Multi-messenger astrophysics with star clusters

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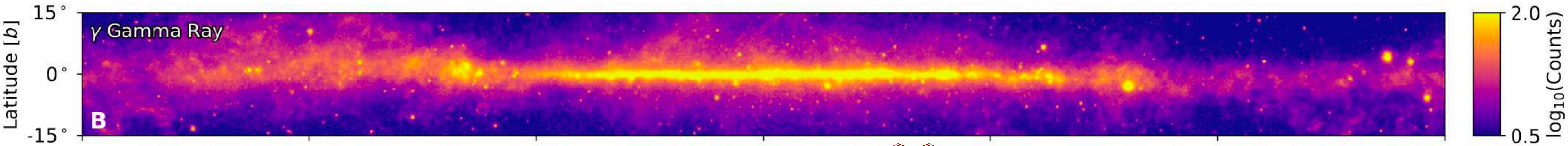
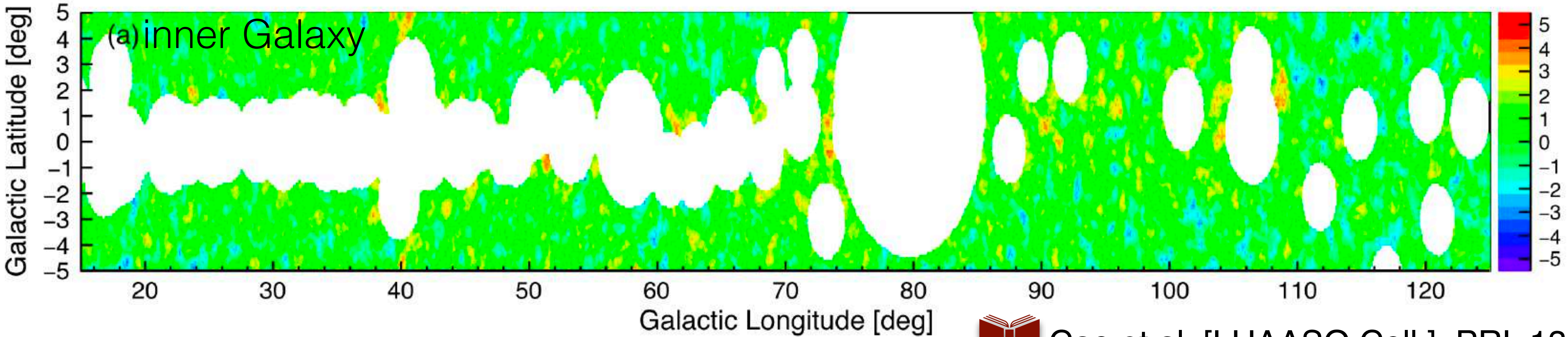
Oct 29th 2024 - Topical Overview on Star Cluster Astrophysics

The Galactic Plane in MWL-MM

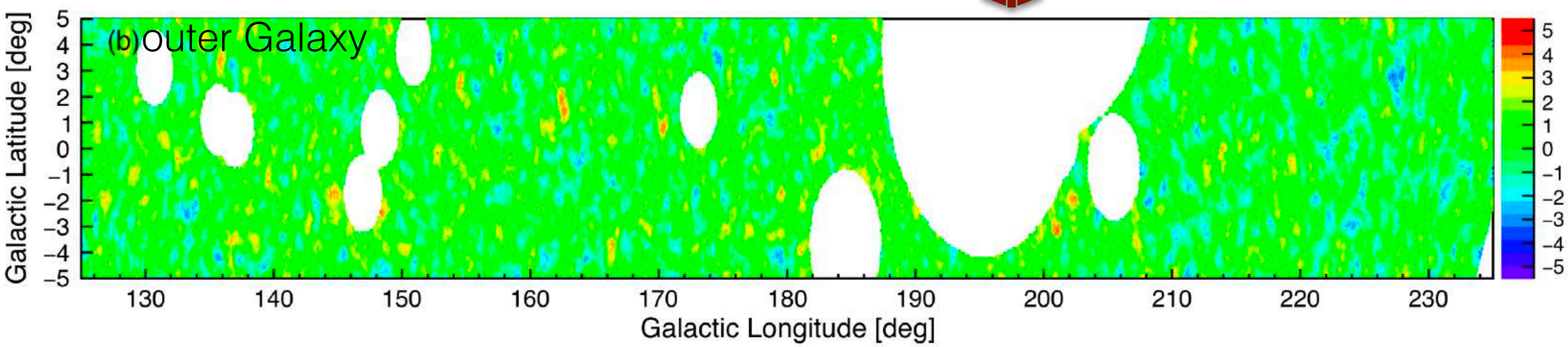


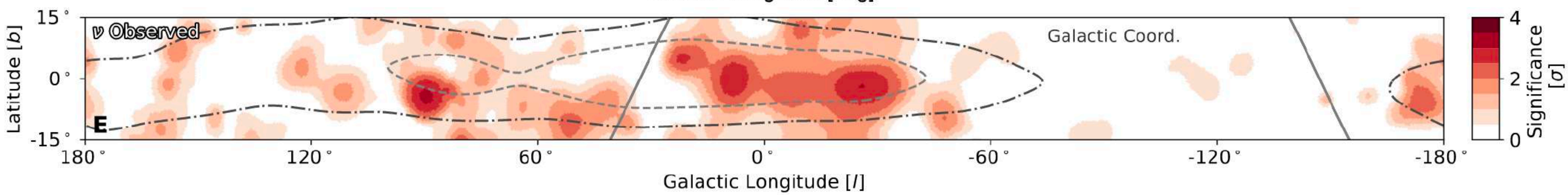
Fermi's 12-year View of the Gamma-ray Sky

UHE γs



Cao et al. [LHAASO Coll.], PRL 131 (2023) 151001



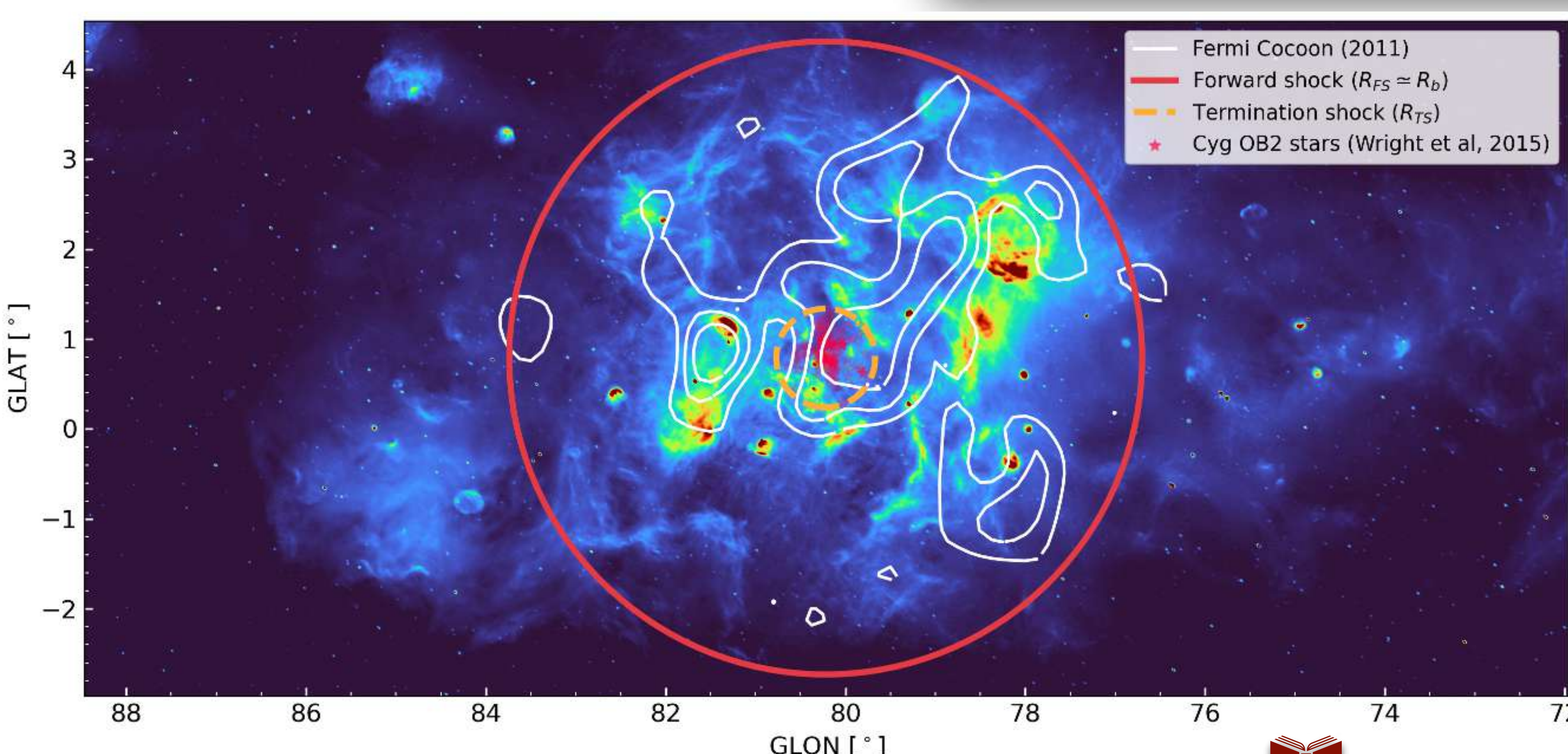


Abbasi et al. [IceCube Coll.], Science 380 (2023) 6652

A new population of gamma-ray sources

- **Extended** gamma-ray emission (1°-3°) detected by many star clusters
- **Origin of emission?**
- Emission size consistent with projected dimension of the wind-blown bubble
- Difficult to disentangle diffuse and low-surface brightness sources

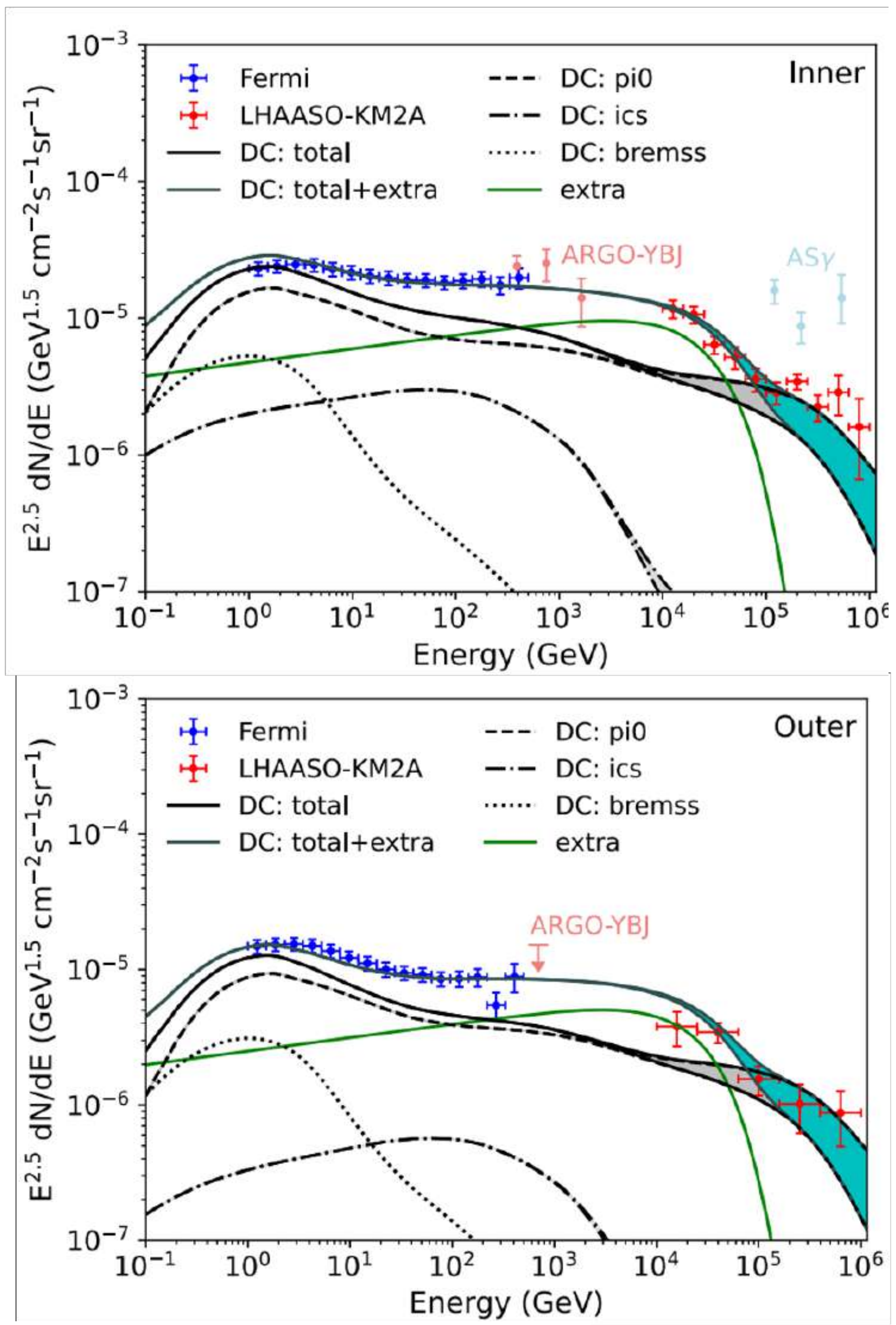
Name	$\log M/M_{\odot}$	r_c [pc]	D [kpc]	Age [Myr]	L_w [erg s^{-1}]
Westerlund 1	4.6 ± 0.045	1.5	4	$4-6$	10
Westerlund 2	4.56 ± 0.035	1.1	2.8 ± 0.4	$1.5-2.5$	2
Cygnus OB2	4.7 ± 0.3	5.2	1.4	$2-7$	2
NGC 3603	4.1 ± 0.1	1.1	6.9	$2-3$	-
BDS 2003	4.39	0.2	4	1	-
W40	2.5	0.44	0.44	1.5	-
RSGC 1	4.48	1.5	6.6	$10-14$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

