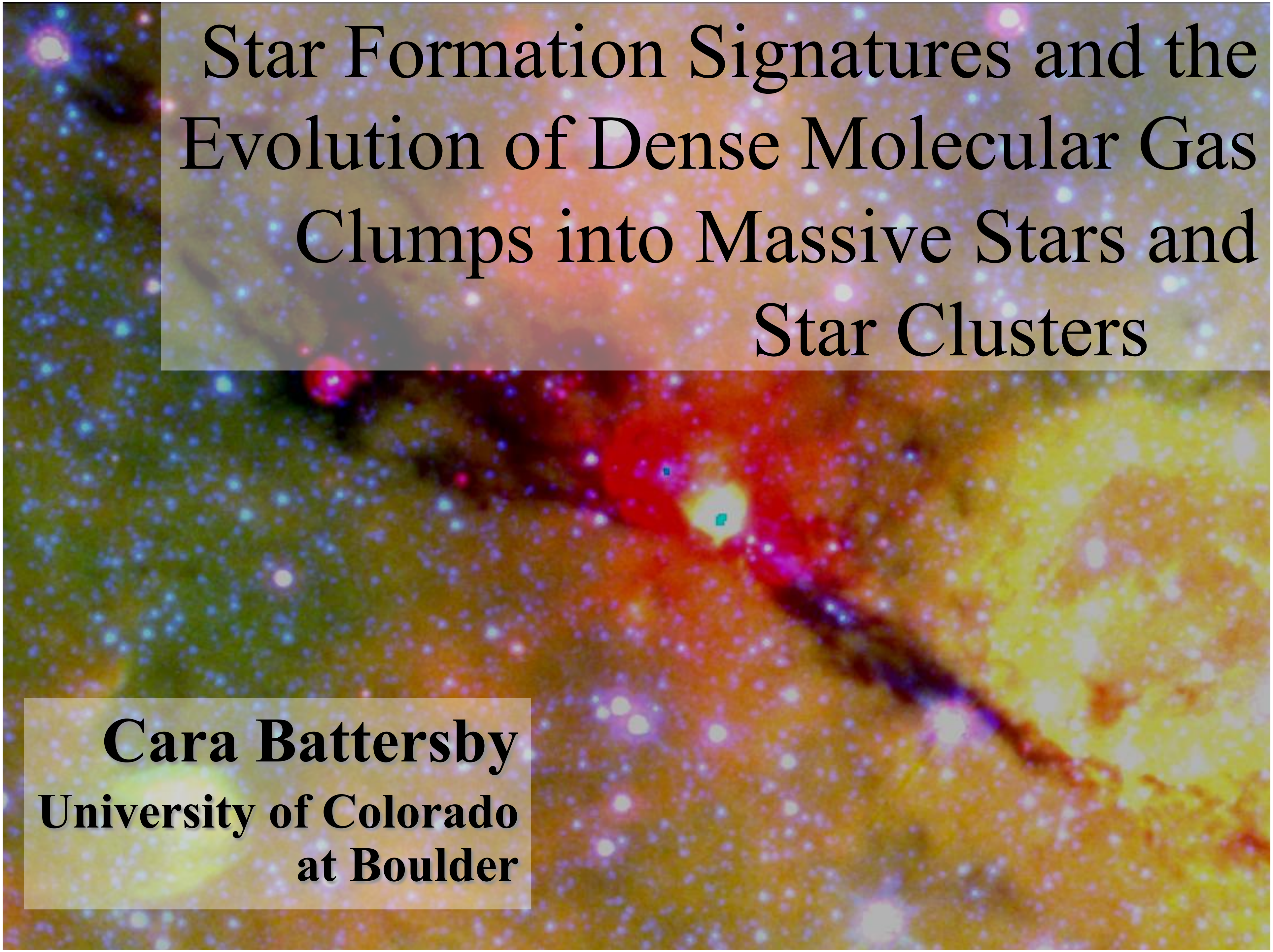


Star Formation Signatures and the Evolution of Dense Molecular Gas Clumps into Massive Stars and Star Clusters

Cara Battersby

University of Colorado at Boulder

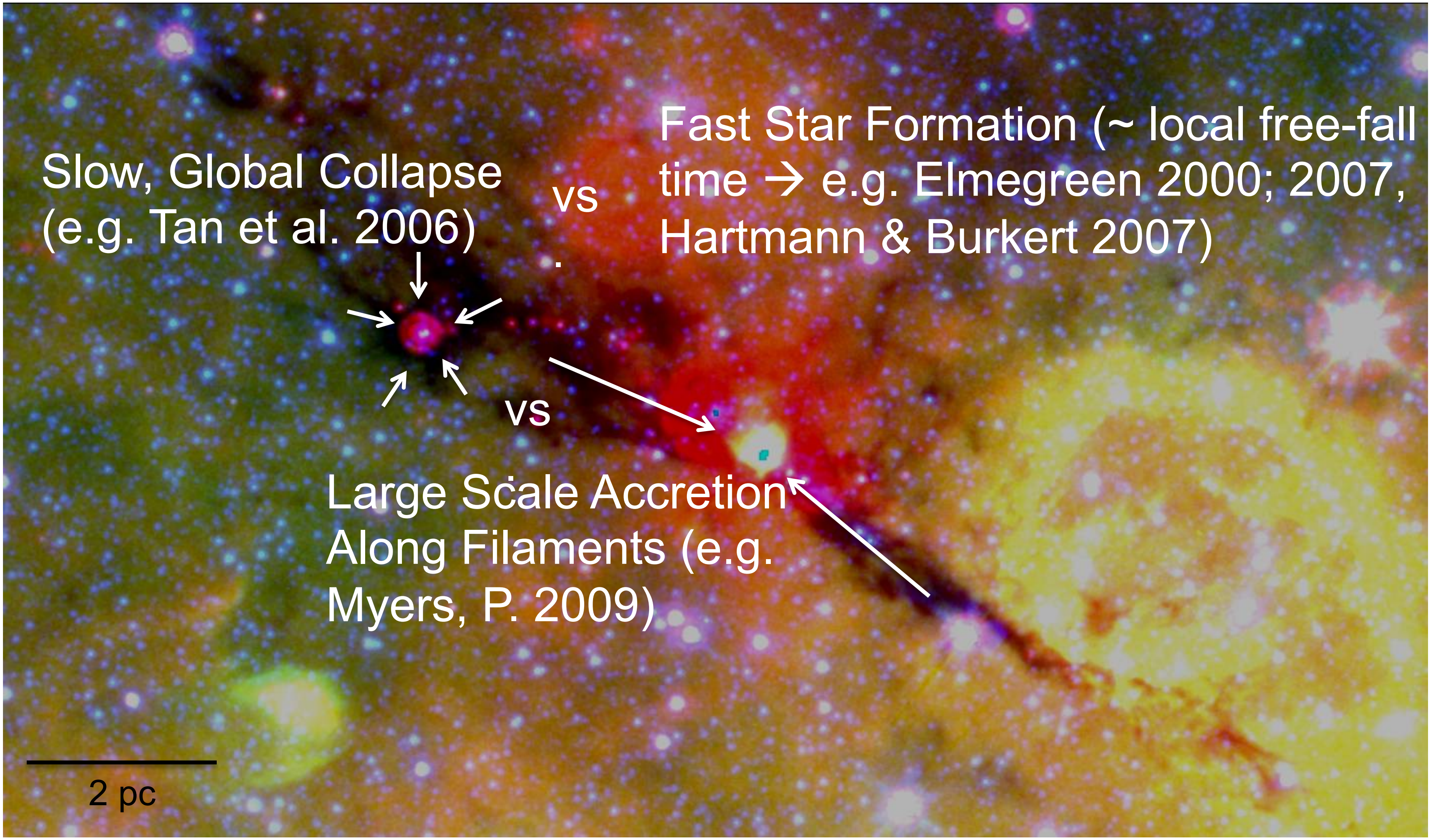
Local Collaborators:

John Bally, Adam Ginsburg, Jeremy Darling, Miranda Dunham

International Collaborators:

J.P. Bernard, E. Bressert, C. Brunt, G. A. Fuller, S. Longmore, P. Martin, S. Molinari, J. Mottram, N. Peretto, L. Testi, and M. A. Thompson

Slow vs. Fast Star Cluster Formation



Open Questions

"How does the forming massive star influence its immediate surroundings, possibly limiting its final mass and/or the final mass of its neighbors?"

"What is the sequence of observable states leading from molecular clouds to young high-mass stars?"

"How do young massive stars influence their global environment, either by inhibiting or by triggering further star formation? How do we get a starburst?"

"Do massive stars always form in dense stellar clusters or can they form in isolation? What special conditions are necessary to allow coalescence, i.e., mergers of stars?"

"Which clues to the origin can be gleaned from multiplicity observations? How do we explain the very tight massive spectroscopic binaries and OB runaway stars?"

"What are the initial conditions of massive star formation (gas densities, temperatures, clump masses, etc.) and how do they come about?"

Is the IMF universal? If so, what is it's origin or physical significance?

Where do star clusters form in the Galaxy? How many are forming?

What is the role of feedback in cluster formation? At what point does it halt star formation?

What is the role of competitive accretion and dynamical interactions?

Is there a maximum stellar mass? What determines it?

Is there a minimum surface density required for massive star and cluster formation? What is it?

What are the phases of massive star and cluster formation? What are the relative lifetimes of each phase?

How do clusters form out of the ISM? Collapse of a single GMC or continuously accrete from the ISM?

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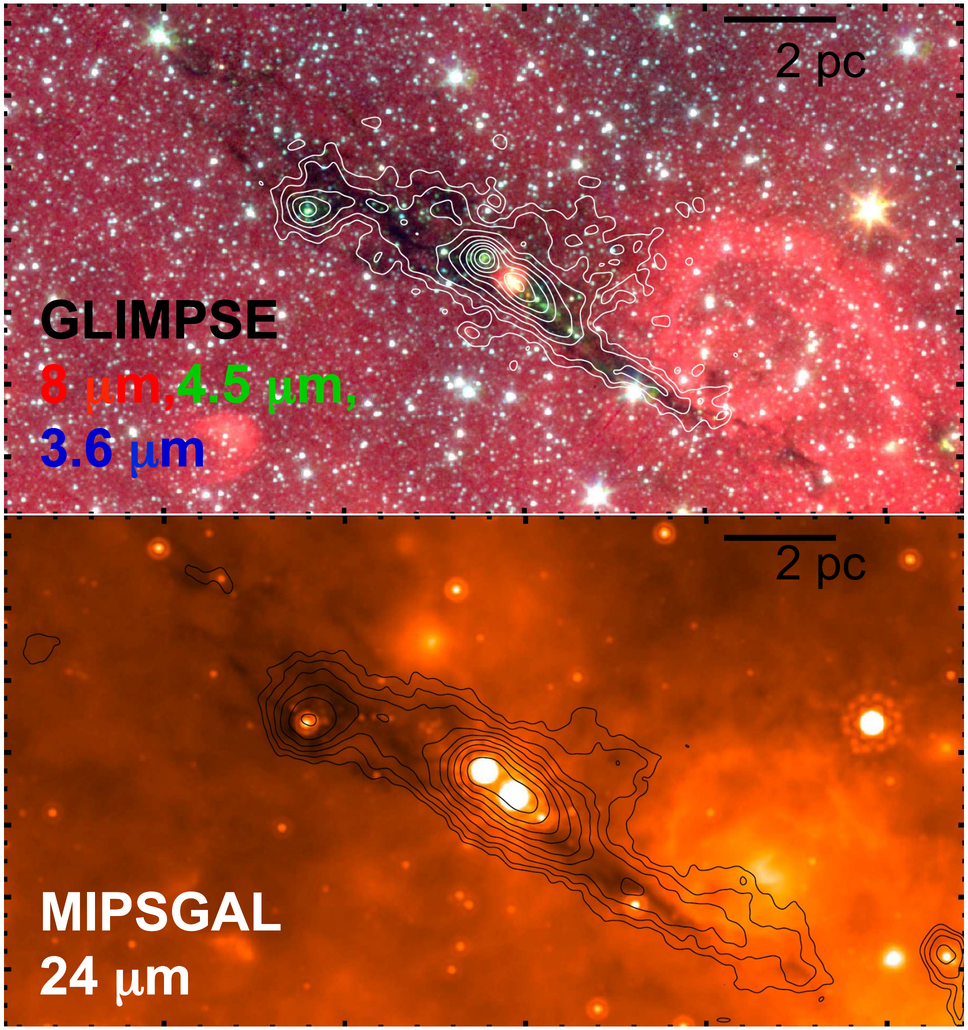
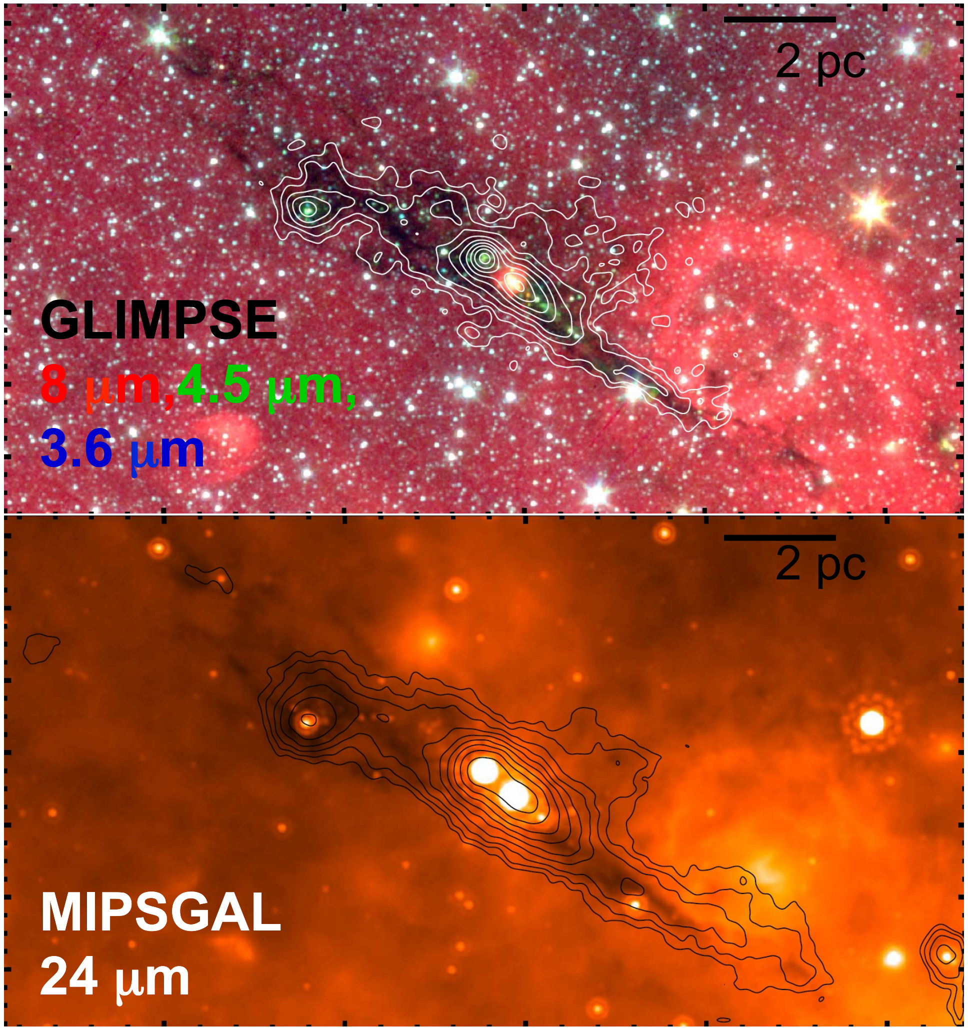
Infrared Dark Clouds (IRDCs) → Stellar Clusters?

