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The Structure of Young Stellar Clusters

with

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Understanding Clustered Star Formation

Question

What is the clustering of stars at birth (and after)?

Key Issues

- *"Typical" length-scales of Stellar Clustering.*
- *Time-scale for Star Formation / Structure survival.*
- *What processes determine these parameters?*

Requirement

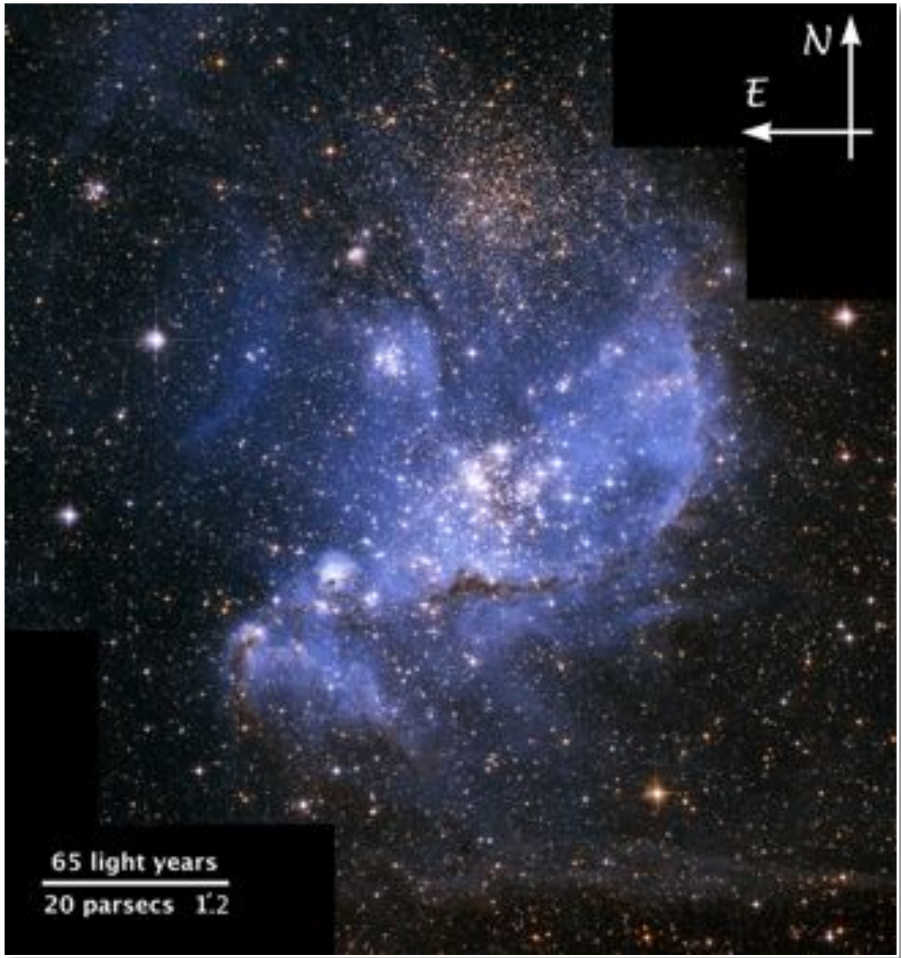
Complete samples of resolved young stellar populations

The MW – Magellanic Clouds System


The Region NGC 346/N66
Walborn et al. 1978
De Boer & Savage 1980
Niemela et al. 1986
Chu & Kennicutt 1988
Massey et al. 1989
Ye et al. 1991
Cortusi et al. 2000
Rubio et al. 2000
Walborn et al. 2000
Koenigsberger et al. 2000
Hoopes et al. 2001
Nazé et al. 2002
Danforth et al. 2003
Nazé et al. 2004
Reid et al. 2006
Evans et al. 2006
Gouliermis et al. 2006
Sabbi et al. 2007
Simon et al. 2007
Hennekemper et al. 2008
Hunter et al. 2008
Gouliermis et al. 2008
Sabbi et al. 2009
Schmeja et al. 2009
Cignoni et al. 2010
Cignoni et al. 2011
Gouliermis et al. 2014
eso1008 - Photo Release
Credit: Henri Boffin

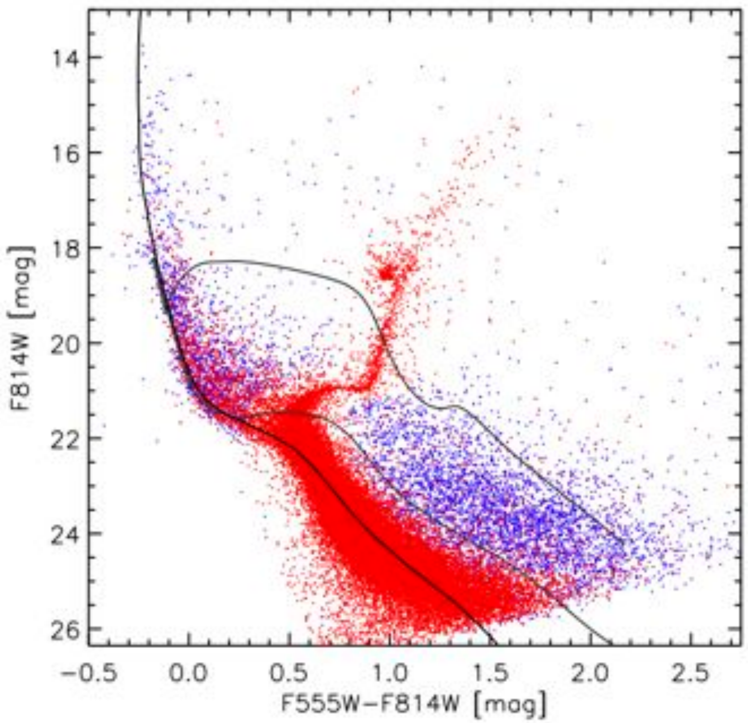
The Star-Forming Complex NGC 346

NGC 346 (N66) in the SMC
HST Program GO-10248 (PI: A. Nota)



Credit: NASA/ESA HST & A. Nota (STScI)

Template of mixed populations



Photometric Catalogs:
Nota et al. 2006 ApJL, 640, 29
Gouliermis et al. 2006 ApJS, 166, 549

60% of the star formation
occurred earlier than ~ 5 Gyr ago
(Cignoni et al. 2011 AJ, 141, 31)

Stellar Clustering in NGC 346

Schmeja, Gouliermis & Klessen 2009 (ApJ, 694, 367)

