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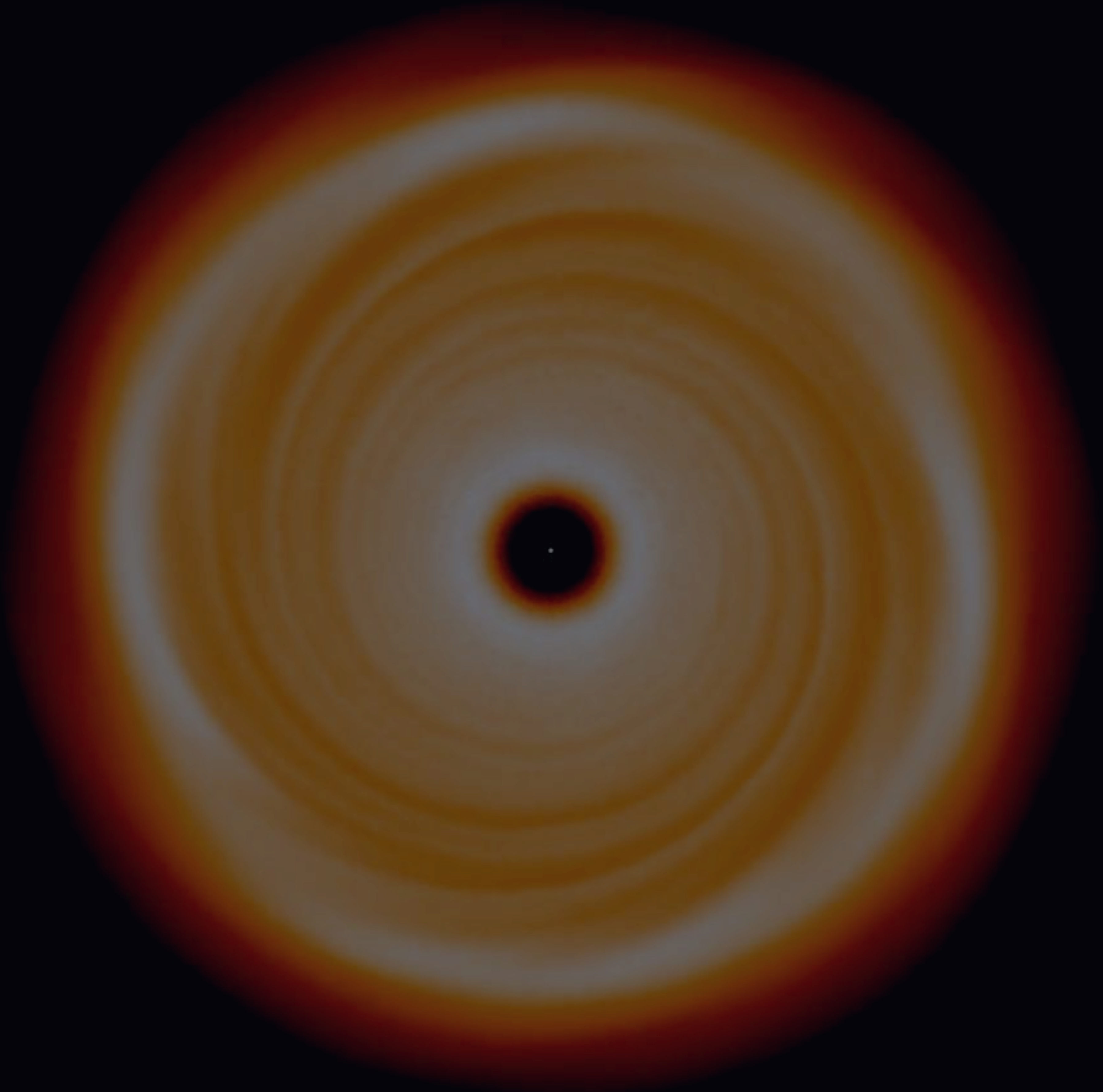

Gravitational Instability In Irradiated Discs

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Rebecca Nealon, Farzana Meru, and Richard Alexander

