VLA (AND ALMA) OBSERVATIONS OF YOUNG STELLAR CLUSTERS

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Fundación BBVA

Universitat de Barcelona

IEEC

COLD CORES MEETING

May 23, 2023

ICCUB

Institut de Ciències del Cosmos
Universitat de Barcelona

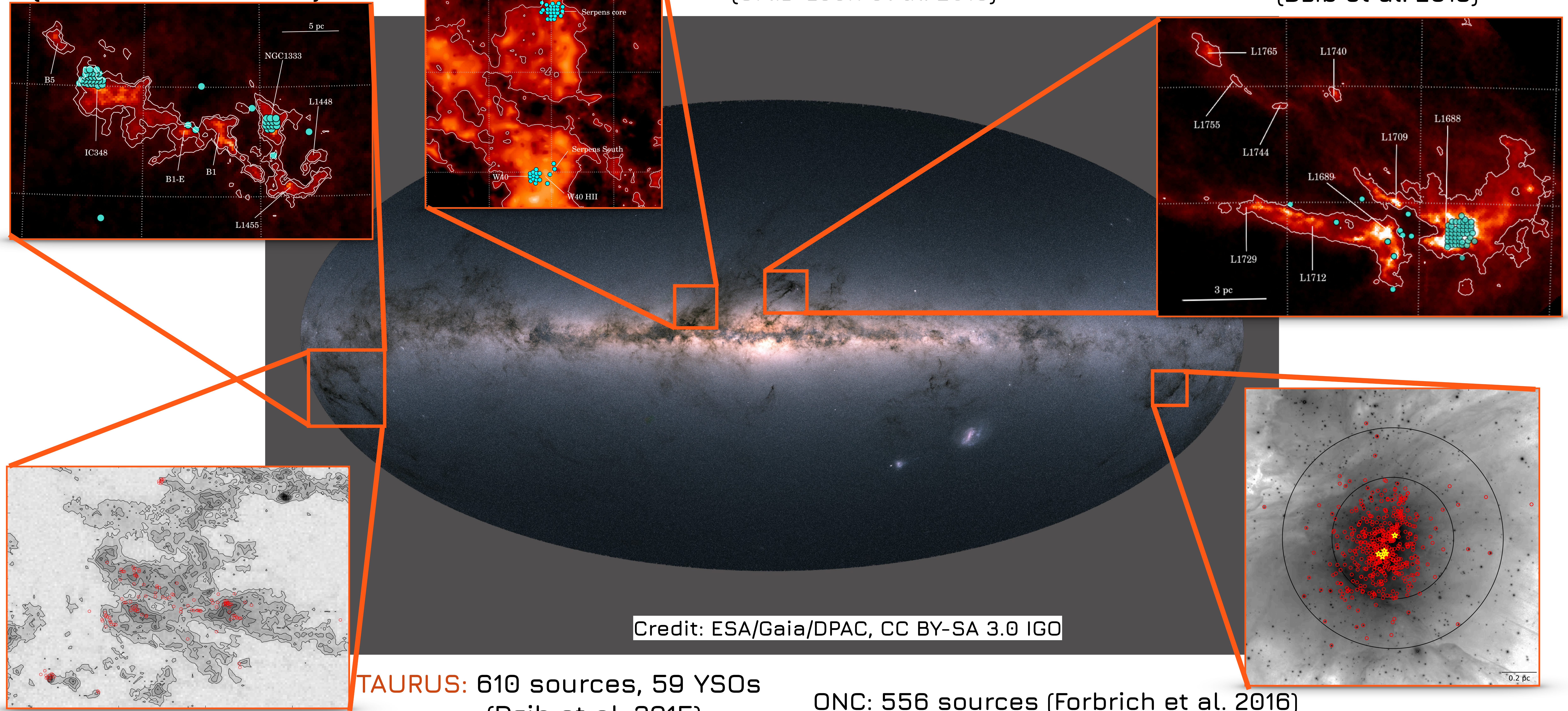
Excelencia María de Maeztu 2020-2023

YSOs IN THE SOLAR NEIGHBOURHOOD

PERSEUS: 206 sources, 42 YSOs
(Ortiz-León et al. 2015)

SERPENS: 146 sources, 29 YSOs
(Ortiz-León et al. 2015)

OPHIUCHUS: 189 sources, 56 YSOs
(Dzib et al. 2013)



TAURUS: 610 sources, 59 YSOs
(Dzib et al. 2015)

ONC: 556 sources (Forbrich et al. 2016)
ORION: 376 sources, 234 YSOs (Kounkel et al. 2014)

WHY STAR CLUSTER FORMATION?

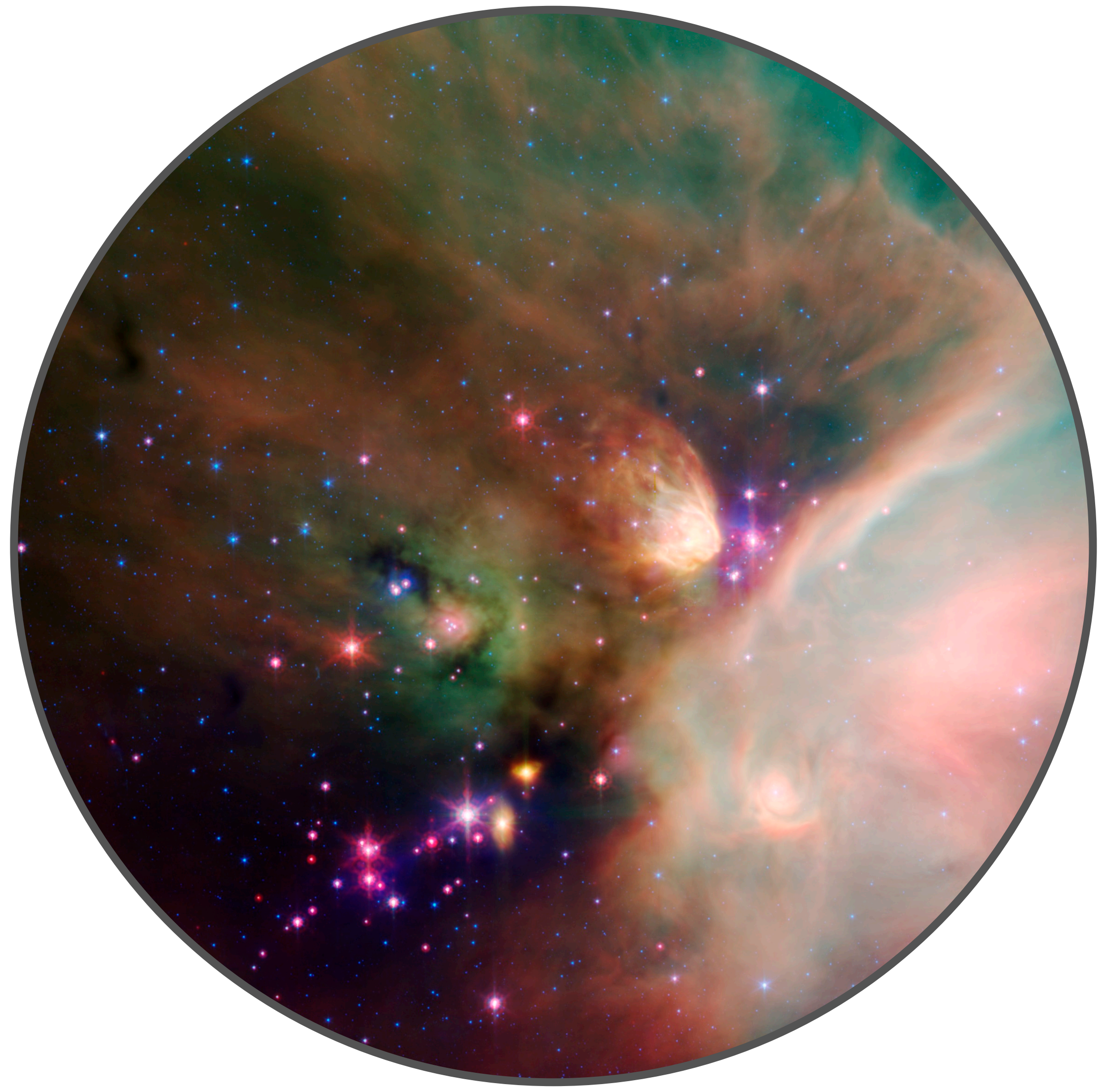
- ★ Most stars in the Galaxy form in clusters or in groups of at least a few tens of stars (e.g., Lada & Lada 2003)
- ★ Our Sun was born in a cluster environment (Adams 2010)

THE ORION NEBULA CLUSTER

Image credit: ESO/H. Drass et al.

THE TARGETS

THE IRDC
G14.225-0.506



THE VLA OphA PROJECT

THE VOLS PROJECT

THE IRDC G14.225-0.506 (M17 SWex)

- ★ d=1.6 kpc (Zucker et al. 2020) in the M17 region (Omegą Nebula)
- ★ Rich population of protostars and YSOs (Povich & Whitney 2010, Povich et al. 2016)
- ★ 2 Hub-filament systems, each one harbouring a deeply embedded protocluster (Busquet et al. 2013, Busquet et al. 2016, Ohashi et al. 2016, Chen et al. 2019)
- ★ G14.2 is forming stars at a furious rate but has not yet spawned the most massive O-type stars (Povich et al. 2016)

What are the characteristics of the stellar population?

Do massive stars form coeval to the low-mass cluster members?

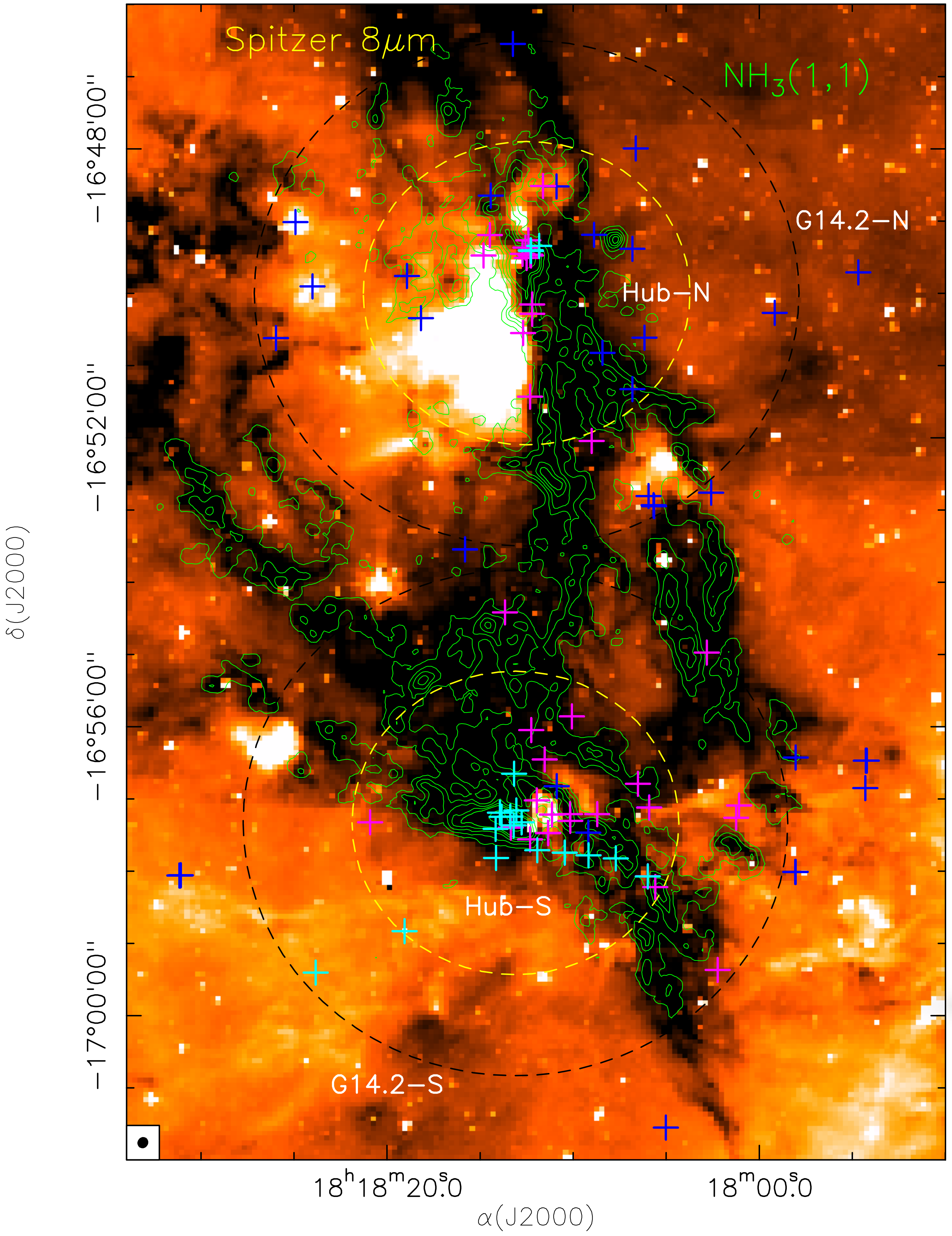
Image Credit : NASA/JPL-Caltech/Matthew Povich (Penn State)

UNVEILING THE EMBEDDED POPULATION

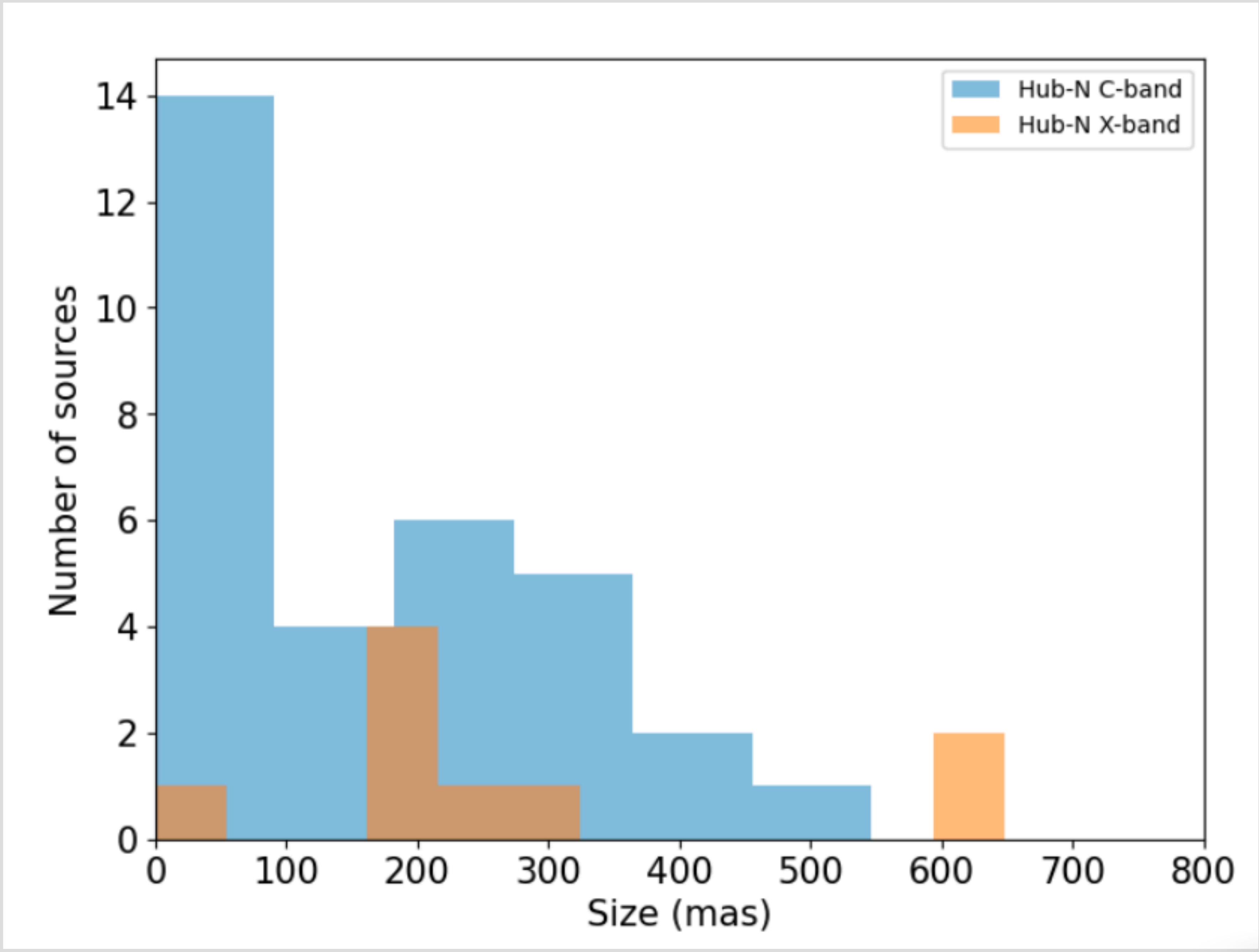
PILOT PROGRAM WITH THE JVLA

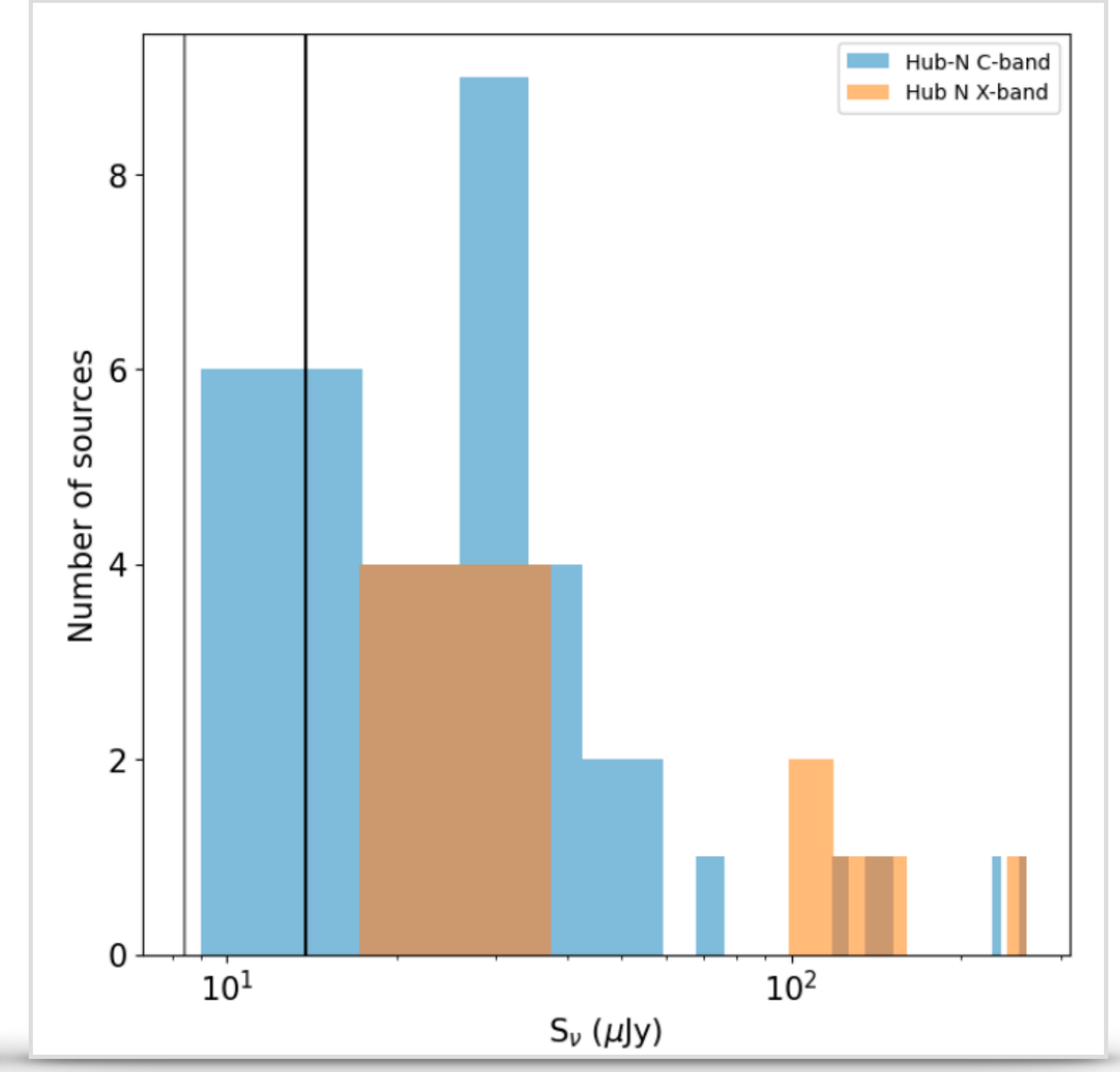
- ★ **Most extended A-array** configuration (beam~0.3"~500 au)
- ★ **Sensitivity:** 1.5 μJy/beam @10 GHz (3.6 cm) and 2 μJy/beam @6 GHz (6 cm)
- ★ **Observing time per pointing:** 10.8 hours at 3.6cm and 3.4 hours at 6 cm
- ★ **34** radio sources detected in **Hub-N** and **35** radio sources detected in **Hub-S**

