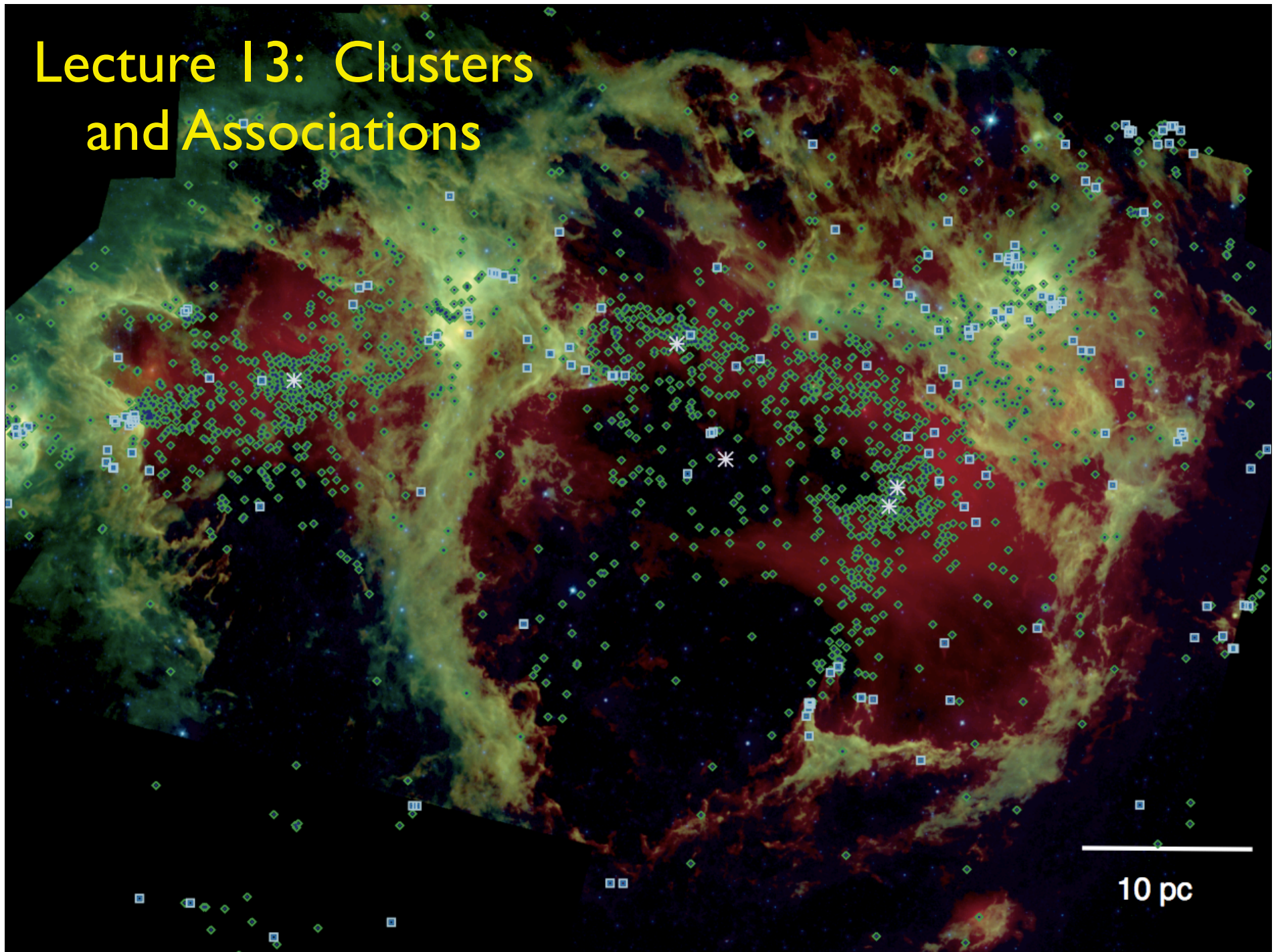


Lecture 13: Clusters and Associations



The Salpeter IMF

The initial mass function is a function describing the distribution of stellar masses in a newly formed population (i.e. none of the stars have had a chance to lose mass or undergo supernova). The initial mass function, IMF, was first derived by Ed Salpeter in 1955, who found that:

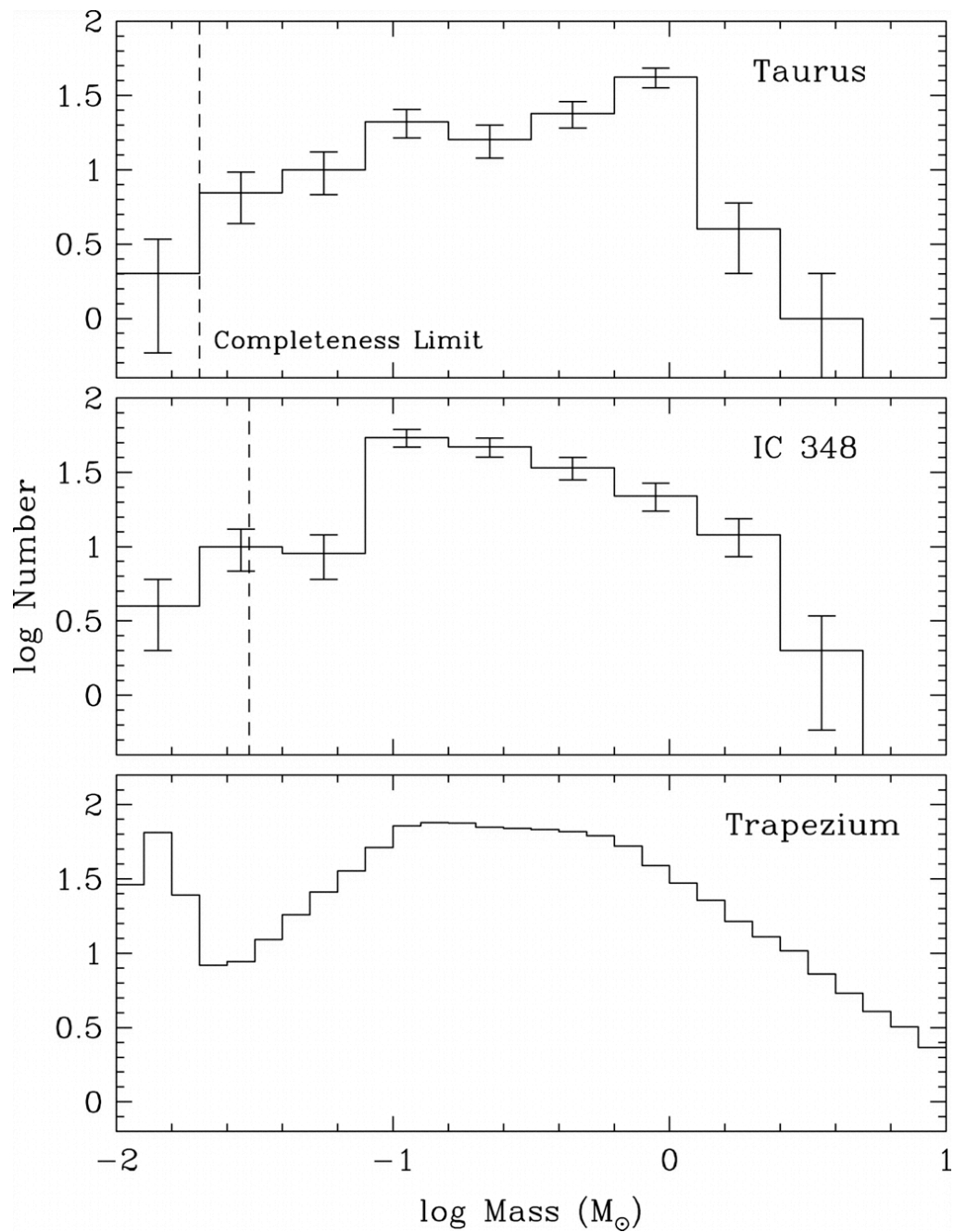
$$\xi(\log M) = \frac{dN}{d\log(M)} = k_1 M^{-\Gamma} = k_1 M^{-1.35} \quad (1)$$

A similar function is the mass spectrum

$$\frac{dN}{dM} = k_2 M^{-\alpha} = k_2 M^{-2.35} \quad (2)$$

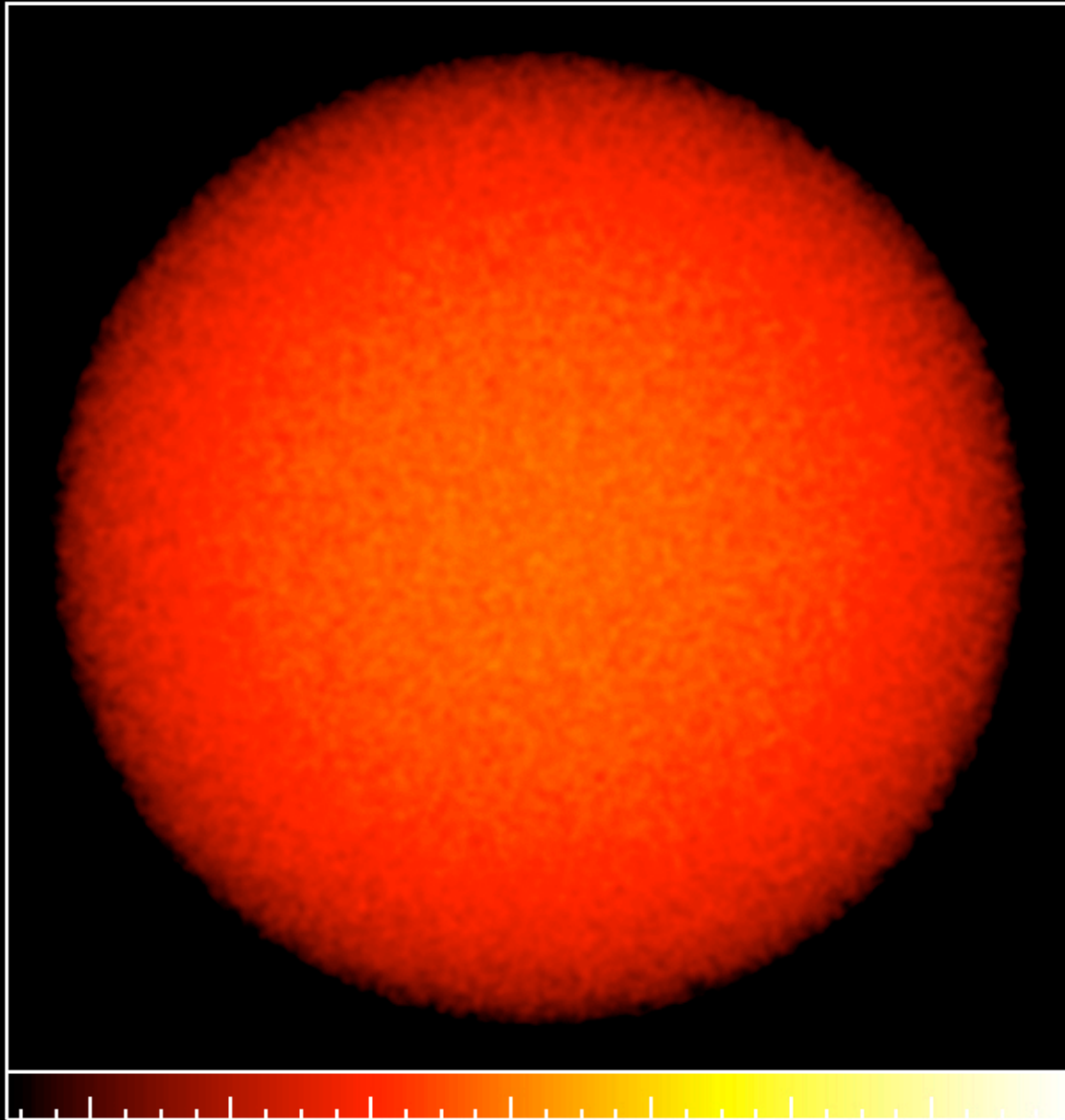
where $\alpha = \Gamma + 1$.

IMFs from star forming regions



Dimensions: 82500. AU

Time: 0. yr



-1.4

-1.2

-1.0

-0.8

-0.6

-0.4

-0.2

0.0

Log Column Density [g/cm^2]

Matthew Bate

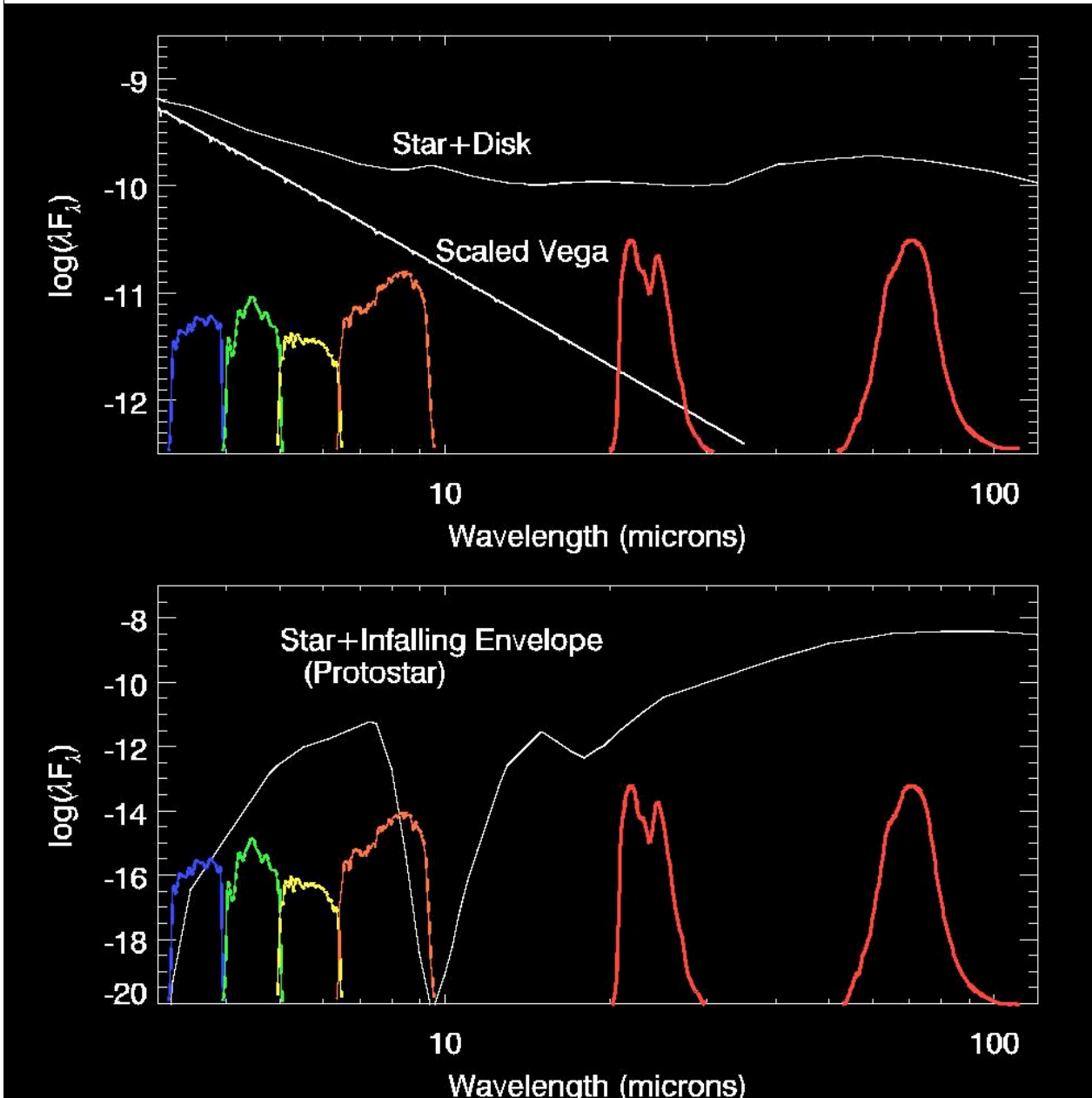
Competitive Accretion Models

$$\dot{M} = 4\pi\rho \frac{(GM_{\star})^2}{(v^2 + c_s^2)^{3/2}}$$

Mapping The Distribution of YSOs: Infrared Excess

Disk models from
D'Alessio et al.
2004

Protostar models
generated using
method of
Kenyon, Calvet
& Hartmann
(1993)



The IRAC Survey of Orion A & B

Lynds 1622
(Orion B)

NGC 2068/2071
(Orion B)

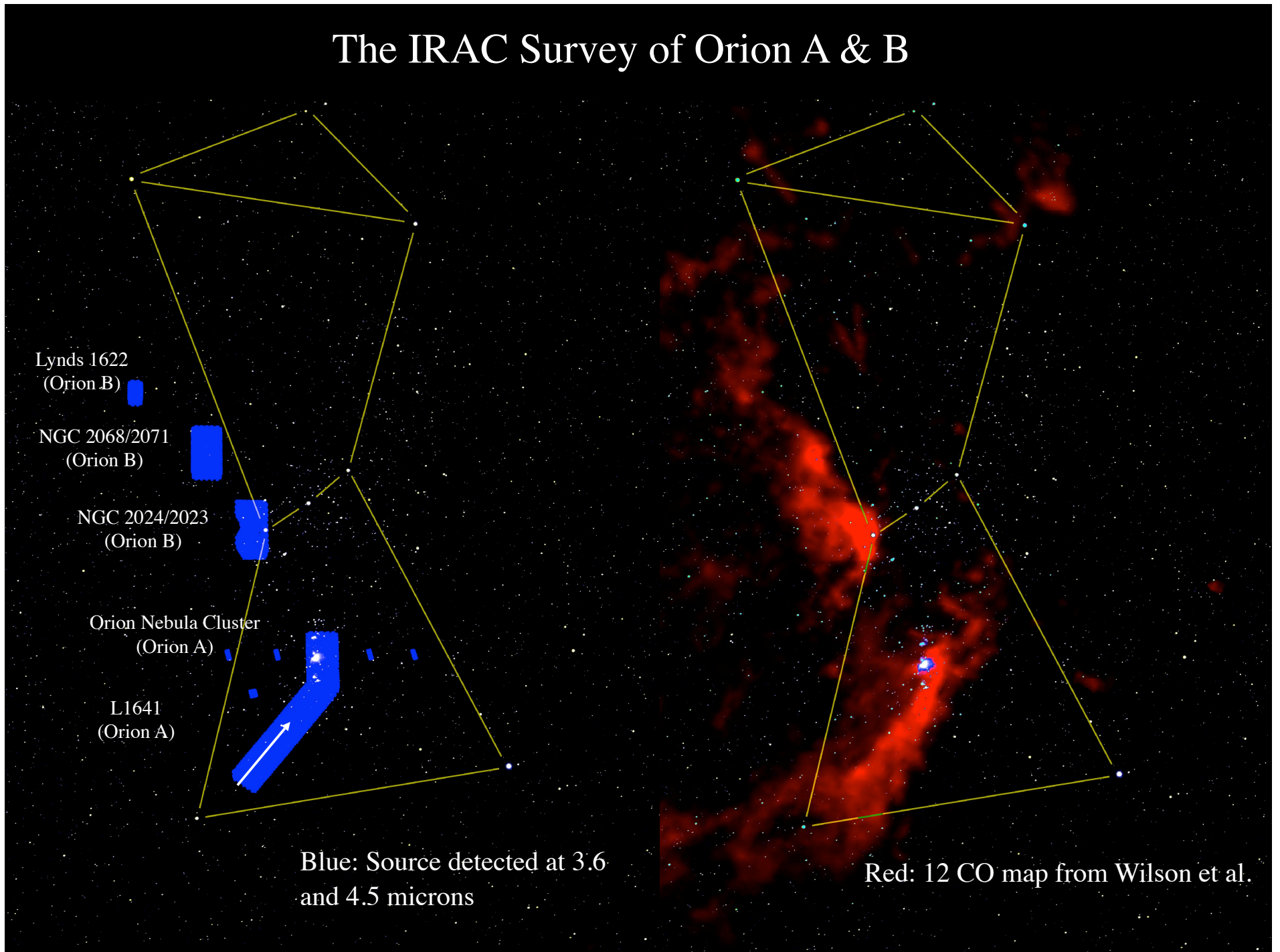
NGC 2024/2023
(Orion B)

Orion Nebula Cluster
(Orion A)

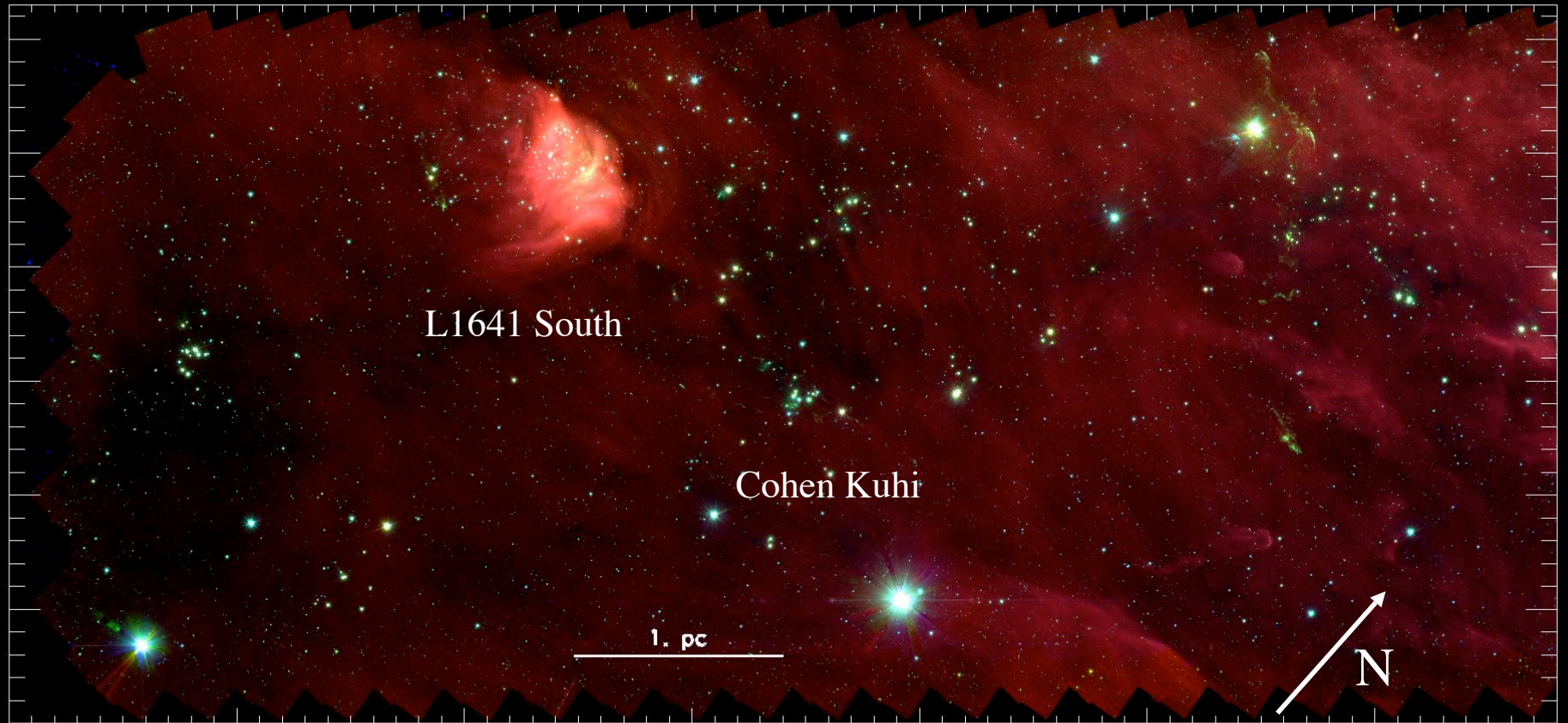
L1641
(Orion A)

Blue: Source detected at 3.6
and 4.5 microns

Red: 12 CO map from Wilson et al.



