A MULTI-SCALE AND MULTI-WAVELENGTH VIEW OF THE STAR FORMATION PROCESS

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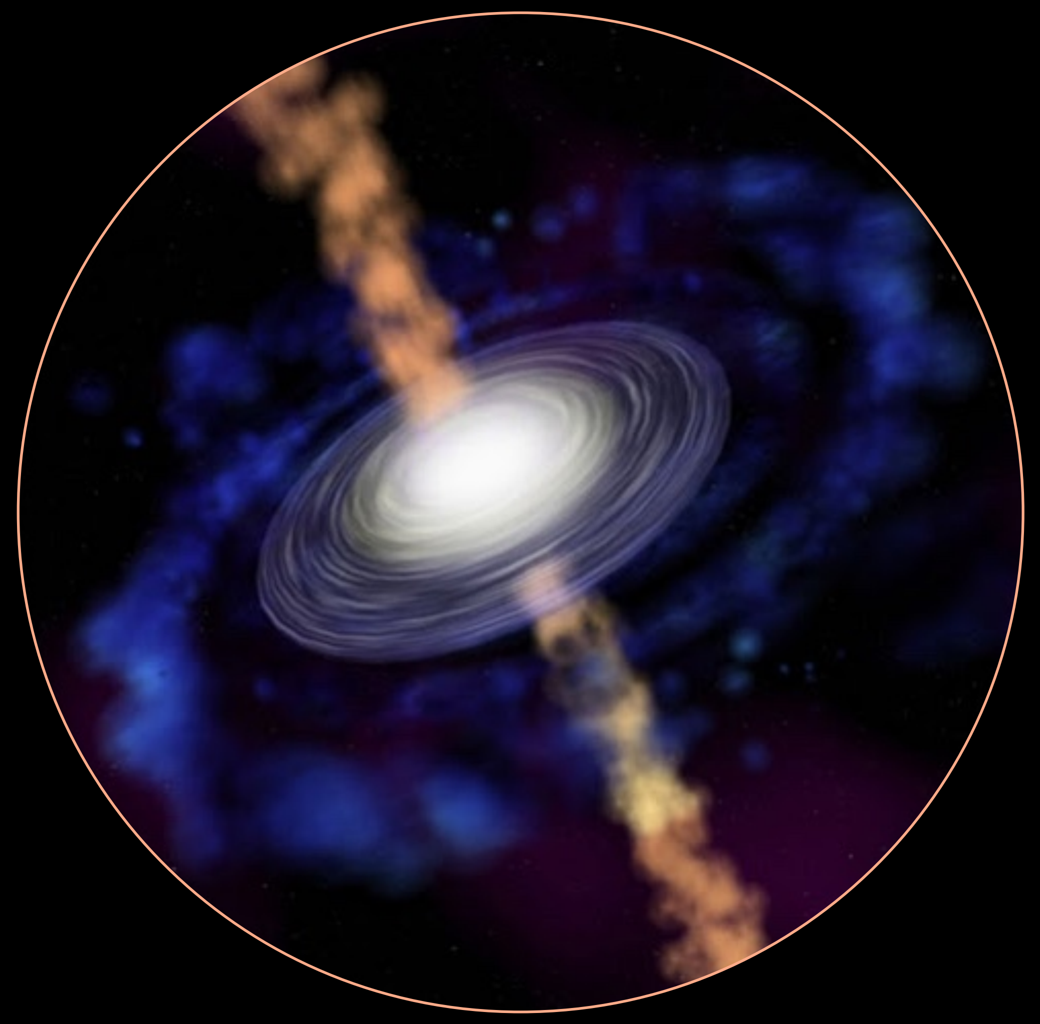
(Office: 720)



ICCUB Winter meeting

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Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA

THE GROUP

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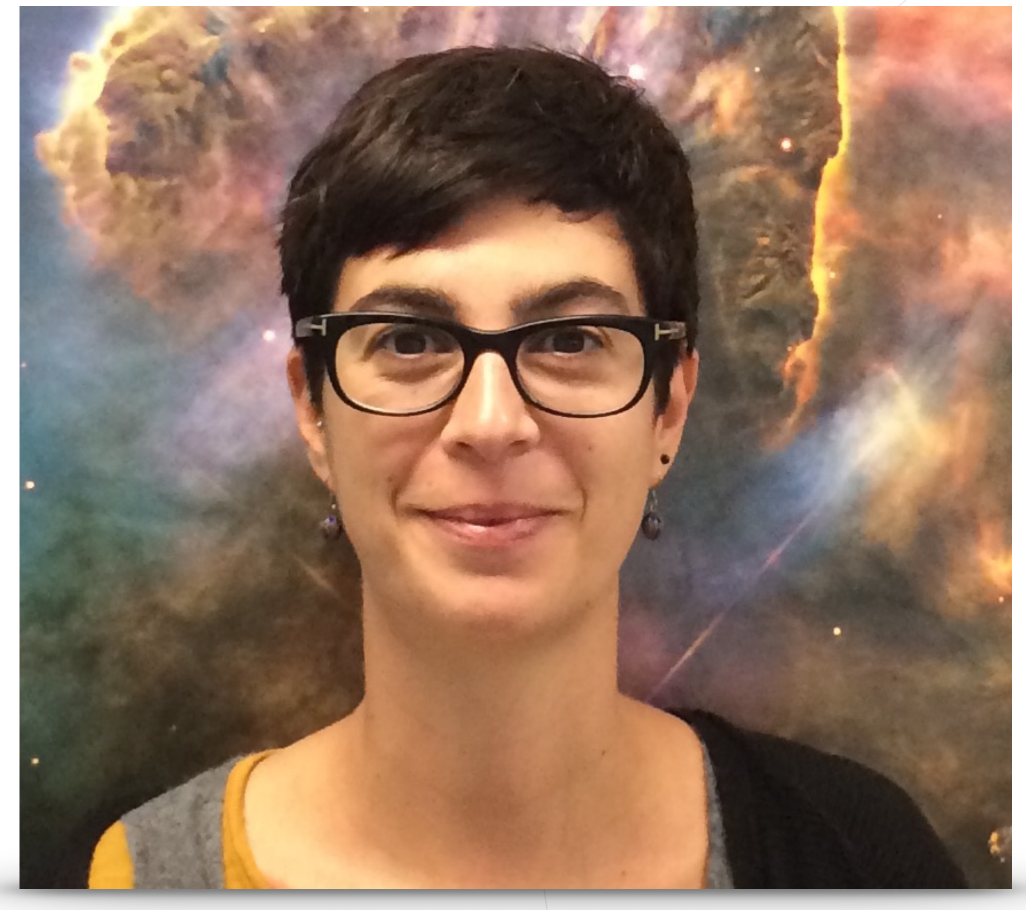
Paolo Padoan



Gemma Busquet

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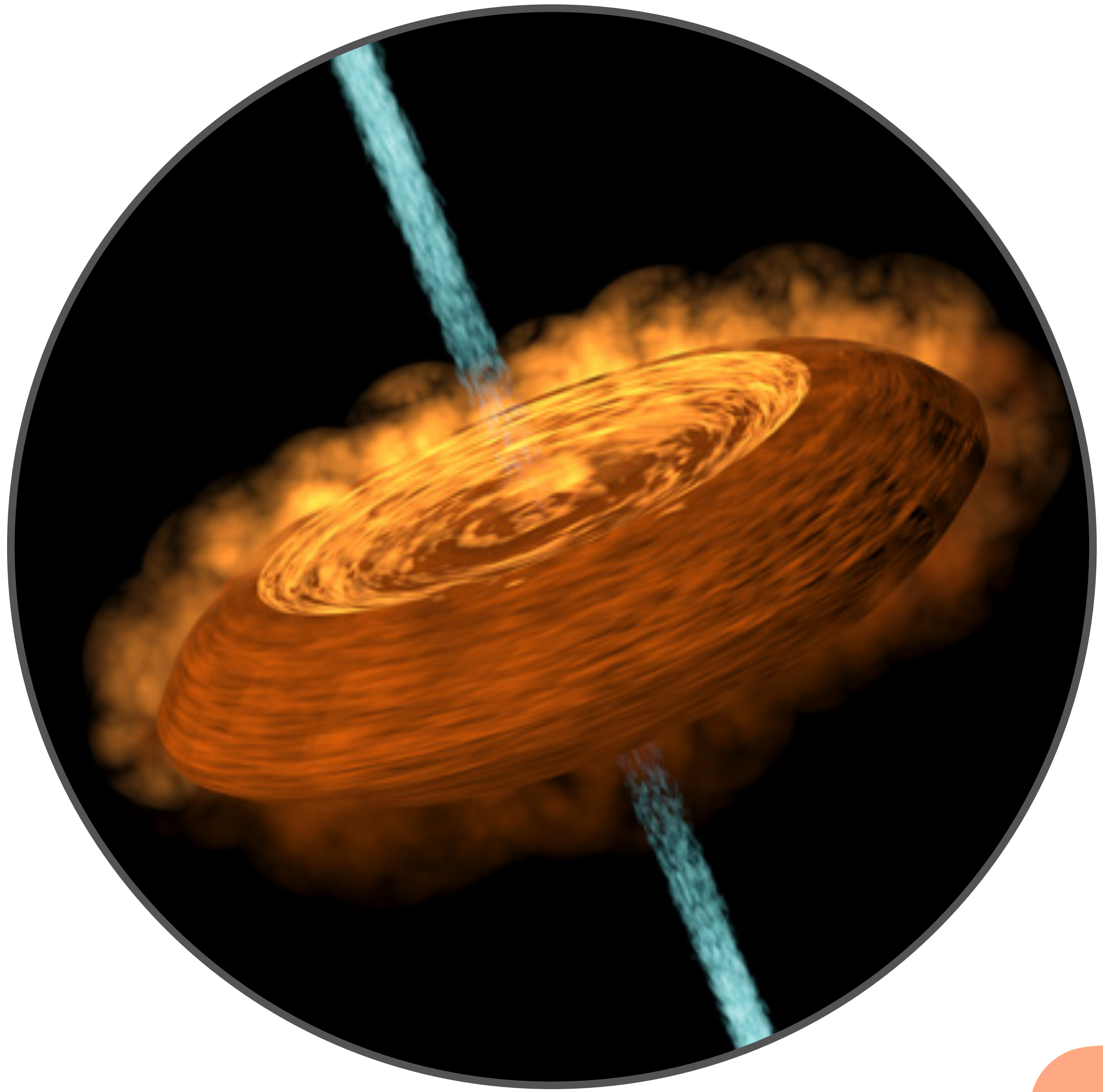
Veli-Matti Pelkonen

ZuJia Lu

OUTLINE



SCIENTIFIC CONTEXT

- THE STAR FORMATION CYCLE
- RADIO EMISSION FROM YSOs
- HIGH-MASS STARS AND STELLAR CLUSTERS
- OPEN QUESTIONS

CURRENT WORK

FUTURE PROJECTS

THE STAR FORMATION CICLE

- **GMC:** 10^5-10^6 $M_\odot$, T~10 K, $n(H_2)$~10^2 cm^{-3}
- **Pre-stellar cores** [0.01-0.1 pc] onset of future star formation
- **Protostar** (0.1-1 $M_\odot$) **+ disk system:** powerful jets + a natal disk (0.01-0.1 $M_\odot$) + large scale envelope [0.1 pc in size]
- **Protoplanetary disk:** envelope is dissipated. A young star (or stars) and a disk (1-10% $M_\star$) remain
- **Main sequence phase:** cessation of accretion on the star and dispersal of the molecular gas

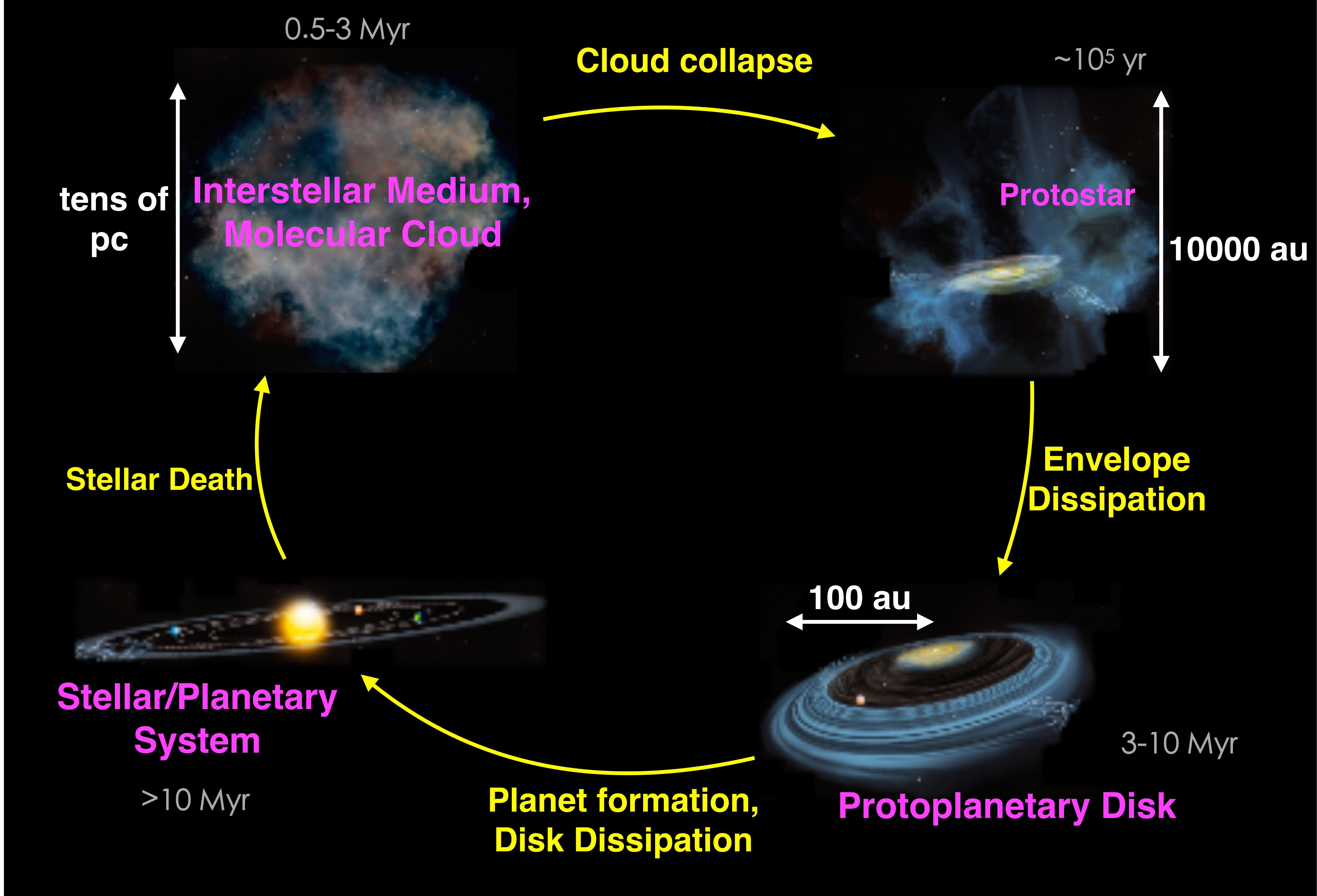
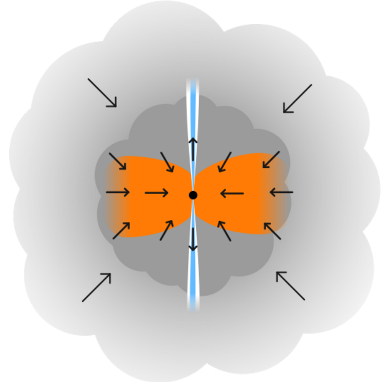
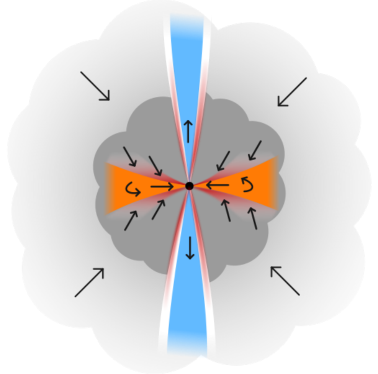
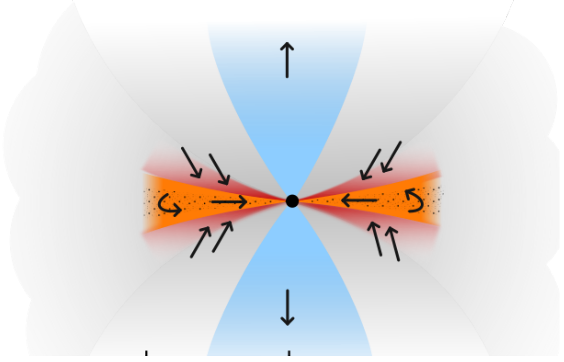
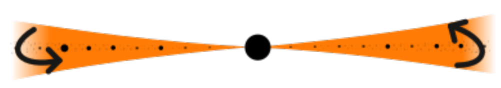
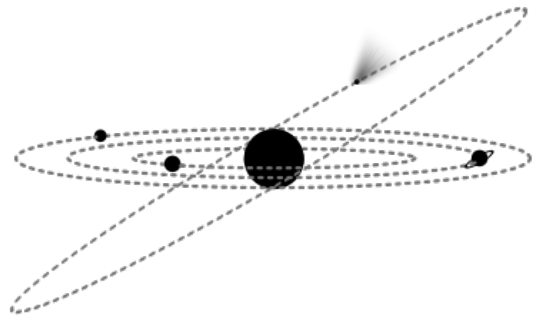
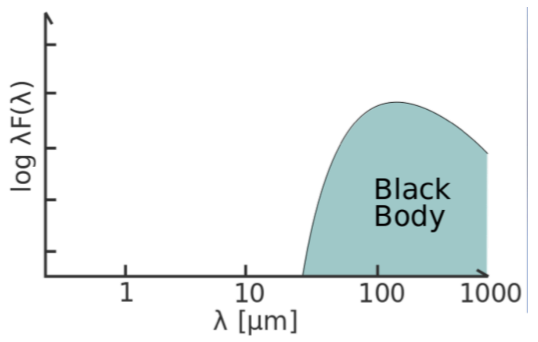
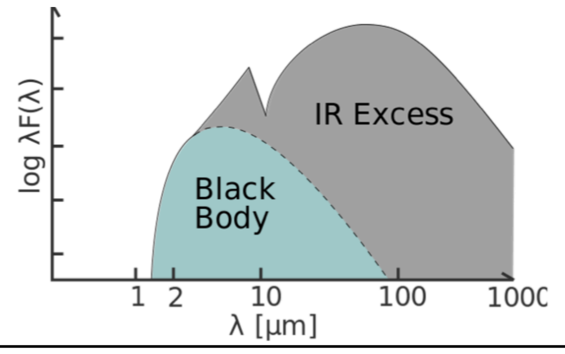
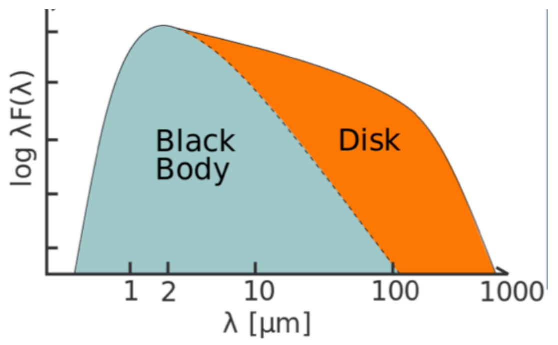
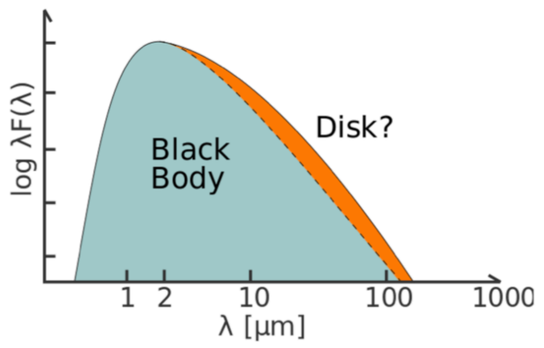


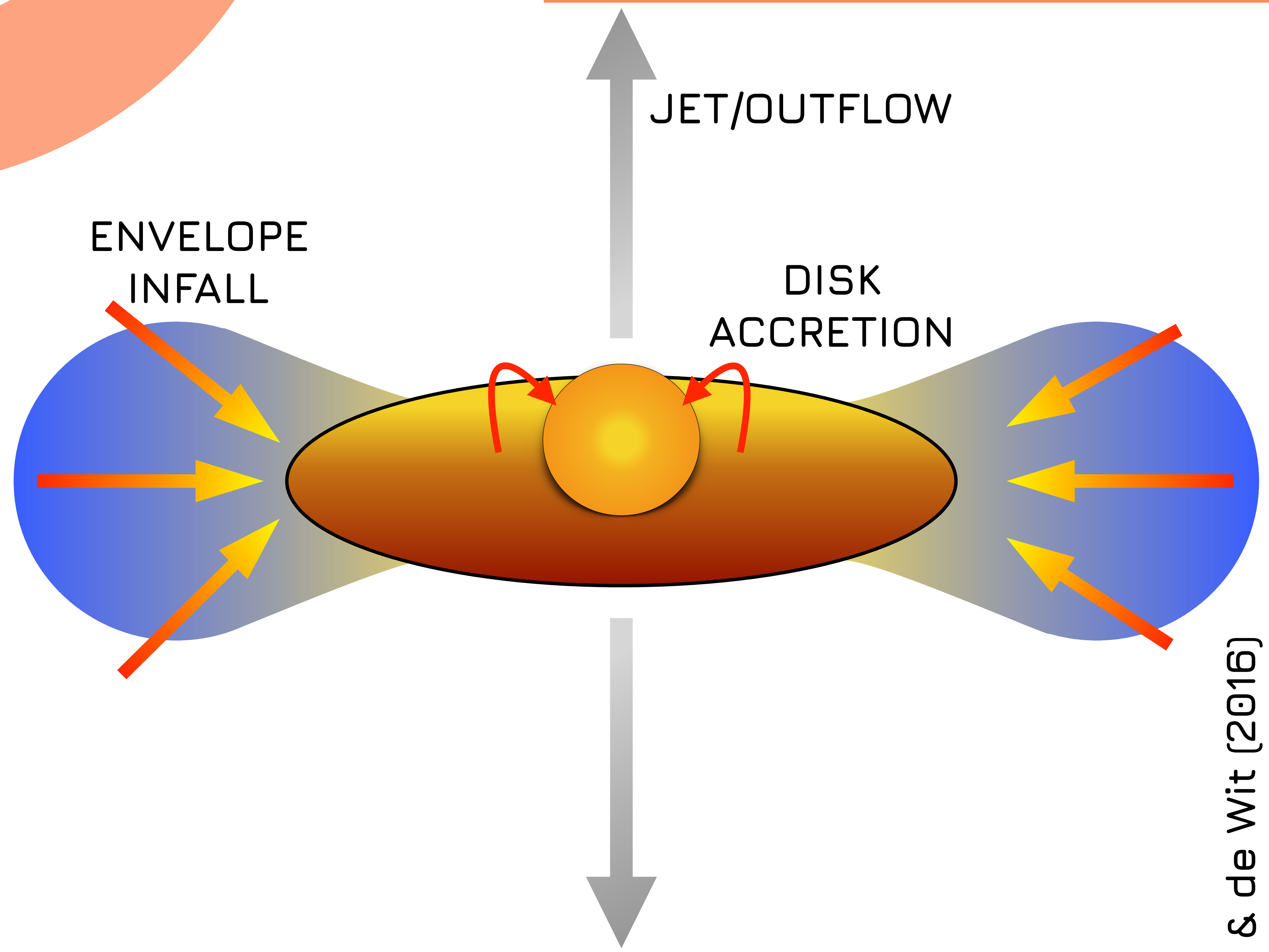
Image Credit: L. I. Cleeves, PhD Thesis (adapted from Bill Paxton (NSF/AUI/NRAO))

RADIO EMISSION FROM YSOs

PROPERETIES	Infalling protostar	Evolved protostar	Classical T Tauri star	Weak T Tauri star	Main sequence star
SKETCH					
AGE (YEARS)	10^4	10^5	10^6-10^7	10^6-10^7	$>10^7$
MM/INFRARED CLASS	Class 0	Class I	Class II	Class III	(Class III)
DISK	Yes	Thick	Thick	Thin or non-existent	Planetary System
THERMAL RADIO	Yes	Yes	Yes	No?	No
NON-THERMAL RADIO	No?	Yes	No?	Yes	Yes
SED					

Adapted from Feigelson & Montmerle (1999)

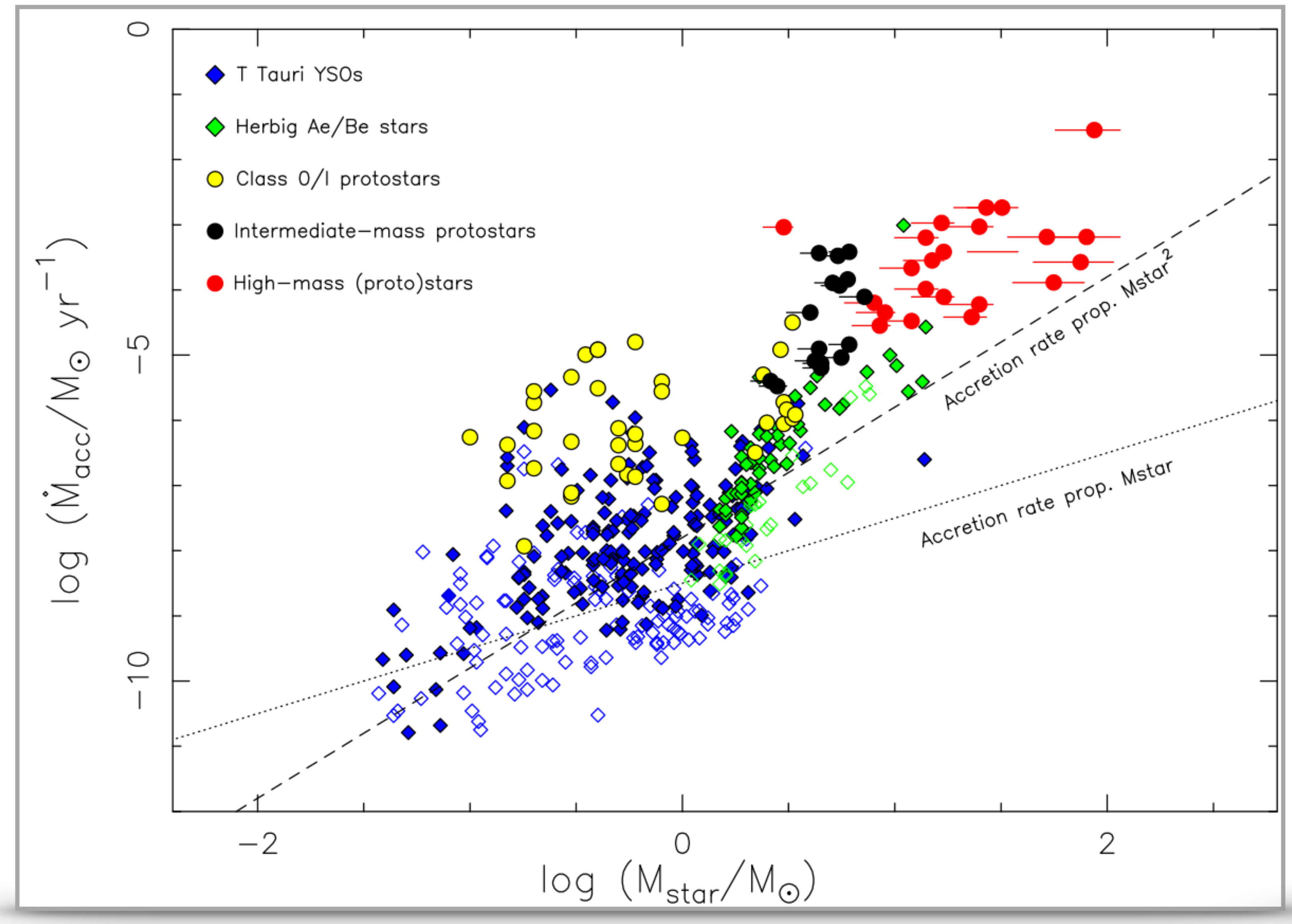
THE $\dot{M}_{ACC}$ - $\dot{M}_{LOSS}$ CONNECTION



