Class 12: Stellar clustering

ASTR 4008 / 8008, Semester 2, 2020

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Opening note: this is an area where a lot has changed since the textbook was written; most of this lecture is based on the review Krumholz, McKee, & Bland-Hawthorn (2019, ARA&A)

Outline

- Cluster demographics
  - Clustering as a function of stellar age
  - Mass, age, and density distributions
  - Bound mass fraction
- Cluster formation
  - Gas, stars, and their relationship
  - Feedback and termination of star formation
- Origins of cluster demographics
  - Mass distribution
  - Age distribution and bound fraction

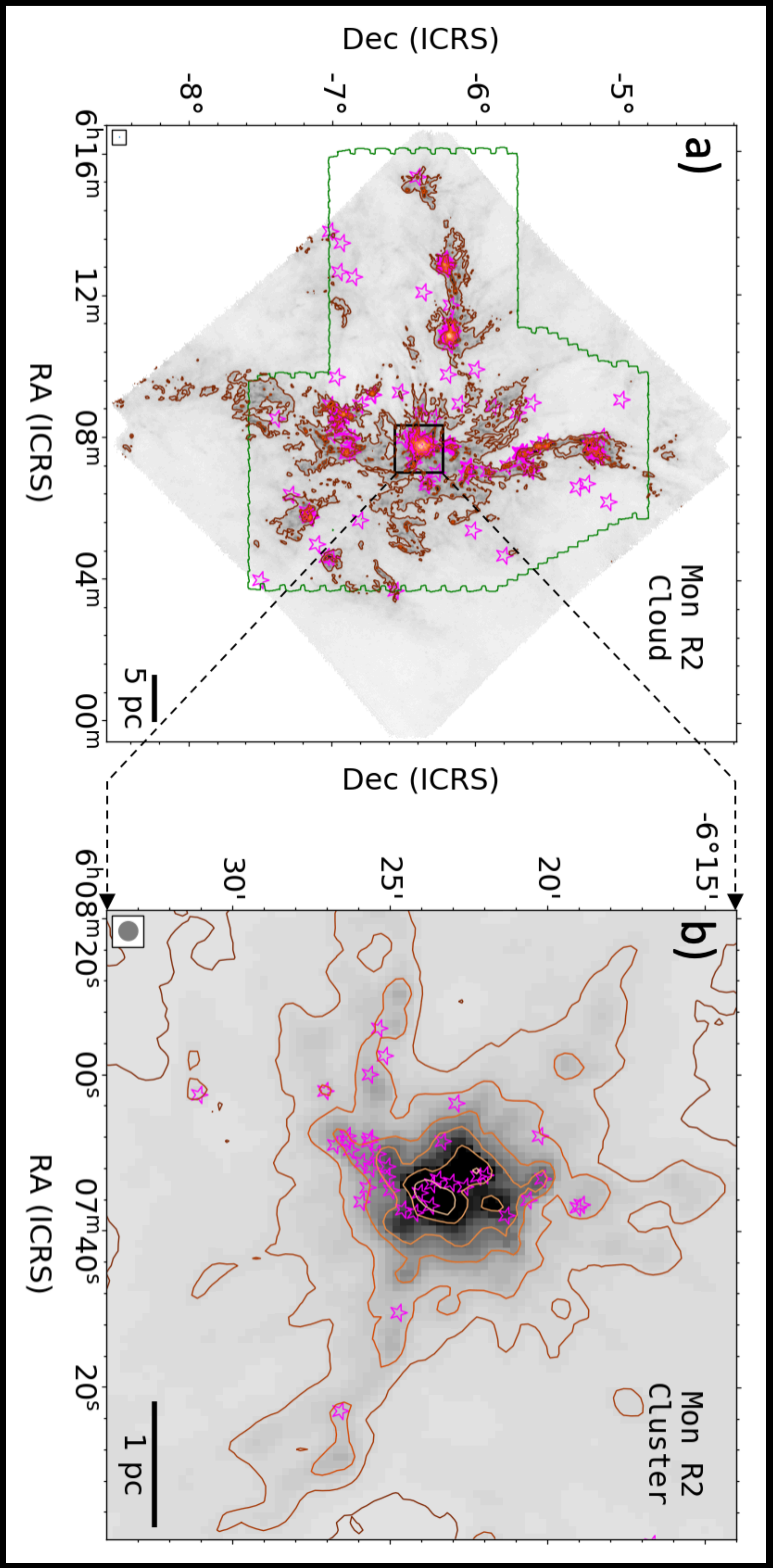
Opening clarification on terminology

- We are focusing in this class on clusters found in the planes of modern-day galaxies, not globular clusters, which form at high redshift and are found in galactic halos today
- Groups of stars in the planes of galaxies go by lots of different names: “open clusters”, “associations”, “young massive clusters”, “rich clusters”, etc. — historically this has caused a great deal of confusion
- We will try to avoid this by being clear in our terminology, and avoiding vague distinctions that are not physical in origin, but, beware when you encounter these terms in the literature — not everyone does this, and not everyone means the same thing when they say “star cluster”!

Clustering of stars

Basic considerations

- Mean stellar density in Solar neighbourhood ~ 0.04 $M_\odot$ pc^{-3} ~ 1 H cm^{-3} ≪ ~10 $M_\odot$ pc^{-3} density in GMCs
- Tidal density ~1 $M_\odot$ pc^{-3}: structures less dense than this will be pulled apart by Galactic tides
- Most stars not in clusters above tidal density
- Density of ~1 Myr old stars substantially larger: ~ 10^2 $M_\odot$ pc^{-3}, depending on spatial averaging scale
- Implication: stars are born “clustered”, but clustering / density must drop precipitously post-formation