PMS Stars Sub-Clusters

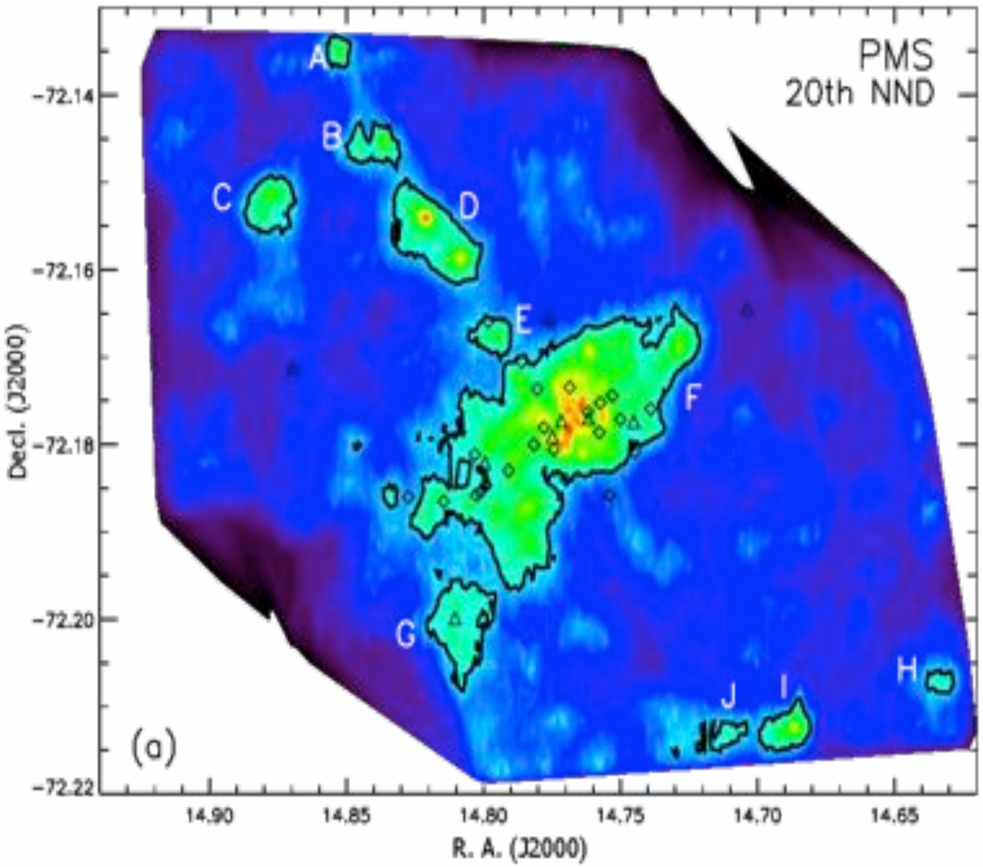
- Ten individual stellar structures
- One dominant aggregate

- Sizes: 1 – 20 pc
- Stellar Numbers: few – ~1500
- Brightness: V = 20 – 10^{mag}

- ~ 70% PMS stars within 1σ
- ~ 40% Clustered PMS stars (2σ)

- Q = 0.59 – 0.93
- Substructure in 70% of clusters

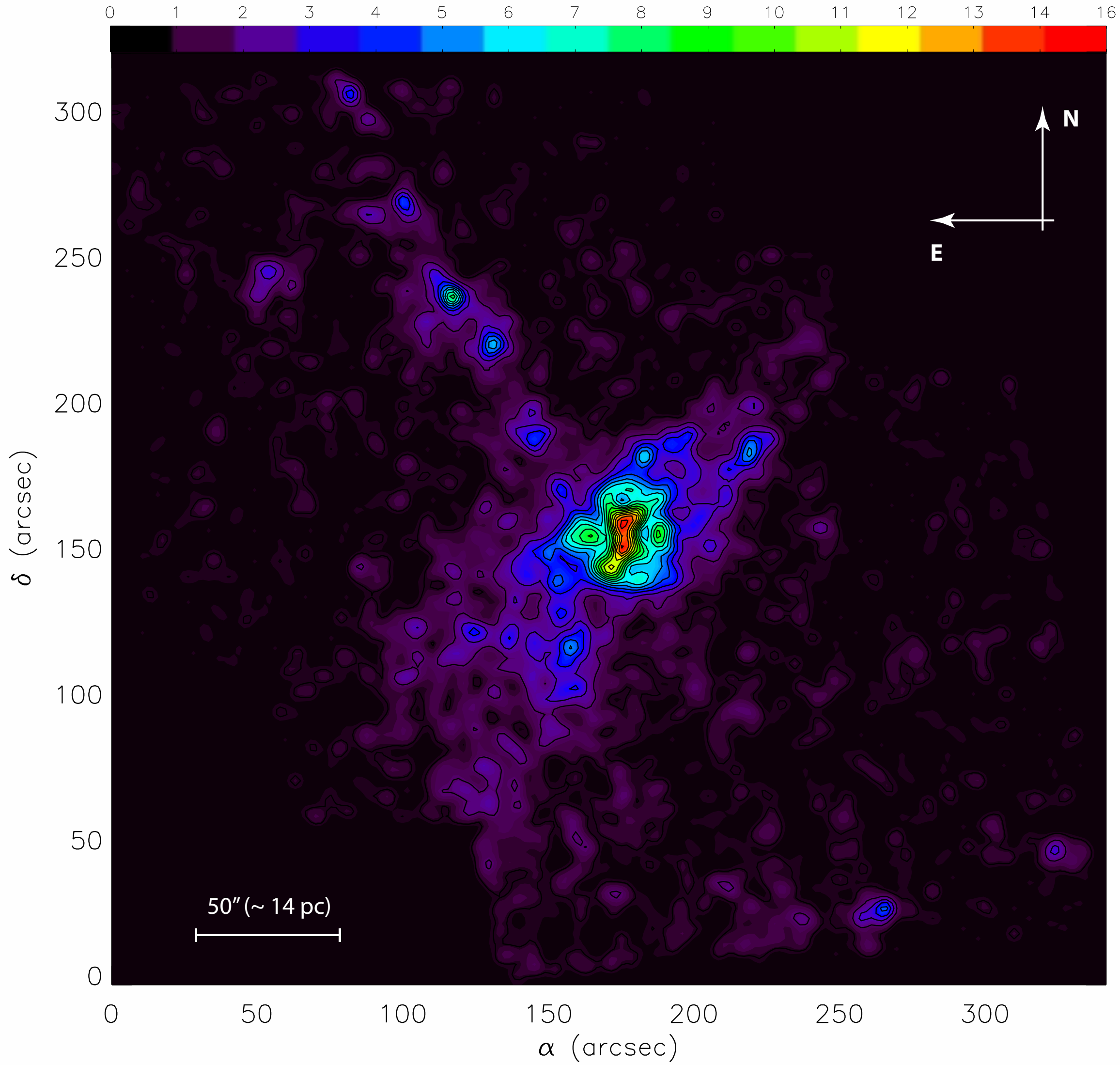
Nearest-Neighbor Density Map



Stellar Clustering Morphology in NGC 346

Gouliermis, Hony & Klessen 2014 (MNRAS, 439, 3775)