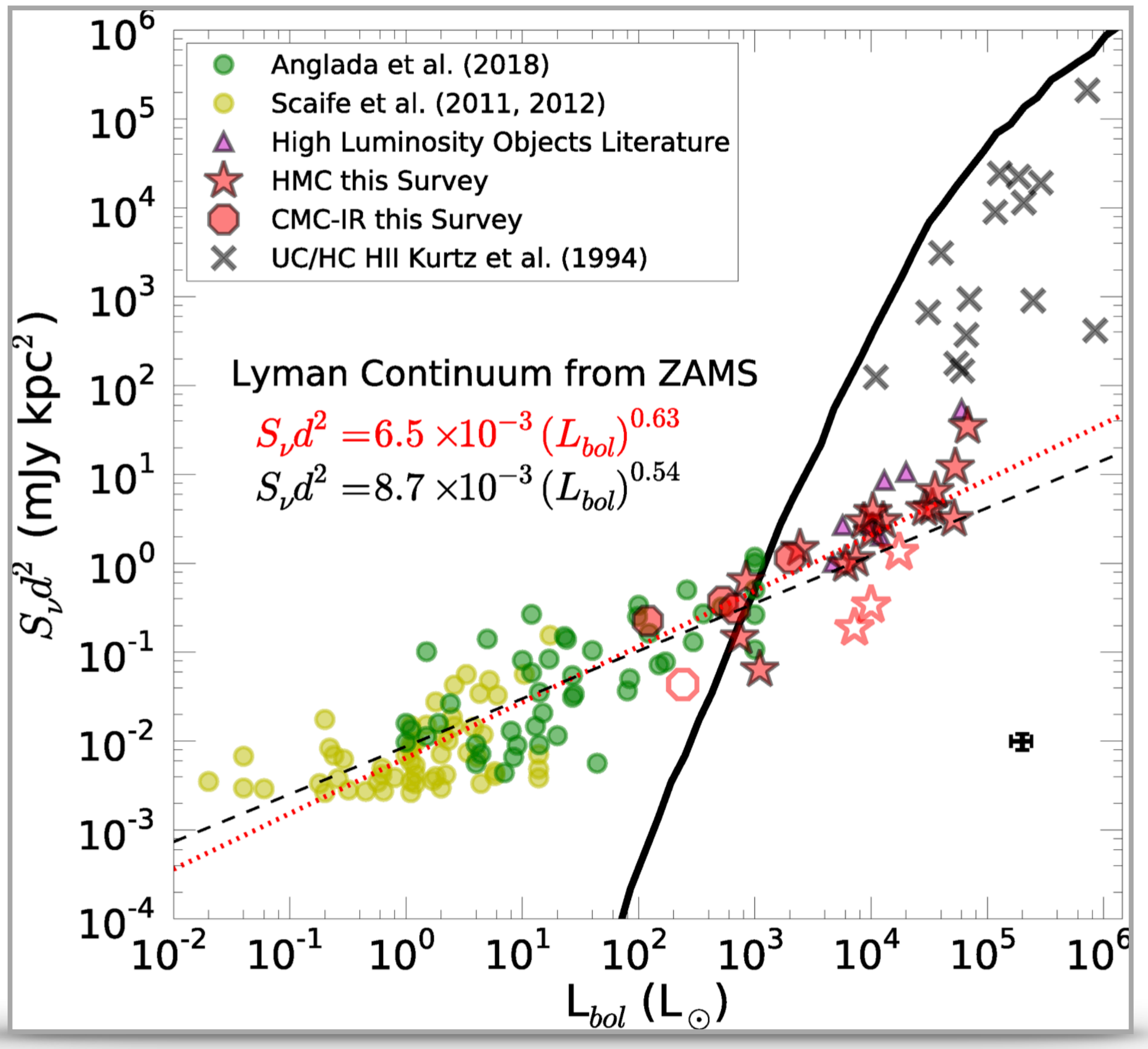
★ **Infall** onto the star-disk system from the parental envelope

★ **Accretion** from the disk on the star

★ Highly collimated **jets** with high velocities (~100 - 1000 km/s): remove angular momentum



Beltrán & de Wit (2016)



Rosero et al. (2019)

- **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)

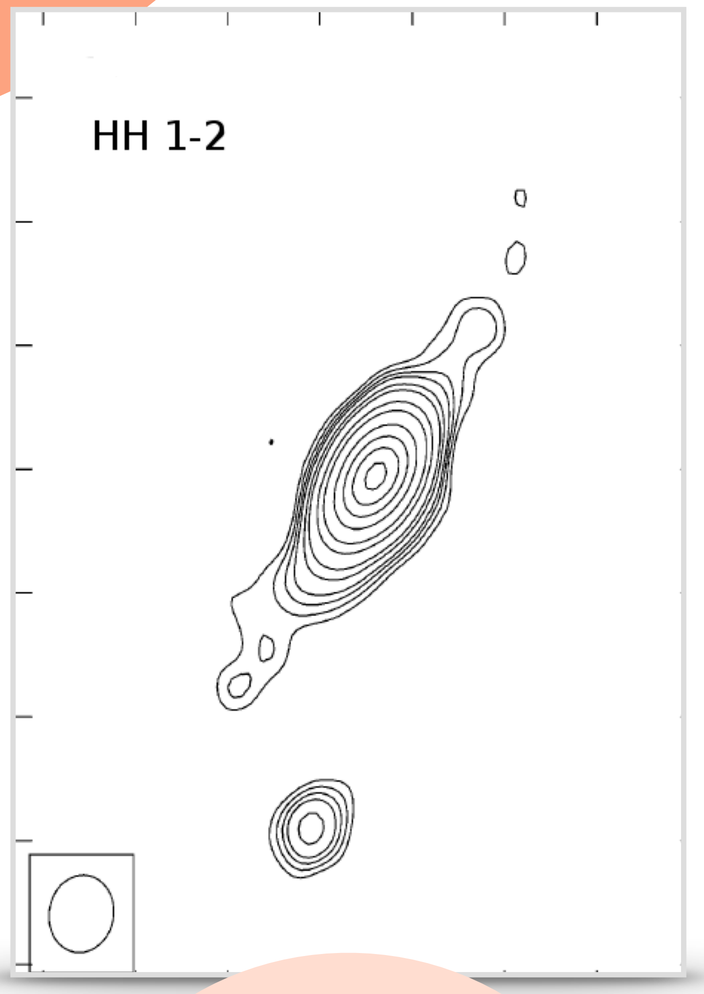
RADIO CONTINUUM OBSERVATIONS: POWERFUL TOOL TO INVESTIGATE THE CONNECTION BETWEEN EJECTION (TRACED BY THE RADIO LUMINOSITY) AND ACCRETION (TRACED BY L_{BOL})

JETS AND HIGH-VELOCITY SHOCKS

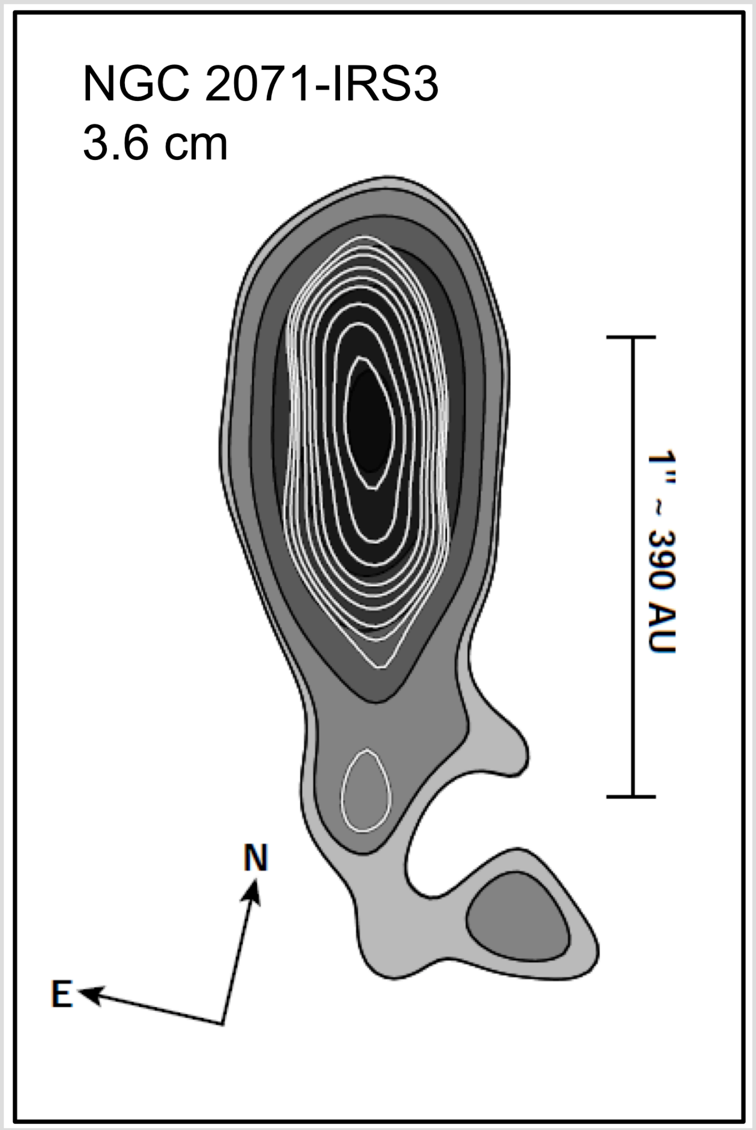
Angularly Resolved Radio Jets in YSOs

Anglada, Rodríguez, Carrasco-González (2018)

Rodríguez et al. (2000)



Source	L_{bol} ($L_\odot$)	$M_\star$ ($M_\odot$)	d (kpc)	S_ν (mJy)	α	θ_0 (deg)	Size (au)	v_j (km s^{-1})	t_{dyn} (yr)	ϵ	$\dot{M}_{ion}$ ($M_\odot$ yr^{-1})	r_0 (au)	Refs.
HH 1-2 VLA1	20	~1	0.4	1	0.3	19	200	270	2	0.7	1×10^{-8}	≤11	1, 2, 3, 4
NGC 2071-IRS3	~500	4	0.4	3	0.6	40	200	400[a]	1	1.0	2×10^{-7}	≤18	5, 6, 2, 7
Cep A HW2	1×10^4	15	0.7	10	0.7	14	400	460	2	0.9	5×10^{-7}	≤60	8, 9, 10, 11, 12
HH 80-81	2×10^4	15	1.7	5	0.2	34	1500	1000	4	0.6	1×10^{-6}	≤25	13, 14, 15, 16, 17, 18
IRAS 16547-4247	6×10^4	20	2.9	11	0.5	25	3000	900[a]	8	0.9	8×10^{-6}	≤310	19, 20, 21, 22
Serpens	300	3	0.42	2.8	0.2	<34	280	300	2	0.6	3×10^{-8}	≤9	23, 24, 25, 26, 27
AB Aur	38	2.4	0.14	0.14	1.1	<39	24	300[a]	0.2	3.5	2×10^{-8}	≤3	28, 29, 30
L1551 IRS5[b]	20	0.6	0.14	0.8	0.1	36	39	150[a]	0.6	0.6	1×10^{-9}	≤1	31, 32, 33
HH 111[c]	25	1.3	0.4	0.8	~1	<79	110	400	0.7	2.3	2×10^{-7}	≤12	34, 35, 36, 37, 38
HL Tau	7	1.3	0.14	0.3	~0.3	69	27	230[a]	0.3	0.7	2×10^{-9}	~1.5	39, 40, 41
IC 348-SMM2E	0.1	0.03	0.24	0.02	~0.4	45[d]	<100	~50[a]	<2	0.8	2×10^{-10}	≤1	42, 43, 44
W75N VLA3	750	6[d]	2.0	4.0	0.6	37	420	220	4.6	1.0	6×10^{-7}	≤70	45, 46
OMC2 VLA11	360	4[d]	0.42	2.2	0.3	10	200	100	4.6	1.0	6×10^{-7}	≤70	2, 47, 48
Re50N	250	4[d]	0.42	1.1	0.7	33	450	400	2.7	1.2	8×10^{-8}	≤13	2, 49, 50



Carrasco-González et al. (2012)

Thermal radio emission

For a conical jet:

★ Injection opening angle: $\theta_0 = 2\,arctan(\theta_{min}/\theta_{maj})$

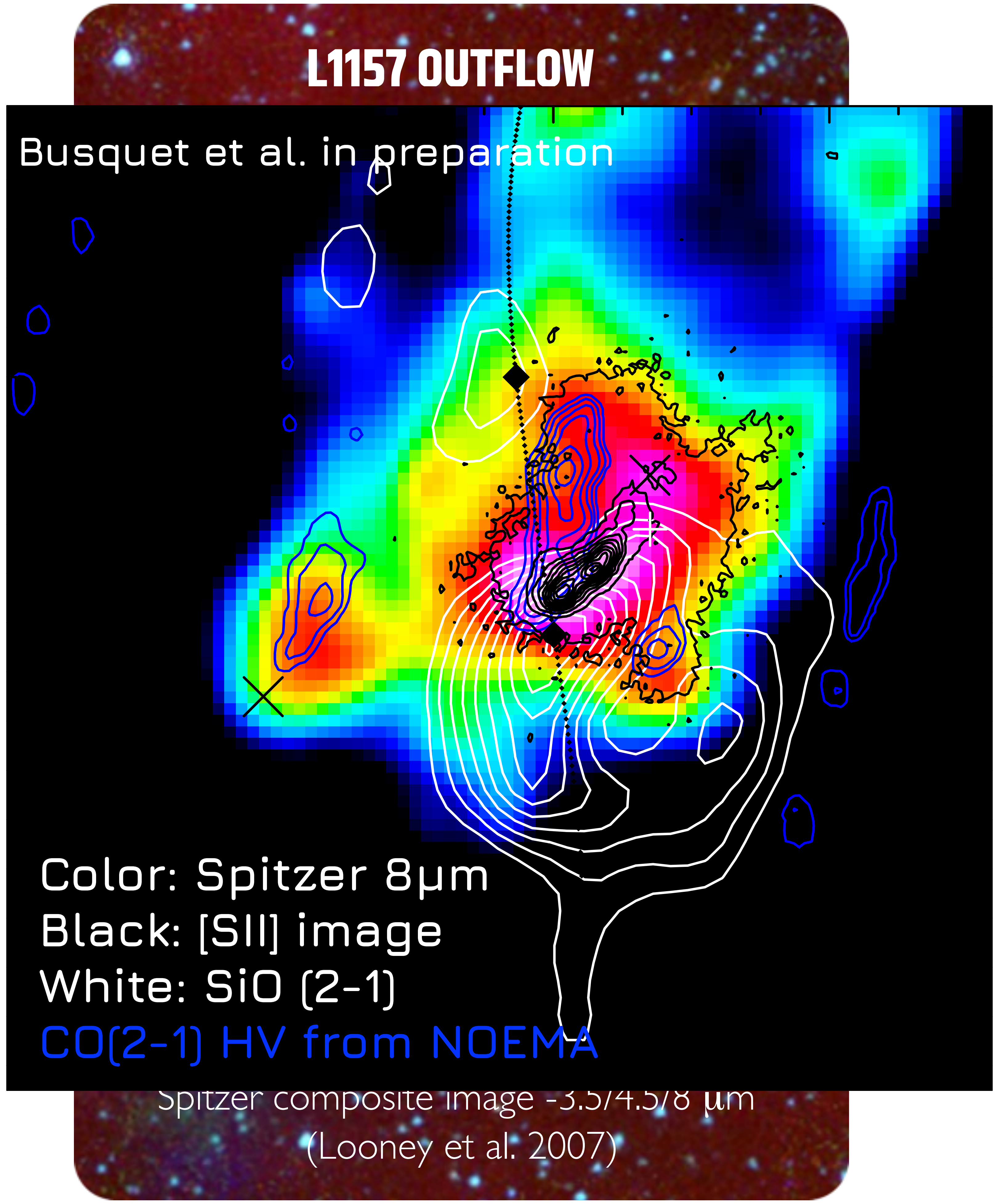
★ Injection radius: $$\left(\frac{r_0}{\mathrm{au}}\right) = 31\left[\left(\frac{S_\nu}{\mathrm{mJy}}\right)\left(\frac{\nu}{10\,\mathrm{GHz}}\right)^{-0.6}\right]^{0.5}\left(\frac{\nu_m}{10\,\mathrm{GHz}}\right)^{-0.7}\left(\frac{\theta_0 \sin i}{\mathrm{rad}}\right)^{-0.5}\left(\frac{d}{\mathrm{kpc}}\right)\left(\frac{T}{10^4\mathrm{K}}\right)^{-0.5}$$

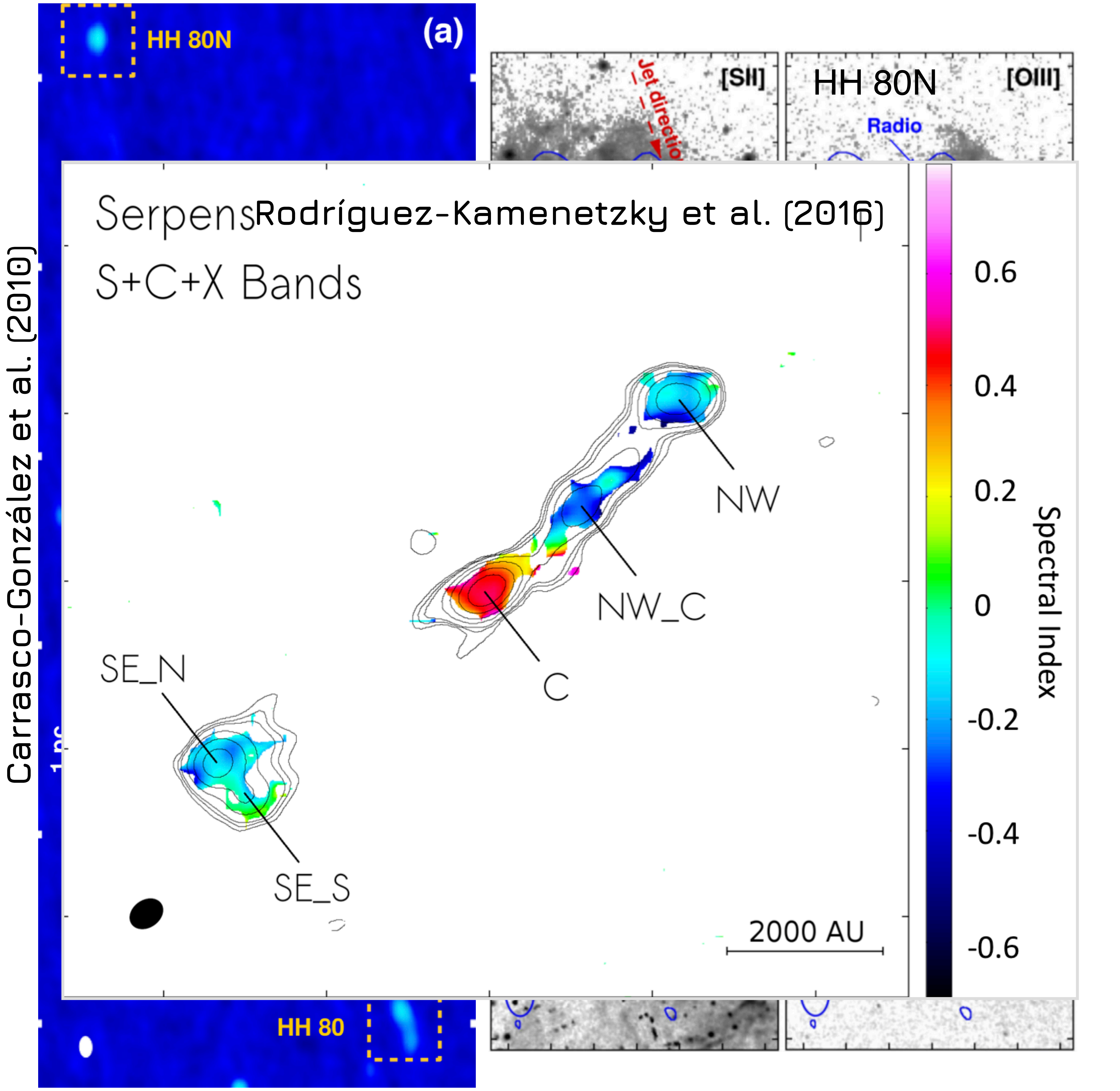
★ Ionized mass loss rate: $$\left(\frac{\dot{M}_{ion}}{10^{-6}\mathrm{M_\odot yr^{-1}}}\right) = 0.139\left[\left(\frac{S_\nu}{\mathrm{mJy}}\right)\left(\frac{\nu}{10\,\mathrm{GHz}}\right)^{-0.6}\right]^{0.75}\left(\frac{v_j}{200\,\mathrm{kms^{-1}}}\right)\left(\frac{\theta_0}{\mathrm{rad}}\right)^{0.75}(\sin i)^{-0.25}\left(\frac{d}{\mathrm{kpc}}\right)\left(\frac{T}{10^4\mathrm{K}}\right)^{-0.075}$$

★ Jet velocity: $$\left(\frac{v_j}{\mathrm{km\,s^{-1}}}\right) \simeq 140\left(\frac{M_\star}{0.5\,M_\odot}\right)^{1/2}$$

JETS AND HIGH-VELOCITY SHOCKS

Protostellar Shocks





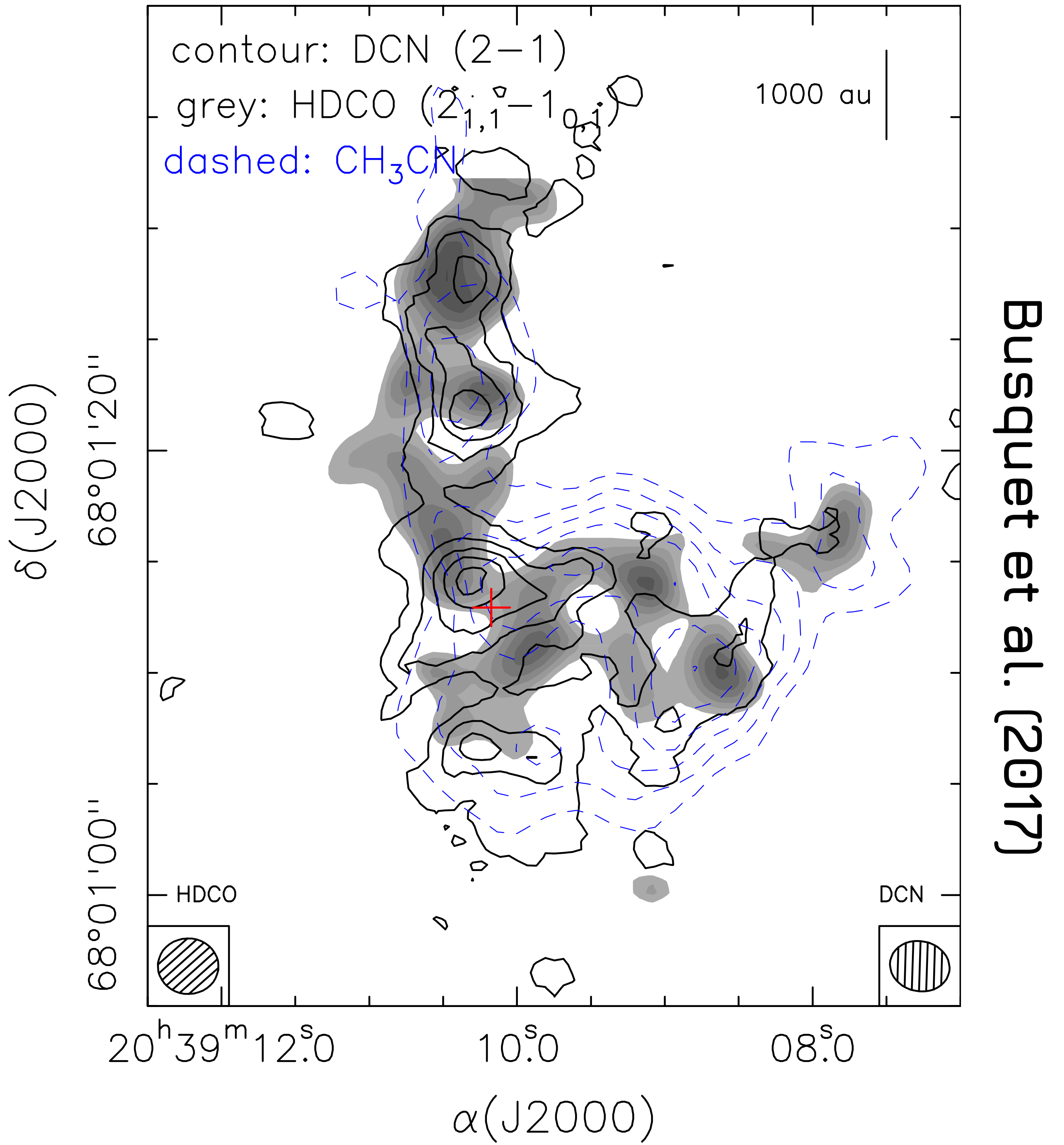
Rodríguez-Kamenetzky et al. (2019)

