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별탄생 연구실
Star Formation Group
Grupo de Formación Estelar

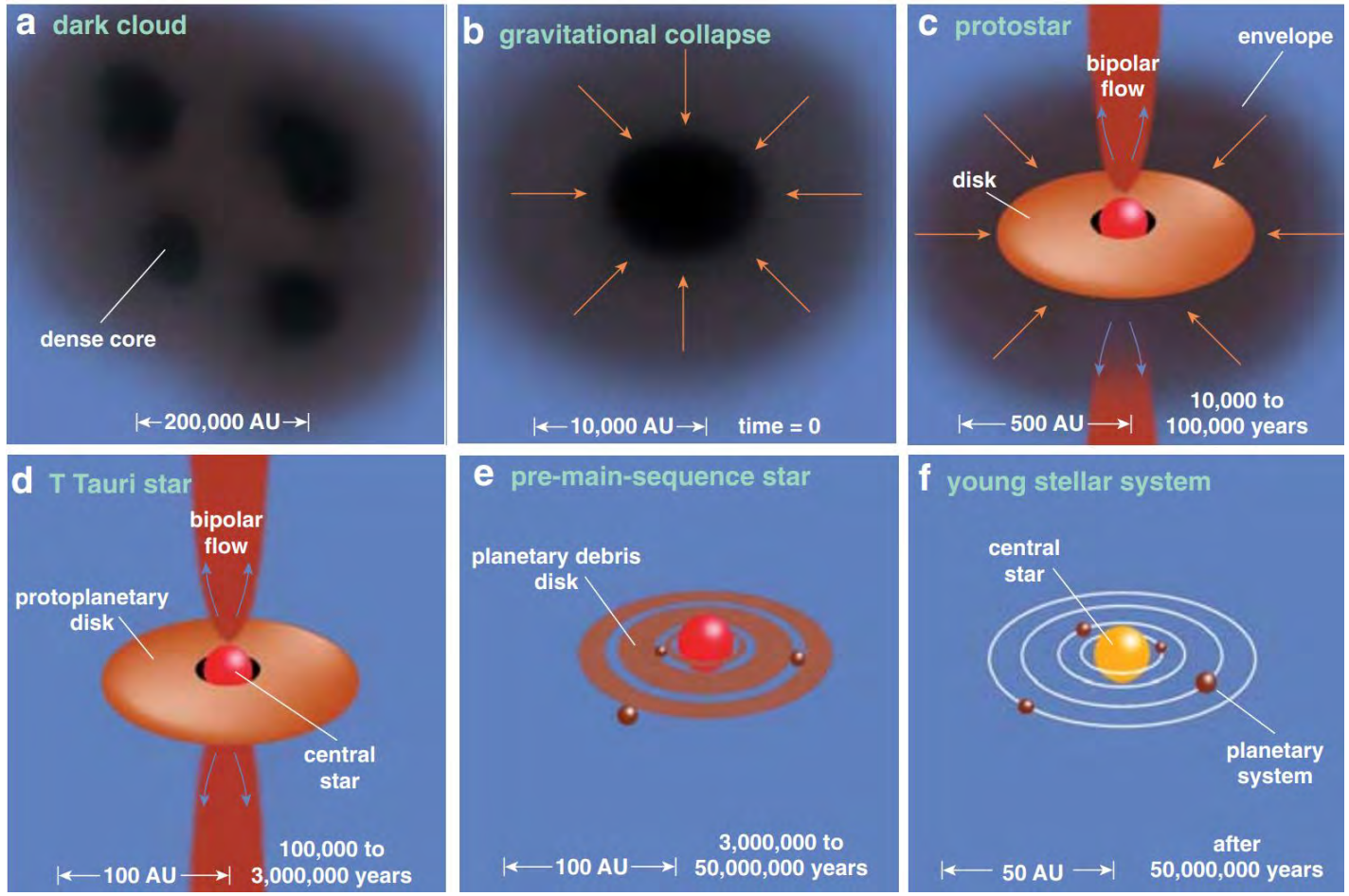
EAMA 11

Protostellar outflows driven by disk winds within planet-forming region in HOPS 358



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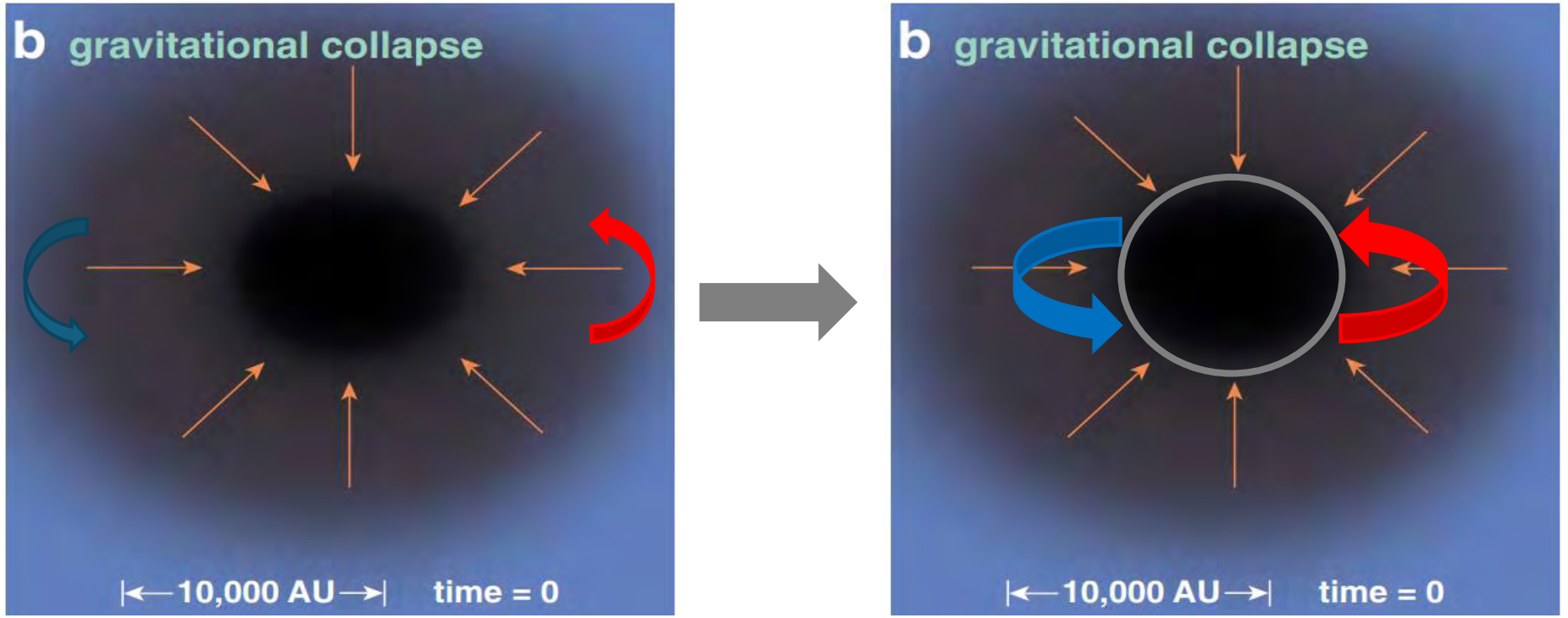