Roger Grau, Master Thesis (2020), Díaz et al. in preparation

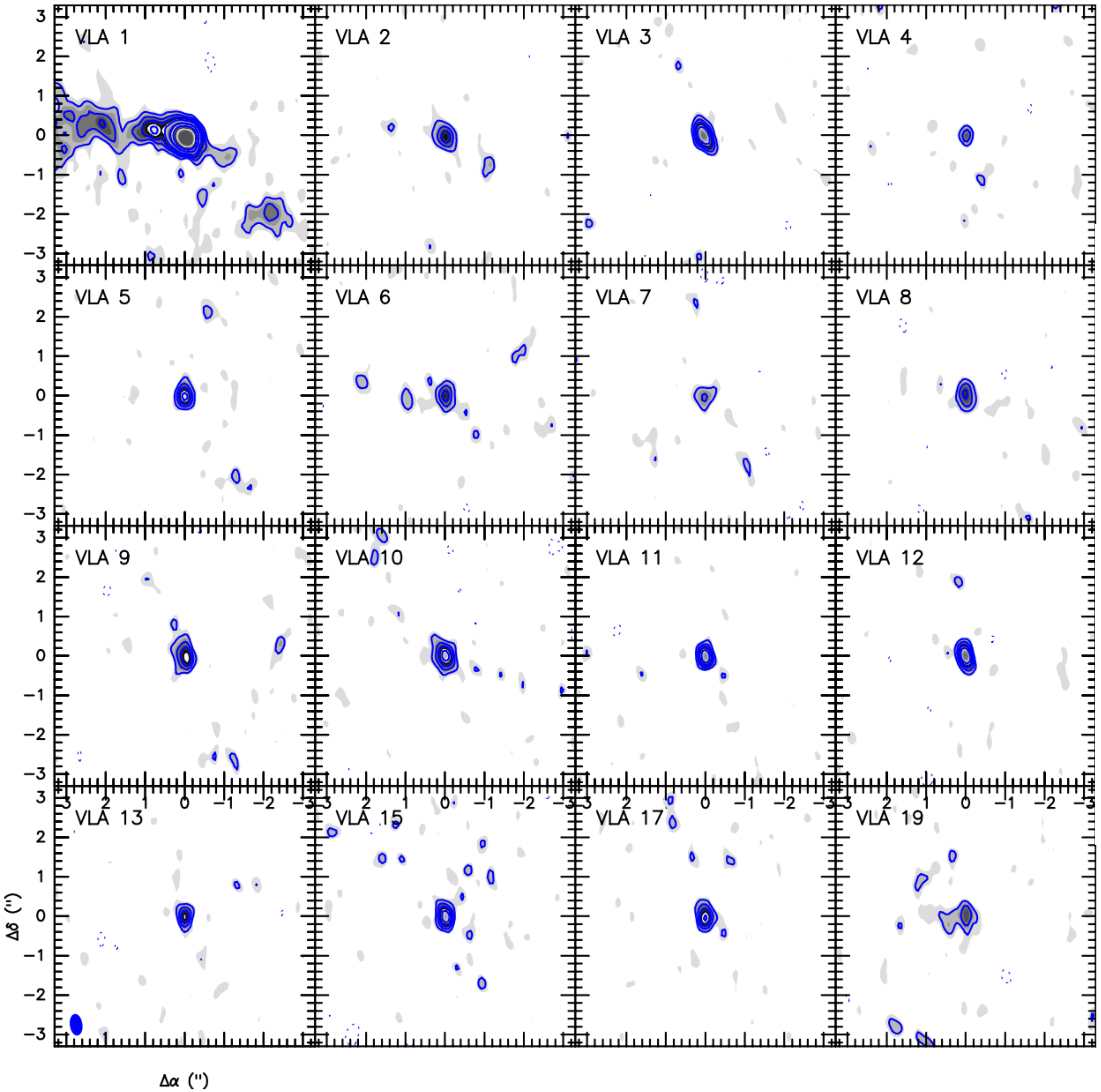


+ DETECTED @ 6CM
+ DETECTED @ 3.6 CM
+ DETECTED AT BOTH BANDS

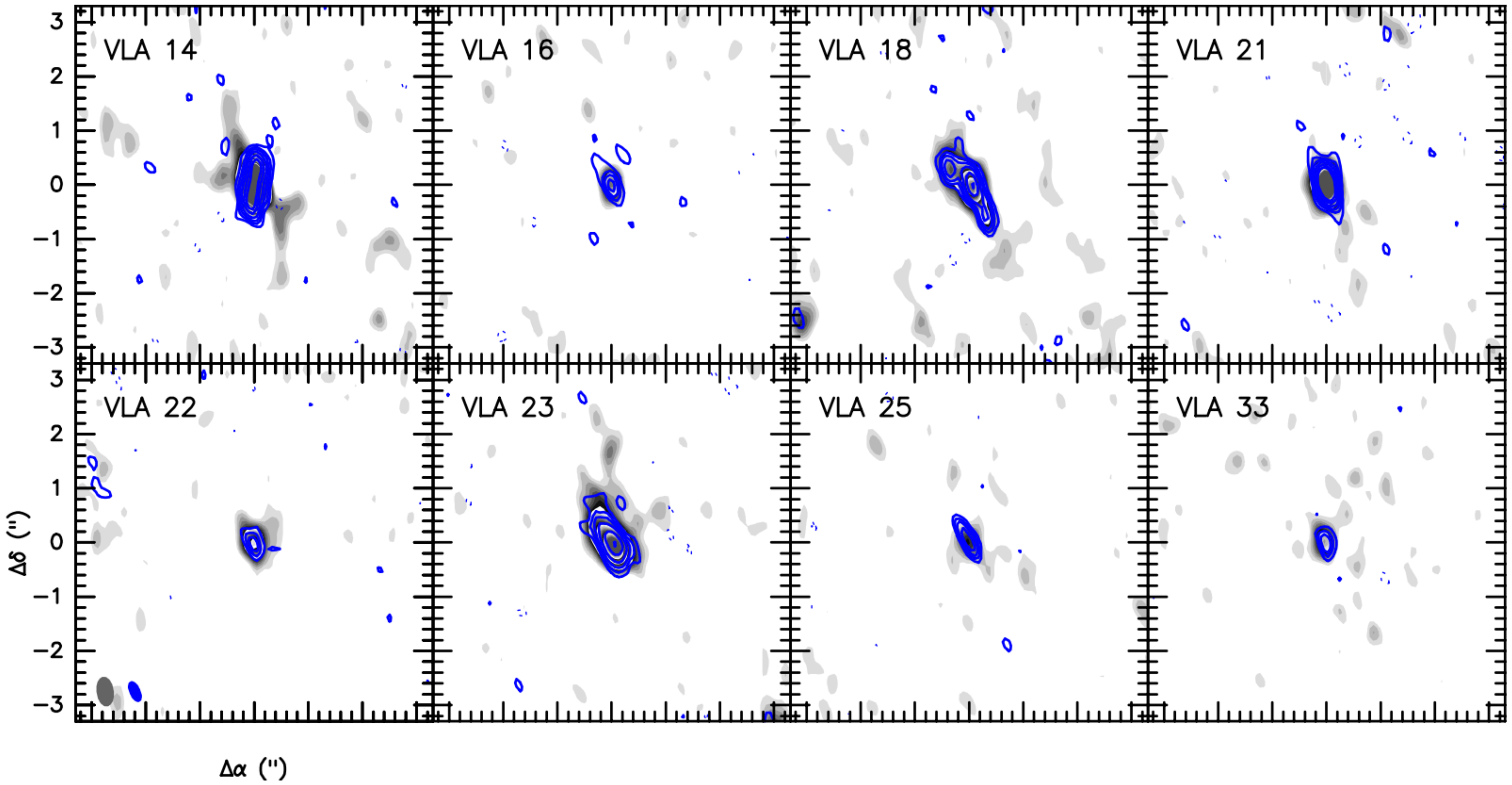




HUB-N

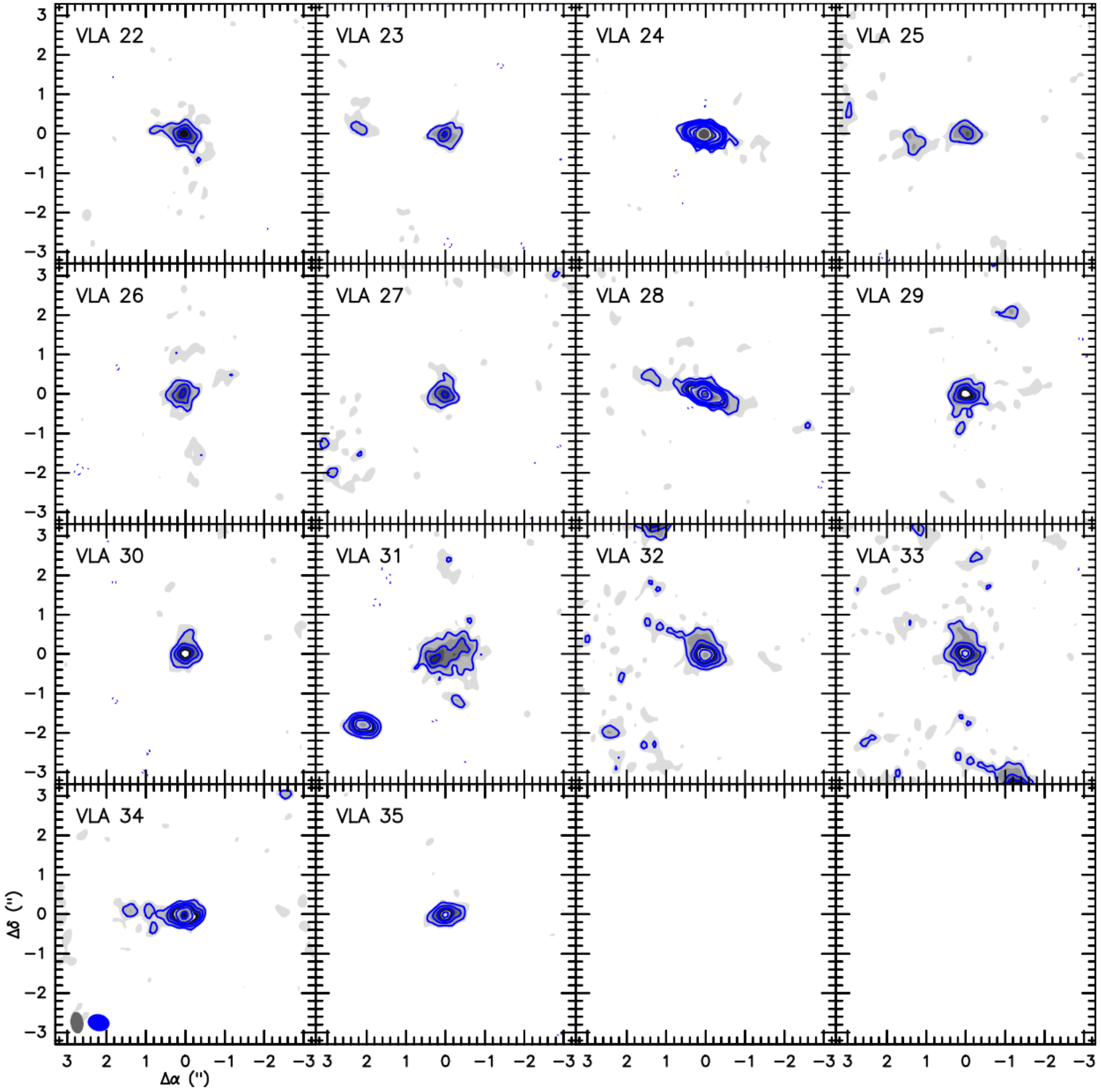


Detected at 6 cm and 3.6 cm

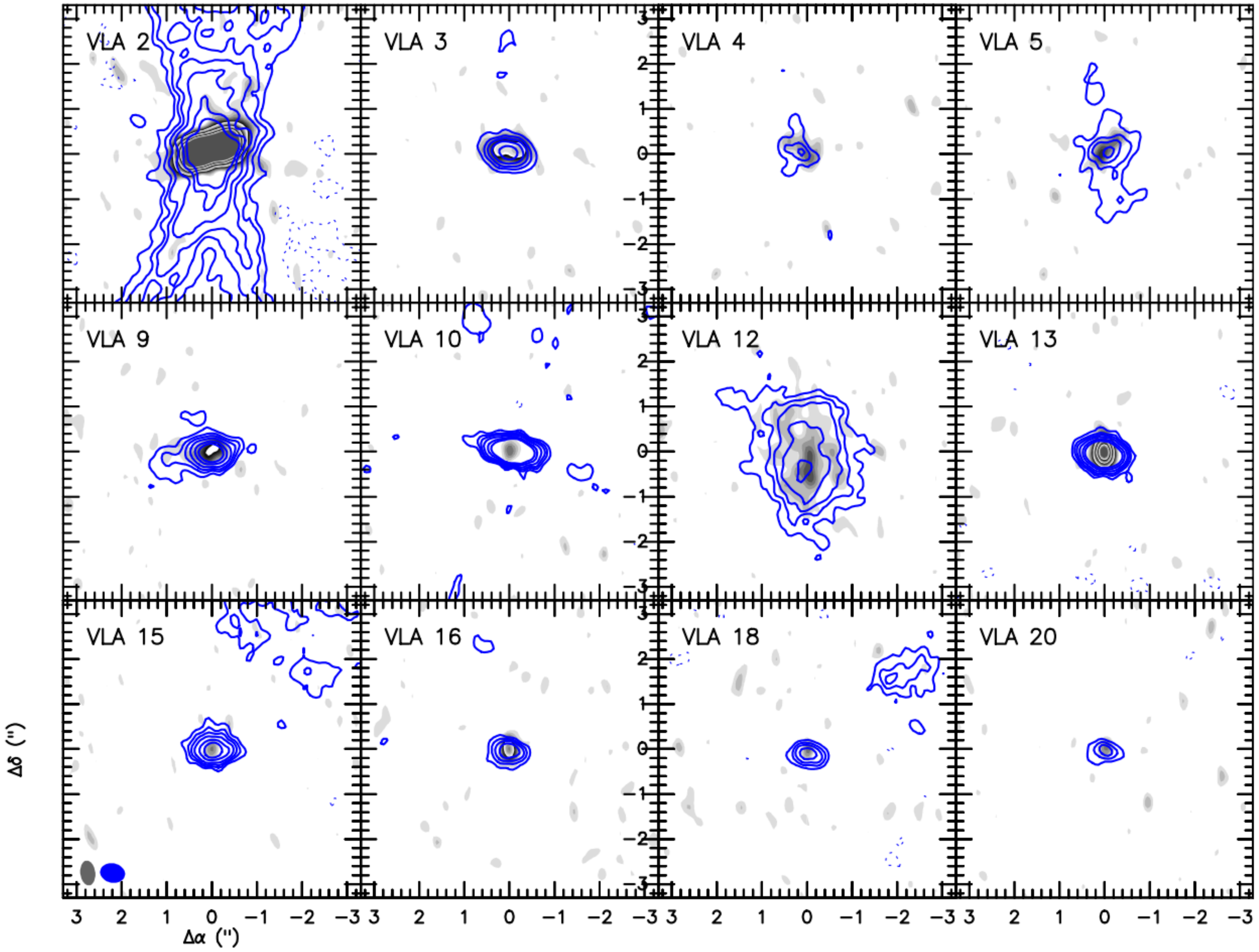


Roger Grau, Master Thesis (2020), Díaz et al. in preparation

HUB-S

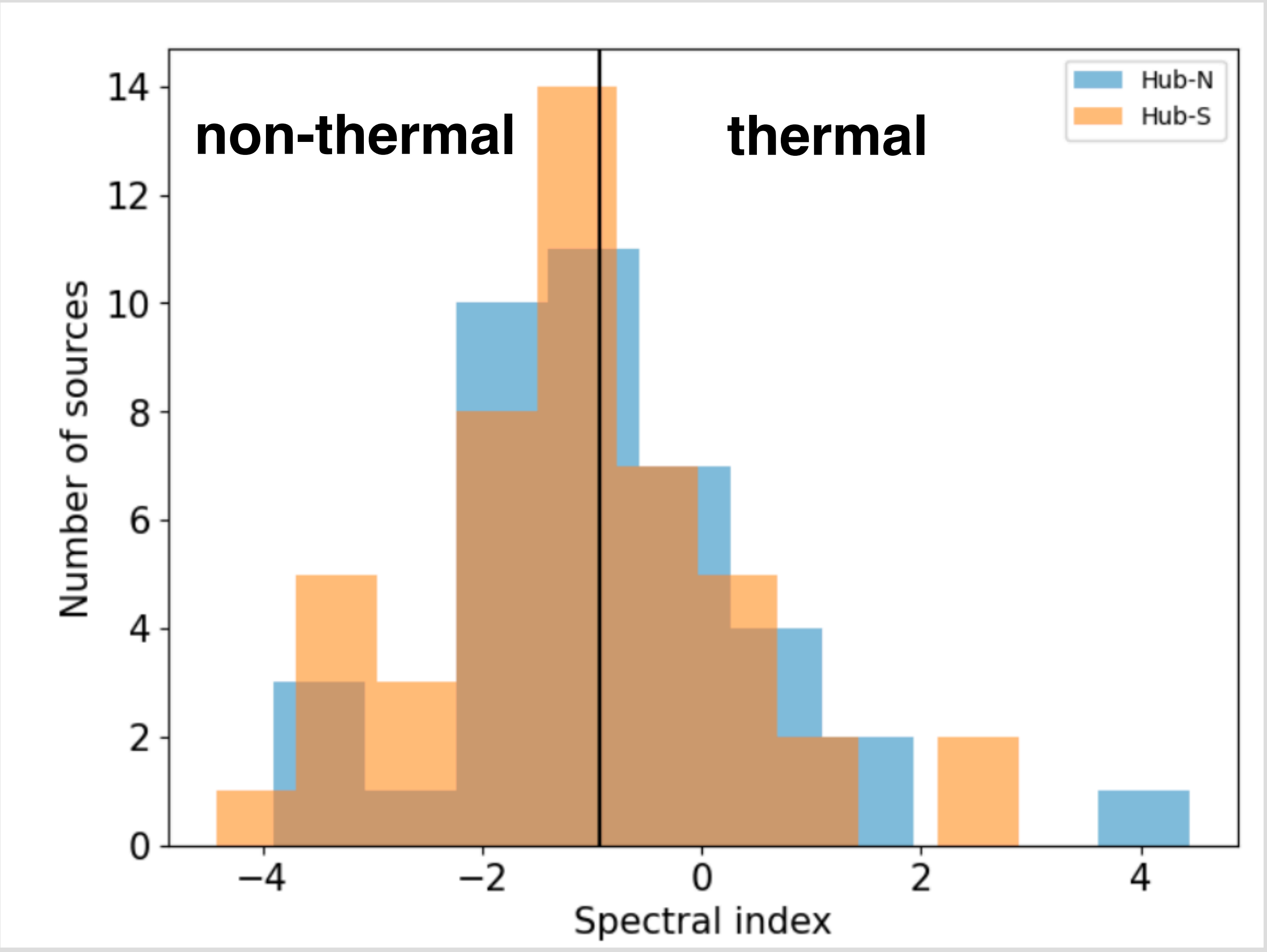


Detected at 6 cm and 3.6 cm

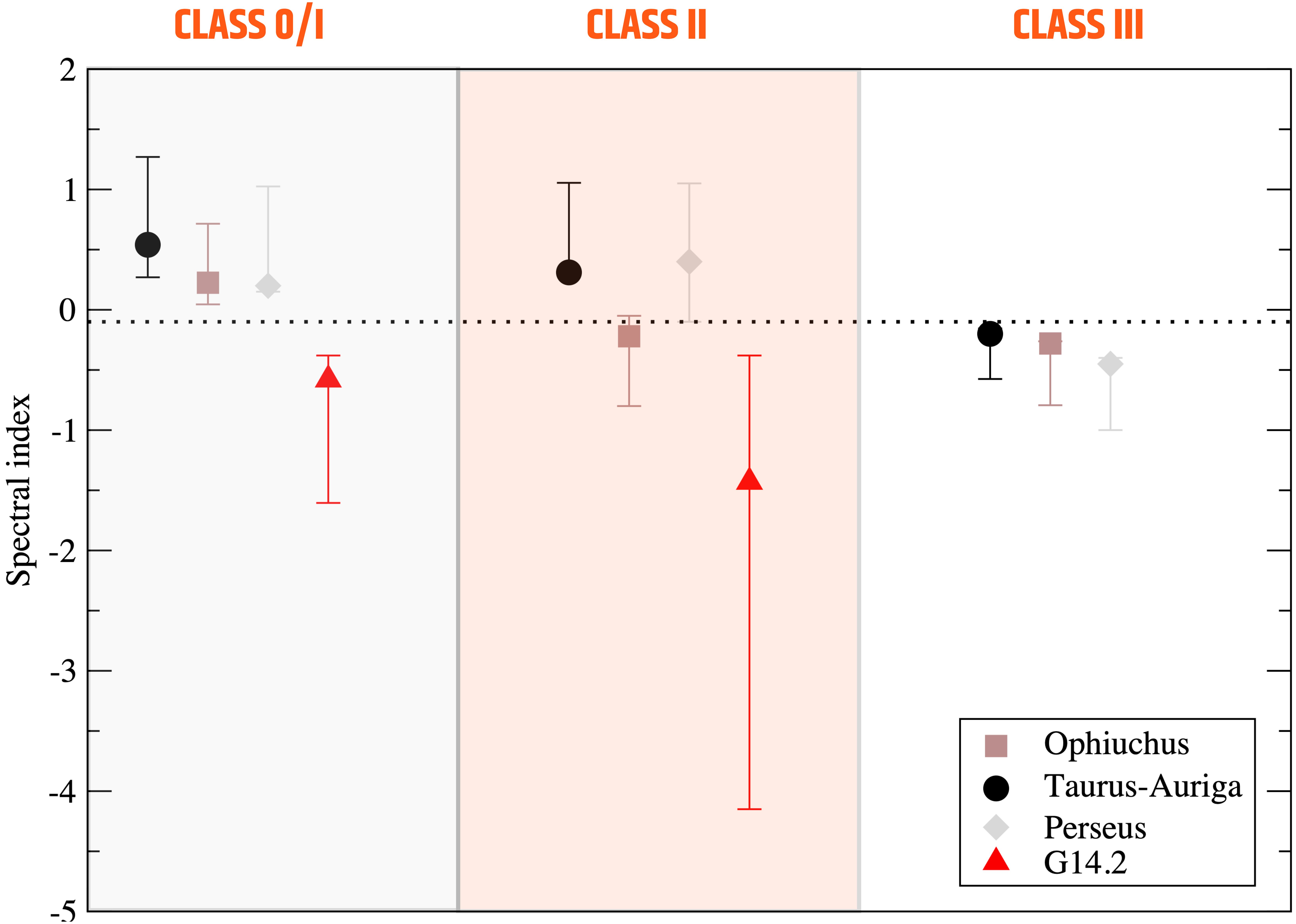


Roger Grau, Master Thesis (2020), Díaz et al. in preparation

NATURE OF THE CM EMISSION



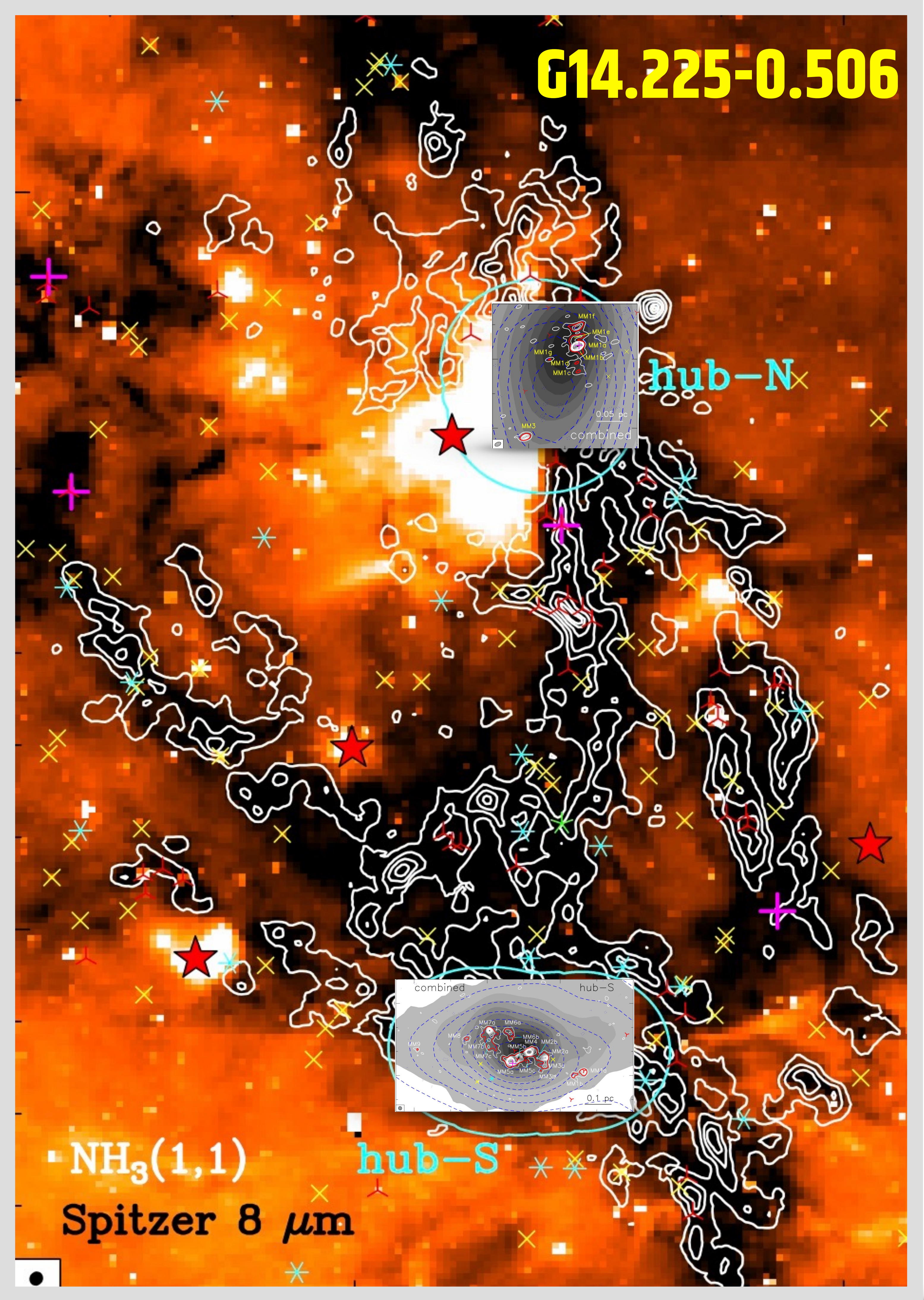
Díaz et al. in preparation



TAURUS-AURIGA (Dzib et al. 2015)
OPHIUCHUS (Dzib et al. 2013)
PERSEUS (Pech et al. 2016)

FILAMENTS AND THEIR FRAGMENTATION

TOWARD A DETAILED UNDERSTANDING OF THE STAR FORMATION PROCESS IN G14.225-0.506



Busquet et al. (2013)

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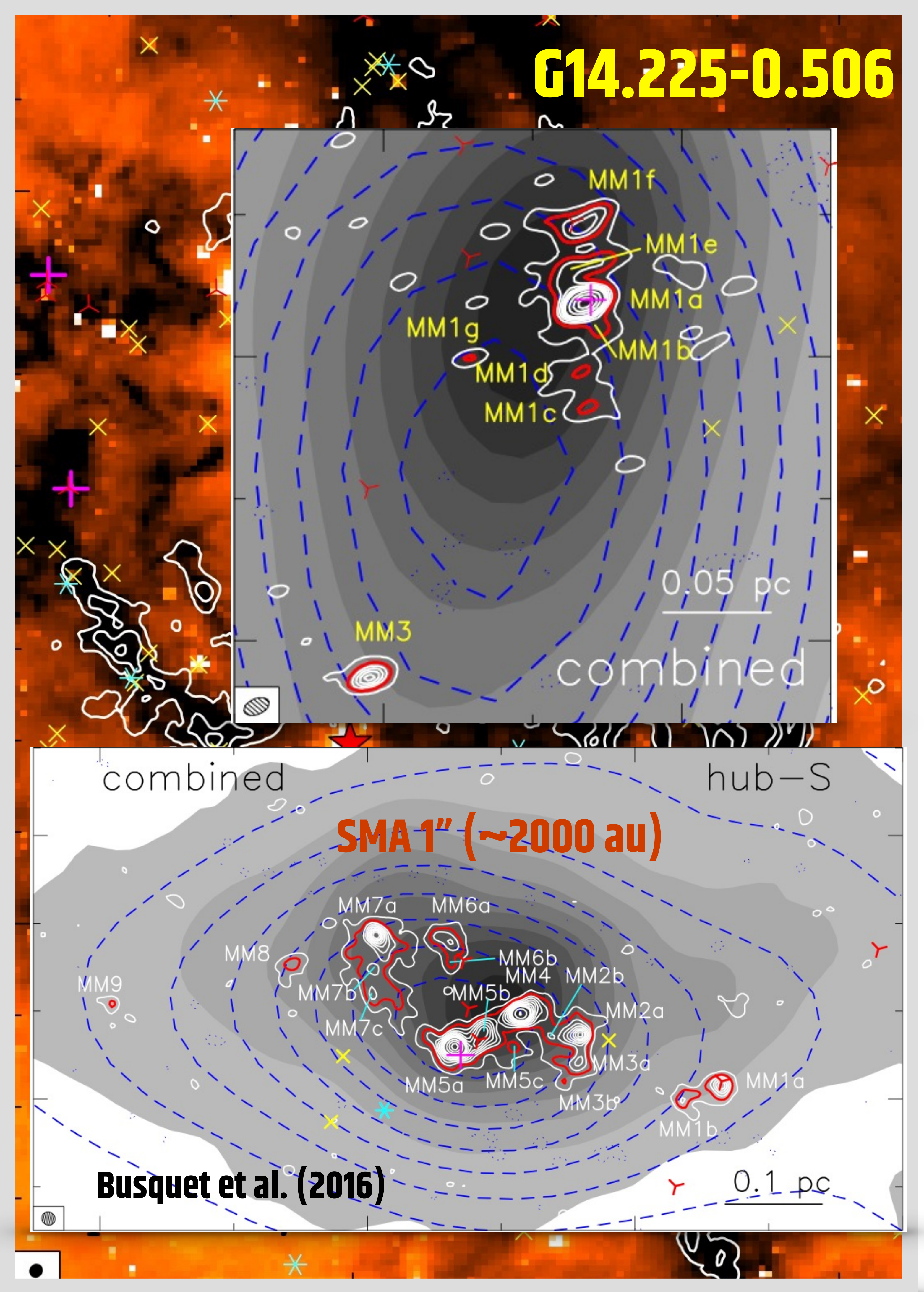
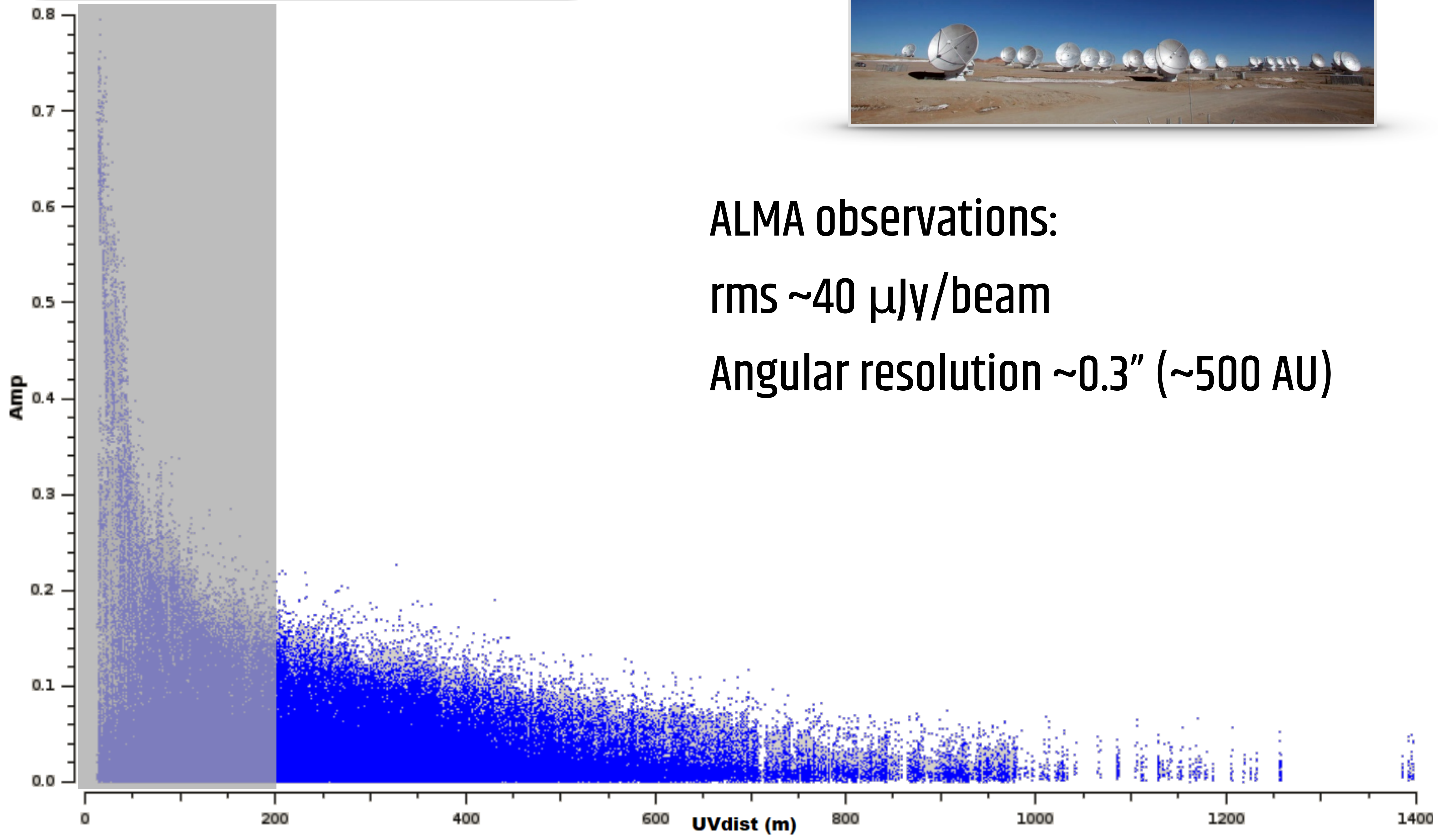


Busquet et al. (2013)

- HUB-N: 9 FRAGMENTS
- HUB-S: 17 FRAGMENTS



ALMA observations:

rms ~40 μJy/beam

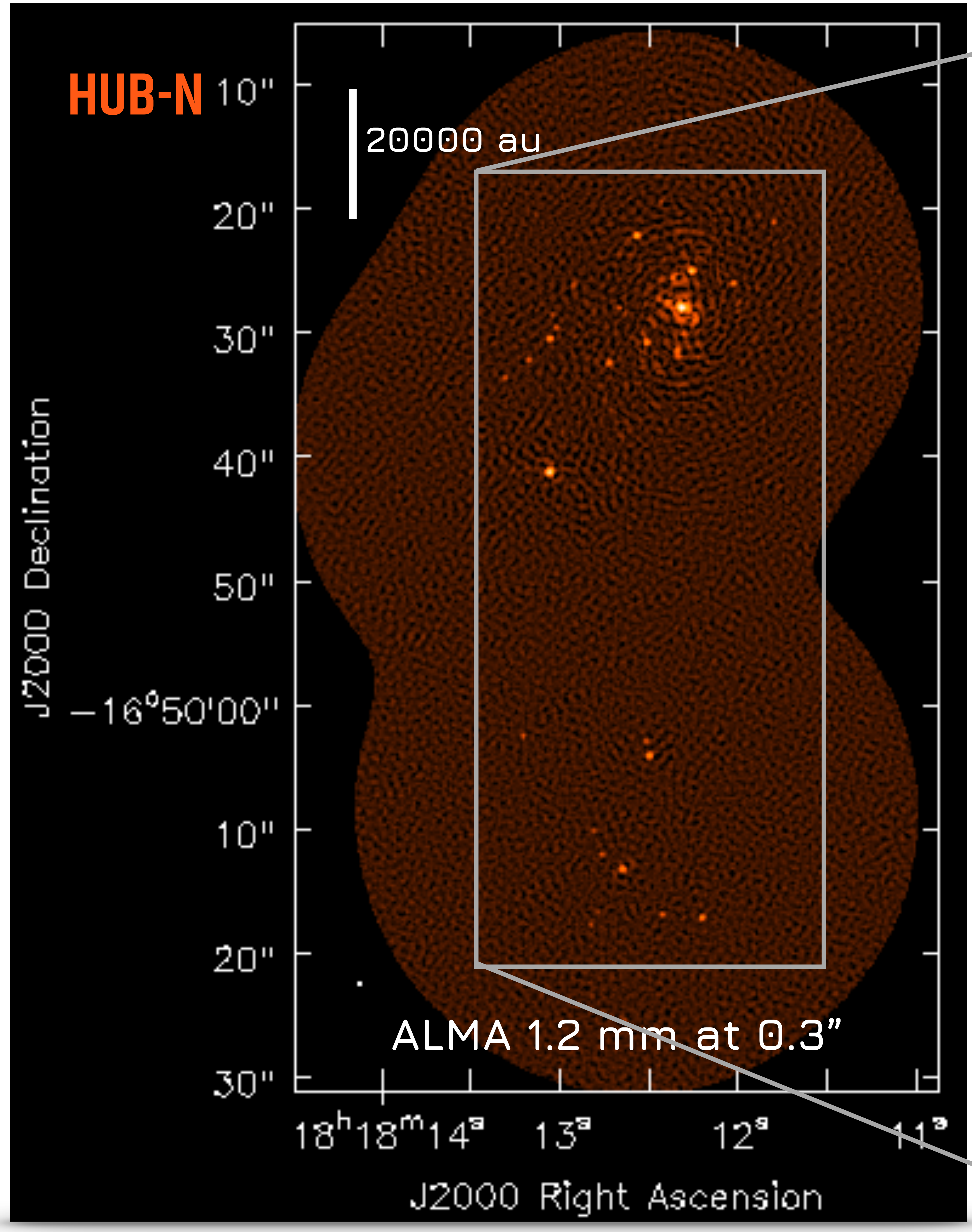
Angular resolution ~0.3" (~500 AU)

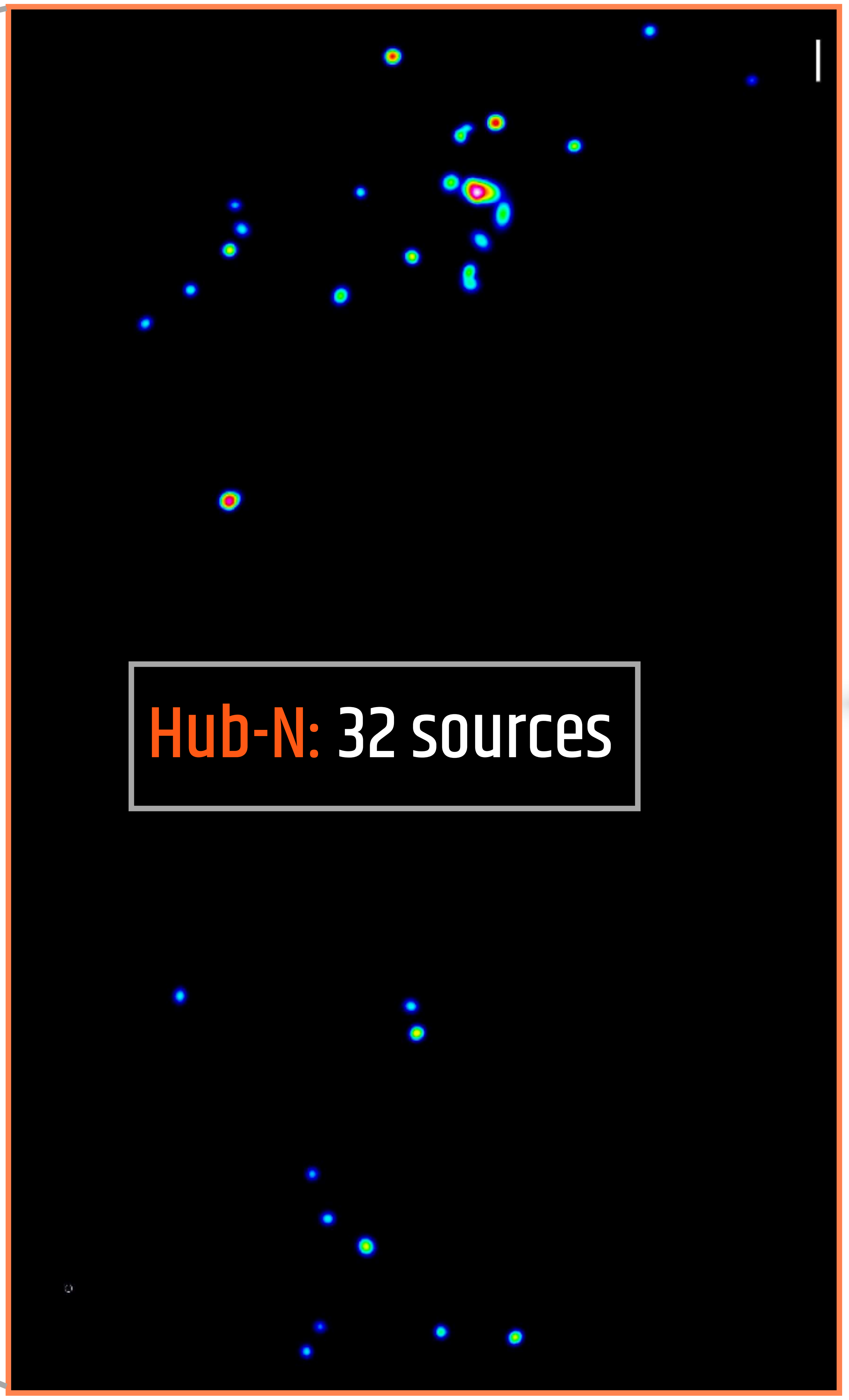
FRAGMENTATION AT 500 AU

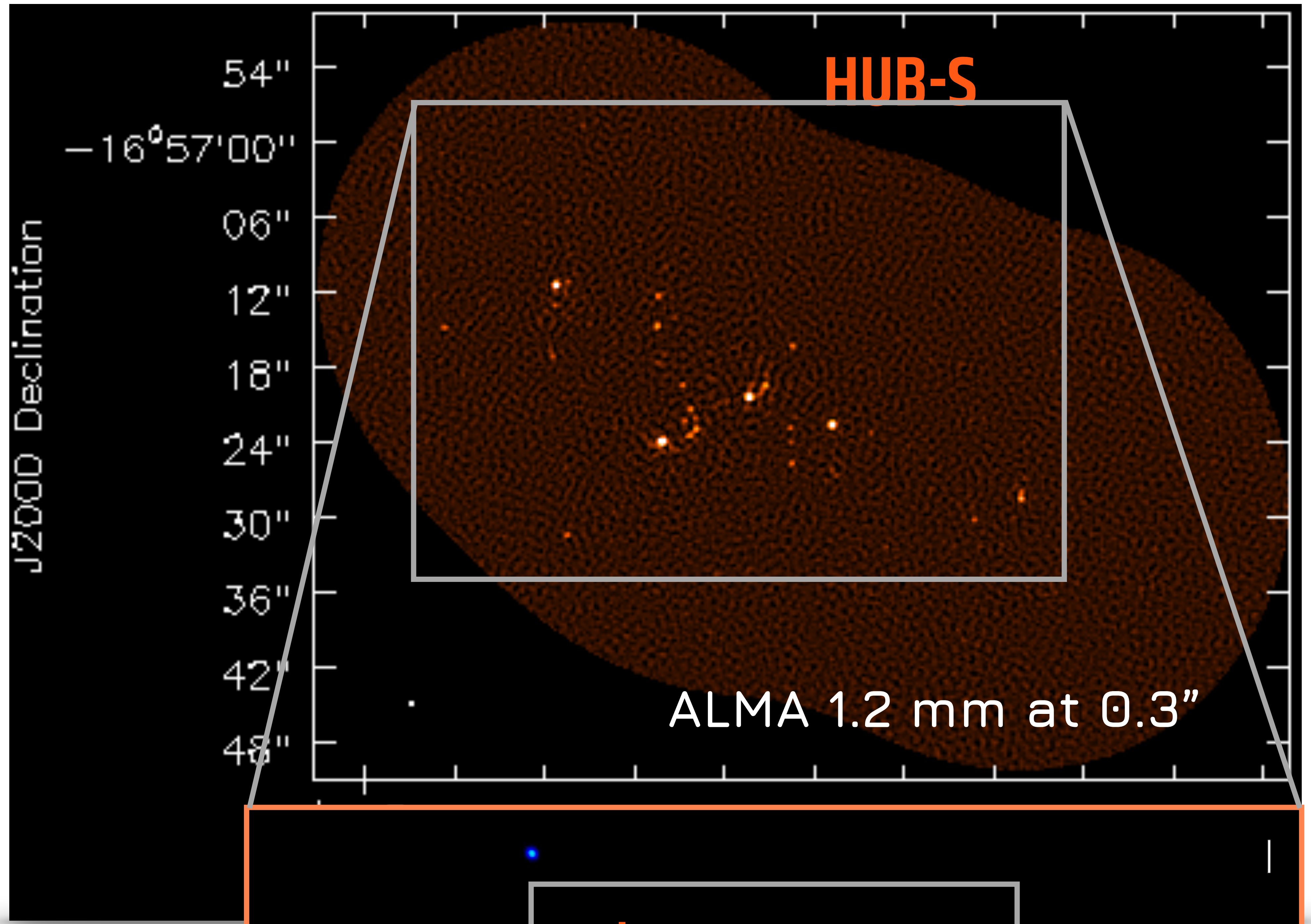
ALMA @0.3”

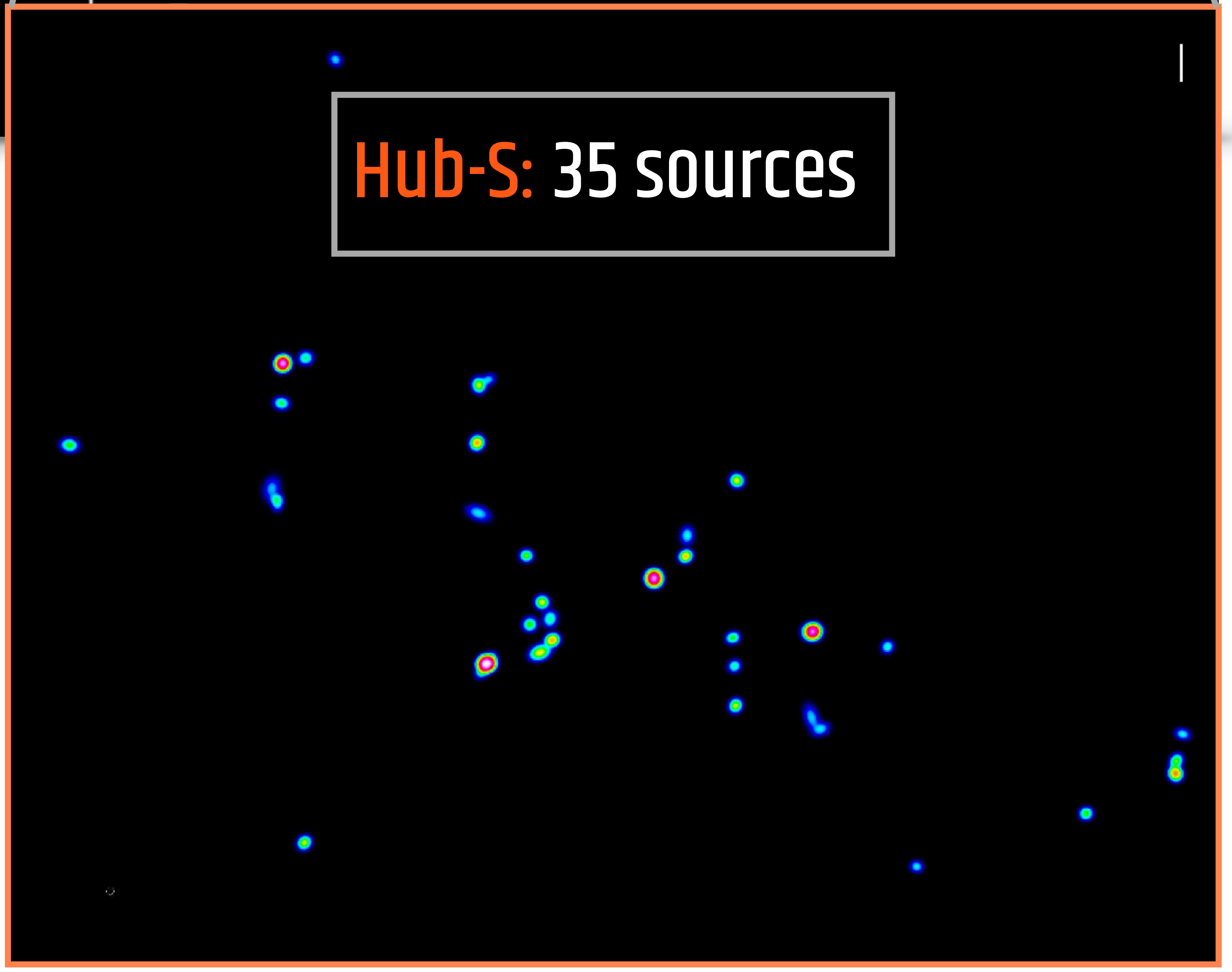
ALMA observations rms ~40 μJy/beam

PyBDSF to identify sources: Radii~50 - 470 au



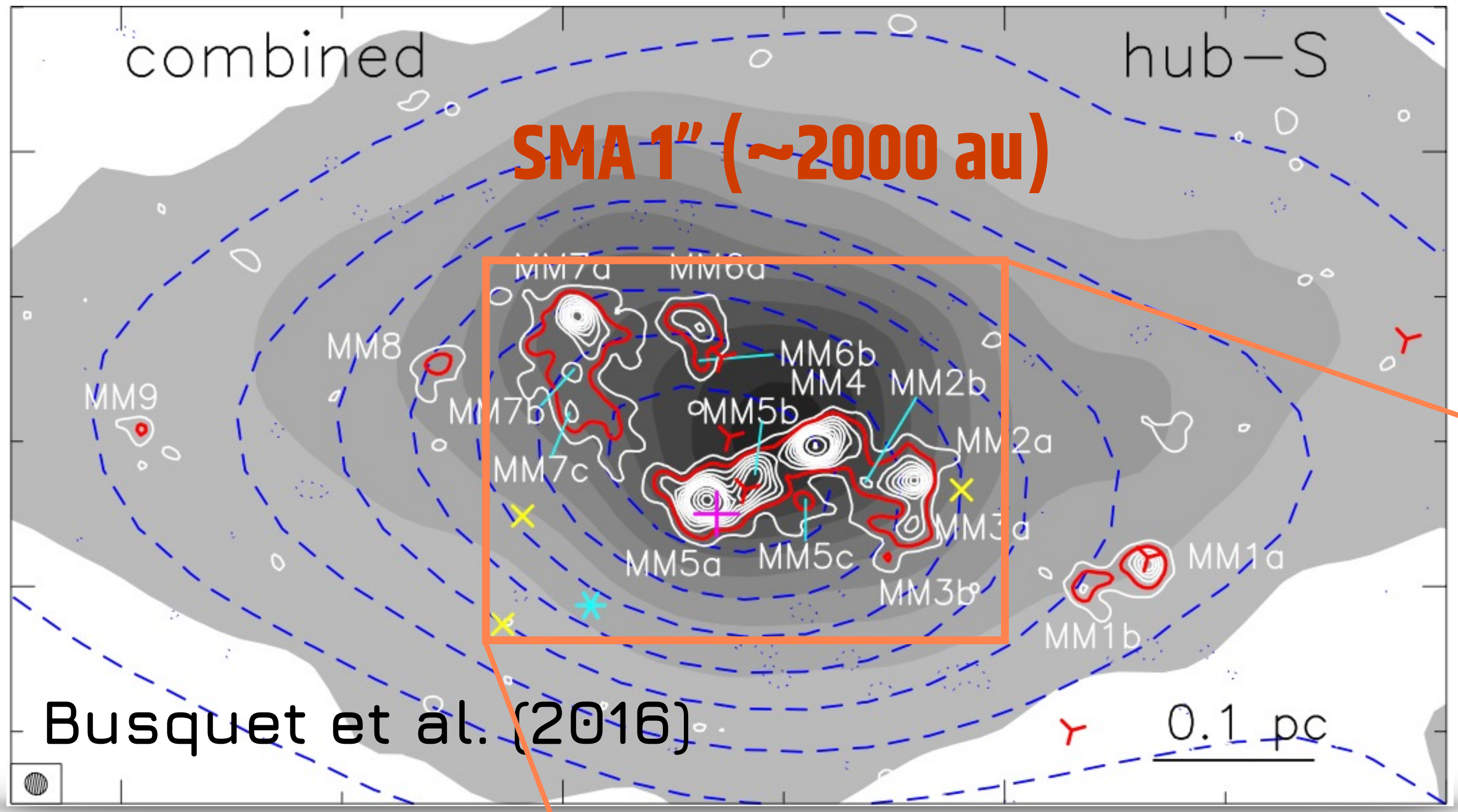






Aina Brichs, BSc Thesis (2021)