- Massive Stars form predominantly in clusters

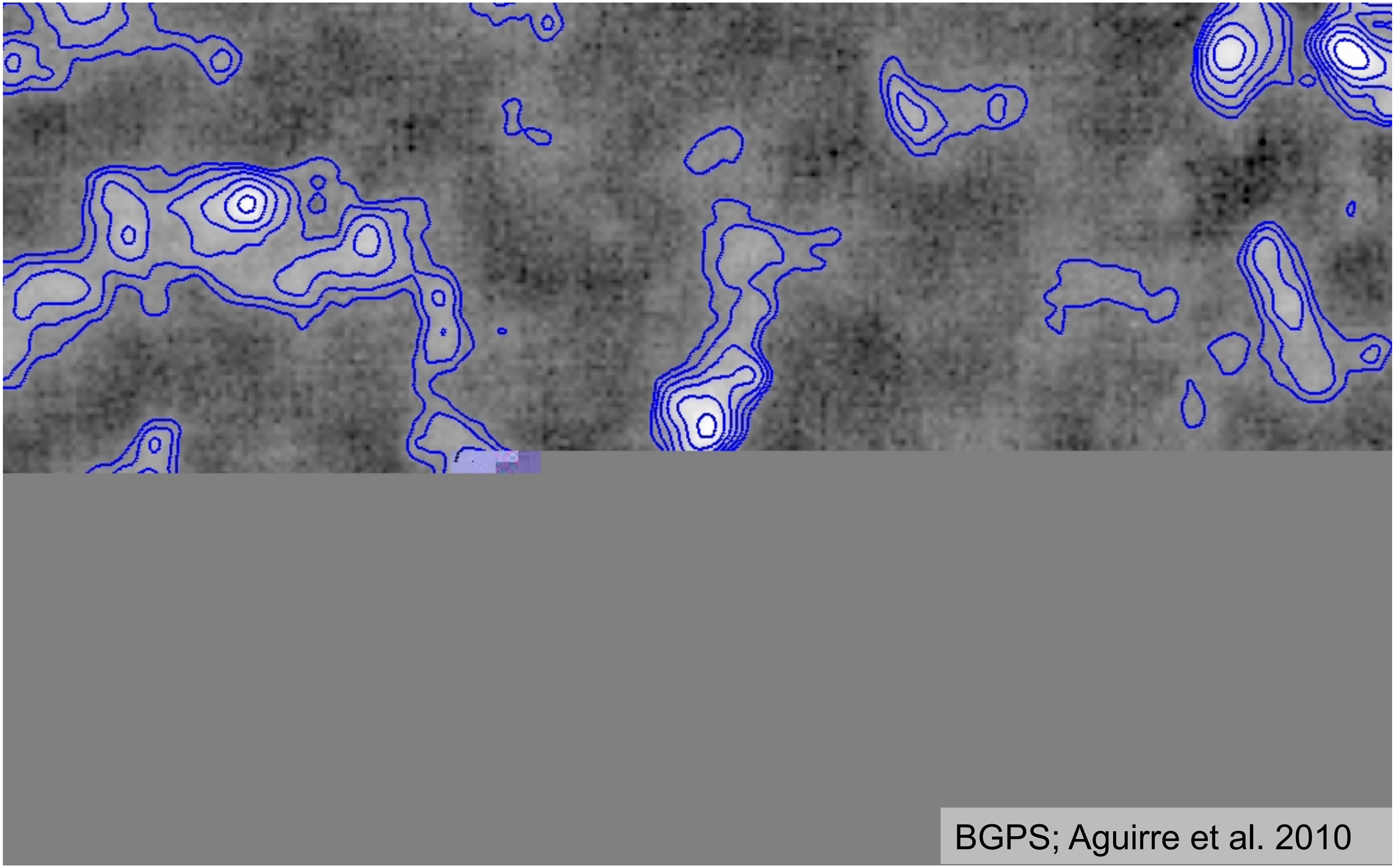


Infrared Dark Clouds (IRDCs) → Stellar Clusters?

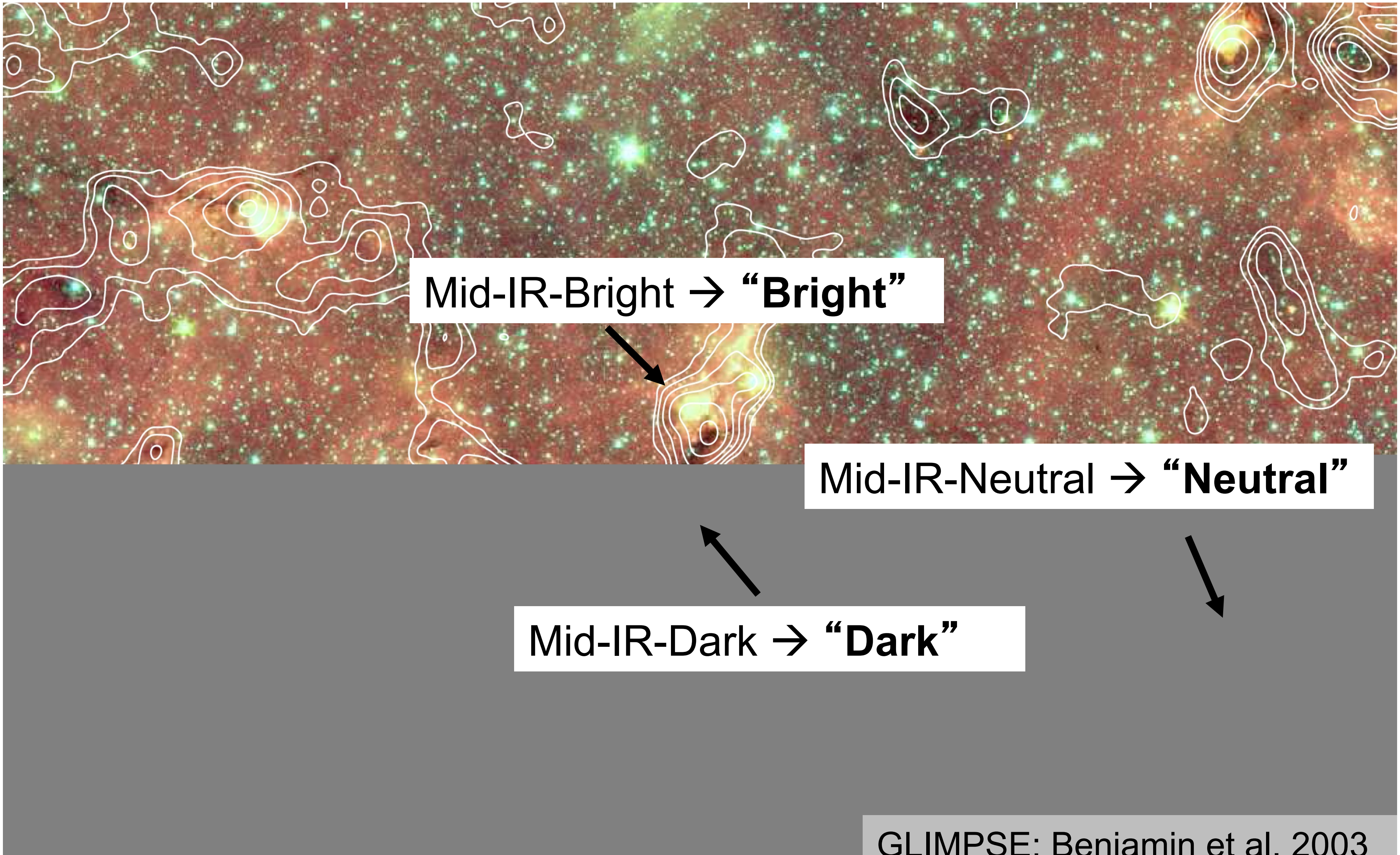
- Massive Stars form predominantly in clusters
- Bok Globules
  - Cold (10 – 20 K)
  - Isolated
  - Density ~ 10^3 - 10^4 cm^{-3}
  - Mass ~ 0.3 – 80 $M_\odot$
- IRDCs
  - Cold (10 – 20 K)
  - Dense > 10^5 cm^{-3}
  - Massive 10^2 – 10^4 $M_\odot$



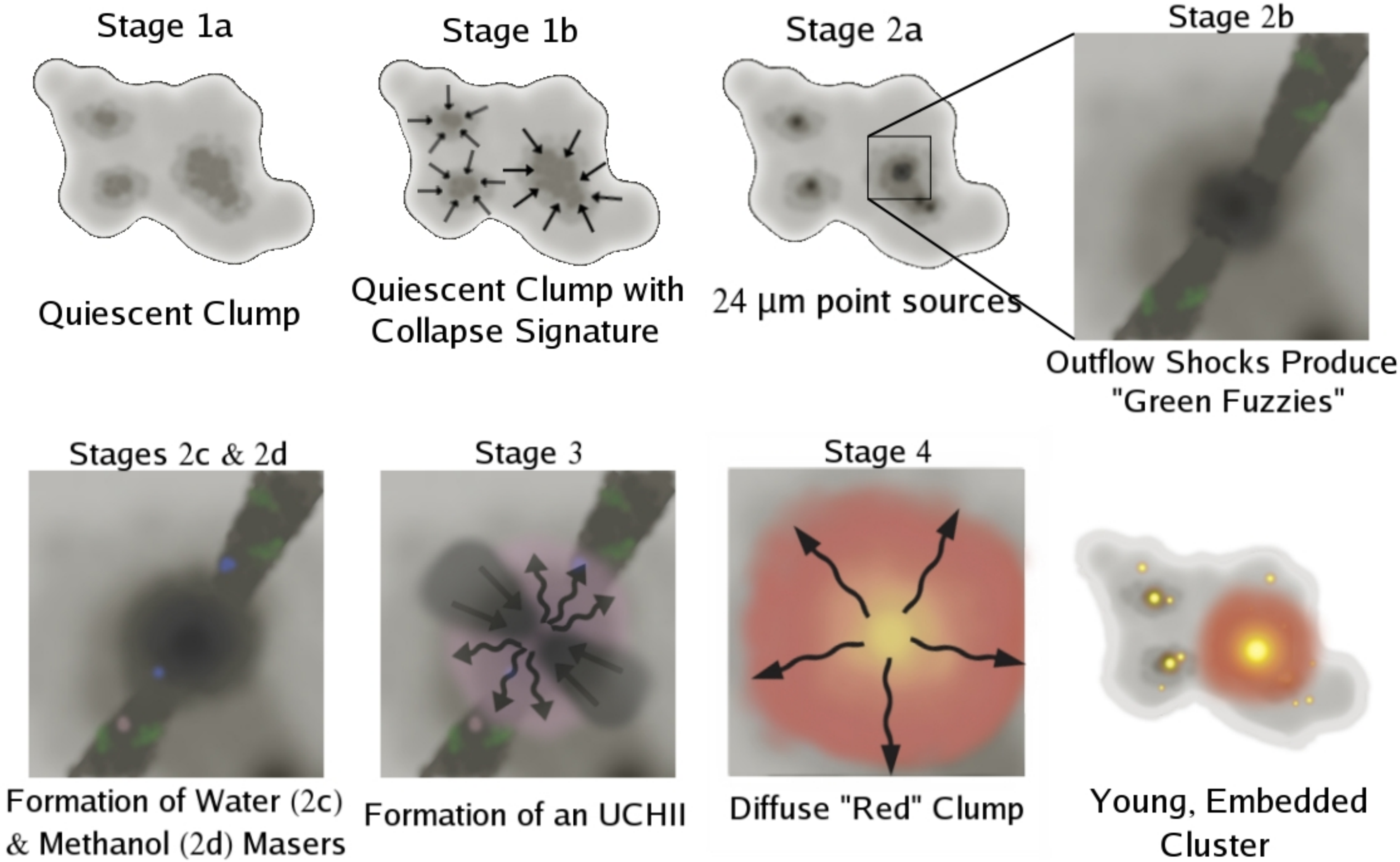
Bolocam Galactic Plane Survey (BGPS)
1.1 mm dust continuum