Credits: Greene 2001

During the star formation

One of the important questions :

Angular Momentum Problem



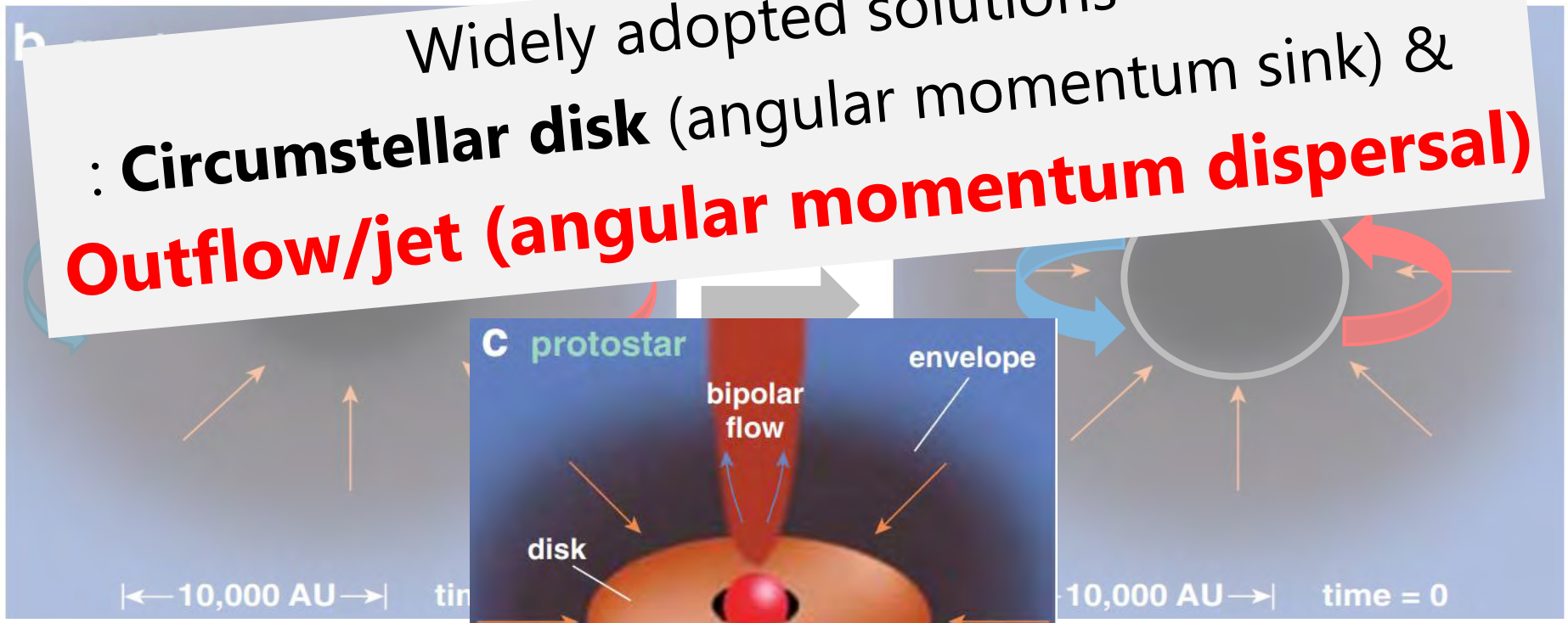
Angular Momentum Problem

: If the angular momentum of this core were conserved during collapse and subsequent protostellar accretion, the forming star would attempt to rotate faster than its break-up speed

Widely adopted solutions

: **Circumstellar disk** (angular momentum sink) &

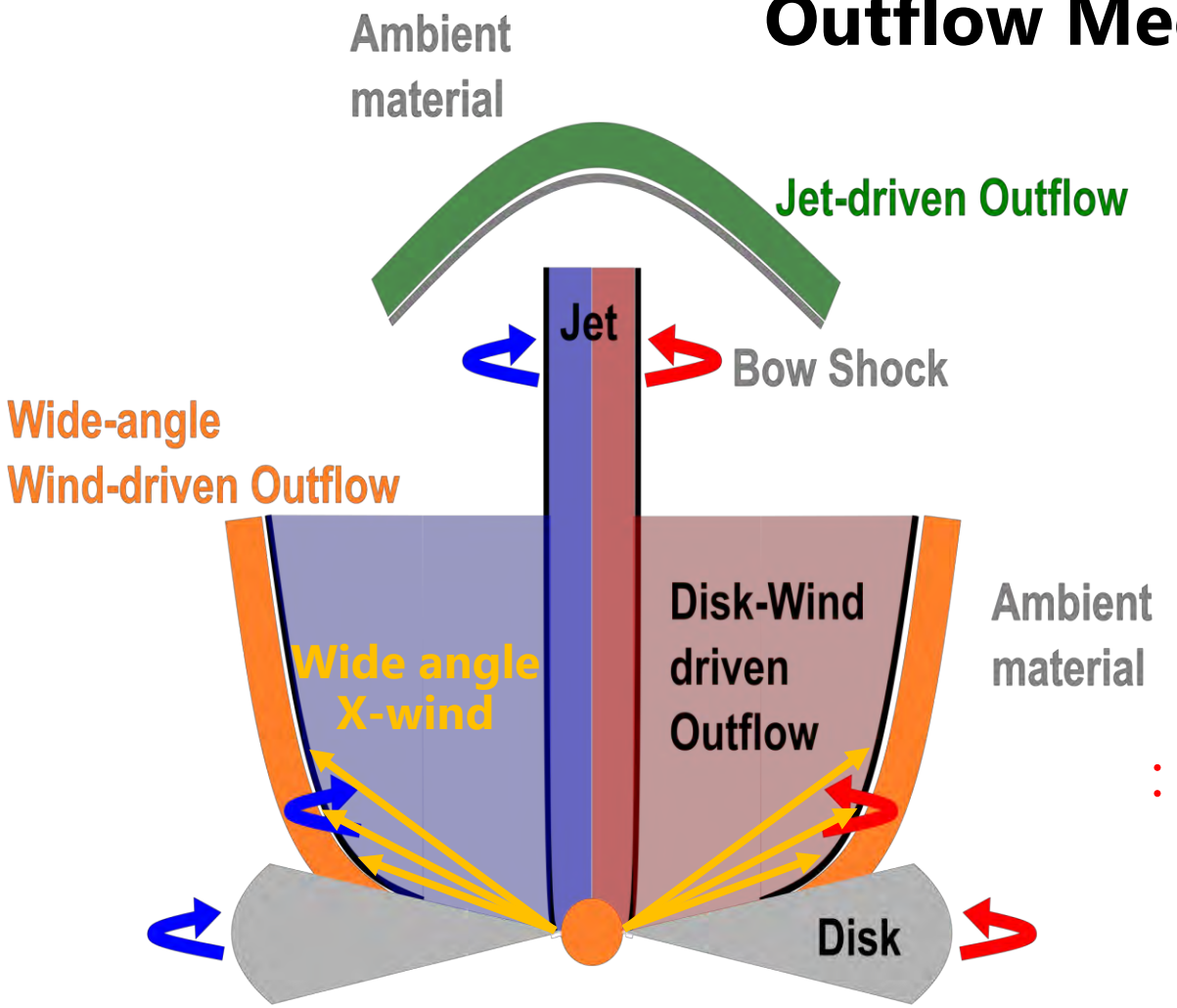
Outflow/jet (angular momentum dispersal)



