The location, clustering, and propagation of massive star formation in giant molecular clouds
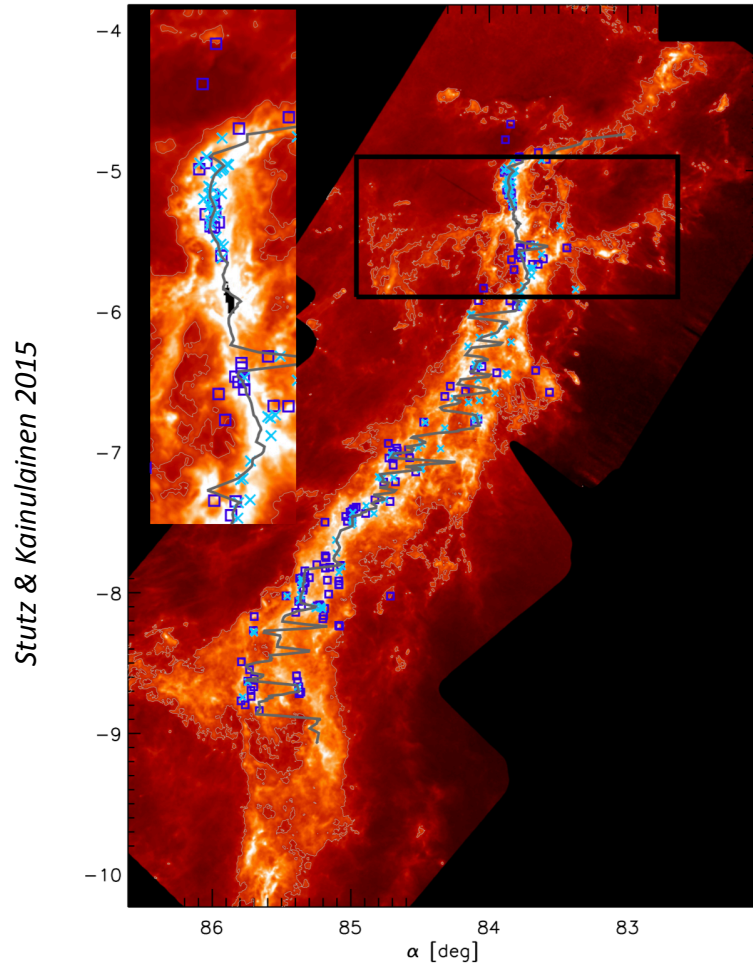
Bram Ochsendorf (Johns Hopkins University)

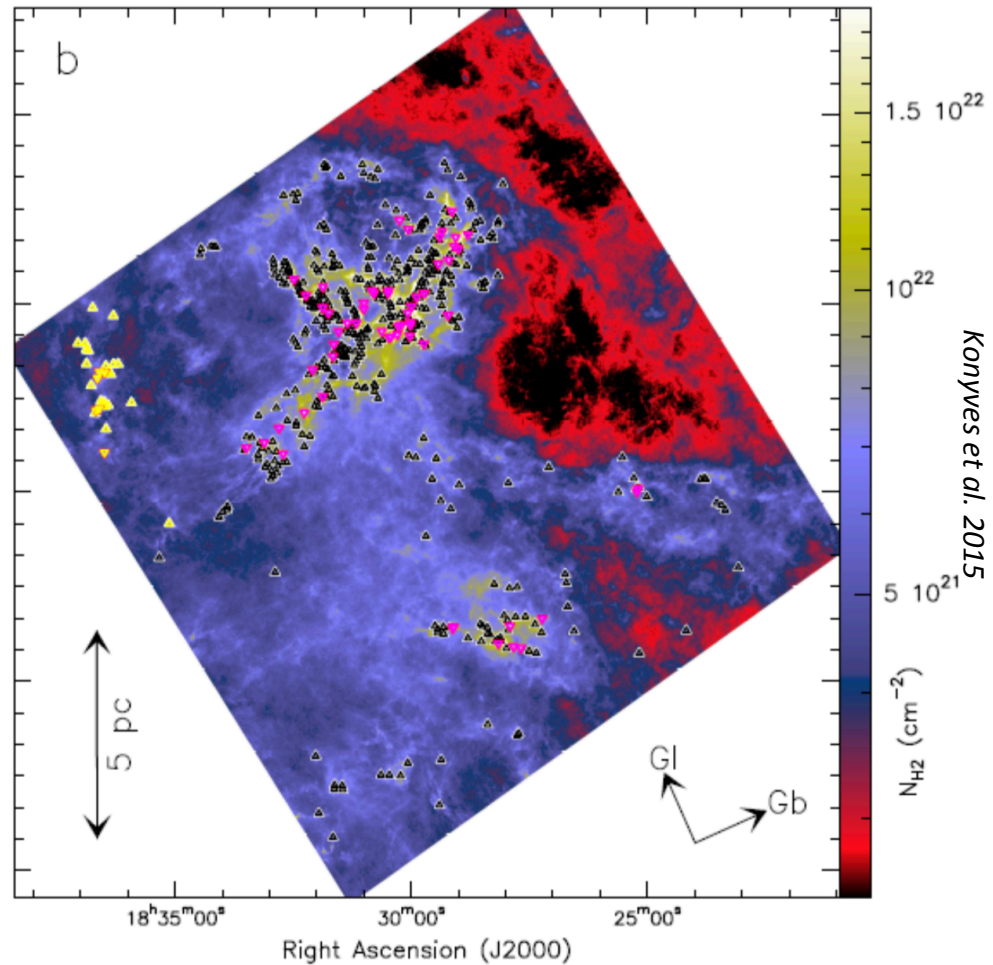Margaret Meixner, Jeremy Chastenet, Xander Tielens, Julia Roman-Duval

Star formation

- Low mass stars are almost exclusively found on top of filaments

Orion

Aquila

Massive star formation

- But where do massive stars form?

In infrared dark clouds (IRDCs)?

M17
Color = ^{13}CO
Contour = 90 cm cont.

Edges of molecular clouds?

→ *most IRDCs in the Galaxy are quiescent (Chambers et al. 2009)*

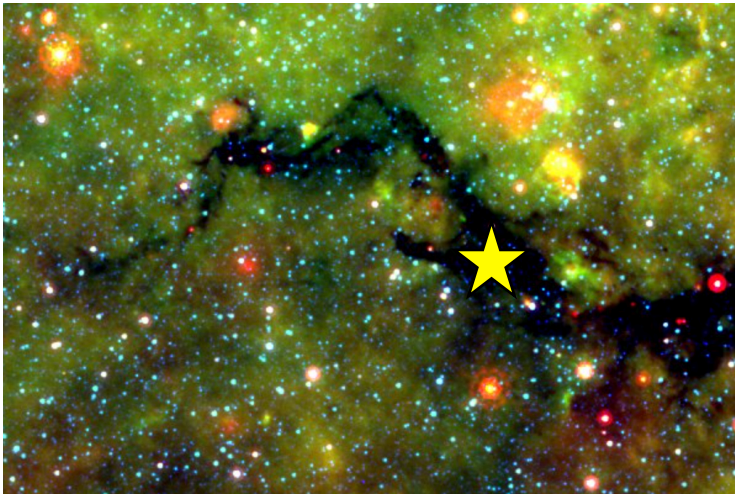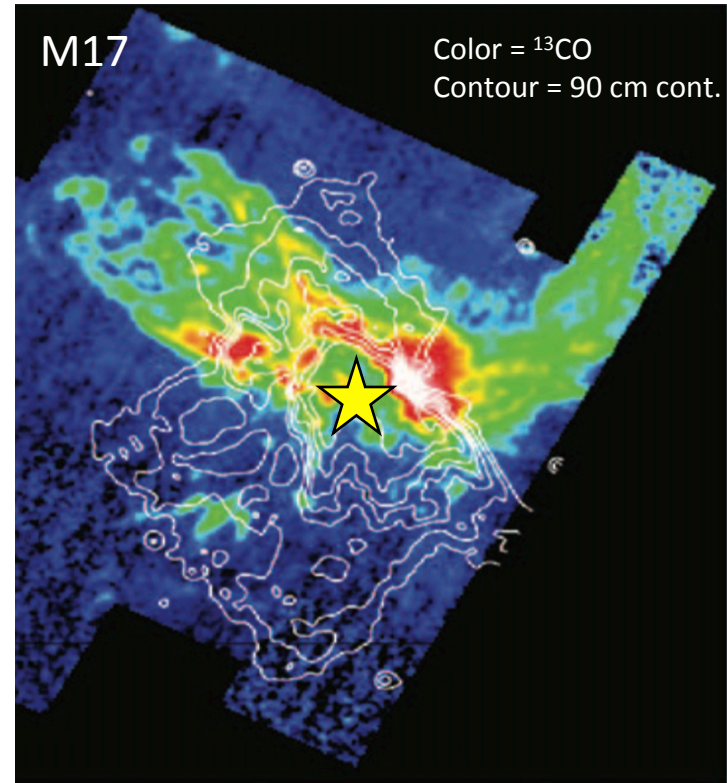→ *External triggers? (Elmegreen & Lada 1977, Walborn 2002, Zavagno et al. 2010)*

Massive star formation

- But where do massive stars form?

In infrared dark clouds (IRDCs)?

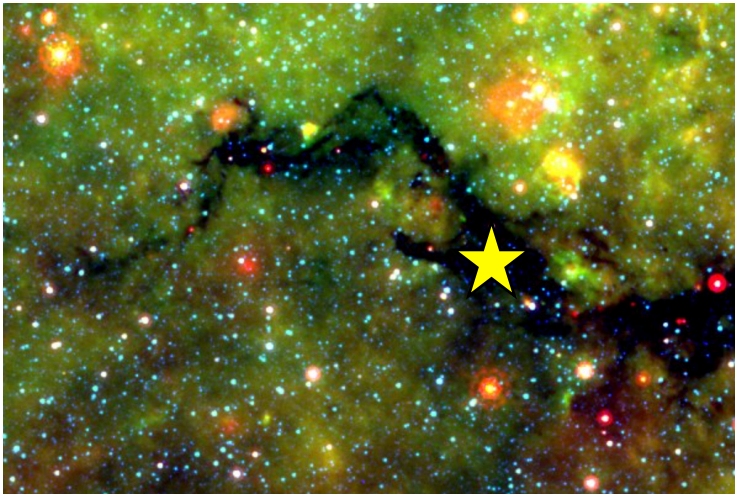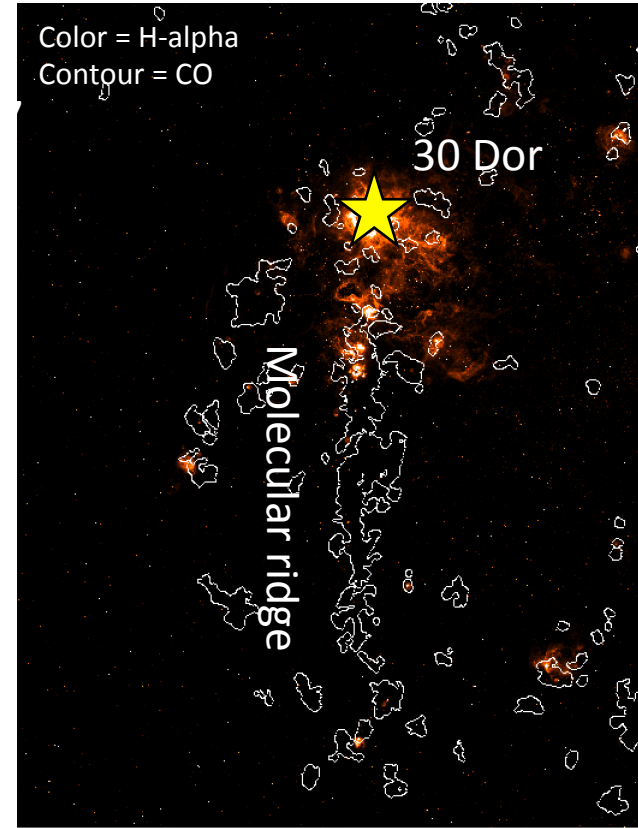→ *most IRDCs in the Galaxy are quiescent (Chambers et al. 2009)*

Color = H-alpha
Contour = CO

30 Dor

Molecular ridge

Edges of molecular clouds?

