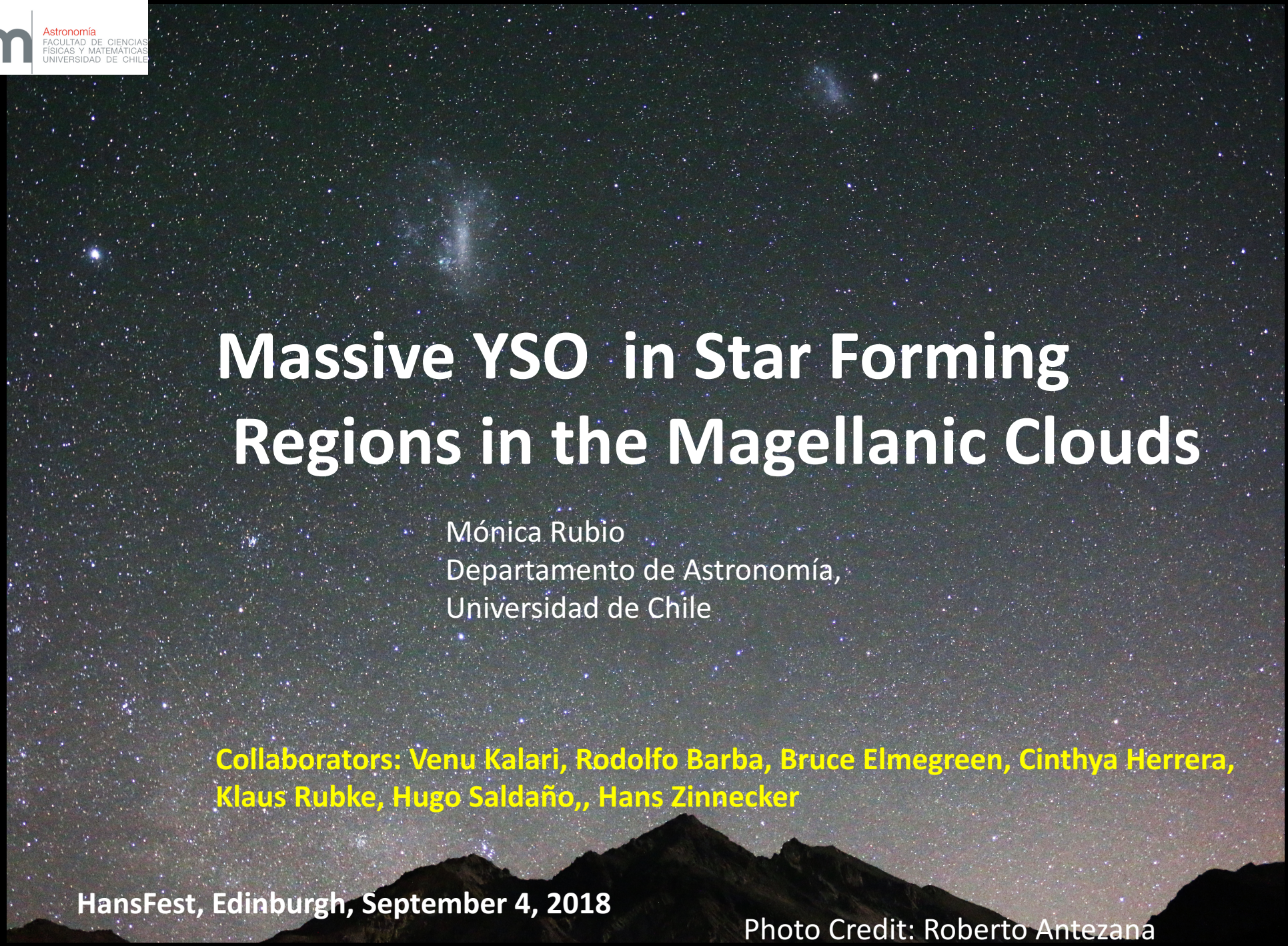

# Massive YSO in Star Forming Regions in the Magellanic Clouds

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**Collaborators: Venu Kalari, Rodolfo Barba, Bruce Elmegreen, Cinthya Herrera, Klaus Rubke, Hugo Saldaño,, Hans Zinnecker**

**HansFest, Edinburgh, September 4, 2018**

Photo Credit: Roberto Antezana

# Outline

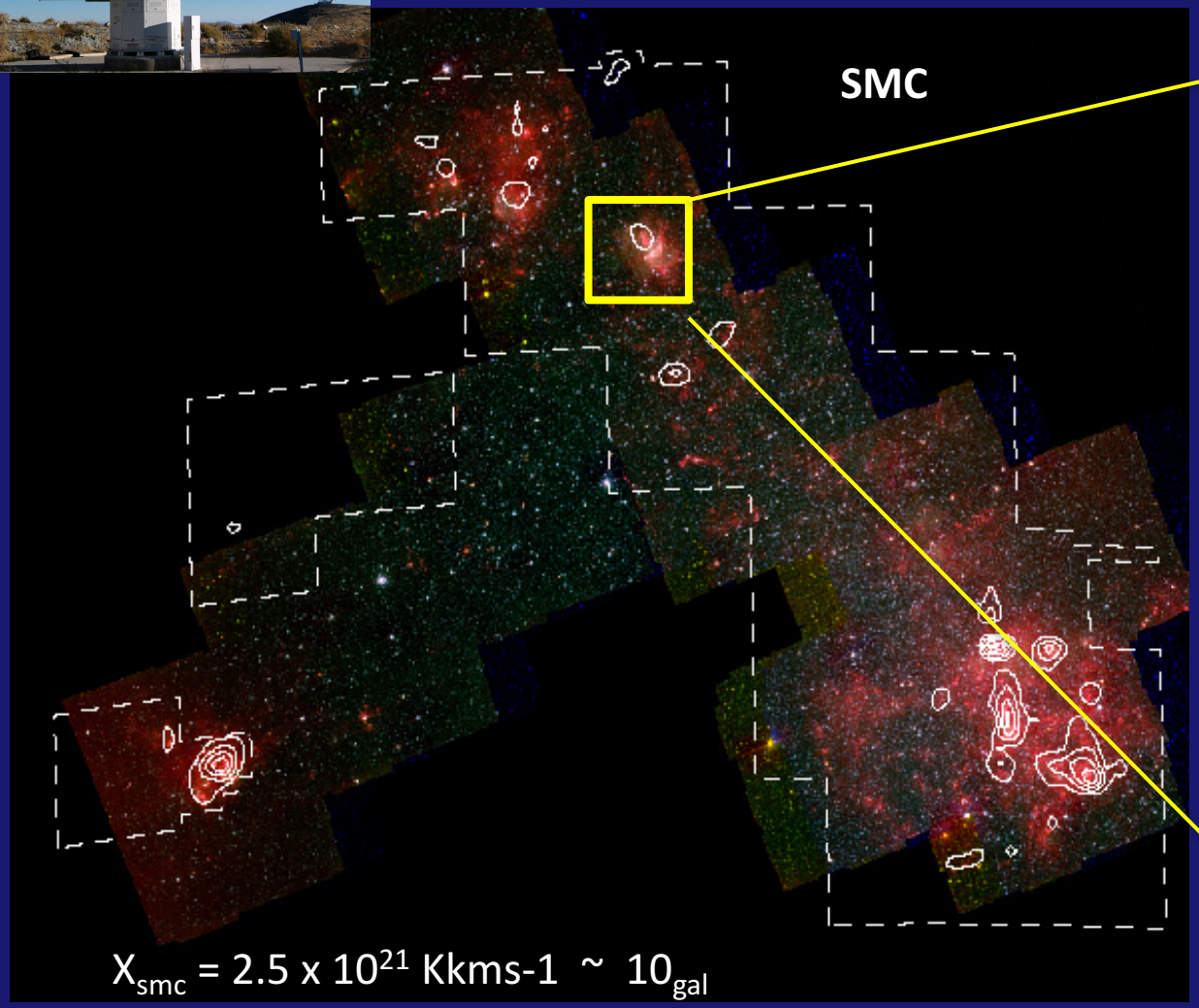
- The Large and Small Magellanic Clouds are regions of current star formation.

- Focus on
- - N66 in the Small Magellanic Cloud
- - 30 Doradus in the Large Magellanic Cloud

- Multiple populations- “two-stage starburst” (Walborn & Parker 1992) in 30 Doradus

- Sequential star formation N66 (Rubio et al 2000)

# CO in the Small Magellanic Clouds


$M(H_2)$ = 4.6 x $10^{6}$ Mo

Mizuno, Rubio et al. 2001

N66

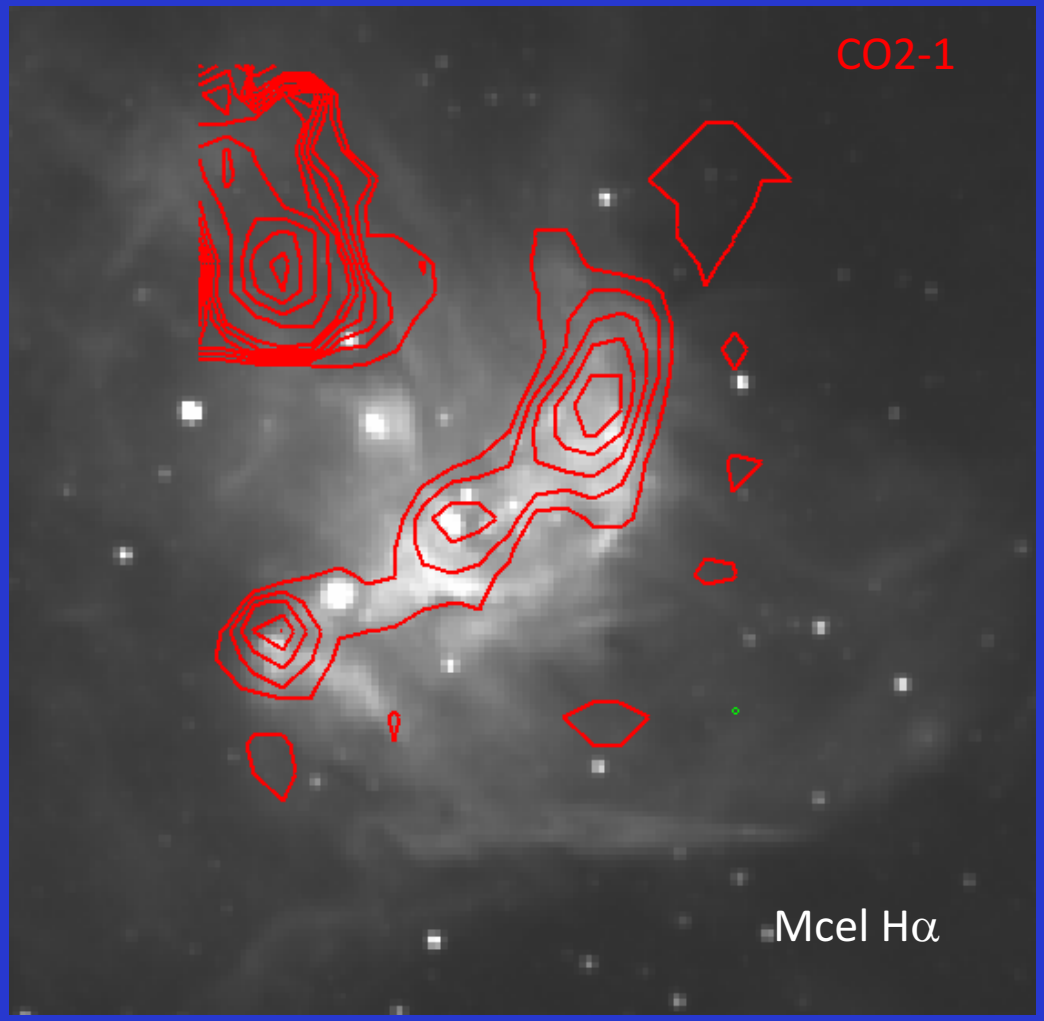
HST

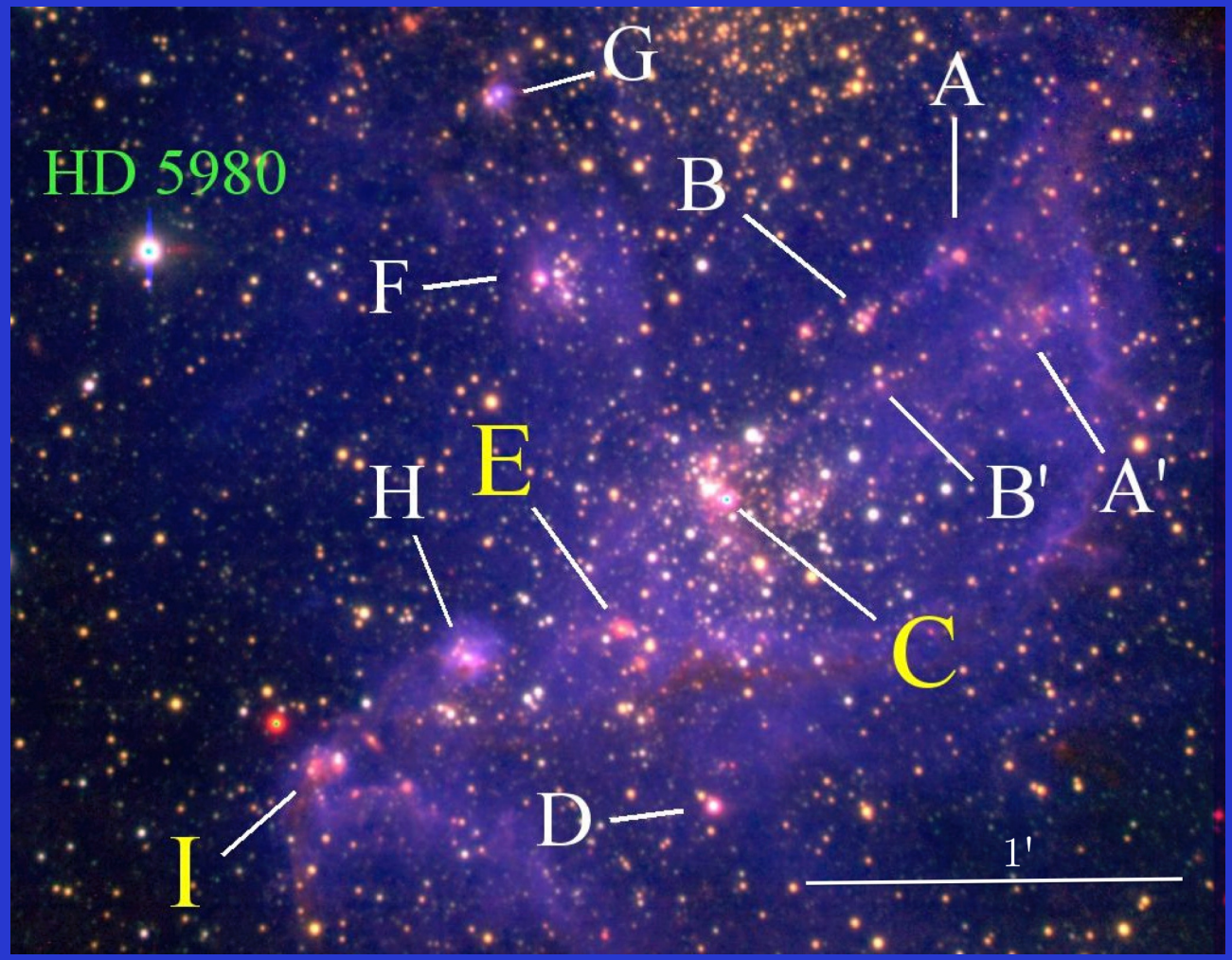
NGC346

33 O type Stars
11 Earlier O6

Massey et al. 1989

## CO in N66




Rubio et al. 2000.

