Simulating the population of young massive stellar clusters in the Milky Way

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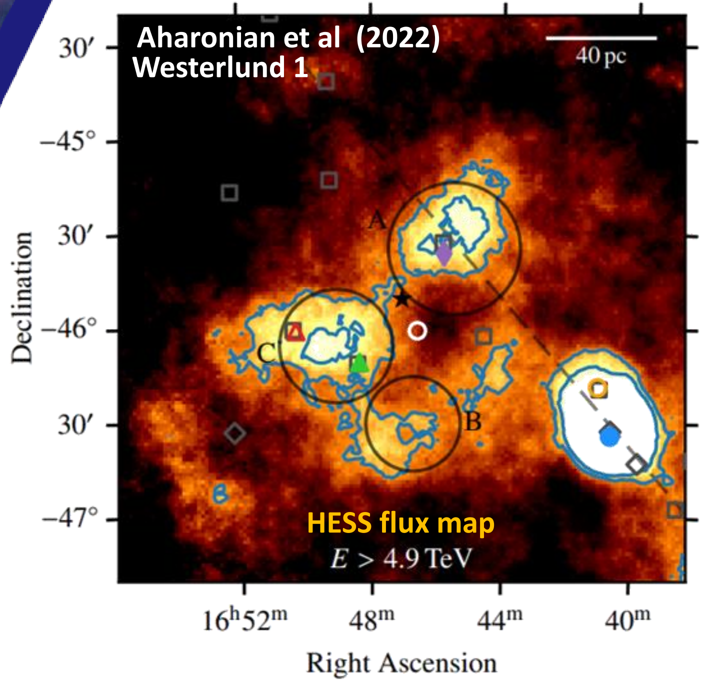
From star clusters to field populations:
survived, destroyed and migrated clusters
Florence – 22/11/2023

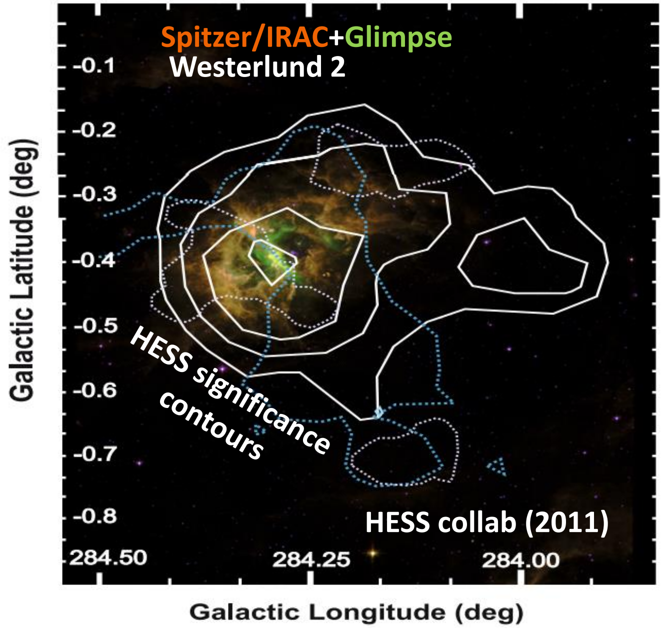
Young massive star clusters: Cosmic rays accelerators and γ-ray sources

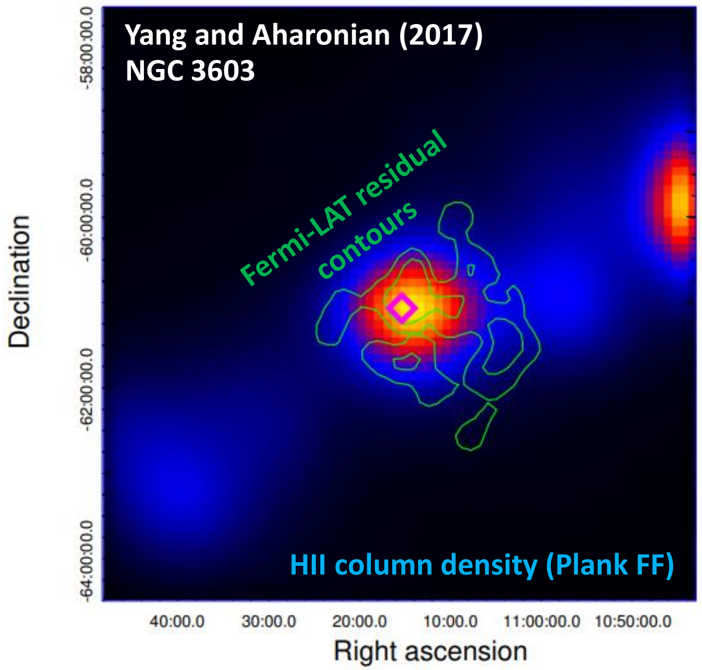
Young (<10 Myr) massive (>10^3 $M_\odot$) stellar clusters (YMSCs) are cosmic ray factories

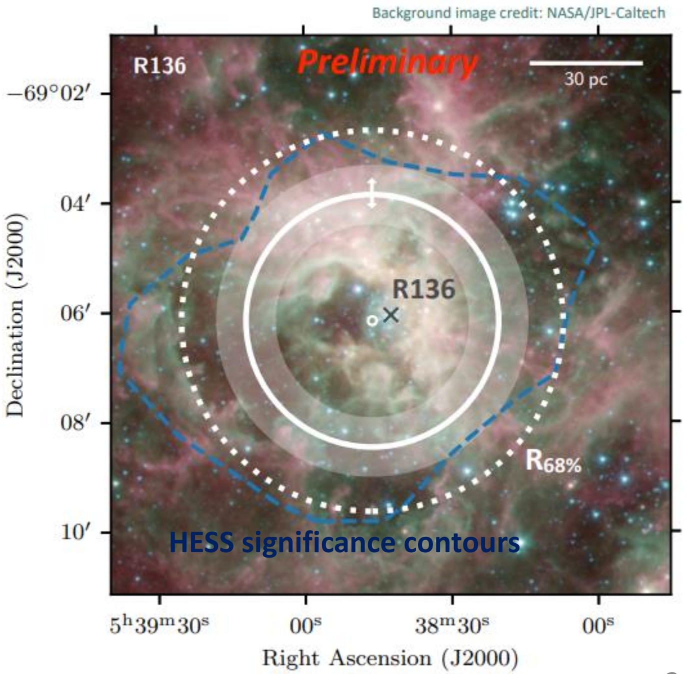
γ-ray emission detected in coincidence with **12 YMSC!**

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	









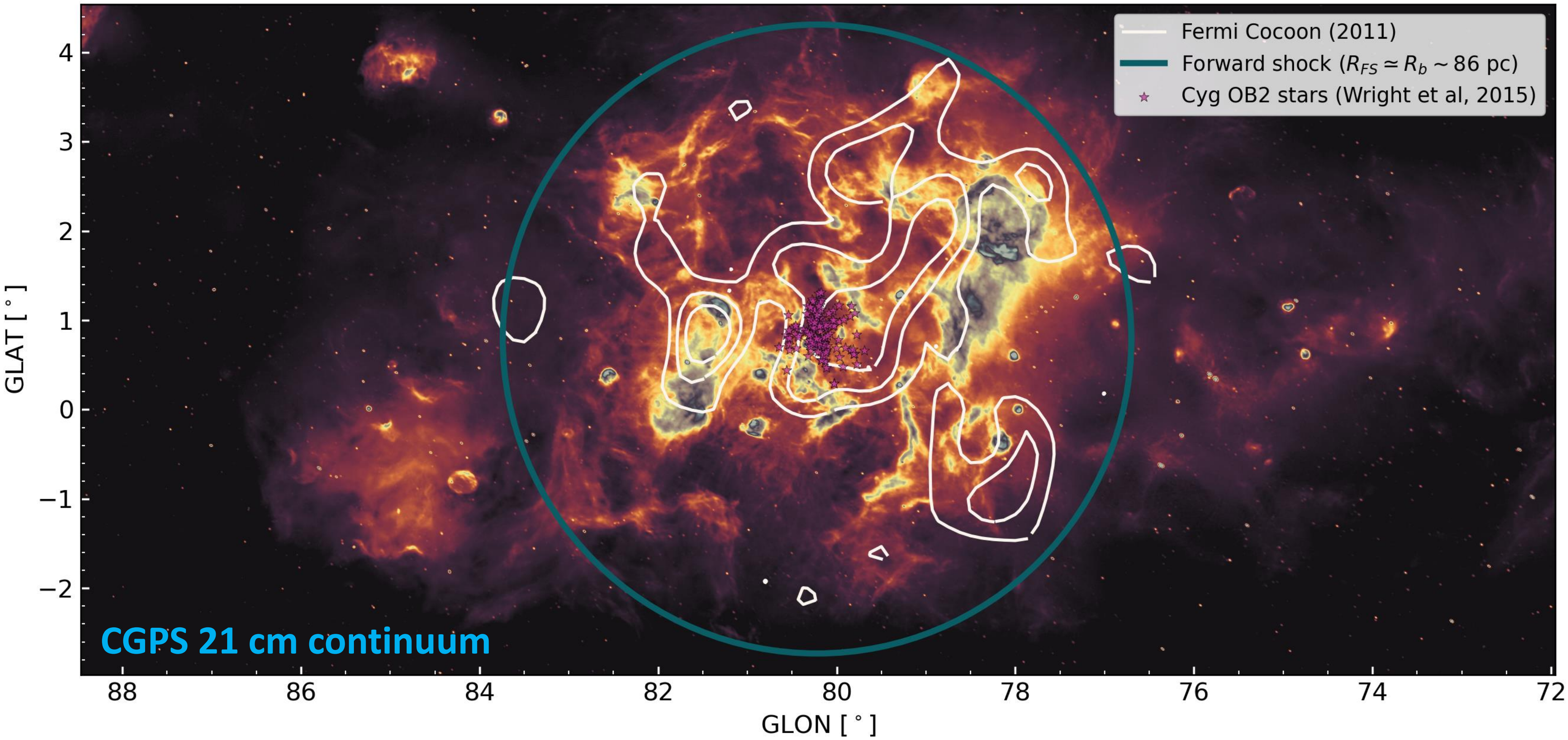
L. Mohrmann (TeVPA 2023)

Diffuse γ-ray emission

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

→ Emission size consistent with projected dimension of wind-blown bubbles

→ **Detecting and analyzing diffuse γ-ray emission is a challenging task!**
Detection bias for low surface brightness sources



Work motivation

Detection of individual YMSCs is challenging…

⇓

Collective emission from YMSCs could be detected as a non-resolved contribution to diffuse galactic gamma-ray emission!

⇓

To estimate this contribution the knowledge of YMSCs population is required

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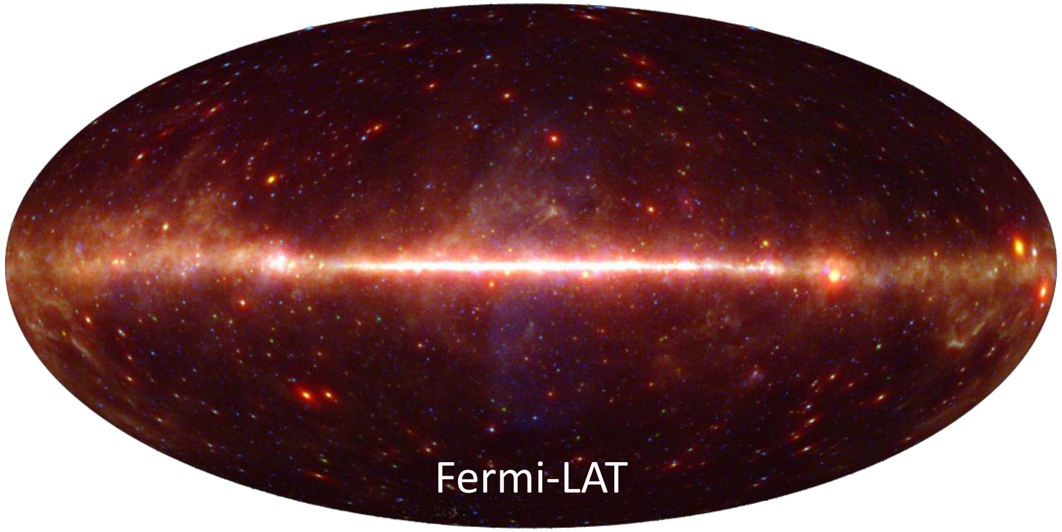
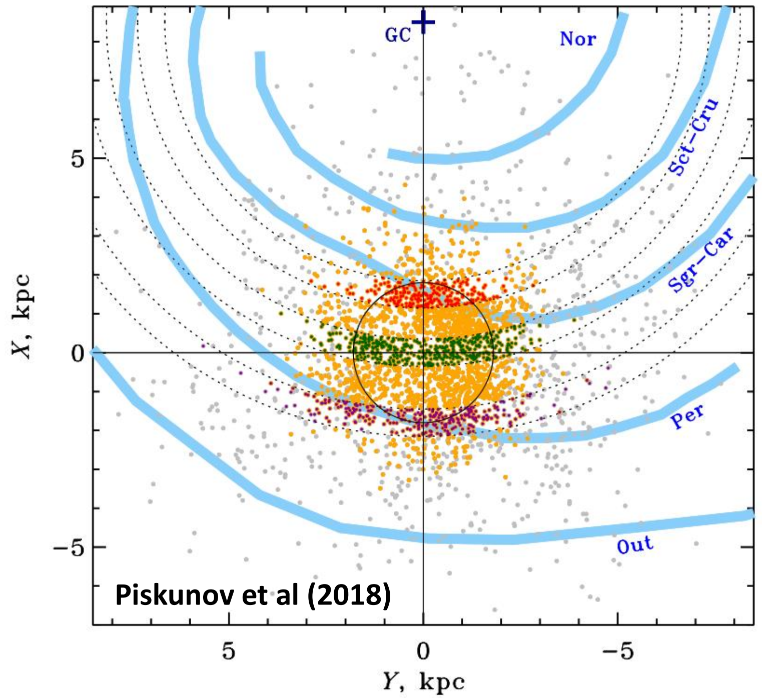
Population of YMSCs only know locally…

⇓

Simulation of a synthetic population!

Diffuse emission = CRs sea **+ unresolved sources**





Work objective

Cosmic rays are accelerated thanks to winds from massive stars and supernova explosions (Morlino's talk)

Gamma-ray emission traces extension of wind-blown bubbles

What do we need?

