Spatial Properties of Star Forming Regions

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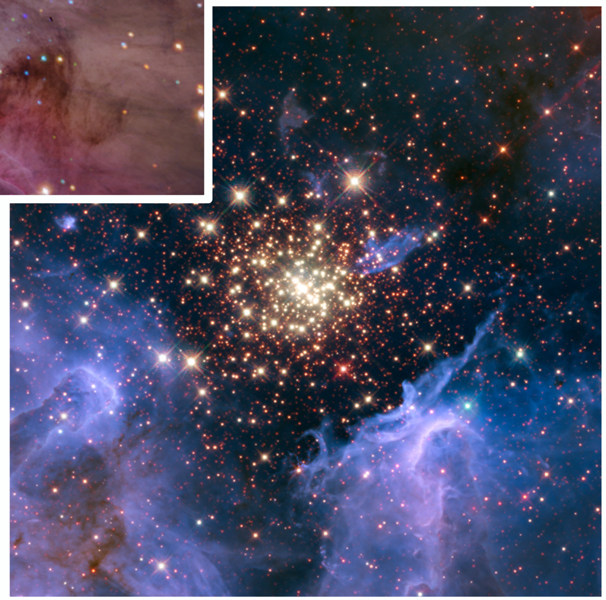
Introduction & Motivation

Young stars predominantly observed in groups and clusters.

May be born in such environments and certainly spend the first few Myrs of their lives in them.

Understanding how stars are distributed at their birth and during the first few Myrs of their lives is important for:

- star formation and the IMF
- properties of binary systems
- evolution of protoplanetary disks
- formation of planetary systems
- origin of open & globular clusters



Organisation of this review

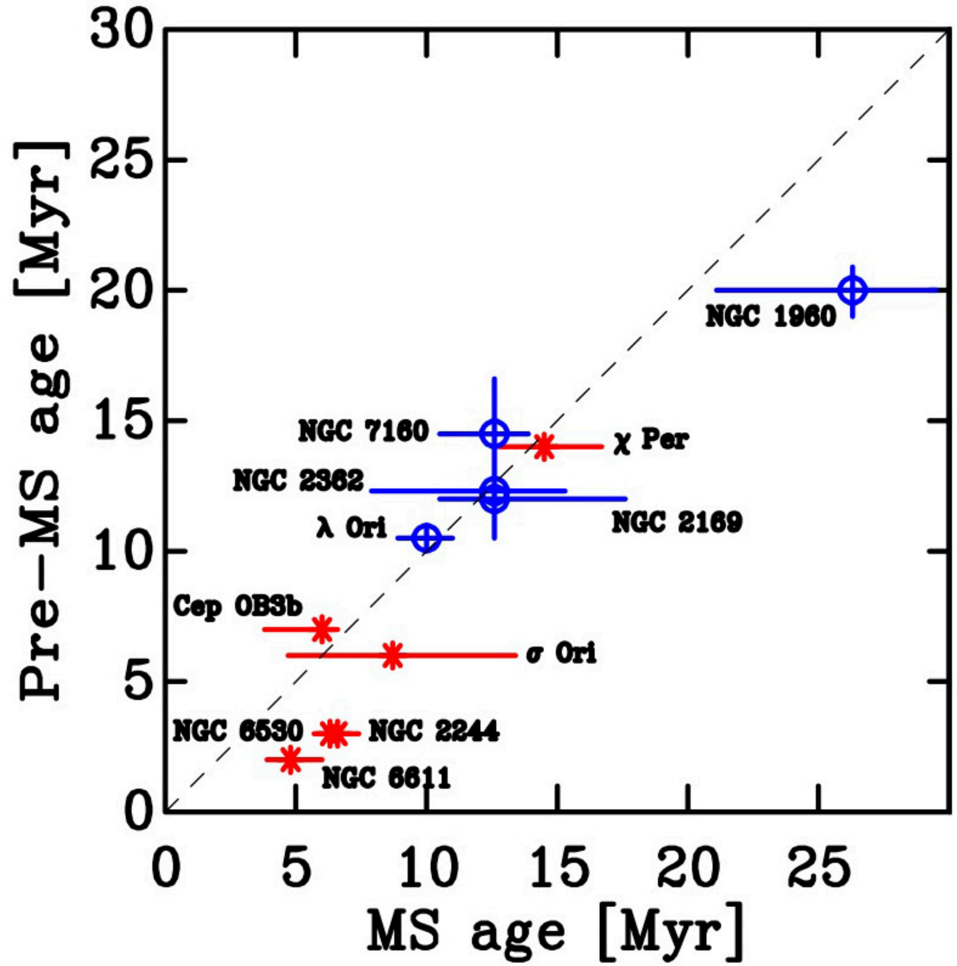
Organisation based on the key phases in the evolution of young stellar structures:

- Spatial distribution of gas during star formation
- Initial spatial distribution of protostars
- Evolution of structure and dynamics of young stars
- Formation of star clusters and OB associations

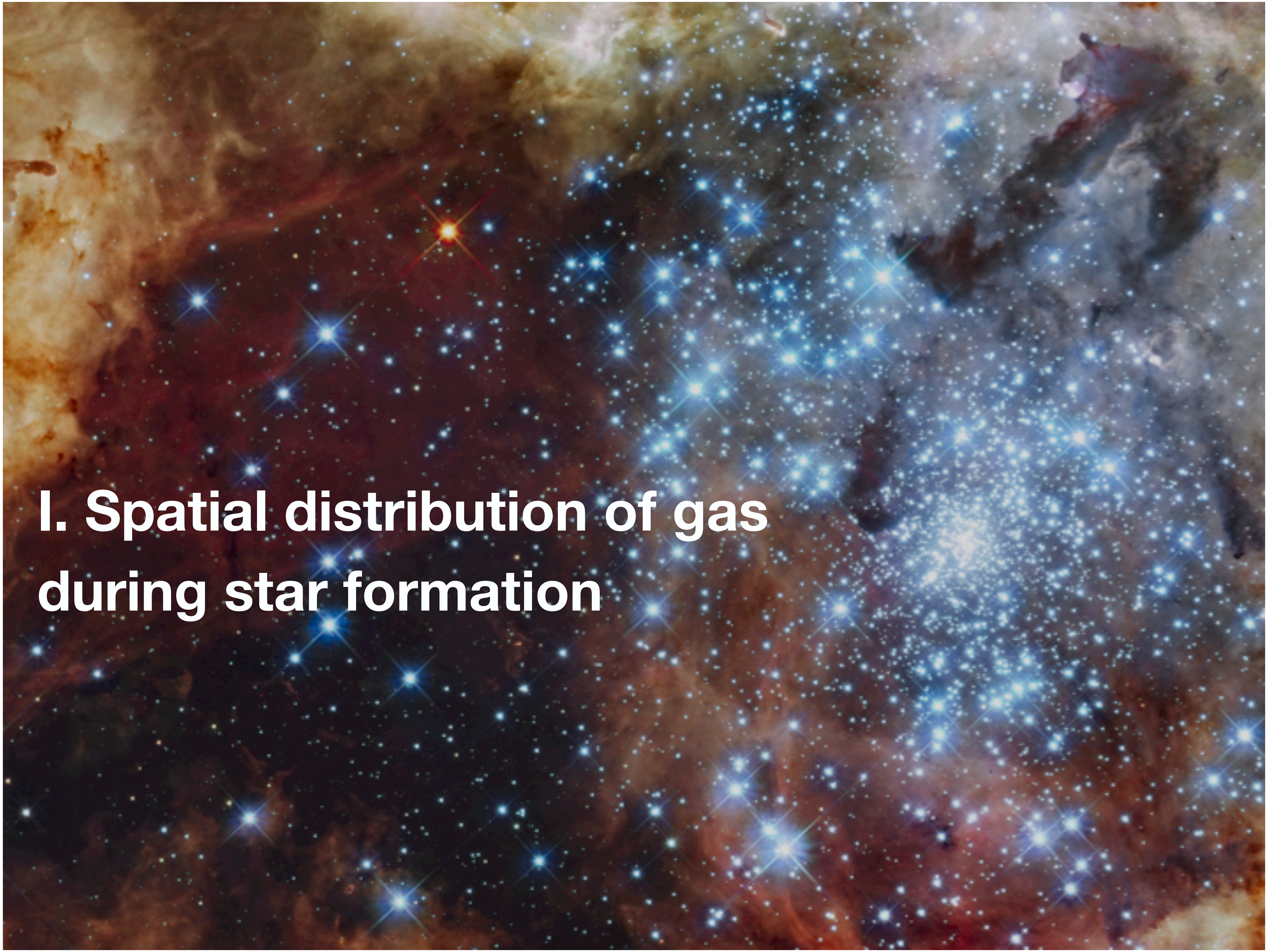
Short note on timescales

Recent observations suggest young clusters (< 10 Myr) may be twice as old as once thought (e.g., Kraus+ 2012, Bell+ 2013).

This provides more time for stars to move from their birth places and for systems to dynamically evolve.



Bell+ (2013)

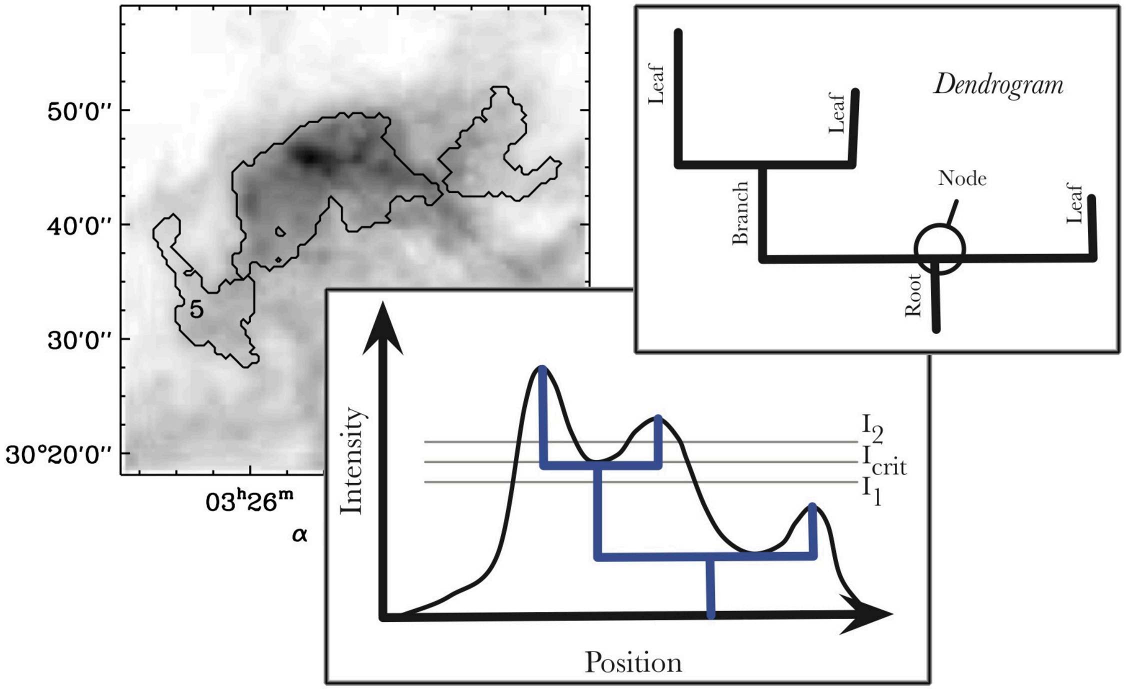


I. Spatial distribution of gas during star formation

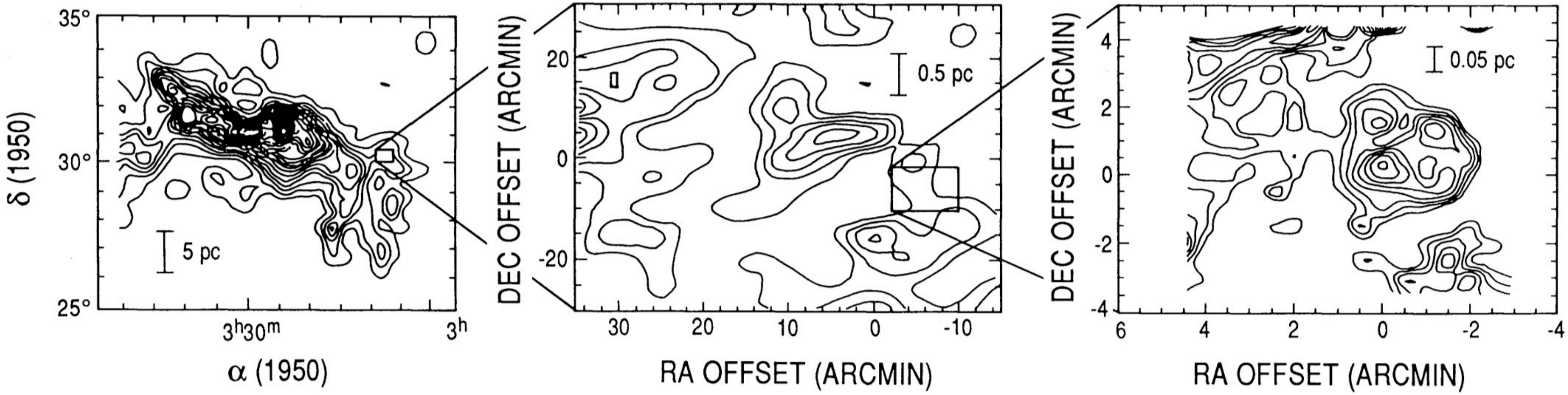
Hierarchical structure of molecular clouds

Molecular clouds are observed to have a hierarchical structure (e.g., Larson 1981, Blitz & Stark 1986, Falgarone+ 1991).

Many attempts to quantify or represent this hierarchical structure in some way (e.g., Houlahan & Scalo 1992, Rosolowsky+ 2008)



Rosolowsky+ (2008)



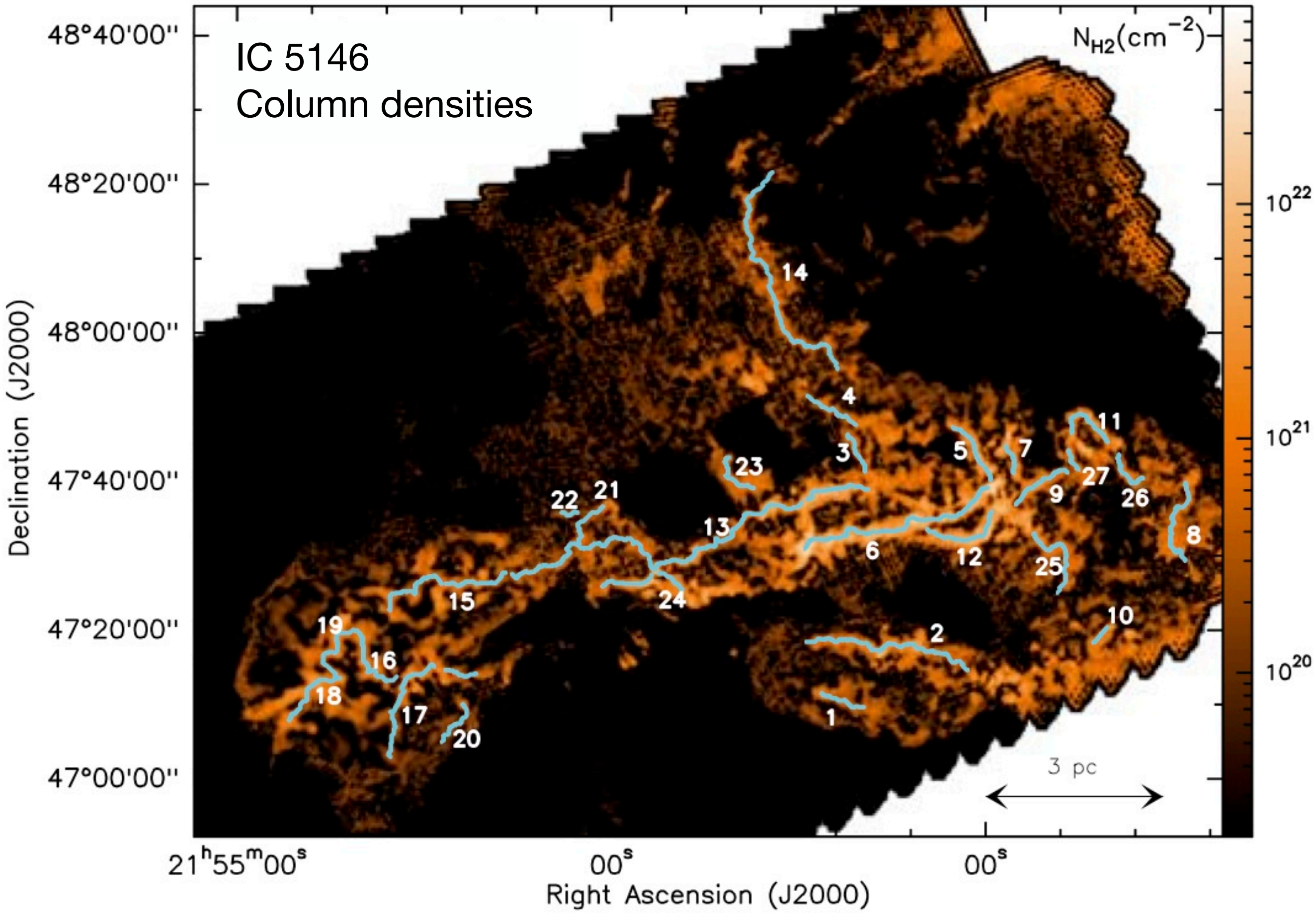
Falgarone+ (1991)

Filaments in molecular clouds

Filaments in molecular clouds known for many decades (e.g., Schneider & Elmegreen 1979, Mizuno+ 1995).

Herschel observations demonstrated them to be common in molecular clouds (e.g., Andre+ 2010, 2014, Menshchikov+ 2010).

Evidence that filaments have a universal width of ~0.1pc (Arzoumanian+ 2011) may however be due to the width-measuring method (Panopoulou+ 2016).

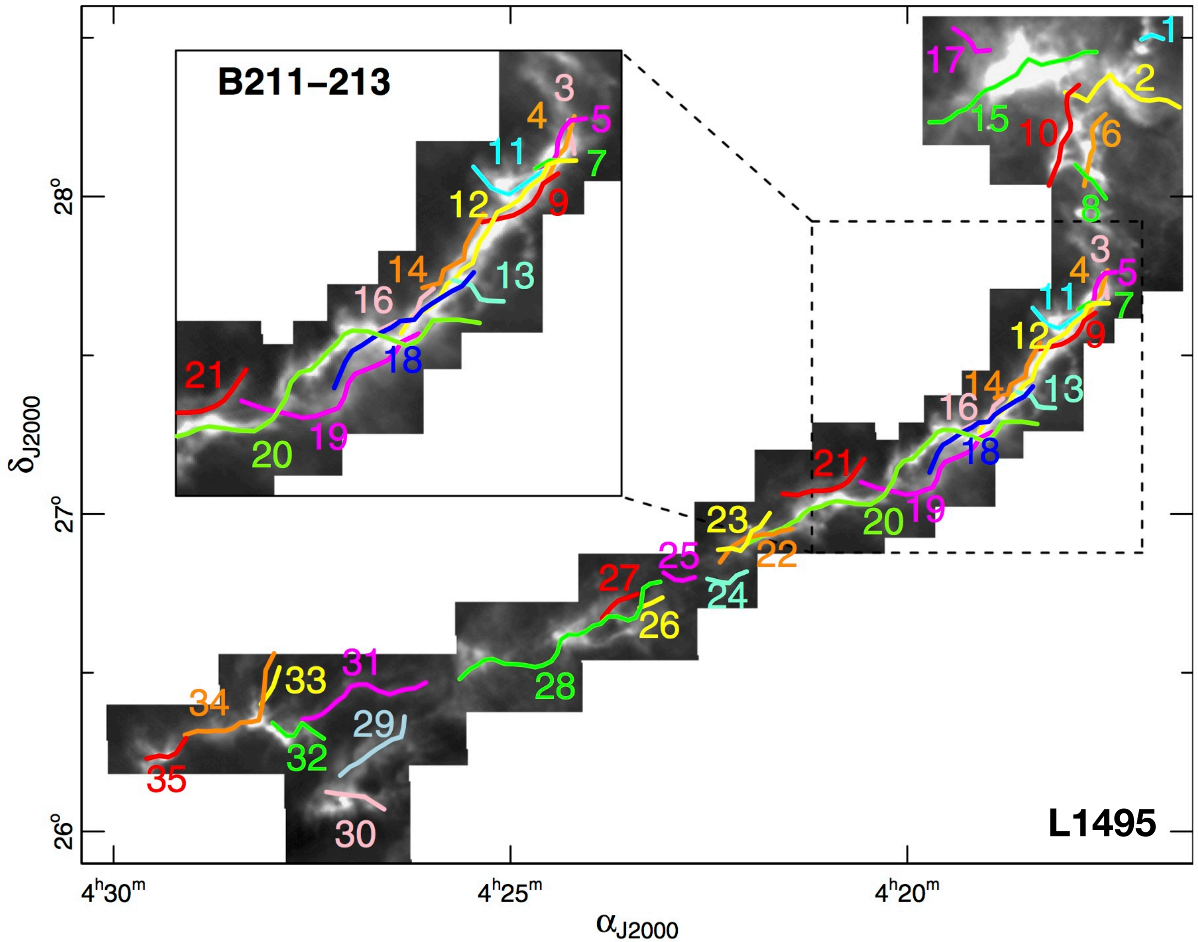


Arzoumanian+ (2011)

Substructure within filaments: Sub-filaments and fibers

Filaments may be divided into smaller filamentary structures referred to as either sub-filaments (Henshaw+ 2016a,b) or fibers (Tafalla & Hacar 2015, Hacar+ 2017), though they haven't been observed everywhere (Friesen+ 2016).

