Clustering Properties in Nearby Star-Forming Systems

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Co-op (undergrad) student work in this talk:

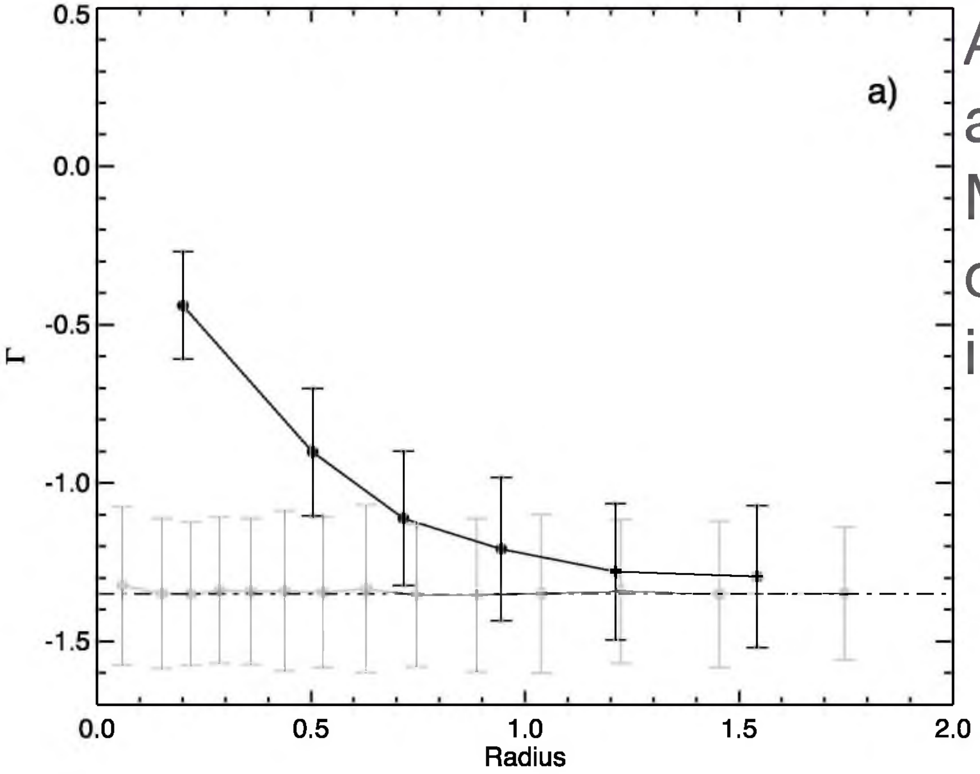
Orion A core clustering: James Lane (grad, U Toronto)

Initial all-GBS core cats: Ronan Kerr (grad, U Arizona)

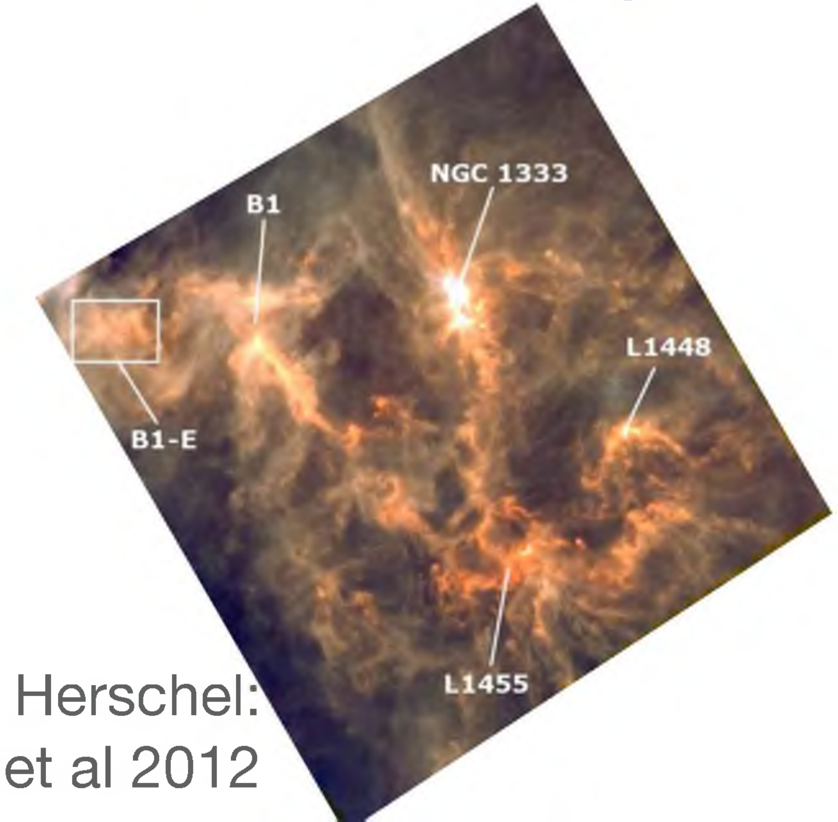
Initial GBS GS clustering & cat vetting: Sammohith Nittala (u.grad, UBC)

Why Nearby Dense Cores?

- Measures of mass segregation can be strongly biased by crowding & incompleteness (preferentially lose low mass sources in clustered environment) - e.g., Ascenso et al 2009
- Nearby sf systems (e.g., in the Gould Belt) provide systems that have good completeness
- Dense cores provide a window into clustering at an earlier time step, reducing protostar-protostar dynamical interactions
- NB: Lack of truly high mass sf may not capture all aspects of clustering



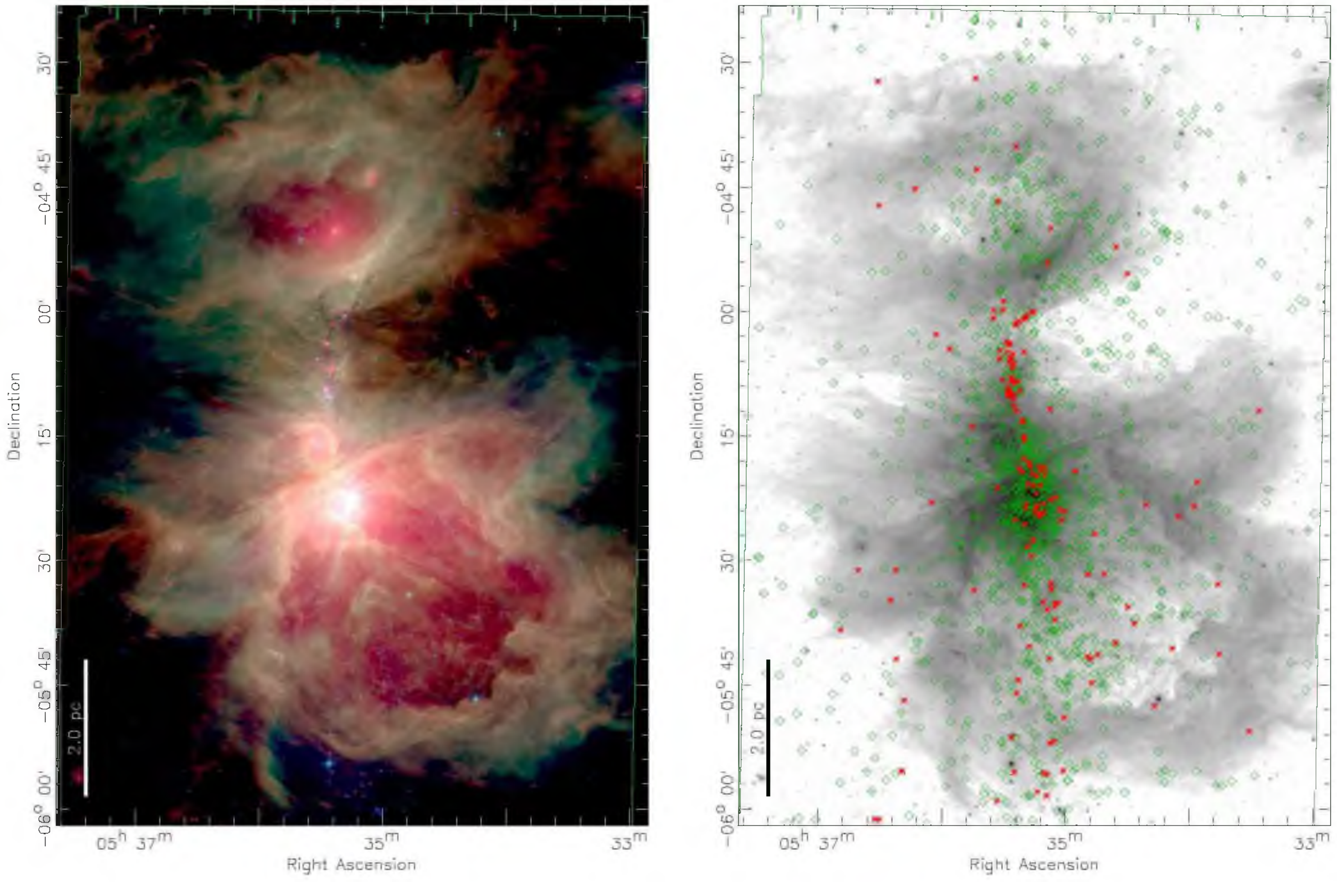
Ascenso et al 2009: apparent steepening in the MF slope in a synthetic cluster due to incompleteness, etc



Western Perseus with Herschel:
Sadavoy et al 2012

What Can We Measure?

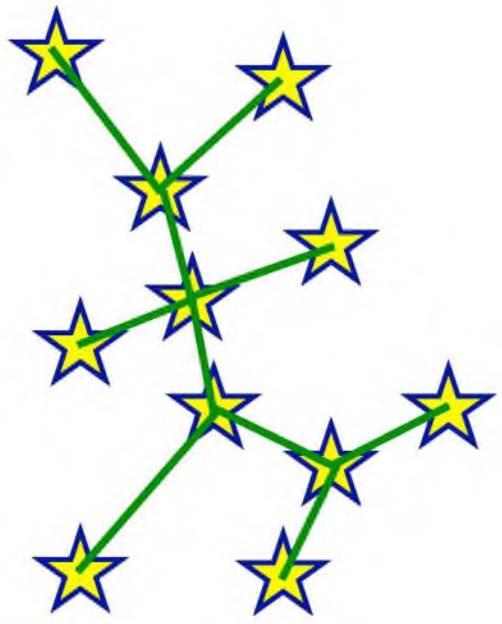
- Mass segregation (focus of this talk)
- Q / substructure measures (e.g., Cartwright & Whitworth 2004)
- Clustering scales (e.g., 2 point correlation function)
- Bulk cluster properties (e.g., elongation, star formation rate, evolutionary state, radial velocity dispersion of members,…)
- Relationship with dense gas (gas mass, velocity dispersion, etc…)



Megeath et al 2012: the ONC as seen by Spitzer

Λ_{MSR}

- Proposed by Allison et al 2009, makes use of Minimum Spanning Tree
- MST: connect all points using shortest path
- Λ_{MSR} compares ratio of mean branch length for N most massive members versus many randomly selected N less-massive members. Run for every value of N.
- Λ_{MSR} >>1 at a given N implies mass segregation. Advantage: Significance indicated by range of values in random samples



