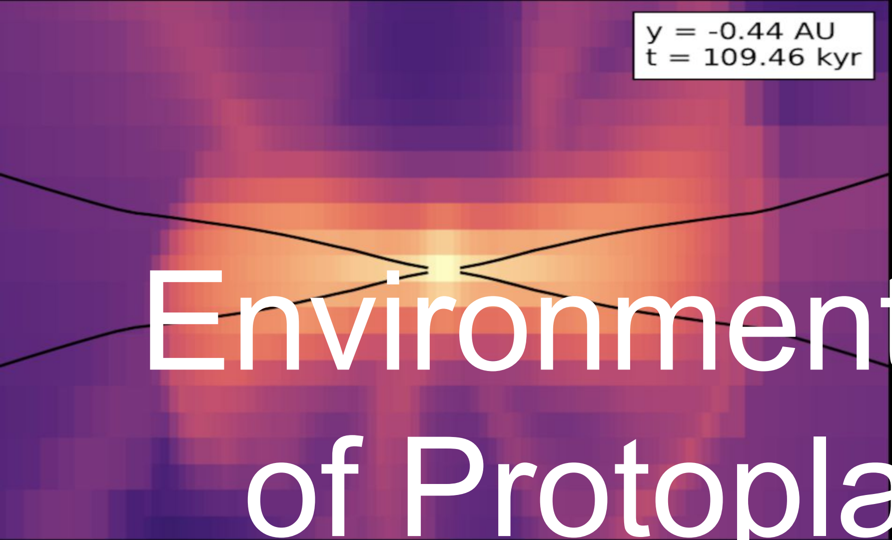
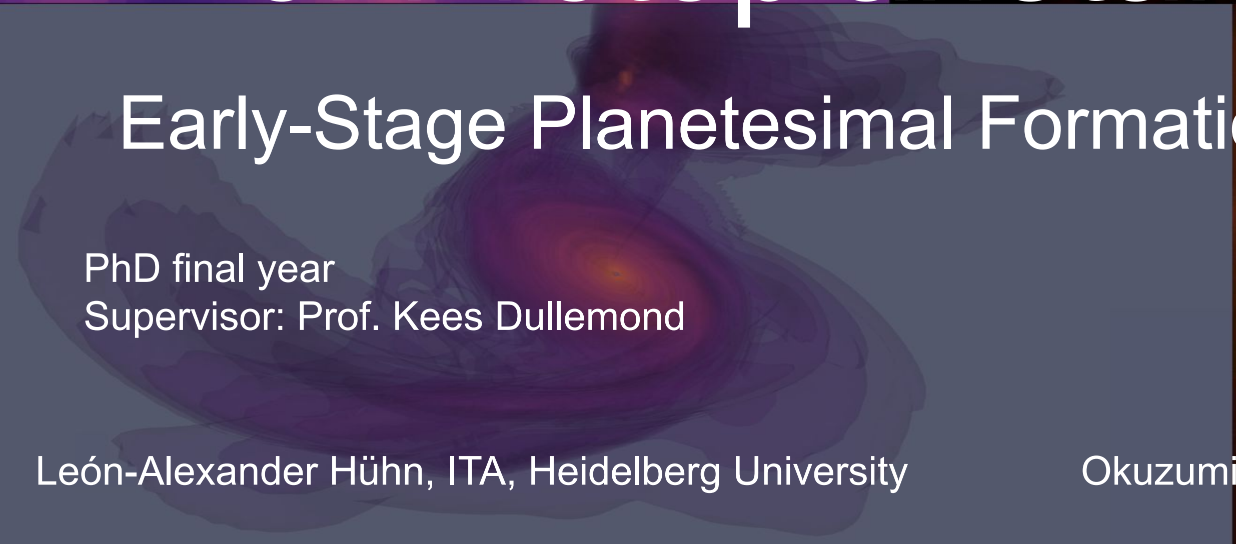
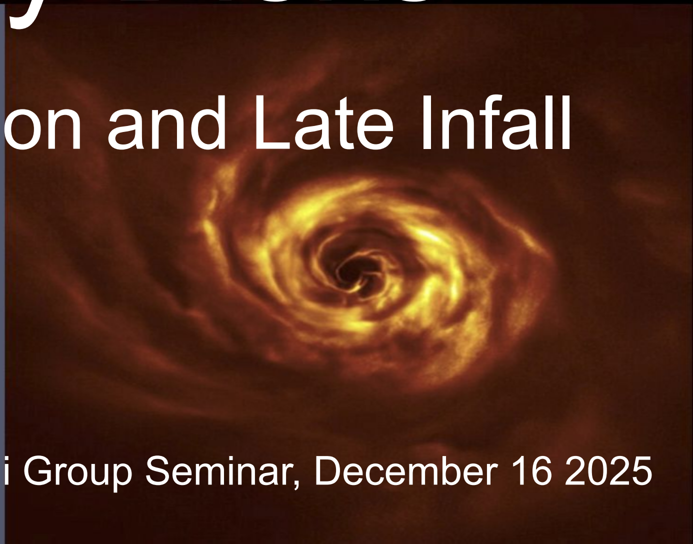


Environmental Interactions of Protoplanetary Disks

Early-Stage Planetesimal Formation and Late Infall

PhD final year
Supervisor: Prof. Kees Dullemond

León-Alexander Hühn, ITA, Heidelberg University

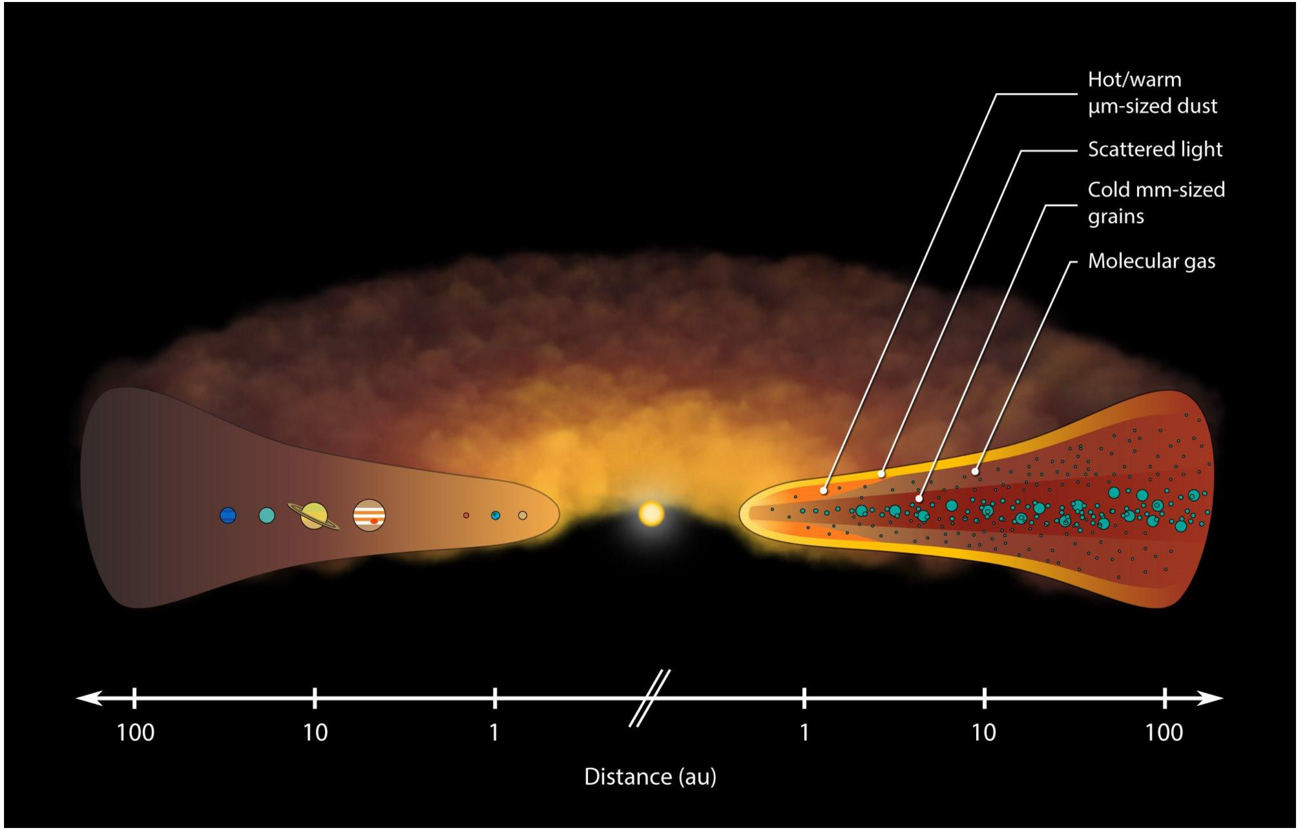
Okuzumi Group Seminar, December 16 2025

Table of Contents

1. Early-stage infall:
Planetesimal formation in Class 0/I disks

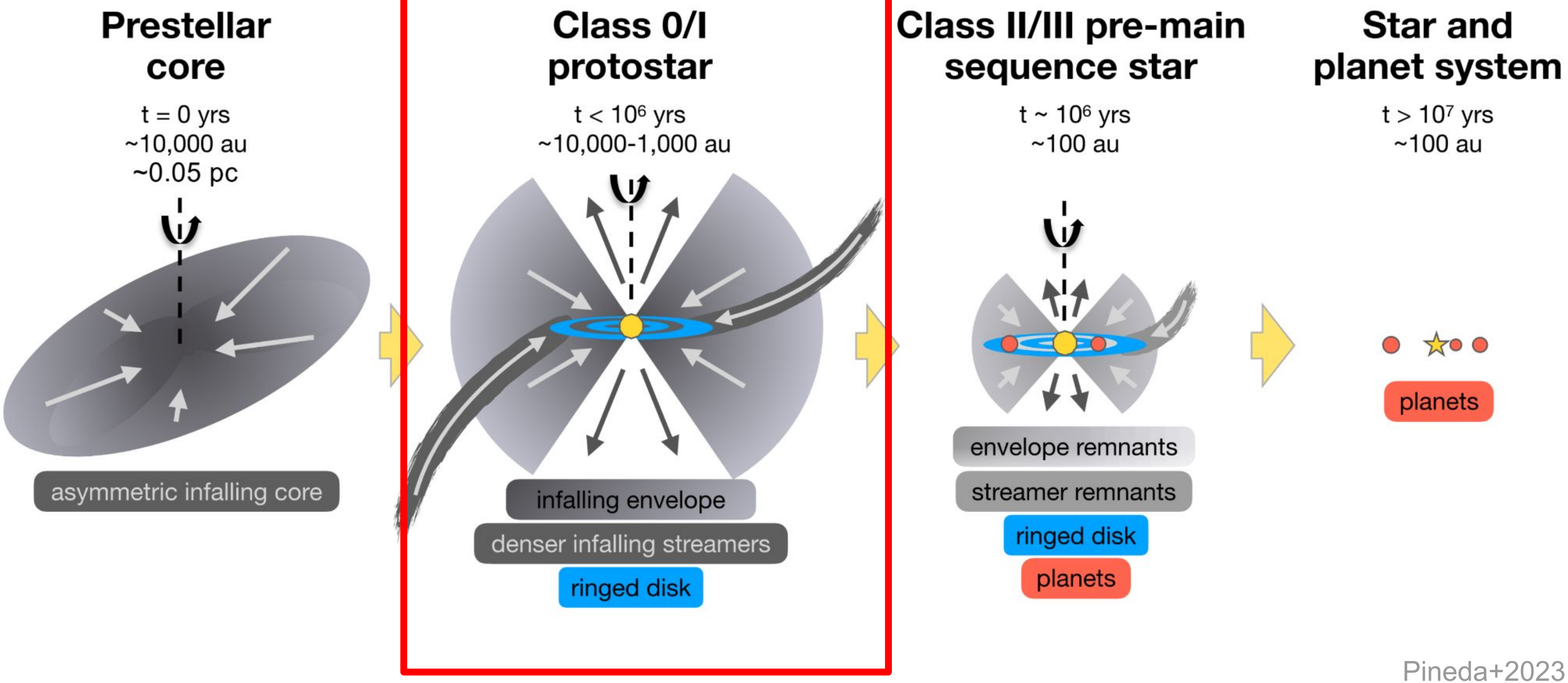
Hühn, Dullemond, Lebreuilly, et al. 2025, A&A, 696, A162

The classical picture of planet formation



Testi+2014, mod.

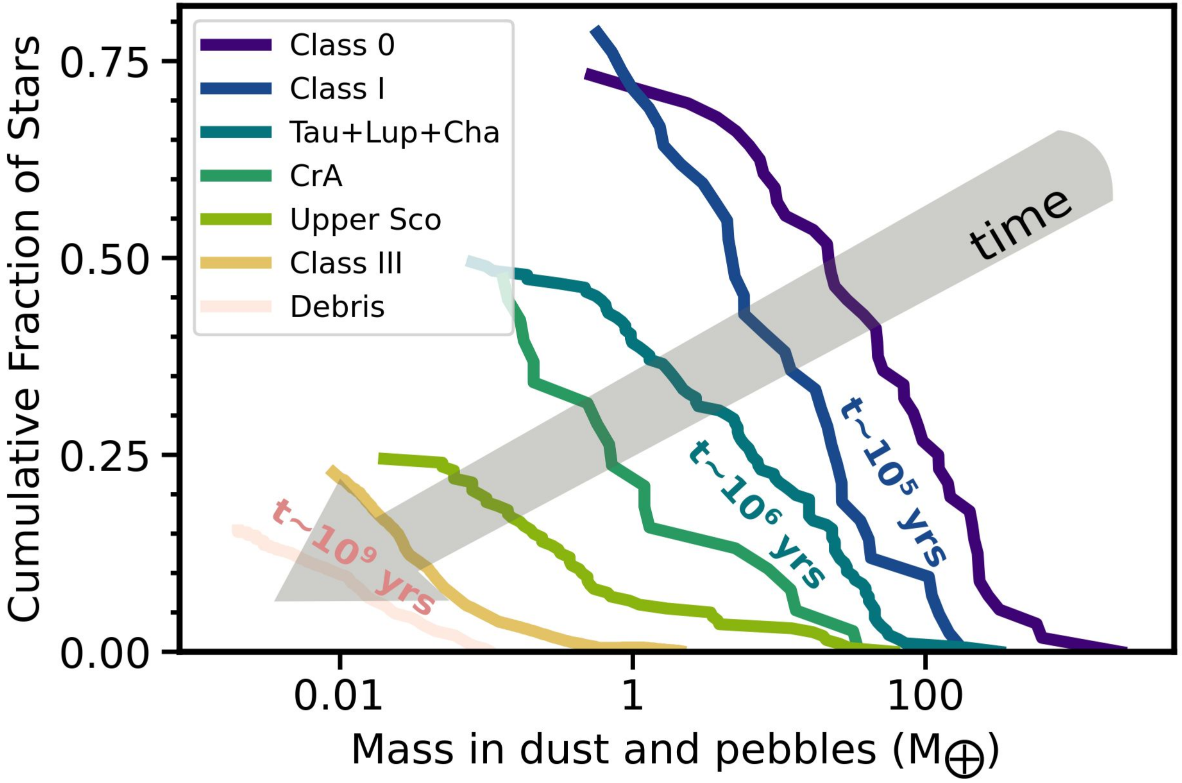
Evolutionary stages of protoplanetary disks



Pineda+2023

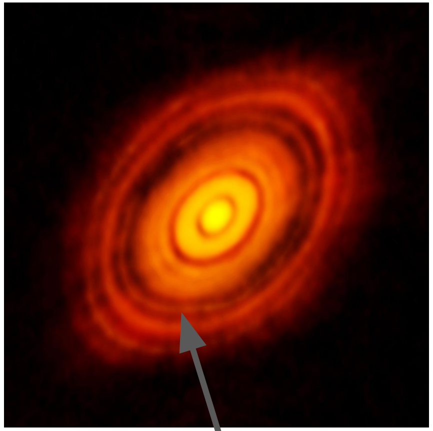
Mass budget problem

Drazkowska+2022



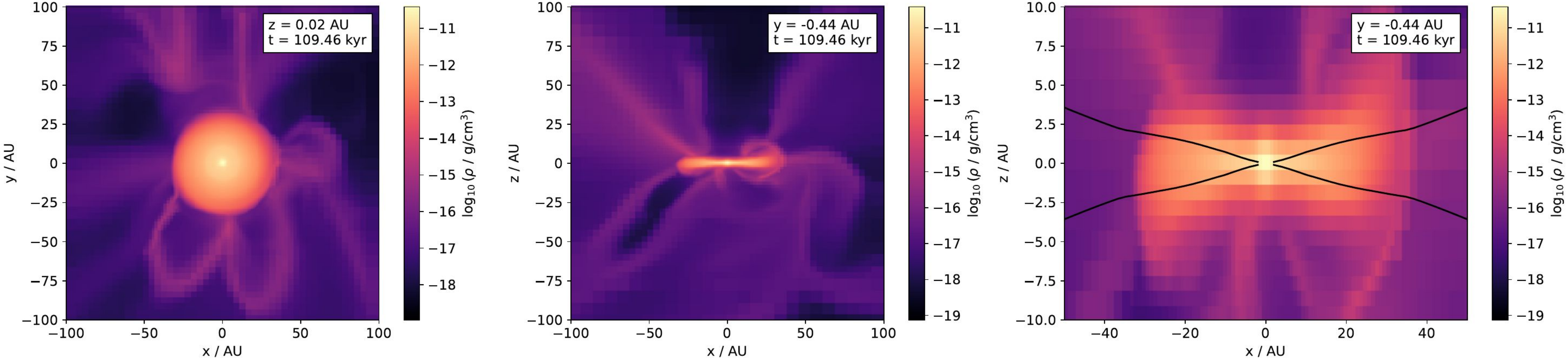
Not enough dust to from giant planets?

ALMA (ESO/NAOJ/NRAO)



Early substructure?

