Why Care About Young Massive Clusters?

- ❑ Possible examples of present-day globular cluster formation

Nearby objects allow us to:

- ❑ Explore locations and physical conditions of extremes of high-mass, high-density star formation; test predictions of theoretical models
- ❑ Explore disruption vs. longevity; contributions to field populations
- ❑ Explore impact of environment on intense, high-mass star formation
- ❑ Explore (non-)universality of (initial) mass function in high-density, high-mass objects little affected by evolution
- ❑ Explore primordial vs. evolutionary mass segregation
- ❑ Explore duration of star formation and possible age spreads
- ❑ Explore impact of massive stars in high-density regions on forming low-mass stars (and planets)
- ❑ Explore feedback effects on surrounding GMC and ISM
- ❑ Explore impact on dust properties and reddening laws

What Are "Young Massive Clusters"?

No general consensus on the definition, but properties include being:

- ❑ "massive", i.e., masses $M \geq 10^4$ $M_\odot$
- ❑ "compact", i.e., radii $r \sim 1$ pc
- ❑ "dense", i.e., core stellar densities $\varrho_c \geq 10^3$ $M_\odot/pc^3$
- ❑ "young", many definitions, e.g., ≤ 100 Myr to ≤ 5 Myr

If age range is up to a few Myr, entire mass function will still be populated. Such young massive clusters occasionally referred to as "starburst clusters". Sometimes also called "super star clusters" (usually for $M \geq 10^5$ $M_\odot$).

Dense, massive clusters are rare in the Milky Way, but common in, e.g.,

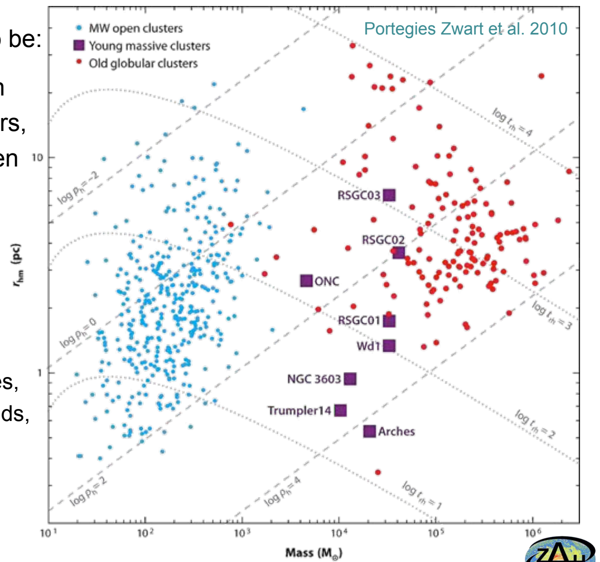
- ❑ the Magellanic Clouds (a.k.a. populous clusters; wide age range),
- ❑ interacting galaxies,
- ❑ starburst galaxies.

Radius – Mass Relation for Different Cluster Types

Galactic YMCs tend to be:

- ❑ More massive than typical open clusters,
- ❑ are located between open and globular clusters,
- ❑ overlap with low-mass, compact globular clusters.

But note: in other galaxies, e.g., the Magellanic Clouds, this diagram would be filled differently.



Modes of Star Formation

Very small fraction of the stellar populations in the Milky Way presently in clusters.

Classical idea: Two modes of SF, namely distributed and clustered.

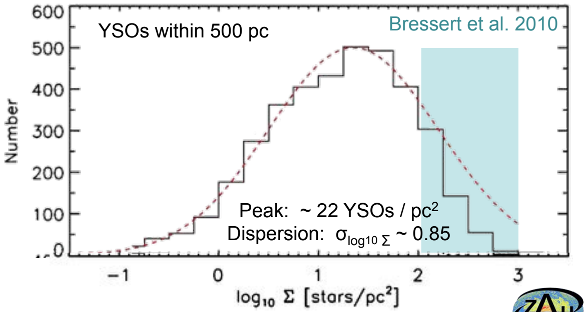
How important are clusters in generating field populations?

