Setting the Planet Formation Stage: The Dynamics of Infall and Accretion Shocks in Protostar Disks

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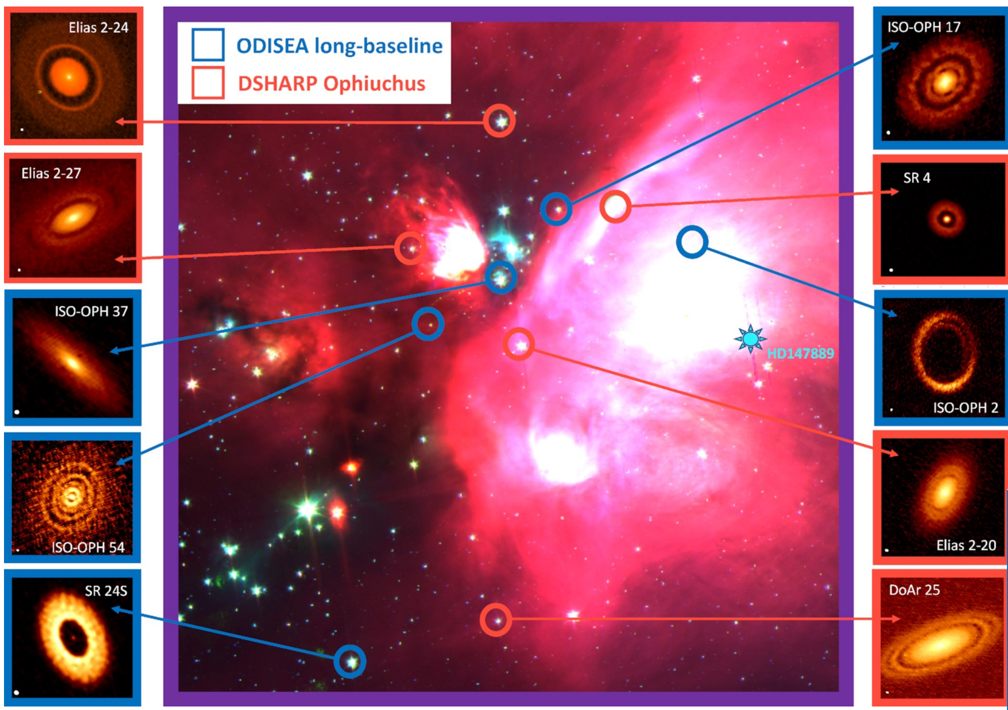
L1688 in ρ Oph: Image credit: NASA/JPL-Caltech/Harvard-Smithsonian CfA

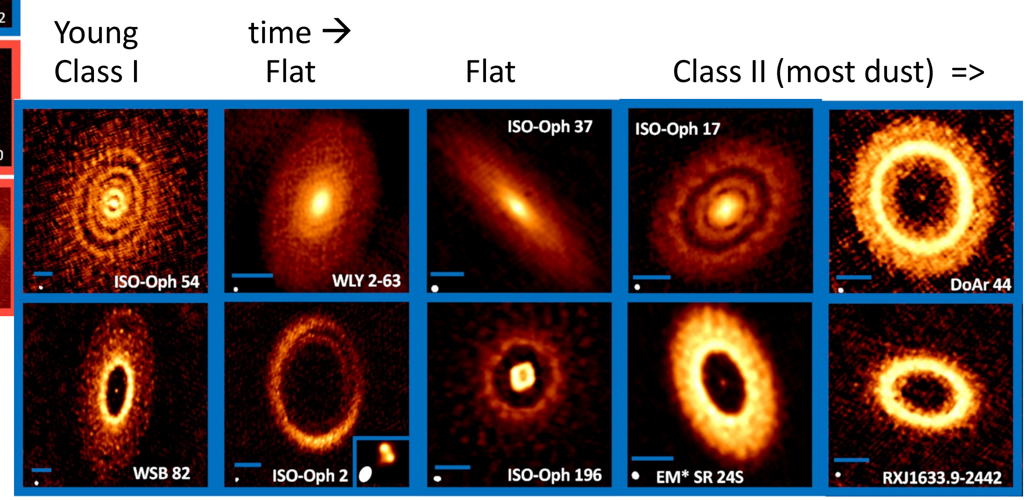
A closer look at L1688 - ALMA images of *largest* and brightest disks reveal structure



Cieza+2021 ODISEA (blue frames) and DSHARP (red frames)
Andrews+2018 in the L1688 star-forming region

Rich structure in outer disks (gaps, rings, spiral waves, warps)
related to planet formation, snowlines (CO, H_2O), multiplicity, tilted inner disk, etc

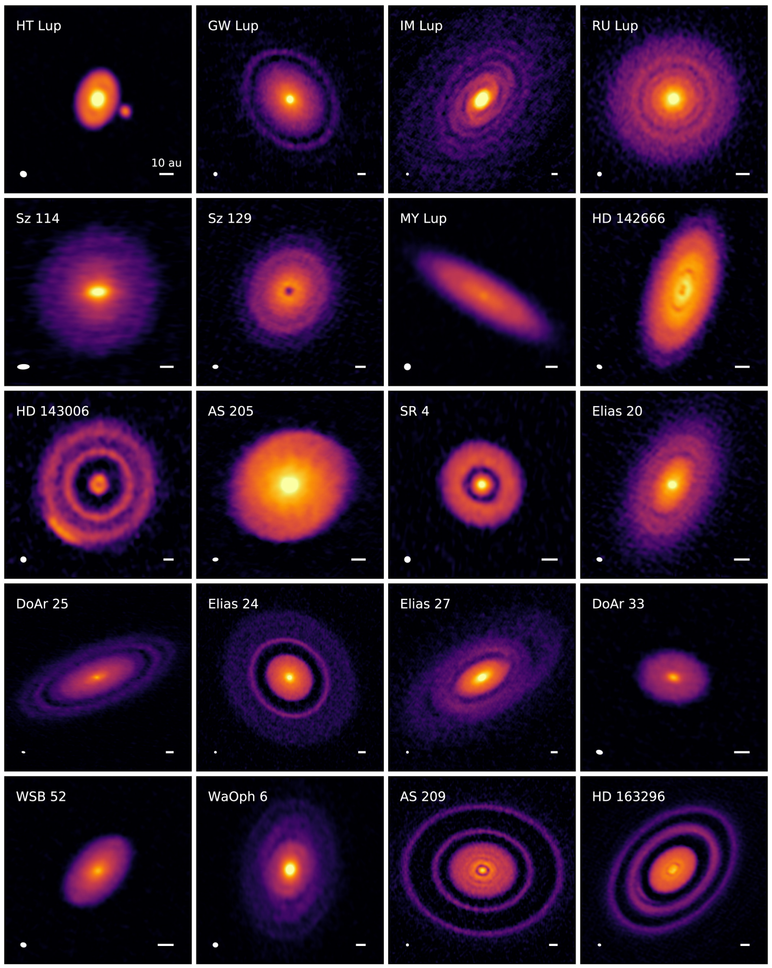
See PPVII including Pinte+2023, Lesur+2023



