High angular resolution study of the Super Stellar Cluster population in IRAS 17138-1017

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Super Star Cluster

Super Star Clusters (SSCs), or Young Massive Clusters (YMCs):

- Young (<100 Myr), massive ($\gtrsim 10^4$ $M_\odot$), compact ($\gtrsim 10^3$ $M_\odot$ pc^{-3} at core)
- Often found in interacting galaxies, especially (ultra) luminous infrared galaxies ((U)LIRGs; $\log(L_{IR}/L_\odot) > 11$)
- Manifestation of extreme star formation (>1000 SFR_{MW})
- First stage enshrouded in dust, prominent in infrared
- Remain poorly understood due to large distance to ULIRGs (~10^2 Mpc)

Nearby SSC analogue R136 - HST

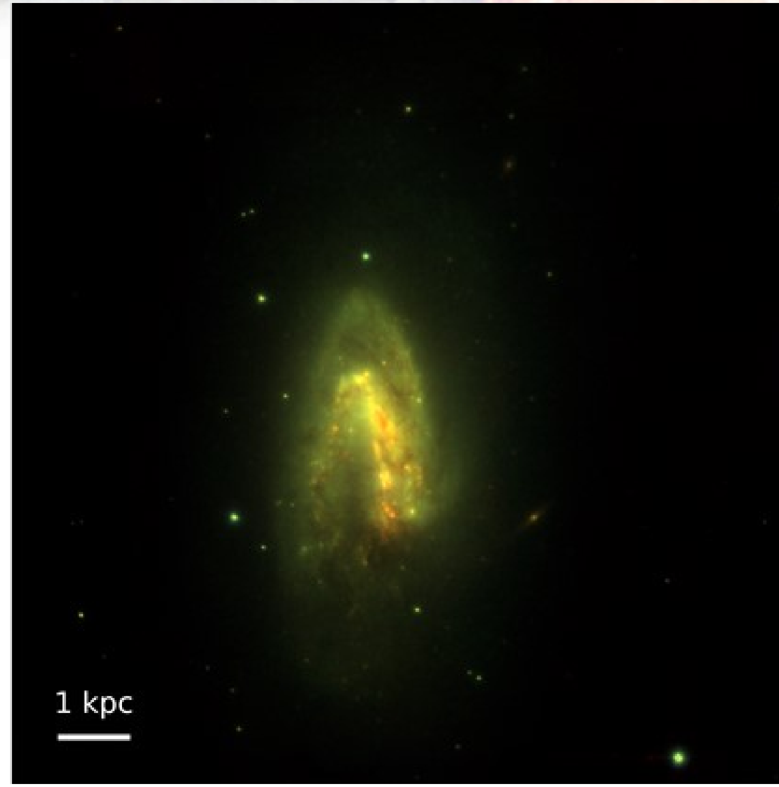
- Adaptive optics (AO) or space telescope (e.g. JWST) required to resolve
- Open questions:

what are their global characteristics: mass function, luminosity function, stellar content, dust content, gas content and dynamics, supernovae rate…, whether they are precursors to globular clusters

IRAS 17138-1017

- A highly obscured starburst LIRG in a late stage of interaction ($\log(L_{IR}/L_{\odot})$=11.42, D_L=75.9 Mpc)
- Imaging data in J, H and K_S band obtained using Gemini Multi-Conjugate Adaptive Optics System (GeMS)/ Gemini South Adaptive Optics Imager (GSAOI) (pixel scale 0.02")
- Source extraction and PSF photometry:

StarFinder, an IDL code developed for the analysis of crowded fields in AO images (Diolaiti et al. 2000)



- Cluster selection:

Cross-matching 3 bands, comparison with a nearby control field, star count from Besançon model (Robin et al. 2003), GalaxyCount (Ellis & Bland-Hawthorn 2007) and visual inspection