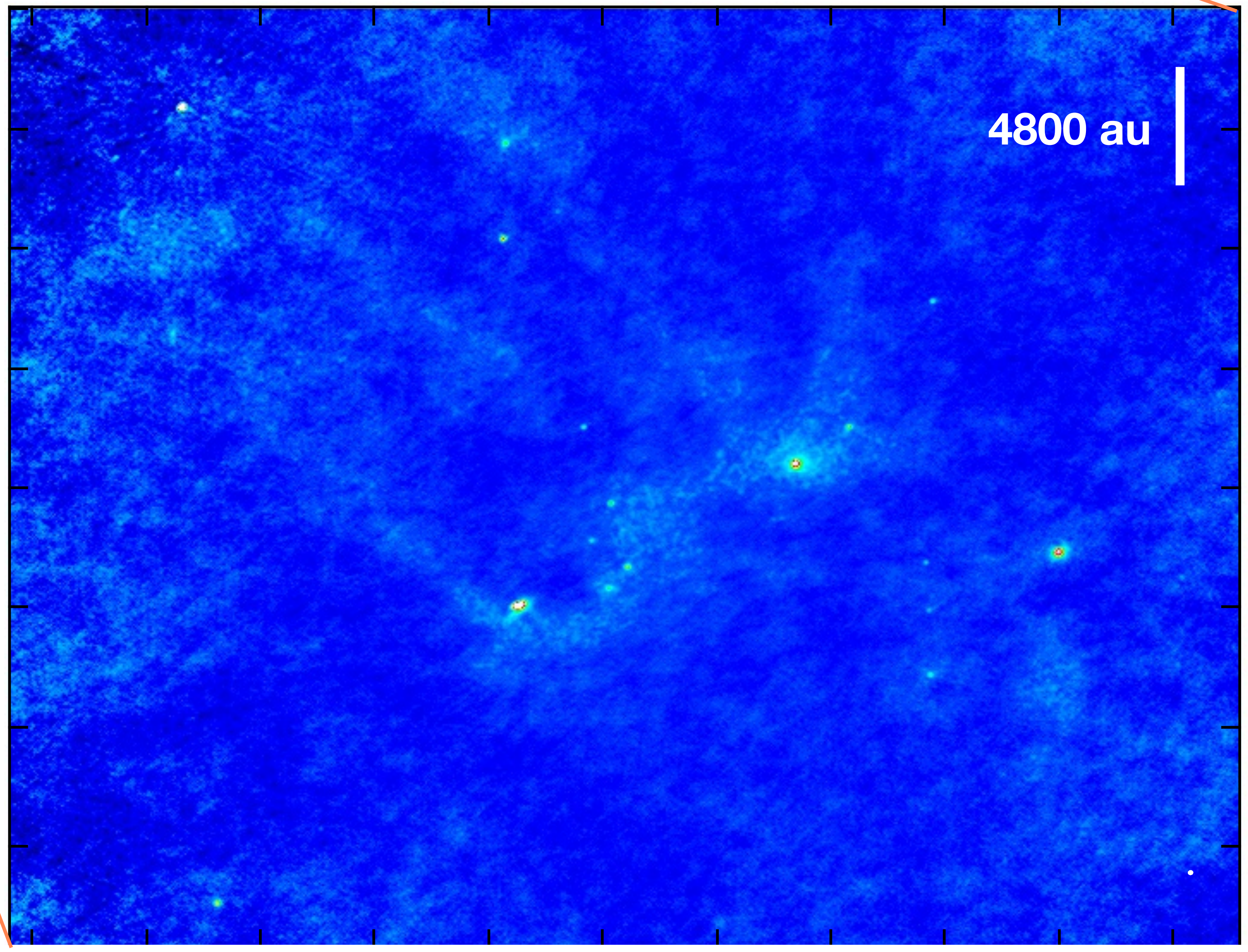
FRAGMENTATION AT 60 AU

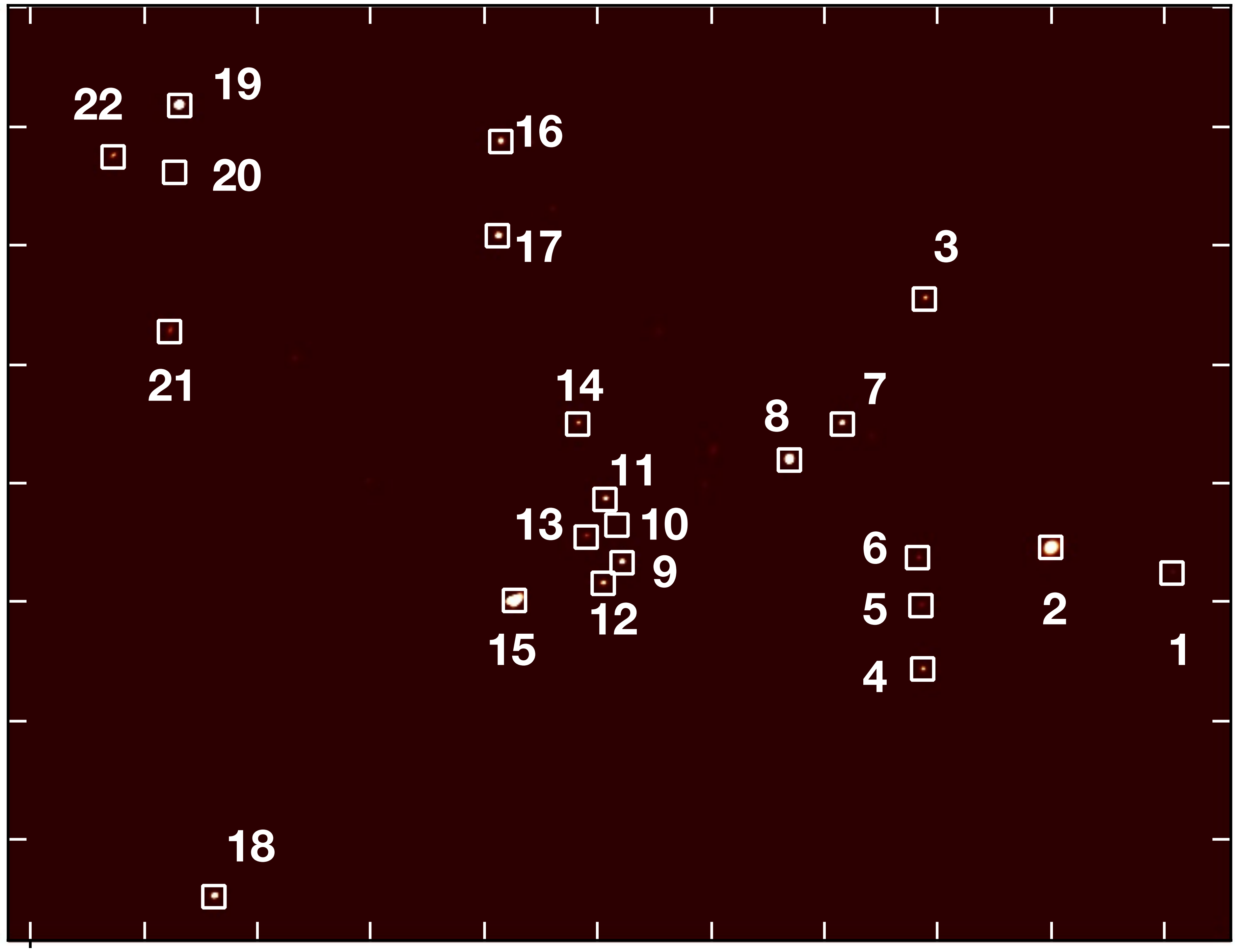


★ Mass(gas+dust)= 0.01- 1.3 M_{sun}

★ Radii: 10- 80 AU R_{sun}

Protostellar disk candidates





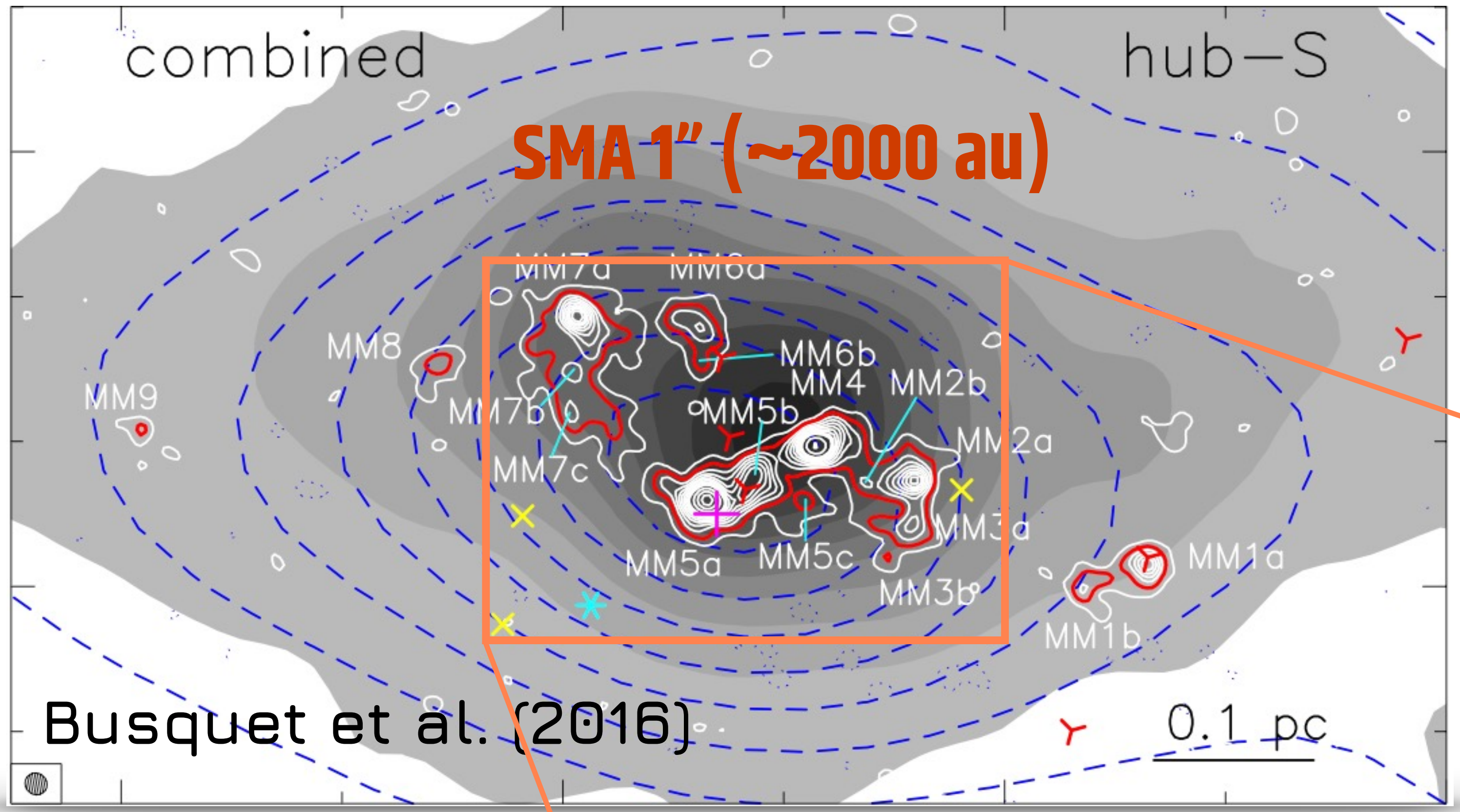
Eduard Torres, BSc Thesis (2022), Busquet et al. in preparation

ALMA observations at 1.2 mm

rms ~50 μJy/beam

22 sources identified with PyBDSF

FRAGMENTATION AT 60 AU



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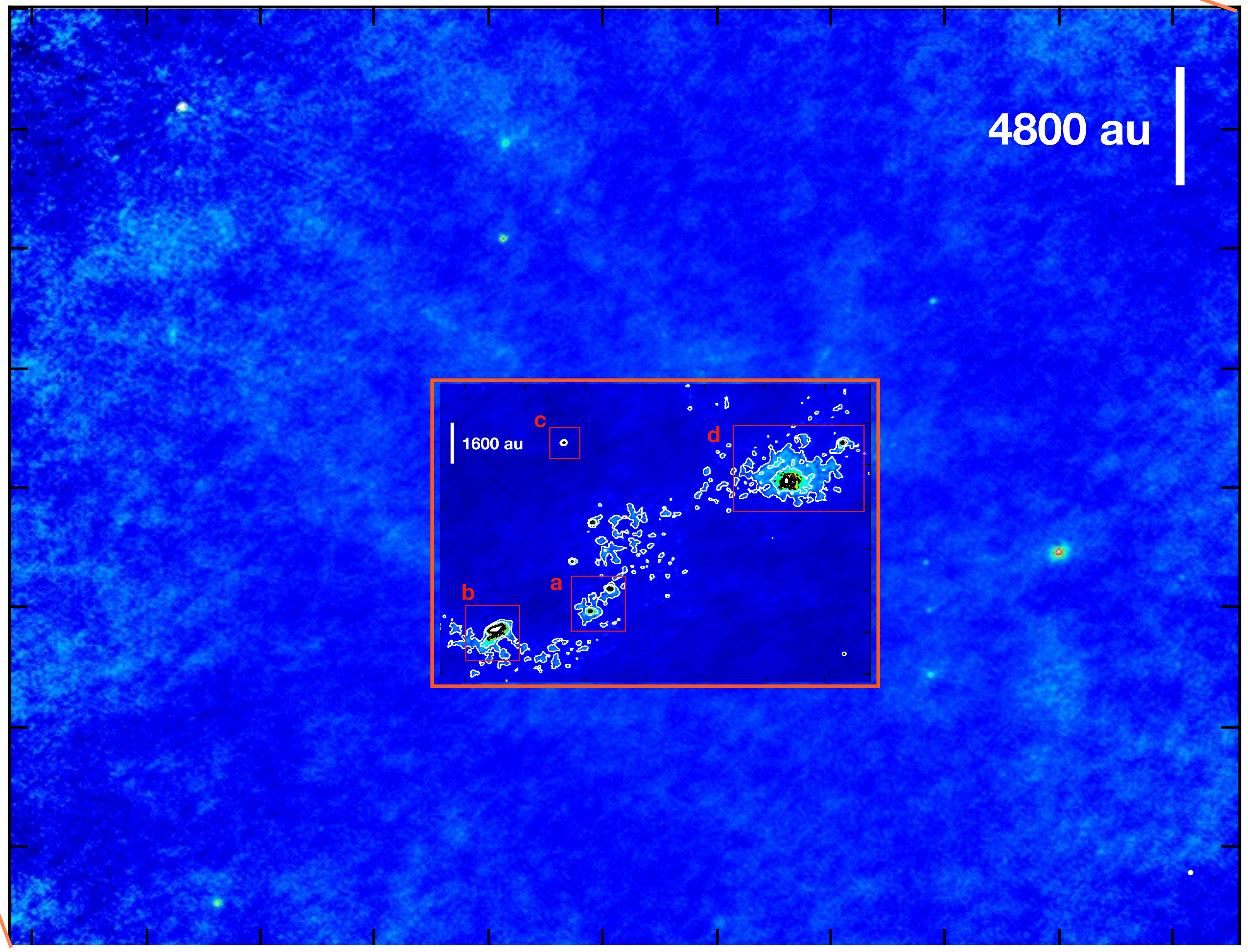
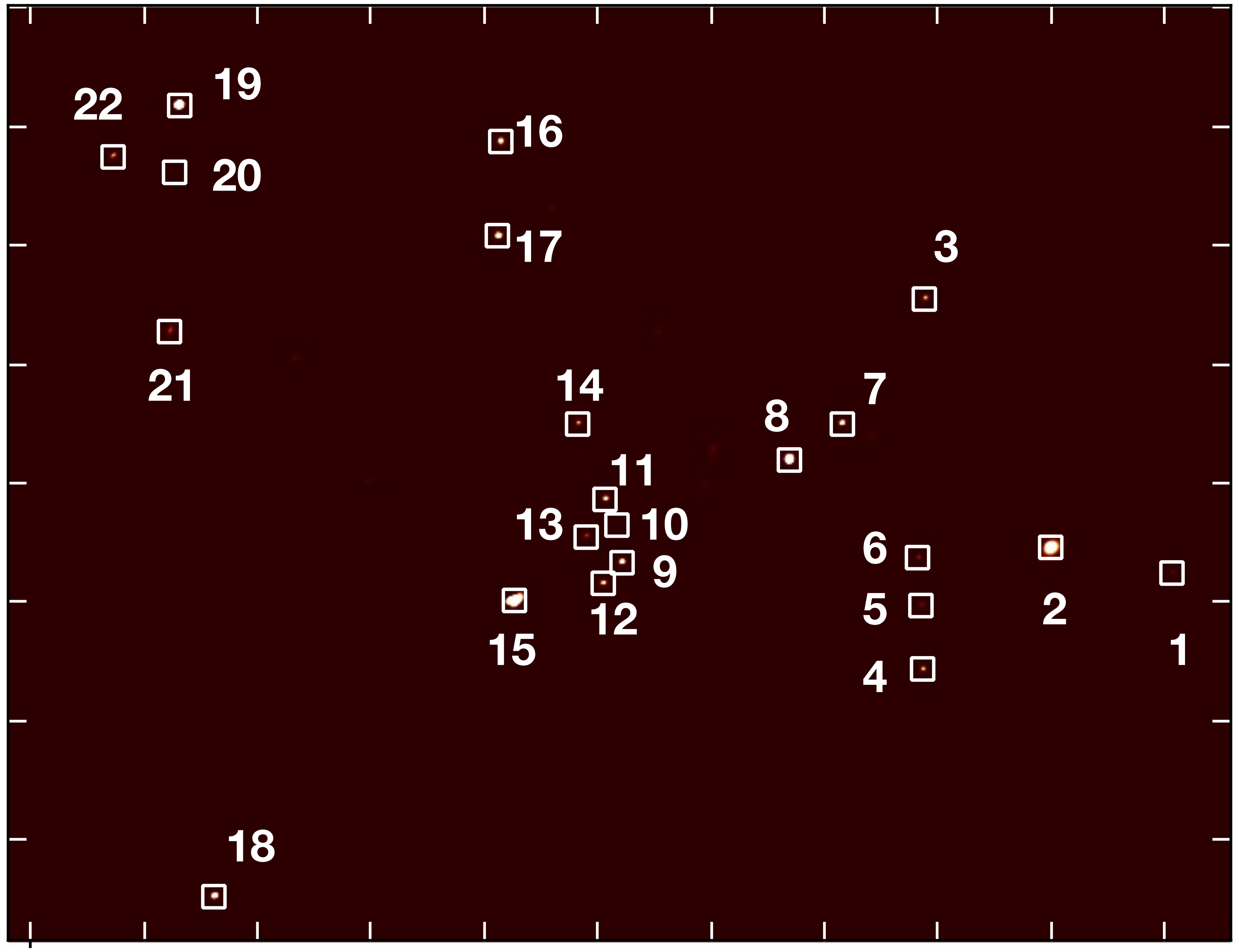


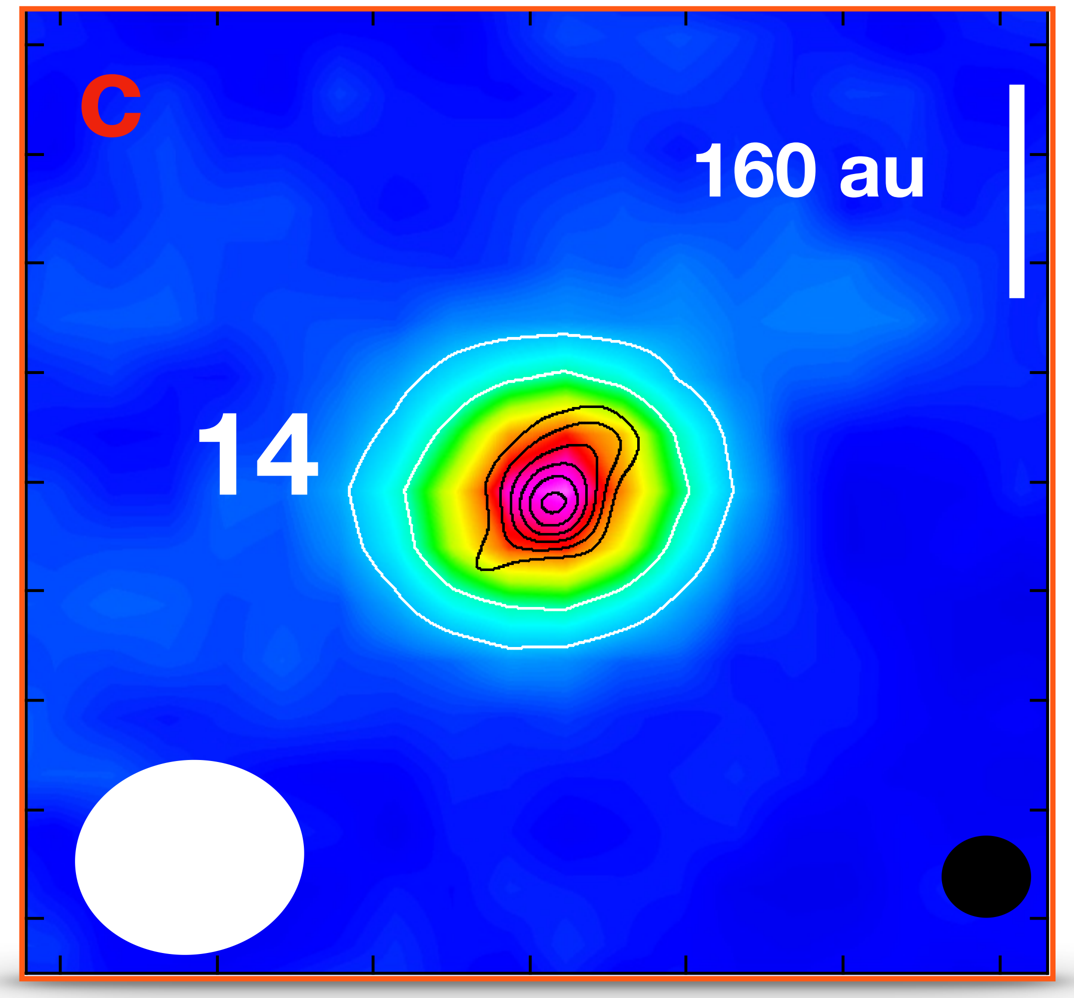


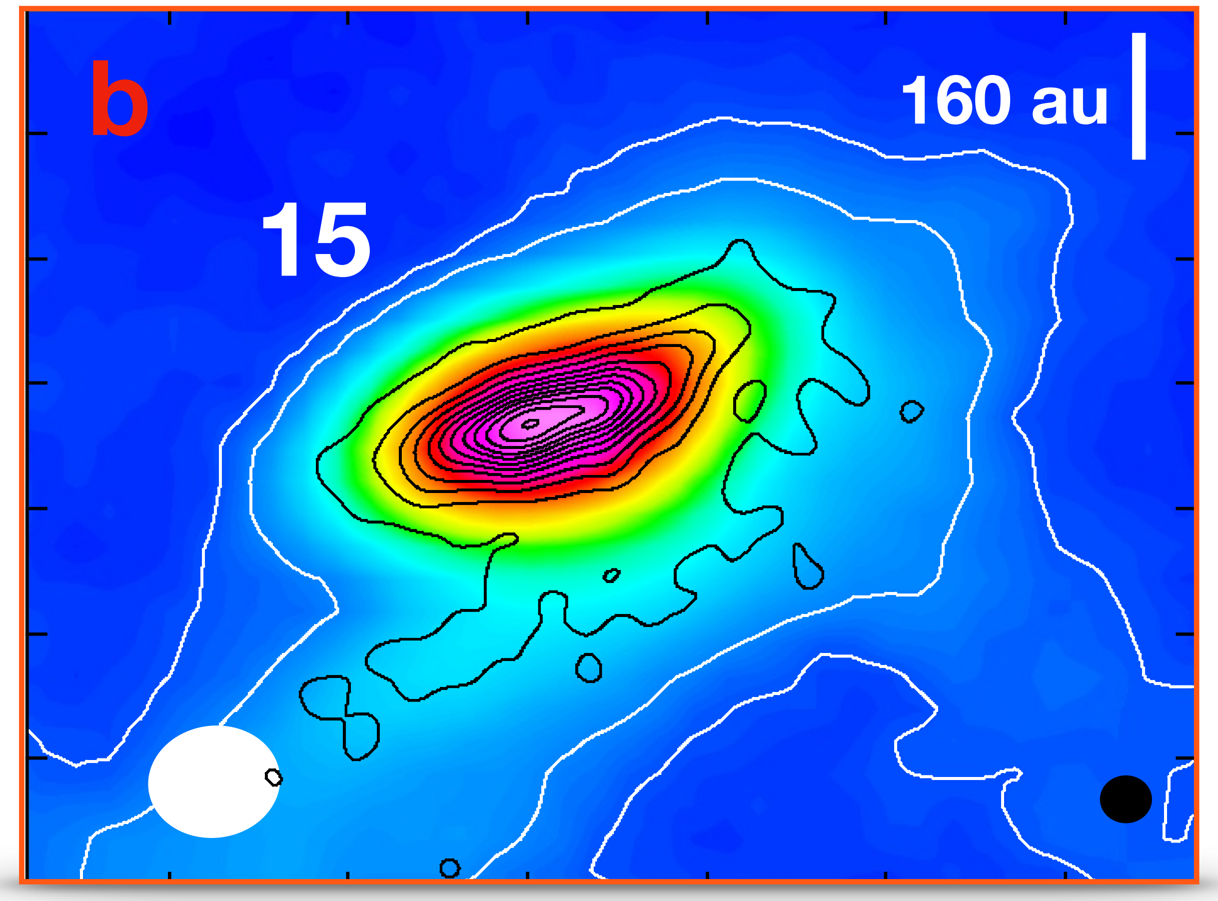
Eduard Torres, BSc Thesis (2022), Busquet et al. in preparation

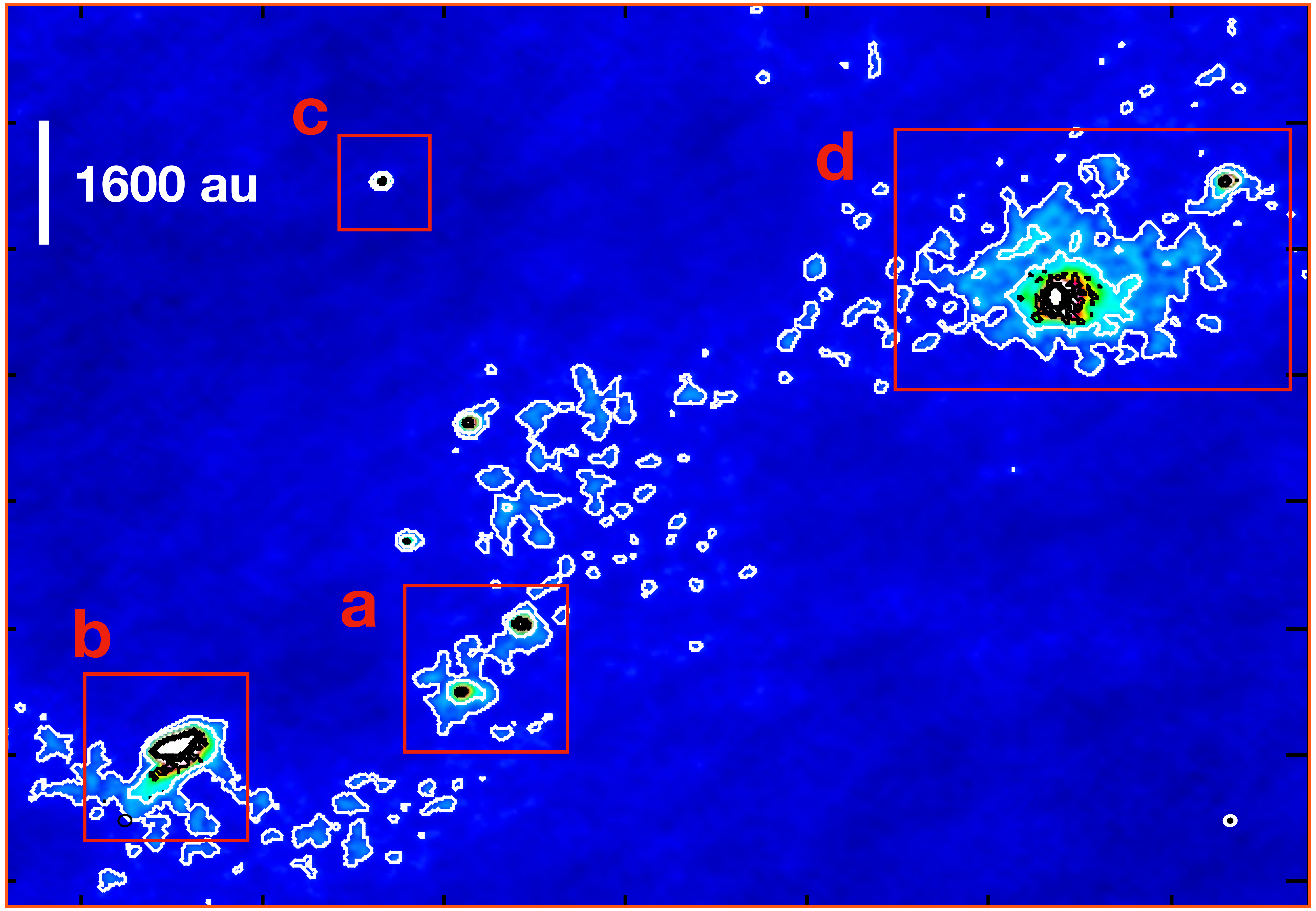
FRAGMENTATION AT 60 AU

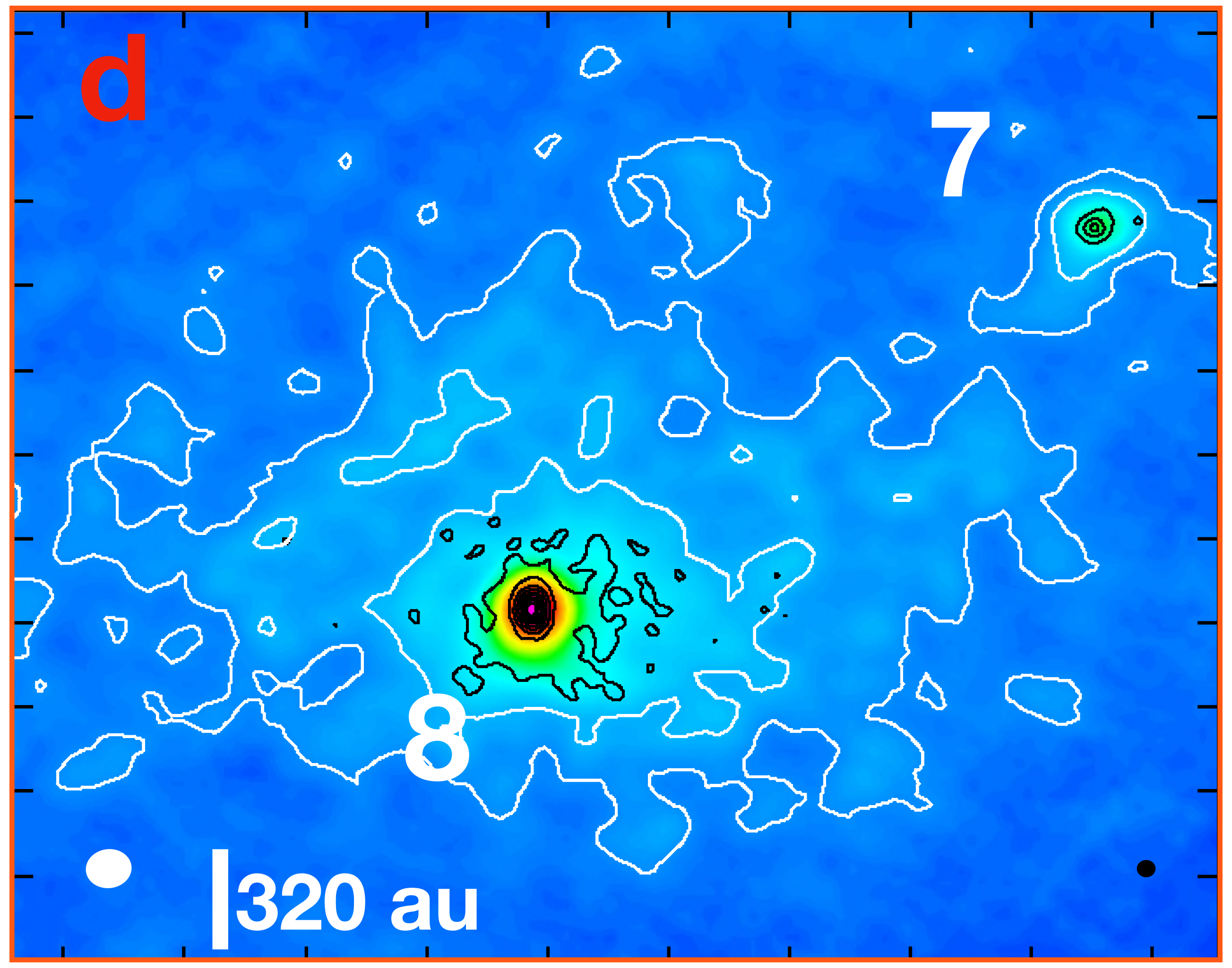
Color scale and white contours: naturally weighted image

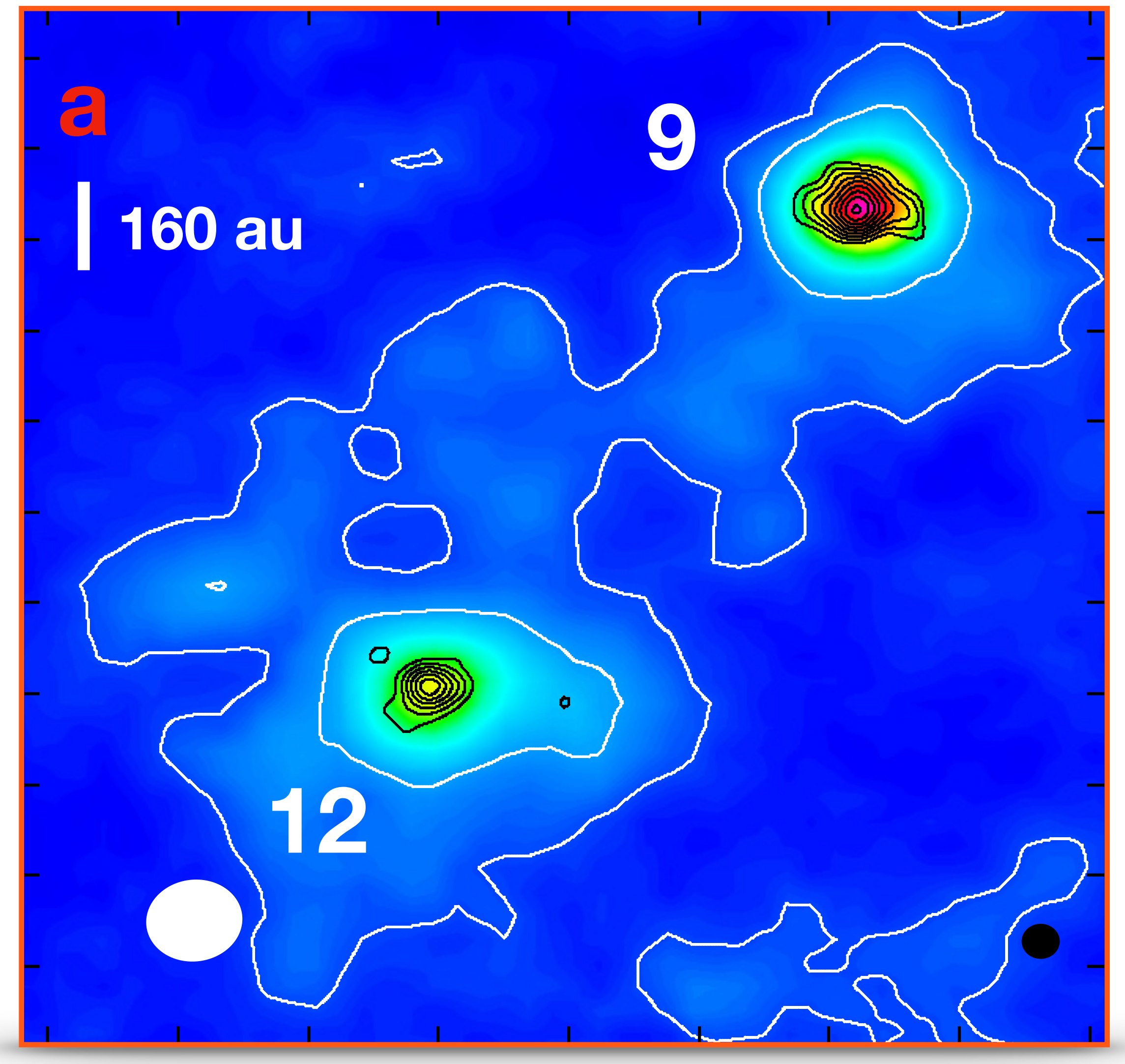
Black contours: Robust=0 image











Eduard Torres, BSc Thesis (2022)