Angu lem

: If the angular momentu d during collapse and subsequent protostellar acc d attempt to rotate faster

Outflow Mechanism



Models

Jet-driven Outflow

Wide-angle Wind-driven Outflow

Disk-wind driven Outflow

: Directly ejected material from the disk

: Rotation feature

Disk Wind : **Magnetohydrodynamics (MHD) vs Photoevaporative**

MHD

- ✓ Driven by magnetic field
- ✓ Launched over a broad range of disk radii
- ✓ Effectively removes angular momentum across the disk radii

→ Contribute the accretion activity

Photoevaporative

- ✓ Driven by high-energy radiation
- ✓ Disk clearing
- ✓ Not influence accretion activity

Determining when and where each mechanism dominates remains crucial for understanding the protostellar evolution.

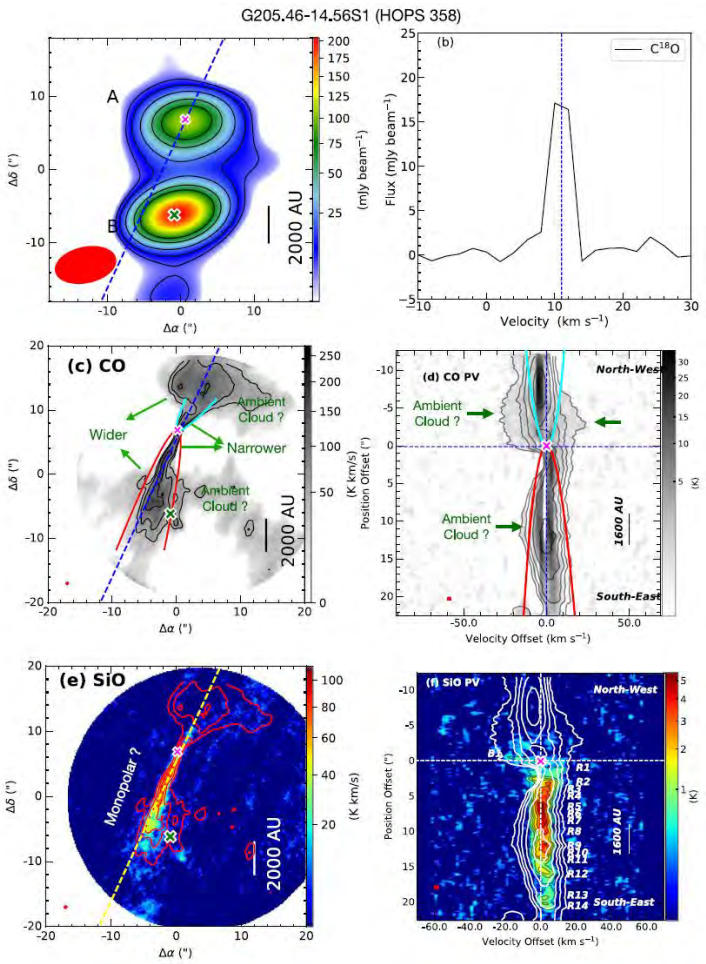


Figure B3 in Dutta et al. 2024

Science Target : HOPS 358

Class 0 (PACS Bright Red Source)

Inclination of outflow (LoS) : ~ $\mathbf{85^{+2}_{-2}}$ ° (Jhan et al. 2022)

v_{sys} : **11 km/s**

Distance : **404 pc**

(Dutta et al. 2024)

L_{tot} $(\sim L_{\mathrm{acc}})$: **60.4** $\boldsymbol{L_{\odot}}$ (Furlan et al. 2016)

P.A of disk : $\mathbf{\sim 253.4^{+0.2}_{-0.1}}$° (Sheehan et al. 2025)

ALMA



Project Code : 2023.1.01245.S (Cycle 10)

PI : Chul-Hwan, Kim

Obs date : 2023 October

Baseline : 92.1 m ~ 8.5 km (C-8)