$M \sim 10^3 - 10^4$ Mo

Labels: Contursi et al 2000

# NIR photometry of N66

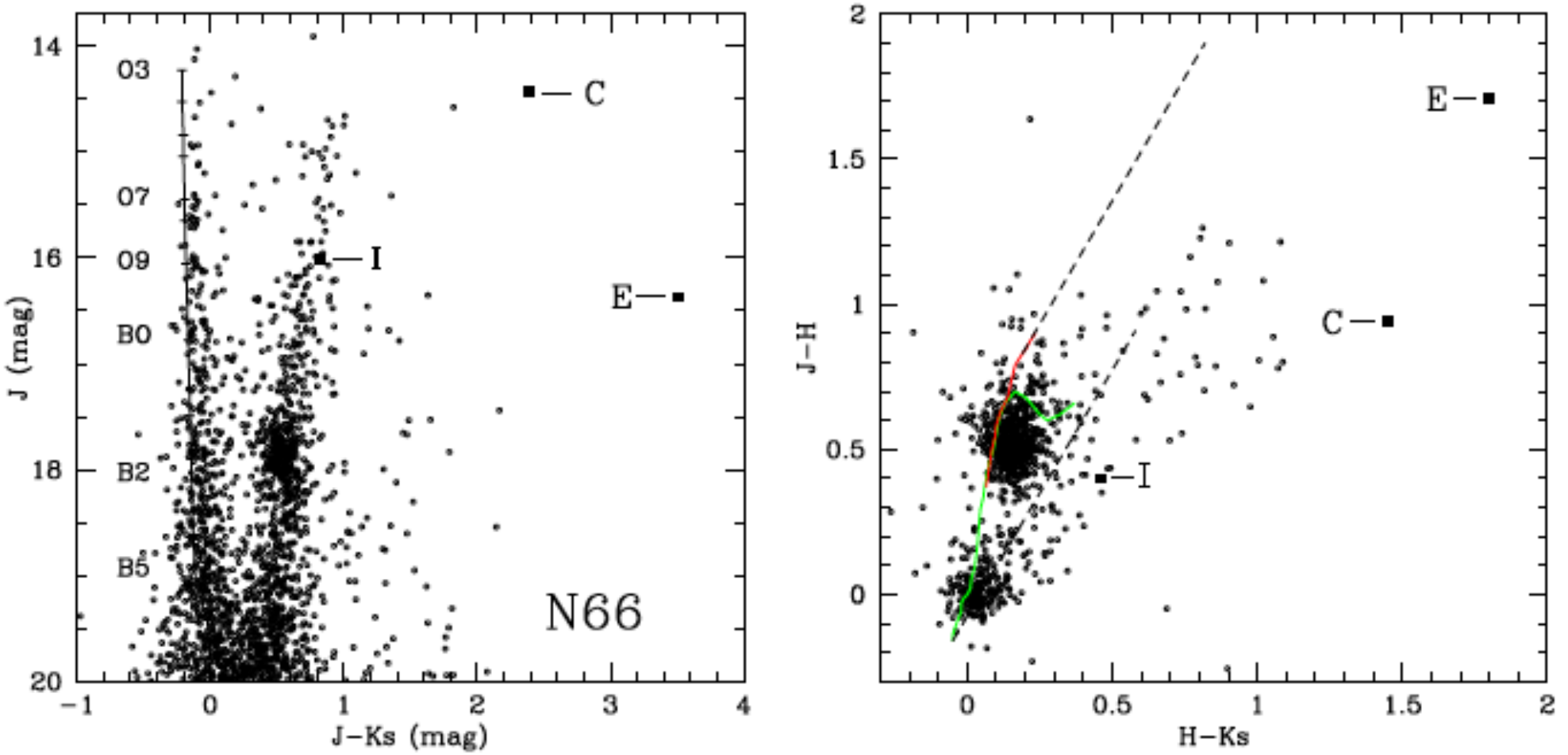
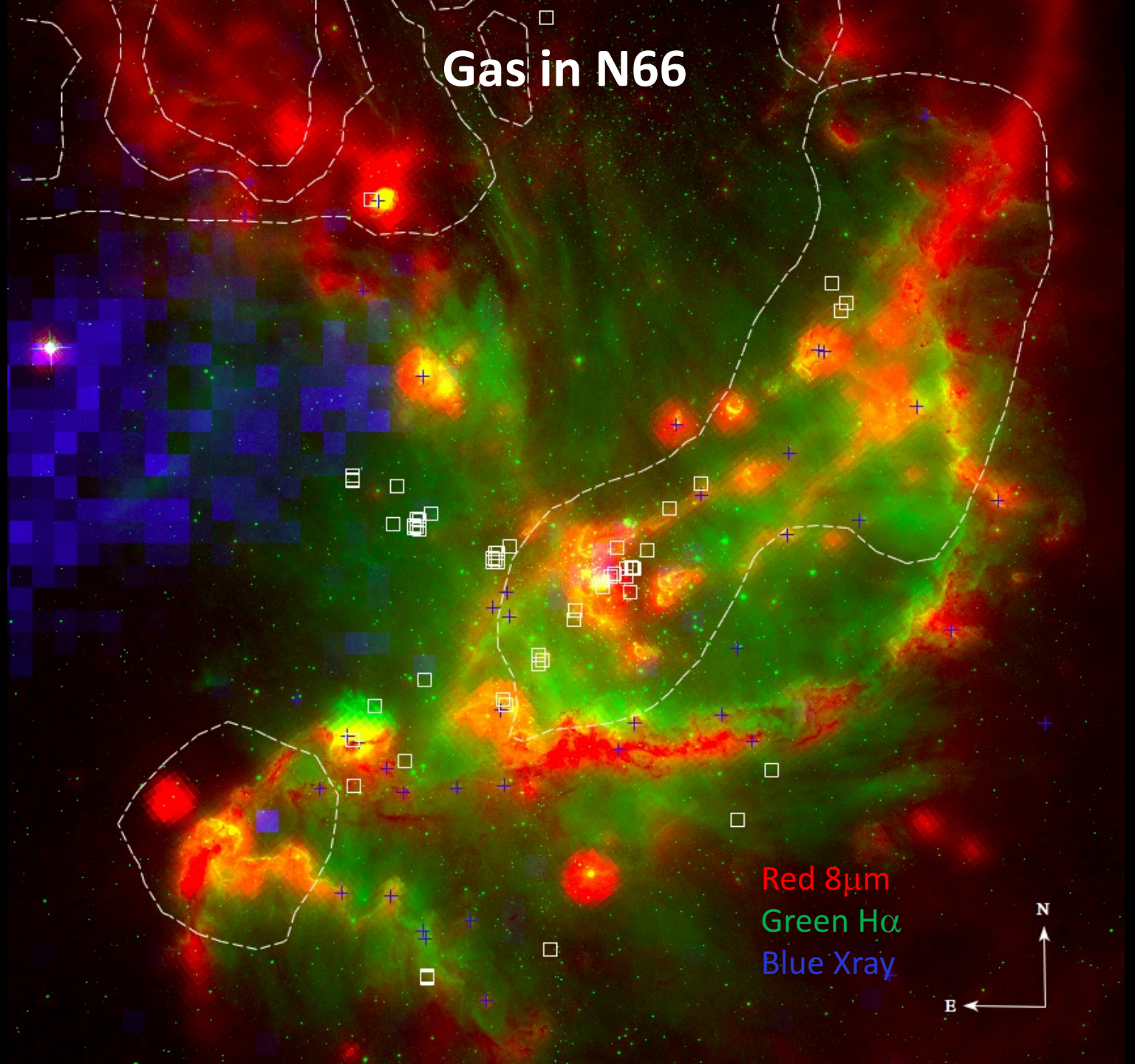


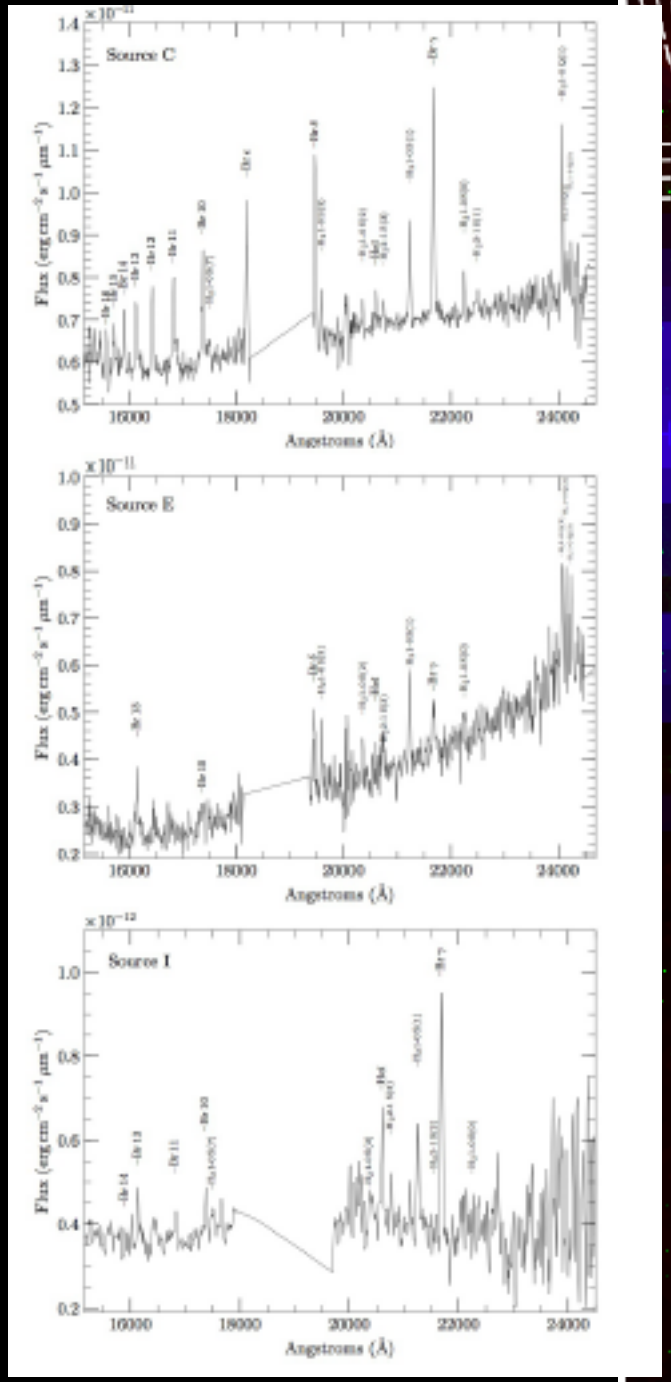

**Figure 2.** VLT/ISAAC NIR color–magnitude and color–color diagrams of N66, with the positions of the selected sources marked. The three sources correspond to the the brightest infrared excess sources in their respective molecular clumps.

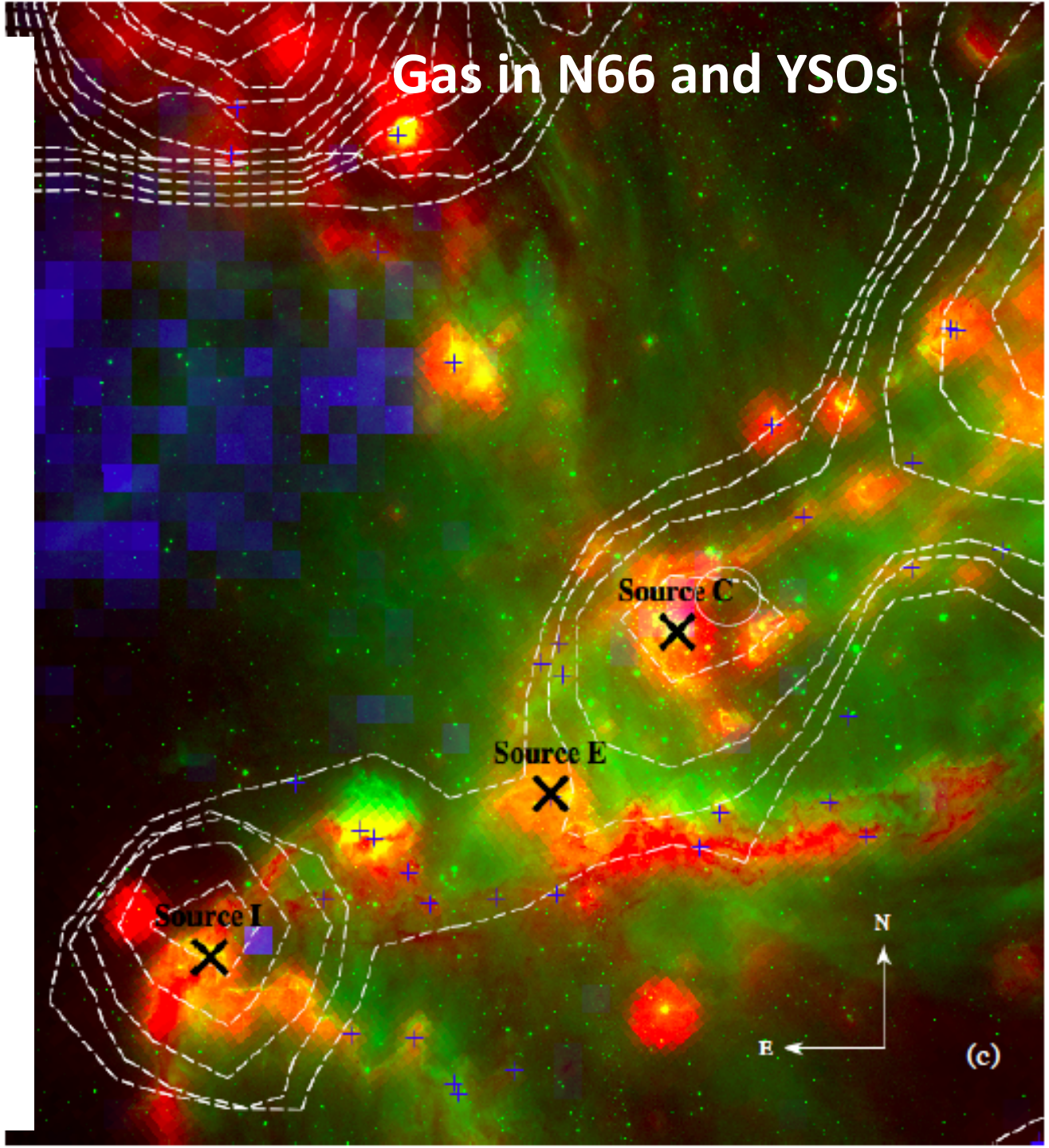
Rubio, Kalari & Barba 2018
Gouliermis et al 2006