Kernel Density Estimation Map

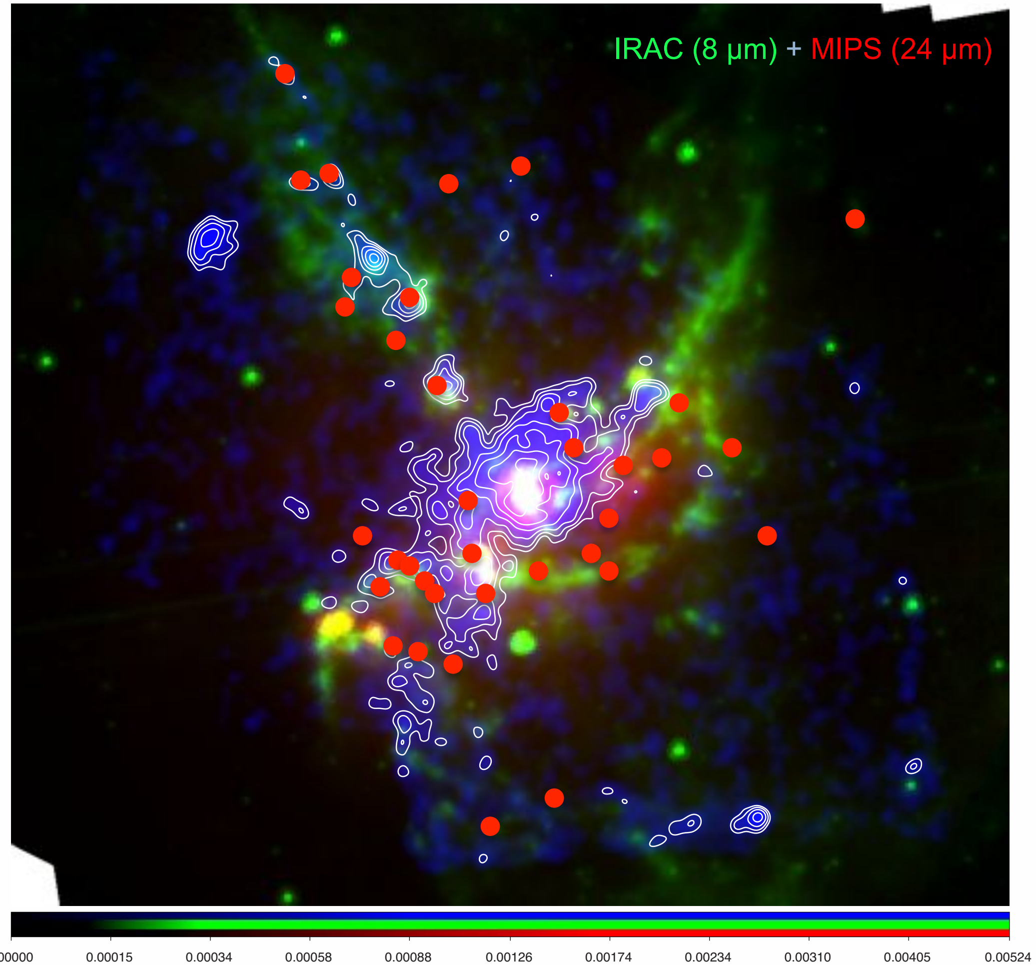


Stellar Clustering and Star Formation

Different Stages of Cluster formation

Correlation *and* Anti-correlation of IR peaks with PMS Sub-clusters

- Obvious relation between stellar clustering and SF centers.
- Connection between stellar and ISM morphology.
- YSO candidates indicate that SF is ongoing.



YSO candidates (Spitzer): Simon et al. 2007, ApJ, 669, 327

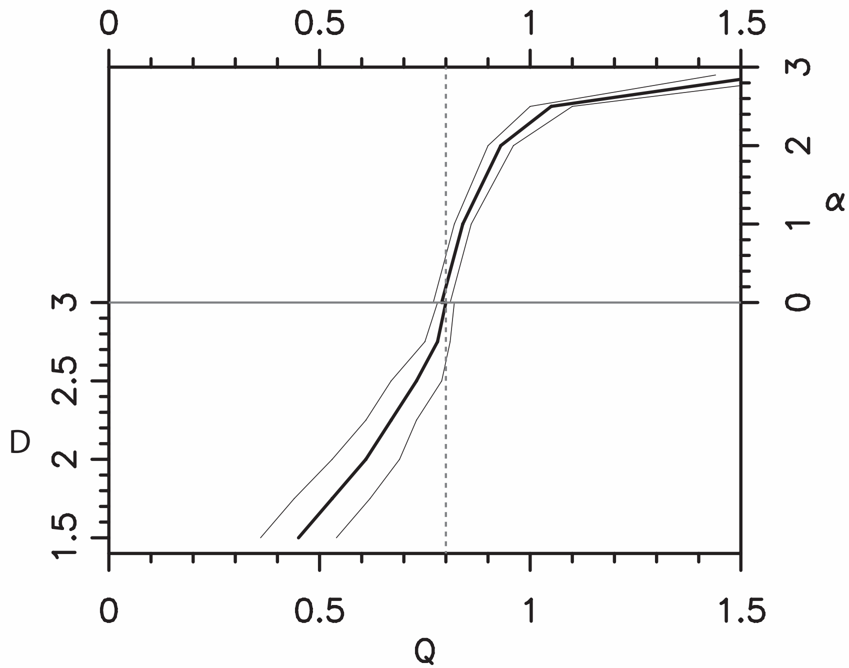
Characterizing Clustering with the Q-Param

