Multiwavelength mysteries in Sagittarius B2

Nazar Budaiev (UF)

Adam Ginsburg (UF)

Second lunch talk…

August 5, 2019 at 1:20 PM

I am part of the GBT Diffuse Ionized Gas survey, which looks at Warm Ionized Medium regions
HII - 1-10^5 cm^-3
20% of Milky Way gas mass
Low density ionized gas 0.1 cm^-3
10^4 K

Massive star formation,
Influence on inerstelar medi
Lifecycle of gas
Evolution
Comparison
Filements in supernovas
Clouds that do not form stars
I make A C-Band (4 MHz - 8 MHz) Continuum Map of the Inner Galactic Plane Between -5 deg and 32 deg

How the telescope collects the data
4 scans, 2 in vertical 2 in horizontal

Cube files at several frequencies
Averages to make cont files
Destreaks
Averages over all frequencies and polarizations

Current state: all telescope files converted

Future plans: stitch files to make a big map
Compare intensities with similar maps
Get rid of artifacts (some images are better then others)

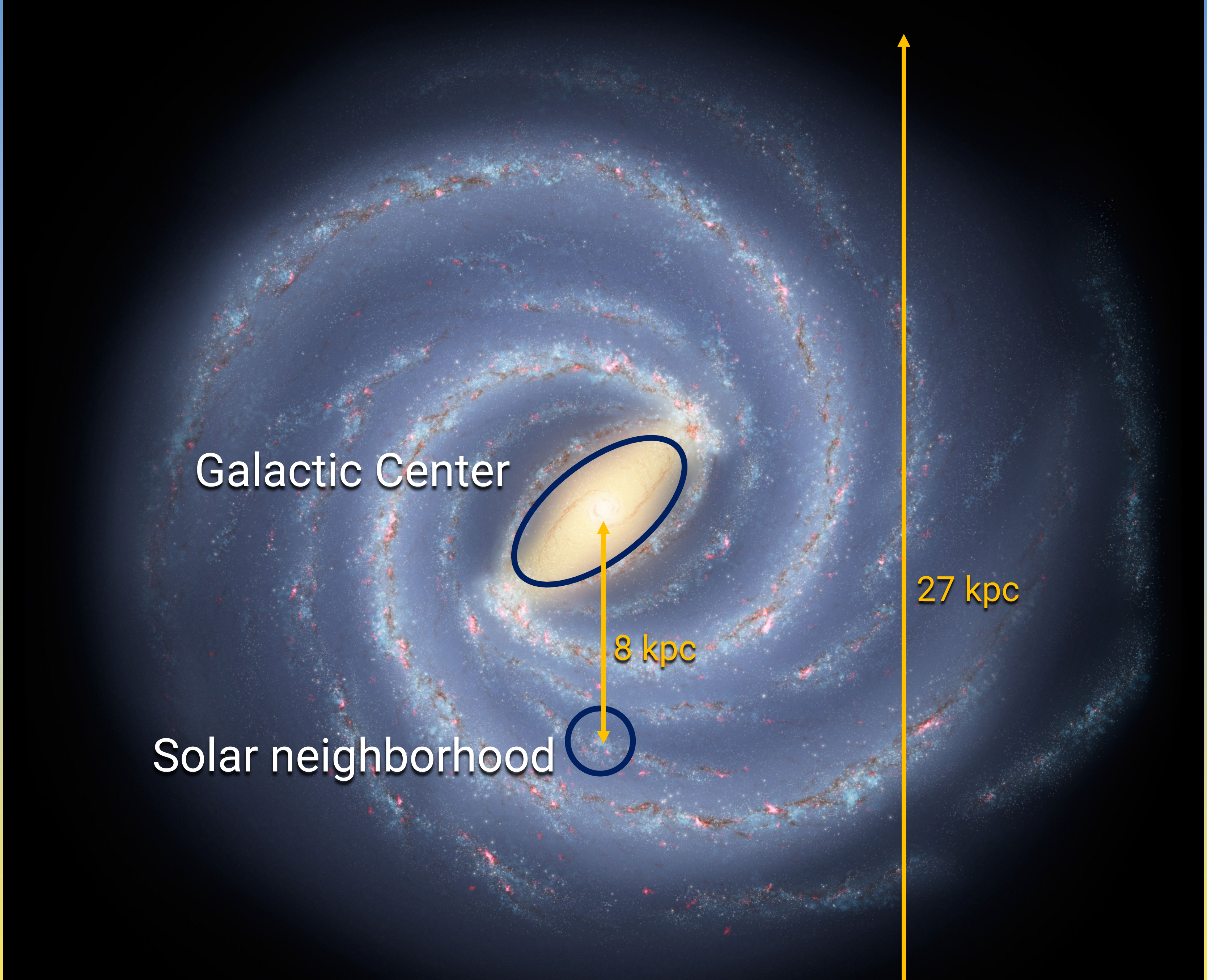
NRAO CENTRAL DEVELOPMENT LABORATORY AGENDA
5 August 2019
10:15 a.m. – 1:30 p.m
NRAO and GBO summer students

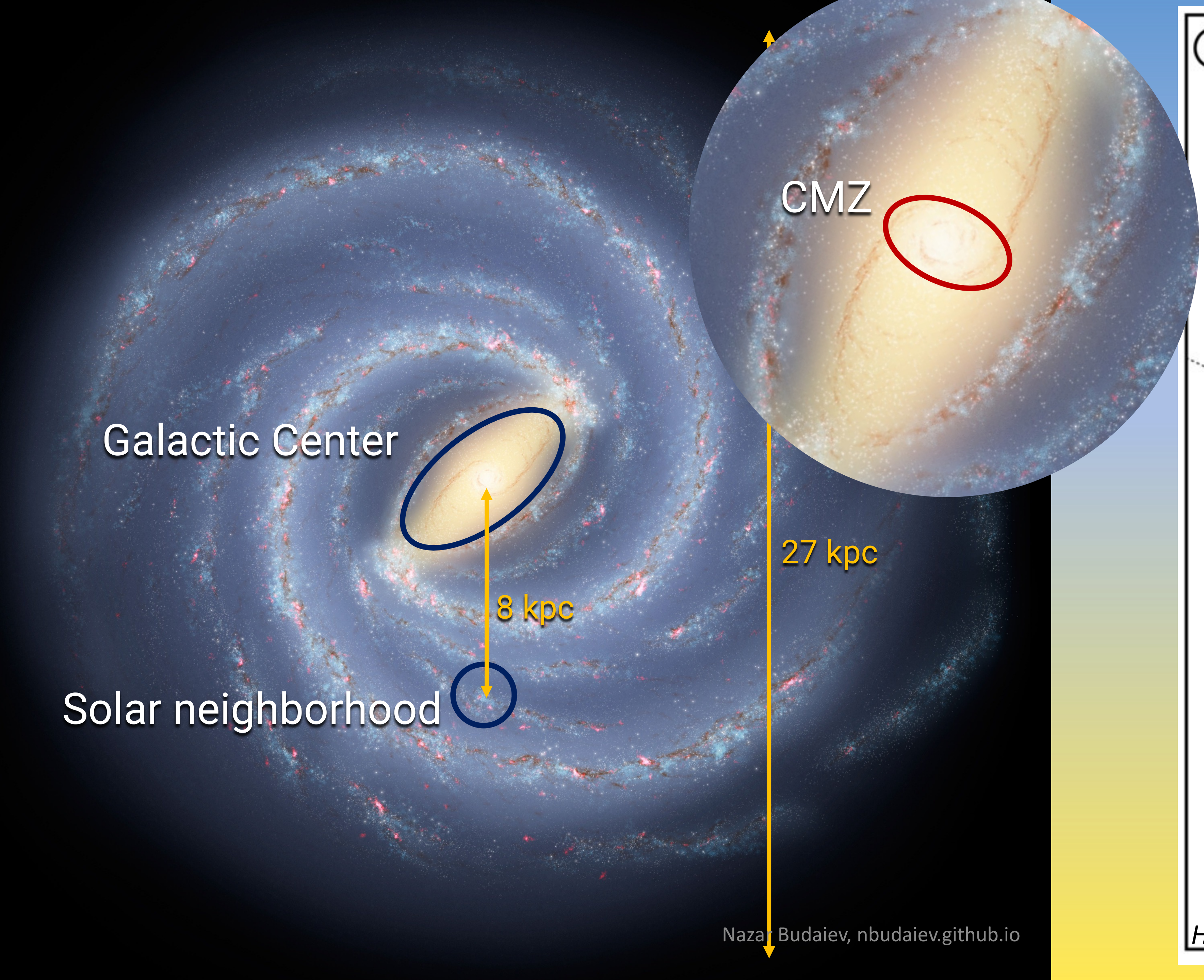
Host/Contact:
Morgan McLeod
434-296-0332
mmcleod@nrao.edu

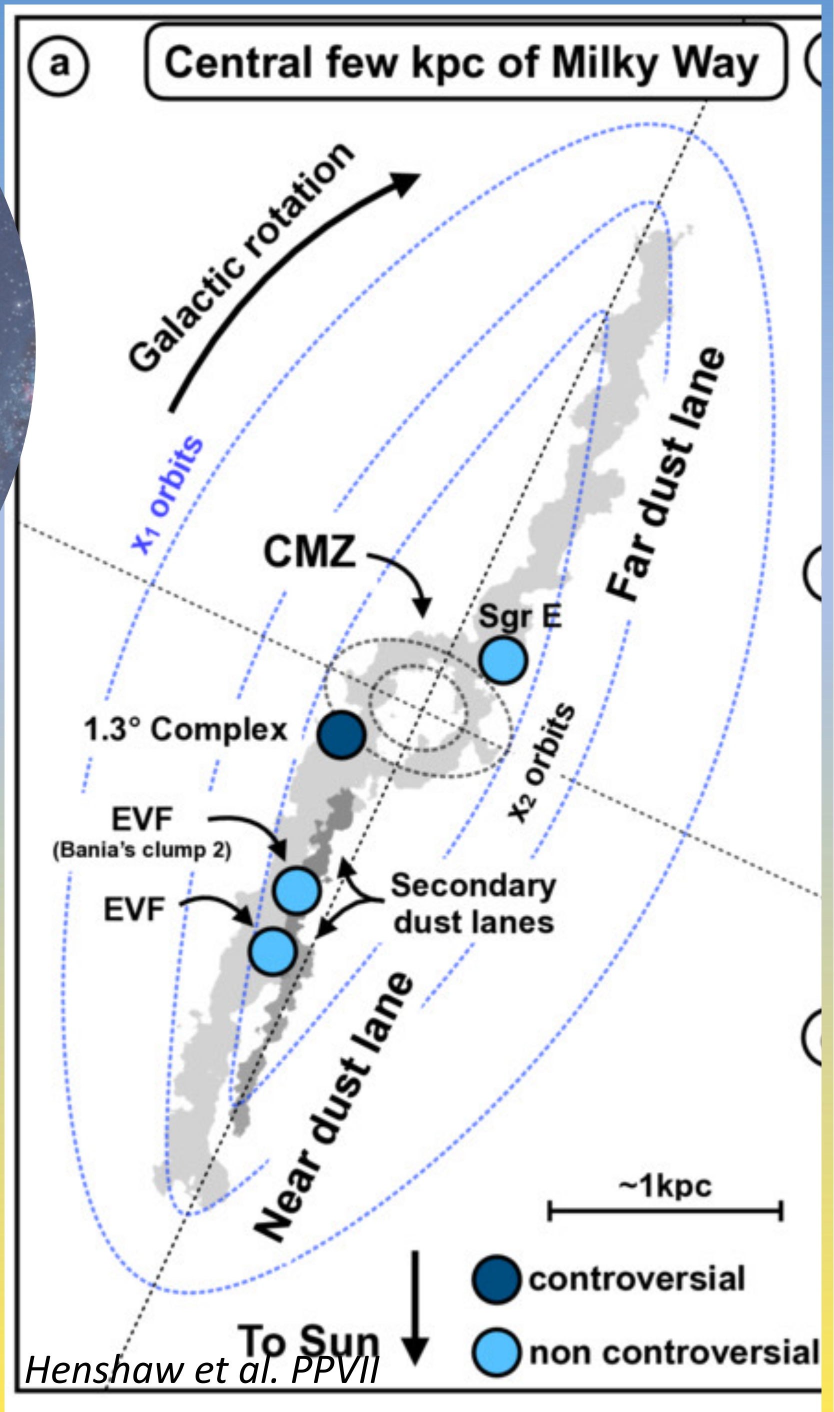
Time	Meeting with	Location	Subject
10:15 – 10:25 a.m.	M. McLeod	Room 400	CDL Overview
10:30 – 10:43 a.m.	T. Kerr	2nd Floor Lobby	MMW receivers
10:45 – 10:58 a.m.	G. Petencin	Room 303A	Chemistry Lab
11:00 – 11:13 a.m.	Matt Morgan	Room 306	Integrated Receivers
11:15 – 11:28 a.m.	M. Pospieszalski	Room 306	LNAs
11:30 – 11:40 a.m.	M. McLeod	Room 104	FEIC Lab
11:42 – 11:55 a.m.	G. Morris	Room 102	Machine Shop
12:00 - 12:13 p.m.	C. Jacques	Room B129	Photonics Lab
12:15 – 12:25 p.m.	R. Amestica	Room B107	Correlator Lab
12:30 - 1:30 p.m.		Room 400	Lunch and research summaries

Outline

- Introducing CMZ and Sagittarius B2
- A bunch of results (solved mysteries)
- Putting the results together (to solve mysteries)
- New data (new mysteries)


Galactic Center
27 kpc
8 kpc
Solar neighborhood

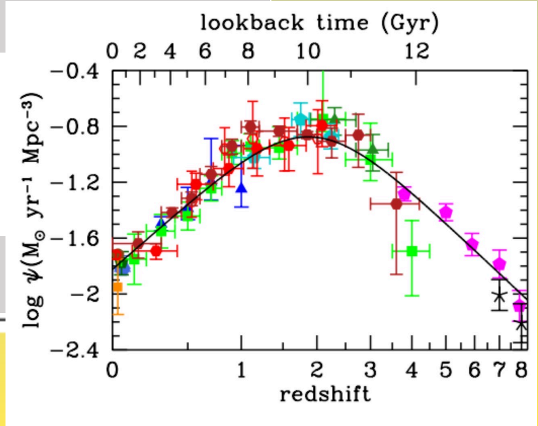




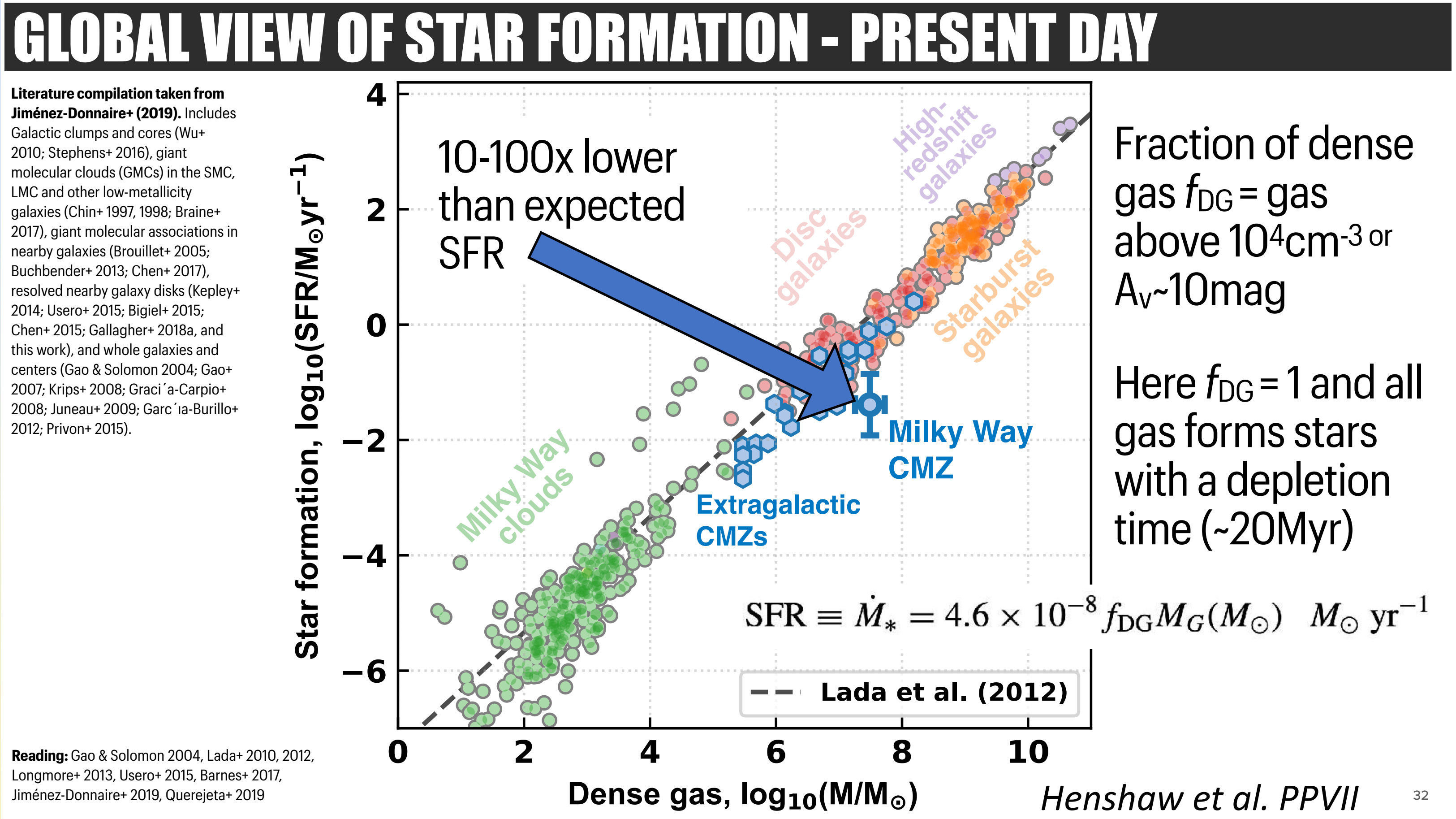
Henshaw et al. PPVII

Physical Quantity	CMZ	Solar Neighborhood	
Distance [kpc][a]	8.2	0.1 to 0.5	
SFR [$M_\odot \mathrm{yr}^{-1}$][b]	0.07 (0.012 to 0.14)	0.002	
Σ_{gas} [$\log_{10}(M_\odot \mathrm{pc}^{-2})$][c]	3.1 (2.8 to 3.2)	1.5	x100
Σ_{SFR} [$\log_{10}(M_\odot \mathrm{yr}^{-1} \mathrm{kpc}^{-2})$][d]	0.3 (−0.4 to 0.6)	−2.5	x100
Σ_* [$\log_{10}(M_\odot \mathrm{pc}^{-2})$][e]	3.9	1.5	x100
t_{dep} [Gyr][f]	0.5 (0.4 to 1.5)	1	
t_{dyn} [Myr][g]	5	220	
$B[\mu\mathrm{G}]$[h]	10 to 1000	1 to 100	x10-100
Metallicity, Z[i]	2	1	
CRIR [$\log_{10}(\mathrm{s}^{-1})$][j]	−15 to −13	−17 to −15	
Linewidth, $\sigma(10\mathrm{pc})$ [km s^{-1}][l]	12	3	x4
Linewidth scaling, b[m]	0.7	0.5	
IMF slope, α[n]	≤2.35	2.35	
DGMF, $f(n > 10^4)$[o]	0.95	0.03	x30
T_{gas} [K][p]	50 to 100	10 to 30	x3-5
T_{dust} [K][q]	20 to 50	10 to 30	x2
$P_{\mathrm{ext}}/k_{\mathrm{B}}$ [K cm^{-3}][r]	$\gtrsim 10^7$	$\gtrsim 10^5$	

Physical Quantity	CMZ	Solar Neighborhood		$z \sim 2$
Distance [kpc][(a)]	8.2	0.1 to 0.5		$\sim 10^6$ ($z \sim 2$)
SFR [$M_\odot \mathrm{yr}^{-1}$][(b)]	0.07 (0.012 to 0.14)	0.002		1 to 100
Σ_{gas} [$\log_{10}(M_\odot \mathrm{pc}^{-2})$][(c)]	3.1 (2.8 to 3.2)	1.5	x100	1.5 to 3.5
Σ_{SFR} [$\log_{10}(M_\odot \mathrm{yr}^{-1} \mathrm{kpc}^{-2})$][(d)]	0.3 (−0.4 to 0.6)	−2.5	x100	−1.5 to 1.5
Σ_* [$\log_{10}(M_\odot \mathrm{pc}^{-2})$][(e)]	3.9	1.5	x100	1 to 4
t_{dep} [Gyr][(f)]	0.5 (0.4 to 1.5)	1		0.2 to 1
t_{dyn} [Myr][(g)]	5	220		?
B[μG][(h)]	10 to 1000	1 to 100	x10-100	?
Metallicity, Z[(i)]	2	1		0.2 to 0.6
CRIR [$\log_{10}(\mathrm{s}^{-1})$][(j)]	−15 to −13	−17 to −15		?
Linewidth, σ(10pc) [km s^{-1}][(l)]	12	3	x4	20 to 70
Linewidth scaling, b[(m)]	0.7	0.5		?
IMF slope, α[(n)]	≤2.35	2.35		
DGMF, $f(n > 10^4)$[(o)]	0.95	0.03	x30	
T_{gas} [K][(p)]	50 to 100	10 to 30	x3-5	
T_{dust} [K][(q)]	20 to 50	10 to 30	x2	
$P_{\mathrm{ext}}/k_{\mathrm{B}}$ [K cm^{-3}][(r)]	$\gtrsim 10^7$	$\gtrsim 10^5$		



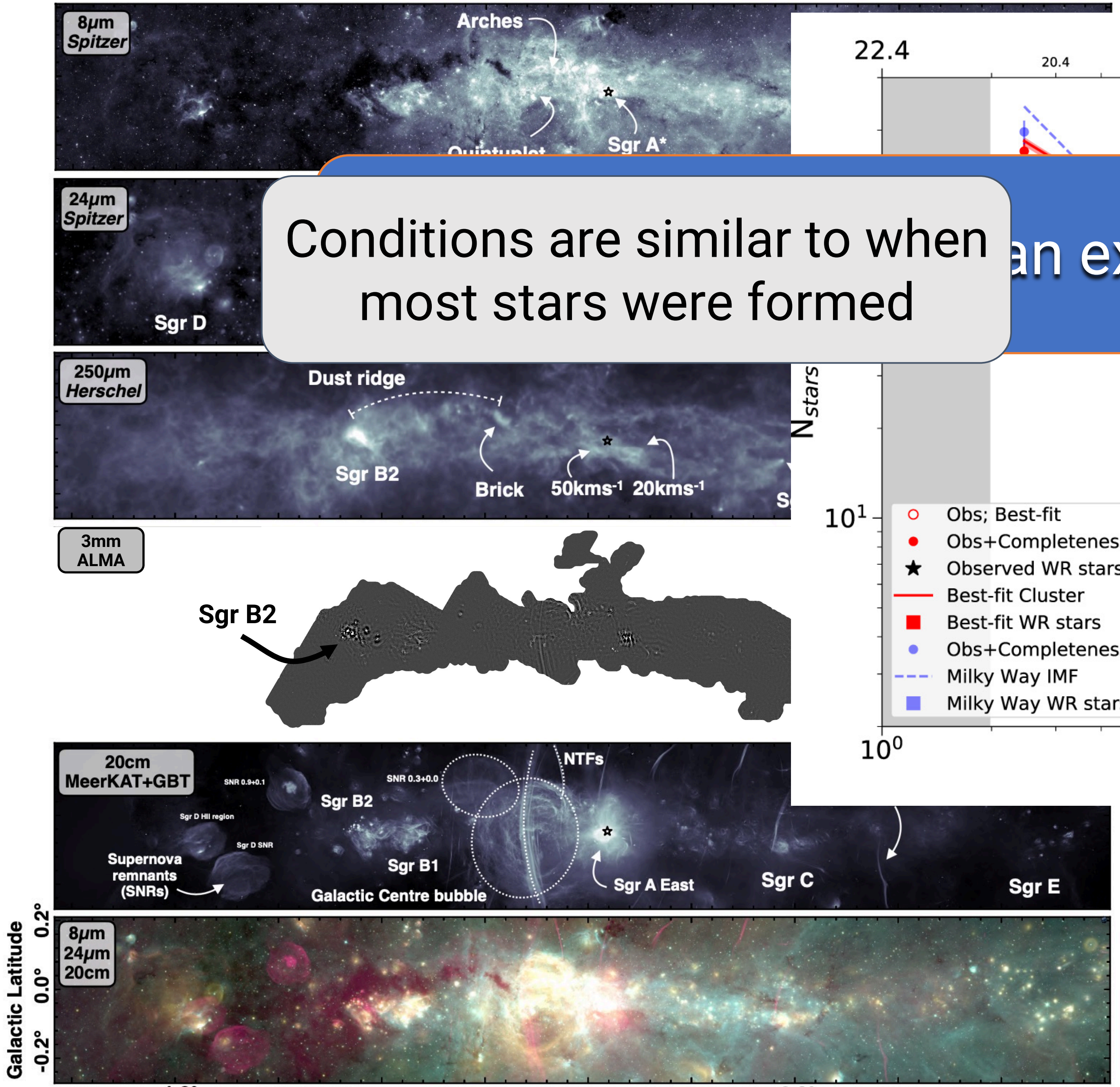
SFR is 10-100x lower than expected!



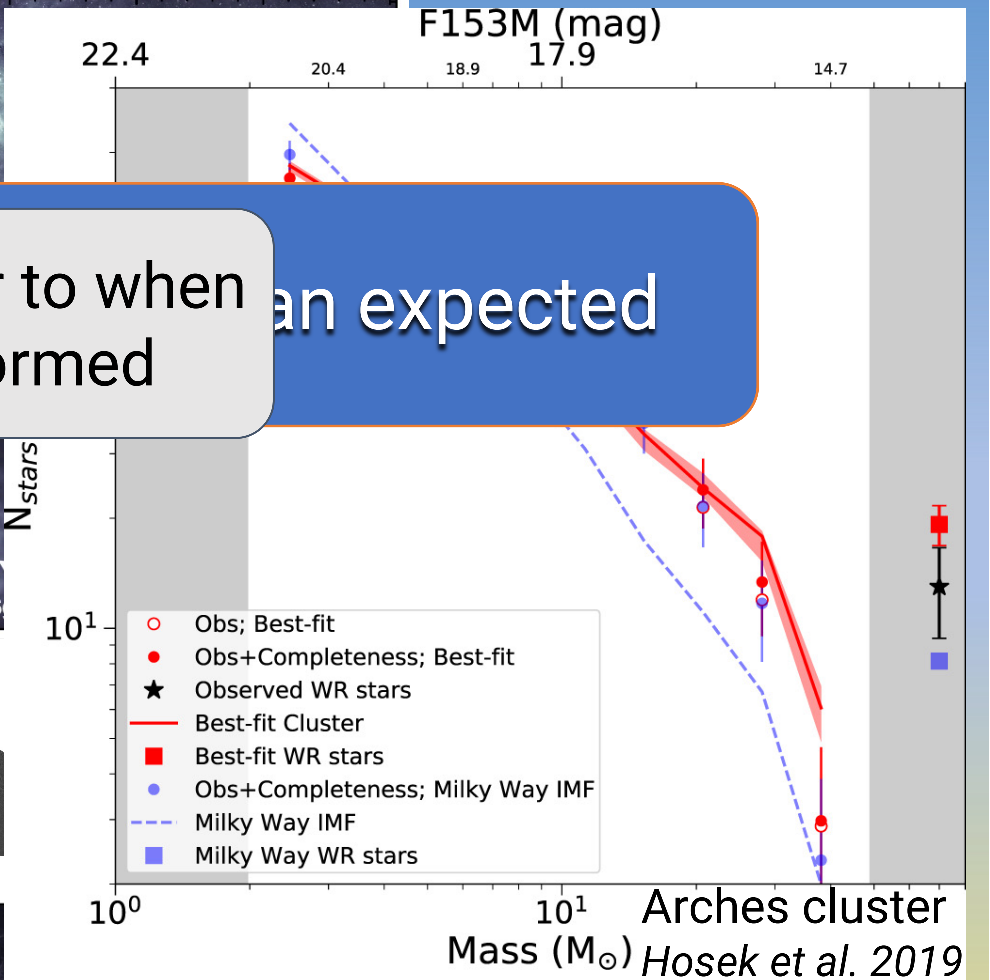
Fraction of dense gas f_{DG} = gas above $10^4 \mathrm{cm}^{-3}$ or A_V~10mag

Here $f_{DG} = 1$ and all gas forms stars with a depletion time (~20Myr)

$$\mathrm{SFR} \equiv \dot{M}_* = 4.6 \times 10^{-8} f_{\mathrm{DG}} M_G(M_\odot) \quad M_\odot \ \mathrm{yr}^{-1}$$



Henshaw et al. PPVII



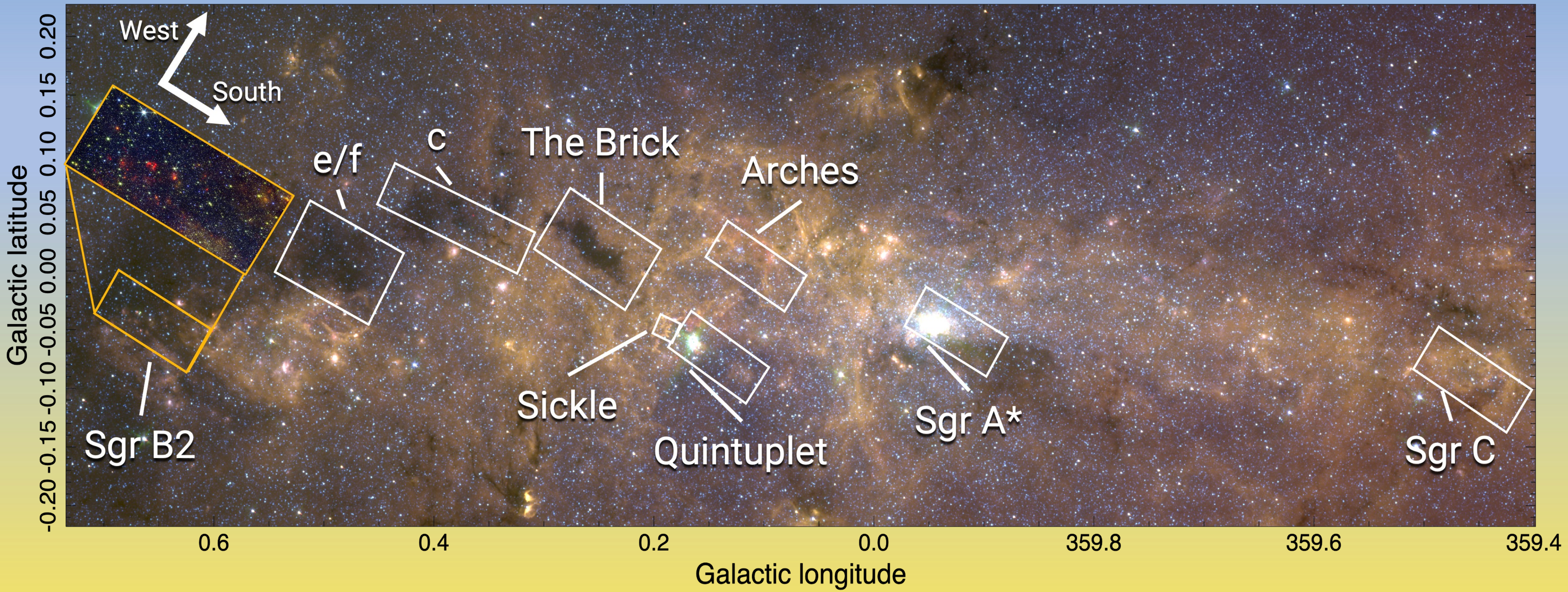
Arches cluster

Hosek et al. 2019

…an expected

Conditions are similar to when most stars were formed

JWST coverage of the CMZ

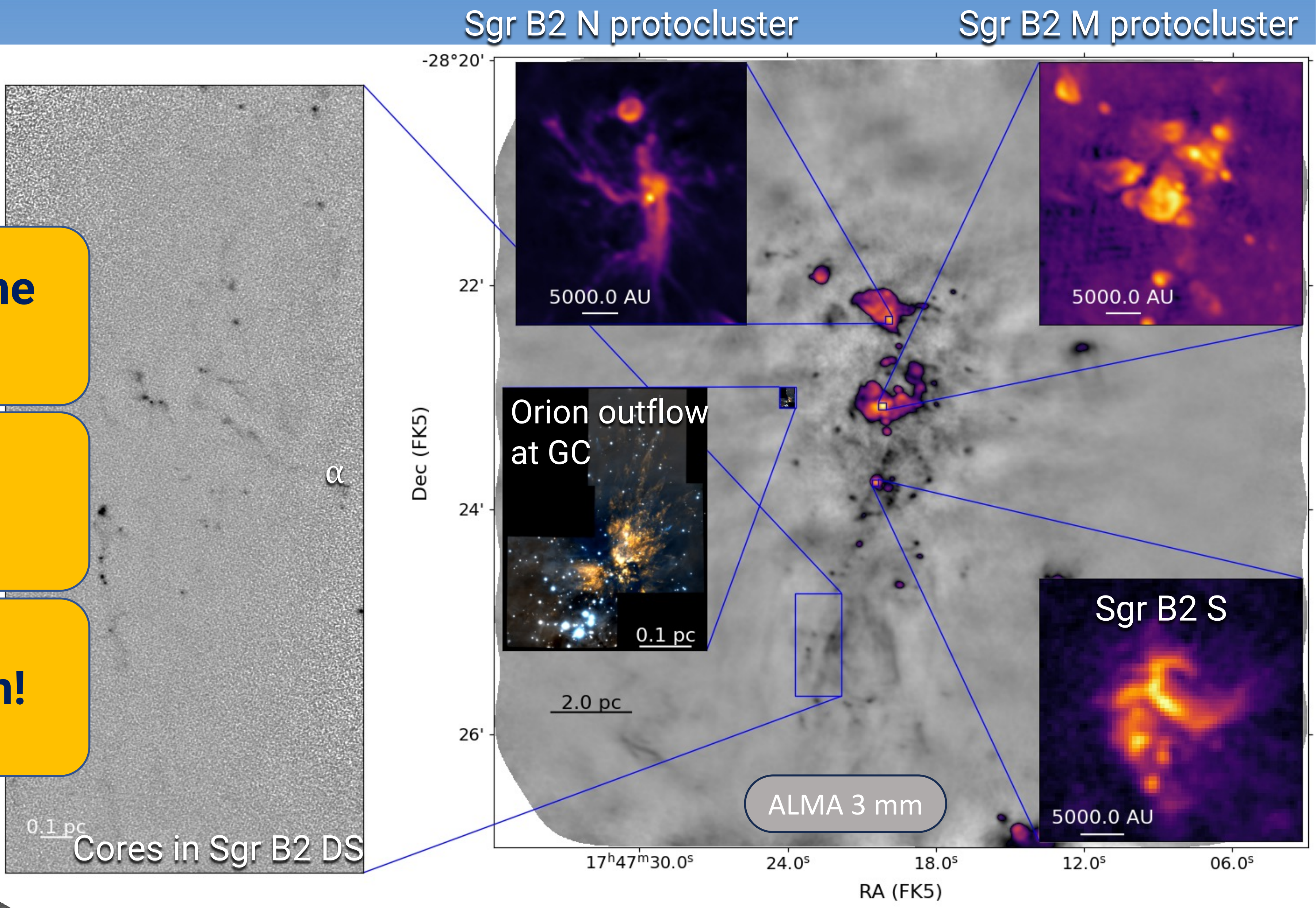


Sagittarius B2

<1% of the CMZ volume (5×10^4 pc³)

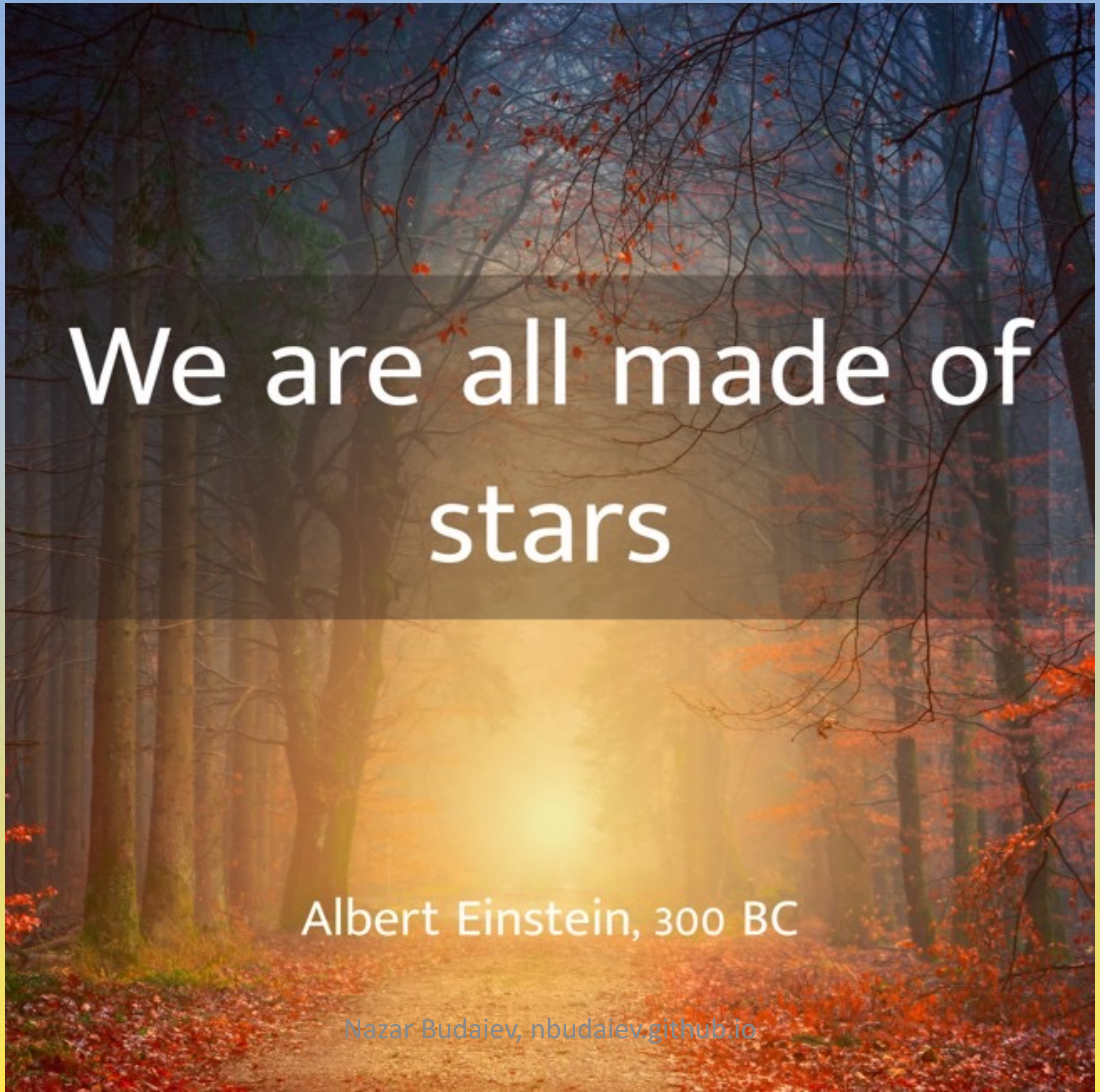
~10% of the mass ($8\times10^6 M_\odot$)

50% of star formation!

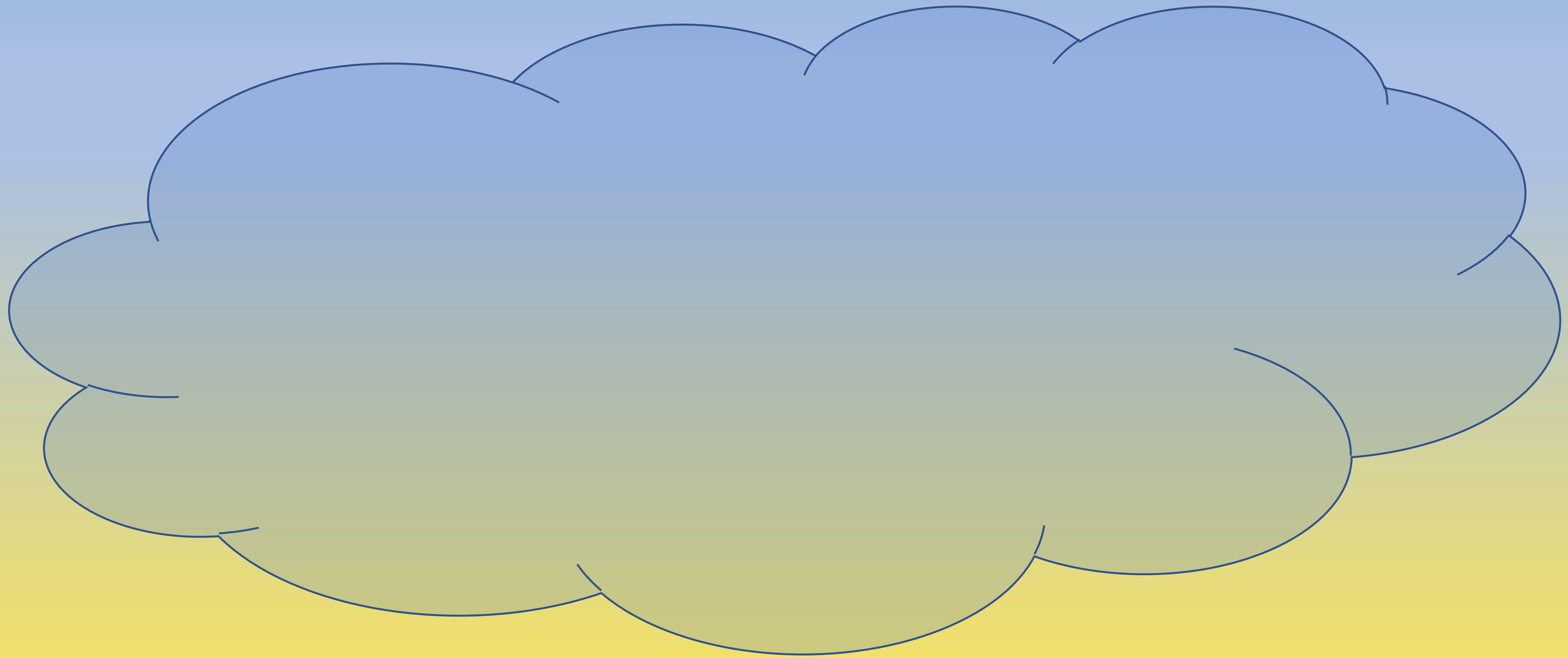


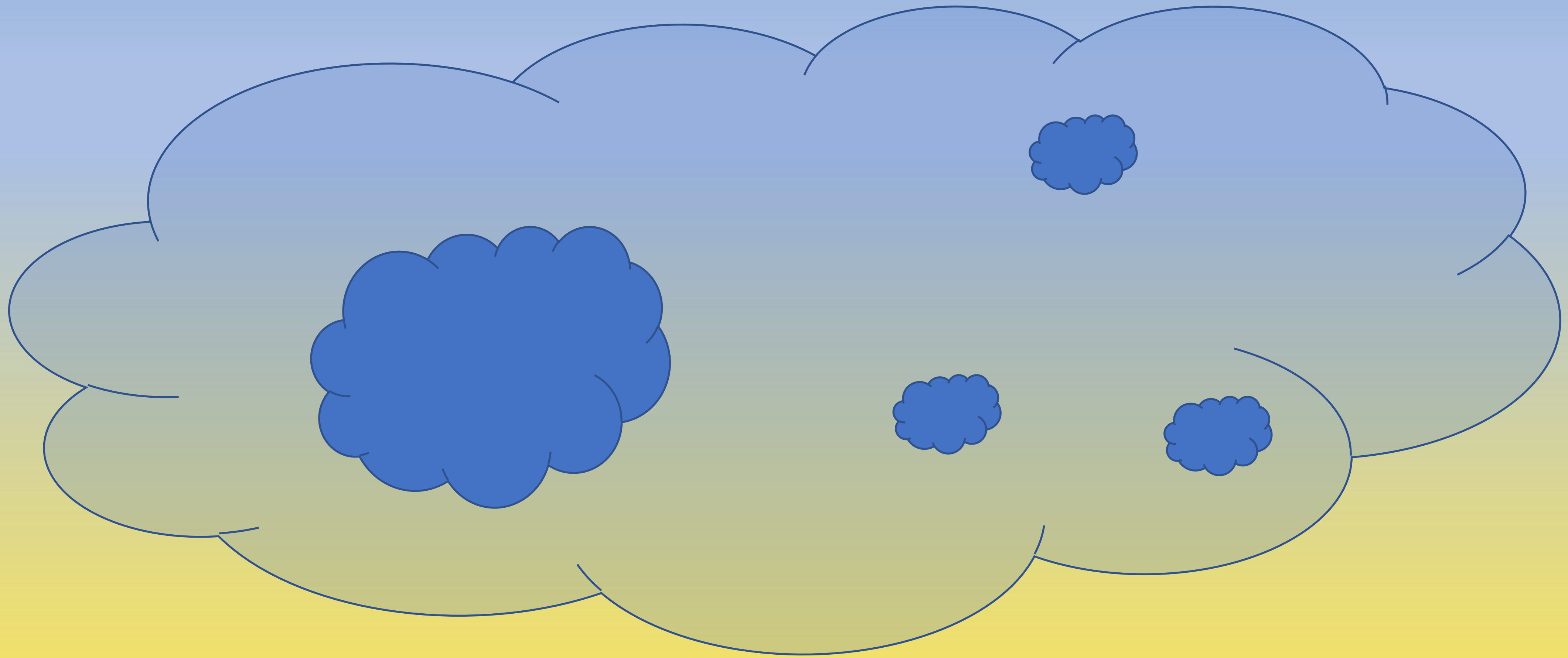
♠ACES: The ALMA CMZ Exploration Survey

How do we find the stars?