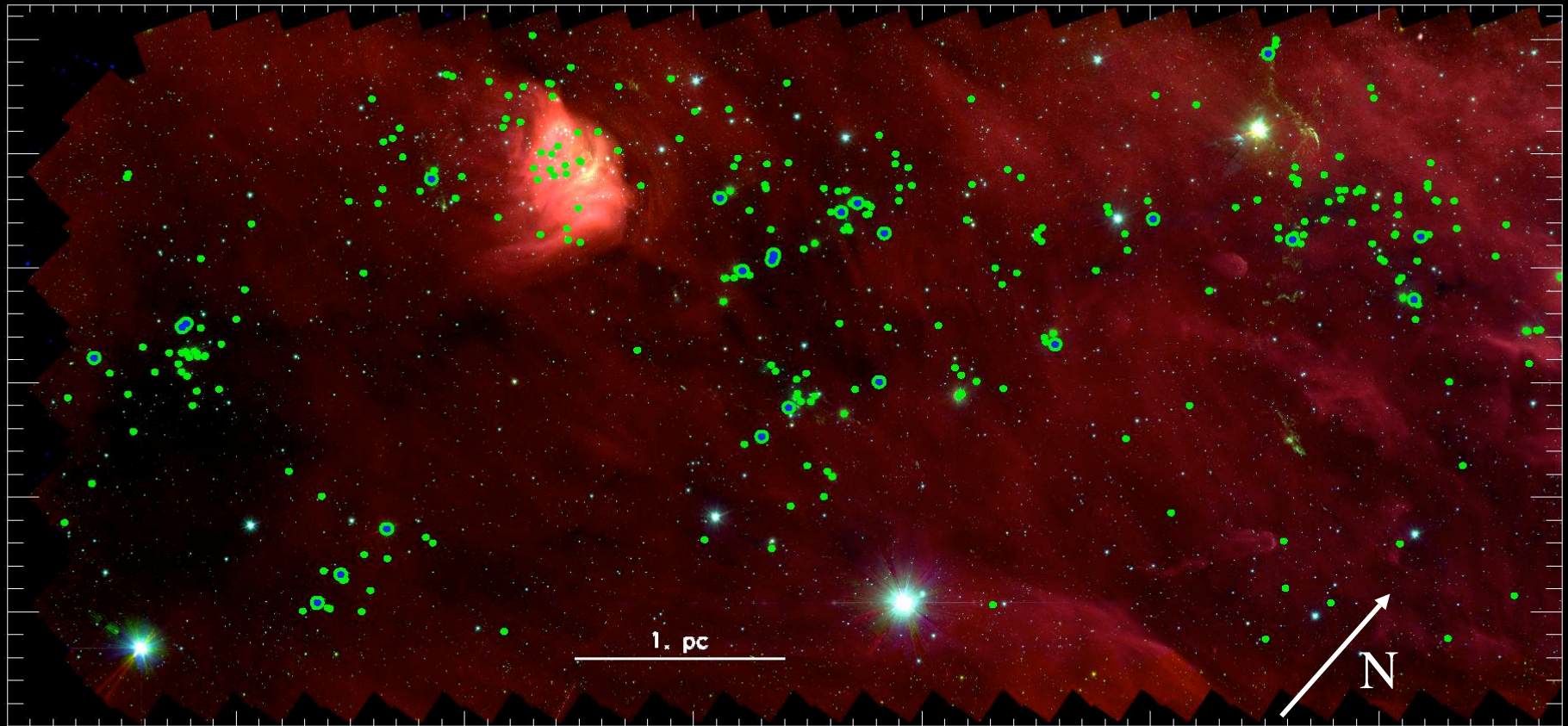
L1641 Cloud Images



Red: 8 micron **Green: 4.5 micron** **Blue: 3.6 micron**

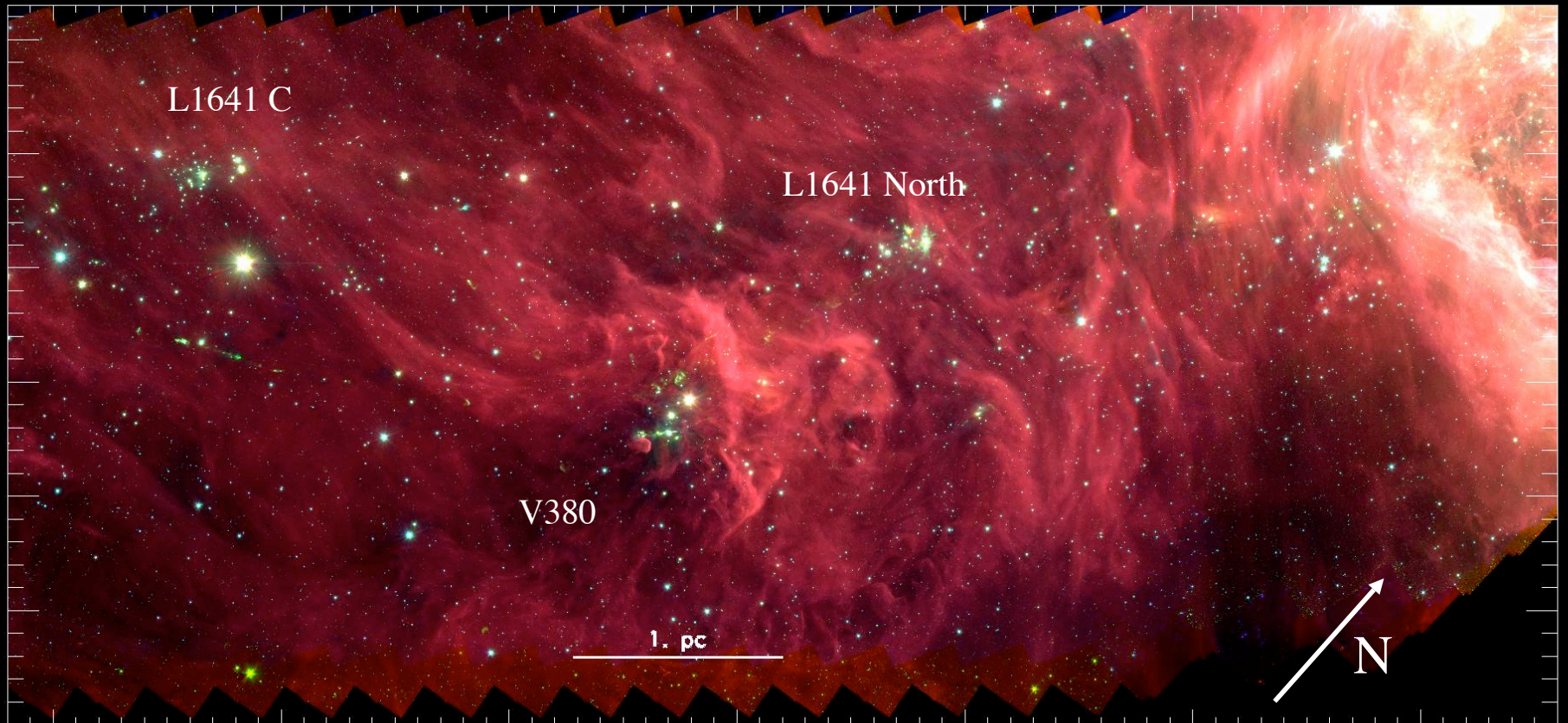
L1641 Cloud Images

Small Green Circles: IR-ex sources, Big Green/Blue Circles: IRAC selected Protostars



Red: 8 micron **Green: 4.5 micron** **Blue: 3.6 micron**

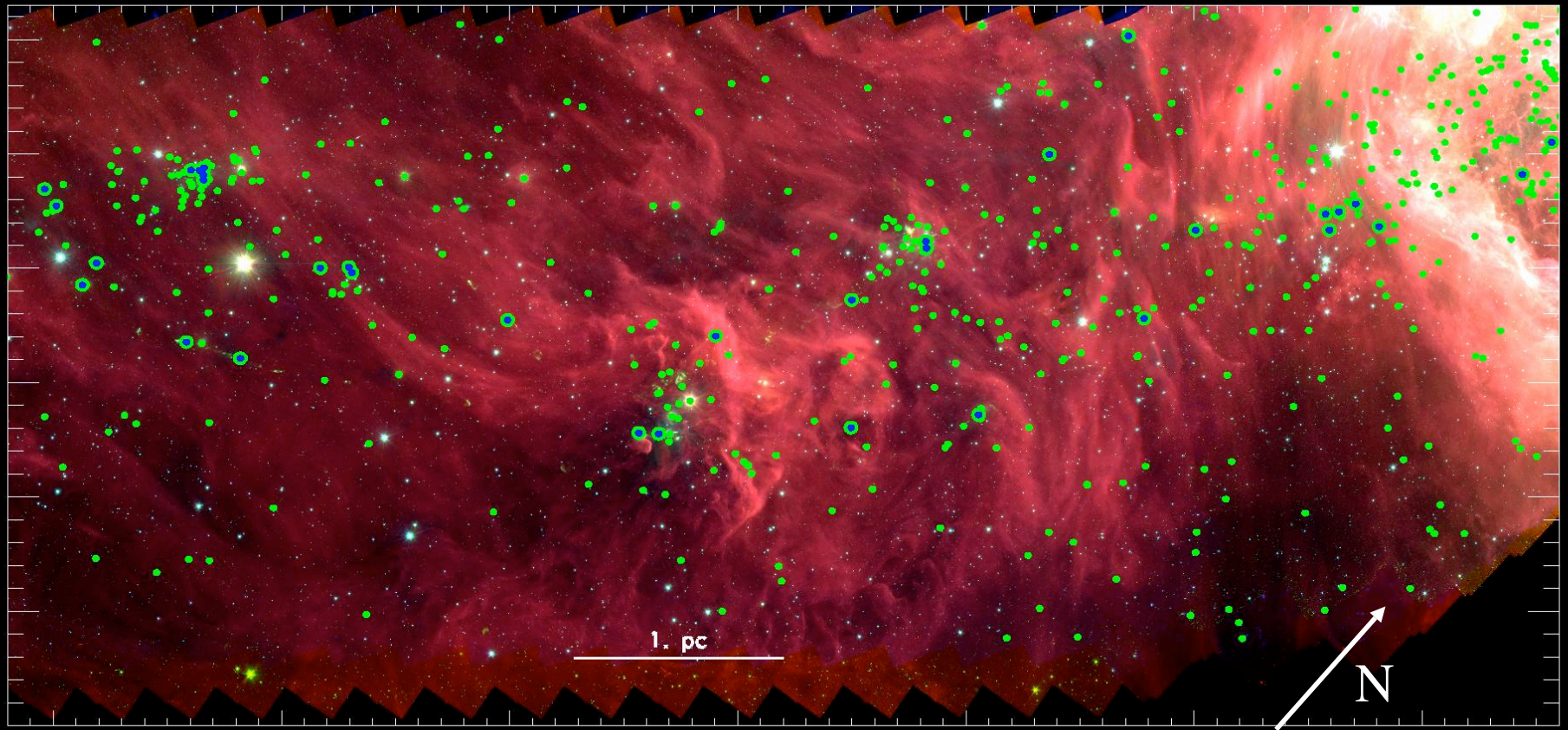
L1641 Cloud Images



Red: 8 micron **Green: 4.5 micron** **Blue:3.6 micron**

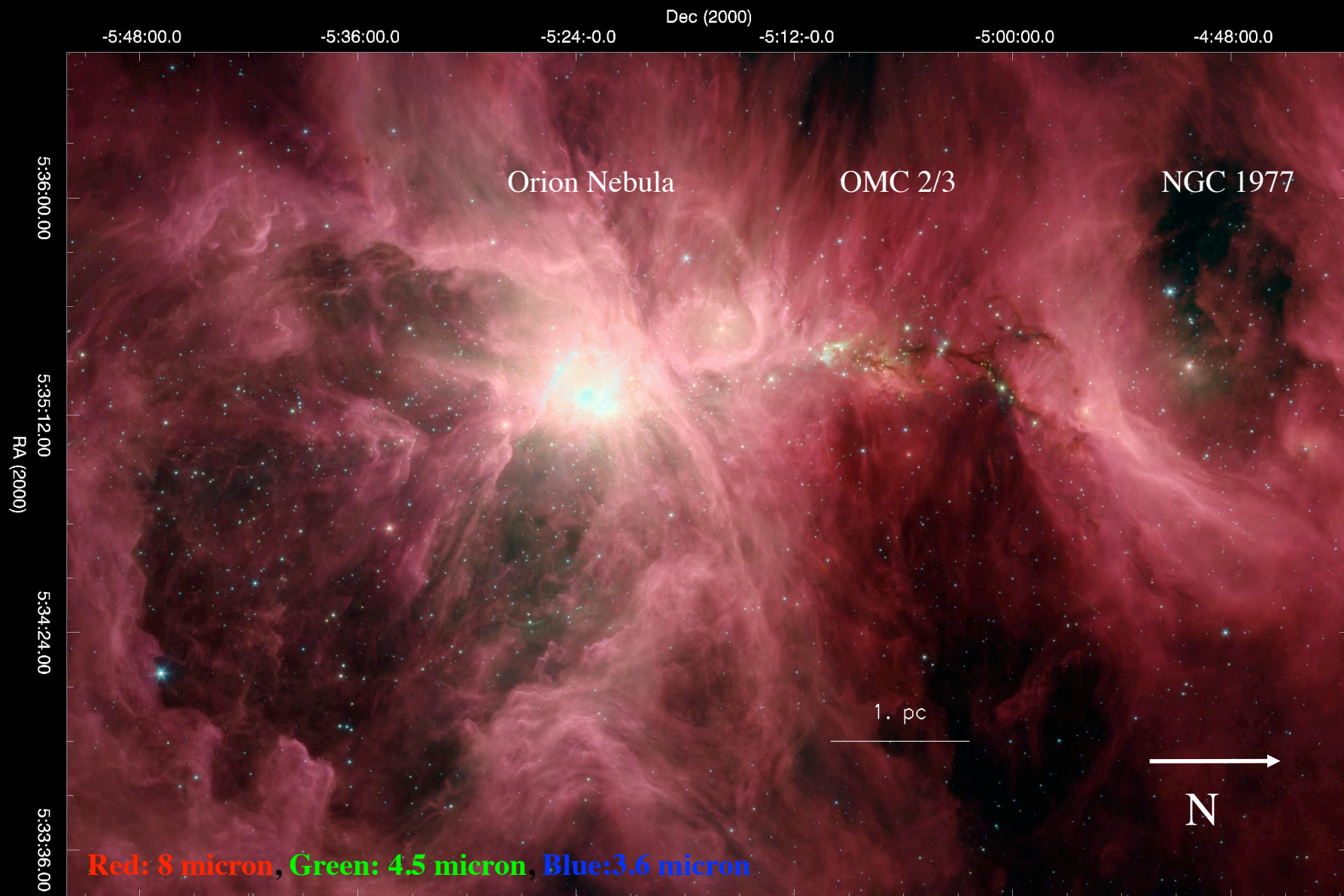
L1641 Cloud Images

Small Green Circles: IR-ex sources, Big Green/Blue Circles: IRAC selected Protostars

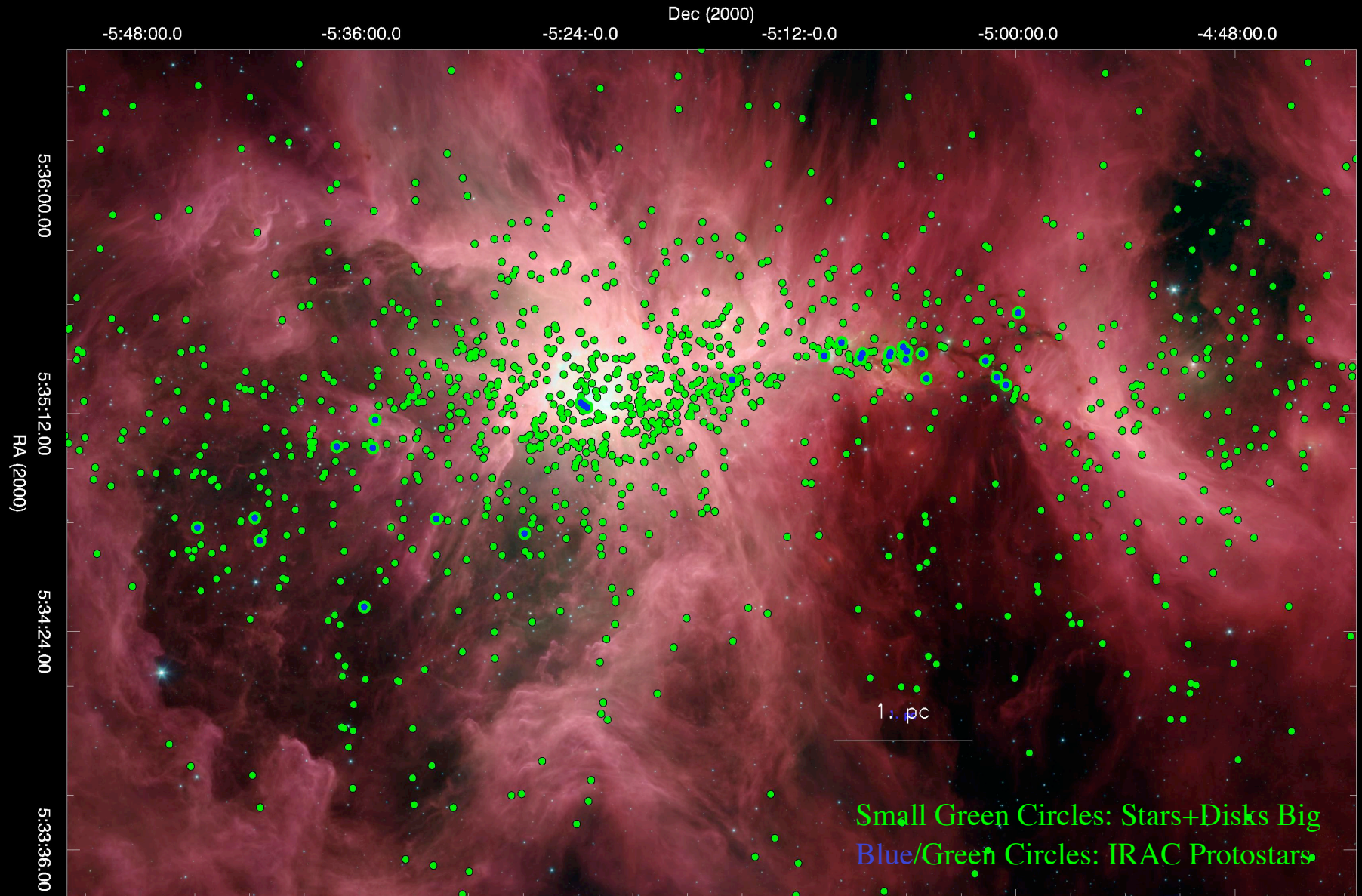


Red: 8 micron Green: 4.5 micron Blue: 3.6 micron

The Orion Nebula Cluster



The Orion Nebula Cluster



The IRAC Survey of Orion A & B

Lynds 1622
(Orion B)

NGC 2068/2071
(Orion B)

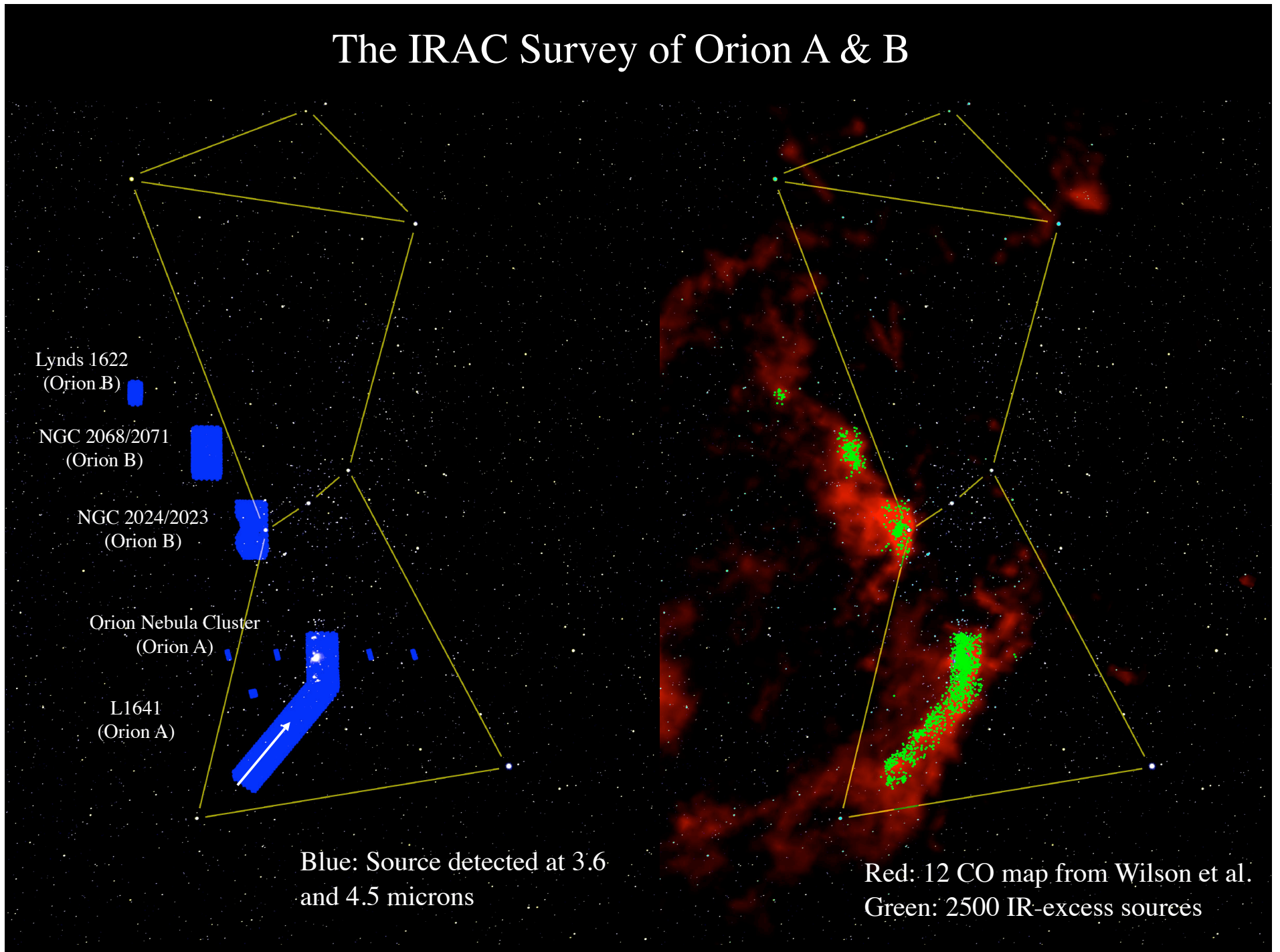
NGC 2024/2023
(Orion B)

Orion Nebula Cluster
(Orion A)

L1641
(Orion A)

Blue: Source detected at 3.6
and 4.5 microns

Red: 12 CO map from Wilson et al.
Green: 2500 IR-excess sources



Mapping the Distribution of Pre-main sequence stars

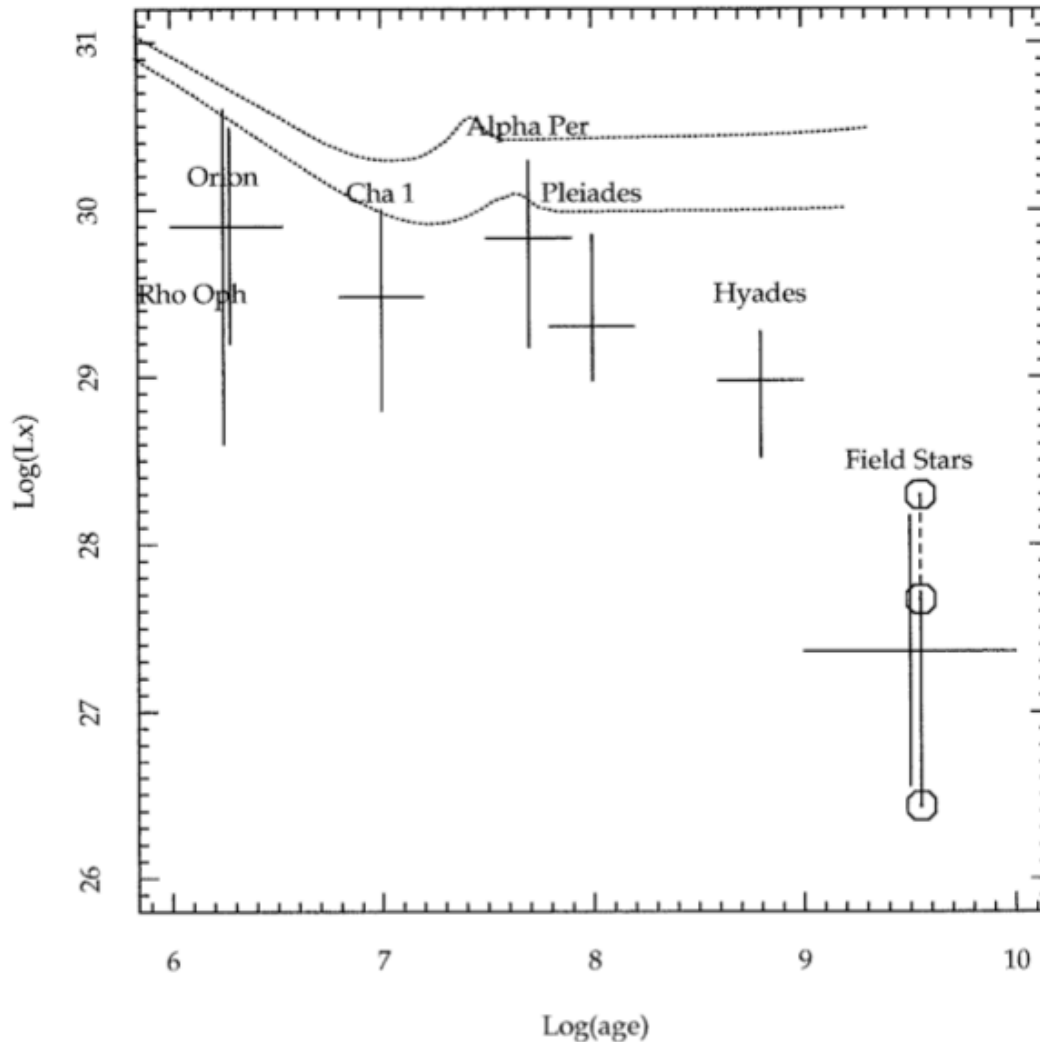
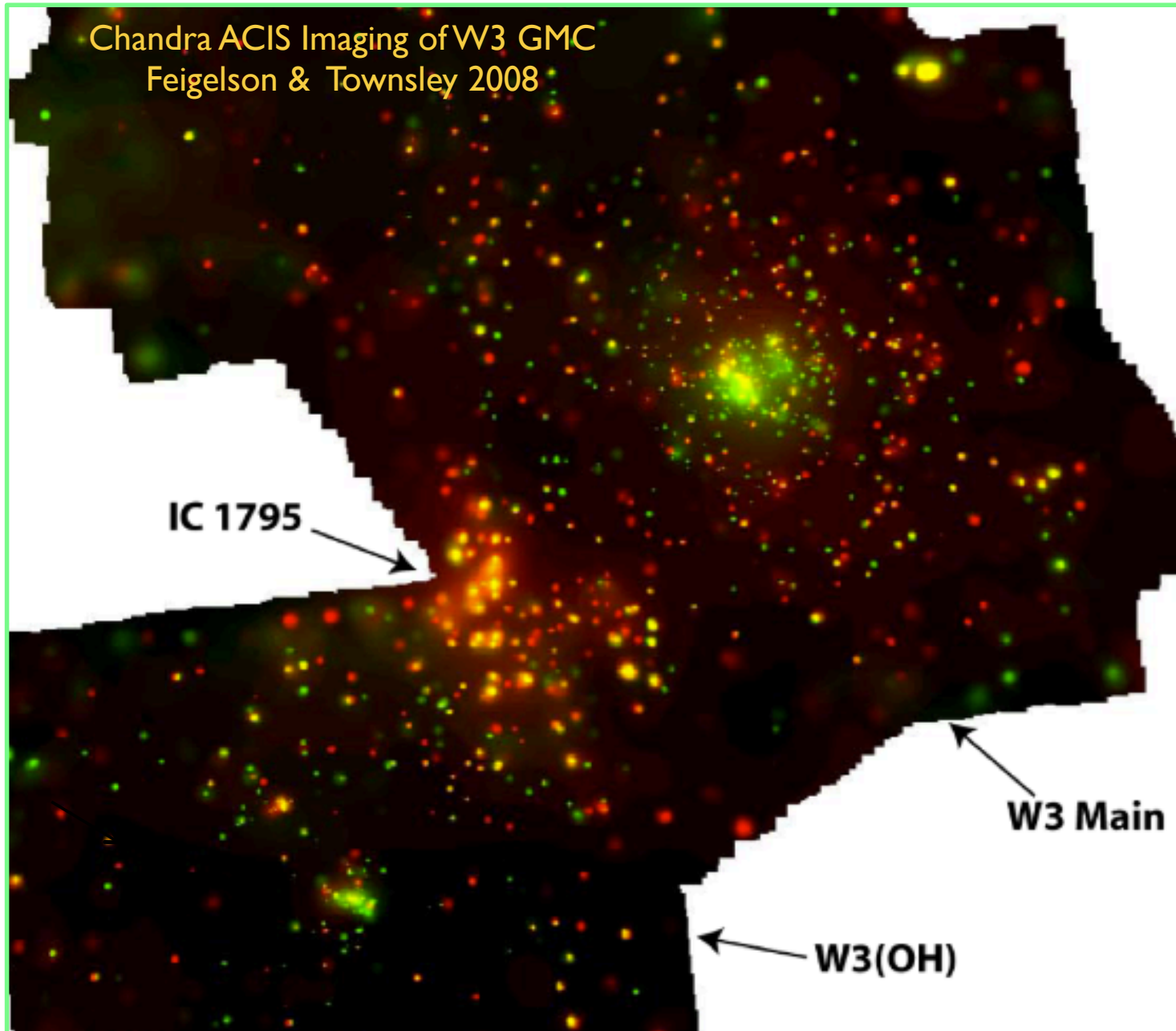


Figure 21. Medians of distributions of the X-ray luminosity for dG stars for a number of star-forming regions, open clusters and nearby stars, plotted as a function of age. Vertical segments represent the 1σ equivalent spread of the data (data from Casanova et al., 1995; Feigelson et al., 1993; Flaccomio et al., 2003a; Micela et al., 1999b; Randich et al., 1996b; Schmitt, 1997; Stern et al., 1995b). For comparison the data corresponding to the Sun (circles) during the solar minimum and maximum and during a bright flare are reported (Peres et al., 2000). Dashed lines represent the saturation level for dG stars (see text).

