Universität Potsdam Mathematisch-Naturwissenschaftliche Fakultät

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H.E.S.S.

The population of Galactic young massive star clusters in the TeV range

Outline

- What are we looking for?
- YMSC population model
- Properties of the YMSC population investigated
- Results

What are we looking for?

- YMSCs are thought to be a good candidate for accelerating cosmic rays up to PeV energies.

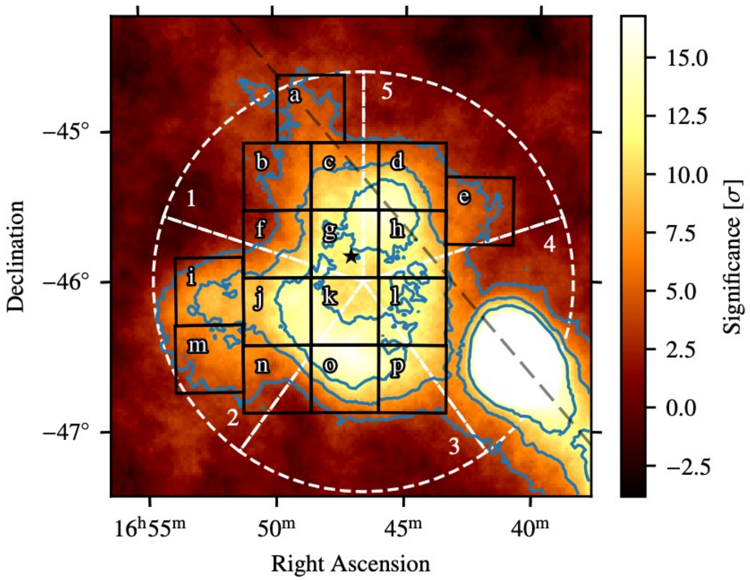
- There are a few known vhe (>1 TeV) gamma ray emitting YMSCs, but not a lot is known about this population of sources.

- Questions to answer:
  - Can we describe the observational data (HGPS, 1st LHAASO cat)?
  - What is the spectrum of accelerated particles?
  - What is the efficiency of particle acceleration?
  - Which diffusion regime takes place in YMSCs?

H.E.S.S. (High Energy Stereoscopic System)

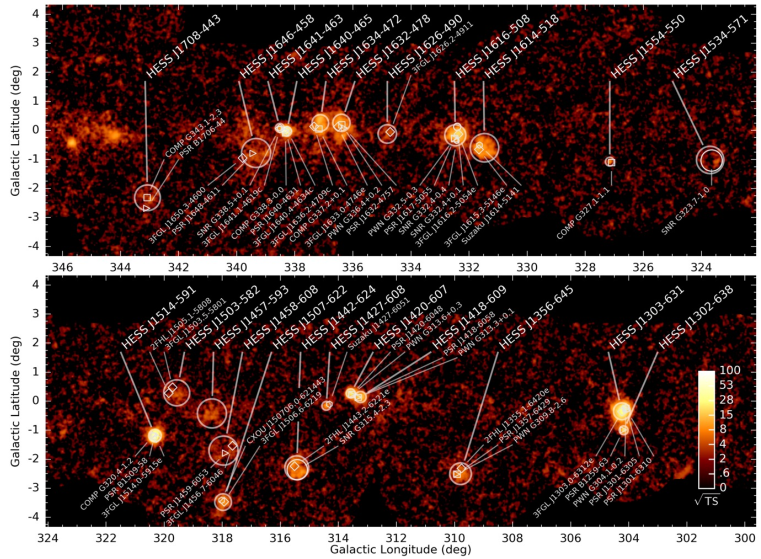
H.E.S.S.

Westerlund 1 detected by H.E.S.S.



From Westerlund 1 paper

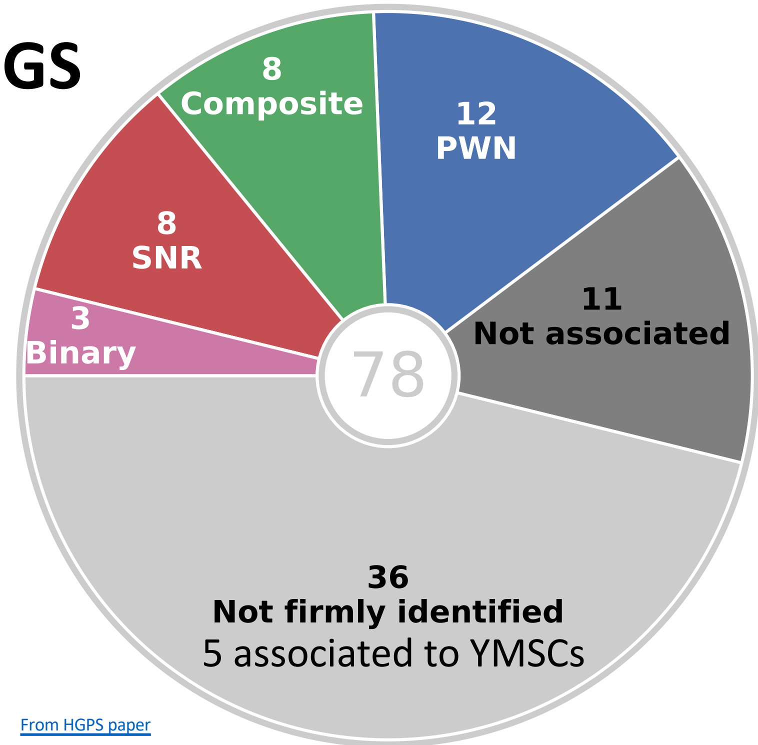
H.E.S.S. Galactic Plane Survey (HGPS)



