THE ROYAL SOCIETY

ARE GRAVITATIONALLY UNSTABLE PROTOPLANETARY DISCS RARE?

PT 1 – AN INTRODUCTION

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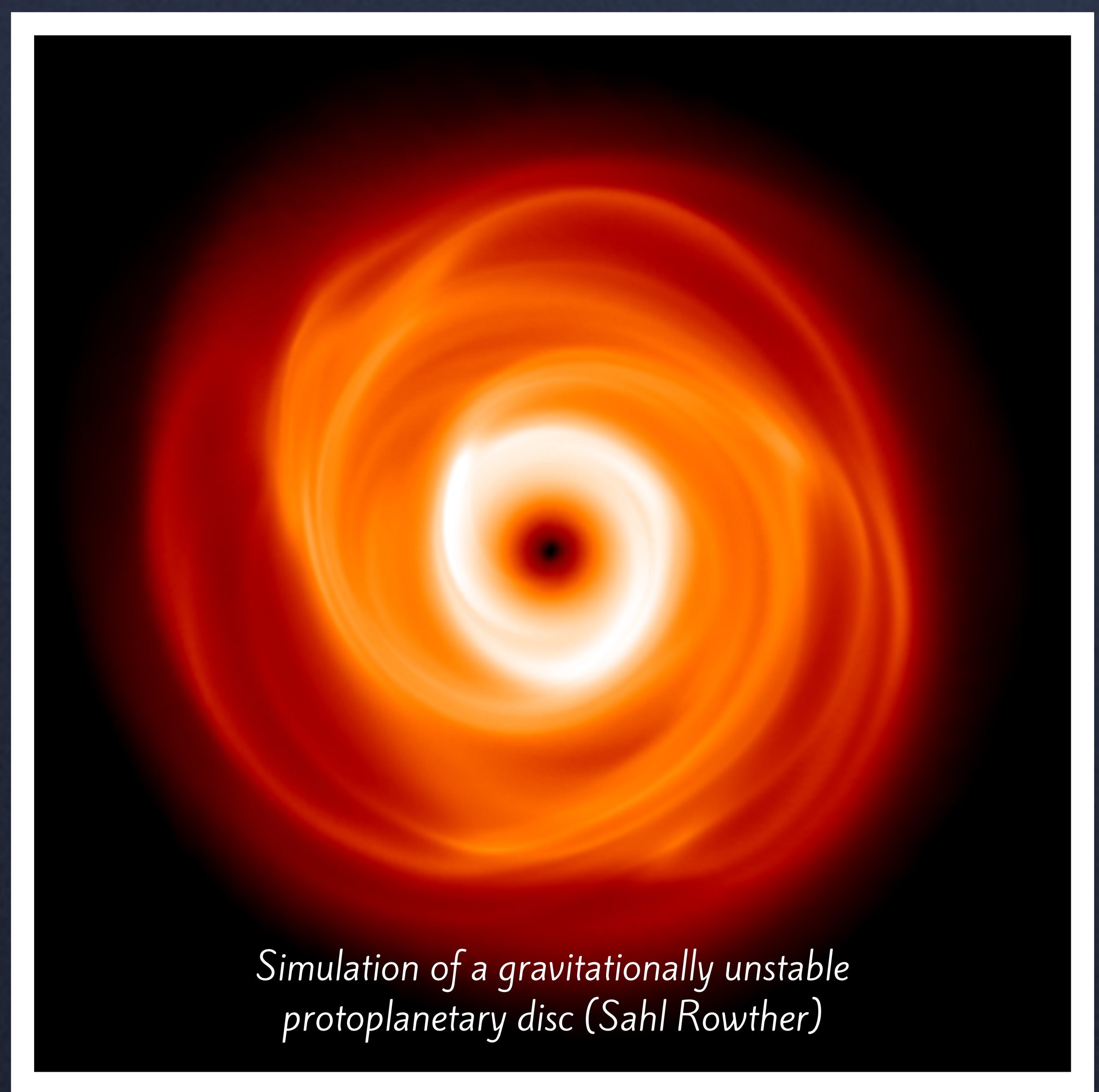
What are gravitationally unstable protoplanetary discs?