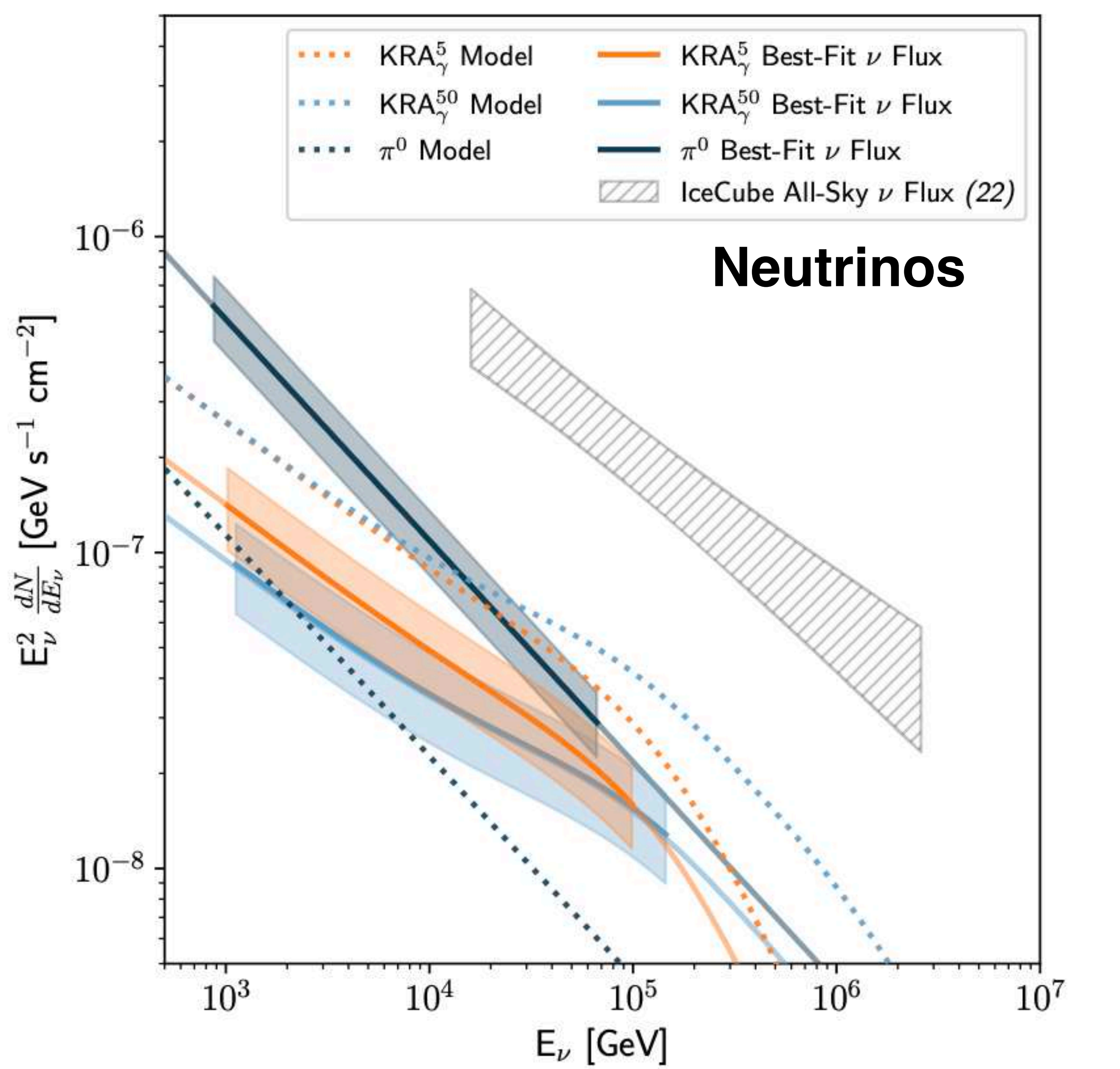


Menchiari et al., A&A (2023)

Do young and massive star clusters contribute to the MM diffuse emission?

- What is the **unresolved source** contribution to the diffuse **gamma-ray** and **neutrino** emissions observed from our Galaxy?





Zhang et al. (2023), arXiv:2305.06948

Abbasi et al. [IceCube Coll.], Science 380 (2023) 6652

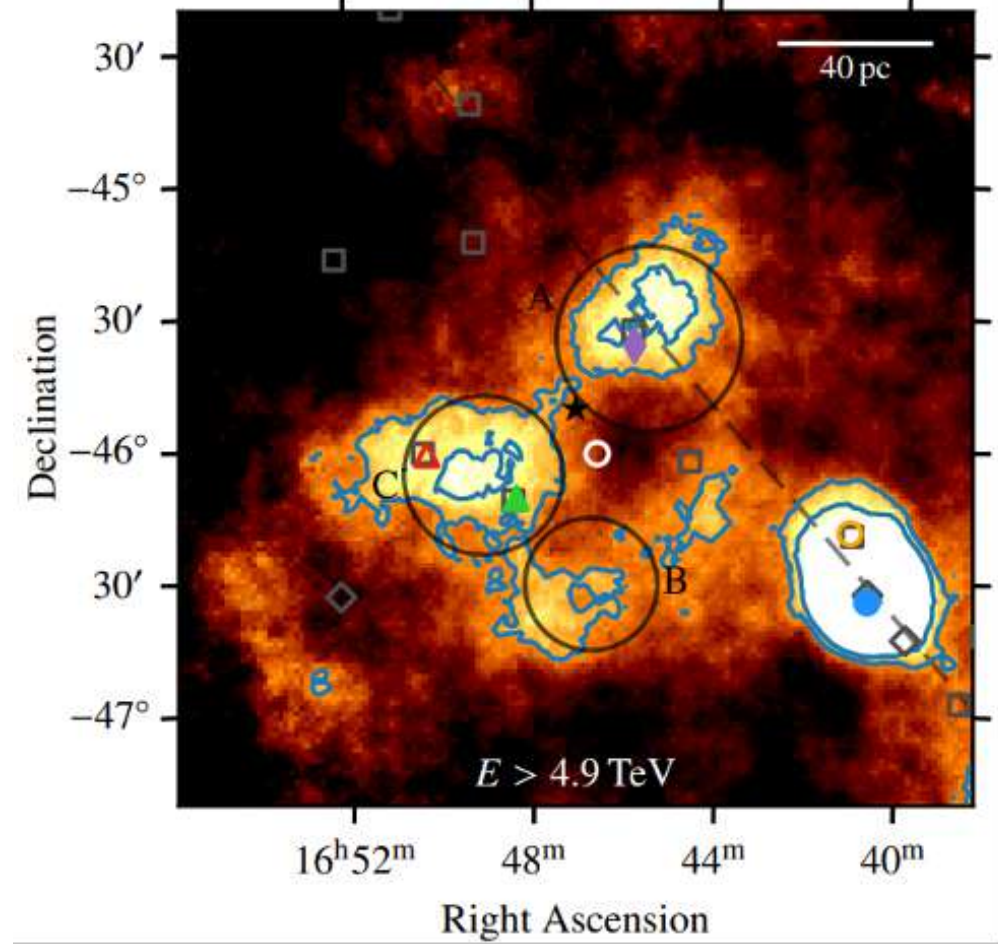
YMSCs

- Clusters of hundreds OB-type ($M_{\star}$>3 $M_{\odot}$) stars distributed over few pc.

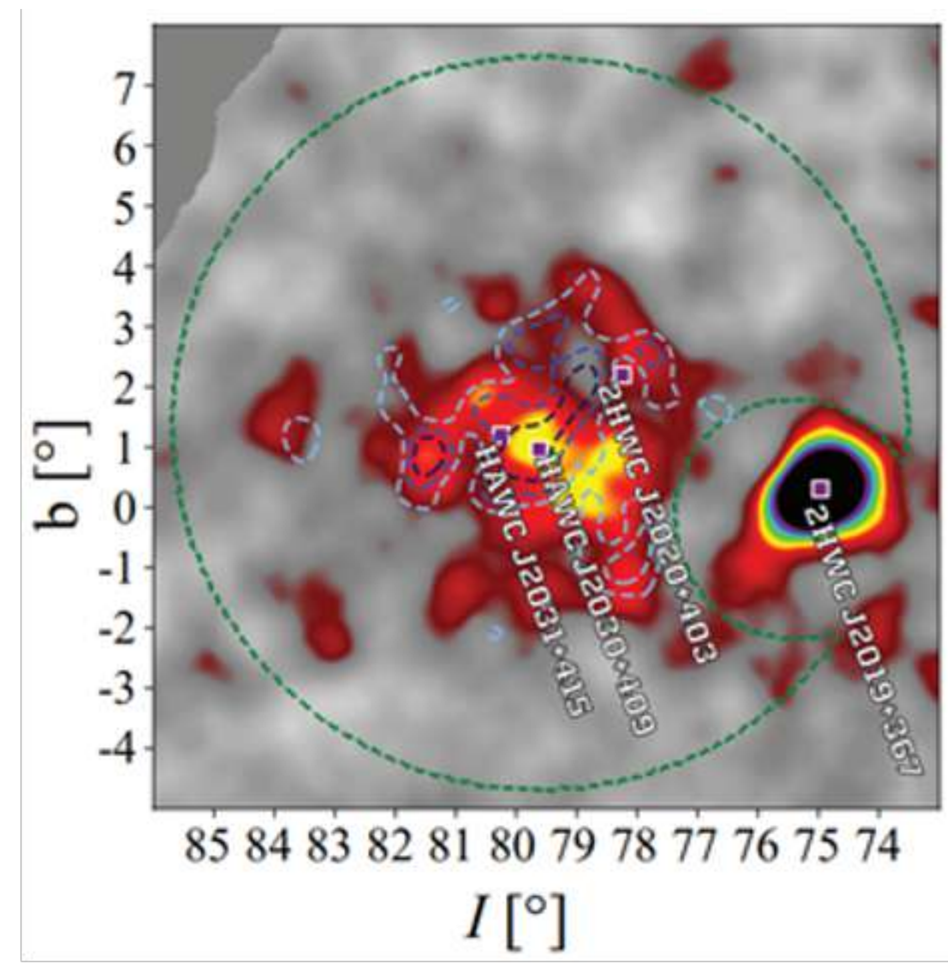
  Young: Age < 10 Myr
  Massive: M_{SC} >10^3 $M_{\odot}$

- Recently emerged as a new **gamma-ray** source population

- Several **acceleration sites** proposed:
  - massive star winds
    - Casse & Paul, ApJ 237 (1980) 236G
  - collective wind termination shock
    - Morlino et al., MNRAS 504 (2021) 4
  - SNRs in cluster cores
    - Vieu et al., MNRAS 512 (2022) 1275
    - Vieu & Reville, MNRAS 519 (2023) 136V