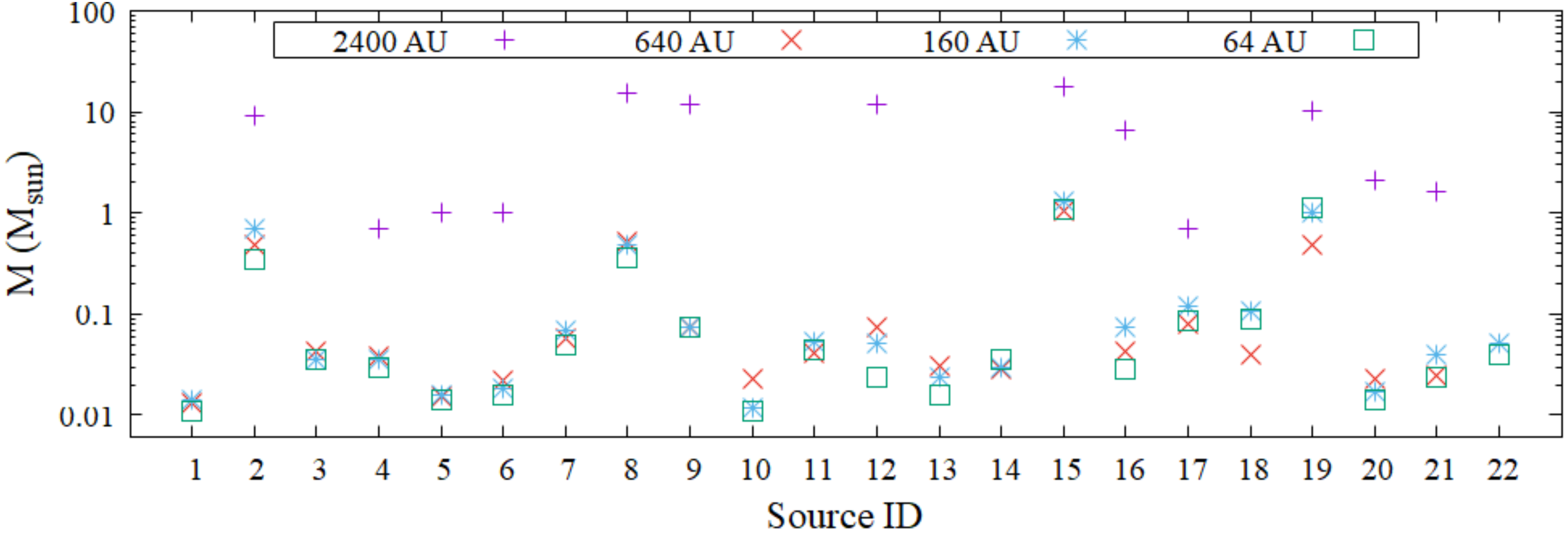
Busquet et al. in preparation

MASS RESERVOIR AND MASS ASSEMBLY

$M_{disk}/M_{envelope}$ (%)

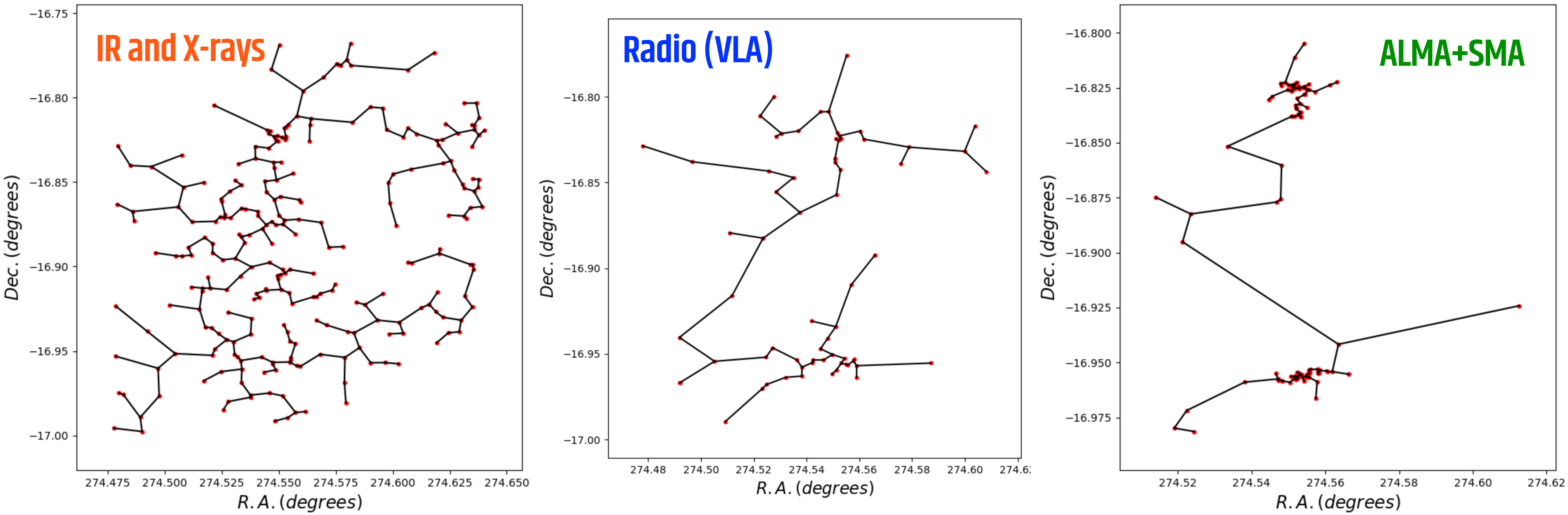
All protostars can still grow in mass and become cluster of massive stars

3.8 6.0 7.3 13.1 6.1 4.1 11.2 1.5 11.2



Eduard Torres, BSc Thesis (2022), Busquet et al. in preparation

MINIMUM SPANNING TREE



Median length = 21.92 arcsec~0.15 pc
Minimum length = 2.54 arcsec~3500 au

Median length = 24.22 arcsec~0.16 pc
Minimum length = 0.06 arcsec~84 au

Median length = 1.71 arcsec~2400 au
Minimum length = 0.02 arcsec~28 au

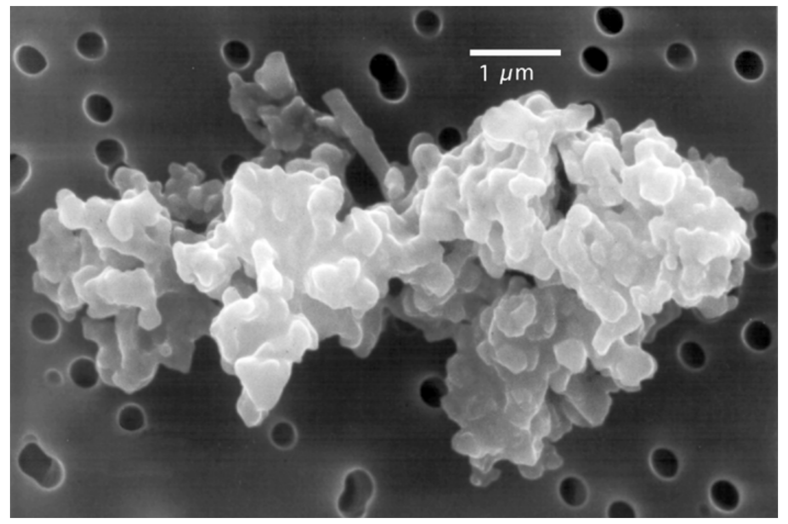
Díaz et al. in preparation

A cm-wavelength survey of the Ophiuchus A cluster at 10 au resolution

Image Credit: NASA/JPL-Caltech/Harvard-Smithsonian CfA

Isaac Radley, John Ilee, Melvin Hoare, Josep Miquel Girart, Tyler Bourke, Izaskun Jiménez-Serra, Marc Audard, Eleonora Bianchi, Paola Caselli, Cecilia Ceccarelli, Claudio Codella, Audrey Coutens, Marta De Simone, Hauyu Baobab Liu, Olja Pánic, Linda Podio, John Tobin and the JVLA Ophiuchus team as part of the SKA “Cradle of Life” SWG

FROM ISM DUST TO PLANETARY SYSTEMS

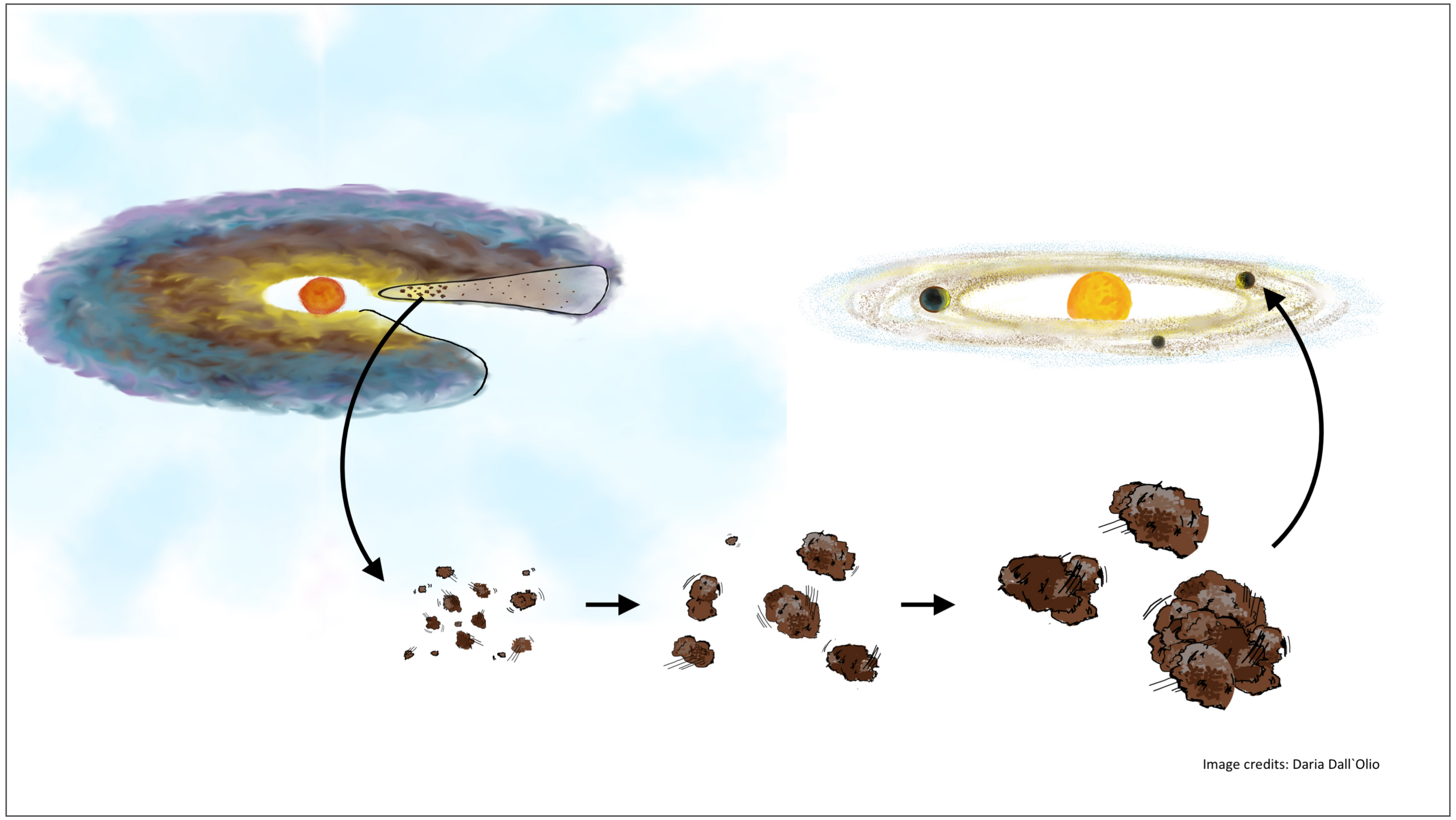


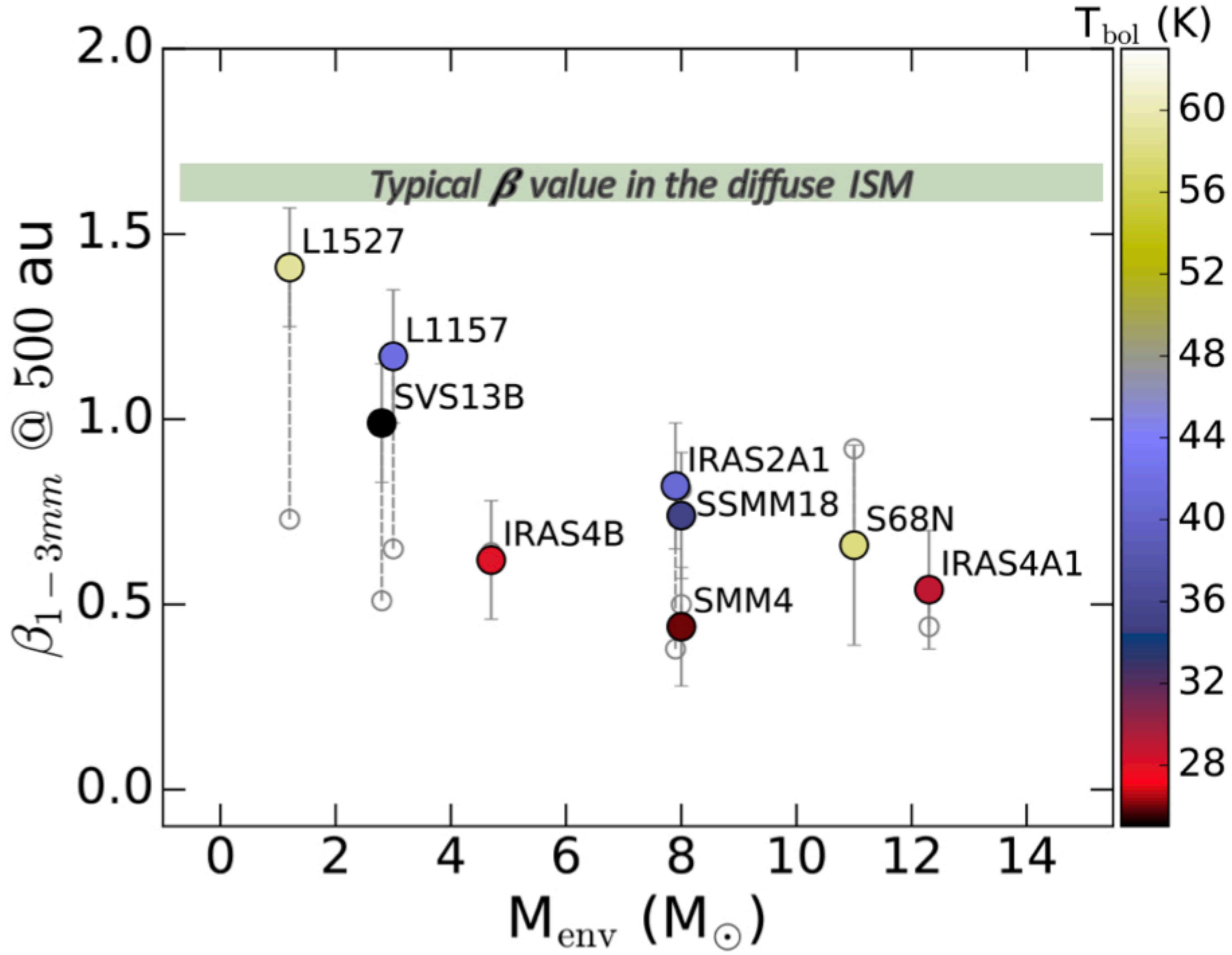
Size= μm

Size= Mkm

✦ Low dust emissivity index (β<1)

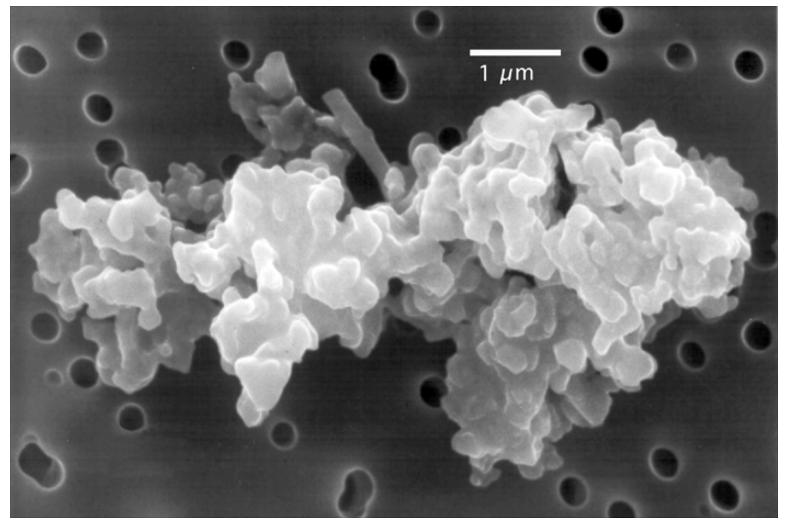
✦ Presence of large (mm-sized) dust grains in **Class 0 envelopes**



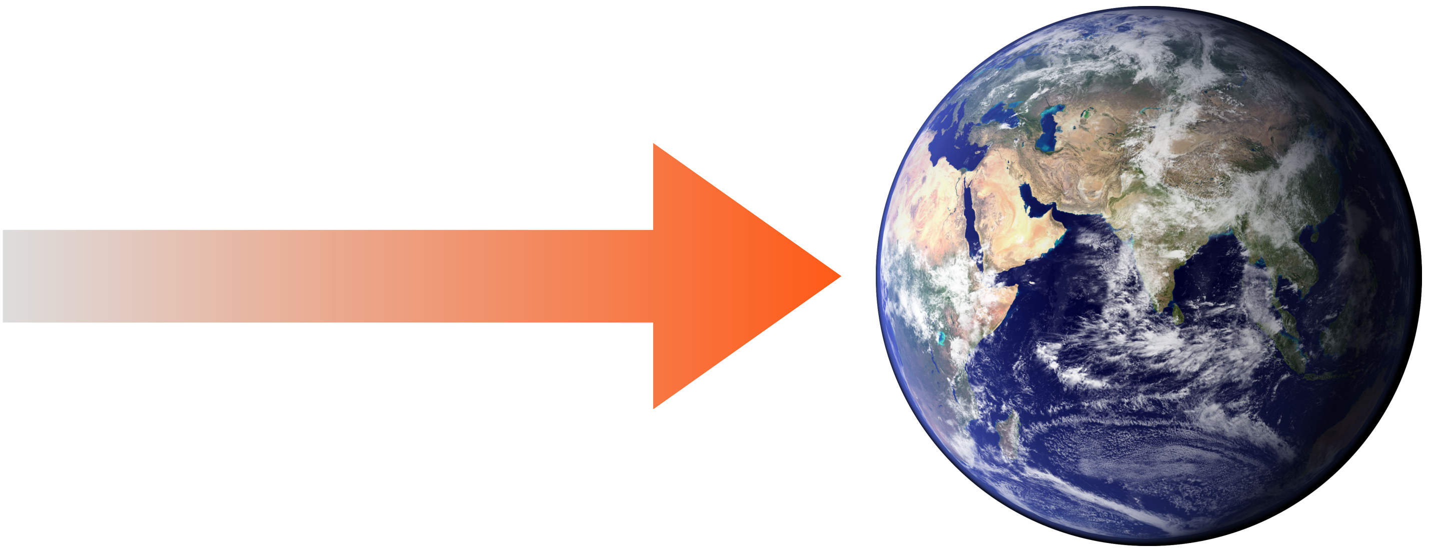


Galametz et al. (2019), Maury et al. (2022)
See also: Tychoniec et al. (2020), Bouvier et al. (2021)

FROM ISM DUST TO PLANETARY SYSTEMS



Size= μm



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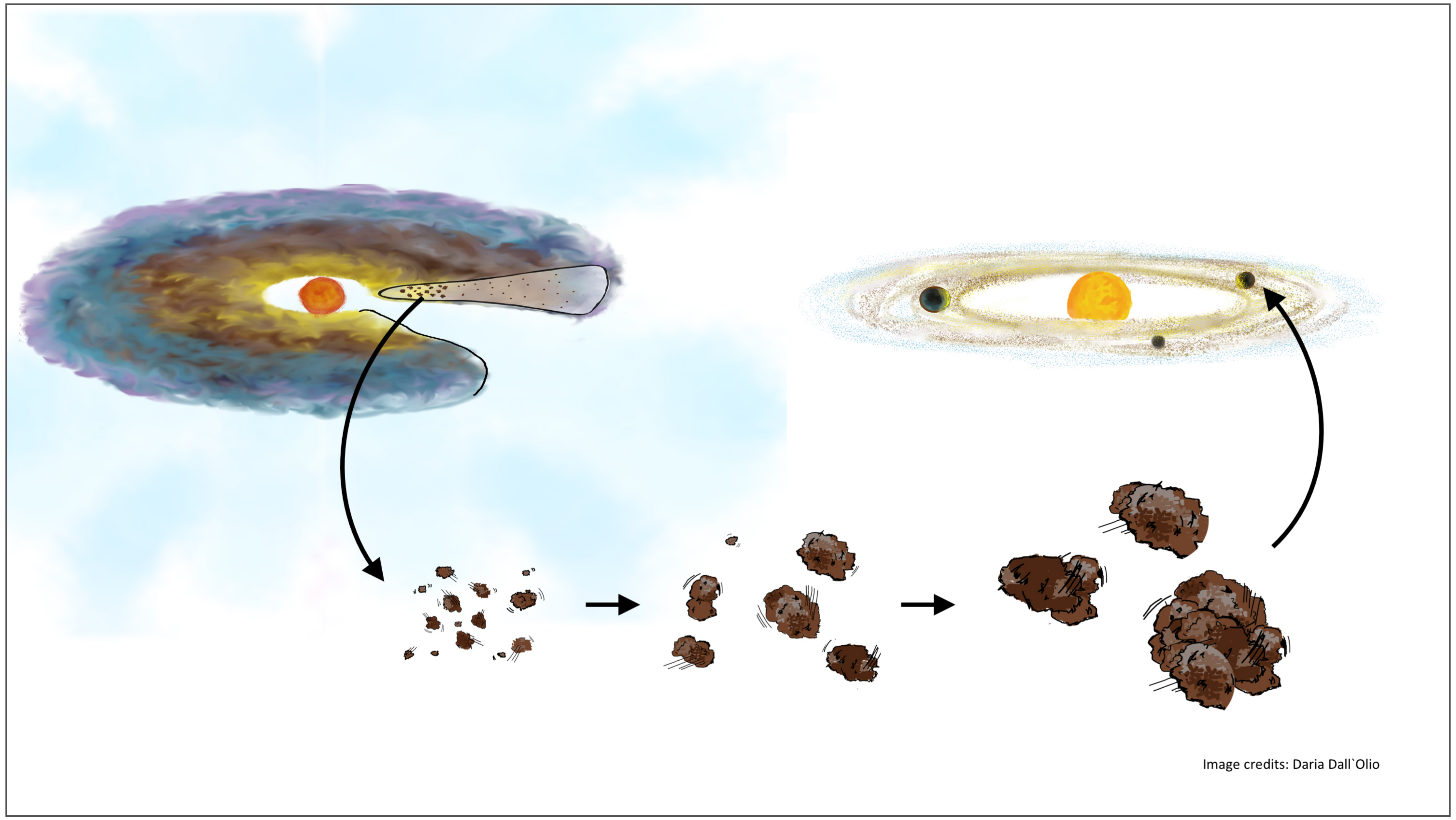


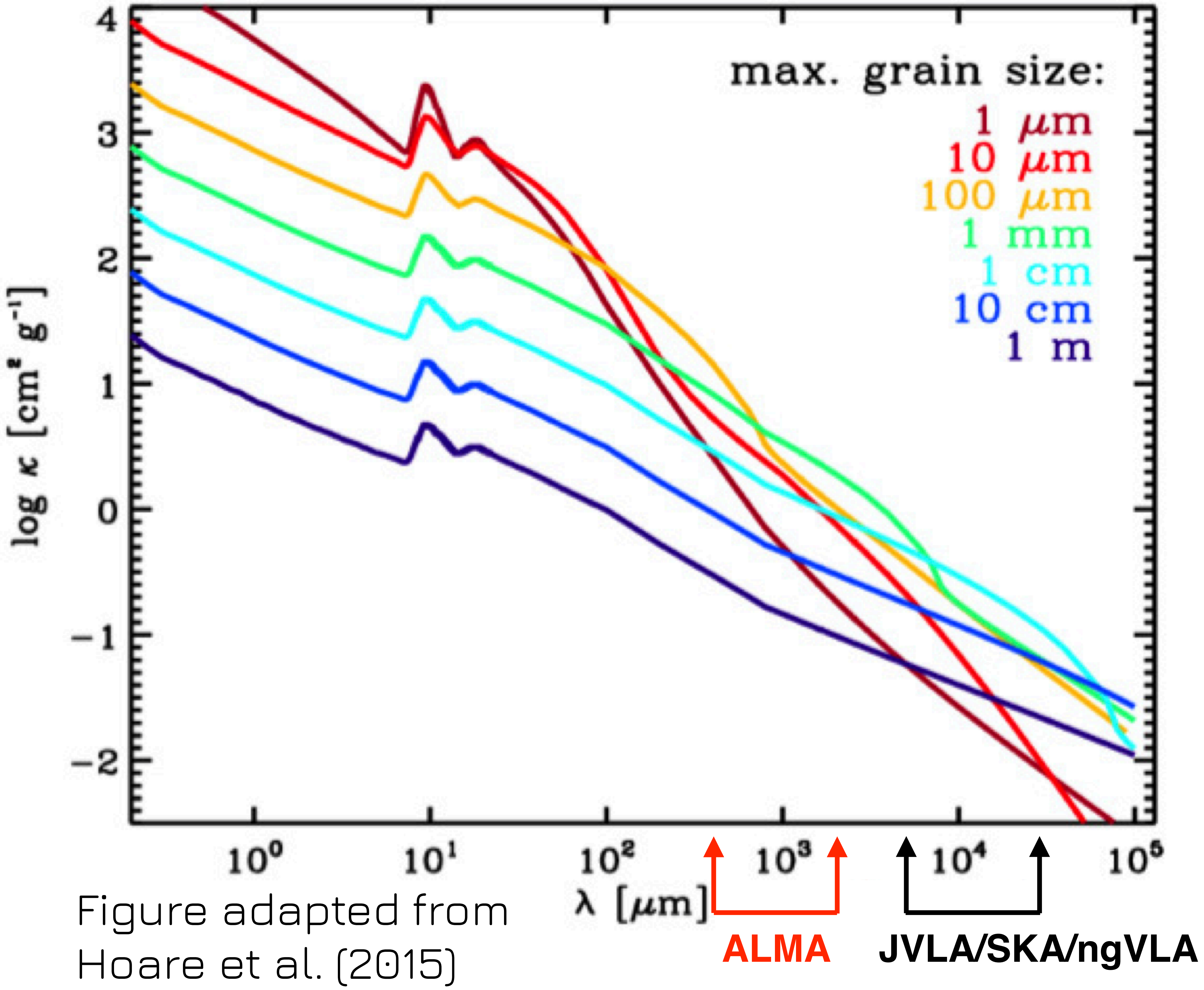


Figure adapted from Hoare et al. (2015)

THE OPHIUCHUS A CLUSTER

✦ Distance ~139 pc (Zucker et al. 2020)

Previous VLA observations

(Coutens et al. 2019)

✦ 18 sources detected in at X-band (16 YSOs)

✦ Different types of emission (gyro-synchrotron, free-free from thermal jets, free-free from photoevapoated disks, synchrotron emission)

✦ Dust emission contributes < 30 %

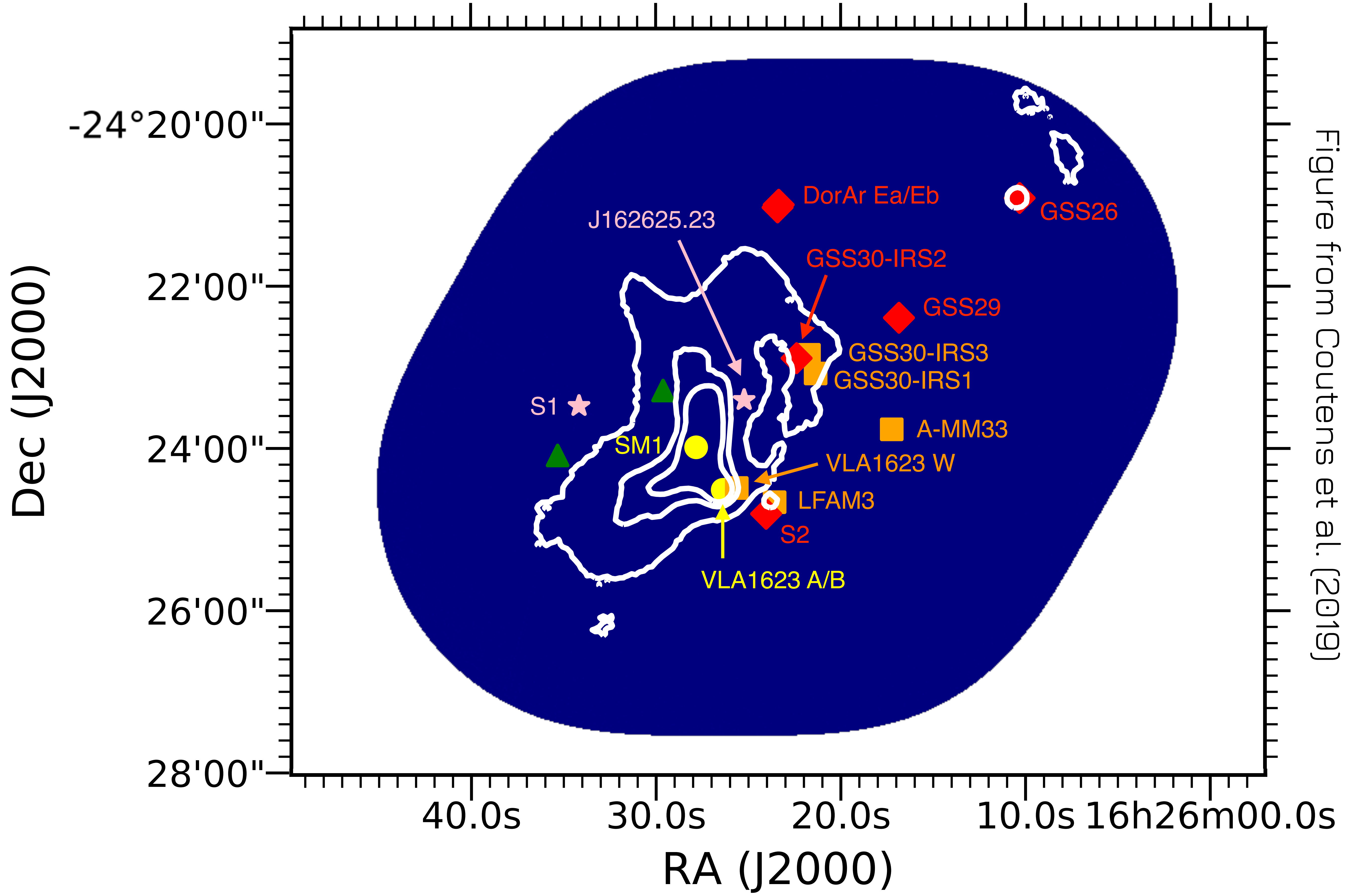


Figure from Coutens et al. (2019)

ALMA observations at 3 mm and 1 mm are available

(Kirk et al. 2017, Cieza et al. 2018, 2021, Friesen et al. 2018)

THE OPHIUCHUS A CLUSTER

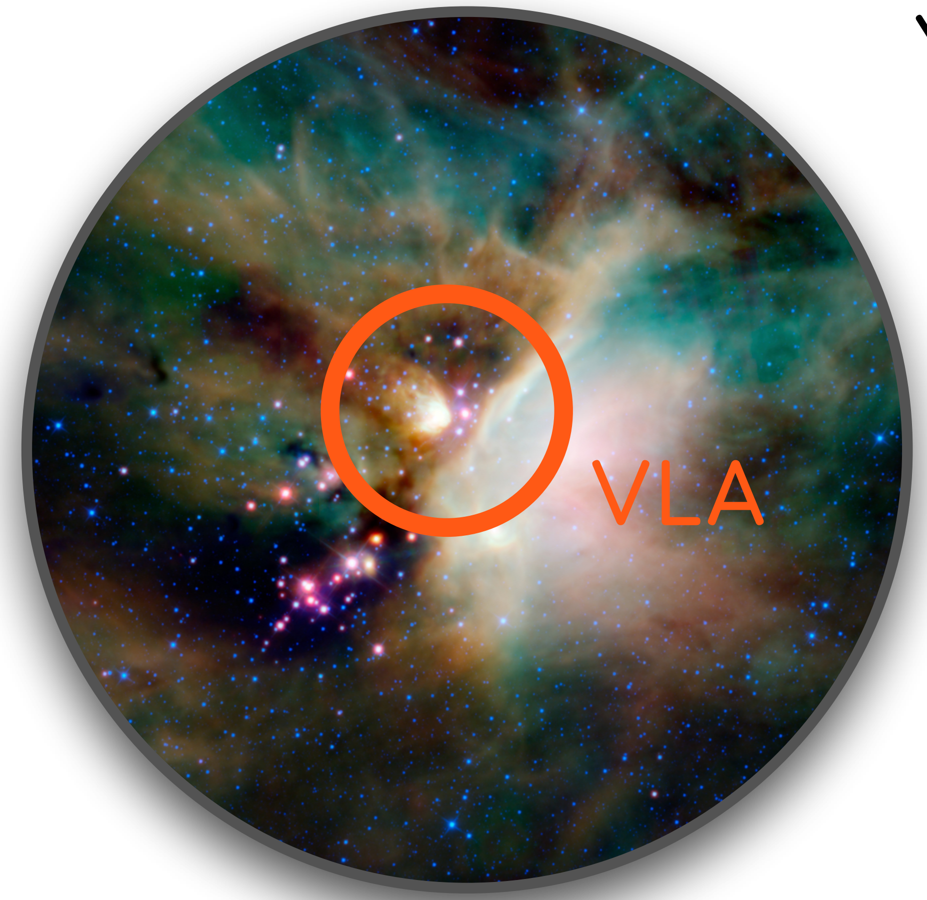
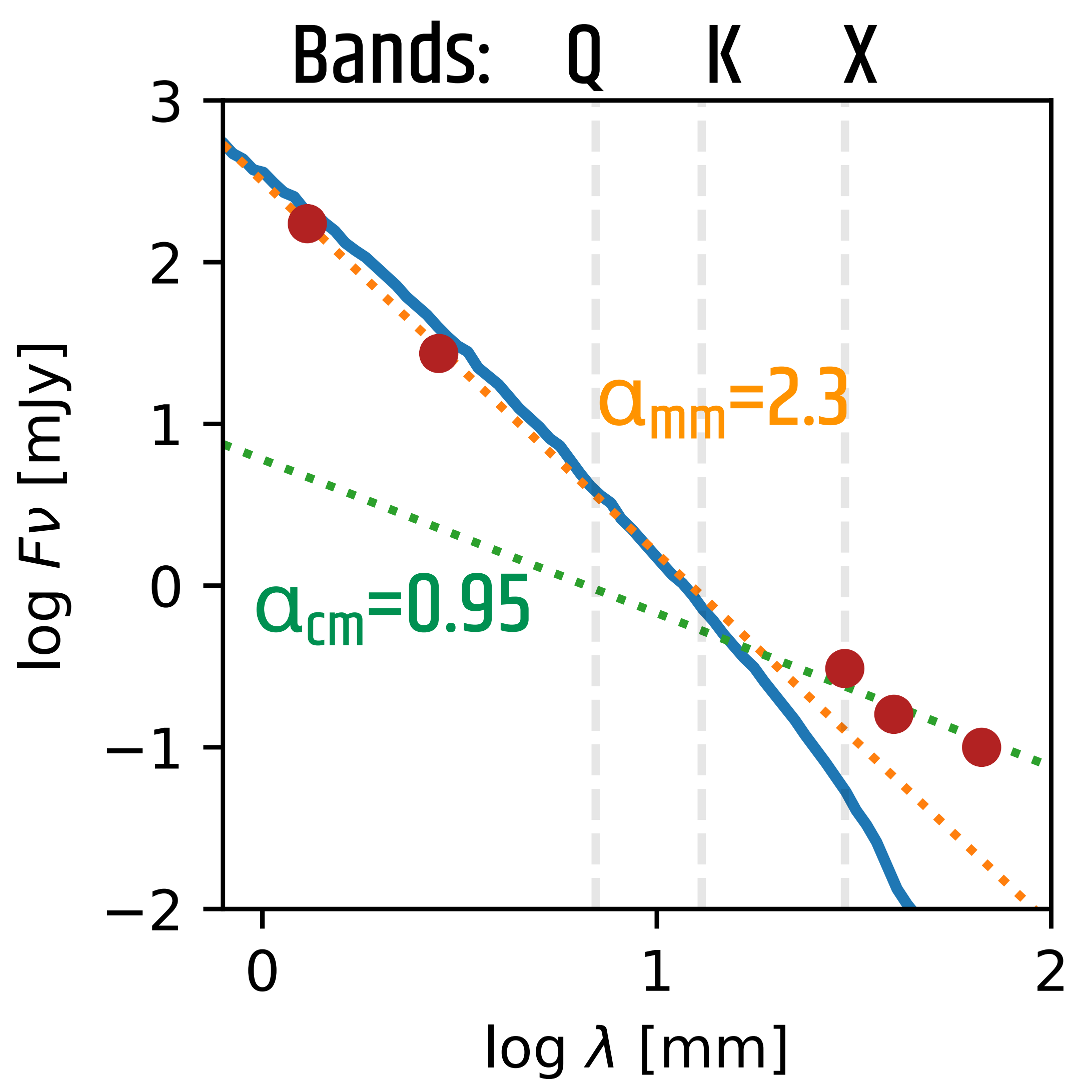


