Accretion drives accretion

Numerical Insights into Disk Accretion, Eccentricity, and Kinematics in the Class 0 phase

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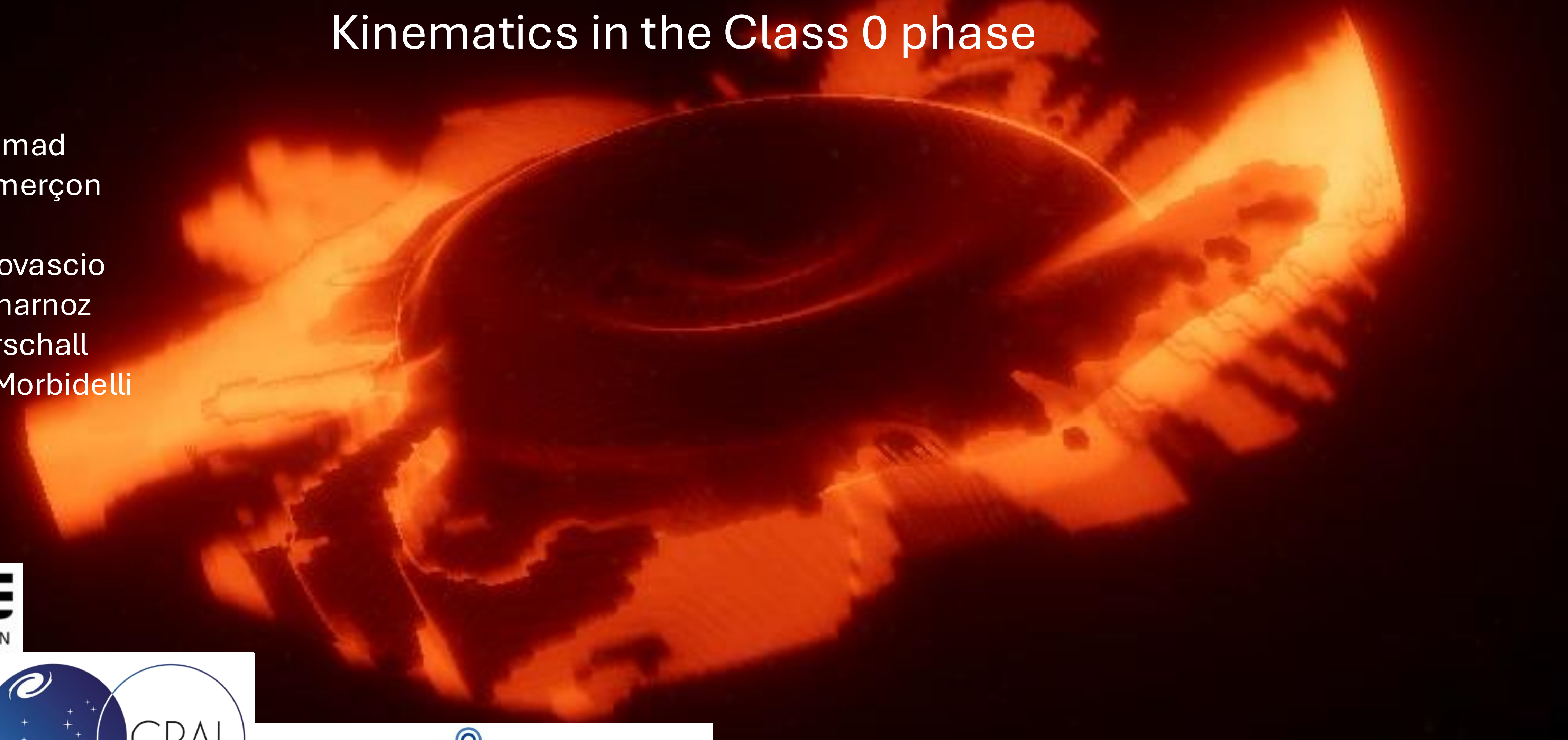

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Video credits: Alex Andrix (www.alexandrix.com)

Context: Disk formation

- Observations can now probe Class 0 systems (< 100 kyr objects)

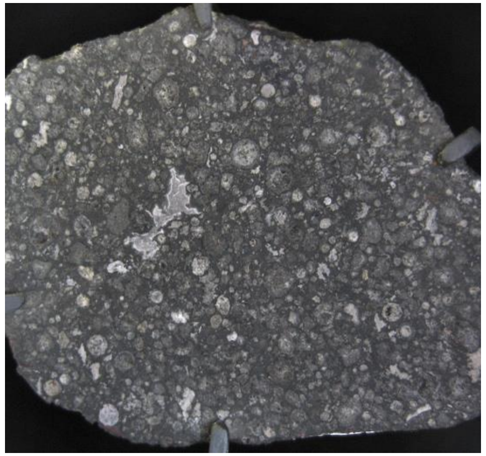
  Tobin+ 2020, Ohashi+ 2023

- Cosmochemistry now probes early disk kinematics
  - Refractory inclusions (formed at $T > 1300\ \mathrm{K}$) transported beyond orbit of Jupiter

    Nanne+ 2019, Morbidelli+ 2024

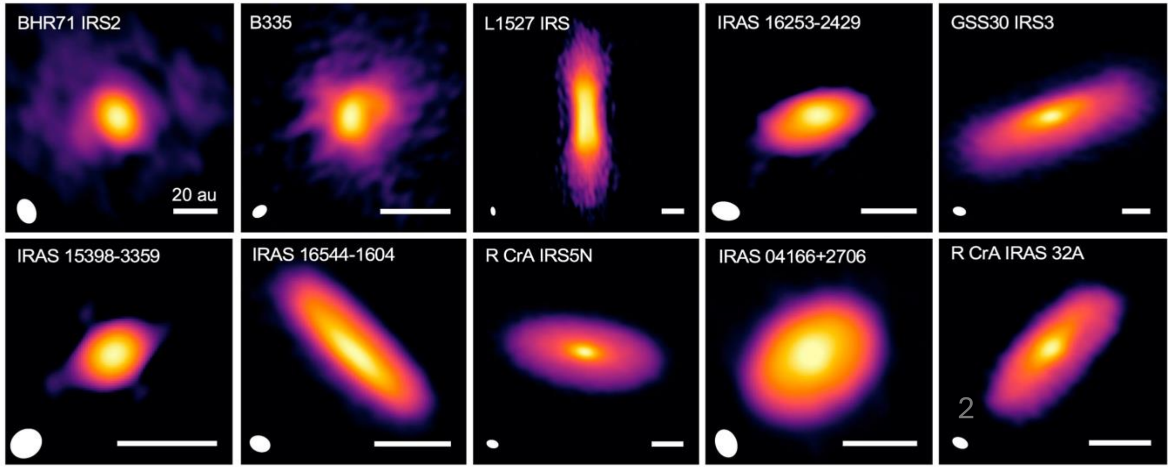
- **Constraints on early-disk kinematics**

Allende meteorite



eDisk Survey (Class 0)

Ohashi+ 2023



Context: Disk formation

Textbook disk evolution

Mass + angular momentum conservation (Pringle 1981)

$$\frac{\partial\Sigma}{\partial t} = \frac{3}{R}\frac{\partial}{\partial R}\left[\sqrt{R}\frac{\partial}{\partial R}\left(\nu\Sigma\sqrt{R}\right)\right] + S(R,t)$$

Effective viscosity $\nu = \alpha H^2 \Omega$
(Shakura & Sunyaev 1973)

Source term (accretion)

$$S(R,t) = S\left(\dot{M}_d, j\right)$$

I. Efficiency of **angular momentum transport** within disk → **Accretion in** the disk

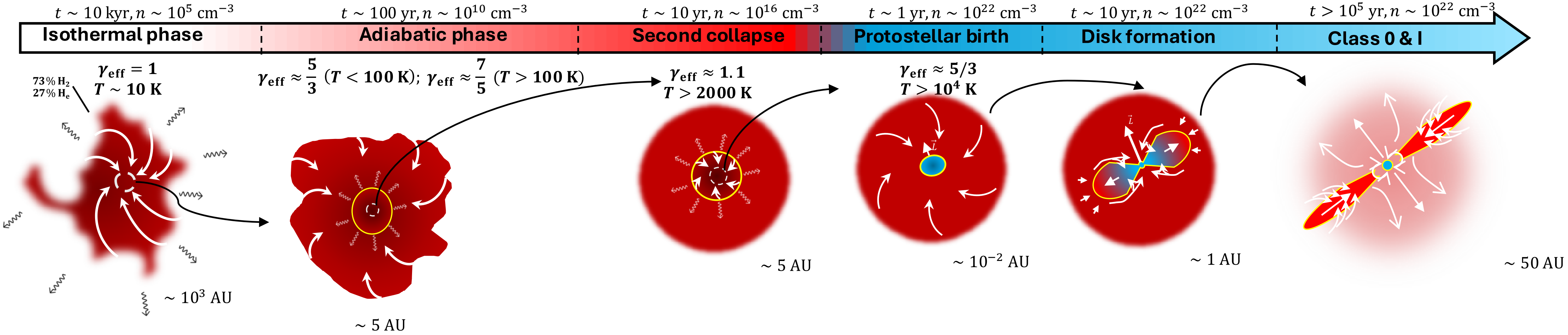
II. The physics of the **collapse** → **Accretion** into the disk
   a) Mass accretion rate into disk $\dot{M}_d(t)$
   b) Angular momentum content of accreted material $j(t)$