★ Shocks produced by the interaction of a supersonic jet with the environment

★ Emit in a wide range of wavelengths: from **radio to X- and γ-rays**

★ Usually associated with **non-thermal synchrotron** emission

★ Molecular outflows and shocks display a **rich chemistry**



DISKS IN YSOs

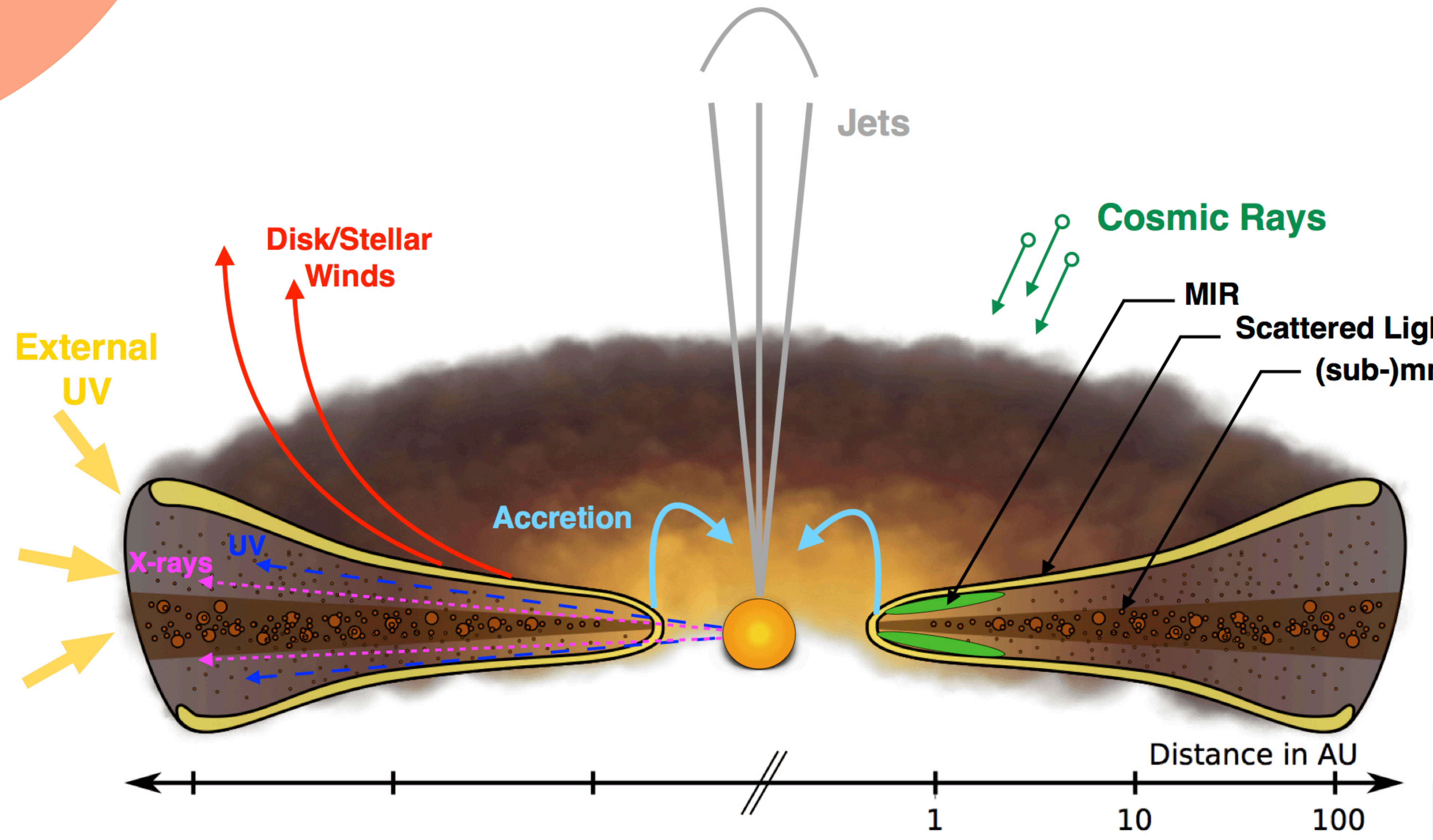
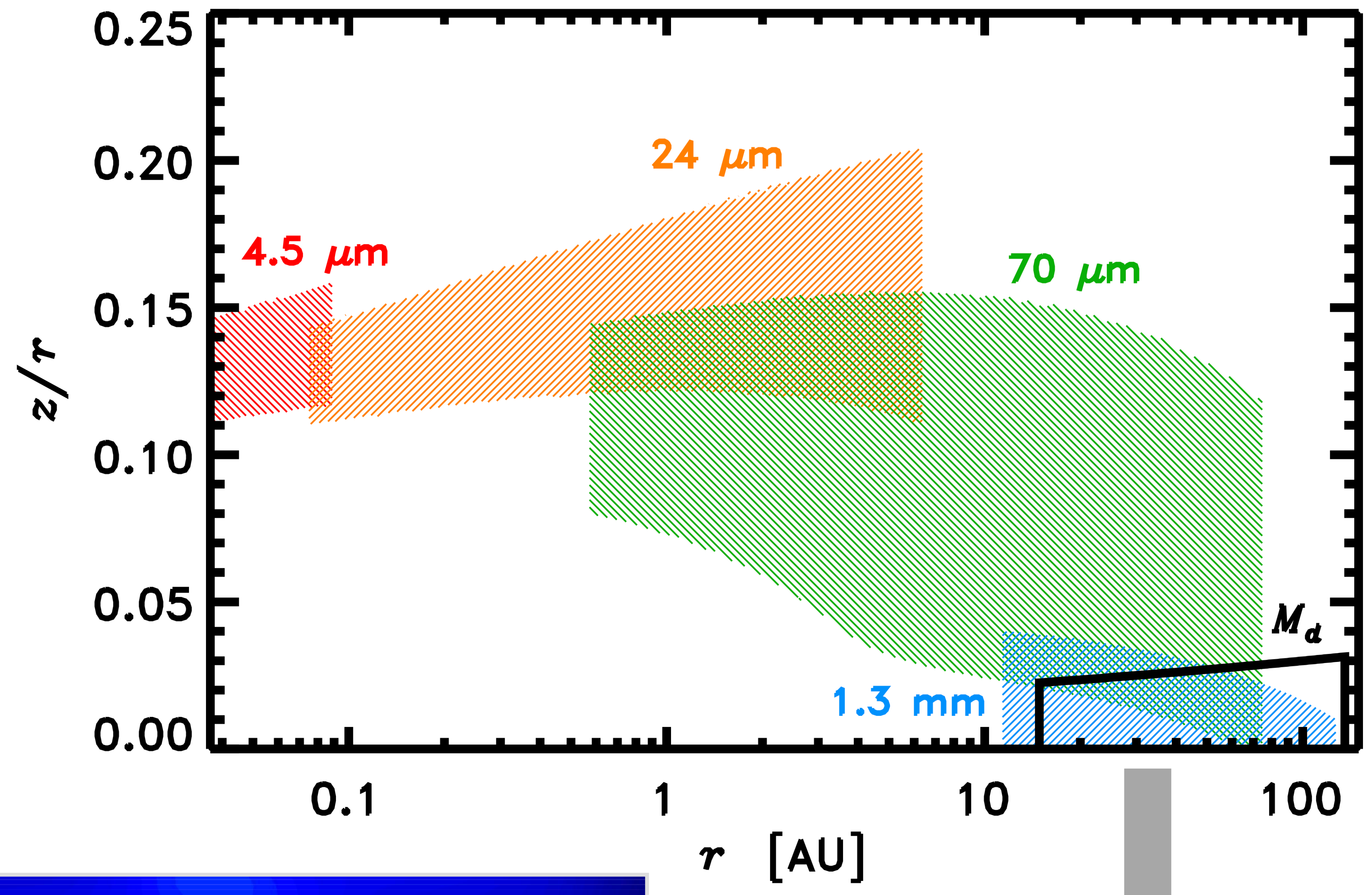


Figure adapted from Testi et al. (2014)

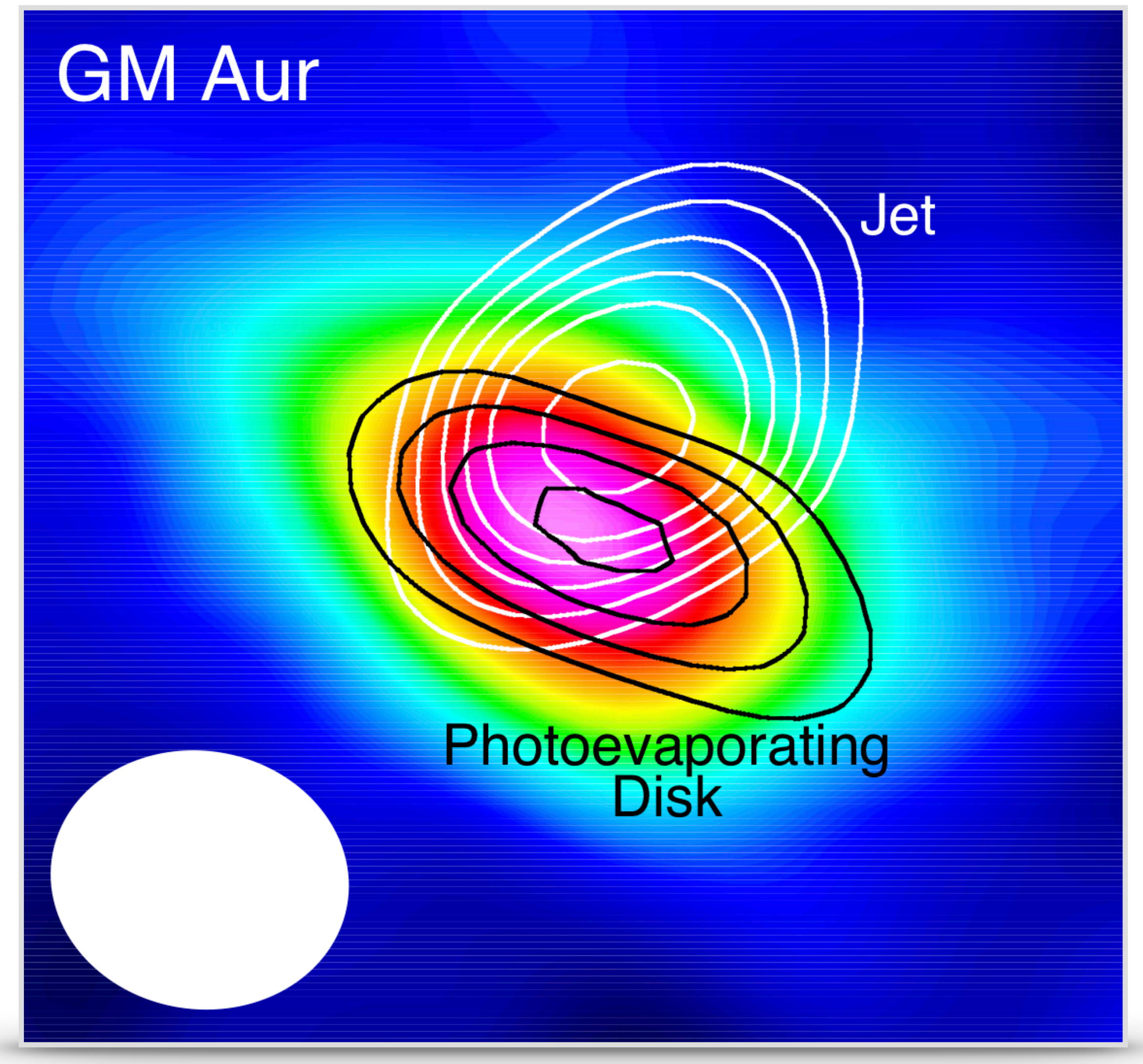
IR/mm wavelength observations:



Andrews (2015)

Radio (cm) wavelength observations:

Free-free emission at cm wavelengths produced by a photo evaporating disk assuming the disk is headed by EUV or X-ray radiation

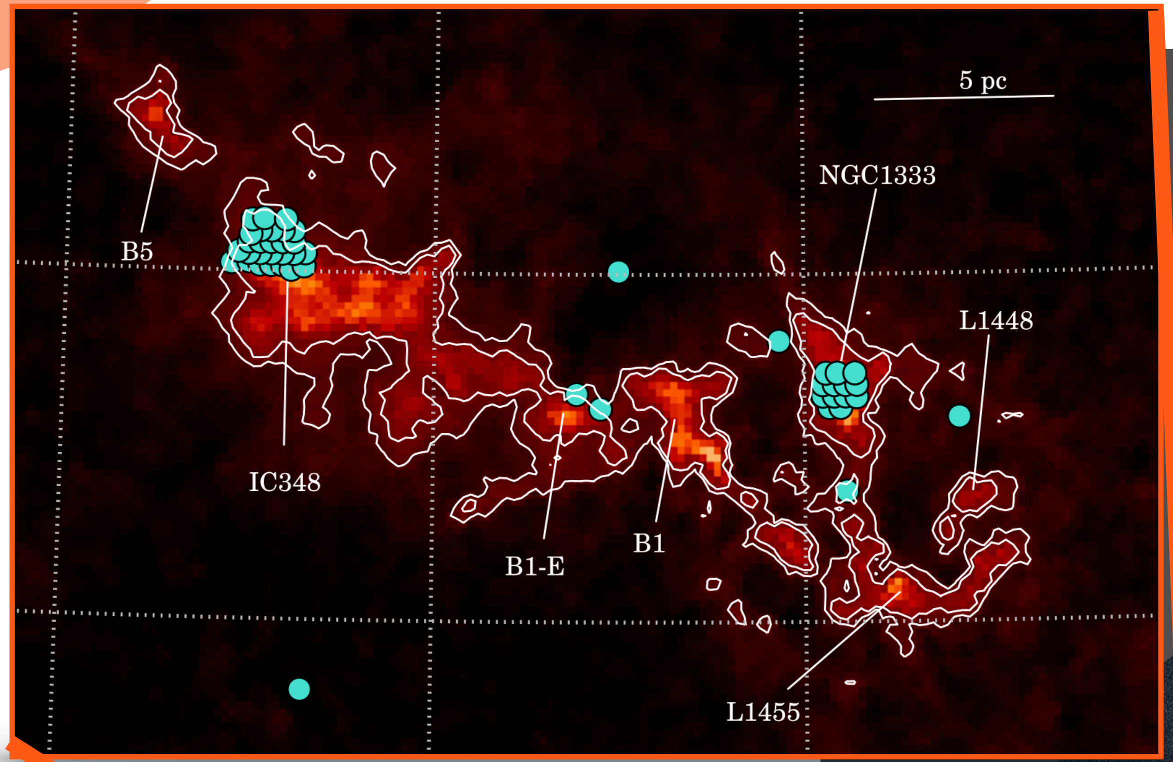


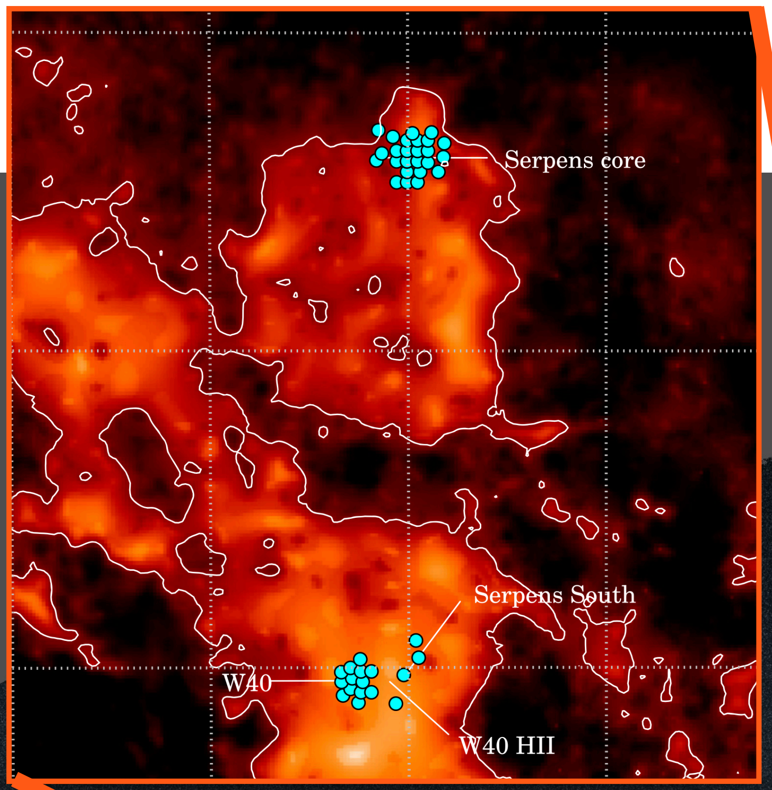
Macías et al. (2016)

Unique access to cold material in the disk mid plane

YSOs IN THE SOLAR NEIGHBOURHOOD

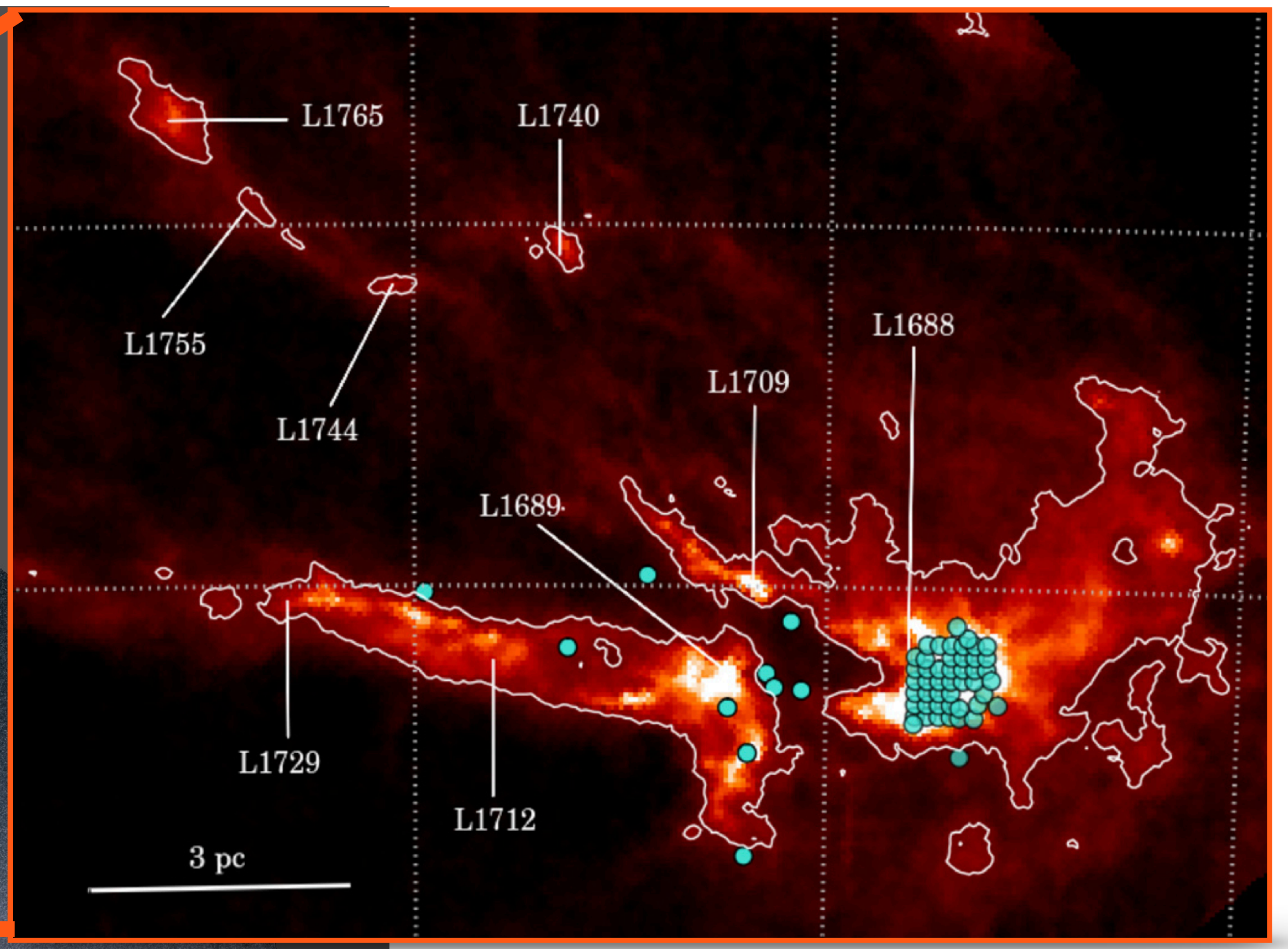
PERSEUS: 206 sources, 42 YSOs (Ortiz-León et al. 2015)

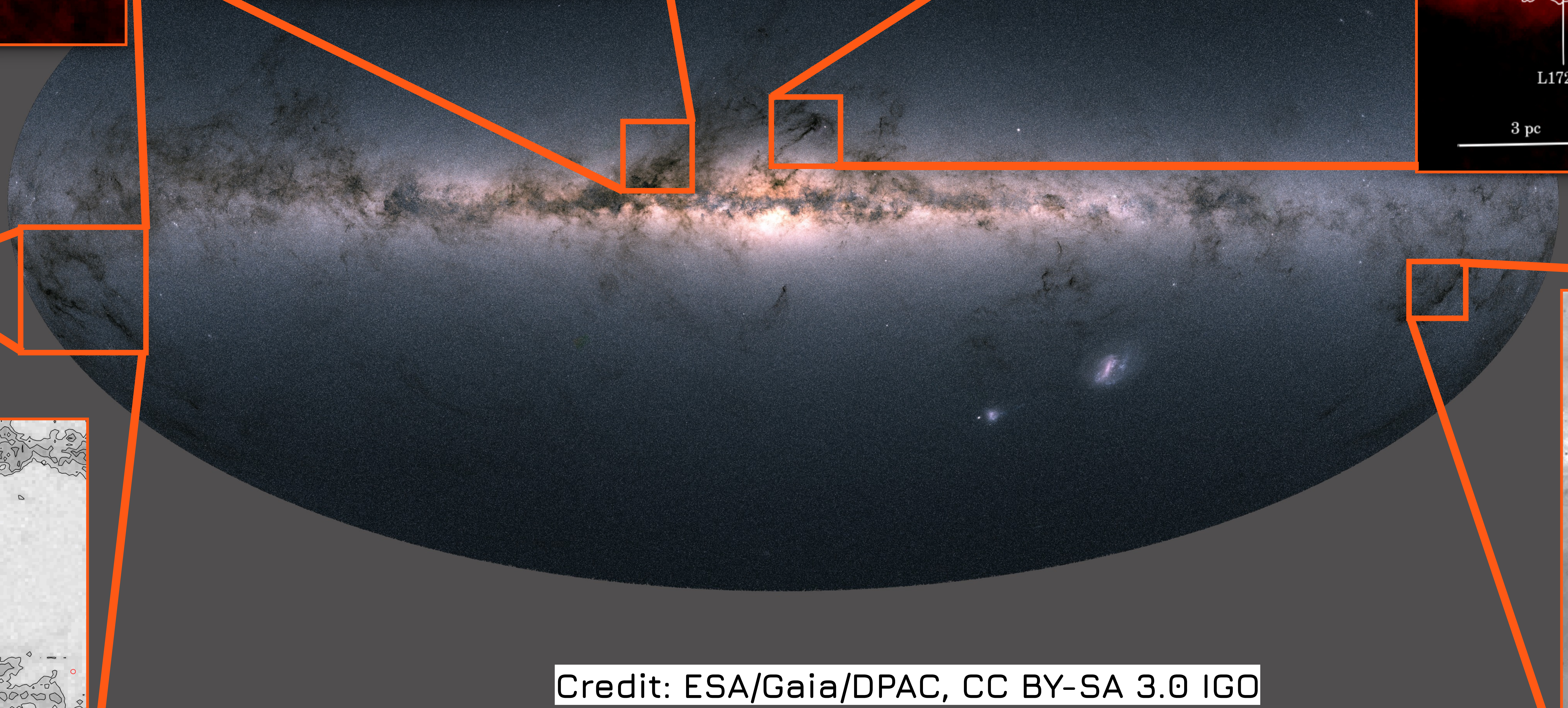


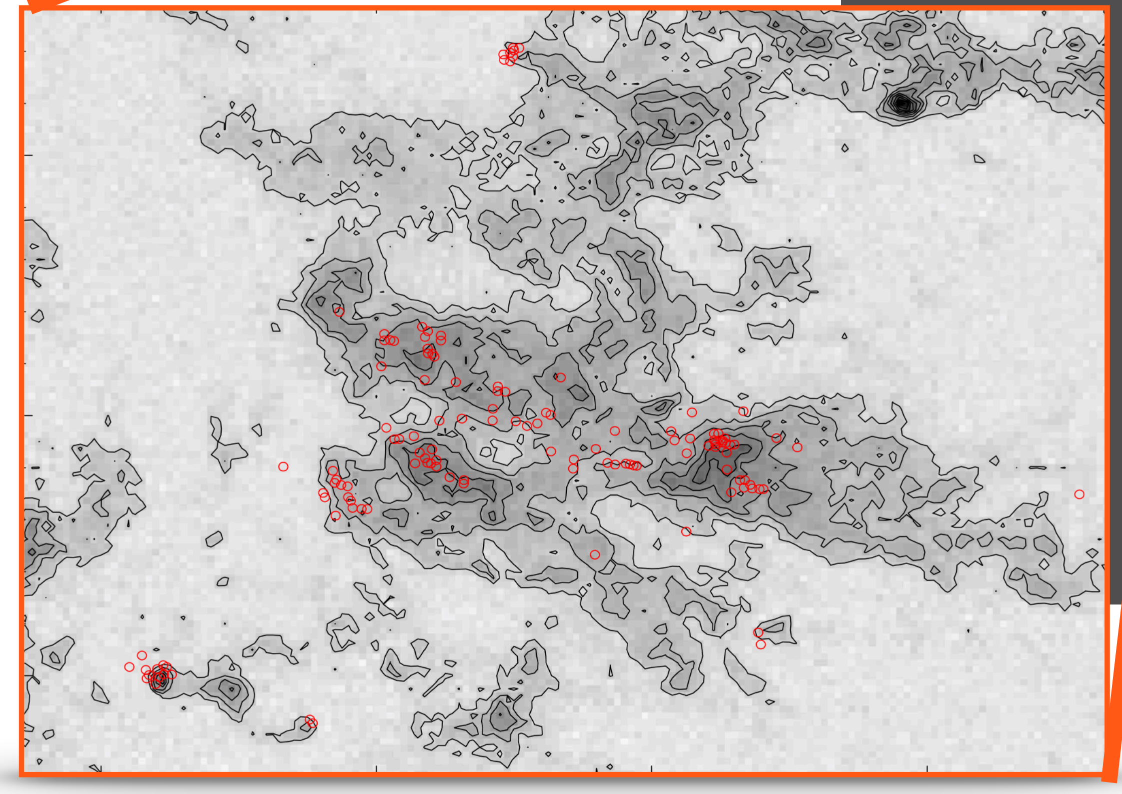


SERPENS: 146 sources, 29 YSOs (Ortiz-León et al. 2015)

