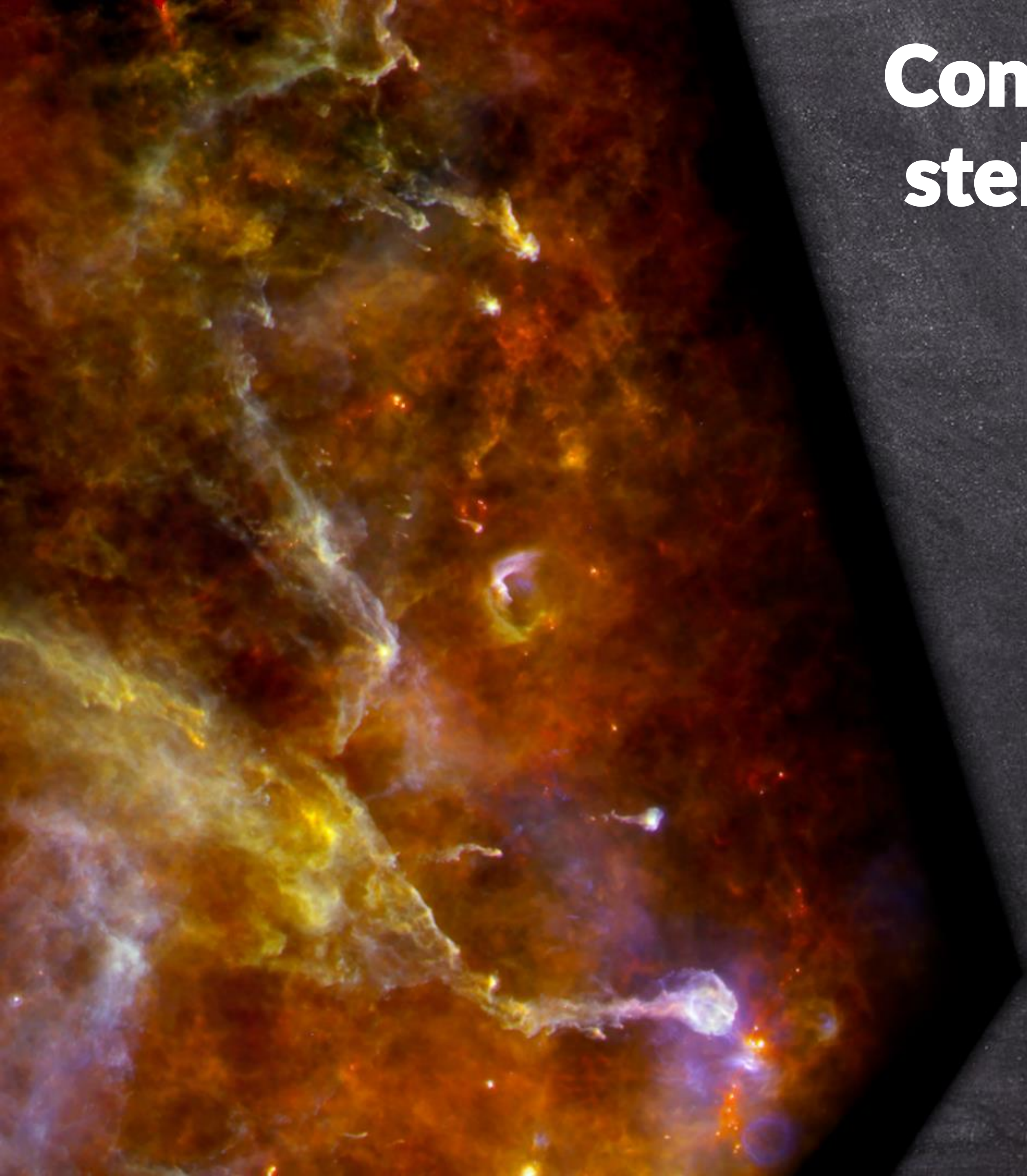

Contribution of young massive stellar clusters to the Galactic diffuse γ-ray emission

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High-Energy Gamma-Ray Astronomy
Milano – 04/09/2024

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

YMSCs: **Clusters of hundreds OB-type** ($M_{\star}$>3 $M_{\odot}$) **stars** packed in few pc.

Young: Age <10 Myr

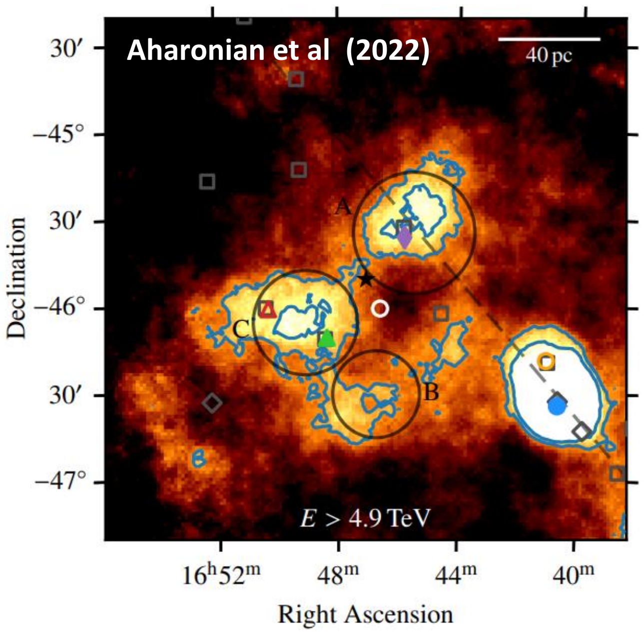
Massive: M_{SC}>10^3 $M_{\odot}$

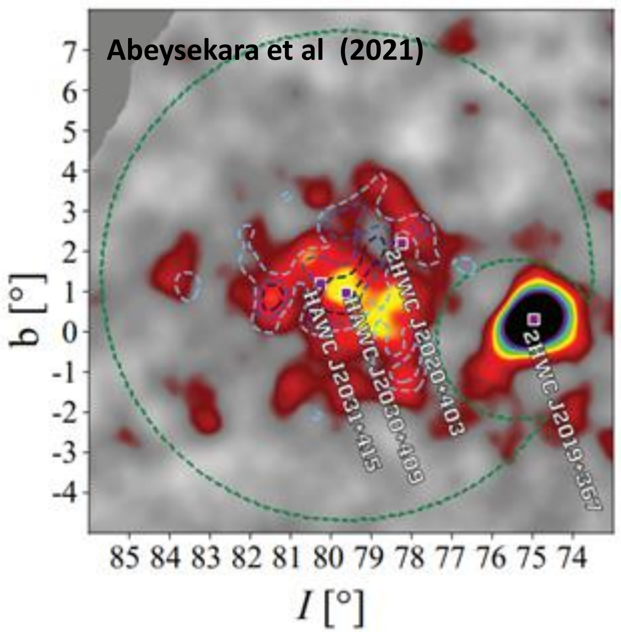
Several cosmic ray (CR) acceleration mechanisms proposed in YMSCs.

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 core by SNRs (Vieu et al. 2022, Vieu & Reville 2023)

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

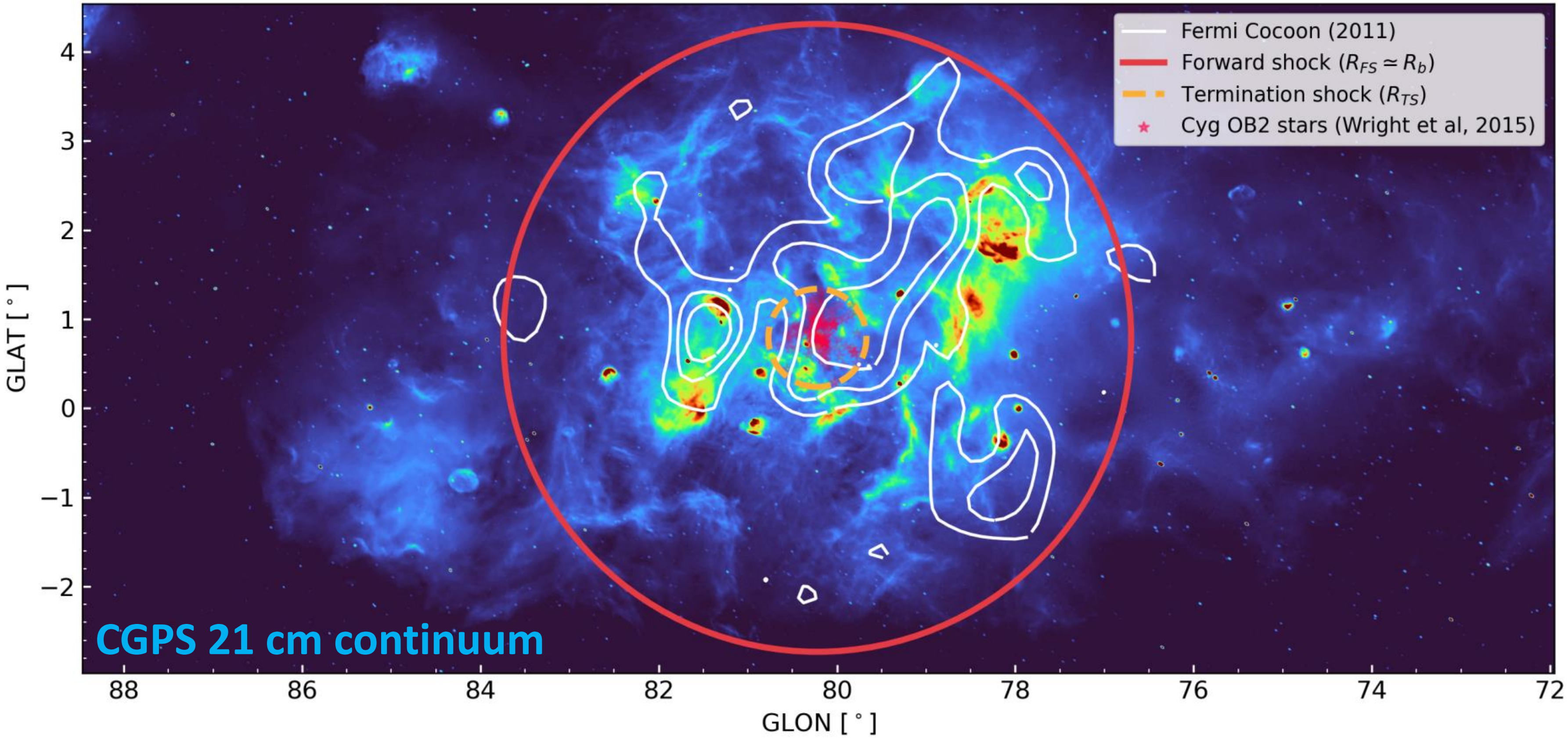


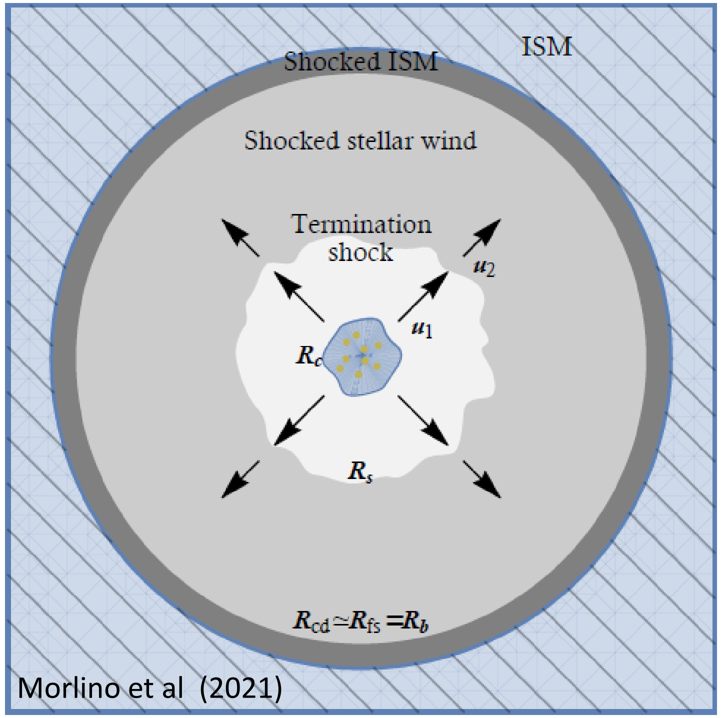


Name	log $M/M_{\odot}$	r_c [pc]	D [kpc]	Age [Myr]	L_w [erg s^{-1}]
Westerlund 1	4.6 ± 0.045	1.5	4	$4-6$	10
Westerlund 2	4.56 ± 0.035	1.1	2.8 ± 0.4	$1.5-2.5$	2
Cygnus OB2	4.7 ± 0.3	5.2	1.4	$2-7$	2
NGC 3603	4.1 ± 0.1	1.1	6.9	$2-3$	-
BDS 2003	4.39	0.2	4	1	-
W40	2.5	0.44	0.44	1.5	-
RSGC 1	4.48	1.5	6.6	$10-14$	-
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	