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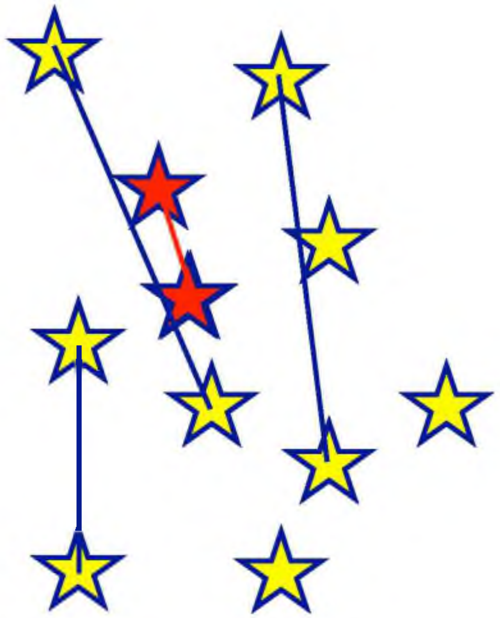
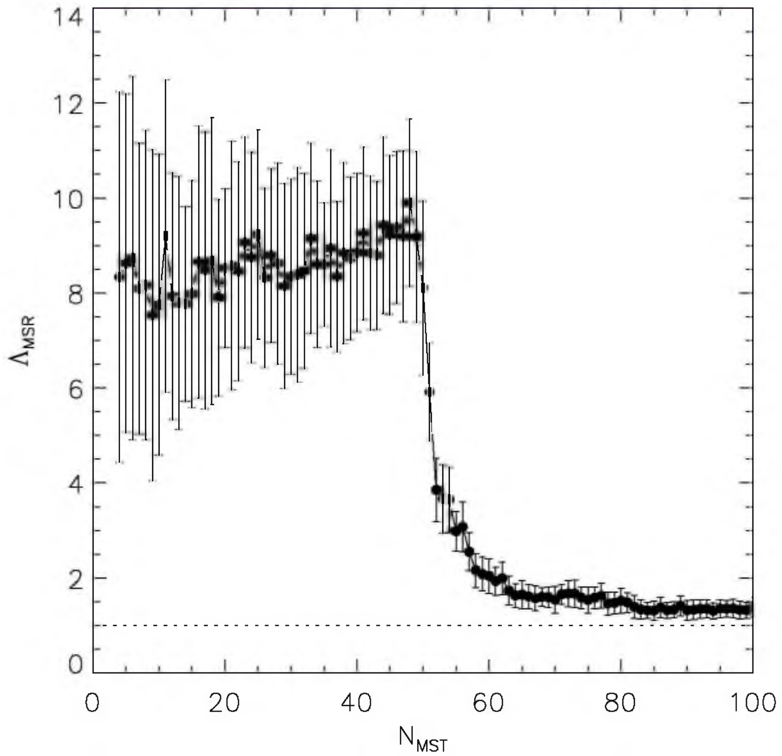
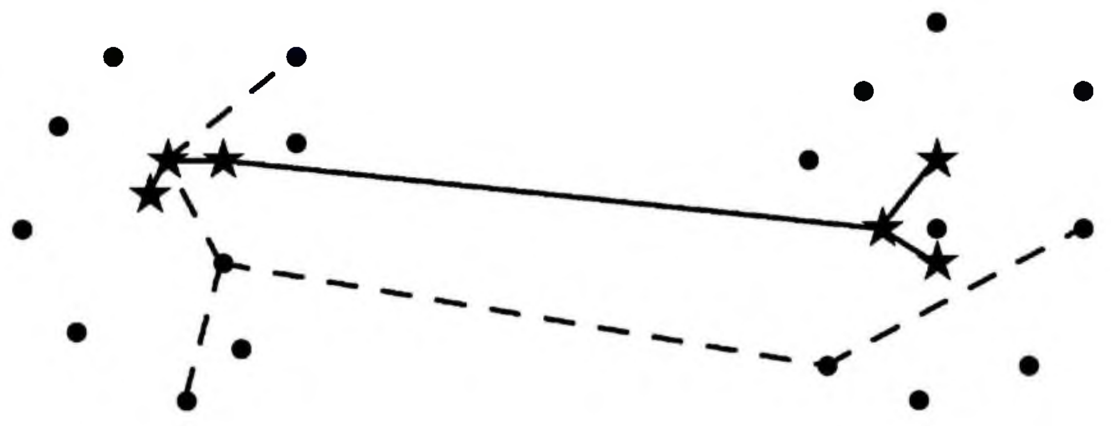




Allison et al 2009 : example of Λ_{MSR} using simulated dataset. Mass segregation for ~50 most massive members; less significant for largest N_{MST} values / lowest mass members

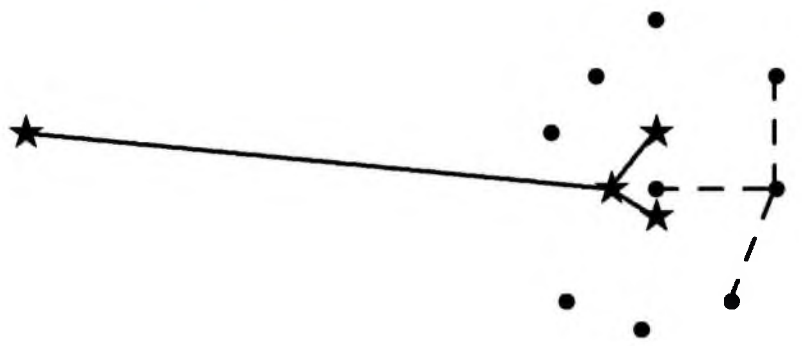
Challenges with Λ_{MSR}

Challenge: distinct clusters



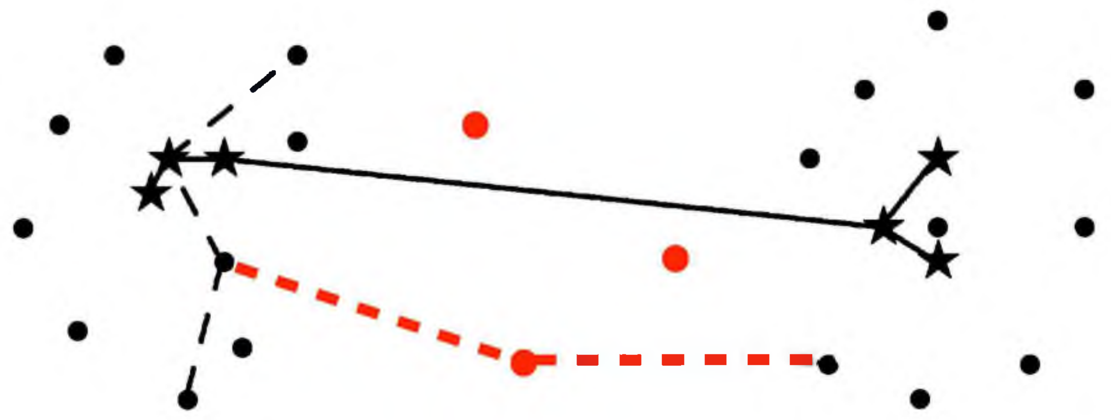
Maschberger & Clarke 2011

Challenge: outliers



Maschberger & Clarke 2011

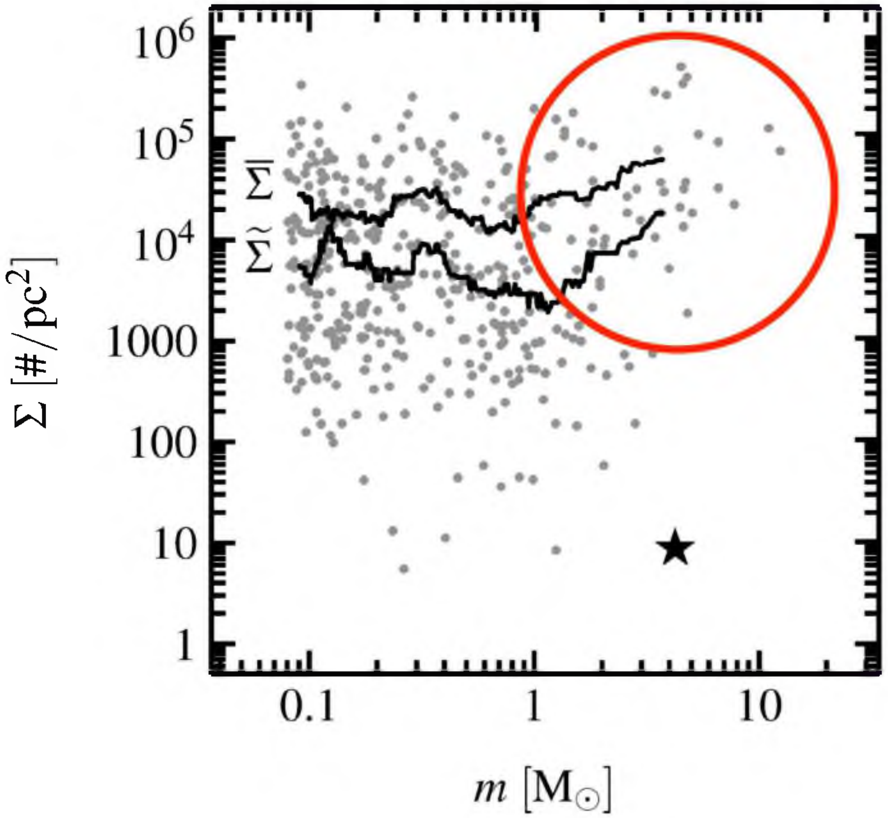
Or even worse: clusters separated by a sparse low-mass population



- Using median branch lengths (Maschberger & Clarke ’11) or geometric mean (Olczak ea ’11) reduces challenges
- Local mass segregation per cluster may still be hidden by cluster-cluster separation

M-Σ

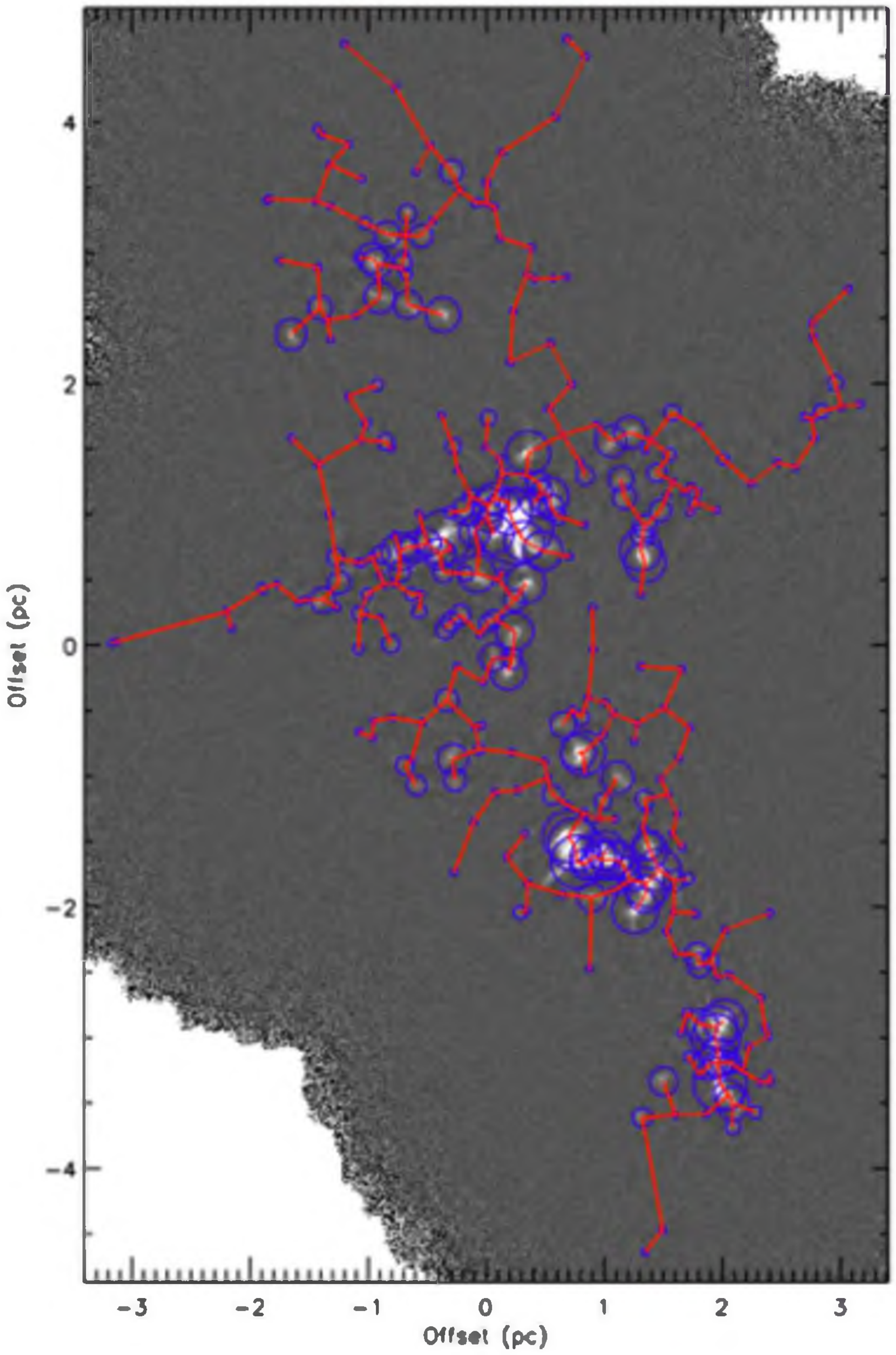
- Proposed by Maschberger & Clarke 2011 to avoid some of the challenges with Λ_{MSR}
- Compare local surface density of objects with the mass of each object: mass segregation implies higher masses at higher surface densities



Maschberger & Clarke 2011

- Advantage: is geometry-independent (single or multi-cluster systems)
- Disadvantage: no built-in stat. significance (can run tests such as KS or MW, for an overall measure)
- Disadvantage: can look 'noisier'
- Disadvantage: relies on local surf. density measure (sensitive to # nearby neighbours used, filamentary vs circular geometry, etc). Should test, e.g., with multiple # neighbours.