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PHANTOM + MCFOST

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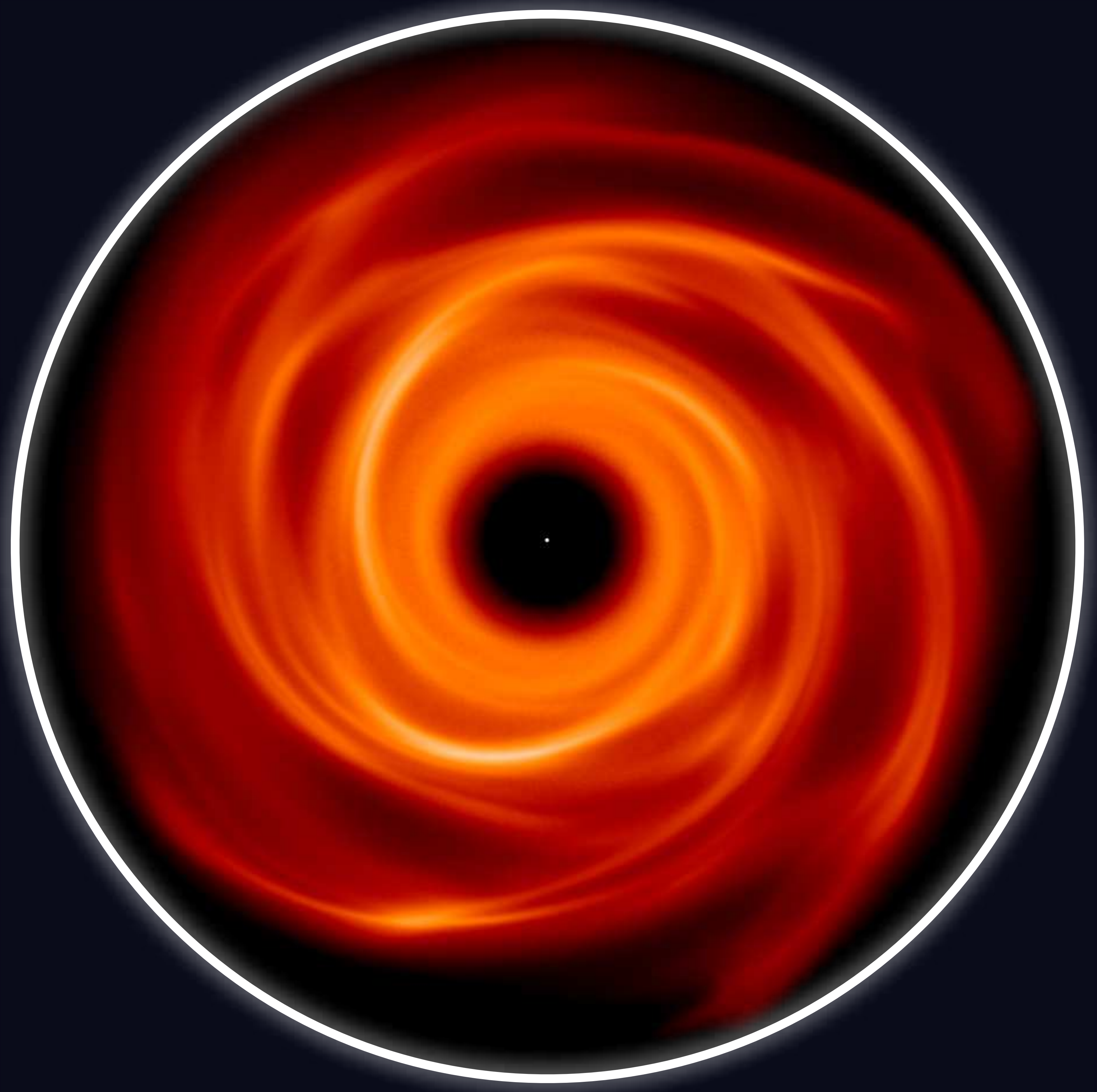
When are Discs Gravitationally Unstable?

- In their youth, discs can be massive enough that the disc's self-gravity is important.
- When the disc mass is comparable to its host star ($\gtrsim 10\% \, M_\star$), gravitational instabilities (GI) can occur resulting in spiral arms.



