Dual-band Unified Exploration of Three CMZ clouds (DUET) -- I.the 3mm and 1.3mm Continuum Emission and Dense Cores in the Dust Ridge cloud e

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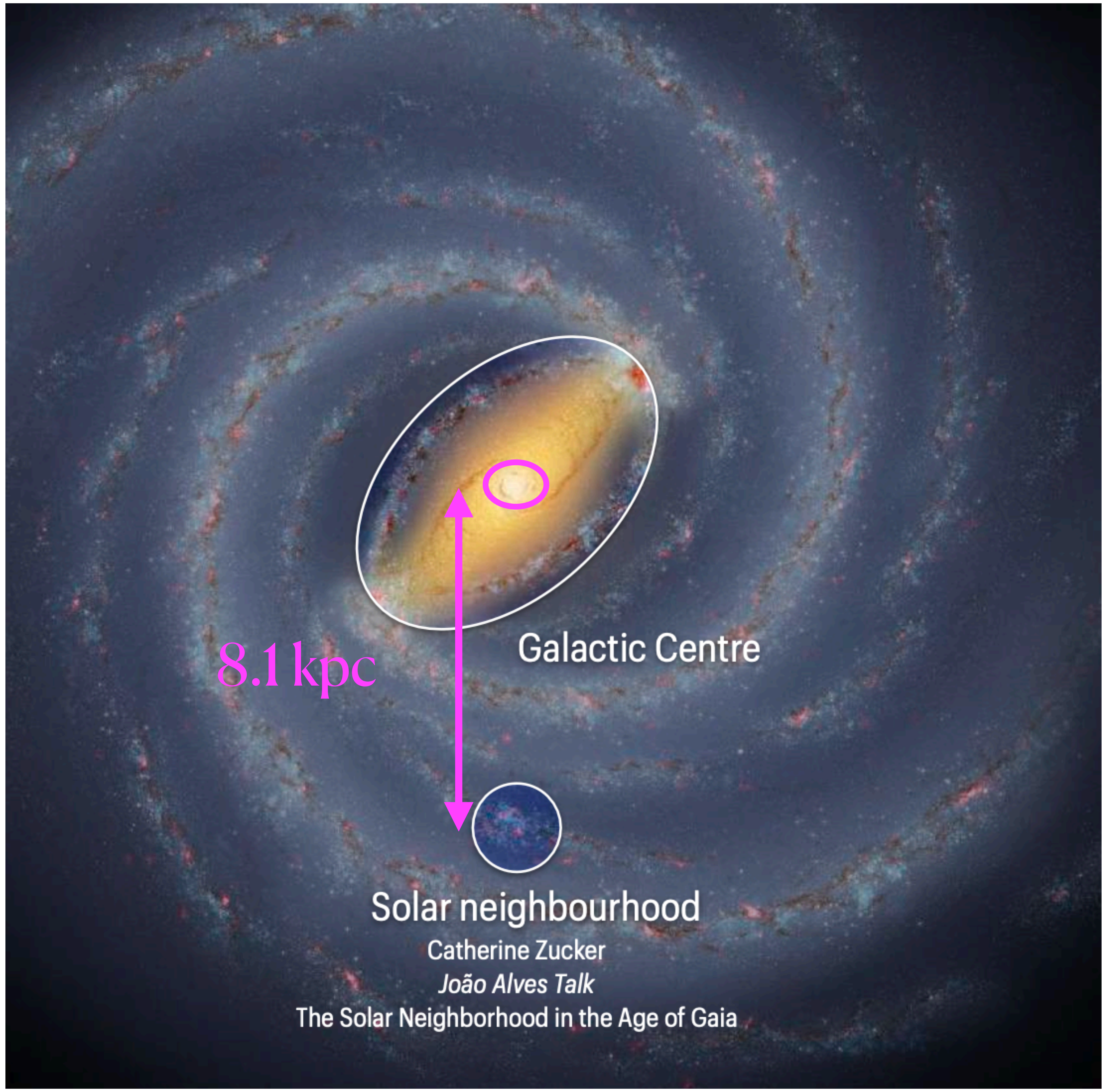
Context

