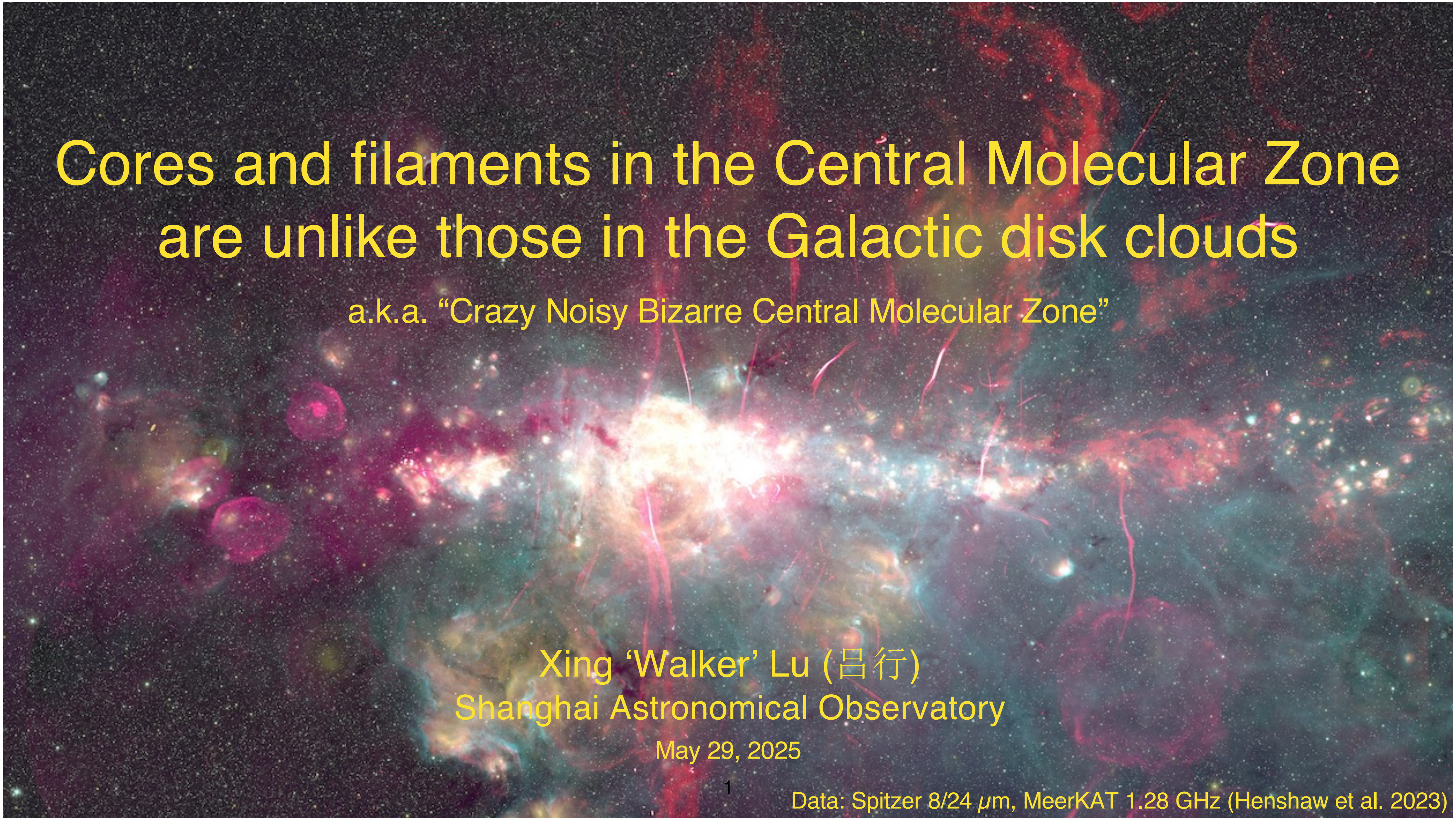


Cores and filaments in the Central Molecular Zone are unlike those in the Galactic disk clouds

a.k.a. “Crazy Noisy Bizarre Central Molecular Zone”

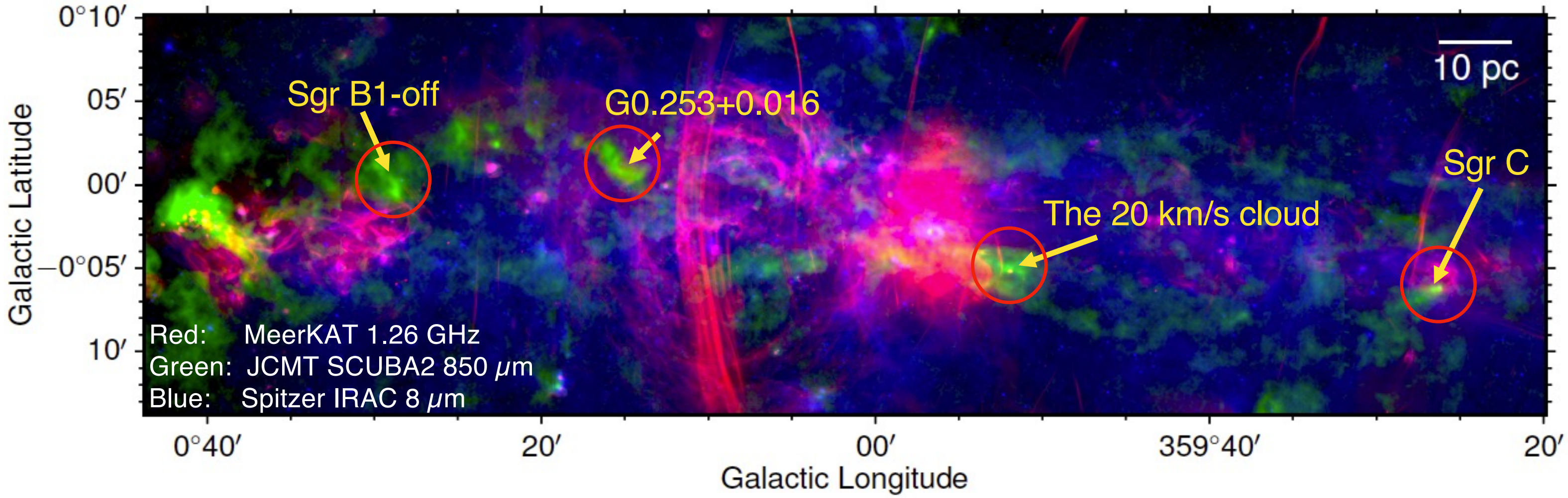
Xing ‘Walker’ Lu (吕行)
Shanghai Astronomical Observatory

May 29, 2025

Data: Spitzer 8/24 μm, MeerKAT 1.28 GHz (Henshaw et al. 2023)

What do we do in the era of ACES/JACKS/FIREPLACE...?

- The ongoing large programs at ALMA, JVLA, SOFIA, JCMT, etc. provide unparalleled spatial coverages/sample sizes.
- We focus on **a smaller sample**, and **go deeper and finer**, to study:
  - gas excitation conditions constrained by multi-frequency observations
  - magnetic fields using the full-polarization mode
  - accretion disks (<1000 AU) by longbaseline observations
  - other serendipitous discoveries…



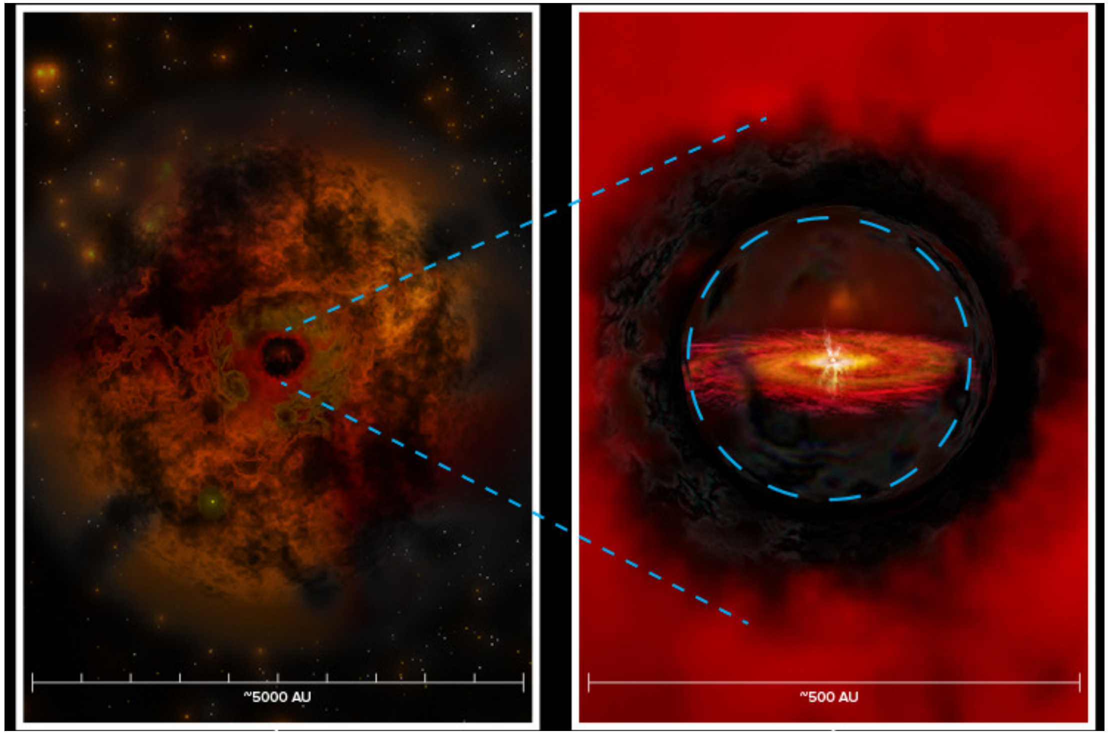
Coordinated Observations of Nebulae in the CMZ Exploring gas Recycling and Transformation

CONCERT: a multi-wavelength, multi-scale, multi-mode campaign to explore filaments, magnetic fields, disks, etc. in the CMZ

ALMA Cycles	Band/Resolution	Data Features	(Expected) Results	Status
Cycle 4	1.3 mm/0.2 arcsec	mosaics	Fragmentation, outflows, slim filaments	Lu et al. 2020, 2021 Z. Zhang et al. 2025 K. Yang et al. 2025
Cycle 6	1.3 mm/0.04 arcsec	longbaseline (300 AU resolution)	Disks, clusters of envelopes/disks	Lu et al. 2022 S. Zhang et al. 2025
Cycle 6	3 mm/0.2 arcsec	mosaics	Cores, bubbles, filaments, SiO v=1 masers	F. Xu et al. 2025.
Cycle 8	0.87 mm/0.2 arcsec	polarization	Magnetic fields in cores	Y. Liu et al. in prep. Lu et al. in prep.
Cycle 8/9/10/11	0.65, 1.1, 1.7, 3 mm/0.5 arcsec	multiple band 12m+7m+TP mosaics	Detailed excitation conditions (densities, temperatures)	data delivered
Cycle 9	0.87 mm/0.01 arcsec	longbaseline (resolution~100 AU)	Cavity, spirals, streamers in the Sgr C disk	data delivered
Cycle 10/11	0.87 mm/0.2 arcsec	polarization	Magnetic fields in all massive cores in the CMZ	partially observed
Cycle 11	7mm/0.2 arcsec	matching resolution w/ Bands 3 & 6	Excitation conditions in filaments and outflows	partially observed
Cycle 11	0.87 mm/0.03 arcsec	polarization + longbaseline (300 AU resolution)	Polarization in the Sgr C disk	approved

What is a ‘dense core’?