From HGPS paper

HGPS (H.E.S.S. Galactic Plane Survey) data

HPGS



From HGPS paper

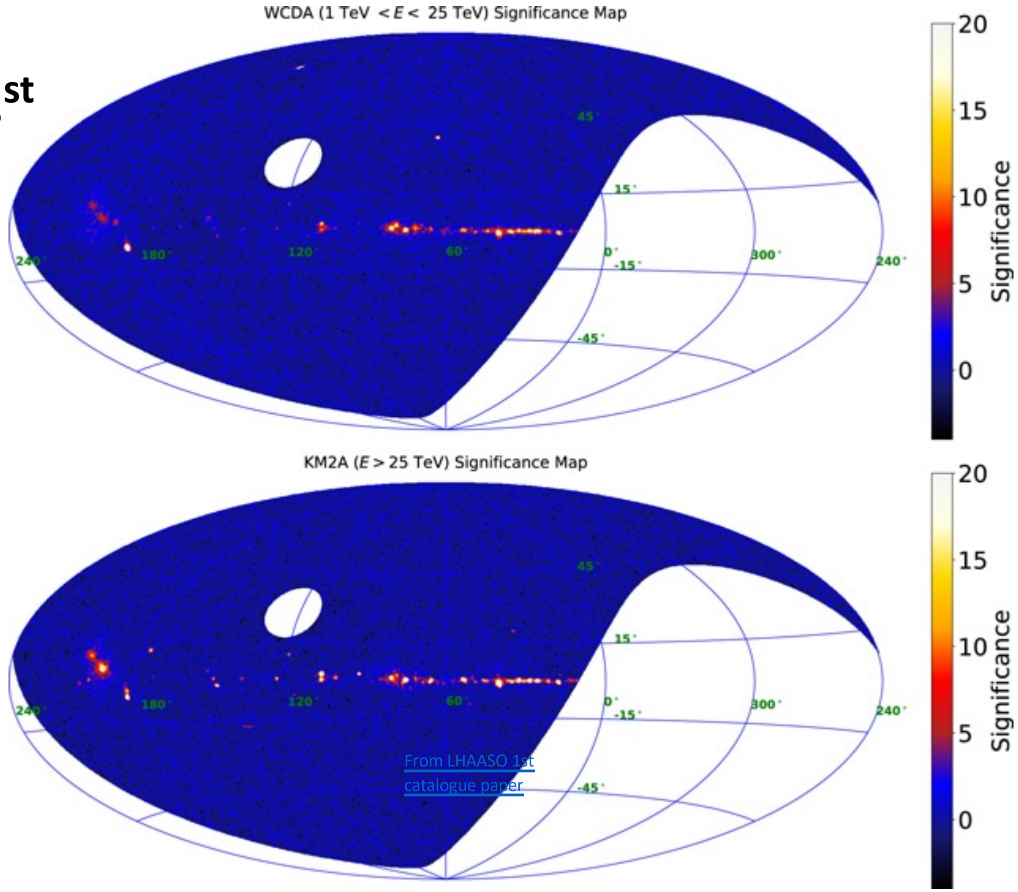
Comparison

- Lower limit of 1
- Upper limit of 5

LHAASO (Large High Altitude Air Shower Observatory)

LHAASO

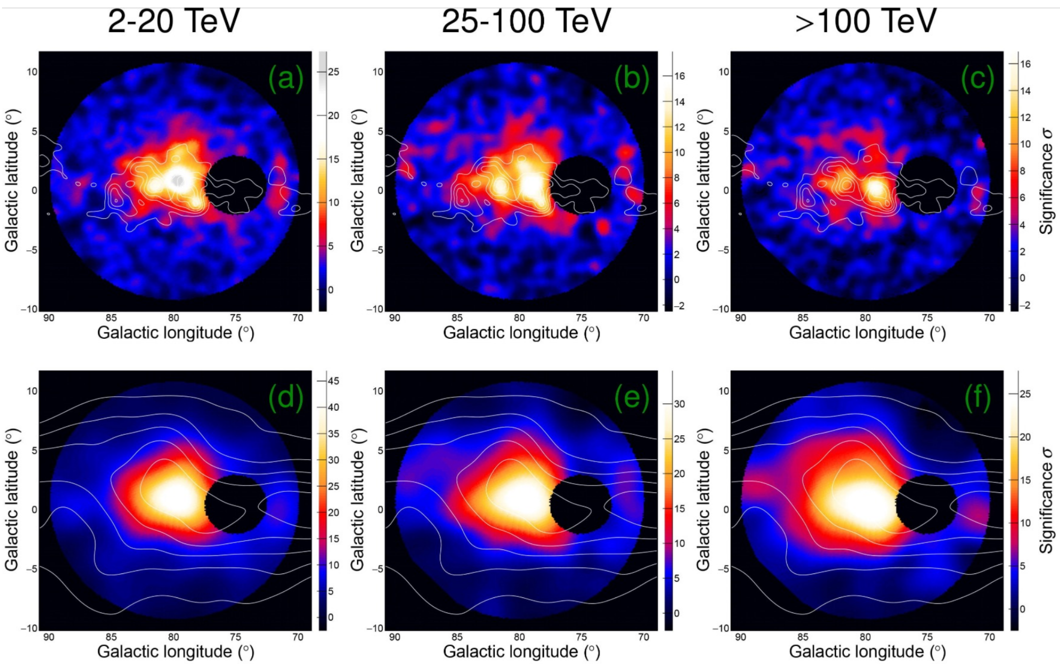
LHAASO 1st catalogue



From LHAASO 1st catalogue paper

1st LHAASO catalogue

Cygnus cocoon detected by LHAASO



[From LHAASO Cygnus X paper]

Comparison

- Lower limit of 1
- upper limit of 12 (WCDA)
- upper limit of 9 (KM2A)

YMSC population model

- Physics of the cluster
  - Evolution of the radius and velocity of the combined shock of all stars in the cluster
  - Maximum energy of accelerated particles

- Distribution of sources and matter
  - Where in the Milky way
  - Number of expected YMSCs
  - Mass and age distribution of clusters
  - Mass distribution of stars in individual clusters

