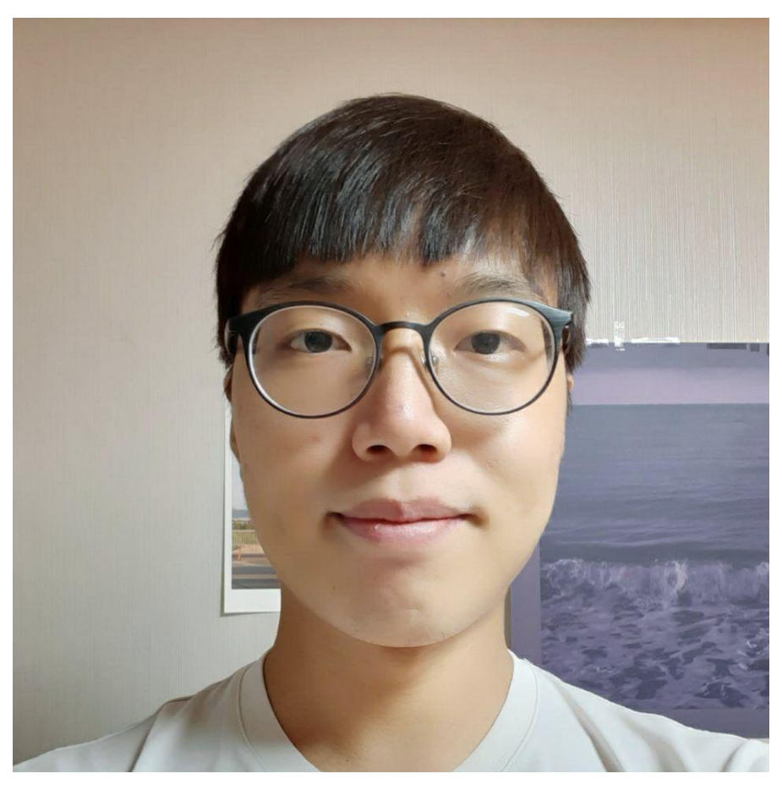
Early Planet Formation in Embedded Disks (eDisk): A Compact but Structured Keplerian Disk and Large-scale Spiral Structures Revealed in the Class I Protostellar System IRAS 04169+2702*

*Han et al. (2023, in prep)



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Introduction

- Taurus B213 region (156 pc)
- M3 **Class I** protostar[1]: $T_{\rm bol}$ = 163 K; $L_{\rm bol}$ = 1.5 $L_{\rm Sun}$
- **Counter-rotation** between disk and envelope[2]
- Potential **binary** system in infrared[3]
- **More complicated** than typical protostars

