Probing 3D Gas Kinematics of the HD 163296 Protoplanetary Disk

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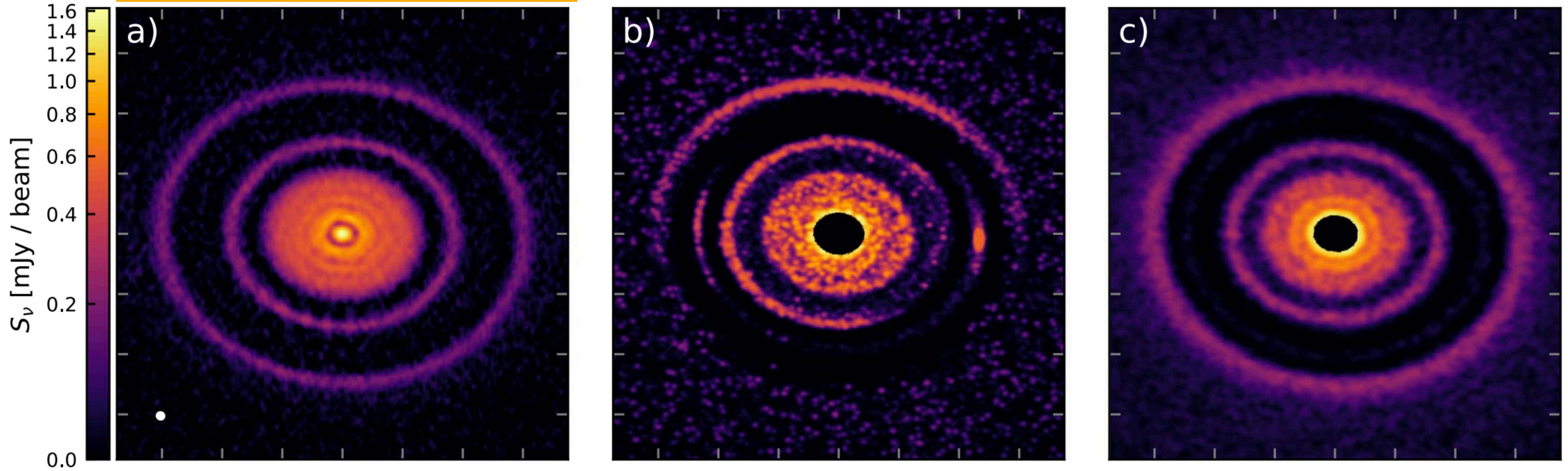
ASROC Annual Meeting 2025

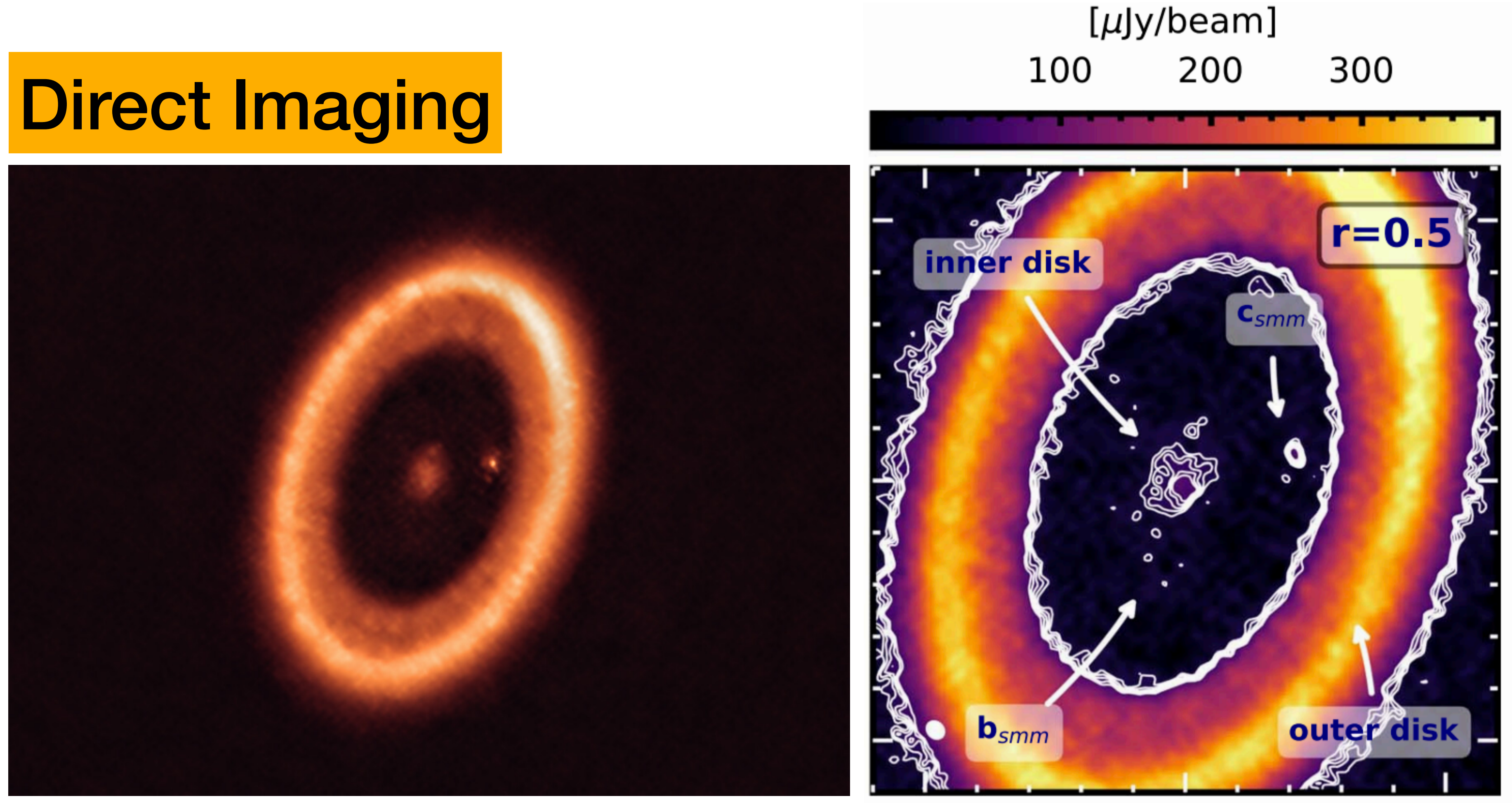
The Hunt for Protoplanets: Recent Studies

Disk Substructures



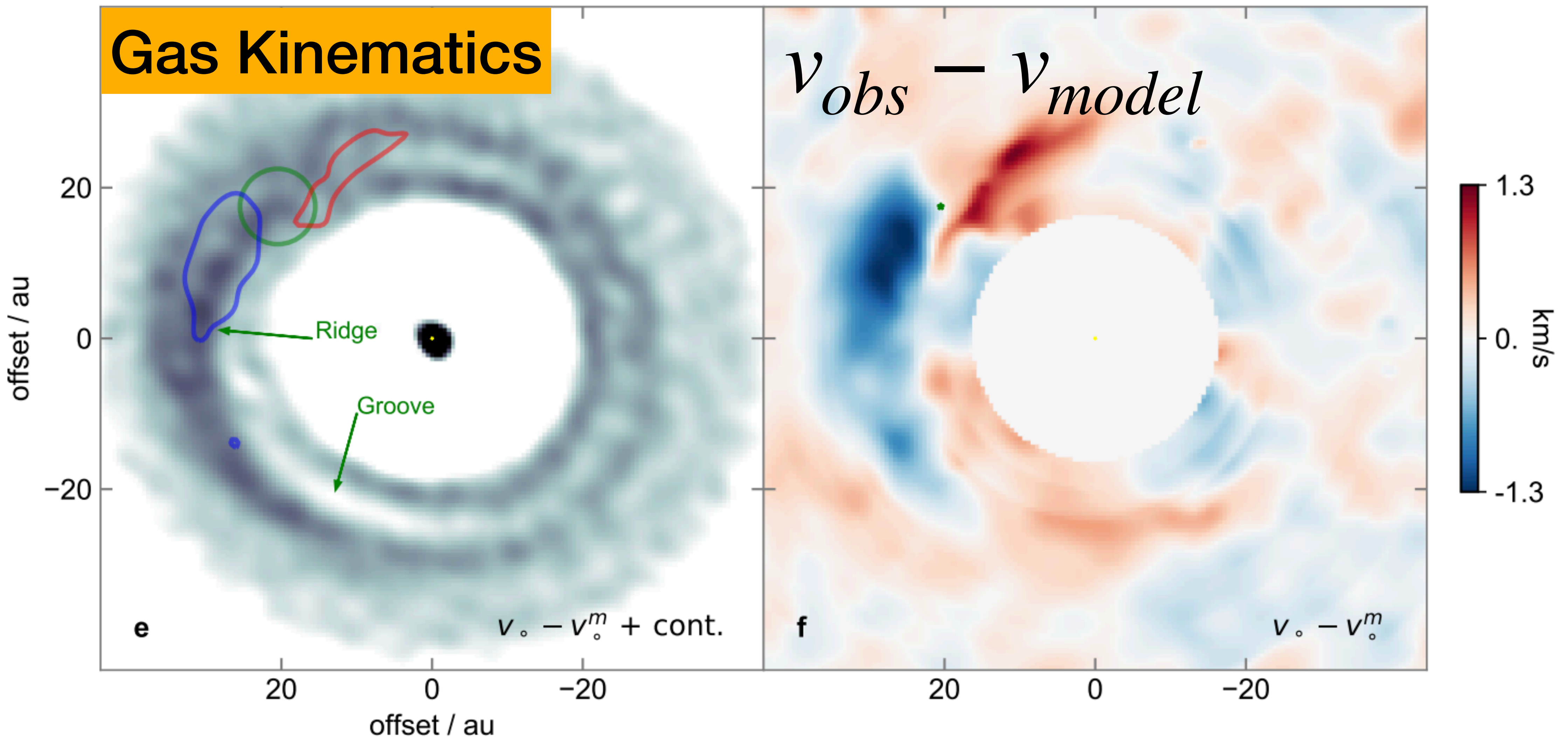
▲ Planet-disk simulation explains substructures in AS 209 (DSHARP VII. 2018)

Direct Imaging



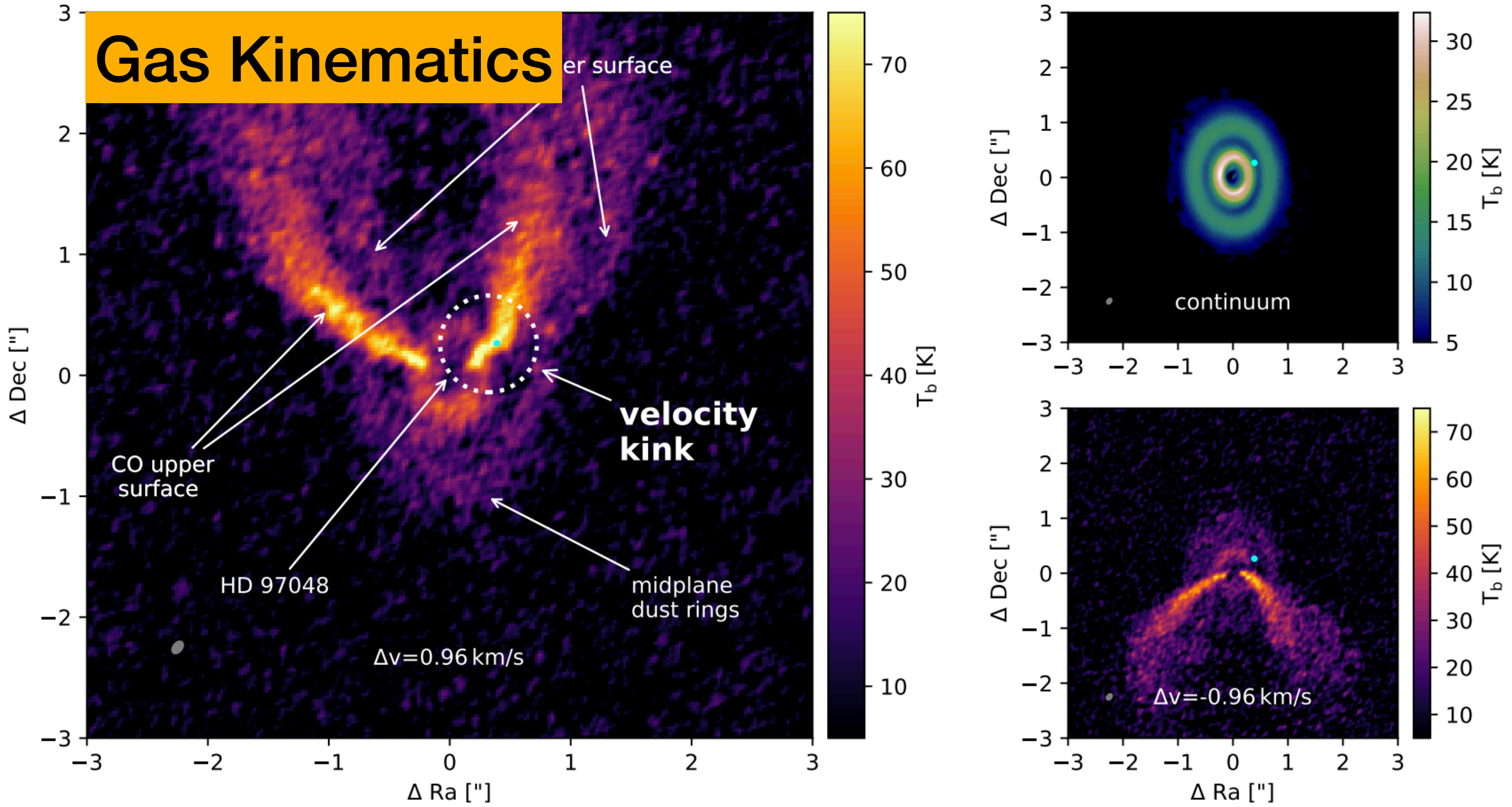
▲ Circumplanetary Disk (CPD) detected in PDS70 (Benisty et al. 2021)

Gas Kinematics



▲ Doppler-flip signature in HD 100546 (Casassus & Pérez 2019)

Gas Kinematics



▲ Kinematic “kink” features associates with the dust gap in HD 97048 (Pinte et al. 2019)

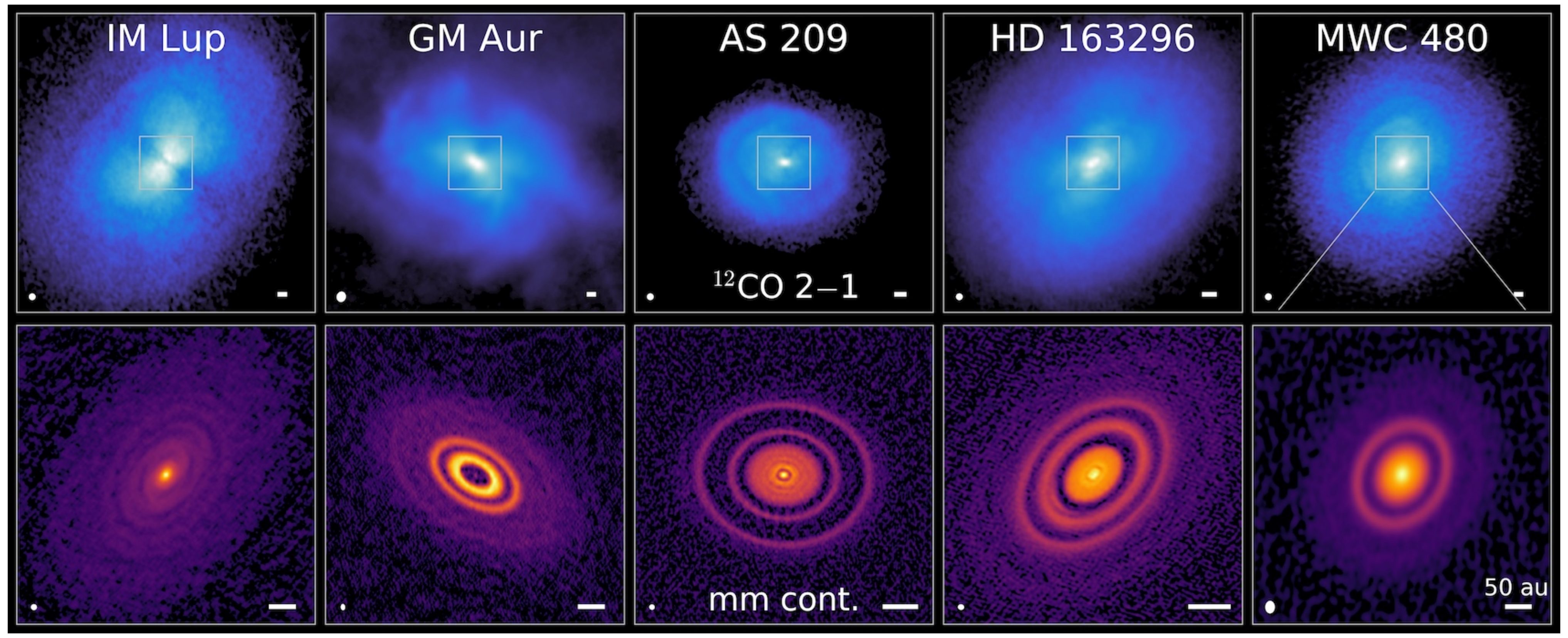
Observation

ALMA's Program
Molecules with ALMA at Planet-forming Scales (MAPS)