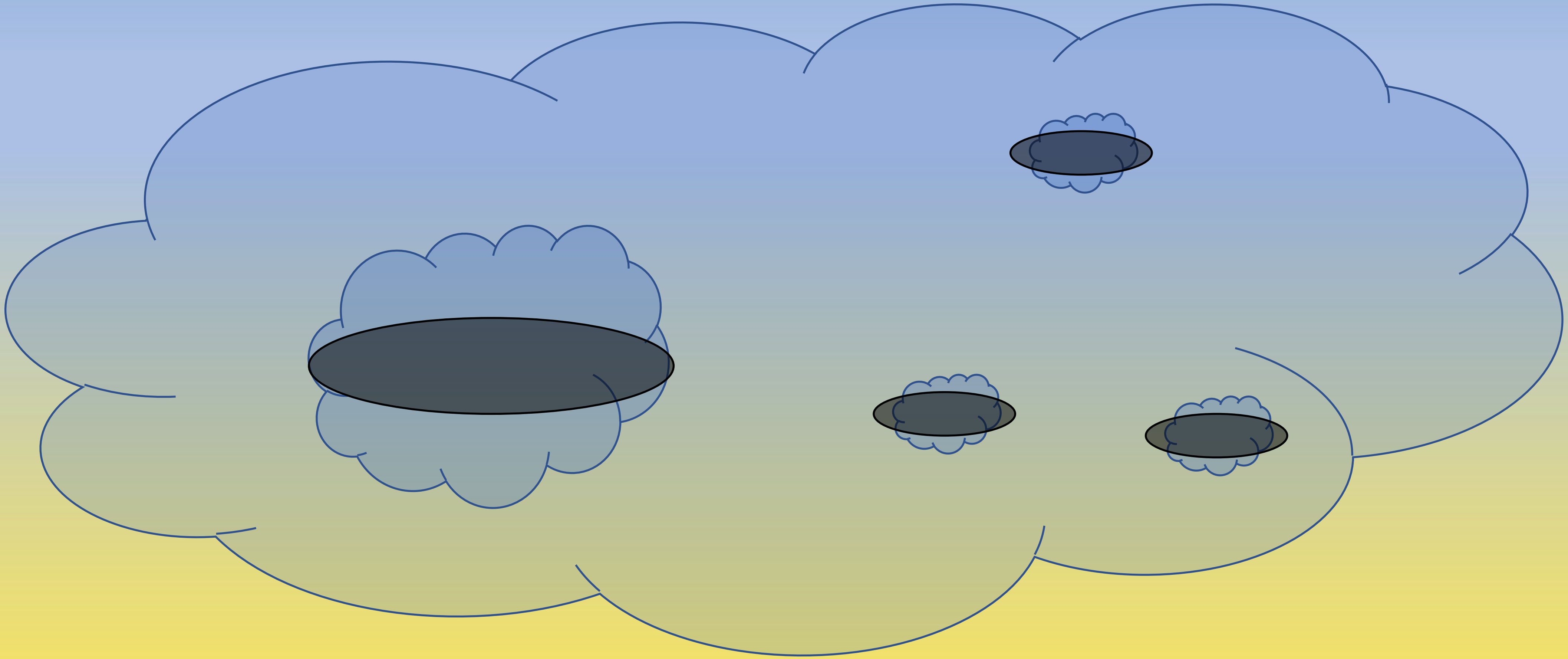


A simplified model of a star-forming cloud



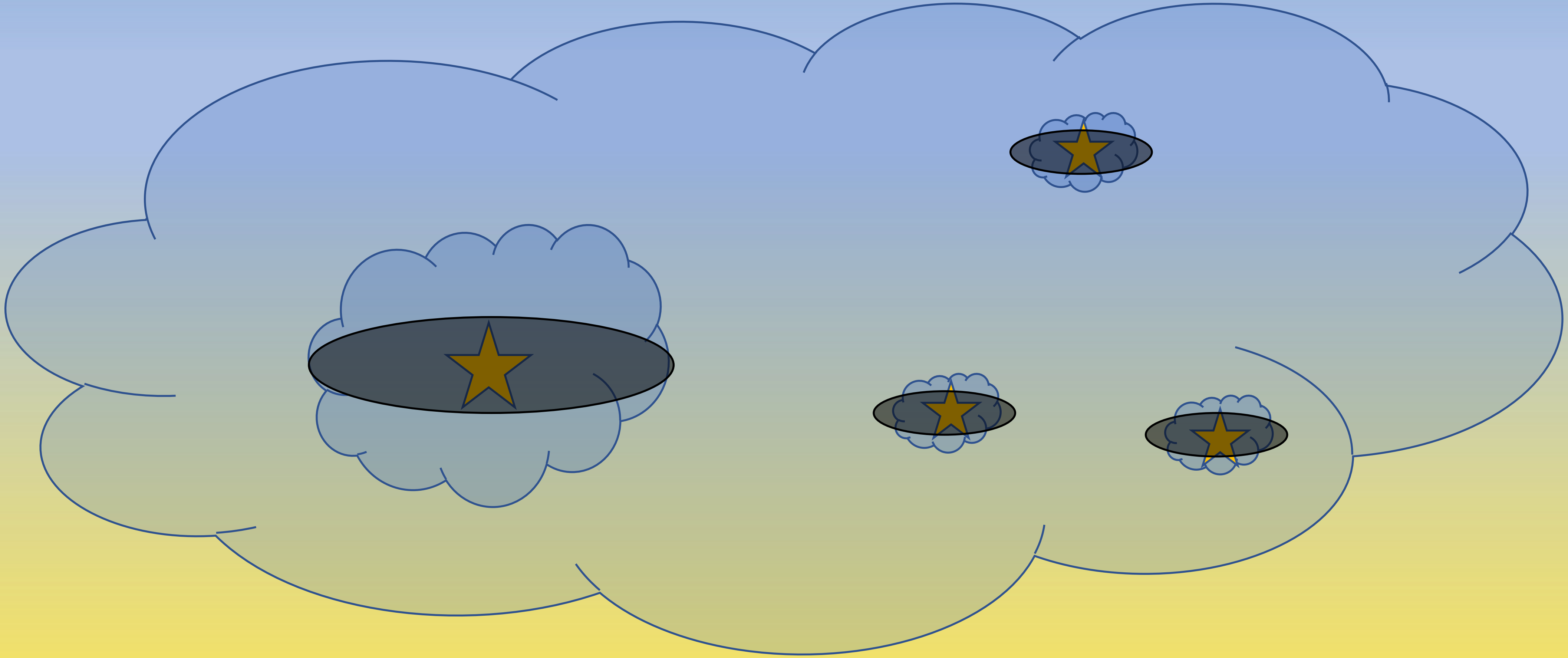


Accretion



Dusty YSOs

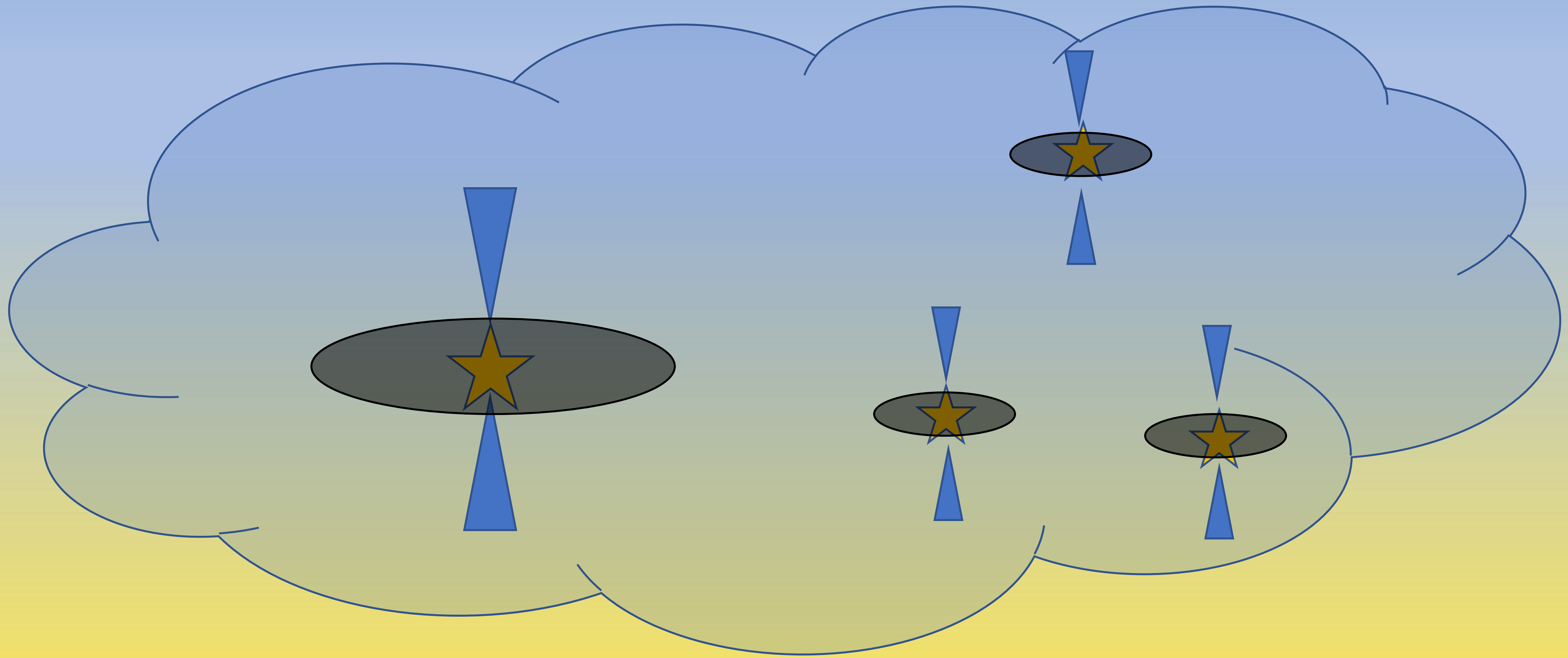
Accretion



Dusty YSOs

Outflows

Accretion

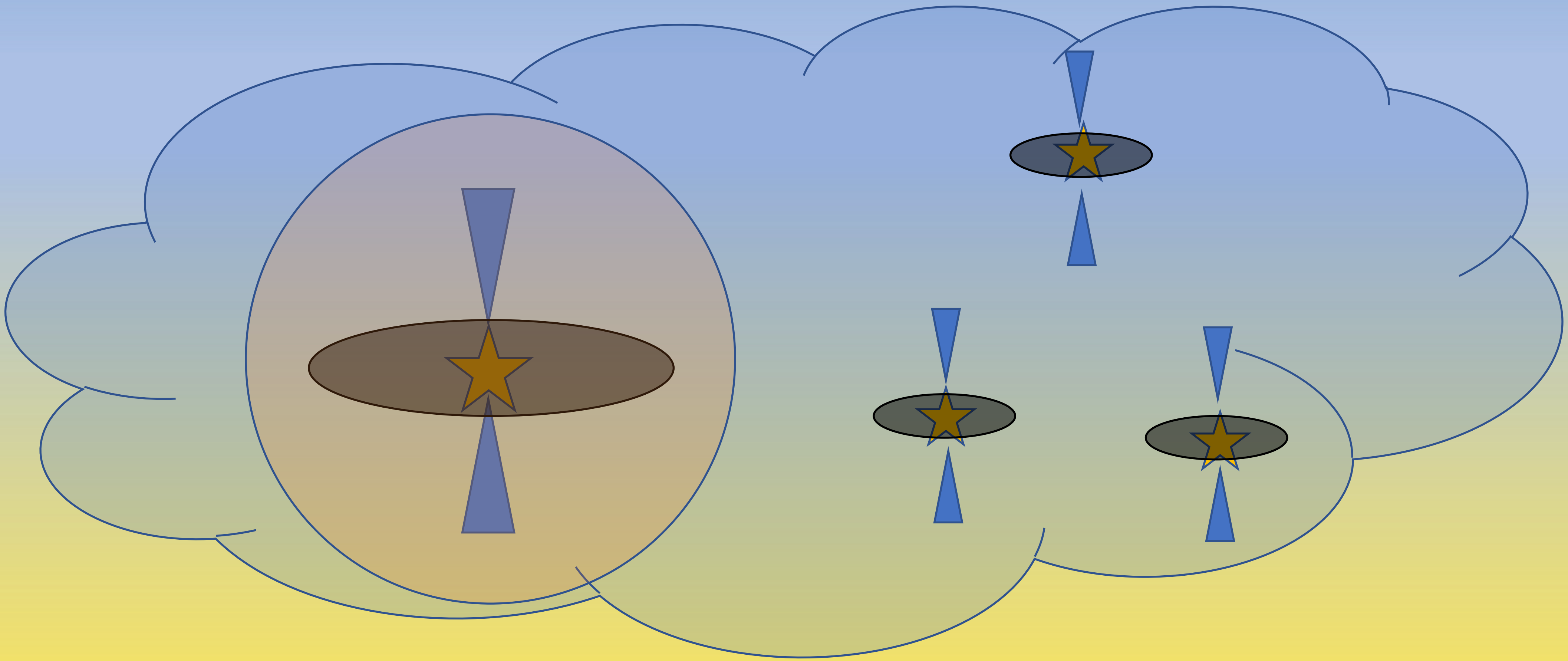


Dusty YSOs

Outflows

Accretion

HII regions



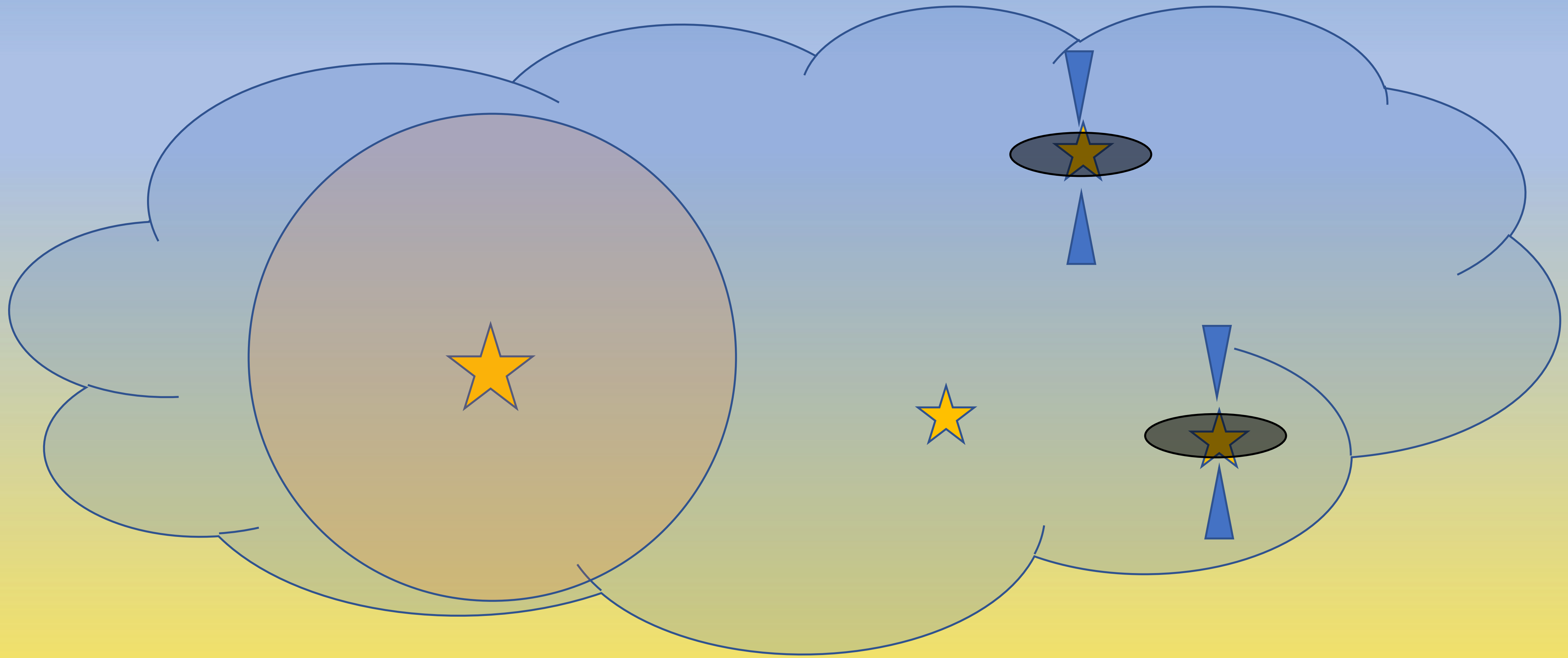
Dusty YSOs

Outflows

Evolved YSOs

Accretion

HII regions



Dusty YSOs

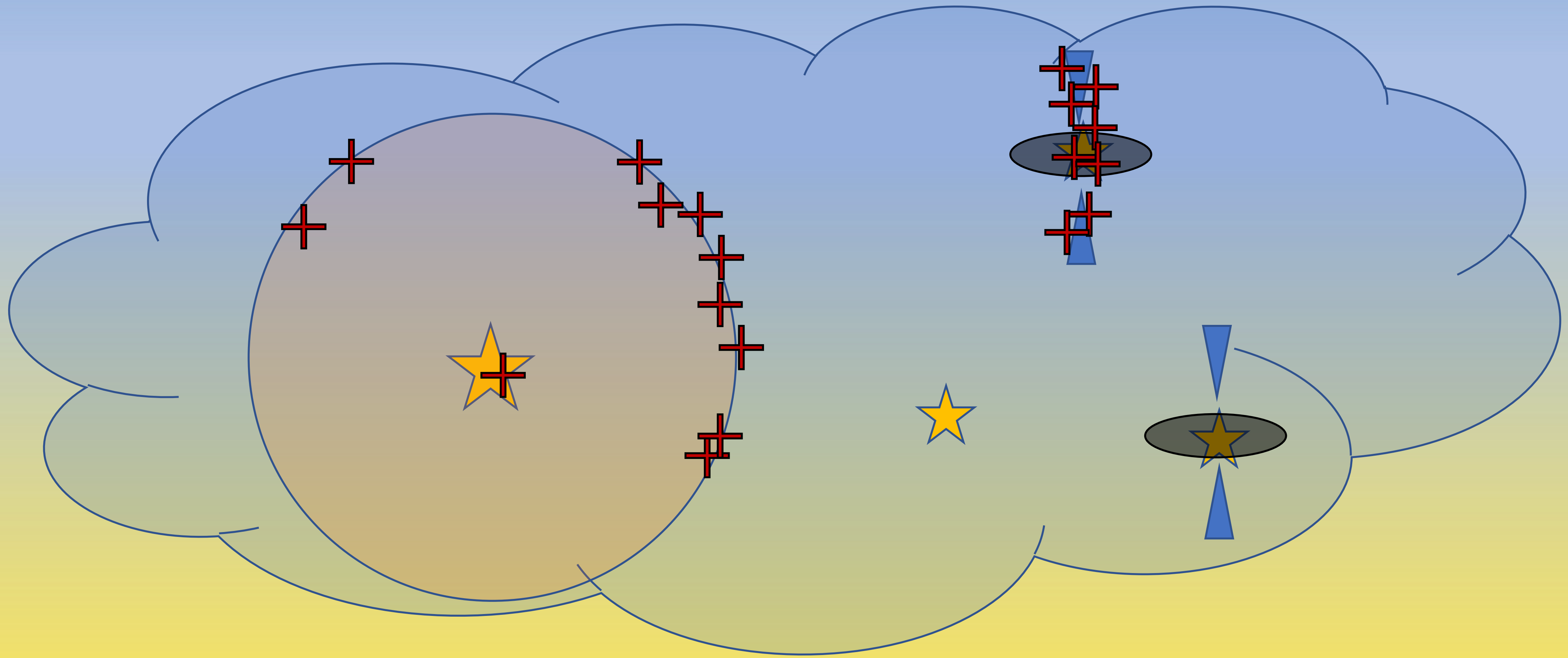
Outflows

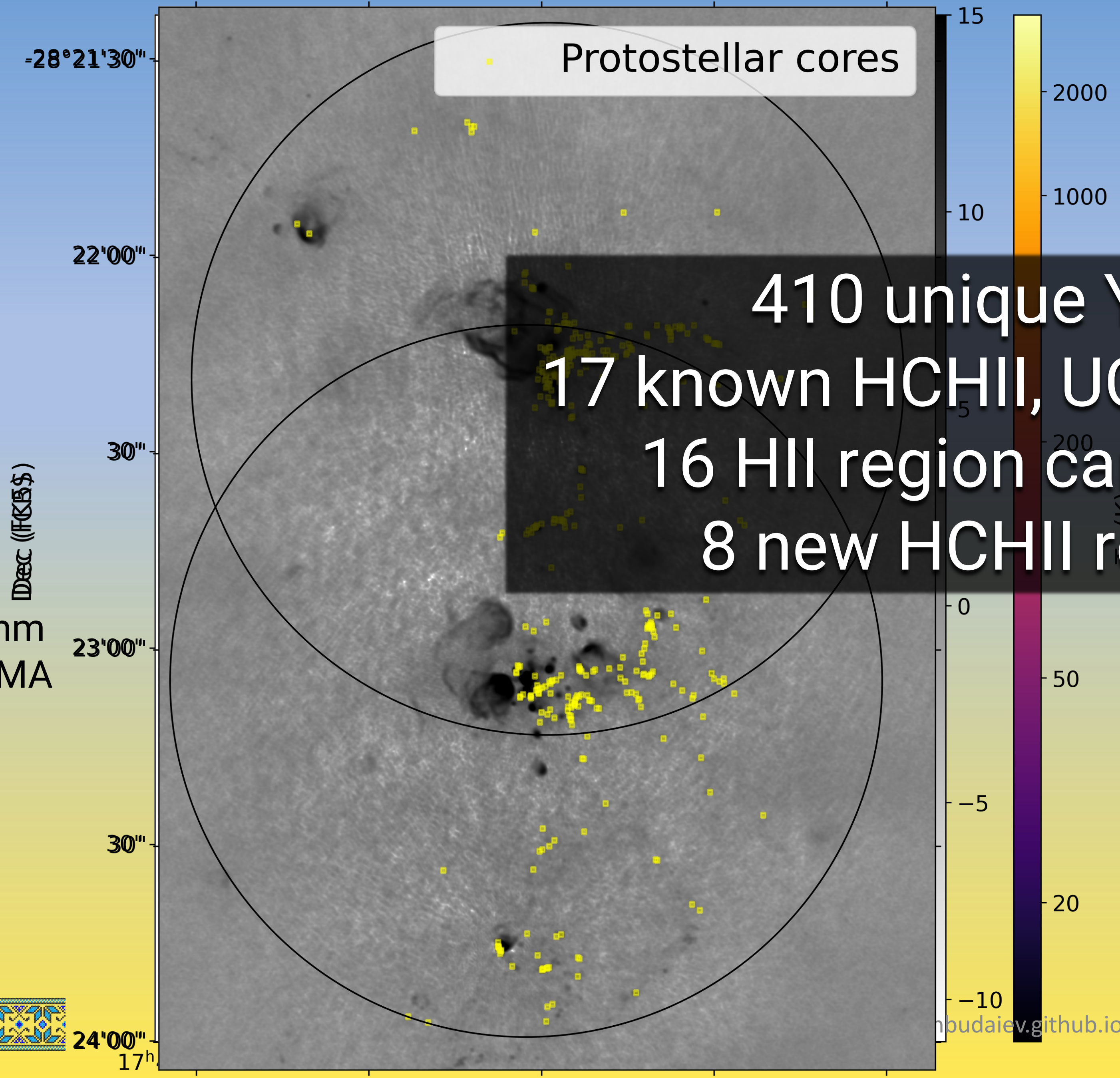
Evolved YSOs

Masers

Accretion

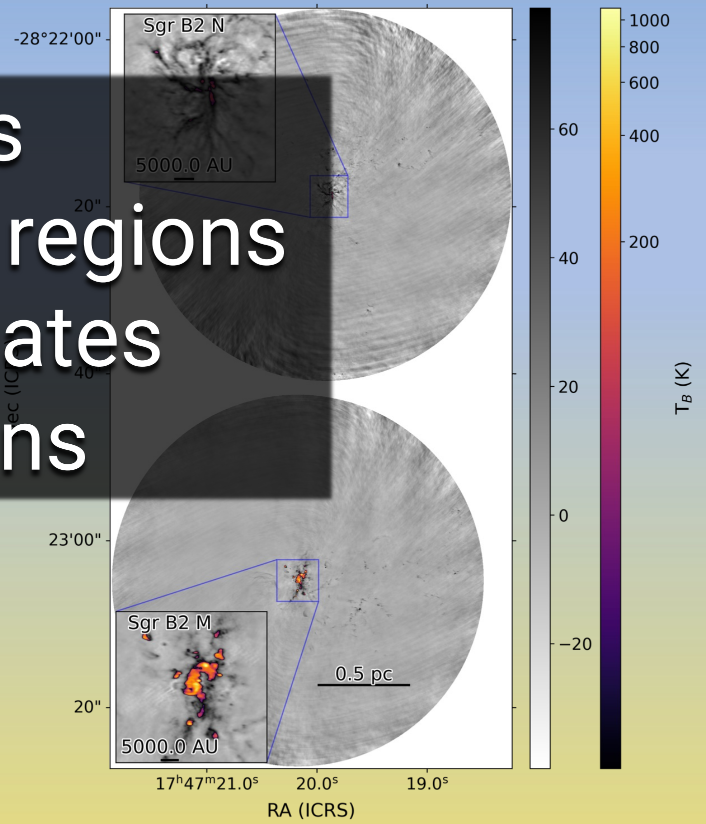
HII regions



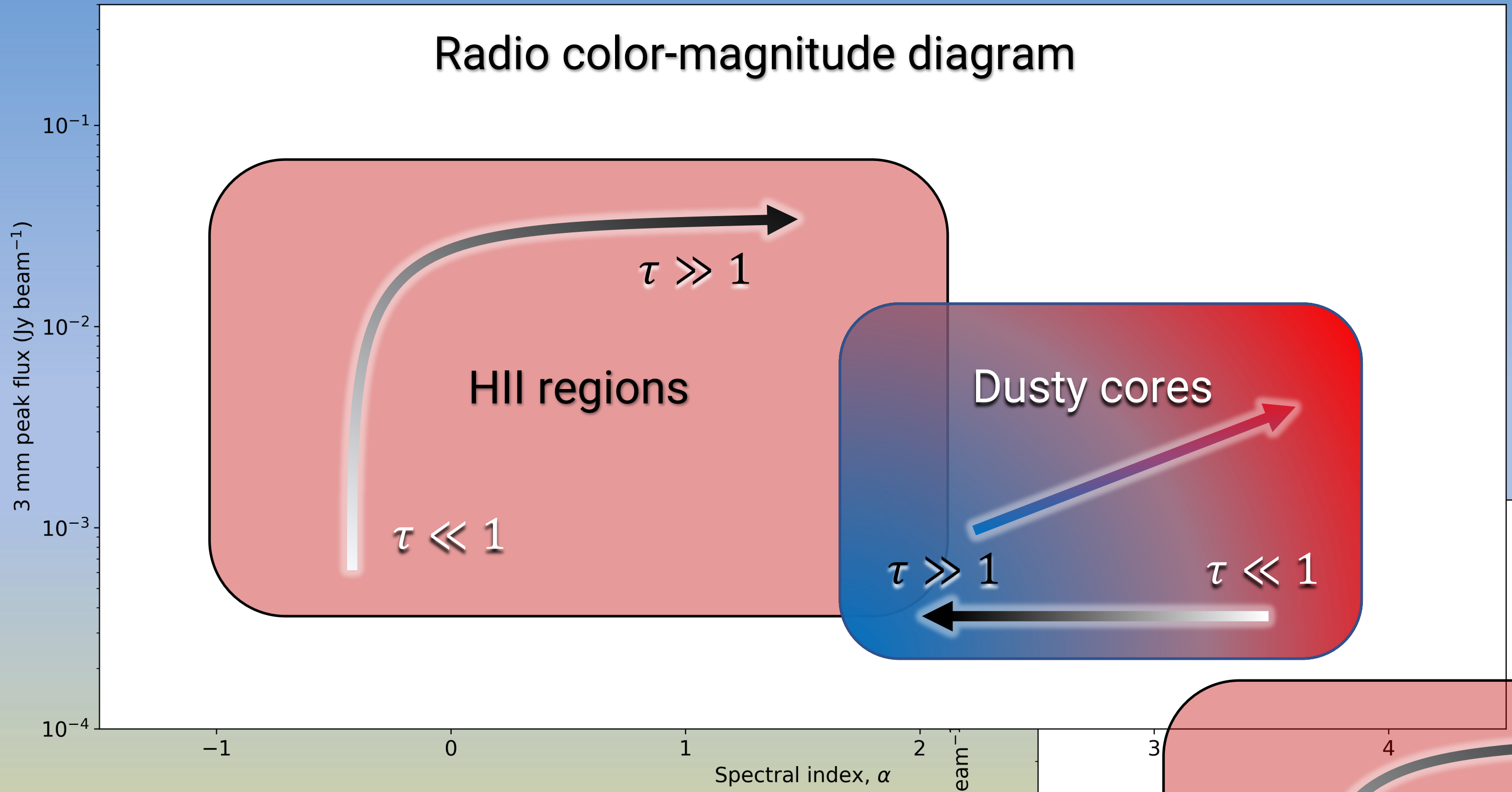


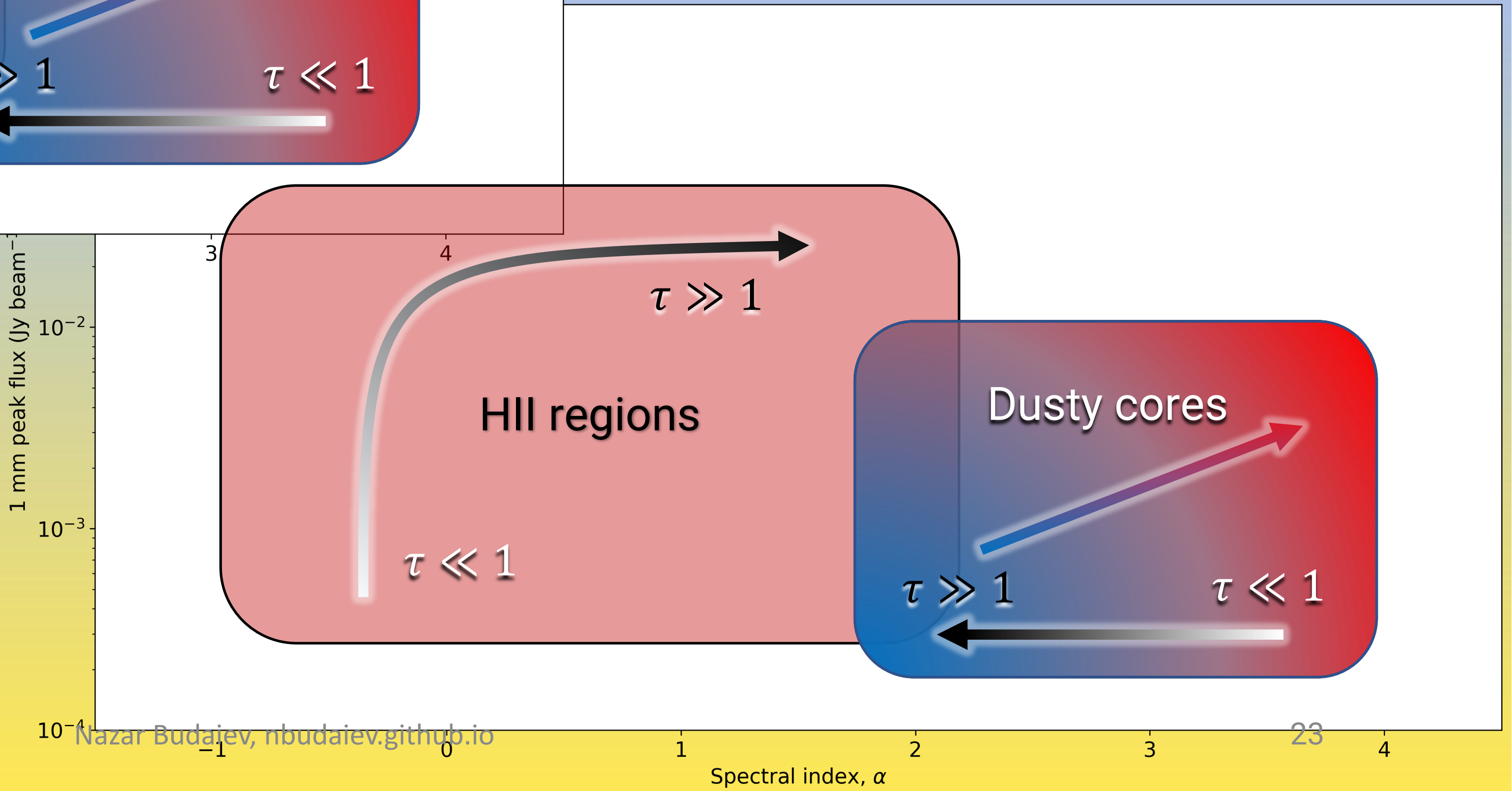
3mm ALMA

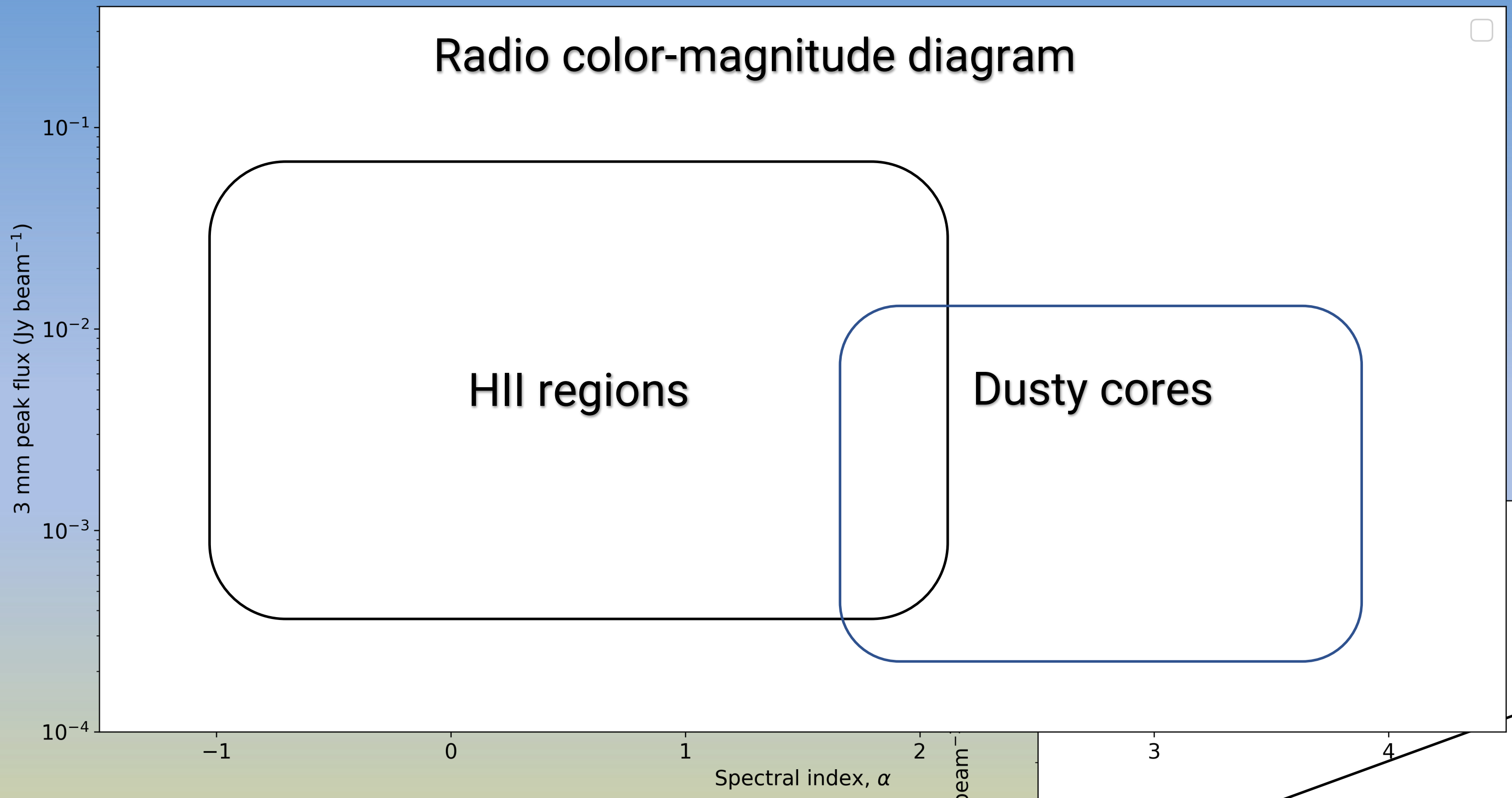
410 unique YSOs
17 known HCHII, UCHII regions
16 HII region candidates
8 new HCHII regions

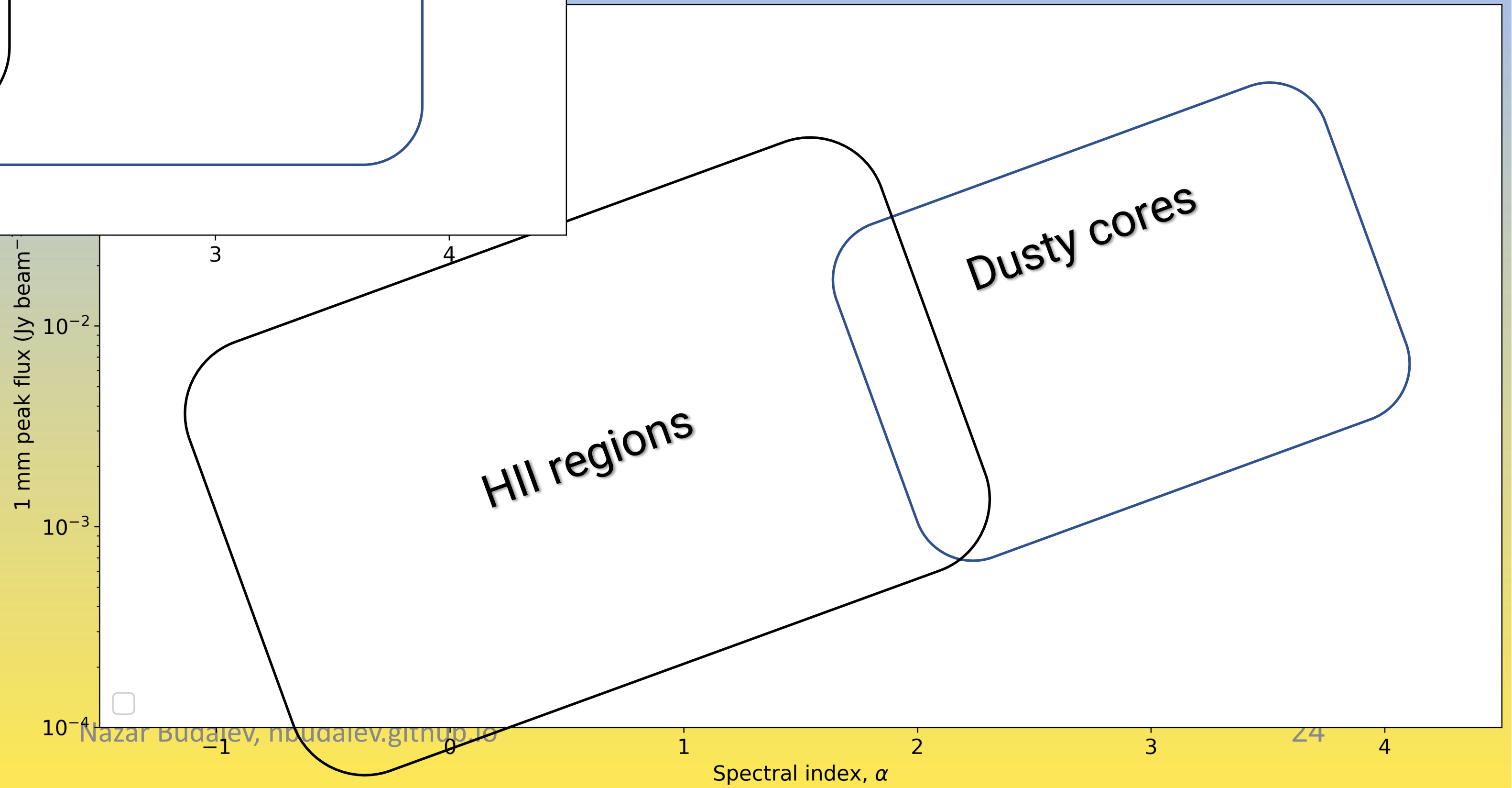


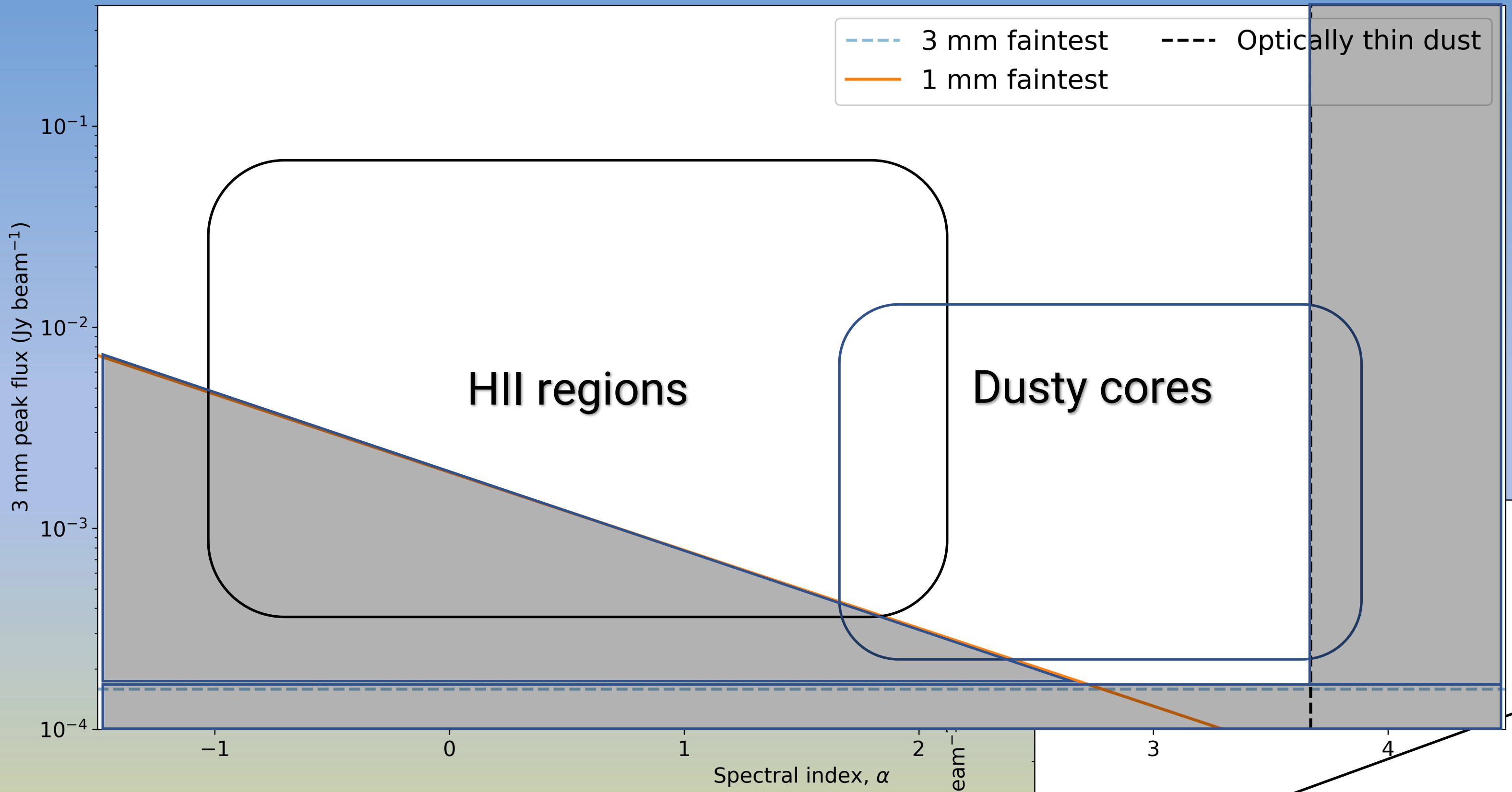
1mm ALMA

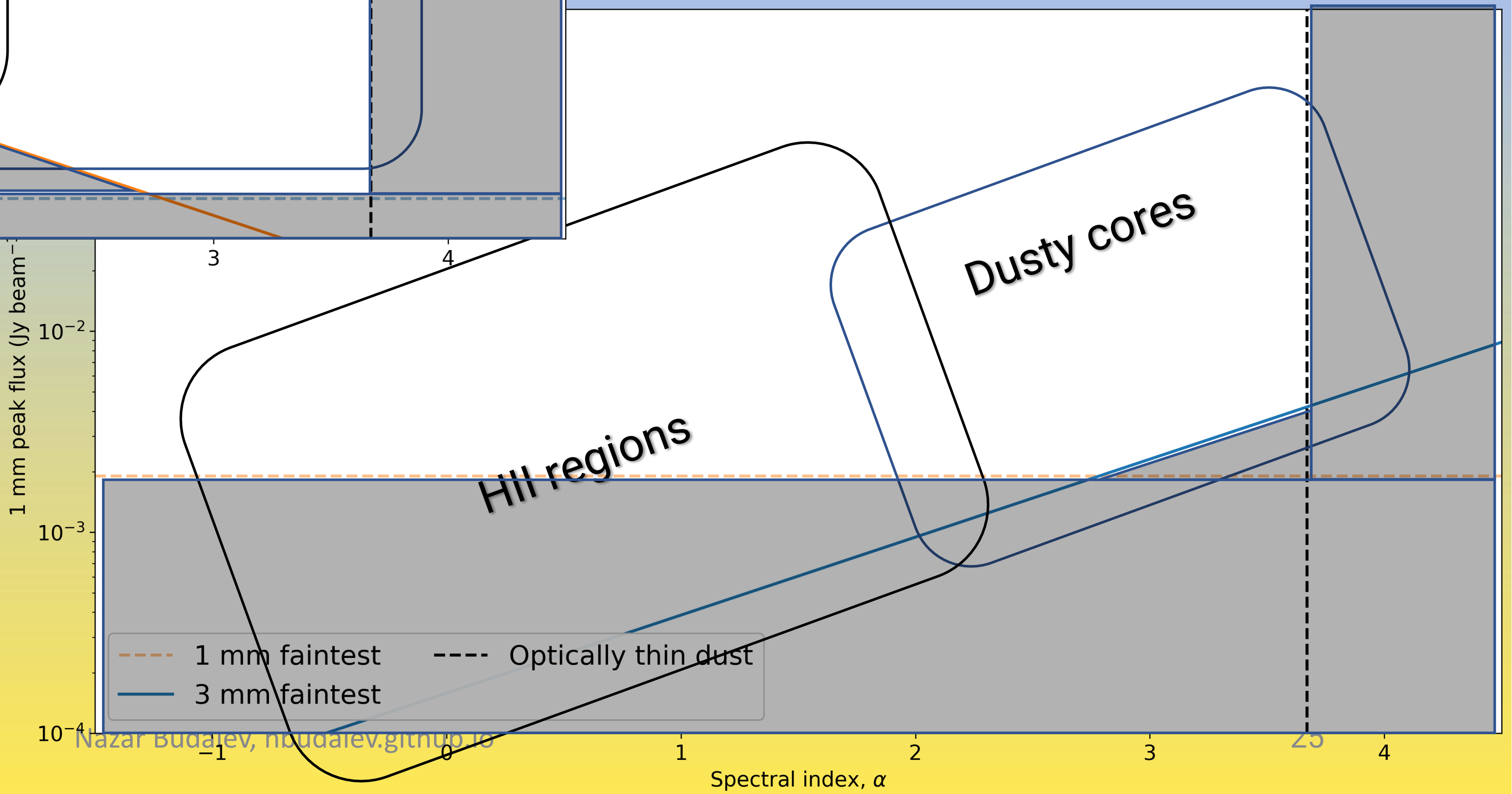

Radio color-magnitude diagram
3 mm peak flux (Jy beam^{-1})
10^{-1}
10^{-2}
10^{-3}
10^{-4}
HII regions
$\tau \gg 1$
$\tau \ll 1$
Dusty cores
$\tau \gg 1$
$\tau \ll 1$
−1
0
1
2
3
4
Spectral index, α

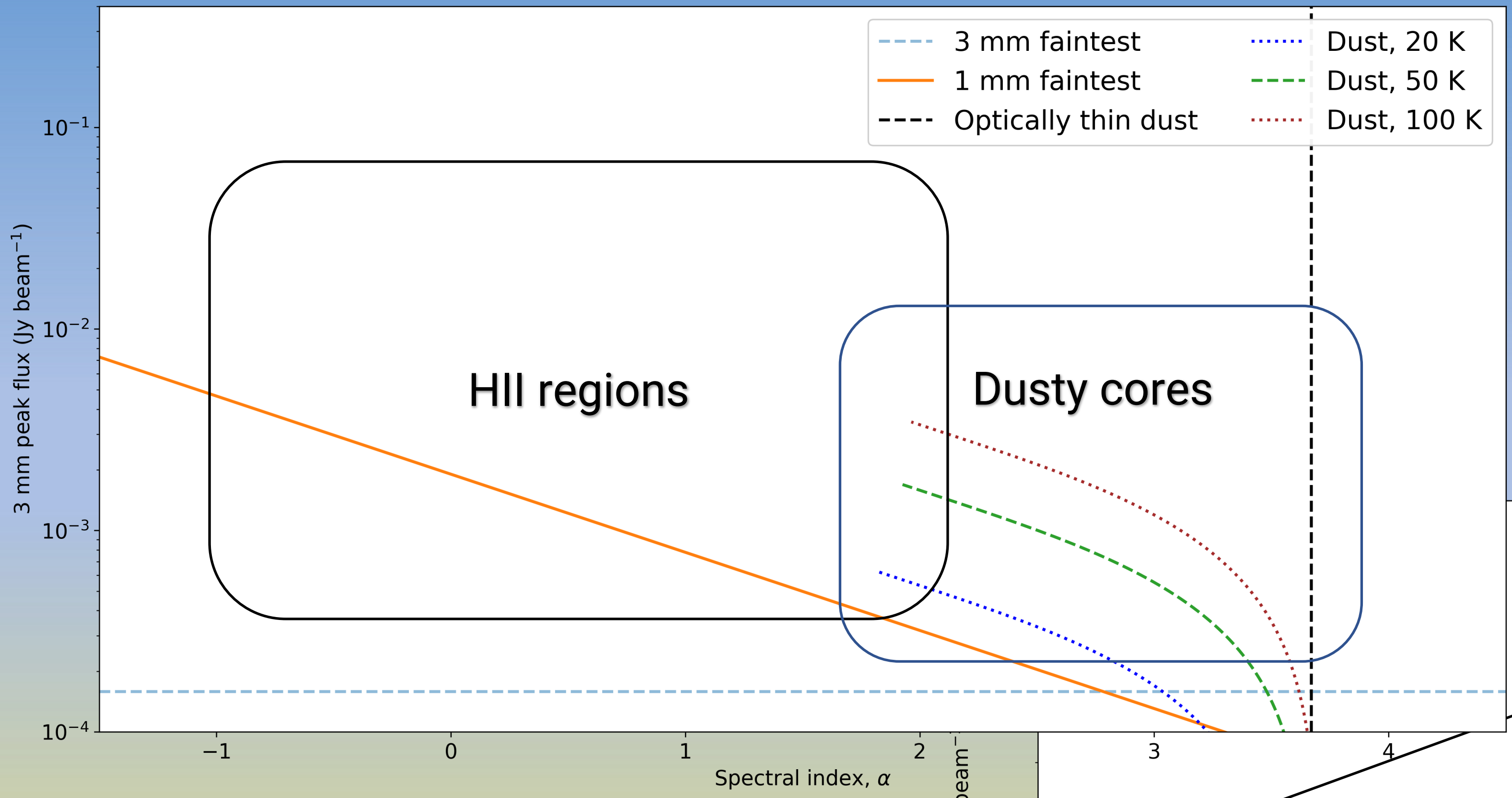

1 mm peak flux (Jy beam^{-1})
10^{-2}
10^{-3}
10^{-4}
HII regions
$\tau \gg 1$
$\tau \ll 1$
Dusty cores
$\tau \gg 1$
$\tau \ll 1$
−1
0
1
2
3
4
Spectral index, α

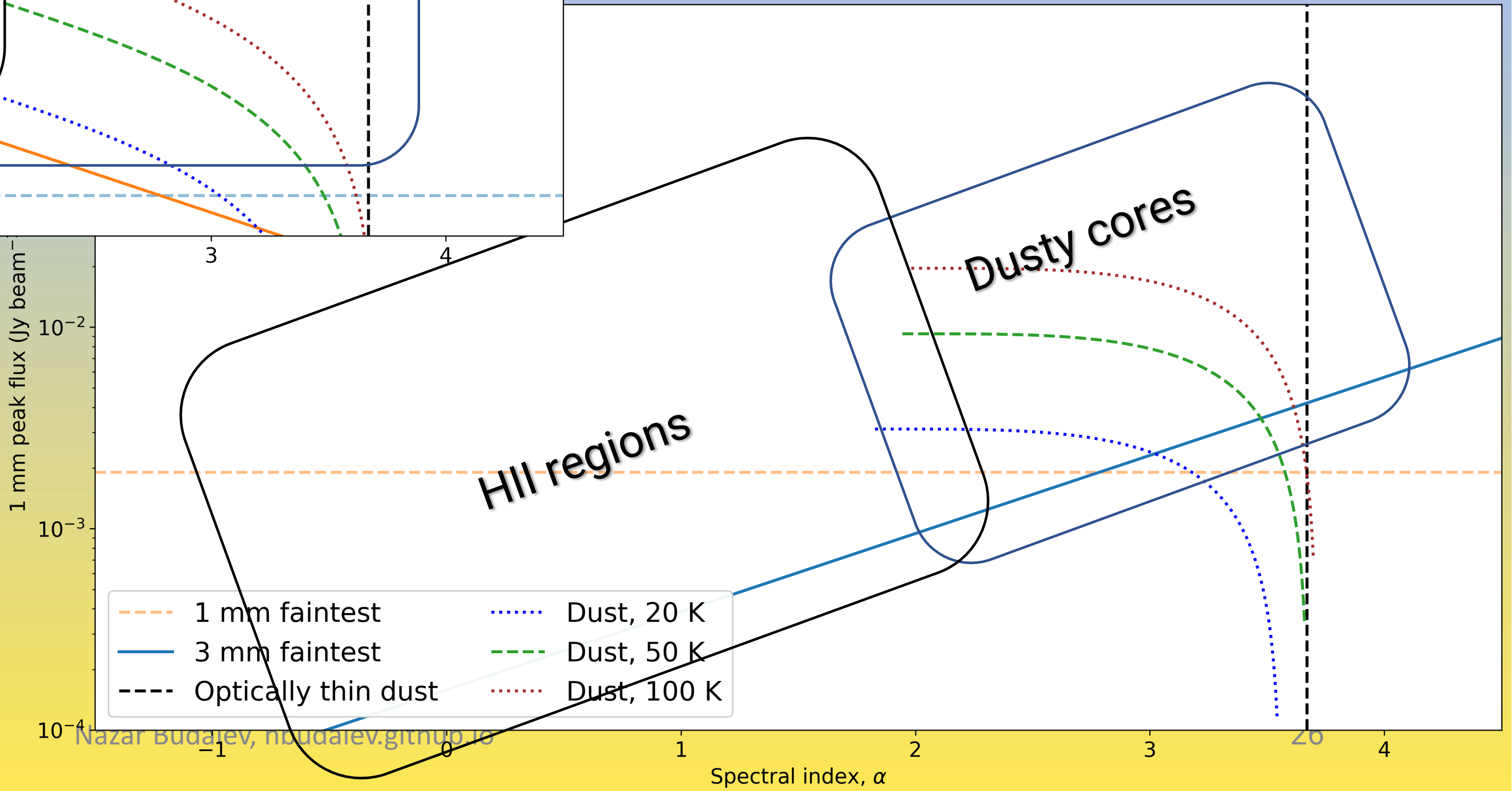

Radio color-magnitude diagram
HII regions
Dusty cores
3 mm peak flux (Jy beam^{-1})
10^{-1}
10^{-2}
10^{-3}
10^{-4}
−1
0
1
2
3
4
Spectral index, α