⇒ 66 SSC candidates detected

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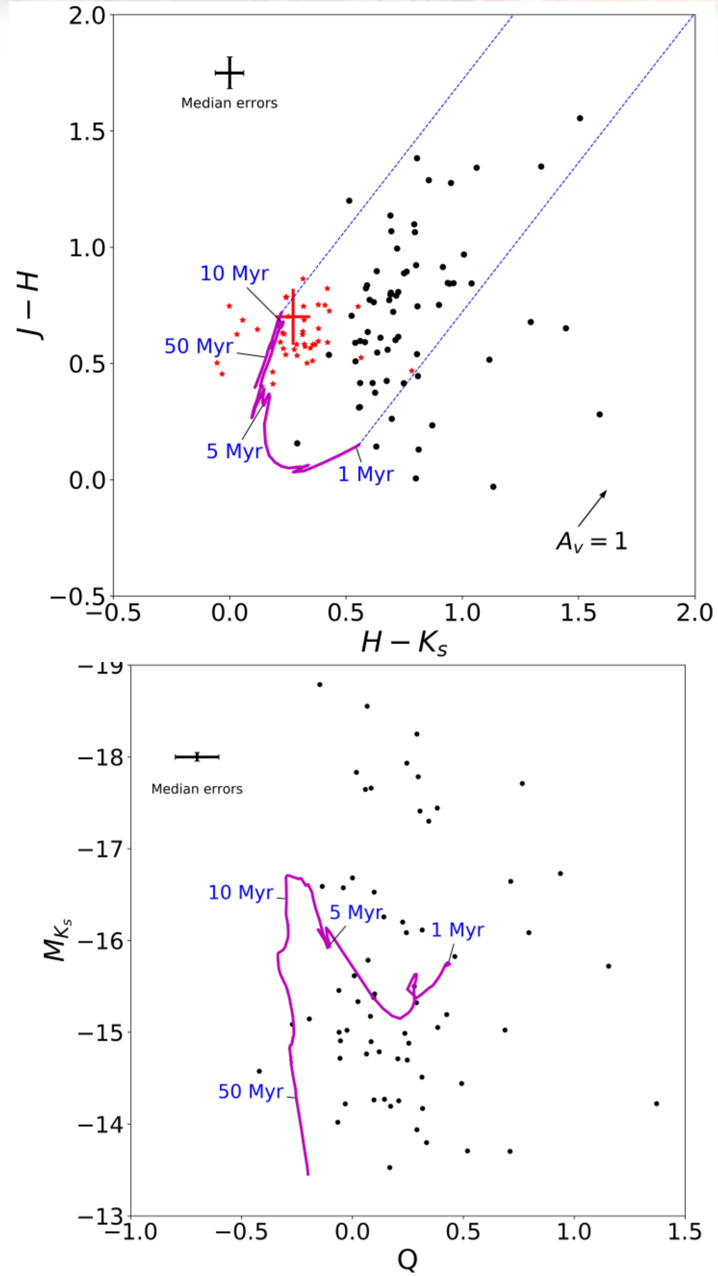
Color - Color/Magnitude Diagram

- Starburst99 (Leitherer et al. 1999, 2014) evolutionary synthesis model (∿):

Simple stellar population (SSP) 10^6 $M_\odot$, Kroupa (2008) IMF 0.1 $M_\odot$ –100 $M_\odot$, solar metallicity (Z = 0.014), instantaneous burst, stellar and nebular emission

- Sources detected in the control field (⋆)
- Average colors and standard deviations of 2MASS galaxies (Jarrett et al. 2003) (†)
- Calzetti et al. (2000) extinction law for starburst galaxy (↗): R_V = 4.05
- Reddening-independent color index Q = $(H - K_S) \times E(H - K_S)/E(J - H) \times (J - H)$
- Most of SSCs (•) are very young (< 5 Myr)
- Age-reddening degeneracy occurs at evolved ages
- Some outliers could not be explained by the evolutionary model



Color and SED Fitting

- Color fitting: minimize the quantity to derive age τ, extinction A_V (mass M derived from Starburst99 M/L)

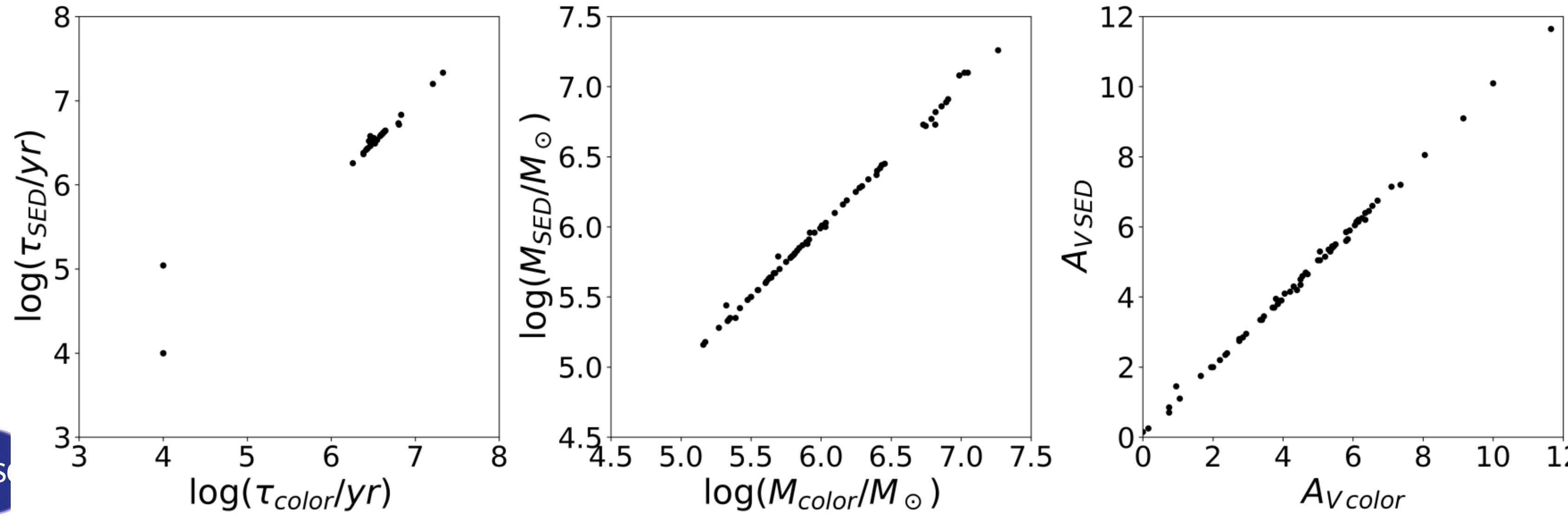
$$\chi^2(\tau, A_V) = \sum_{C=J-H, H-K_S} \frac{(C_{obs} - C_{SB99})^2}{{\sigma_C}^2}$$