→ *External triggers? (Elmegreen & Lada 1977, Walborn 2002, Zavagno et al. 2010)*

(massive) Star formation

Where do massive stars form within GMCs?

The truth is: **we don't know.**

- No statistical sample: rarity, obscuration, lifetimes, confusion, distance ambiguity

Galaxy-wide massive star formation

The Large Magellanic Cloud

- Close enough (~50 kpc) to resolve individual clouds and stars

- Face on → no confusion or distance ambiguities

- Wealth of observational data

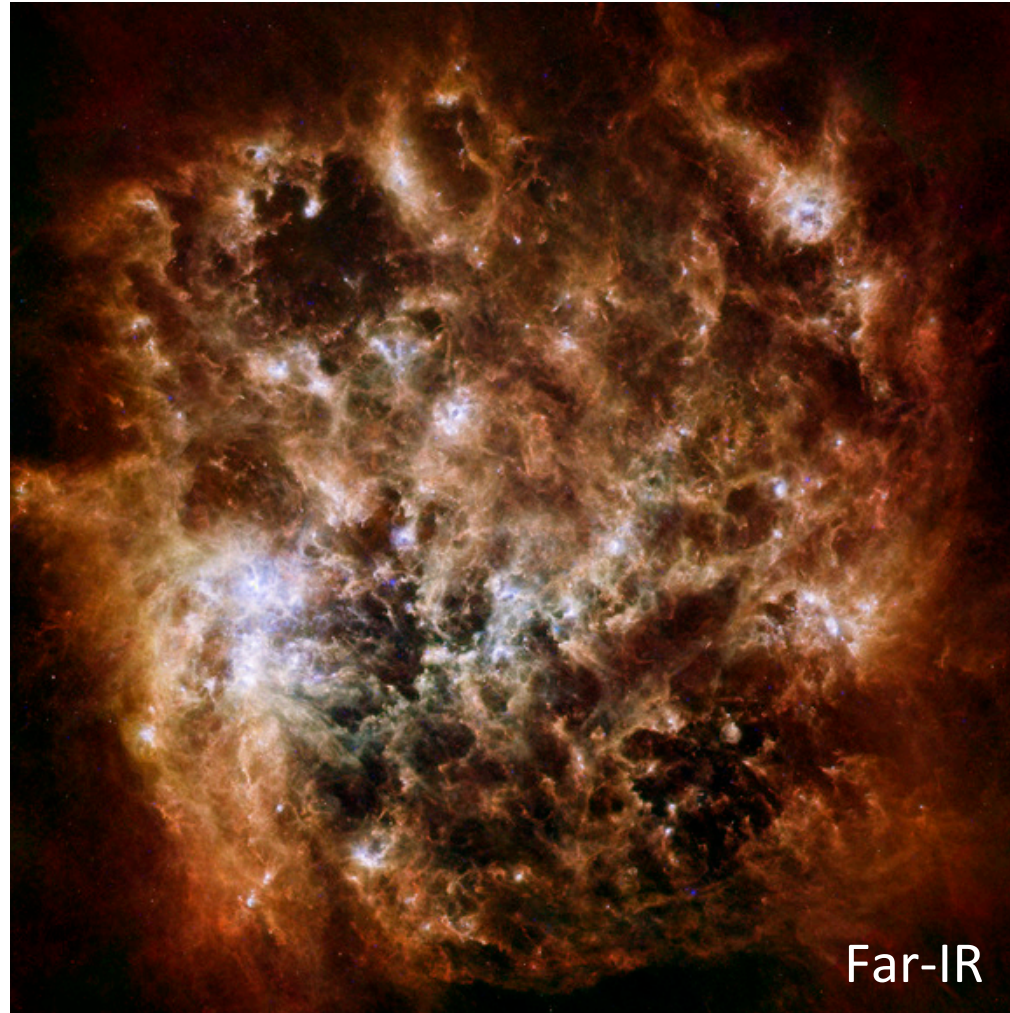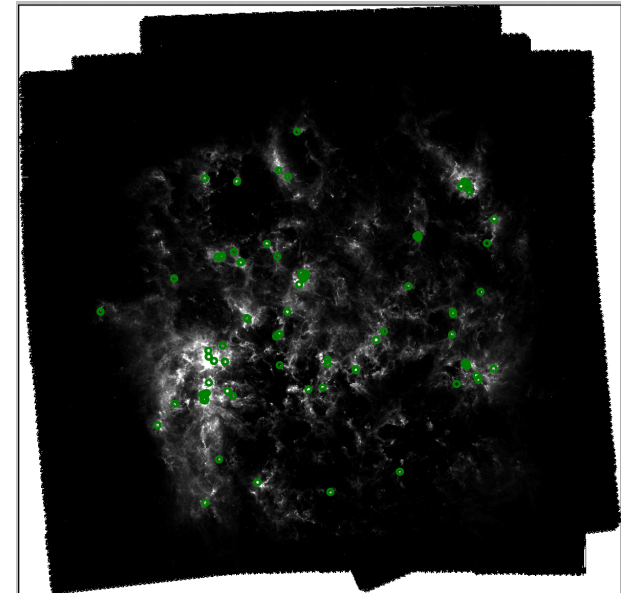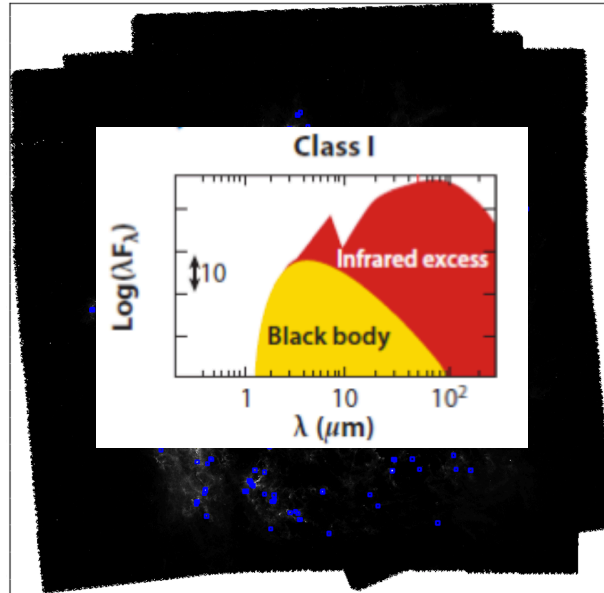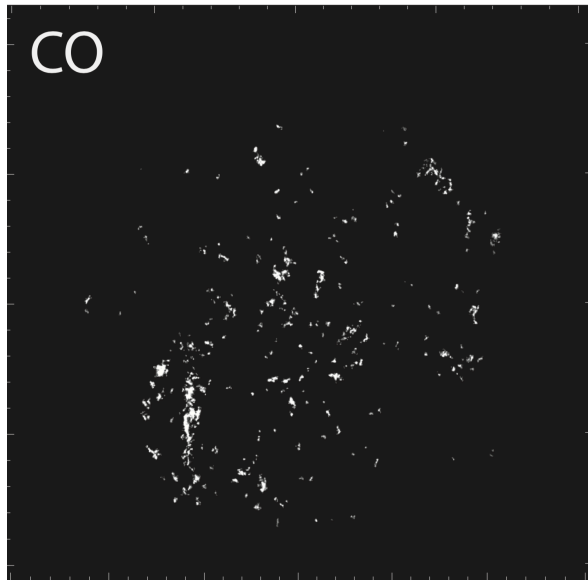**An ideal place to study massive star formation!**

Far-IR

Figure from HERITAGE; Meixner et al. 2013

Data

~ 200 GMCs ($M > 10^4$ M$_{sun}$)   ~ 700 MYSOs ($M > 8$ M$_{sun}$)   ~ 100 SCs (< 10 Myr)

- Test shows that we have a *complete* census of all Stage 1 (~ 10^5 yr) MYSOs of $M > 8$ M$_{sun}$