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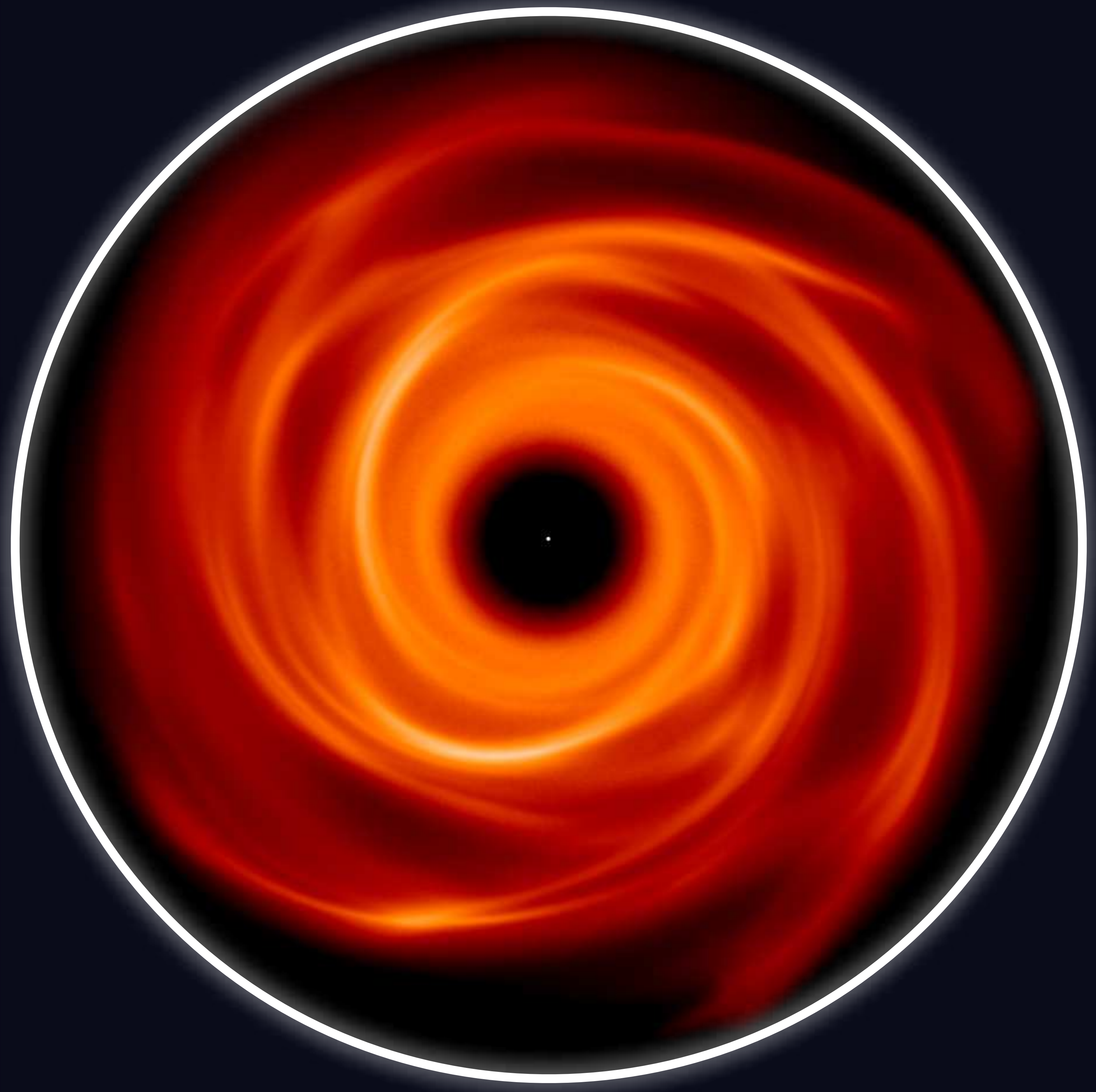
When are Discs Gravitationally Unstable?