- SED fitting: minimize the quantity to derive age τ, extinction A_V and mass M

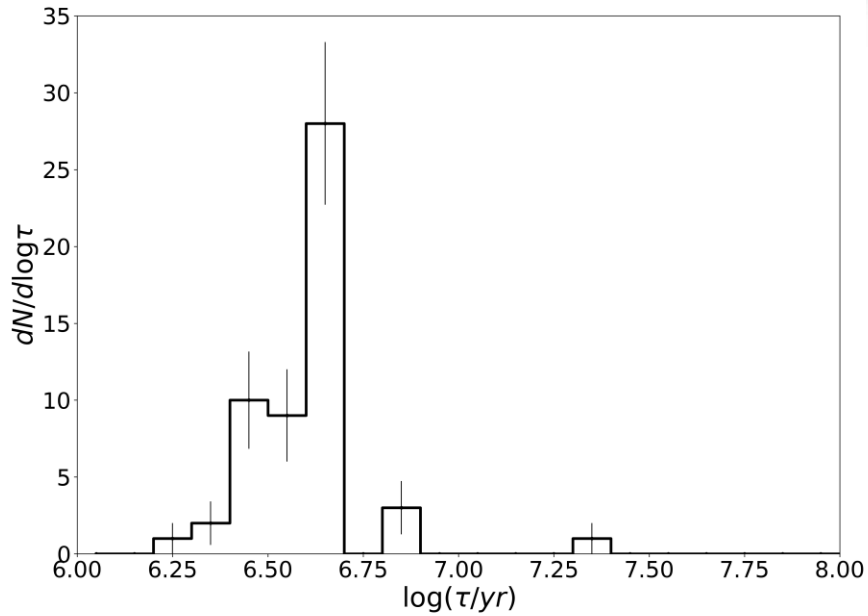
$$\chi^2(\tau, A_V, M) = \sum_{\lambda=J,H,K_S} \frac{\left(m_{obs,\lambda} - m_{SB99,\lambda} + 2.5 \log \frac{M}{10^6}\right)^2}{{\sigma_\lambda}^2}$$

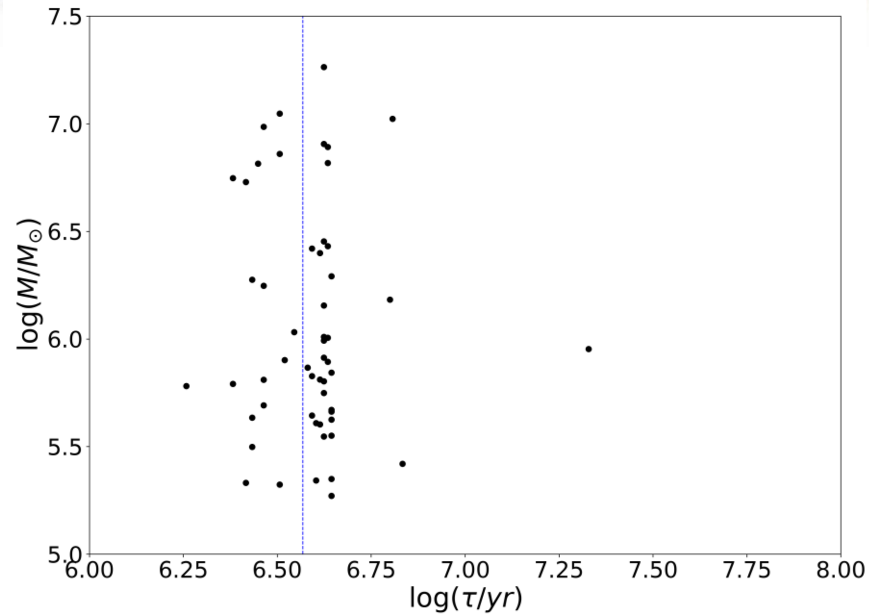
- Two methods provide consistent results, excluding an outlier

⇒ 54 SSC candidates left



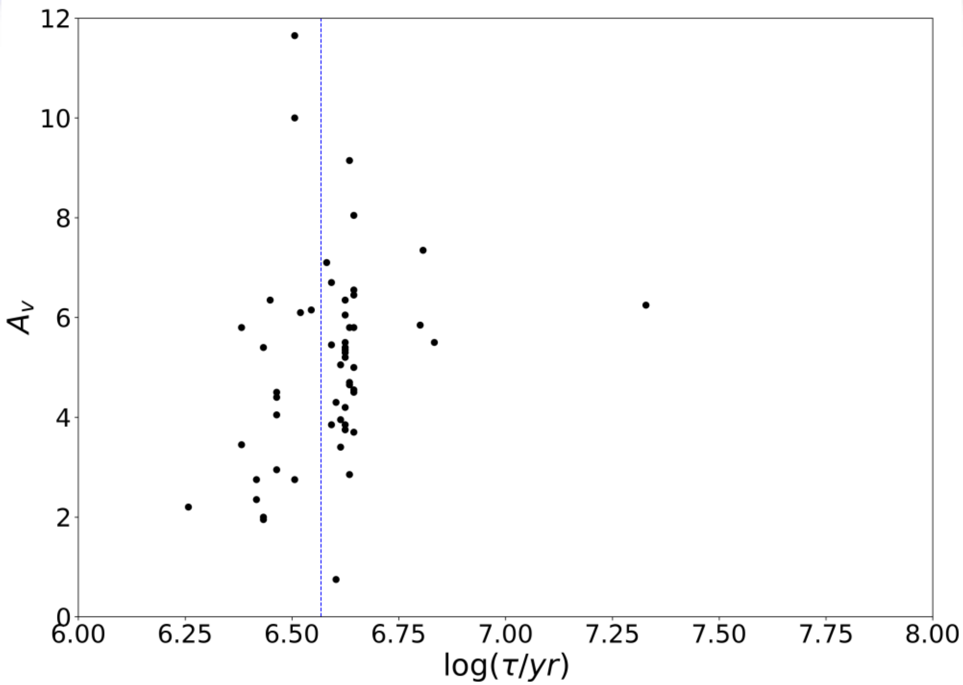
Age Distribution and Star Formation History