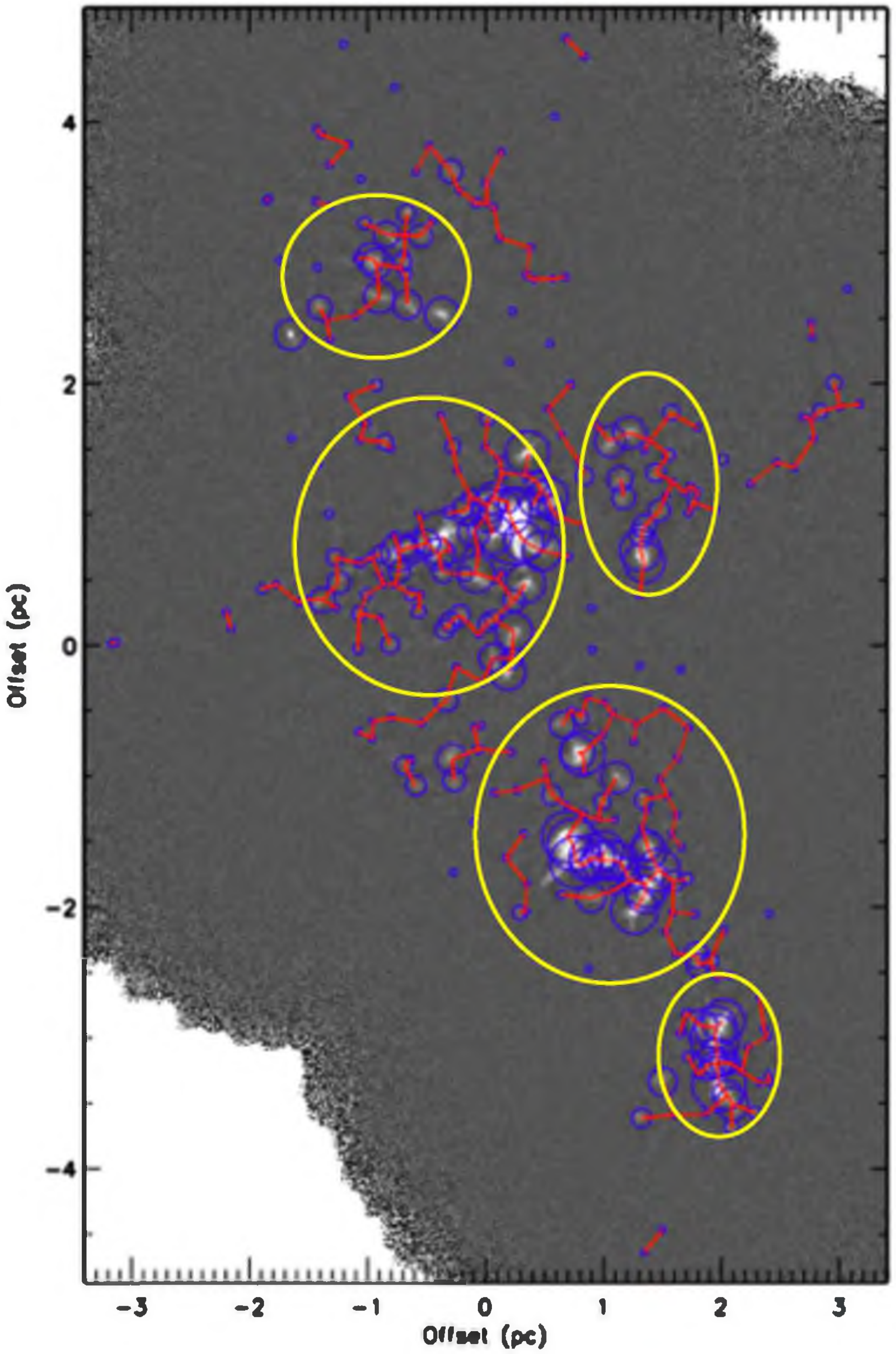
Offset Ratio



Orion B groups: Kirk et al 2016b

- Proposed by Kirk & Myers 2011 for small, distinct clusters
- Identify distinct clusters using MST and connections less than some critical length
- Compare separation/offset of most massive cluster member from the cluster centre to the median offset of other cluster members

Offset Ratio



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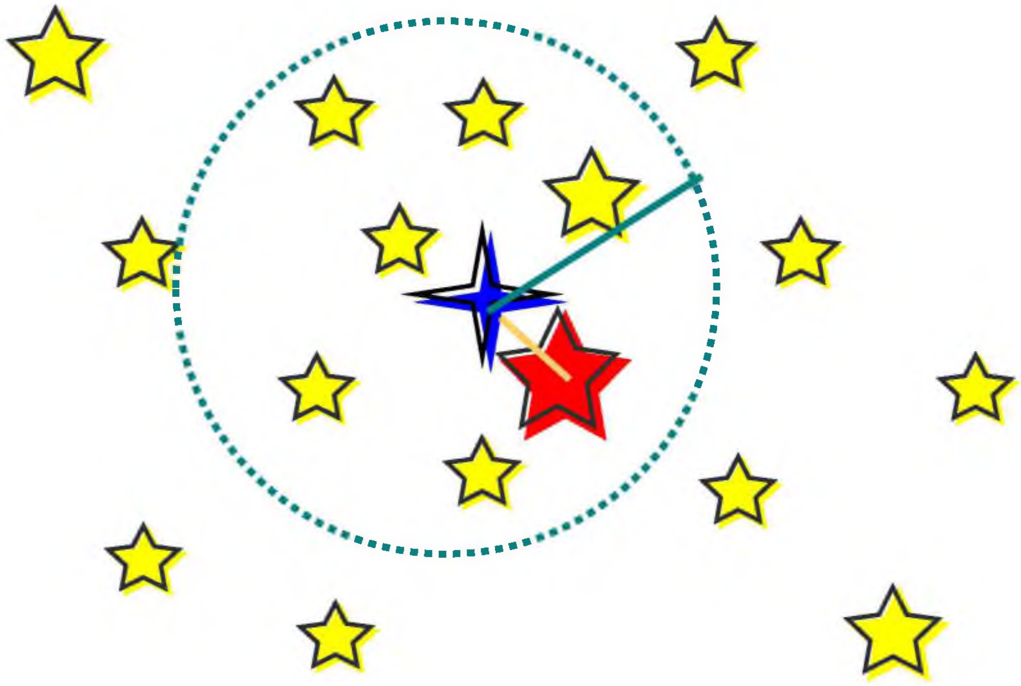

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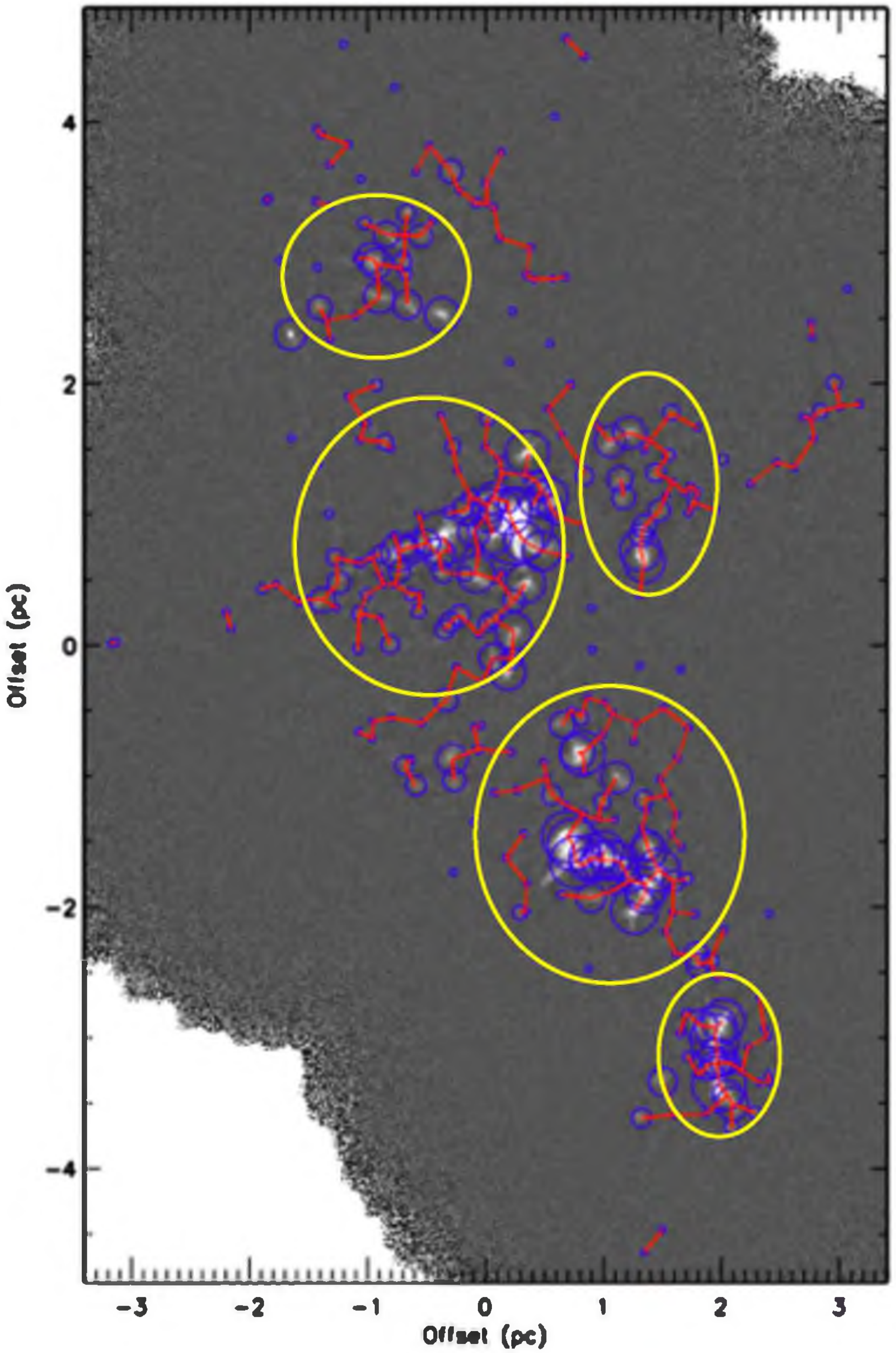
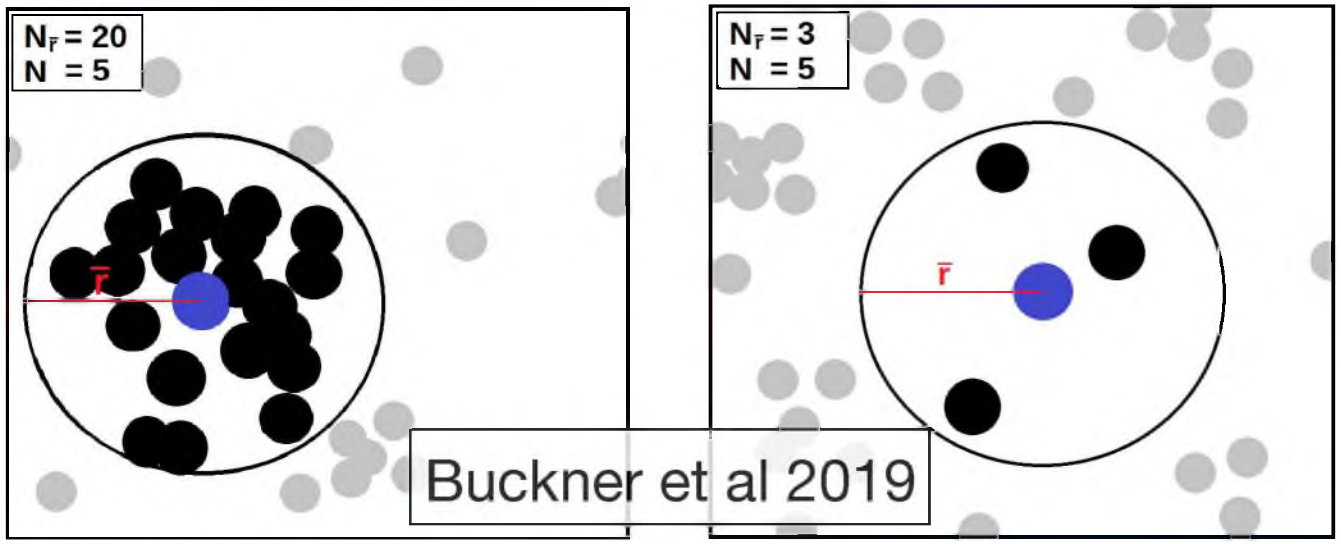