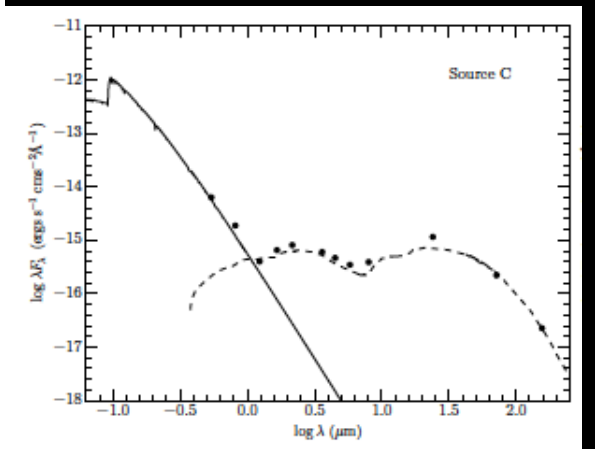
# Gas in N66

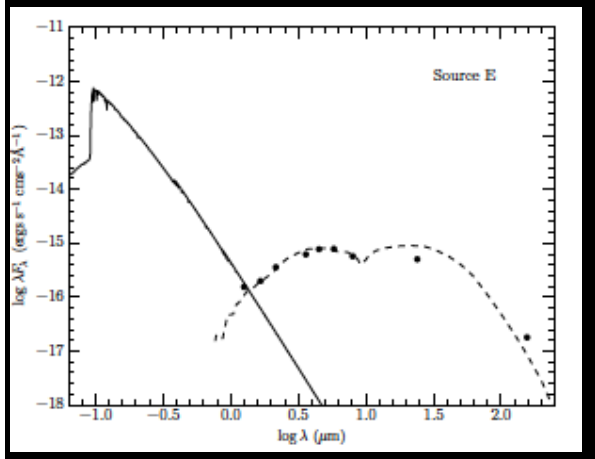


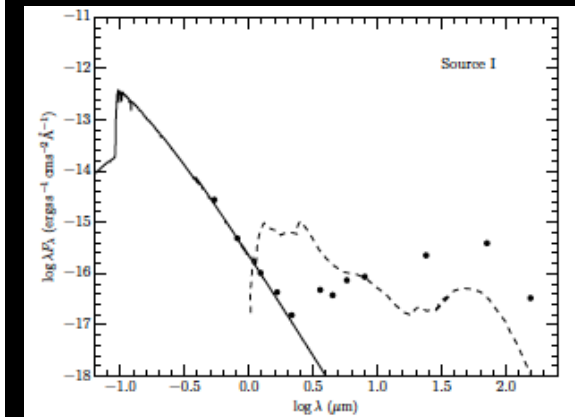
# Gas in N66 and YSOs



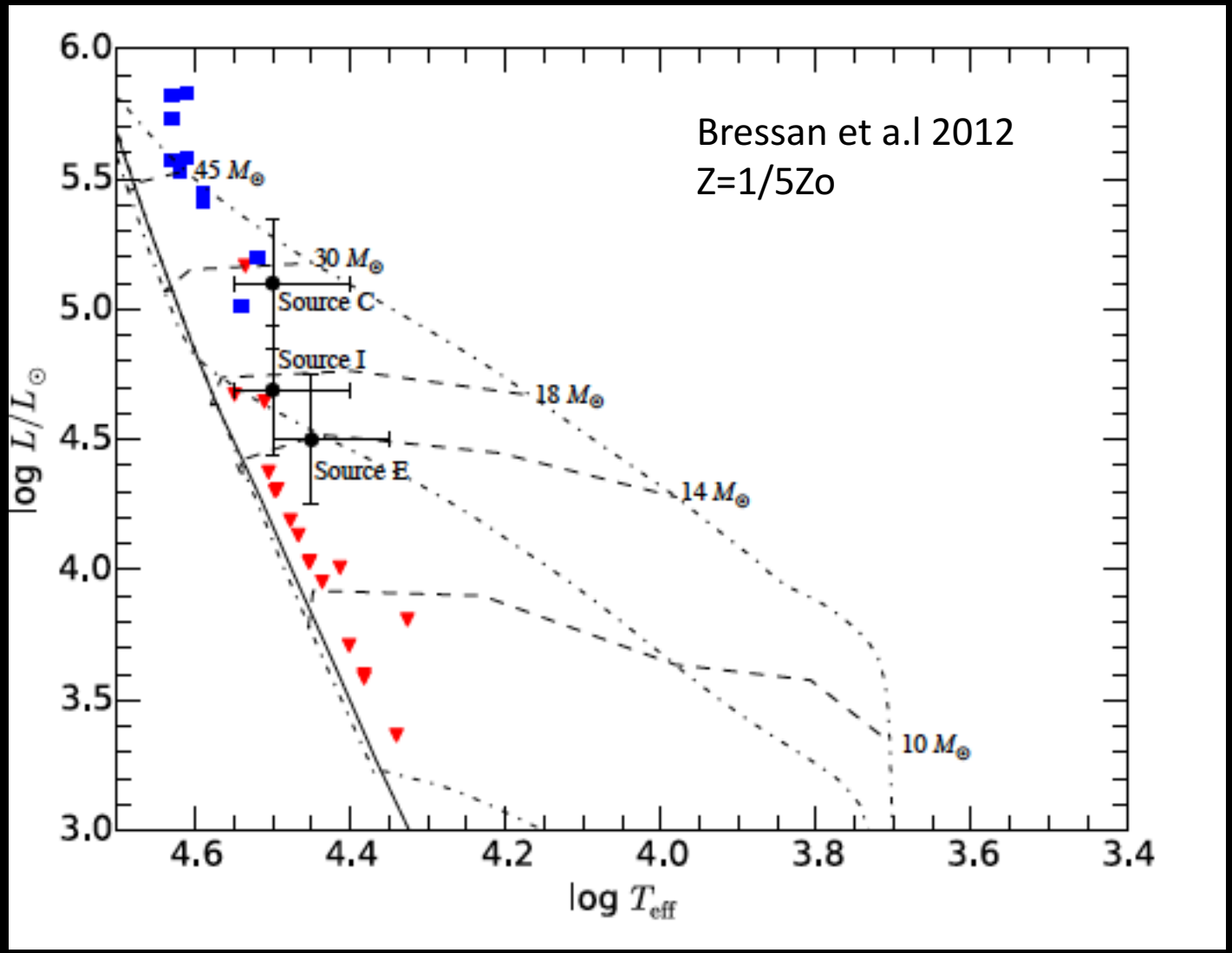



# A new generation of massive star associated to dense CO clouds




**Results**

**Source C: Late O to early B type star**
**Mass= 26.0 +- 0.5 Mo**

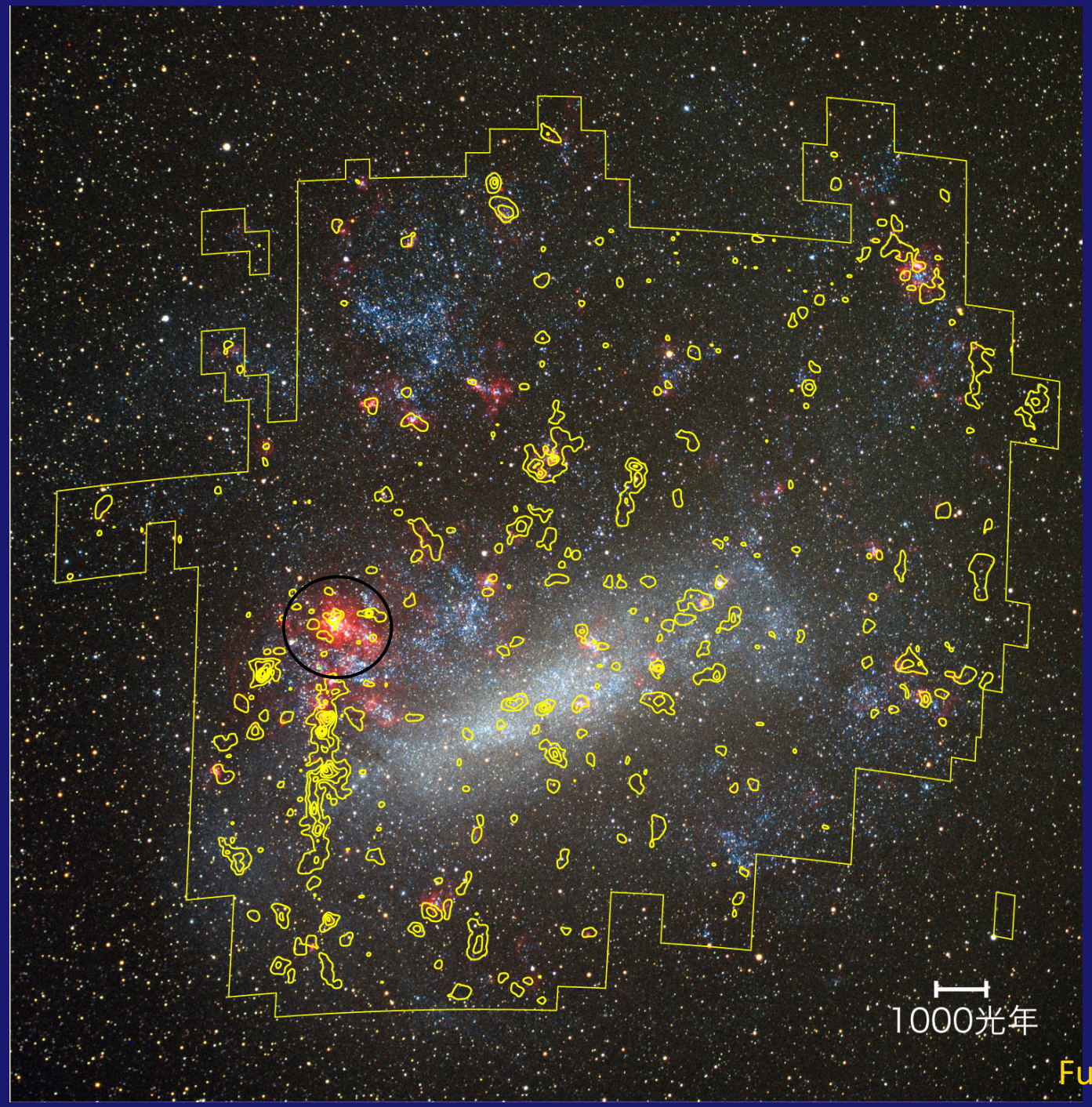
**Source E : B type**
**M= 19.7 +- 4.0 Mo**

