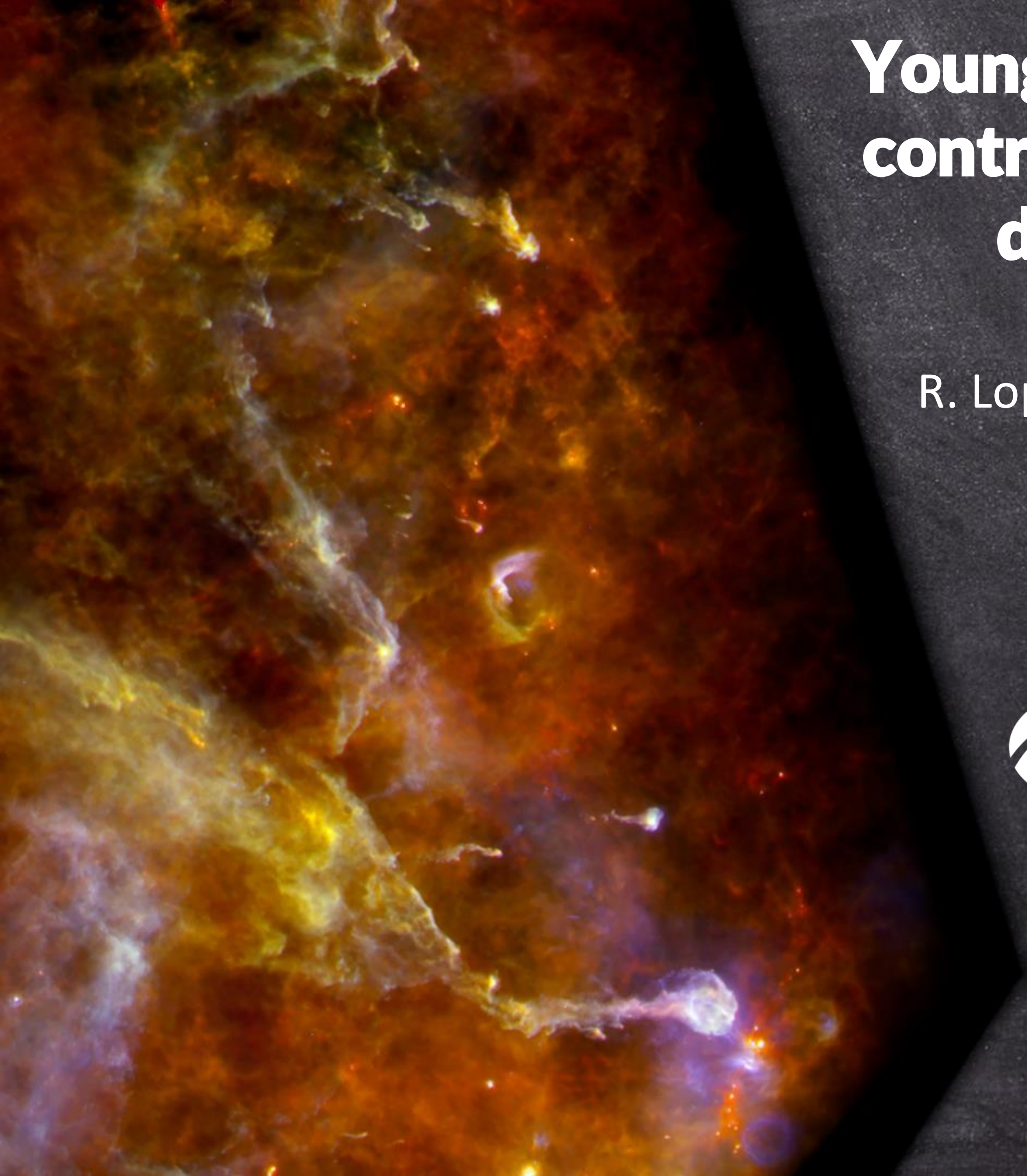

Young massive star clusters and their contribution to galactic neutrino and diffuse gamma-ray emission

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TeV Particle Astrophysics TeVPA Valencia 2025
VHEGA

Neutrino – 18:15-18:30

TeVPA 2025 – Valencia – 4/11/2025

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.

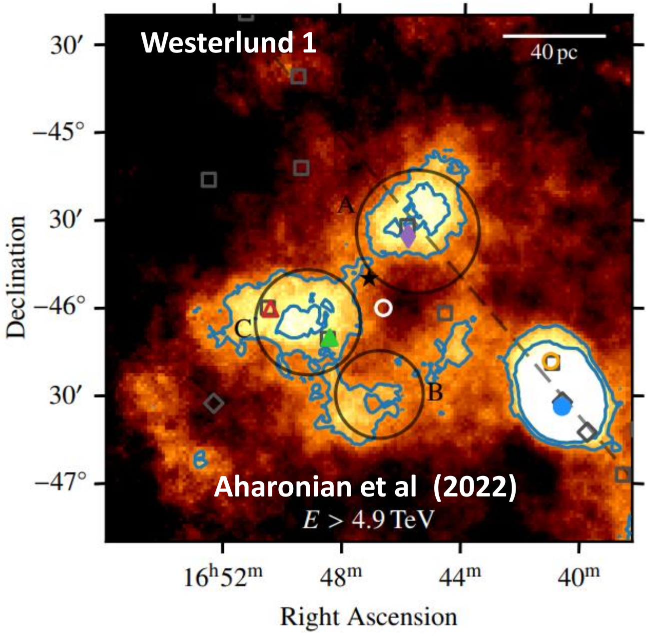
Young: Age <30 Myr

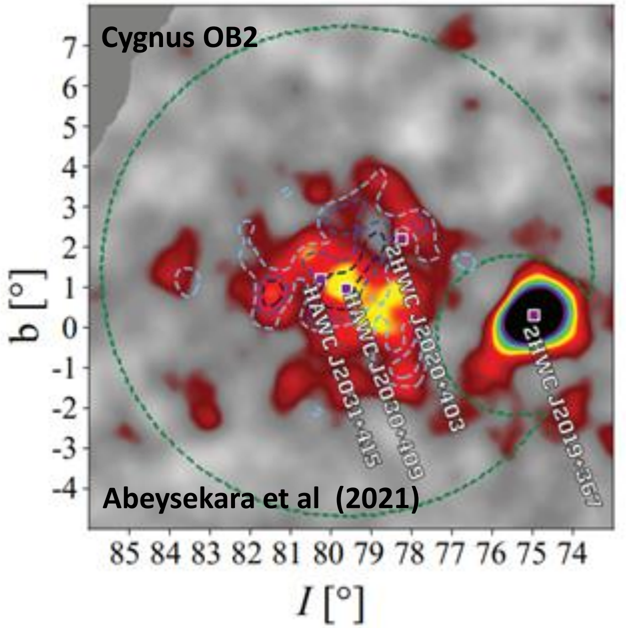
Massive: $M_{SC}>10^3$ $M_{\odot}$

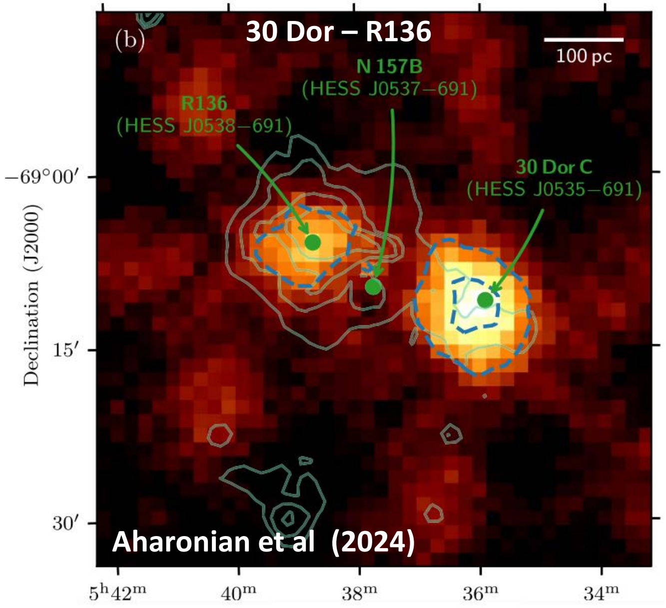
γ-ray emission detected in coincidence with more than **a dozen YMSC!**

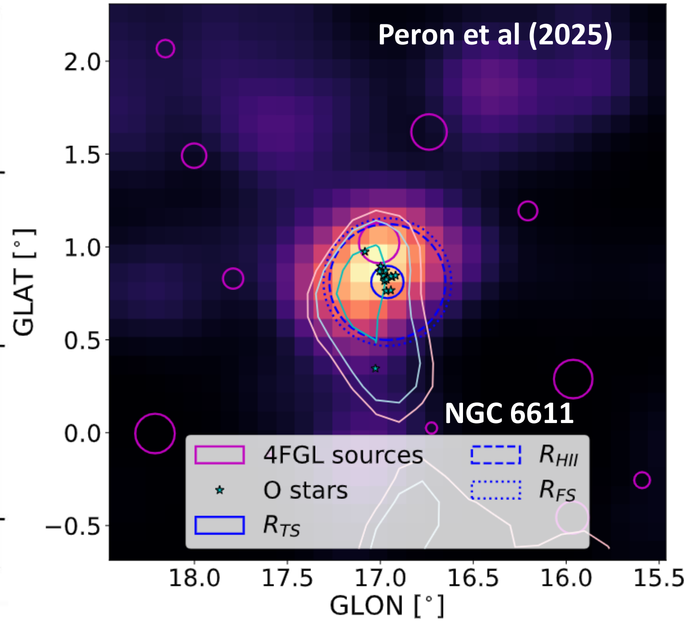
HE – VHE – UHE

- Westerlund 1
- Westerlund 2
- NGC 3603
- RCW 38
- RCW 36
- RCW 32
- NGC 6618
- W40
- W43
- Berkley 59
- Cygnus OB2
- NGC 6611
- R 136
- 30 Doradus









YMSC: extended γ-ray sources

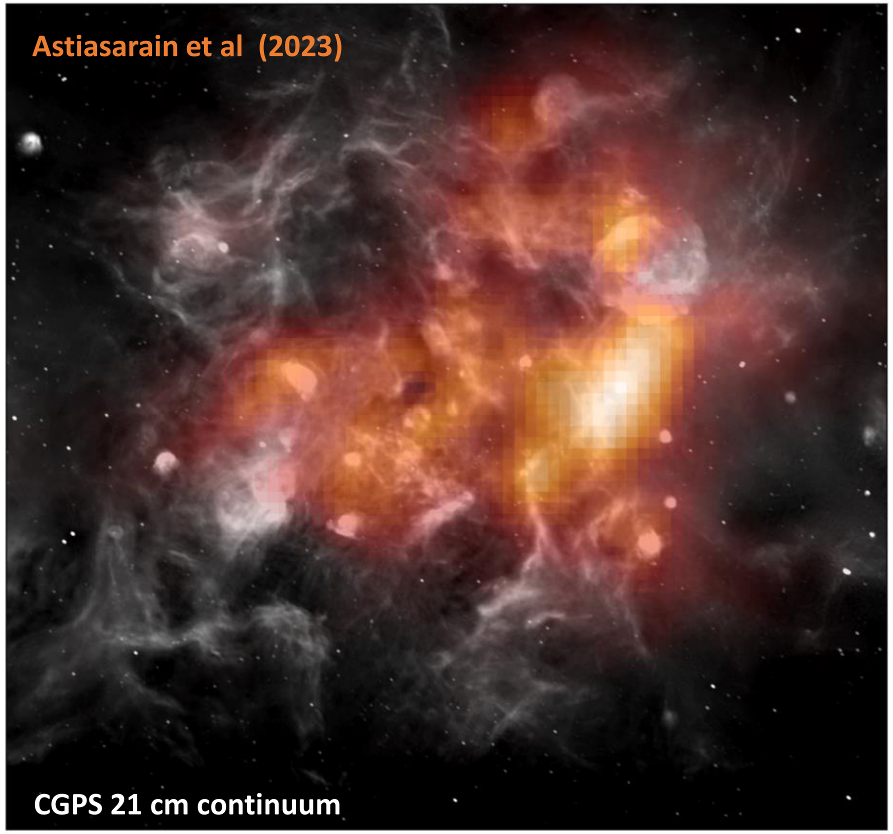
Most of YMSCs shows emission sizes consistent with projected dimension of wind-blown bubble