YMSC population model

- The wind of the cluster is modelled like that of a single star but with the combined mass and wind luminosity of all the stars in the cluster.
- Only the total flux of the cluster is considered and not the individual sources in the cluster.
- $f \propto \eta_{CR}\, p^{-\alpha} e^{-\Gamma(p)}$

Number of clusters in the Milky way

- $N_{SC} = \int_{M_{\min}}^{M_{\max}} \int_{t_{\min}}^{t_{\max}} \int_{0}^{R_{MW}} f(M)\, \nu(t)\, \rho(r,\theta)\, r\, dr\, d\theta\, dt\, dM$
- f(M) - mass distribution
- $\nu(t)$ - formation rate
- $\rho(r,\theta)$ - spatial distribution
- f(M) and $\nu(t)$ are taken from Piskunov et al. (2018) Global survey of star clusters in the Milky Way
- $\rho(r,\theta)$ follows the Steiman-Cameron et al. (2010) distribution

Total number of clusters

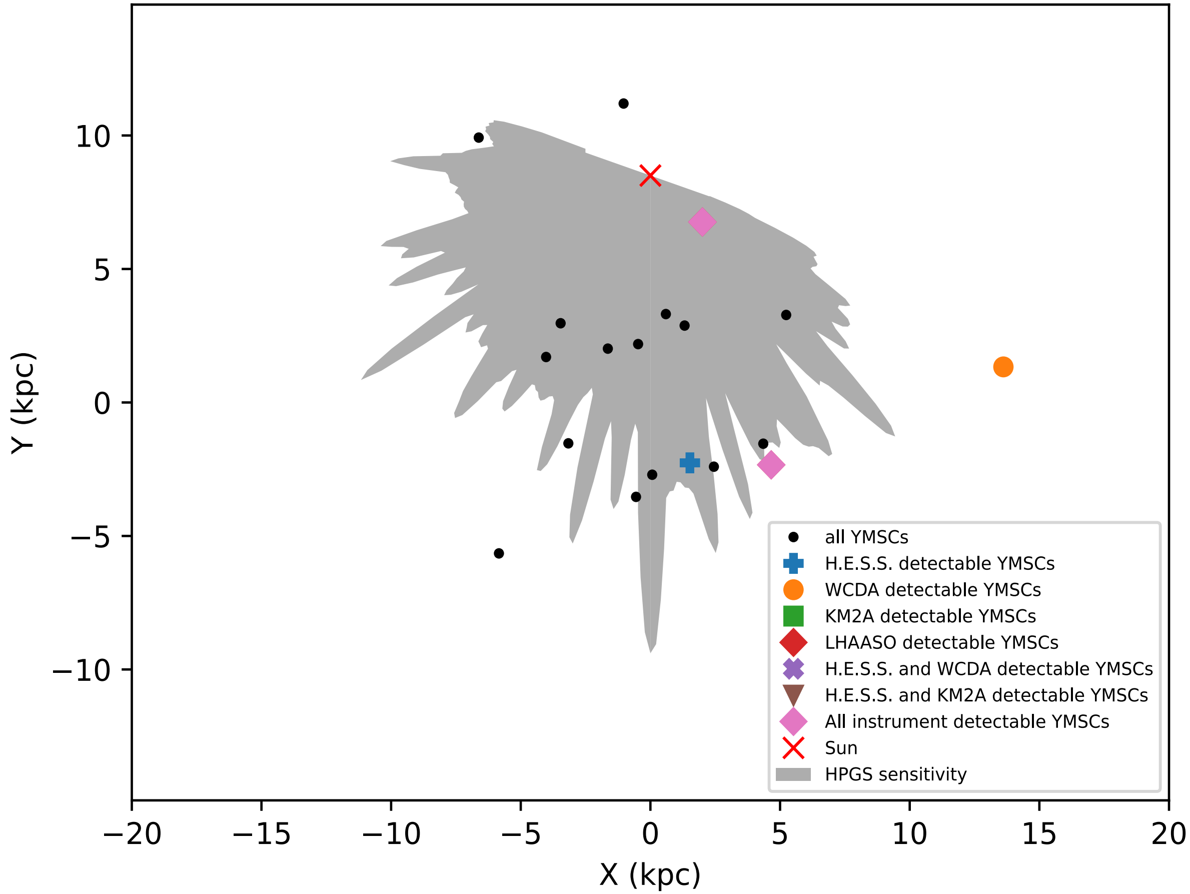
- Normalise the function to the 2 kpc ring around the Sun.
- $N_{SC} = A \int_{M_{\min}}^{M_{\max}} \int_{t_{\min}}^{t_{\max}} \int_{0}^{R_{MW}} f(M)\, \nu(t)\, \rho(r,\theta)\, r\, dr\, d\theta\, dt\, dM$
- $1581 = A \int_{2.3\, M_\odot}^{6.3\times10^4 M_\odot} \int_{0}^{5\mathrm{Gyr}} \int_{0}^{2\ \mathrm{kpc}} f(M)\, \nu(t)\, \rho(r,\theta)\, r\, dr\, d\theta\, dt\, dM$
- We are interested in clusters with: $M > 1000 M_\odot$ and age < 10 Myr
- $\mathrm{N_{SC}} = A \int_{1000\, M_\odot}^{6.3\times10^4 M_\odot} \int_{0}^{10\mathrm{Myr}} \int_{0}^{15\ \mathrm{kpc}} f(M)\, \nu(t)\, \rho(r,\theta)\, r\, dr\, d\theta\, dt\, dM$
  $\mathrm{N_{SC}} \sim 16$

Properties of the SNR population investigated

- Spectral index, α (3.5 to 4.5)
- Efficiency of gamma-ray production, η_{CR} (0.01% to 10%)
- Fraction of wind luminosity converted into magnetic field, η_B (0.01% to 10%)
- Diffusion regime (Bohm, Kraichnan and Kolmogorov)