Band : Band 6

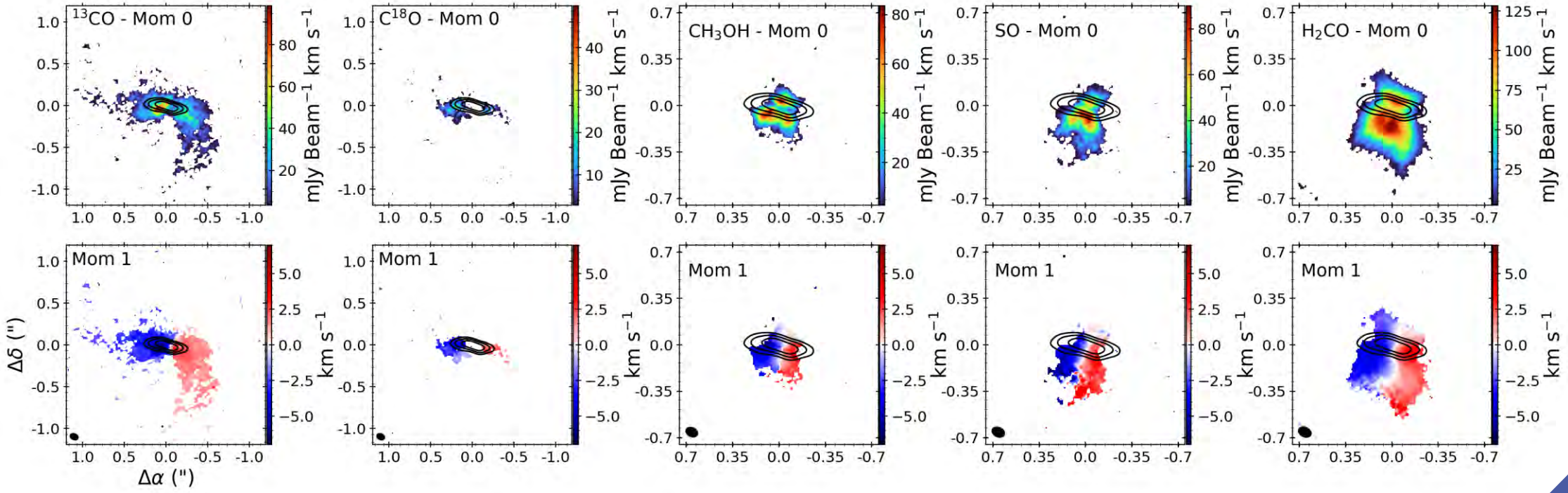
Covered Molecules : SiO, H_2CO, SO, CH_3OH, CO (outflow tracer), $C^{18}O$, ^{13}CO (disk tracer)

Weighting : Natural (to improve the S/N)

Channel width : ~ 0.122 & 0.244 MHz (~0.17 & 0.34 km/s)

Beam size : 0.08~0.1″ x 0.07″

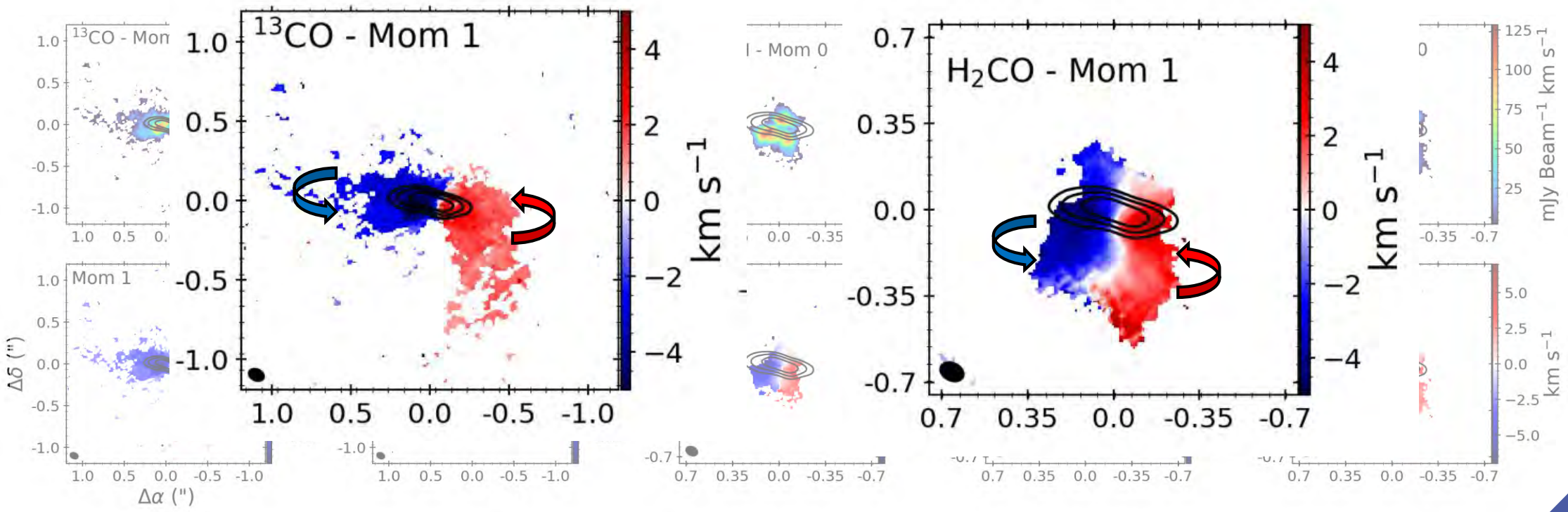
Integrated intensity (moment 0) & Intensity-weighted velocity (moment 1) map