This study: attempt to characterize both in the Class 0 phase

Context: Scales and Physics

- Need to describe collapse of dense core to **sub-AU scales**

- Wide variety of physical processes involved
  Self-gravitating hydrodynamics
  Magnetic fields & resistive effects
  Radiative transfer

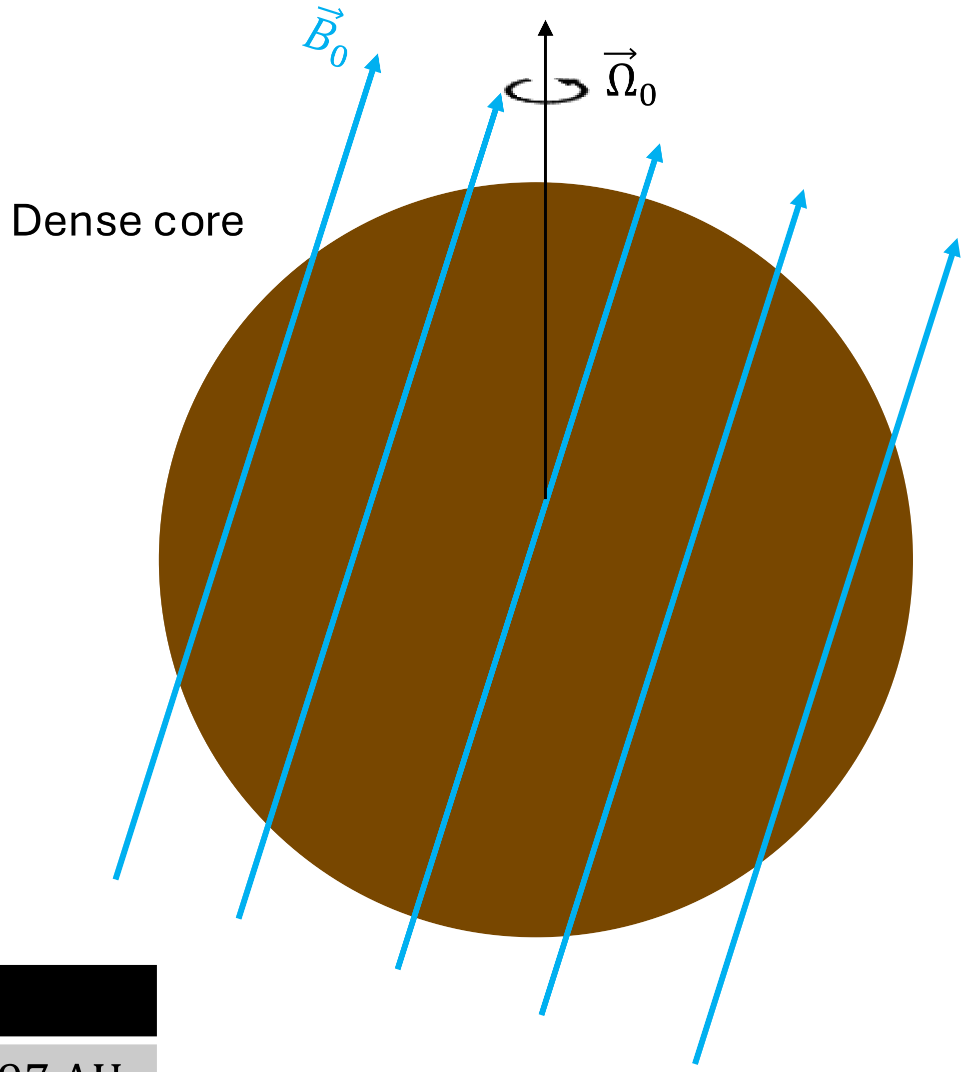


Simulating disk formation with RAMSES

Teyssier 2002

NIMHD + M1 + FLD

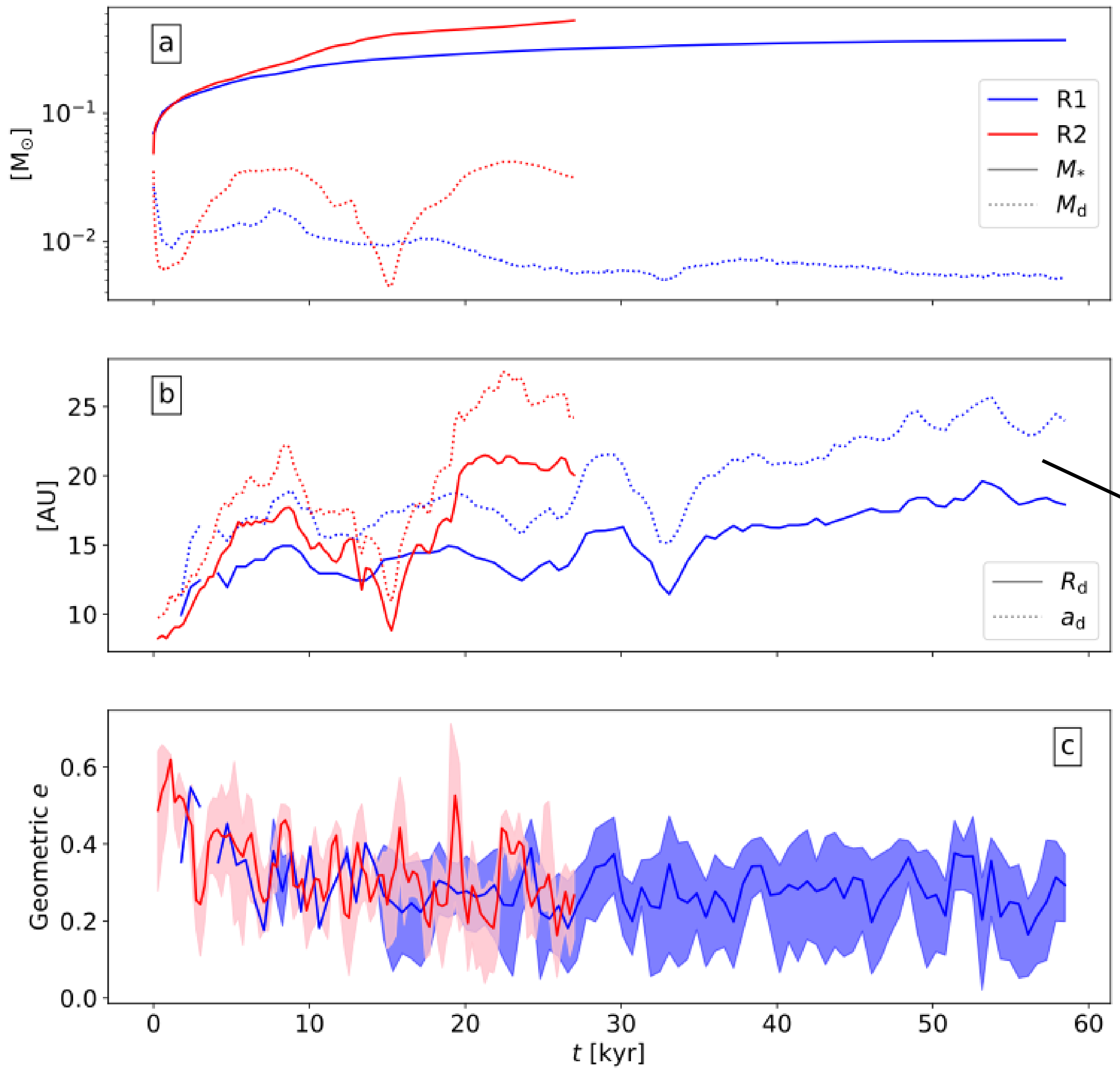
Fromang+ 2006, Teyssier+ 2006, Masson+ 2012, Commerçon+ 2011, 2014, Mignon-Risse+ 2021a,b



- Uniform density sphere
- M_0
- $T_0 = 10\ K$
- Thermal to gravitational energy ratio $\alpha = 0.4$
- Solid body rotation $\beta_{\mathrm{rot}} = \frac{R_0^3 \Omega_0^2}{3 G M_0} = \frac{E_{\mathrm{rot}}}{E_{\mathrm{grav}}} = 4 \times 10^{-2}$
- Mass-to-flux ratio $\mu = \frac{(M/\phi)}{(M/\phi)_{crit}} = \frac{10}{3}$
- 10 deg inclination of $\vec{B}_0$ w.r.t $\vec{\Omega}_0$
- $m = 2$ density perturbation with 10% amplitude

Run label	M_0	ℓ_{max}
R1	$1\ \mathrm{M}_\odot$	14; $\Delta x_{\mathrm{min}} \approx 0.97\ \mathrm{AU}$
R2	$3\ \mathrm{M}_\odot$	16; $\Delta x_{\mathrm{min}} \approx 0.72\ \mathrm{AU}$

Global disk evolution



Magnetically regulated disk radius (Hennebelle+ 2016)