Parsec-scale core-collapse simulations



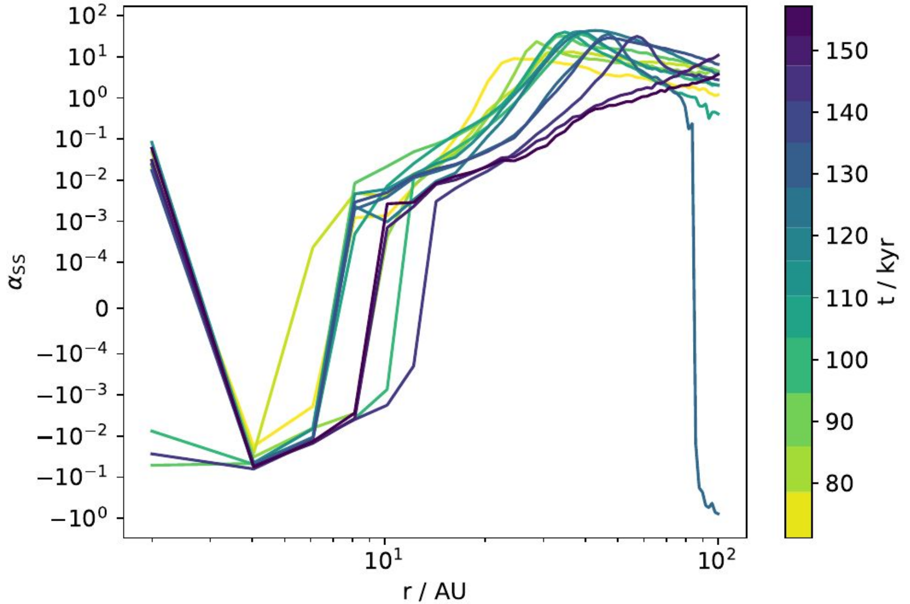
- 3D non-ideal MHD simulation with AMR
- Collapsing cloud, star modeled as sink
- Runtime: ~100 kyr after first sink formation

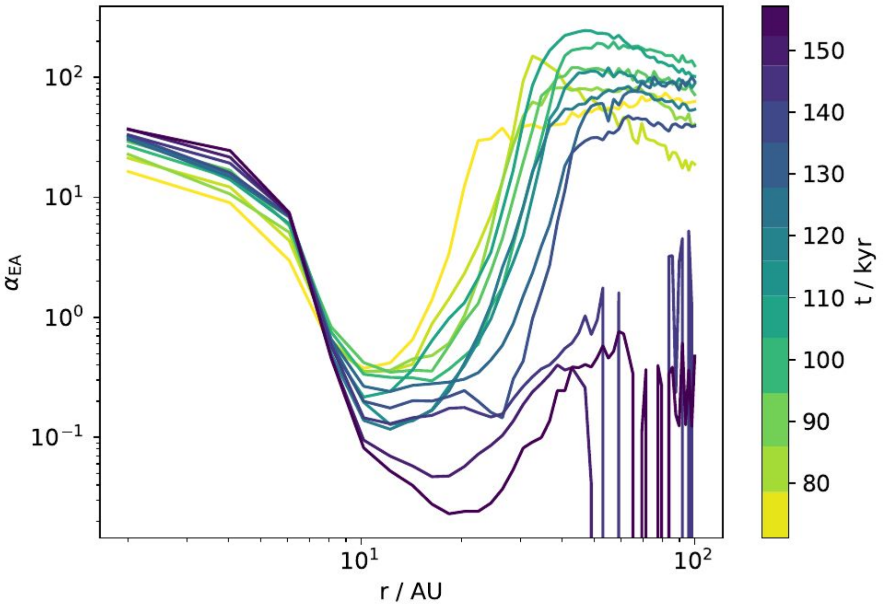
- Poor resolution (0.5 cps)
- Gas only
- (Over-)simplified temperature

1D Model

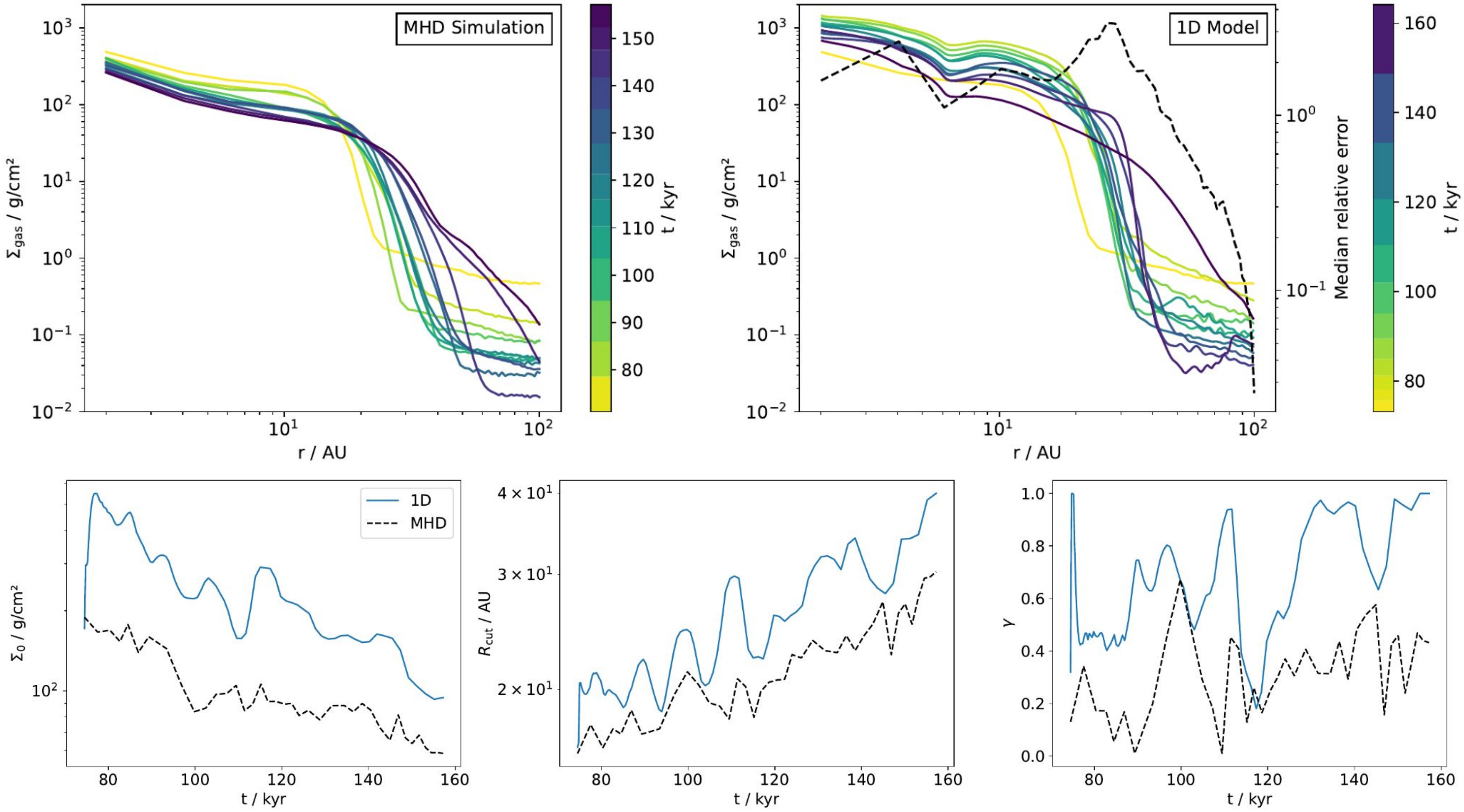
“Viscous” alpha

Alpha for external torque

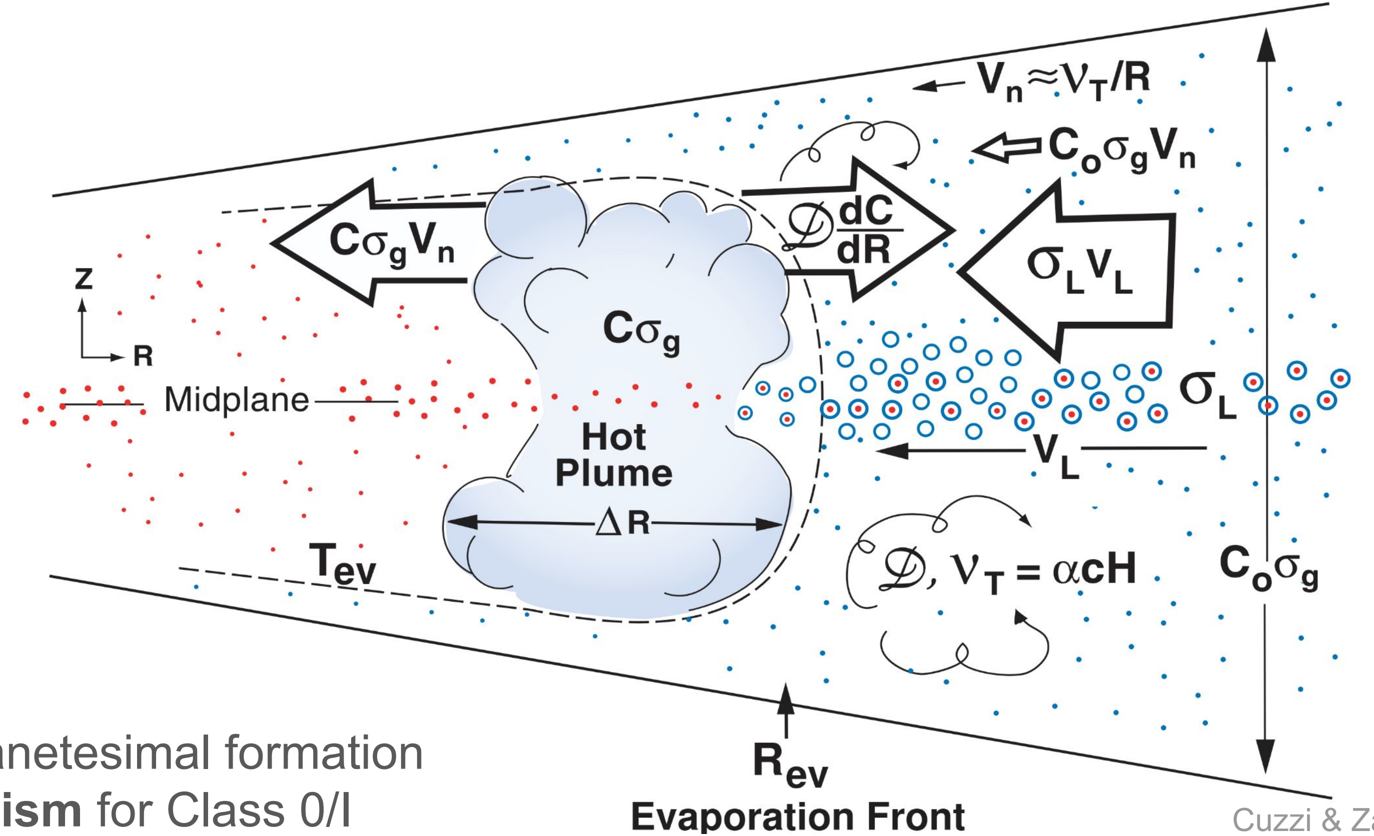




Negative α_{SS}: Not suitable for 1D treatment


MHD Simulation
1D Model
Σ_{gas} / g/cm²
r / AU
t / kyr
Median relative error
1D
MHD
Σ_0 / g/cm²
R_{cut} / AU
γ
t / kyr

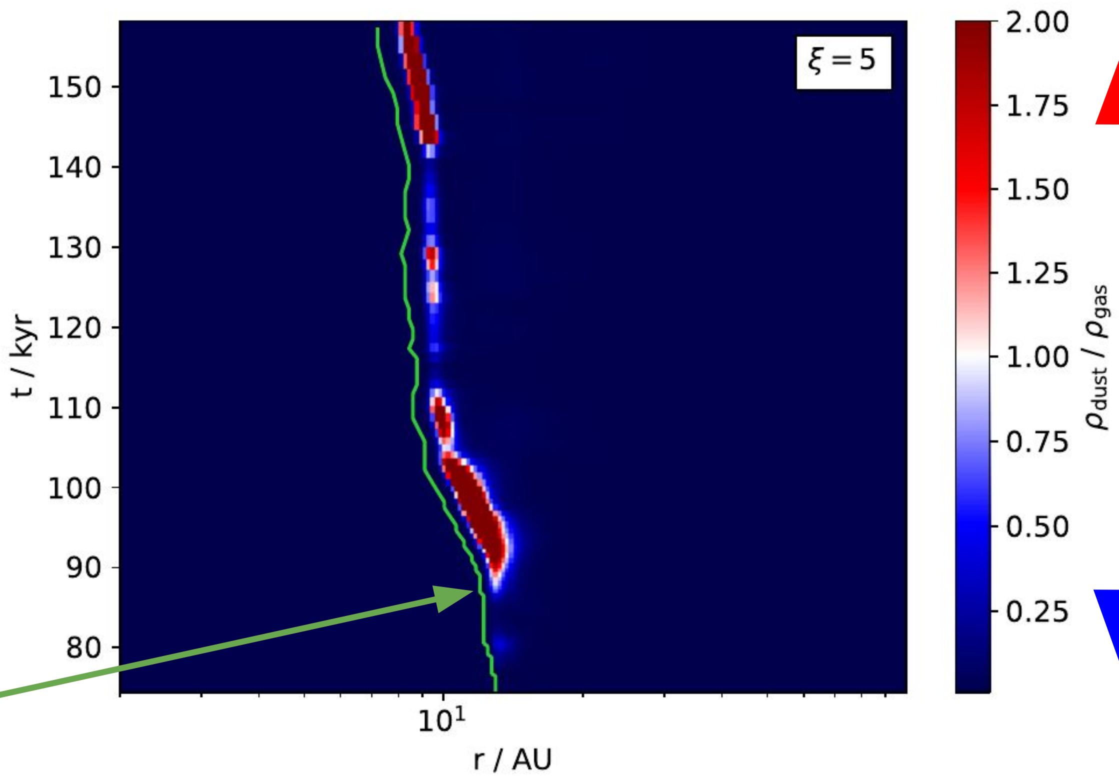
Cold-finger effect: Enhancing solid concentration



Main planetesimal formation **mechanism** for Class 0/I

Cuzzi & Zahnle 2004

Early planetesimal formation?



Planetesimal formation possible

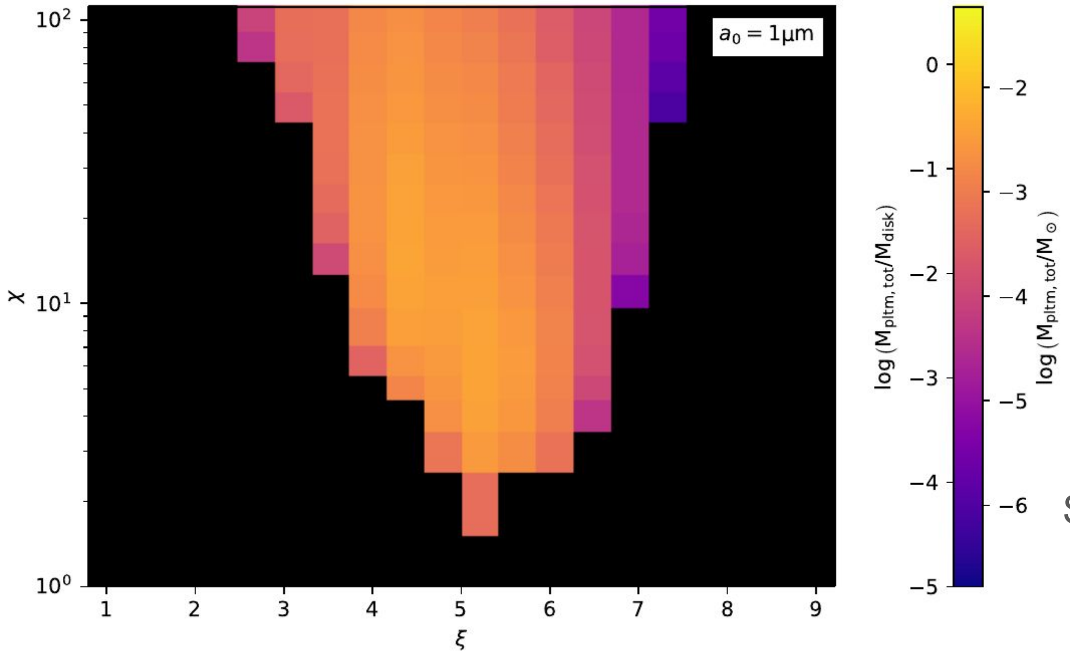
Planetesimal formation not possible

Water snow line

Early planetesimal formation?

$$\log Z_{\rm crit}(\tau_s,\, \alpha_{\rm D}) = A'(\log \alpha_{\rm D})^2 + B' \log \tau_s \log \alpha_{\rm D} + C' \log \tau_s + D' \log \alpha_{\rm D}, \quad (19)$$