Spitzer study of distribution of YSOs in Solar neighborhood (R ≤ 500 pc):

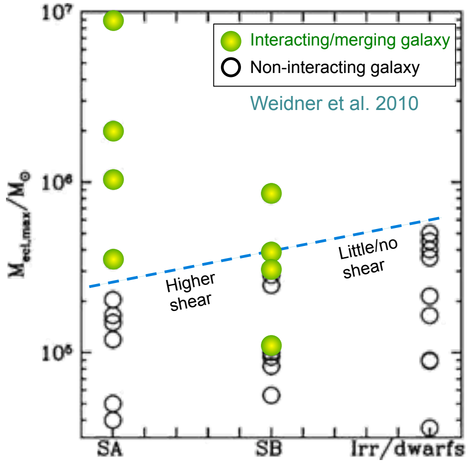
- No bimodality, but a continuum
- Young stellar systems exist in a continuous range of stellar densities and masses.
- Fraction of stars "in clusters" depends on definition for cluster.

Most dissolve quickly.

YMCs then represent extreme examples at the high-mass, high-density tail of the distribution.



Where Are Young Massive Clusters Found?

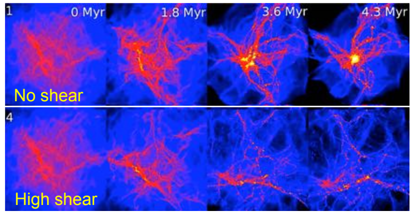


Mass of the *most massive young* (<50 Myr) star cluster in nearby spiral, barred spiral, and irregular (dwarf) galaxies.

LMC: shear Ω ~ $6 \cdot 10^{-16}$ rad/s.

MW pattern speed: Ω ~ 10^{-15} rad/s.

In several MW GMCs: Inferred velocity gradients Ω ~ 0.3 − $0.6 \cdot 10^{-14}$ rad/s.



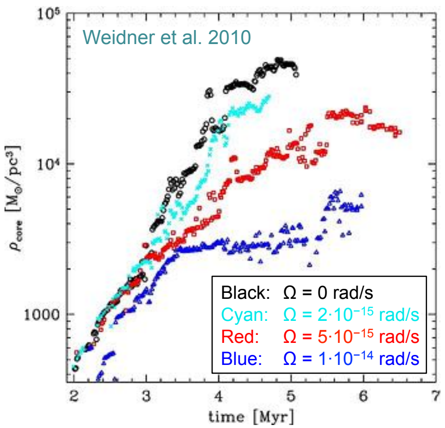
Weidner et al. 2010

3-D SPH simulations:

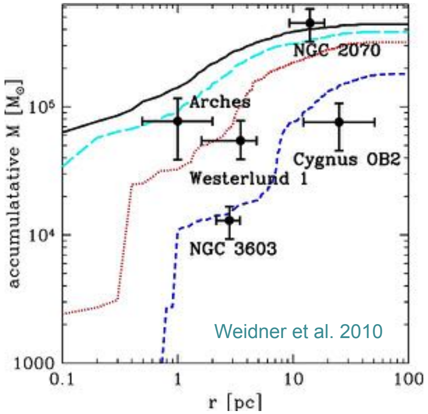
Low shear: More sinks, more highly concentrated towards center of cloud.

Amount and concentration of SF decreases with increasing shear.

The Role of Shear



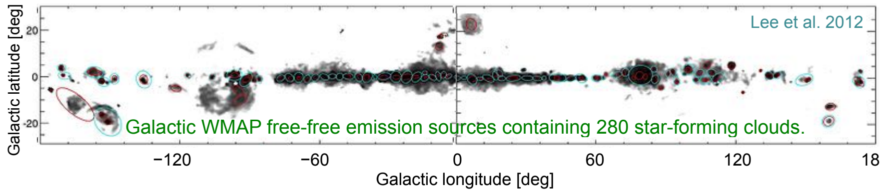
Temporal evolution of mass density in a core with r_{core} = 1.0 pc. After about 3 Myr of very similar evolution of all four models, the calculation without shear collapses more quickly and to higher densities (3 – 15 times larger densities than with shear).