A 10^3 AU envelope plus A 10^2 AU disk



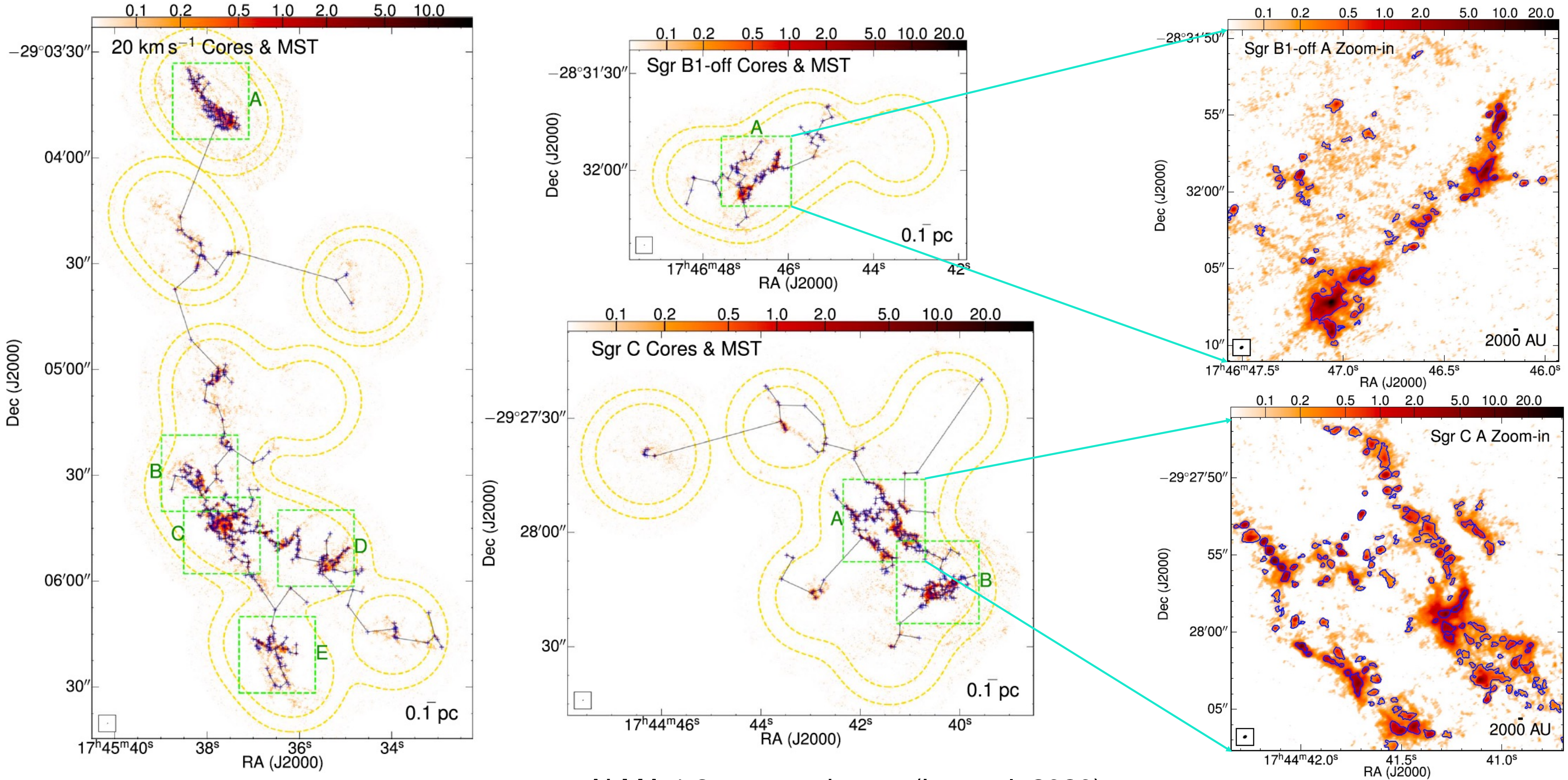
Credit: ALMA (ESO/NAOJ/NRAO), N. Karnath; NRAO/AUI/NSF, B. Saxton and S. Dagnello

A dense core refers to a compact region of cold, dense gas and dust within a molecular cloud. These structures are the sites where star formation begins, as their high density and low temperature allow the gas to collapse under the influence of gravity, leading to the formation of protostars.

---GPT-4o

Cores in the CMZ are pressure-bound

About 800 cores of ~0.01 pc sizes identified in three clouds



ALMA 1.3 mm continuum (Lu et al. 2020)

Cores in the CMZ are pressure-bound

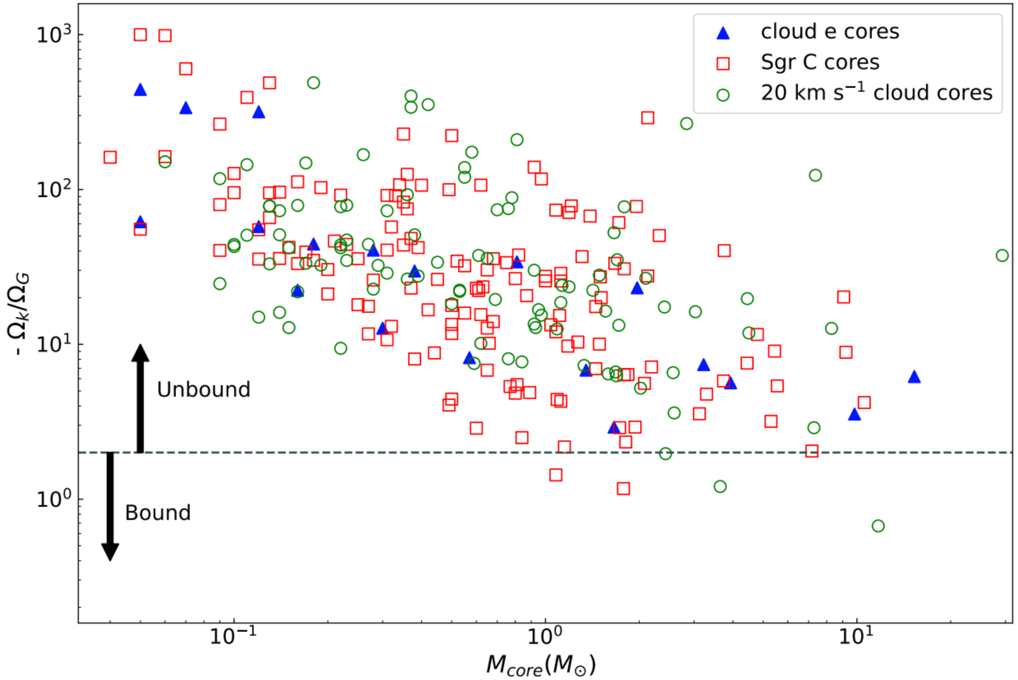
- We fit H_2CO and/or CH_3CN lines in the cores to derive their velocity dispersions.
- The cores would be unbound when only self-gravity and non-thermal motions are considered.

Zhenying Zhang
(grad student @ Yunnan U.)

$$\Omega_k = \frac{3}{2} M_{\rm core} \sigma_{\rm tot}^2$$

$$\Omega_G = -\frac{3}{5} a \frac{G M_{\rm core}^2}{R}$$

$$\alpha_{\rm vir} = -\Omega_k / \Omega_G$$



Z. Zhang et al. 2025 (arXiv:2412.01593)

Cores in the CMZ are pressure-bound

- We fit H_2CO and/or CH_3CN lines in the cores to derive their velocity dispersions.
- The cores would be unbound when only self-gravity and non-thermal motions are considered.
- Once external pressure is considered, most of the cores become bound.

