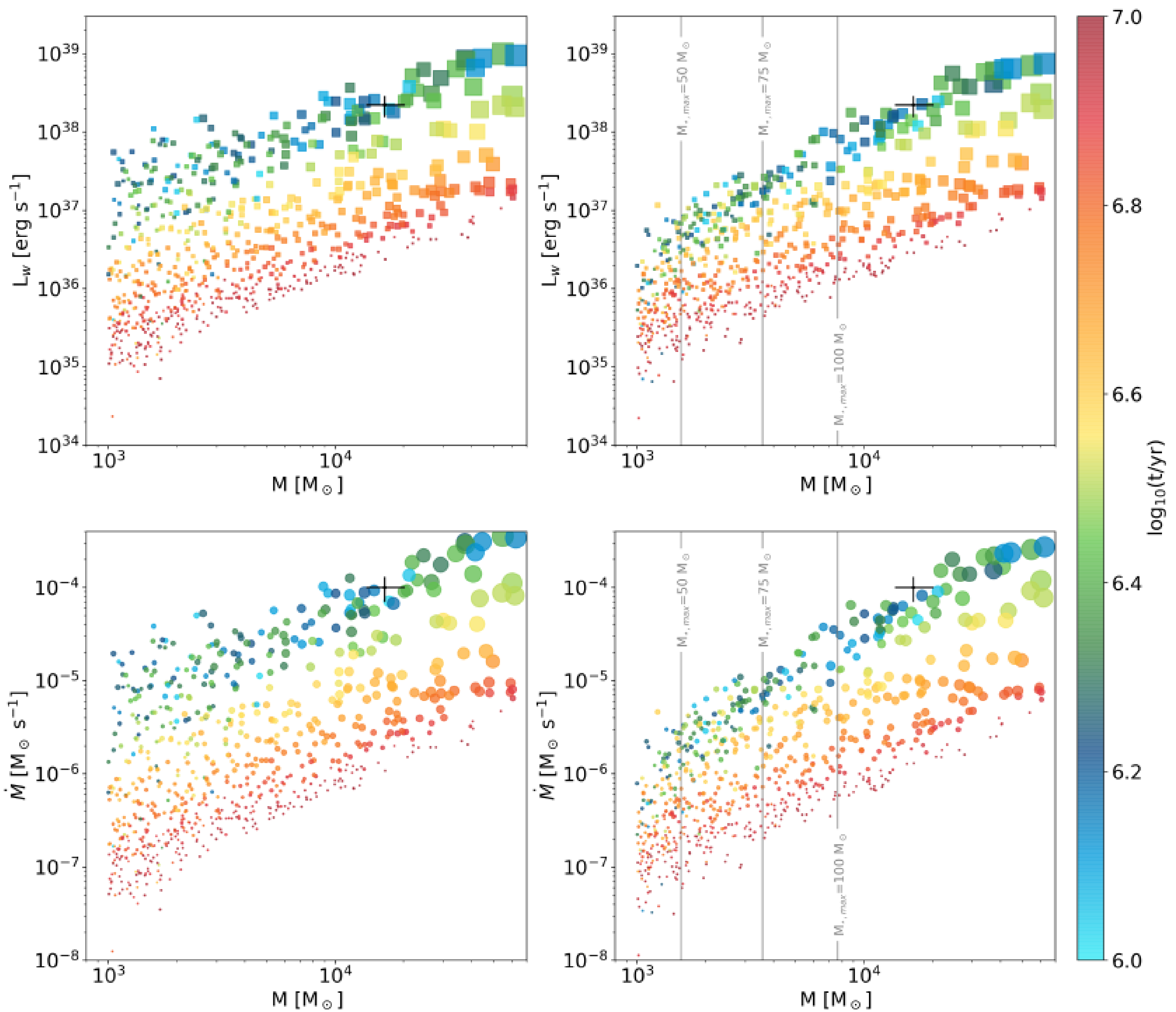
CR accelerated by YMSC (2)



Cluster population study (II)

Left column: Wind luminosity (top) and Mass loss rate (bottom) if maximum stellar mass is 150 $M_\odot$