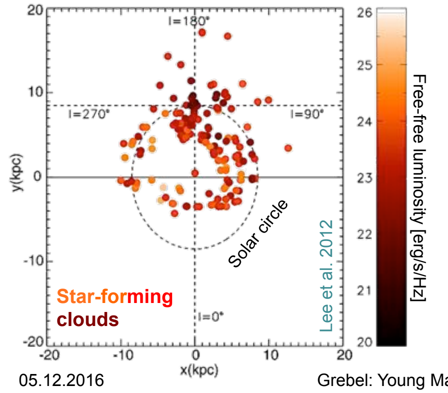


Radial dependence of the accumulated mass for all four simulations after 4.3 Myr.

NGC 2070: LMC; *Arches*: near Galactic Center; *Westerlund 1*: outer edge of bar; *NGC 3603, Cygnus OB 2*: MW disk.

Where Do Galactic Young Massive Clusters Form?





Most star formation in Milky Way occurs in molecular clouds.

Most SF clouds lie within Galactic plane.

Distribution falls off rapidly beyond Solar circle. Molecular ring: R_{GC} ~ 3.6 kpc.

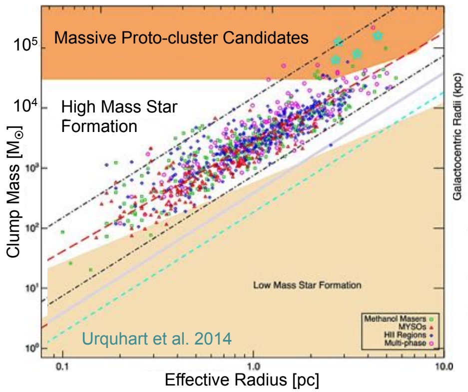
SFR of MW: $\dot{M}_\star$ ≈ 1.2 ± 0.2 $M_\odot$/yr.

SF clouds within Solar circle account for ~ 80% of the SF activity in the MW.

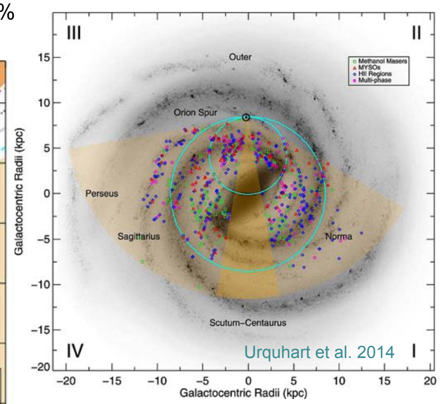
Half of current SF activity in MW: in the 24 most massive GMCs!

Where Do Galactic Young Massive Clusters Form?

ATLASGAL: blind 870 μm survey of ~ 70% of MW disk.



ATLASGAL: Mass – size relation of clumps. 16 massive proto-cluster candidates ($M_{gas} \geq 10^4$ $M_\odot$; $r \leq 2.5$ pc) in disk (orange region) and within 200 pc from Galactic Center (cyan stars).



ATLASGAL: Galactic distribution of all massive star-forming clumps with masses larger than 1000 $M_\odot$.

Location and Formation Modes of Galactic YMCs

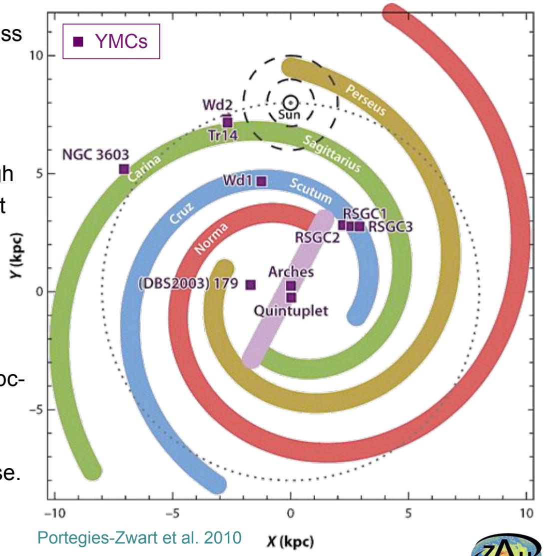
Environment: 2 "modes" of mass accumulation/star formation:

Galactic Center region:

"Slow, in-situ formation". Gas reaches high densities, but high turbulent pressure acts against collapse until parts collapse under own gravity.

