2025 ALMA Summer School
Group 3 result sharing

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| Group leaders : Drs. Yusuke Aso, Spandan Choudhury

Introduction

The protostar is the youngest object in the course of star formation.

Because of active mass accretion at this evolutionary stage, various kinematics are expected to appear in a protostellar system.

Our group analyzed spectral line data of protostellar systems to explore the kinematics as well as the morphology and physical quantities in the gas.

Data

The ALMA Large Program eDIsk (2019.1.00261.L; PI N. Ohashi), Band 6 (~1.3 mm, ~225 GHz)

- **Class I protostar**, IRAS 04302+2247
  ^{12}CO, ^{13}CO (혜원), $C^{18}O$ (수연)
- **Class 0 protostar**, Ced110 IRS4A
  ^{12}CO, ^{13}CO (민규), $C^{18}O$
- **Class 0 protobinary**, R CrA IRAS32
  ^{12}CO (우재), ^{13}CO (성휘), $C^{18}O$

Angular resolution: ~ 0.4″ x 0.4″ (uvrange= 30 to 500 kλ)

Velocity resolution: ^{12}CO : 0.333 km/s, ^{13}CO : 0.167 km/s, $C^{18}O$: 0.167 km/s

Sensitivity: ^{12}CO : 3 mJy/beam, ^{13}CO : 6 mJy/beam, $C^{18}O$: 3mJy/beam

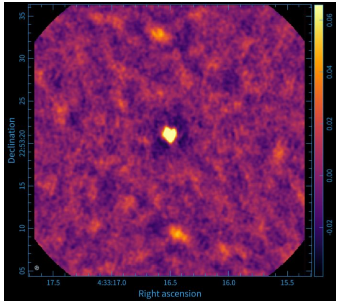

IRAS 04302
Class 1 protostar

Class I protostar, IRAS 04302+2247 (Lin et al. 2023, ApJ, 951, 9) ^{13}CO

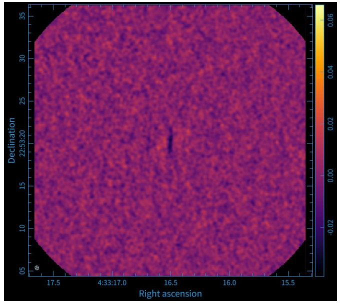
IRAS 04302

Basic information

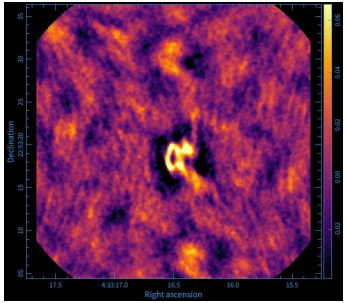
- Coordinate: RA: 4h33m16.50s / DEC: 22d53m20.2s
- T_bol: 88K
- Disk Inclination: 84 deg (edge-on)
- Disk physical size: 4″ (640 au)
- Total flux (continuum image): 182.6 mJy



channel 19 of 72
2.8661 km/s



channel 37 of 72
5.8667 km/s



channel 45 of 72
7.2003 km/s

04302+2247 - Tclean iteration comparison of ^{13}CO & $C^{18}O$

IRAS 04302

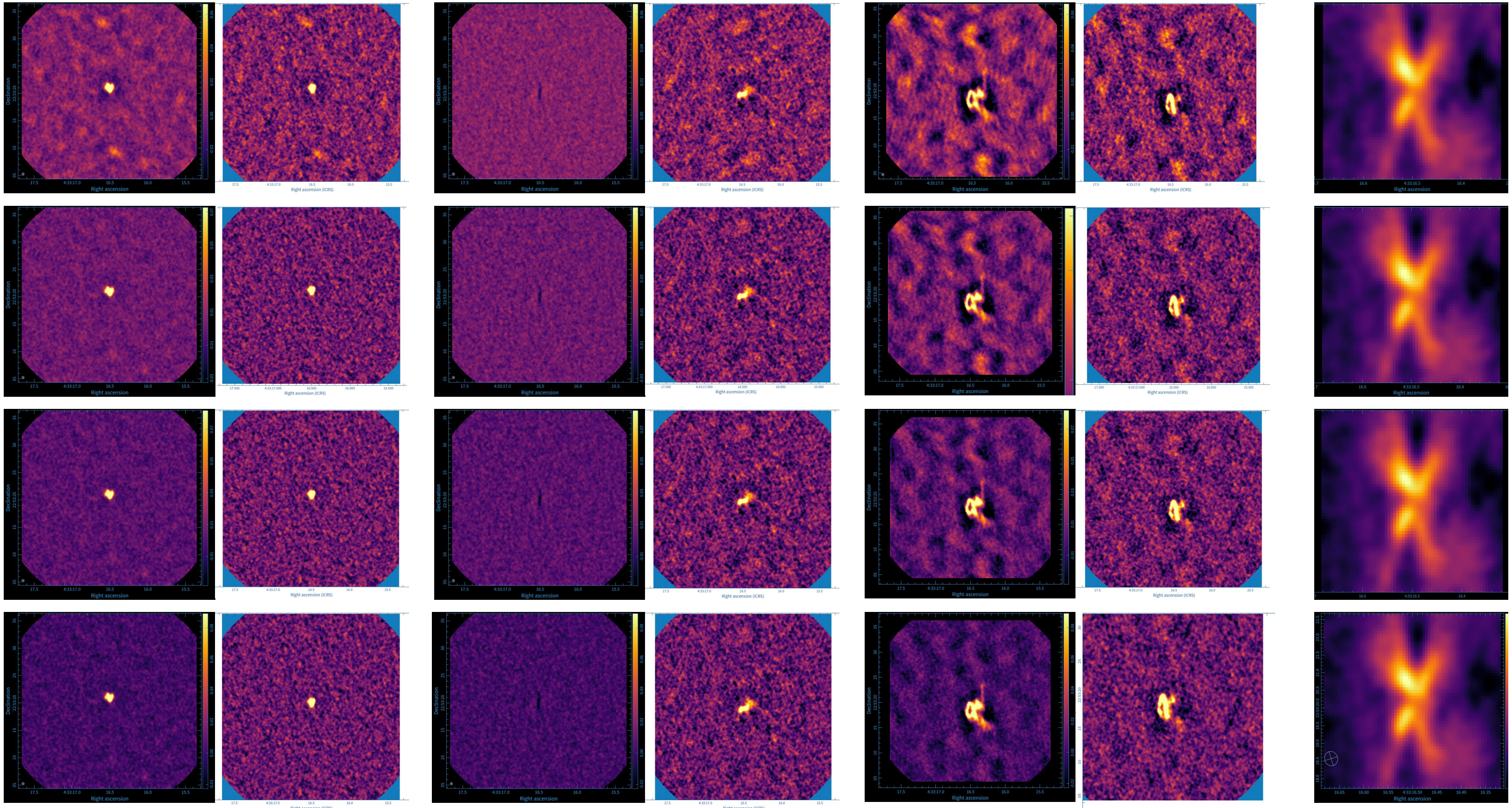
ch19 image | ch37 image | ch45 image | moment 0

niter = 10

niter = 100

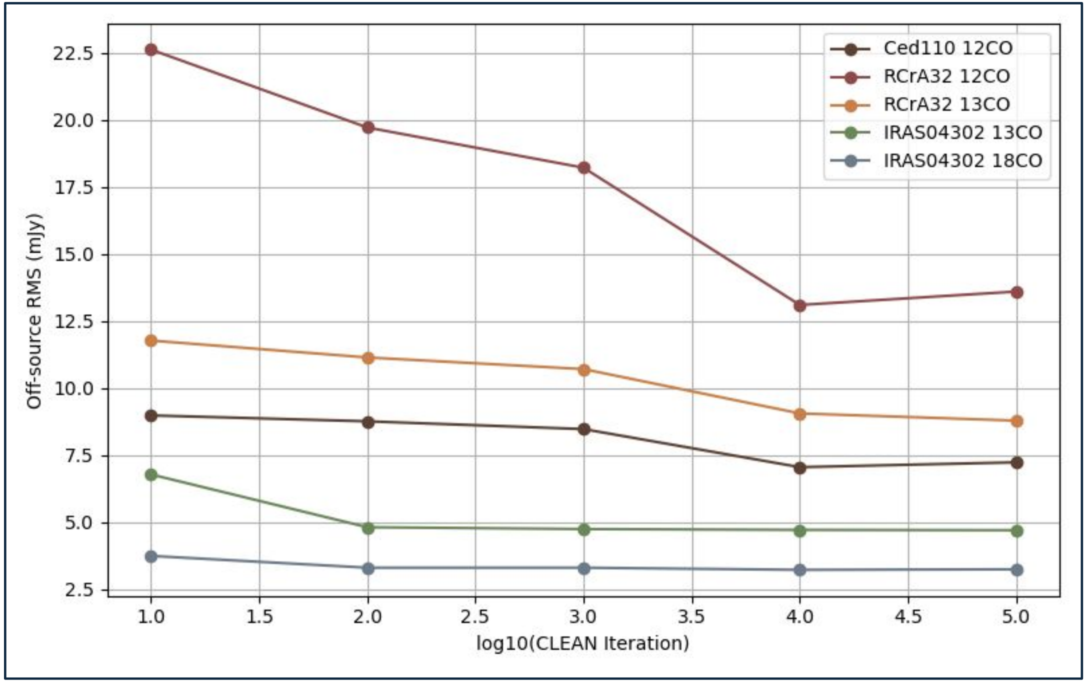
niter = 1000

niter = 10000



^{13}CO | $C^{18}O$ | ^{13}CO | $C^{18}O$ | ^{13}CO | $C^{18}O$ | ^{13}CO

Tclean



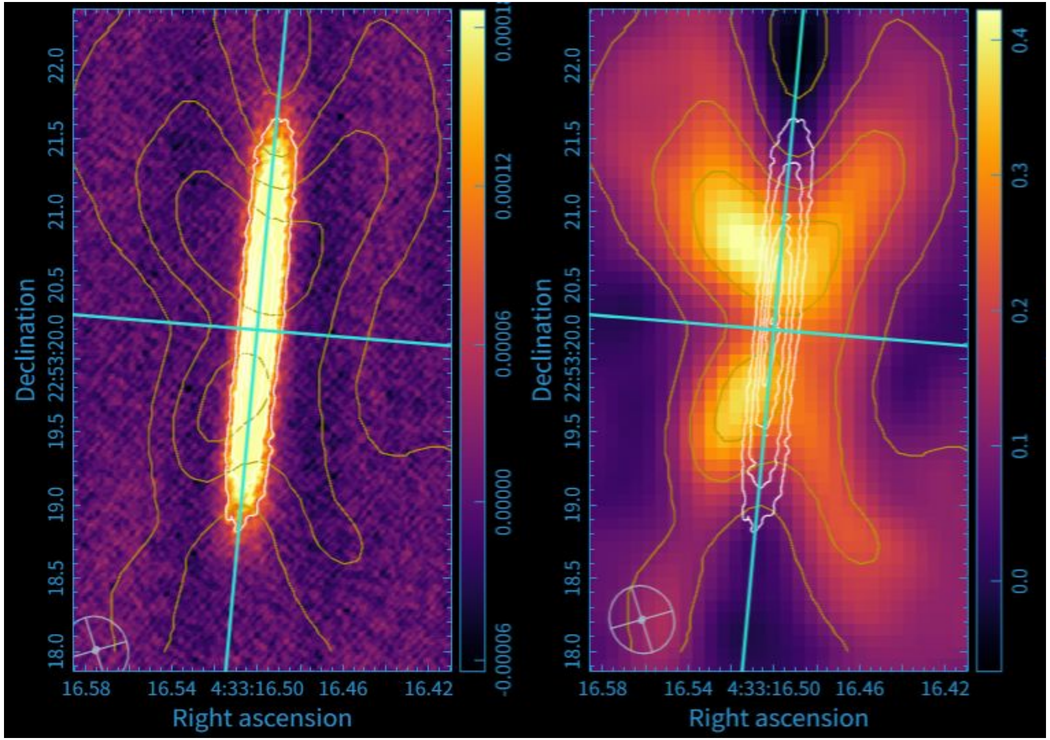
Tclean is cleaning process which reduces the sidelobes in the dirty beam.