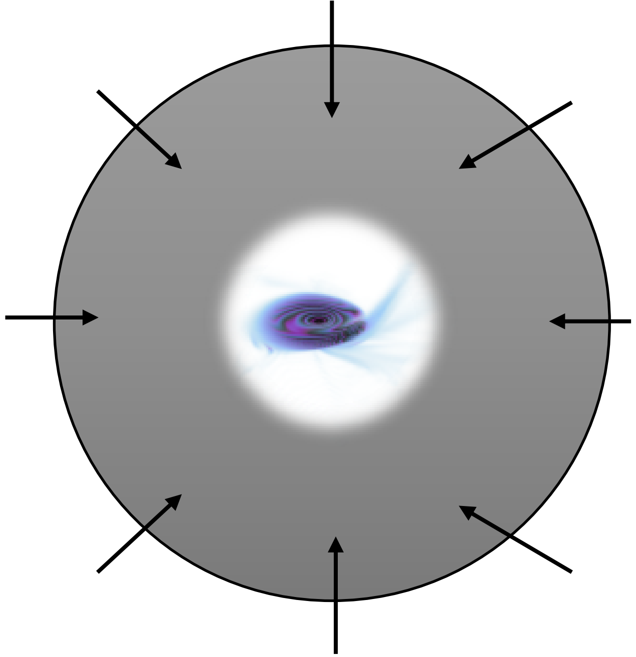
R2 3D render

Disk morphology changes significantly over time

Accretion into the disk

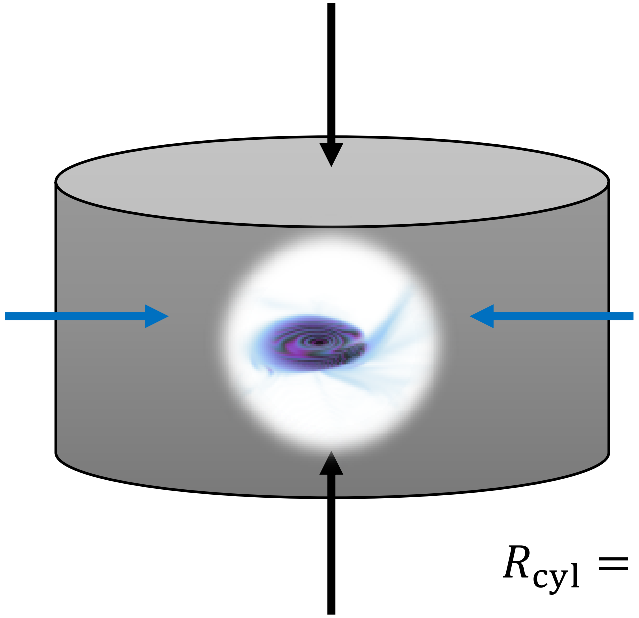
Measuring mass fluxes into the disk

$$\dot{M}(\phi, \Lambda, t) = -\rho v_r R_{\mathrm{shell}}^2 \cos(\Phi) d\phi d\Lambda$$



$R_{\mathrm{shell}} = 30$ AU

$$\dot{M}_{\mathrm{z}}(R, \phi, t) = -\mathrm{sgn}(z) \rho v_z R dR d\phi$$



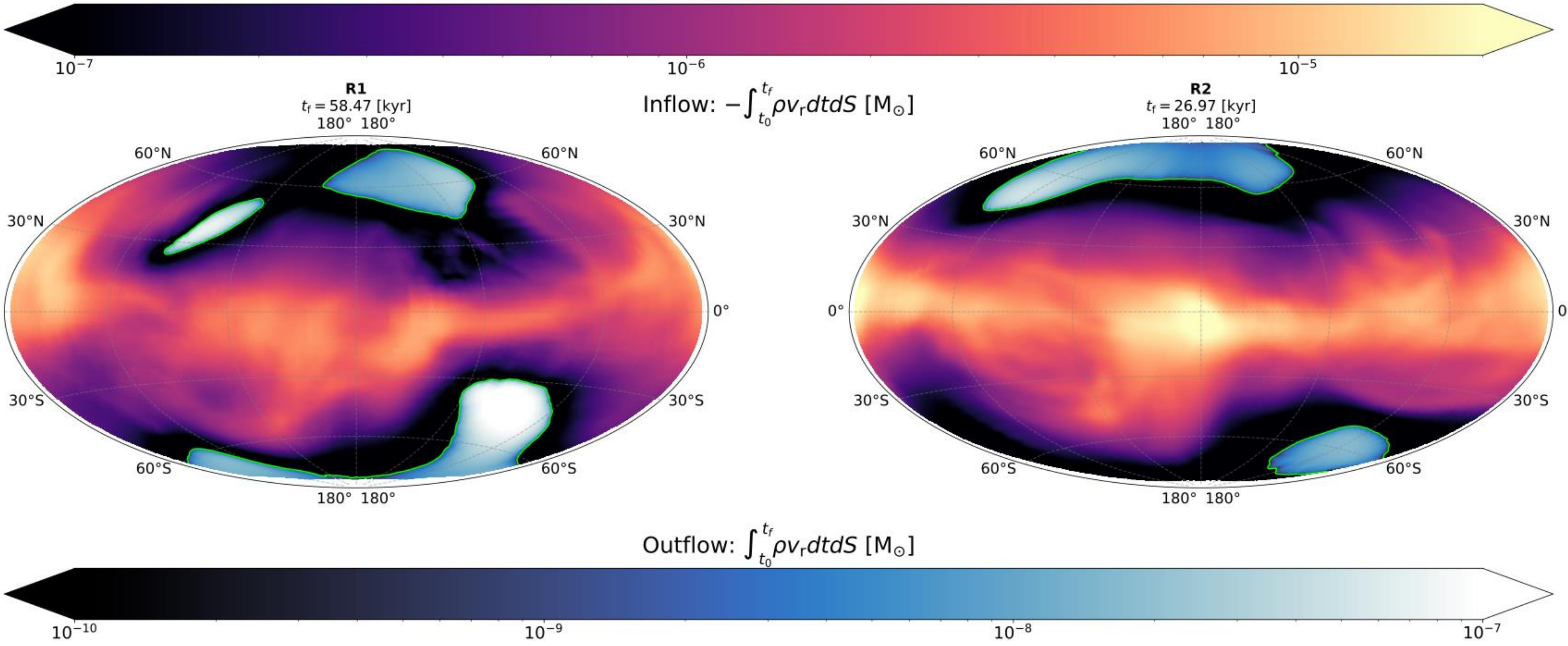
$$\dot{M}_{\mathrm{cyl}}(z, \phi, t) = -\rho v_R R_{\mathrm{cyl}} d\phi dz$$