→ **The γ-ray emission is extended (0.1°-5°)!** →

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

Detection bias for low surface brightness sources

Non-detected (unresolved) YMSCs can contribute to the galactic diffuse emission



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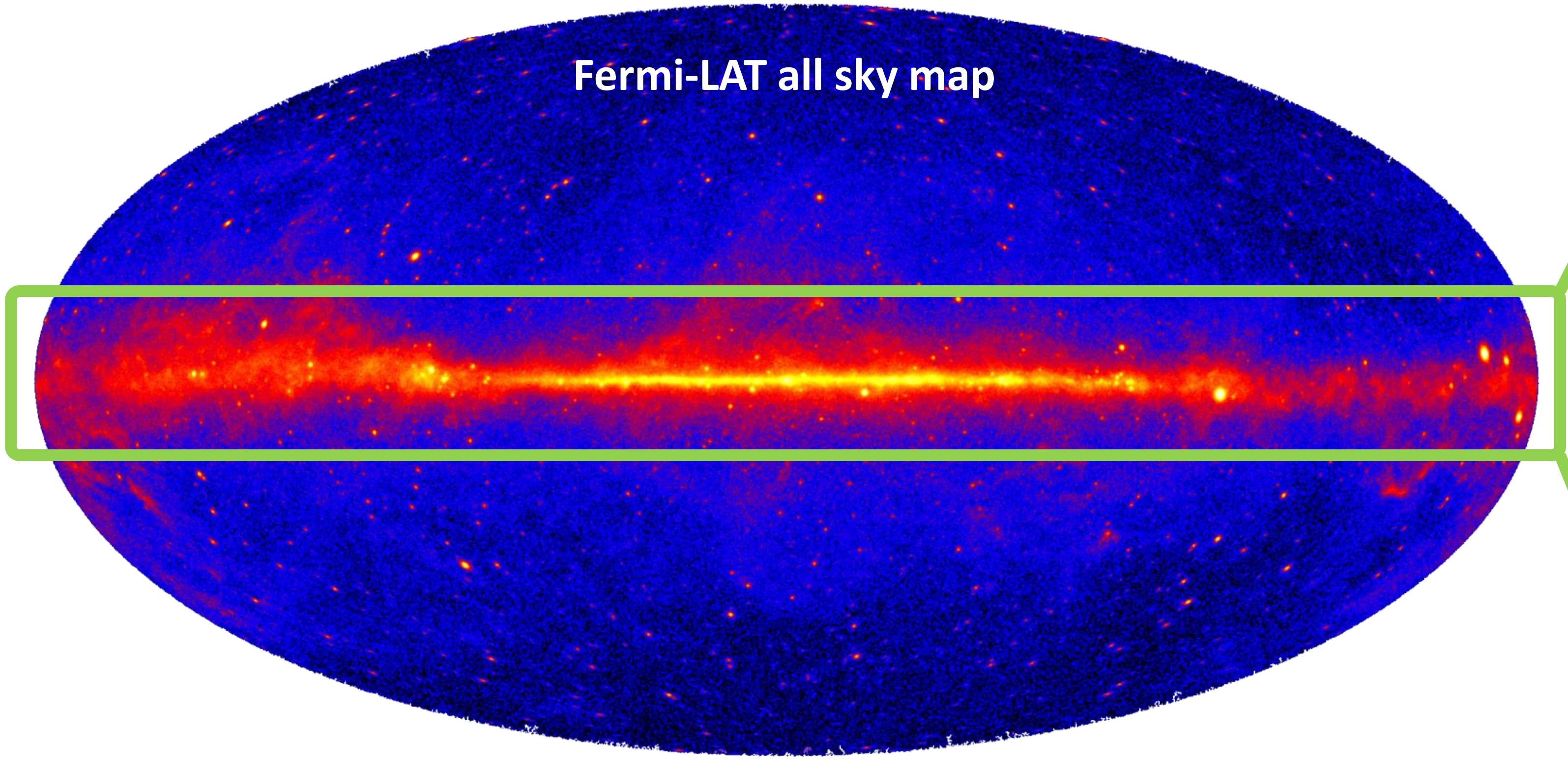
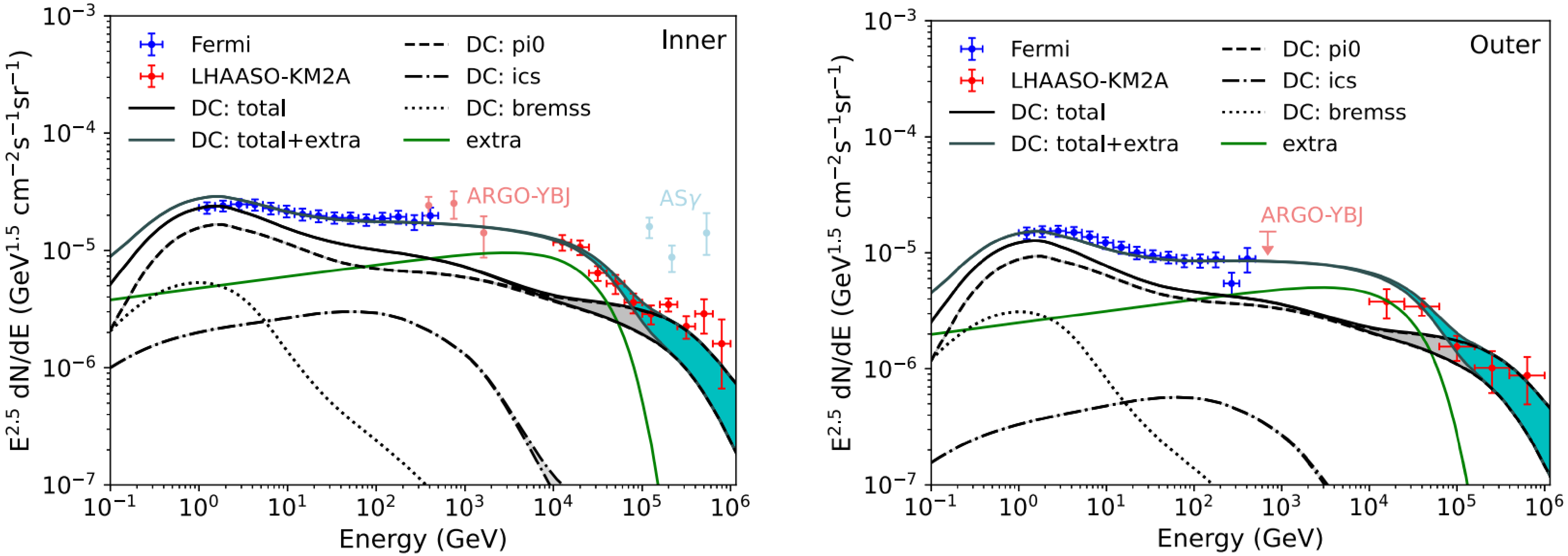


$$\phi_{\mathrm{GDE}} = \phi_{\mathrm{sea}} + \phi_{\mathrm{US}}$$

Galactic diffuse emission | Cosmic ray sea | **Unresolved sources**

Galactic diffuse emission

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

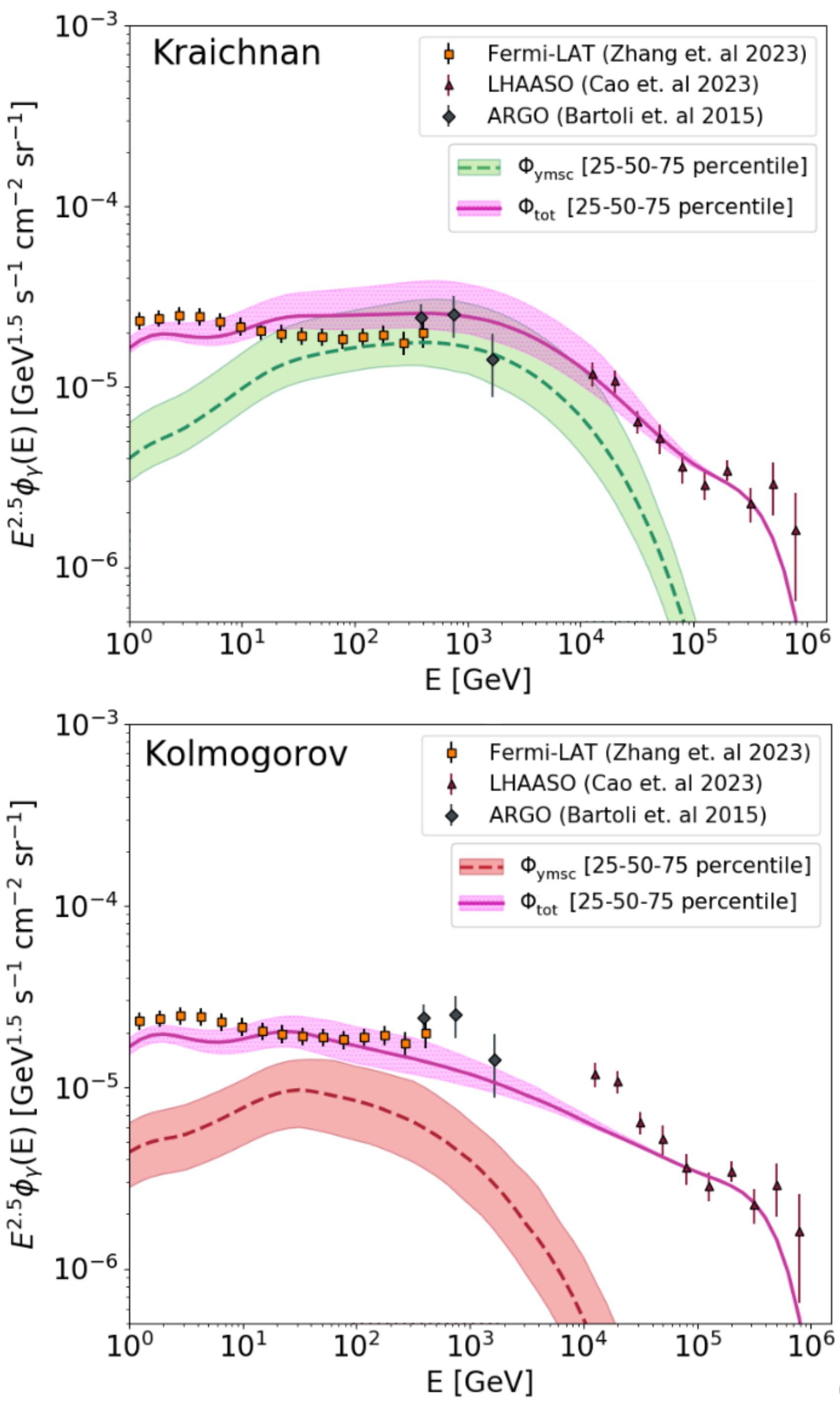


Work objective

Do YMSCs contribute to the GDE?