Lower turbulence



Higher temperature

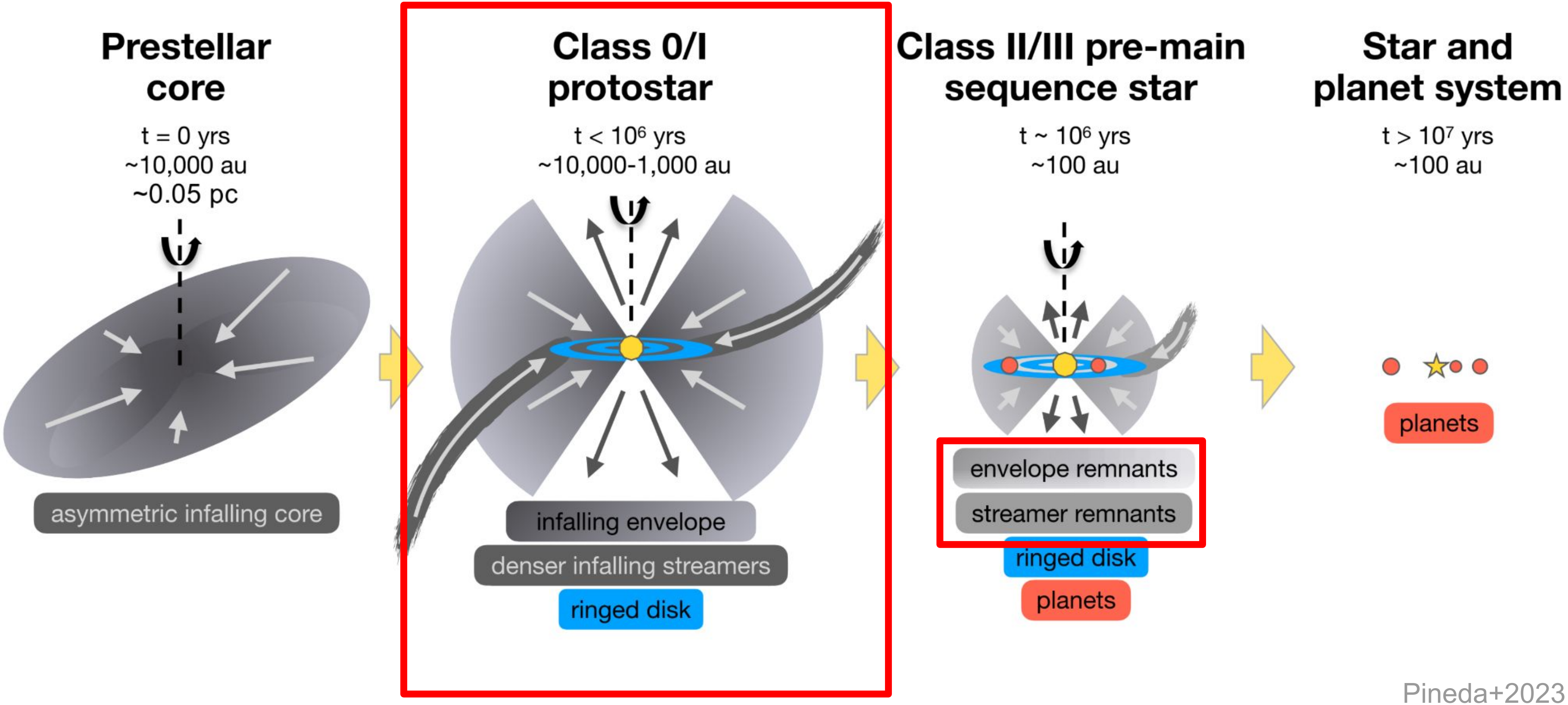
Lim+2024 criterion:
Size + Turbulence ⇒ Dust Density

Project 1: Take-home messages

1. **Icy planetesimals can form via the cold-finger effect in Class 0/I disks**
2. **They could act as seeds for planet formation during Class II**

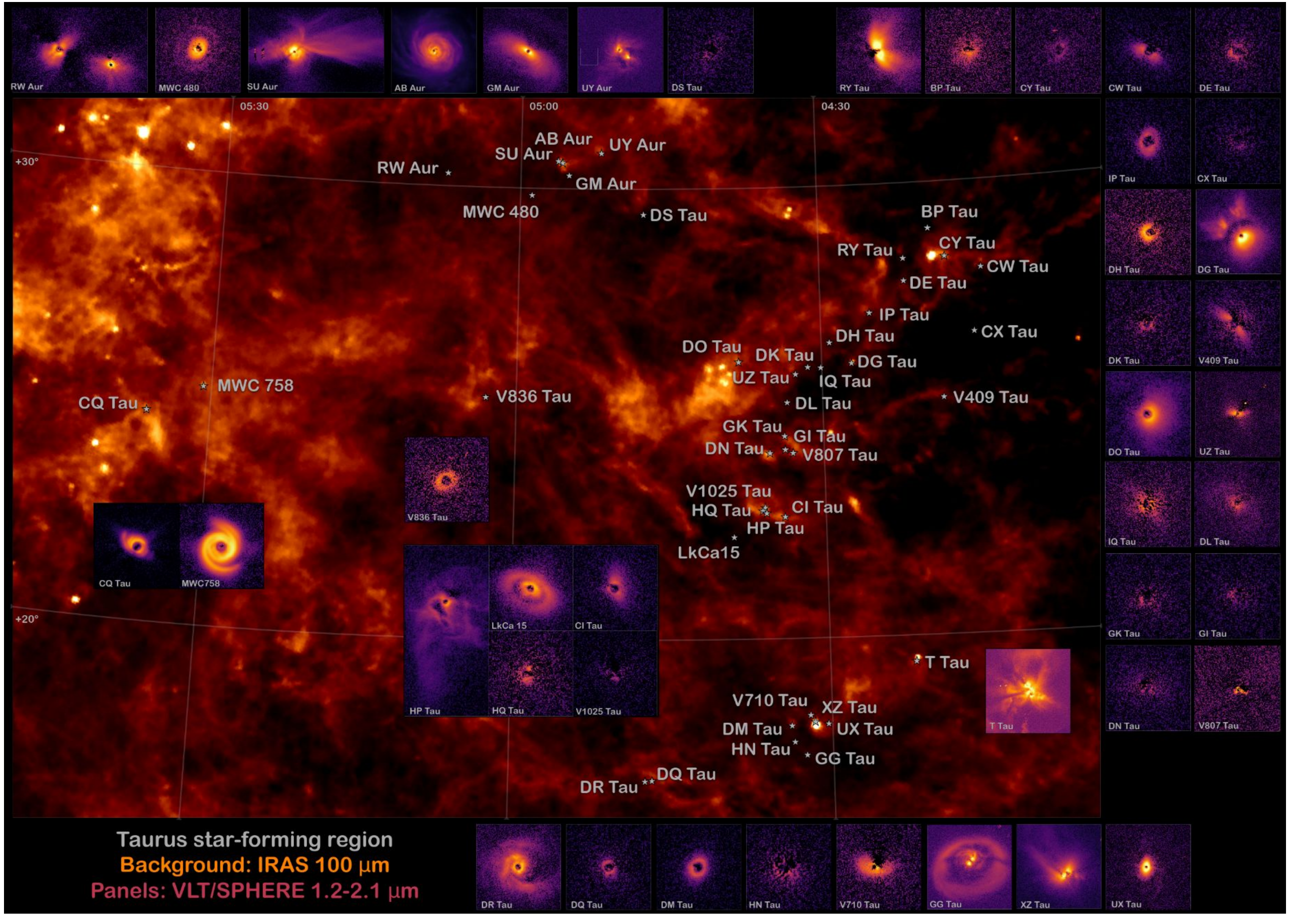
2. Late infall

The current picture of planet formation



Pineda+2023

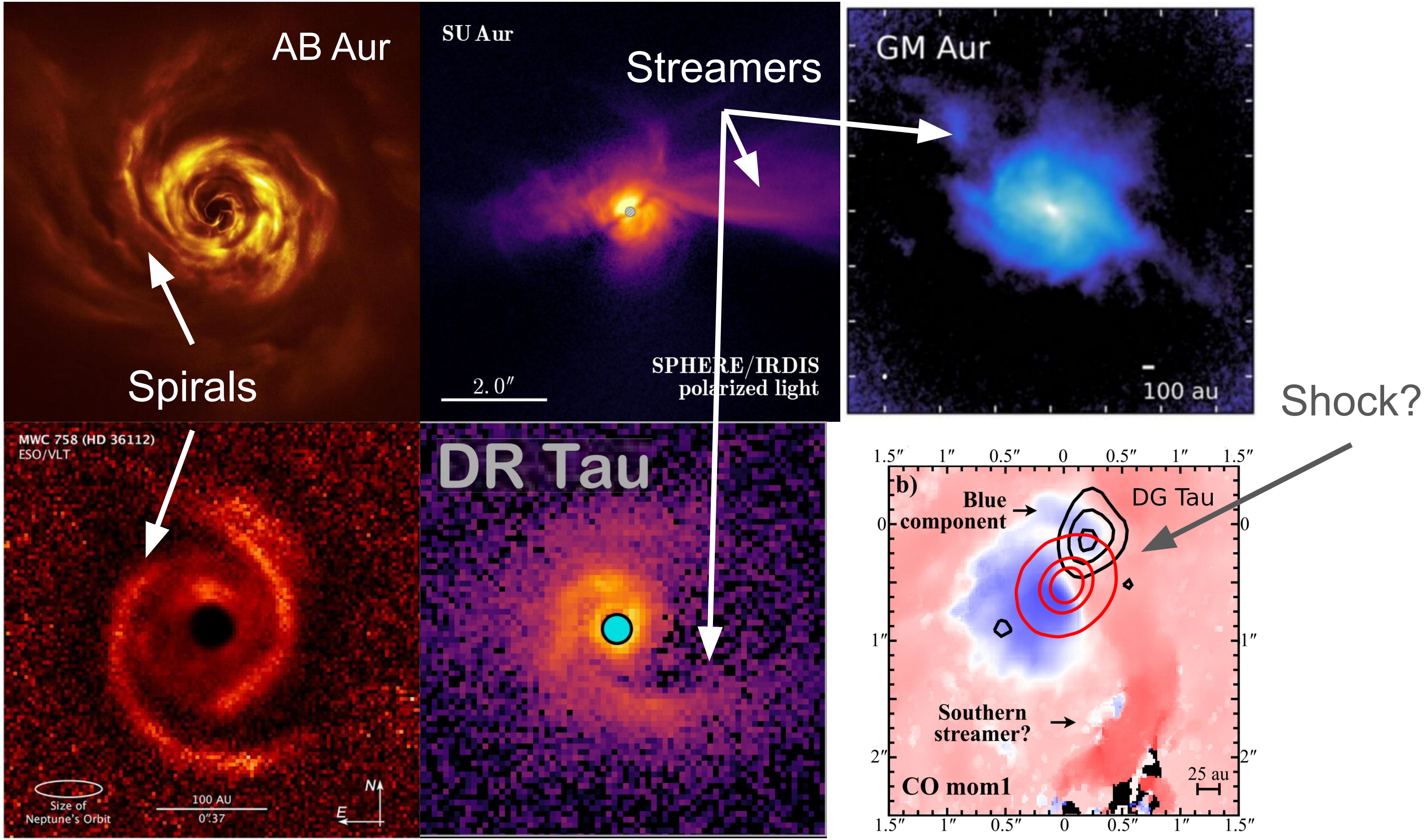
How isolated are disks during the Class II stage?



⅓ of sampled disks show ambient signal!

Garufi+2024

How isolated are disks during the Class II stage?

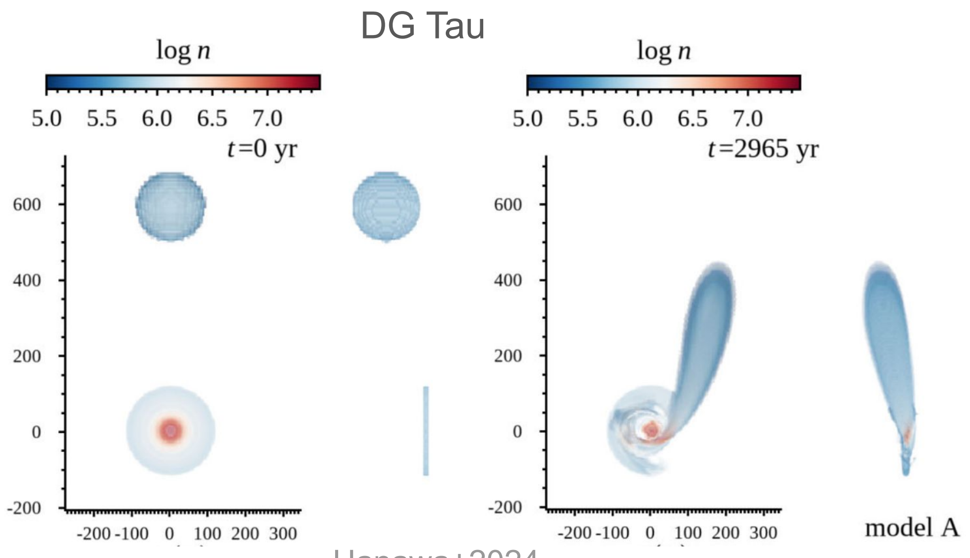


2a. Emergence of streamers in simulations of late infall

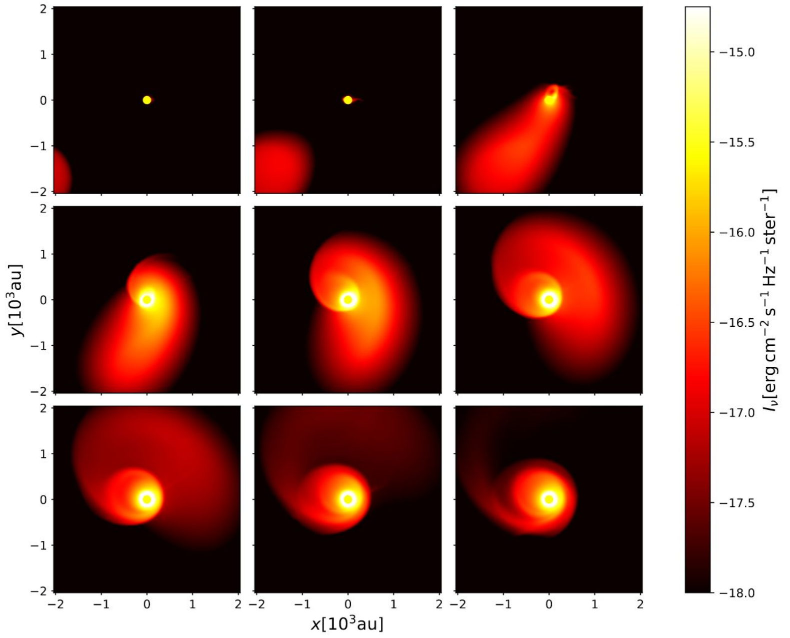
Hühn & Dullemond 2025, A&A in press
arXiv:2510.24269

Are the large-scale structure inflow?

Dullemond+2019



Hanawa+2024



Material inflow modeled as the capture of a spherical gas cloudlet

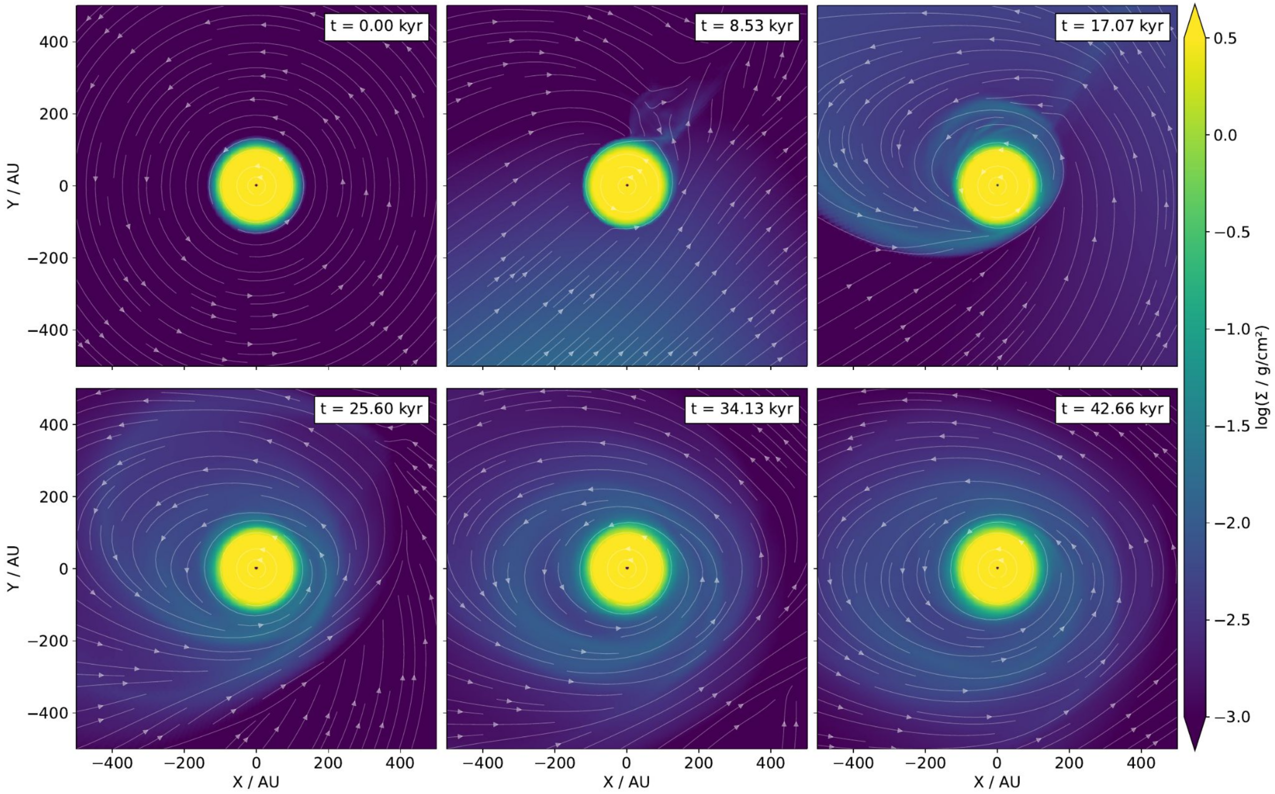
Simulation setup: Cloudlet capture

- 3D hydrodynamical simulations using FARGO3D
- Accretion model: Encounter with spherical gas cloudlet
- Grid: Log-radial spherical grid
- Resolution: 3 cells per scale height @ 100 AU
- Domain: 5 AU to 5000 AU in radius
- Temperature: Isothermal EOS, passive stellar heating