$R_{\mathrm{cyl}} = 30$ AU

Accretion into the disk

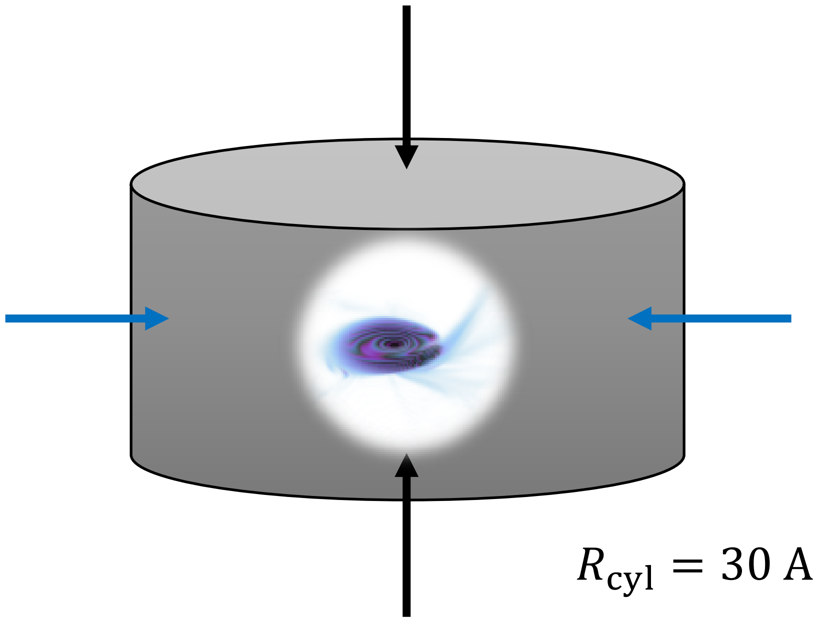
Measuring mass fluxes into the disk

Time integrated measurements



Accretion into the disk

Measuring mass fluxes into the disk

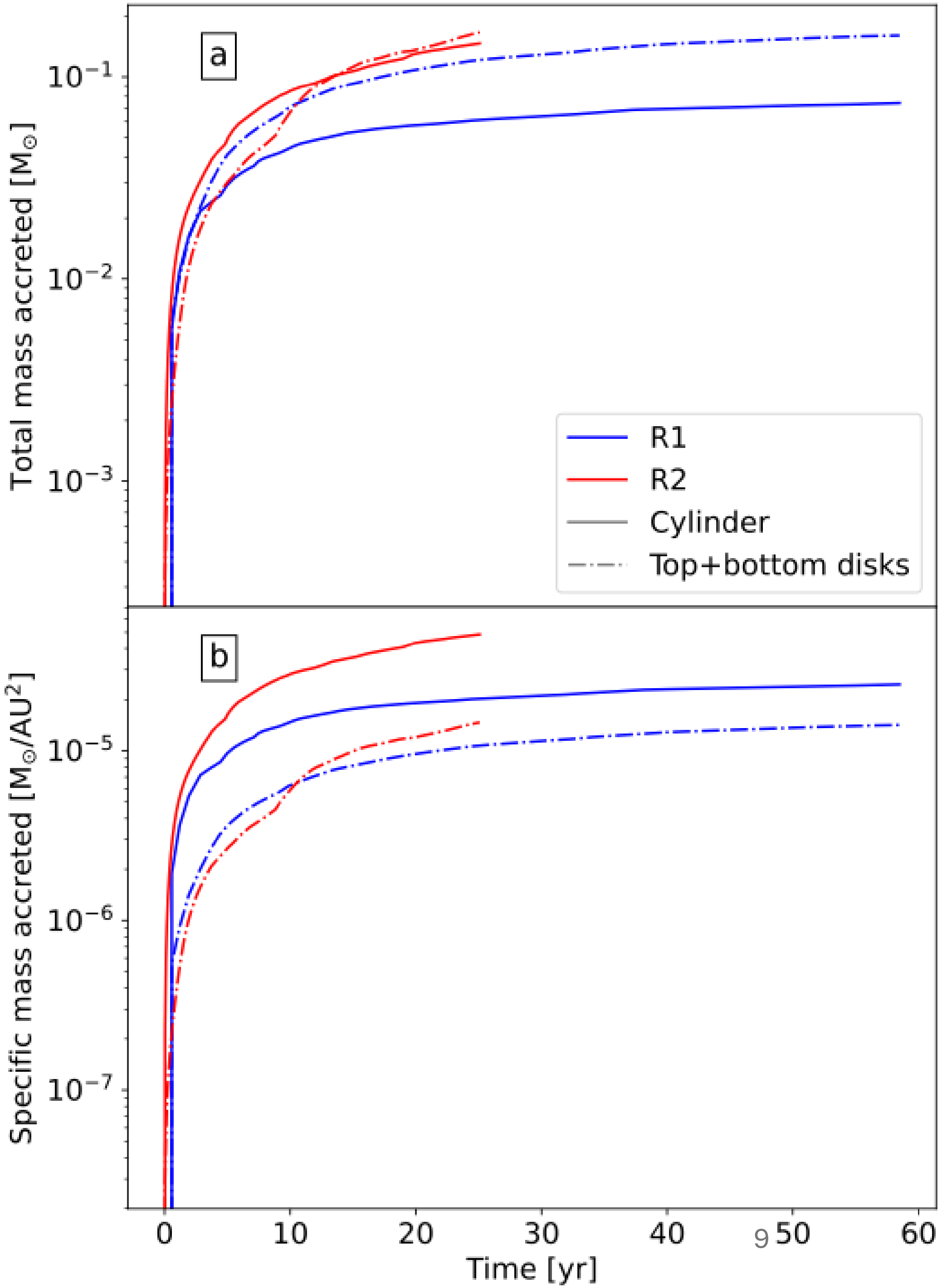


$$\dot{M}_{\mathrm{z}}(R,\phi,t) = -\mathrm{sgn}(z)\rho v_{\mathrm{z}} R dR d\phi$$

$$\dot{M}_{\mathrm{cyl}}(z,\phi,t) = -\rho v_R R_{\mathrm{cyl}} d\phi dz$$

$R_{\mathrm{cyl}} = 30$ AU

$h_{\mathrm{cyl}} = 16$ AU

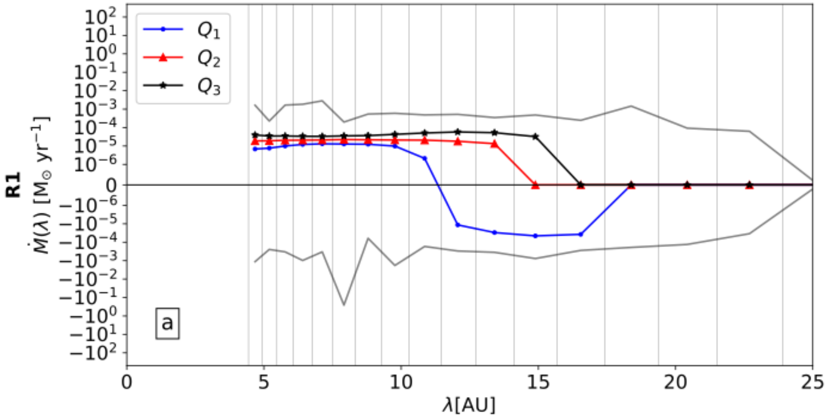


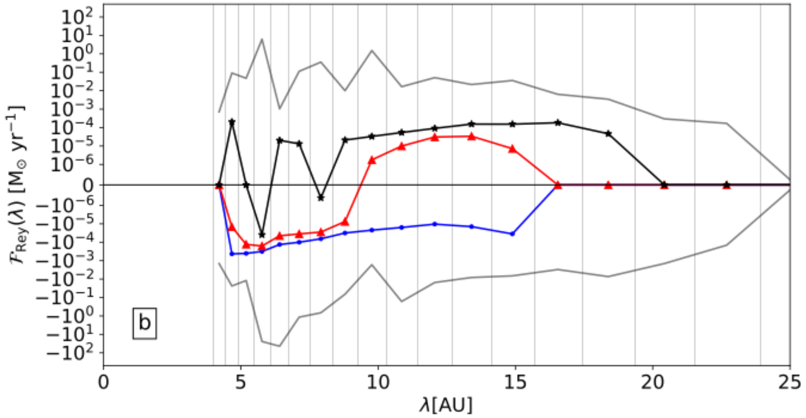
Accretion in the disk

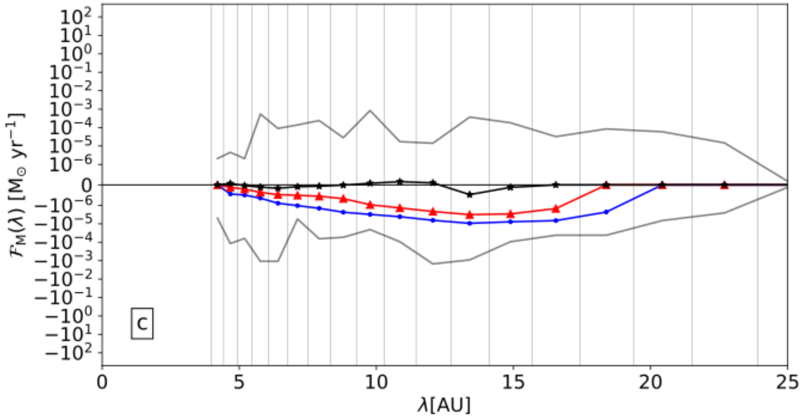
Measuring mass fluxes in the disk

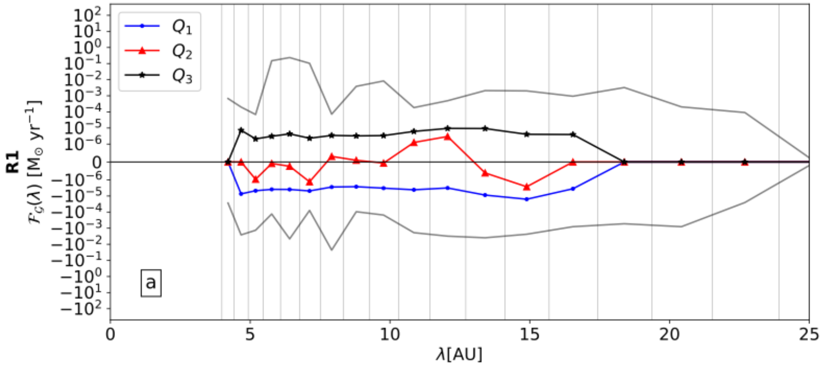
Statistical measurements for R1, over ~ 60 kyr