Overarching goal:
- quantify the location, clustering, and propagation of massive star formation
- relate to the internal structure of GMCs
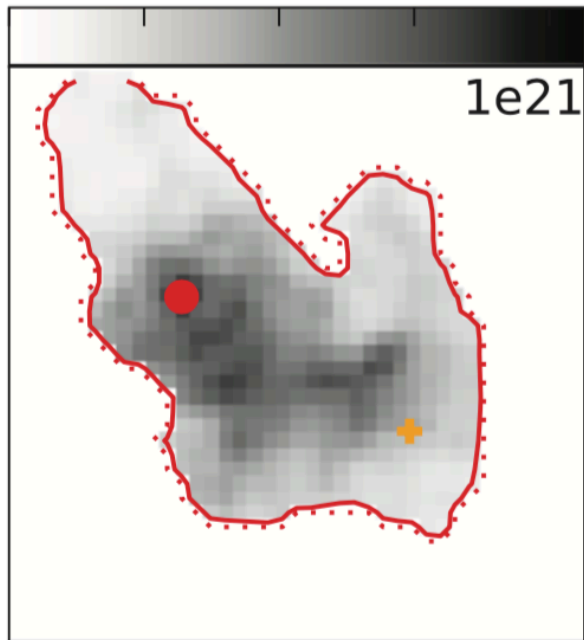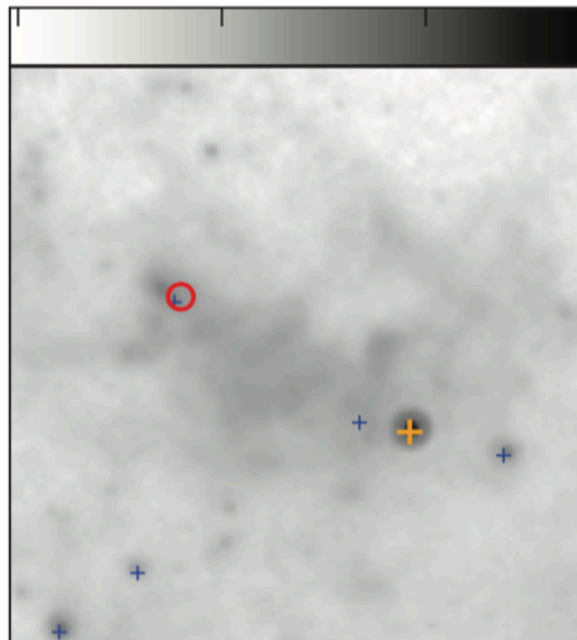
H₂ column density
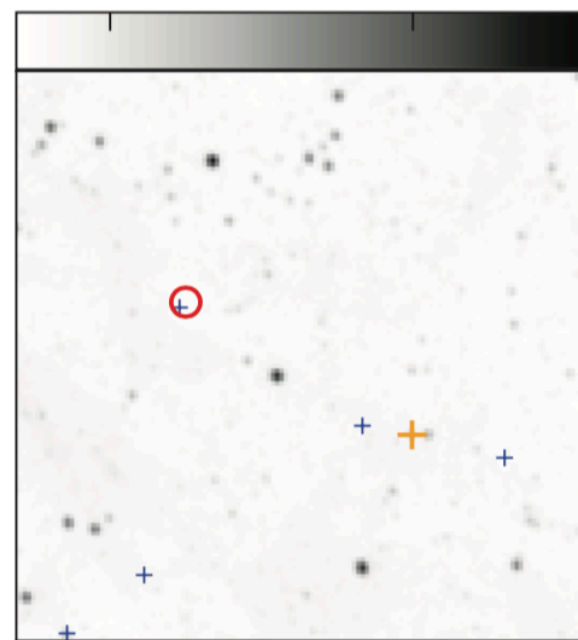
.0   0.2   0.4   0.6   0.8

1e21

24 micron

10^{-1} 10^0 10^1

H-alpha

10^0 10^1

Image spans 100 x 100 pc

Deeply embedded!

No large-scale feedback!

✚ MYSO ($M > 8\ M_{sun}$)   🔴 N_{max}

H₂ column density

0.0 0.3 0.6 0.9 1.2

1e21

24 micron

10⁰   10¹   10²

H-alpha

10⁰   10¹   10²

Image spans 100 x 100 pc

Deeply embedded!

No large-scale feedback!

✚ MYSO ($M > 8$ M$_{sun}$)   ● N_{max}

H₂ column density

0.0   0.4   0.8   1.2   1.6

10^0 10^1 10^2

1e21

Image spans 100 x 100 pc

24 micron

10^0 10^1 10^2
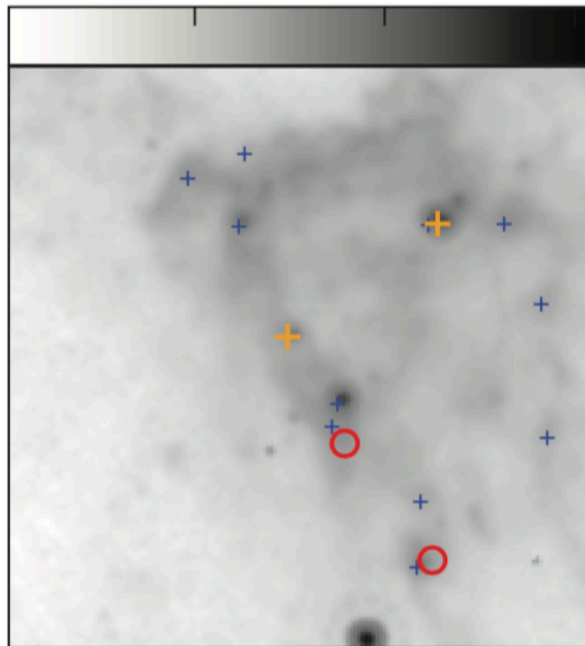
H-alpha

10^0 10^1 10^2

Large-scale feedback from exposed clusters!

✚ MYSO ($M > 8\,M_{sun}$)   ⬤ N_{max} ★ SC

H₂ column density

.0   0.2   0.4   0.6   0.8

1e21

24 micron

10^{-1} 10^0 10^1

H-alpha

10^0 10^1

Image spans 100 x 100 pc

Deeply embedded!

No large-scale feedback!

✚ MYSO ($M > 8\ M_{sun}$)   ● N_{max}

H₂ column density

0.0 0.3 0.6 0.9 1.2

1e21

24 micron

10^0 10^1 10^2

H-alpha

10^0 10^1 10^2

Image spans 100 x 100 pc

Deeply embedded!
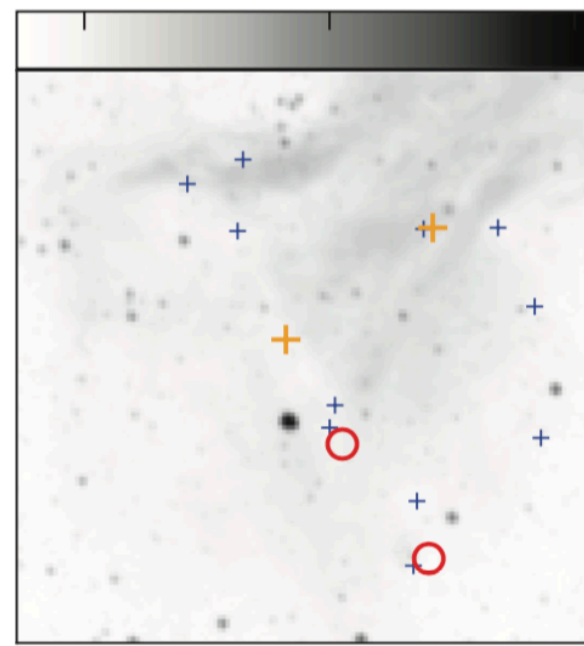
No large-scale feedback!

+ MYSO ($M > 8$ M$_{sun}$)

● N_{max}

H₂ column density

0.0   0.4   0.8   1.2   1.6

24 micron

10^0 10^1 10^2

H-alpha

10^0 10^1 10^2

1e21
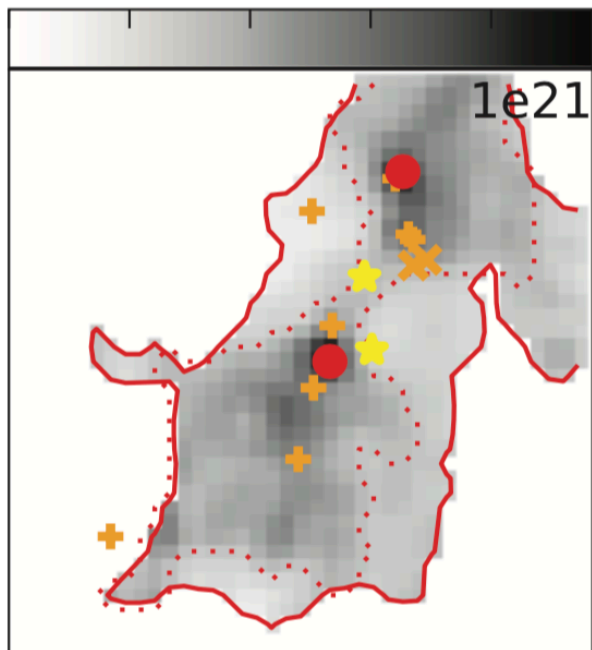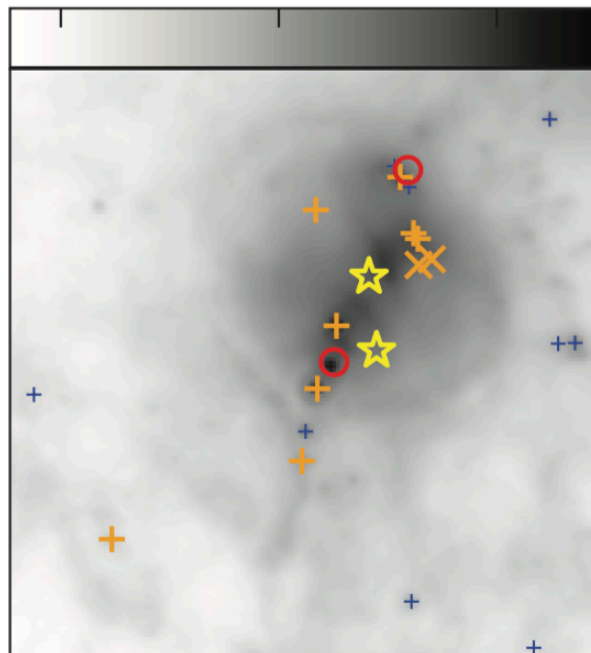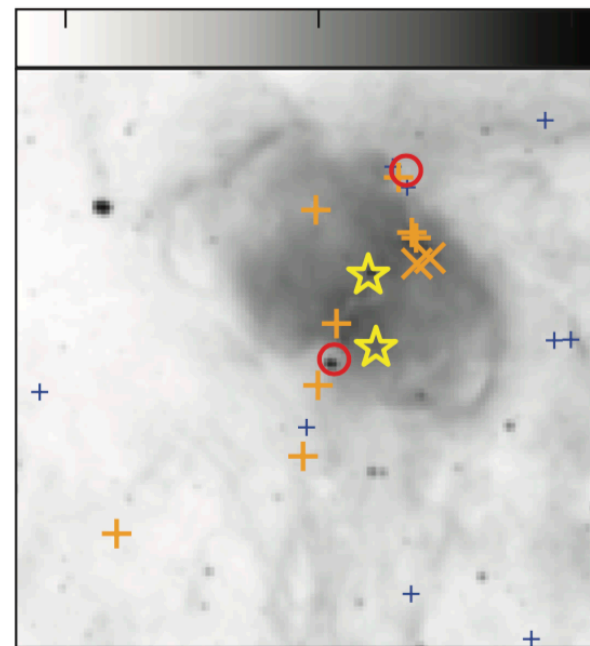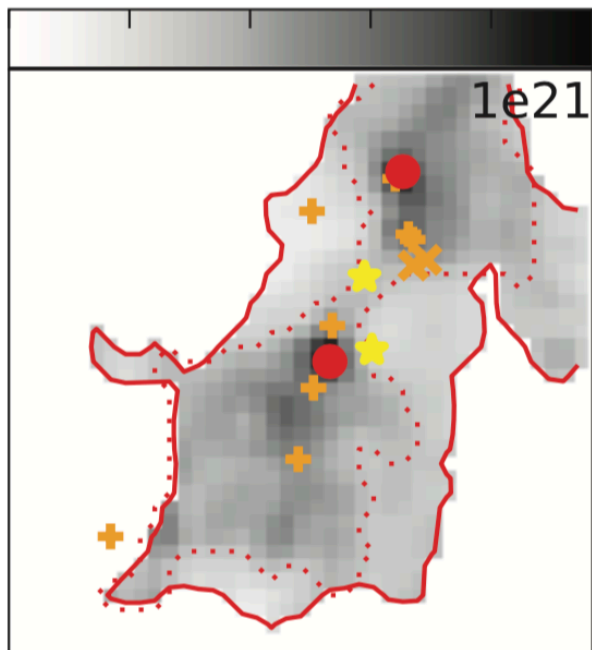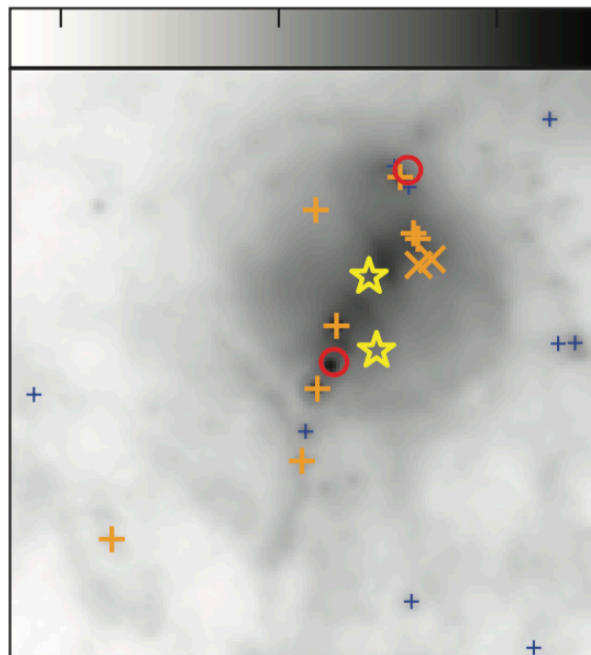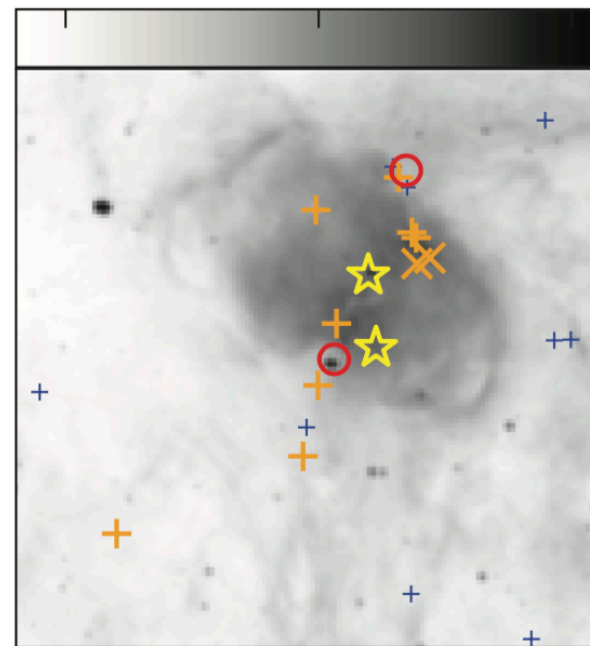
Image spans 100 x 100 pc

