MASSIVE STAR CLUSTER FORMATION: THE ROLE OF THE MAGNETIC FIELD AND THE ENVIRONMENT

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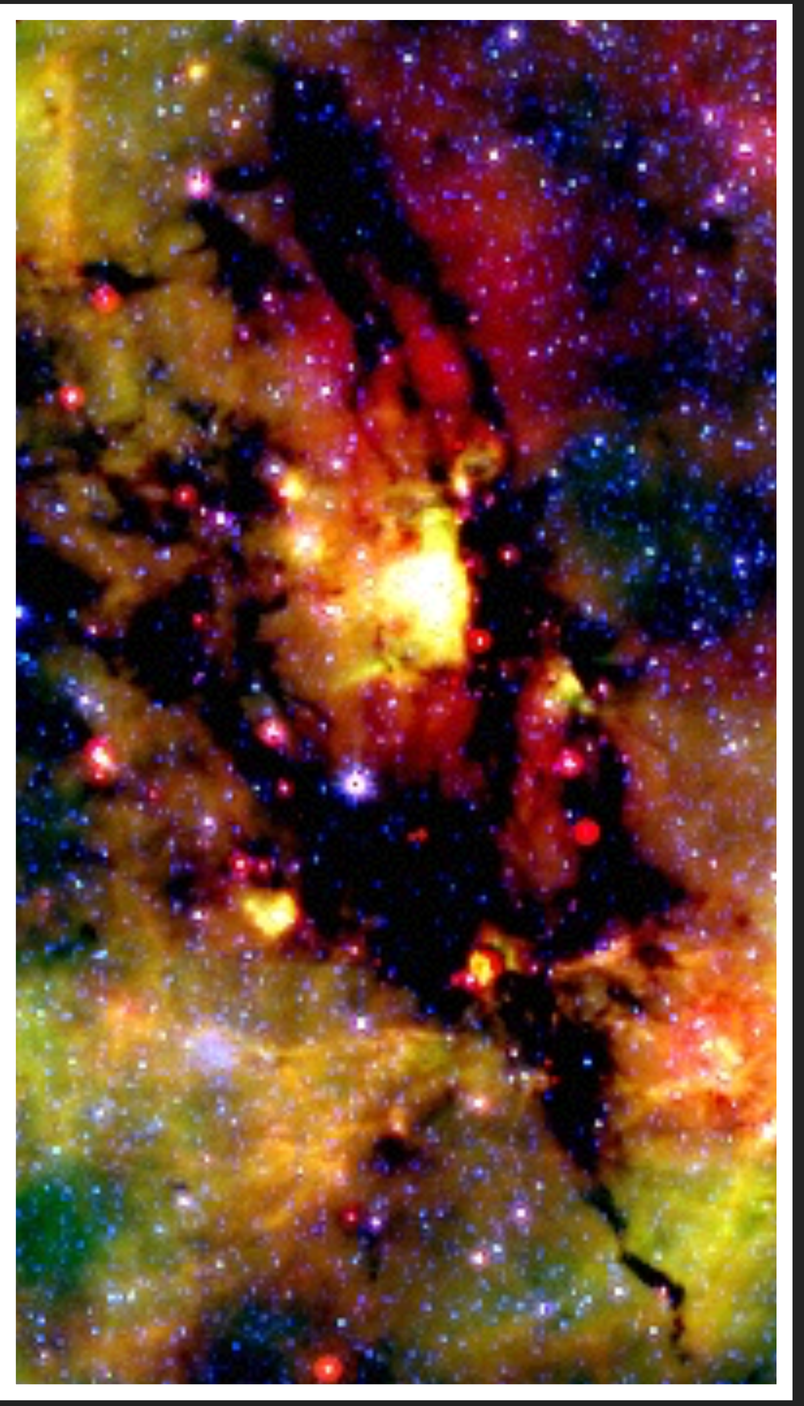
Tracing the Flow: Galactic Environments and the Formation of Massive Stars

Lake Windermer, Tuesday 3rd July 2018

★ The Infrared Dark Cloud G14.225-0.506: from filaments to dense cores and the role of the magnetic field



Ph.D Thesis of Nacho Añez-López

Collaborators: N.L. Chapman, R. Estalella, G.A.P. Franco, J.M. Girart, P.T.P. Ho, H.Baobab Liu, G. Novak, A. Palau, R. Rao, F. P. Santos, Q. Zhang

★ Unveiling a cluster of protoplanetary disks around the massive protostar GGD 27 MM1

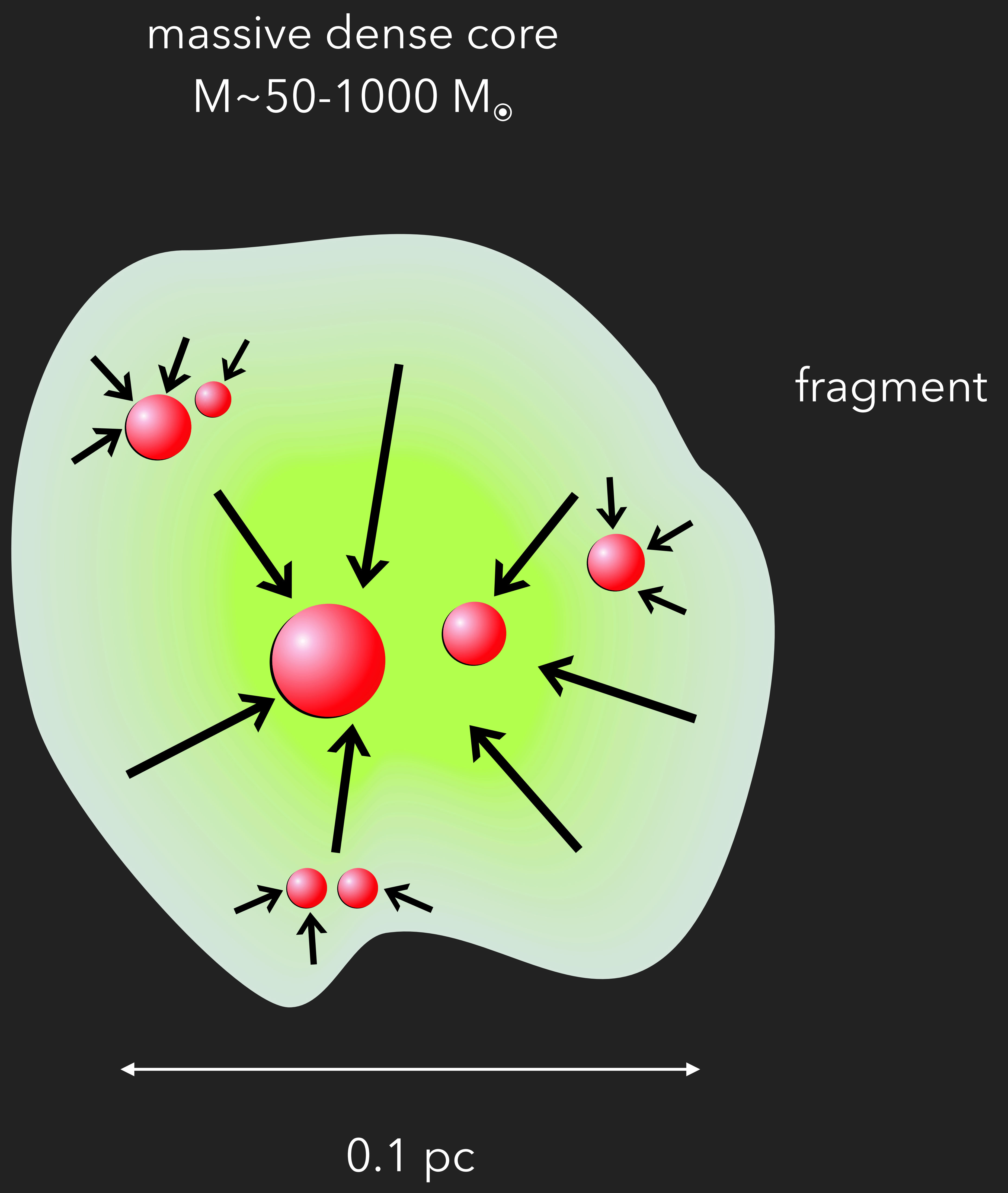
Busquet et al. A&A Letters submitted

Collaborators: J.M. Girart, R. Estalella, M. Fernández-López, R. Galván-Madrid, G. Anglada, C. Carrasco-González, N. Añez-López, S. Curiel, M. Osorio, L.F. Rodríguez, J.M. Torrelles

THE INFRARED DARK CLOUD G14.225-0.506: FROM FILAMENTS TO DENSE CORES AND THE ROLE OF THE MAGNETIC FIELD

WHAT CONTROLS THE FRAGMENTATION PROCESS?

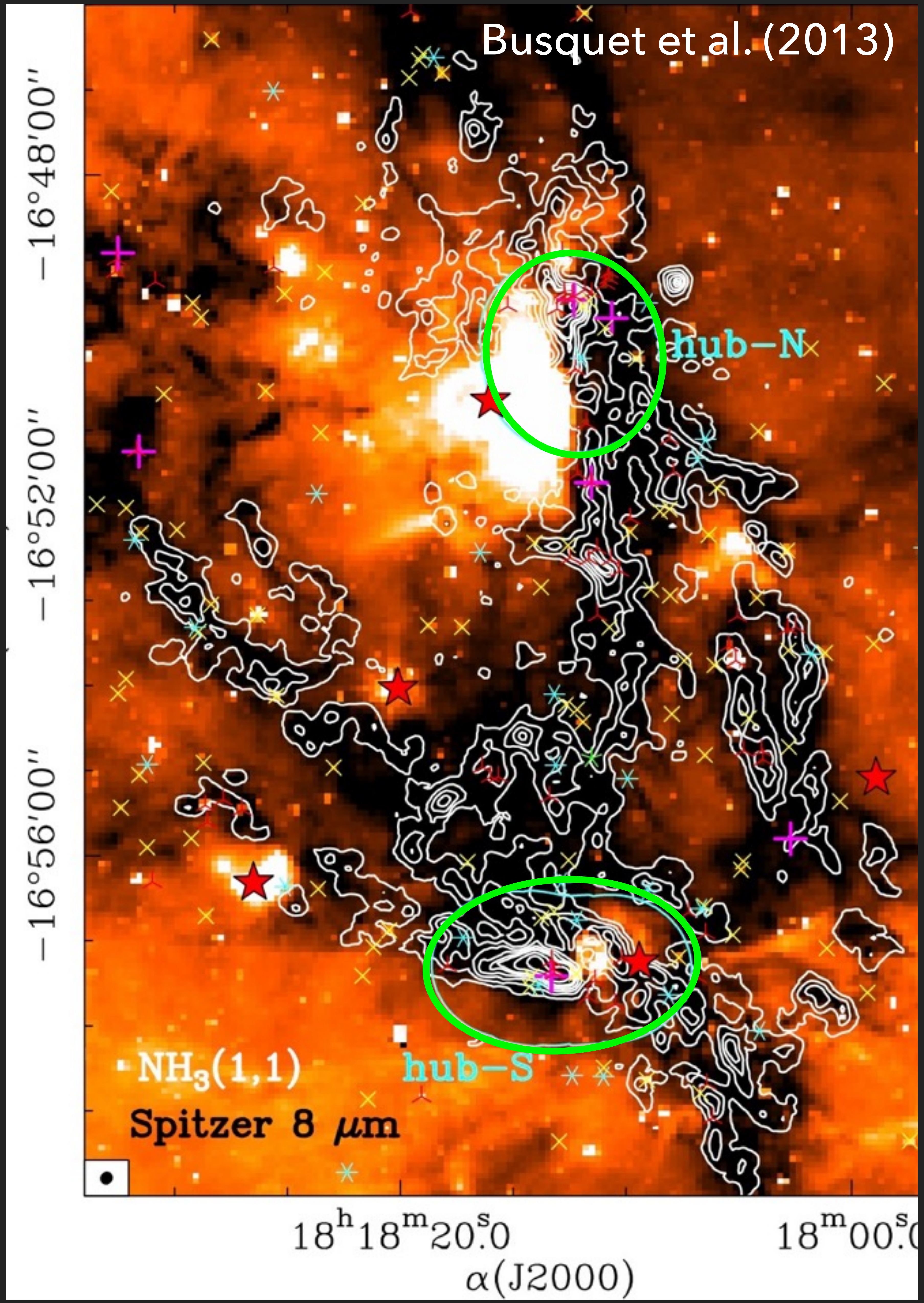
- Gravity: density and temperature structure
- Turbulence
- Magnetic fields
- Angular momentum
- Stellar feedback



THE IRDC G14.225-0.506

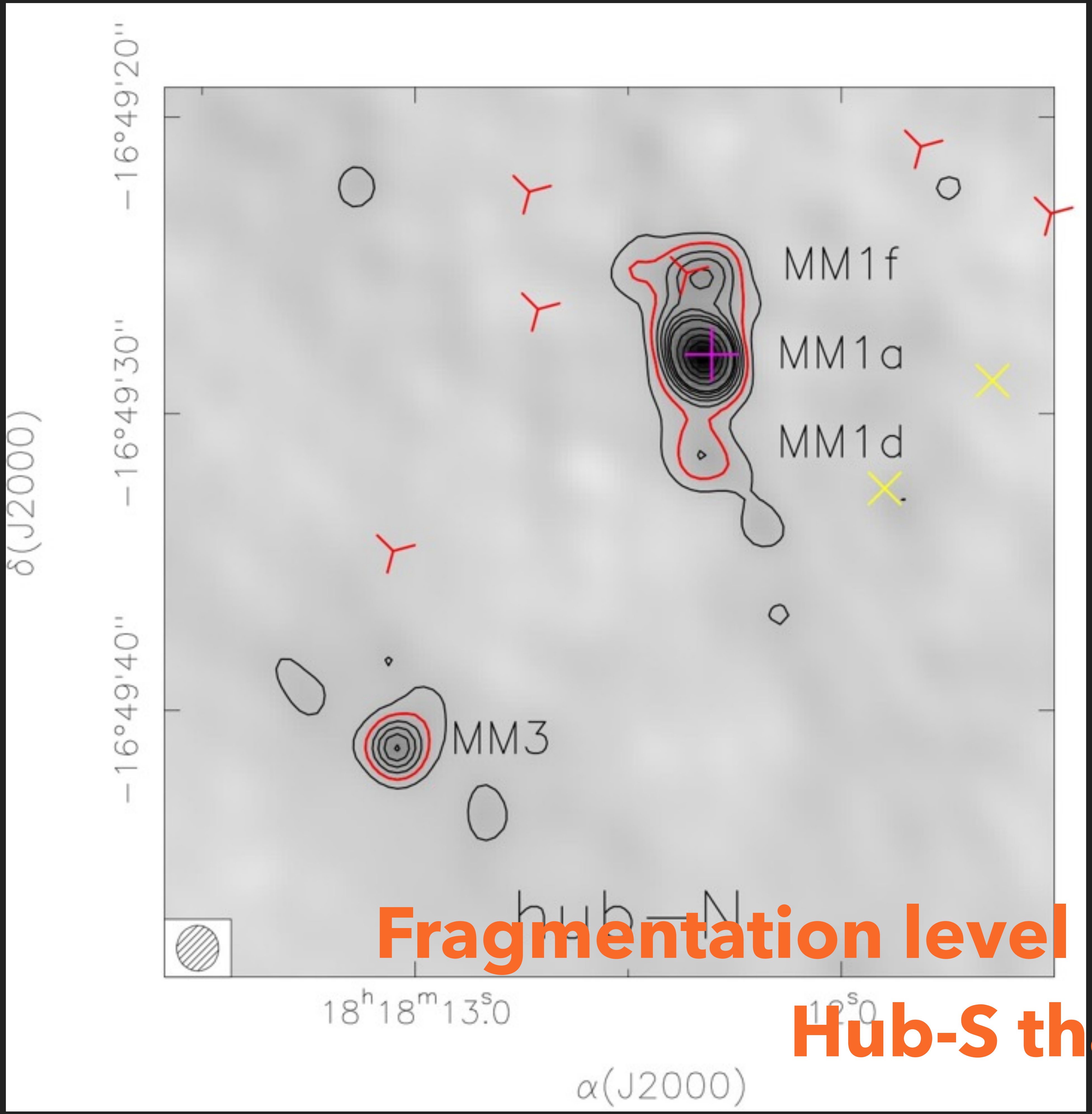
- Distance 1.98 kpc (Xu et al. 2011)
- Network of 8 filaments and 2 hubs
- Several intermediate-mass YSOs identified using Spitzer and Chandra (Povich & Whitney 2010, Povich et al. 2016)
- H_2O maser emission (Wang et al. 2006)
- Hubs are warmer, larger line widths: main sites of stellar activity within the cloud

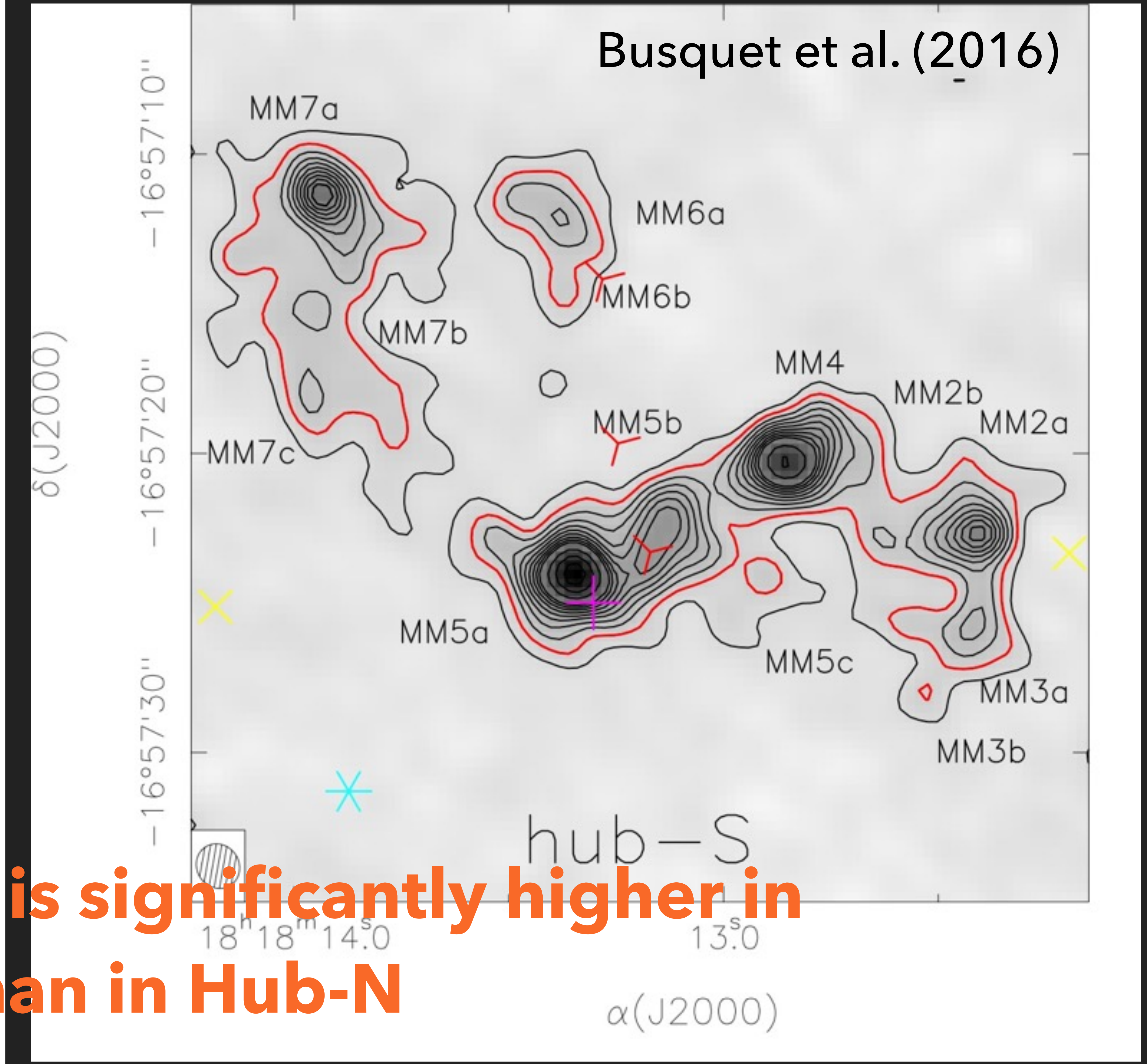
Vivien Chen Poster #21!