1. Substructure

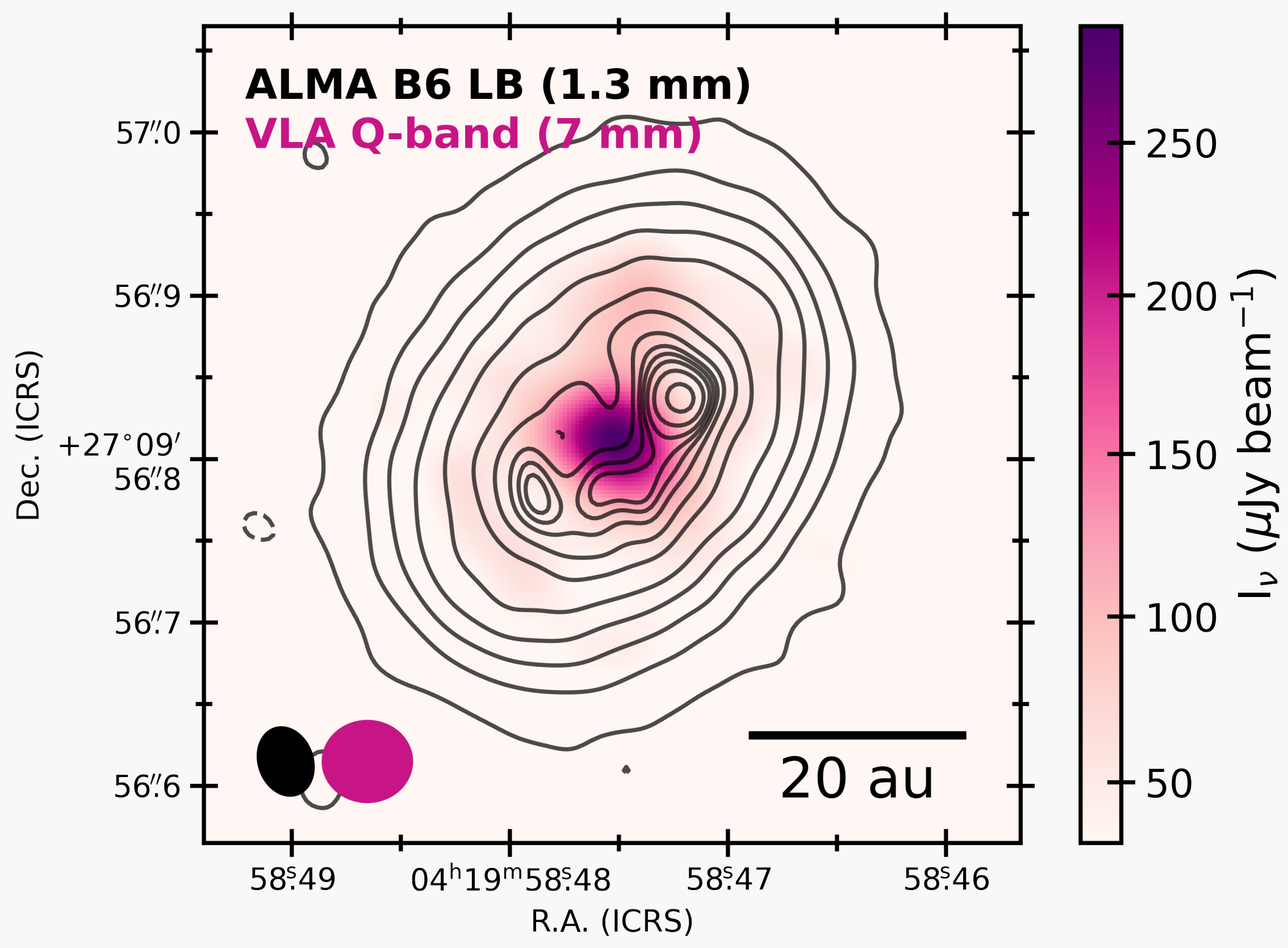


Figure 1. ALMA Band 6 (1.3 mm; long-baseline only) and VLA Q-band (7 mm) continuum images of IRAS 04169+2702 with angular resolutions of 0.04″ and 0.05″, respectively.