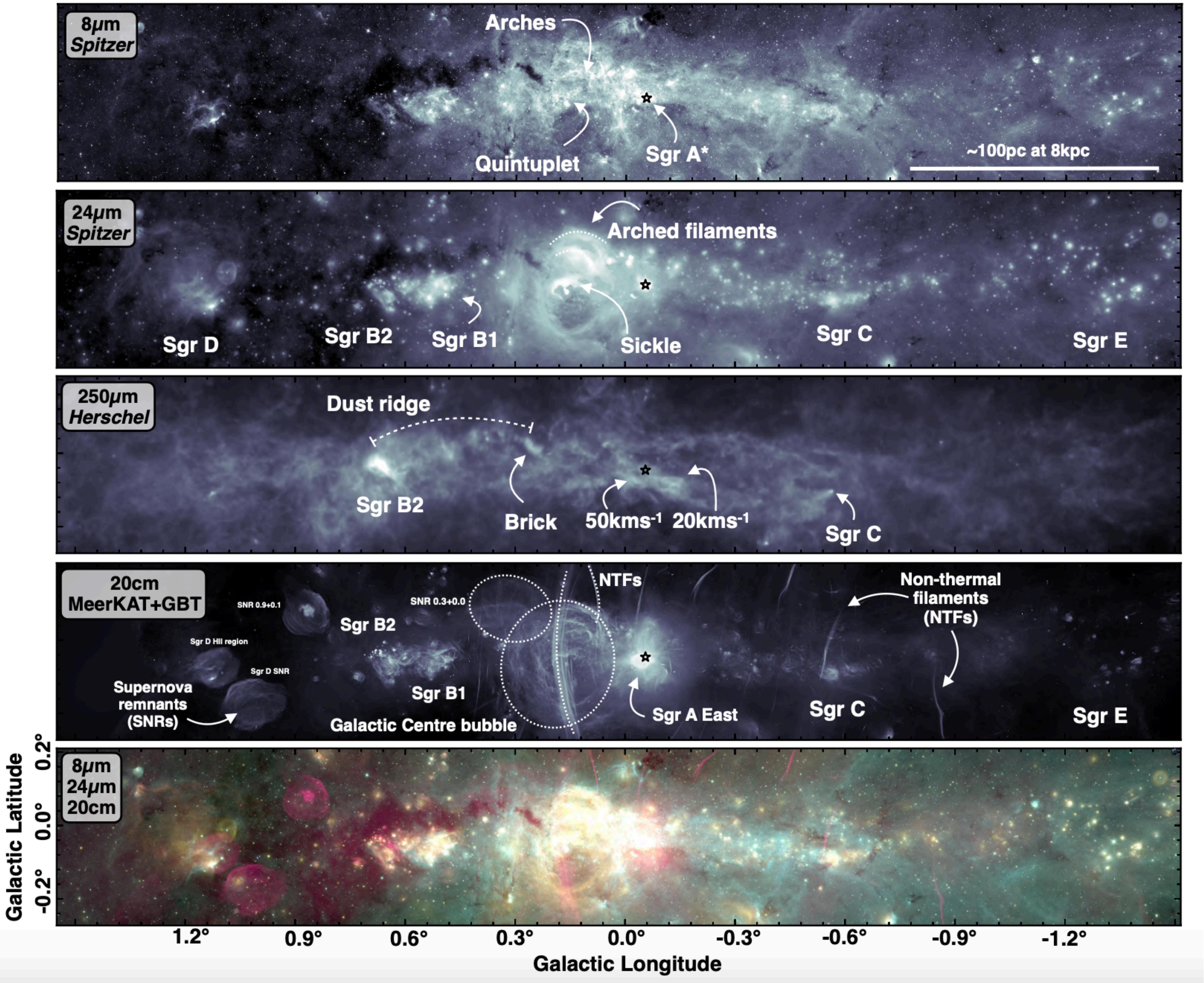
1.Backgrounds
  1.1 A Brief Introduction to the Central Molecular Zone (CMZ)
  1.2 Features of CMZ
  1.3 How do we find Cloud 'e' ?
  1.4 Why chose ALMA bands 3 & 6 ?
2. Data Analysis and Results
  2.1 Calculation of Spectral Index in each Pixel & Identification of Cloud Cores
  2.2 Calculation of Cloud Core Mass and Spectral Index
  2.3 Fragmentation of Filaments
  2.4 Spatial Core Distribution & Mass Segregation
3. Summary

1. Backgrounds

A Brief Introduction to the Central Molecular Zone (CMZ)