These subsubstructures are typically identified in PPV space (e.g., Hacar+ 2013).



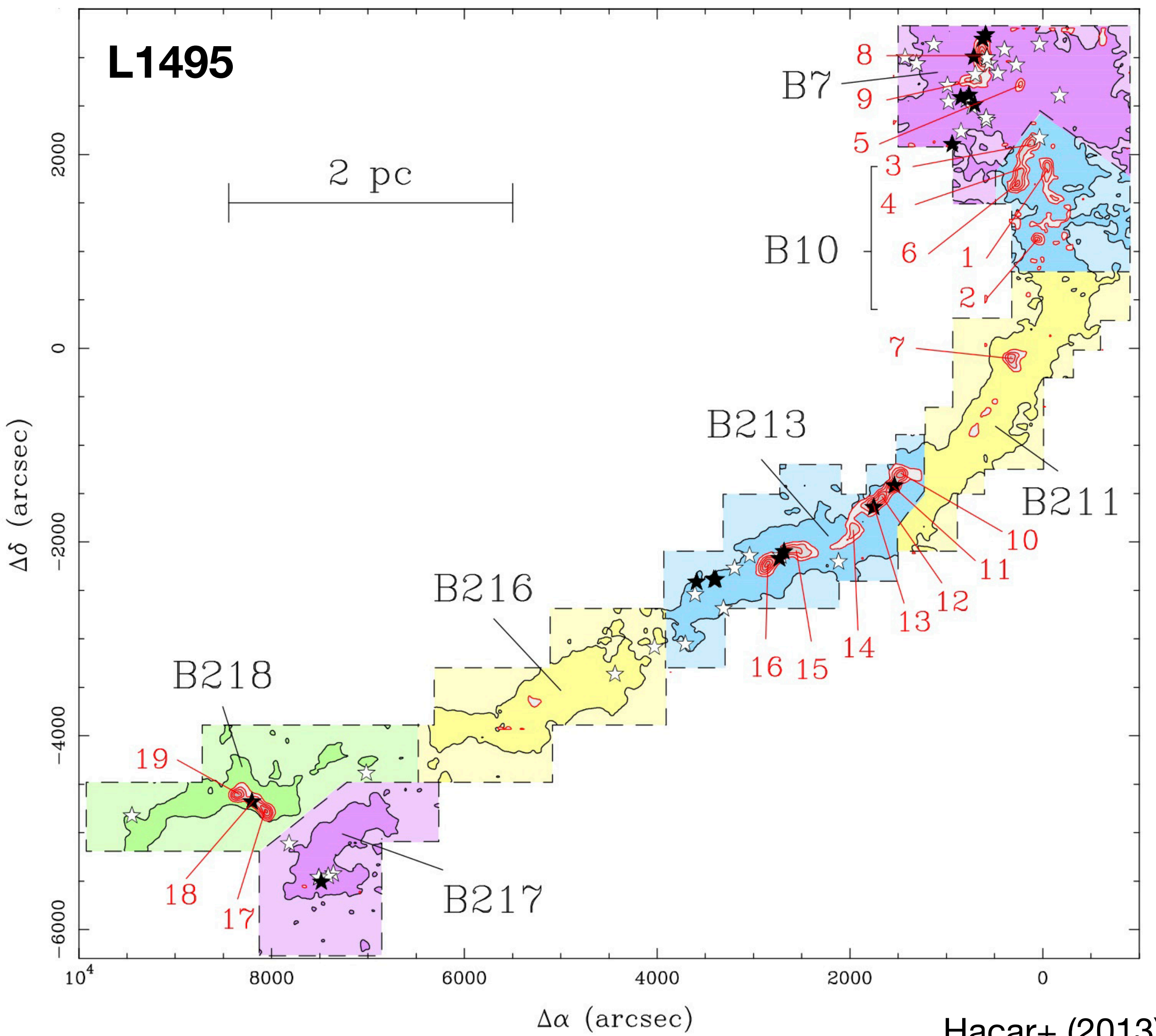
Hacar+ (2013)

Substructure within filaments: Dense clumps and cores

Filaments, or sub-filaments, contain multiple clumps or cores (e.g., Beuther+ 2013).

Cores exhibit semi-regular spacing along the filament of 0.2-0.3pc (e.g., Hacar+ 2013, Ragan+ 2015).

Thought to be due to fragmentation from either gravitational or magnetohydrodynamical instabilities (e.g., Henshaw+ 2016).



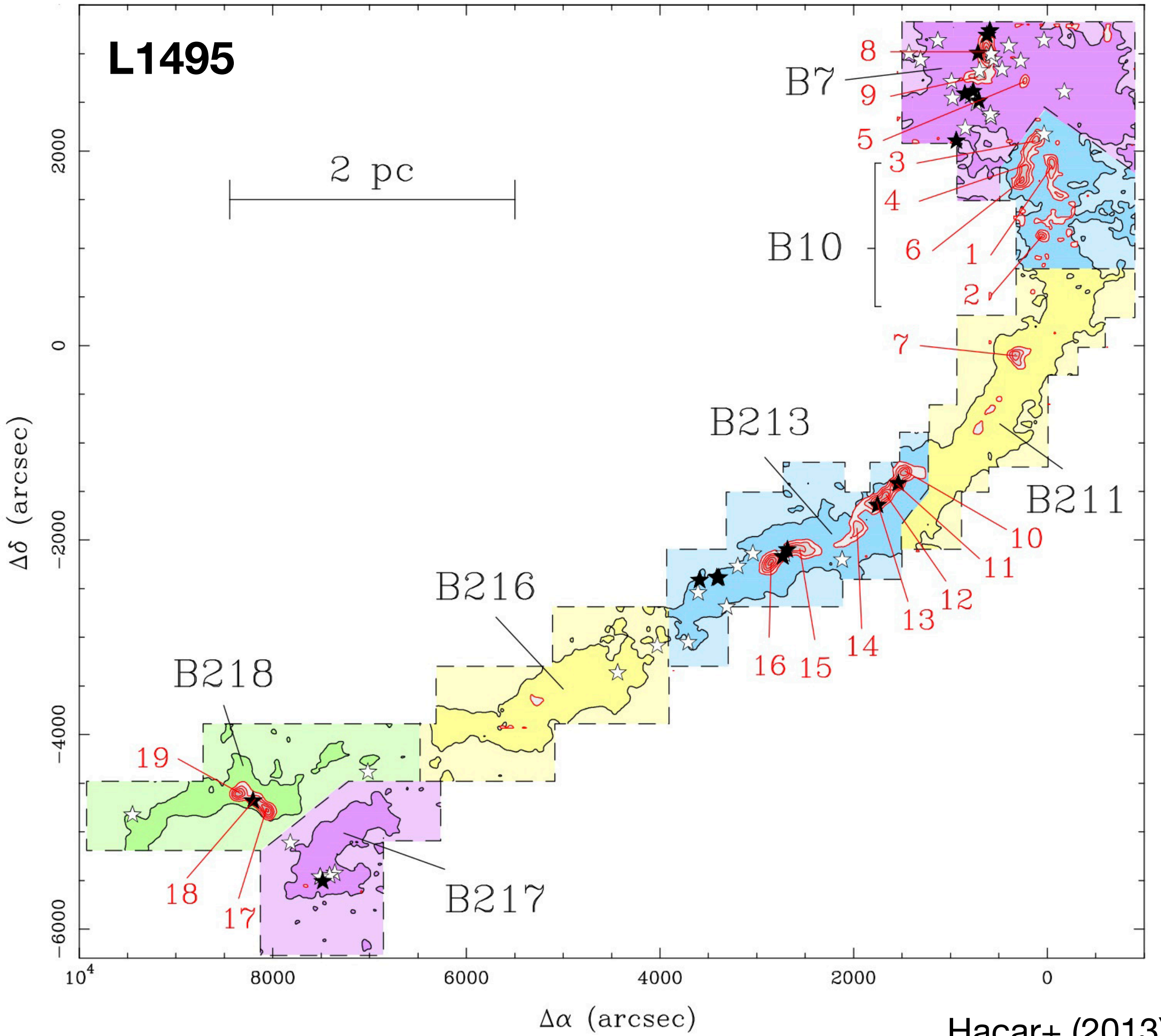
Hacar+ (2013)

Substructure within filaments: Dense clumps and cores

Not all filaments seem to be forming dense cores (e.g., Hacar+ 2013).

Cores found preferentially in the densest filaments (Hacar+ 2013, Andre+ 2014, Konyves+ 2015).

Equivalent to the observation that regions with the most high column density material have the highest star formation efficiencies (e.g., Lada+ 2010, Sadavoy+ 2014).

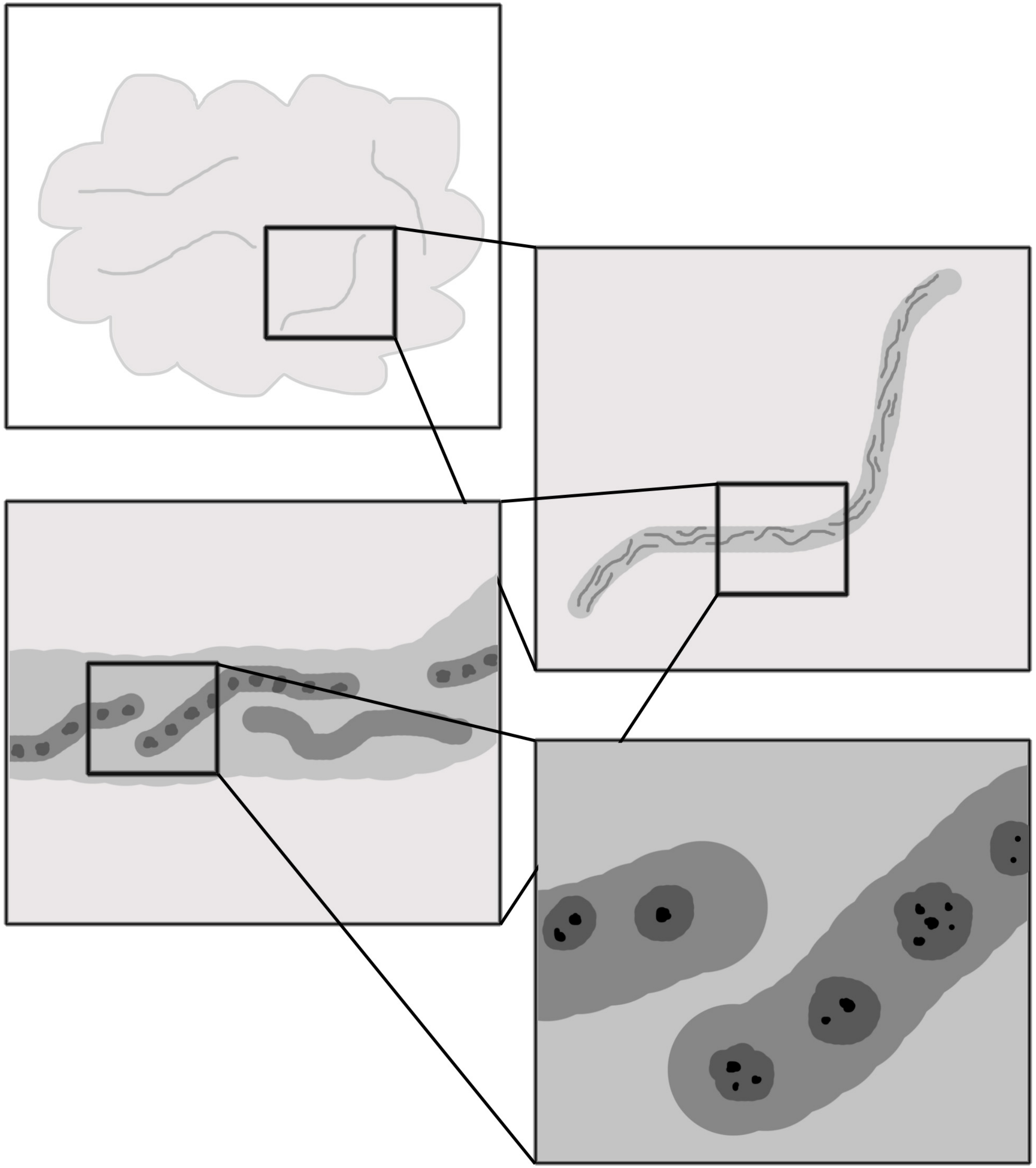


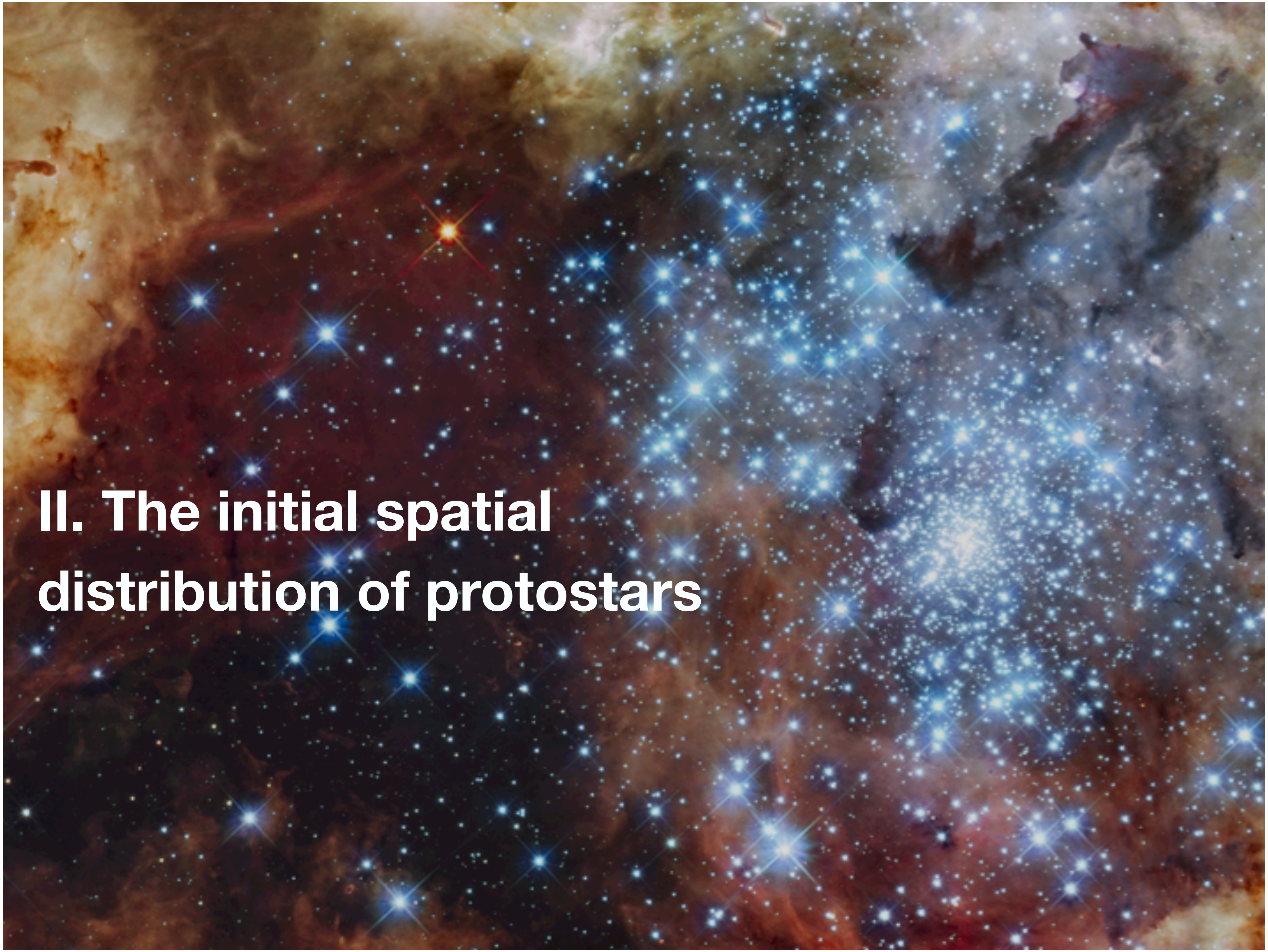
Hacar+ (2013)

The growth of substructure during star formation

Turbulence generates over-densities (substructure) that are accentuated by fragmentation, leading to smaller and denser structures.

The entire star formation process generates and enhances substructure within star forming regions, and thus in the resulting stellar distribution.



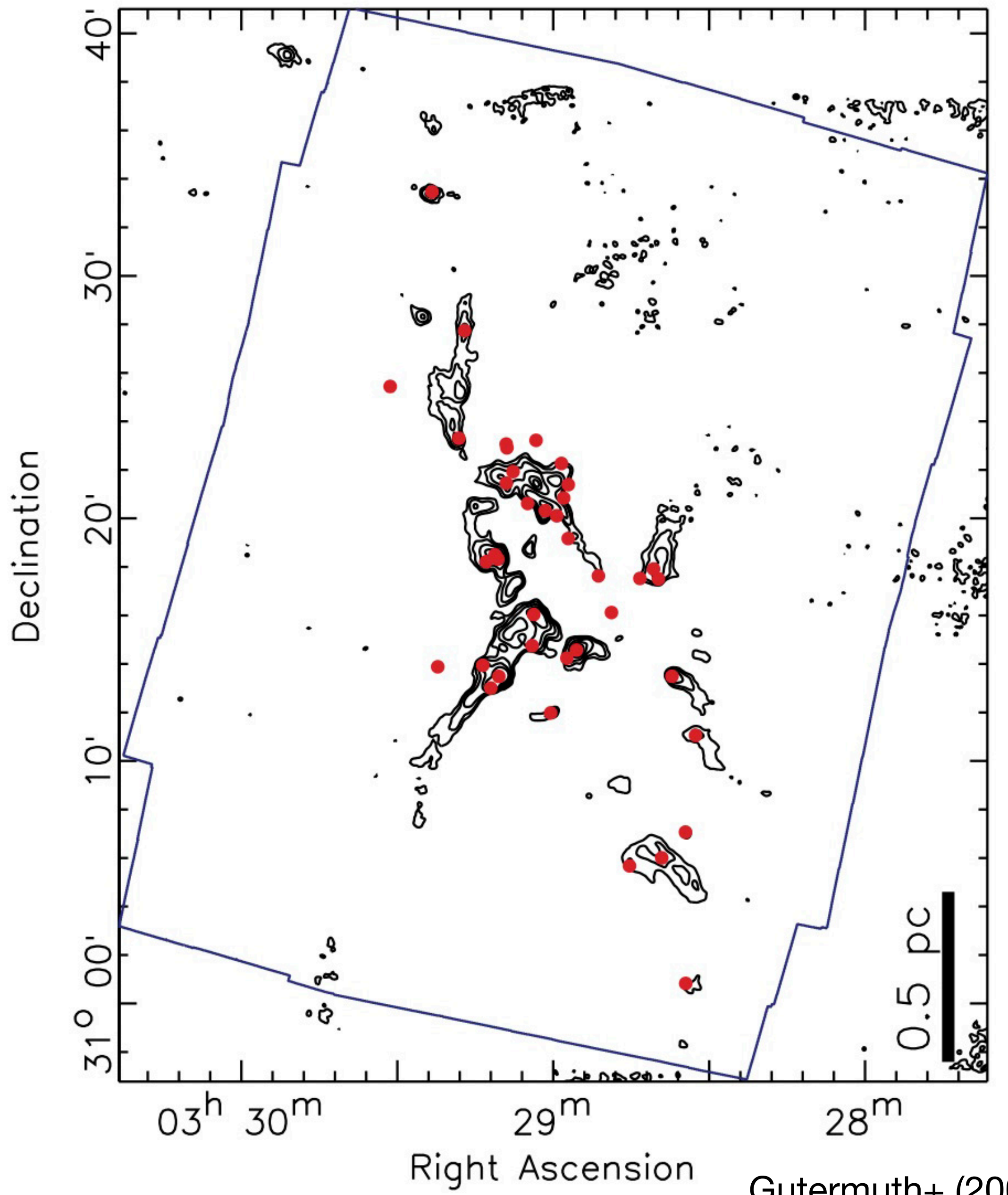

II. The initial spatial
distribution of protostars

Initial distribution of protostars follows the dense gas

Spatial distribution of protostars follows the dense gas: 69% of Class I sources trace high column density gas (Gutermuth+ 2008, Heiderman & Evans 2015).