S. Menchiari et al 2025: Lower limit estimate to the contribution of YMSCs to the GDE.

Non-resolved emission from YMSCs is not negligible!!!



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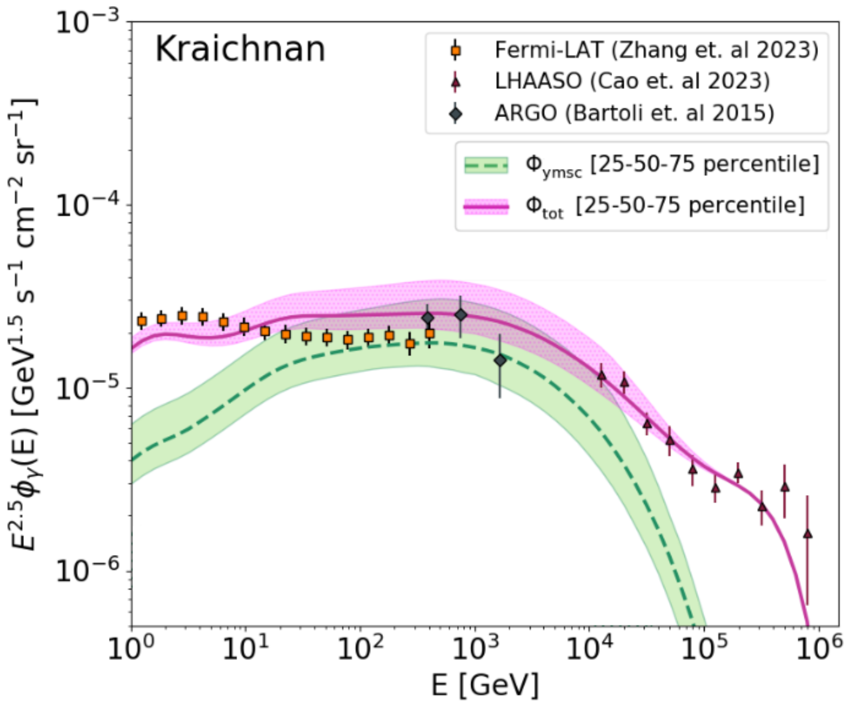
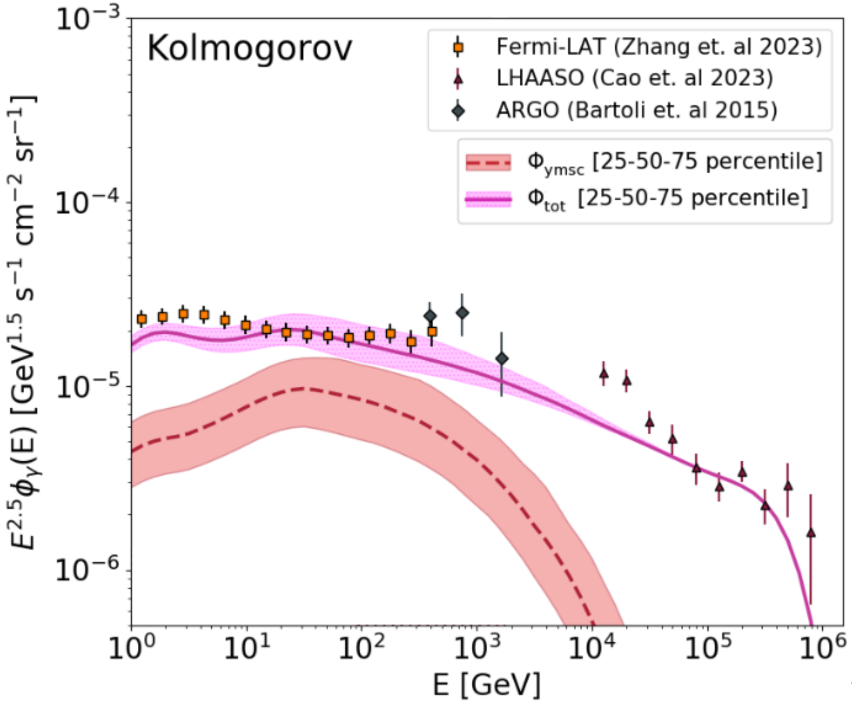
OBJECTIVES:

1) Estimate **neutrino emission** and cross check with IceCube observations
2) Estimate number of YMSCs detected with KM3NeT
3) Provide a public template for the analysis of Galactic neutrino emission
4) Improve the work of *S. Menchiari et al 2025*
   a) Include contribution from supernovae
   b) Refine the target density profile for hadronic emission





Method

Method employed in Menchiari et al 2025

A similar method is employed in this work

STEP 1

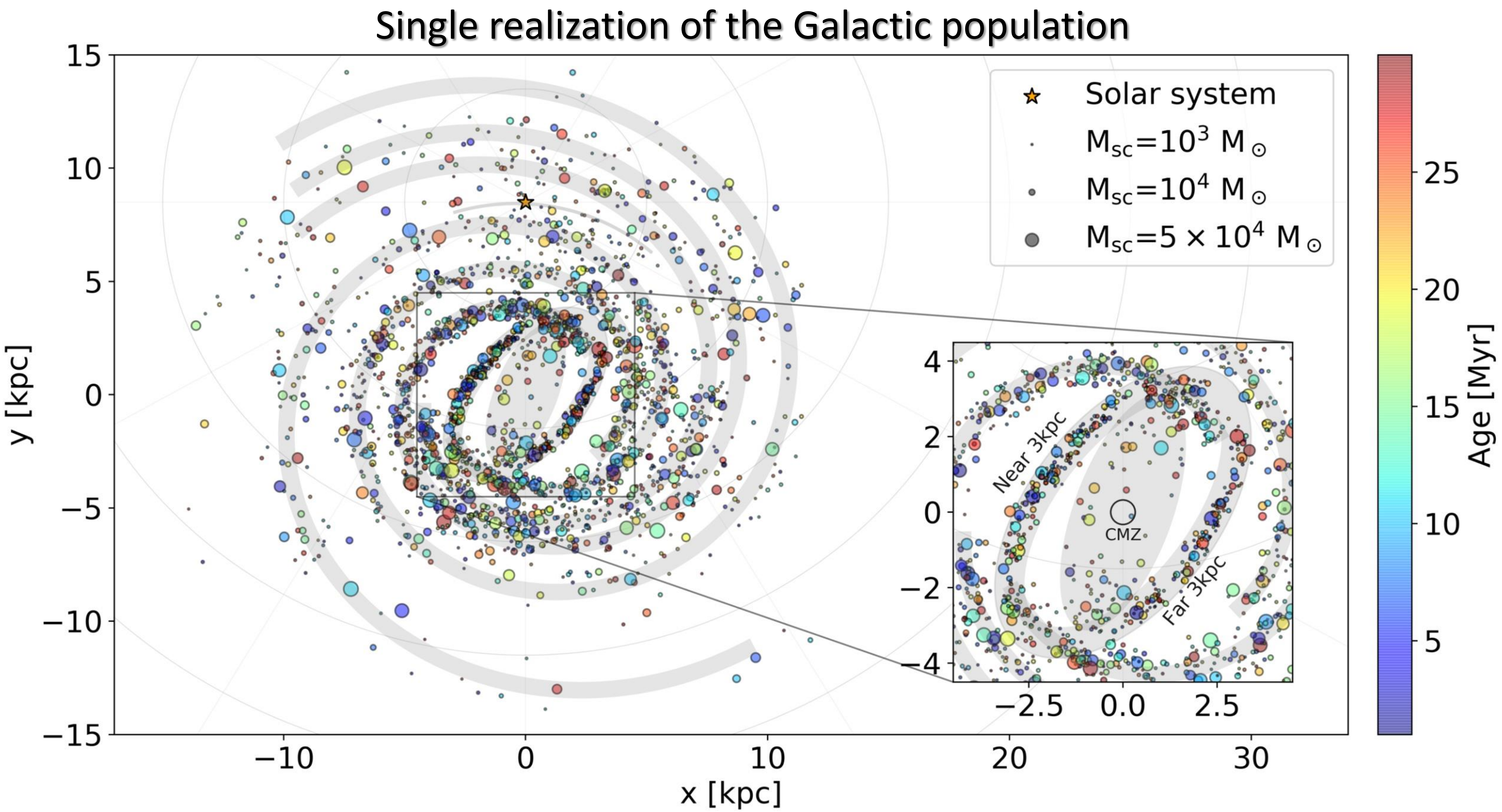
Modeling galactic population of YMSCs:

a) Use info from local population of YMSCs [cluster formation rate and mass distribution]

b) Extrapolate to the Milky Way using realistic spiral pattern

Synthetic YMSCs population

Total number of YMSCs: 2243
(Age <30 Myr, M_{SC} >10^3 $M_\odot$)



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a) Generate and evolve the mock population