Realisation of a single population

- Taking into account the HGPS sensitivity
- Shaded region: $L = 5{\times}10^{33}$ ph s^{-1} ($\sim 4{\times}10^{-11}$ TeV^{-1} cm^{-2} s^{-1} at 1 kpc)

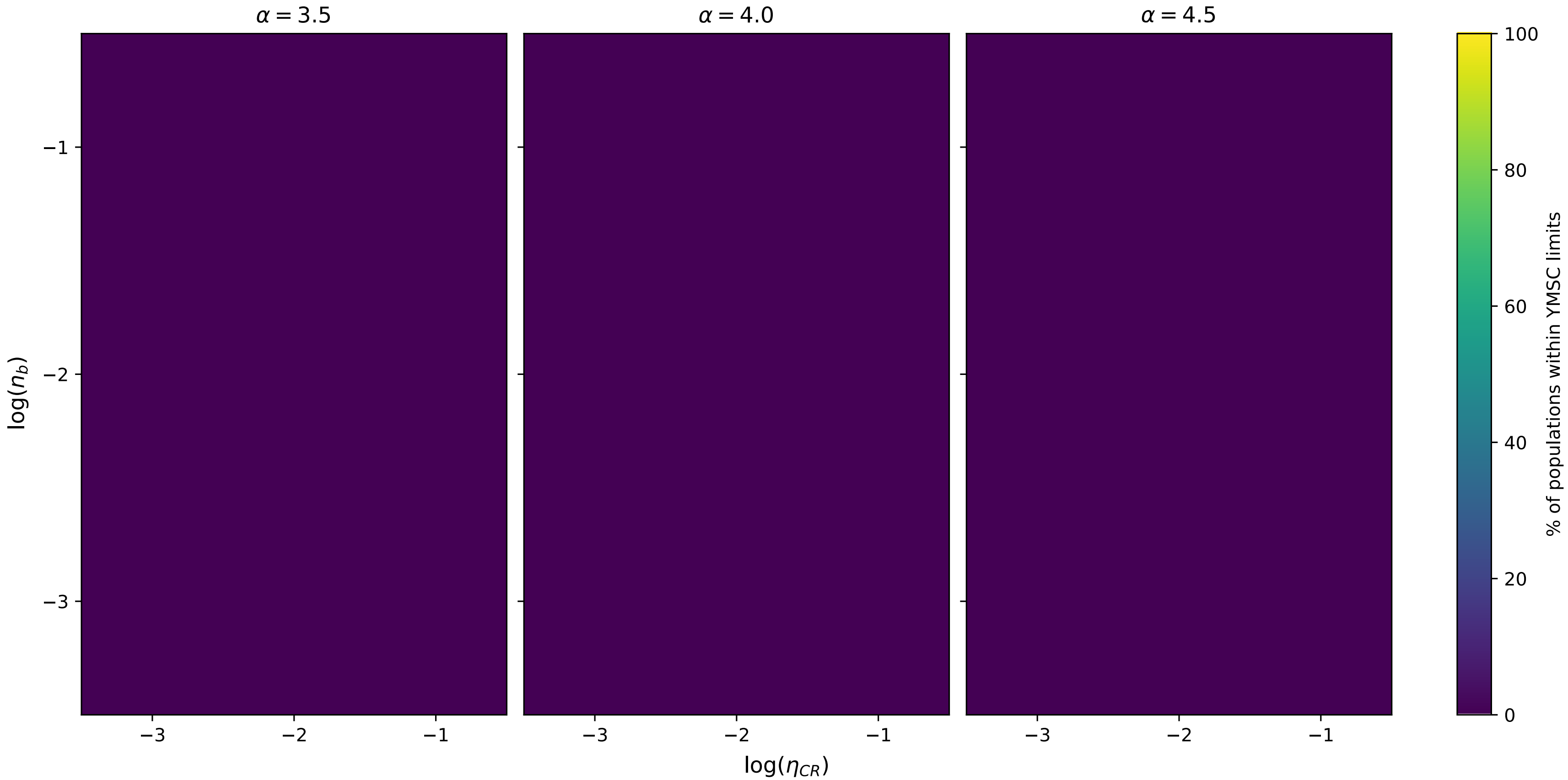


Parameters:

Diffusion regime = Bohm
$\alpha = 4.0$
$\eta_{CR} = 1\%$
$\eta_B = 1\%$

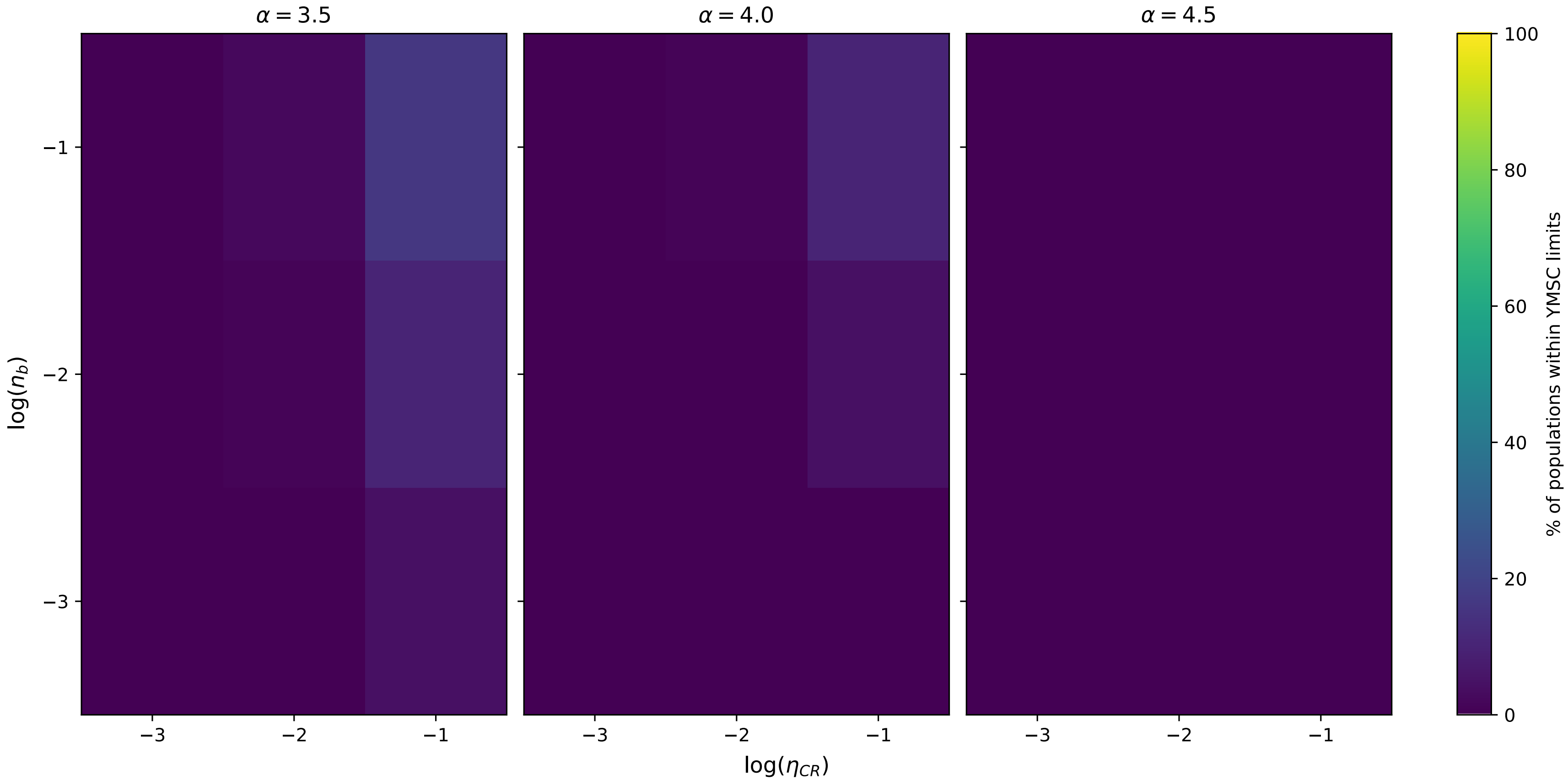
Results – Kolmogorov

Percentage of populations within the HGPS and LHAASO limits



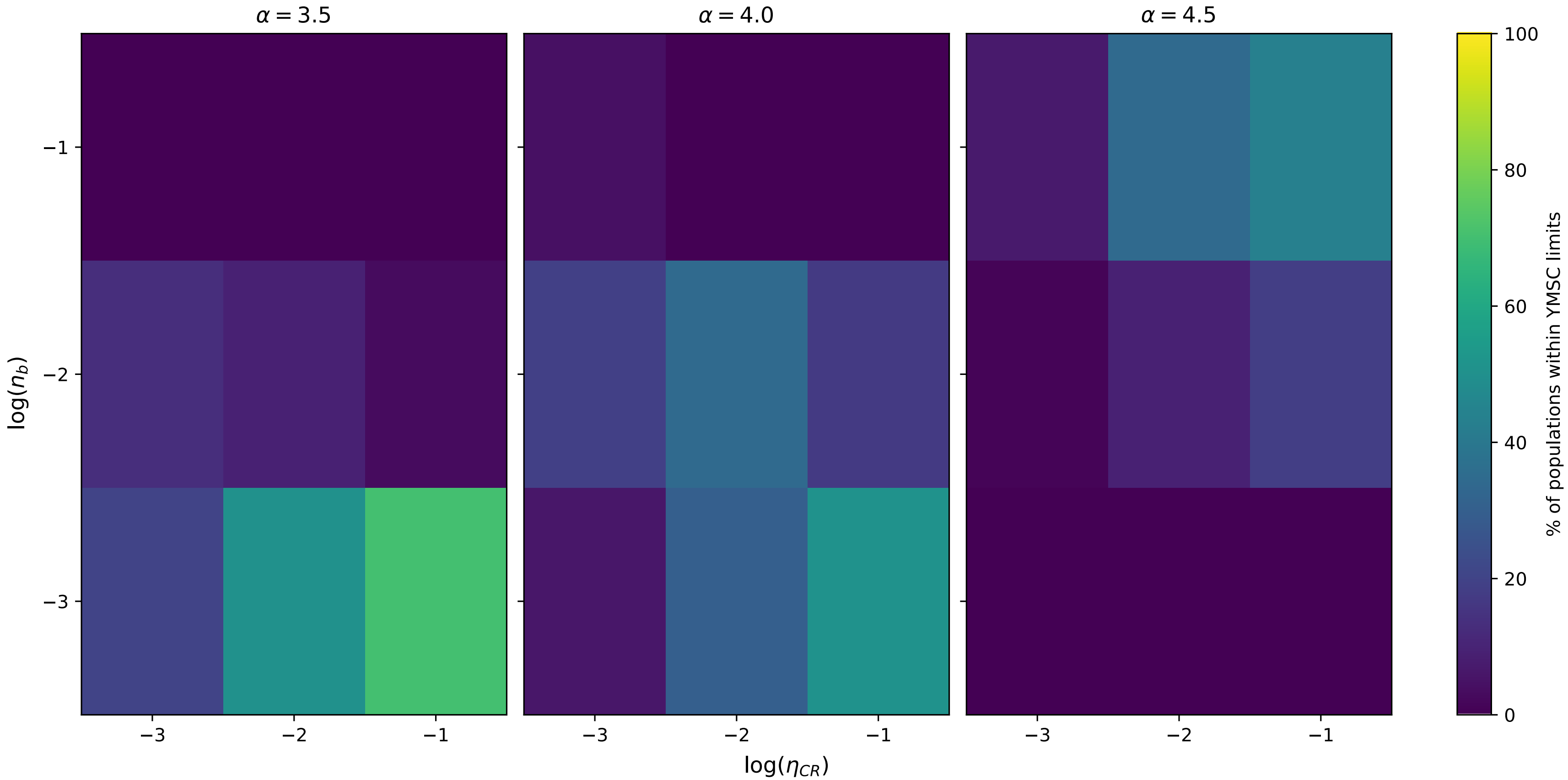
Results – Kraichnan

Percentage of populations within the HGPS and LHAASO limits



Results – Bohm

Percentage of populations within the HGPS and LHAASO limits



Summary

- Confronted YMSC population model to HGPS, taking into account the multi-dimensional exposure and also to the 1st LHAASO catalogue.
- Explored a large parameter space but correlations prevent the identification of an optimal combination.
- The choice of diffusion regime has a large impact.
- A large maximum energy is required to have populations agree with the observations.
- The expected number of stellar clusters also has a significant bearing on this result.

Backup slides

Gamma rays from single cluster

- Wind velocity: $v_w = \sqrt{\frac{2\, L_w}{\dot{M}}}$
- Termination shock radius: $R_{TS} = \sqrt{\frac{(3850\pi)^{\frac{2}{5}}}{28\pi}\, \dot{M}^{\frac{1}{2}}\, v_w^{\frac{1}{2}} L_w^{-\frac{1}{5}} n_0^{-\frac{3}{10}} t^{\frac{2}{5}}}$
- Forward shock radius: $R_b = \left(\frac{125}{154\pi}\right)^{\frac{1}{5}}\, \mathrm{L}_\mathrm{w}^{\frac{1}{5}}\, n_0^{-\frac{1}{5}}\, t^{\frac{3}{5}}$
- Maximum energy of protons is highly diffusion regime dependant: $E_{max}(\eta_b, L_w, n_0, L_{inj}, age, \dot{M})$

Gamma rays from single cluster

$$\Theta_\gamma(E_\gamma) = \frac{c n_H}{4\pi d^2} \int F_{CR}(E_p) \frac{d\sigma(E_p, E_\gamma)}{dE_p} dE_p$$