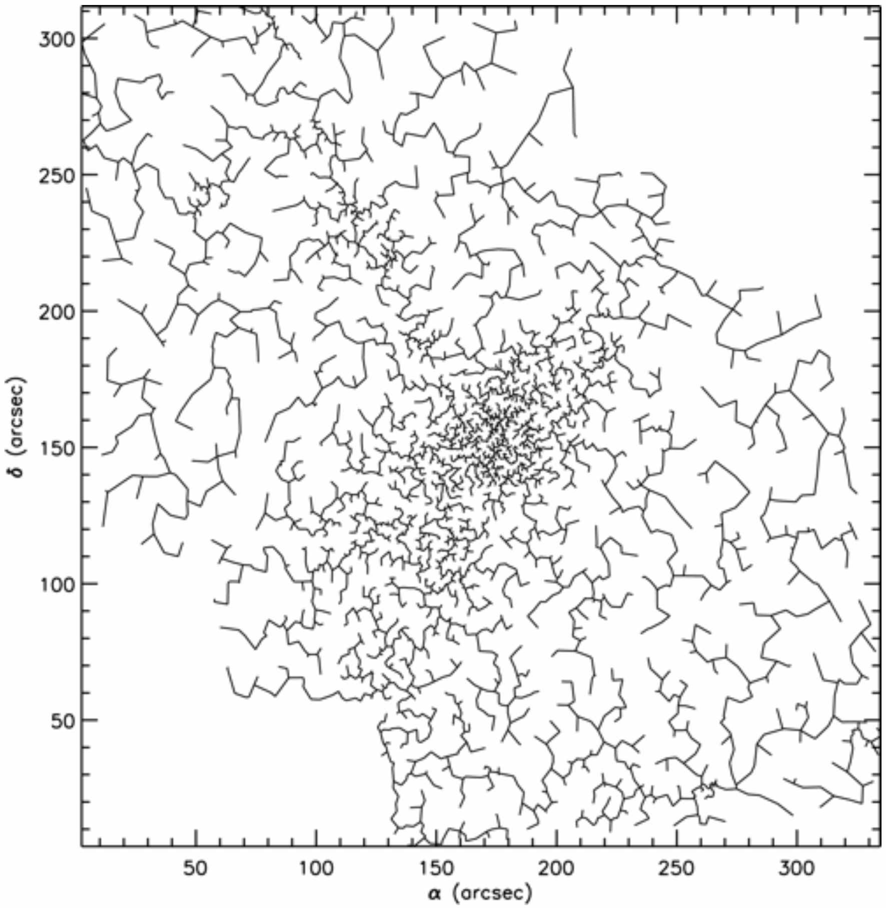
Minimal Spanning Tree and Q

Cartwright & Whitworth 2004, MNRAS 348, 589

$$Q = \frac{\text{MST mean edge-length}}{\text{Average separation}} \equiv \frac{m}{\langle s \rangle / R_c}$$

$Q_{\mathrm{NGC346}} \approx 0.8$





The Q-Parameter method is inconclusive in determining the nature of NGC 346

The Autocorrelation Function (ACF)

Peebles, P. J. E. 1973, ApJ, 185, 413
Gomez, M. et al. 1993, AJ 105,1927

$$\boxed{1+\xi(r)=\frac{1}{\overline{n}N}\sum_{i=1}^{N}n_i(r)}$$

Definition based on Peebles P. J. E. & Hauser M. J., 1974, ApJSS, 28, 19

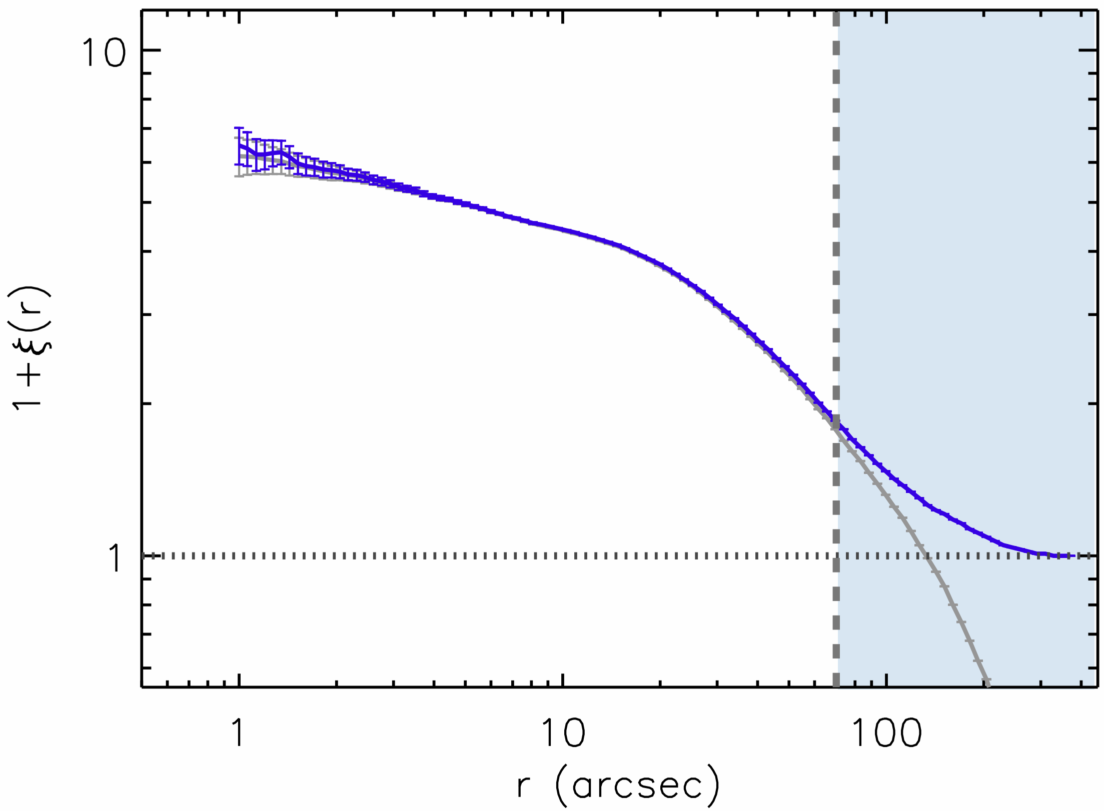
The fractal dimension D_2 of the structure is related to the autocorrelation function slope (power-law index) η as:

$$D_2=\eta+2$$

Typical values of turbulent-driven hierarchy in the ISM: D_2 = 1.3 – 1.5

(Sreenivasan K.R. 1991, Ann. Rev. Fluid Mechanics 23, 539;
Elmegreen & Scalo 2004, ARA&A, 42, 211)