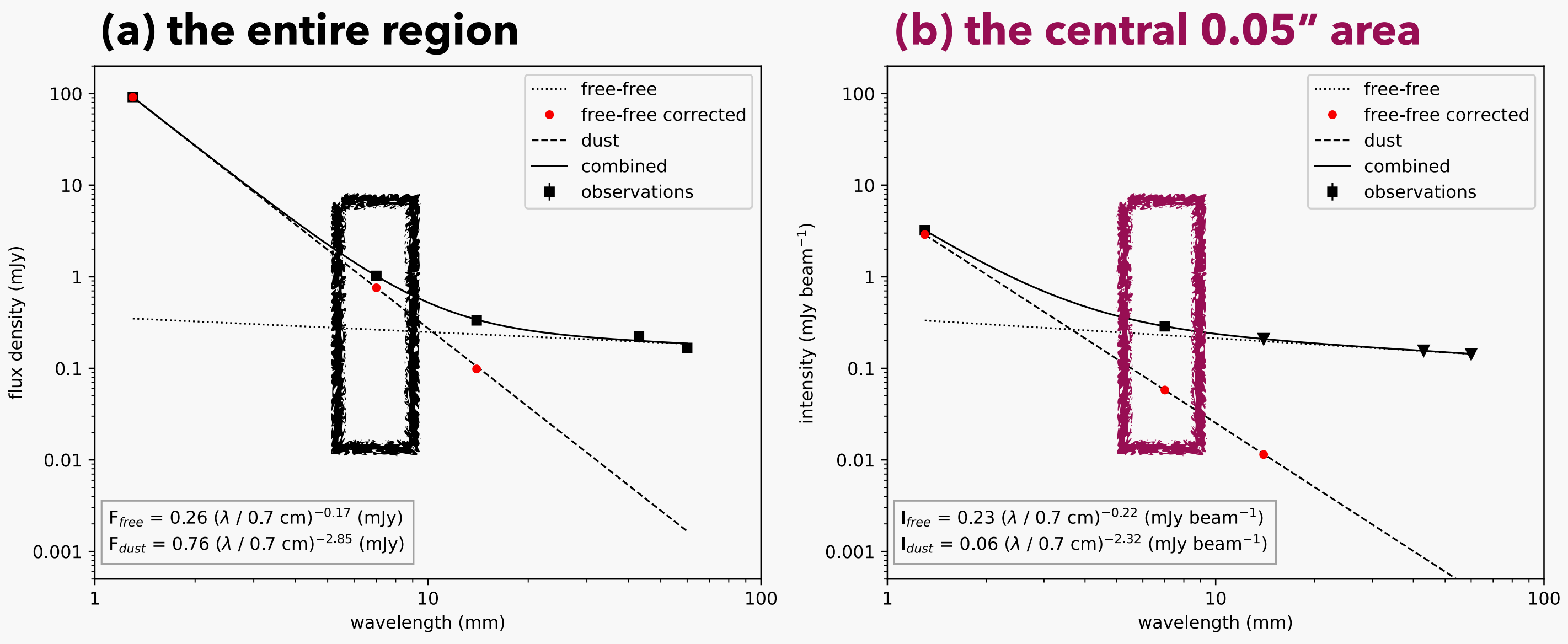


Figure 2. Radio spectra of the entire and central regions. The black points indicate the ALMA Band 6 (1.3 mm), VLA Q- (7 mm), K- (1.4 cm), C_1- (4.0 cm), and C_2-band (6.0 cm) data from the left. The dashed and dotted lines are the best-fit dust thermal emission and free-free emission curves. The red points denote the dust thermal emission only, without free-free emission.

A. *Continuum image (Fig 1)*
   - IRAS 04169+2702 is **a single protostar**, not a binary.
     - All the VLA images show a single central peak.
   - **A bean-shaped structure** connecting two dust **clumps**

B. *Radio spectrums (Fig 2)*
   - Dust thermal emission is dominant in the entire region, while free-free emission is dominant at the center in 7 mm.
   - Low spectral index ($\alpha_{\rm mm}$) implies **grain growth** to mm/cm[4].

