The effect of radiative transfer on the properties of disc-instability protoplanets

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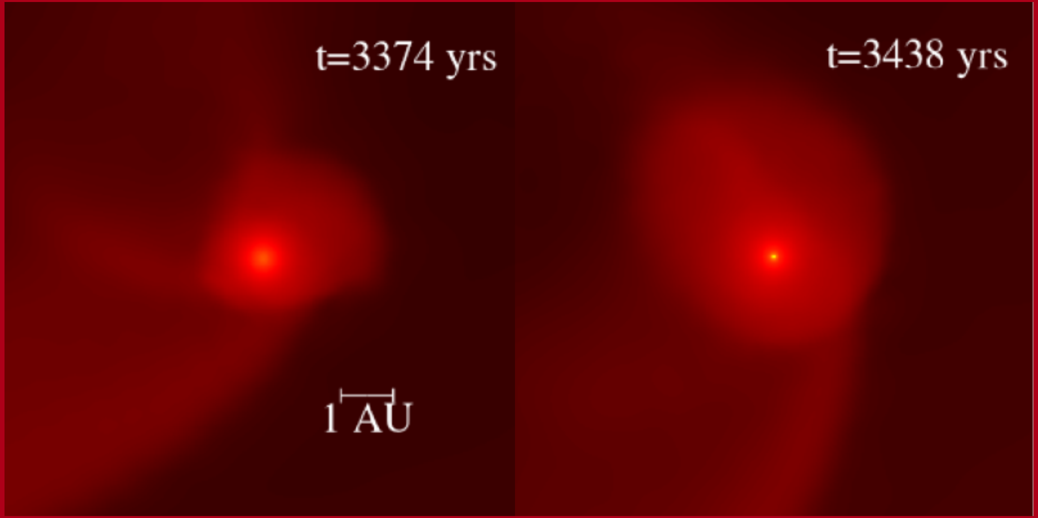

Giant Planet Formation Theories

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Core Accretion

- Bottom-up approach to planet formation.

- Predicts the formation of close-in giant planets (≲10AU).

- Requires ~10^6 years (longer than the expected disc lifetime).

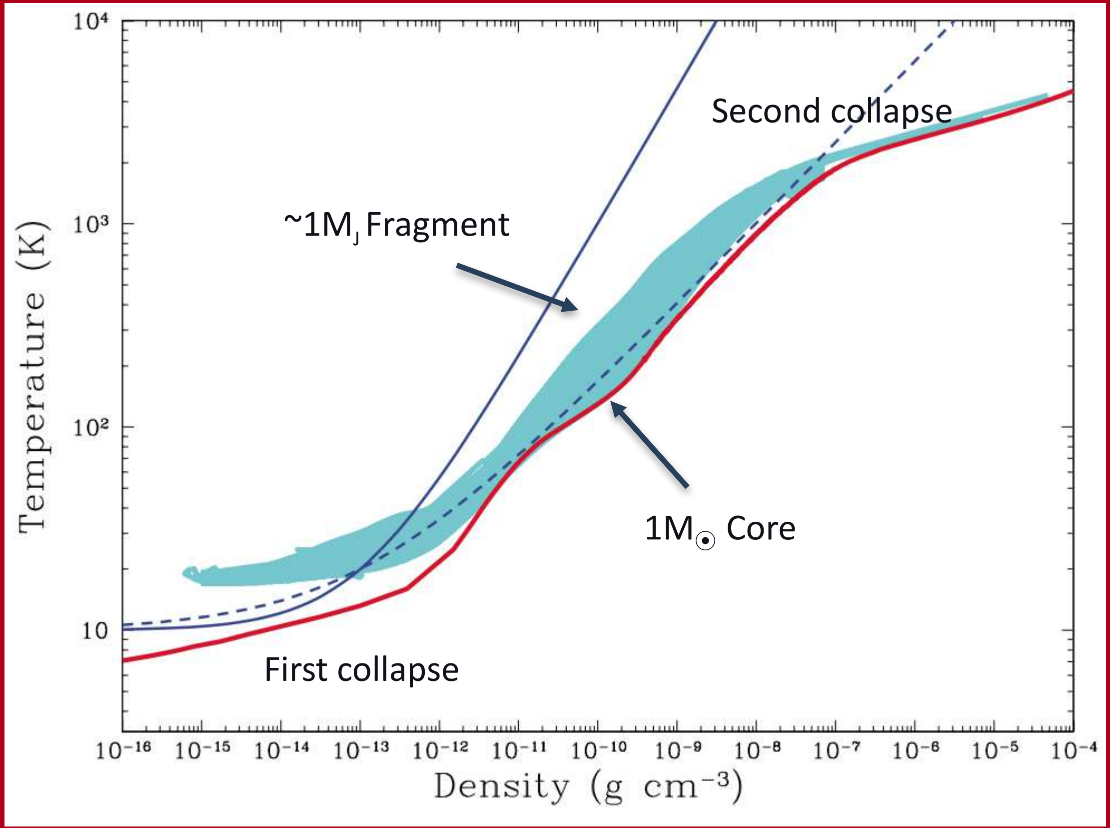
Disc Instability

- Top-down approach to planet formation.

