Infall as a Source of Substructures in Protoplanetary Discs

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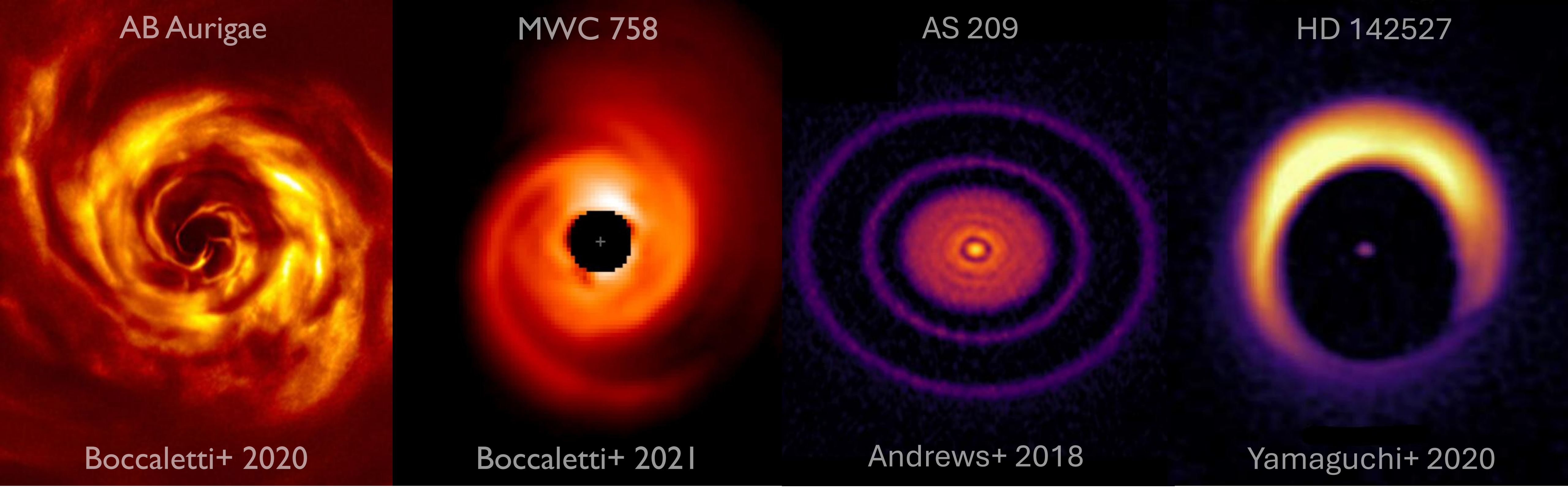


Spiral Arms, Rings, Gaps, and Cavities

Can be generated by:

- Planetary/Stellar Companions
- Instabilities, icelines
- Gravitational Instability

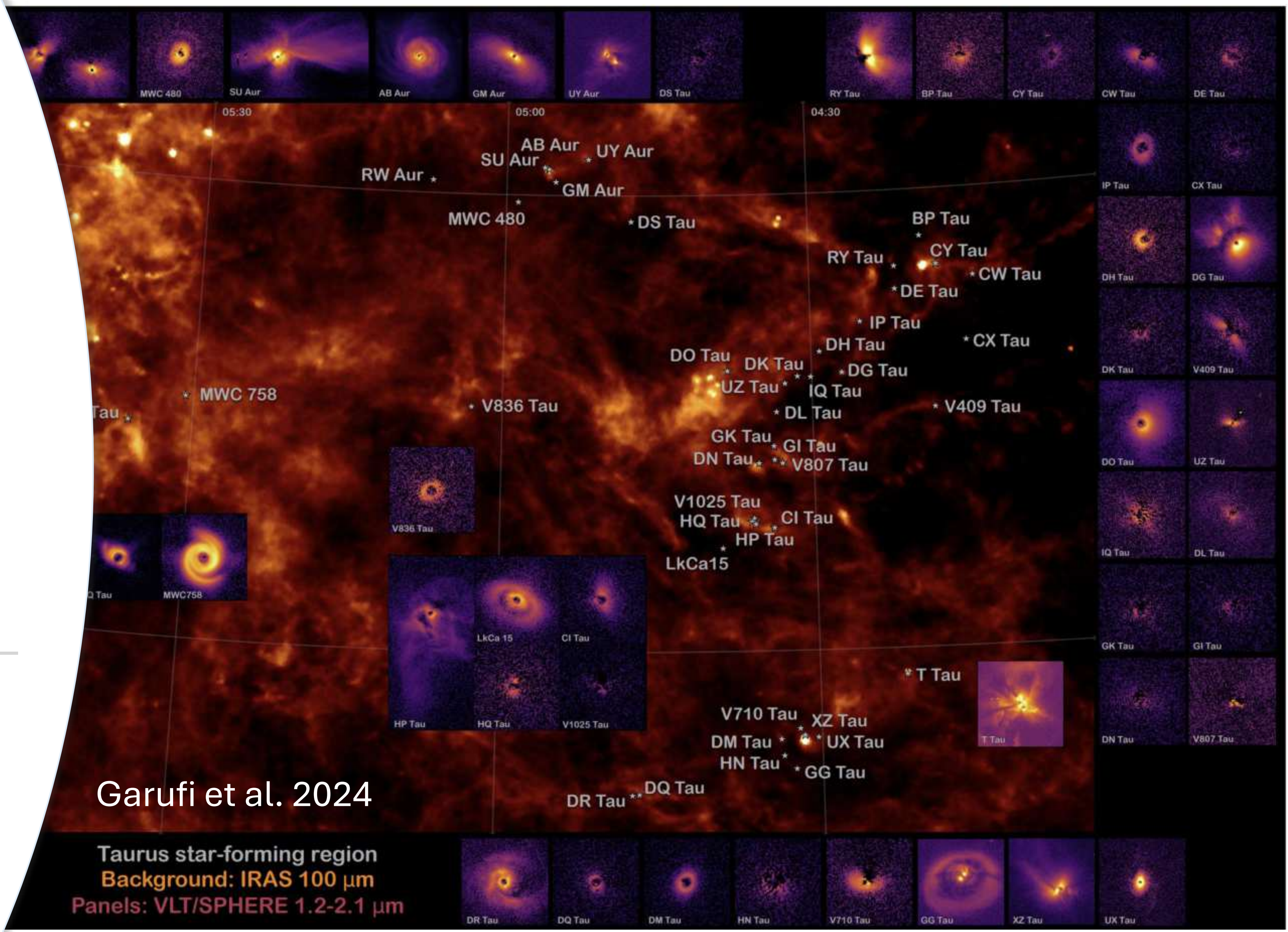
My work: Infalling material

Very few disc substructures have been directly linked with confirmed companions or phenomena

Protoplanetary Discs Are not Isolated Systems

30% of discs sampled in Taurus show some ambient signal in scattered light.

May be relevant for many of the well studied discs in the literature!