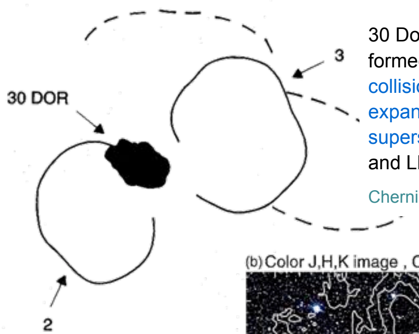
Disk (incl. ends of bar):

"Fast, conveyor belt". Massive but extended gas clouds with pc-scale high-density subregions fed by rapidly infalling large-scale gas streams until collapse. Cloud-cloud collisions may contribute. Longmore et al. 2014



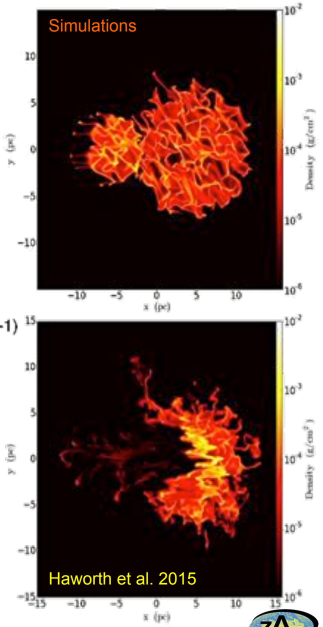
Portegies-Zwart et al. 2010

Cloud-Cloud Collisions



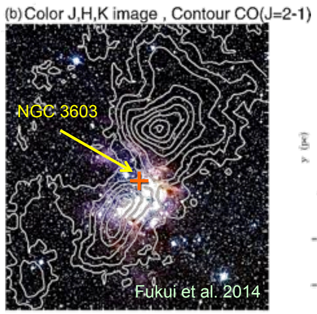
30 Dor may have formed through collision of expanding supershells LMC2 and LMC3.

Chernin et al. 1995



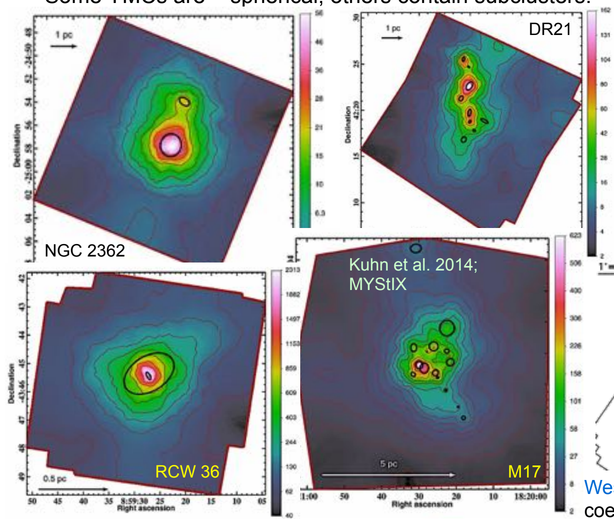
NGC 3603 (and other YMCs) may have formed through collision of giant molecular clouds.

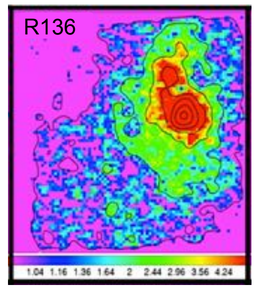
Fukui et al. 2014



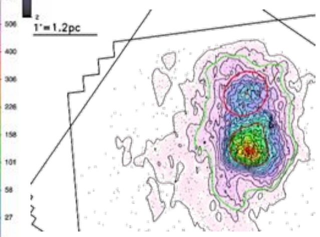
Substructure in YMCs

Some YMCs are ~ spherical, others contain subclusters.