Stellar and gas velocities also correlated, from the dense core stage (Walsh+ 2004) to the protostellar stage (Covey+ 2006).

Initial distribution of stars results directly from the fragmentation of dense gas.



Gutermuth+ (2008)

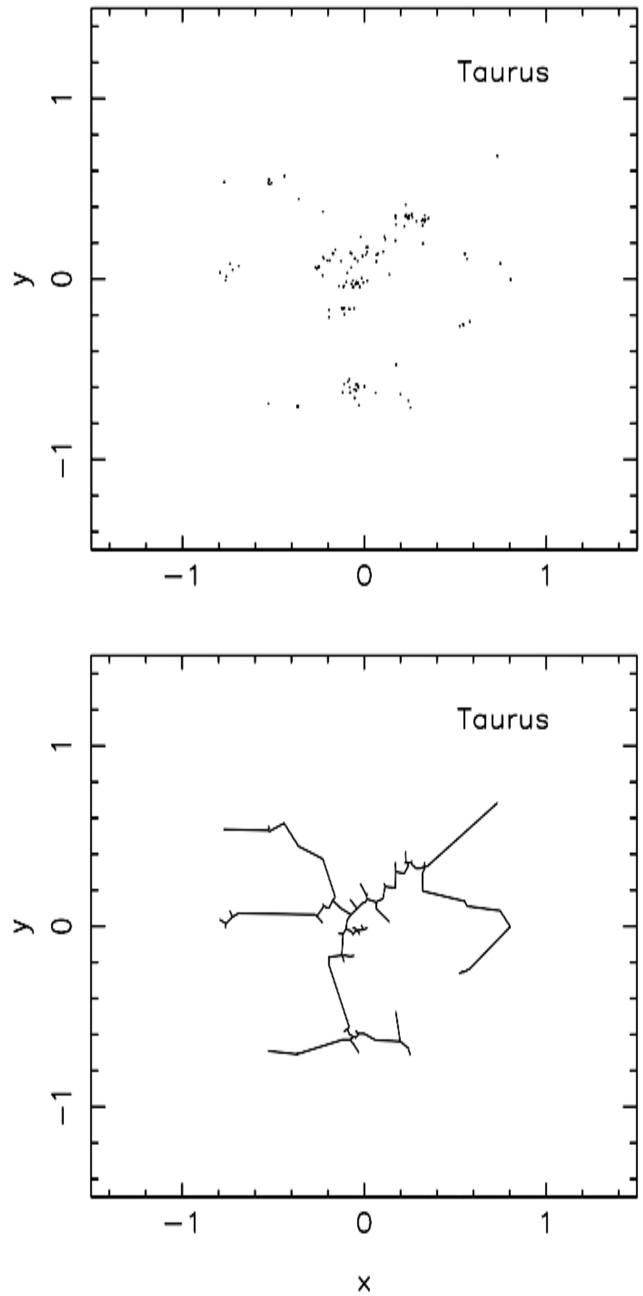
The Q parameter and substructured distribution of YSOs

Substructure can be quantified using the Q parameter (Cartwright & Whitworth 2004):
- $Q < 0.8$: Substructured
- $Q > 0.8$: Centrally concentrated

Very young (< 1 Myr) regions have low Q values thought to be due to primordial (fractal?) structure:
- Corona Australis: $Q = 0.38$ (Parker 2014)
- Taurus: $Q = 0.47$ (Cartwright & Whitworth 2004)
- Rho Oph: $Q = 0.56$ (Parker+ 2012)

Recent variants such as Q^{+} (Jaffa+ 2016) go even further in quantifying the fractal structure of star forming regions in a multidimensional way.

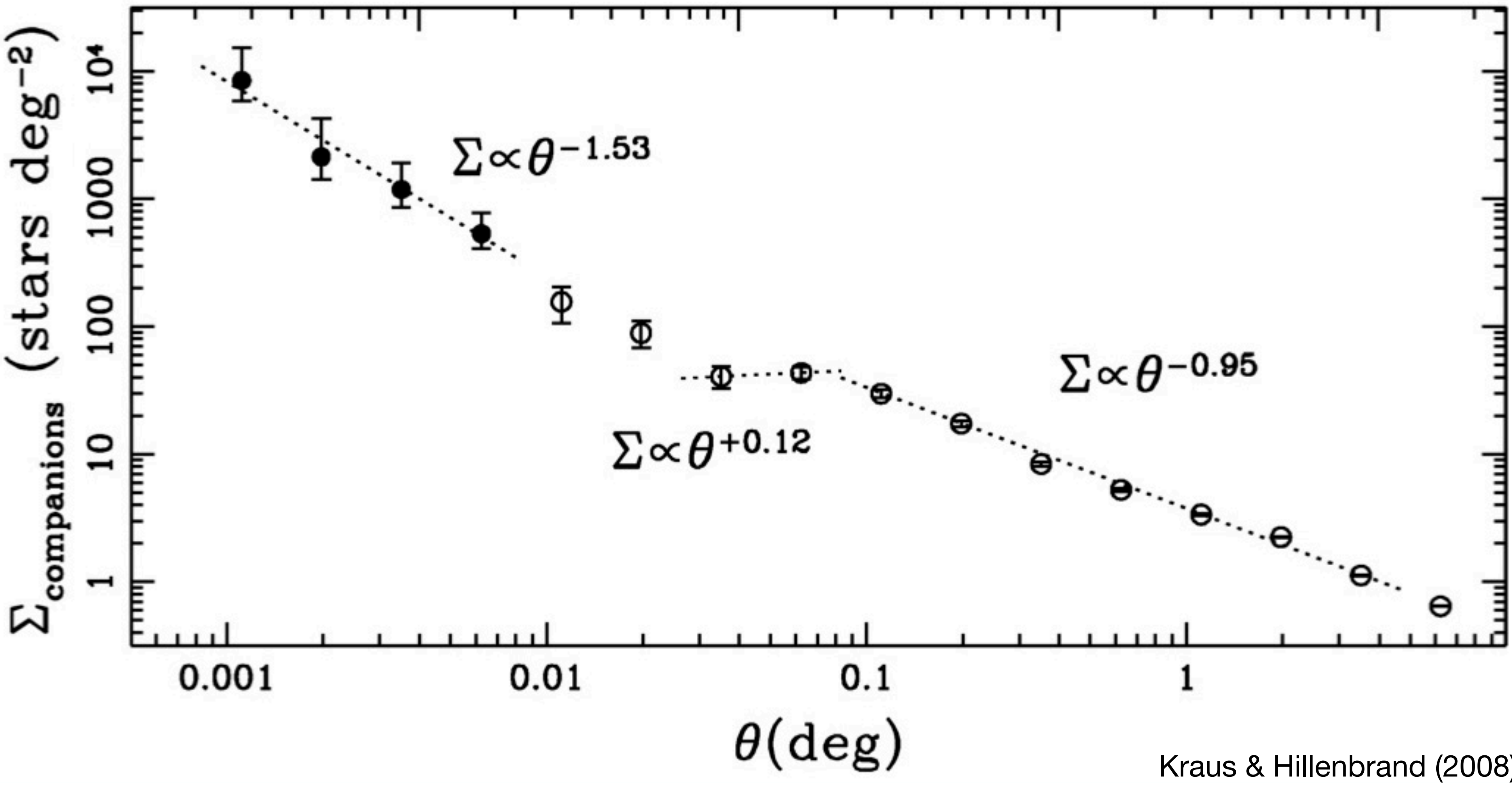
Note that Q is dependent on many observational issues such as incompleteness (Bastian+ 2009), sample size (Lomax+ 2011, Parker & Dale 2015), and contamination (Bastian+ 2009). These issues typically cause Q to converge towards intermediate values of ~0.8.



Cartwright & Whitworth (2004)

The 2-point correlation function

The 2-point correlation function (2PCF) shows two distinct power-laws: a steep binary regime at small scales and a smoother clustering regime beyond a breaking point (e.g., Gomez+ 1993, Larson 1995, Bate+ 1998, Kraus & Hillenbrand 2008).



Kraus & Hillenbrand (2008)

The 2-point correlation function: Binary regime

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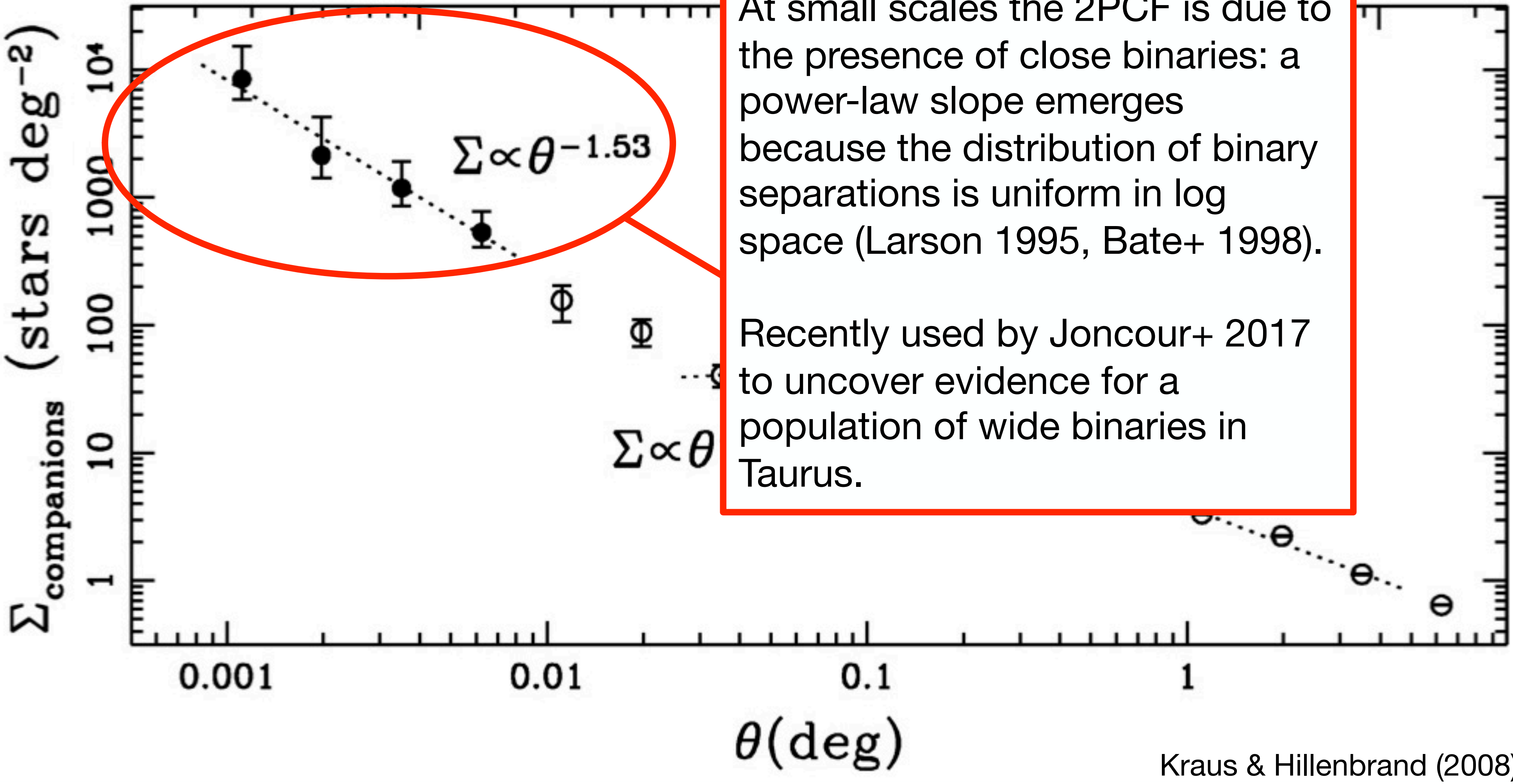


At small scales the 2PCF is due to the presence of close binaries: a power-law slope emerges because the distribution of binary separations is uniform in log space (Larson 1995, Bate+ 1998).

Recently used by Joncour+ 2017 to uncover evidence for a population of wide binaries in Taurus.

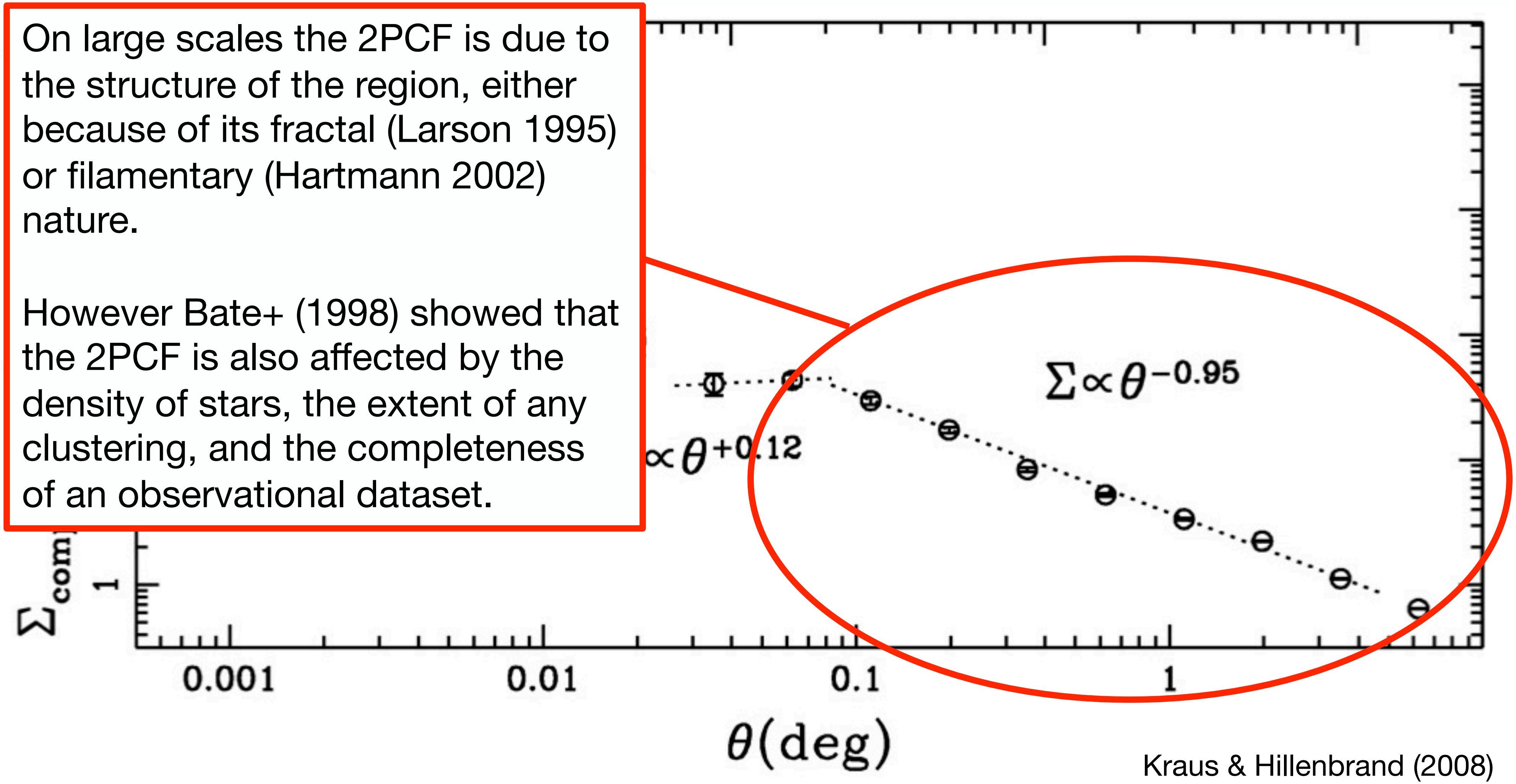
Kraus & Hillenbrand (2008)

The 2-point correlation function: Primordial structure

The 2-point correlation function (2PCF) shows two distinct power-laws: a steep binary regime at small scales and a smoother clustering regime beyond a breaking point (e.g., Gomez+ 1993, Larson 1995, Bate+ 1998, Kraus & Hillenbrand 2008).

On large scales the 2PCF is due to the structure of the region, either because of its fractal (Larson 1995) or filamentary (Hartmann 2002) nature.

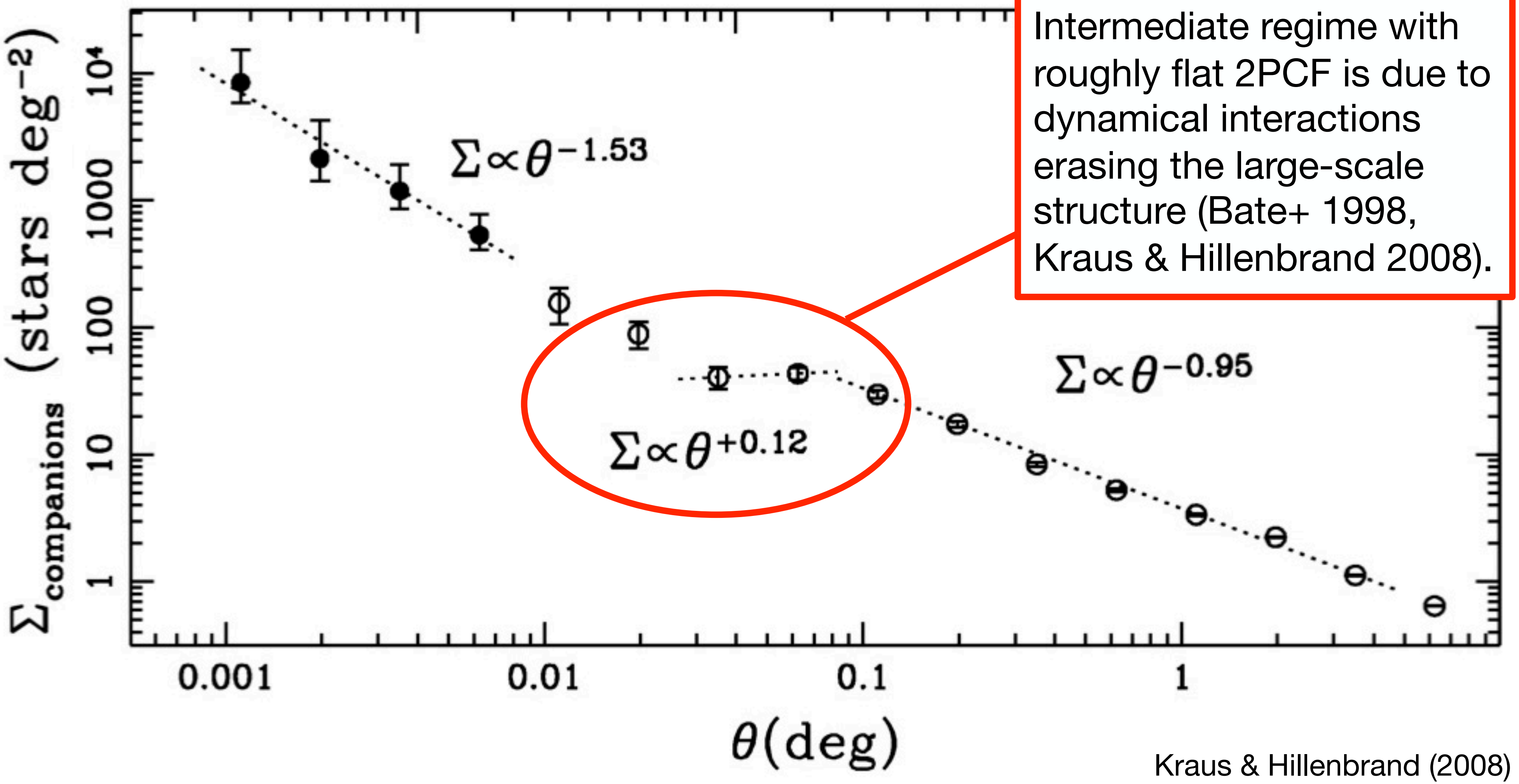
However Bate+ (1998) showed that the 2PCF is also affected by the density of stars, the extent of any clustering, and the completeness of an observational dataset.



Kraus & Hillenbrand (2008)

The 2-point correlation function: Dynamical mixing regime

The 2-point correlation function (2PCF) shows two distinct power-laws: a steep binary regime at small scales and a smoother clustering regime beyond a breaking point (e.g., Gomez+ 1993, Larson 1995, Bate+ 1998, Kraus & Hillenbrand 2008).