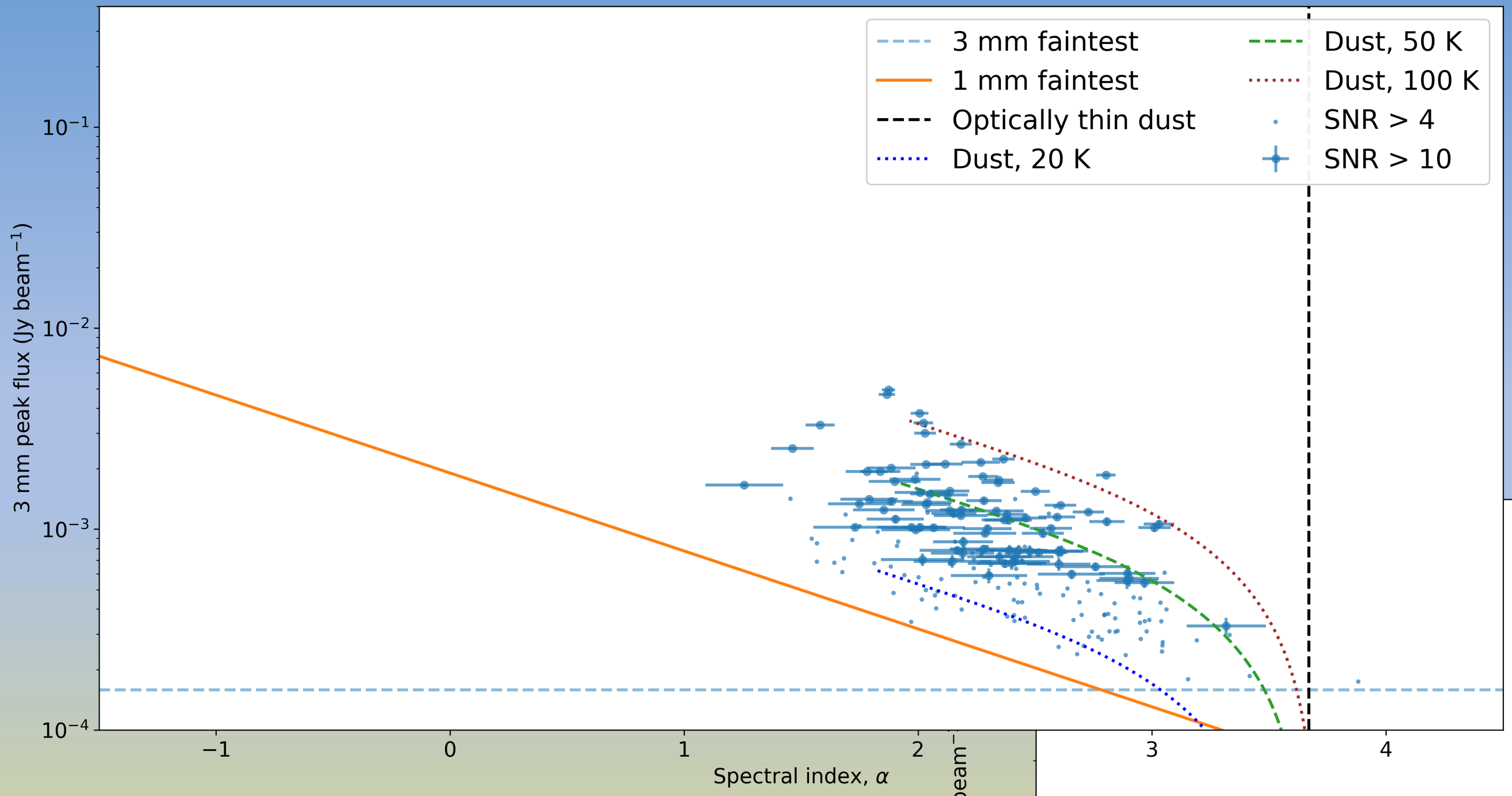

HII regions
Dusty cores
1 mm peak flux (Jy beam^{-1})
10^{-2}
10^{-3}
10^{-4}
−1
0
1
2
3
4
Spectral index, α

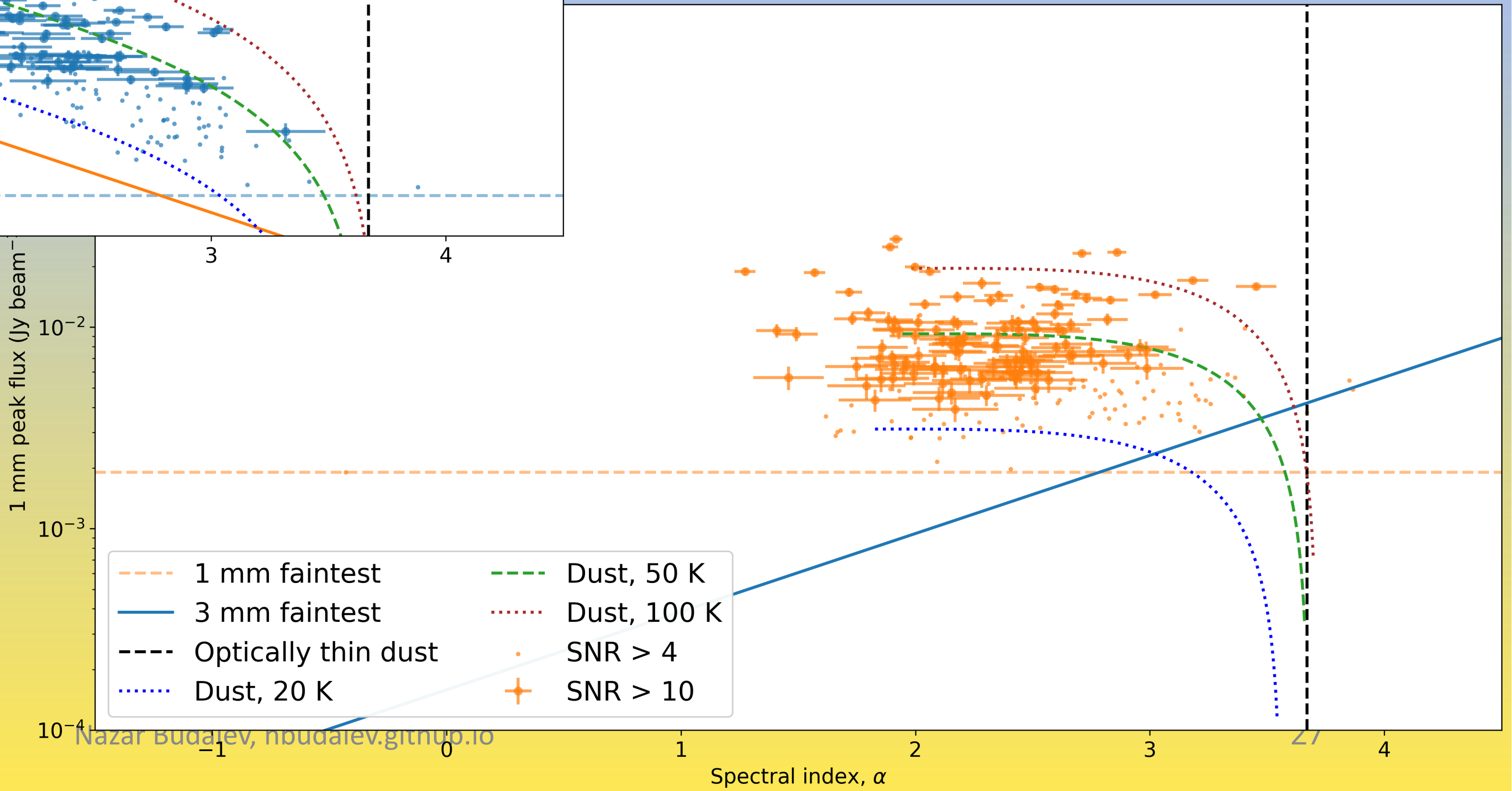

3 mm faintest
1 mm faintest
Optically thin dust
HII regions
Dusty cores
3 mm peak flux (Jy beam^{-1})
Spectral index, α
10^{-1}
10^{-2}
10^{-3}
10^{-4}
−1
0
1
2
3
4

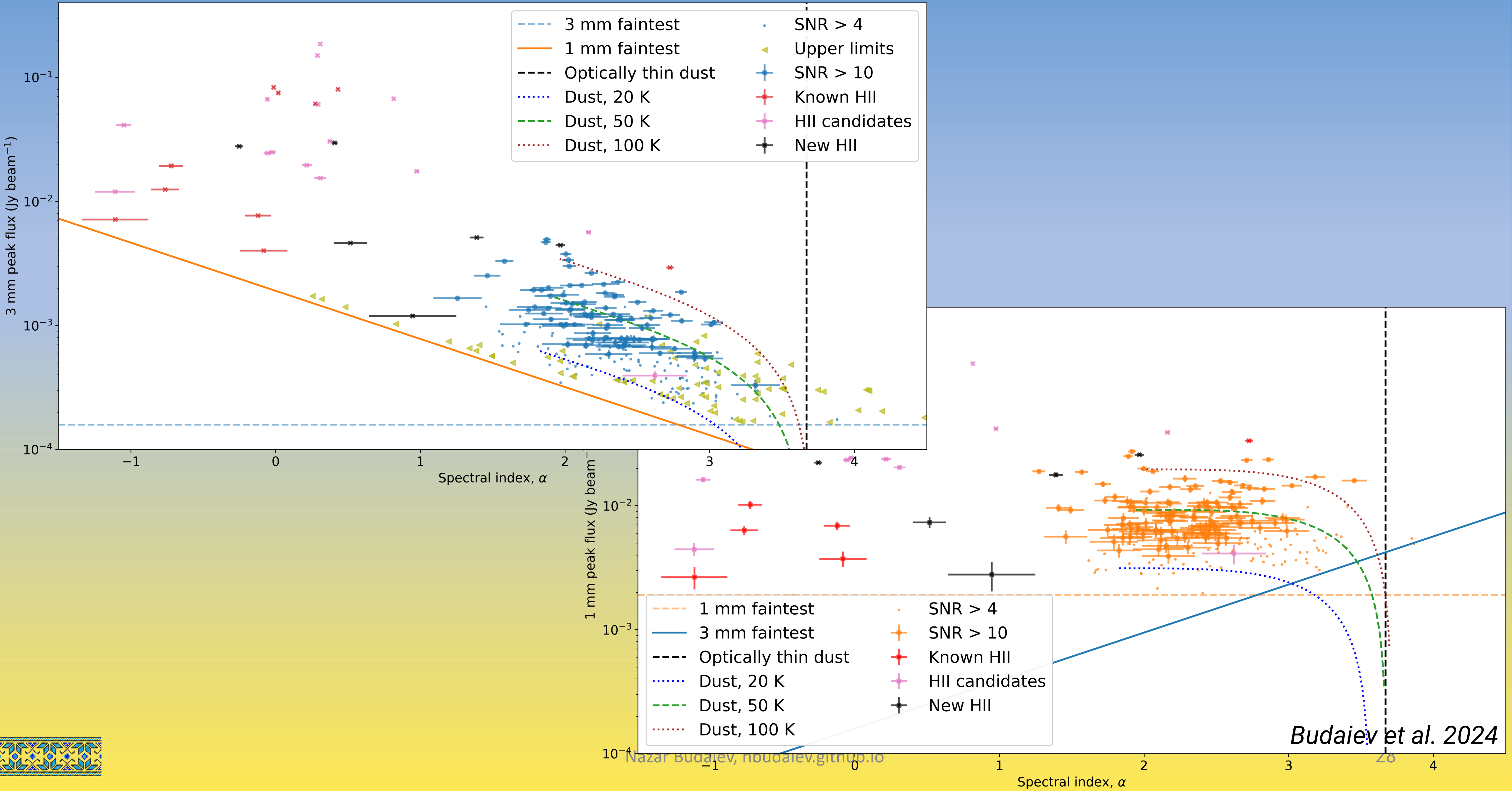

1 mm faintest
3 mm faintest
Optically thin dust
HII regions
Dusty cores
1 mm peak flux (Jy beam
Spectral index, α
10^{-2}
10^{-3}
10^{-4}
−1
0
1
2
3
4

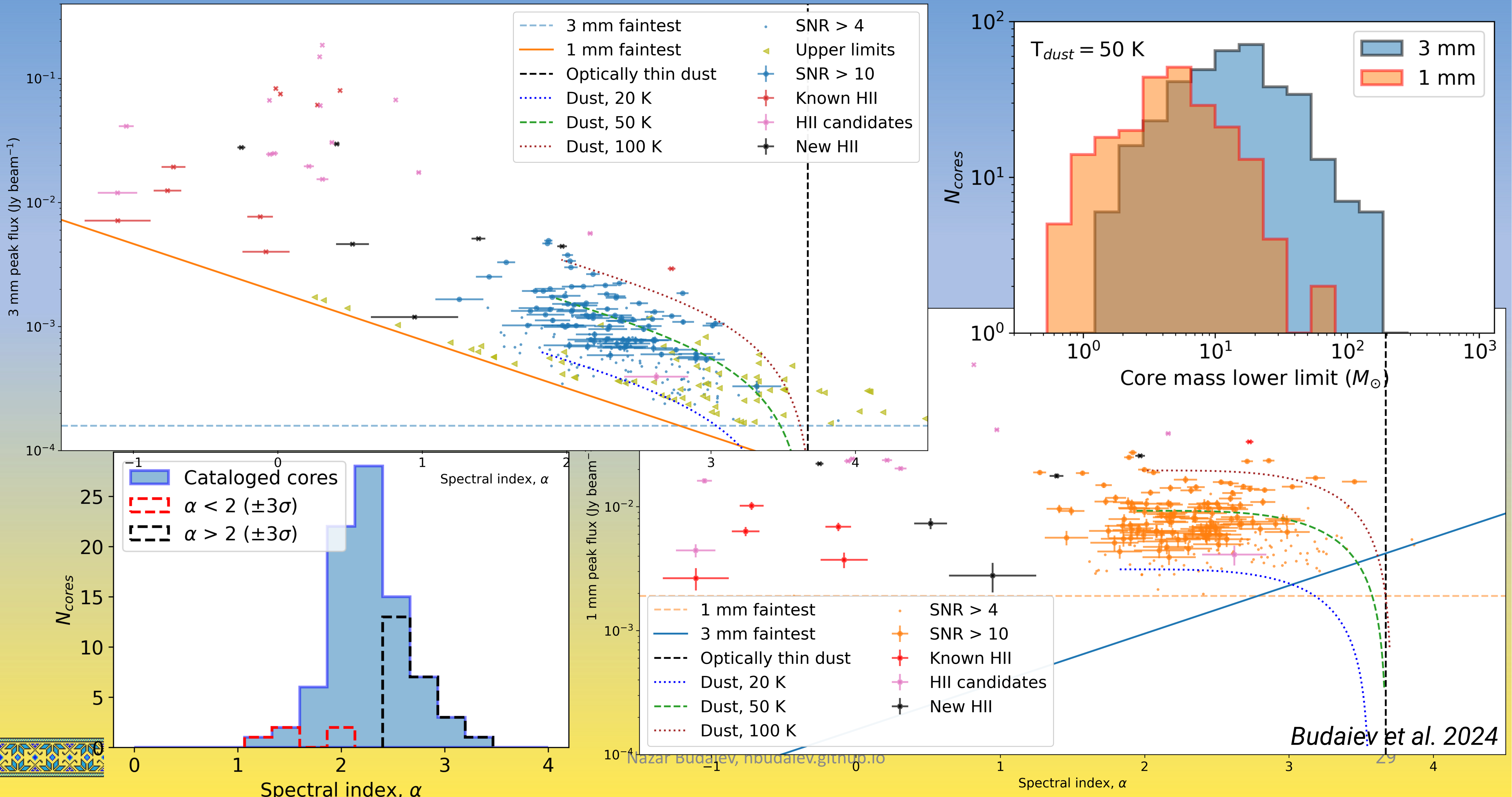

3 mm faintest
1 mm faintest
Optically thin dust
Dust, 20 K
Dust, 50 K
Dust, 100 K
HII regions
Dusty cores
3 mm peak flux (Jy beam^{-1})
Spectral index, α


HII regions
Dusty cores
1 mm faintest
3 mm faintest
Optically thin dust
Dust, 20 K
Dust, 50 K
Dust, 100 K
1 mm peak flux (Jy beam
Spectral index, α


3 mm faintest
1 mm faintest
Optically thin dust
Dust, 20 K
Dust, 50 K
Dust, 100 K
SNR > 4
SNR > 10
3 mm peak flux (Jy beam^{-1})
10^{-1}
10^{-2}
10^{-3}
10^{-4}
−1
0
1
2
3
4
Spectral index, α

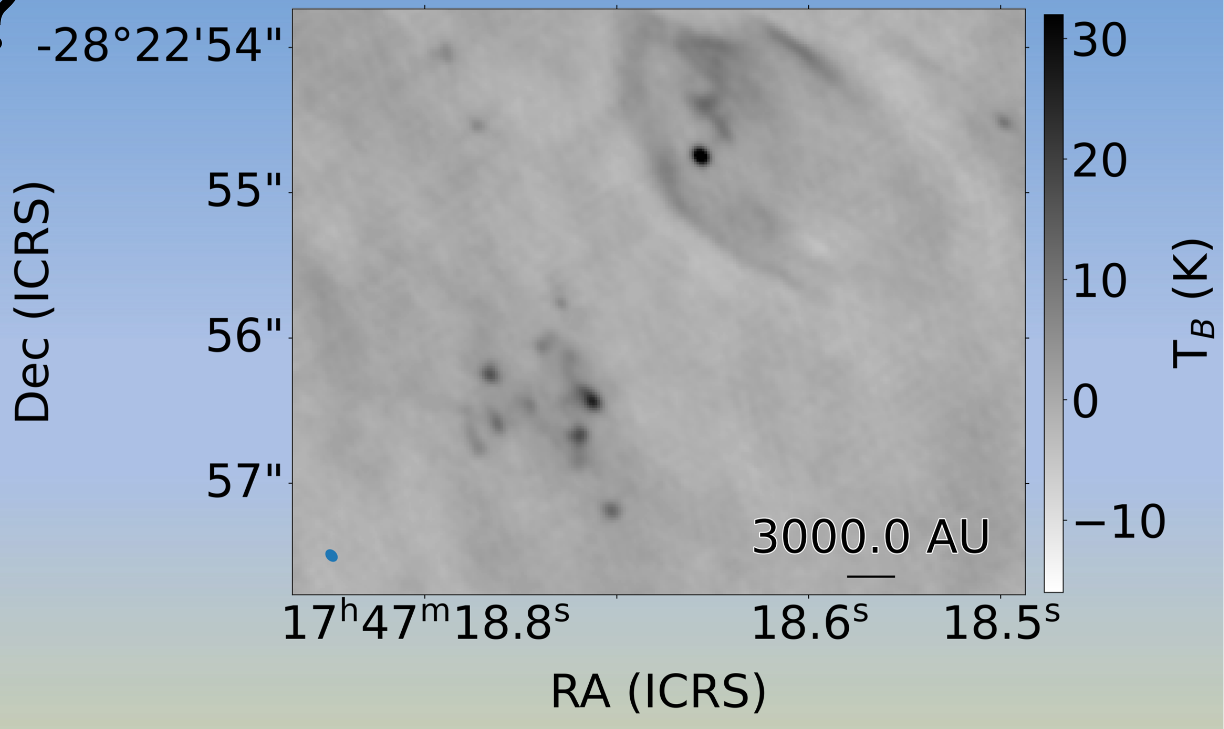

1 mm faintest
3 mm faintest
Optically thin dust
Dust, 20 K
Dust, 50 K
Dust, 100 K
SNR > 4
SNR > 10
1 mm peak flux (Jy beam^{-1})
10^{-2}
10^{-3}
10^{-4}
−1
0
1
2
3
4
Spectral index, α


3 mm faintest
1 mm faintest
Optically thin dust
Dust, 20 K
Dust, 50 K
Dust, 100 K
SNR > 4
Upper limits
SNR > 10
Known HII
HII candidates
New HII
3 mm peak flux (Jy beam^{-1})
Spectral index, α
1 mm peak flux (Jy beam
Budaiev et al. 2024


3 mm faintest
1 mm faintest
Optically thin dust
Dust, 20 K
Dust, 50 K
Dust, 100 K
SNR > 4
Upper limits
SNR > 10
Known HII
HII candidates
New HII
3 mm peak flux (Jy beam^{-1})
Spectral index, α
$T_{dust} = 50$ K
3 mm
1 mm
N_{cores}
Core mass lower limit ($M_\odot$)
Cataloged cores
$\alpha < 2$ ($\pm 3\sigma$)
$\alpha > 2$ ($\pm 3\sigma$)
1 mm peak flux (Jy beam^{-1})
Budaiev et al. 2024

What are our sources?

400+ Stage 0/I YSOs:
- Compact dusty sources
- Rotationally supported
- 200-1000 AU
- 50 K



Prestellar cores?

$$t_{ff} = \sqrt{\frac{3\pi}{32G\rho}}$$

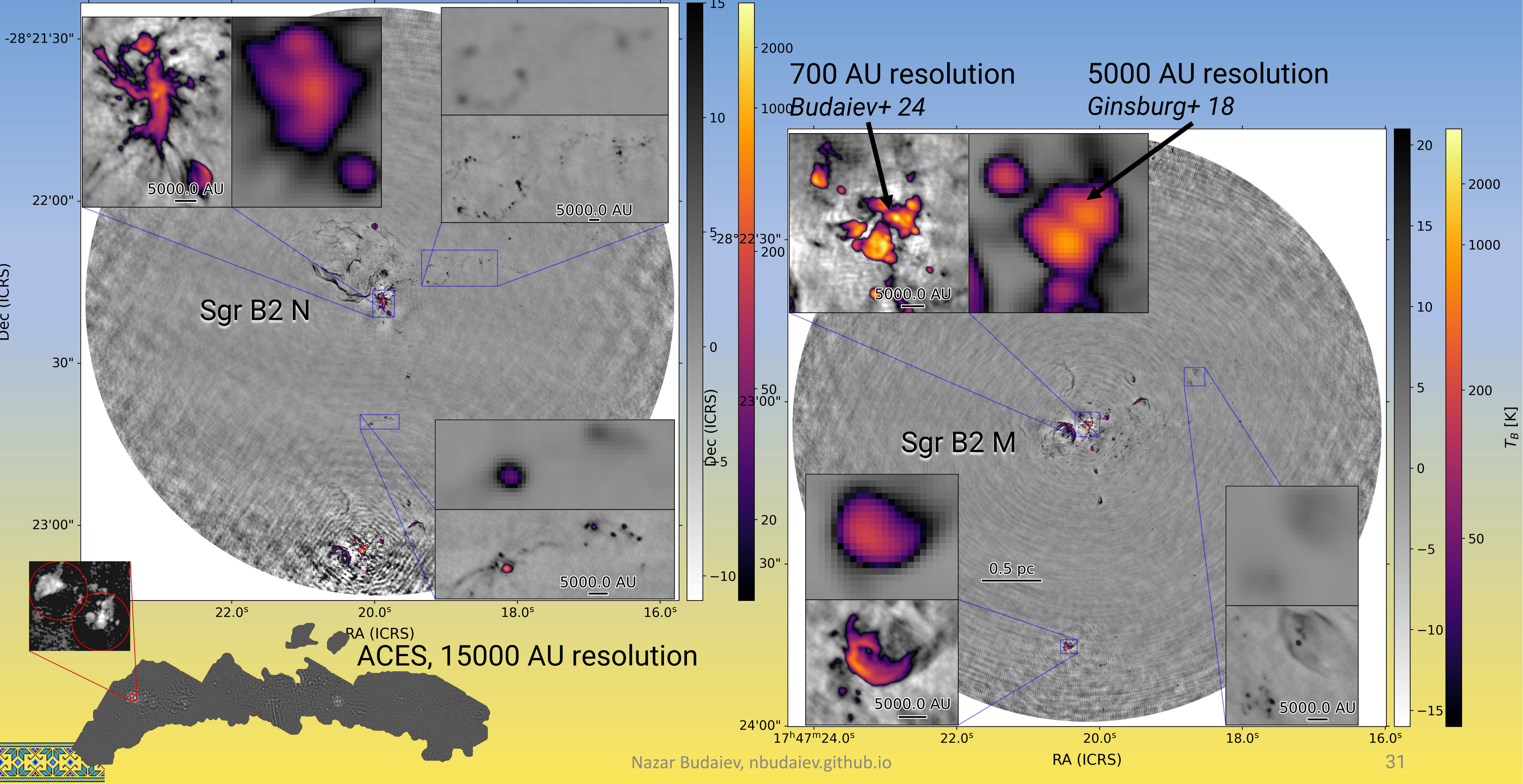
~1200 years at 1 Msun

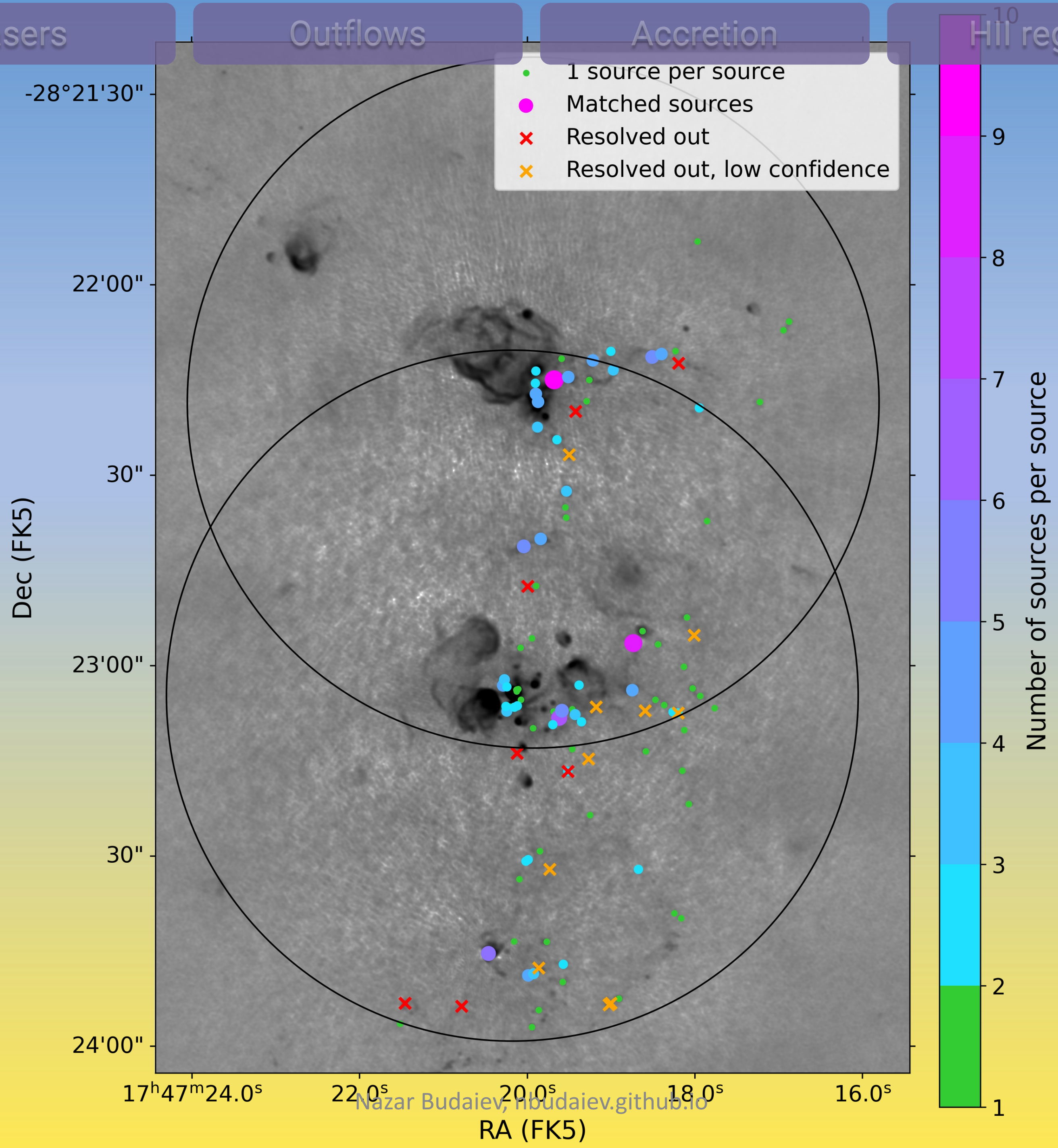
Stage II YSOs?

Faintest source -> 30 Msun central star

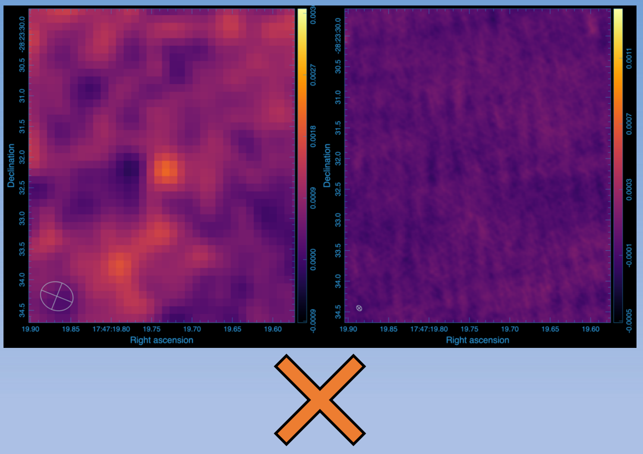
HII regions?

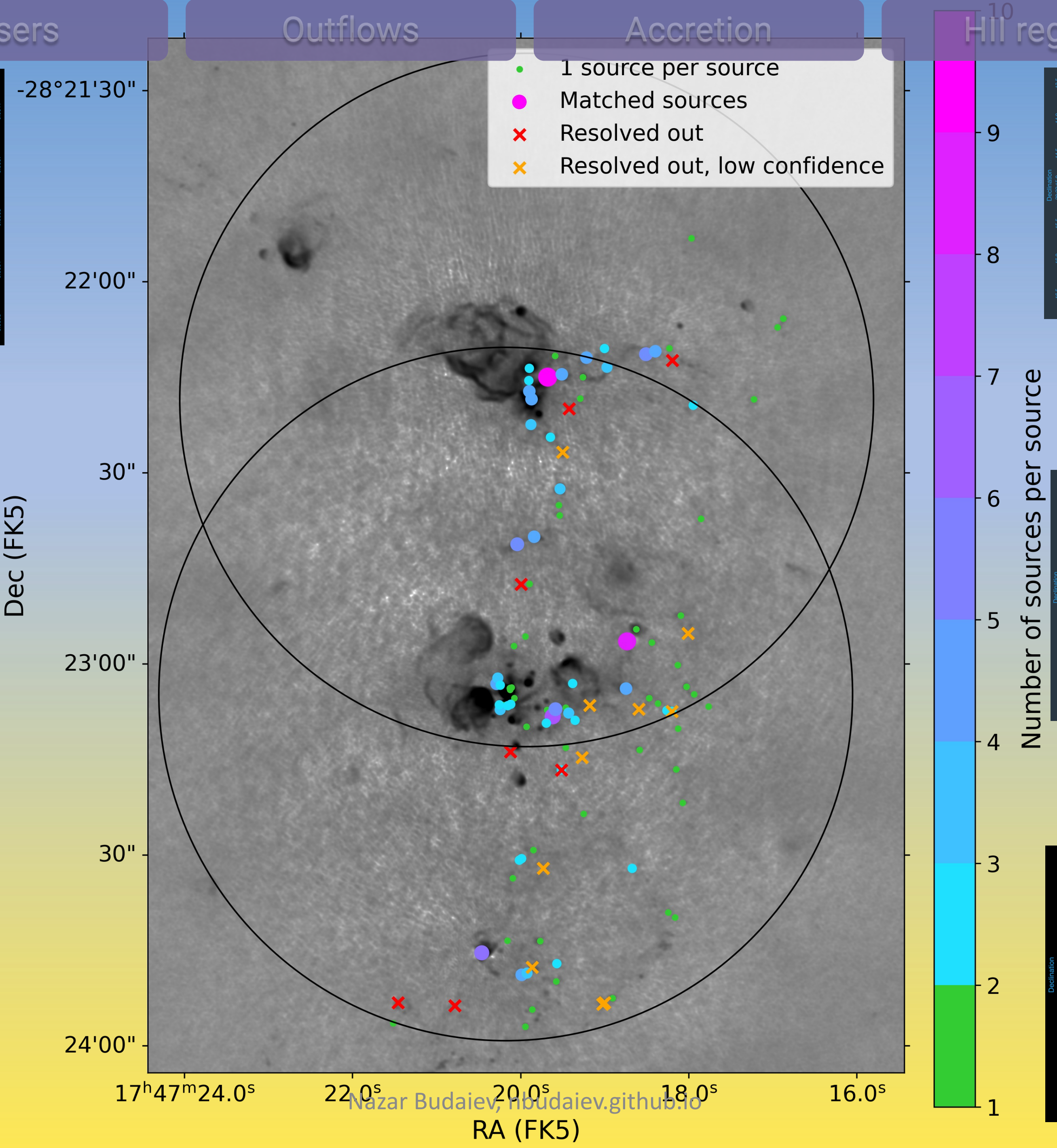
Only optically thick, 30-80 AU in diameter

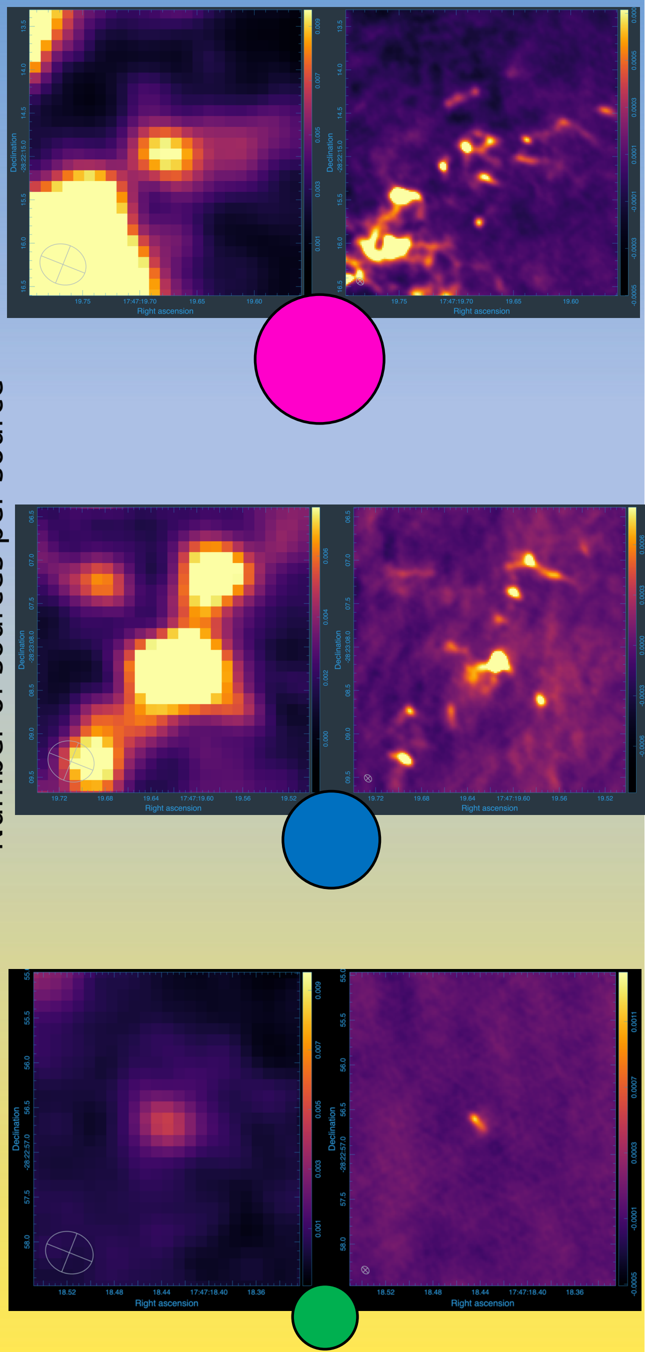

700 AU resolution
Budaiev+ 24
5000 AU resolution
Ginsburg+ 18
Sgr B2 N
Sgr B2 M
ACES, 15000 AU resolution
5000.0 AU
0.5 pc
RA (ICRS)
Dec (ICRS)
T_B [K]


1 source per source
Matched sources
Resolved out
Resolved out, low confidence
-28°21'30"
22'00"
30"
23'00"
30"
24'00"
Dec (FK5)
17h47m24.0s
22.0s
20.0s
18.0s
16.0s
RA (FK5)
Number of sources per source
1
2
3
4
5
6
7
8
9
10

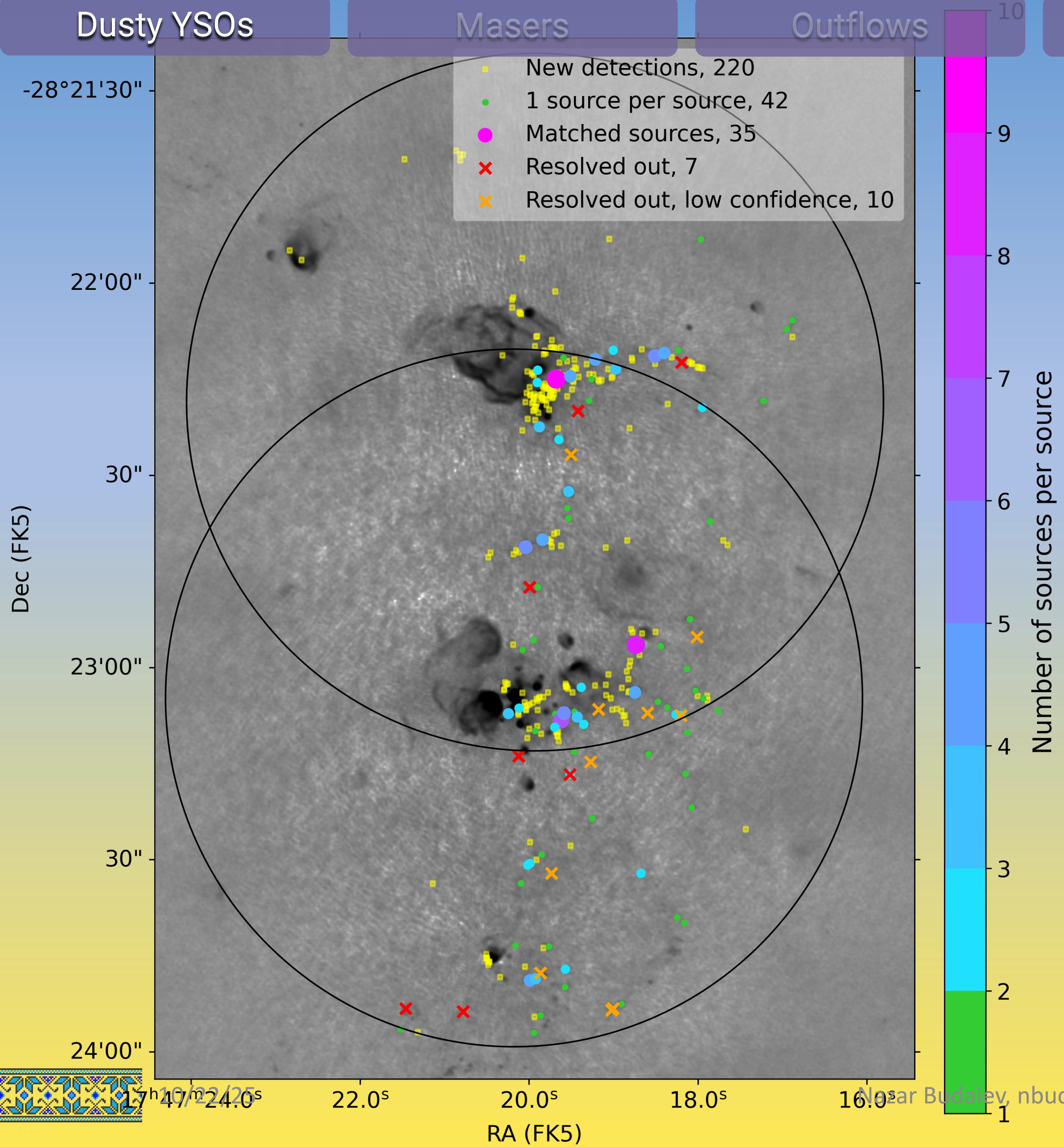
Dusty YSOs | Masers | Outflows | Accretion | HII regions | Evolved YSOs

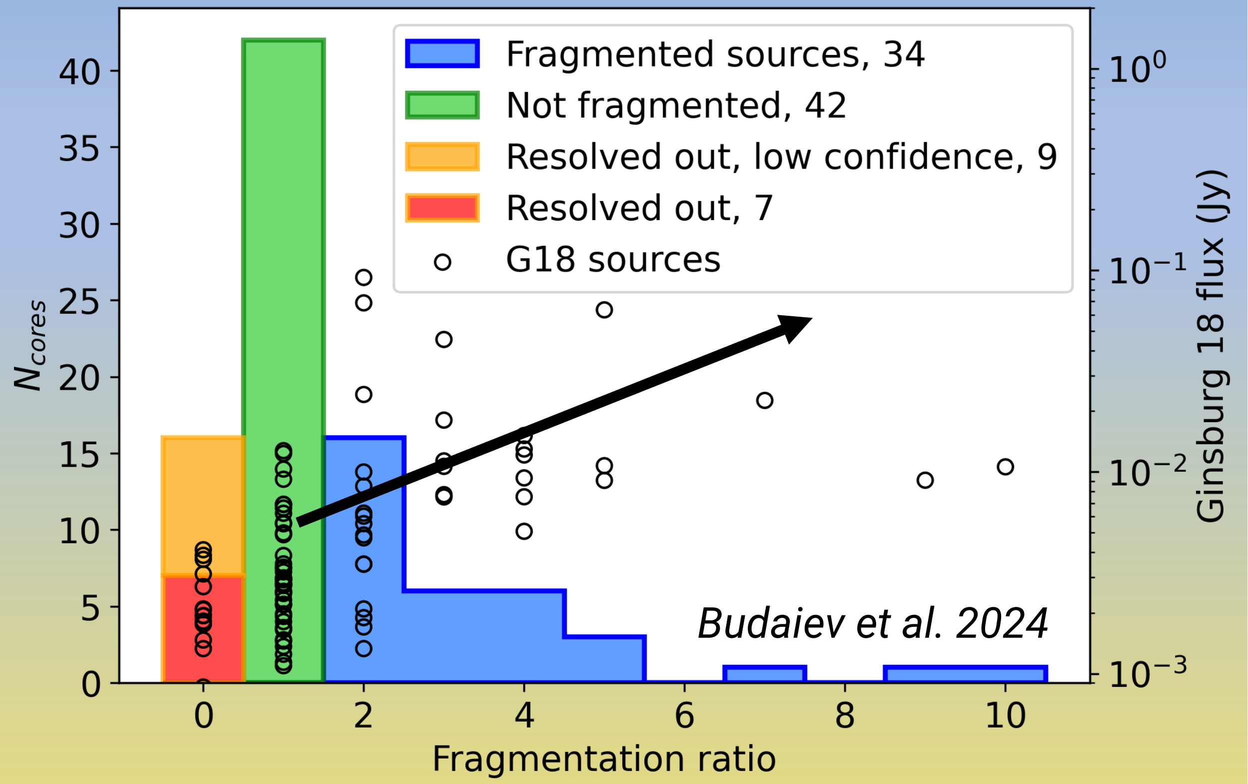




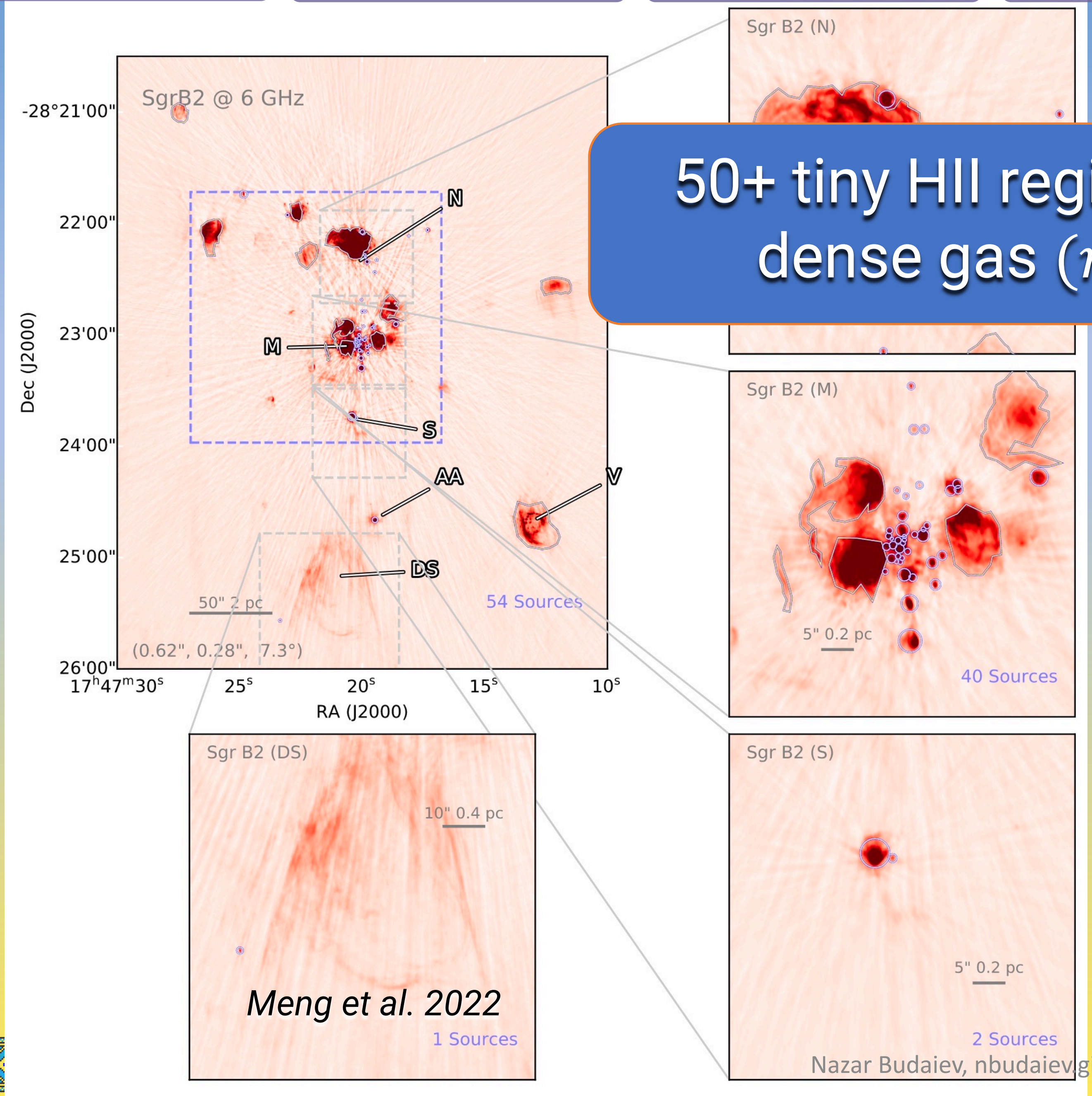


Nazar Budaiev, nbudaiev.github.io

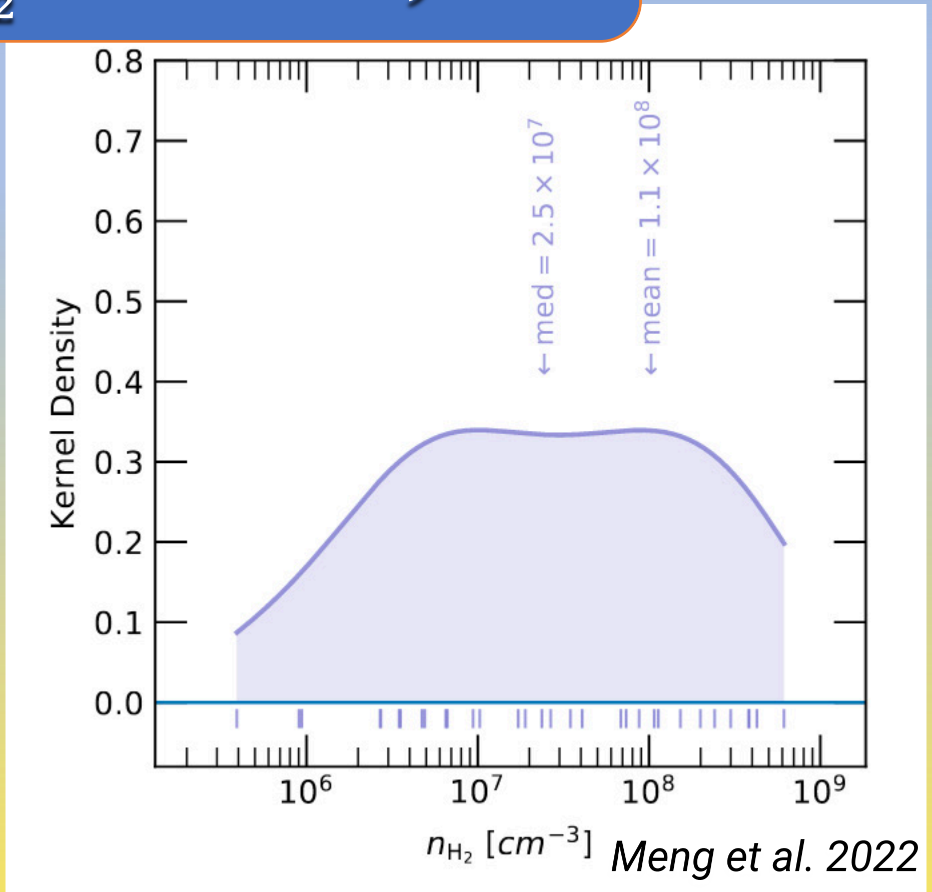

New detections, 220
1 source per source, 42
Matched sources, 35
Resolved out, 7
Resolved out, low confidence, 10
-28°21'30"
22'00"
30"
23'00"
30"
24'00"
Dec (FK5)
22.0s
20.0s
18.0s
16.0s
RA (FK5)
Number of sources per source
1
2
3
4
5
6
7
8
9
10


Fragmented sources, 34
Not fragmented, 42
Resolved out, low confidence, 9
Resolved out, 7
G18 sources
N_{cores}
Fragmentation ratio
Ginsburg 18 flux (Jy)
10^0
10^{-1}
10^{-2}
10^{-3}
Budaiev et al. 2024

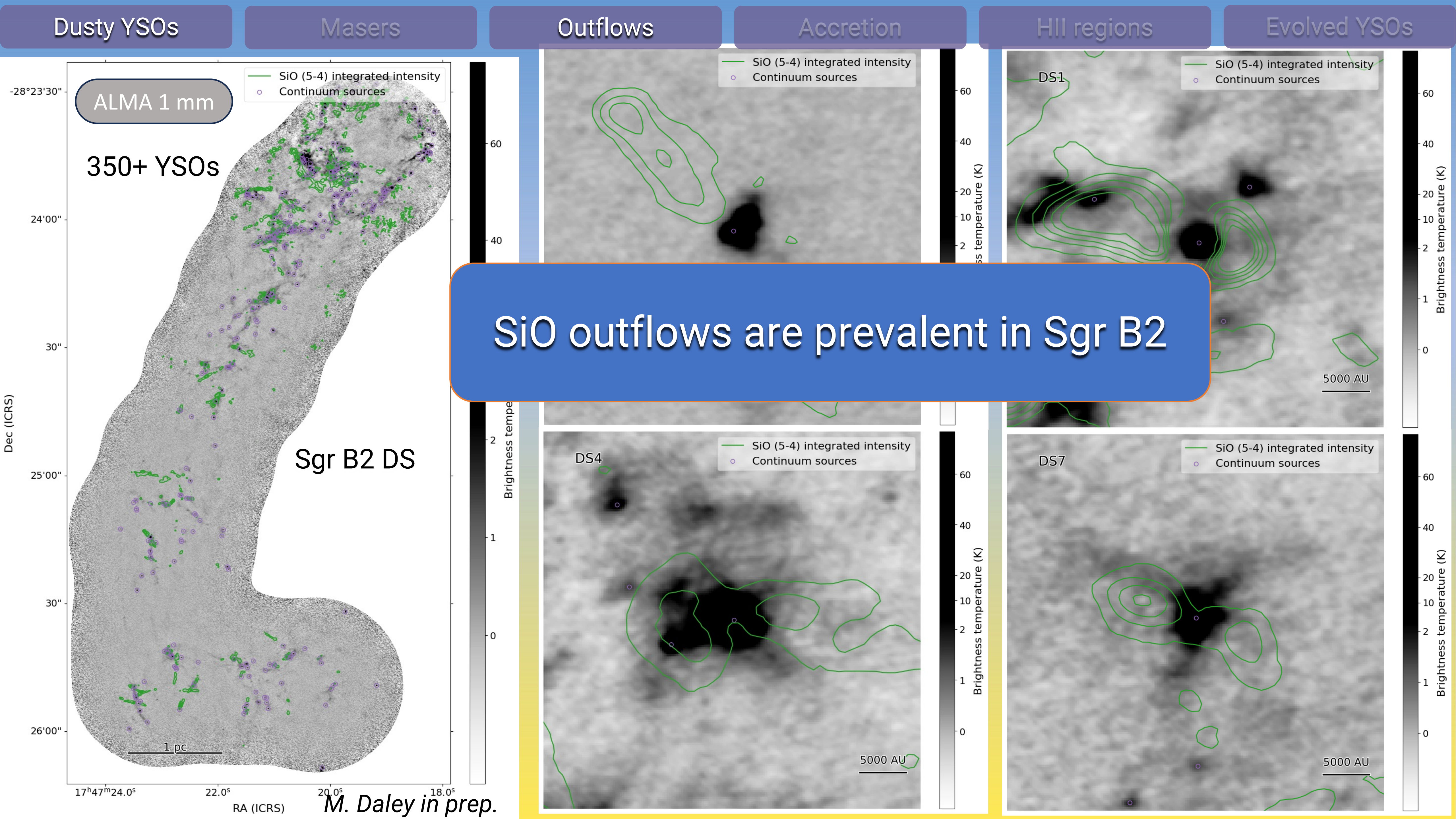
50+ tiny HII regions surrounded by dense gas ($n_{\mathrm{H_2}} > 10^7\,\mathrm{cm}^{-3}$)