Orion B groups: Kirk et al 2016b

- Advantage: allows measurement for small distinct systems
- Advantage: provides a local measure - most massive in small cluster may be small overall
- Disadvantage: statistical power reduced (one measure per cluster)
- Disadvantage: relies on uncertain definitions (cluster members & centre). Compensate: test a range
- Disadvantage: uses only most massive cluster member (what about the second most massive member, etc?) and isolated (non-cluster) massive sources are ignored

INDICATE

- INdex to Define Inherent Clustering And TEndencies - a new method by Buckner et al (2019)
- Measure of local clustering, based on nearest neighbour surface density, compared with a uniform/unclustered distribution
- Define typical radius to enclose N sources in unclustered distribution, measure ratio, I, of # sources in data to unclust
- M-Σ segregation from massive vs non-massive with high I (higher fraction of high I in massive sources = segregation)
- Λ_{MSR} segregation by recomputing I for only massive subset. High fraction with high I means single-cluster segregation.

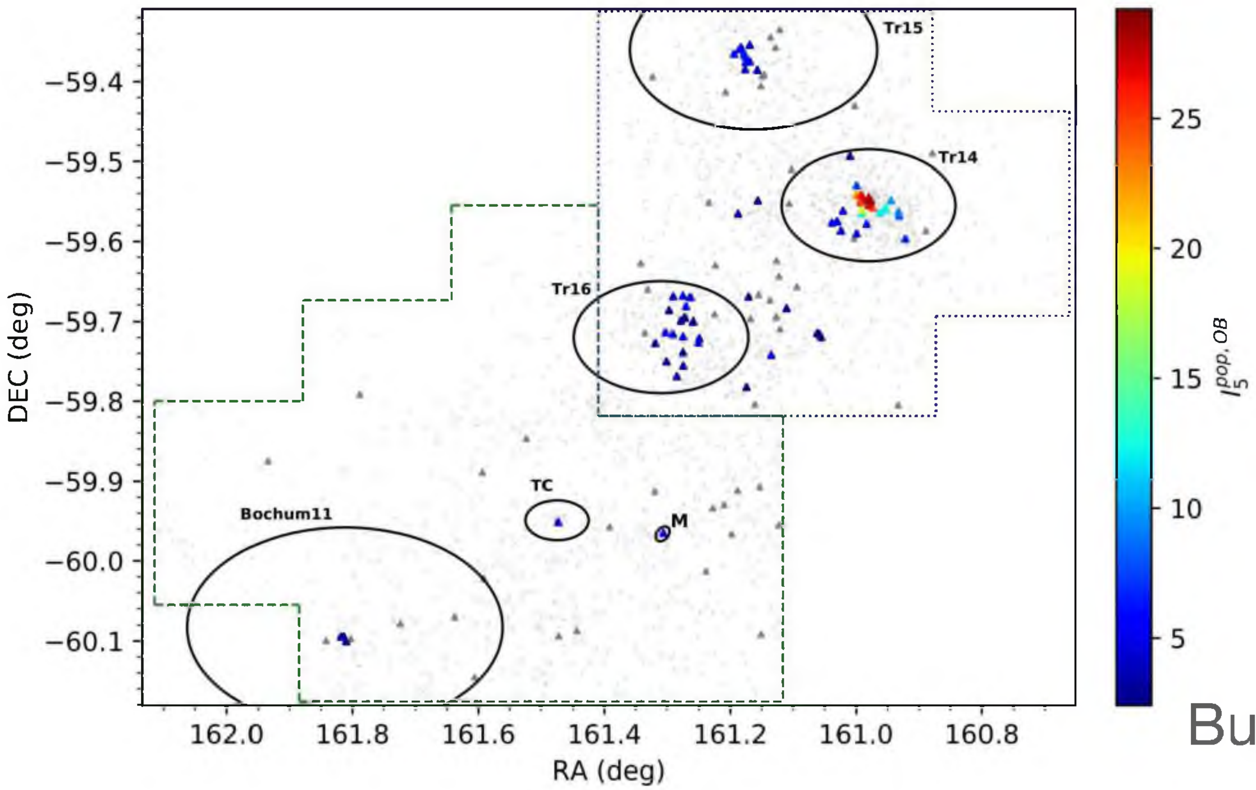


Buckner et al 2019

clustered: $I_5=20/5=4$ sparse: $I_5=3/5=0.6$

INDICATE

- Advantages: can measure both types of mass segregation (allowing for sub-structure or not) with the same basic tool
- Advantages: easily quantifiable statistics (compare I values versus random samples to get significance levels, etc)
- Disadvantages: uses nearest neighbours - may need to test on different nearest neighbour numbers



- (Dis)advantage: a very new method - needs more people trying & testing it!

Buckner et al 2019: values of I5 for OB stars in the Carina Nebula

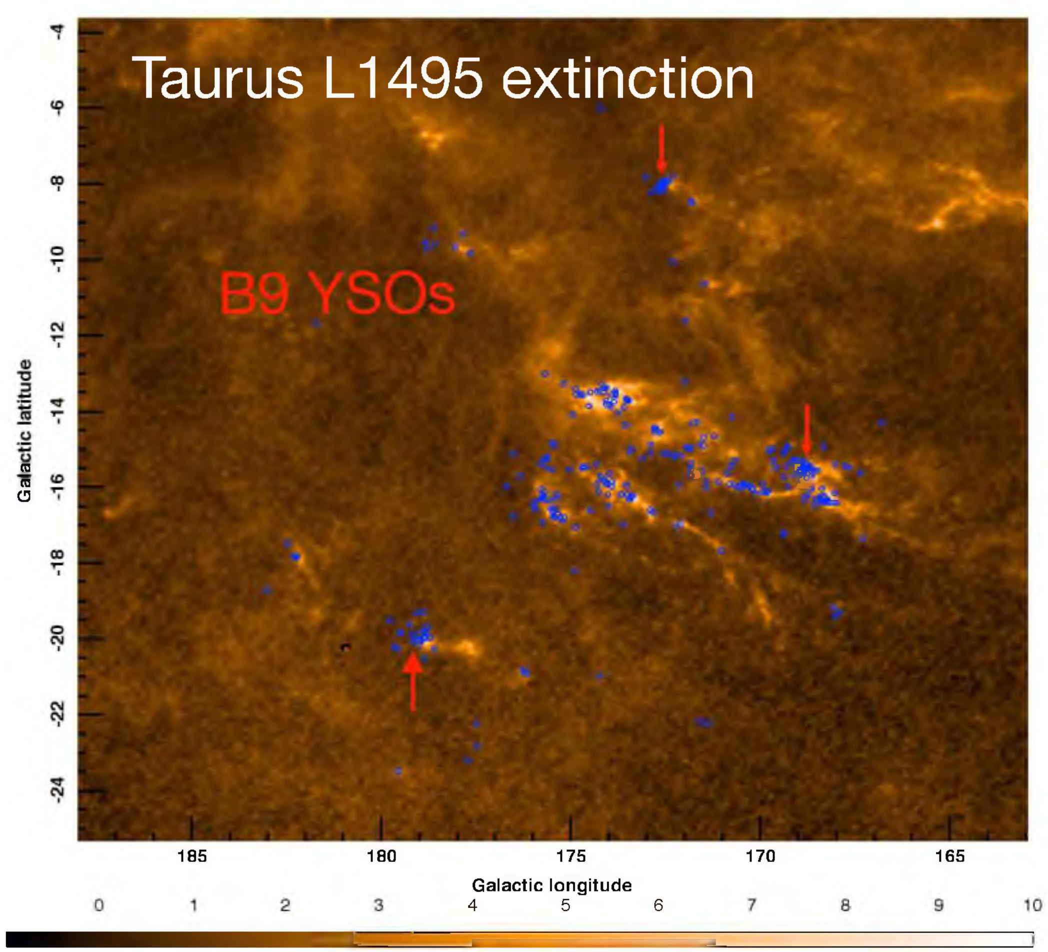
Tangent: defining clusters & mass segregation

- Girichidis et al 2012: "… whether a cluster shows … mass segregation sensitively depends on the definition of mass segregation and spatial demarcation of the region in question"

- Extreme example: Kirk & Myers 2011 find mass seg in L1495 (offset ratios, or M-Σ), while Parker et al 2011 find inverse mass segregation (Λ_{MSR}). Difference due to how substructure treated.

- Solution? Separate if no time for dynamical interactions? Other ideas?

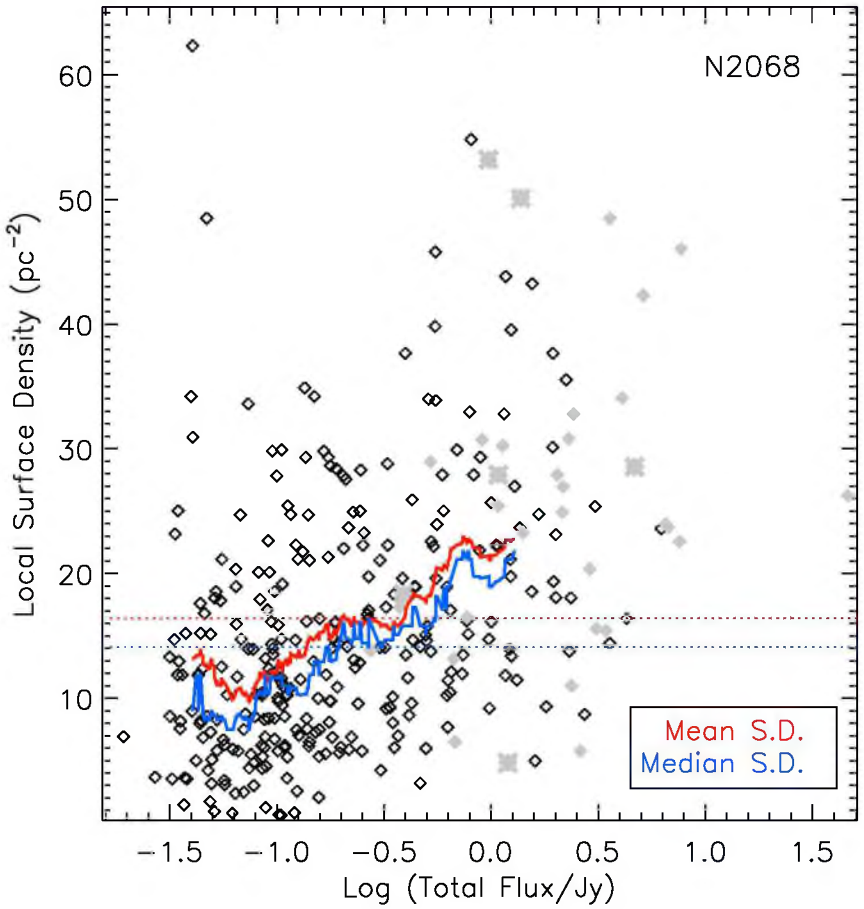
See also: Gonzalez-Garcia, Robitaille (Weds am), Hacar (Fri am)