  ⇒ **No pressure support**
- Gas only, no dust

Cloudlet capture

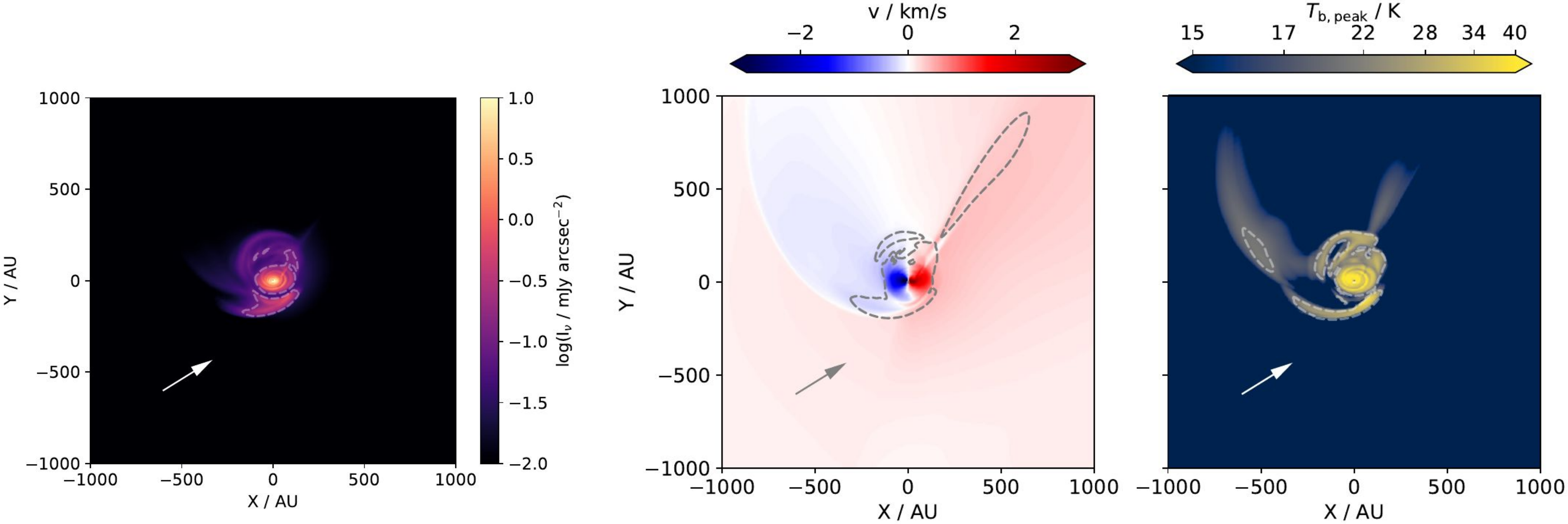
“Fallback shock” streamer



Key difference:

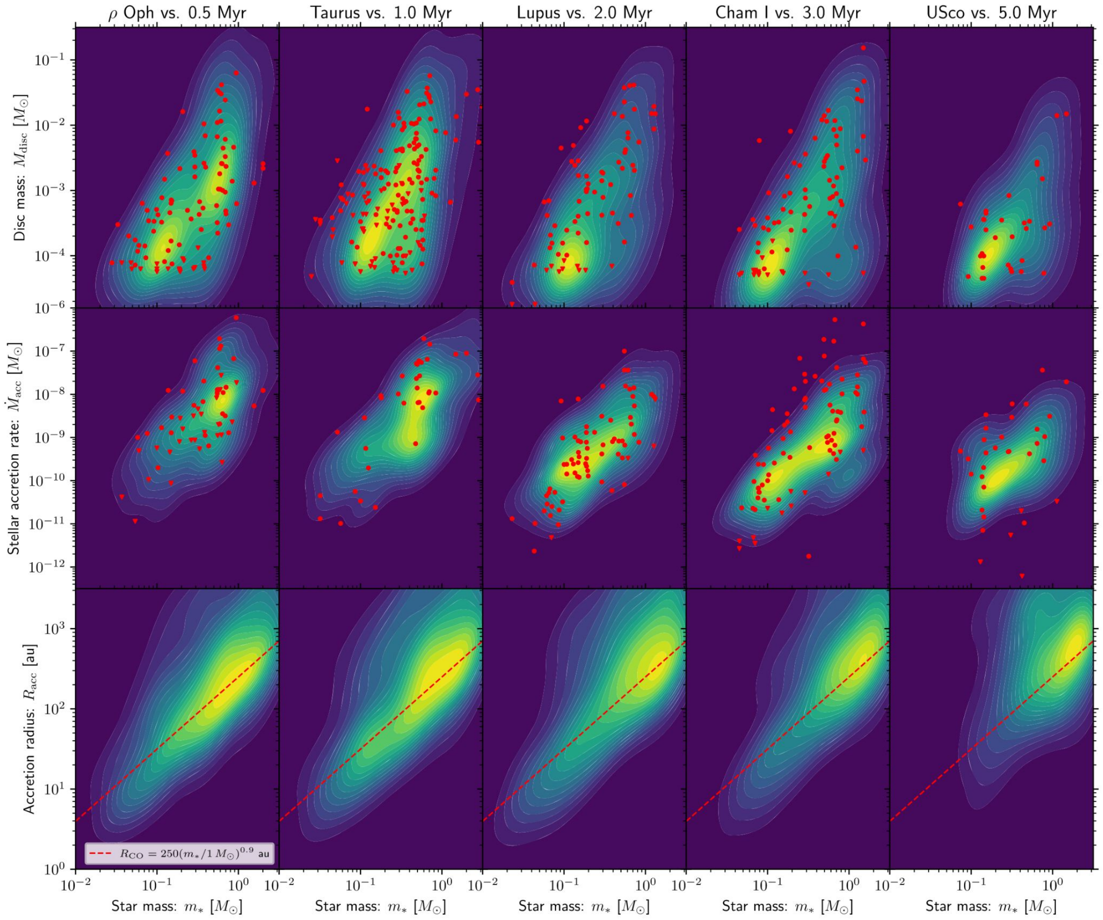
Cloudlet expands

Cloudlet capture



RADMC3D: Clear streamer in scattered light & CO, but short-lived (~10 kyr)

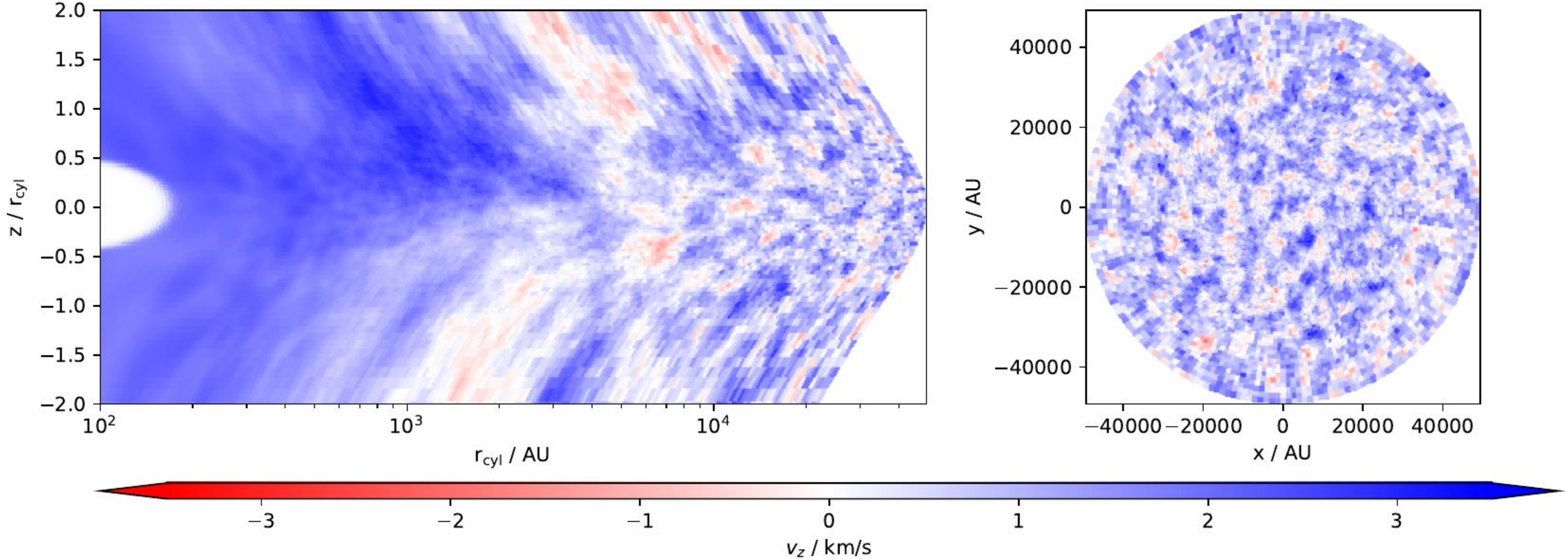
More realistic accretion mechanism?



Models of **Bondi-Hoyle-Lyttleton accretion** can explain correlations of disk parameters with stellar mass

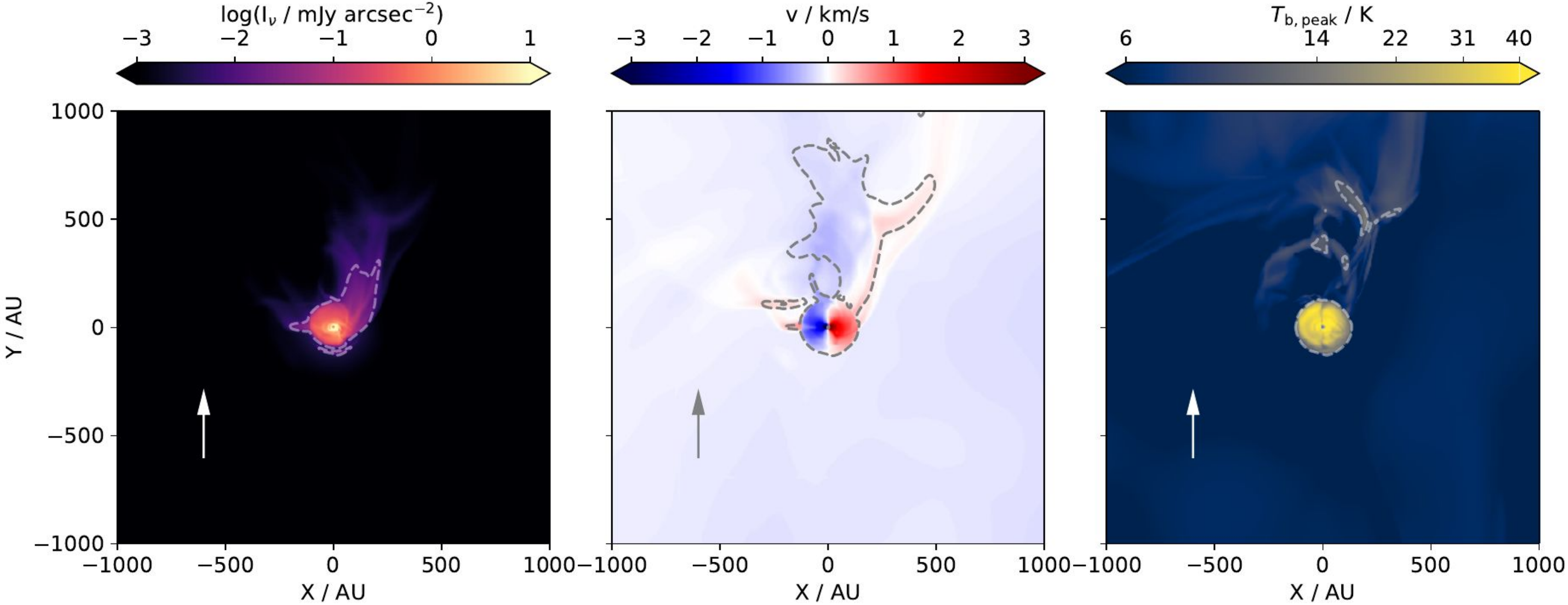
Winter+2024

Bondi-Hoyle accretion: Initial condition

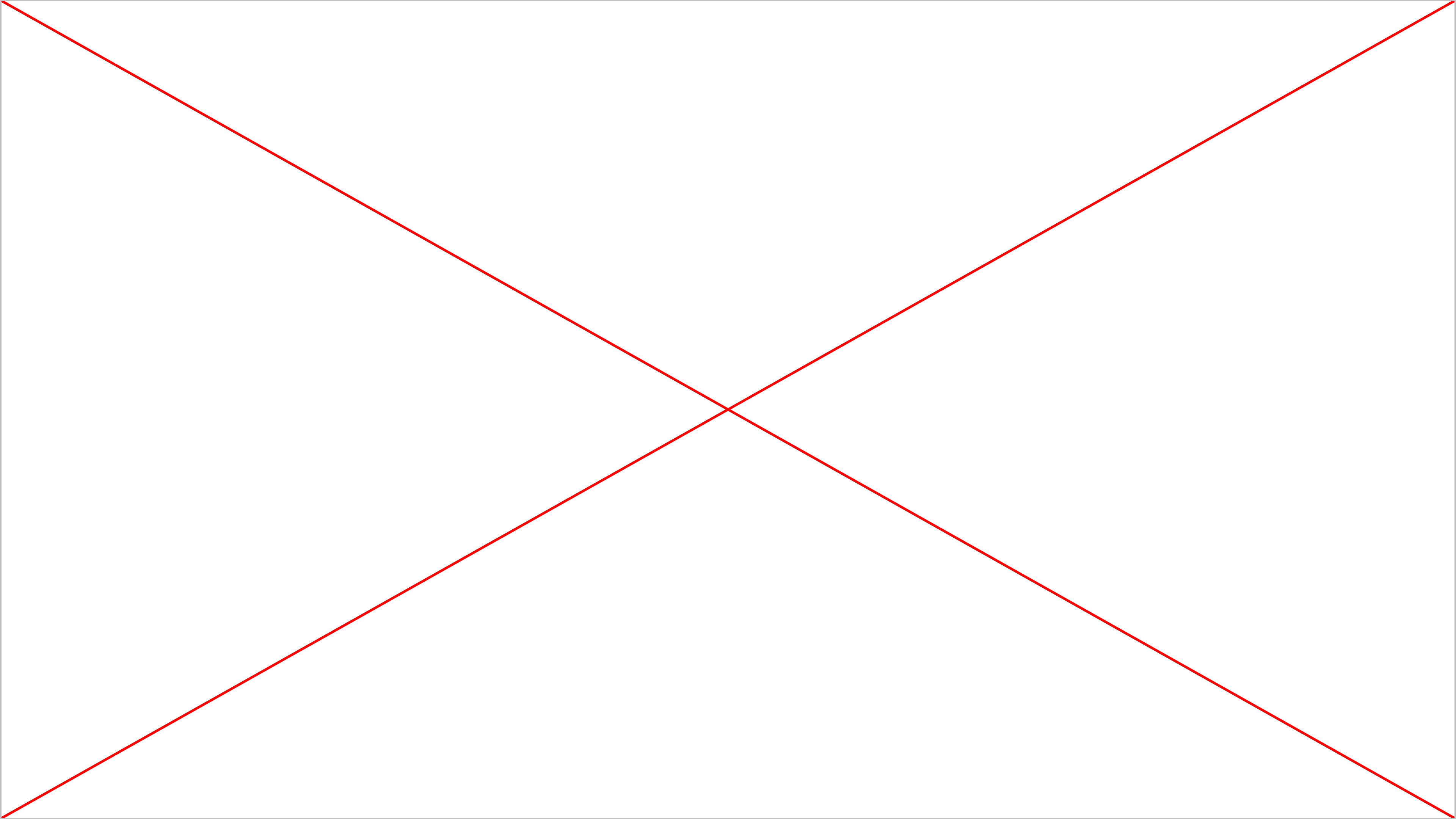


Compressible turbulence (Gaussian random field) with given power spectrum

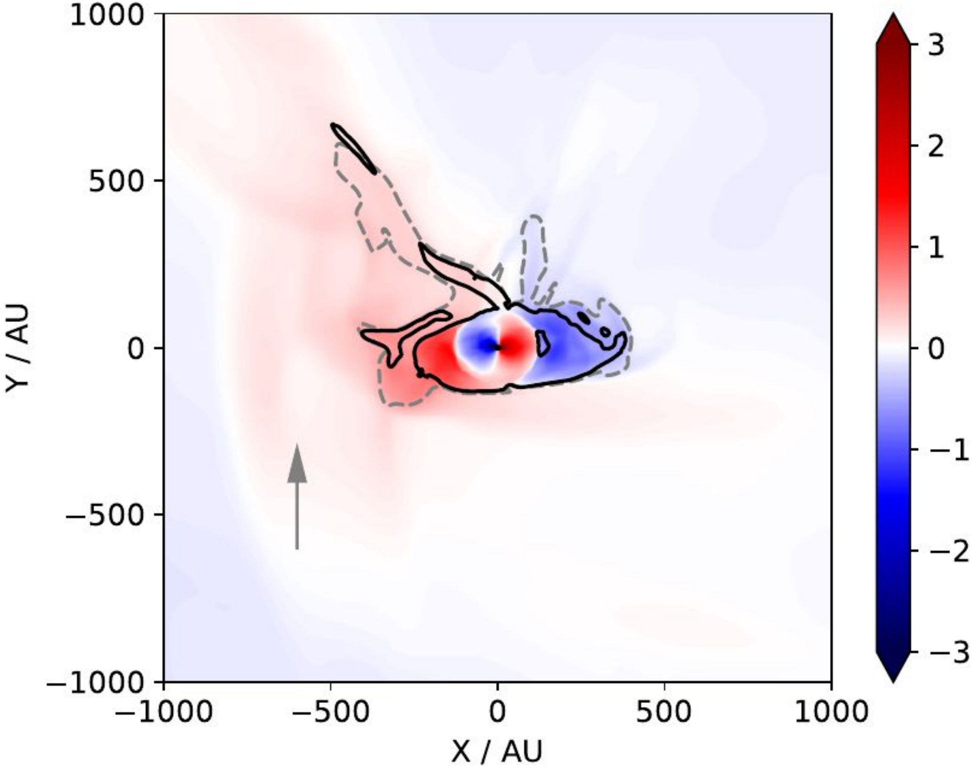
Bondi-Hoyle accretion: Strong turbulence, small scales