**Source I, late O or early B star**
**M= 15.9 +- 3.0 Mo**

**Ages 10.000 to 50.000 years**

Rubio, Barba & Kalari 2018

LMC




CO gas

Fukui et al. 2008

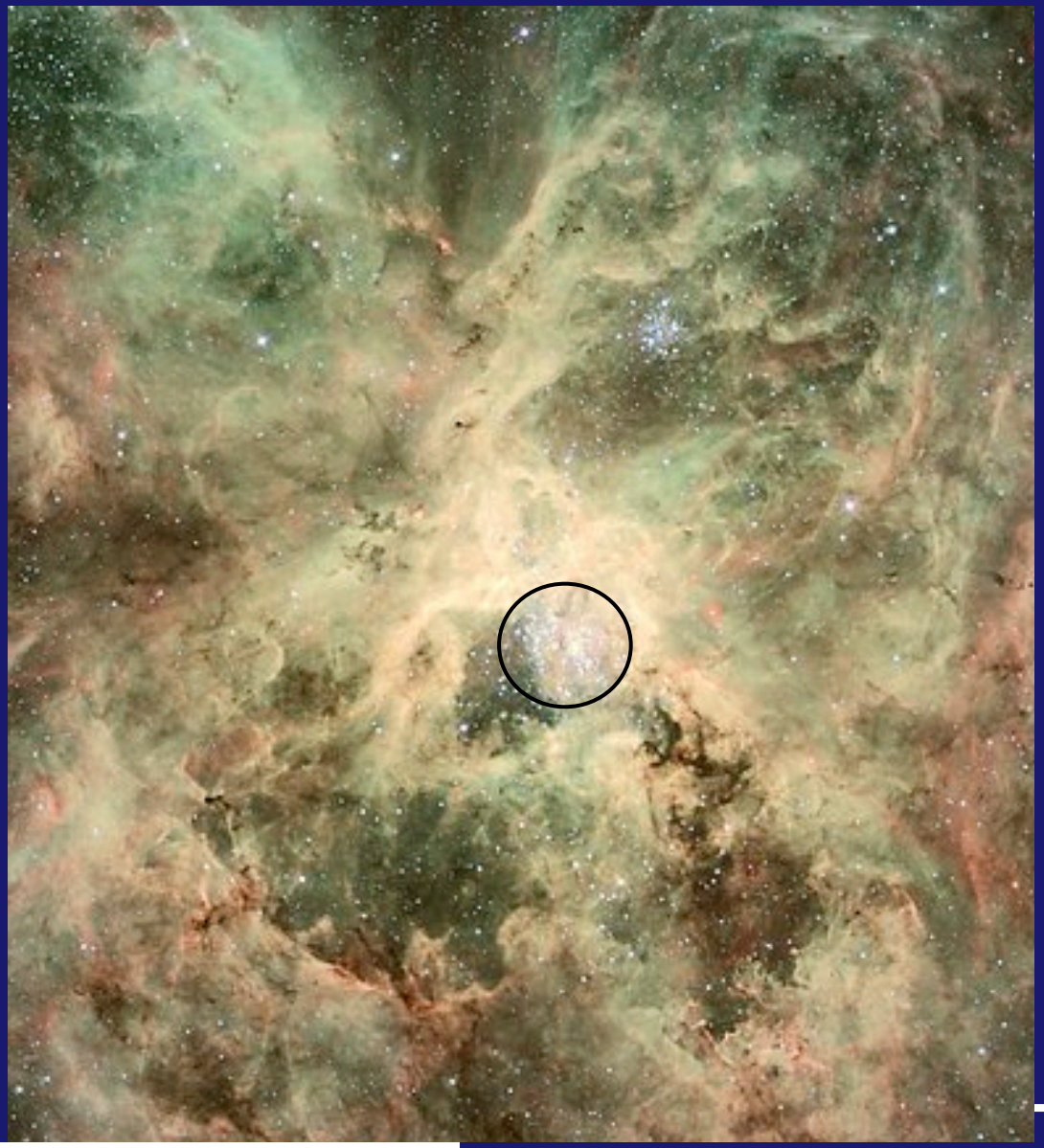
# 30 Doradus

Stellar mass M > $10^5$ Mo

Arc are ionized radiation

O,B stars ~ 2 Myr

Star formation thought to be triggered along arcs




30 Doradus- HII region ~ 200 pc

ESO/Alves, Vandame & Bialetski


## R136- Central cluster

<297 OB,WR stars

$0.5\text{-}1.3\text{x}10^5 \mathcal{M}_\odot$

$1.3\text{x}10^8 L_\odot$

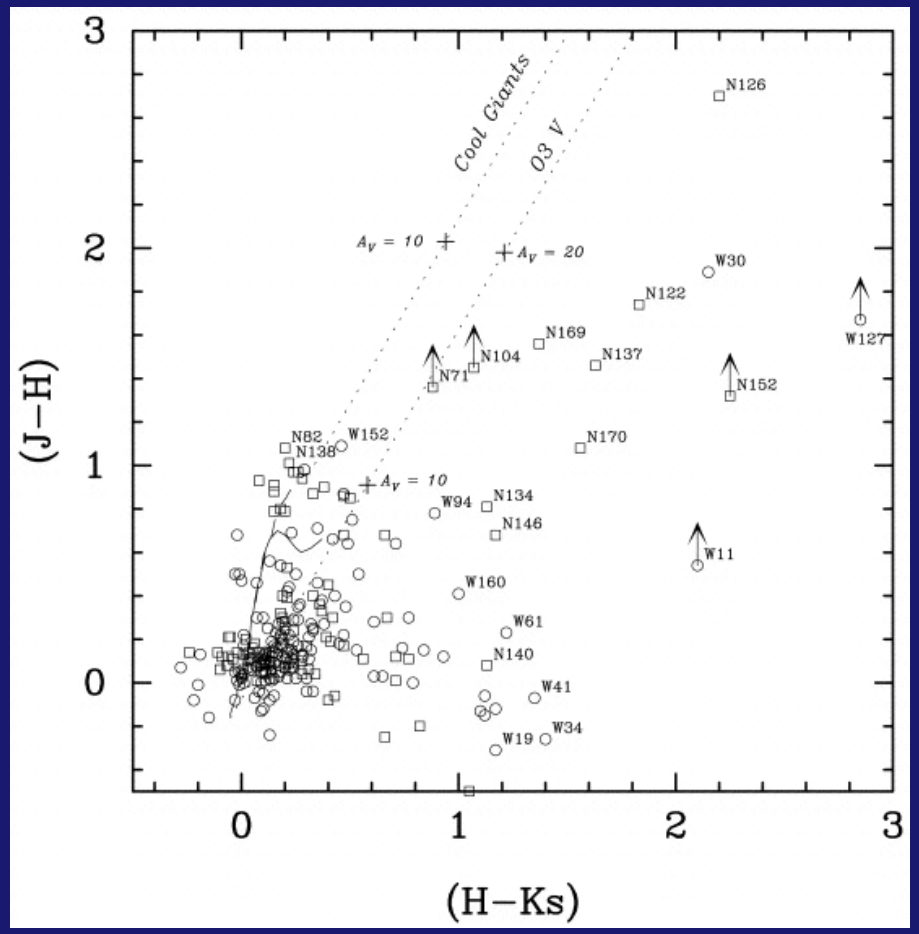
2 Myr

Within 10 pc