**Large-scale feedback
from exposed clusters!**

✚ MYSO ($M > 8\,M_{sun}$)   ● N_{max} ★ SC

Location of massive star formation in GMCs

DATA

RANDOM

MYSO located outside cloud

MYSO located at peak column
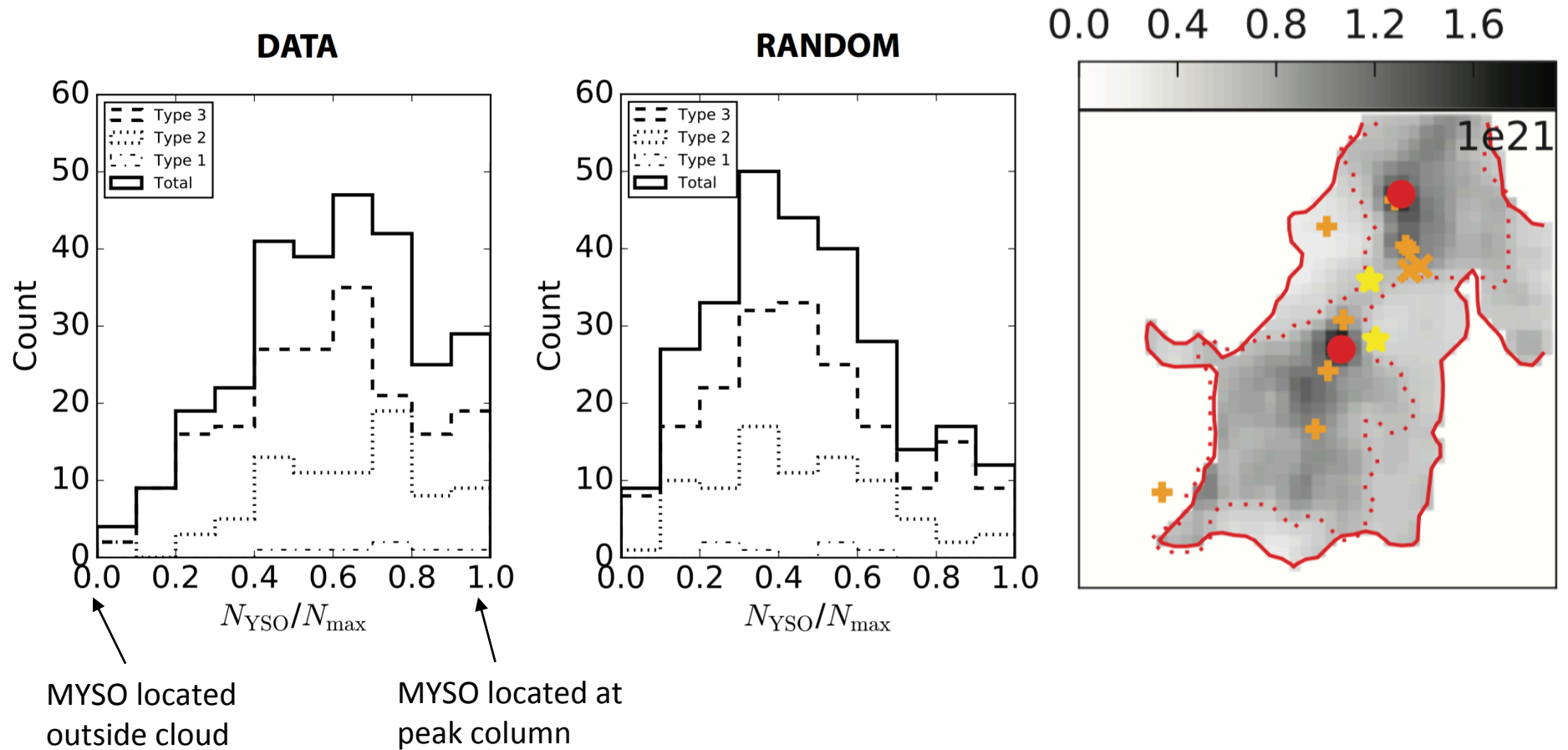
Conclusion:
Massive stars do not typically form at highest column density of GMC!

Location of massive star formation in GMCs
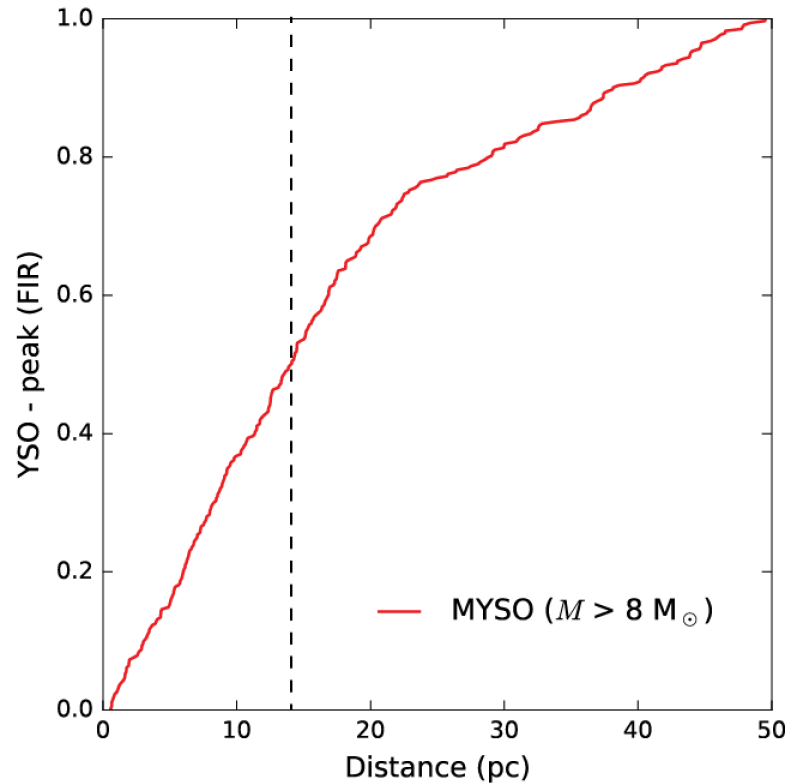
~ 50% of MYSOs form ~15 pc away from highest column densities of GMCS!

Conclusion:

Massive stars do not typically form at highest column density of GMC!

Presence of SCs and the rate of massive star formation

'w/ SC'

R_s

'w/ SC'
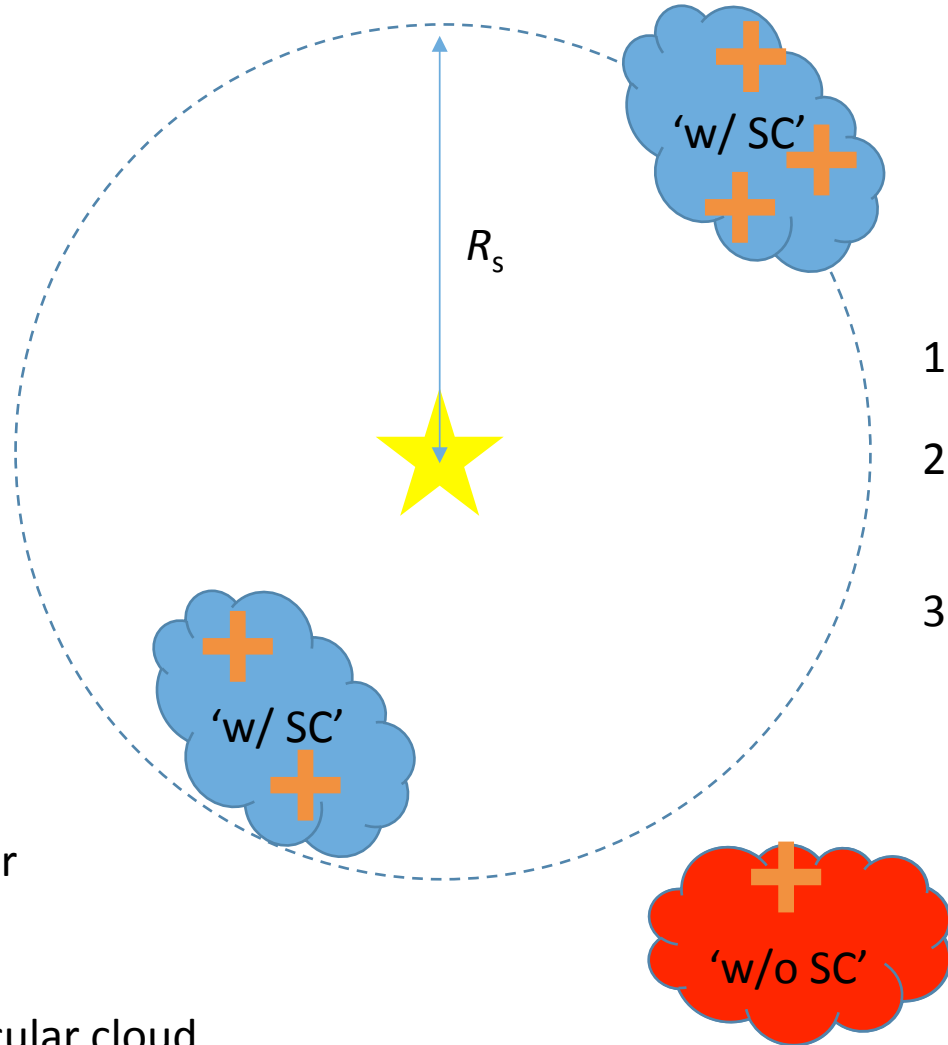
'w/o SC'