GLIMPSE mid-IR image (red: 8 μm, green: 4.5 μm, blue: 3.6 μm) with BGPS contours



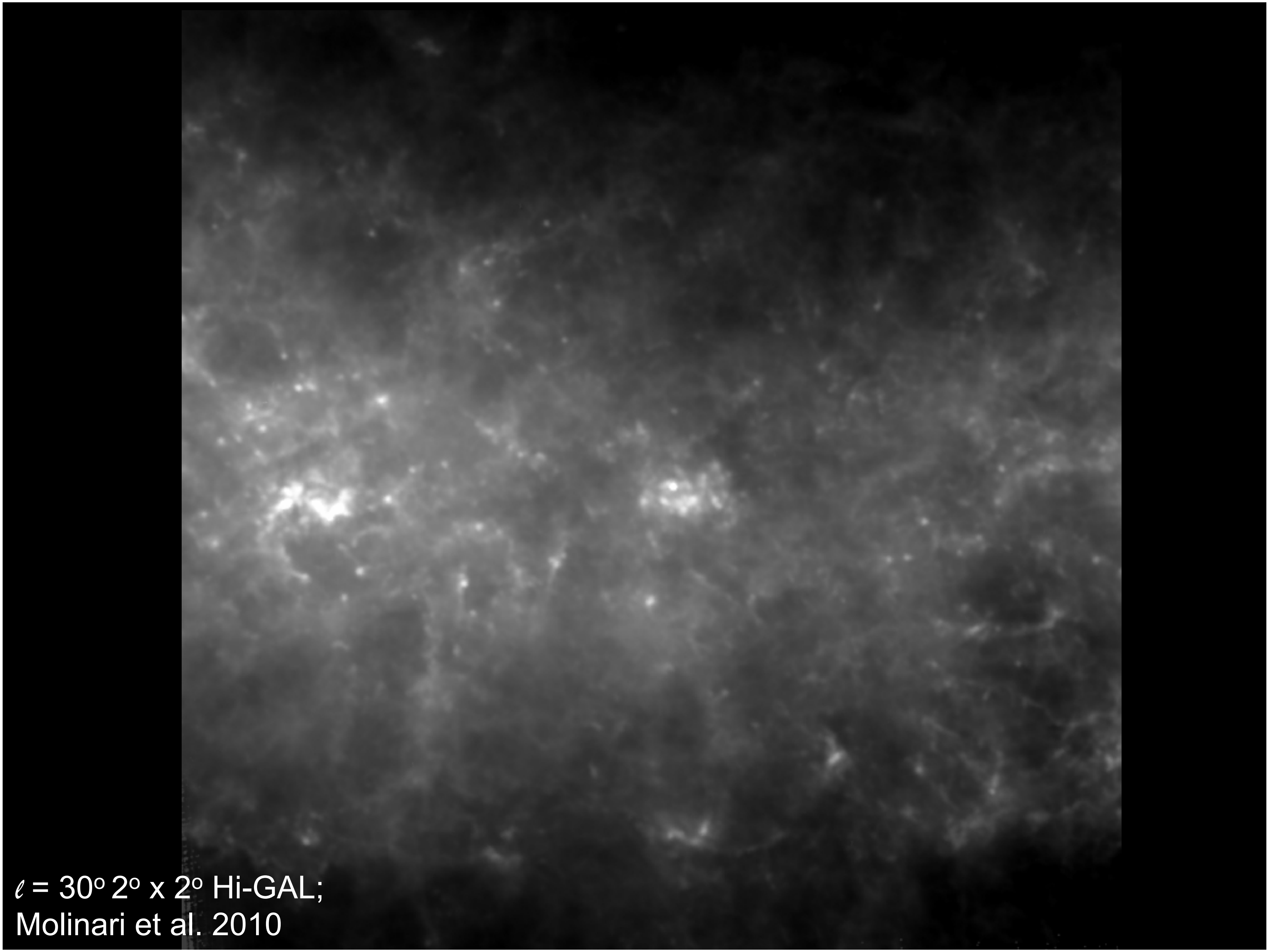
Evolution

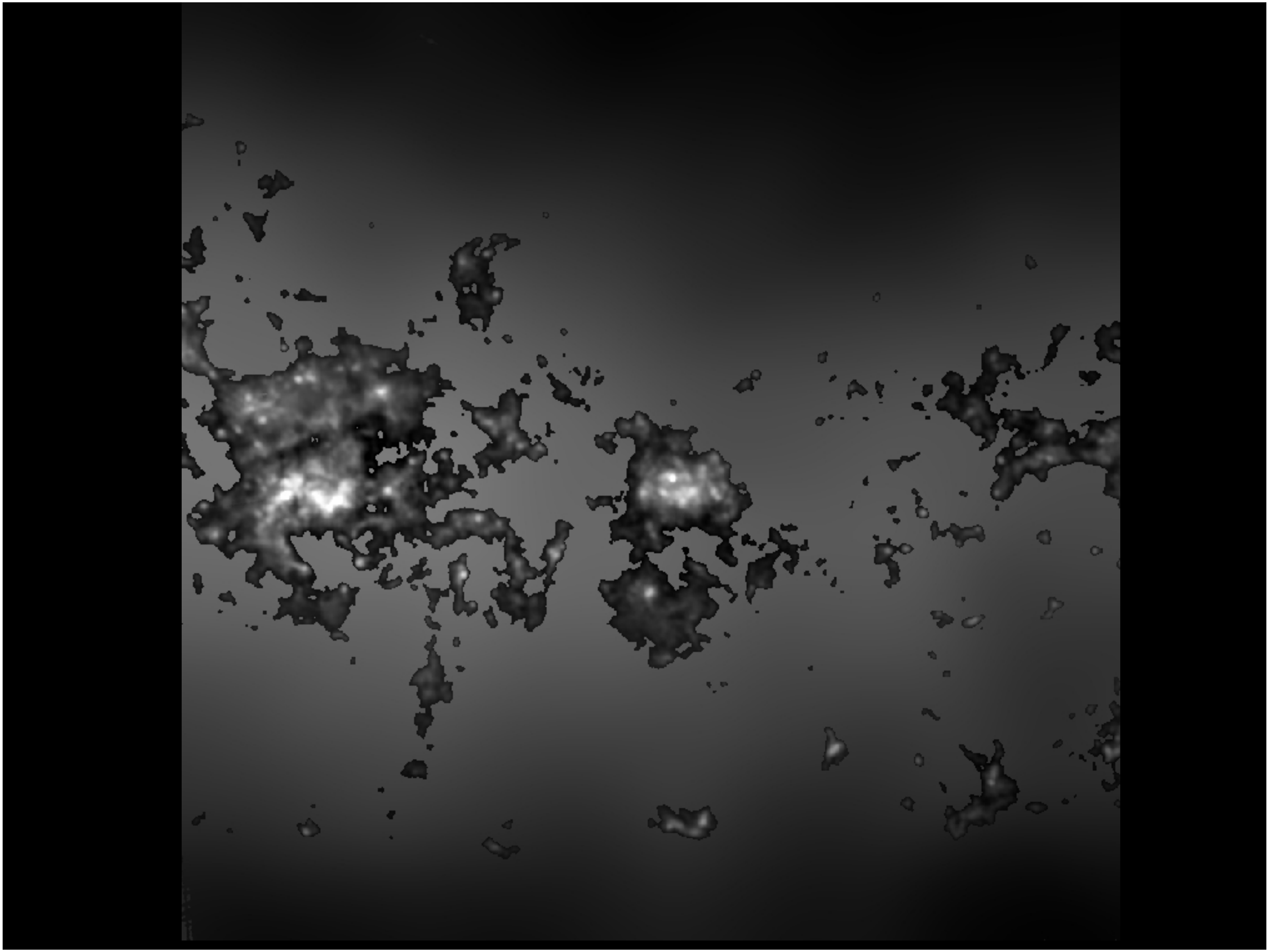


Battersby et al., ApJ, 2010

Plan of Attack

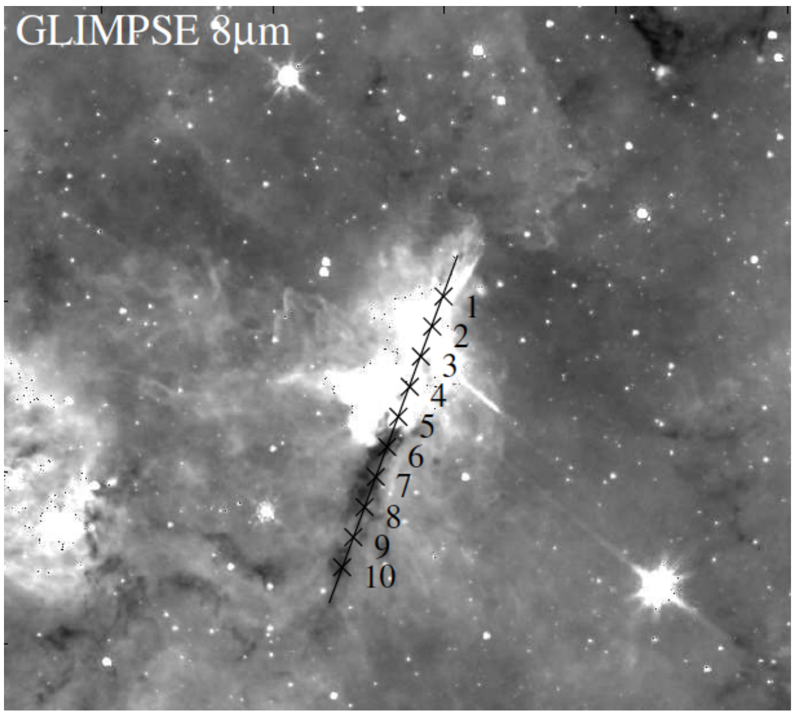
- Use Herschel 70 – 500 μm dust continuum data from Hi-GAL to identify dense clumps → potential precursors to stellar clusters
- Use graybody fits to determine the dust temperature and column density
- Complement with mid-IR (GLIMPSE, MIPSGAL) and methanol maser surveys to determine and then correlate star formation activity and determine lifetimes

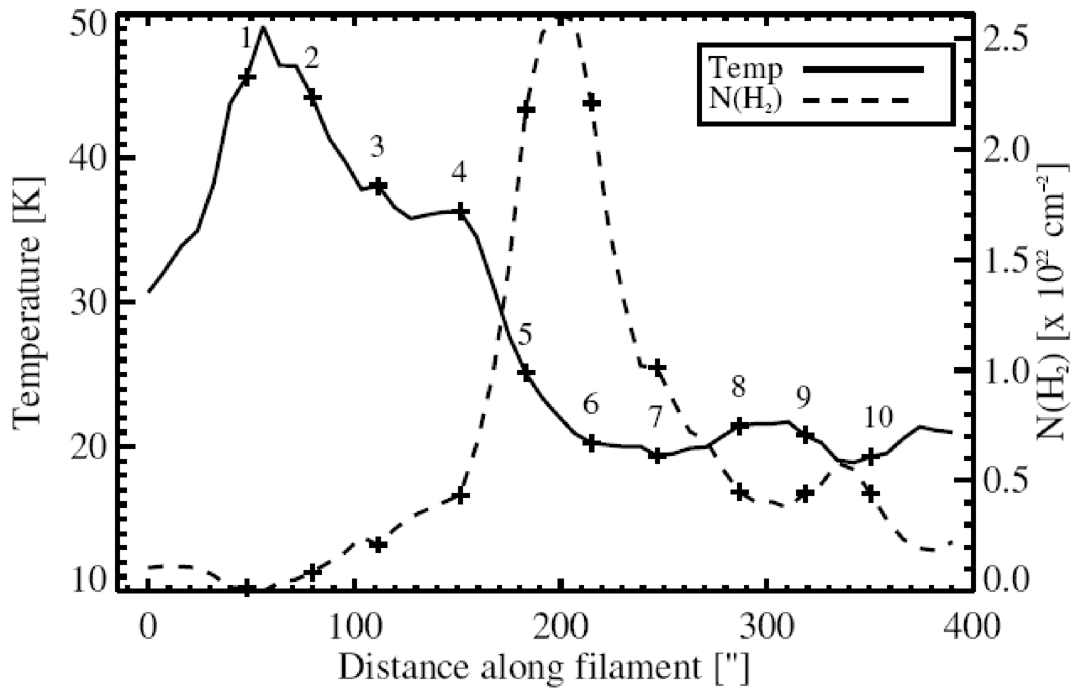

ℓ = 30º 2º x 2º Hi-GAL;
Molinari et al. 2010



T and $N(H_2)$ along the Filamentary Source

Battersby et al. 2011

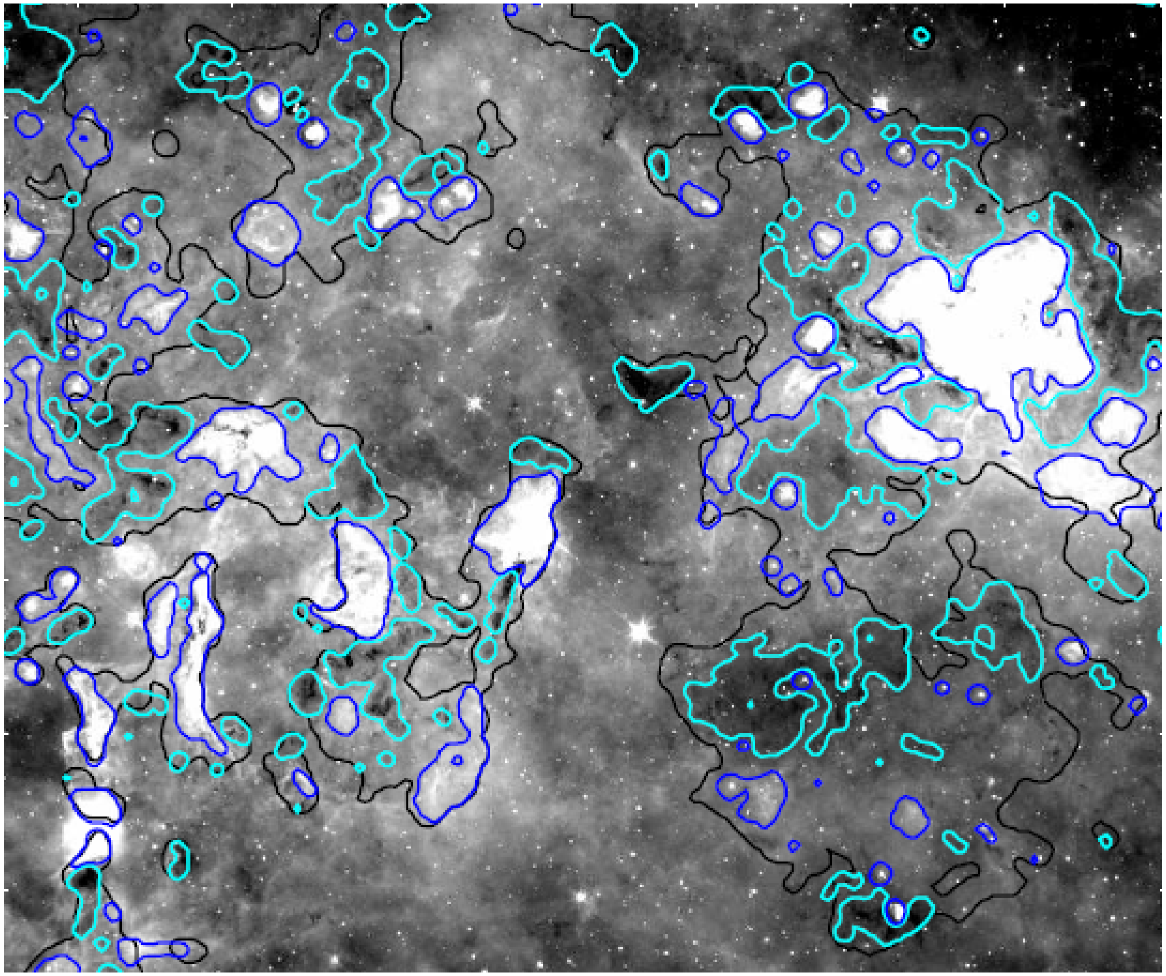




Recent results show that these dust-measured temperatures and column densities agree reasonably well with NH3-measured temperatures and column densities (Battersby et al, 2012, in prep)