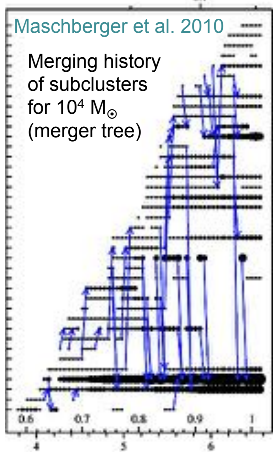
R136 (SW): 1 – 2 Myr.
NE clump: 2 – 5 Myr.
Sabbi et al. 2012



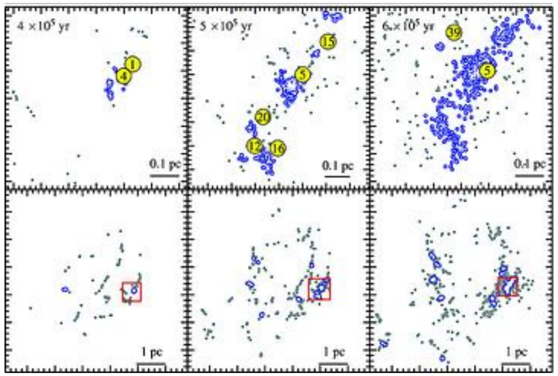
Westerlund 2: Clumps ~ 1 Myr, coeval. Zeidler et al. 2016

Time Evolution of Subclusters: Hierarchical Merging

Subclustering can occur in conveyor-belt scenario. Likely to merge eventually.



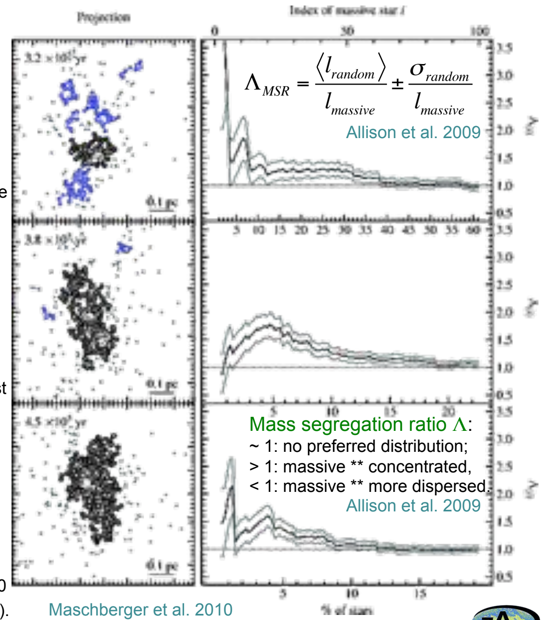
Hierarchical build-up of clusters.



Time evolution of the projected spatial distribution of the sink particles. Large dots: sinks in subclusters. Small dots: 'field' sinks. Total mass: 10^4 $M_\odot$, total area: 6 x 6 pc.

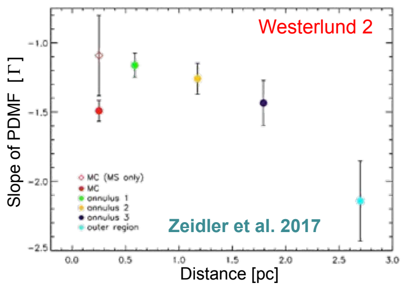
Mass Segregation

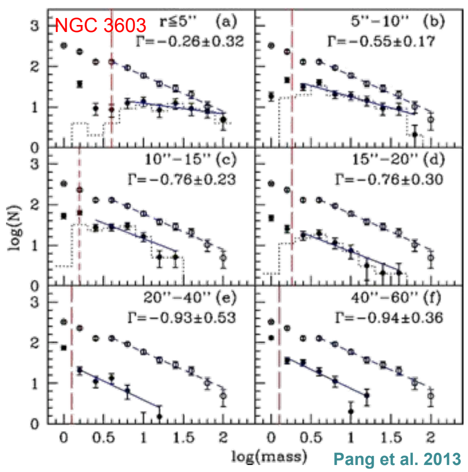
Evolution of mass segregation of a subcluster during merging event. Left: Projected distribution of sink particles. Analyzed subcluster: black dots. Right: Λ (Allison et al. 2009) for the 100 most massive sinks. As subcluster grows in number, the percentages for massive sinks of the total number are given at bottom axis of each panel. Before merger (top row): subcluster is already mass segregated, Λ > 1 for the ≈60 most massive sinks (40%). During the merger (middle panel): the ≈15 most massive sink particles are not mass segregated as they are still in the centers of the merging subclusters, but not randomly distributed (Λ > 1). After the merger (bottom row), the ≈10 most massive sinks quickly reach a state of strong central concentration (large Λ) and general mass segregation is at a 10 per cent level (Maschberger et al. 2010).