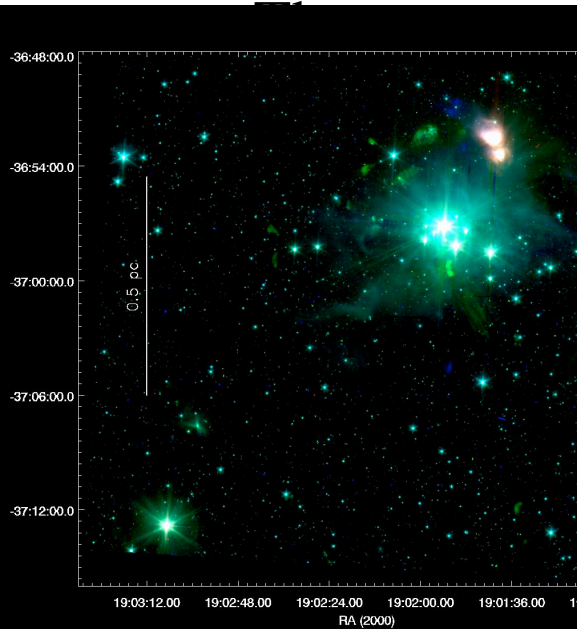
Imaging with the Chandra X-ray Observatory



Statement of the Obvious

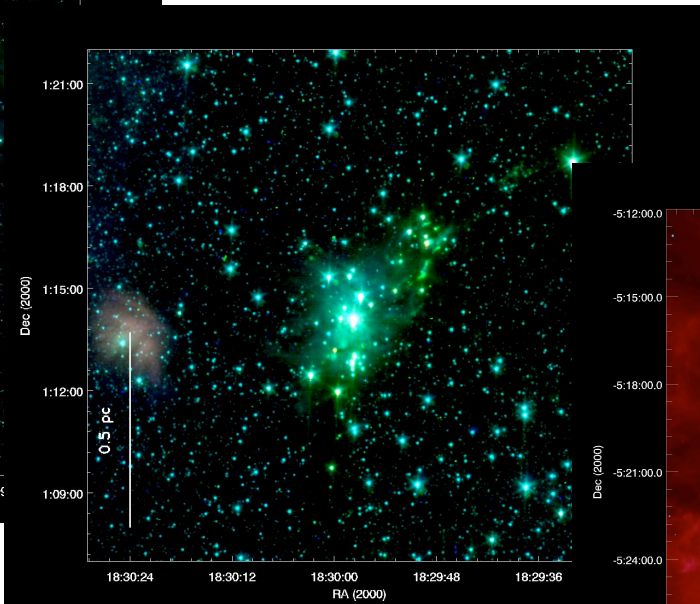
There is a bewildering diversity of star-forming regions

Corona Australis

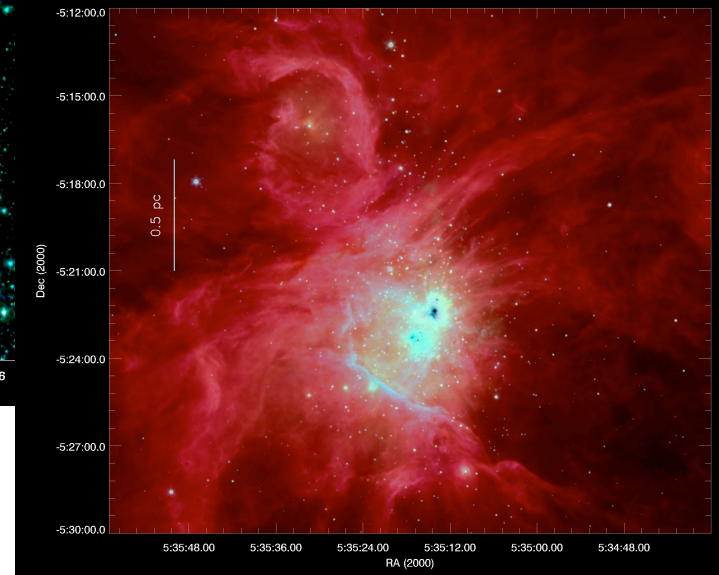


Spitzer IRAC

Serpens



Orion Nebula Cluster



Modes of Star Formation?



In the classic star formation scenario, there is a distributed mode (Taurus) and clustered mode (Orion) of star formation (Herbig 1964).

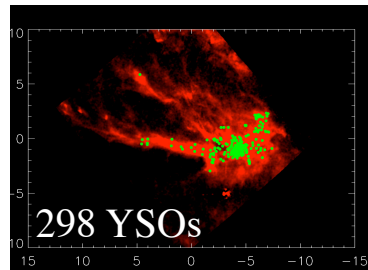
Where do most stars form? The Nearest 500 pc

Ophiuchus & Perseus

A_V cloud map:

Complete YSOs:
IR-ex from Spitzer
C2D

Ophiuchus

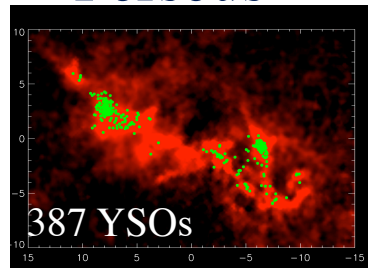


Taurus

A_V cloud map:

Lombardi & Alves
YSOs: all known
from K Luhman

Perseus

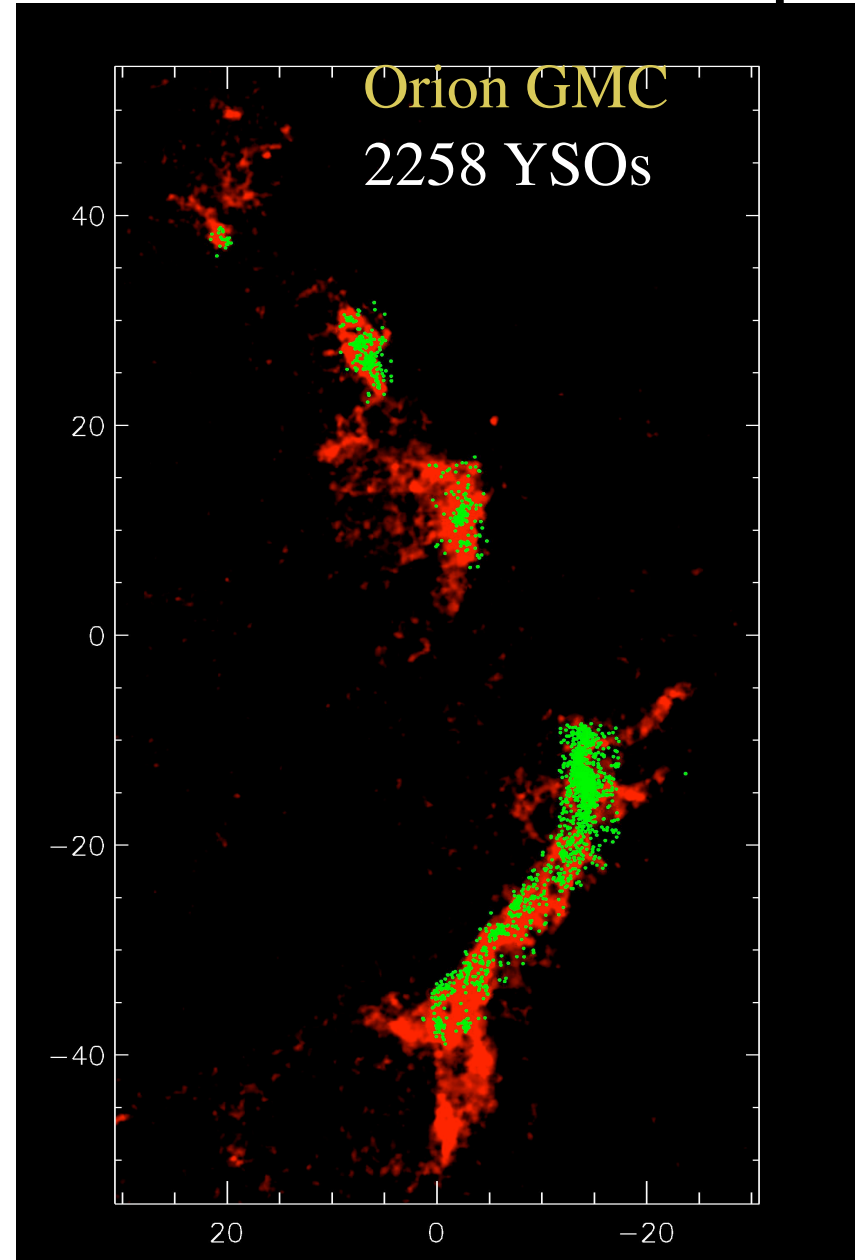
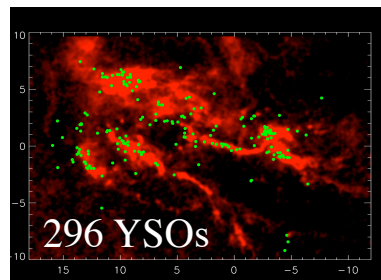


Orion

A_V cloud map: R.
Gutermuth

YSOs: IR-ex from
Spitzer Megeath in
prep.

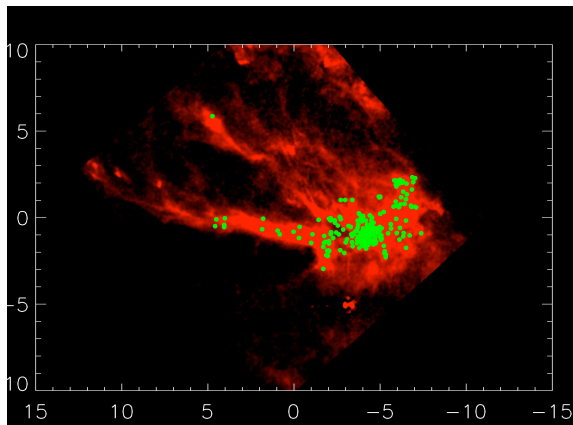
Taurus



Stellar Densities of YSOs in < 1 kpc Clouds

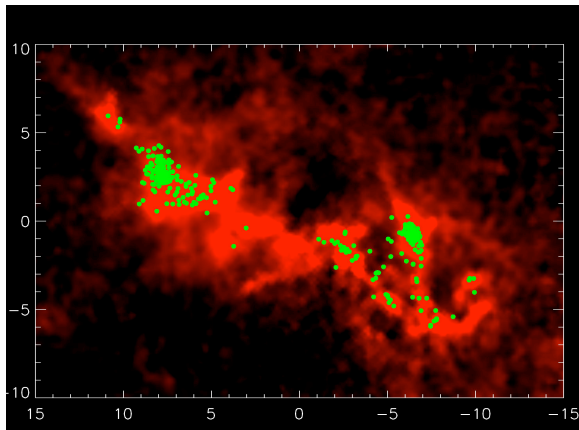
Ophiuchus

298 YSOs



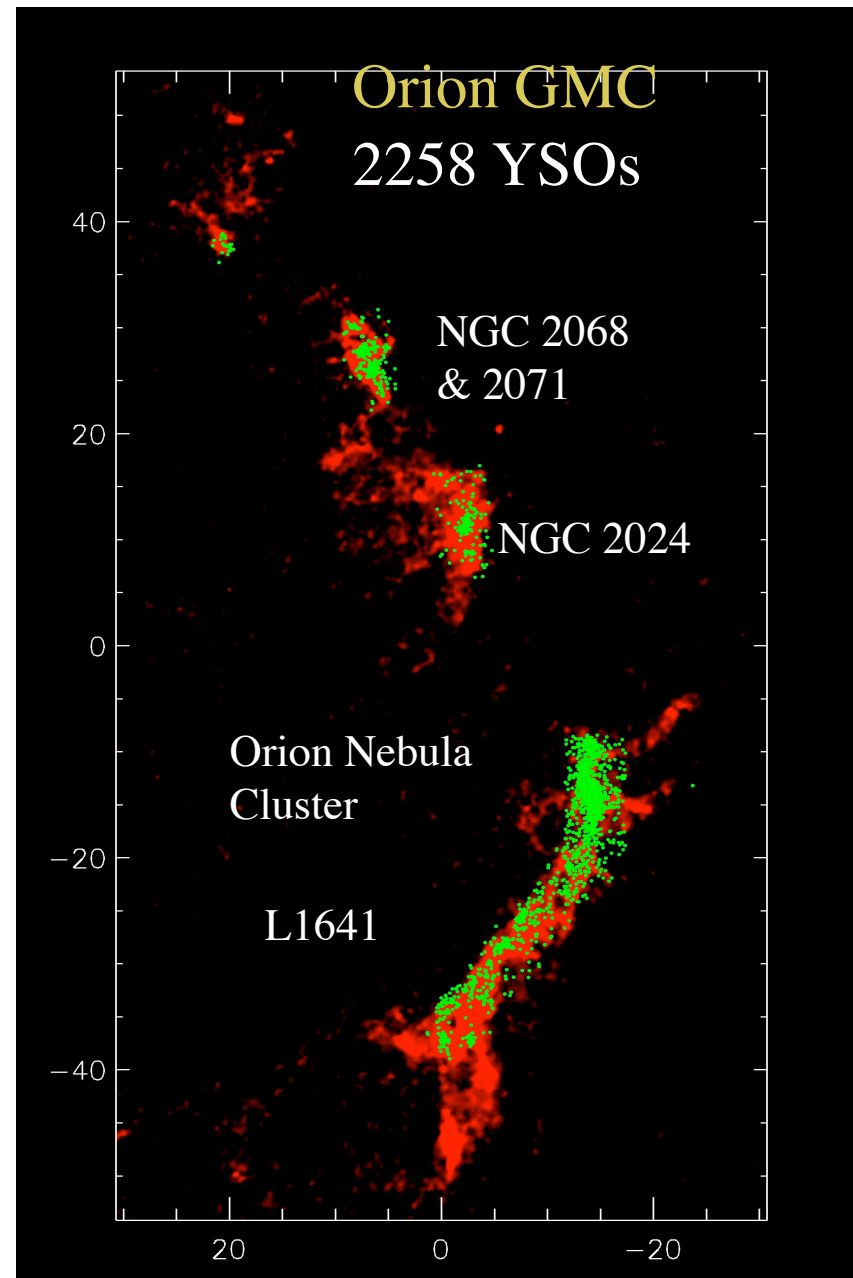
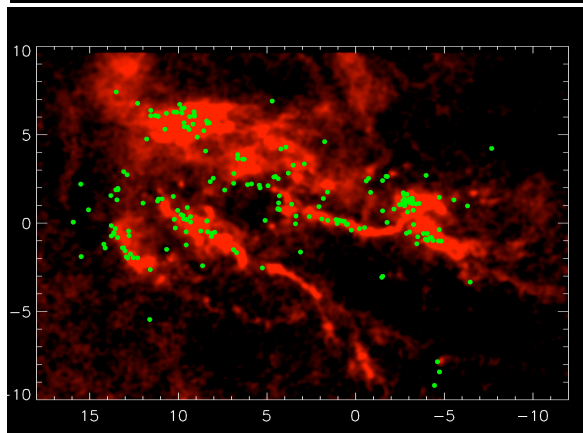
Perseus

387 YSOs

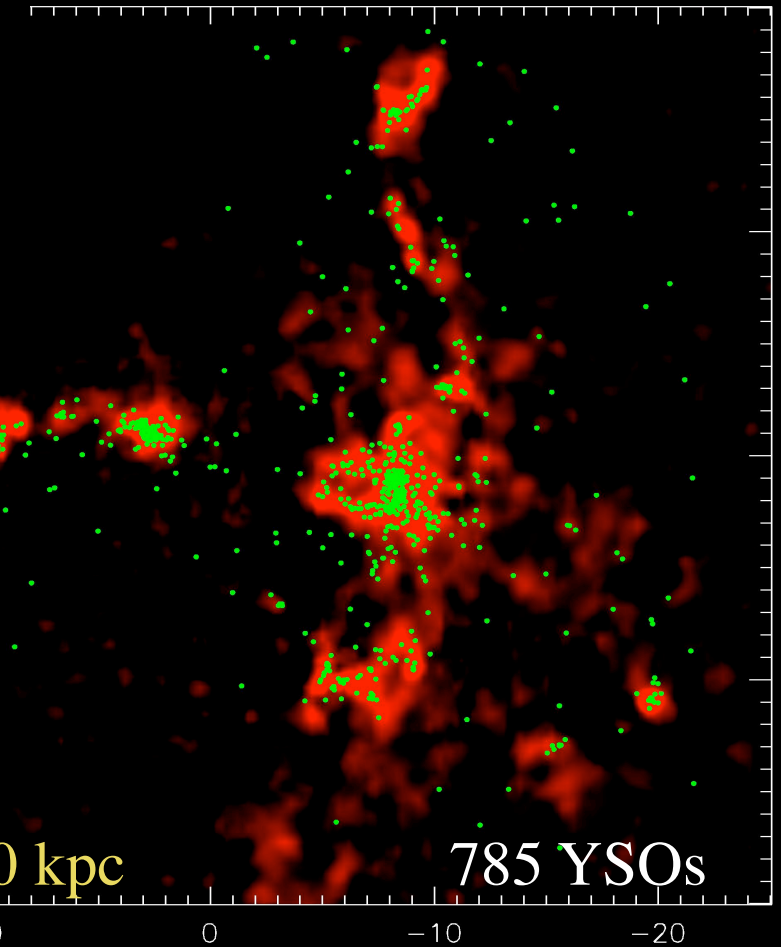
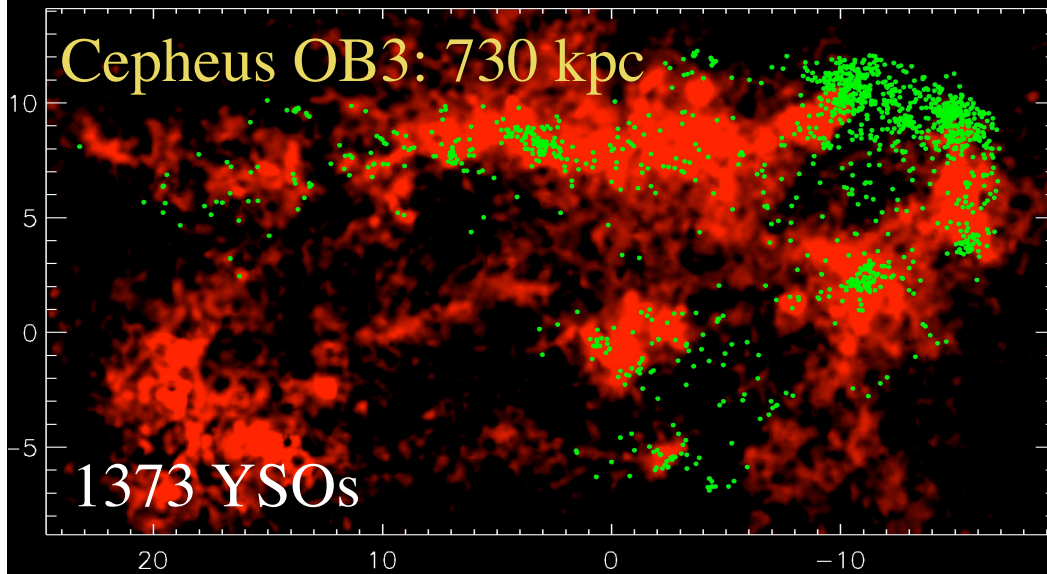


Taurus

296 YSOs

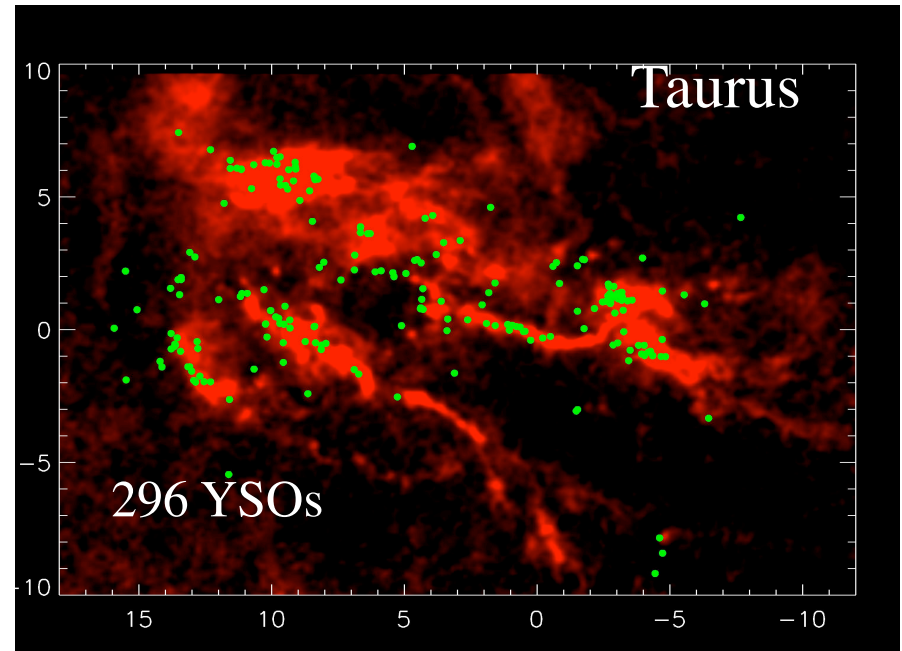
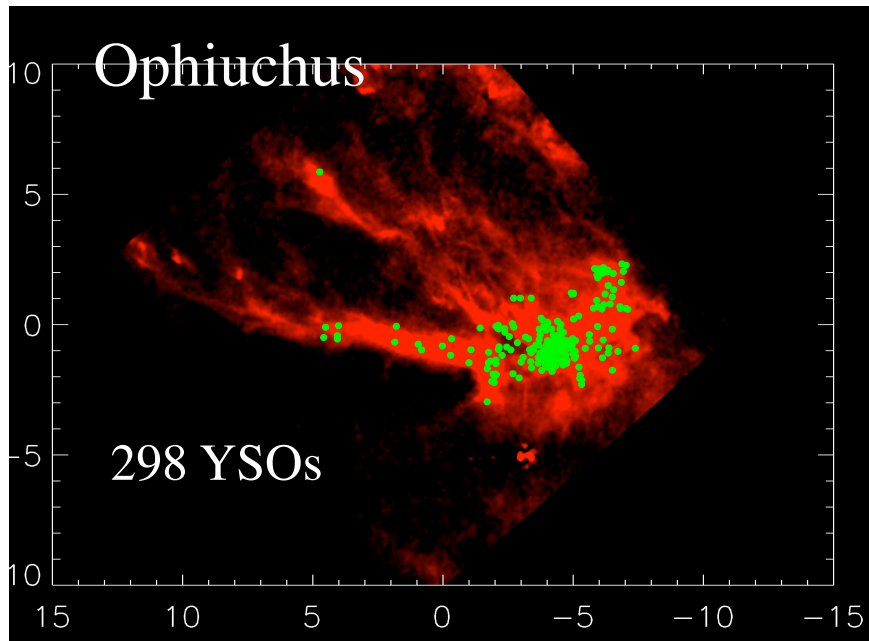