Image credit: NASA/JPL-Caltecg/WISE Team

YSOs at different evolutionary stages: from Class 0/I protostars to more evolved Class II and Class III objects

VLA observations with the A configuration

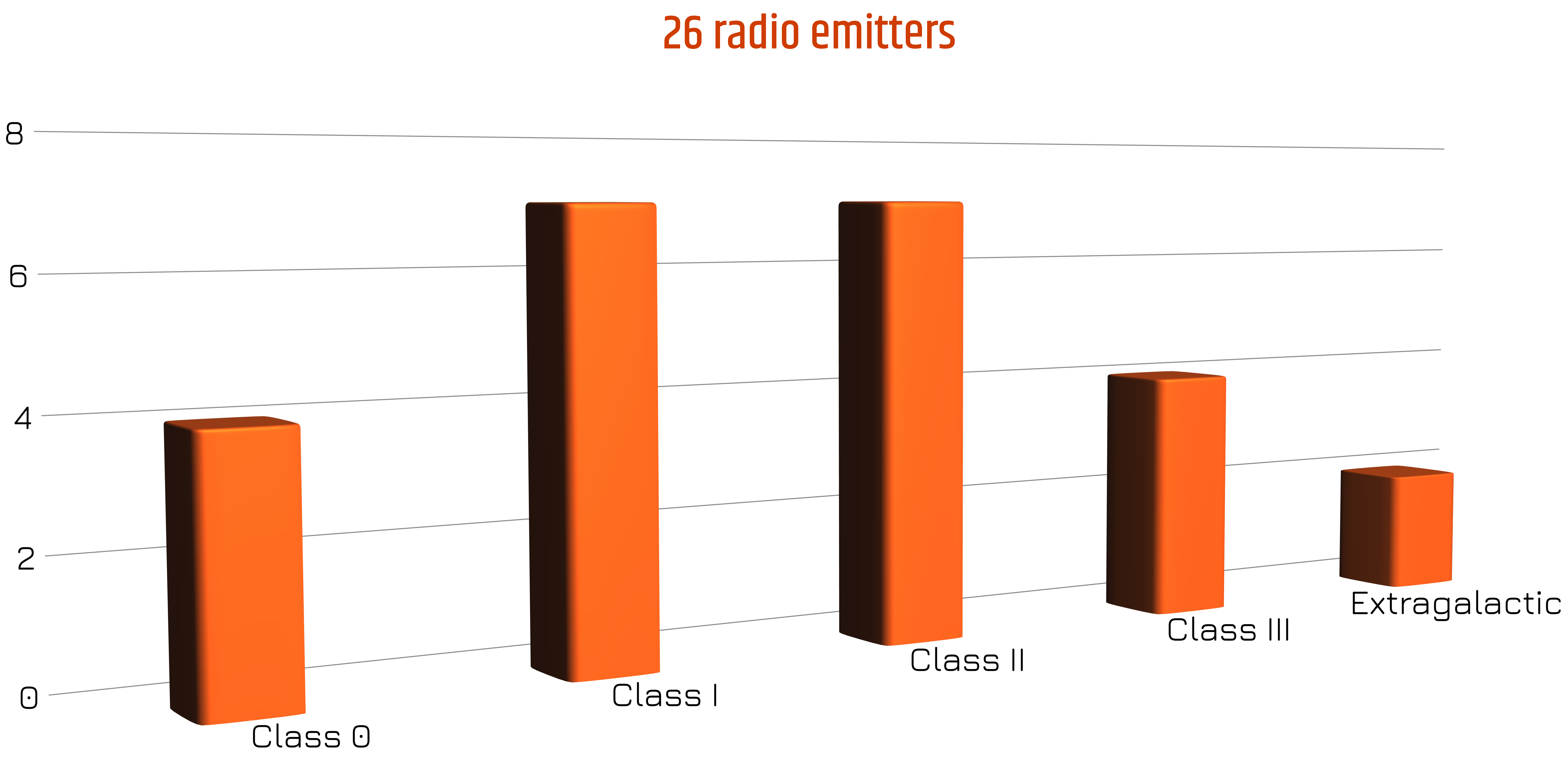
- ✦ Receivers: **X** (8 - 12 GHz), **K** (18-26 GHz) and **Q** (40-48 GHz)
- ✦ Individual pointings at K and Q bands covering 18 YSOs
- ✦ 2 Pointings in band X (FoV~15'~0.6 pc)
- ✦ 18 Epochs in band X, rms~3-4 μJy/beam (dynamic range~800)
- ✦ beam ~0.39"x0.21", P.A.=9.7º



GOALS:

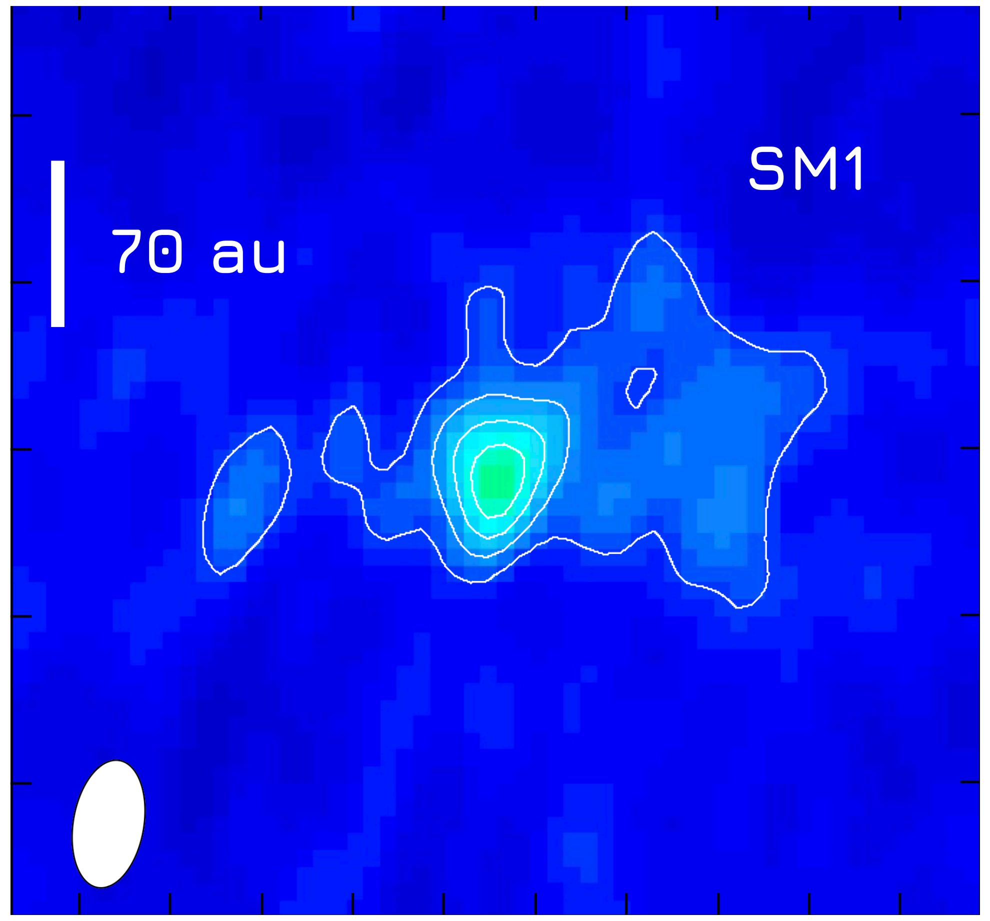
- ✦ Disentangle any thermal/non-thermal ionized gas emission from dust in the disks
- ✦ Trace the evolution of solids across different stages of disk evolution

VLA X-BAND DETECTIONS

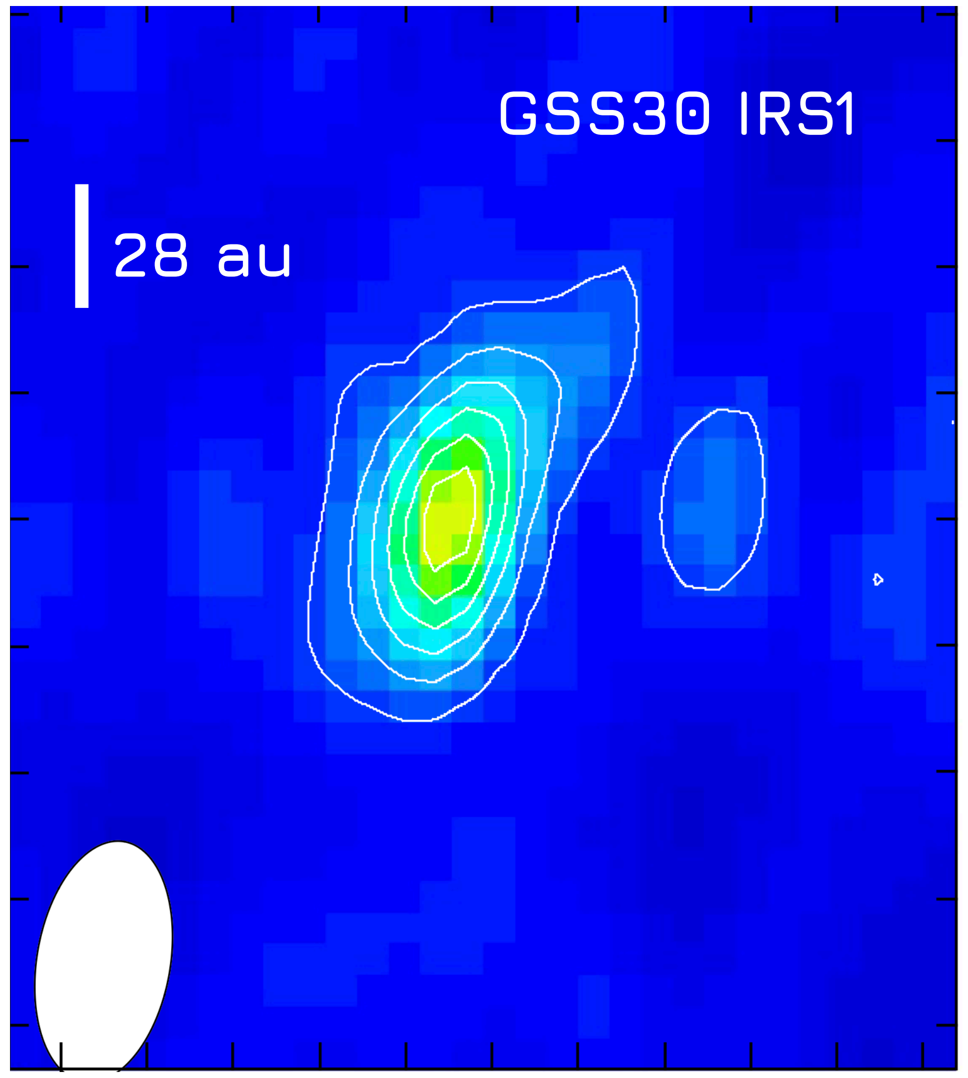


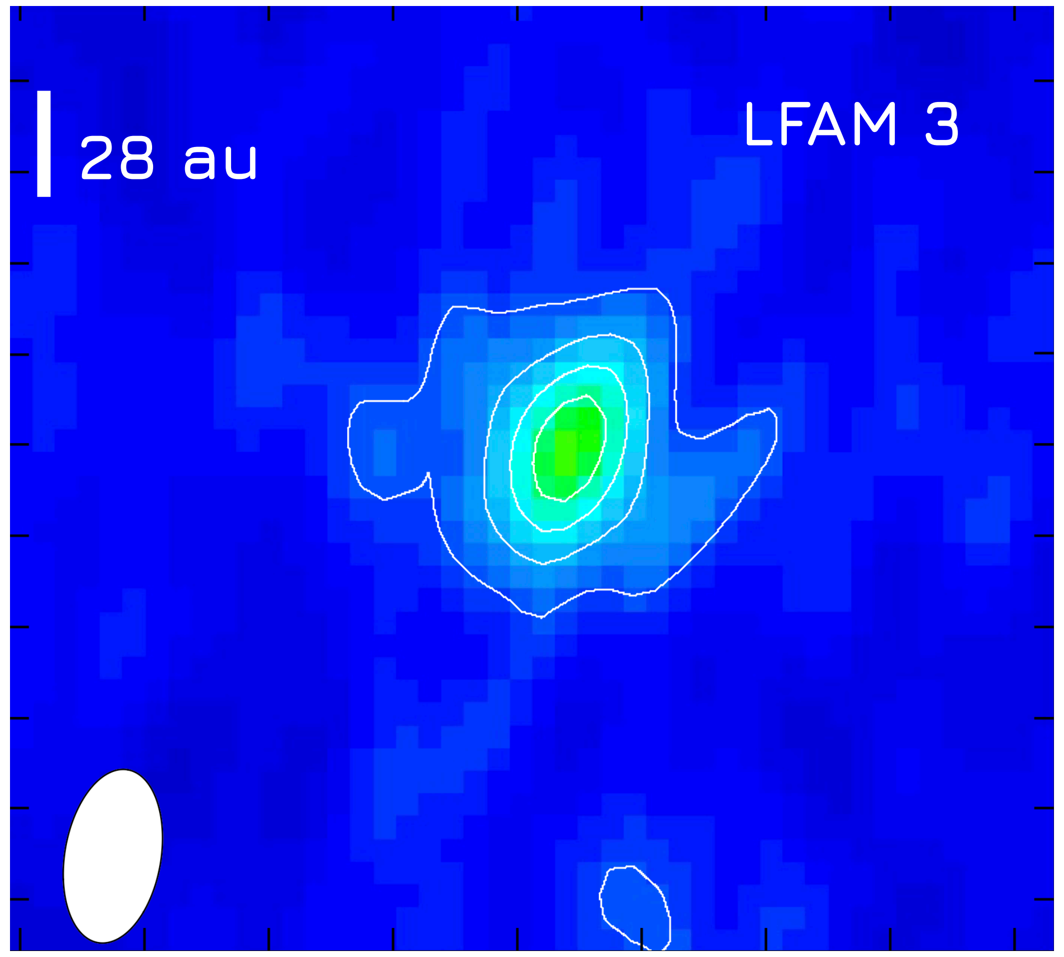
VLA X-BAND GALLERY

Class 0

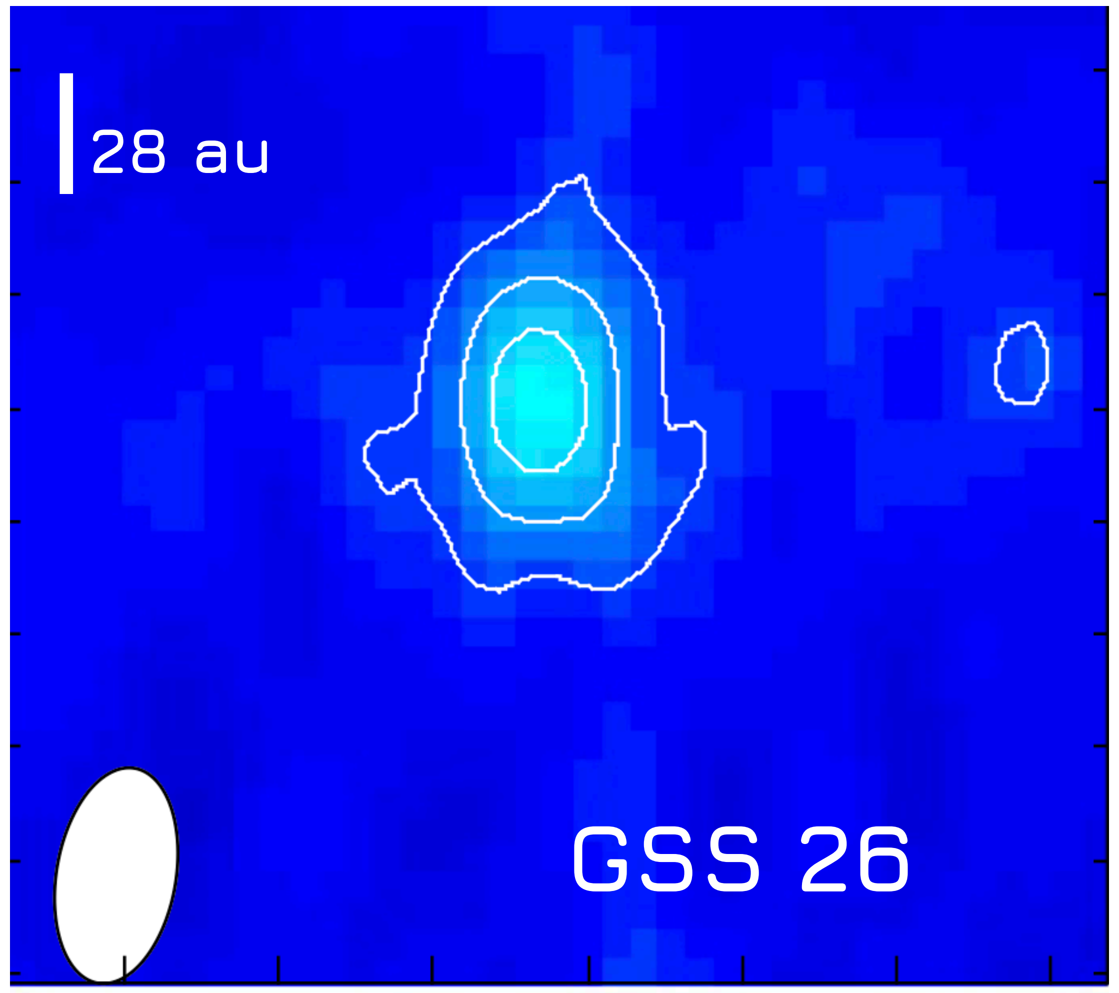


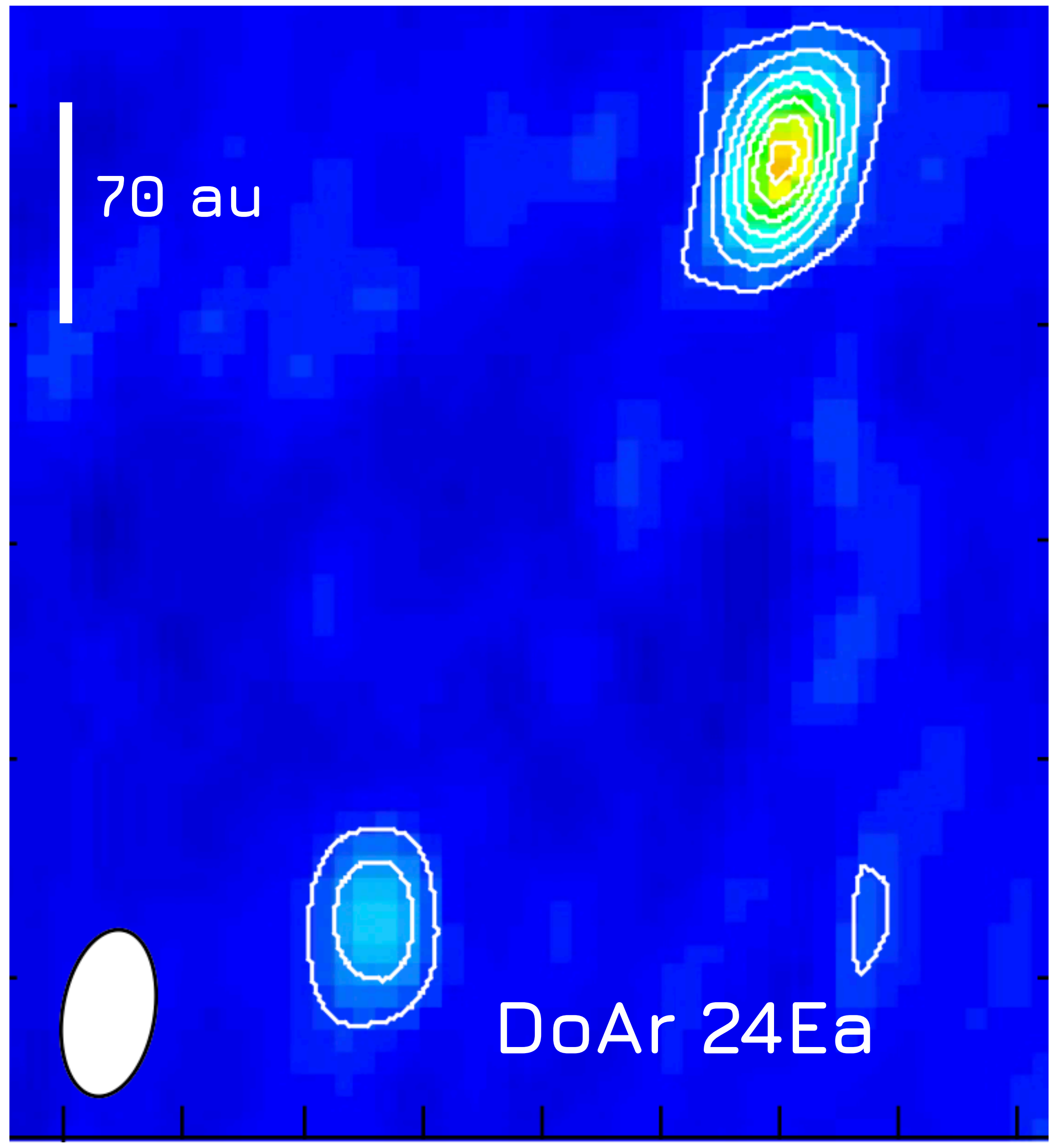
Class I



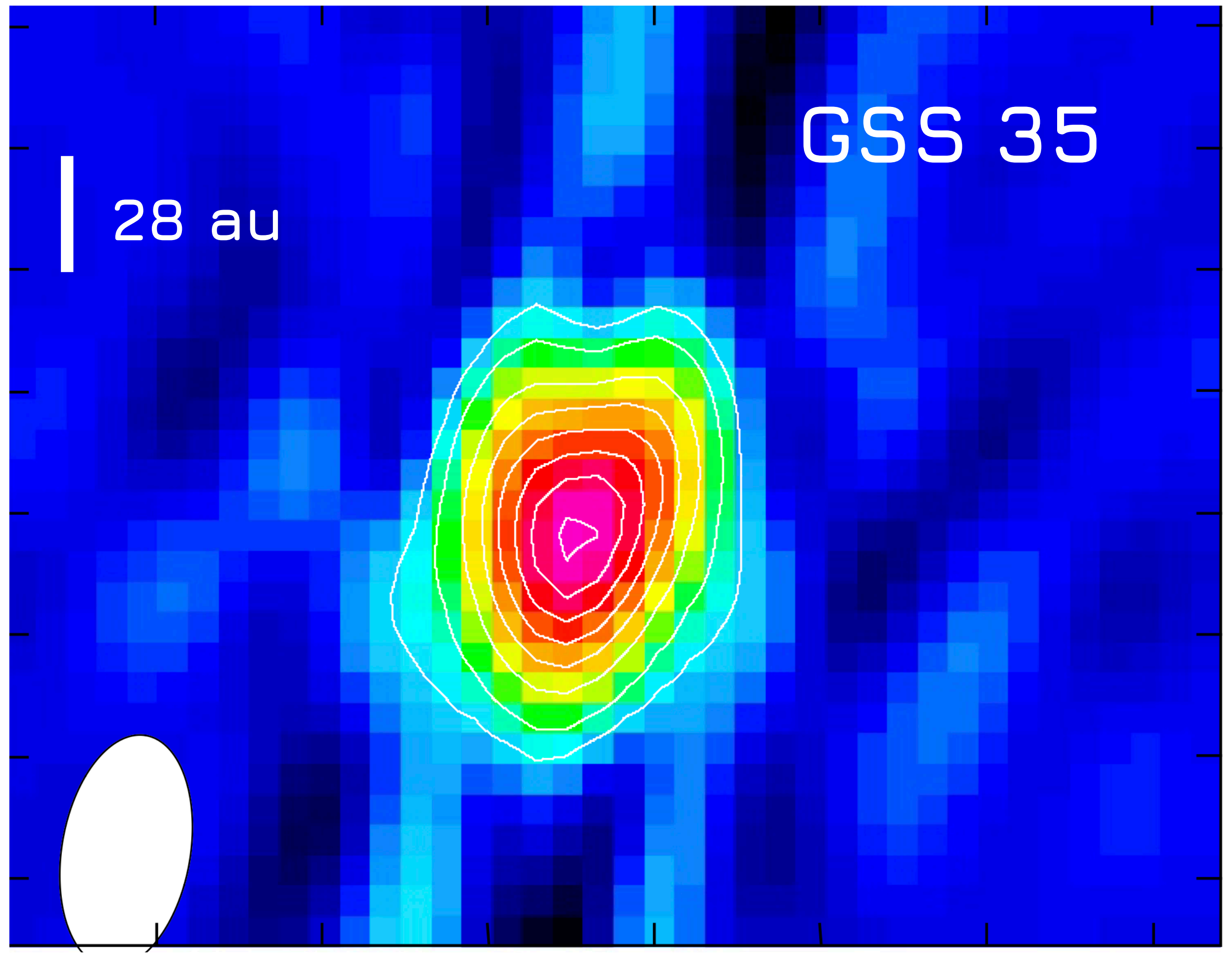


Class II

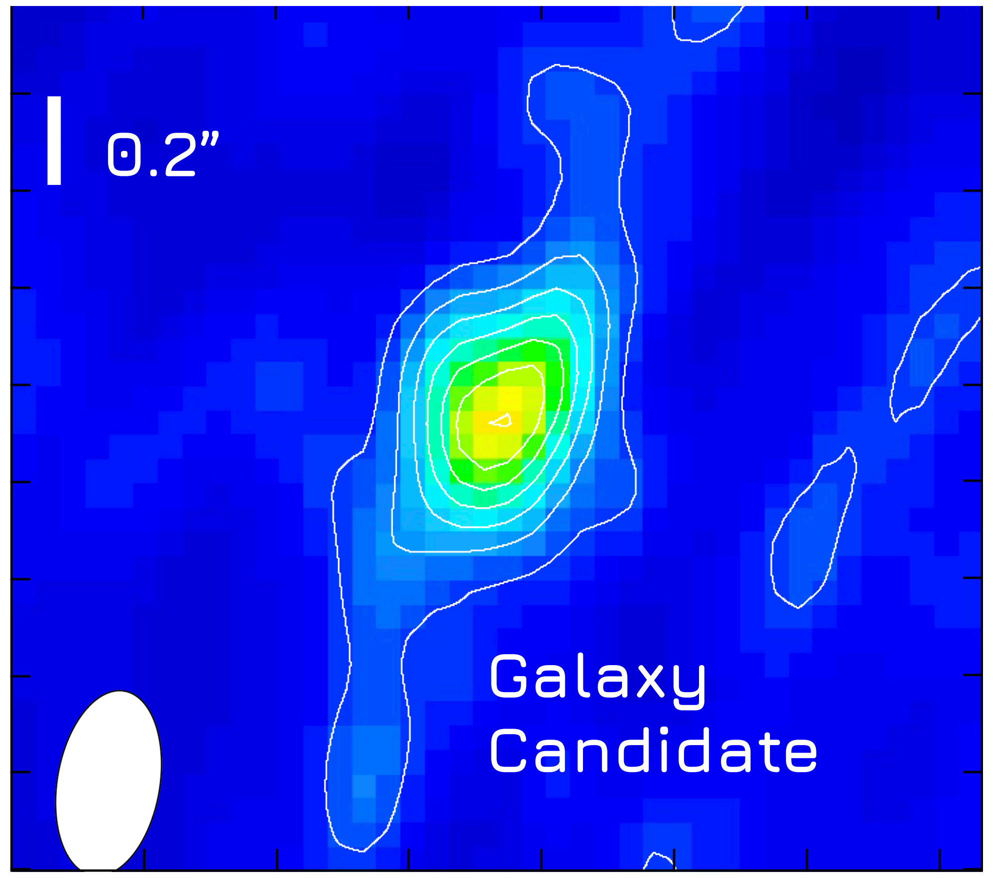




Class III



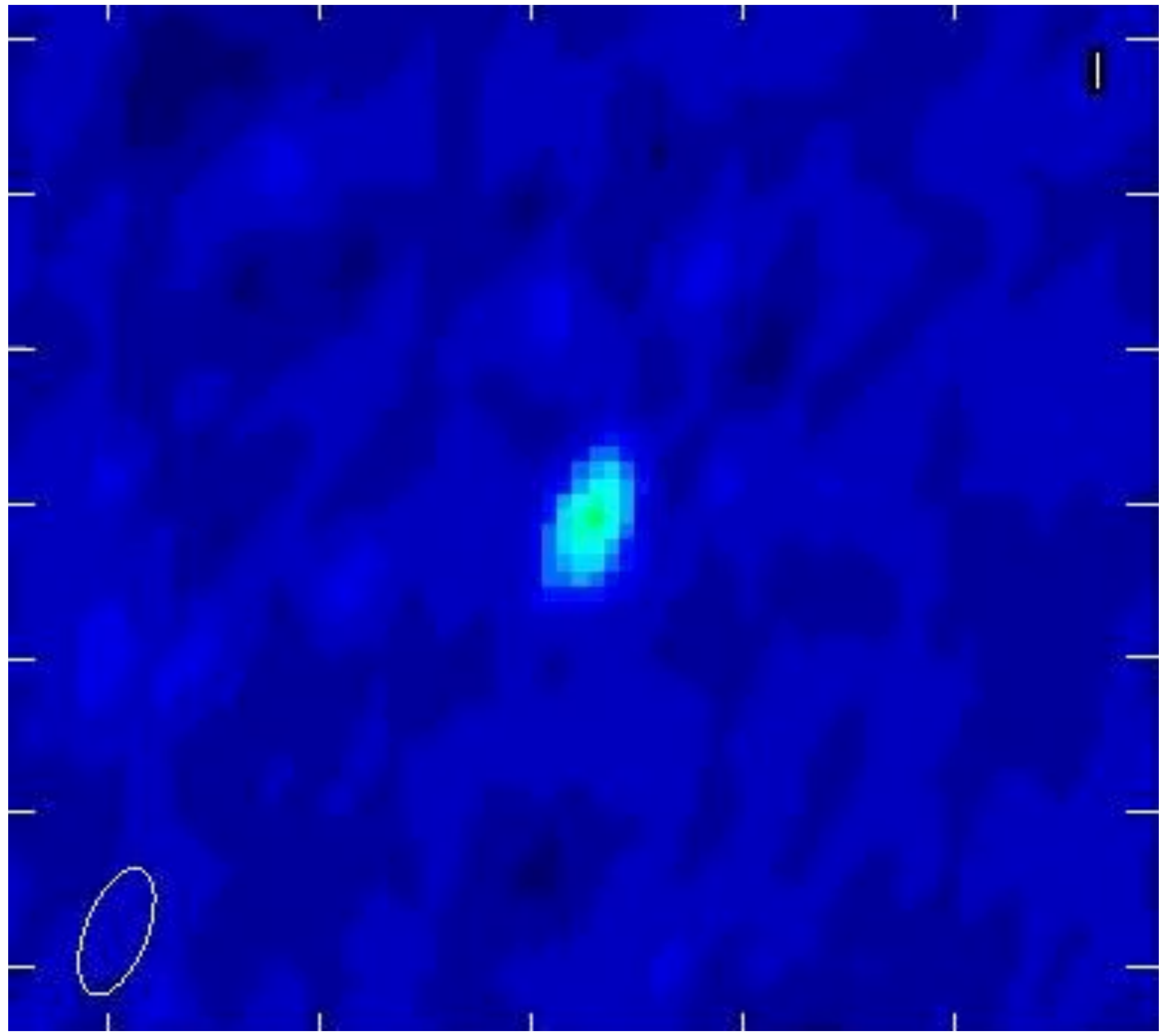
Extragalactic

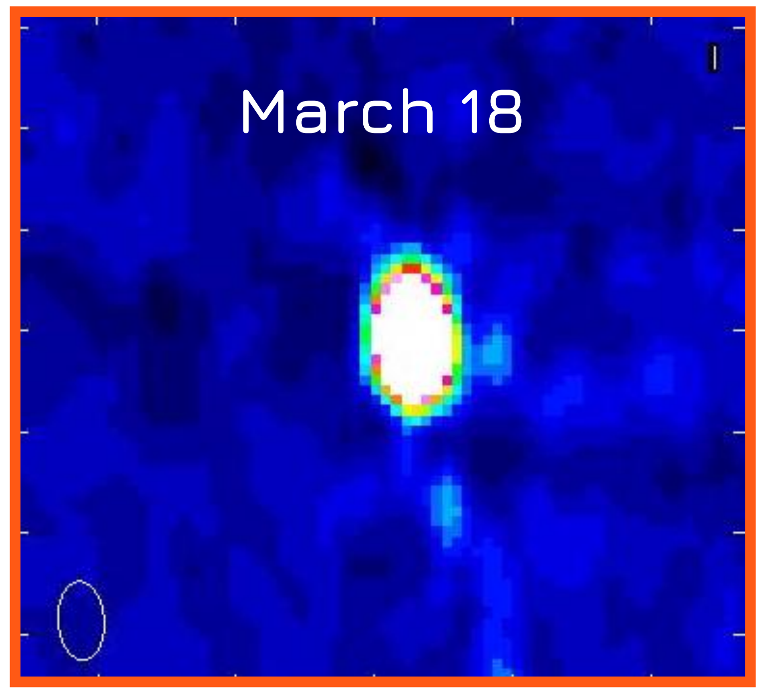


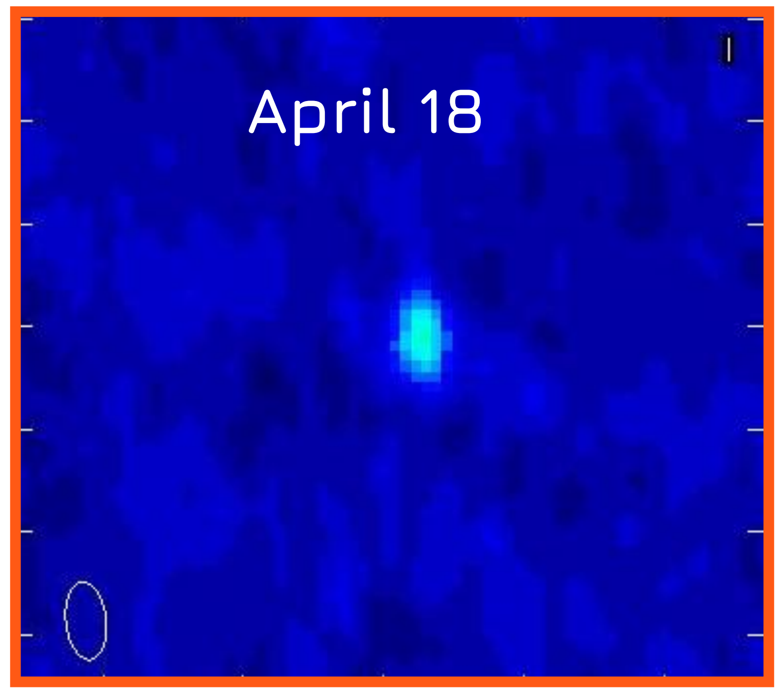
Same color scale in all panels
First contour: 3σ (steps of 3σ)