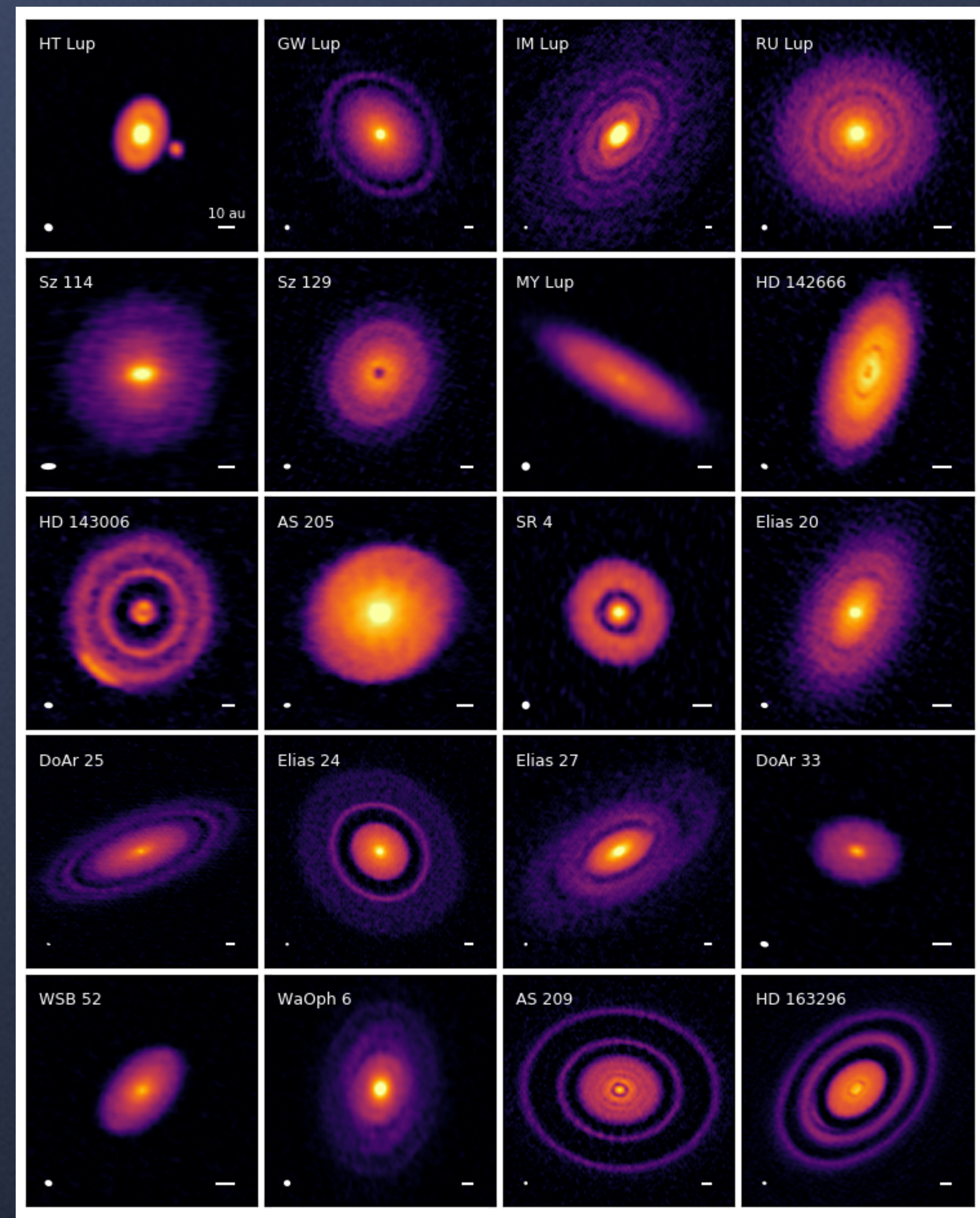
- Protoplanetary discs are the birth sites of planets around young stars. Their masses can be comparable to the host star in their youth.
- Gravitationally instability - formation of irregular structure under the influence of gravity.
- The disc is considered to be gravitationally unstable if the disc is massive enough that the disc's self-gravity results in gravitational instabilities in the form of large-scale spiral features.


Simulation of a gravitationally unstable protoplanetary disc (Sahl Rowther)

Observed substructures

- Rings & gaps (axisymmetric) are very common.
- Spiral (non-axisymmetric) features are rare.
- Planets are often assumed to carve out the rings & gaps by interacting with the disc.