$$\Omega_k = \frac{3}{2} M_{\rm core} \sigma_{\rm tot}^2$$

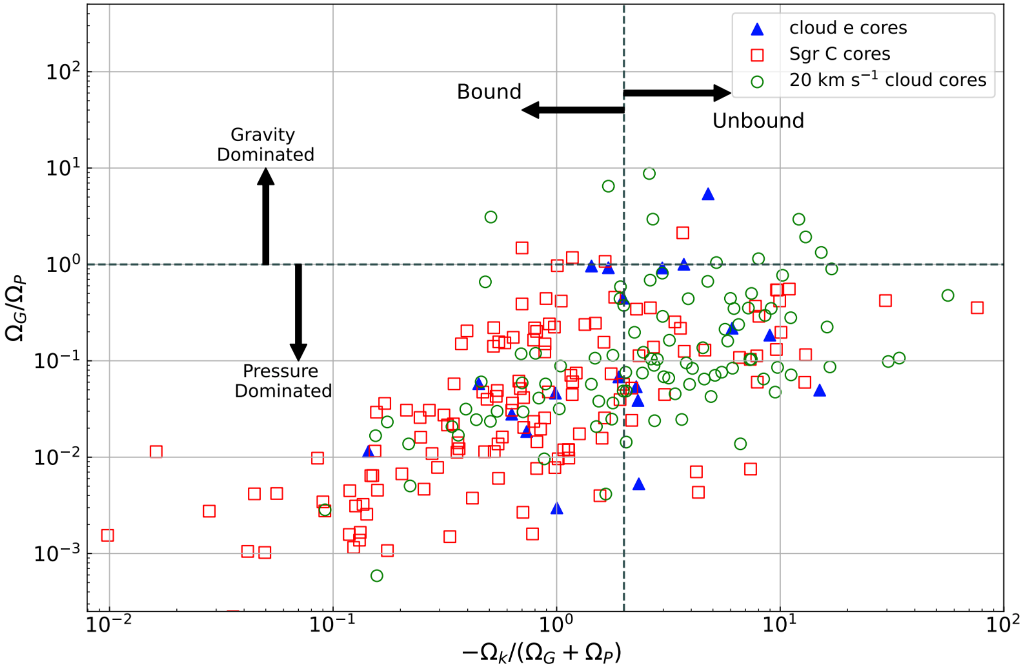
$$\Omega_G = -\frac{3}{5} a \frac{G M_{\rm core}^2}{R}$$

$$\Omega_P = -4\pi P_{\rm out} R^3$$

$$P_{\rm out} = \rho_{\rm out} \sigma_{\rm tot,out}^2$$

$$\alpha_{\rm vir,p} = -\frac{\Omega_k}{\Omega_G + \Omega_P}$$

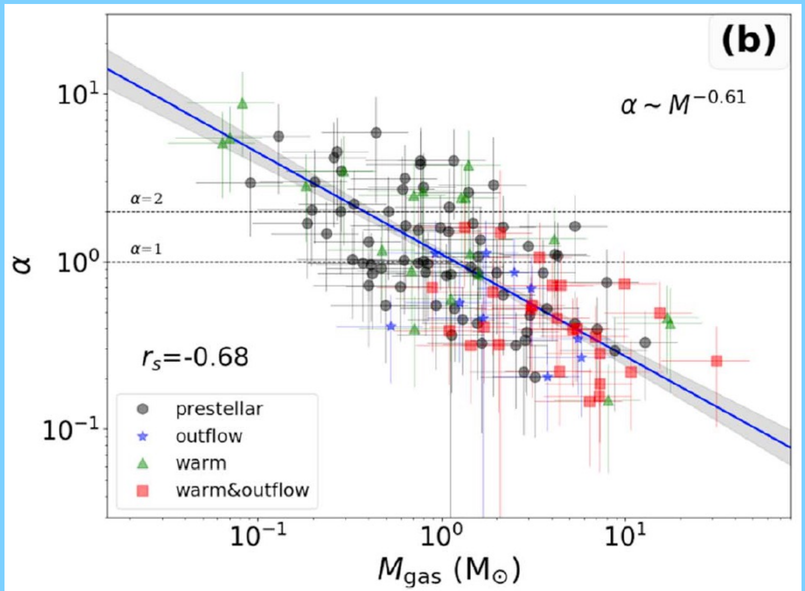
Z. Zhang et al. 2025 (arXiv:2412.01593)



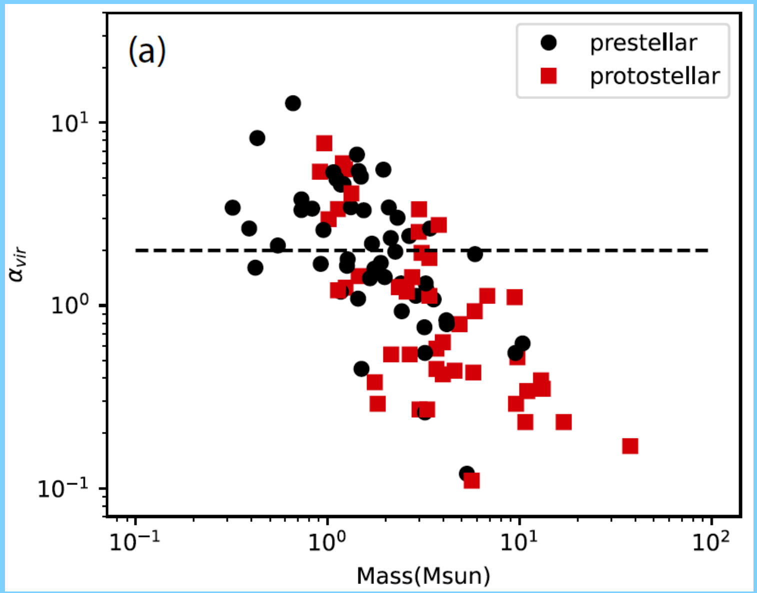
Cores in the CMZ are pressure-bound

External pressure is often insignificant for gas dynamics of dense cores in the Galactic disk…

Dense cores in Galactic disk surveys:



Li et al. 2023



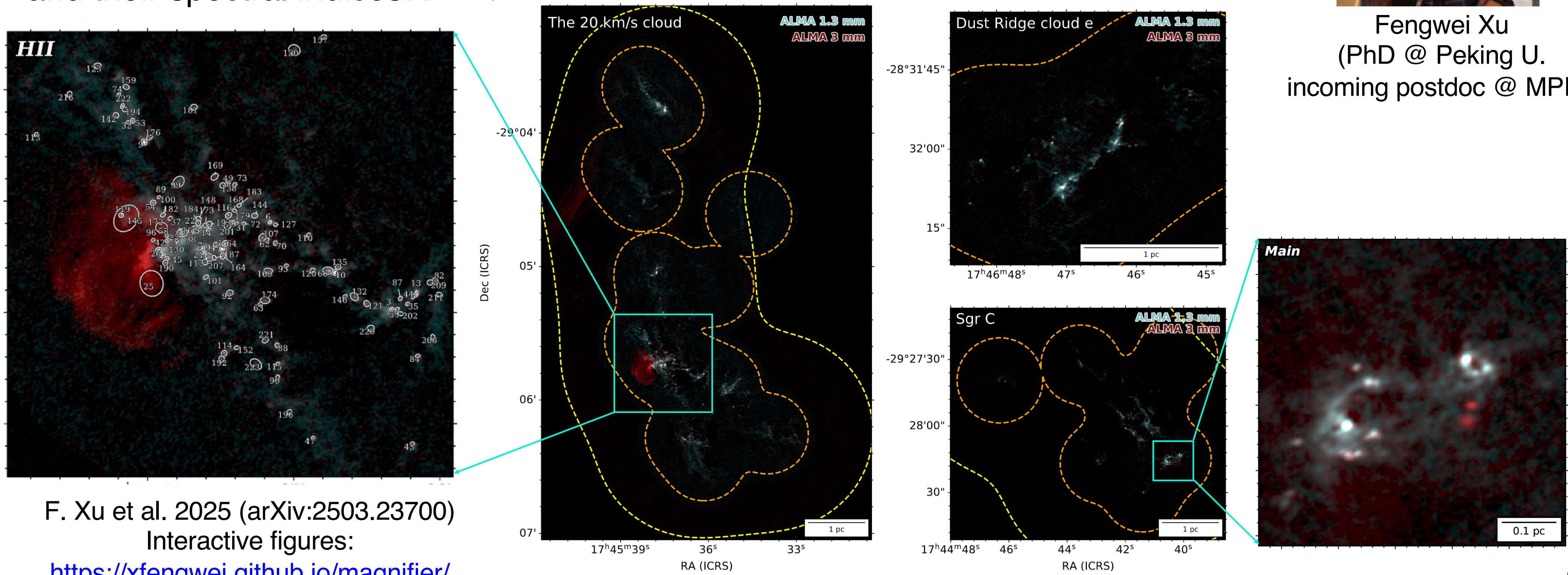
Cheng et al. 2024

-> ‘Dense cores’ in the CMZ may be not the conventionally defined self-gravitating objects

Cores in the CMZ are redder

DUET: A dual-band mapping of three clouds in the CMZ with ALMA Band 3 (3 mm) and Band 6 (1.3 mm) at 2000-AU resolution:
~450 marginally resolved cores identified simultaneously in the two bands and their spectral indices: $I \propto \nu^{\alpha}$

Fengwei Xu
(PhD @ Peking U.
incoming postdoc @ MPIA)



F. Xu et al. 2025 (arXiv:2503.23700)
Interactive figures:
https://xfengwei.github.io/magnifier/

Cores in the CMZ are redder

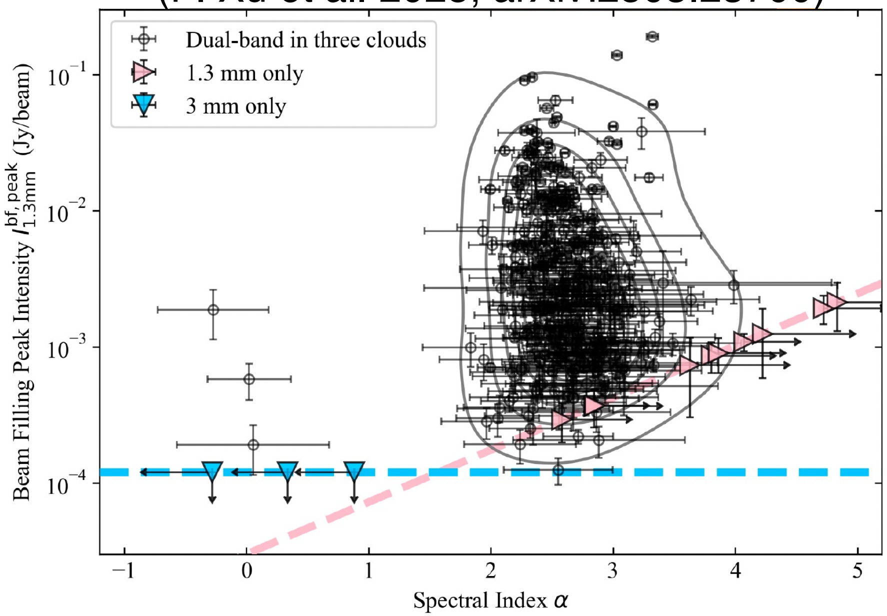
In the Rayleigh-Jeans limit, for optically thin dust emission:

$$I \propto \nu^{\alpha} = \nu^{2}\kappa, \text{ where } \kappa \text{ is the dust opacity.}$$

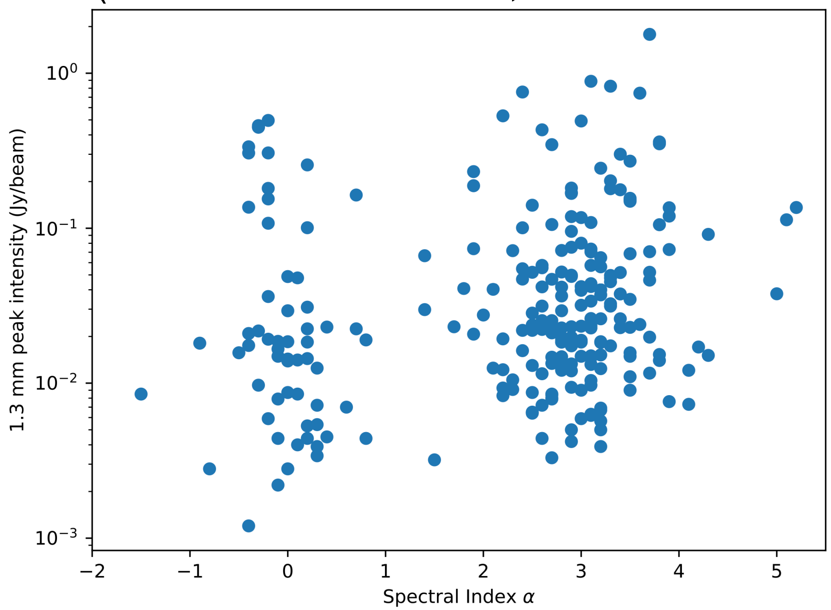
κ can be fit with a power law $\kappa \propto \nu^{\beta}$, where β is usually 1.5-1.7 for the ISM.