Mass Segregation

Even YMCs with ages of ~ 1 Myr usually already mass-segregated.





Dynamical time scales in 1 Myr YMCs are so short that mass segregation may well be dynamical (as opposed to primordial). For NGC 3603, this is also supported by the mass dependence of the Λ mass segregation ratio (**Pang et al. 2013**).
Mass segregation can be achieved on a dynamical time scale even in YMCs as also show in simulations (Allison et al. 2009).

Mass Functions and Mass Segregation

Since all these YMCs have already undergone dynamical evolution, we cannot measure their true initial mass function, but the present-day mass function (PDMF).

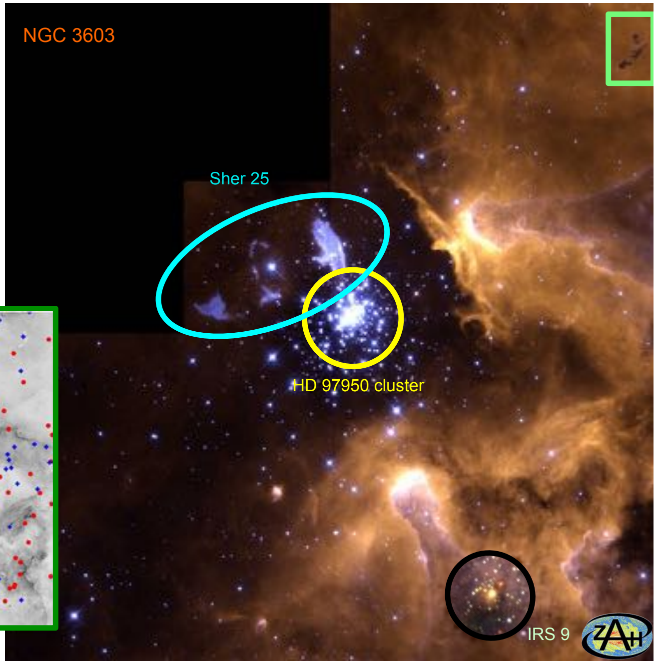
Name	Age [Myr]	Mass [10^4 $M_\odot$]	PDMF	Segregation
ONC	1.5 – 3.5	0.46	−1.2 ± 0.2	✔
Trumpler 14	1 – 3	~ 1	−1.3 ± 0.1	probably
NGC 3603	~ 1	~ 1	−0.9 ± 0.2	✔
Arches	~ 2	~ 1	−0.8 ± 0.2	✔
Westerlund 2	~ 1	~ 4.6	−1.5 ± 0.1	✔
Westerlund 1	4 ± 0.5	3.6 – 5.7	−1.4 ± 0.2	✔
NGC 346	~ 3	~ 8	−1.4 ± 0.2	✔

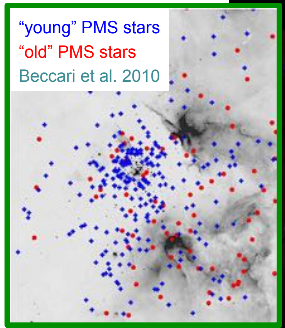
Incomplete listing including only YMCs in which mass segregation has been found.

Apart from possible subclusters, many YMCs are embedded in extended star-forming complexes with continuing star formation activity and a range of ages. Occasionally seemingly isolated, more evolved massive stars are found in their vicinity.

Age Spreads

or extended/ repeated episodes of star formation in star-forming complexes.