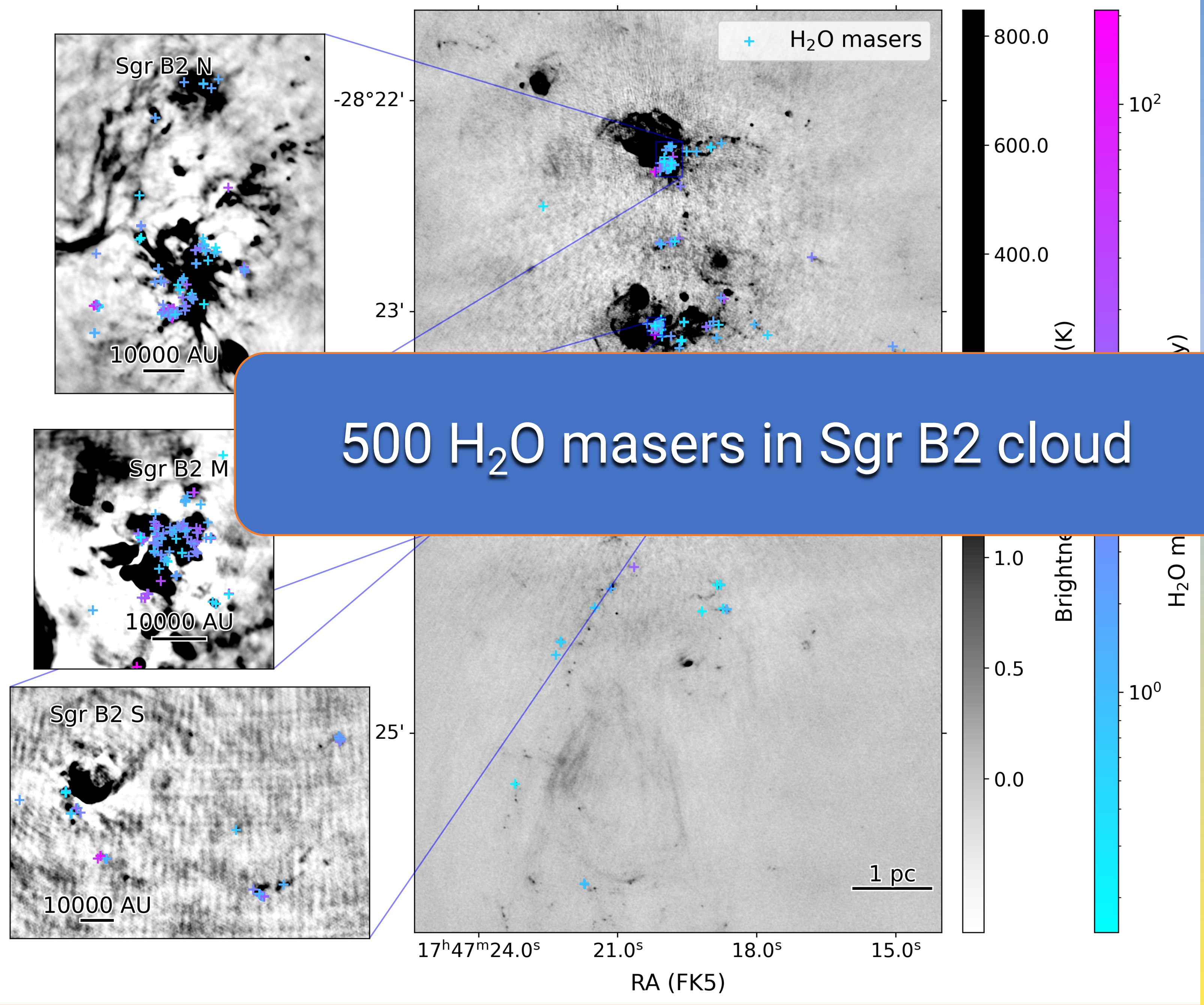


Meng et al. 2022



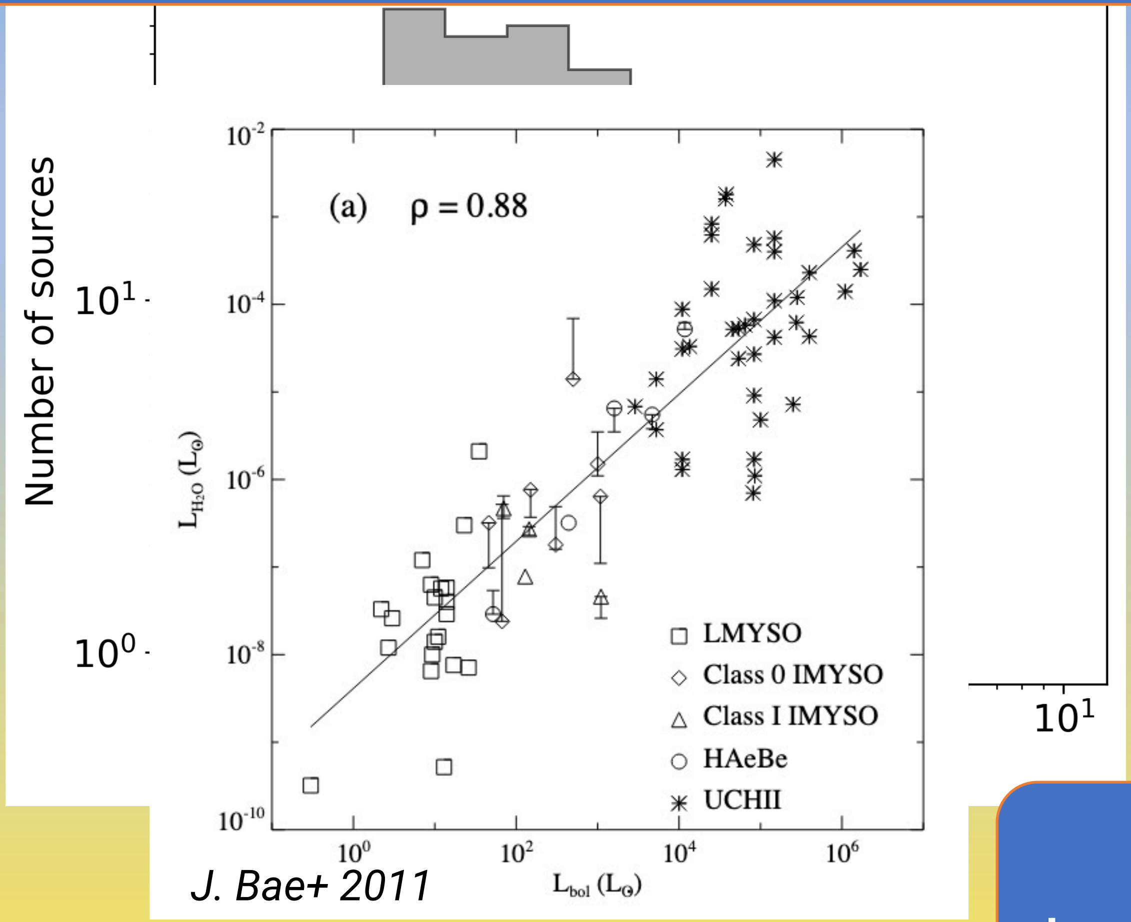
Meng et al. 2022


Dusty YSOs
Masers
Outflows
Accretion
HII regions
Evolved YSOs
ALMA 1 mm
350+ YSOs
Sgr B2 DS
SiO (5-4) integrated intensity
Continuum sources
DS1
DS4
DS7
5000 AU
1 pc
Dec (ICRS)
RA (ICRS)
Brightness temperature (K)
SiO outflows are prevalent in Sgr B2
M. Daley in prep.

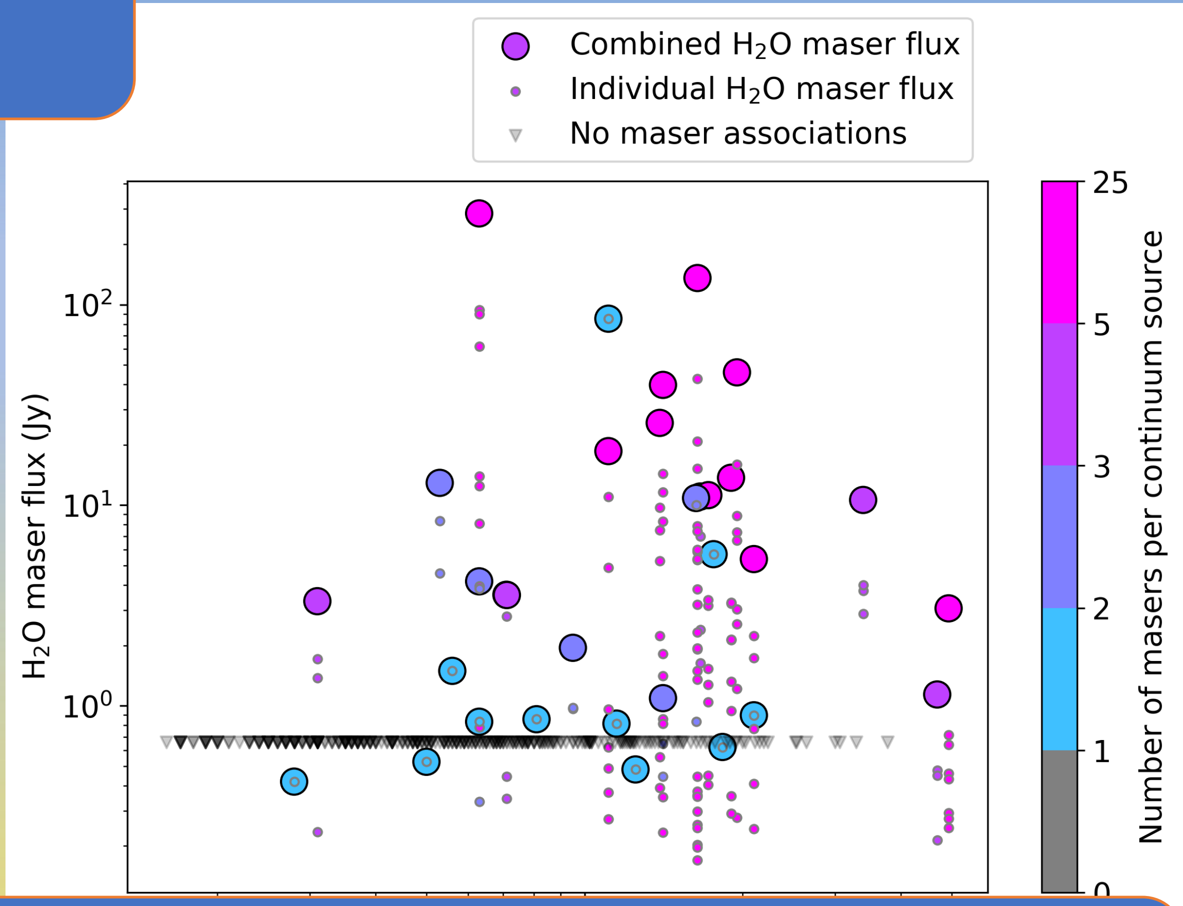


500 H_2O masers in Sgr B2 cloud

Dust continuum is brighter in the presence of H_2O masers

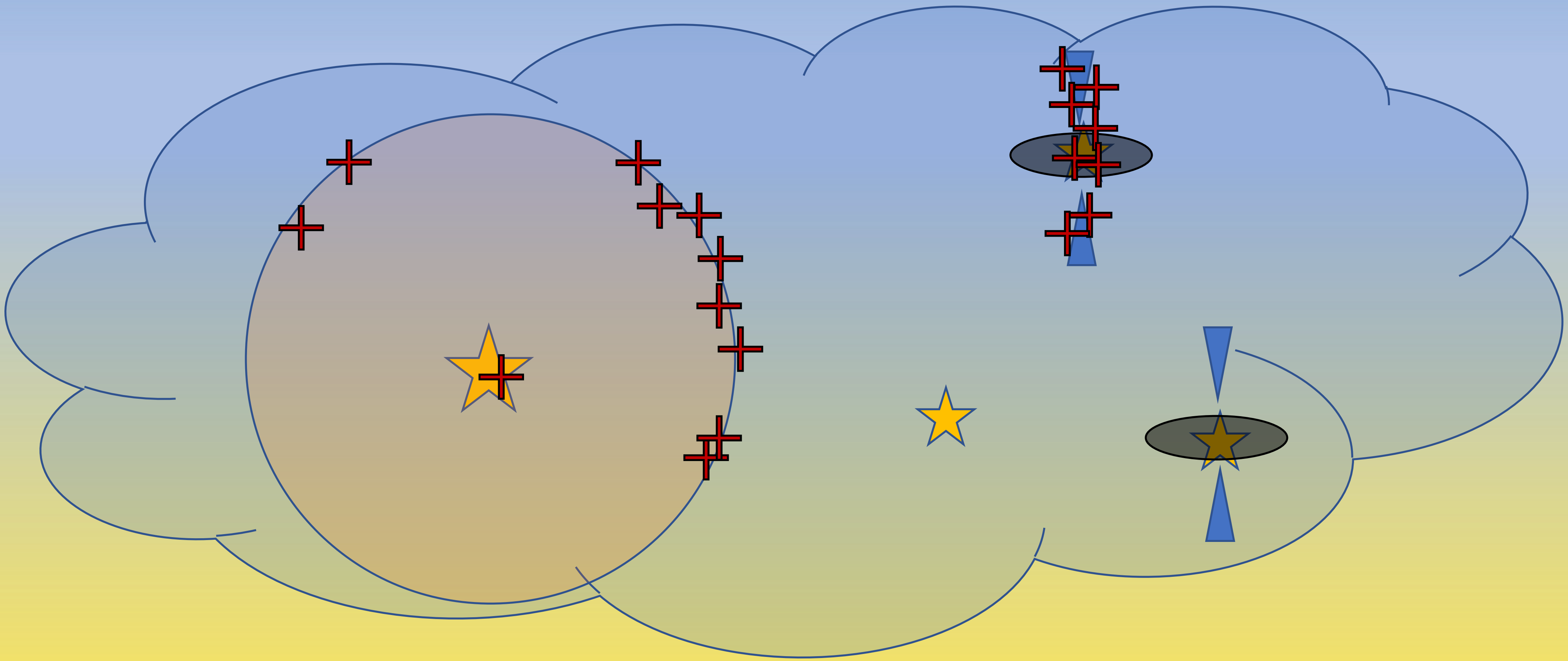


J. Bae+ 2011

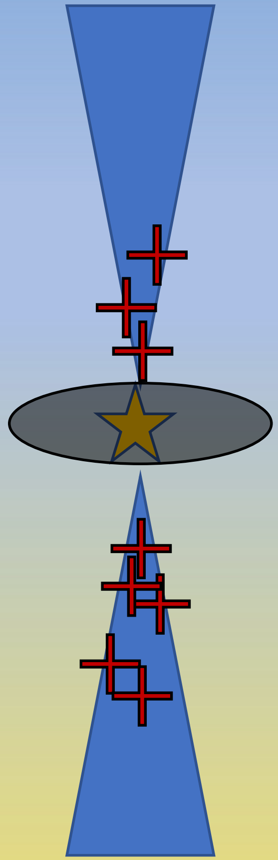


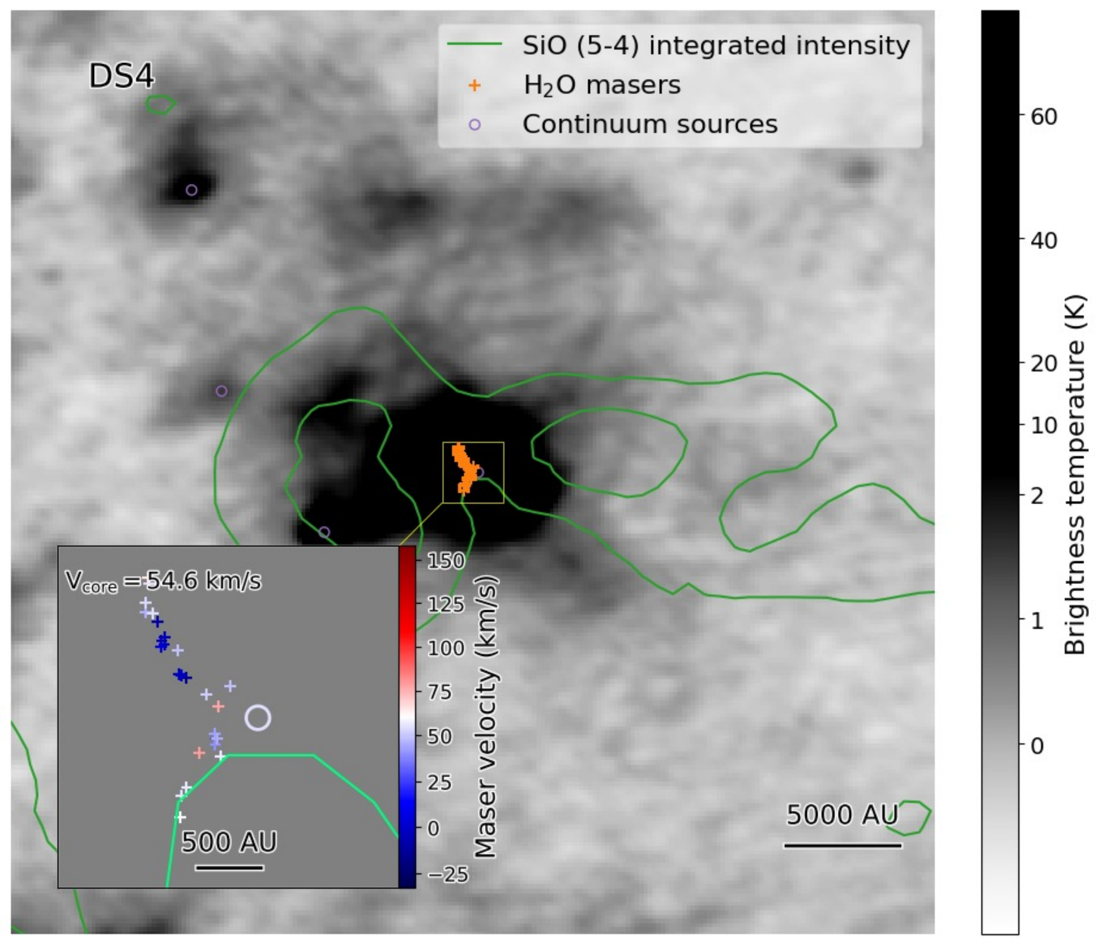
There is no strong correlation between maser and continuum fluxes

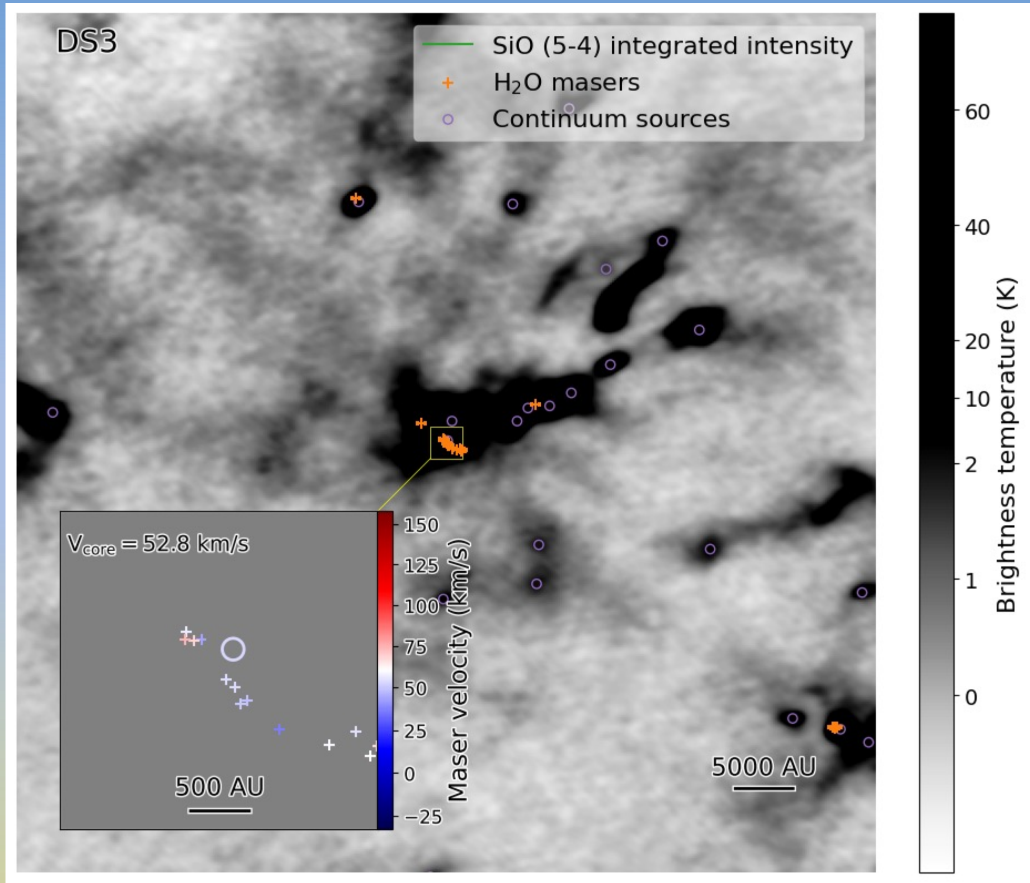
Where can we find water masers?



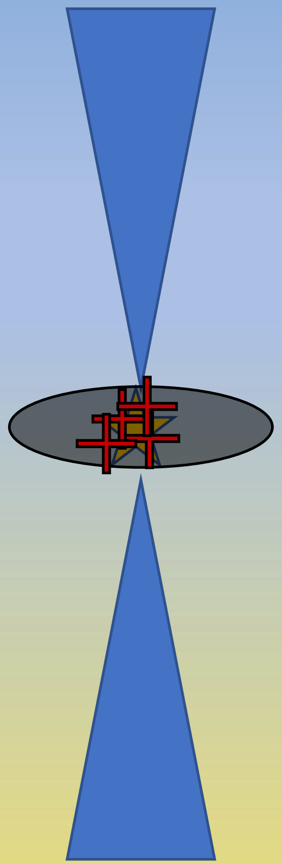
Outflow-associated

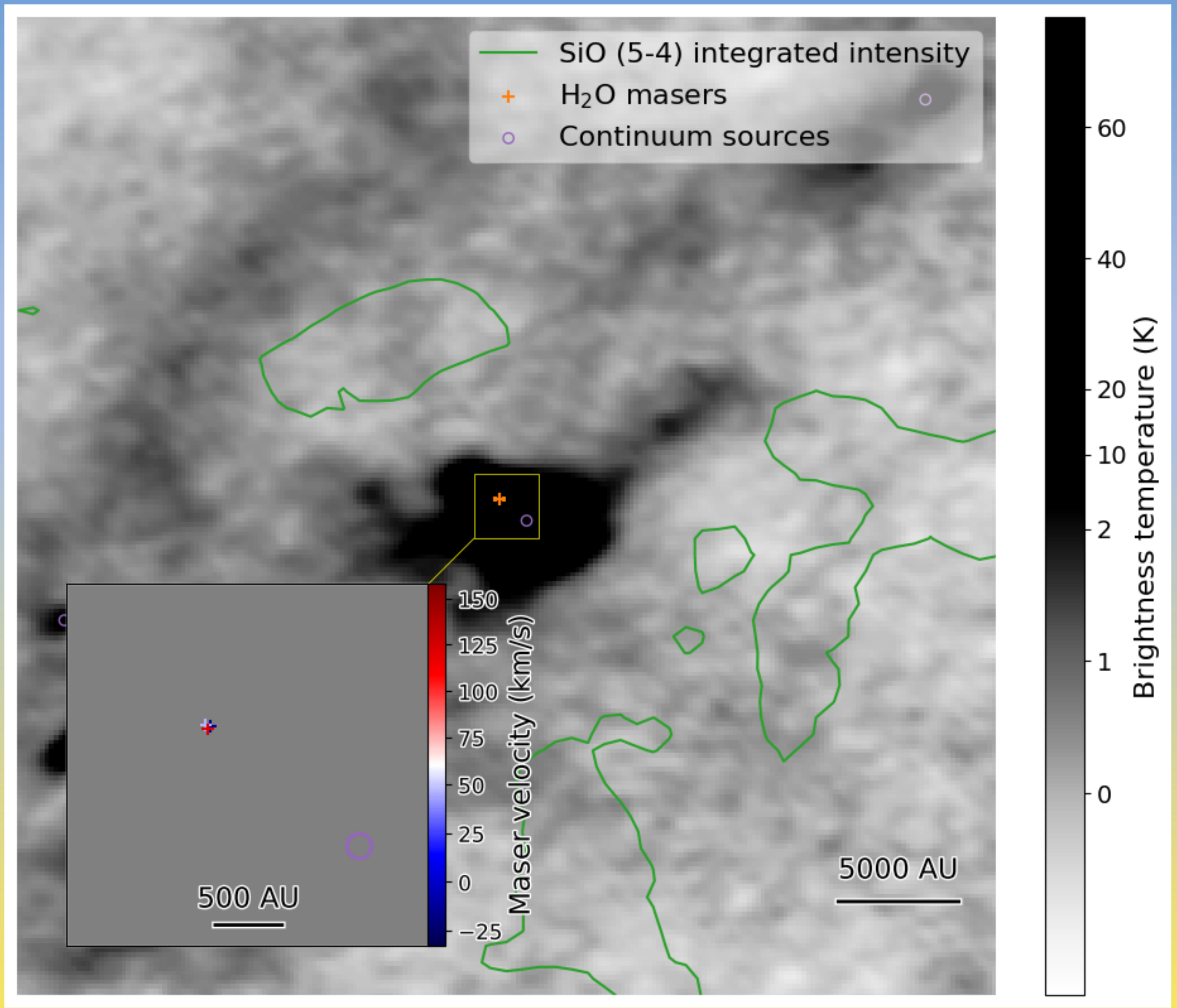




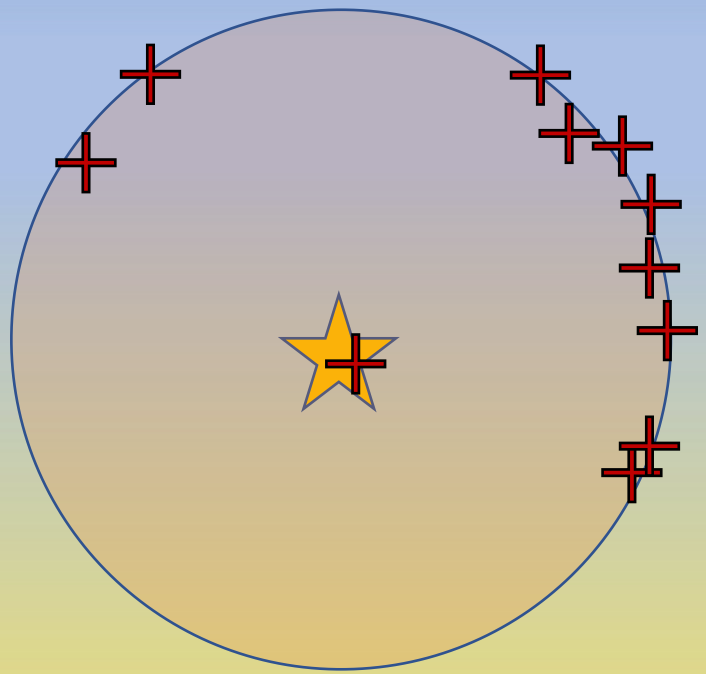


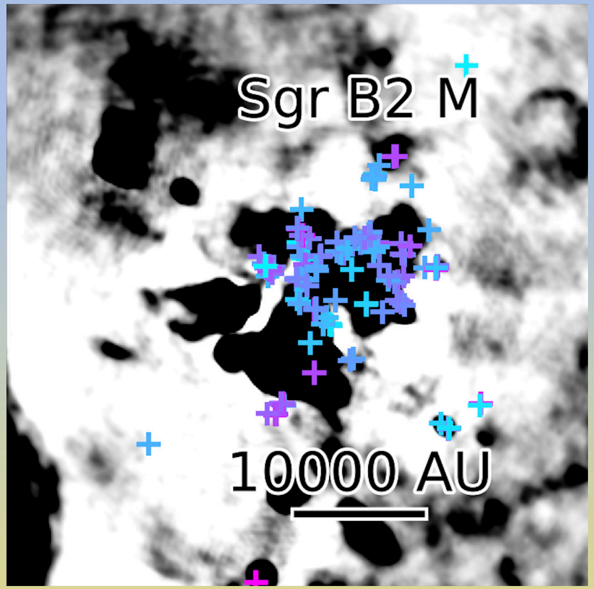
YSO-associated

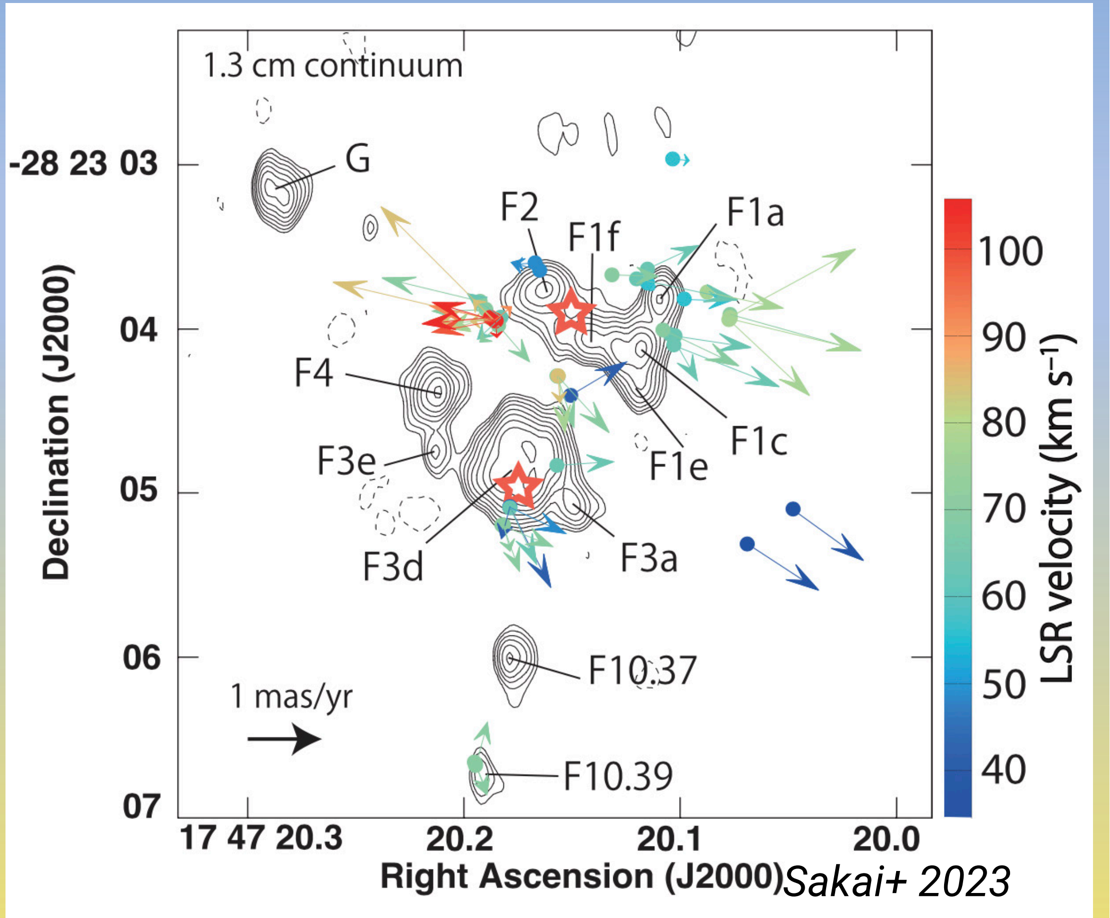




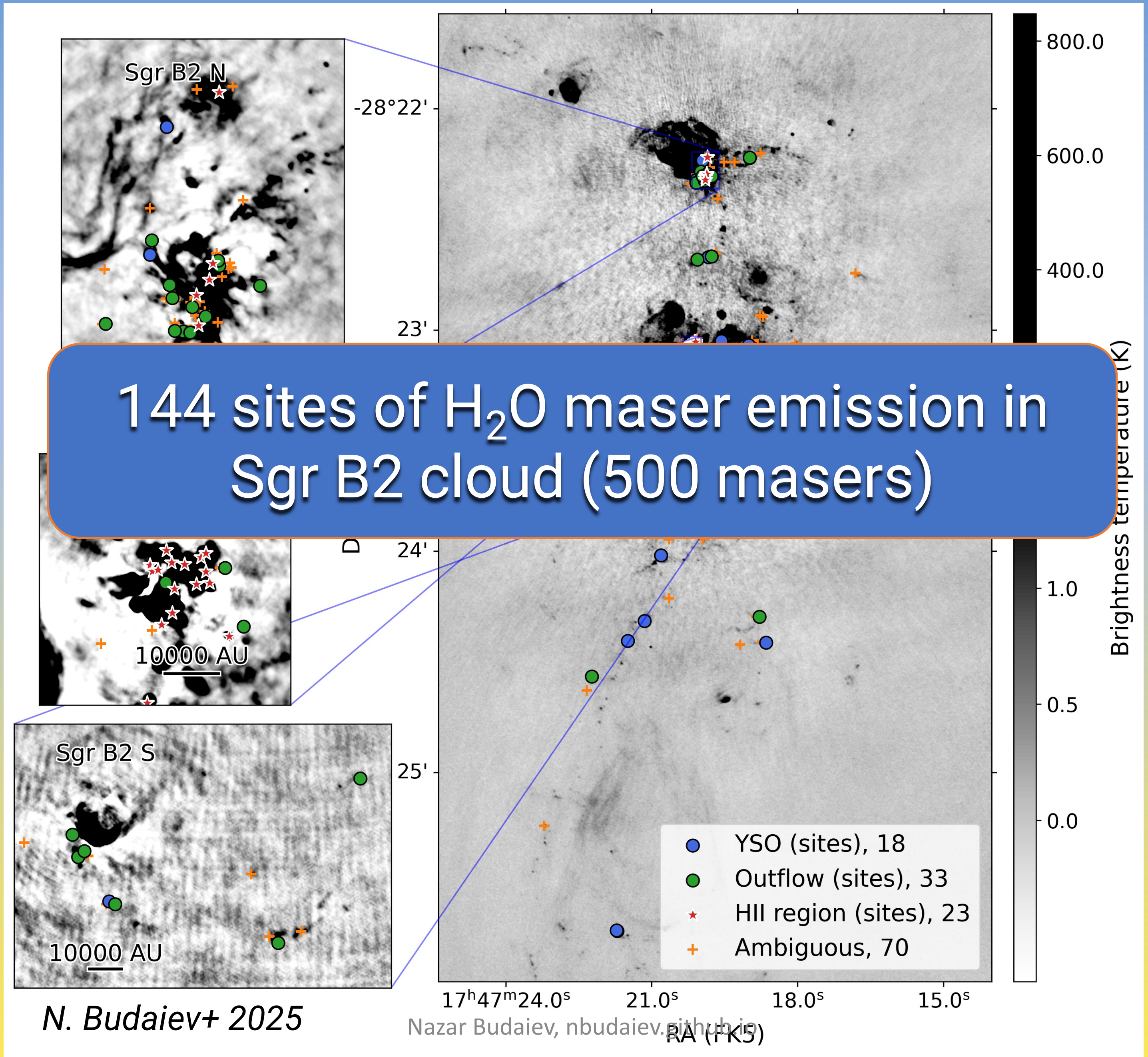
HII region-associated







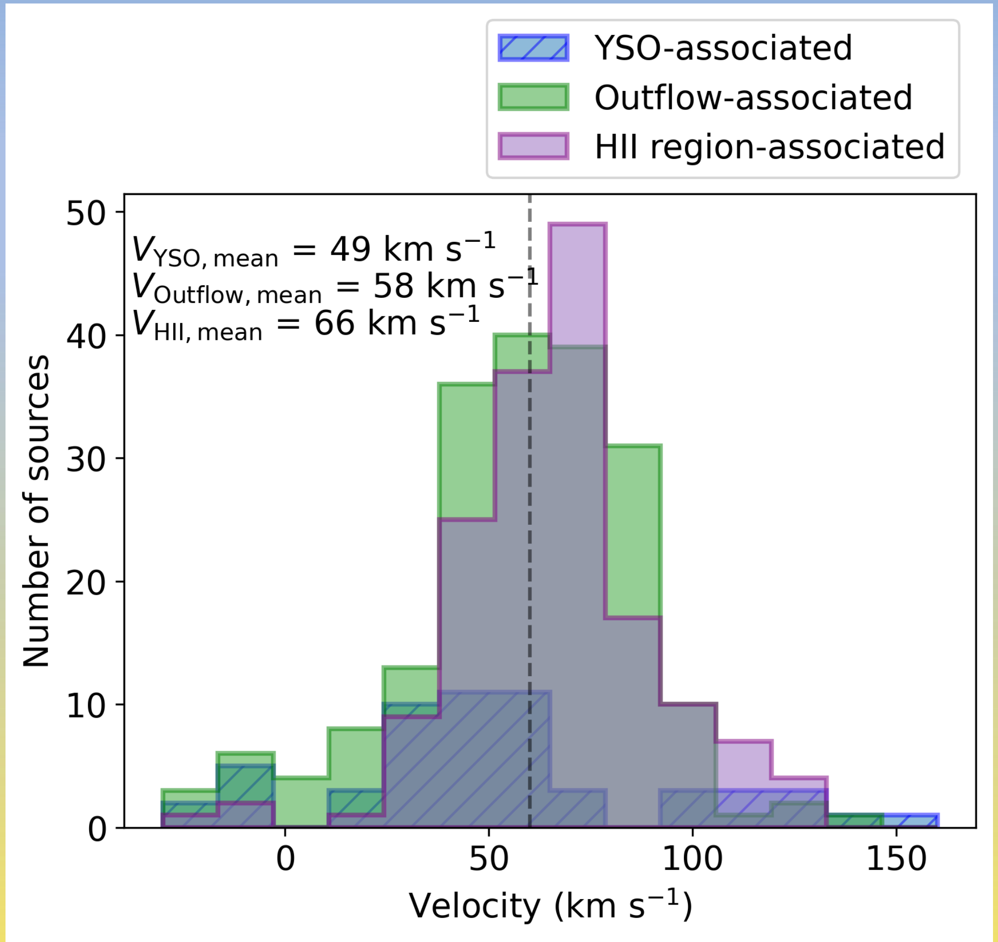
Sakai+ 2023

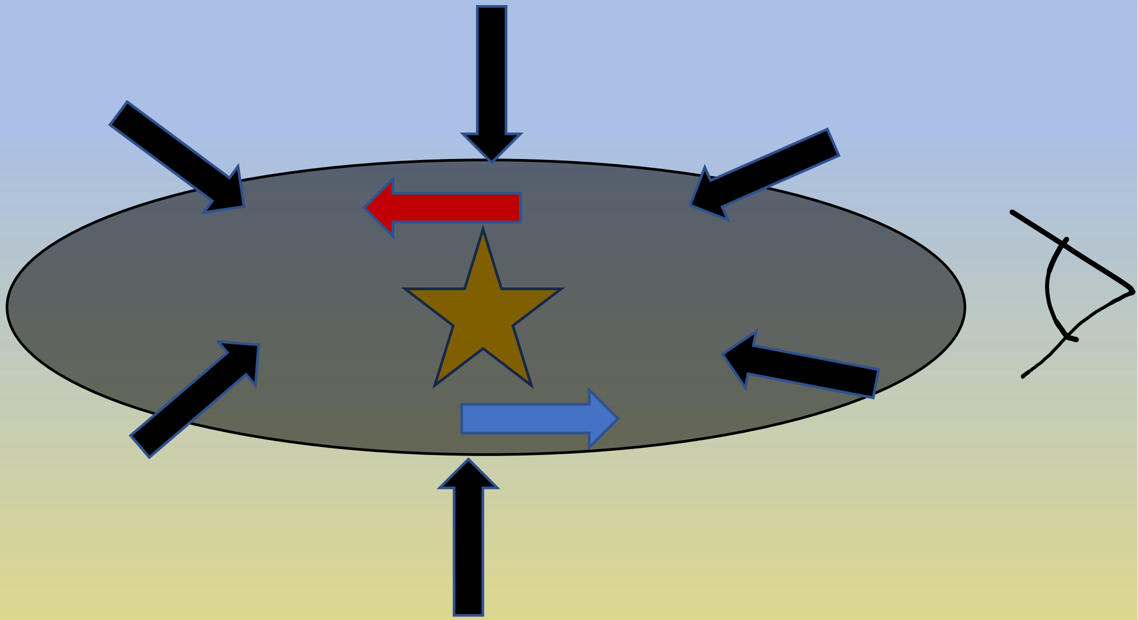


144 sites of H_2O maser emission in Sgr B2 cloud (500 masers)

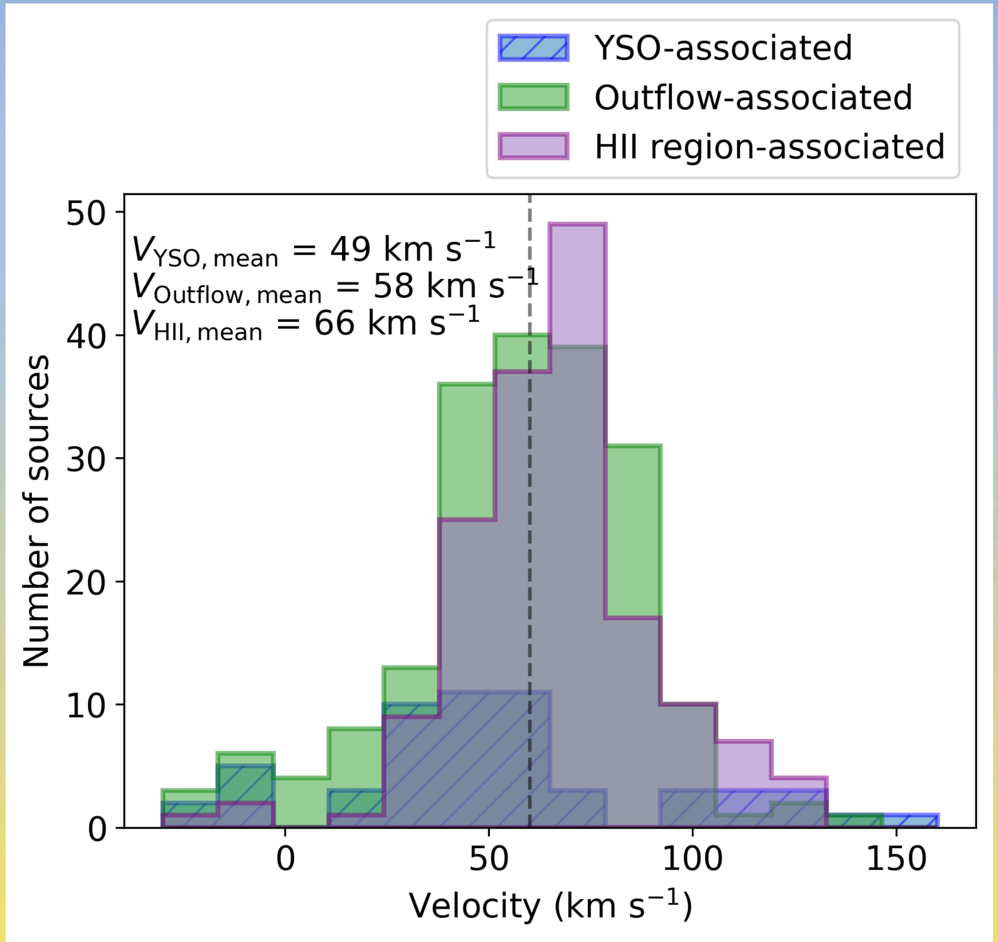
N. Budaiev+ 2025

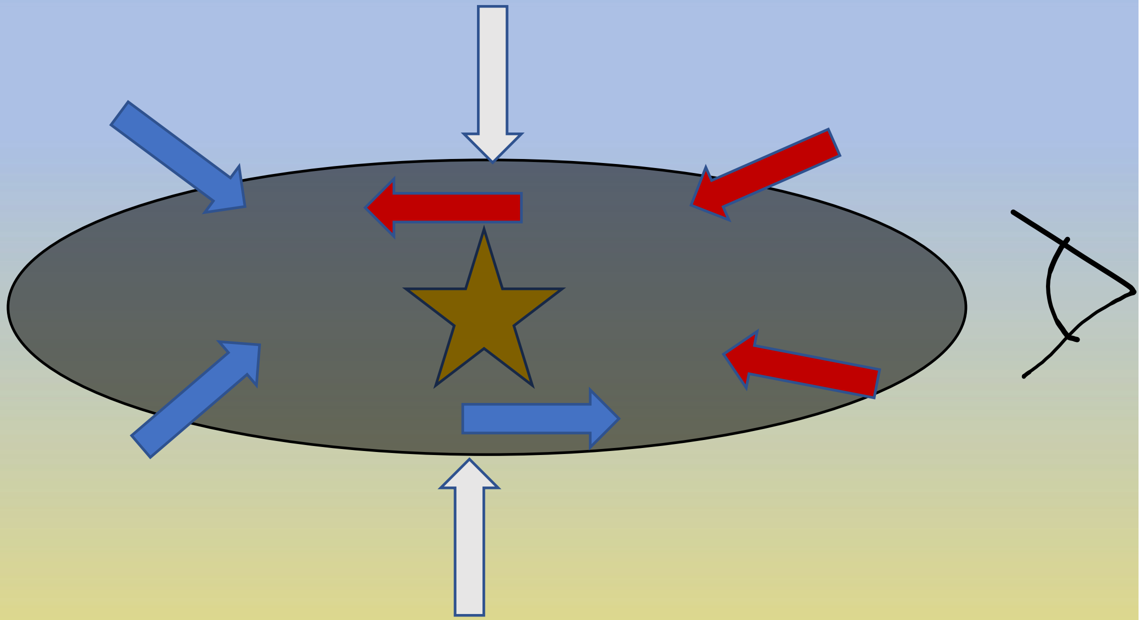
Maser velocity by source nature



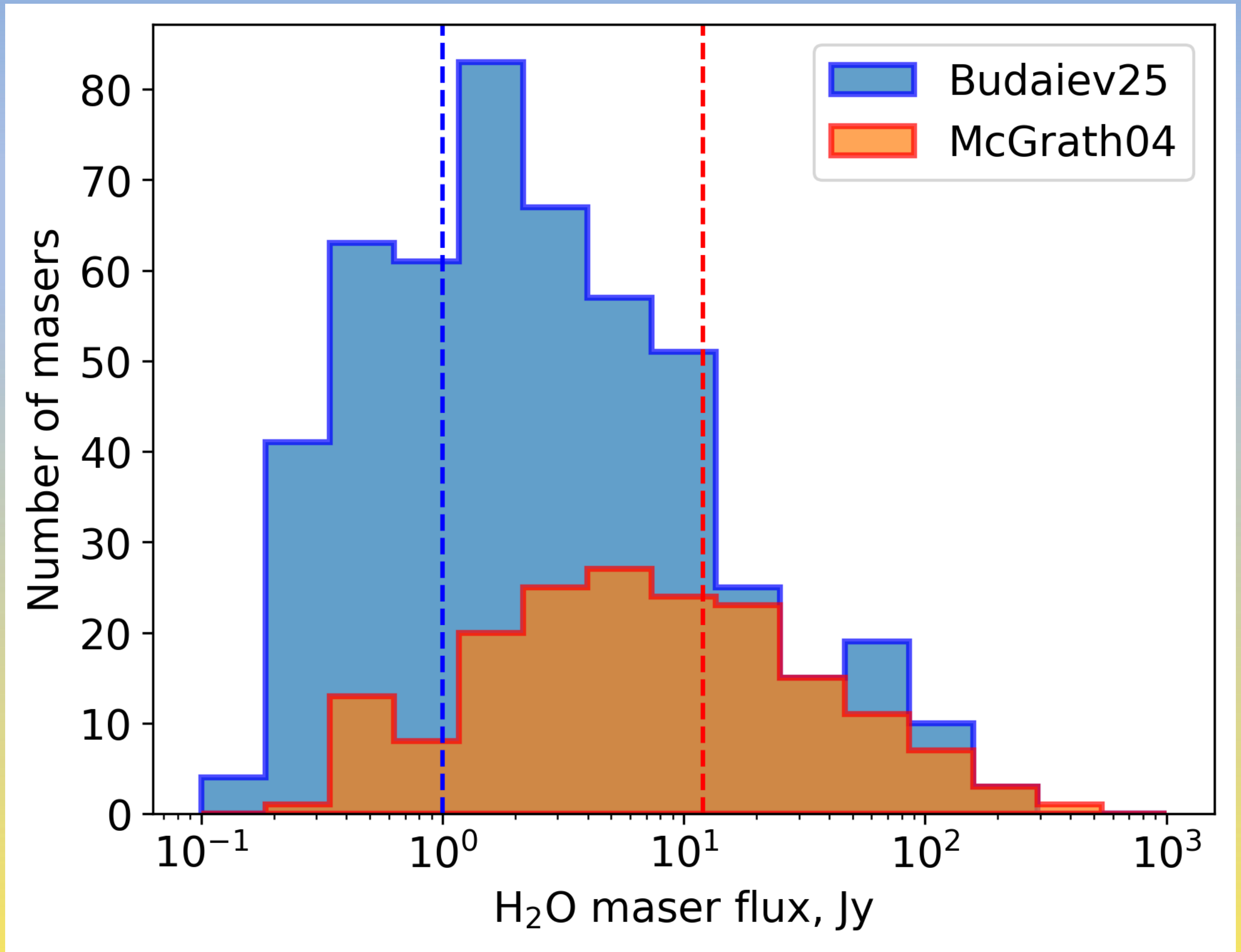


Maser velocity by source nature

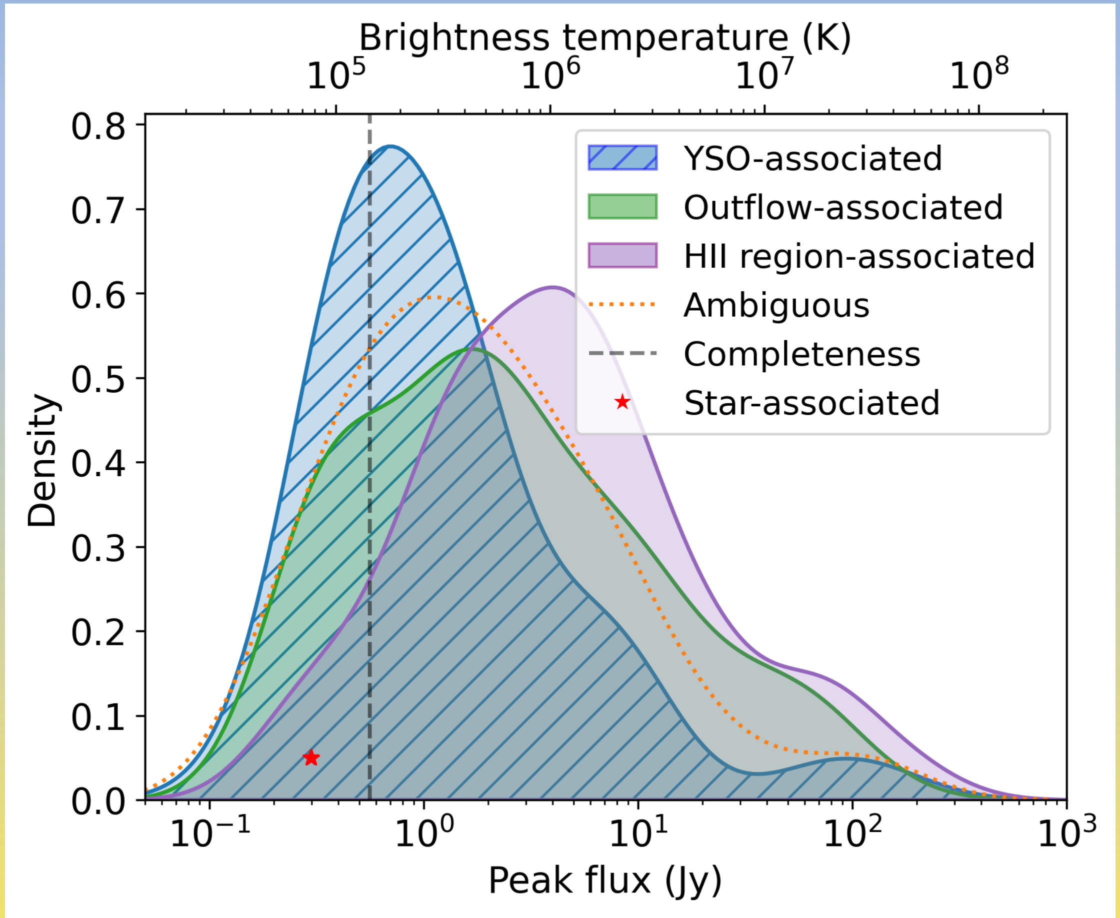


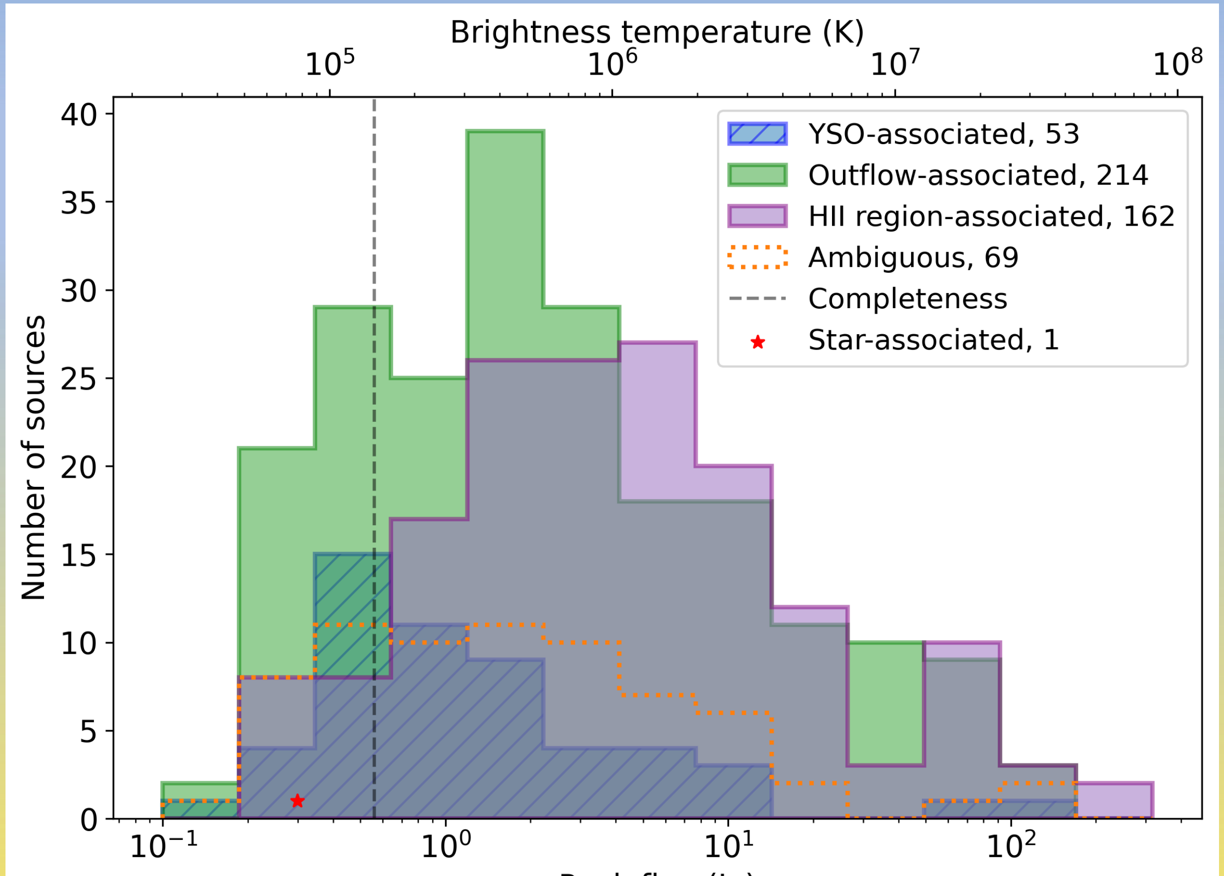


Are maser *populations* time invariable?