Orion-Like GMCs in the nearest 1 kpc

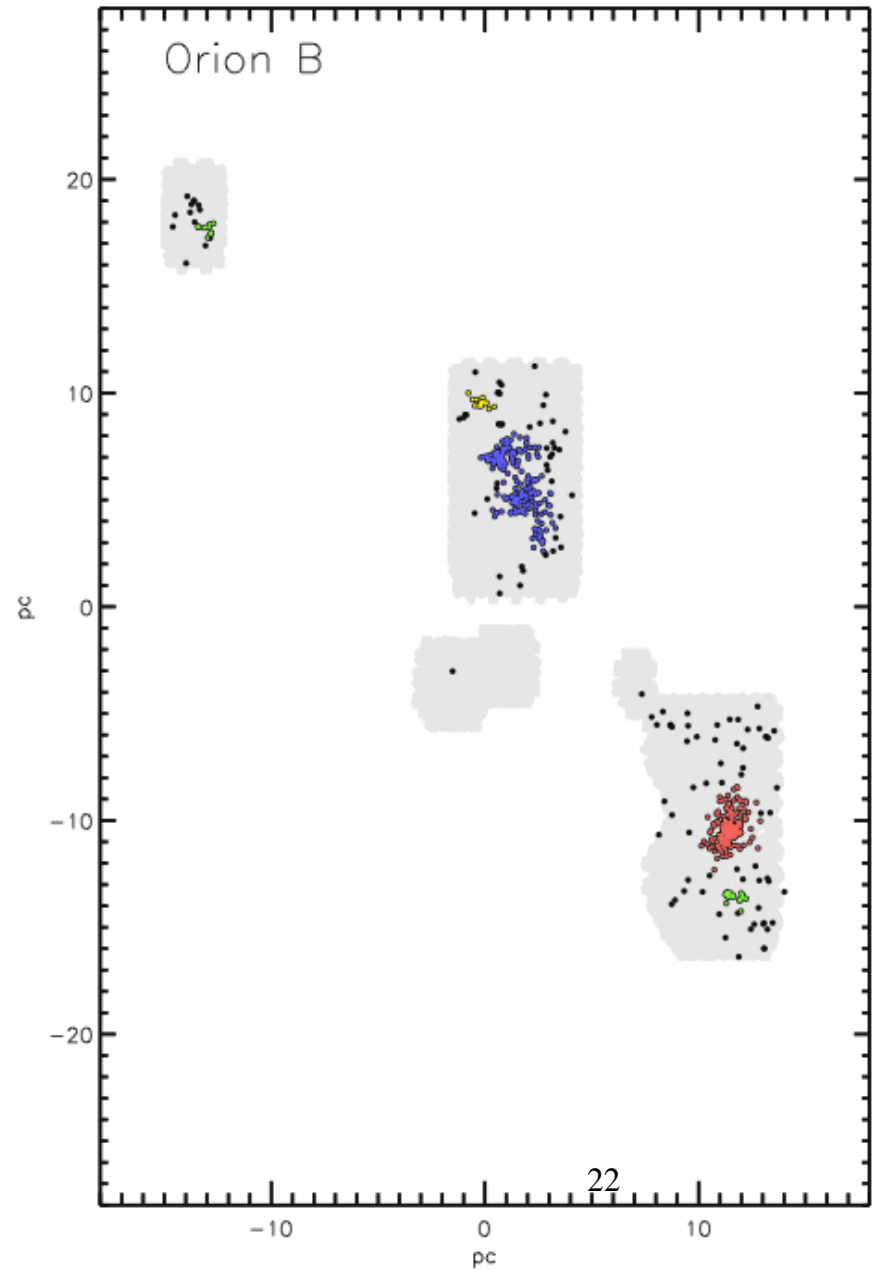
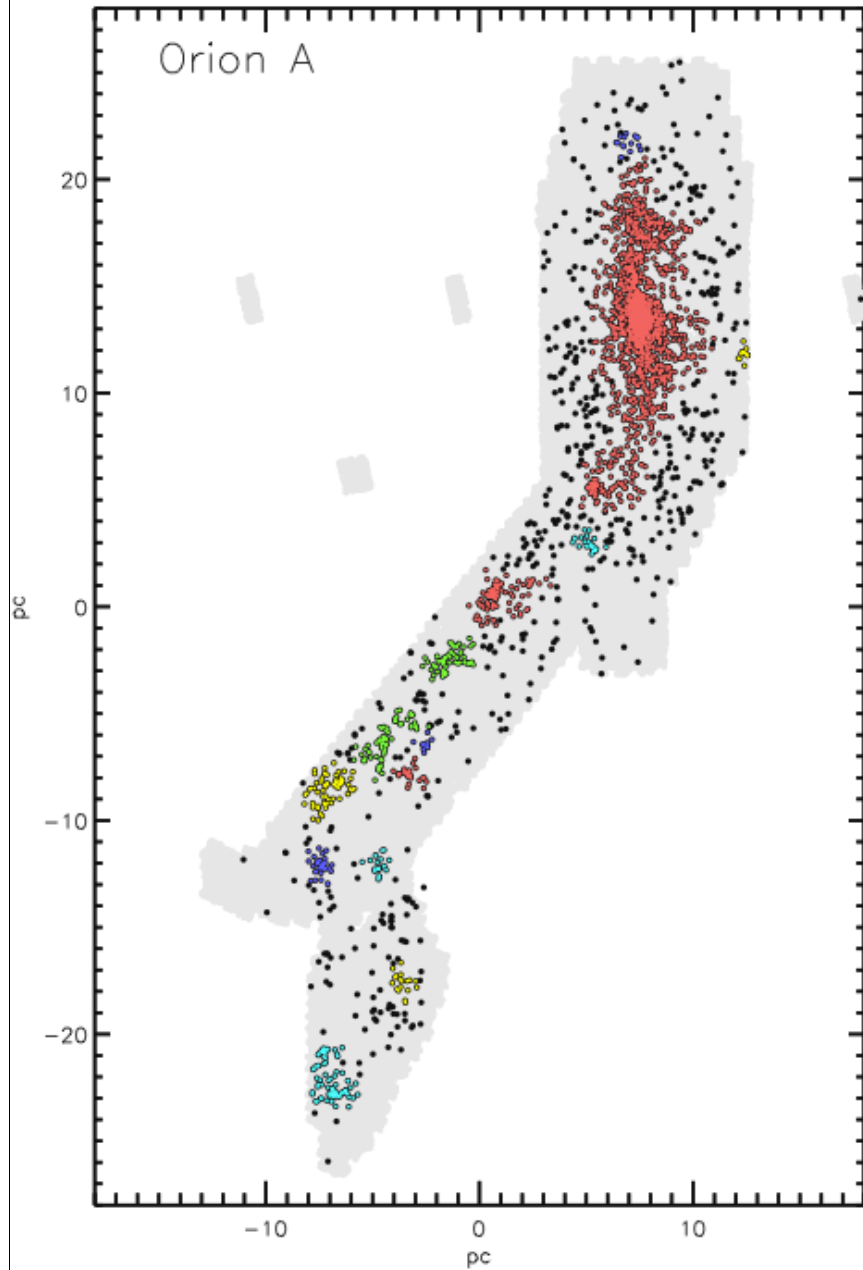


Note: one big cluster
a few smaller clusters
and groups
and a number of
distributed stars

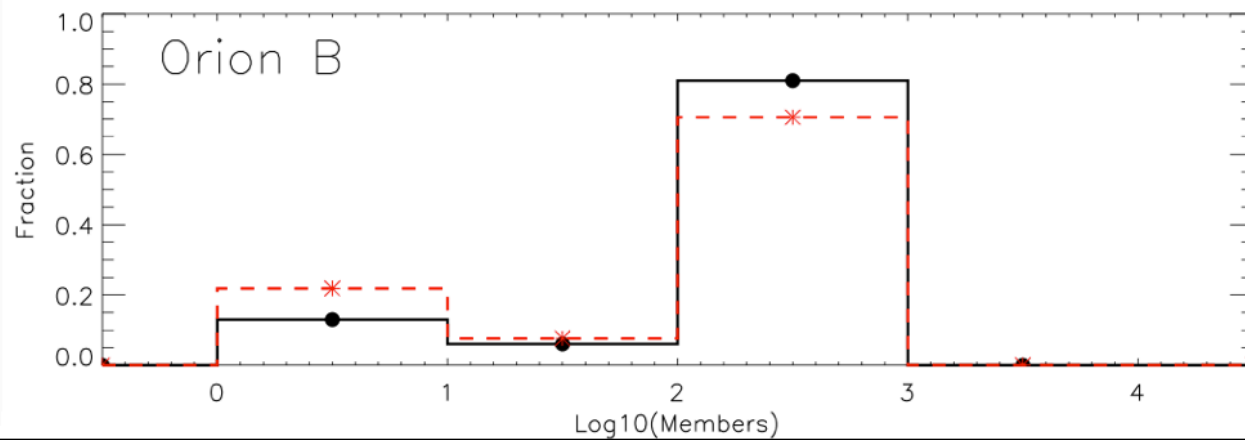
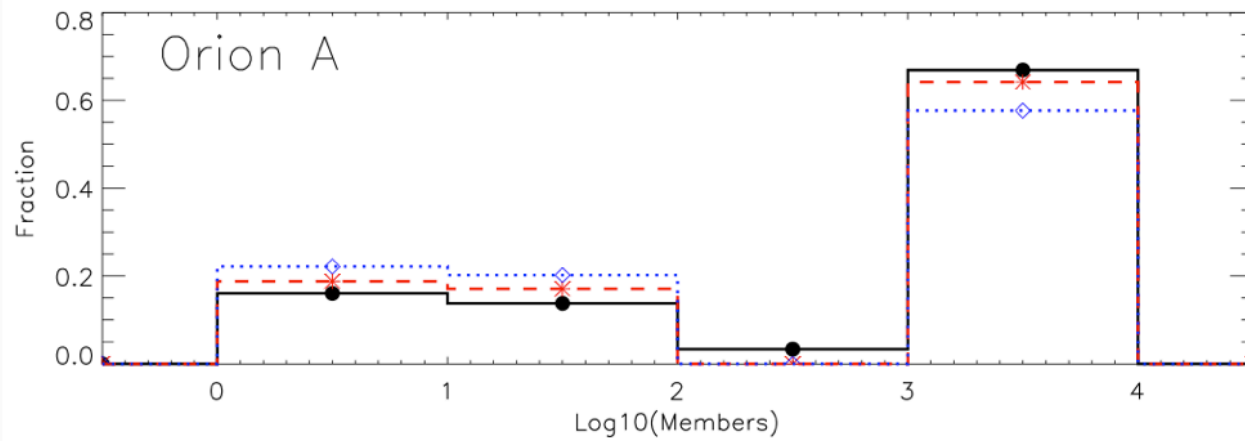
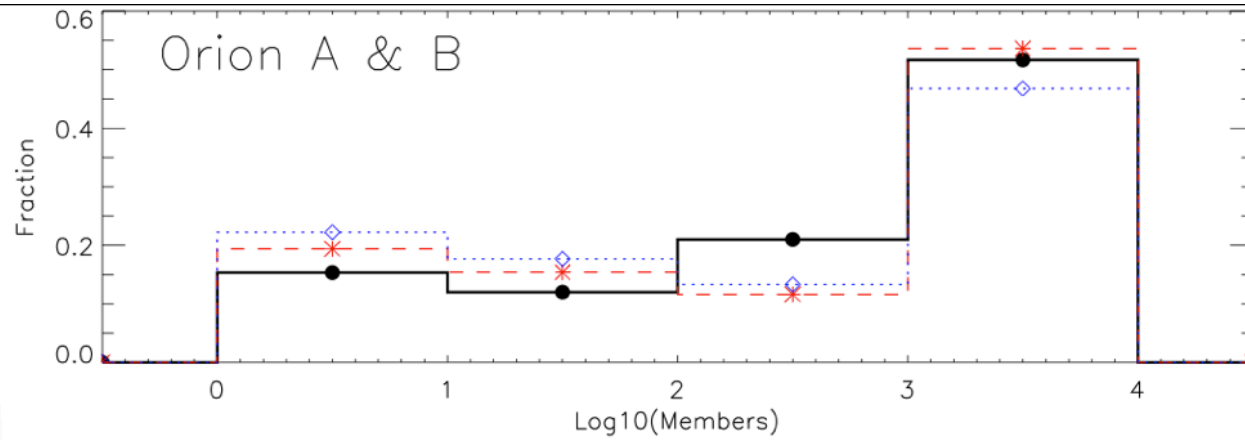
Clustered and Distributed Populations



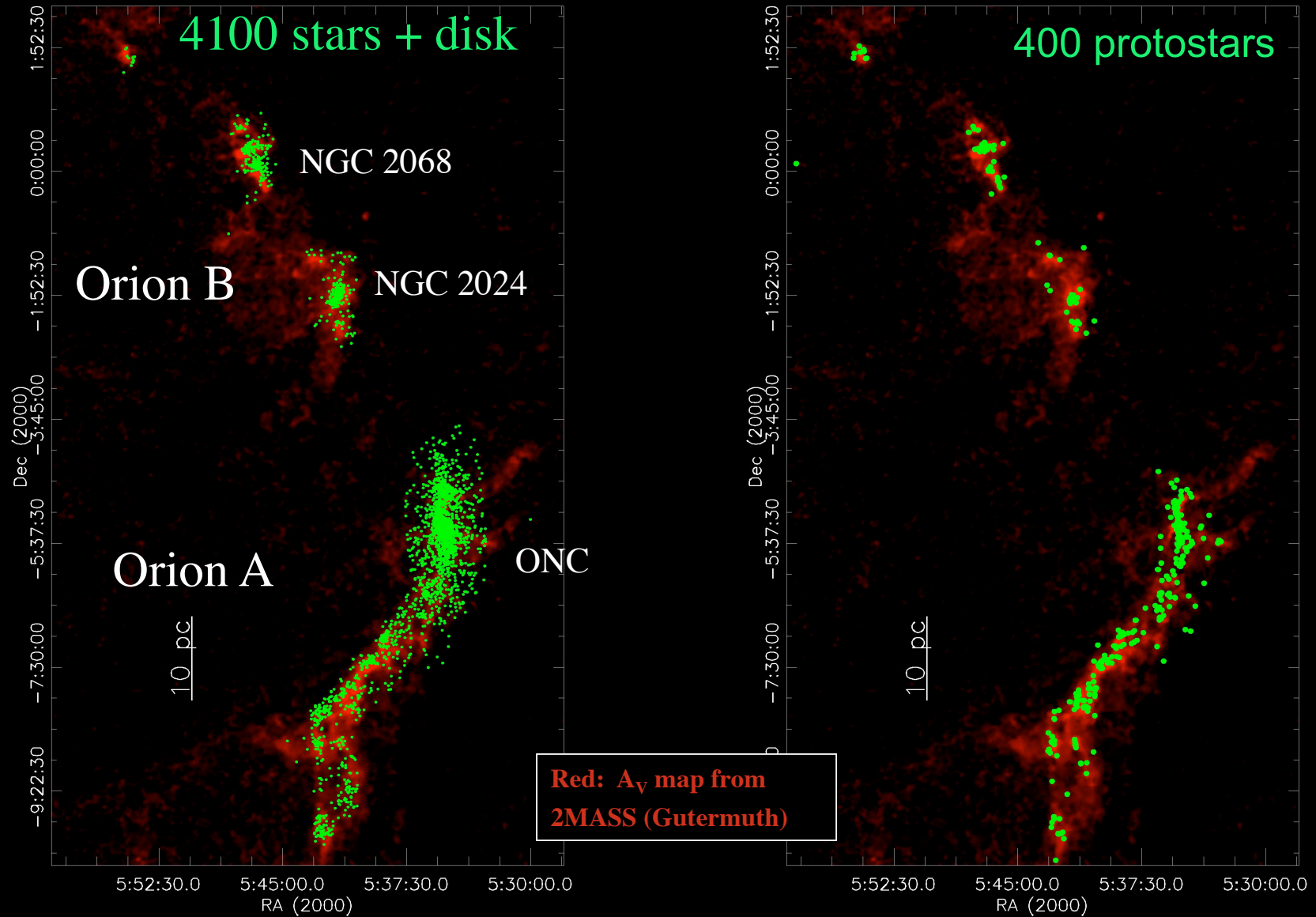
Demographics of YSOs

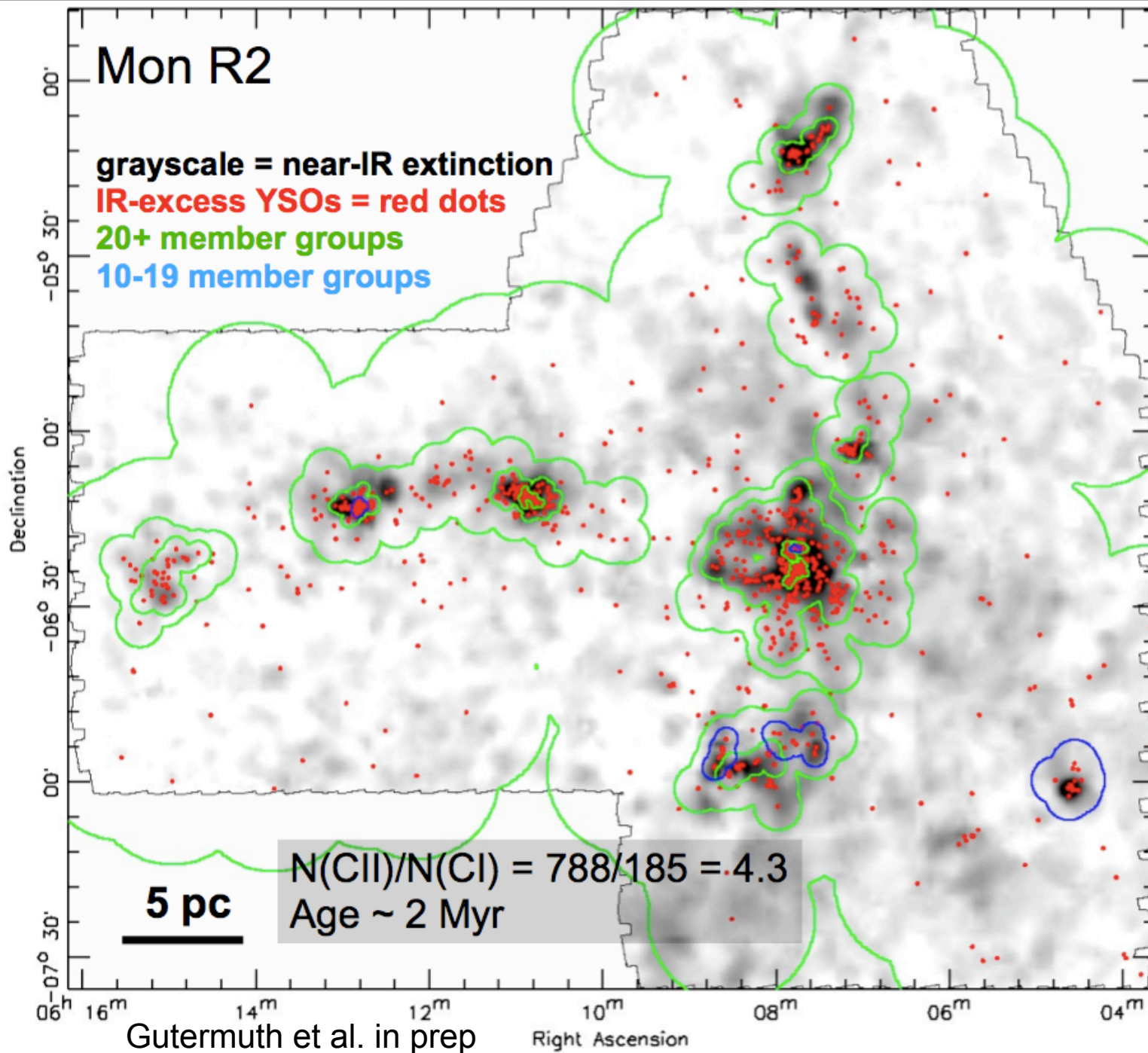


Demographics of YSOs



How does the density of stars depend on the properties of the gas?





Gutermuth et al. in prep

A Correlation Between Star and Gas Surface Density in MonR2!

YSO surface densities:

- 11th nearest neighbor
- Each YSO ~ 0.5 Msun

Gas surface densities:

- Near-IR reddening maps

1 $A_v \sim 15$ Msun / pc²

Uniform baseline removed

Class I YSOs in red

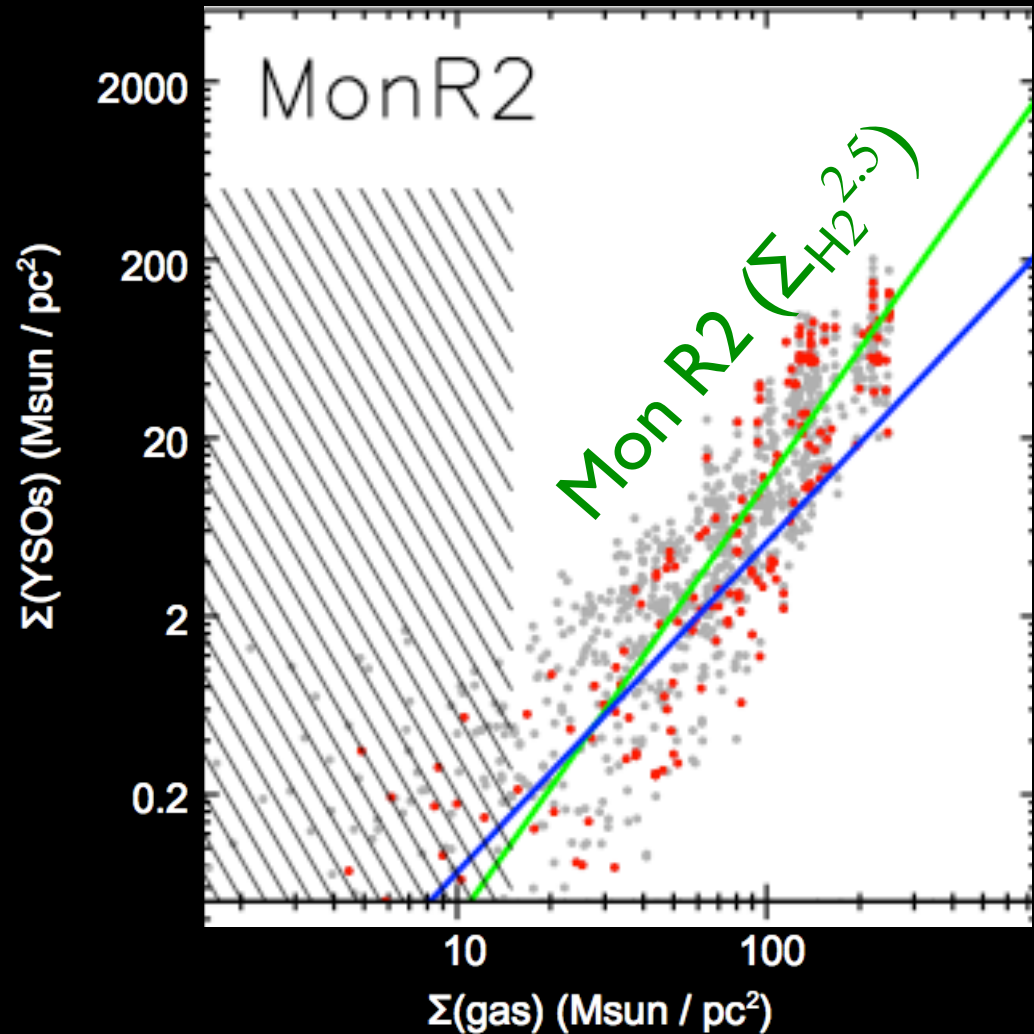
Class II YSOs in gray

Diagonal shading:

- Lower A_v limit on left
- Lower YSO surface density limit on bottom (AGN)

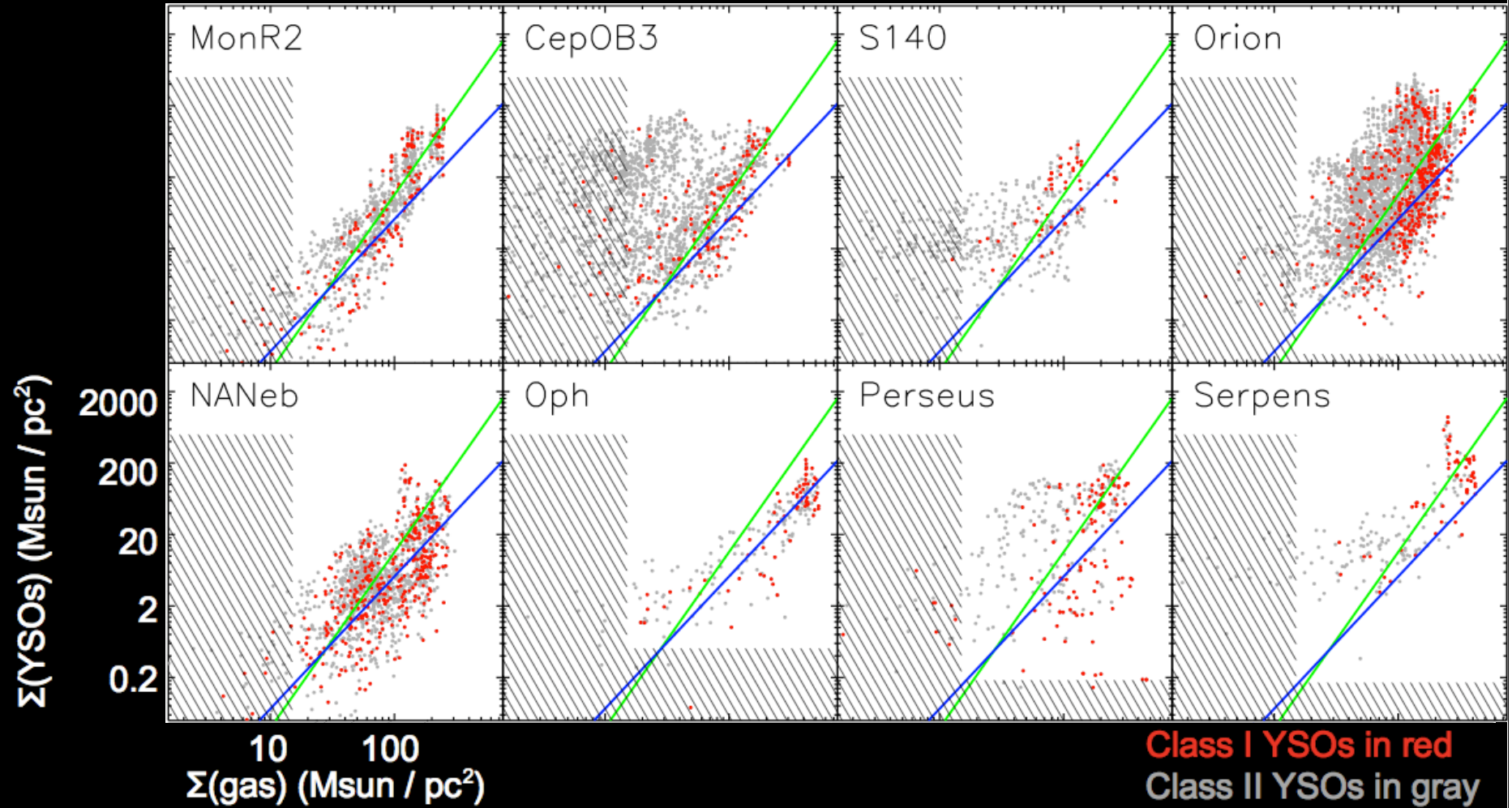
Power law fit in green

Alpha = 2.5



Gutermuth et al. submitted

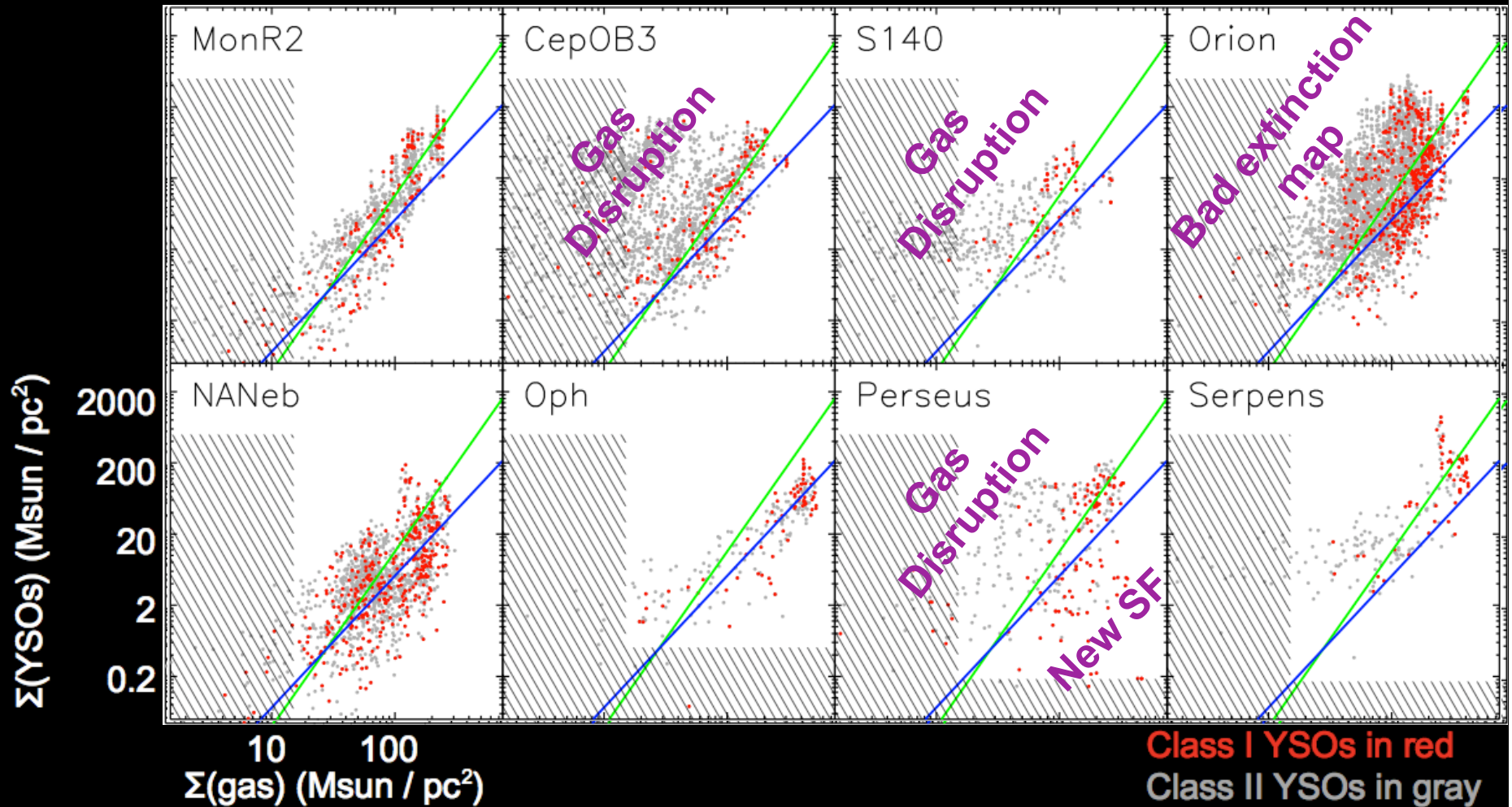
A Correlation Between Star and Gas Surface Density in Eight Clouds!