Weaker streamers, but frequent and natural creation



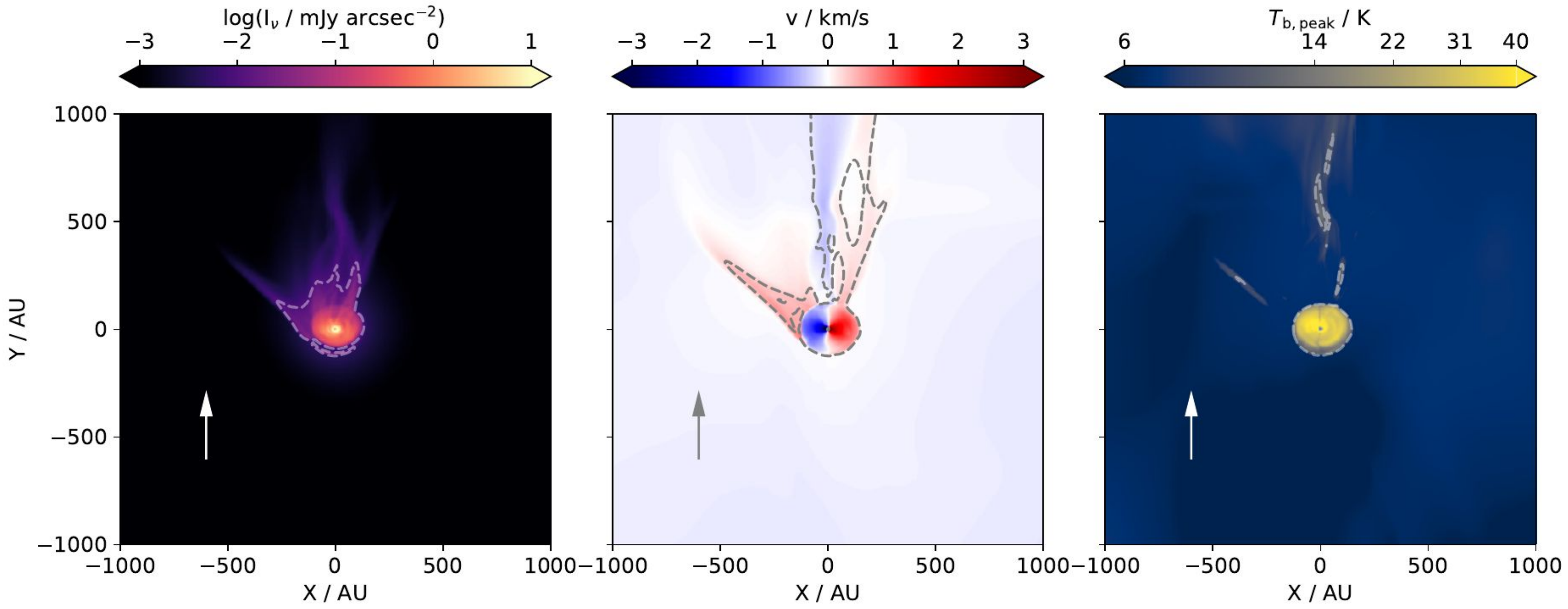
Bondi-Hoyle accretion: Strong turbulence, large scales



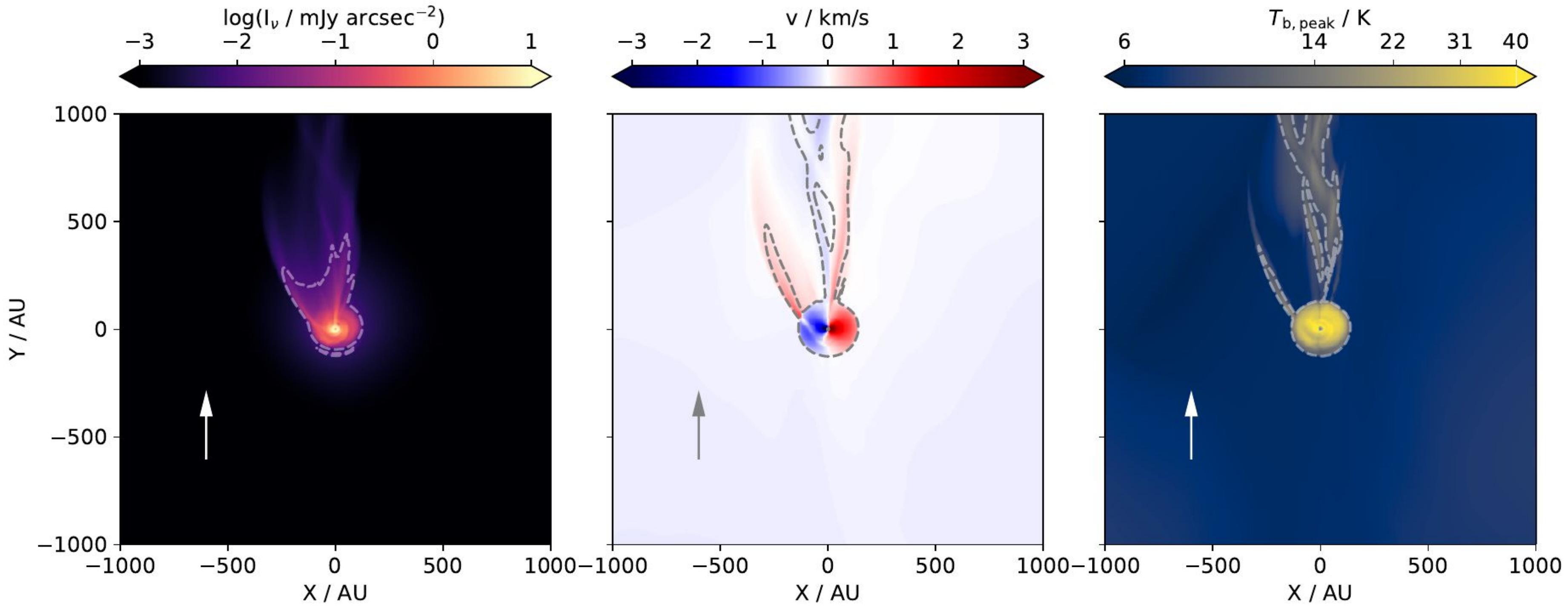
Morphology and multiplicity of the streamers depend on environmental conditions:

- Systemic velocity
- Turbulent scale
- Turbulent velocity
- Infall rate

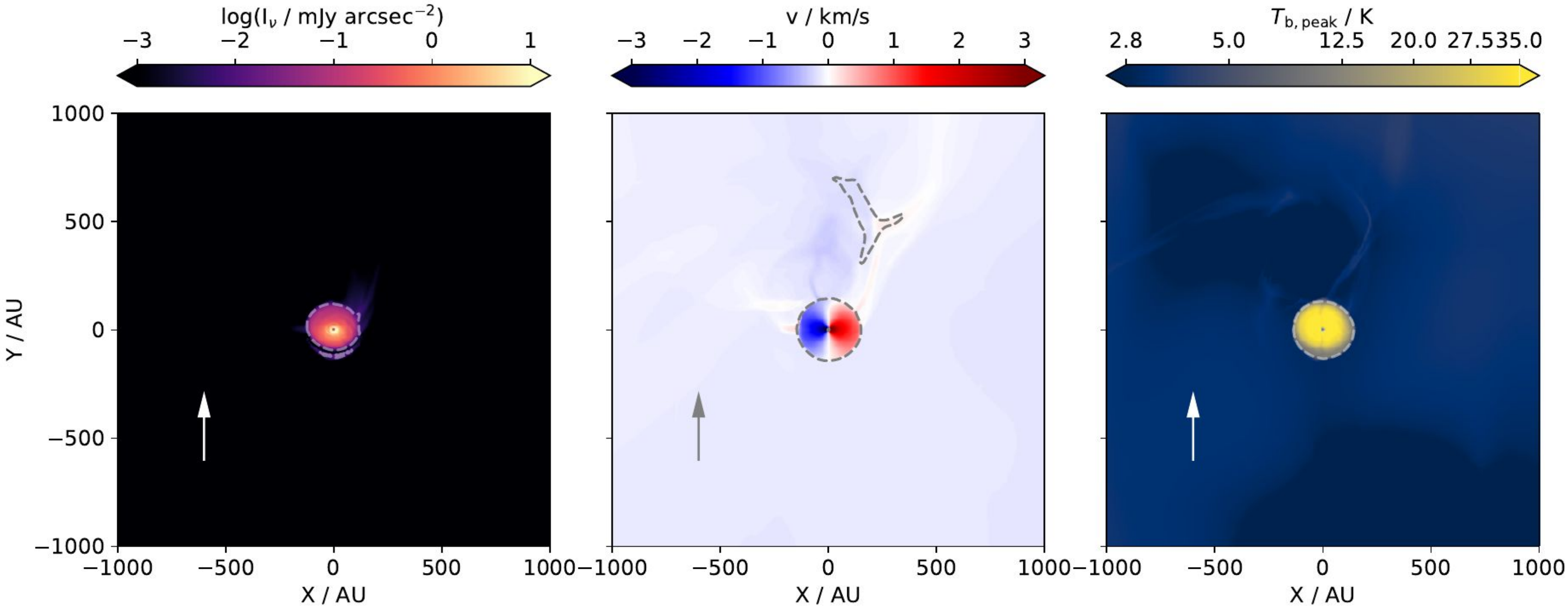
Bondi-Hoyle accretion: Medium turbulence



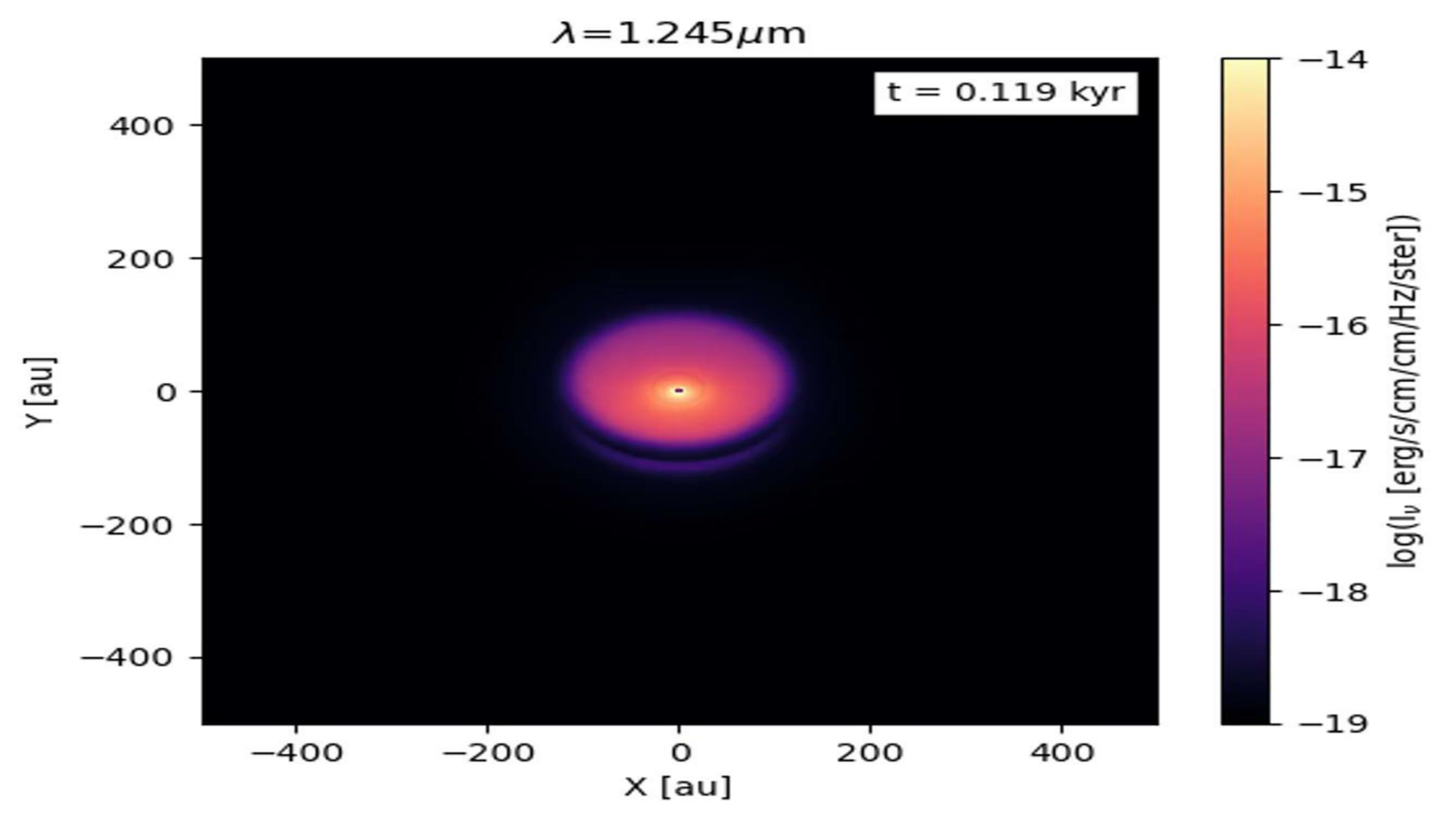
Bondi-Hoyle accretion: Low turbulence



Bondi-Hoyle accretion: Low infall rate



No visible streamer, but the disk might still be affected



λ=1.245μm
t = 0.119 kyr
400
200
0
−200
−400
Y [au]
X [au]
−14
−15
−16
−17
−18
−19
log(Iν [erg/s/cm/cm/Hz/ster])

Project 2a: Take-home messages

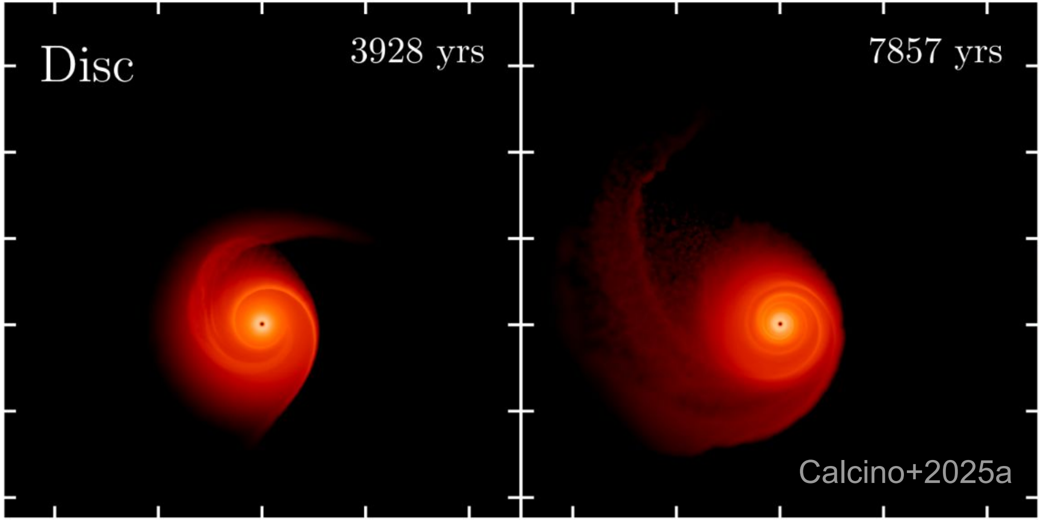
1. **Streamers arise naturally through Bondi-Hoyle accretion**
2. **The apparent infall direction can be unrelated to mass reservoirs**
3. **Their morphology can be used to infer environmental conditions**
4. **Low infall rates do not create visible streamers, but might still impact disk**

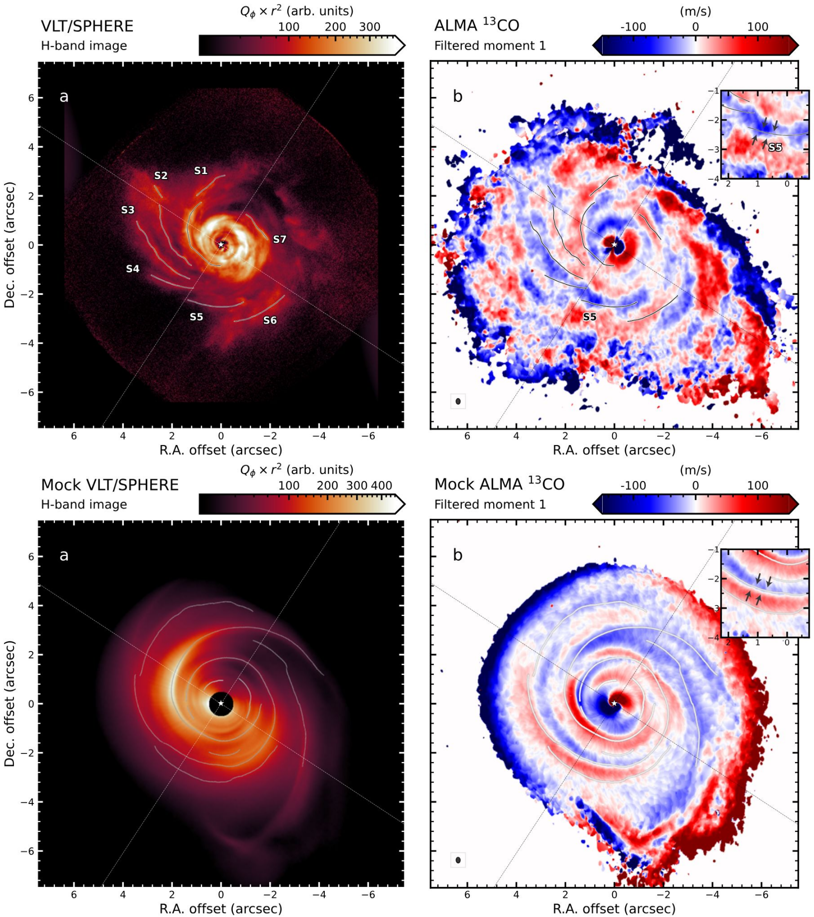
2b. Formation of spirals via late infall

Hühn, Kimmig, Dullemond 2025, in prep.