Q2: median


Mass accretion rate


Turbulent stress


Maxwell stress

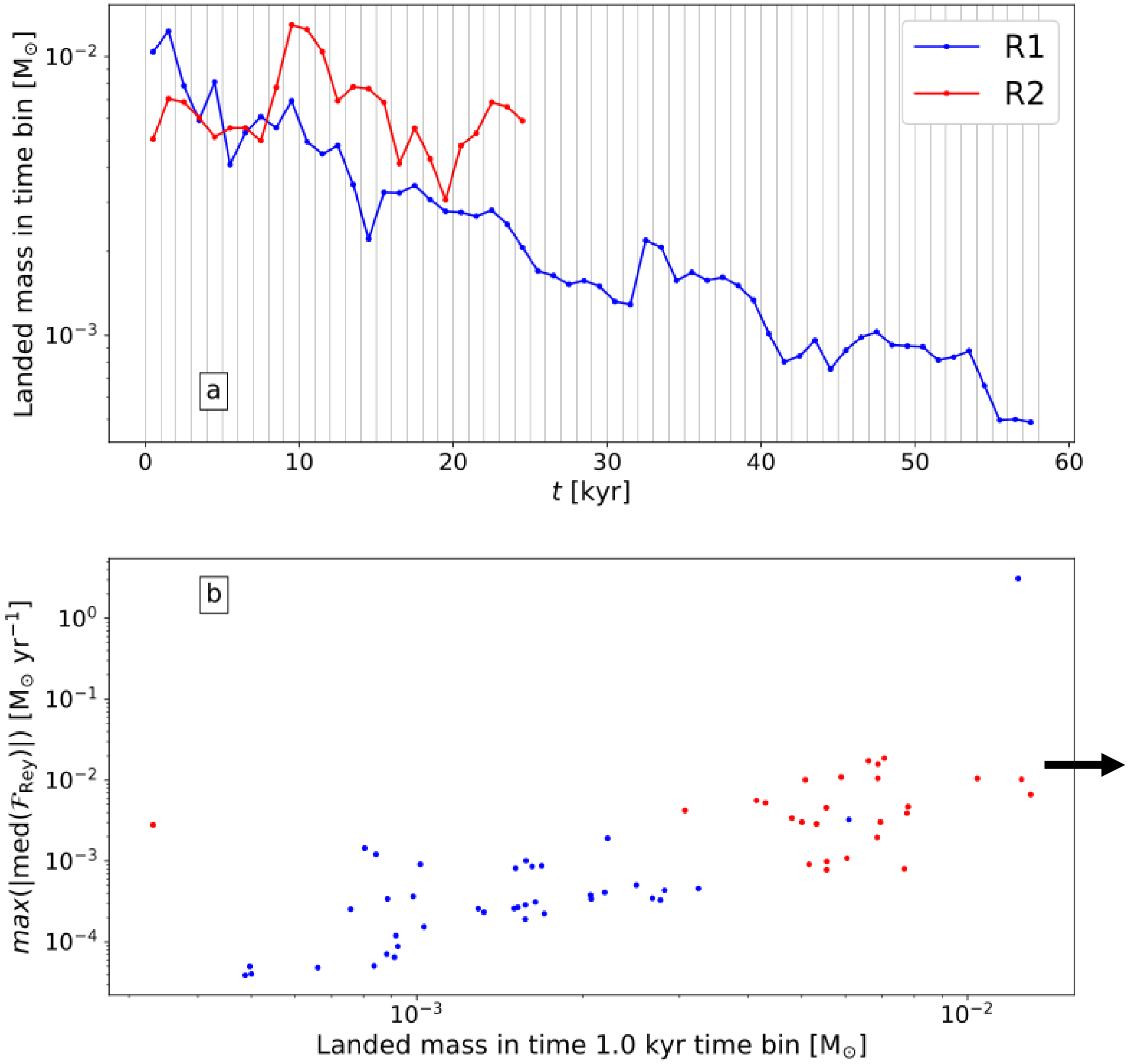

Gravitational stress

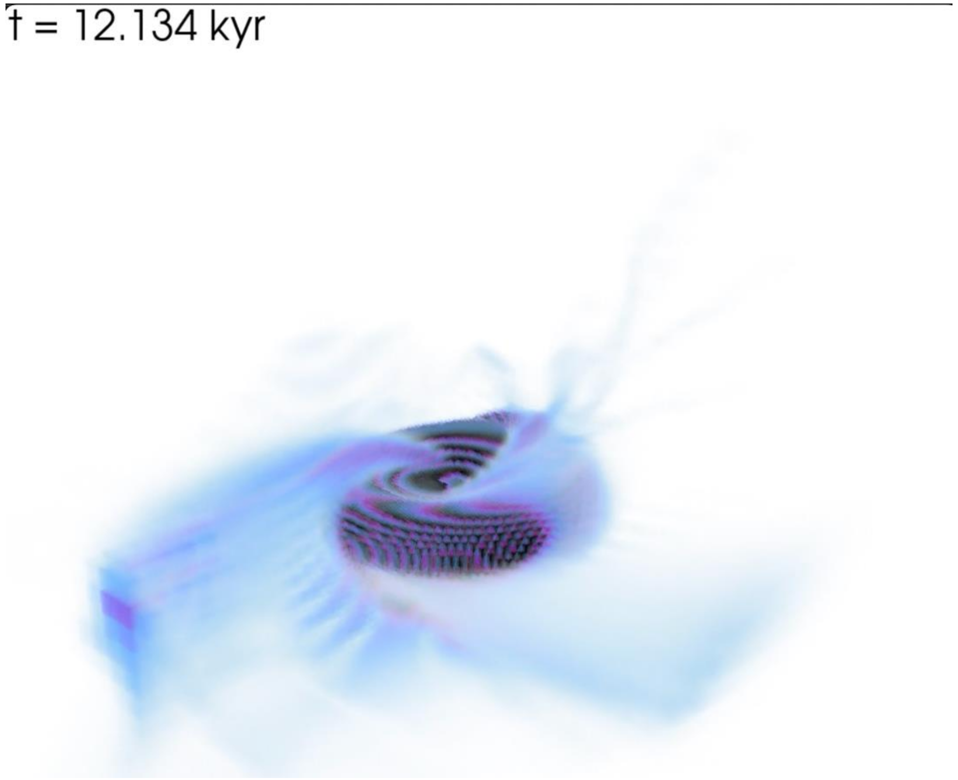
$\dot{M} \sim 10^{-5}\ \mathrm{M_\odot\ yr^{-1}}$, equivalent to $\alpha \sim 0.1$

Similar results for R2

Accretion in the disk

Measuring mass fluxes in the disk





→ **Accretion into** the disk drives **accretion in** the disk → **Accretion drives Accretion**

Take-home messages

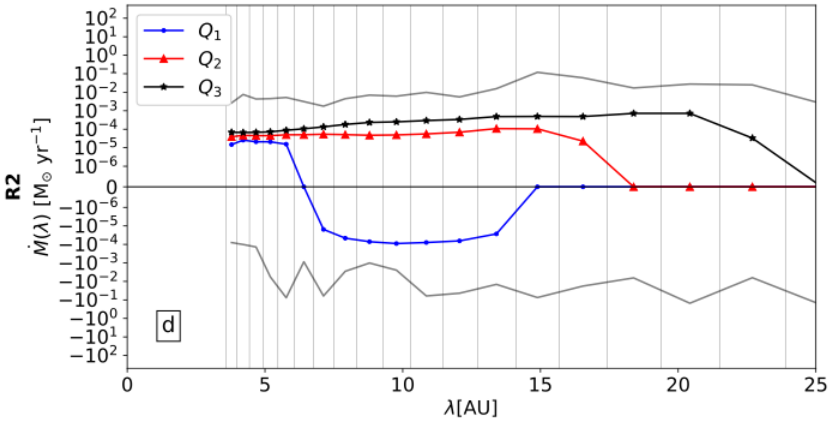
- Magnetic fields regulate disk radius through braking
- Collapse leads to **anisotropic** accretion, creating streamers and driving **turbulence** & **eccentricity** within the disk
- Turbulent stresses drive **accretion within** the disk
- Observations of **disk eccentricity** can help constrain **disk dynamics**

Accretion in the disk

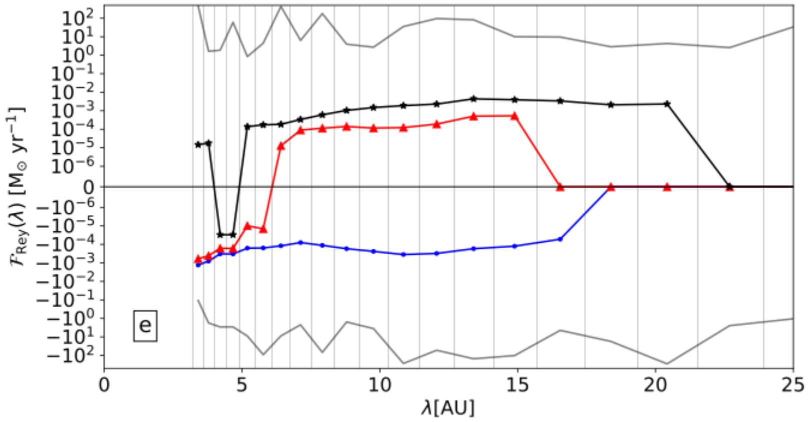
Measuring mass fluxes in the disk

Statistical measurements for R2, over ~ 25 kyr

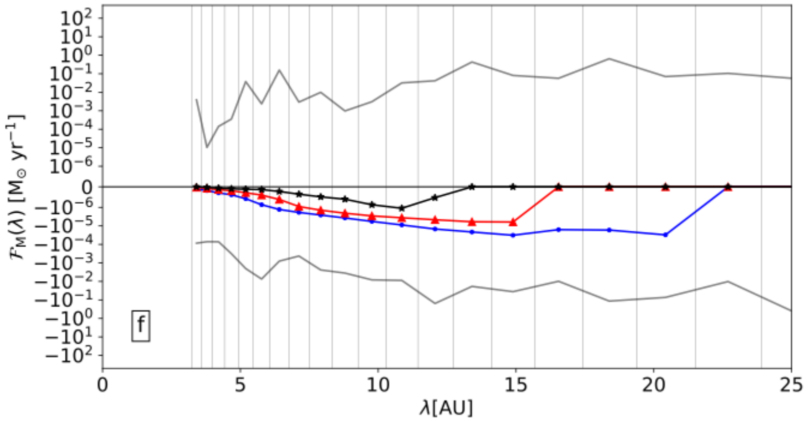
Q2: median



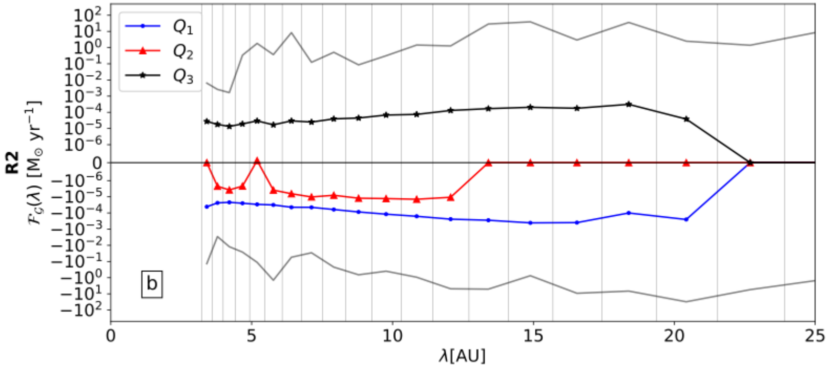
Mass accretion rate



Turbulent stress



Maxwell stress



Gravitational stress

$\dot{M} \sim 10^{-5}\ \mathrm{M_\odot\ yr^{-1}}$, equivalent to $\alpha \sim 0.1$