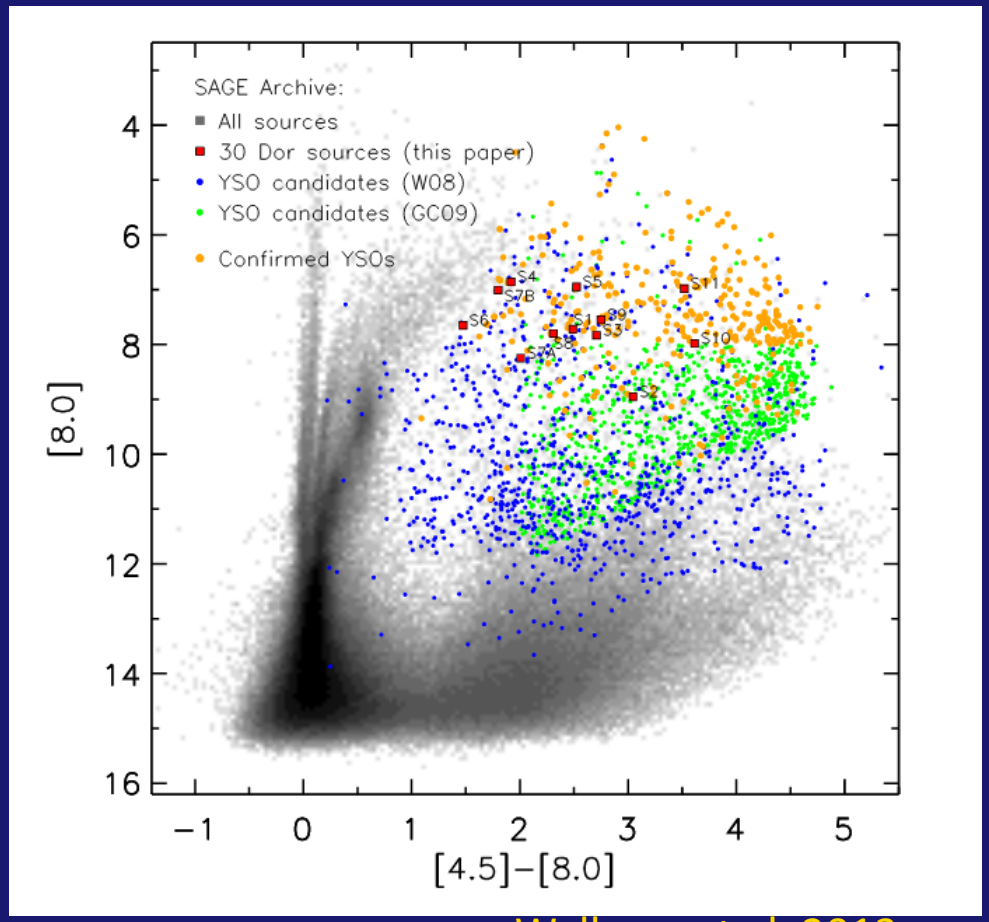
Selman & Melnick 2012

Doran+ 2013

# High-mass YSOs

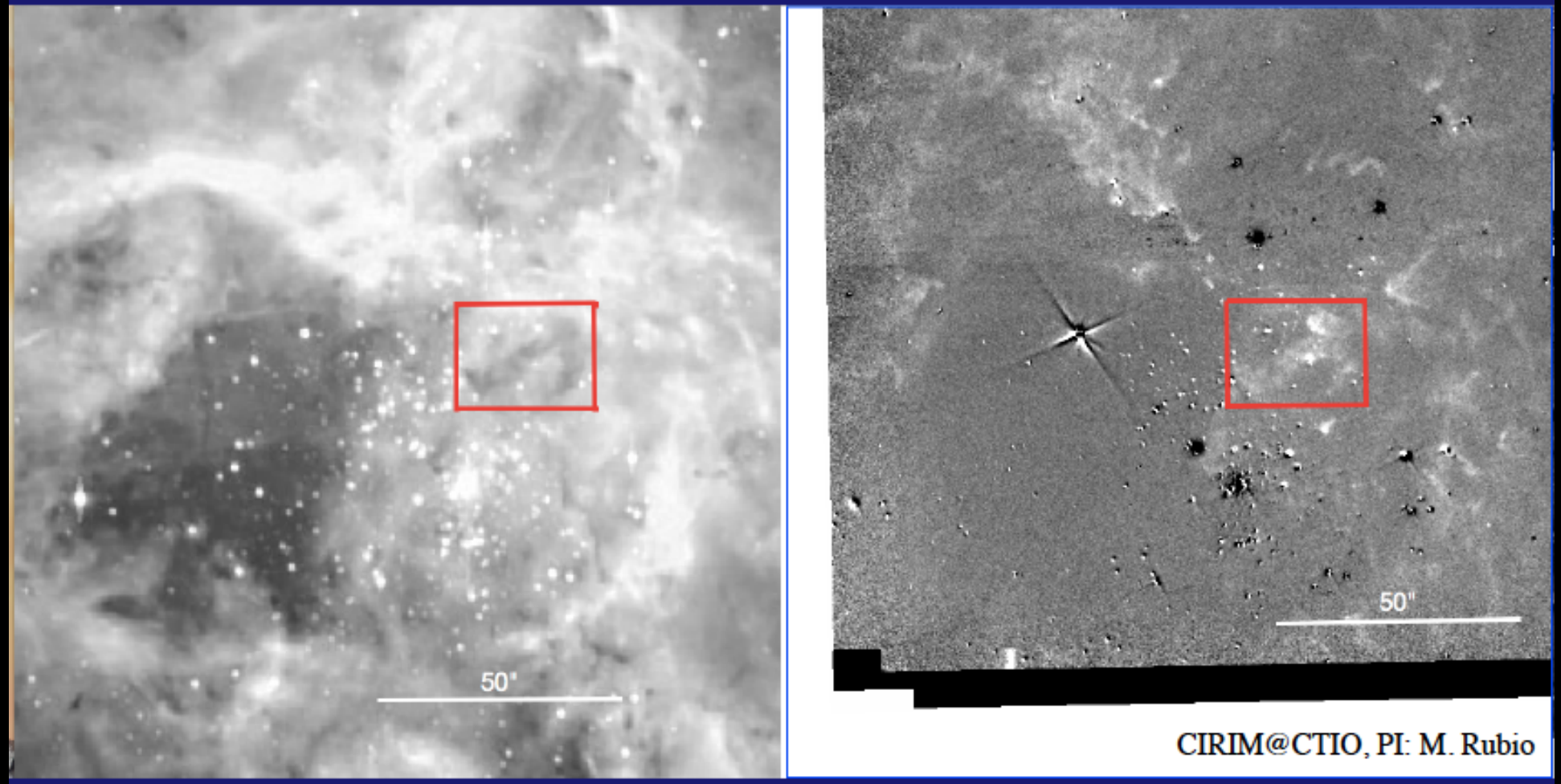



Rubio et al. 1998
NICMOS/HST NIR photometry




Walborn et al. 2013
Mssive yso form spitzer colors

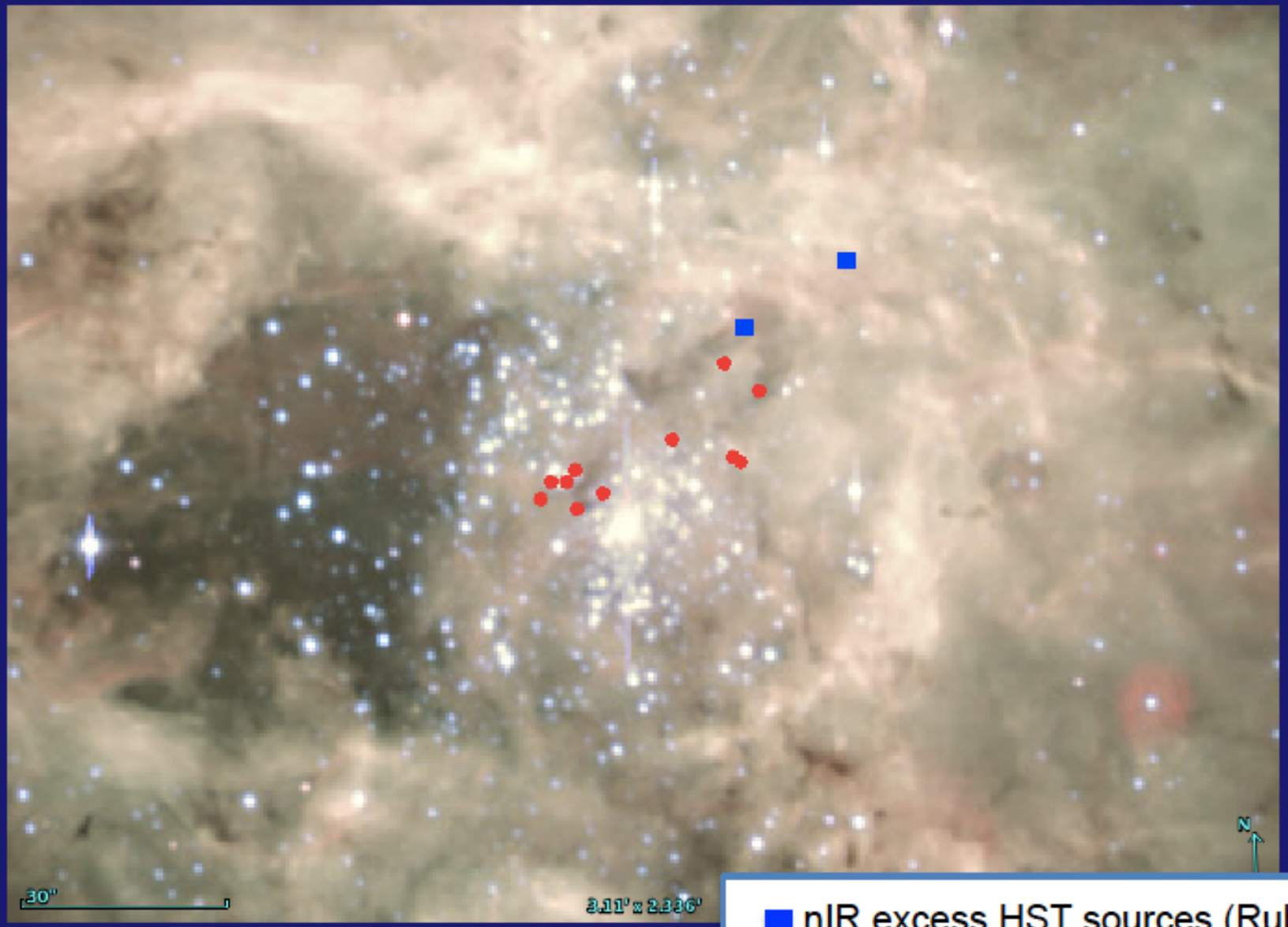
# Evidence of molecular gas near R136



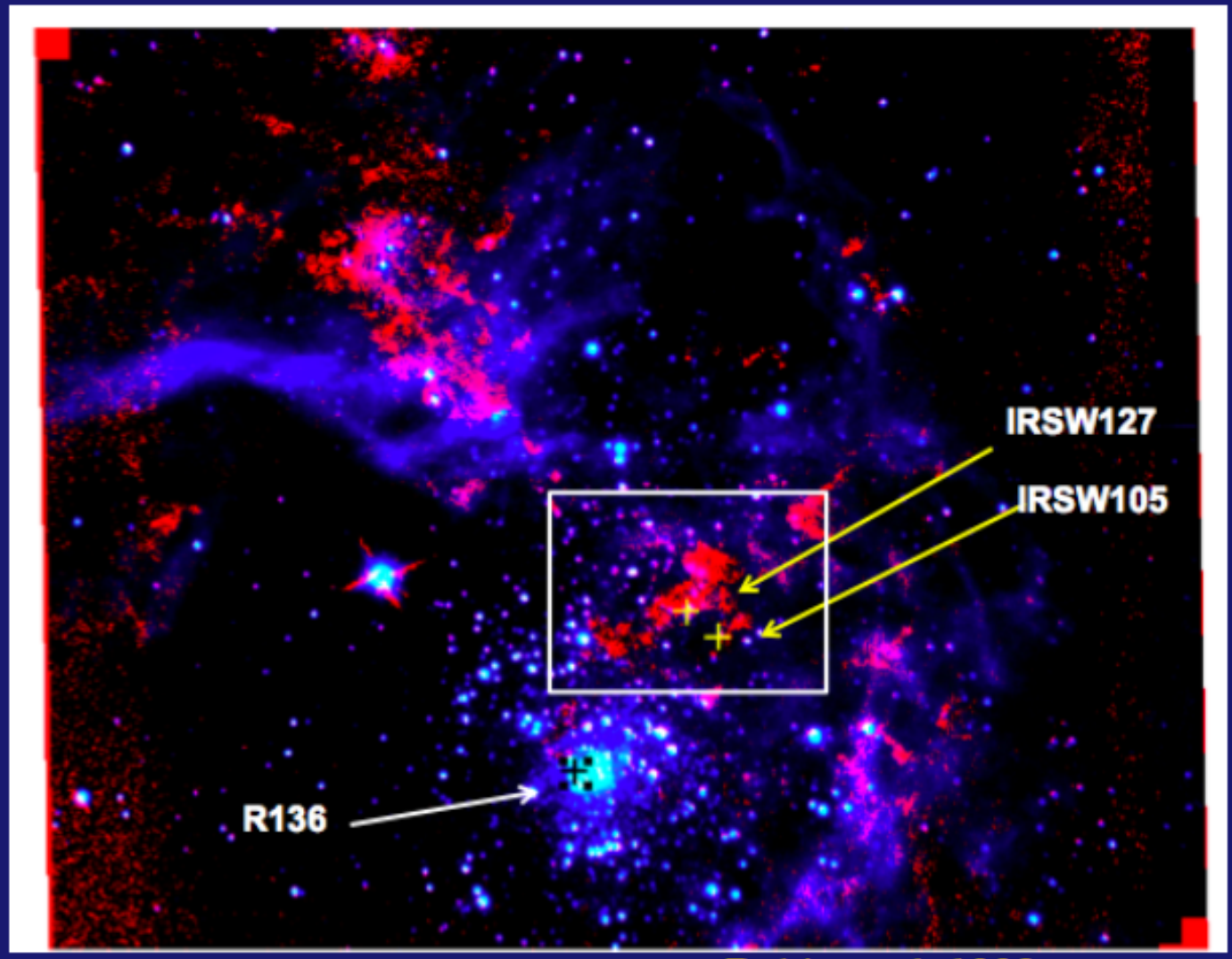

Optical

$H_2$ 2.12μm

# Is there evidence for ongoing star formation?



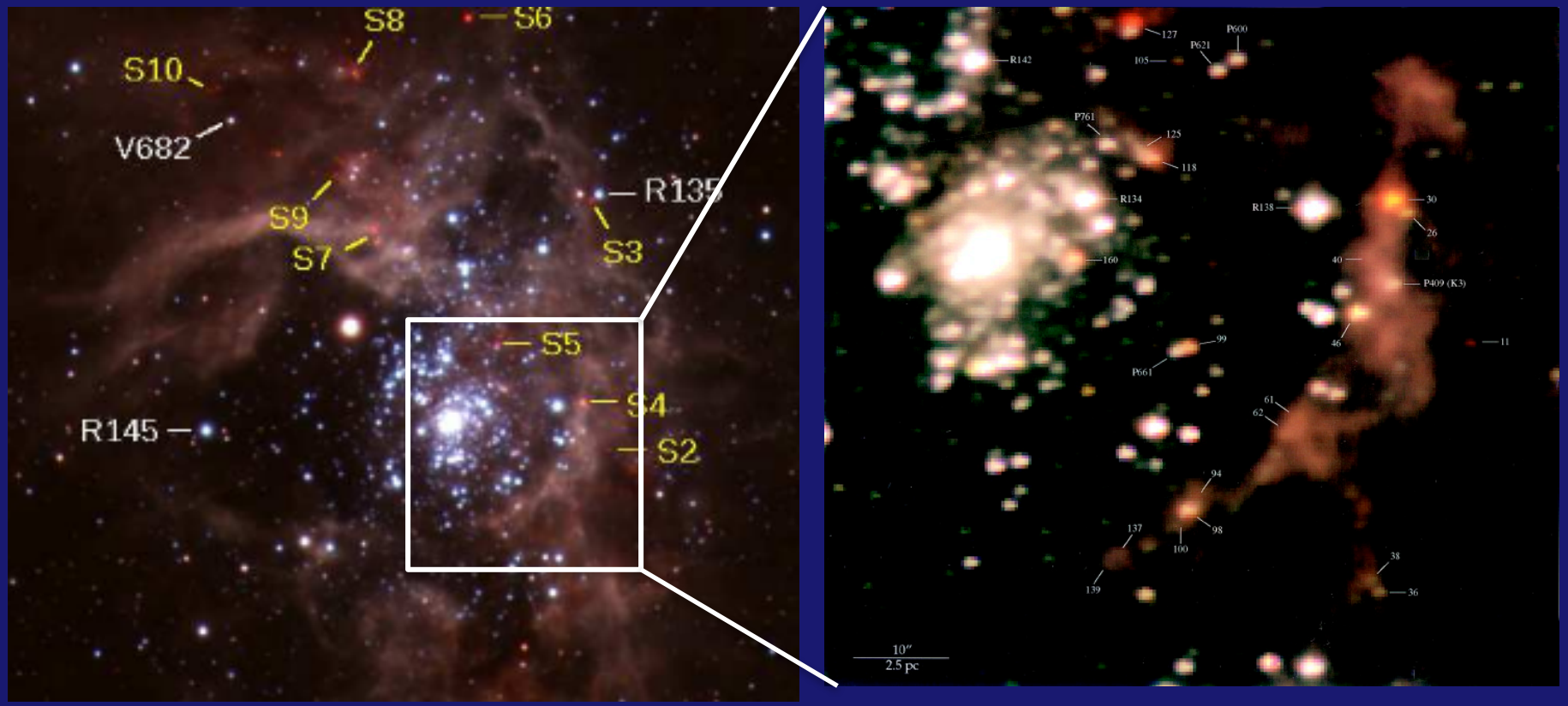
# 1. nIR excess sources




Rubio et al. 1998;
Rubio, Paron & Dubner 2009

SPITZER

HST/NICMOS

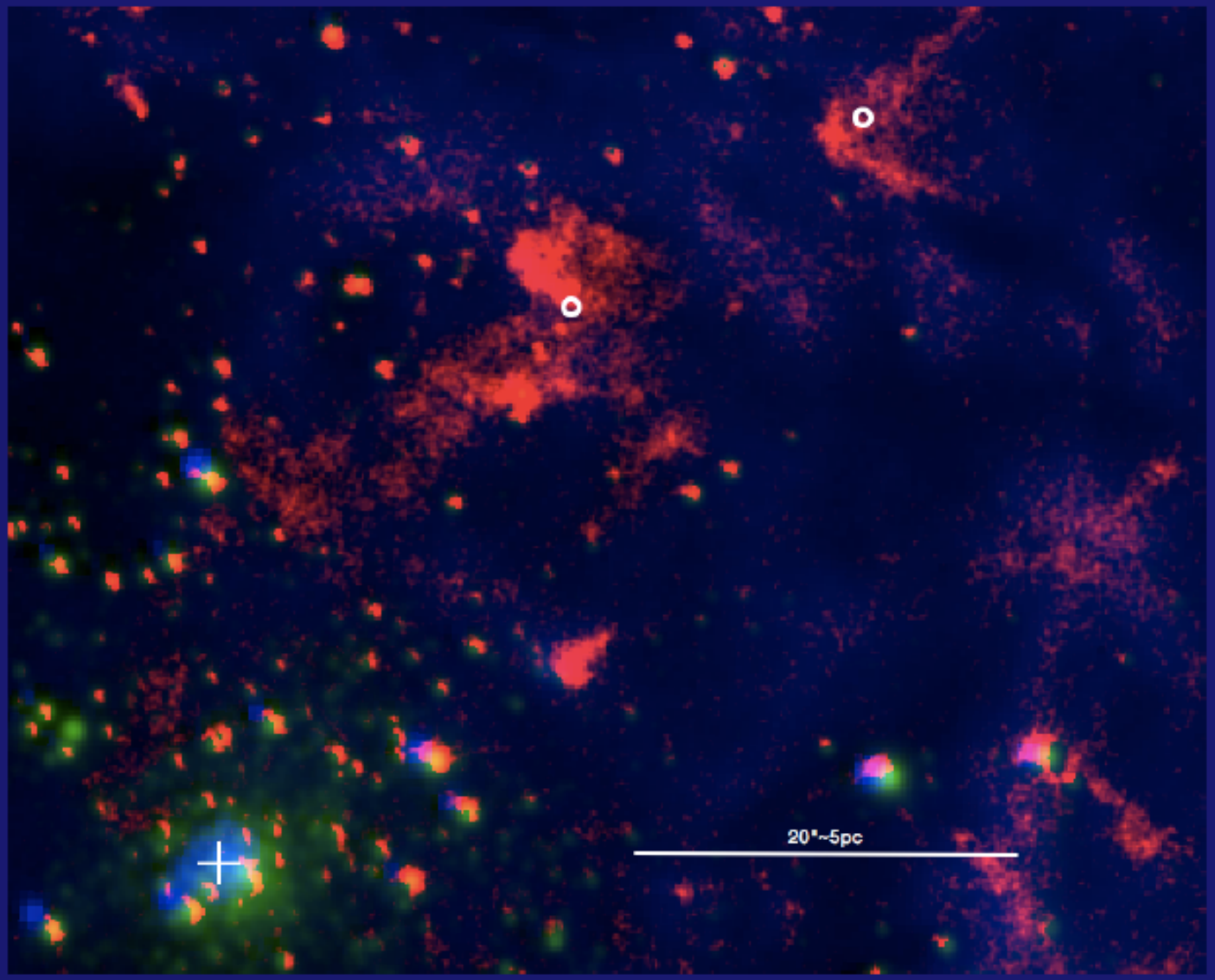