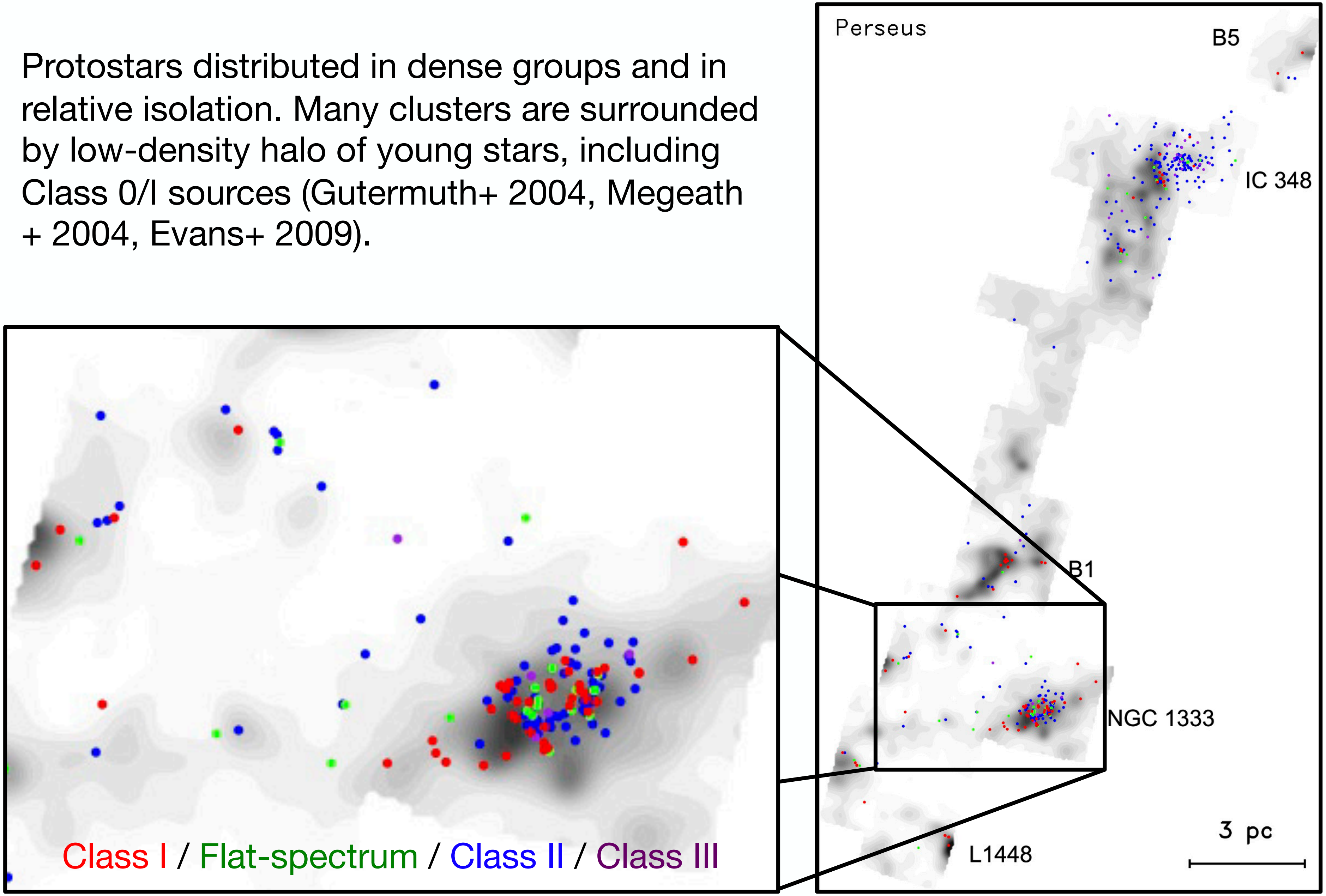


Intermediate regime with roughly flat 2PCF is due to dynamical interactions erasing the large-scale structure (Bate+ 1998, Kraus & Hillenbrand 2008).

Kraus & Hillenbrand (2008)

Initial density distribution of protostars

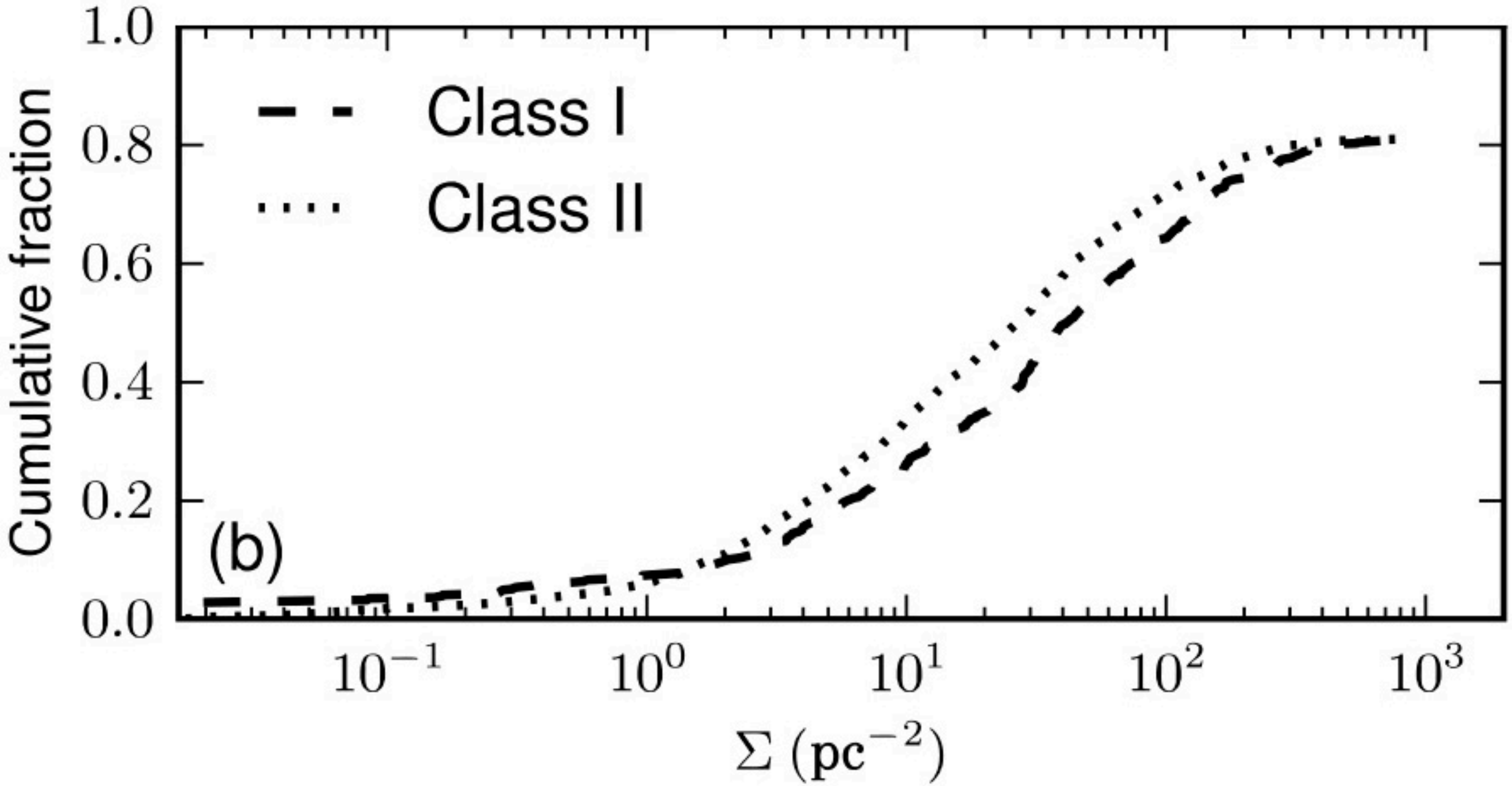
Protostars distributed in dense groups and in relative isolation. Many clusters are surrounded by low-density halo of young stars, including Class 0/I sources (Gutermuth+ 2004, Megeath + 2004, Evans+ 2009).



Adapted from Evans+ (2009)

Surface density distribution of young stars

Surface density distribution of young stars appears continuous, i.e. there is no preferred scale for star formation (Bressert+ 2010 - but see also Gieles+ 2012, Parker & Meyer 2012 for the impact of dynamics on this distribution).



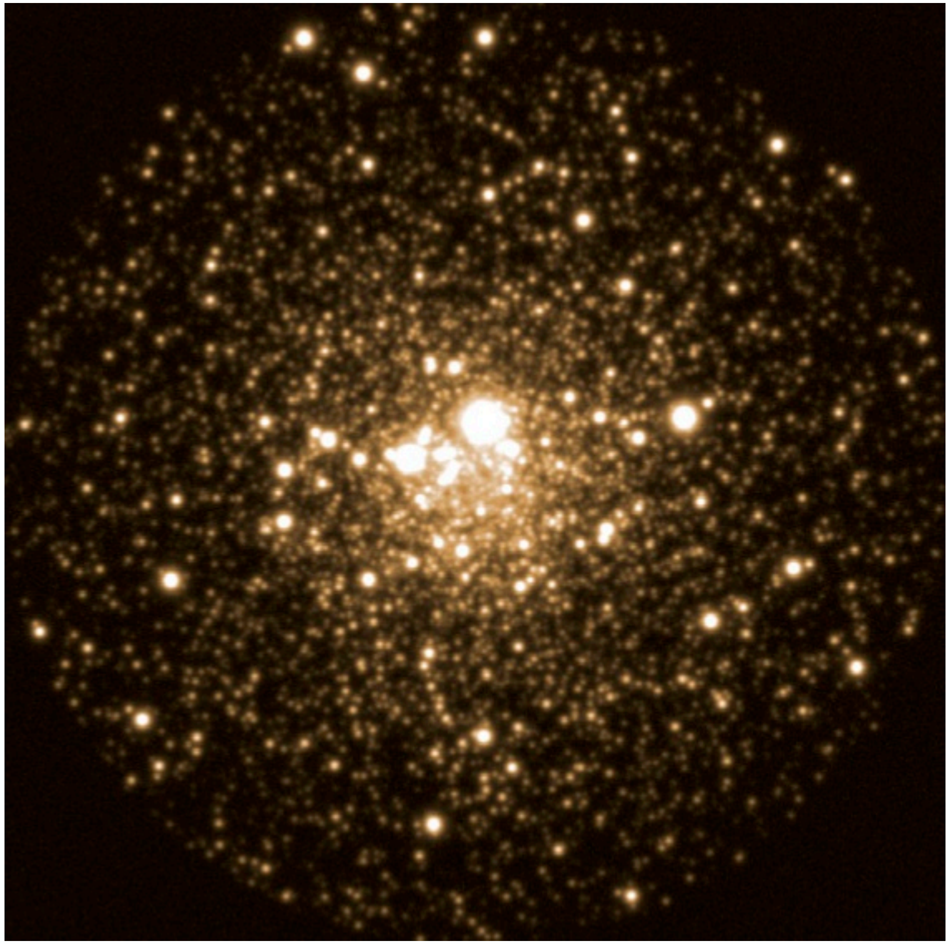
Mass segregation

Mass segregation is the apparent preference for massive stars to be found in the densest parts of a star forming region or star cluster.

Commonly observed in many young clusters (e.g., Hillenbrand & Hartmann 1998, Stolte+ 2006, Gennaro+ 2011) – though not ubiquitous (e.g., Chen+ 2007, Parker+ 2011, Wright+ 2014).

Thought to be a primordial effect of SF as there is insufficient time for it to occur dynamically (Bonnell & Davies 1998).

Recent simulations show that dynamical mass segregation can occur very quickly given the right initial conditions (the cool collapse of a substructured distribution, McMillan+ 2007, Allison+ 2009 – see also Parker+ 2016).



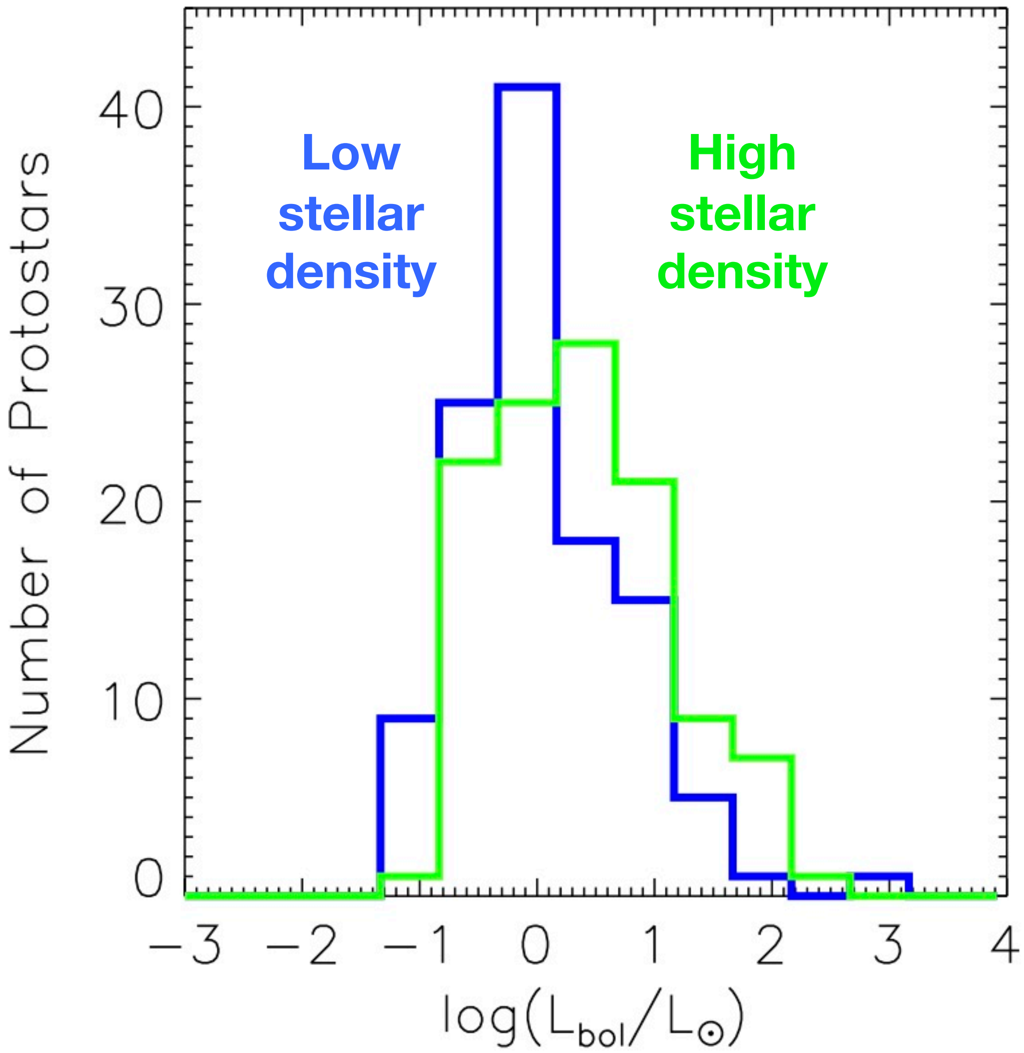
Ascenso+ (2009)

Mass segregation in dense cores and protostars

Mass segregation typically observed in young stars, but some evidence that it may be present in the distribution of dense cores and protostars.

Kryukova+ (2012, 2014) and Elmegreen+ (2014) found that the densest areas of star forming regions include more luminous protostars (potentially implying more massive).

Kirk+ (2016) found that dense cores in Orion B exhibited mass segregation.

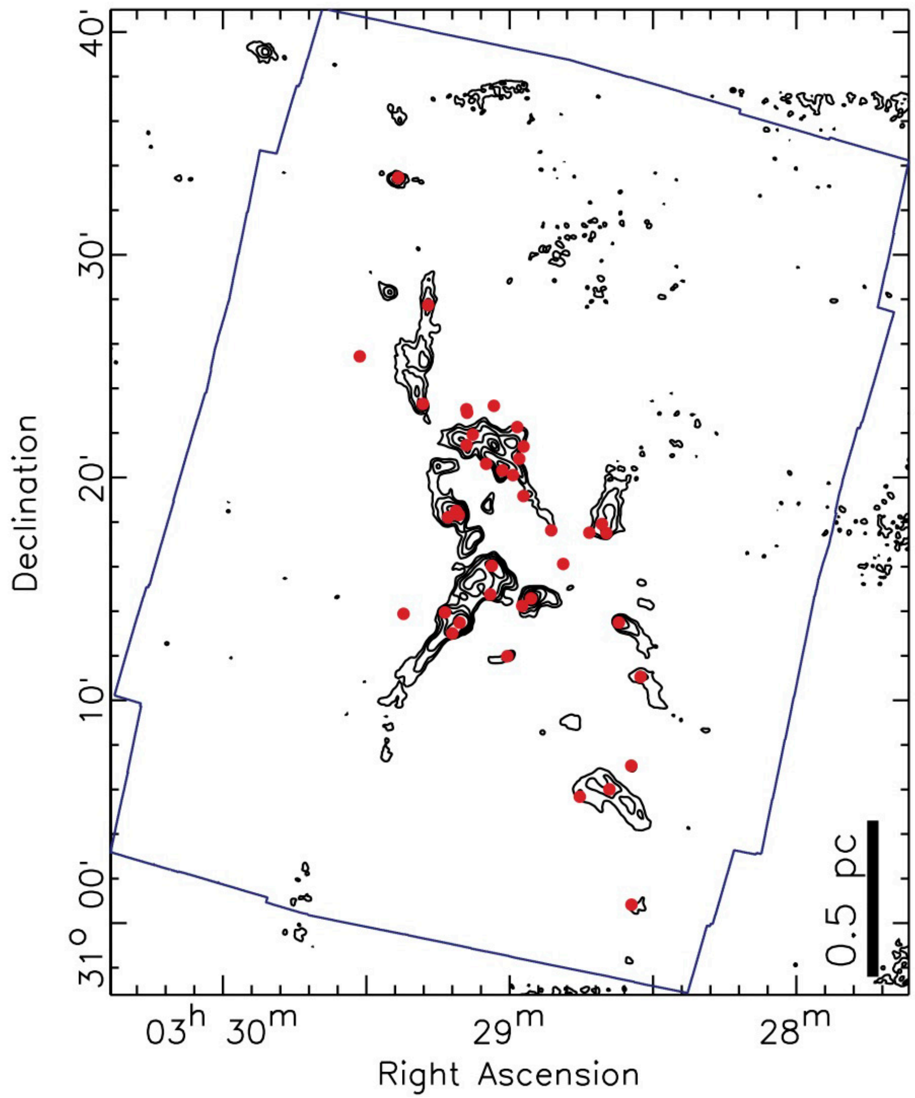


Kryukova+ (2012)

Mass segregation: uncertainties and biases

Measuring mass segregation prone to many uncertainties and biases:

- Subclustering (e.g., Girichidis+ 2012)

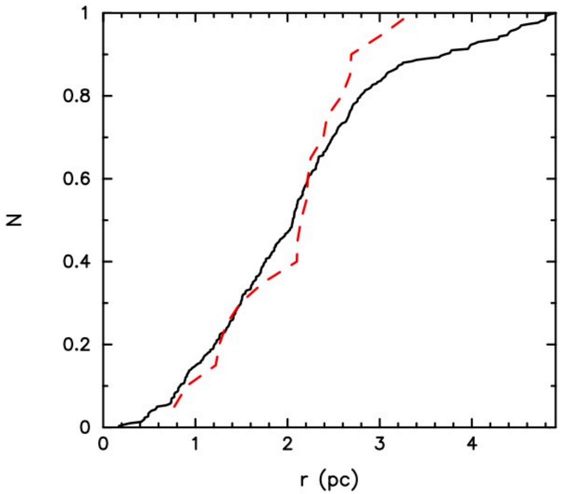


Gutermuth+ (2008)

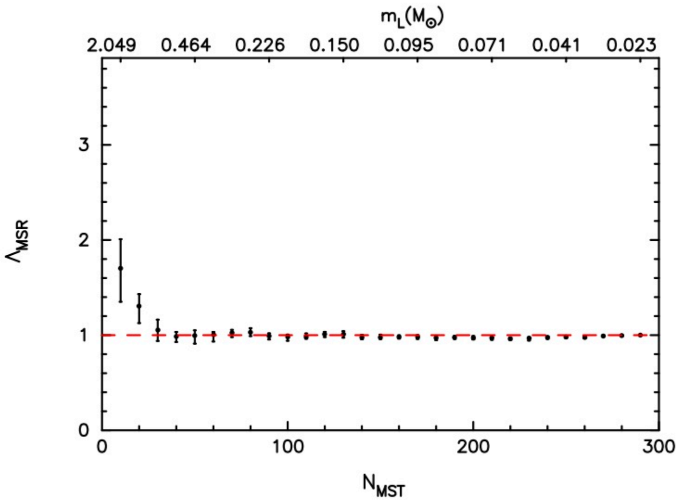
Mass segregation: uncertainties and biases

Measuring mass segregation prone to many uncertainties and biases:

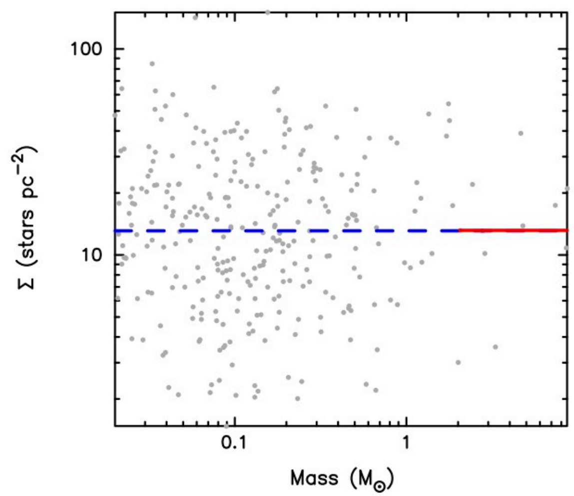
- Subclustering (e.g., Girichidis+ 2012)
- Different measurement methods (Parker & Goodwin 2015)



(a) $\mathcal{M}_{\rm MF}$



(b) $\Lambda_{\rm MSR}$



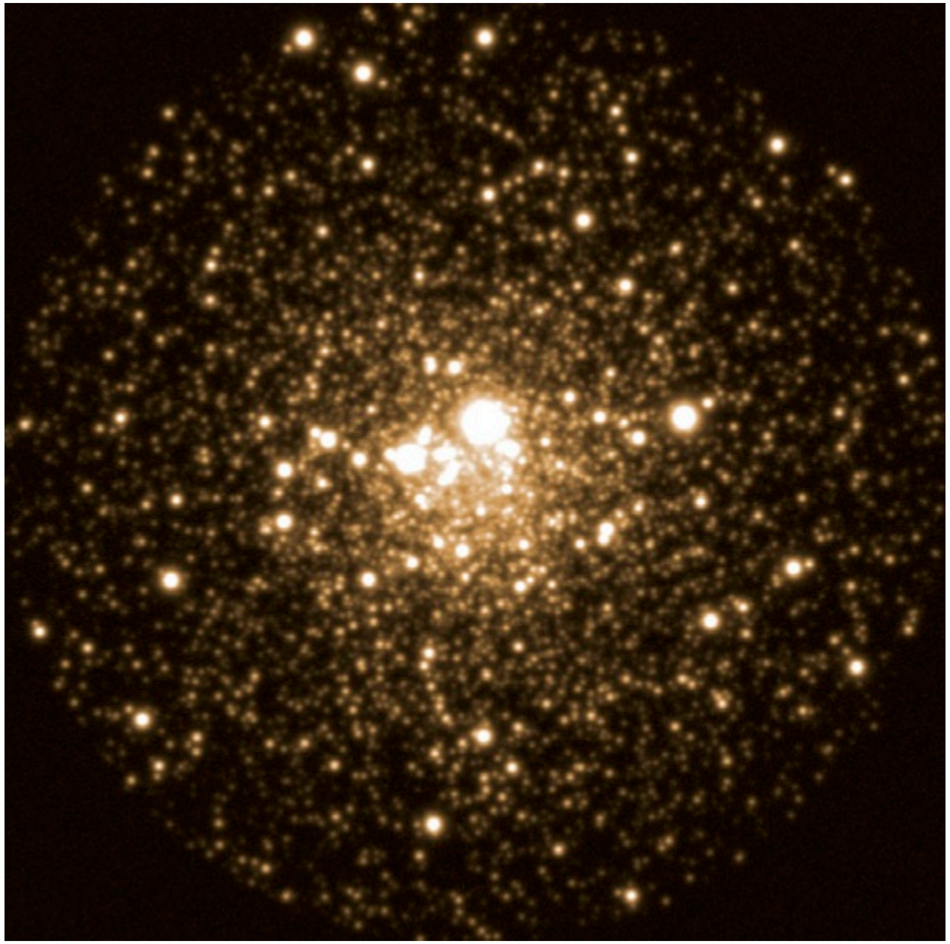
(c) $\Sigma_{\rm LDR}$

Parker & Goodwin (2015)

Mass segregation: uncertainties and biases

Measuring mass segregation prone to many uncertainties and biases:

- Subclustering (e.g., Girichidis+ 2012)
- Different measurement methods (Parker & Goodwin 2015)
- Crowding and low-mass incompleteness (Ascenso+ 2009)

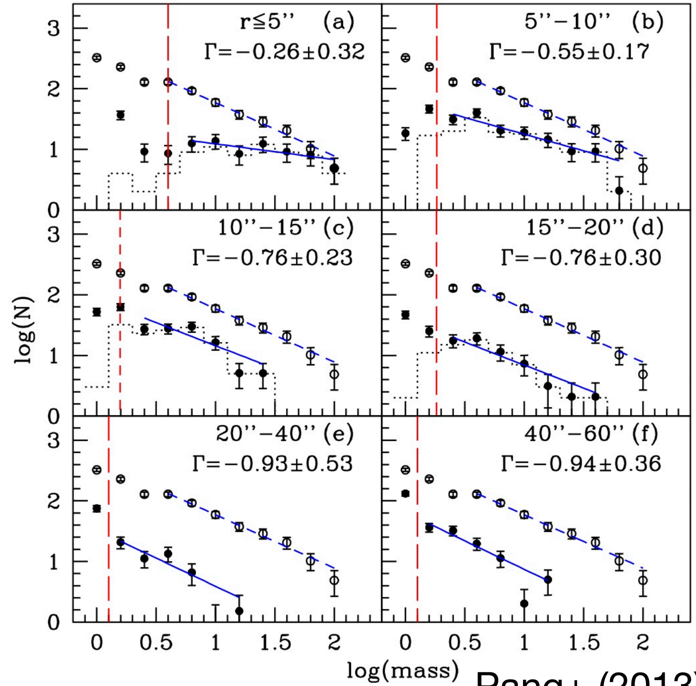


Ascenso+ (2009)

Mass segregation: Crowding at work in dense clusters

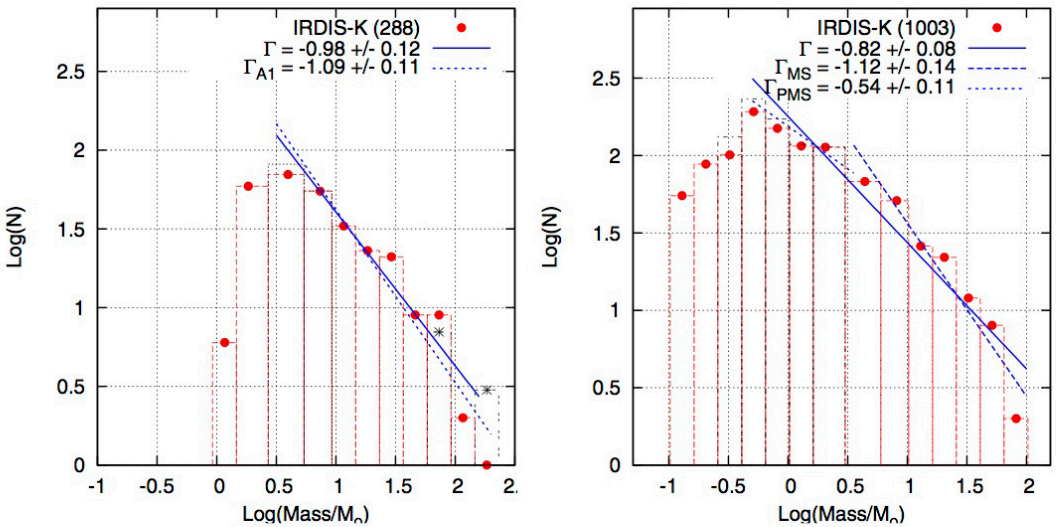
The apparent mass segregation in NGC 3603 (Pang+ 2013) was no longer evident when observed with high-resolution VLT/SPHERE adaptive-optics (Khorrami+ 2016).

HST: Mass segregated



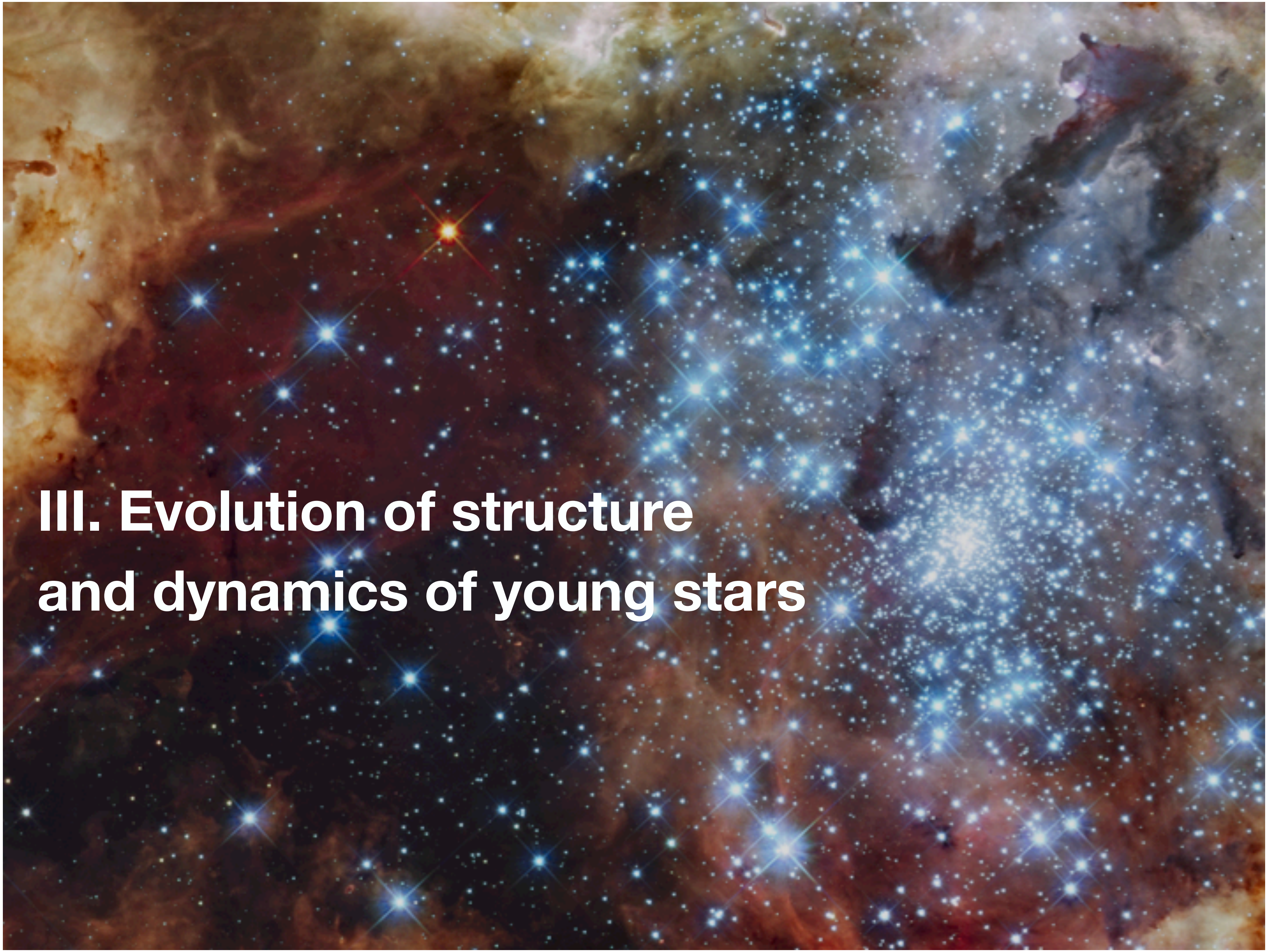
Pang+ (2013)

VLT/SPHERE: Not mass segregated



Khorrami+ (2016)

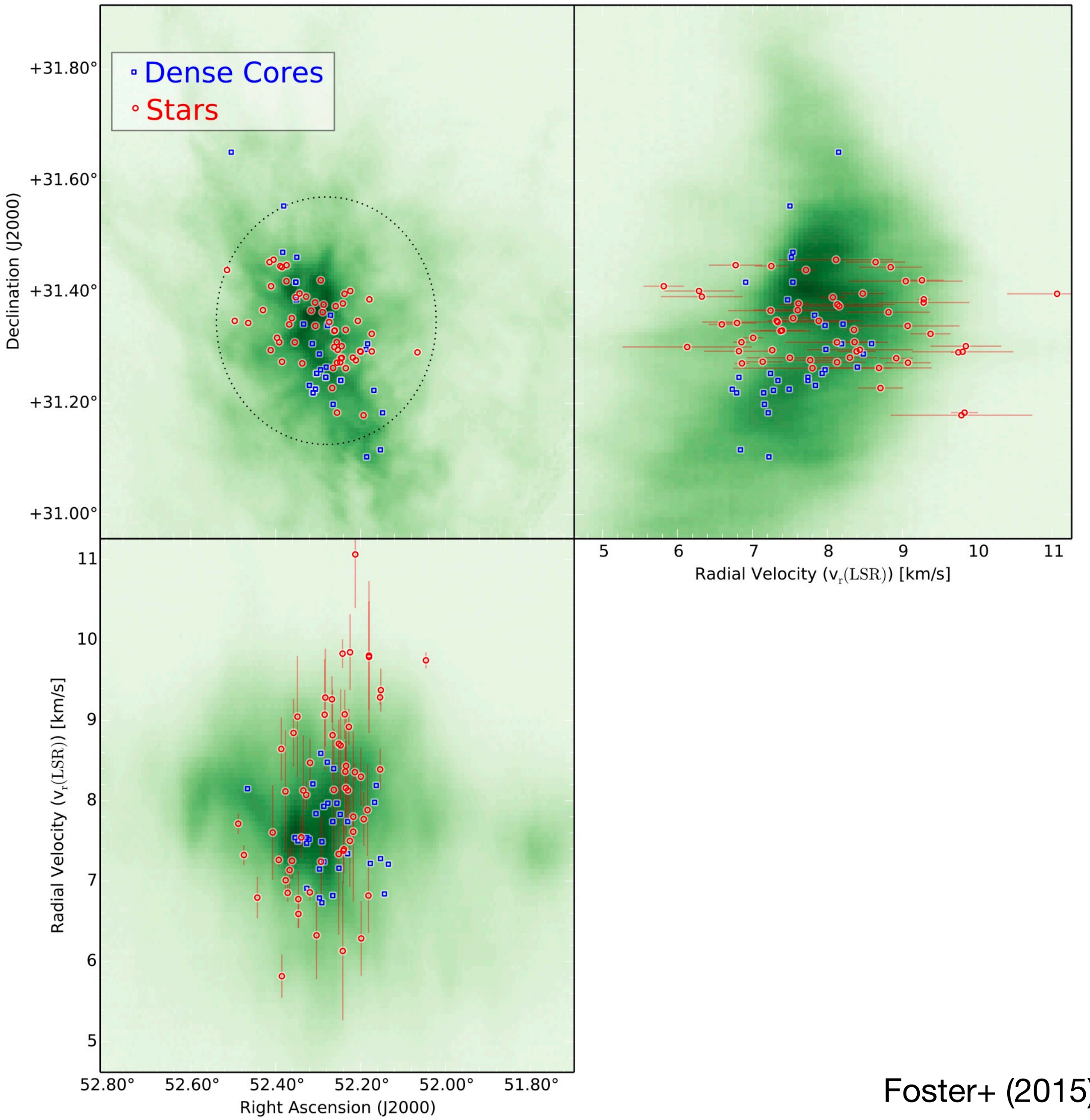
III. Evolution of structure and dynamics of young stars



Spatial and kinematic decoupling of stars and gas

Stars and gas become spatially and kinematically decoupled by the Class II stage (e.g., Foster+ 2015, Rigliaco+ 2016, Stutz & Gould 2016).

Decoupling may be due to feedback, localised gas exhaustion (e.g., Peters+ 2010), or just different dynamics.

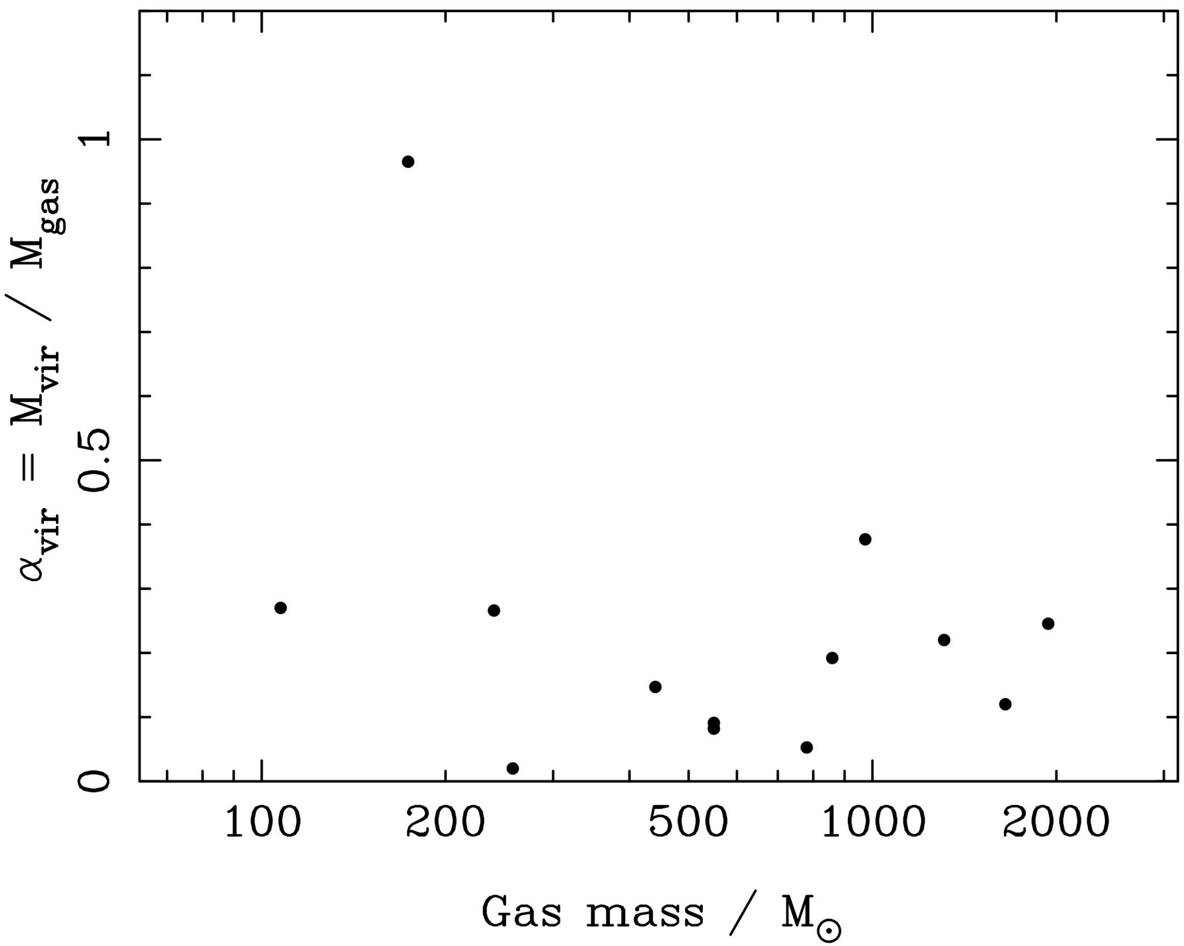


Foster+ (2015)

Subvirial velocity dispersions in young stars

Groups of dense cores have velocity dispersions that are subvirial within the gas potential (e.g., Peretto+ 2006, Andre+ 2002, Kirk+ 2007) and smaller than that of the dense gas out of which they formed (Walsh+ 2004, Andre+ 2007).

This suggests groups should collapse under gravity to form more compact clusters.