Similar results for R1

Accretion in the disk

Measuring mass fluxes in the disk

Problem: Disk made of nested **eccentric orbits**

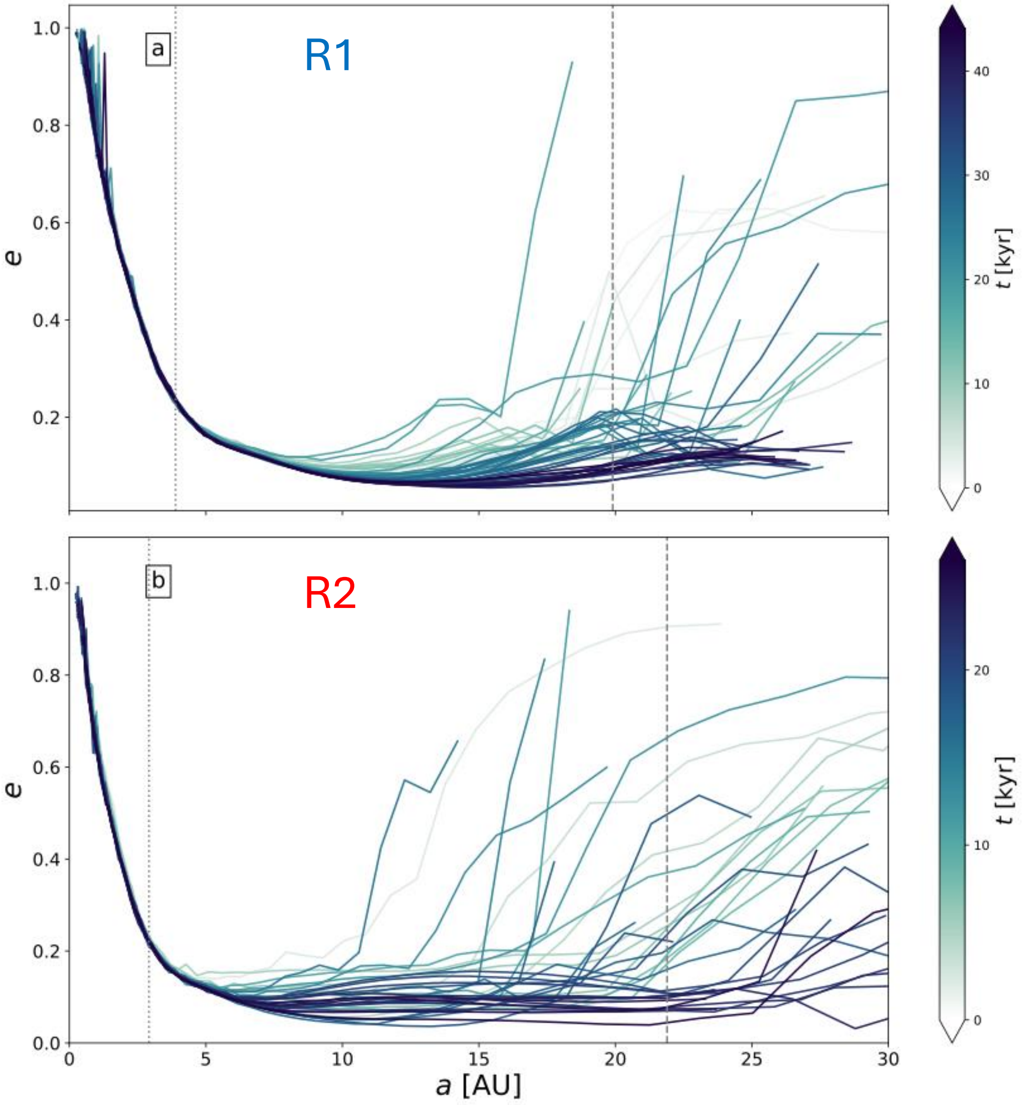
Solution: Orbital formalism (Ogilvie & Barker 2014)

Quasi-radial coordinate: $\lambda = a(1-e^2) = \frac{j^2}{GM_*}$

$$\boldsymbol{\dot{M}(\lambda) = \int\int J\rho\left(\frac{v_r}{R_\lambda} - \frac{R_\phi}{R_\lambda}\Omega\right) d\phi dz}\,, \qquad J = \frac{\partial(x,y,z)}{\partial(\lambda,\phi,z)}$$

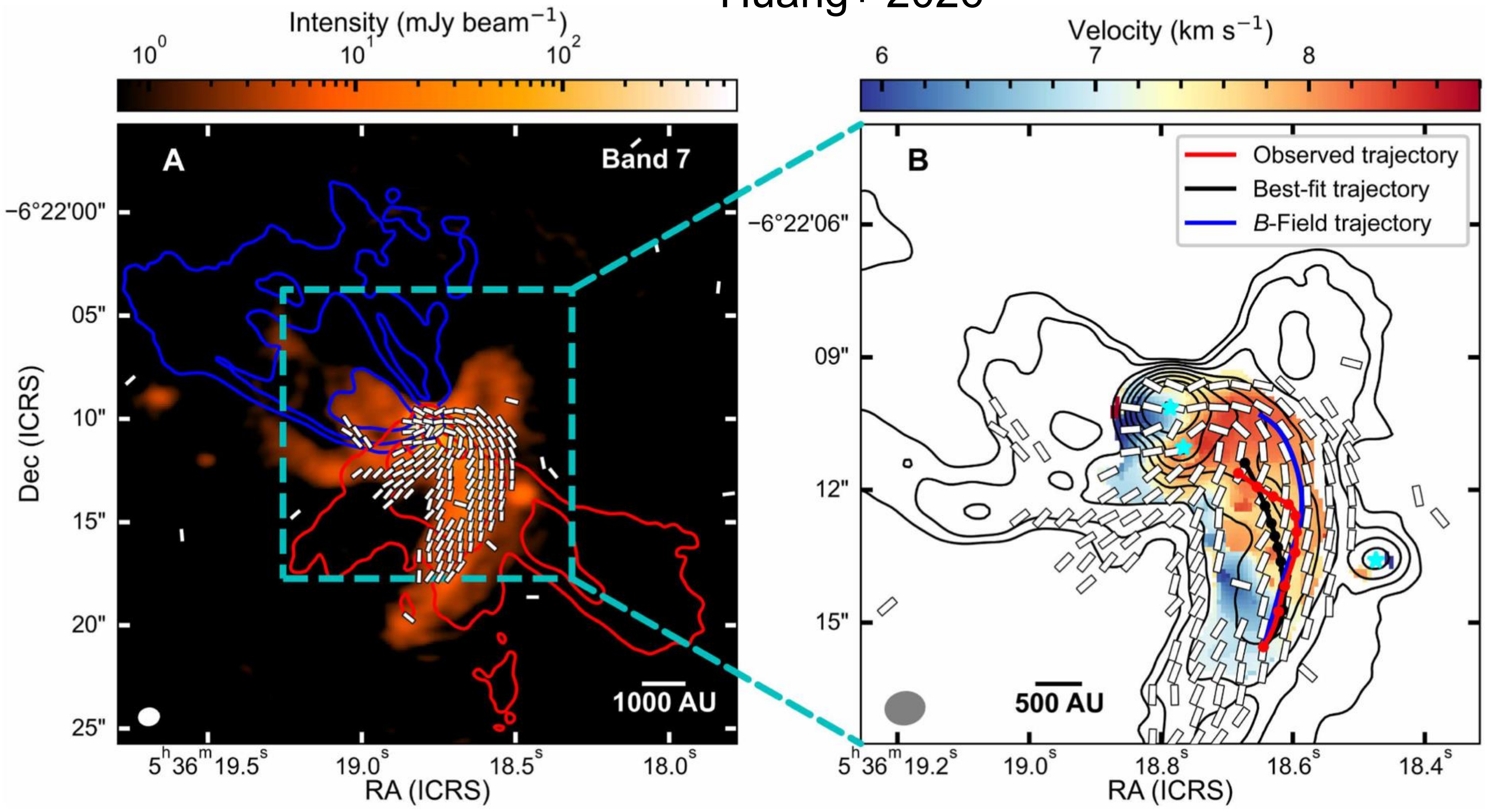
$$\mathcal{G} = -\int\int J R^2 T^{\lambda\phi} d\phi dz$$

$$\boldsymbol{\mathcal{F}(\lambda) = -\frac{\partial\mathcal{G}/\partial\lambda}{dj/d\lambda}}$$



Why don’t we see Class 0 streamers ?