Cieza+2021. ODISEA 1.3 mm ALMA images. 30au scalebar

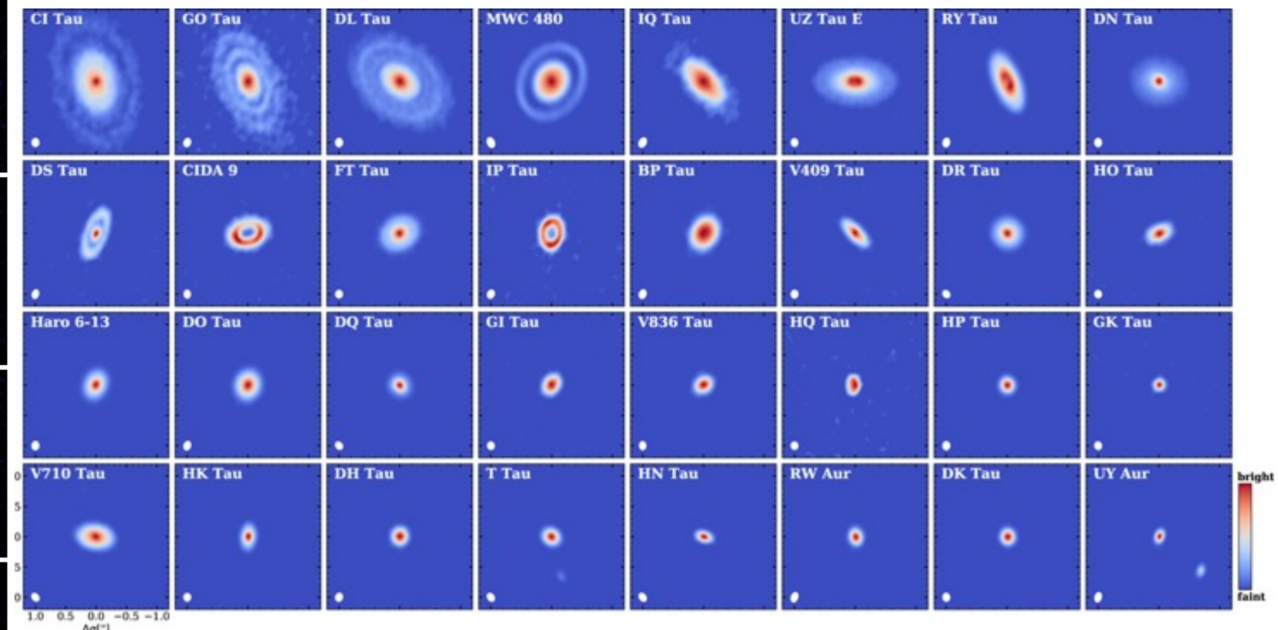
ALMA, VLA surveys of mostly Class II disks

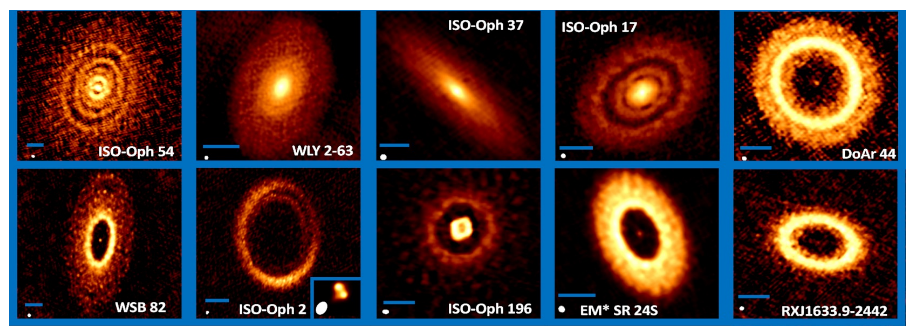
Small disks are more common than large disks.



10au scalebar DSHARP ALMA images of **large** disks. **Anrdrews+2018.**

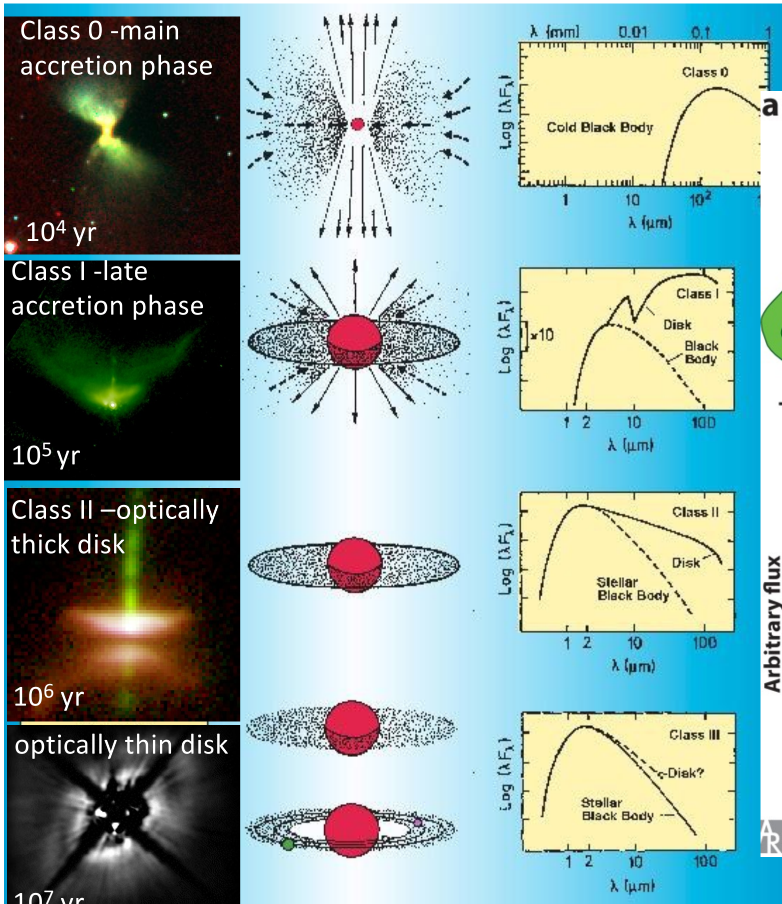
Long+2019. Small disks are more common and show less structure. scale FOV=340au





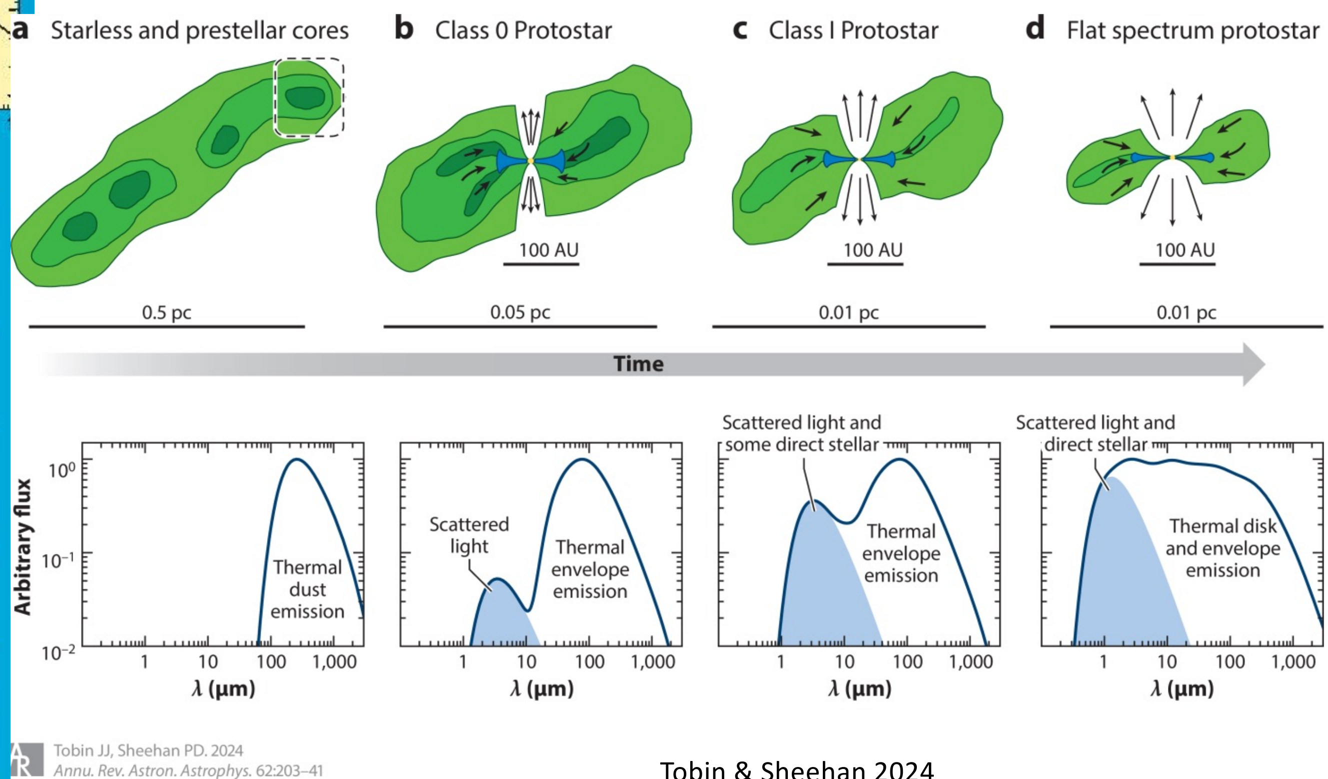
Cieza+2021. ODISEA ALMA images of **large** disks. 30au scalebar