Oph, Perseus, Serpens; YSOs and A_v maps: c2d delivery products
North America Nebula; YSOs: Guieu et al. 2009; A_v map: Gutermuth
Small/Low density clouds consistent! (Chameleon, Lupus, Taurus)

Gutermuth et al. submitted

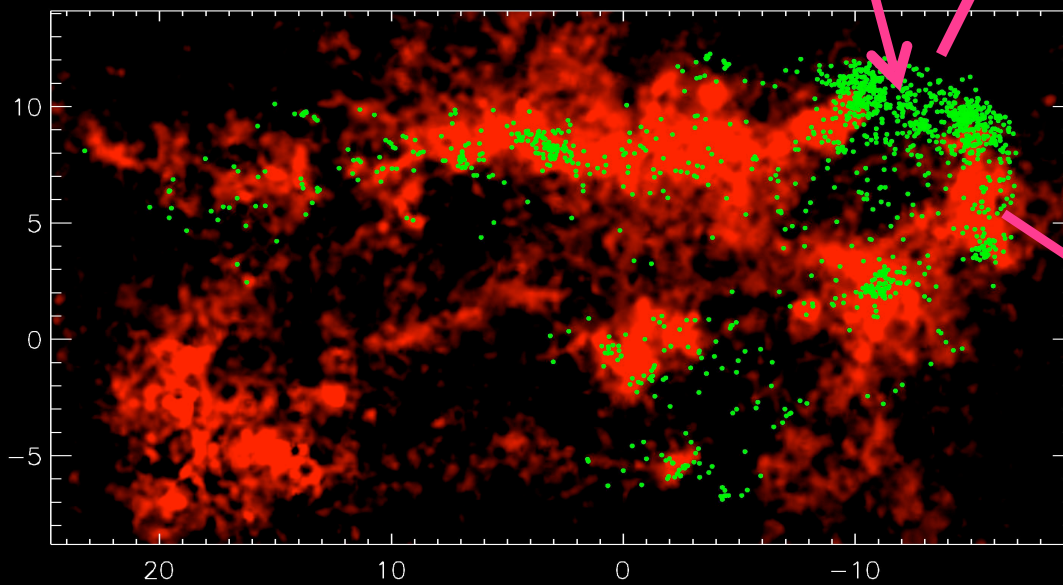
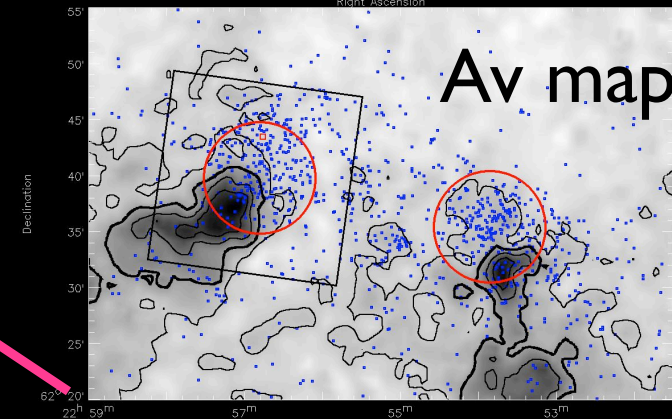
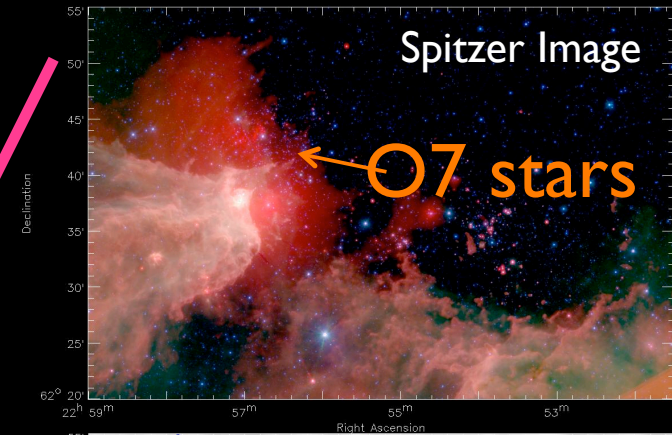
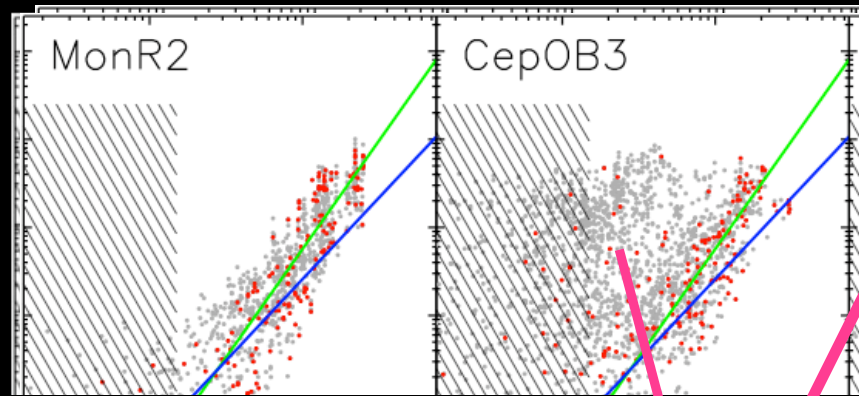
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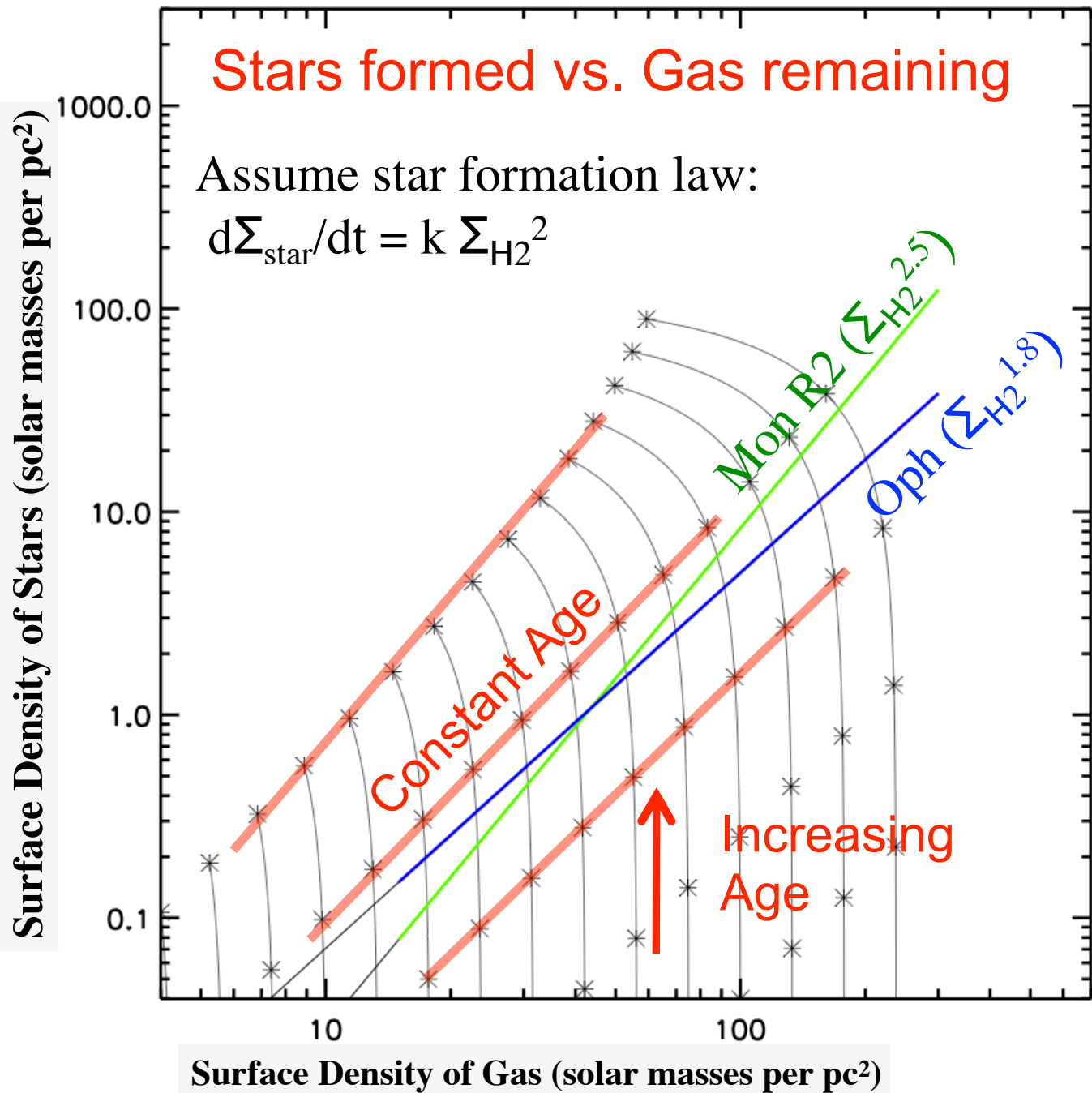
Gutermuth et al. submitted

A Correlation Between Star and Gas Surface Density in Eight Clouds!



Red Av map, Green dots: YSOs

Gutermuth et al. submitted



Comparison to power-law star formation rate:

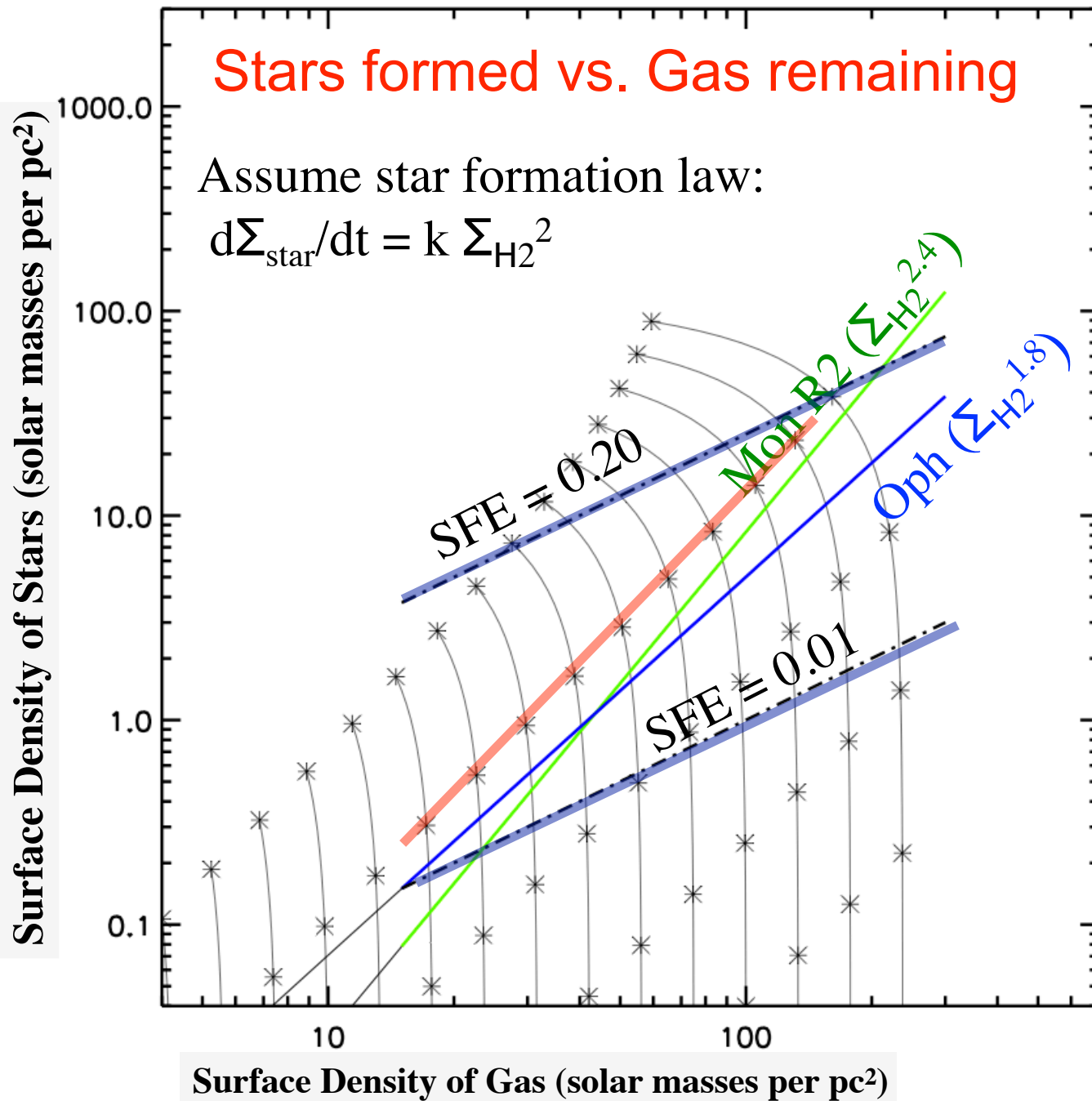
1. Assume power-law dependence.
2. Integrate number of stars over time.
3. When 1 M of stars form, 2M of gas disappears.
4. Show for several time steps.

(note time is degenerate with constant k)

Stars formed vs. Gas remaining

Assume star formation law:

$$d\Sigma_{\text{star}}/dt = k \Sigma_{\text{H}_2}^2$$



In regions with initially high gas column density: high star rate and high star formation efficiency (i.e. clusters!!!)

In regions with initially low gas column density: low star rate and low star formation efficiency.

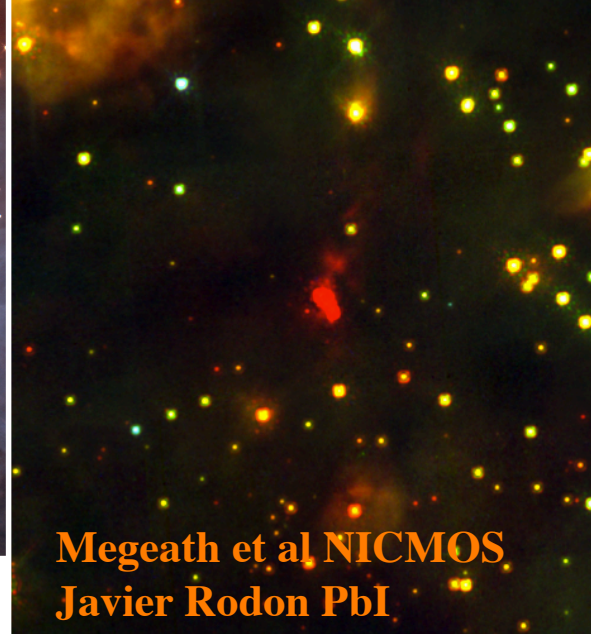
Young Clusters and the Formation of Massive Stars

OB stars in the ONC



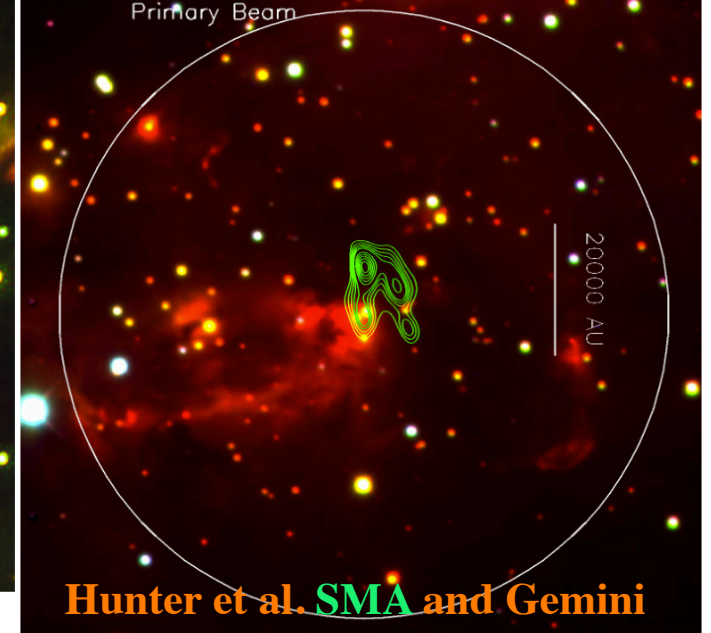
Luhman et al NICMOS

Protocluster in W3 Main



Megeath et al NICMOS
Javier Rodon Pbl

Protocluster in NGC 6334 I



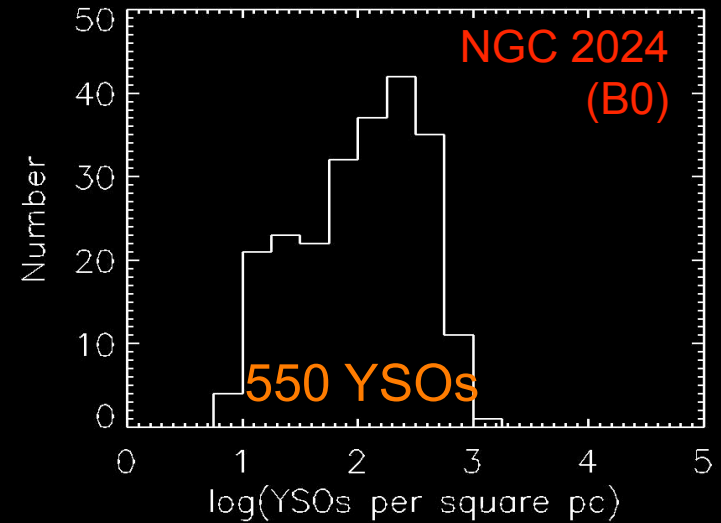
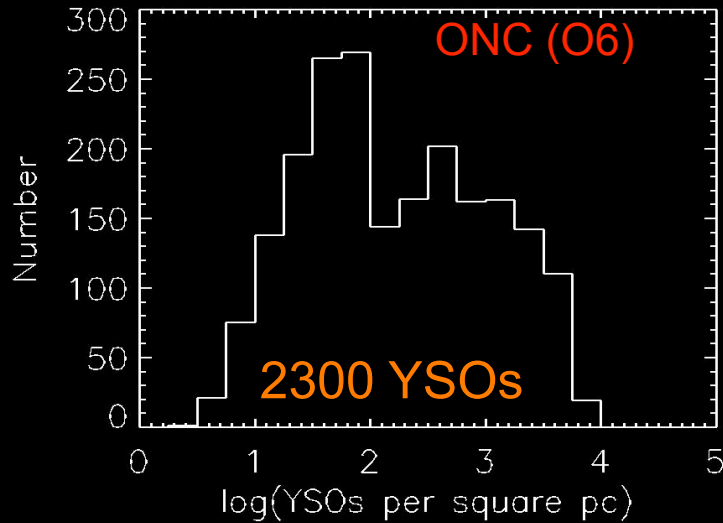
Hunter et al. SMA and Gemini

- Dense groups of massive stars/protostars $< 30,000$ AU in diameter
- Clusters of low mass stars in regions ~ 0.5 pc in diameter

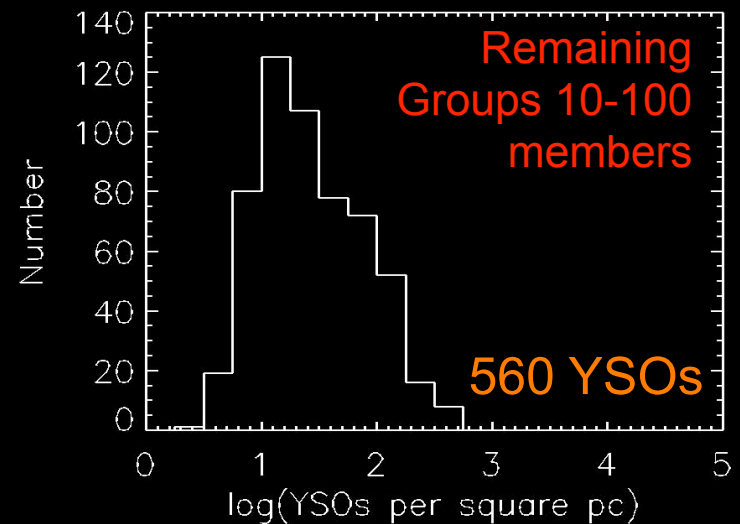
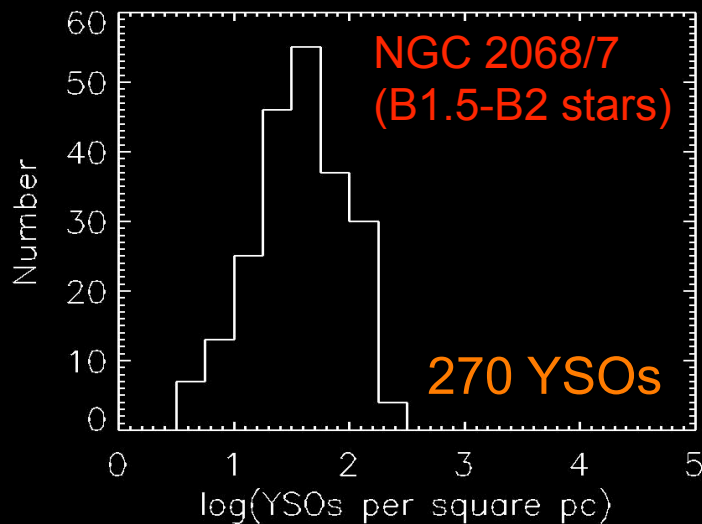
Need to distinguish mass segregation from dynamical evolution

YSO Densities in Clusters with Massive Stars

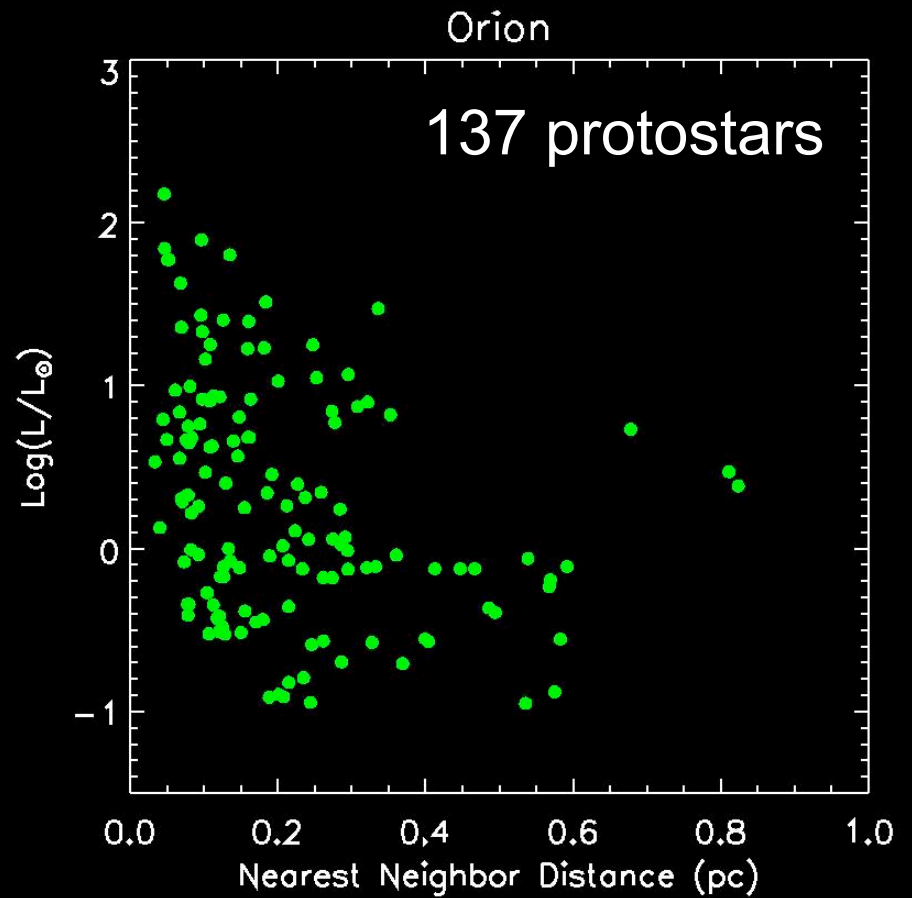
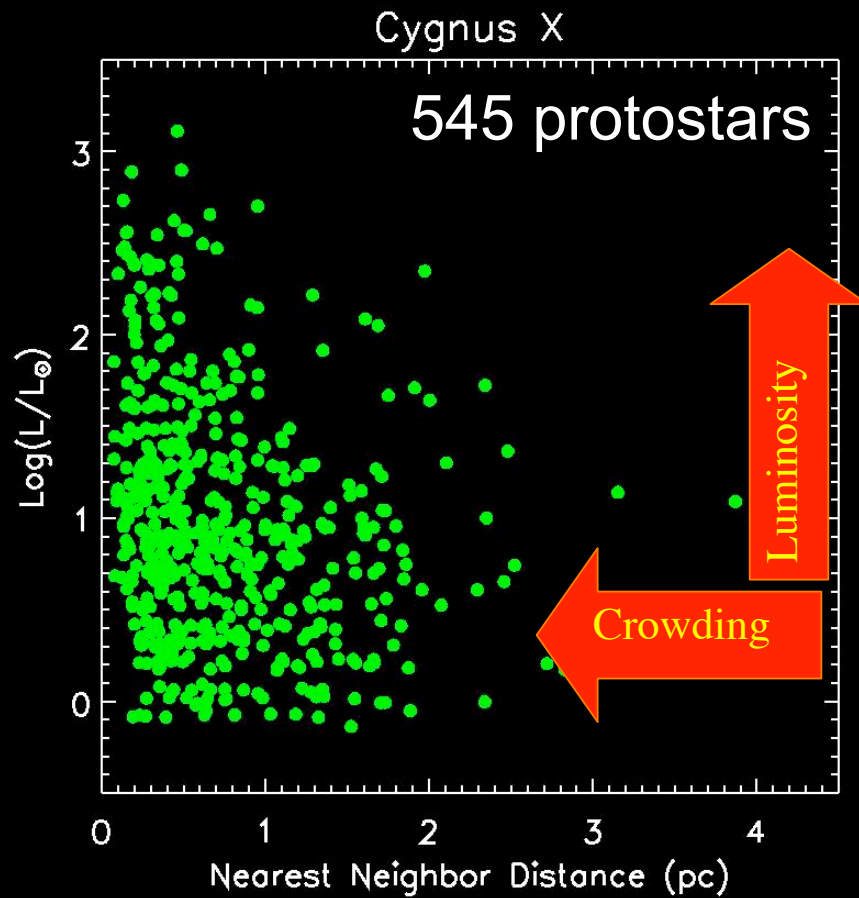
Clusters forming high mass stars