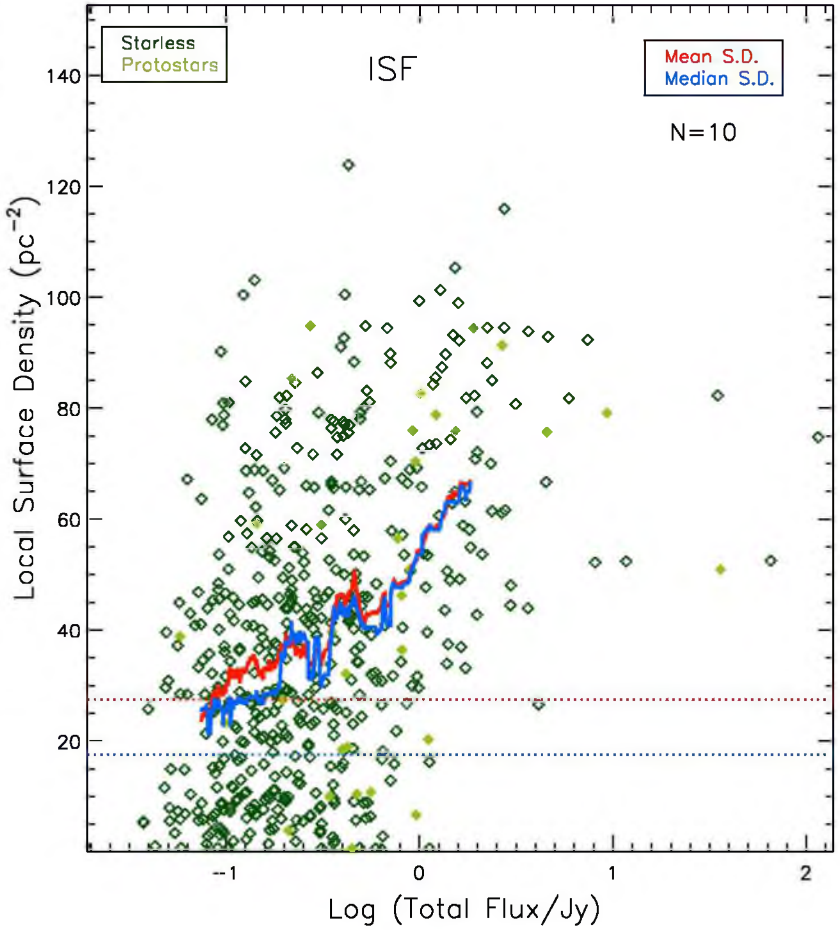


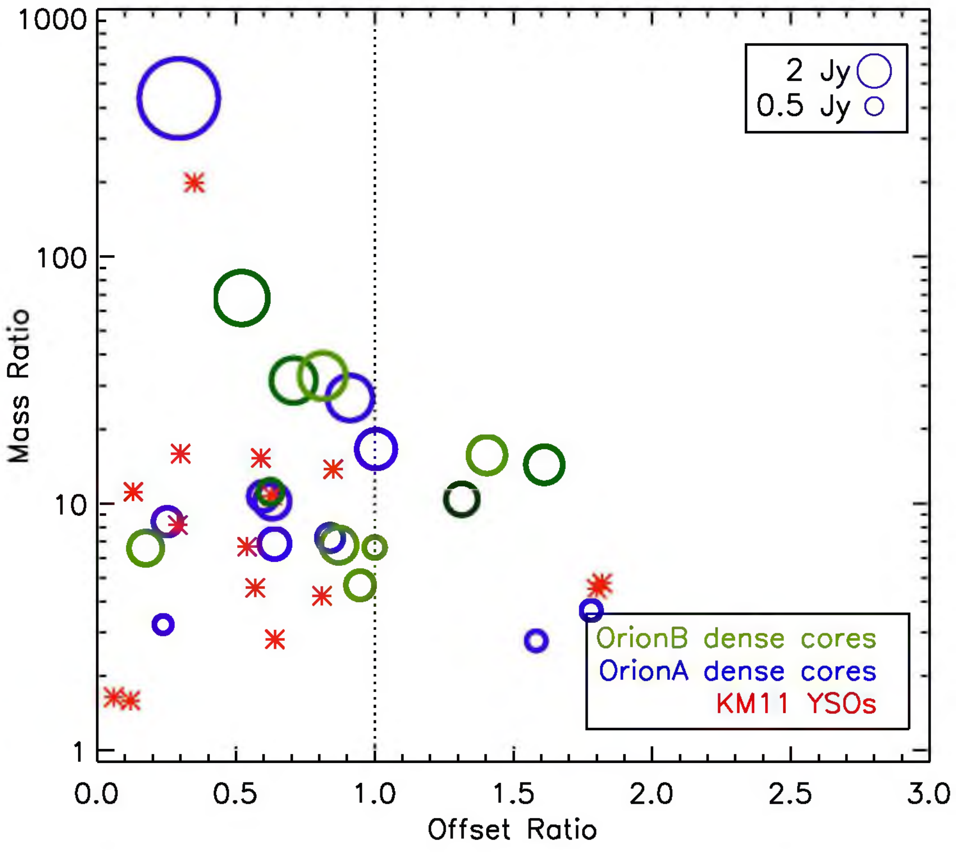
extinction map: Froebrich et al 2007
YSOs: Luhman et al 2010

JCMT Gould Belt Survey: Orion A & B

- JCMT 850 & 450 μm data, resolution ~15”, maximum scale several arcmin
- Cores id’d using FellWalker (and GetSources—OrionA), mass from tot 850 μm flux
- Signs of mass segregation using both M-Σ and Offset Ratios
- Orion B mass segregation confirmed by independent Λ_{MSR} analysis (Parker 2018)







Kirk et al 2016b and Lane et al 2016

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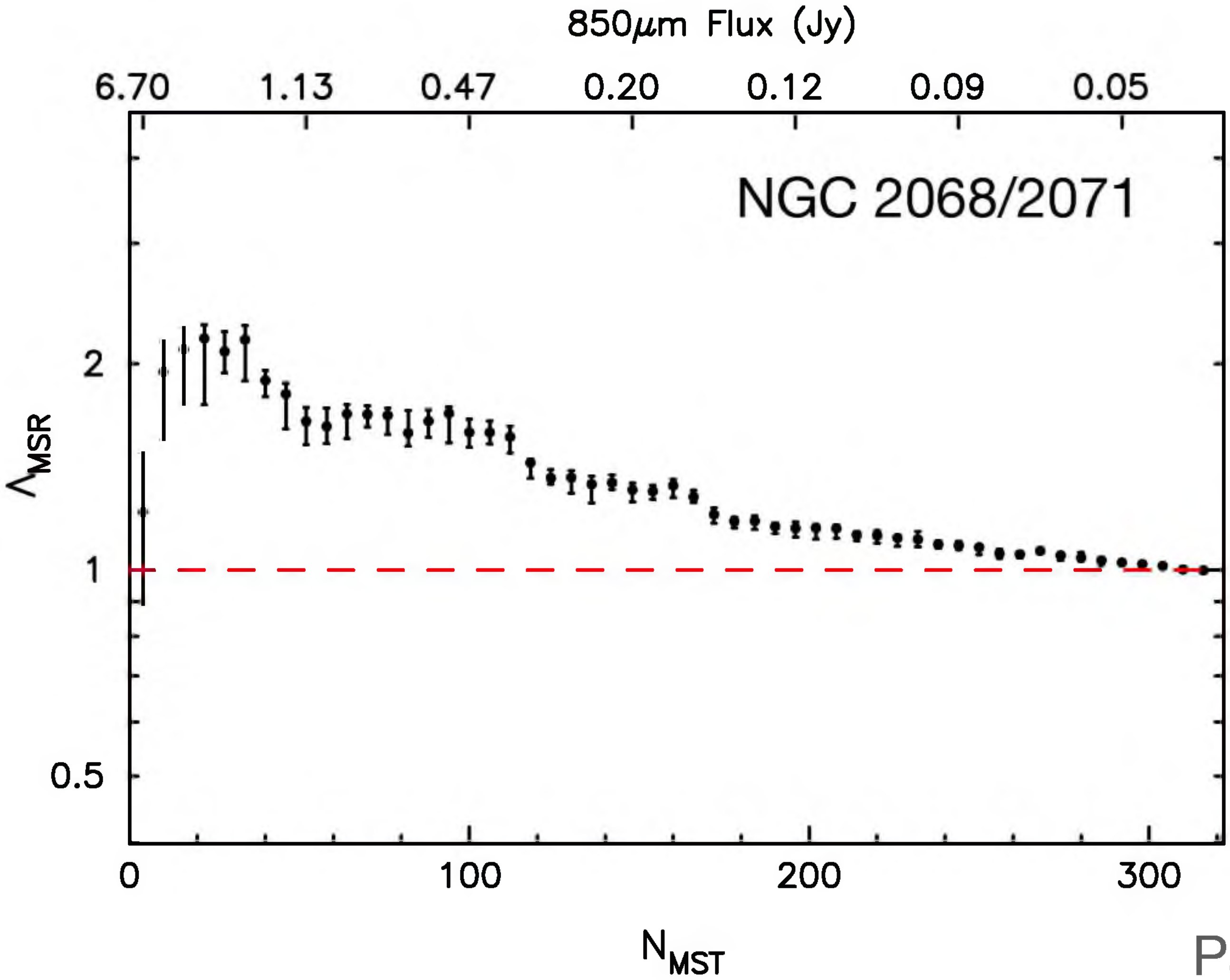
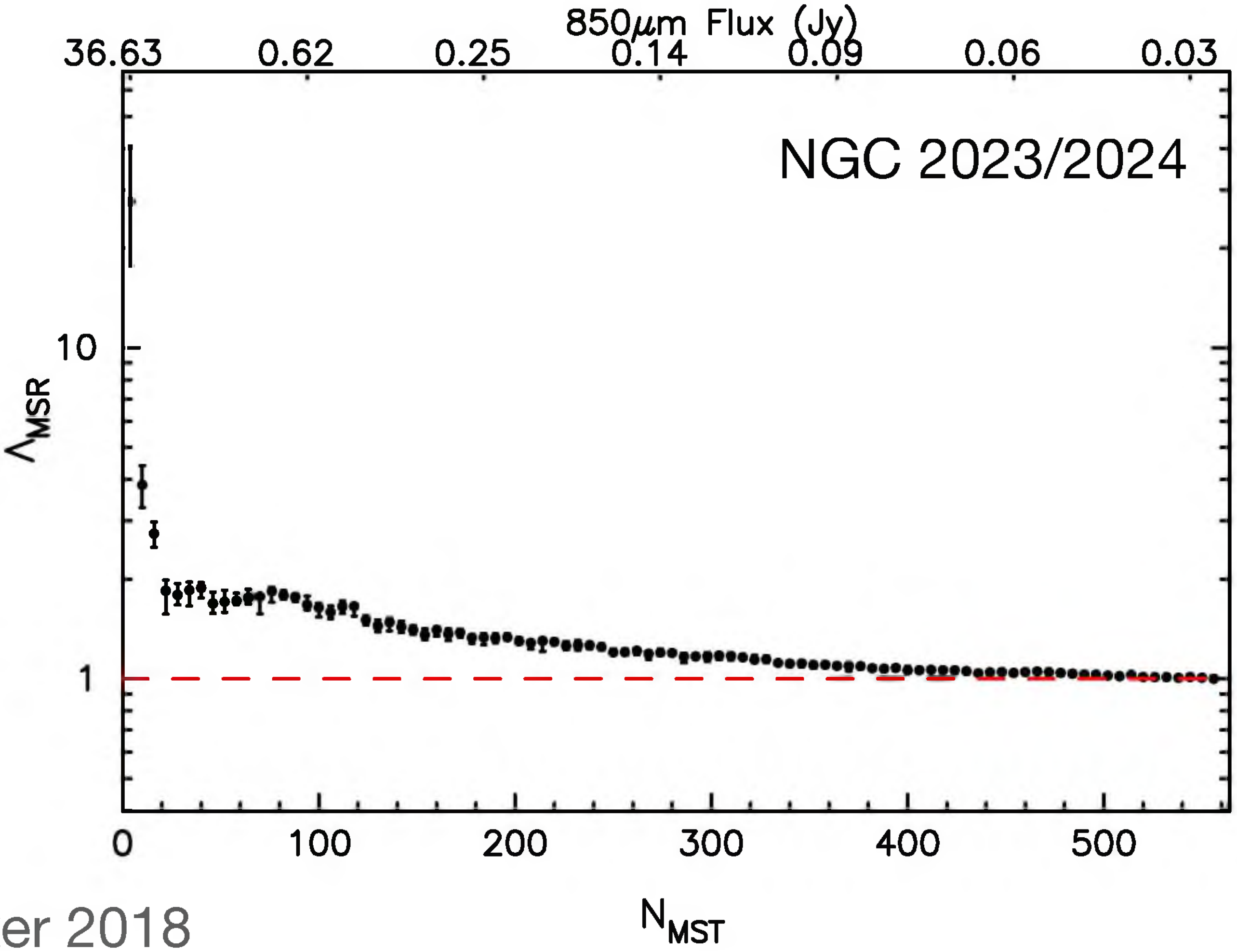
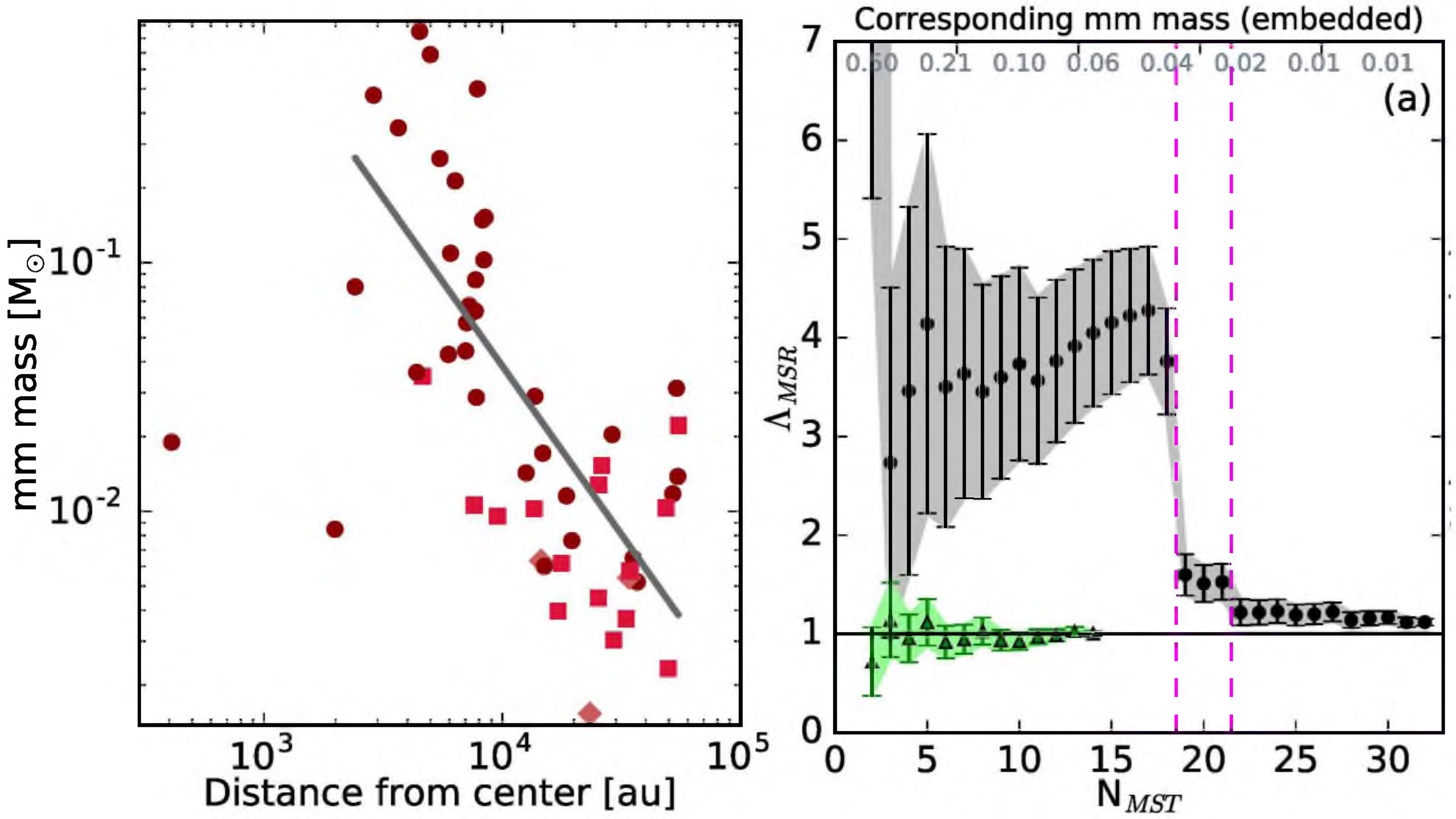