Stages of Protostar Evolution – let's focus now on earlier Class 0 & I phases (10^4-10^5 yr)



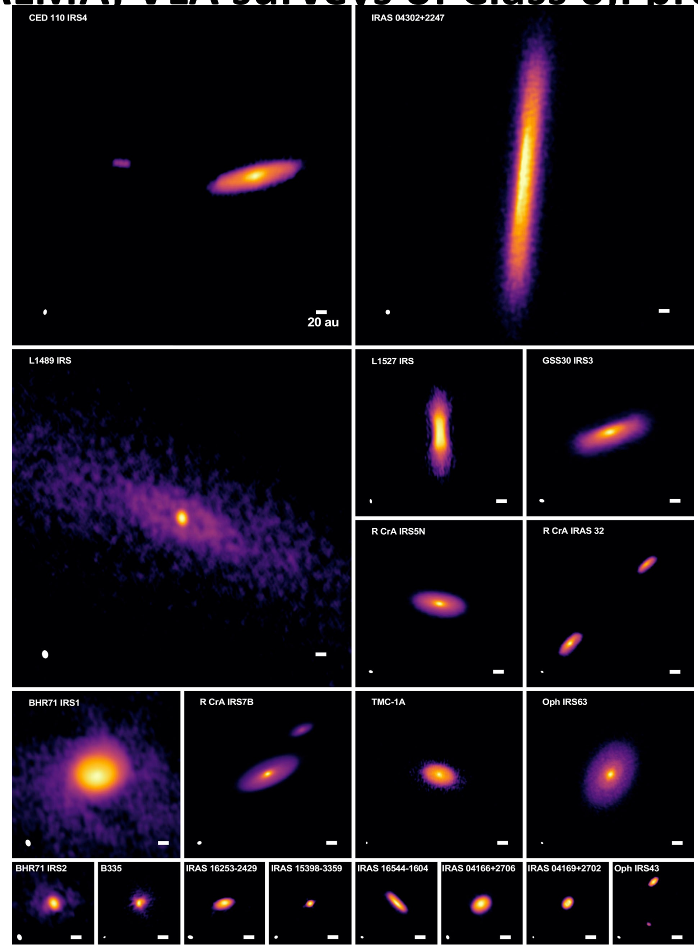
Andre et al. 1993

Collapse phase is gas rich – rotating envelope gas falls inward, achieving free-fall and conserving angular momentum



Tobin & Sheehan 2024

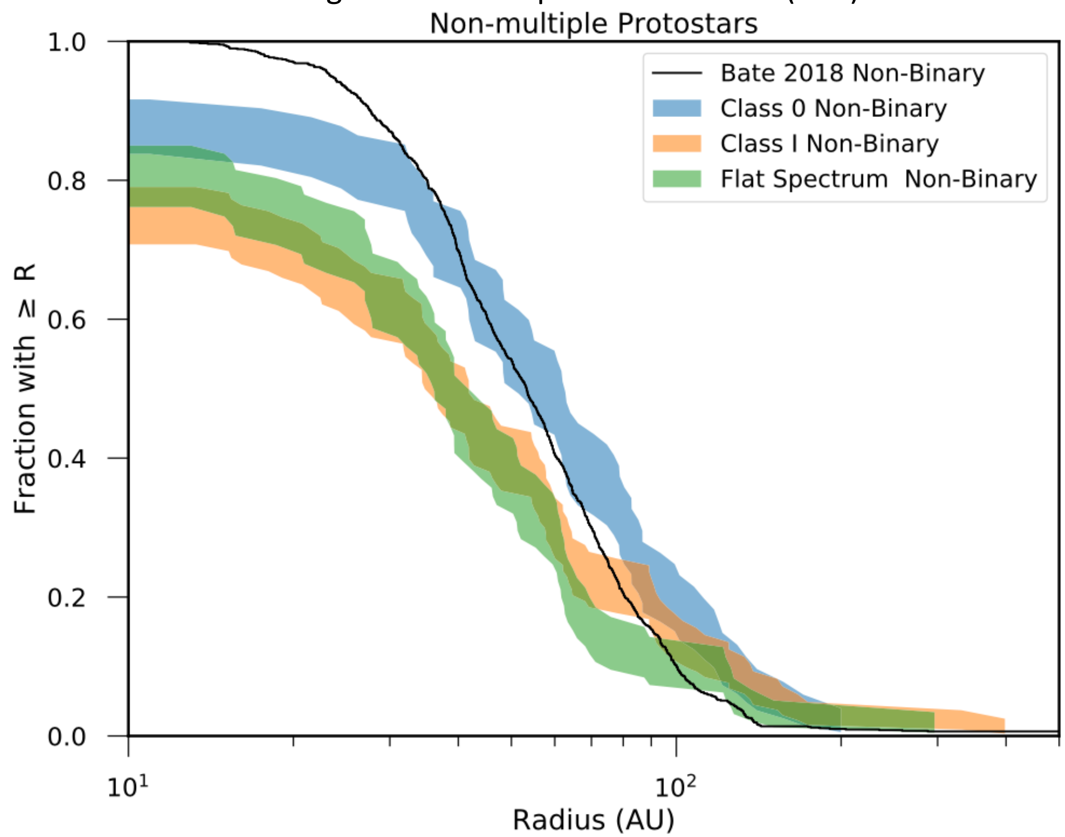
ALMA, VLA surveys of Class 0,I protostars



