Observational constraints on clustered star formation

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A more complete picture of clustered star formation emerging

Susanne Pfalzner

Max-Planck-Institut für Radioastronomie, Bonn, Germany

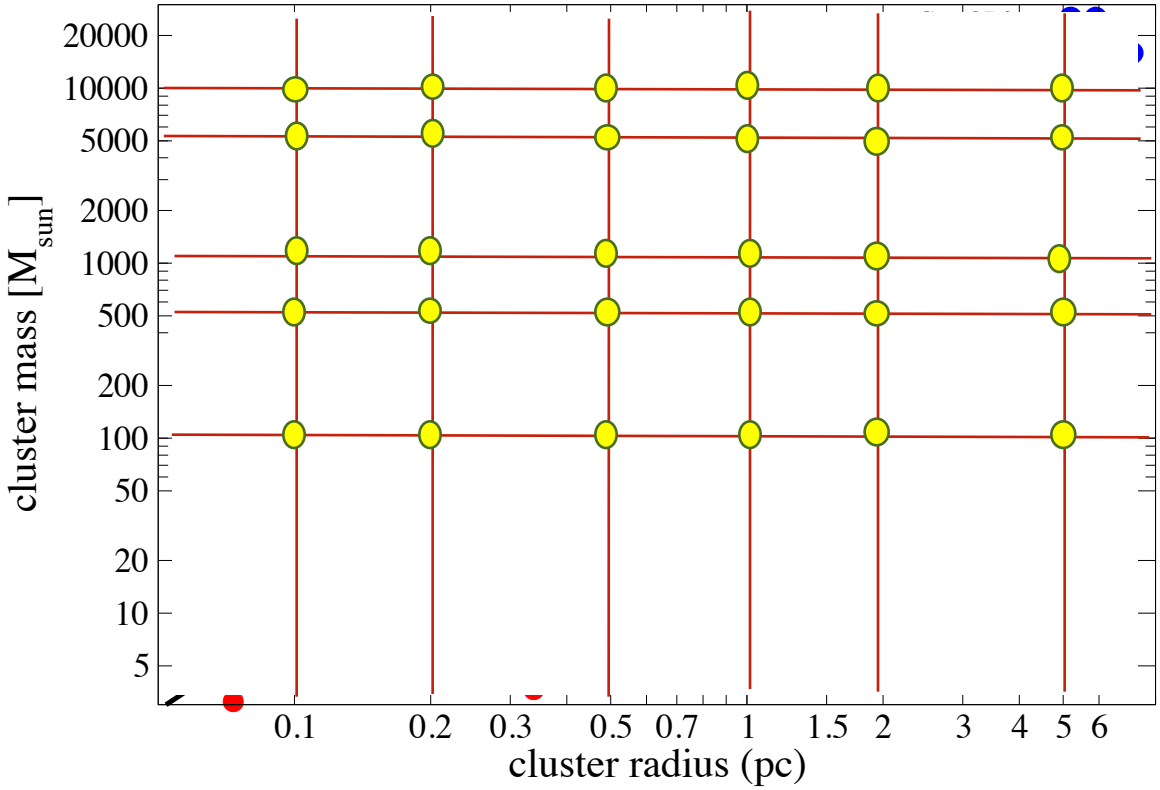
STARTING POINT

- **Most stars form in clusters**
- **Clusters span wide range of masses and sizes**
- **Most clusters dissolve within 10 Myr**
- **Clusters that survive are initially more massive**

Which additional information do observations give us to guide theories of clustered star formation?

MASS-RADIUS RELATION FOR **EMBEDDED CLUSTERS**

Clusters span wide range of masses and sizes, BUT ...



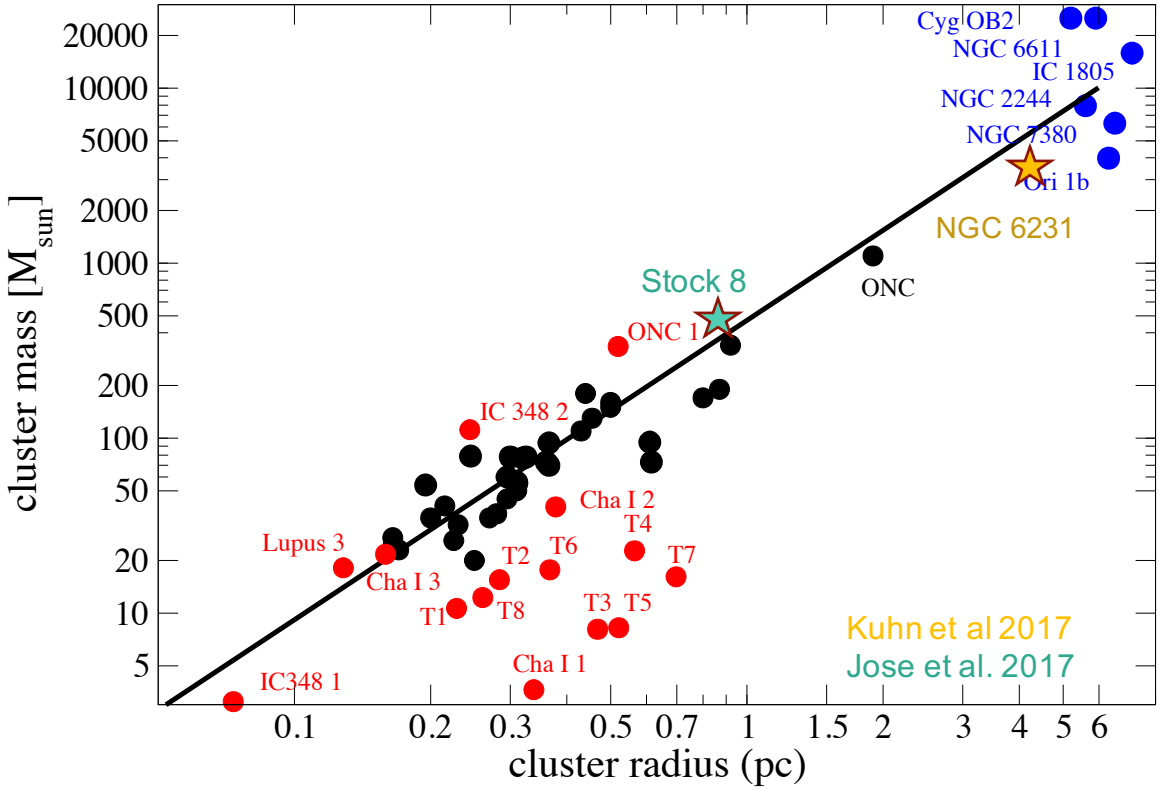
Pfalzner, 2009, Pfalzner et al. 2016

MASS-RADIUS RELATION FOR **EMBEDDED CLUSTERS**

Clusters span wide range of masses and sizes, BUT ...

