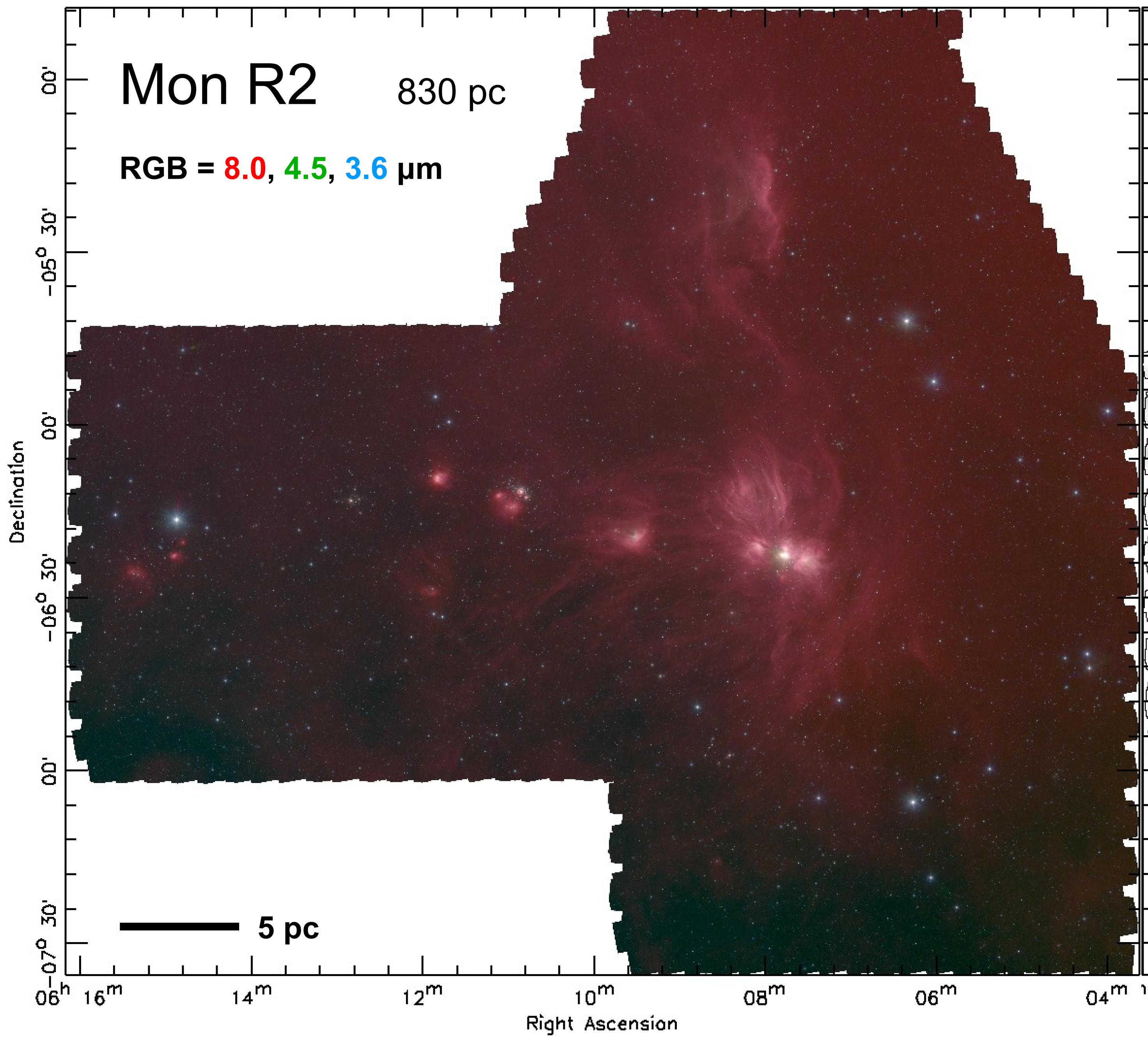