$$F_{CR}(E_p) = 4\pi \int_0^{R_{b,i}} r^2 f_{CR}(r, E_p) dr$$

$$f_{CR} = \begin{cases} f_{TS}(p) \exp\left[-\int_r^{R_{TS}} \frac{v_w}{D_1(r', p)} dr'\right] & r \leq R_{TS} \\ f_{TS}(p) e^{\alpha \frac{1+\beta(e^{\alpha_B - \alpha} - 1)}{1+\beta(e^{\alpha_B} - 1)}} & R_{TS} \leq r \leq R_b \\ f_{TS}(p) \frac{e^{\alpha_B}}{1+\beta(e^{\alpha_B} - 1)} \frac{R_b}{r} & r \geq R_b \end{cases}$$

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

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

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

$$f_{TS}(x) \simeq \frac{3 n_1 \mu_1^2 \epsilon_{CR}}{4\pi \Lambda_p \left(m_p c\right)^3 c^2} (x)^{-s} \left[1 + a_1 \left(\frac{p}{p_{max}}\right)^{a_2}\right] e^{-a_3 (p/p_{max})^{a_4}}$$

$$x = \frac{p}{m_p c}$$

$$\Lambda_p = \int_{x_{inj}}^{\infty} x^{2-s} e^{-\Gamma(x)} \left(\sqrt{1+x^2} - 1\right) dx \quad e^{\Gamma(p)} \simeq \left[1 + a_1 \left(\frac{p}{p_{\max}}\right)^{a_2}\right] e^{-a_3 (p/p_{\max})^{a_4}}$$

Maximum energy

- Bohm: $10\left(\frac{\eta_B}{0.1}\right)^{\frac{1}{2}}\left(\frac{\dot{M}}{10^{-4}M_{\odot}\,yr^{-1}}\right)^{-\frac{1}{4}}\left(\frac{L_w}{10^{39}\,erg\,s^{-1}}\right)^{\frac{3}{4}}$ PeV
- Kraichnan:

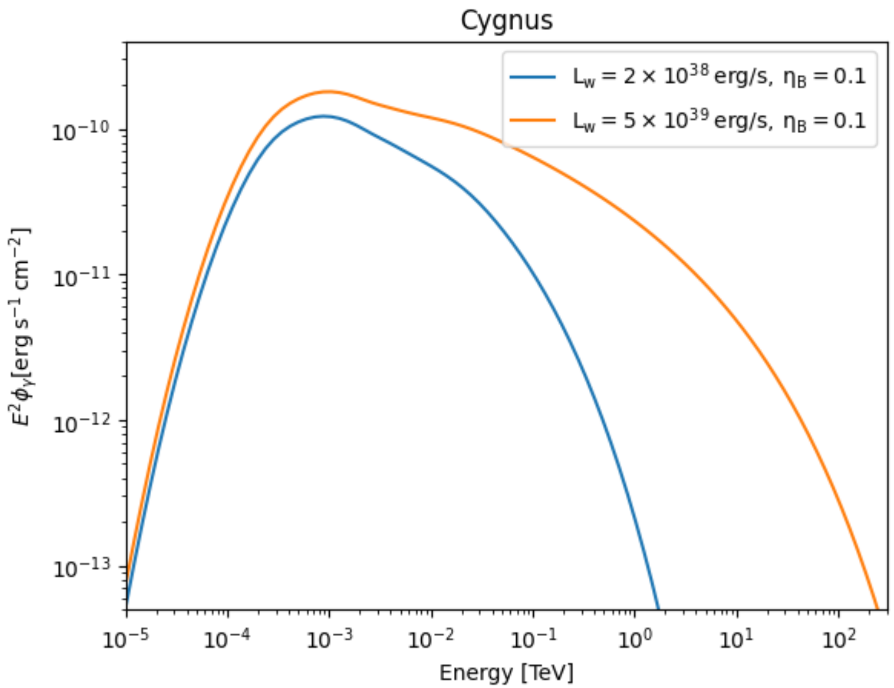
$$2.84\left(\frac{\eta_B}{0.1}\right)^{\frac{1}{2}}\left(\frac{\dot{M}}{10^{-4}M_{\odot}\,yr^{-1}}\right)^{-\frac{5}{10}}\left(\frac{L_w}{10^{39}\,erg\,s^{-1}}\right)^{\frac{13}{10}}\left(\frac{\rho_0}{20\,m_p\,cm^{-3}}\right)^{-\frac{3}{10}}\left(\frac{t_{age}}{3\,Myr}\right)^{\frac{2}{5}}\left(\frac{L_{inj}}{2pc}\right)^{-1}\text{ PeV}$$