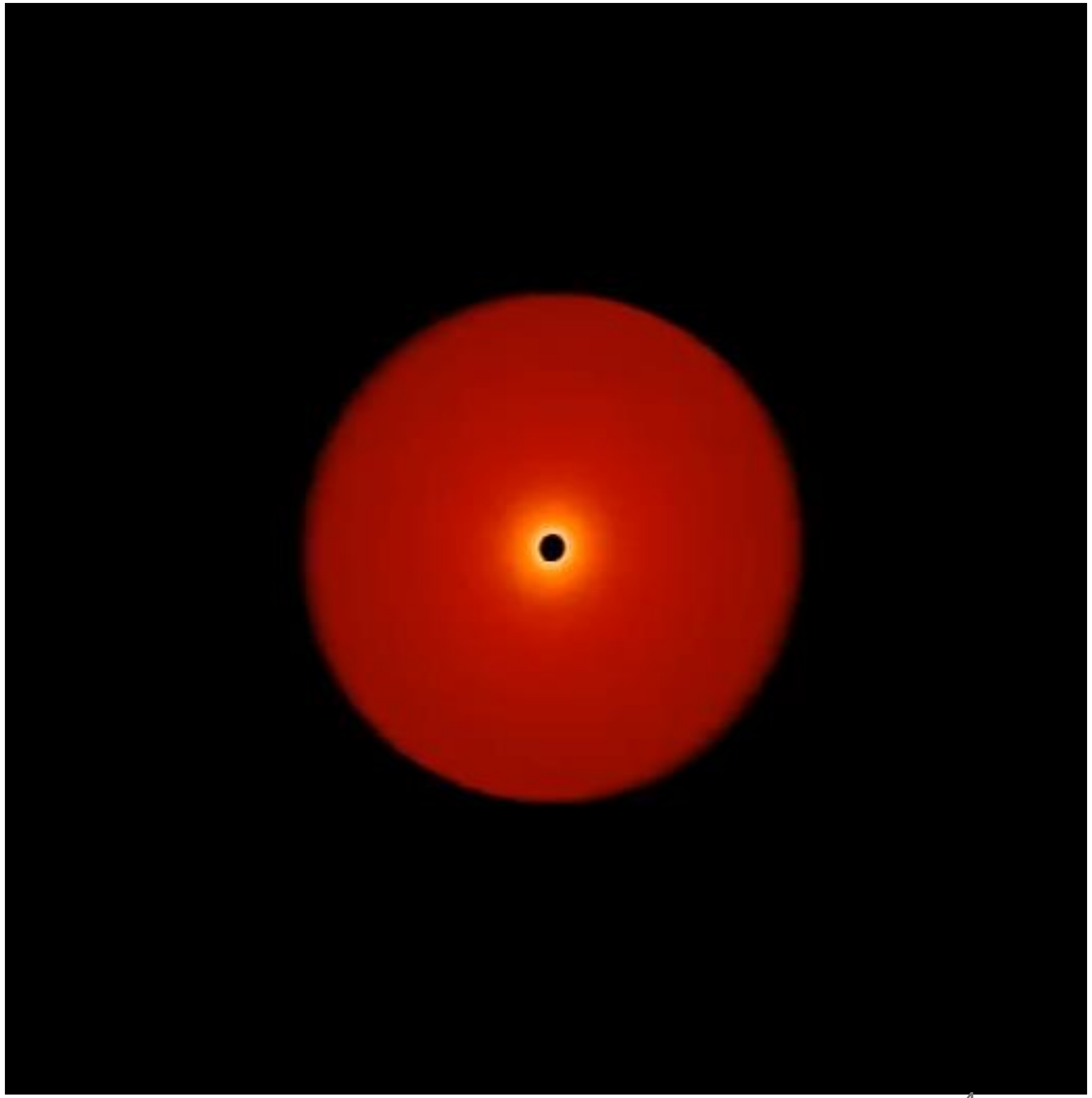
Garufi et al. 2024

Calcino et al. 2025, also in prep

Anatomy of a Fall

Main research goal is to understand what infall does to a disc.

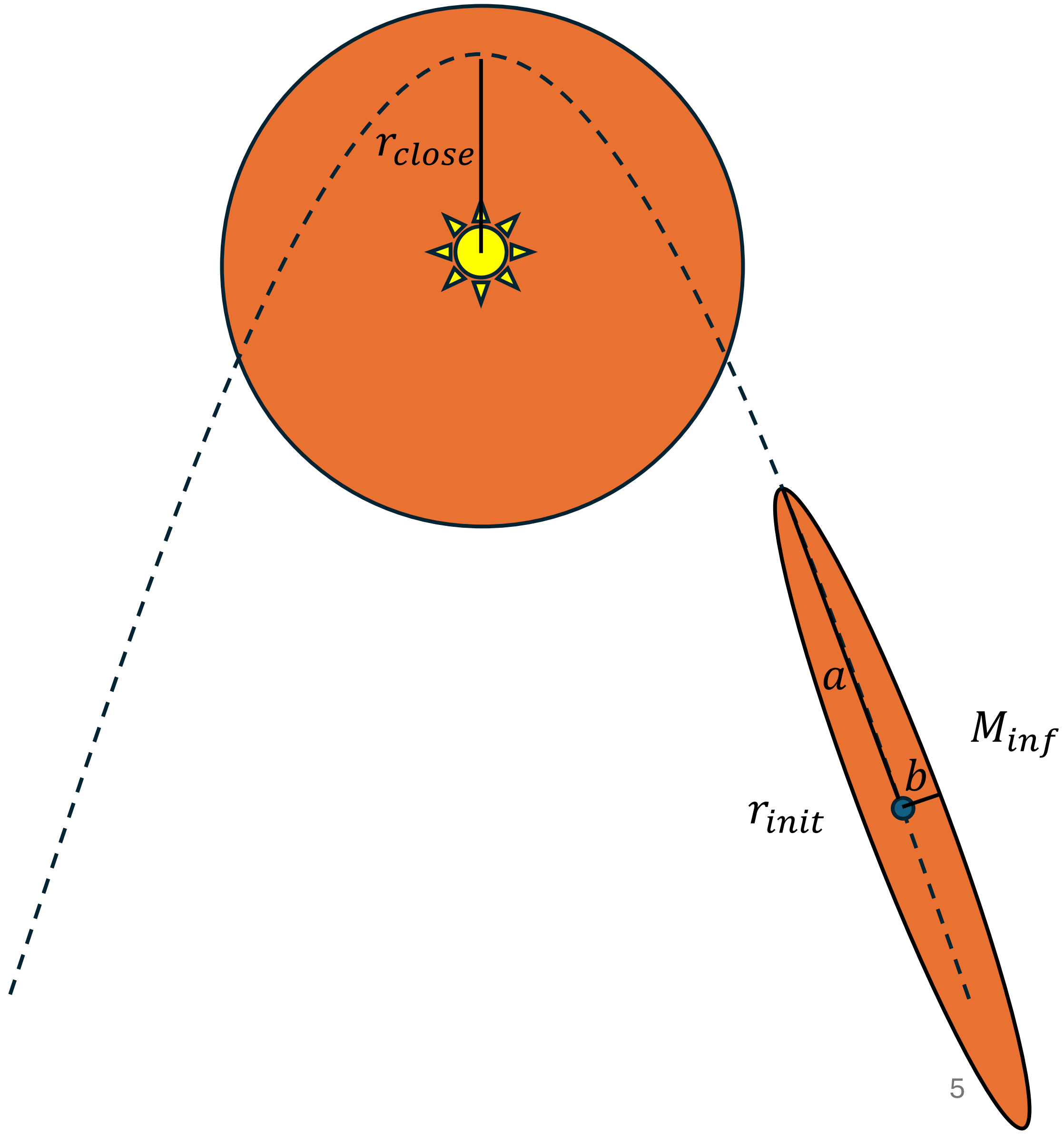
- How does infall impact the size? Final mass, size, eccentricity profile, Mdot, etc.
- How do the parameters of the infall affect the final parameters of the disc?
- What substructures can we generate?
- How do the spirals evolve?
- What does this look like in observations?
- How long do the observational signals last for?