- Predicts the formation of wide-orbit giant planets (≳50AU).

- Capable of forming giant planets on a dynamical timescale.

Disc-instability planets follow a star-like formation pathway



- Initially isothermal collapse.

- ~10^{-13} gcm^{-3}, fragment becomes opaque and begins to increase in density and temperature rapidly. Formation of the first hydrostatic core.

- Growth of the first core.

- 2000K, H_2 begins to dissociate. Formation of the second hydrostatic core.

Stamatellos & Whitworth, 2009, MNRAS

Disc-instability protoplanets are not spherically symmetric

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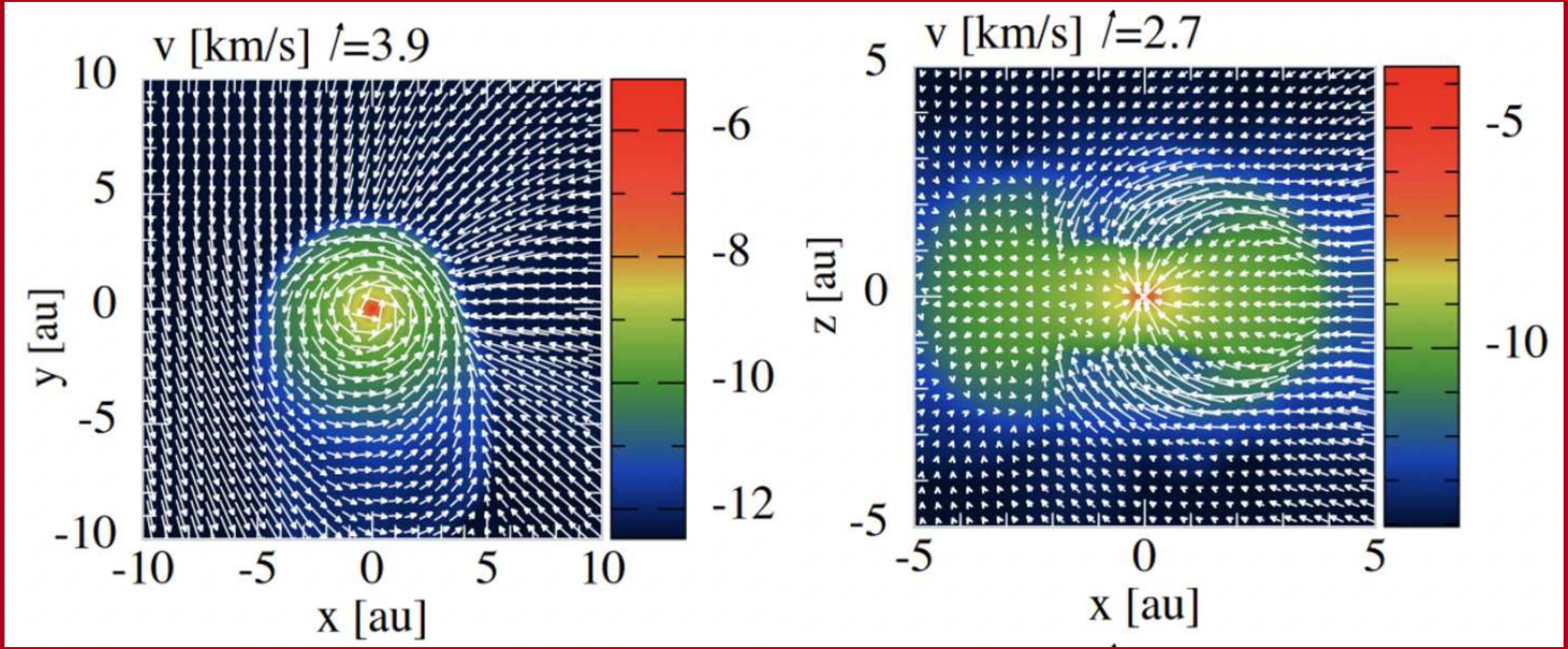

Disc-instability protoplanets are not spherically symmetric, but oblate spheroids.