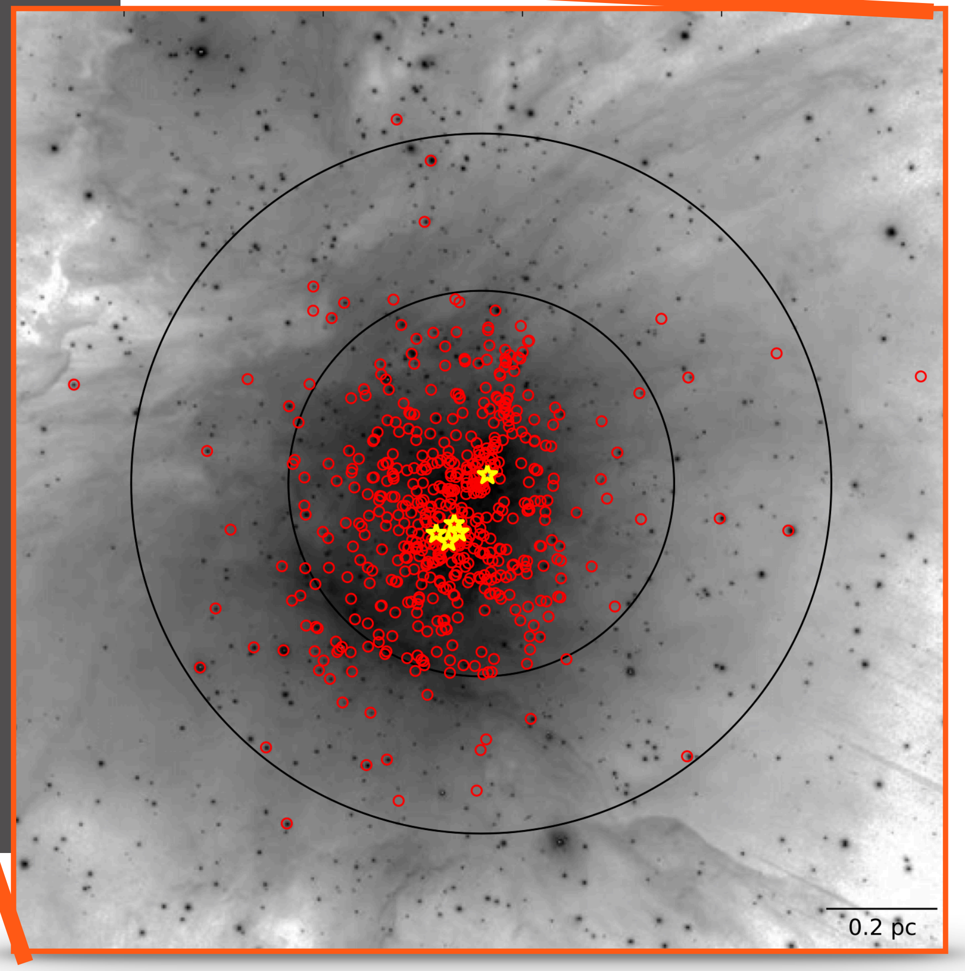
OPHIUCHUS: 189 sources, 56 YSOs (Dzib et al. 2013)







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



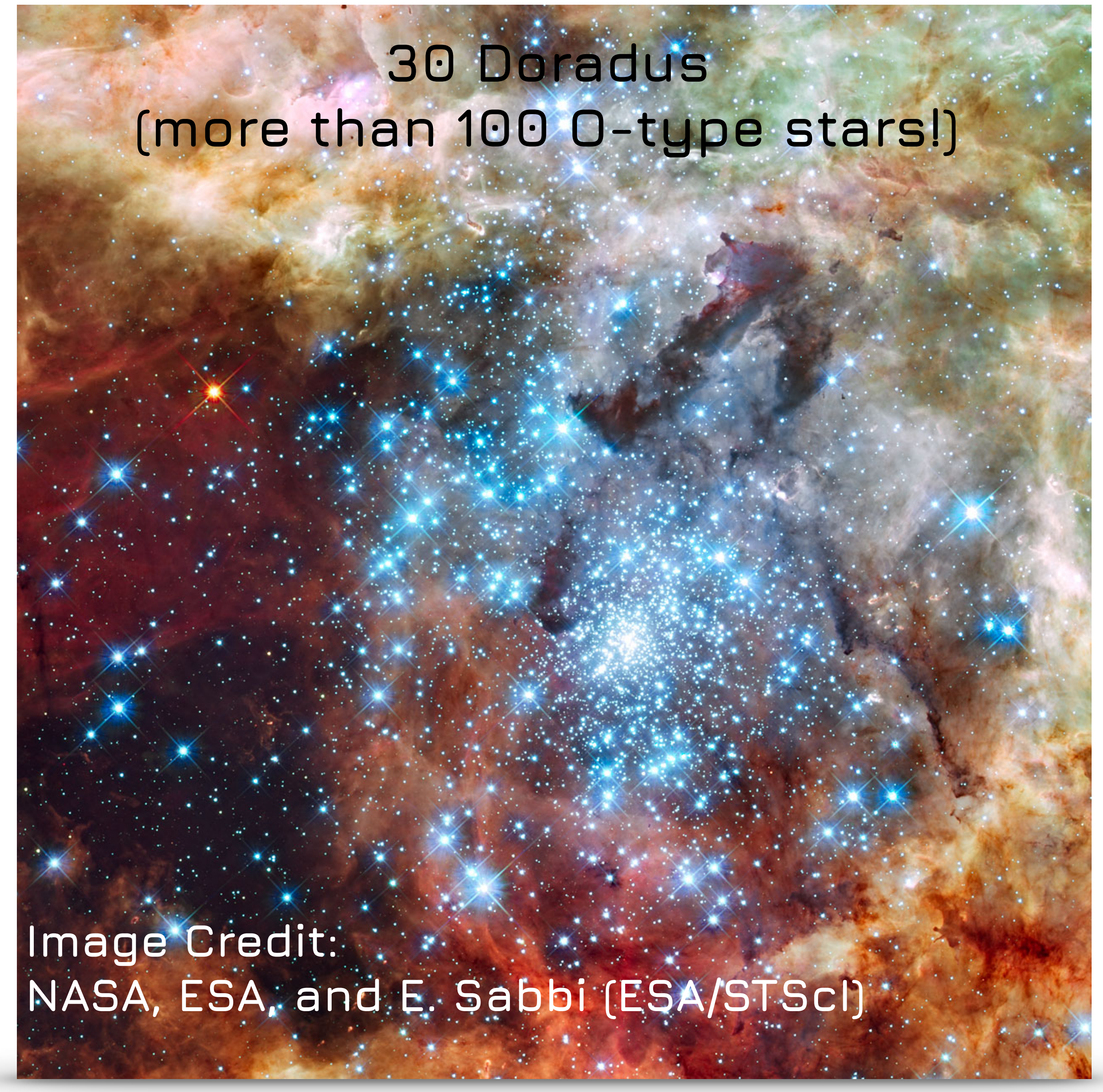
ONC: 556 sources (Forbrich et al. 2016)

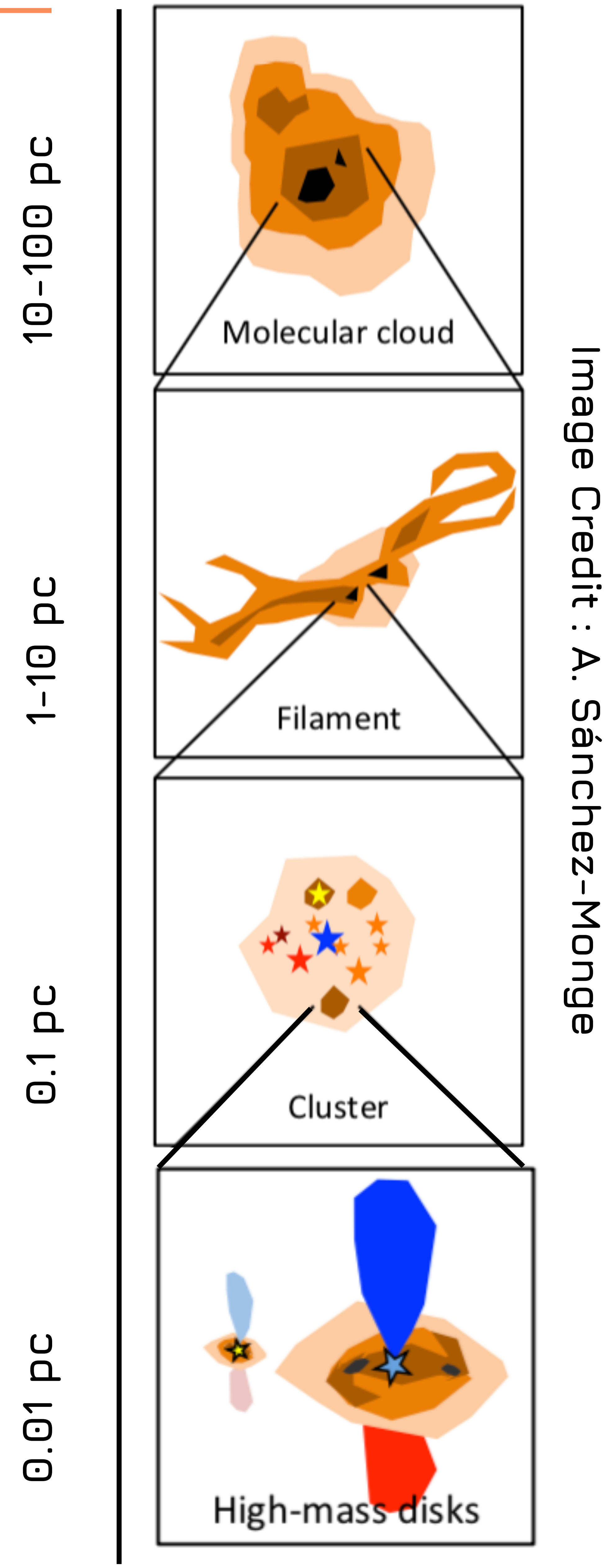
ORION: 376 sources, 234 YSOs (Kounkel et al. 2014)

HIGH-MASS STARS AND STAR CLUSTERS

ISOLATED

CLUSTERED





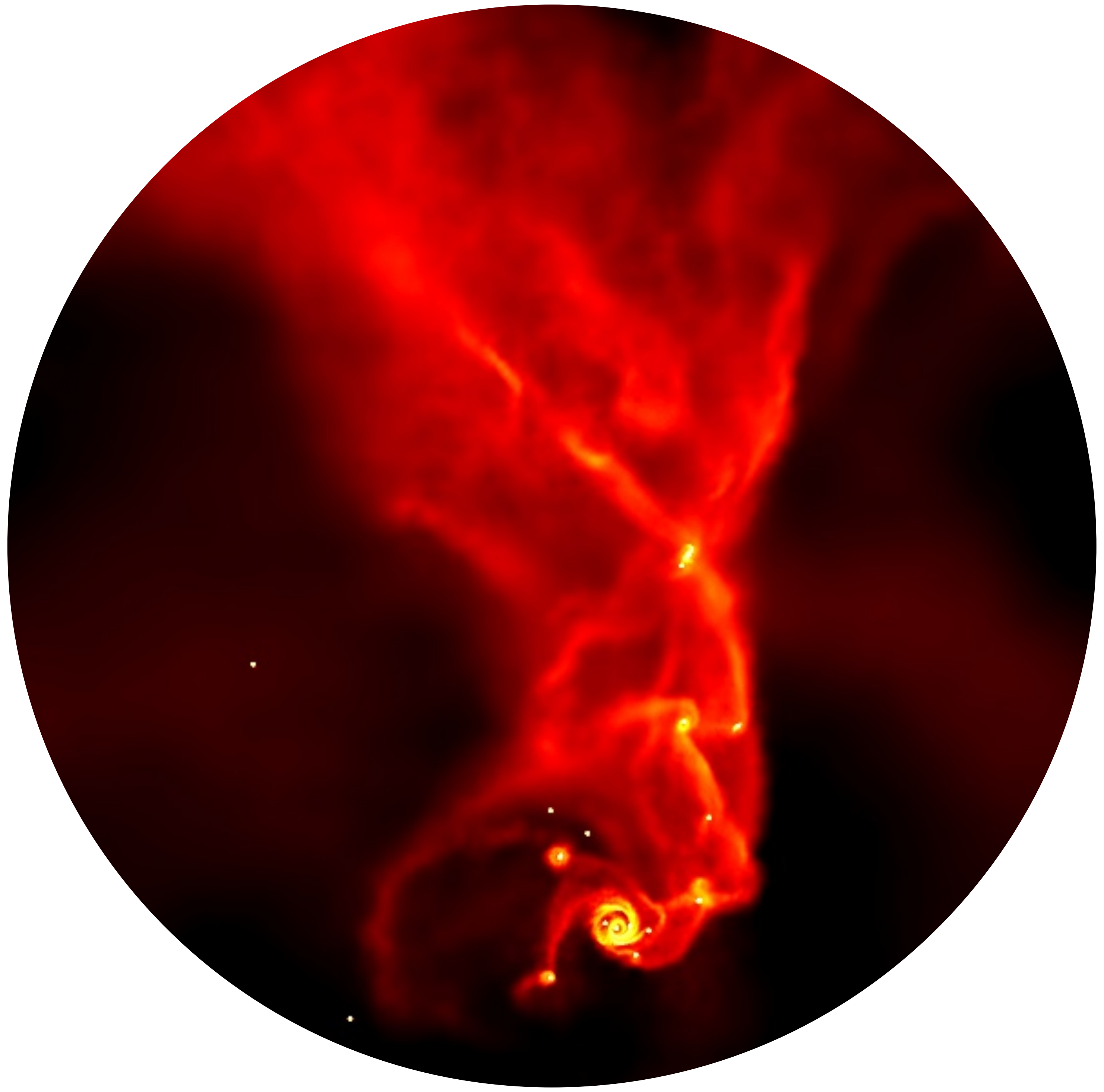
Most stars in the Galaxy, including our Sun, form in groups and **clusters**

(e.g., Lada & Lada 2003, Adams 2010)

HIGH-MASS STARS AND STAR CLUSTERS

STRONG UV/X-RAY RADIATION FIELD

EXPLOSIVE MOLECULAR OUTFLOWS



DYNAMICAL ENCOUNTERS

PRESENCE OF MASSIVE STARS AND STAR CLUSTER MAY HAVE SIGNIFICANT EFFECTS ON THE STAR AND PLANETARY FORMATION PROCESSES

Images Credit: ESO; ALMA (ESO/NAOJ/NRAO), J. Bally/H. Drass et al.; ESO/M. McCaughrean et al. (AIP); Matthew Bate, University of Exeter

OPEN QUESTIONS

Previous radio continuum studies conducted toward **high-mass star-forming regions** suffer from **sensitivity limitations** (1σ noise level is at most ~5-10 μJy/beam) that allowed to **detect ONLY the most massive objects**

(e.g., Sánchez-Monge et al. 2013, Mosacadelli et al. 2016; Rosero et al. 2016, 2019)

HOW THE ENVIRONMENT INFLUENCES THE FORMATION OF STAR CLUSTERS AND PLANETARY SYSTEMS?

WHAT DETERMINES THE NUMBER OF OBJECTS AND THEIR STELLAR DENSITIES IN NASCENT CLUSTERS?

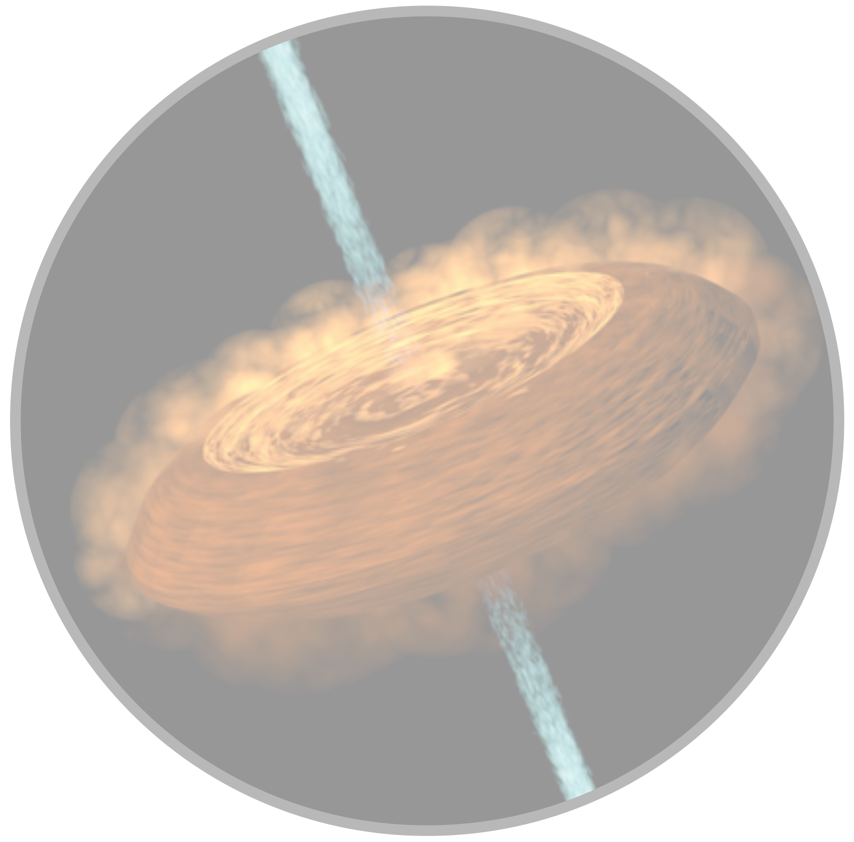
PRESENT WORK

HOW DO $\dot{M}_{acc}$ AND $\dot{M}_{loss}$ EVOLVE WITH TIME? DO THEY PROCEED IN THE SAME WAY ACROSS THE ENTIRE MASS SPECTRUM?

ARE THE RADIO, IR, AND X-RAY PROPERTIES OF THE CLUSTER MEMBERS SIMILAR TO THOSE INFERRED IN LOW-MASS STARS FORMED IN ISOLATION?

FUTURE WORK

OUTLINE



SCIENTIFIC CONTEXT

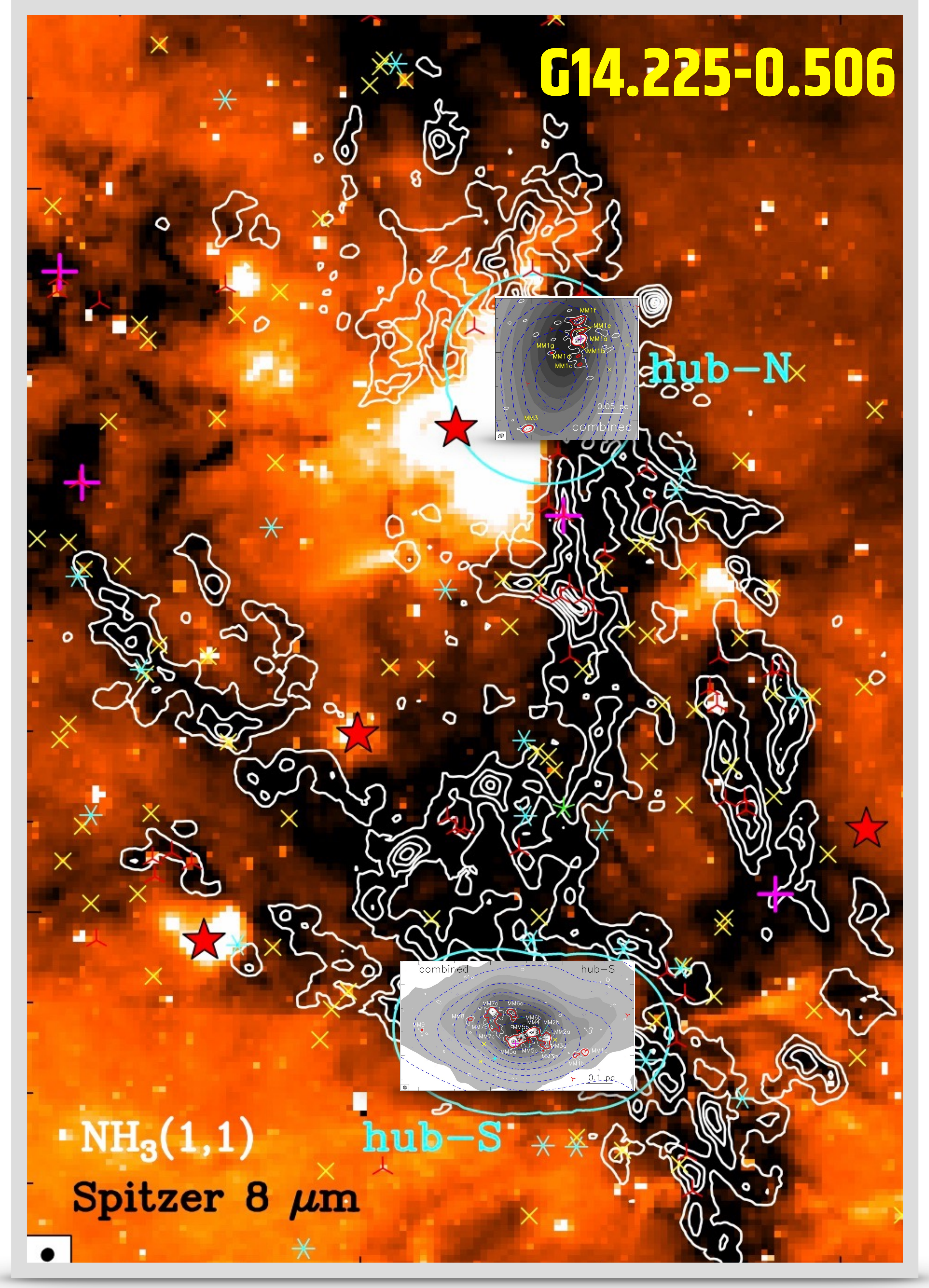
- FILAMENTS AND THEIR FRAGMENTATION
- FRAGMENTATION AT 500 AU
- UNVEILING THE EMBEDDED POPULATION

CURRENT WORK

FUTURE PROJECTS

FILAMENTS AND THEIR FRAGMENTATION

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



Busquet et al. (2013)

★ Network of dense filaments emanating from the two hubs (Busquet et al. 2013, Chen et al. 2019)

★ Rich population of protostars and YSOs detected with Spitzer (Povich & Whitney 2010, Povich et al. 2016)

★ Population of X-ray emitting intermediate-mass pre-main sequence stars detected with Chandra (Povich et al. 2016)

★ SMA and ALMA observations reveal an embedded cluster (Busquet et al. 2016, Ohashi et al. 2016) toward each hub with different levels of fragmentation

FILAMENTS AND THEIR FRAGMENTATION

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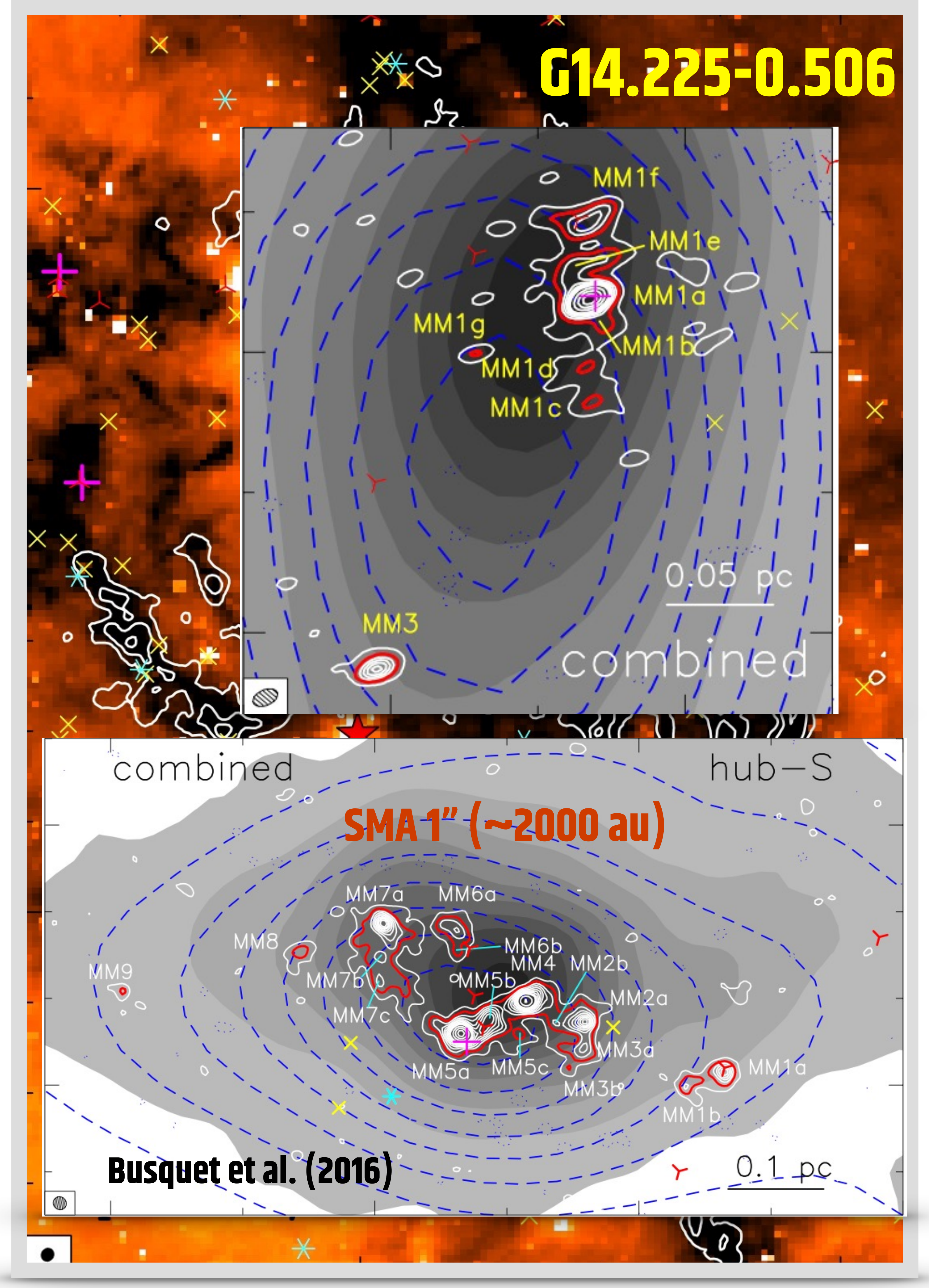
Busquet et al. (2013)



- ★ Network of dense filaments emanating from the two hubs (Busquet et al. 2013, Chen (incl. Busquet) et al. 2019)
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- HUB-N: 9 FRAGMENTS
- HUB-S: 17 FRAGMENTS

FILAMENTS AND THEIR FRAGMENTATION

WHAT ARE THE PHYSICAL AGENTS RESPONSIBLE FOR SHAPING THE ISM INTO FILAMENTARY STRUCTURES?