Parker 2018

Serpens South

- ALMA Band 6 (1.3mm) observations, sensitive to ~1” to 29”; also CARMA (CLASSy) N_2H^+(1-0) emission (7” res)
- Peaks identified by eye & fit with 2D Gaussians, mass from total flux at 1.3mm



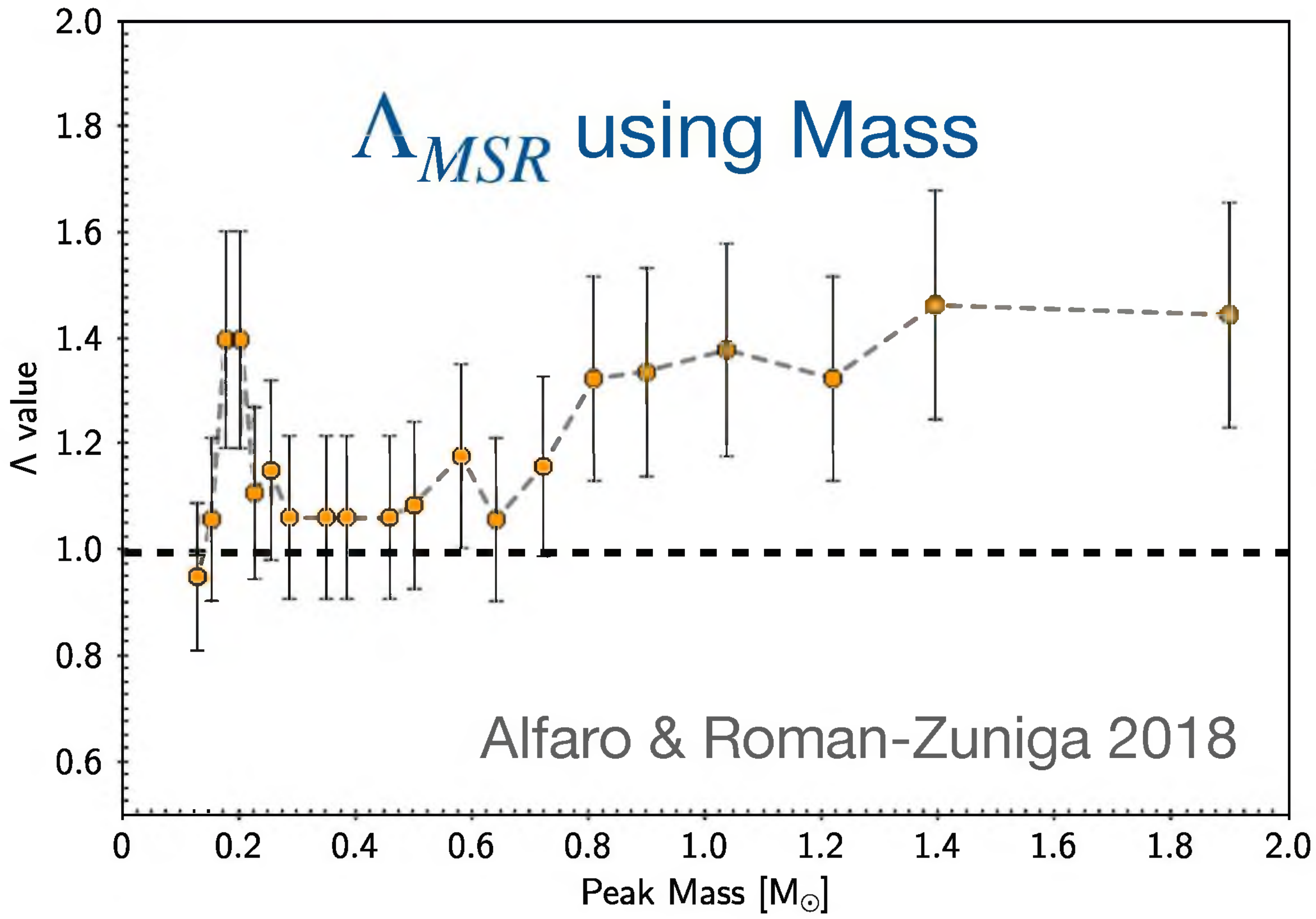
Plunkett et al 2017

Mass segregation identified by:

- central location of massive cores
- Λ_{MSR} analysis
- co-location of massive cores and N_2H^+ gas

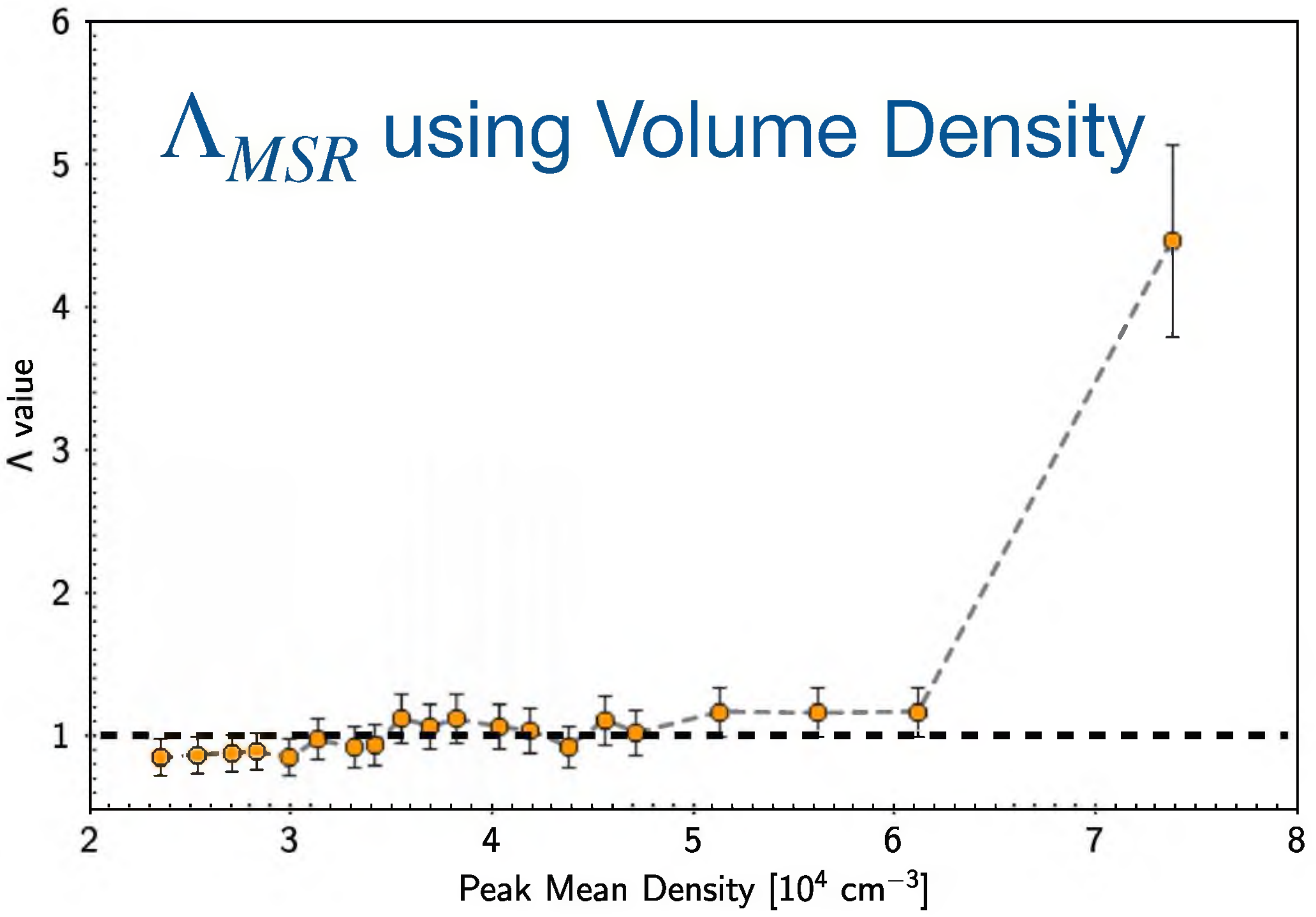
Pipe Nebula

- Peaks ID’d using clumpfind on near-IR-based column density map
- Calculate mass segregation using Λ_{MSR} as well as Q
- Mass segregation much more pronounced when using sources’ volume density instead of mass
- Q decreases with increasing ρ & segregation