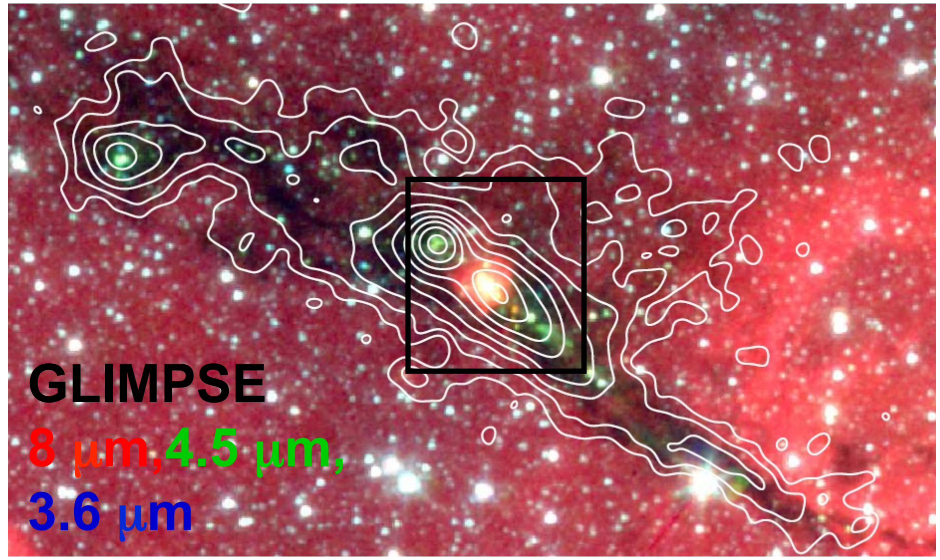
Dark vs. Bright

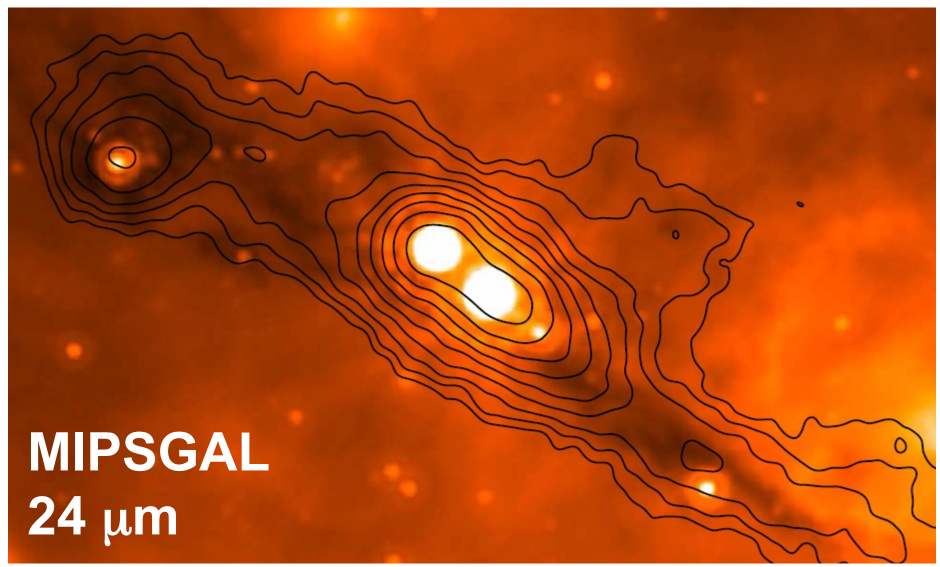
- map of **"dark"** (cyan) and **"bright"** (blue) pixels within source masks (black contours)



Star Formation Tracers

- Shock/Outflow indicators
  - Methanol Masers (e.g. Pestalozzi et al. 2005, Szymczak et al. 2002, Ellingsen et al. 1996)
  - Extended Green Objects (EGOs) (e.g. Cyganowski et al. 2008, Chambers et al. 2009)
- Embedded Star
  - 24 μm point source (MIPS; Carey et al. 2009)
- UCHII region
  - indicated by a “red clump” 8 μm bright source (Battersby et al. 2010)





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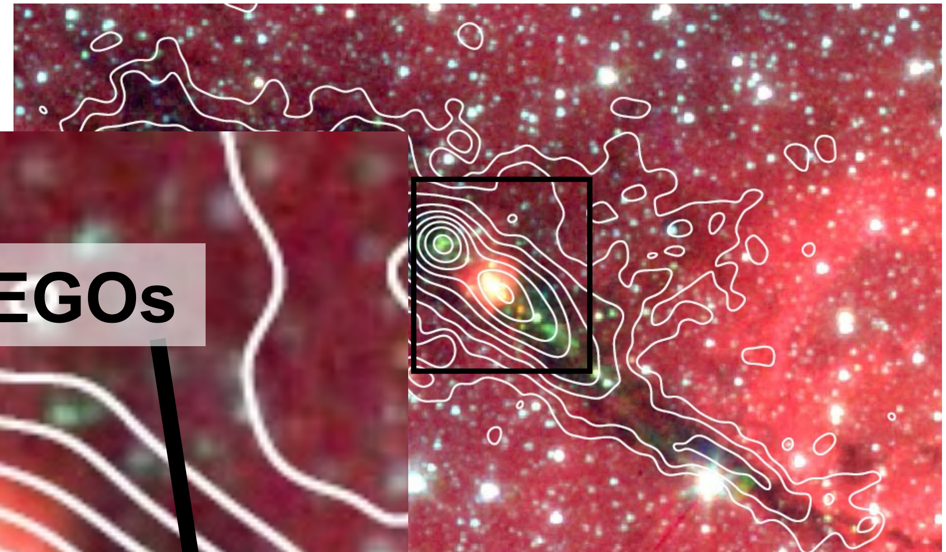

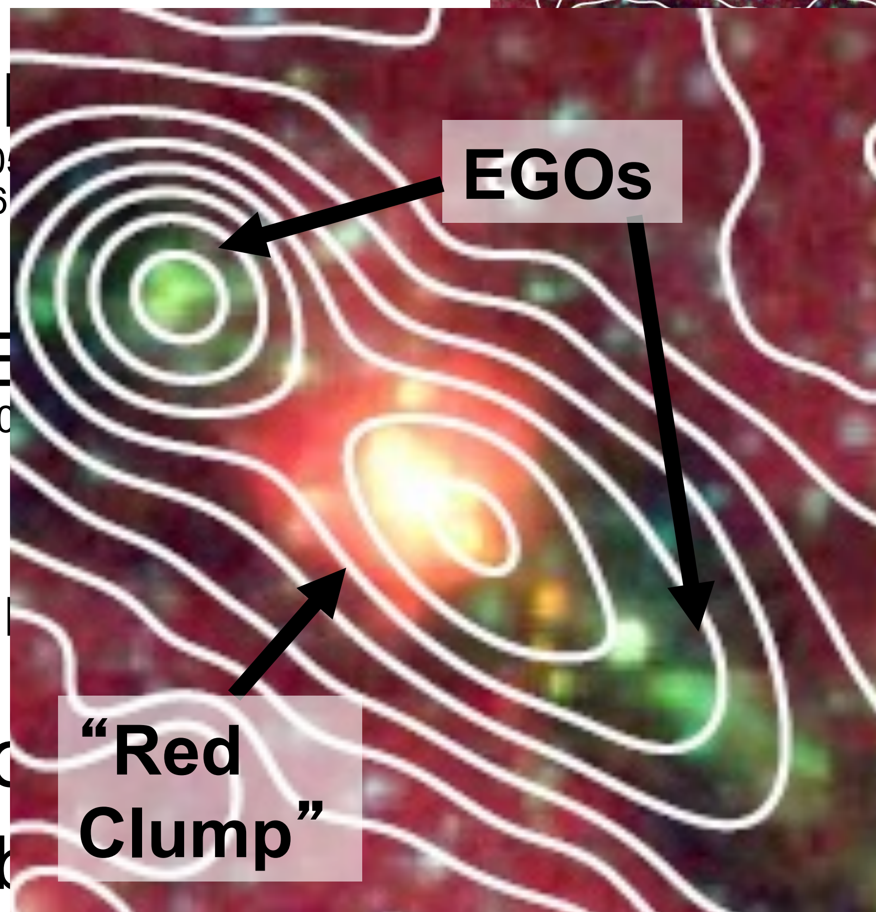

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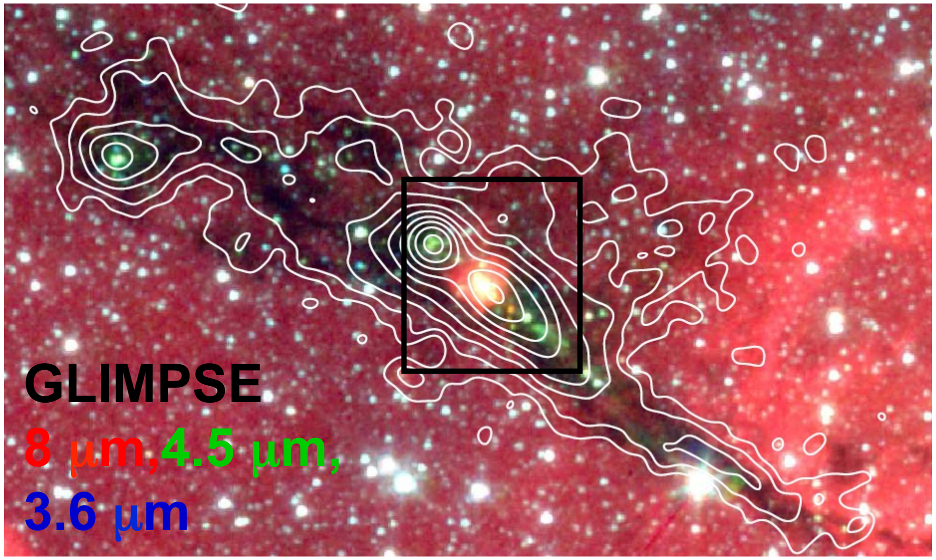
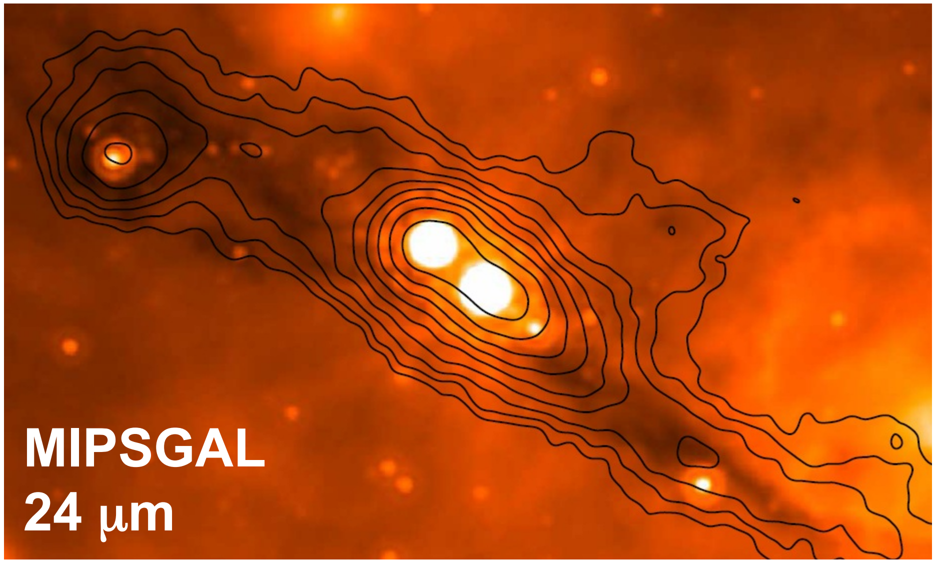
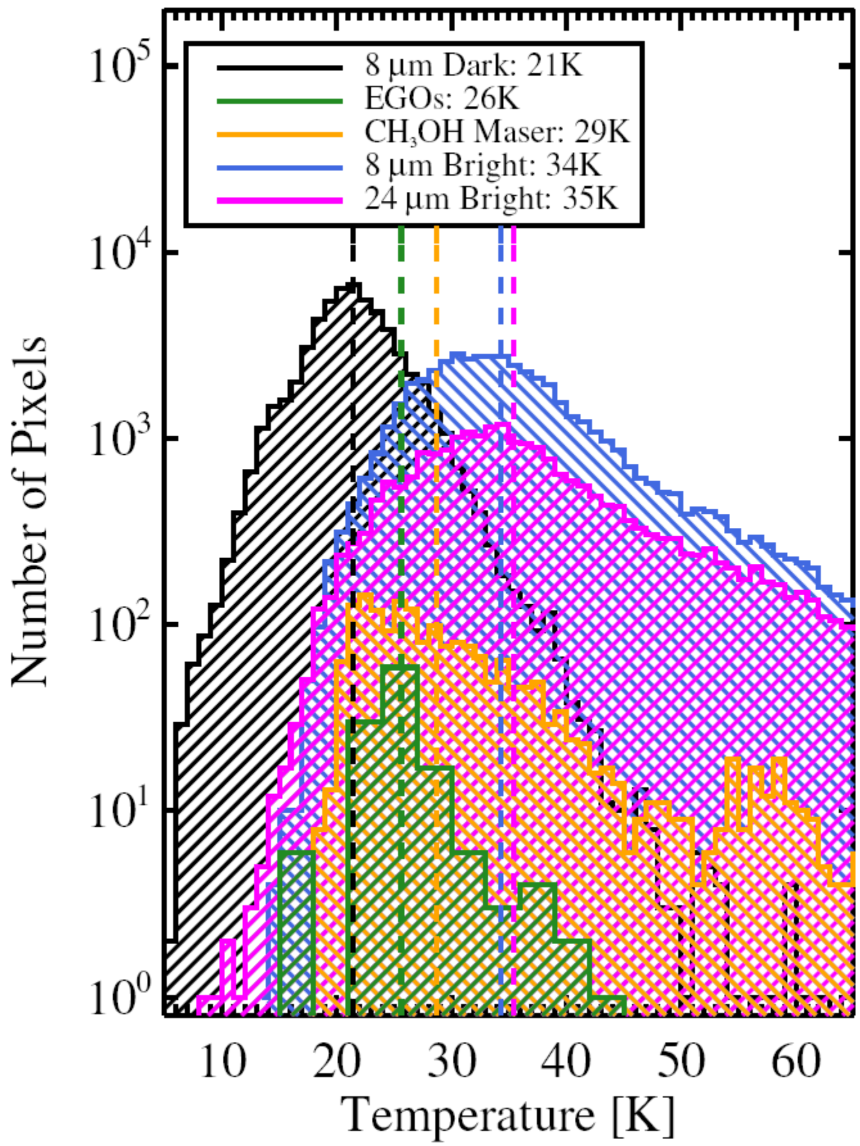
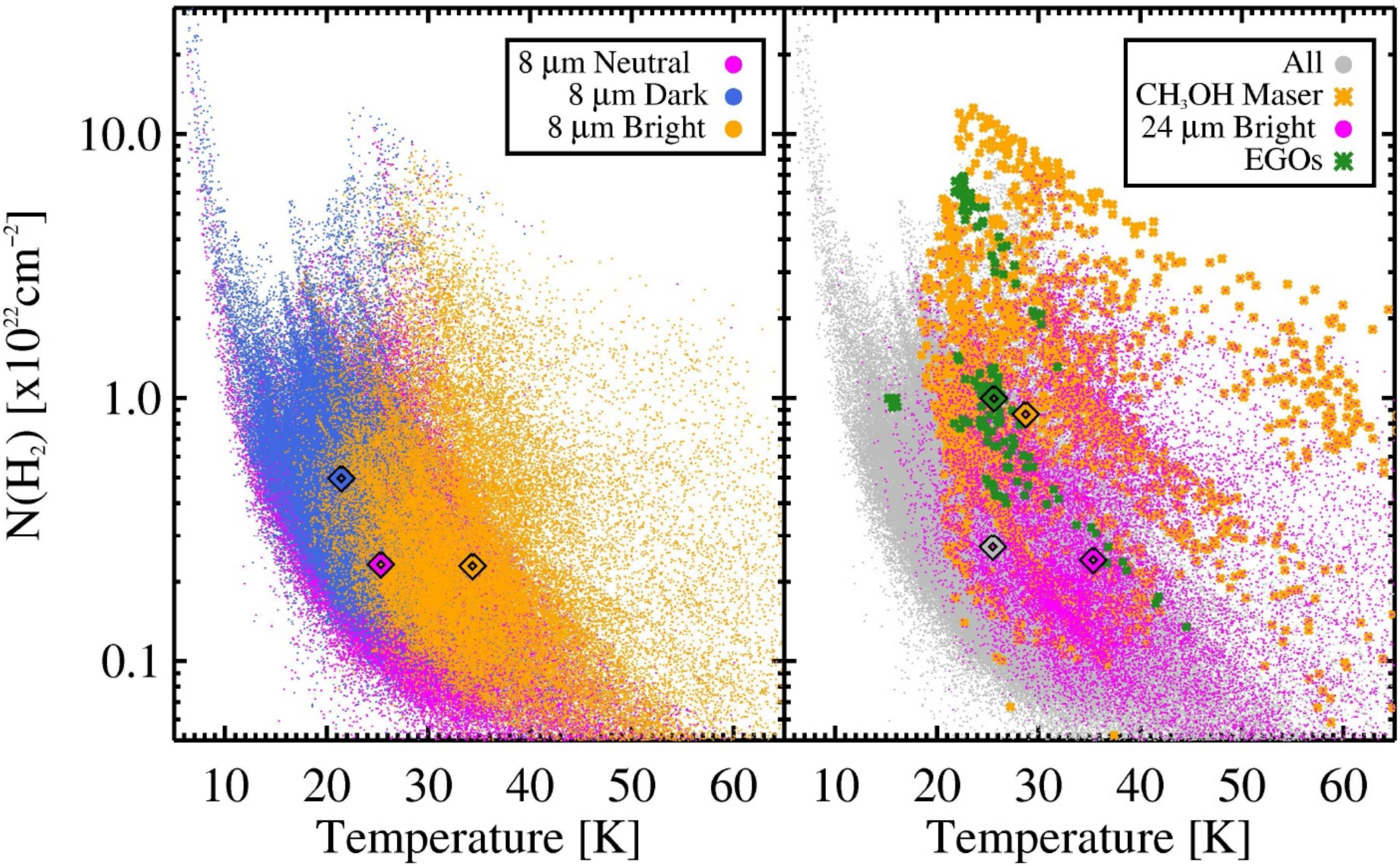