b) Modeling stellar wind physics using pure empirical approach

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STEP 3

CR acceleration, ν and γ-ray emission

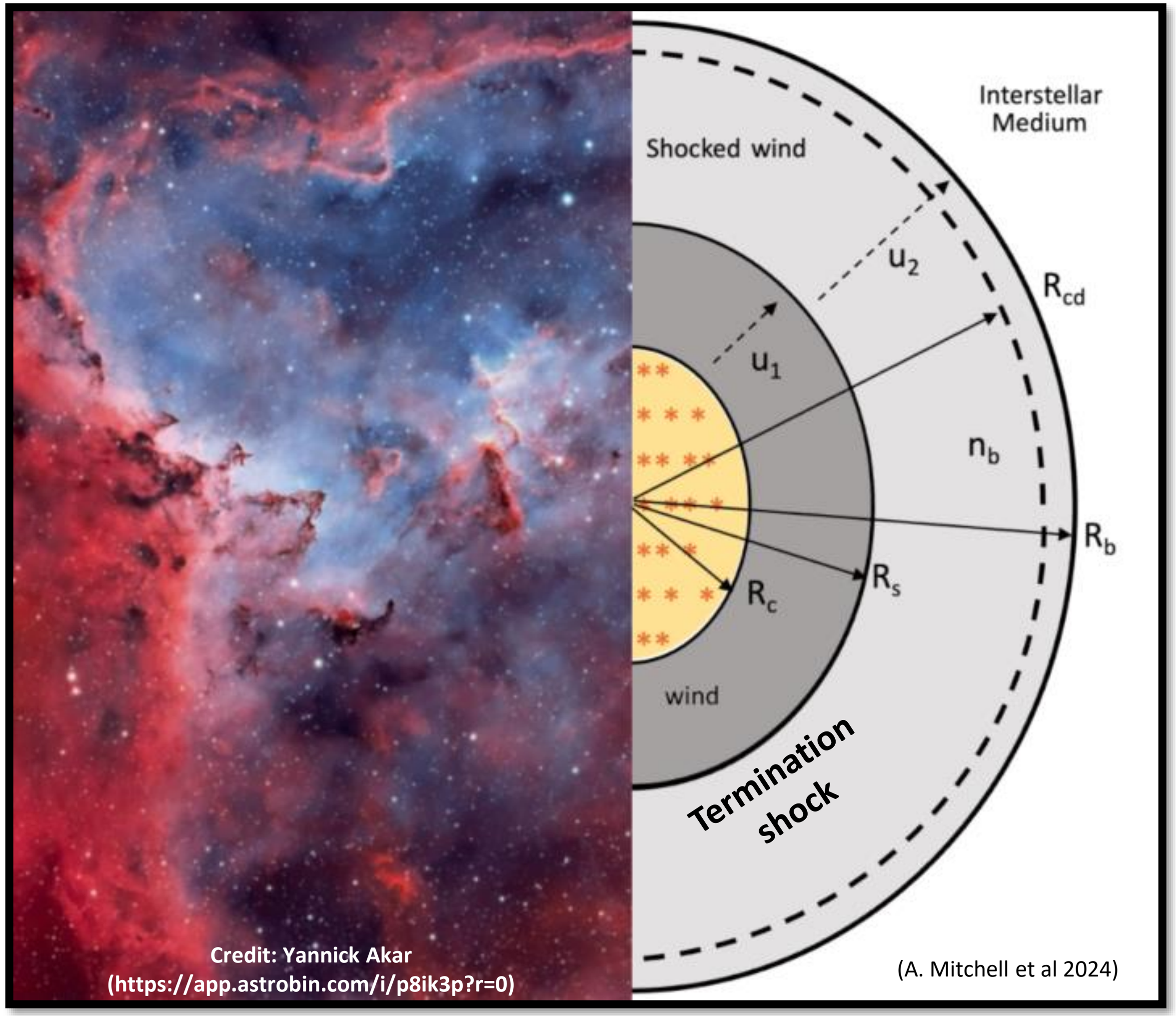
a) CR injection (cluster wind + supernovae)

b) Calculate γ-ray (pure hadronic) and ν emission

c) Mask resolved emission from YMSCs

CR distribution in YMSCs

1) **Acceleration at the cluster wind TS (Morlino et al 2021)**
   A. Spectral slope: $p^{-4.2}$
   B. Normalization: 10% of L_w spent to accelerate CRs
2) **Acceleration by SNe (Mitchell et al 2024)**
   A. Only SNe exploded in one advection time
   B. Spectral slope: $p^{-4.3}$
   C. Normalization: 10% efficiency



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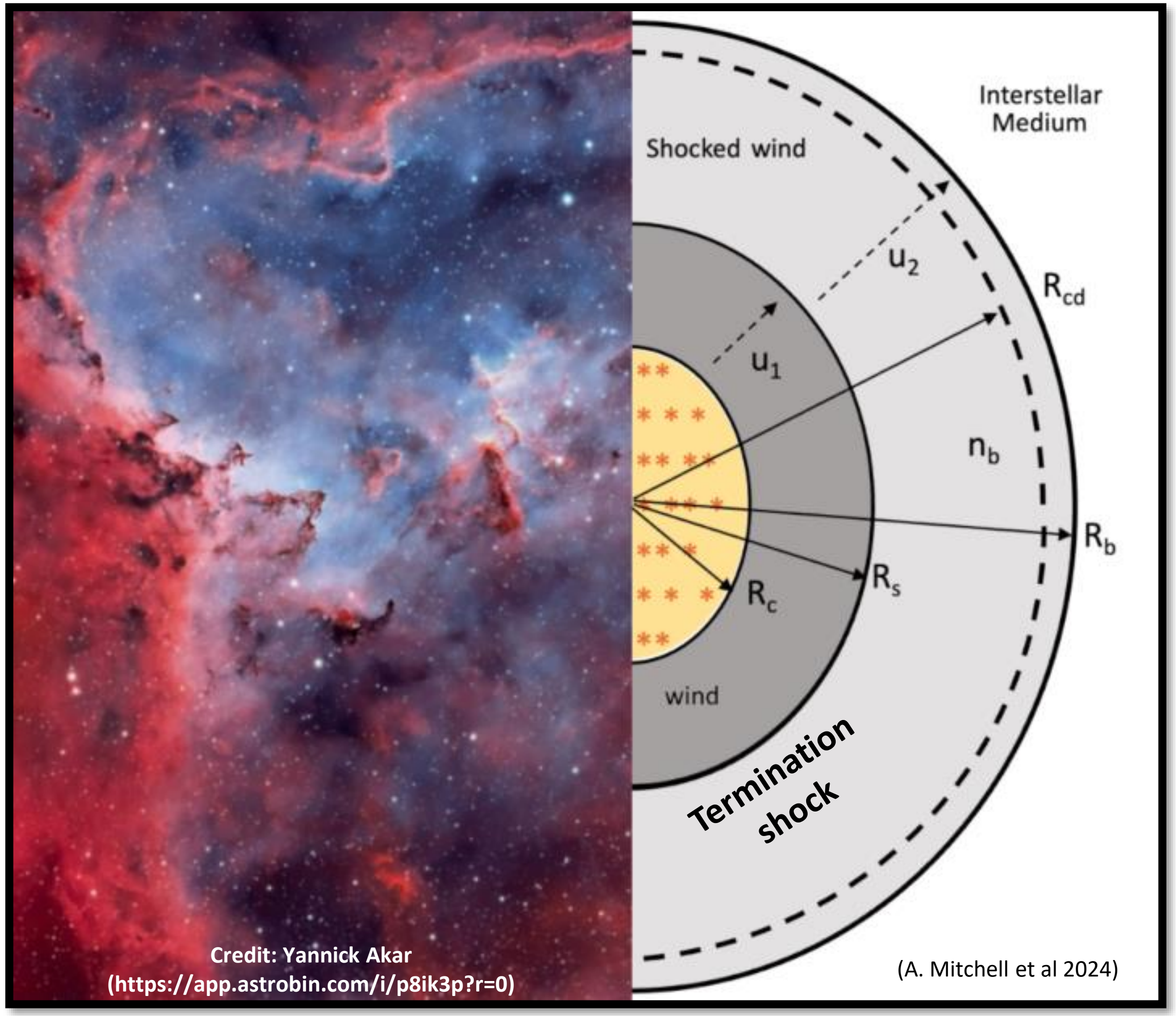


Total CR distribution

$$f_{cr}(r,E) = [\langle f_{SN}(E)\rangle + f_{ts}(E,D)] \times \Gamma(r,E,D)$$

- $\langle f_{SN}(E)\rangle$: **Injection by SNe** (Mitchell et al 2024)
- $f_{ts}(E,D)$: **Injection by winds** (Menchiari et al 2024)
- $\Gamma(r,E,D)$: **Bubble propagation**

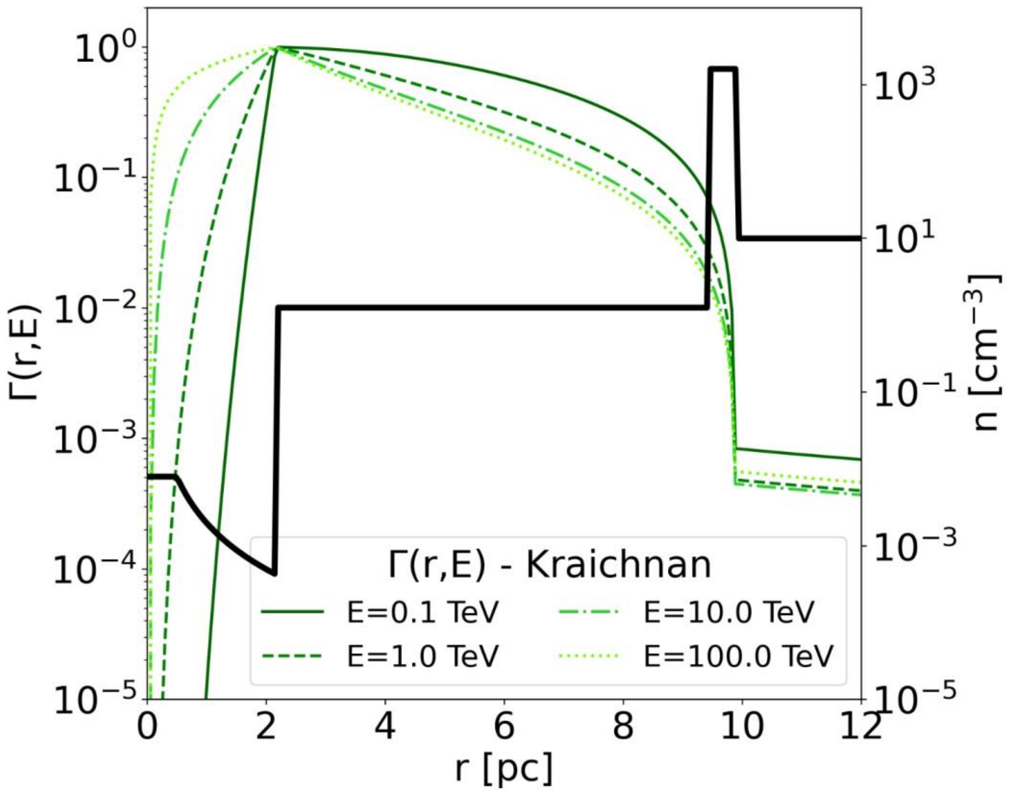
→ *Three cases of different diffusion coefficient considered*
- Kolmogorov
- Kraichnan
- Bohm

Emission from YMSCs

Neutrino and gamma-ray emission

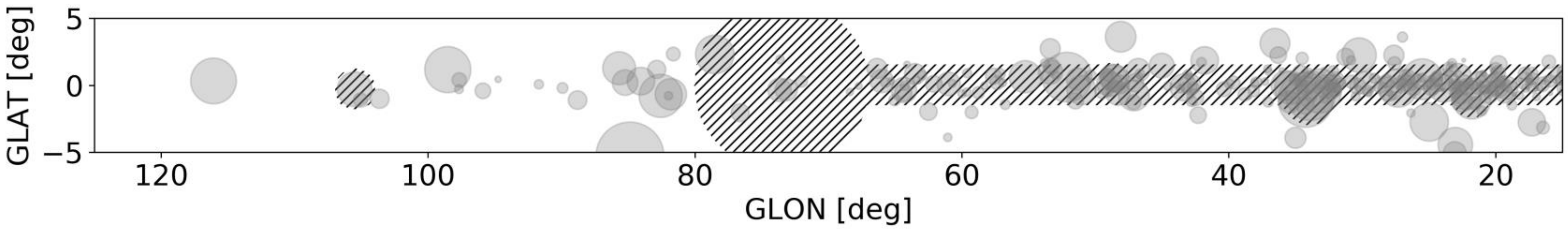
$$\phi_{\nu,\gamma}(E_{\nu,\gamma}) = \frac{c}{d^2} \int \int_0^{R_b} r^2 f_{cr}(r, E_p) n(r) \frac{d\sigma_{\nu,\gamma}(E_p, E_{\nu,\gamma})}{dE_p} dr dE_p$$

