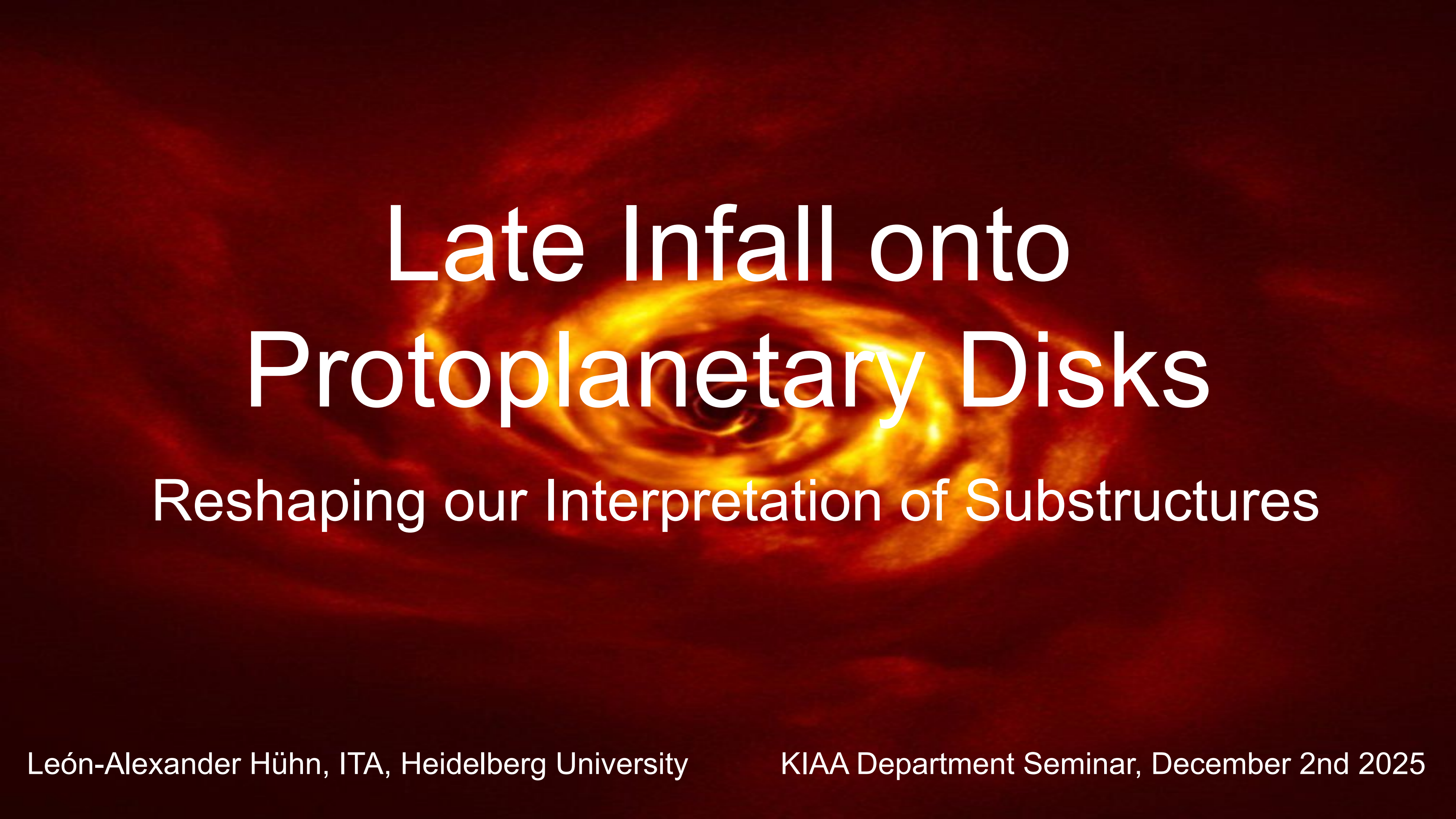


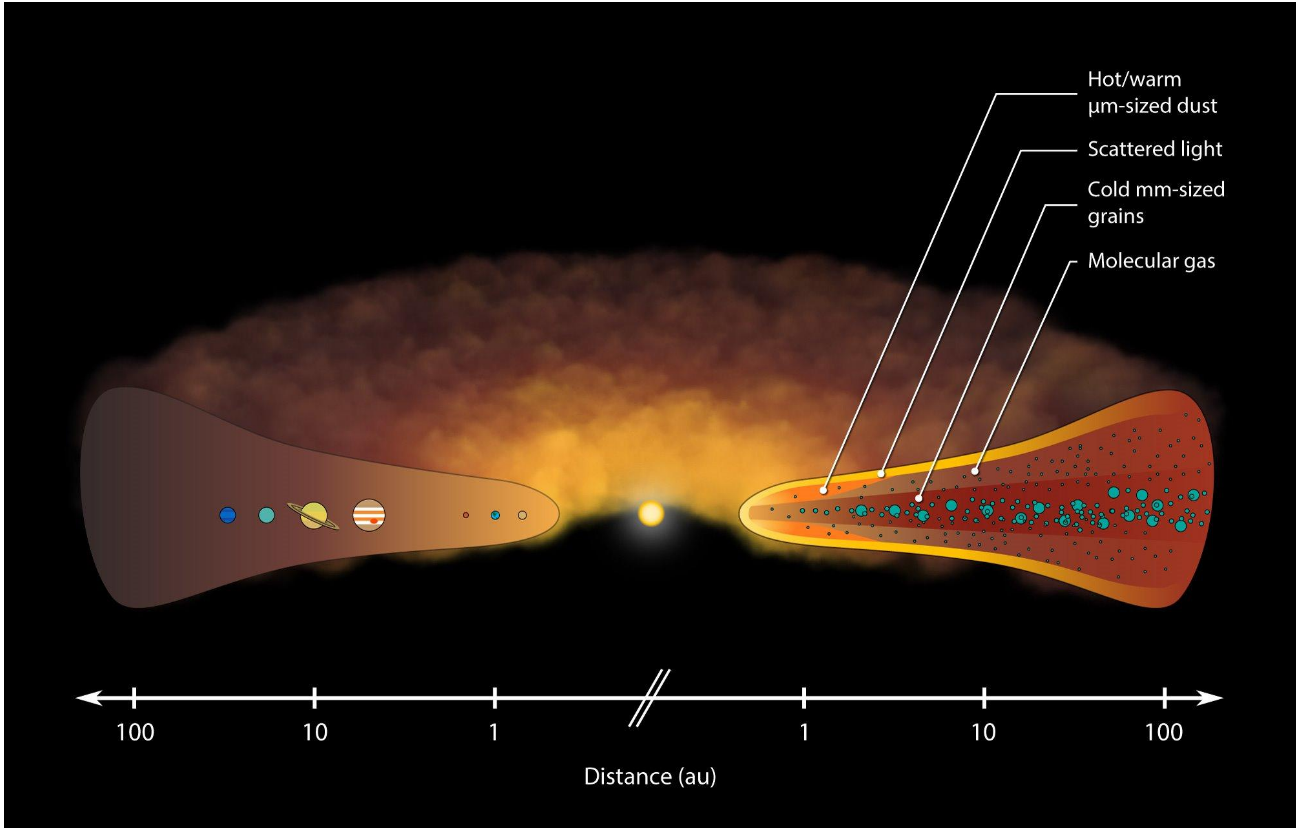
Late Infall onto Protoplanetary Disks

Reshaping our Interpretation of Substructures

León-Alexander Hühn, ITA, Heidelberg University

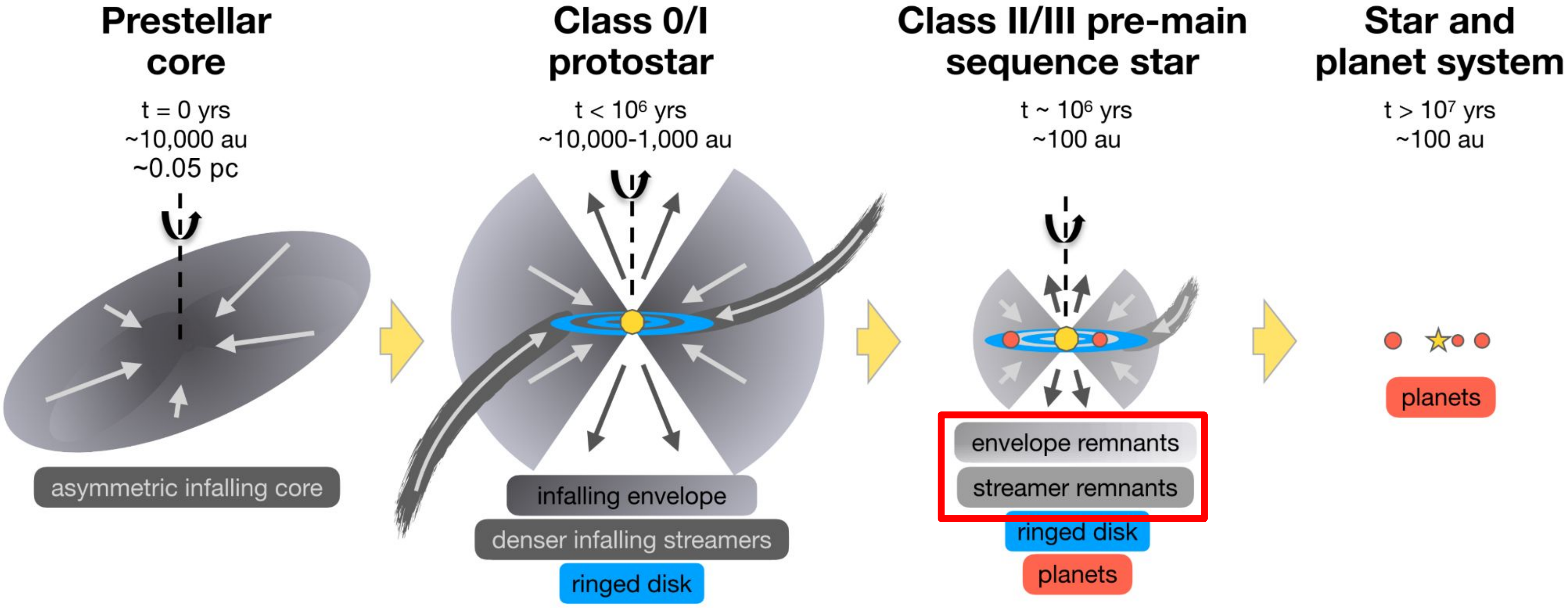
KIAA Department Seminar, December 2nd 2025