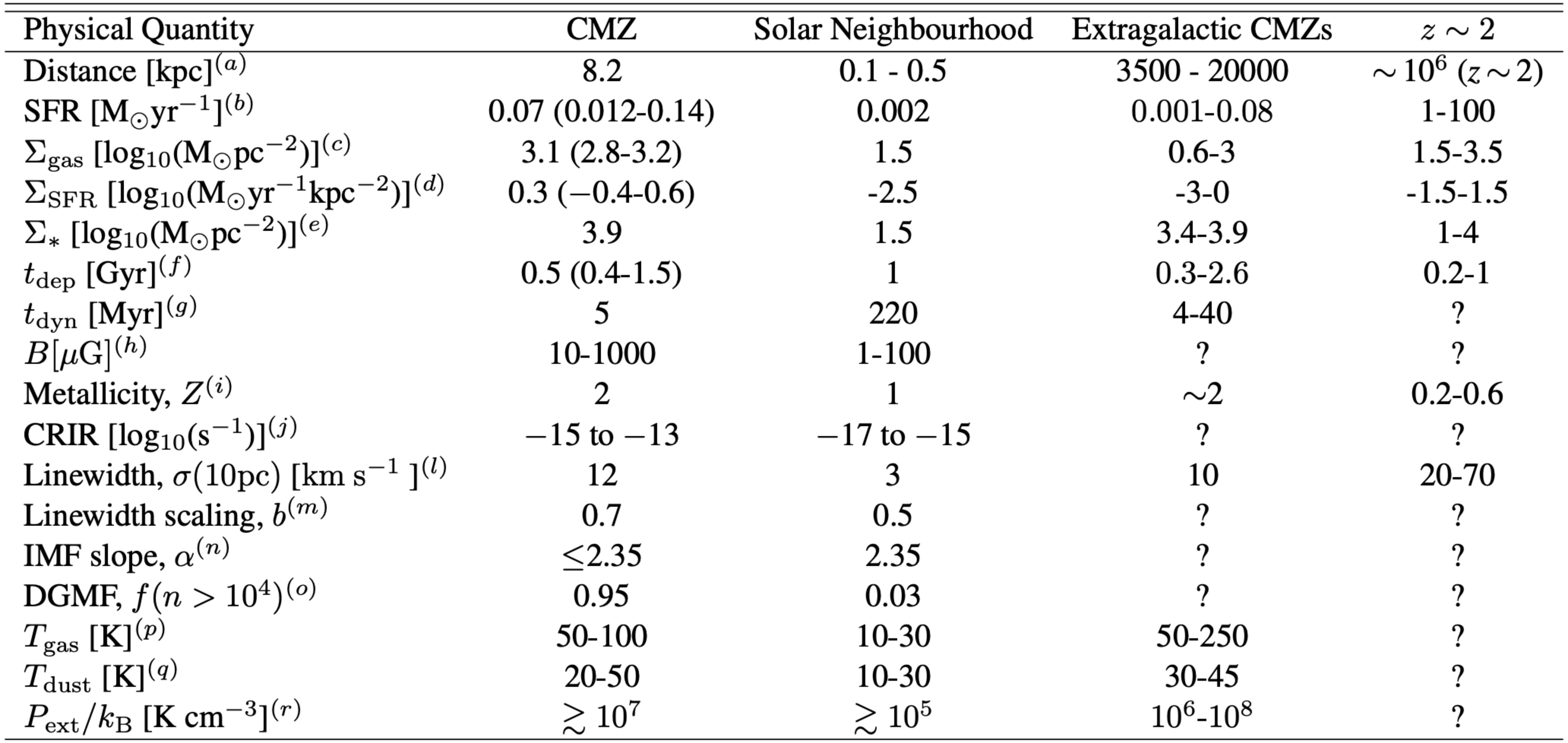
Chapter 3, Protostars and Planets VII



Henshaw et al. 2023

Features of CMZ

1. High density (10^4 cm^{-3}), high temperature (70-100K or higher), strong turbulence (FWHM~10-20 km/s) in the gas



Physical Quantity	CMZ	Solar Neighbourhood	Extragalactic CMZs	$z \sim 2$
Distance [kpc](a)	8.2	0.1 - 0.5	3500 - 20000	$\sim 10^6$ ($z \sim 2$)
SFR [$\mathrm{M_\odot yr^{-1}}$](b)	0.07 (0.012-0.14)	0.002	0.001-0.08	1-100
$\Sigma_{\rm gas}$ [$\log_{10}(\mathrm{M_\odot pc^{-2}})$](c)	3.1 (2.8-3.2)	1.5	0.6-3	1.5-3.5
$\Sigma_{\rm SFR}$ [$\log_{10}(\mathrm{M_\odot yr^{-1} kpc^{-2}})$](d)	0.3 (-0.4-0.6)	-2.5	-3-0	-1.5-1.5
Σ_* [$\log_{10}(\mathrm{M_\odot pc^{-2}})$](e)	3.9	1.5	3.4-3.9	1-4
$t_{\rm dep}$ [Gyr](f)	0.5 (0.4-1.5)	1	0.3-2.6	0.2-1
$t_{\rm dyn}$ [Myr](g)	5	220	4-40	?
$B[\mu\mathrm{G}]$(h)	10-1000	1-100	?	?
Metallicity, Z(i)	2	1	~2	0.2-0.6
CRIR [$\log_{10}(\mathrm{s^{-1}})$](j)	-15 to -13	-17 to -15	?	?
Linewidth, σ(10pc) [km s^{-1}](l)	12	3	10	20-70
Linewidth scaling, b(m)	0.7	0.5	?	?
IMF slope, α(n)	$\leq$2.35	2.35	?	?
DGMF, $f(n > 10^4)$(o)	0.95	0.03	?	?
$T_{\rm gas}$ [K](p)	50-100	10-30	50-250	?
$T_{\rm dust}$ [K](q)	20-50	10-30	30-45	?
$P_{\rm ext}/k_{\rm B}$ [K cm^{-3}](r)	$\gtrsim 10^7$	$\gtrsim 10^5$	10^6-10^8	?