Emission used only above 4σ

Velocity range: -11 ~ 11 km/s

Rotation feature : Disk & Outflow

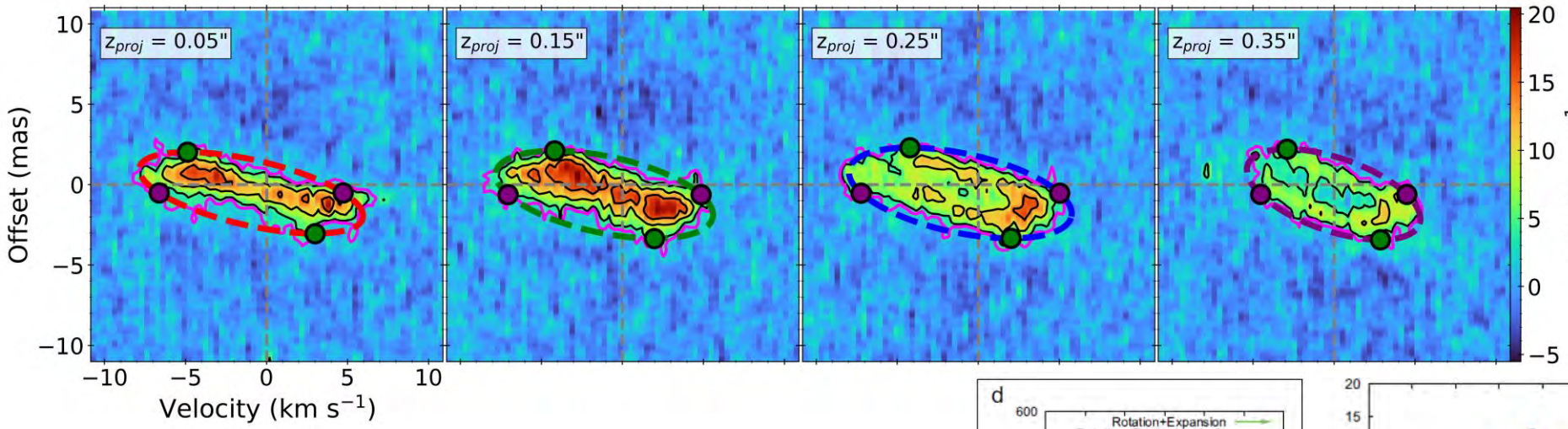


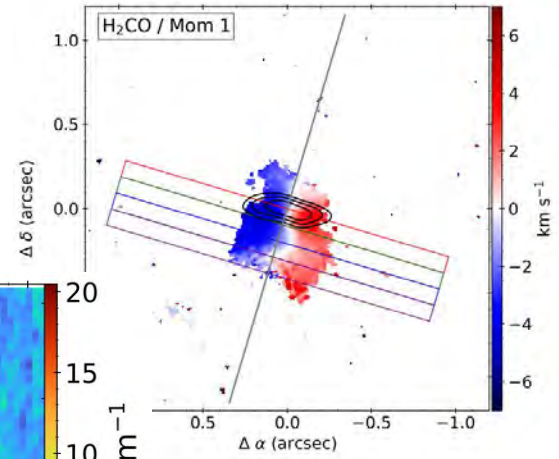
Emission used only above 4σ

Velocity range: -11 ~ 11 km/s

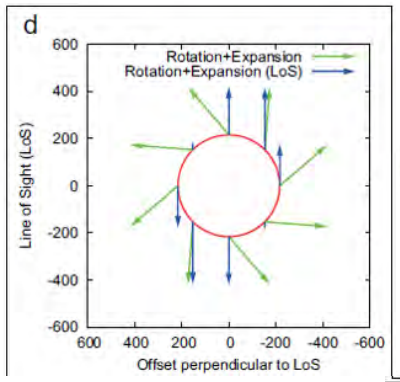
Transverse PV diagram : providing the insight into the outflow kinematics

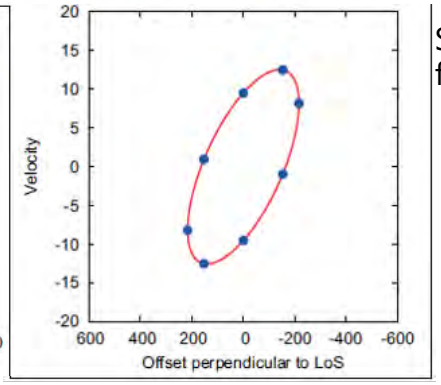
H_2CO





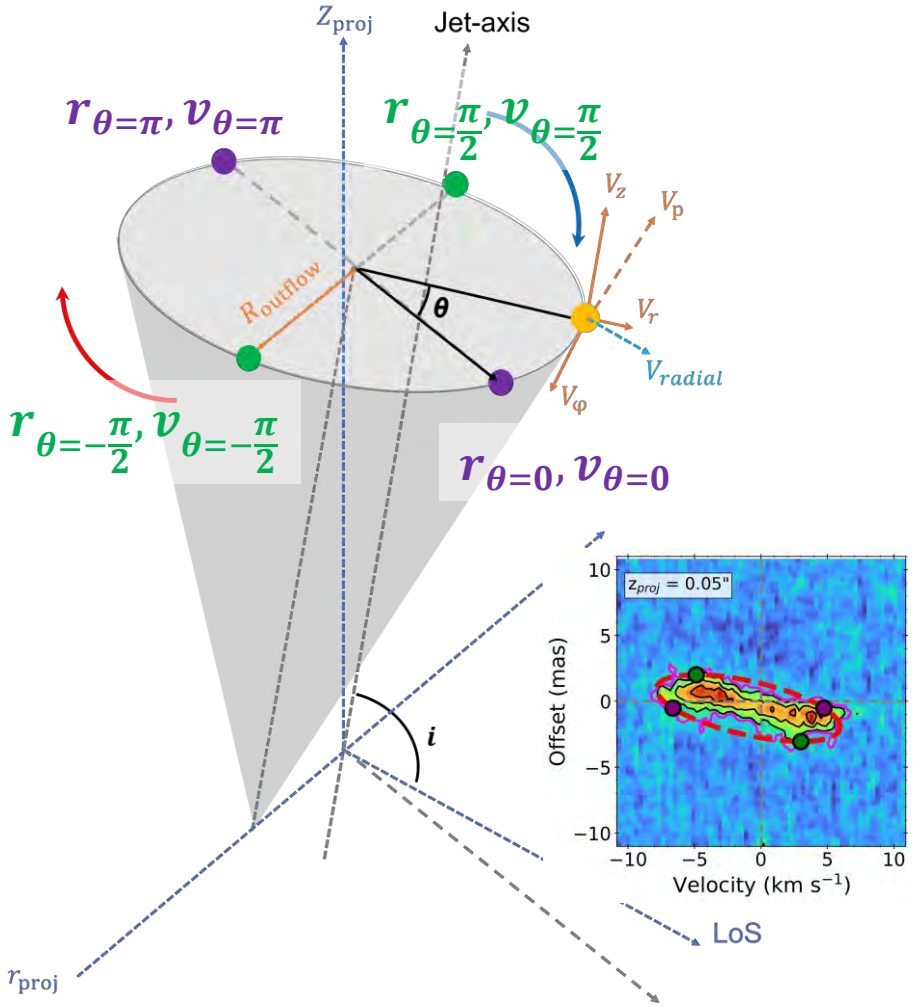
Modeled PV diagrams for the slices of the edge-on rotating and radially expanding outflow





Supplementary Figure 1 from Hirota et al. 2017

Determining the outflow properties



$$R_{\text{outflow}} = \frac{\left|r_{\theta=\frac{\pi}{2}}\right| + \left|r_{\theta=-\frac{\pi}{2}}\right|}{2} \qquad v_\phi = \frac{v_{\theta=-\frac{\pi}{2}} - v_{\theta=\frac{\pi}{2}}}{2\sin i}$$

$$v_r = \frac{v_{\theta=\pi} - v_{\theta=0}}{2\sin i} \qquad v_z = -\frac{v_{\theta=-\frac{\pi}{2}} + v_{\theta=\frac{\pi}{2}}}{2\cos i}$$