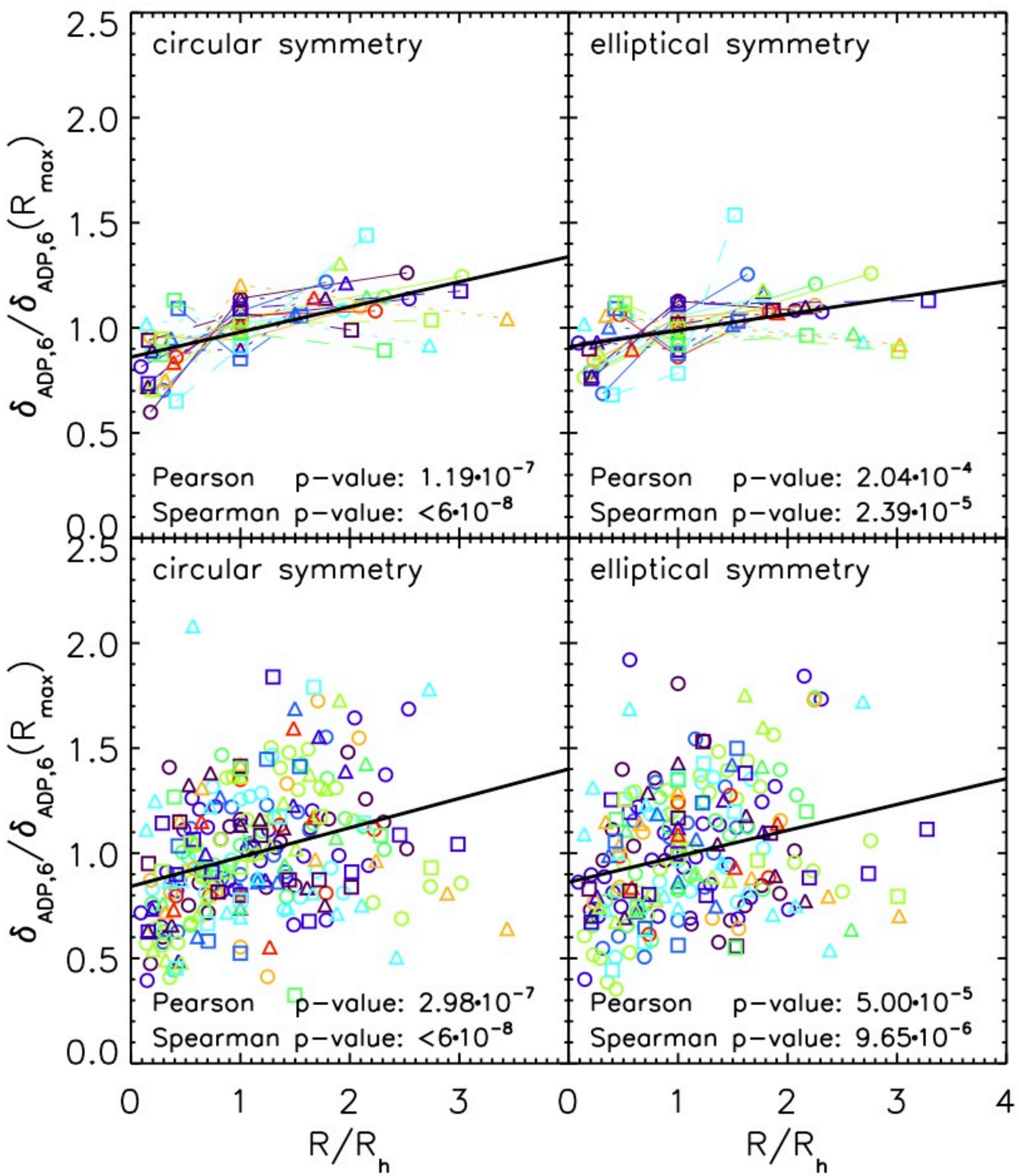


Data taken from Peretto+ (2006), Andre+ (2007) & Kirk+ (2007)

Erasing primordial substructure

Primordial substructure is erased due to dynamical interactions (e.g., Schmeja+ 2008).

Spatial scale over which substructure destroyed increases with dynamical age (e.g., Kraus & Hillenbrand 2008, Da Rio+ 2014, Jaehnig+ 2015).



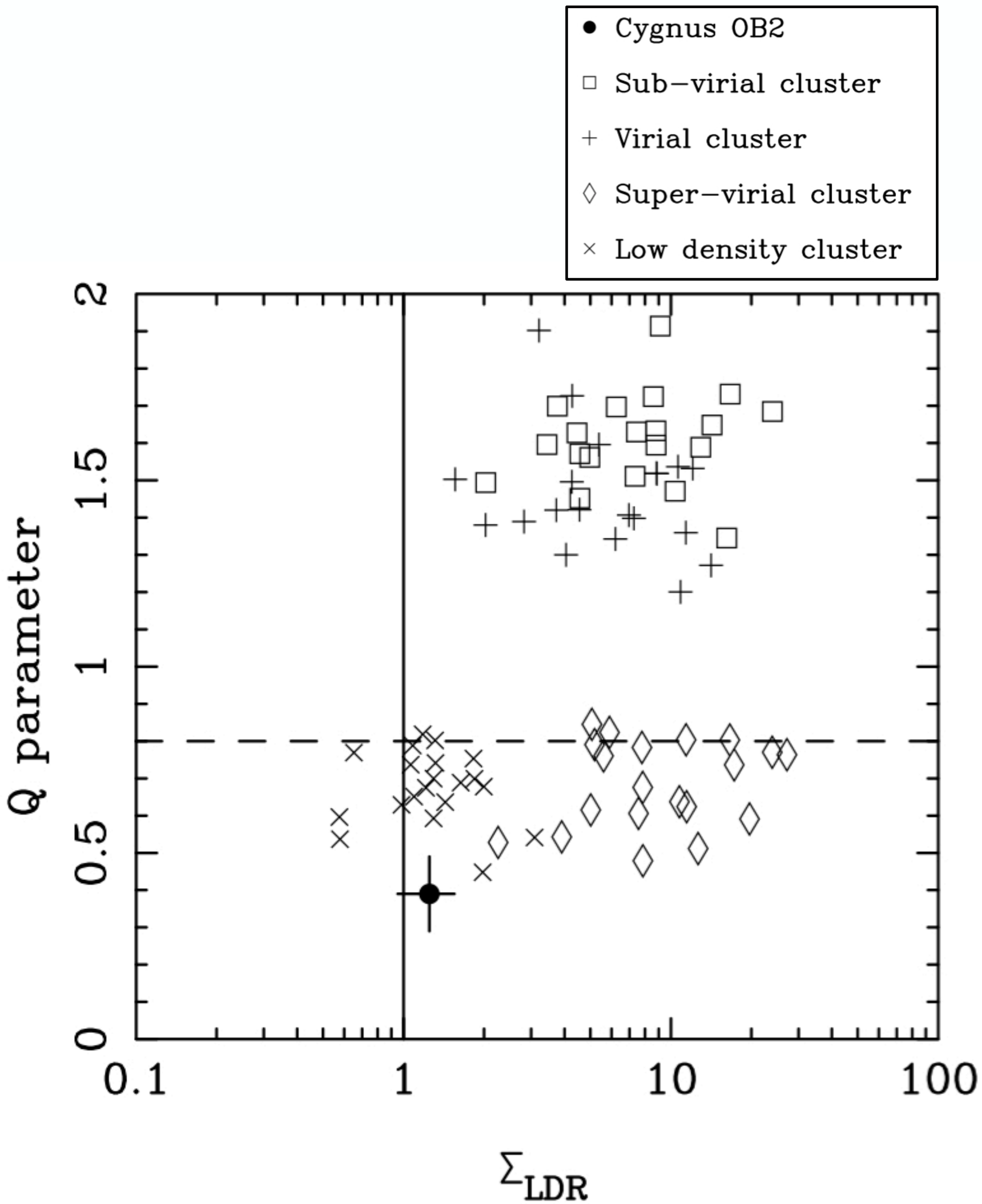
Jaehnig+ (2015)

Preserving primordial substructure

Primordial substructure preserved in regions that are not dynamically evolved.

Existence of substructure can be used to constrain the past dynamical evolution of a region and potentially initial conditions.

Cygnus OB2 shown to be dynamically unevolved and therefore unlikely to have been a dense star cluster in the past (Wright+ 2014).

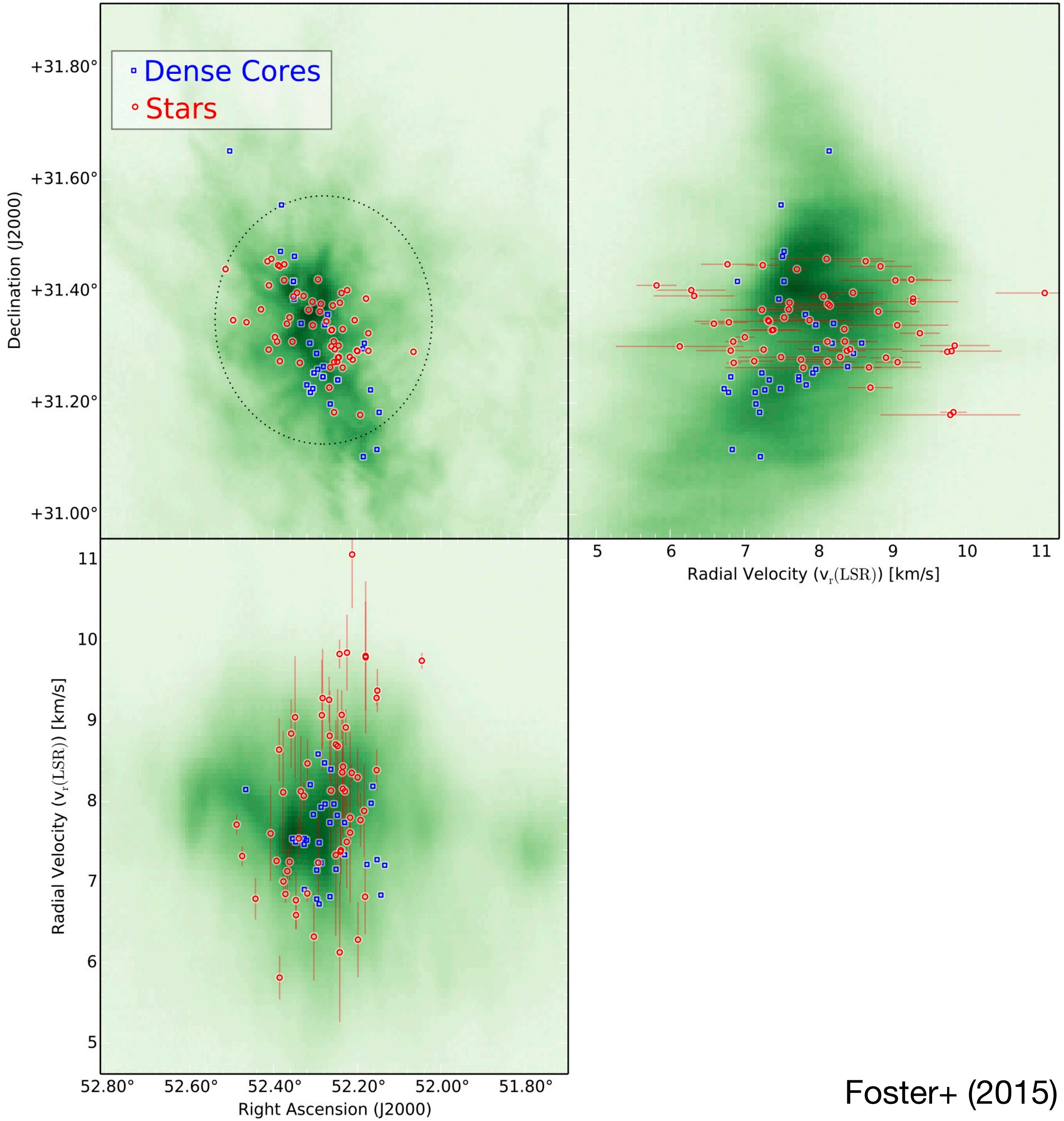


Parker+ (2014), Wright+ (2014)

Collapse and expansion of star forming regions

Dense cores and protostars have subvirial velocity dispersions, and clear evidence that collapse and rapid mixing occurs.

Yet Class II sources are typically more spatially dispersed, with velocity dispersions closer to virial equilibrium (e.g., Foster+ 2015, Rigliaco+ 2016).

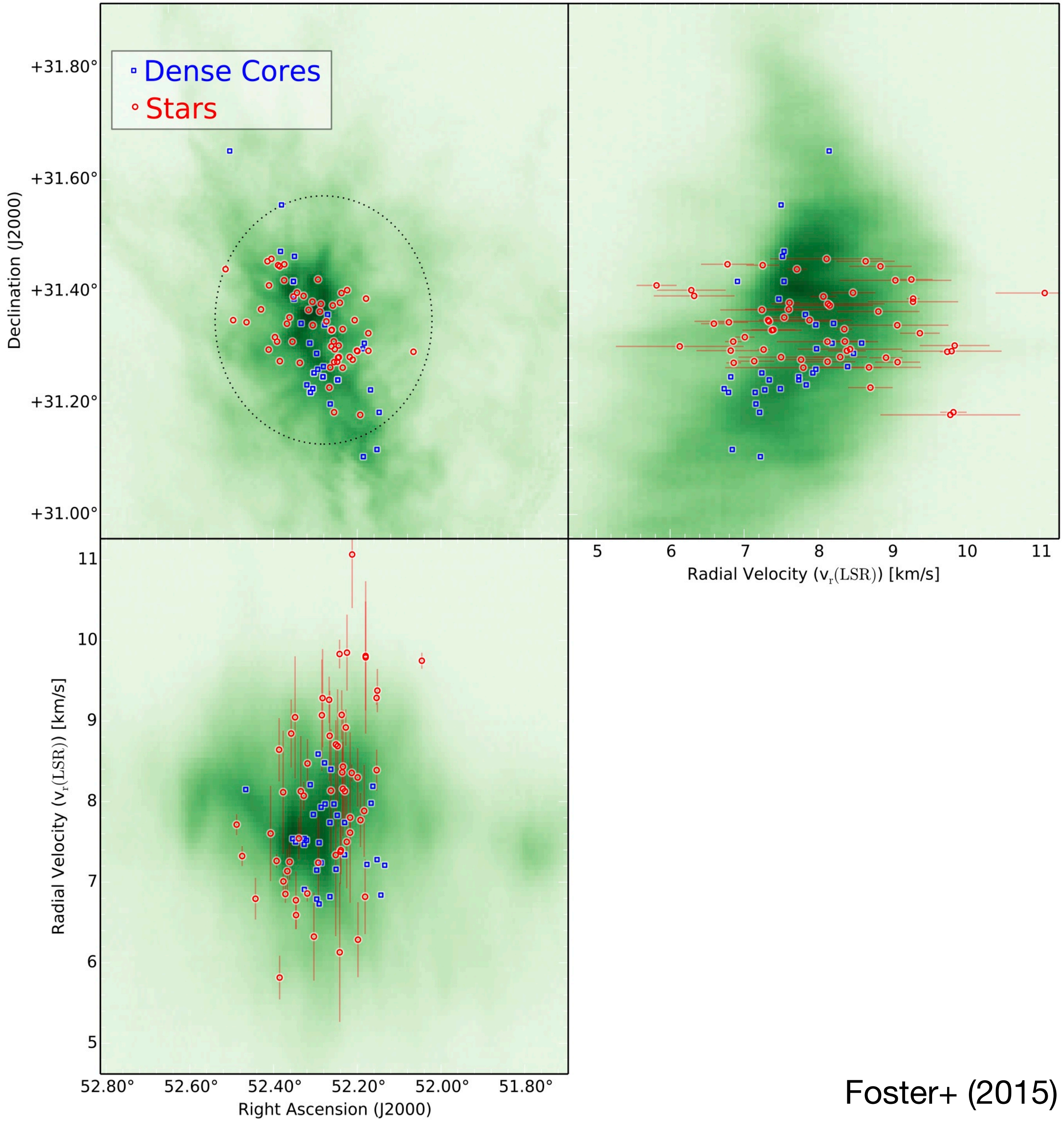


Foster+ (2015)

Collapse and expansion of star forming regions

Some process must inflate velocity dispersions during the dense phase following cool collapse.

Most likely candidates are the fragmentation of dense cores into multiple stars, and the disruption of binary systems, both of which release energy and can inflate the velocity dispersion.



Foster+ (2015)

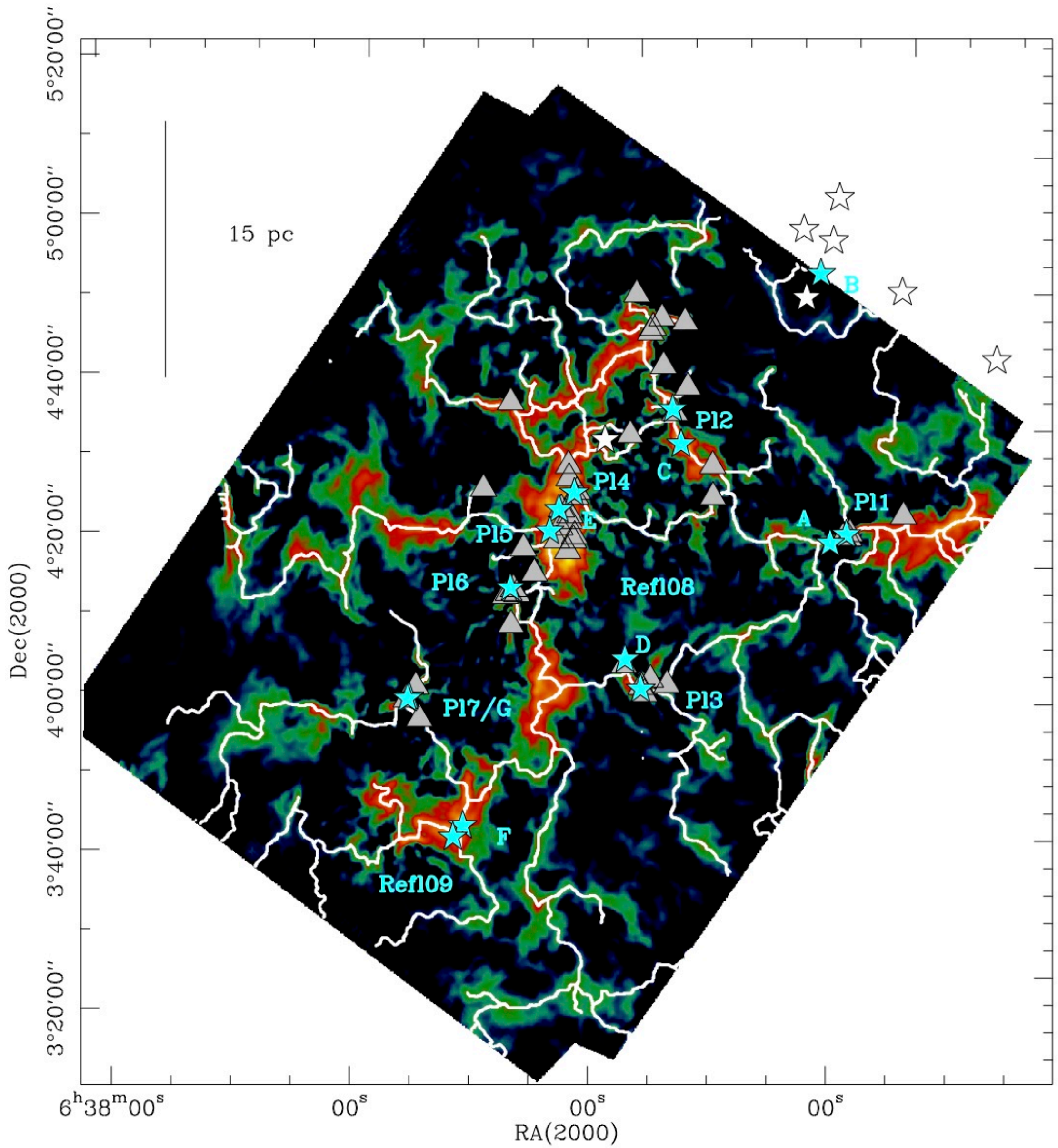
IV. Formation and structure of star clusters and OB associations

Star clusters forming at filament junctions

If star formation follows the filamentary structure of molecular clouds, clusters of stars appear to form where filaments overlap.

Schneider+ (2012) found that 13 out of 14 known IR clusters in the Rosette Molecular Cloud were found at filament junctions.

Manifests in “hub and spoke” morphologies where clusters are “hubs” surrounded by “spokes” of filaments (Myers 2009).