Not anything goes

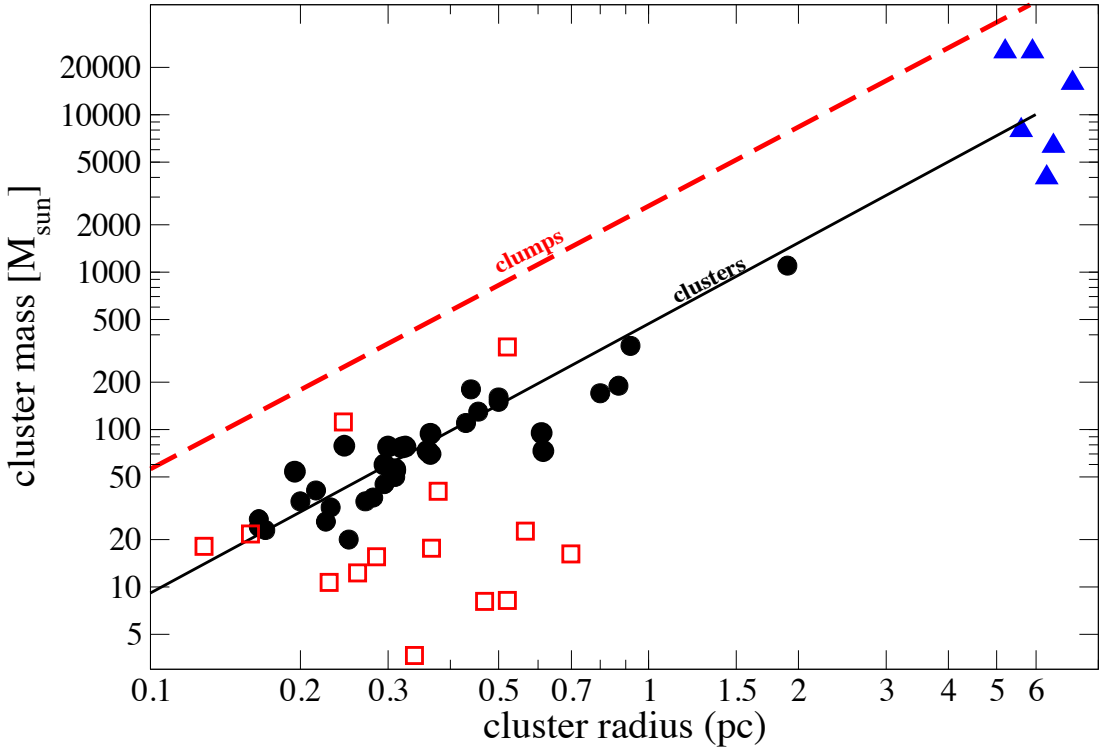
Mass-radius relation holds over many orders of magnitude