WHAT CONTROLS THE FRAGMENTATION PROCESS?

WHAT ARE THE CHARACTERISTICS OF THE STELLAR POPULATION?

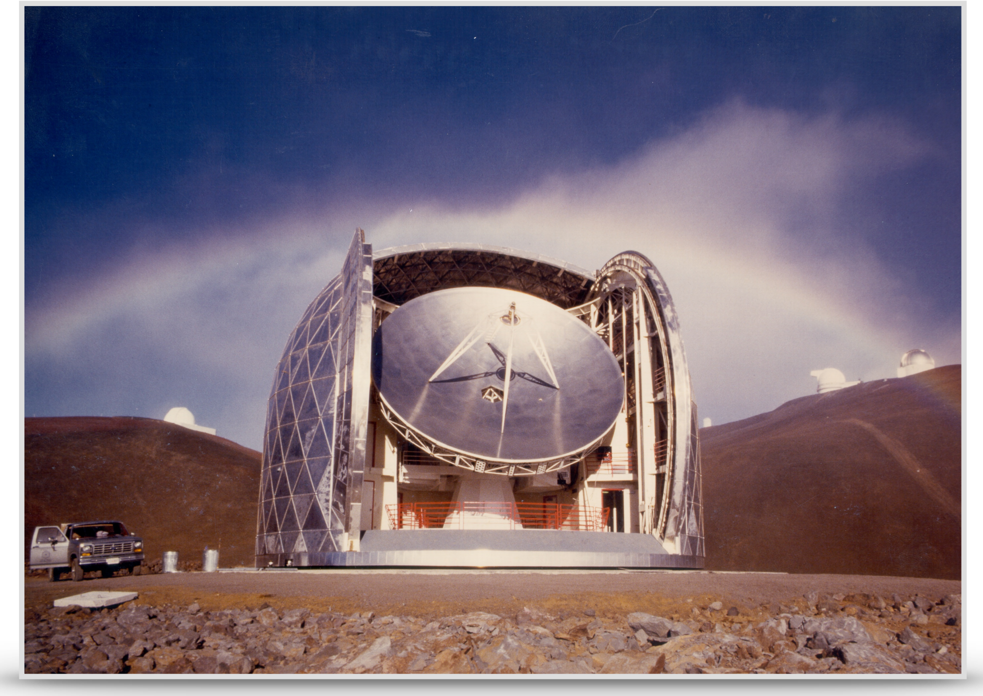
DO MASSIVE STARS FORM COEVAL TO THE LOW-MASS CLUSTER MEMBERS?

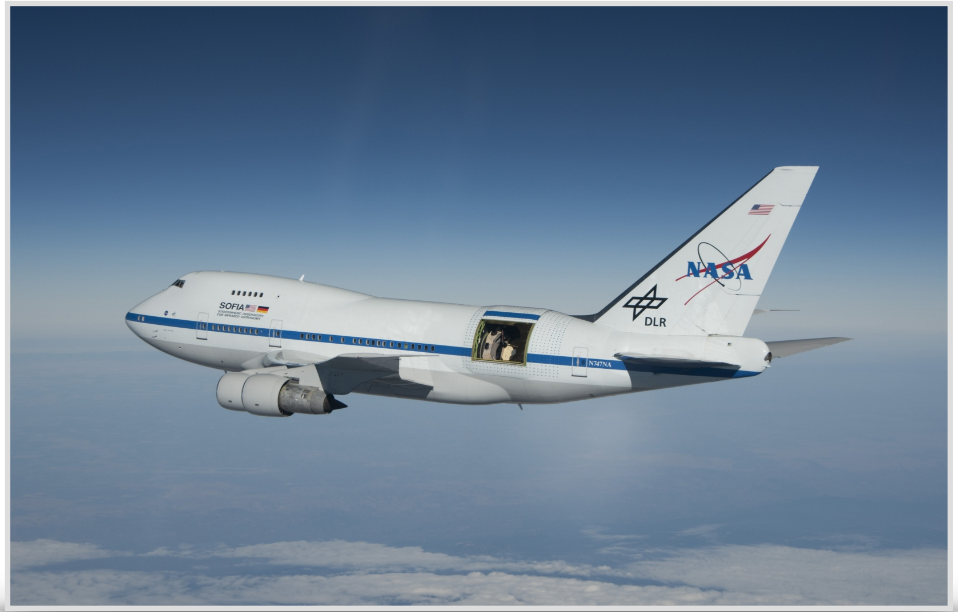
ALMA MOLECULAR LINE AND CONTINUUM OBSERVATIONS

POLARIMETRIC OBSERVATIONS:

SOFIA, CSO, SMA, ALMA

JVLA RADIO CONTINUUM OBSERVATIONS

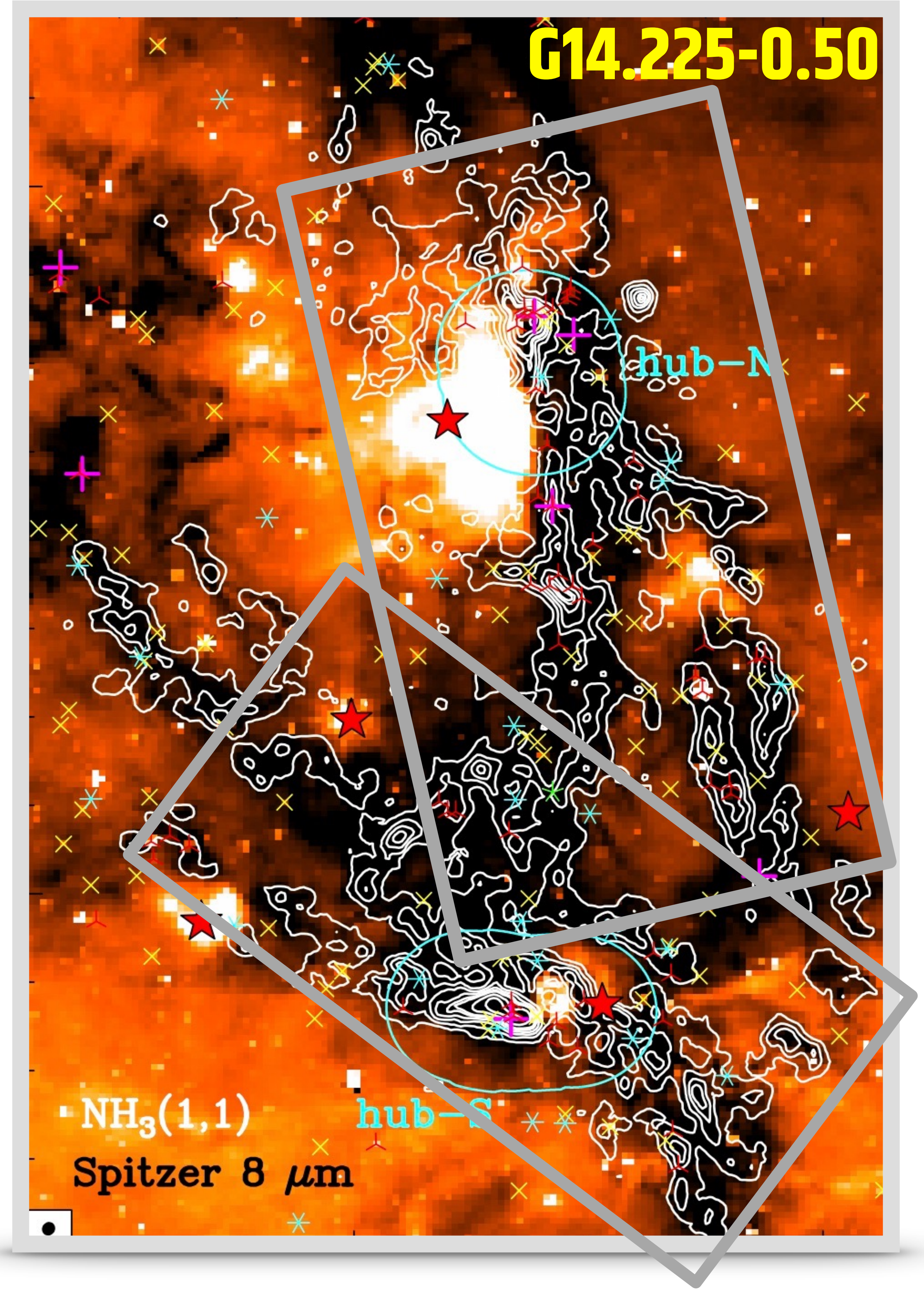


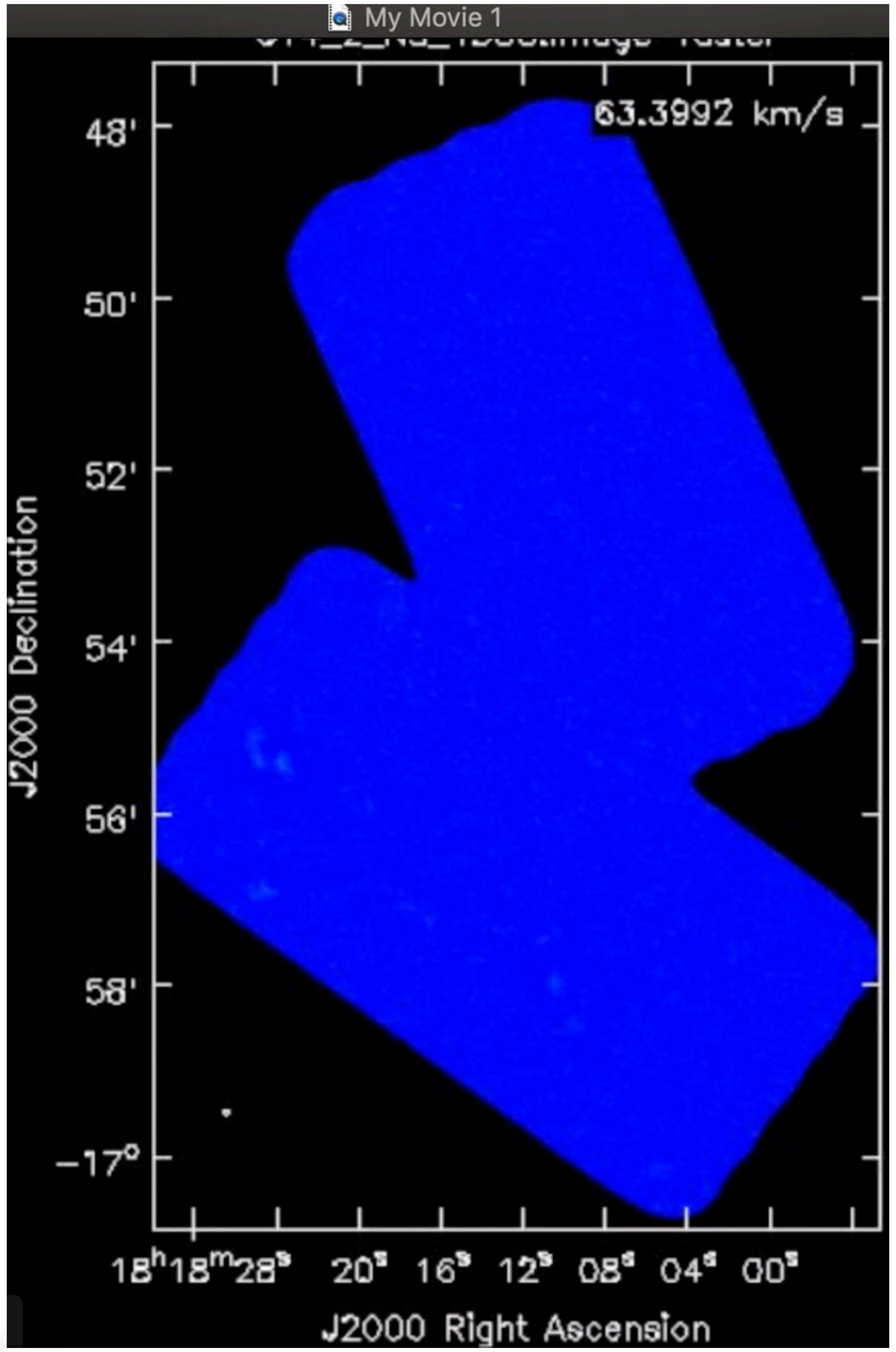


FILAMENTS AND THEIR FRAGMENTATION

ALMA cycle 6 project (12 m + ACA): $^{13}CO(1\text{-}0)$, $C^{18}O(1\text{-}0)$, CS(2-1), $C^{34}S(2\text{-}1)$, SO $3_{(2)}\text{-}2_{(1)}$, $^{34}SO\ 3_{(2)}\text{-}2_{(1)}$ + 3mm continuum

Busquet et al. (2013)





Is it raining over hub-filament systems?

- ★ Probe the **kinematical imprints of filaments** and **their surrounding** and discern whether the collapse signature prevail on scales ranging from several pc to a few times 0.01 pc
- ★ Compare with **numerical simulations of global, multi-scale collapse** (e.g., Gómez & Vázquez-Semadeni et al. 2014, Vázquez-Semadeni et al. 2019) with different treatments for turbulence, gravity and magnetic fields: which of these ingredients is the main driver of structure and dynamics?

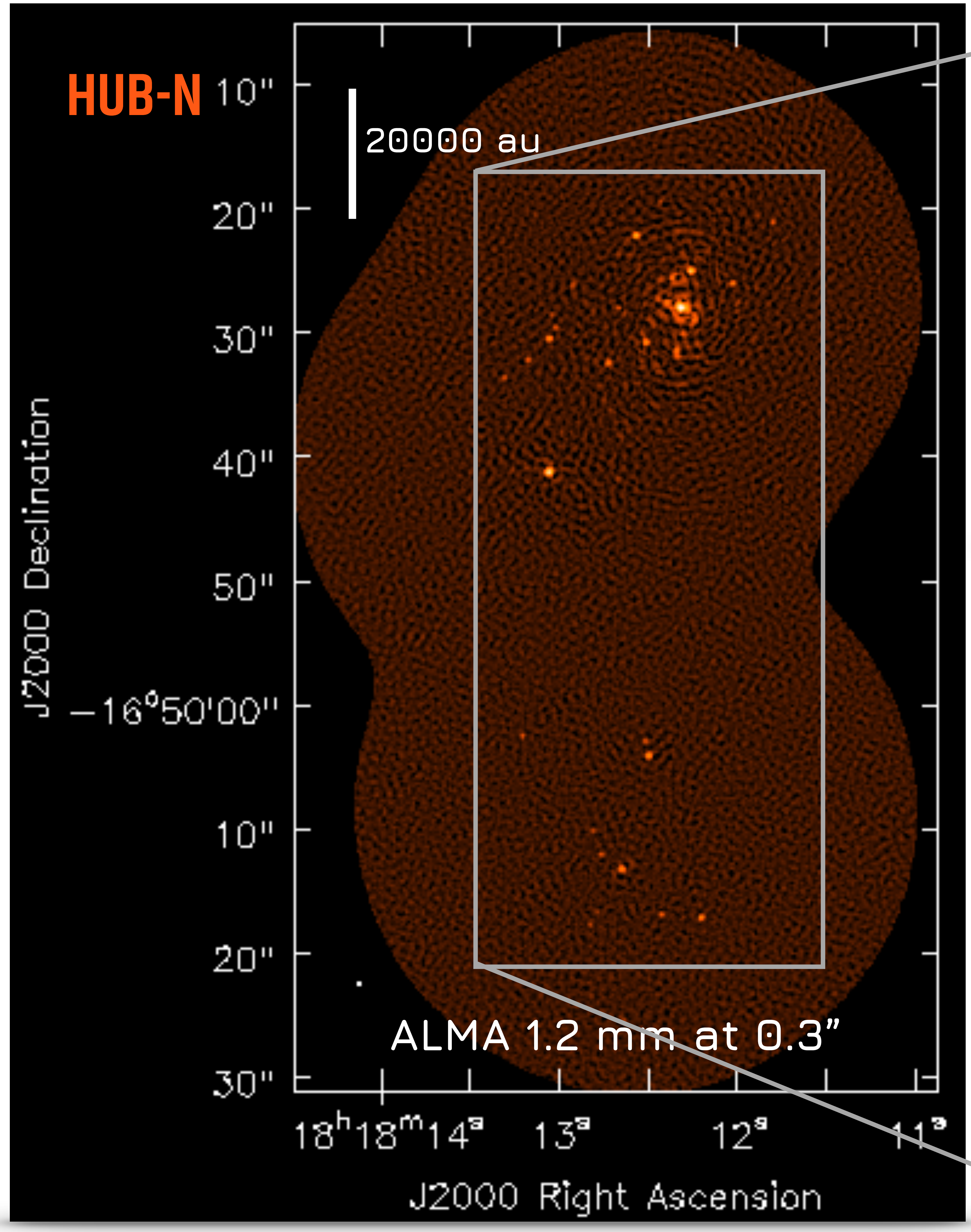
Collaboration: UB - ICE - IRyA - CfA- ASIAA

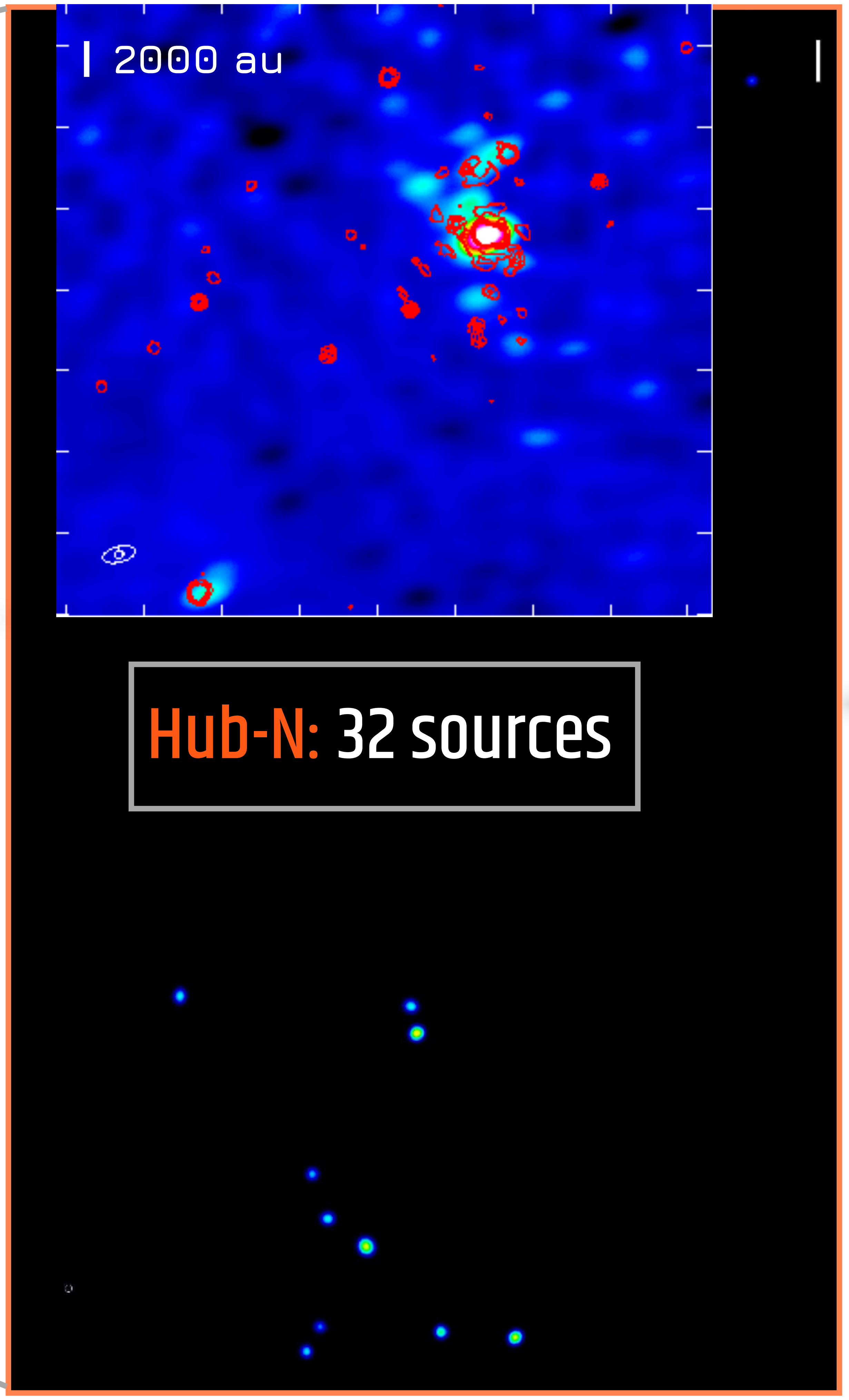
FRAGMENTATION AT 500 AU

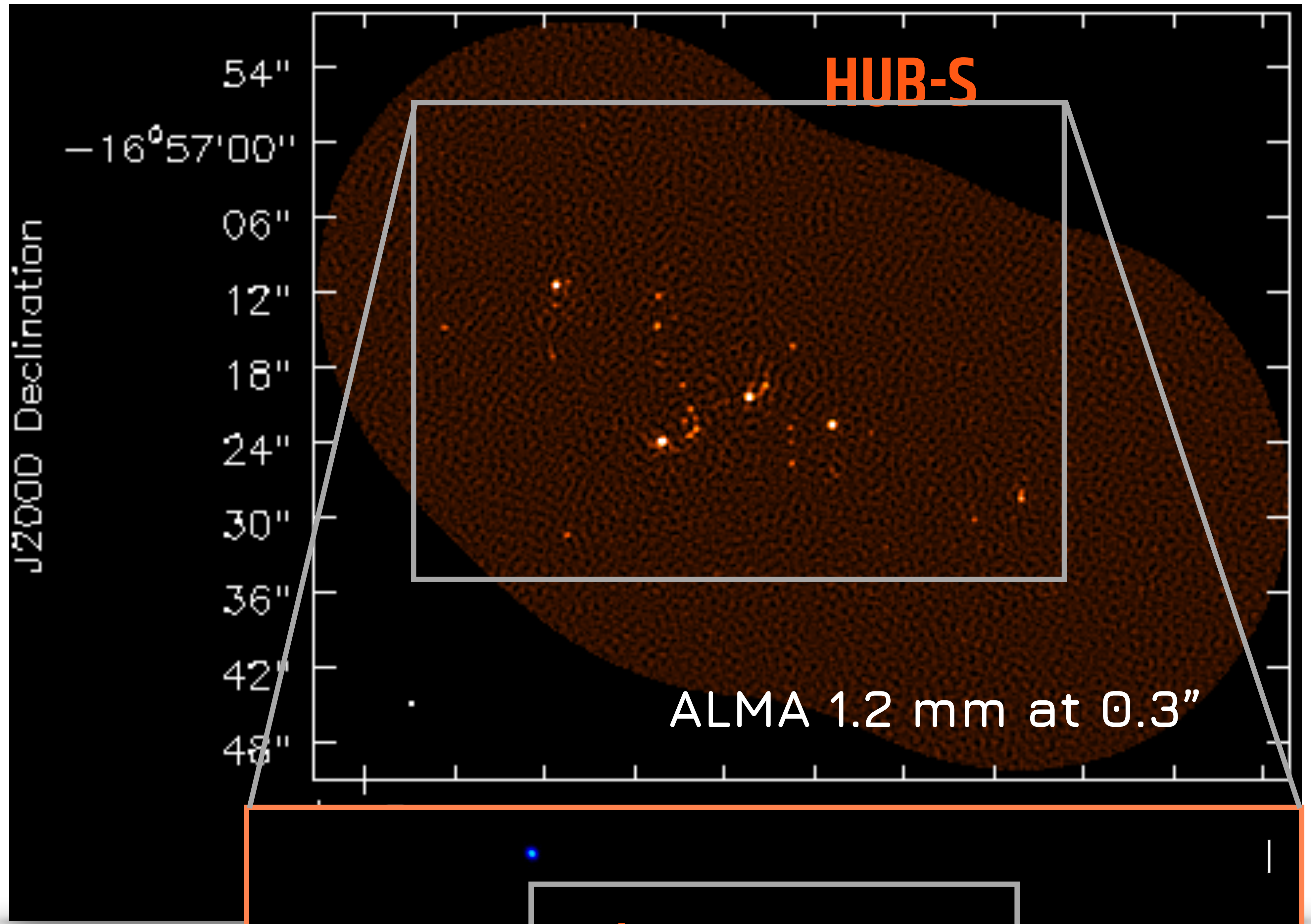
ALMA observations rms ~40 μJy/beam

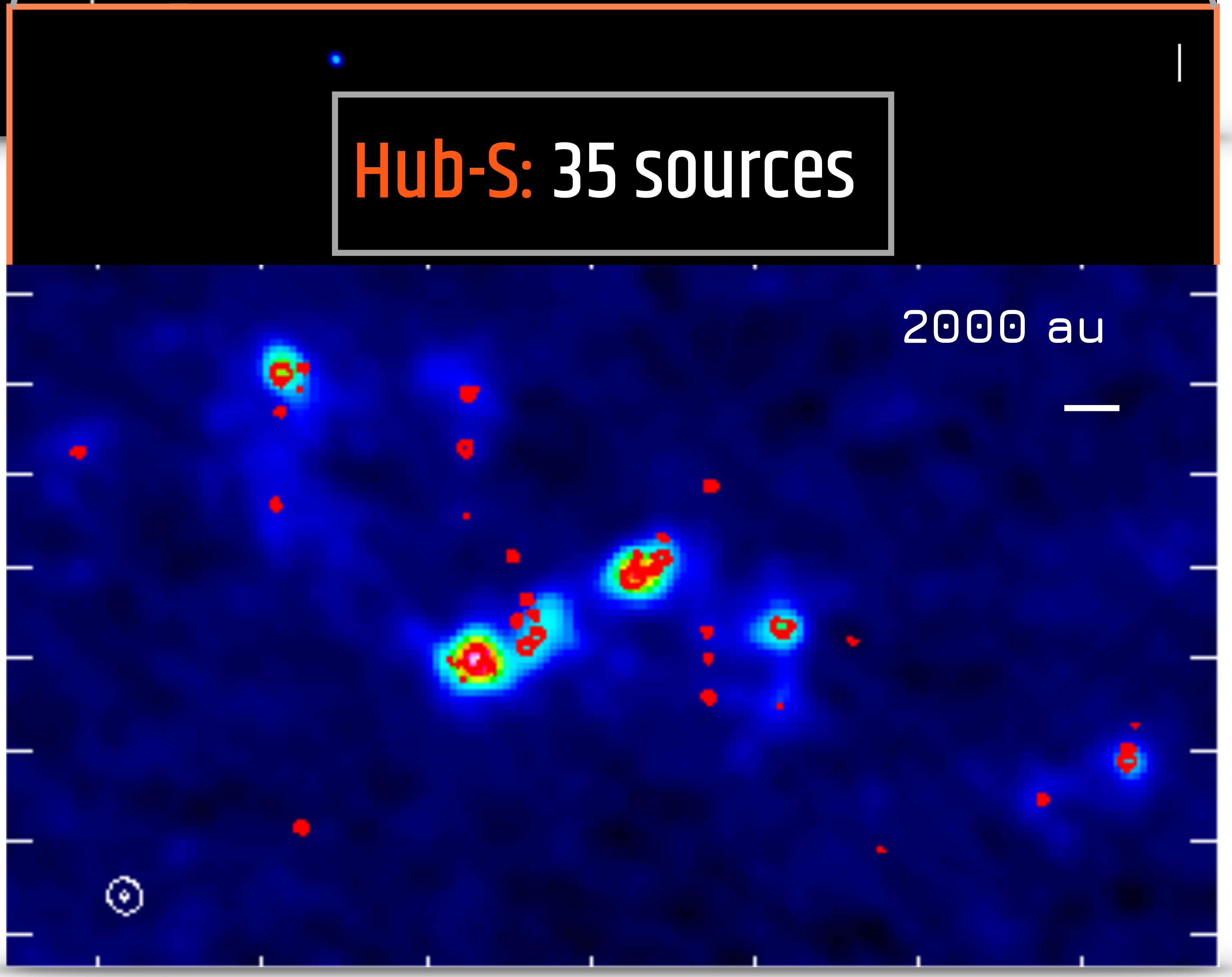
PyBDSF to identify sources: Radii~50 - 470 au

color scale: SMA @ 1”
red contours: ALMA @0.3”