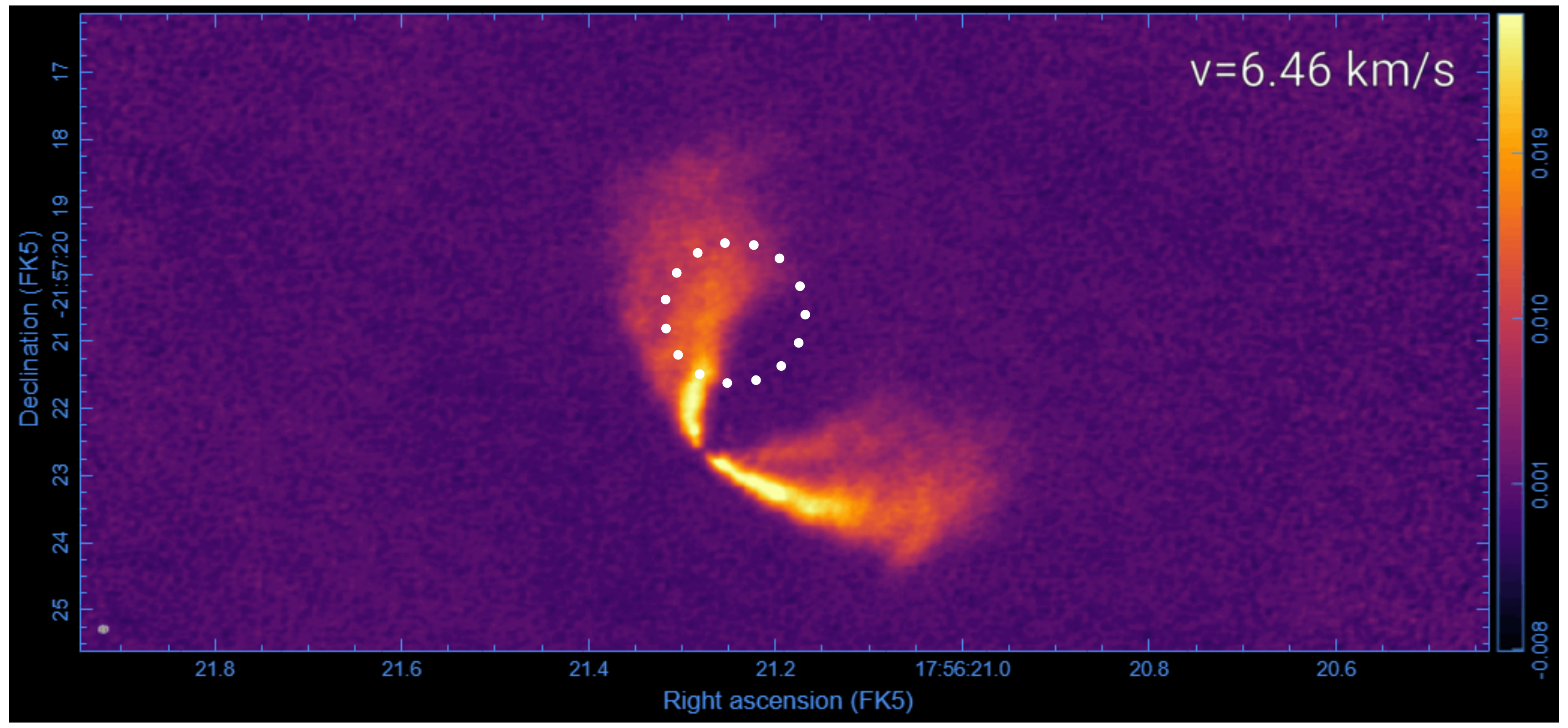
Target
HD 163296 (~101pc)

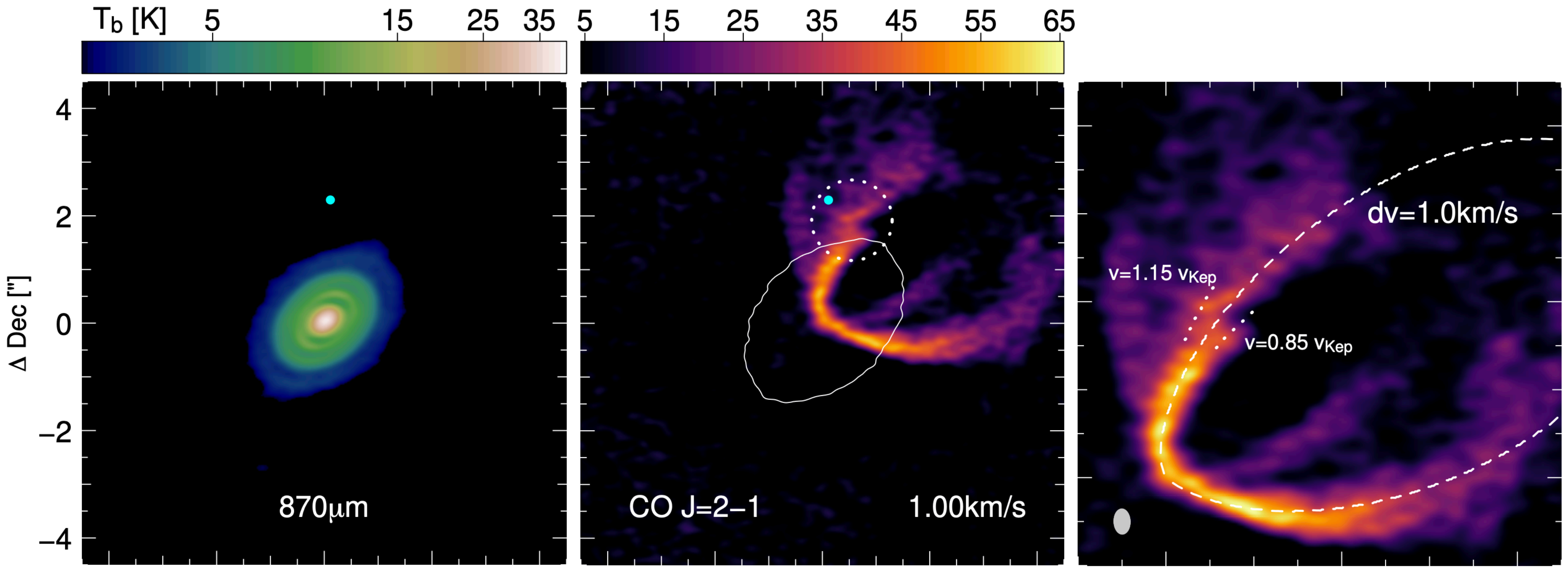
Line emissions
^{12}CO (2-1), ^{13}CO (2-1) and C^{18}O (2-1)

Resolution
~0.15″ angular resolution (~15 au) with 0.2 km/s spectral resolution

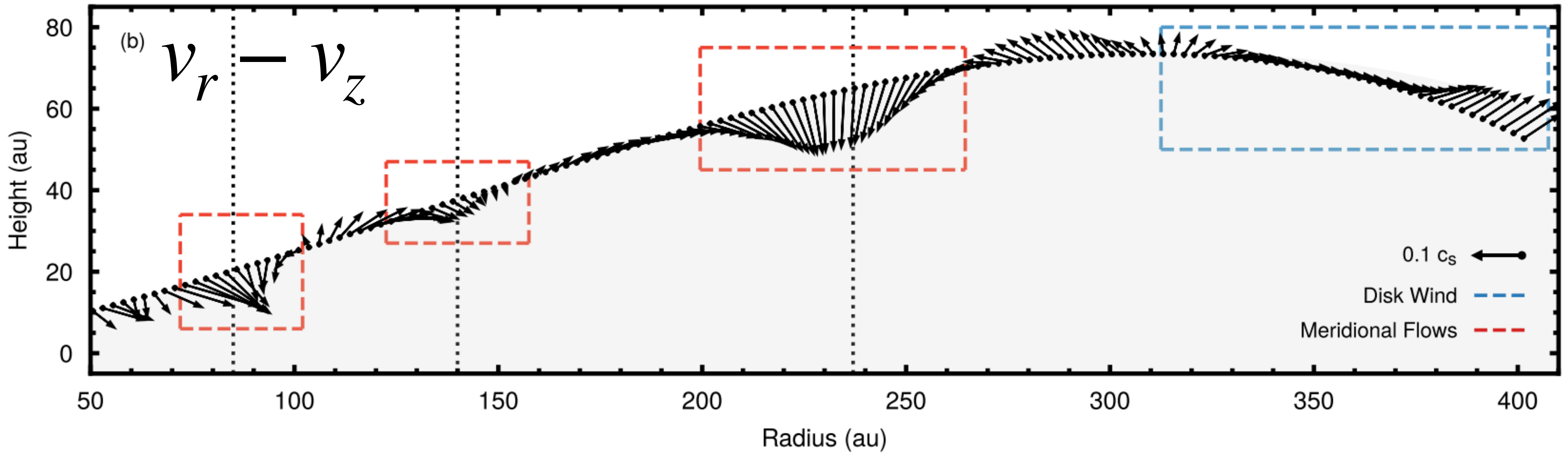


MAPS website

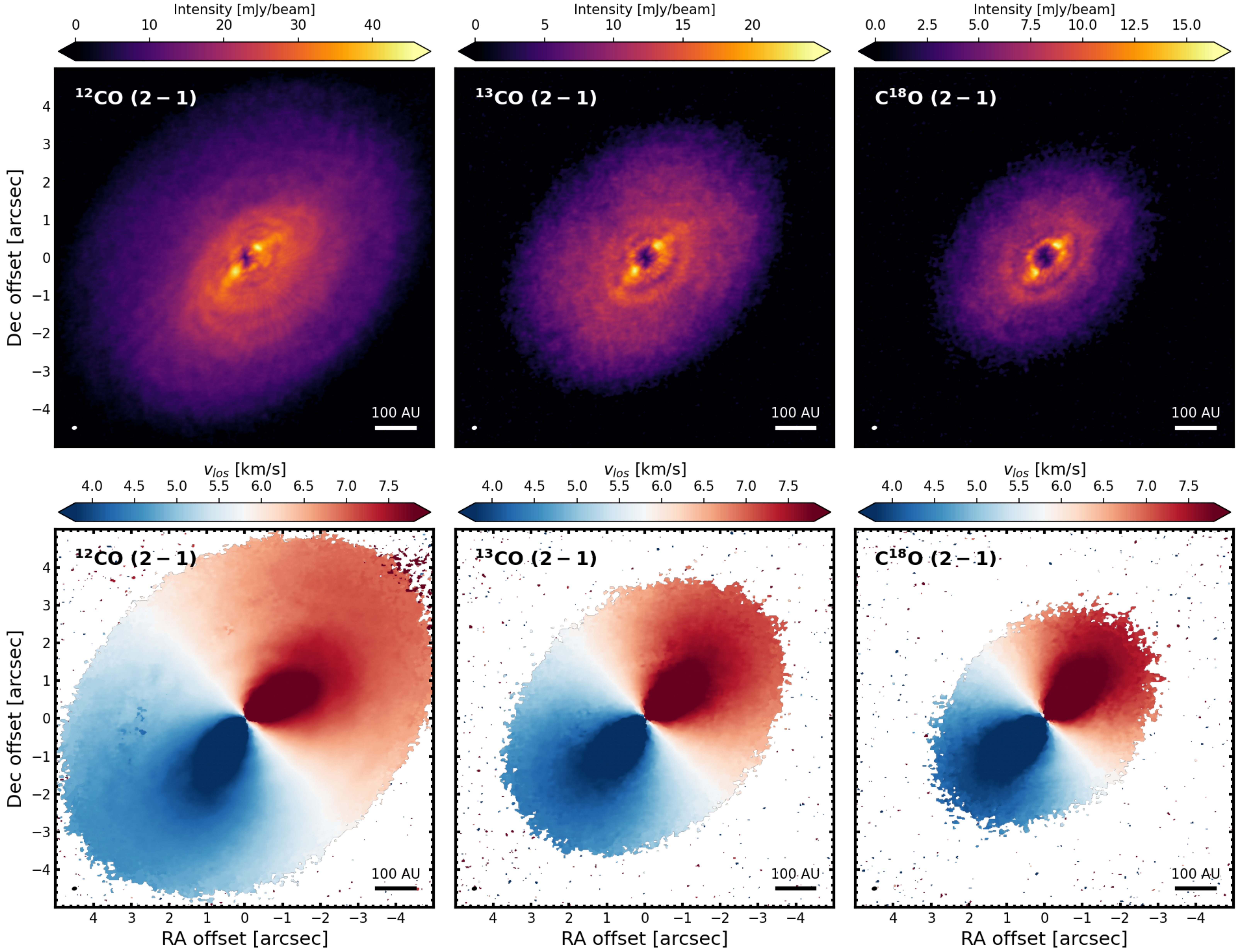




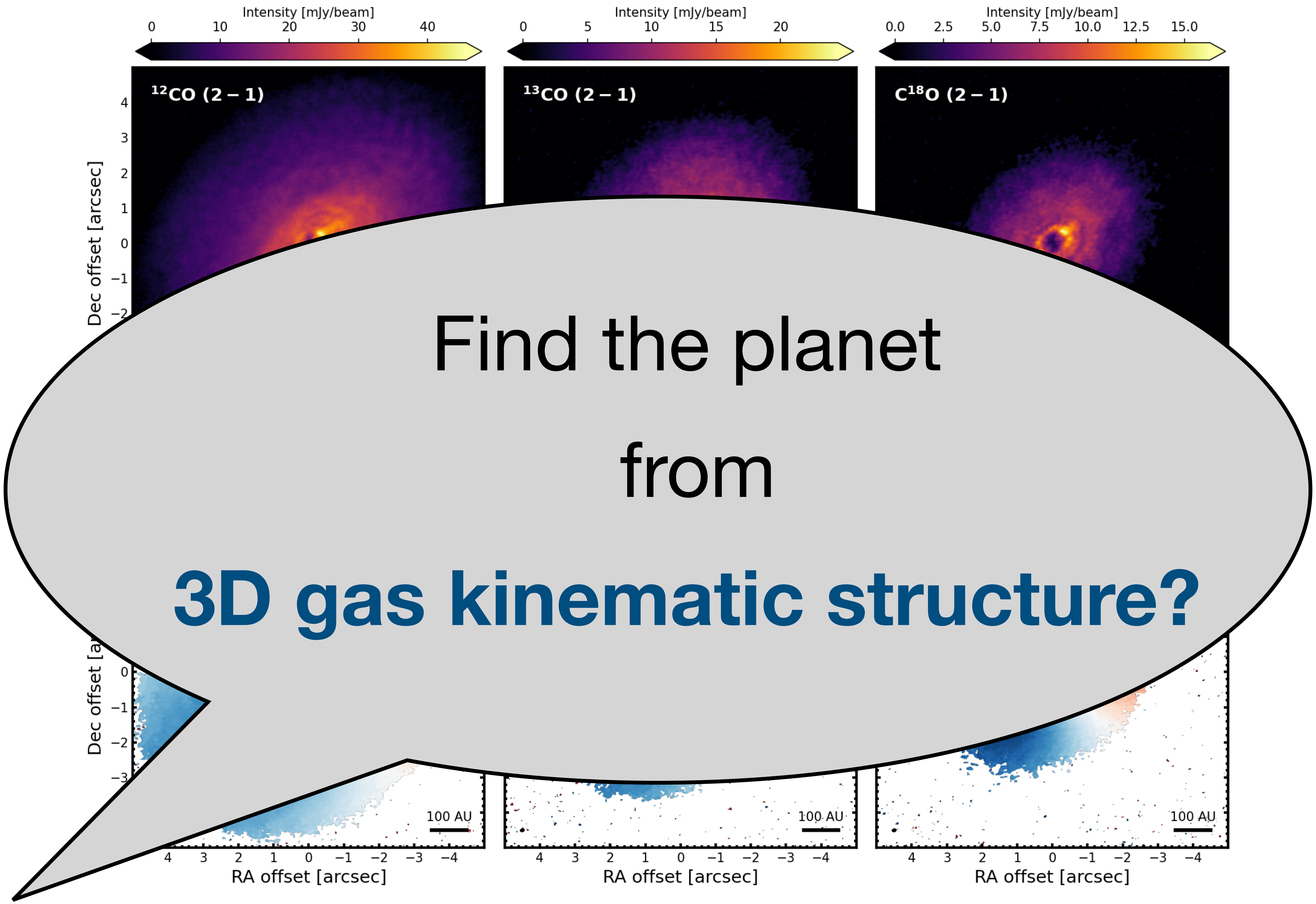
^{12}CO Kink in HD 163296 (Pinte et al. 2018)



Meridional circulation traced in ^{12}CO emission in HD 163296 (Teague et al. 2019)



- All moment maps were generated by `bettermoments` with 3-sigma clipping to the signal.
- ^{12}CO (2-1) traces the uppermost surface, while C^{18}O (2-1) traces the closest surface to the midplane.