Fenton & Stamatellos, 2024 A&A

Disc-instability protoplanets are not spherically symmetric

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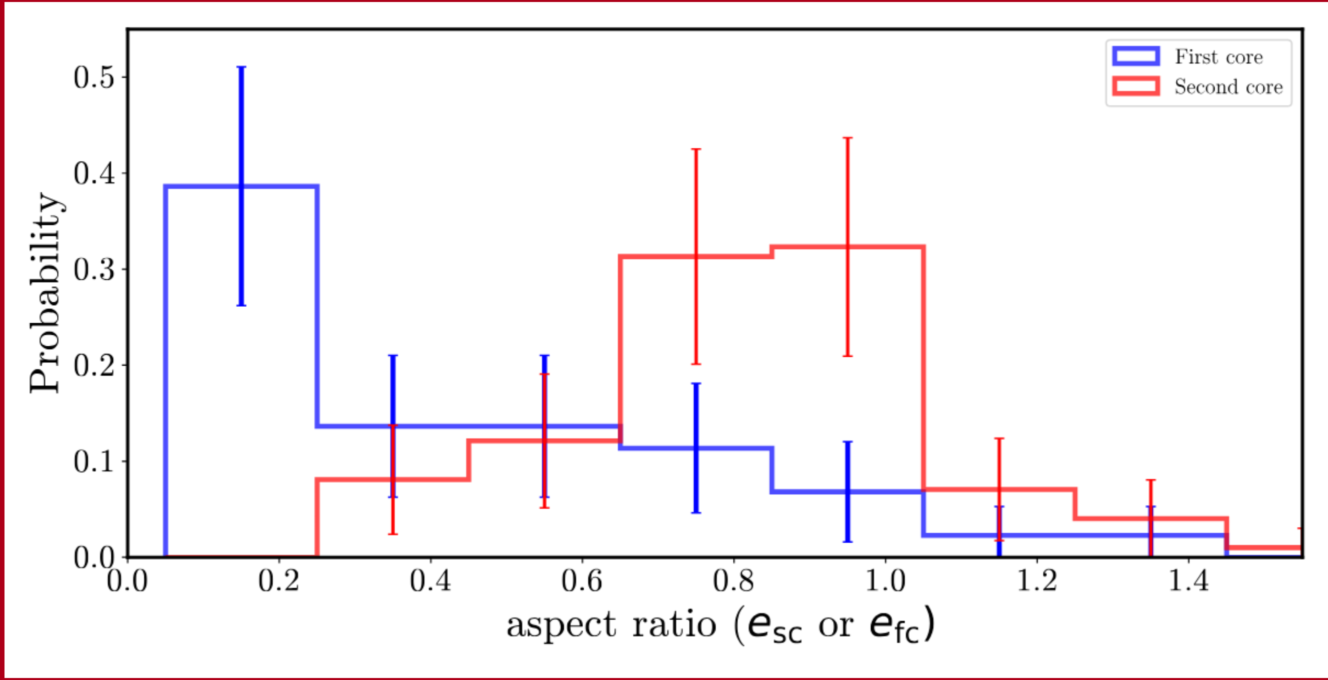

First cores are highly flattened, whilst most second cores are almost spherical.