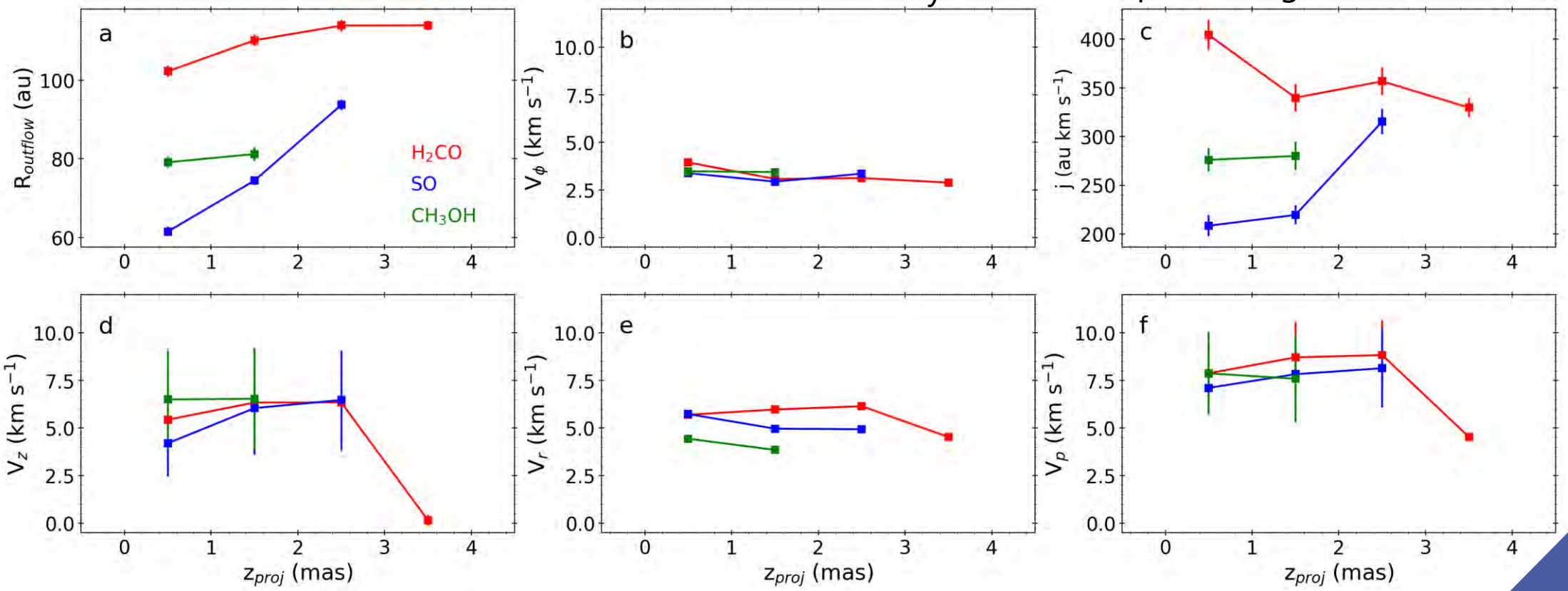
$$v_{\text{p}} = \sqrt{v_z^2 + v_r^2} \qquad j_z = R_{\text{outflow}} \times v_\phi$$

Determining the outflow properties

Outflow radius

Rotation velocity

Specific angular momentum

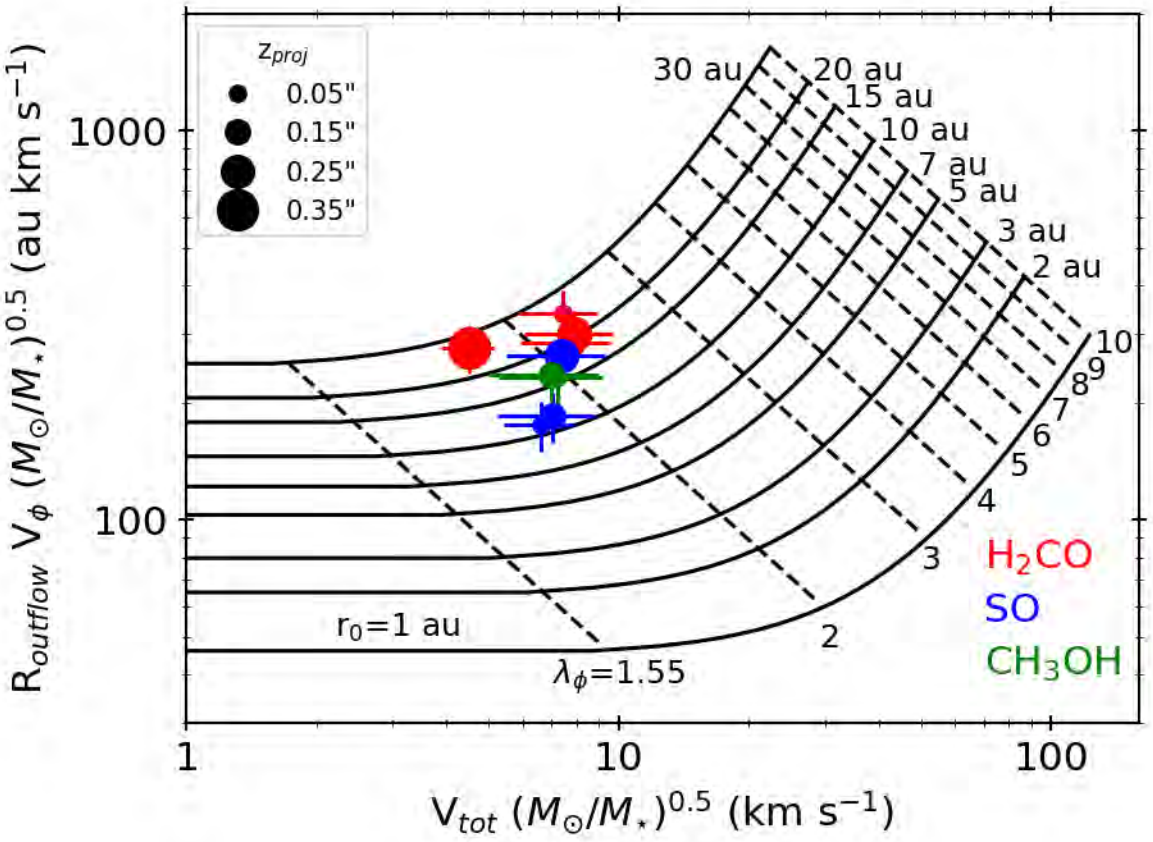


Axial velocity

Radial expanding velocity

Poloidal velocity

Magnetic Lever Arm Parameter



$$(R_{\rm outflow} v_\phi \times v_{\rm tot})/GM_* = \lambda_\phi \sqrt{2\lambda_\phi - 3}$$

Magnetic lever arm parameter

$$\lambda_{BP} = \frac{l_{\rm outflow}}{(GMr_0)^{1/2}}$$

λ_ϕ is lower limit of λ_{BP}, $\lambda_{BP}$from Blandford & Payne 1982

For MHD disk winds, the magnetic level arm parameter should be larger than 1.5, PE disk wind ≈ 1 (Louvet et al. 2018).