Extended emission

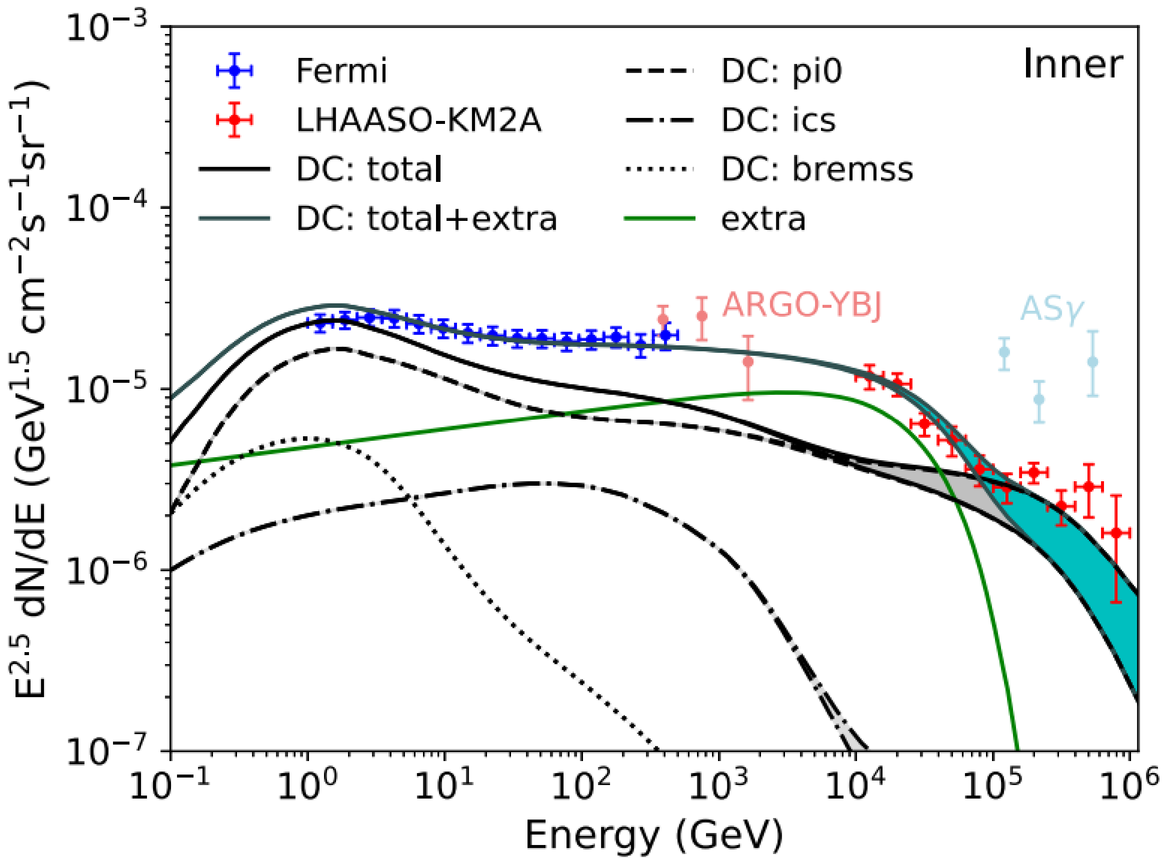
The γ-ray emission is diffuse and extended (1°-3°)! → Emission size consistent with projected dimension of wind-blown bubble → **Detecting and analyzing diffuse γ-ray emission is a challenging task!** Detection bias for low surface brightness sources

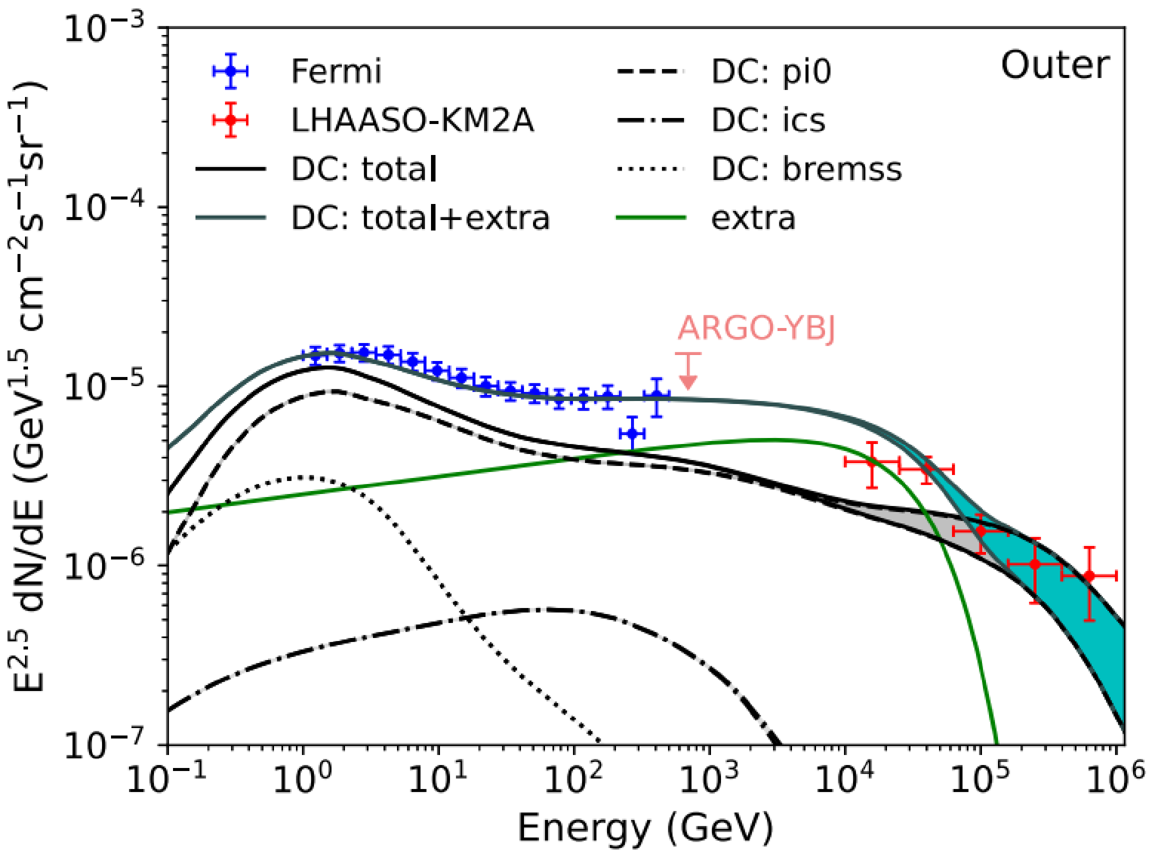




Diffuse emission data

Analysis of GDE (LHAASO+Fermi-LAT) reveals contribution from unresolved sources (Zhang et al 2023)!!!





Work objective

OBJECTIVES:

1) Estimate a lower limit contribution to Galactic diffuse emission from YMSCs

2) Comparison with observations

15°<l<125°, |b|<5° (ROI1)

125°<l<235°, |b|<5° (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 a lower limit contribution to Galactic diffuse emission from YMSCs

2) Comparison with observations

15°<l<125°, |b|<5° (ROI1)

125°<l<235°, |b|<5° (ROI2)

Nota bene:

Population of YMSCs in Milky Way is not known!

Use a synthetic population of YMSC

STEP 1

Modeling galactic population of YMSCs:

Use info from local population of YMSCs

STEP 2

a) Modeling stellar population in a YMSC

b) Modeling stellar wind physics:

Use pure empirical approach

STEP 3

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

STEP 1
Milky Way YMSCs population

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)

Synthetic YMSCs population (I)

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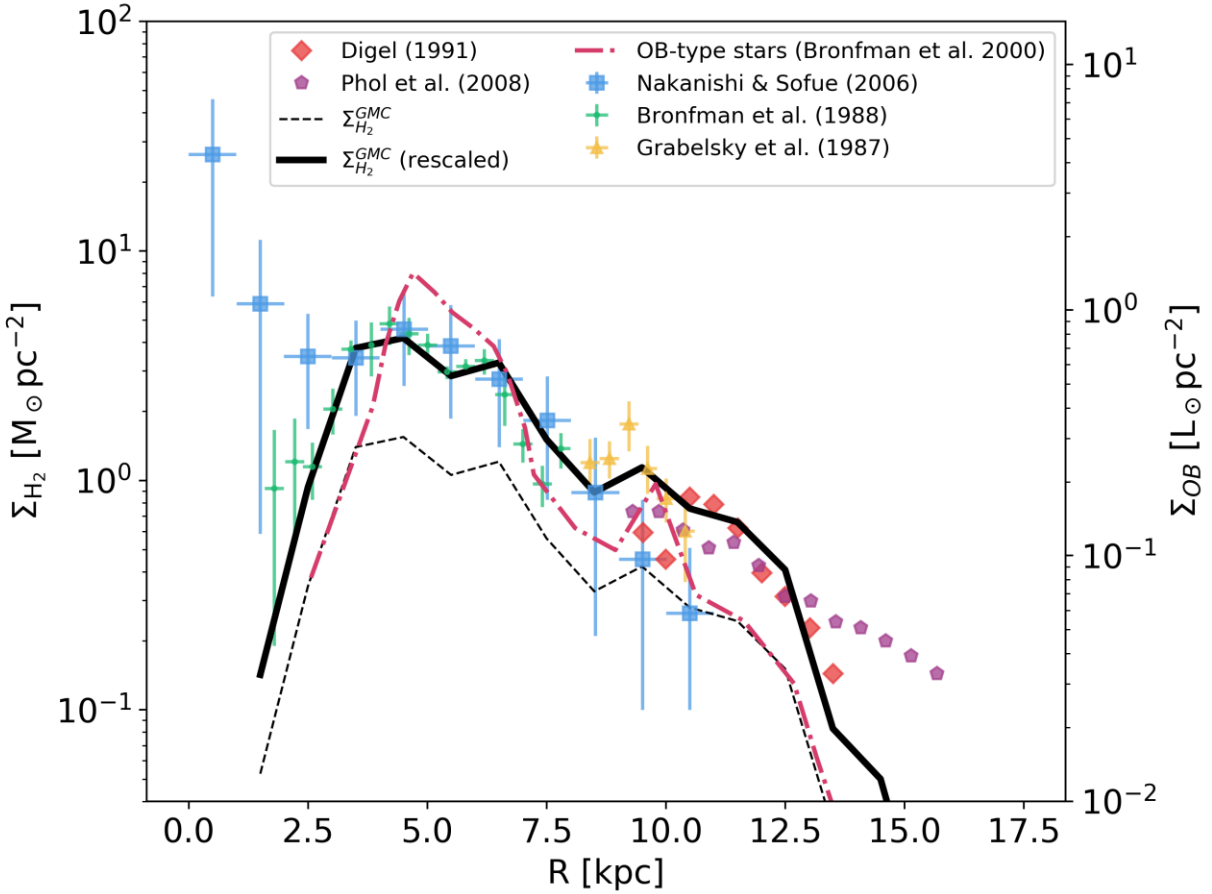
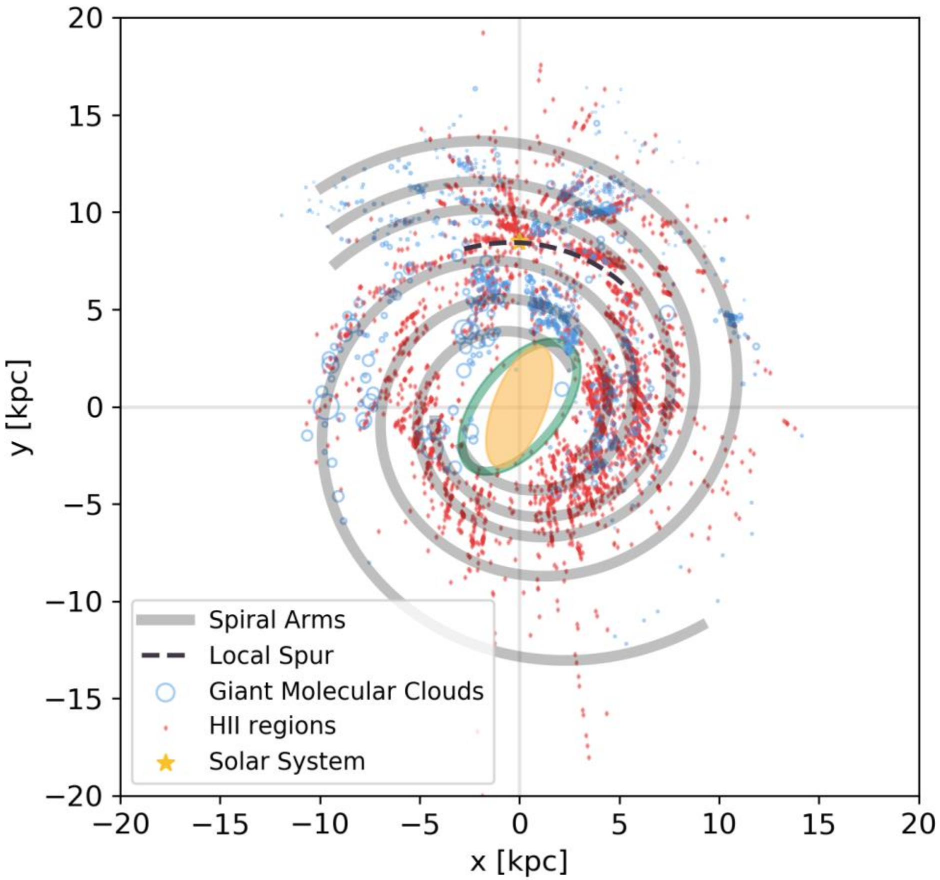
- Cluster radial distribution follow giant molecular cloud (Hou & Han 2014)