Fenton & Stamatellos, 2024 A&A

Equations of state (EOS) in simulations

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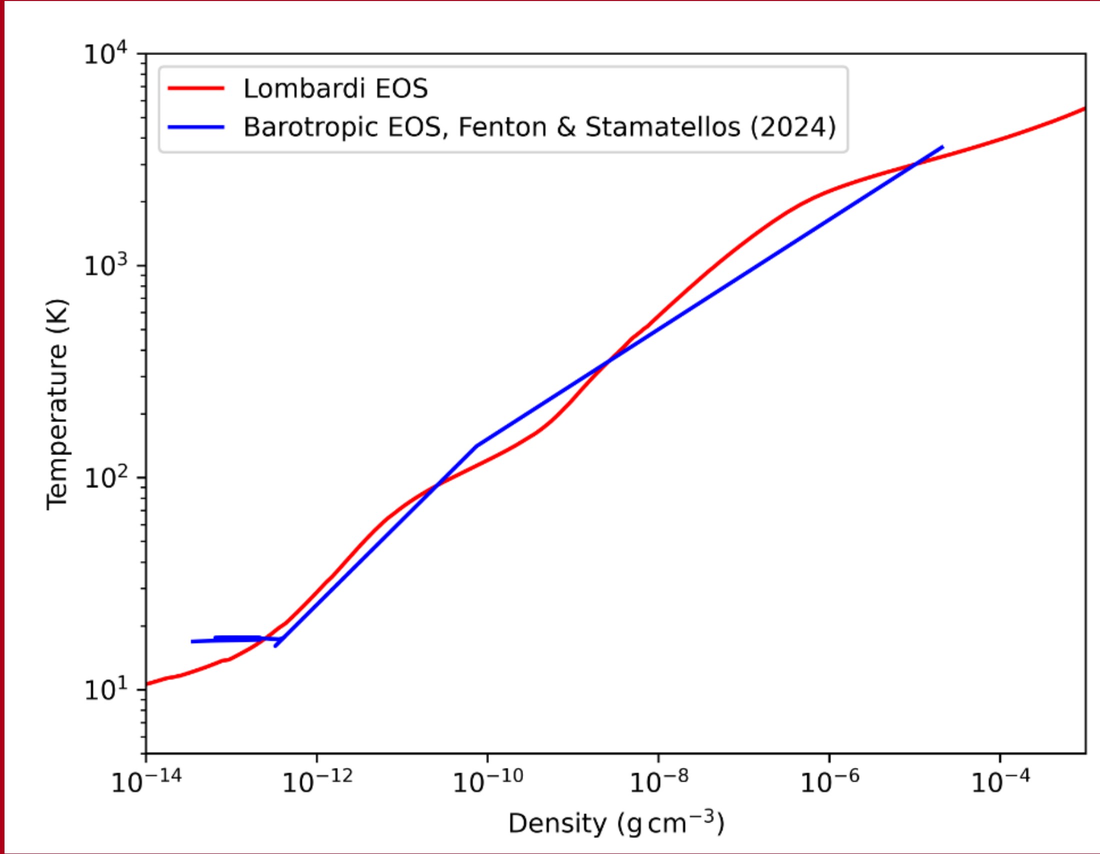

- A barotropic equation of state roughly approximates the heating and cooling in the disc through a power-law relation.

- A barotropic EOS does not consider the local environment.

- Radiative transfer approximation methods allow us to treat the thermodynamics in the disc in a more realistic way without the need for full radiative transport.

Radiative transfer approximation methods in SPH

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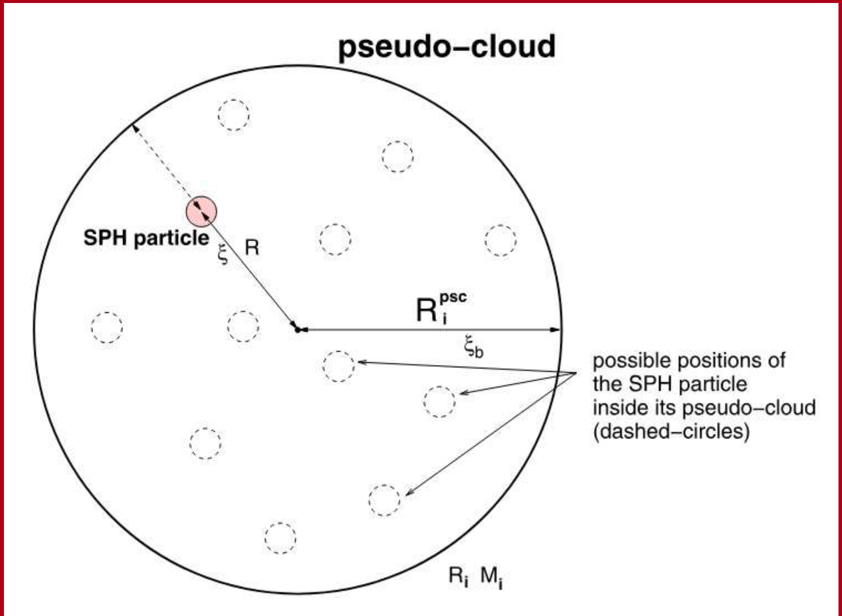

$$\left.\frac{du_i}{dt}\right|_{rad} = \frac{4\sigma\left[T_0^4(r_i) - T_i^4\right]}{\bar{\Sigma}^2\bar{\kappa}_i(\rho_i, T_i) + \kappa_i^{-1}(\rho_i, T_i)},$$

- RT approximation methods consider the local environment around each particle.
- Assume each particle is embedded in a polytropic pseudo-cloud.
- Estimate a mean column density an estimate for the mean opacity from the particle to the surface.
- Calculate the radiative heating rate.
- Update the energy, temperature and density.