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Clustering of stars

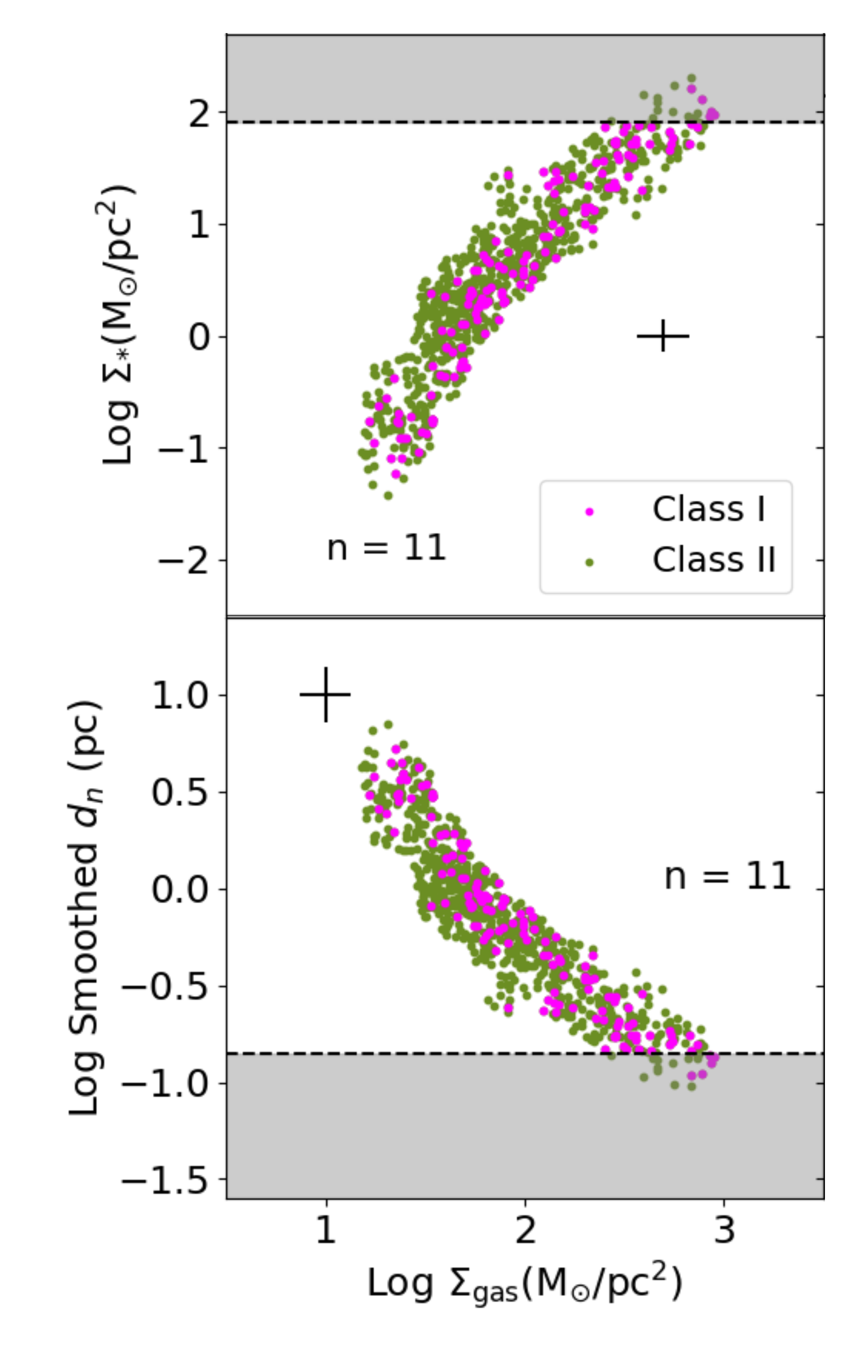
Basic considerations II

- Density ~100 $M_\odot$ pc^{-3} → crossing time ~few Myr
- Implication: systems $\lesssim$ 10 Myr old will not be dynamically relaxed
  - Bound stars will not have reached energy equilibrium / equipartition, so do not expect round, smooth structures
  - Unbound stars will not have had time to disperse, and so might appear to be clustered even if unbound
- For this reason it makes sense to divide stellar populations up into dynamically “young” and “old”, and analyse them somewhat differently

Clustering of young stars

Ages ≲ 2 Myr

- Characterise young stellar distributions in several possible ways:
    - 2-point correlation function $\xi(r)$, defined by $dP/dA = N\,[1 + \xi(r)]$: excess probability of finding star at distance r from existing star
    - distance to nth nearest neighbour d_n and equivalent surface density $N_n = (n-1) / \pi d_n^2$
- General result: density falls off as a power law away from densest stars, well-correlated with local gas density; no obvious breaks