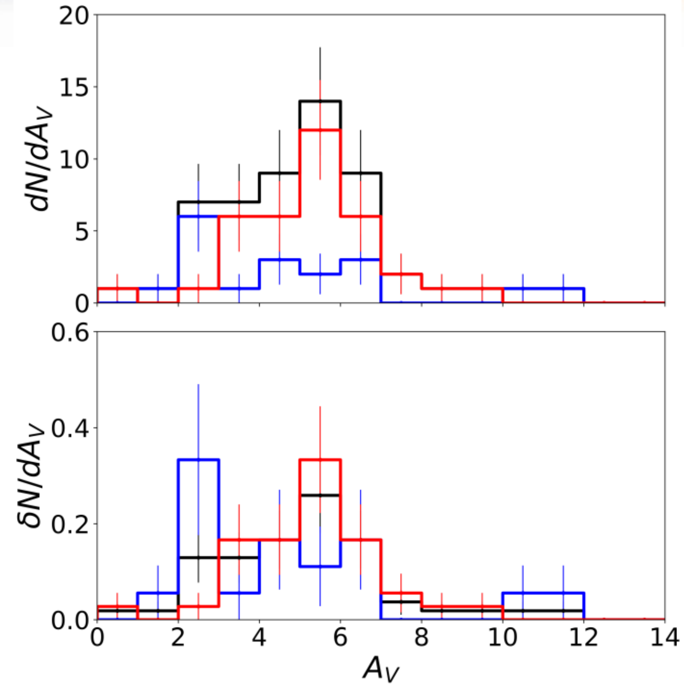




- Age distribution reveals 2 clear peaks at τ = 2.8 and 4.5 Myr
- Cluster disrupts over time due to interaction with giant molecular clouds in their vicinity, given high surface density of IRAS 17138-1017
- Cluster formation efficiency Γ = CFR/SFR = $(\Sigma M_{cluster}/\Delta\tau)$/SFR ≈ 33.4% for τ = 1 – 10 Myr as expected for starburst galaxies and Kruijssen (2012) $\Gamma - \Sigma_{SFR}$ relation, assuming Σ_{SFR} = 89 $M_{\odot}$ yr^{-1} kpc^{2} (Piqueras López et al. 2016)
- Lower Γ= 17% for τ =10 – 100 Myr (Randriamanakoto 2015) suggests *infant mortality*: rapid disruption during the first 10 Myr due to gas expulsion

Extinction





- Frequency distribution of the extinction (right): whole sample (black), 2.8 Myr burst (blue), 4.5 Myr burst (red). Top: absolute numbers. Bottom: relative numbers. Error bars assume Poisson uncertainties
- 2.8 Myr burst has less extinct SSCs than 4.5 Myr burst, despite hosting 2 most extinct ones
- First burst has consumed/expelled a part of the interstellar medium (ISM) or triggered the second one in a less dense component of the giant molecular cloud (GMC)

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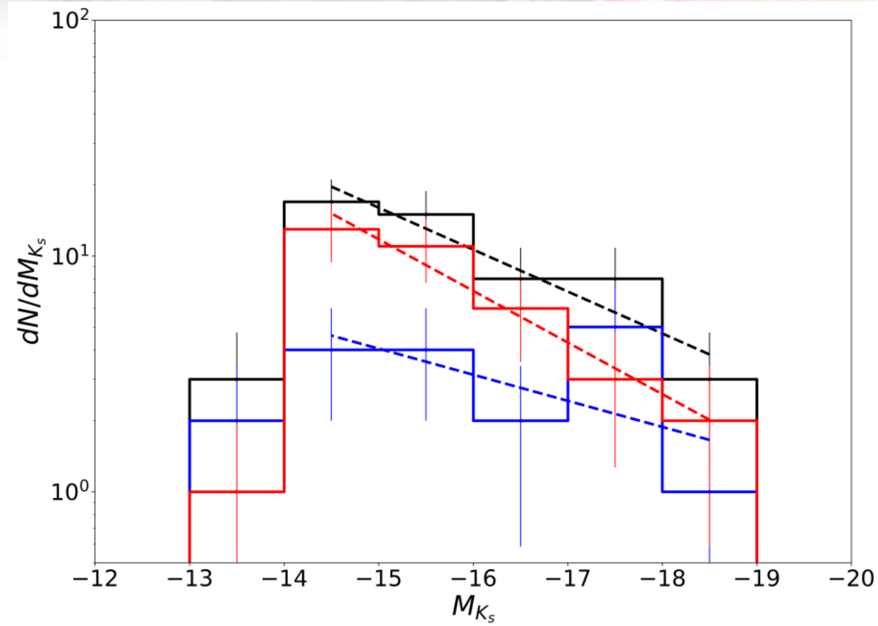
Cluster Luminosity Function