- γ-ray cross section: Kafexhiu et al 2014
- Neutrino cross section: Koldobskiy et al 2021
- Gamma-ray morphology modeled as a disk



Non resolved gamma-ray emission calculated after applying masks:

1) Remove clusters detected by LHAASO @100 TeV
2) Remove inner galactic plane and local arm where most of other sources are expected to be located

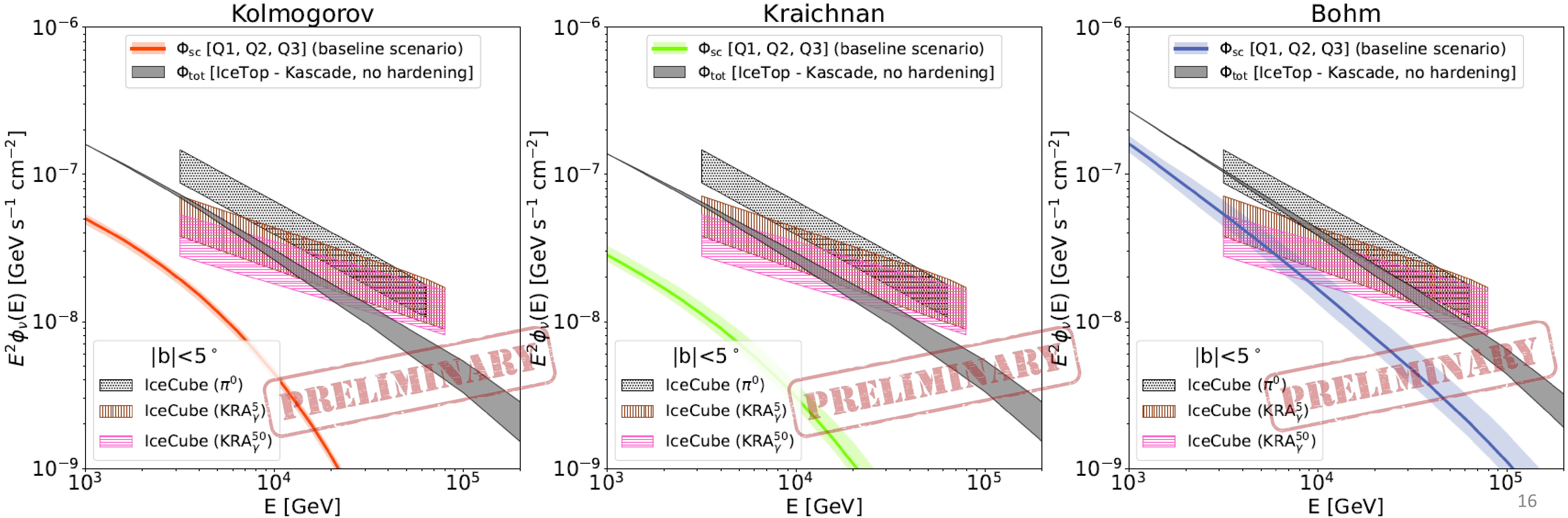


Comparison with neutrino and γ–ray data

Neutrino emission ($|b|<5°$)

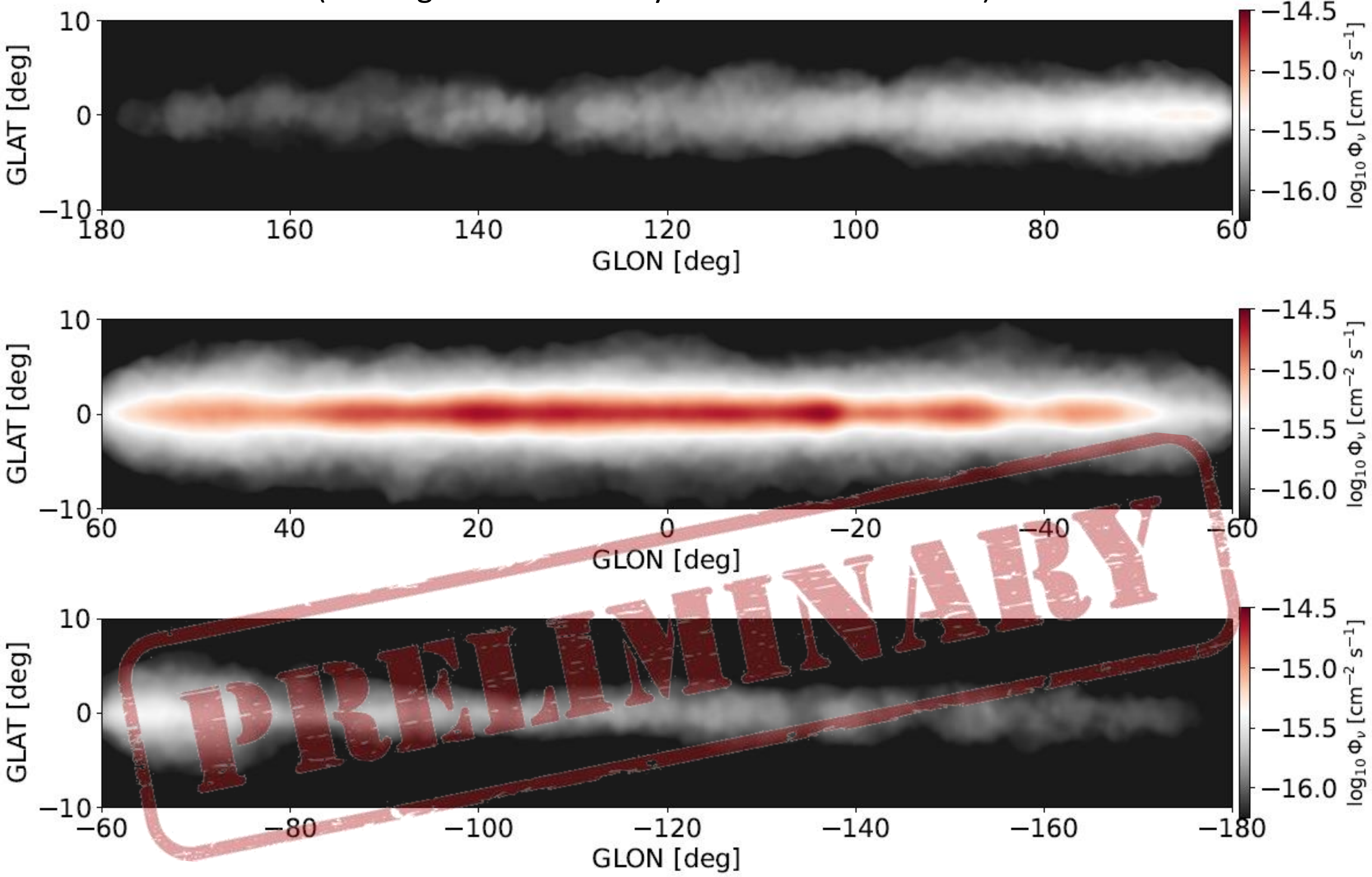
(ϕ_{sea} from Vecchiotti et al 2025)

- *Hatched bands:* IceCube data (Icecube Collab., 2023)
- Grey Band: Total neutrino flux ($\phi_{tot} = \phi_{sea} + \phi_{sc}$) [$\phi_{sea}$: no hardening considered]
- Colored band + solid line: contribution from YMSCs (Quartile: 25, 50, 75)
- ➢ ϕ_{sc}/ϕ_{sea} (10 TeV) < 15% for Kolmogorov and Kraichnan
- ➢ ϕ_{sc}/ϕ_{sea} (10 TeV) = 60% for Bohm



Integrated neutrino emission

(Kolmogorov case – Only emission from YMSCs)



Integrated all flavor neutrino emission (E>1 TeV)

A public template of the expected neutrino emission will be published

Median emission obtained from 100 different realizations of the Milky Way

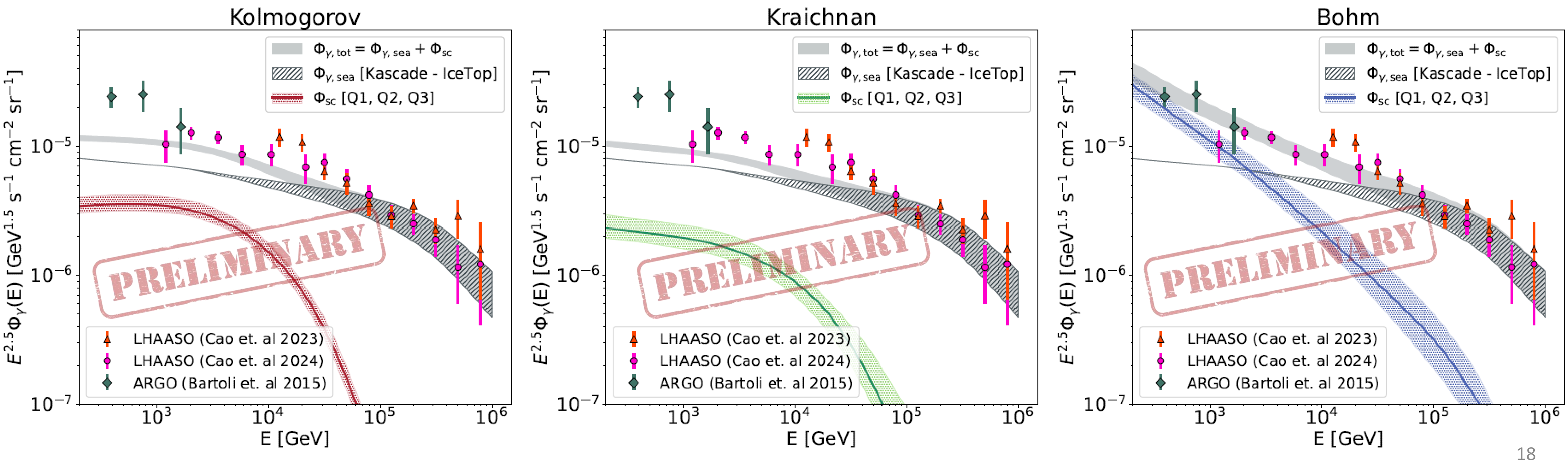
γ–ray emission (15°<ℓ<125°)

- *Hatched band:* Galactic CR emission [ϕ_{sea}: no hardening considered] (Vecchiotti et al 2025)
- Grey Band: Total neutrino flux (ϕ_{tot}= ϕ_{sea} + ϕ_{sc})
- Colored band + solid line: contribution from YMSCs (Quartile: 25, 50, 75)