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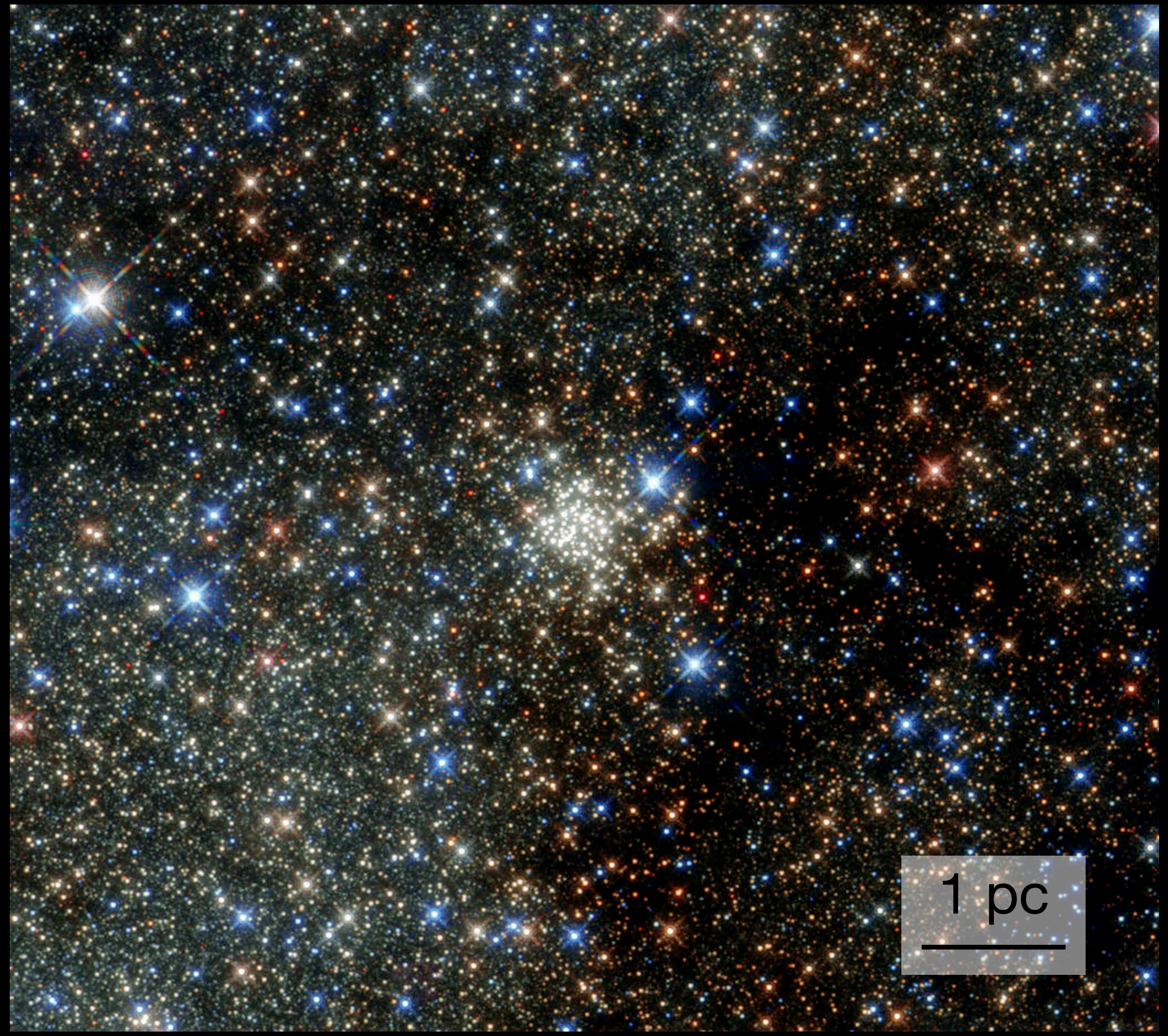
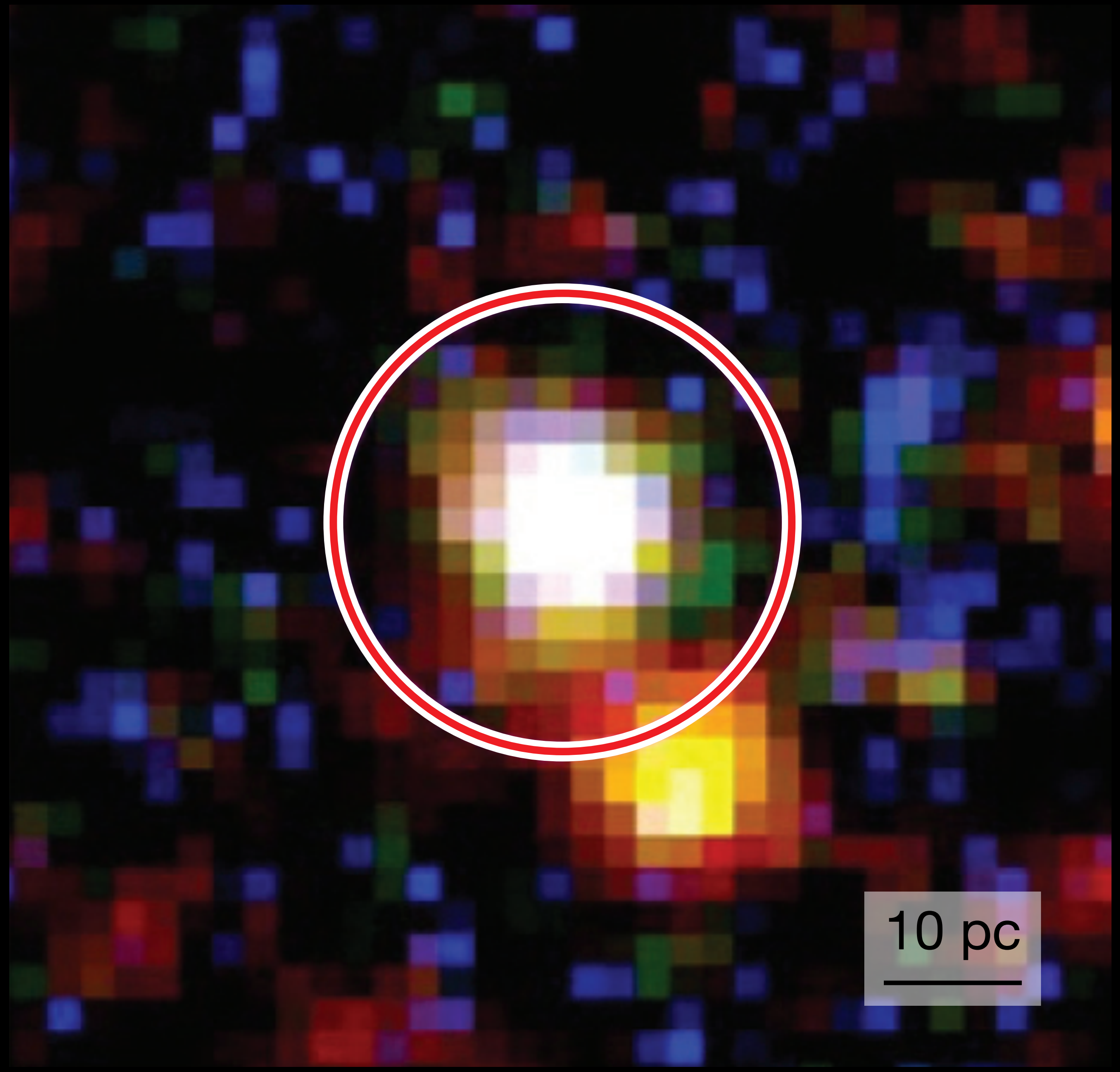
Clustering of older stars

Ages $\gtrsim$ 10 Myr

- Older star clusters clearly much denser than background — clear size and edge, rather than smooth power law fall off in density
- Clusters are rare: contain only a small fraction of total light from a galaxy
- Because clusters have clean edges, can estimate mass, age, other characteristics by placing stars on CMD (for resolved clusters) or fitting colour to simple stellar population models (for unresolved clusters)