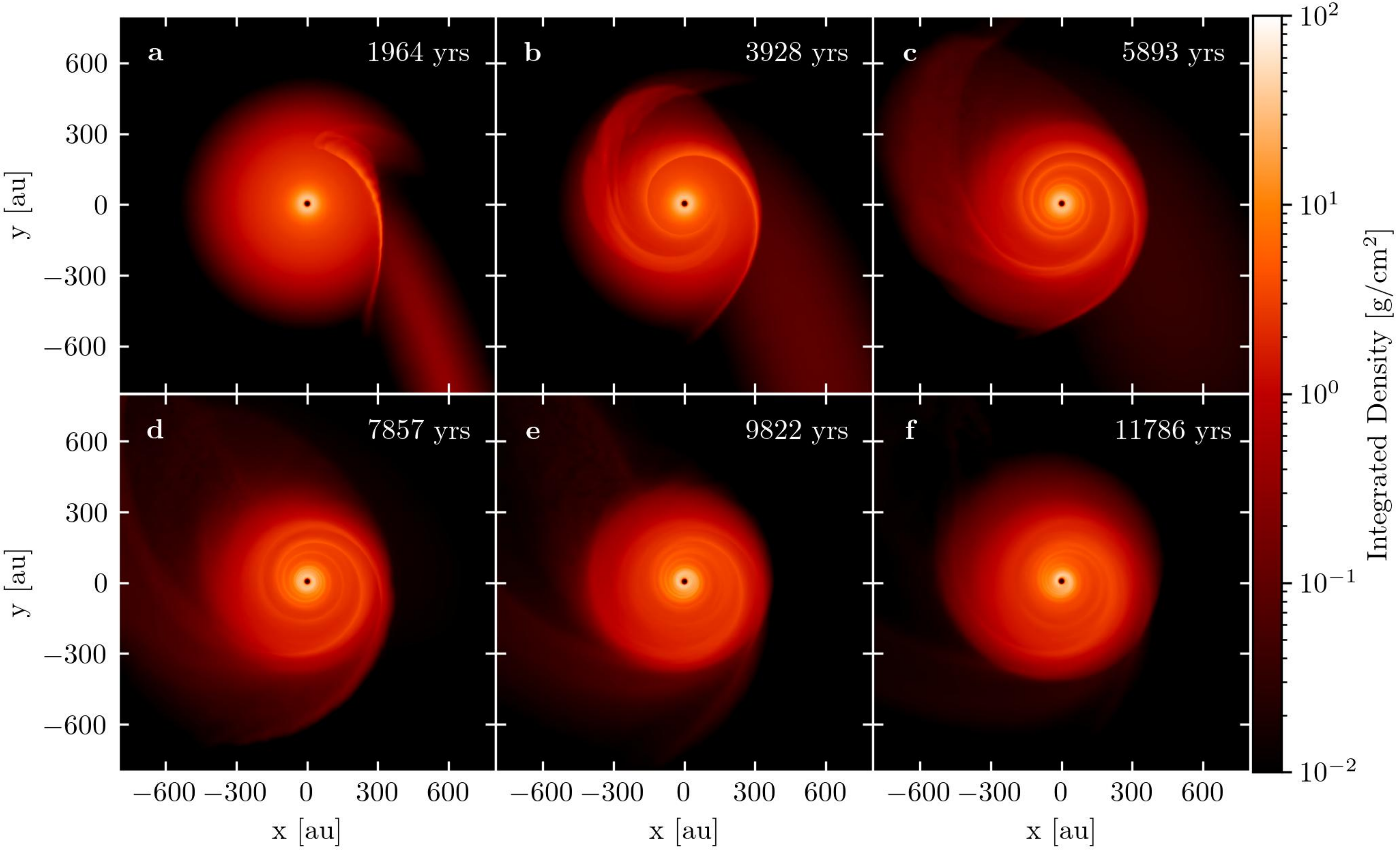
Assumptions

Simplistic simulations

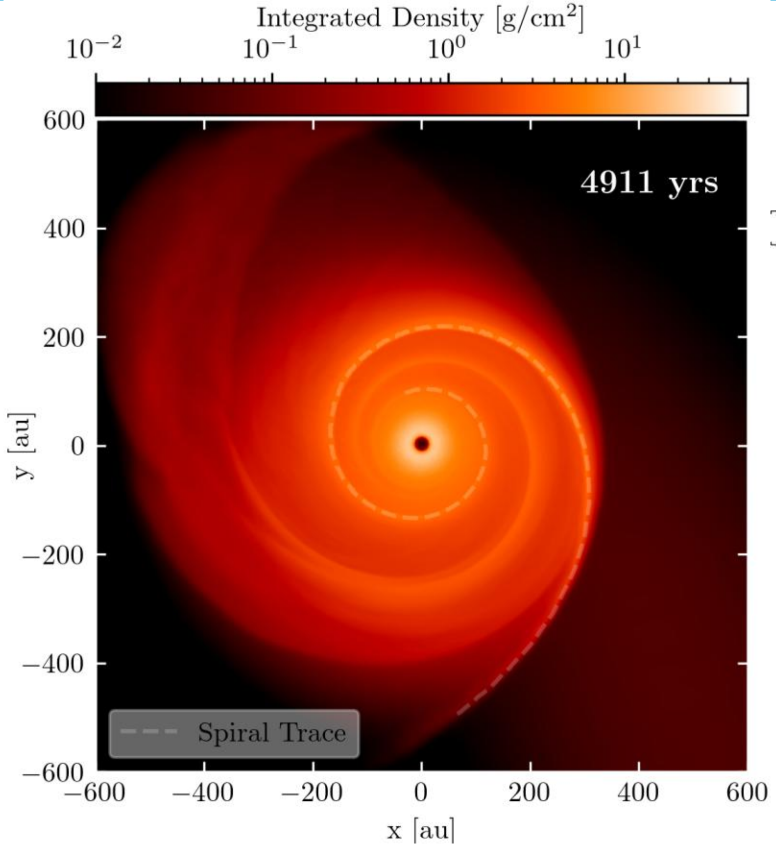
- Locally isothermal EOS
- Infall follows a parabolic orbit, with velocities set to the free-fall velocity at each particle's particular radial distance
- Infall is initialized as an ellipse with some assumed semi-major and semi-minor axis, a and b
- Infall is added to a disc which has relaxed, evolved for ~10 orbits at the outer radius (~500 au)
- $a = 1000$au, $b = 50$au, $M_{inf} = 10\% \; M_{disc}$
- $r_{close} = 100$au