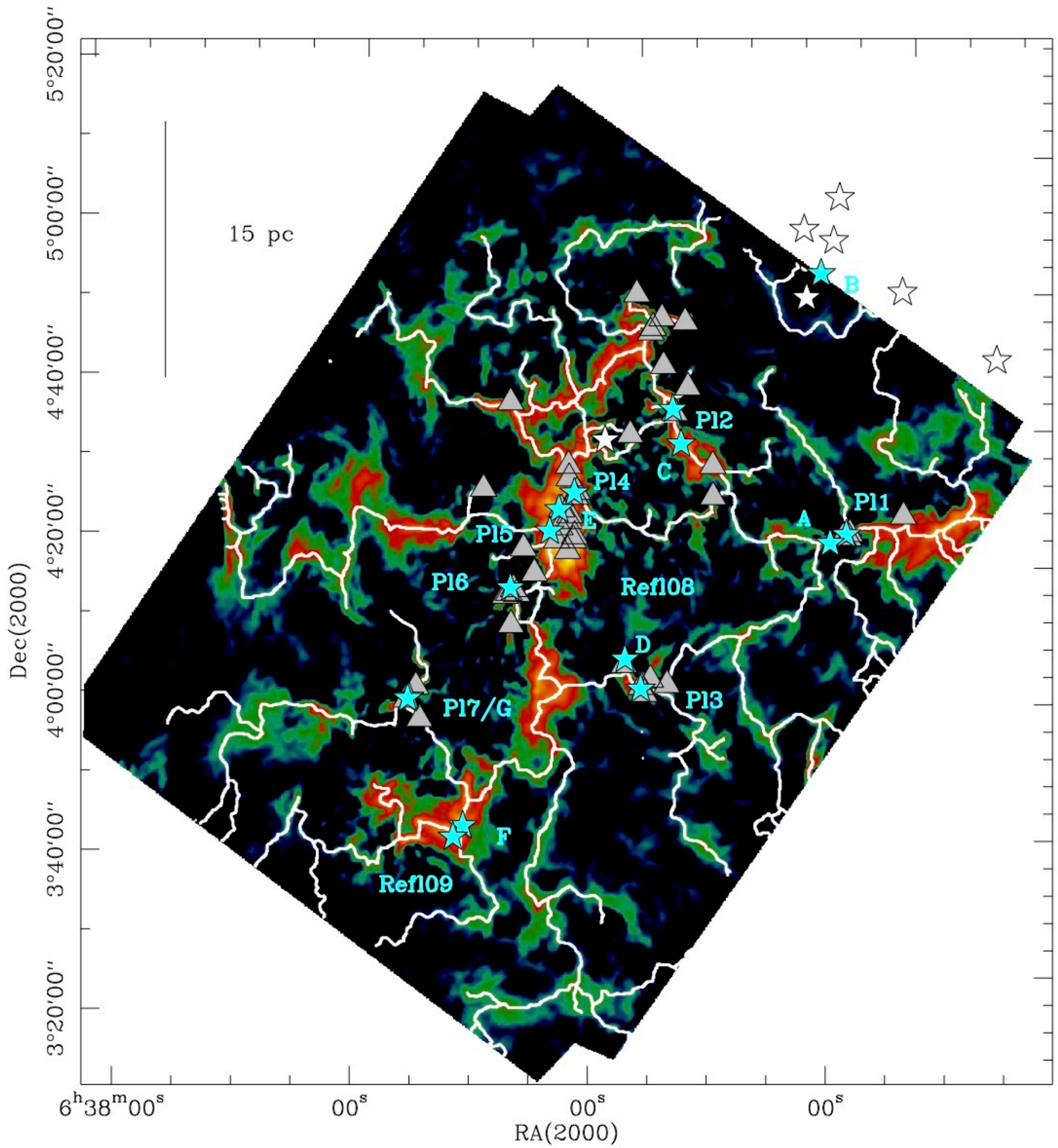
Schneider+ (2012)

Star clusters forming at filament junctions

The important question:

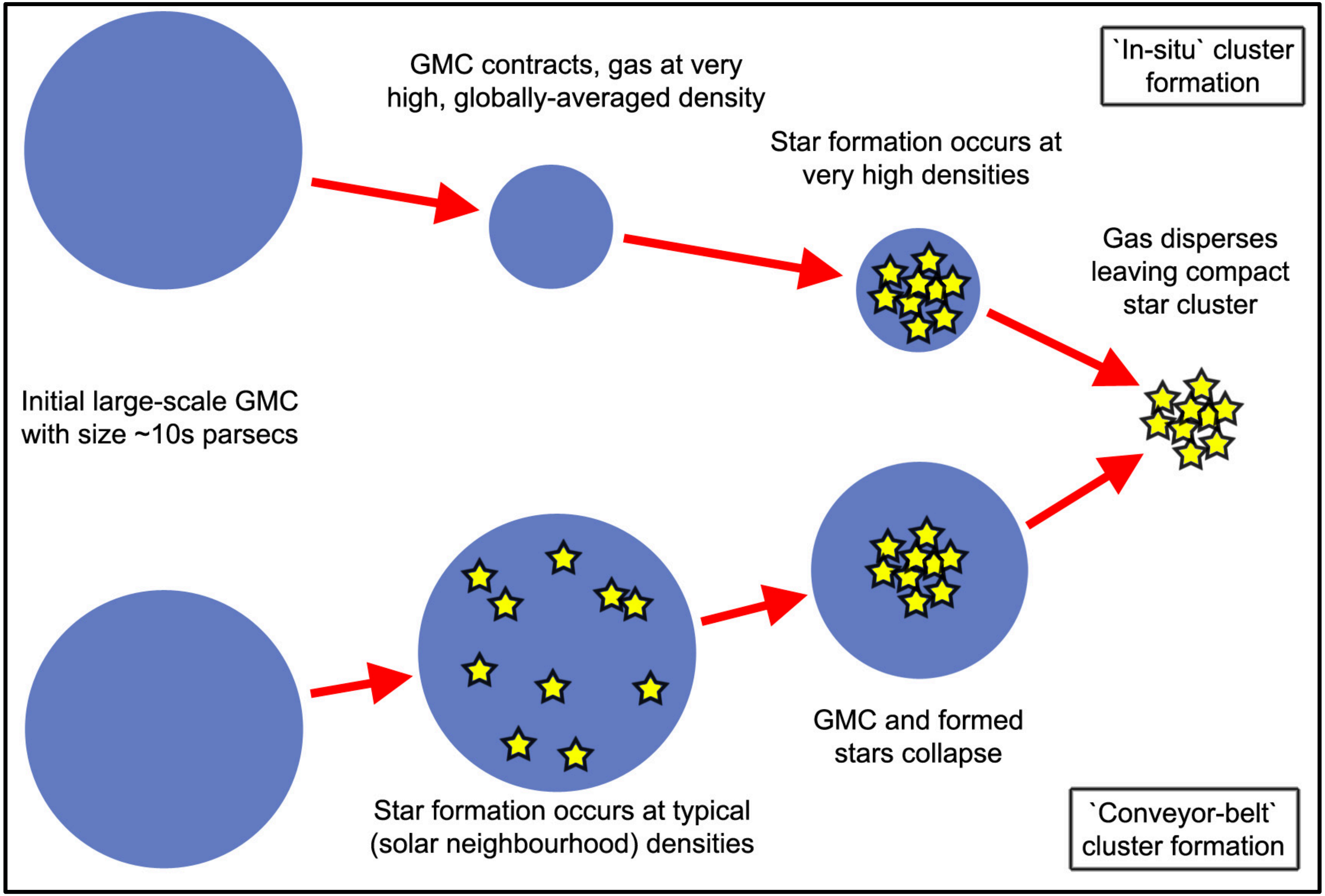
Do stars form in great numbers where filaments have collided? (*in-situ* cluster formation)

Or do filament collisions bring together already formed stars? (*conveyor-belt* cluster formation)



Schneider+ (2012)

“In-situ” versus “conveyor-belt” cluster formation



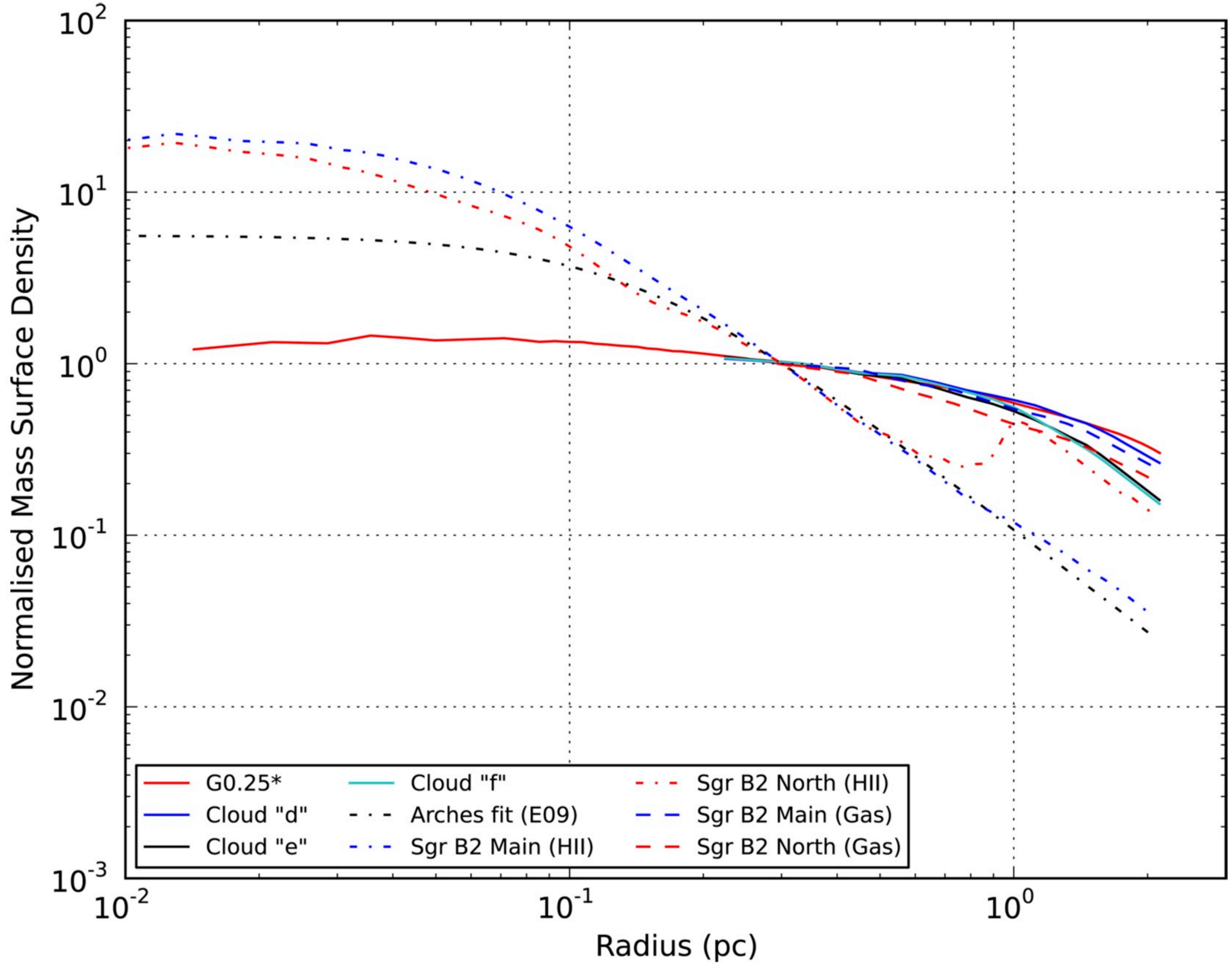
Adapted from Longmore+ (2014)

Surface density profiles of GMCs and YMCs

Surface density of GMCs shallower than those of young massive clusters (Walker+ 2015, 2016).

No known quiescent GMCs in the Milky Way with sufficient mass in compact areas to form YMCs (Ginsburg+ 2012, Urquhart+ 2013).

Supports a picture of *conveyor-belt* cluster formation.



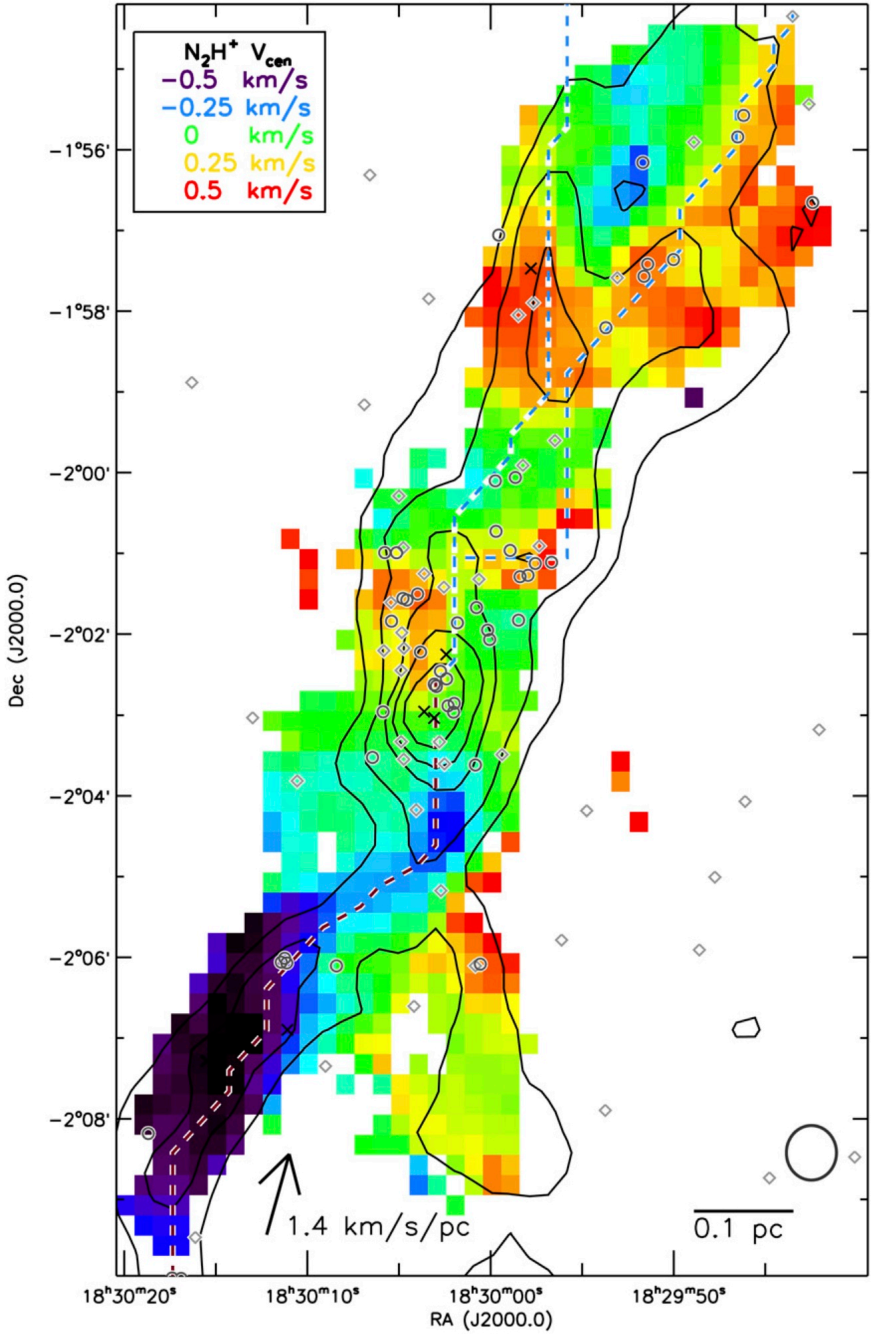
Walker+ (2015)

Accretion flows onto central clusters

Material observed to flow along filaments towards hubs / central clusters (e.g., Kirk+ 2013).

This can provide sufficient material in the hub for clustered star formation, supporting a picture of *in-situ* cluster formation.

Note however that this velocity pattern could be caused by the super-position of sub-filaments within these structures (Henshaw+ 2016).

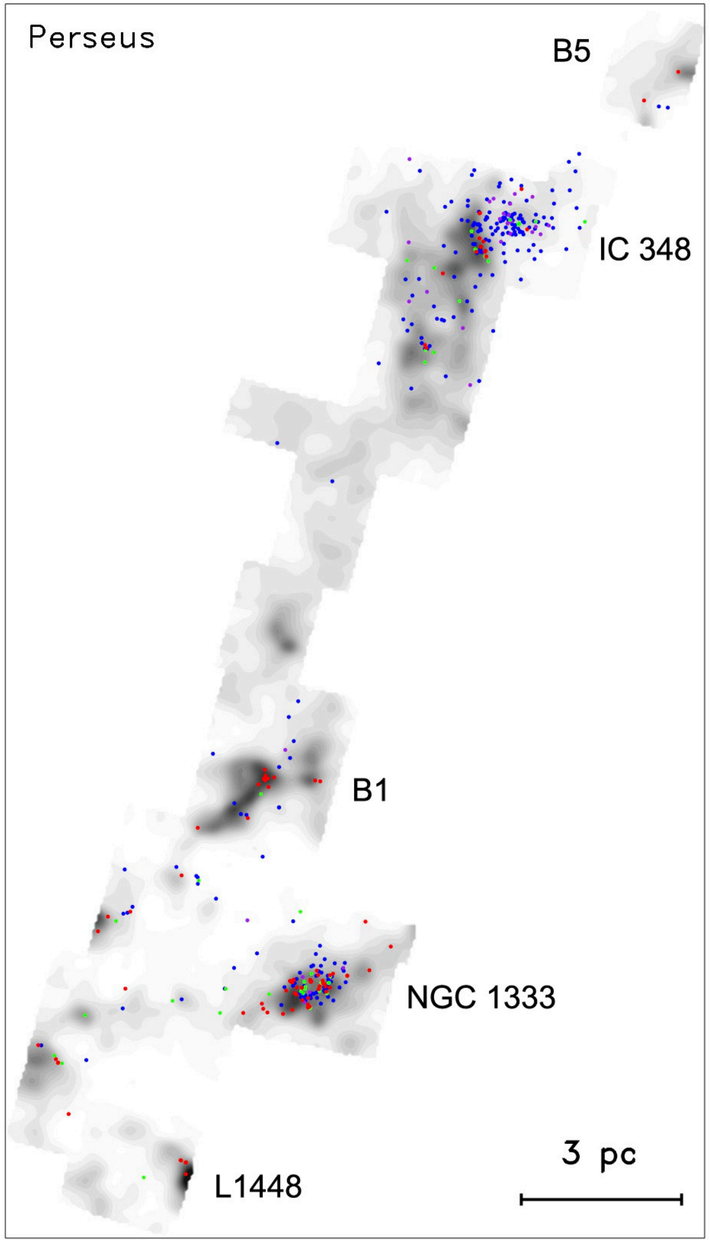


Kirk+ (2013)

Hierarchical mergers between star clusters

Once groups and clusters form there is evidence they may undergo hierarchical mergers to form more massive clusters:

- Older groups of stars have been found to be larger (e.g., Evans+ 2009, Spitzer c2d Legacy Survey).



Evans+ (2009)

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Once groups and clusters form there is evidence they may undergo hierarchical mergers to form more massive clusters:

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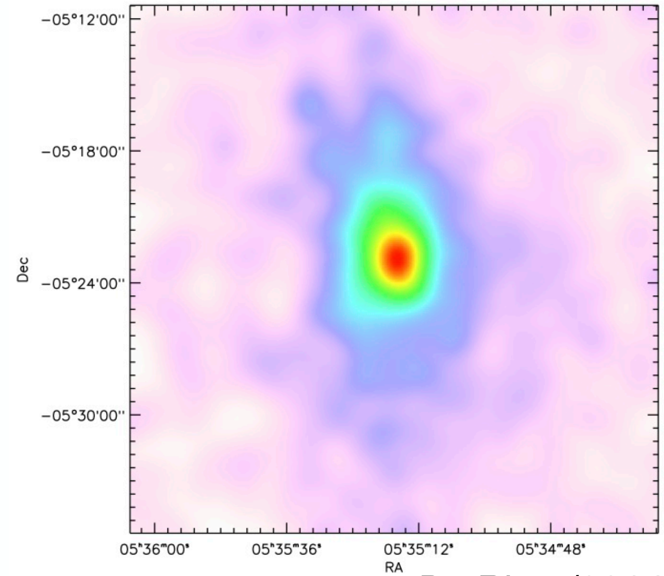
- Many young clusters are elongated despite being old enough to be dynamically evolved (e.g., ONC, Hillenbrand & Hartmann 1998, Da Rio+ 2014 & Wd1, Gennaro+ 2011).