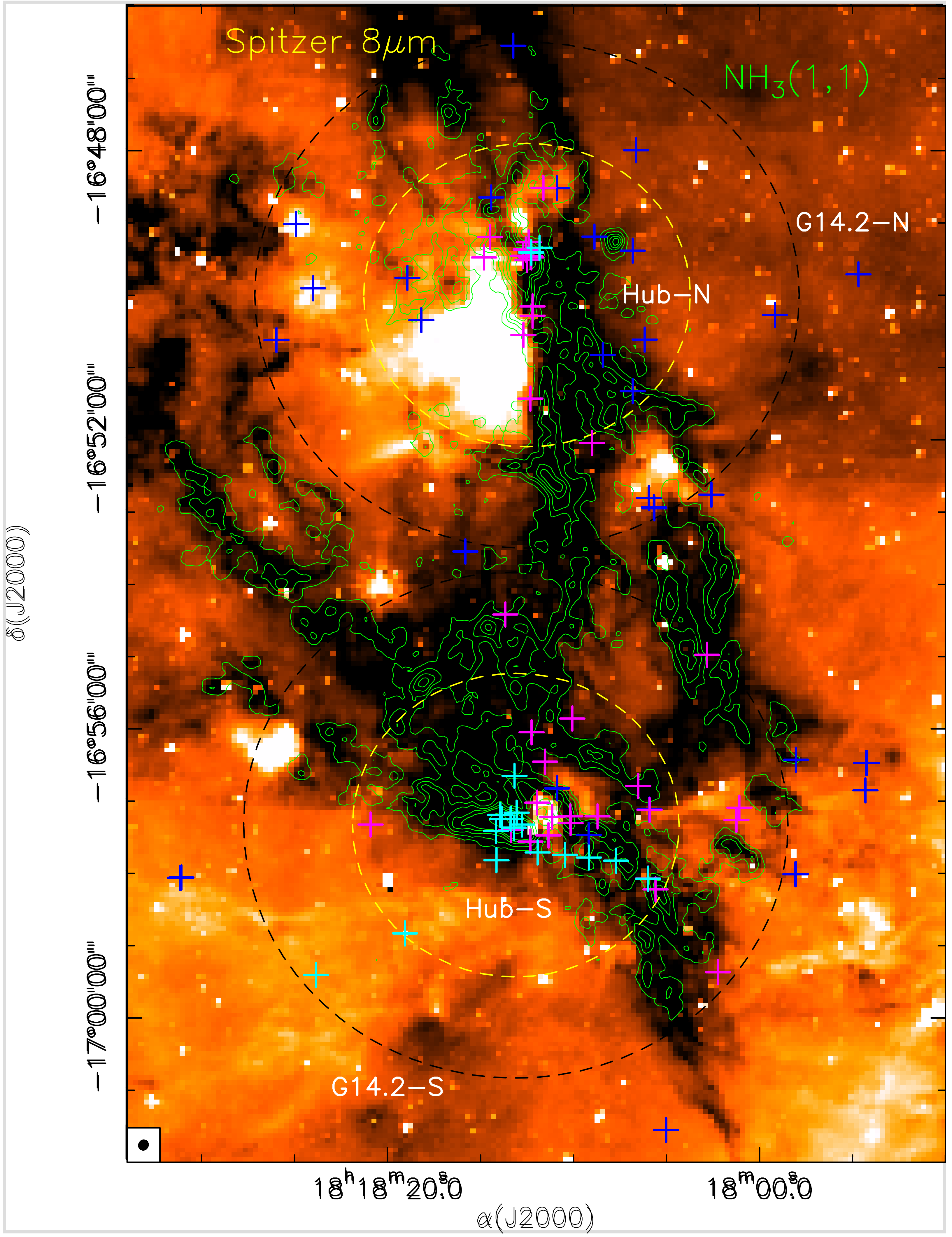




Aina Brichs, BSc Thesis (2021)

UNVEILING THE EMBEDDED POPULATION

Roger Grau, Master Thesis (2020)



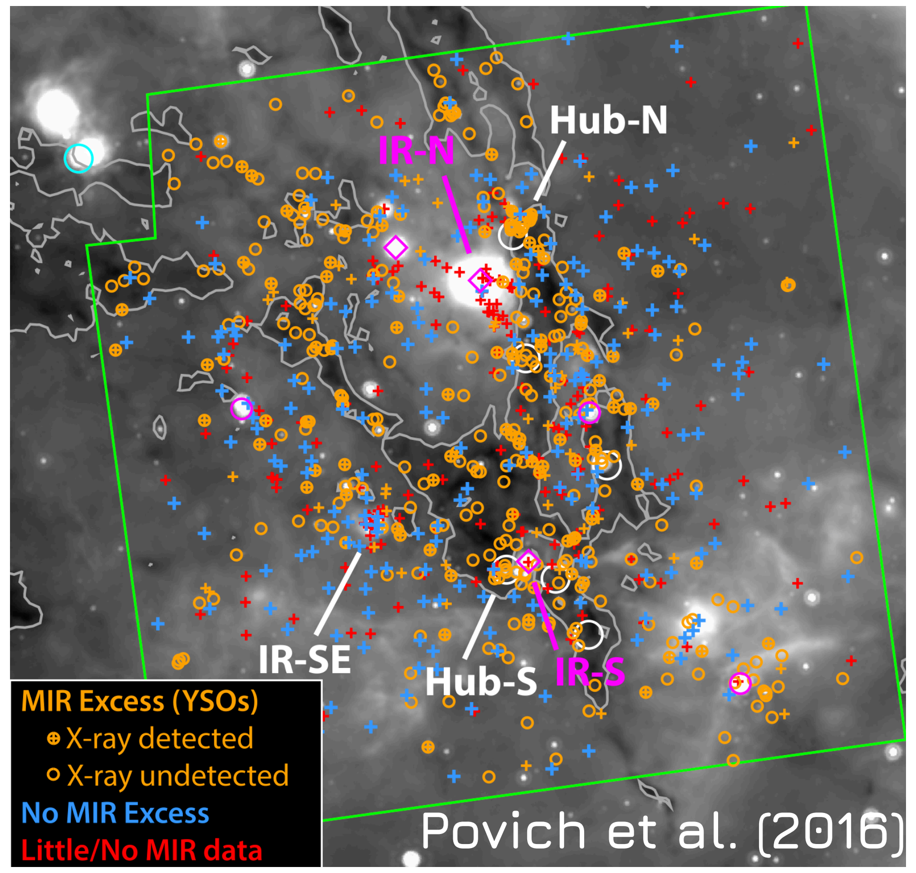
+ DETECTED @ 6CM
+ DETECTED @ 3.6 CM
+ DETECTED AT BOTH BANDS

PILOT PROGRAM WITH THE JVLA

★ **Most extended A-array** configuration (beam~0.3"~600 au)

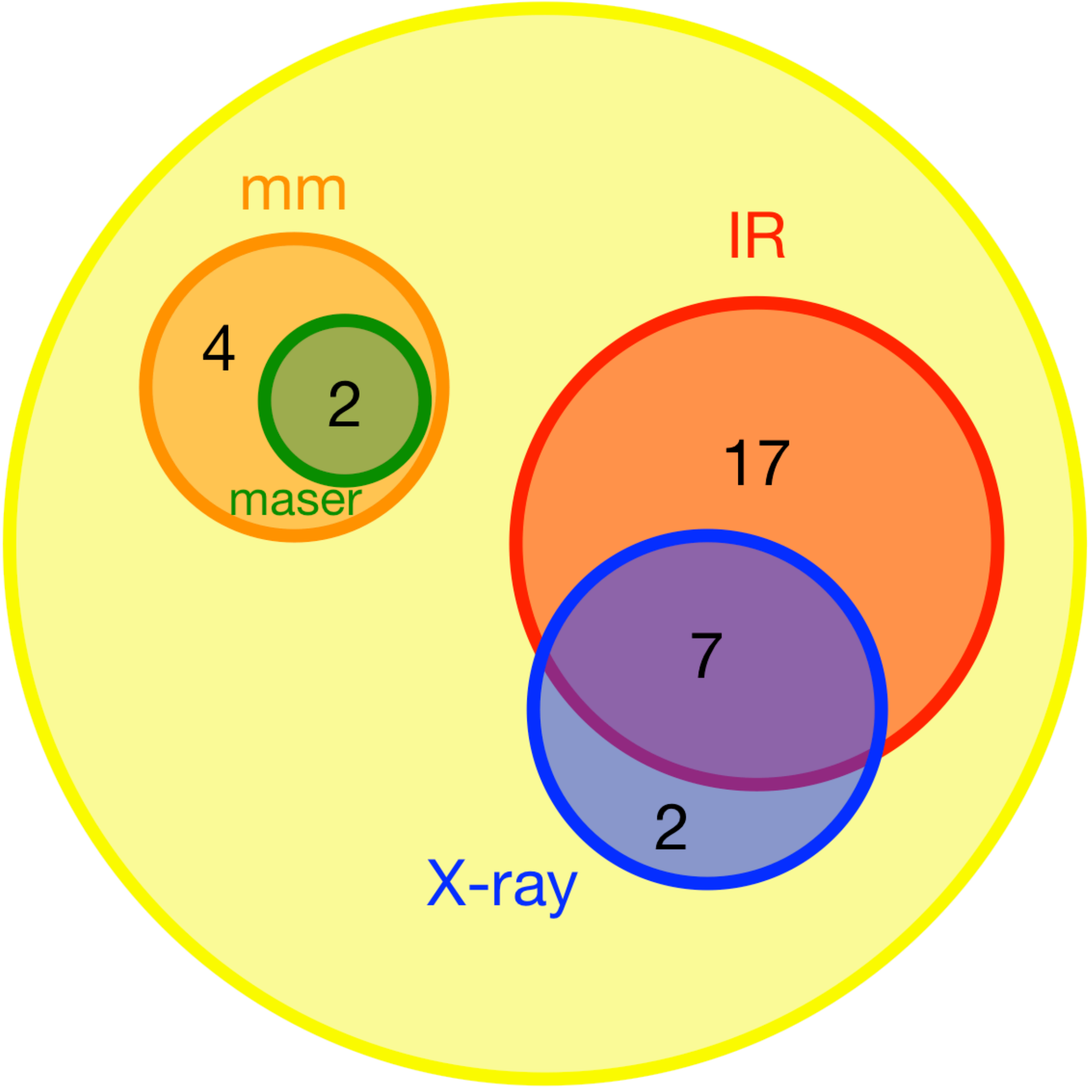
★ **Sensitivity:** 1.5 μJy/beam @10 GHz (3.6 cm) and 2 μJy/beam @6 GHz (6 cm)

★ **Observing time per pointing:** 10.8 hours at 3.6cm and 3.4 hours at 6 cm



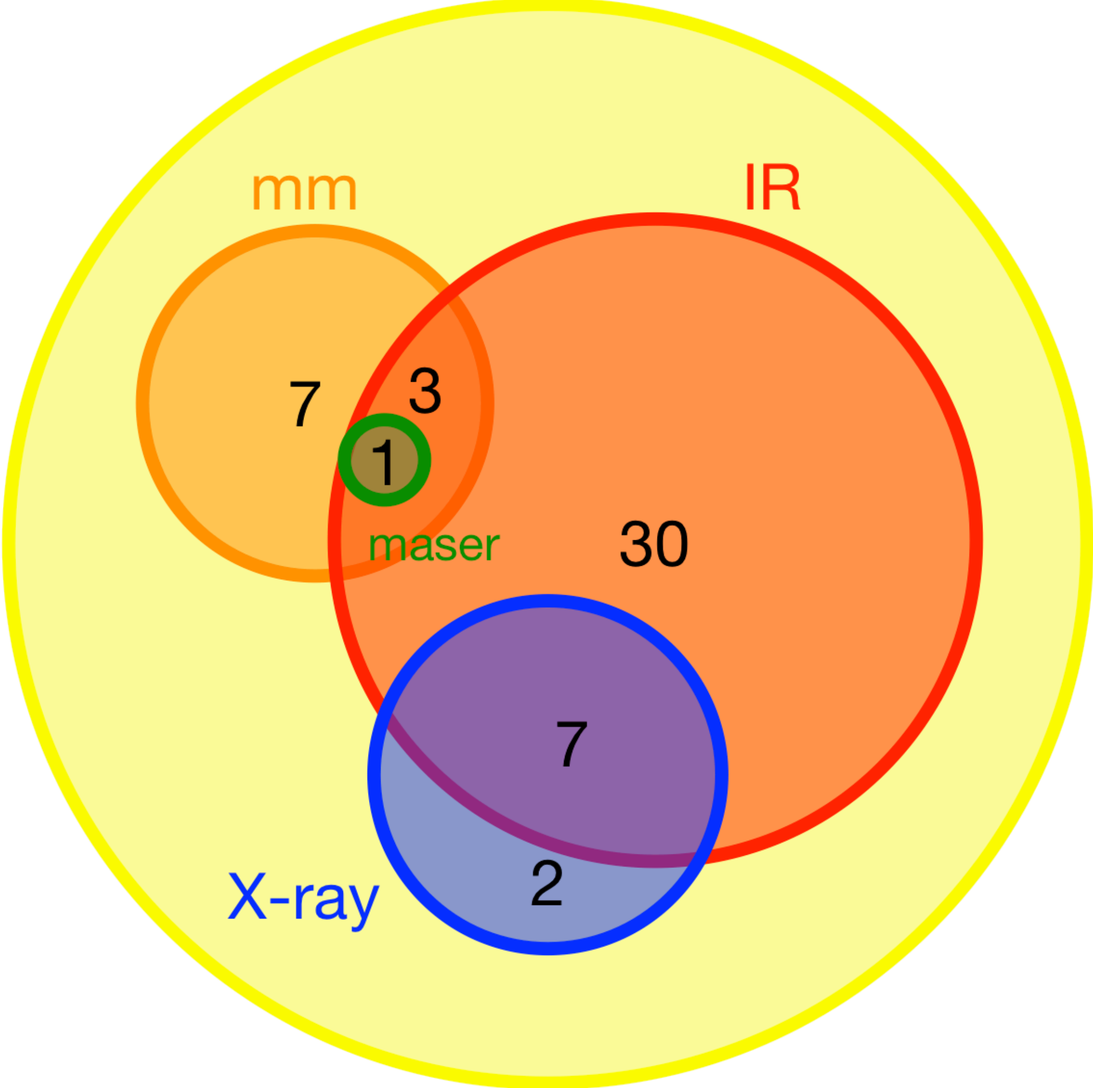
G14.2-N

36 RADIO SOURCES



G14.2-S

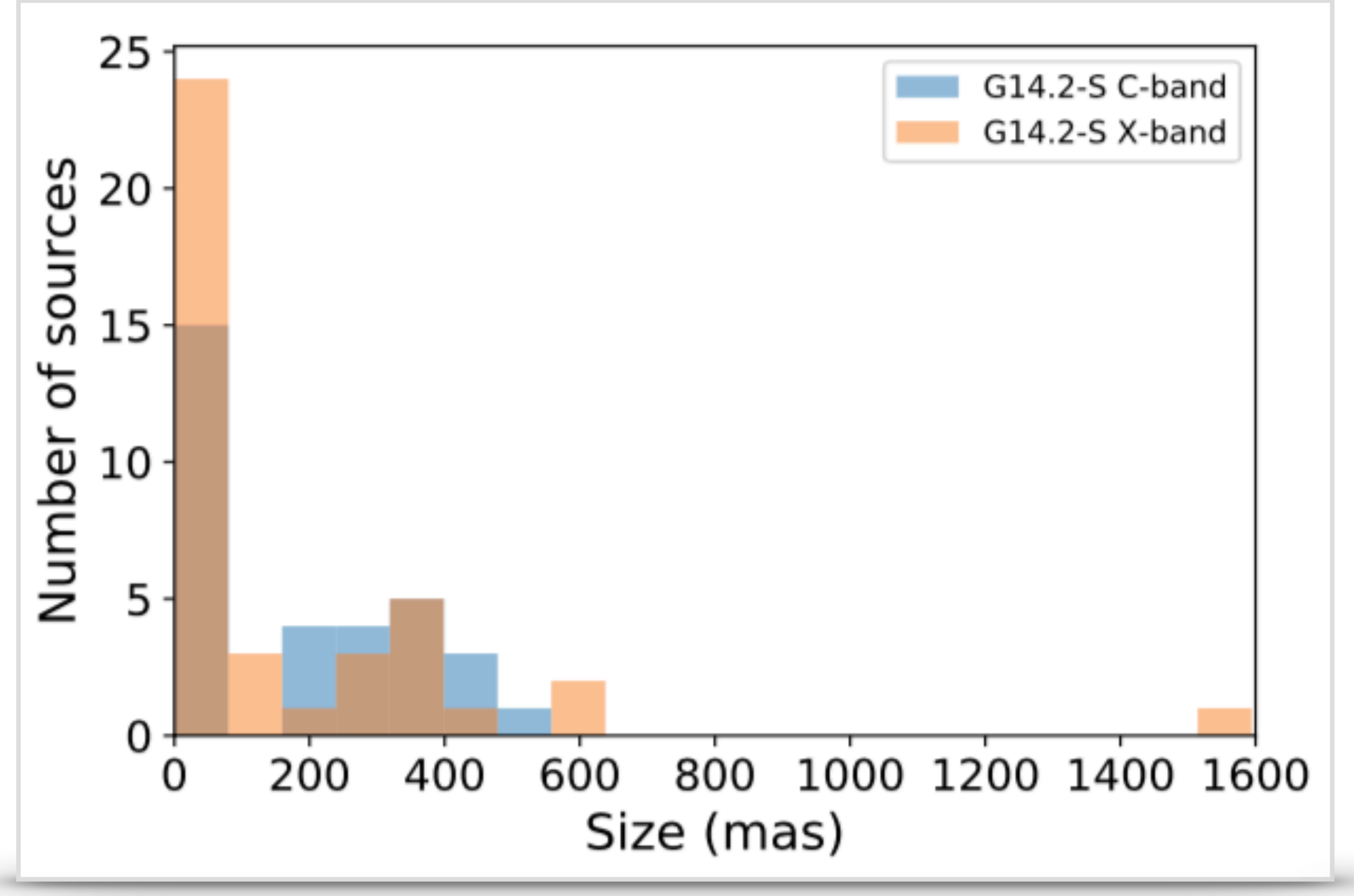
46 RADIO SOURCES

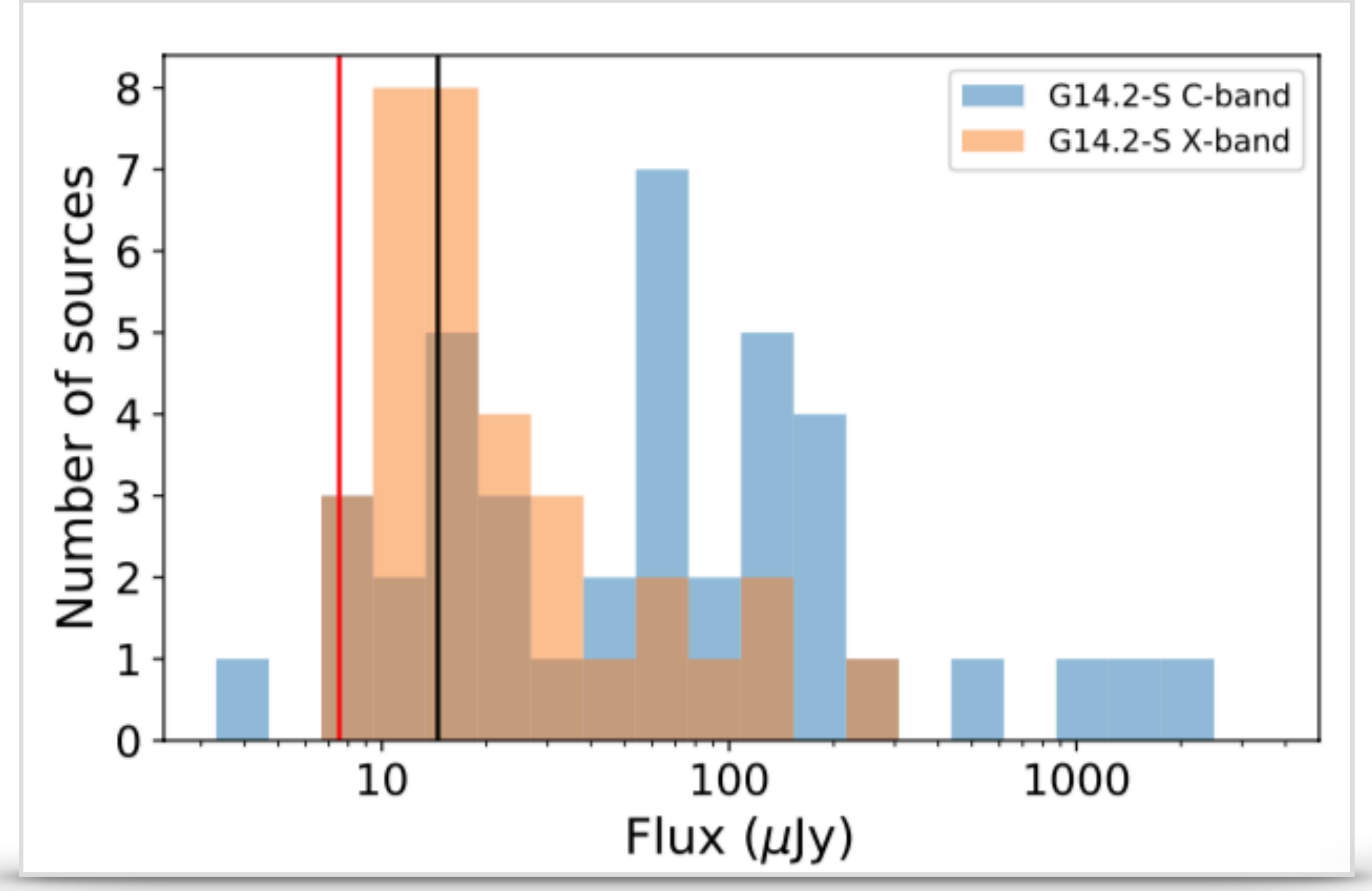


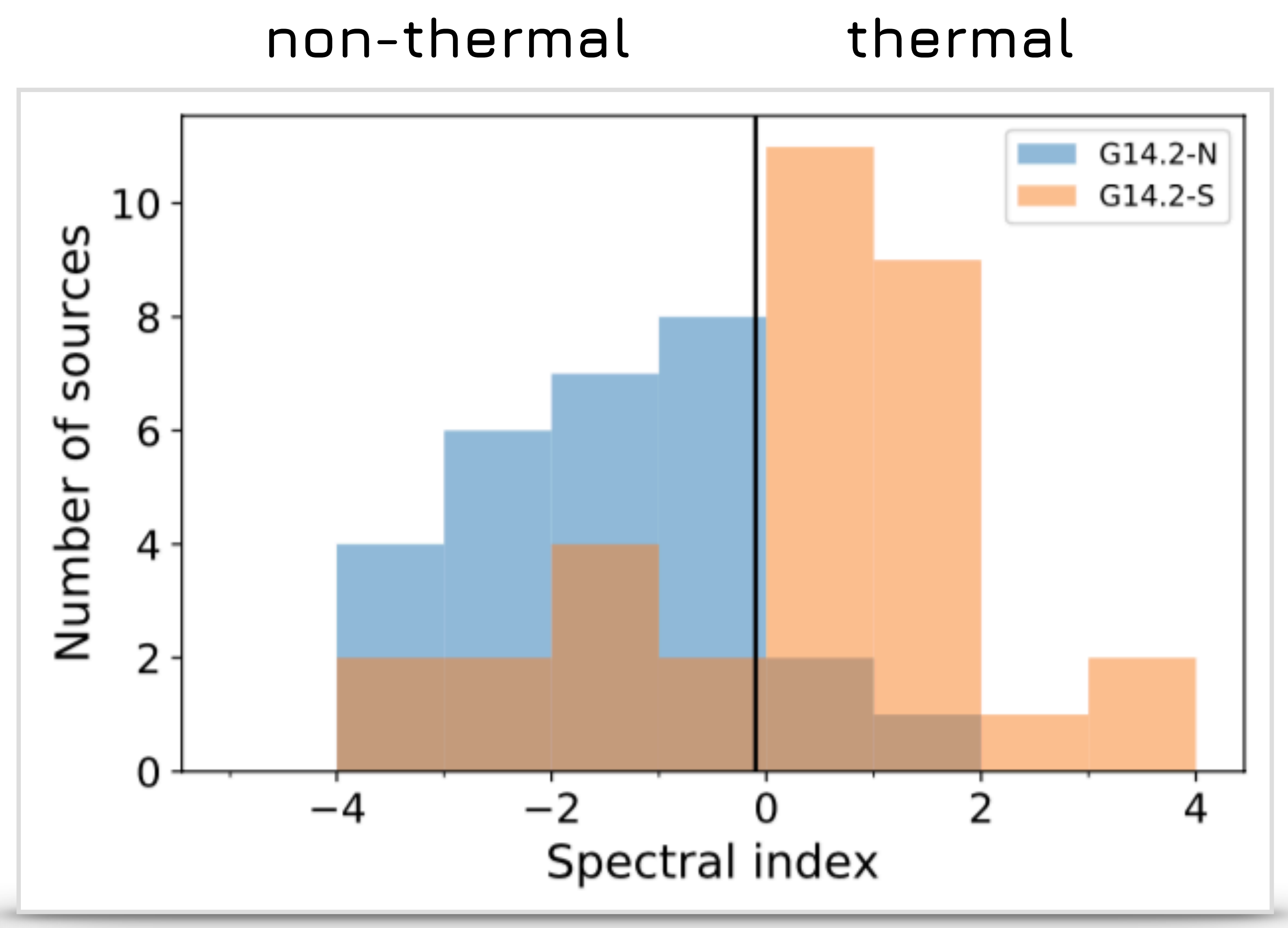
Collaboration: UB - CfA - ICE- ASIAA - Univ. Köln - Cal. Polytechnic Univ.