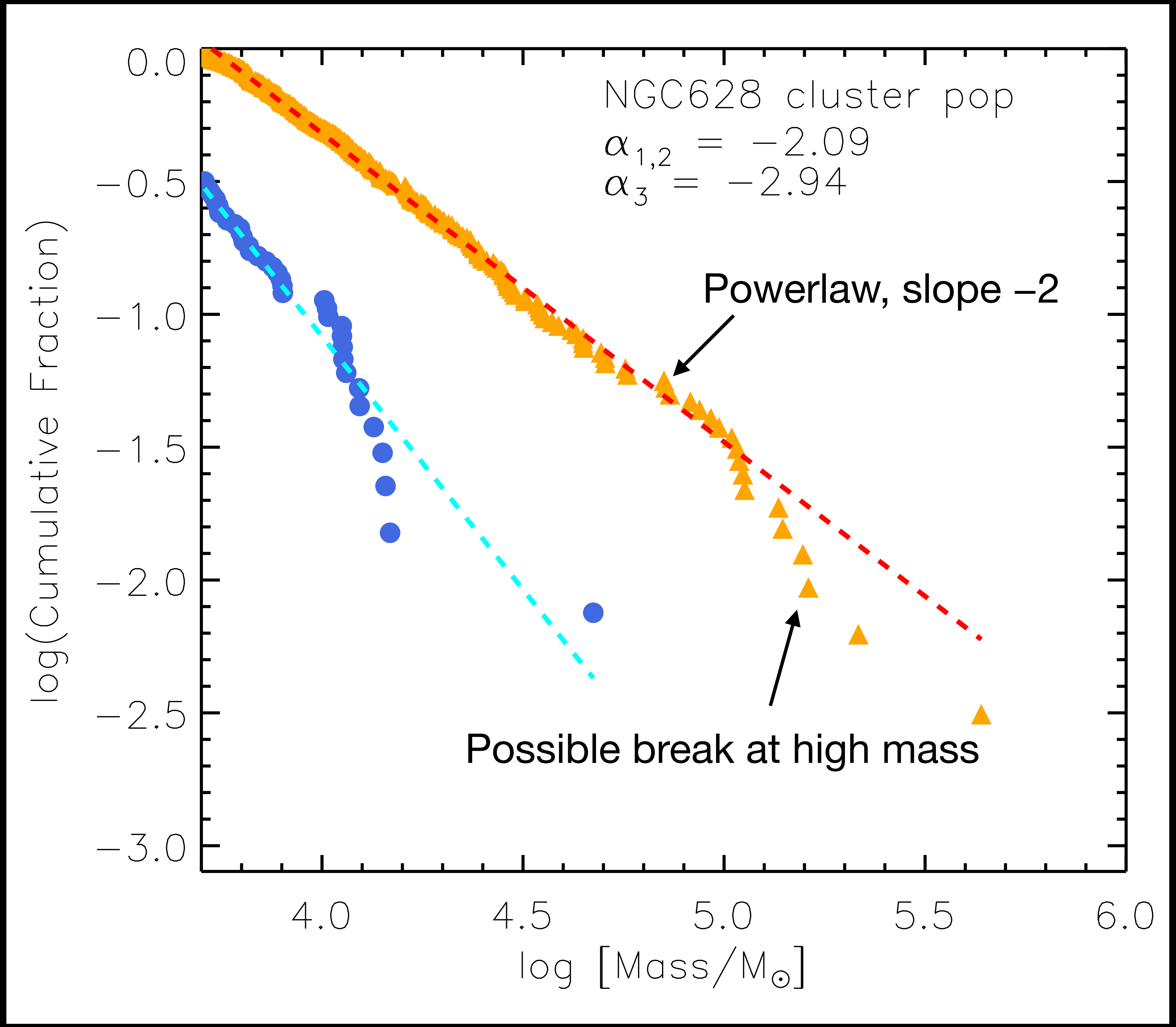
Arches cluster (Milky Way)



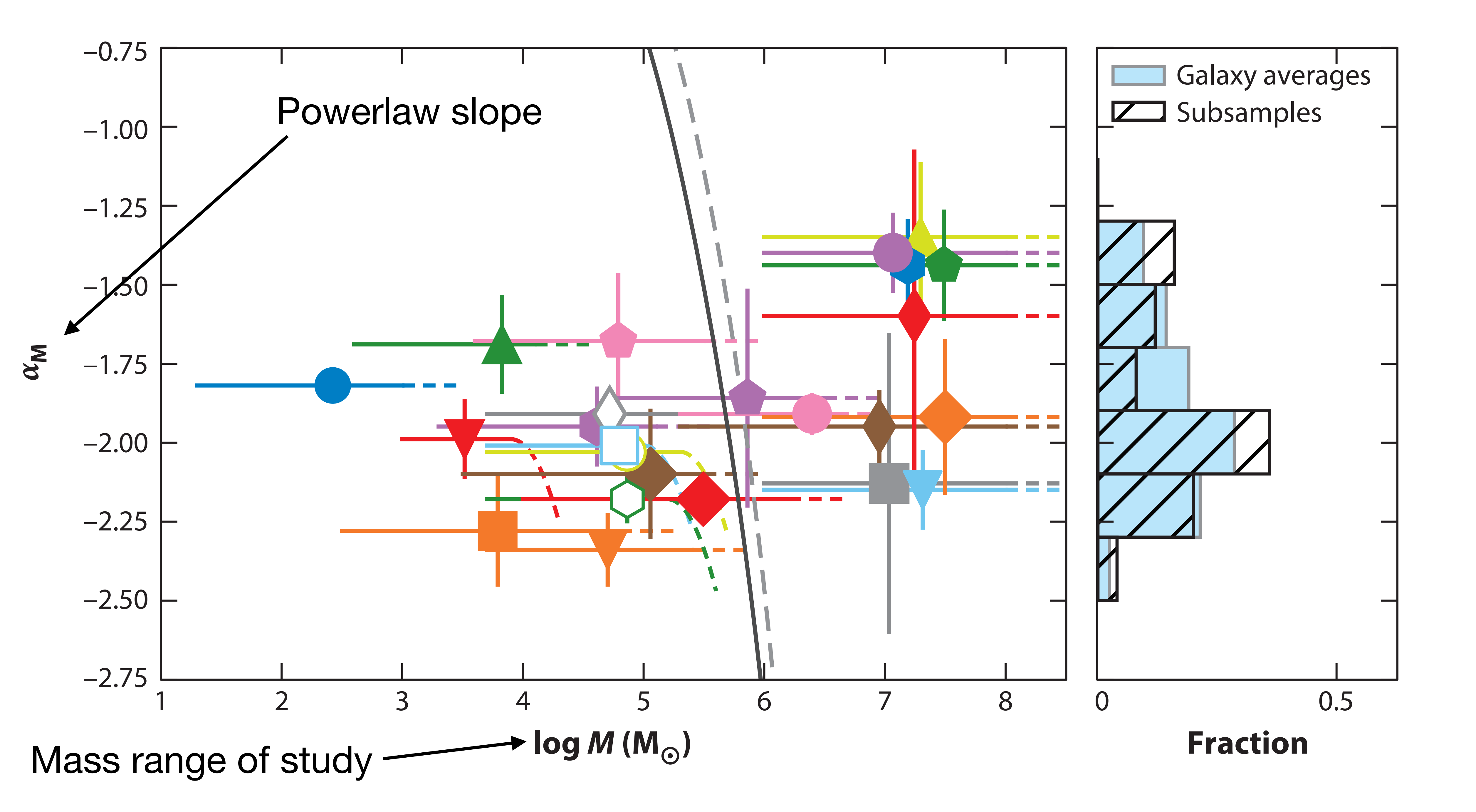
Cluster in galaxy NGC 628 (d ≈ 10 Mpc)