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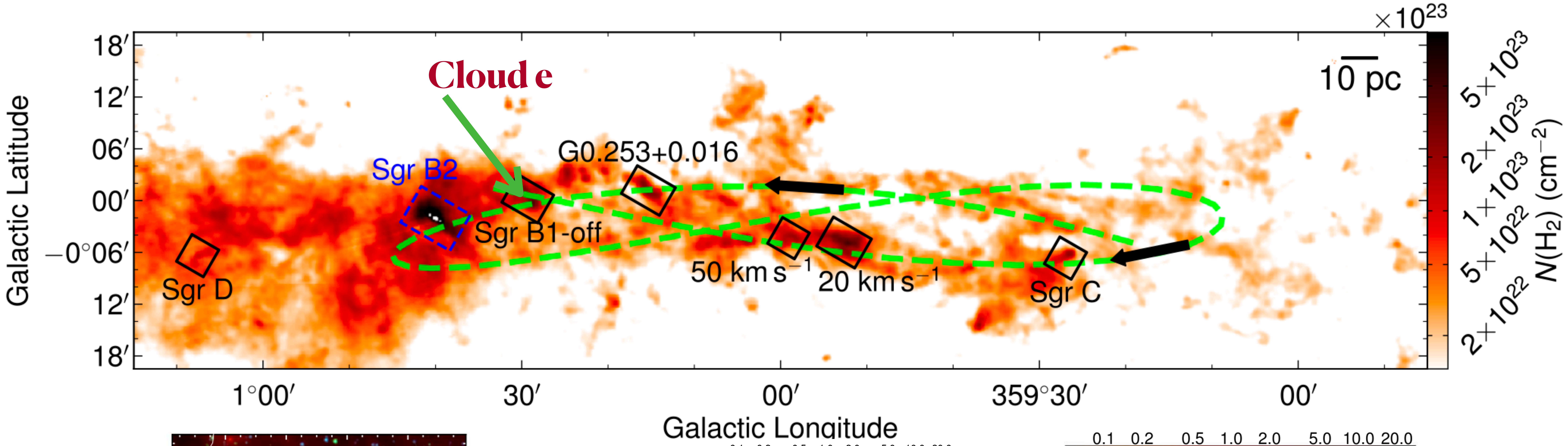
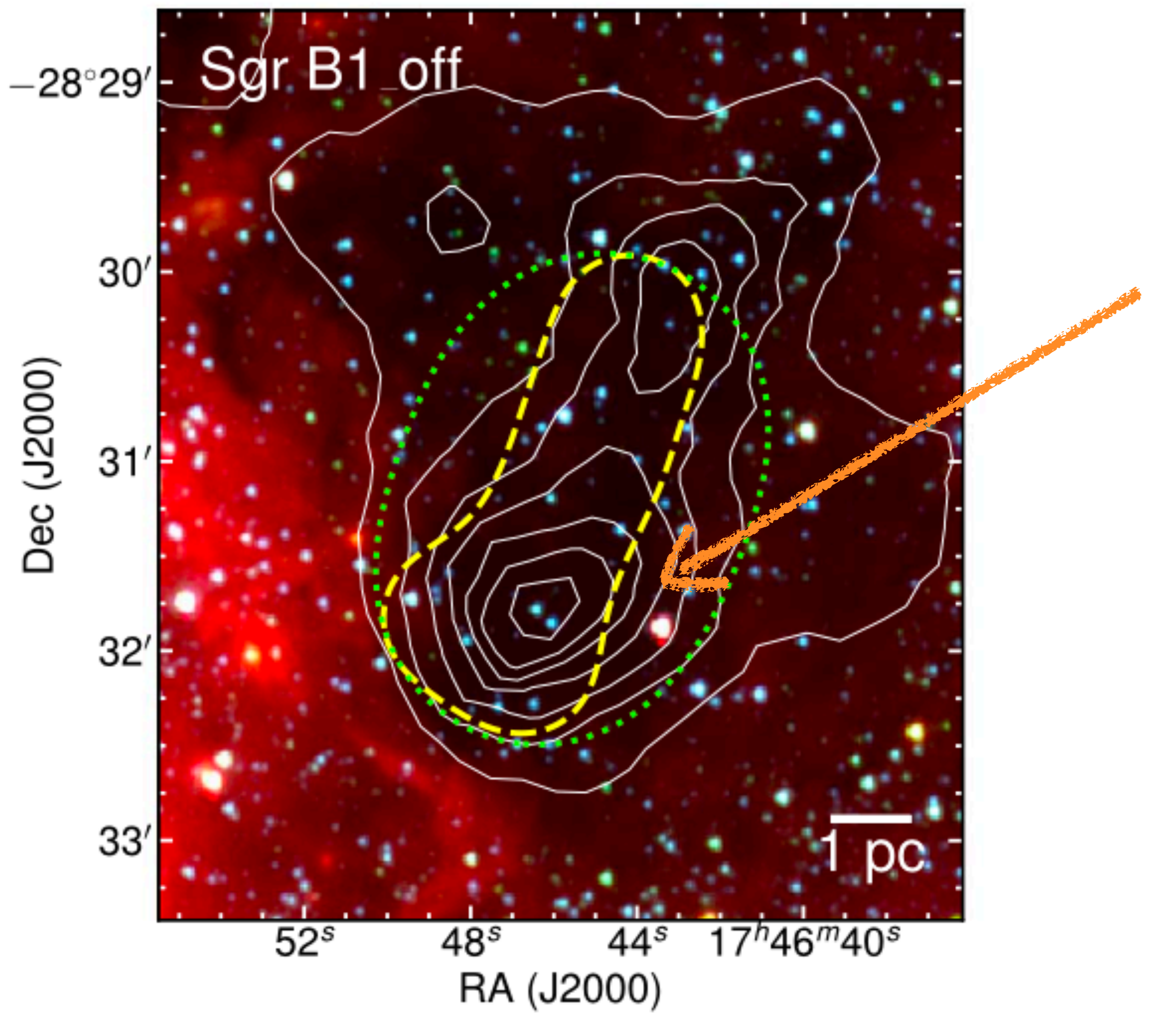
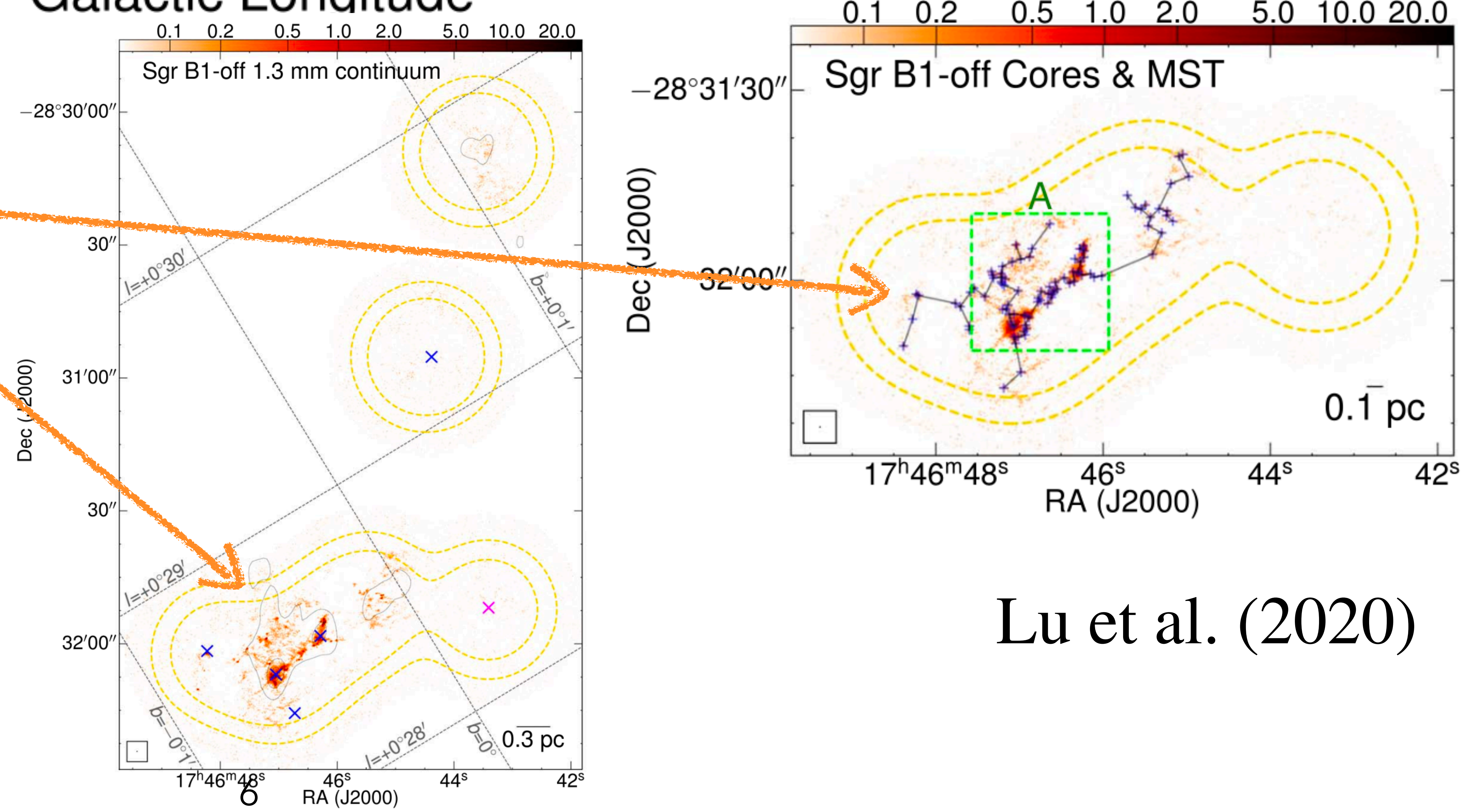
How do we find Cloud 'e'?





Lu et al. (2019)



Lu et al. (2020)

Why choose ALMA Band 3&6 ?

ALMA's Central Array on the Chajnantor plains

Credit: C. Padilla, NRAO/AUI/NSF

Table 1. Summary of the ALMA Band 3 observations.