Λ_{MSR} using Mass

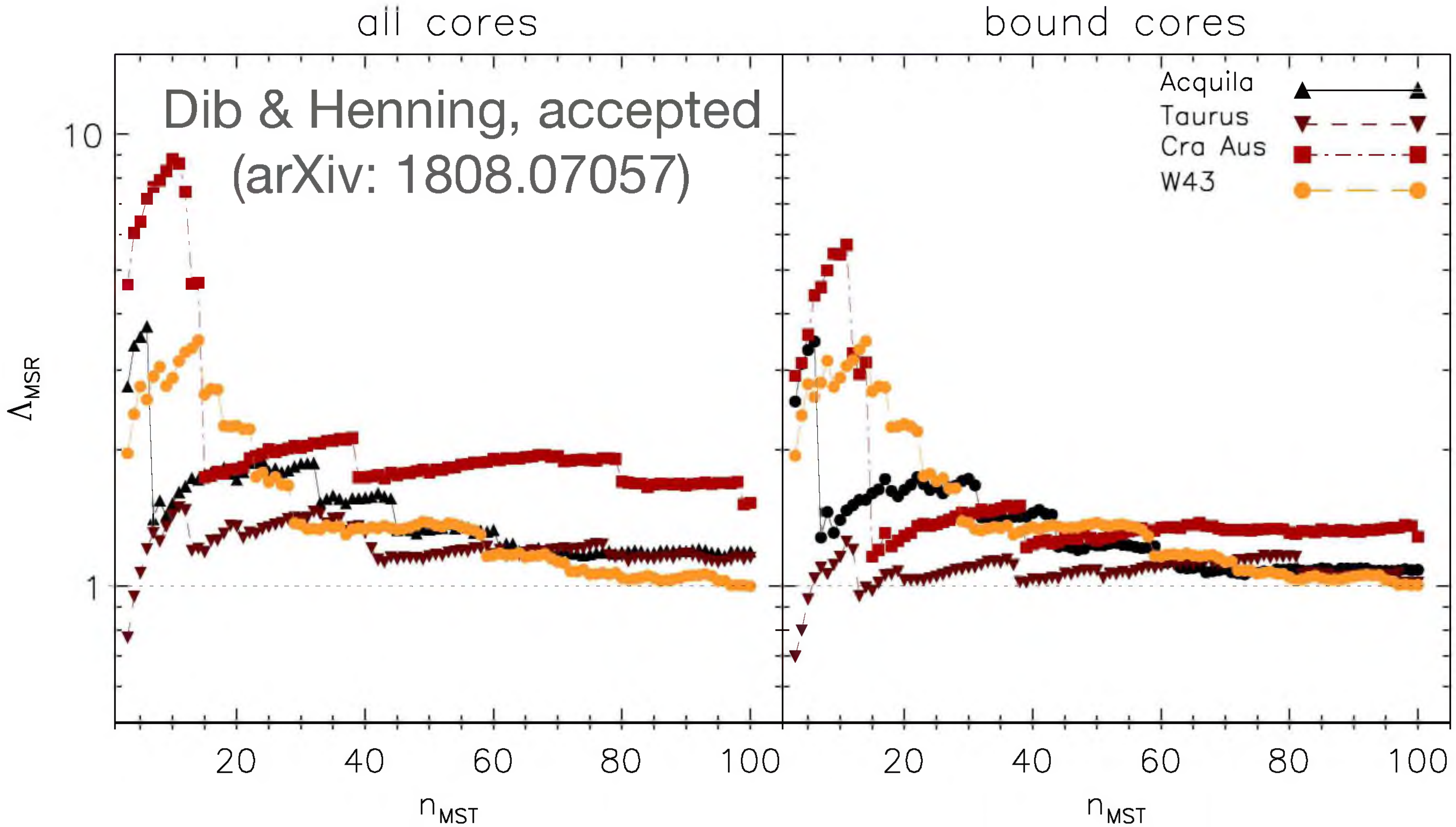
Alfaro & Roman-Zuniga 2018



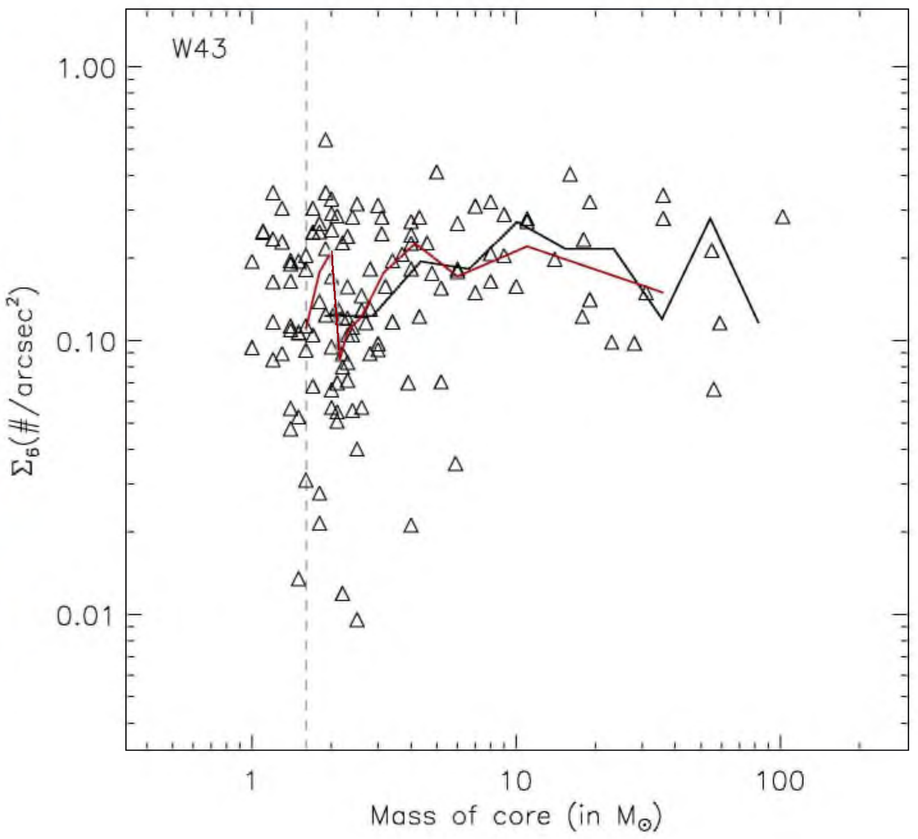
Λ_{MSR} using Volume Density

Taurus, CrA, Aquila, W43

- Archival study using GetSources-based Herschel cores (Taurus-L1495, CrA, Aquila) and ALMA 1.3mm cores (W43)
- Λ_{MSR} shows strong mass seg (weak in Taurus)
- M-Σ much weaker seg (all regions)
- Segregation may be tied to Q. Taurus: lowest Q & least mass seg. W43: highest Q and most mass seg.


Dib & Henning, accepted (arXiv: 1808.07057)

M-Σ in W43



JCMT GBS-wide results

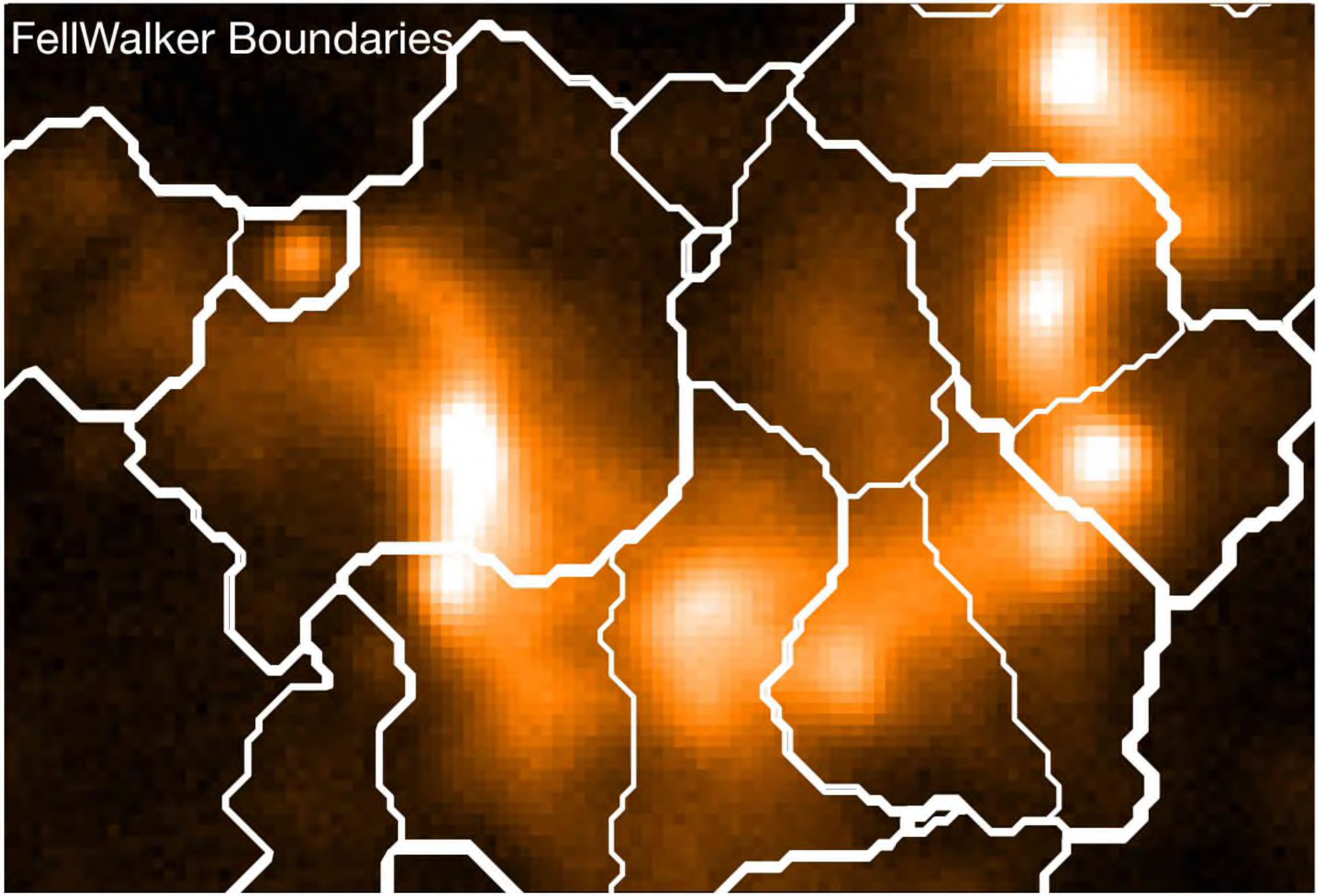
- Best quality maps now publicly available across the entire Gould Belt (incl Orion, Ophiuchus, Perseus, Serpens/ Aquila, Taurus, Cepheus, etc) — see Kirk et al 2018 for DOI
- As with earlier Orion work: use JCMT 850 μm maps to identify cores (GetSources, FellWalker) and estimate their masses
- *Preliminary results*: all steps still being vetted

- Mass segregation seen in some, but not all regions - perhaps more likely in the 'bigger' ones
- Multiple methods being tested (Λ_{MSR}, M-Σ, Offset ratios so far)
- Stronger trend seen when using volume density rather than total flux
- Testing ongoing using multiple source ID algorithms, etc

[NB: preliminary results plots removed from public version of talk]

Complications I: Core ID

- How to separate emission in most clustered areas difficult
- Implications for mass segregation: likely bias to fewer & more massive sources (or over-split low-mass sources)



An example: part of Aquila. How many cores do you see?