The classical picture of planet formation



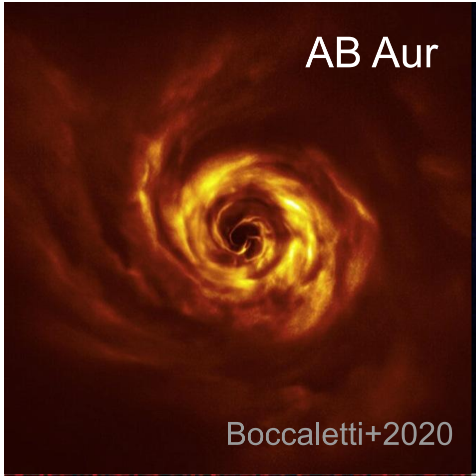
Testi+2014, mod.

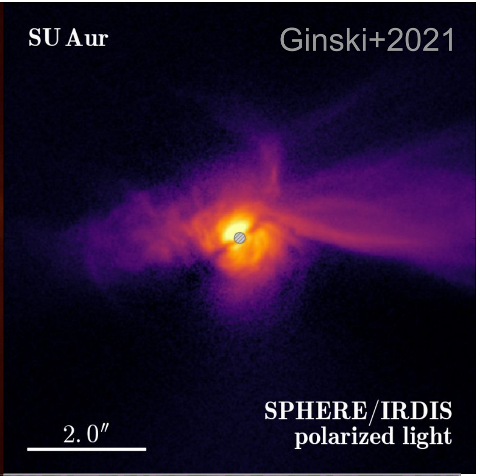
The current picture of planet formation

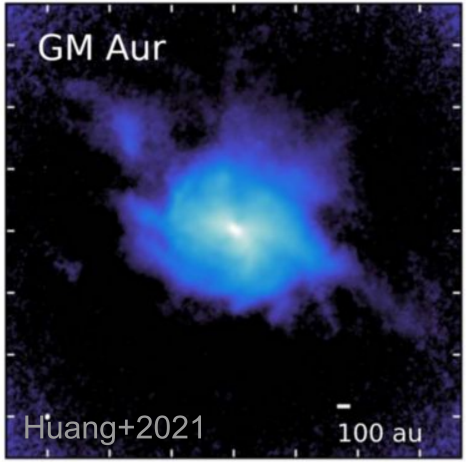


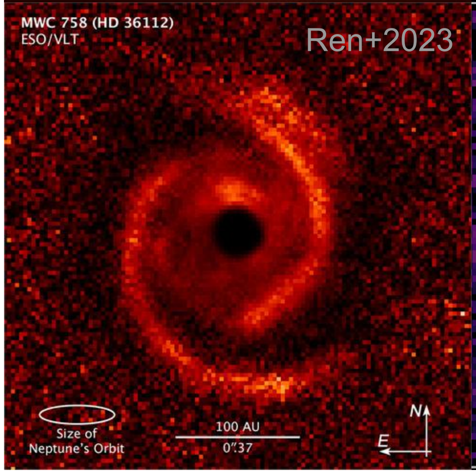
Pineda+2023

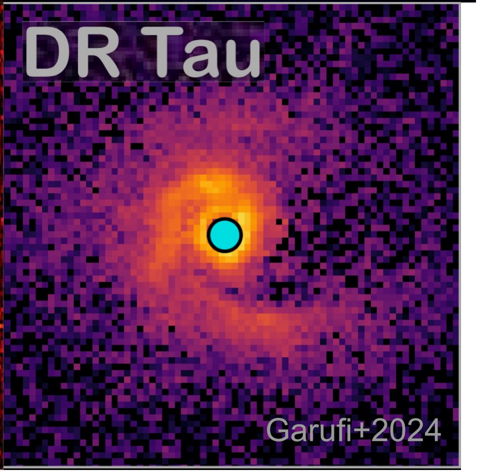
How isolated are disks during the Class II stage?

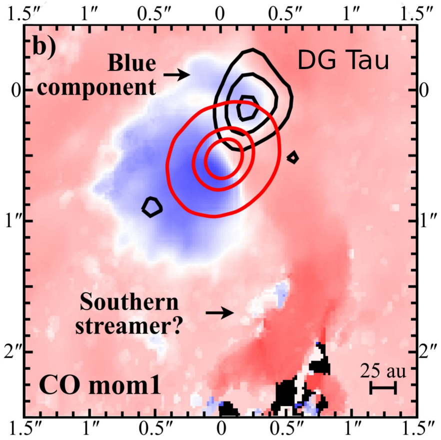








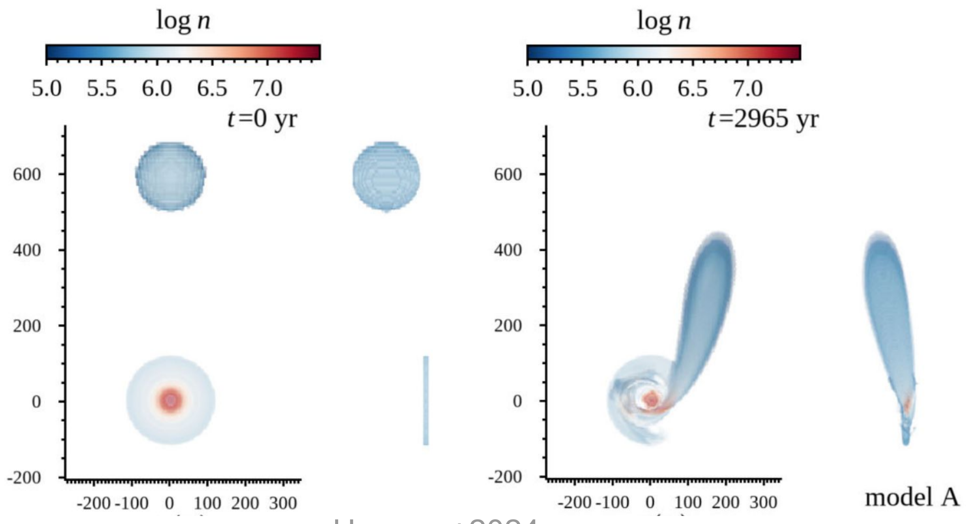




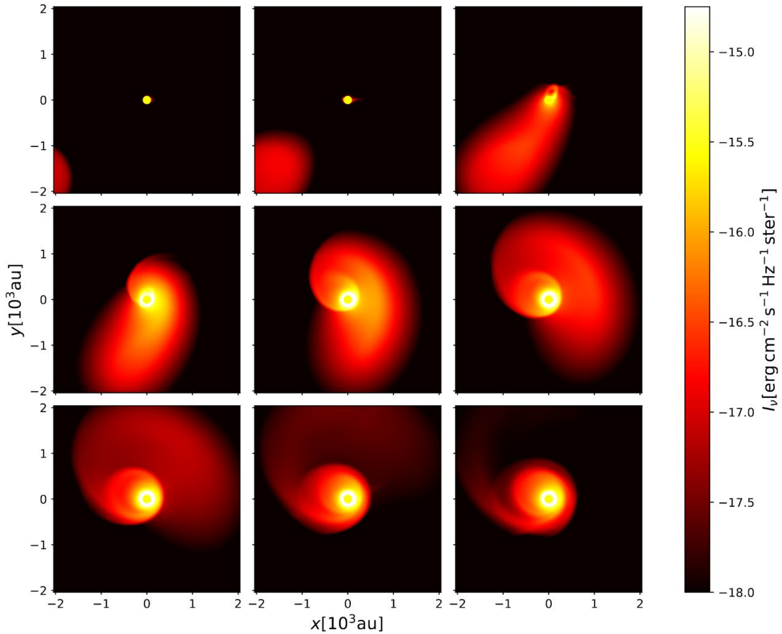
Garufi+2022

Are the large-scale structure inflow?