We used auto mask (auto-multithresh).

If the niter is increased, rms converges.

04302+2247 ^{13}CO - Moment 0 map: butterfly shape

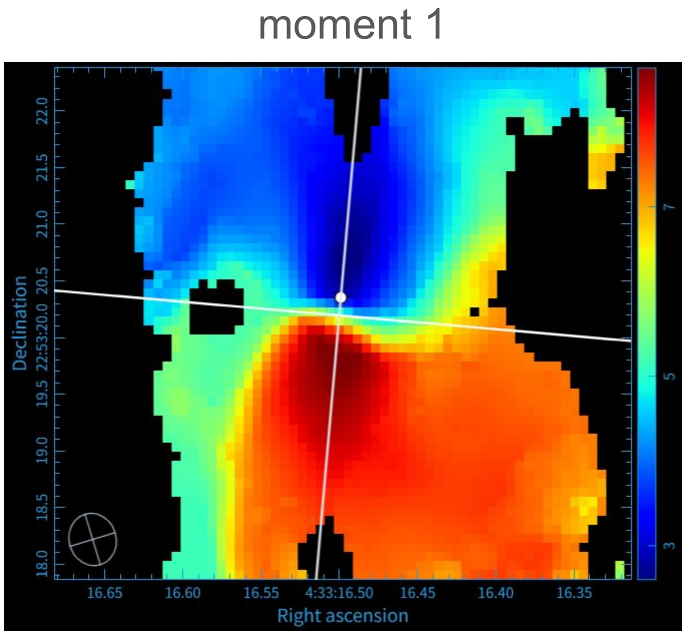
1.3mm continuum, ALMA   moment 0



- white contour :continuum
- orange contour : ^{13}CO mom0
- skyblue lines show the major and minor axes directions

We can see X-shape in the moment 0 map and it is because of the frozen out of ^{13}CO.

04302+2247 ^{13}CO - Moment 1 map

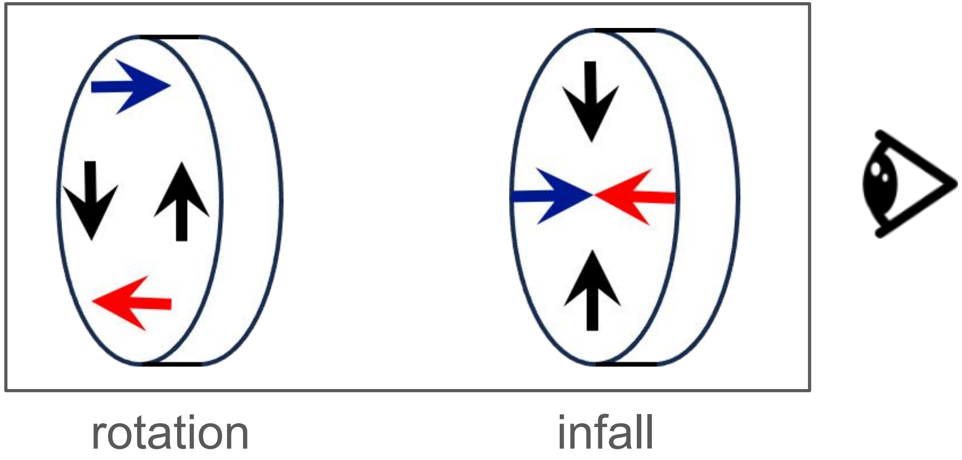


The blueshift appears on the north of minor axis, while the redshift appears on the south of it.

Blueshift appears on the east side of the major axis, while redshift appears on the west side.

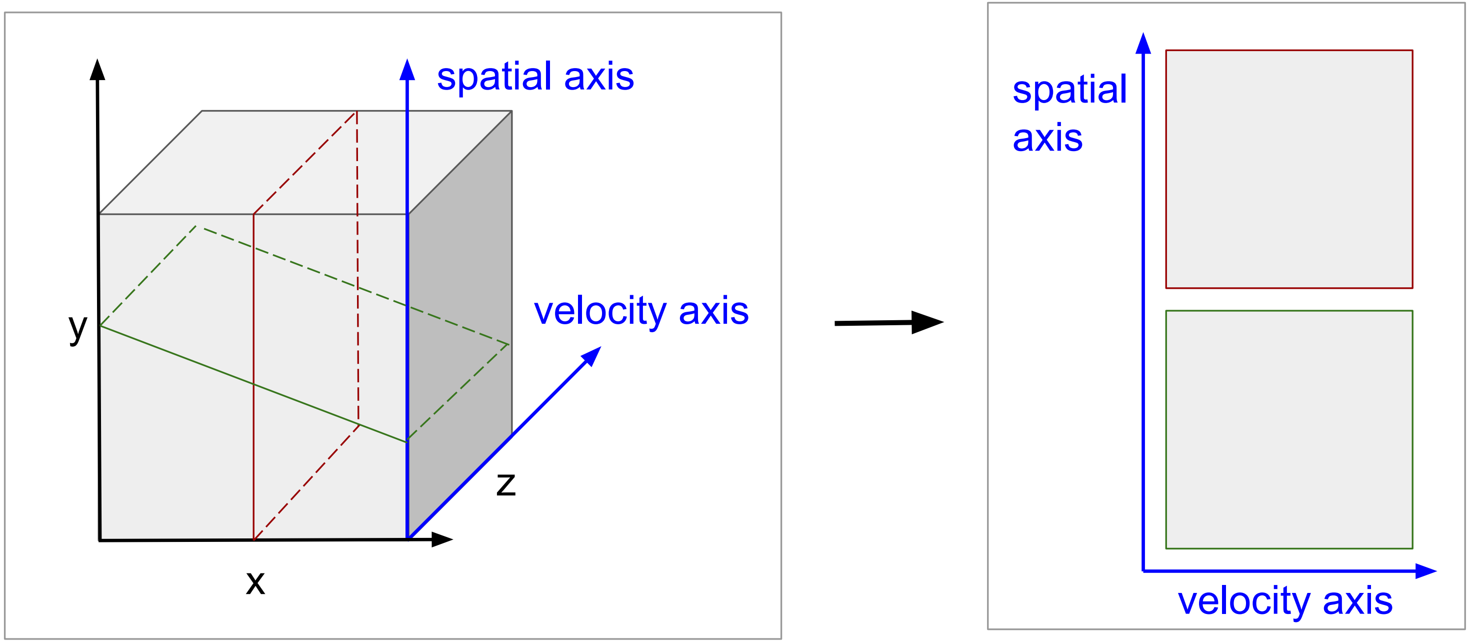
We made PV diagrams based on major & minor axes.

- Center position:
  RA: 4h 33m 16.50s, DEC: 22d 53m 20.2s
- Major axis PA: 175 degree
- Minor axis PA: 85 degree



04302+2247 ^{13}CO - PV diagram

Data Cube PV diagram

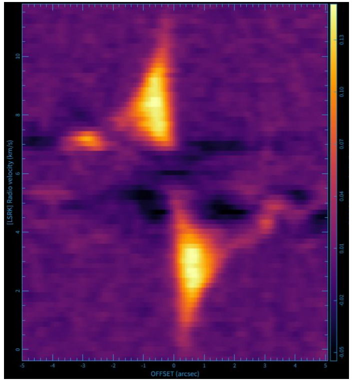


A PV diagram is a 2D slice of 3D data cube.
The spatial axis includes x-axis and y-axis.

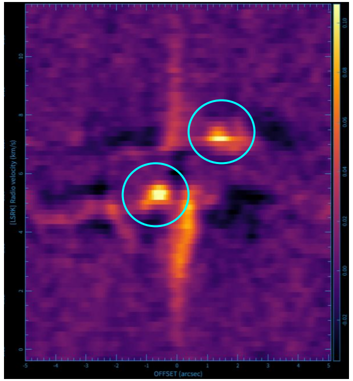
04302+2247 ^{13}CO - Moment 1 map: infall gas

IRAS 04302

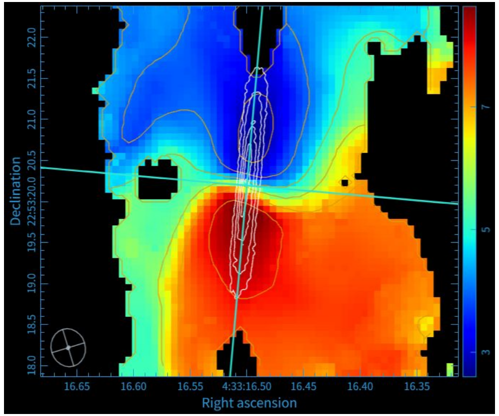
major axis



minor axis



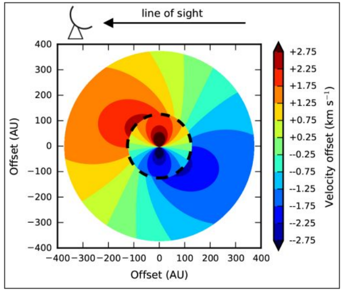
moment 1 map



continuum contour + mom1 contour

PV-diagrams show velocity gradients.
Major axis pv diagram shows spin-up rotation, which suggests the Keplerian rotation.
Two blobs in the minor one mean a velocity gradient along the E-W direction as seen in the mom1 map.
This suggests infall gas of the protostar.

Mom1 can be explained by the combination of an inner Keplerian disk and an outer infalling rotating envelope.
Rotation+infall makes a velocity gradient in a diagonal direction.



(van 't Hoff et al. 2018, A&A, 615, A83)

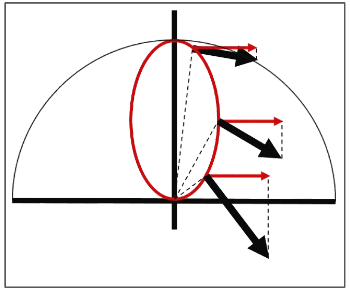
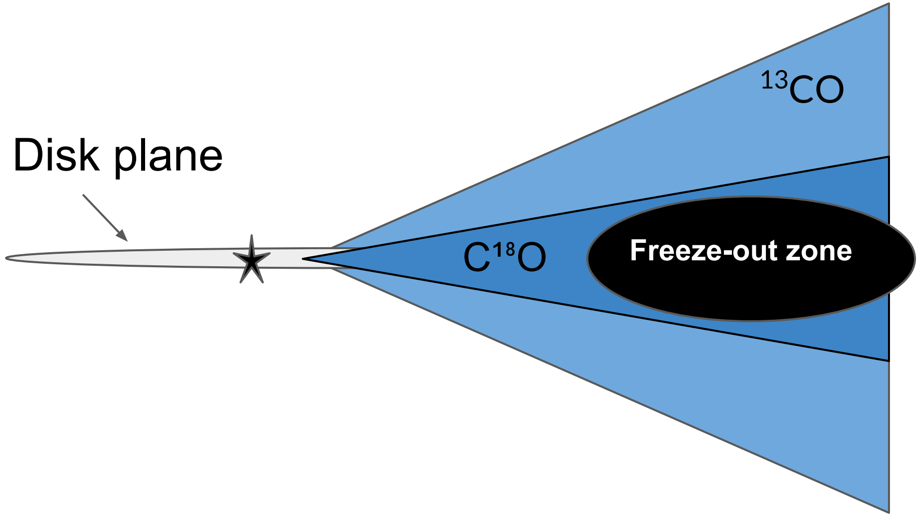