Are the disk substructures caused by infall?

Calcino+2025b

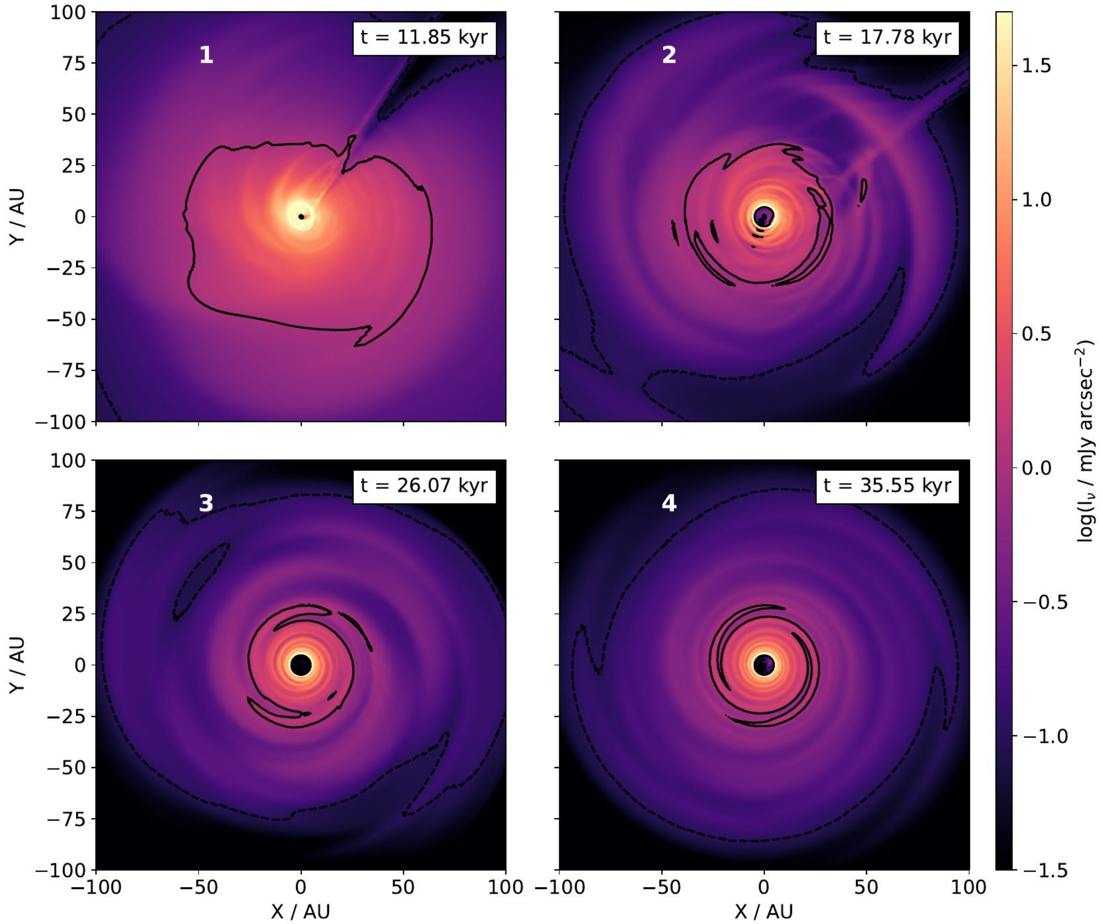




Cloudlet capture* SPH simulations find spiral patterns, structure similar to AB Aur

* modeled as free-falling parabolic orbit

In-plane cloudlet capture



Different spiral structures in one simulation:

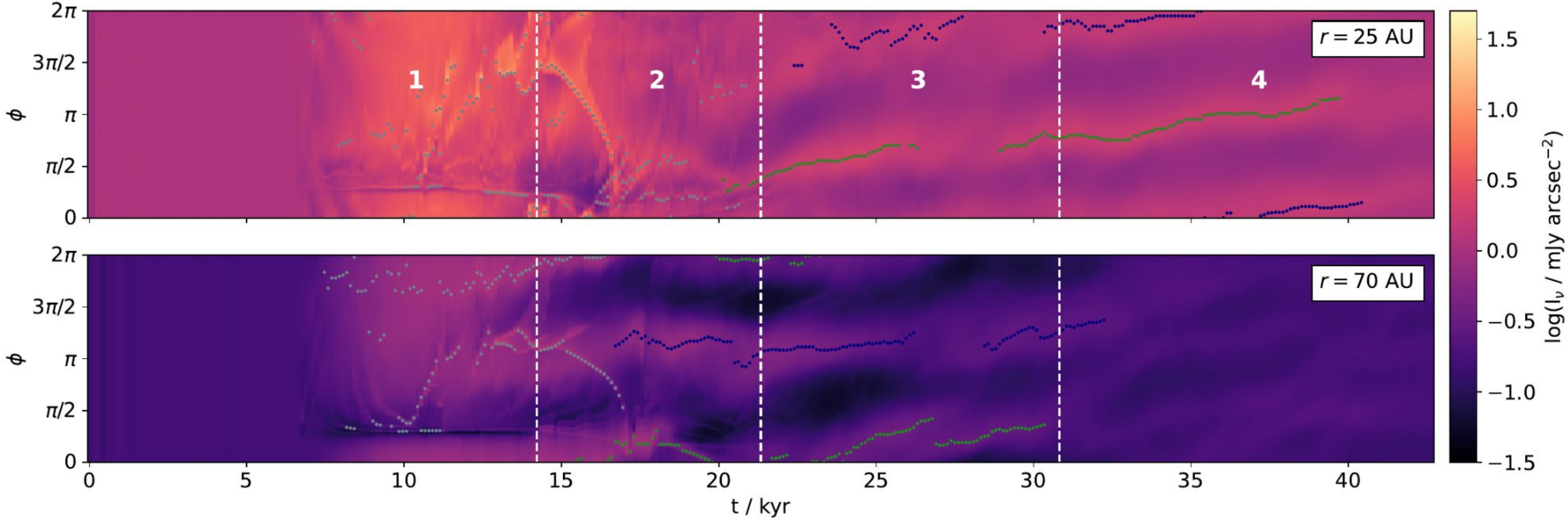
1: Flocculent shape in inner disk, smooth outer disk

2: m=2 pattern in outer disk

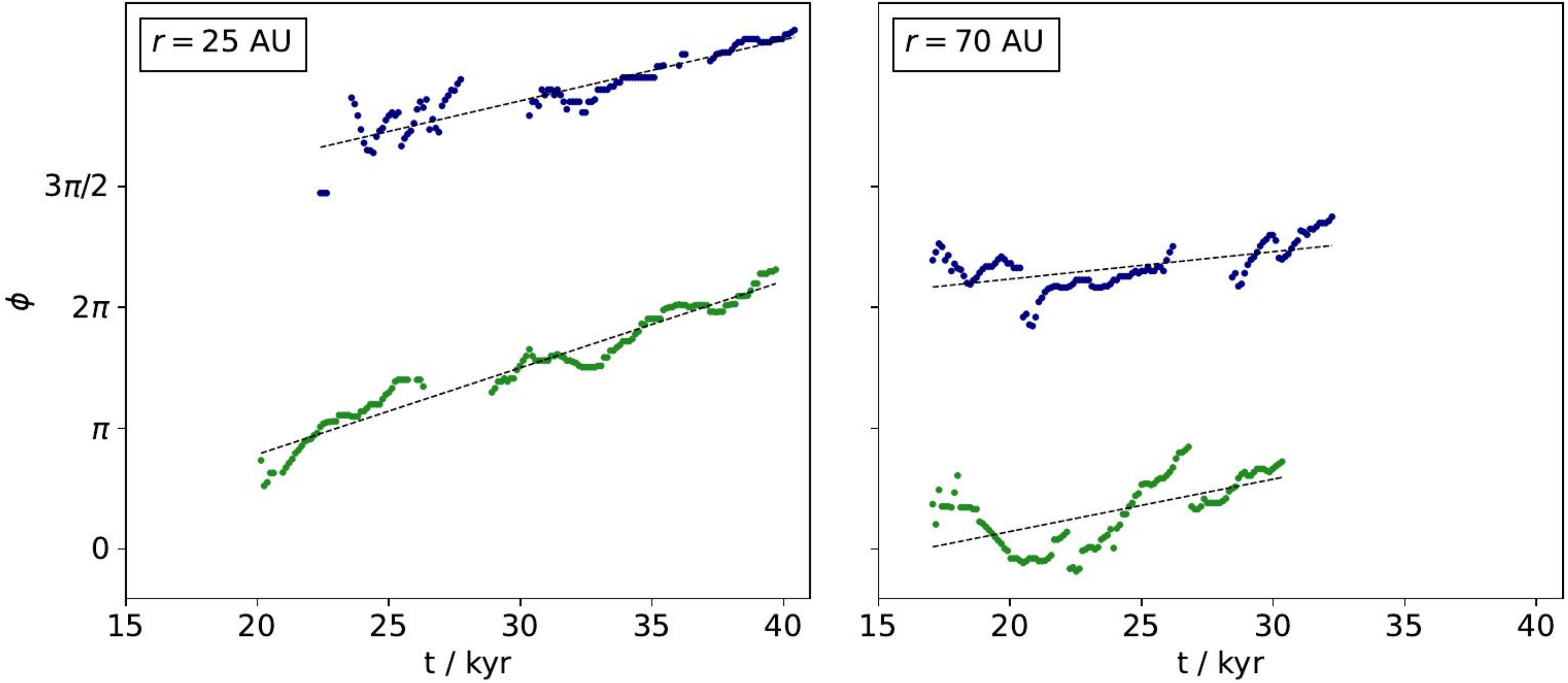
3: m=2 pattern in inner disk

4: Pattern in outer disk vanishes

Pattern speed of the m=2 spirals



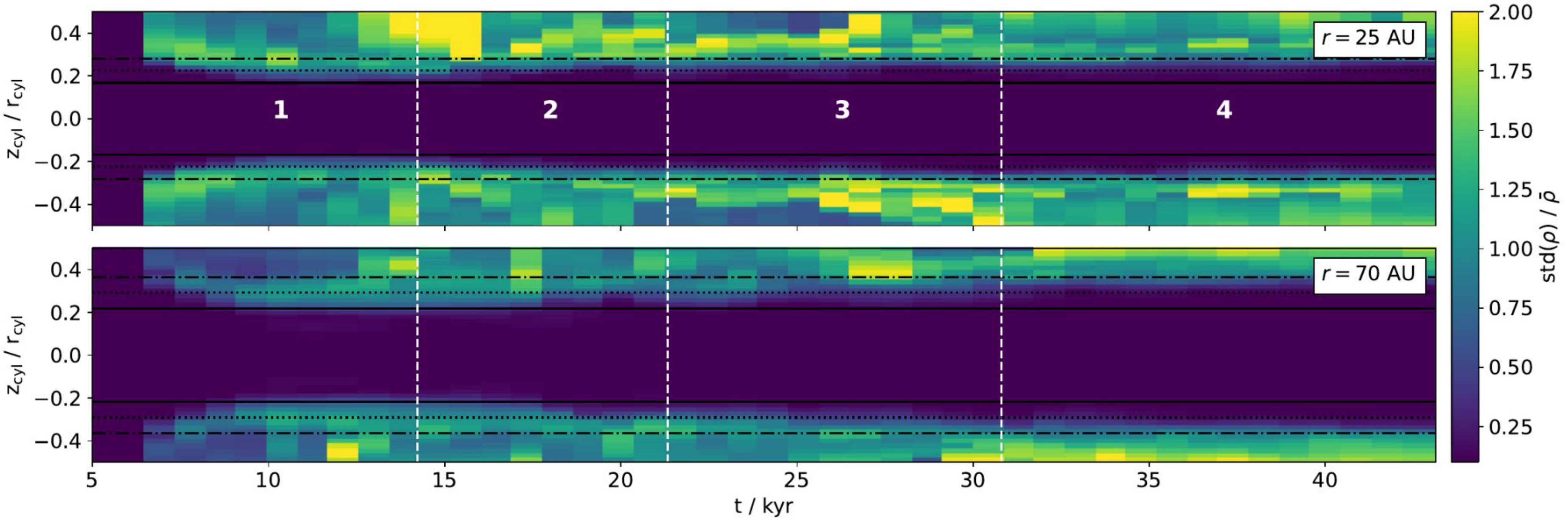
Pattern speed of the m=2 spirals



Outer spirals (almost) **stationary**! (~ 0.05 – 0.1 kyr^{-1})

What layers of the disk are affected?

$M_d = 0.05\ M_\odot$

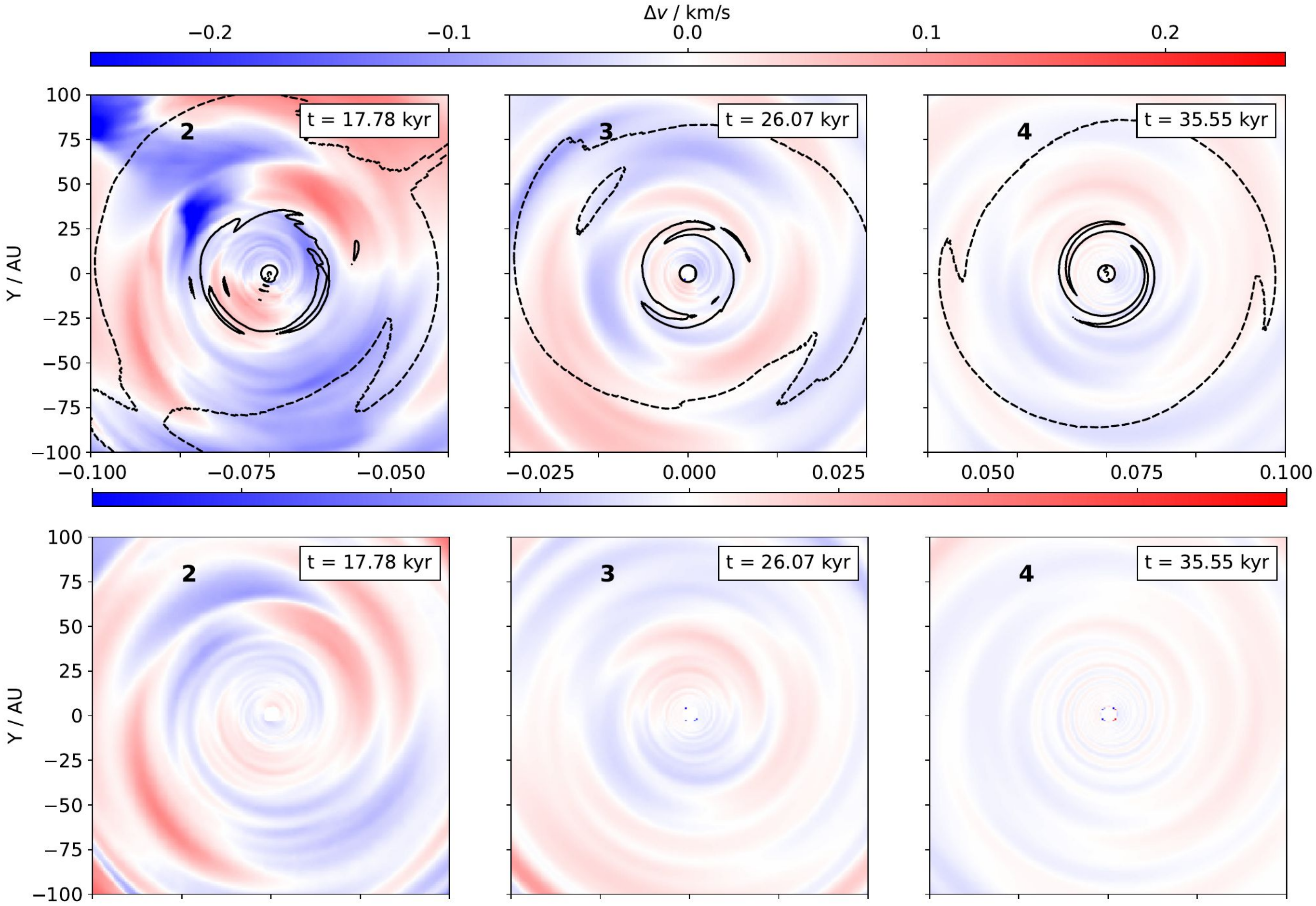


Even at the main impact, layers with z < 3H are unaffected
-> Spirals are only **on the surface**