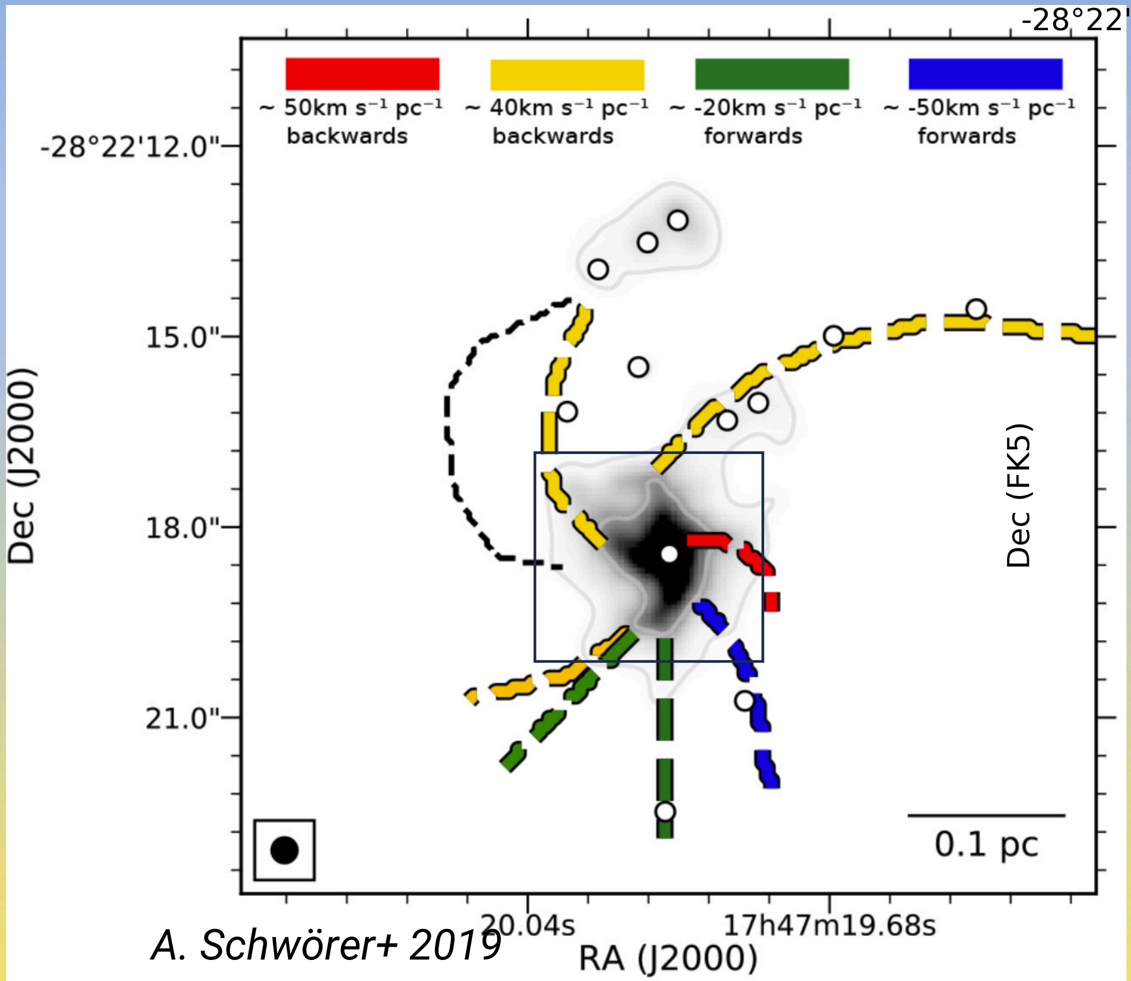
Interpretation for surveys



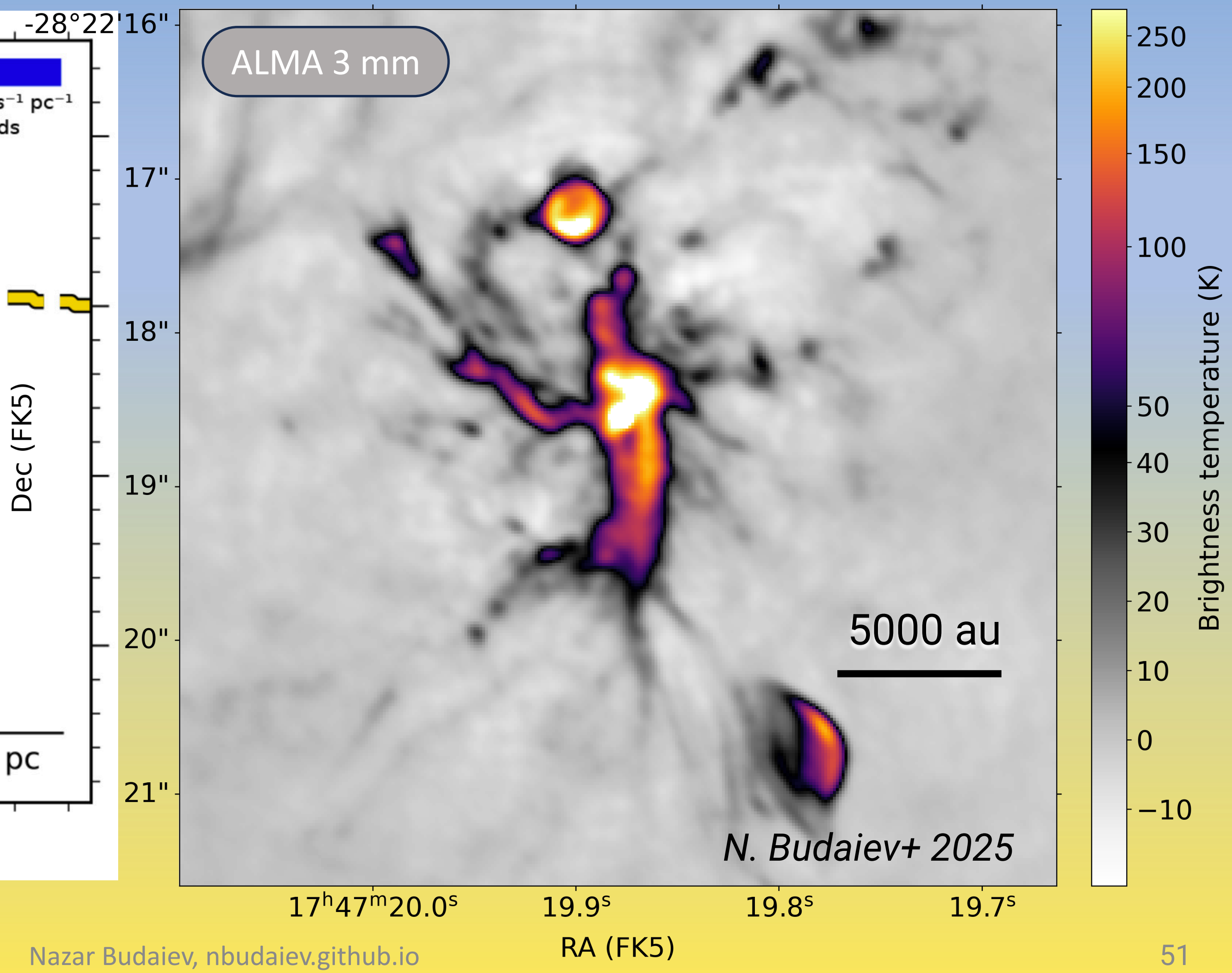


N. Budaiev+ 2025

Large-scale material flow in Sgr B2 N

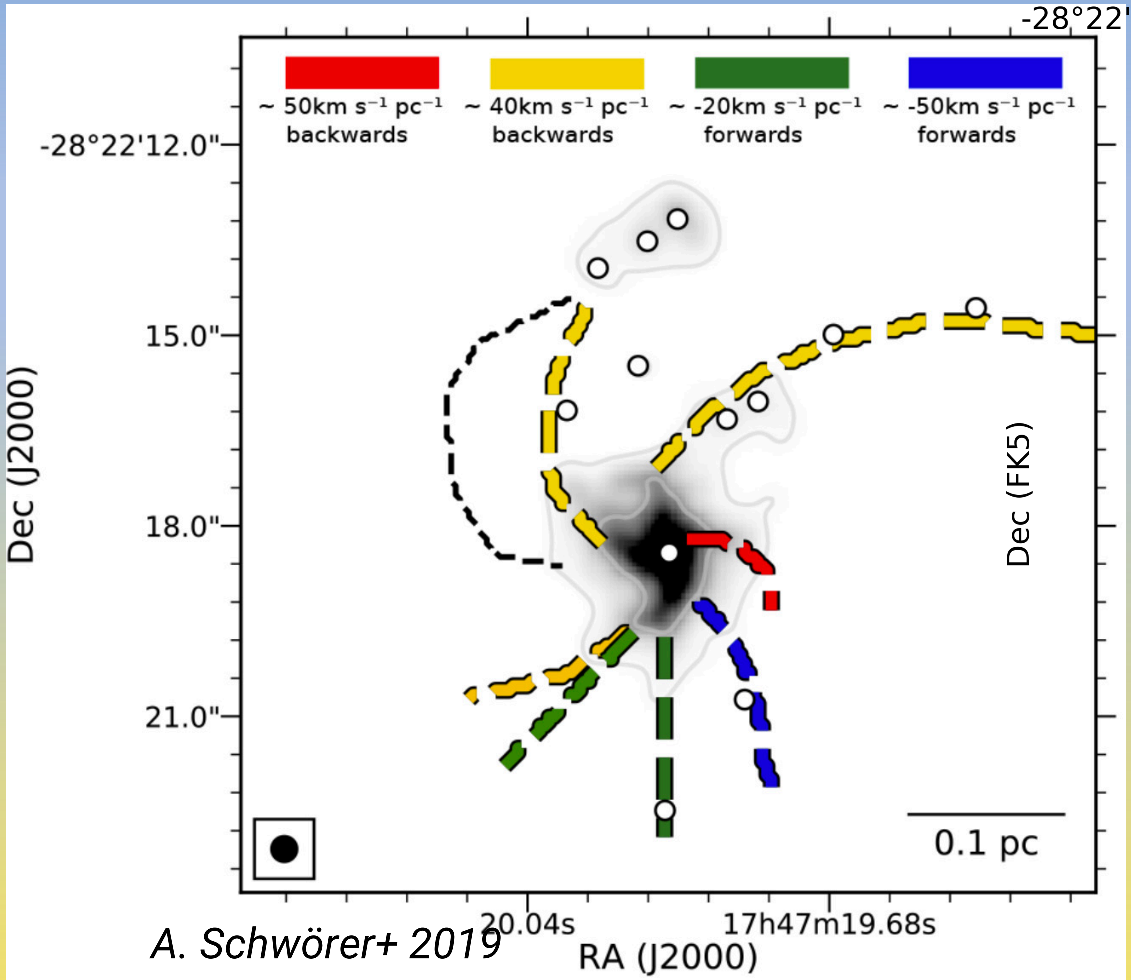


A. Schwörer+ 2019

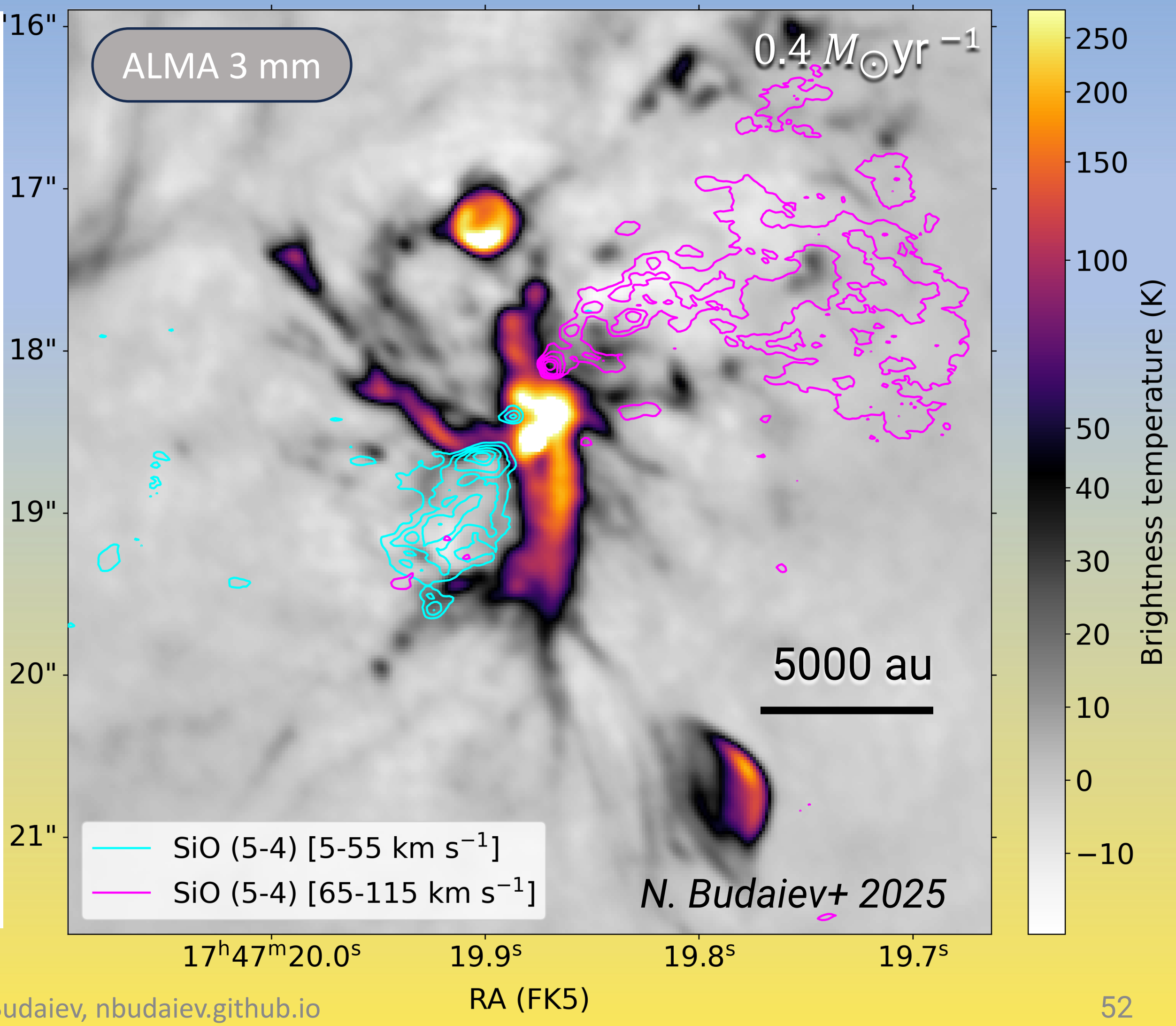


N. Budaiev+ 2025

Large-scale material flow in Sgr B2 N



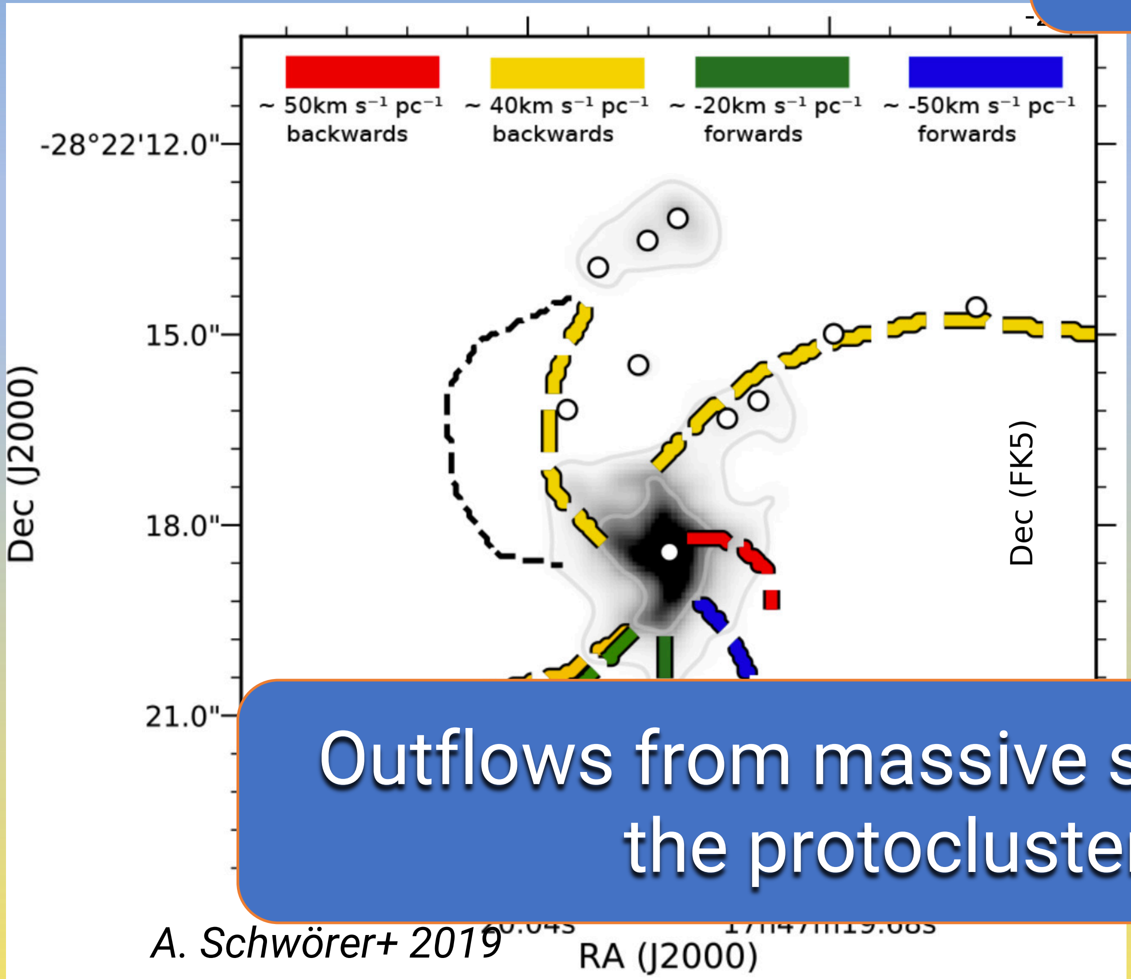
A. Schwörer+ 2019



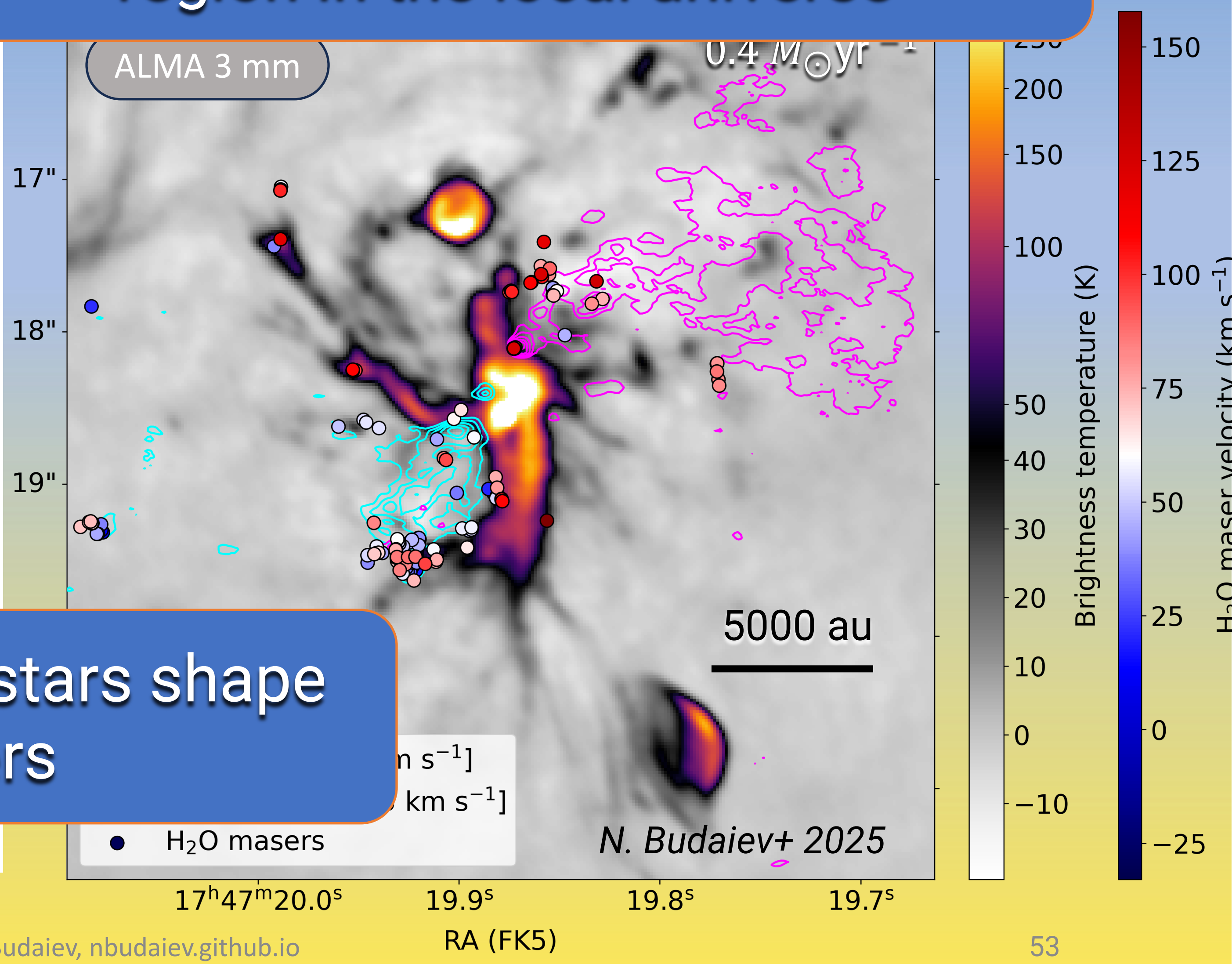
N. Budaiev+ 2025

Large-scale mate

Resolved feedback in the densest region in the local universe

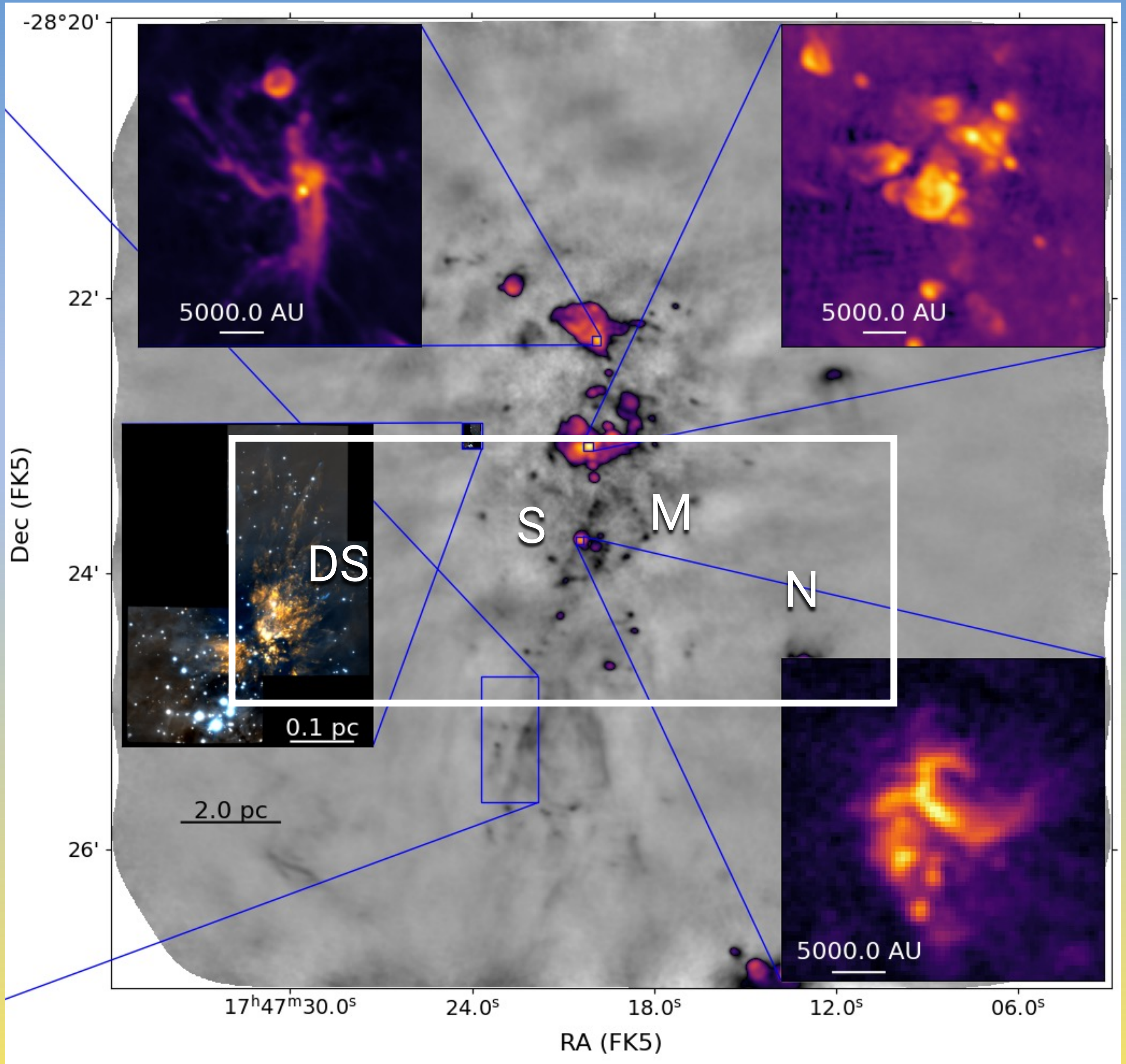


A. Schwörer+ 2019



N. Budaiev+ 2025

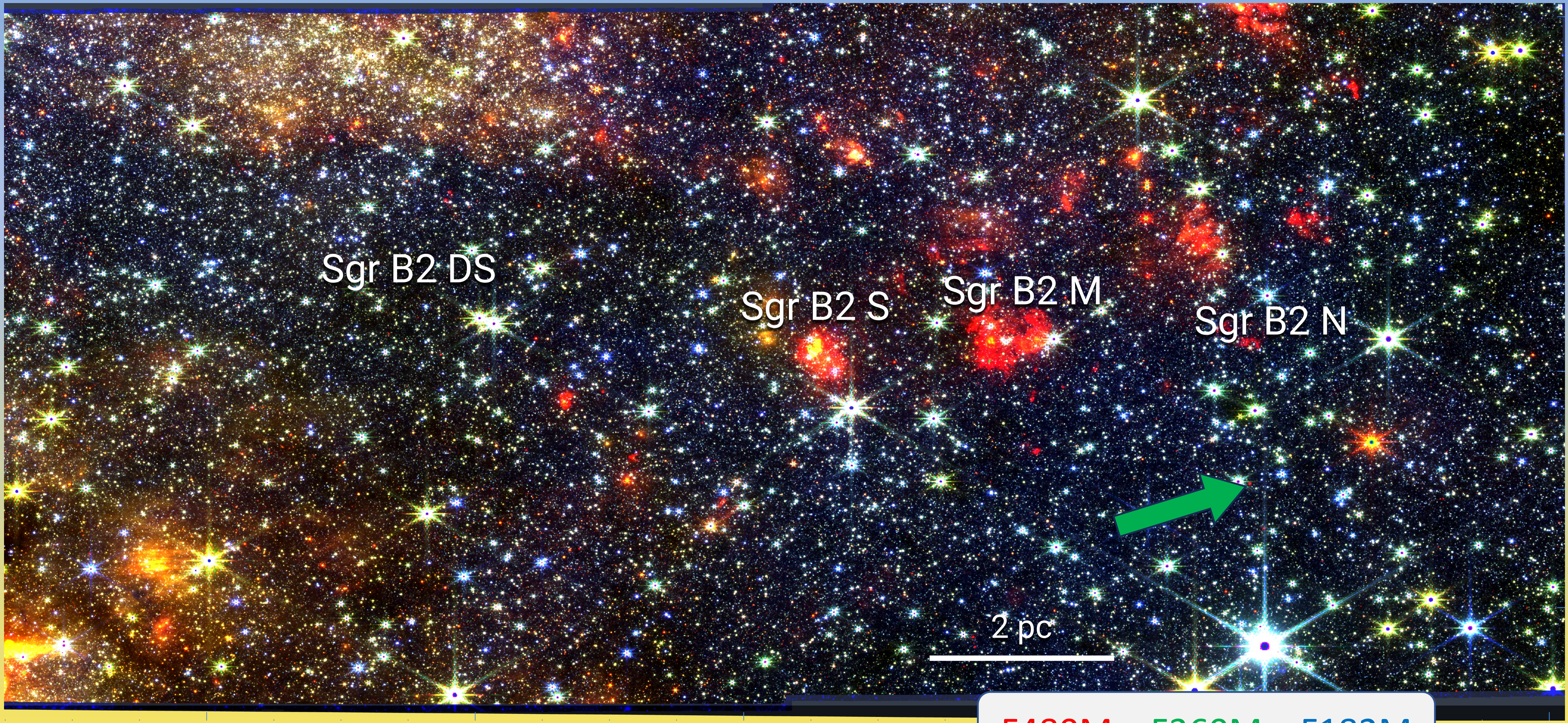
Outflows from massive stars shape the protoclusters



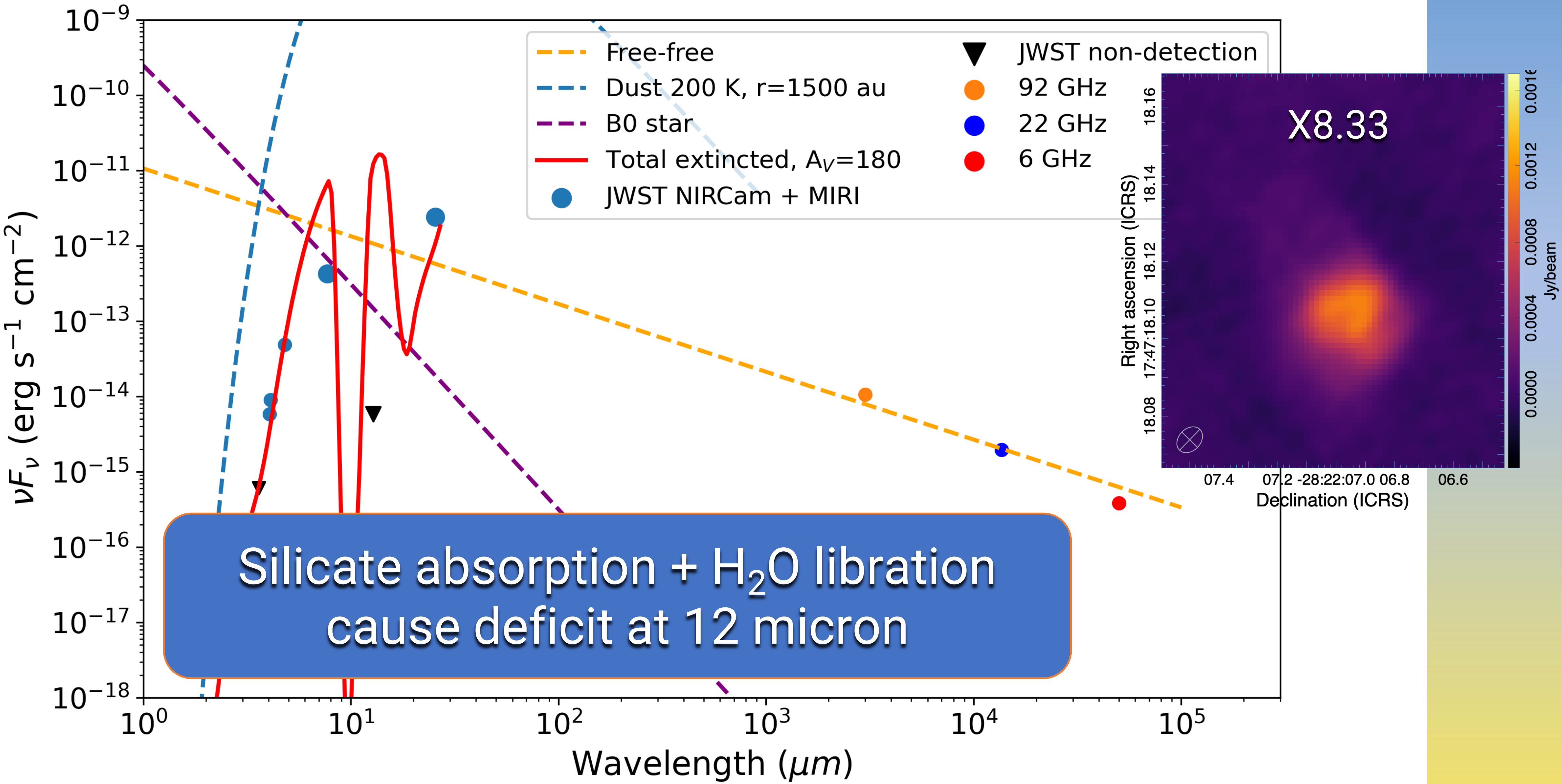
-28°20'
22'
24'
26'
Dec (FK5)
17h47m30.0s
24.0s
18.0s
12.0s
06.0s
RA (FK5)
5000.0 AU
5000.0 AU
5000.0 AU
0.1 pc
2.0 pc
DS
S
M
N

F150W, F182M, F187N, F210M, F212N, F300M, F360M, F405N, F410M, F466N, F480M; F770W, F1280W, F2550W

Paα H$_2$ H$_2$O ice Brα CO ice PAH Hot dust

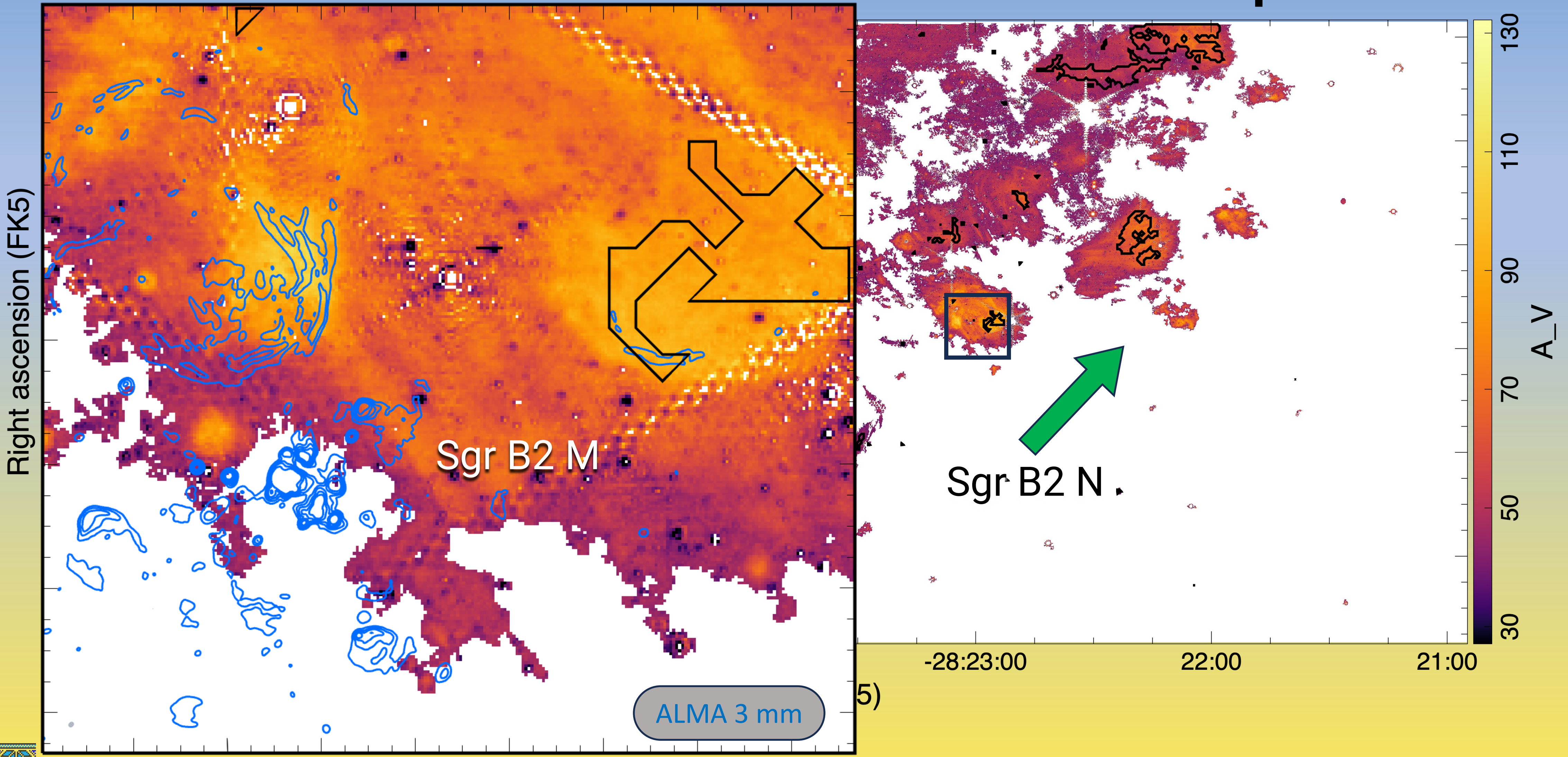


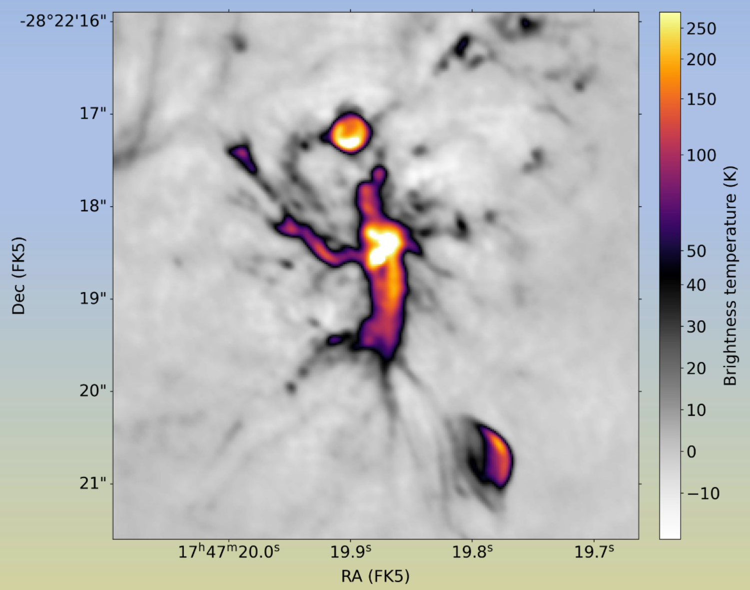
F480M + F360M + F182M



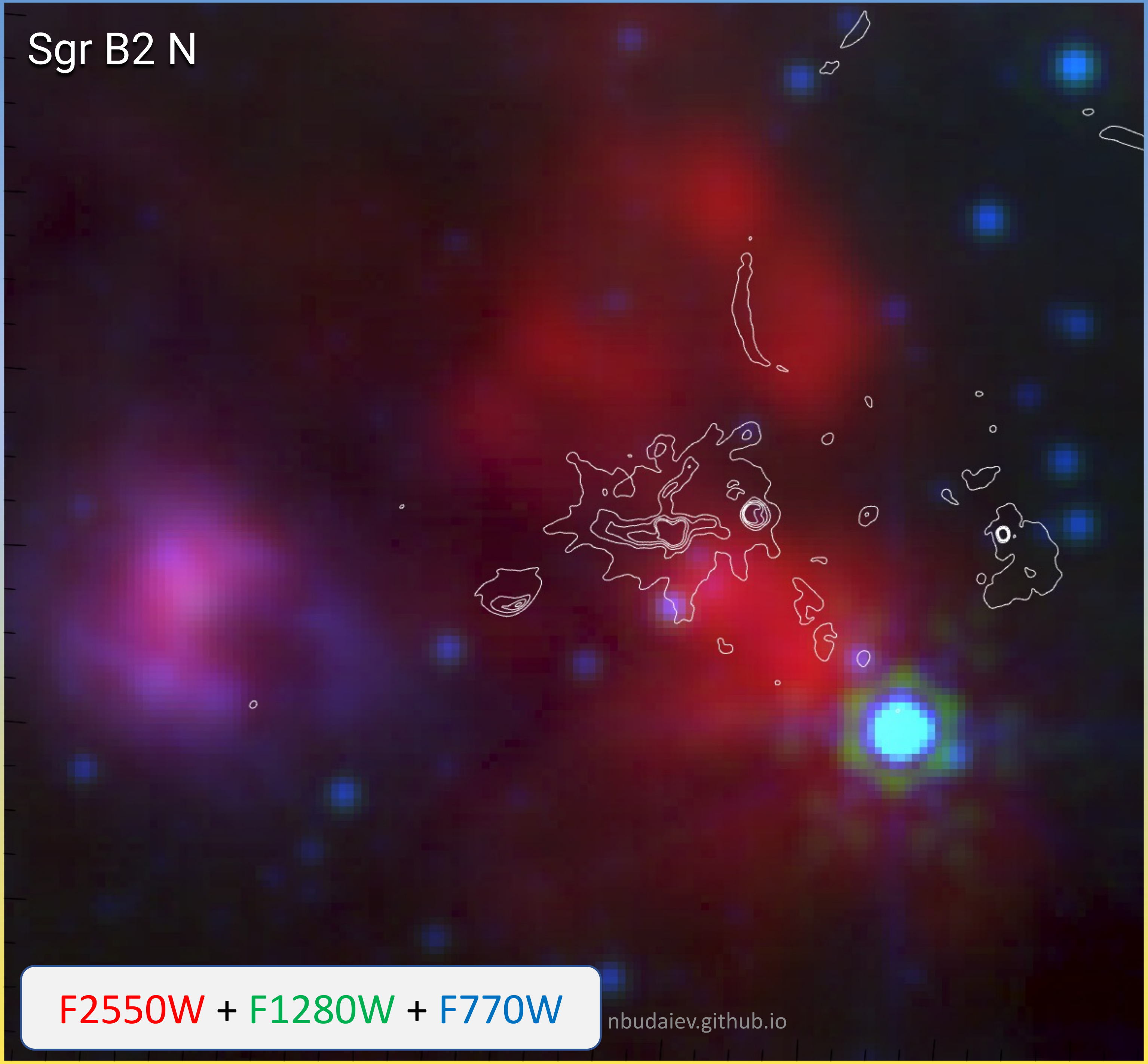
Silicate absorption + H_2O libration cause deficit at 12 micron