Star cluster demographics

Mass functions



Adamo+ 2017



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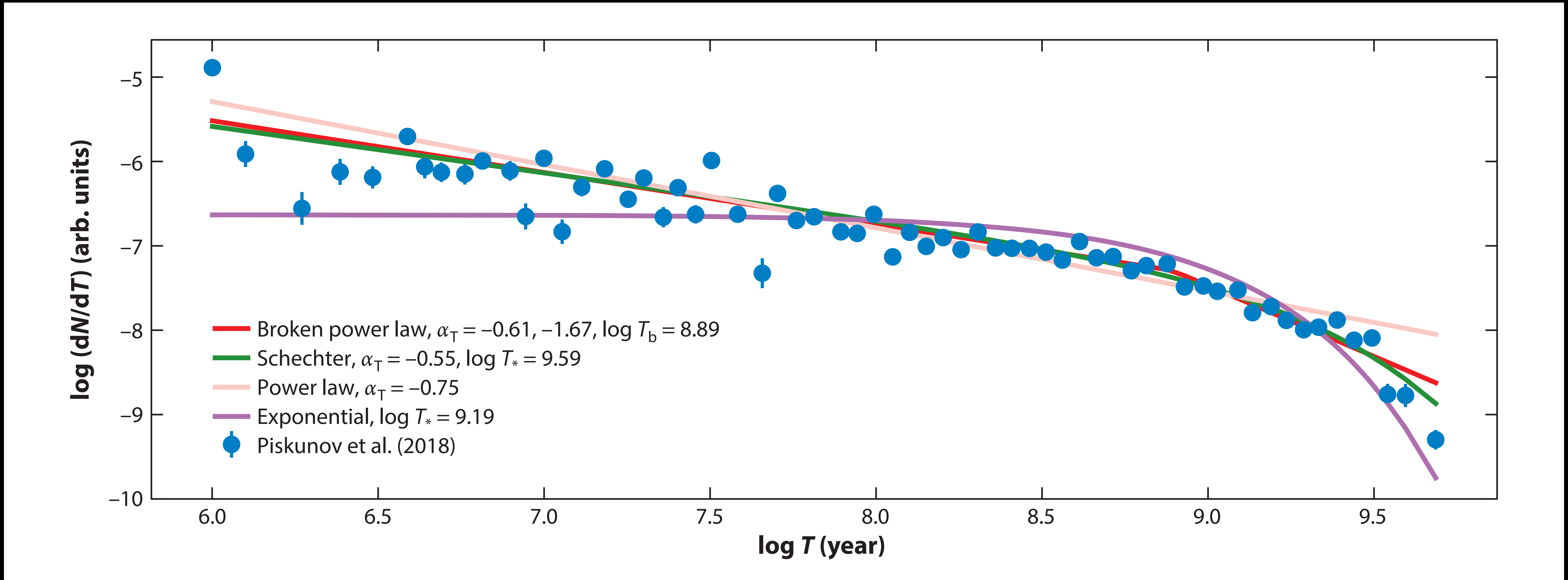
Star cluster demographics

Age distributions



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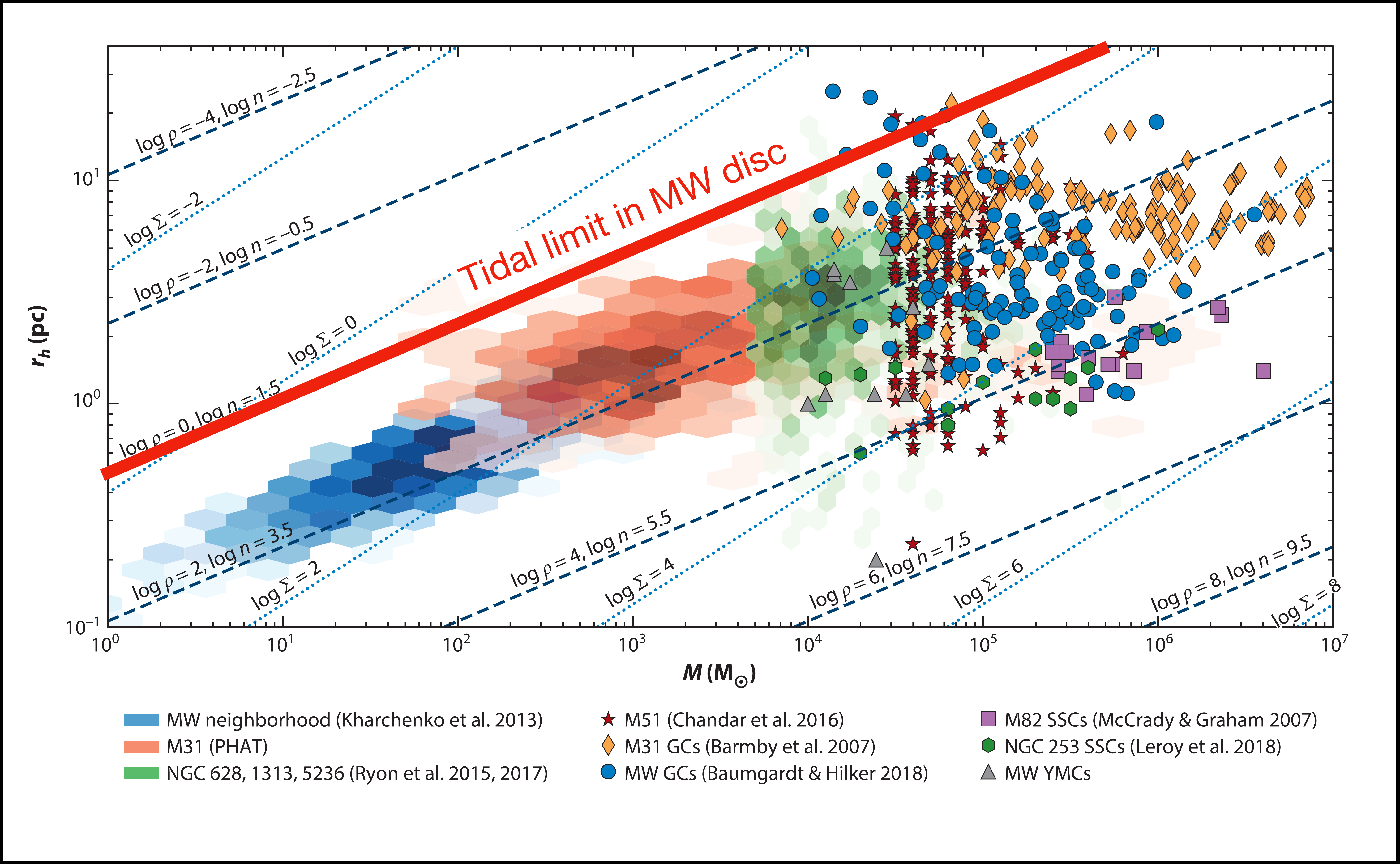
Cluster demographics