Dullemond+2019

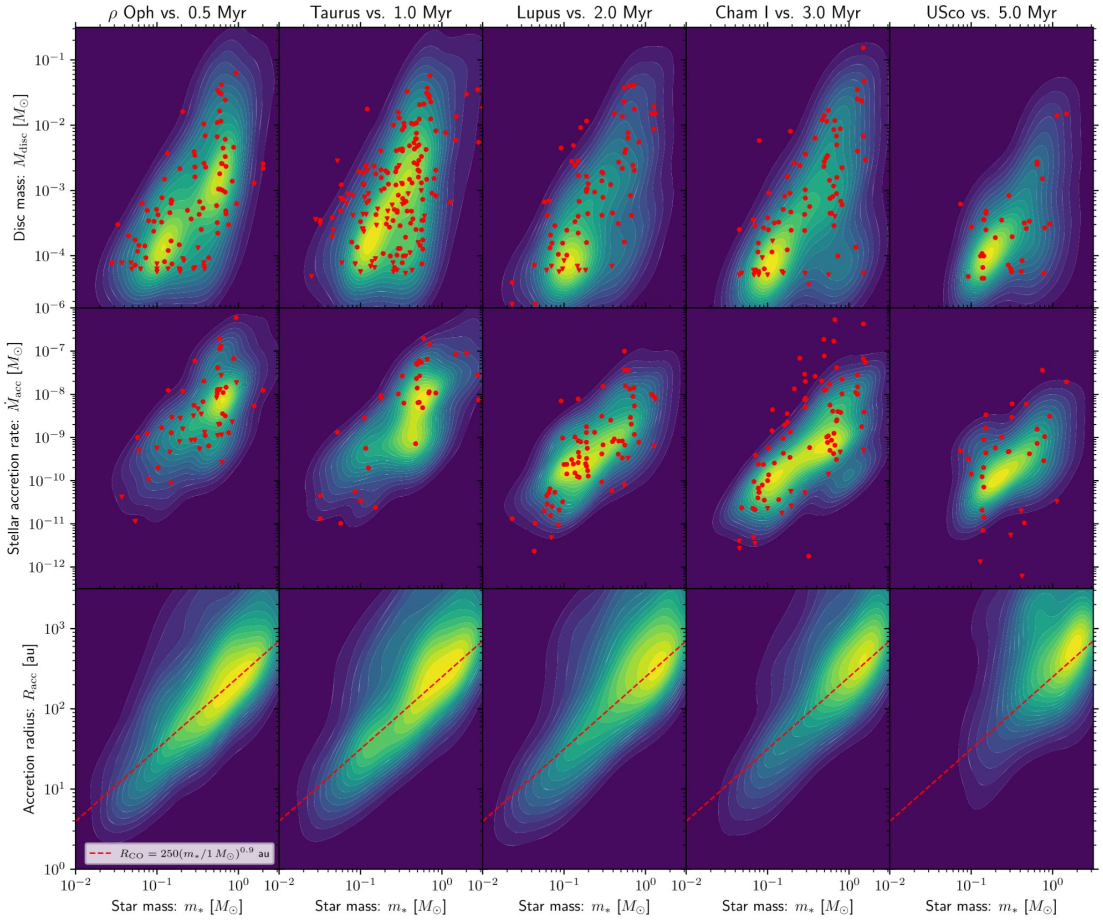


Hanawa+2024



Material infall modeled as the capture of a spherical gas cloudlet

Other observational evidence of inflow



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

Winter+2024

What is the nature of late infall streamers?

L.-A. Hühn, C. P. Dullemond

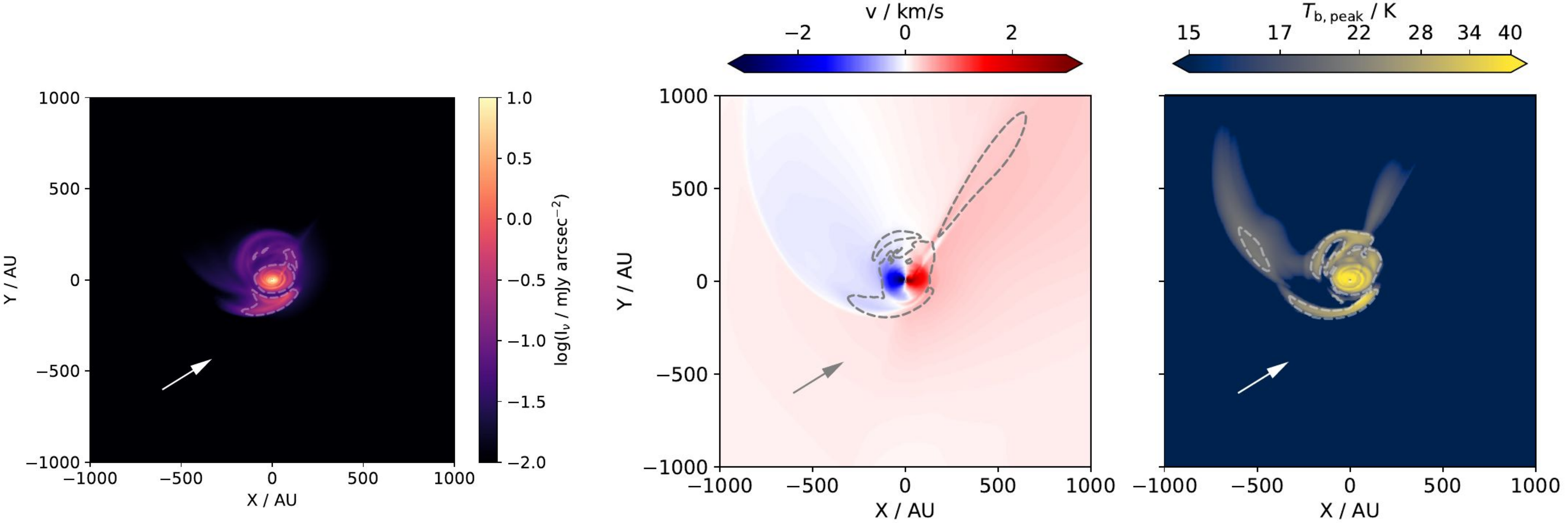
Simulation setup: Cloudlet capture

- 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
- Temperature: Isothermal EOS, passive stellar heating