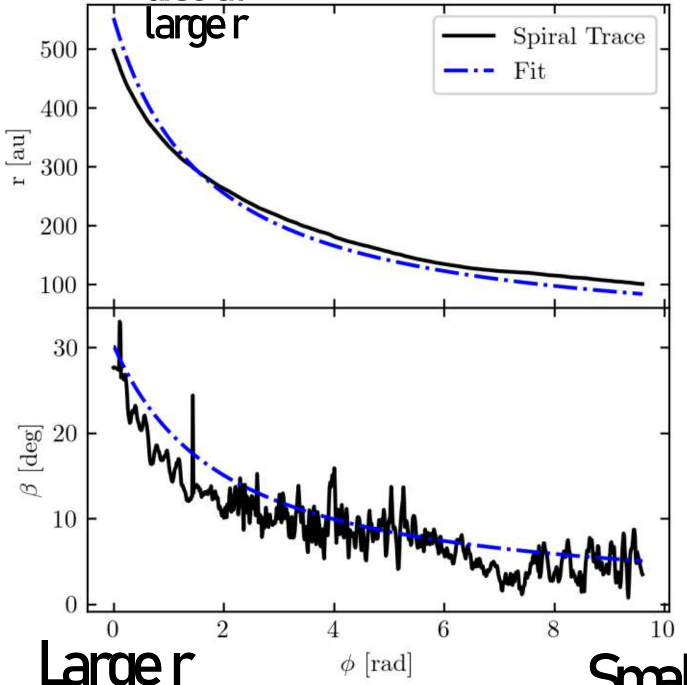
Time evolution



Infall induced spirals look like planet induced spirals

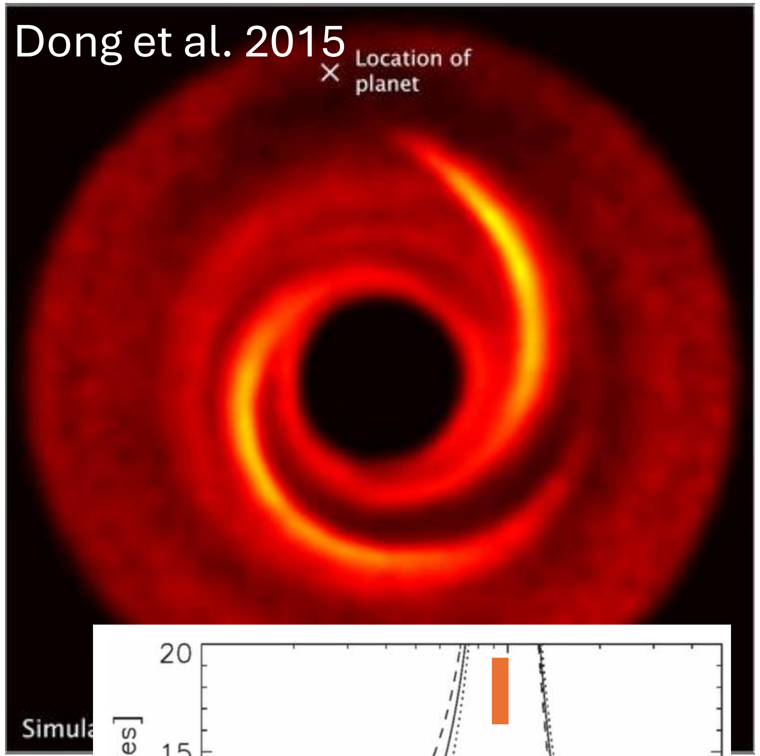


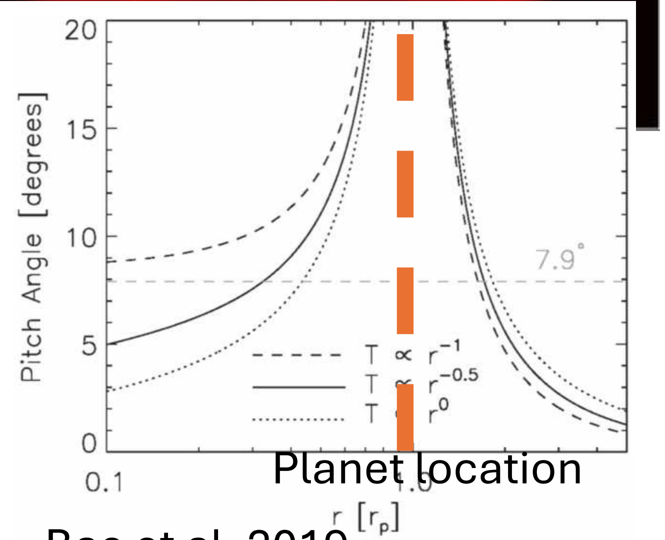
Infall hits disc at large r



Large r

Small r



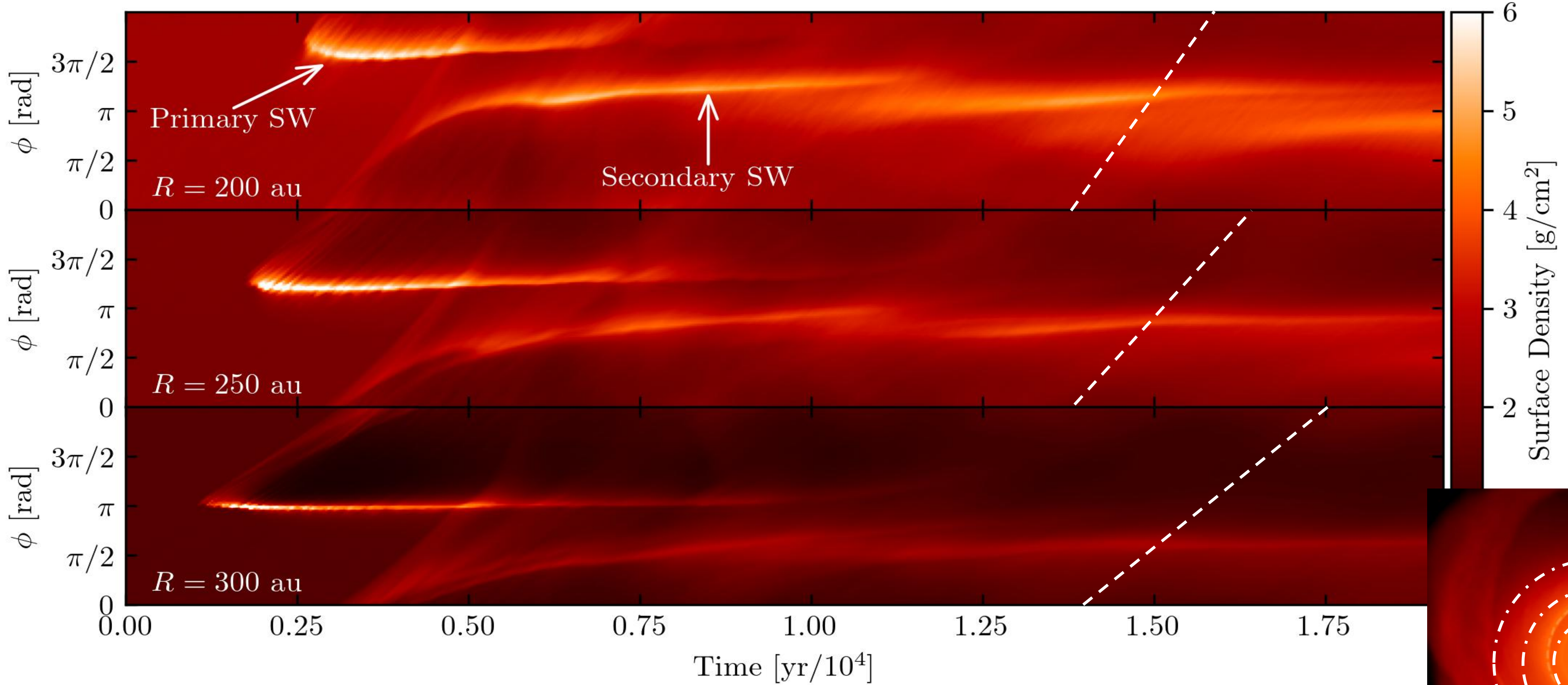


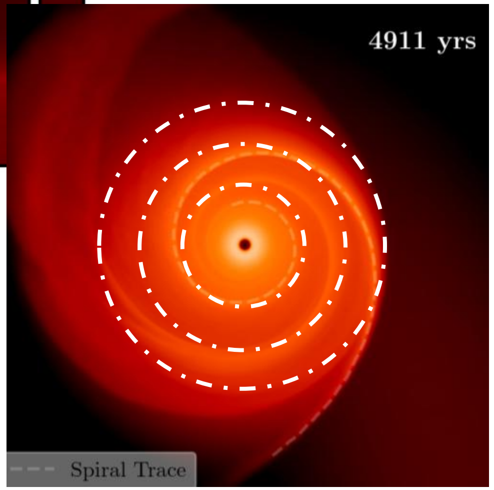
Bae et al. 2019

- Infall induced spirals look quite like those generated by massive planets
- Their pitch angle increases as a function of distance towards their launching point.
- Large beta: radial structure, low beta: more circular structure

$$\beta = \left| \frac{dr}{r\, d\phi} \right|$$

Stationary Spirals

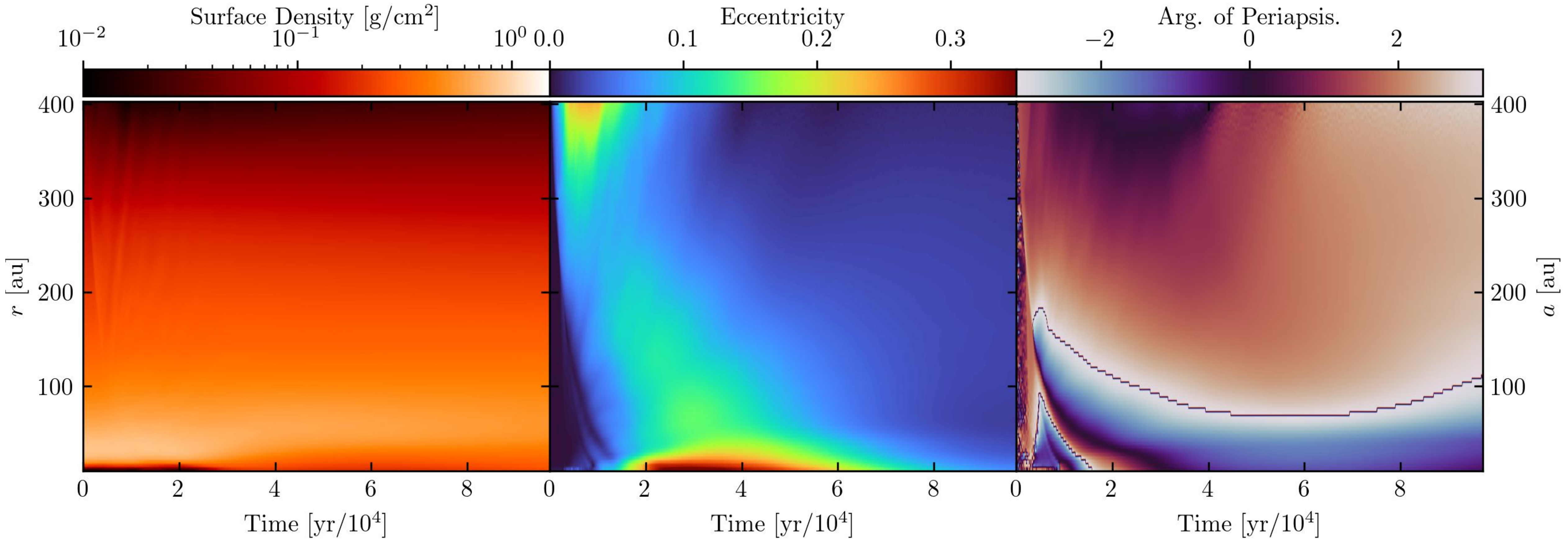




- Plot is a map of azimuthal density vs time for 3 different radial locations
- Multiple stationary spirals generated
- Evident for several 10^4 years

Measuring spiral rotation rate is possible and has been done in some discs (MWC 758, HD135344B, V1247 Ori) Ren et al. 2018, Xie et al. 2024, Ren et al. 2024