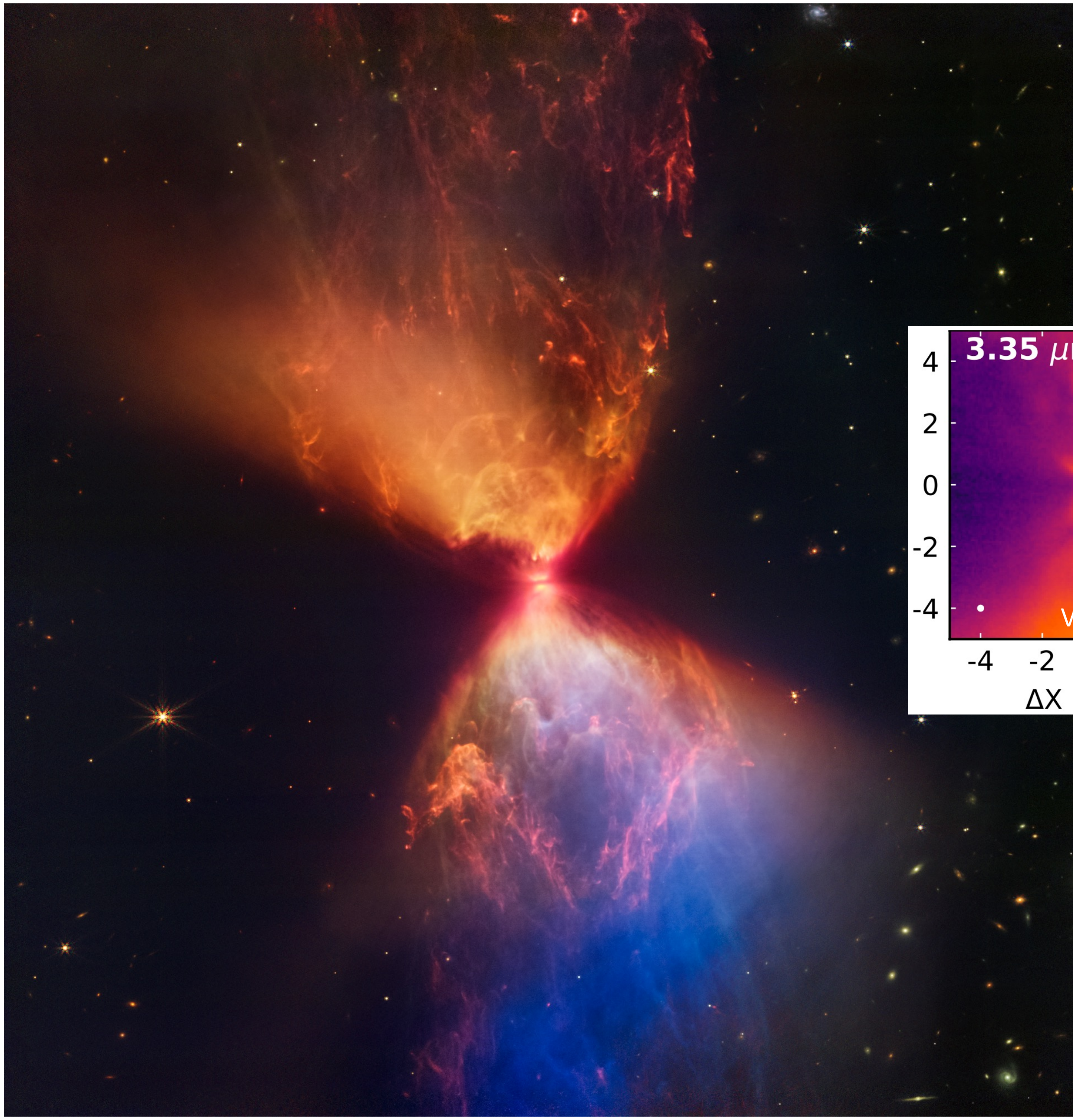
Class 0,I disks are smoother but still show structure including rings and asymmetries.
Caveat: the disks are optically thick. White scalebar=20 au.

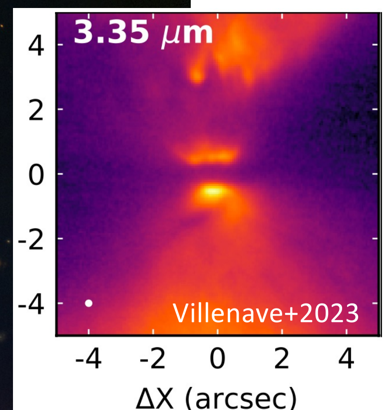
Ohashi+2021. eDisk ALMA survey of class 0,I disks.

Average disk size is **small** 45, 37, 28 au for Class 0,I,flat.
Average disk mass is 26, 15, 12 Mearth for Class 0,I,flat.
Abundant evidence for larger than ISM grains even for class 0. Detected grain sizes comparable to ~9mm (VLA)



VanDam ALMA/VLA survey of 328 protostars at 0.87mm and 9mm.
Tobin+2020.

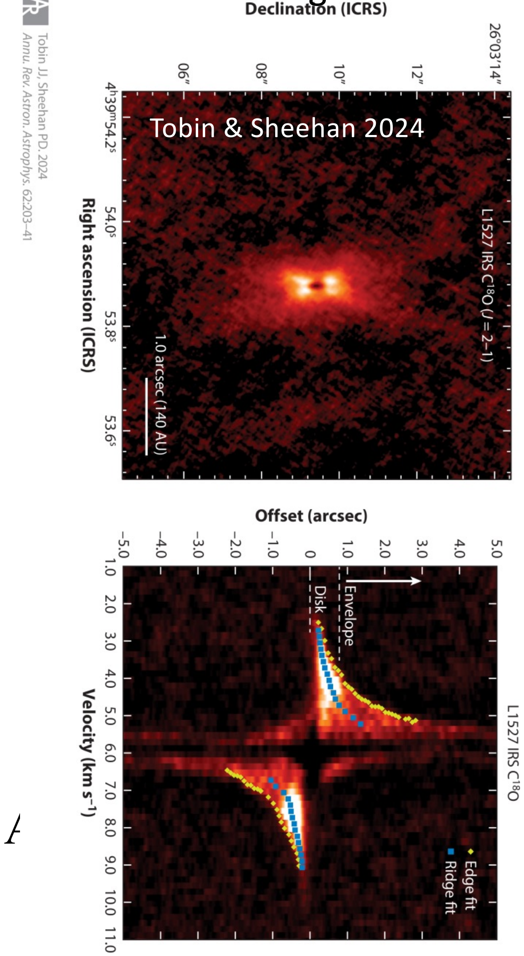




Close-up look at class 0 protostar L1527(edge-on disk)

Left: JWST image of outflow cavity in NIR scattered light

Below: $C^{18}O$ line emission from gaseous disk

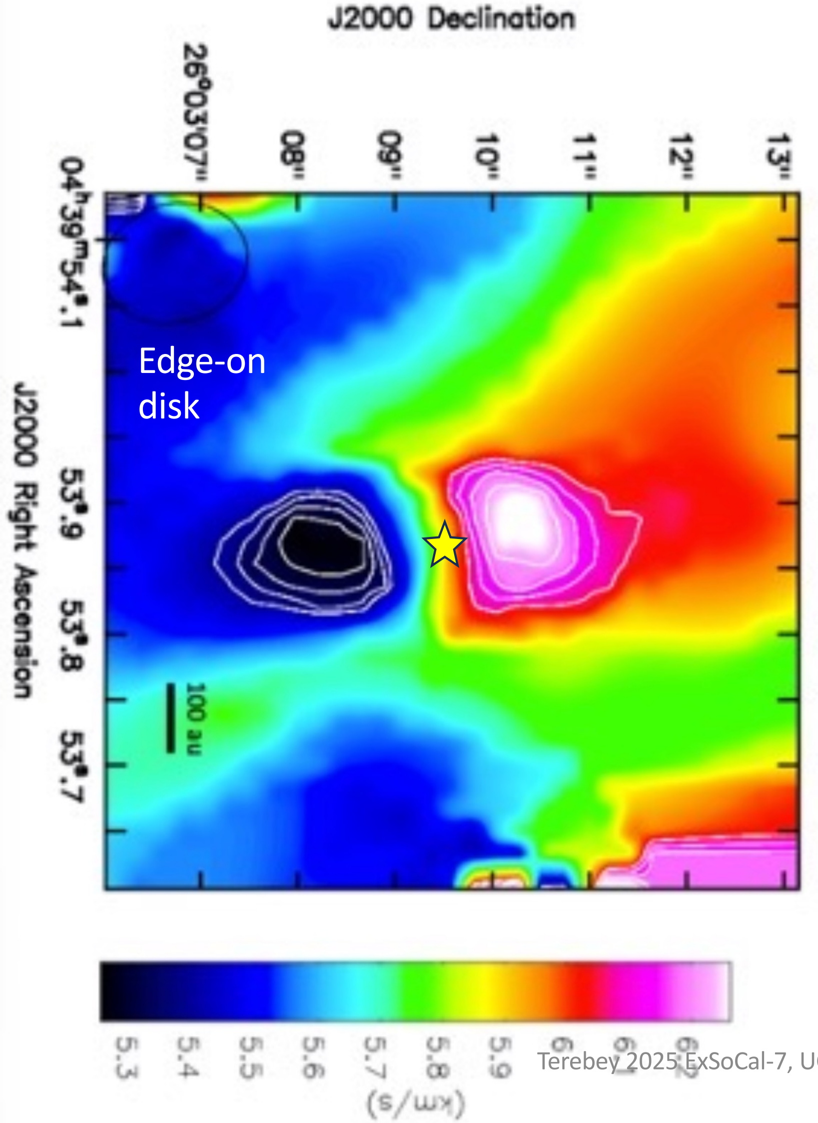


Velocity Moment Map

L1527 ALMA $c\text{-}C_3H_2$

Class 0/I Taurus @140pc

Panehal2023



Science Questions:

Study disks around protostars, because planet formation starts early

Some protostars show evidence for noncircular Keplerian motion in their outer disks (Sakai+2014,Oya+2015)

SO and CS emission could be associated with shocks at envelope-disk outer boundary.

Sakai+(2014) initially proposed ballistic free-fall orbits instead of circular Keplerian disk orbits.

We present a new theoretical solution, that we call the

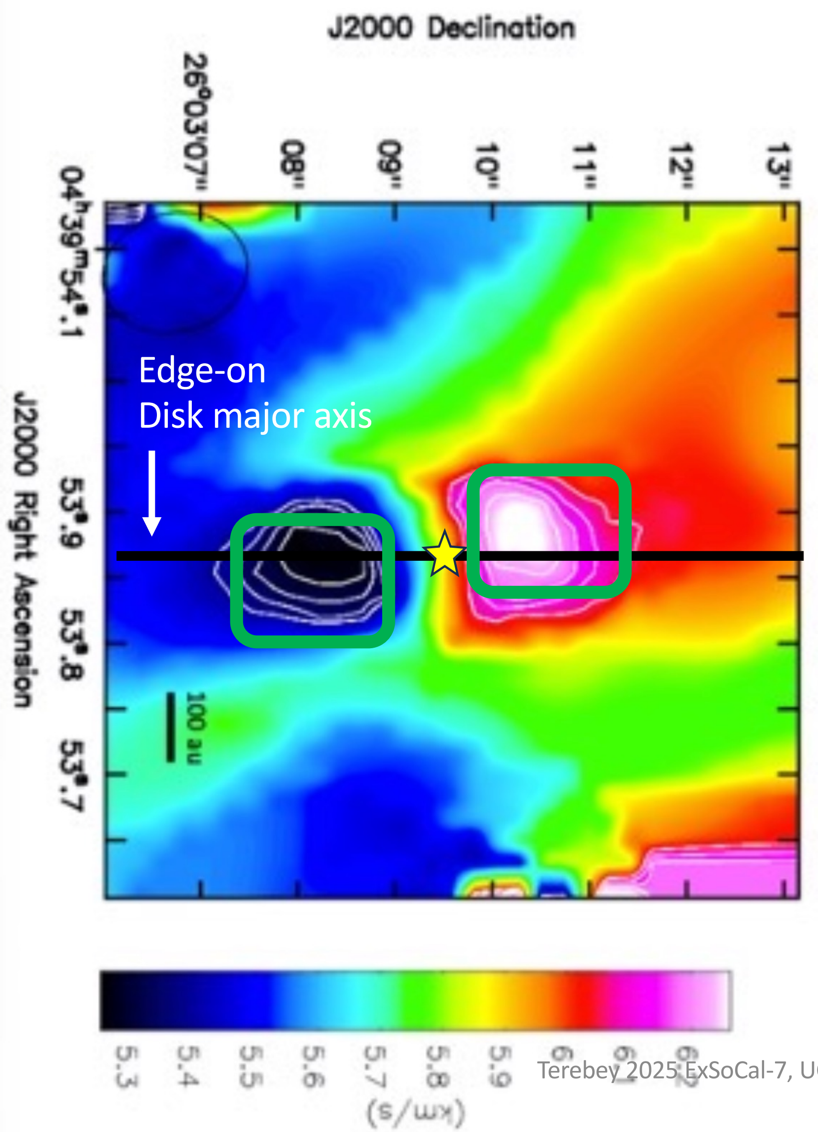
Shock Twist Angle Keplerian (STAK) disk

Velocity Moment Map

L1527
ALMA
$c\text{-}C_3H_2$

Class 0/I
Taurus
@140pc

Panehal2023



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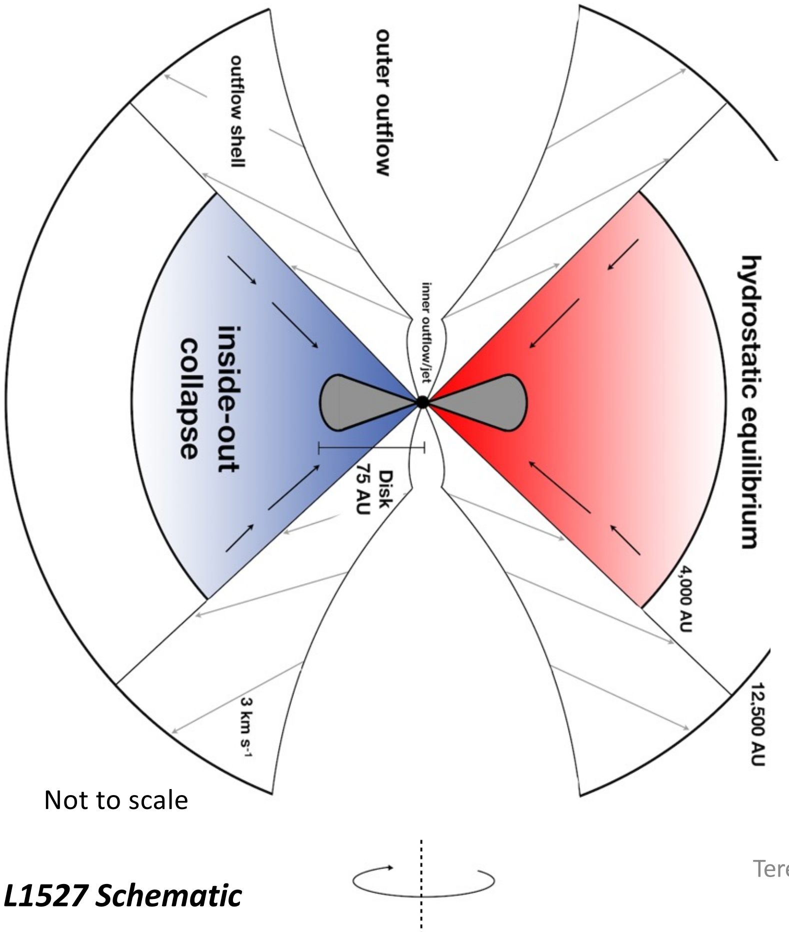
Simulation: new STAK disk adds shocks and gas motion to comprehensive protostar model
Package: RadChemT -Radiation and Chemistry in Time (Flores-Rivera+2021)

Initial Collapse MODEL : *ADD Shock Physics to Disk-Envelope:* *Predict and COMPARE:*