- Wind luminosity and mass loss rate of stellar winds
- Number of supernovae and Wolf-Rayet stars
- Structure of the wind blown bubble

Workflow

1

a) Modeling stellar population in a YMSC

b) Modeling stellar wind physics:
Use pure empirical approach

2

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

Modeling stellar population and wind physics

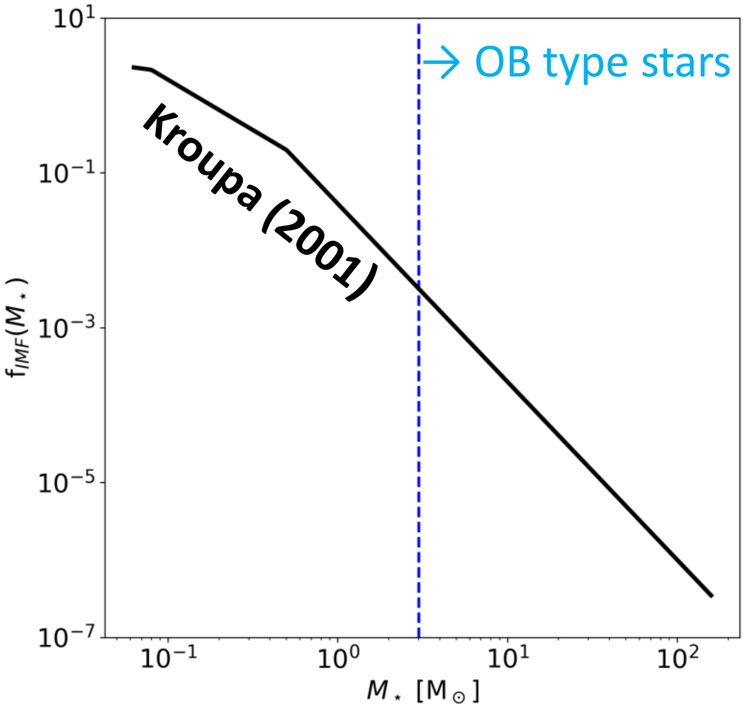
(Photo credit: astroanarchy.blogspot.com)

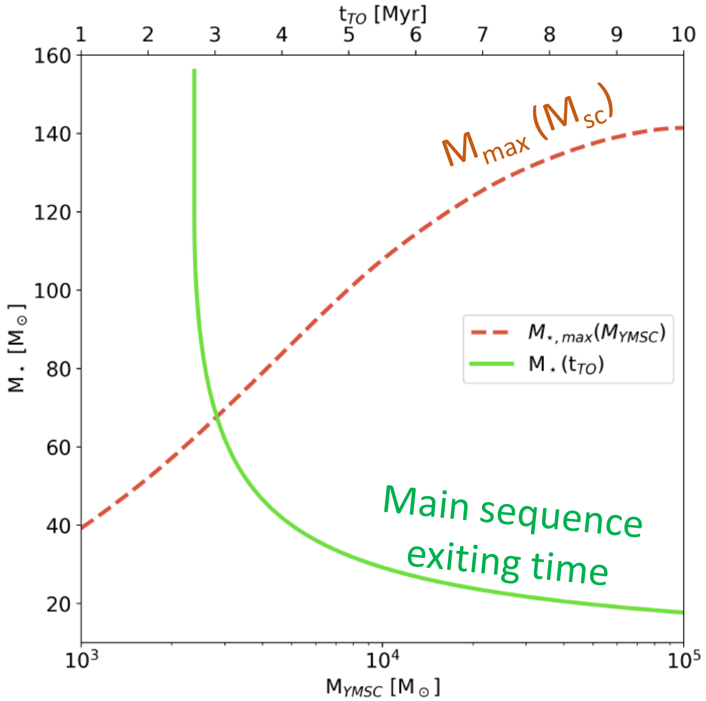
Stellar population in YMSC

- Stars are spawned by random sampling the initial mass function (IMF) (Kroupa 2001)
- Number of stars in a cluster of mass M_{sc} is that

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

- Two possible cases for maximum stellar mass:
  - Constant (150 $M_\odot$)
  - Function of the cluster mass (Weidner et al 2010)
- Label WR and supernovae according to cluster age and turn over time (Buzzoni et al 2002):
  - If $t_{age} > \tau_{to}$: Main sequence star
  - If $\tau_{to} < t_{age} < \tau_{to} + 0{,}3$ Myr and $M_\star > 25\ M_\odot$: WR star (Celli et al 2023)
  - If $t_{age} > \tau_{to} + 0{,}3$ Myr: Supernova (removed)



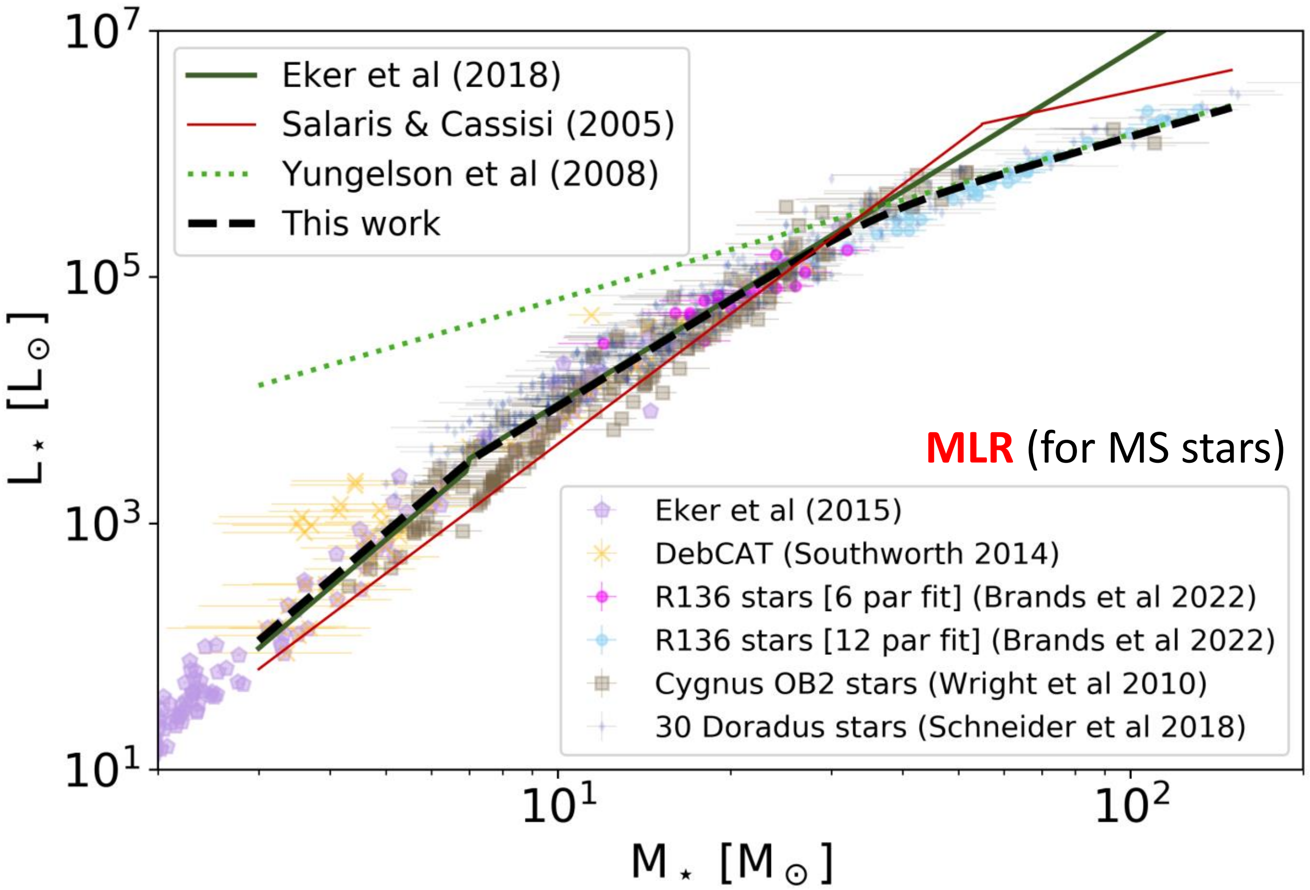


Stellar parameters (MLR)

Stellar parameters calculated using empirical relations

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

$$L_\star = \begin{cases} L_{\rm b1}\left(\frac{M_\star}{7\,{\rm M}_\odot}\right)^{\alpha_1}\left[\frac{1}{2}+\frac{1}{2}\left(\frac{M_\star}{7\,{\rm M}_\odot}\right)^{1/\Delta_1}\right]^{(-\alpha_1+\alpha_2)\Delta_1} & \text{for } 2.4 \leq \frac{M_\star}{{\rm M}_\odot} < 12 \\ \mathcal{K}\,L_{\rm b2}\left(\frac{M_\star}{36\,{\rm M}_\odot}\right)^{\alpha_2}\left[\frac{1}{2}+\frac{1}{2}\left(\frac{M_\star}{36\,{\rm M}_\odot}\right)^{1/\Delta_2}\right]^{(-\alpha_2+\alpha_3)\Delta_2} & \text{for } M_\star \geq 12\ {\rm M}_\odot \end{cases}$$



For WR stars we adopt Schaerer & Maeder (1992):

$$\log\frac{L}{L_\odot} = 3.0321 + 2.695\log\frac{M}{M_\odot} - \left(\log\frac{M}{M_\odot}\right)^2$$

NB: for WRs the mass loss is taken into account!

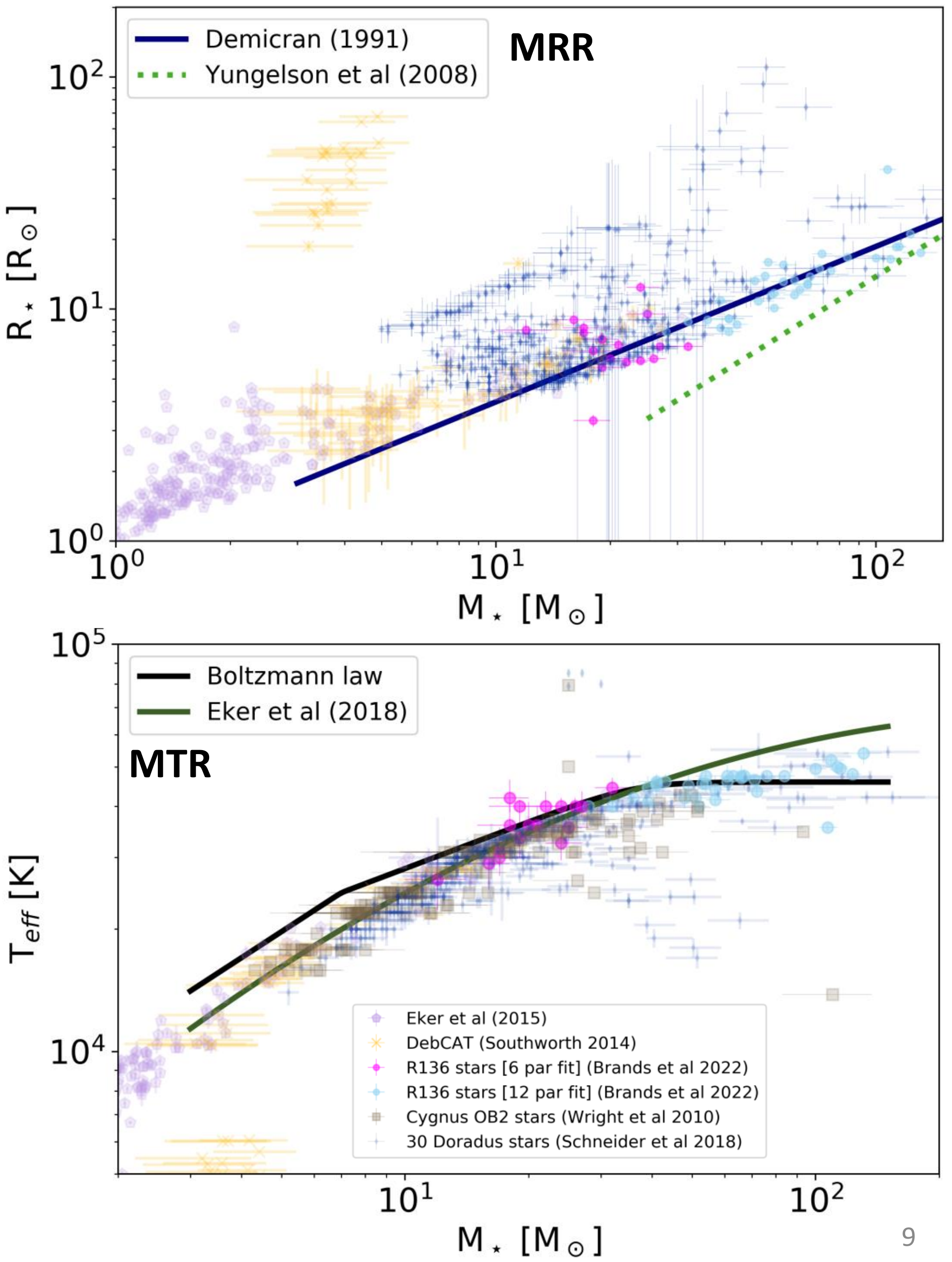
Stellar parameters (MRR-MTR)

Stellar parameters calculated using empirical relations

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

$$R_\star = 0.85 \left(\frac{M_\star}{M_\odot}\right)^{0.67} R_\odot$$

$$T_{\mathrm{eff},\star} = \left(\frac{L_\star}{4\pi R_\star^2 \sigma_b}\right)^{1/4}$$



Stellar wind physics

Wind physics modeled using empirical approach

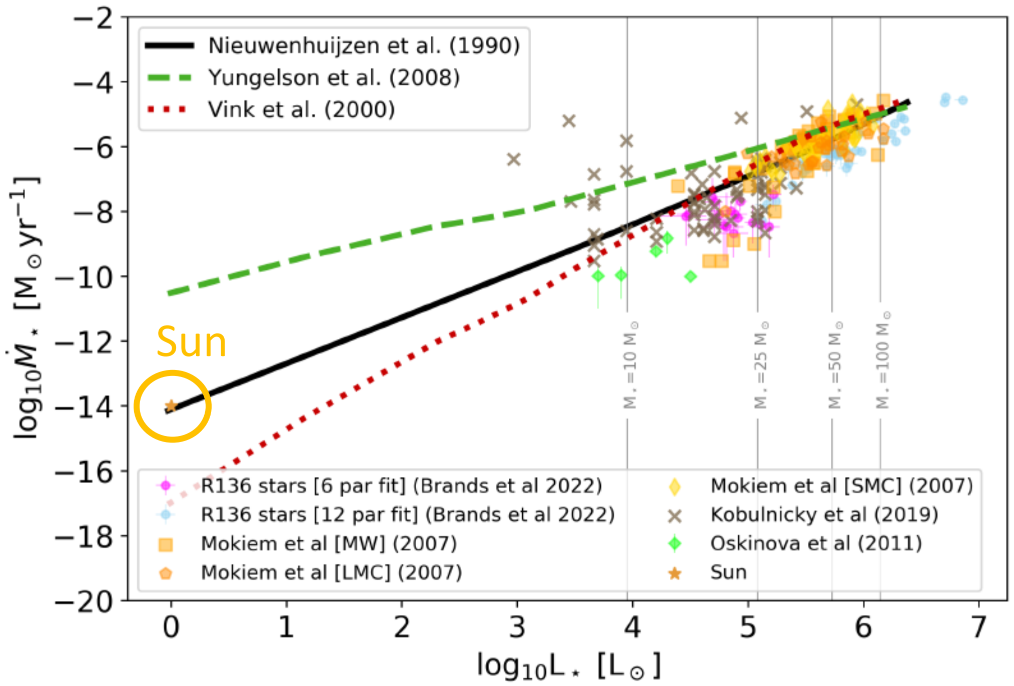
For main sequence stars:

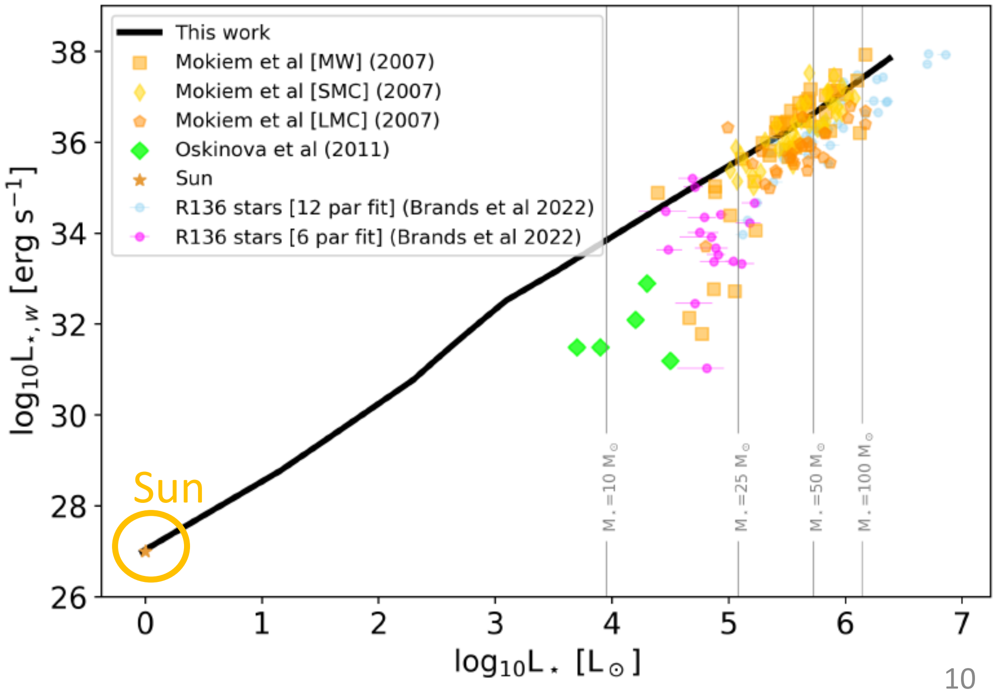
Mass loss rate ($\dot{M}_\star$): Nieuwenhuijzen et al. (1990)