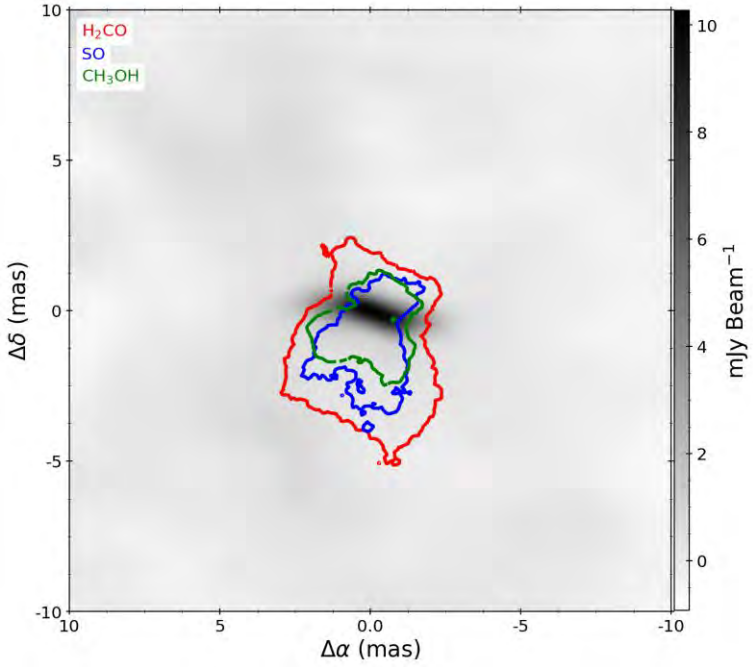
Based on the outflow properties and magnetic lever arm parameter

Outflows traced by three molecules originate from MHD disk wind outflow.

Outer Launching Radius

From Anderson's relation (Equation 4)

$$\left(v_{\mathrm{p}}^2 + v_{\phi}^2\right) r_0^{3/2} + 3(GM_*) r_0^{1/2} - 2R_{\mathrm{outflow}} v_{\phi} (GM_*)^{1/2} \approx 0$$



For a cold, steady, axisymmetric MHD disk wind

Outer launching radii, r_0, of outflows

23.1 ± 2.9 au (H_2CO)

16.2 ± 2.3 au (CH_3OH)

13.8 ± 3.54 au (SO)

Comparing the mass-loss rate and mass accretion rate

Mass-loss rate vs Mass accretion rate

(Estimated from H_2CO outflow)

$(5.1 \pm 1.2) \times 10^{-6}\ M_\odot\ yr^{-1}$ **vs** $(2.7 \pm 0.8) \times 10^{-6}\ M_\odot\ yr^{-1}$

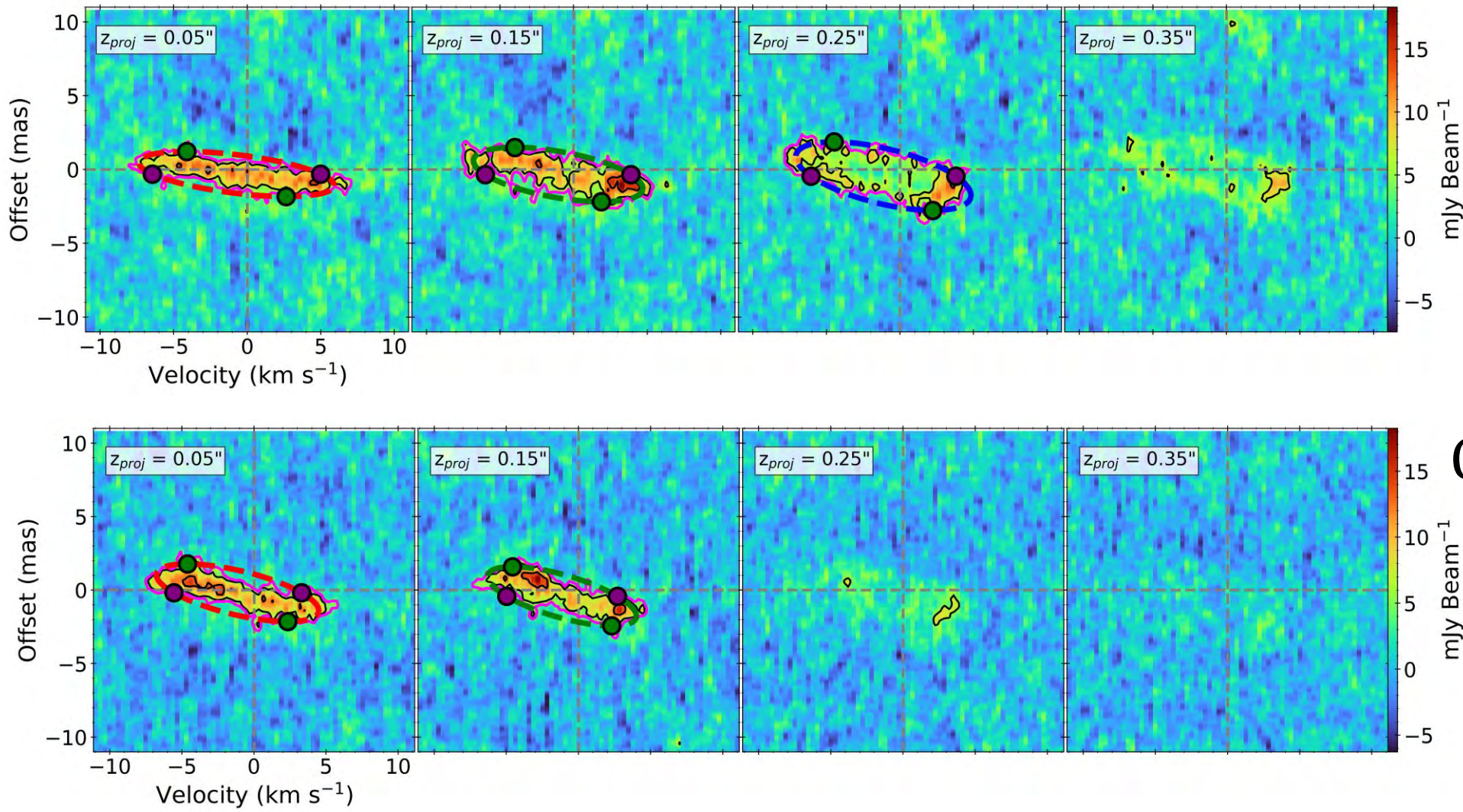
Mass loss rate is about 2 times higher than the accretion rate.