Aharonian et al. [H.E.S.S. Coll.], A&A 666 (2022) A124

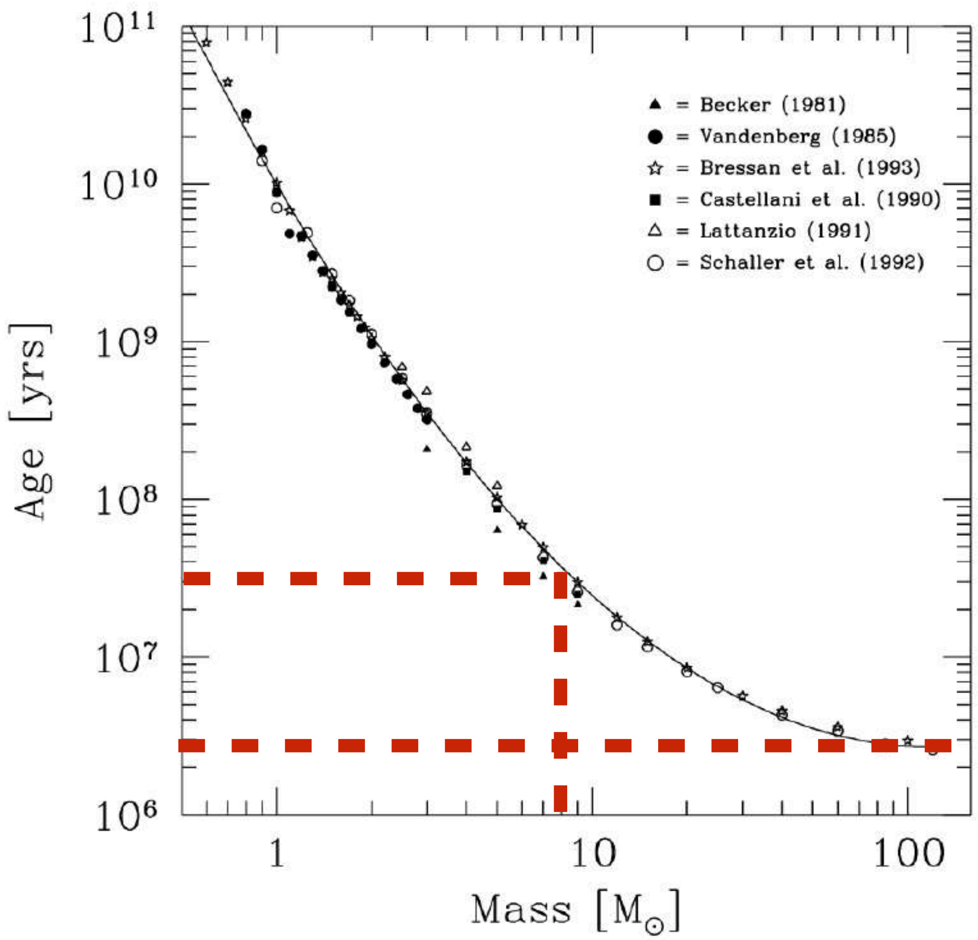


Abeysekara et al. [HAWC Coll.], Nat. Astr. 5 (2021) 465

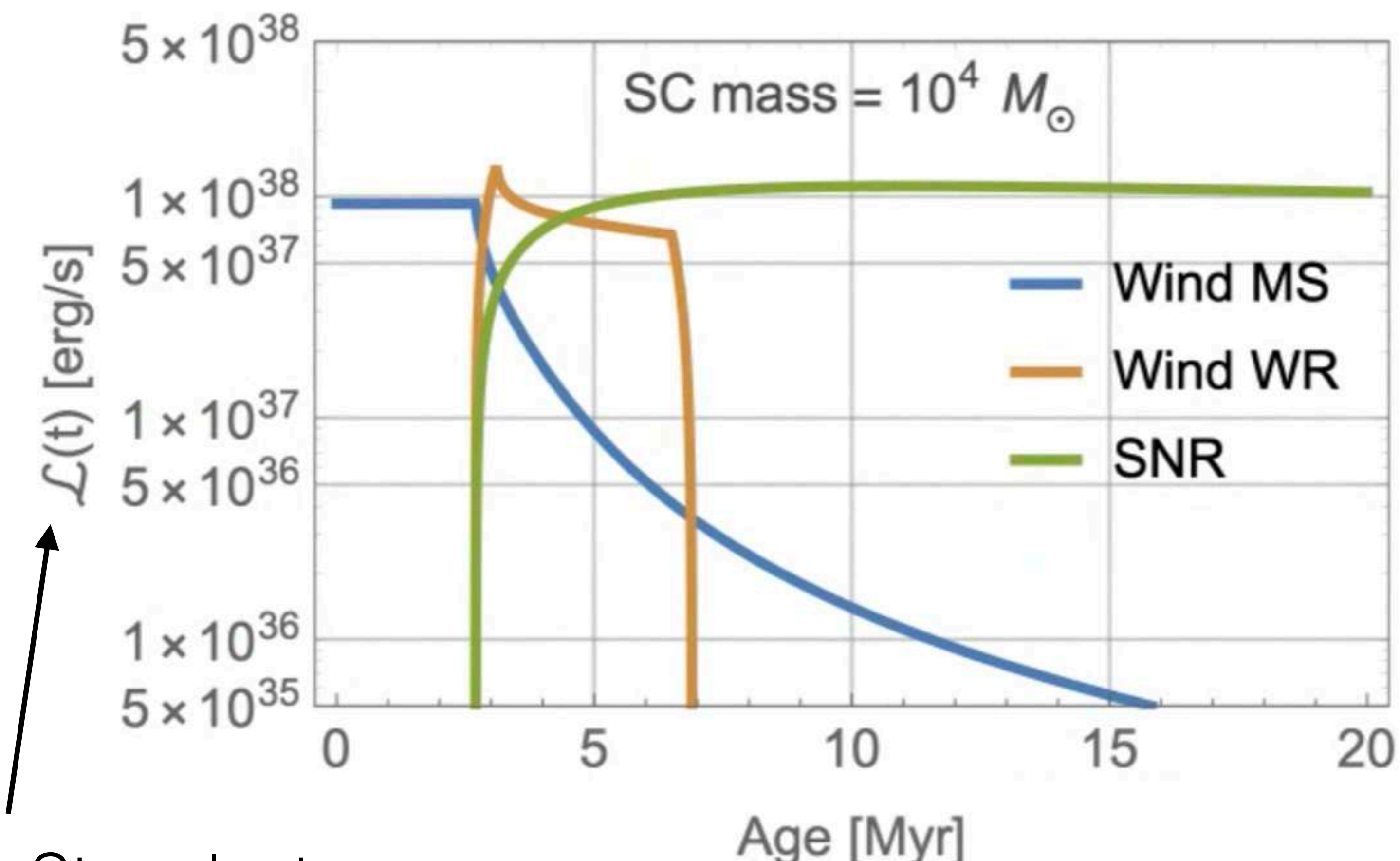
What powers stellar clusters?

Different sources of power:

Phase	Source	Single episode	Model
$t \lesssim 3\,\mathrm{Myr}$	MS stellar winds	$t \gtrsim$ 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



Buzzoni, ApJ 123 (2002) 1188



Star cluster luminosity

What do we need to describe the cumulative hadronic emission from star clusters?

Cluster population: space distribution and formation rate

Stellar wind physics for the population inside clusters

Cluster dynamics:
- → the wind-blown bubble
- → SNR shock evolution
- → HD & MHD turbulence

Target gas distribution:
- → wind ejecta + shell
- → uniform? clumpy?

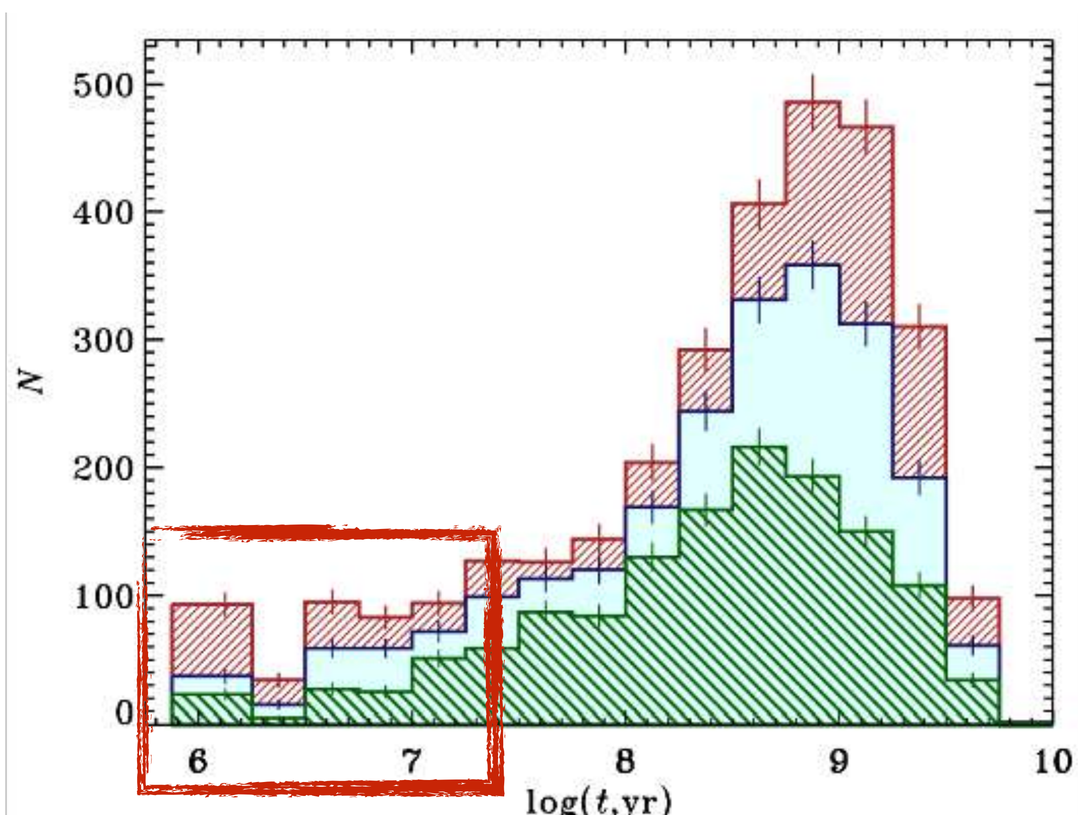
Particle acceleration model:
- → Wind Termination Shock (WTS)
- → SNR Shocks

→ We follow the approach defined in Menchiari et al., arXiv:2406.04087, submitted

1. Cluster distribution

- Because the Milky Way population of YMSCs is not known, information from **local population** will be used

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



Piskunov et al., A&A 614 (2018) A22

cluster IMF

$$f(M_{SC}) \propto M_{SC}^{-1.54}$$

Piskunov et al., A&A 614 (2018) A22

$$2.5 \leq M_{SC}/M_{\odot} \leq 6.3 \times 10^4$$

local cluster formation rate

$$\bar{\psi} = 1.8\,\mathrm{Myr}^{-1}\,\mathrm{kpc}^{-2}$$

Bonatto & Bica, MNRAS 415 (2011) 2827B

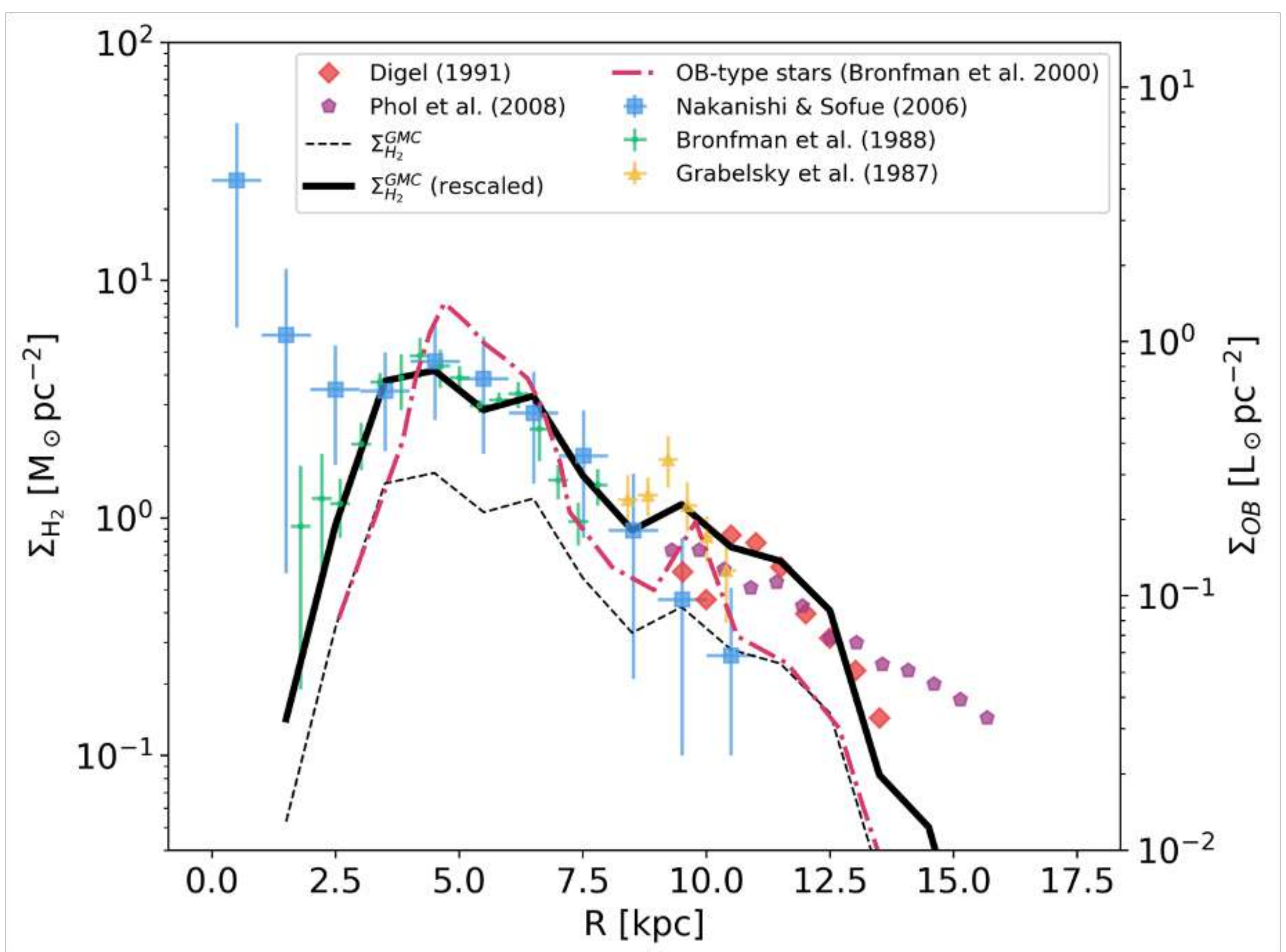
1. Cluster distribution

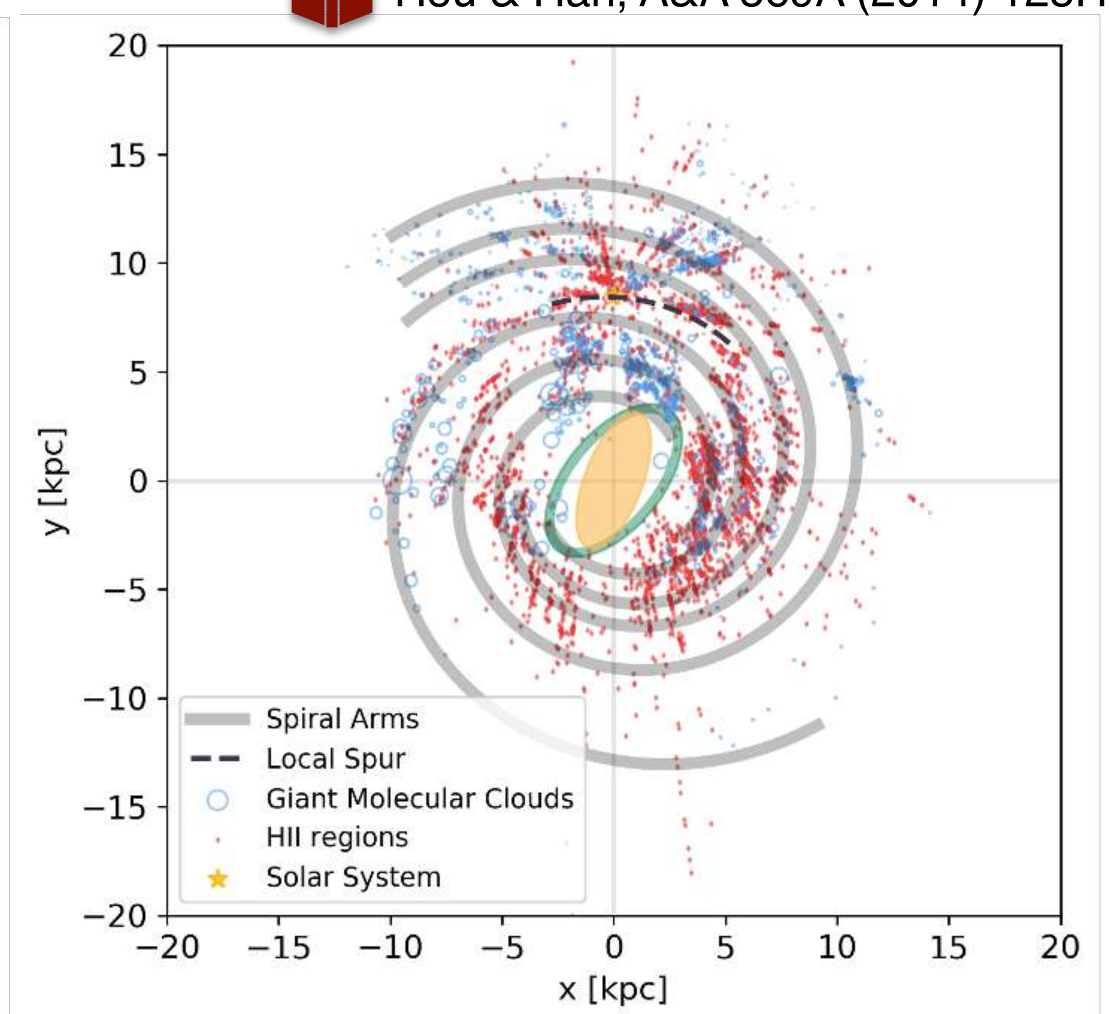
- Because the Milky Way population of YMSC is not known, information from **local population** will be used