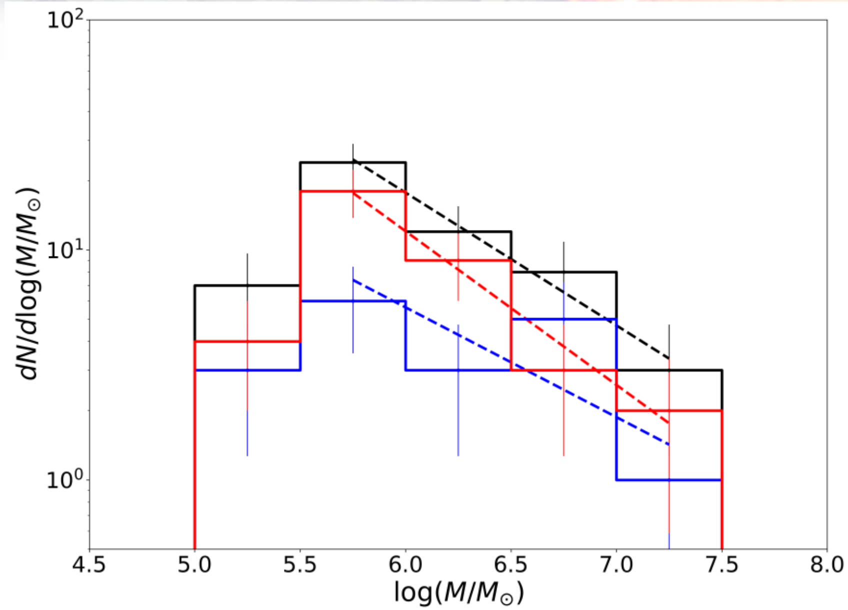
- Luminosity function for the entire sample (black), $\tau \leq 3.7$ Myr (blue), $\tau > 3.7$ Myr (red) plotted. Red and black dash lines correspond to linear regressions ($dN/dL \propto L^{\alpha}$). Error bars assume Poisson uncertainties
- $\alpha = -1.44$ (entire sample),

$\alpha=-1.28$ ($\tau\leq3.7$ Myr), $\alpha=-1.55$ ($\tau>3.7$Myr)



- In the lower end of $\alpha \approx -1.87\pm0.3$ for SSCs in (U)LIRGs (Randriamanakoto et al 2013, Vavilkin 2011, Miralles-Caballero et al. 2011, Adamo et al. 2010, 2011)
- Flatter than $\alpha \approx -2.2\pm0.3$ for spiral or non-LIRG star forming galaxies (Elmegreen & Efremov 1997, Gieles et al. 2006, Bastian 2008, Haas et al. 2008 and Larsen 2009)
- In case of IRAS 17138-1017, without dereddening α=-1.57 close to -1.53 and -1.64 for constant and variable bin widths respectively (Randriamanakoto et al. 2013b)