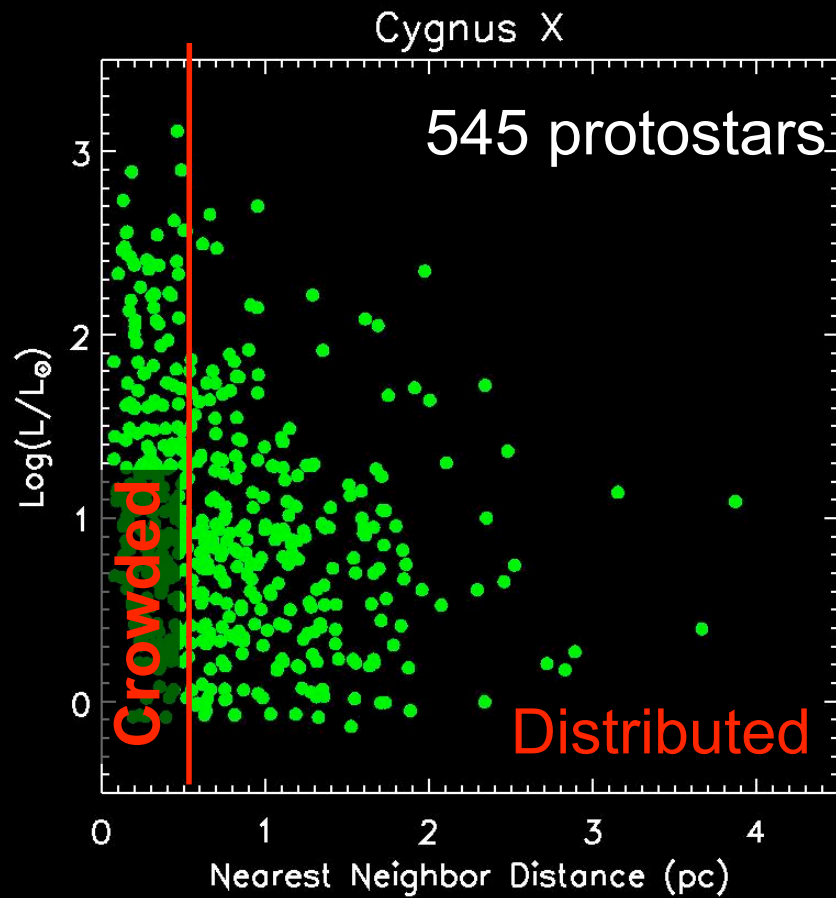
Clusters forming only low to intermediate mass stars



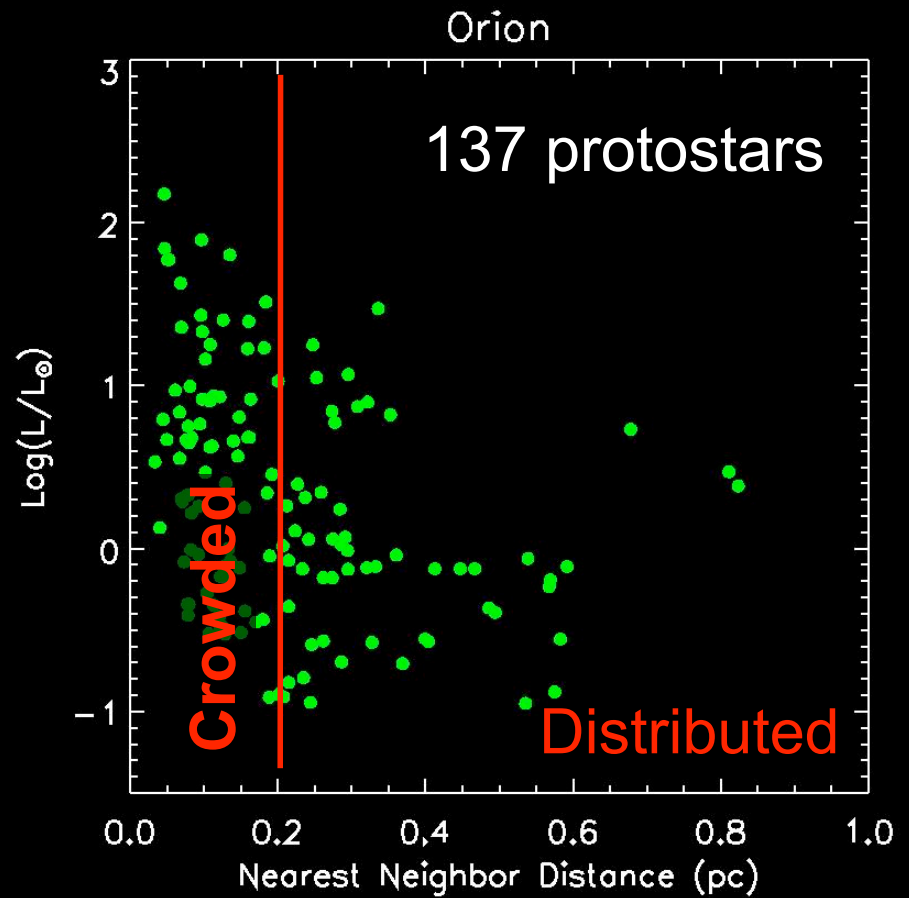
Does Protostellar Luminosity Depend on Crowding? Luminosity vs Distance to 5th nearest YSO



Use critical distance to split sample into two luminosity functions: crowded and distributed

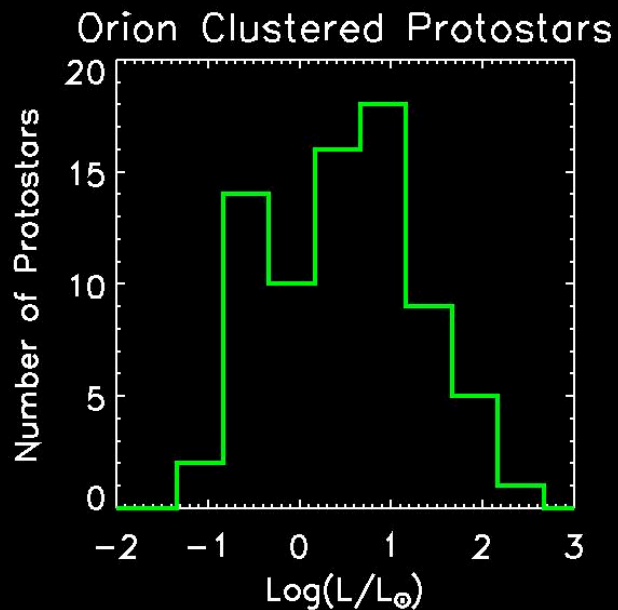


Critical distance of of 0.18 pc

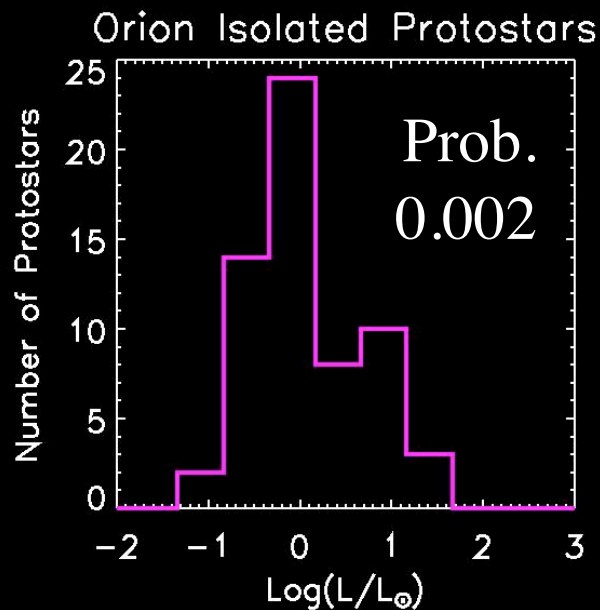


Critical distance of of 0.2 pc

Kryukova et al. in prep.

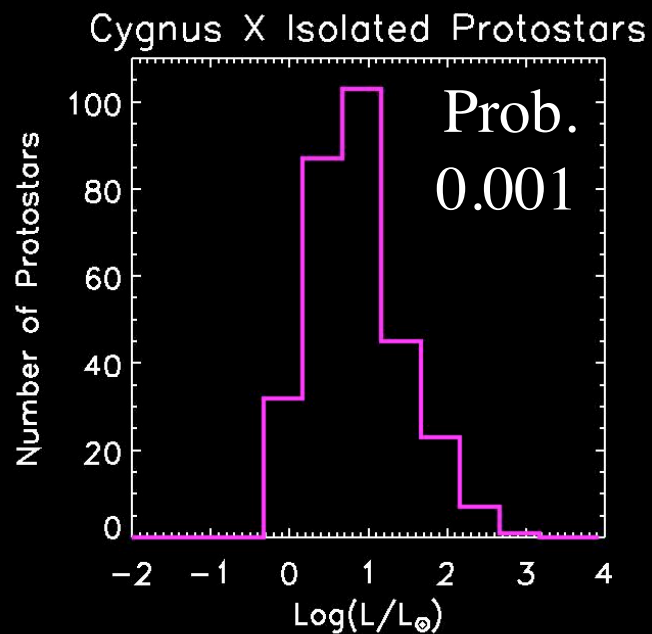
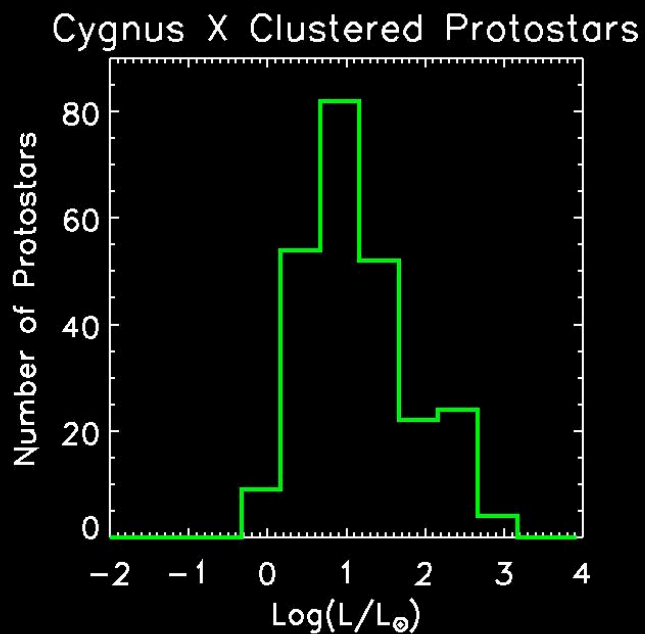


Crowded



Distributed

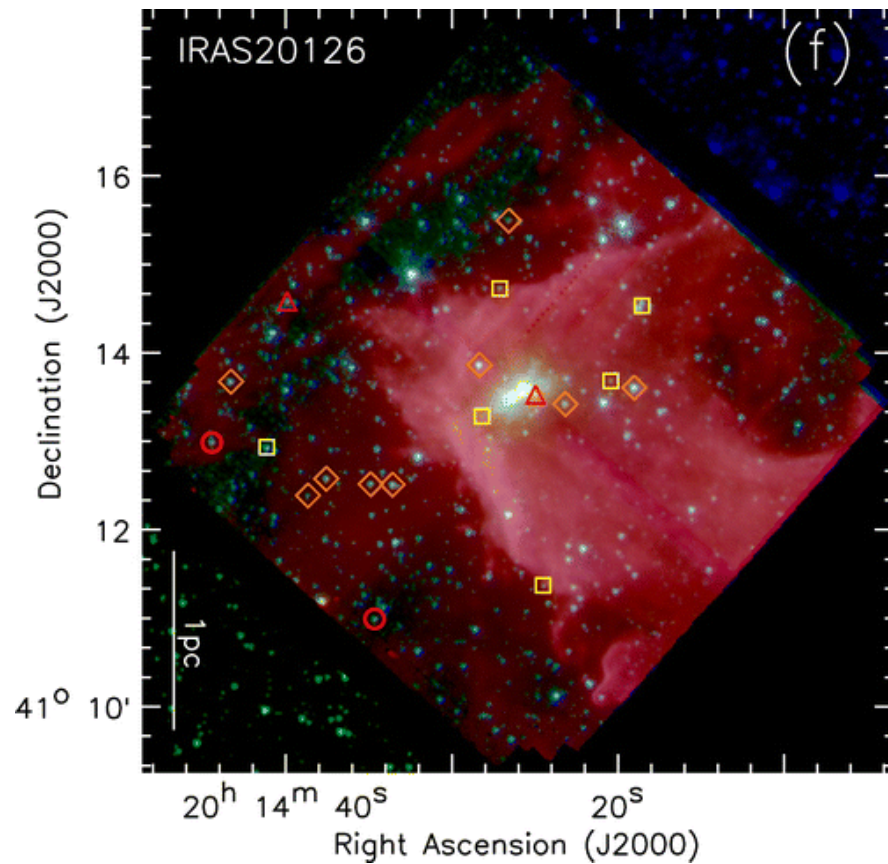
Probability that luminosity functions are drawn from same parent distribution



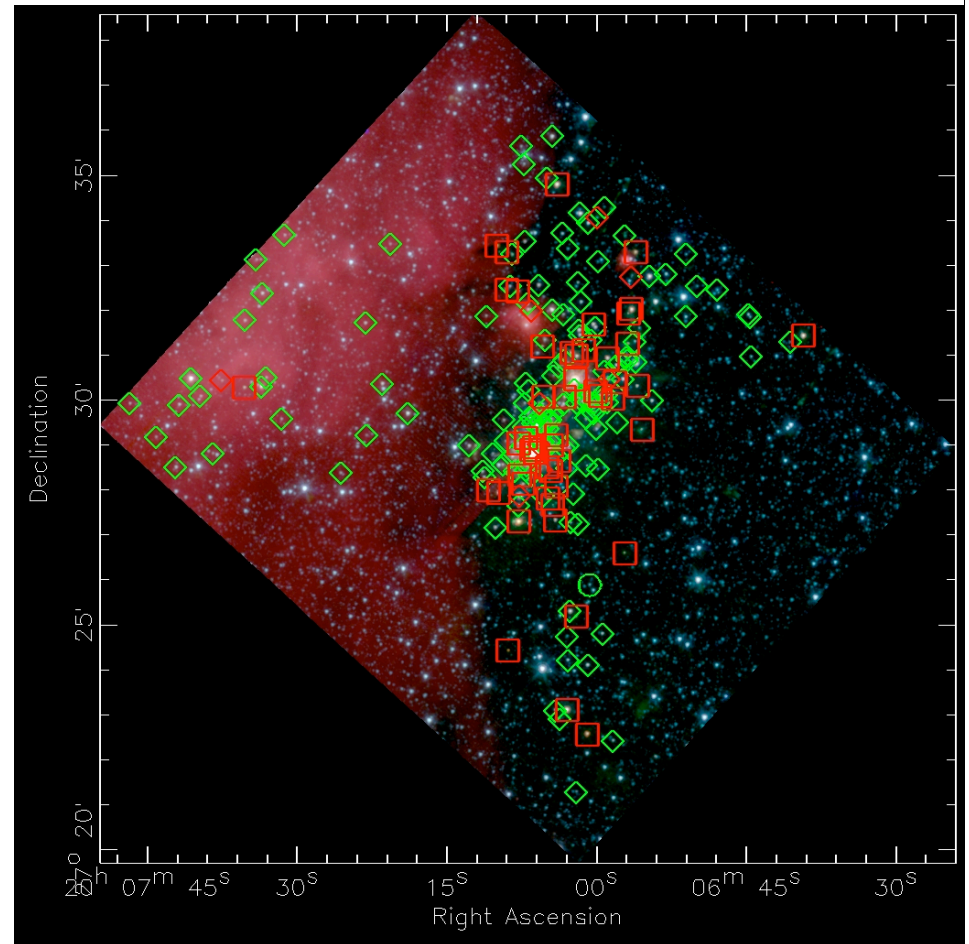
Clustered regions in Orion and Cyg-X show enhancement of luminous sources.

Kryukova et al.

Crowding vs Luminosity: The Exceptions

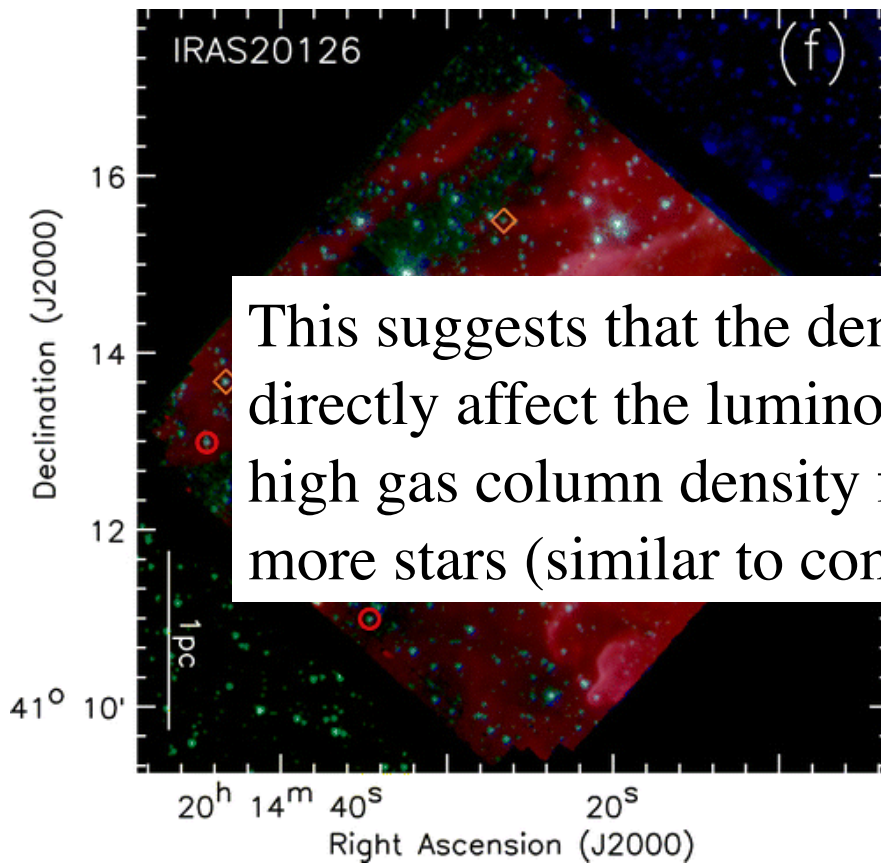


IRAS 20126 – a 10^4 Lsun source without a rich cluster.
Qiu et al. 2008



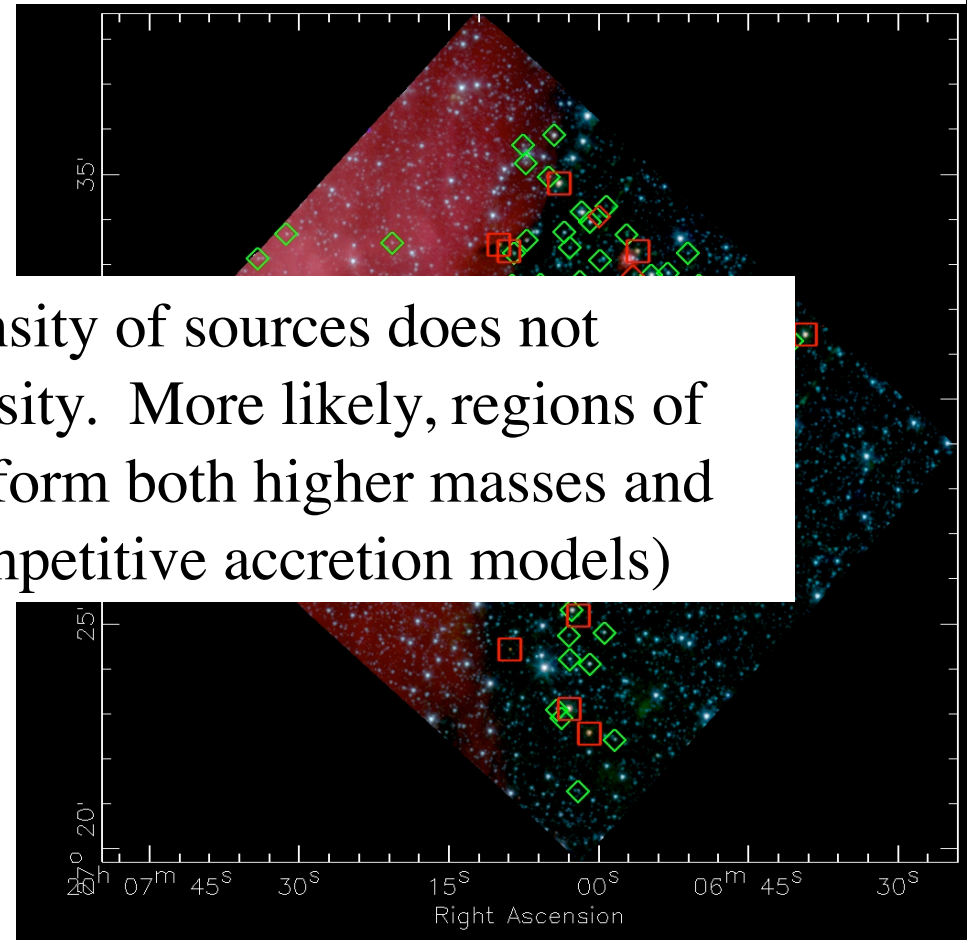
IRAS 20050 – a rich (200 member) cluster with only a 10^2 Lsun source.
Gutermuth et al. 2009

Crowding vs Luminosity: The Exceptions



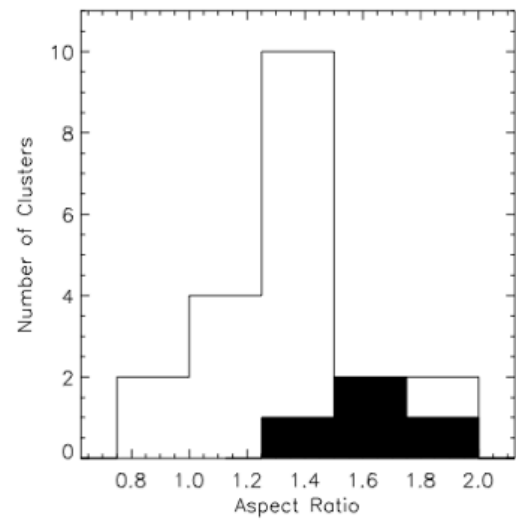
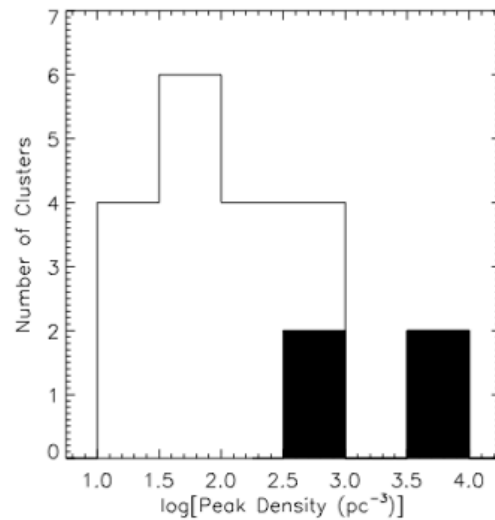
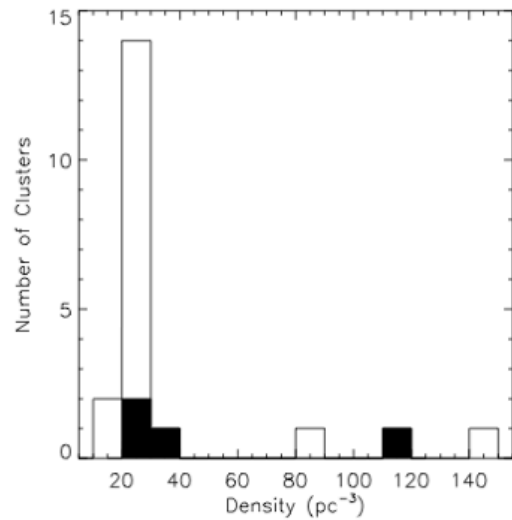
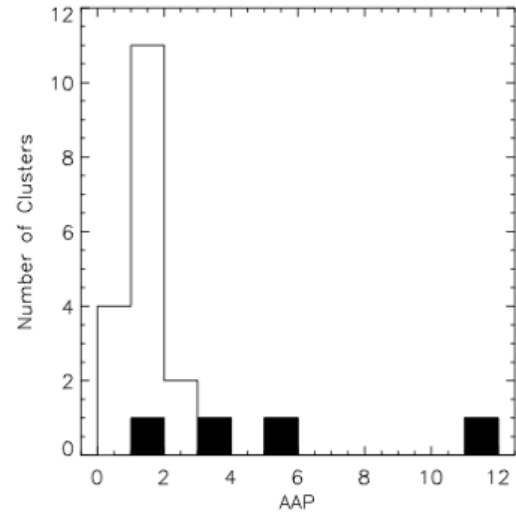
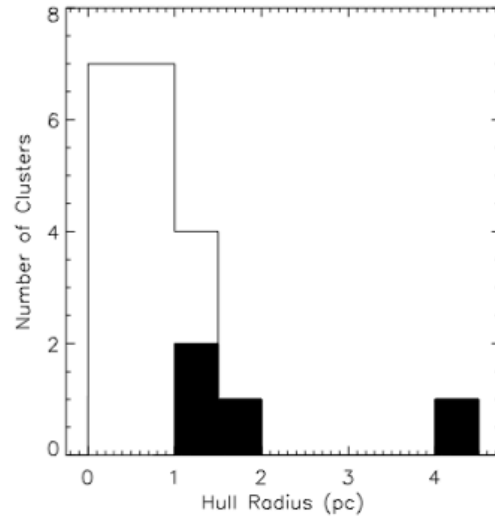
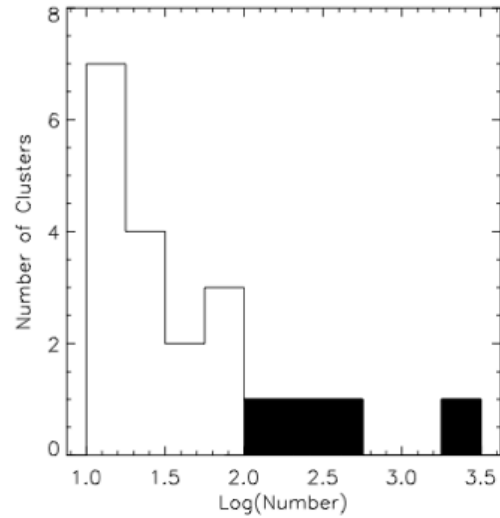
This suggests that the density of sources does not directly affect the luminosity. More likely, regions of high gas column density form both higher masses and more stars (similar to competitive accretion models)