Combined mass and age distributions

- Mass distribution of young clusters is a power law with slope close to –2; this means equal mass per logarithmic bin
- Age distribution also a power law at young ages with a slope of –0.9 to –0.6, with a turn-down at older ages, possibly dependent on cluster mass
- Interpretation of age distribution:
  - Suppose probability / time that a cluster of age T is destroyed is $1/aT$
  - Cluster number N changes with time as $dN/dT = -N/aT \rightarrow N = N_0\,(T\,/\,T_0)^{-1/a}$
  - Thus index -0.9 means $a = 1.1$, expected lifetime = slightly longer than current age; index -0.6 means $a \approx 1.7$, so typical cluster survives for a bit under twice its current age

Sizes of star clusters



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Bound mass fraction

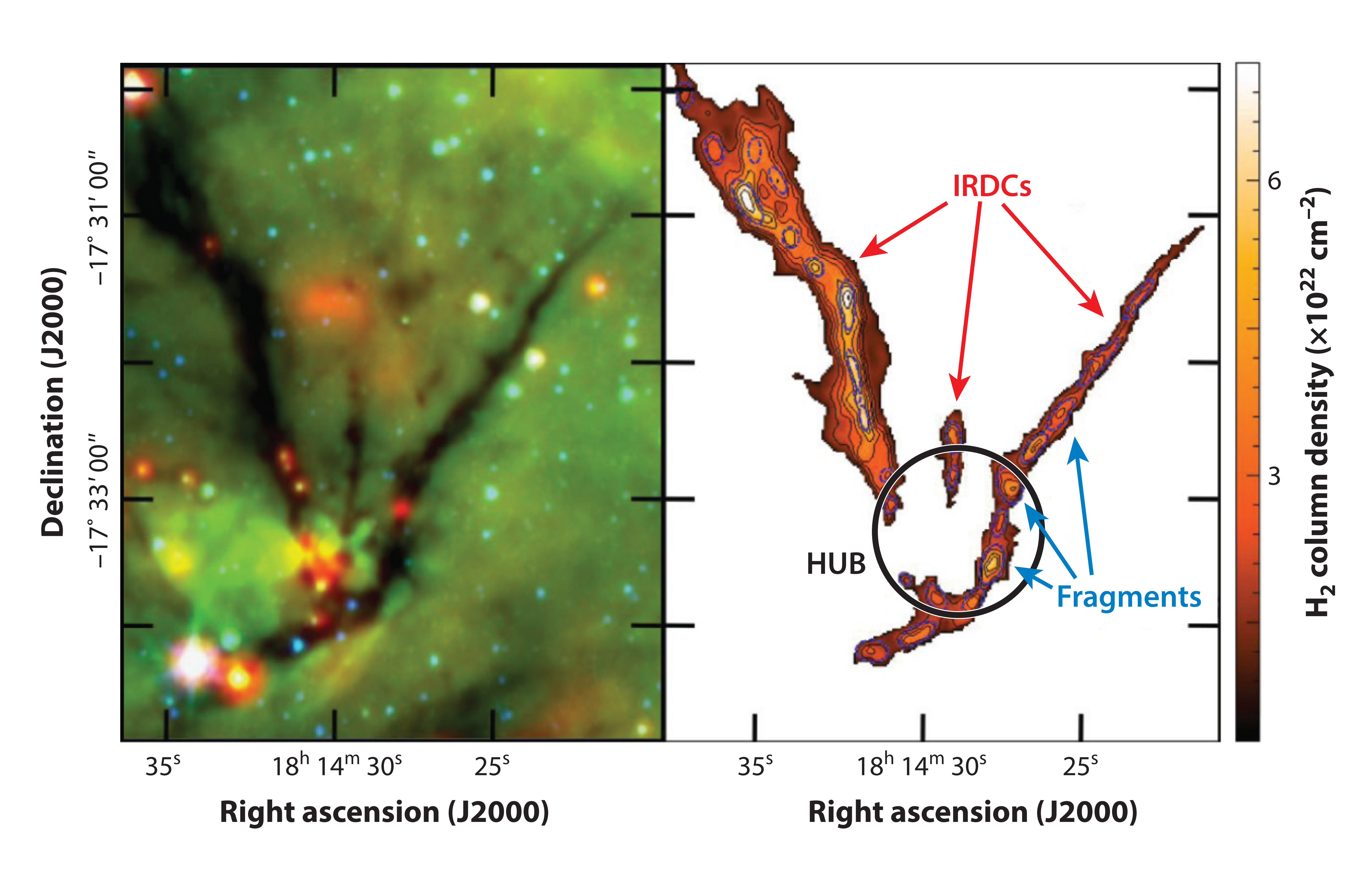
The most uncertain quantity of all

- Define $\Gamma(T)$ = fraction of stars of age T that are in gravitationally-bound clusters
- Hard to measure at ages $\lesssim$ 10 Myr, because even stars that are unbound may not have had time to drift apart yet; if one ignores this complication, Γ ~ 10-100% at young ages
- At ages ~10 - 100 Myr in Milky Way-like galaxies, Γ = 1-10%, declining at larger ages as cluster disrupt
- May be higher in starburst systems, but uncertain due to methodological biases — measurements in these systems are all for younger clusters, and it is unclear if high measured Γ is a result of youth or of higher SFR

Regions of cluster formation

The gas view

- Regions where star clusters are forming often appear to be “hubs” at the confluence of filamentary molecular clouds
- Mass flows along the filaments into the central hubs
- Stars form both in the central hub and, at lower density, along and around the filaments