The ACF of NGC 346



At $r \leq 6$ pc

$$1 + \xi(r) \propto r^{-0.18}$$

$D_2 \approx 1.8$

At $6 \leq r \leq 20$ pc

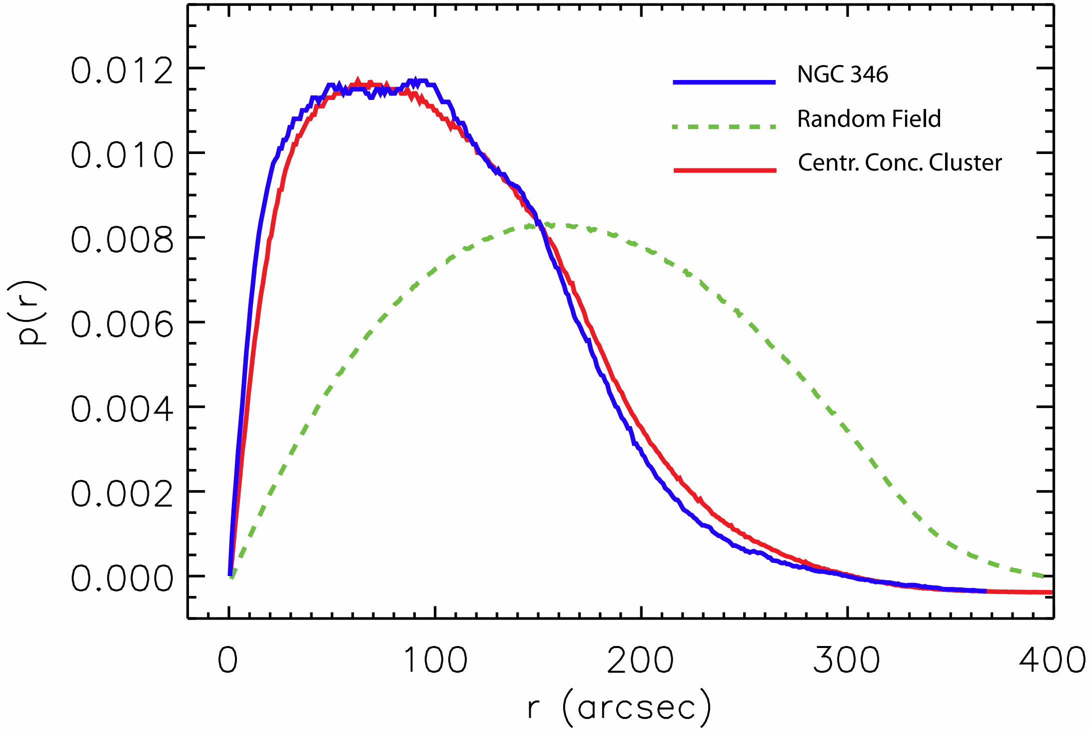
$$1 + \xi(r) \propto r^{-0.58}$$

$D_2 \approx 1.4$

Characterizing Clustering is strenuous

Stellar Pair Separations PDF

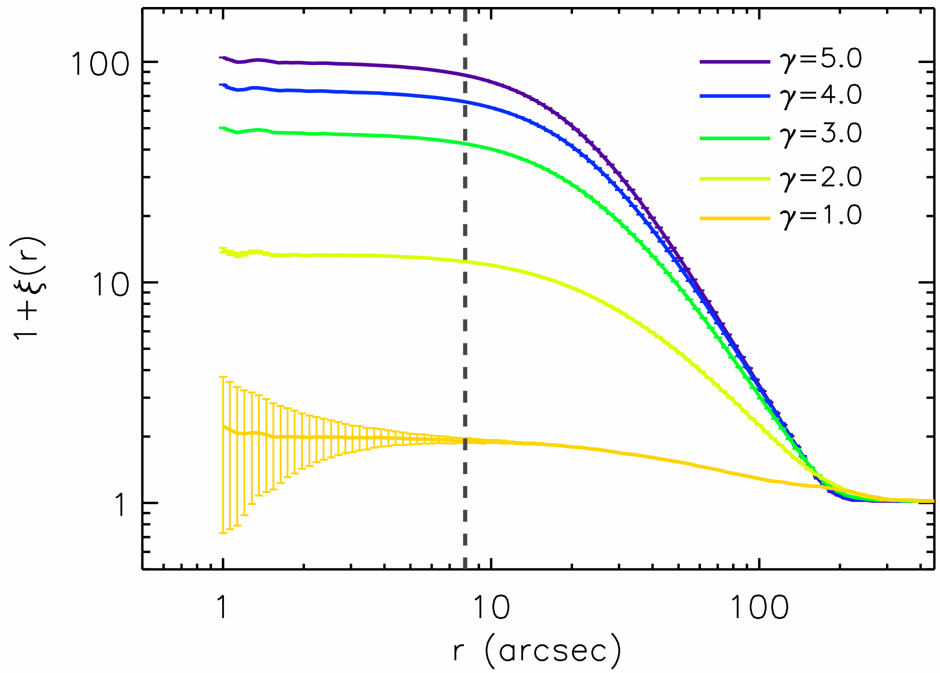
$$p(r_j) = \sum_{i=1}^{N} \frac{2N_{ij}}{N(N-1)dr}$$



- The separations PDF gives false evidence of a condensed cluster!