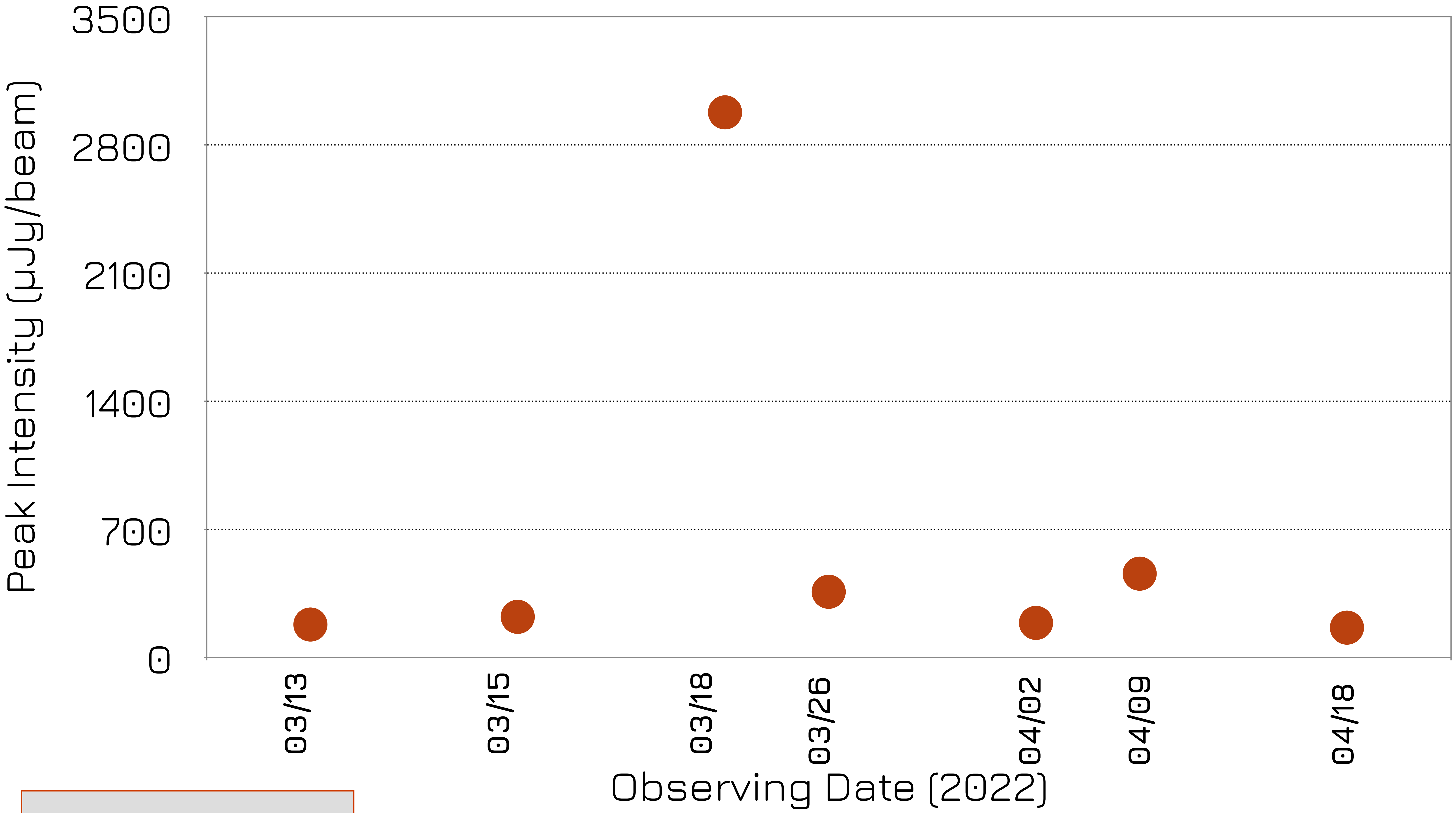
VLA X-BAND VARIABILITY

GSS 30-IRS2





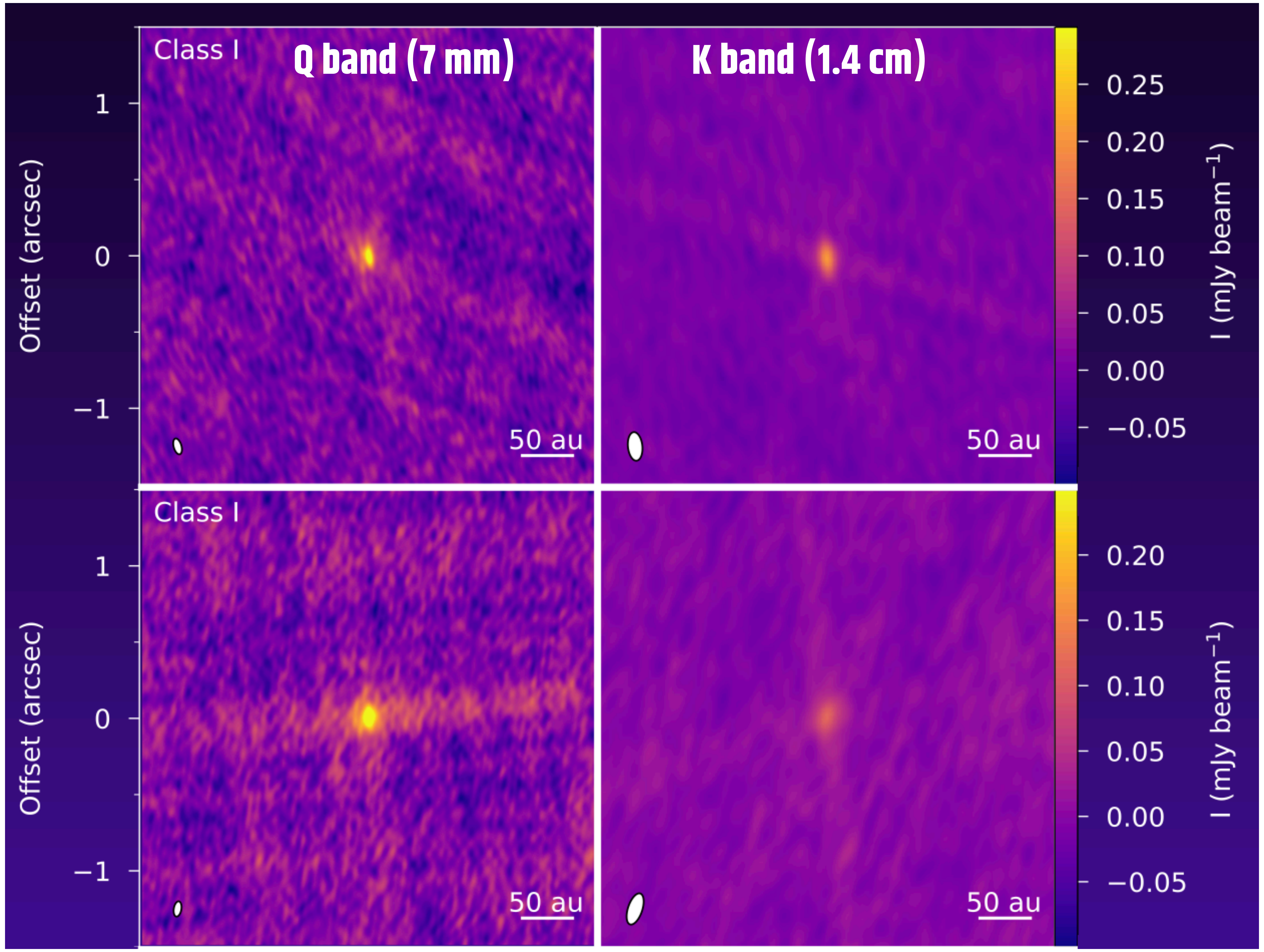


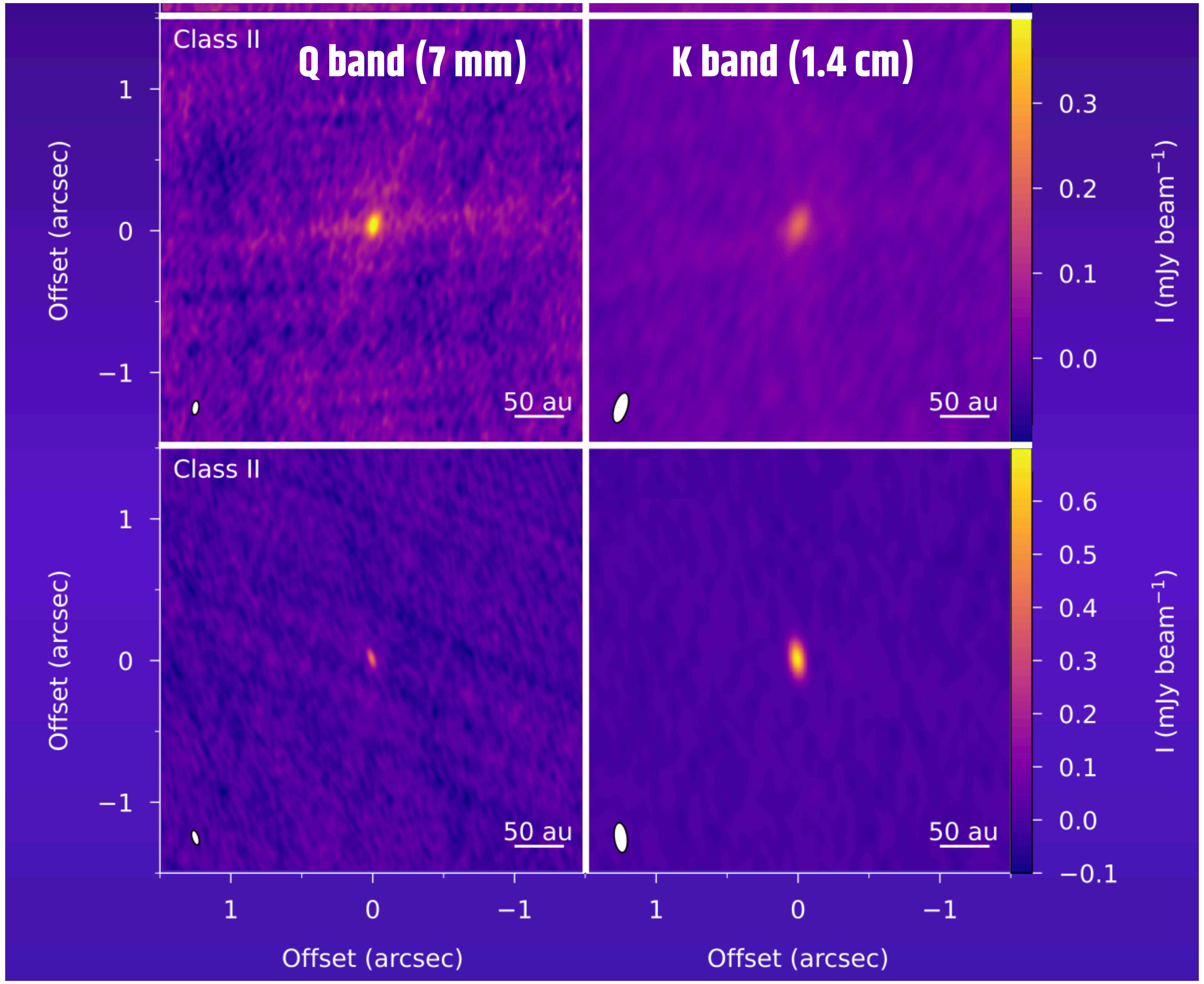


Variability ~94%

VLA K- AND Q-BAND DETECTIONS

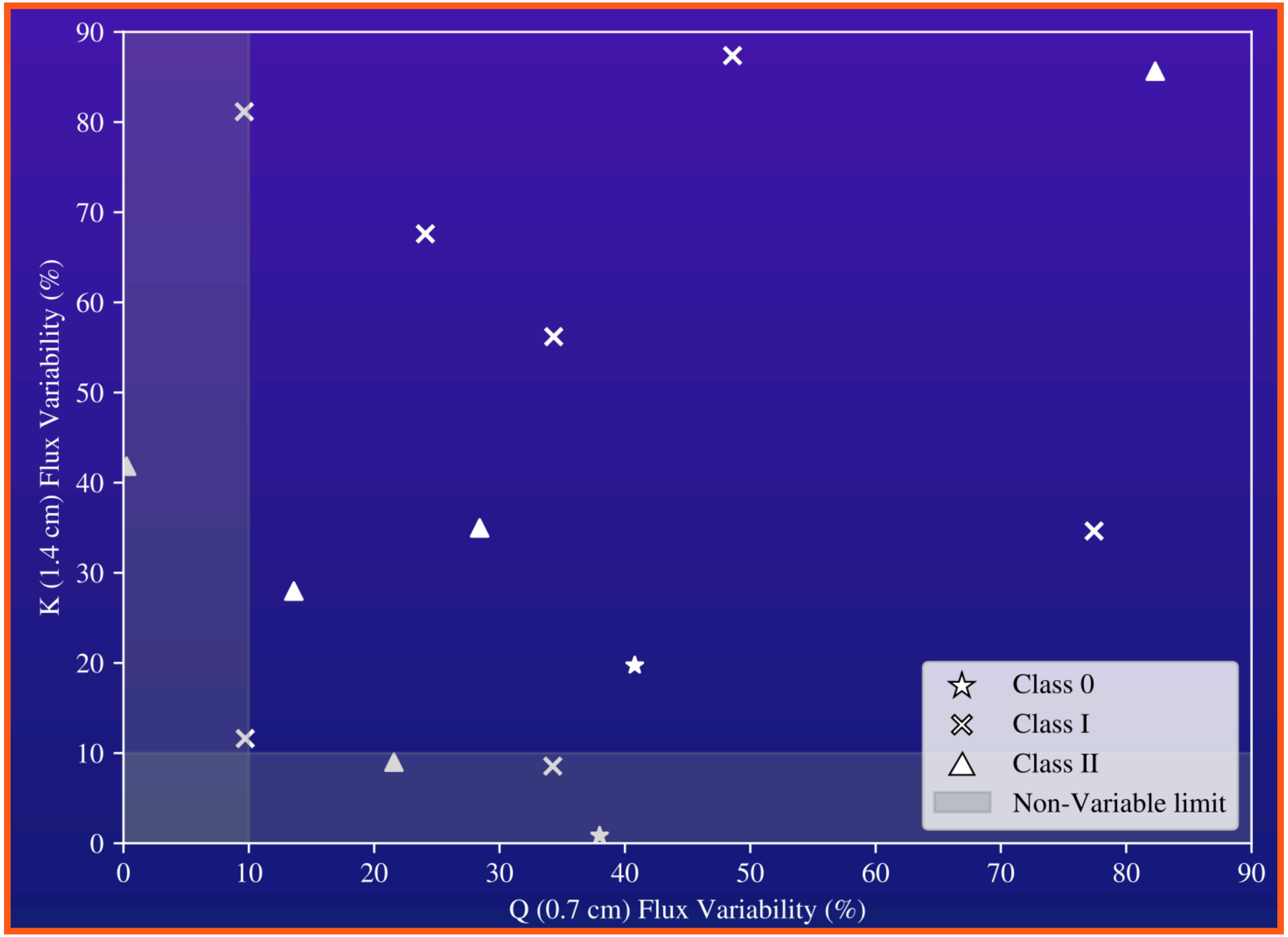
- ☆ 16 YSOs detected at 7 mm (beam ~10 au) and 19 YSOs detected at 1.4 cm (beam ~20 au)
- ☆ Majority of YSOs are unresolved, indicating the extremely compact nature of the cm emission





(Radley et al. in preparation)

VARIABILITY AT VLA K- AND Q-BANDS



(Radley et al. in preparation)

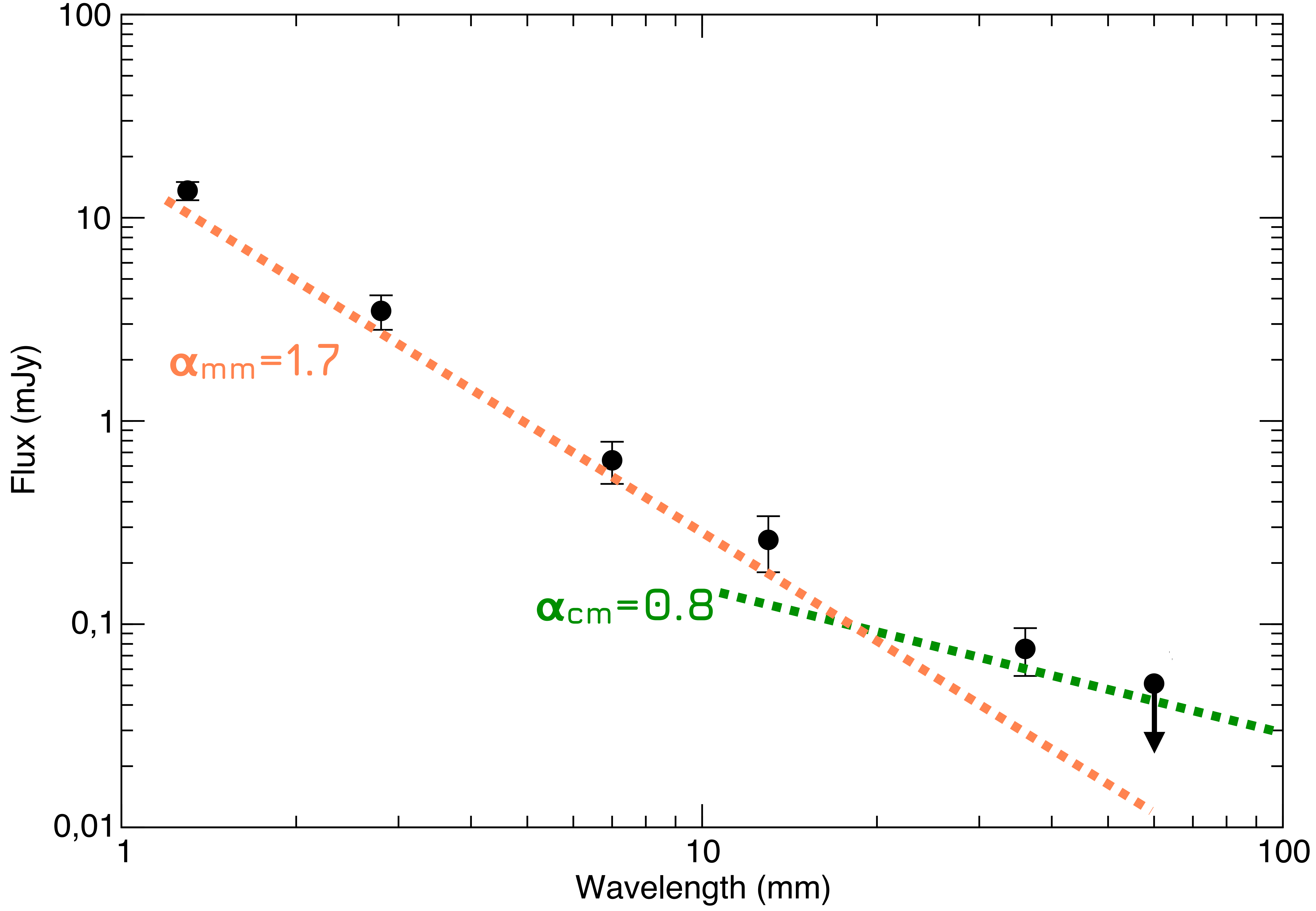
- Multi-epoch observations cover **timescales of 1 to 37 days**
- **2/3** of our sample exhibit high **variability** in both K and Q bands
- **Class I** sources are, on average, the **most variable** objects at K-band

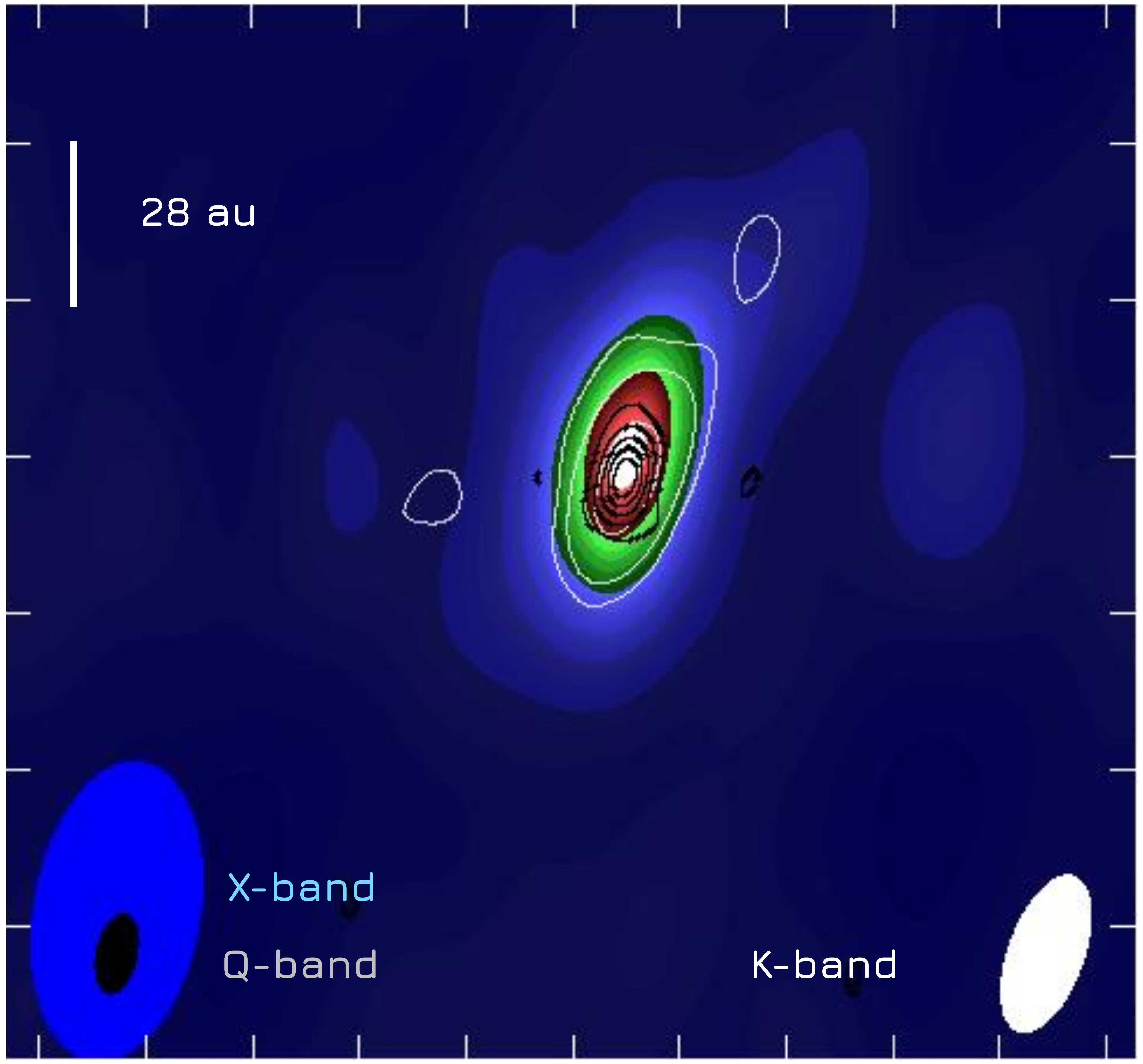
SPECTRAL ENERGY DISTRIBUTION

Work in progress

GSS30 IRS1 - Class I

α~2 → β~0: Bigger grains





6cm data from Dzib et al. (2013), ALMA data from Kirk et al. (2017), Cieza et al. (2018) and Friesen et al. (2018)


THE VLA ORION A LARGE SURVEY
(VOLS)
https://vols.fqa.ub.edu
vols
Fundación
BBVA
Proyecto realizado con la Beca Leonardo a Investigadores en Física 2022
de la Fundación BBVA
Image Credit: NRAO/VLA

VOLS: THE VLA ORION A LARGE SURVEY

Large Project for the JVLA, 306 hours of observing time awarded

PI: **G. Busquet**, co-PIs: P. Hofner (USA), M. Fernández-López (Argentina), P. Texeira (UK)

C- and Ku band observations with the **A and B configurations** (~120 au): **continuum + lines** (RRL and masers emission)

Improve the sensitivity by a factor of 20 compared to previous surveys in Orion (Kounkel et al. 2014)

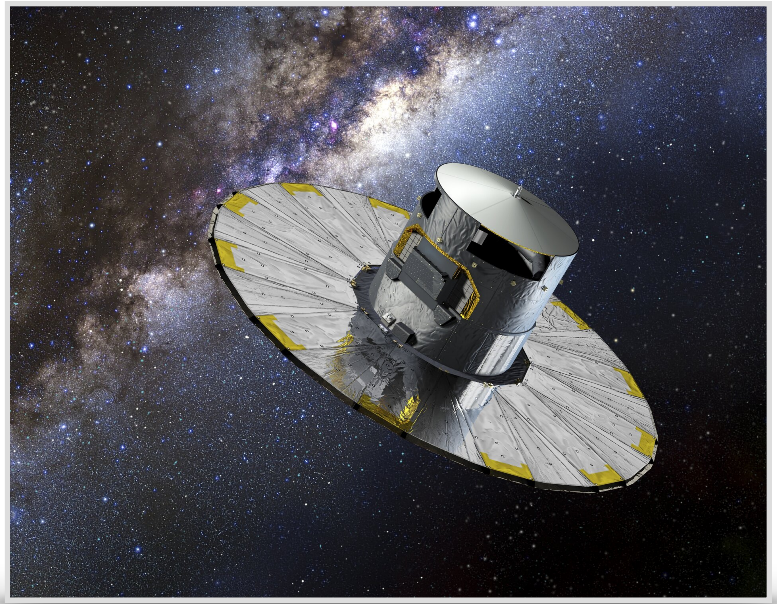
Global collaboration: 45 researches from 25 institutions worldwide

RADIO OBSERVATIONS

&

GAIA DR3 CATALOG

(U-band excess and H_α line profile)



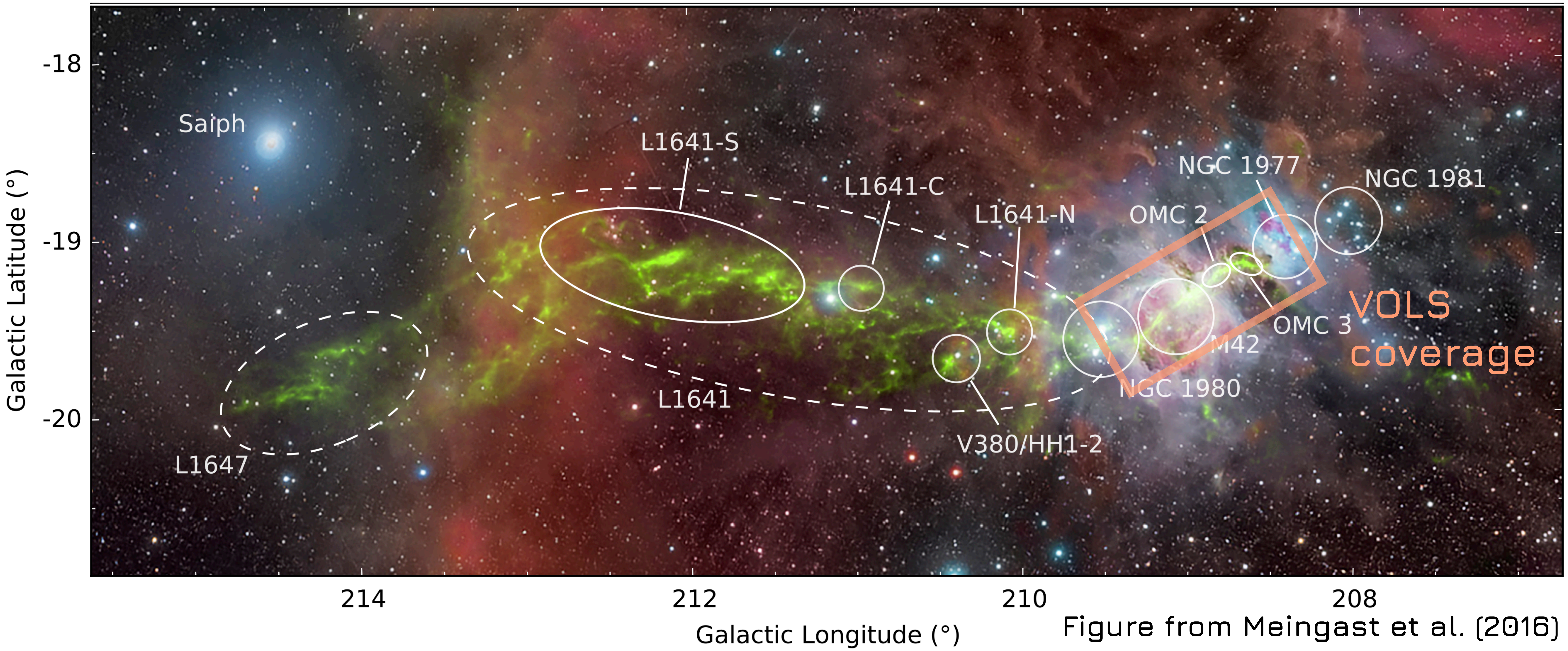
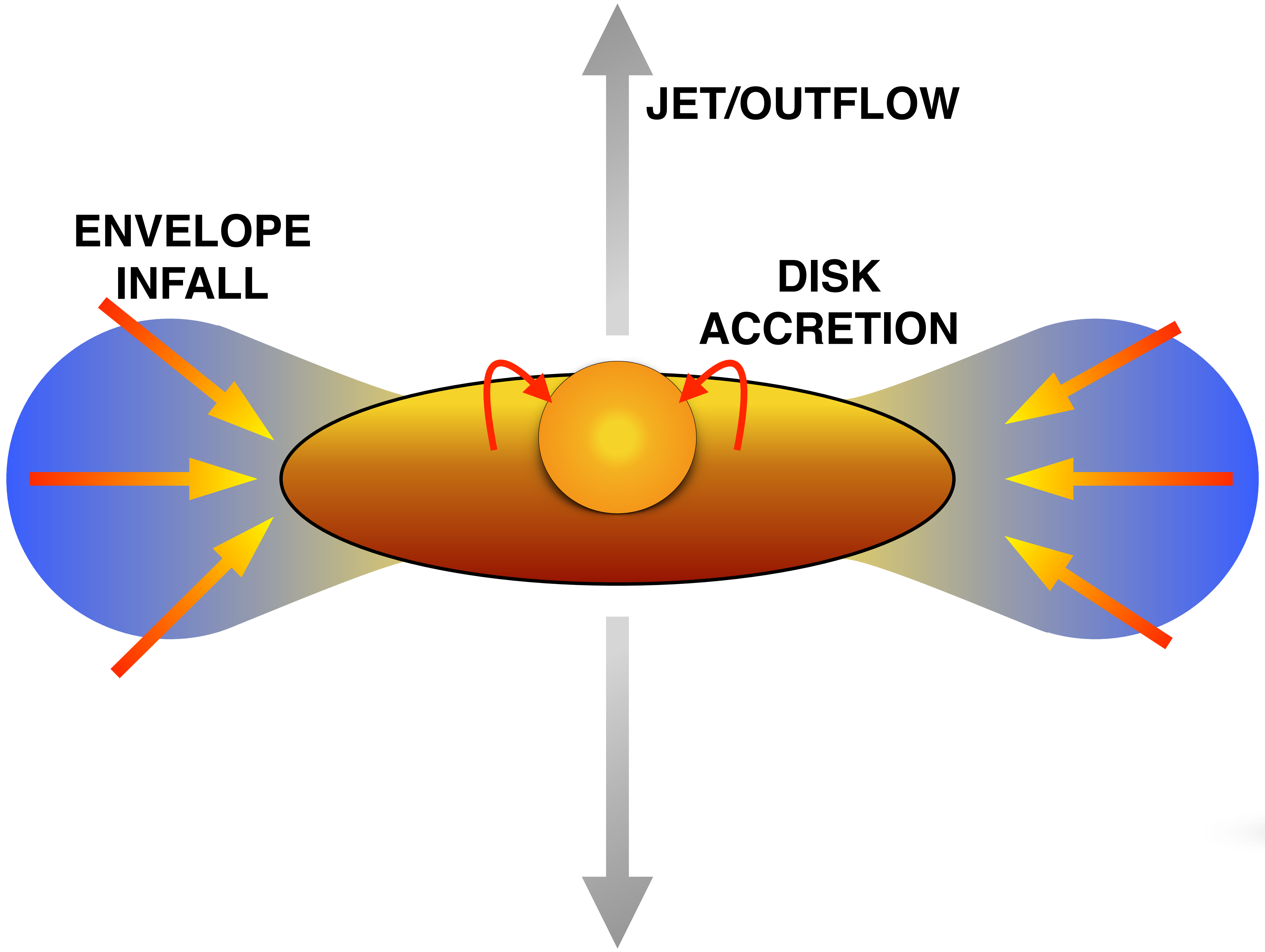


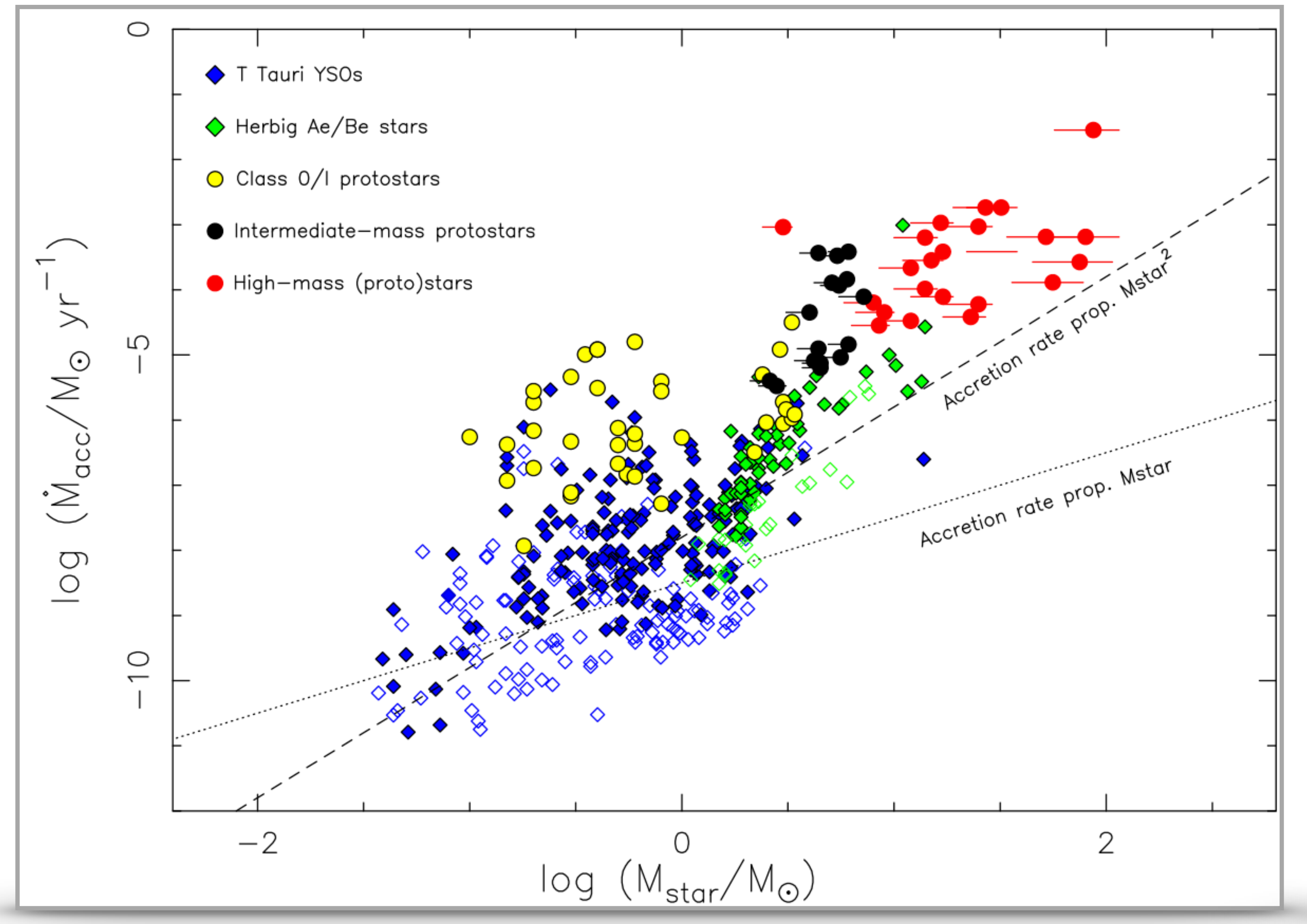
Figure from Meingast et al. (2016)

VOLS: IMMEDIATE OBJECTIVE

How do $\dot{M}_{acc}$ and $\dot{M}_{loss}$ evolve with time?

How do they depend on the initial conditions (i.e., environment) and on the mass of the central object?