Observation dates	Array configurations	Baseline ranges	No. of antennas	Bandpass/flux calibrators	Phase calibrators	Targets
2018-11-23	C43-4	15.1 m–1.4 km	47	J1924−2914	J1744−3116	cloud e
2018-11-27	C43-4	15.1 m–1.3 km	44	J1617−5848	J1744−3116	the 20 km s^{-1} cloud, Sgr C
2018-11-27	C43-4	15.1 m–1.3 km	44	J1617−5848	J1744−3116	the 20 km s^{-1} cloud, Sgr C
2018-11-27	C43-4	15.1 m–1.3 km	45	J1924−2914	J1744−3116	the 20 km s^{-1} cloud, Sgr C
2019-08-27	C43-7	38.4 m–3.6 km	48	J1924−2914	J1744−3116	cloud e
2019-08-28	C43-7	38.4 m–3.6 km	48	J1924−2914	J1744−3116	the 20 km s^{-1} cloud, Sgr C
2019-08-28	C43-7	38.4 m–3.6 km	48	J1924−2914	J1752−2956	the 20 km s^{-1} cloud, Sgr C
2019-08-29	C43-7	38.4 m–3.6 km	47	J1517−2422	J1744−3116	the 20 km s^{-1} cloud, Sgr C
2019-08-29	C43-7	38.4 m–3.6 km	46	J1924−2914	J1744−3116	the 20 km s^{-1} cloud, Sgr C
2019-08-30	C43-7	38.4 m–3.6 km	47	J1924−2914	J1744−3116	the 20 km s^{-1} cloud, Sgr C
2021-07-30	C43-7	46.8 m–5.2 km	41	J1924−2914	J1744−3116	cloud e
2021-08-02	C43-7	46.8 m–5.2 km	37	J1924−2914	J1744−3116	the 20 km s^{-1} cloud, Sgr C

Table 2. Properties of the Band 3 and Band 6 continuum images of cloud e.

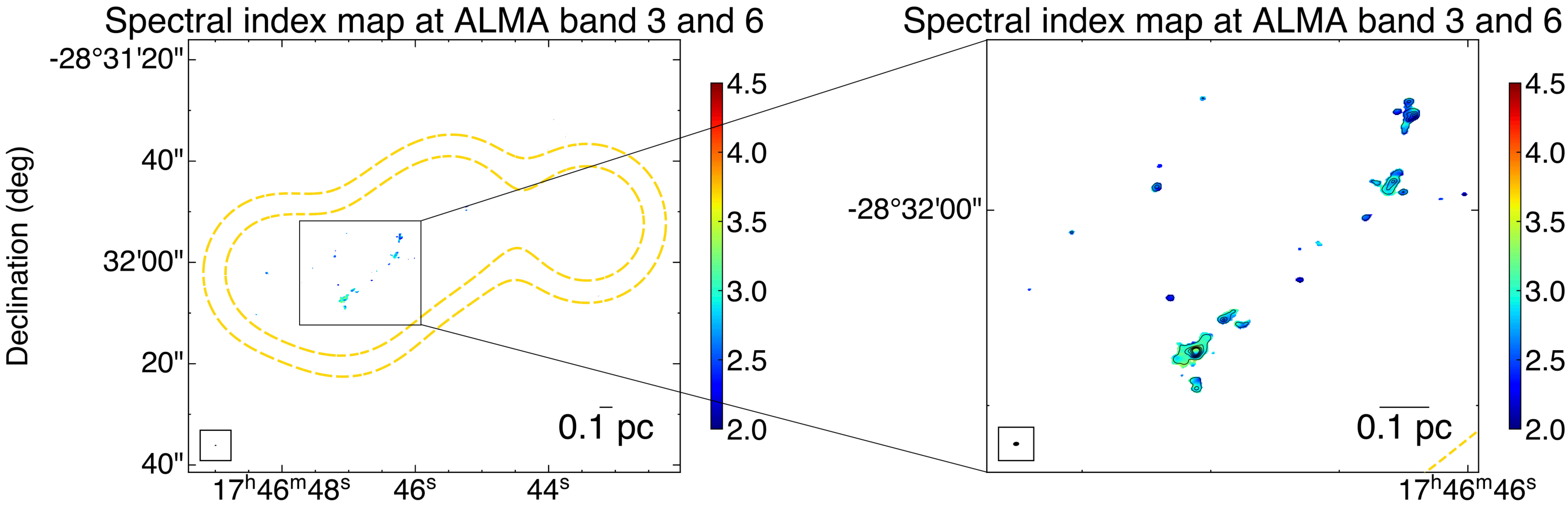
ALMA Bands	Central frequencies (GHz)	Initial beams ($B_{maj}\times B_{min}$, PA)	Minimum common beam ($B_{maj}\times B_{min}$, PA)	Sensitivity^a (μJy beam^{-1})	Mass sensitivity^b ($M_\odot$ beam^{-1})
Band 3	93.6	$0''.305\times0''.203$, -85.76°	$0''.306\times0''.206$, -84.64°	8.6	1.17
Band 6	226.0	$0''.251\times0''.172$, -55.88°	$0''.306\times0''.206$, -84.64°	40.0	0.30

a: The intensity sensitivity is represented by the image rms measured on the smoothed images.

b: The mass sensitivity is derived based on the intensity sensitivity assuming that it is purely contributed by optically thin thermal dust emission and with a dust temperature of 20 K.