Progression of SF Tracers



Battersby et al. 2011



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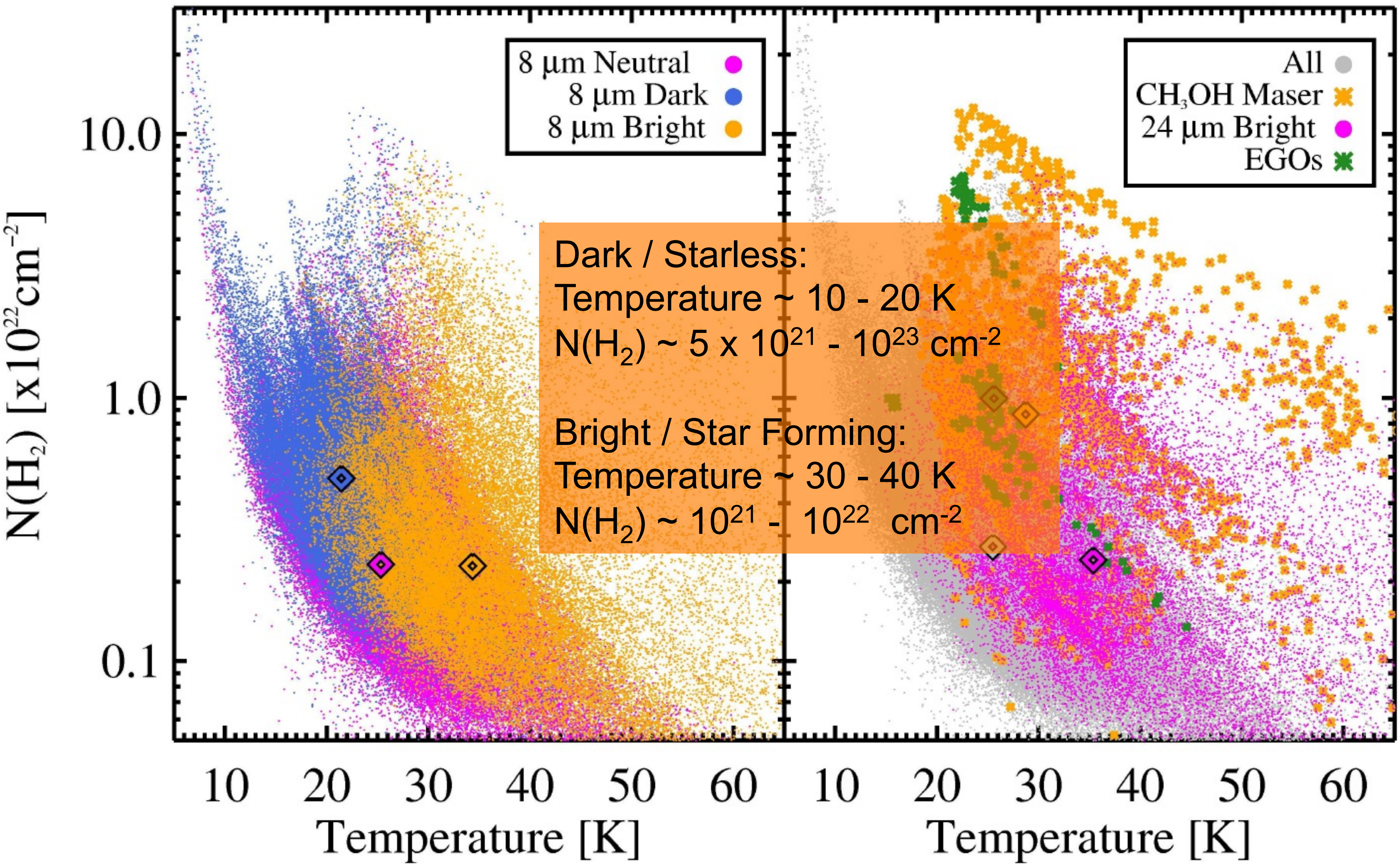

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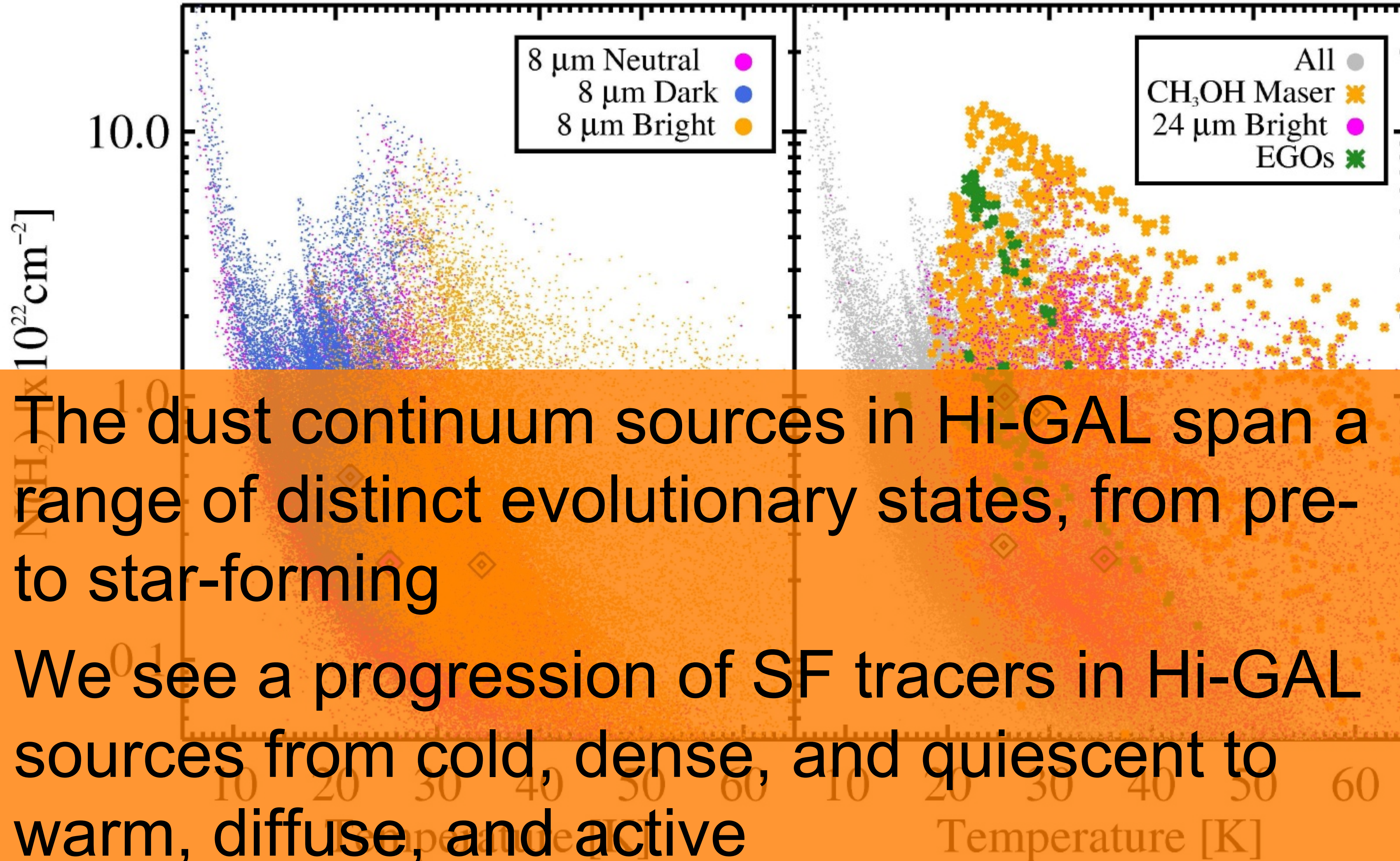