Wind speed ($v_{\star,w}$): Kudritzki & Puls (2000)

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

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





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For WR stars:

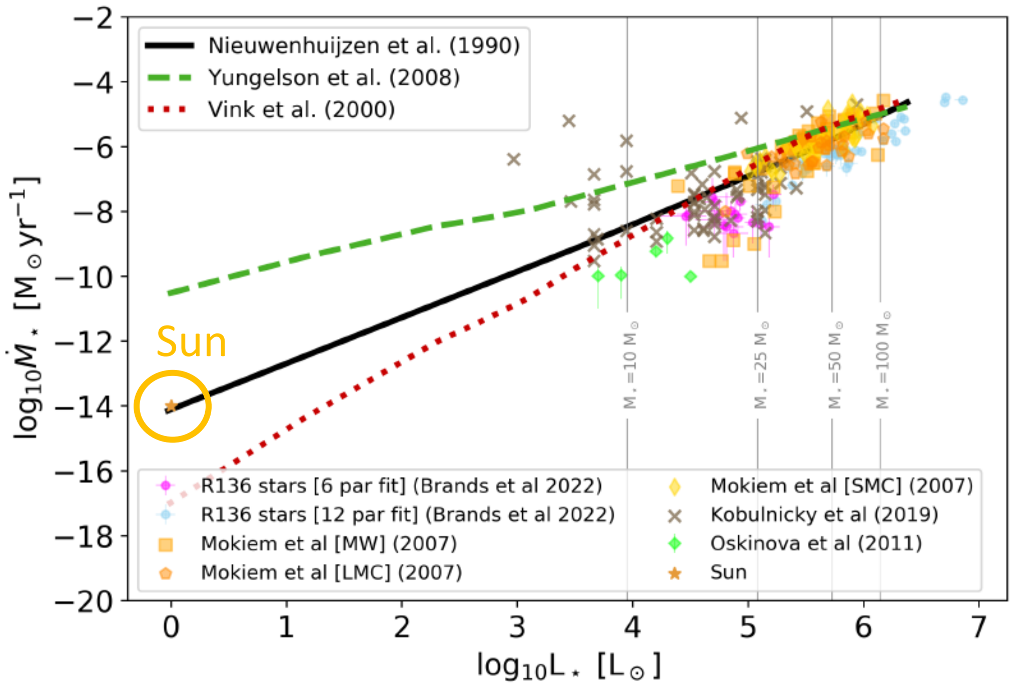
Mass loss rate ($\dot{M}_\star$): Nugis & Lamers (2000)

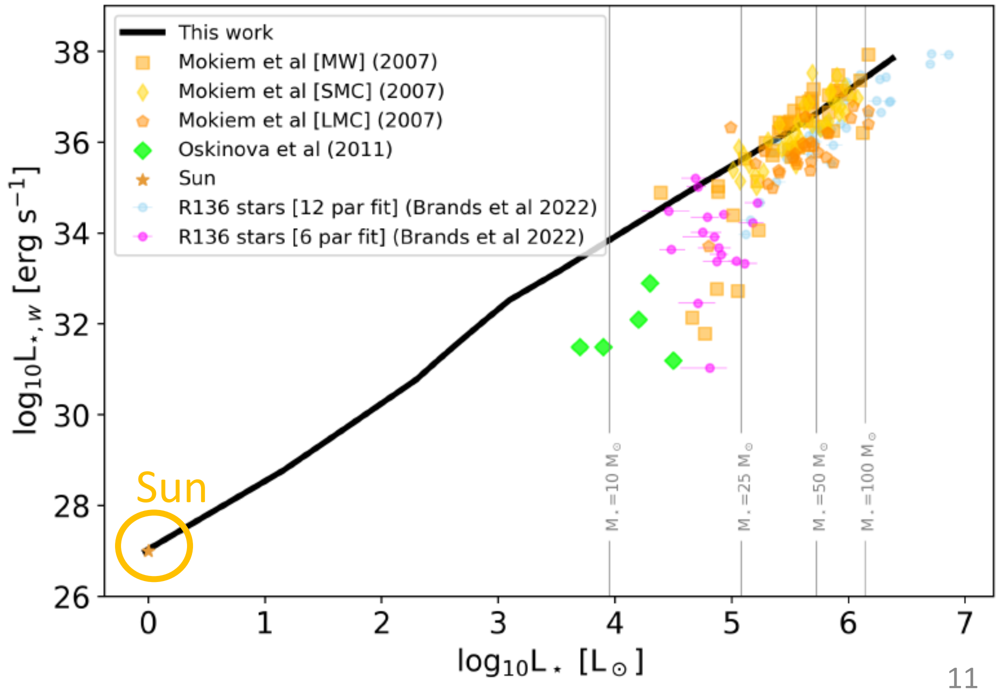
Wind speed ($v_{\star,w}$): 2000 km/s

Assumed solar metallicity

$$\log_{10}\left(-\frac{\dot{M}_{\mathrm{WR},\ i}}{M_\odot yr^{-1}}\right) = -11.0 + 1.29(14)\log_{10}\left(\frac{L_{\mathrm{WR},\ i}}{10^5\ L_\odot}\right) + 1.73(42)\log_{10}\left(\frac{Y_{\mathrm{WR},\ i}}{Y_\odot}\right) + 0.47(09)\log_{10}\left(\frac{Z_{\mathrm{WR},\ i}}{Z_\odot}\right)$$

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





Modeling cluster population

(Photo credit: astroanarchy.blogspot.com)

YMSCs distribution function

Assume factorization!

$$\xi_{SC}(M_{SC}, t, r, \theta) = \frac{dN_{SC}}{dM_{SC}\,dt\,dr\,d\theta} = f(M_{SC})\psi(t)\rho(r,\theta)$$

Initial cluster mass function

Cluster age distribution

Cluster spatial distribution

Generate YMSCs population (I)

YMSC distribution function:

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

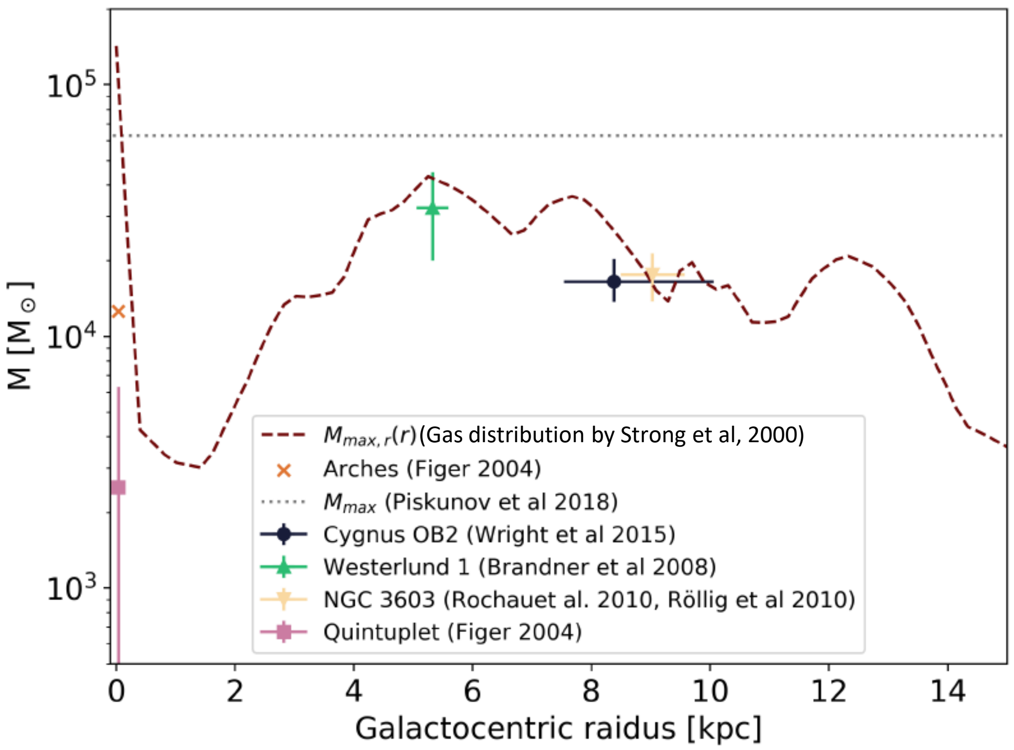
Cluster IMF (Piskunov et al, 2018)

$f(M_{SC}) \propto M_{SC}^{-1.54}$ [2.5 – 6.3x10^4] $M_\odot$

NB: the maximum cluster mass depends on the gas profile

$$M_{max,r}(r) = M_{max}\left[\frac{\Sigma_{gas}(r)}{\Sigma_{gas}(r=0)}\right]^{3/2}$$ (Pflamm-Altenburg&Kroupa, 2008)

For simplicity we consider it constant



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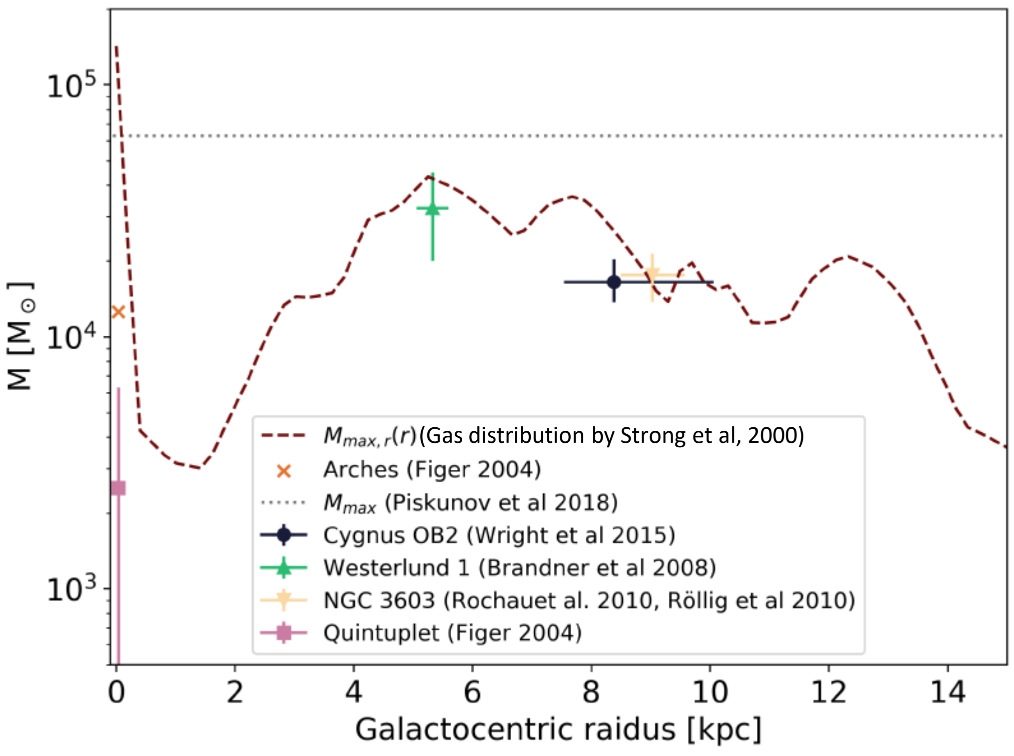
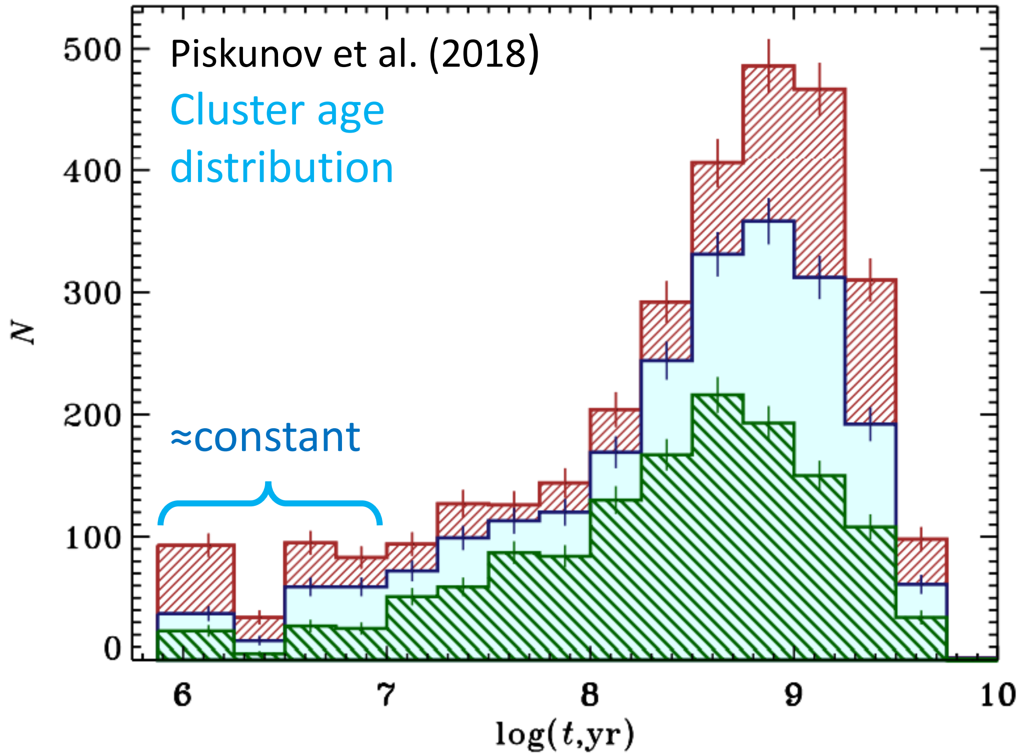


Cluster formation rate

SFR_{sc} = 790 M$_\odot$ Myr^{-1} kpc^{-2} (Bonatto et al 2011)

$$\bar{\psi} = \frac{SFR_{sc}}{\int M_{sc} f(M_{sc}) dM_{sc}} = 1.8\,\text{Myr}^{-1}\text{kpc}^{-2}$$



Generate YMSCs population (II)

YMSC distribution function:

$$\xi_{SC}(M_{SC}, t, r, \theta) = \frac{dN_{SC}}{dM_{SC}\,dt\,dr\,d\theta} = f(M_{SC})\psi(t)\underline{\rho(r,\theta)}$$