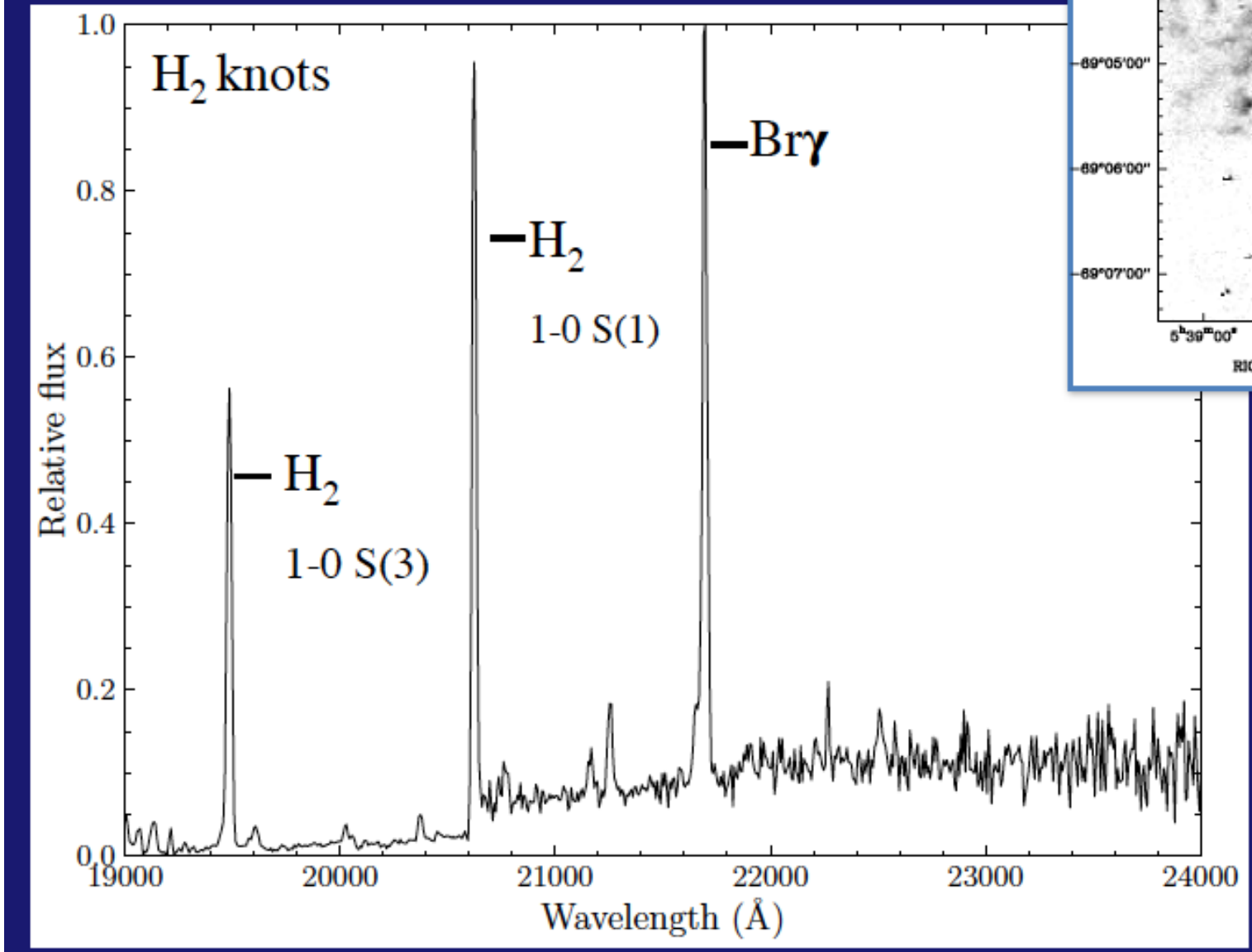

Walborn et al. 2013

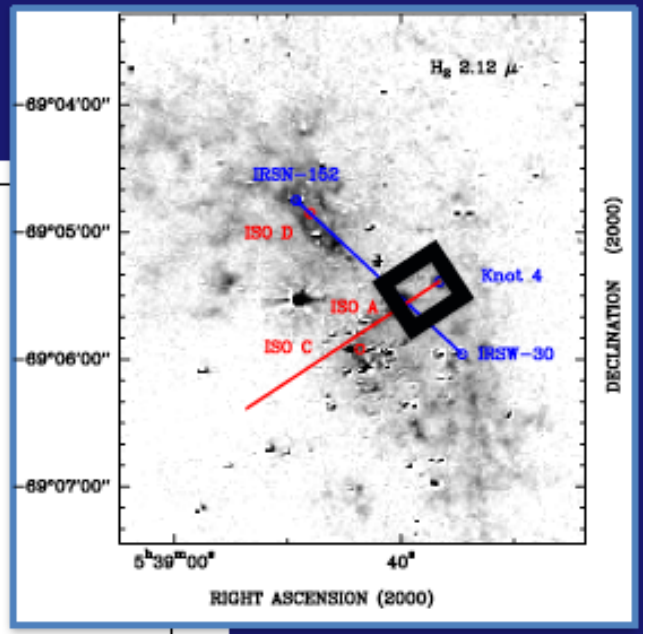
Rubio et al. 1998

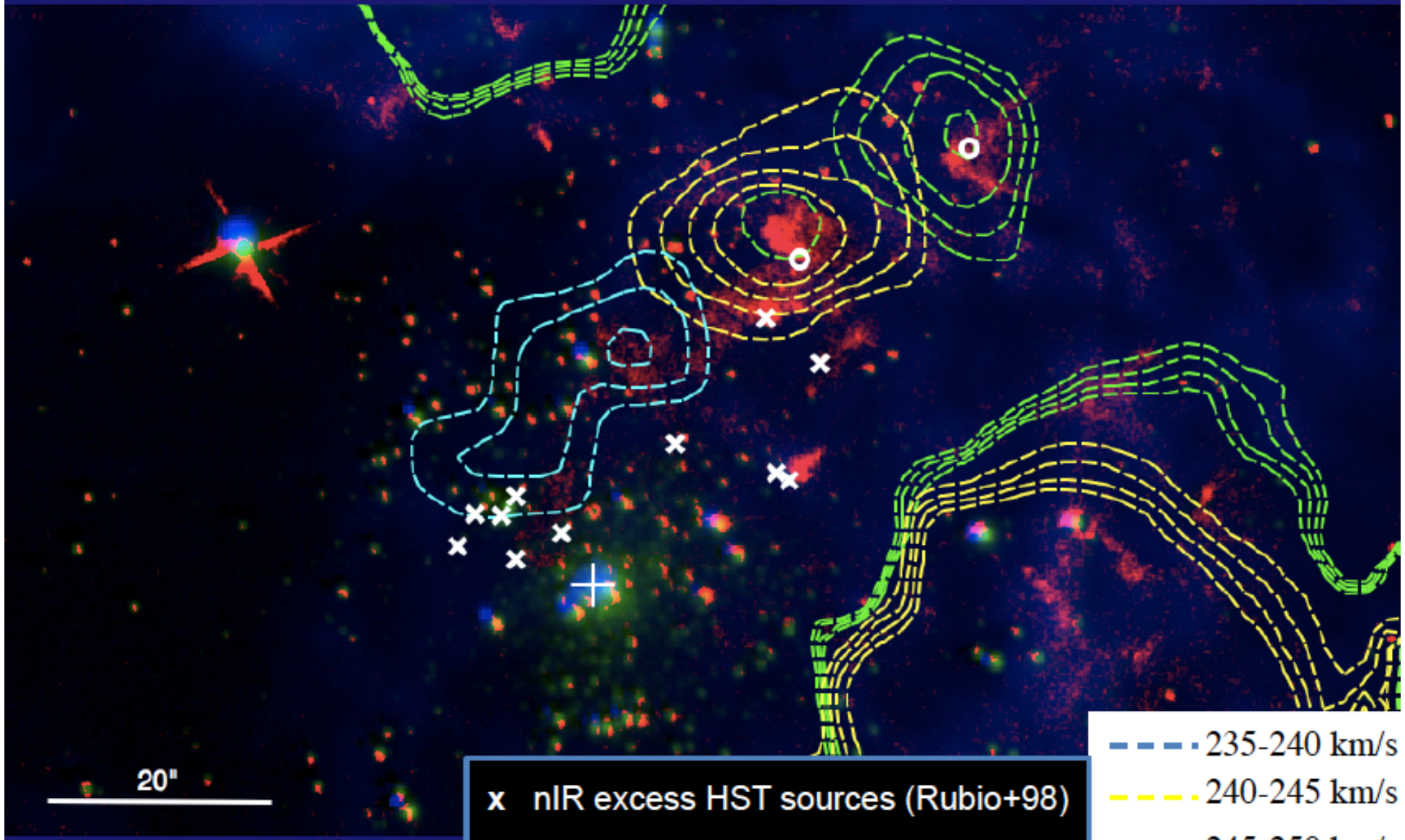

Walborn, Barba & Sewilo 2013

# 2. MIR excess sources

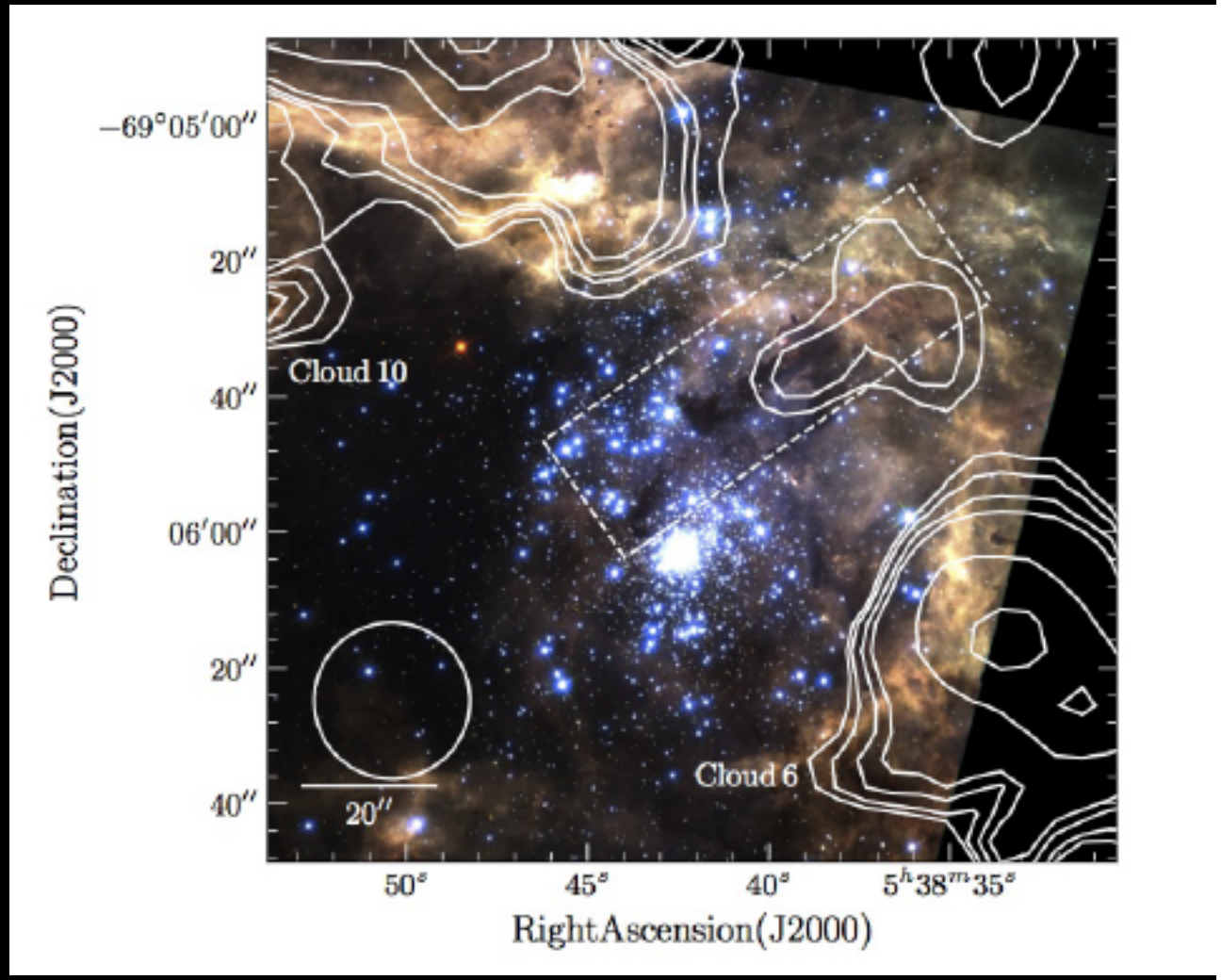


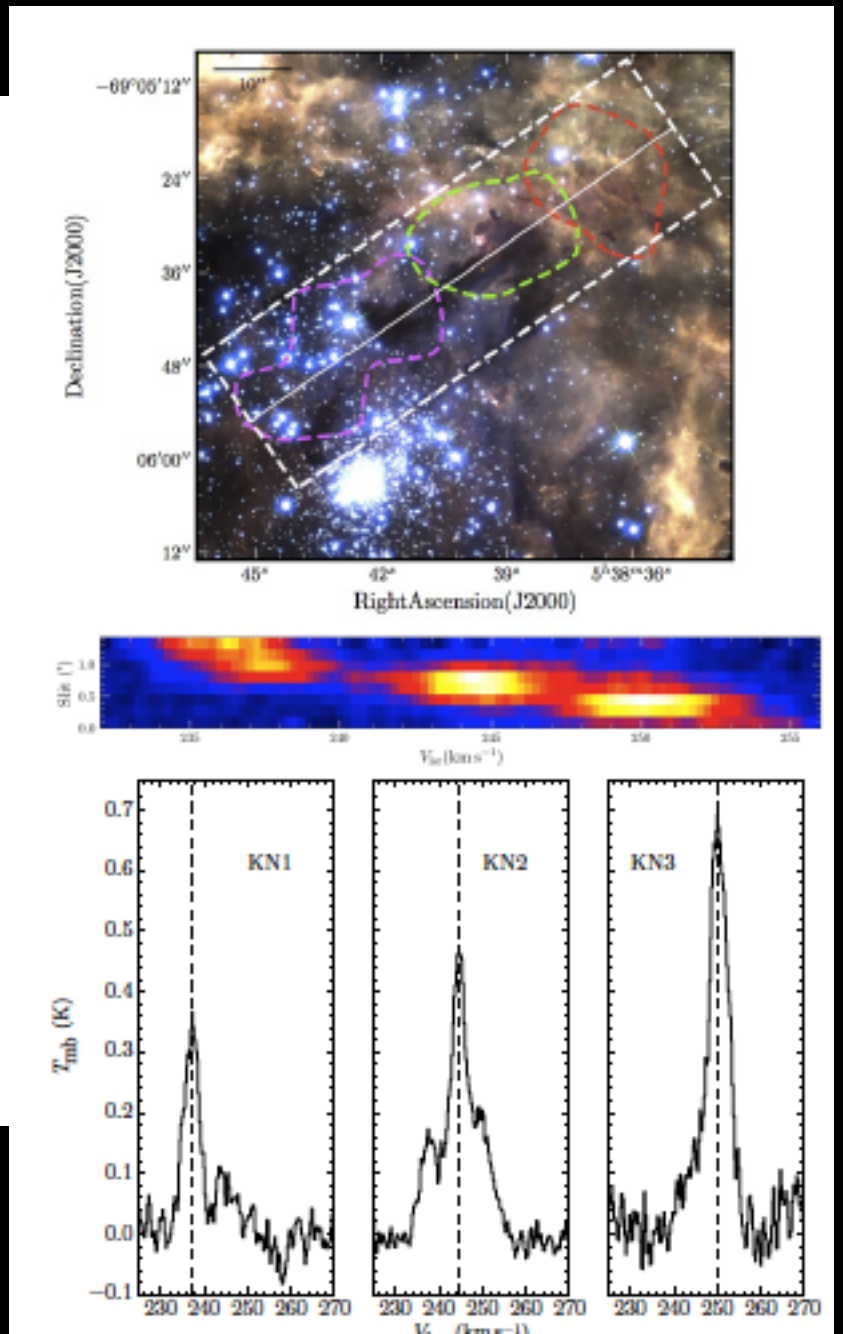

H2 knots
Brγ
H2
1-0 S(1)
H2
1-0 S(3)
Relative flux
Wavelength (Å)
1.0
0.8
0.6
0.4
0.2
0.0
19000
20000
21000
22000
23000
24000


H2 2.12 μ
IRSN-152
ISO D
Knot 4
ISO A
ISO C
IRSW-30
69°04'00"
69°05'00"
69°06'00"
69°07'00"
5h39m00s
40s
RIGHT ASCENSION (2000)
DECLINATION (2000)