This means $\alpha = 3.5 - 3.7$!

DUET CMZ sample 'color-magnitude diagram'
(F. Xu et al. 2025, arXiv:2503.23700)



Galactic disk sample
(taken from ALMA-IMF; Louvet et al. 2024)

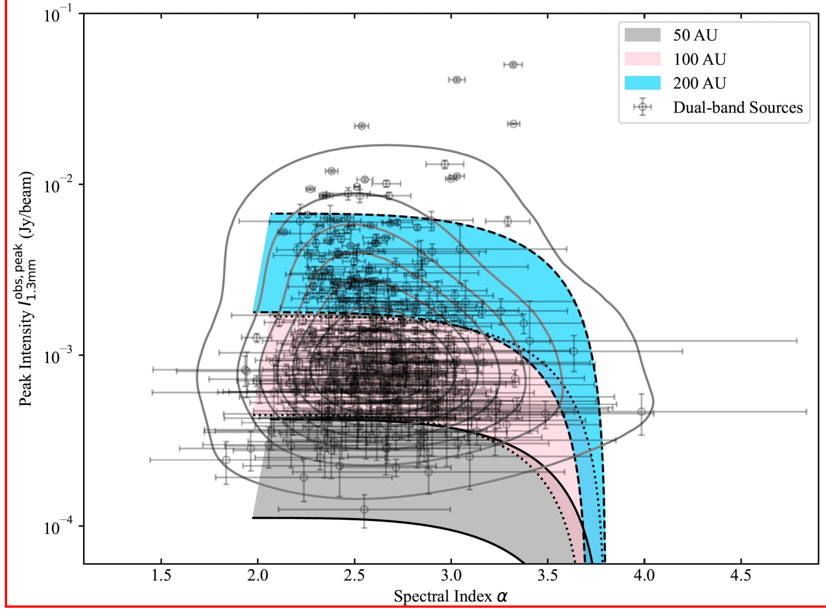


Cores in the CMZ are redder

Tsukamoto et al. 2021
Sabatini et al. 2025

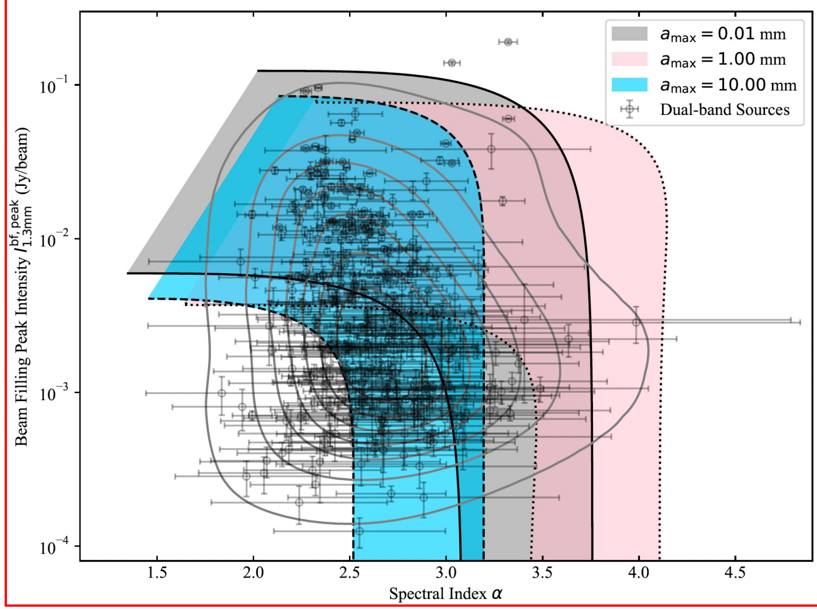
Possibility 1: the 1.3-mm emission of the 'cores' is dominated by beam-diluted, optically thick substructures (e.g., 100-AU YSOs).

- This would lead to significant underestimate of the mass.



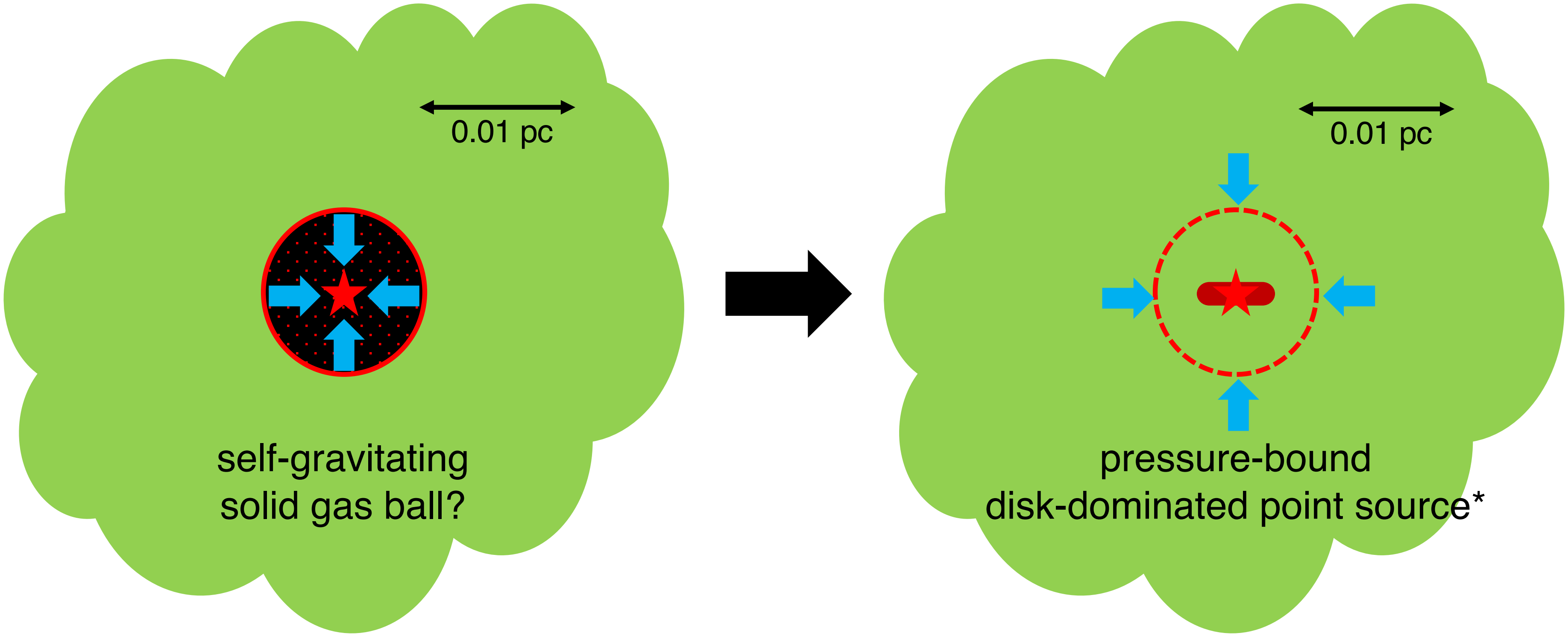
Possibility 2: large dust grains exist in the cores, resulting in low β values.

- Do the large dust grains form in-situ? Unlikely.
- Are they transported outwards from protoplanetary disks by outflows?



F. Xu et al. 2025 (arXiv:2503.23700)

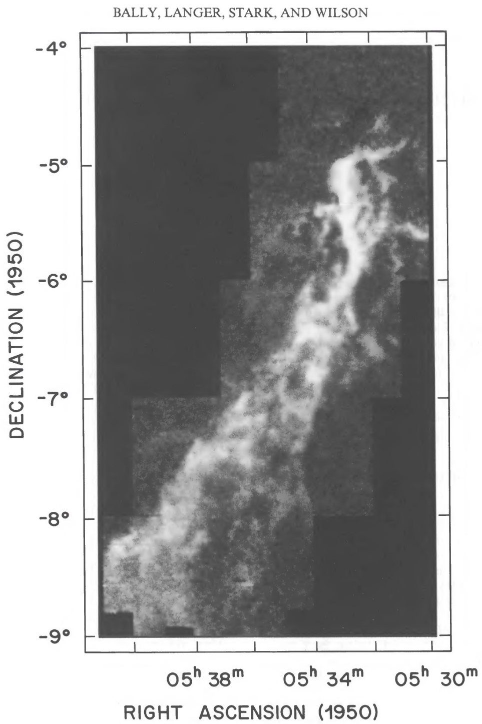
Wrap-up: cores in the CMZ are pressure-bound and redder



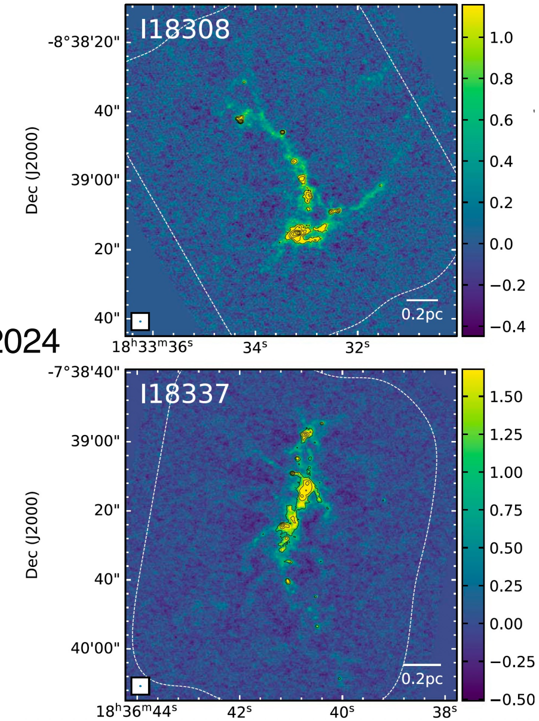
* In ~0.01-pc resolution
ALMA 12-m array observations

What is a ‘filament’?