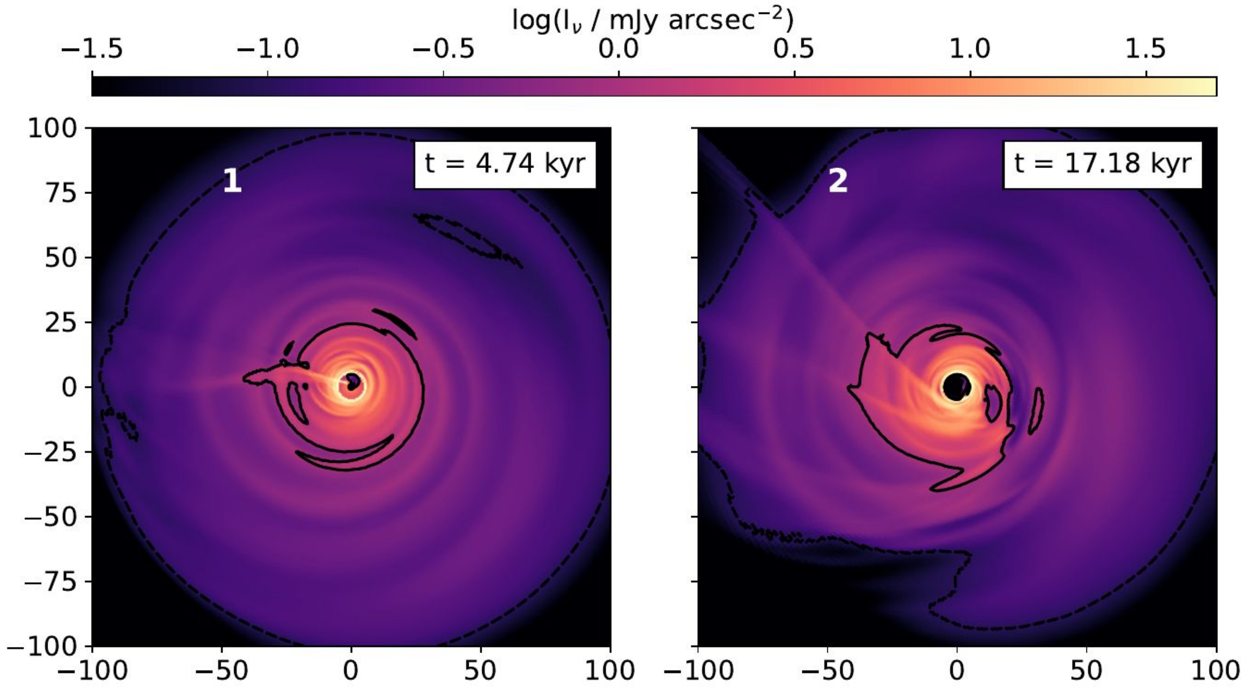
Disk kinematics: CO isotopologue residuals

^{12}CO

^{13}CO



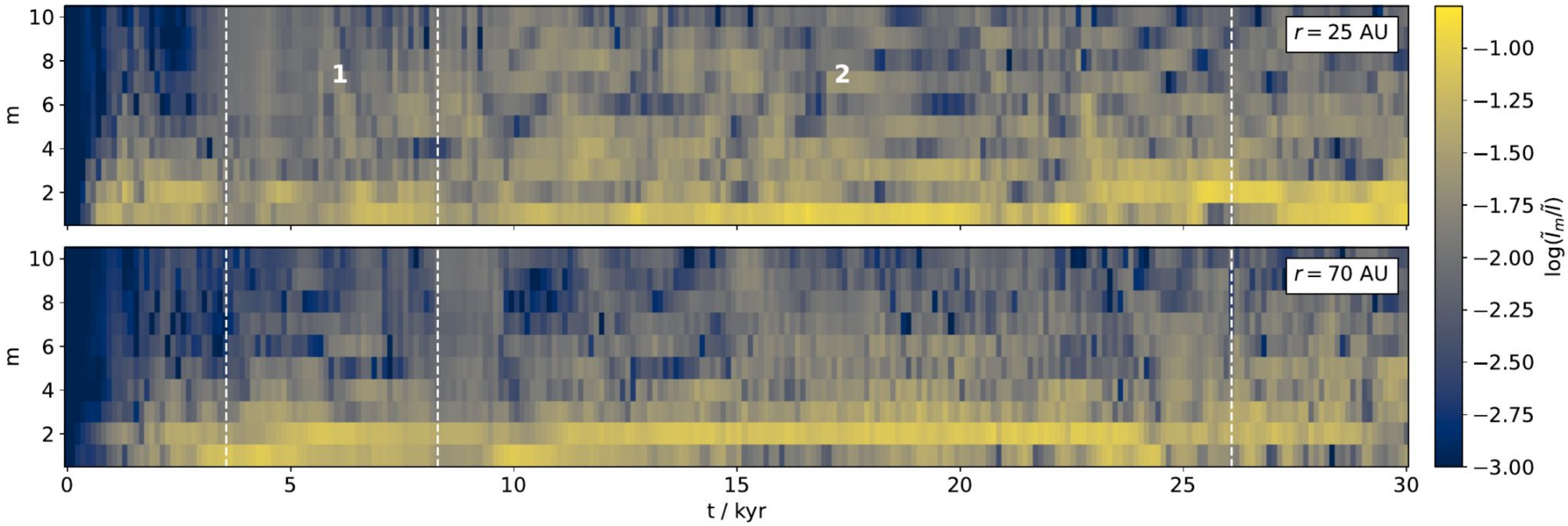
Bondi-Hoyle-Lyttleton accretion: Scattered light



1: m=2 spiral in inner and outer disk

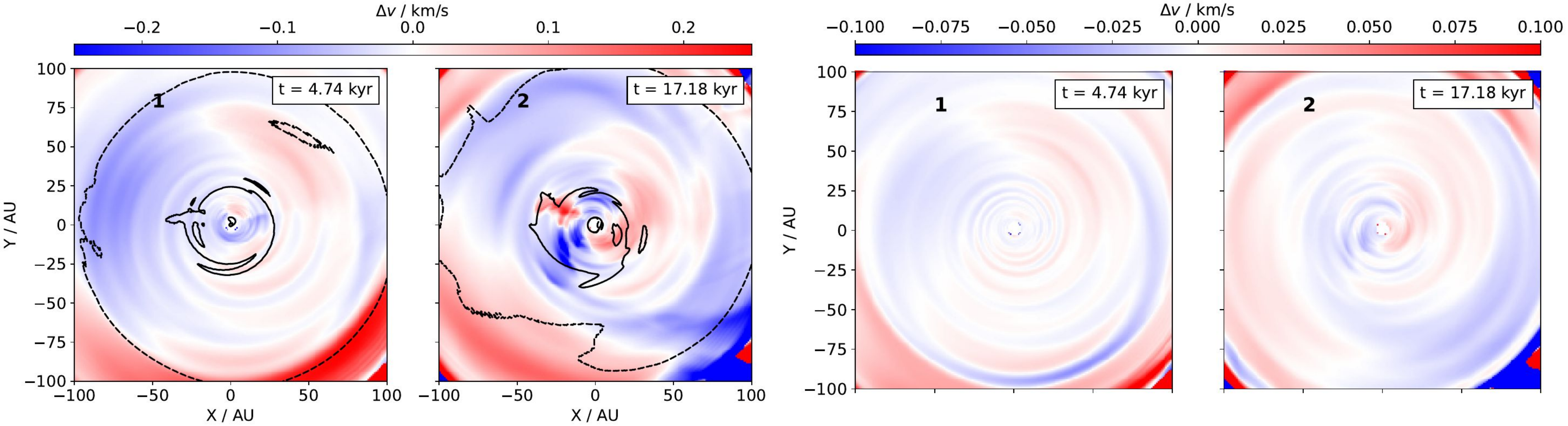
2: Spirals are flocculent in inner disk, low-armed in outer disk

Fourier analysis: Angular spectrum



Angular spectrum does not match expectation: Streamer contamination?

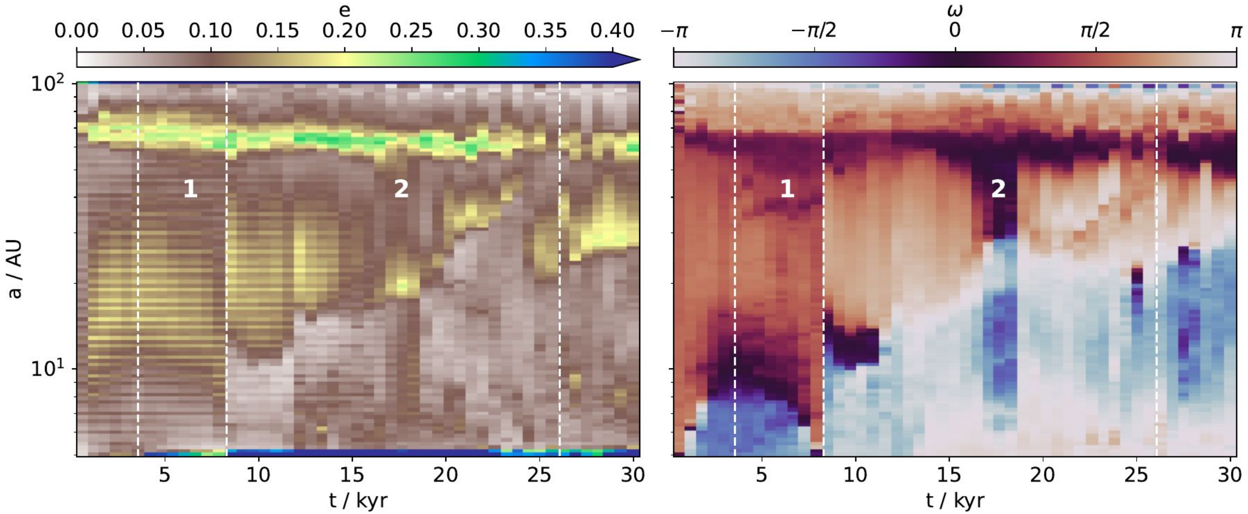
Bondi-Hoyle-Lyttleton accretion: CO isotopologues

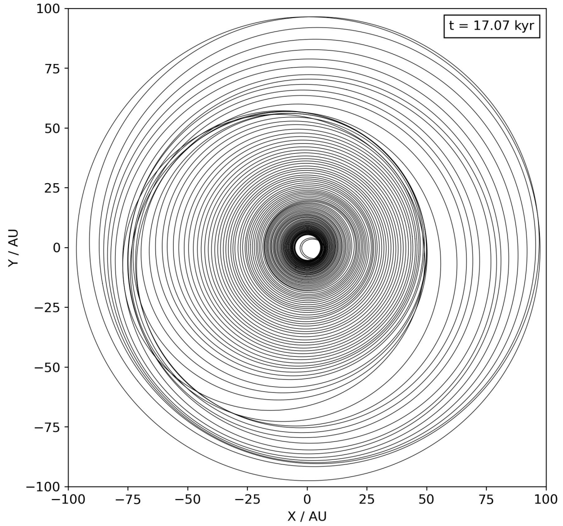


^{12}CO ^{13}CO

Spiral patterns **differ** considerably between **scattered light, ^{12}CO and ^{13}CO**

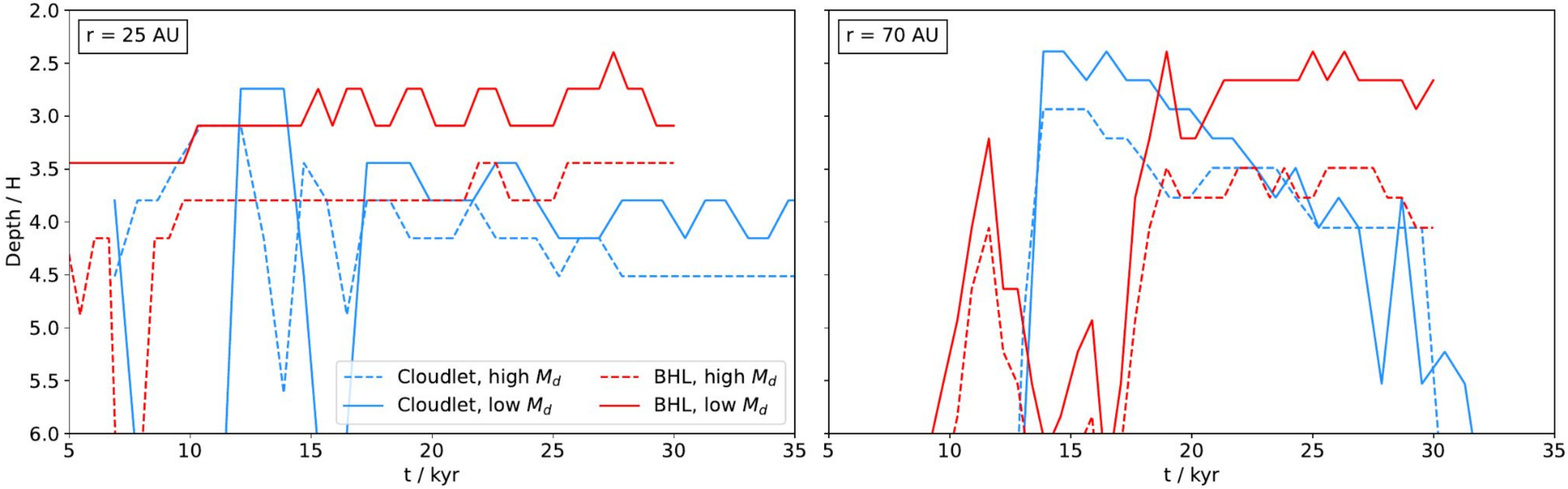
Is the m=1 mode related to disk eccentricity?





Orbital structure of disk surface should result in m=1 mode, but it can be **invisible**
⇒ m=1 mode in scattered light is just **streamer contamination**
⇒ Scattered light spirals are not disk kinematics, but they can be seen in ^{13}CO

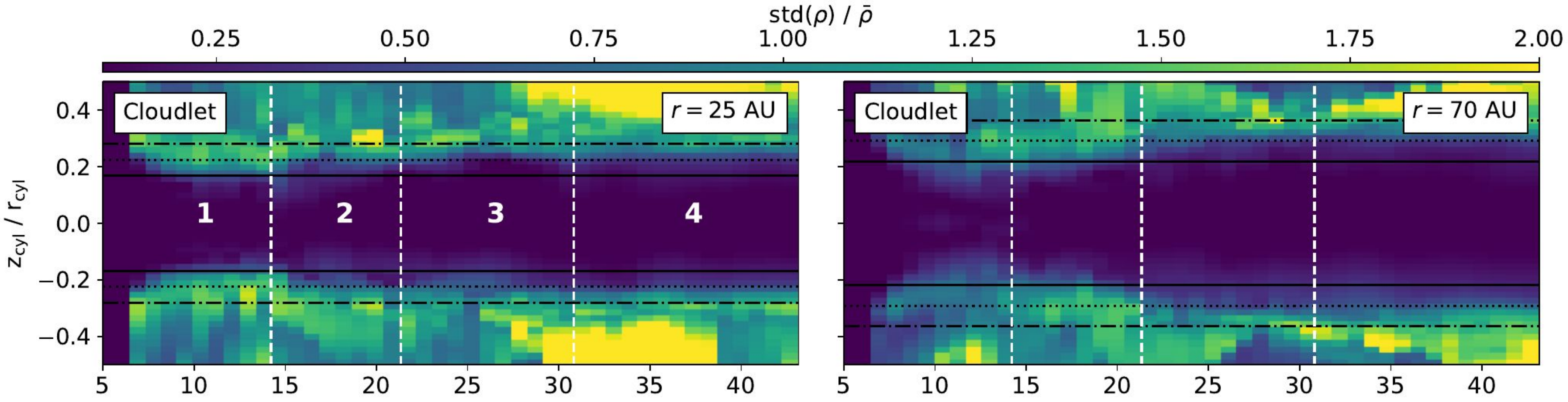
Comparison of affected disk layers



- Cloudlet capture affects deeper disk layers at the time of impact
- Bondi-Hoyle-Lyttleton accretion affects deeper disk layers over time
- Deeper layers affected for lighter disk ⇒ Late infall **important for older disks**

What layers of the disk are affected?

$M_d = 0.005\ M_\odot$



Hühn+ in prep.

For lighter disks, **midplane layers** can be affected, especially in the outer disk

⇒ Late infall is more important for **older disks**

⇒ Different mechanisms for **planet formation here**?

Formation of spirals: Take-home messages

1. **Cloudlet capture can create m=2 and flocculent spirals in scattered light due to surface-level perturbations, unrelated to other mechanisms**
2. **Their pattern speed appears to be almost stationary**

⇒ Discernable from flyby or warp-induced spirals

3. **Bondi-Hoyle accretion creates more flocculent spiral structure**
4. **Scattered light spirals are unrelated to disk kinematics**

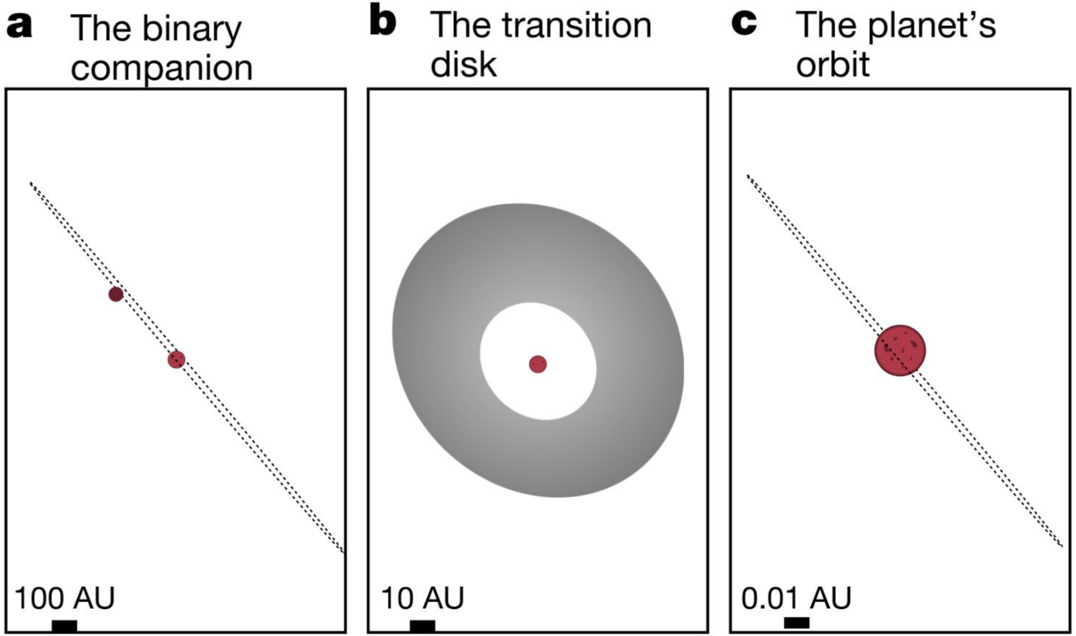
⇒ Observed spirals can be caused by infall alone, not deeply affecting the disk

⇒ Late infall is likely more impactful for lighter, more evolved disks

2c. The disk around IRAS 04125+2902

Hühn, Jiang, Dullemond 2025, A&A, 701, L15

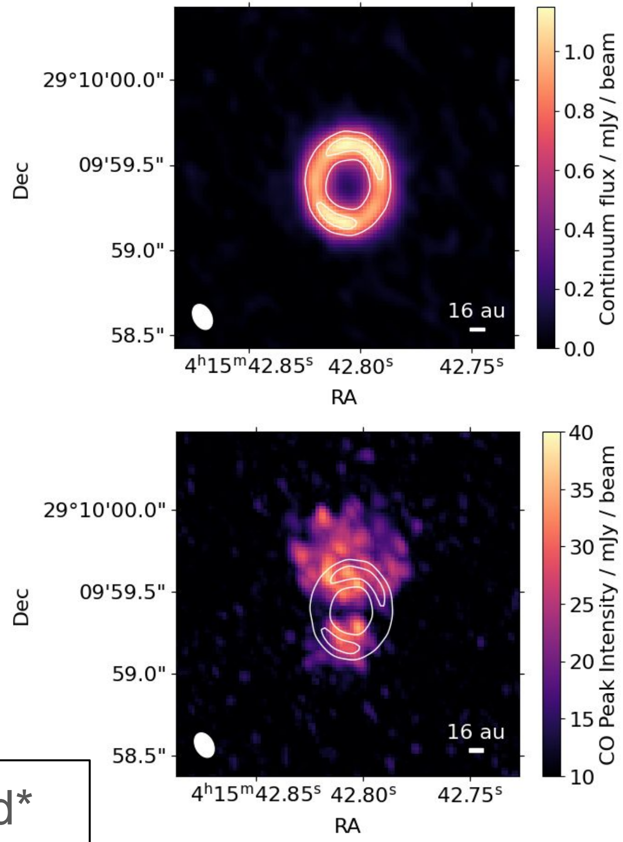
Late infall in IRAS 04125+2902?