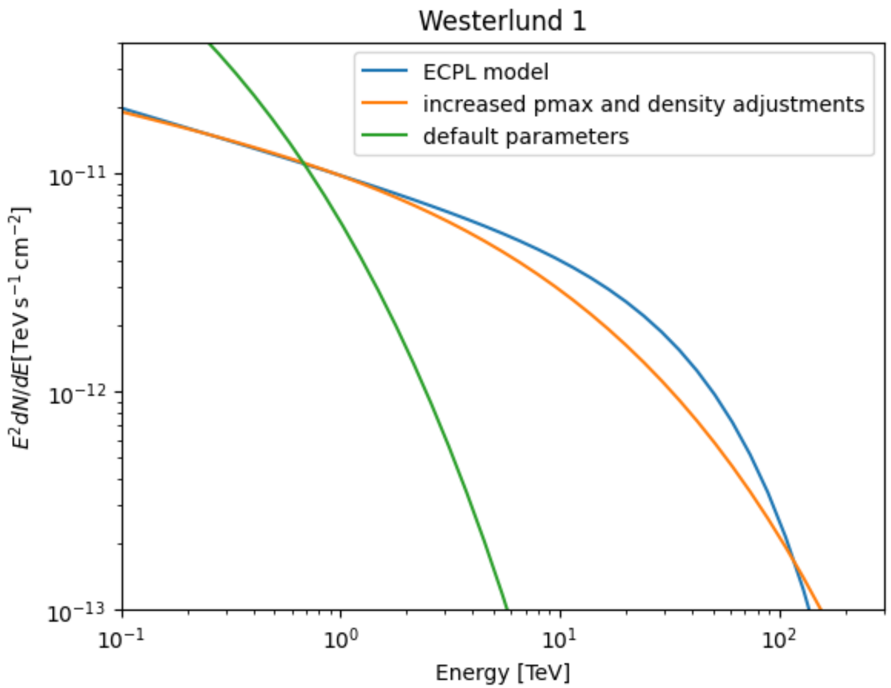
- Kolmogorov:

$$1.2\left(\frac{\eta_B}{0.1}\right)^{\frac{1}{2}}\left(\frac{\dot{M}}{10^{-4}M_{\odot}\,yr^{-1}}\right)^{-\frac{3}{4}}\left(\frac{L_w}{10^{39}\,erg\,s^{-1}}\right)^{\frac{37}{20}}\left(\frac{\rho_0}{20\,m_p\,cm^{-3}}\right)^{-\frac{3}{5}}\left(\frac{t_{age}}{3\,Myr}\right)^{\frac{4}{5}}\left(\frac{L_{inj}}{2pc}\right)^{-2}\text{ PeV}$$