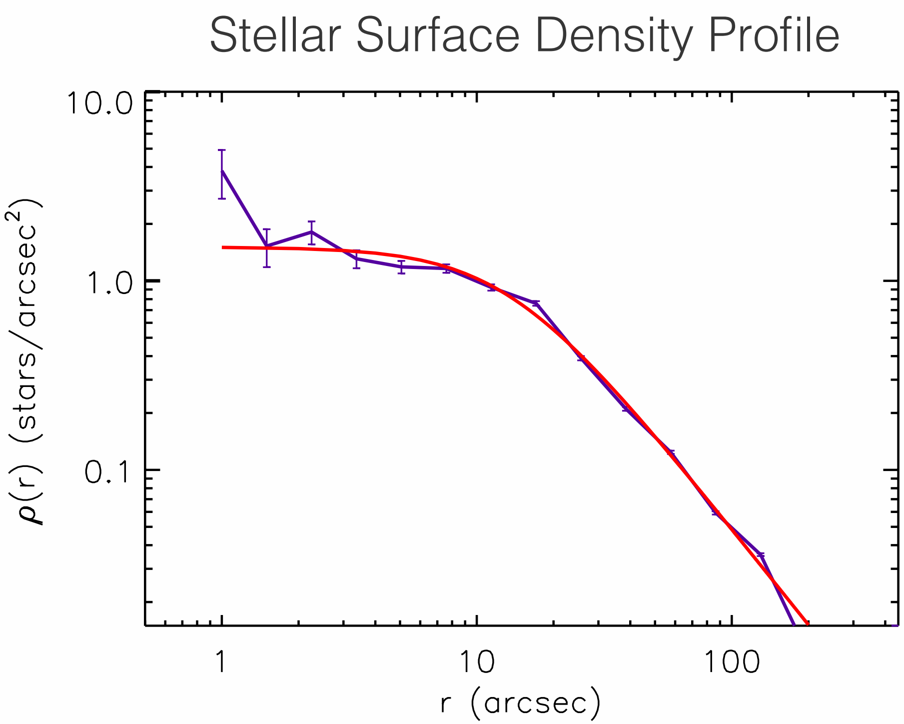
The ACF of Centrally Condensed Clusters

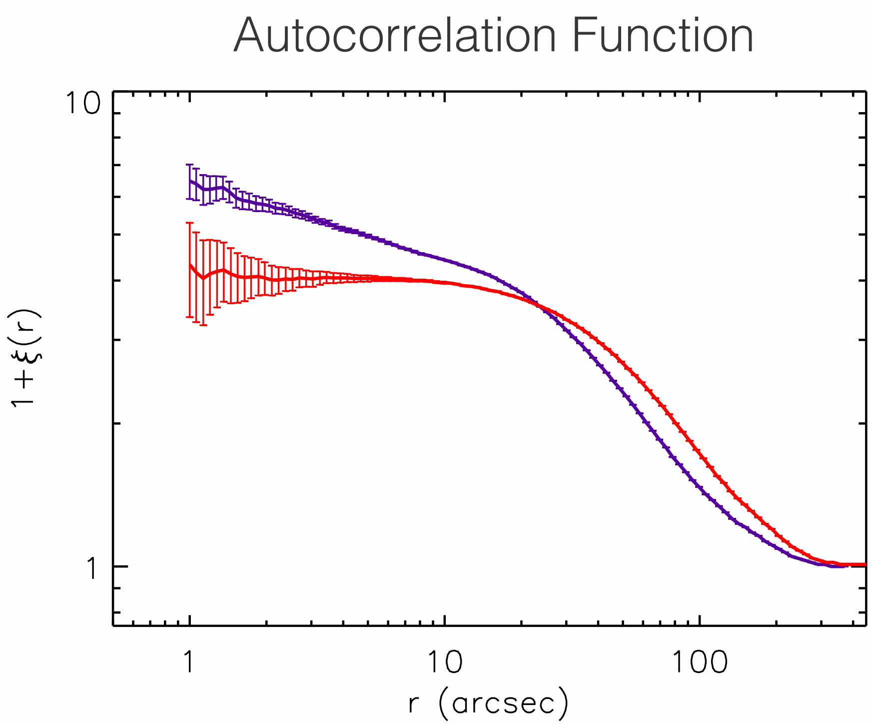
Clusters Models from Elson, Fall & Freeman (1987, ApJ, 323, 54)



$$f(r) = f_0\left[1+\left(\frac{r}{\alpha}\right)^2\right]^{-\gamma/2} + f_{\rm field}\ , \quad r_{\rm c} = \alpha\left(2^{2/\gamma}-1\right)^{1/2}$$

Surface Density Profiles can be misleading



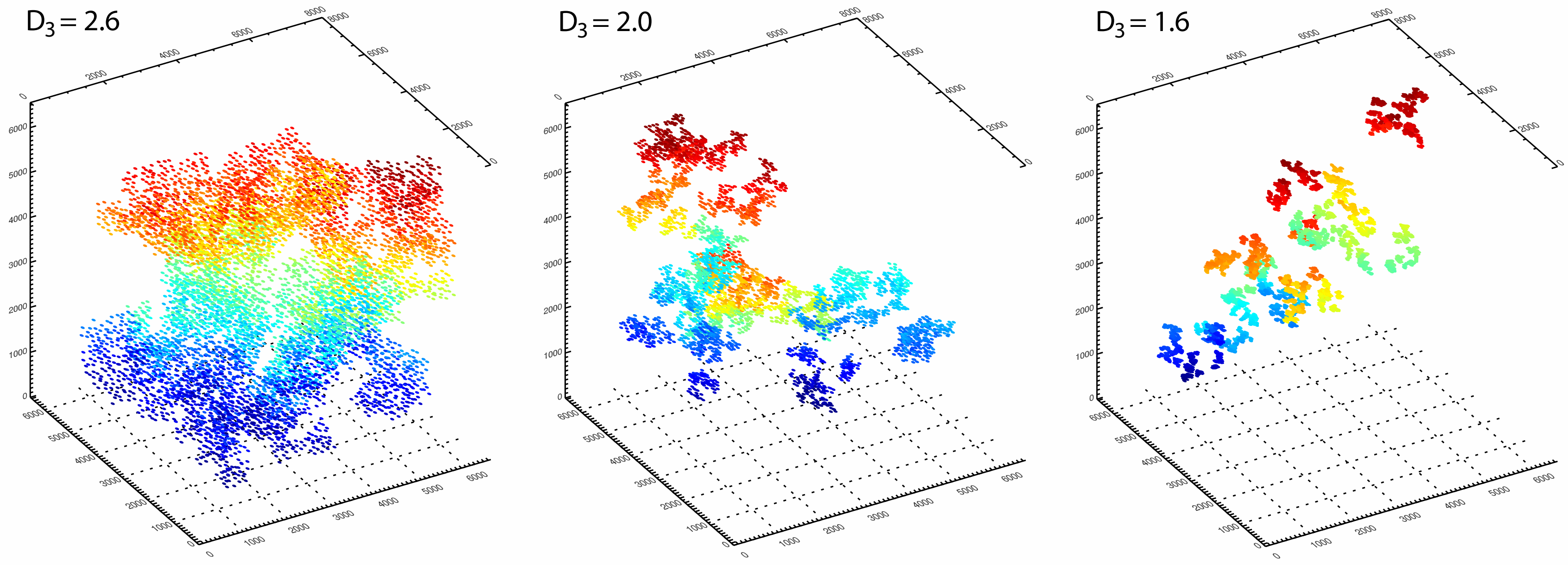


- A good-fitting density profile misinterprets stellar clustering.
- The Autocorrelation function is a more robust representation.