  ⇒ **No pressure support**
- Gas only, no dust
- Postprocessing: RADMC3D

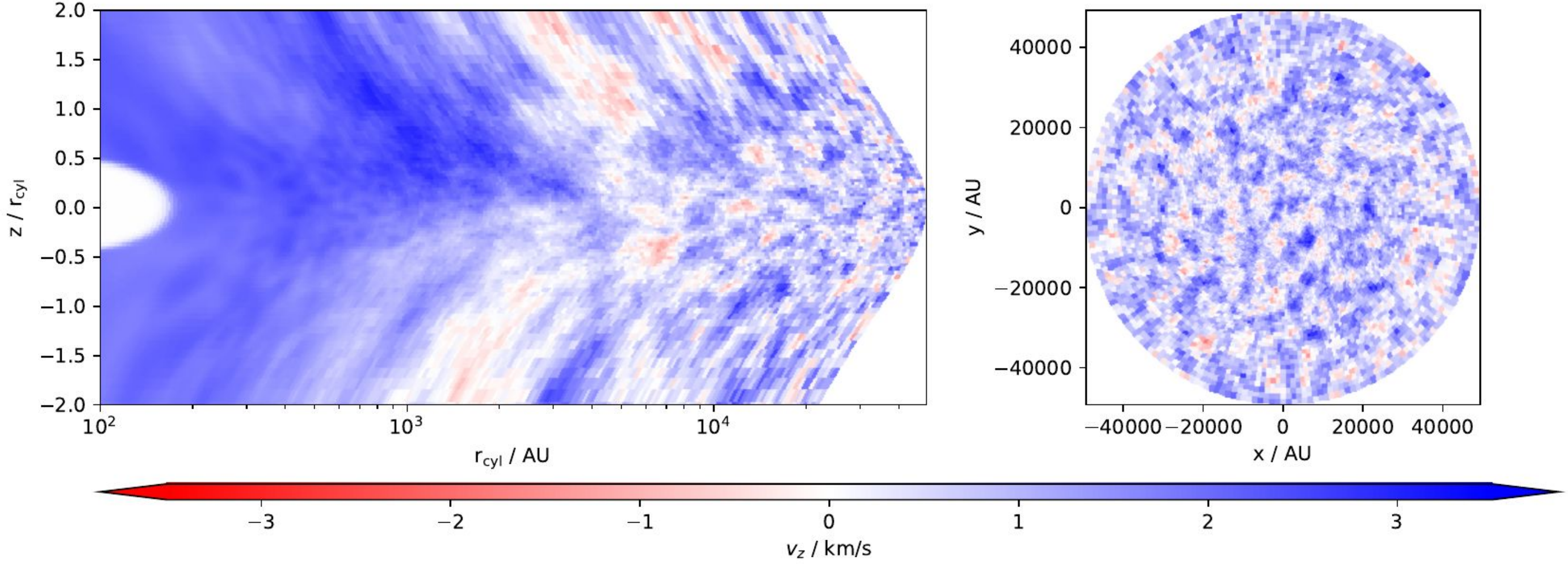
Cloudlet capture

Key difference: **Cloudlet expands**



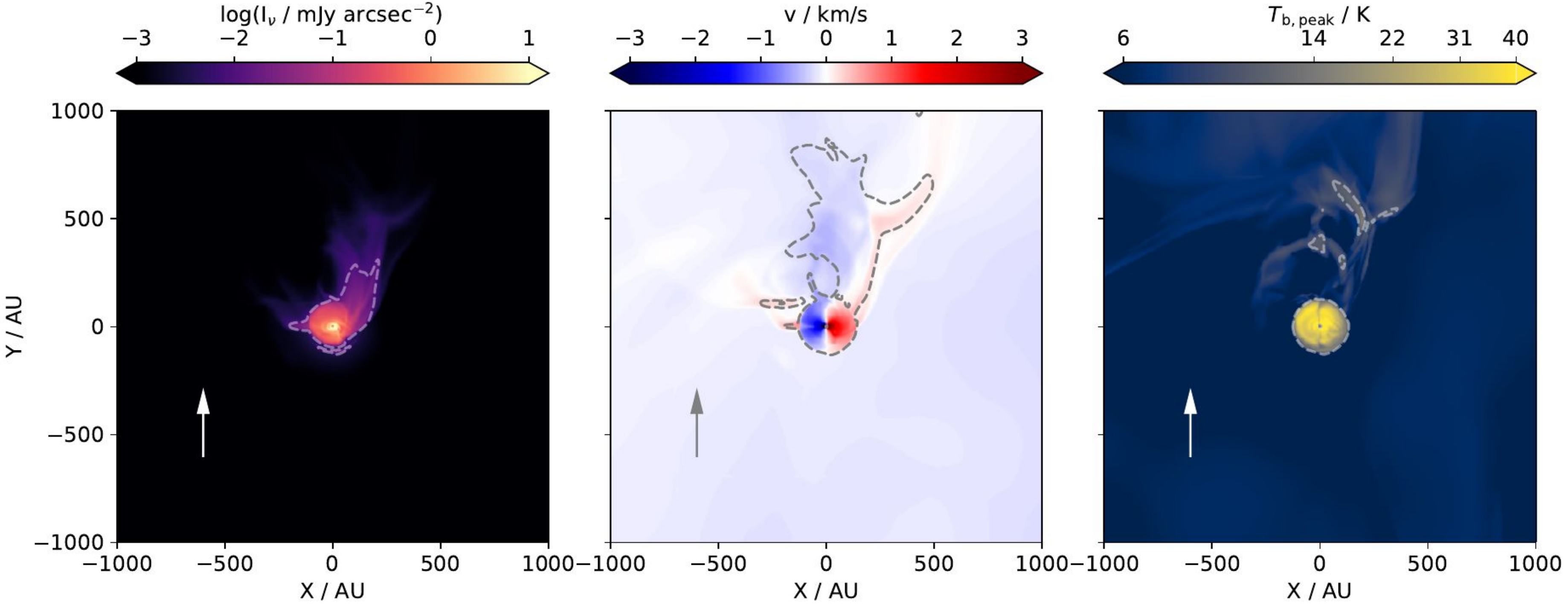
Clear streamer in scattered light & CO, but short-lived (~10kyr)

Bondi-Hoyle accretion: Initial condition



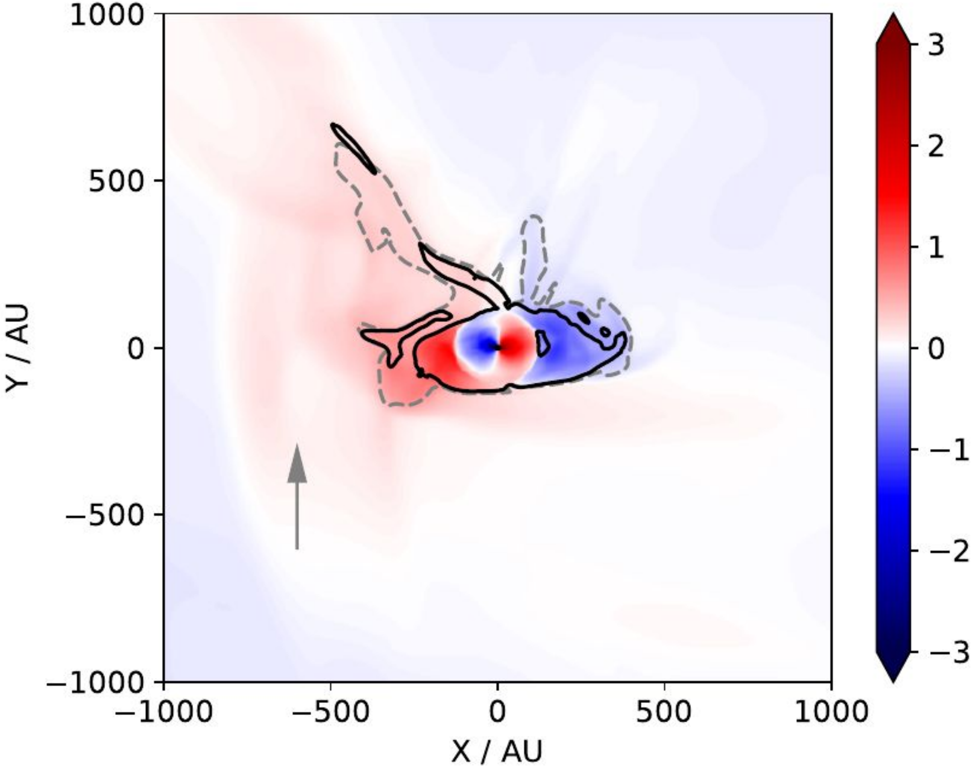
Compressible turbulence (Gaussian random field) with given power spectrum

Bondi-Hoyle accretion: Strong turbulence, small scales



Weaker streamers, but frequent and natural creation

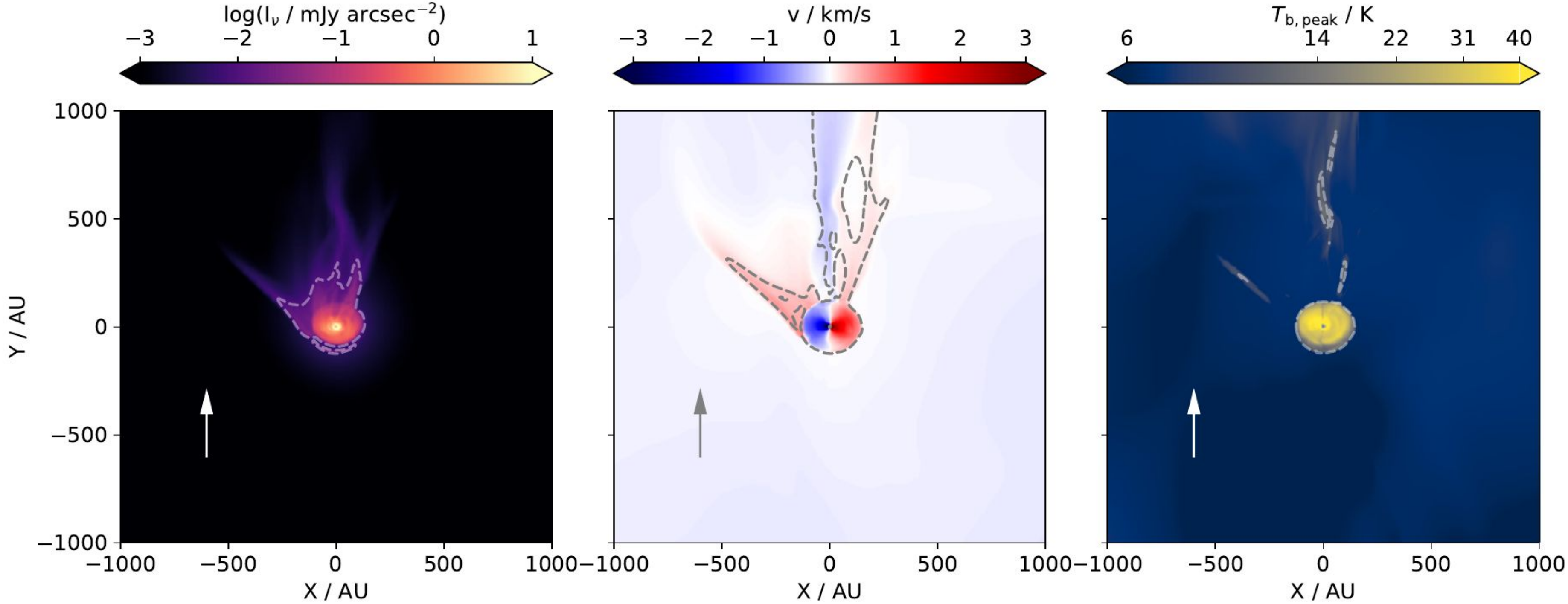
Bondi-Hoyle accretion: Strong turbulence, large scales