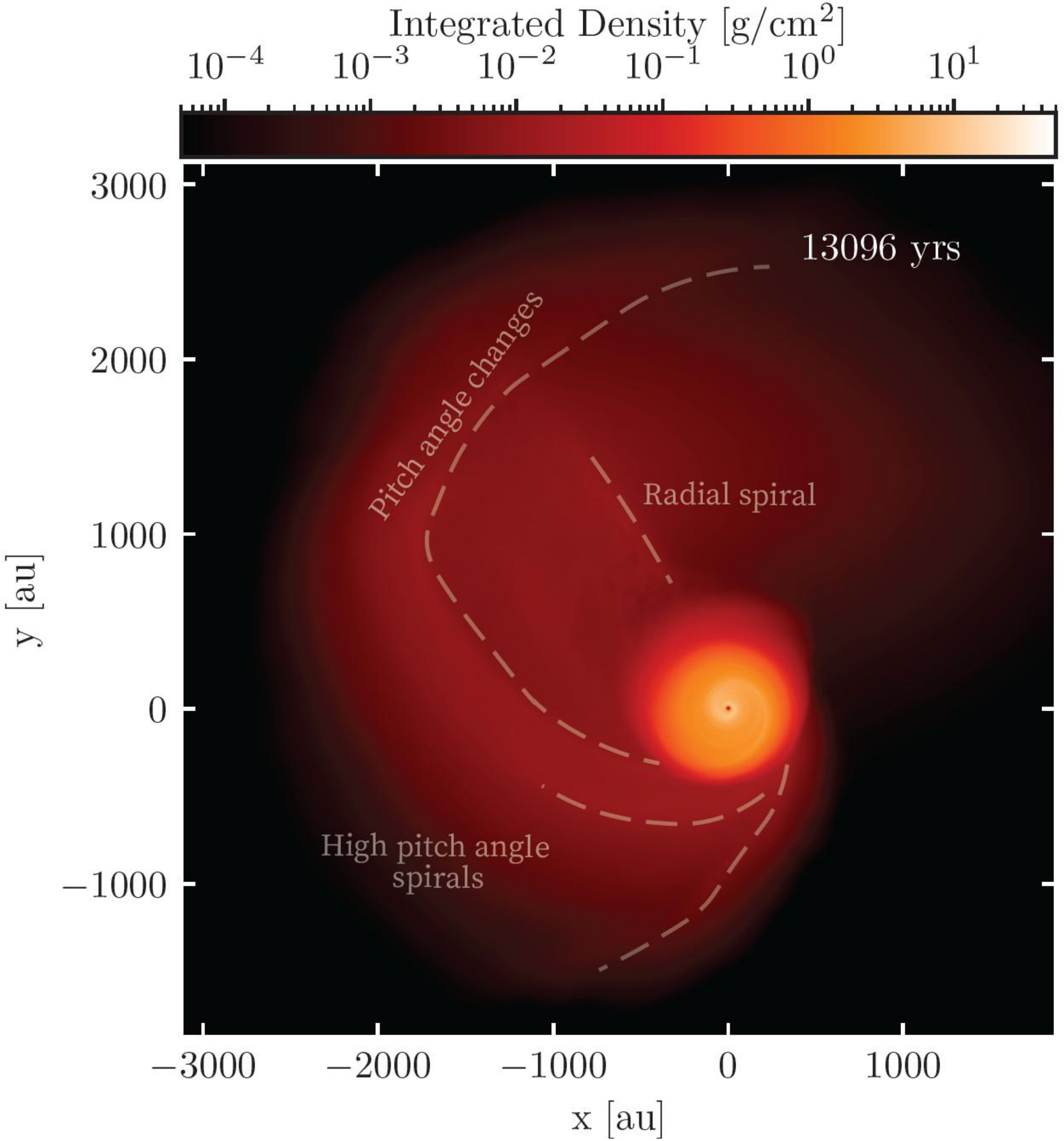
Disc Evolution

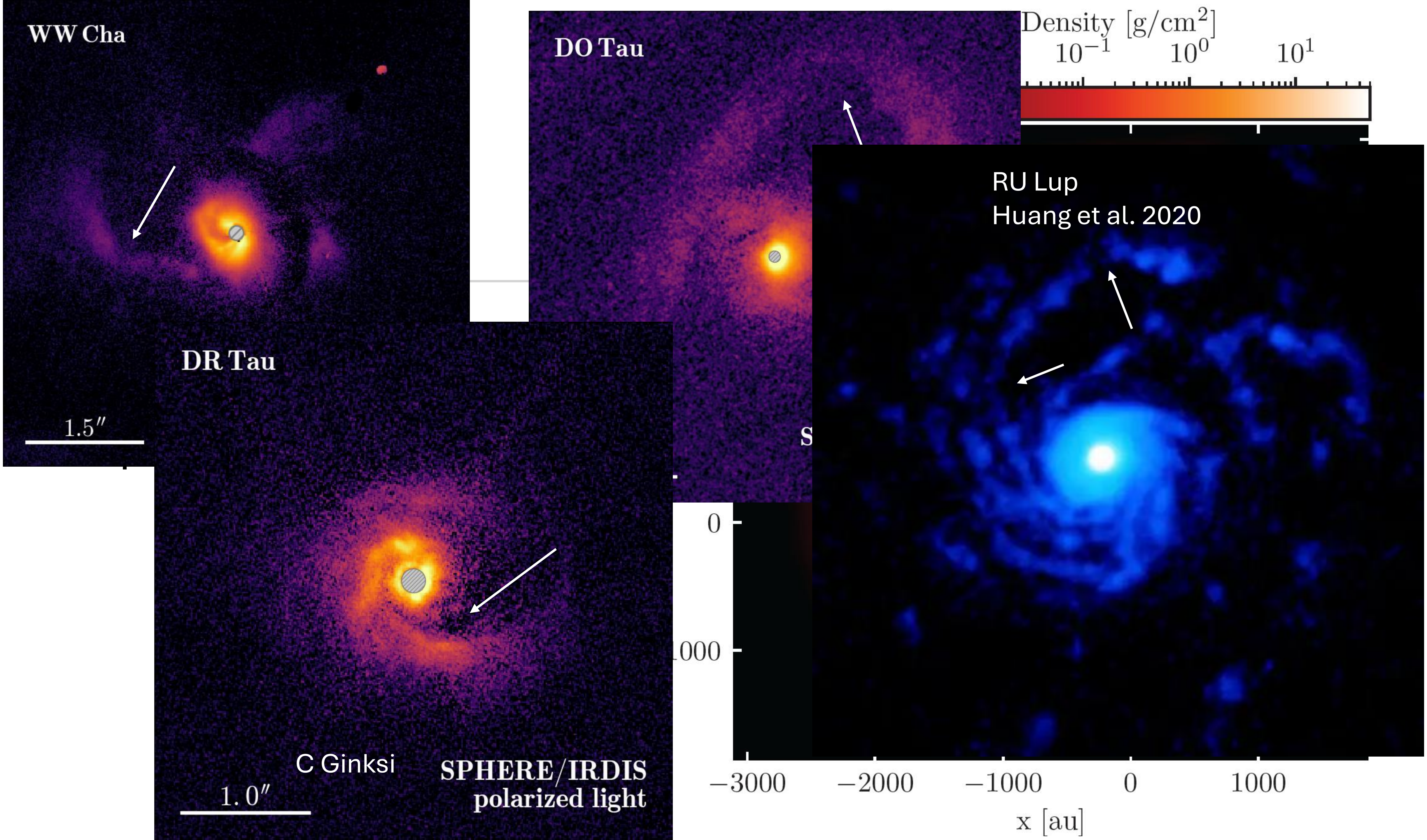


- Azimuthally averaged surface density, eccentricity, and arg. of periapsis
- Outer disc experiences eccentricity pumping, which migrates inwards
- Largest eccentricities seen close to the sink, perhaps due to the region close to the sink initially being depleted and then refilled with eccentricity material? Need to explore further.

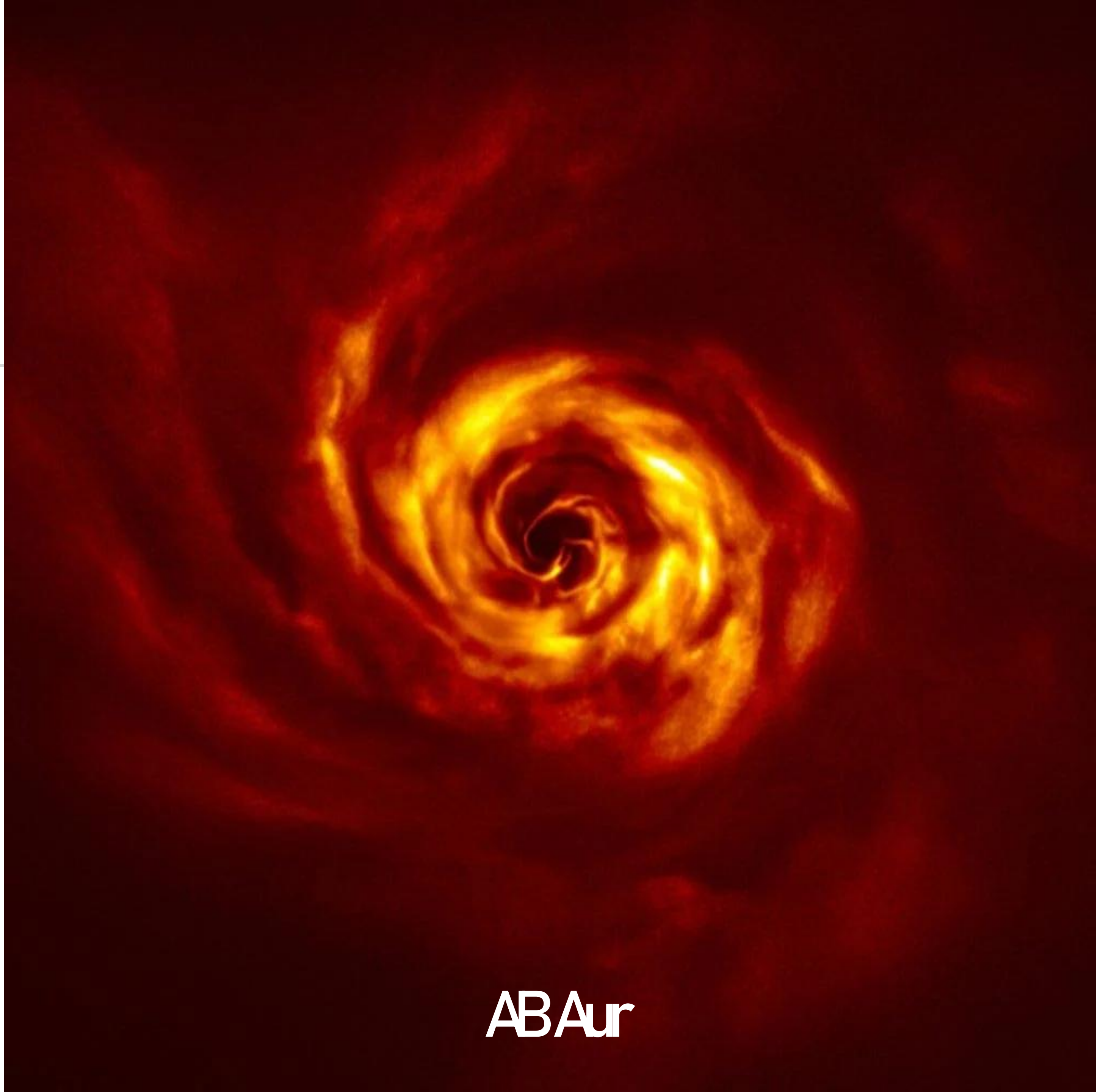
The Kilo-au environment

- Secondary infall occurs from the bound but highly eccentric ejecta
- Weird spiral pitch angles
- Not certain what causes it, but large pitch angle changes appear close to intersection of material with drastically different angular momentum




WW Cha
1.5″
DO Tau
DR Tau
C Ginksi
1. 0″
SPHERE/IRDIS
polarized light
Density [g/cm^2]
10^{-1}
10^{0}
10^{1}
RU Lup
Huang et al. 2020
0
−3000
−2000
−1000
0
1000
x [au]