UNVEILING THE EMBEDDED POPULATION

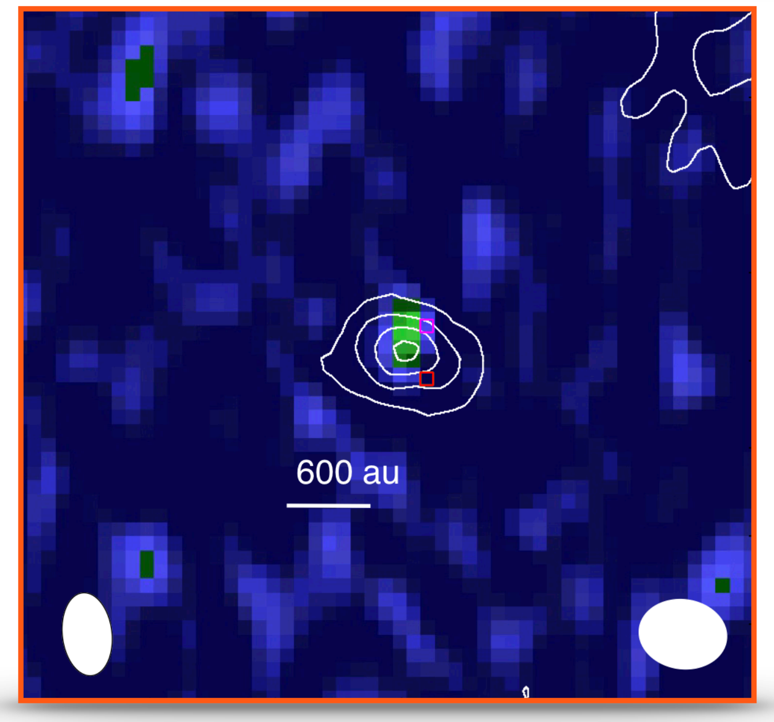
PILOT PROGRAM WITH THE JVLA

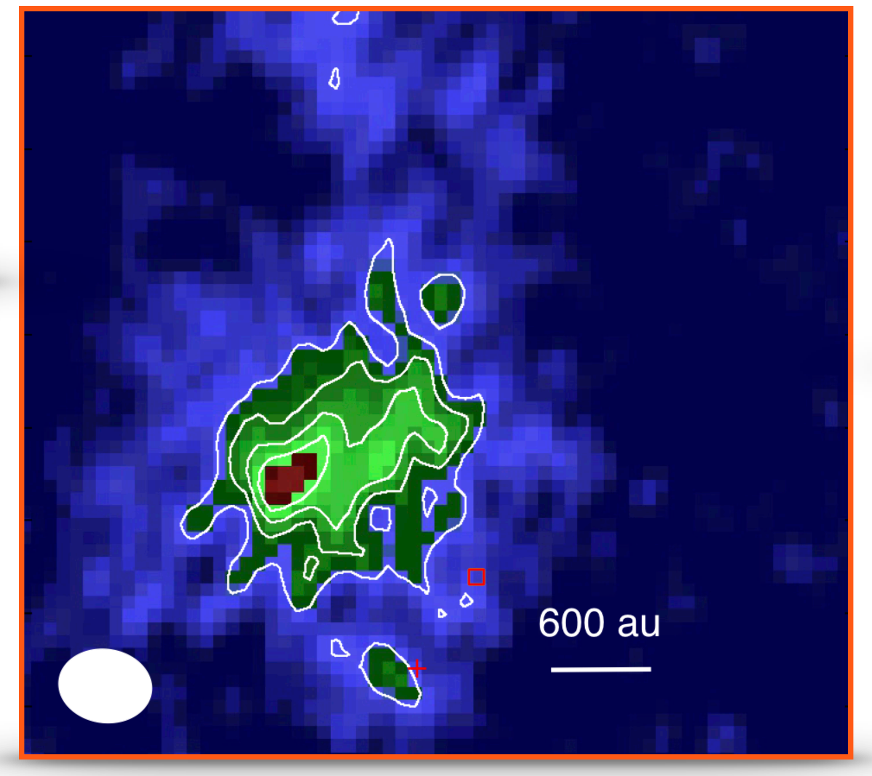


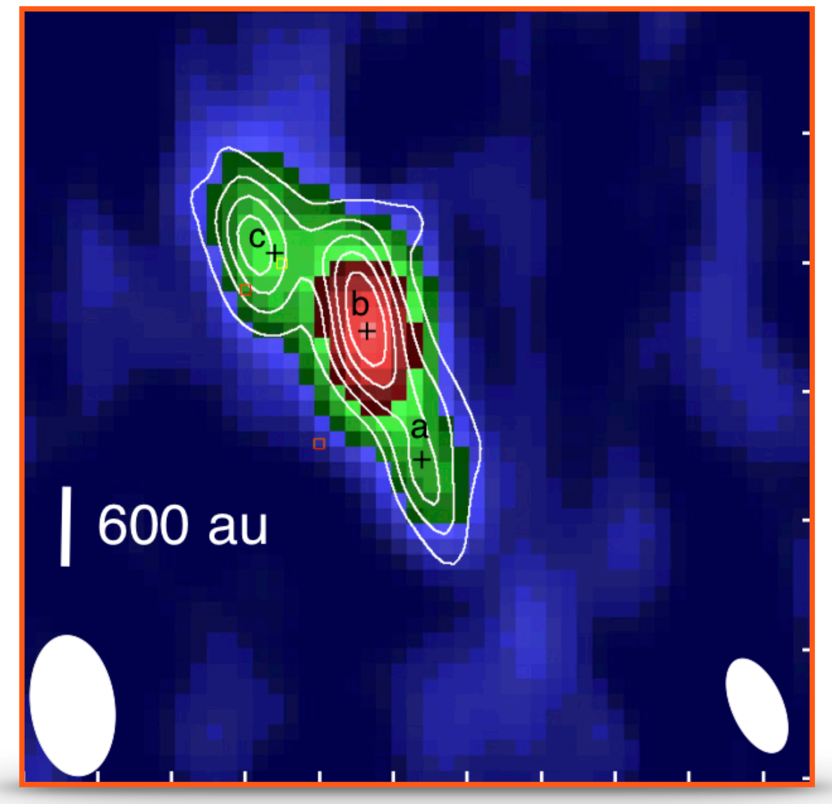


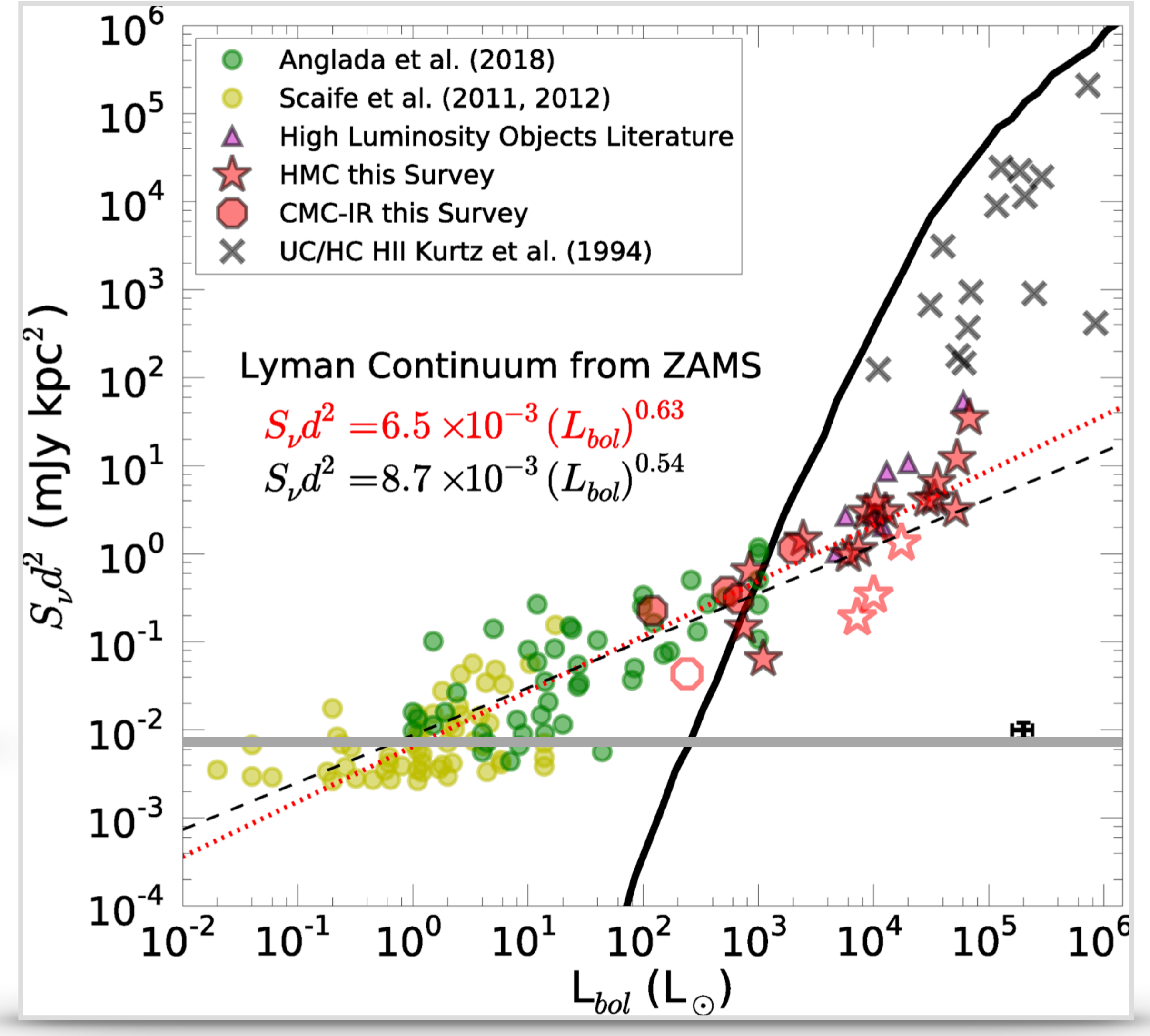


Roger Grau, Master Thesis (2020)





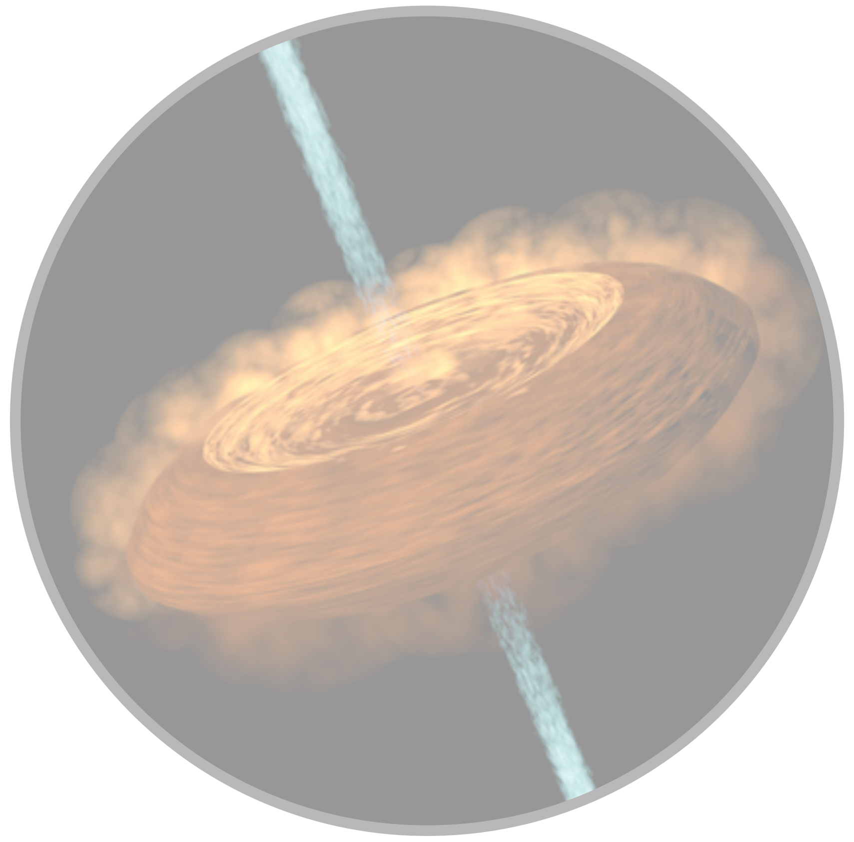




Rosero et al. (2019)

Investigate the ionising mechanism: radio jets vs. HII regions

OUTLINE



SCIENTIFIC CONTEXT

CURRENT WORK

- A NEW ERA FOR RADIO ASTRONOMY
- THE VOLS PROJECT

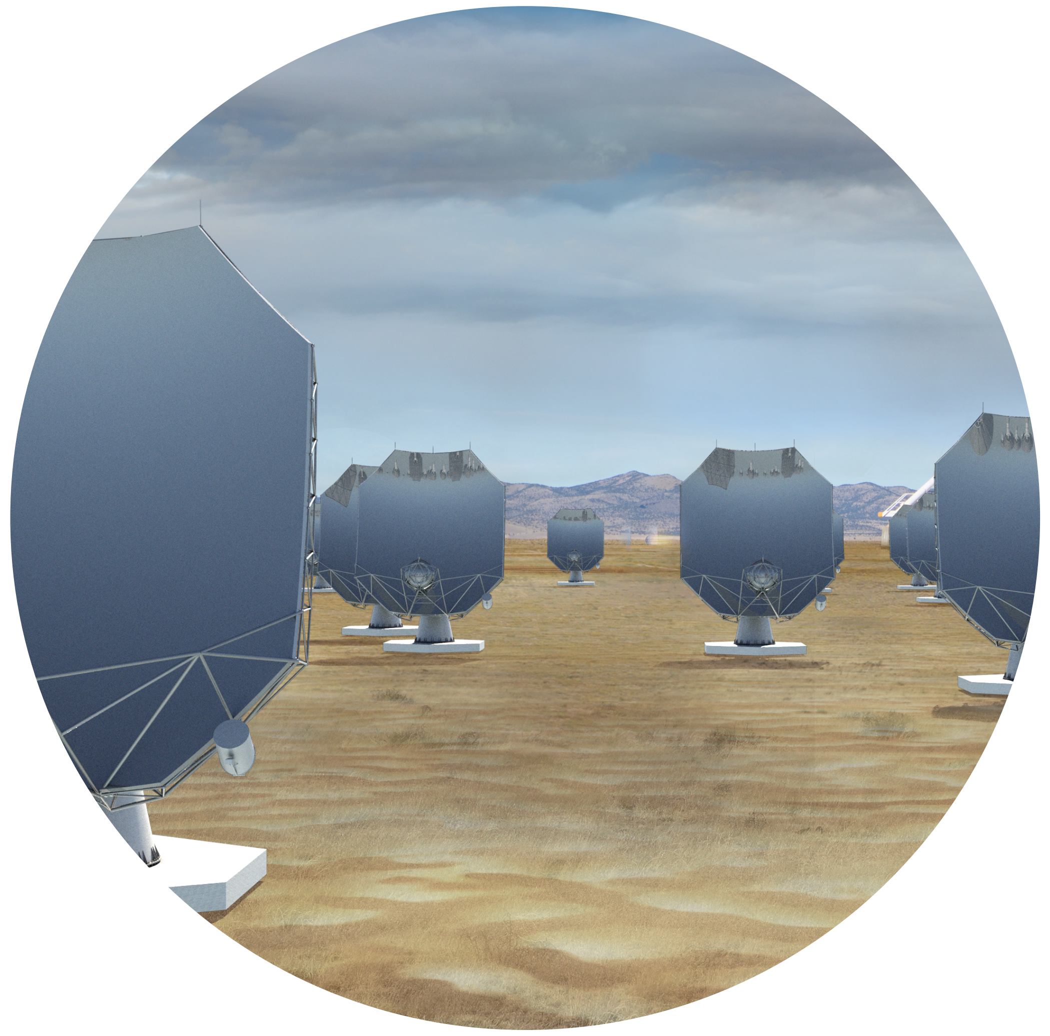
FUTURE PROJECTS

A NEW ERA FOR RADIOASTRONOMY

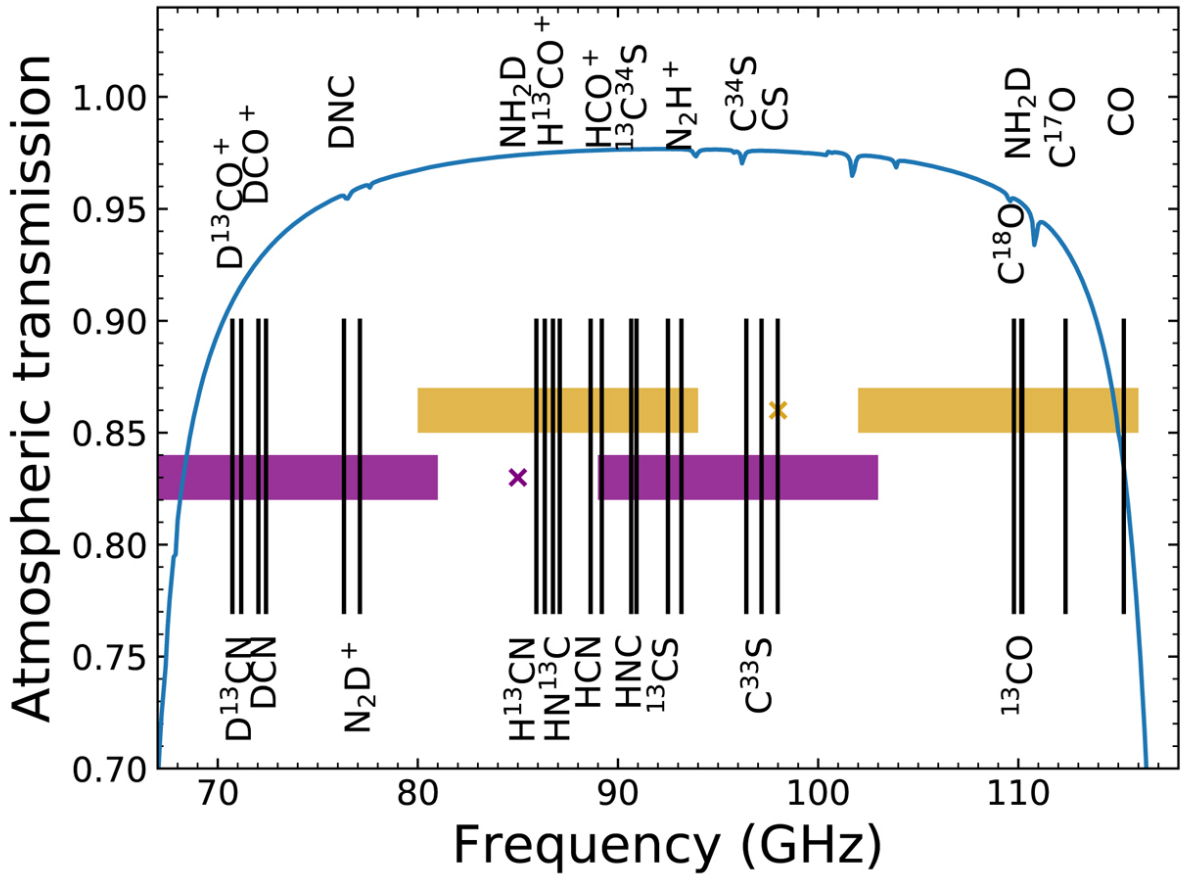
ALMA
Atacama Large Millimeter / submillimeter Array

SKA
SQUARE KILOMETRE ARRAY

ngvla



New Receivers:
Band 2: 67 - 116 GHz
Band 1: 35 - 50 GHz
(under construction)



Yagoubov et al. (2020)

SKA 1: 50 MHz - 15.4 GHz
SKA 2: 15- 50 GHz

263 antennas
1.2 - 116 GHz

★ **RESOLUTION:** 0.08" at 6.7 GHz ~160 au @ 2 kpc ; 0.04" at 12.5 GHz ~80 au @2kpc

★ **CONTINUUM SENSITIVITY:** 1.3 μJy/beam @6.7 GHz; 1.2 μJy/beam @ 12.5 GHz GHz

in **ONLY 1 hour of observing time!**

VOLS: THE VLA ORION A LARGE SURVEY

Large Proposal 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)

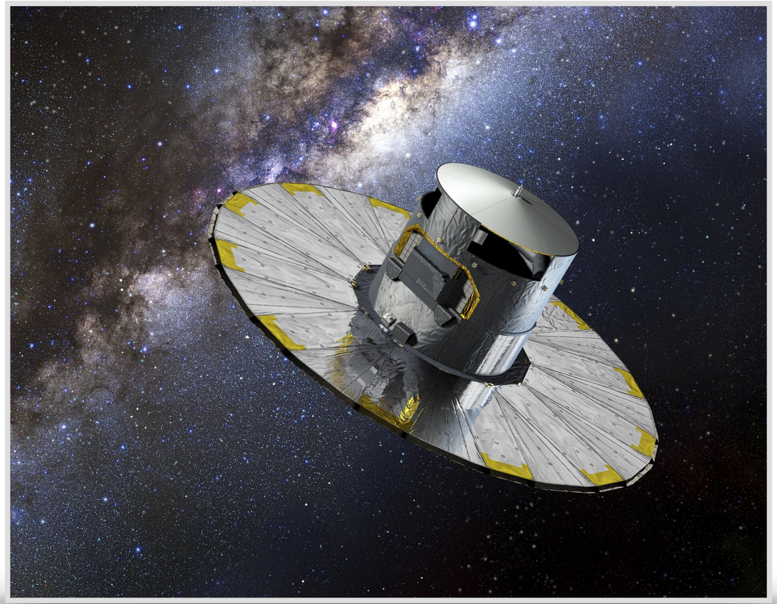
Global collaboration: 44 researches from 25 institutions worldwide

RADIO OBSERVATIONS

&

GAIA DR3 CATALOG

(U-band excess and H_α line profile)



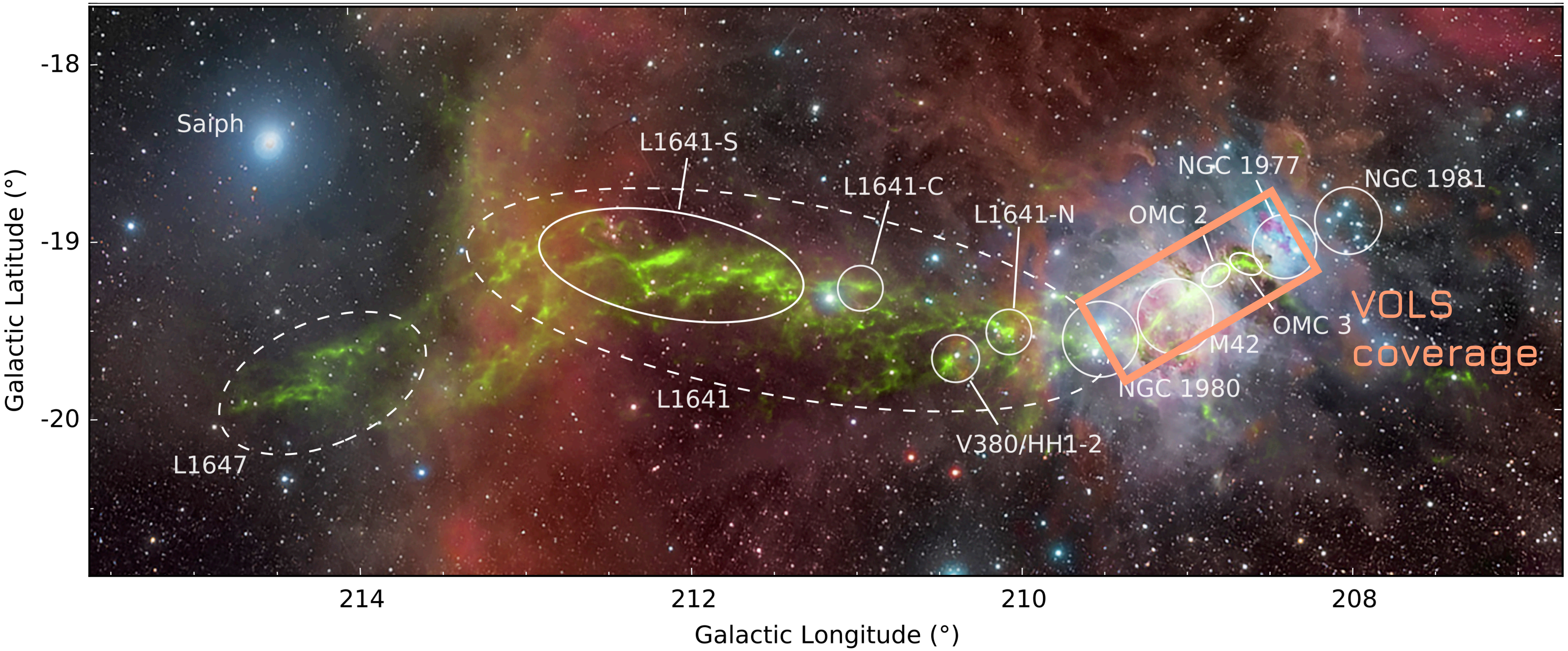


Figure from Meingast et al. (2016)

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, Großschedl 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.