Bally et al. 1987



Cheng et al. 2024



Hacar et al. 2023
PPVII review chapter

Family$^{(\#)}$	Targets	M ($M_\odot$)	L (pc)	FWHM (pc)	N_0 (10^{21} cm^{-2})	T (K)	$\sigma_{\rm tot}$ (km s^{-1})	$\sigma_{\rm NT}$ (km s^{-1})	m ($M_\odot$ pc^{-1})	f ($= m/m_{\rm crit}$)	$\nabla v_{\rm LSR,\parallel}$ (km s^{-1} pc^{-1})	B_0 (μG)
Nearby Filaments	707	2.1 – 13.4	0.4 – 1.0	0.07 – 0.16	3.2 – 9.0	13 – 16	0.28 – 1.32	0.21 – 1.30	4.4 – 18.6	0.2 – 0.7	1.02 – 1.60	70 – 70
Galactic Plane Surveys	18854	98 – 2.3×10^3	3.6 – 14	0.3 – 1.3(?)	5.9 – 14.4	15 – 19	1.02 – 1.55	1.00 – 1.54	23 – 191	0.8 – 6	0.22 – 0.55	?
IRDCs	115	46 – 239	1.2 – 2.8	$\sim$ 0.3(?)	13 – 40	16 – 25	0.40 – 0.62	0.35 – 0.62	31 – 115	0.9 – 2.5	0.20 – 0.90	45 – 500
Giant Filaments	153	7.8×10^3–1.5×10^5	32 – 83	$\sim$ 1(?)	6.0 – 8.4	15 – 19	1.1 – 3.57	2.43 – 3.93	250 – 2513	15 – 35	0.04 – 0.08	?
Dense fibers	127	1.5 – 15.0	0.2 – 0.5	0.03 – 0.10	12 – 69	10 – 22	0.26 – 0.36	0.15 – 0.24	9.3 – 33.5	0.3 – 1.4	0.35 – 3.23	40 – 1000$^{(2)}$
Striations	2$^{(*)}$	2.5 – 5.6	1.0	0.2 – 0.4(?)	0.5 – 1.0	15 –20$^{(2)}$	0.71 – 0.90	?	2.5 – 5.6	0.1 – 0.2	?	26 – 30
HI filaments	2823	0.1 – 0.5	1.4 – 3.6	?	$<$ 1(?)	100$^{(3)}$	0.88(?)	0.65(?)	0.05 – 0.15	?	?	5$^{(3)}$

Filaments in the CMZ are transient

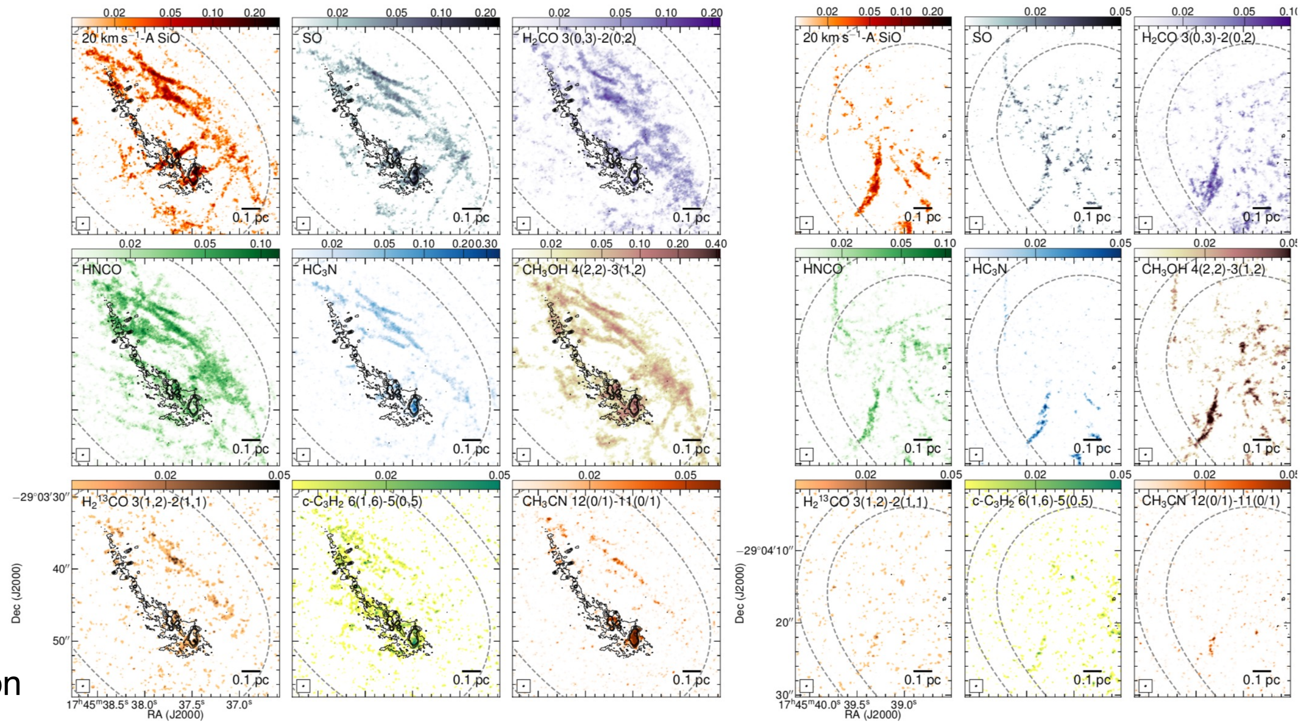
Kai Yang (postdoc @ Shanghai Jiaotong U.)

'Slim filaments' (length~pc, width~0.01 pc) seen in Band 6 (1.3 mm) lines at 0.2” resolution (K. Yang et al. 2025, arXiv:2502.03913)

- No detectable continuum emission
- Line emission in SiO/SO/CH_3OH/CH_3CN/…, with abundances similar to those in protostellar outflows
- Consistent Vlsr along major axes
- Unlikely to be in radial equilibrium

$$\boxed{\begin{array}{l} P_{\rm turb} = \rho\,\sigma_{\rm v}^2 \\ P_{\rm gravity} \propto {\rm G}\,\rho^2 L^2/\pi \end{array}} \qquad \boxed{\begin{array}{c} P_{\rm turb} \sim 10^9\ {\rm K\,cm^{-3}} \\ P_{\rm gravity} \sim 10^7\ {\rm K\,cm^{-3}} \end{array}}$$

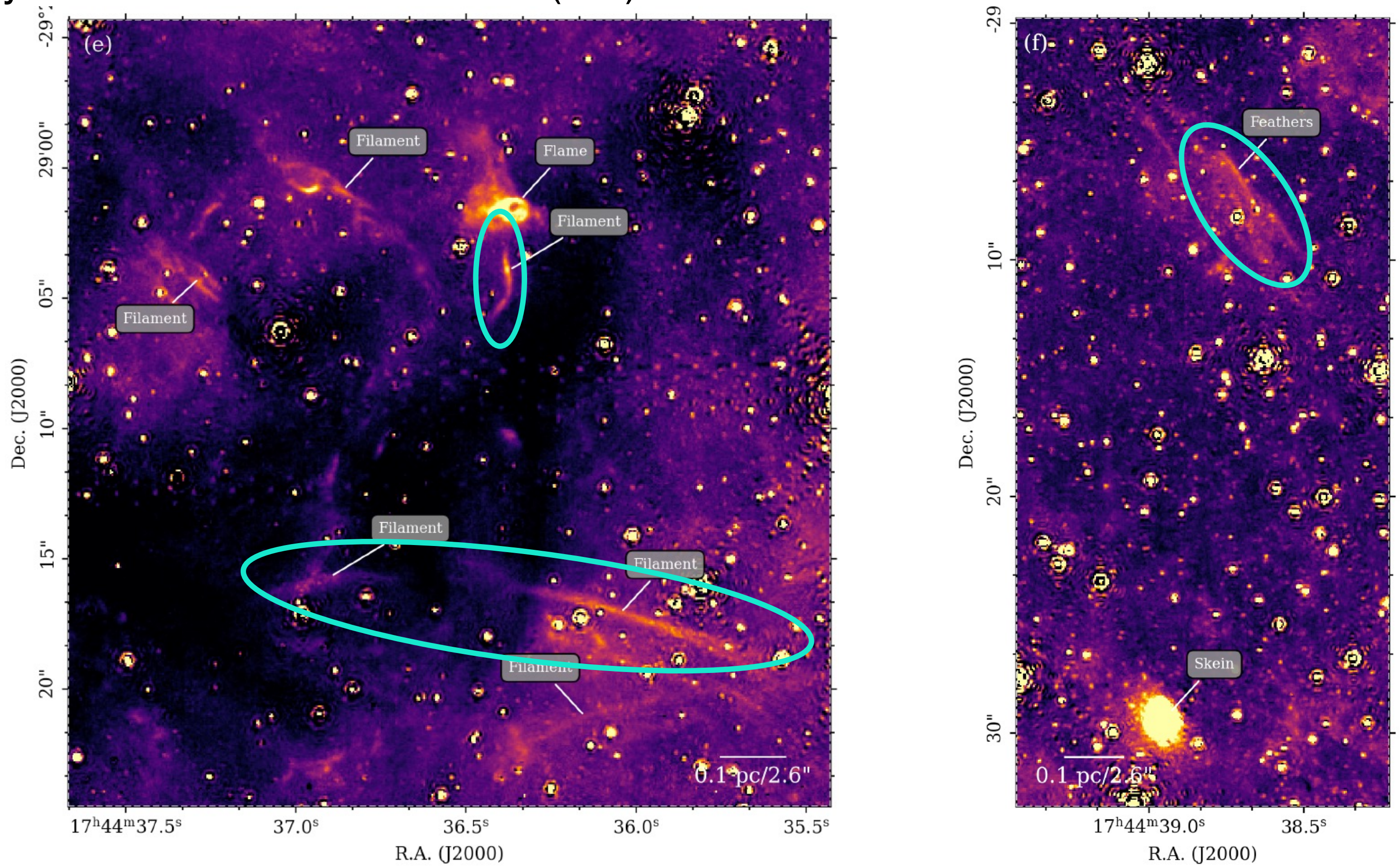
$$\boxed{P_{\rm turb} \gg P_{\rm gravity}(+P_{\rm thermal} + P_{\rm mag} + P_{\rm external})}$$