1. Define search radius R_s

2. Clouds within R_s --> 'w/ SC'
   Clouds outside R_s --> 'w/o SC'

3. Count MYSOs within each cloud

★ cluster

✚ MYSO

☁ Molecular cloud

Presence of SCs and the rate of massive star formation
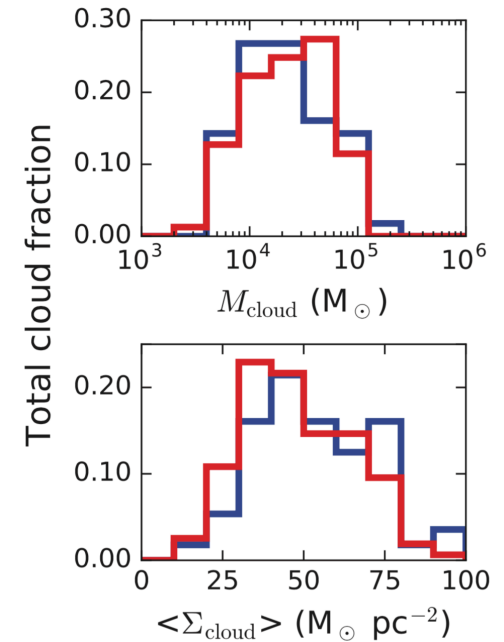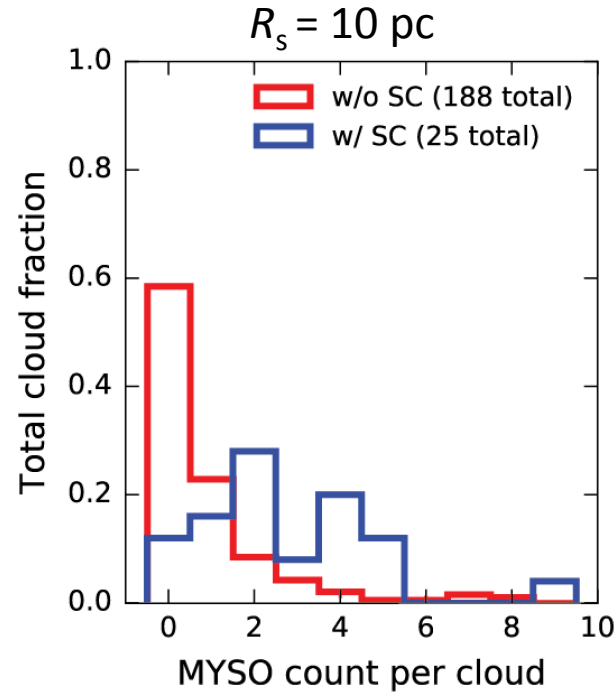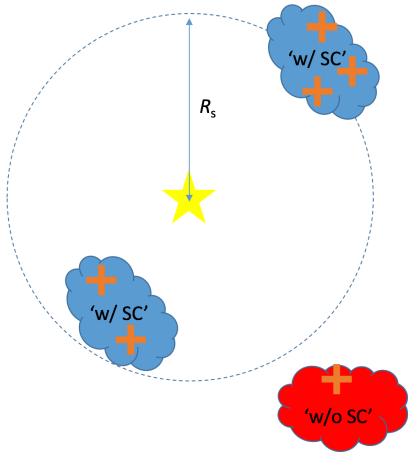
$R_s = 10$ pc

w/o SC (188 total)
w/ SC (25 total)

Total cloud fraction

MYSO count per cloud

M_{cloud} (M$_\odot$)

$<\Sigma_{cloud}>$ (M$_\odot$ pc^{-2})

Conclusion

Massive star formation
is significantly boosted near SCs

However global properties
of clouds very similar!

- Connection between massive stars on timescales up to 10 Myr!
- Triggered star formation?

Main points:

1. Massive stars do not typically form at the highest column densities of parent GMCs

2. The rate of massive star formation is significantly elevated in GMCs near optical stellar clusters

how does this fit together?

1. Massive stars do not typically form at the highest column densities of parent GMCs

- Completeness?
  - Extensive false source injection test shows we are complete for Stage 1 M > 8 M_{sun} sources

- Feedback?
  - Measure how many MYSOs have reached UC-HII phase
  - Detailed observations show only small fraction ~10-20% have accompanying maser/UCHII (e.g. Indebetouw 2004)
  - However, in ~10^5 yrs large-scale feedback not possible; Hα images support this

- Beam dilution?
  - Typical IRDCs (~5000 M_{sun}) should be easily visible!
  - Gas clumps of <500 M_{sun} may be hidden from view

H-alpha

100 x 100 pc

N(H$_2$) Column density
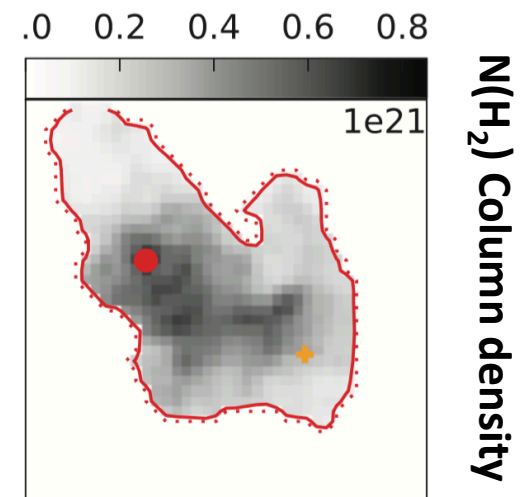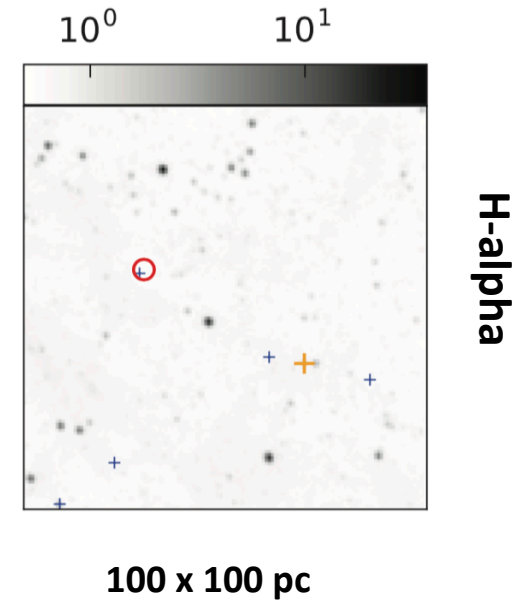
Modes of massive star formation

Still consistent with massive stars forming in cores of ~500 M_{sun} (Tan et al. 2014).

➢ **Massive cores appear to form outside of the dense, opaque regions of GMCs!**

1) Implications for GMC collapse?
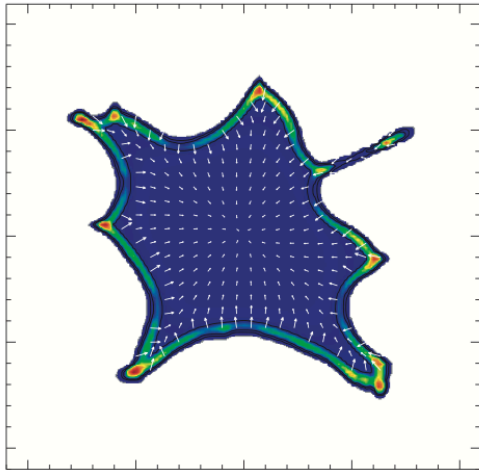
'edge effect?'
figure from Burkert et al. 2004

flow-driven core formation?
figure from Heitsch et al. 2008

2) Triggered star formation?

➢ Triggering explains:
  - Location of MYSOs.
  - Connection between MYSOs and SCs.
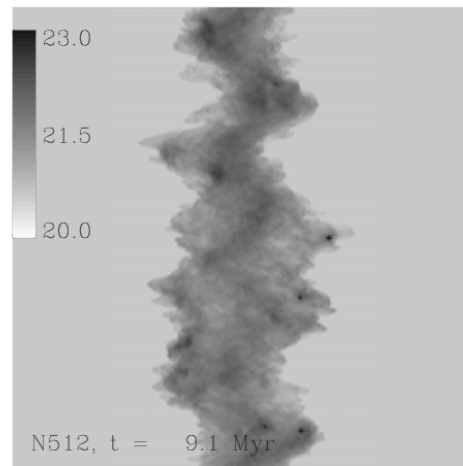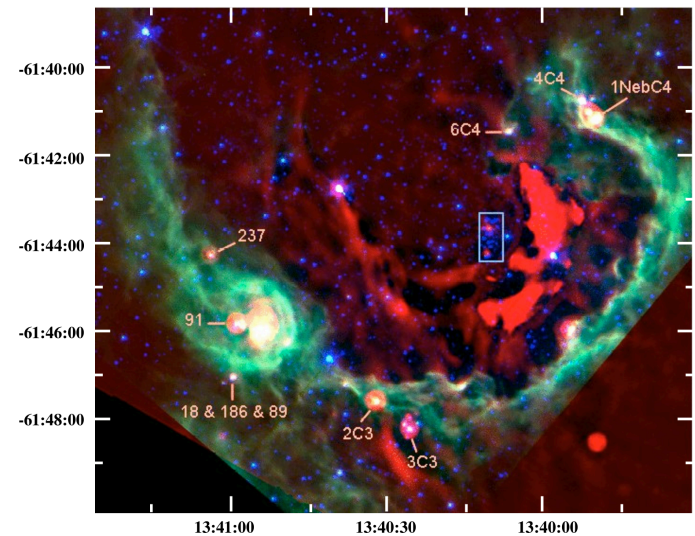
1. Massive stars do not typically form at the highest column densities of parent GMCs

Still consistent with massive stars forming in cores of ~500 M_{sun} (Tan et al. 2014).