Synthetic Self-Similar Distributions

Box-counting algorithm

Bate et al. 1998, MNRAS, 297, 1163
Cartwright & Whitworth 2004, MNRAS, 348, 589



$$\boxed{D = \ln N_{\mathrm{ran}} / \ln N_{\mathrm{div}}}$$

$$N_{\mathrm{ran}} = N_{\mathrm{div}}^{D}$$

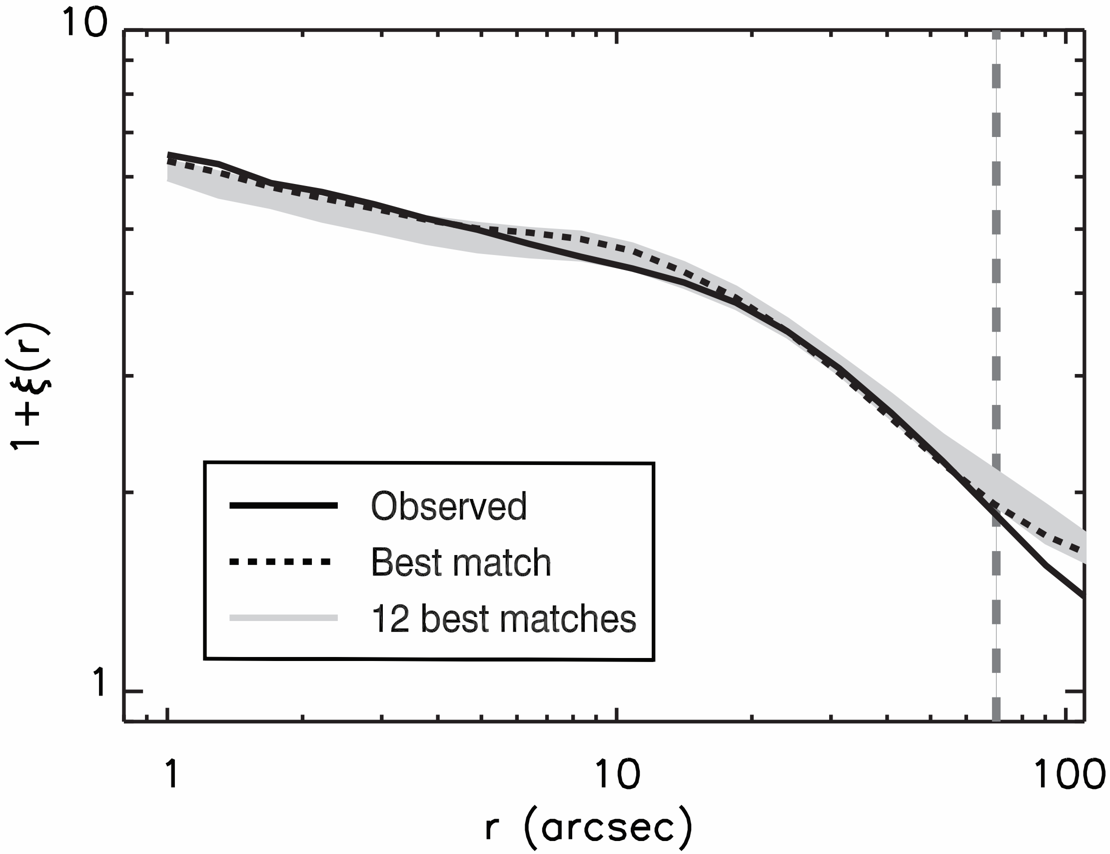
N_{div} : N_{div}^3 number of total subcubes

N_{ran} : Number of cubes to be further divided

NGC 346 is a Centrally Condensed Cluster …

… embedded in a Fractal Stellar Distribution

Gouliermis, Hony & Klessen 2014 (MNRAS, 439, 3775)



- Best-Models Parameters:
  - $r_c \approx 9''$ (2.5 pc)
  - $\gamma \approx 2.2 - 2.35$
  - $D_3 \approx 2.3$
  - $f_{cl} \approx 40\%$
  - Power-law break at ~6 pc

- *Shift in the correlated properties of young stars on scales <100 pc.*

Implications in our Understanding of CSF

The Origin of the bimodal distribution can be due to …

- **Nature:** Bimodal star formation (clustered + distributed).
  (Bonnell et al. 2011)
- **Nurture:** Dynamically merging sub-structures
  (Klessen & Burkert 2000; Bonnell, Bate & Vine 2003)

… and depends on the initial conditions (Parker et al. 2013)
Sub-structured *super-virial* agglomerations can evolve to systems like NGC 346

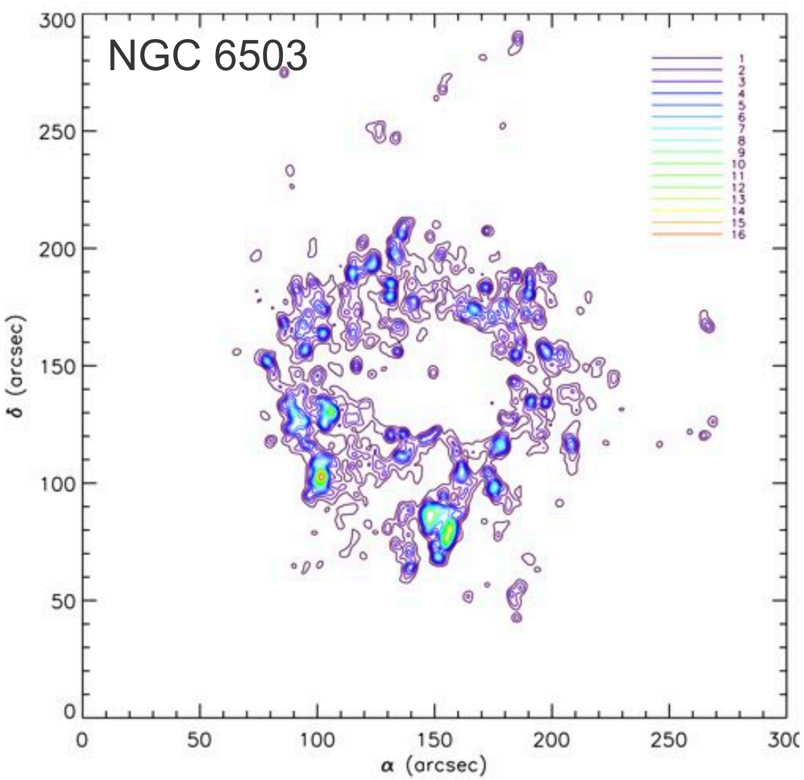
Implications about Self-similar Distributions

- Turbulent-Induced Hierarchy produces D_3~1.5 – 2.5.
  (Federrath et al. 2009; Girichidis et al. 2012; Dale, et al. 2013)
- However, early dynamical evolution will partly erase substructure
  (Scally & Clarke 2002; Goodwin & Whitworth 2004)

- How much of the original Hierarchy has been retained in the last 3 to 5 Myr?