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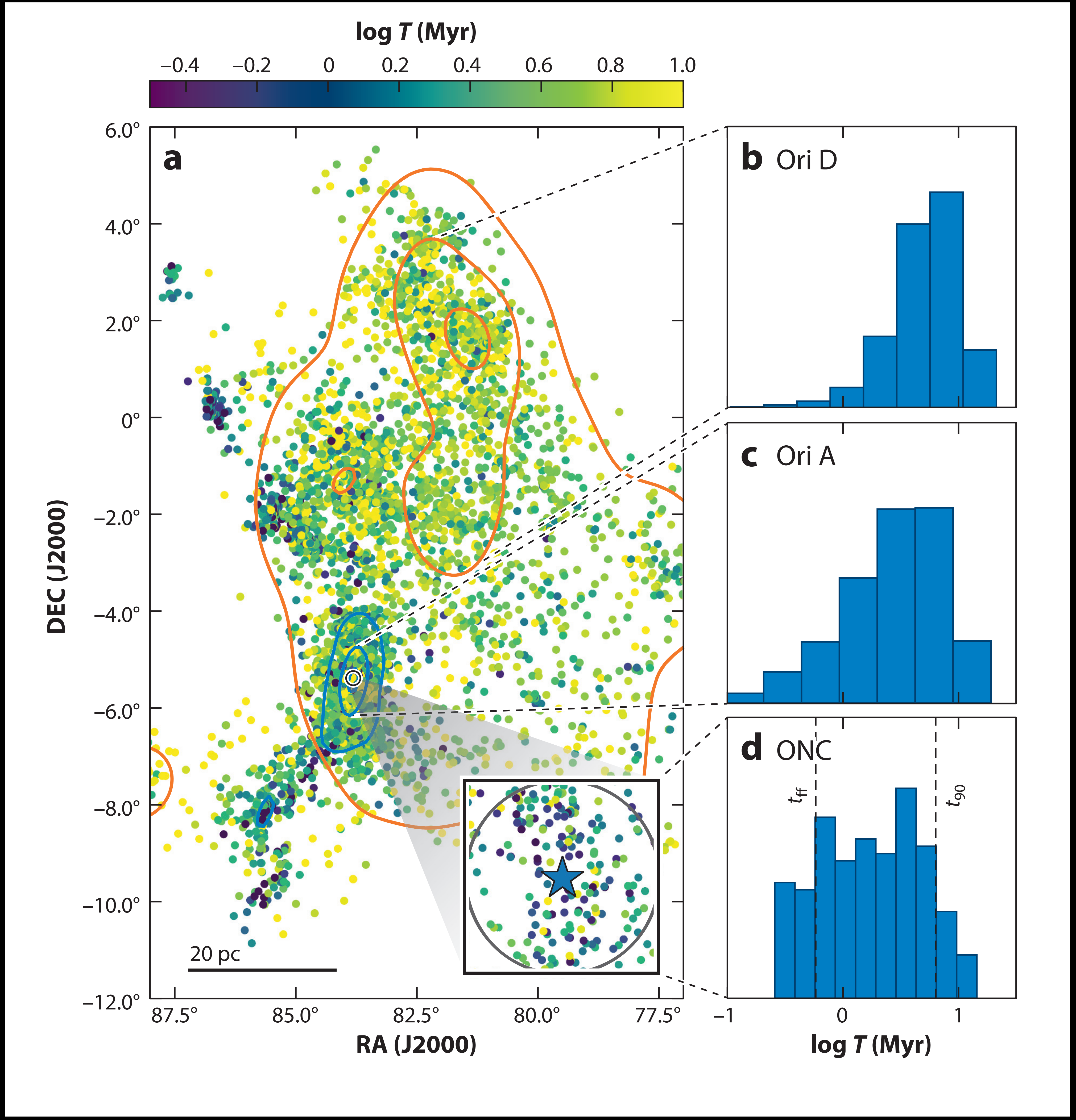
Regions of cluster formation

The stellar view

- Stars form at a wide range of densities
  - Most in low-density outskirts; stars here have filamentary distribution
  - ~10% in dense regions that correspond to “hubs” seen in gas; stars here round and smooth
- Kinematics suggest stars in “hub” are bound and relaxed, stars outside it unbound and unrelaxed
- Stars in hub younger, but only slightly



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Suggested scenario

The “conveyor belt” model

- Clouds start to collapse, feed mass inward toward central hub, while at the same time forming stars throughout
- Most gas mass doesn’t make it to central hub, so majority of stars form outside the hub, in the extended region
- In the hub, density is high, free-fall time low, so star formation can go on for several free-fall times — gives stars chance to relax and become bound
- In lower density outskirts, even though star formation goes on slightly longer, free-fall time is much longer, so stars cannot relax
- When star formation ends, hub regions left bound; rest unbound

Feedback mechanisms

- Big question: what ends star formation / unbinds the low-density stars?
- Something must, or else eventually all gas would transform into stars and we would have $\Gamma = 1$
- Candidate mechanisms:
  - Protostellar outflows
  - Photoionisation
  - Direct radiation pressure
  - Indirect (dust-reprocessed) radiation pressure
  - Hot star winds
  - Supernovae

Where are different mechanisms effective?

Order of magnitude estimates

- Outflows limited by low ejection speed, which makes it difficult to unbind material completely — Matzner & Jumper (2015) find ejection only from clouds with $v_{\mathrm{esc}} \lesssim 1$ km/s

- Ionised gas also limited by speed: sound speed in ionised gas is ~10 km/s, and gas freely-expanding into a vacuum rockets off at $2c_s$, so can't eject material from regions with escape speed $\gtrsim$ 10-20 km/s

- Hot star winds: evidence so far suggests generally not important

- SNe have lots of power, but don't explode until $t_{\mathrm{SN}} \approx 4$ Myr after stars form, but which time fraction of mass converted to stars is $\varepsilon \approx \varepsilon_{\mathrm{ff}}\, t_{\mathrm{SN}} / t_{\mathrm{ff}}$ → keeping ε low requires $t_{\mathrm{ff}} \lesssim \varepsilon_{\mathrm{ff}}\, t_{\mathrm{SN}}$ → $\rho \lesssim 10^4\ M_\odot\ \mathrm{pc}^{-3}$

Where are different mechanisms effective

Order of magnitude estimates II

- Direct radiation pressure:
  - Light to mass ratio of young stars is $\Psi \approx 1100\ L_\odot / M_\odot$
  - In a cloud of mass M, radius R, surface density Σ that converts a fraction ε of its mass to stars, force per unit gas mass is $f_{\mathrm{rad}} = \Psi\varepsilon M / 4\pi R^2(1-\varepsilon)\Sigma c$
  - Gravitational force per unit mass is $f_{\mathrm{grav}} = GM/R^2$
  - Importance of radiation depends on ratio: $f_{\mathrm{Edd}} = (\Psi / 4\pi\Sigma Gc)\ [\varepsilon / (1-\varepsilon)] \rightarrow$ expect radiation to be significant for $\Sigma \lesssim \Psi / 4\pi Gc \approx 340\ M_\odot\ \mathrm{pc}^{-2}$
  - Turbulence allows significant mass loss even at surface densities a factor of several higher than this