Cluster Mass Function

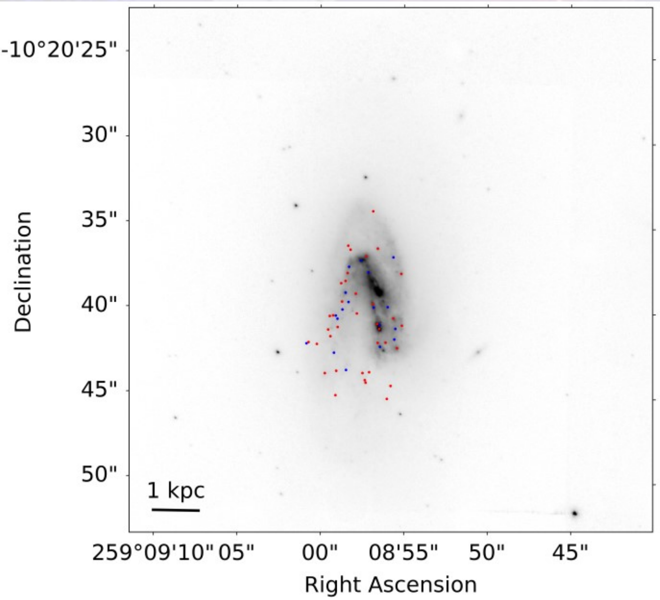


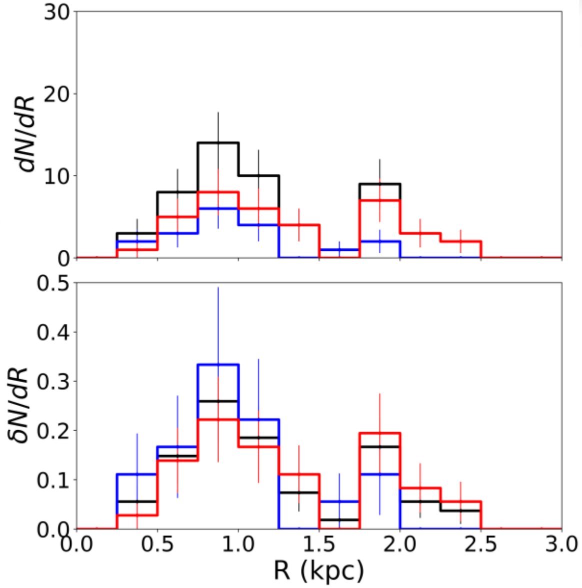
- Mass function for the entire sample (black), $\tau \leq 3.7$ Myr (blue), $\tau > 3.7$ Myr (red) plotted. Red and black dash lines correspond to linear regressions ($dN/dM \propto M^{\beta}$). Error bars assume Poisson uncertainties
- β = -1.58 (entire sample),

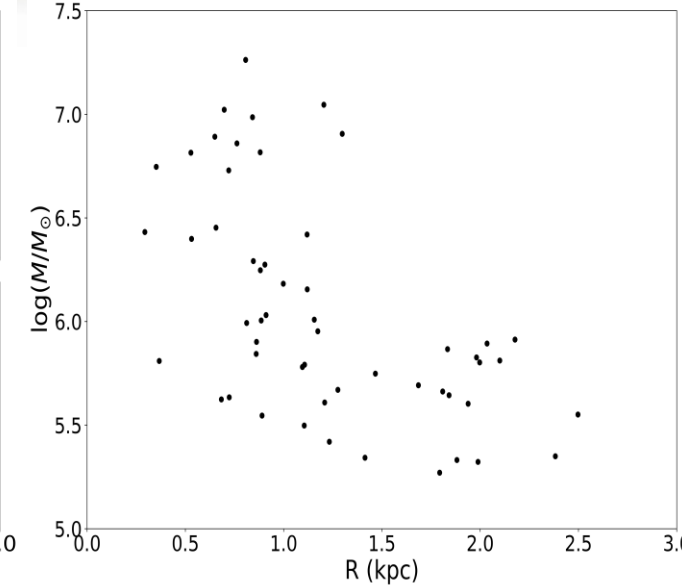
β=-1.48 ($\tau \leq 3.7$ Myr), β=-1.67 ($\tau > 3.7$Myr)

- Much shallower than the canonical $\beta \approx -2$ found in the literature (Krumholz et al. 2019)
- Shallower than $\beta = -1.95 \pm 0.11$ but nevertheless fall in the observed range for LIRGs in the GOALS survey (Linden et al. 2017)
- Randriamanakoto (2015) finds values of β = -1.86 and 1.61 for SSCs in IRAS 17138-1017 with $\tau < 3.5$ Myr and 30 Myr $\leq \tau <$ 1 Gyr respectively, but suffering from cluster mass overestimation and age-extinction degeneracy in BIK_S bands
- Flatter cluster mass function may originate from blending effect or *cruel craddle effect*: disruption of lower mass SSCs due to tidal shock heating

Spatial Distribution







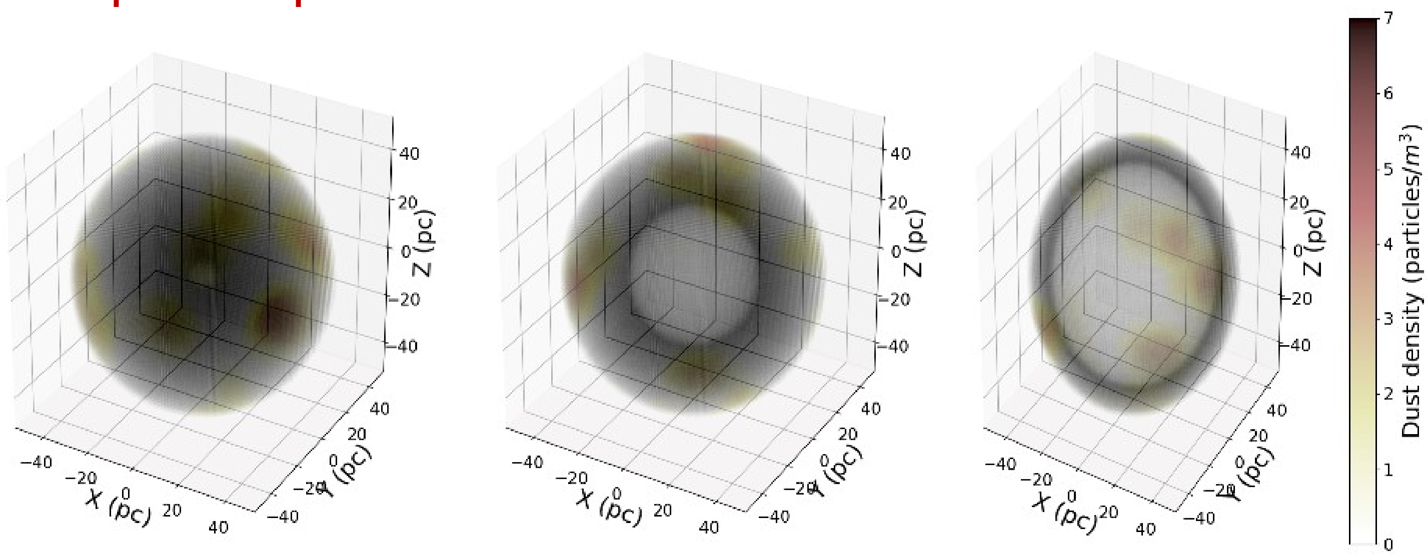
- Locations of the SSCs on the K_S image (left): $\tau \leq 3.7$ Myr(blue), $\tau > 3.7$ Myr (red)
- Number of SSCs per ring of increasing diameter centered on the nucleus (middle): the whole sample (black), 2.8 Myr burst (blue), 4.5 Myr burst (red). Top: absolute numbers. Bottom: relative numbers. Error bars assume Poisson uncertainties
- Youngers burst populates around central region rather than peripheral one
- *Cruel craddle effect*: older clusters survive by escaping into more quiescent regions, only young clusters exist in gas-rich environment
- Cluster mass decreases over galactocentric distance (right) $\Rightarrow$ environment-dependent cluster formation as Γ and Σ_{SFR} decrease radially