diagram which explains rotation

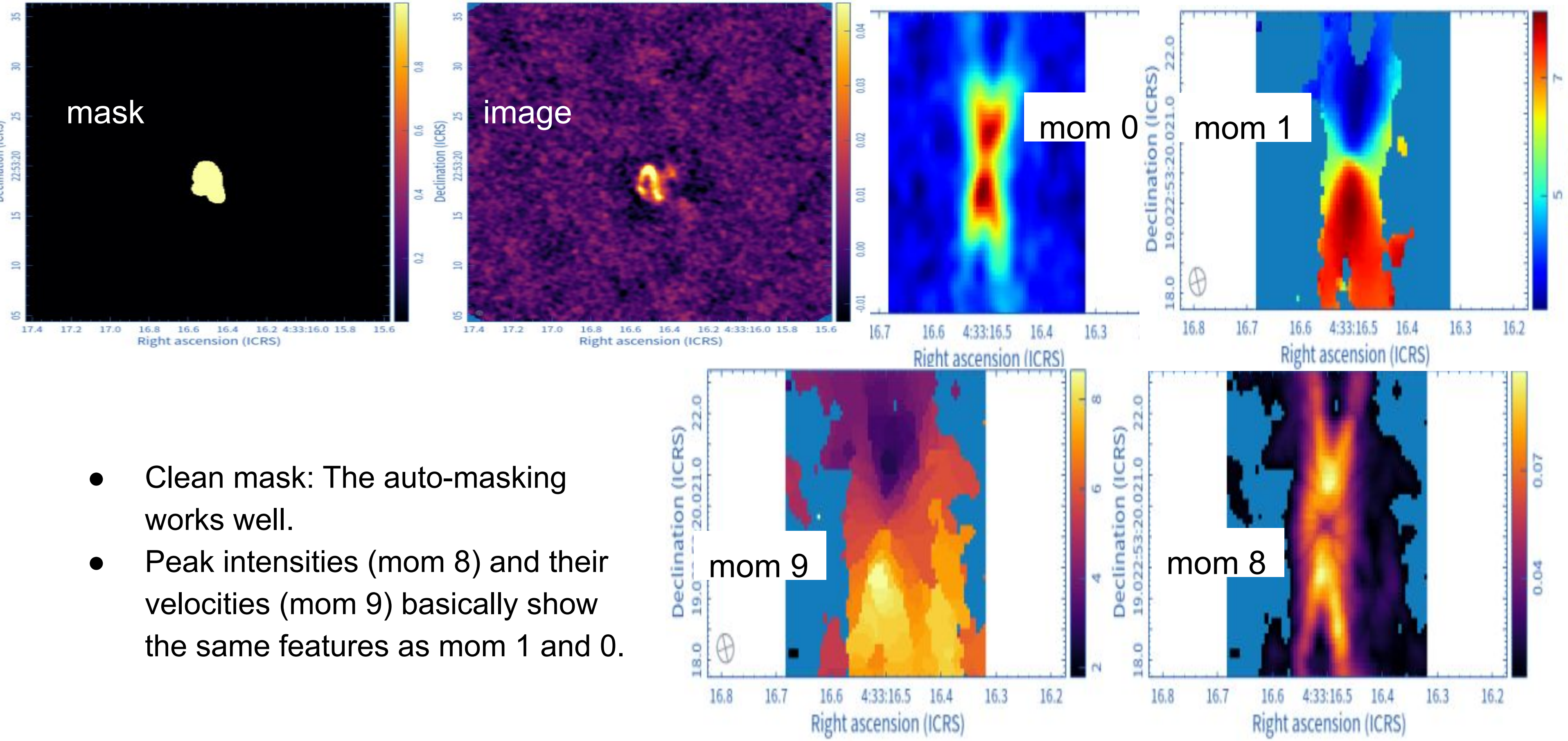
Gas Structure of Disk - ^{13}CO & $C^{18}O$



adapted from Dullemond et al., (2006)

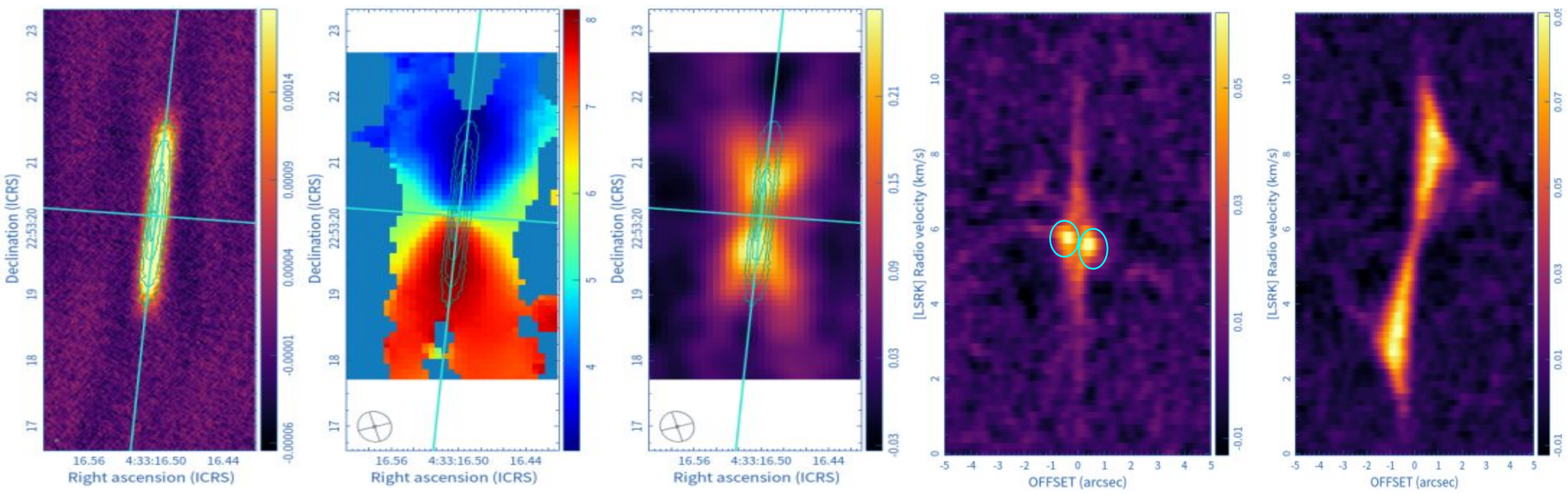
- Rarer molecules can trace denser regions. Particularly, $C^{18}O$ is rarer than ^{13}CO and thus traces denser regions.
- While **the optically thinner $C^{18}O$** probes **the snow line and the immediate snow surface** at small impact parameters, **^{13}CO** reveals a **complete freeze-out zone**.

IRAS 04302 C18O



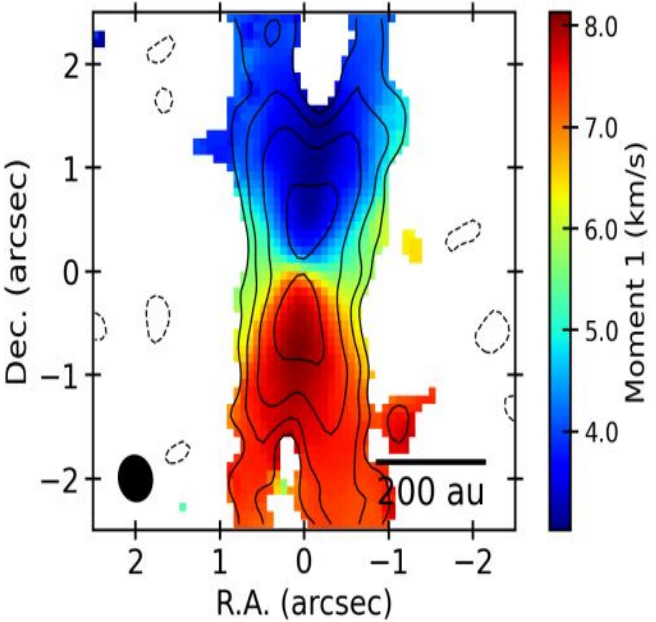
- Clean mask: The auto-masking works well.
- Peak intensities (mom 8) and their velocities (mom 9) basically show the same features as mom 1 and 0.

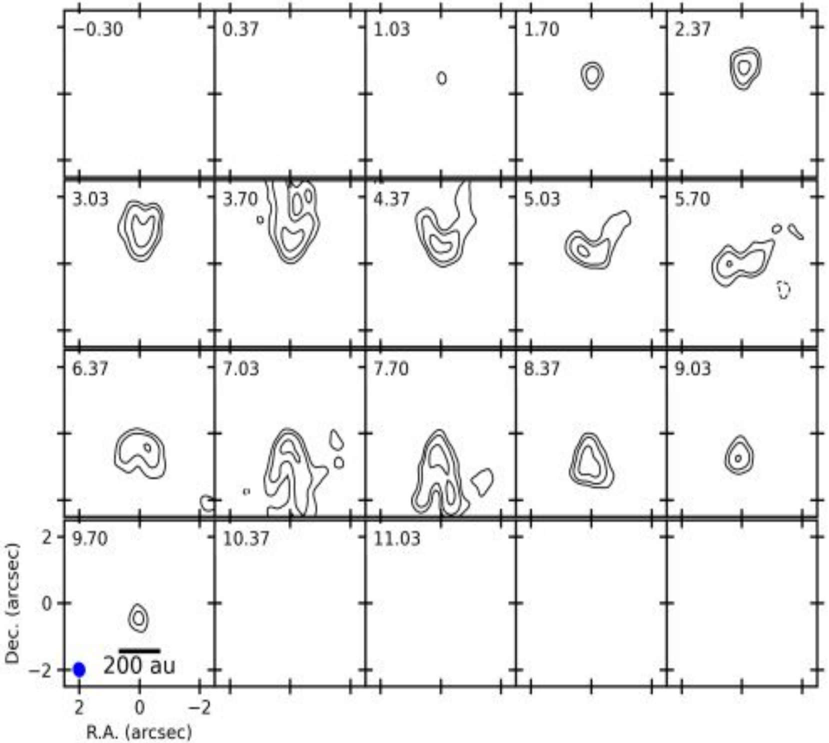
1.3mm continuum mom1 mom0 PV (minor axis) PV (major axis)



- Continuum image : Very thin, simple morphology → edge-on disk
- Moment 0: More extended than the continuum, showing an X shape.
- Moment 1: Velocity gradient along the disk major axis.
- PV major: The main velocity gradient, showing the spin-up rotation.
- PV minor: Hint of velocity gradient, but not so clear as in ^{13}CO. →Difference between the two molecules.

IRAS 04302 C18O channel maps

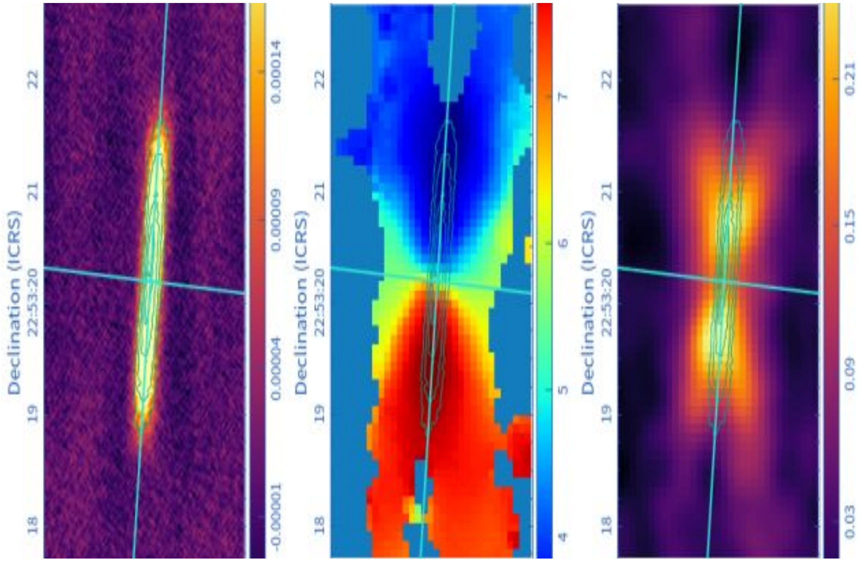




- Simple velocity structure.
- Channel maps: They clearly show the spin-up rotation. High-velocity compact near the center, while low-velocity extended in the major axis direction. Channel maps show simple structures as expected from the disk rotation only.