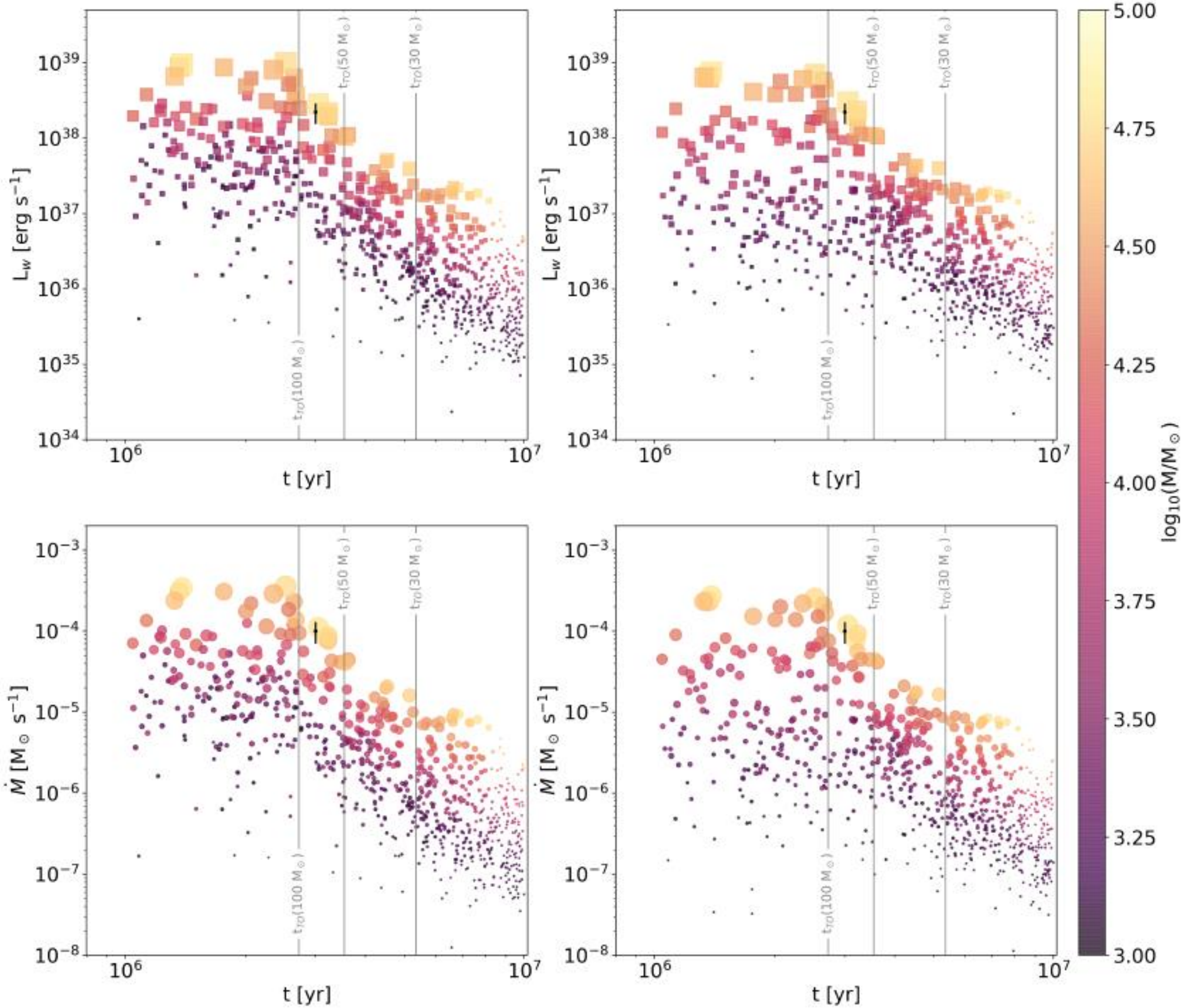
Right column: Wind luminosity (top) and Mass loss rate (bottom) if maximum stellar mass depends on the cluster mass



Cluster population study (III)

Left column: Wind luminosity (top) and Mass loss rate (bottom) if maximum stellar mass is 150 $M_\odot$

Right column: Wind luminosity (top) and Mass loss rate (bottom) if maximum stellar mass depends on the cluster mass



Density environment close to YMSC