FRAGMENTATION LEVEL

- Imaging with the same uv-range of visibilities; convolution to the same beam (1.5″x 1.4″); region of 0.15 pc in radius (FoV~30″), which is the typical radii of compact and embedded clusters





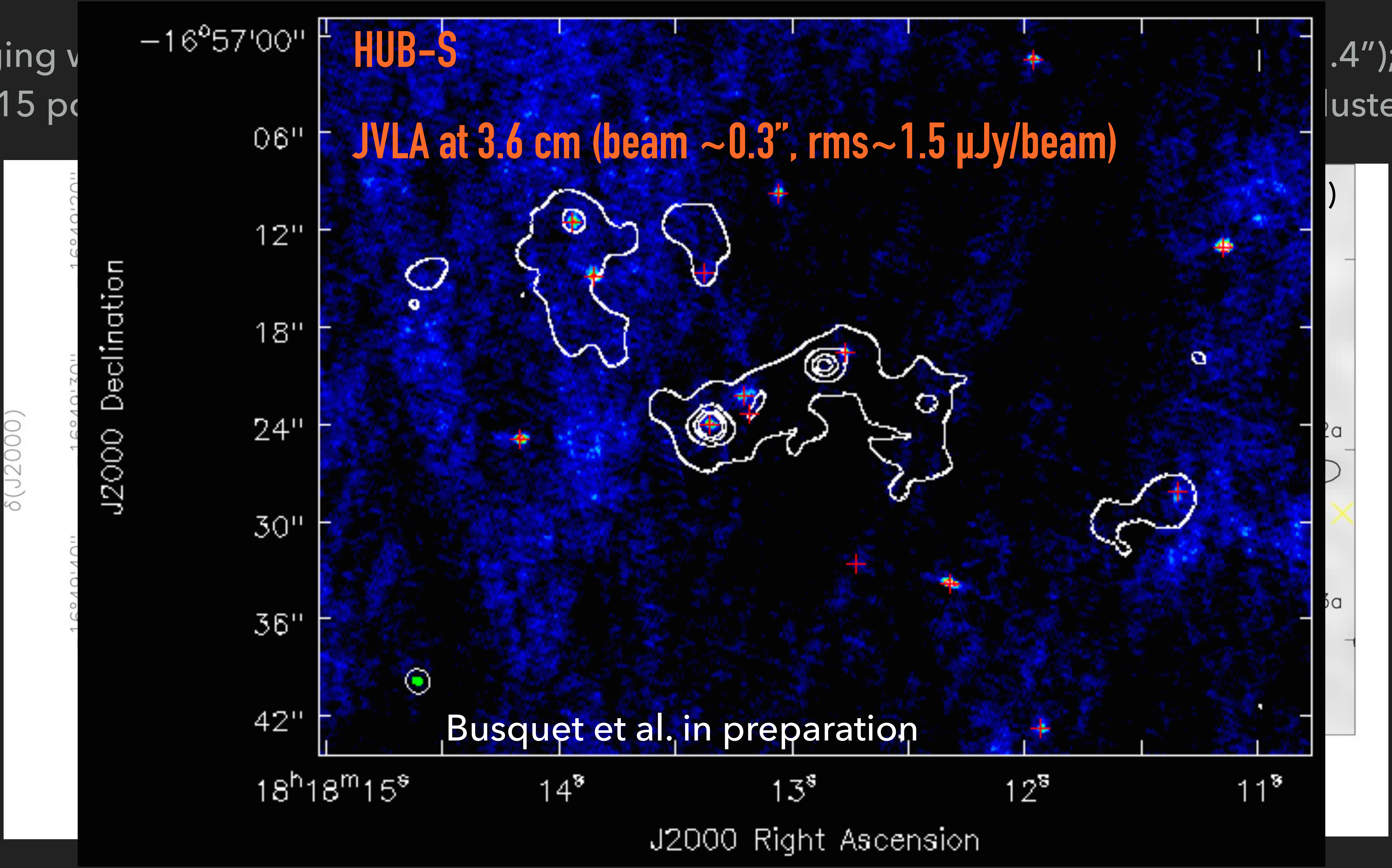
HUB-N=4

Fragmentation level is significantly higher in Hub-S than in Hub-N

HUB-S=13

FRAGMENTATION LEVEL

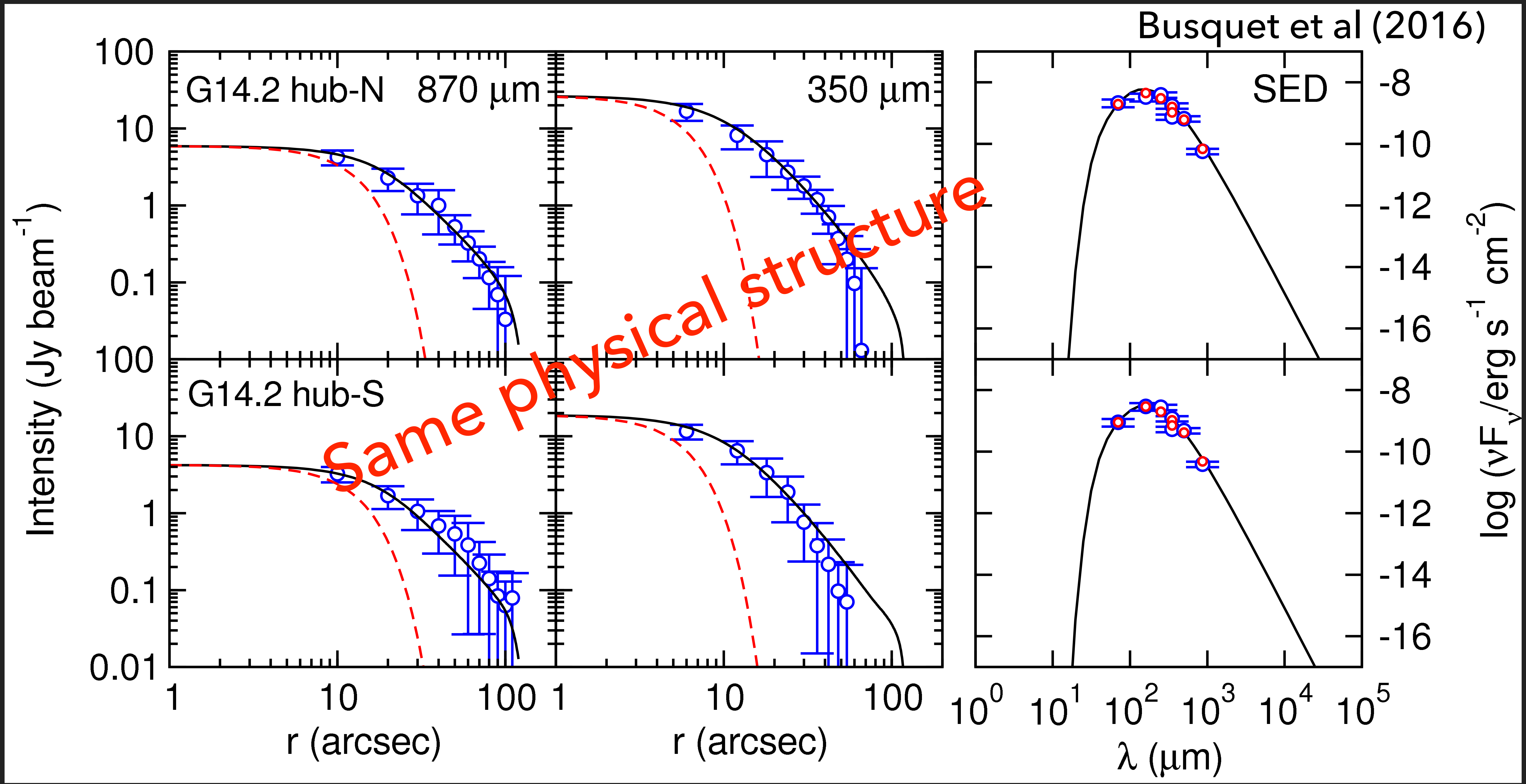
- Imaging v… .4"); region of 0.15 p… lusters

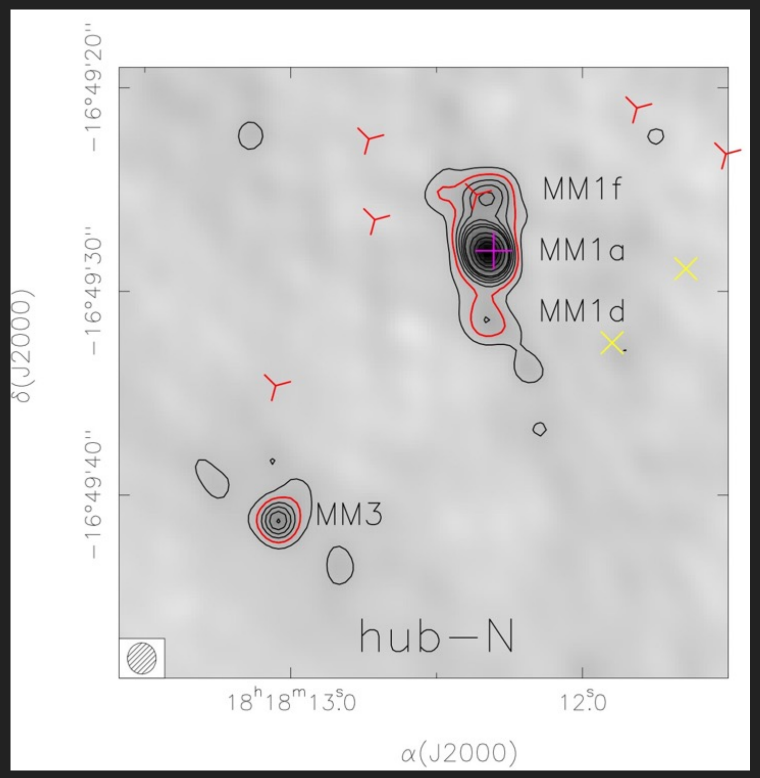


HUB-N=4

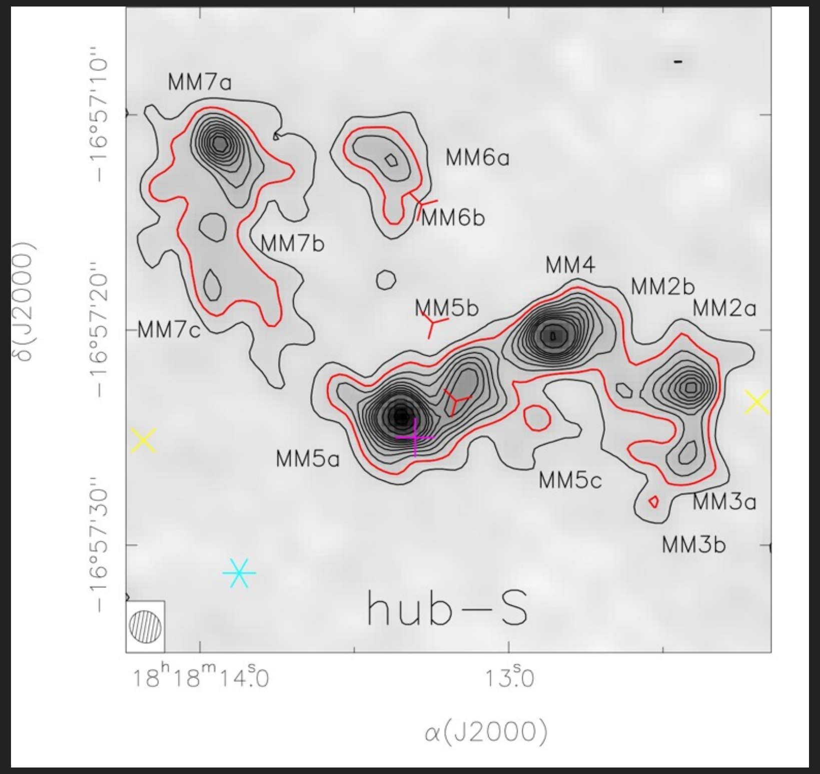
HUB-S=13

TWIN HUBS?





4 fragments



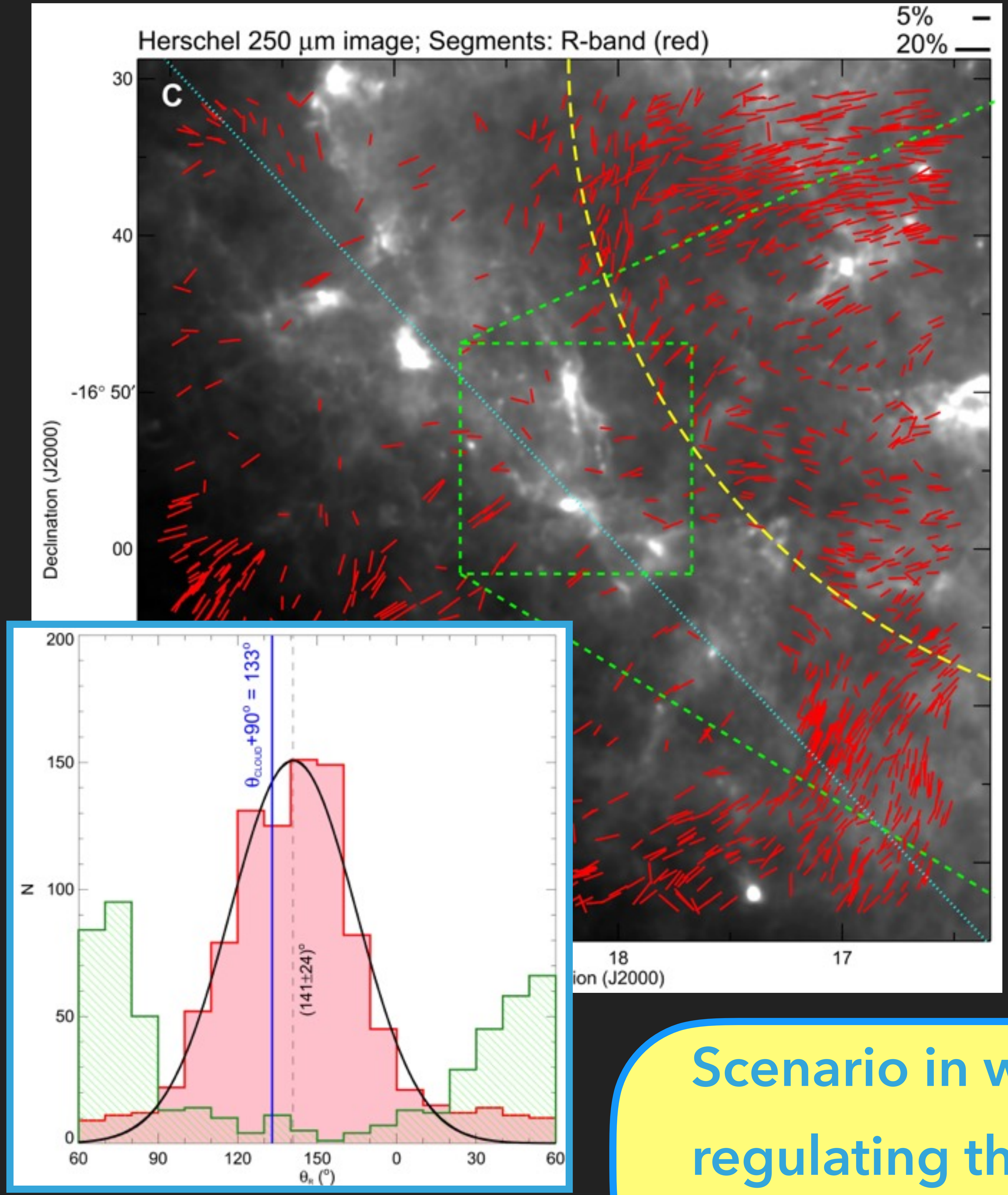
13 fragments

ENERGY BALANCE

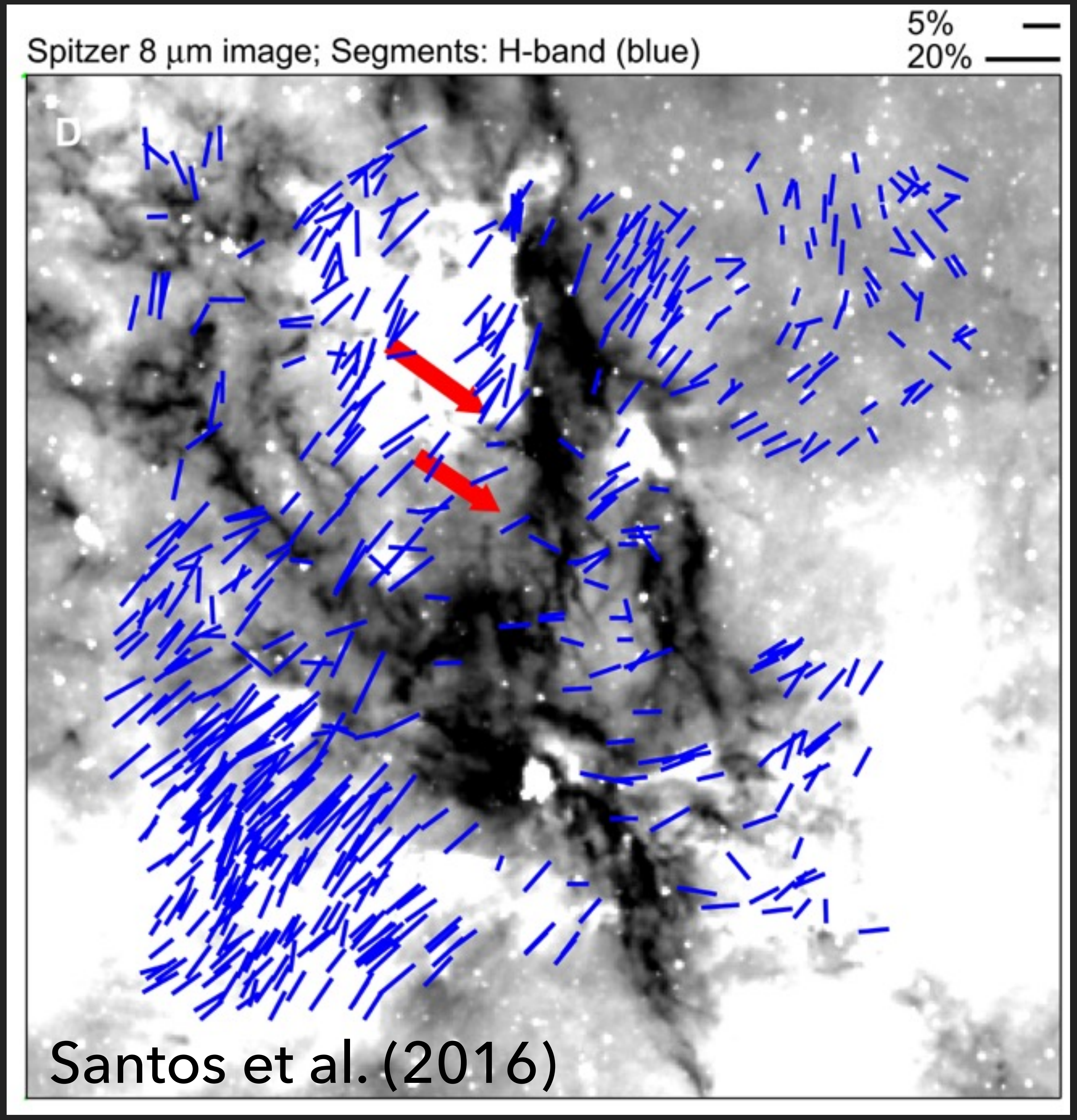
- Turbulence to thermal energy (Mach number): M=6
- Turbulence to magnetic field (Alfvén Mach number): M_A=0.3-0.4
- Rotational-to-gravitational energy: βrot=0.02