2. Keplerian rotation

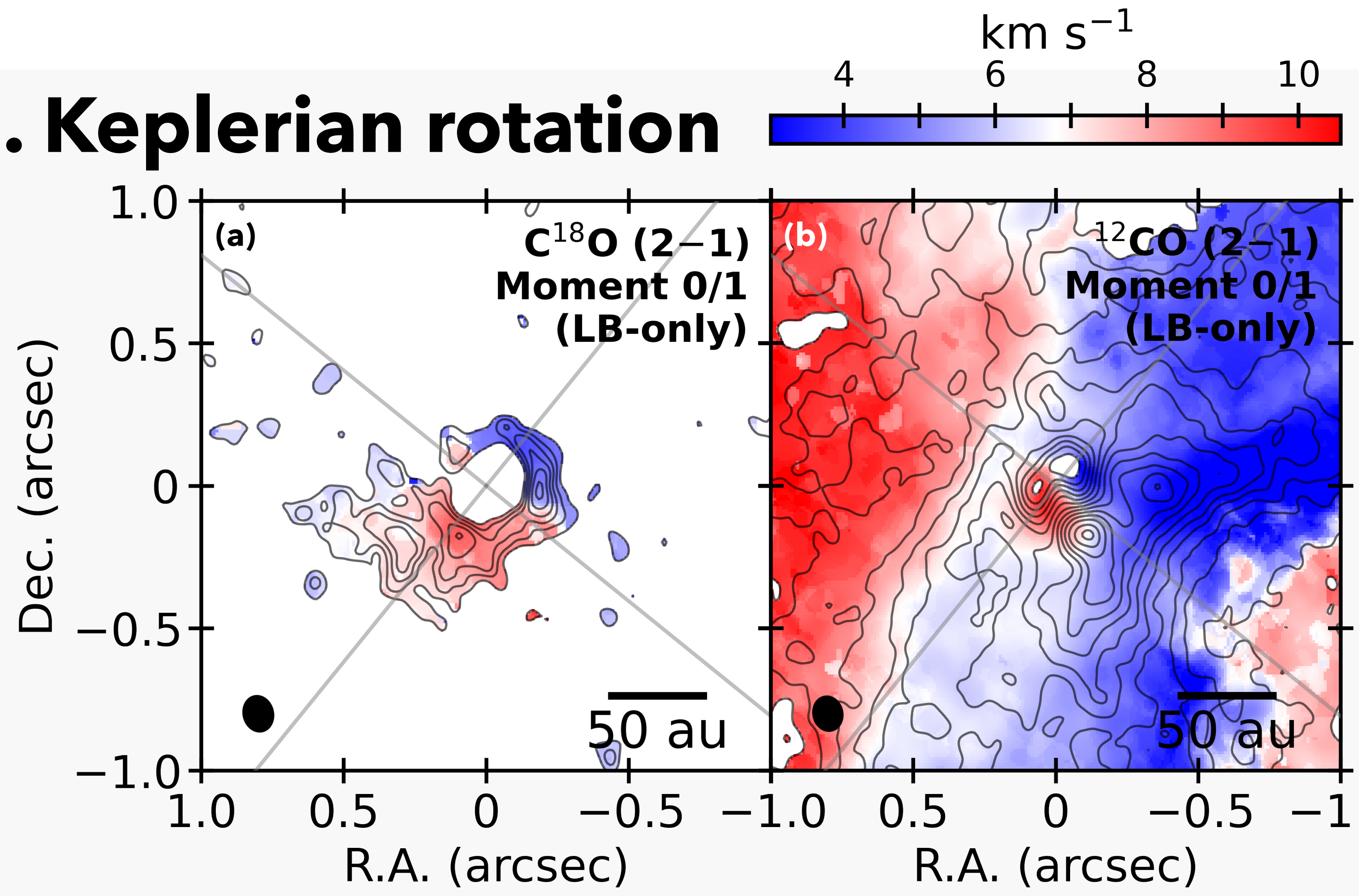


Figure 3. Integrated intensity (moment 0; black contour) and mean velocity (moment 1; color background) maps for the C¹⁸O and ¹²CO emissions with an angular resolution of 0.1", using the LB-only data.