Sound speed

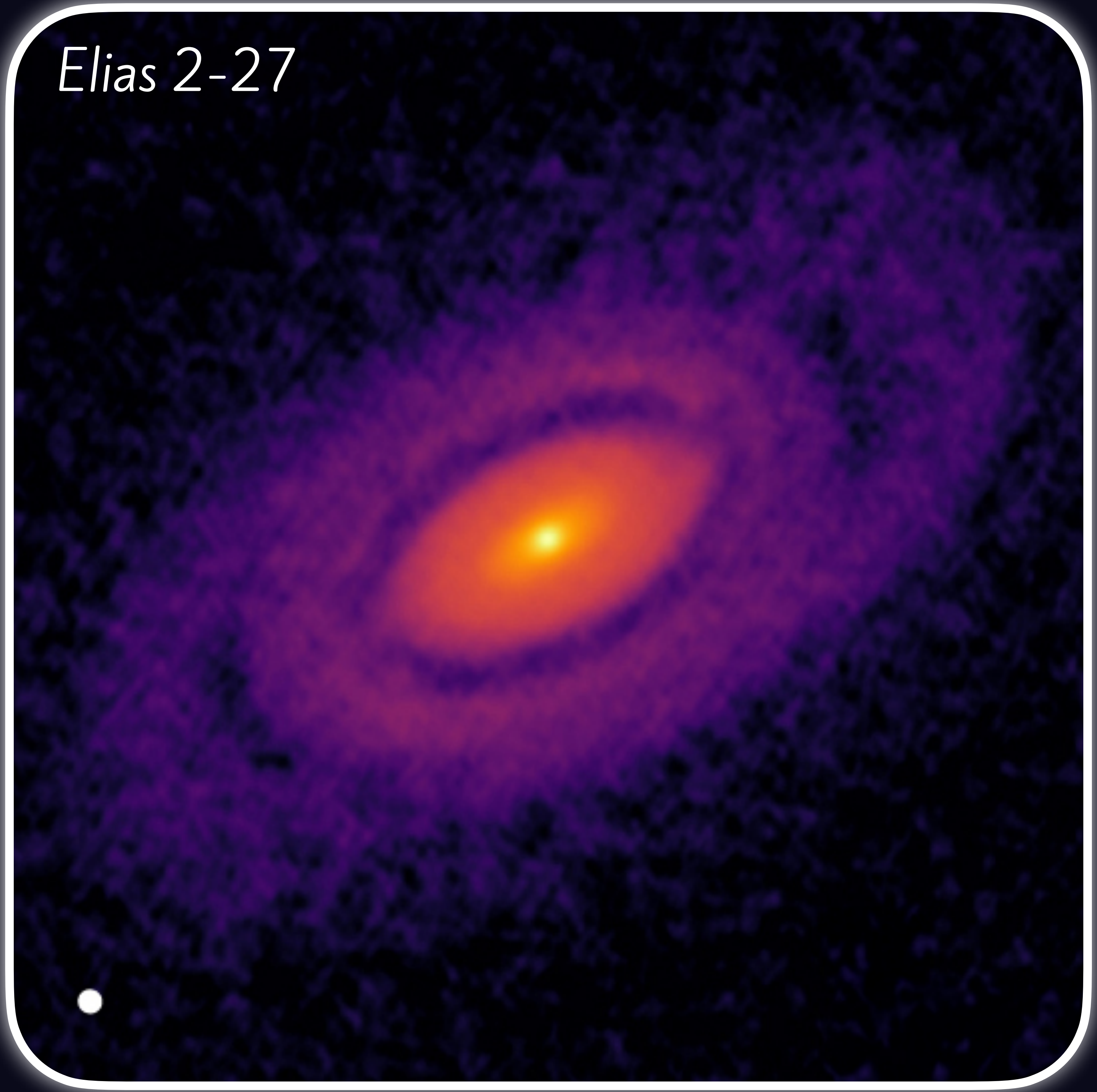
$$Q = \frac{c_s \Omega}{\pi G \Sigma} \lesssim 1.7$$