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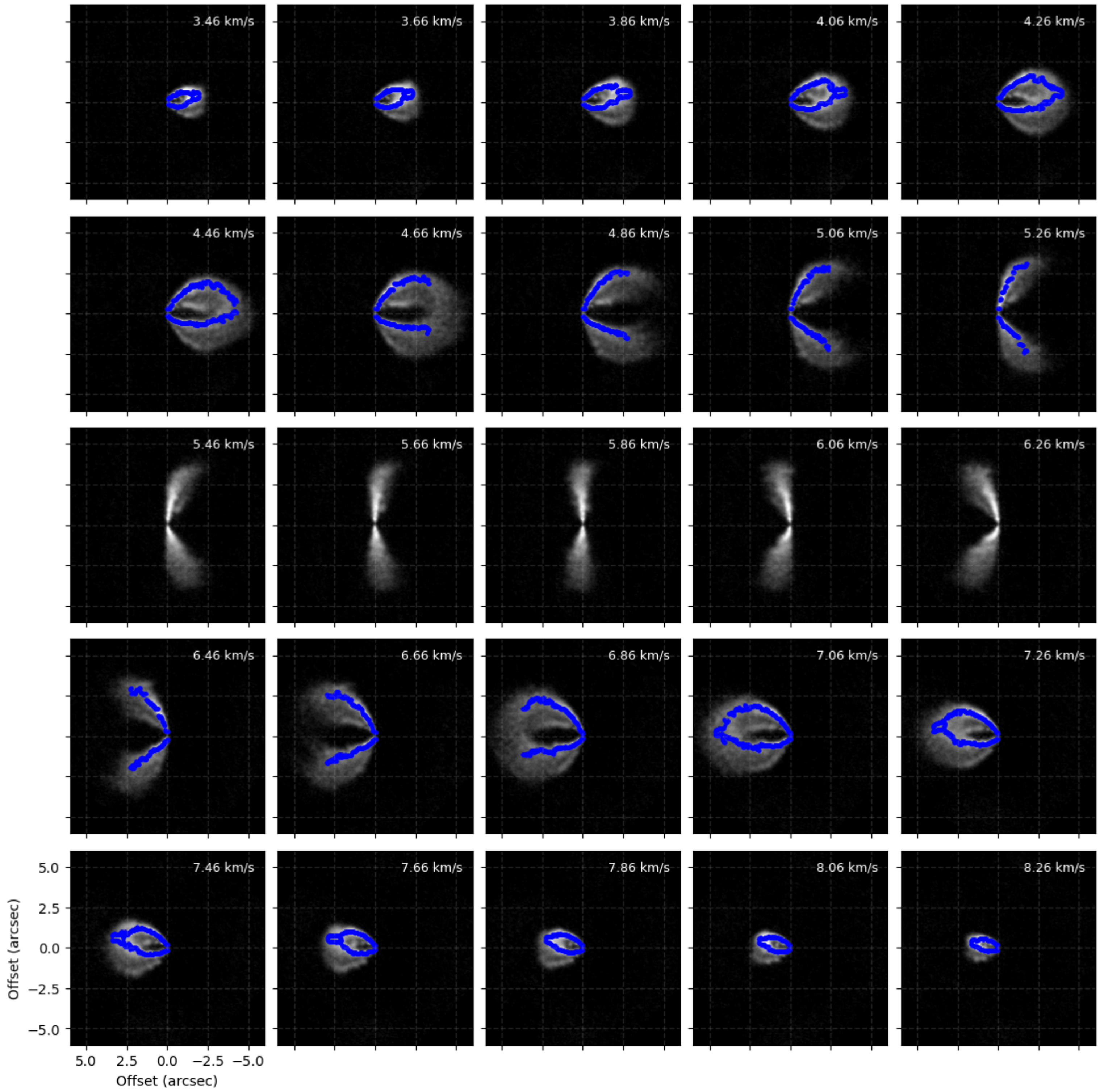
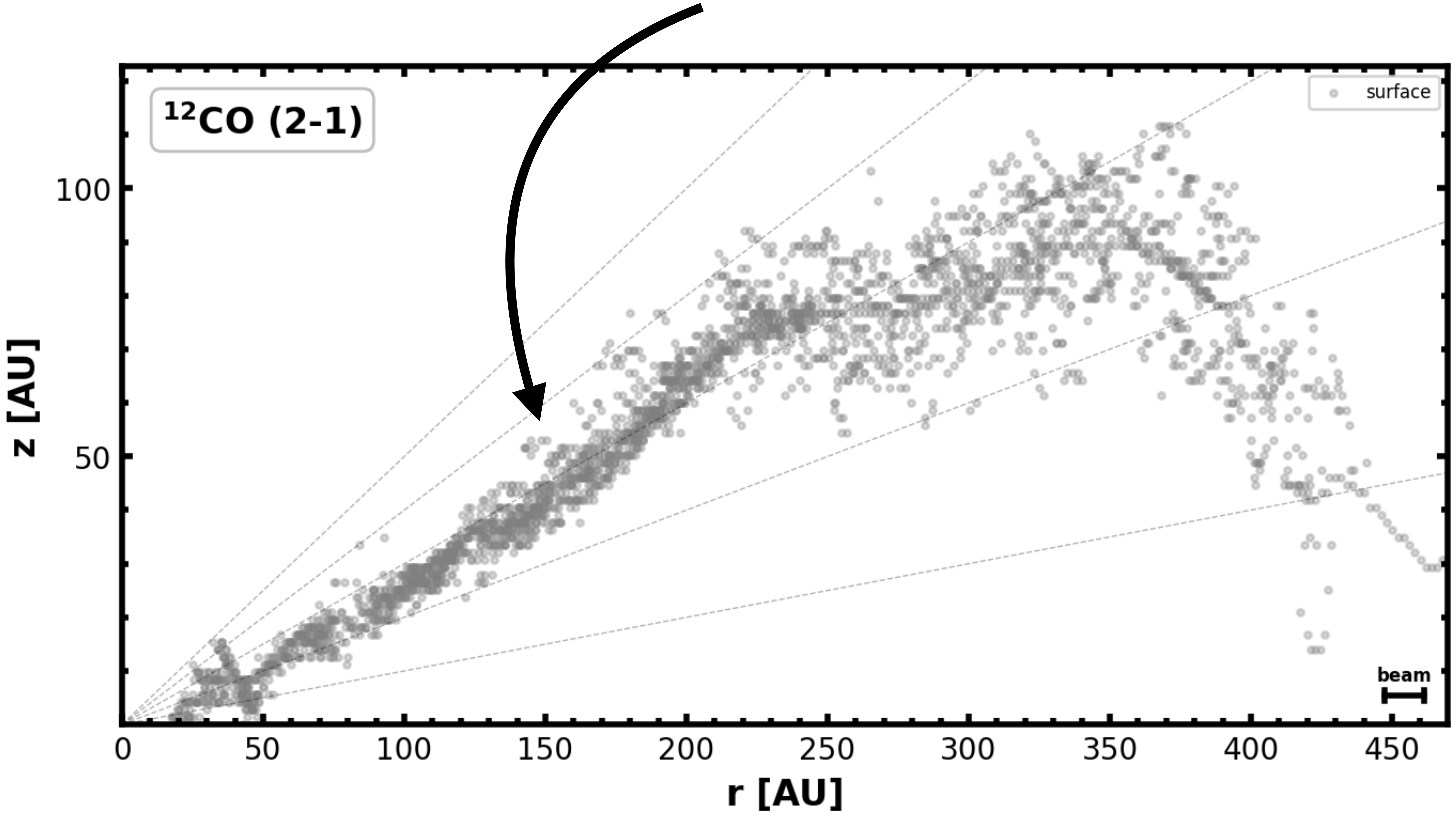
Emission Surface

Where ^{12}CO (2-1) traces

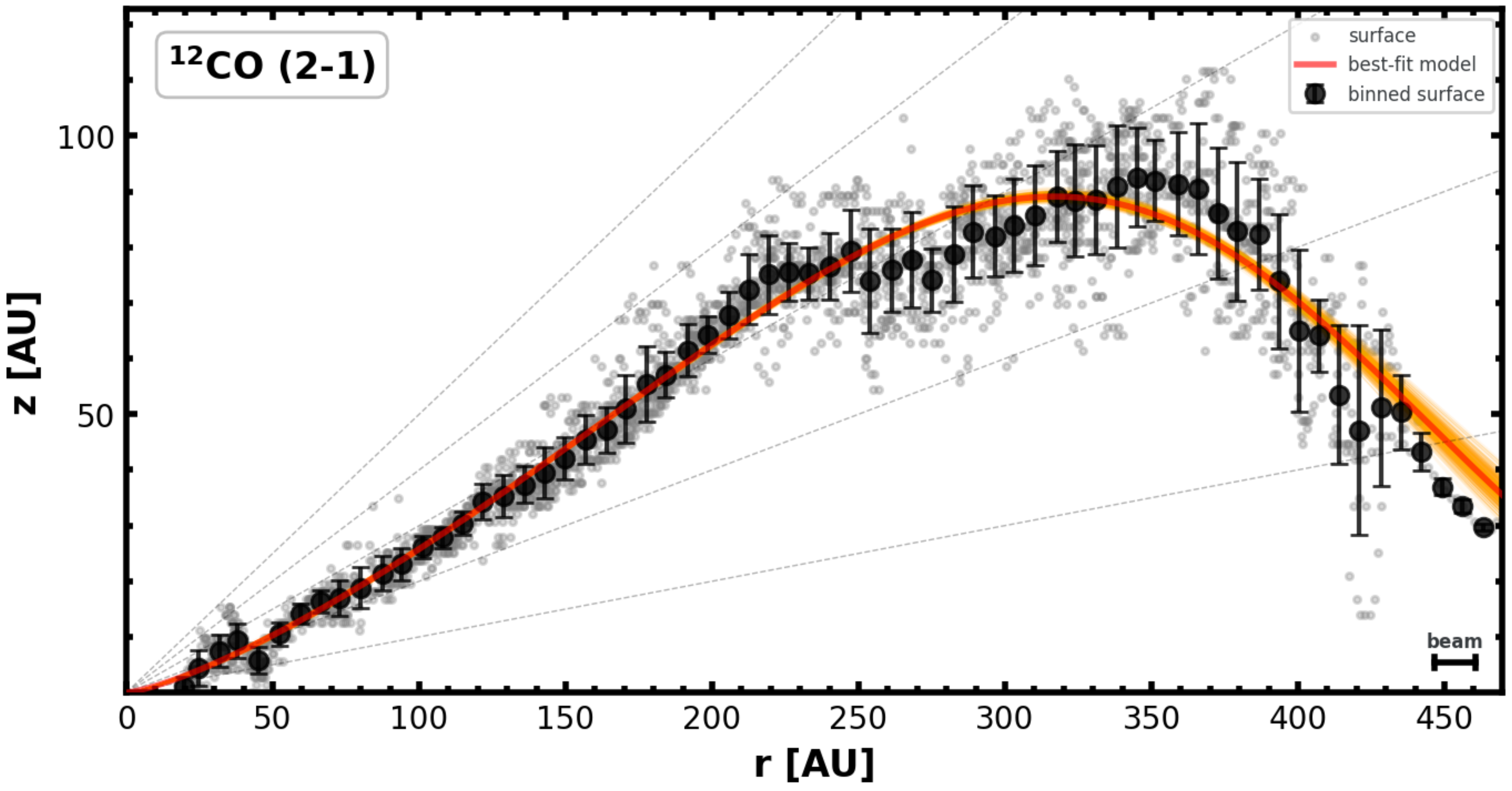


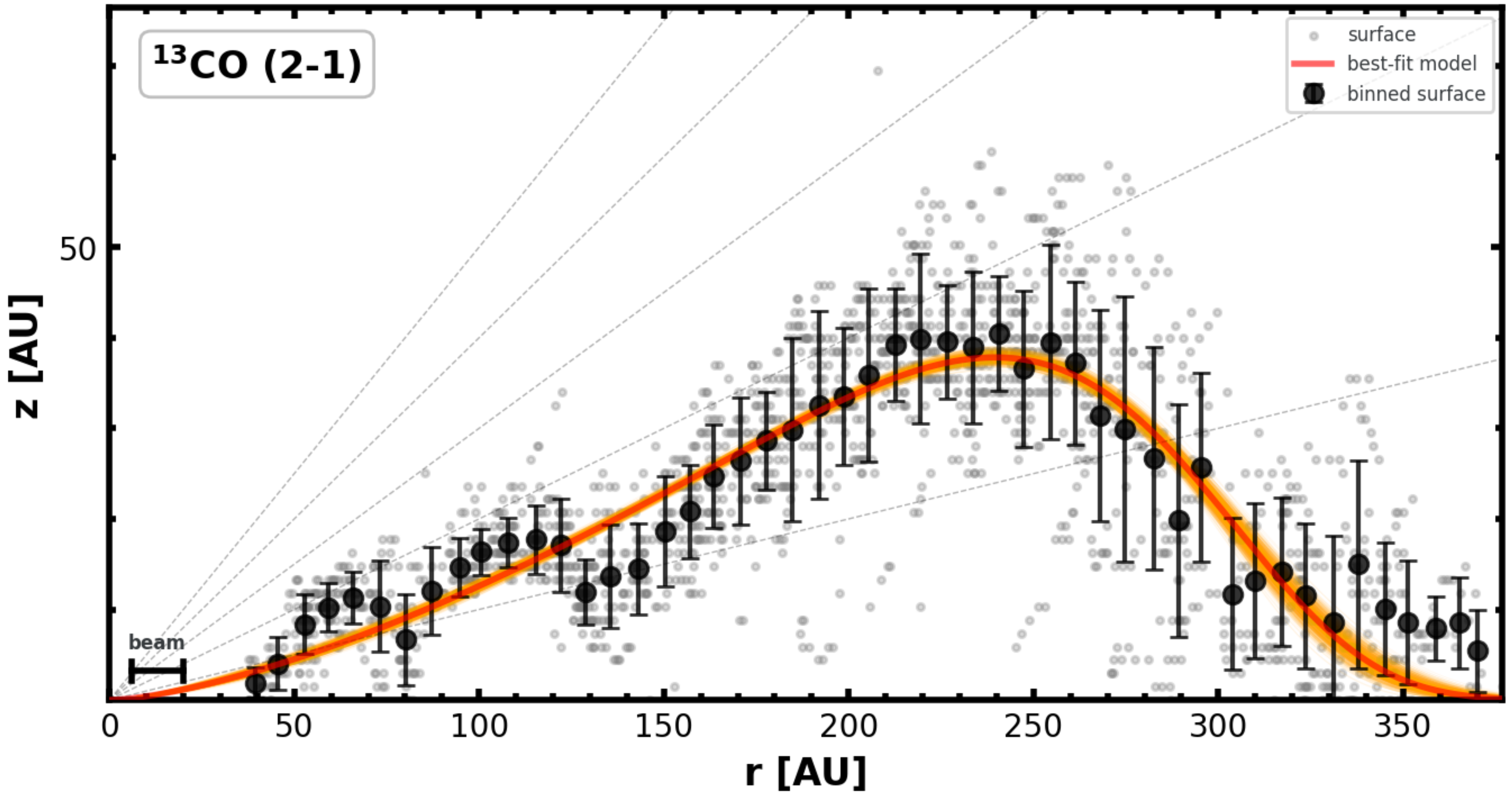


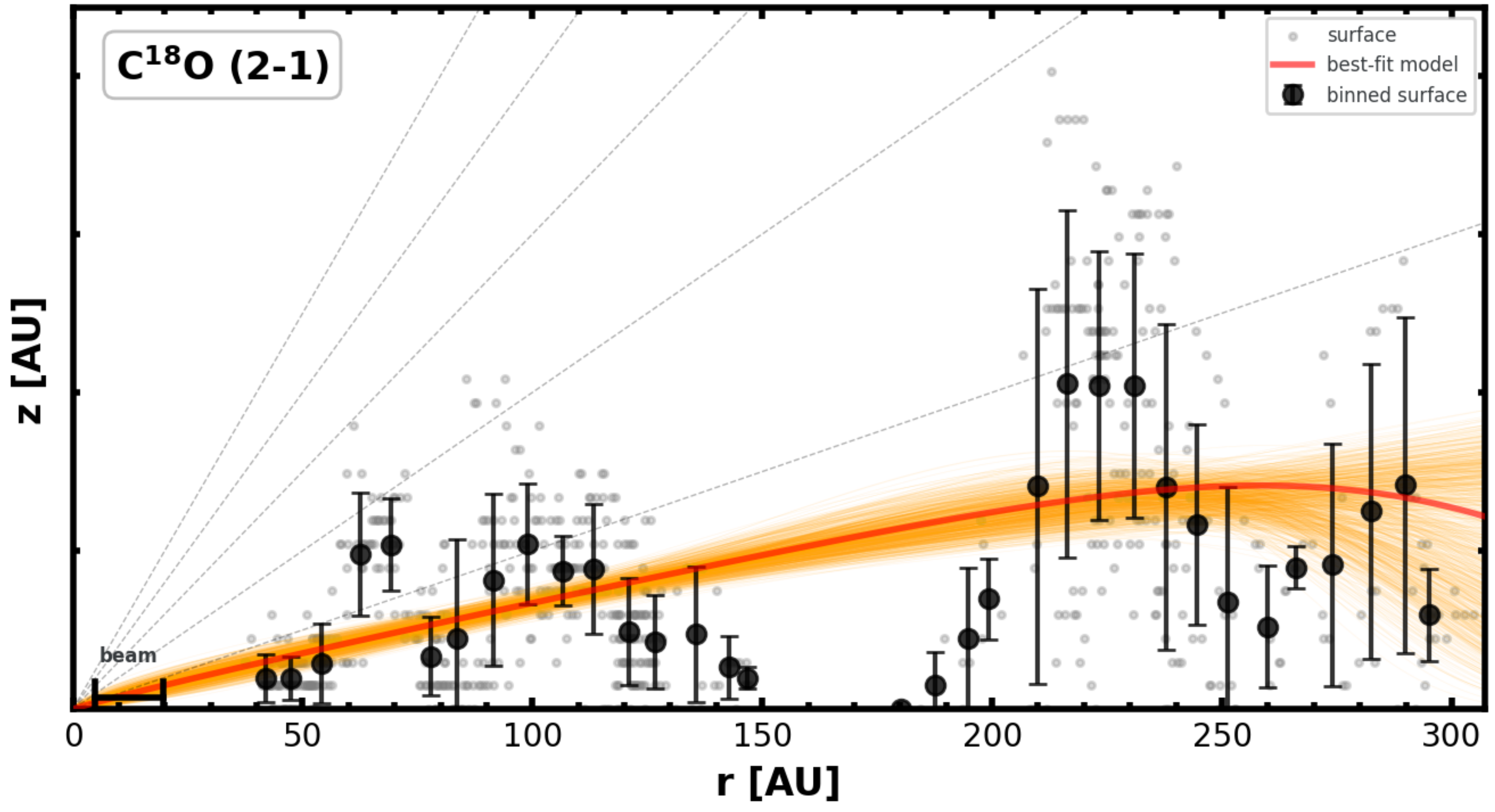
- `disksurf` (Pinte at al. 2018b)
- Fitted with exponentially tapered power-law surface function.

$$z(r) = z_0 \left(\frac{r}{r_0}\right)^{\psi} \times \exp\left[-\left(\frac{r}{r_{taper}}\right)^{q_{taper}}\right]$$

Teague et al. 2021







Parameters	Unit	^{12}CO (2–1)	^{13}CO (2–1)	$C^{18}O$ (2–1)
z_0	arcsec	$0.26^{+0.00}_{-0.00}$	$0.13^{+0.00}_{-0.00}$	$0.07^{+0.00}_{-0.00}$
ψ	-	$1.33^{+0.02}_{-0.02}$	$1.48^{+0.06}_{-0.05}$	$0.92^{+0.16}_{-0.14}$
r_{taper}	-	$4.12^{+0.02}_{-0.02}$	$2.94^{+0.02}_{-0.02}$	$3.42^{+3.66}_{-0.48}$
q_{taper}	-	$4.51^{+0.24}_{-0.23}$	$7.73^{+0.50}_{-0.46}$	$6.96^{+2.17}_{-3.83}$

^{12}CO (2-1) traces z/r ~ 0.3

^{13}CO (2-1) traces z/r ~ 0.2 → **Probing the disk at different scale heights**

$C^{18}O$ (2-1) traces z/r < 0.1

Disk Rotation - Keplerian & Non-Keplerian Model

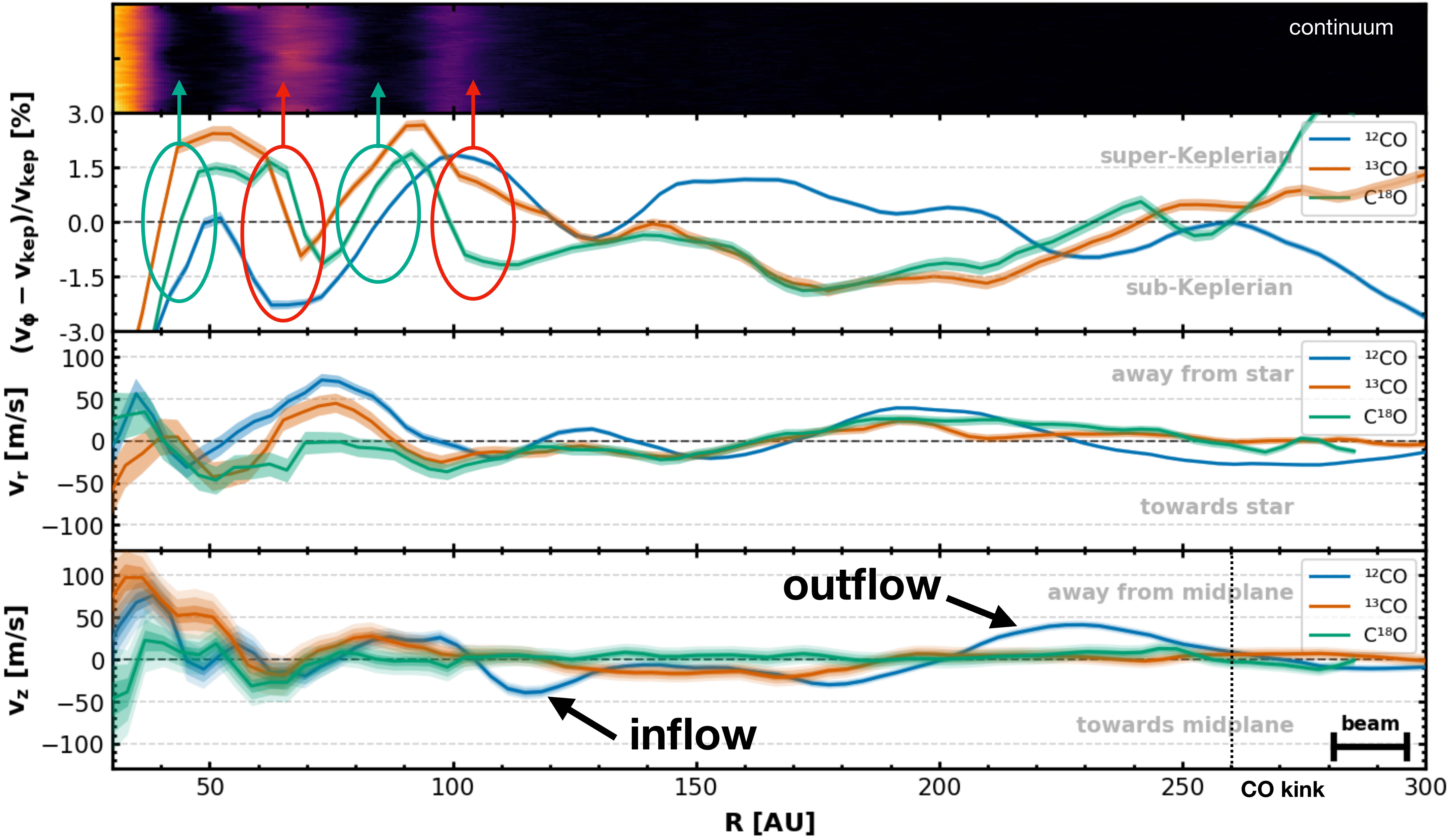
Keplerian: $v_o(r,\phi) = v_{kep}(r)cos\phi sini + v_{lsr}$