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

radial distribution following giant molecular clouds

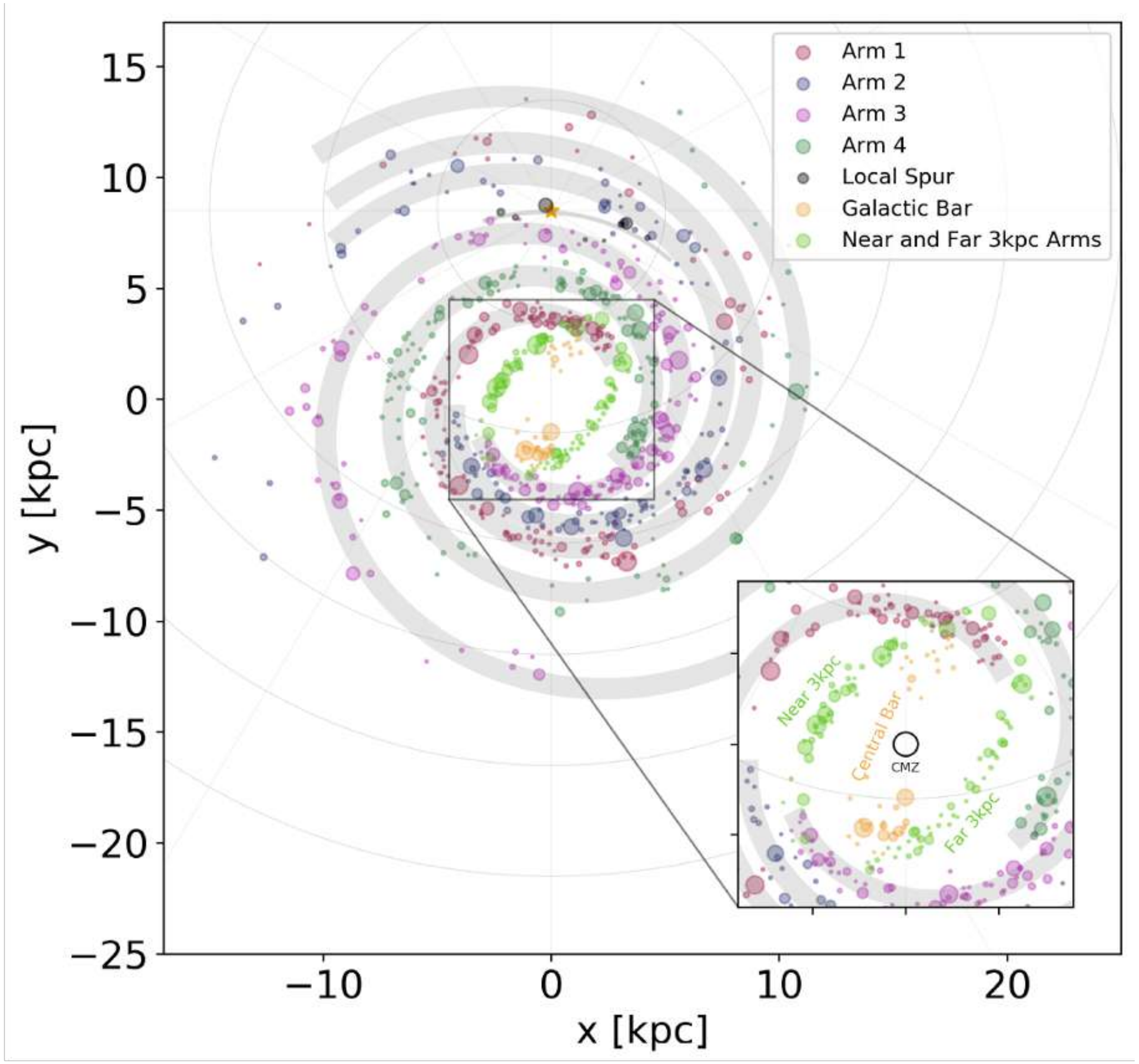
Hou & Han, A&A 569A (2014) 125H



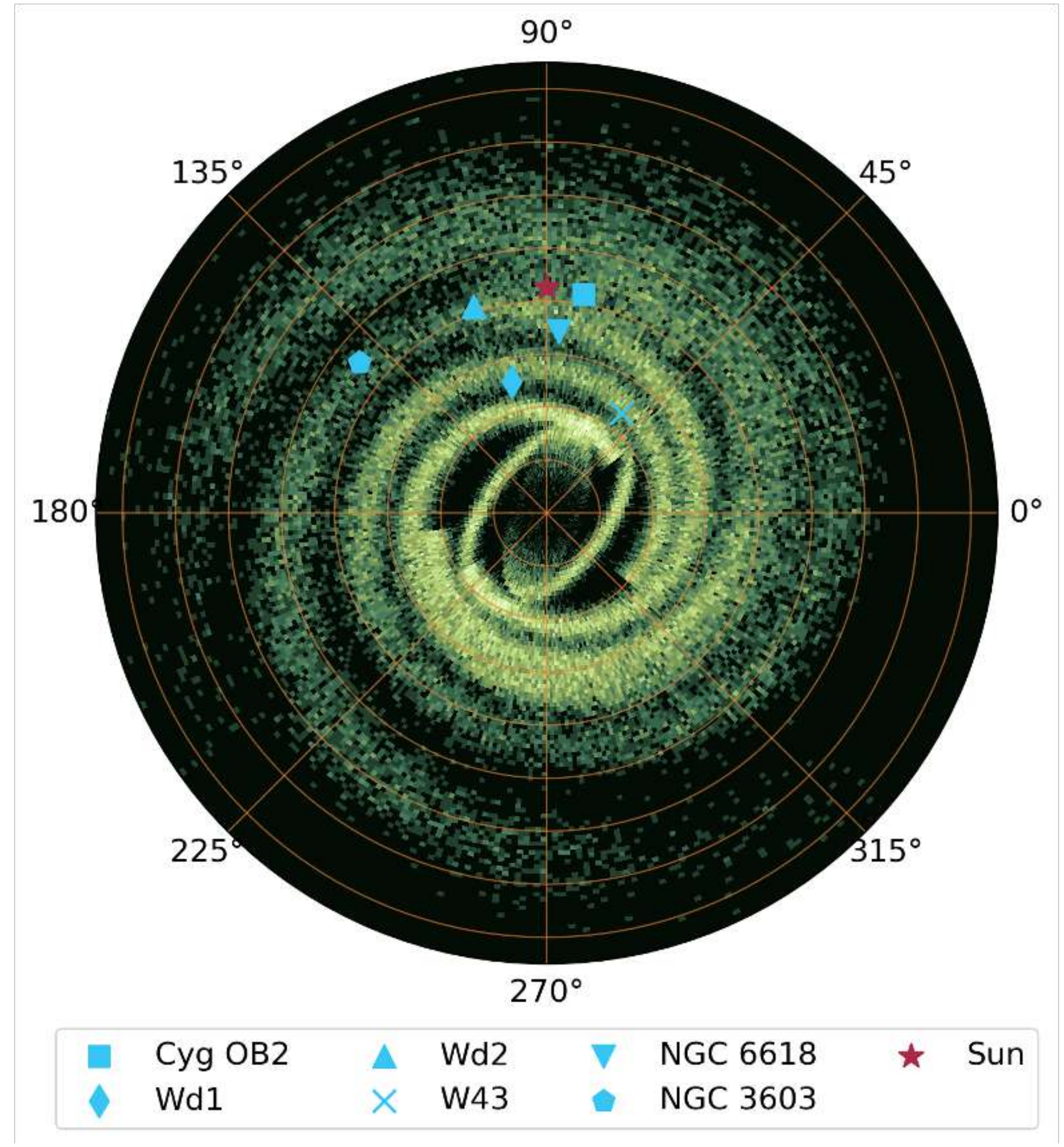


Synthetic cluster population

Total number of YMSCs: 747 (Age < 10 Myr, M_{SC} > 10^3 M_{sun})



Single realization of the Galactic population



100 realizations

2. Stellar population in star clusters

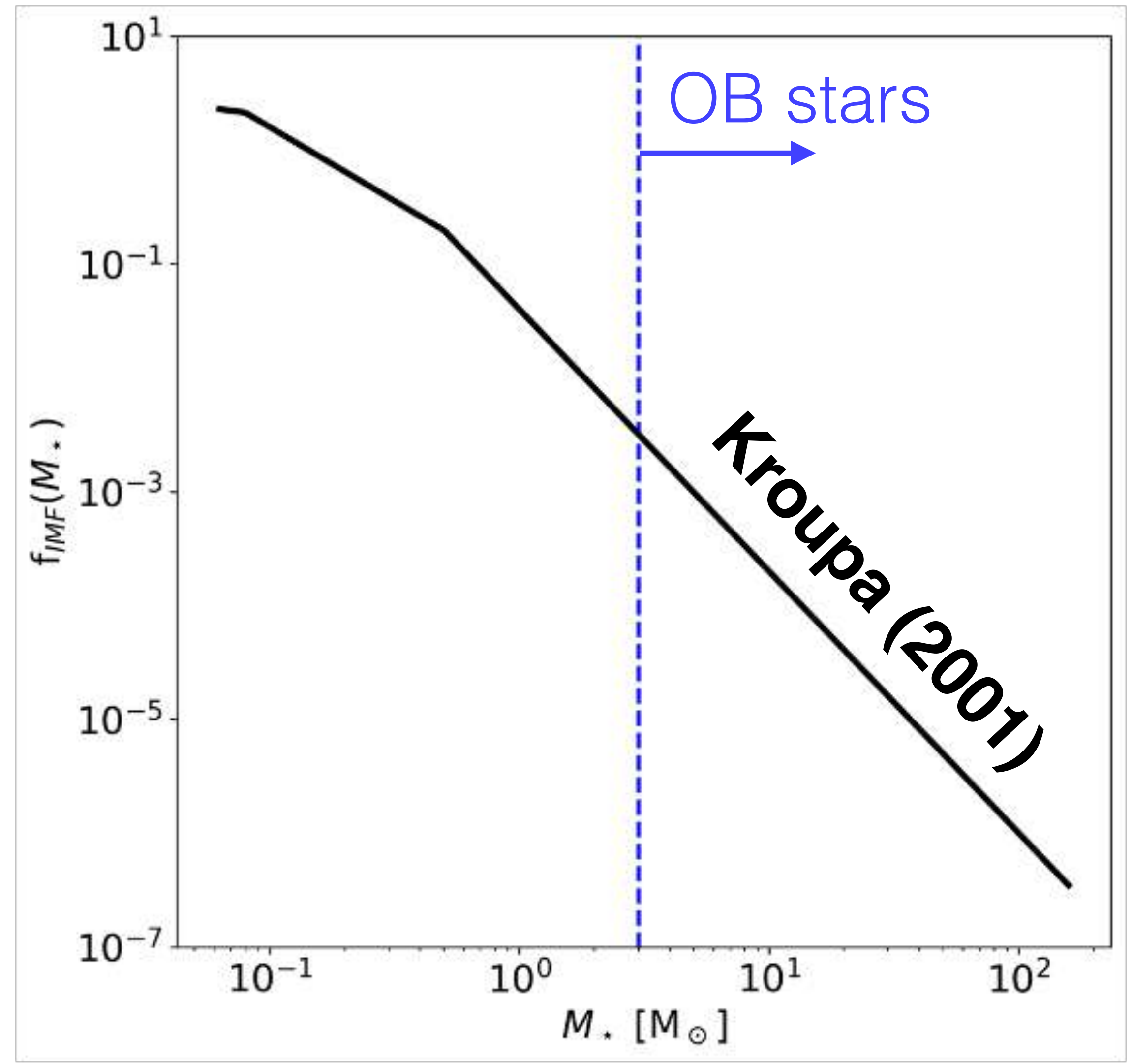
Total number of stars per cluster

$$N_\star = \Lambda M_{\rm SC}$$

with

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

and $M_{☆,\rm max} = 150\ M_\odot$



stellar IMF

Kroupa et al., MNRAS 322 (2001) 231

$$f_\star(M_\star) \propto M_\star^{-\alpha_i}$$

$$\alpha_0 = +0.3 \pm 0.7, \quad 0.01 \leq m/\mathrm{M}_\odot < 0.08,$$
$$\alpha_1 = +1.3 \pm 0.5, \quad 0.08 \leq m/\mathrm{M}_\odot < 0.50,$$
$$\alpha_2 = +2.3 \pm 0.3, \quad 0.50 \leq m/\mathrm{M}_\odot < 1.00,$$
$$\alpha_3 = +2.3 \pm 0.7, \quad 1.00 \leq m/\mathrm{M}_\odot,$$

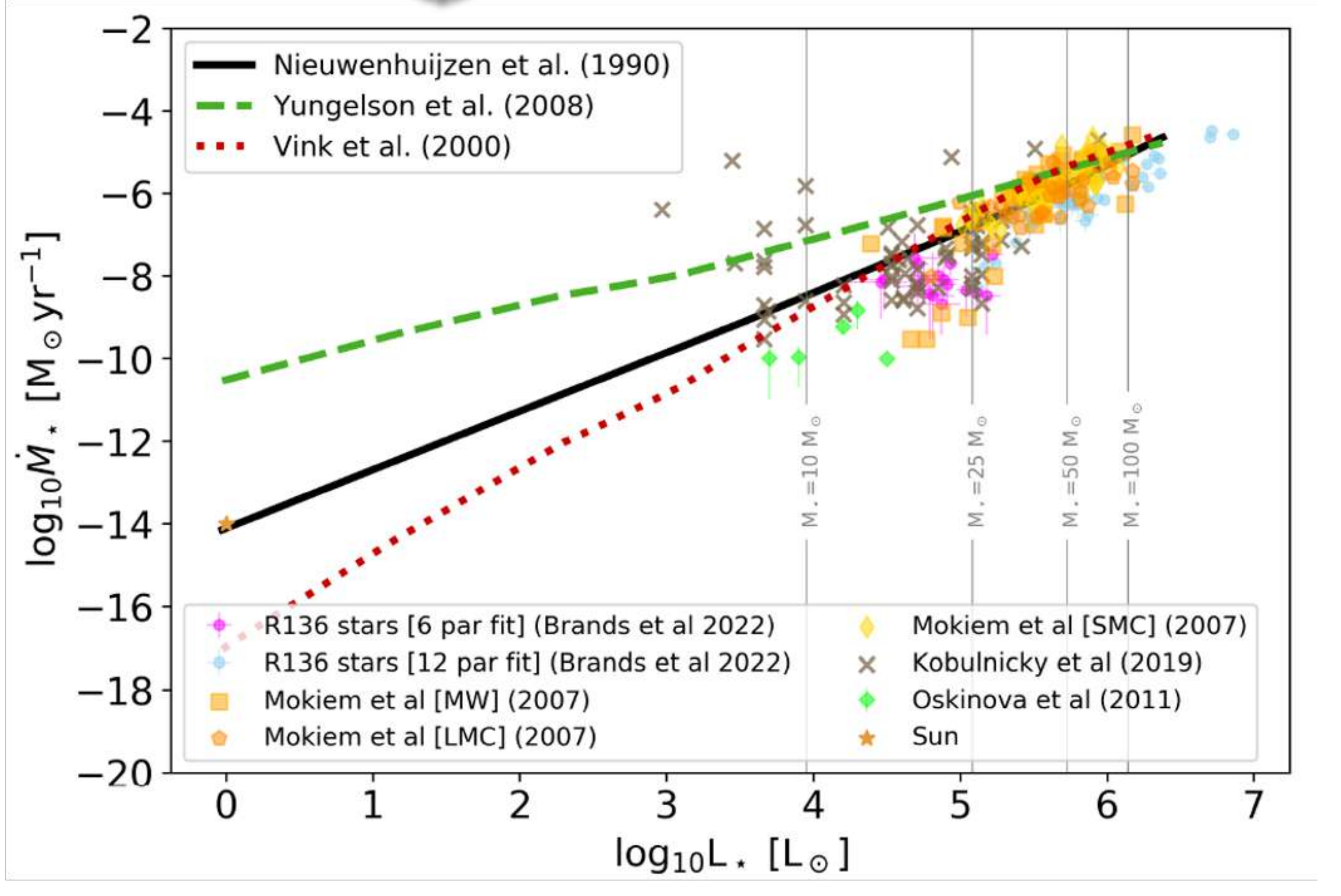
MS & WR stellar wind physics

Both MS and WR stars are included, the latter phase being of duration ΔT=0.3 Myr relevant only for stars with $M_\star > 25\ M_\odot$