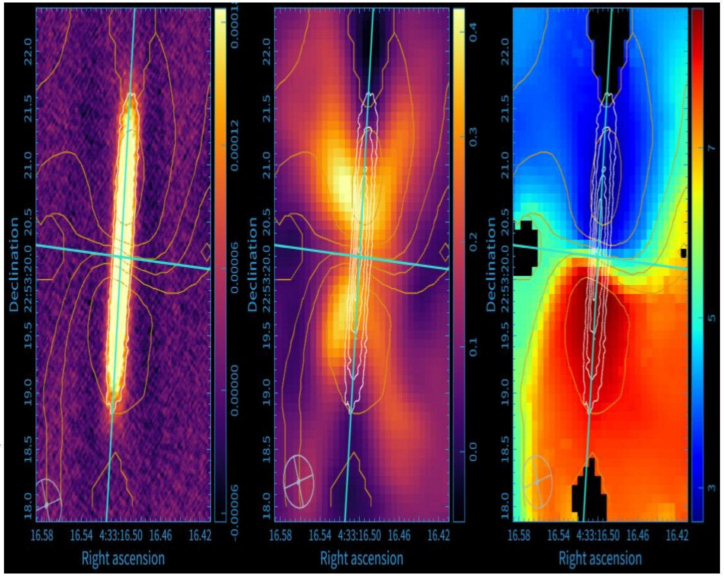
Difference between $C^{18}O$ & ^{13}CO

IRAS 04302



$C^{18}O$

^{13}CO



- ^{13}CO is brighter, because it is more abundant.
- ^{13}CO covers the east and west more, because it traces an upper layer in a disk.
- ^{13}CO shows asymmetry in the E-W direction, because of the difference between the face and back sides. Asymmetry also in the N-S direction → intrinsic asymmetry (density or temperature).

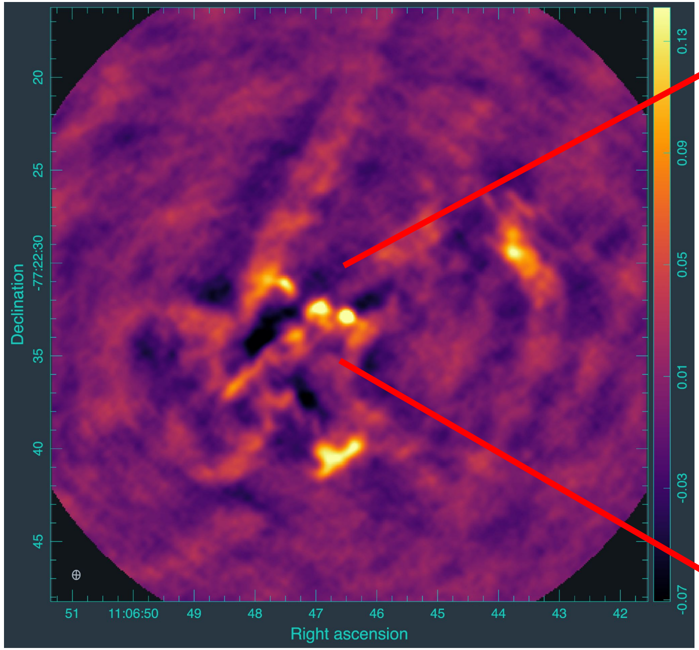
➡ *Those differences suggest that $C^{18}O$ is likely better to study the disk, without the effects of infall motion or asymmetry.*

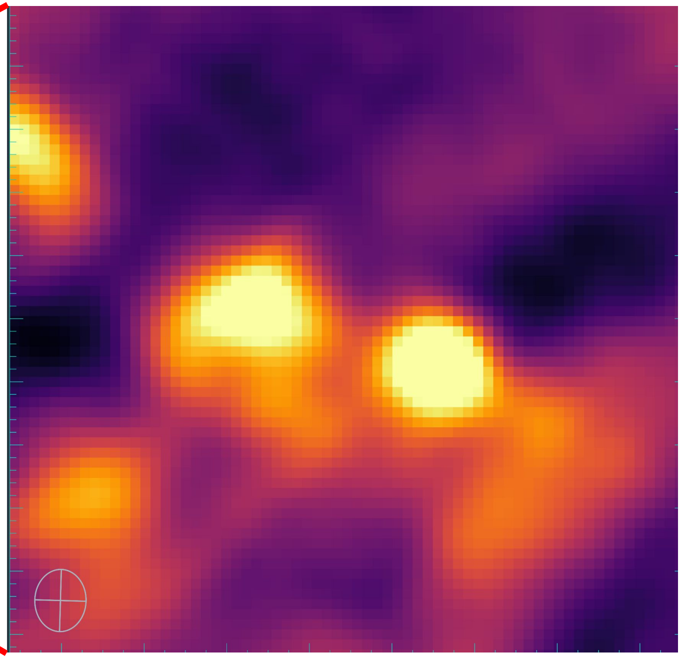

Ced 110
Class 0 protostar
Credit : JWST

Cleaning result

channel number 28 of 118 for 12CO

Are these structure disk?

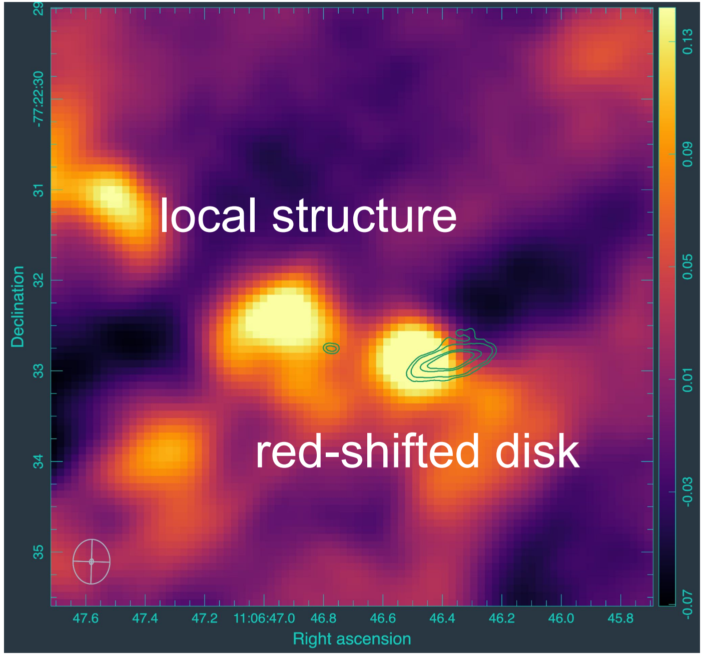




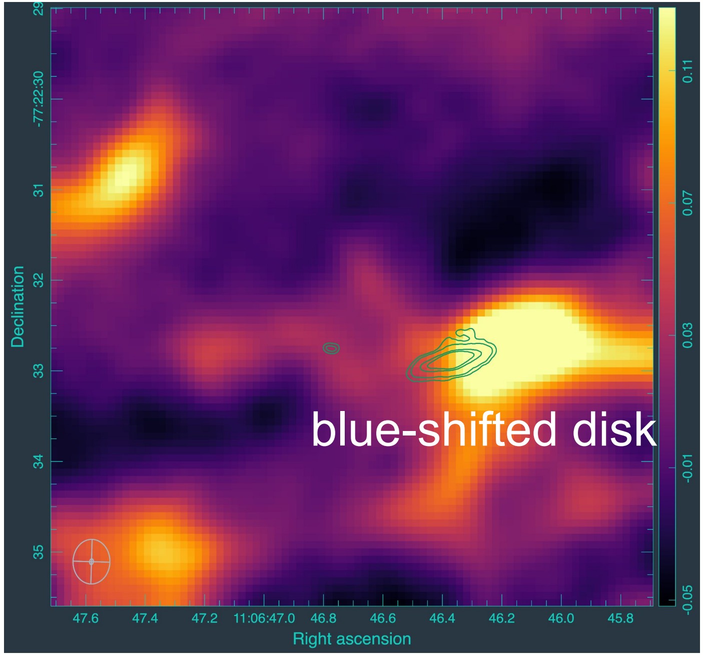
Cleaning result

Ced 110

channel number **28** of 118 for 12CO



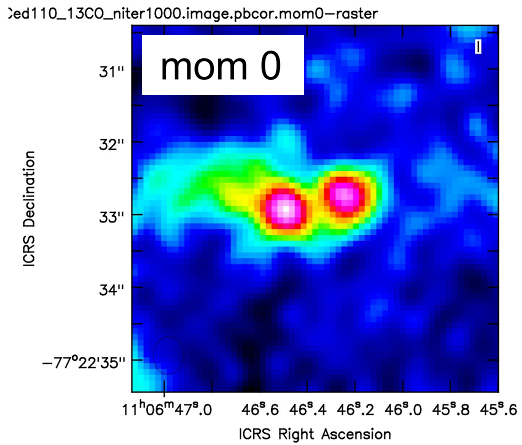
channel number **45** of 118 for 12CO

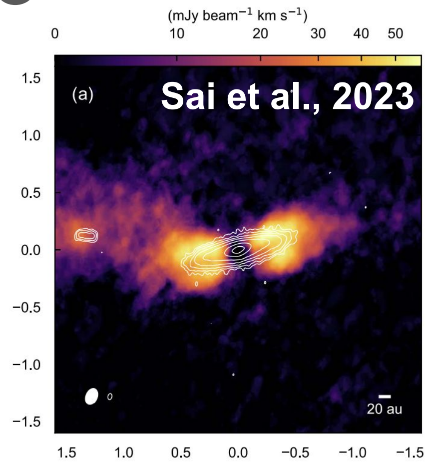


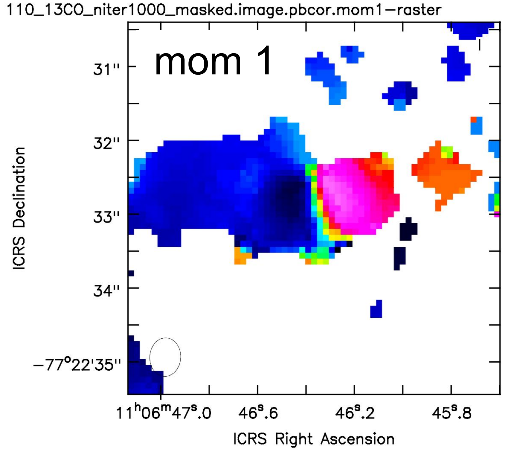
We should check continuum structure in wide channel to find correct system velocity and other values.

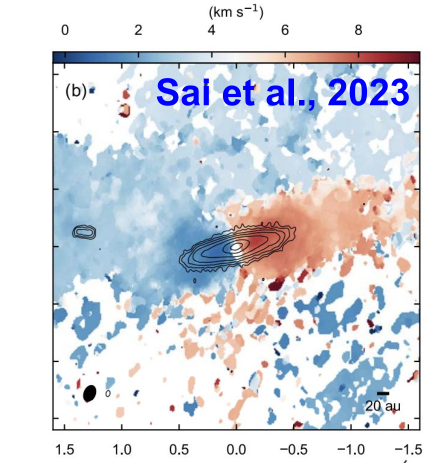
Moment map of 13CO

Ced 110









- Moment 0 map shows a double-peak with extension toward NE.
- Moment 1 map shows a velocity gradient along the W-E direction.
- Our moment maps well match with reference.
- It allows to calculate (1) **central stellar mass** and (2) **molecular column density**

upper images: moment 0 map of ^{13}CO
(Right: my result / Left: reference)

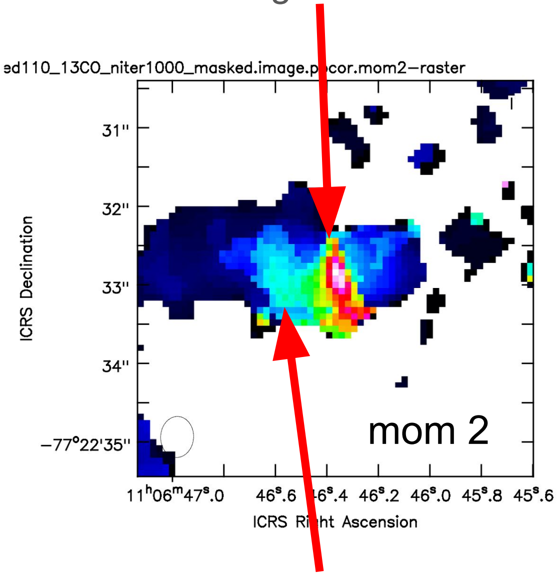
lower images: moment 1 map of ^{13}CO
(Right: my result / Left: reference)