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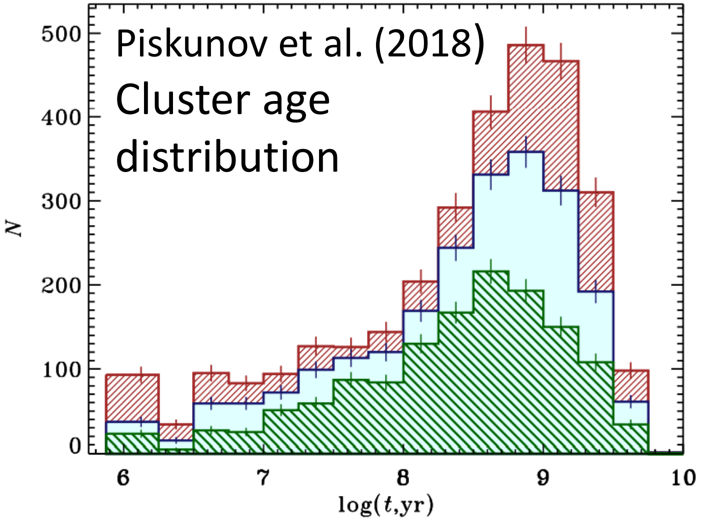
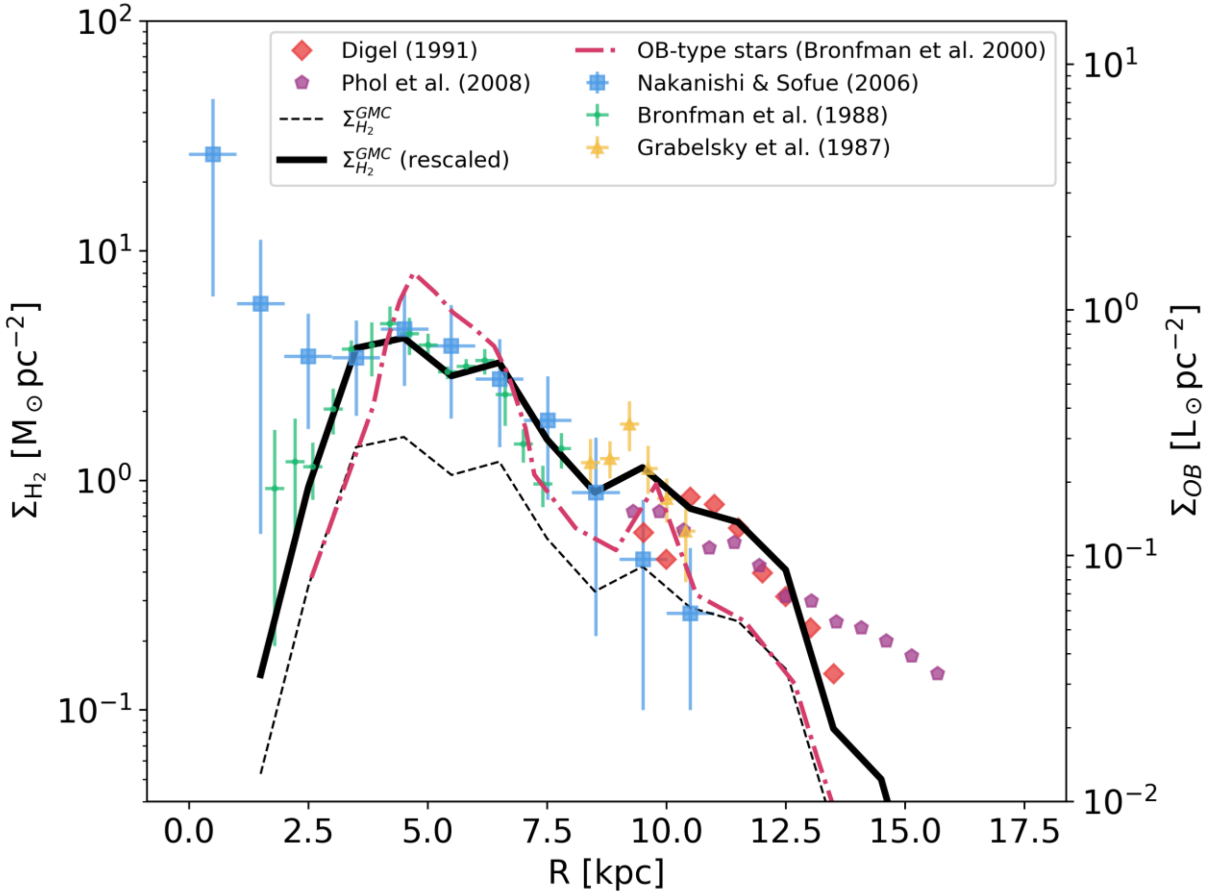
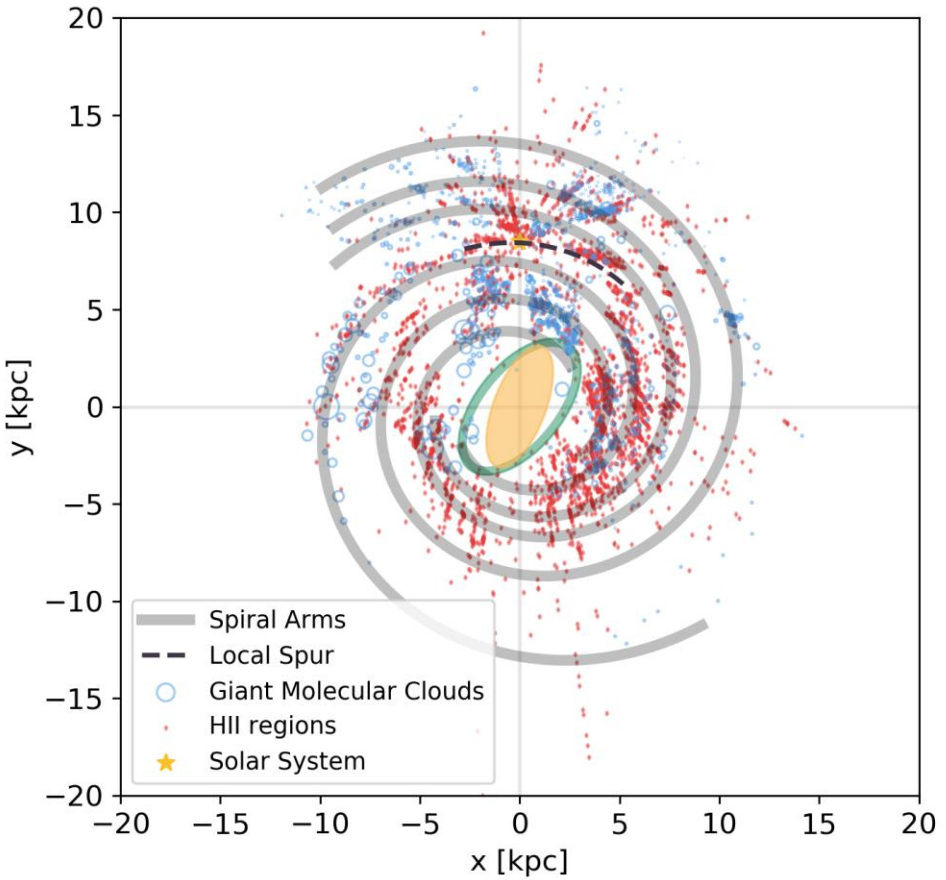
- Cluster radial distribution follow giant molecular cloud (Hou & Han 2014)
- Local cluster formation rate: $\overline{\psi}$ = 1.8 Myr^{-1} kpc^{-2} (Bonatto et al 2011)