Non-Keplerian: $v_o(r,\phi) = v_\phi(r)cos\phi sini - v_r(r)sin\phi sini - v_z(r)cosi + v_{lsr}$

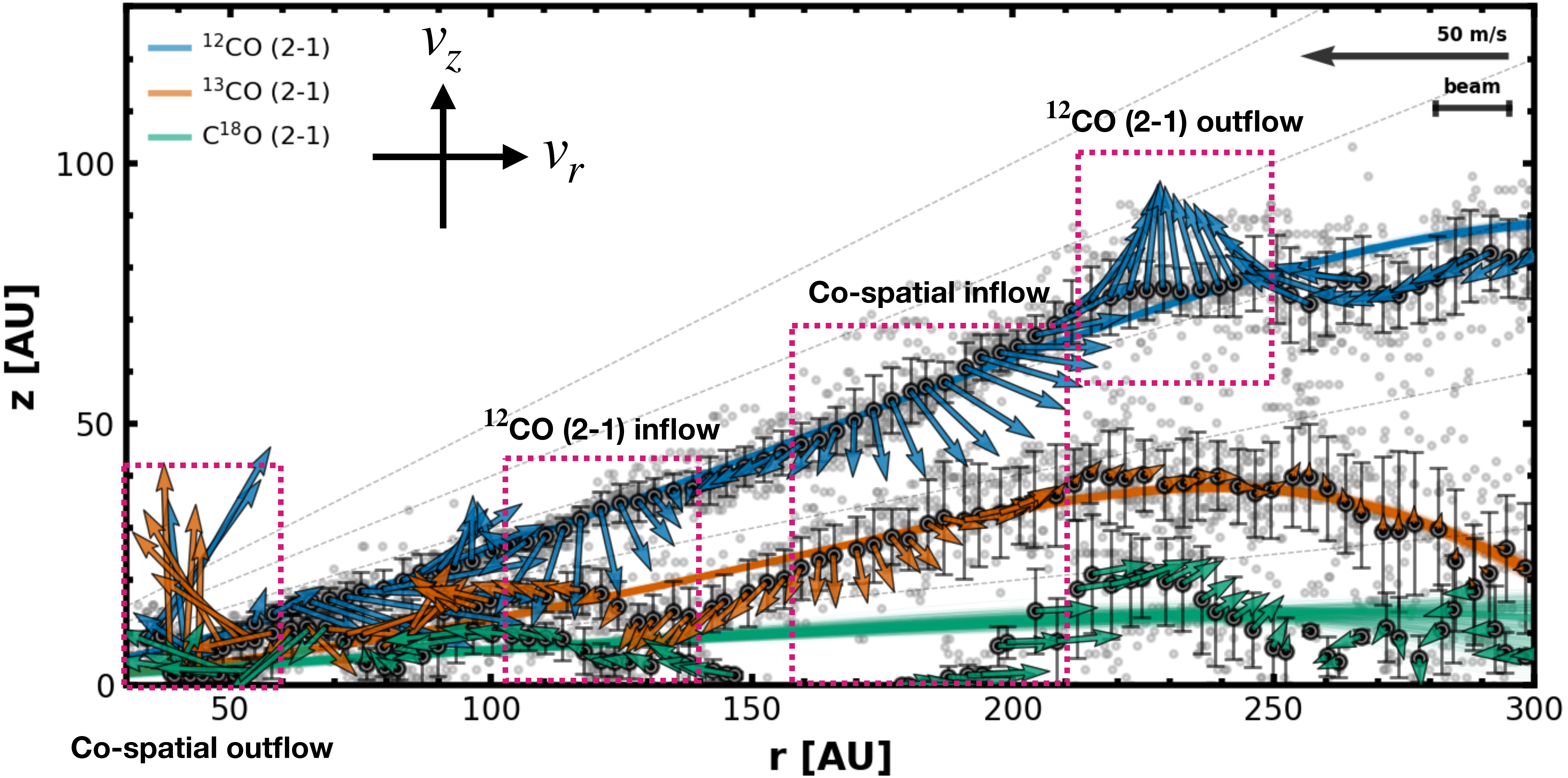
Decouple $\mathbf{v_o}$ to $\mathbf{v_\phi}$, $\mathbf{v_r}$, $\mathbf{v_z}$

Velocity Profiles

Rotational velocity gradients are consistent with observed substructures

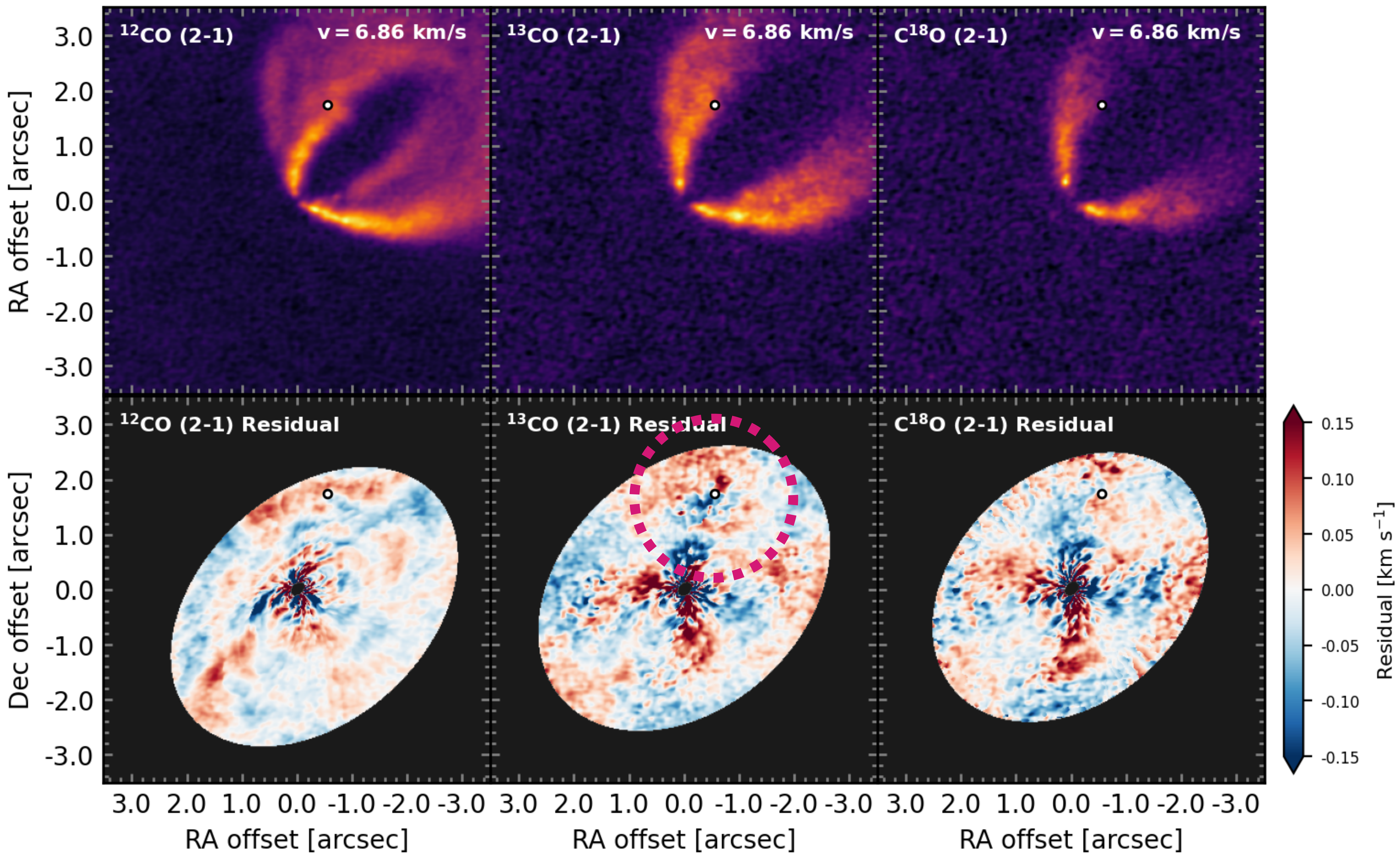


Gas Kinematics within the HD 163296 Protoplanetary Disk



Evidence of Planet — ^{13}CO Doppler-flip

- Non-axisymmetric
- Spatially coincided with ^{12}CO kink structure
- Distance ~ 220 AU
- Only detectable in ^{13}CO residual map
- Pinte et. al 2018 proposed a $2M_J$ planet at 260 AU based on CO kink modeling



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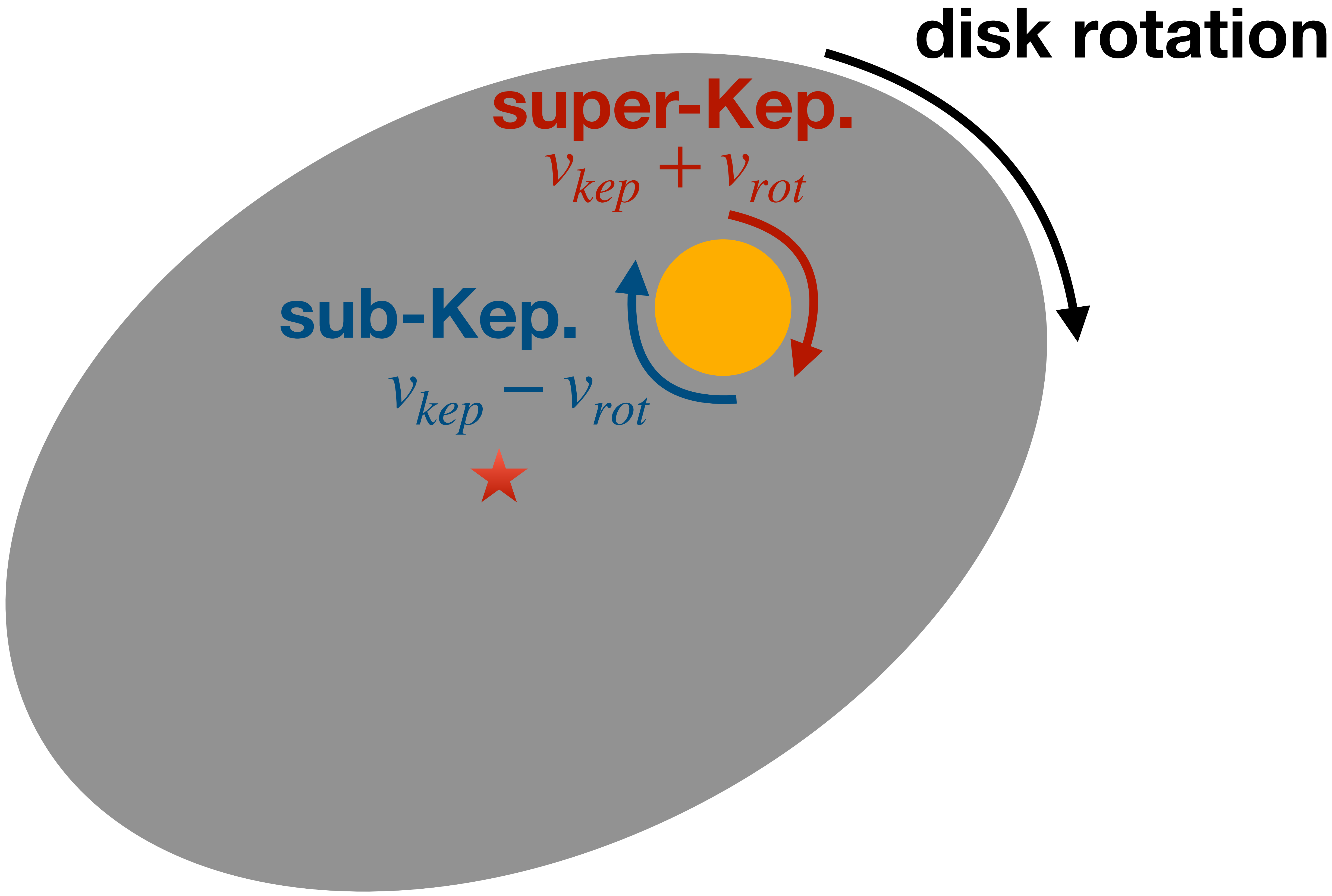
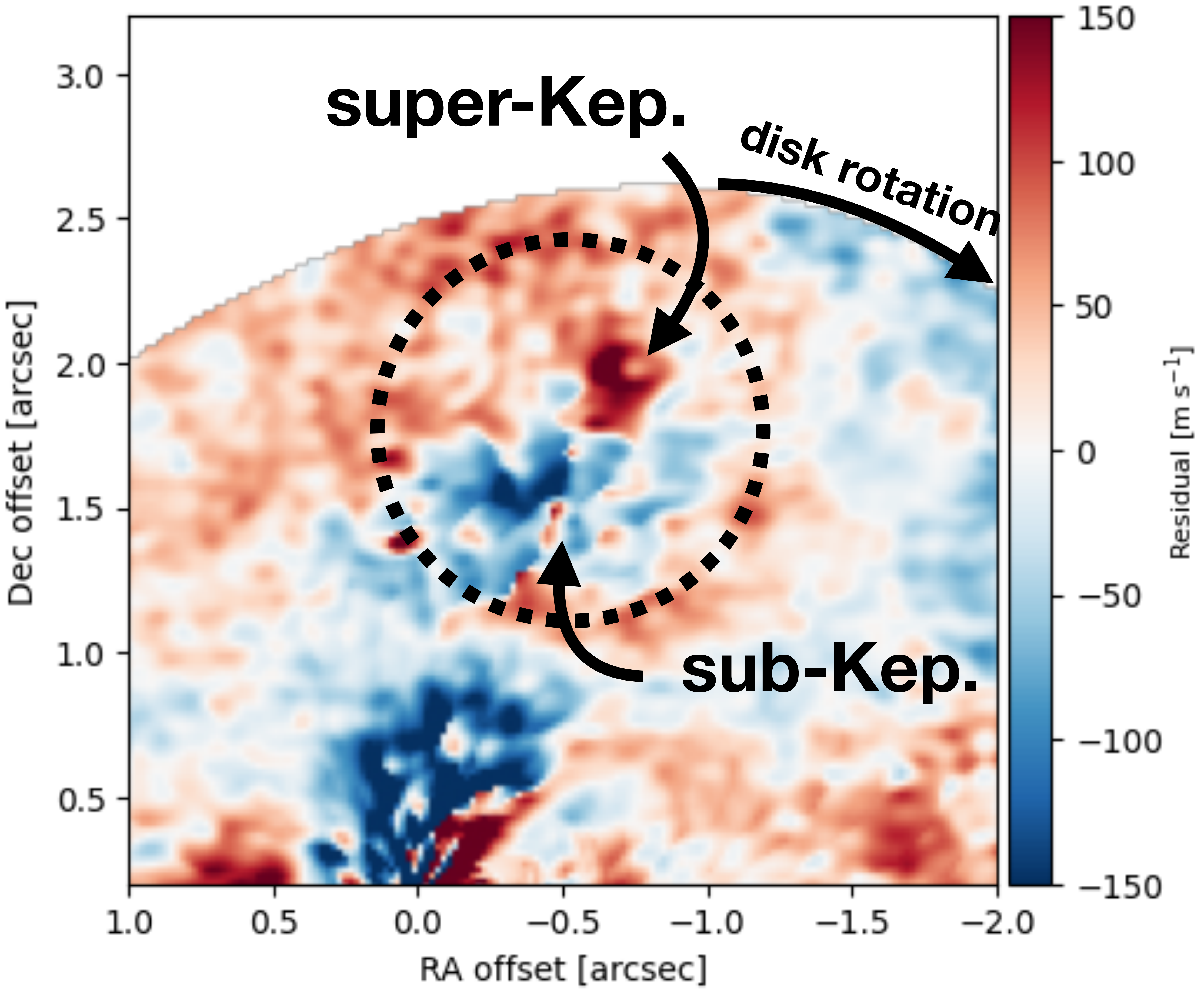