- **Mass loss rate** $\dot{M}_\star$
  - OB-type stars
    - Nieuwenhuijzen & de Jager, A&A 231 (1990) 134
  - WR stars
    - Nugis & Lamers, A&A 360 (2000) 227N
- **Wind speed** $v_{\star,w}$
  - OB-type stars
    - Kudritzki & Puls, ARev A&A 38 (2000) 613
  - WR stars, constant to 2000 km/s
- **Wind luminosity**

$$L_{\star,w} = \frac{1}{2}\dot{M}_\star v_{\star,w}^2$$

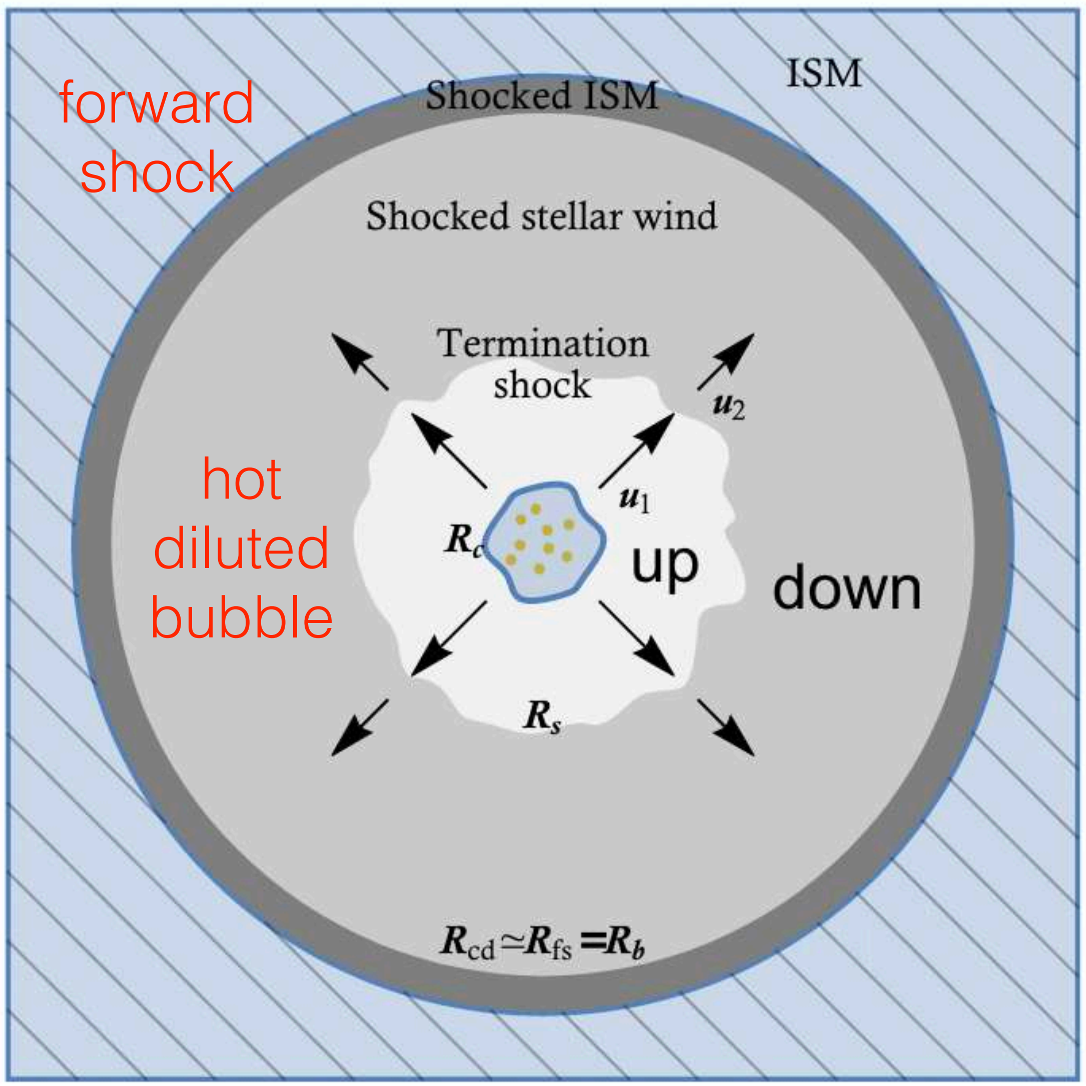
S. Menchiari, PhD thesis (2023)



No SN included yet in these computations ⟶ lower limit to the SC energy conversion into CRs

3. Particle acceleration @ WTS

T_{age} < 3 Myr: only stellar winds



Morlino et al., MNRAS 504 (2021) 4

Constant injection of energy in spherical symmetry:

- **Stellar Cluster core:**

~ few pc radius

- **Collective Wind Termination Shock (WTS):**

$$R_s(t) = 48.6 \left(\frac{n}{\mathrm{cm^{-3}}}\right)^{-0.3} \left(\frac{\dot{M}_c}{10^{-4} \mathrm{M_\odot yr^{-1}}}\right)^{0.3} \left(\frac{v_{w,c}}{1000\,\mathrm{km\,s^{-1}}}\right)^{0.1} \left(\frac{t}{10\,\mathrm{Myr}}\right)^{0.4} \mathrm{pc}$$

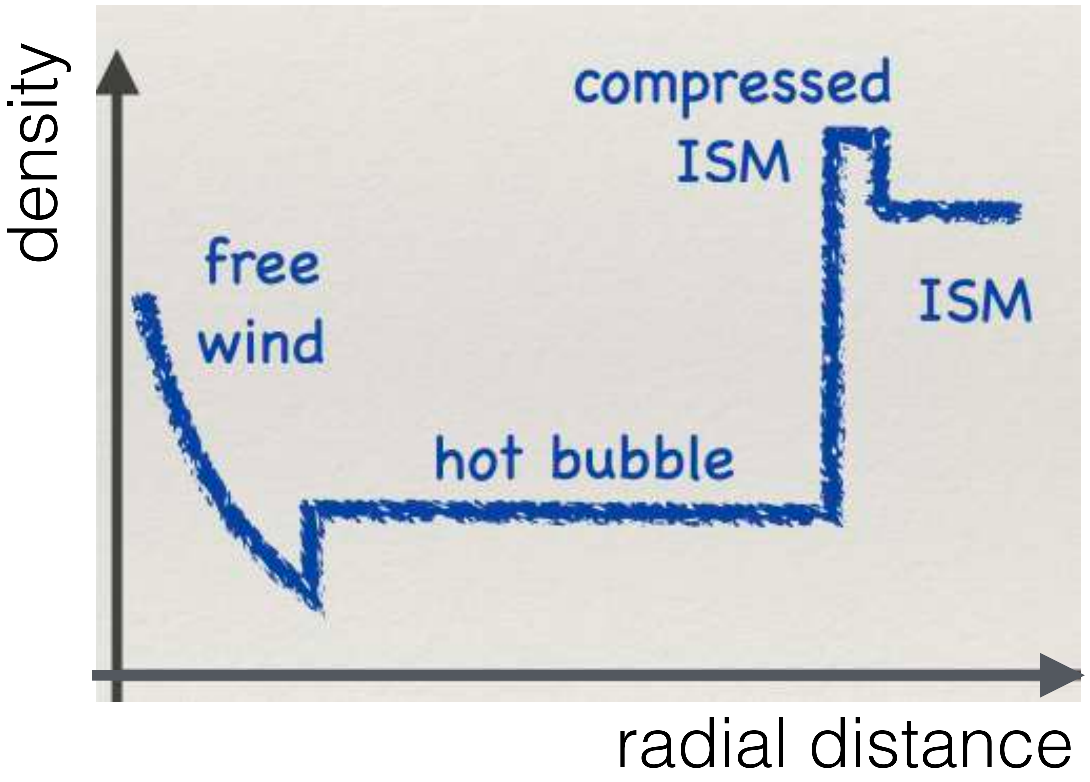
- **Bubble:**

$$R_b(t) = 174 \left(\frac{n}{\mathrm{cm^{-3}}}\right)^{-0.2} \left(\frac{L_{w,c}}{10^{37}\,\mathrm{erg\,s^{-1}}}\right)^{0.2} \left(\frac{t}{10\,\mathrm{Myr}}\right)^{0.6} \mathrm{pc}$$

Weaver et al., ApJ 218 (1977) 377W

Target gas distribution in wind bubbles

- We adopt an idealized **purely adiabatic spherical** model
- A more realistic density profile should consists of a **complex fractal structure of filaments and clumps**, as induced by shell fragmentation and development of hydro instabilities (induced by e.g. cooling effects, wind clumpiness and ISM inhomogeneities)



Mitchell et al. (2024)
arXiv:2403.16650, submitted

$$n_0 = 10\,\mathrm{cm}^{-3}$$

1. $R_c < r < R_s$ ⟶ free cold wind profile

$$n_w(r) = \frac{\dot{M}_c}{4\pi r^2 v_w}$$

2. $R_s < r < R_{cd}$ ⟶ hot bubble

$$n_b = \frac{M_b}{\frac{4}{3}\pi(R_{cd}^3 - R_s^3)}$$

$$M_b = (\dot{M}_{sh} + \dot{M}_w)\, t_{age} - \frac{\dot{M}_w}{v_w(R_s - R_c)}$$

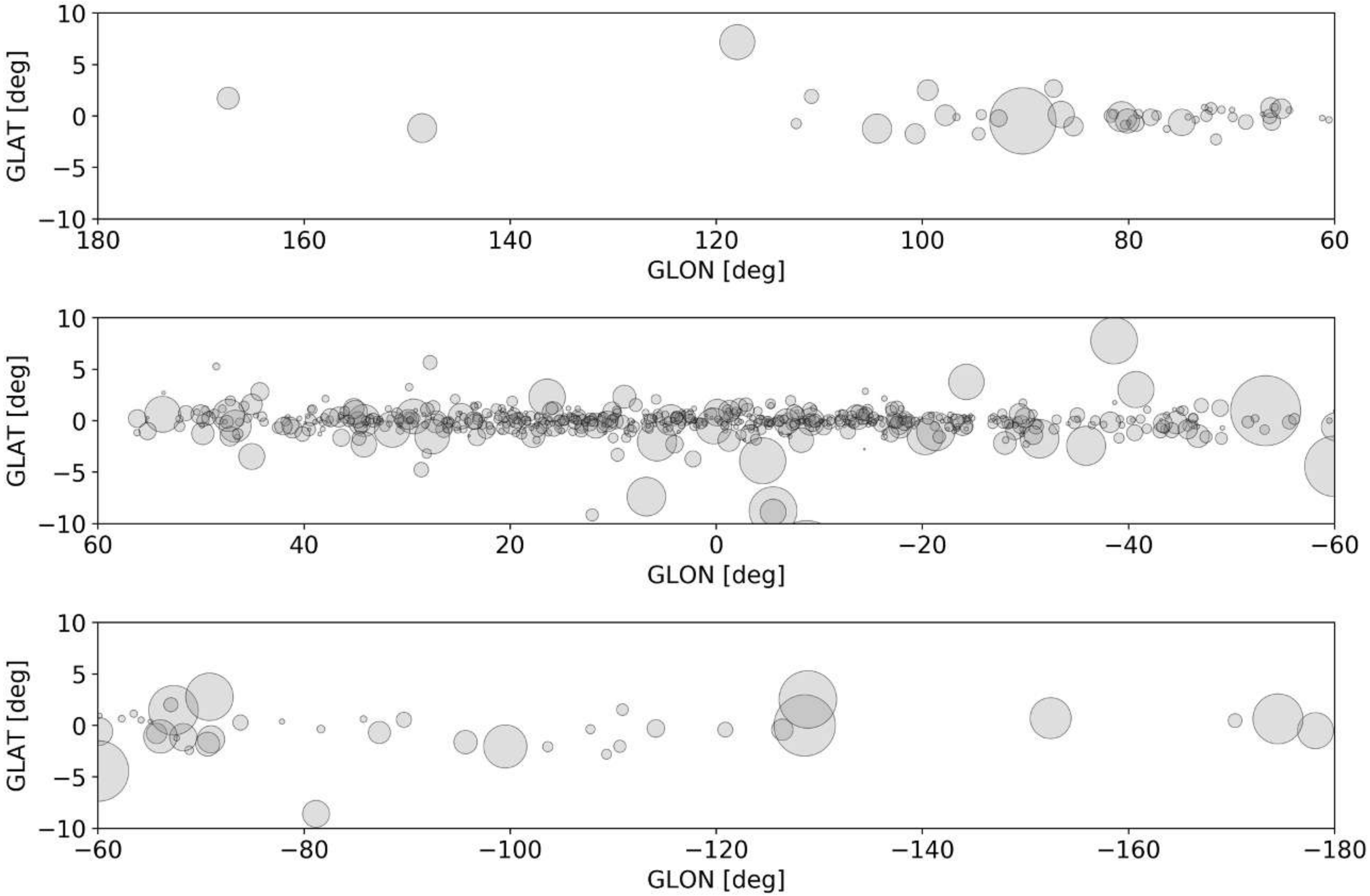
$$\dot{M}_{sh} = 2\times10^{-4}\left(\frac{L_{w,c}}{10^{37}\,\mathrm{erg/s}}\right)^{\frac{27}{35}}\left(\frac{n}{10\,\mathrm{cm}^{-3}}\right)^{-\frac{2}{35}}\left(\frac{t}{1\,\mathrm{Myr}}\right)^{\frac{6}{35}} M_\odot\,\mathrm{yr}^{-1}$$