➢ **Massive cores appear to form outside of the dense, opaque regions of GMCs!**

-> Need to consider *entire GMC complexes* (Hernandez & Tan 2015)
-> Construct a large, statistical sample in the Galaxy
-> Large-scale surveys of the Galactic plane will allow this
   (maser parallaxes + GRS, ThrUMMS, ATLASGAL, BGPS, Hi-Gal, etc..)
 -> Detailed follow-up with ALMA, SOFIA and the upcoming JWST.

.0   0.2   0.4   0.6   0.8

1e21
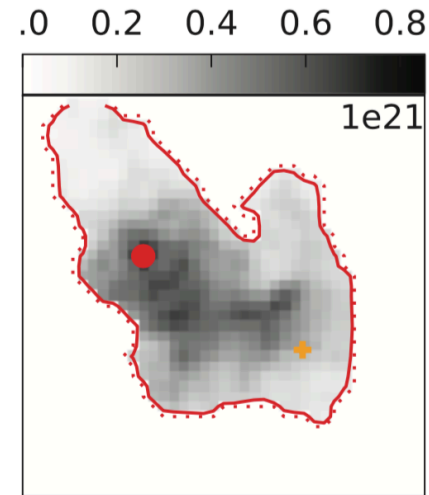
$N(H_2)$ Column density

Zooming in: ALMA
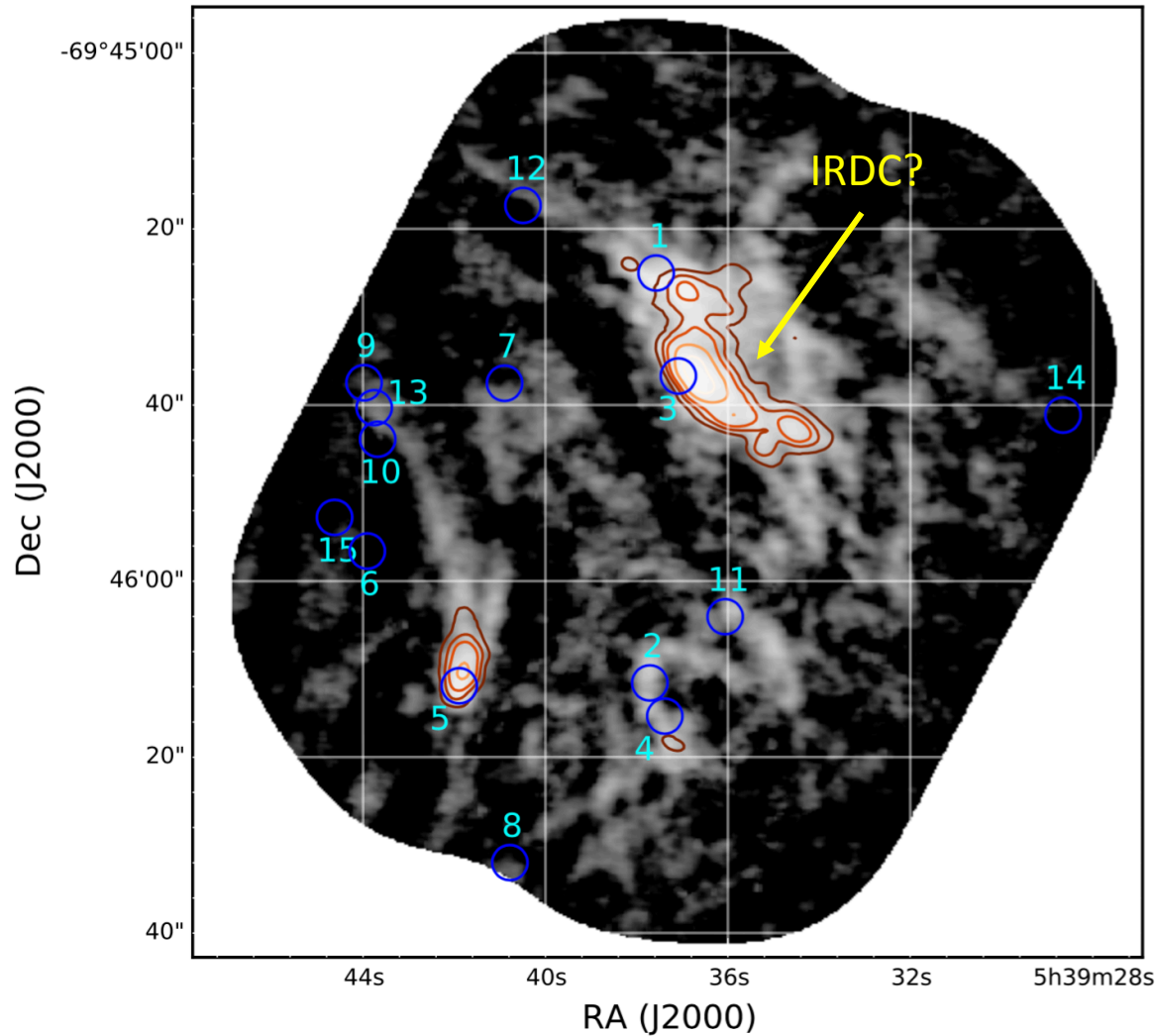
**N159-E complex
in the LMC**

ALMA
Grayscale: ^{12}CO
Contours: CS
Blue circles: MYSOs

**IRDCs may not be
the most efficient
sites to form
massive stars!**

Nayak et al. in prep

Zooming in: SOFIA

1) Where do massive stars form?

~half of MYSOs are not matched with CO
 → our current CO completeness limit is ~10^4 M$_{sun}$.
  → *What fraction of massive stars form in 'CO-dark' phase?*

2) Quantify correlation between SFR and stellar clusters.
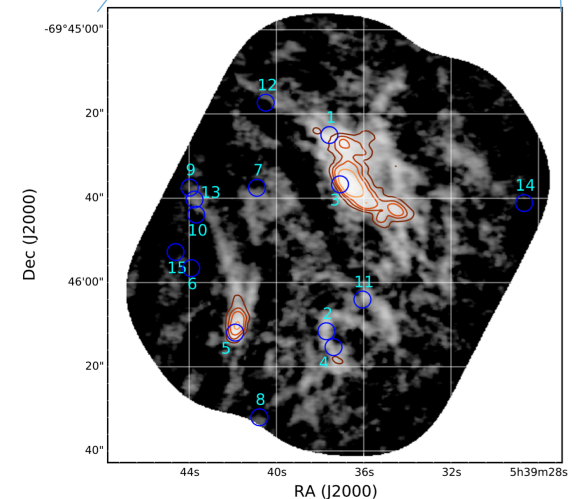
→ SOFIA will quantify this by measuring radiation field and
   density of the affected (star formation) layer

3) Adress evolutionary state of MYSOs

→ Molecular outflows through the C11-10 line
   (see talk I. Nayak tomorrow)
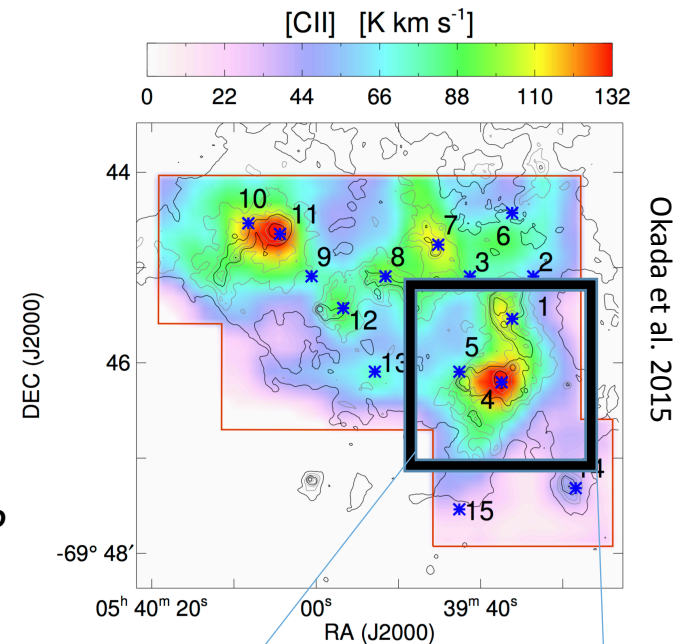
N159 region in the LMC

Okada et al. 2015

Yet again: what have we learned?

We have performed a galaxy-wide study of massive star formation
and its relation to the internal structure of GMCs.

✓ massive stars do not typically form at the highest column densities of their parent GMCs

Clues to the collapse of GMCs and the initial conditions of massive star formation

✓ massive star formation clusters over multiple generations and on size scales much smaller than the size of the parent GMC

**Massive star formation is a local process in GMCs**

✓ massive star formation is significantly boosted in clouds near stellar clusters, yet independent on global cloud properties

May confirm triggering as a key mode for massive star formation on galactic scales.