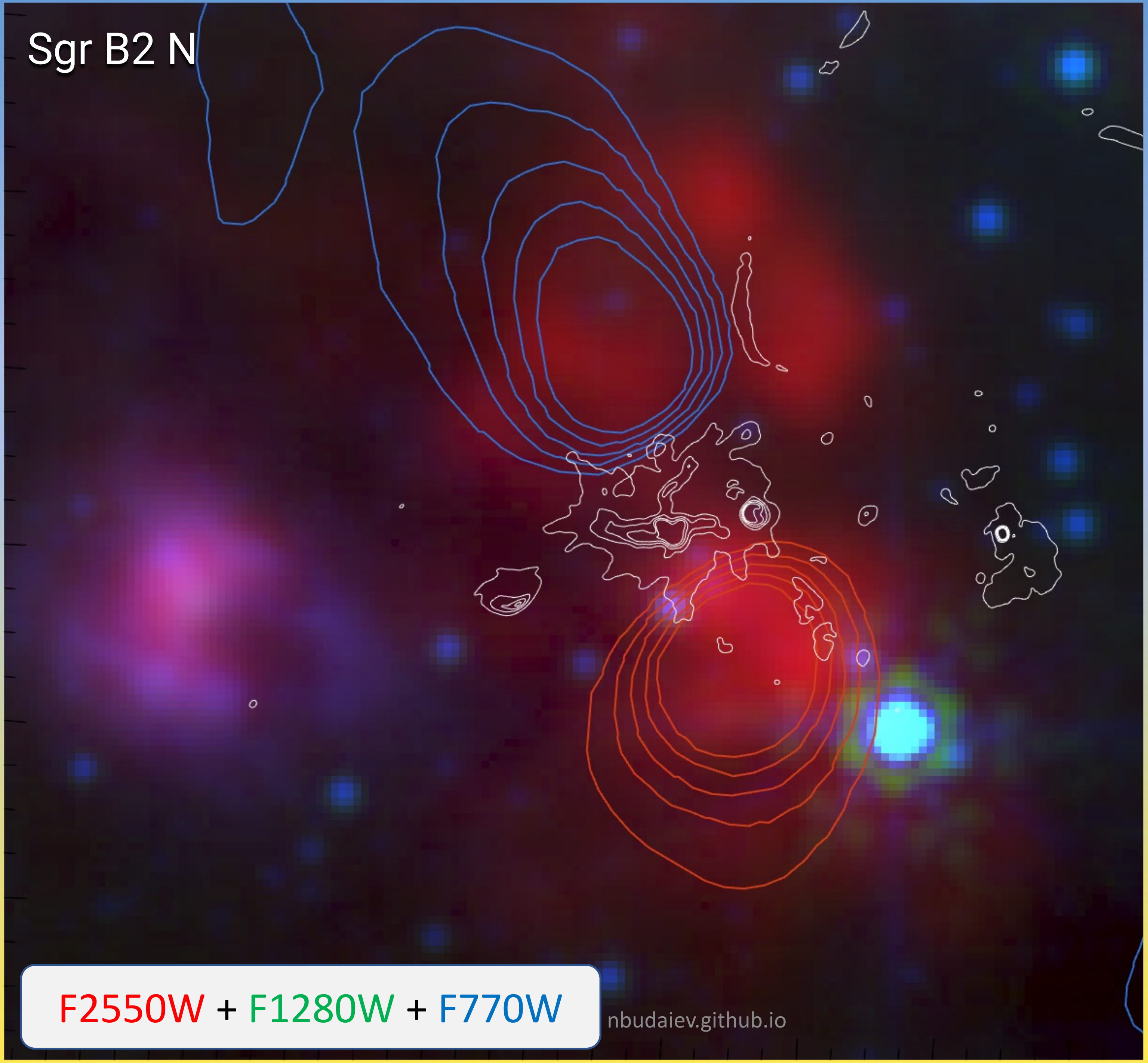
Recombination line extinction map



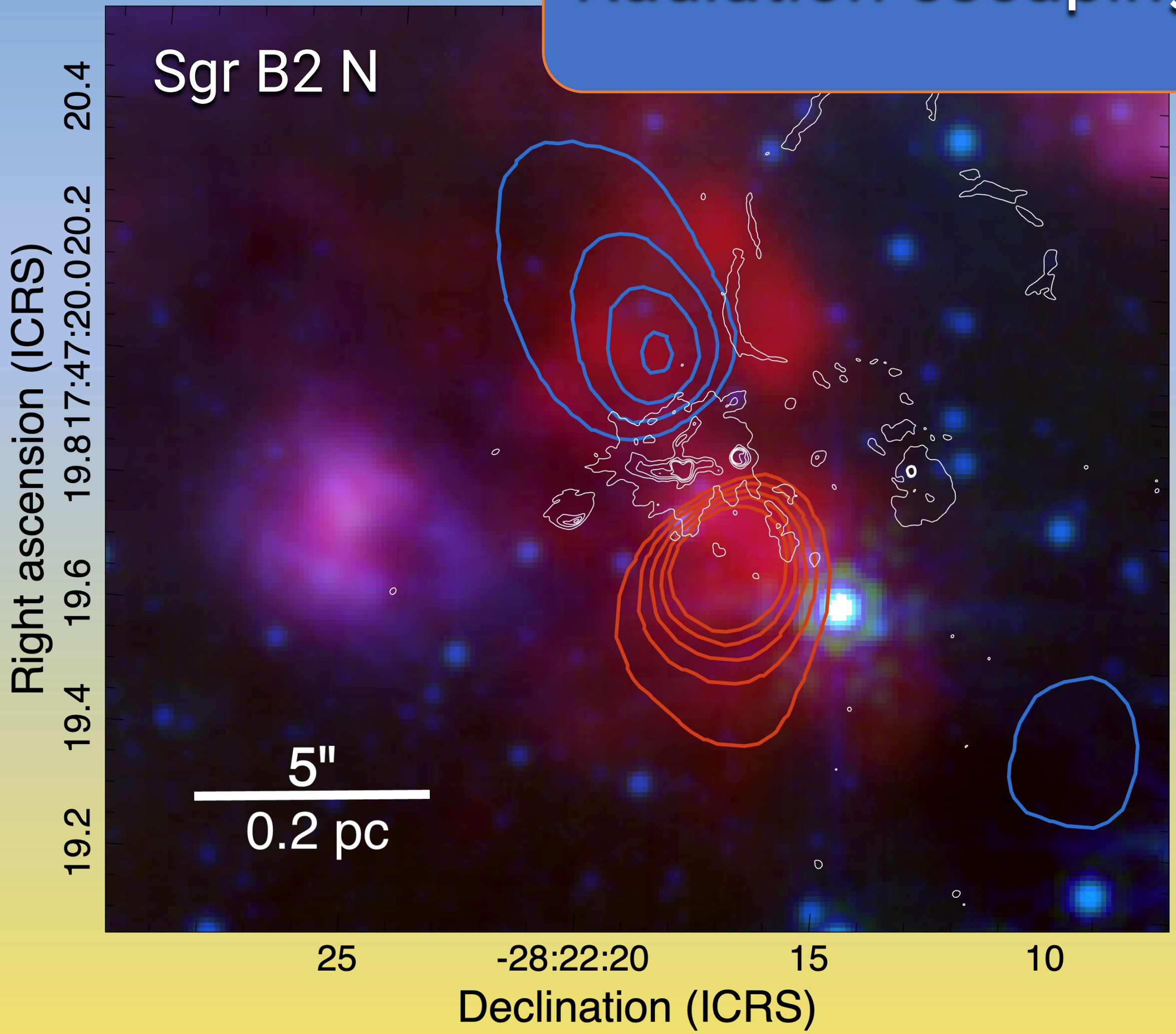

-28°22'16"
17"
18"
19"
20"
21"
Dec (FK5)
17h47m20.0s
19.9s
19.8s
19.7s
RA (FK5)
250
200
150
100
50
40
30
20
10
0
−10
Brightness temperature (K)

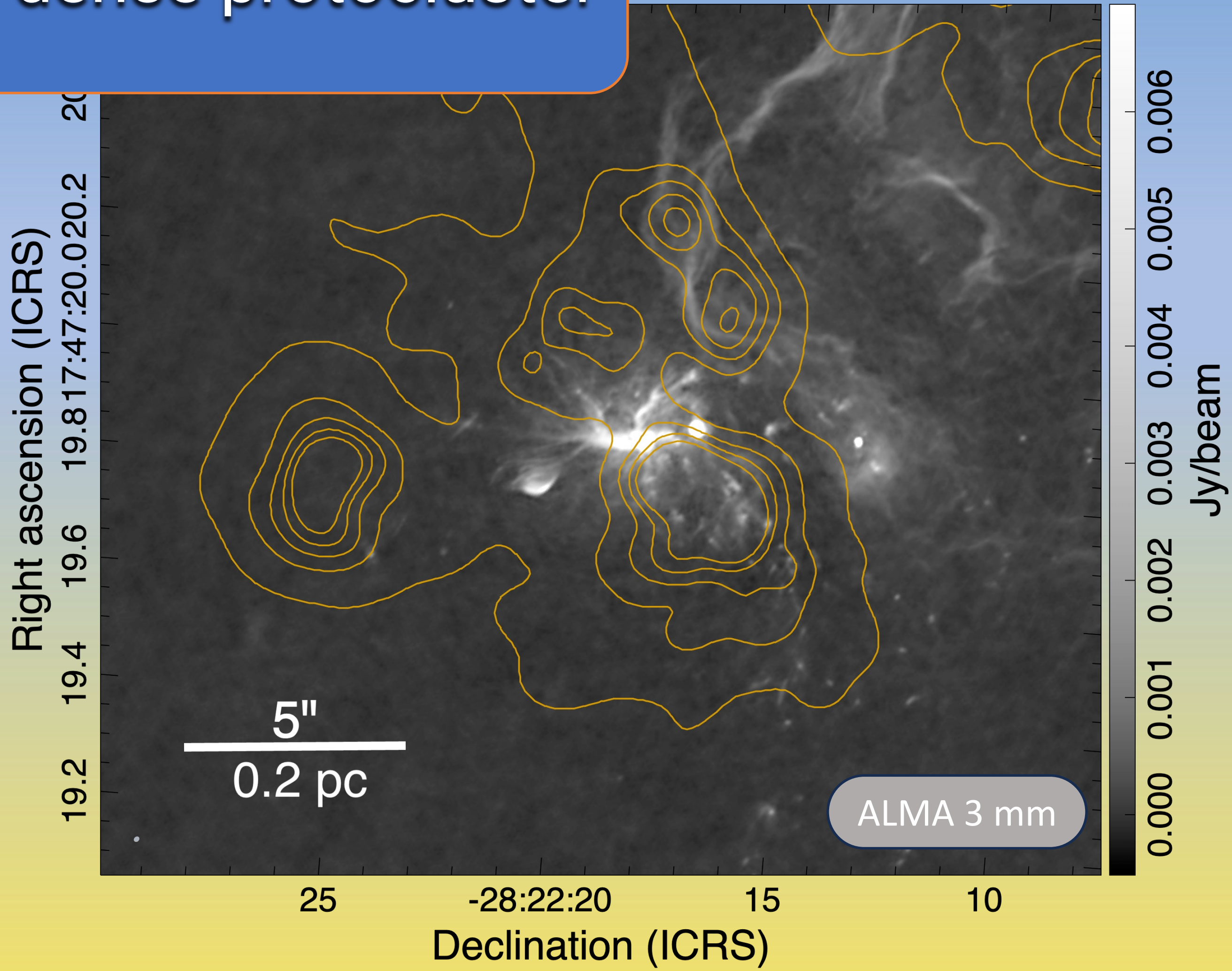
nbudaiev.github.io

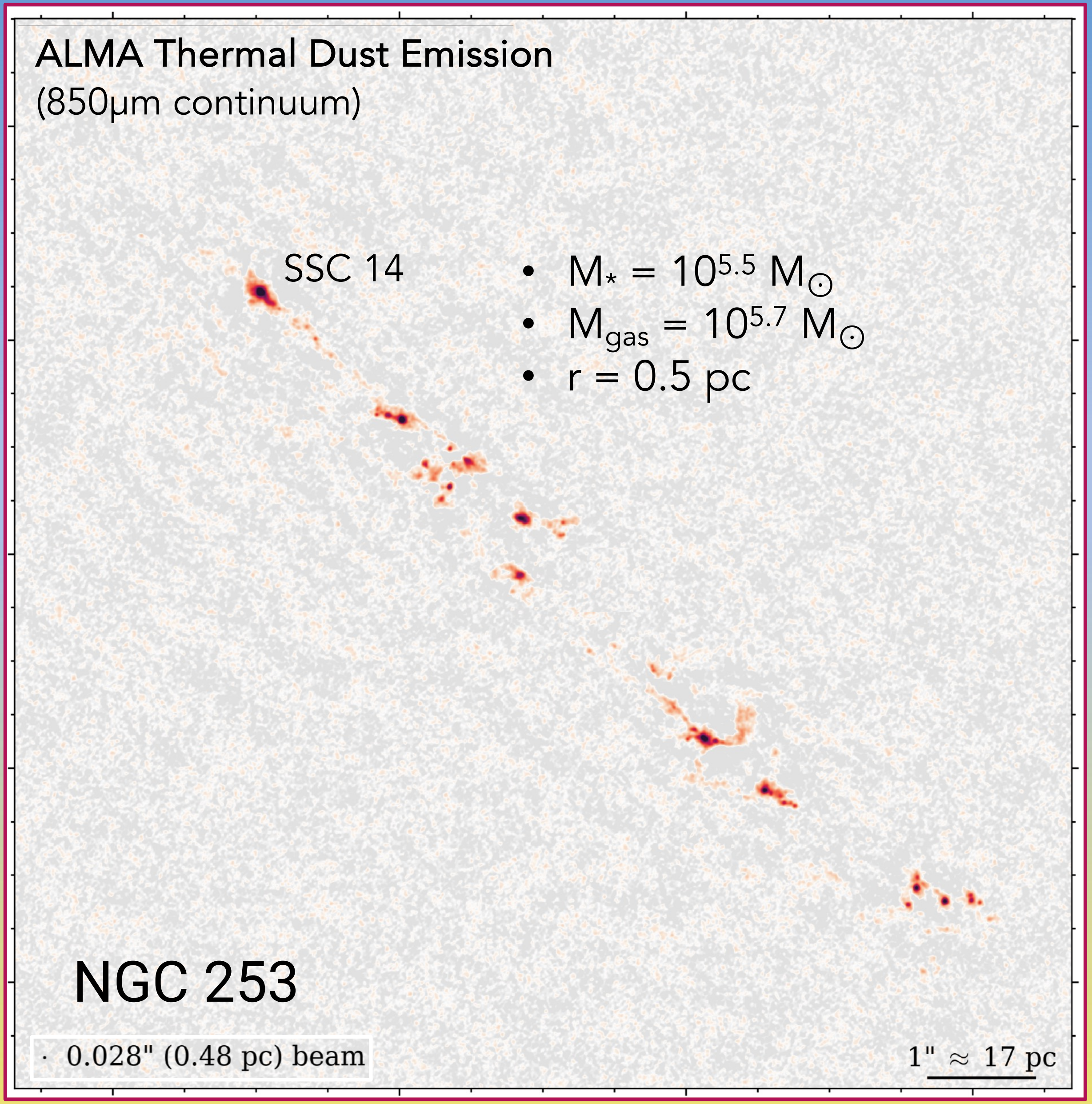

Sgr B2 N
F2550W + F1280W + F770W


Sgr B2 N
F2550W + F1280W + F770W
nbudaiev.github.io

Radiation escaping dense protocluster







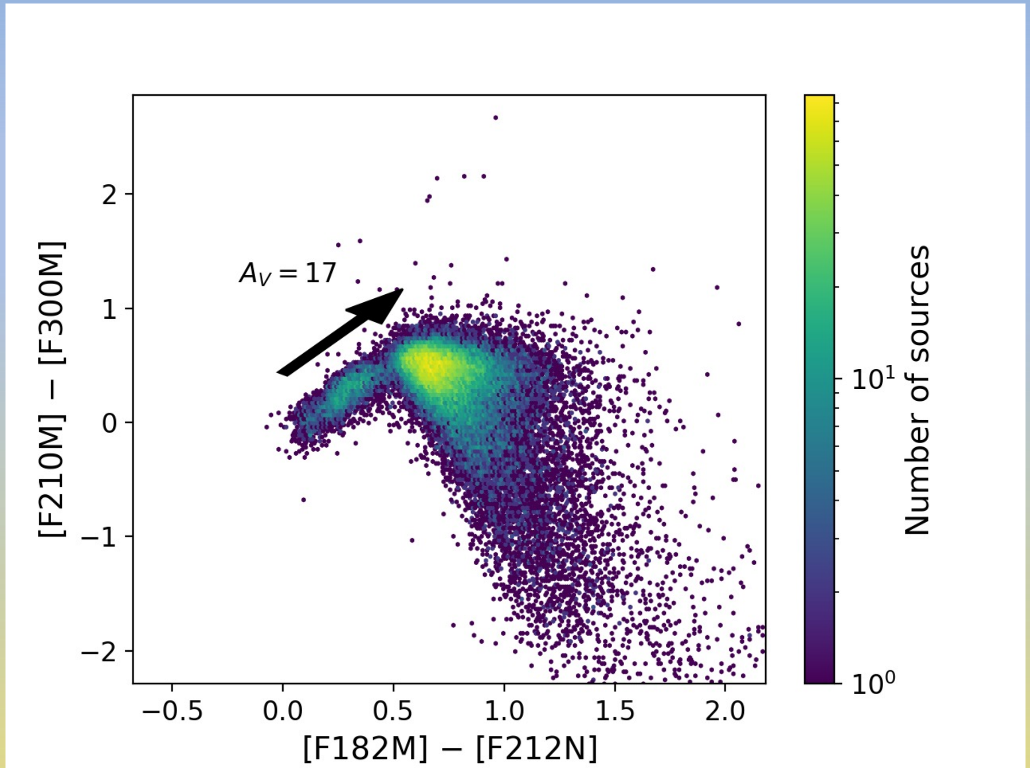
♠ACES: The ALMA CMZ Exploration Survey

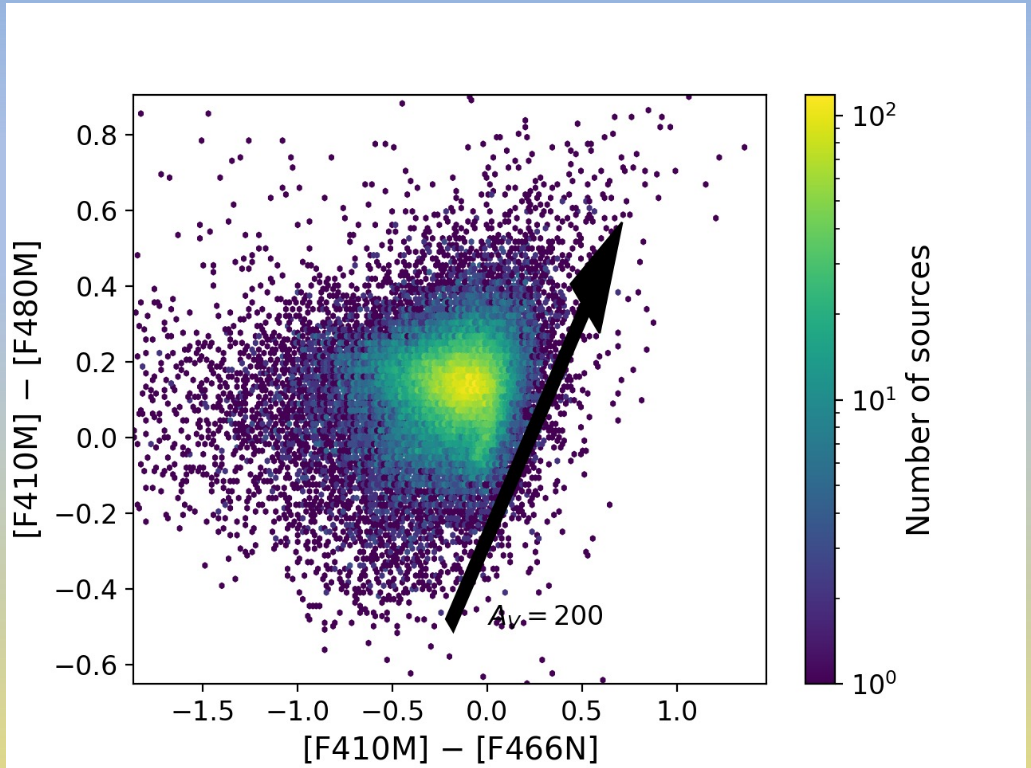
Levy et al. (2021, 2022)
Building on Turner & Ho (1985), Ulvestad & Antonucci (1997), Paglione et al. (2004), Sakomoto et al. (2006, 2011), Bendo et al. (2015), Ando et al. (2017), Leroy et al. (2018), Rico-Villas et al. (2020), Krieger et al. (2020), Mills et al. (2021)

Lots of ice

Adam Ginsburg+ 25
Savannah Gramze+ 25

H_2O

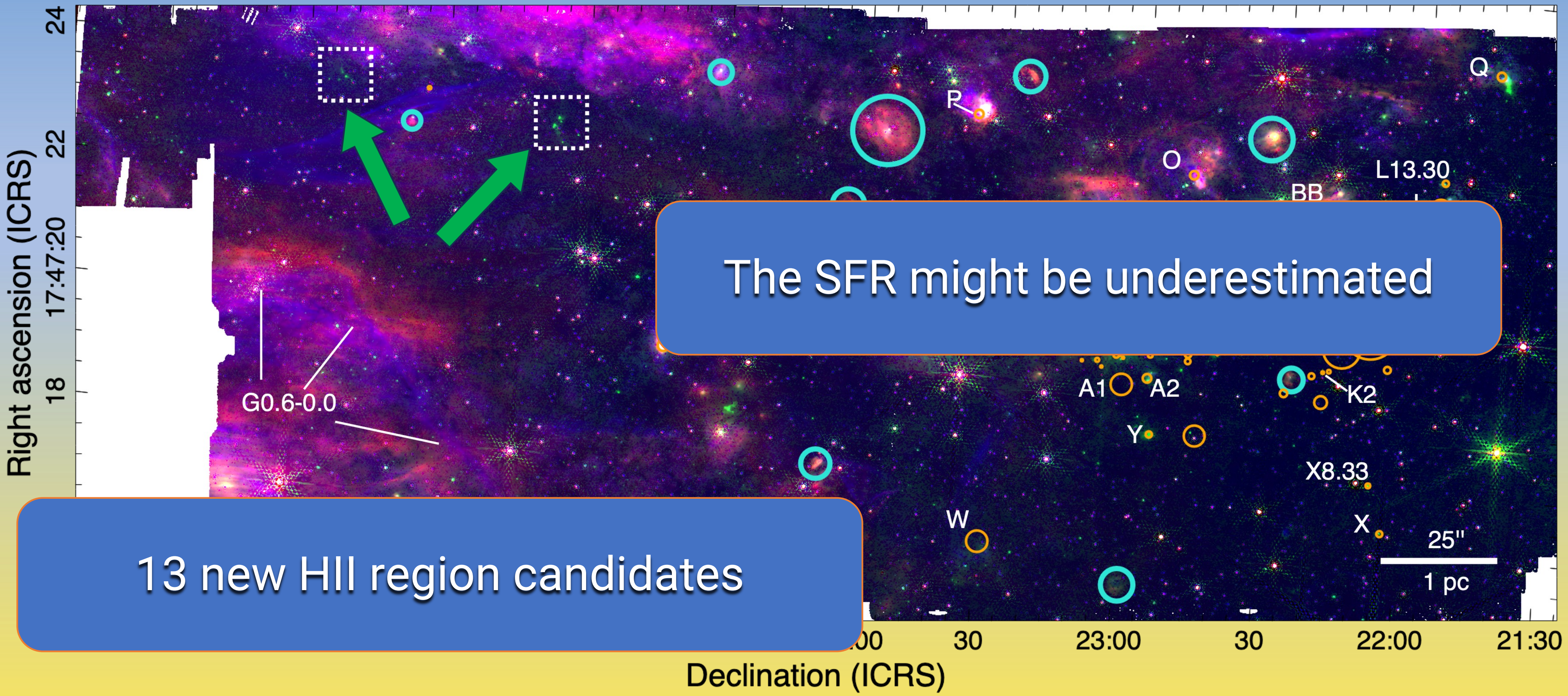




CO

F770W + F480M-(F410M-F405N) + F410M - F405N

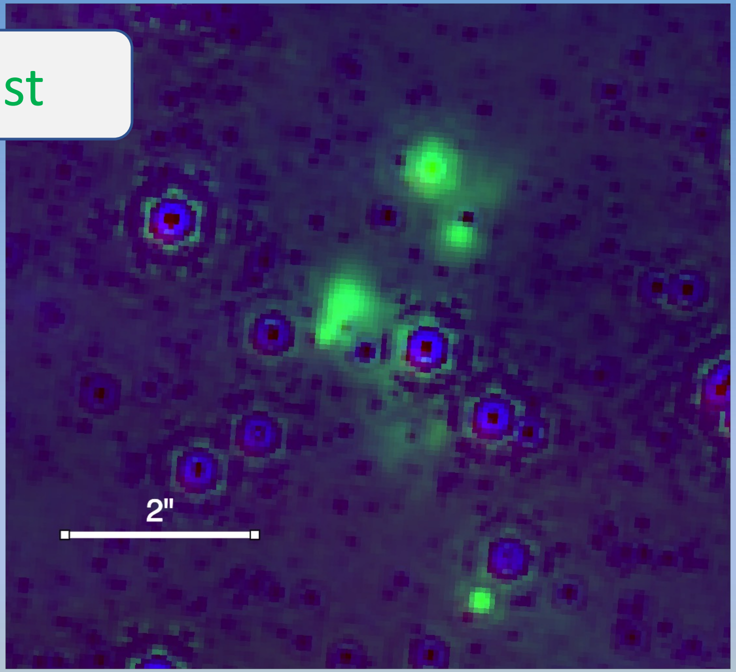
PAH + warm dust + Brα

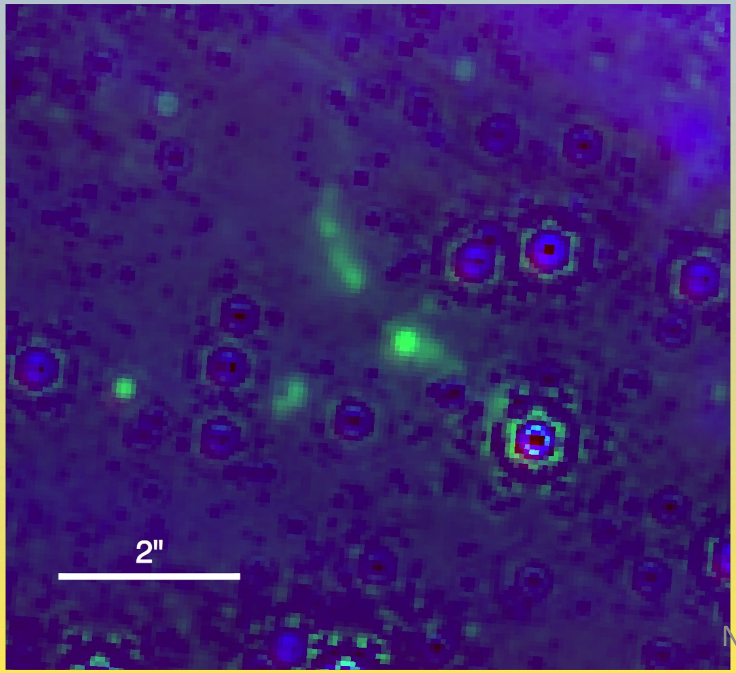


The SFR might be underestimated

13 new HII region candidates

warm dust

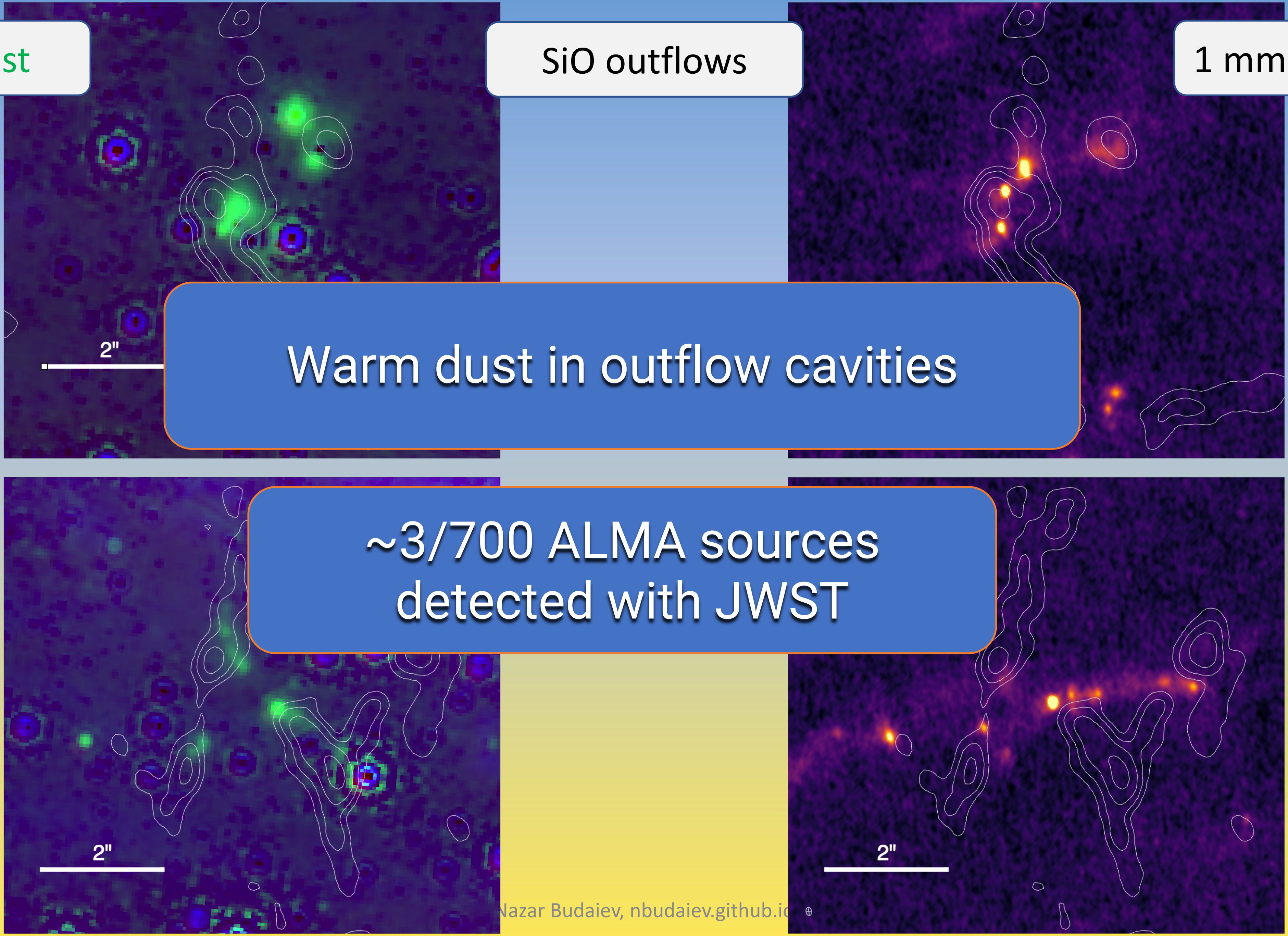




warm dust

SiO outflows

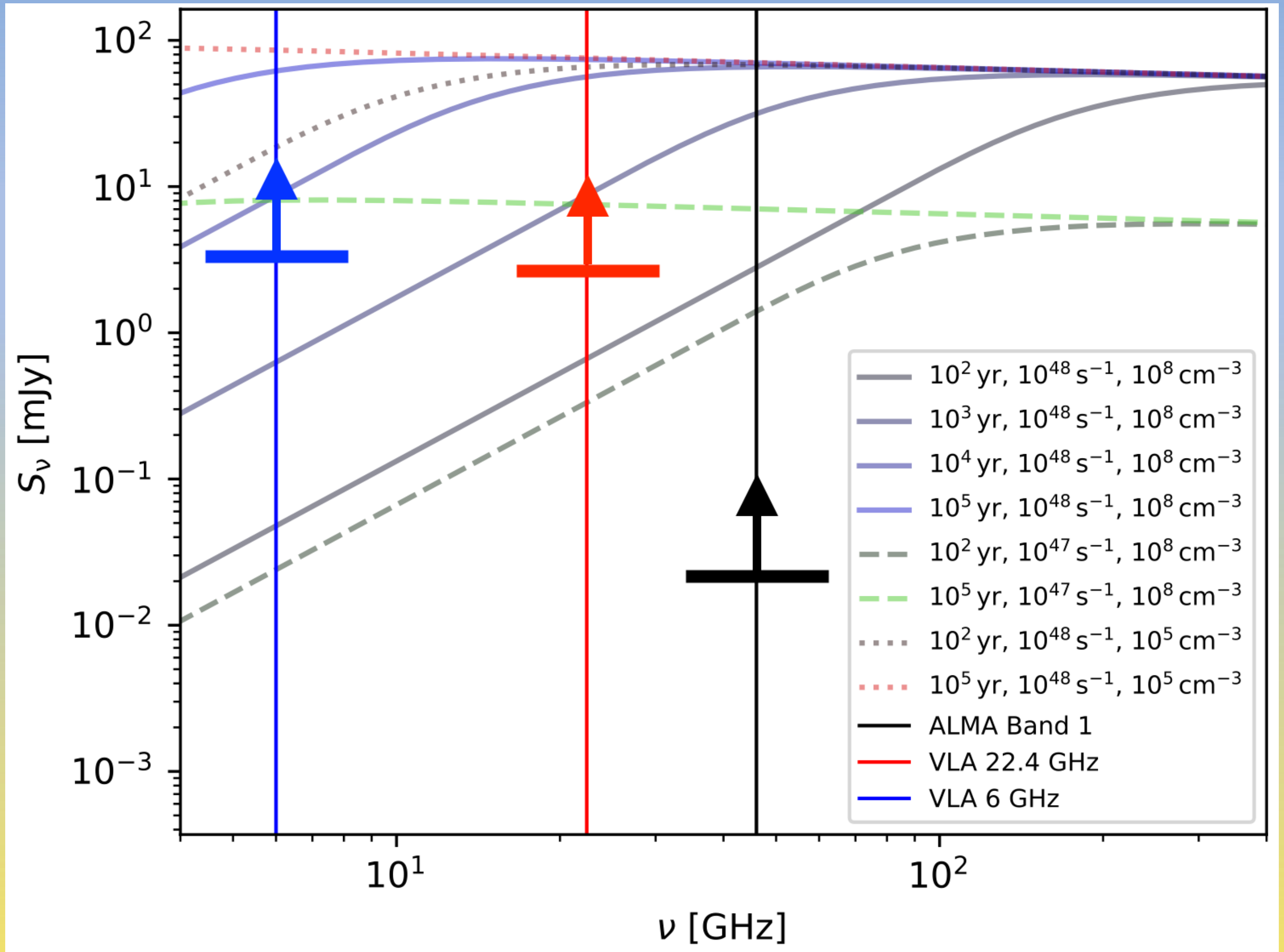
1 mm continuum

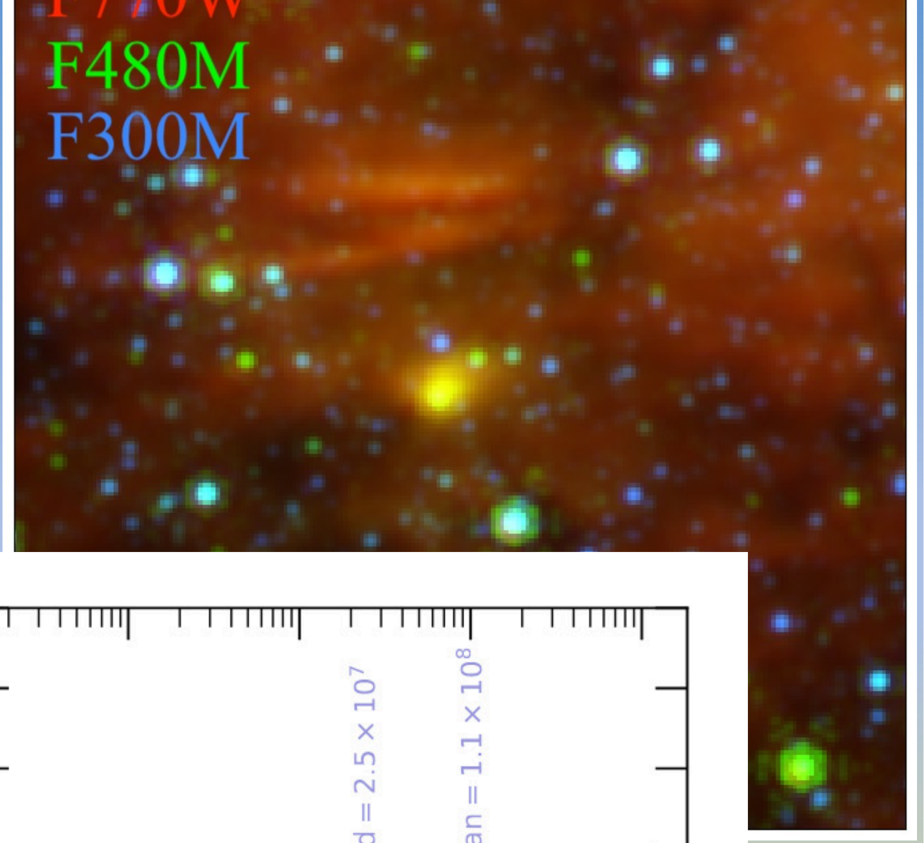


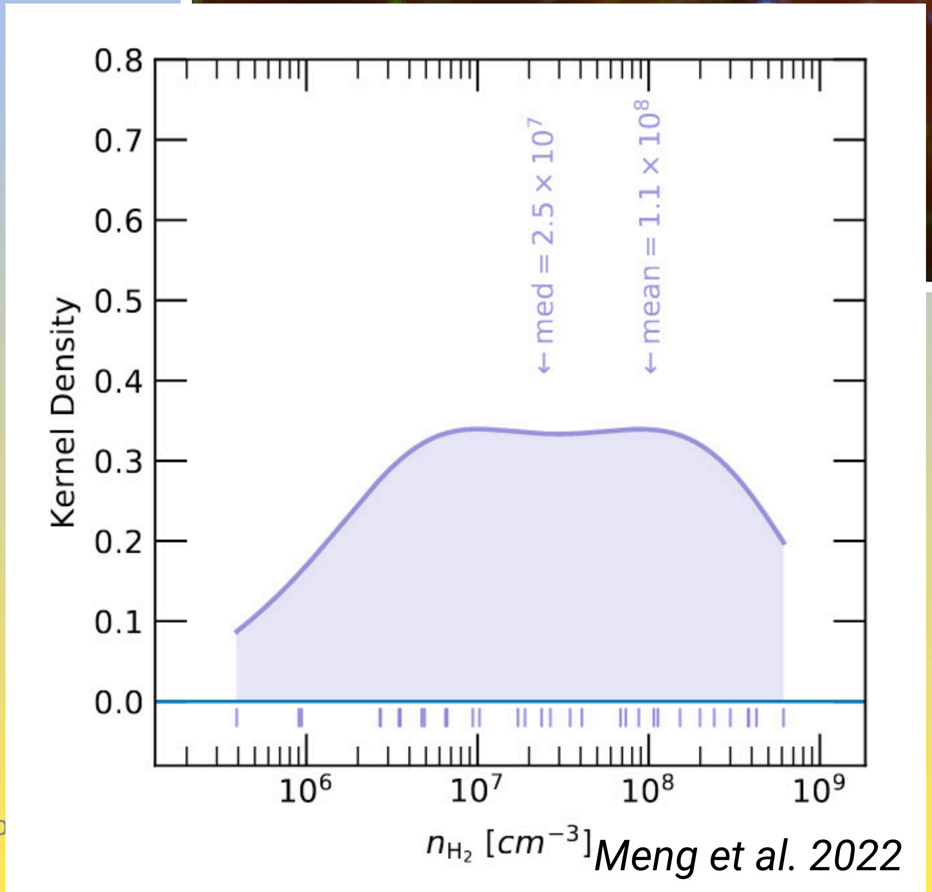
Warm dust in outflow cavities

~3/700 ALMA sources detected with JWST

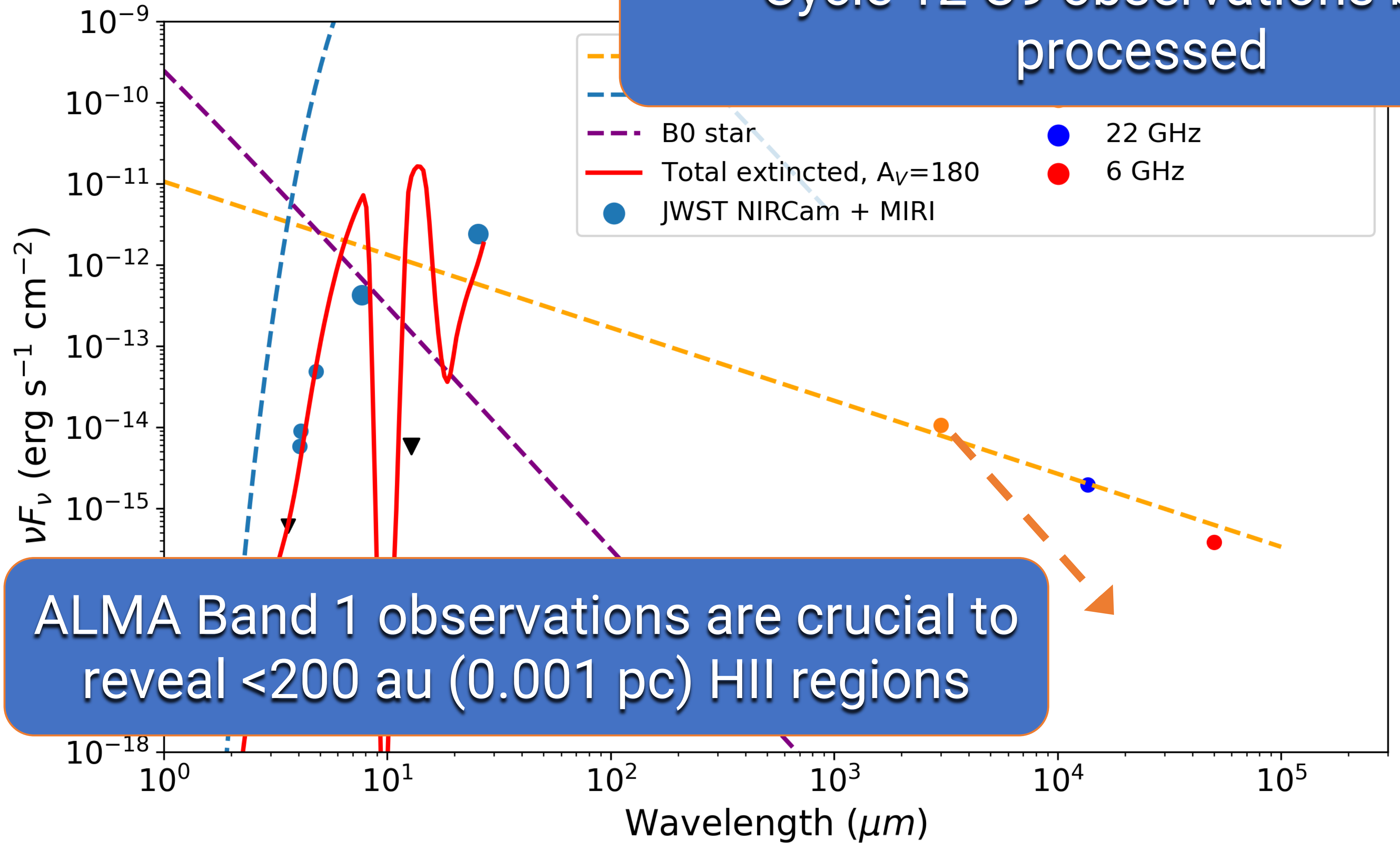
Tiny HCHII regions?







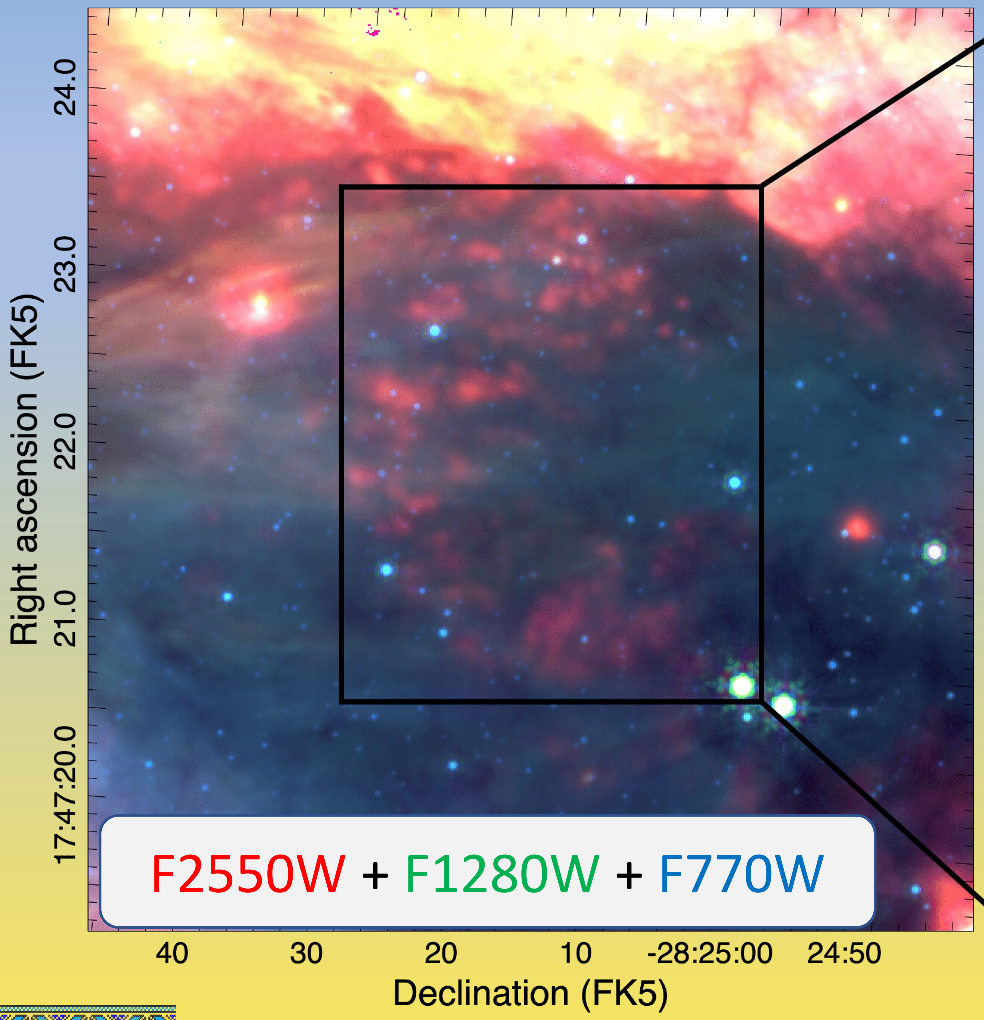
Meng et al. 2022

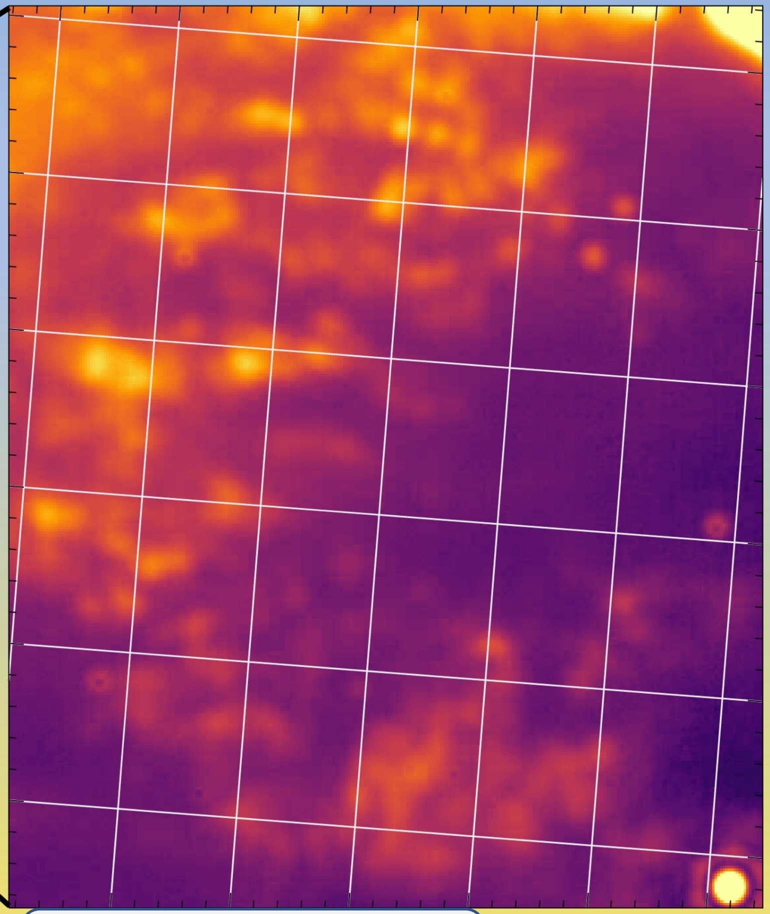


Cycle 12 C9 observations being processed

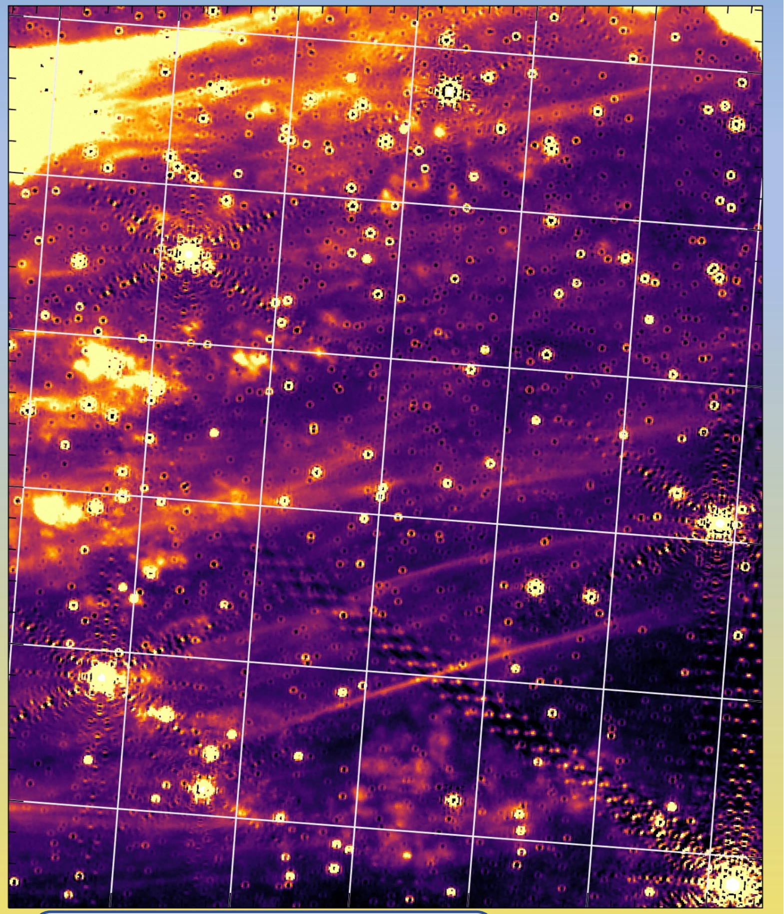
ALMA Band 1 observations are crucial to reveal <200 au (0.001 pc) HII regions