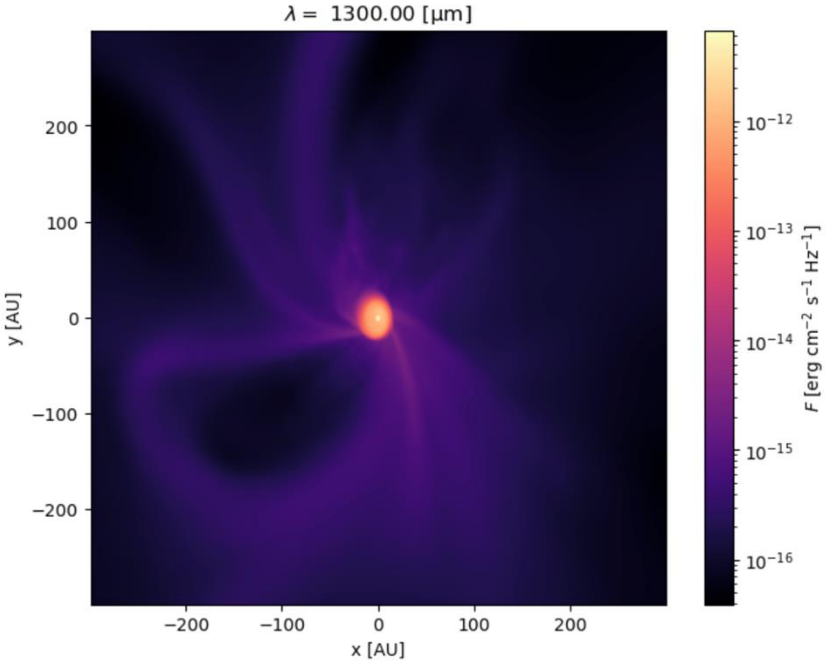
Huang+ 2026



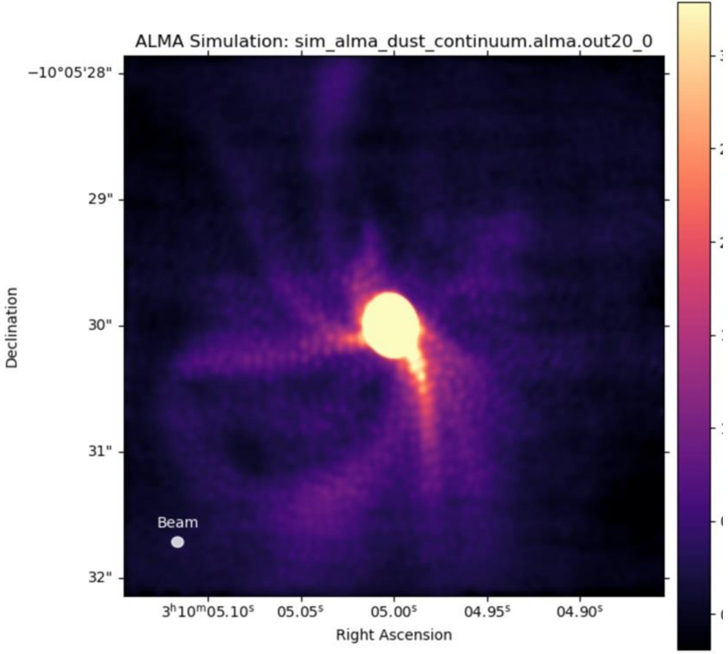
Why don’t we see class 0 streamers ?

Synthethic observations (RADMC3D) + 5 hrs ALMA observation

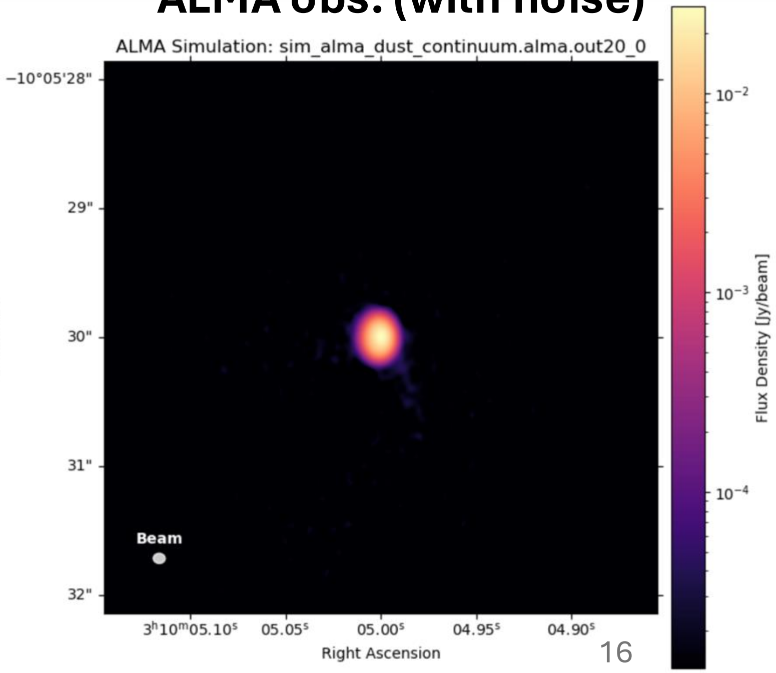
Intensity map



ALMA obs. (noise-free)

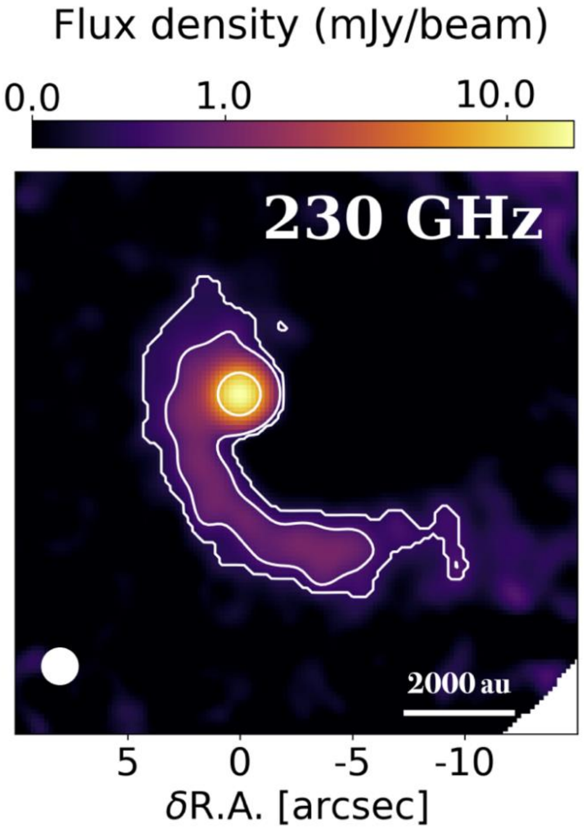


ALMA obs. (with noise)