localized circular motion



consistent with this scenario

Estimate Planet's Mass — ^{13}CO Doppler-flip

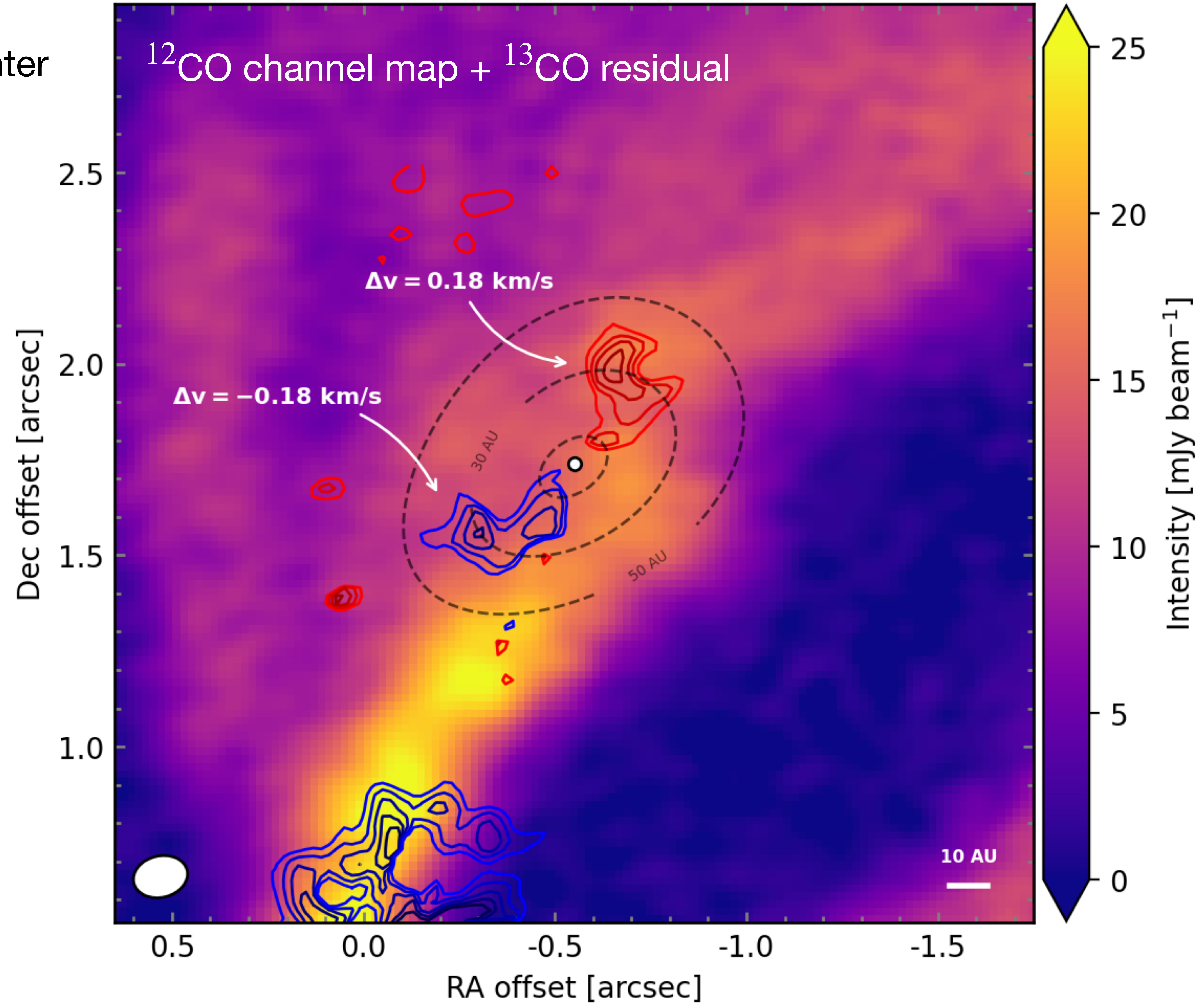
- $\Delta v_{los} = \pm 0.18$ km/s at 30 AU from the center

Estimate from simple circular motion
(only consider rotational velocity)

$$v_{rot} = \sqrt{\frac{GM_p}{r}} \rightarrow M_p = \frac{r v_{rot}^2}{G}$$

$$\Delta v_{los} \approx \Delta v_\phi cos\phi sini$$

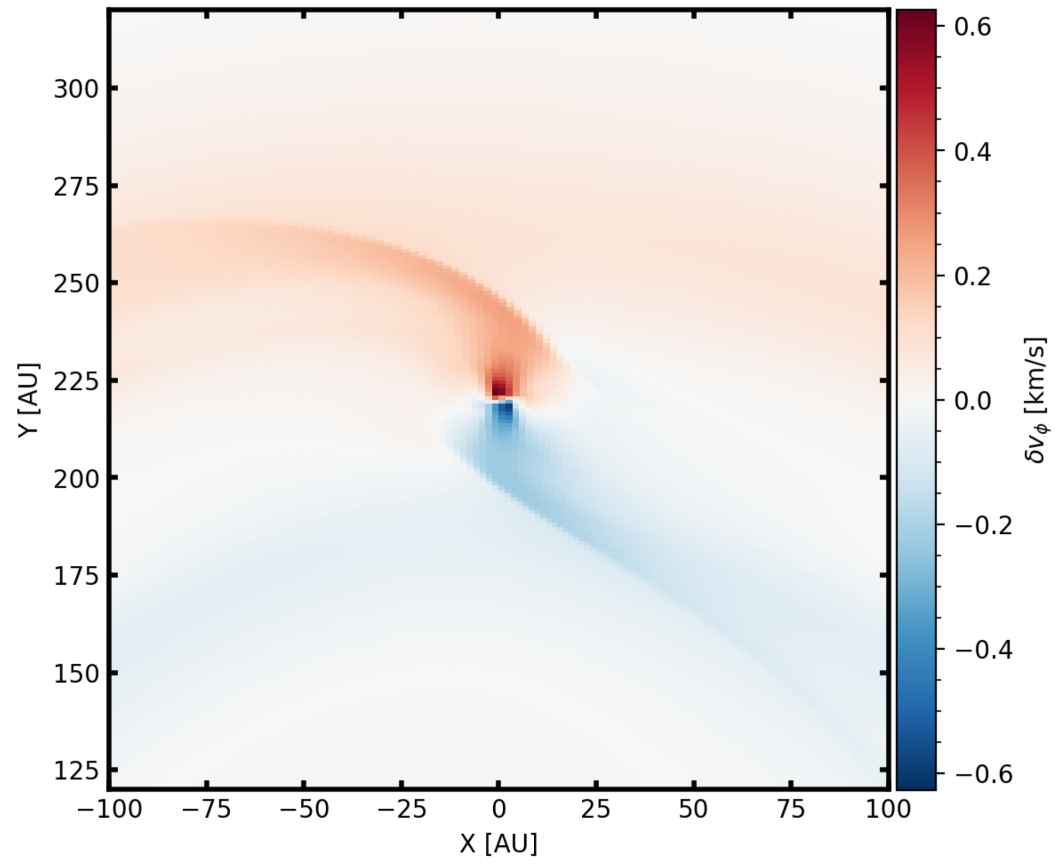
$M_p \approx 4.82\ M_J$

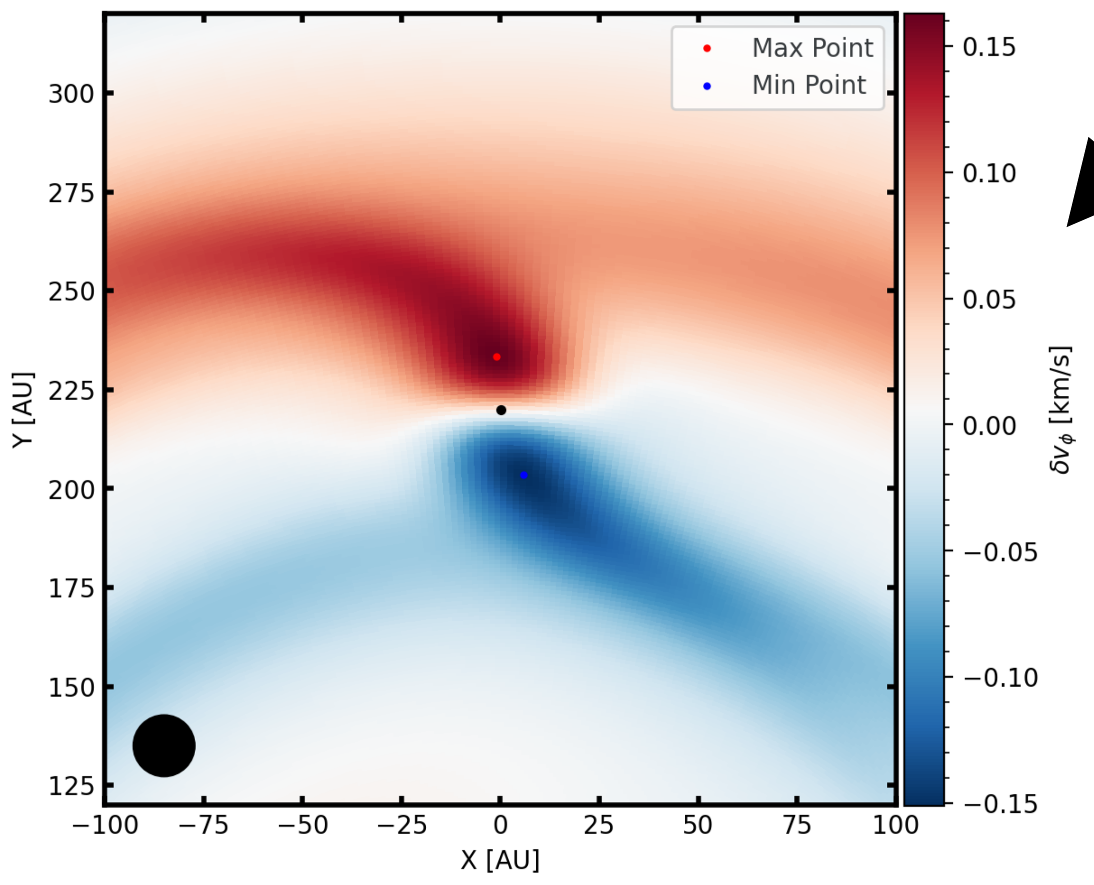


Estimate Planet's Mass — ^{13}CO Doppler-flip

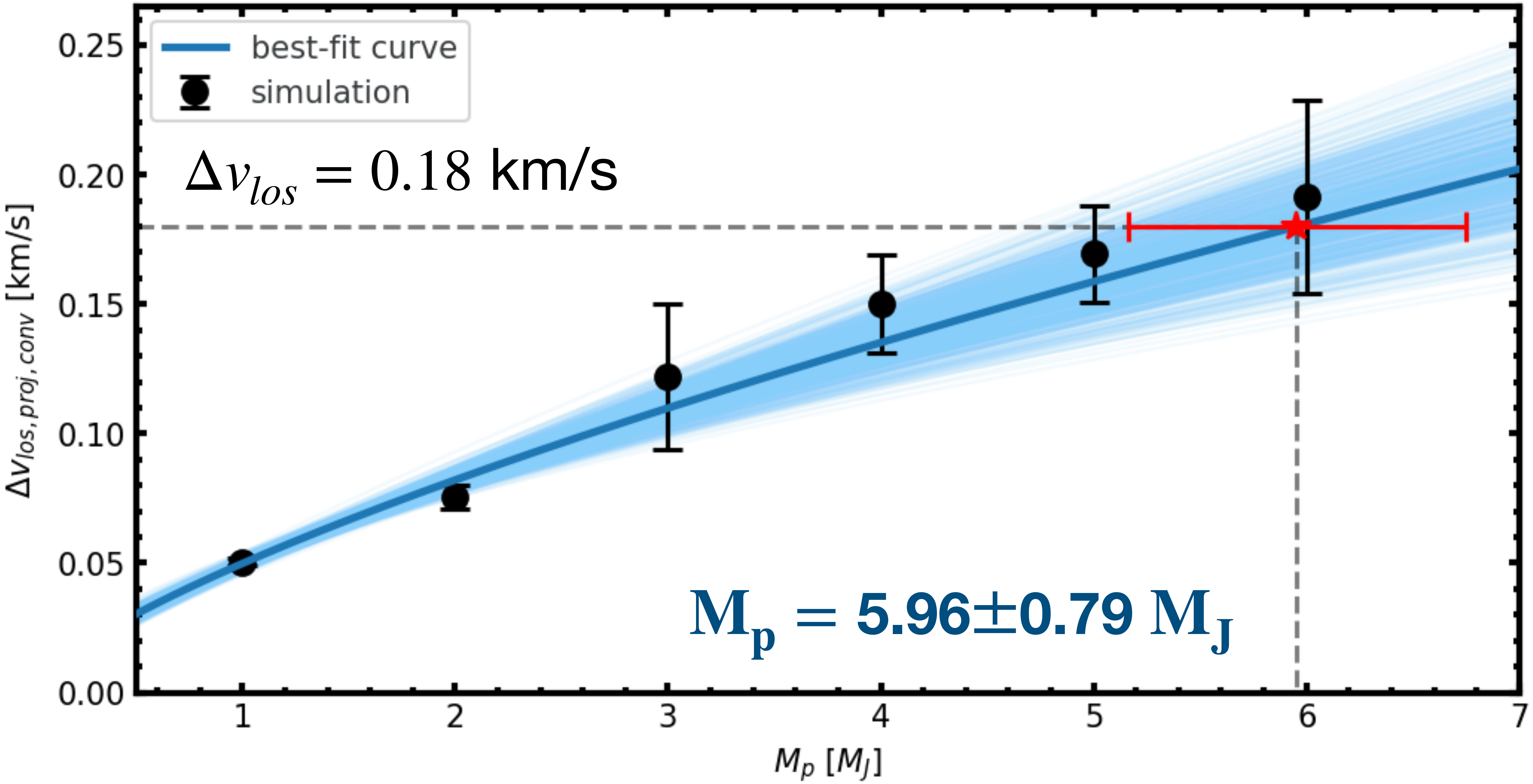
Estimate planet's mass from FARGO-3D hydrodynamic simulation

Stellar mass: $M_* = 2M_\odot$
Viscosity: $\alpha = 10^{-3}$
Planet at $r = 220$ AU after 100 orbits