→ The observed wind could plausibly drive the accretion flow.

Both values represent the lower limit of true values.

- ✓ First clear detection the **MHD disk-wind outflow** feature in **HOPS 358 as various molecules** ($H_2CO, SO,$ and CH_3OH)
- ✓ **Three molecules** trace the **different MHD disk-wind layer.**
- ✓ Revealing the **MHD disk wind properties**, **magnetic lever arm parameters**, and **outer launching radii**
- ✓ The observed MHD disk wind could plausibly drive the accretion flow.

Appendix


SO
CH_3OH
z_{proj} = 0.05"
z_{proj} = 0.15"
z_{proj} = 0.25"
z_{proj} = 0.35"
Offset (mas)
Velocity (km s^{-1})
mJy Beam^{-1}

Mass-loss rate

Assuming the optical thin case

(Lower limit)

$$N_u = \frac{8\pi k\nu^2}{A_{ul}hc^3}\int T_{\rm mb}dv$$

$$N_{\rm tot} = N_u Q(T_{\rm ex}) e^{\frac{E_u}{kT_{\rm ex}}}/g_u$$

$$N(H) = N_{\rm tot}/X_{\rm mole}$$

$$M_w = 1.4 m_H N(H) A, \qquad A = \text{area of outflow}$$

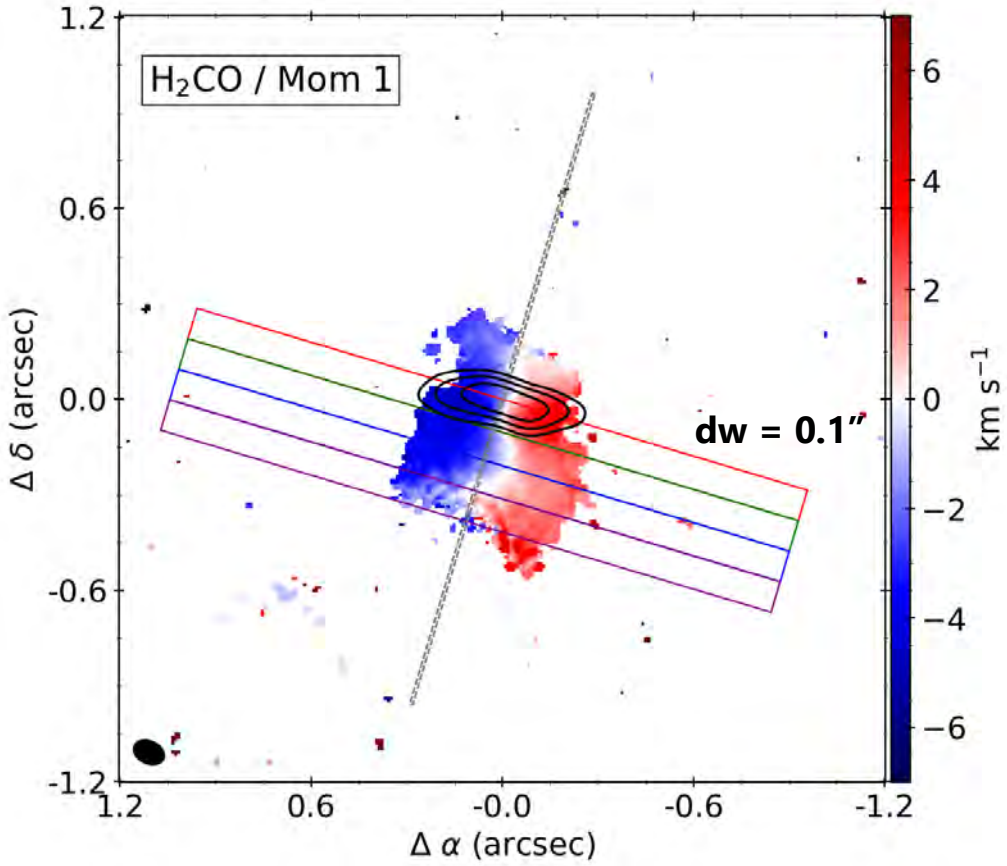
$$P_w = M_w \times v_z$$

$$\dot{M}_w = \frac{M_w}{t_{\rm dyn}} = 1.4 m_H N(H) dr v_z \;\; / \;\; v_z = \frac{dw}{t_{\rm dyn}}$$

For H2CO 3(2,1) – 2(2,0) transition line info

- $X_{H2CO} = 3 * 10^{-7}$ (Jorgensen et al. 2004)
- $A_{ul} = 10^{-3.80205}\ \mathrm{s}^{-1}$ / $\nu = 218.766066$ GHz
- $E_u \left(= \frac{E_u}{k}\right) = 68.11081$ K / $g_{ul} = 7$
- $A =$ (# of pixel in the area) × (area of a pixel) arcsec^2 $= dr \times dw$
- $dr = A/0.1''$ (width of extracted region)
- $T_{\rm ex} = 22.4$ K (Lower limit)
- $Q(22.4\ K) = 10^{1.7402}$
- $v_z = 5.44 \pm 2.23$ (0.05"), 6.34 ± 2.57 (0.15"), 6.35 ± 2.56 (0.25"), 0.16 ± 0.27 (0.35") km/s

Mass-loss rate



Integrated Flux, $\int T_{\mathrm{mb}} dv$

For $Z_{\mathrm{proj}} = 0.05"$ → 2.75×10^2 K km/s

For $Z_{\mathrm{proj}} = 0.15"$ → 3.19×10^2 K km/s

For $Z_{\mathrm{proj}} = 0.25"$ → 2.54×10^2 K km/s

For $Z_{\mathrm{proj}} = 0.35"$ → 1.59×10^2 K km/s

Mass accretion rate

$$\dot{M}_{\mathrm{acc}} = \frac{L_{\mathrm{acc}} R_*}{f_{\mathrm{acc}} G M_*}$$ (Hartmann et al. 2016)

f_{acc}: fraction of the accretion energy that is radiated

$L_{\mathrm{acc}} (= L_{\mathrm{tot}}) = \sim 60.4\ L_\odot$ (Furlan et al. 2016)

$R_* = 2\ R_\odot$ (assumed, Lee et al. 2020; Podio et al. 2021)

$M_* = 1.42 \pm 0.40\ M_\odot$

$f_{acc} = 1$ (assumed, lower limit)

Central Mass

(using *SLAM* ; Aso & Sai 2023)