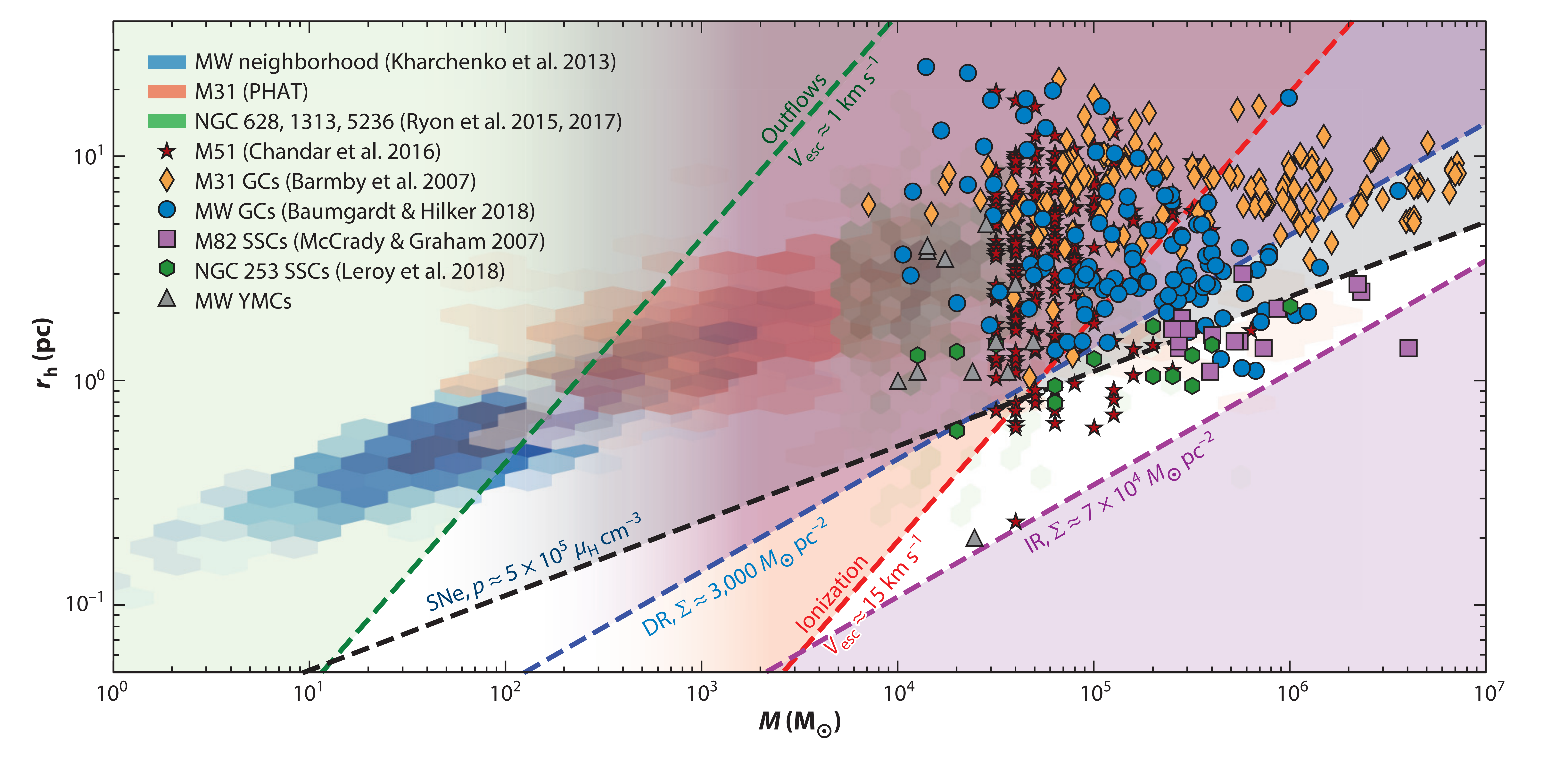
Where are different mechanisms effective

Order of magnitude estimates III

- Indirect radiation pressure:
  - Dust absorbs stellar radiation and re-radiates in IR; if column density is high enough, IR photons absorbed again, exert more force → feedback mechanism most effective at high column
  - Limiting factor #1: as photons repeatedly re-absorbed, they shift to lower frequency, where opacity is reduced, becoming more likely to escape
  - Limiting factor #2: radiation Rayleigh-Taylor instability allows radiation to escape through low-density channels
  - Including both limits, IRP effective if $\Sigma \gtrsim [16\,(\pi G \sigma_{\mathrm{SB}}/c)^{1/2} / \Psi]\,[\kappa_{10\mathrm{K}} / (10\ \mathrm{K})^2]^{-1} \approx 10^5\ \mathrm{M}_\odot\ \mathrm{pc}^{-2}$

Where are different mechanisms effective

Putting it all together



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Origin of cluster mass function

- Mass function of molecular clouds and clumps within them is $dN/dM \sim M^{-2}$ or slightly shallower — similar to cluster mass function
- Thus cluster mass function results naturally if fraction of gas transformed into stars ε, and fraction that remain bound, do not depend on M
- Dominant feedback mechanisms likely direct radiation pressure and ionisation
  - For DRP, ε depends only on Σ, not directly on M
  - Photoionisation mass loss scales as $M_{\mathrm{ion}} \sim S^{4/7} t^{9/7} \rho^{-1/7}$; if $S \sim \varepsilon M$, $t \sim \varepsilon t_{\mathrm{ff}}/\varepsilon_{\mathrm{ff}}$, and SF ceases when $M \sim M_{\mathrm{ion}}$, then $\varepsilon \sim \Sigma^{33/52} M^{1/52}$
- Thus ε (nearly) independent of M as long as Σ does not depend on M, which, observationally, it does not

Origin of bound fraction

- For rapid gas removal, boundedness depend only on stellar fraction ε:
  - Consider cloud in virial balance, $\mathcal{T} = -\mathcal{W}/2$
  - After sudden mass loss, new energies are: $\mathcal{T}' = (1-\varepsilon)\,\mathcal{T}$ and $\mathcal{W}' = (1-\varepsilon)^2\,\mathcal{W}$
  - Cloud remains bound if $\mathcal{T}' + \mathcal{W}' < 0 \rightarrow \varepsilon > 1/2$

- Real-life complications:
  - t_{ff} is shorter in denser regions, so ε is higher there, and mass removal is not necessarily fast compared to t_{ff}
  - Stars and gas not uniformly mixed
  - Pre-removal state probably not virialised, at least in lower-density regions
  - All this is taking place in a galactic tidal field, not in a vacuum

- Bottom line: this is still far from a solved problem!

Post-formation evolution

Origin of the age distribution

- Drop in cluster numbers from ~1 - 10 Myr age probably due to mass removal and dispersal of unbound stars
- However, clusters continue to decrease in number even at older ages, for reasons that are debated. Possible culprits:
  - Unbinding due to stellar mass loss (ages $\lesssim$ 100 Myr)
  - Tidal shocking by GMCs near the cluster at birth (ages $\lesssim$ 100 Myr)
  - Two-body relaxation and evaporation (ages ~Gyr)
  - Tidal shocking by GMCs unrelated to the cluster's birth place (ages ~ Gyr)