Stamatellos et. al, 2007, A&A

Radiative transfer approximation methods in simulations

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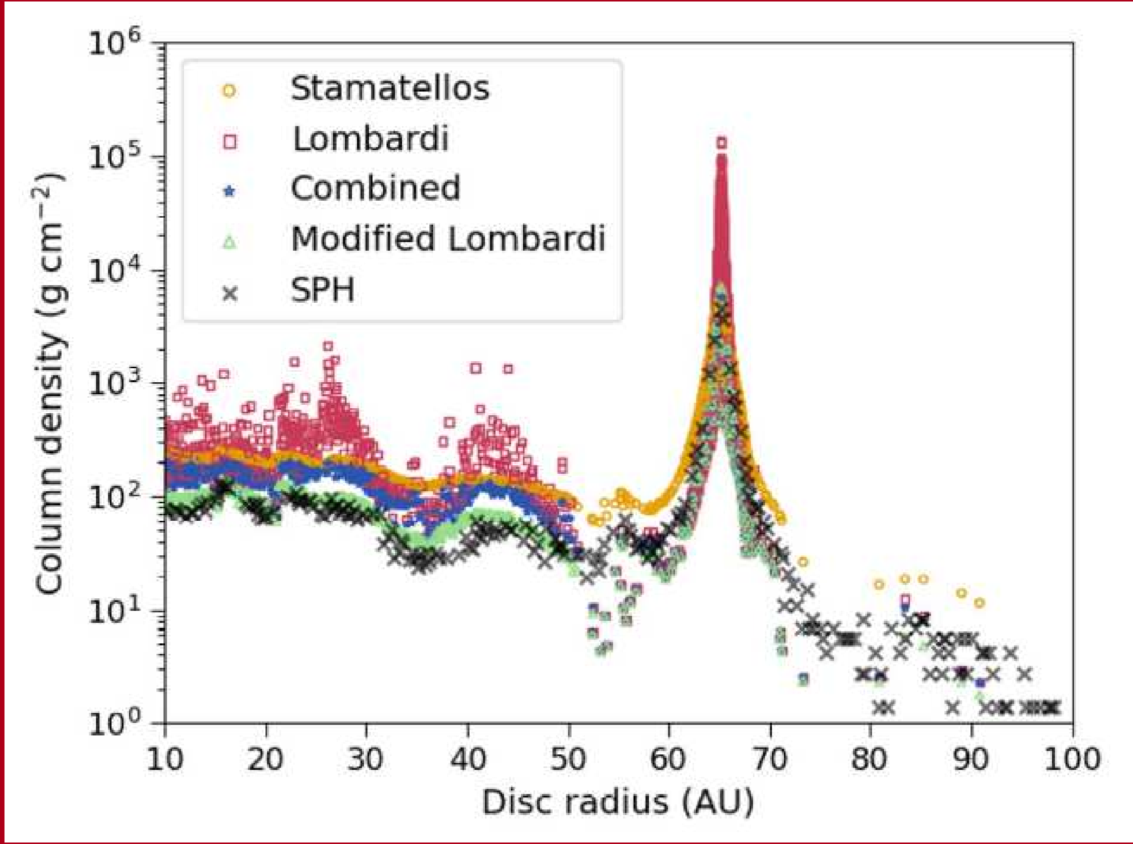

- Stamatellos et. al – gravitational potential.
- Lombardi et. al – pressure scaleheight.
- Combined – Lombardi + Stamatellos.
- Modified Lombardi – relates mid-plane density, scale height and column density – available in Phantom!