Pfalzner et al. 2016

MASS-RADIUS RELATION FOR **CORES**

Slope for mass radius relation for clusters and cores approximately the same



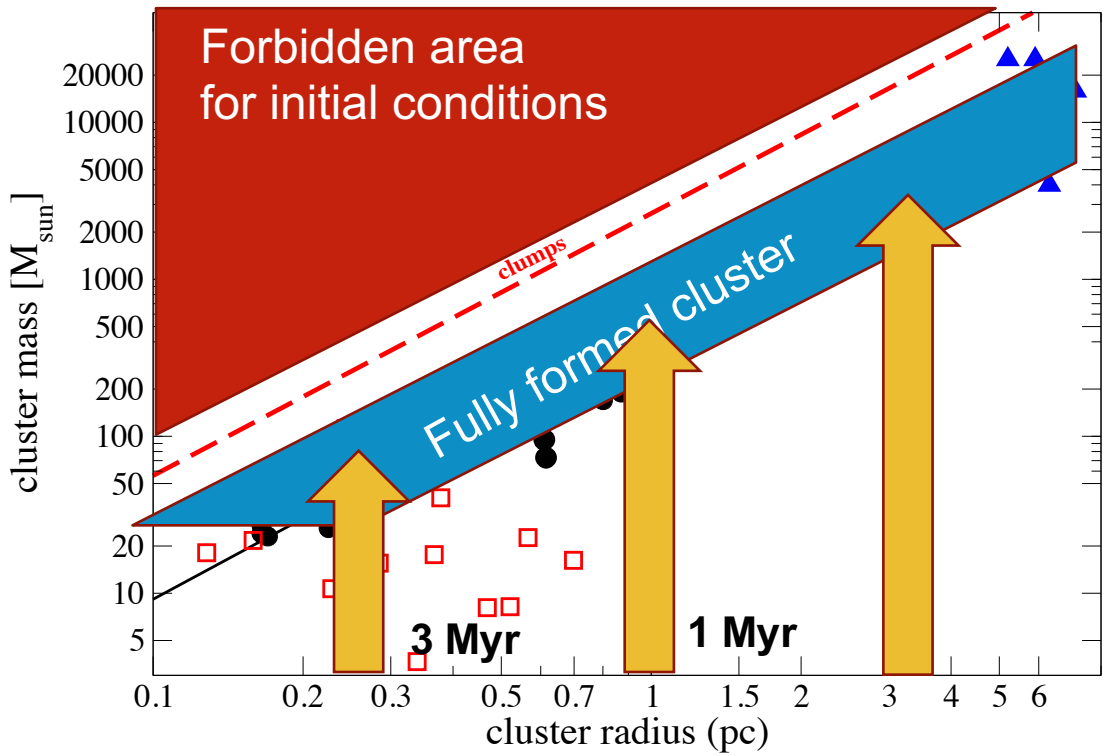
Urquhart et al. 2014

CONSTRAINTS FOR THEORIES

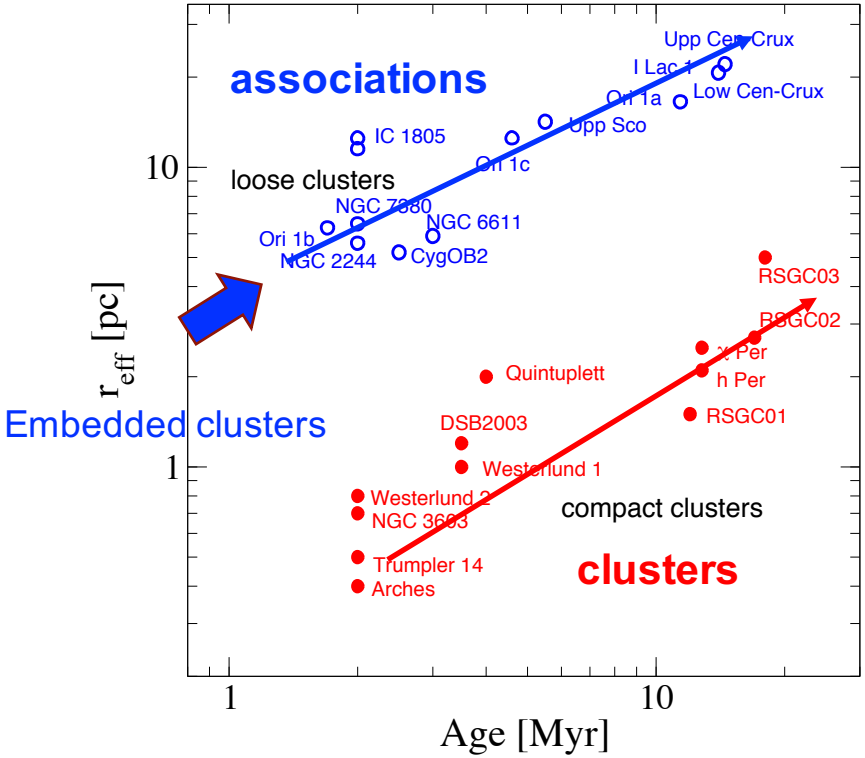
Core relation:
constraints for initial conditions

Cluster relation
Constraints for conditions at end of formation

Clusters age: < 3-5 Myr
Constrains on formation time scale



HOW DO CLUSTERS DEVELOP AFTER FORMATION?



Pfalzner A&A 2009

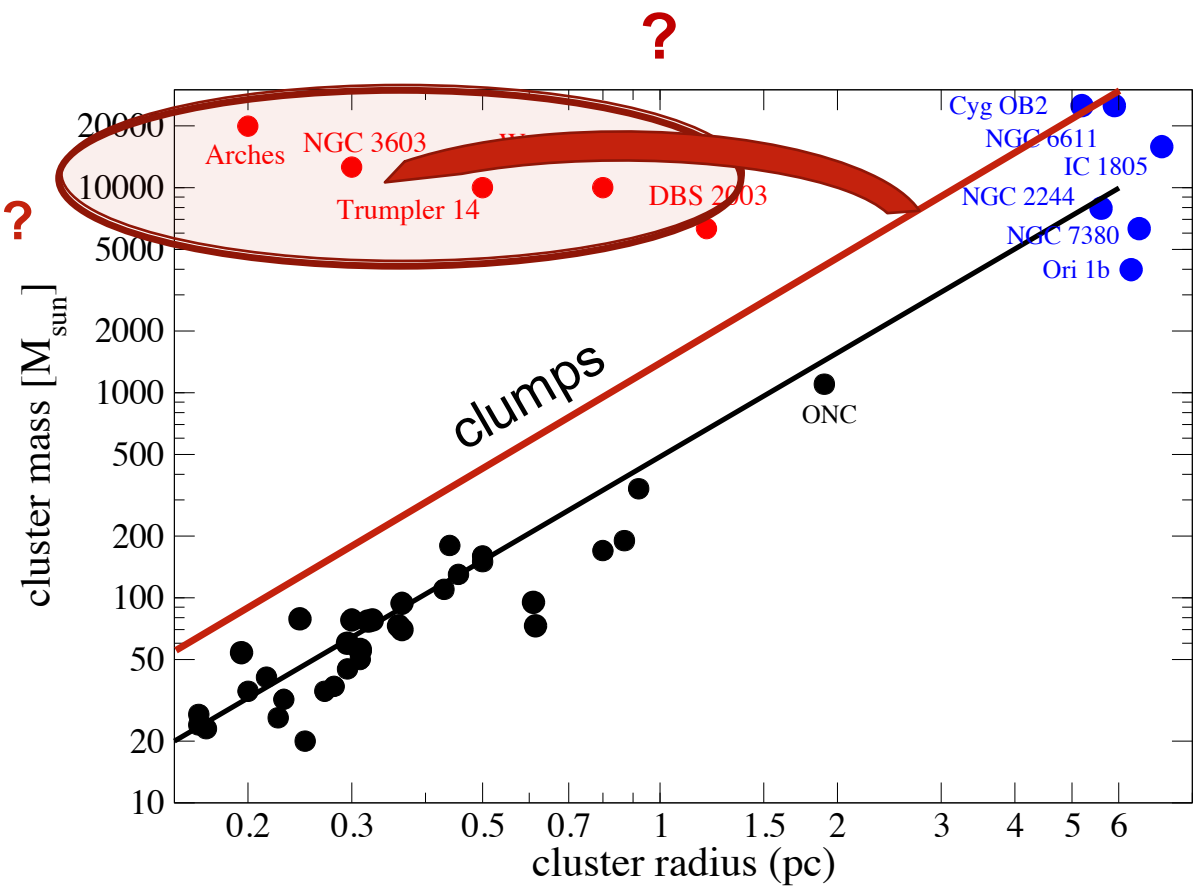
Name convention: Portegies Zwart 2010

- Full information over first 20 Myr only available for massive clusters
- **Two types of "clusters":**
  each increases in size with age but along different tracks
- Loose clusters successors of the clusters investigated in embedded phase
- Embedded clusters → associations