Barber+2024

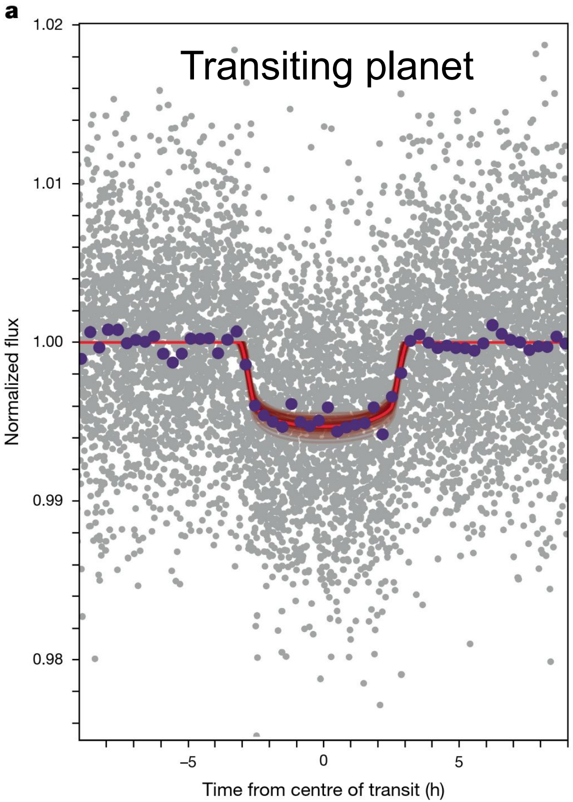
Binary and planet are aligned*
But: Protoplanetary disk is not!

Circum-primary disk



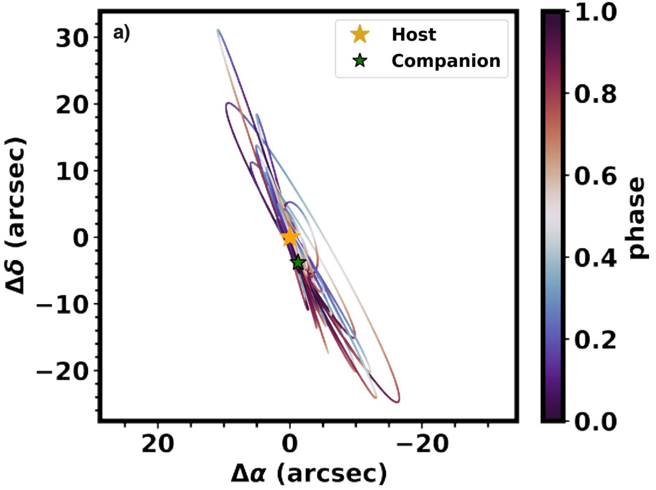
Bosschaart+2025
Shoshi+2025

System configuration: Wide binary



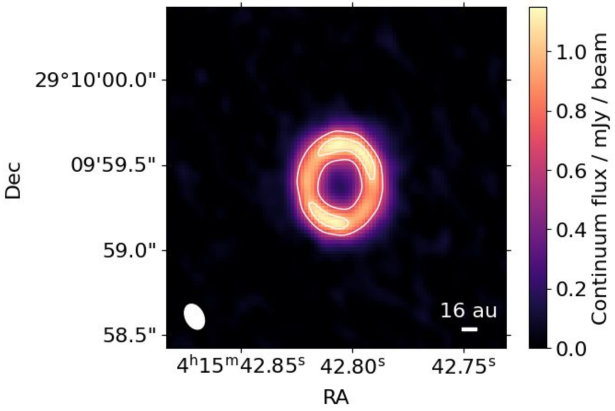
Barber+2024

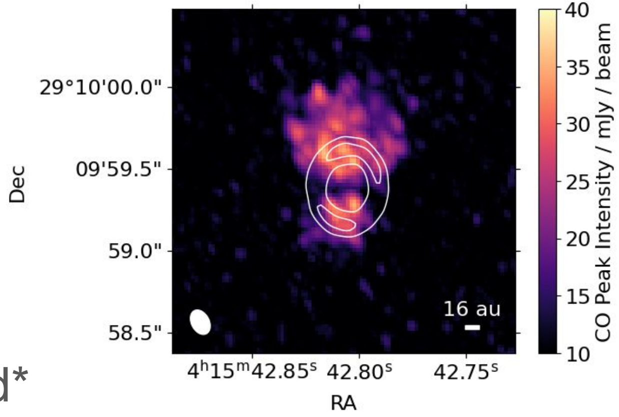
Binary



Binary and planet are aligned*
But: Protoplanetary disk is not!

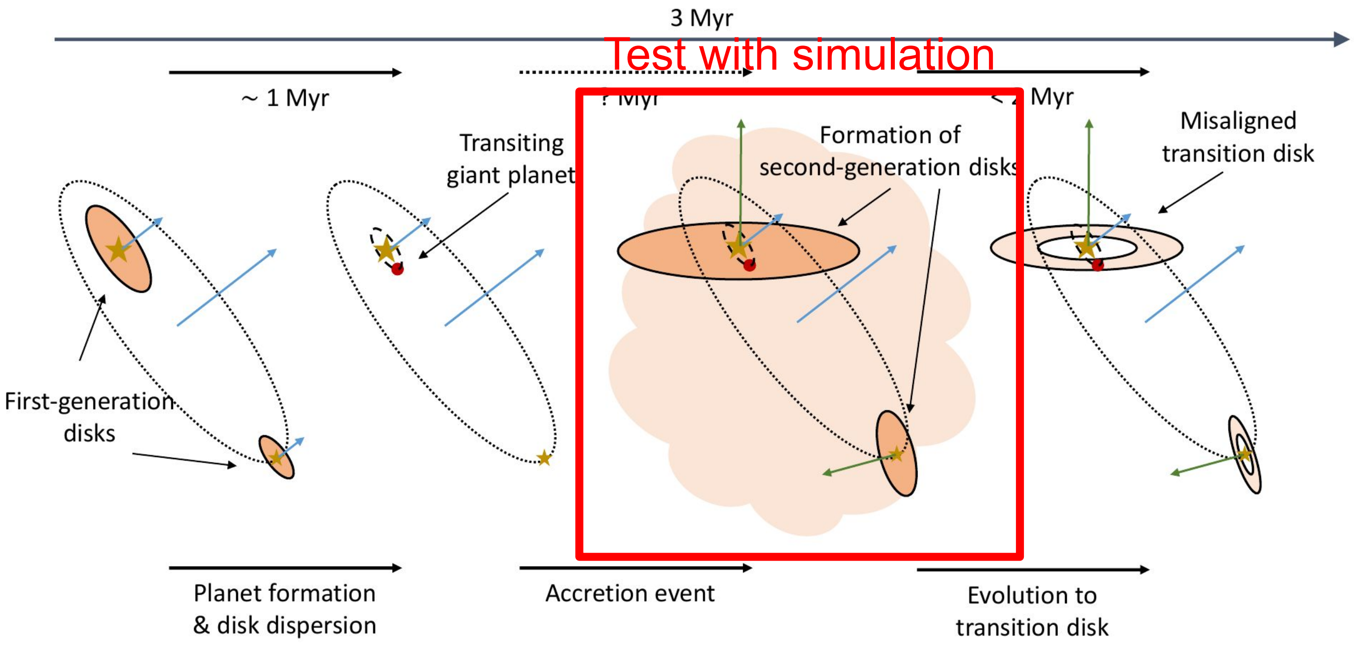
Circum-primary disk





Bosschaart+2025
Shoshi+2025

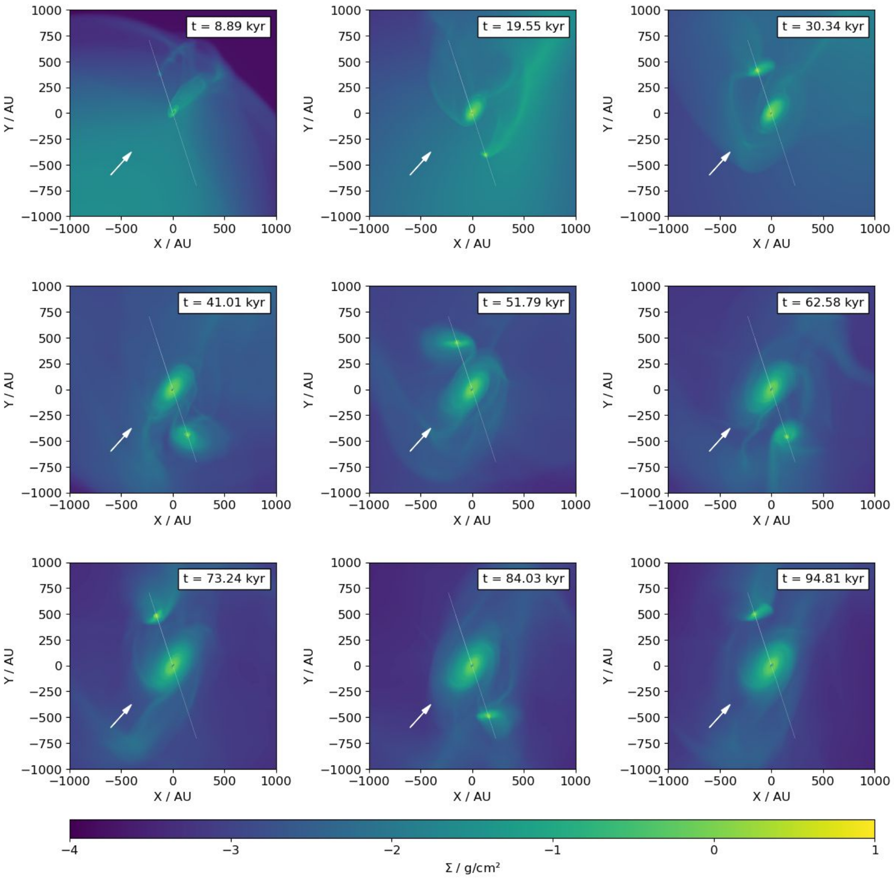
Proposed formation scenario



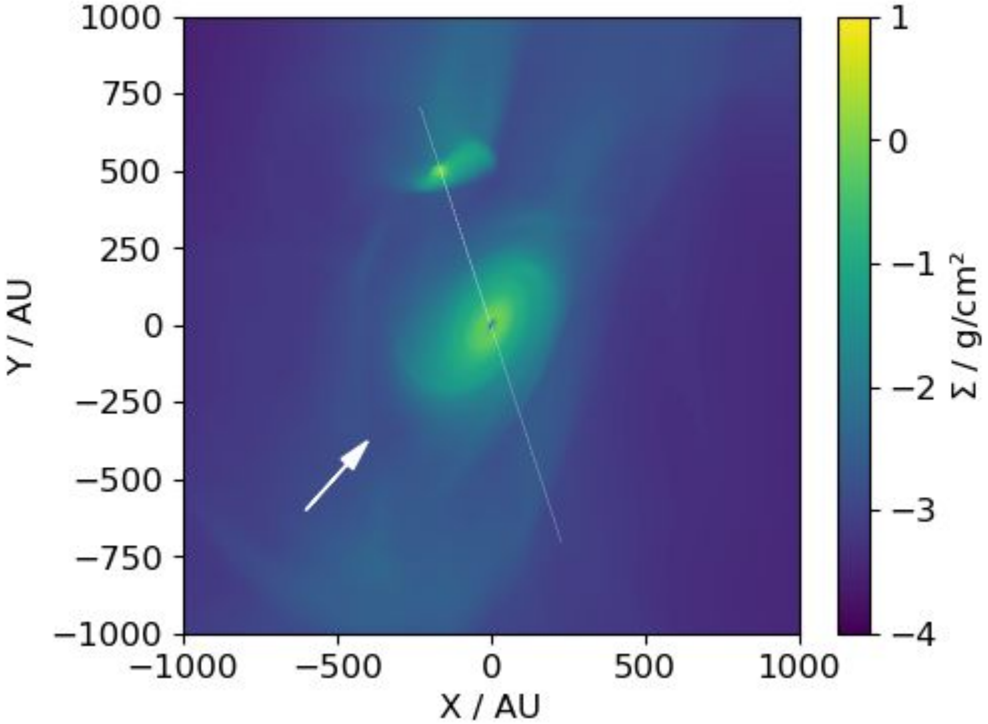
Second-generation disk?

Gas-only simulation
Initial condition: Spherical cloudlet

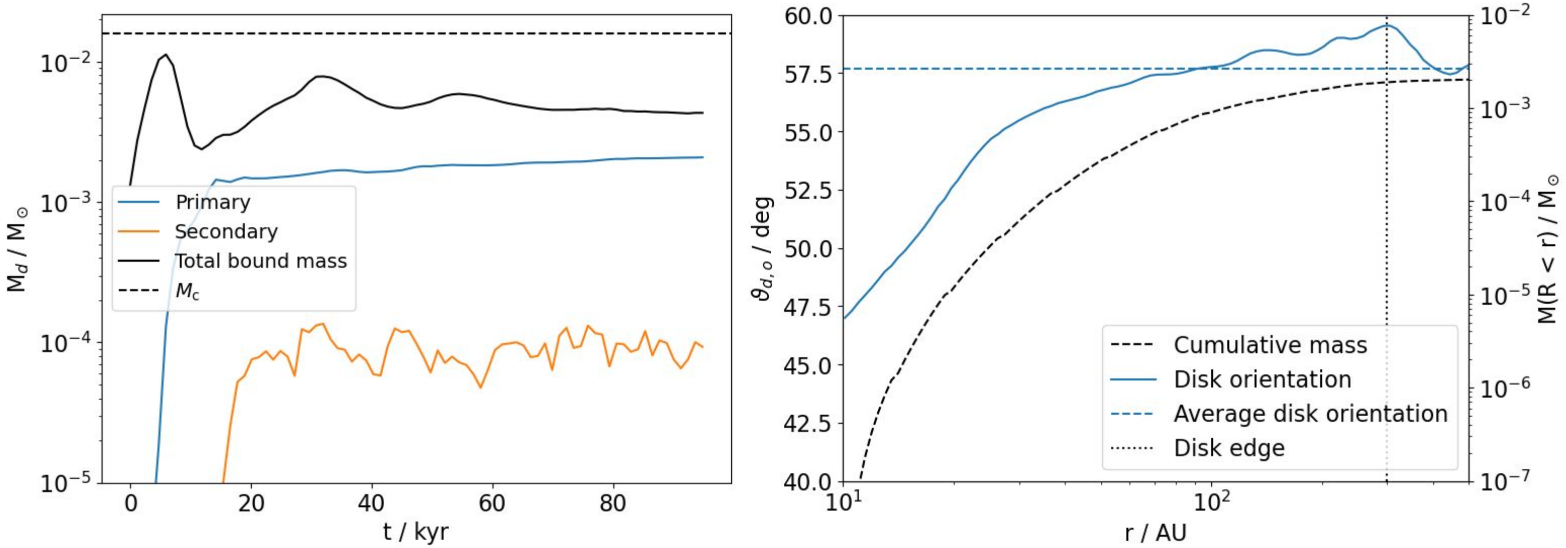
Second-generation disks?



Second-generation disk?



Second-generation disk?



Project 2c: Take-home message

1. **Misaligned disk in IRAS 04125+2902 could be the result of late infall**

2. **Scenario can be tested by checking for a circum-secondary disk**

Summary: Impact of environmental interactions

- (Early) infall influences planet formation **initial conditions**
- (Late) infall causes **streamers**, delivering new material

→ Enhance mass budget of first generation

- (Late) infall causes **spirals** of many different shapes
- (Late) infall can create new **2nd generation** disks

→ Rejuvenating planet formation?