Contours: 1.3 mm continuum
Images: Integrated line emission

Filaments in the CMZ are transient

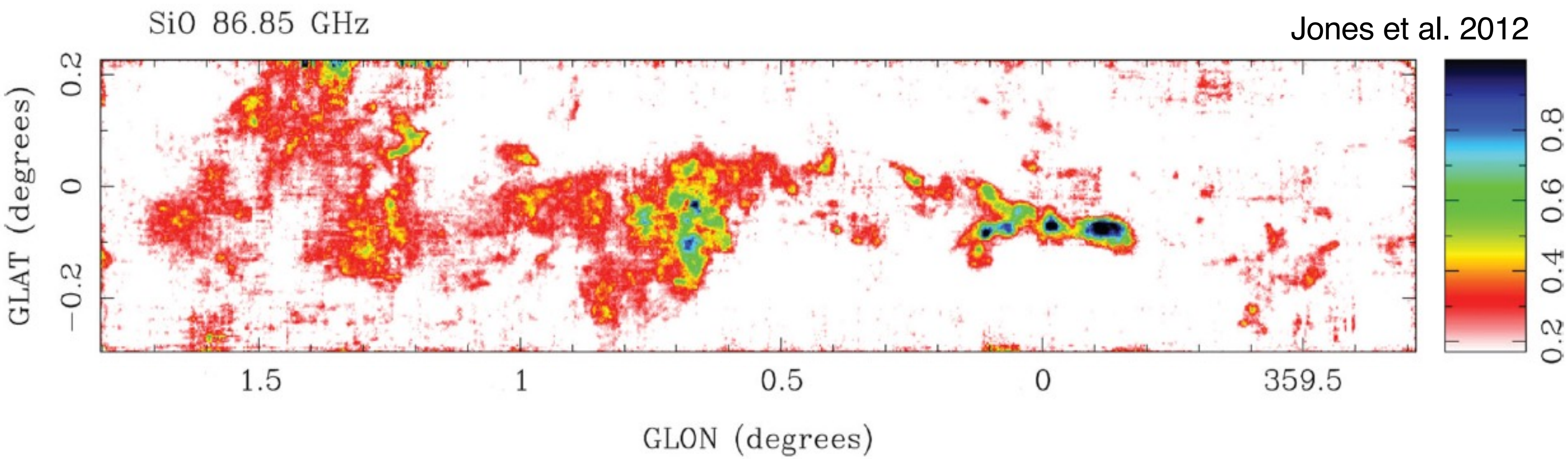
Also seen in JWST NIRCam image of Sgr C, F470N filter / H_2 (S. Crowe et al. 2024)
But they are not seen in ACES SiO (2-1) emission



Filaments in the CMZ are transient

Implication I: could be the key to decoding the widespread shock tracers (SiO etc.) and complex organic molecules in the CMZ

Jones et al. 2012



Dissipation timescale (filament width / σ_v) ~10^4 yrs vs. SiO depletion timescale in the ISM ~10^4 yrs

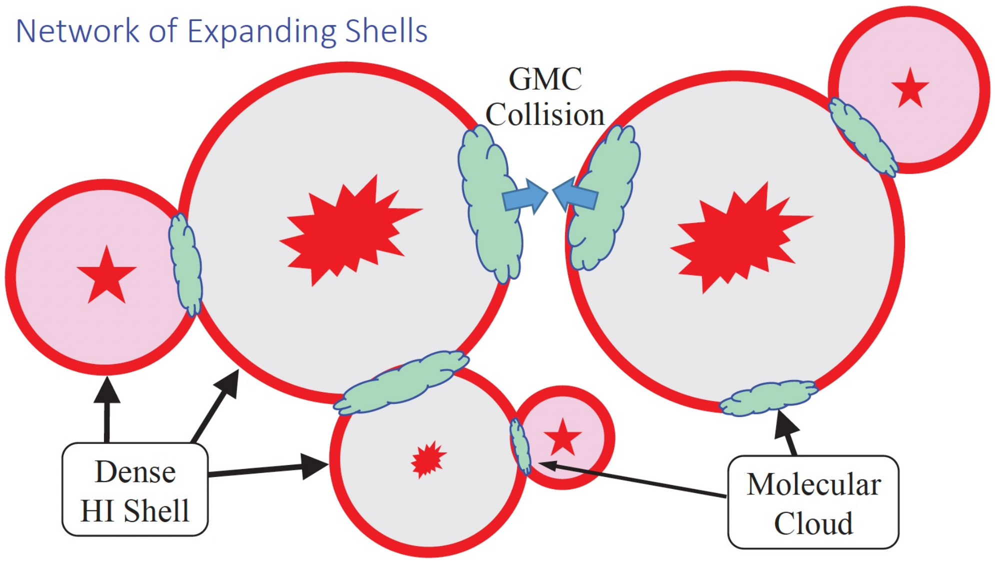
SiO replenish rate of each filament ~10^{-8} $M_\odot$/yr vs. SiO depletion rate in the CMZ ~10^{-4} $M_\odot$/yr

Dissipation of ~10^4 slim filaments could replenish the widespread SiO (& COMs) in the CMZ?

Filaments in the CMZ are transient

Implication II:

- Could be tracing pc-scale shocks?
- Origin of the pc-scale shocks: shear/collision between clouds, or remnants of SNR/HII?
- Frequent dynamic interactions could explain the low SFE (Li & Zhang 2020) and top-heavy IMF (Fukui et al. 2021).



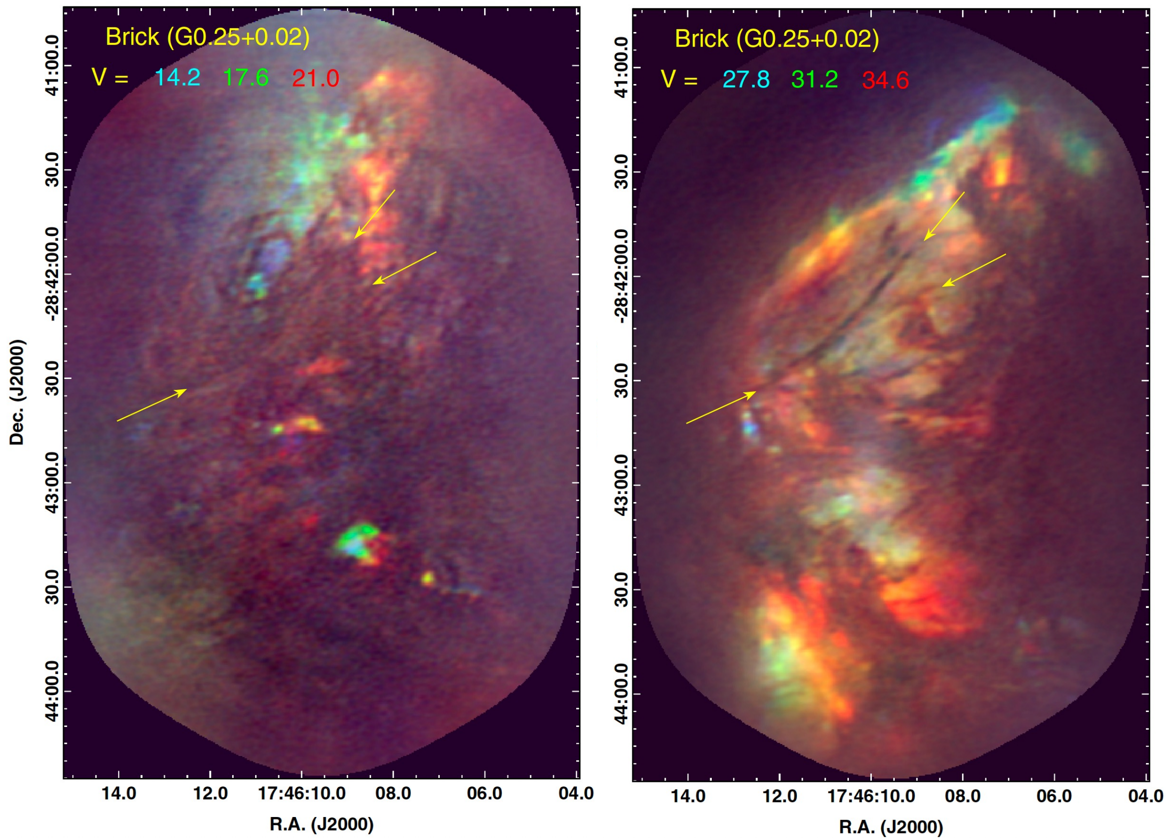
Inutsuka 2021

Filaments in the CMZ are absorbing

Absorption filaments discovered in HCO^+/HCN (1-0) in G0.253+0.016 cloud:

"The BLAs … may trace HCO+ molecules gyrating about highly ordered magnetic fields located in front of G0.253+0.016 or edge-on sheets formed behind supersonic shocks propagating orthogonal to our line of sight in the foreground."