Young et. al, 2024 MNRAS

Methodology and initial conditions

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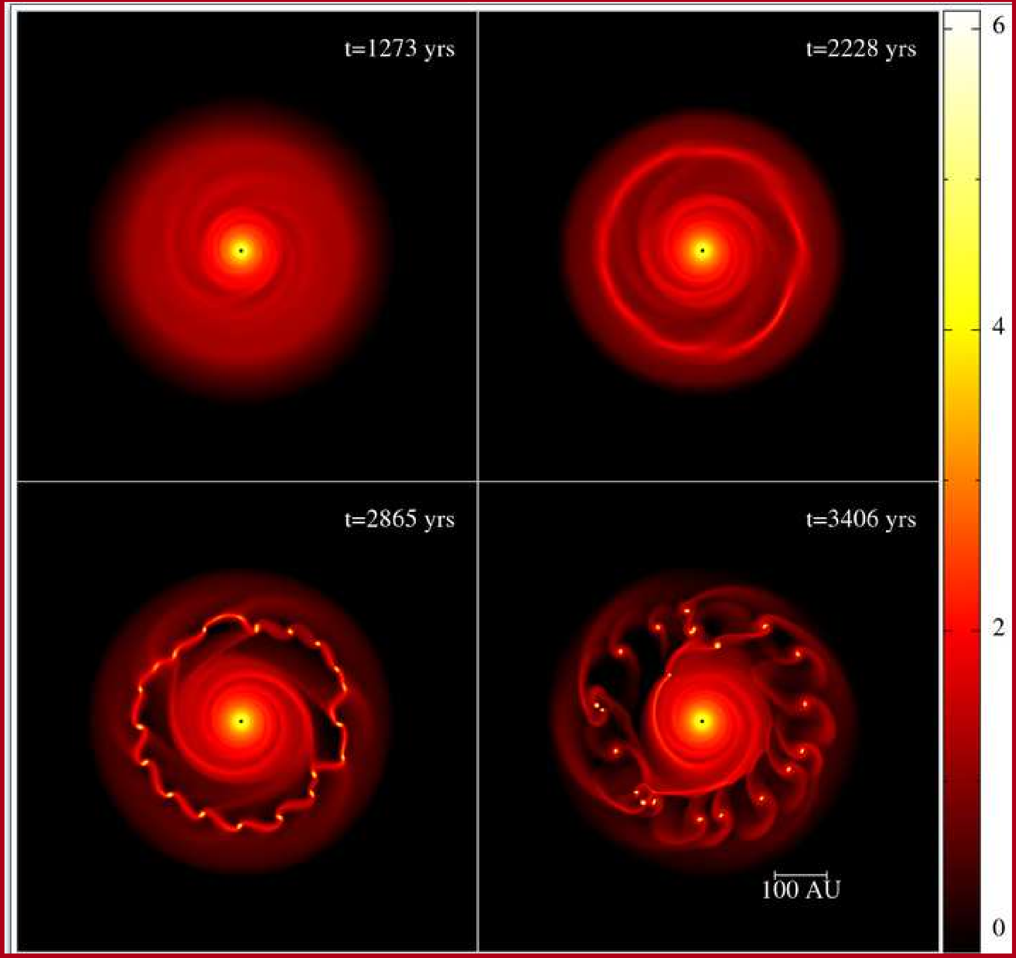
Parameter	Values
M_*	$0.8\,M_\odot$
M_D	$0.6\,M_\odot$
R_{in}	10 AU
R_{out}	300 AU
$T_{1\,AU}$	150, 200 K
T_{floor}	10 K
p	3/2

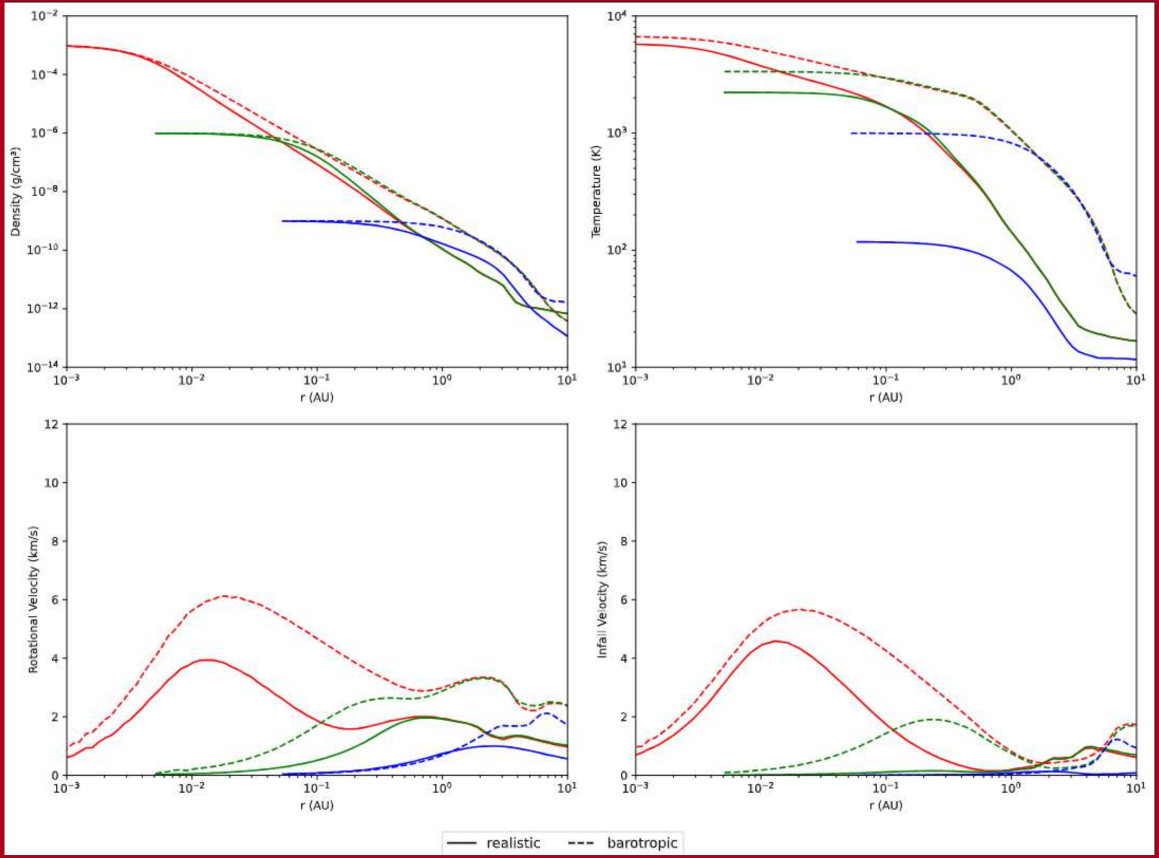
- Simulate a massive, gravitationally unstable disc.
- 4×10^6 SPH particle simulations using Phantom.
- Treat the heating and cooling in the disc using the Lombardi RT approximation method.
- Investigate the effect of using a more realistic EOS on the properties of disc-instability protoplanets.