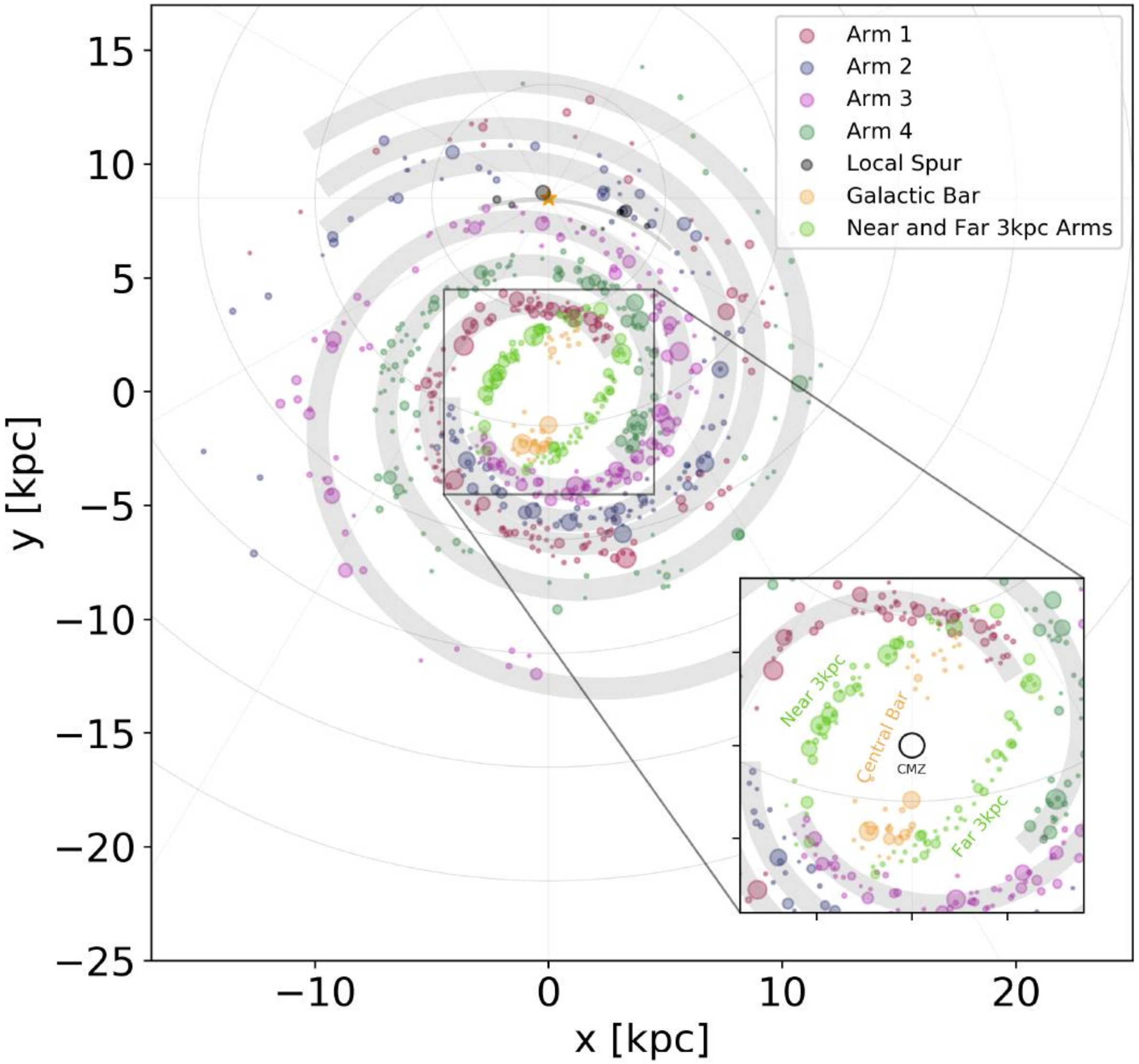




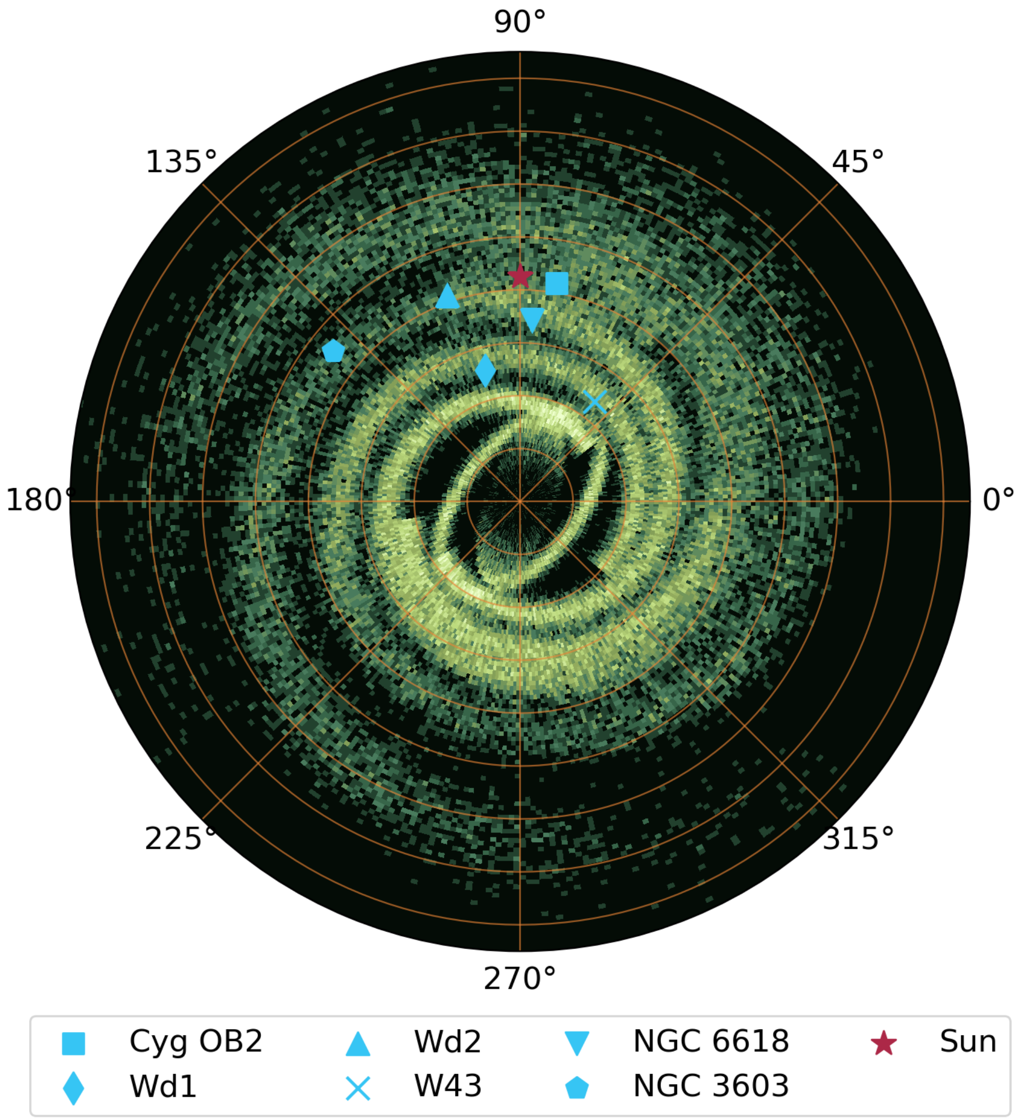
Synthetic YMSCs population (II)

Total number of YMSCs: 747

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



Single realization of the Galactic population



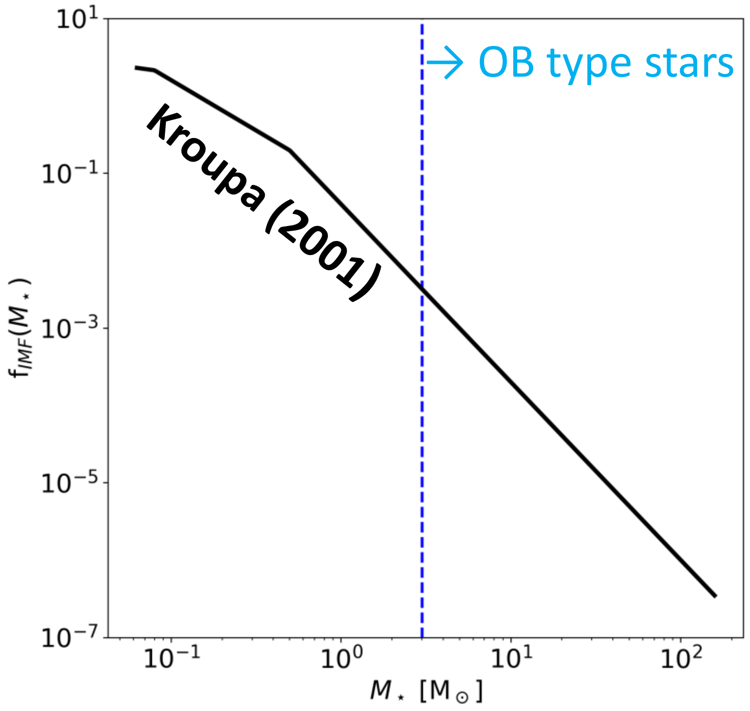
Spatial distribution (100 realizations)

STEP 2
Stellar population in clusters

Stellar population in YMSC

- Total number of stars:

$$N_\star = \Lambda M_{\rm SC} \quad \text{where} \quad \Lambda = \frac{\int_{M_{\star,\rm min}}^{M_{\star,\rm max}} f_\star(M_\star) dM_\star}{\int_{M_{\star,\rm min}}^{M_{\star,\rm max}} M_\star f_\star(M_\star) dM_\star}$$



- Stellar initial mass function (IMF) according to Kroupa (2001)
- Maximum stellar mass is 150 $M_\odot$

Stellar population in YMSC

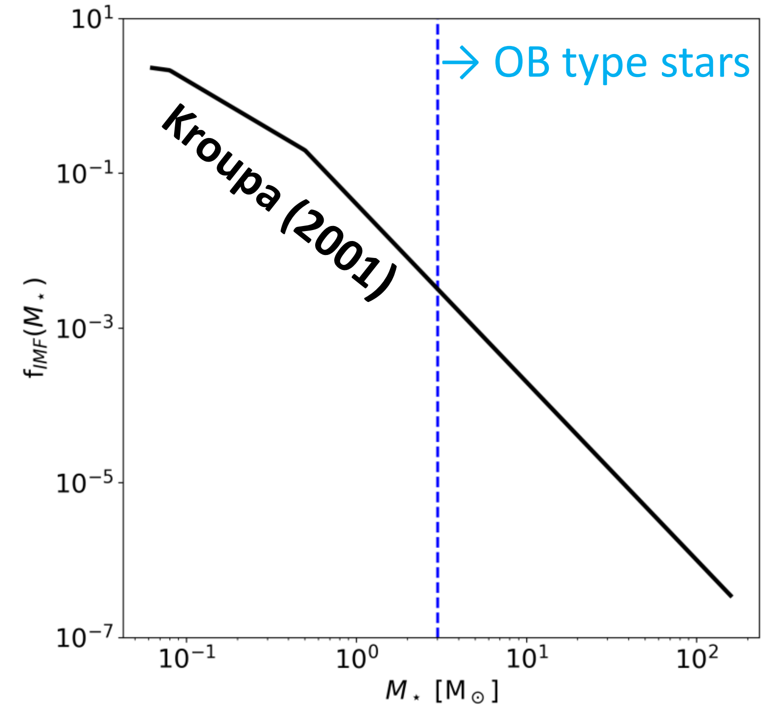
- Total number of stars:

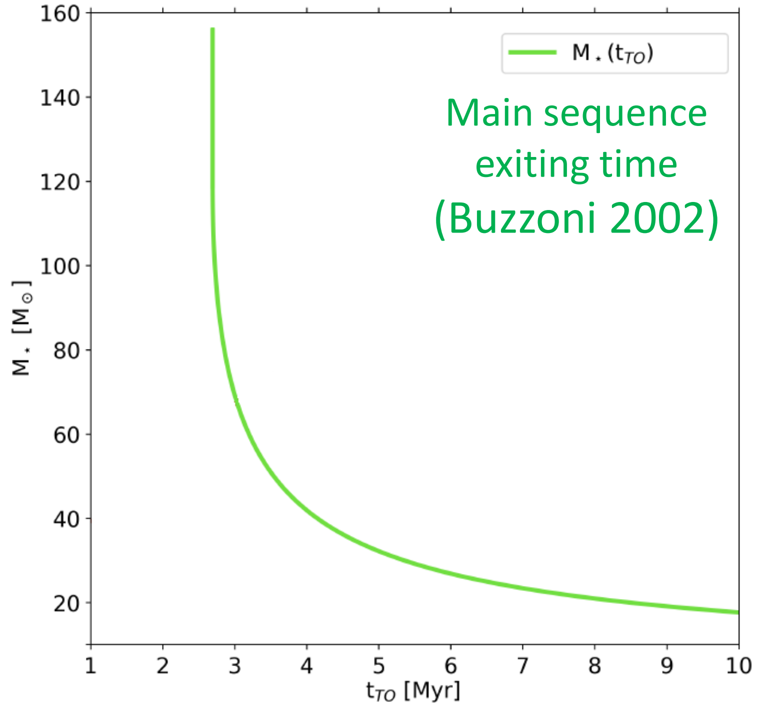
$$N_\star = \Lambda M_{SC} \quad \text{where} \quad \Lambda = \frac{\int_{M_{\star,\min}}^{M_{\star,\max}} f_\star(M_\star) dM_\star}{\int_{M_{\star,\min}}^{M_{\star,\max}} M_\star f_\star(M_\star) dM_\star}$$

- Stellar initial mass function (IMF) according to Kroupa (2001)
- Maximum stellar mass is 150 $M_\odot$
- *All stars that have left the main sequence at a time equal to the age of the cluster are removed*, **with exception of WR stars** ($t_{TO} < t < t_{TO}$+0.3Myr and $M_\star$>25$M_\odot$)

WE DO NOT ACCOUNT FOR THE ENERGY INJECTED BY SUPERNOVE!