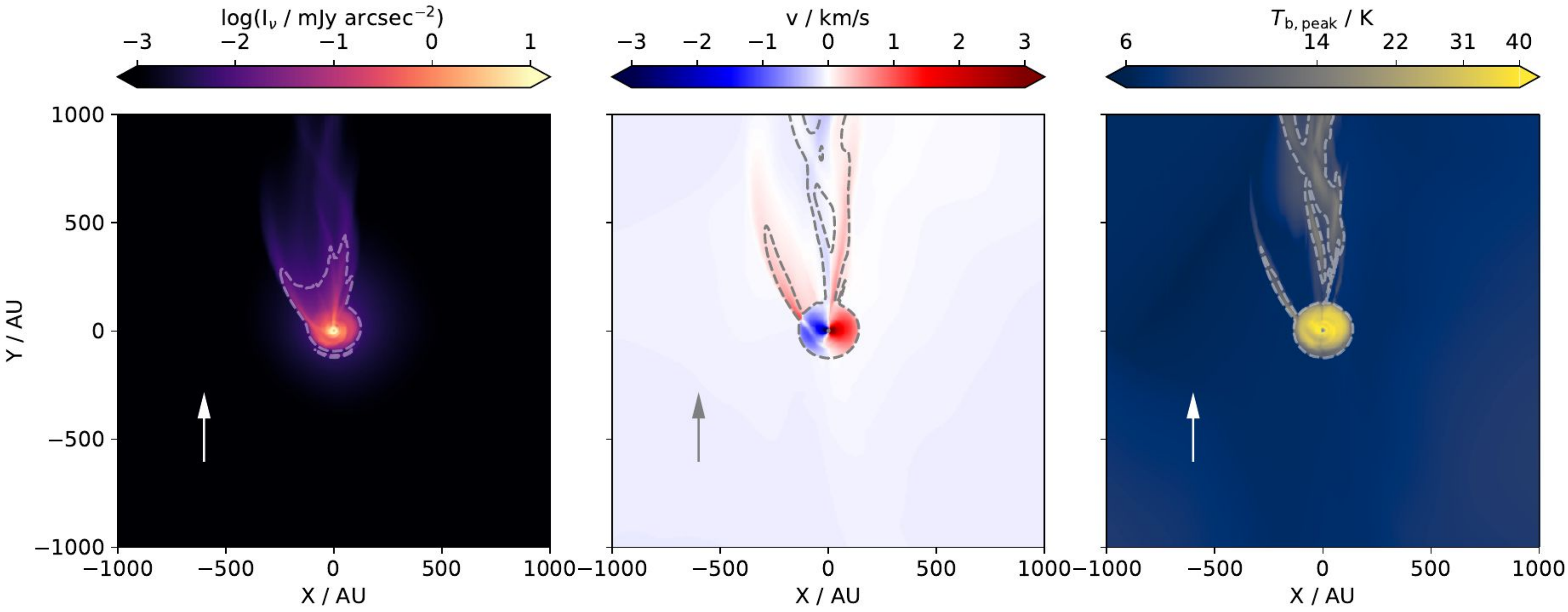
Morphology and multiplicity of the streamers depend on environmental conditions:

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

Bondi-Hoyle accretion: Medium turbulence



Bondi-Hoyle accretion: Low turbulence



Nature of streamers: Take-home messages

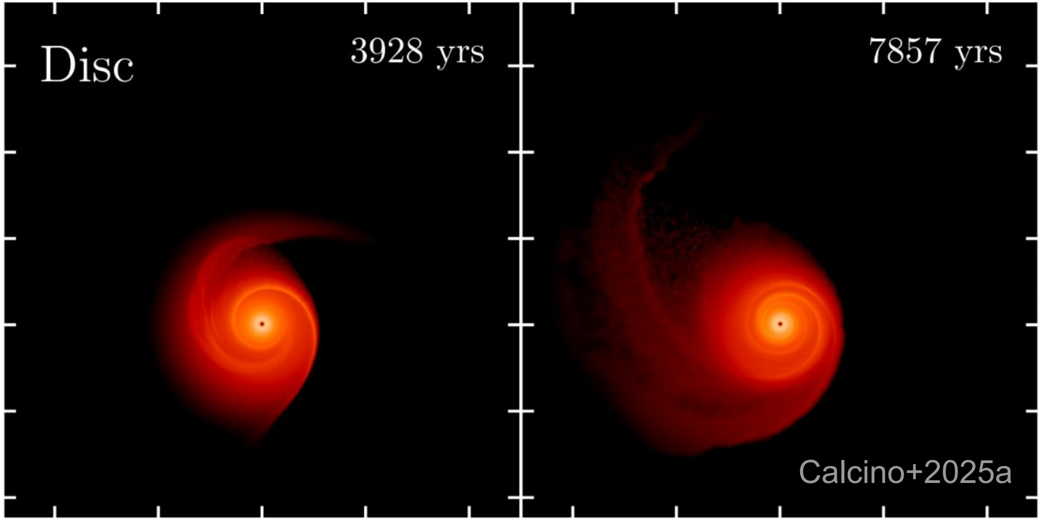
1. **Streamers arise naturally through Bondi-Hoyle accretion**
2. **The apparent infall direction can be unrelated to mass reservoirs**
3. **Their morphology can be used to infer environmental conditions**

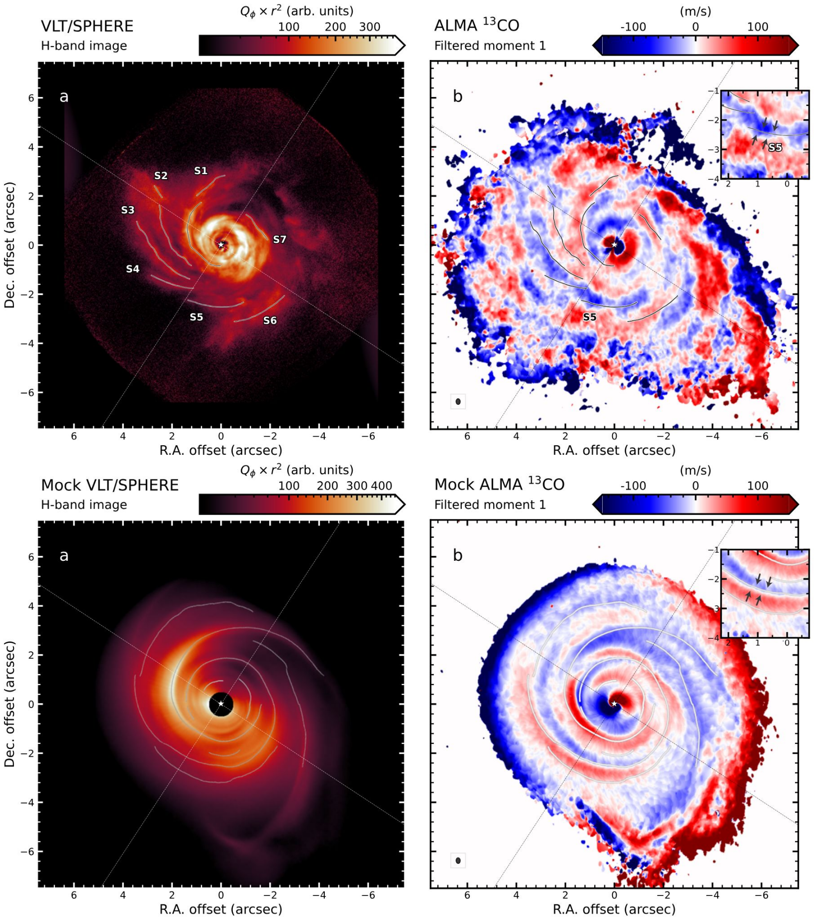
Formation of spirals via late infall

L.-A. Hühn, C. N. Kimmig, C. P. Dullemond

Are the disk substructures caused by infall?

Calcino+2025b

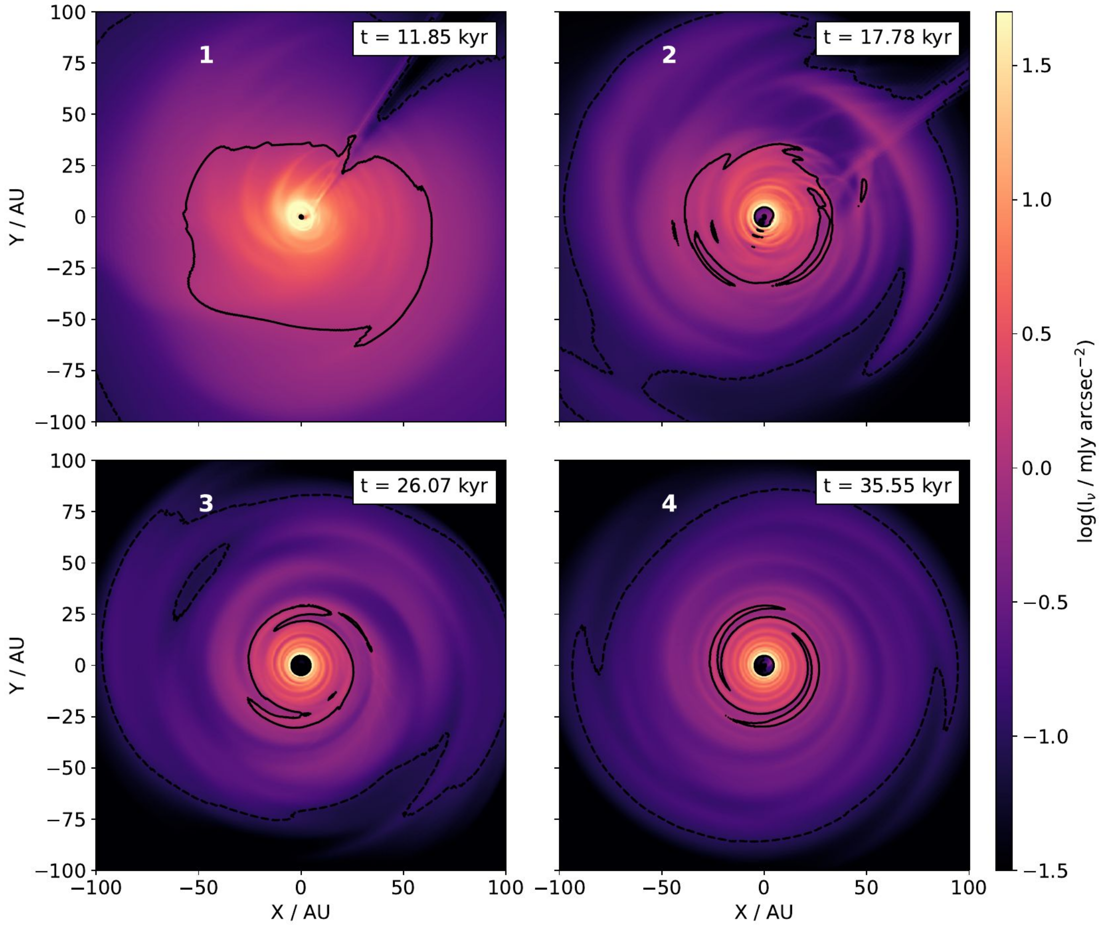




Cloudlet capture* SPH simulations find spiral patterns, structure similar to AB Aur