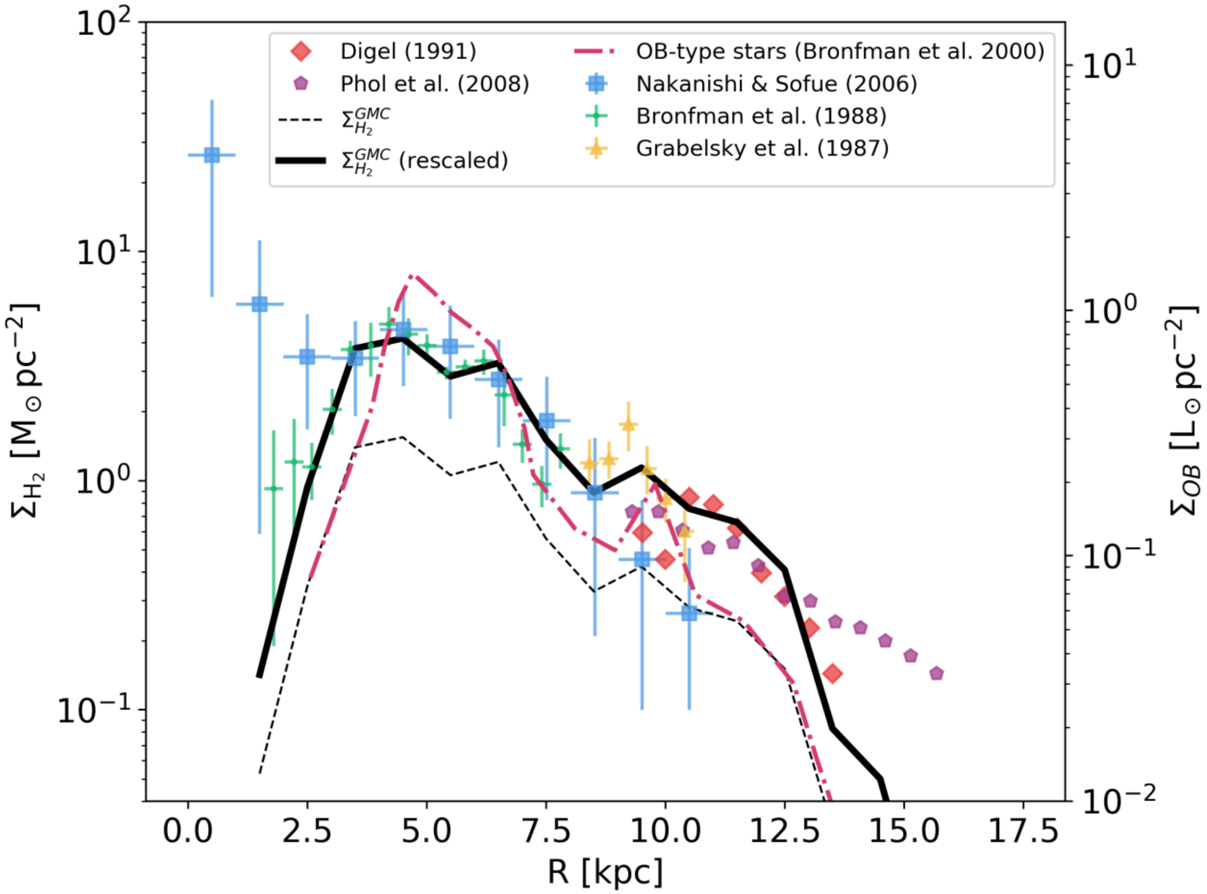
Cluster distribution in galaxy

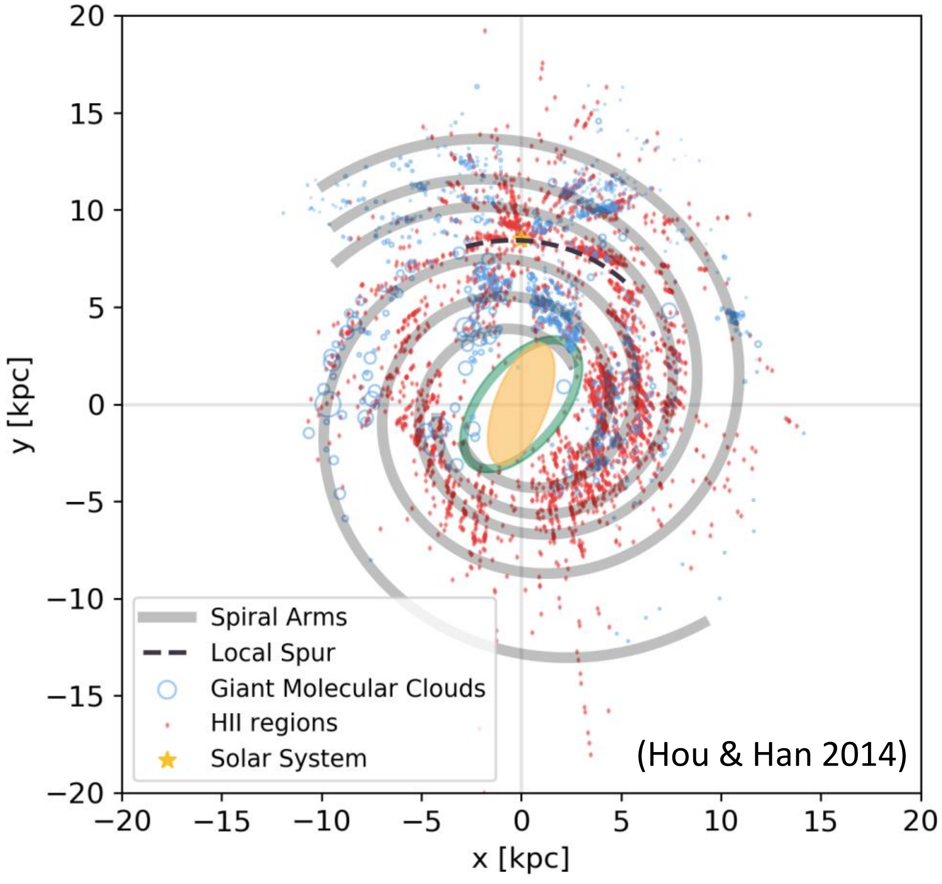
Radial position traced by giant molecular clouds

Position in (x,y): random (r, θ) -> associate with structures [*see backup slides*]

Position in (z): random (z) following gas distribution (Strong et al 2000)

Parameters	Arm 1	Arm 2	Arm 3	Arm 4	Local Spur
R_i [kpc]	3.27	4.29	3.58	3.98	8.16
Ψ_i [°]	9.87	10.51	10.01	8.14	2.71
θ_i [°]	38.5	189	215.2	320.1	50.6

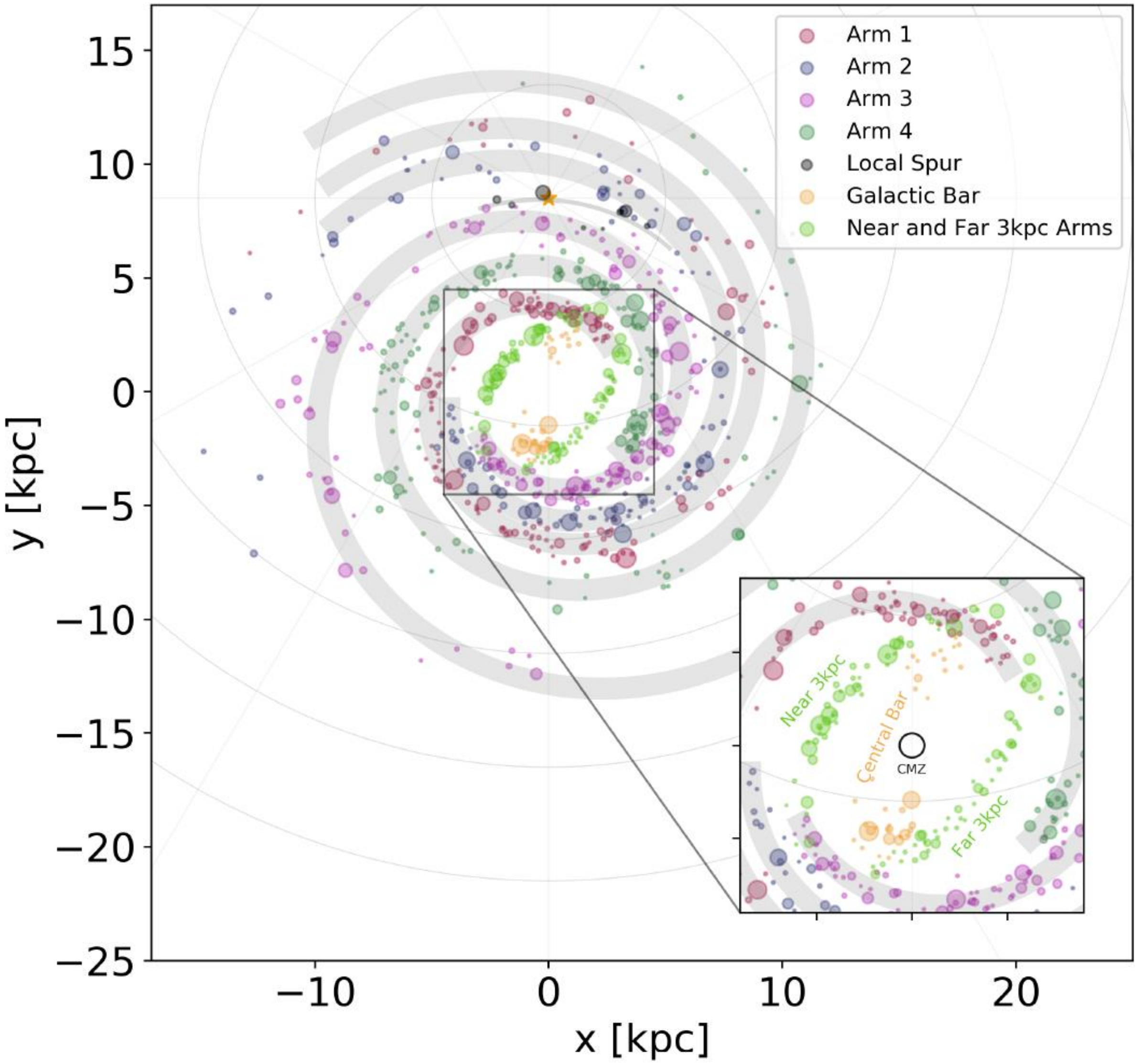




Results

(Photo credit: astroanarchy.blogspot.com)

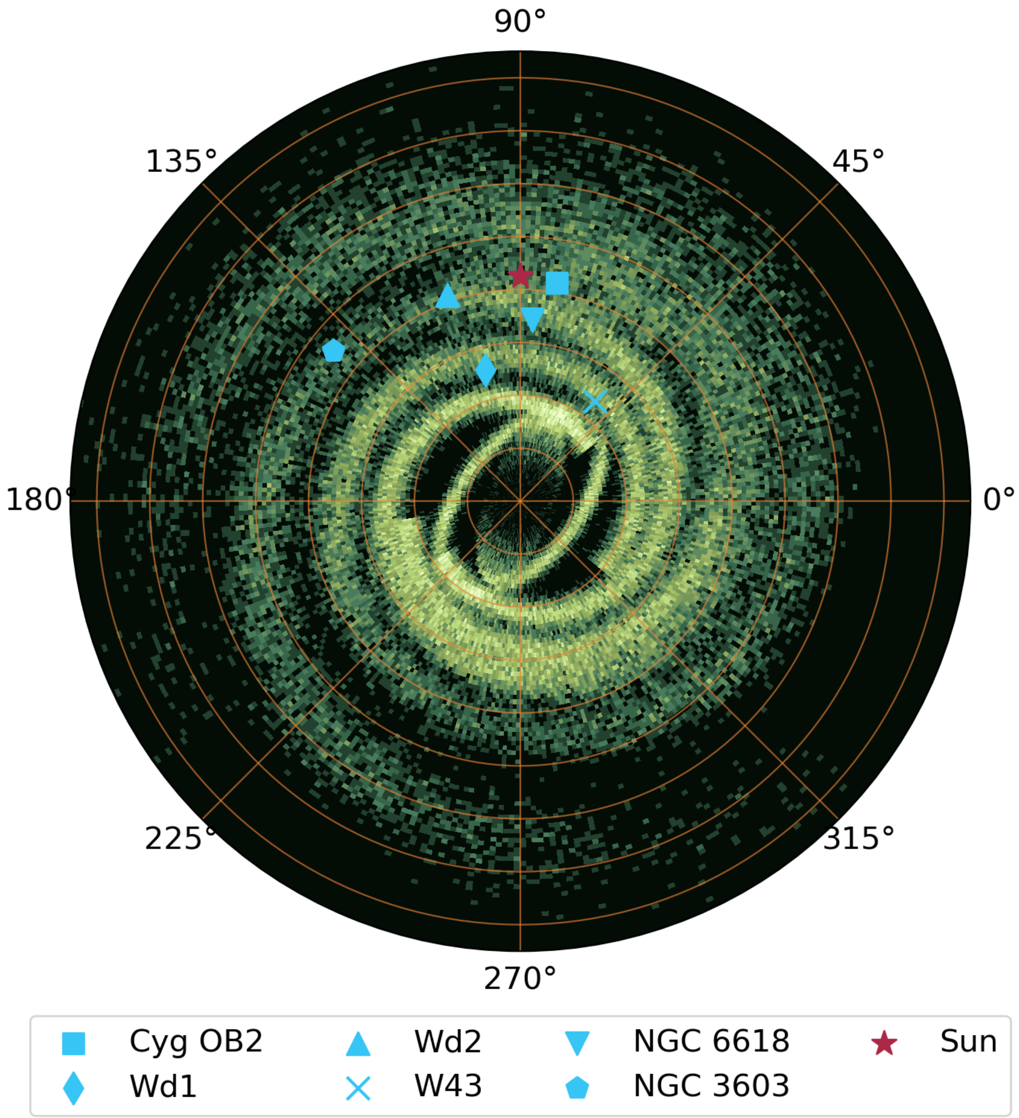
Synthetic YMSCs spatial distribution



Single realization of the Galactic population

Total number of YMSCs: 747

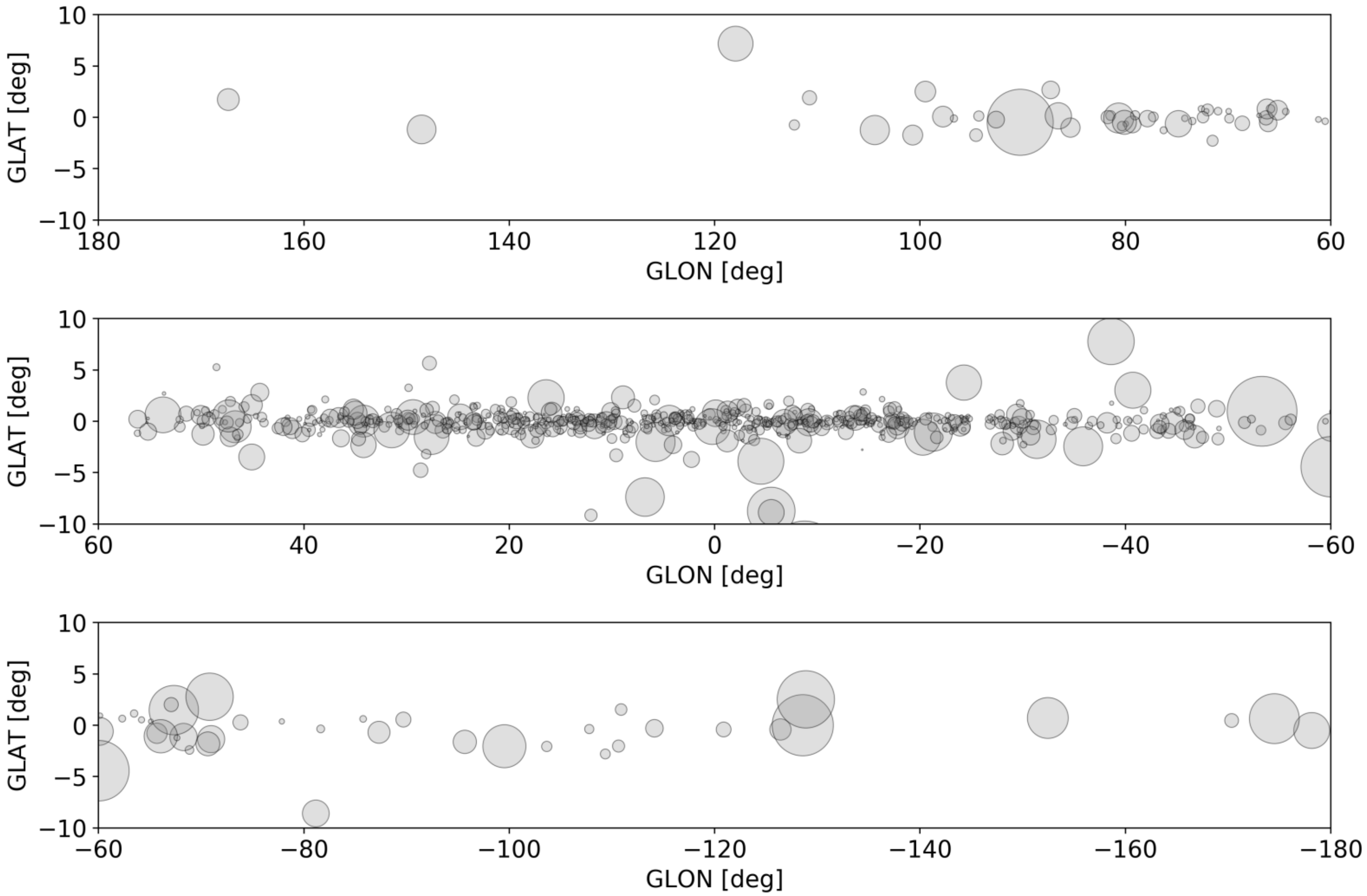
(Age <10 Myr, M_{SC} >10^3 $M_{\odot}$)