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

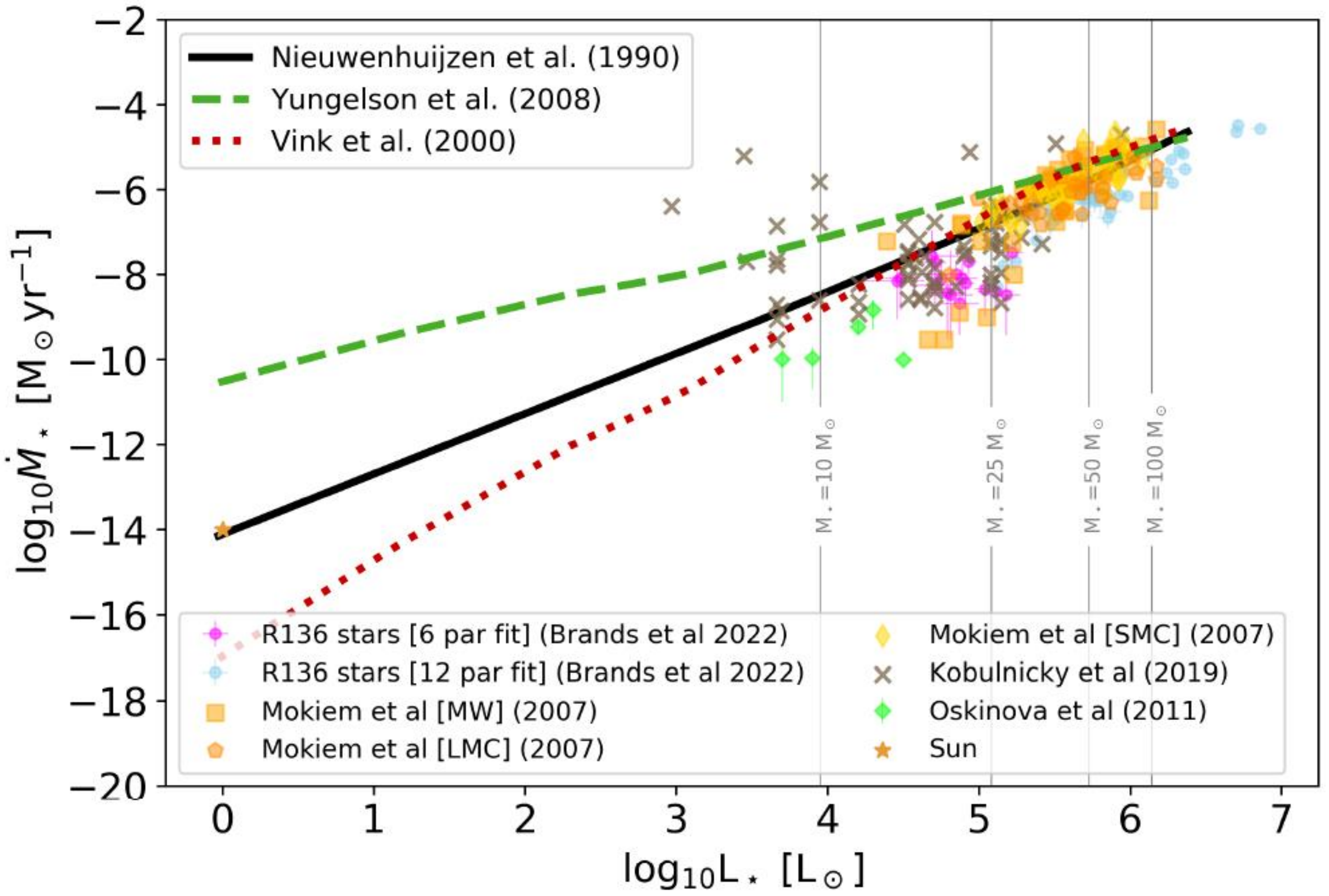


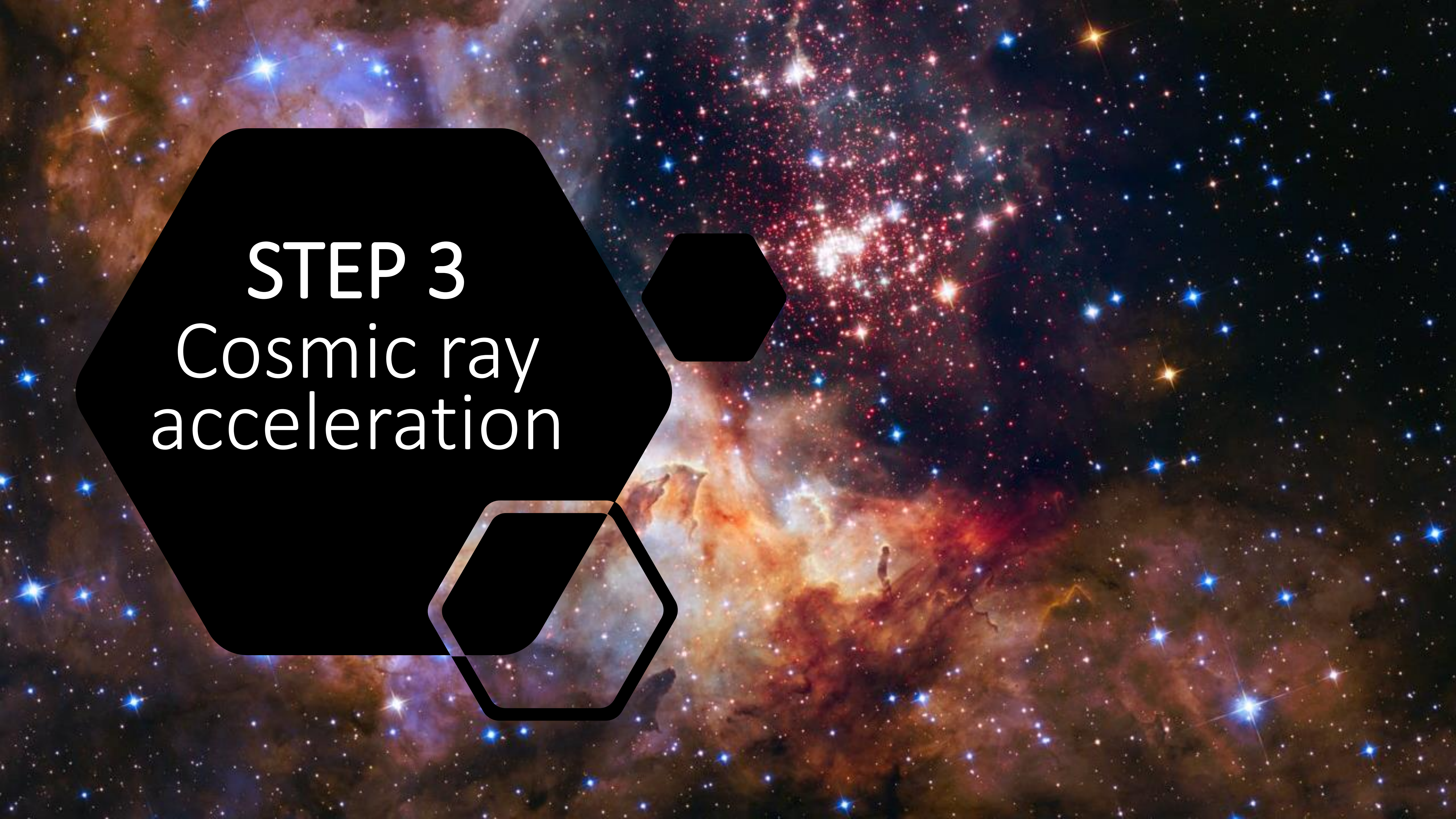


Stellar wind physics

1. Calculate mass loss rate:
   - **OB-type** stars ($\dot{M}_{\star}$) (Nieuwenhuijzen et al. 1990)
   - **WR** stars ($\dot{M}_{\star,WR}$) (Nugis & Lamers, 2000)
2. Calculate wind speed ($v_{\star,w}$):
   - **OB-type** stars (Kudritzki & Puls, 2000)
   - **WR** is kept constant to 2000 km/s
3. Calculate wind luminosity: $L_{*,w} = \frac{1}{2}\dot{M}_{*}v_{*,w}^{2}$

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




STEP 3
Cosmic ray acceleration

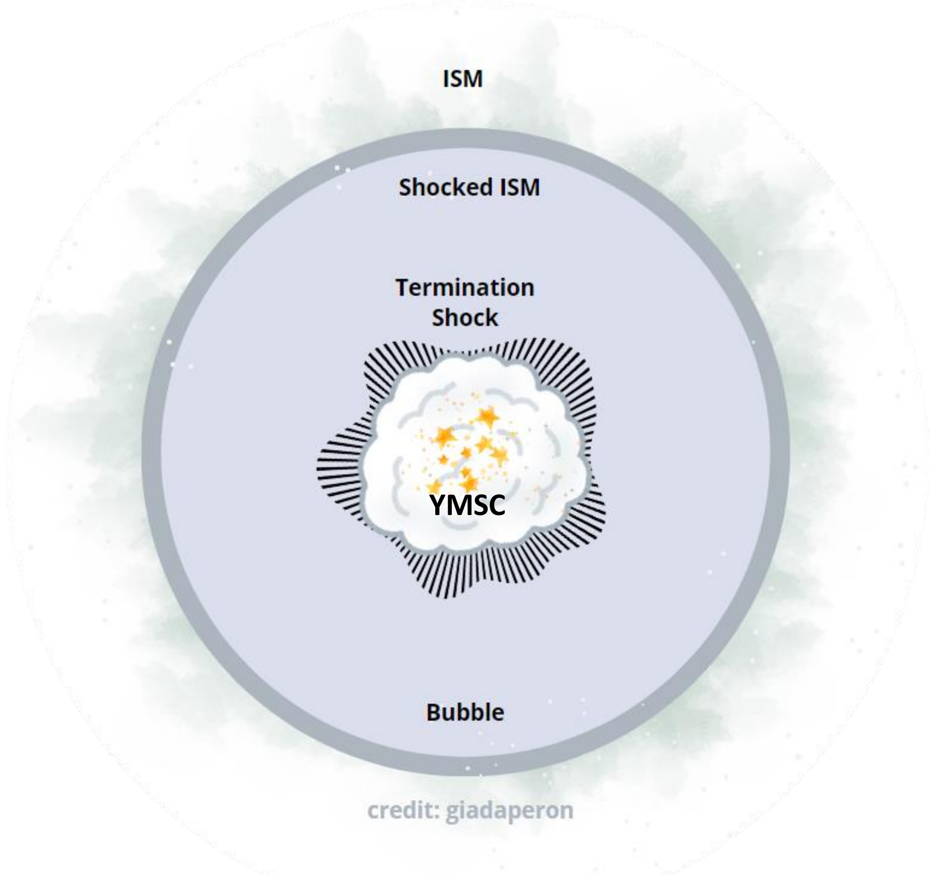
CR distribution in YMSCs

Morlino et al (2021)

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

1) Spectral slope: $\propto p^{-4.2}$

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



CR distribution in YMSCs

Morlino et al (2021)