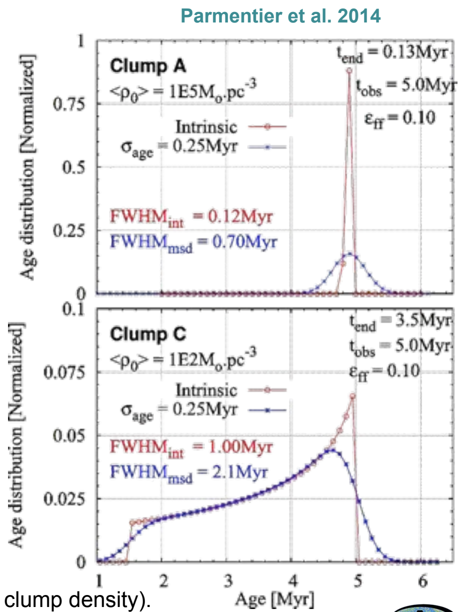
Age Spreads

Age spreads are small within YMCs.

Challenge: Constrain age range for very young MCs as upper main sequence becomes degenerate and pre-main-sequence stars are hard to age-date due to biases (variable accretion etc).

Models: Stars formed in high-density clumps form faster than stars in low-mass clumps; anti-correlation between the clump density and the duration of star formation.

→ Denser molecular clumps yield narrower star age distributions in clusters, i.e., small age spread expected in YMCs (↔ imprint of parent clump density).



Parmentier et al. 2014

Velocity Dispersions and Longevity

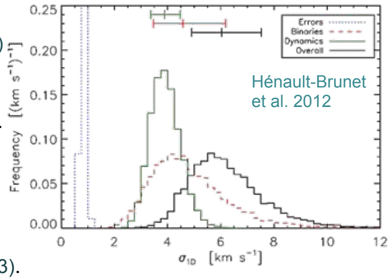
Tangential velocity dispersions of YMCs from proper motions, e.g.:
Arches: 5.4 ± 0.4 km/s (Clarkson et al. 2012)

Radial velocity dispersions from spectra of massive stars in YMCs, e.g.:
R136: 4 – 5 km/s (Hénault-Brunet et al. 2012)
Westerlund 1: 2.1 ± 3 km/s (Cottaar et al. 2012)

→ Clusters are subvirial, bound.

→ Gas expulsion did not alter their dynamics.

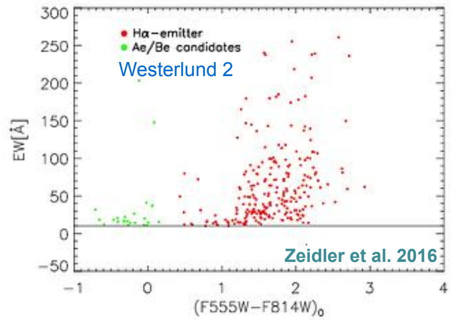
→ Potentially long-lived! [External tides, encounters with GMC, etc. notwithstanding]

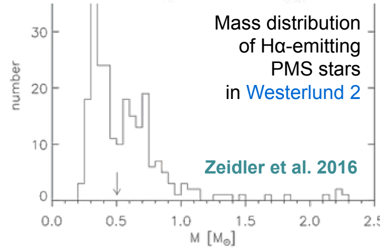


NGC 3603, velocity dispersion based on HST proper motions: 6.8 ± 0.8 km/s (Pang et al. 2013). Equipartition seems to hold so far only for most massive stars; cluster as a whole not yet virialized (due to slightly younger age?).

Stay tuned for Westerlund 2, for which proper motion and spectroscopic results are forthcoming (Zeidler et al., in prep.).

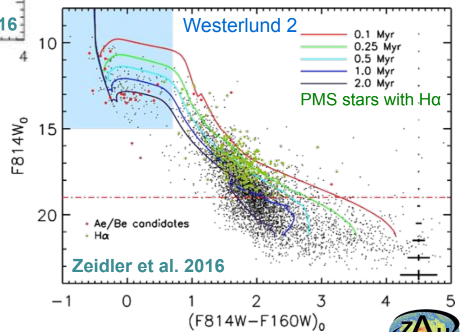
Internal Environment and Mass-Accreting Stars





Photometric identification of mass-accreting pre-main-sequence stars via their Hα emission (same principle as for Be and other emission-line stars).

Hα luminosity can be converted into mass accretion rate (see De Marchi et al. 2010).