Surface Density

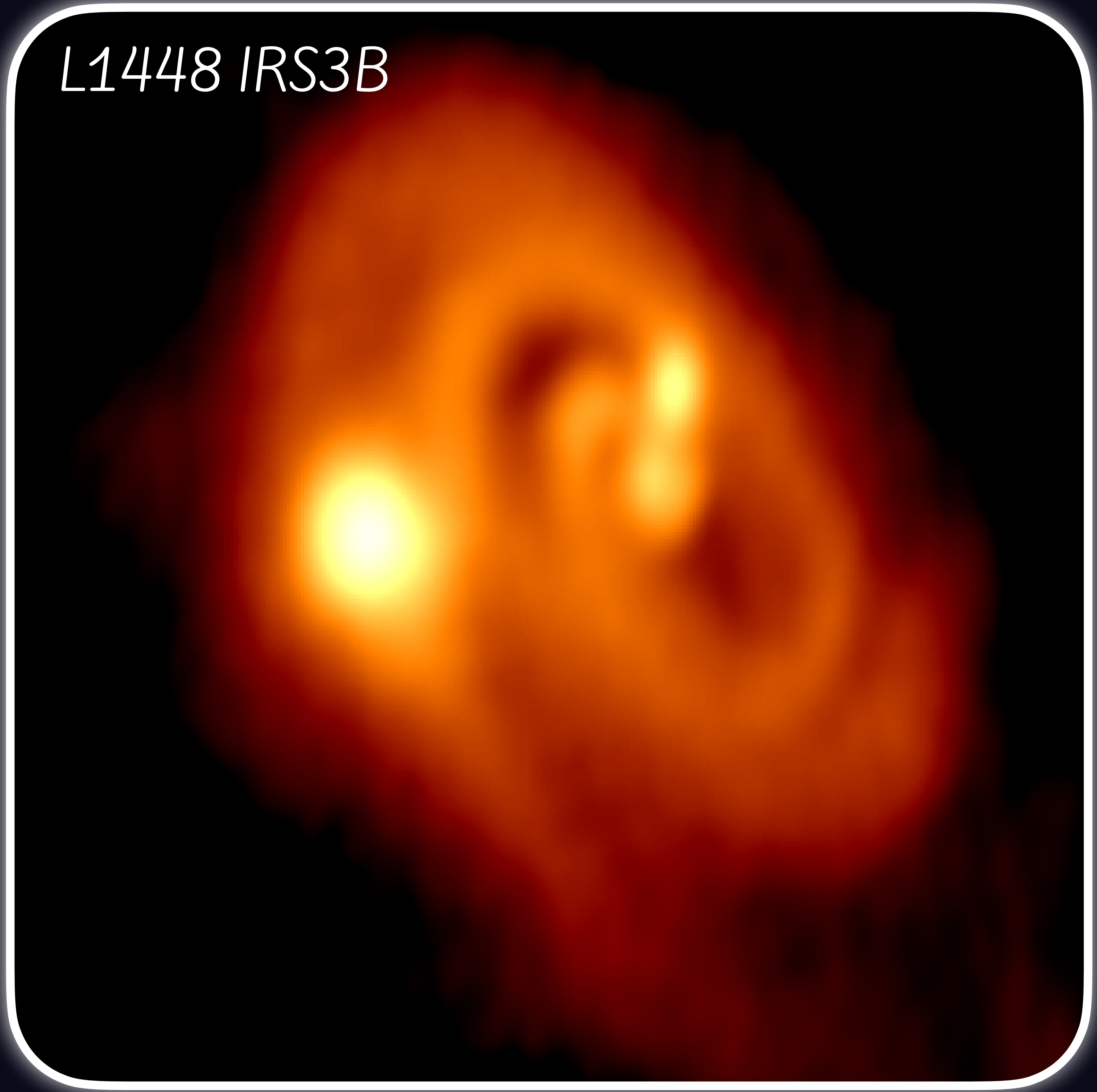
Toomre 1964



Observations of Gravitationally Unstable Discs



Andrews+ 2018, Huang+ 2018



Tobin+ 2016, Reynolds+ 2020

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Thermodynamics

Radiative Transfer

+ Models the disc realistically.
- Slow and computationally expensive.

β cooling

+ Fast and computationally inexpensive.
- Disc model is not consistent with expectations.