2. Data Analysis and Results

Calculation of Spectral Index in each Pixel



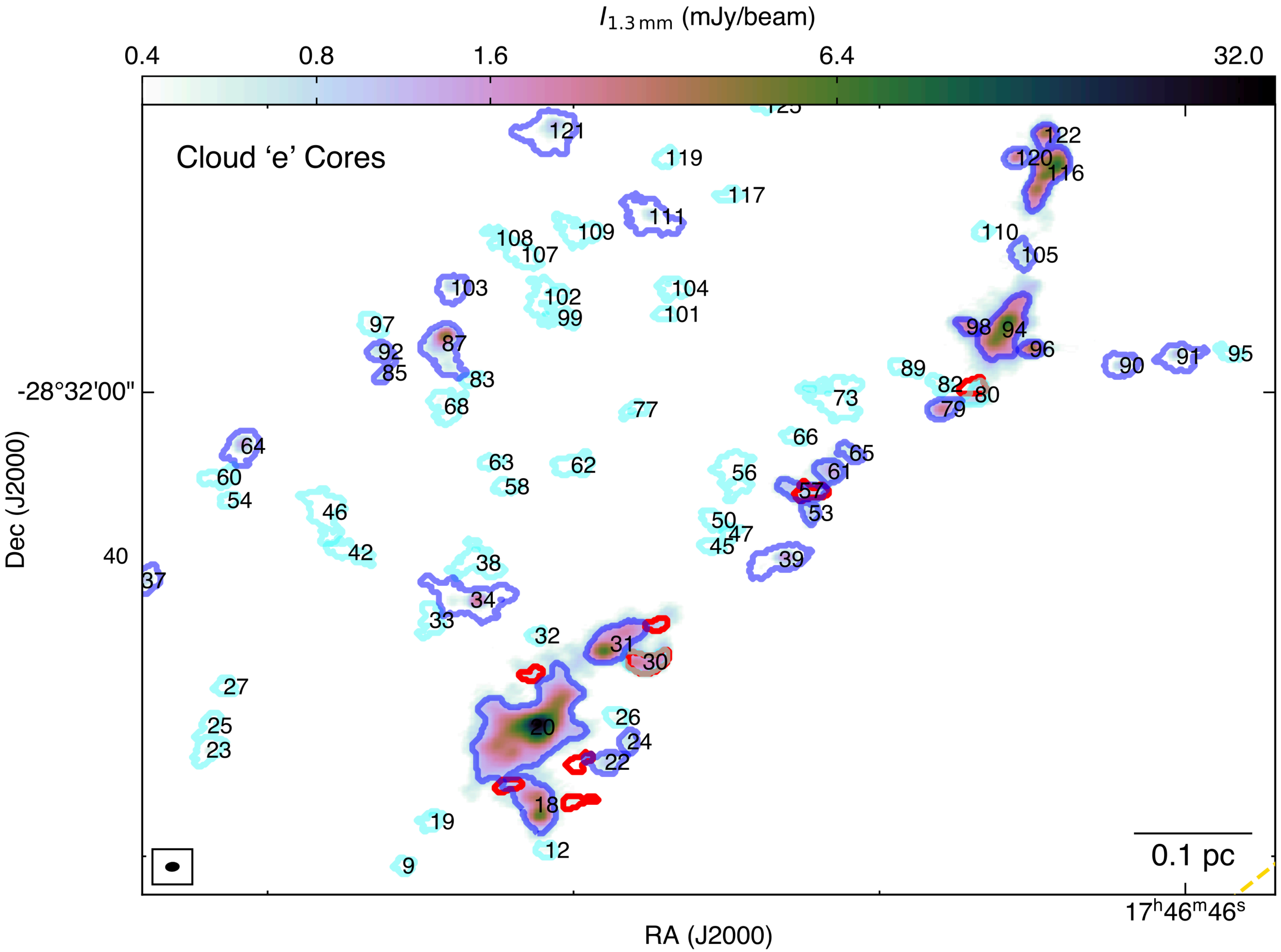
We retained only the pixels with high signal-to-noise ratios in both bands and performed spectral index calculations on these pixels.

$$S_\nu \propto \nu^\alpha$$

$$\alpha(\nu) = \frac{\partial \log S_\nu(\nu)}{\partial \log \nu}$$

Identification of Cloud Cores

We have smoothed the band 3 & 6 continuum images to a common resolution (0.3" * 0.2", ~2000 AU).



`Dendrogram`:

An algorithm for identifying dense cores in images.

Band 3 rms = 0.0097 mJy/beam

Band 6 rms = 0.045 mJy/beam

Dense cores identified with >5 rms criteria

75 cyan contours: cores identified in band6 only

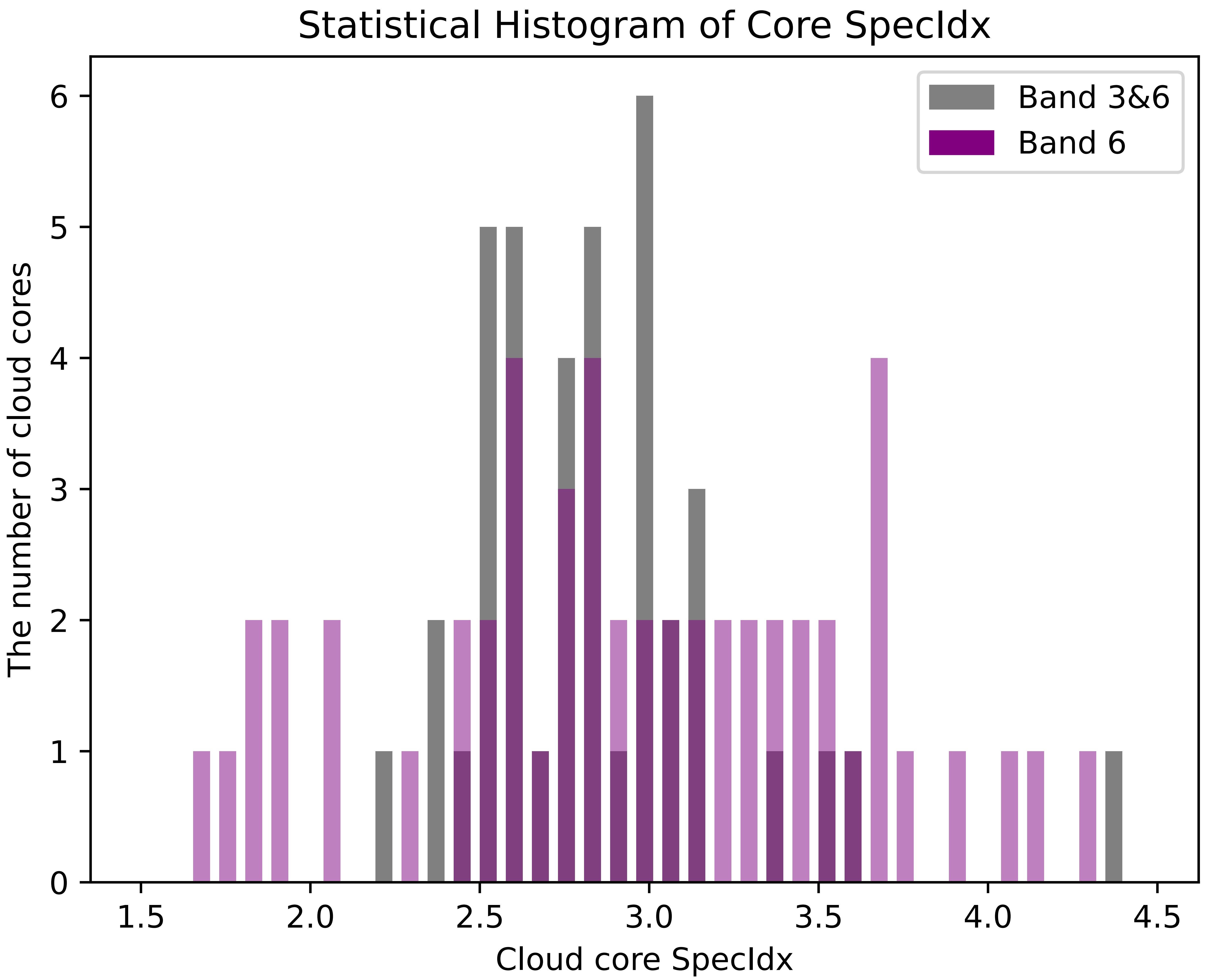
33 purple contours: cores identified in band 3&6