NO INFORMATION HOW COMPACT CLUSTERS FORM

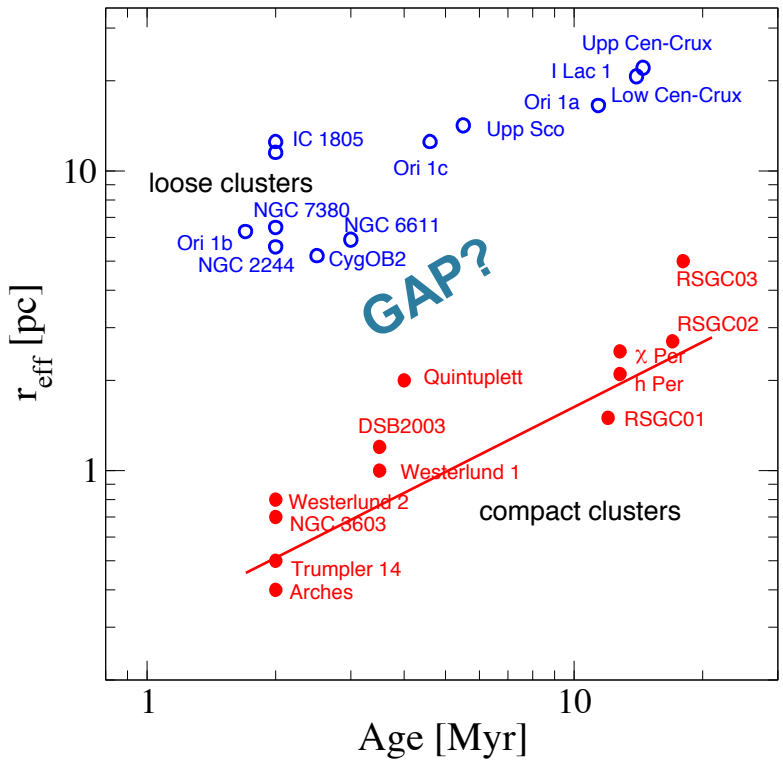
Next big challenge:

How do massive compact clusters form?