★ CARMA-NRO Orion Survey: inventory of filament (Suri et al. 2019), level of turbulence and feedback and presence of expanding shells (Feddersen et al. 2018, 2019)

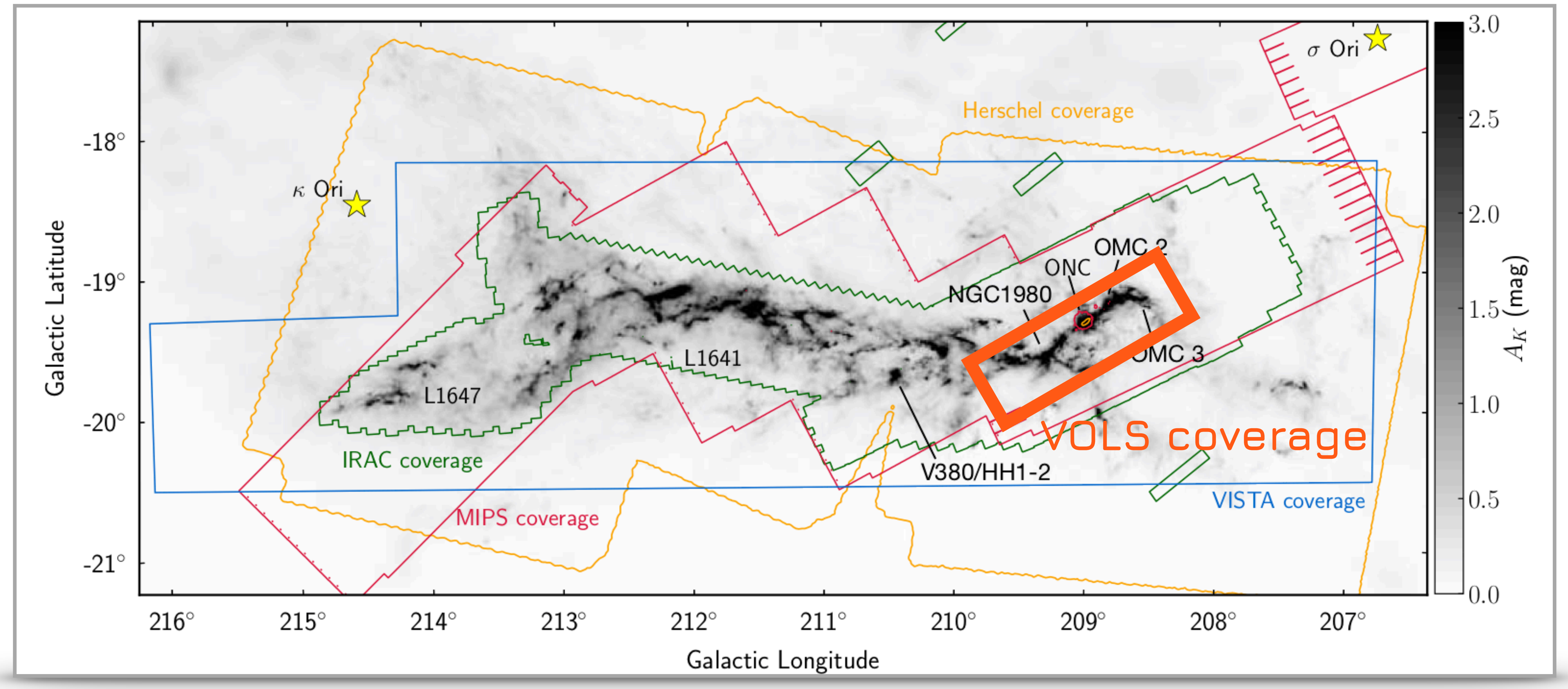


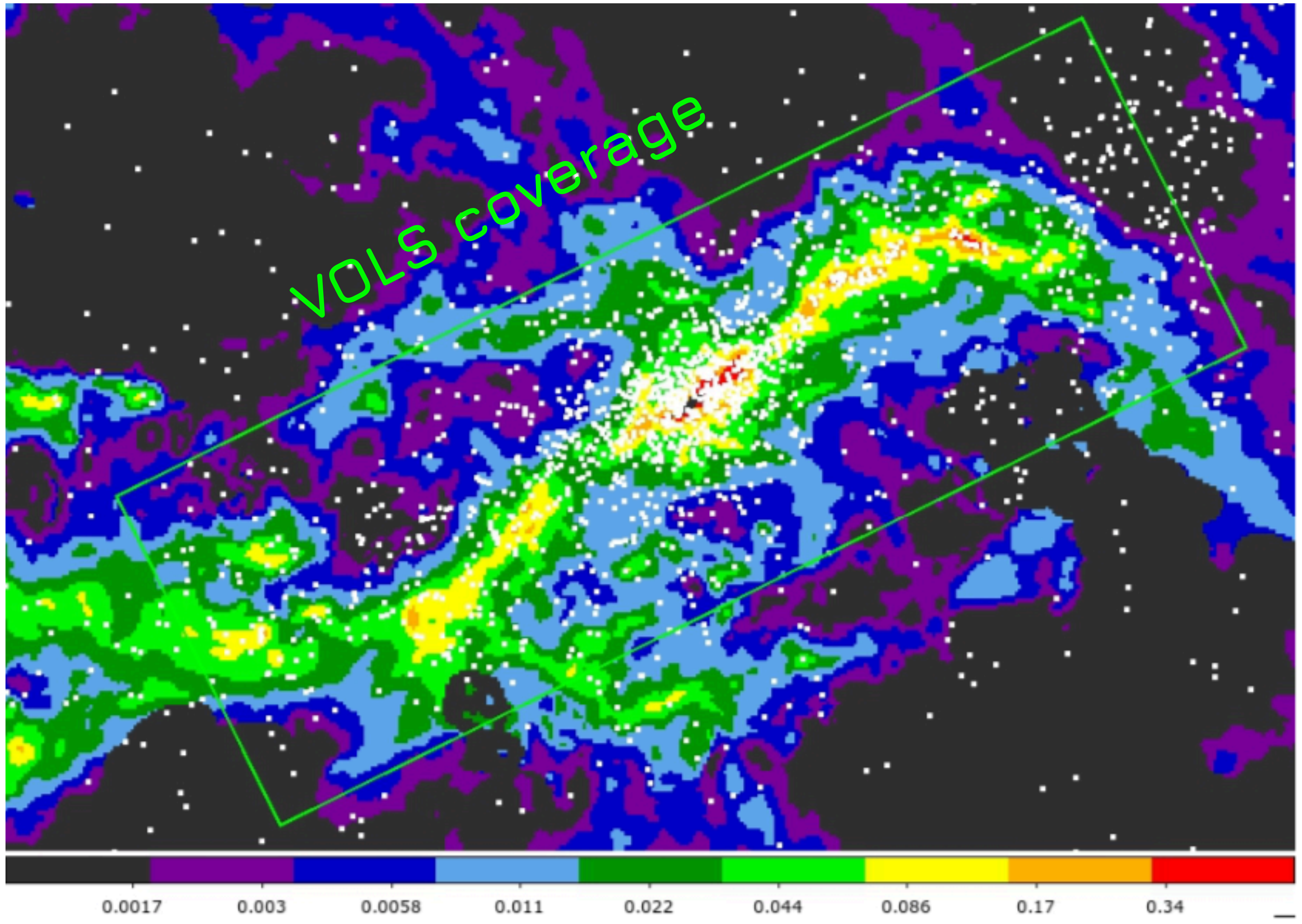
Figure from Großschedl et al. (2019)

VOLS: THE VLA ORION A LARGE SURVEY

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?



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

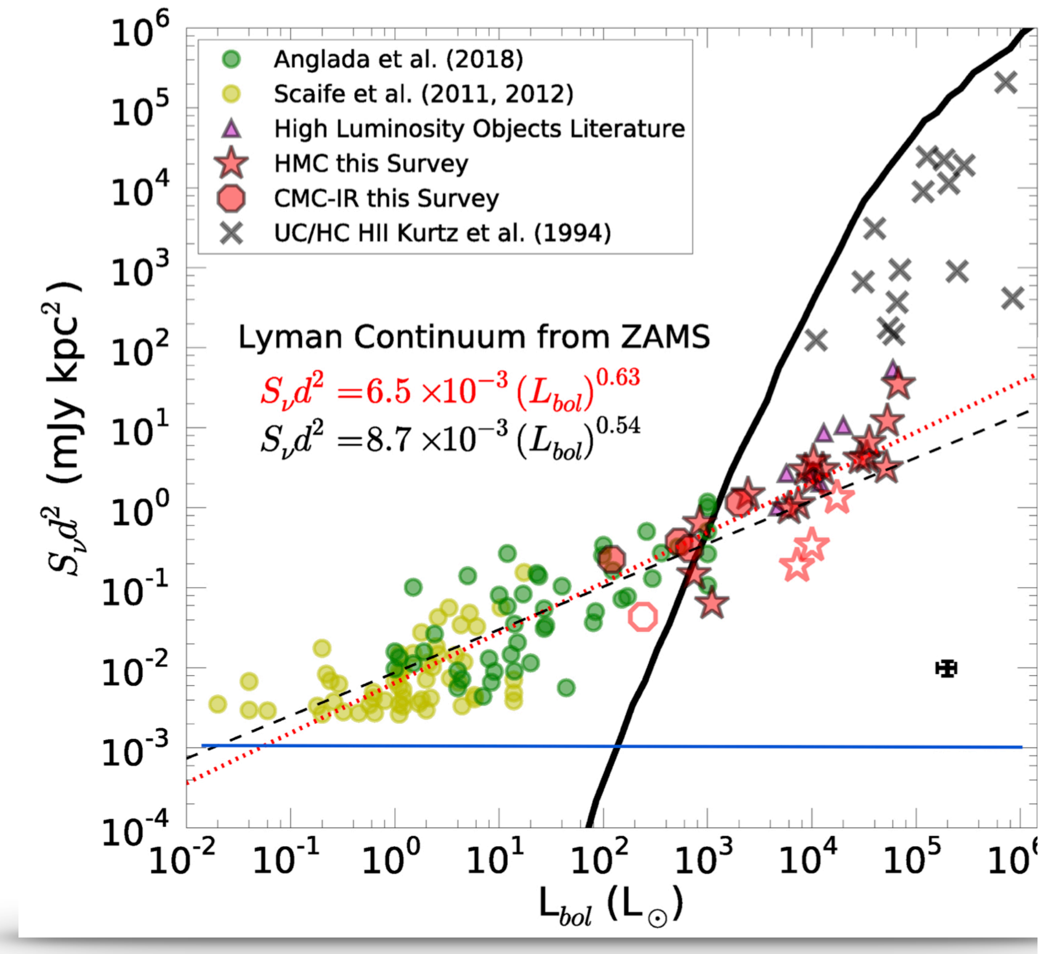
VOLS: THE VLA ORION A LARGE SURVEY

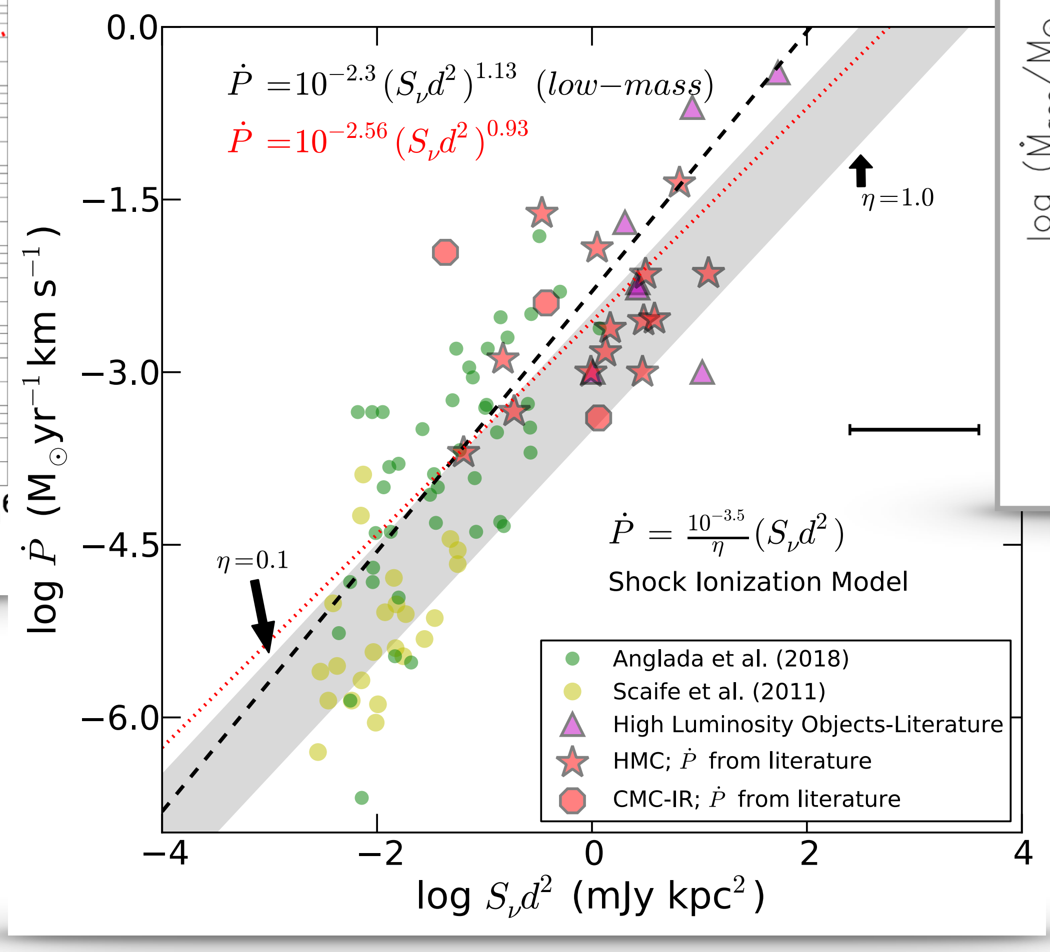
Obtain a census of the stellar population at cm wavelengths of Orion A

★ Build the Radio Luminosity Function over a wide range of masses/luminosities, evolutionary stages, and environmental conditions

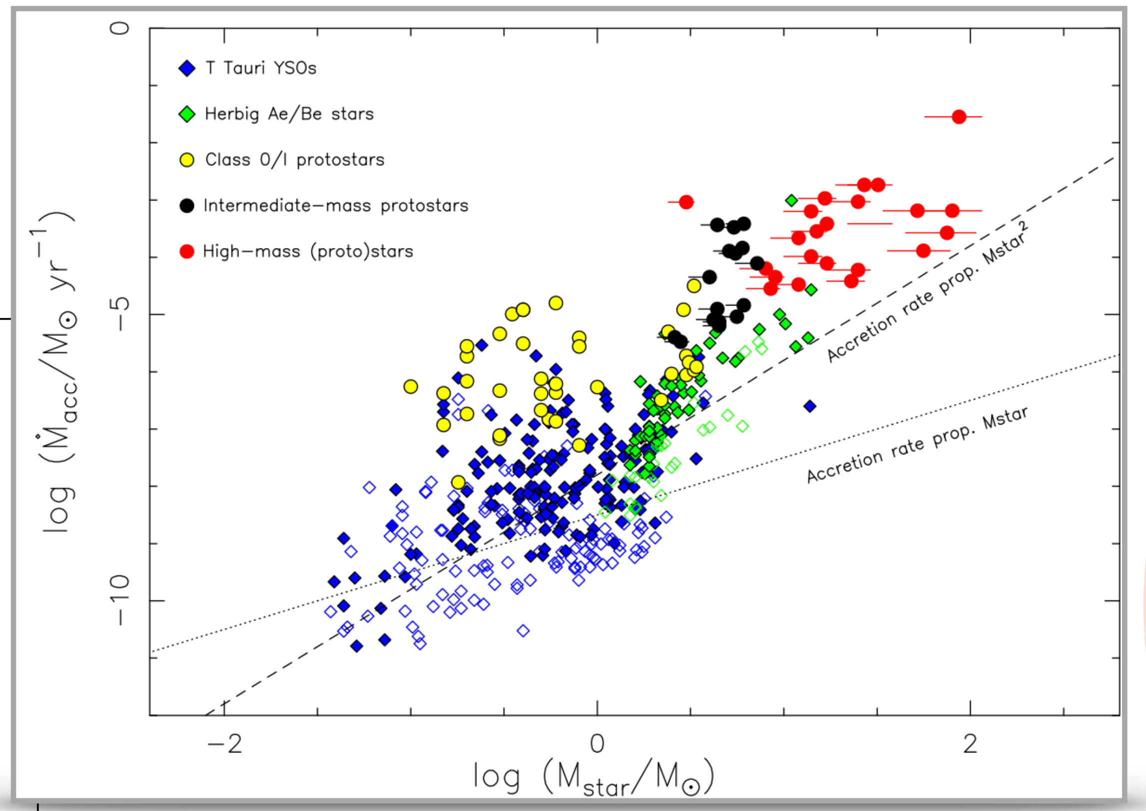
★ Accurate spectral indices (distinguish thermal and non-thermal emission)

★ Together with previous ancillary datasets across the EM spectrum: correlation between the characteristics of the radio emission from YSOs and their stellar properties





Rosero et al. (2019)



Beltrán & de Wit (2016)

Explore these correlations by spectral index, evolutionary stages and environment

Quantify how accretion and mass-loss proceeds

VOLS: THE VLA ORION A LARGE SURVEY

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

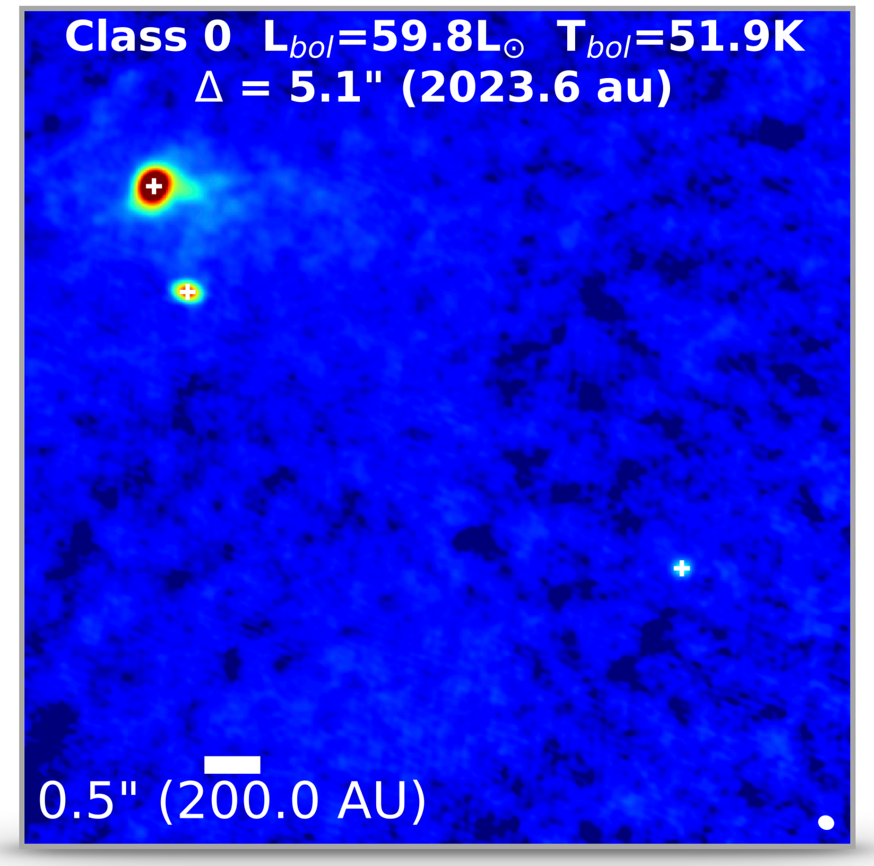
Possible to detect embedded early-type stars earlier than B6

SUBSTELLAR REGIME

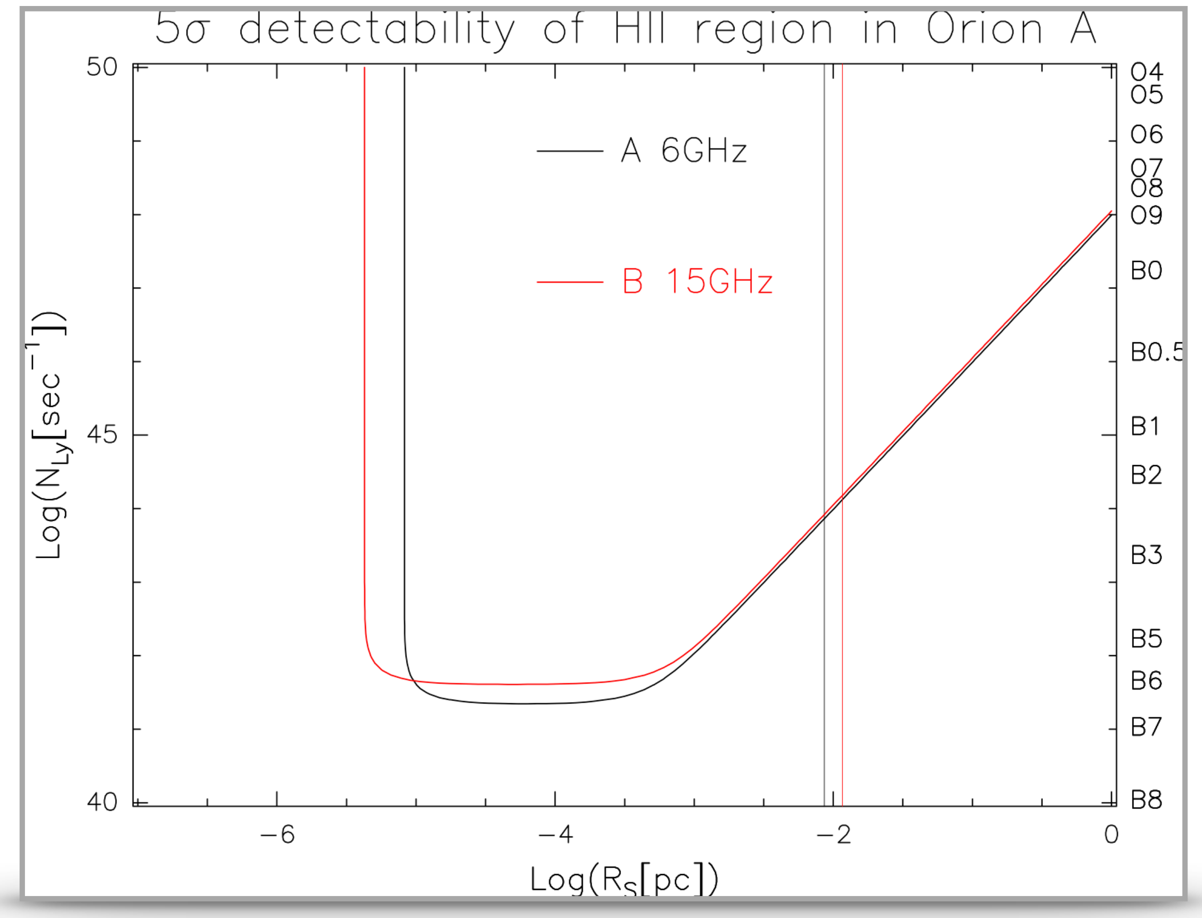
Unbiased survey searching for thermal radio jets driven by porto-brown dwarfs

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

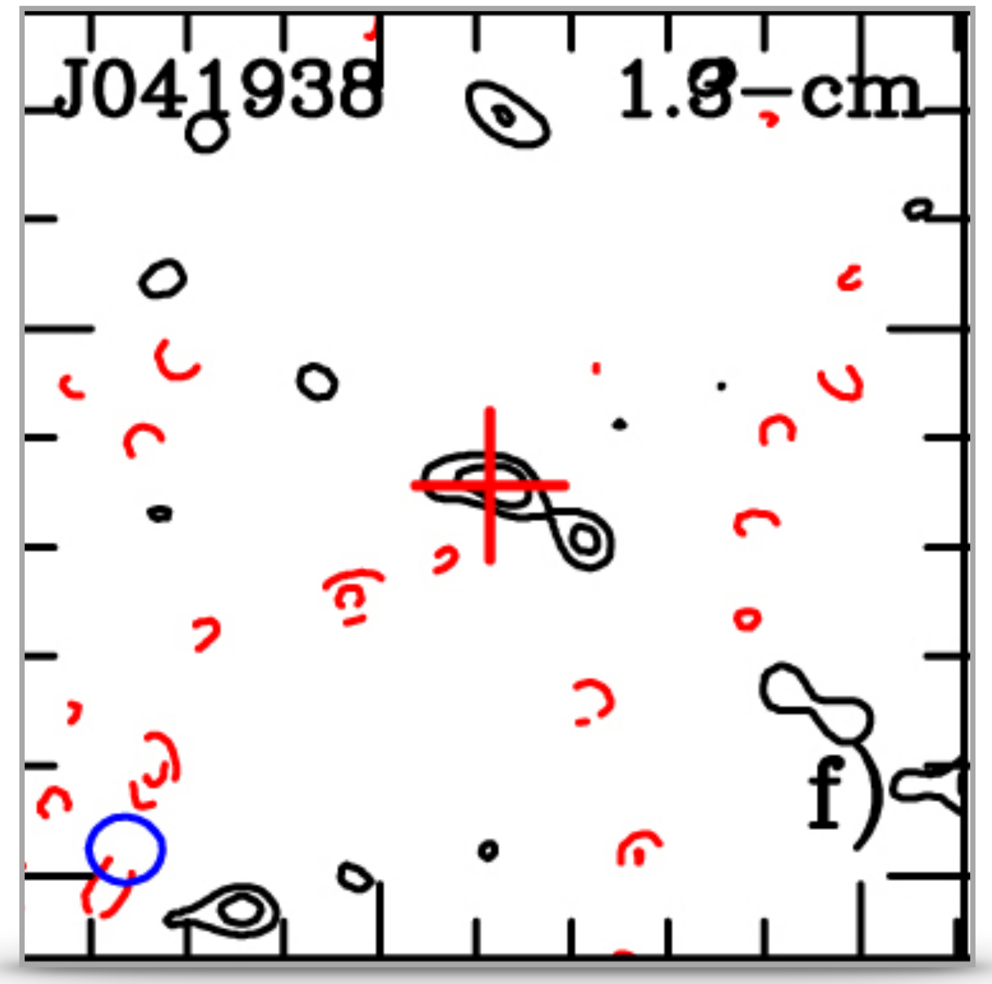
Tobin et al. (2020)



Courtesy R. Cesaroni



Morata et al. (2015)



THANK YOU!