POLARIZED EMISSION FROM CLOUD TO FILAMENT SCALES

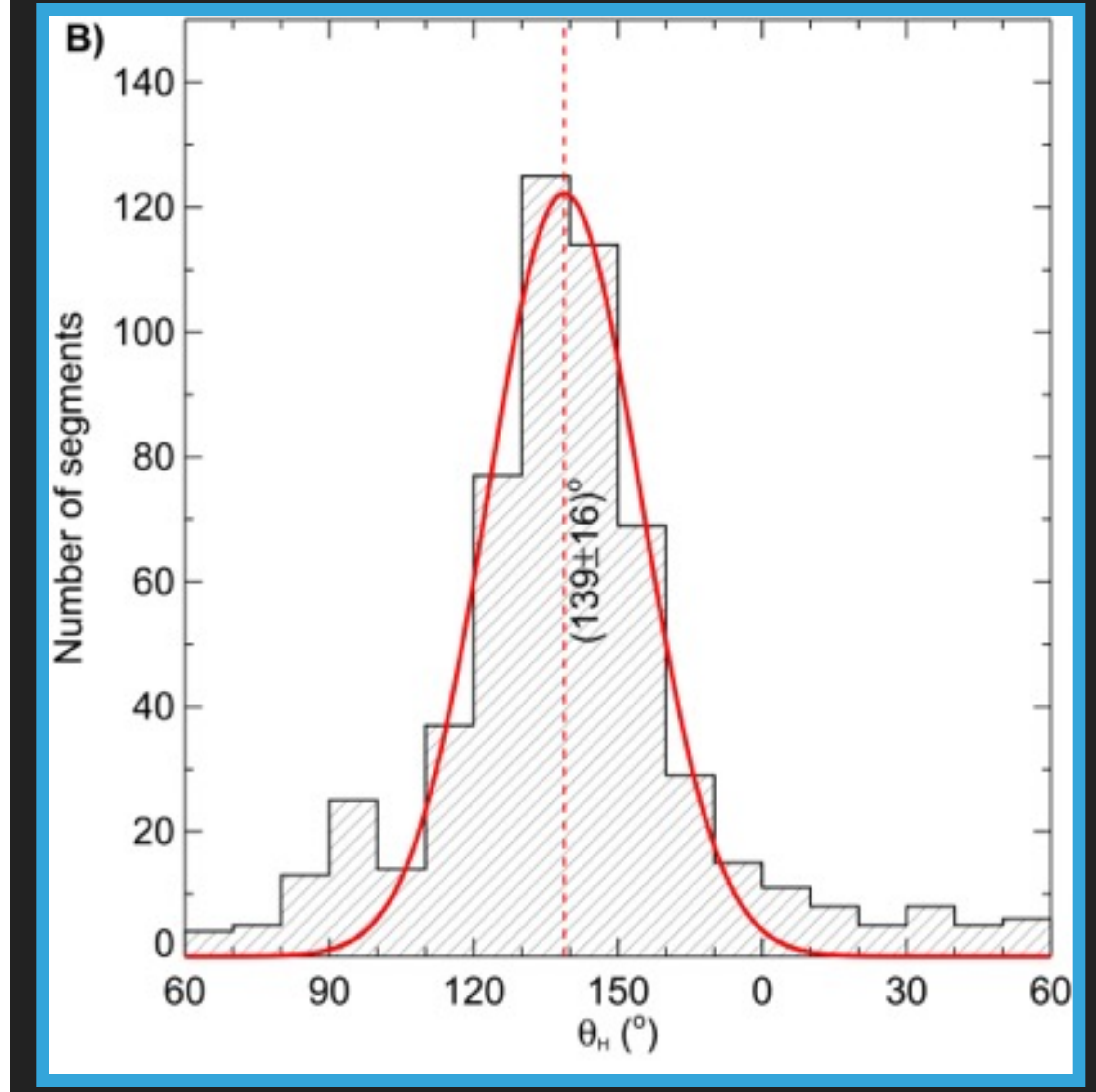
Optical (R-band) polarization map



Near-infrared (H-band) polarization map



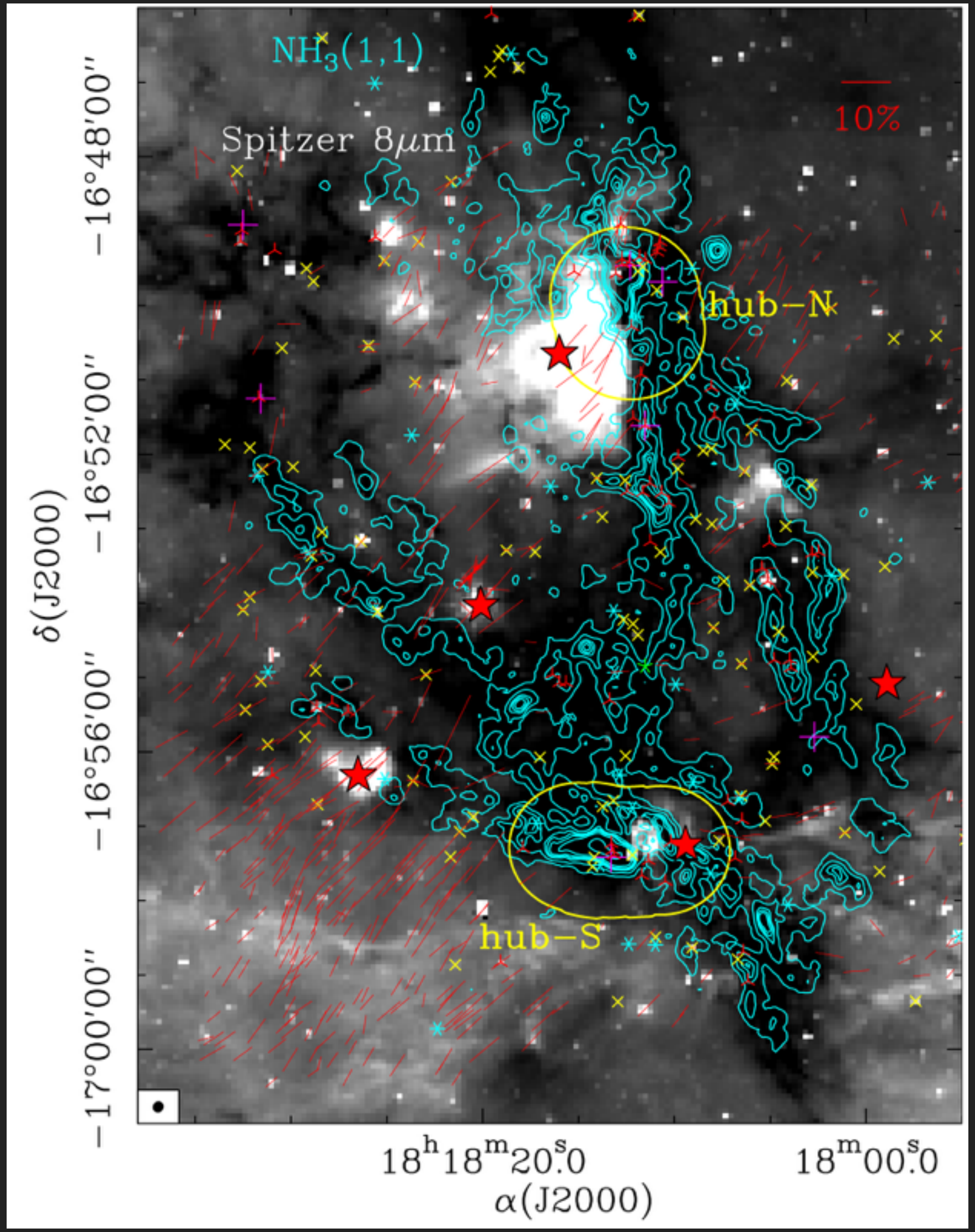
The main orientation at filament scales of 1-3 pc matches the average orientation at large (cloud) scales



Scenario in which magnetic fields have played an important role in regulating the gravitational collapse, being dynamically important in shaping the ISM structures from size scale of 30 pc down to 2 pc

TRACING THE MAGNETIC FIELD IN DENSE FILAMENTS AND HUBS

- CSO-SHARP 350 µm observations (Añez-López et al. in prep.)



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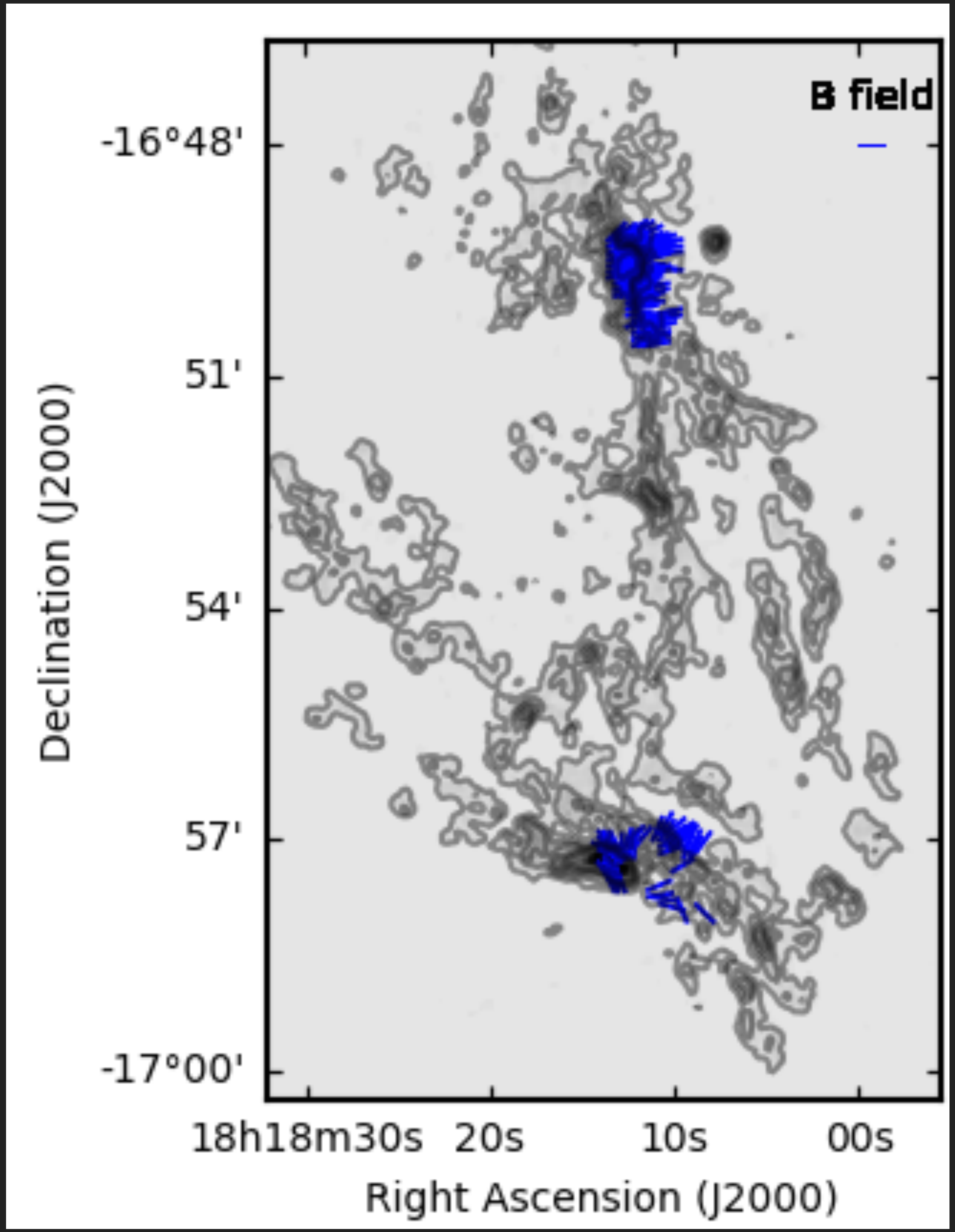

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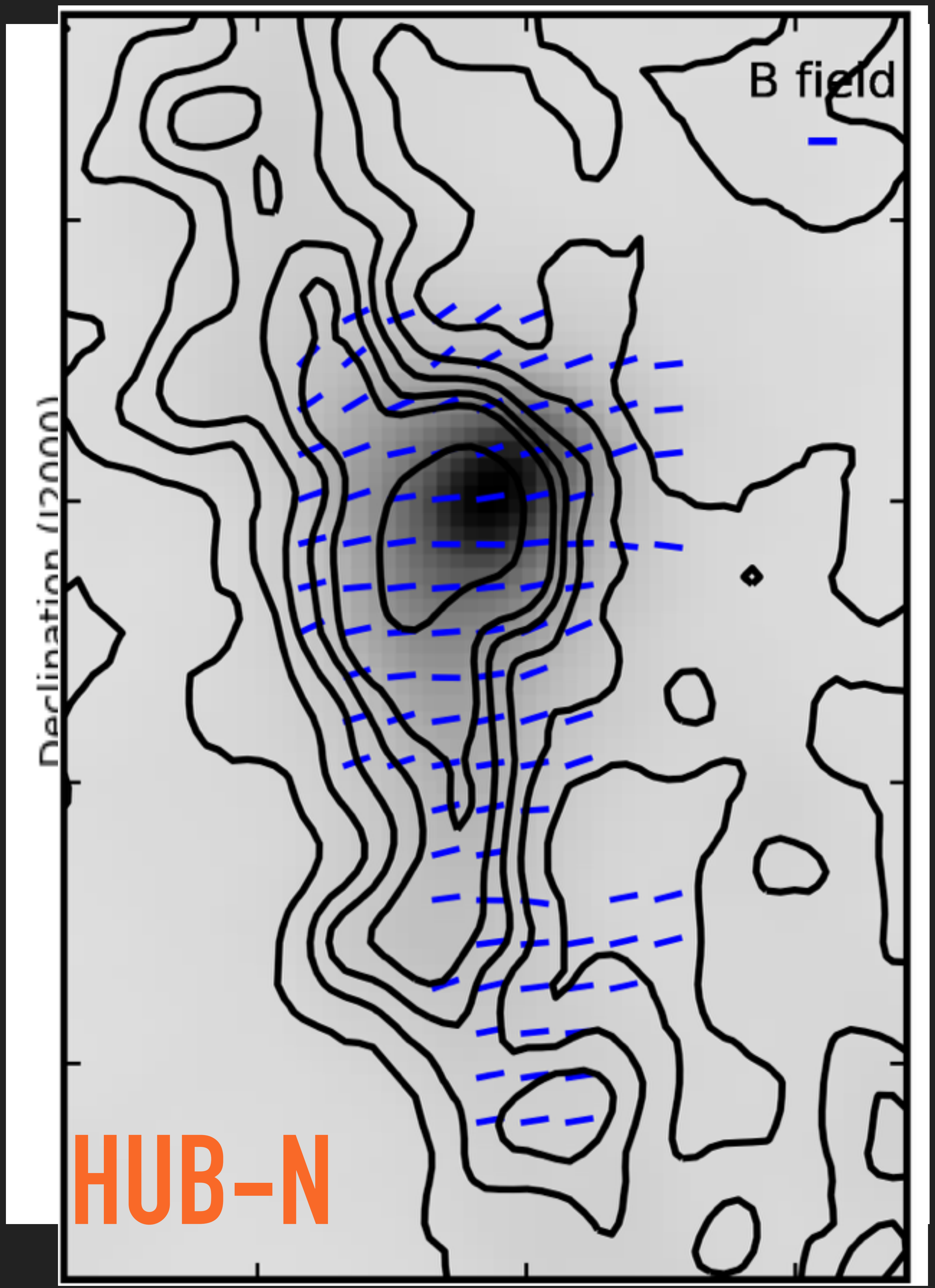
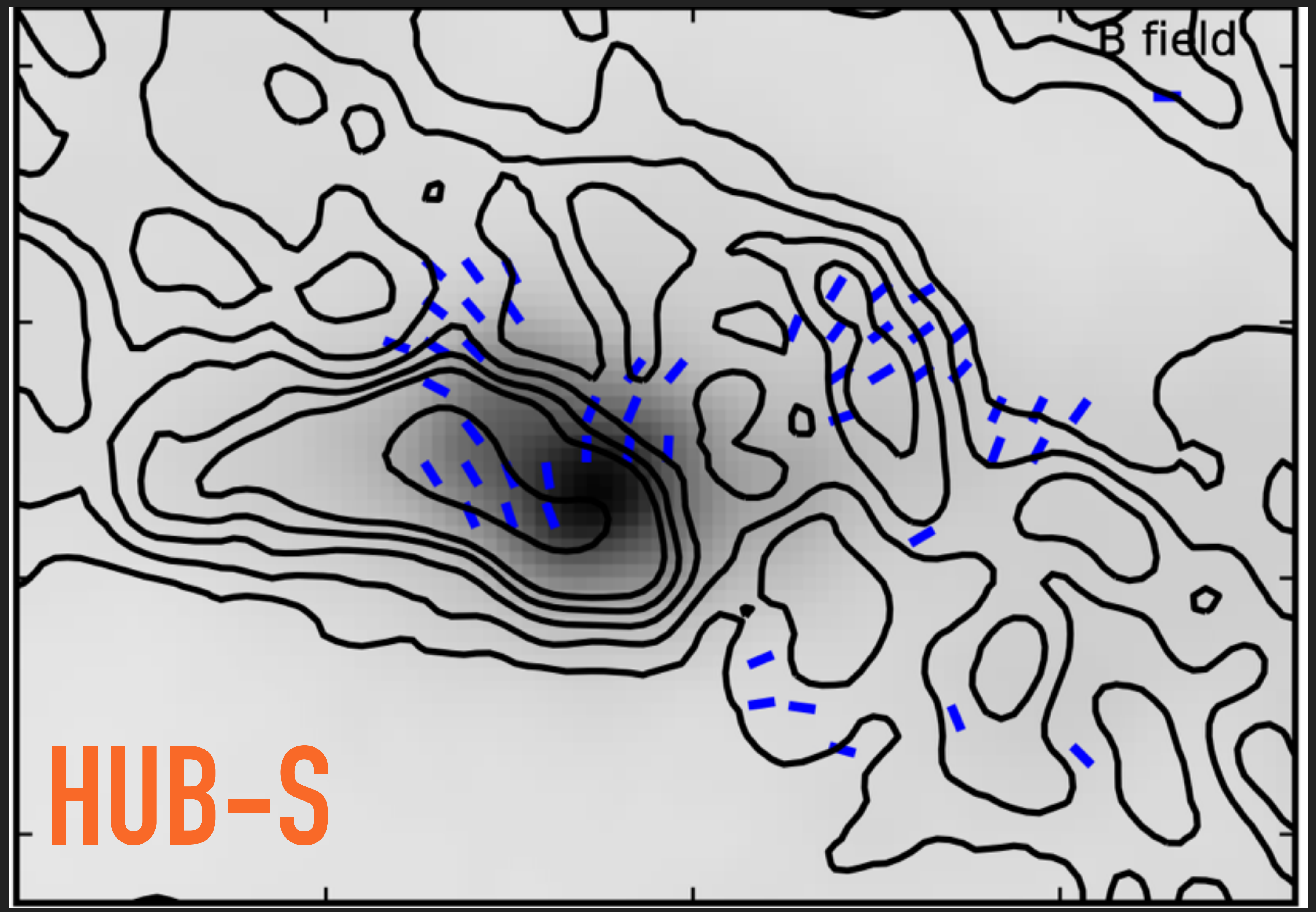
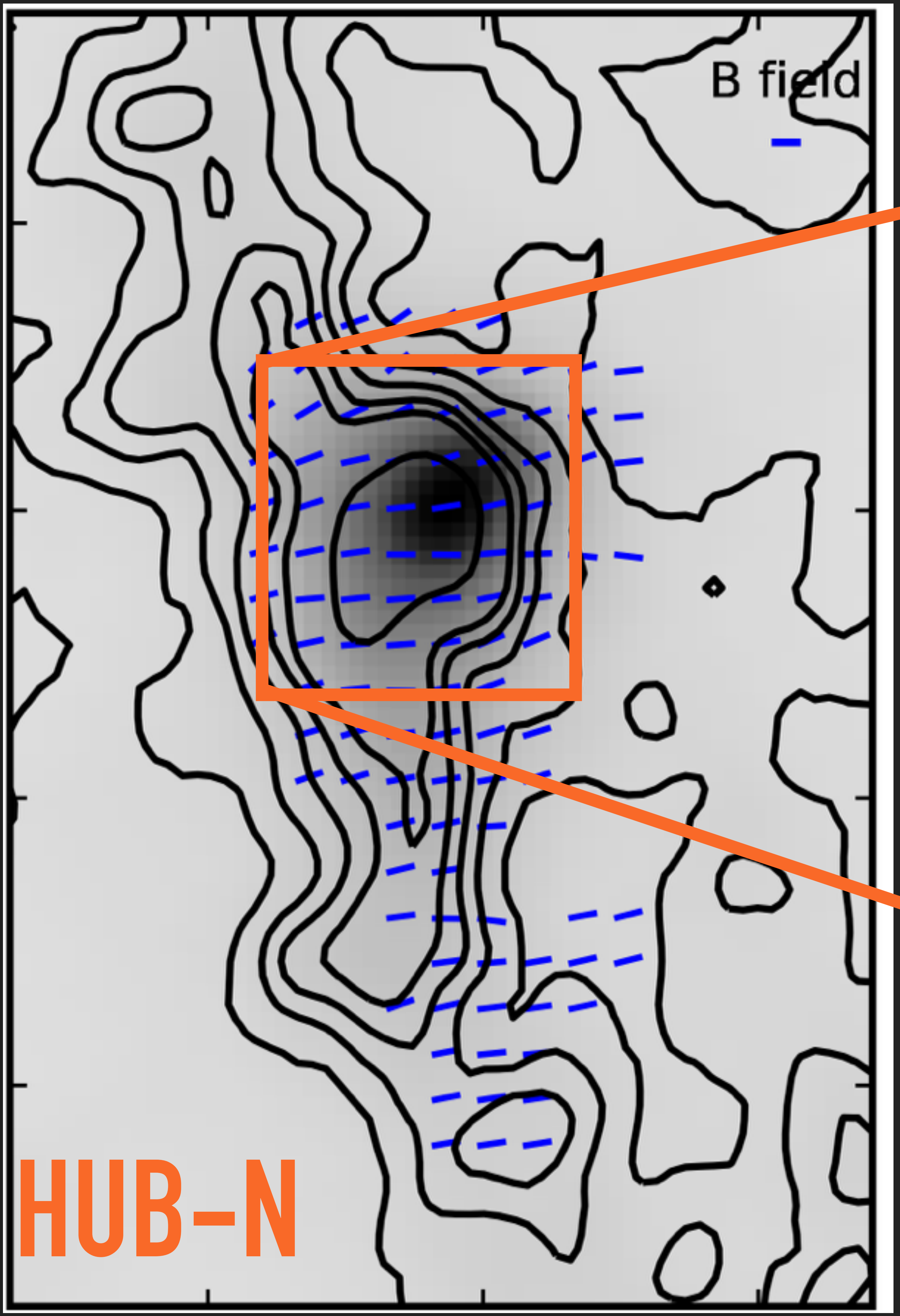


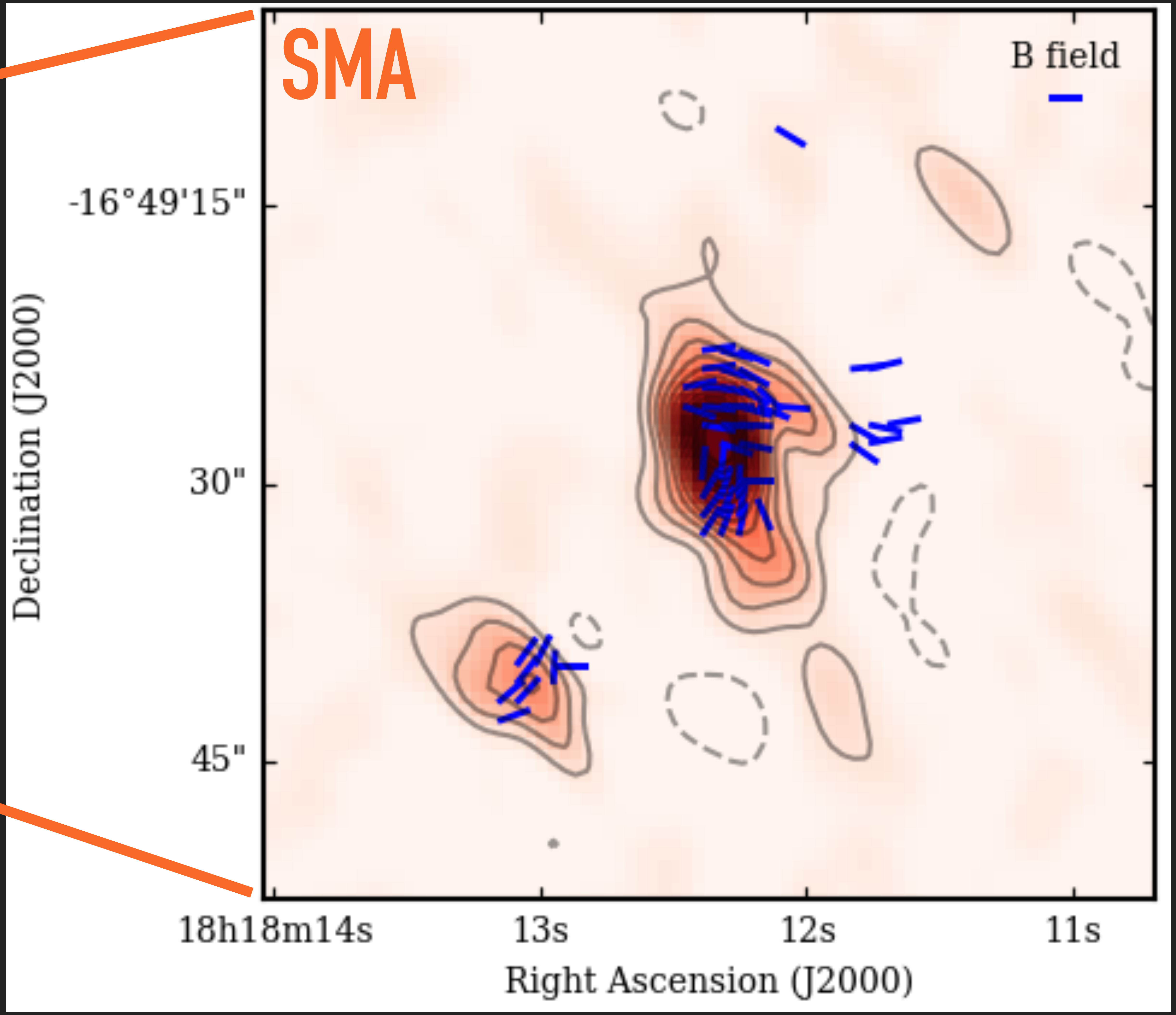


- **Hub-N:** The magnetic field direction and uniformity is preserved (polarization angle dispersion ~10°), B_{pos}=1mG
- **Hub-S:** Larger dispersion (polarization angle dispersion ~18°) and weaker B_{pos}~0.5 mG