9 red contours: cores identified in band3 only

Calculation of Spectral Index

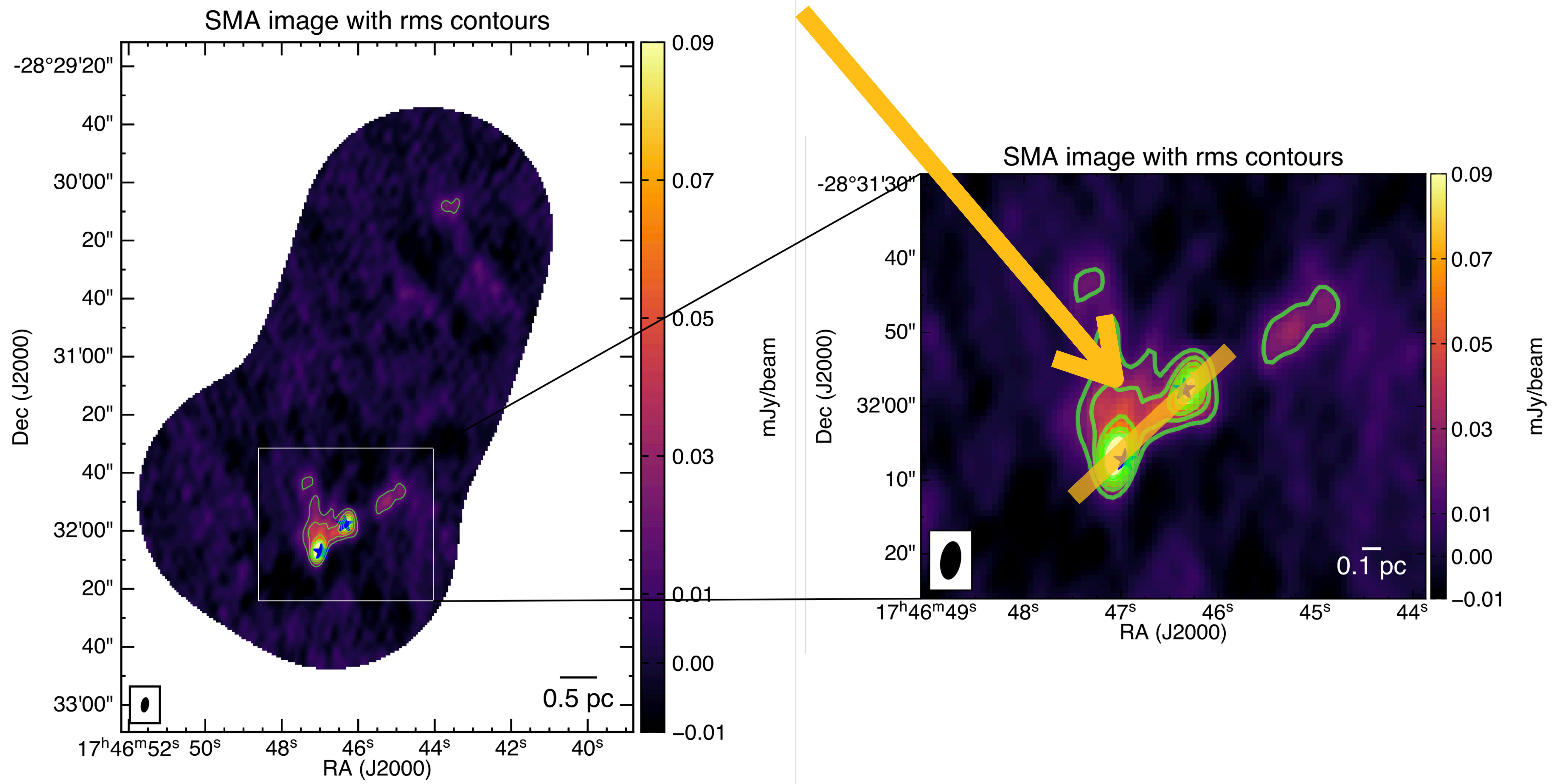
Spectral index in each core

All core identified by band6 have spectral indices greater than 2, indicating that these radio sources are generated by optically thin dust emission.



Fragmentation of Filaments

Isothermal cylindrical model



R.A.and Decl. (J2000)	Length of the filament (arcsec)	Mass of the Dense Core ($M_\odot$)	Gas Density (cm^{-3})	Spectral Line Width (km s^{-1})	$(M/l)_{crit}$ ($M_\odot pc^{-1}$)	$(M/l)_{obs}$ ($M_\odot pc^{-1}$)
17:46:49.81, -28:31:32.09	14.745"	329	$3 \times 10^6 - 3 \times 10^7$	1.34	834.954	939.526
17:46:49.08, -28:31:20.89	——	215	——	——	——	——

Derive the critical mass per unit length expected from the isothermal cylindrical collapse models

$$(M/l)_{\rm crit} = 2\sigma_v^2/G = 465\left(\frac{\sigma_v}{1\ {\rm km\ s^{-1}}}\right)^2 M_\odot\ {\rm pc}^{-1}$$