Simulating Gravitationally Unstable Discs with β Cooling

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The Internal Energy Equation

$$\frac{\mathrm{d}u}{\mathrm{d}t} = -\frac{P}{\rho}(\nabla \cdot v) + \Lambda_{\mathrm{shock}} - \frac{\Lambda_{\mathrm{cool}}}{\rho}$$

↓ PdV Heating

↓ Shock Heating

↓ Cooling Term

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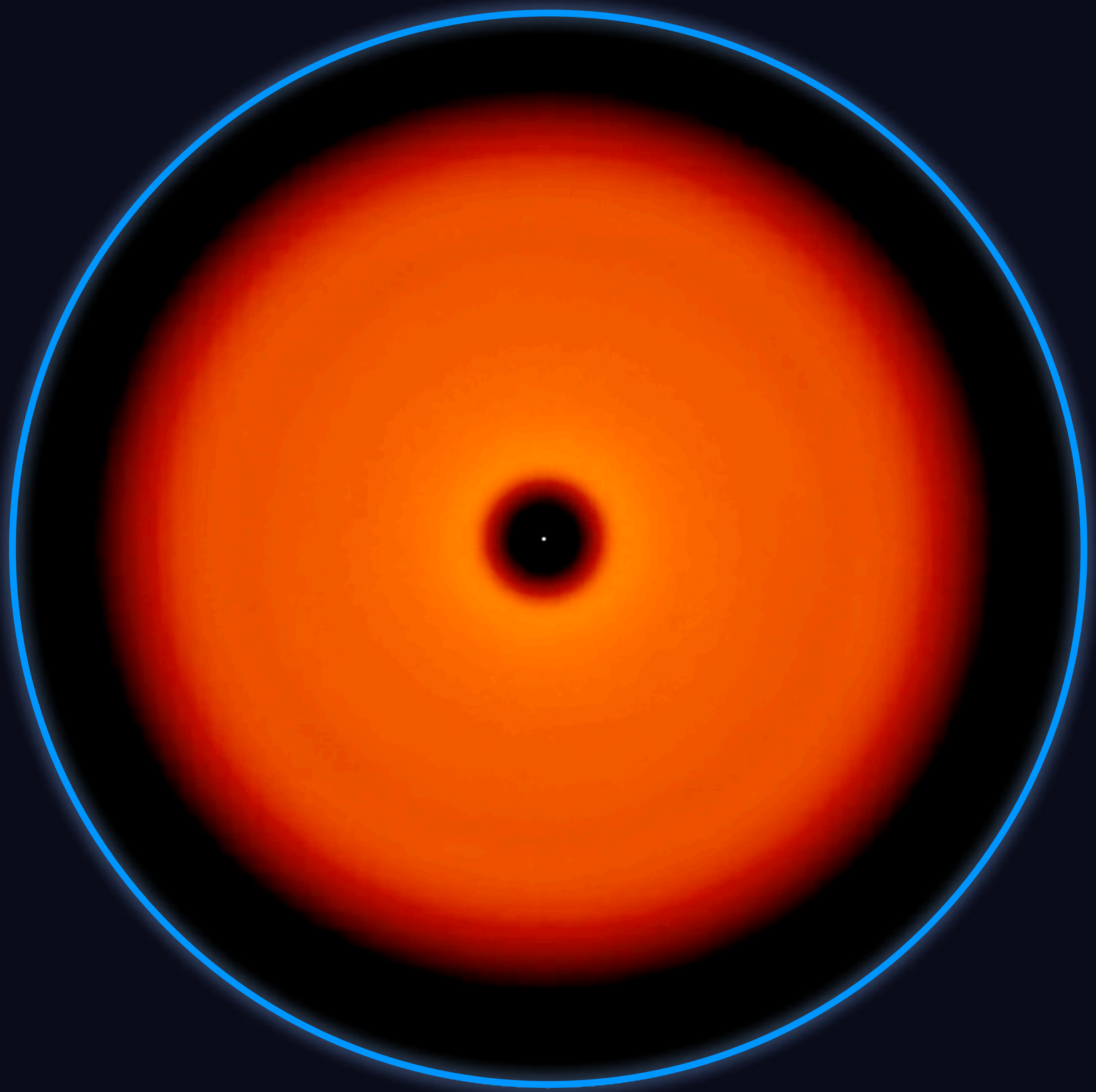
High Toomre Q

- *Very little PdV or shock heating.*
- *The disc is free to cool until gravitational instabilities develop.*



Low Toomre Q

- Dense spiral structures have formed.
- PdV and shock heating become more important.