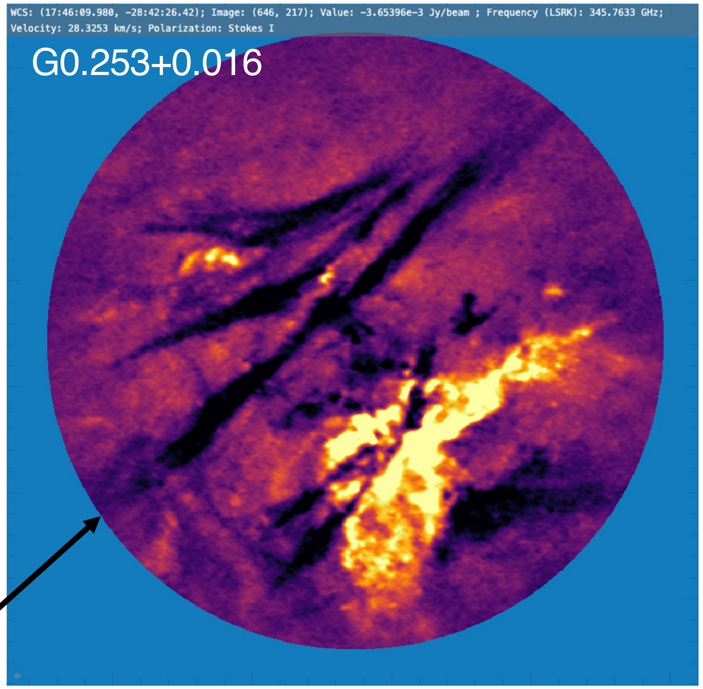
-- John Bally et al. 2014



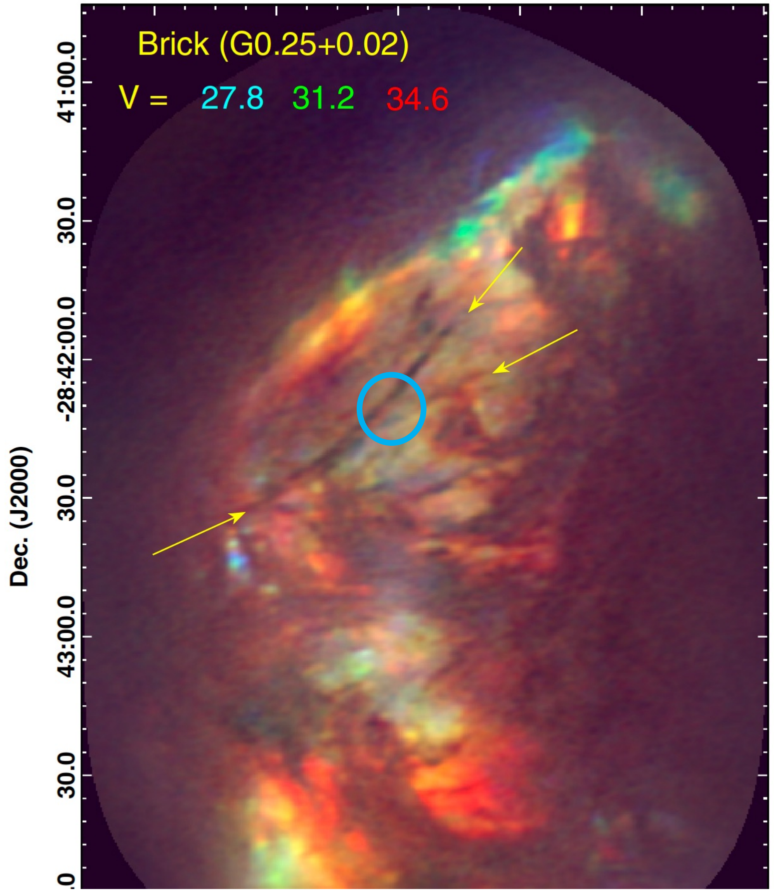
Bally et al. 2014

Filaments in the CMZ are absorbing

~10 years later… new absorption filaments clearly seen in CO (3-2) in several clouds

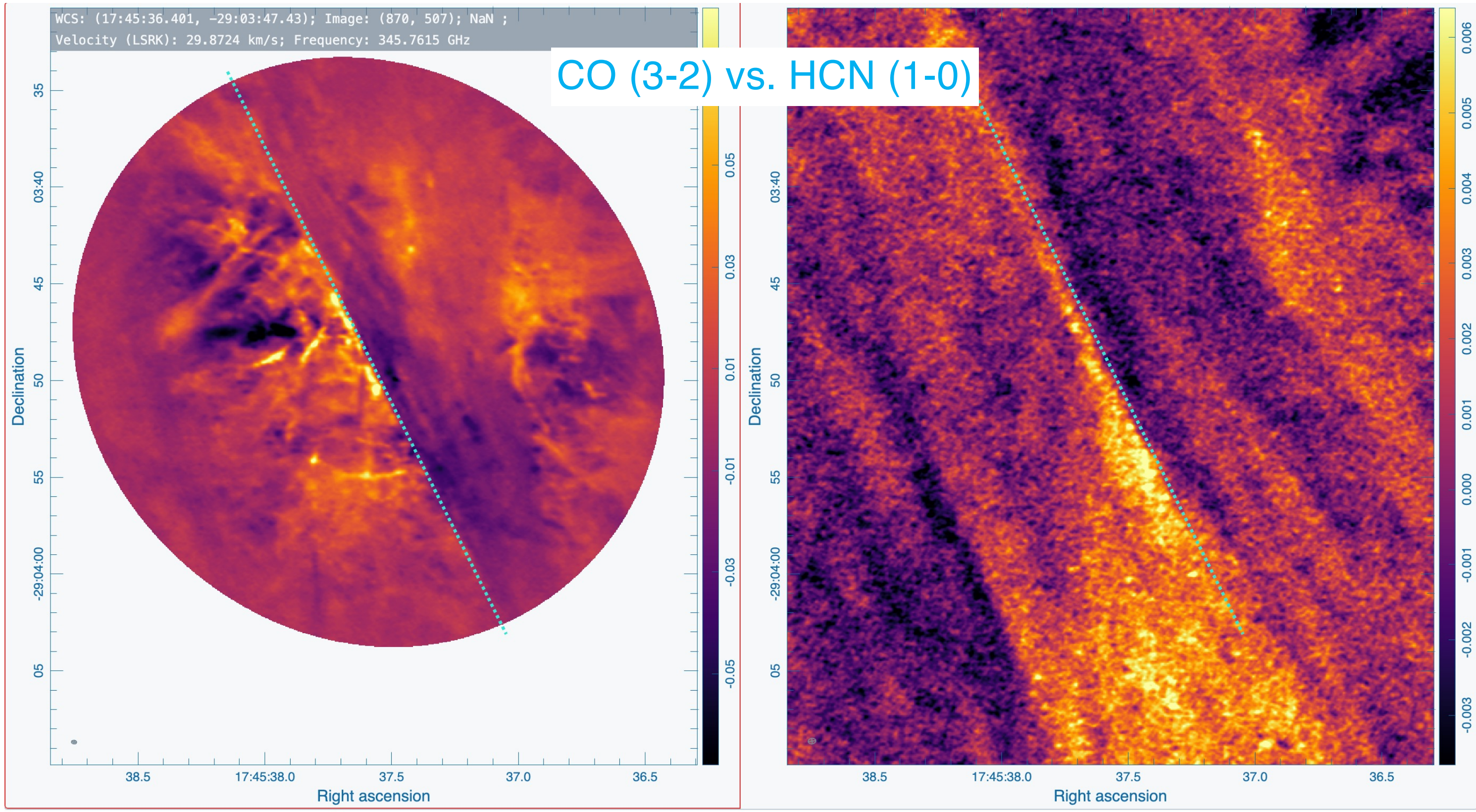


Morphologically consistent with the HCO^+ (1-0) absorption filaments in the same region from Bally et al. (2014)



Filaments in the CMZ are absorbing

Absorption filaments also seen in SiO (2-1), HCN (1-0), $H^{13}CN$ (1-0), etc.:
ubiquitous in the CMZ?

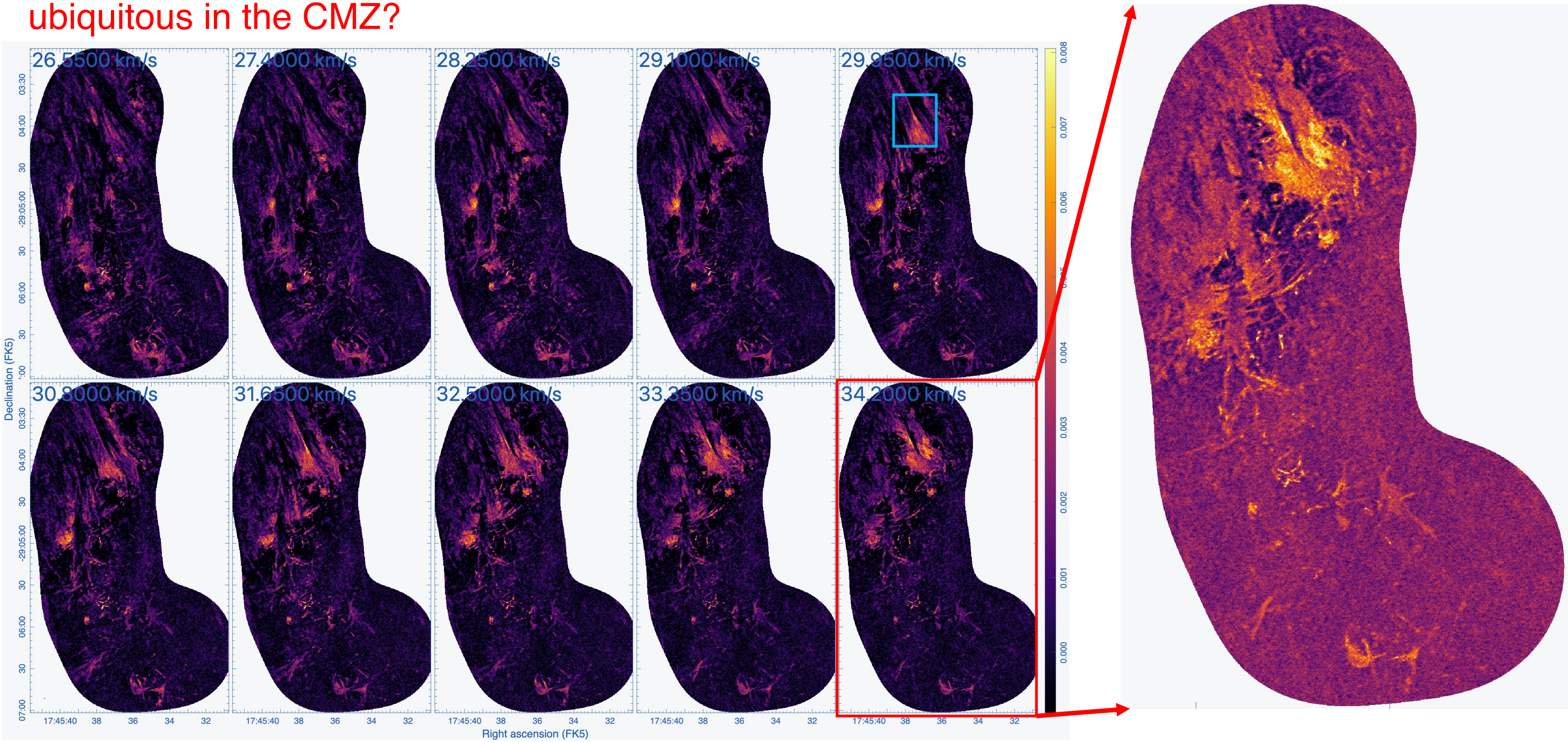


One channel towards the 20 km/s cloud (Vlsr ~ 30 km/s)