L1527 Schematic

Radiative Transfer

+

Chemistry

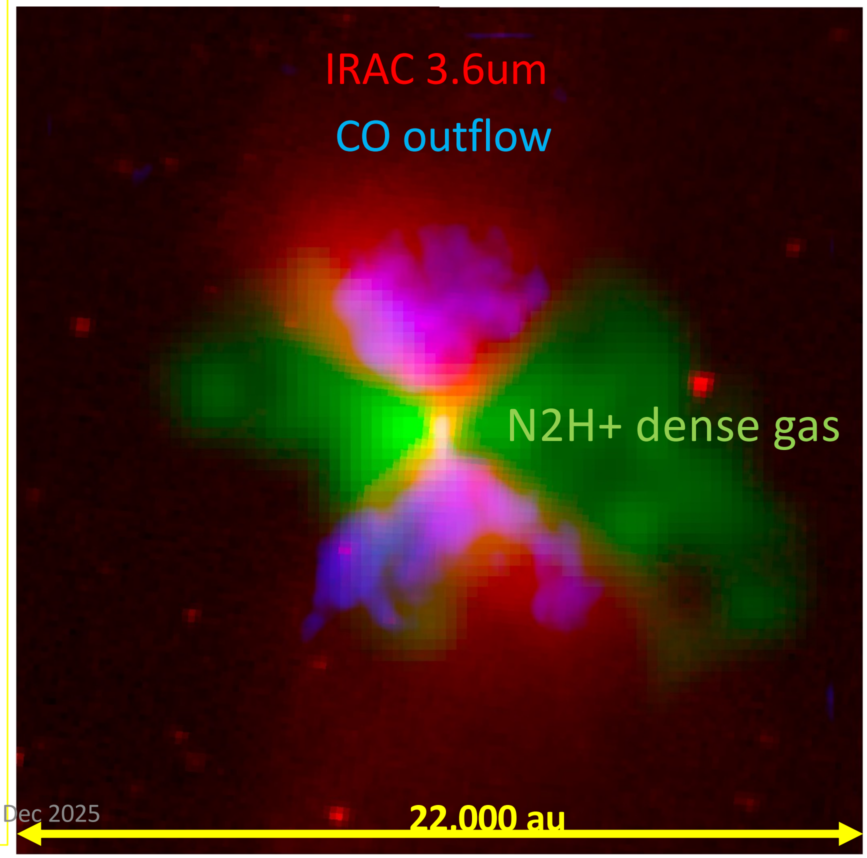
+

Dynamics

+

Shocks, New disk orbits

DATA: L1527 class 0/I protostar

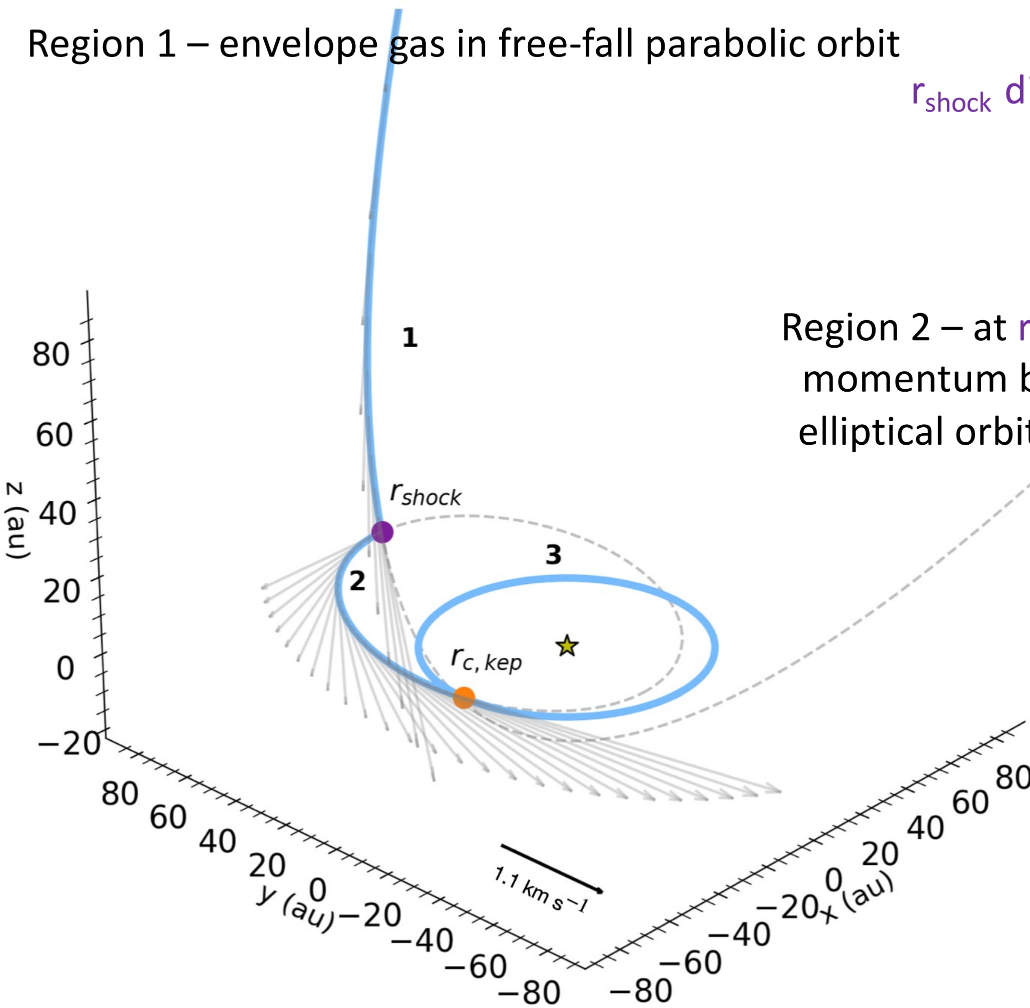


STAK adds shock at the disk boundary

Region 1 – envelope gas in free-fall parabolic orbit

r_{shock} disk boundary set using ram pressure boundary condition

$$\rho_{\rm disk} c_{s_{\rm disk}}^2 = \rho_{\rm env}(c_{s_{\rm env}}^2 + v_{\perp_{\rm env}}^2)$$