Recent ALMA observations (Andrews+ 2018)



Aim: Can the rarity of gravitationally unstable discs be explained by planet-disc interactions?

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PT 2 - THE THERMODYNAMICS

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When are discs gravitationally unstable?

- Non-axisymmetric gravitational instabilities (spiral features) can be formed when the Toomre parameter

$$Q = \frac{c_s \Omega}{\pi G \Sigma} \lesssim 1.7.$$

Where Ω is the orbital frequency, Σ and c_s are the disc surface density and sound speed (temperature) respectively, and G is the gravitational constant.

- Additionally, the disc must cool fast enough to remain gravitationally unstable. If cooling is too slow, the disc can be stabilised by internal heating due to turbulence from gravitational instability.
- Hence, the disc thermodynamics must be modelled realistically.

Traditionally

The cooling is modelled such that β, the ratio between the cooling and orbital time is constant. Although this method is computationally inexpensive, the entire disc becomes gravitationally unstable, which is not expected in realistic self-gravitating discs.

In this work

β is radially dependent. Only the outer regions of the disc becomes gravitationally unstable. This mimics a realistic self-gravitating disc (Rowther & Meru 2020) whilst remaining computationally inexpensive.

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PT 3 – IMPACT OF PLANET ON DISC STRUCTURE

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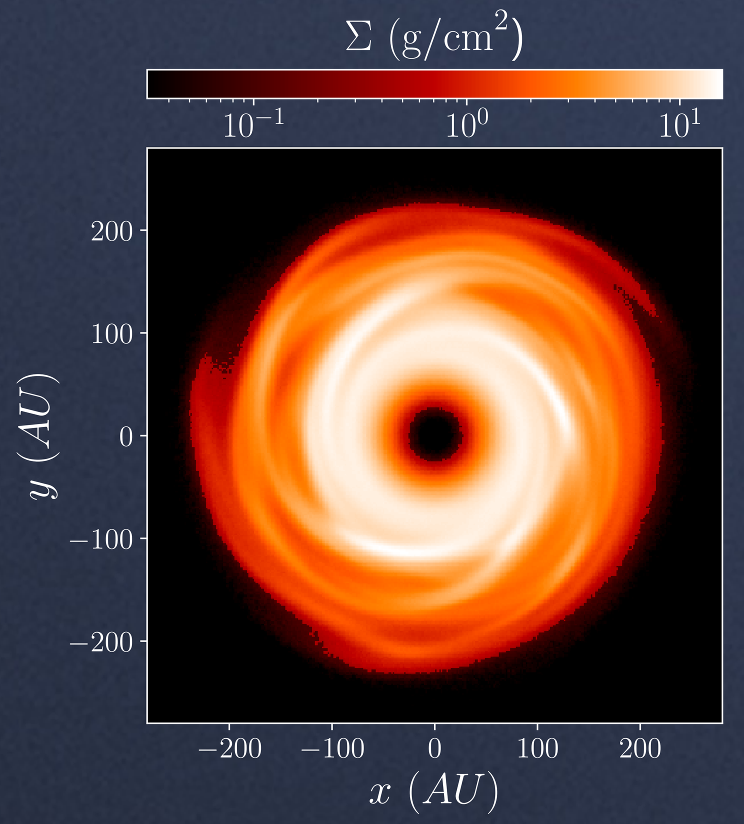
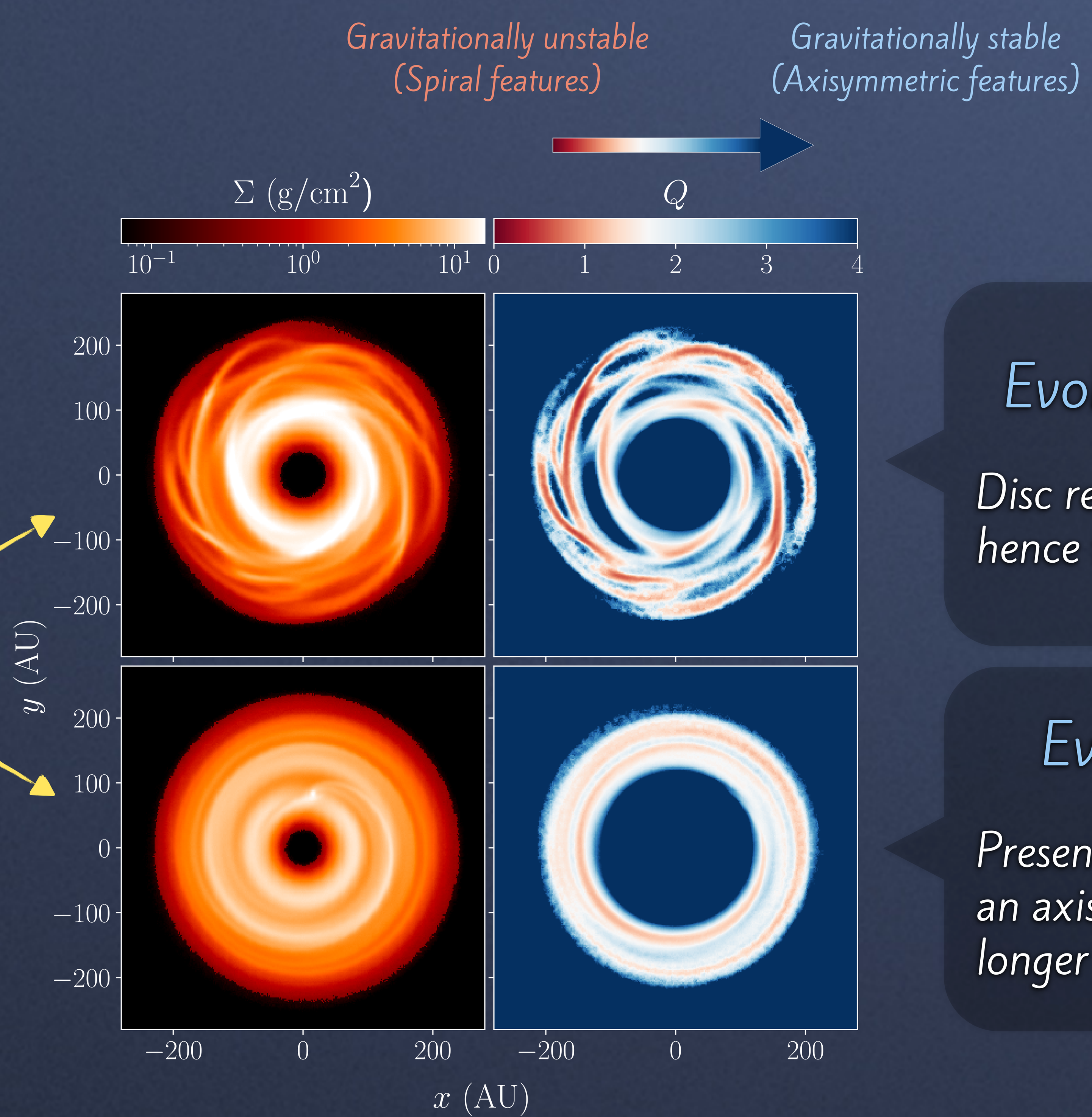