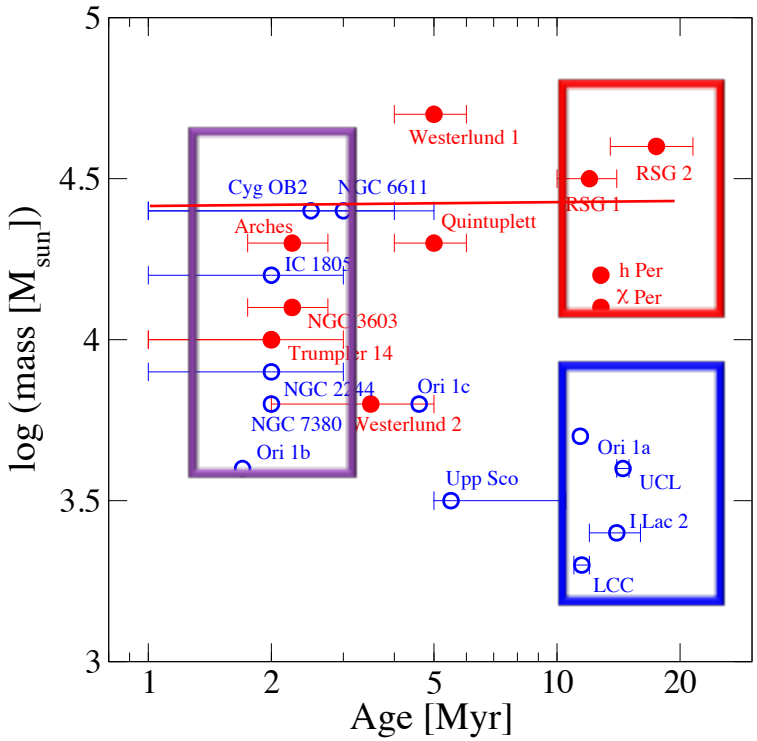
CLUSTERS DYNAMICS AFTER FORMATION

Clusters expand by factor 5-10



Pfalzner A&A 2009

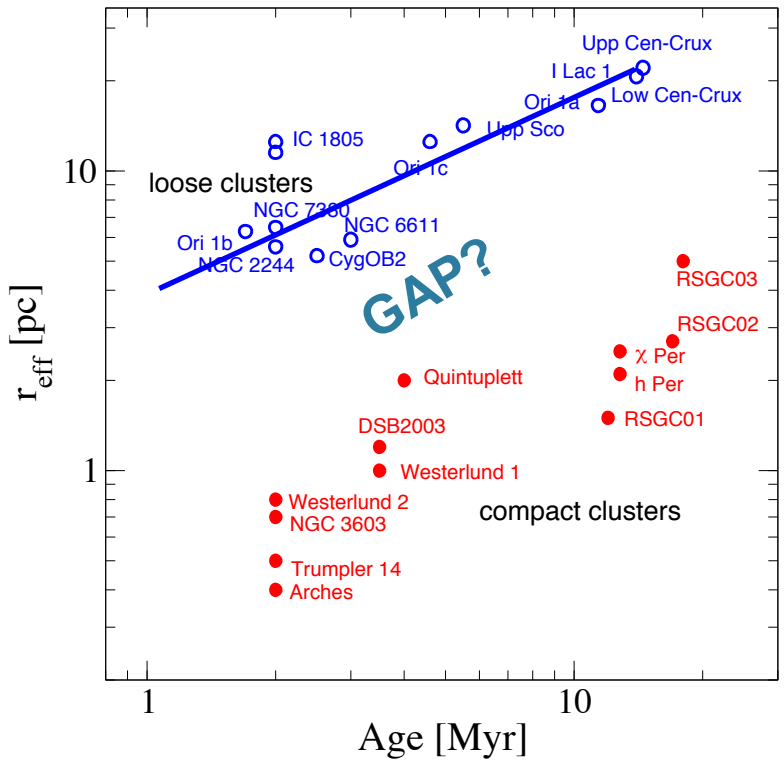
Little mass loss

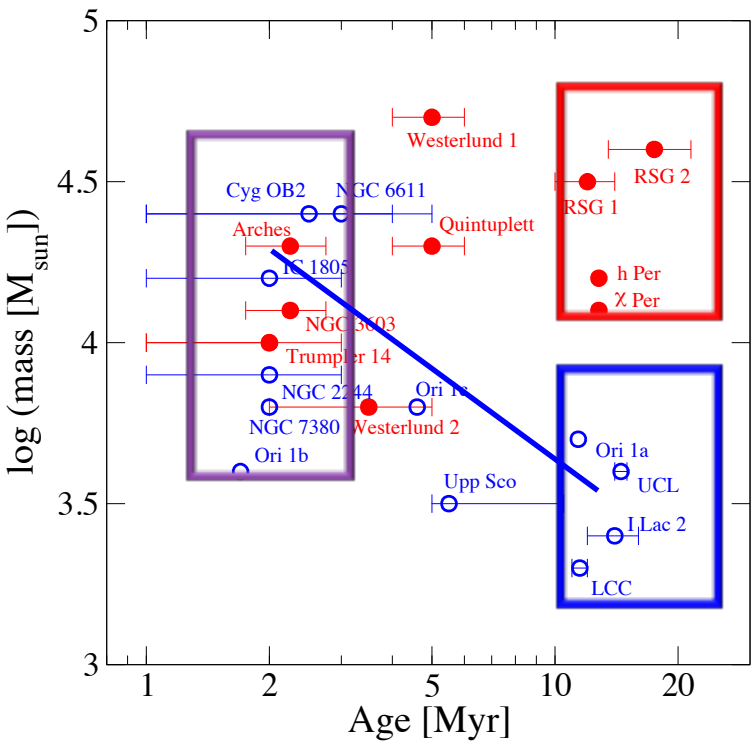


ASSOCIATION DYNAMICS AFTER FORMATION

Associationss expand by factor 5-10

Loose 80-90% of their mass

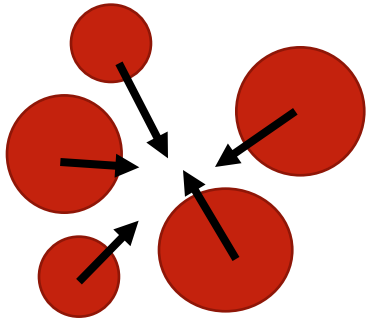




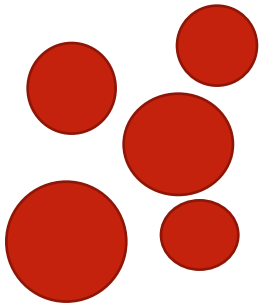
Pfalzner A&A 2009

MODELS OF CLUSTER FORMATION

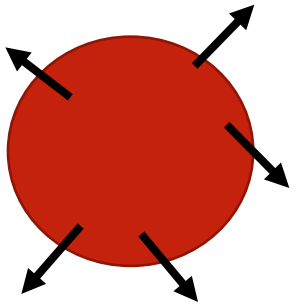
- **Distribution of subclusters that merge**
  Increasing size with age not straightforward



- **Clusters form, no dynamics afterwards**
  Increasing size with age not straightforwar