* modeled as free-falling ellipses

In-plane cloudlet capture



Different spiral structures in one simulation:

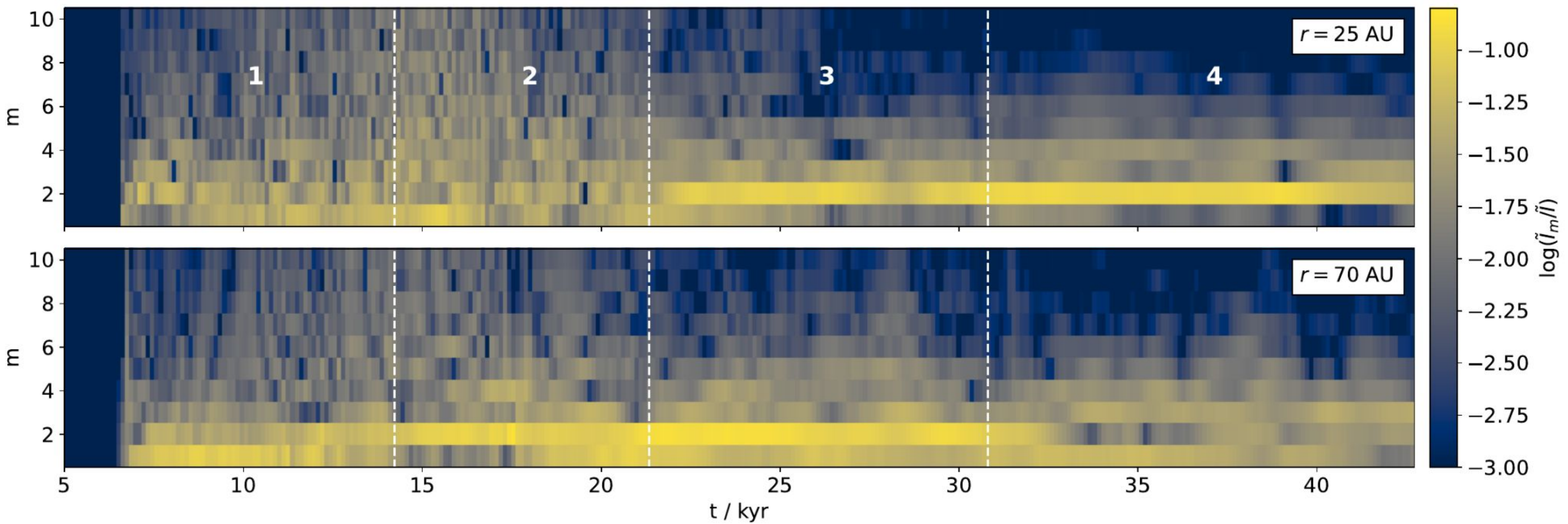
1: Flocculent shape in inner disk, smooth outer disk

2: m=2 pattern in outer disk

3: m=2 pattern in inner disk

4: Pattern in outer disk vanishes

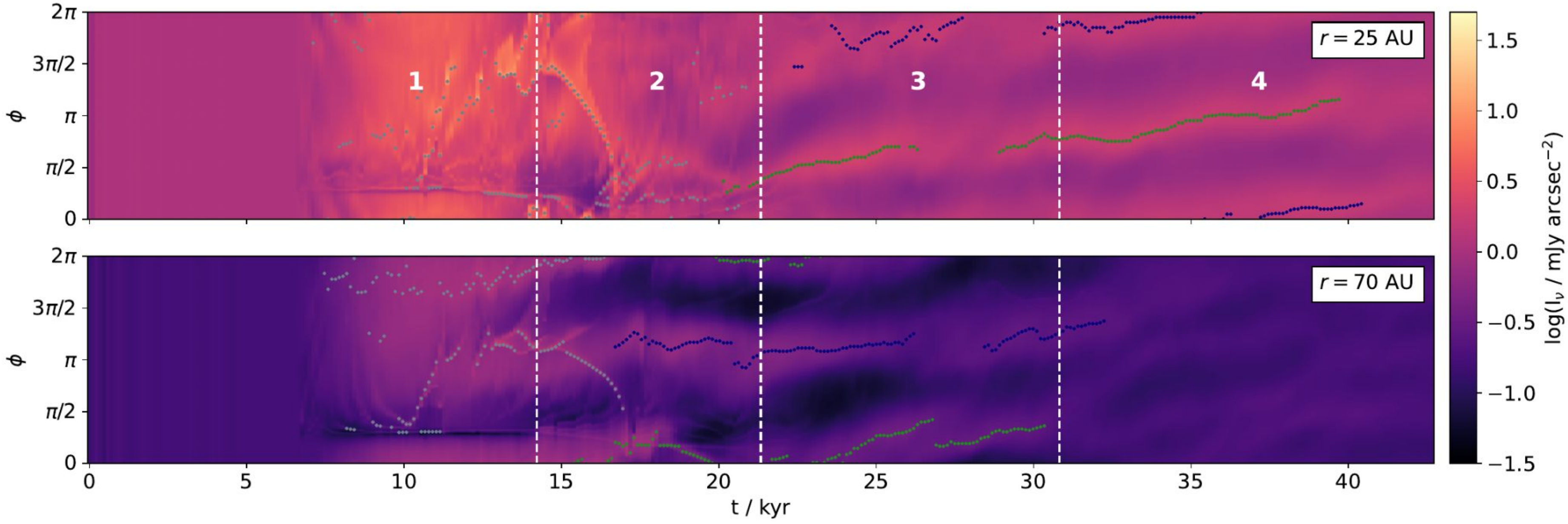
Angular spectrum



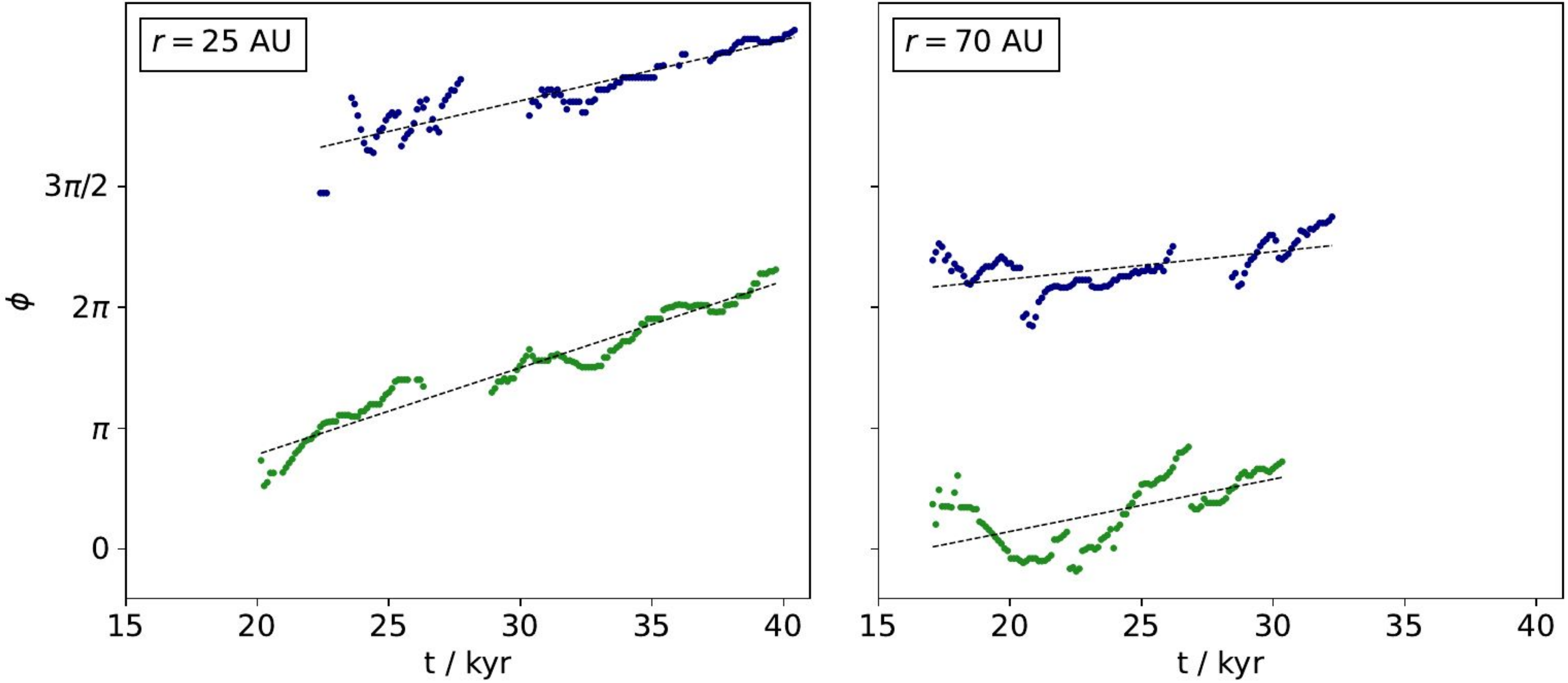
Angular spectrum matches visual classification

During period 1, m=1 “mode” in the outer disk is actually **a streamer**!