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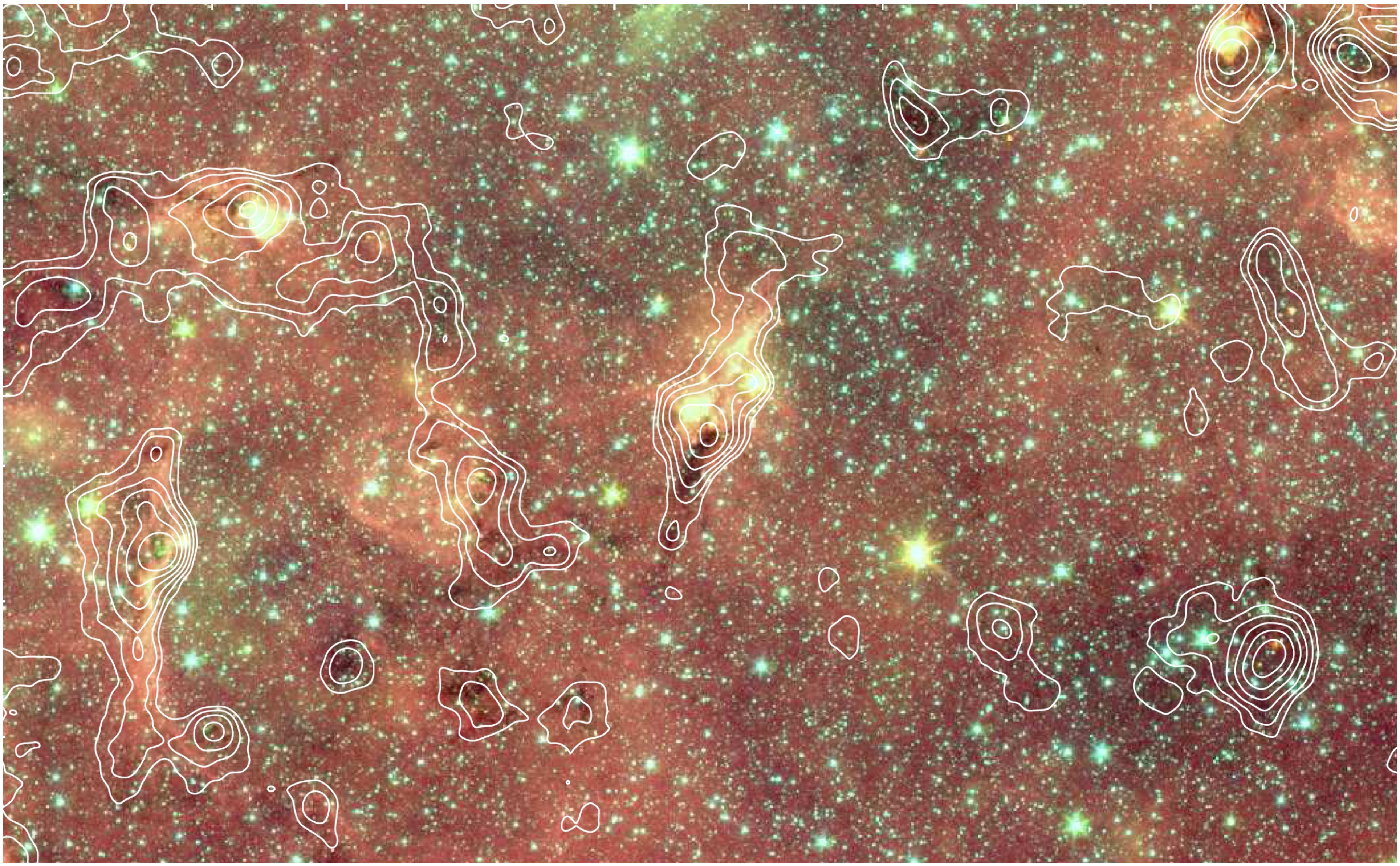
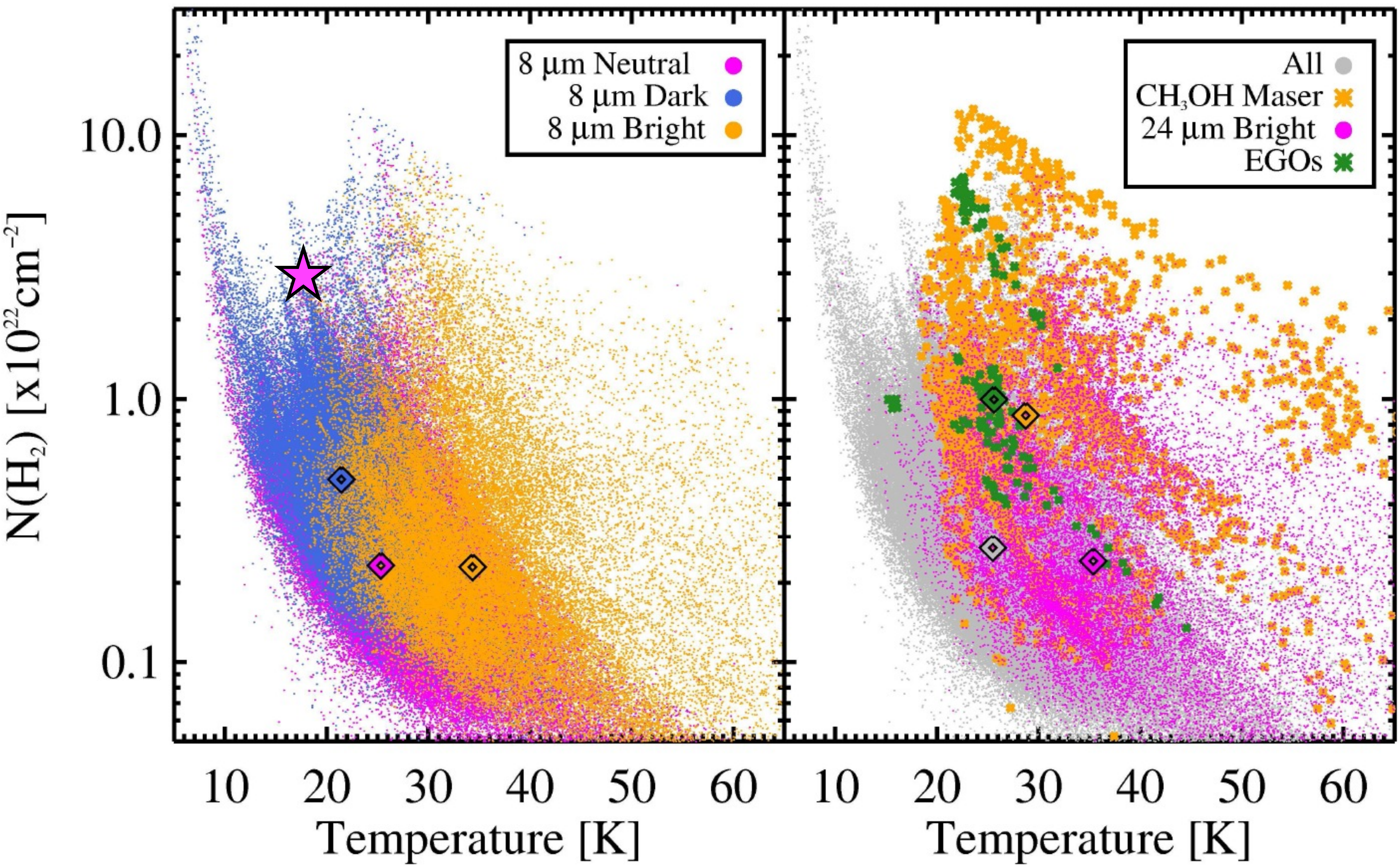
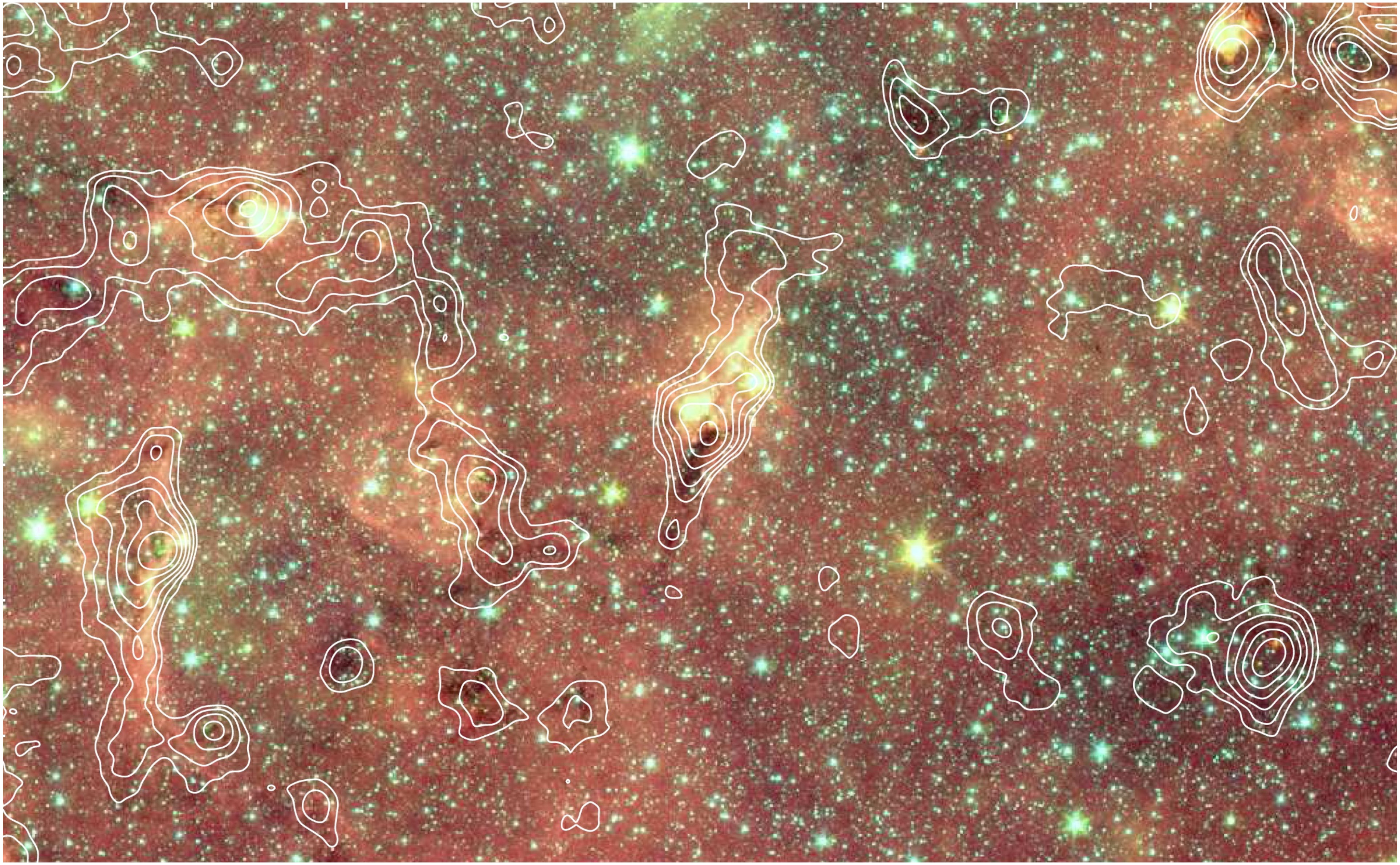




8 µm Neutral
8 µm Dark
8 µm Bright
All
CH3OH Maser
24 µm Bright
EGOs
N(H2) [x10^22 cm^-2]
10.0
1.0
0.1
10
20
30
40
50
60
Temperature [K]
Temperature [K]

5 Candidate Galactic Far-Side IRDCs



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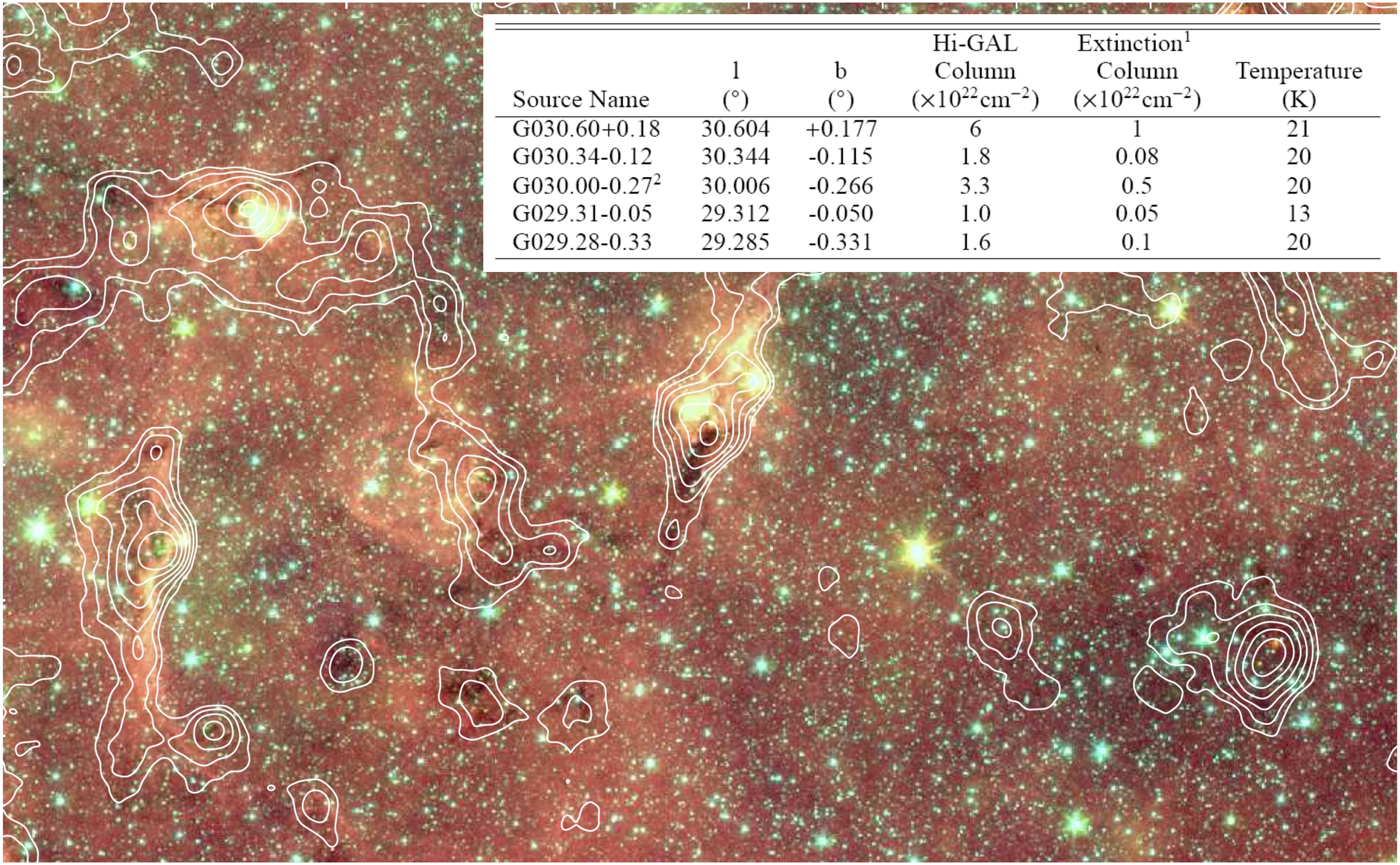

Source Name	l (°)	b (°)	Hi-GAL Column ($\times10^{22}$cm^{-2})	Extinction[1] Column ($\times10^{22}$cm^{-2})	Temperature (K)
G030.60+0.18	30.604	+0.177	6	1	21
G030.34-0.12	30.344	-0.115	1.8	0.08	20
G030.00-0.27[2]	30.006	-0.266	3.3	0.5	20
G029.31-0.05	29.312	-0.050	1.0	0.05	13
G029.28-0.33	29.285	-0.331	1.6	0.1	20