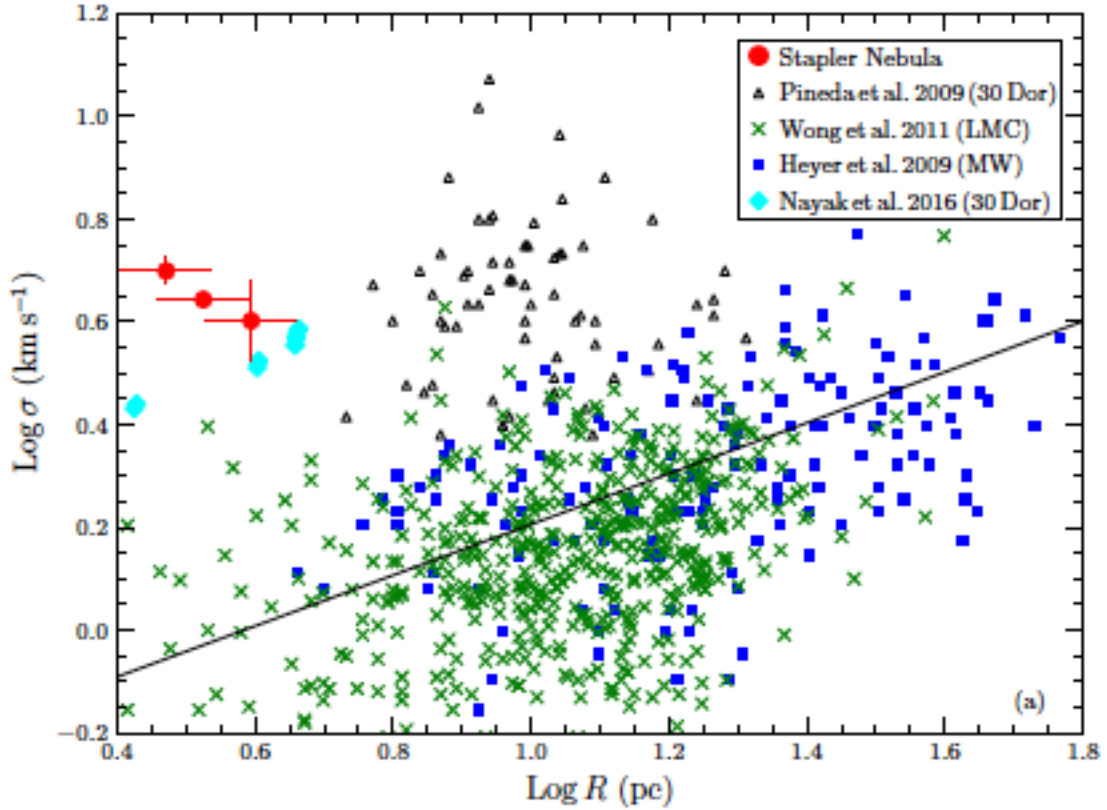


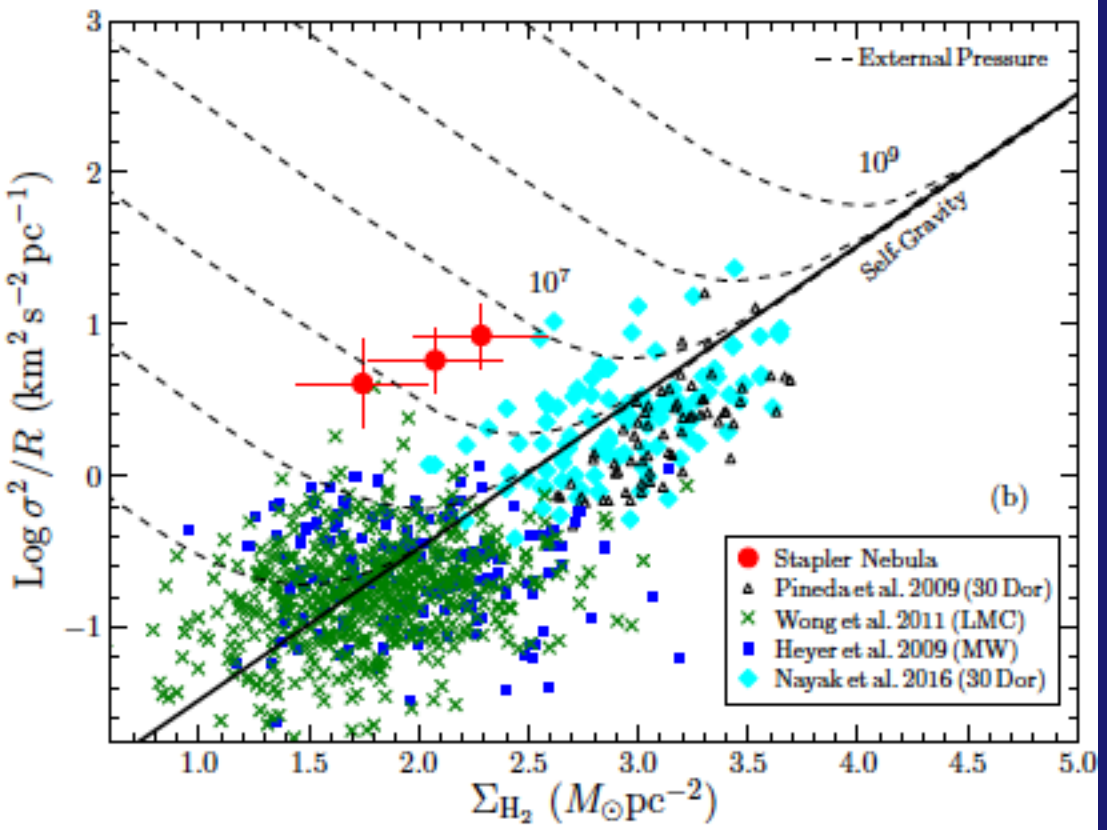

Infrared sources are located preferentially in the 240-250 km/s clumps



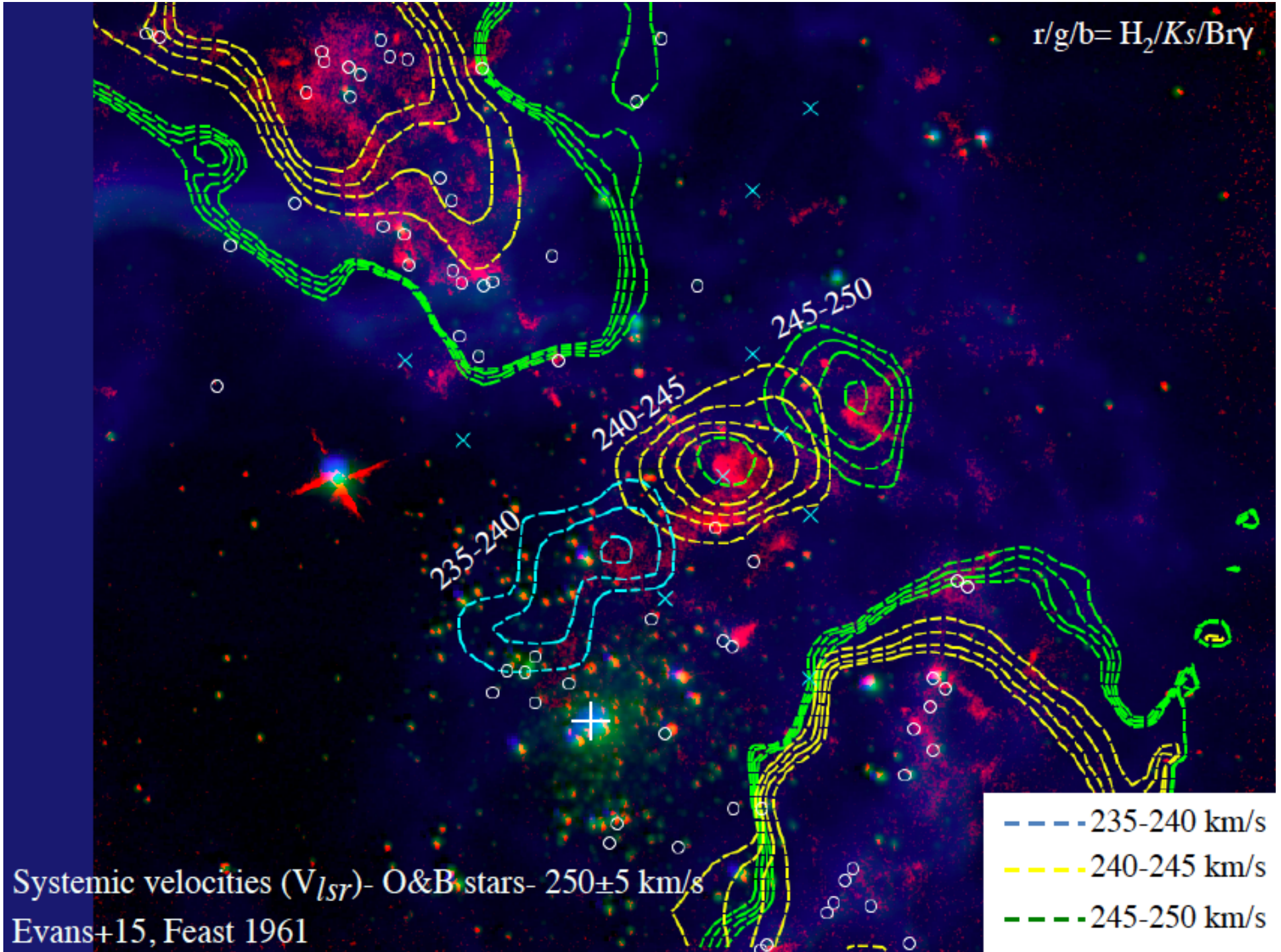

Kalari et al. 2018



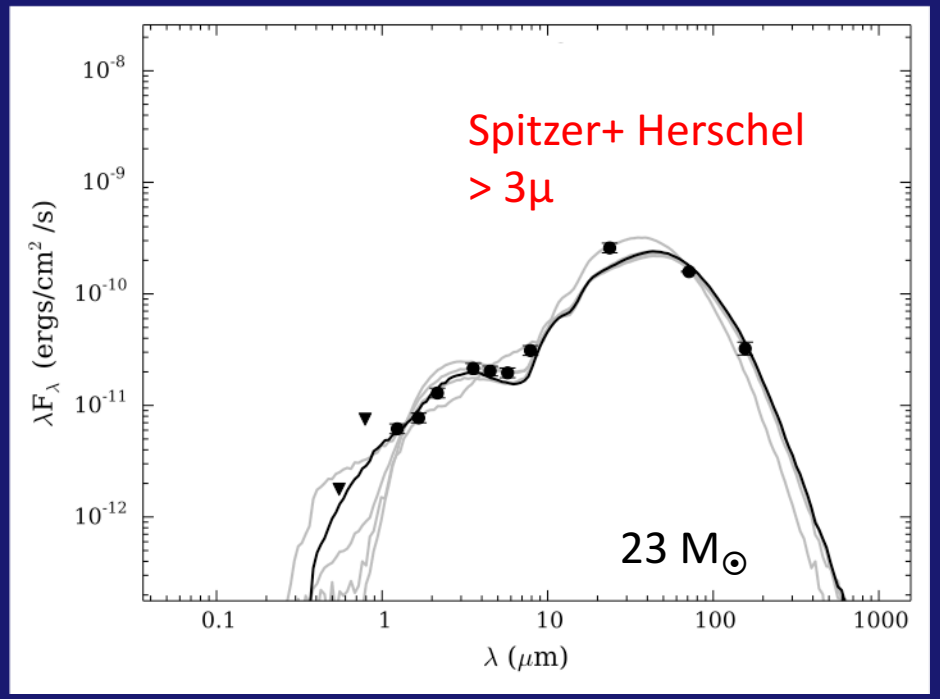



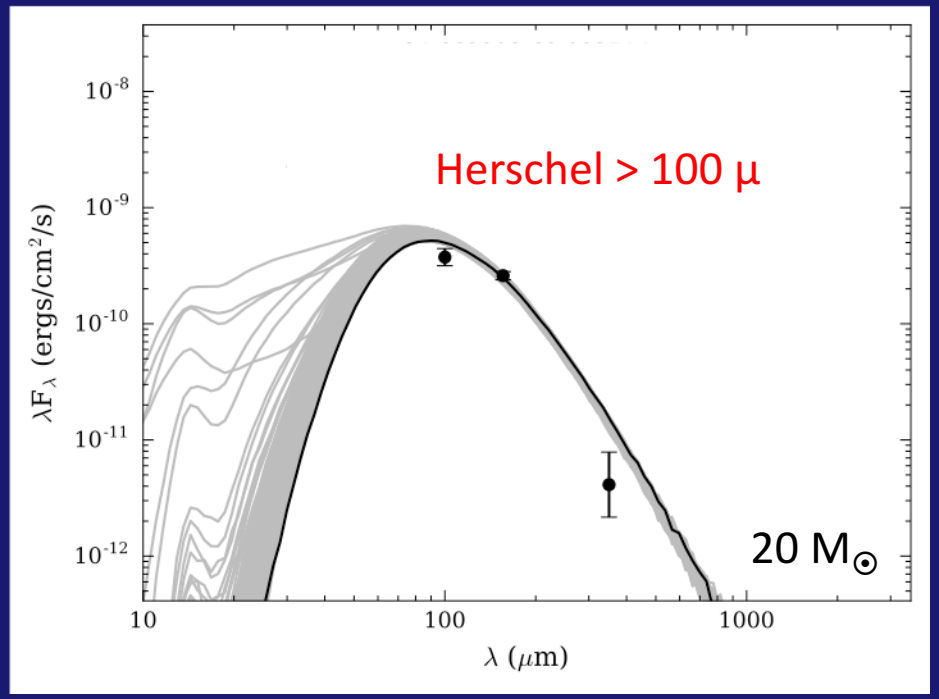

Masses ~ 10^4 Mo

**Kalari et al 2018**


r/g/b= $H_2$/*Ks*/Brγ
245-250
240-245
235-240
Systemic velocities ($V_{lsr}$)- O&B stars- 250±5 km/s
Evans+15, Feast 1961
235-240 km/s
240-245 km/s
245-250 km/s

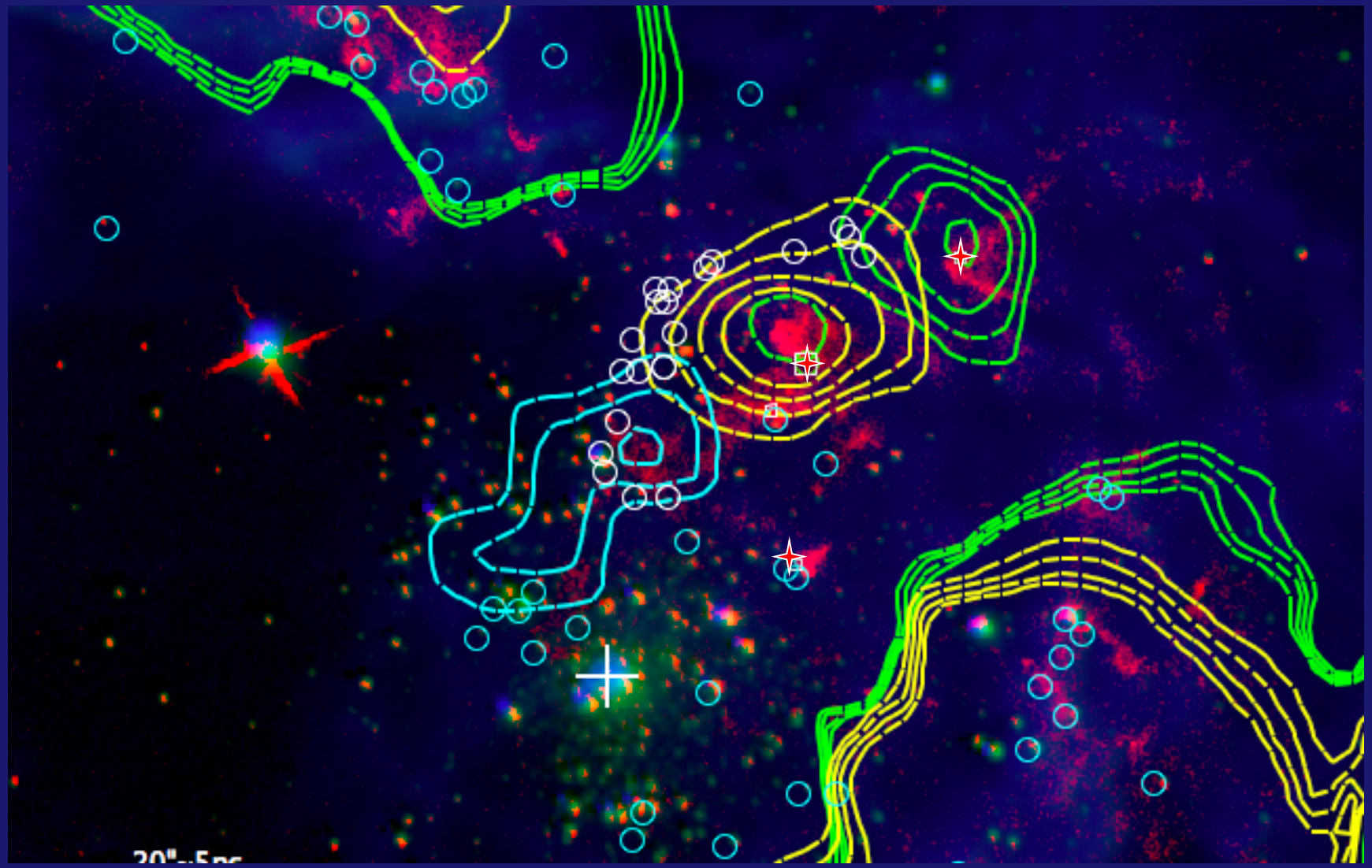
# High-mass YSOs




Kalari, Rubio et al. in prep.

# Molecular clouds



> 10 Mo  < 8 Mo  NIR sources

Kalari, Rubio et al. in prep.