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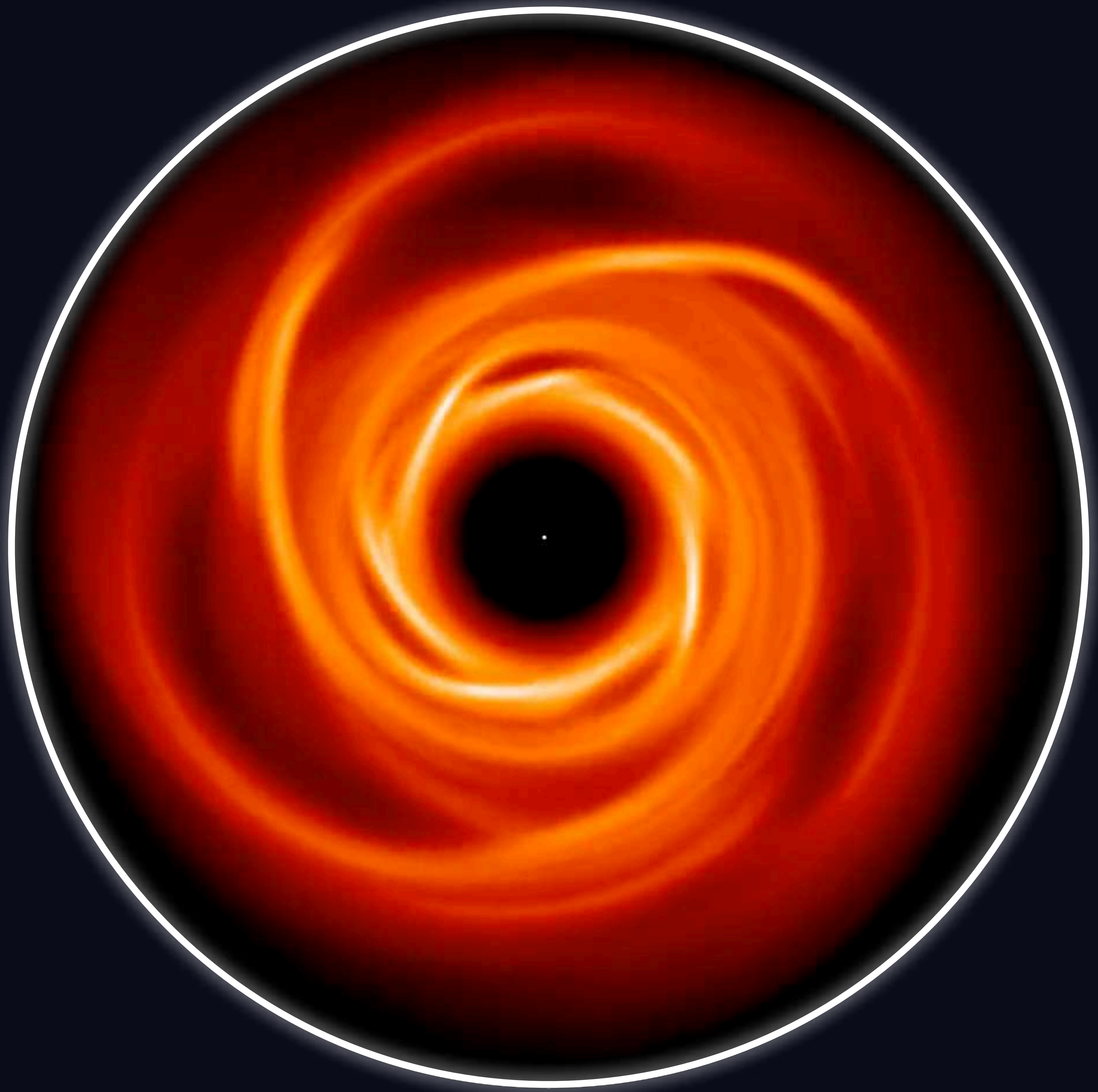
Heating and Cooling in Balance

- PdV and shock heating balance the cooling in the disc.
- The disc cannot fragment. Or become stable.
- It will remain gravitationally unstable with spiral arms.