➢ ϕ_{sc}/ϕ_{sea} (1 TeV) = 50% for Kolmogorov

➢ ϕ_{sc}/ϕ_{sea} (1 TeV) = 30% for Kraichnan

➢ ϕ_{sc}/ϕ_{sea} (1 TeV) = 150% for Bohm

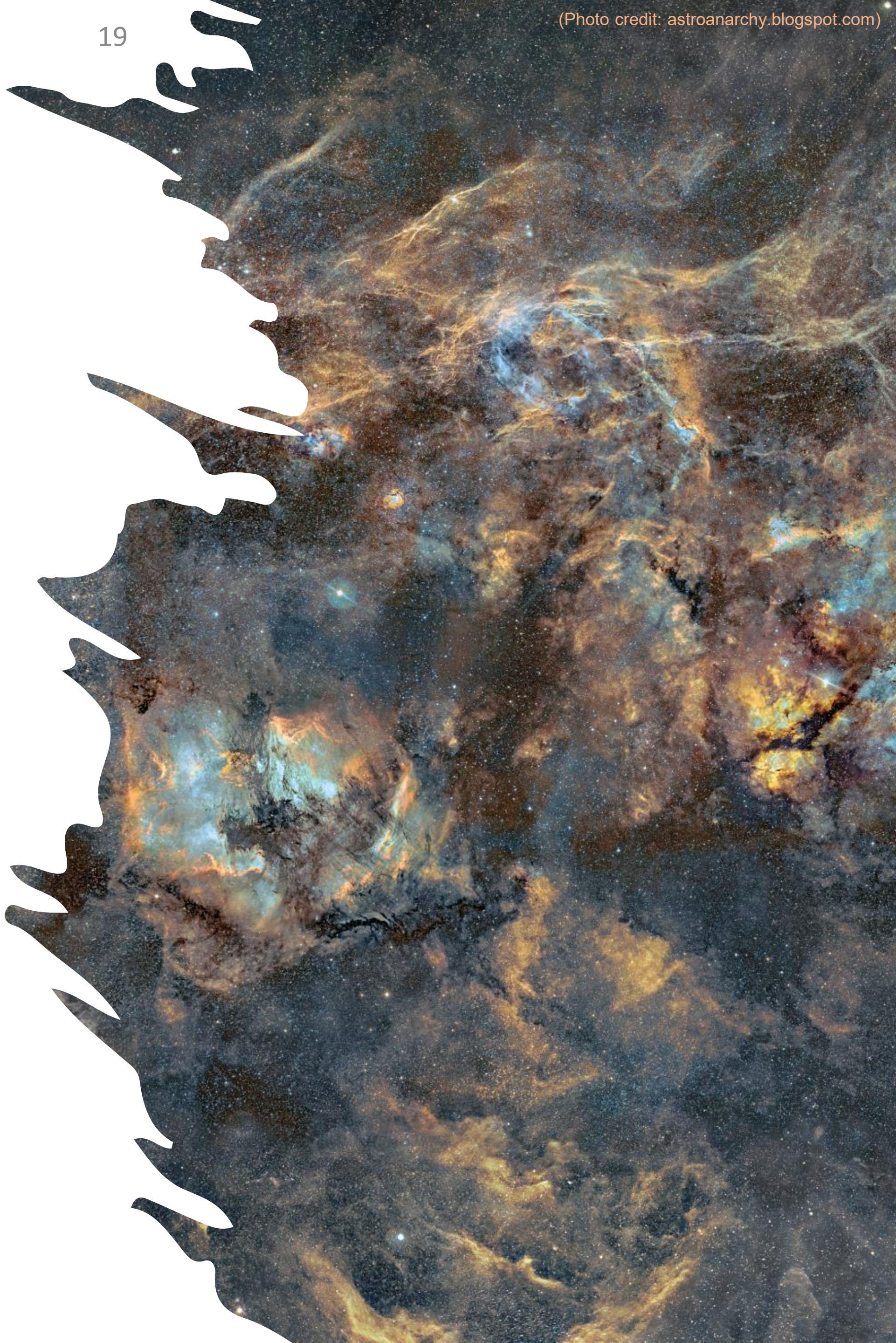


Conclusions

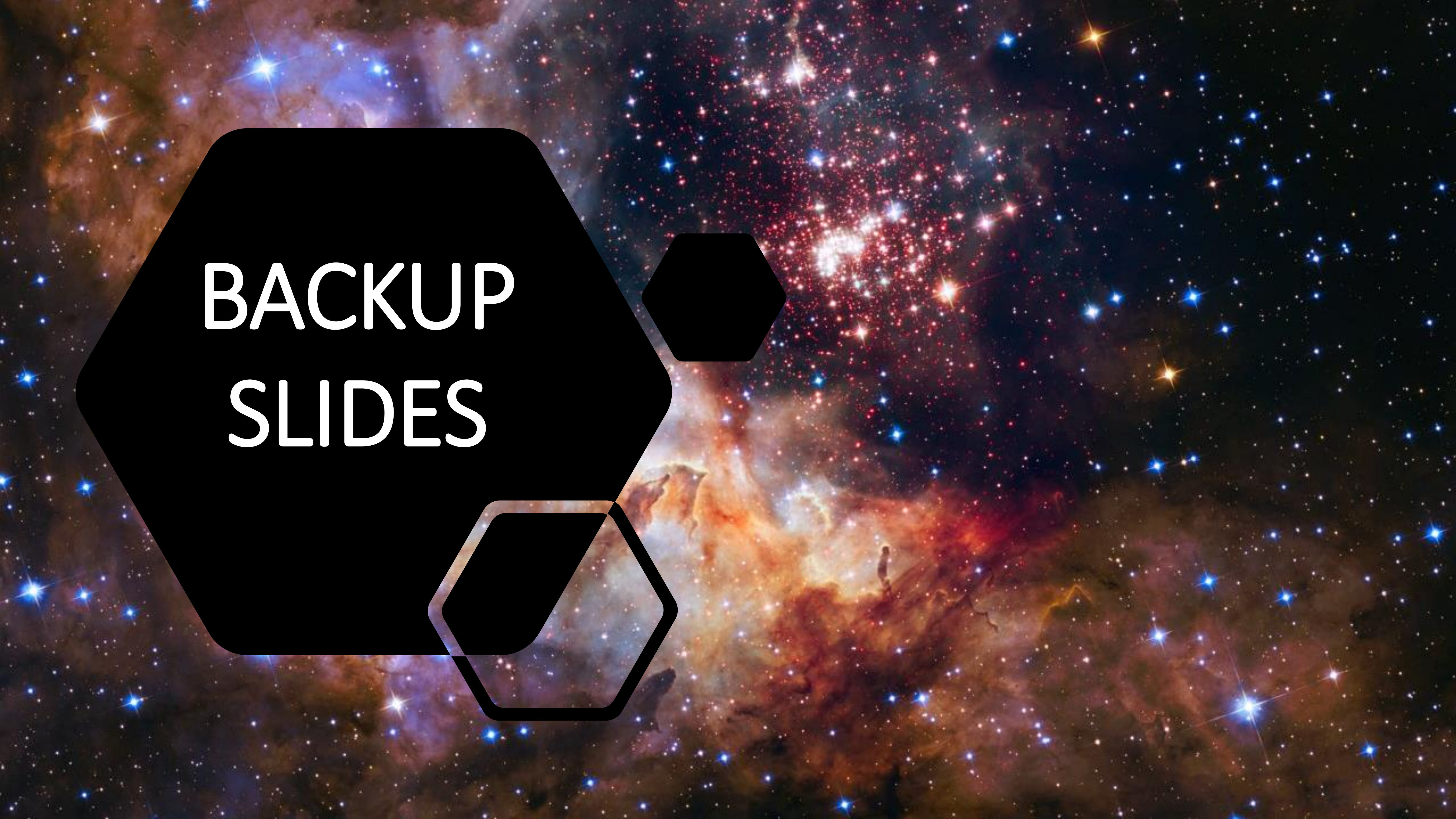
- Importance of YMSCs as high energy sources has constantly growing in the last decades
- **Contribution to the neutrino emission ranging within 10-60% at 10 TeV.**
- **Contribution to the diffuse gamma-ray emission ranging within 30-150% at 1 TeV.**

Future steps

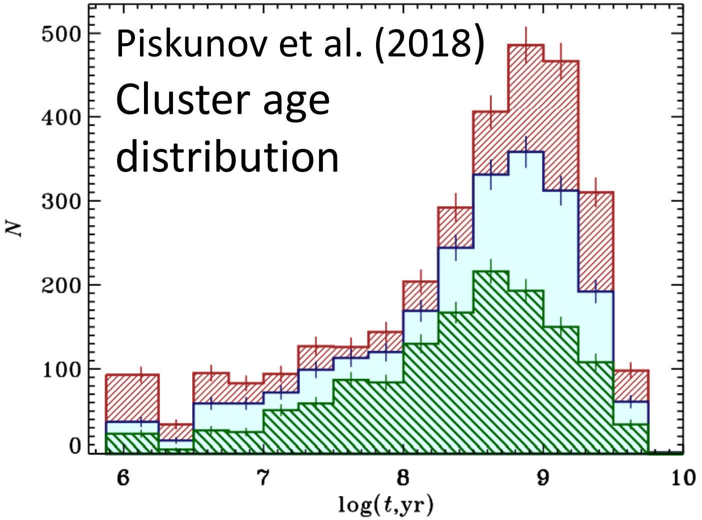
- Evaluate how many YMSCs are statistically expected to be detected by KM3NeT


(Photo credit: astroanarchy.blogspot.com)