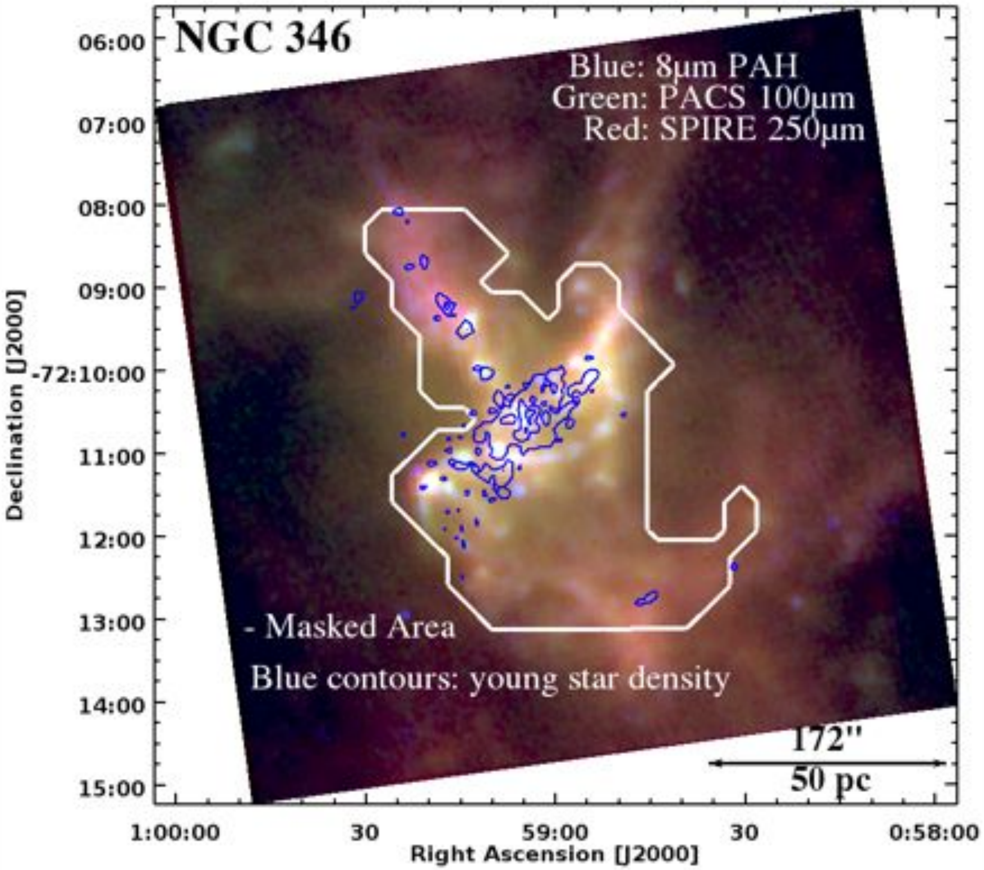
PoI: Large Scale Structure & ISM relation

Daniela Calzetti & 20+ collaborators



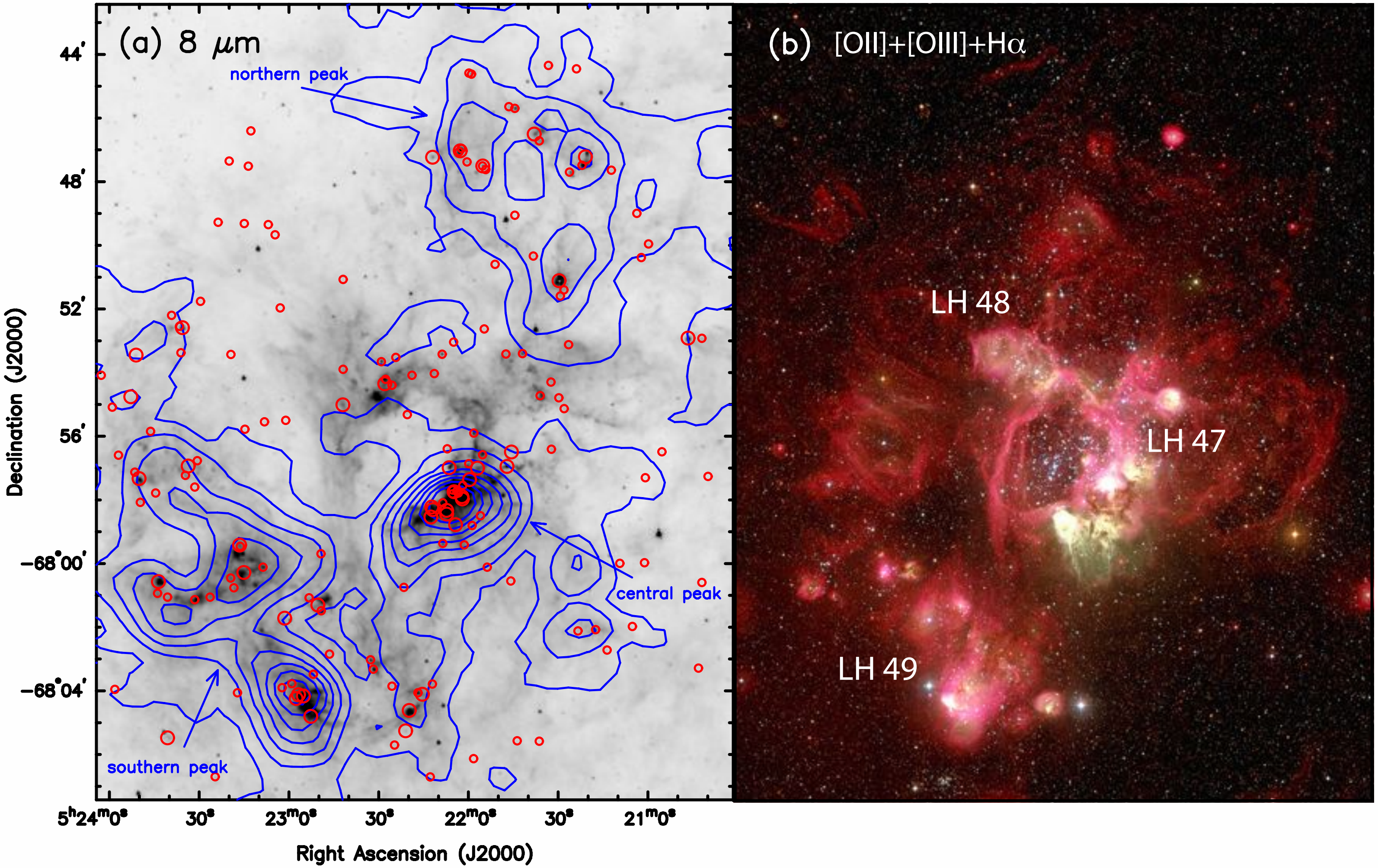
Gouliermis & the LEGUS Team, in preparation

See Sacha Hony's talk later today



- Star counts follow roughly the gas, i.e., dust column density.

Clusters typically form in Groups



a) Spitzer 8µm (PAH and dust emission).
Blue contours: CO emission (Wong et al. 2011).
Red dots: YSOs (Chen et al. 2009; Carlson, et al. 2012).

b) MPG/ESO 2.2m WFI.
Credit: F. Comeron and N. Delmotte (ESO).

Take-away messages

- Stellar clustering at birth is complex.
- Analysis methods require simulations.
- Clusters are born in Clusters.
- Bimodal stellar clustering on GMC-scales verified.
- Scale where Gravity prevails identified at few pc.
- Turbulence induces self-similar stellar topology in SF regions.