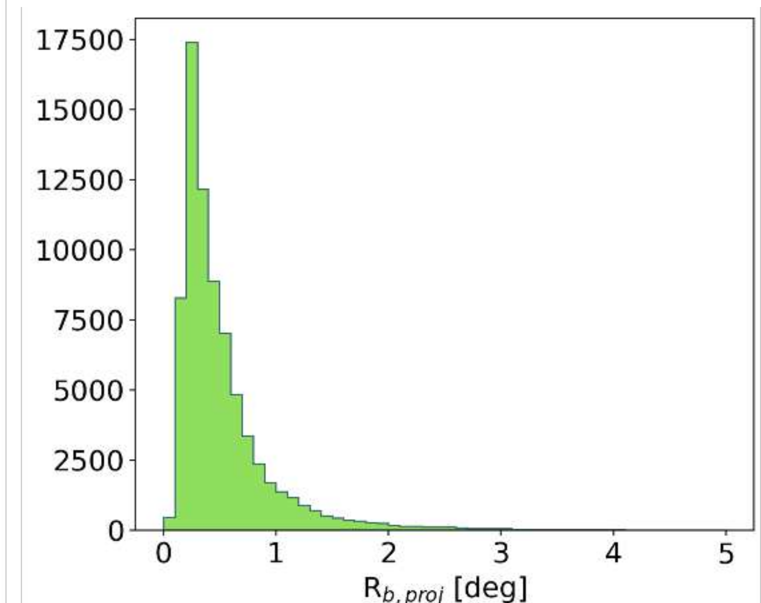
3. $R_{cd} < r < R_b$ ⟶ shell

$$n_{sh} = \frac{n_0}{1 - R_{cd}^3/R_b^3} - \frac{\dot{M}_{sh} T_{age}}{m_p V_{sh}}$$

Synthetic YMSC population

Single realization of the Galactic population

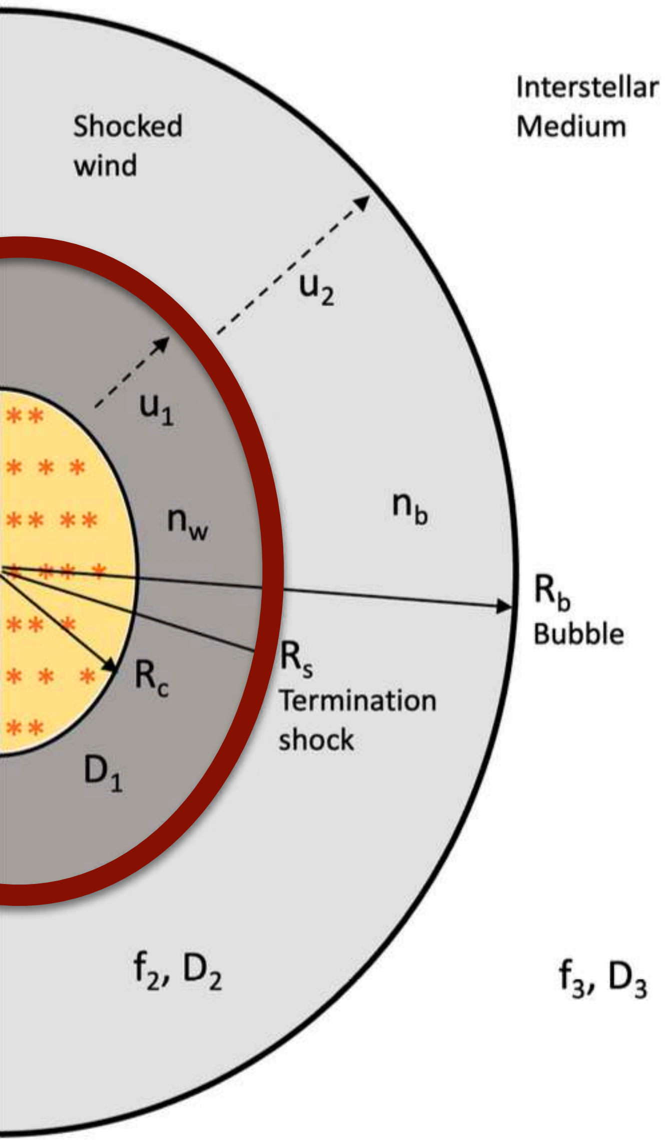




Bubble radii distribution for one realization

Menchiari et al., arXiv:2406.04087, submitted

Particle acceleration @ WTS of YSCs



Morlino et al., MNRAS 504 (2021) 4

Time-stationary transport equation in spherical geometry:

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

- Arbitrary diffusion coefficient $D(r,p)$
- Injection only at the termination shock $\quad Q(r,p) \propto \delta(p - p_{\rm inj})\,\delta(r - R_s)$
- Wind velocity profile: $\quad u(r) = \begin{cases} u_1 = v_w & \text{for } r < R_s\,, \\ \frac{u_1}{\sigma}\left(\frac{R_s}{r}\right)^2 & \text{for } R_s < r < R_b\,, \\ 0 & \text{for } r > R_b\,; \end{cases}$

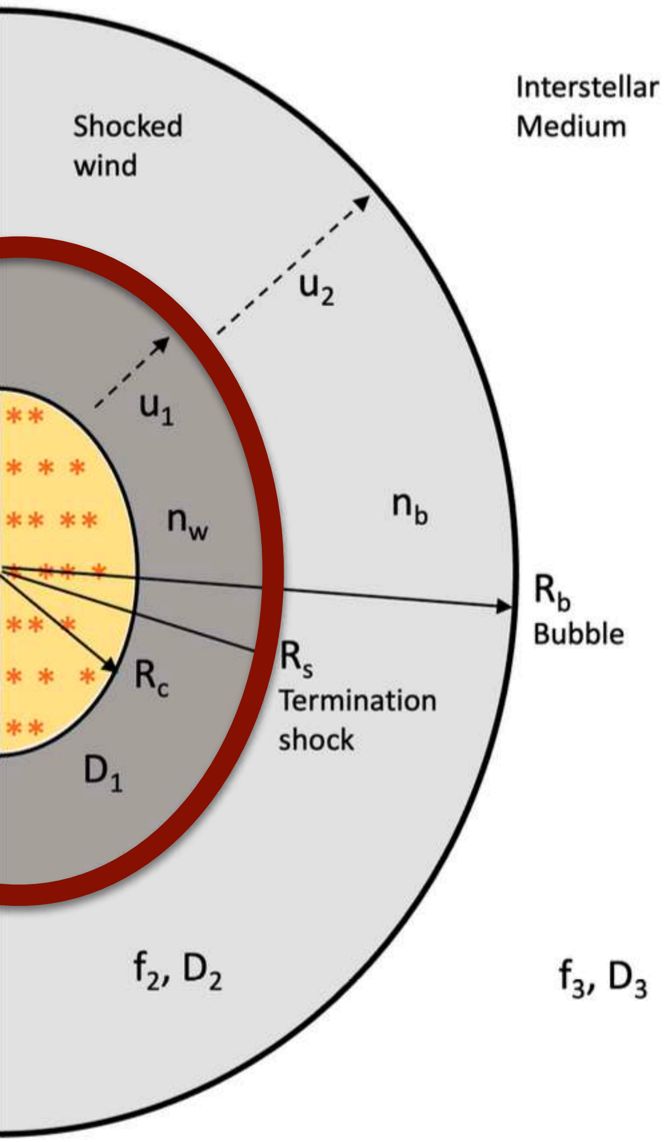
Boundary conditions:

1. No net flux at the cluster center: $\quad r^2[D\partial_r f - uf]_{r=R_c} = 0$

2. Matching the Galactic distribution: $\quad f(r \to \infty, p) = f_{\rm gal}(p)$

“Reversed” geometry wrt supernova remnants

Particle acceleration @ WTS of YSCs



Acceleration at the collective WTS is calculated under the following assumptions:

- **CR acceleration efficiency** is a few % of the wind kinetic luminosity:

$$L_{cr} = \epsilon_{cr} L_w,$$

- **Magnetic turbulence** is produced by wind non-stationarity and inhomogeneities

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

⟶ few % of wind kinetic energy converted into magnetic energy;

- **Diffusion coefficient** depends on the turbulence inside the bubble **(unknown)**: most likely, it is generated by wind itself (MHD instabilities, flow non stationarity) and it impacts both transport and maximum energy of particles

$$\xi_{CR} = 0.10$$

$$f_{WTS} \propto p^{-4.2}$$

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

Morlino et al., MNRAS 504 (2021) 4

WTS particle acceleration: spectrum & E_{max}

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

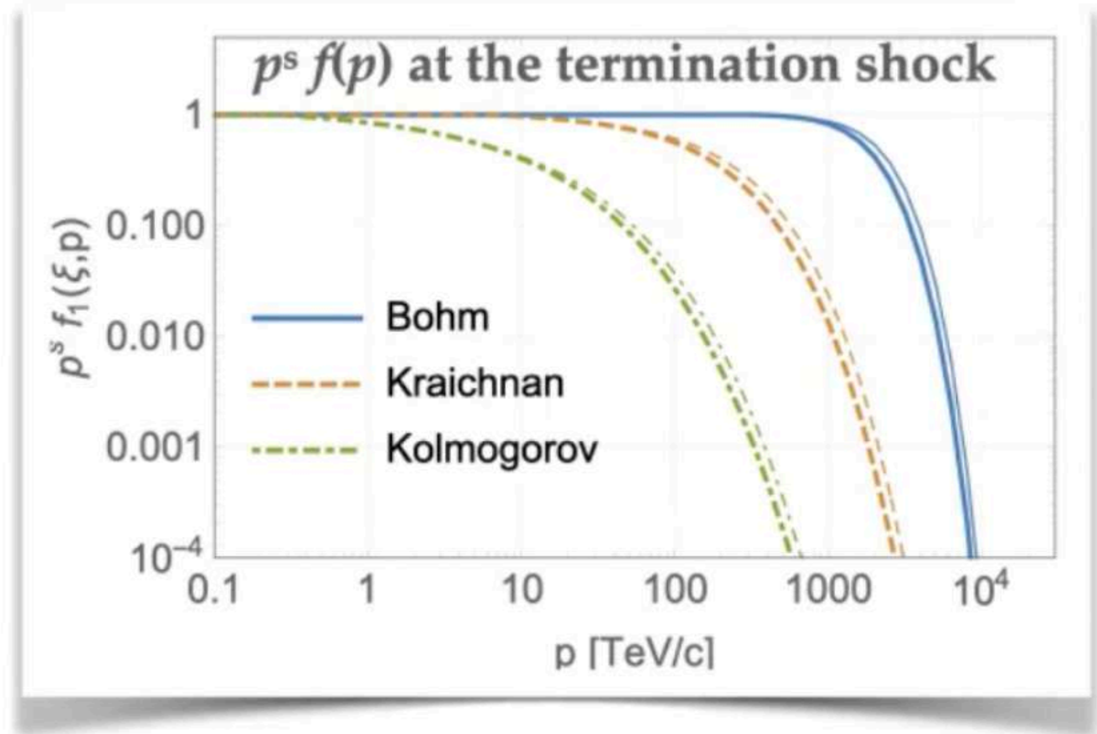
Standard power-law for plane shocks

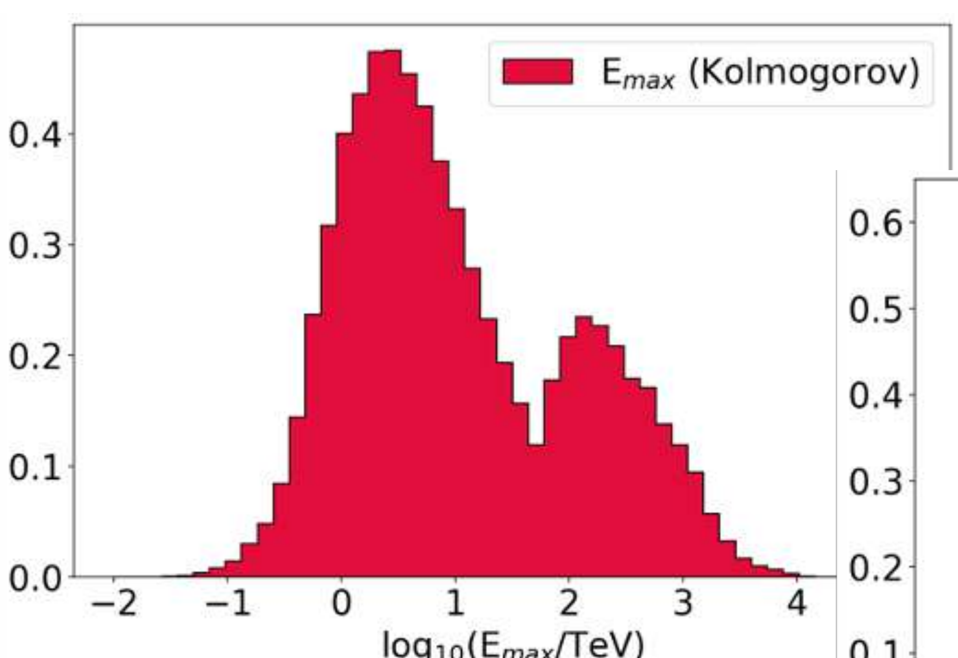
$$s = \frac{3\sigma}{\sigma - 1}$$

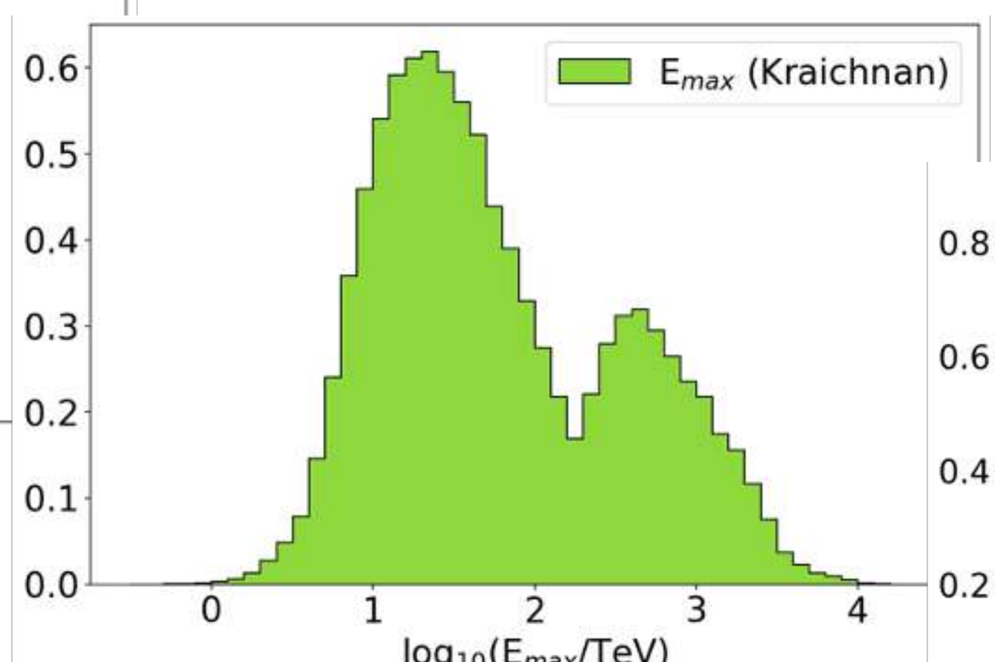
Cutoff due to particle confinement upstream in a spherical geometry