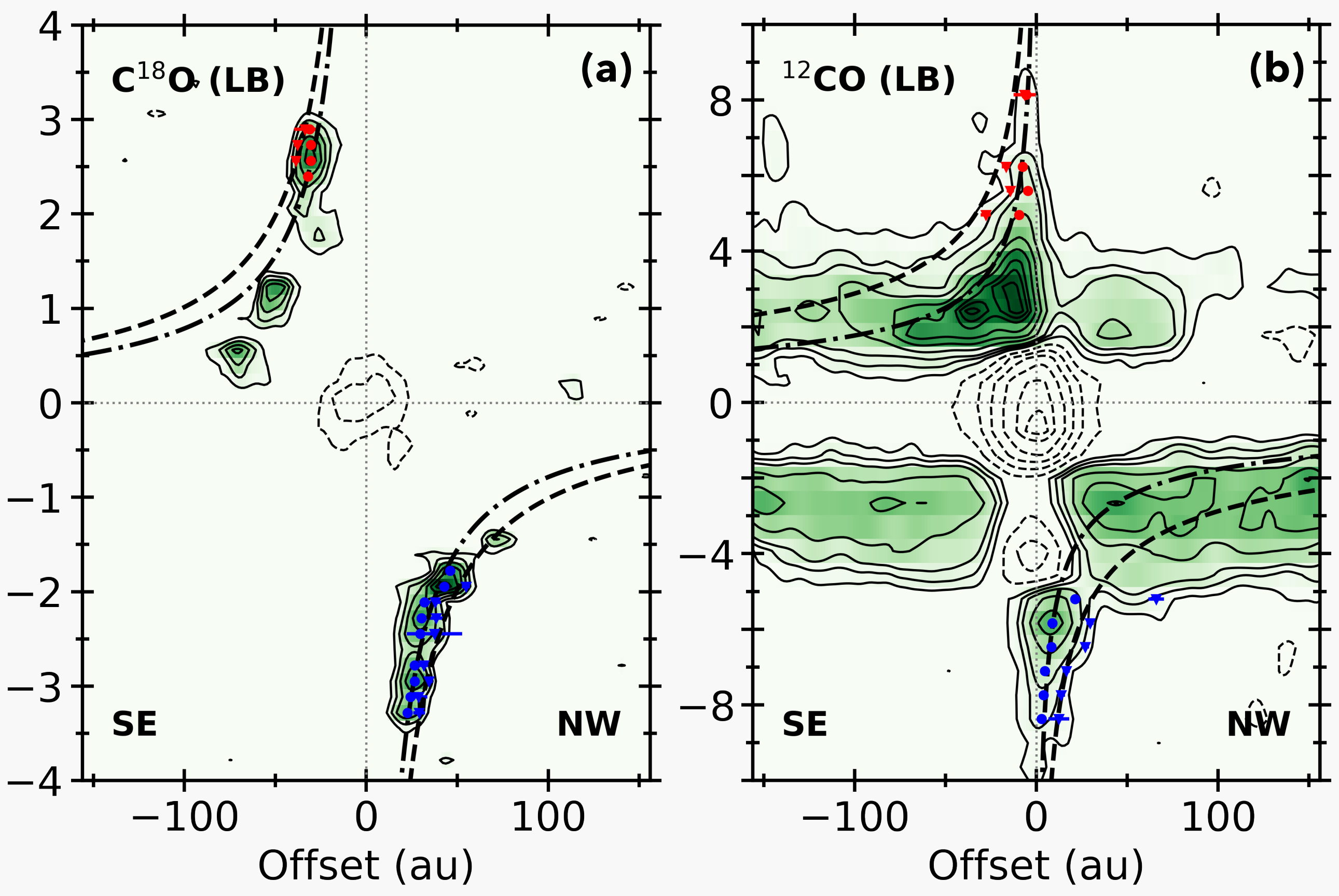


Figure 4. Position-Velocity (PV) diagrams of the LB-only C¹⁸O and ¹²CO emissions along the disk major axis (P.A. = 141°) and the best-fit rotation curves. The systemic velocity is fixed at 6.8 km/s. The dashed and dashed-dotted lines indicate the best-fit rotation curves obtained by the edge and ridge methods, respectively.

- **Velocity gradients** along the disk major axis (P.A. = 141°):
  - $C^{18}O$ (Fig 3a), ^{12}CO (Fig 3b), ^{13}CO, SO, and H_2CO
- Edge and ridge methods by Spectral Line Analysis/Modeling (SLAM)[5]
  - $V_{\rm rot} \propto R^{-p}$: ($C^{18}O$; Fig 4a) p = 1.0 - 1.2, (^{12}CO; Fig 4b) p = 0.4 - 0.6
- $C^{18}O$: **an infalling envelope** under conservation of angular momentum
- ^{12}CO: **a Keplerian disk** around a 1-$M_{\rm Sun}$ protostar