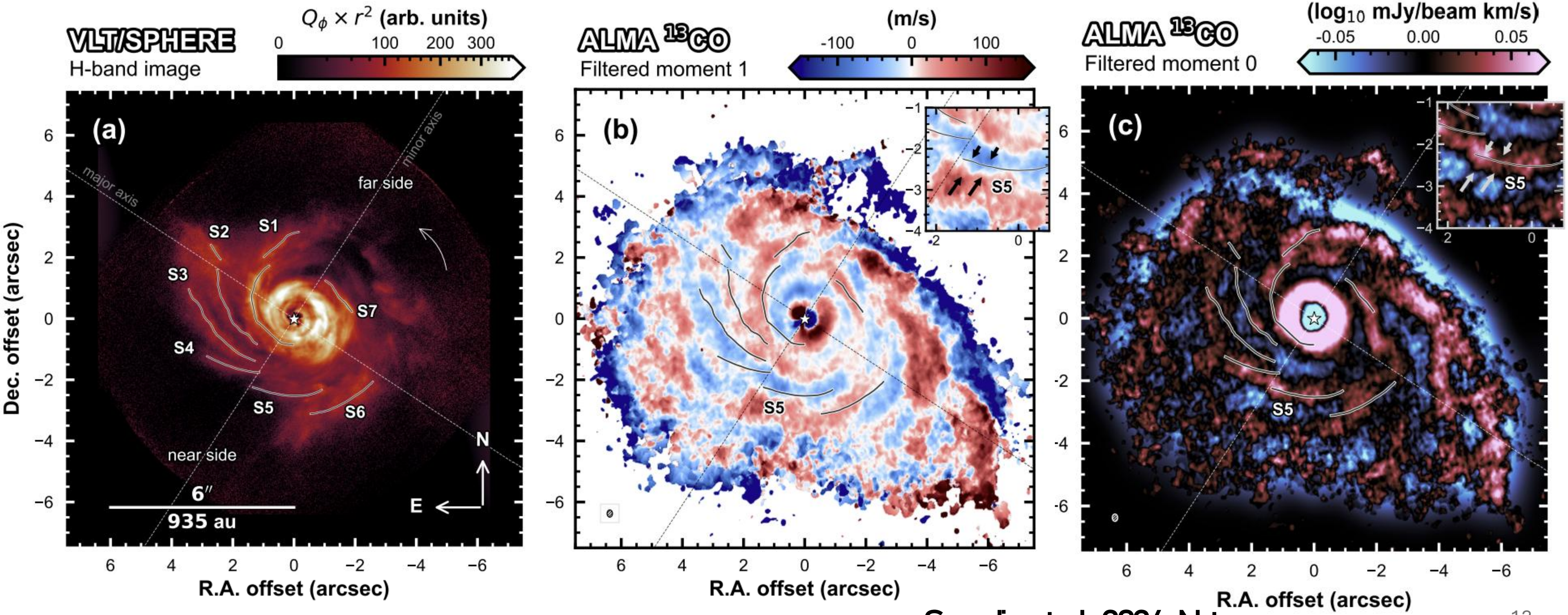
Comparison with AB Aur



AB Aur

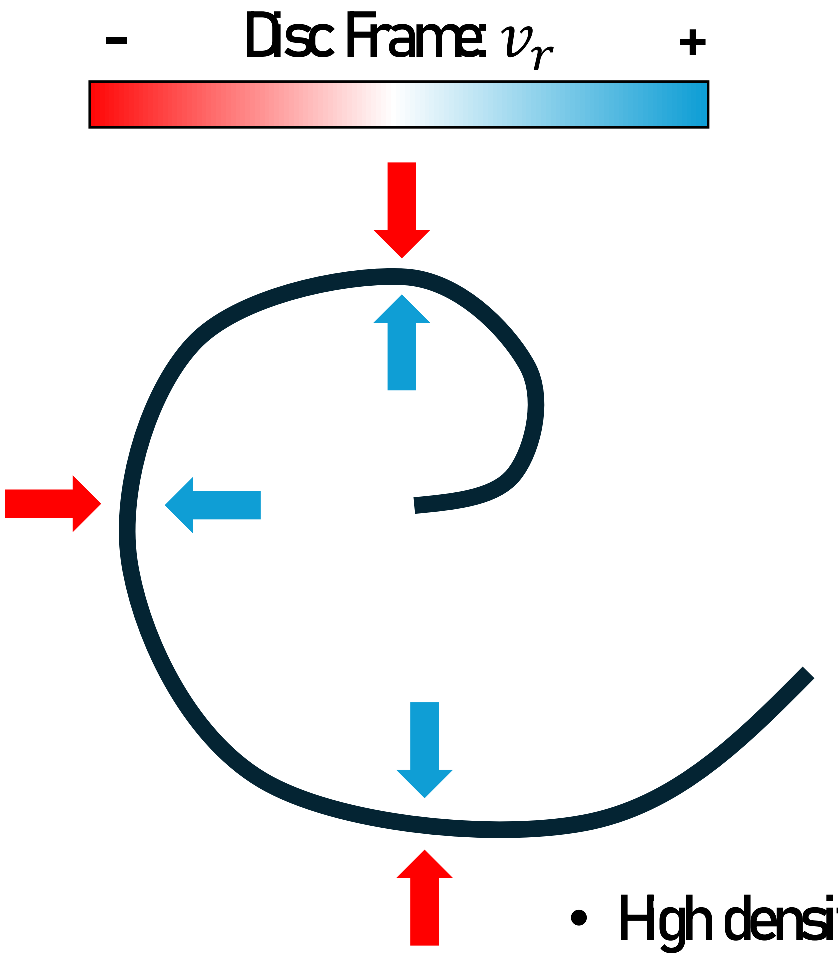
- Loads of spirals in scattered light and CO intensity
- Central cavity in 13CO
- Accretion rate ~10^7 Msun/yr

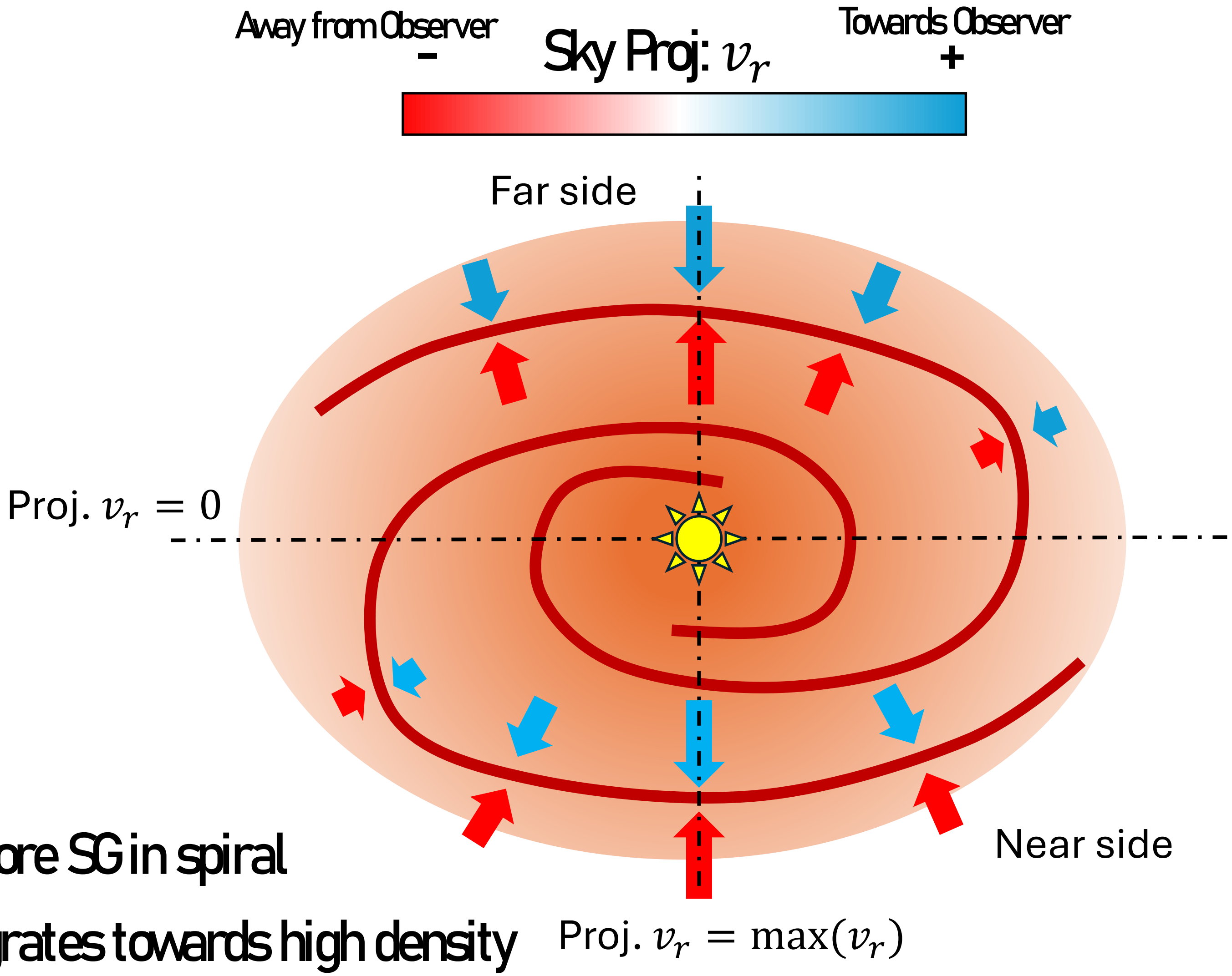
- Radially convergent motion towards the center of a spiral arm seen in scattered light, evidence for GI