Pattern speed of the m=2 spirals



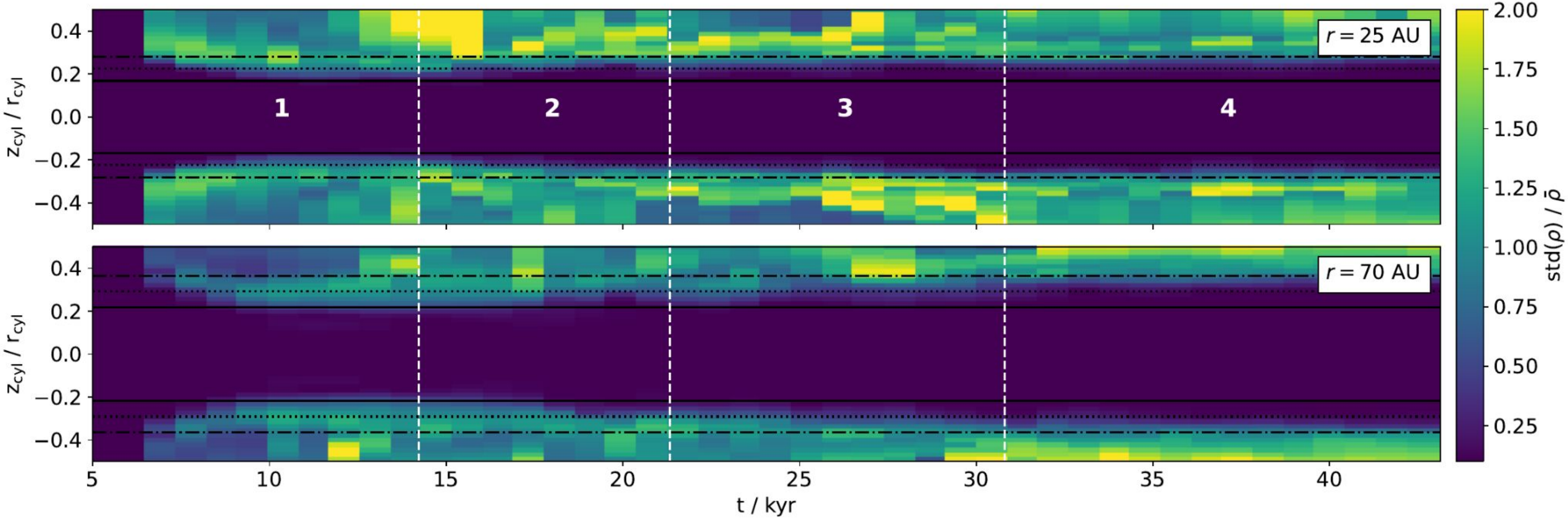
Pattern speed of the m=2 spirals



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

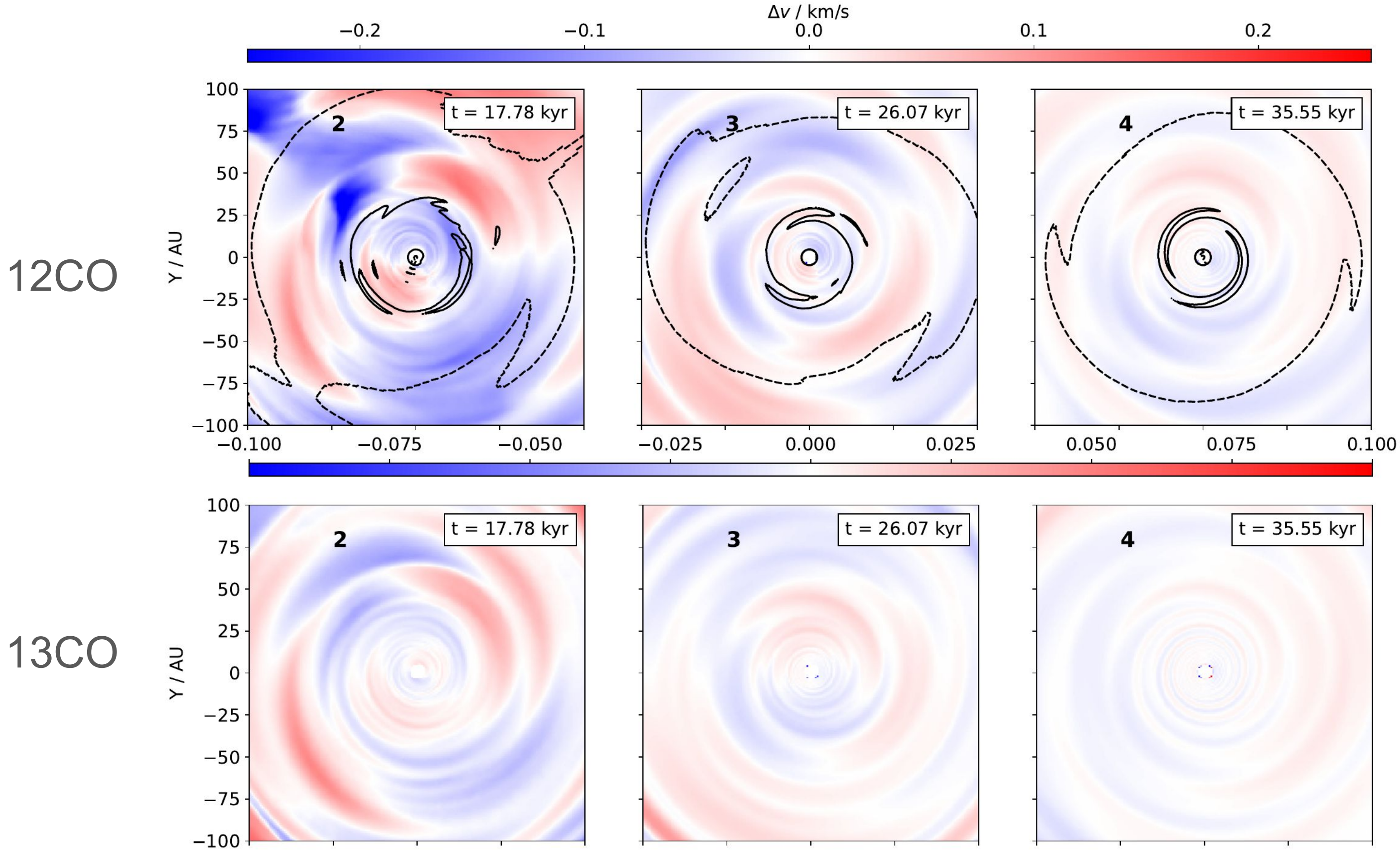
What layers of the disk are affected?

$M_d = 0.05\ M_\odot$

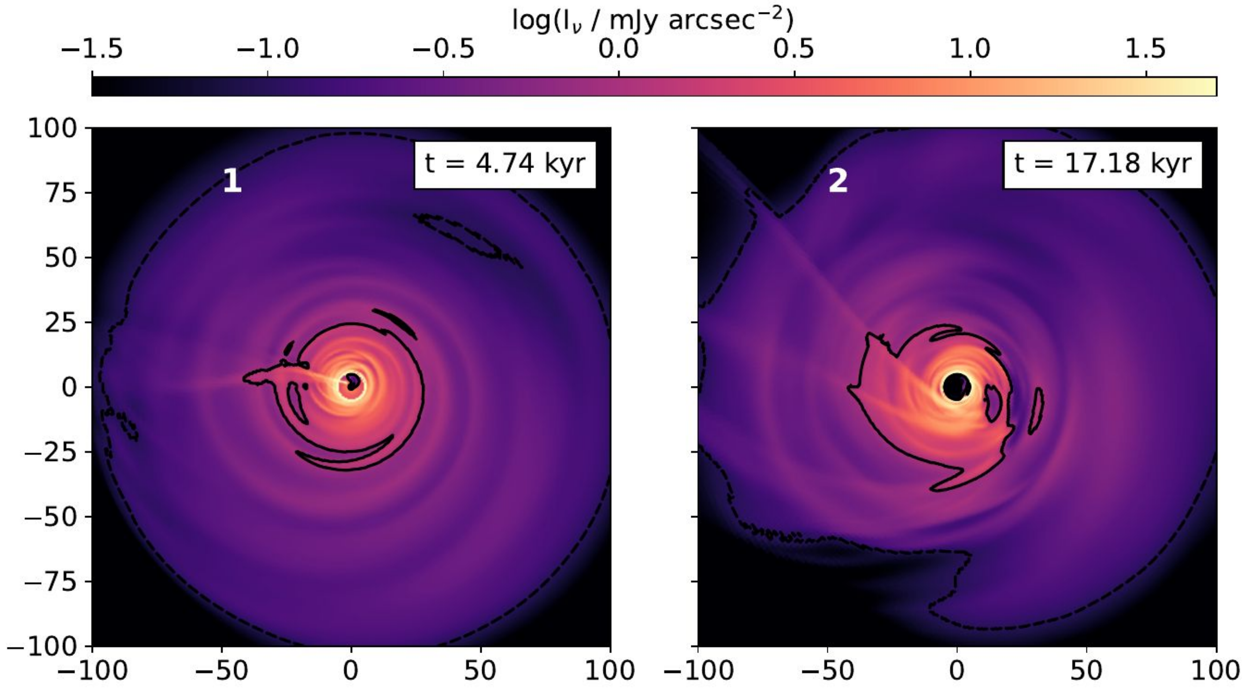


Even at the main impact, layers with z < 3H are unaffected
-> Spirals are only **on the surface** during early Class II