3. Spirals: streamers accreting material

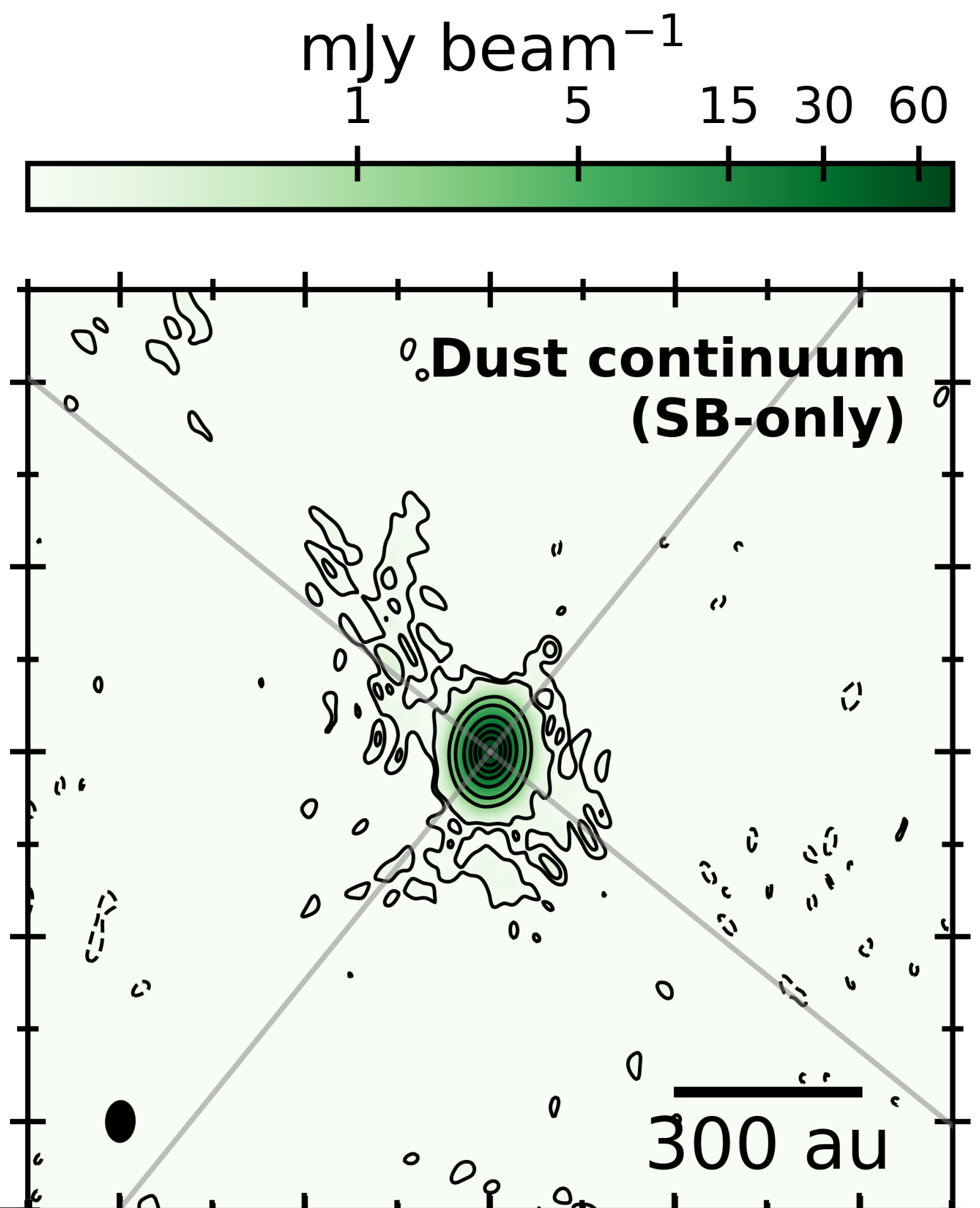
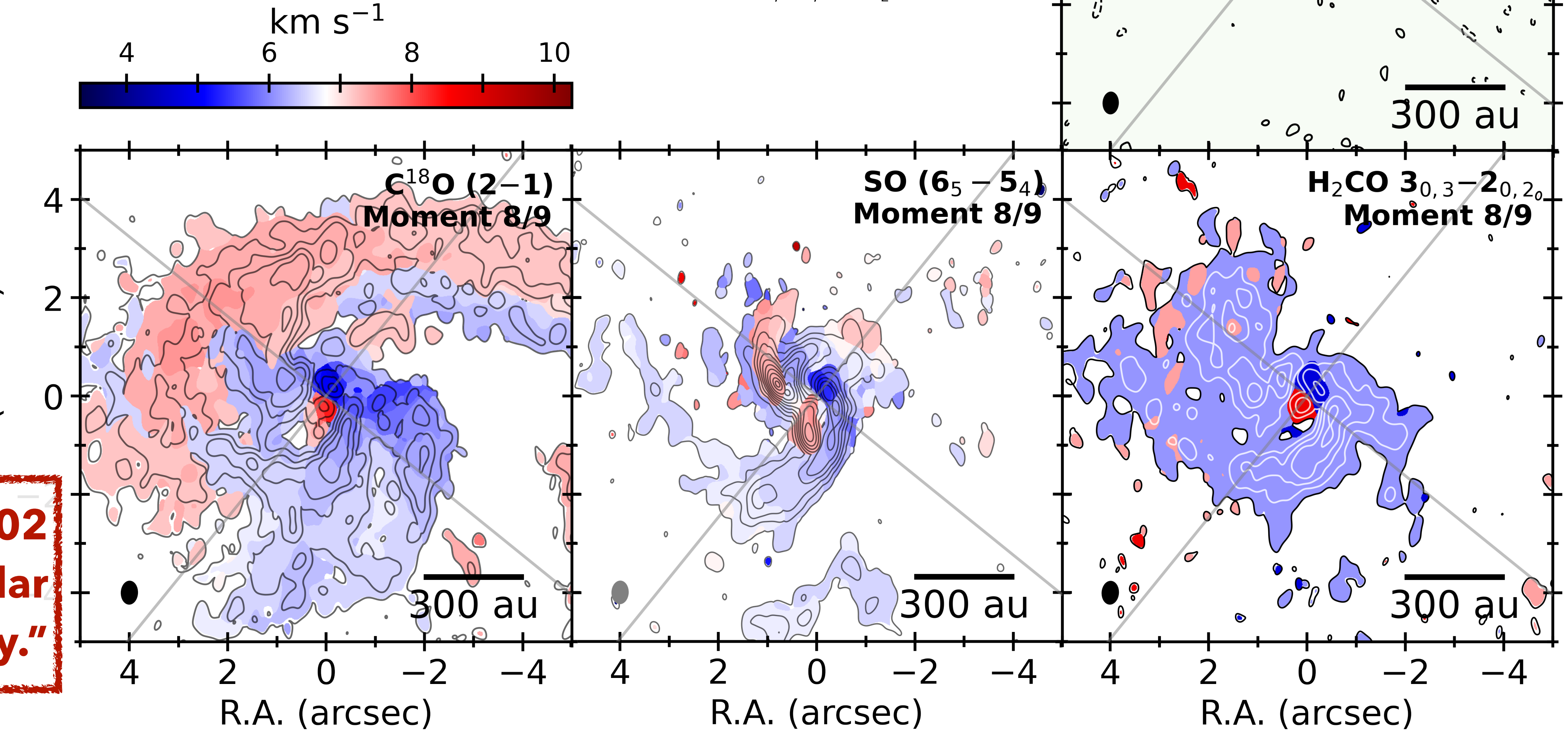


Figure 5. ALMA Band 6 (short-baseline only) dust continuum image. Peak intensity (moment 8; black contour) and velocity at peak intensity (moment 9; color) maps for the C¹⁸O, SO, and H₂CO emissions.



- **S-shaped spirals** are traced by the dust continuum, $C^{18}O$, SO, and H_2CO emissions.
- Velocities increase closer to the protostar along the spirals: **an infall motion**
- SO coincides with $C^{18}O$: **accretion shock**

→ **Streamers accreting material,** rather than counter-rotation

> **"The complexity of IRAS 04169+2702 will help us understand protostellar evolution more realistically."**

References
[1]Ohashi et al., 2023, submitted
[2]Takakuwa et al. 2018, ApJ, 865, 51
[3]Connelley et al. 2008, AJ, 135, 2496
[4]Draine 2006, ApJ, 636, 1114
[5]Aso & Sai 2023, SLAM