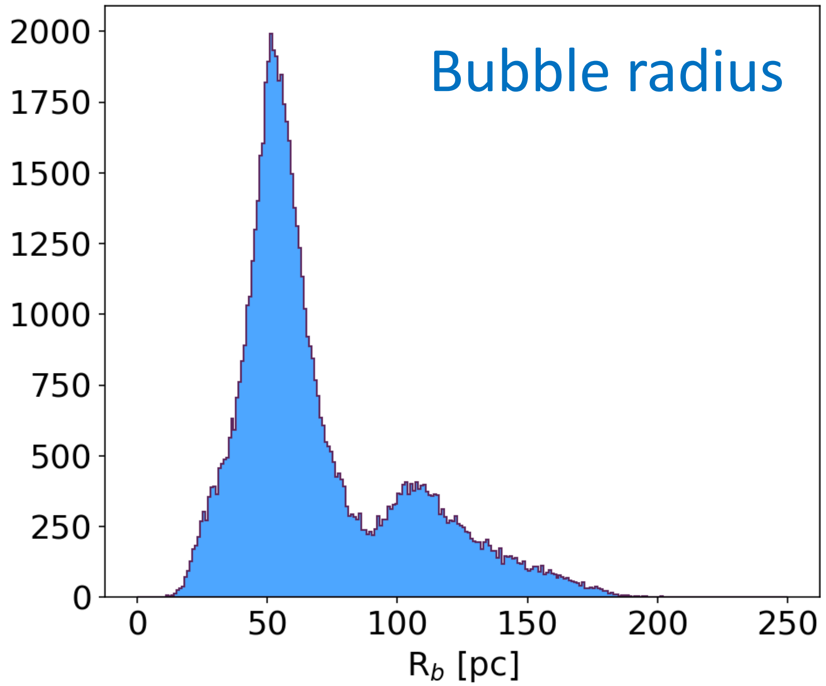


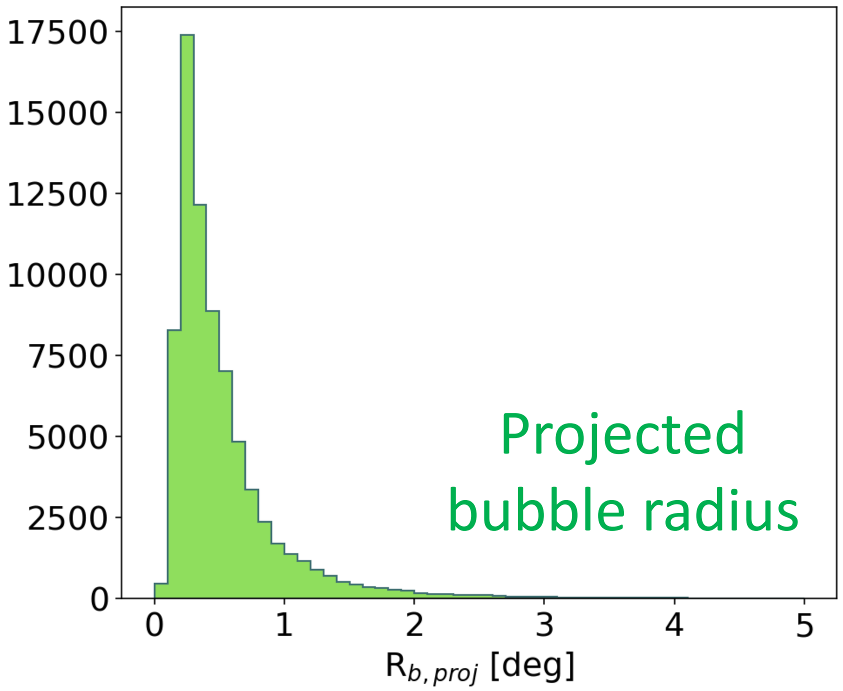
Spatial distribution (100 realizations)

Wind blown bubbles

Single realization of the Galactic population







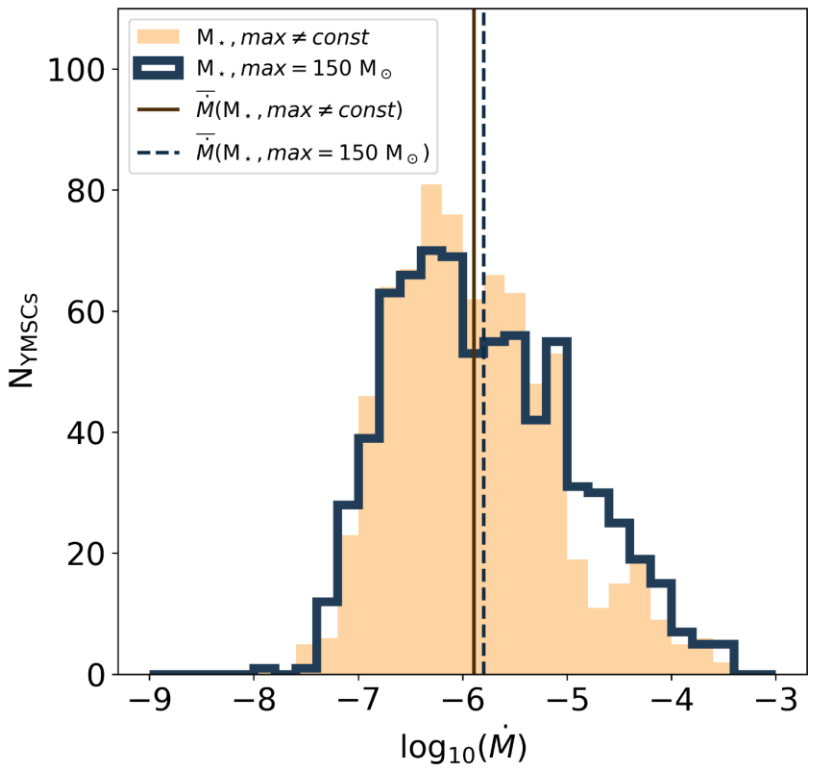
YMSCs wind properties (I)

<u>Results shown are for a single galactic realization</u>

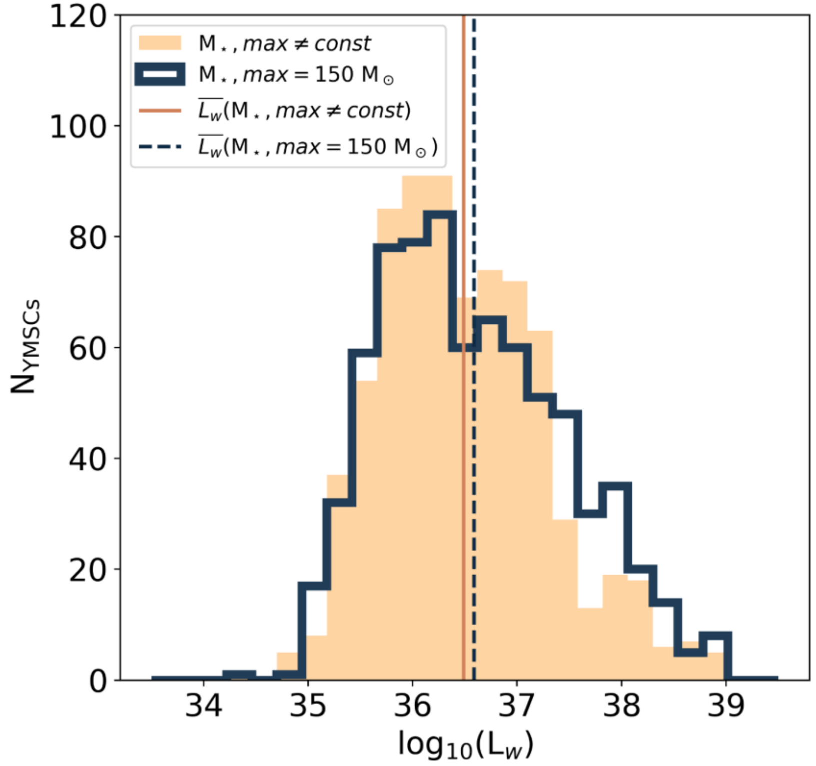
No significant difference from changing $M_{\star,max}$

(<u>Contribution of WRs here is not considered!</u>)

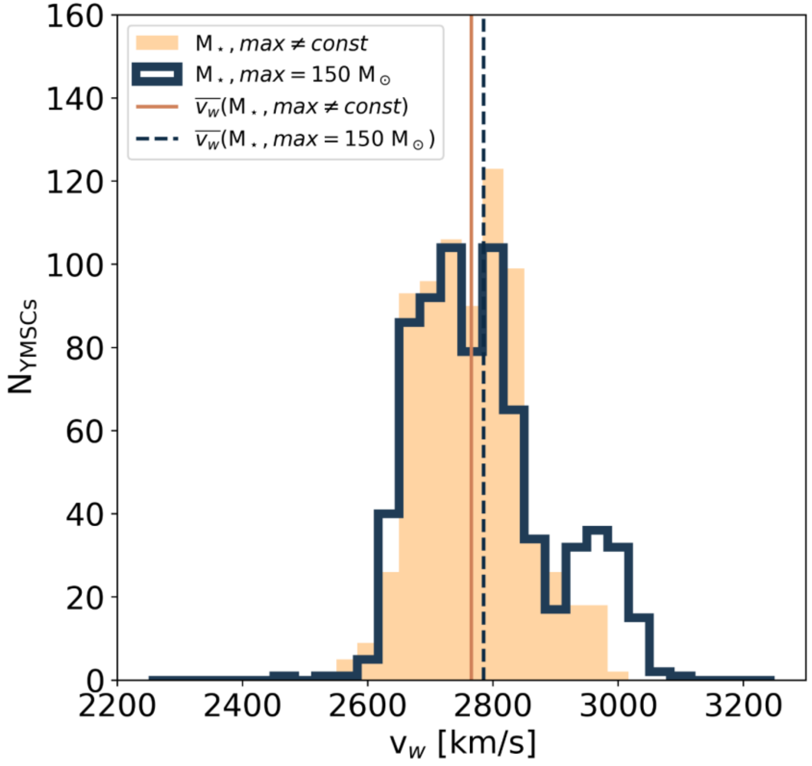
Mass loss rate



Wind luminosity



Wind speed



YMSCs wind properties (II)

Single realization of the Galactic population

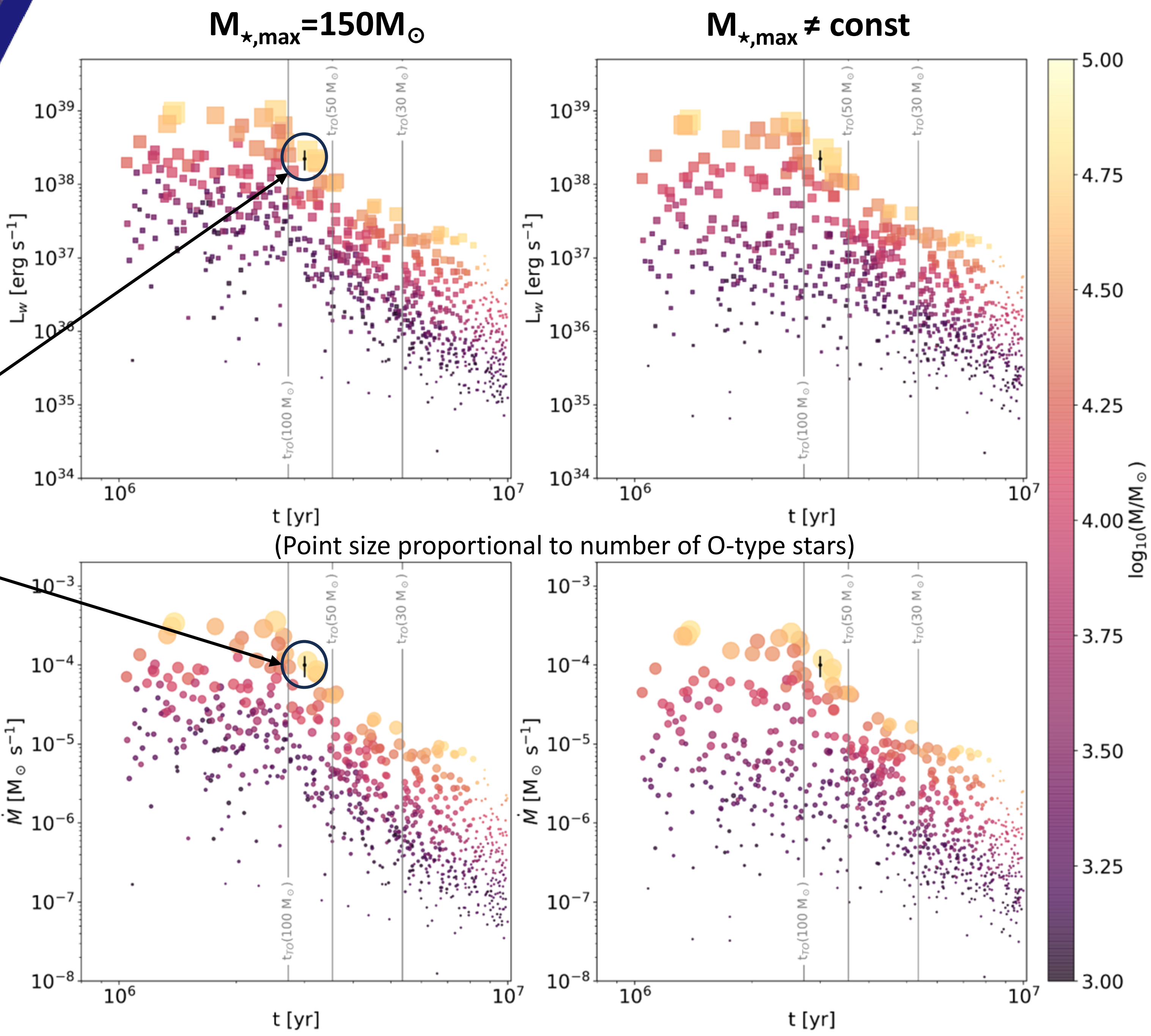
WR contribution is not considered

Mass loss rate and wind luminosity start decreasing after 2 Myr

Cluster wind luminosity vs cluster age

Cygnus OB2
(Menchiari 2023)