TRACING THE MAGNETIC FIELD IN DENSE CORES

Añez-López et al. (in preparation)



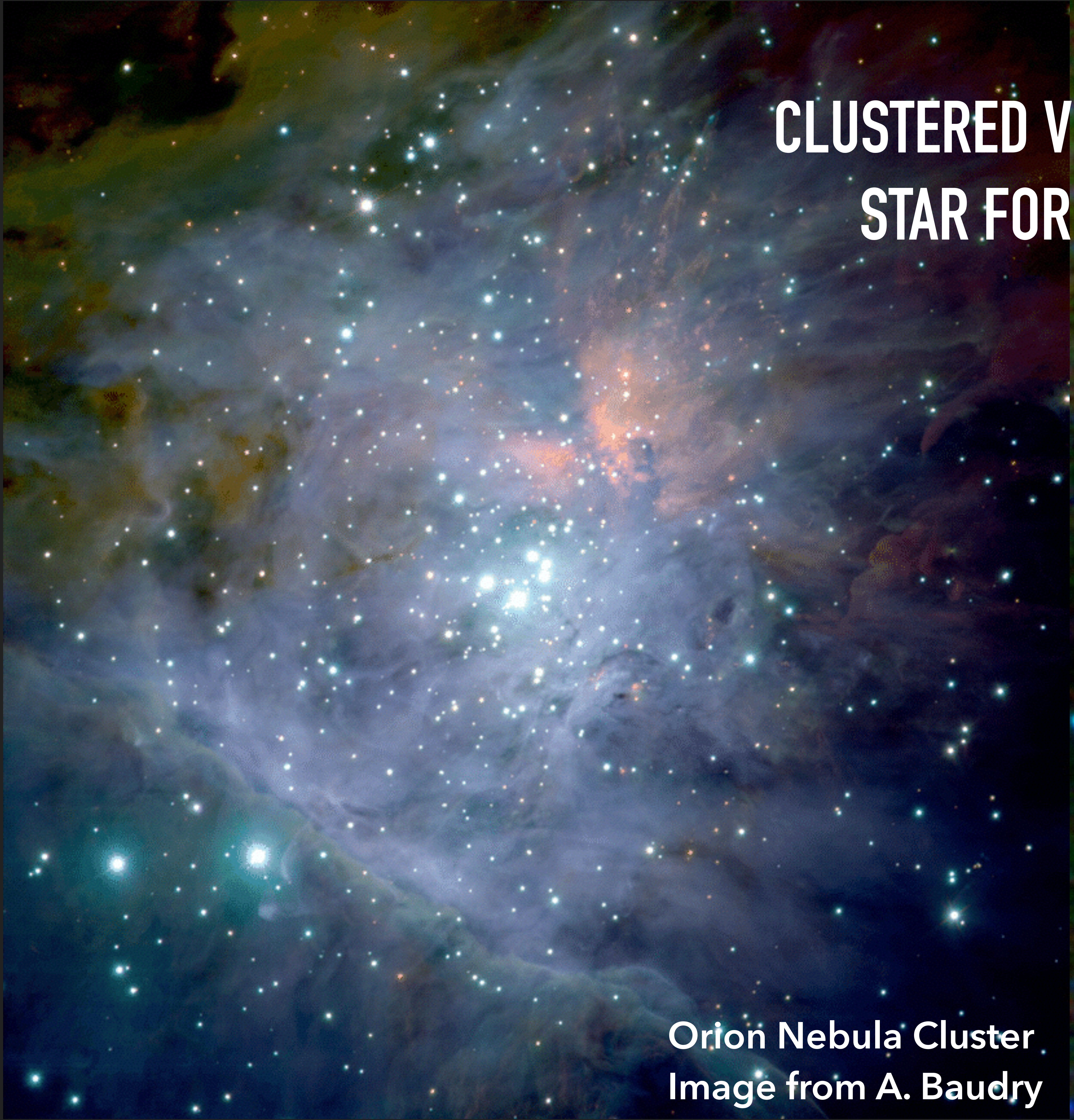


SUMMARY AND CONCLUSIONS: THE ROLE OF THE MAGNETIC FIELD

- Magnetic fields are perpendicular both to the large-scale cloud and small-scale filamentary features, consistent with a scenario in which magnetic fields regulated the gravitational collapse from large (30 pc) to small (0.1 pc) scales
- Structures are predominantly sub-alfvénic and close to critical conditions, suggesting that magnetic fields are strong enough to overcome turbulent motions but not sufficient to prevent the gravitational collapse
- Different level of fragmentation can be explained by the role of the magnetic field
  - ★ A more homogeneous and stronger magnetic field corresponds to a distribution in which matter is concentrated almost in a single location (HUB-N)
  - ★ Larger fragmentation corresponds to a weaker magnetic field coupled with larger dispersion of the magnetic field (HUB-S)

UNVEILING A CLUSTER OF PROTOPLANETARY DISKS AROUND THE MASSIVE PROTOSTAR GGD27 MM1

CLUSTERED VS ISOLATED STAR FORMATION

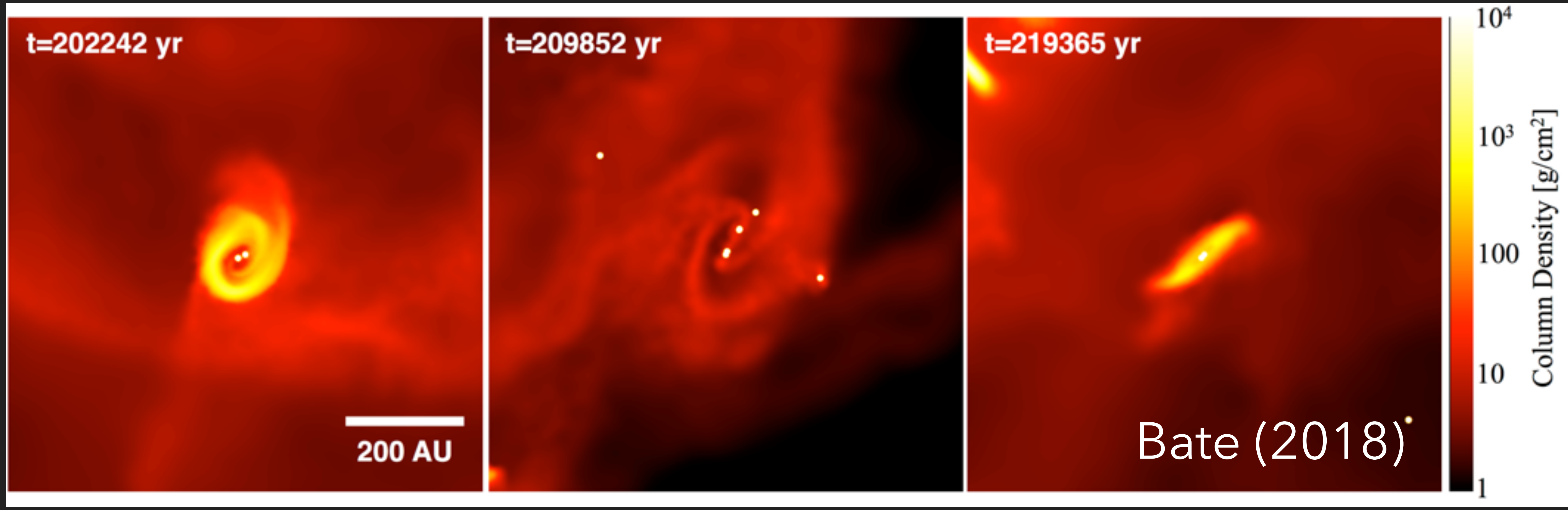


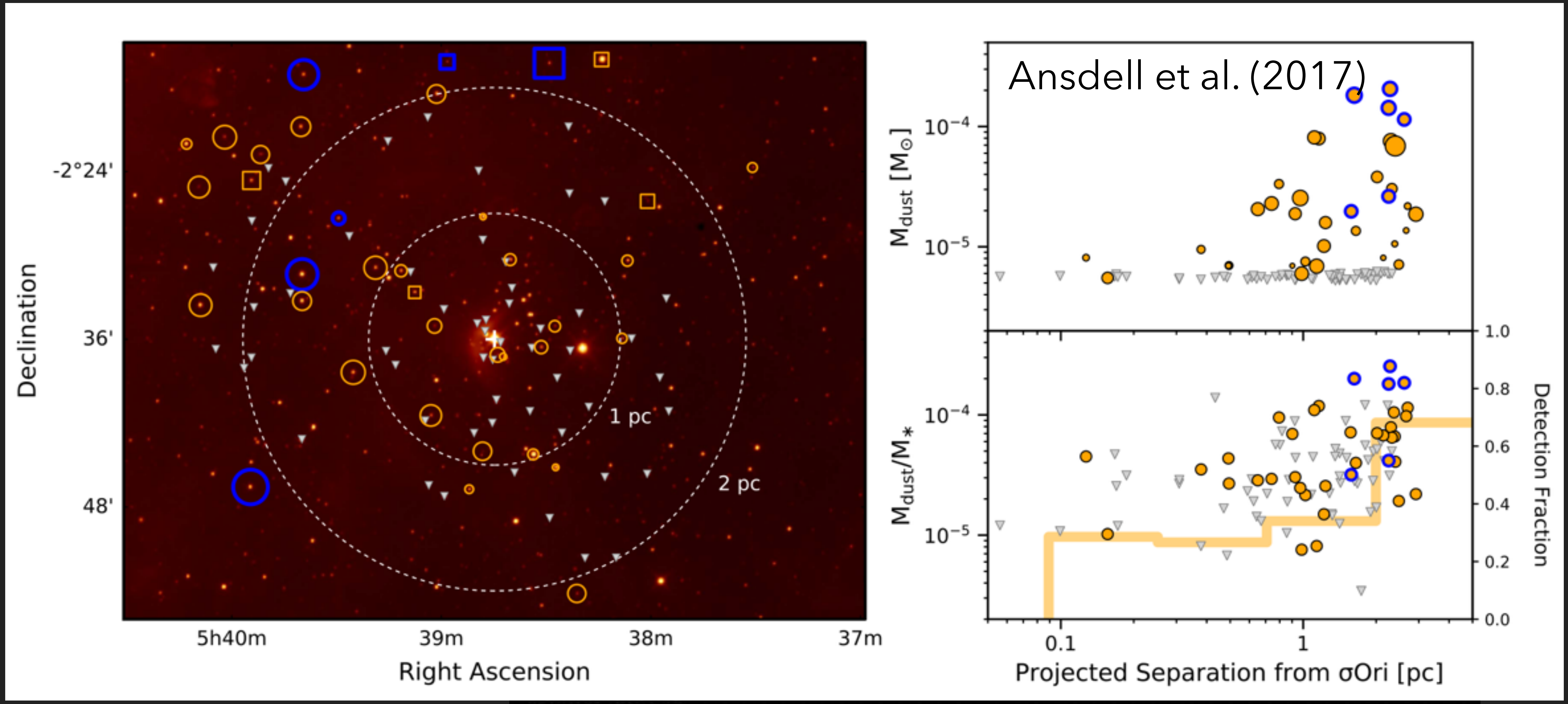
Orion Nebula Cluster
Image from A. Baudry

Spitzer image of L1014
Young et al. (2004)

DISK FORMATION IN MASSIVE STAR CLUSTER ENVIRONMENTS

- Tidal and dynamical interactions
- UV radiation
- Powerful molecular outflows
- Stellar winds



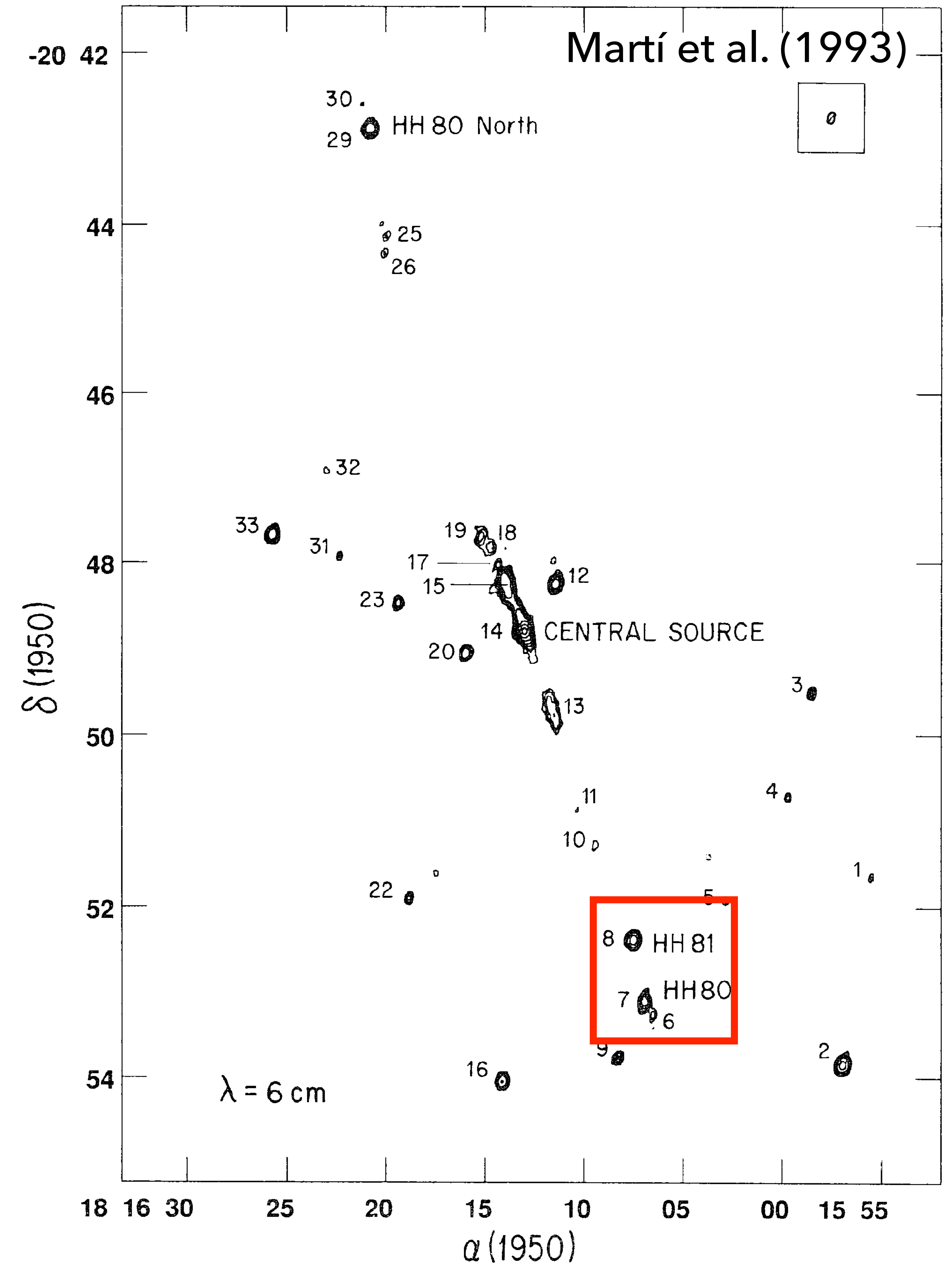


Presence of the massive star and star cluster may have significant effects on the disk formation, structure and evolution

Credit: Gemini Obervatory /AURA

THE PC-SCALE HH80-81-80N JET

- IRAS 18162-2047 (L~1.7x10^4 $L_\odot$, d~1.7 kpc) - massive B0-type YSO
- VLA at cm: collimated jet spanning over 14 pc (Martí et al. 1993, Masqué et al. 2012)
- Herbig-Haro objects HH80 and HH81 at 4′-5′ south of IRAS source (Reipurth & Graham 1988)
- HH80-81 are the brightest HH objects known



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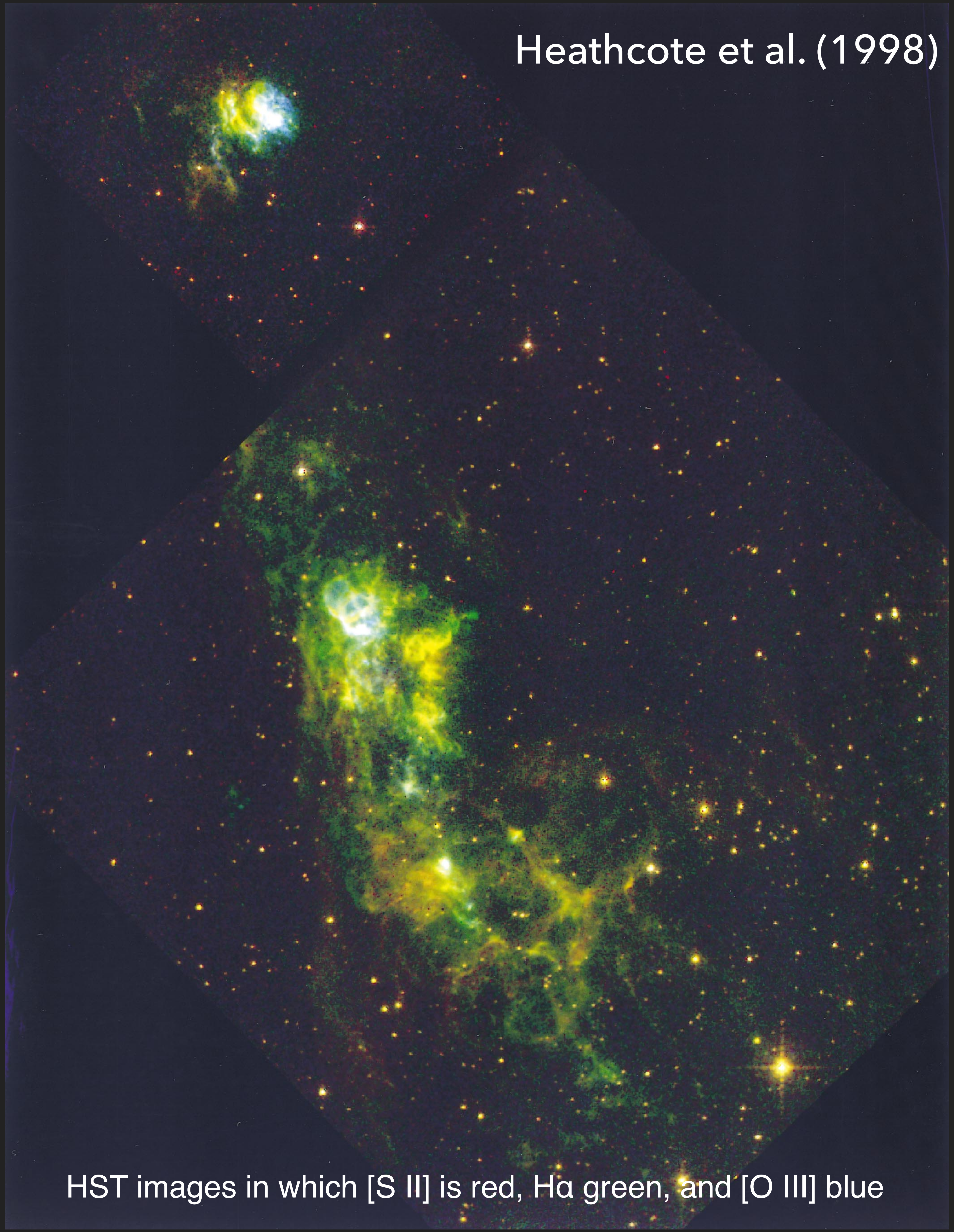

Heathcote et al. (1998)