Backup

YSO characterization

- Multiband photometry (2MASS – Spitzer – Herschel)
- Color cuts to minimize contaminants → only complete for Stage 1 sources.
- Artificial star tests provide completeness limits in varying backgrounds.
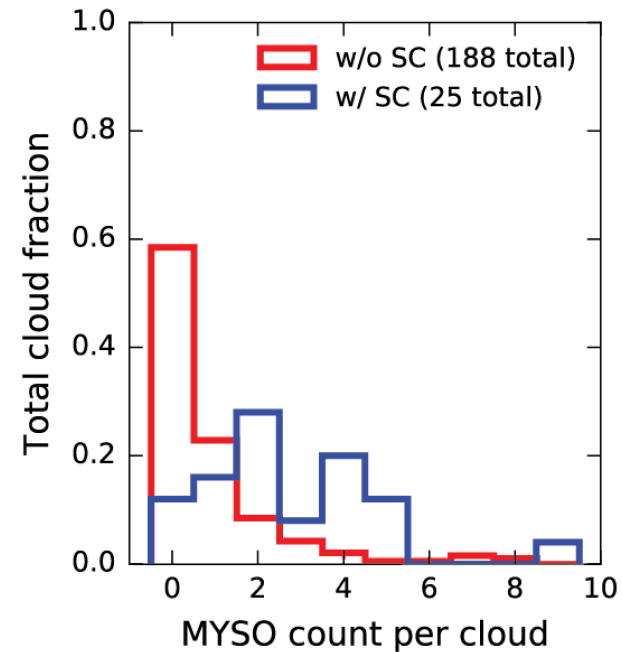- Compare this limits with predicted flux from models
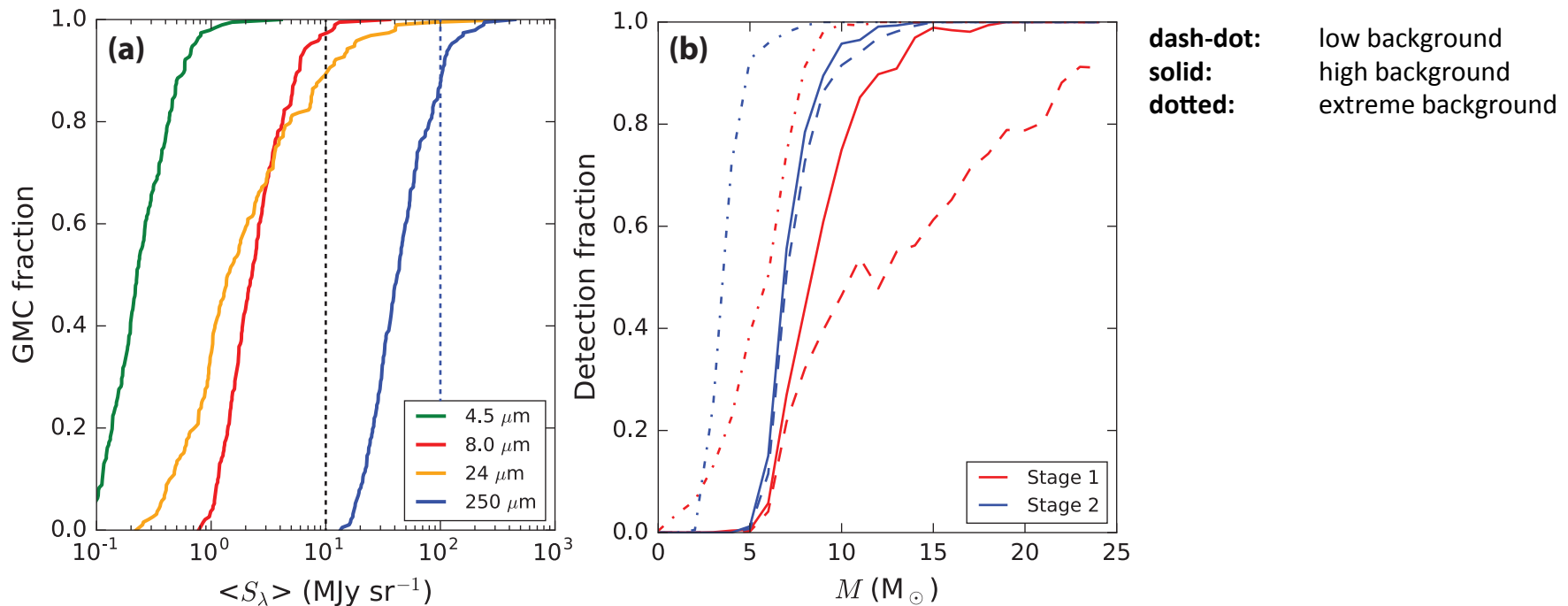
dash-dot: low background
solid: high background
dotted: extreme background

Modes of massive star formation

➢ **massive cores appear to form outside of the dense, opaque regions of GMCs!**

2) Triggered star formation?
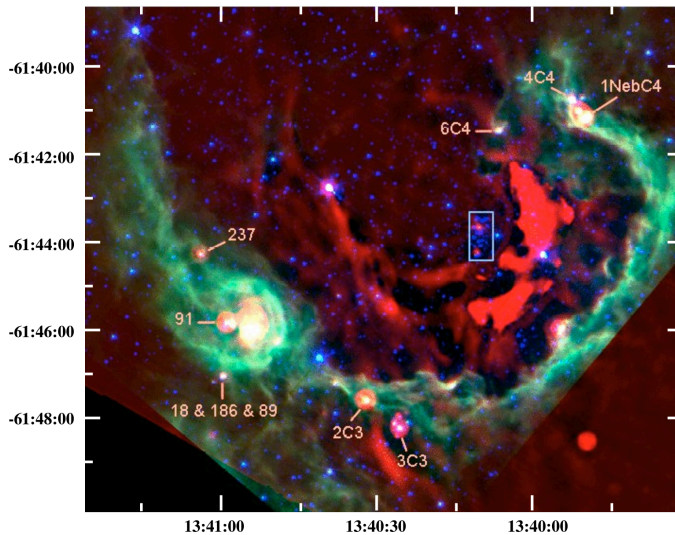
RCW 79; Martins et al. 2010

➢ Triggering as a key mode of massive star formation may explain:
- Location of massive star formation
- The connection of different generations of massive stars up to 10 Myr
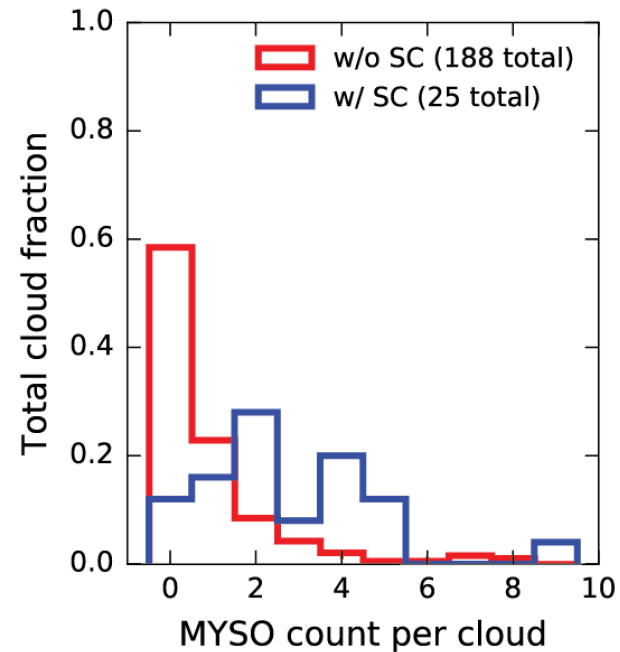
Modes of massive star formation

➤ **massive cores appear to form outside of the dense, opaque regions of GMCs!**
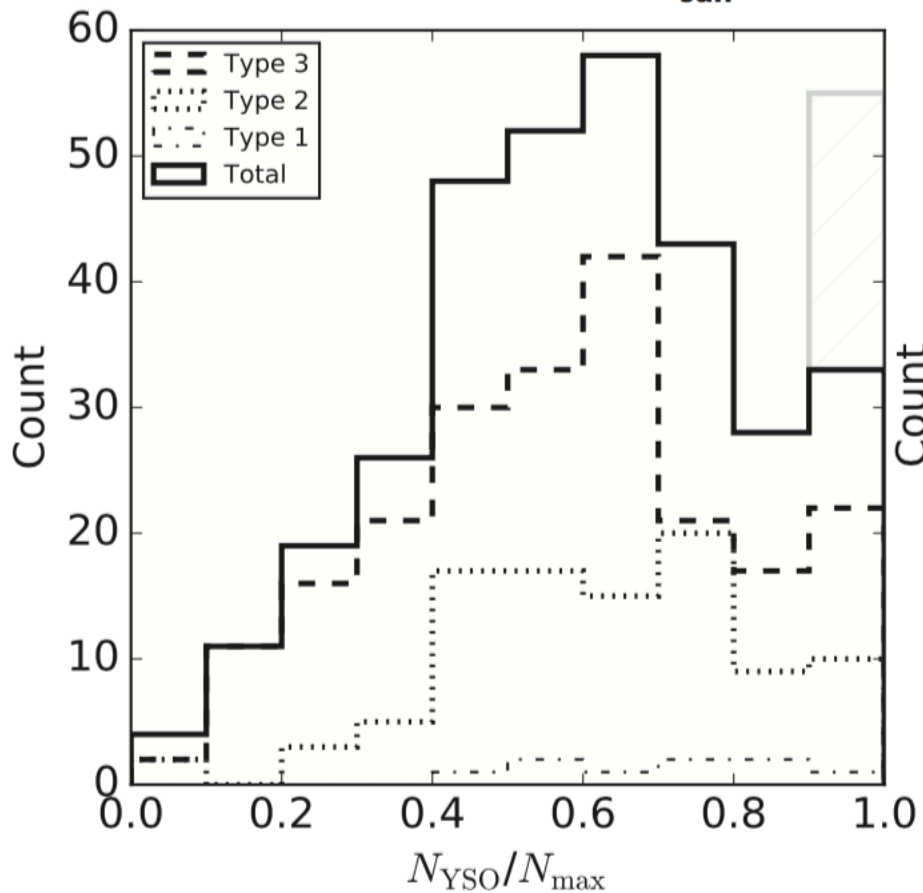
2) Triggered star formation?

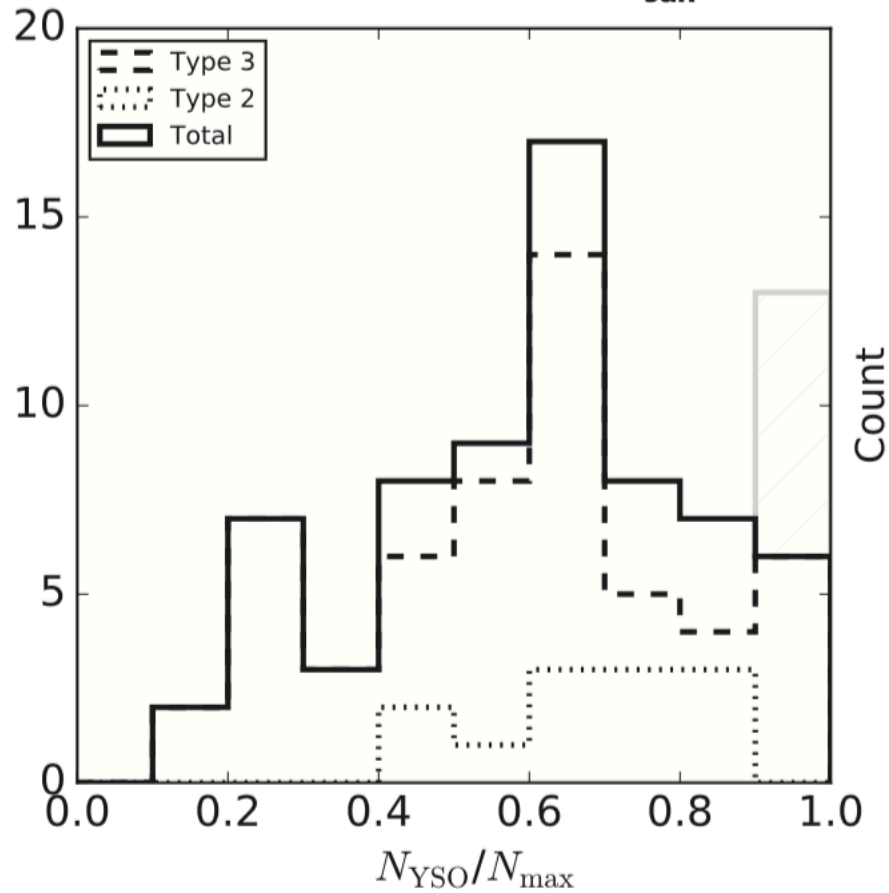N11; C. Aguilera, C. Smith and S. Points/NOAO/AURA/NSF,
Walborn & Parker 1992