Cluster wind mass loss rate vs cluster age

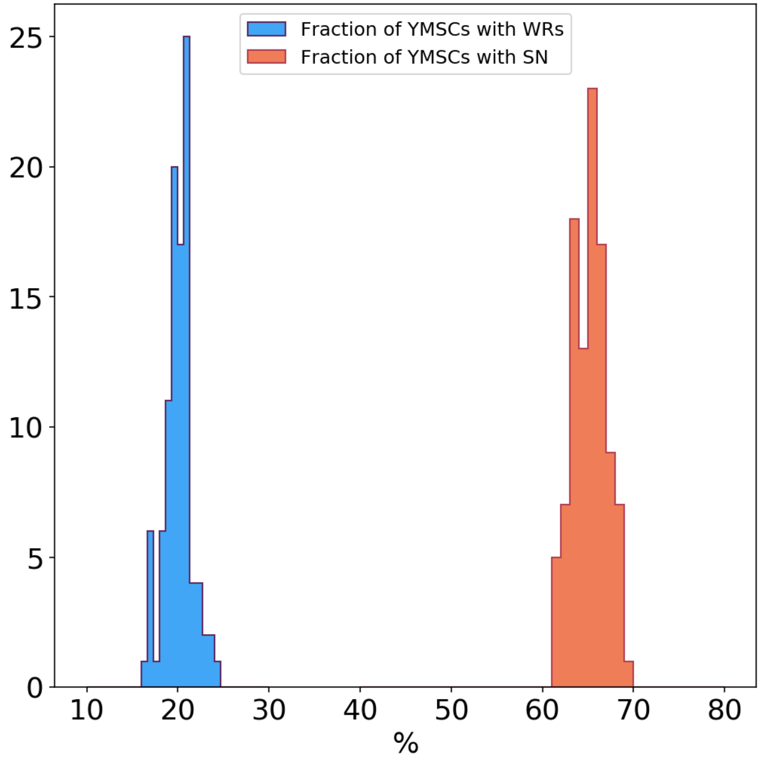


Effect of WRs and SNe

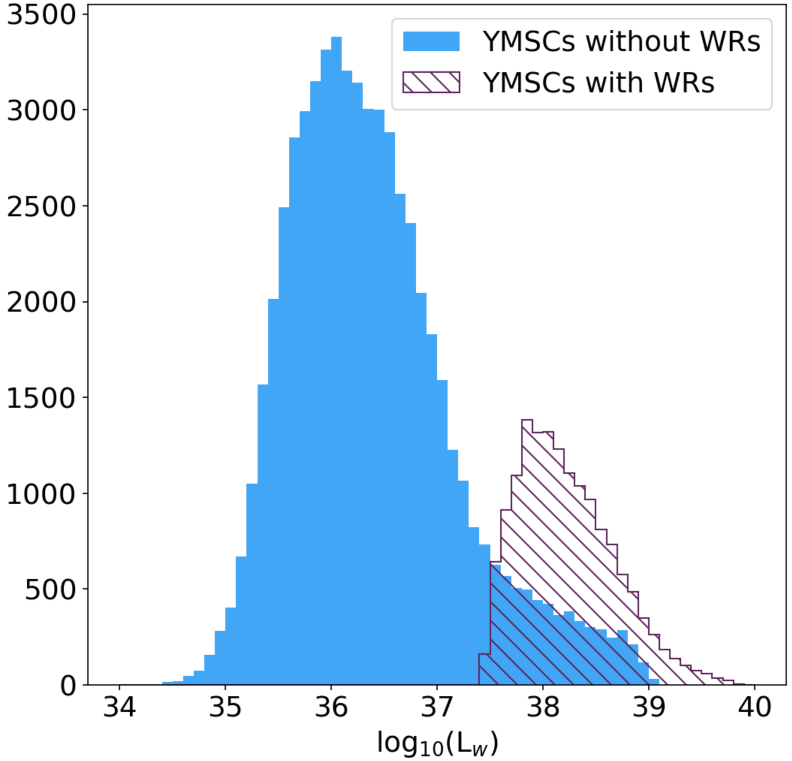
We now fix $M_{\star,max}=150M_{\odot}$

We consider 100 different realization of the galactic population

Percent of YMSCs with WRs and with at least 1 SN in their life

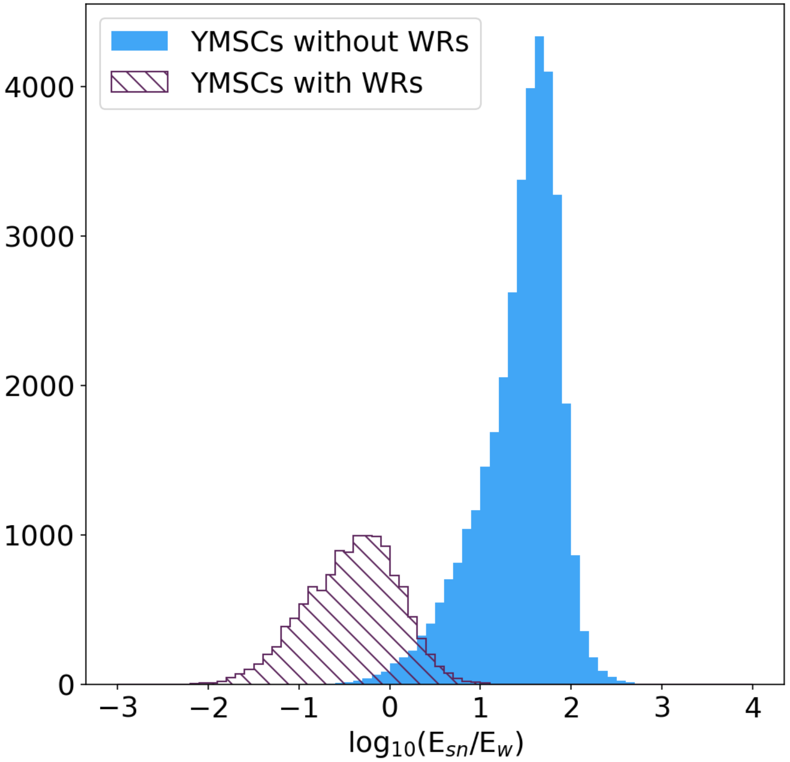


Wind luminosity



Ratio between energy injected by supernovae and winds

NB: the history of wind is not considered! This is a lower limit!!!



What about the gamma-ray emission?

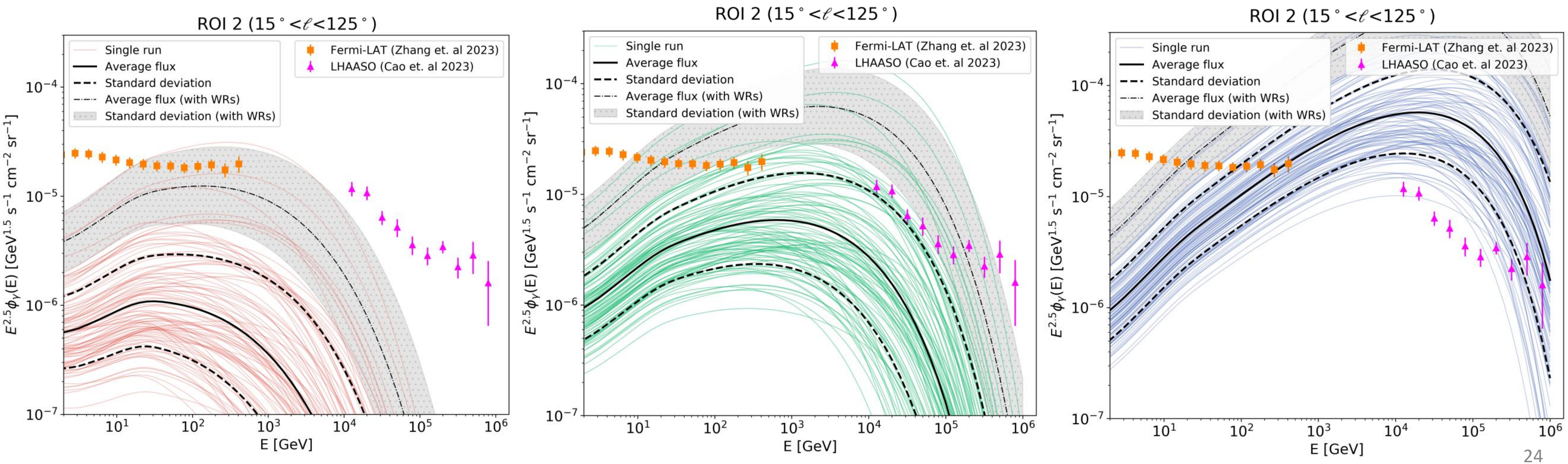
(Photo credit: astroanarchy.blogspot.com)

Contribution to diffuse γ-ray emission

We consider 100 different realization of the galactic population

γ-ray emission depends on many parameters:

- Efficiency in accelerating cosmic rays (10% of L_w)
- Density of target material (10 cm^{-3})
- Particles confinement within the bubble



Conclusions

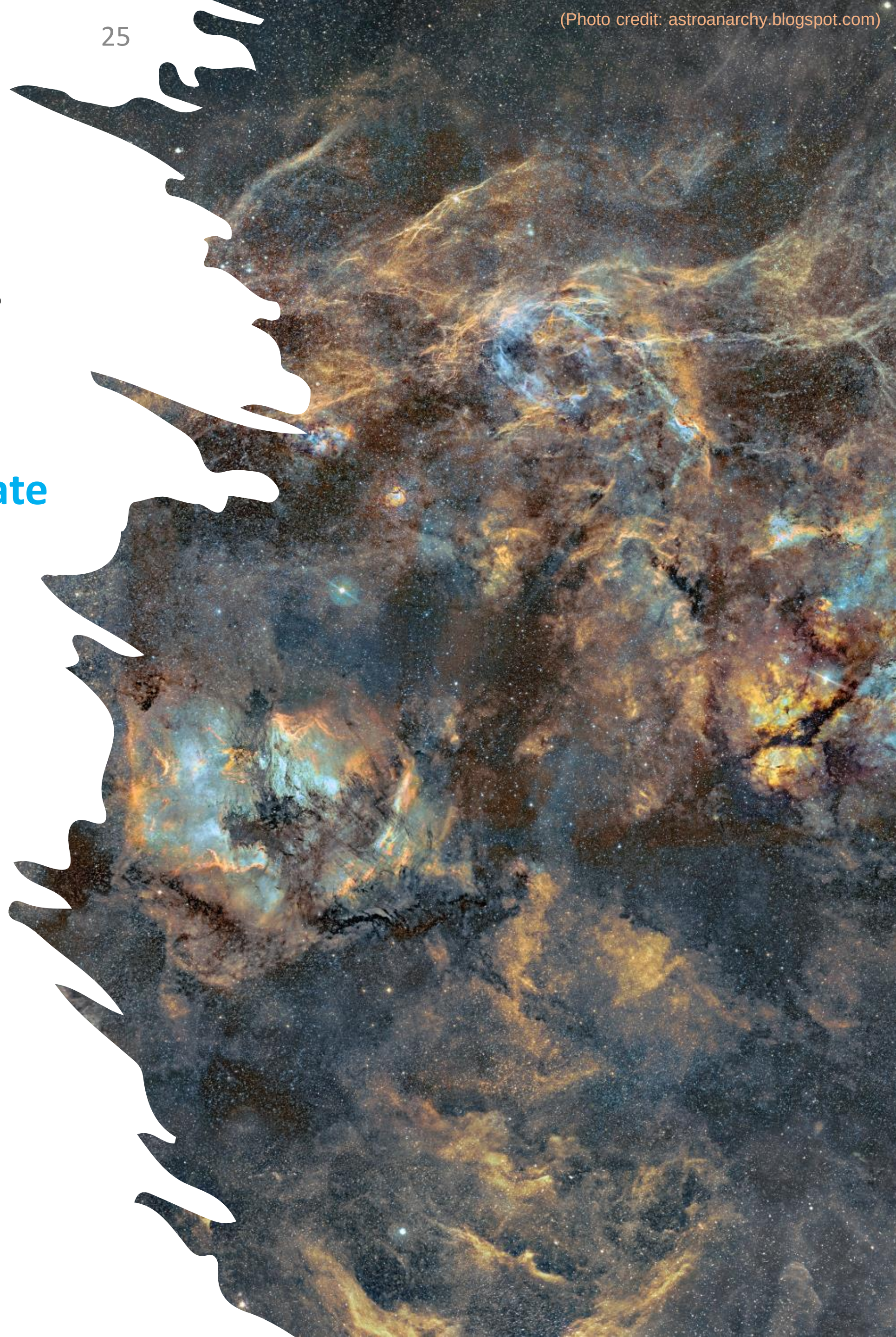
- Importance of YMSCs as high energy sources has constantly growing in the last decades
- **To estimate their contribution to γ-ray emission, simulation of synthetic population is required**
  - **We expect 750 YMSCs in the Milky Way**
  - **Maximum stellar mass does not affect wind power and mass loss rate of MS stars**
  - **Contribution of WRs is important**
- **Contribution to the diffuse emission likely not negligible!**

Future prospects

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

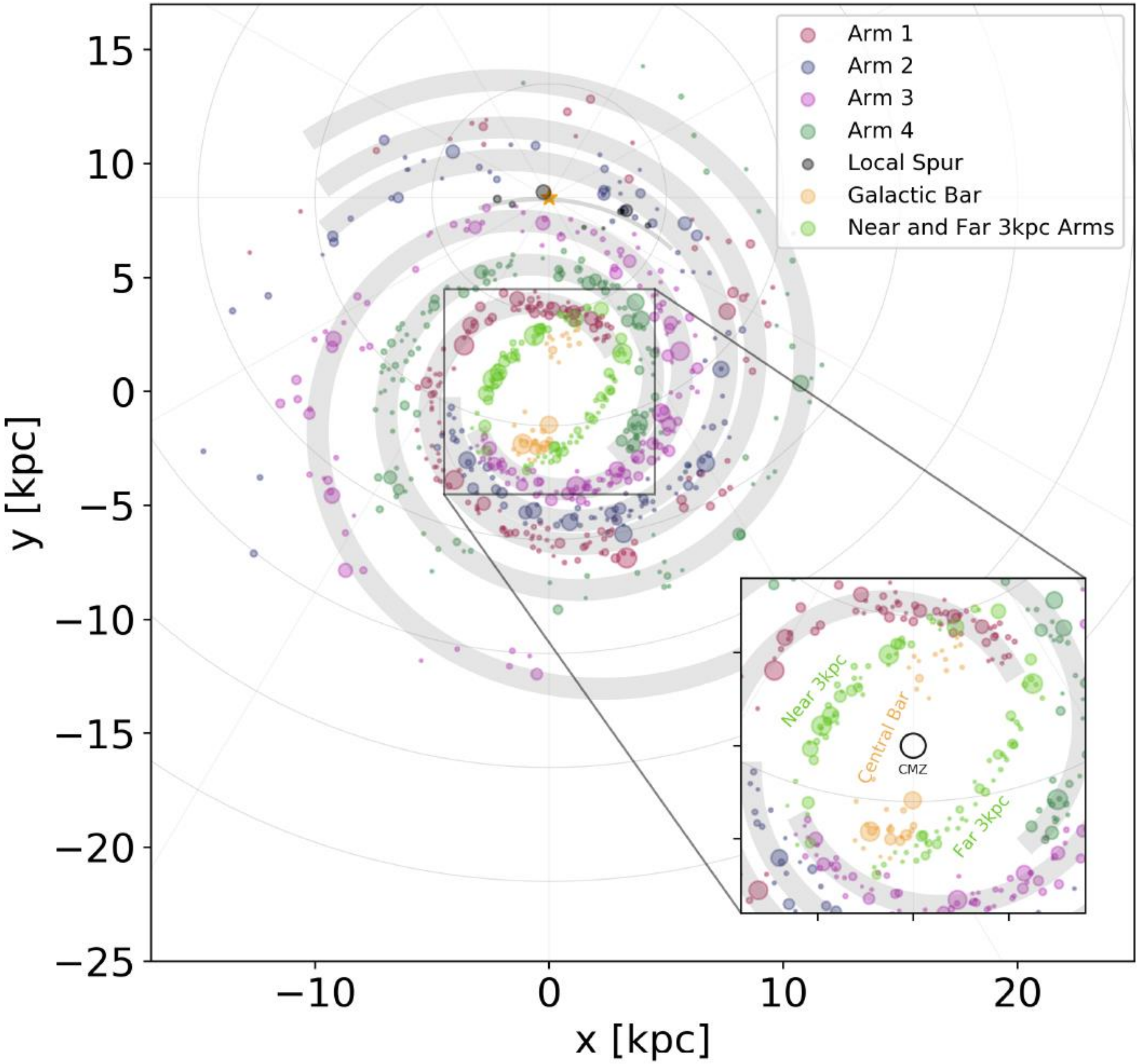
COMING SOON

Workshop on young massive star clusters from different prospective
END SPRING/BEGINNING SUMMER 2024 – Florence/Siena