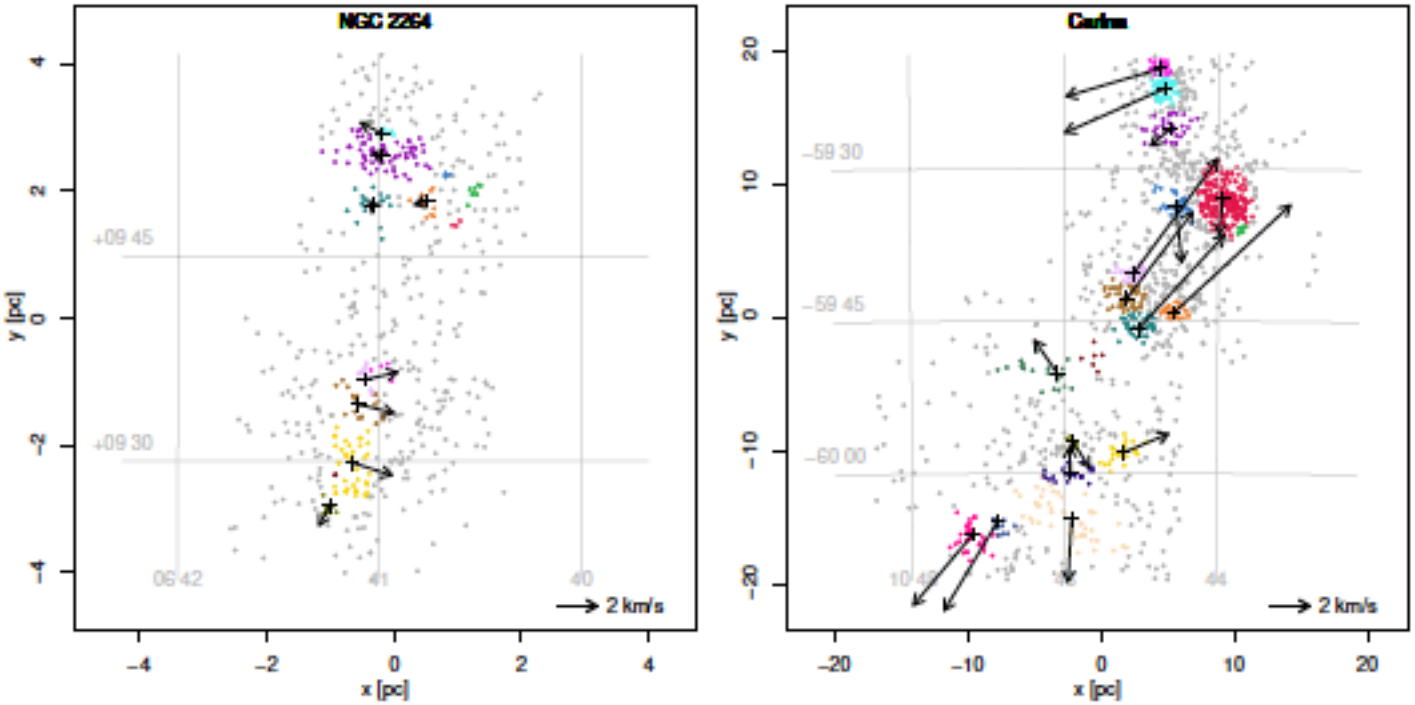


- **Formation as single entity**
  Gas expulsion: explanation for cluster growth



NO SUBCLUSTER MERGING

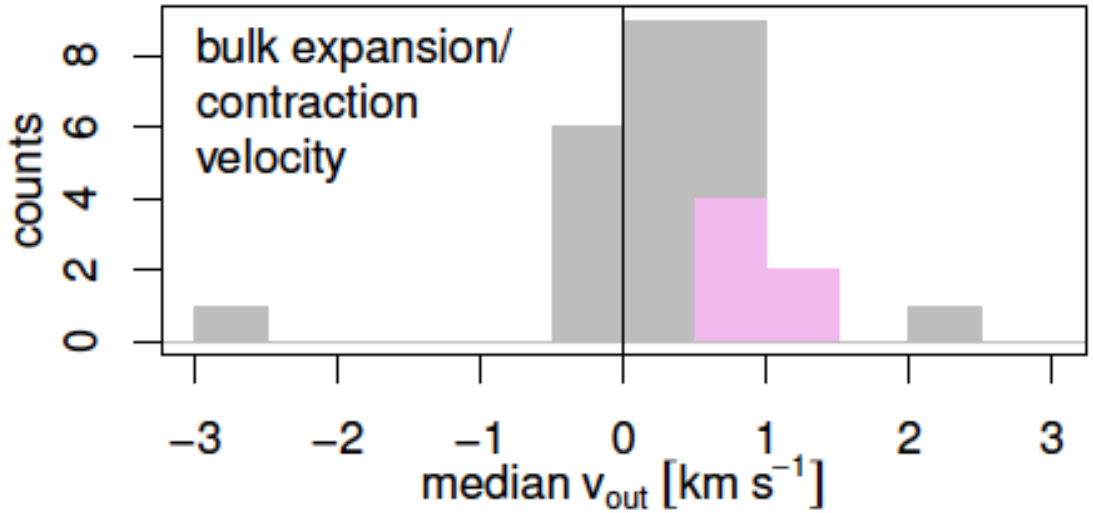
Kuhn et al. arXiv:1807.06085



No signs of subcluster merging

CLUSTER EXPANSION

Kuhn et al. arXiv:1807.06085



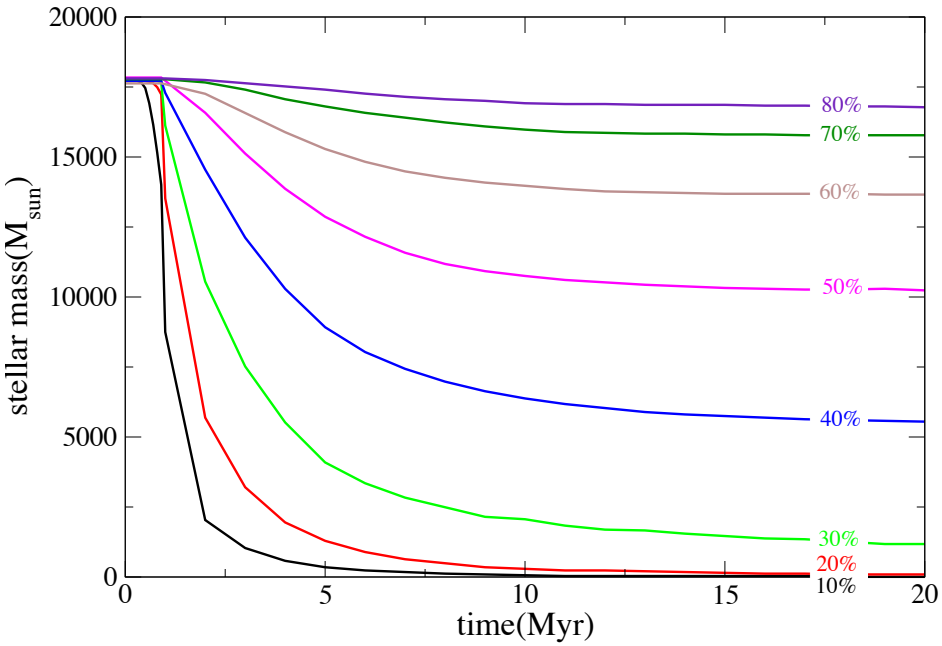
Gaia 2DR
Clusters
Age range 1-5Myr

Expansion speed:
1 km/s

1pc/Myr

75% of clusters show clear sign of cluster expansion

RESULT OF GAS EXPULSION DEPENDS ON ....