Beltrán & de Wit (2016)

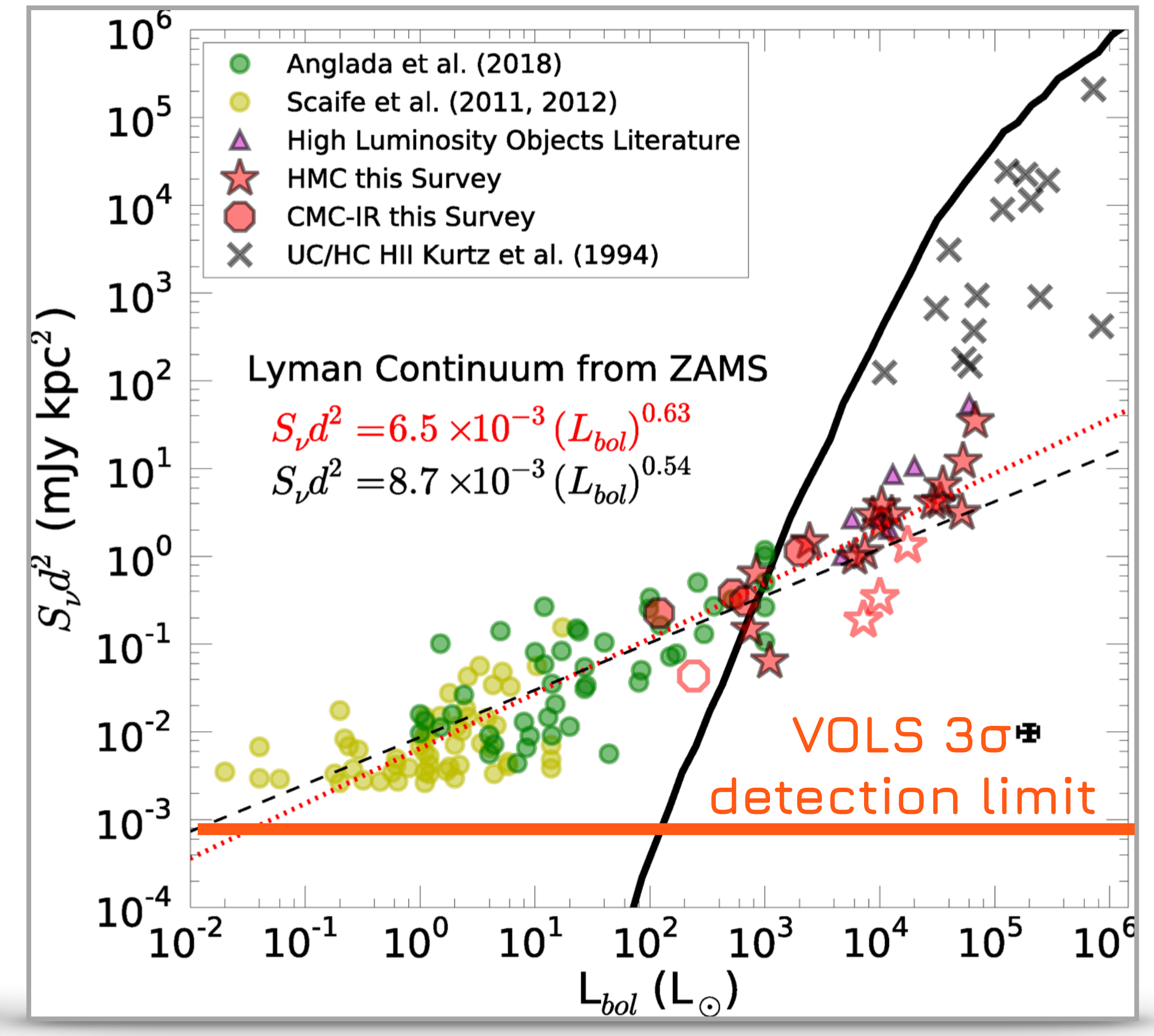


Figure from Rosero et al. (2019)
see also: Anglada et al. (2018),
Purser et al. (2021), Kavak et al. (2021)

- **Pre-main sequence stars:** $\dot{M}_{acc}$ inferred from optical lines, (e.g. Hα; Gullbring et al. 1998)
- **Embedded protostars:** indirect methods (using $\dot{M}_{loss}$ or L_{bol} arises from stellar component)

VOLS: SECONDARY GOALS

MULTIPLICITY

Complement previous studies (targeting Class 0/I)

Detect companions without significant dust emission but strong sources of free-free or gyro synchrotron radiation

HII REGIONS

Reveal radio emission from many more embedded OB-type stars

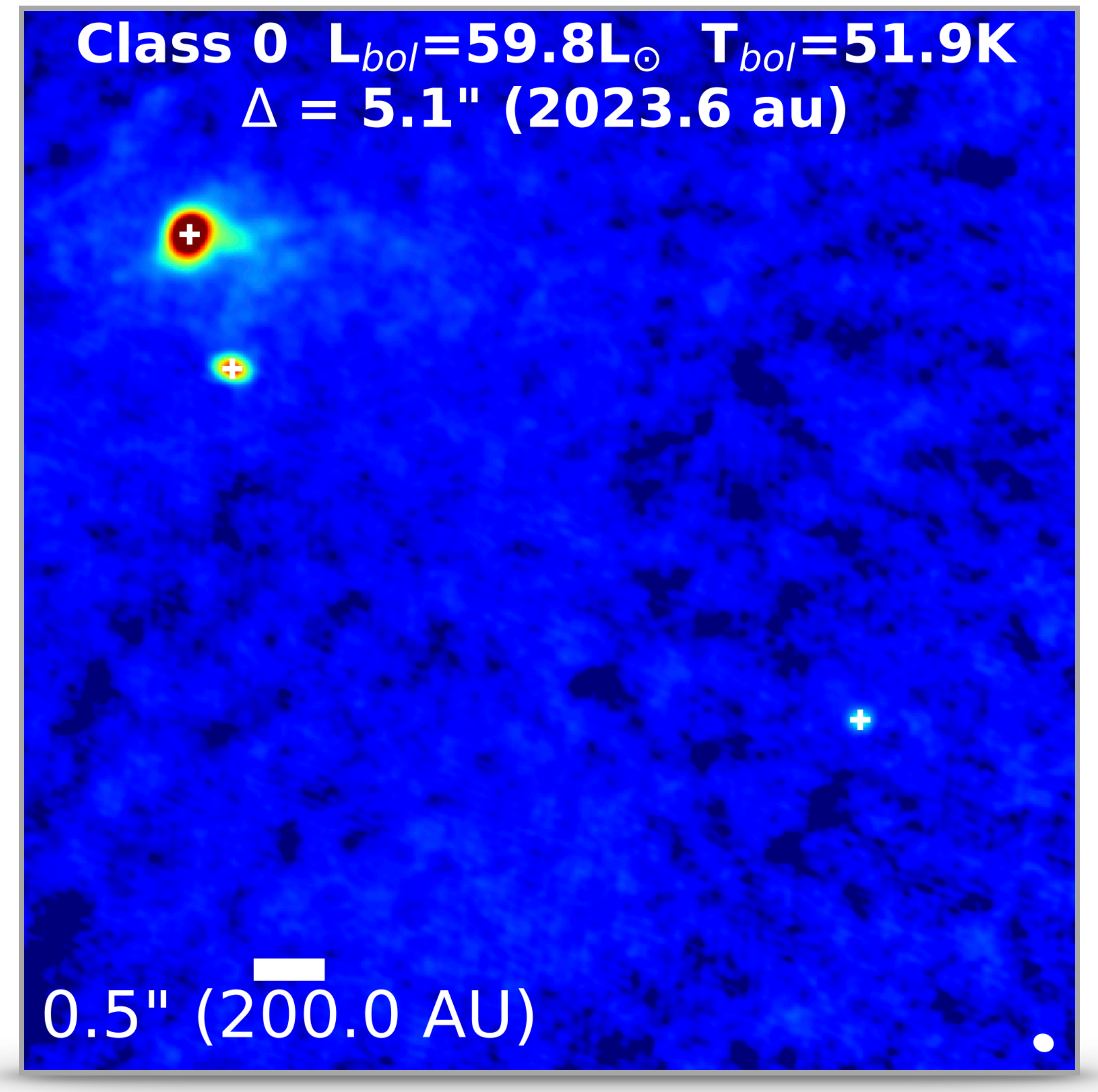
Possible to detect embedded early-type stars earlier than B6

SUBSTELLAR REGIME

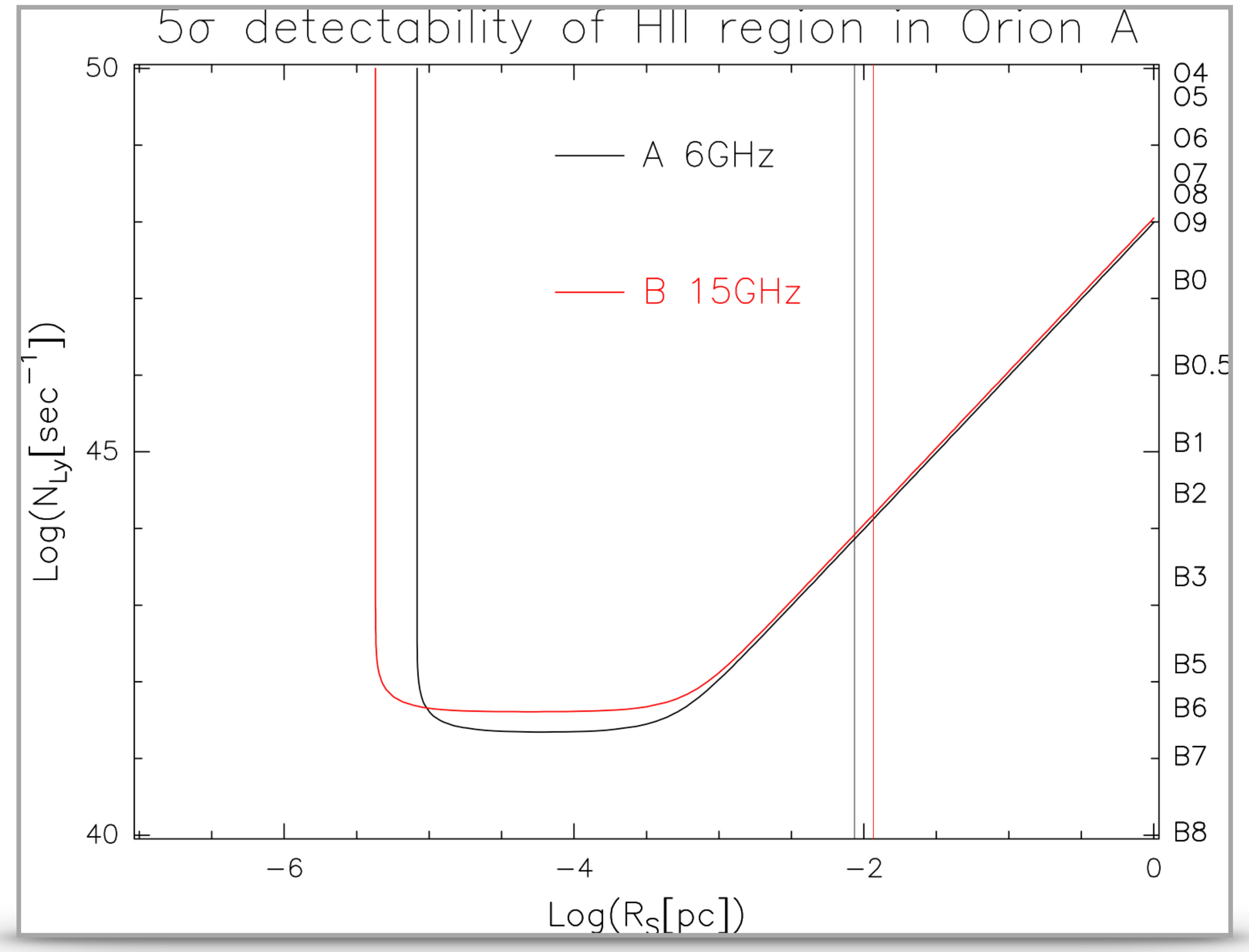
Unbiased survey searching for thermal radio jets driven by porto-brown dwarfs

First clues about the number of such objects formed in a cloud

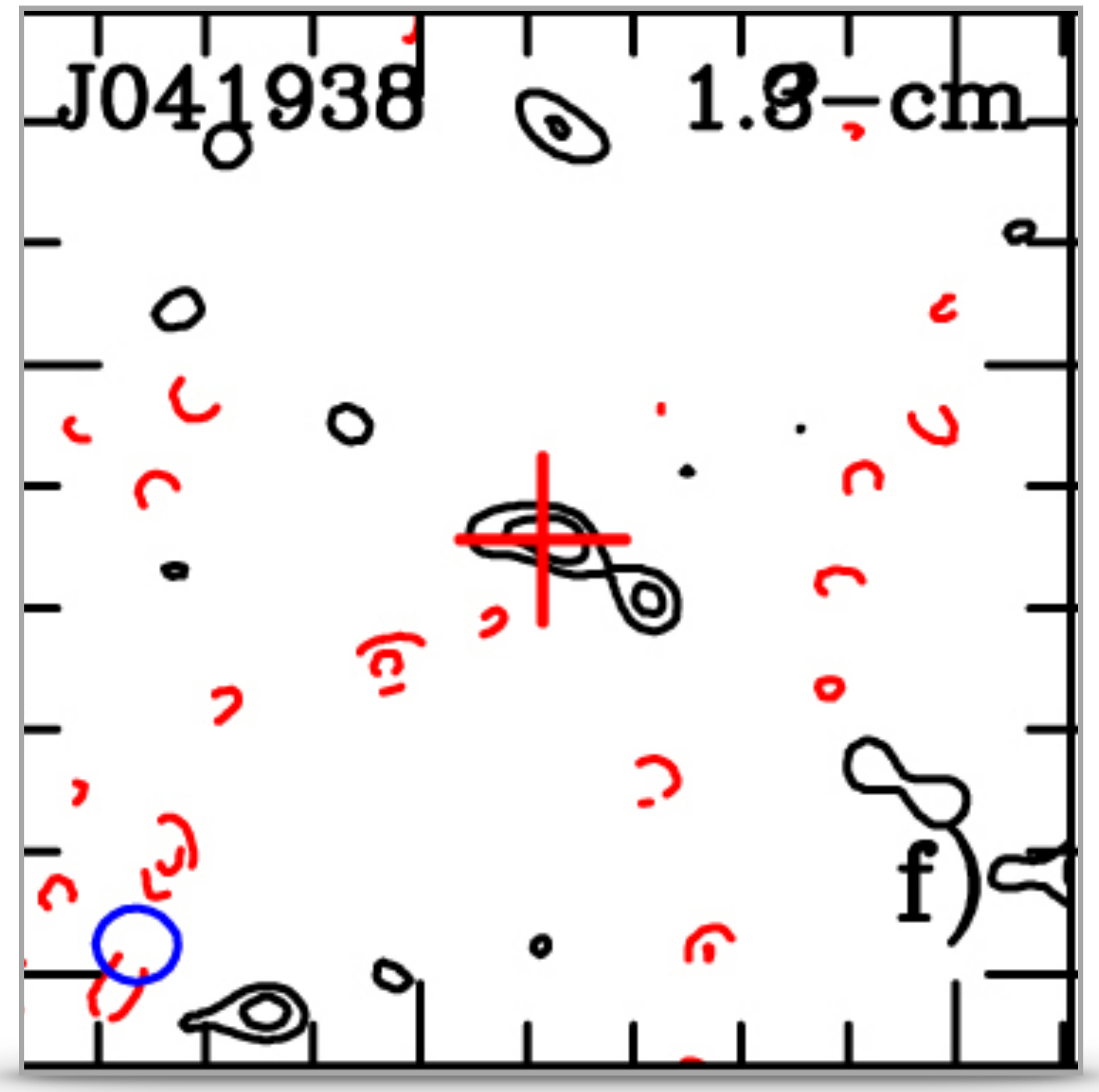
Tobin et al. (2020)



Courtesy R. Cesaroni



Morata et al. (2015)



WHY ORION?

A TESTBED FOR STAR FORMATION THEORIES

i) Harbours high-mass star formation

ii) Largest cloud of low- and intermediate-mass star formation within 500 pc

iii) Contains a wide range of environments, from rich clusters emerging from massive filaments to a more scattered population in low density regions

iv) Strongly interacting with a young OB association

FOCUS OF DEDICATED OBSERVATIONS:

★ Stellar content, spatial distribution, and SED (Megeath et al. 2012, 2016, Furlan et al. 2016, Groβschedl et al. 2019)

★ Spectroscopic data from APOGEE-2: kinematics and physical properties (stellar luminosities, masses, radii, ages) of the YSOs (Kounkel et al. 2018)

★ High-energy X-ray regime: Chandra Orion Ultra-deep Project (Getman et al 2005) and XMM-Newton.

★ Inventory of filament (e.g., Hacar et al. 2018, Suri et al. 2019), level of turbulence and feedback and presence of expanding shells (Feddersen et al. 2018, 2019)

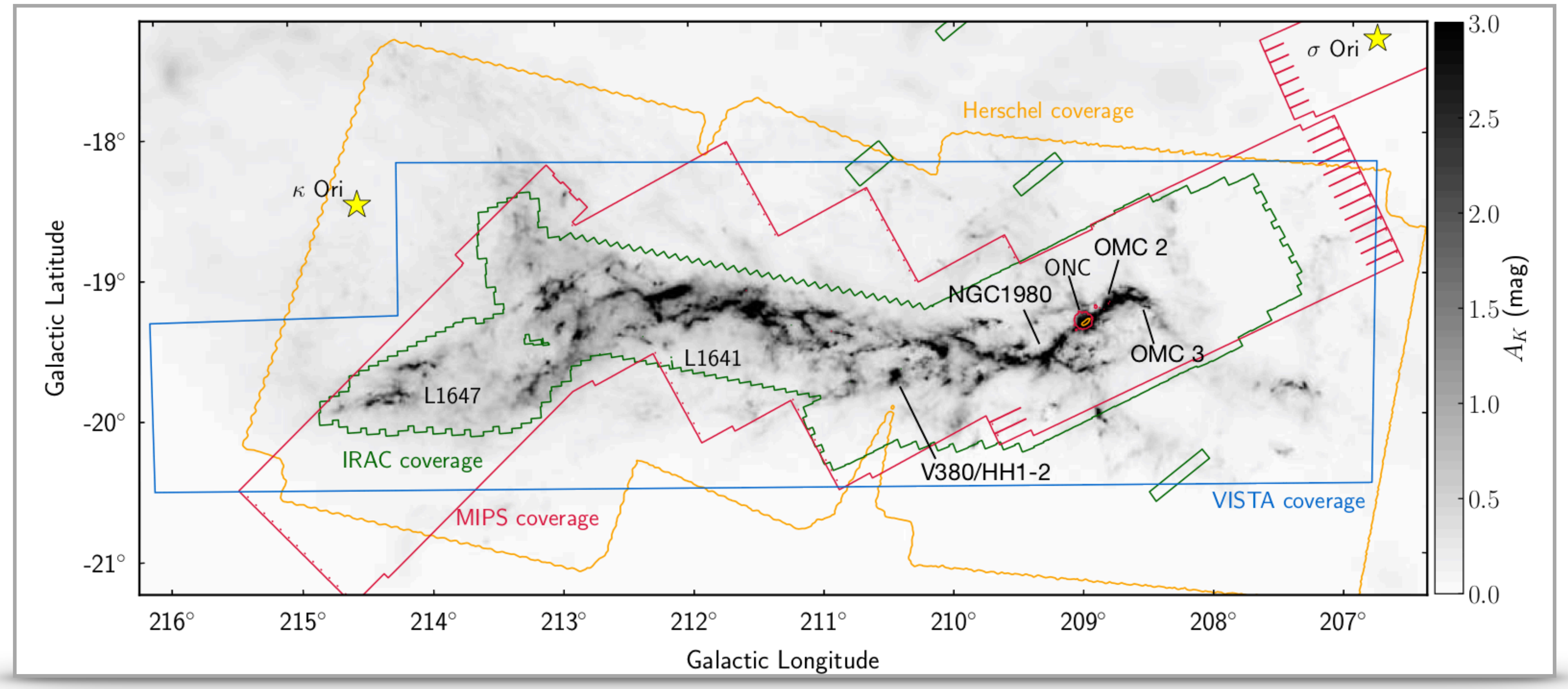


Figure from Groβschedl et al. (2019)

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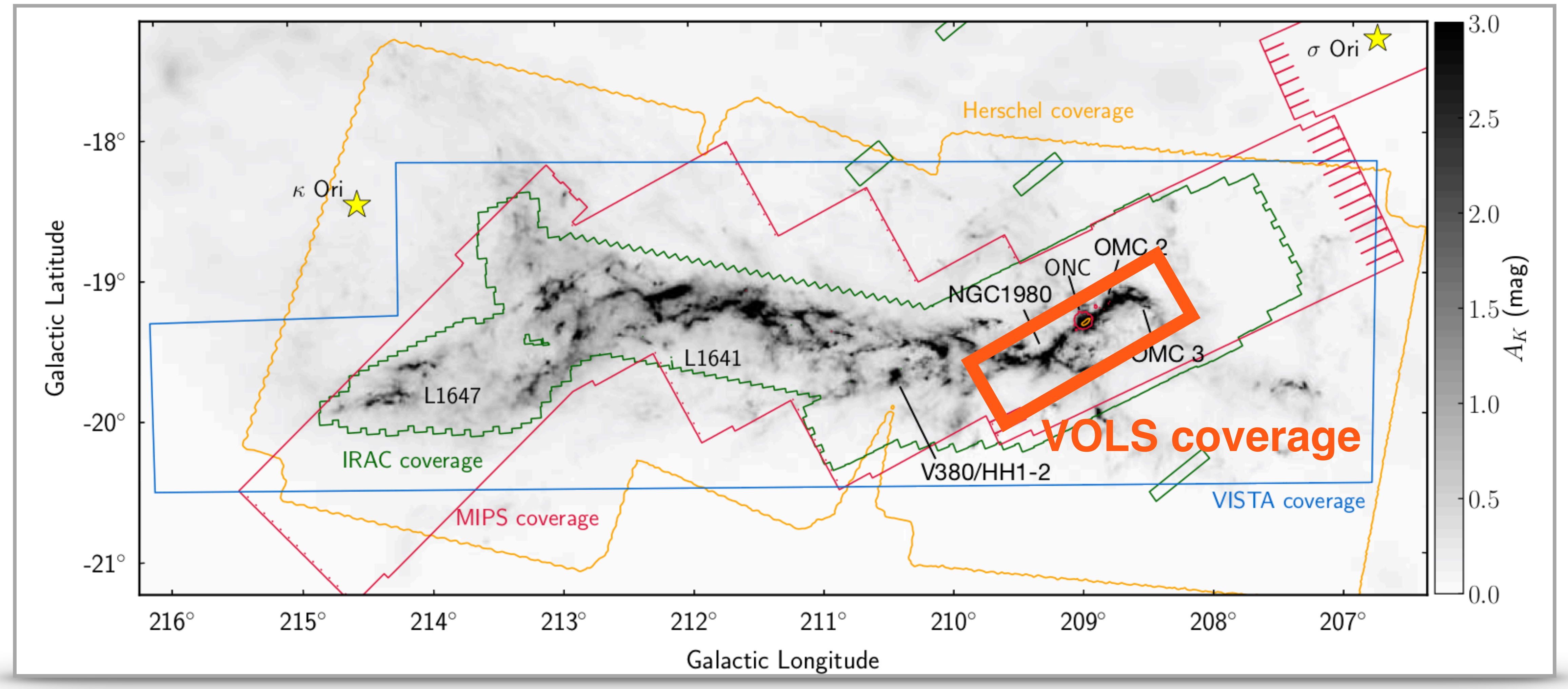

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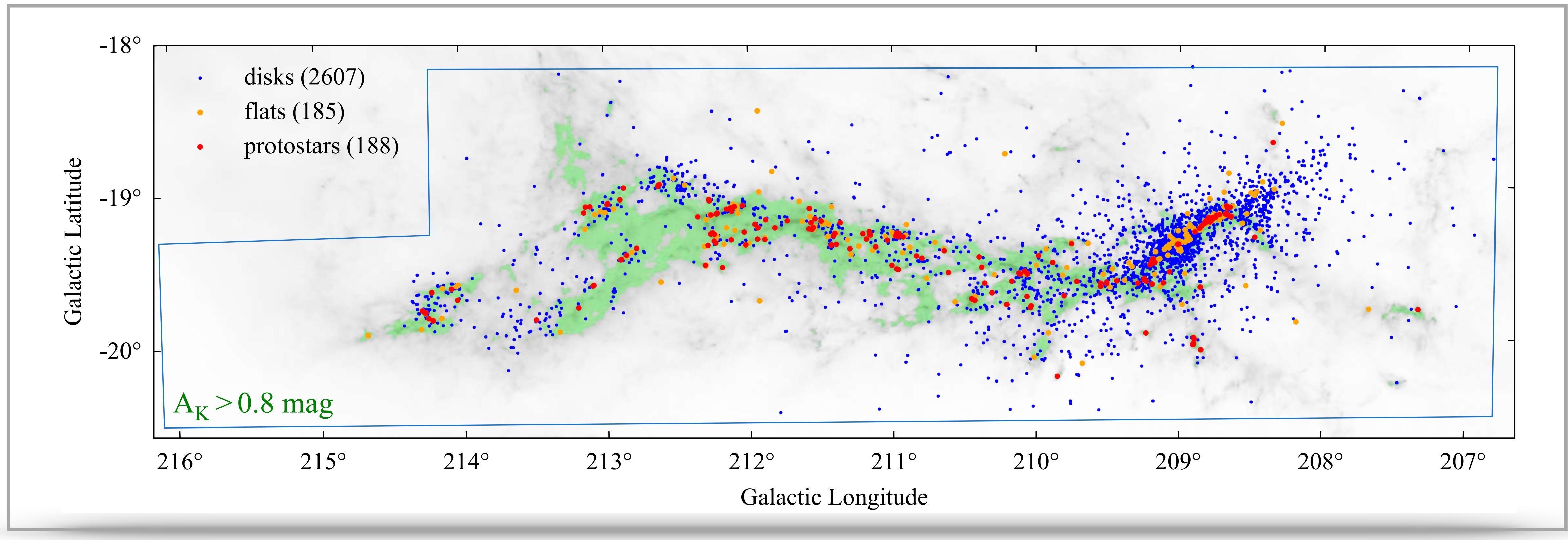

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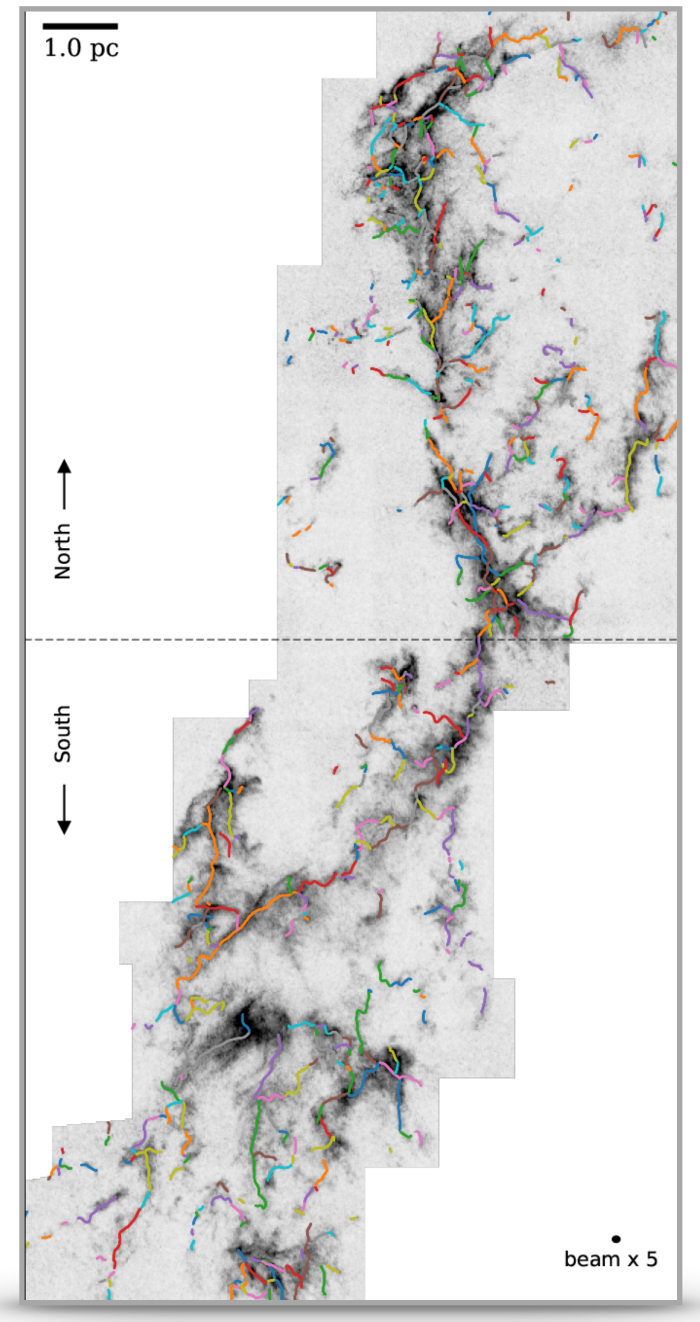


Figure from Suri et al. (2019)

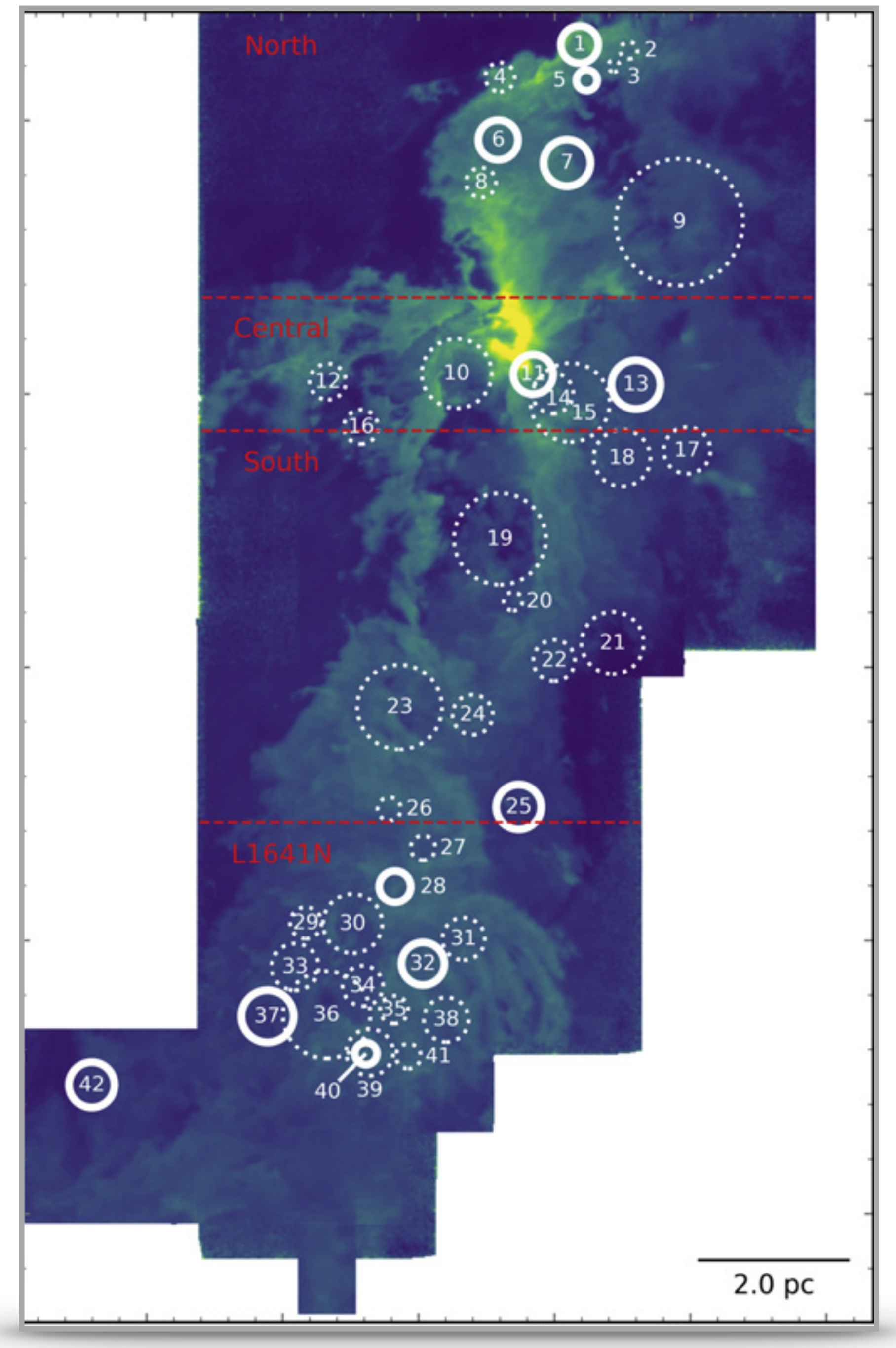


Figure from Feddersen al. (2018)

VOLS: STATUS OF THE OBSERVATIONS

83 hours of observing time at **C-band (~6 cm)** with the **A configuration completed** (April - July 2022)

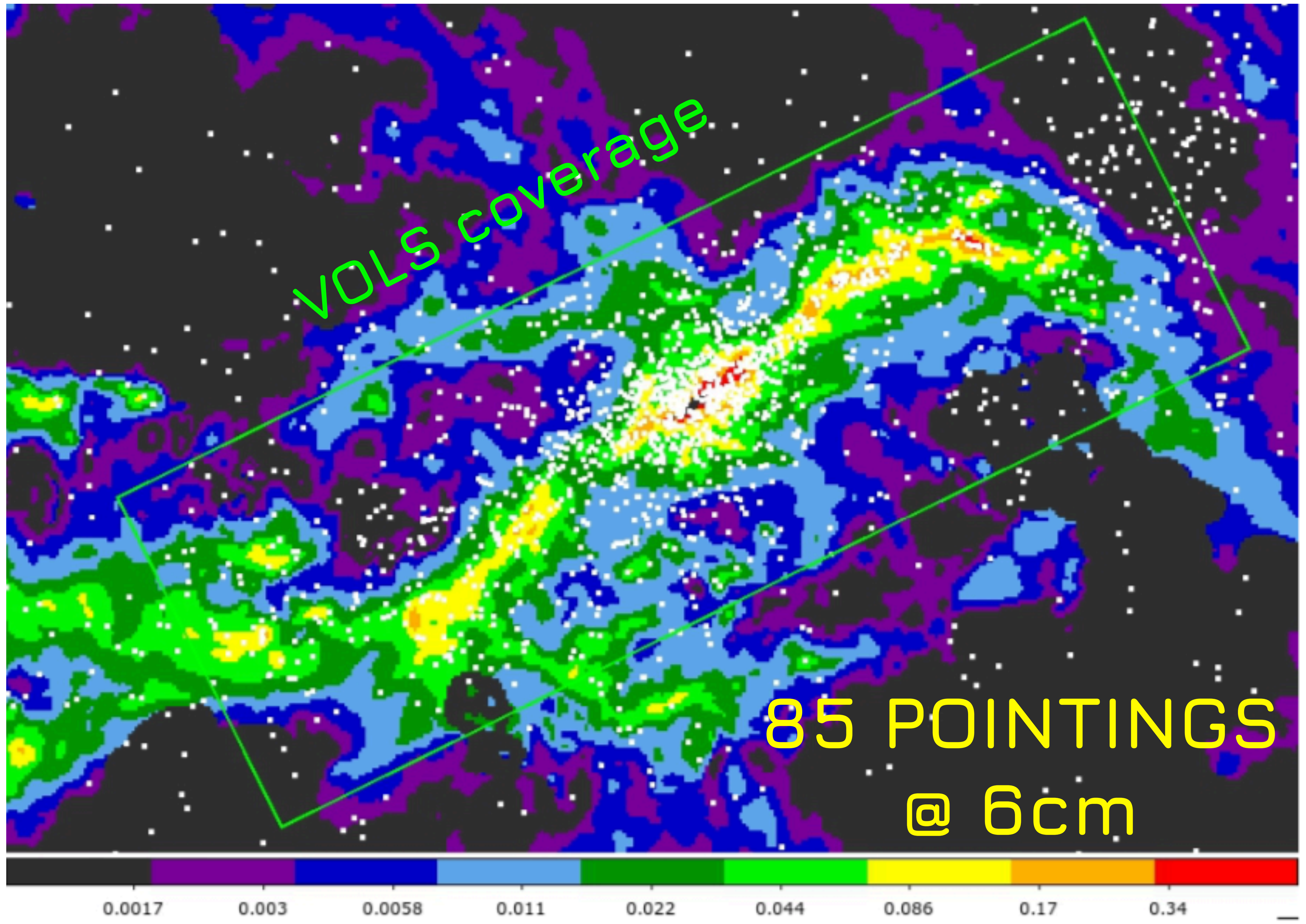
Full polarization, CH_3OH and OH masers, 10 Hydrogen RRL

Each pointing observed 2 times (~1.2 minutes) in a single scheduling block (of ~3 hours), rms~ 15-20 μJy/beam (final rms ~3 μJy/beam)

26 epochs: time variability from hours to months

Observations at **Ku-band (2 cm)** with the **B configuration** (**225 hours**) will be conducted during January-May 2023 and May-September 2024