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

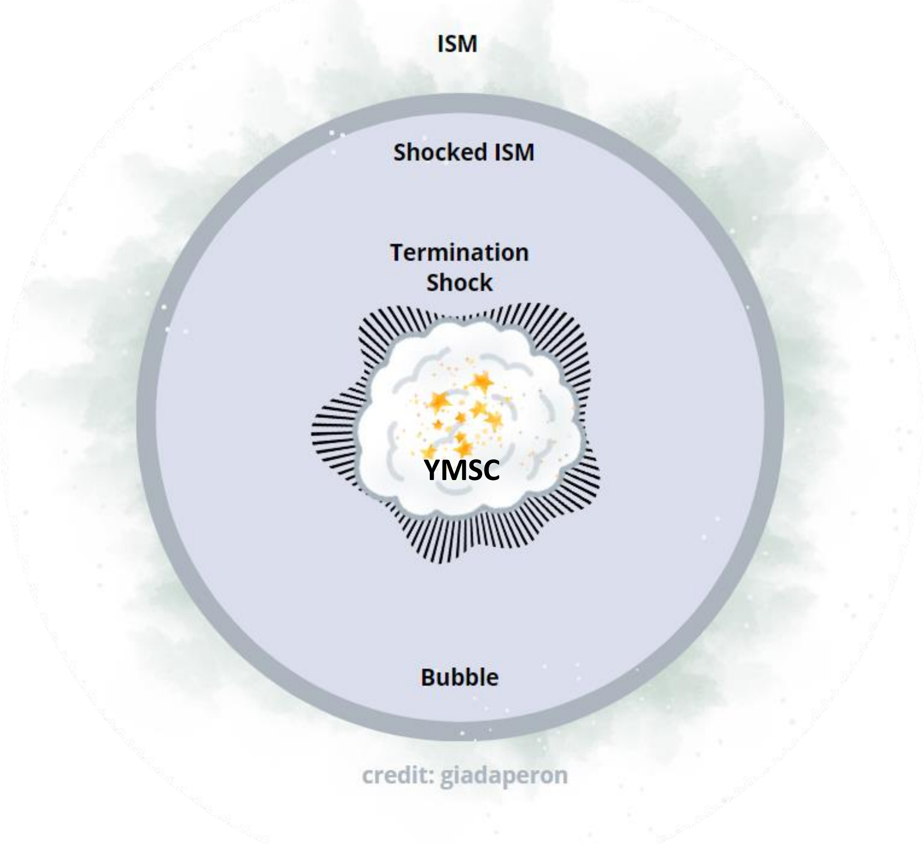
1) Spectral slope: $\propto p^{-4.2}$

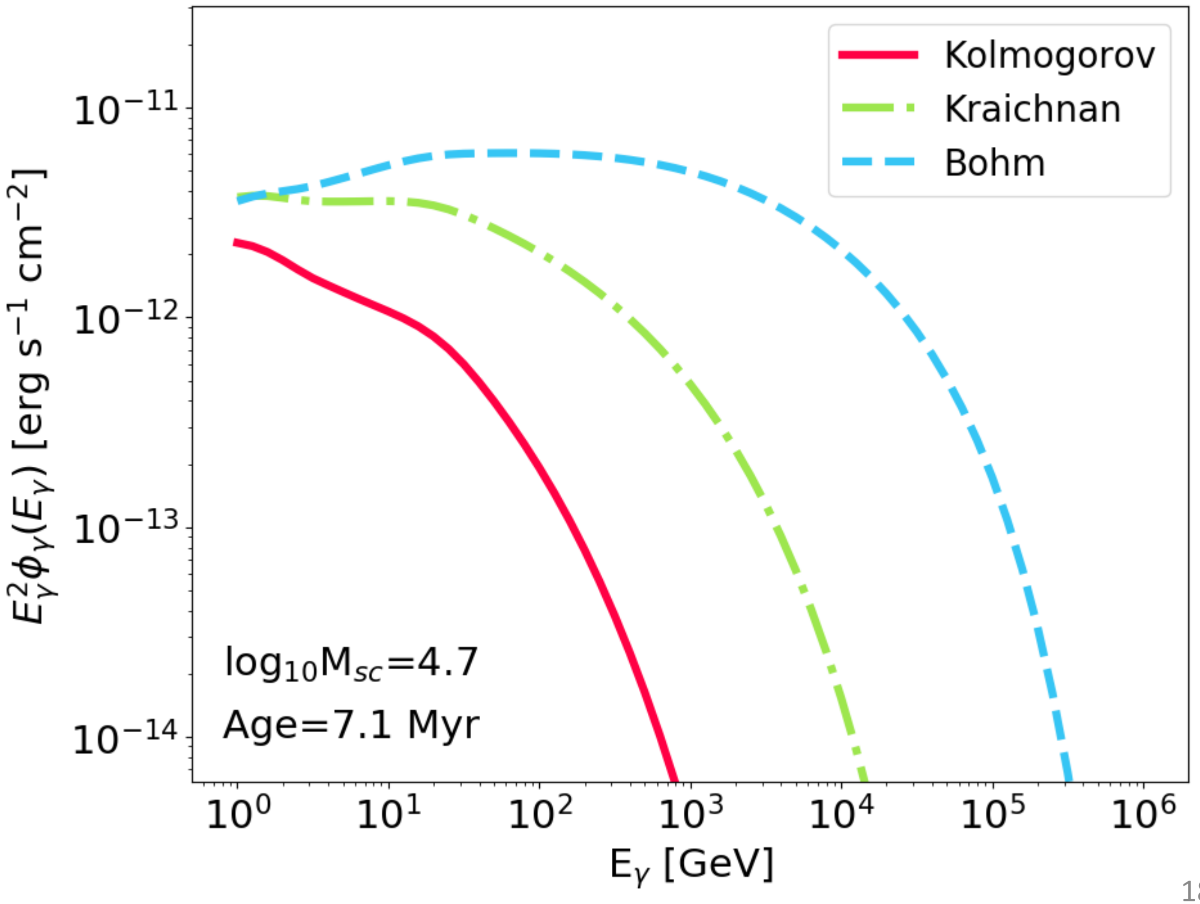
2) Normalization: 10% of wind power spent to accelerate CRs

3) Target gas density for hadronic gamma emission: 10 cm^{-3}

4) Particle spectrum (and so the gamma flux) depends on diffusion coefficient!

THREE CASES CONSIDERED:



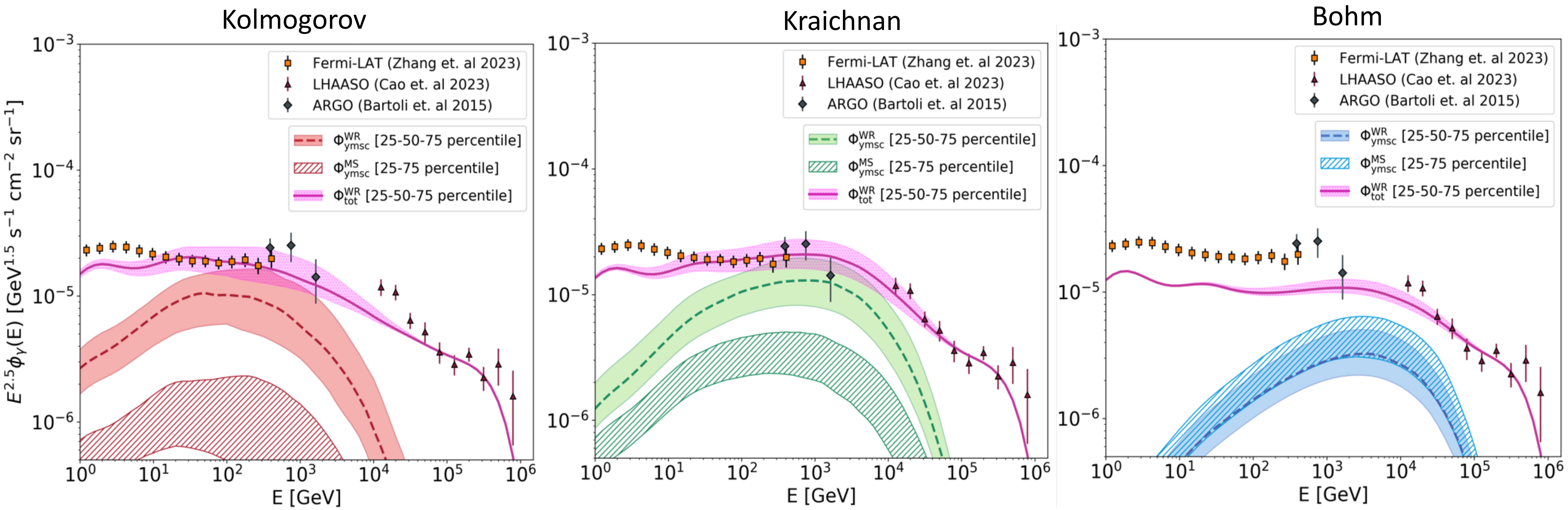


Comparison with γ–ray data

Diffuse γ-ray emission (ROI1)

- **Pink:** diffuse CR sea emission + contribution from YMSCs
- Filled regions: contribution from YMSCs
- Dashed regions: contribution from YMSCs without WRs

Note:
Contribution from detectable YMSCs is removed

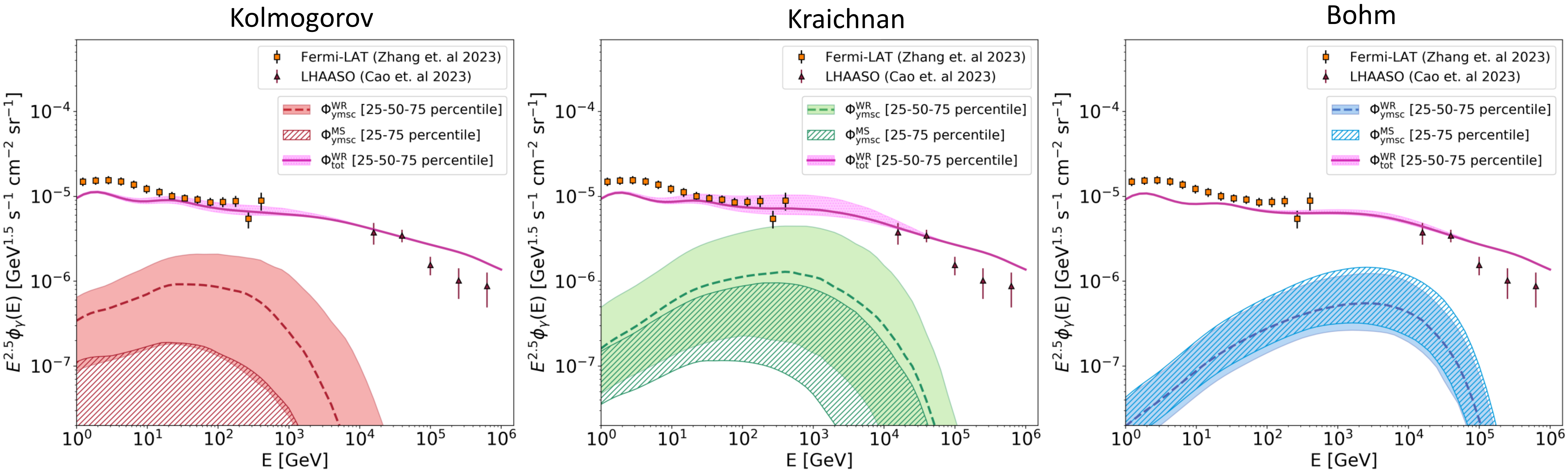


ROI1: 15°<glon<125°, |glat|<5°

Diffuse γ-ray emission (ROI2)

ROI2: 125°<glon<235°, |glat|<5°

Pink: diffuse CR sea emission + contribution from YMSCs
Filled regions: contribution from YMSCs
Dashed regions: contribution from YMSCs without WRs



Conclusions

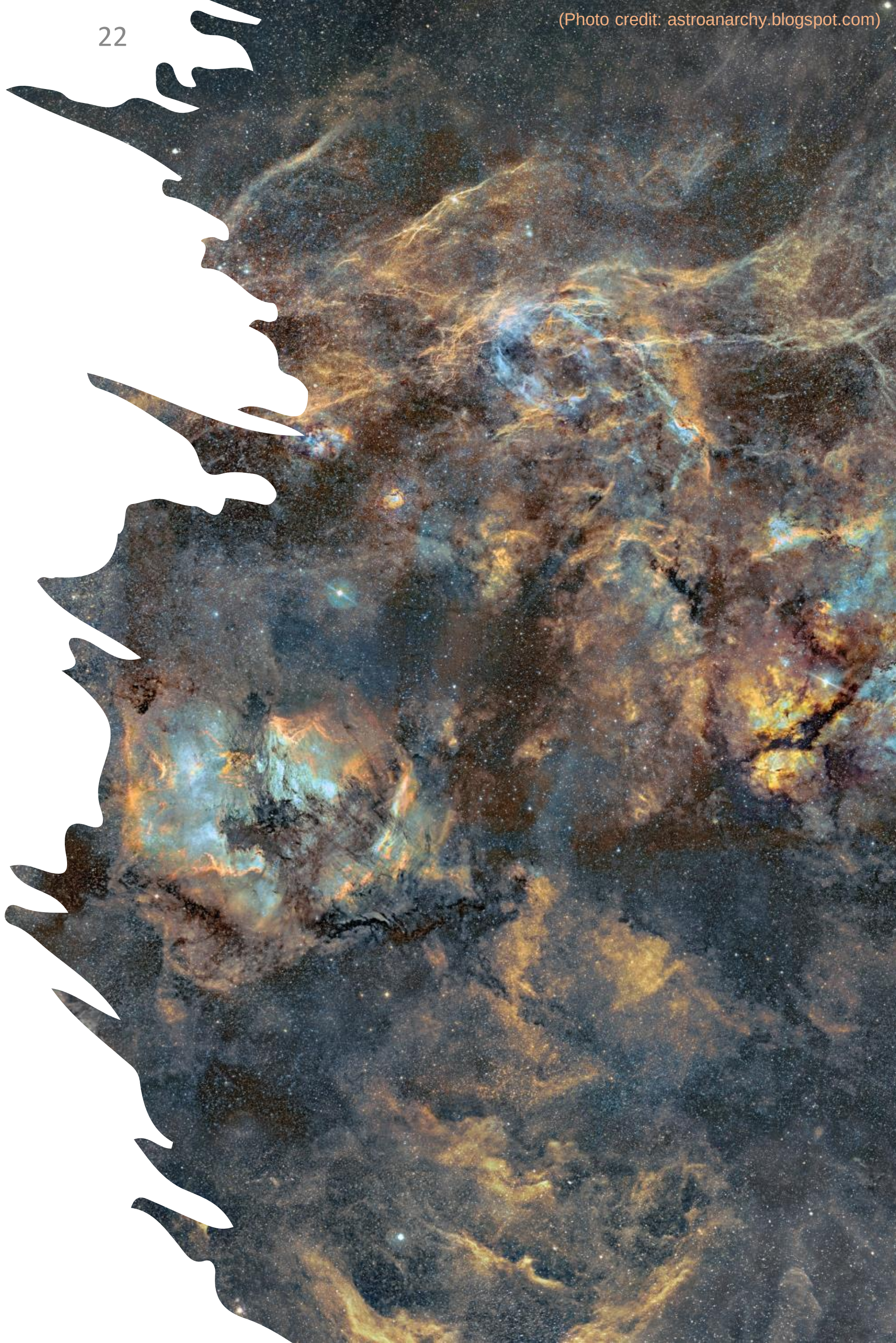
- ❖ Importance of YMSCs as high energy sources has constantly growing in the last decades
- ❖ **First comprehensive study of Galactic population of YMSCs**
- ❖ **Contribution to the diffuse emission likely not negligible from hundreds of GeV to hundreds of TeV.**