Disc evolution



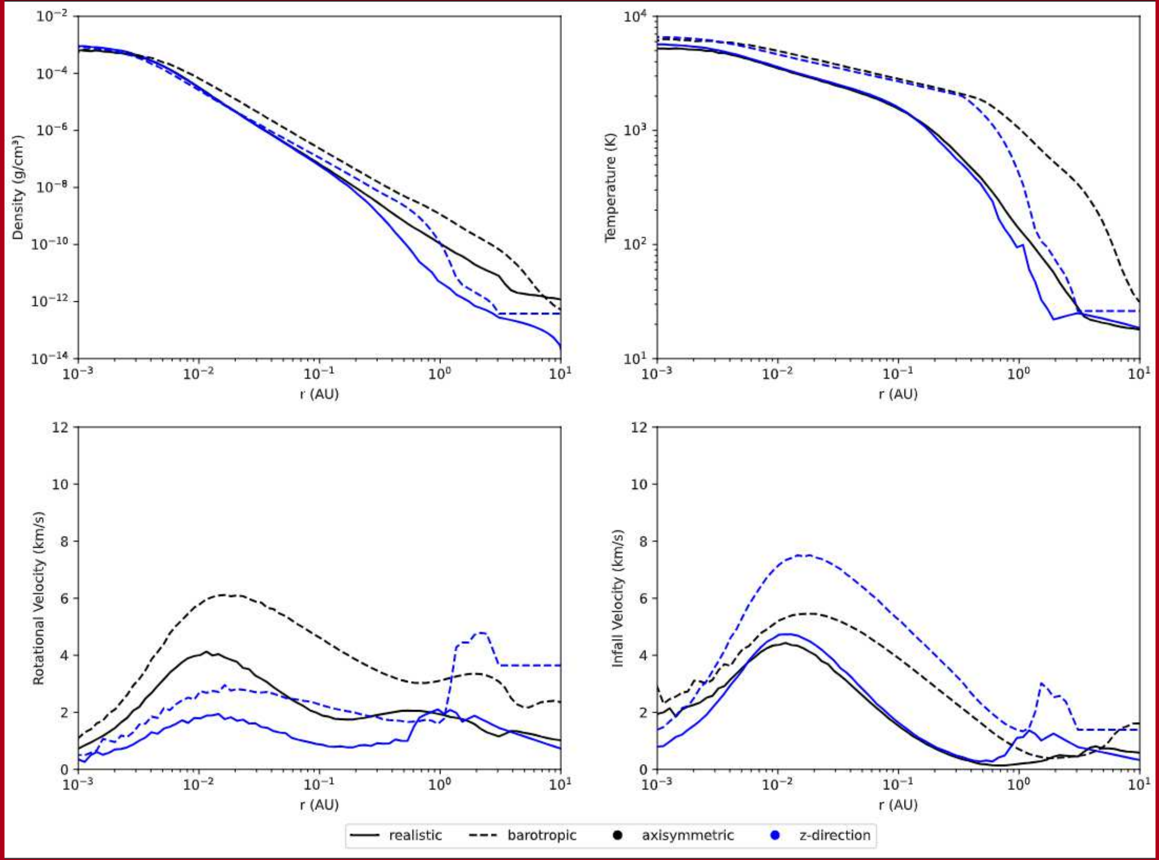
- The disc quickly becomes gravitationally unstable.
- Several fragments are formed on a short timescale.
- Fragments evolve rapidly.
- Follow the evolution of the fragments that form until the central density reaches 10^{-3} gcm^{-3}.