- FellWalker: split using gradients (peaks/valleys)
- GetSources: multi-λ Gaussian fits
- (many other methods)

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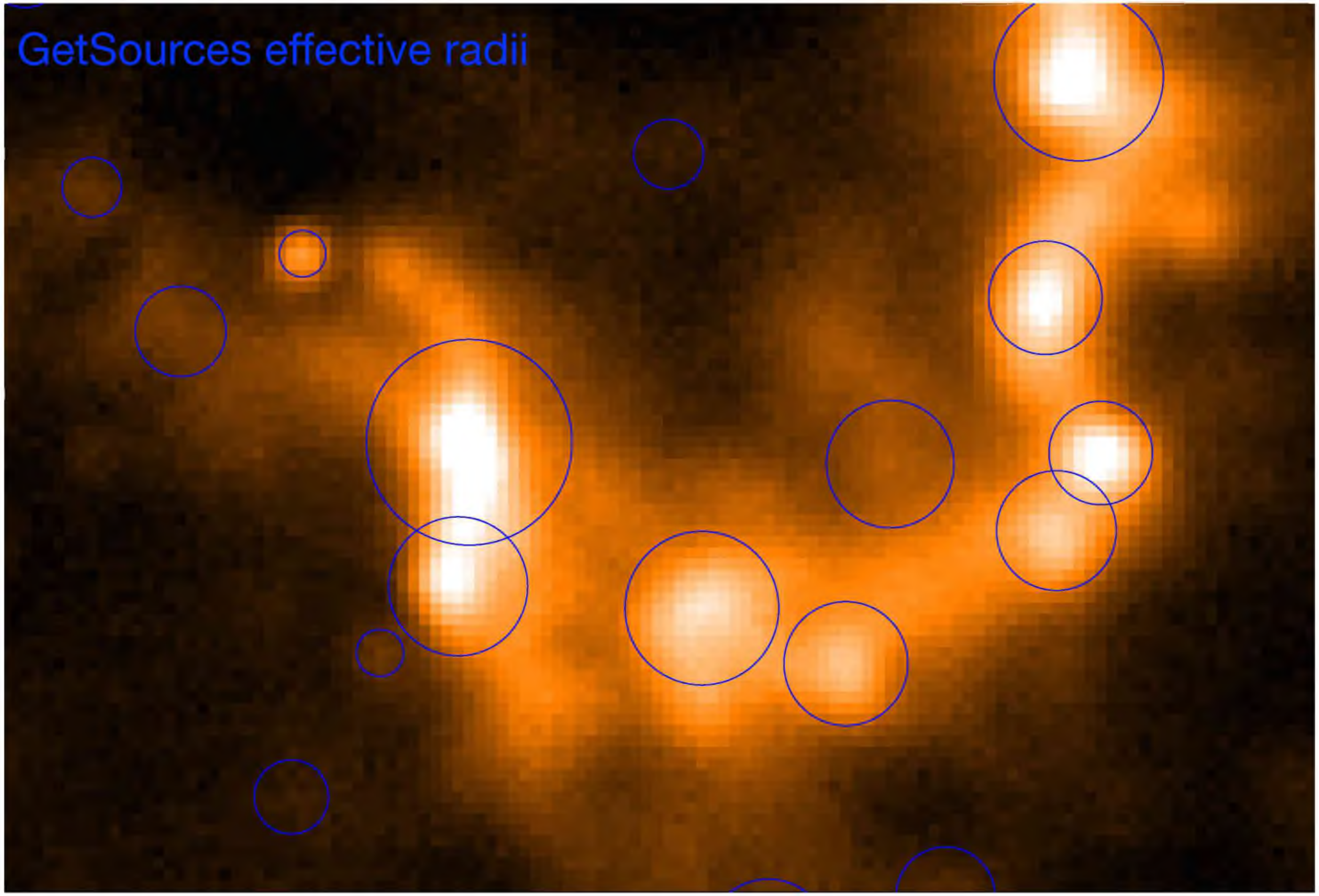

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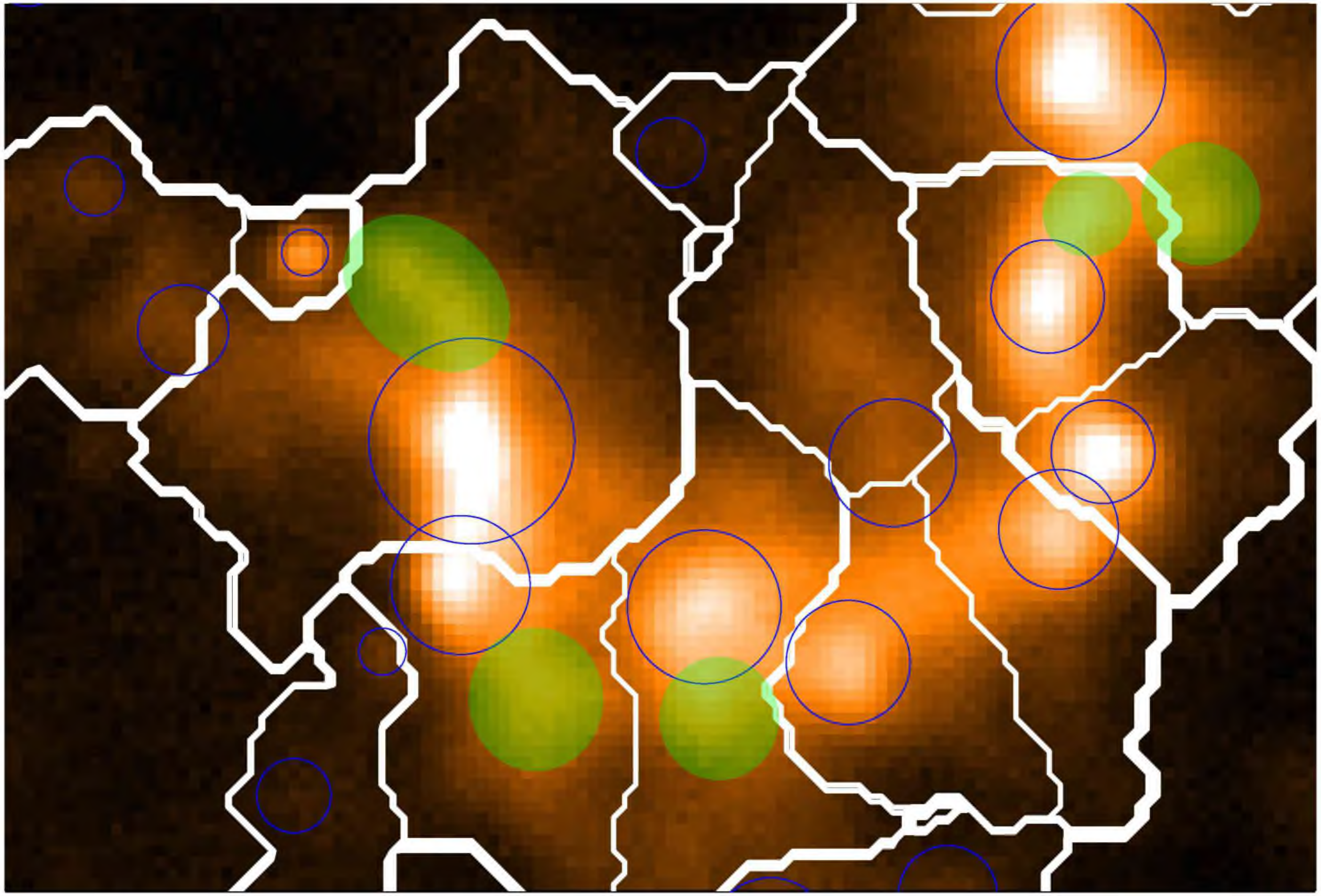

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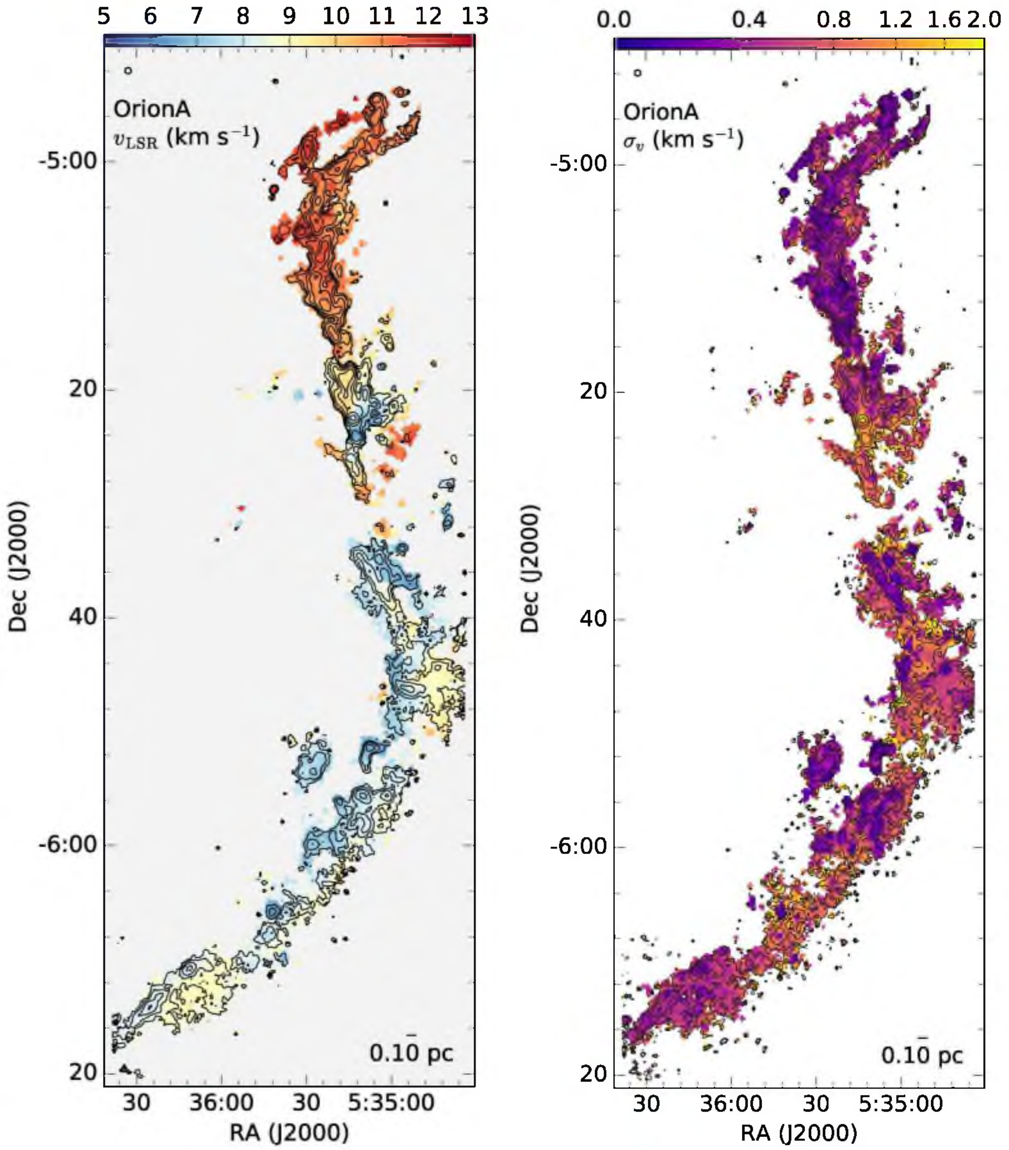
Other Complications II

- Core-protostar relationship: assume 1-1 but fragmentation, further evolution, etc, complicate tying dense core clusters to stellar clusters. Higher resolution observations (e.g., ALMA) should help with fragmentation.

Offner et al 2014 (PPVI)

Left: not all cores form protostars
Middle: variable formation efficiency
Right: variable core fragmentation

- 2D obs vs 3D reality: Kinematic data helps, e.g., Green Bank Ammonia Survey measures NH_3 across significant fraction of nearby molecular clouds. Ongoing work (Keown et al submitted, M. Chen et al in prep) identify multiple velocity components in dense gas; could be used to separate apparent vs actual clusters.



Orion A v_{lsr} (left) and line width (right) using a single velocity component fit from GAS
Friesen & Pineda et al 2017

Relevant talks: Lopez (Weds am)

Summary

- Despite challenges, nearby star-forming regions offer an important avenue to understand early stages of cluster formation
- To fully understand uncertainties, need:
  - multiple core ID techniques
  - multiple clustering / mass segregation measures
  - multiple clouds to look for regional variations
  - etc…
- Recent observations suggest mass segregation is present at least for bigger nearby star-forming regions. Sparse star-forming groups may not be mass segregated (preliminary)
- For the observers:
  - JCMT GBS maps publicly available: https://doi.org/10.11570/18.0005 Catalogue paper(s) in progress
  - GAS NH3 maps publicly available for initial 4 regions; remaining are in progress for public release : https://dataverse.harvard.edu/dataverse/GAS_DR1

Thank You!