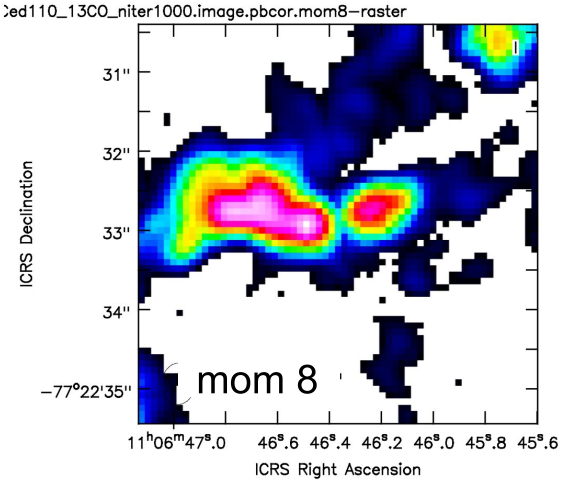
Moment map of 13CO

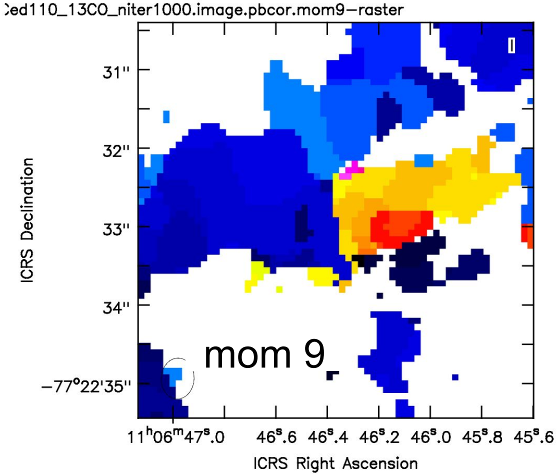
Ced 110

Highest velocity dispersion in the central region

Moment 8 and 9 similar with moment 1 and 0, more clearly exhibiting local structures.





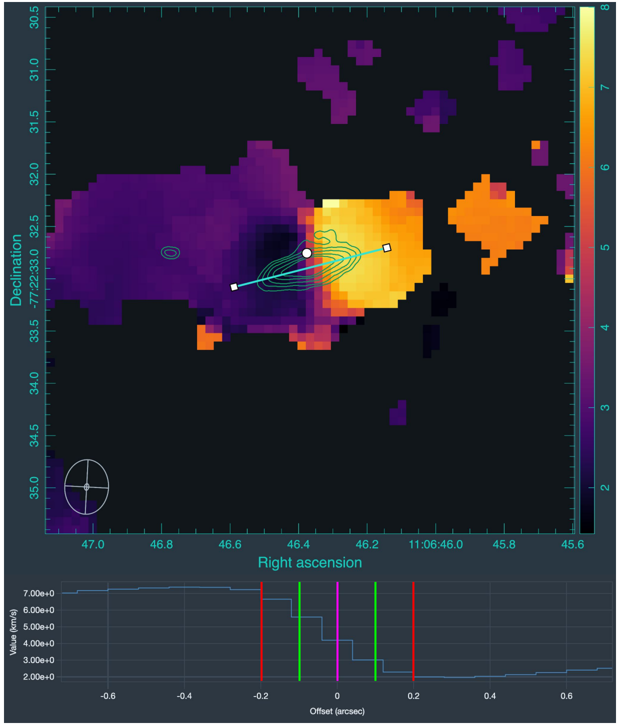


The NE region’s increase in dispersion seems to related with the extension in mom0.

Center stellar mass

Ced 110

moment 1 of ^{13}CO and continuum contours



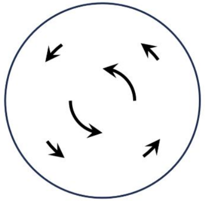
velocity profile along with blue line

radius, R from angular distance (0.05 arcsec = 10 au)

system velocity = average velocity of the target system
>> We also can get rotation velocity v

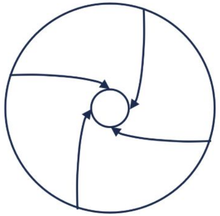
Keplerian motion

$$V_\phi = \sqrt{\frac{GM_*}{R}}$$



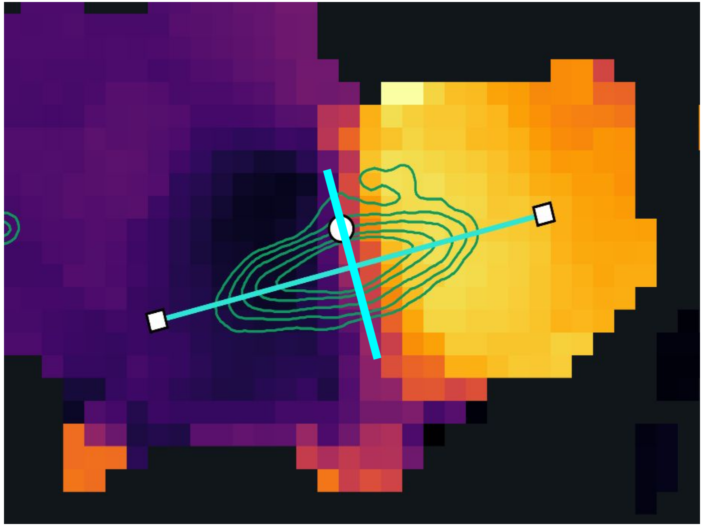
infall + rotation motion

$$V_\phi = \frac{\sqrt{GM_* R_c}}{R}, V_R = \sqrt{\frac{2GM_*}{R}\left(1 - \frac{R_c}{2R}\right)}$$



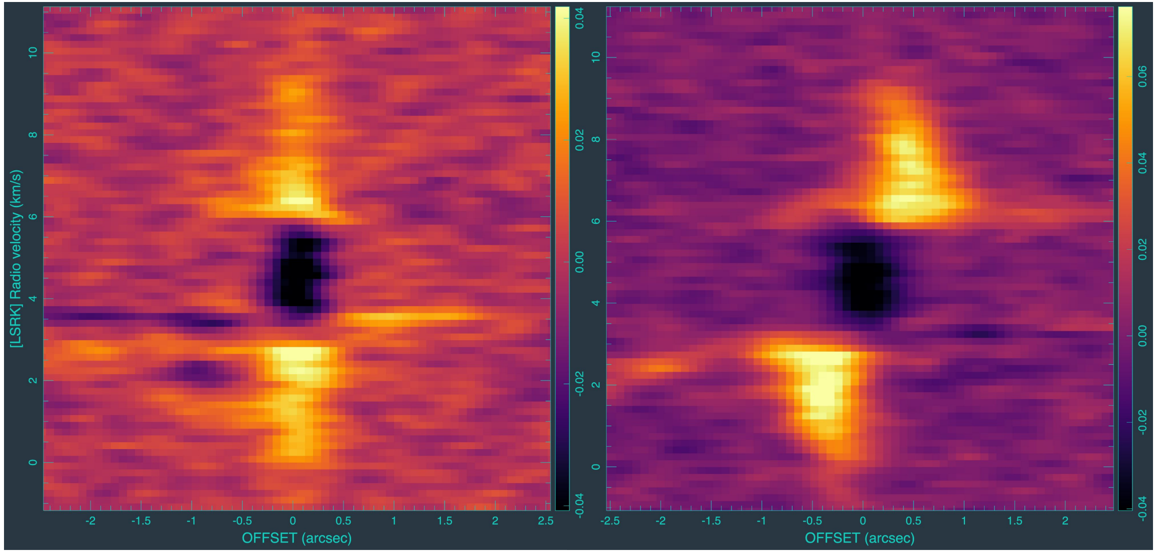
Center stellar mass

moment 1 of 13CO and continuum contour



Blue lines are the major and minor axes.

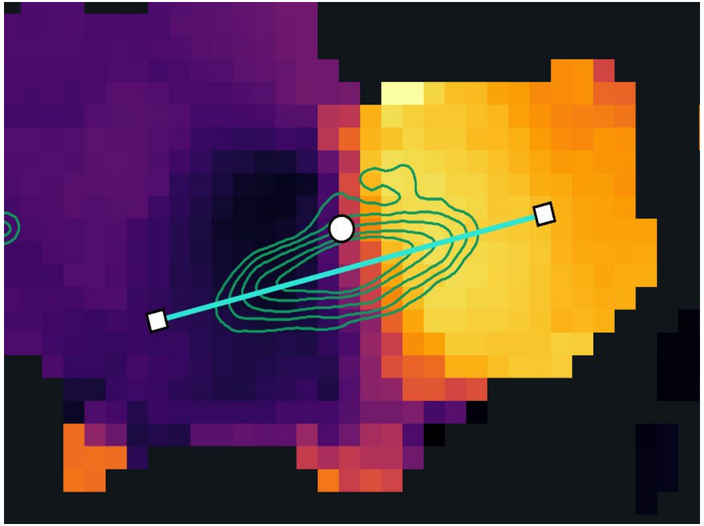
PV diagram (minor axis) PV diagram (major axis)



The ^{13}CO gas clearly exhibits the Keplerian rotation.

Center stellar mass

moment 1 of 13CO and continuum contour



radius, R from angular distance (0.05 arcsec = 10 au)

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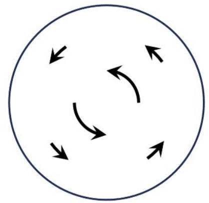


M ~ 1.15 solar mass

Very good agreement with 0.99-1.22 solar mass estimated by Sai et al., 2023.

Column density: number of particles along the LoS.

Ced 110

Calculation & Results

moment 0 maps for both ^{13}CO and ^{12}CO in Ced 110

→

Brightness temperature

I_{12CO} = 14.7 K

optically thick, abundant

I_{13CO} = 2.8 K

optically thin, less abundant

→

Excitation temperature

T_{ex} = 18 K

This shows that the gas is still cold like surrounding dust. It may reflect the young age of this system.