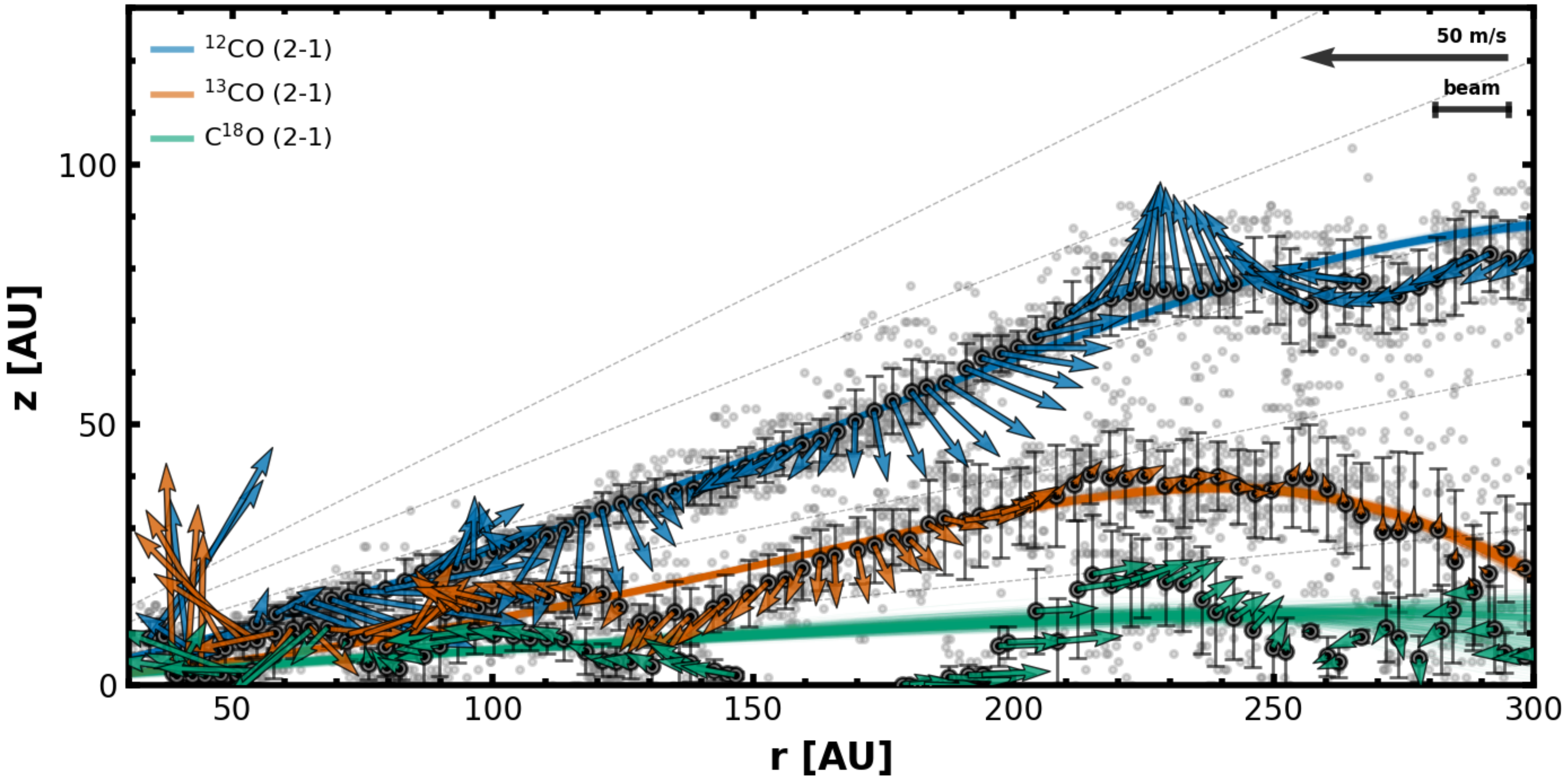


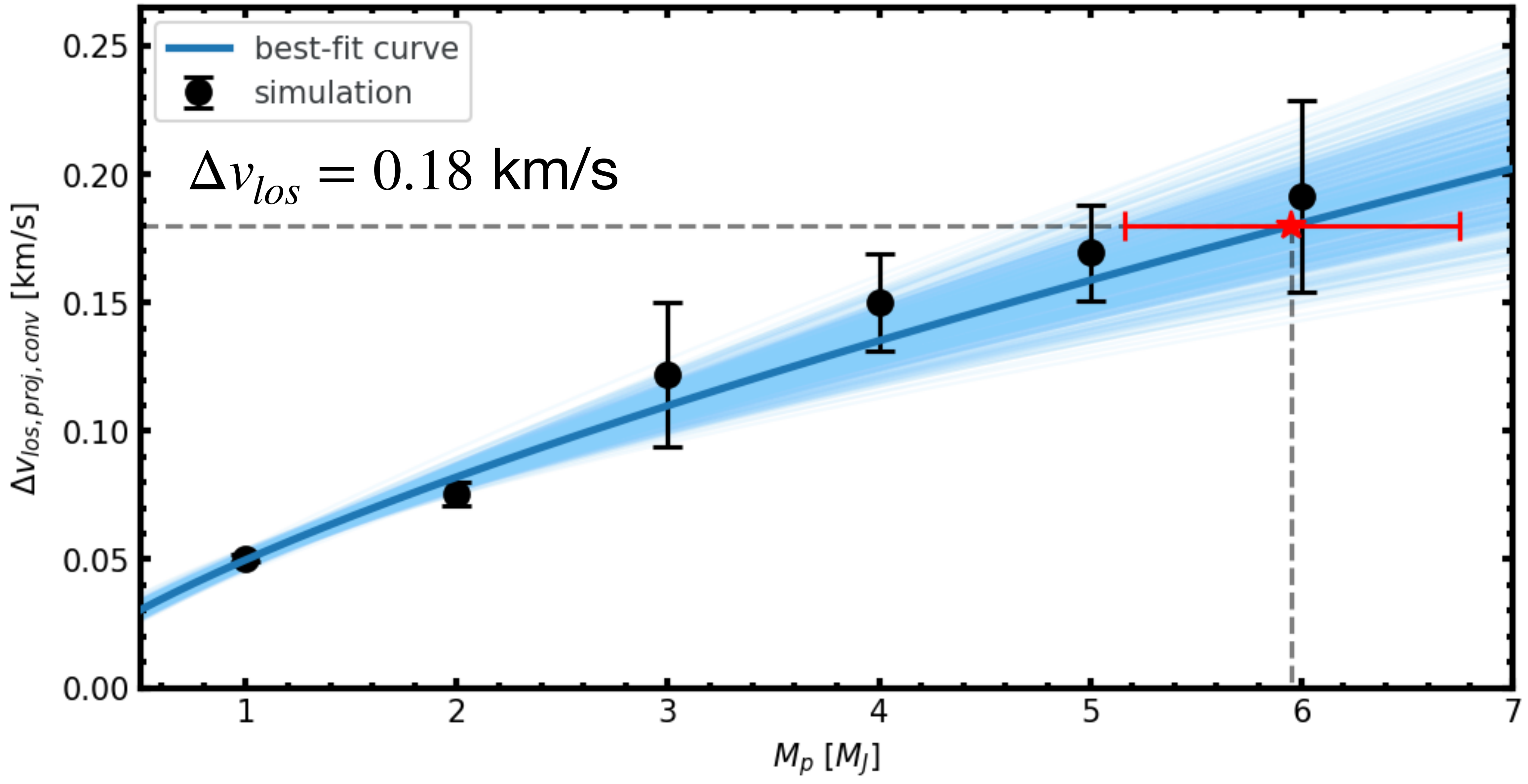


convolve with 0.15" beam



Conclusion



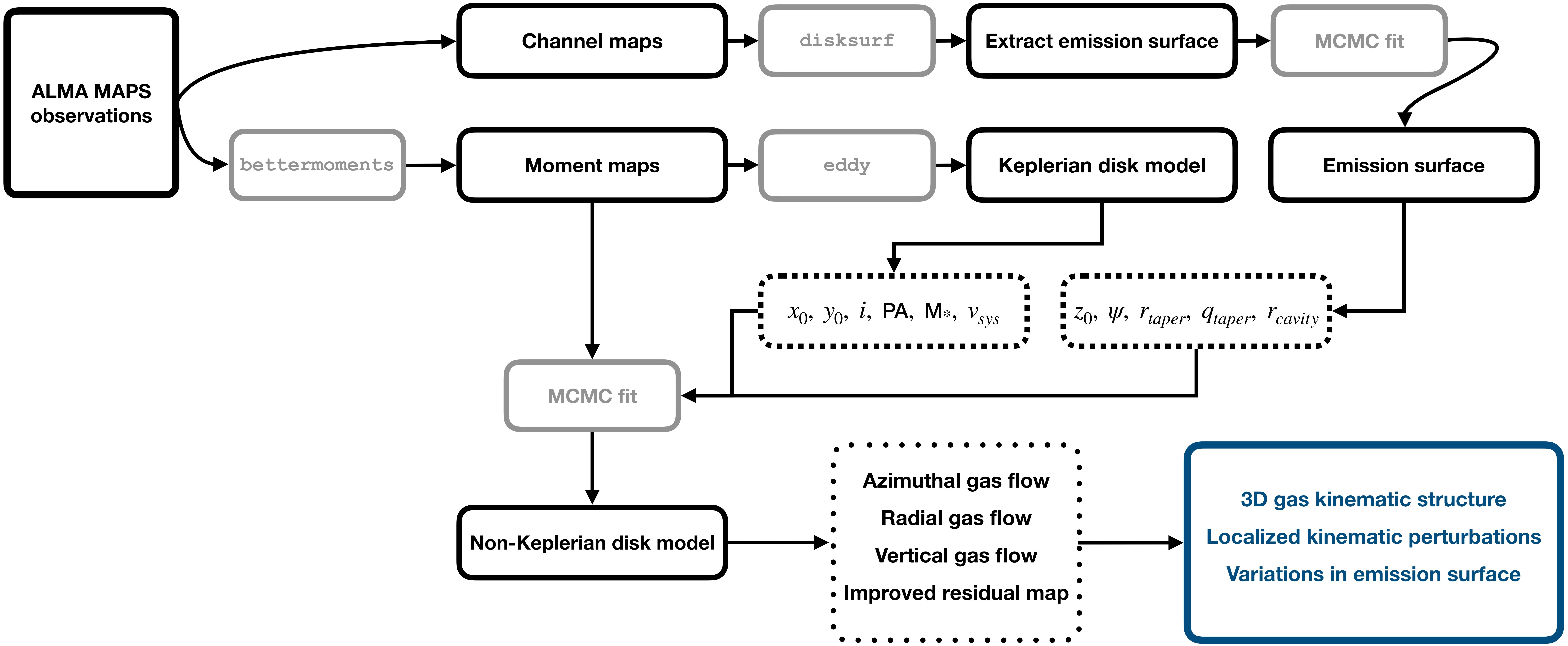


3D Gas Kinematics
We successfully obtain three-dimensional gas dynamics within HD 163296 disk with multi-transition CO observations from ALMA MAPS.

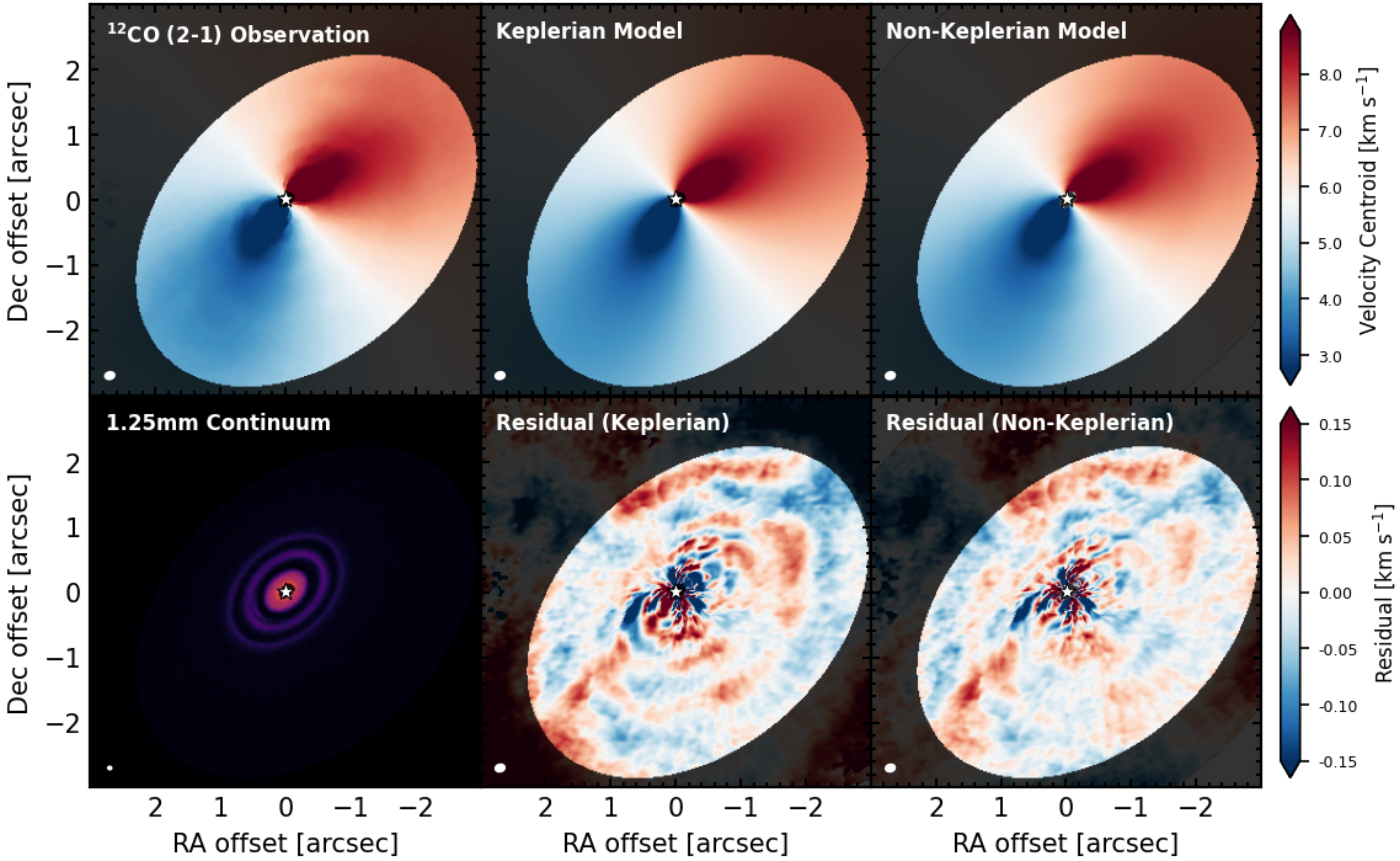
Radial and Vertical Gas Flow
Our results show co-spatial inflow and outflow, potentially indicating organized meridional circulation within the disk.

Planet Signature and Mass Estimation
We highlight the Doppler-flip feature observed in ^{13}CO residual map at 220 AU, suggesting the presence of an embedded planet with the estimated mass to be 5~6 M_J constrained by hydrodynamic simulations.

Workflow Summary



APPENDIX



^{12}CO (2-1) Observation
Keplerian Model
Non-Keplerian Model
1.25mm Continuum
Residual (Keplerian)
Residual (Non-Keplerian)
Dec offset [arcsec]
RA offset [arcsec]
Velocity Centroid [km s^{-1}]
Residual [km s^{-1}]

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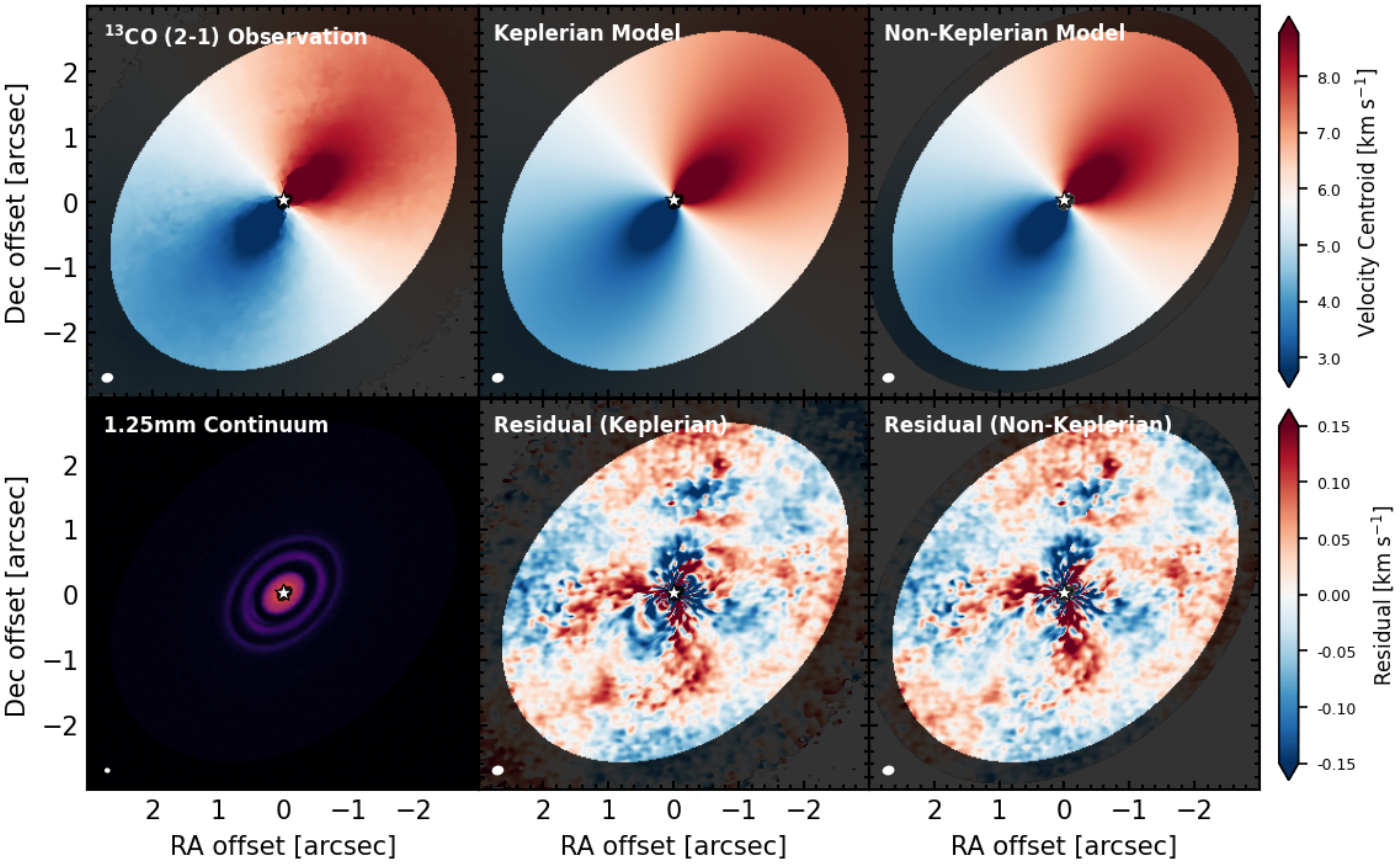

^{13}CO (2-1) Observation
Keplerian Model
Non-Keplerian Model
1.25mm Continuum
Residual (Keplerian)
Residual (Non-Keplerian)
Dec offset [arcsec]
RA offset [arcsec]
Velocity Centroid [km s^{-1}]
Residual [km s^{-1}]
8.0
7.0
6.0
5.0
4.0
3.0
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15