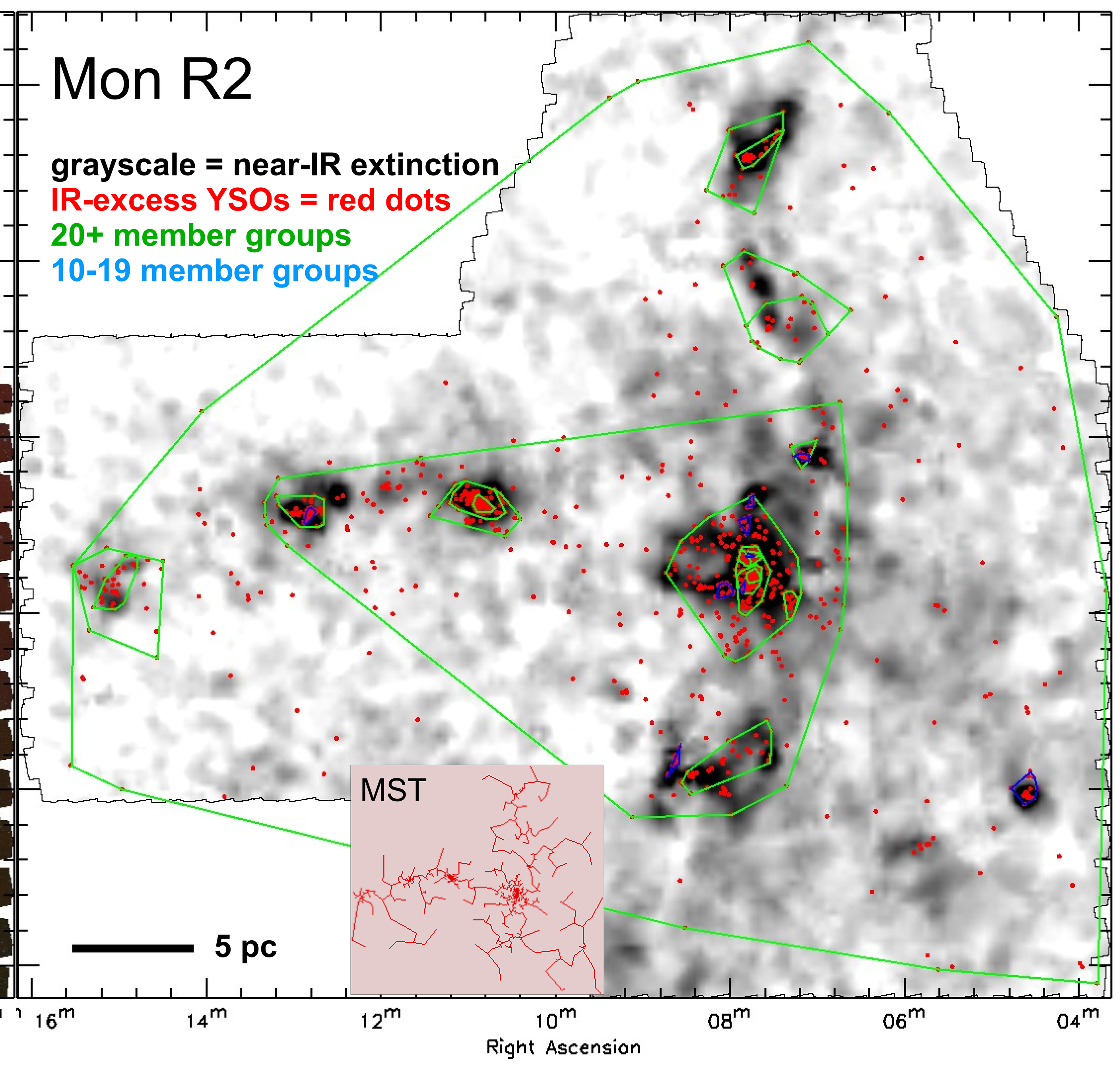
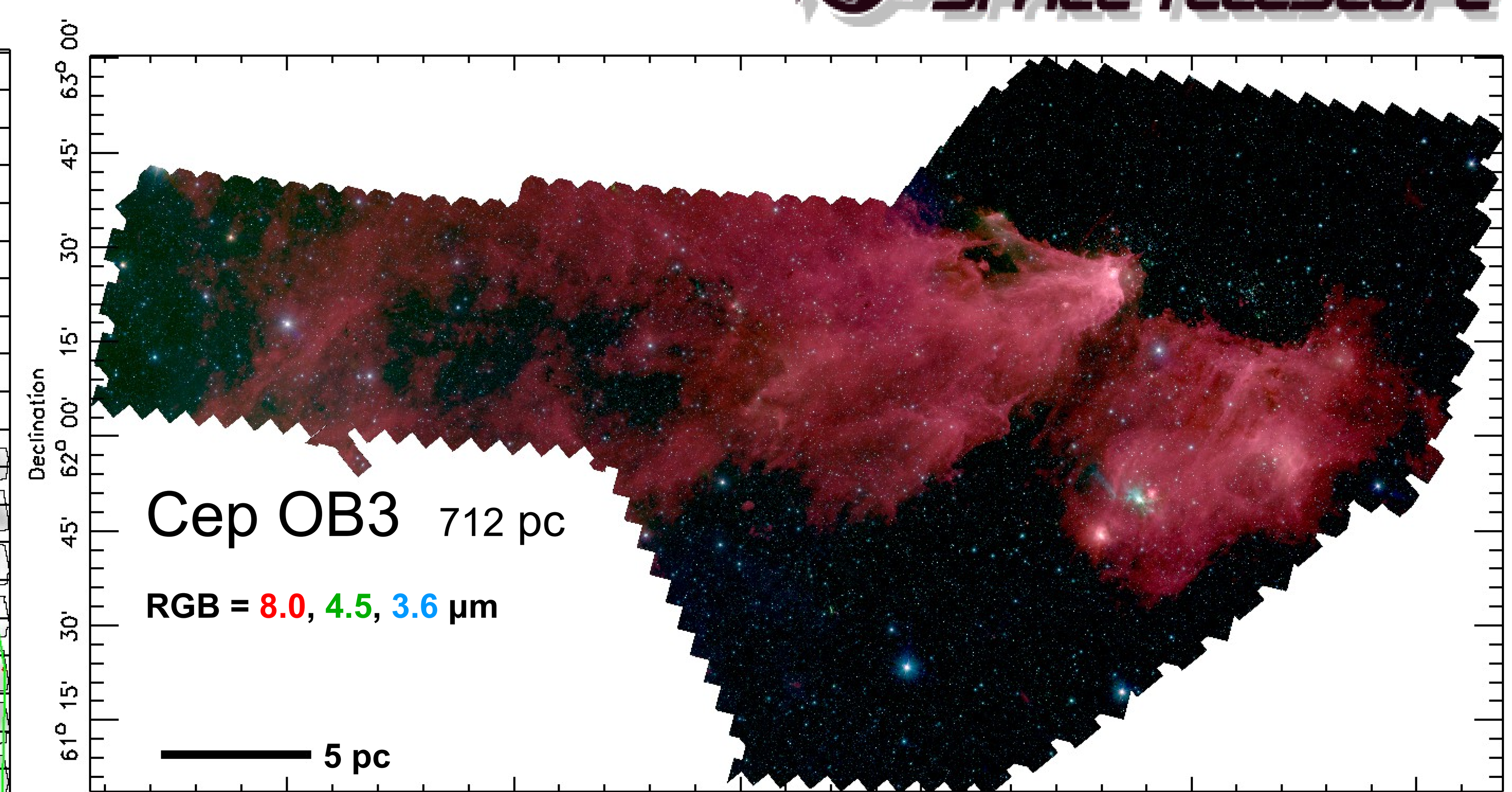