Modelling SSCs with MontAGN

- Dereddening using Calzetti et al. (2000) extinction law not applicable for some outliers
- Starburst99 evolutionary model considers stellar and nebular emission only
- Possible contribution of thermal emission from hot dust cocoon and scattered radiation in clumpy medium
- MontAGN (Monte Carlo for Active Galactic Nuclei) is a radiative transfer code written in Python 2.7
- Photons propagated in form of packets with polarisation, scattering, absorption, optional thermal re-emission and temperature update
- Simulations can also be launched in parallel on clusters of processors
- Highly versatile but initially optimised for simulations of AGN in the near-infrared
- Polycyclic aromatic hydrocarbons (PAHs) and fractal structuration added for SSC simulations

Model Description

- Central point source: Starburst99 simple stellar population (SSP) 10^6 $M_\odot$, Kroupa (2008) IMF 0.1 $M_\odot$ –100 $M_\odot$, solar metallicity (Z = 0.014), instantaneous burst, stellar and nebular emission
- Hierarchically clumped dust shell (Elmegreen 1997): 50% clumpy apart from smooth dust distribution, R_{in} = 5 pc – 40pc, R_{out} = 50 pc resembling cluster evolution, H = 5 hierarchical levels, N = 32 positions per level and fractal dimension D = 2.6, standard dust-to-gas ratio 0.01 (Whelan et al 2011), SFE = 33% (Banerjee & Kroupa 2017)
- Dust composition: 75% silicate, 13.33% ortho-graphite, 6.67% para-graphite and 5% PAH (Draine 2011)
- 10 000 000 photon packets launched for each simulation