Includes: CH_3OH and OH masers + 8 Hydrogen RRL + HC_5N + SO



Summary of the known YSOs covered by VOLS

(# known objects/ # radio counterparts)

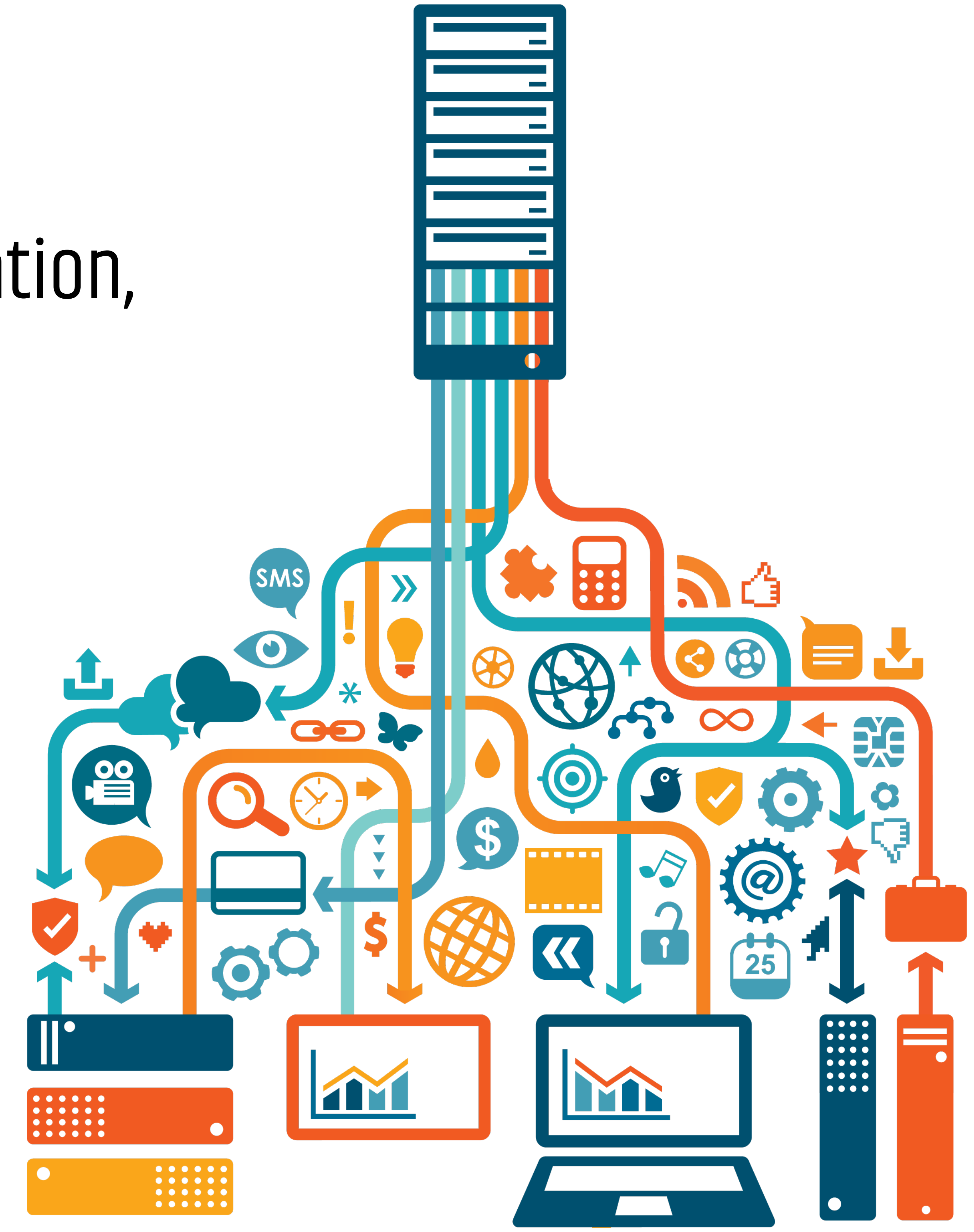
SURVEY	VOLS (0.5 deg²)
INFRARED (VISION, Spitzer)	1640 / 145 (~9%)
HOPS (Herschel)	75 / 5 (~7%)
VANDAM (ALMA, VLA)	108
GAIA	1311*

* Number of Gaia sources (EDR3) with a counterpart in the VISION catalog

VOLS: FIRST IMAGES

☆VOLS data reduction pipeline already developed by VOLS members (Girart, Tobin, Rosero, Carrasco-González, Passetto): includes gain compression correction, polarization, line emission, and self-calibration

☆Each image: 24.000 x 57.600 pixels ~ **1.38×10^9 pixels!**



1 SB of 3 hours →

- ☆ 0.5 TB of raw data
- ☆ Continuum image: 24 GB
- ☆ Line image: 77 GB

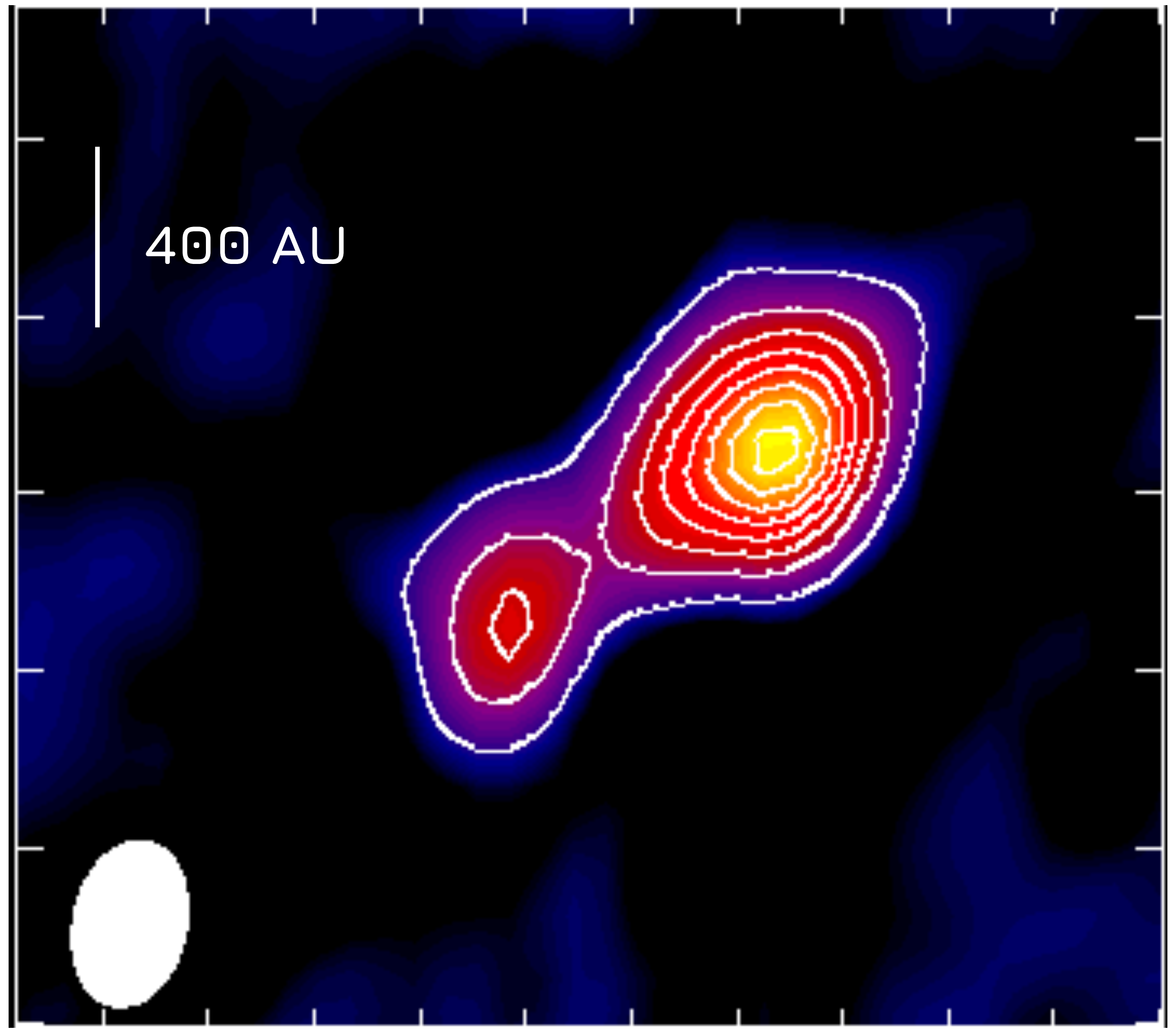
~3 TB of images for C-band only

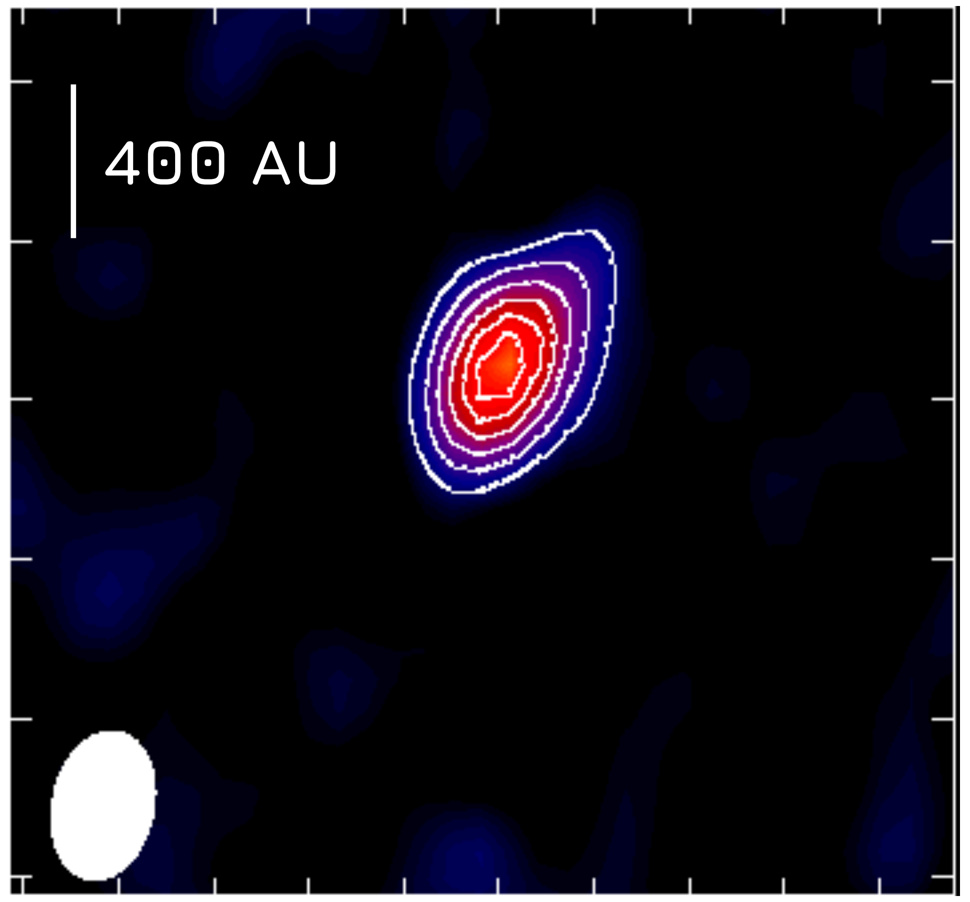
31 TB of raw data

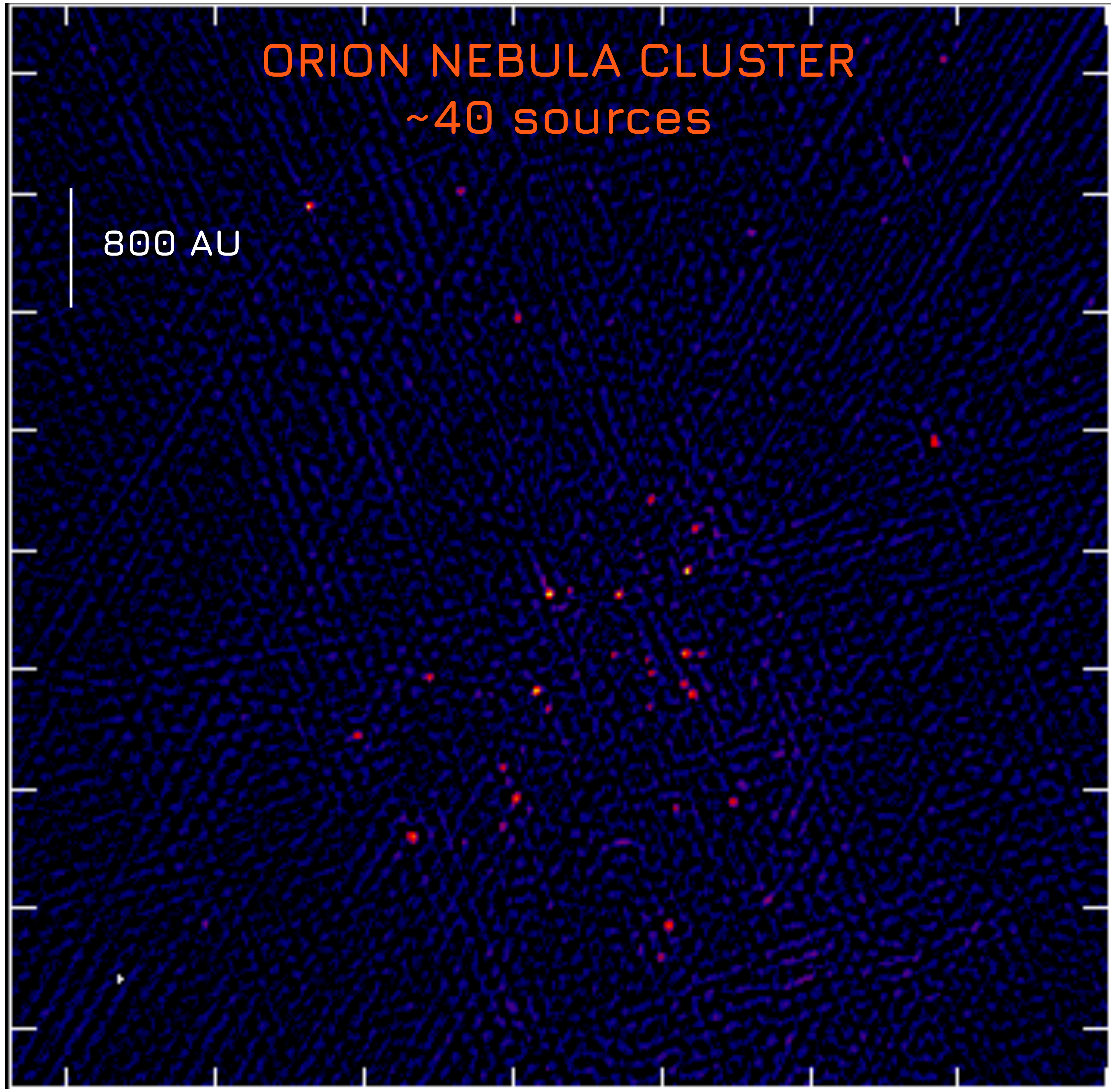
Disk space and CPU are key factors:

Calibration and imaging will require 4 x 31 TB

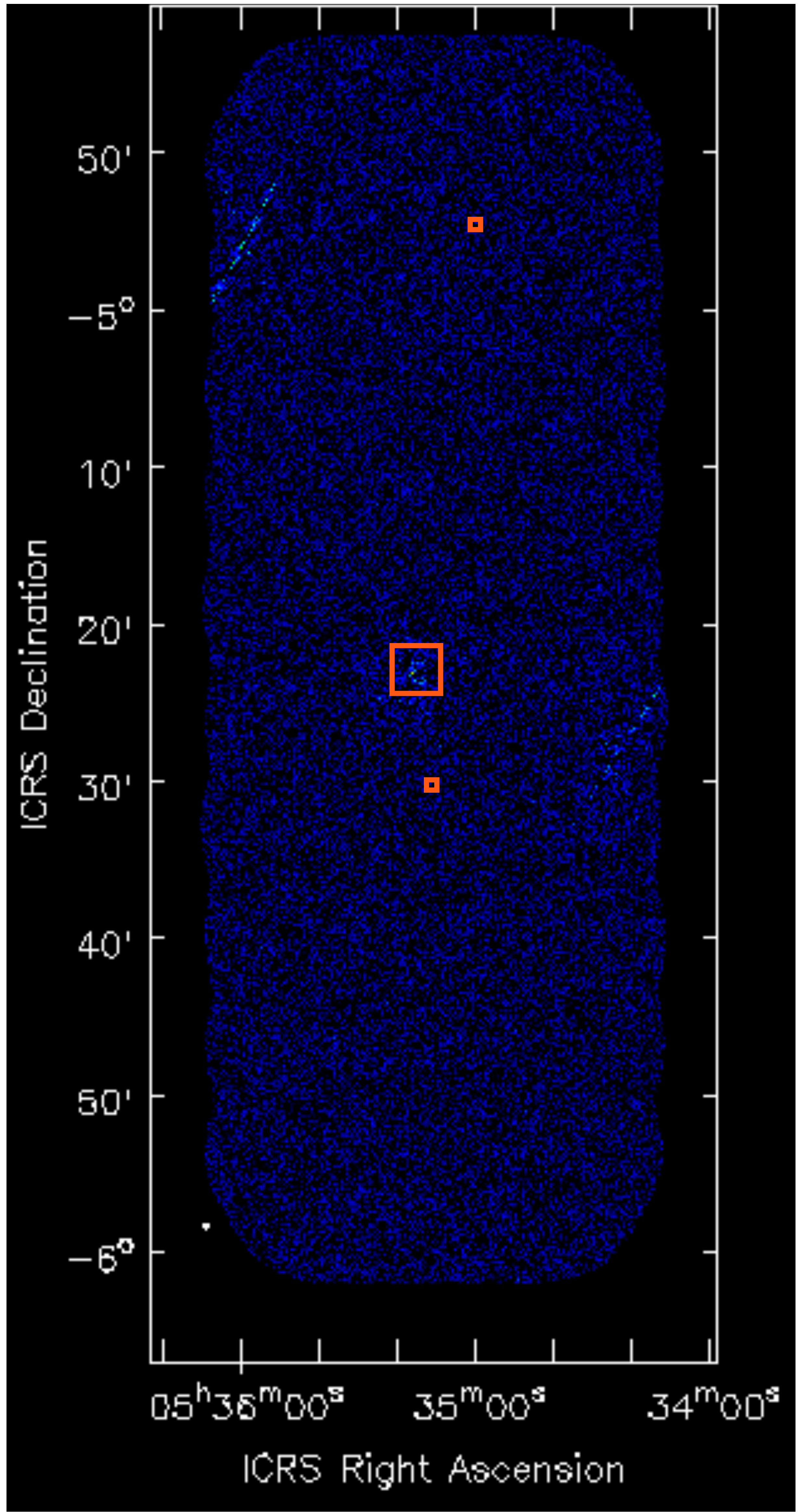
VOLS: FIRST IMAGES







C-band
Observed on 01/05/2022



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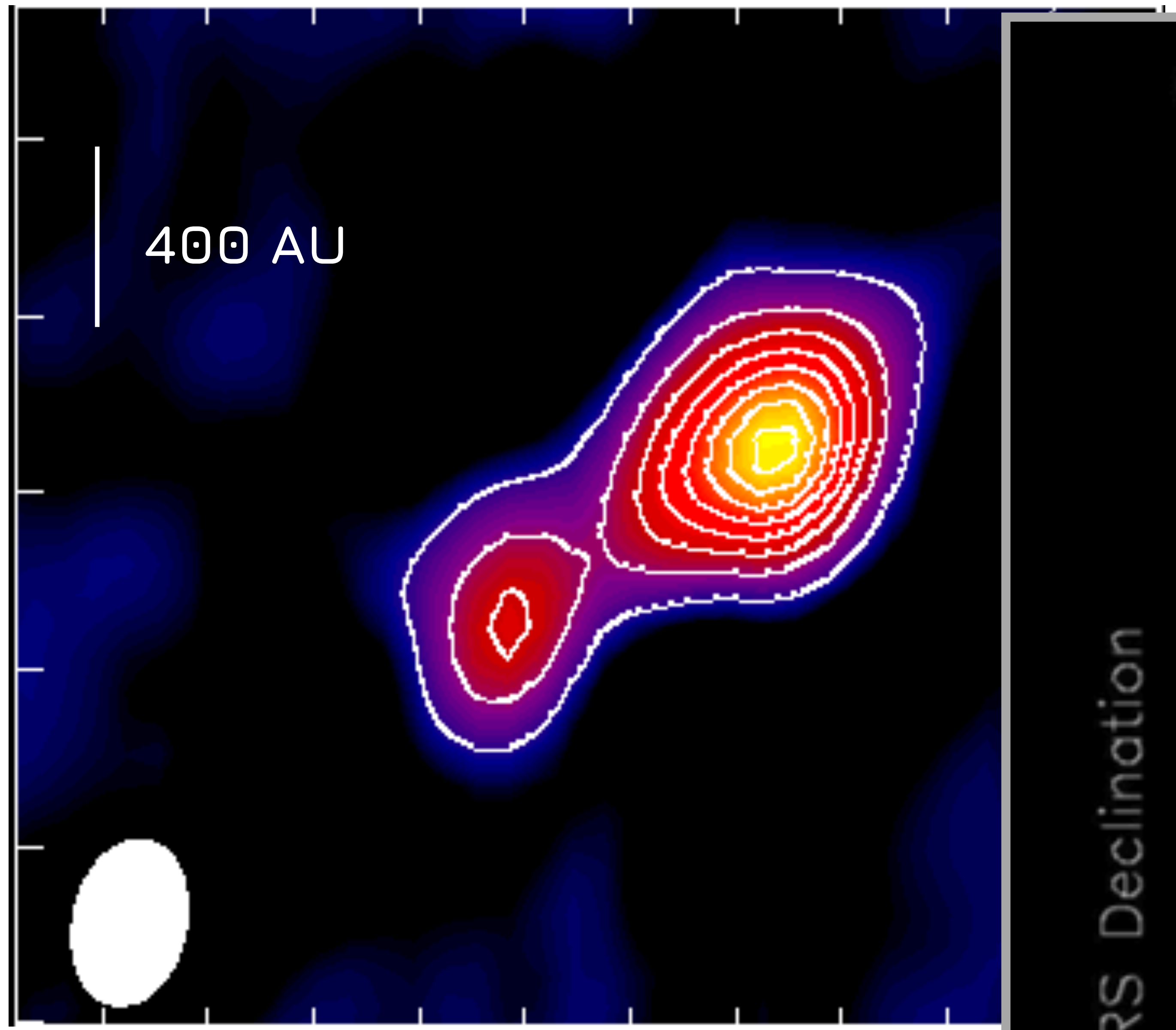
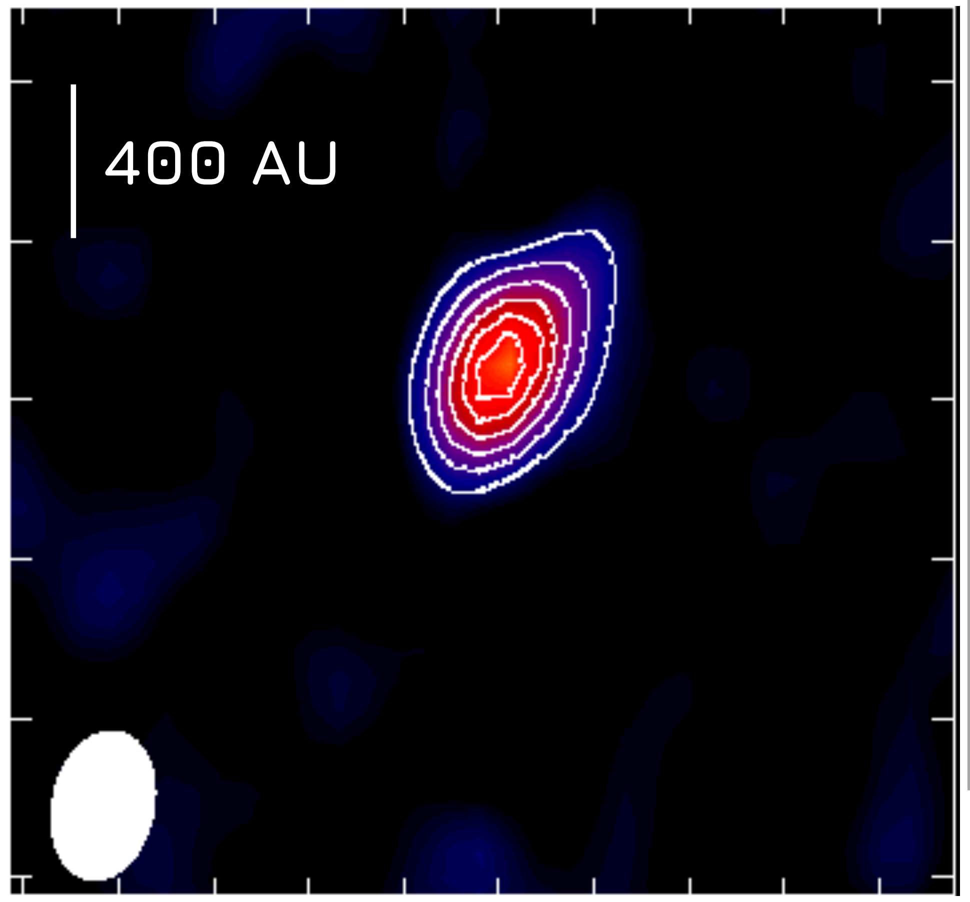
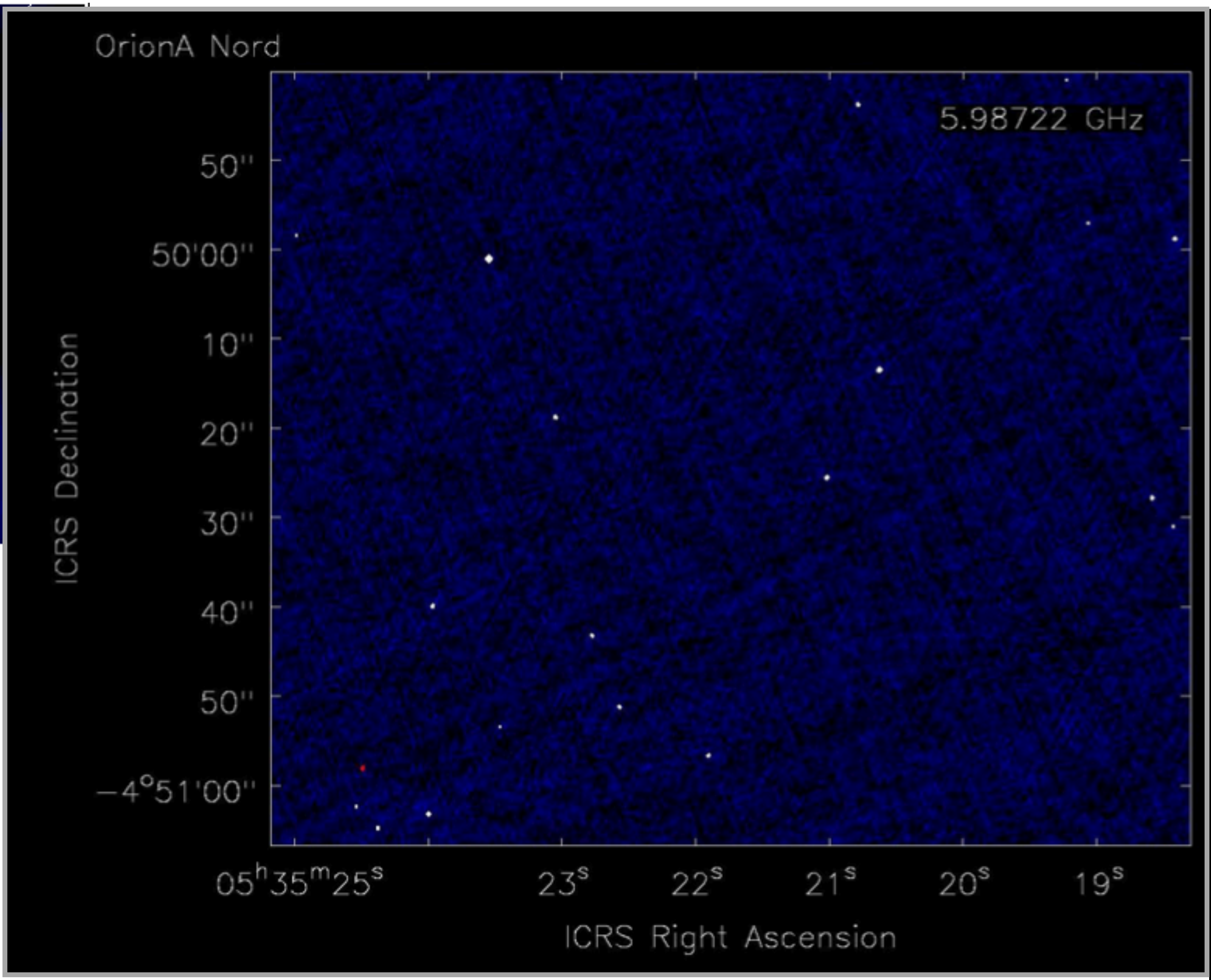
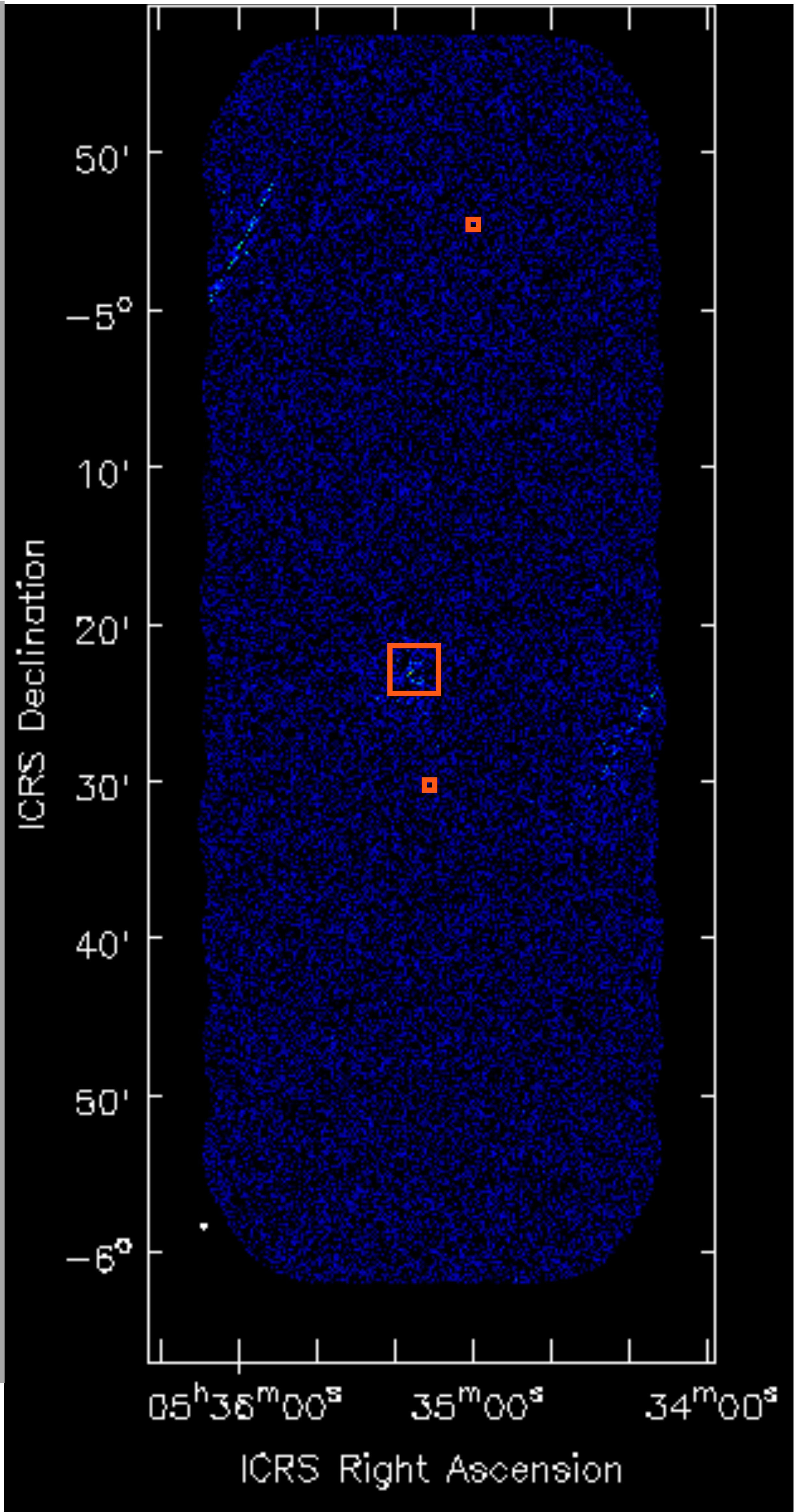
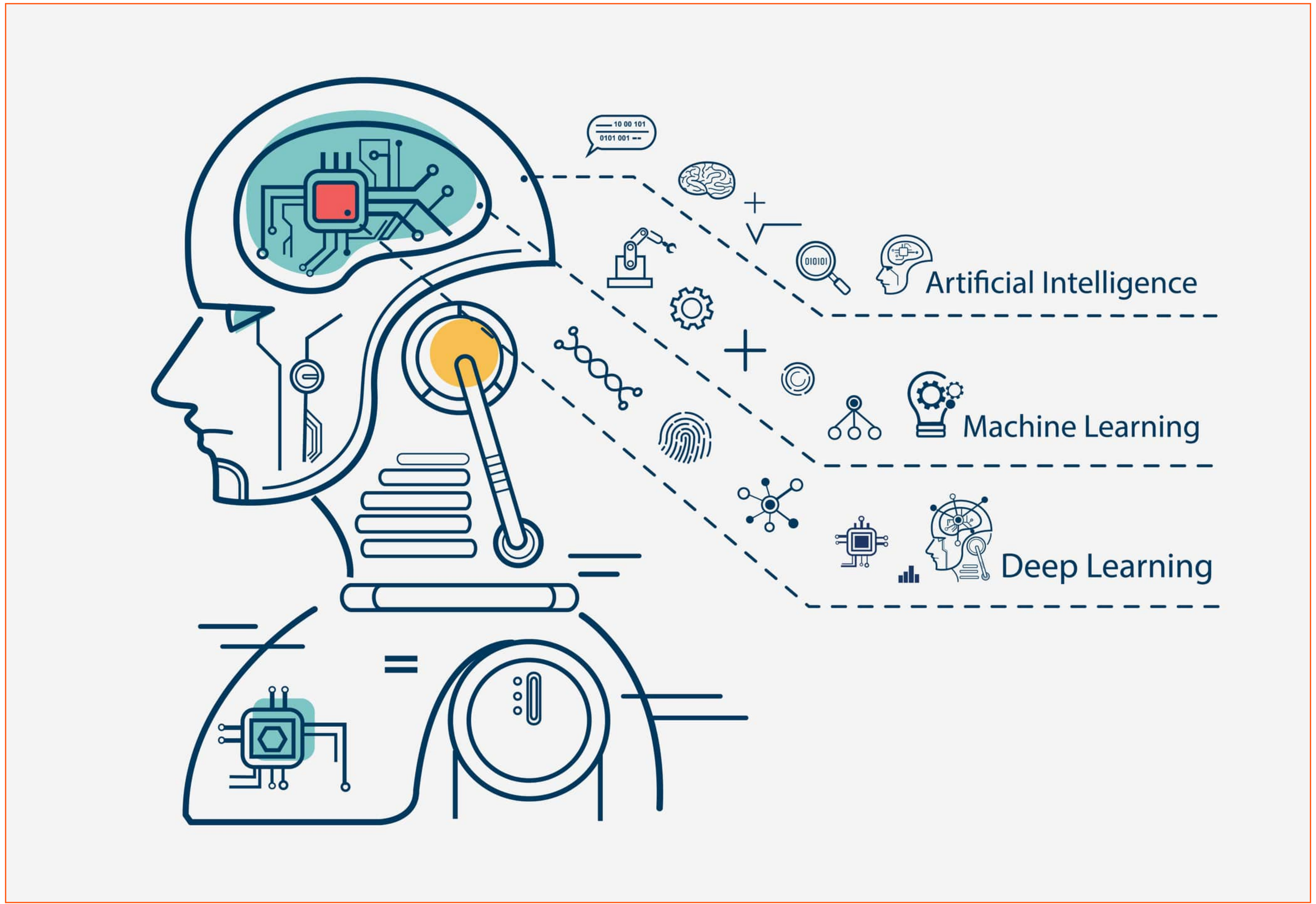








MACHINE LEARNING IMPLEMENTATION



- ☆Source detection and classification
- ☆ Cross-correlation at other wavelengths
- ☆ Radio template for future radio facilities (SKA, ngVLA)

Proyecto realizado con la Beca Leonardo a Investigadores en Física 2022 de la Fundación BBVA

Fundación BBVA