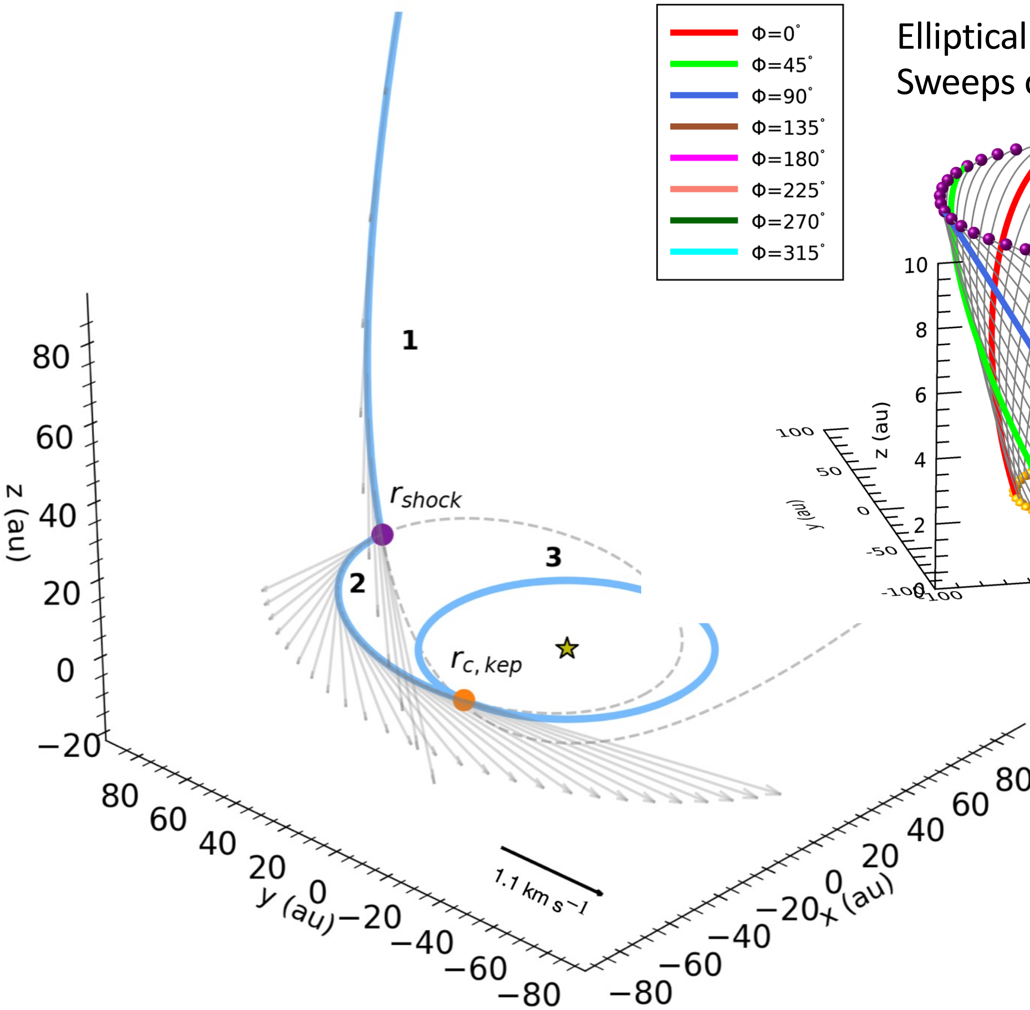
Region 2 – at r_{shock} location, gas conserves angular momentum but loses energy, and transitions to elliptical orbit inside the disk. Grey arrows show velocity vectors

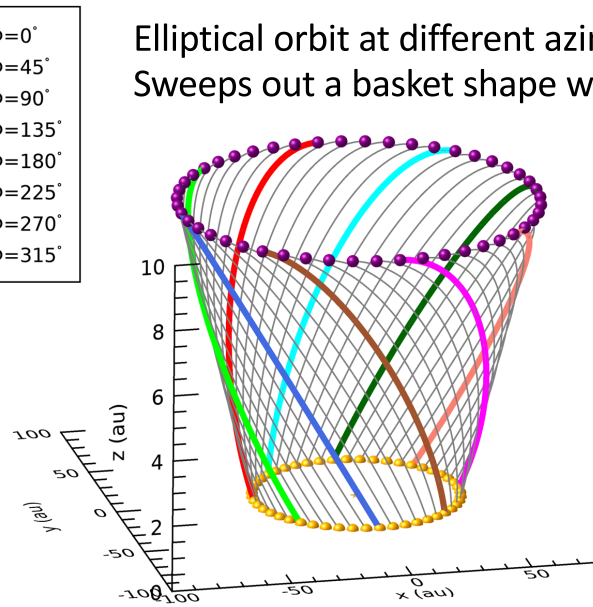
Region 3 –inside the disk, gas follows elliptical orbit to disk midplane, where it undergoes a second shock, and settles into a circular orbit at $r_{c,kep}$

Terebey+2025

STAK elliptical orbits within the disk

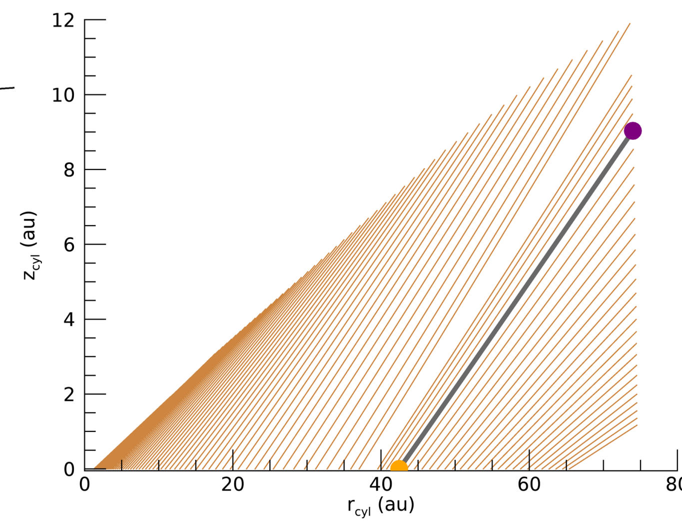
Terebey+2025

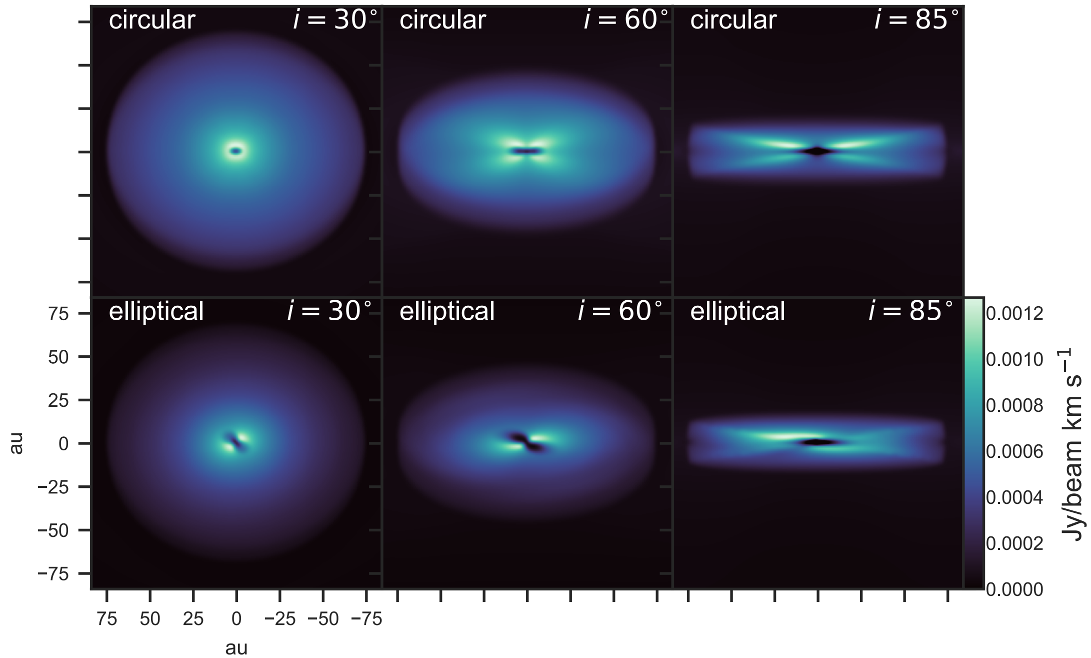




Elliptical orbit at different azimuthal angles
Sweeps out a basket shape within the disk

Meridional plot within the disk for different r_{shock} entry points





Intensity moment 0 map

$C^{18}O$(2-1) synthetic images for ALMA
Continuum (dust) subtracted
Protostar at image center
75 au radius disk

Diagnostics: Can see the inner twist of STAK disk elliptical orbits compared with circular Keplerian

Depends on source inclination.
Asymmetric gas motion with respect to underlying disk (offset from dust disk major axis)