➤ Triggering as a key mode of massive star formation may explain:
 - Location of massive star formation
 - The connection of different generations of massive stars up to 10 Myr

Backup

Global properties of embedded massive SF

~50% of GMCs in the LMC are actively forming massive stars

TABLE 1
EMBEDDED MASSIVE STAR FORMATION IN GMCs

	Number of GMCs	p_{MYSO}	$<N_{MYSO}>$
Type 1	42	14%	0.2
Type 2	93	49%	1.0
Type 3	52	75%	3.9
TOTAL	187	48%	1.6

GMC EVOLUTION
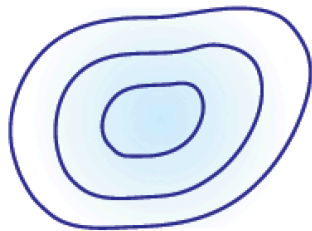
Type 1
no massive star formation
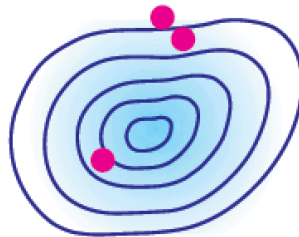
Type 2
only HII regions

Type 3
HII regions + exposed stellar clusters

Backup
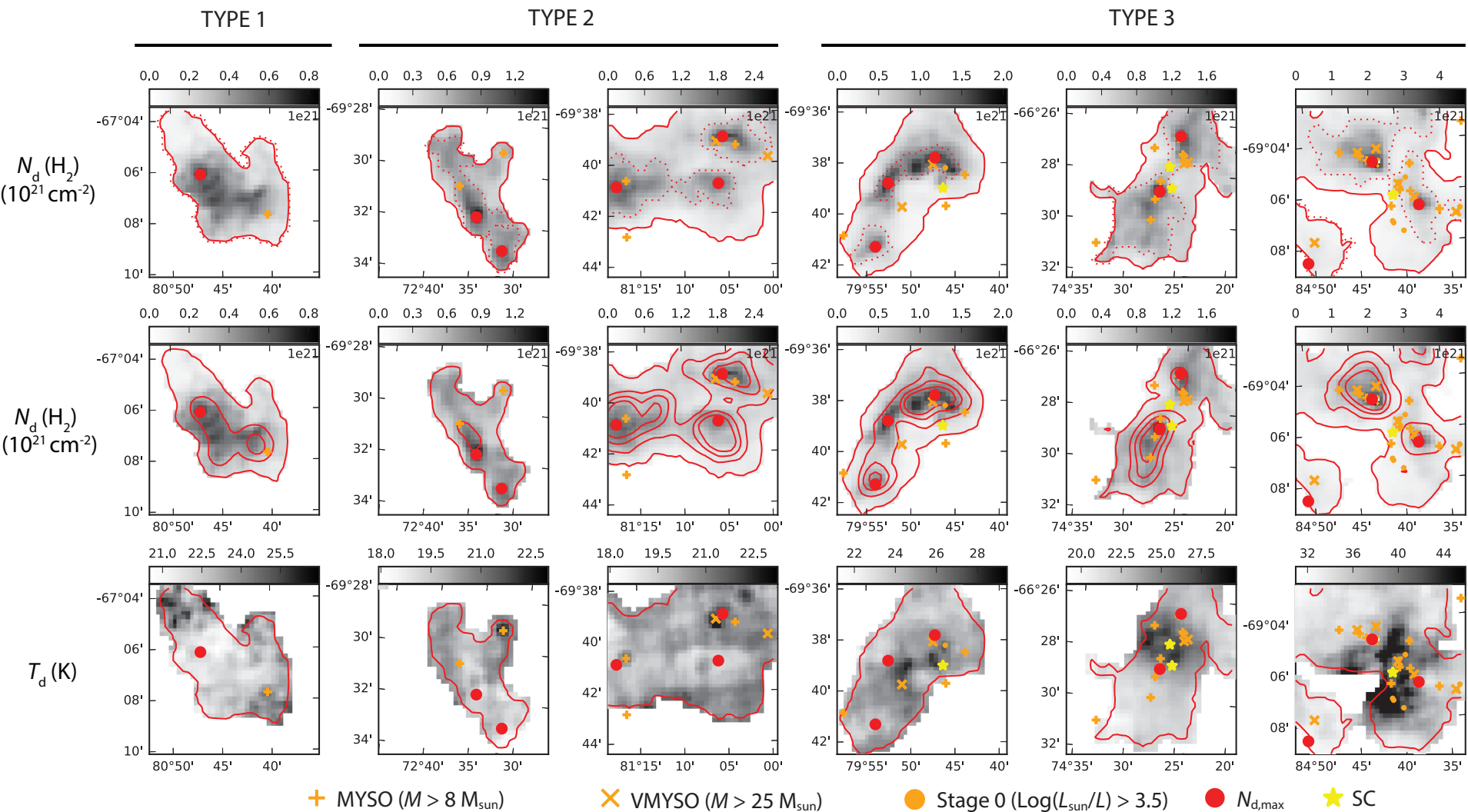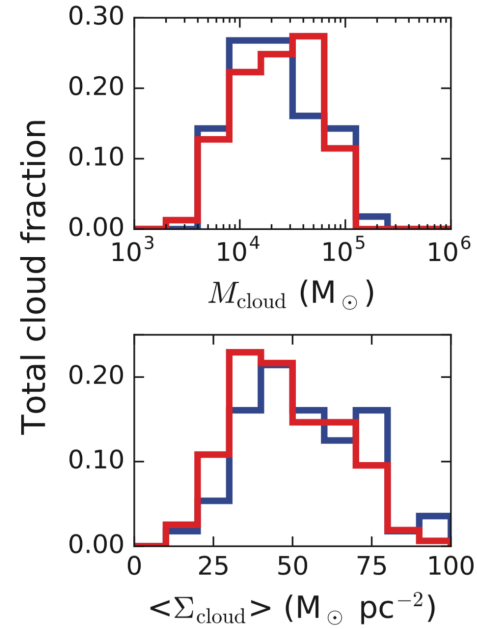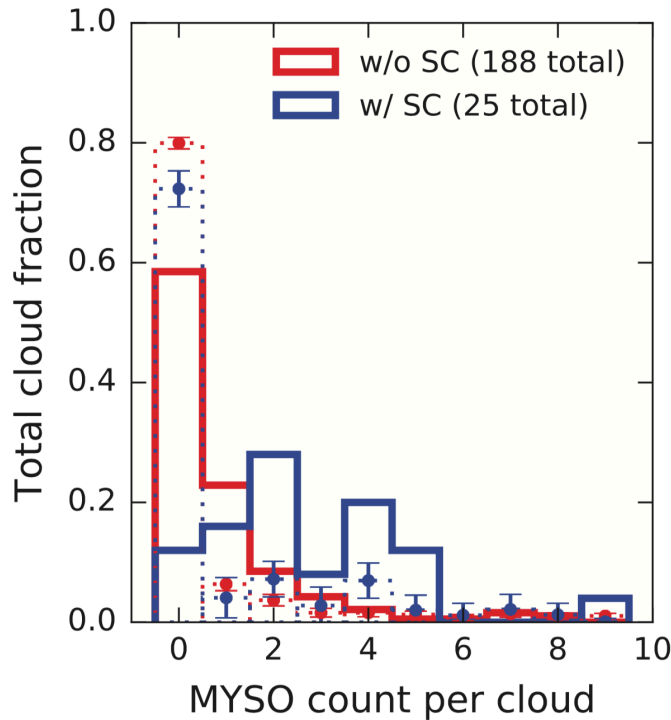
TYPE 1　　　　TYPE 2　　　　TYPE 3

Rows (left axis labels): $N_d(H_2)$ $(10^{21}\,cm^{-2})$; $N_d(H_2)$ $(10^{21}\,cm^{-2})$; T_d (K)

Legend:
+ MYSO ($M > 8\,M_{sun}$)　　× VMYSO ($M > 25\,M_{sun}$)　　● Stage 0 (Log(L_{sun}/L) > 3.5)　　● $N_{d,max}$　　★ SC
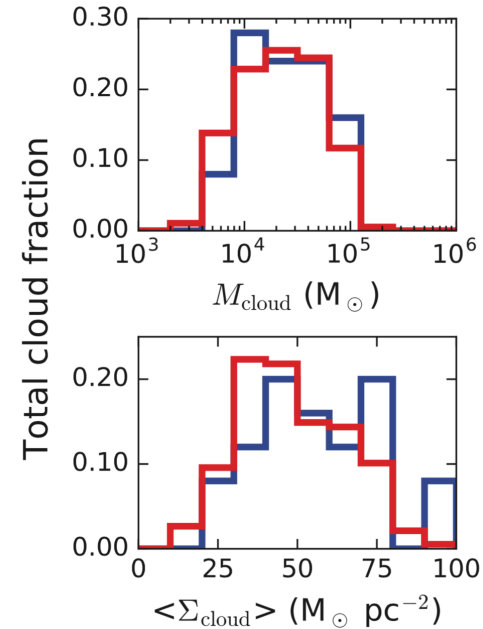
Clustering of massive star formation

Conclusion

Massive star formation
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However global properties of
clouds very similar!

Connection between massive stars on timescales up to 10 Myr!
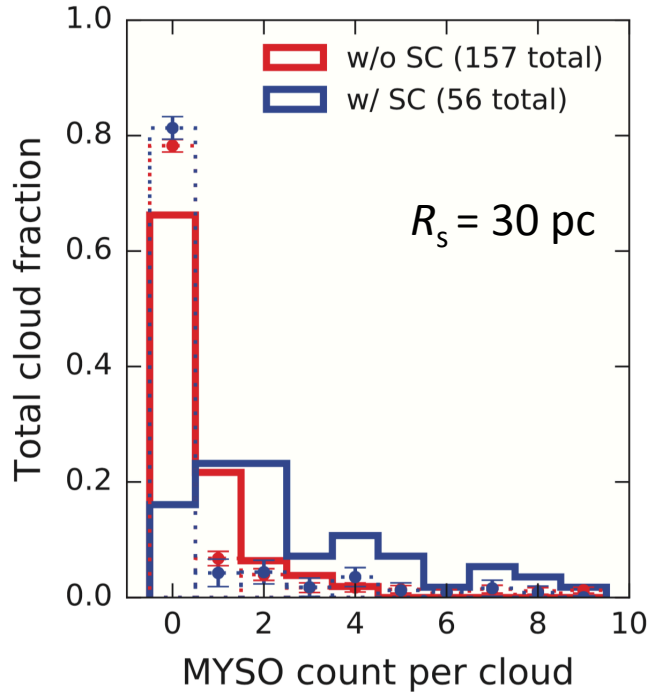
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