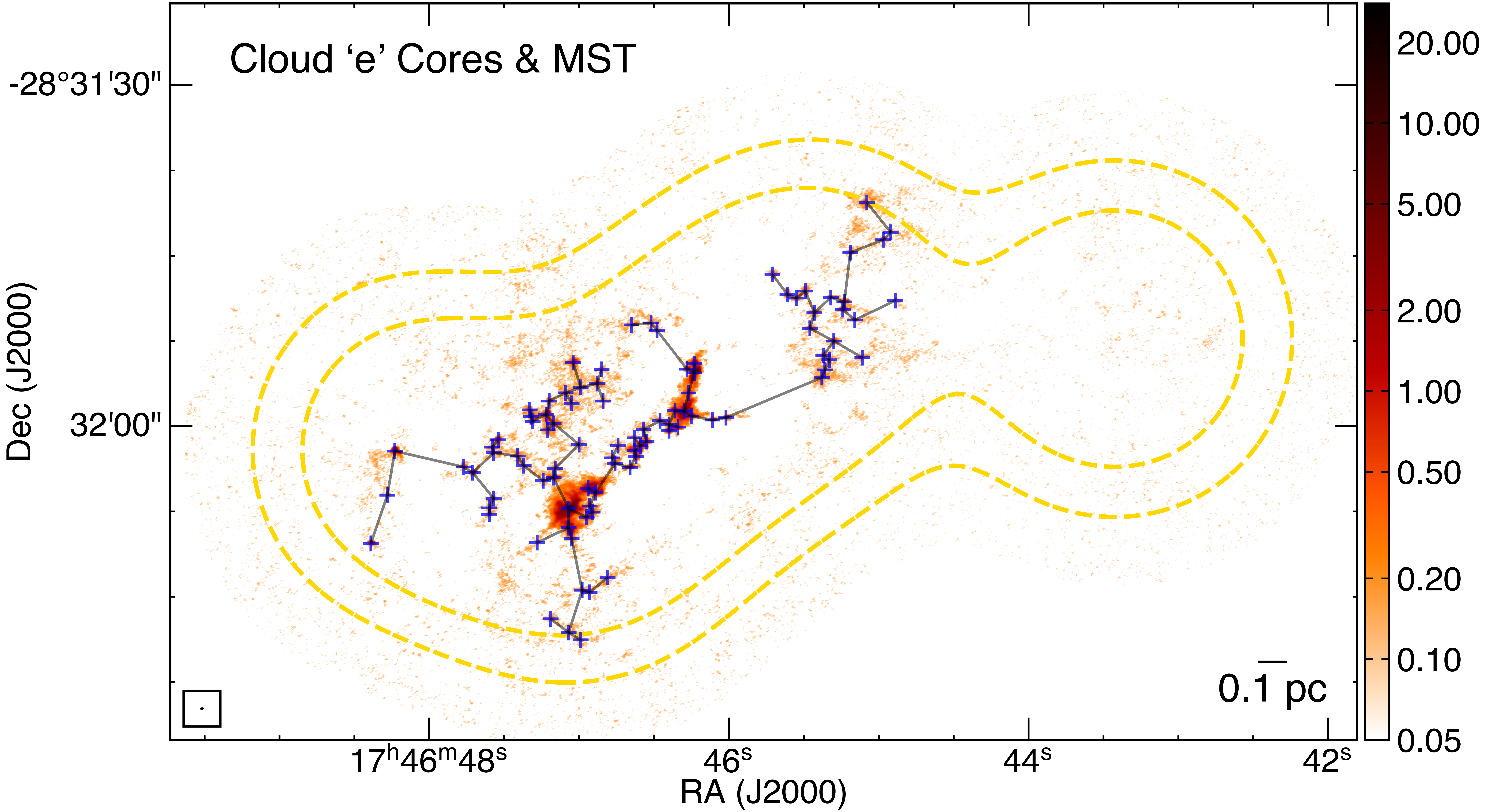
$$(M/l)_{crit} = 834.954 M_\odot pc^{-1}$$

$$(M/l)_{obs} = 939.526 M_\odot pc^{-1}$$

Critical value ~ observed value

- Consistent with the isothermal cylindrical model and filamentary fragmentation scenario

MST Algorithm



Spatial Core Distribution & Mass Segregation

$$\bar{m} = \sum_{i=1}^{N_c-1} \frac{L_i}{(N_c A)^{1/2}}, \qquad \bar{s} = \frac{L_{\rm av}}{R_{\rm cluster}}.$$

$$Q = \frac{\bar{m}}{\bar{s}},$$

$\bar{m}$	$\bar{s}$	Q
0.37	0.62	0.60

$Q > 0.8$, Q is correlated with centrally condensed spatial distributions with radial density profiles of the form.

$Q \simeq 0.8$, it implies uniform density and no

$Q < 0.8$, Q is associated with the fractal dimension.

To quantify mass segregation, we use the mass segregation ratio (MSR), $\Lambda_{\rm MSR}$, as defined by Allison et al. (2009) and $\Gamma_{\rm MSR}$ as defined by Olczak et al. (2011), both based on the MST method.

$$\Lambda_{\rm MSR}(N_{\rm MST}) = \frac{\langle l_{\rm random} \rangle}{l_{\rm massive}} \pm \frac{\sigma_{\rm random}}{l_{\rm massive}}$$

$$\Gamma_{MSR}(N_{\rm MST}) = \frac{\gamma_{\rm random}}{\gamma_{\rm massive}} (d\gamma_{\rm random})^{\pm 1}$$

In fact, the $\Lambda_{\rm MSR}$ method can provide more accurate calculations, so we will primarily utilize the $\Lambda_{\rm MSR}$ method for analysis.

3. Summary

1. Why we observed the Central Molecular Zone and cloud 'e' with ALMA bands 3&6 — a unique environment with low star formation efficiency.
2. Data analyses & results: smoothing continuum images of bands 3 & 6 , core identification using `dendrogram`, calculation of spectral indices, fragmentation of filaments, spatial core distribution, and mass segregation.
3. These results suggest that the massive star cluster currently forming in cloud e undergoes similar processes as protoclusters in the Galactic disk, through turbulence-mediated filamentary fragmentation, hierarchical clustering, and primordial mass segregation.

Thanks !

Appendix

The full table of dense cores and the figure of spectral index are put in this link:

https://foisliu.github.io/resume/appendix.pdf