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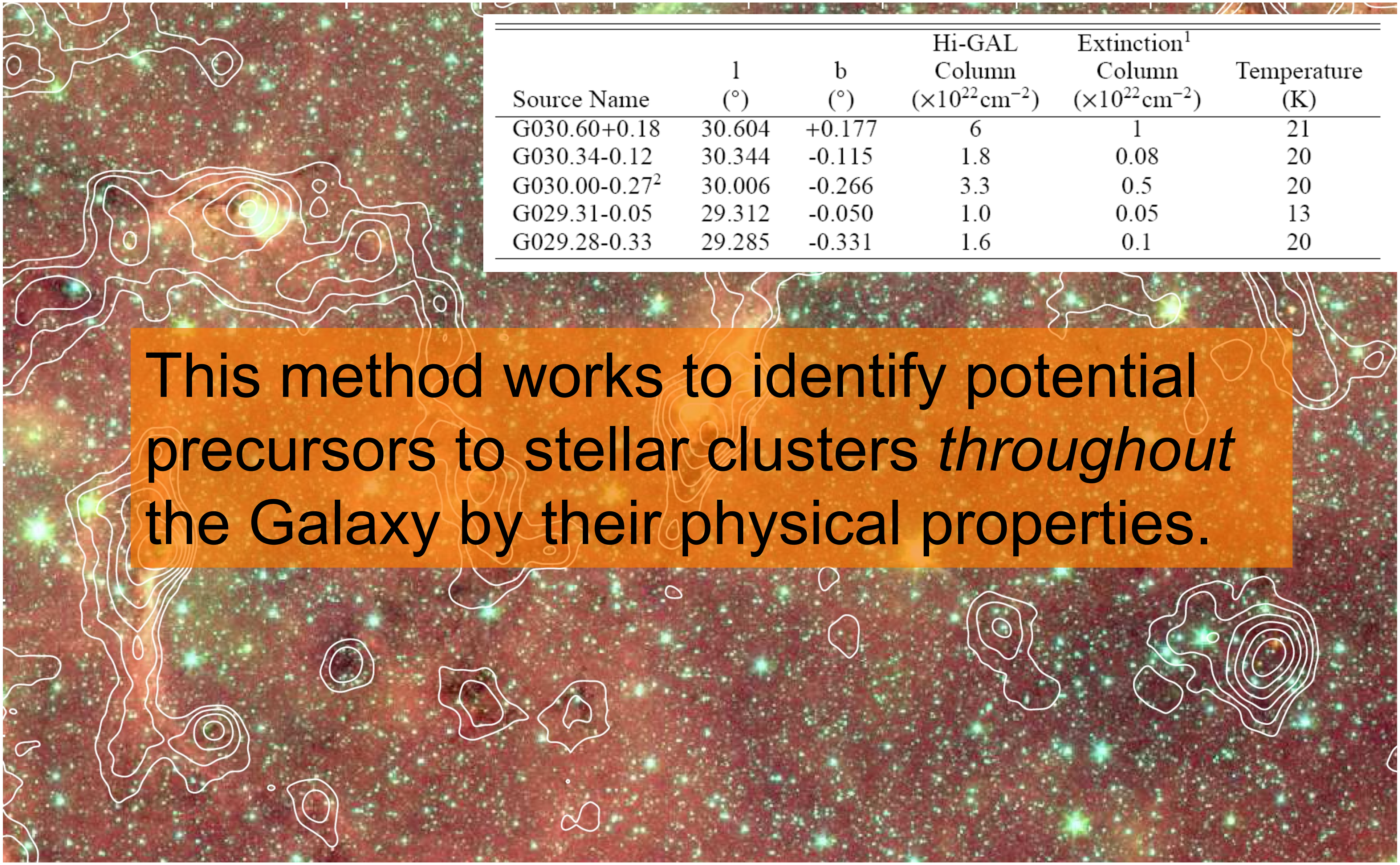

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This method works to identify potential precursors to stellar clusters *throughout* the Galaxy by their physical properties.

Lifetimes

- Above a column density threshold of $N(H_2) > 10^{22}$ cm^{-2}

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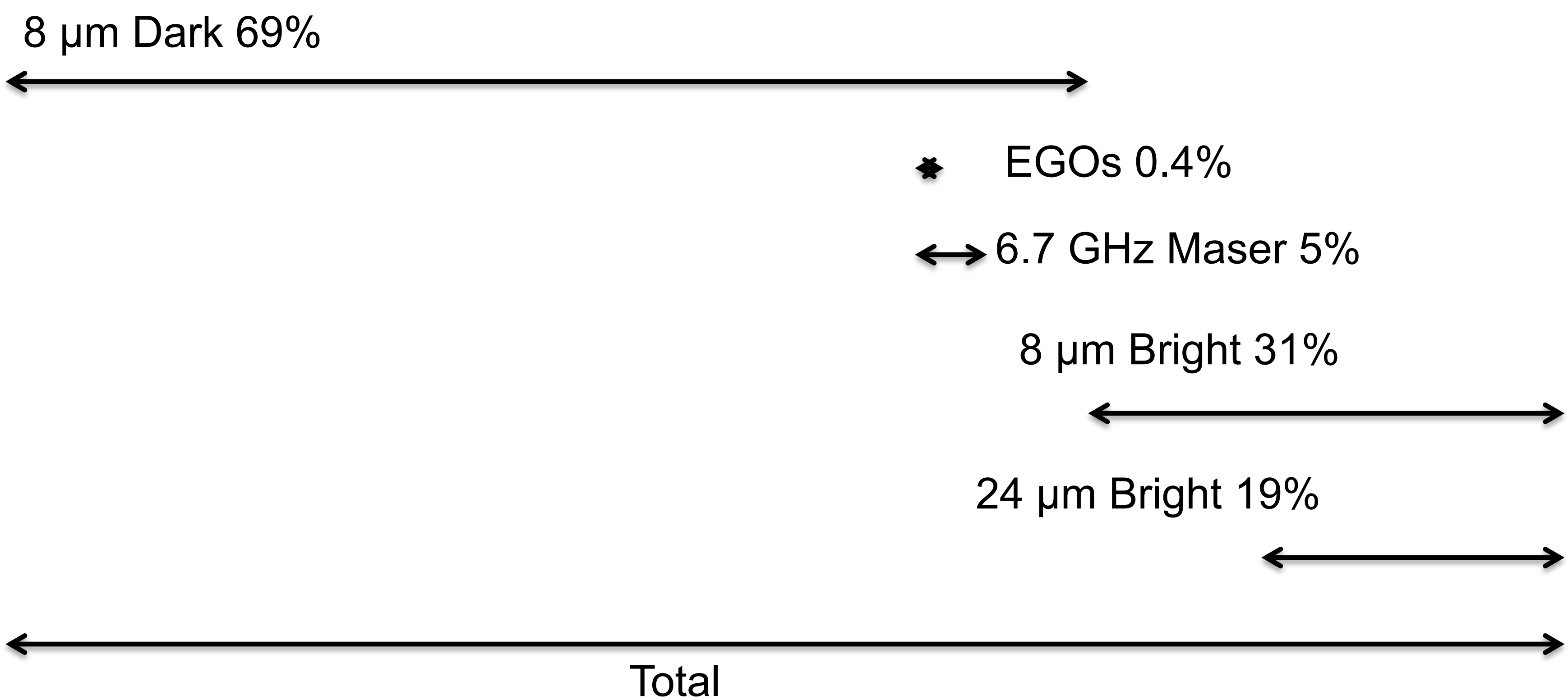
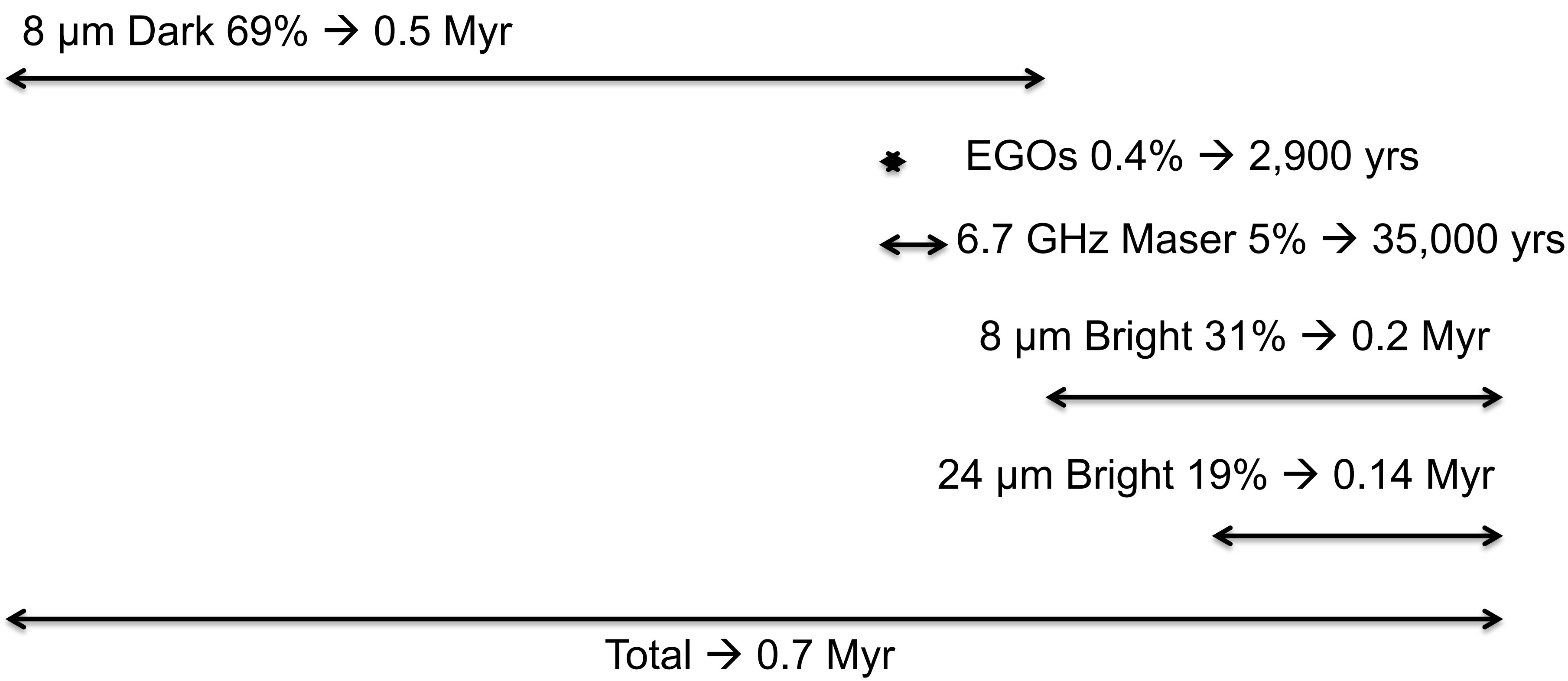


Agrees with Chambers et al. 2009 sample of IRDC cores

Lifetimes

- Above a column density threshold of $N(H_2) > 10^{22}$ cm^{-2}
- Assume a lifetime of Class II 6.7 GHz Methanol Masers of 3.5×10^4 years (van der Walt 2005, Breen et al. 2010, Ellingsen 2007, Caswell 2009)