Flocculent structure in Sgr B2 DS



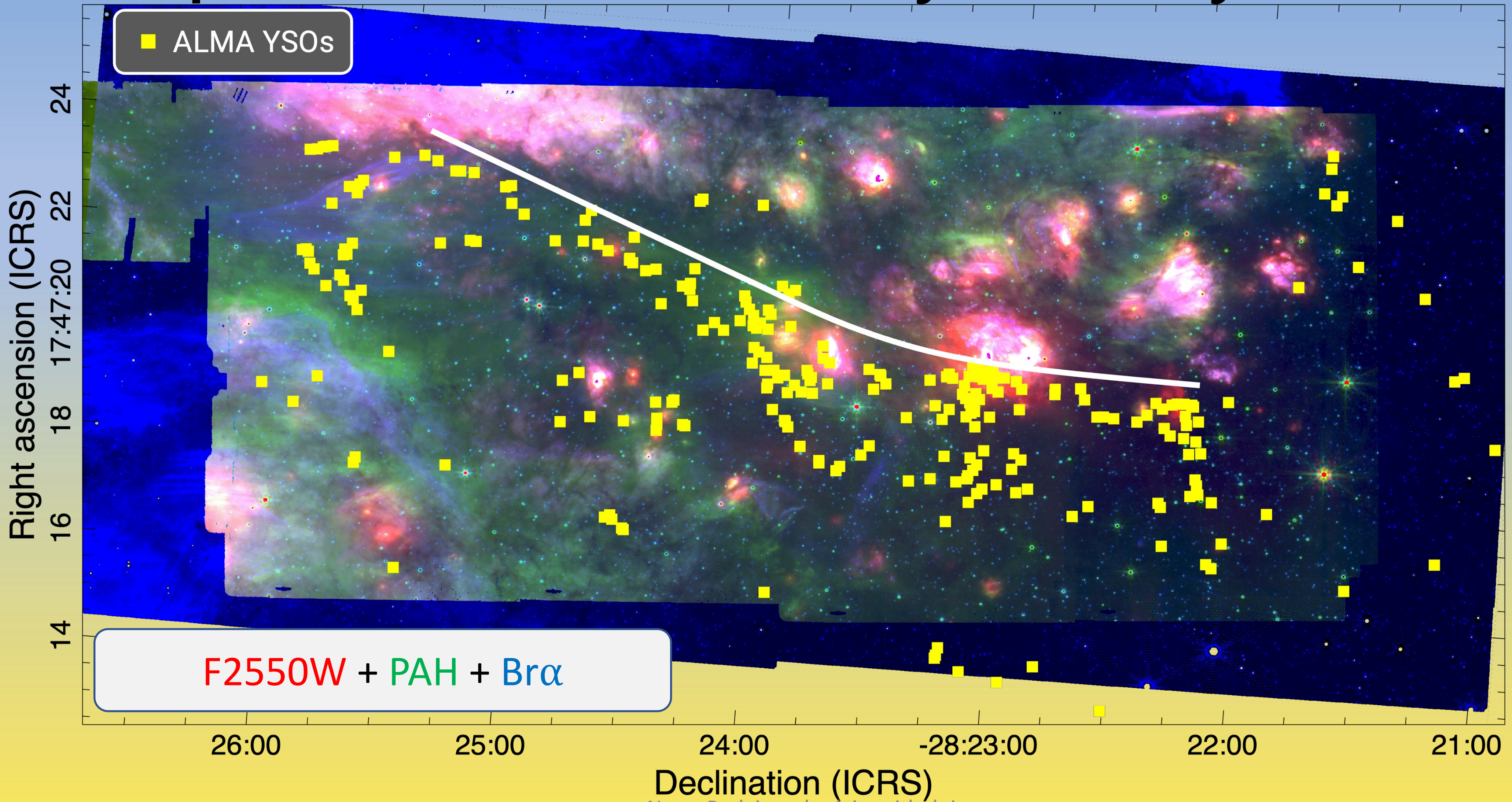


F2550W



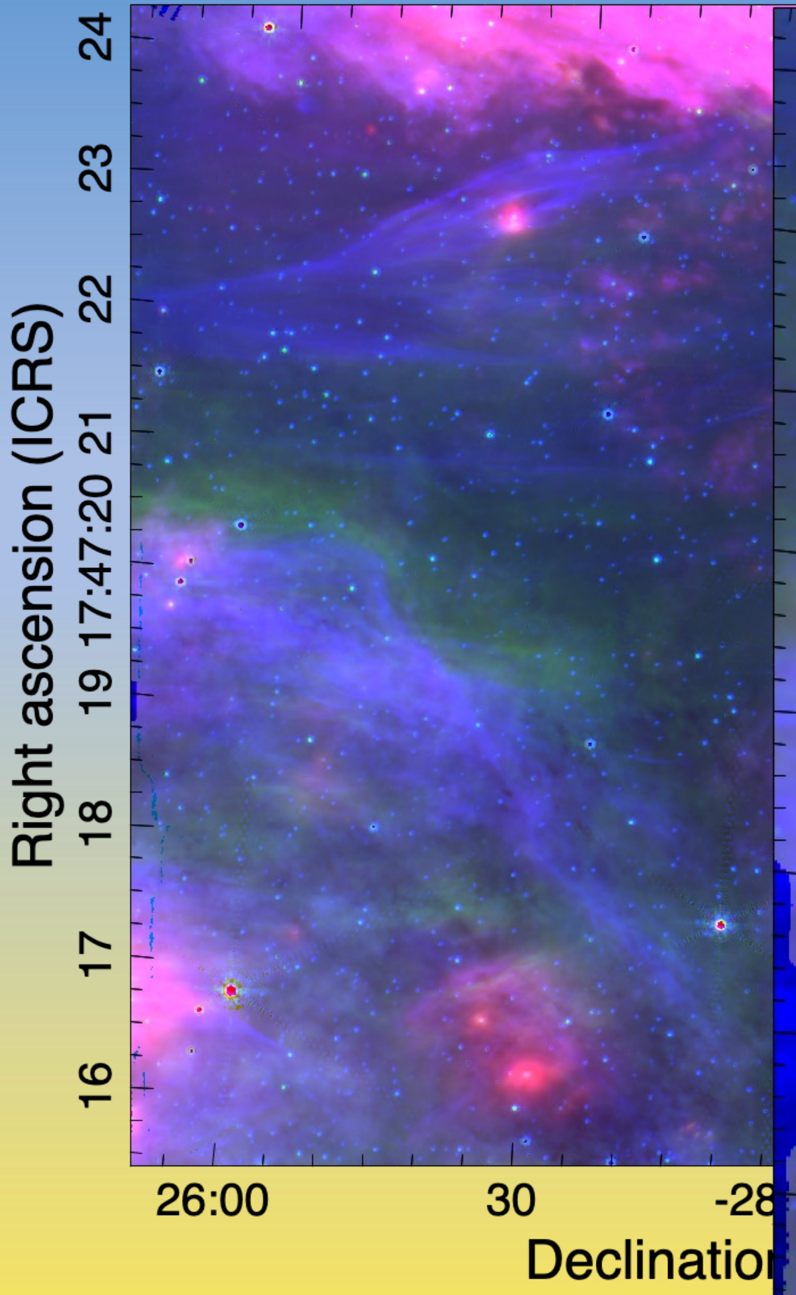
Brackett-alpha

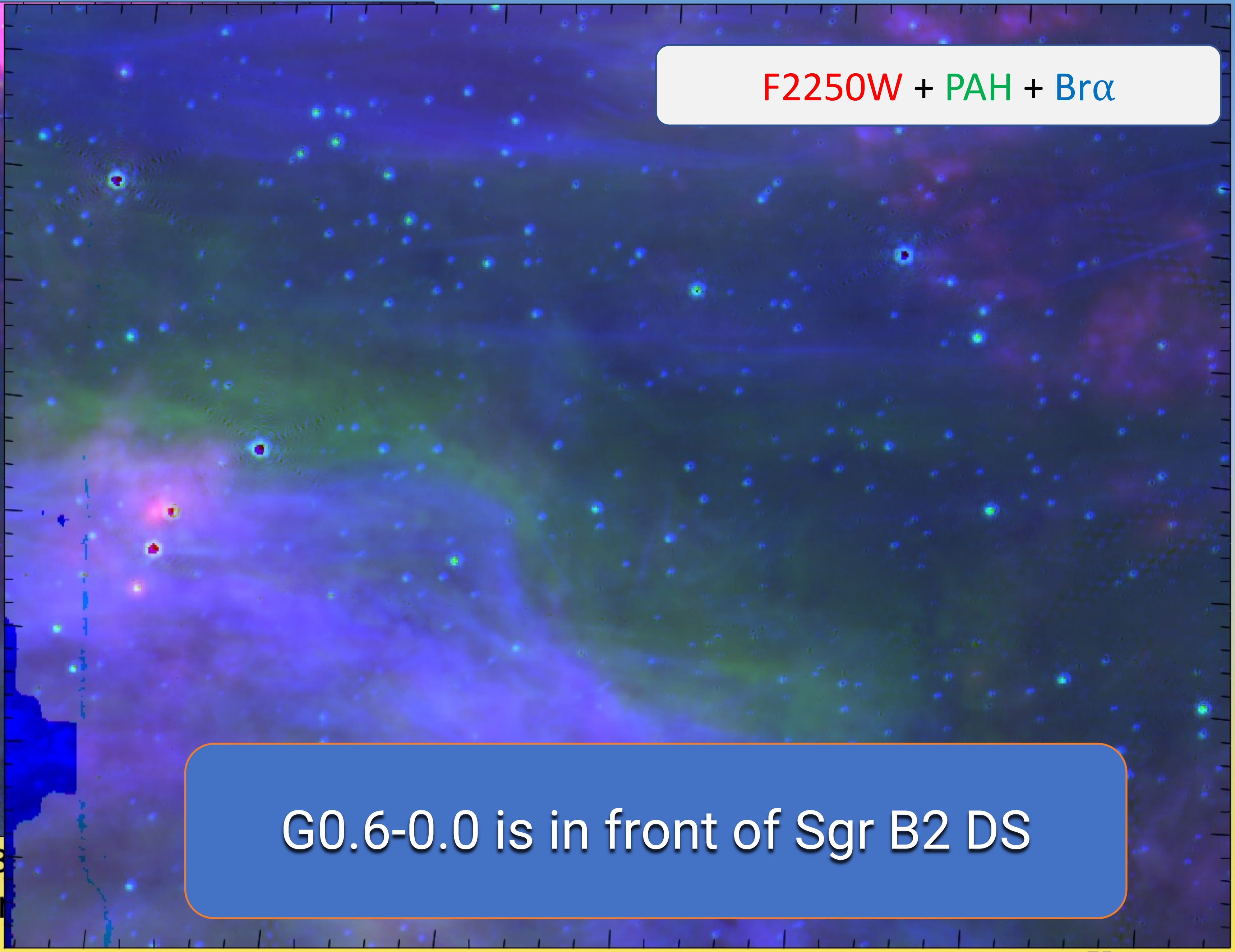
Sharp star formation asymmetry



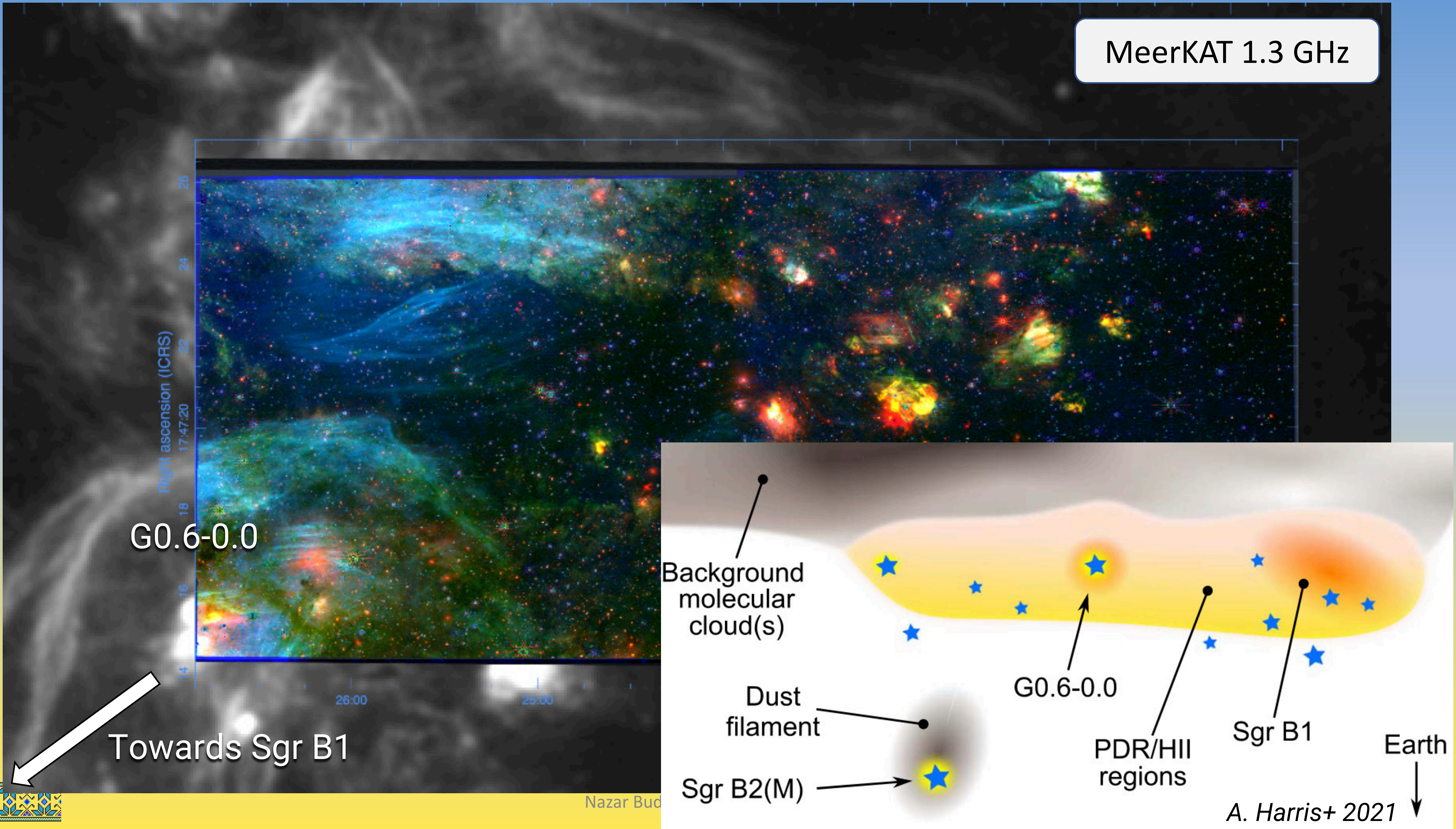
F2250W + PAH + Brα

Very sharp cloud edge

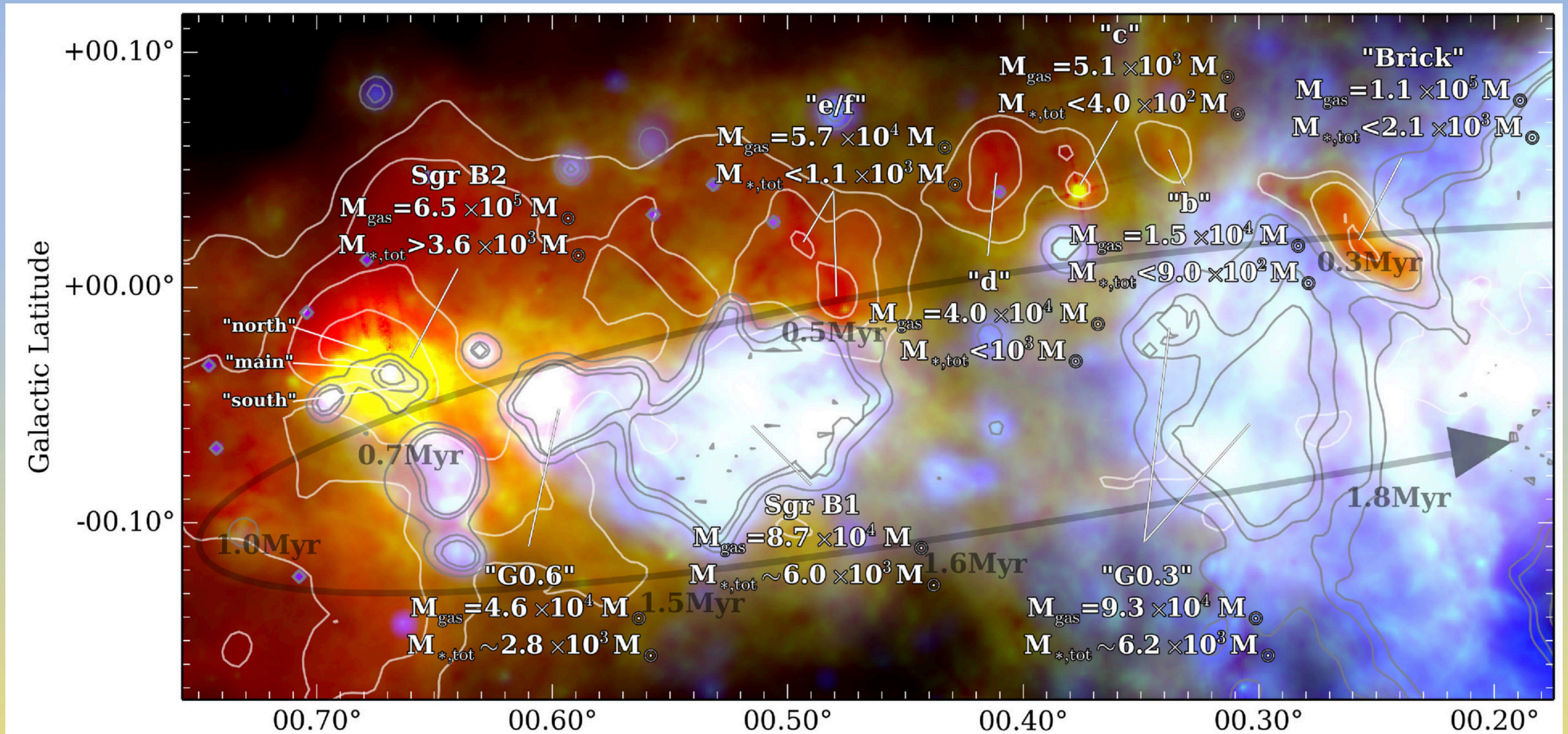




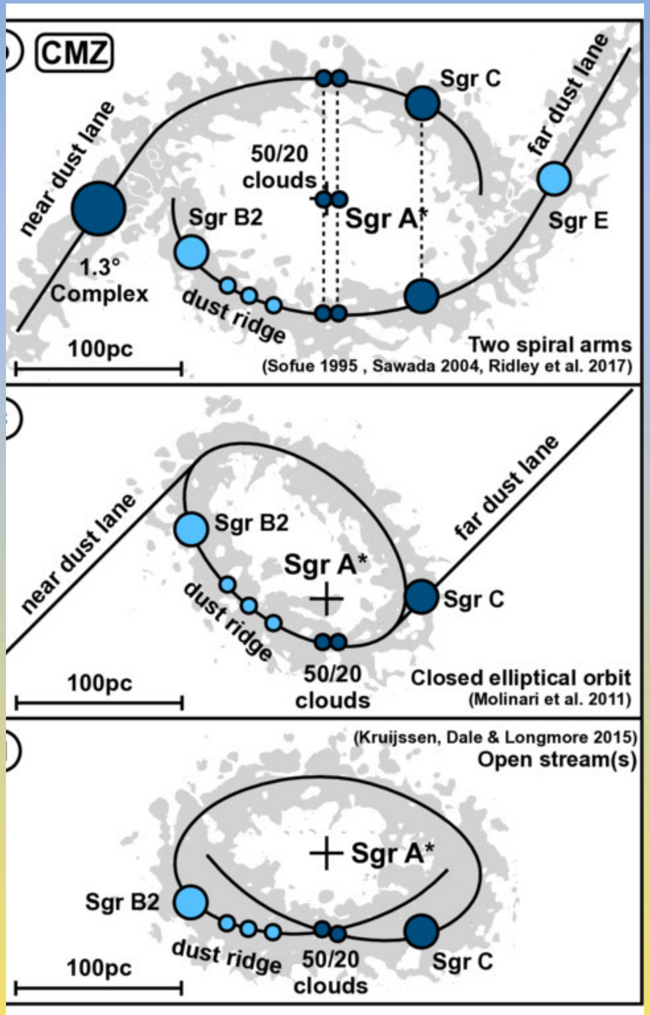
G0.6-0.0 is in front of Sgr B2 DS


MeerKAT 1.3 GHz
Right ascension (ICRS)
26:00
25:00
G0.6-0.0
Towards Sgr B1
Background molecular cloud(s)
Dust filament
Sgr B2(M)
G0.6-0.0
PDR/HII regions
Sgr B1
Earth
A. Harris+ 2021

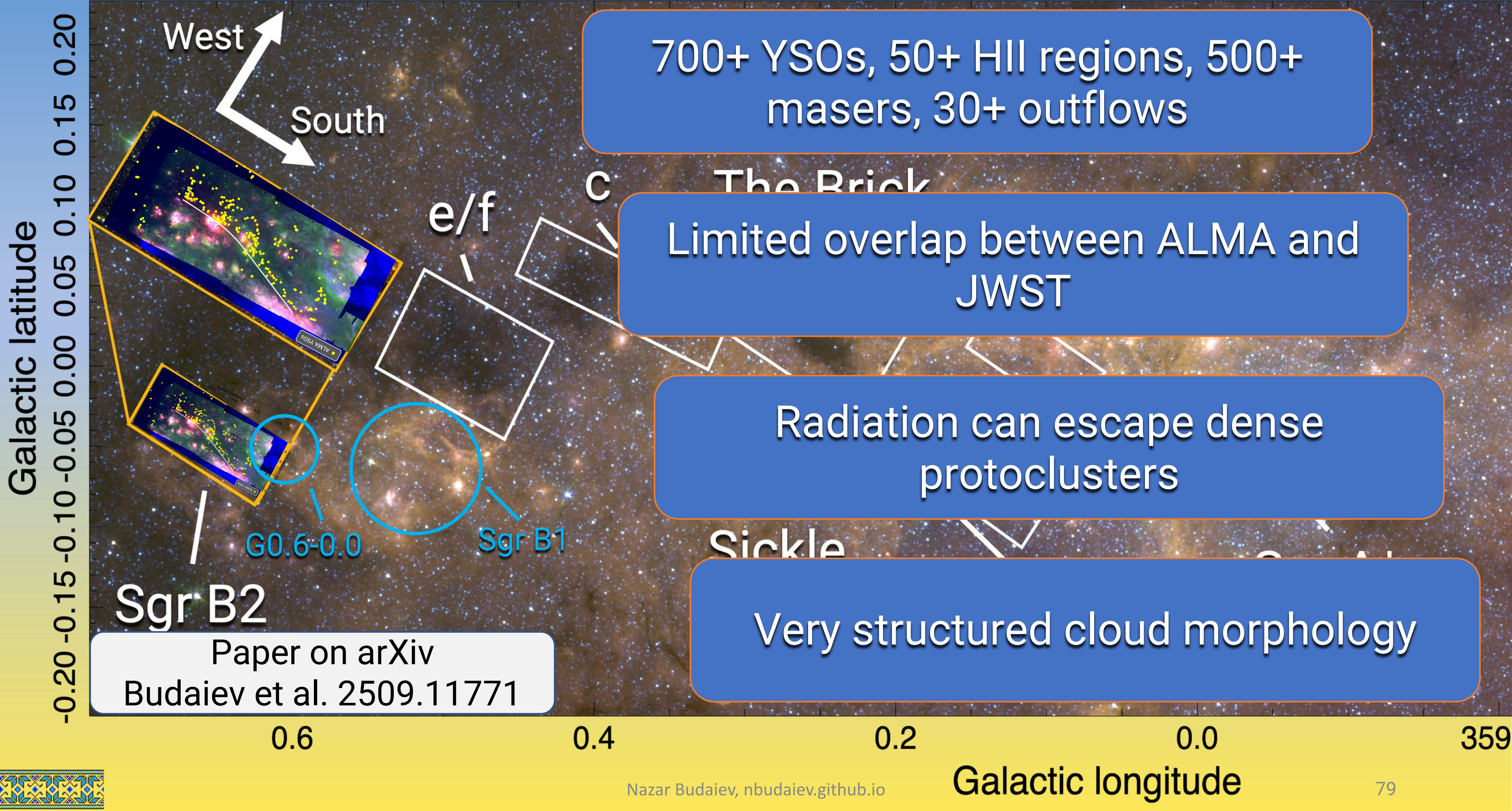
What does it say about the orbit?



A. Barnes+ 2017



J. Henshaw+ 2023



700+ YSOs, 50+ HII regions, 500+ masers, 30+ outflows

Limited overlap between ALMA and JWST

Radiation can escape dense protoclusters

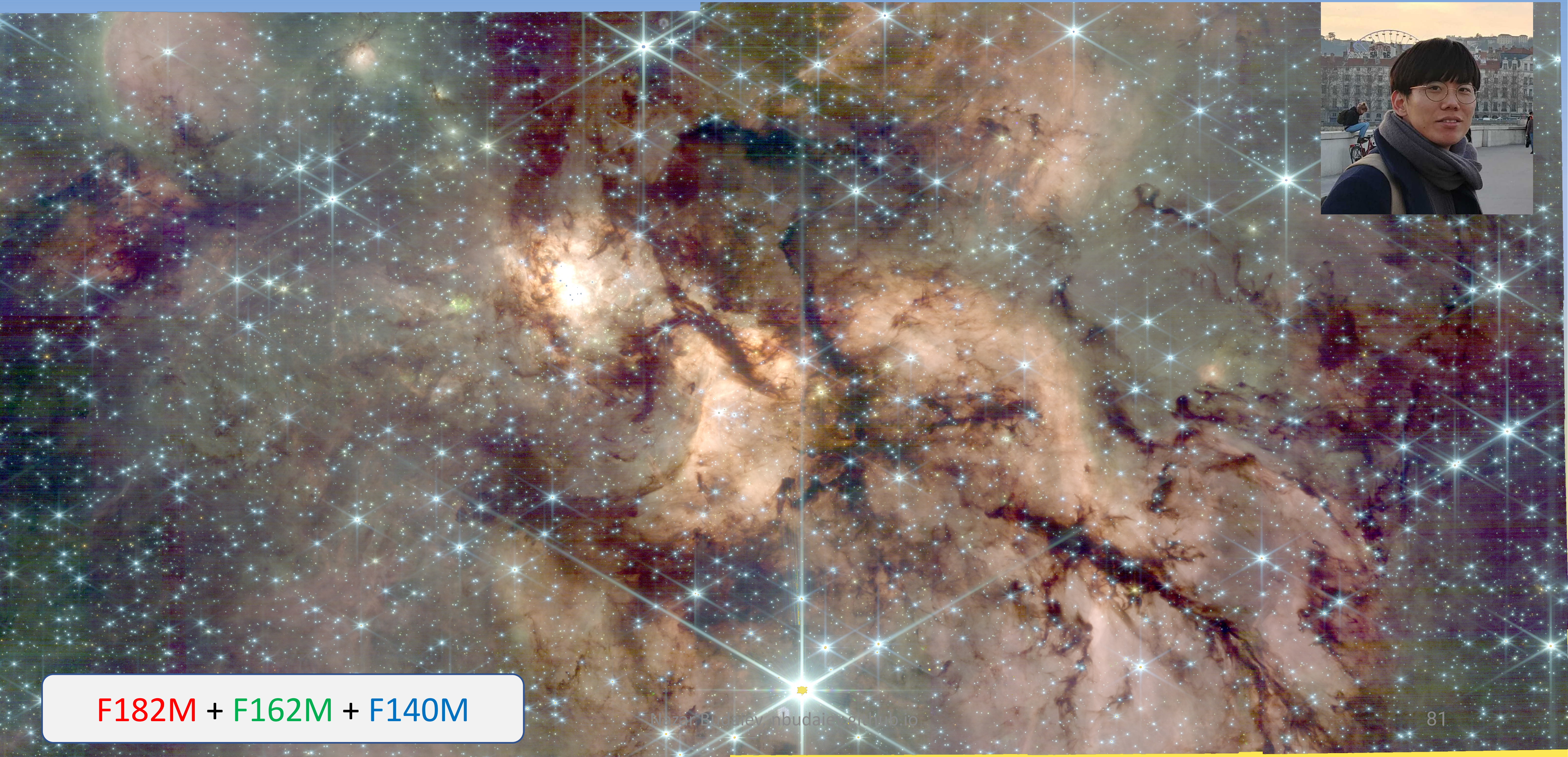
Very structured cloud morphology

Paper on arXiv
Budaiev et al. 2509.11771

JWST's view of W51

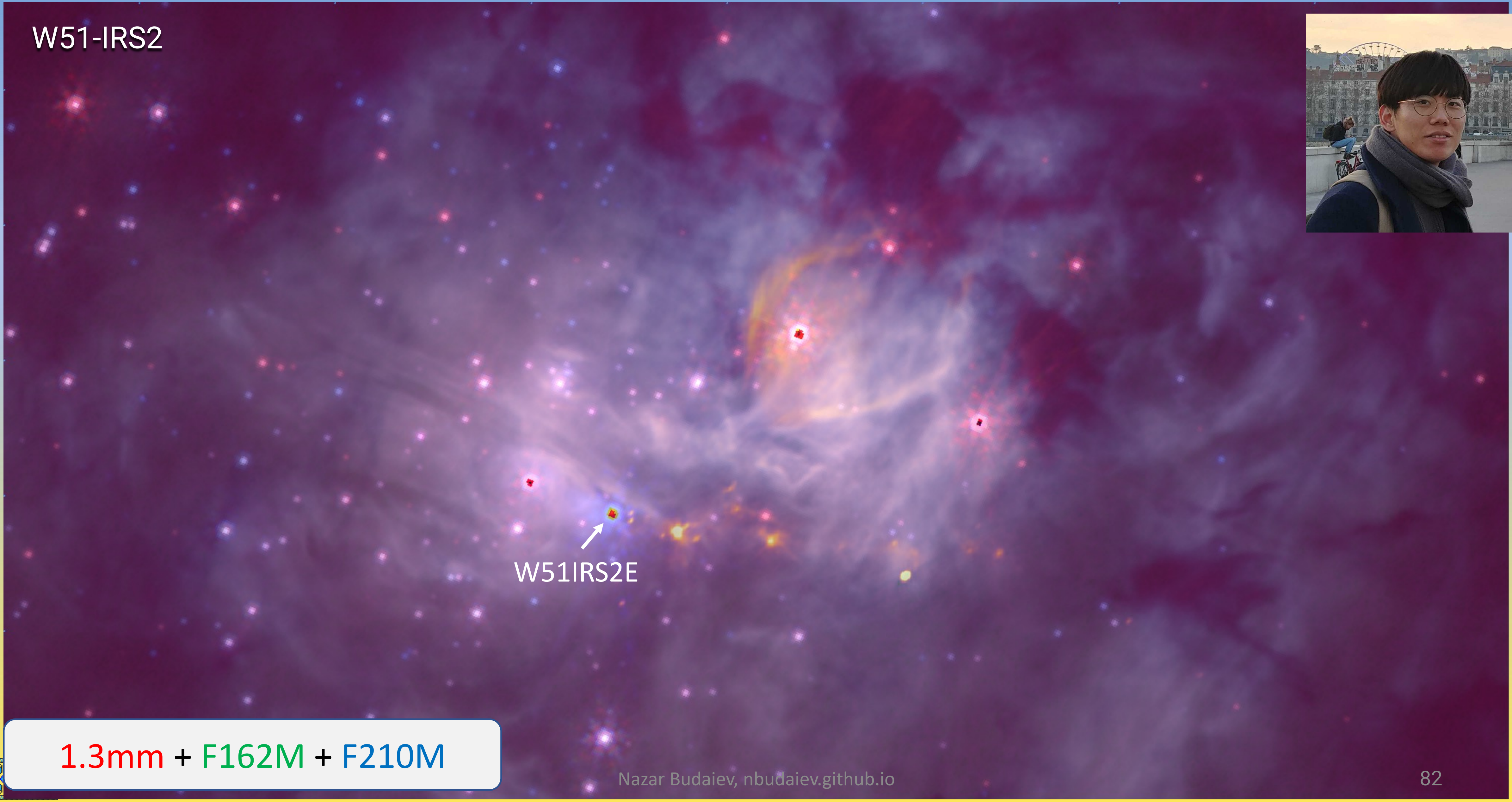
Taehwa Yoo

Yoo+ subm



Taehwa Yoo

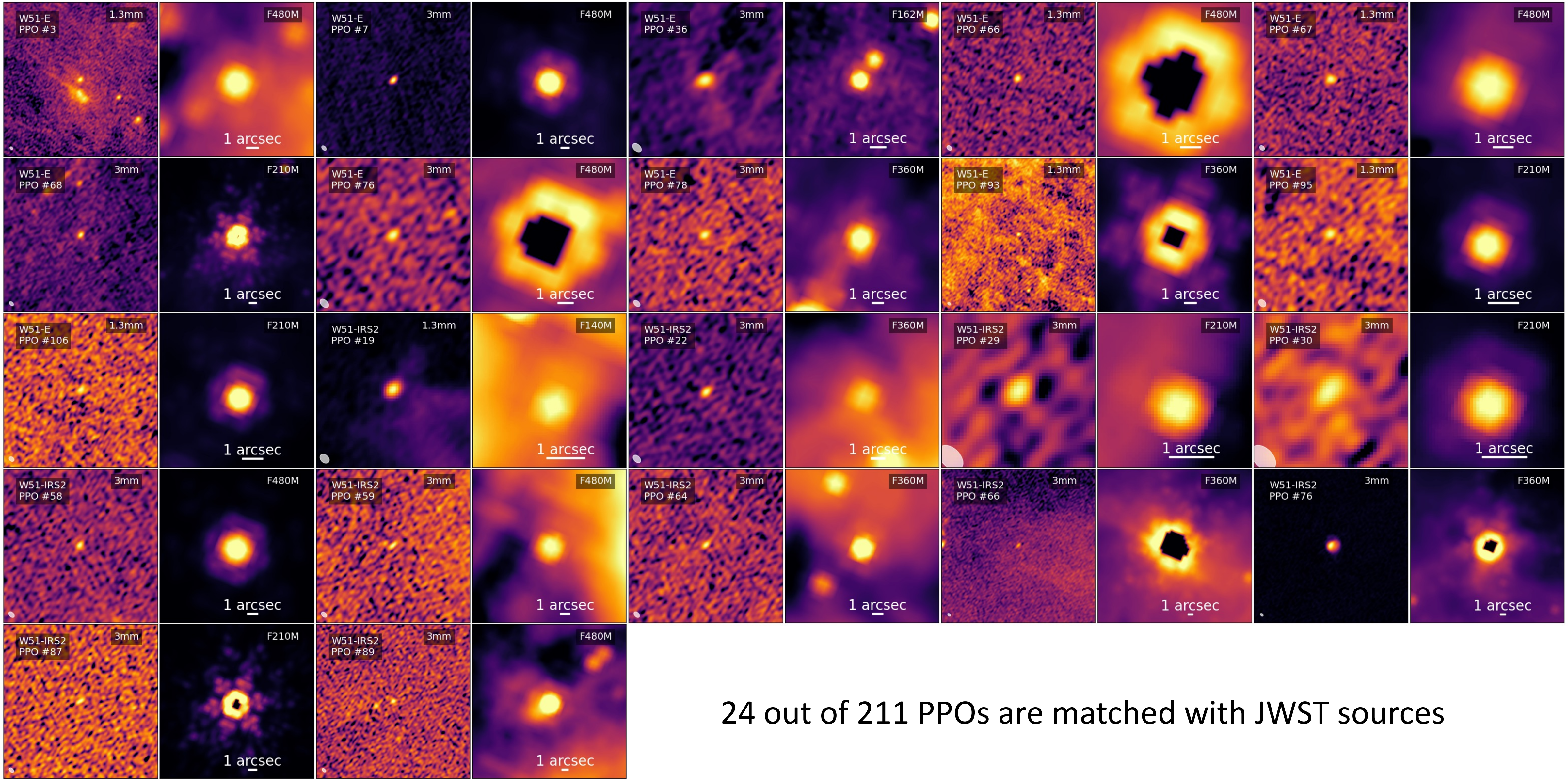
Yoo+ 25, Yoo+ subm



1.3mm + F162M + F210M

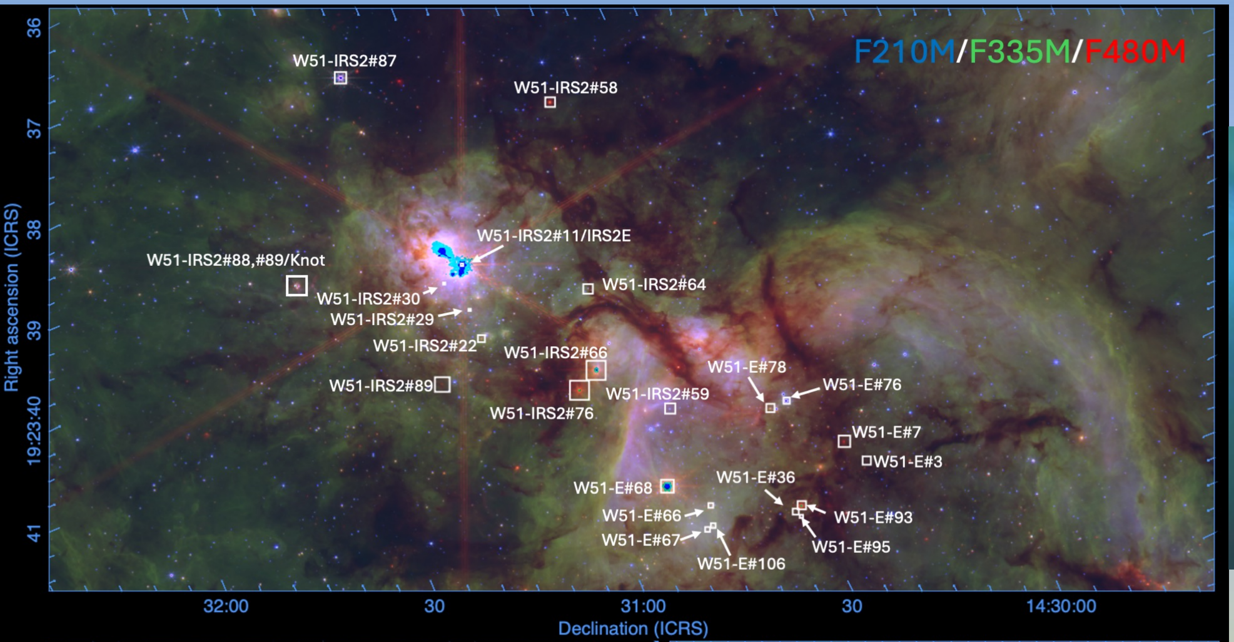

a
F480M/F360M/F210M
1 arcsec
dust filament
b
F210M/F162M/F140M
IRS2W
IRS2E
1 arcsec
W51-IRS2
protocluster
c
F335M/F405N/F480M
cometary objects?
d
F480M/F360M/F210M
1 arcsec
W51-E
protocluster
e
F480M/F405N/F335M
1 arcsec
bar?
g
F405N/F335M/F187N
wrinkle?
O9.5 star
W51b1 HII region
1 arcsec
h
F405N/F335M/F187N
W51b2 HII region
+O9.5 star
YSO
1 arcsec
i
F405N/F335M/F187N
1 arcsec
W51e7
HII region
j
F405N/F335M/F187N
1 arcsec
W51c1
HII region
k
F405N/F335M/F187N
1 arcsec
HII region
l
F2100W/F480M/F335M
1 arcsec
HII region

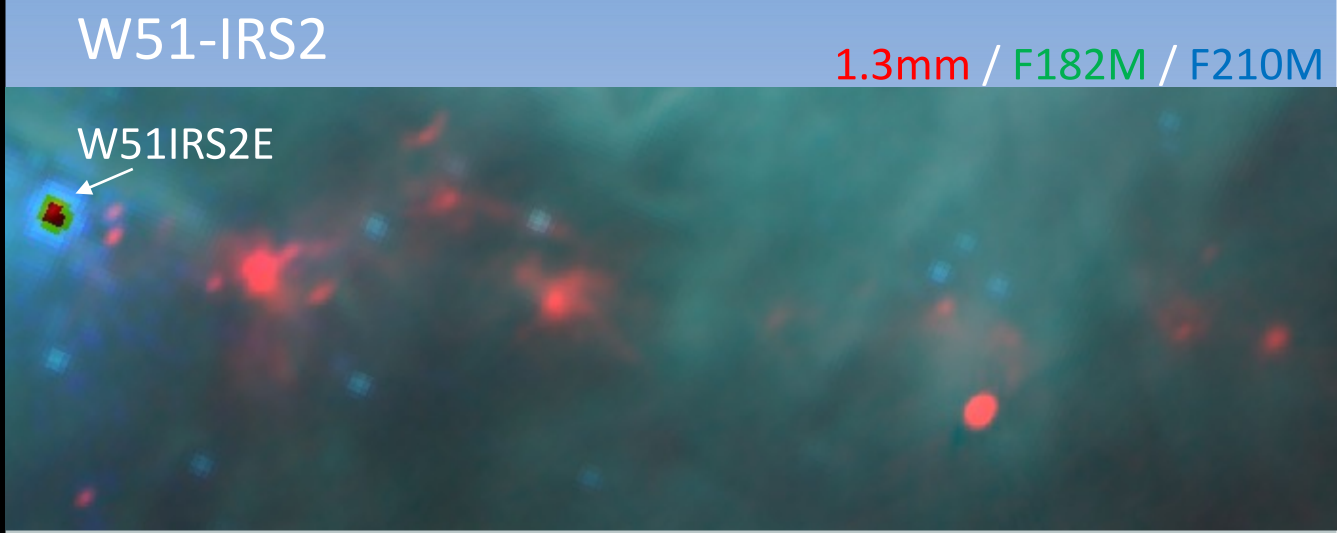
Only 10% of ALMA compact sources have overlap with JWST sources

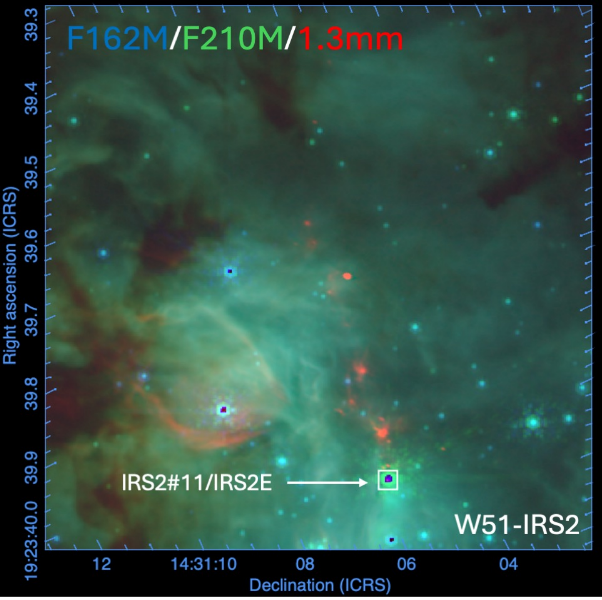


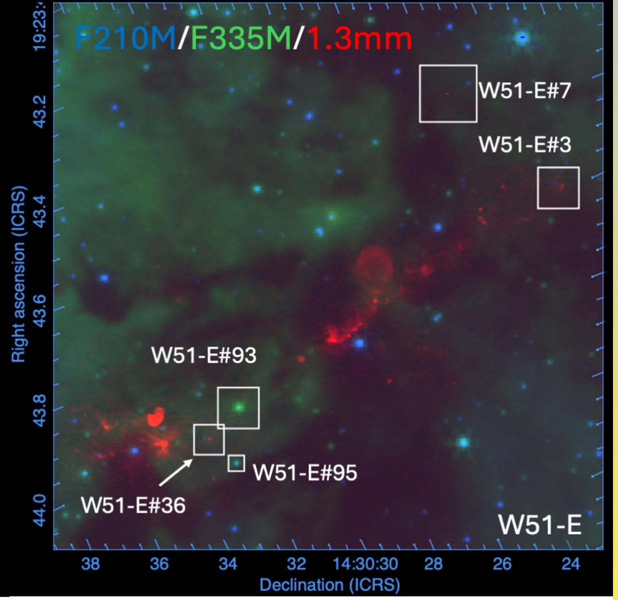
24 out of 211 PPOs are matched with JWST sources

Only 10% of ALMA compact sources have overlap with JWST sources









Among 24 matched sources,

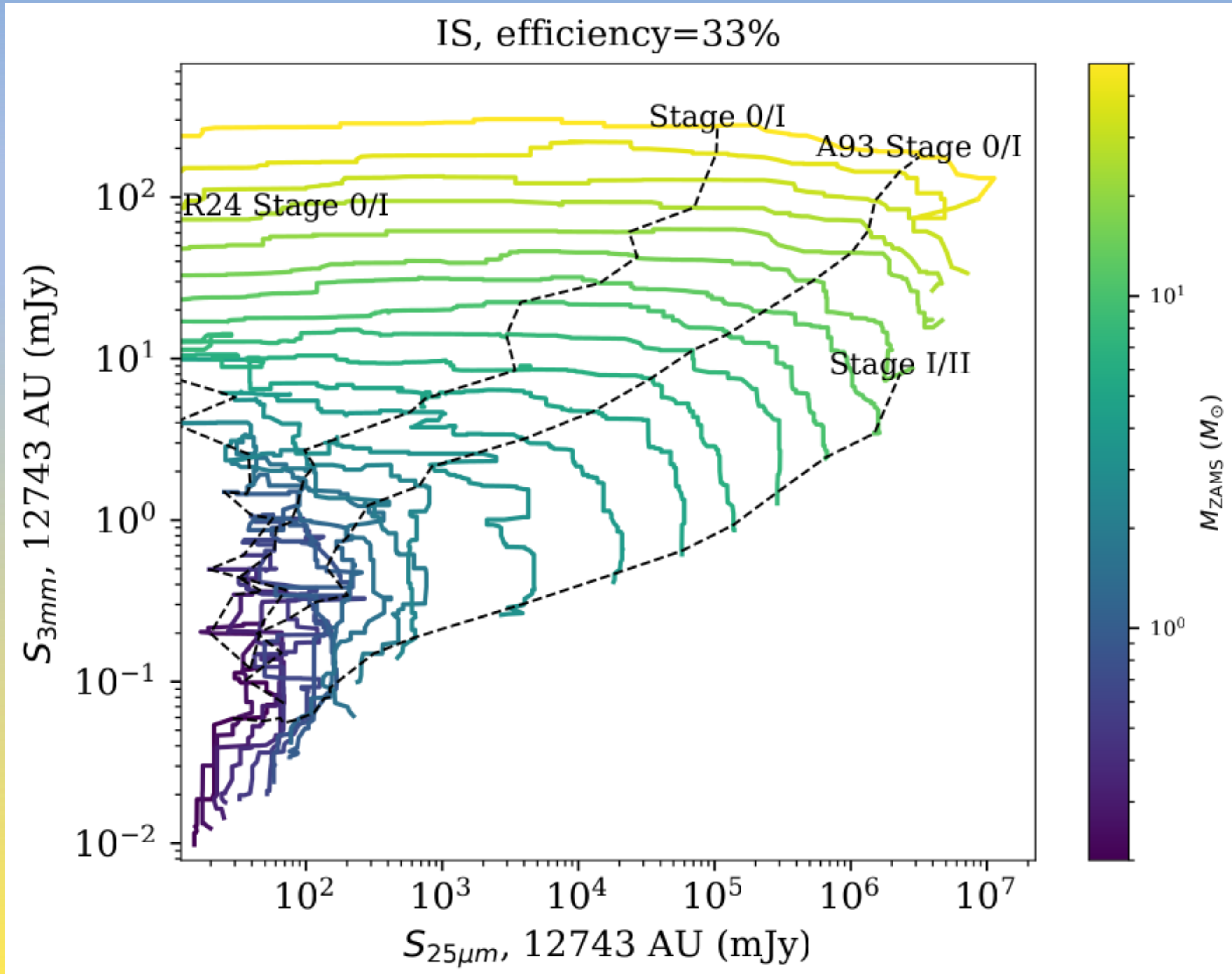
- 2 possible outflow knots
- 4 HII regions
- 1 YSO candidate
- 1 AGB candidate
- 1 massive protostar? (IRS2E)
- 15 unknowns

JWST measures ice abundance across the Galaxy

Savannah Gramze

Gramze+ 25

YSO model grid to test accretion models

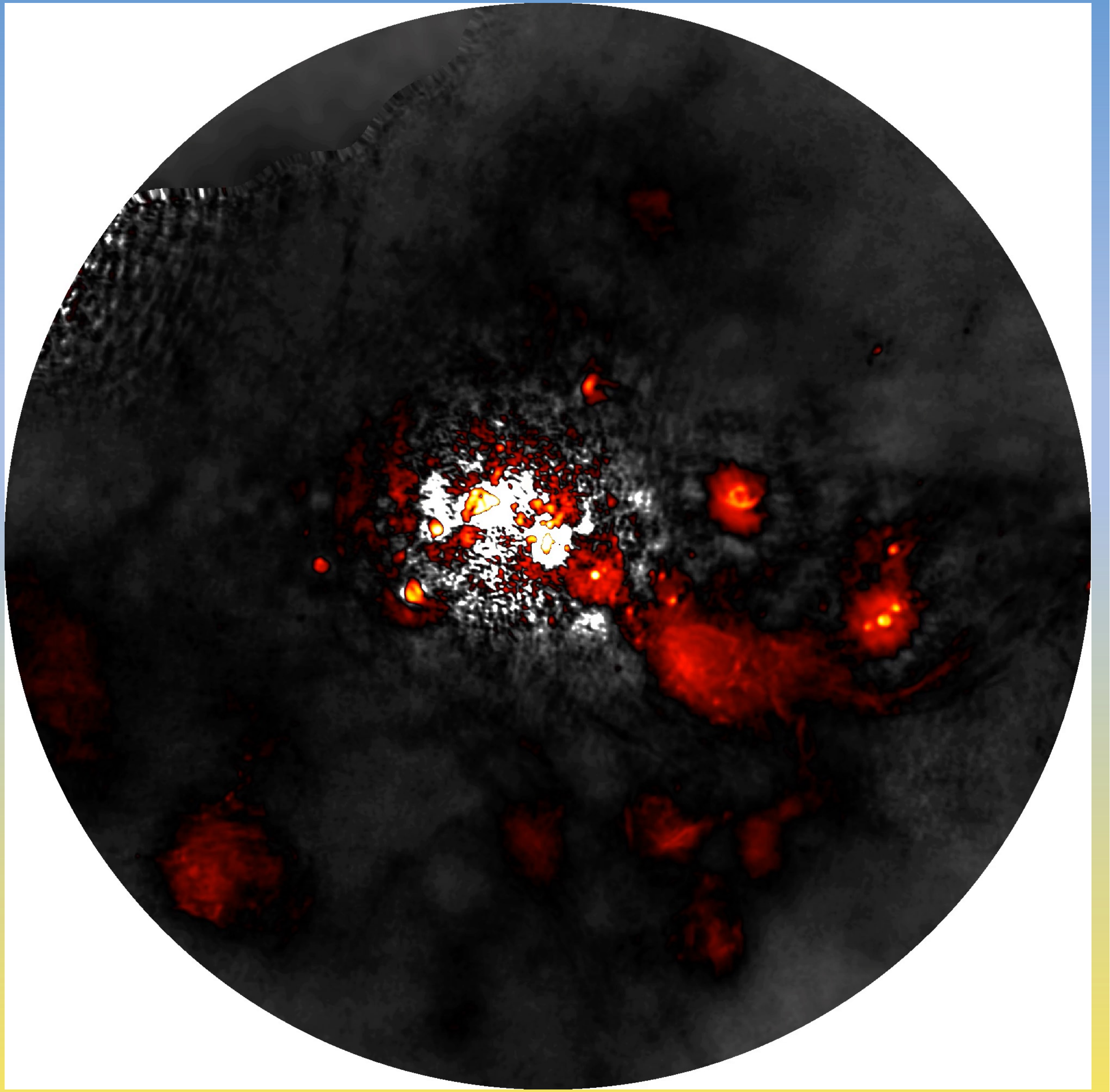


Theo Richardson

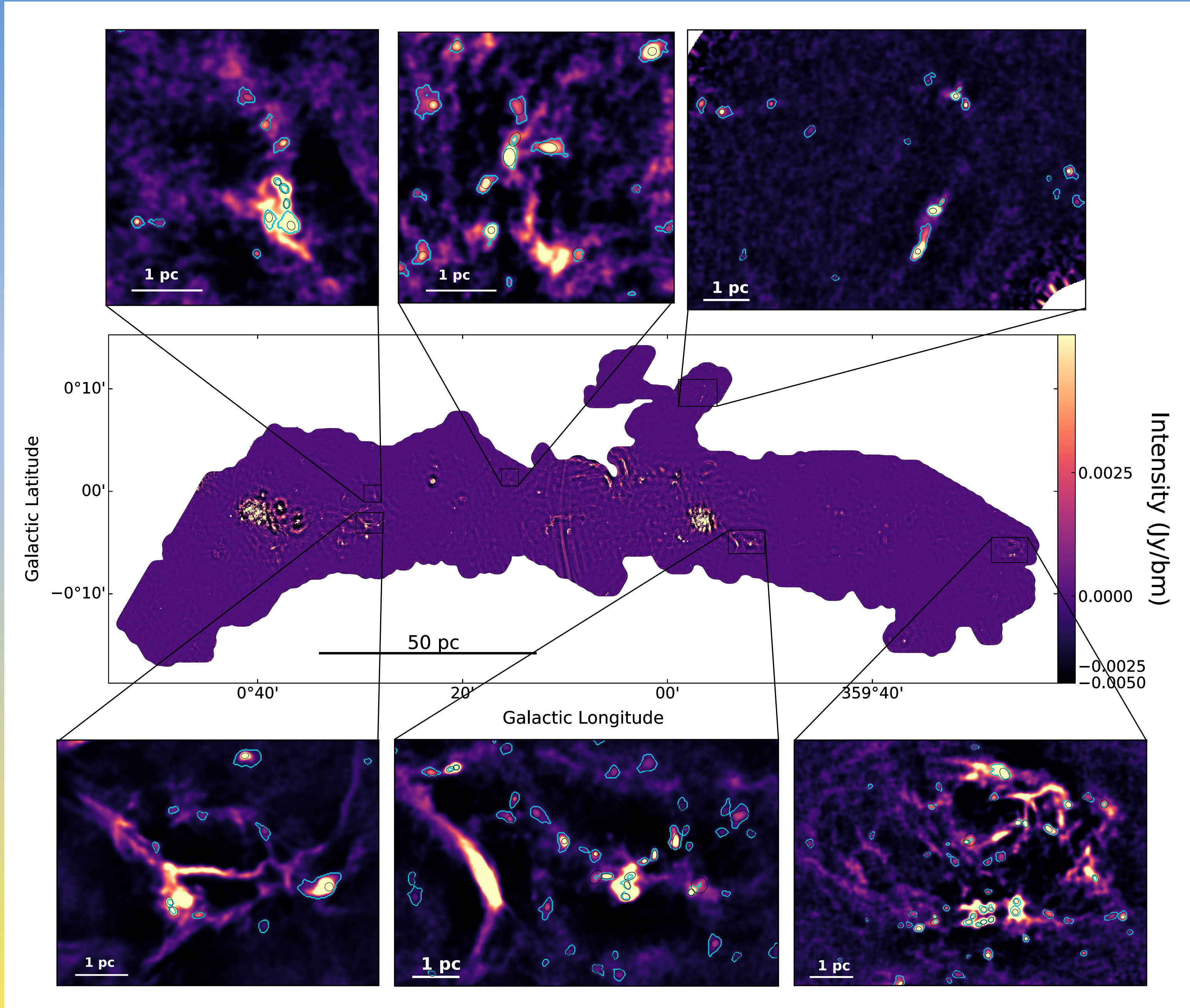
Richardson+ 24, 25

ACES survey

- First five data papers submitted July 2025.
- Six early result papers out: https://sites.google.com/view/aces-cmz/publications