HST images in which [S II] is red, Hα green, and [O III] blue

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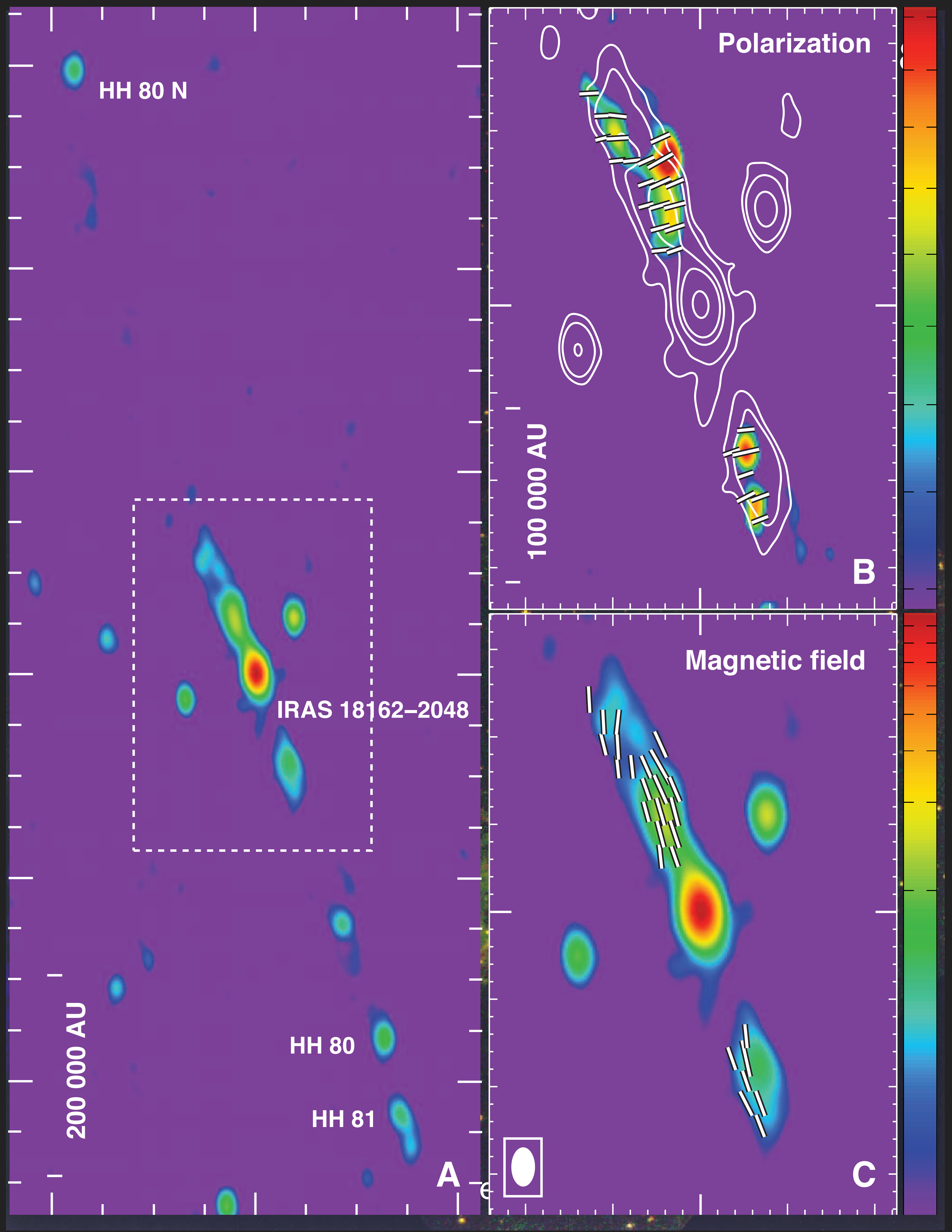
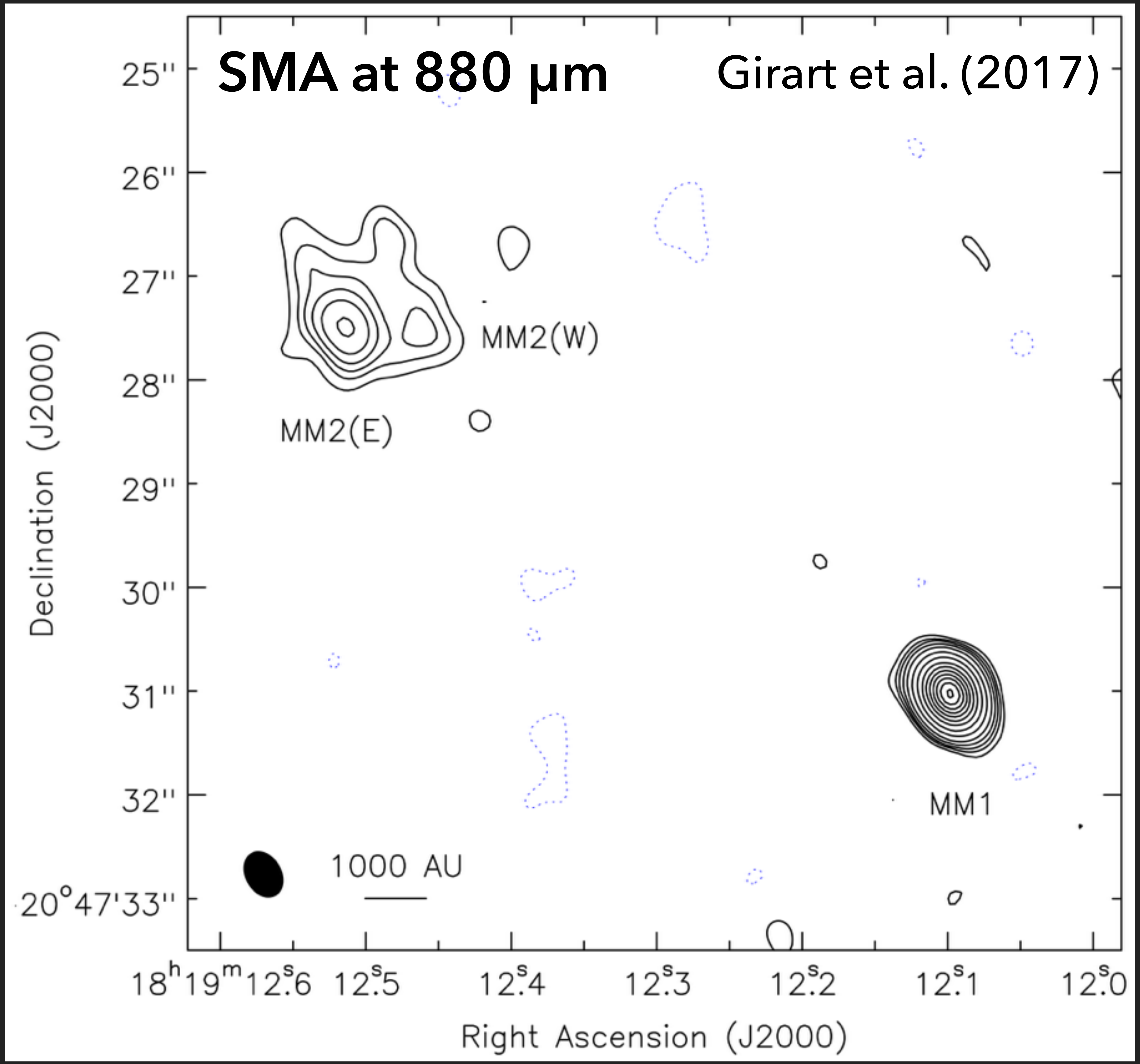
- Herbig-Haro objects HH80 and HH81 at 4′-5′ south of IRAS source (Reipurth & Graham 1988)
- HH80-81 are the brightest HH objects known
- Radio jet emission is polarized: non-thermal synchrotron emission. Helical magnetic field within the jet
- Some shocks in the jet may have enough energy to accelerate electrons to relativistic velocities (Carrasco-González et al. 2010, 2012, Rodríguez-Kamenentzky et al. 2017)



Carrasco-González et al. 2010

THE CENTRAL SOURCE GGD27-MM1

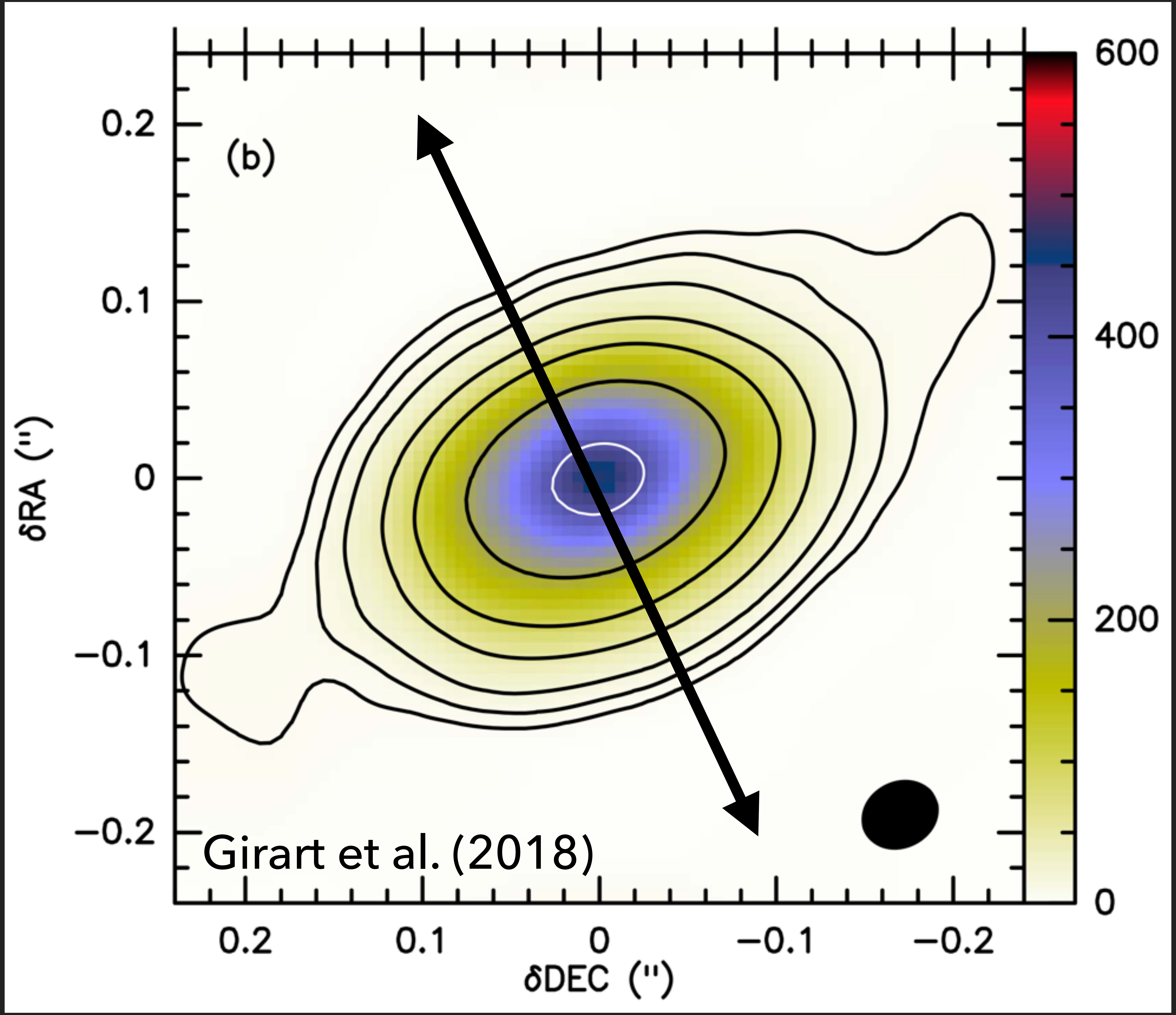
- Two massive circumstellar dense cores MM1 and MM2 (Fernández-López et al. 2011, Girart et al. 2017)
- MM1 powers the spectacular radio jet



ALMA REVEALS A DISK AROUND MM1

- A massive disk around the B-type star powering the radio jet
- Hot optically thick disk
- Disk radius ~290 au, P.A.=112 and inclination ~47°
- accretion disk model with dust settling (D'Alessio et al. 2006, Osorio et al. 2016) as part of PhD thesis of N. Añez-López

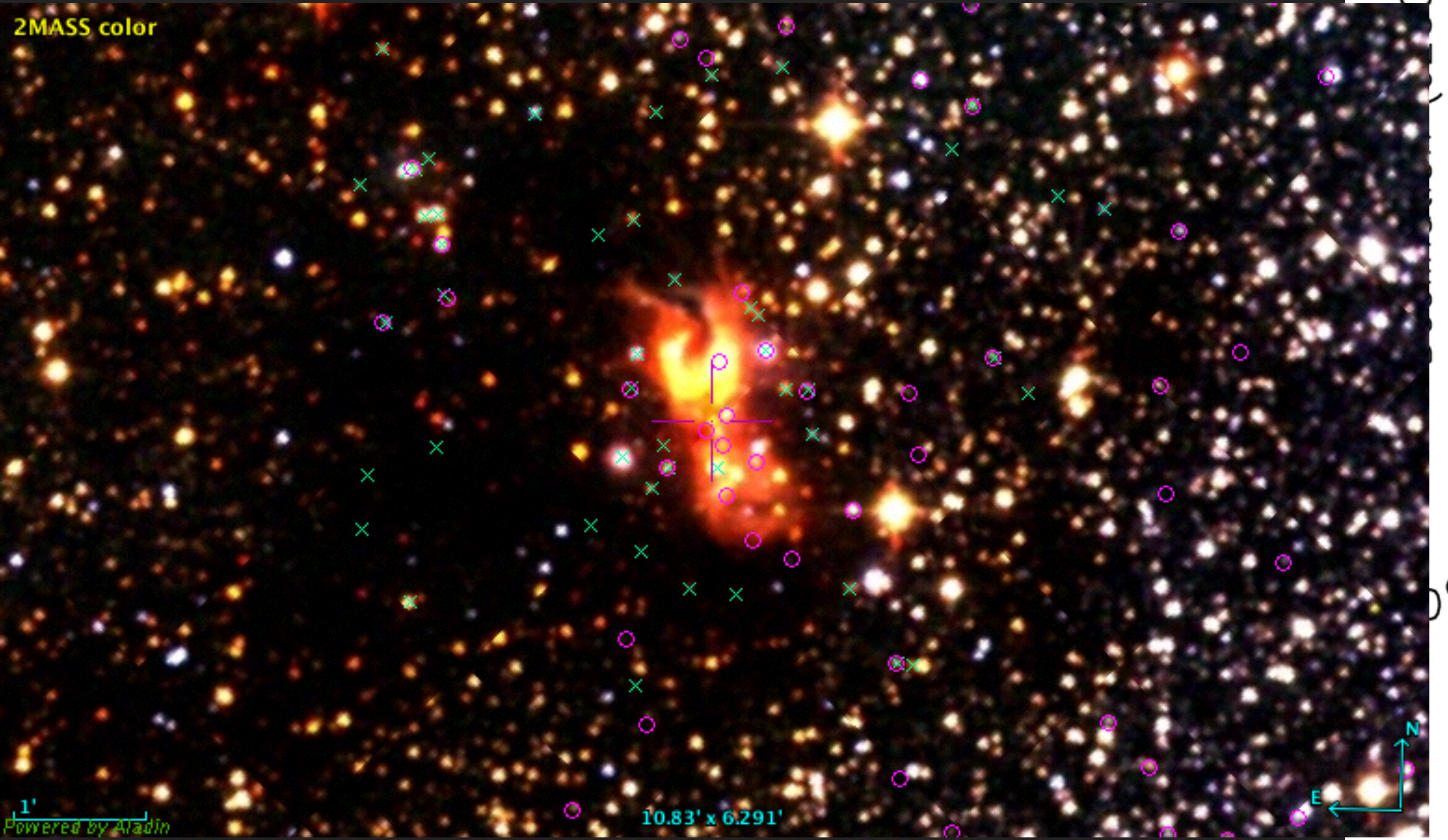
Mayra Osorio Talk on Thursday!



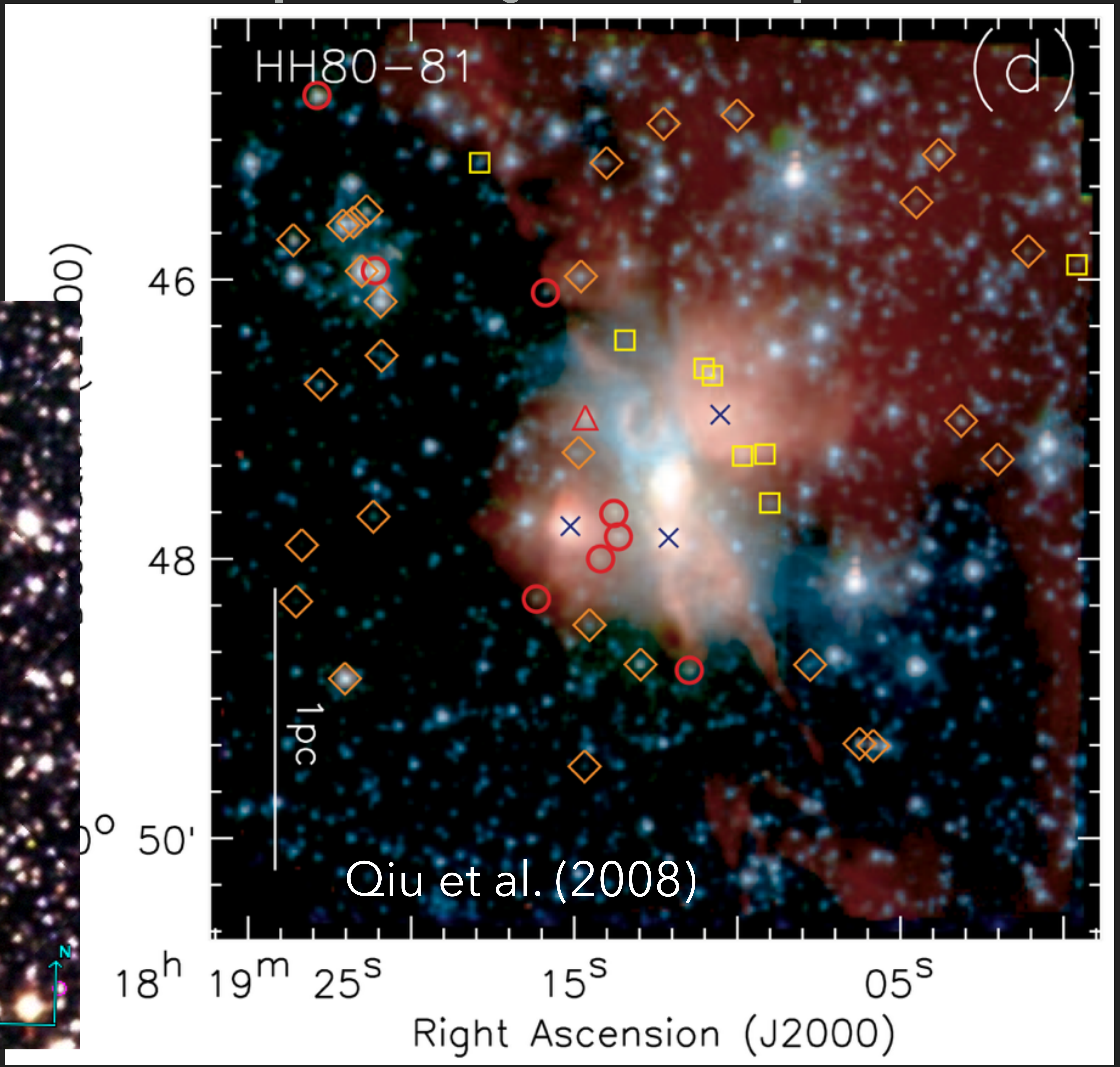
Girart et al. (2018)

THE CLUSTER

- 48 YSOs identified using near- to mid-infrared color-color diagram (Qiu et al. 2008)
- Cluster of X-ray sources (Pravdo et al. 2004, 2009)



Spitzer image (3.6/4.5/8 µm)



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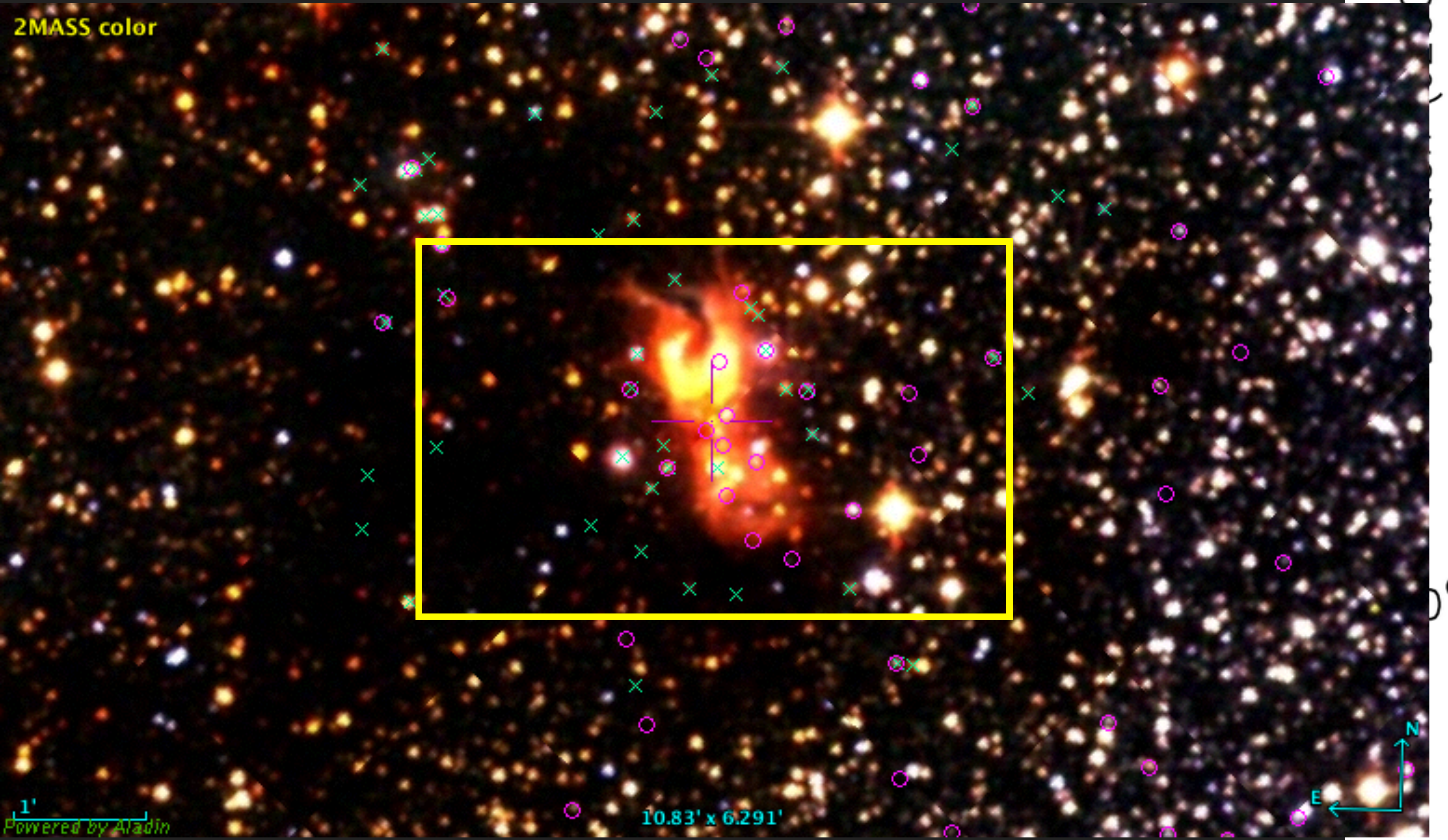