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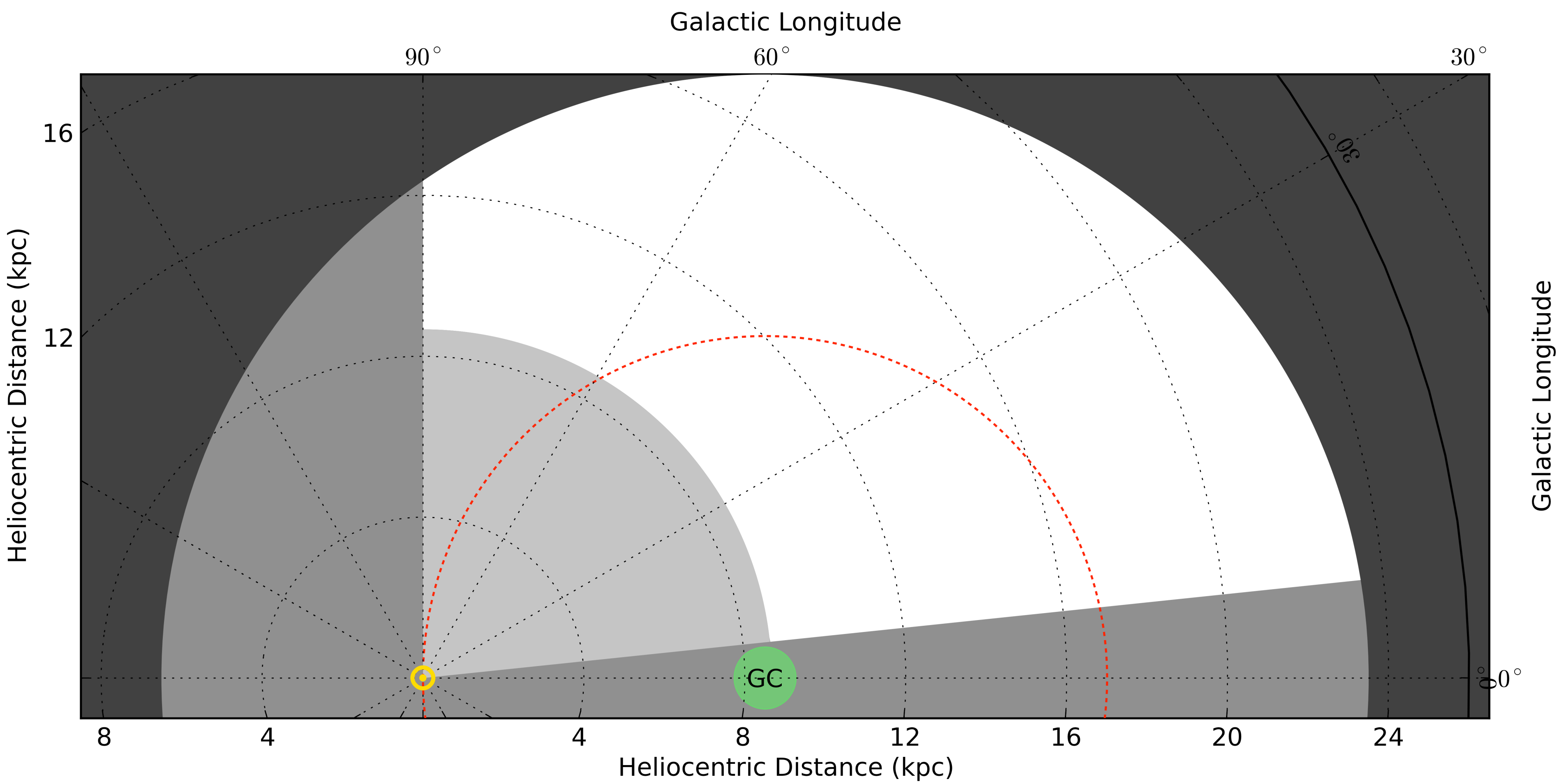
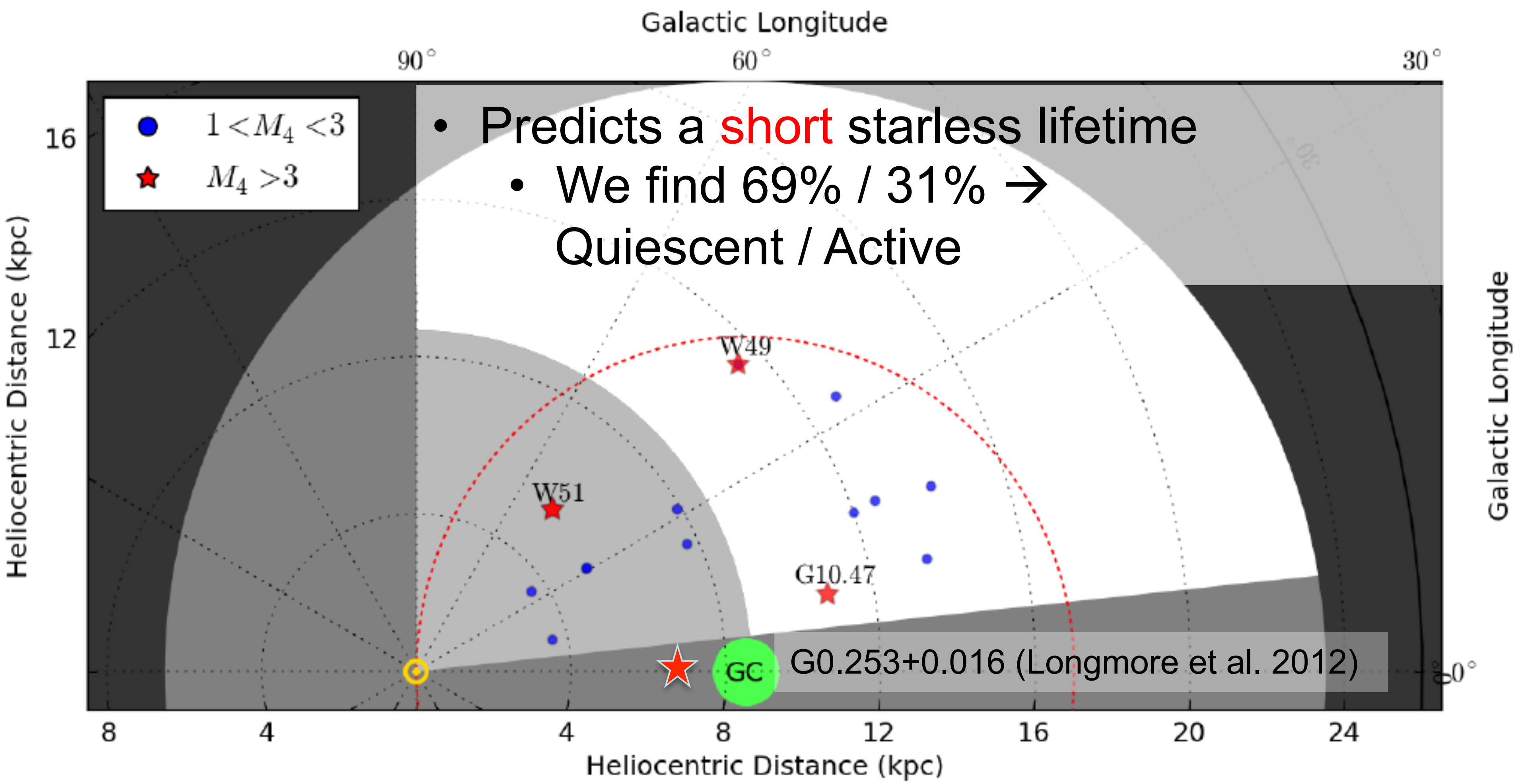
Complete search for Proto-Massive Clusters (Massive, Tightly Bound: 3 x10^4 $M_\odot$, r < 2.5 pc) in the First Quadrant using the Bolocam Galactic Plane Survey…



Ginsburg, A., Bressert, E., Bally, J., Battersby, C., ApJL, submitted 2012
See Poster # ###

Complete search for Proto-Massive Clusters (Massive, Tightly Bound: 3 x10^4 $M_\odot$, r < 2.5 pc) in the First Quadrant using the Bolocam Galactic Plane Survey… yields 3 sources – none of which are starless!

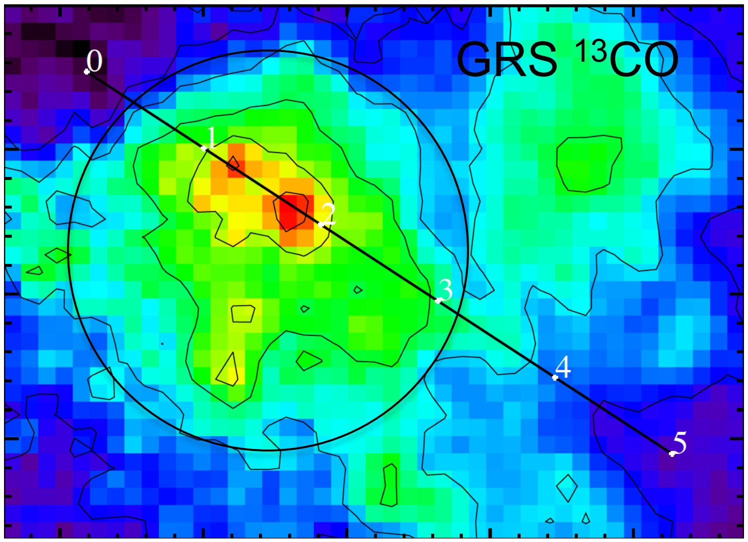


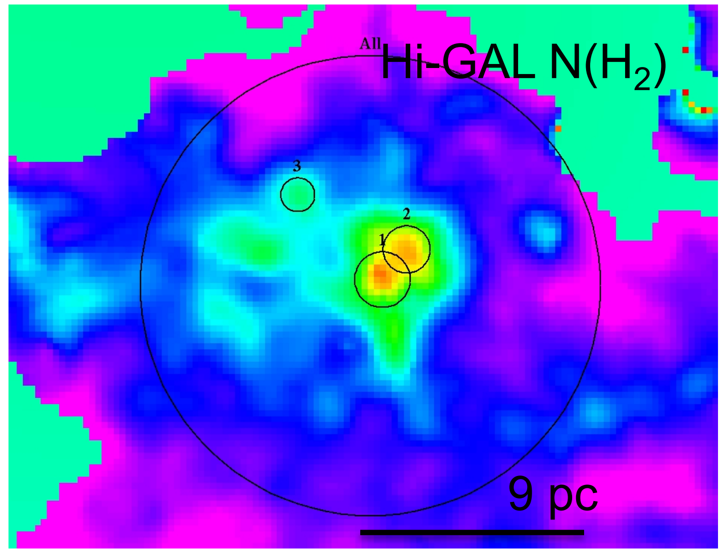
- Predicts a short starless lifetime
  - We find 69% / 31% → Quiescent / Active

Ginsburg, A., Bressert, E., Bally, J., Battersby, C., ApJL, submitted 2012

See Poster # ###

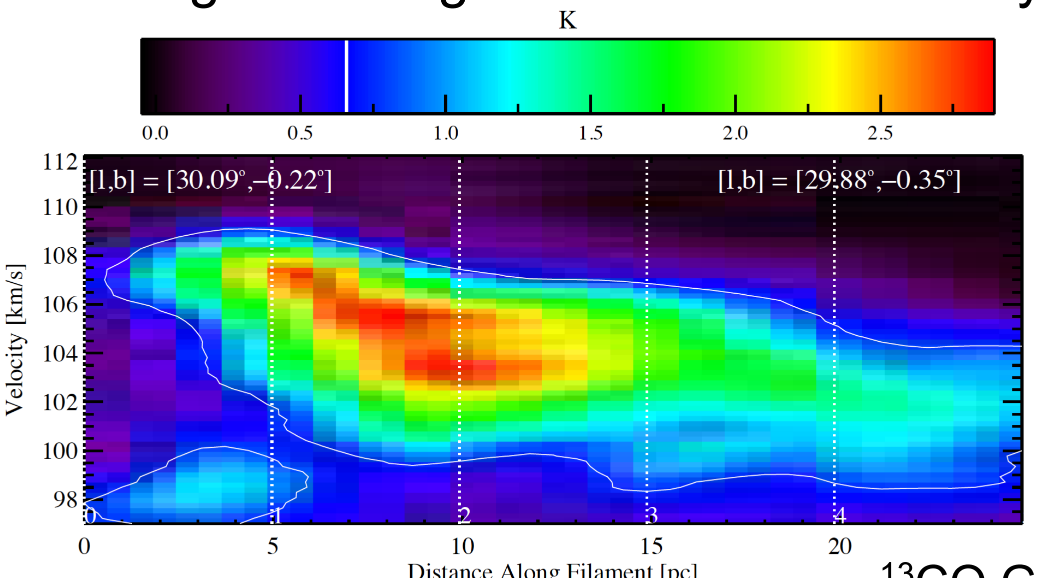
Large Scale Infall?





Total Mass
~ 3 x 10^4 $M_\odot$
in a 9 pc
radius

PV Diagram along above slice → Velocity Gradient ~ 5 km/s → 5 pc / Myr



Could this collapse to
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< 2 Myr?

Battersby et al. 2012, in prep

^{13}CO Galactic Ring Survey; Jackson et al. 2006

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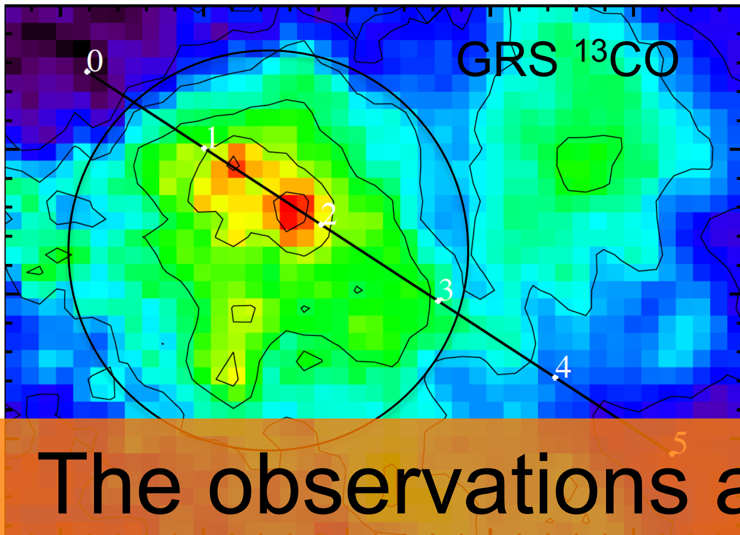

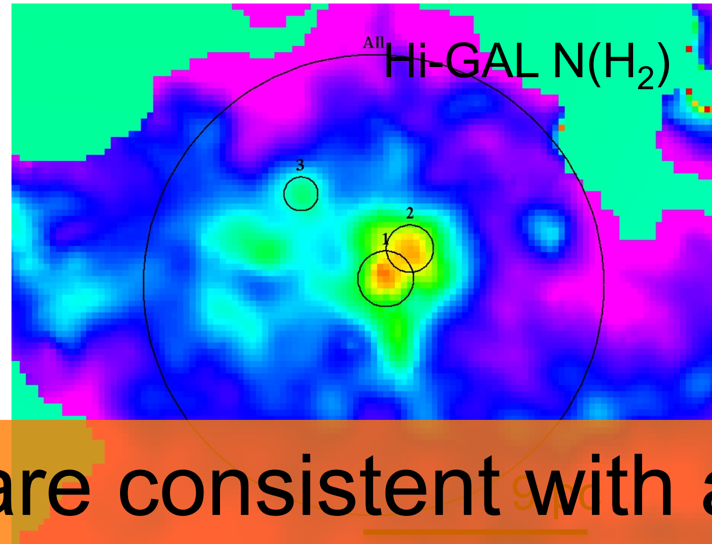

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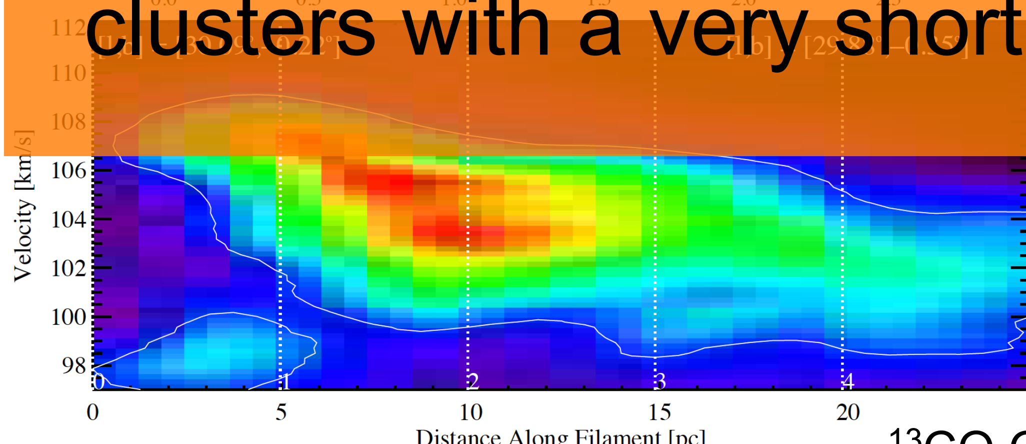
- The observations are consistent with a relatively long starless lifetime for IRDC-like clouds, some of which may then collapse into proto-massive clusters with a very short starless lifetime

PV Diagram along above slice > Velocity Gradient ~5 km/s > 5 pc / Myr



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Conclusions

- We can identify protocluster candidates by their column density and temperature *throughout* the Galaxy
- The dust continuum sources in Hi-GAL span a range of distinct evolutionary states, from pre- to star-forming
- We see a progression of SF tracers in Hi-GAL sources from cold, dense, and quiescent to warm, diffuse, and active
- The Starless to Star-Forming Lifetimes in IRDCs vs. Proto-Massive Clusters May Indicate Large Scale Accretion