Speedie et al. 2024, Nature

Spiral Arms from Self-Gravity

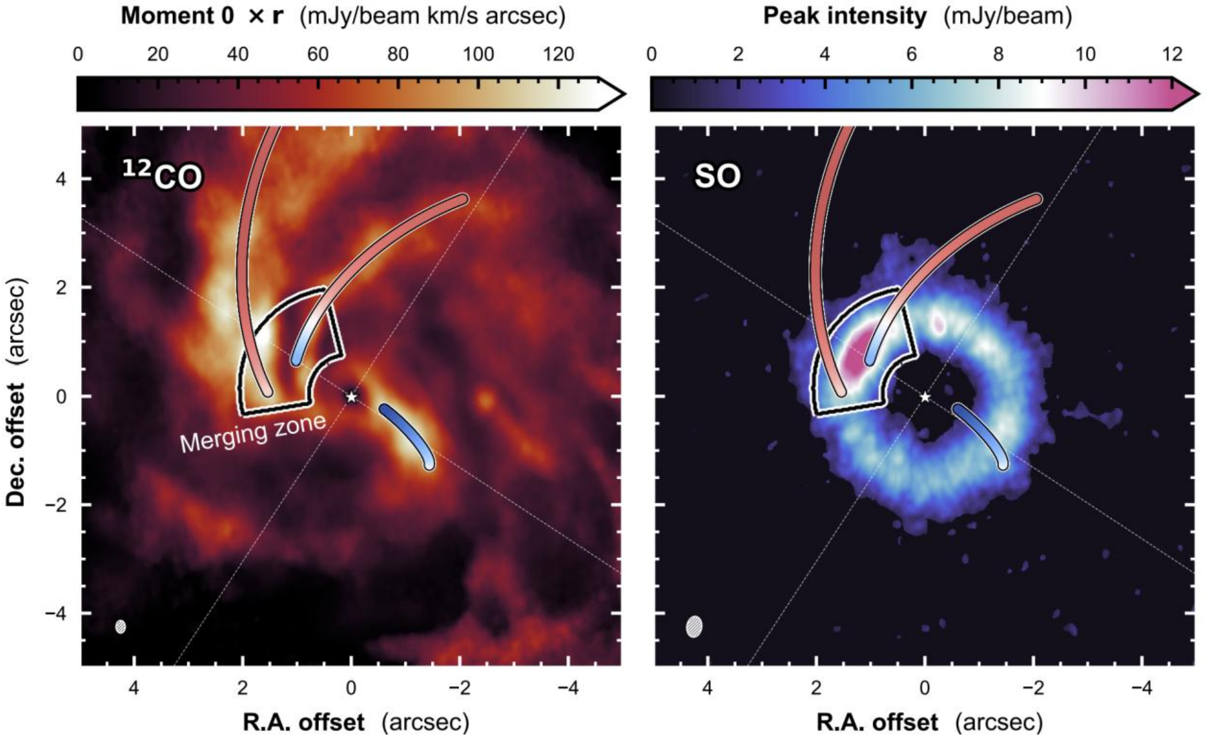


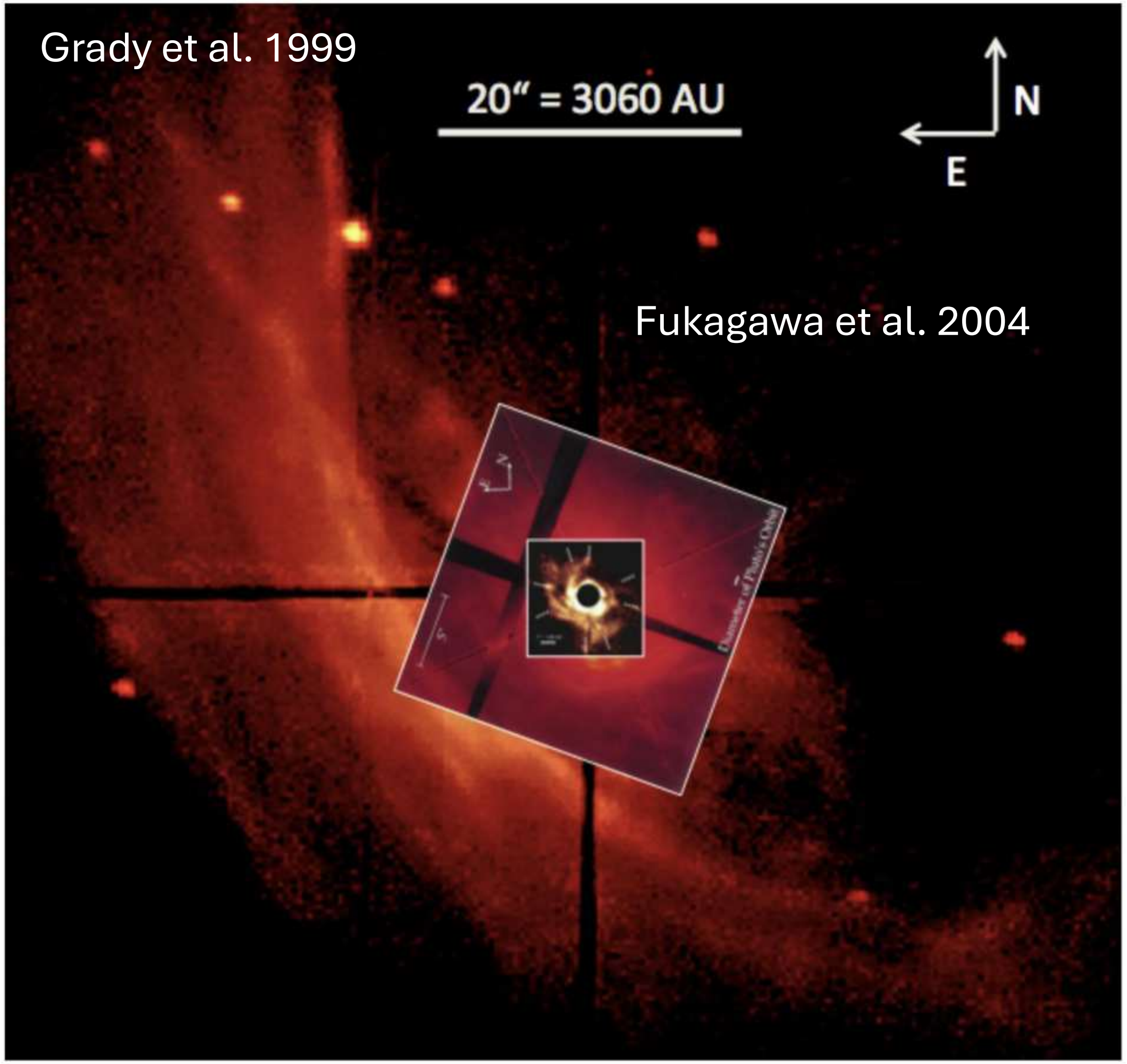


- Hgh density -> more SG in spiral
- Disc material migrates towards high density
- Radial perturbations dominate over azimuthal at disc minor axis

AB Aur seems to have infall

- University of Hawaii 2.2m telescope observations of AB Aur taken in 1999
- Ambient material seen on even larger scales
- Simulations by Dullemond et al. 2019 can reproduce this general structure assuming a cloudlet capture
- Recent work by Jess Speedie traces the streamers hitting the disc