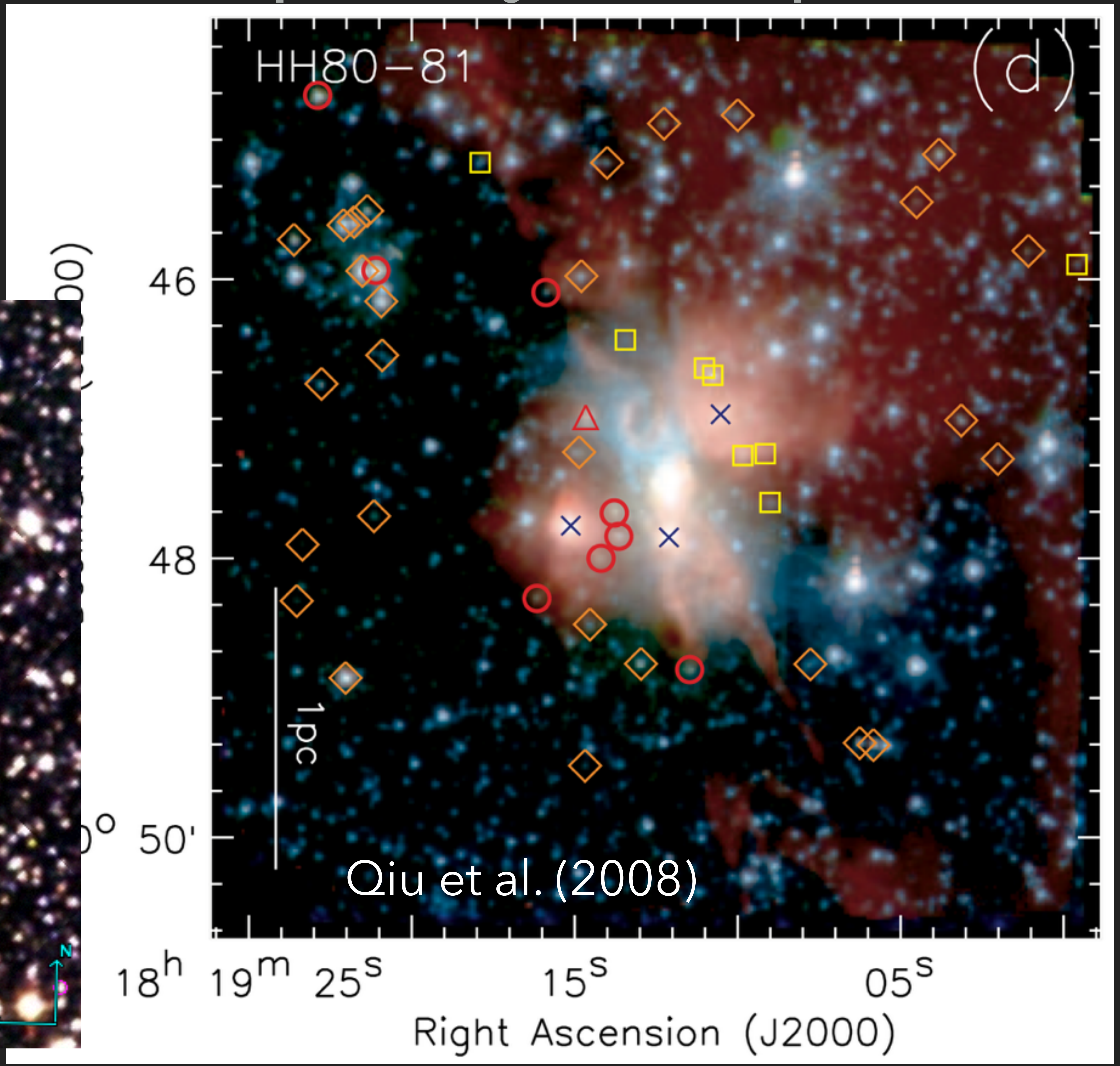

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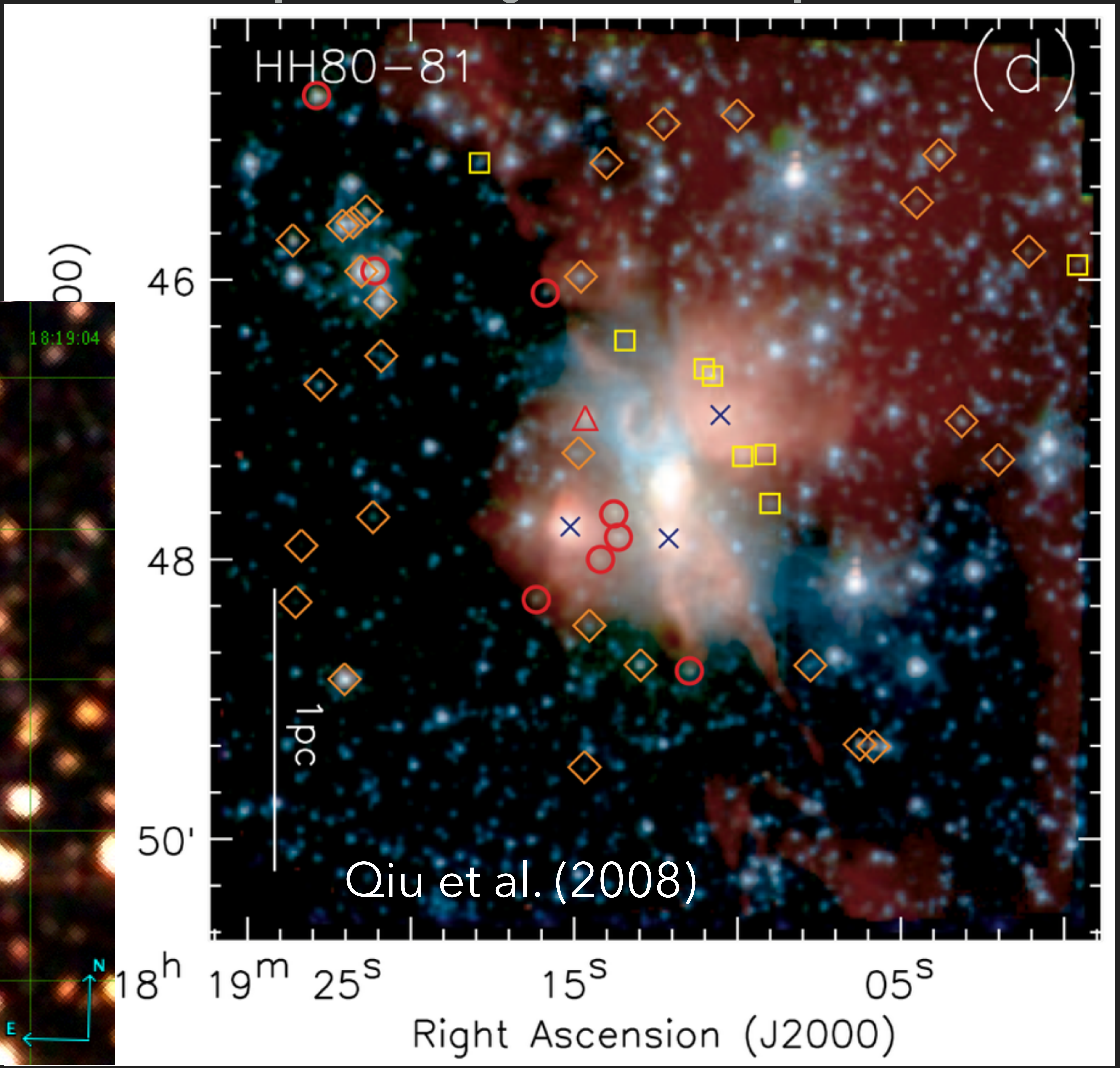

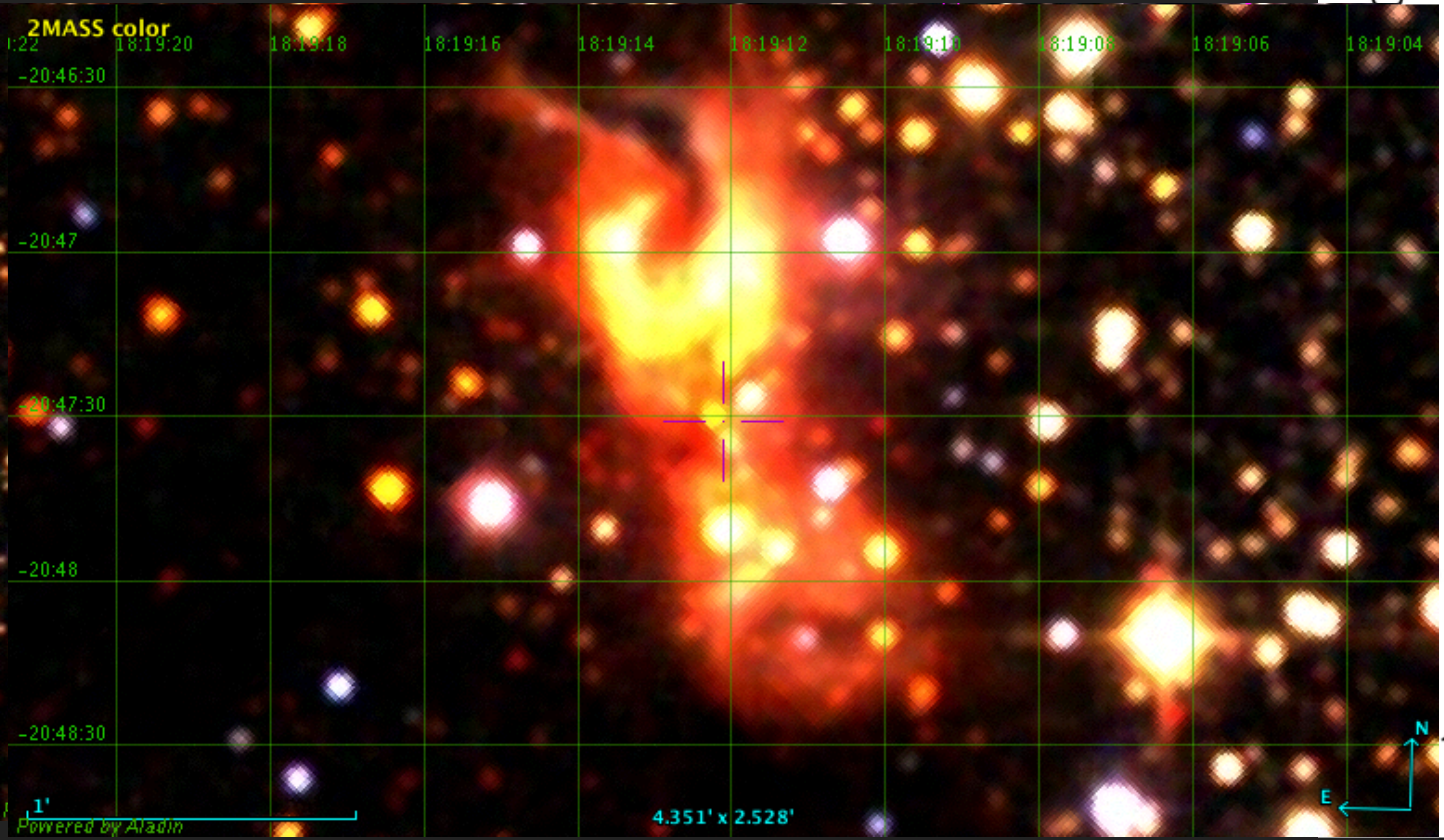

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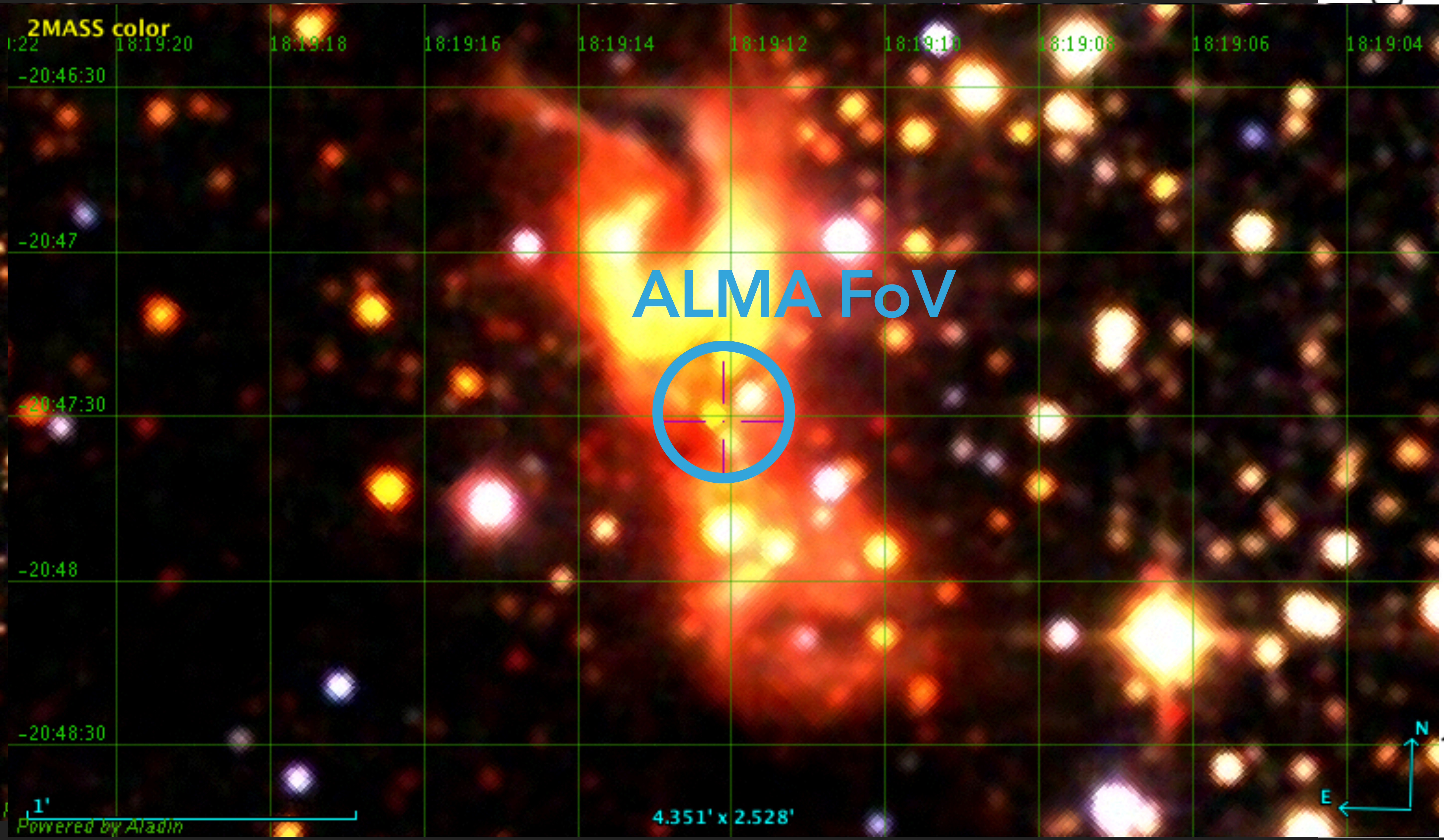

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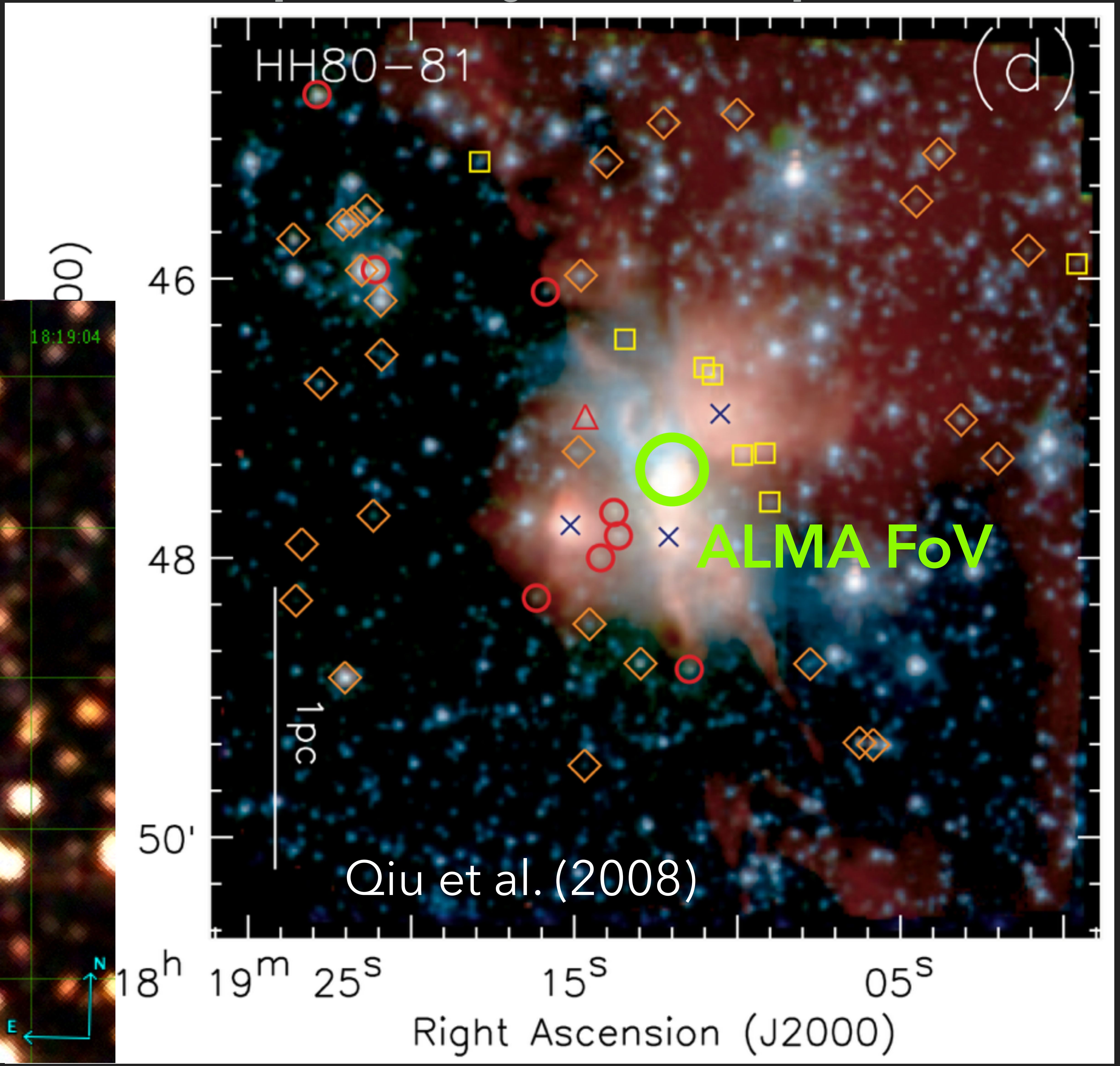
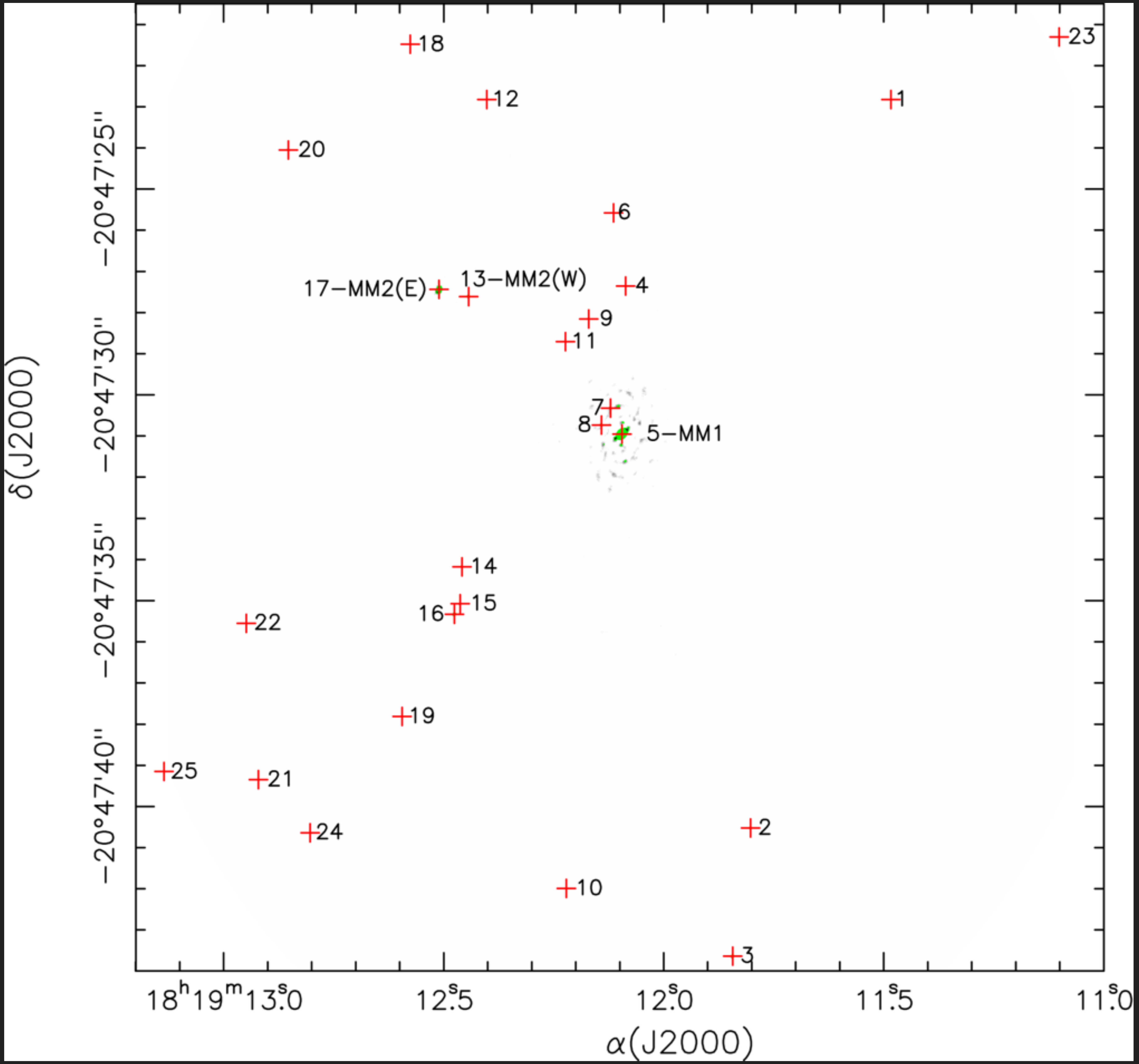