BACKUP SLIDES

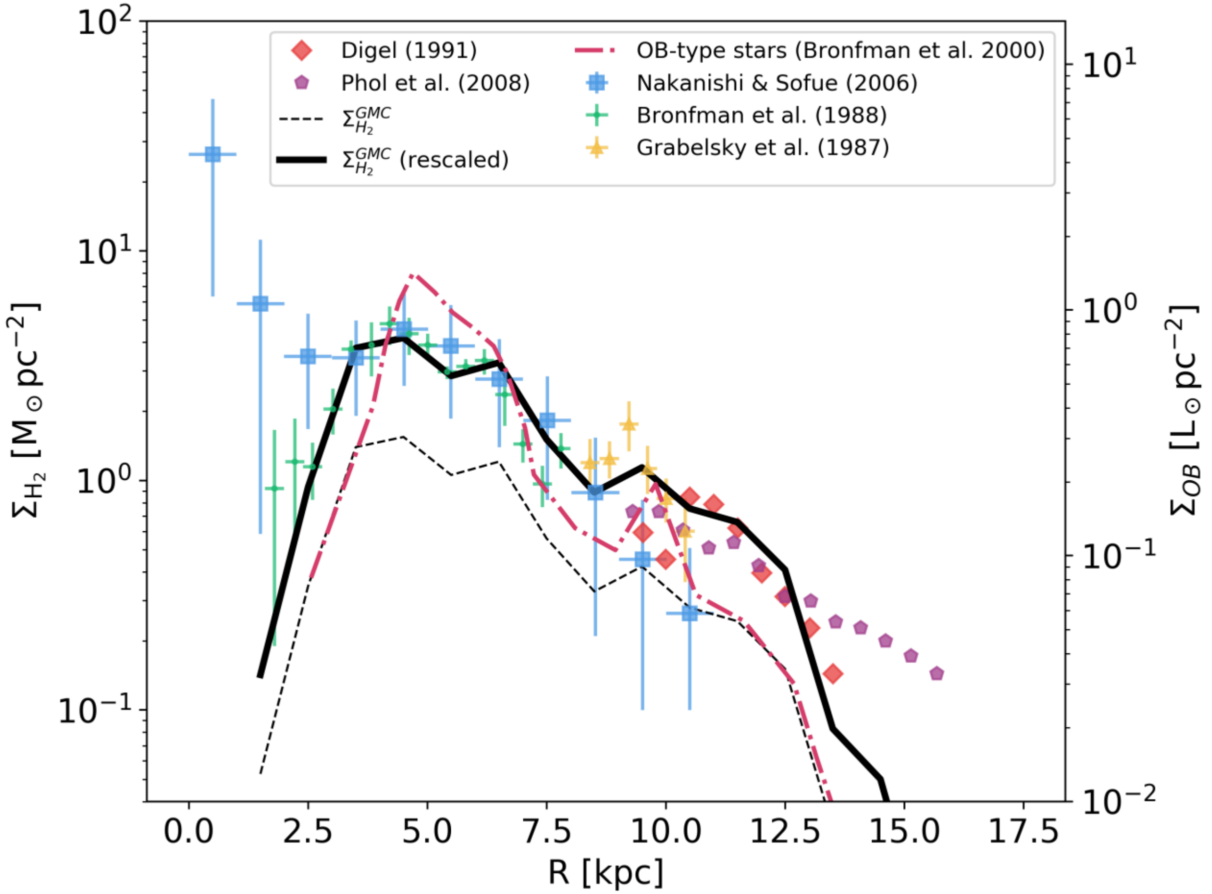


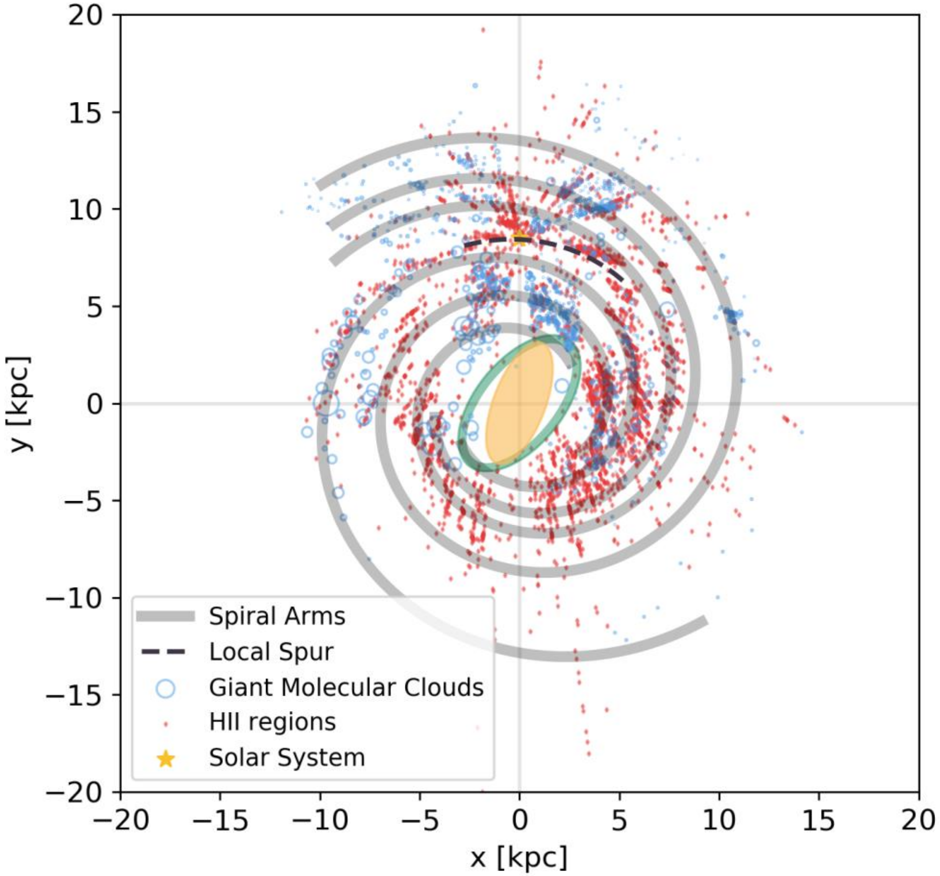
Synthetic YMSCs population (I)



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 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)



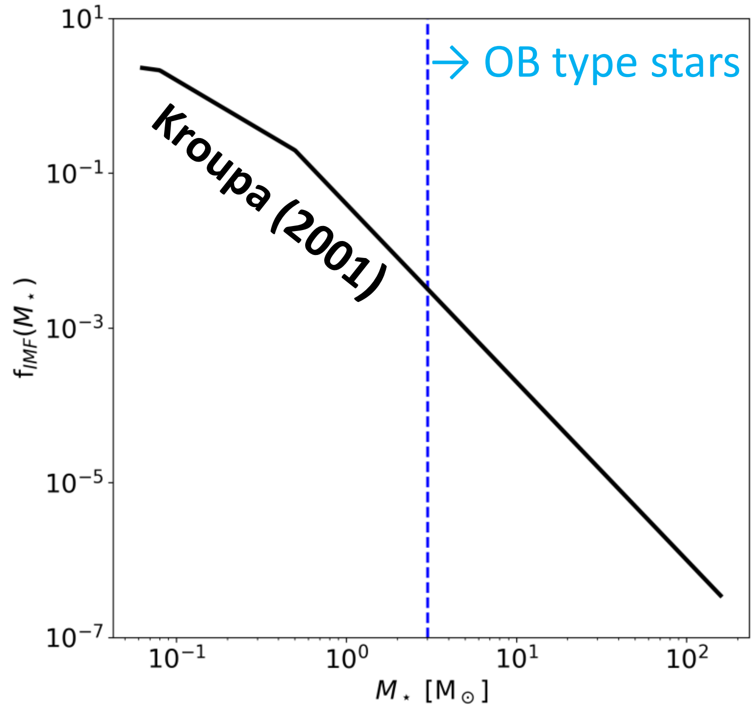


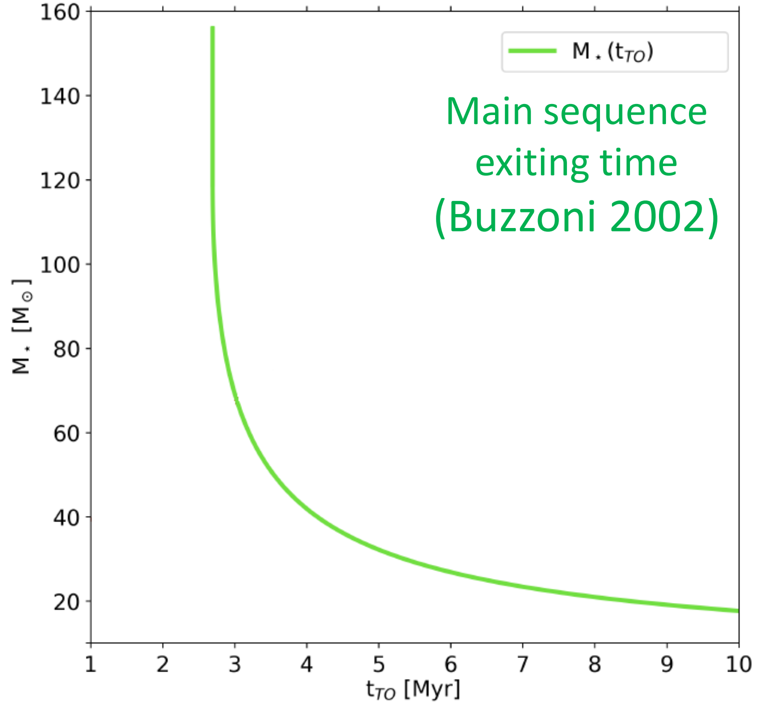
Stellar population in YMSC

- 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 $M_\odot$
- *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$M_\odot$)
- Stellar wind power ($L_{\star,w}$) and mass loss rate ($\dot{M}_\star$) calculated using empirical formulae (see back up slides)
- Cluster wind luminosity and mass loss rate obtained by summing all $L_{\star,w}$ and $\dot{M}_\star$
- Stars exploded as SN are considered for **CR production** and for the **dynamic of the system**





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)]

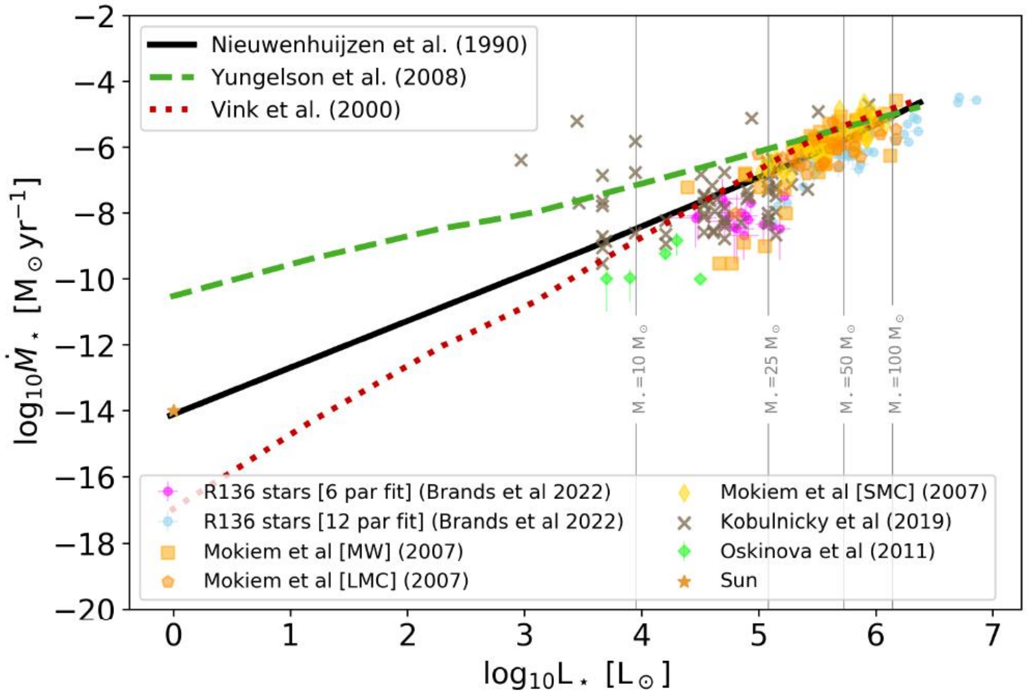
$$L_{\star,w} = \frac{1}{2}\dot{M}_\star \underbrace{\left\{C(T_{\rm eff})^2\left[\frac{2GM_\star(1-L_\star/L_{\rm Edd})}{R_\star}\right]\right\}}_{v_{\star,w}^{\;2}}$$

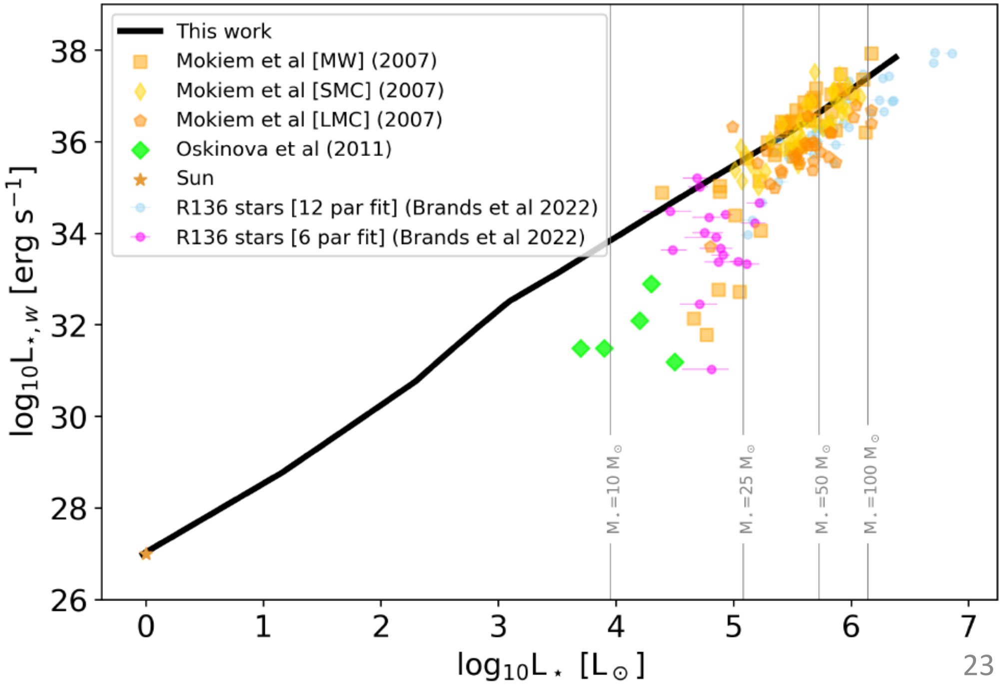
- Mass loss rate **WR** stars ($\dot{M}_{\star,WR}$) by Nugis & Lamers (2000)

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

- 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.