Disk kinematics: CO isotopologue residuals



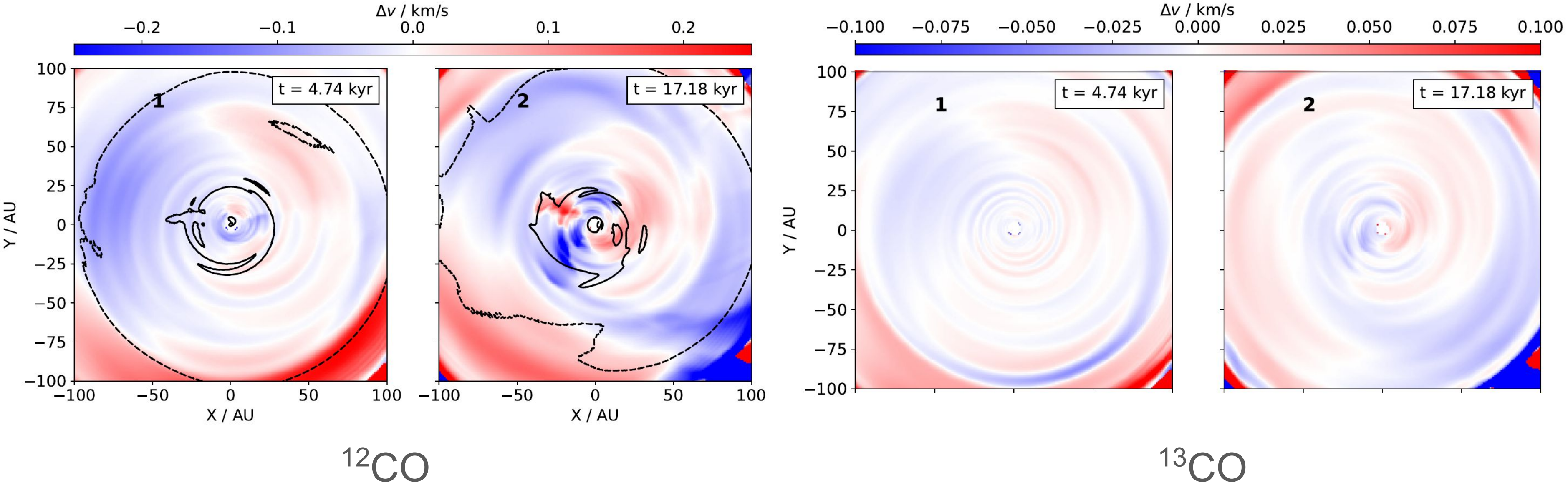
Bondi-Hoyle-Lyttleton accretion



1: m=2 spiral in inner and outer disk

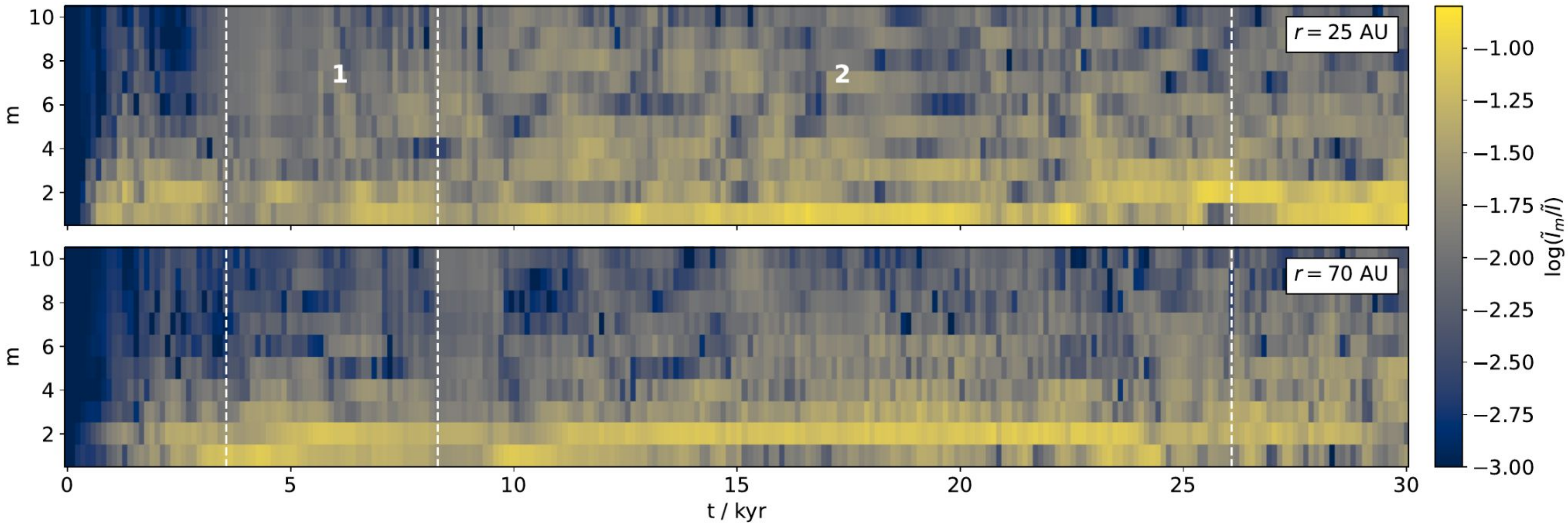
2: Spirals are flocculent in inner disk, low-armed in outer disk

Bondi-Hoyle-Lyttleton accretion: CO isotopologues



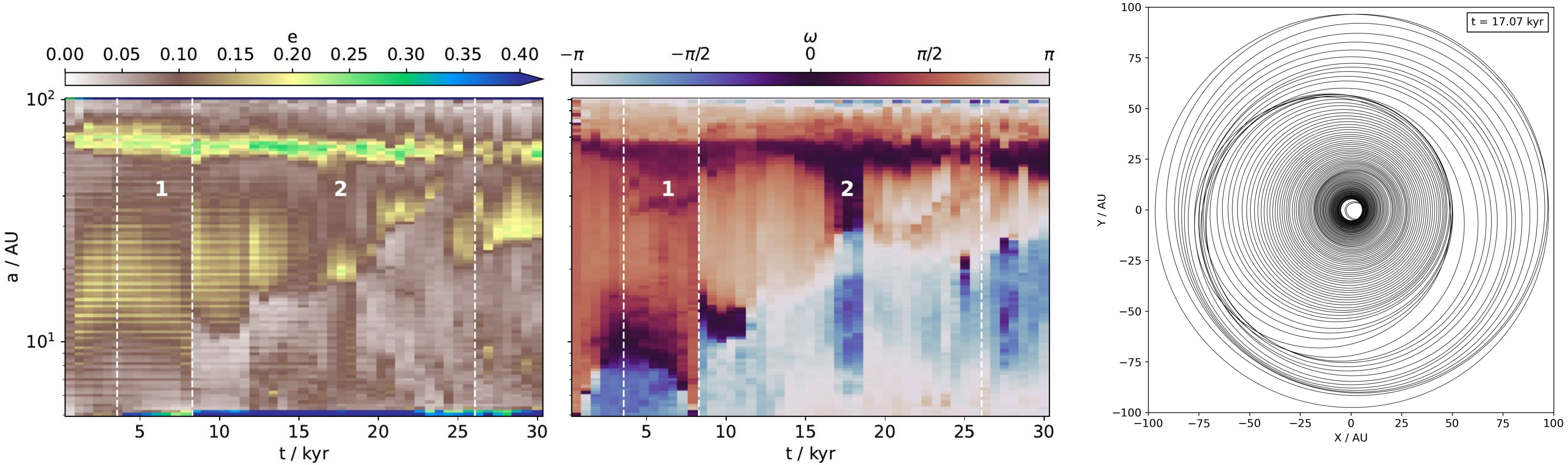
Spiral patterns **differ** considerably between **scattered light, ^{12}CO and ^{13}CO**

Fourier analysis: Angular spectrum



Angular spectrum does not match expectation: Streamer contamination?

Is the m=1 mode related to disk eccentricity?



Orbital structure of disk surface should result in m=1 mode, but it is **invisible**
⇒ m=1 mode in scattered light is just **streamer contamination**
⇒ Scattered light spirals are unrelated to disk kinematics

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 affecting the disk