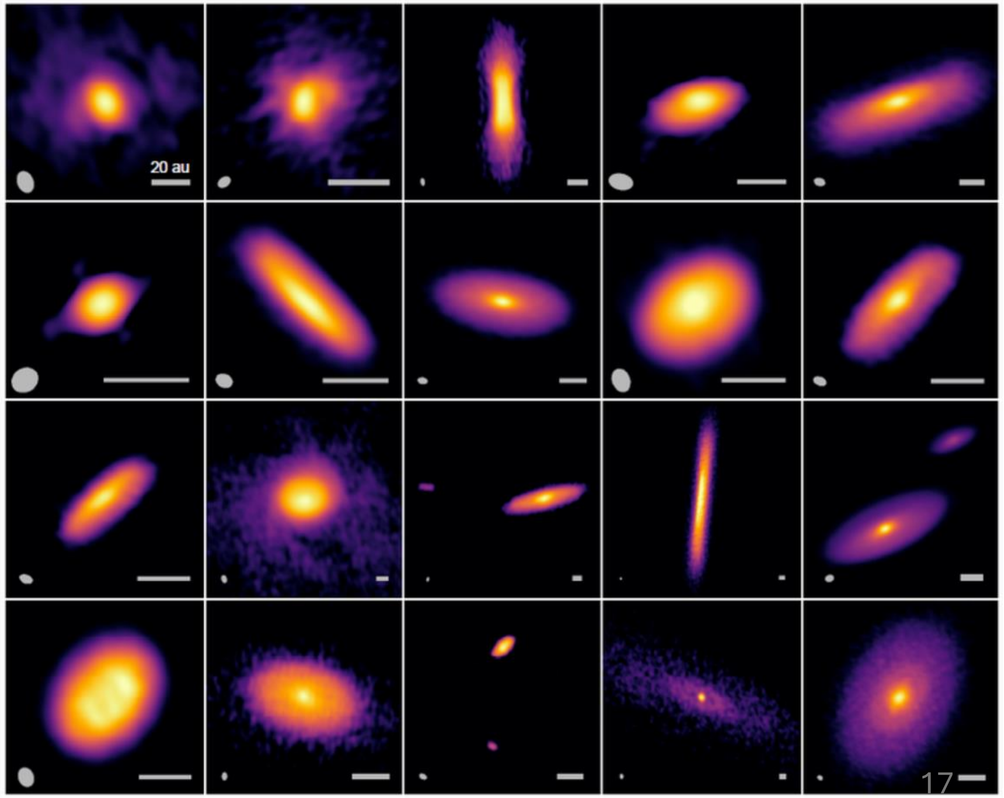


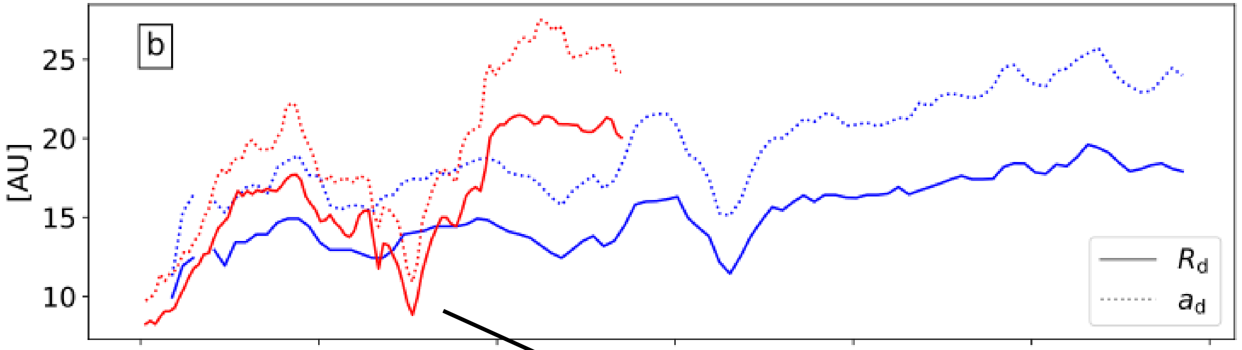
Why don’t we see Class 0 streamers ?

Class II observations (Cacciapuoti+ 2024)

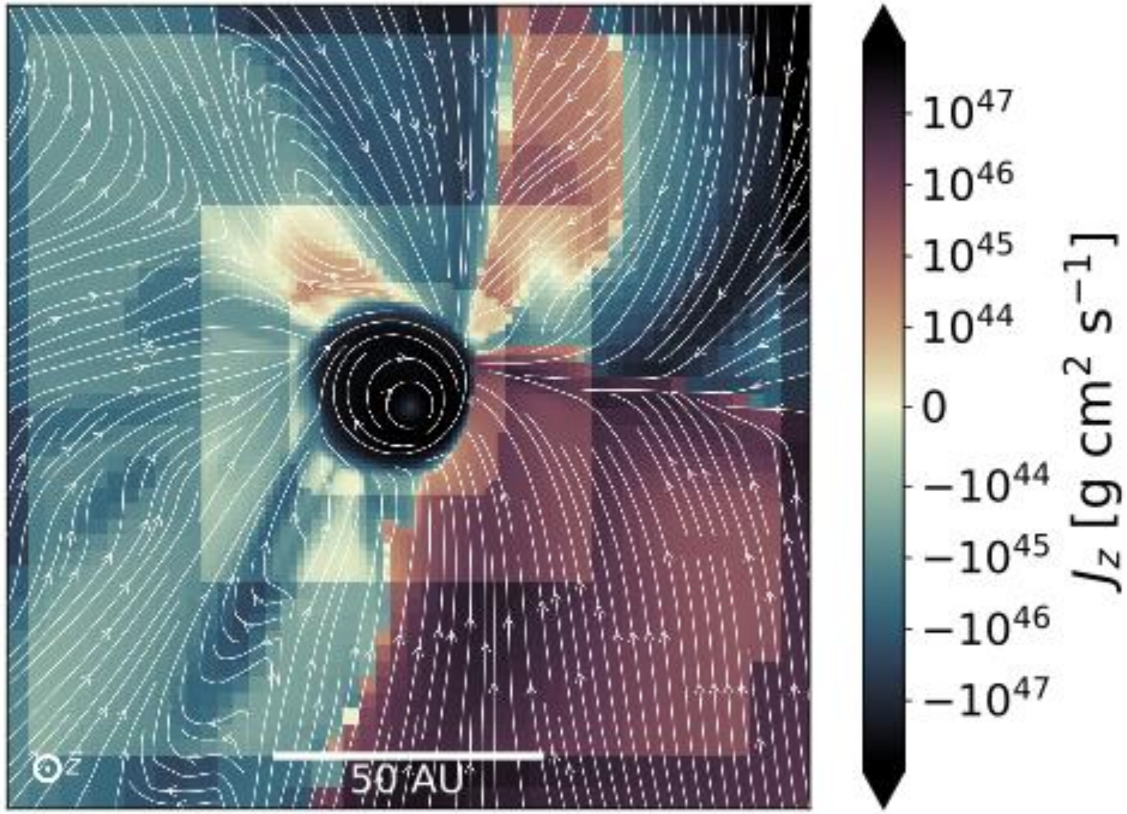


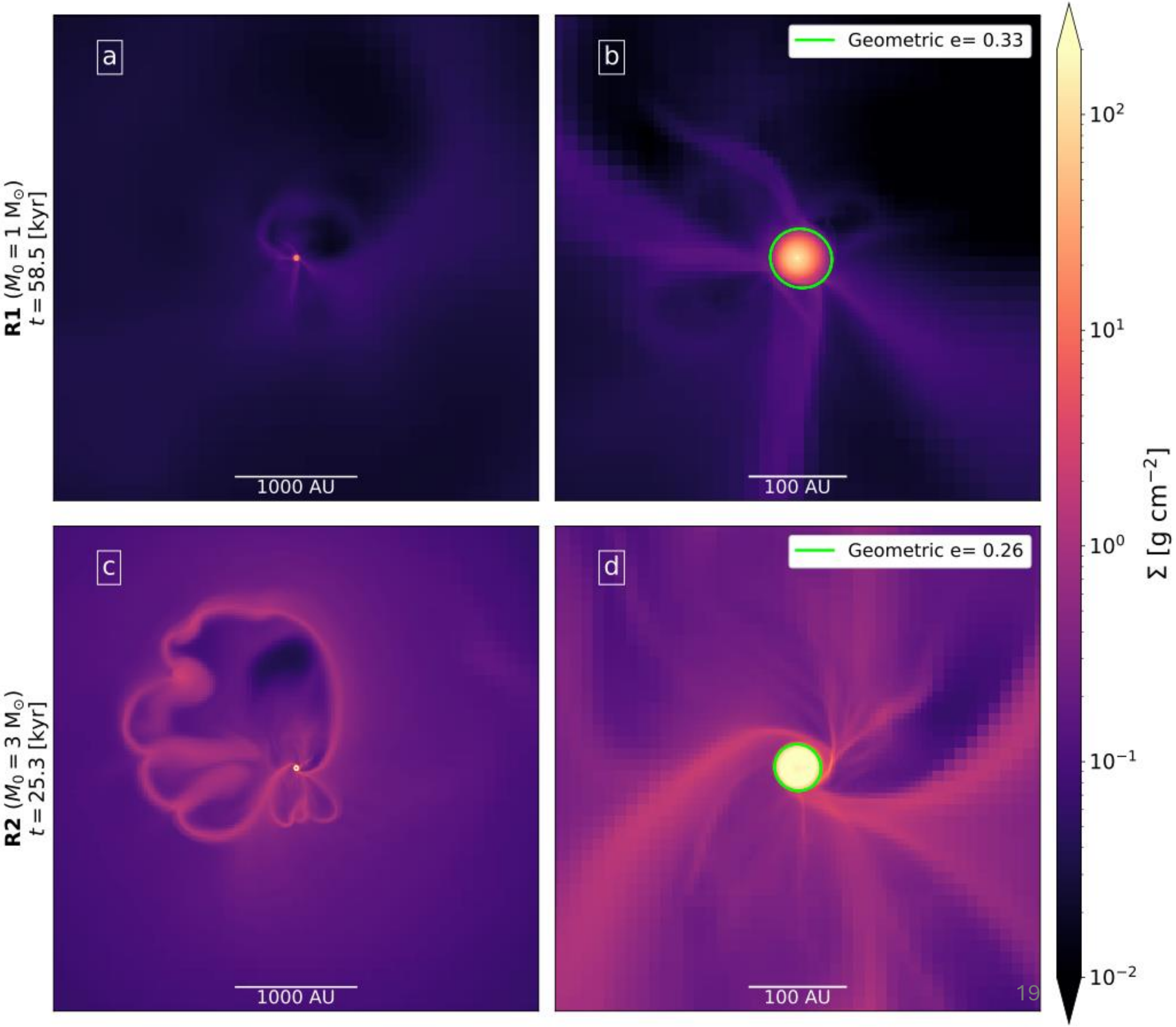
Class 0 observations (Ohashi+ 2023)





Accretion of a **counter-rotating** streamer




R1 ($M_0 = 1$ M$_\odot$)
$t = 58.5$ [kyr]
R2 ($M_0 = 3$ M$_\odot$)
$t = 25.3$ [kyr]
a
b
c
d
Geometric e= 0.33
Geometric e= 0.26
1000 AU
100 AU
1000 AU
100 AU
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
Σ [g cm^{-2}]

Accretion in the disk

Where is material landing ?