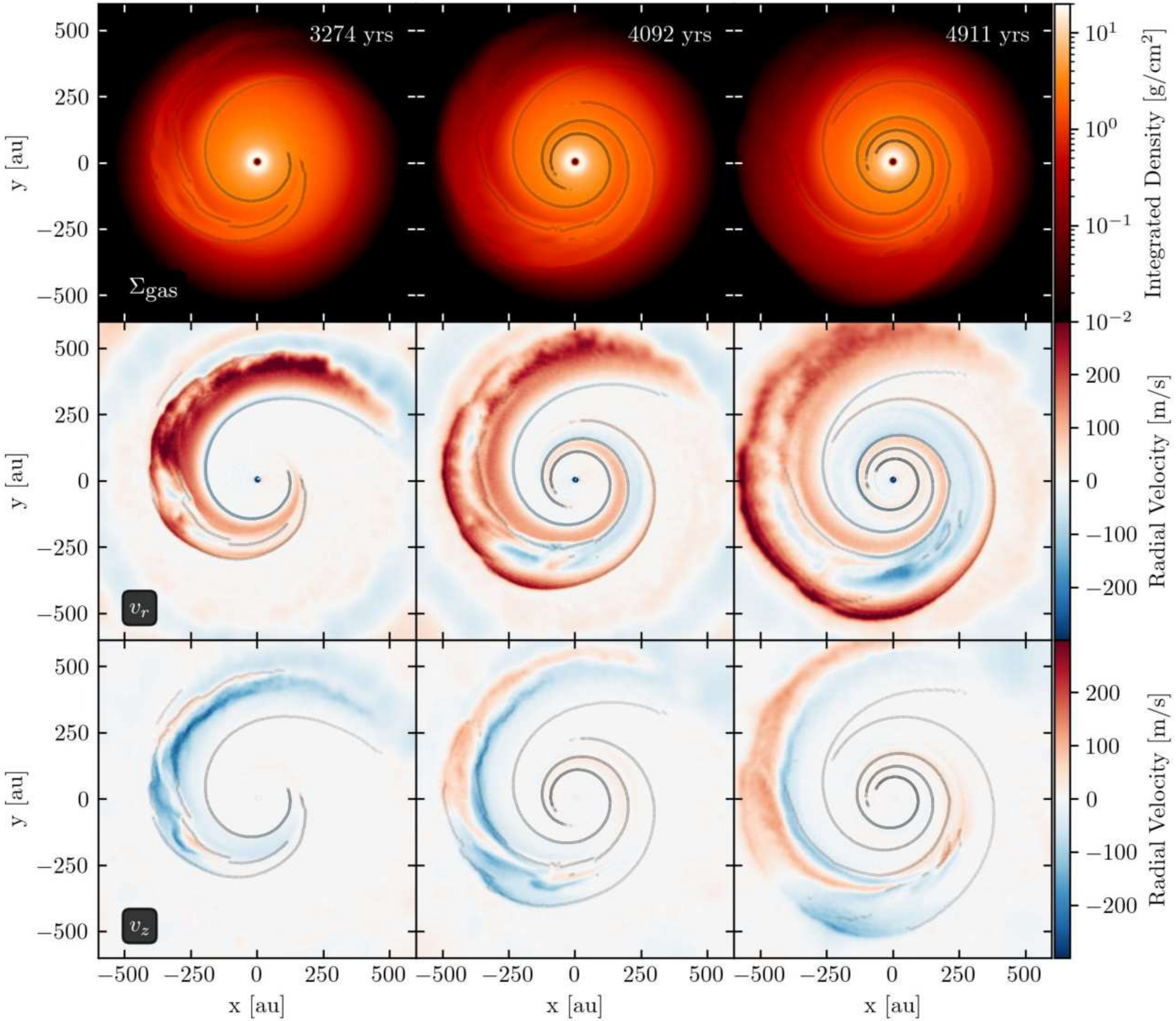


Speedie et al. 2025

Infall Perturbations

The infall here is two small streamers inclined from the disc mid-plane

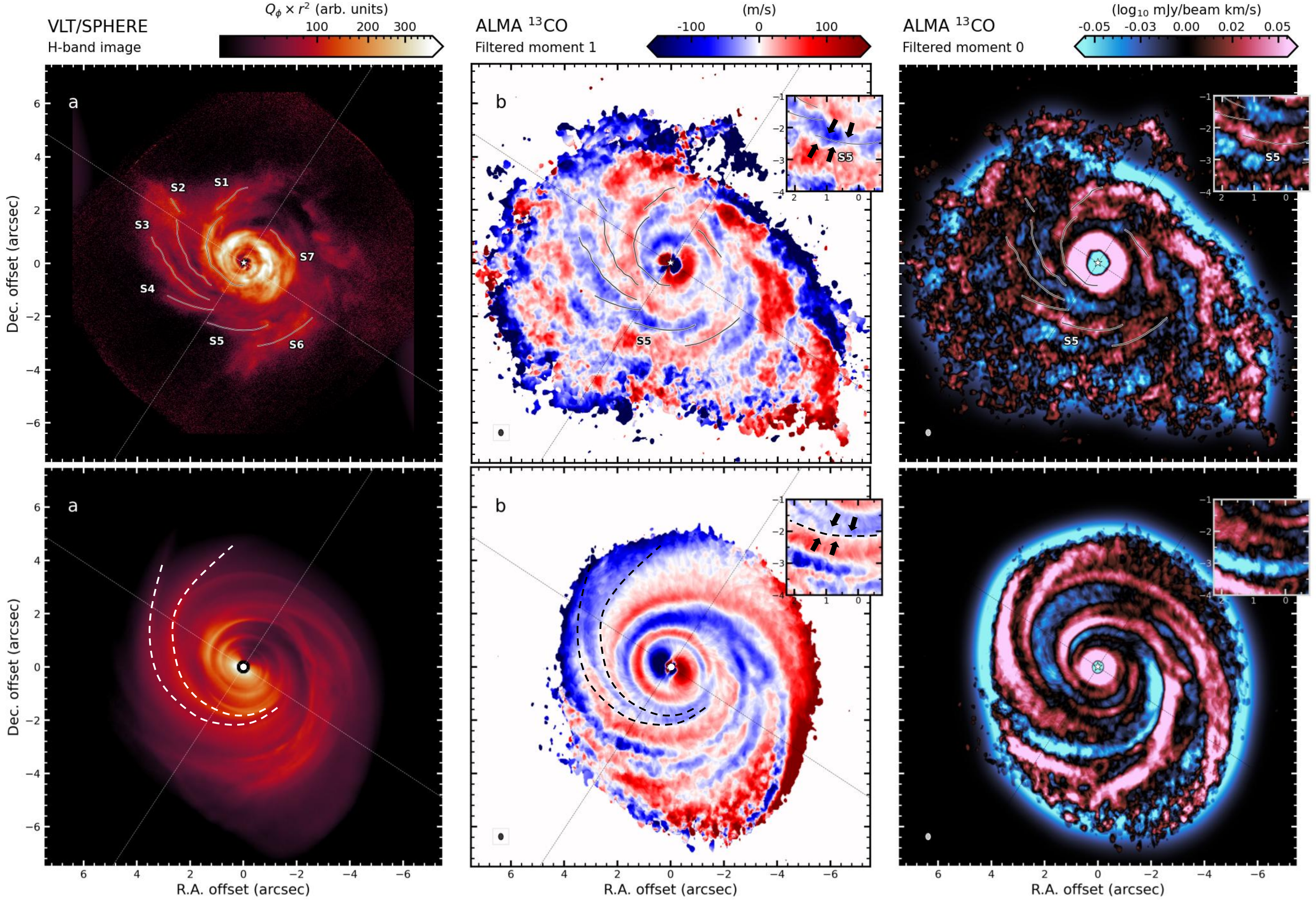
- Lines trace spiral arms in the surface density
- Abundant spiral arms
- Radial and vertical velocity perturbations dominate (azimuthal not shown)



Infall in AB Aur

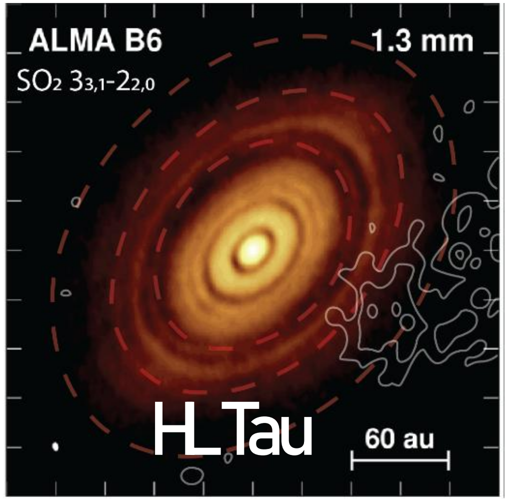
Infall can reproduce many features in the disc

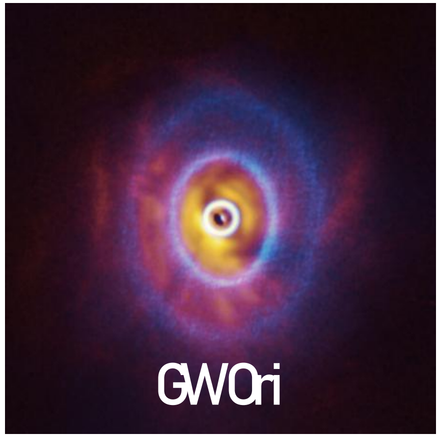
- Abundant spirals
- Perturbed kinematics
- Radially convergent flows

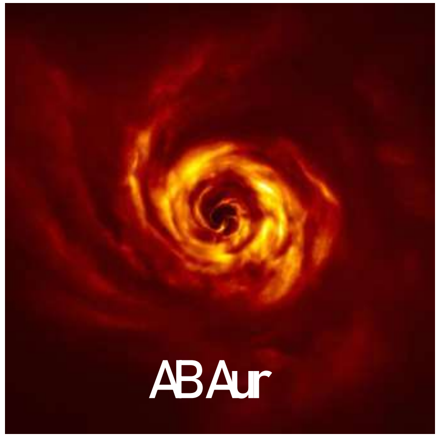


Where to from here...?

- Infall is stochastic since it is seeded from a turbulent environment – May make understanding individual systems even more difficult than it already was..
- We should understand better what substructures can be generated in dust
- How does it affect planet formation and disc evolution?
- GI and infall are not mutually exclusive and may be occurring in unison, but infall also induces a lot of ambiguity!







Each of these systems has infall, and substructures that are often associated with planet-disc interactions.