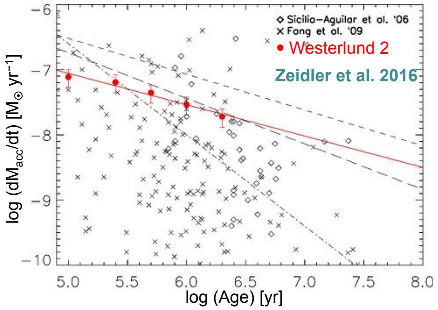


Massive Stars vs. Protostellar Disks

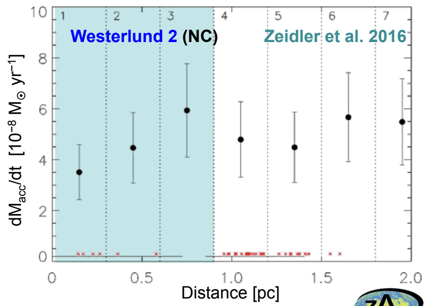
- ❑ The PMS mass accretion rate decreases with increasing stellar age.
- ❑ Lower mass accretion rate in proximity to massive stars; more rapid disk dispersal due to radiative and wind feedback.

[Observationally, many uncertainties, e.g., projection, variable Hα emission, viewing angle]

Median mass accretion rate as function of stellar age. Red: Westerlund 2; black: Tr 37, NGC 602,NGC 346, Orion GMC.



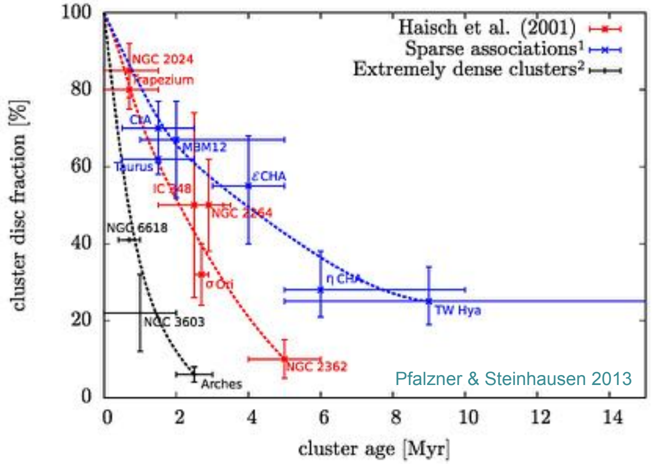
Mean mass accretion rate as function of projected distance from one of the clump centers (red dots mark location of OB stars)



Massive Stars and Protostellar Disks

Disk dispersal time scales depend on environment.

Mechanisms: Photo-evaporation, tidal effects (strongest in cluster centers).



Summary

- ❑ YMCs: Rare in the Milky Way, but common in interacting/starbursting galaxies or (dwarf) irregulars with little/no shear.
- ❑ Star (cluster) formation: "slow, in situ" (Galactic Center) and "fast, conveyor belt" (Galactic disk).
- ❑ YMCs: PDMF Γ values between −1.4 and −0.8.
- ❑ Even very young MCs: Already mass-segregated (dynamical segregation possible; may already start in subclusters).
- ❑ YMCs usually part of extended complexes with longer duration of star formation / multiple episodes.
- ❑ Age spread <u>within</u> YMCs seems small.
- ❑ YMCs after gas expulsion: virialized, bound structures with good prospects of long-term survival.
- ❑ Internal YMC environment reduces PMS mass accretion and erodes disks.

LEGUS: HST Treasury Program that has imaged 50 local (closer than 12 Mpc) galaxies in multiple colours with WFC3 and ACS (PI: D. Calzetti).
One of the results: **YMC census and properties in 50 nearby star-forming galaxies!**
We are using the observations to (1) quantify how the clustering of star formation evolves both in space and time, (2) discriminate among models of star cluster evolution, (3) investigate the effects of SFH on the UV SFR calibrations, (4) explore the impacts of environment on star formation and cluster evolution across the full range of galactic and ISM properties, (5) investigate UV-excess globular clusters across multiple environments, (6) study the environment surrounding supernovae, etc. **(https://legus.stsci.edu/)**