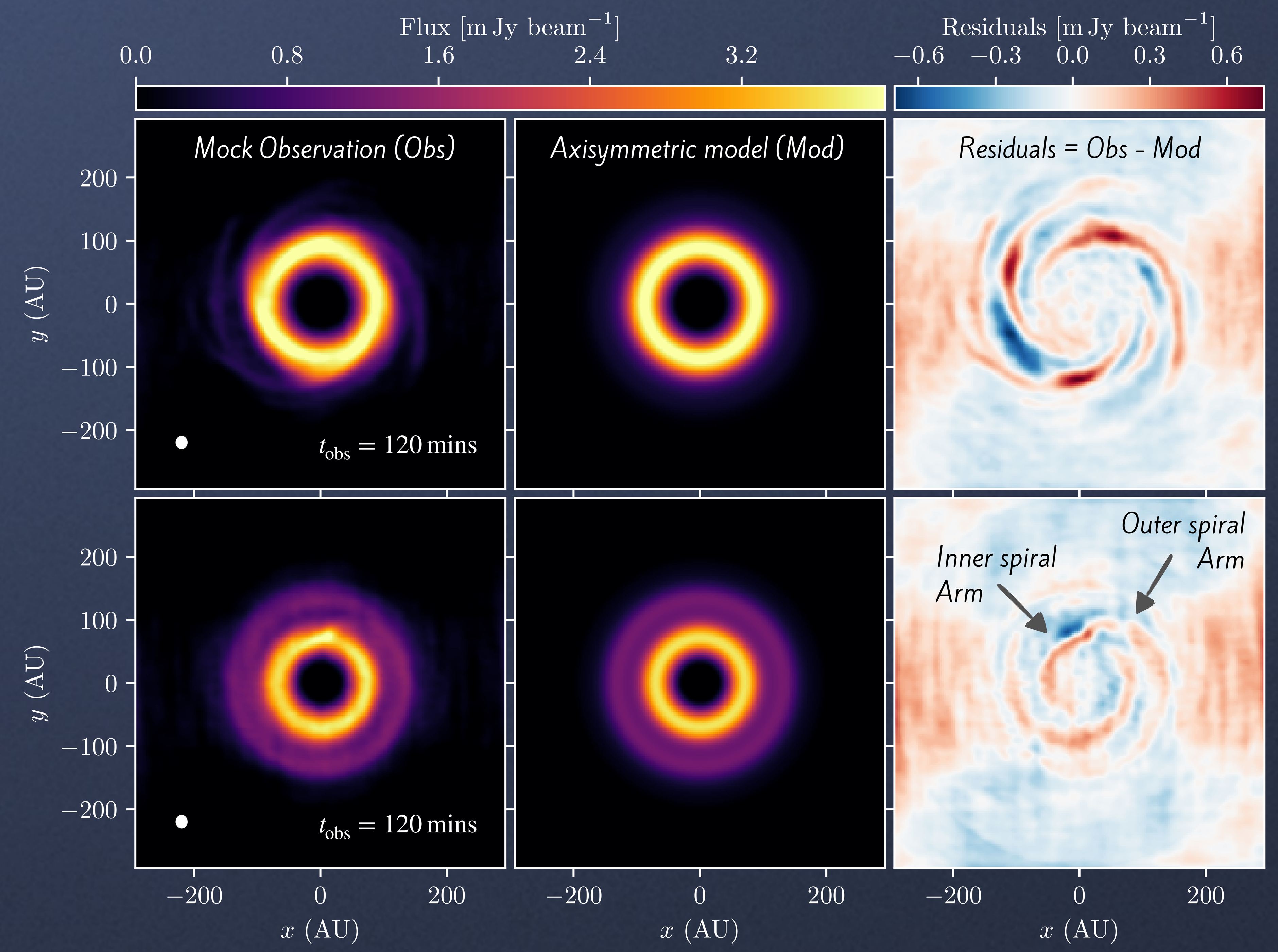


Evolution without a planet

Disc remains gravitationally unstable, hence the presence of spiral structure.

Evolution with a planet

Presence of a giant planet results in an axisymmetric disc which is no longer gravitationally unstable.



Implications on observations

- In some observations of axisymmetric discs, the observed dust mass can be high enough such that inferring the gas mass via a fixed dust-gas mass ratio (canonically 0.01) results in a disc that is massive enough to be gravitationally unstable.
- But, a gravitationally unstable disc is expected to show large-scale spiral structure.
- Therefore in the absence of large-scale spiral structure, a higher dust-gas mass ratio is assumed when modelling the disc to ensure a less massive gravitationally stable disc.
- However this assumption is not necessary as in the presence of a giant planet, we show that spiral structures expected from massive discs can be suppressed, thus appearing axisymmetric.

Mock ALMA continuum observations

- Without a planet (top row) - spiral arms due to gravitational instability are seen.
- With a planet (bottom row) - Axisymmetric apart from the spiral arms caused by the planet.