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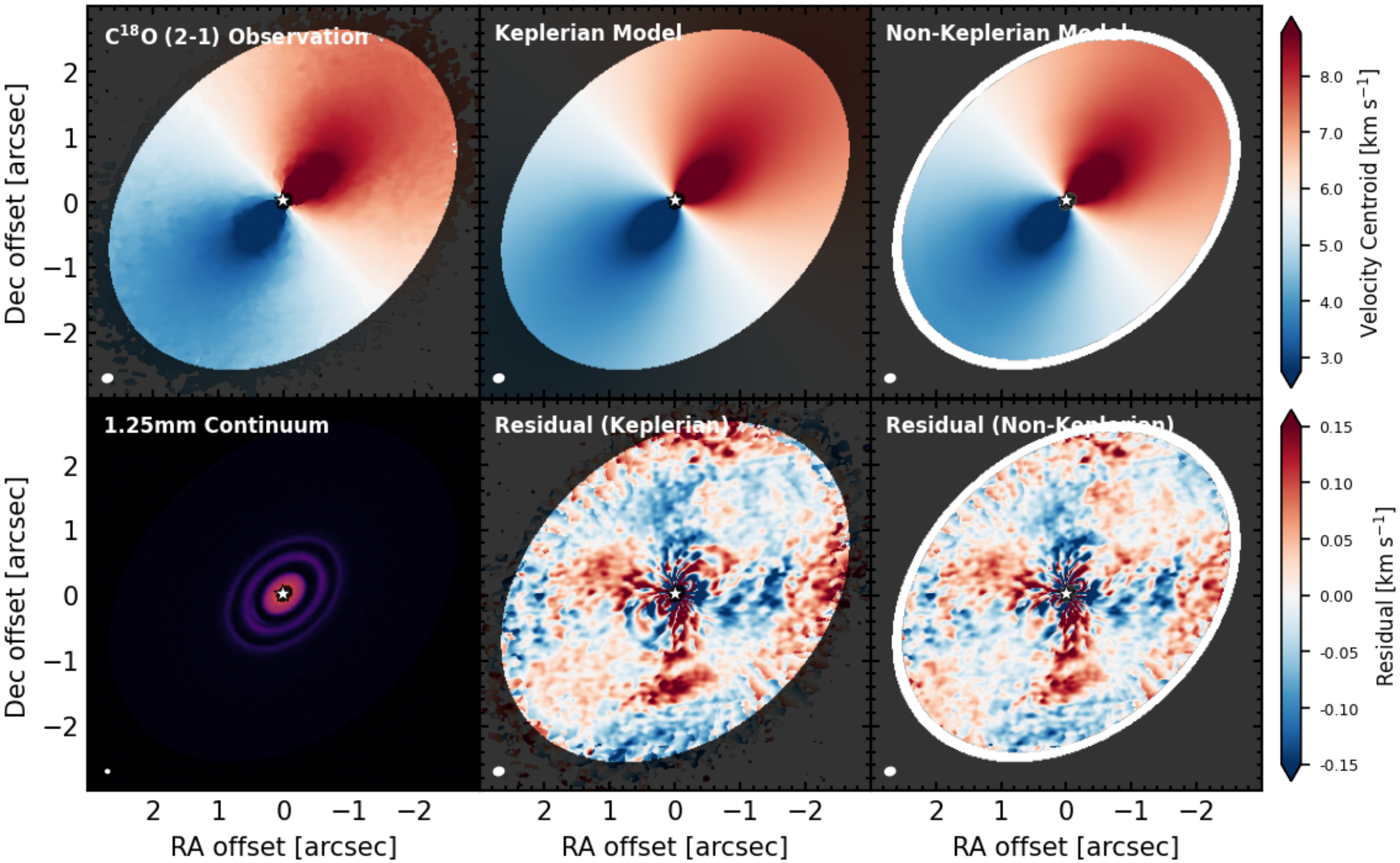
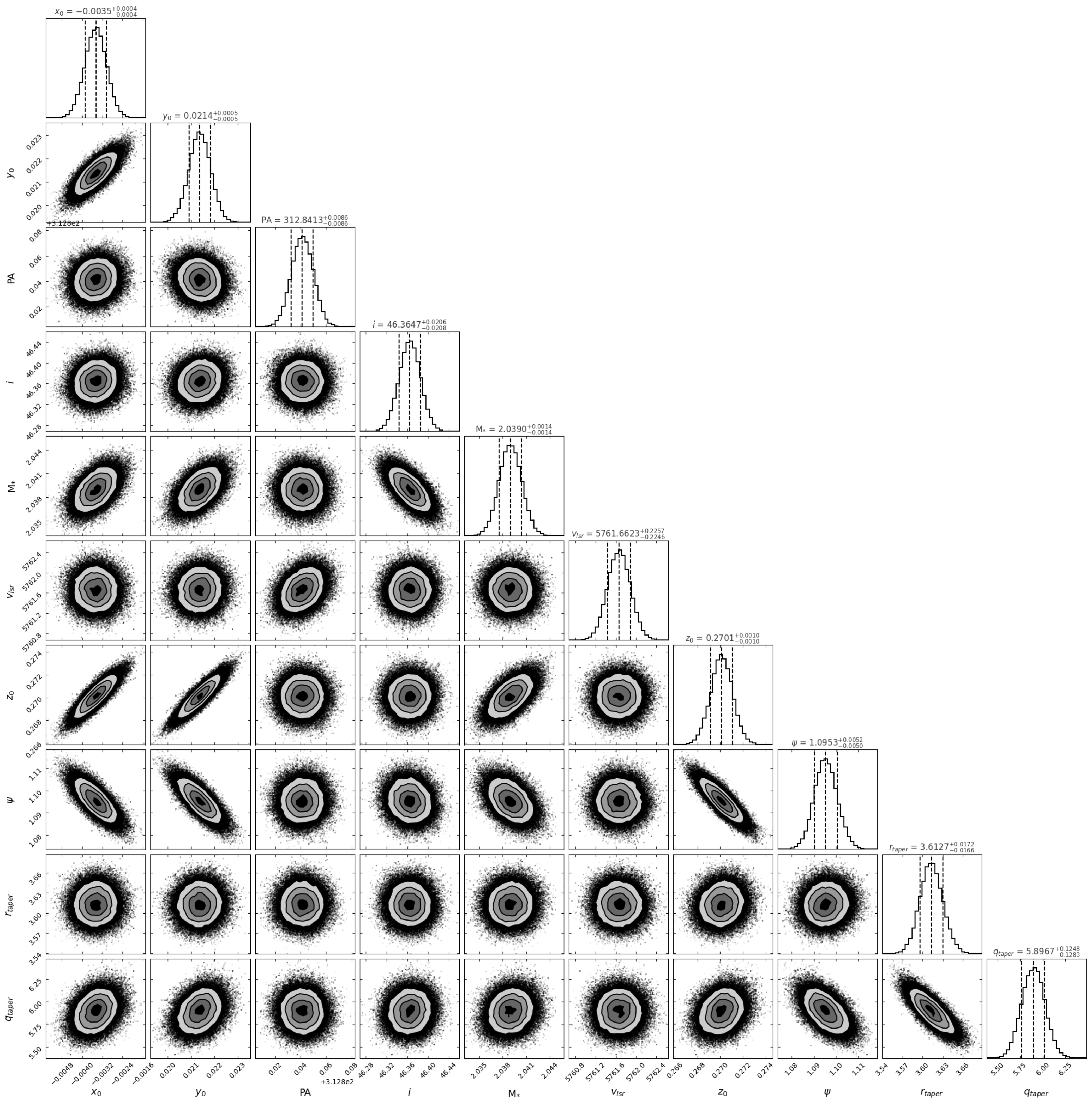
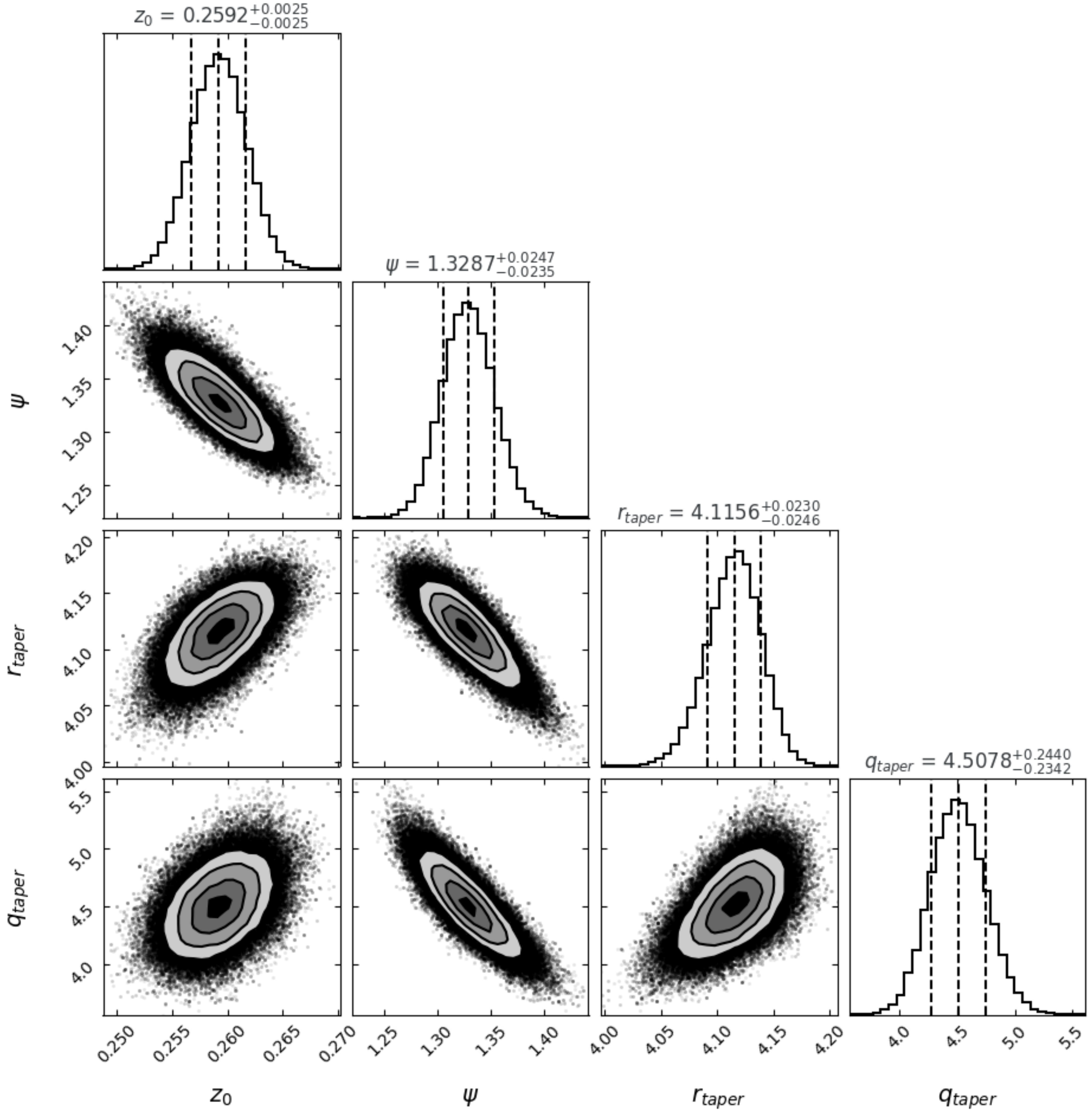


C18O (2-1) Observation
Keplerian Model
Non-Keplerian Model
1.25mm Continuum
Residual (Keplerian)
Residual (Non-Keplerian)
Dec offset [arcsec]
RA offset [arcsec]
Velocity Centroid [km s−1]
Residual [km s−1]

APPENDIX

^{12}CO MCMC Corner Plot





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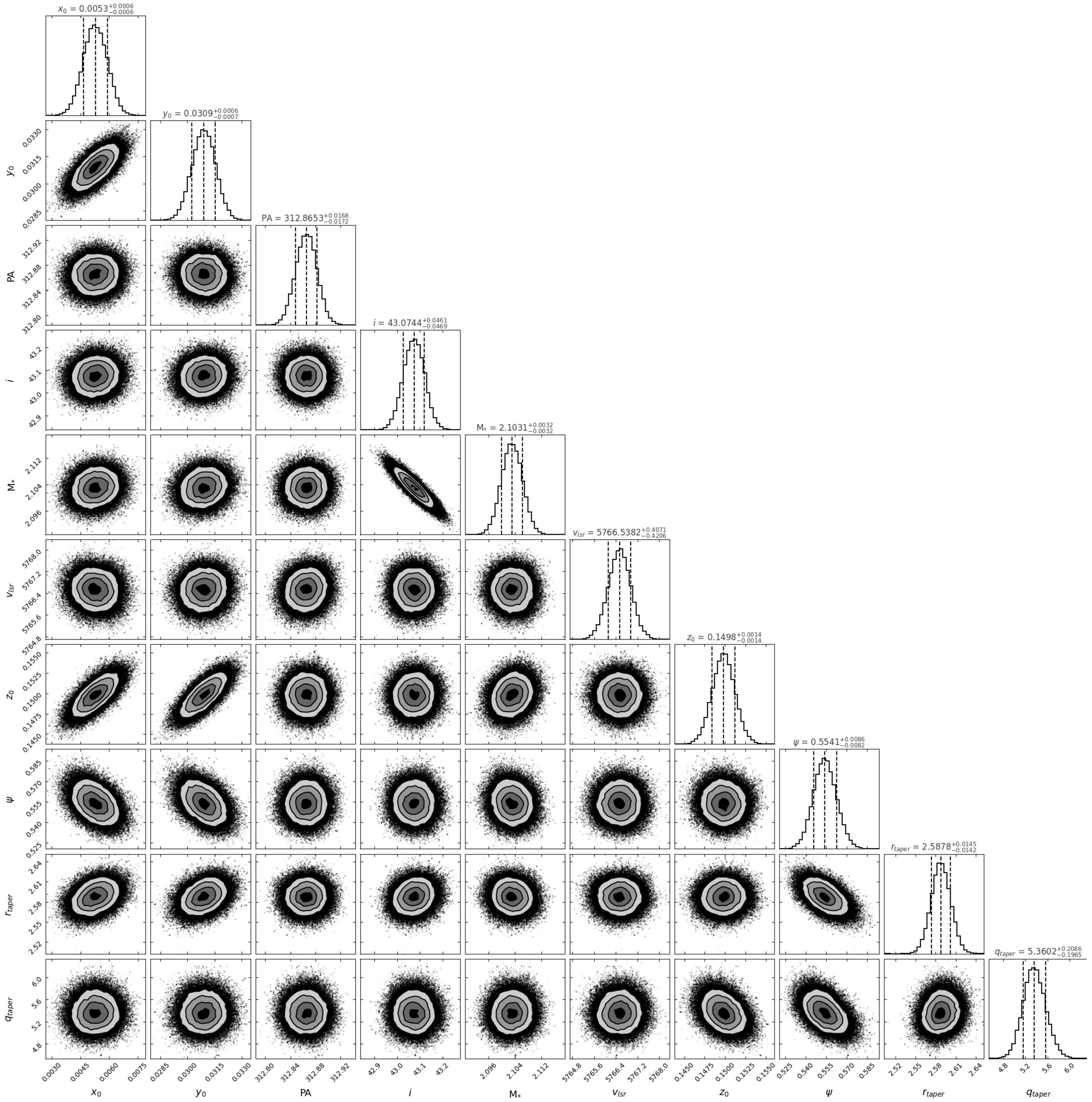
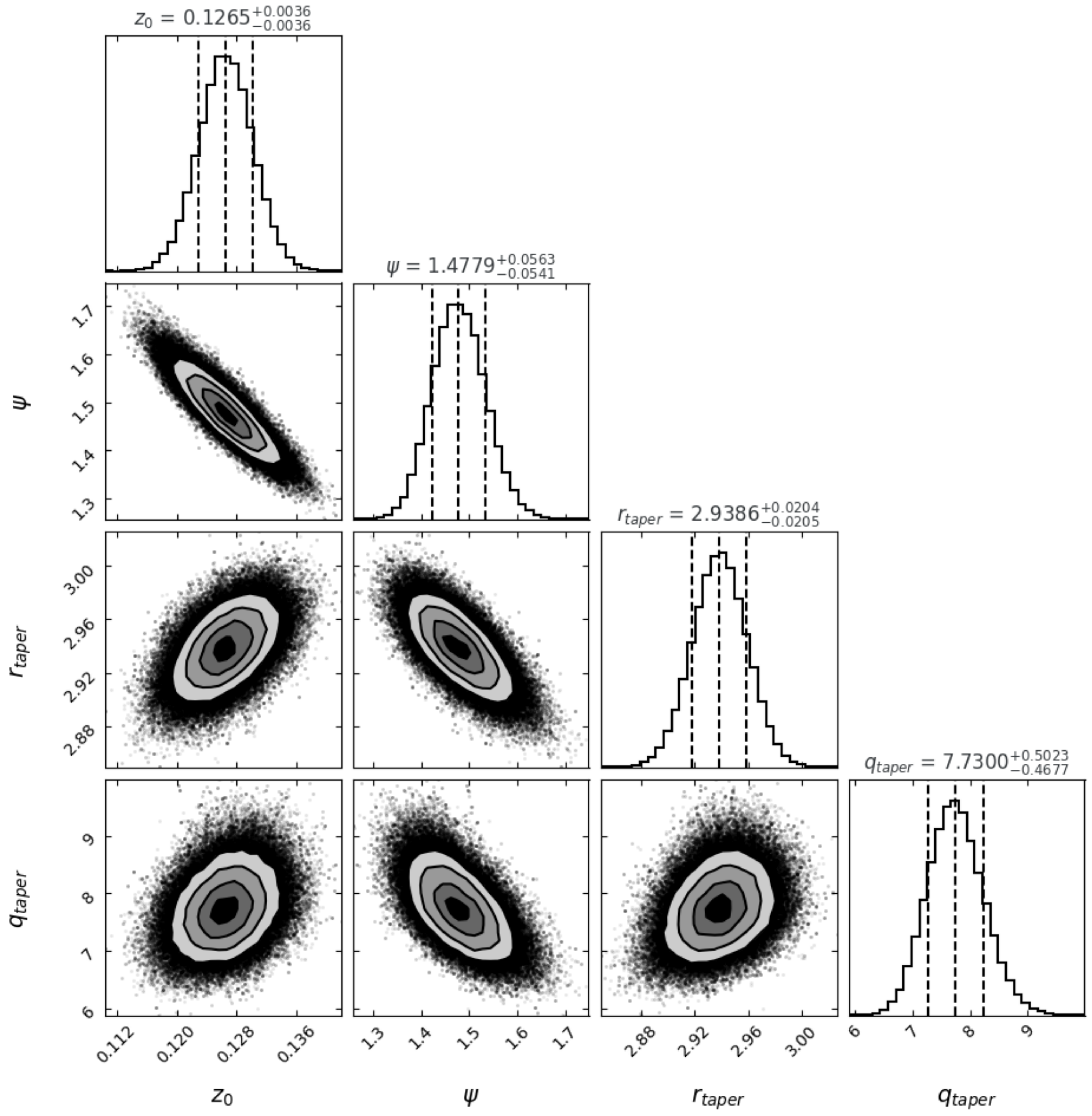


^{13}CO MCMC Corner Plot



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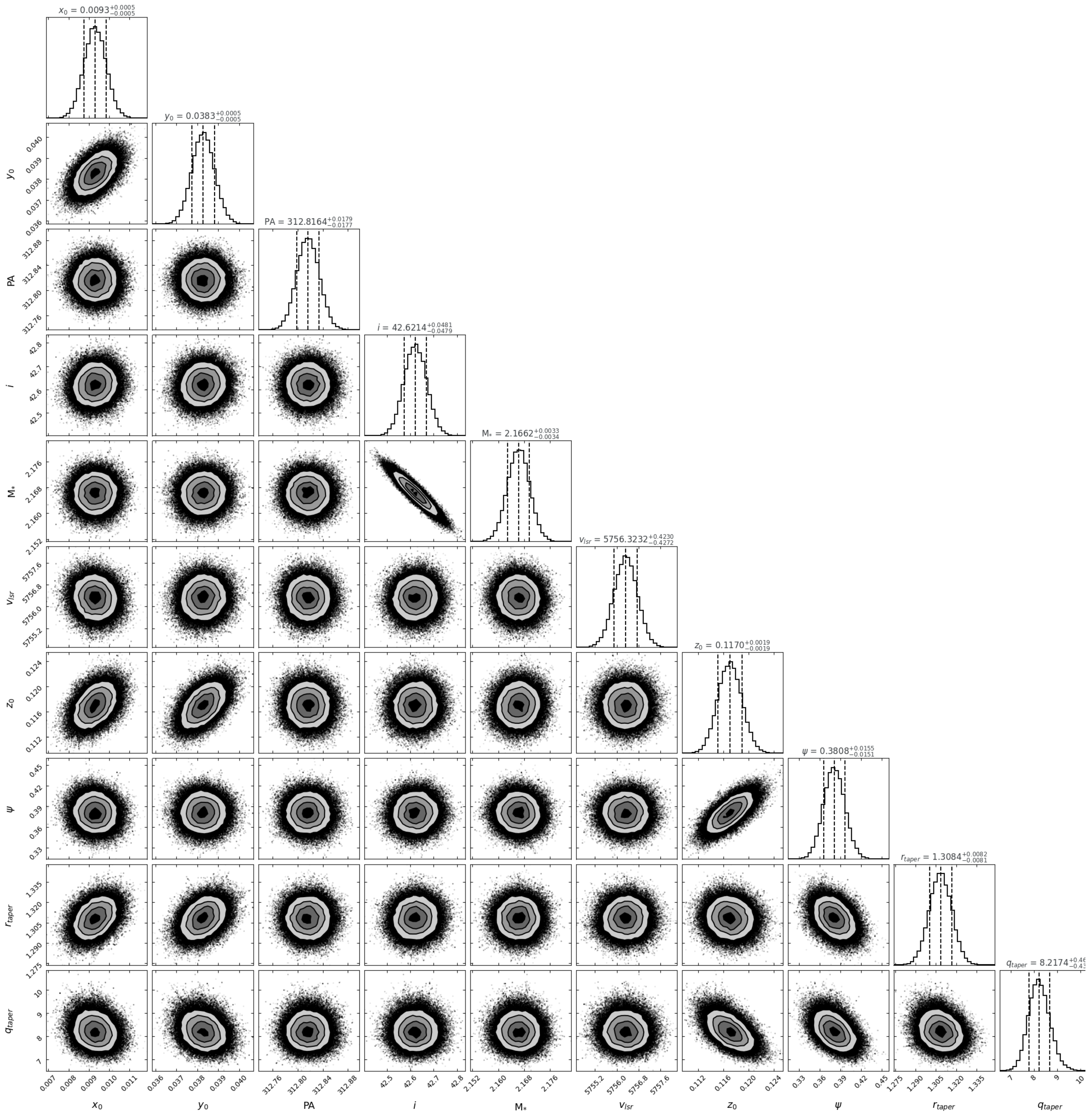
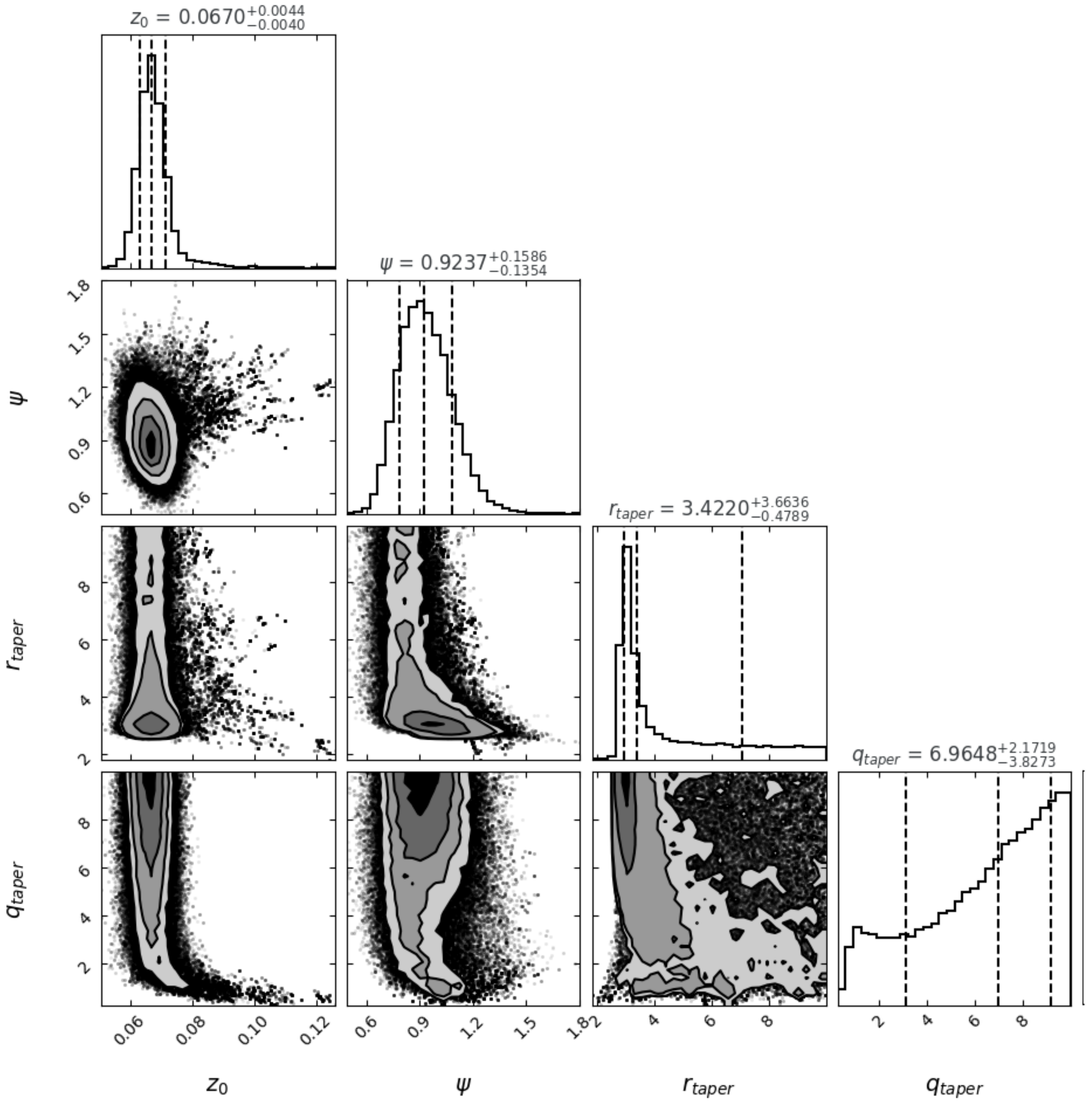
$C^{18}O$ MCMC Corner Plot