Future prospects

- ➢ Evaluate contribution to neutrino flux

Scan me to access the pre-print

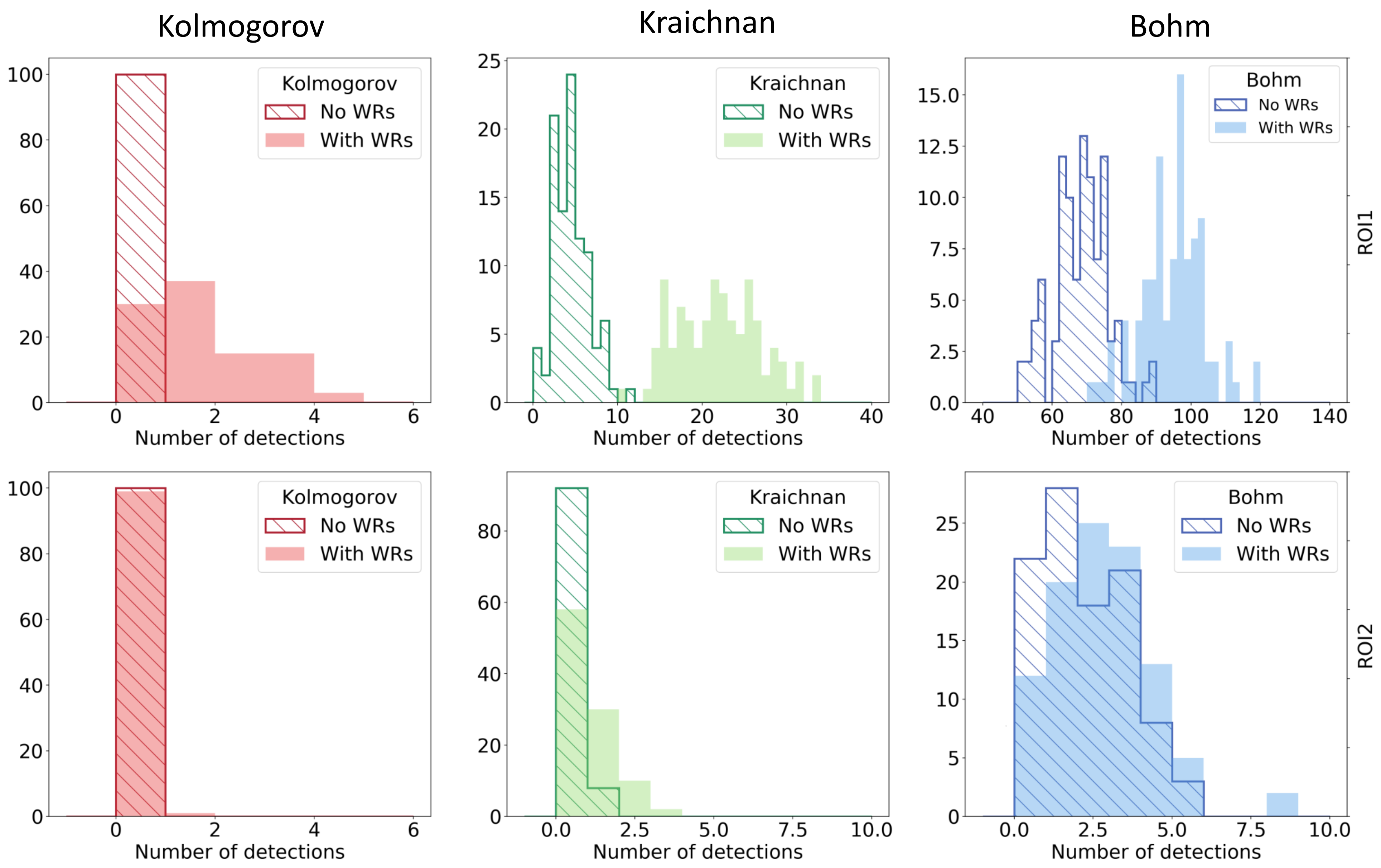
https://arxiv.org/abs/2406.04087



(Photo credit: astroanarchy.blogspot.com)

BACKUP SLIDES

Expected detections

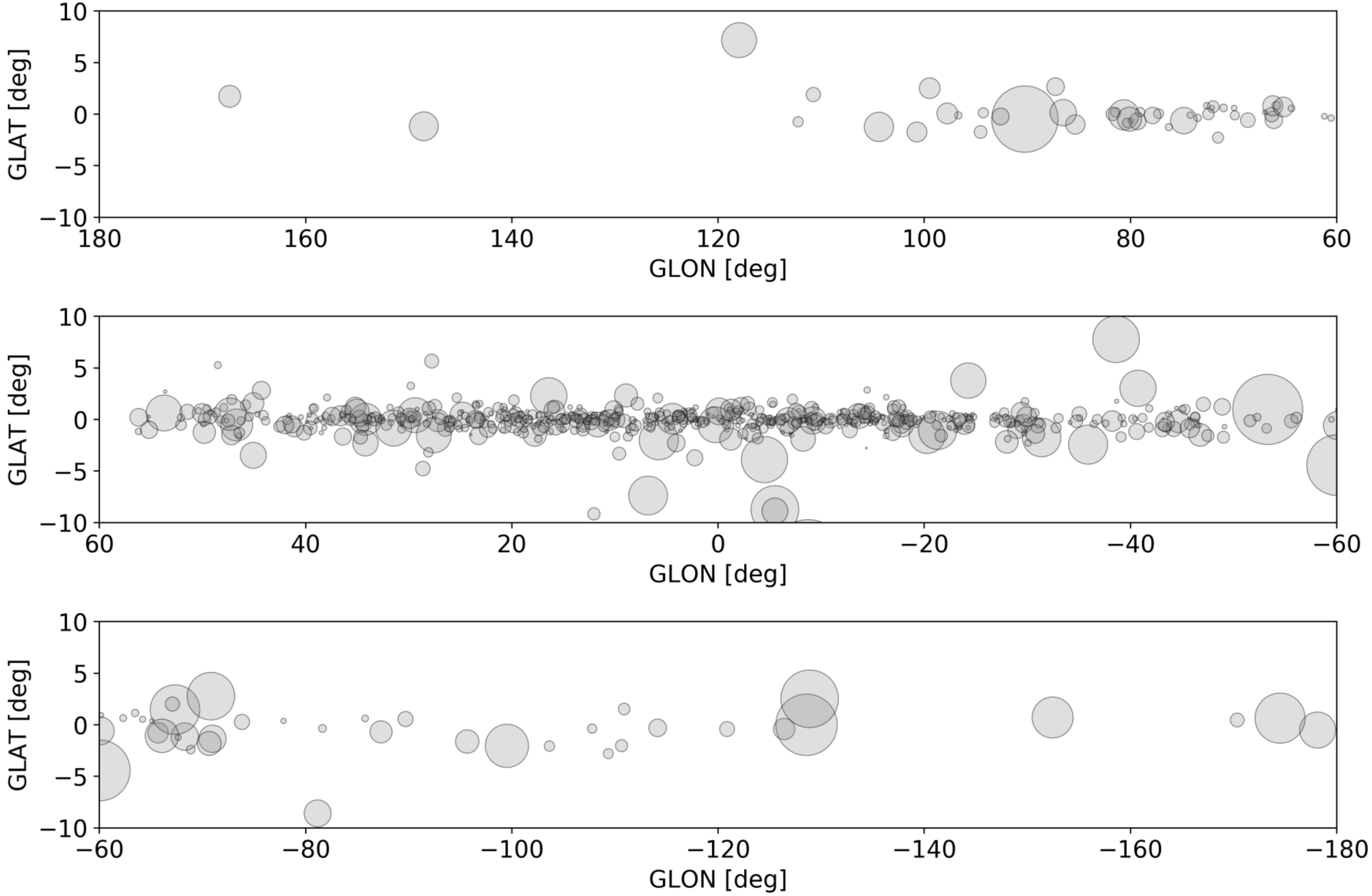


LHAASO catalogue includes 90 sources

Number of expected detections in Bohm case is too high!

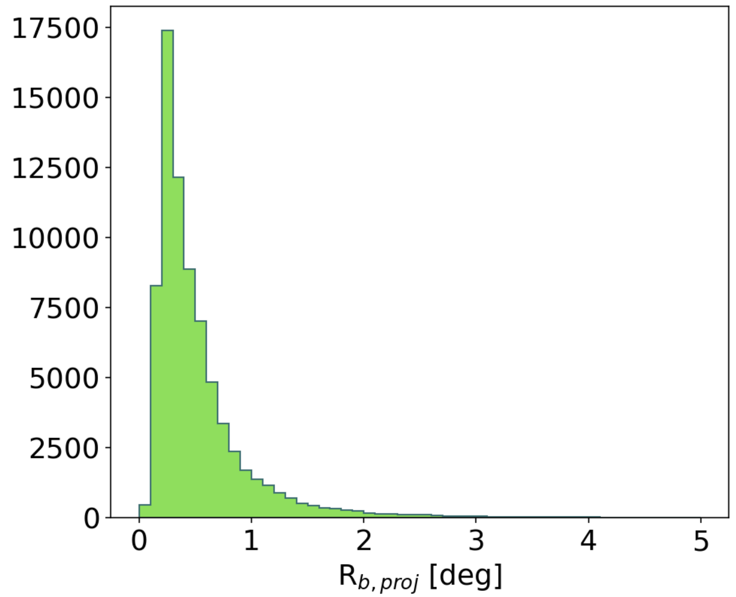
Synthetic YMSCs population (III)

Single realization of the Galactic population



Wind bubble physics from Weaver et al 1977

Projected bubble radius



Stellar wind physics

- Mass loss rate **OB-type** stars ($\dot{M}_\star$) by Nieuwenhuijzen et al. (1990)

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

- Wind luminosity **OB-type** stars [stellar winv speed $v_{\star,w}$ by Kudritzki & Puls (2000)]

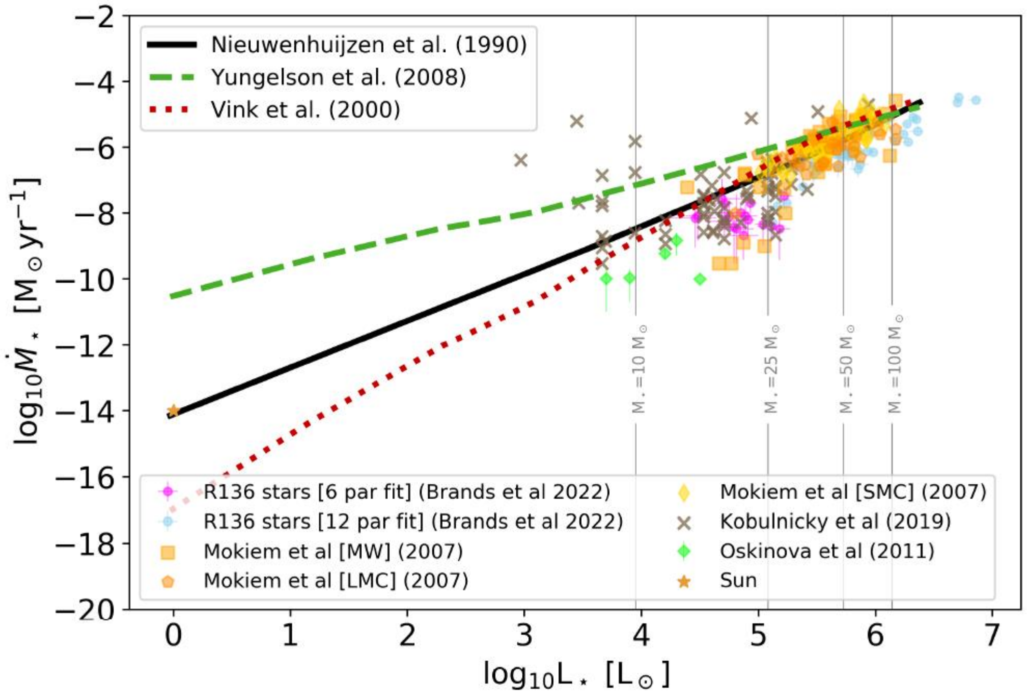
$$L_{\star,w} = \frac{1}{2}\dot{M}_\star \underbrace{\left\{C(T_{\mathrm{eff}})^2\left[\frac{2GM_\star(1-L_\star/L_{\mathrm{Edd}})}{R_\star}\right]\right\}}_{v_{\star,w}^{\;2}}$$