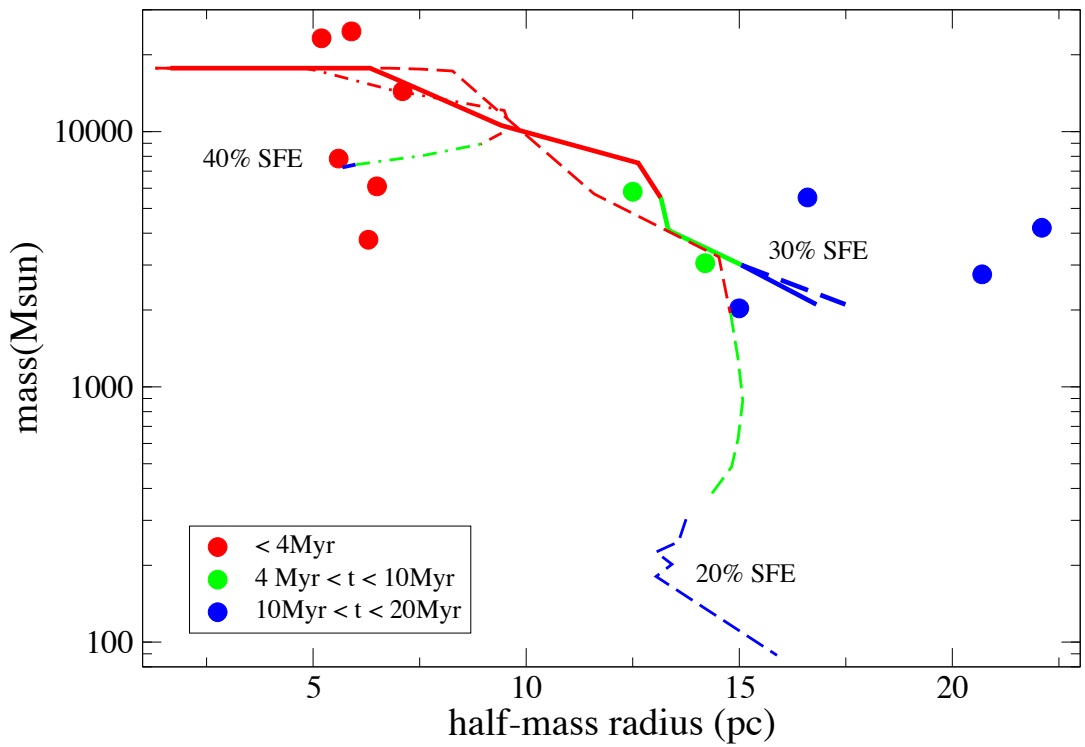
Highly deterministic

- **Star formation efficiency**

  Tutukov 1978, Hills 1980, Mathieu 1980, Adams 2000, Geyer & Burkert 2001, Kroupa et al. 2001, Boily &Kroupa 2003, Bastian & Goodwin 2006, Converse & Stahler 2011 ... many more

- **Remant cluster**
- Mass depends on SFE
- 30% SFE :
  10% of stars in remnant cluster

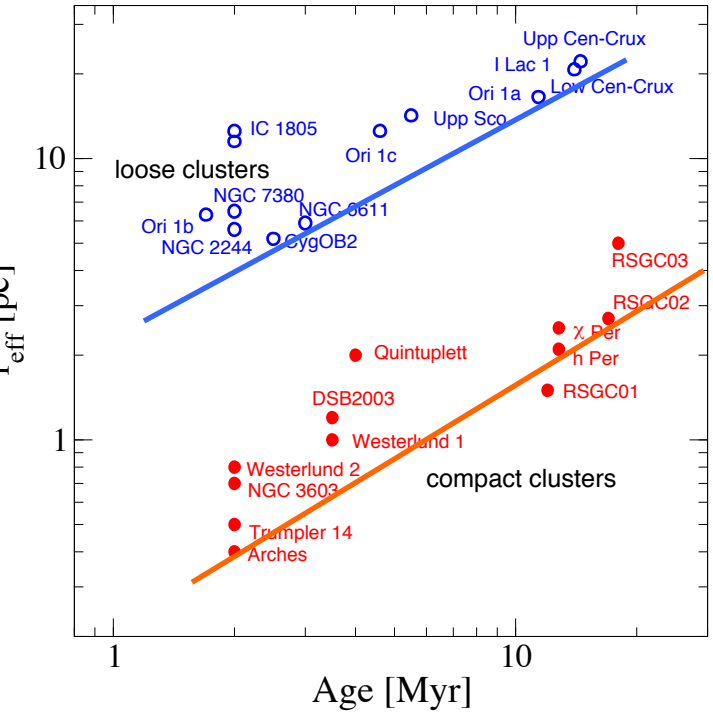
ASSOCIATIONS/ EXTENDED CLUSTERS



Sequence corresponds to **30% SFE**

Corresponds to maximum observed SFE in solar neighbourhood

WHAT DRIVES MASSIVE CLUSTER EXPANSION?