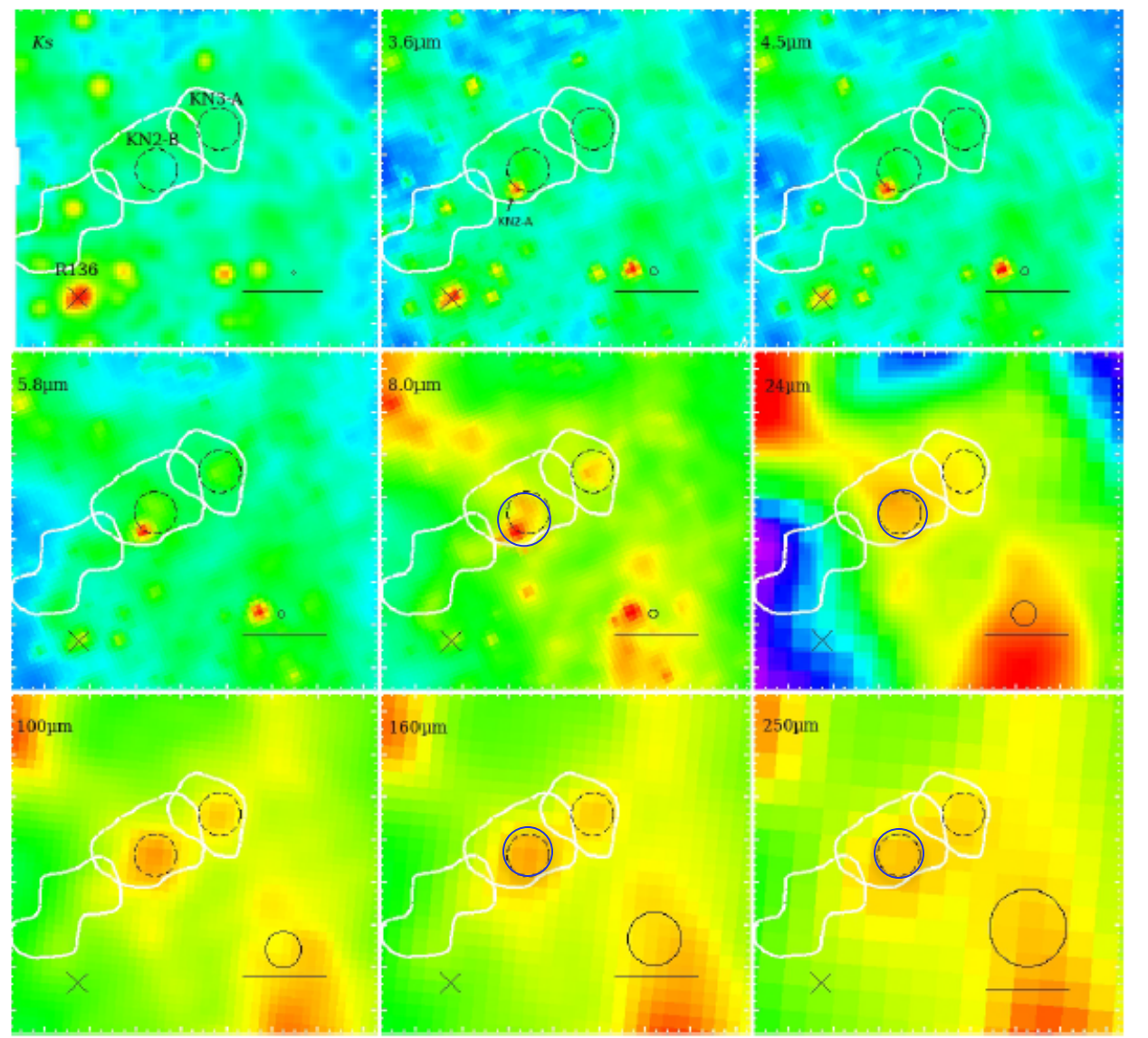



FIG. 6.— *Ks*-250μm inverted colour thumbnails with the positions of KN2-B (bottom) and KN3-A (top) overlaid as dashed circles. The stretch is in logarithmic scale. Each circle has a radius of 5″, while the cross marks the position of R136. The scalebar in the bottom right corner is of 20″, or ≈5 pc at the distance to the LMC. The FWHM of each image is given by the solid circle above the scalebar. From the images, KN2-B and KN3-A are not visible at short wavelengths, but have PAH emission associated with them in the 8μm image (the PAH feature is at 8.6μm, and falls within the bandwidth). At 24μm, emission likely arising from protostellar heating of the surroundings is visible at the position of KN2-B, but not in KN3-A. At longer wavelengths of 100 and 160μm from the *Herschel* imaging, both KN2-B and KN3-A are visible as point-like sources. However, at 250μm, KN2-B only appears significant, with KN3-A extended. Also shown are

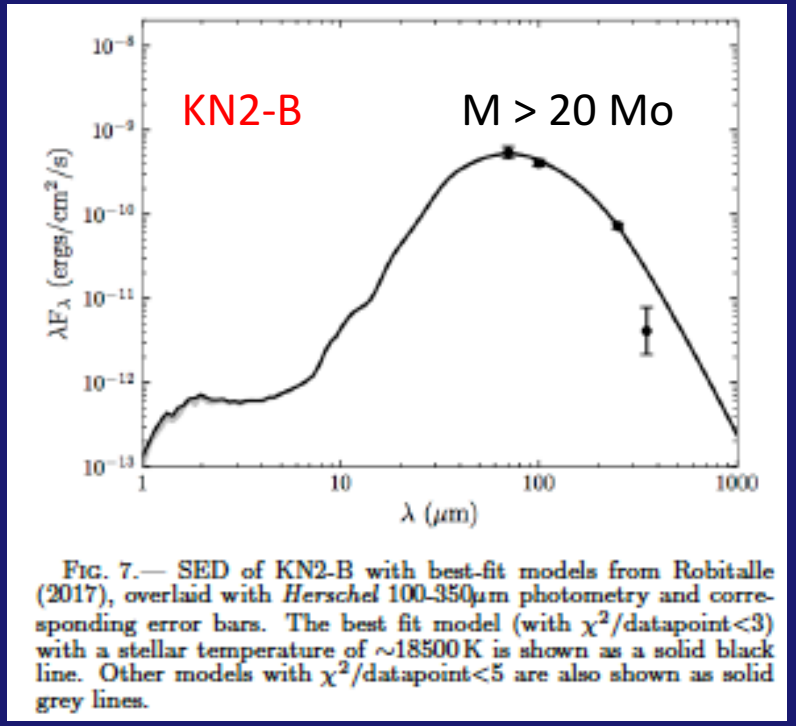



FIG. 7.— SED of KN2-B with best-fit models from Robitalle (2017), overlaid with *Herschel* 100-350μm photometry and corresponding error bars. The best fit model (with $\chi^2$/datapoint<3) with a stellar temperature of ∼18500 K is shown as a solid black line. Other models with $\chi^2$/datapoint<5 are also shown as solid grey lines.

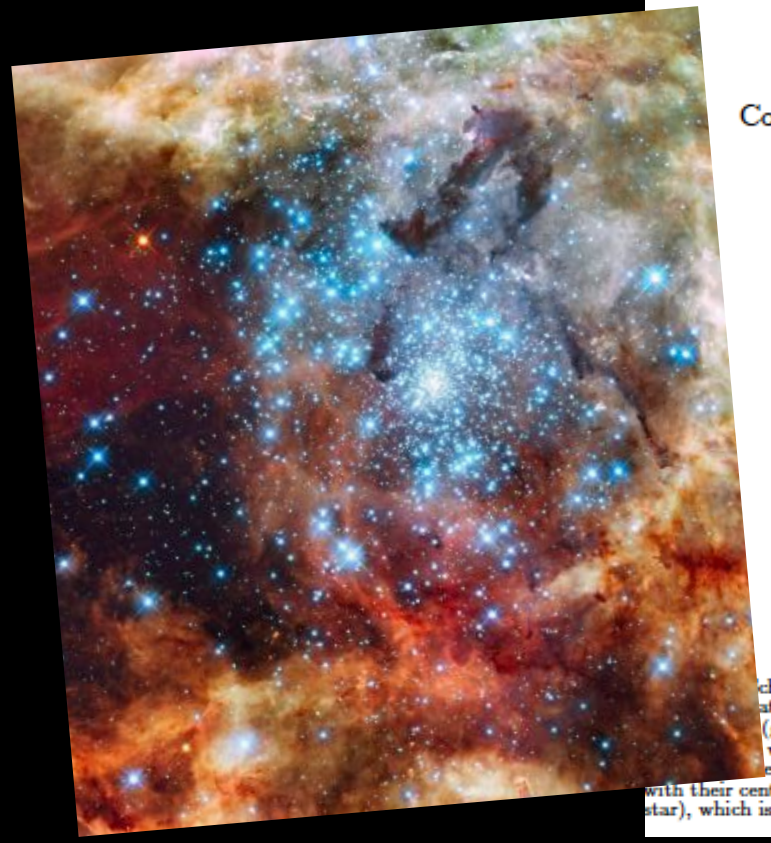
Stellar T 18.000 +- 1000 K

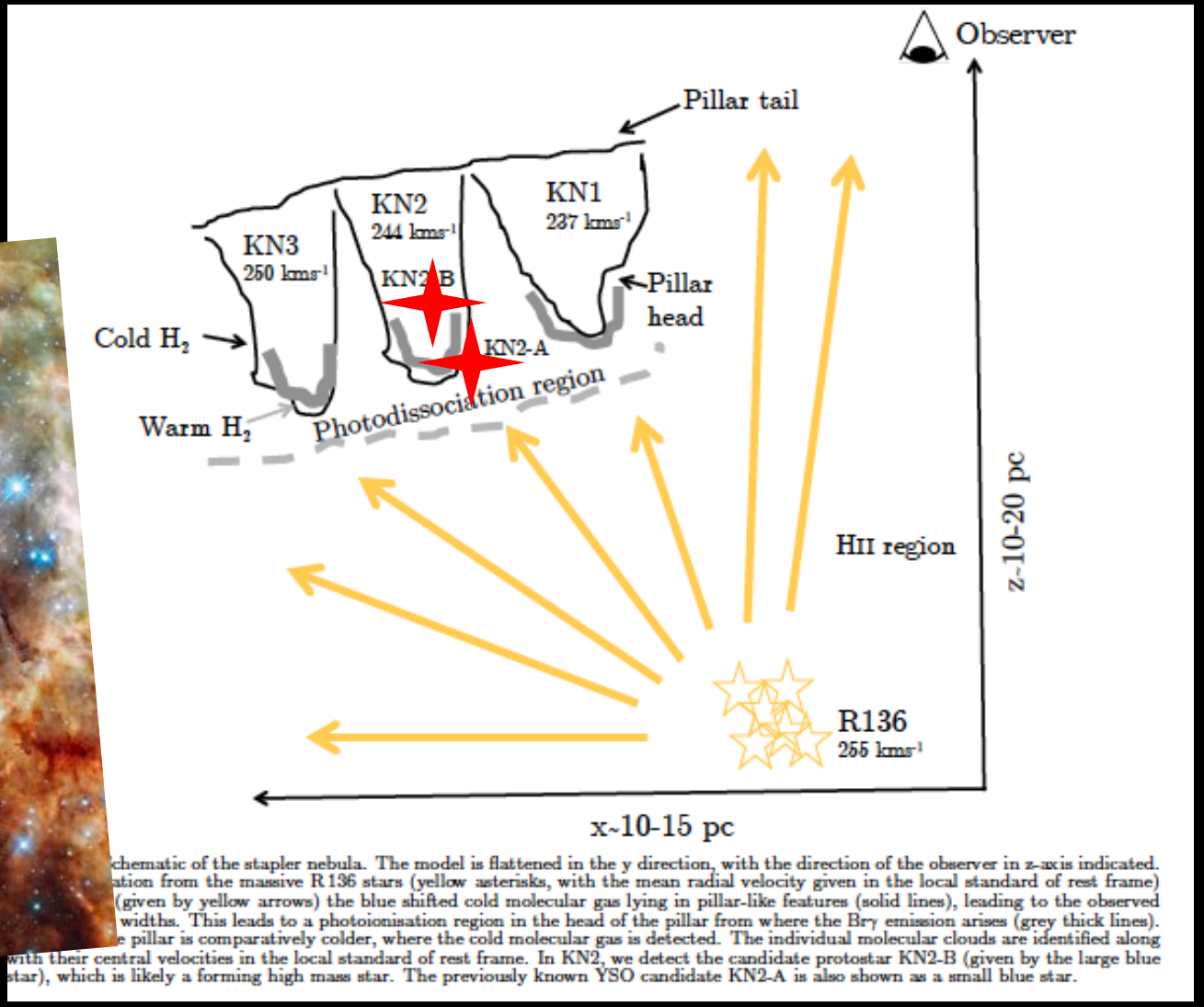
➔ **Class 0 MYSO**

➔ **Age form model fit**

➔ **< 0.1 Myr**

# Pillars?





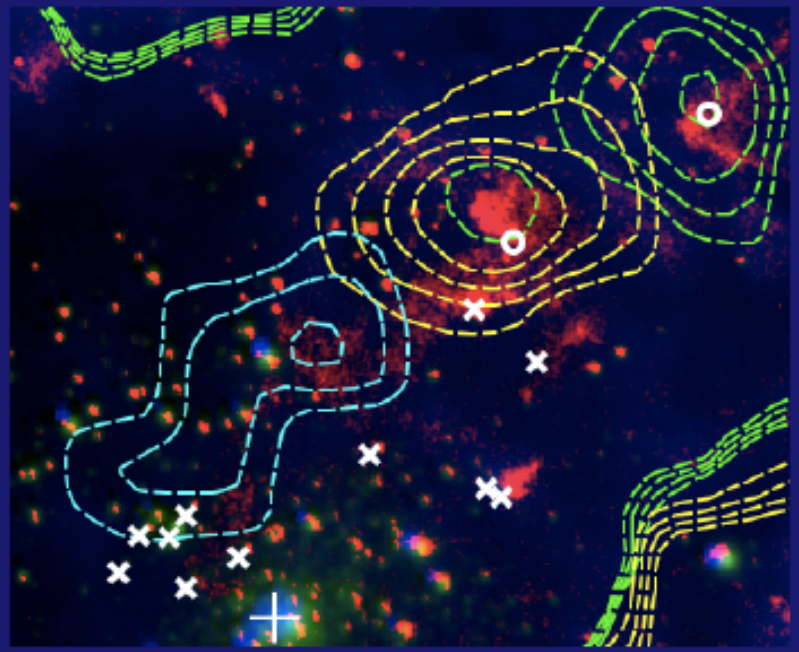

chematic of the stapler nebula. The model is flattened in the y direction, with the direction of the observer in z-axis indicated.
ation from the massive R136 stars (yellow asterisks, with the mean radial velocity given in the local standard of rest frame)
(given by yellow arrows) the blue shifted cold molecular gas lying in pillar-like features (solid lines), leading to the observed
widths. This leads to a photoionisation region in the head of the pillar from where the Brγ emission arises (grey thick lines).
e pillar is comparatively colder, where the cold molecular gas is detected. The individual molecular clouds are identified along
with their central velocities in the local standard of rest frame. In KN2, we detect the candidate protostar KN2-B (given by the large blue
star), which is likely a forming high mass star. The previously known YSO candidate KN2-A is also shown as a small blue star.

KN2- A Class II
KN2- B Class 0
KN-3 pure dust?

Kalari et al. 2018

# Summary

- We found CO (2-1) clumps and $H_2$ knots within 13 pc (projected) of R136 in 30 Doradus expanding at 16 km/s
- nIR excess sources are located at the edges of clumps, MIR sources coincident with the peak in CO (2-1) clumps and dense $H_2$ knots
- These clouds are likely located in front of R136 and moving towards us with the YSOs forming in denser gas.



# Summary

- Massive star formation is going on in dense molecular clouds in the brightes HII regions in th e SMC and LMC

- Multiwavelength studies combined with niR spectroscopy and
- AO optical photometry allow us to characterize the YSO properties, i.e
- mass and age

- Sub –parsec resolution ALMA observations of the molecular gas will r
- esolve the molecular clumps and determine the star formation efficiencies
- and star formation rates in low metallicity molecular gas.

# HansFest 2?

# In Chile