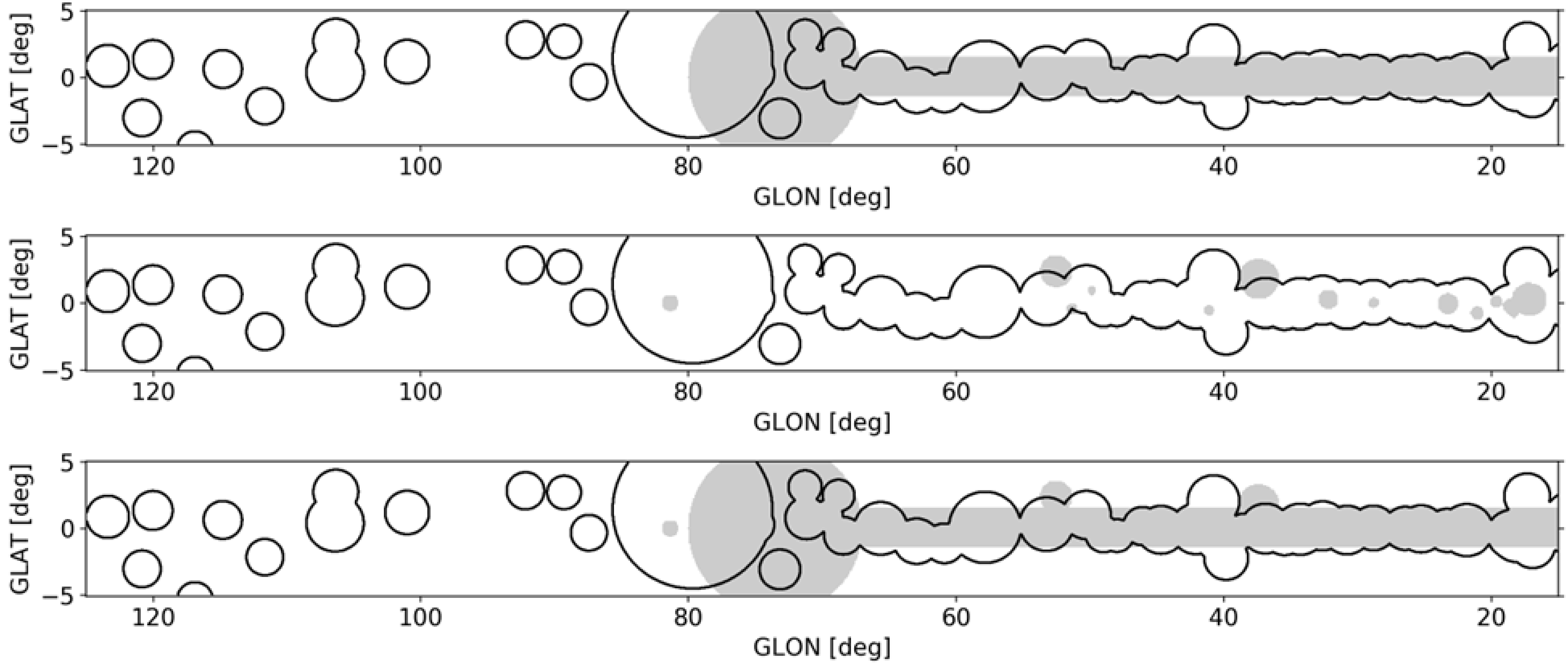
ROI1: 15°<glon<125°, |glat|<5°

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**

CR accelerated by YMSC

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

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

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

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

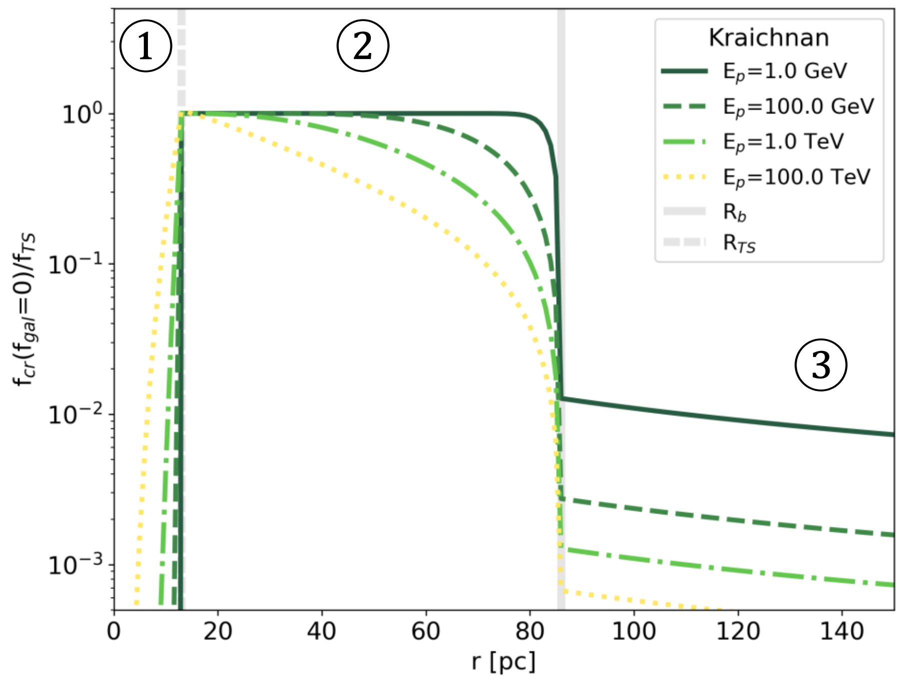
$$f_{TS}(p) \simeq \frac{3 n_1 u_1^2 \epsilon_{CR}}{4\pi \Lambda_p (m_p c)^3 c^2} \left(\frac{p}{m_p c}\right)^{-s} \left[1 + a_1 \left(\frac{p}{p_{max}}\right)^{a_2}\right] e^{-a_3 (p/p_{max})^{a_4}}$$

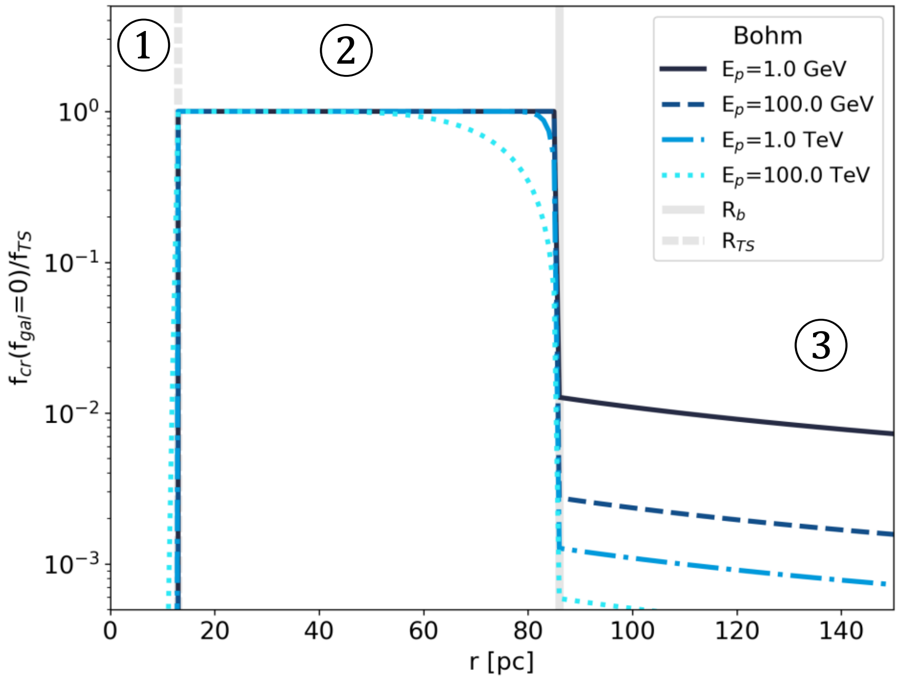
Models	a_1	a_2	a_3	a_4
Kolmogorov	10	0.308653	22.0241	0.43112
Kraichnan	5	0.448549	12.52	0.642666
Bohm	8.94	1.29597	5.31019	1.13245

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

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

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





CR accelerated by SNe

<u>Mitchell et al. (2024):</u> CRs accelerated by SNe in one advection time

$$f_{\rm snr}(p) = \frac{3\,\xi_{\rm cr} n_b u_{\rm sh}^2}{4\pi\,\Lambda (m_p c)^4 c^2} \left(\frac{p}{m_p c}\right)^{-s_{\rm sn}} {\rm e}^{-p/p_{\rm max}}$$

$$\langle f_{\rm snr}(p) \rangle = \mathcal{R}\, f_{\rm ts}(m_p c) \left(\frac{p}{m_p c}\right)^{-s_{\rm snr}} {\rm e}^{-p/p_{\rm max}}$$

$$\mathcal{R} = 1.74\, N_{\rm sn}(t_{\rm esc}) \left(\frac{E_{\rm sn}}{10^{51}\,{\rm erg}}\right) \left(\frac{L_{\rm w,c}}{10^{37} {\rm erg\,s^{-1}}}\right)^{-1} \left(\frac{t}{3\,{\rm Myr}}\right)^{-1}$$

$$E_{\rm max} = 48 \left(\frac{B}{10\,\mu{\rm G}}\right) \left(\frac{L_{\rm coh}}{2{\rm pc}}\right)^{-1} \left(\frac{u_{\rm ed}}{5000\,{\rm km/s}}\right)^{\frac{1}{2}} \left(\frac{R_{\rm st}}{10\,{\rm pc}}\right)^{\frac{1}{2}} {\rm TeV}$$