The effect of radiative transfer on protoplanet evolution



- Follow the evolution of a protoplanet when its central density reaches 10^{-9} gcm^{-3}, 10^{-6} gcm^{-3}, and 10^{-3} gcm^{-3}.
- Simulations with a barotropic EOS overestimate the temperature, rotational velocity and infall velocity.
- Simulations with a more realistic EOS produce colder, slower rotating protoplanets.

The effect of radiative transfer on the 3D structure of protoplanets



- Compare the profiles of protoplanets with a barotropic to those from simulations with a more realistic EOS.
- First cores are more flattened than second cores for both the RT approximation and barotropic EOS.
- Simulations with a more realistic EOS form less flattened planets.

Conclusions

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- The properties of disc-instability protoplanets are heavily affected by the equation of state.

- Protoplanets modeled with a more realistic EOS are less flattened compared to those modeled with a less-realistic barotropic EOS.

- We expect the protoplanets to initially be cooler and more compact when using a more realistic equation of state.

- The evolution of disc-instability protoplanets need to be studied with a more realistic description for the heating and cooling in simulations - the thermodynamics in the disc is not the same everywhere!

The 3D structure of disc instability protoplanets

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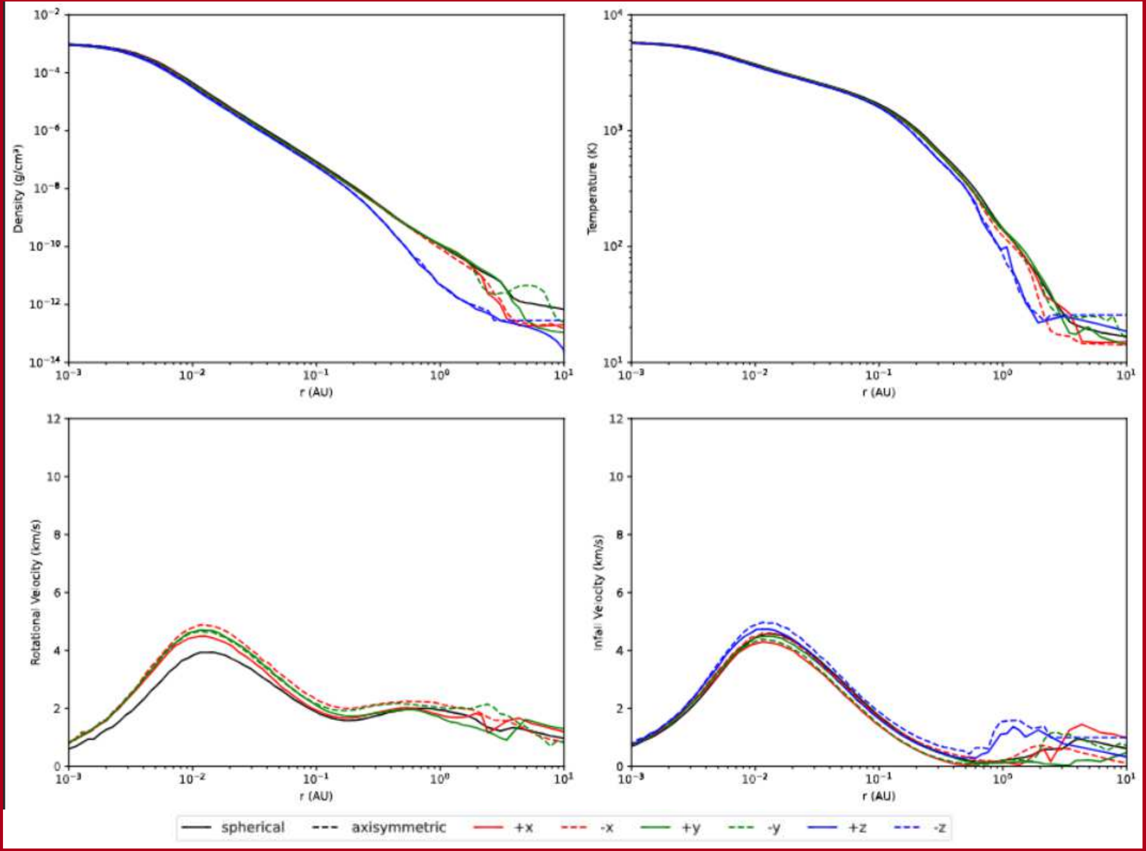

- The density and temperature profiles fall off radially earlier in the z-direction.
- We see slightly enhanced infall in the z-direction.
- When using a more realistic equation of state disc-instability protoplanets are slightly flattened.
- First cores are more flattened than second cores.