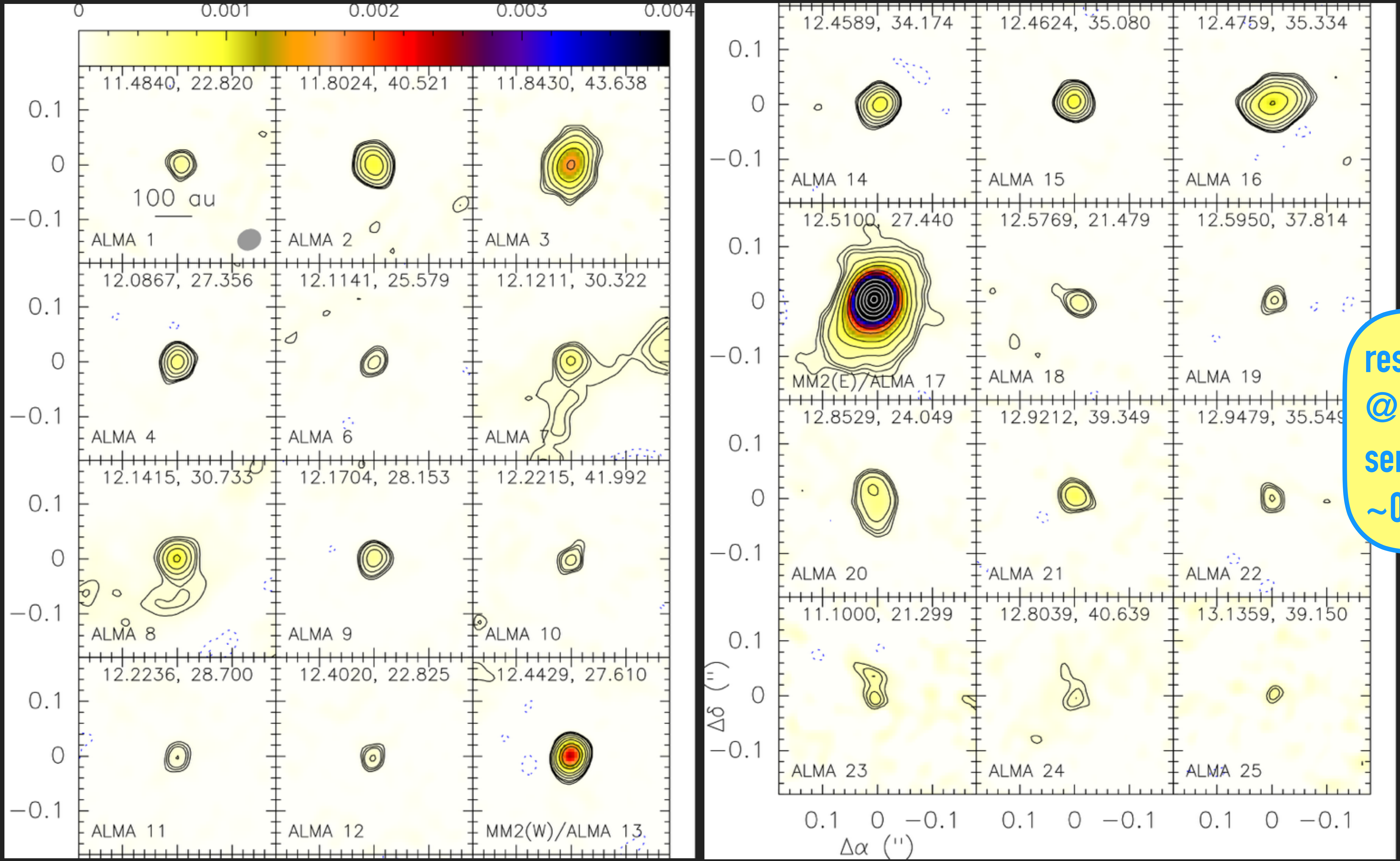
THE ALMA IMAGE AT 1.14 MM

resolution ~40 mas ~70 au @1.7 kpc
sensitivity ~30 μJy/beam ~0.003 $M_\odot$

- cluster of 25 dust continuum sources [22 are new detections]
- Emission arises mainly from disks around Class I protostars
- Excluding the the two most massive YSO MM1 and MM2(E): M_{disk}~0.005- 0.03 $M_\odot$
- Median disk radius is 42 au, and only 3 have R_{disk}>100 au



A CLUSTER OF PROTOPLANETARY DISKS IN GGD27



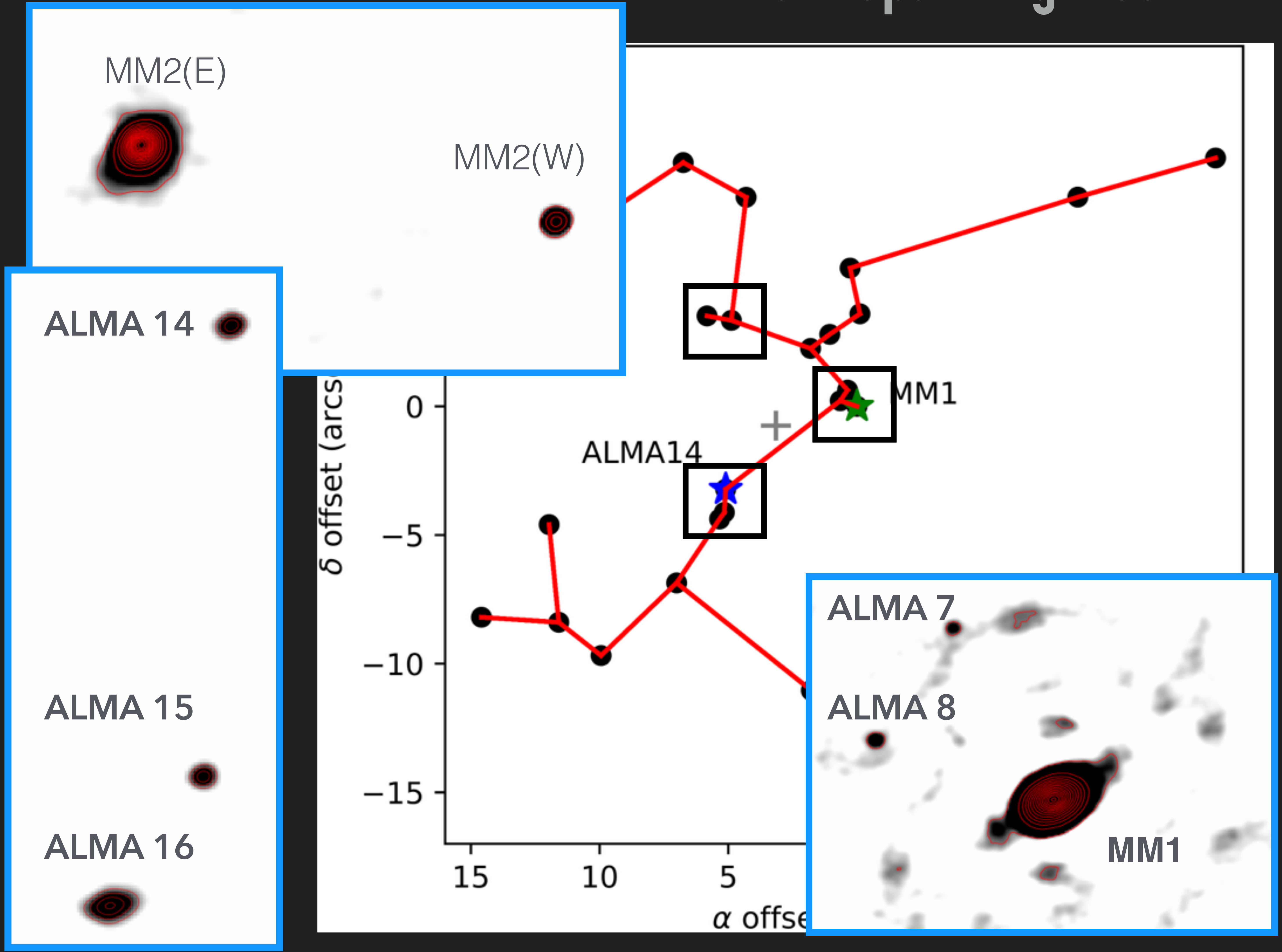
resolution ~40 mas ~70 au @1.7 kpc
sensitivity ~30 μJy/beam
~0.003 $M_\odot$

CLUSTERING

- MST shows sub clustering with 3 subcenters: around MM1, MM2(E)-MM2(W), and ALMA 14-16
- 3 possible multiple systems:

1. MM2(E) and MM2(W), separated ~620 au
2. MM1-ALMA 7- ALMA 8, separated ~1200 au
3. ALMA 14 - ALMA 15 - ALMA 16, separated by ~160 au

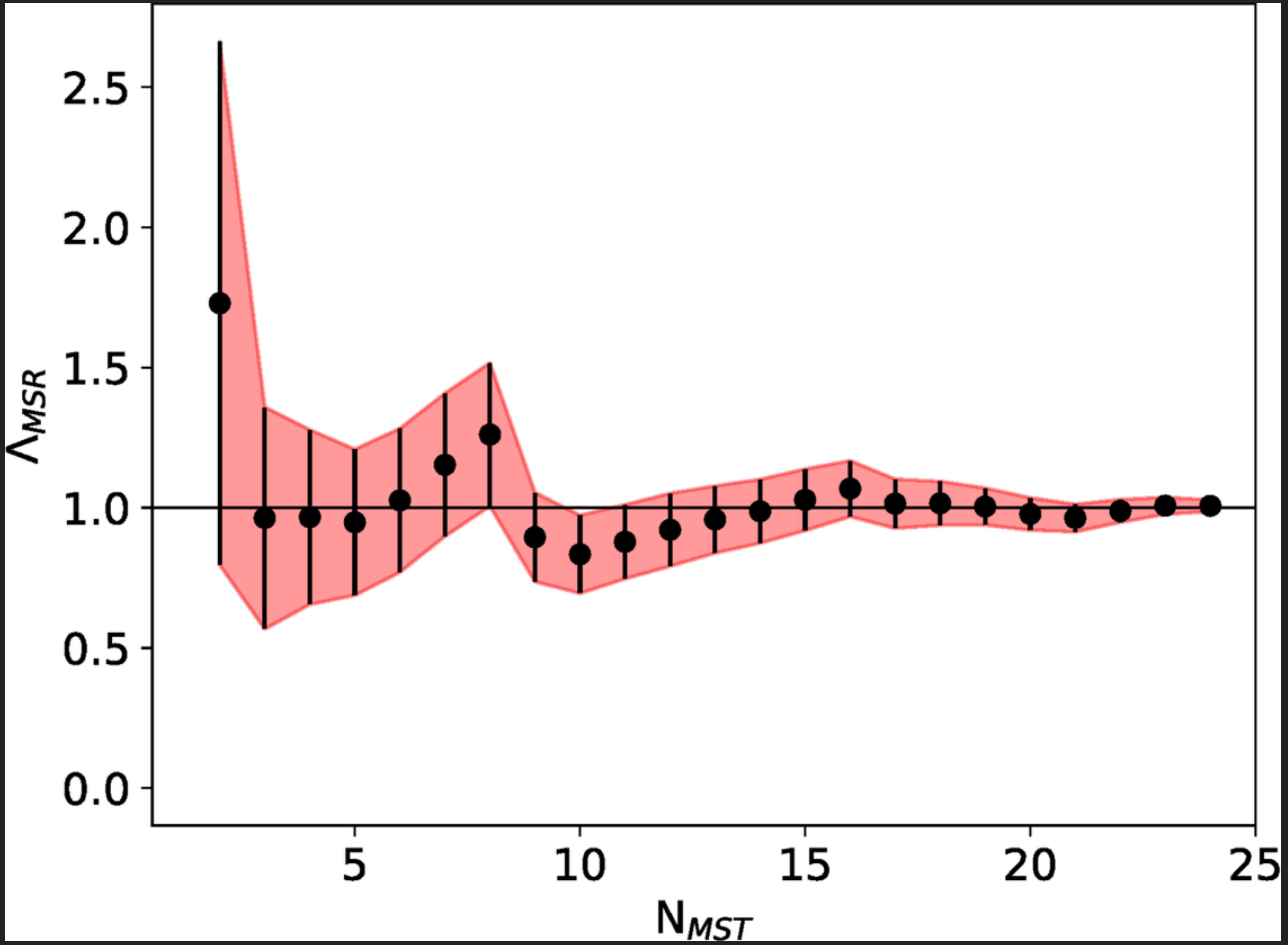
Minimum Spanning Tree



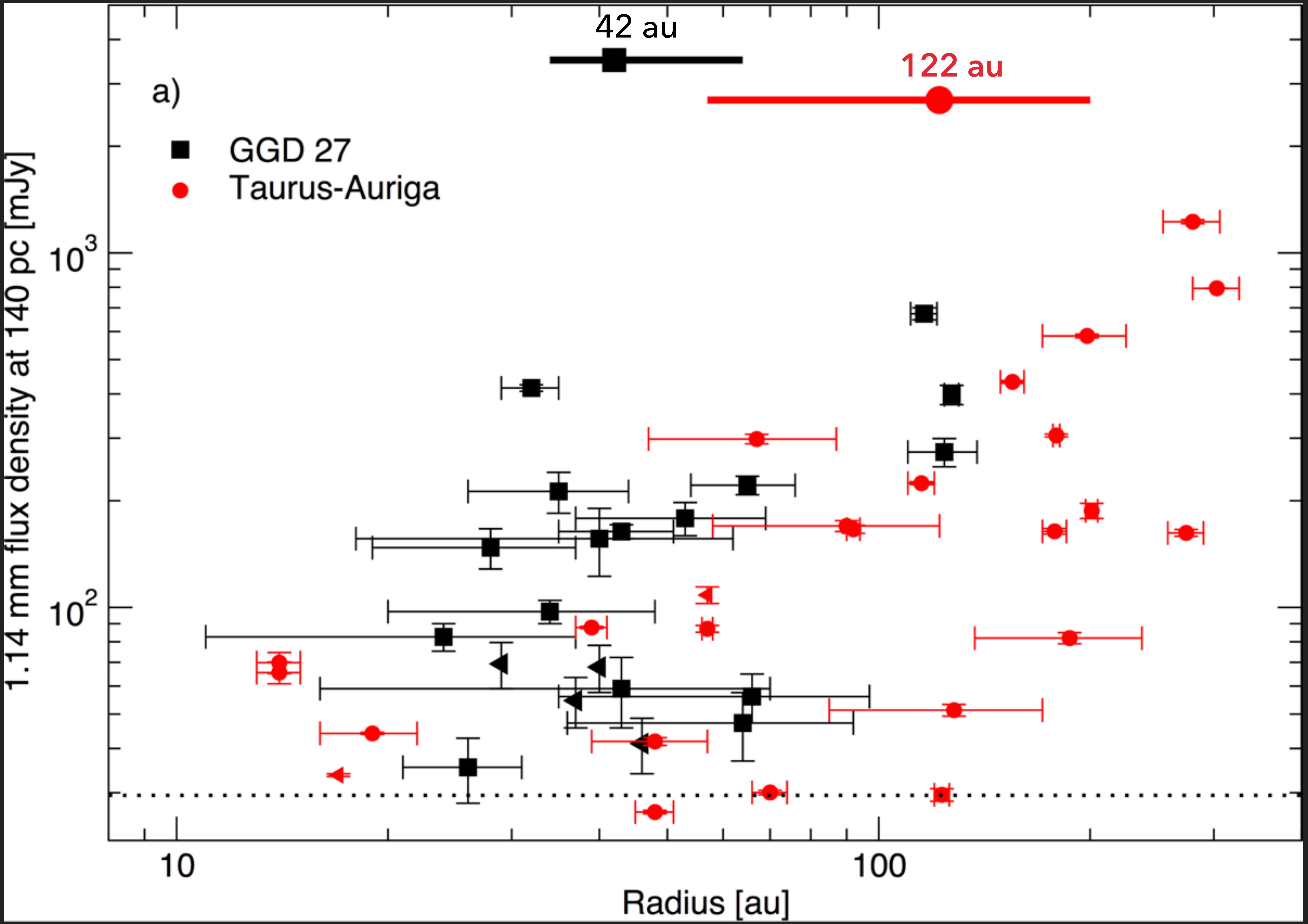
MASS SEGREGATION

- GGD27 shows no mass segregation signatures
- Only the two most massive objects, MM1 and MM2(E) appear segregated from the rest: **Young Cluster**
- Evidence for a **lack of primordial mass segregation** where only the two most massive objects may have already relaxed toward the cluster center

Mass Segregation Ratio

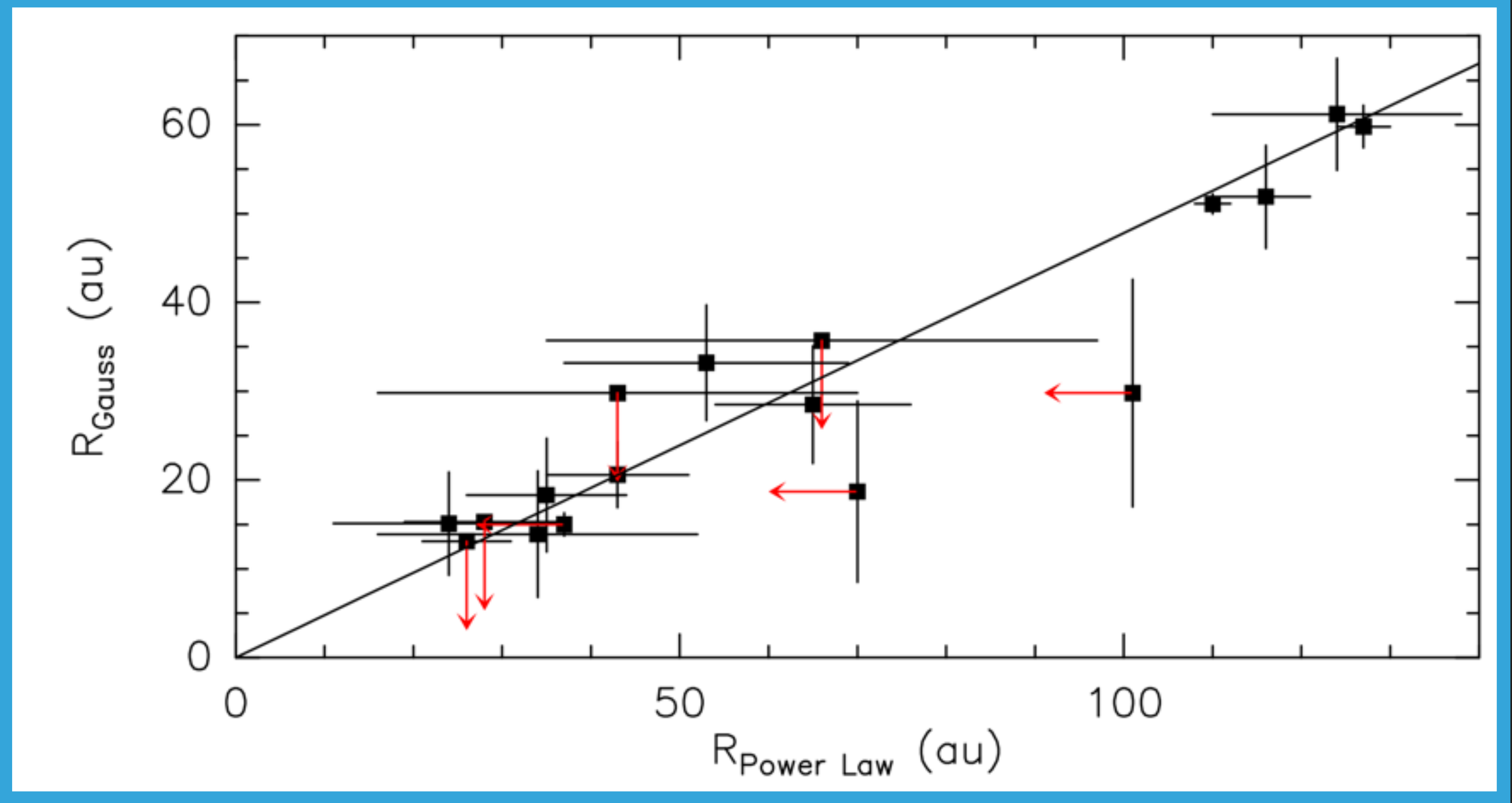


COMPARISON WITH NEARBY REGIONS



HOW DO WE DEFINE THE DISK RADIUS?