Loose Clusters

Large mass loss, strong expansion

Gas expulsion ~30% SFE

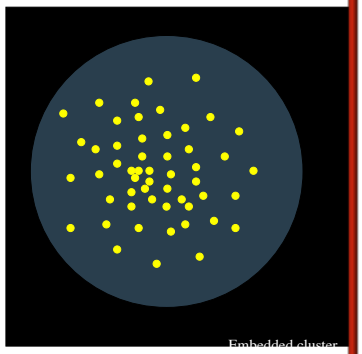
Compact clusters

Little mass loss, strong expansion

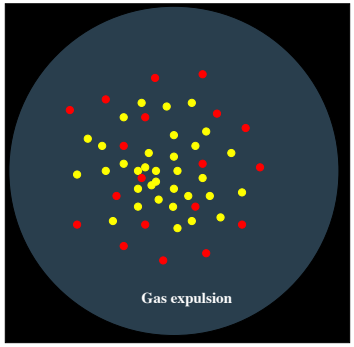
Stellar ejections > 60% SFE

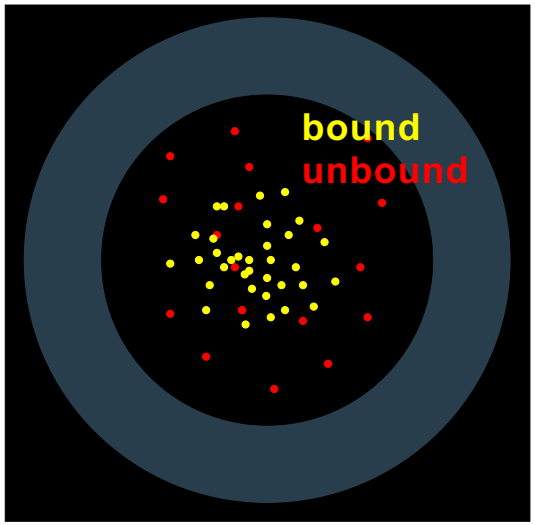
GAS EXPULSION: SCHEMATIC PICTURE

Bound embedded system

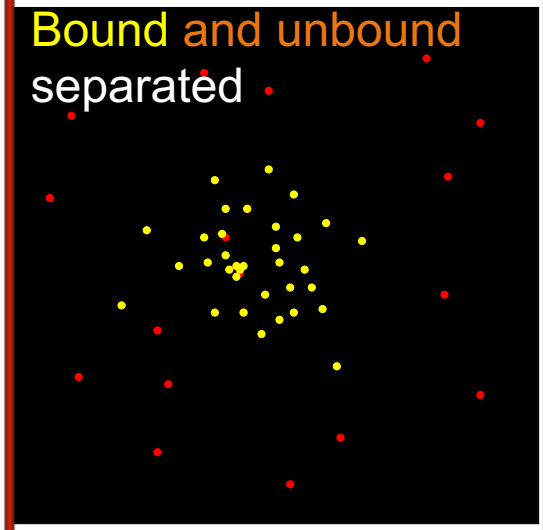


Gas expulsion:
Mixture of bound and unbound stars





Ramnant cluster



Random velocities

Two velocities, not spatially distinguishable

Two velocities, spatially distinguishable

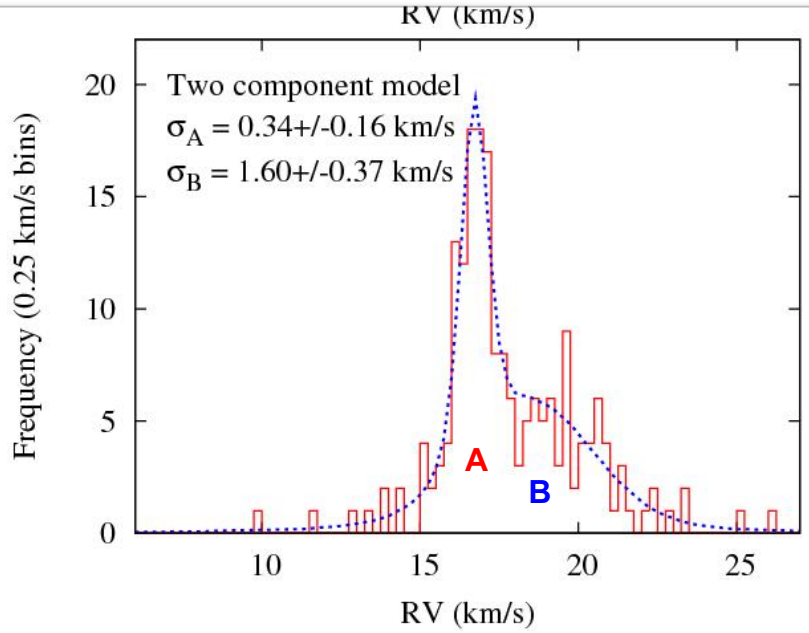
Random velocities

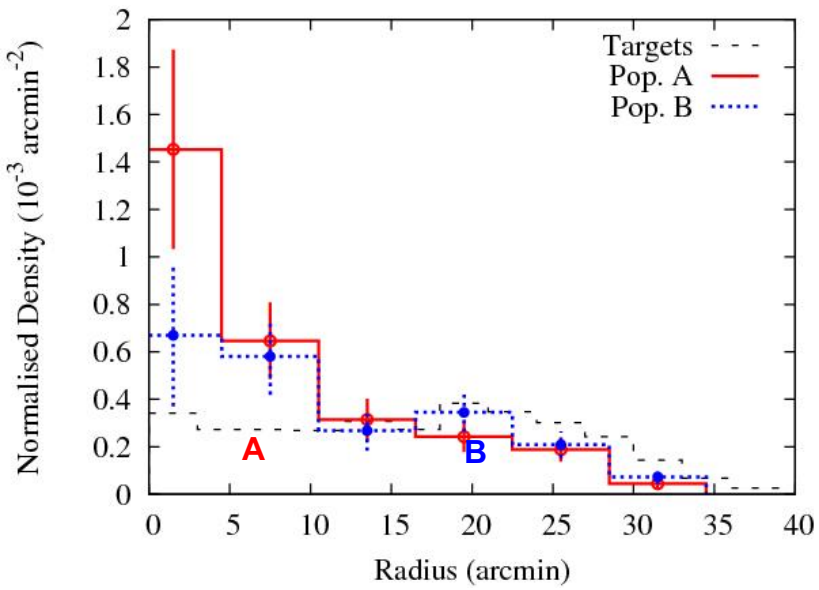
No expansion

Expansion

No expansion

OBSERVATIONAL INDICATION FOR GAS EXPULSION SCENARIO





Gaia-Eso Survey data of γ Velorum cluster (Jeffries et al. 2014)

Two populations well separated in space and velocity

OBSERVATIONS SHOW:

Most stars form in stellar groups

- **either in associations or clusters**
- **so far we only investigated those in associations**
- **distinct mass-size relations exist**

Associations:

- **Gas expulsion driven expansion seems likely explanation**
- **most stars unbound within 10 Myr**
- **their remains a remnant cluster**

Clusters

- **survive because of their compactness, not their mass**
- **we have no idea how they form**