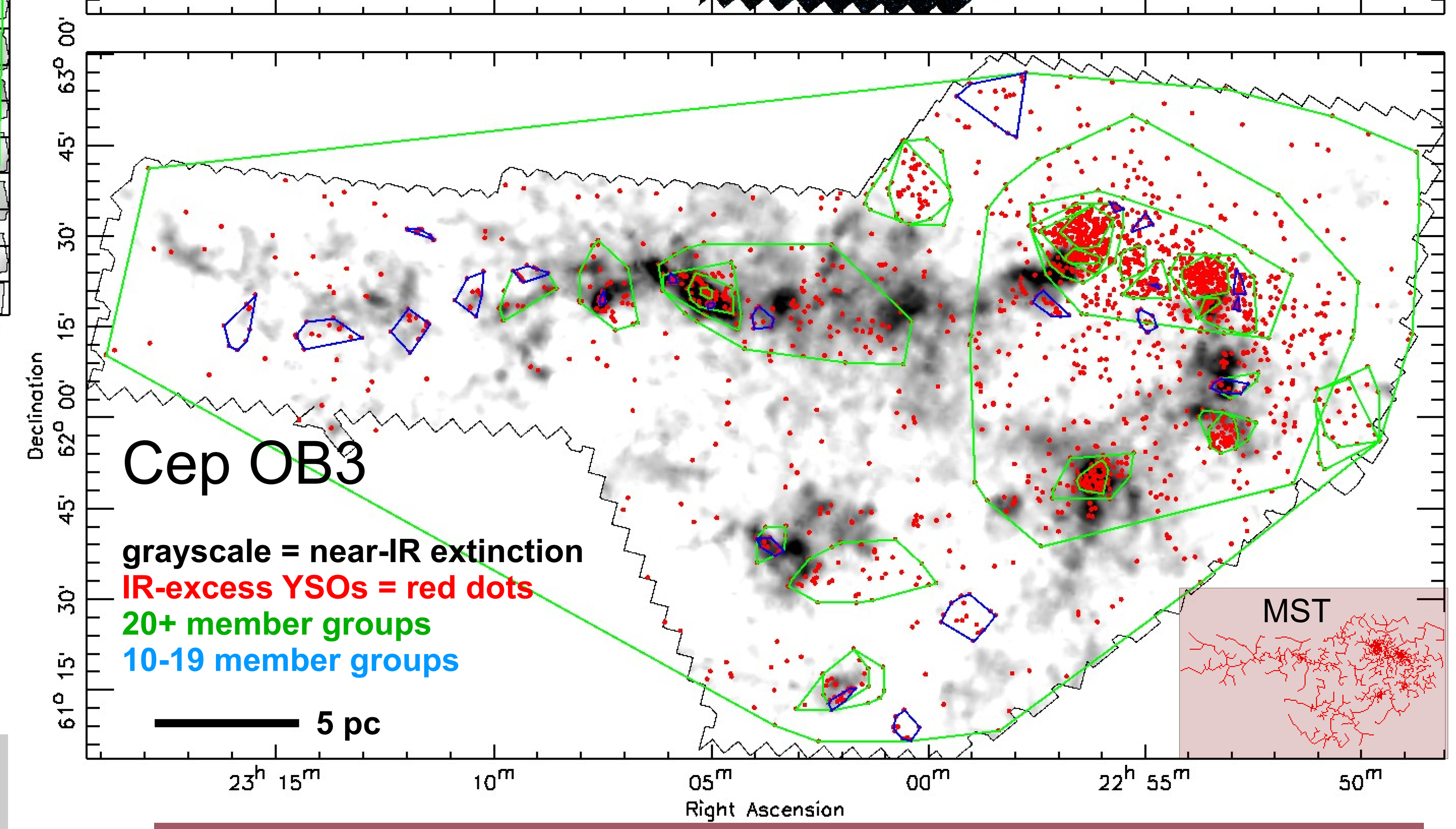
# Structure Characterization in Star-Forming Molecular Clouds: Mon R2 & Cep OB3