Filaments in the CMZ are absorbing

Absorption filaments also seen in SiO (2-1), HCN (1-0), $H^{13}CN$ (1-0), etc.:

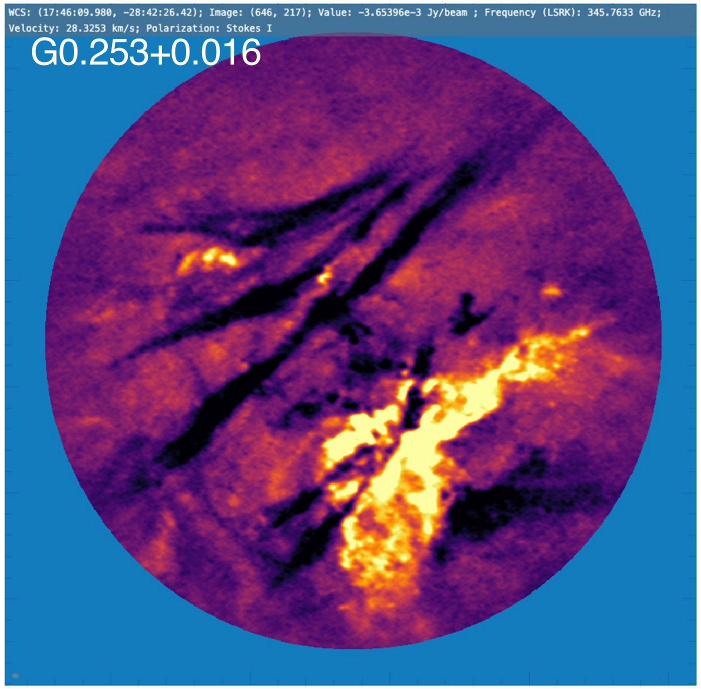
ubiquitous in the CMZ?



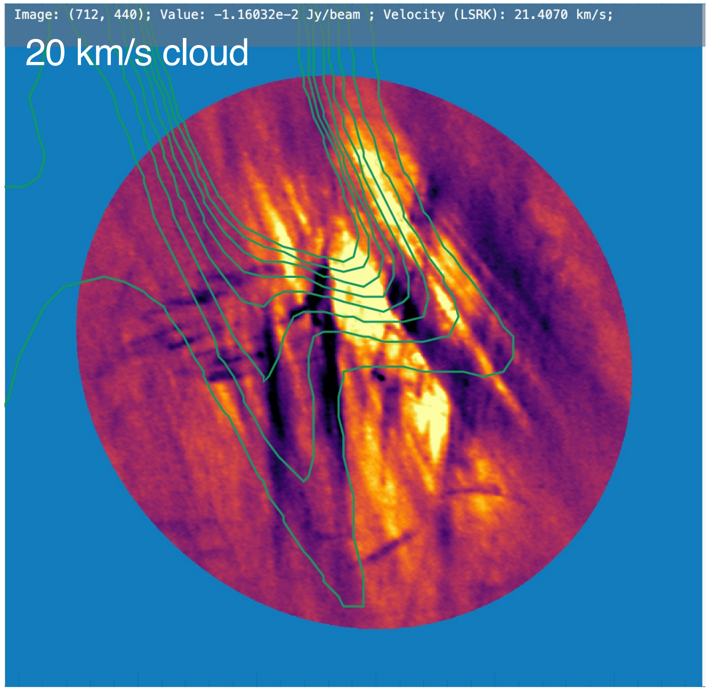
Filaments in the CMZ are absorbing

Molecular absorption filaments vs. non-thermal radio filaments: similar morphology

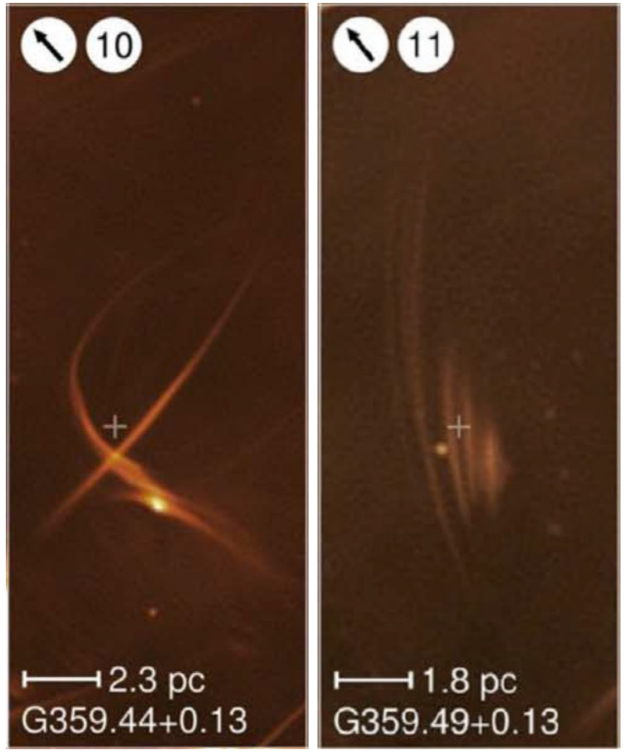
Do they have a common origin?



No radio emission in the field…

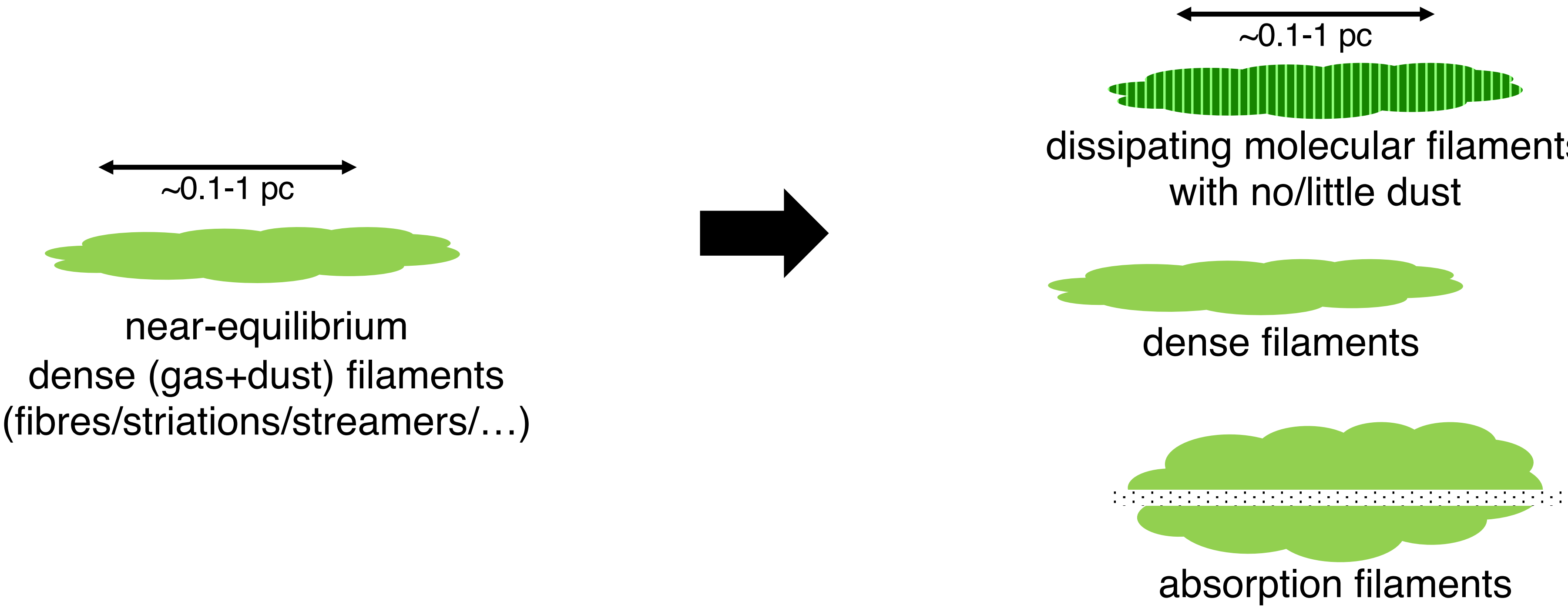


Contours: MeerKAT 1.28 GHz cont.
Unrelated with the absorption filaments?



Non-thermal filaments in MeerKAT 1.28 GHz continuum (Heywood et al. 2022)

Wrap-up: a diversity of ‘filaments’ in the CMZ: some are transient, some are absorbing



Summary

CONCERT: a multi-wavelength (C-band to Band 8), multi-mode (polarization, longbaselines, etc.), multi-scale (100 AU--10^2 pc) observational campaign towards the CMZ using ALMA, JVLA, etc. (& JWST?), finding unique features and gas properties that could be related to the peculiar star formation in the CMZ.

- **Unconventional 'cores': pressure-bound & with low spectral indices**
- **Unconventional 'filaments': some are transient, some are absorbing**
- Ongoing & future works: magnetic fields in cores, fine structures & polarization in protostellar disks, dust grain growth & planet formation via ALMA+JWST, star formation in the circumnuclear disk, etc.

Email: xinglu@shao.ac.cn


workshop announcement
Perspectives in Star Formation: Senior Insights, Young Visions
To bring together senior astronomers and early-career researchers—including students and postdocs—for an open exchange of ideas, experience, and inspiration in the field of star formation
October 13th to 17th, 2025
Shanghai Astronomical Observatory (SHAO), Shanghai, China
https://sf2025.casconf.cn/
The Bund (外滩) in Shanghai
designed by László Hudec
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