- Intensity power law $I \sim r^{-q}$ up to maximum radius: R_{disk} (e.g., Guilloteau et al. 2011, this work)
- Gaussian fit (e.g., Eisner et al. 2018)
- Transition radius R_c between a power law and the exponential zones (e.g., Andrews et al. 2009)
- Effective radius, R_{eff}: radius where 68% of the total flux is located (e.g., Tripathi et al. 2017)

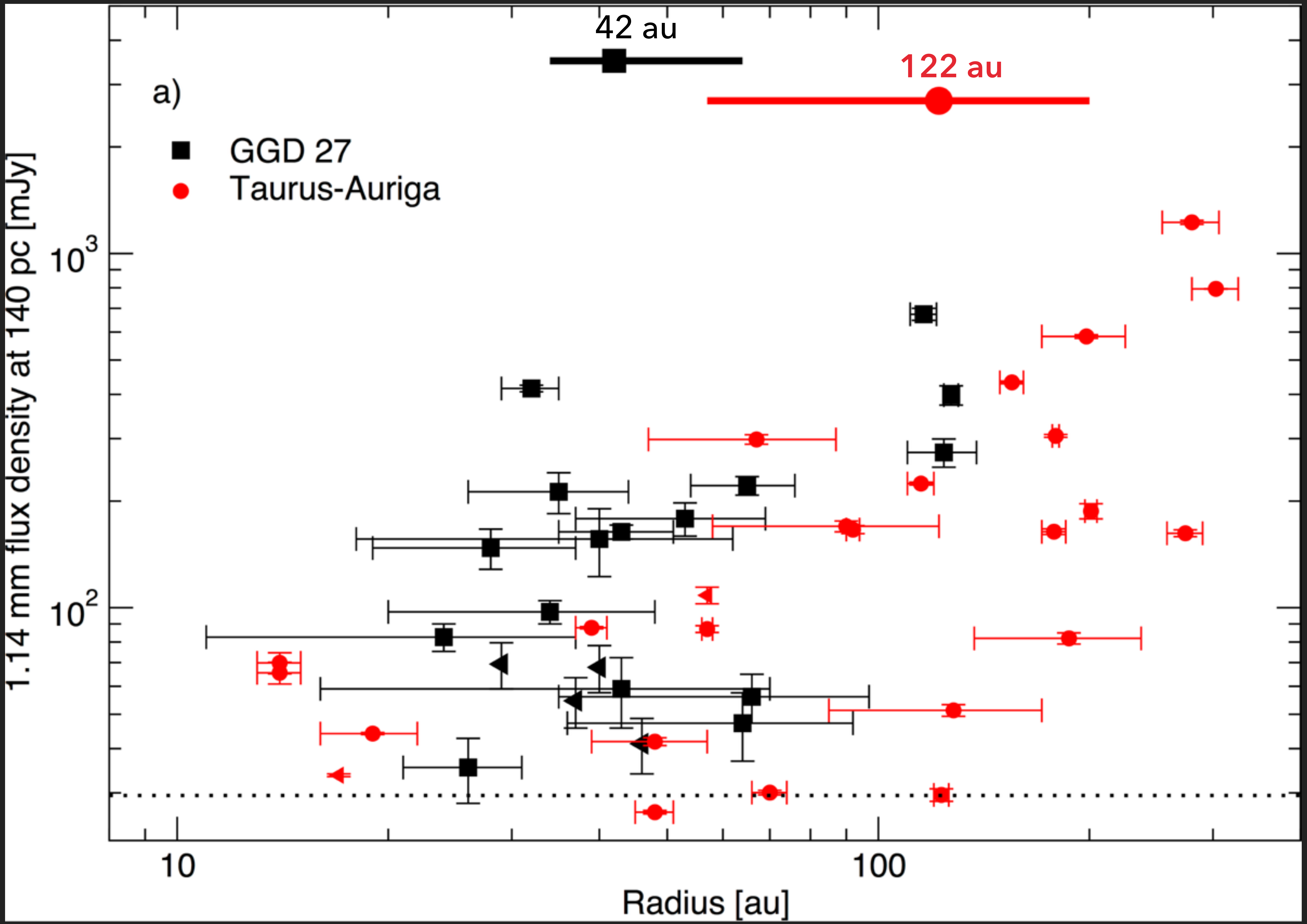


For q=1.1: $R_{Gauss} = 0.48 \pm 0.04 \times R_{power\text{-}law}$

$$R_G = \left[2 \ln 2 \frac{1 - q/2}{4 - q}\right]^{1/2} R_{disk} = 0.46\, R_{disk}$$

COMPARISON WITH NEARBY REGIONS

- For a given flux, disks in GGD27 tend to be smaller than in Taurus (Guilloteau et al. 2011, Pietu et al. 2014)
- Deficit of disks with R_{disk}>100 au
- Median for ONC (Eisner et al. 2018) is ~44 au, similar to GGD27 disks



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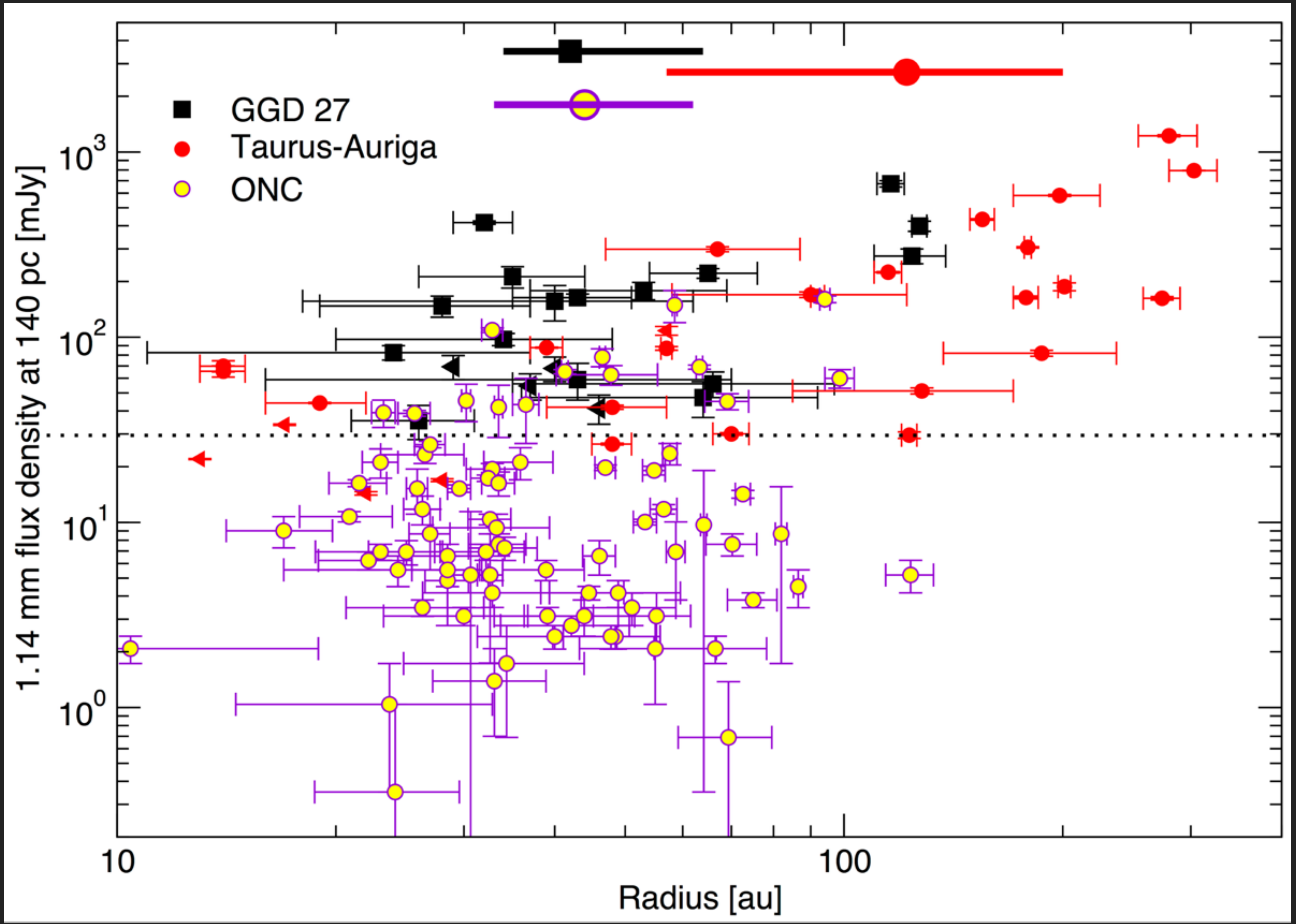

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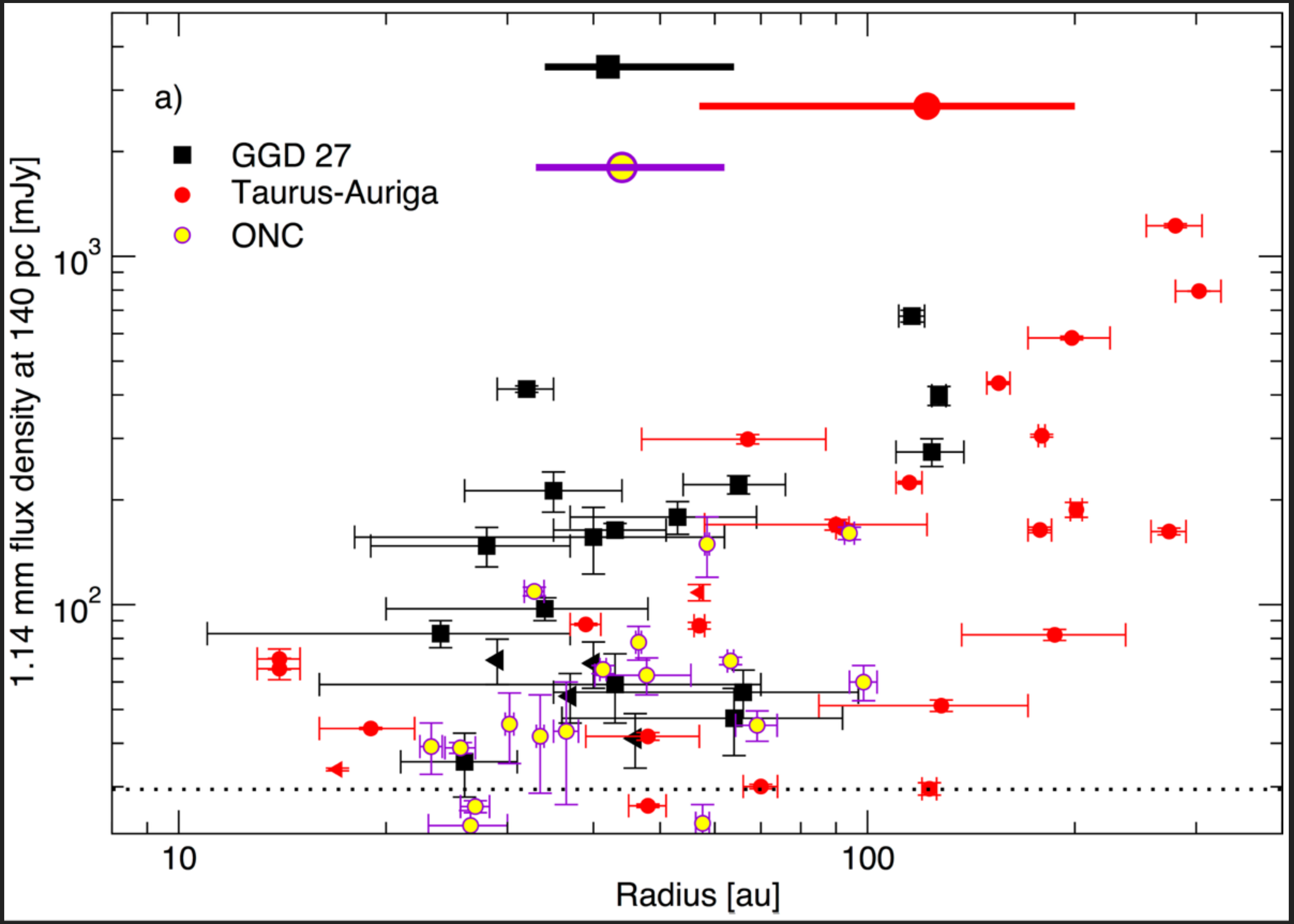
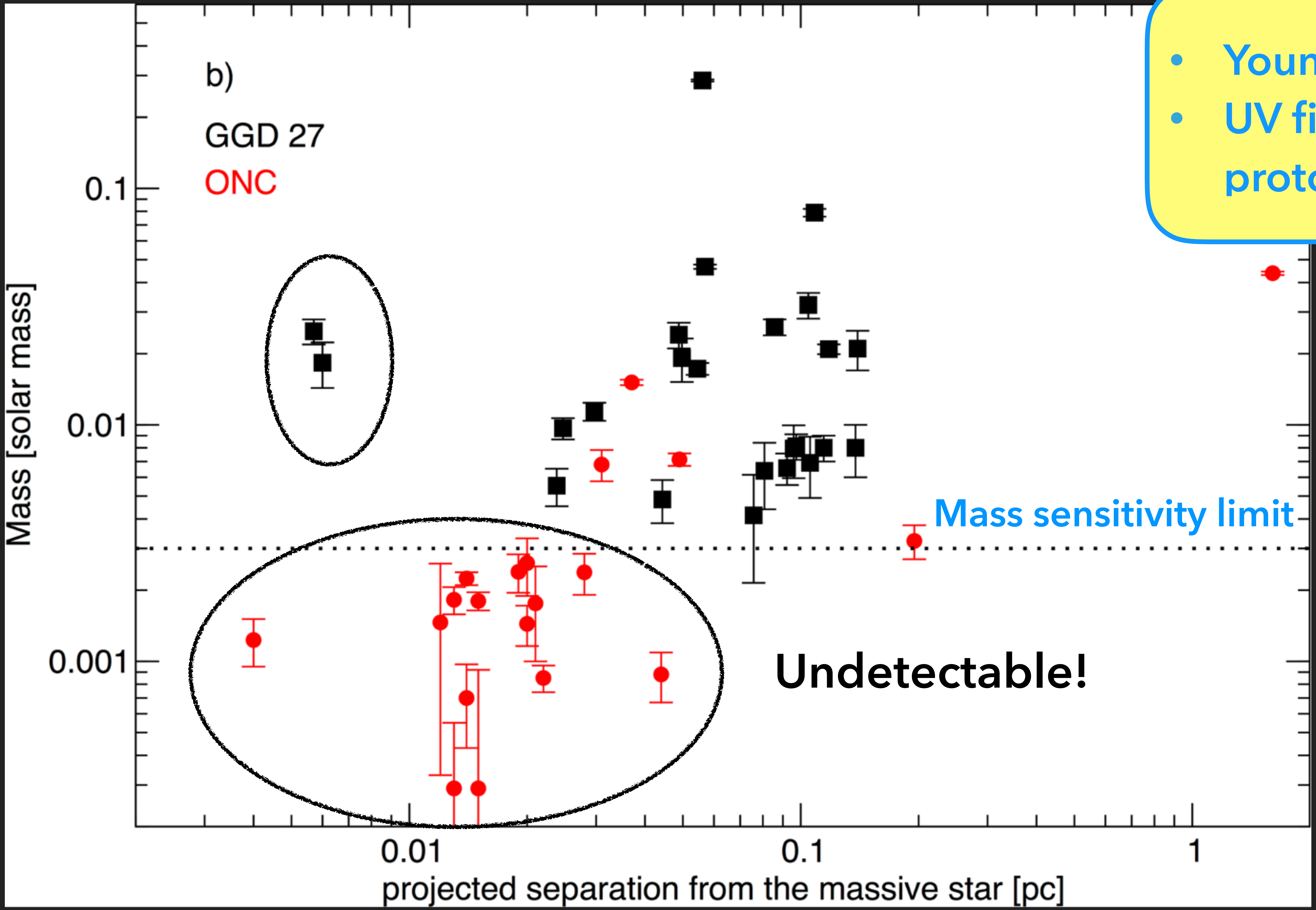
- **Clustered nature**
- **Different initial conditions**
- **Different viscous timescales**
- **Different evolutionary states**

?



ENVIRONMENTAL EFFECTS: UV PHOTOEVAPORATION?

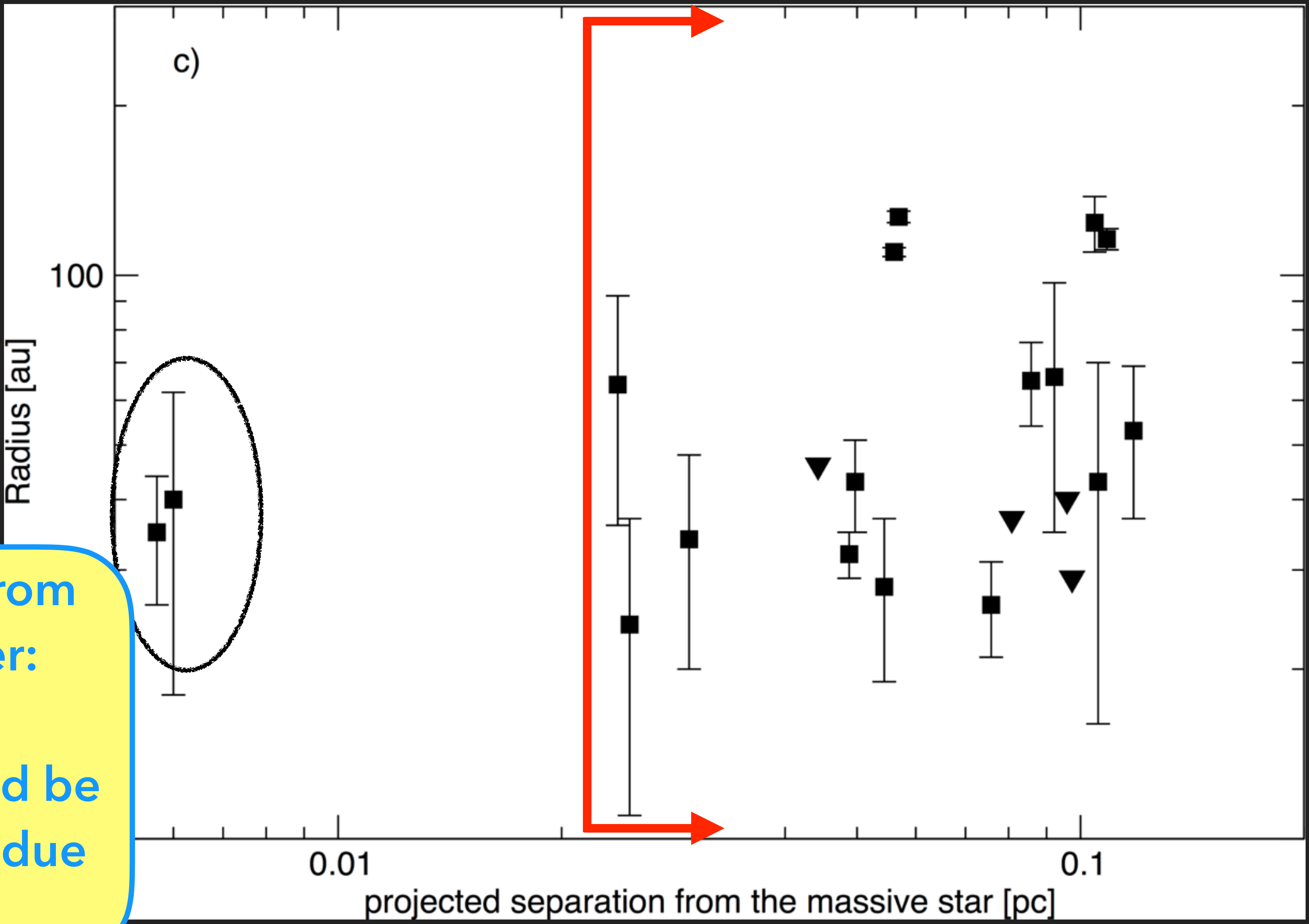


- Young cluster
- UV field from the B0-type protostar is weak

ONC data from Mann et al. (2014)

ENVIRONMENTAL EFFECTS: UV PHOTO EVAPORATION / INTERACTIONS

- Most of the disk population is located at distances > 0.02 pc
- Stars close to the massive star (the cluster center) may not be capable to form disks?
- Only at distances > 0.05 pc disks appear larger (but large dispersion!) and more massive



- **Dynamical interactions far from the cluster center are weaker: disks can easily form**
- **Small disks at >0.02 pc could be the result of disk truncation due to interactions**

SUMMARY AND CONCLUSIONS: THE ROLE OF THE ENVIRONMENT

- The combination of sensitivity and spatial resolution lead us to the serendipitous discovery of a cluster of 25 continuum sources detected at 1.14 mm whose emission most likely arises from disks surrounding Class I protostars
- Disks in the GGD 27 cluster appear smaller than the Taurus disks (form stars in isolated mode) while they are compatible with disks sizes found in Orion Nebula Cluster (old cluster)
- Lack of disks close to the massive protostar suggest that in this cluster environment stars may no be able to form disks
- Unlike in Orion Nebula Cluster, disks in the GGD27 cluster do not display evidence of external photo evaporation due to the massive star but higher sensitivity observations are needed to confirm this result
- Potential al ALMA to unveil a disk population at millimeter wavelengths, whose emission appears completely hidden in the near-infrared due to the strong emission from the massive protostar