Cutoff due to particle escaping from the bubble

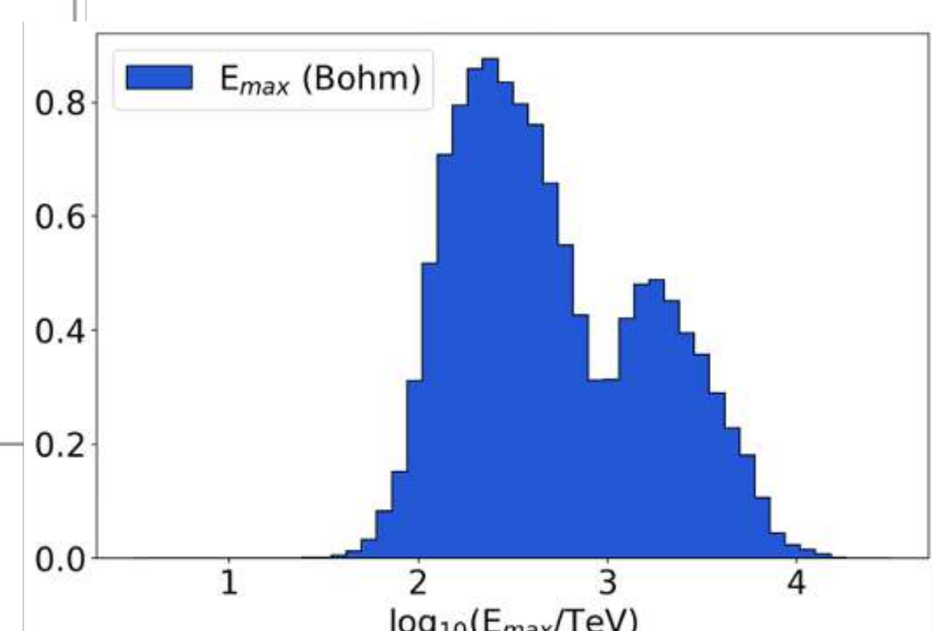
Morlino et al., MNRAS 504 (2021) 4





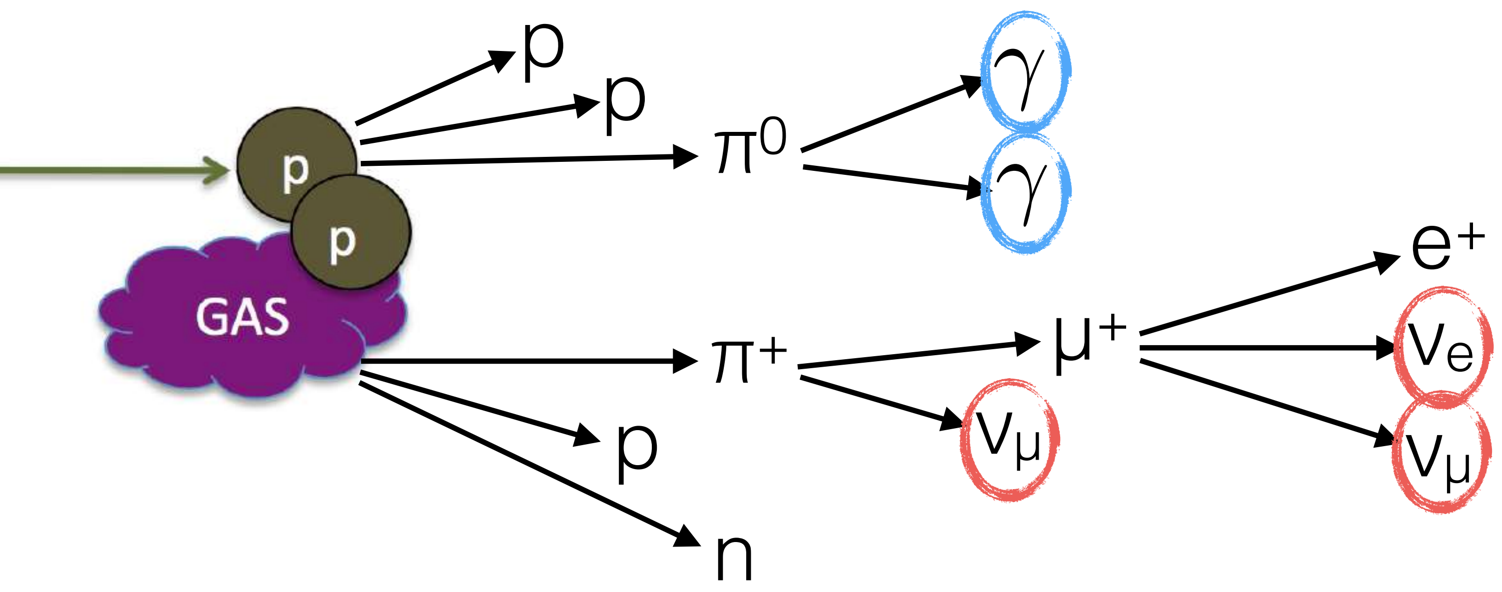


Bimodal distributions due to MS & WR stars

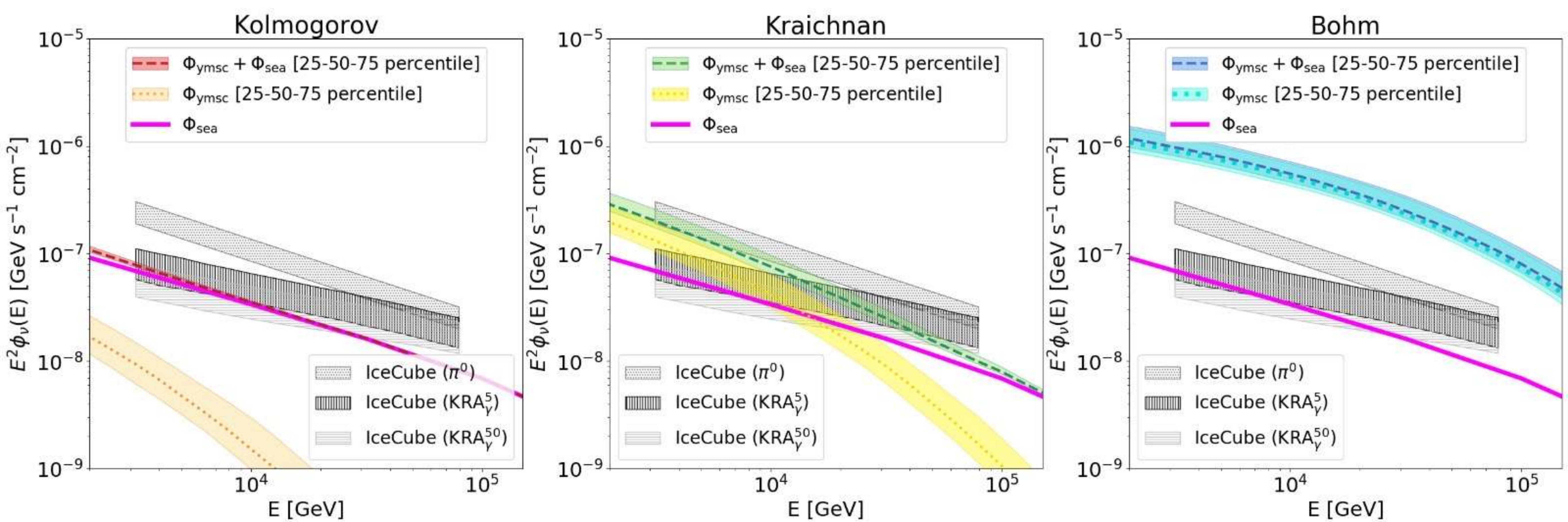


S. Menchiari (2024) private communication

4. Radiative signatures: neutrinos



Inelastic collisions
between accelerated protons and target gas
+
diffuse emission from the CR sea



Menchiari, Celli et al., in prep.