*R. Gutermuth (1), J. Pipher (2), T. Megeath (3), P. Myers (4), T. Allen (3), E. Allgaier (3), J. Muzerolle (5), L. Allen (4)*
*(1) FCAD/Smith College; (2) U. of Rochester; (3) U. of Toledo; (4) Harvard-Smithsonian CfA; (5) Steward Obs., U. of Arizona*



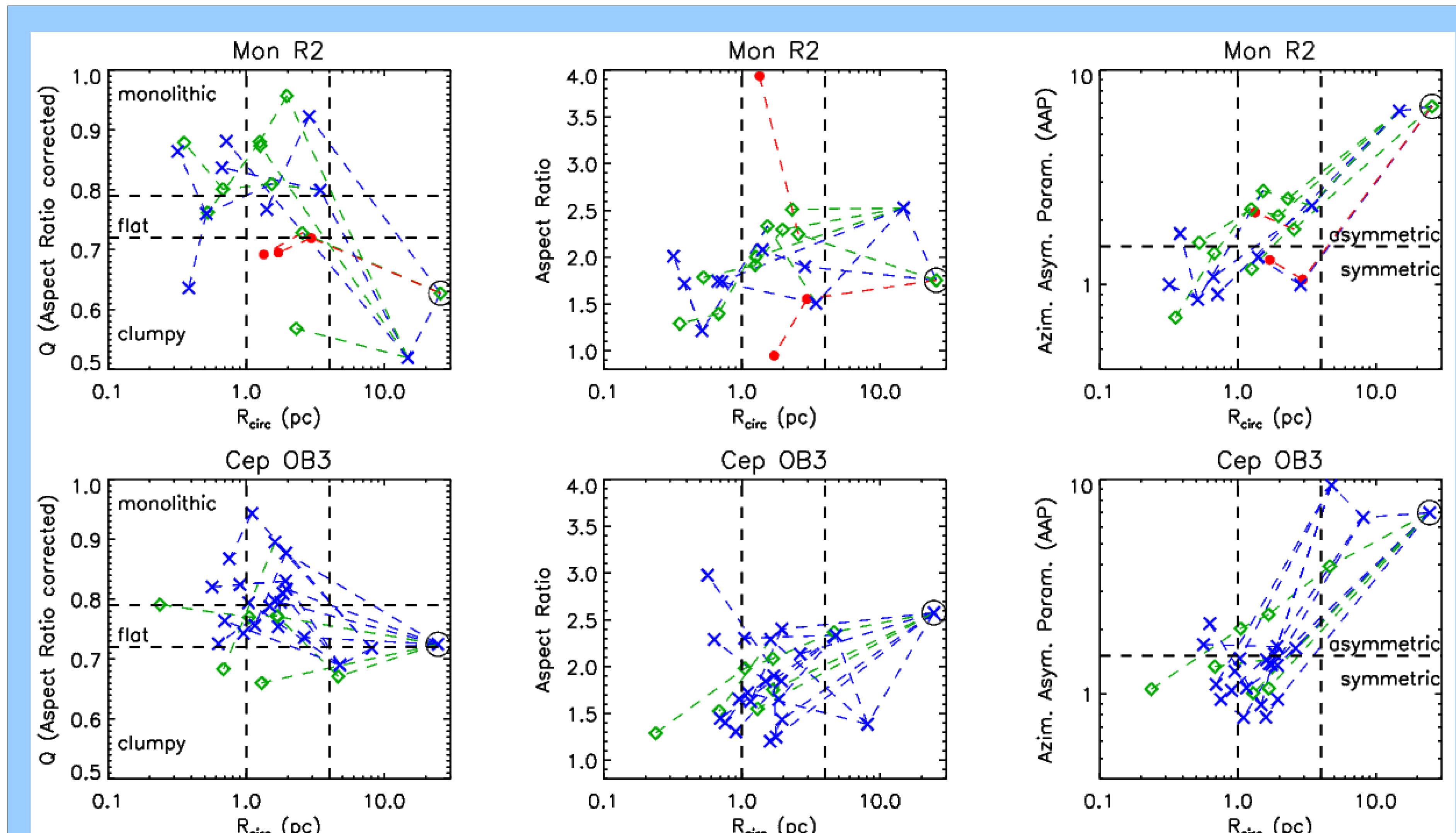




## A new technique for characterizing star-formation structure at multiple length scales

The many unbiased surveys of nearby molecular clouds obtained with *Spitzer* have shown that **embedded clusters are not isolated entities, but rather the surface density peaks of much larger, less dense distributions of YSOs** (e.g. Allen et al. 2007). Attempts to adopt a single surface density threshold that successfully identifies all "clusters" over all clouds have yielded unsatisfying results, since a threshold that works in one cloud may miss some clusters in other clouds. Recent efforts to rectify this issue have involved adopting more than one threshold (e.g. Jorgensen et al. 2008). The successful identification of hierarchical structure with these improved techniques was expected and welcome, but the arbitrariness of empirical adoption of surface density thresholds, whether one or many, left apparent substructure uncharacterized in many regions. *A complete characterization of structure at all scales, customized to each cloud's distribution of YSOs, would be ideal, enabling unbiased intercomparison of the qualities of the identified hierarchy of structures from cloud to cloud.*

We have composed a **fully algorithmic technique** for extracting the entire hierarchy of overdense structures within a given large scale point distribution, utilizing its *Minimal Spanning Tree* (MST) construction (red insets). For a given point distribution, we use the cumulative distribution of MST connection lengths to identify a background surface density and then adopt the critical length that isolates all substructures denser than that background. This process is then applied iteratively to the point distributions of the structures themselves, continuing up the hierarchy until no new, denser structures are found with **N=10** or more members.

**Minimal Spanning Tree**: The network of lines that uniquely connects a set of points together with minimized total length of all connections and without any closed loops. Adopting a connection length threshold, whereby all connections greater than that threshold are deleted, enables efficient subdivision of structures above a given surface density *without smoothing*.