BACKUP SLIDES

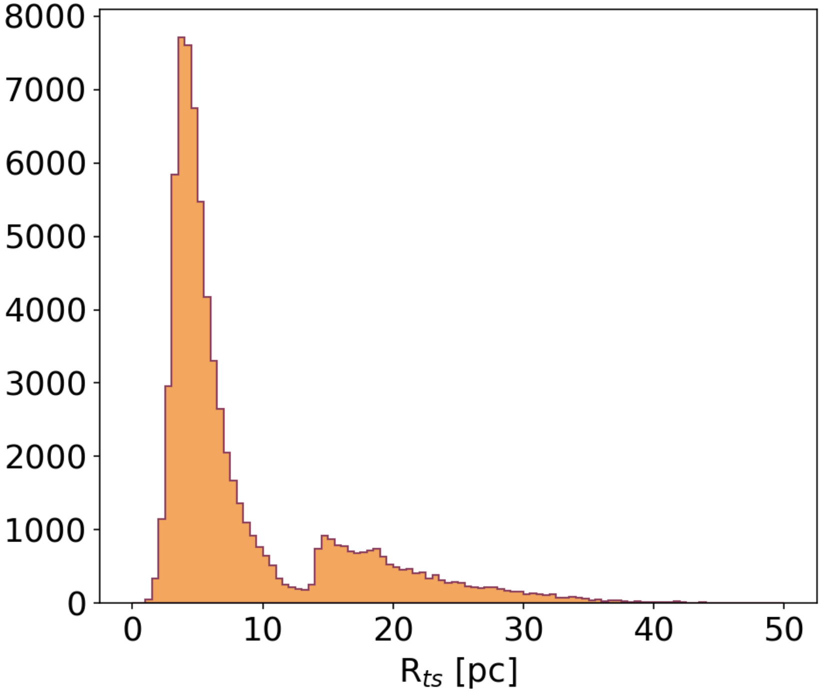
Synthetic YMSCs spatial distribution



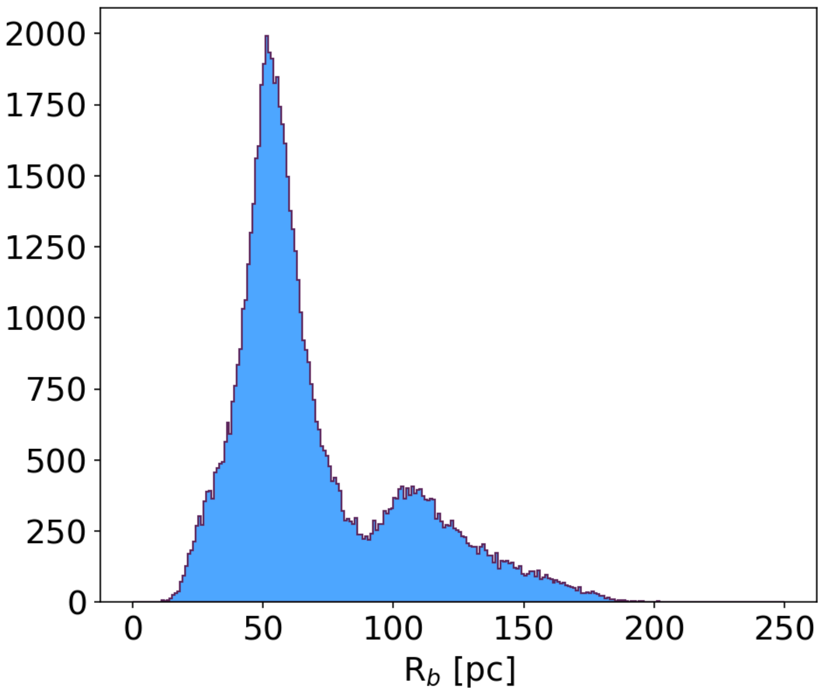
	R	θ
Spiral Arm 1	$R \geq 3.27$ kpc	$\theta < 360°$ (or $50° > \theta > 110°$ if 7.59 kpc $< R < 9.17$ kpc)
Spiral Arm 2	$R \geq 4.29$ kpc	$\theta < 360°$ (or $50° > \theta > 110°$ if 7.59 kpc $< R < 9.17$ kpc)
Spiral Arm 3	$R \geq 3.58$ kpc	$\theta < 360°$ (or $50° > \theta > 110°$ if 7.59 kpc $< R < 9.17$ kpc)
Spiral Arm 4	$R \geq 3.98$ kpc	$\theta < 360°$ (or $50° > \theta > 110°$ if 7.59 kpc $< R < 9.17$ kpc)
Local Spur	7.59 kpc $< R < 9.17$ kpc	$50° \leq \theta \leq 110°$
NF 3kpc / Bar	$R < 4.29$ kpc	$\theta < 360°$

Wind blown bubble dimensions

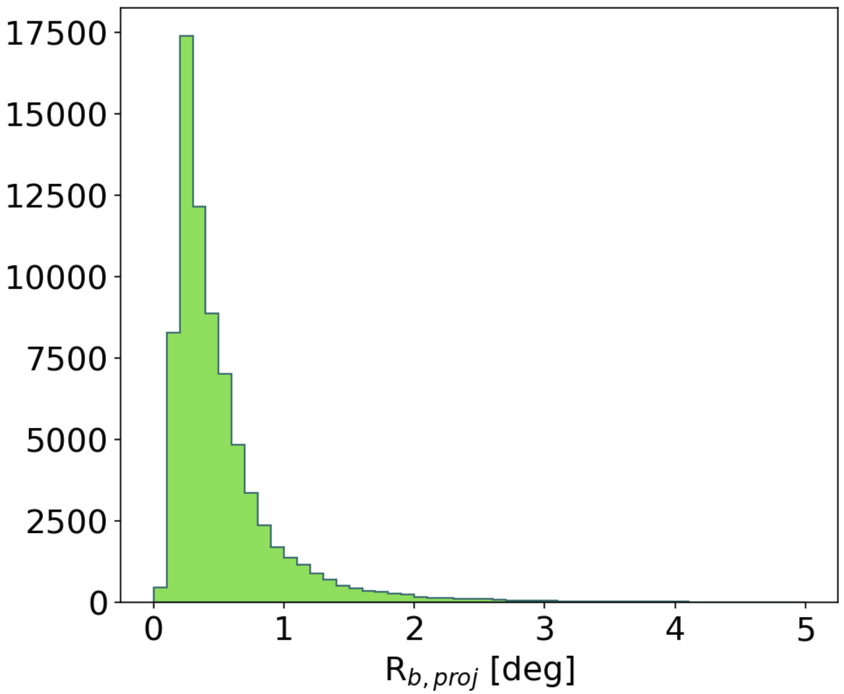
Termination shock



Bubble radius



Projected bubble radius



Effect of WRs and SNe (II)

We now fix $M_{\star,max}$=150$M_{\odot}$

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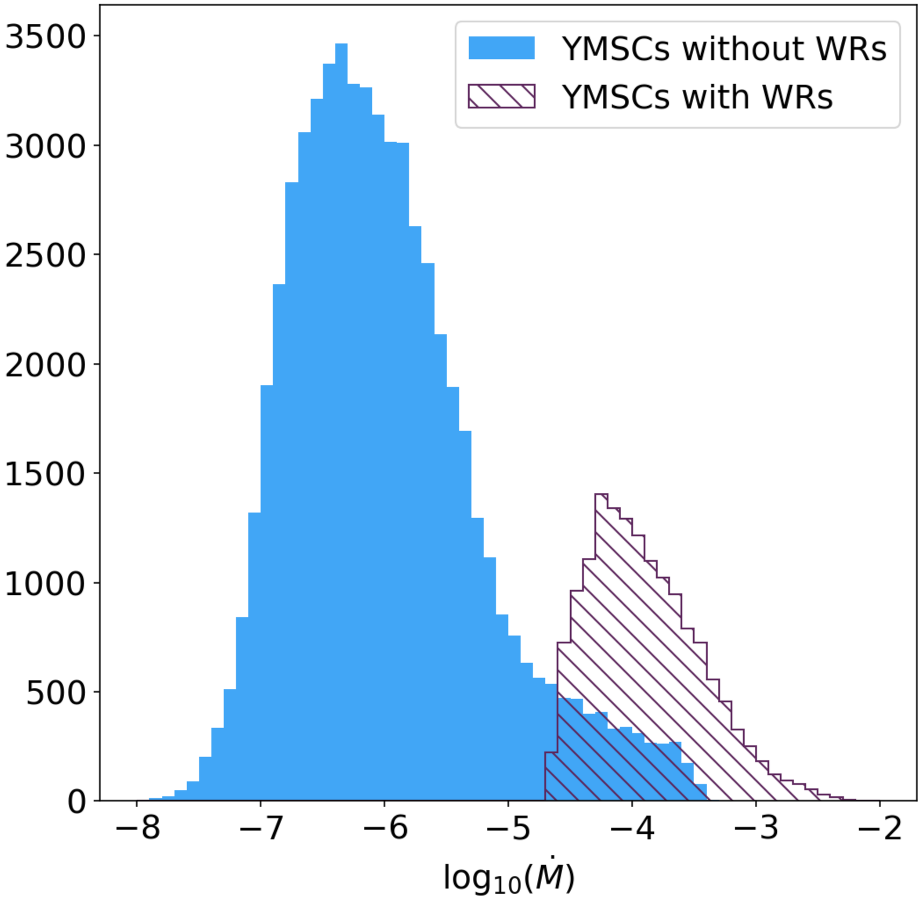
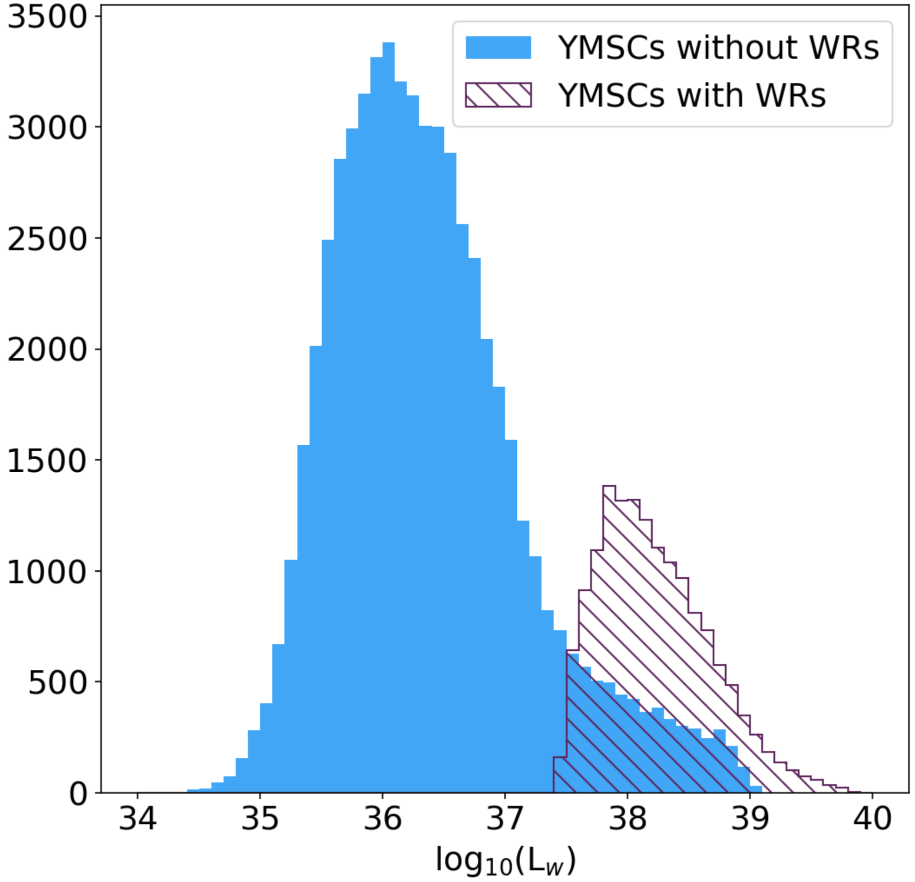
Contribution of WR is not negligible!