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PT 4 – CO KINEMATICS

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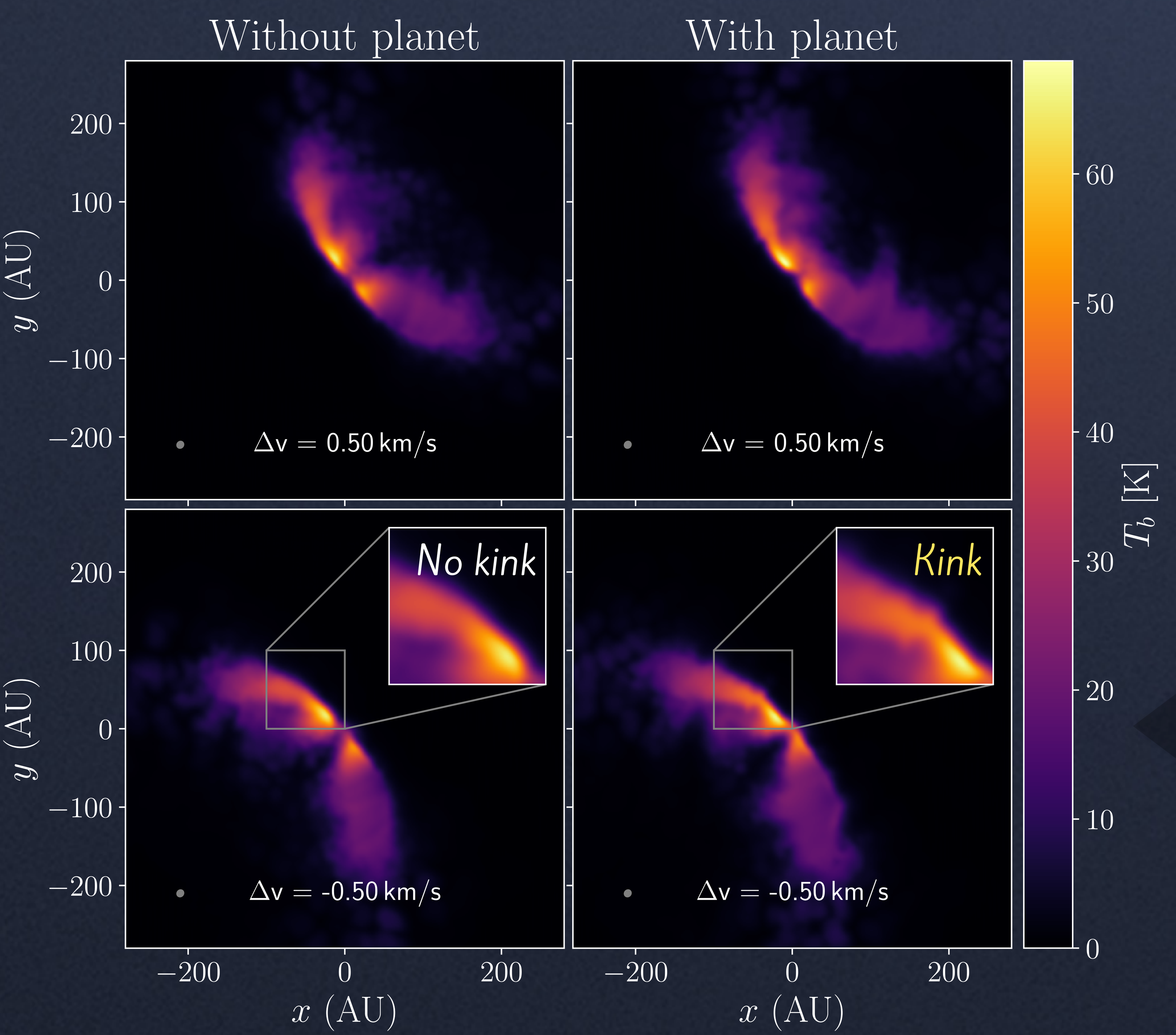
Disc kinematics

- Dominated by Keplerian rotation.
- The spiral waves generated by the embedded planet can cause localised deviations in the Keplerian flow of the disc (Pinte+ 2019, 2020).
- These deviations can be detected as kinks in the gas channel maps.



Synthetic channel maps

- $^{13}C^{16}O$.
- J = 3-2 transition line.
- Kink only seen with a planet in the $\Delta v = -0.5$ km/s channel.
- Can exclude large scale perturbations as kink is not seen in the opposite channel.

Summary

- We investigate whether the rarity of gravitationally unstable protoplanetary discs can be explained by planet-disc interactions.
- A migrating giant planet strongly suppresses the spiral structure in self-gravitating discs; shortening the gravitationally unstable phase.
- In the presence of a migrating giant planet self-gravitating discs can appear axisymmetric in mock ALMA continuum observations.
- The planet can be detected with high resolution kinematics of optically thin CO-isotopologues such as $^{13}C^{16}O$.
- Our results show that with a giant planet it is possible to explain a lack of large-scale spiral structure expected from high mass discs without requiring high dust-to-gas mass ratios to limit the gas mass.

References

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Tools Used: Phantom (Price+ 2018), MCFOST (Pinte+ 2006, 2009), Splash (Price 2007)