IRAS 20126 – a 10^4 L_{sun} source without a rich cluster.
Qiu et al. 2008

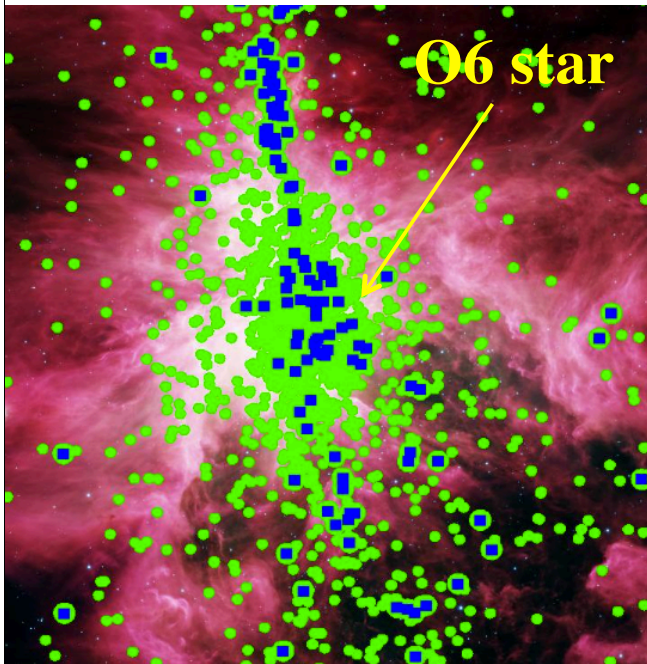


IRAS 20050 – a rich (200 member) cluster with only a 10^2 L_{sun} source.
Gutermuth et al. 2009

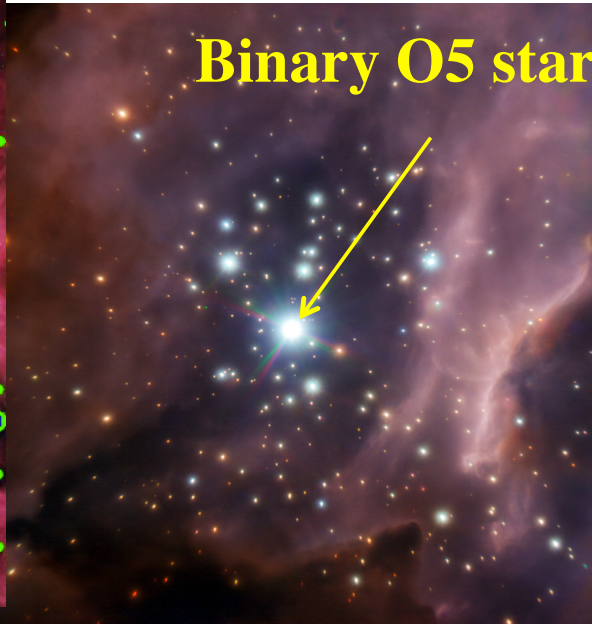
The Properties of Clusters



The Properties of the Most Massive Nearby Clusters (those with O-stars)



The Orion Nebular Cluster
(Megeath et al. 2011)



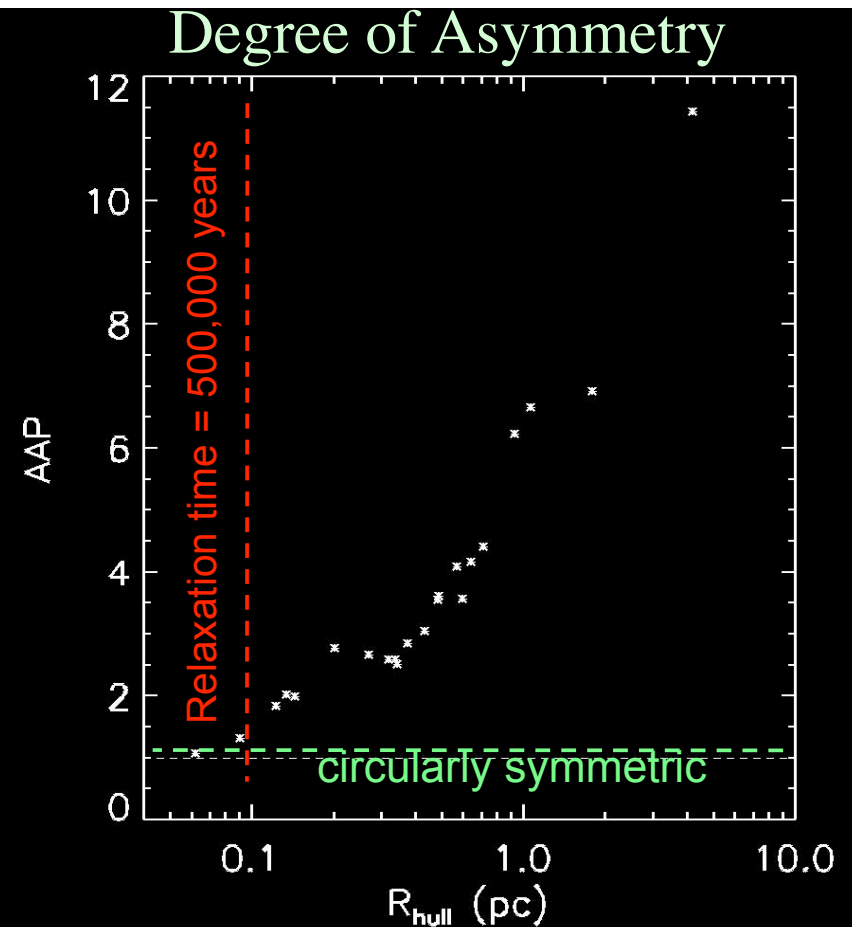
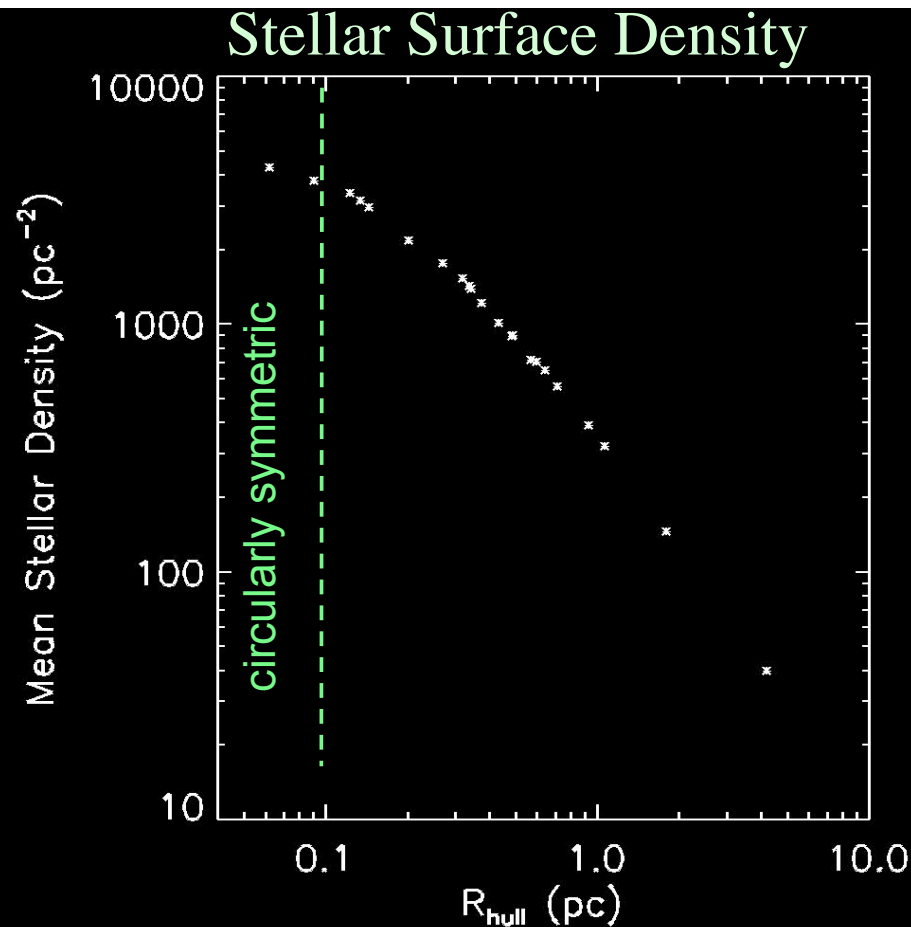
RCW 38 Cluster
(DeRose et al. 2009)

NGC 3603
(Stolte et al 2006)



Clusters containing O stars are often centrally condensed with peak densities $\sim 5000 \text{ pc}^{-2}$ (0.5 gm cm^{-2})

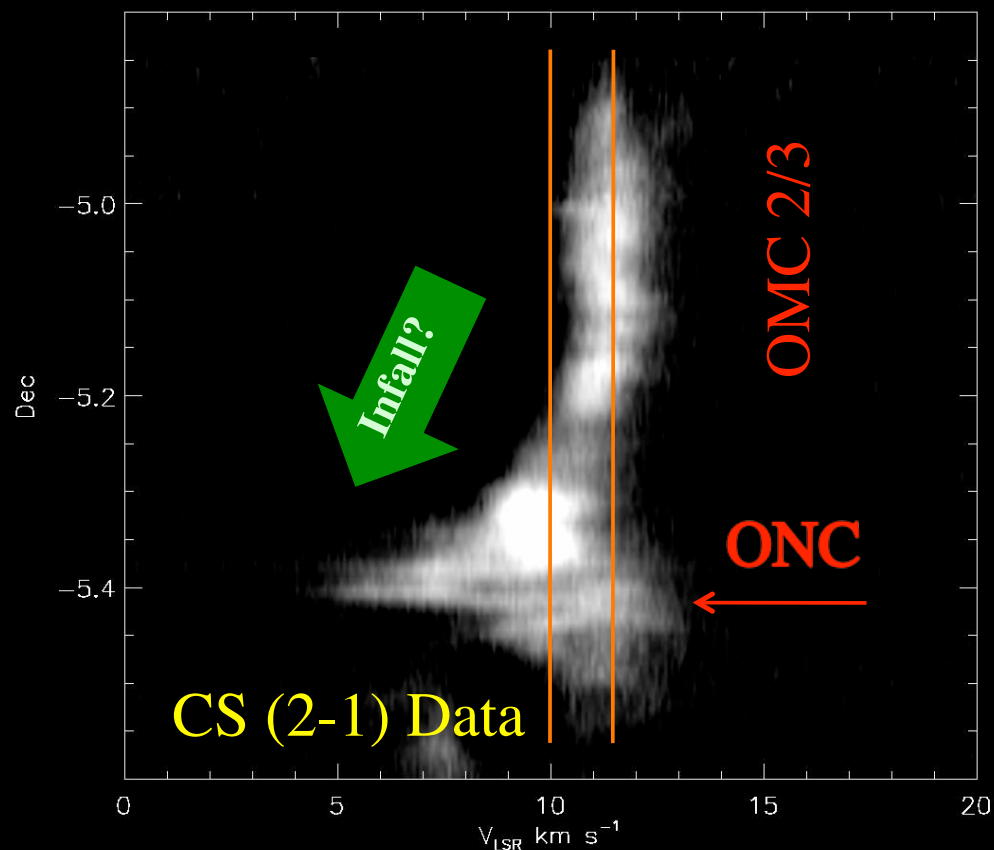
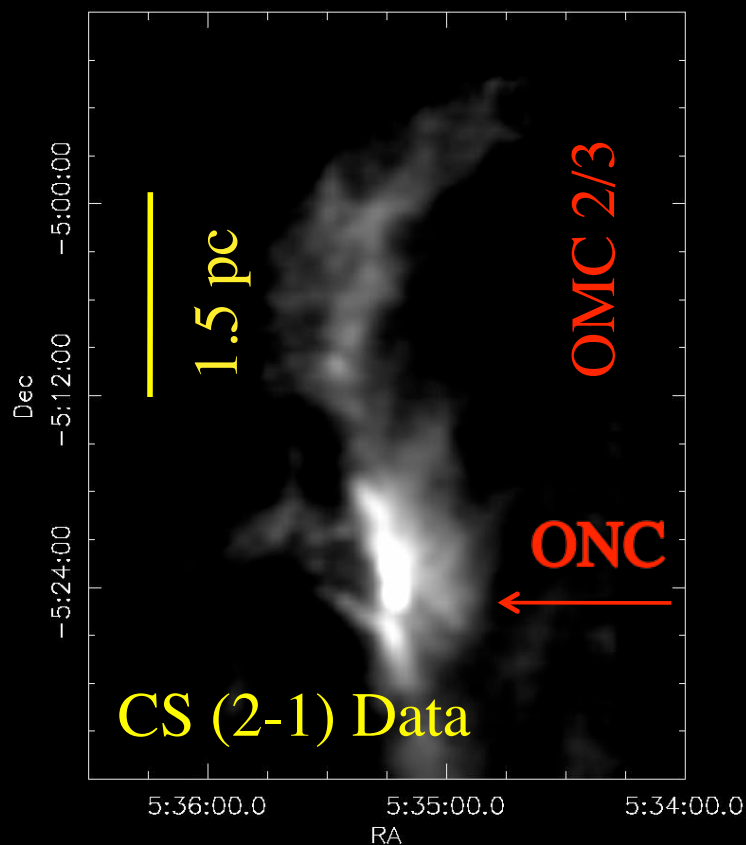
Elongation vs Radius: The ONC is centrally condensed but not relaxed



Azimuthal Asymmetry Parameter
(Gutermuth et al. 2005)

$$\text{AAP}_{\text{raw}} = \frac{\sqrt{\sum_{i=1}^m [(n_i - |n|)^2] / (m - 1)}}{\sqrt{|n|}}$$

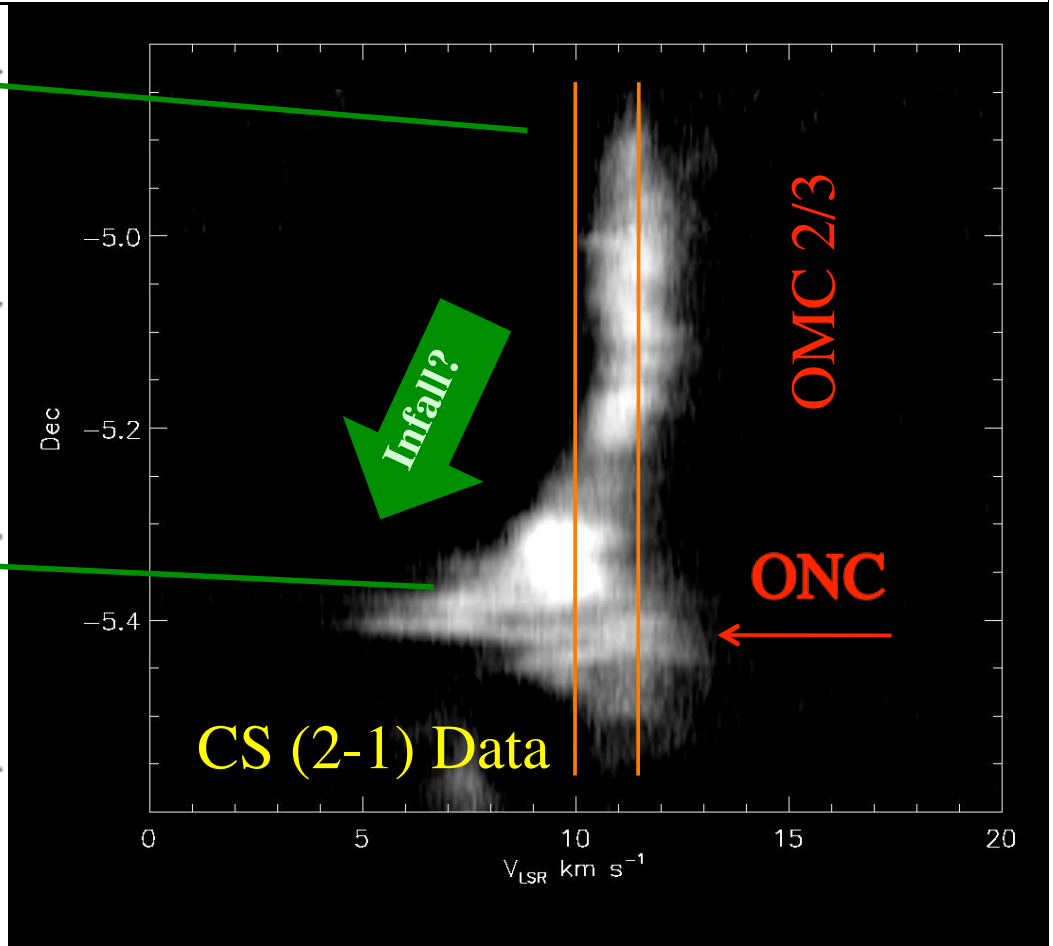
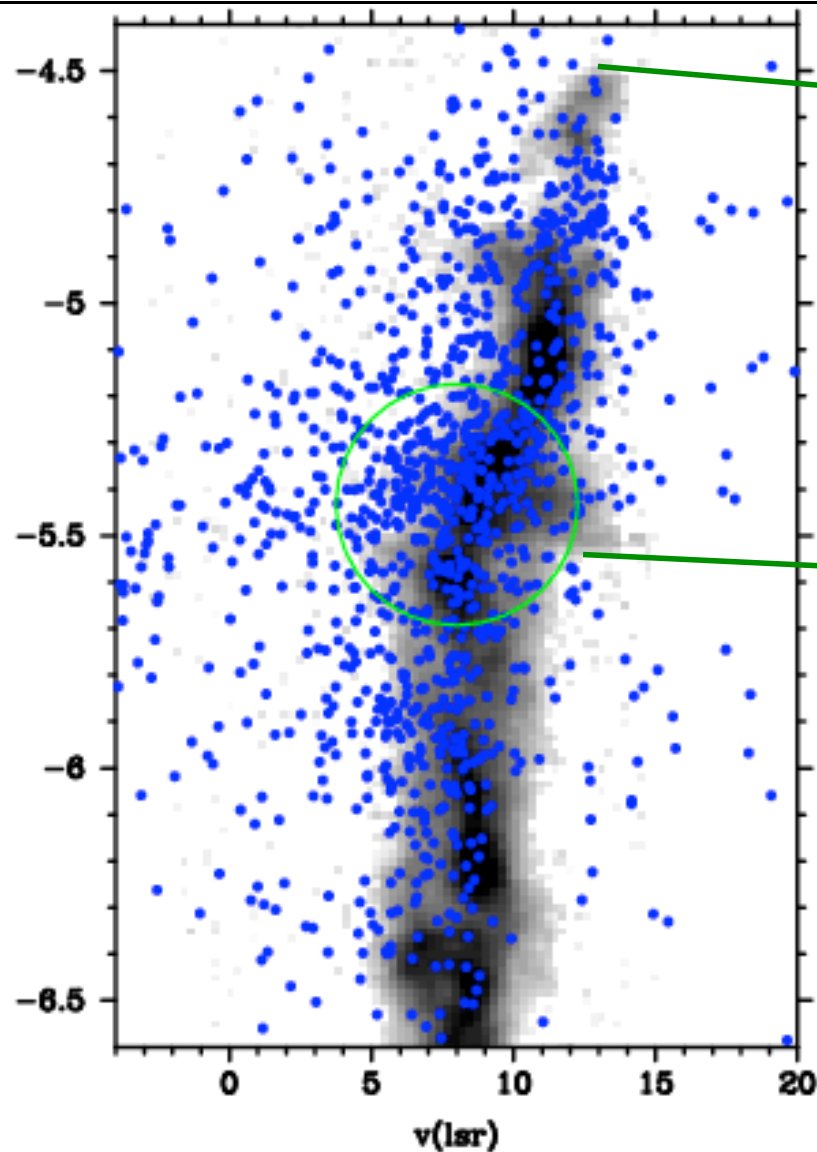
Gas Infall Into the ONC?



Acceleration consistent with material falling from 1.5 parsecs onto a 500 solar mass object.

Flow of gas ~ 10 solar masses every 100,000 years (uncertain!!)

Star & Gas Infall Into the ONC?



Blue: stars with radial velocity measurements,
Grey: ^{13}CO gas - Tobin et al. 2009

Infall and Outflow in the ONC

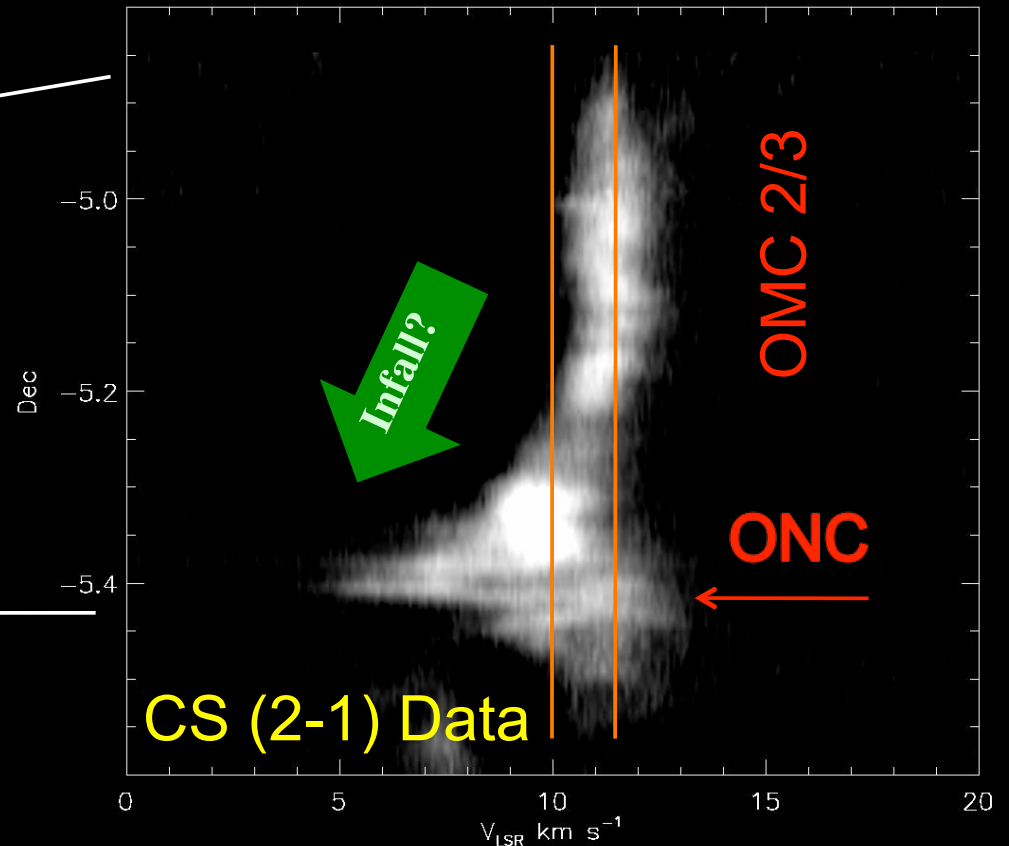
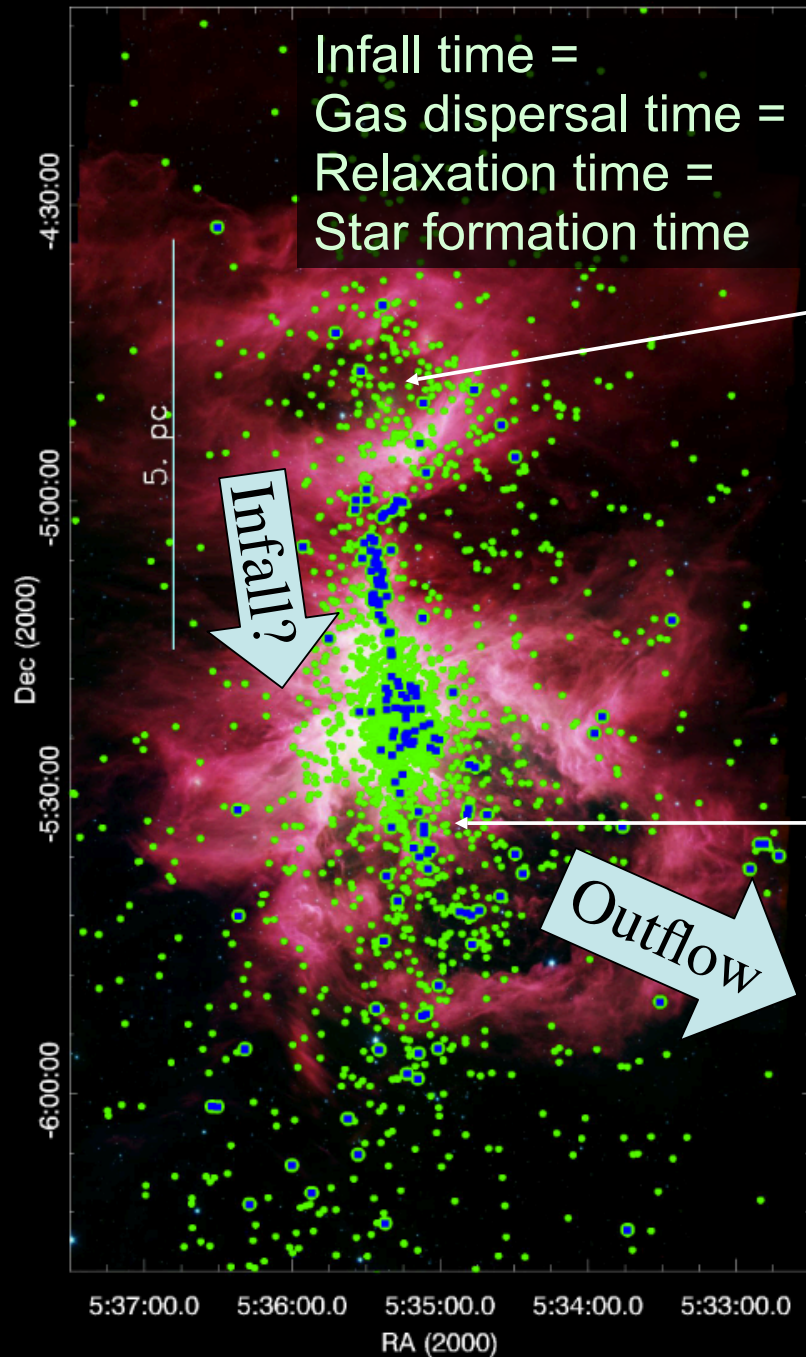
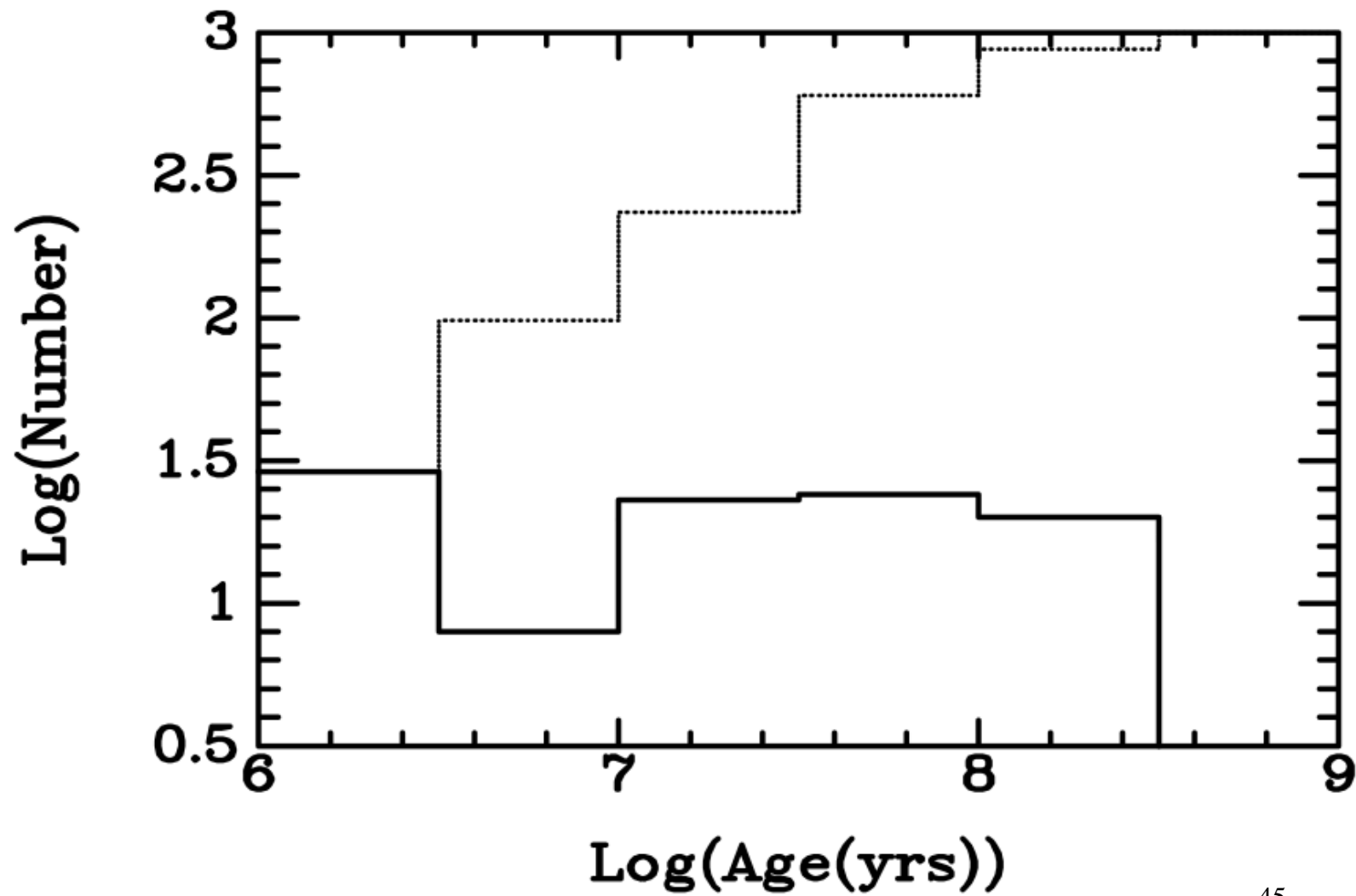