Mass loss rate



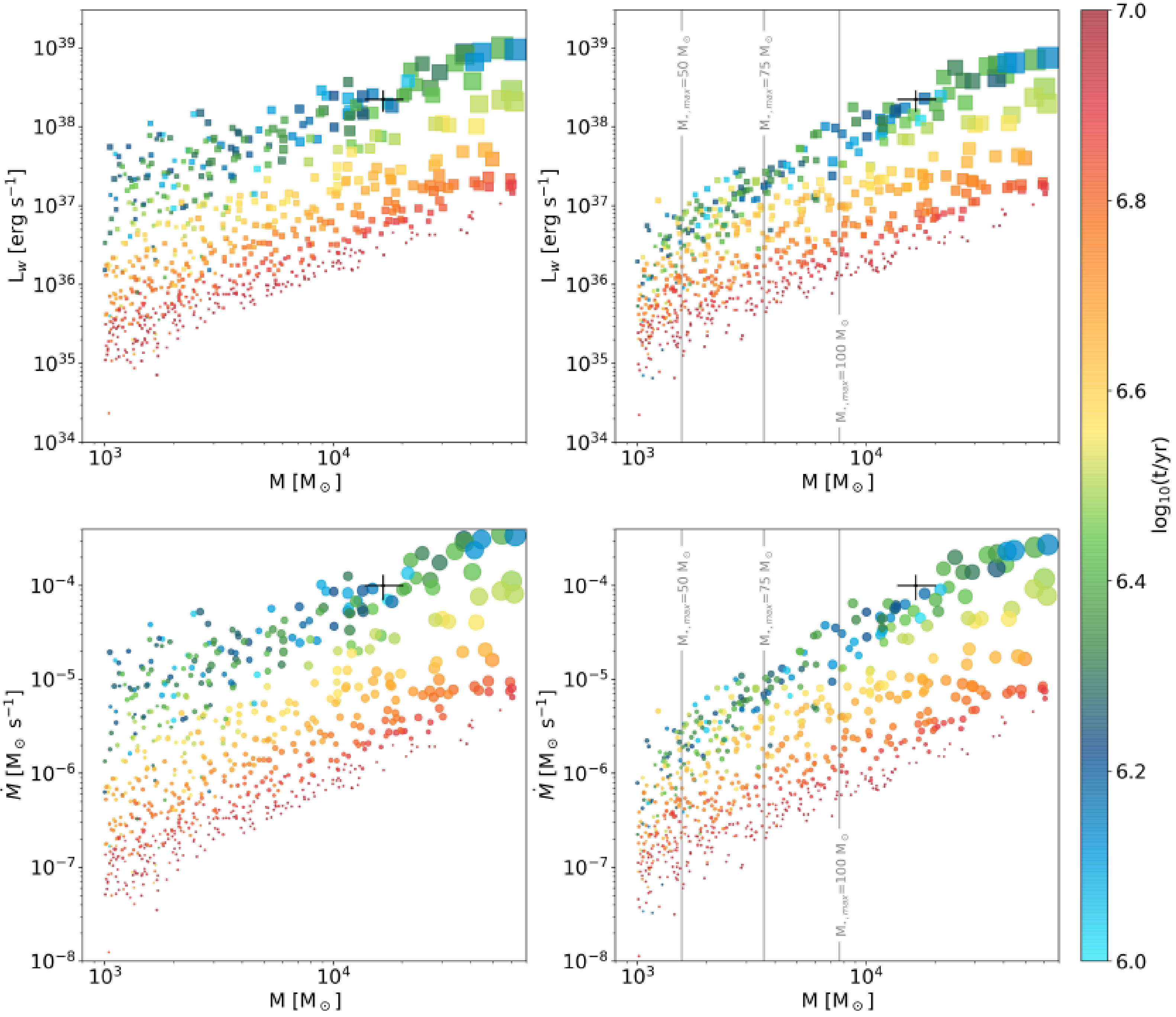
Wind luminosity



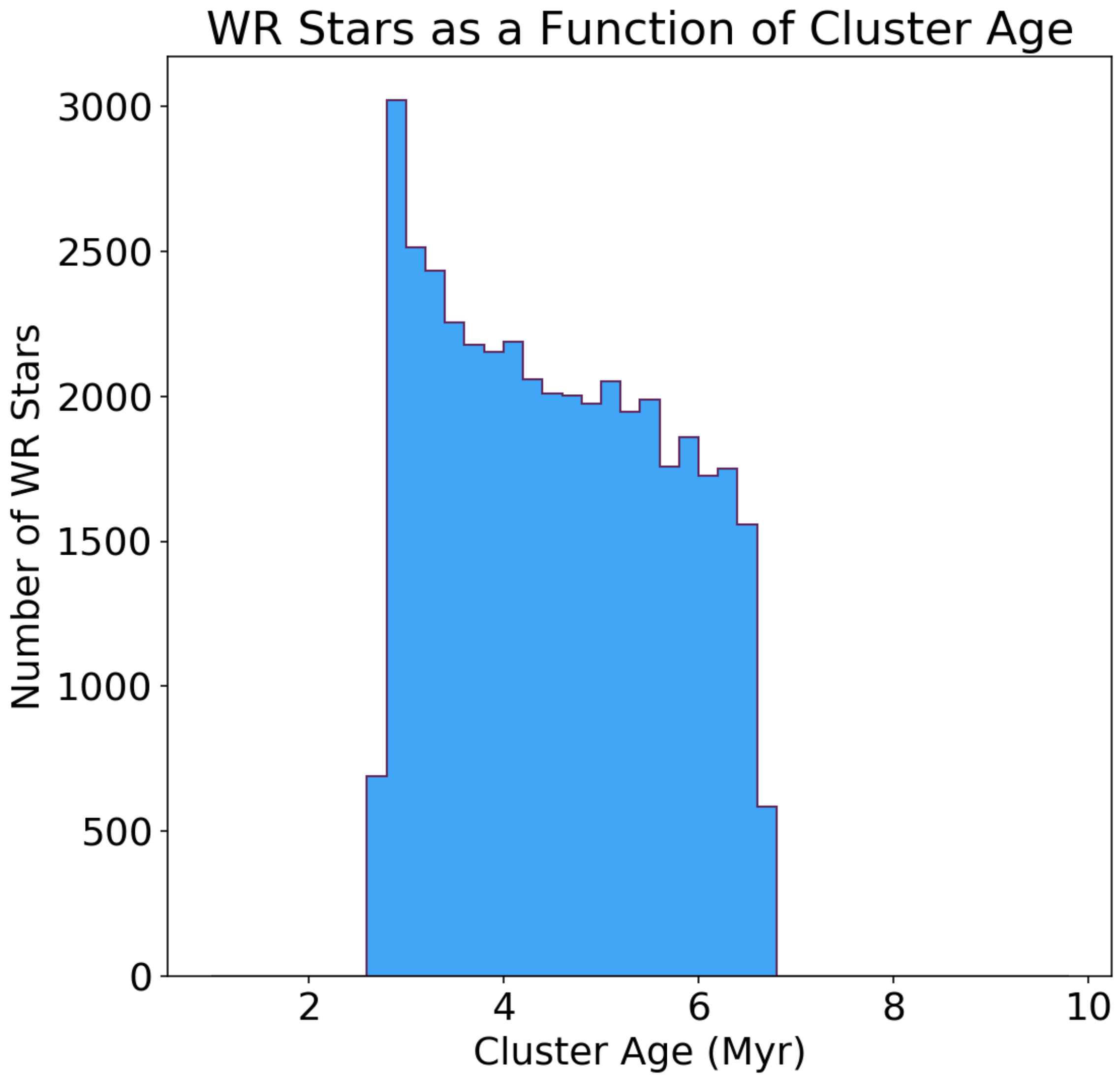
Cluster population study

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

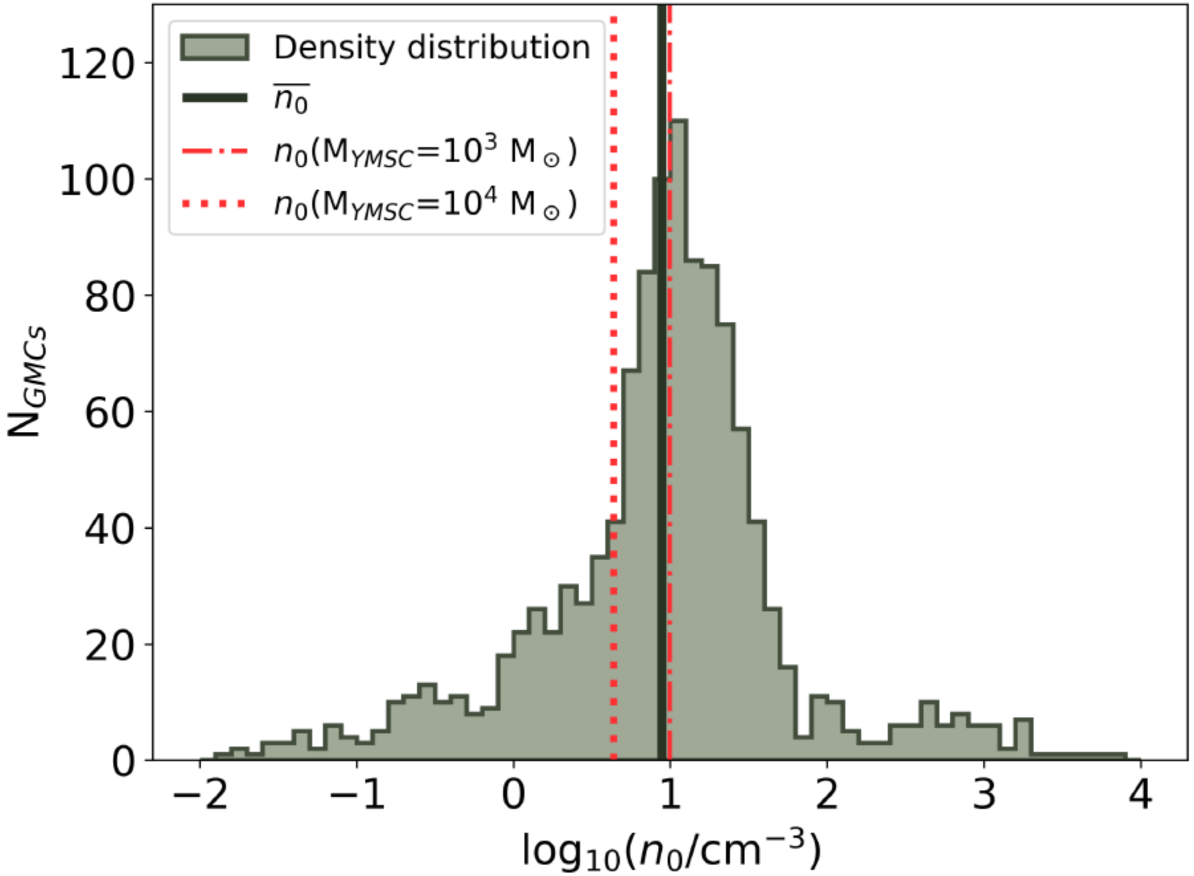


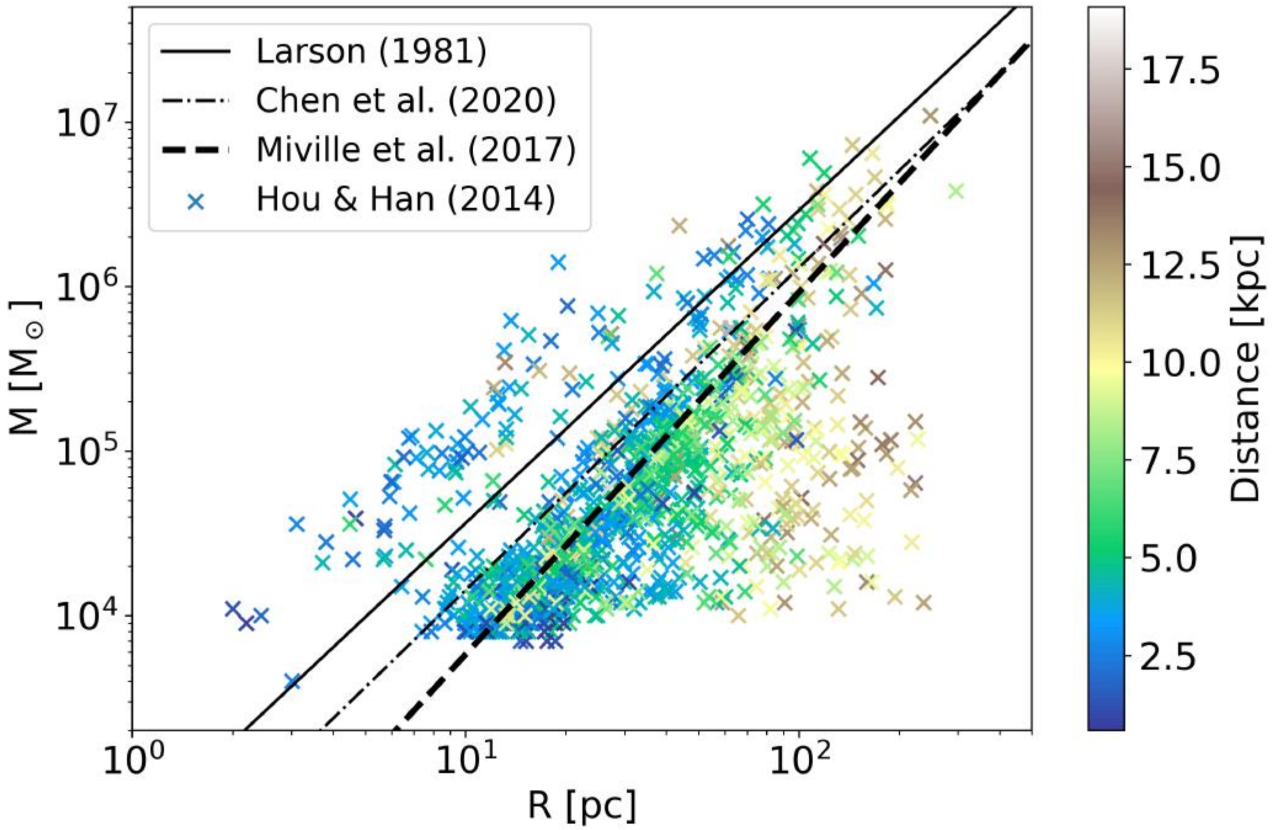
WRs vs tage



WR Stars as a Function of Cluster Age
Number of WR Stars
3000
2500
2000
1500
1000
500
0
2
4
6
8
10
Cluster Age (Myr)

Density environment close to YMSC



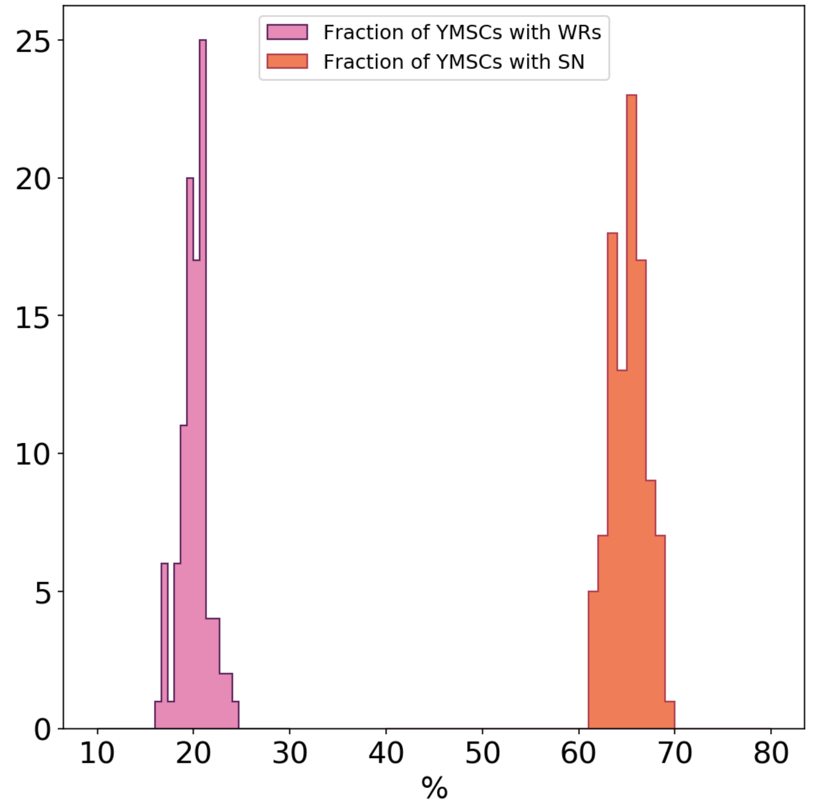


Effect of WRs and SNe

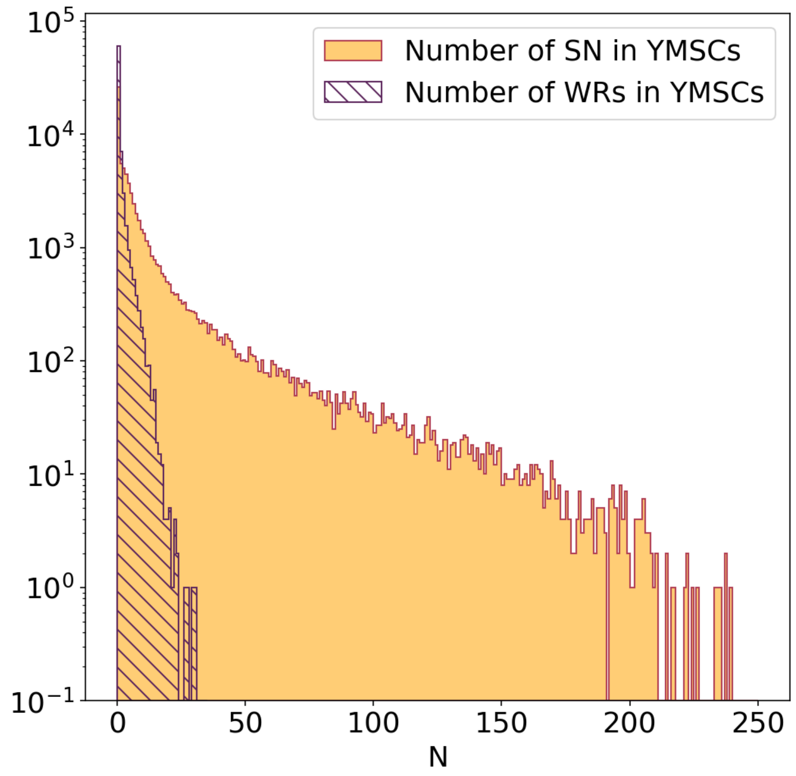
We now fix $M_{\star,max}=150M_\odot$

We consider 100 different realization of the galactic population

Percent of YMSCs with WRs and with at least 1 SN in their life

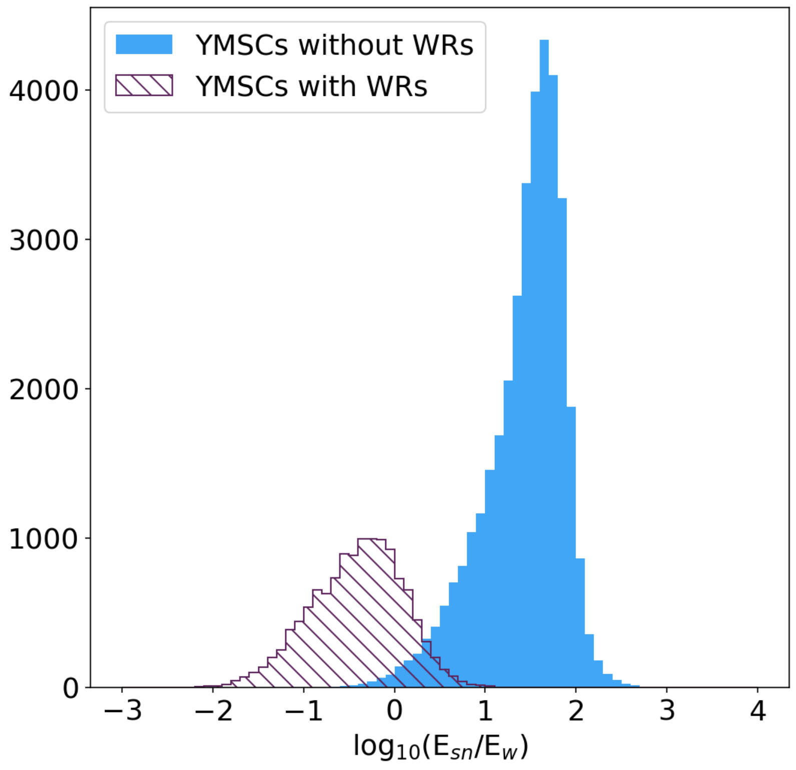


Number of WRs in clusters and number of SNe exploded in the clusters



Ratio between energy injected by supernovae and winds

NB: the history of wind is not considered! This is a lower limit!!!



CR accelerated by YMSC

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

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

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

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

$$f_{TS}(p) \simeq \frac{3n_1u_1^2\epsilon_{CR}}{4\pi\Lambda_p(m_pc)^3c^2}\left(\frac{p}{m_pc}\right)^{-s}\left[1+a_1\left(\frac{p}{p_{max}}\right)^{a_2}\right]e^{-a_3(p/p_{max})^{a_4}}$$

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

$$\alpha = \alpha(r,p) = \frac{u_2R_{TS}}{D_2(p)}\left(1-\frac{R_{TS}}{r}\right)$$

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

$$\beta = \beta(p) = \frac{D_{ism}(p)R_b}{u_2R_{TS}^2}$$