Da Rio+ (2014)


Westerlund 1 (VPHAS+)

Hierarchical mergers between star clusters

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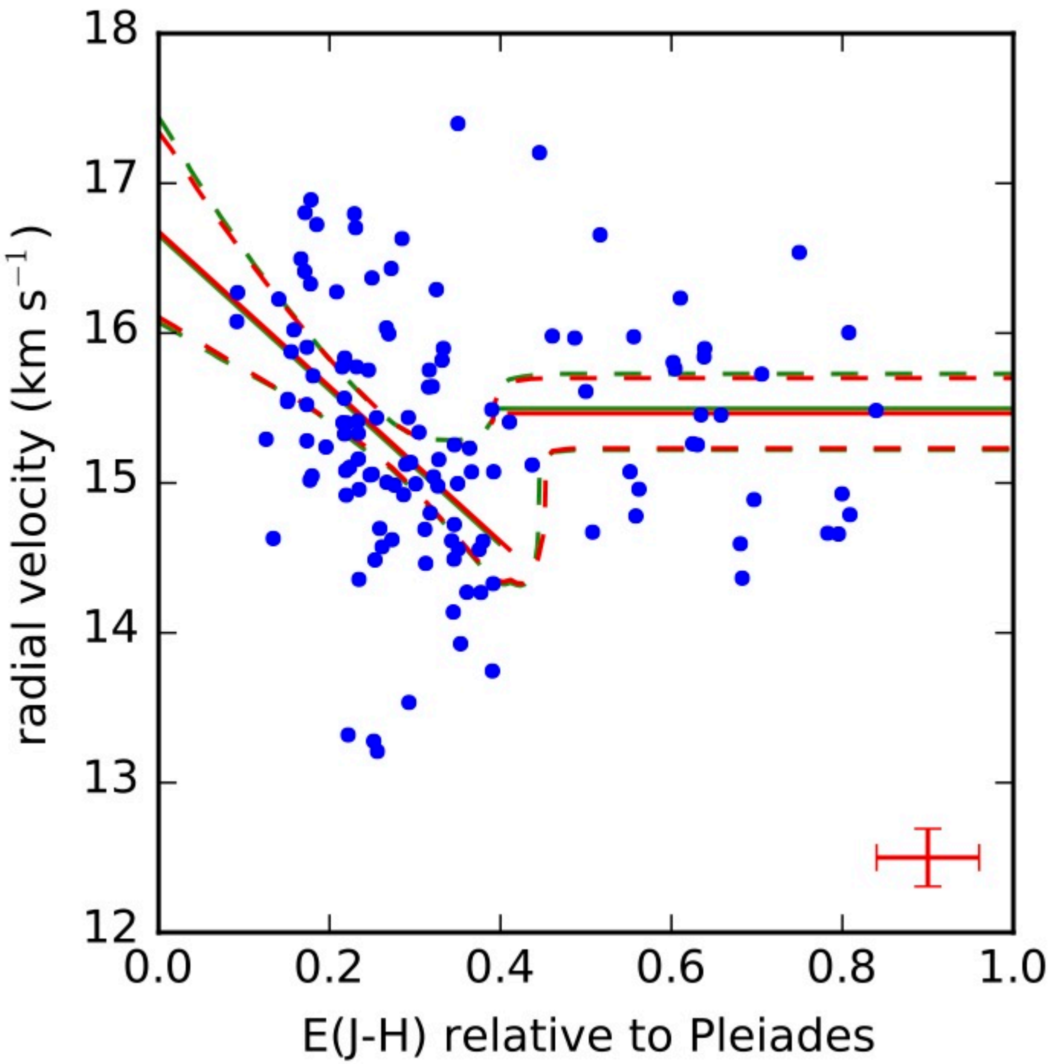
- Older groups of stars have been found to be larger (e.g., Evans+ 2009, Spitzer c2d Legacy Survey).
- Many young clusters are elongated despite being old enough to be dynamically evolved (e.g., ONC, Hillenbrand & Hartmann 1998, Da Rio+ 2014 & Wd1, Gennaro+ 2011).
- Kinematic evidence that IC 348 cluster is either collapsing or subclusters within it are merging (Cottaar+ 2015).



Cottaar+ (2015)

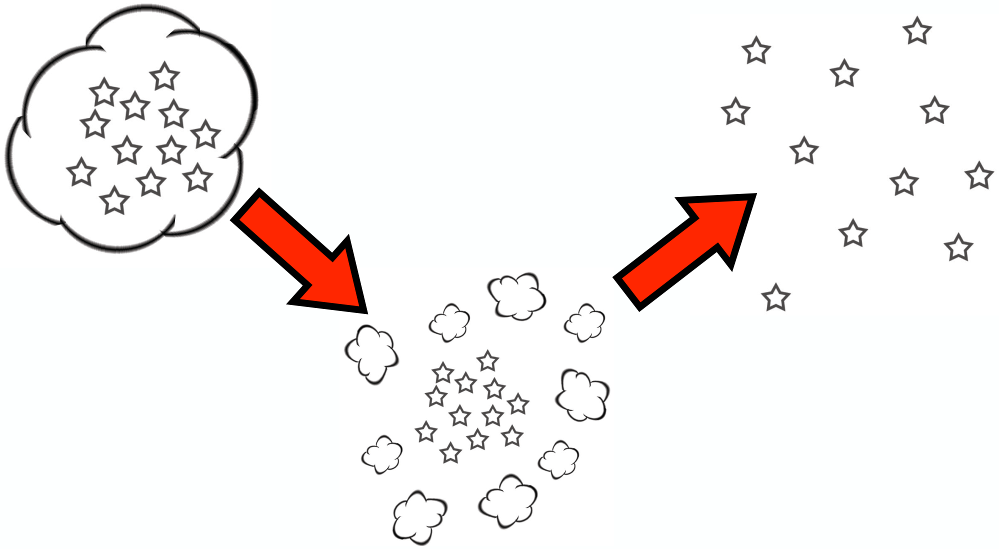
The origin of OB associations

What happens to groups or substructures that don't merge?

OB associations are groups of OB (and low-mass) stars with a low surface density that makes them gravitationally unbound (Ambartsumian 1949, Blaauw 1964, 1991, Brown+ 1999).

Thought to be the expanded remnants of star clusters disrupted by processes such as residual gas expulsion (e.g., Hills 1980, Lada+ 1984, Brown+ 1999, Lada & Lada 2003).

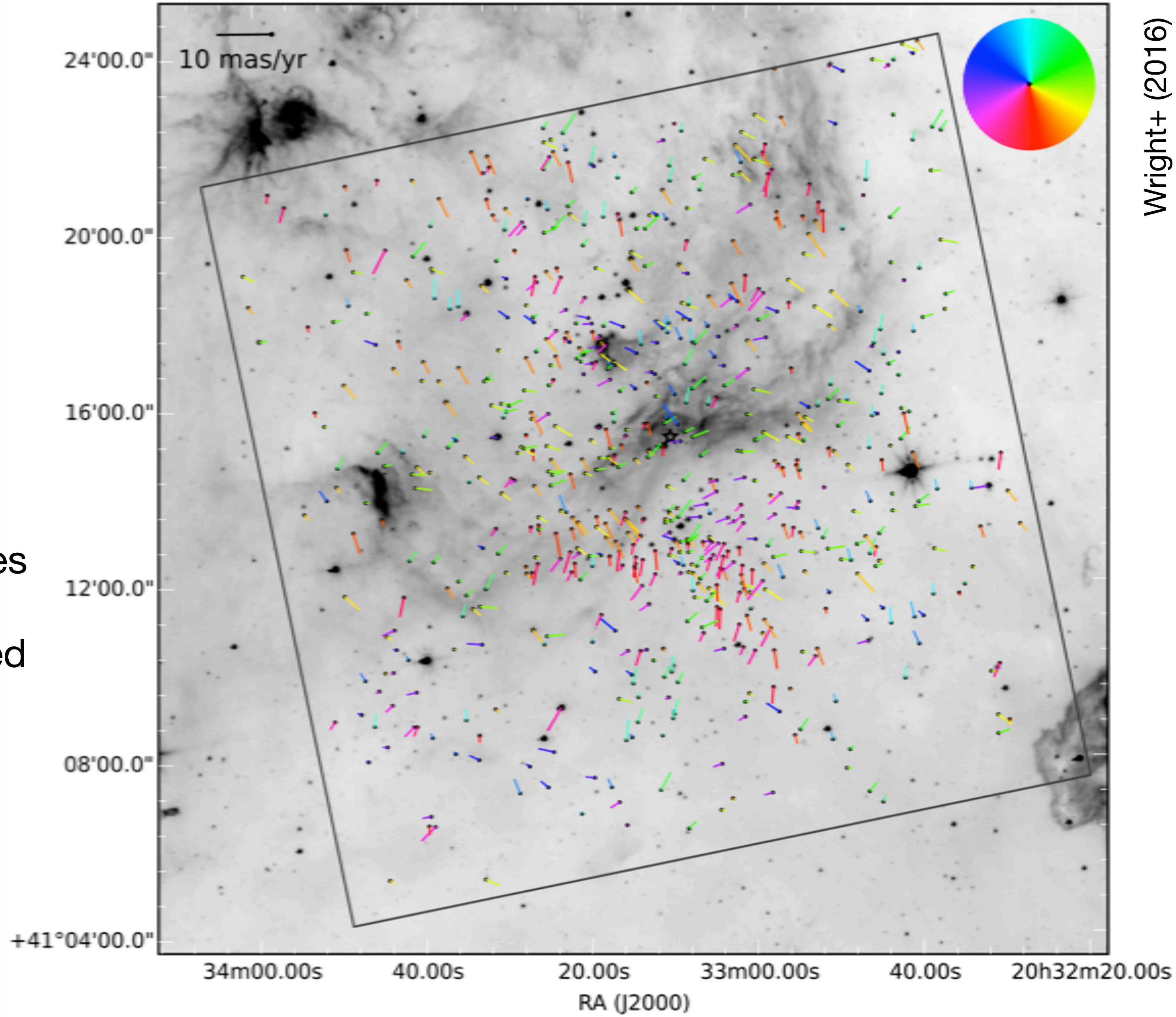
Scorpius-Centaurus OB association



No radial expansion pattern in Cygnus OB2

Proper motions of stars in Cyg OB2 show no evidence for the radial dispersion of stars predicted by residual gas expulsion.

Considerable kinematic substructure implies the region is not dynamically evolved and couldn't have been a dense cluster in the past (Wright+ 2016).

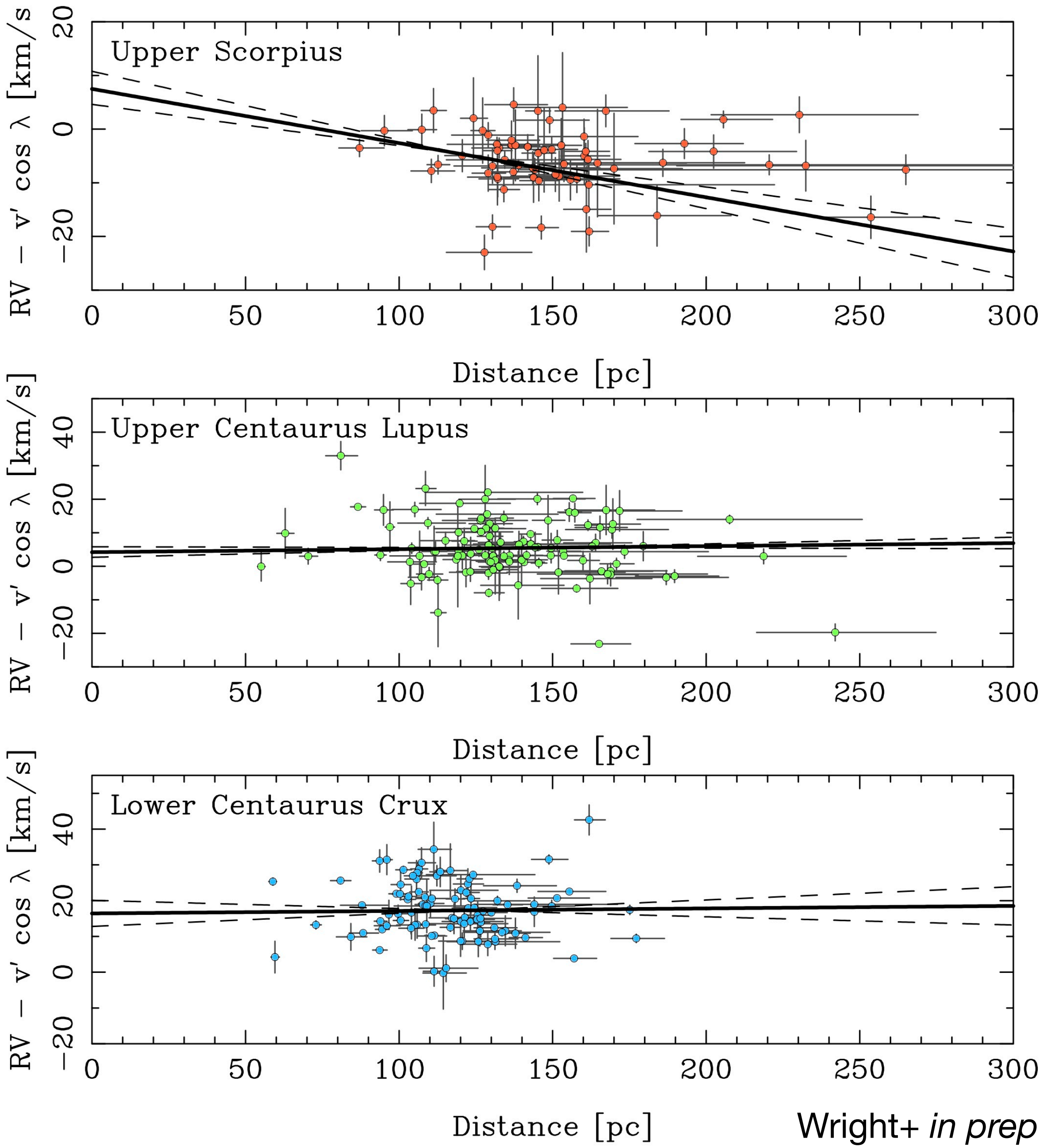


Wright+ (2016)

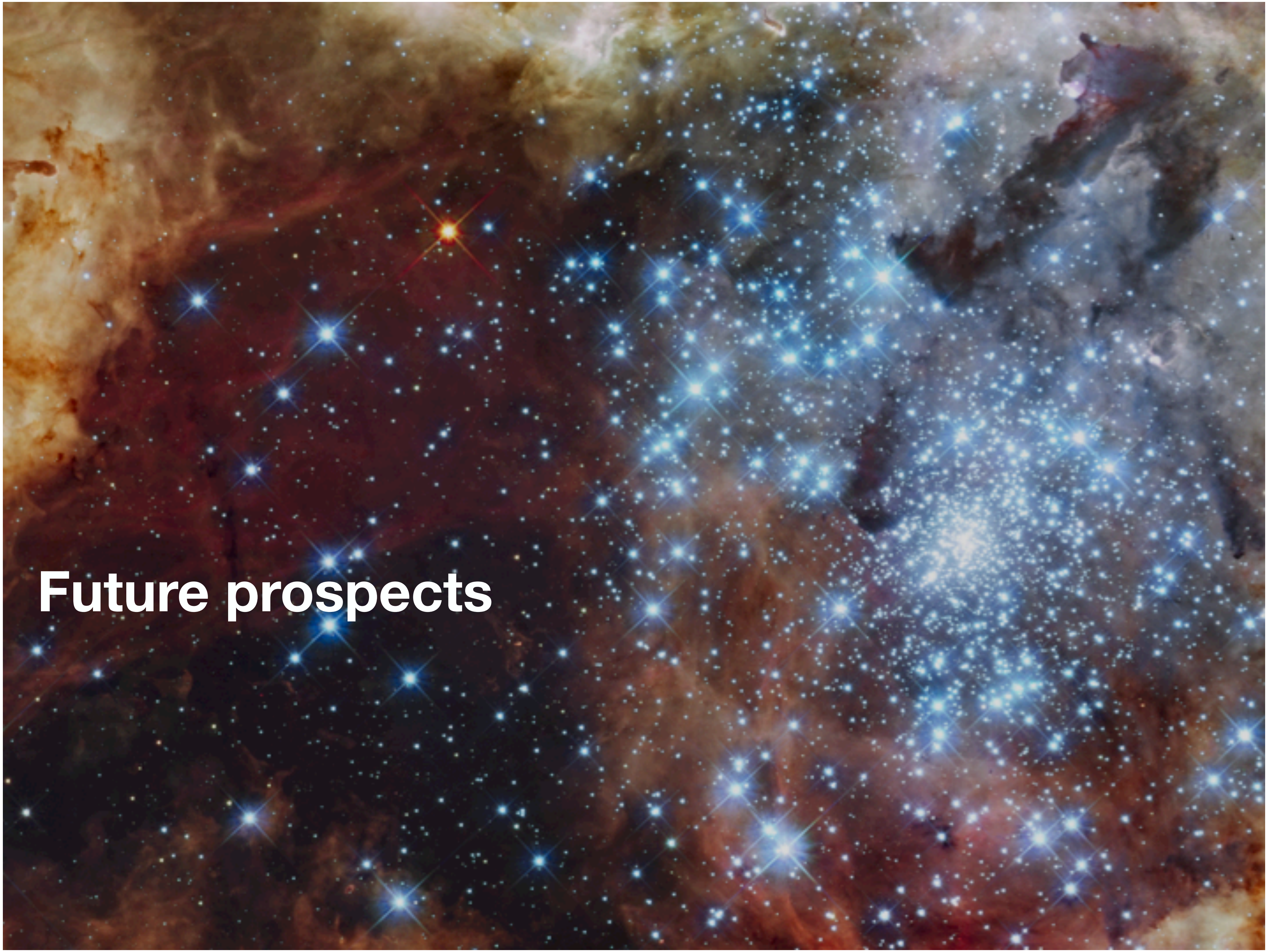
No radial expansion pattern in Scorpius-Centaurus

Gaia DR1 kinematics show no evidence for expansion for the three subgroups of the Scorpius-Centaurus association (Wright+ *in prep).*

This joins existing work that nearby moving groups and OB associations are not expanding and were born with low-density, substructured, and super-virial distributions (Makarov 2007, Wright+ 2014, 2016, Mamajek & Bell 2014).



Wright+ *in prep*


Future prospects

Future prospects

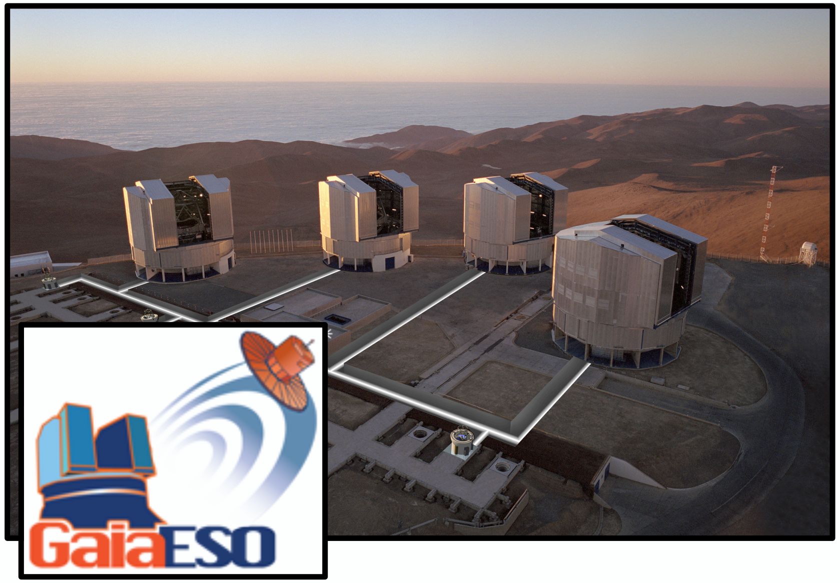
Overcoming confusion and breaking structural degeneracies will come from kinematics!

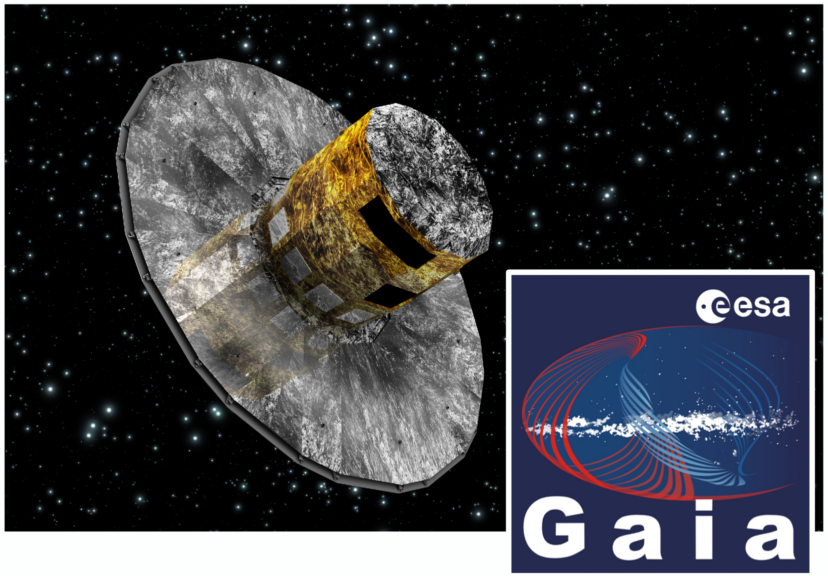
Current spectroscopic RV surveys:
- Gaia-ESO Survey (VLT)
- IN-SYNC (SDSS 3)

Current astrometric (PM) facilities:
- DANCe (Bouy+ 2014)
- Gaia (2016+)

Upcoming spectroscopic RV facilities:
- WHT / WEAVE (2018)
- VLT / MOONS (2019)
- VISTA / 4MOST (2021)

Upcoming astrometric (PM) facilities:
- SKA (2020)
- LSST (2023)





Summary

Summary

Turbulence and fragmentation during star formation increases substructure.

- Do the GMC properties influence the distribution / kinematics of the stars formed?

Stars form in the densest parts of GMCs with an initially highly substructured distribution, but quickly decouple from the gas, both spatially and kinematically.

- Is the decoupling driven by feedback, gas exhaustion or other processes?
- Is observed mass segregation primordial or is it driven by dynamical interactions?

Stars are born with sub-virial kinematics, which leads to collapse into compact groups that dynamically mix, erasing primordial substructure.

- What fraction of stars pass through this compact phase?
- Does this lead to the formation of gravitationally bound clusters?

Star clusters appear to form where filaments overlap or have merged.

- Does this bring together formed stars or lead to in-situ clustered star formation?

Star clusters may grow by mergers between subclusters, while the star forming complexes that don’t merge their substructures appear to form OB associations.

- How common are cluster mergers and by how much do typical star clusters grow?
- Do OB associations form by other methods, e.g., residual gas expulsion?