4. Radiative signatures: gamma rays

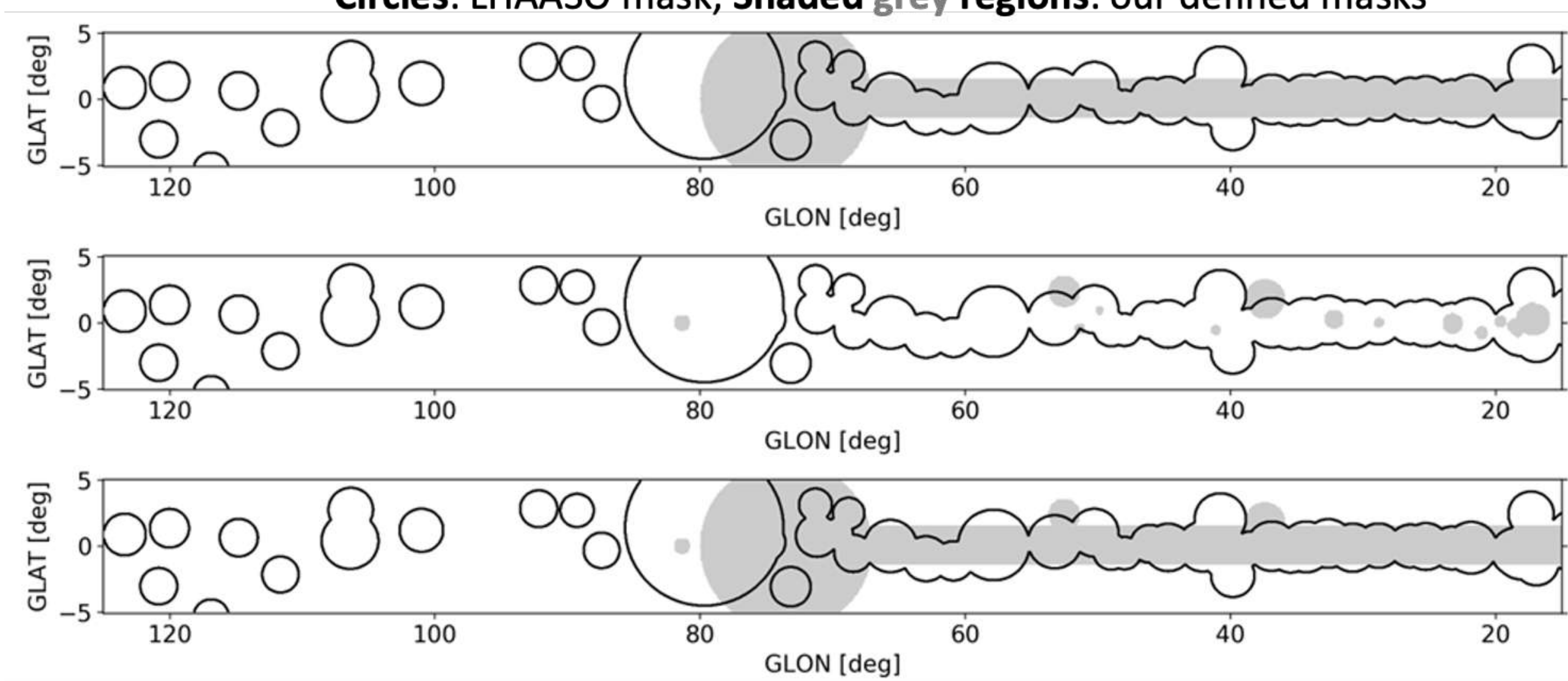
The masking procedure

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

A similar mask is defined for the synthetic simulations

ROI1: 15°<glon<125°, |glat|<5° **ROI2:** 125°<glon<235°, |glat|<5°

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

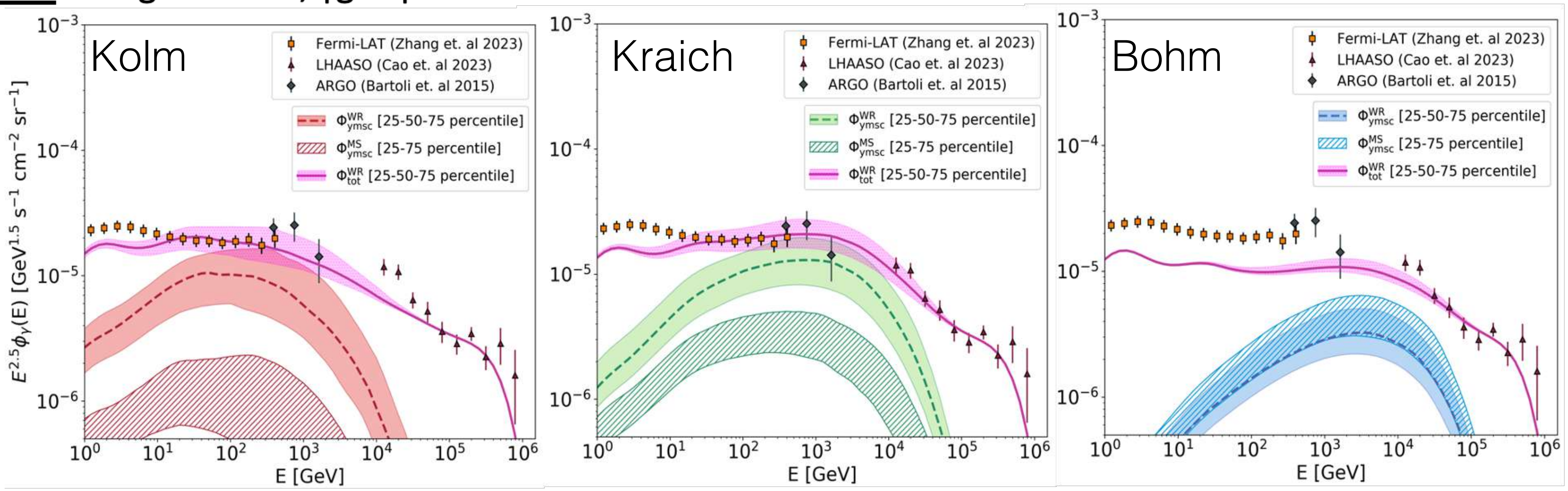
3) Final mask

Menchiari et al., arXiv:2406.04087, submitted

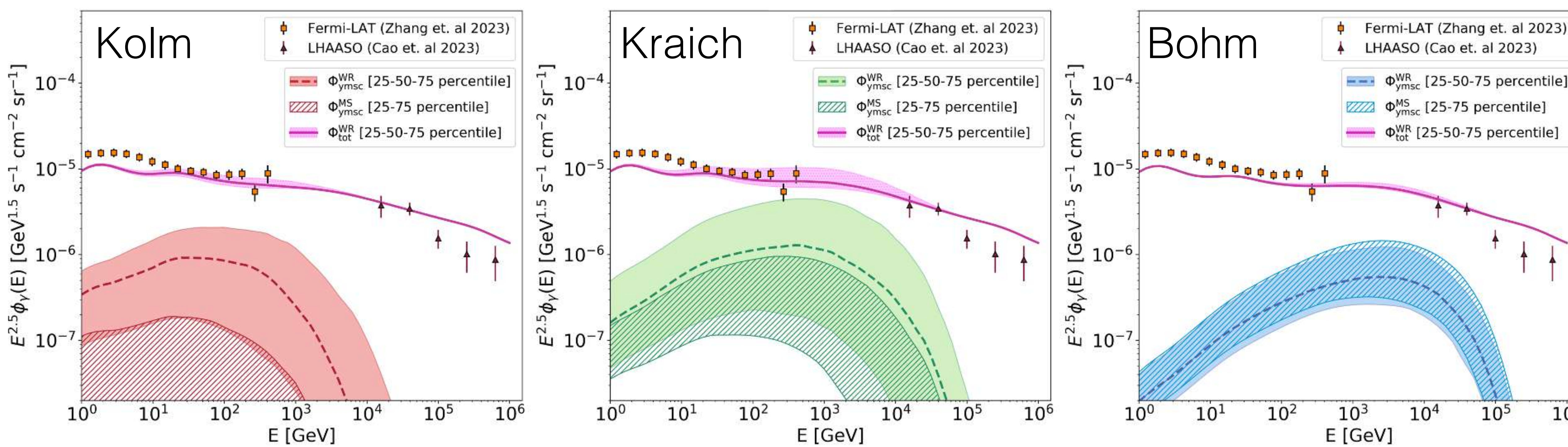
4. Radiative signatures: gamma rays

Diffuse emission

ROI1: 15°<glon<125°, |glat|<5°



ROI2: 125°<glon<235°, |glat|<5°



Menchiari et al., arXiv:2406.04087, submitted

3b. Particle acceleration @ SNRs in SCs

- Why SCs are also important for SNRs?
  - **~100% of massive stars born in SCs** [~80% explode in SCs, ~20% explode as isolated (probably associated to runaway stars)];
  - 80% of SNRs expand into an environment different from the "regular" ISM: **lower density** ($n \sim 0.01$-0.1 cm^{-3}), **higher temperature** ($T \sim 10^6$ -10^8 K), **highly turbulent medium** (+ advection).

- Why SNR explosions in SCs are difficult to treat?
  - SNRs are **transient phenomena** along the SC evolution, introducing non-stationarity effects in the solution;
  - the non-uniform environment of SCs might induce the formation of **multiple reflected shocks**.

A simplified model for particle acceleration @ SNRs in SCs

- SNR dies before reaching the bubble boundary:

$$R_{\rm Sed} = 17 \left(\frac{M_{\rm ej}}{5M_\odot}\right)^{1/3} \left(\frac{n_b}{0.01\,{\rm cm}^{-3}}\right)^{1/3} {\rm pc} \simeq R_{\rm TS}$$

- Particle acceleration @ SNR lasts only for the **ejecta-dominated phase**;
- Ambient magnetic field given by **wind-termination shock turbulence: B_0 ~ 10 μG**;
- Amplification due to **resonant streaming instability** only:

$$\mathcal{F}_{\rm res} = 0.5 \left(\frac{\xi_{\rm CR}}{0.1}\right)^{1/2} \left(\frac{E_{\rm SN}}{10^{51}\,{\rm erg}}\right)^{1/4} \left(\frac{M_{\rm ej}}{5M_\odot}\right)^{-1/4}$$

- **Time-limited acceleration** ($t_{acc}=t_{Sed}$):

$$E^p_{\rm max} = 2\mathcal{F}_{\rm res} \left(\frac{B_0}{10\,\mu G}\right) \left(\frac{M_{\rm ej}}{M_\odot}\right)^{-1/6} \left(\frac{E_{\rm SN}}{10^{51}\,{\rm erg}}\right)^{1/2} \left(\frac{n_0}{0.01\,{\rm cm}^{-3}}\right)^{-1/3} {\rm PeV}$$

- Power-law spectrum at the SNR shock, with **s=4.3** & **10% CR** conversion efficiency:

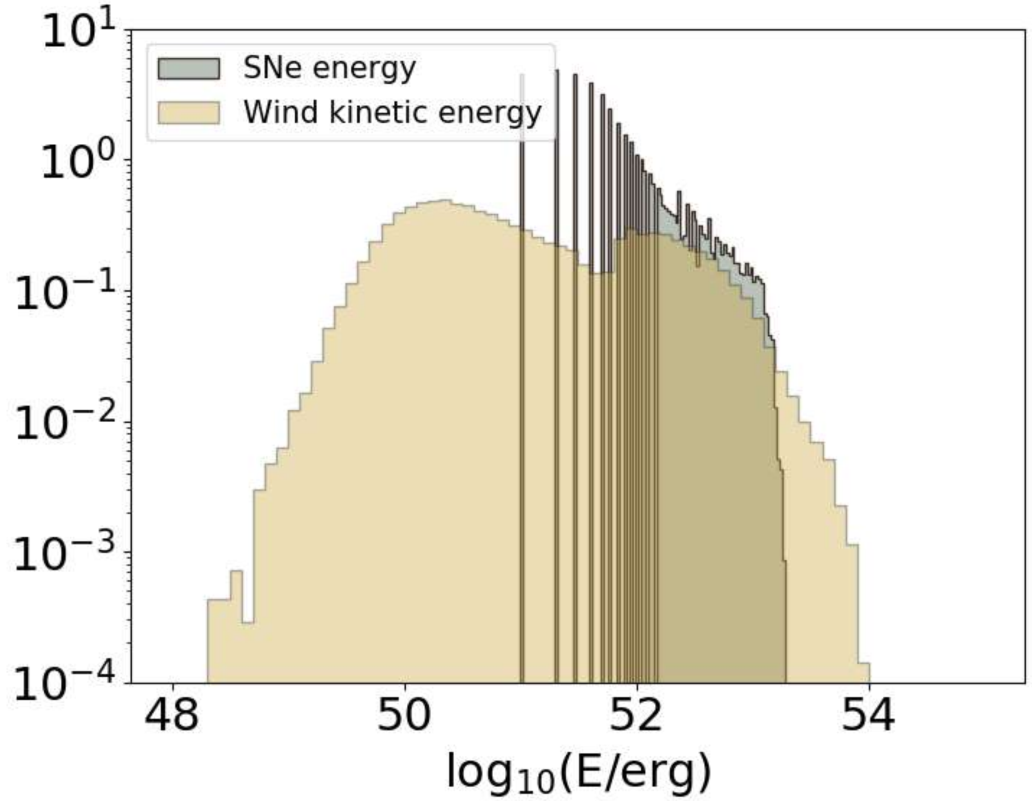
$$f_s(p) = \frac{3\xi_{\rm CR} n_b u_{\rm sh}}{4\pi\Lambda(m_p c)^4 c^2} \left(\frac{p}{m_p c}\right)^{-s} e^{-p/p_{\rm max}}$$

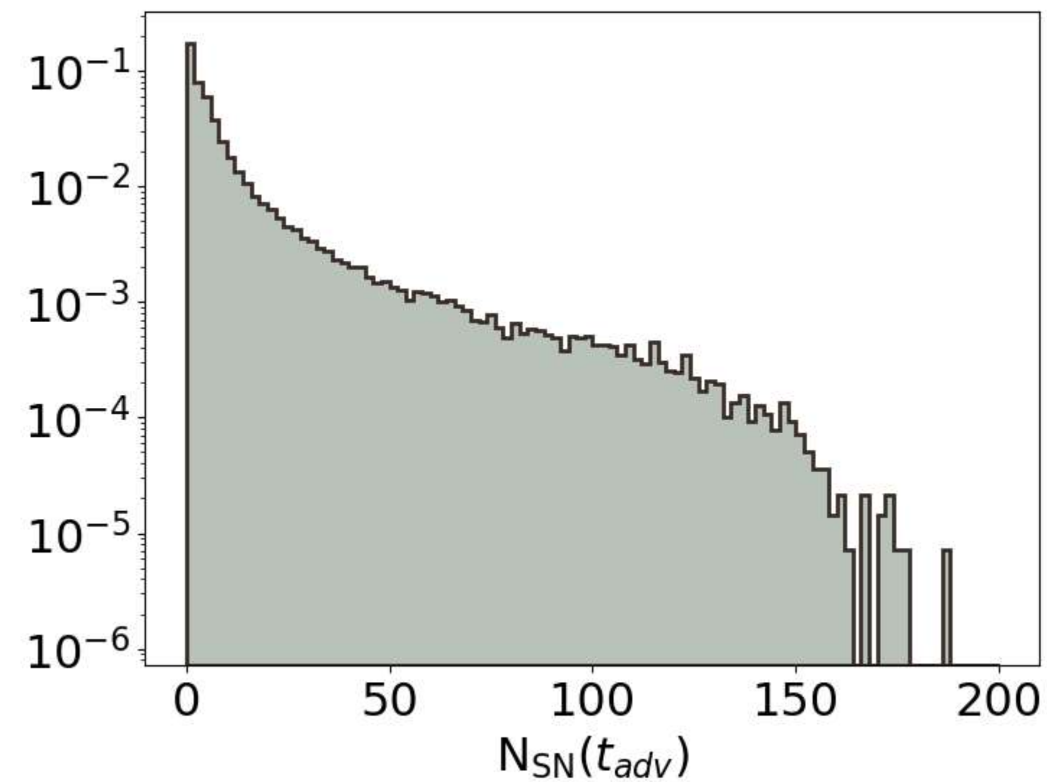
- Particle **confinement** inside the bubble for one advection time:

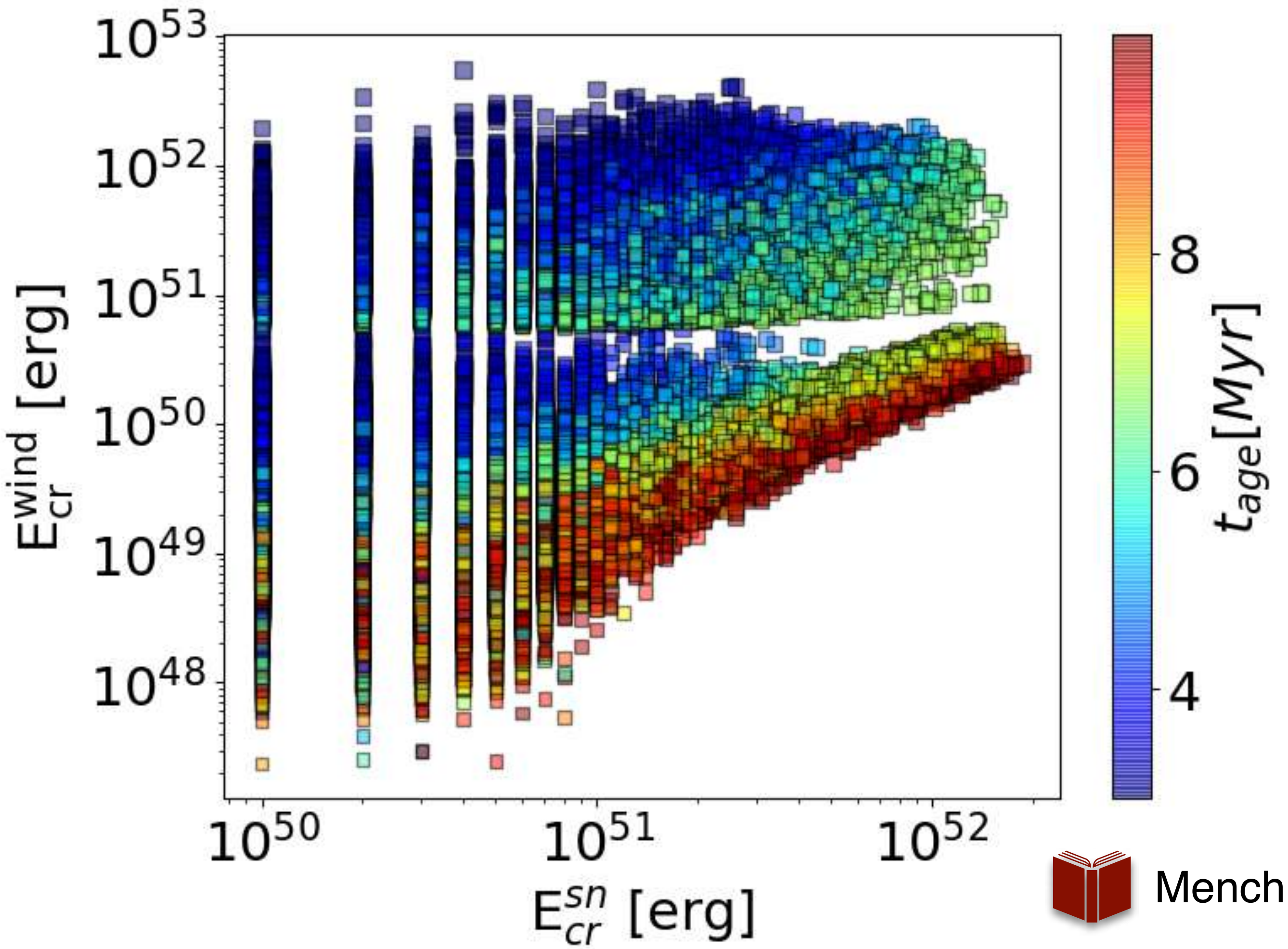
$$t_{\rm adv} = \int_{R_{TS}}^{R_b} \frac{dr}{u(r)} = \frac{R_b^3}{3u_2 R_{TS}^2} = 0.61 t_{SC}$$

Mitchell et al. (2024) arXiv:2403.16650, submitted

Total number of YMSCs: 2241 (Age < 30 Myr, $M_{SC} > 10^3\ M_{sun}$)







Menchiari, Celli et al., in prep.

Conclusions

- **Young and massive star clusters** are powerful particle accelerators, as testified from gamma-ray detections;
- A **comprehensive study** of the Milky Way YMSC population was here presented by means of **synthetic realizations**;
  - Baseline model including **WTSs**;
  - Inclusion of SNRs is a work in progress.
- Non-negligible contribution of unresolved sources to **diffuse gamma-ray emission** above 100 GeV;
- Preliminary results indicate a possible non-negligible contribution to **diffuse Galactic neutrinos** as well;
- Model improvements required to treat properly bubble structure (relevant for SC geometry and hadronic collisions) and diffusion (relevant for transport and diffusion), particularly in the presence of SNRs.

Thanks for your kind attention!