→

Column density

$N_{12CO} = 3 \times 10^{13}$ cm^{-2}

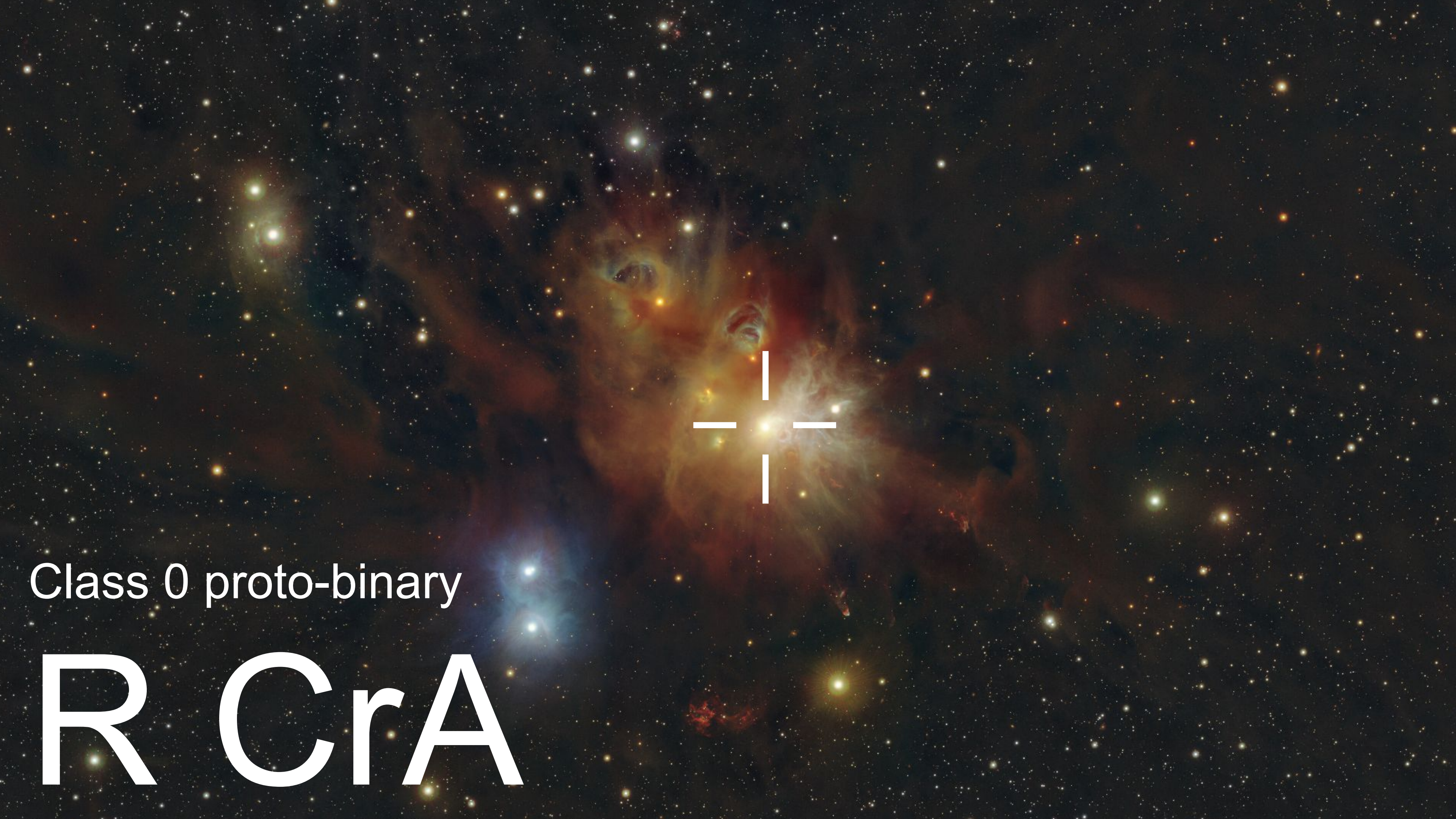
$N_{13CO} = 5 \times 10^{11}$ cm^{-2}

$$N_{tot} = \frac{3h}{8\pi^3 |\mu_{lu}|^2} \frac{Q_{rot}}{g_u} \exp\left(\frac{E_u}{kT_{ex}}\right) \times \left[\exp\left(\frac{h\nu}{kT_{ex}}\right) - 1\right]^{-1} \int \tau_\nu dv.$$

Mangum et al., 2017

Constant

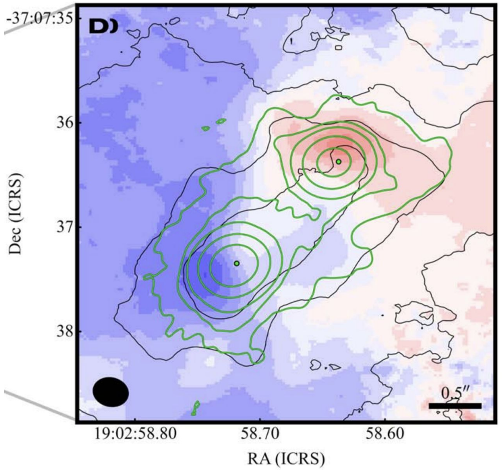
h: Planck constant
k: Boltzmann constant
μ_{lu}: Dipole moment
g_u : Degeneracy of upper energy state
E_u : Energy of upper energy state

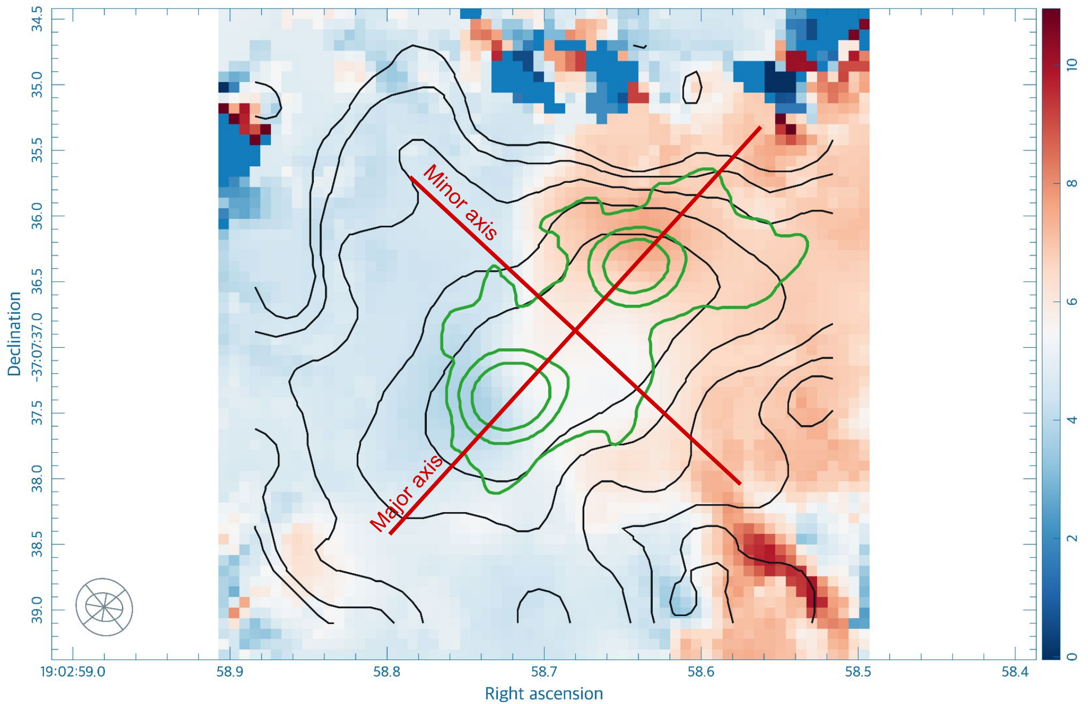

Class 0 proto-binary
R CrA

Moment Map

mom1 Color map with mom0(black contour)

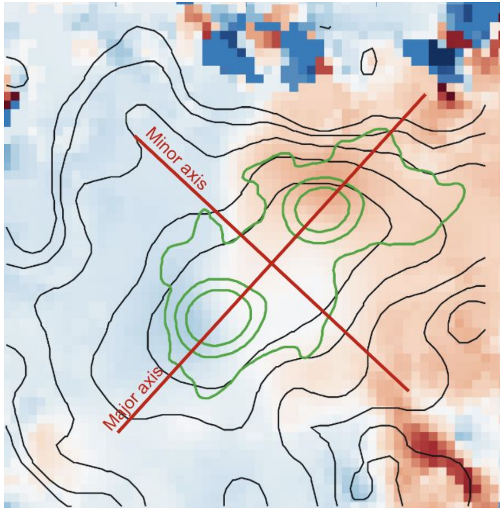
Ref(Encalada et al. 2024)