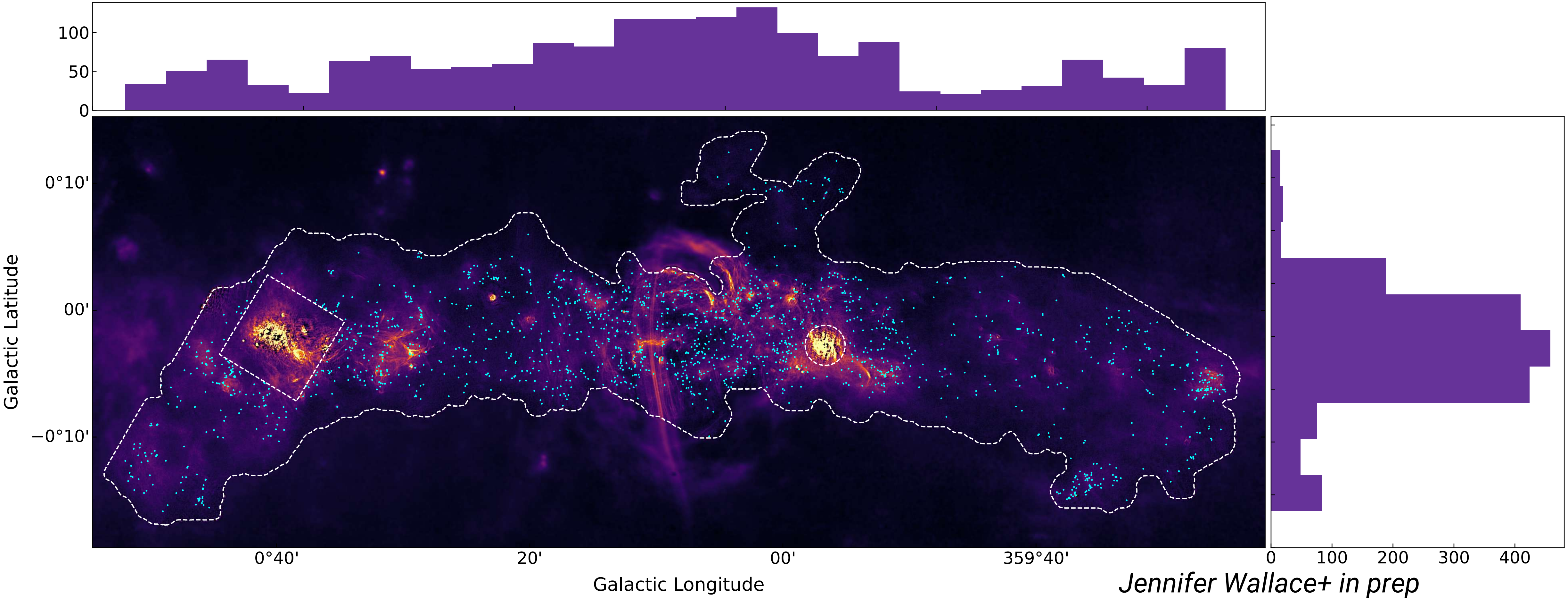
Core catalog



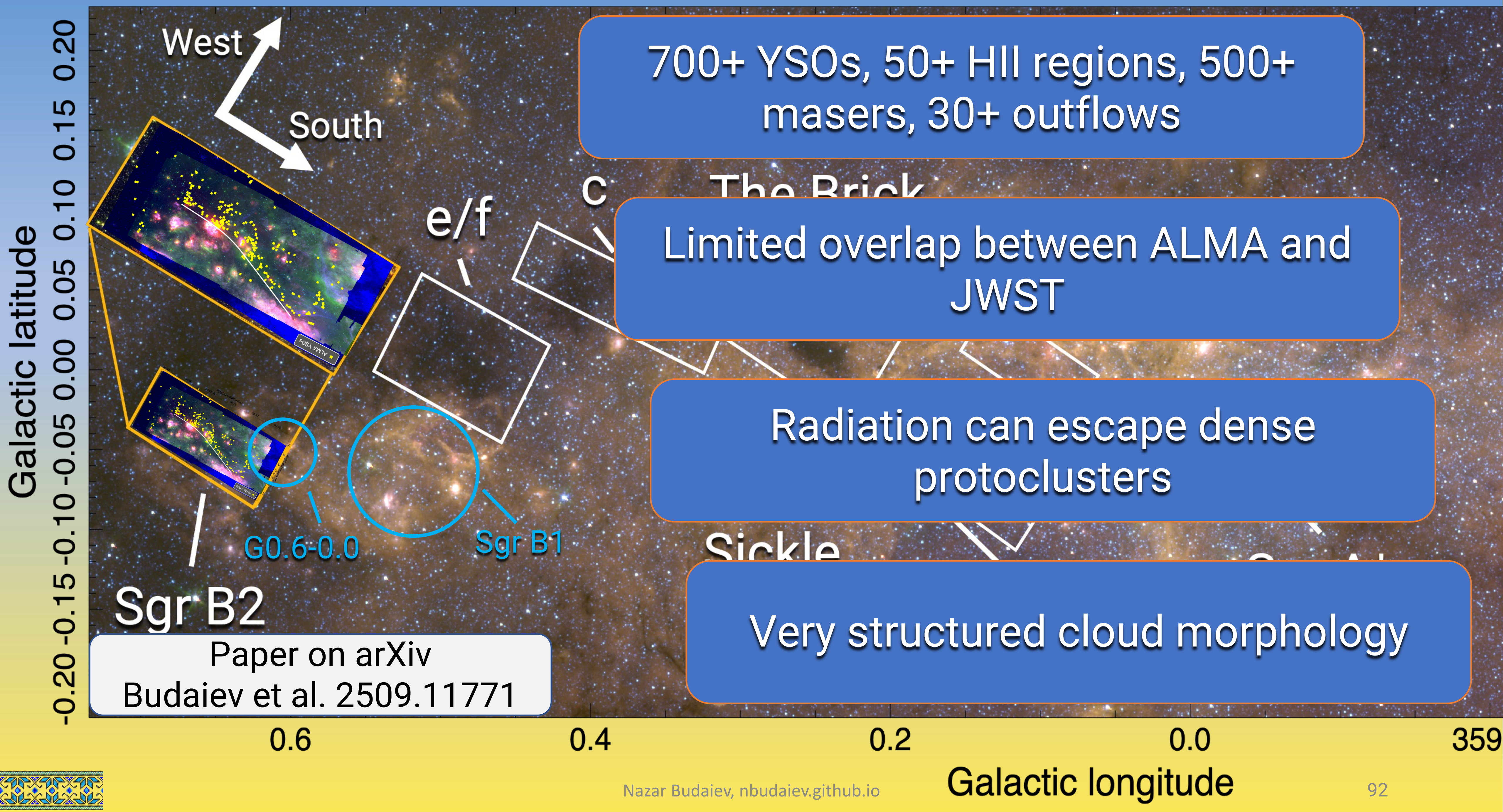
Jennifer Wallace+ in prep

Future work

What is the extended star formation in the CMZ?



Jennifer Wallace+ in prep



700+ YSOs, 50+ HII regions, 500+ masers, 30+ outflows

Limited overlap between ALMA and JWST

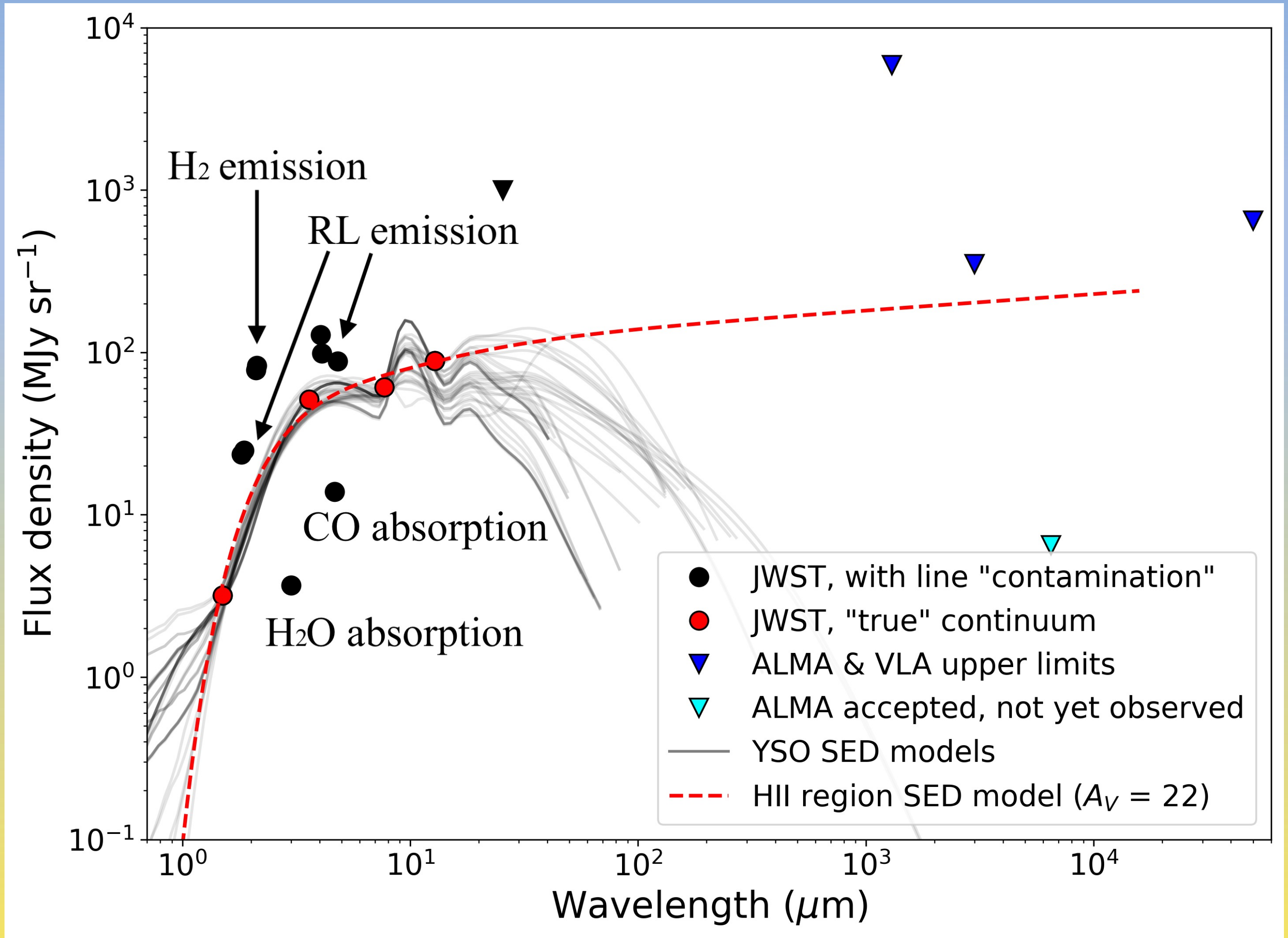
Radiation can escape dense protoclusters

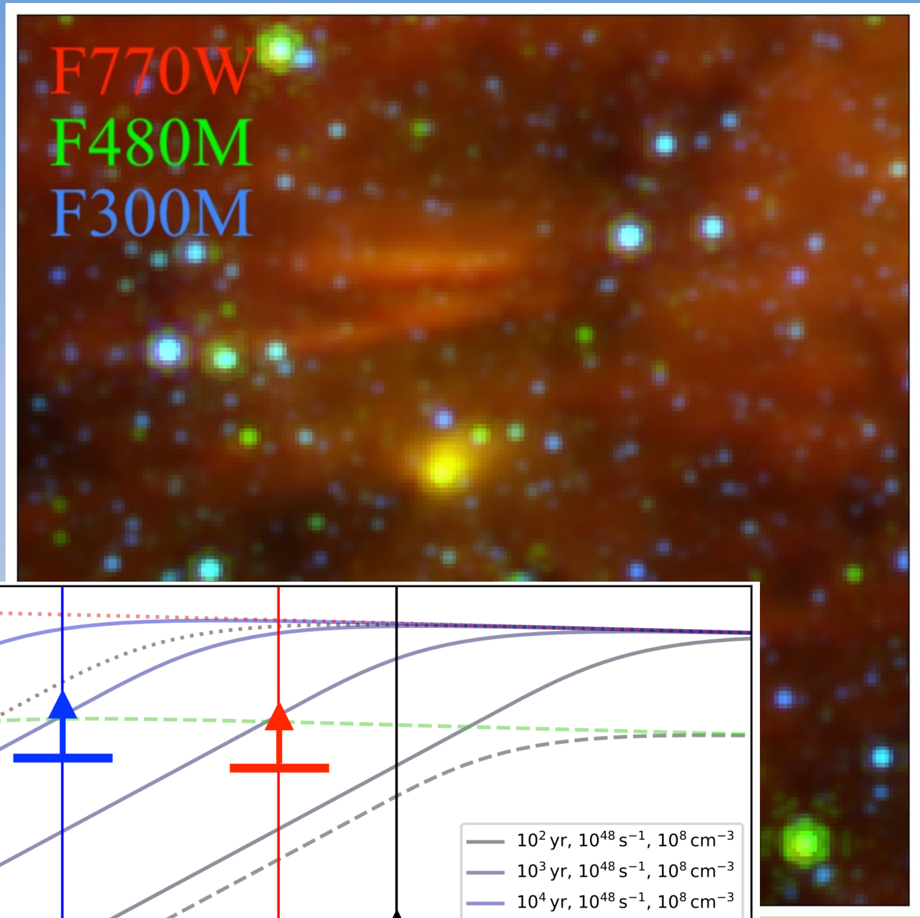
Very structured cloud morphology

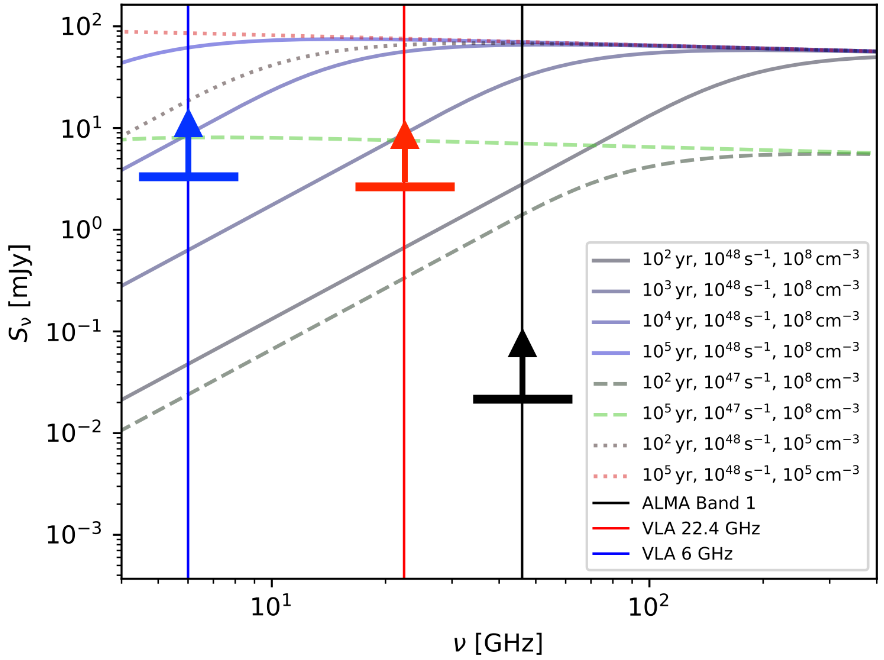
Paper on arXiv
Budaiev et al. 2509.11771

Extra extra slides

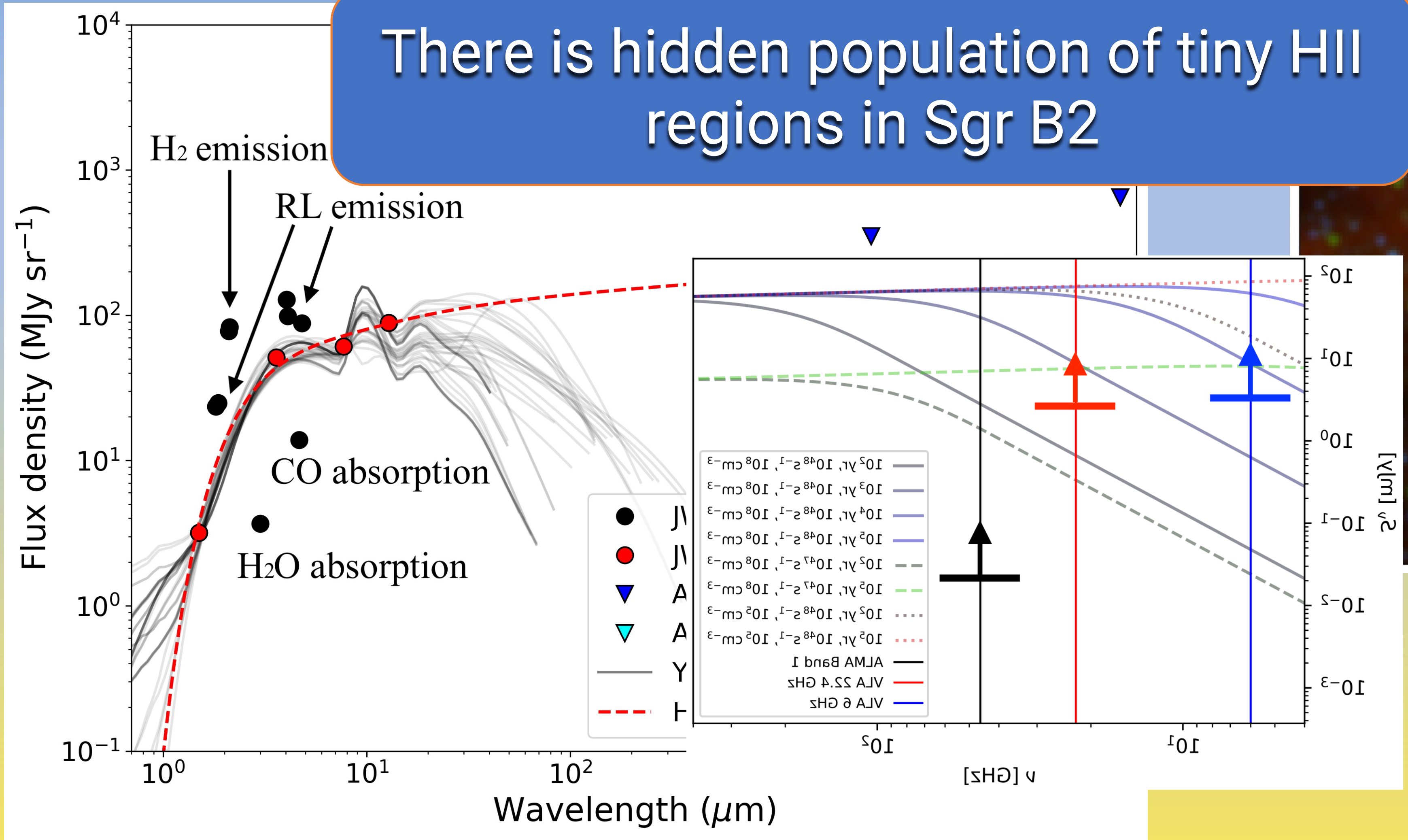
HCHII regions vs YSOs

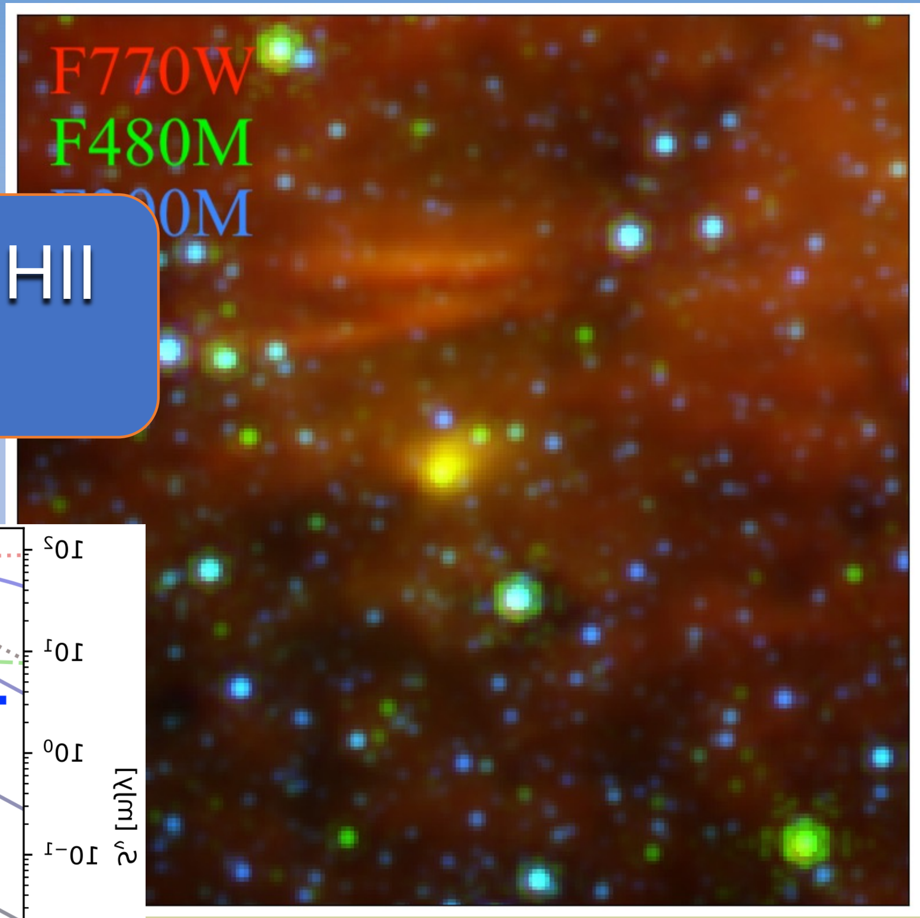






HCHII regions vs YSOs

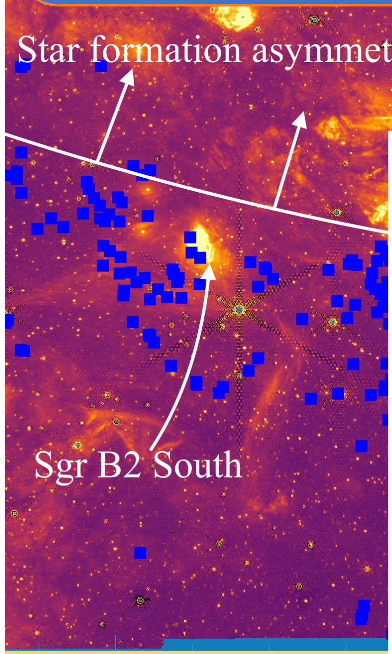


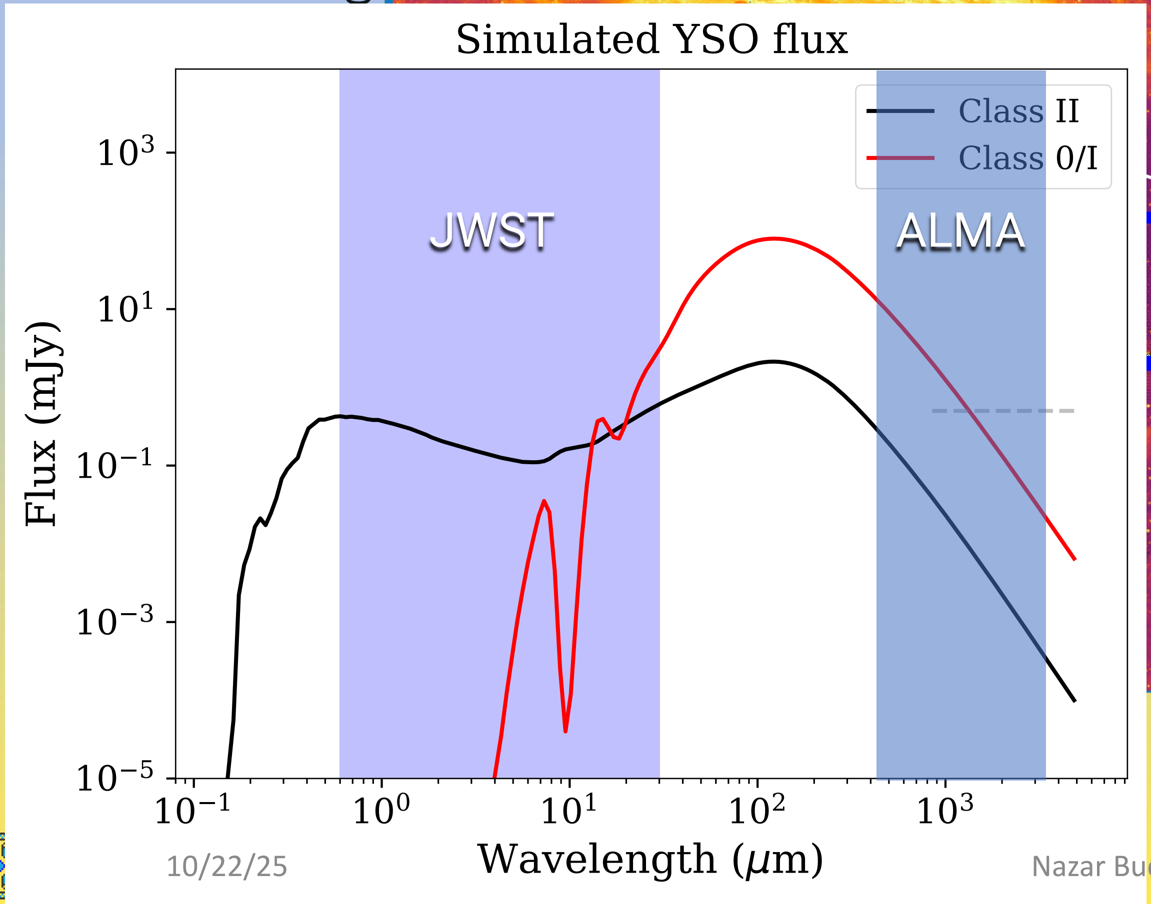


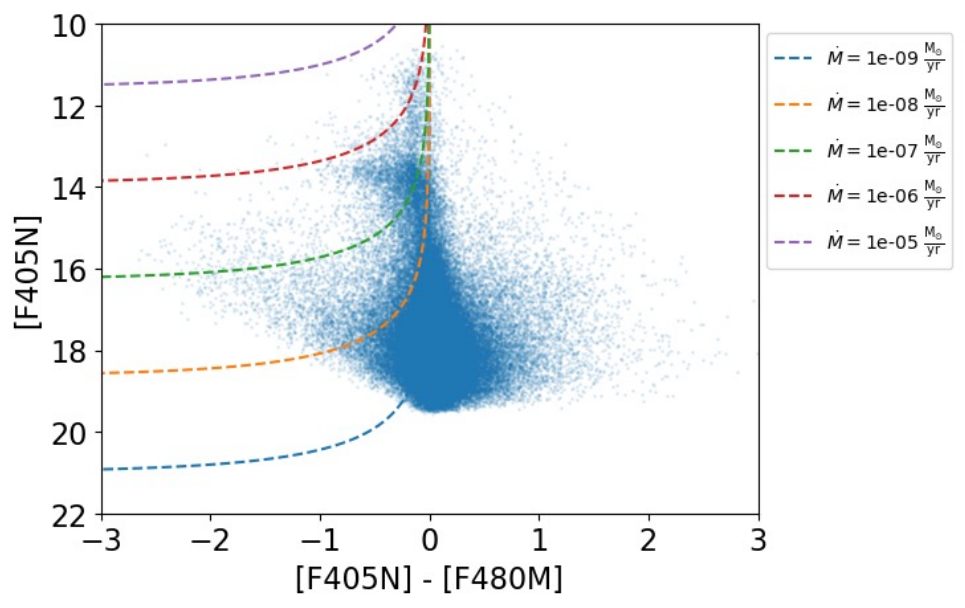
There is hidden population of tiny HII regions in Sgr B2

Star formation asymmetry

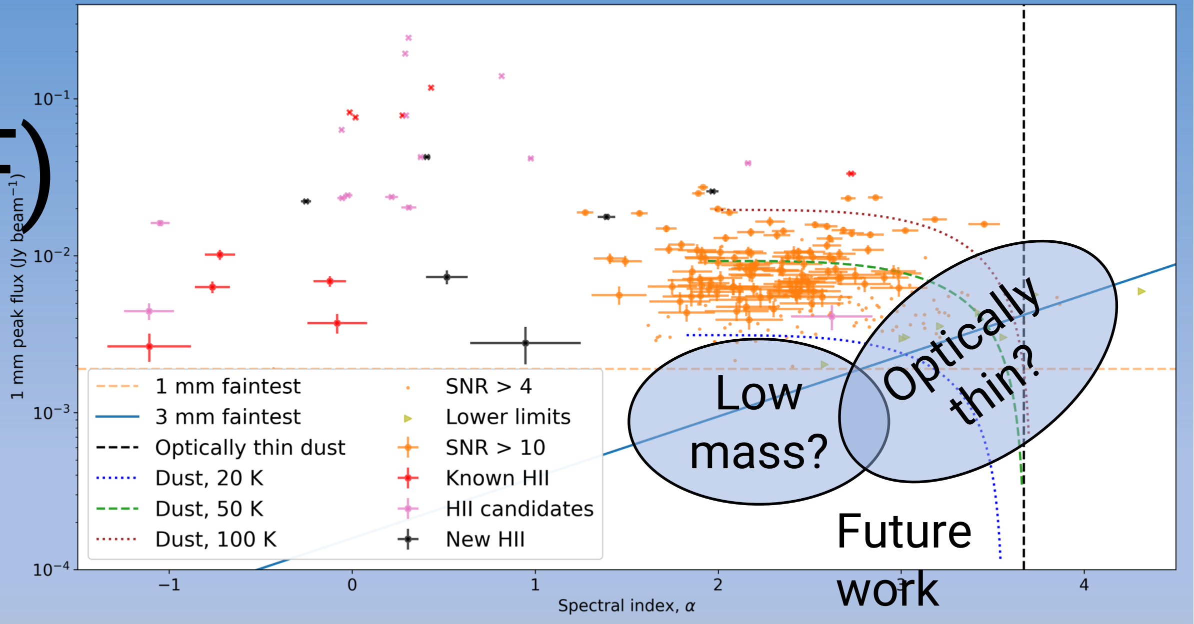
Where are the different populations of forming stars in Sgr B2?

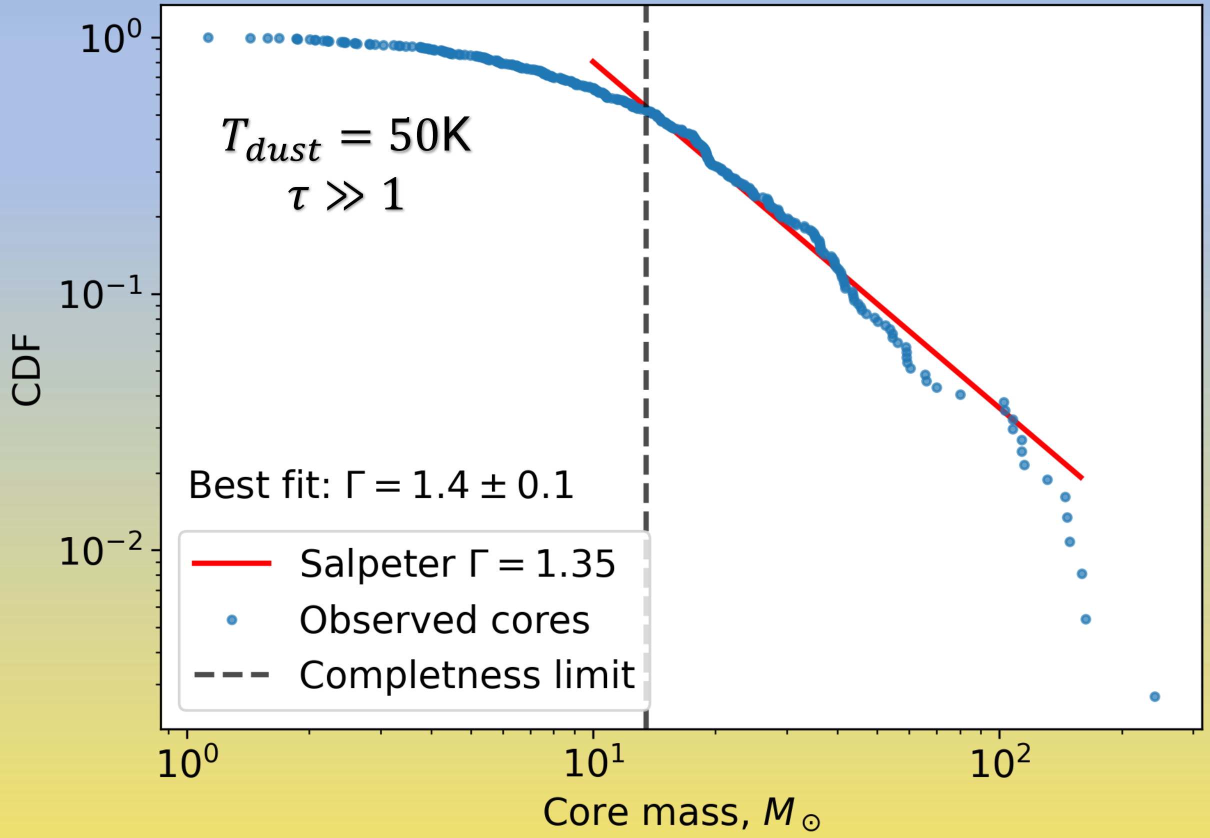


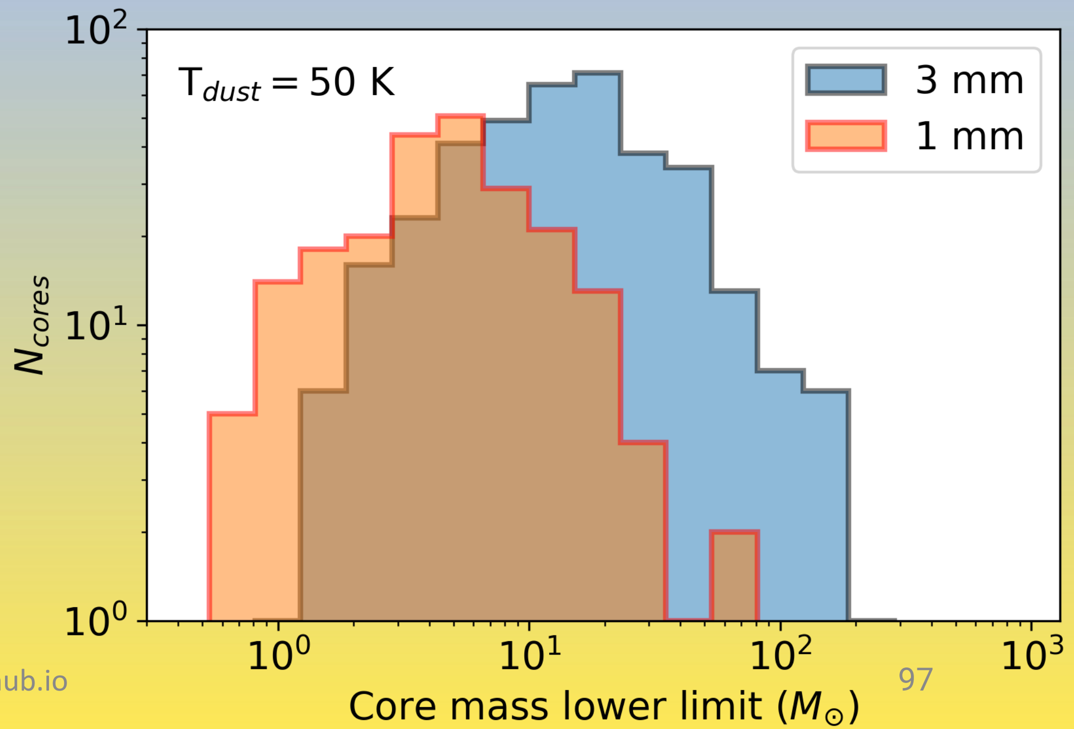




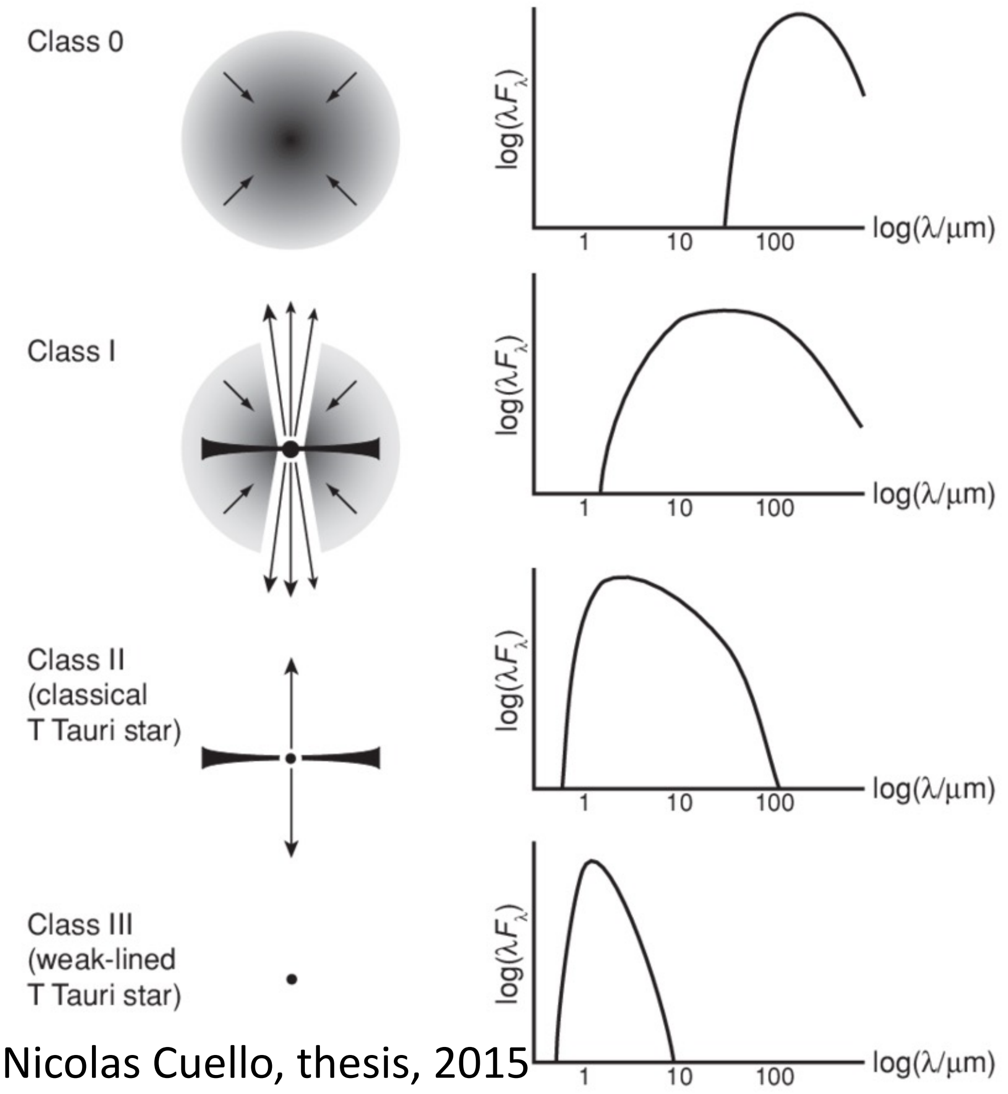
Core Mass Function (CMF)







YSO Classes / Stages



Nicolas Cuello, thesis, 2015

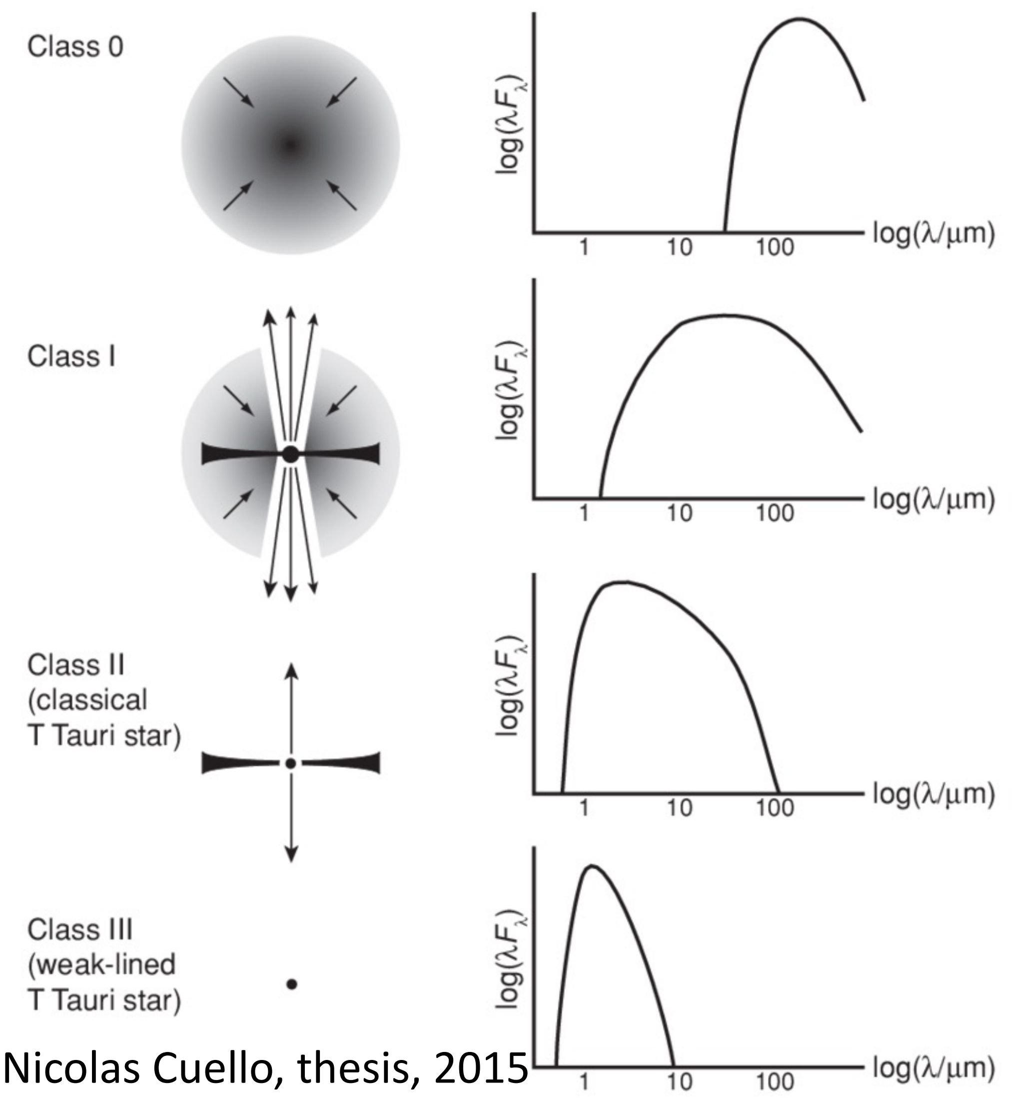
Class: spectral index at 10μm

- **Class 0** sources – undetectable at $\lambda < 20\mu m$
- **Class I** sources have $\alpha > 0.3$
- **Flat spectrum** sources have $0.3 > \alpha > -0.3$
- **Class II** sources have $-0.3 > \alpha > -1.6$
- **Class III** sources have $\alpha < -1.6$

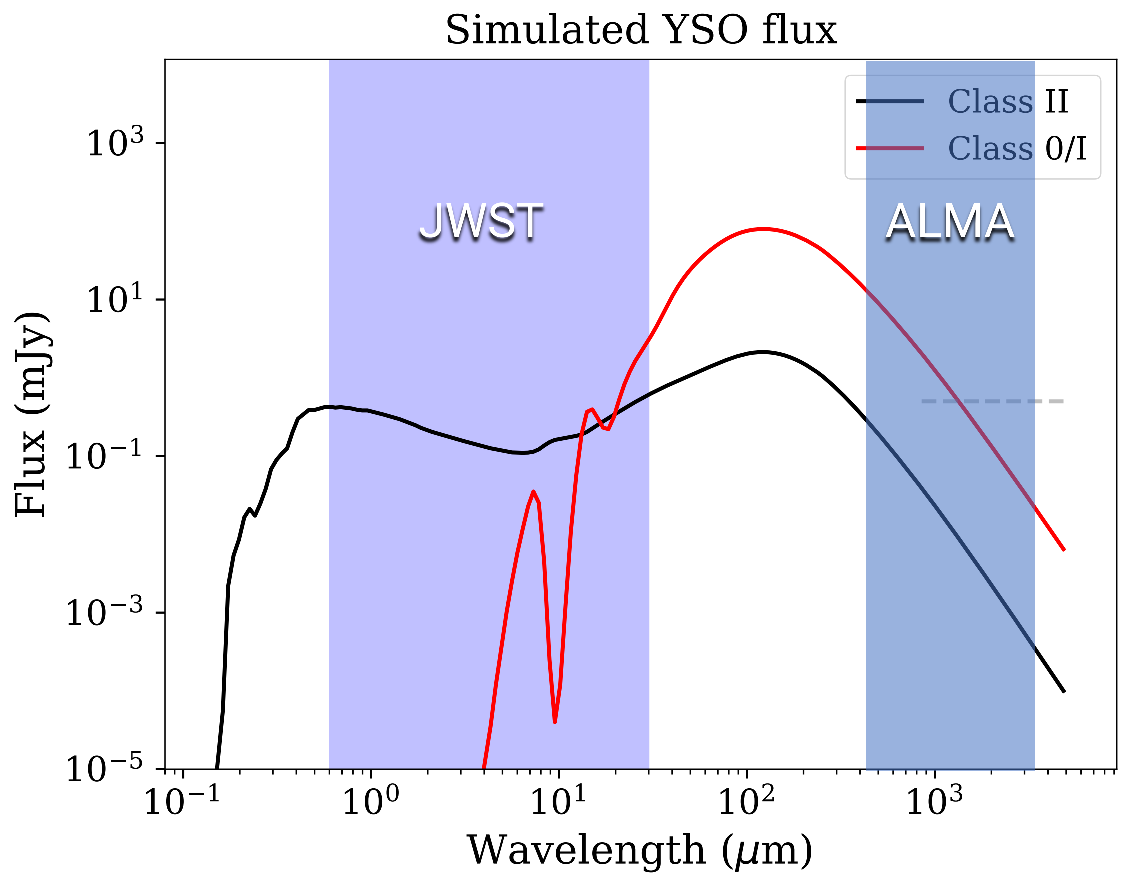
Stage: evolutionary stage, physical properties

The exact boundaries between the different Stages are of course arbitrary in the same way as the Class scheme. In the following sections, we choose to define Stage 0/I objects as those that have $\dot{M}_{\rm env}/M_\star > 10^{-6}$ yr^{-1}, Stage II objects as those that have $\dot{M}_{\rm env}/M_\star < 10^{-6}$ yr^{-1} and $M_{\rm disk}/M_\star > 10^{-6}$, and Stage III objects as those that have $\dot{M}_{\rm env}/M_\star < 10^{-6}$ yr^{-1} and $M_{\rm disk}/M_\star < 10^{-6}$.

YSO Classes / Stages



Nicolas Cuello, thesis, 2015



Class 0:

- $L_{\rm smm}/L_{\rm bol} > 0.005$ (Andre et al. 1993)
- $T_{\rm bol} < 70\,{\rm K}$ (Chen et al. 1995)

Class I:

- $\alpha > 0.3$ (Greene et al. 1994)
- $70\,{\rm K} < T_{\rm bol} < 650\,{\rm K}$ (Chen et al. 1995)

Class "Flat":

- $-0.3 < \alpha < 0.3$ (Greene et al. 1994)
- $350\,{\rm K} < T_{\rm bol} < 950\,{\rm K}$ (no correction), $500\,{\rm K} < T_{\rm bol} < 1450\,{\rm K}$ (dereddened) (Evans et al. 2009b)

Class II:

- $-1.6 < \alpha < -0.3$ (Greene et al. 1994)
- $650\,{\rm K} < T_{\rm bol} < 2800\,{\rm K}$ (Chen et al. 1995)

Class III:

- $\alpha < -1.6$ (Greene et al. 1994)
- $T_{\rm bol} > 2800\,{\rm K}$ (Chen et al. 1995).

Stage 0:

- An envelope-dominated YSO in which a protostar is deeply embedded within its natal material. Outflows and disks may have formed. (Colloquial)
- $M_\star < M_{\rm env}$ (Andre et al. 1993)
- $M_{\rm disk}/M_{\rm env} \ll 1$, $M_\star \sim M_{\rm env} + M_{\rm disk}$, deeply embedded (van Kempen et al. 2009)
- $M_{\rm env} > 0.1 M_\odot$, $M_\star < M_{\star,\,\rm final}/2$ (Richardson et al. 2025)

Stage I:

- A YSO where the envelope is significant, but less so than in Stage 0. Outflows and disks have formed. (Colloquial)
- $\dot{M}_{\rm env}/M_\star > 10^{-6}\,{\rm yr}^{-1}$ (Stage 0/I) (Robitaille et al. 2006)
- $M_{\rm env} > 0.1 M_\odot$ (Crapsi et al. 2008)
- $0.1 < M_{\rm disk}/M_{\rm env} < 2$, $M_\star > M_{\rm env} + M_{\rm disk}$, embedded (van Kempen et al. 2009)
- $M_{\rm env} > 0.1 M_\odot$, $M_\star > M_{\star,\,\rm final}/2$ (Richardson et al. 2025)

Stage II:

- A YSO where the dominant mass component is the protostar/disk system, and any remaining envelope is minimal (or no envelope exists). (Colloquial)
- $\dot{M}_{\rm env}/M_\star < 10^{-6}\,{\rm yr}^{-1}$, $M_{\rm disk}/M_\star > 10^{-6}$ (Robitaille et al. 2006)
- $M_{\rm env} < 0.1 M_\odot$ (Crapsi et al. 2008)
- $M_{\rm env} = 0$, $M_{\rm disk}/M_\star \ll 1$ (van Kempen et al. 2009)

Stage III:

- A protostar with minimal or absent circumstellar material. (Colloquial)
- $\dot{M}_{\rm env}/M_\star < 10^{-6}\,{\rm yr}^{-1}$, $M_{\rm disk}/M_\star < 10^{-6}$ (Robitaille et al. 2006)
- PMS stars with "tenuous" disks (van Kempen et al. 2009).