Image: IRAC 3.6, 4.5, 8 micron
Green dots – stars with disks
Blue dots: protostars

Dispersal of Embedded Clusters



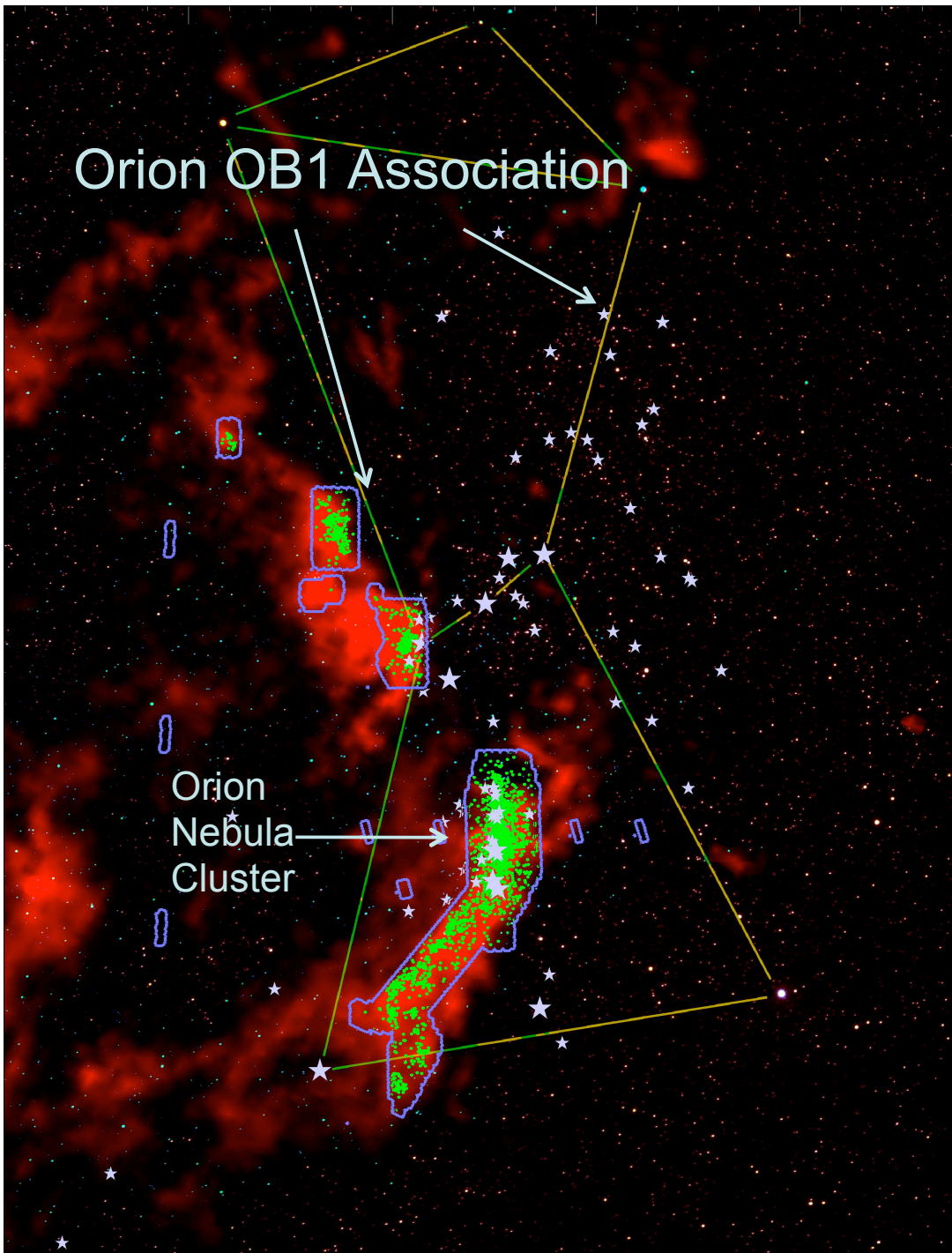
Orion OB1 Association

Orion
Nebula
Cluster

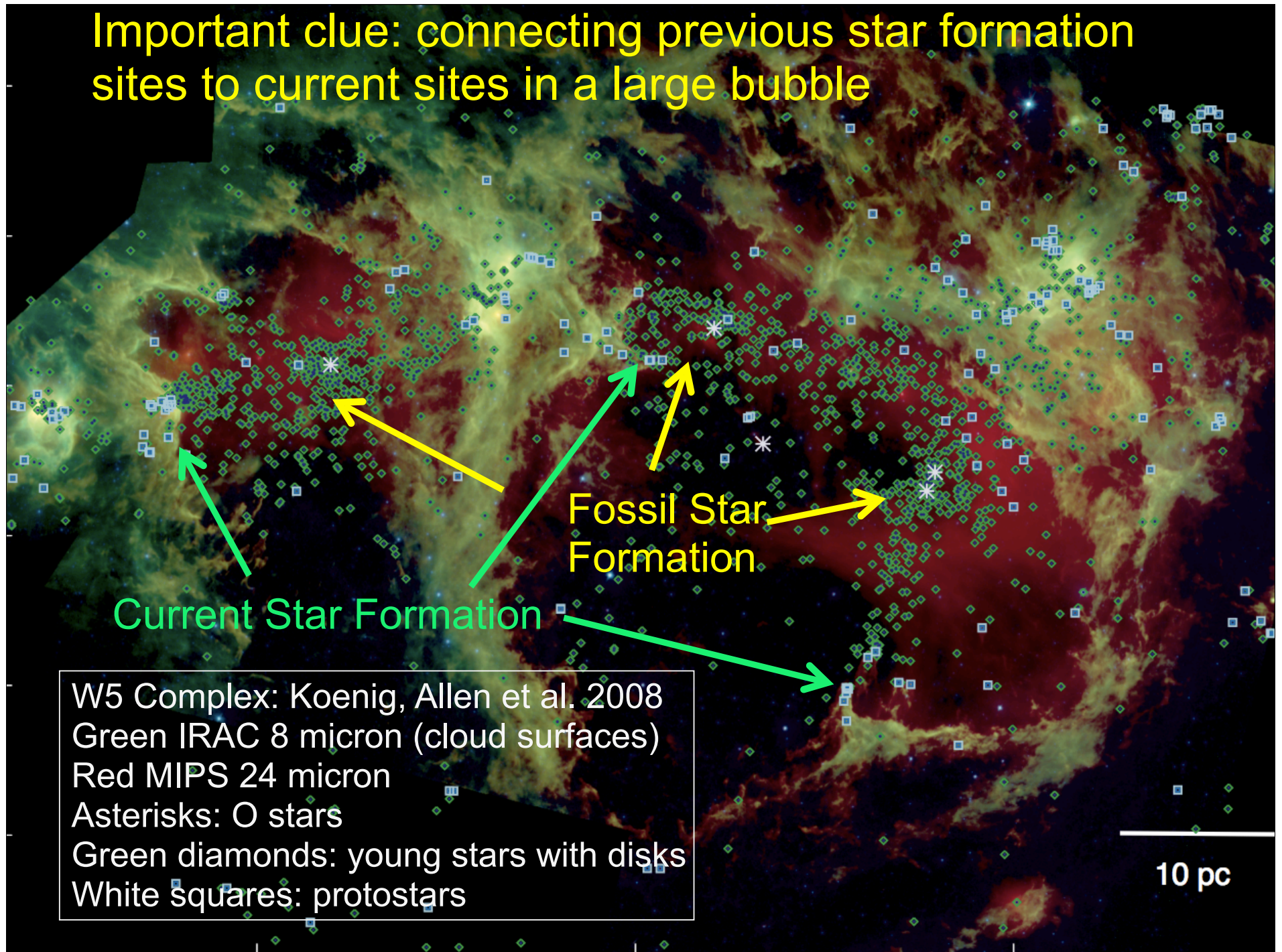
Associations vs Clusters

Associations are spatially extended regions where star formation is sustained over 5-10 Myr periods.

Open clusters probably form from embedded clusters within associations.



Important clue: connecting previous star formation sites to current sites in a large bubble

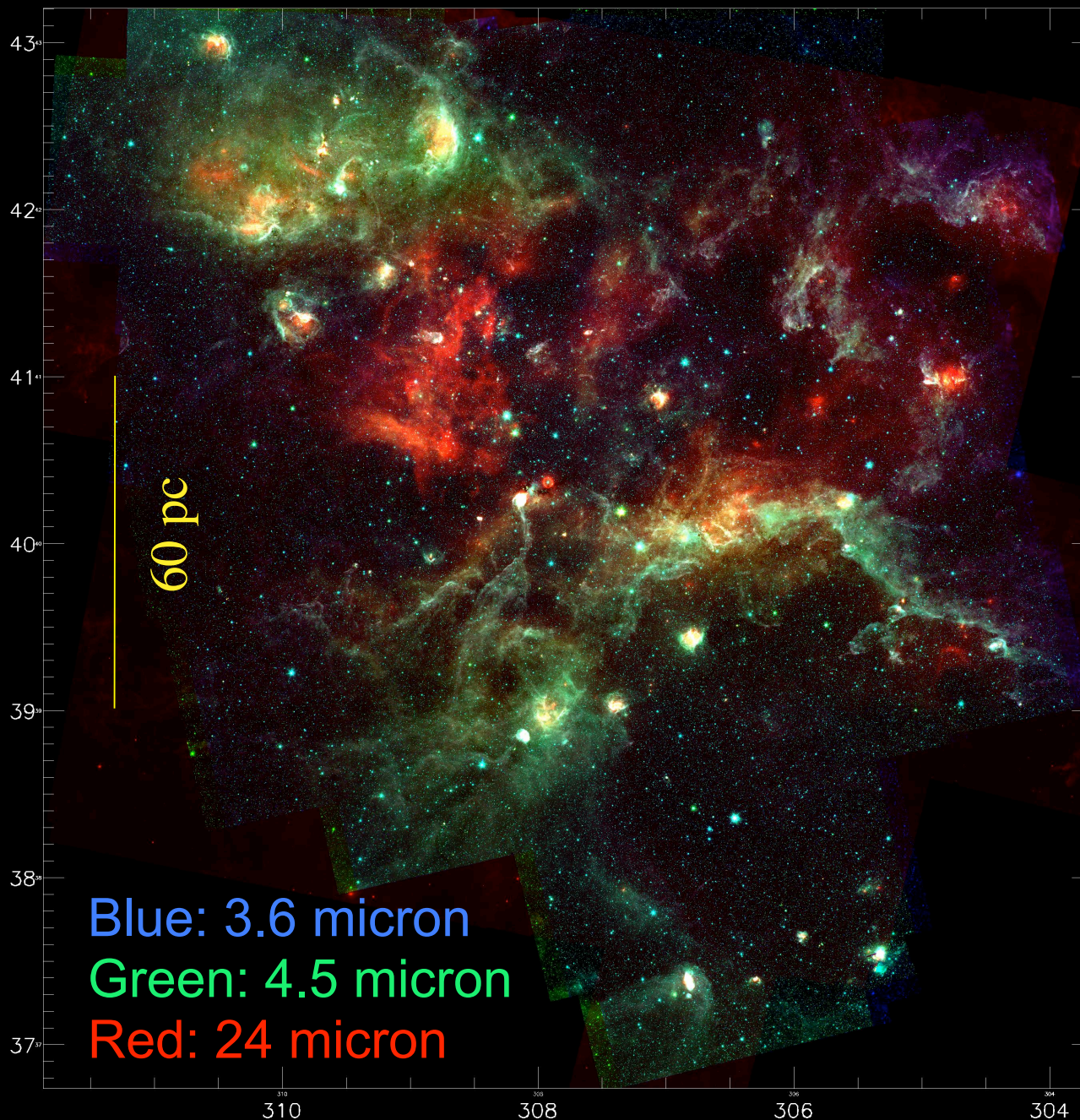


Cygnus-X Legacy Survey

Hora et al. in prep

Appears to be
a complex of star
forming regions at
1700 pc
(Schneider 2006).

Includes Cyg OB2,
with potentially
100 O stars
(Knodlseder 2000).



Cygnus-X Legacy Survey

Green dots:
15600 YSOs
identified with
Spitzer

Age of Cyg OB2: 5 Myr
(Wright et al. 2010)

DR21/W75 a high
active regions of
ongoing star formation.

DR21/W75 (< 2 Myr)

Cyg OB2
~5 Myr

60 pc

Blue: 3.6 micron
Green: 4.5 micron
Red: 24 micron

310

308

306

304

43

42

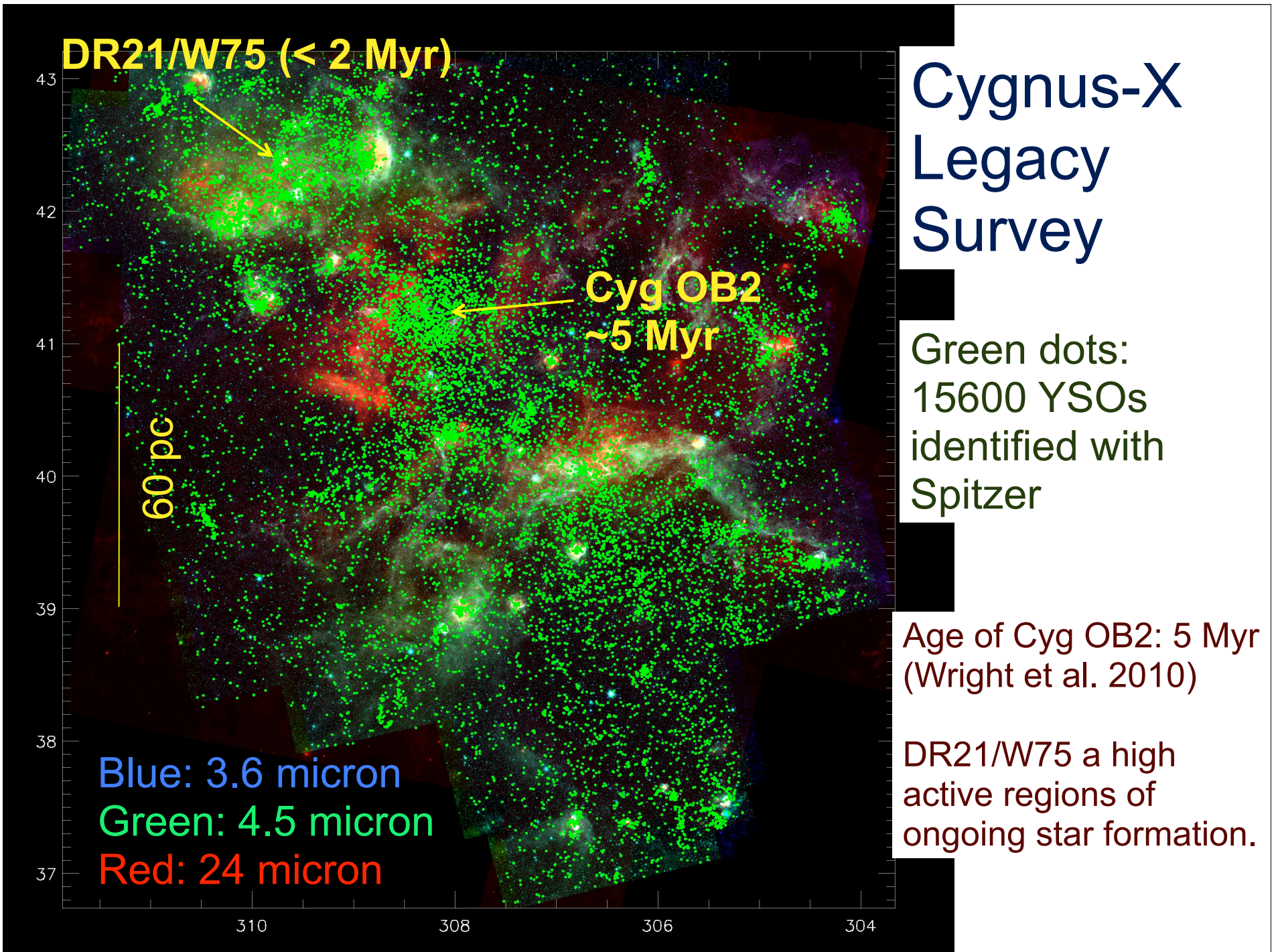
41

40

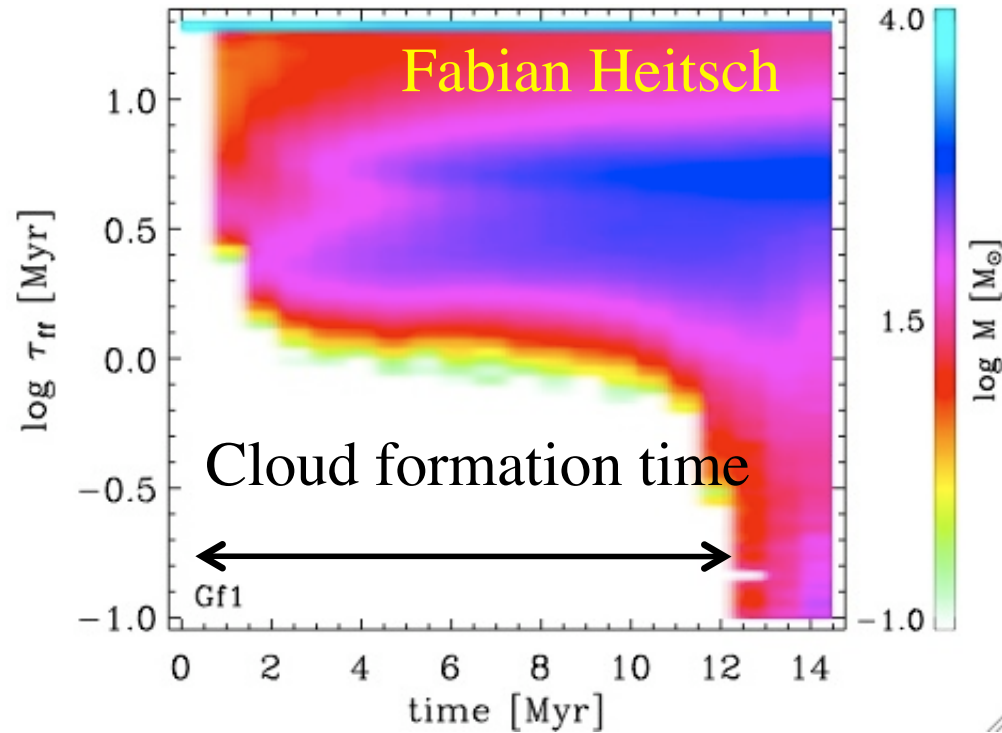
39

38

37



Colliding Flows



The formation of clouds in colliding flows has a 10 Myr timescale set by density of atomic ISM and velocities in ISM ($n_{\text{HI}} \sim 10 \text{ cm}^{-3}$, velocity = 10 kms^{-1}).

Can this cause an age dispersion of a similar magnitude?

Feedback from Supernova



Alternatively, is evolution set by supernova feedback shuffling and compressing low density gas.

An Emerging Picture?

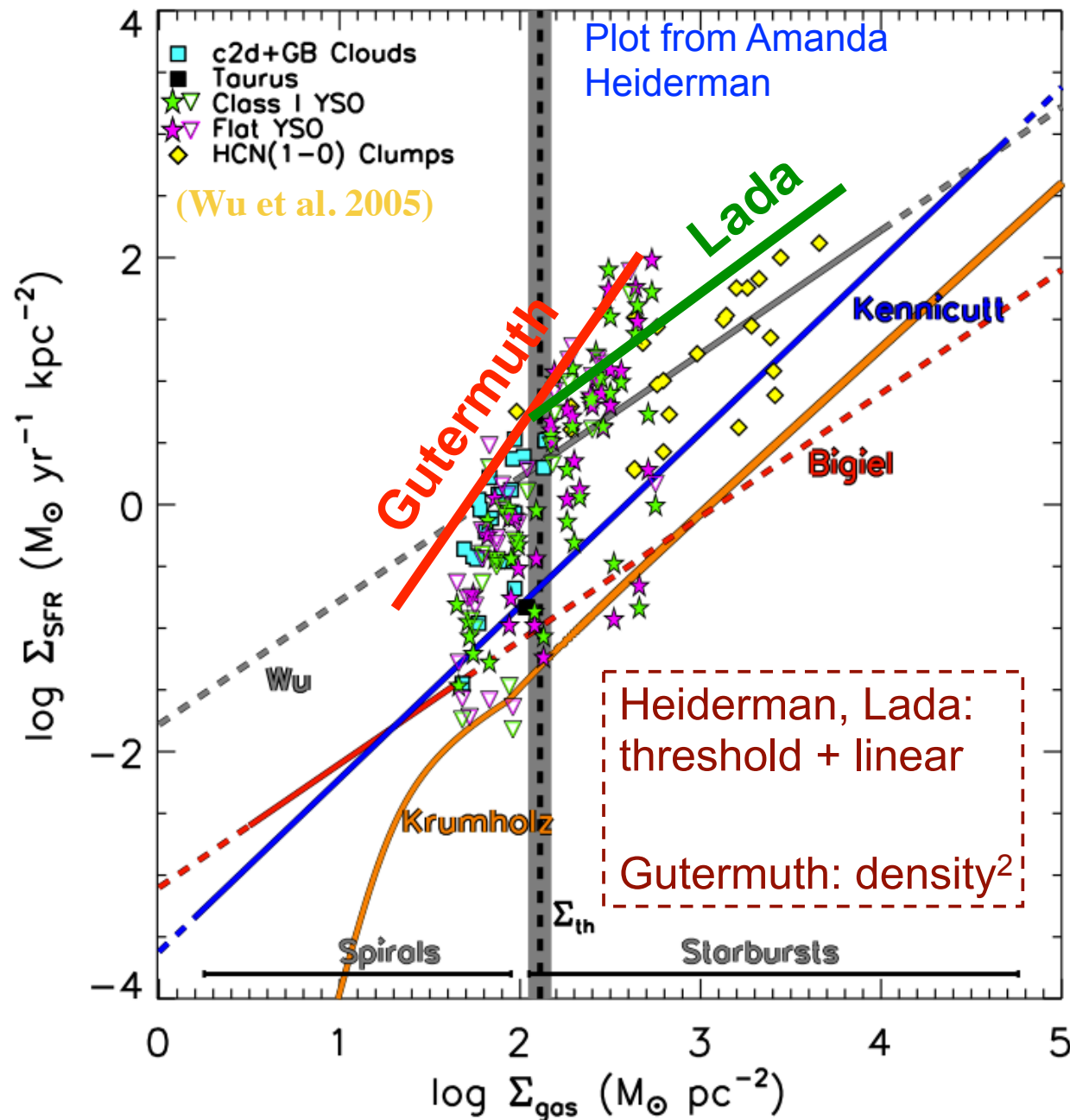
Formation of structured molecular clouds with $A_V > 1$

1. Low mass star formation responds to the column density structure:
 - star formation rate per area proportional to gas column density²

Most of cloud at low column density => overall low star formation rate & efficiency

A small fraction (< 10%) of the cloud has high column density => regions with higher star formation rate & efficiency (i.e. clusters!!)

2. Initial mass function dependent on column density structure:
 - high mass stars form in high column density regions (i.e. clusters!!)
3. Multi-parsec scale collapse and infall may create extended regions of high column density regions => centrally condensed embedded clusters with high mass stars
4. Converging flows and/or sweeping of low density gas by SN/winds/HII regions sustains star formation in large complexes for 5-10 Myr



Star Formation Rate vs Column Density of Gas: the Power-law vs Threshold Controversy

Heiderman et al. submitted
 Lada et al. submitted
 Gutermuth et al. in prep.