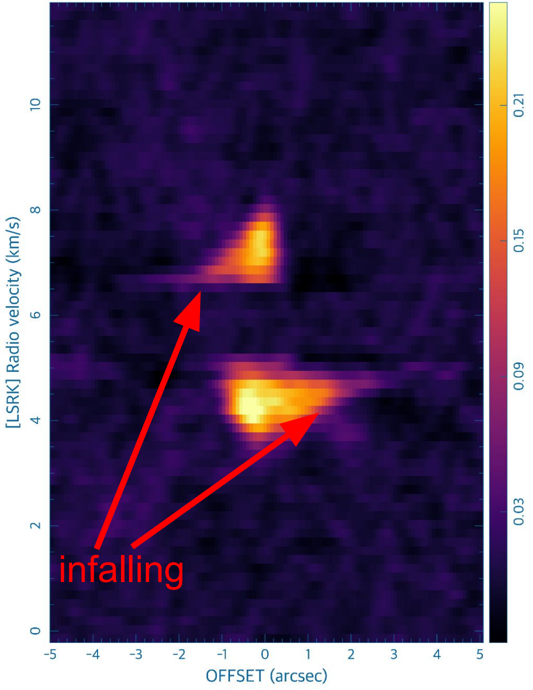


Position Velocity Diagram

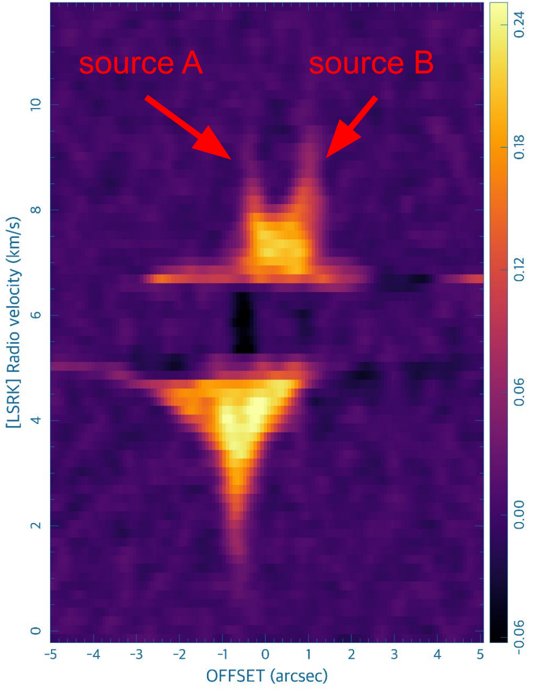
R CrA



Minor Axis

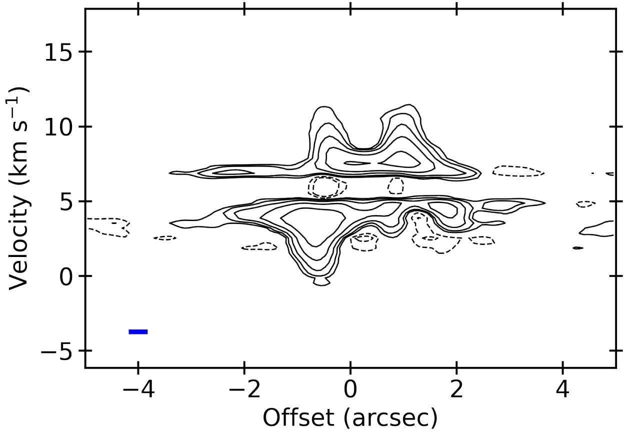


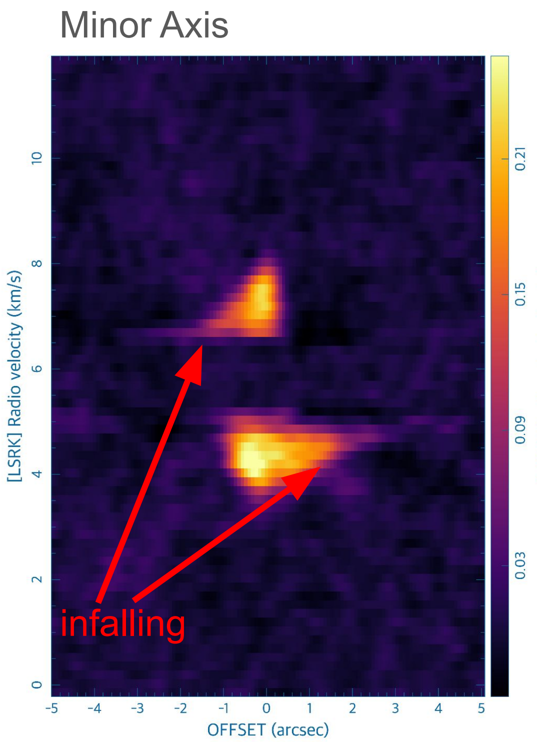
Major Axis

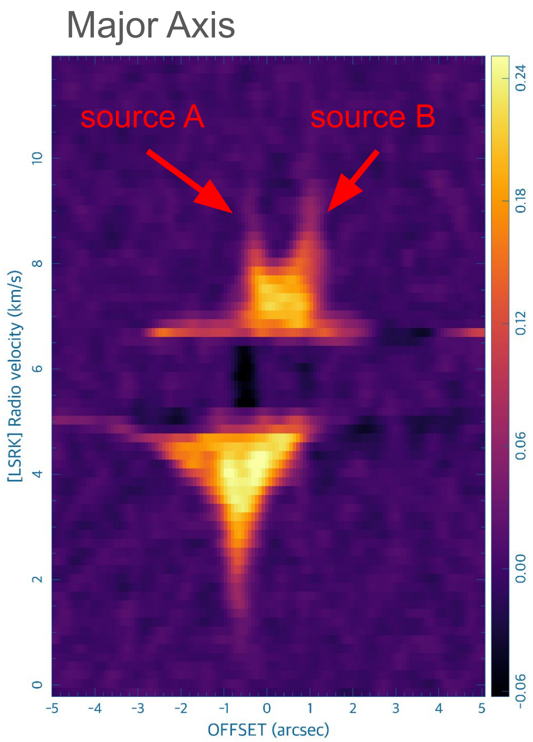


Position Velocity Diagram

R CrA

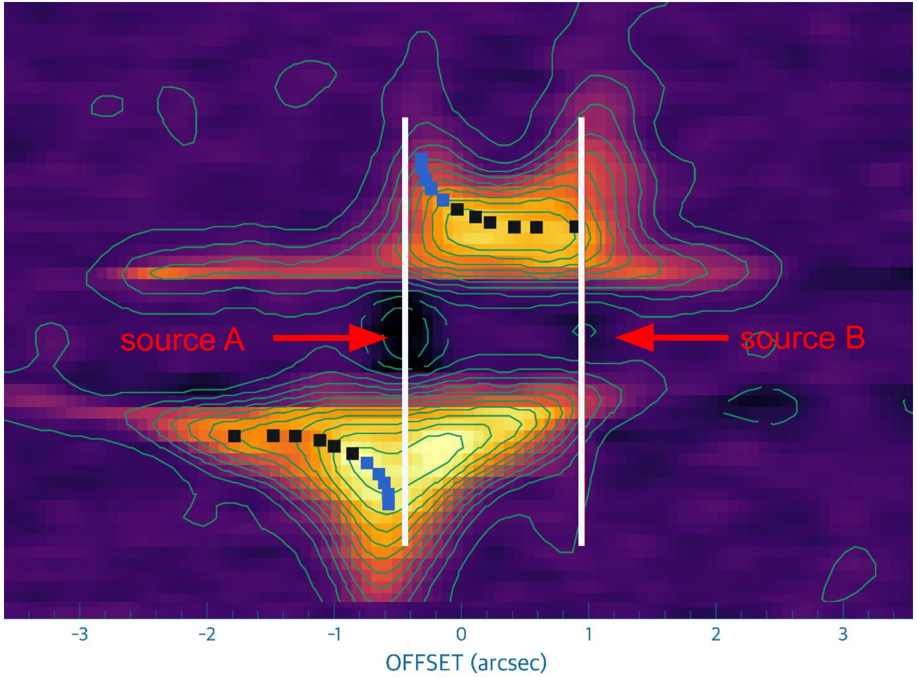


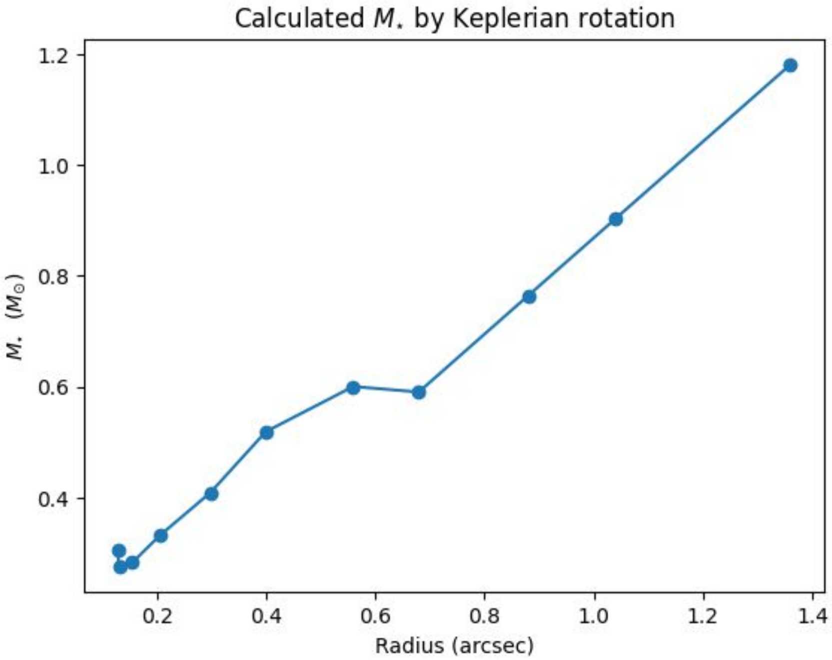




Calculation of stellar mass

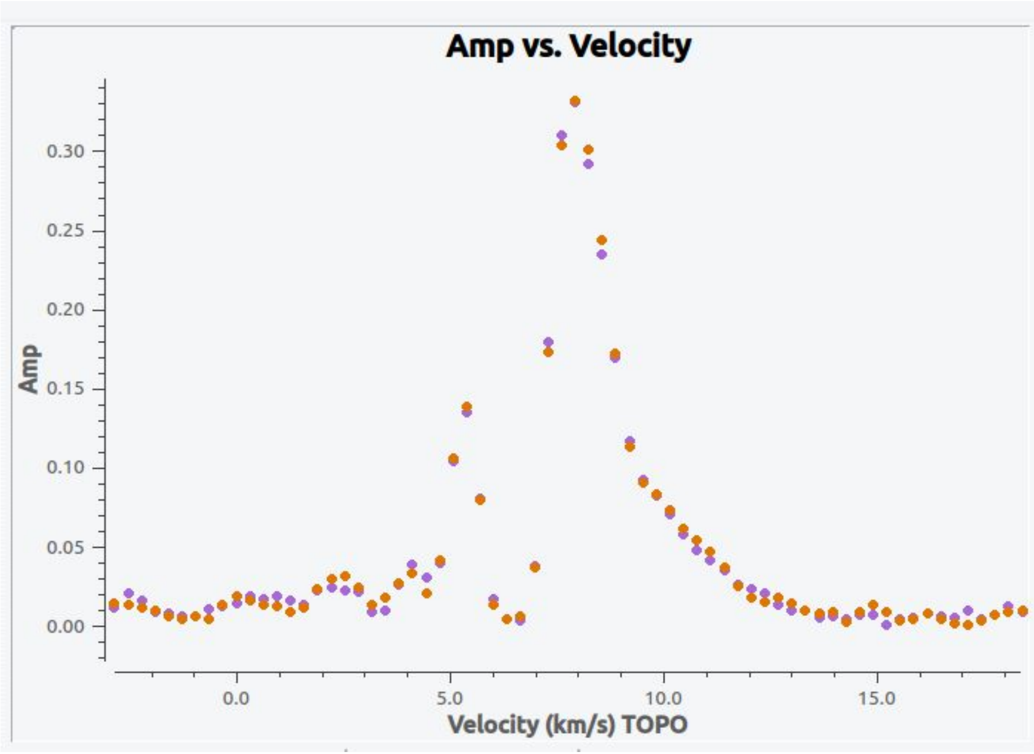
R CrA





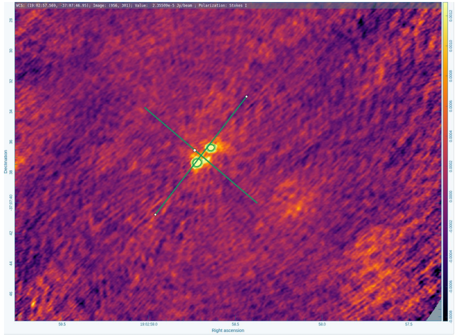
PV Diagram along major axis shows an additional feature apart from rotation.
→ presence of another nearby source.