Blue crosses: "Old" groups (C2/C1 > 5)
Green diamonds: "Intermediate" groups (2 < C2/C1 < 5)
Red dots: "Young" groups (C2/C1 < 2)
Black Circle: entire molecular cloud survey

Blue/green/red dashed lines are meant to indicate the hierarchical "parent" of each structure. The color code matches the child's age color code (defined at left). Black dashed lines mark meaningful boundaries referenced in the text below and at right.

**Q Parameter**: (Cartwright &Whitworth 2004) For a given set of points, a measure of the 2D deviation from a statistically uniform distribution ( **0.72 < Q < 0.79** ). High Q is consistent with a centrally concentrated, monolithic distribution (Q>0.8 traces radial density decay of increasing power law index). Low Q is consistent with a clumpy distribution (Q<0.72 traces fractal dimension; lower more isolated clumps). A bias in Q with increasing aspect ratio of the distribution of points was reported and characterized by Bastian et al. 2008. Their correction for this effect is applied here.

**Azimuthal Asymmetry Parameter (AAP)**: (Gutermuth et al. 2005) For a given set of points, a measure of the radially averaged azimuth distribution deviation from a uniform one. Poisson variant uniform distributions have a mean AAP of 0.9 and sigma 0.2. Thus we adopt a three sigma threshold ( **AAP = 1.5** ) for identifying groups with significant asymmetric structure. *Note that either elongation (high aspect ratio) or clumpiness (low Q) can trigger an asymmetric result in the AAP measurement.*

## Tracing Structure Evolution Through the Hierarchy: Comparing Dynamical and Evolutionary Age Estimates

*Left*: We have made structure measurements for each grouping isolated with our technique and plotted them at left as a function of their semimajor axis length. Many things are evident:

- *Self-similar fractal structure appears to be ruled out at length scales less than 4 pc.* In a self-similar fractal, subdivided structures should preserve the low Q value seen at larger scales. However, most substructures smaller than a few pc seem to be flat or monolithic and weakly centrally concentrated (Q~0.8).

- *Elongation is sufficient to explain the substructure observed in most groupings of size scales less than a few pc.* There are exceptions, of course; some groups do exhibit clumpiness, particularly those that are young. Aspect ratio appears to most often correlate with AAP, while the effects of elongation on Q have been removed to make it a robust clumpiness indicator.

- *Asymmetric structure of some kind (elongation or clumpiness, see AAP measurements) is consistently observed in the Mon R2 groups larger than 1 pc, while asymmetry is only consistently observed in groups 4 pc or larger in Cep OB3.* Assuming that observable asymmetry at a given length scale is erased over a crossing time, and assuming a velocity dispersion of 1 km/s at birth, we can infer the clouds' mean ages since the onset of star formation:

**Mon R2: 1 Myr; Cep OB3: 4 Myr.**

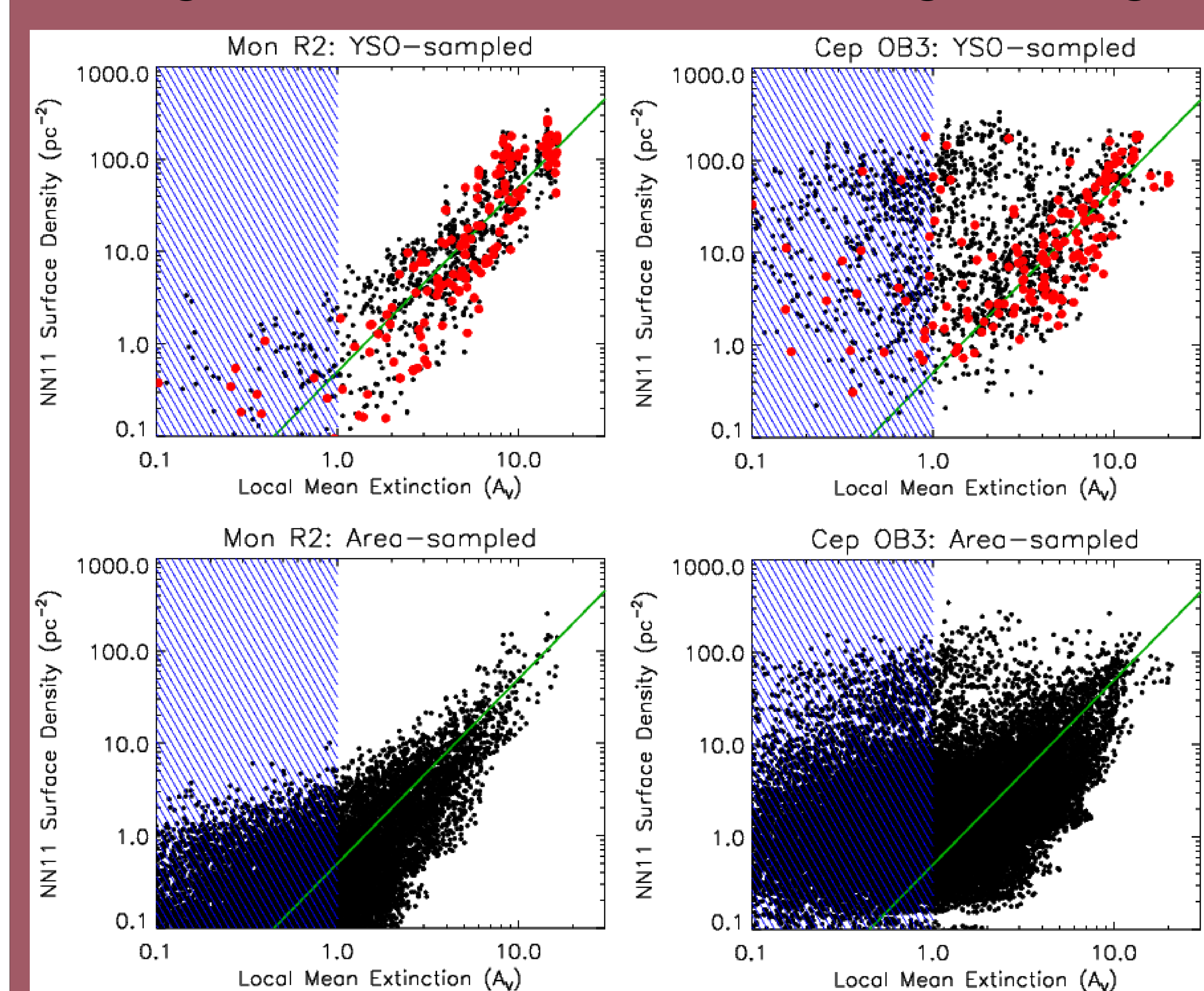
We can also estimate the mean star-forming age of the cloud via the *Class II to Class I YSO count ratio* (C2/C1).

*Mon R2 C2/C1 = 788 / 185 = 4.3*
*Cep OB3 C2/C1 = 1908 / 187 = 10.2*

If we assume the Class I phase lasts 0.5 Myr, this results in ages since the onset of star formation of:

**Mon R2: 2 Myr; Cep OB3: 5 Myr.**

## Fragmentation of an Isothermal, Self-gravitating Layer of Gas?




Black points: Class II
Red points: Class I
Green line: Model
Blue hashed area: extinction consitent with Av=0

Black points: corresponding NN map and Av map values.
Red line: Model
Blue hashed area: extinction consitent with Av=0

Many have observed that YSOs tend to trace the dense gas of their natal cloud. Here, we report the observation of an apparent correlation between the local surface density of embedded YSOs and the local surface density of molecular gas as traced by dust in both clouds. The overlaid trend is **σ{YSOs} ~ σ{gas}^2**, the expected density of thermal Jeans masses within an isothermal, self-gravitating layer of gas of a given mean column density (Myers in prep.). *Mon R2 is relatively young* (see left panel), and its YSOs predominantly trace this locus regardless of evolutionary class. *Cep OB3, however, appears older.* While the same "star-forming locus" is apparent and Class I sources are largely confined there, there is a considerable number of high YSO density, low extinction points (mostly Class II) dominated by the members of the large Cep OB3b cluster. This region has recently ejected its natal gas, exposing a rich young cluster! (Getman et al. 2006, Allen et al. in prep.)

**NN11**: Surface density of the 11 nearest neighbor YSOs, measured with the minimum enclosing cicular area centered on some adopted sample point. *YSO-sampled* implies that the sample points are the IR-excess YSO positions. *Area-sampled* implies that the sample points are a uniformly spaced grid of positions that match the sample grid of the extinction map.

**Local Mean Extinction**: Extinction measurement from the nearest sampled positions in the 2MASS H-Ks derived extinction map. Each extinction measurement is a mean of the values for the nearest 20 stars, and includes outlier rejection to eliminate foreground sources. For standard assumptions of gas-to-dust mass ratio and dust opacity, **1 Av ~ 10^21 N(H) cm^(-2)**.