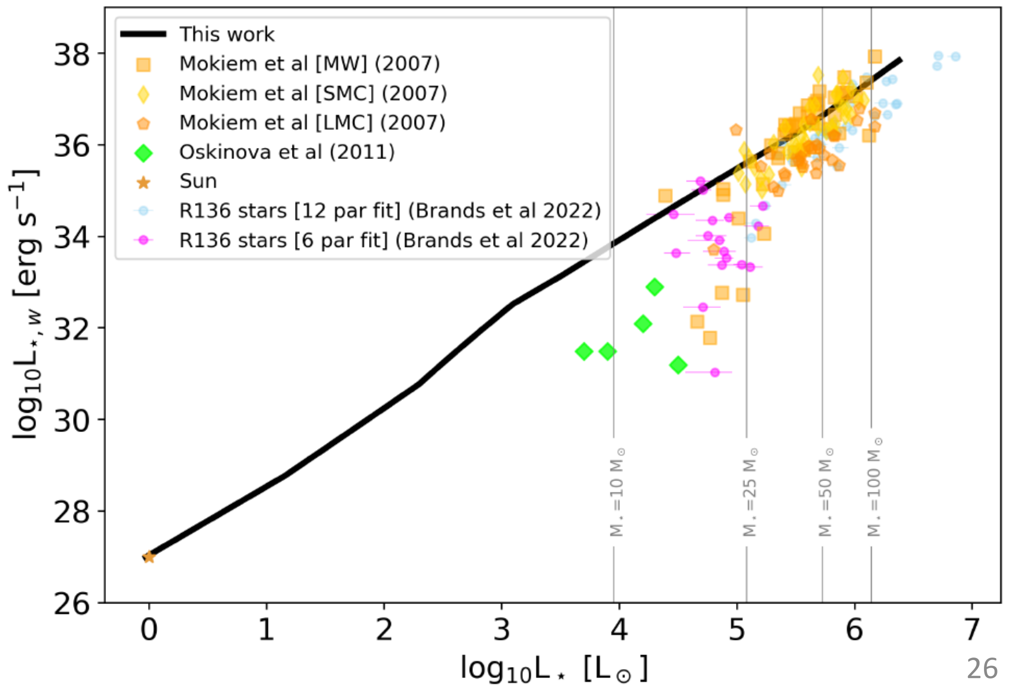
- Mass loss rate **WR** stars ($\dot{M}_{\star,WR}$) by Nugis & Lamers (2000)

$$\dot{M}_{\star,\mathrm{WR}} = 10^{-11.0}\left(\frac{L_{\star,\mathrm{WR}}}{L_\odot}\right)^{1.29}\left(\frac{Y_{\mathrm{WR}}}{Y_\odot}\right)^{1.73}\left(\frac{Z_{\mathrm{WR}}}{Z_\odot}\right)^{0.47}\frac{\mathrm{M_\odot}}{\mathrm{yr}}$$

- Wind speed for **WR** is kept constant to 2000 km/s

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





Diffuse γ-ray emission (GDE)

GDE data: Fermi-LAT, ARGO and LHAASO.

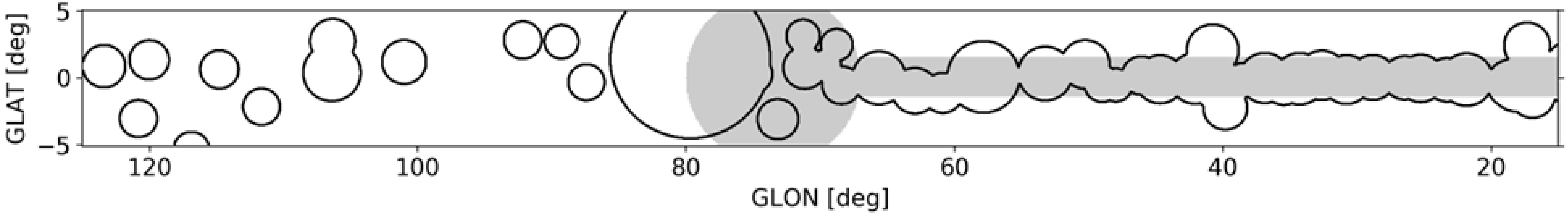
ROI1: 15°<glon<125°, |glat|<5°

ROI2: 125°<glon<235°, |glat|<5°

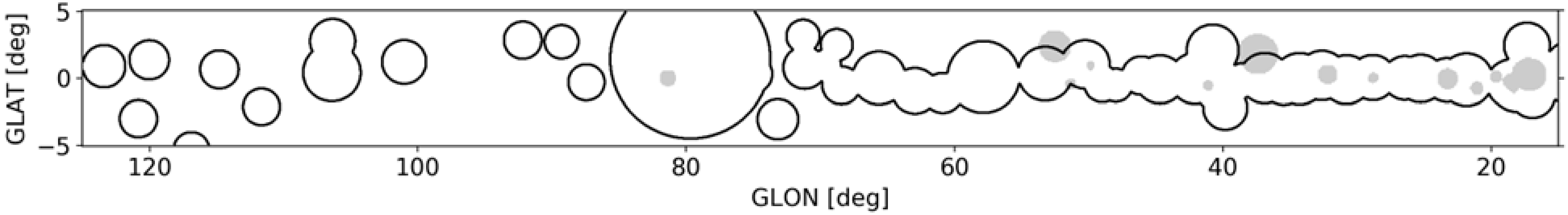
Note: GDE data are provided after masking known detected sources (TeVCat+LHAASOcat)

We define a similar mask for our simulations

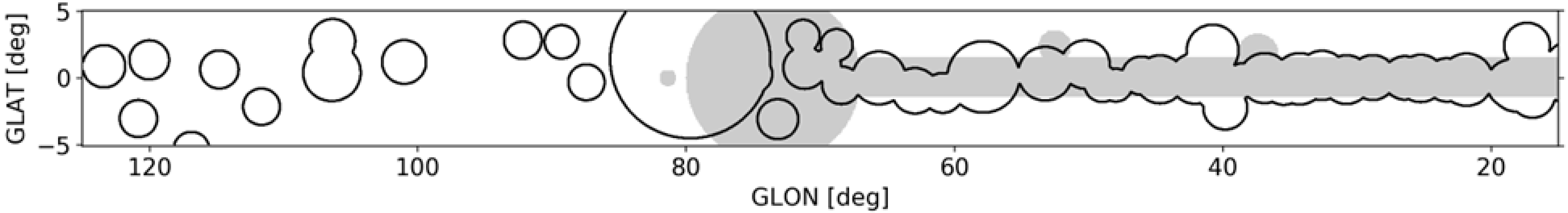
Circles: LHAASO mask; **Shaded grey regions**: our defined masks



1) Mask crowded region of the plane (*Only ROI1*)



2) 5 sigma mask: remove YMSs detected by LHAASO @100 TeV



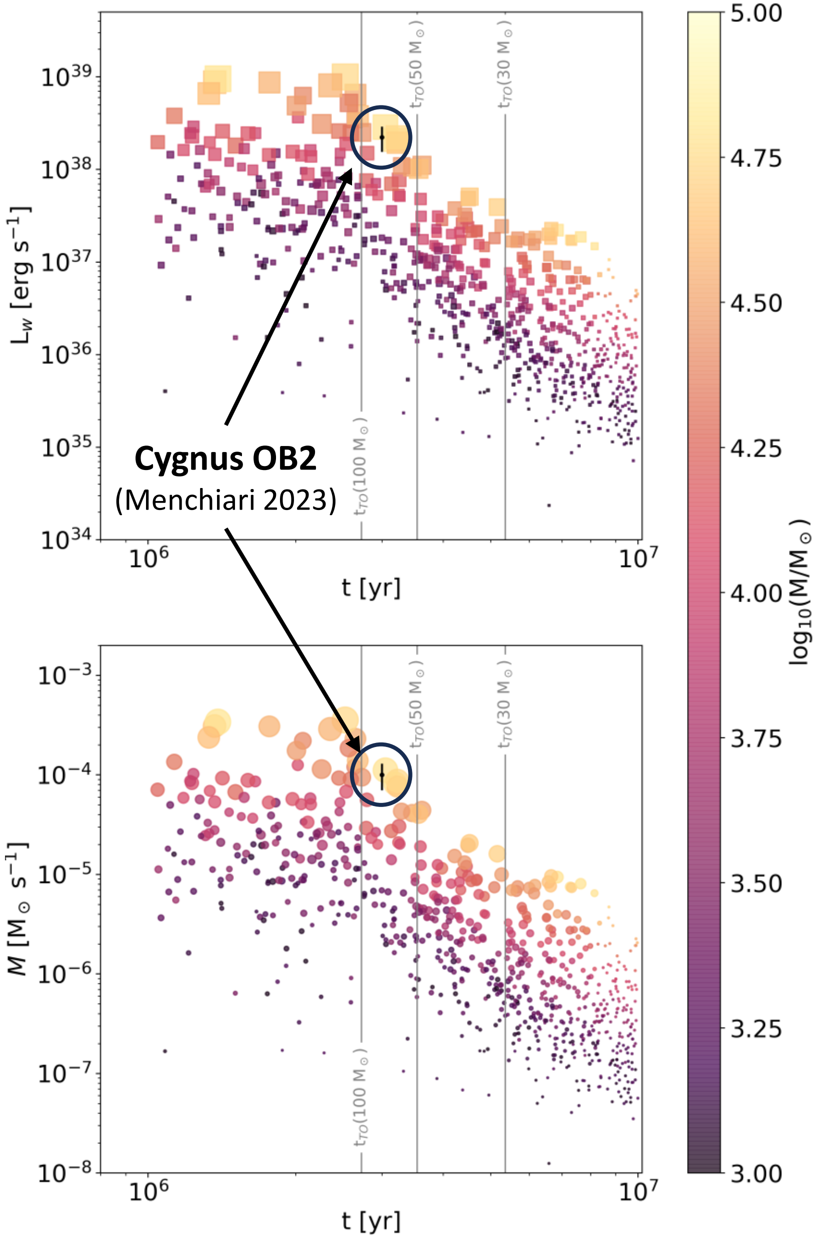
3) Final mask

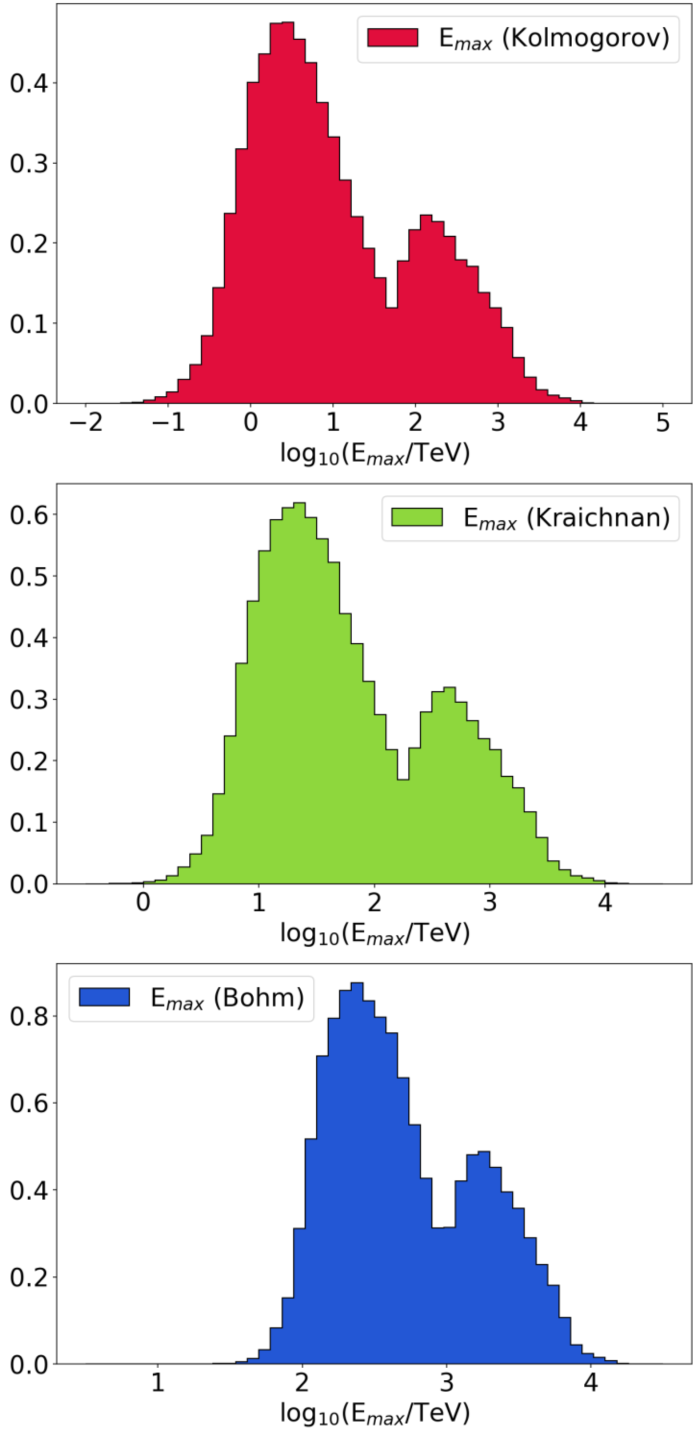
Synthetic YMSCs population (IV)

Cluster wind luminosity vs cluster age (NO WR)

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

Cluster wind mass loss rate vs cluster age (NO WR)





Maximum energy distribution shows bimodality (with and without WR)