Class 0 protobinary, **R CrA IRAS 32**

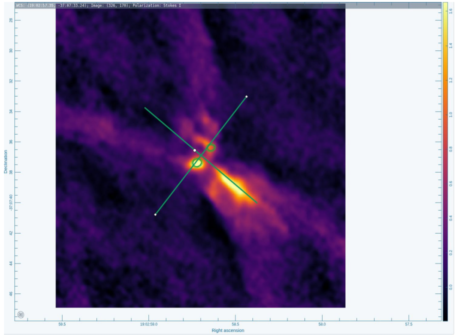


Moment Image & Continuum Image about **12CO**

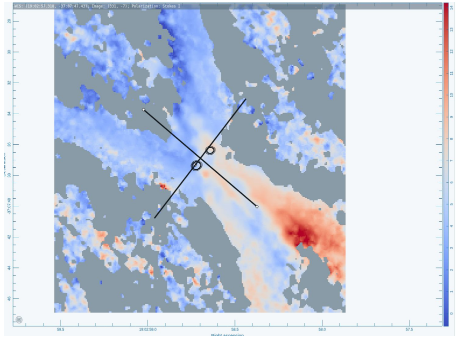
R CrA



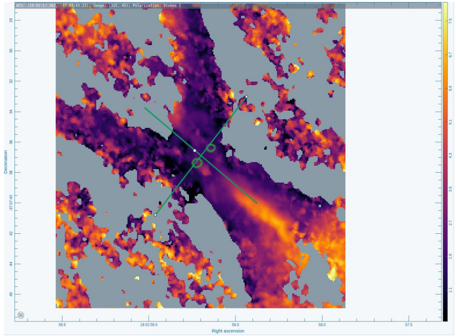
Continuum Image



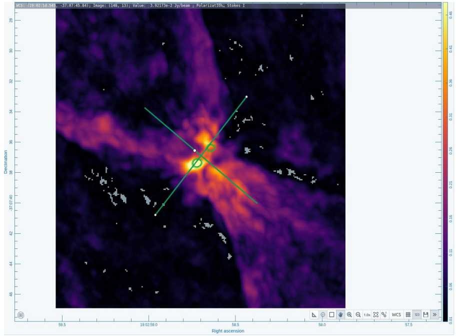
Moment 0



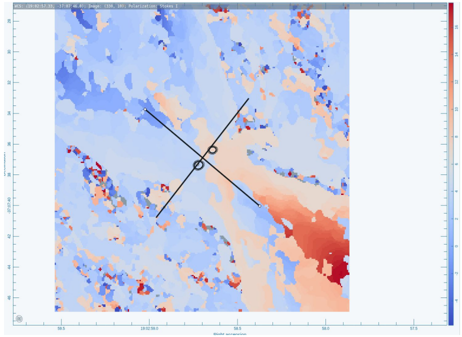
Moment 1



Moment 2

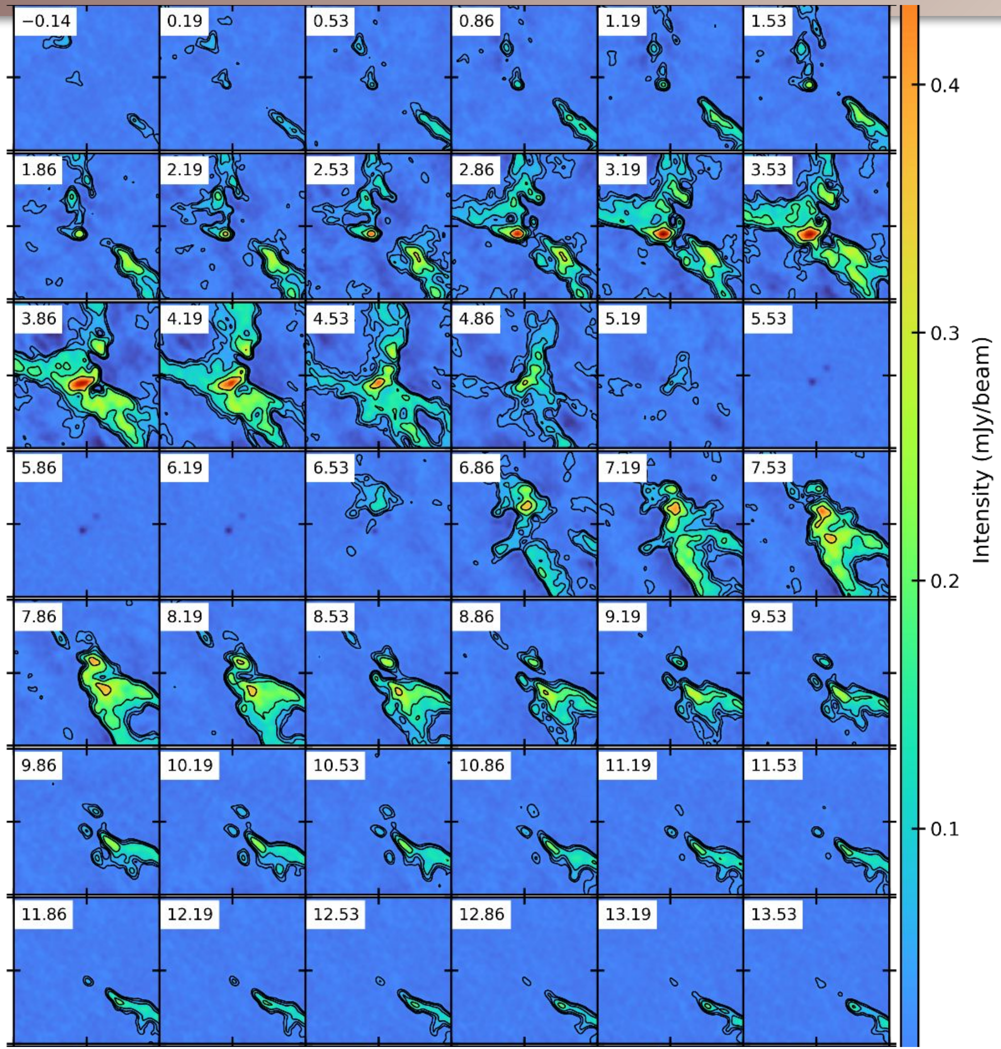


Moment 8



Moment 9

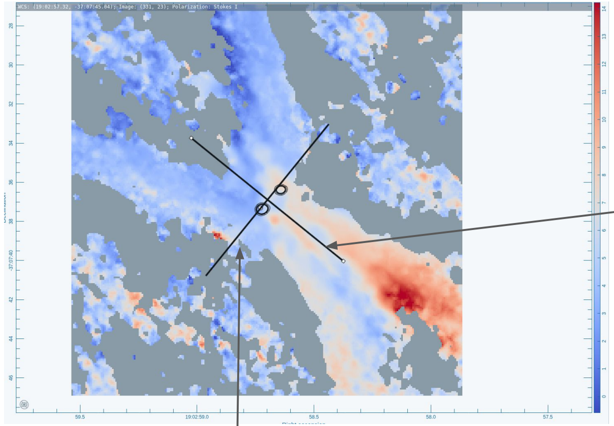
Channel Map



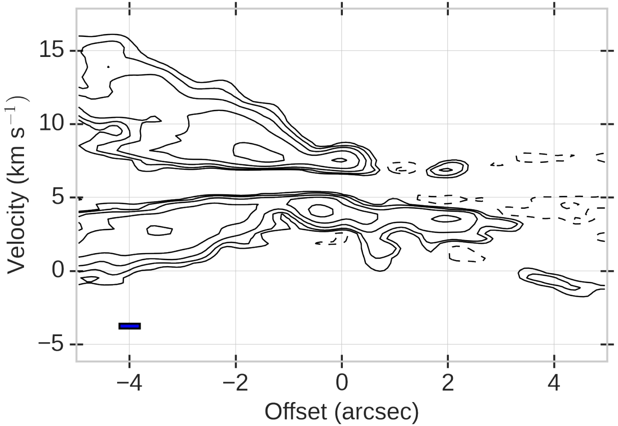
R CrA

Position-Velocity Diagram & Moment 1 Image

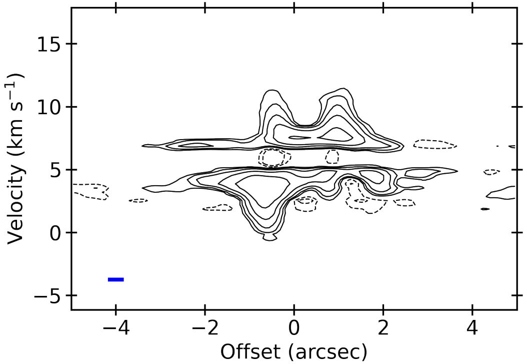
R CrA



moment 1 image



Minor Axis



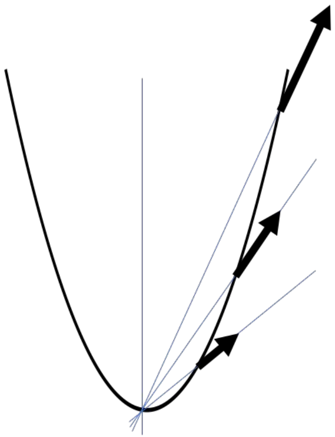
Major Axis

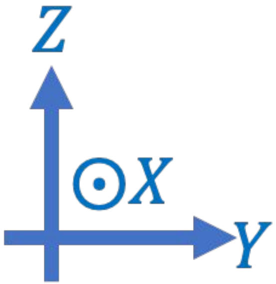
Outflow

$$Z = \pm r_0 \left(\frac{Y}{r_0}\right)^2$$

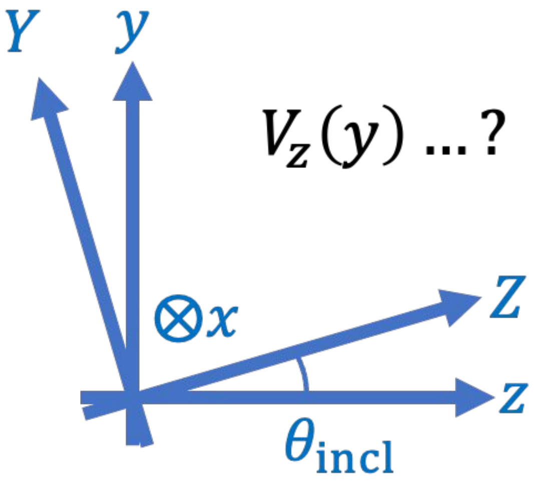
$$V_Y = V_0 \frac{Y}{r_0}$$

$$V_Z = V_0 \frac{Z}{r_0}$$





Outflows often show the Hubble law (acceleration) because outer regions are less dense.
A parabolic shell model is widely used (Lee et al. 2000, ApJ, 542, 925).



Outflow

R CrA

$$\begin{pmatrix} z \\ y \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} Z \\ Y \end{pmatrix}$$

$$\begin{pmatrix} z/r_0 \\ y/r_0 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} (Y/r_0)^2 \\ Y/r_0 \end{pmatrix}$$

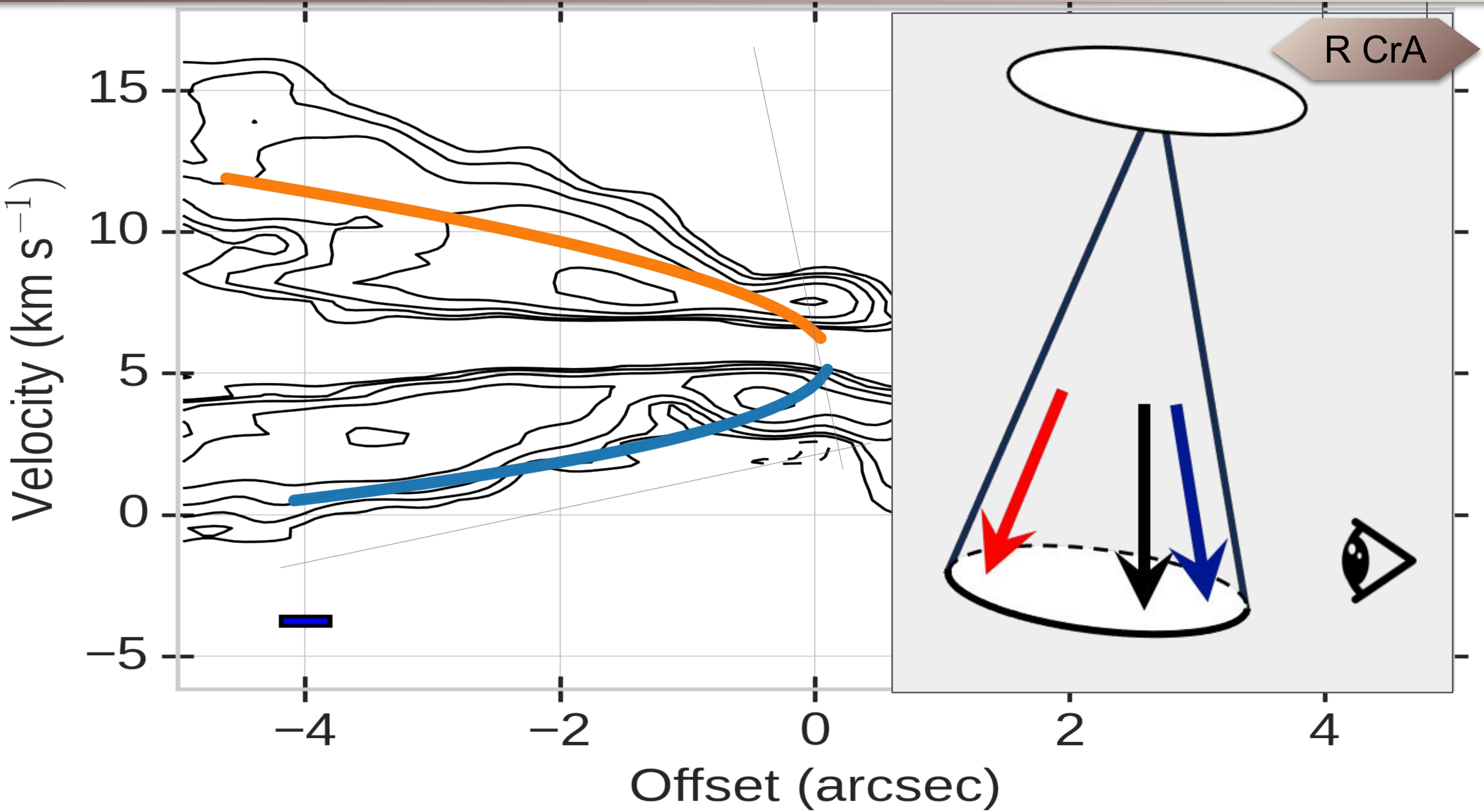
$$\frac{y}{r_0} = \left(\frac{Y}{r_0}\right)^2 \sin\theta + \frac{Y}{r_0}\cos\theta \cdots (1)$$

$$\begin{pmatrix} V_z \\ V_y \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} V_Z \\ V_Y \end{pmatrix}$$

$$\begin{pmatrix} V_z/V_0 \\ V_y/V_0 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} (Y/r_0)^2 \\ Y/r_0 \end{pmatrix}$$

$$\frac{V_z}{V_0} = \left(\frac{Y}{r_0}\right)^2 \cos\theta - \frac{Y}{r_0}\sin\theta \cdots (2)$$

Delete $\frac{Y}{r_0}$ from Eqs. (1) and (2) and plot the relation on the $(\frac{y}{r_0}, \frac{V_z}{V_0})$ plane with $\theta = 60°$, for example.


R CrA
Velocity (km s^{-1})
15
10
5
0
−5
−4
−2
0
2
4
Offset (arcsec)

Summary

We analyzed spectral line data (eDisk ALMA Large program) of three protostellar systems in three different lines to explore kinematics, morphology, and physical quantities.

IRAS 04302:
The ^{13}CO J=2-1 line traces a Keplerian disk and an infalling gas with asymmetric emission, while the C^{18}O J=2-1 line mainly traces the Keplerian disk not affected by the infalling gas or the asymmetric emission.

Ced110:
The ^{13}CO line mainly traces a Keplerian disk, enabling us to estimate the stellar mass. We also estimated temperature and column density using the ^{12}CO and ^{13}CO lines together.

RCrA32:
The ^{13}CO line traces rotating and infalling gas around the binary. The stellar mass estimation needs high-velocity components close to each protostar. In comparison, the ^{12}CO line mainly traces an outflow, which can be explained by the parabolic shell model.

Thank you