Mathematisch-Naturwissenschaftliche Fakultät

Cygnus and Westerlund 1



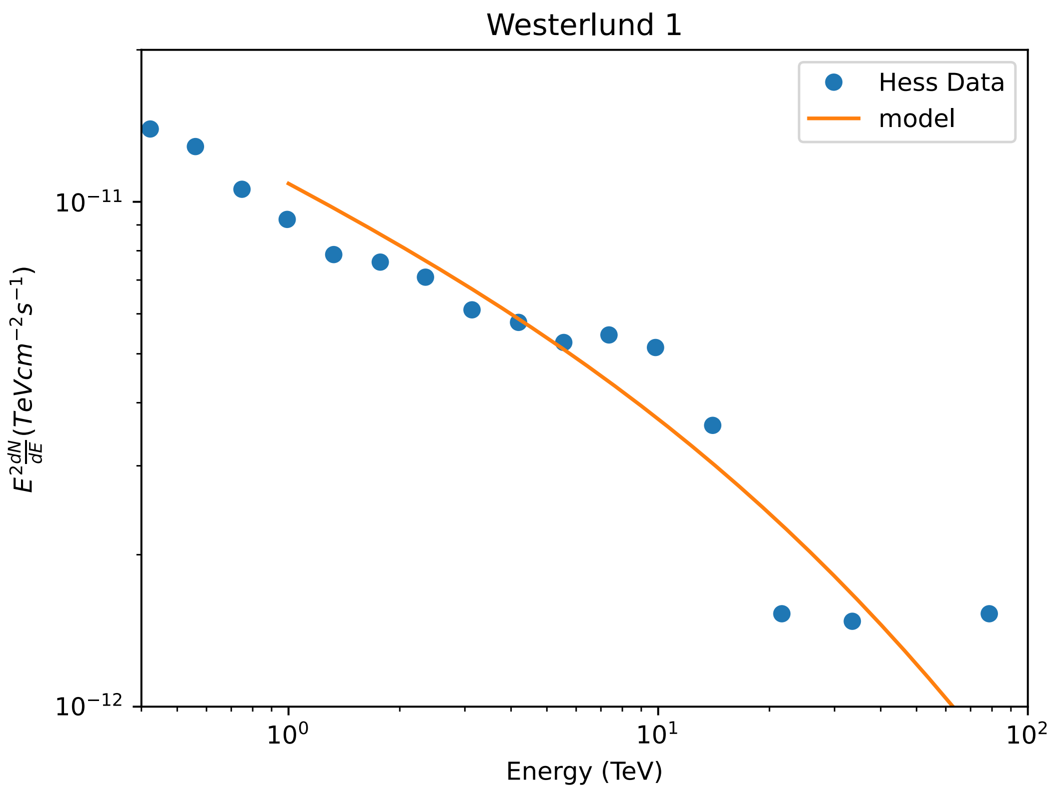


Mathematisch-Naturwissenschaftliche Fakultät

Westerlund 1

- Rts = 15pc expected ~20-60pc
- Rb = 102pc expected ~60-180

- parameters for plot:
  - alpha = 4.4
  - eta_cr = 0.001
  - nH = 7 cm^-3
  - $\dot{M} = 5\times10^{-4}\, M_\odot\, yr^{-1}$
  - $L_w = 10^{39} erg\ s^{-1}$
  - diffusion regime = Bohm
  - nb = 0.1
  - distance – 3.9



Distribution of clusters

Properties required:

- Number
- Position
- age
- $\dot{M}$
- L_w

Number of clusters in the Milky way

- $N_{SC} = \int_{M_{\min}}^{M_{\max}} \int_{t_{\min}}^{t_{\max}} \int_{0}^{R_{MW}} f(M)\, \nu(t)\, \rho(r,\theta)\, r\, dr\, d\theta\, dt\, dM$
- f(M) - mass distribution
- $\nu(t)$ - formation rate
- $\rho(r,\theta)$ - spatial distribution

Mass distribution

- $f(M) = \frac{dN}{dM} = \begin{cases} k_1 M^{-(x_1+1)} \text{ for } \mathrm{M}_{\min} \leq M \leq M_b \\ k_2 M^{-(x_2+1)} \text{ for } M_b \leq M \leq M_{\max} \end{cases}$
- $x_1 = 0.39$
- $x_2 = 0.54$
- $M_b = 100\ M_\odot$
- $M_{\max} = 6.3 \times 10^4 M_\odot$ and $M_{\min} = 2.3\ M_\odot$
- $\int_{M_{\min}}^{M_{\max}} f(M) dM = 1$

Formation rate

- $\nu(t) = A + B\,\exp\left(\mathrm{C}\,\frac{\mathrm{T_p} - \mathrm{T_f}}{T_p}\right)\ \mathrm{Myr}^{-1}\ \mathrm{kpc}^{-2}$
- Tp = 4.8 Gyr – present time
- A = -0.55
- B = 0.57
- C = 1

Age distribution

- Interpolate based on the known clusters within 2 kpc
- Piskunov et al. 2018

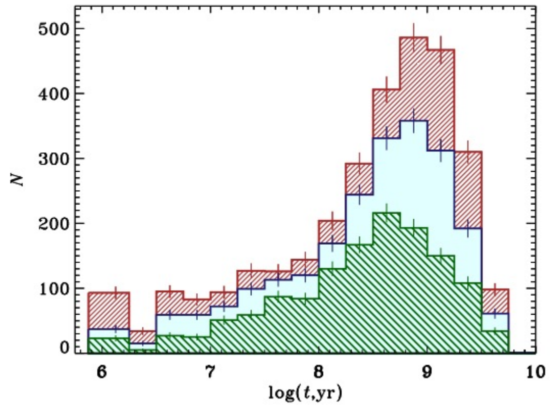


Fig. 1. Distribution of MWSC clusters with age. The total sample is shown with a background (brown) hatched histogram, clusters within individual completeness limits are shown with an intermediate (blue) filled histogram, and those within the general completeness circle are shown with a foreground (green) back-hatched histogram. The vertical bars show Poisson errors.

Stellar masses inside cluster

$$f_\star(M_\star) \propto \frac{dN_\star}{dM_\star} = \begin{cases} M_{star}^{-0.3} & \text{for } M_\star < 0.08 M_\odot \\ 0.08 M_\star^{-1.3} & \text{for } 0.08 M_\odot \le M_\star \le 0.05 M_\odot \\ 0.04 M_\star^{-2.3} & \text{for } M_\star > 0.5 M_\odot \end{cases}$$

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

$M_{\star,min} = 0.08\ M_\odot \quad M_{\star,max} = 150\ M_\odot$

Luminosity and $\dot{M}$

$$L_\star = \begin{cases} L_{b1}\left(\frac{M_\star}{M_{b1}}\right)^{\alpha_1}\left[\frac{1}{2}+\frac{1}{2}\left(\frac{M_\star}{M_{b1}}\right)^{1/\triangle_1}\right]^{(-\alpha_1+\alpha_2)\triangle_1} & \text{for } 2.4 \leq \frac{\mathrm{M}_\star}{\mathrm{M}_\odot} \leq 12 \\ \kappa L_{b2}\left(\frac{M_\star}{M_{b2}}\right)^{\alpha_2}\left[\frac{1}{2}+\frac{1}{2}\left(\frac{M_\star}{M_{b2}}\right)^{1/\triangle_2}\right]^{(-\alpha_2+\alpha_3)\triangle_2} & \text{for } \frac{\mathrm{M}_\star}{\mathrm{M}_\odot} \geq 12 \end{cases}$$

$L_{b1} = 3191\, L_\odot$, $L_{b2} = 368874\, L_\odot$, $M_{b1} = 7\, M_\odot$, $M_{b2} = 36.089\, M_\odot$, $\alpha_1 = 3.97$, $\alpha_2 = 2.86$, $\alpha_3 = 1.34$

$\triangle_1 = 0.01$, $\triangle_2 = 0.15$, $\kappa = 0.817$

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

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