APPENDIX

T = 0.26 Myrs

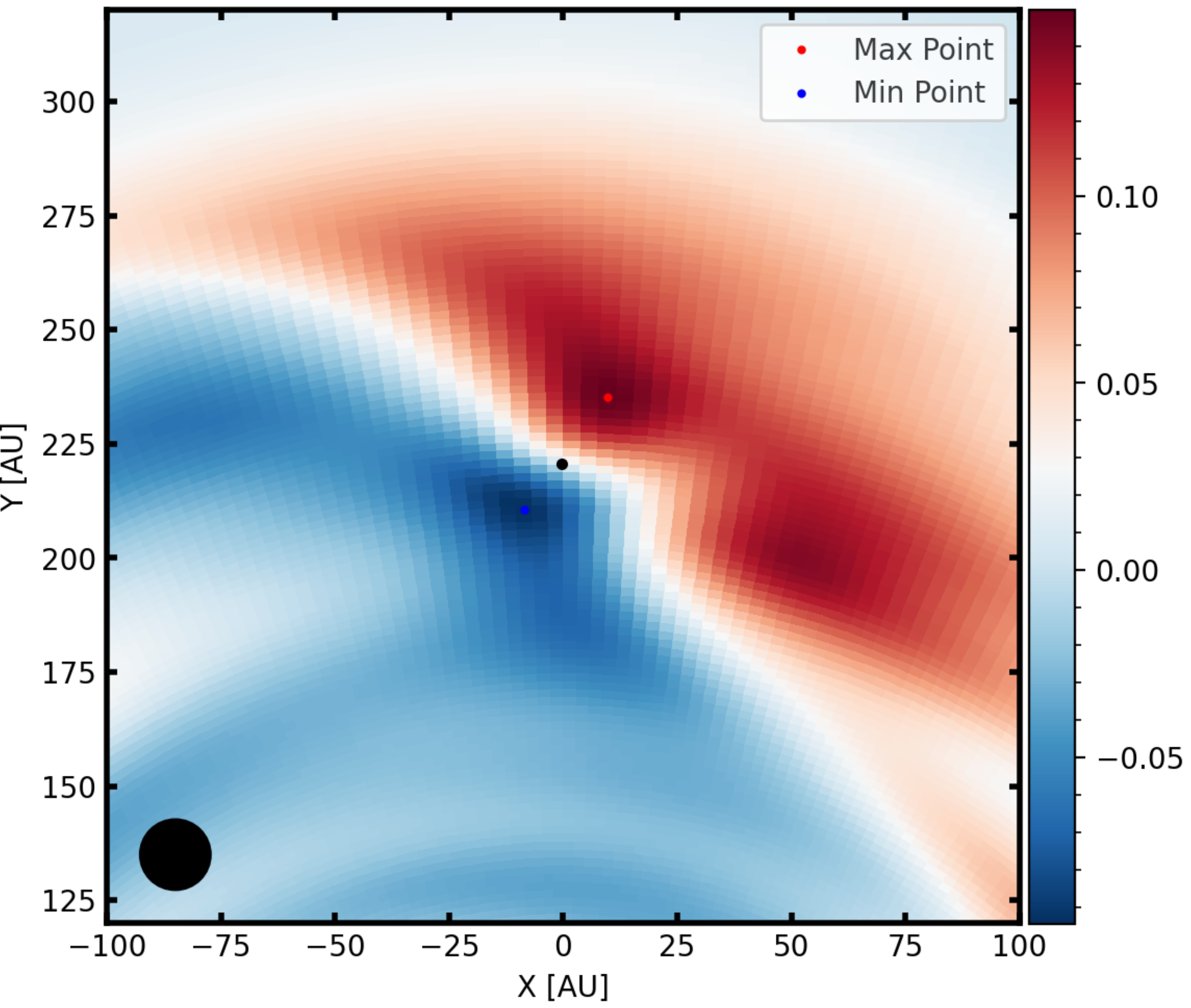
6 MJ

5 MJ

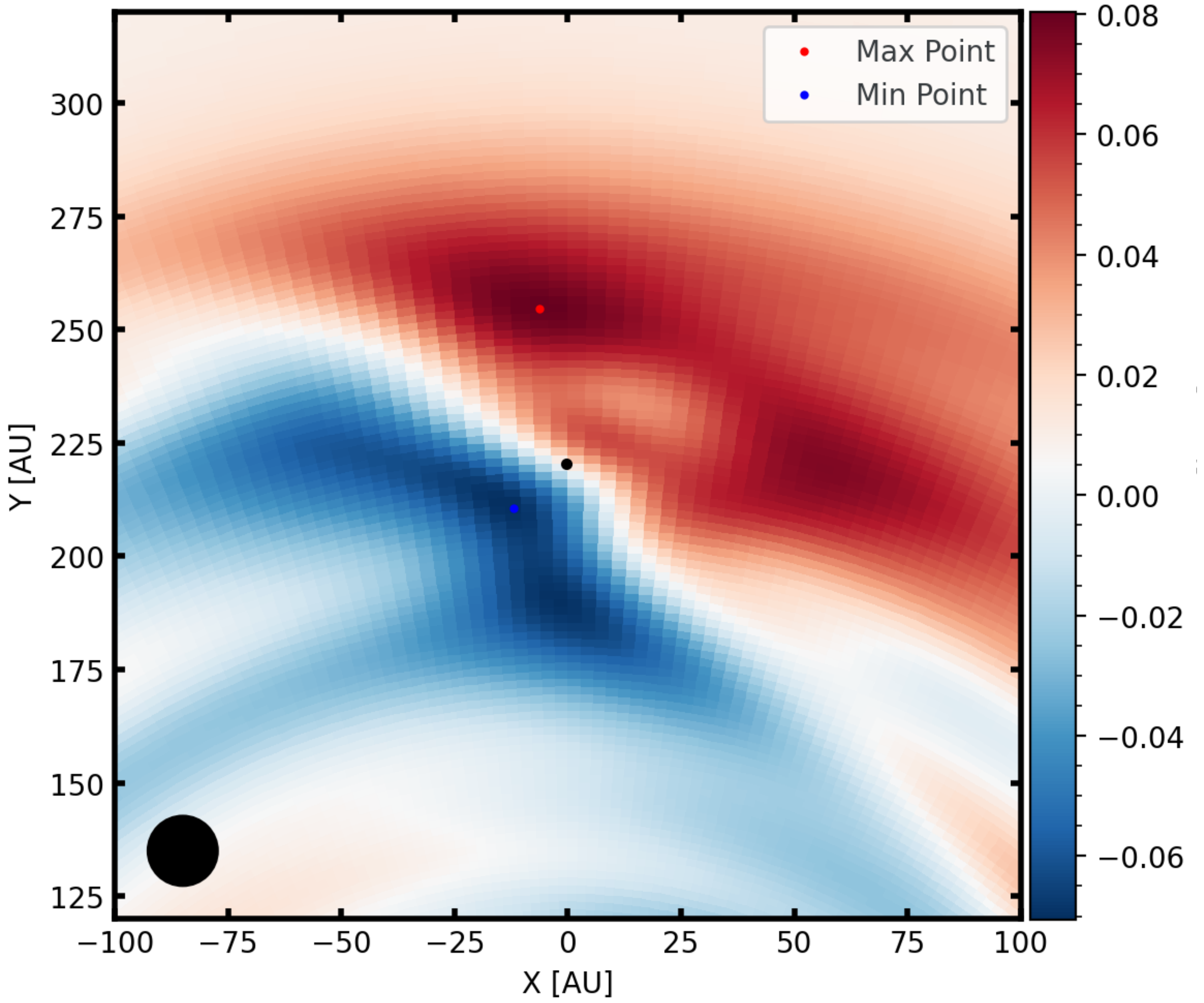
4 MJ

APPENDIX

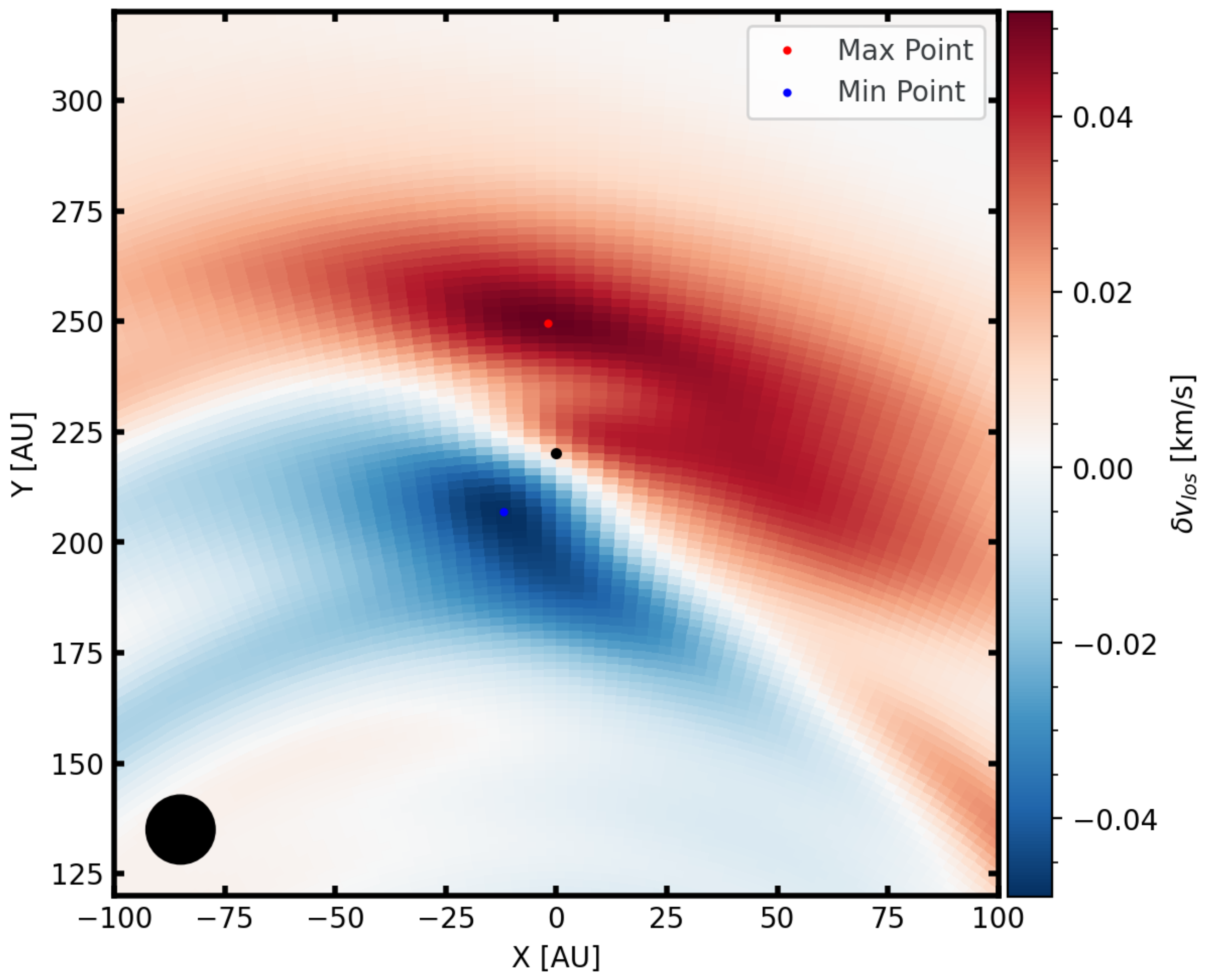
T = 0.26 Myrs



3 MJ



2 MJ



1 MJ

APPENDIX

Model Setup

$M_* = 1 M_\odot$

$r = 10 \sim 700$ AU

$\theta = \pi/2 \sim \pi/2 - 0.5$ (half disk)

$v_{res,channel} = 100\, m/s$

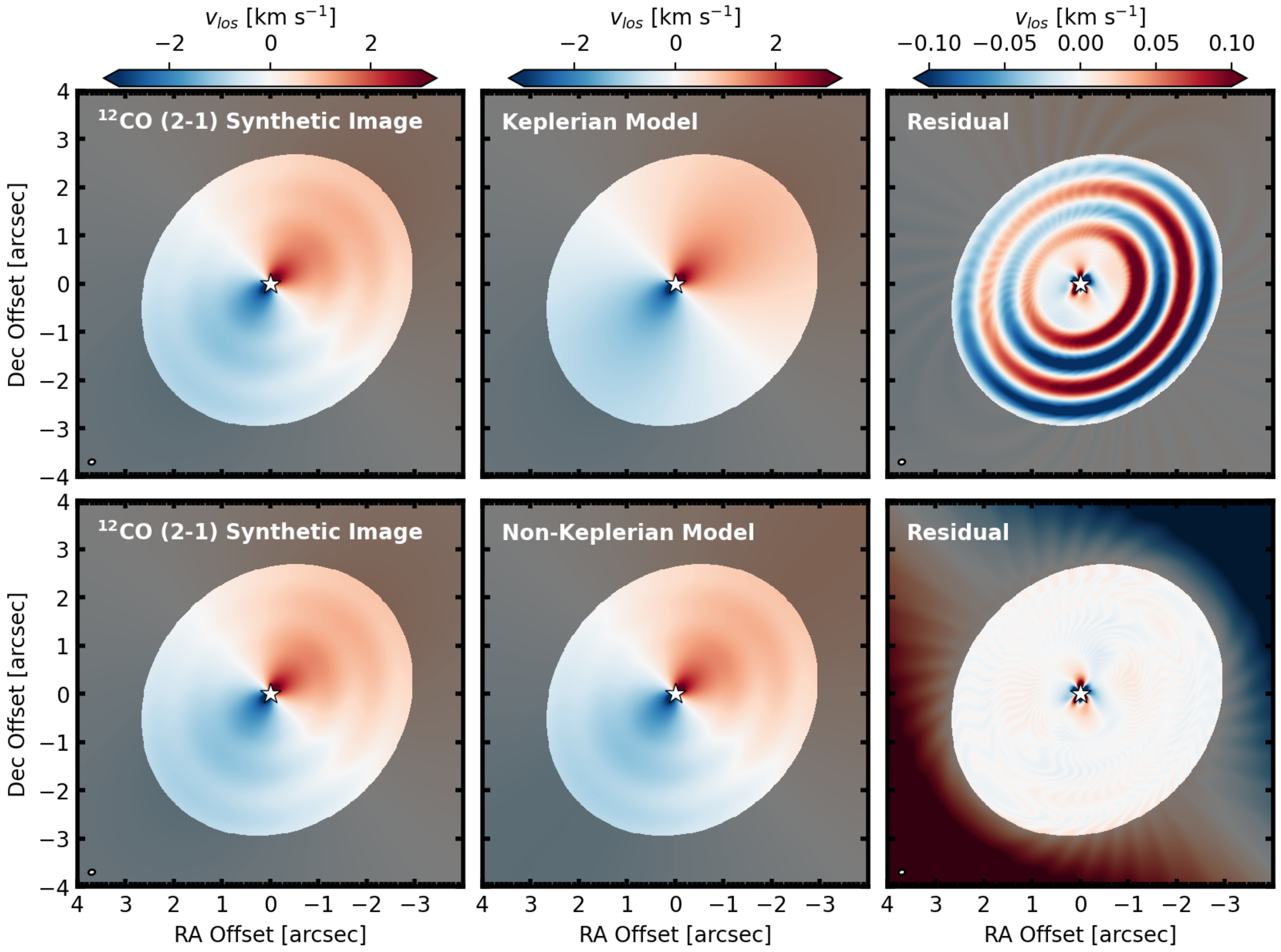
Velocity Field

$v_\phi = v_{kep}$

$v_r = +100 \times sin(2\pi \frac{r}{100\text{AU}})\ m/s$,for r > 100AU

$v_z = -100 \times sin(2\pi \frac{r}{100\text{AU}})\ m/s$,for r > 100AU

Validation of Velocity Decoupling



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