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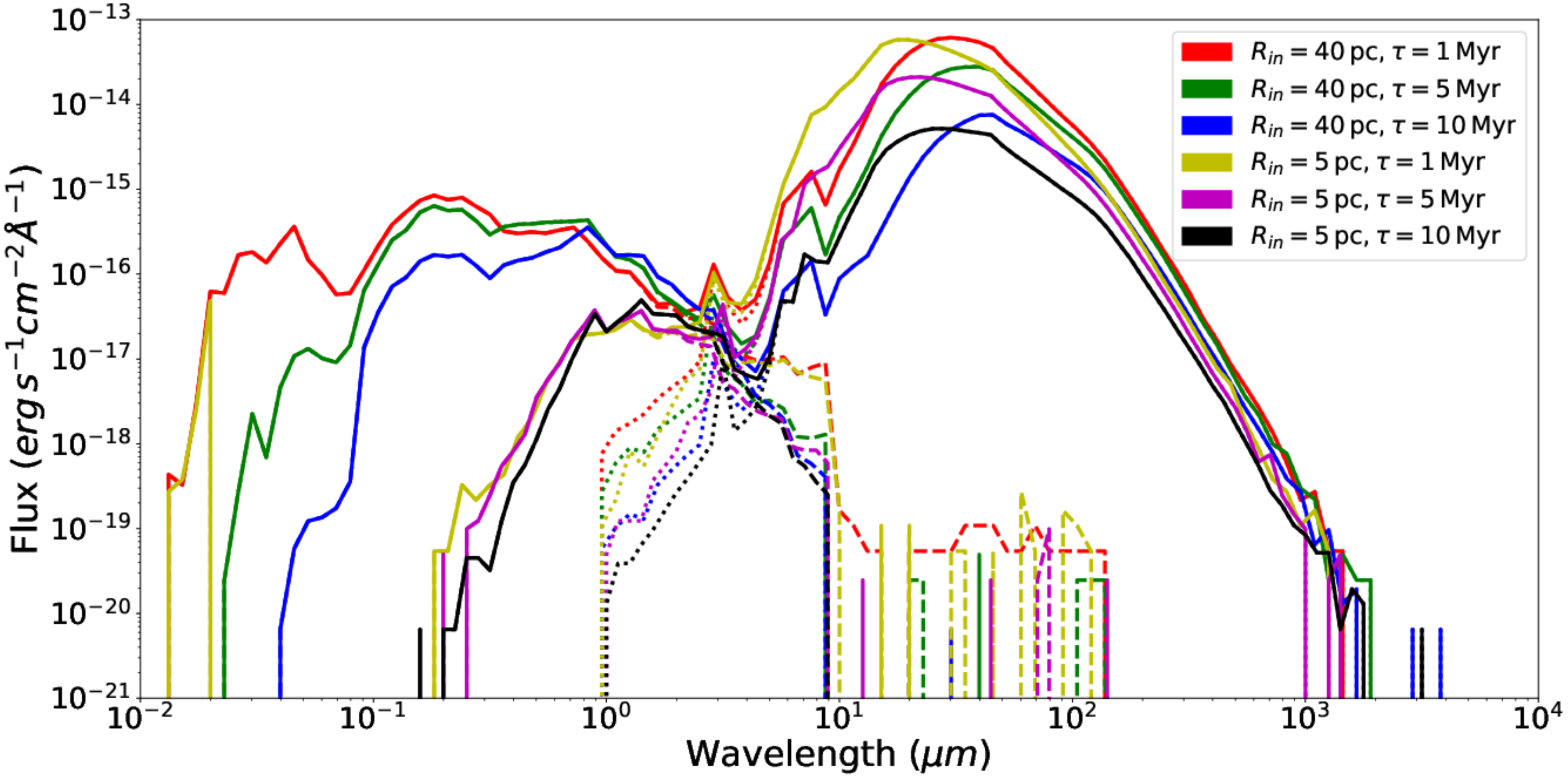
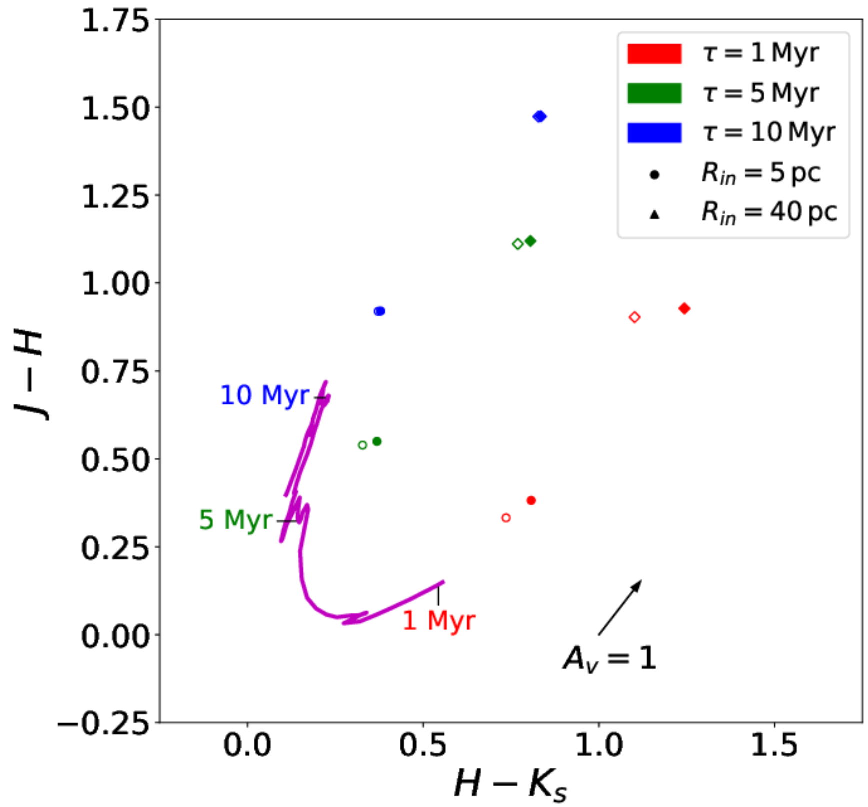
Simulated Spectral Energy Distribution



- Spectral energy distributions obtained with MontAGN for various sets of age τ and inner radius R_{in} of the cavity: total flux (–), dust emission (---), stellar emission (···)
- At 2μm thermal emission can play a very significant role
- Thin envelope models leak out significant star light, much brighter in the visible than NIR $\Rightarrow$ not the case of IRAS 17138-1017

Simulated Color-Color Diagram

- Color-color diagram of the simulated SSCs with various conditions of age τ and inner radius R_{in} of the cavity plotted with Starburst99 evolutionary track (∿) and Calzetti et al. (2000) reddening vector (↗). Empty (∘) and filled (•) circles represent stellar emission and total SED respectively
- Several points could not be deredenned by shifting along the reddening vector
- Significant contribution of thermal emission at $\tau \leq 5$ Myr
- Scattered light produces only a very small additional reddening



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Conclusions

- 54 SSCs in IRAS 17138-1017 identified from J, H and K_S GeMS/GSAOI images at high resolution
- Most of the clusters are very extinct and very young, distributed in two narrow age bins of 2.8 and 4.5 Myr
- Cluster luminosity and mass function follow classical power-law behavior but flatter than observed LIRGs, possibly indicating *cruel craddle effect*: lower mass SSCs produced less efficiently in very high surface density GMCs
- SSCs of youngest starburst gather in the central area, while older clusters are distributed along the spiral arms
- 4.5 Myr burst is more extinct than the 2.8 Myr burst $\Rightarrow$ distinct episodes, causes and GMCs
- Radiative transfer models of SSCs reveal non-negligible contribution of hot dust emission in K_S band

Merci pour votre attention!