Terebey+2025

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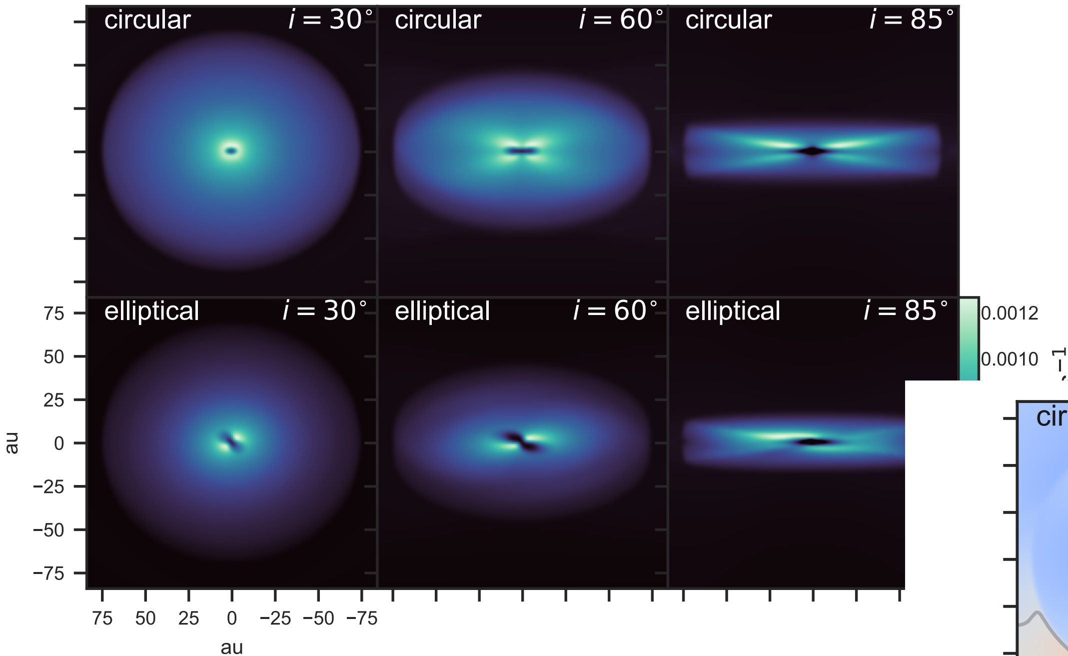
Depends on source inclination.
Asymmetric gas motion with respect to underlying disk   (offset from dust disk major axis)



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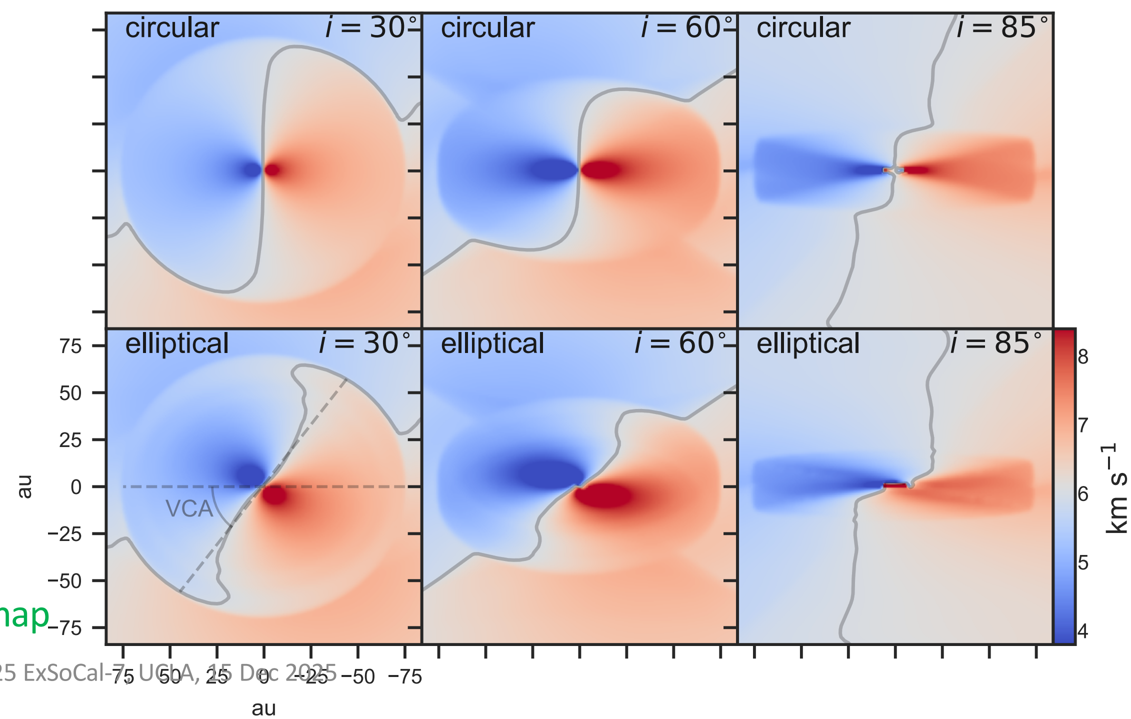

$C^{18}O$(2-1) gas synthetic images for ALMA
Are continuum (dust) subtracted
Protostar at image center
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Terebey+2025

Velocity moment 1 map

Summary

- **Shock Twist Angle Keplerian (STAK) disk is a theoretical framework to include shocks at disk/envelope interface in outer disk**
  - **ram pressure boundary condition gives shock location**
  - **Gas moves on elliptical orbits past the shock, through the disk**

- **STAK disks show distinctive signature. Similar to circular Keplerian disks but *moment maps show an asymmetric inner twist* that deviates from the major axis of the dust continuum.**
- **Observers – Look for these motions! Be sure to resolve the disks well.**

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L1688: Image credit: NASA/JPL-Caltech/Harvard-Smithsonian CfA

Simulating L1527 parameters:

Radius from 10.04 R_* to R_{env} = 12,500 AU

Densities of disk, envelope, and outflow

Disk edge defined using new ram pressure boundary

$$\rho_{\rm disk} c_{s_{\rm disk}}^2 = \rho_{\rm env}(c_{s_{\rm env}}^2 + v_{\perp_{\rm env}}^2)$$

*Add shock motion at the disk edge (STAK)

Equation and Table: Flores-Rivera et al. (2021)

Table 1
Physical Parameters

Parameters	Description	TSC	UCM
R_* ($R_\odot$)	Stellar radius	1.70	:
T_* (K)	Stellar temperature	3300	:
M_* ($M_\odot$)	Stellar mass	0.22	:
$M_{\rm disk}$ ($M_\odot$)	Mass of the disk	0.011	0.006
$R_{\rm disk}$ (au)	Disk outer radius	75	:
$\dot{M}_{\rm disk}$ ($M_\odot$ yr^{-1})	Disk accretion rate	6.6×10^{-7}	:
$\dot{M}_{\rm env}$ ($M_\odot$ yr^{-1})	Envelope infall rate	3.0×10^{-6}	5.0×10^{-6}
θ_1 (deg)	Opening angle of the inner cavity surface	15	:
z (au)	z-intercept, inner cavity surface at $\omega = 0$	75	:
θ_2 (deg)	Opening angle of the outer cavity surface	6	:
$L_{\rm ISRF}$ ($L_\odot$)	Luminosity due to ISRF	0.49	:
Quantities shown below are derived from input parameters above			
$M_{\rm env}$ ($M_\odot$)	Mass of the envelope	1.77	1.04
c_s (km s^{-1})	Thermal sound speed using $\dot{M}_{\rm env} = 0.975 c_s^3/G$	0.23	0.27
$R_{\rm col}$ (au)	Inside-out collapse radius using $R_{\rm col} = c_s t_{\rm age}$	3800	n/a
L_* ($L_\odot$)	Stellar luminosity	0.31	:
$L_{\rm acc,star}$ ($L_\odot$)	Stellar hot-spot accretion luminosity	2.14	:
$L_{\rm acc,disk}$ ($L_\odot$)	Disk accretion luminosity	0.29	:
$L_{\rm int}$ ($L_\odot$)	Internal luminosity	2.74	:

Note. The symbol : means the UCM values are the same as the TSC values.