Simulating Gravitationally Unstable Discs with Radiative Transfer

Calculates the temperatures

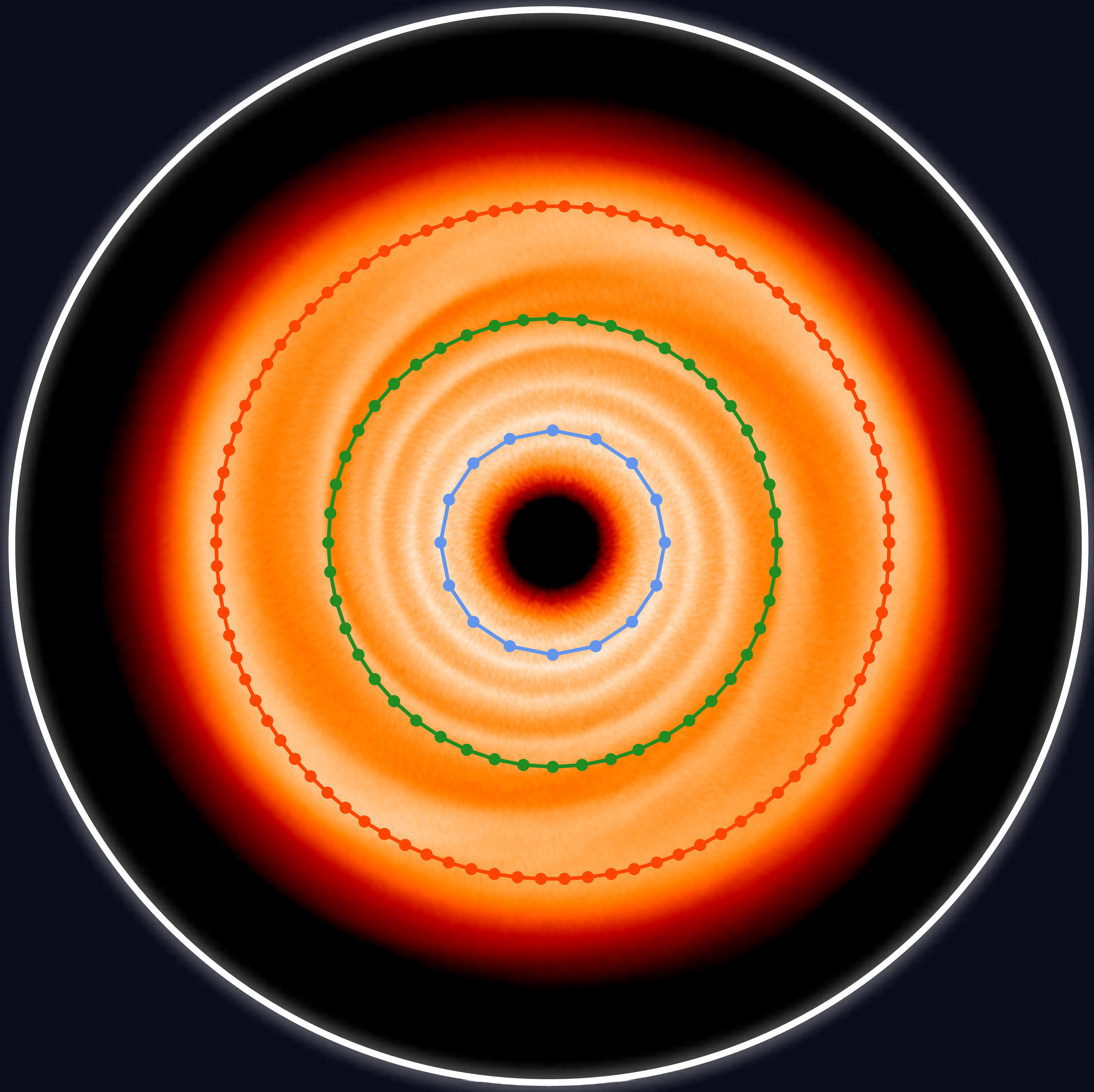
- Using the luminosity of the star,
- Particle data from PHANTOM,
- PdV and Shock heating from PHANTOM.

Moves the particles

- Energy is constant between time-steps.
- At the end of each time-step, MCFOST updates the temperatures.

Frequency of calculations

- The temperature is updated every 7.071 years.
- Ensures that particles do not evolve too much between temperature calculations regardless of where they are in the disc.



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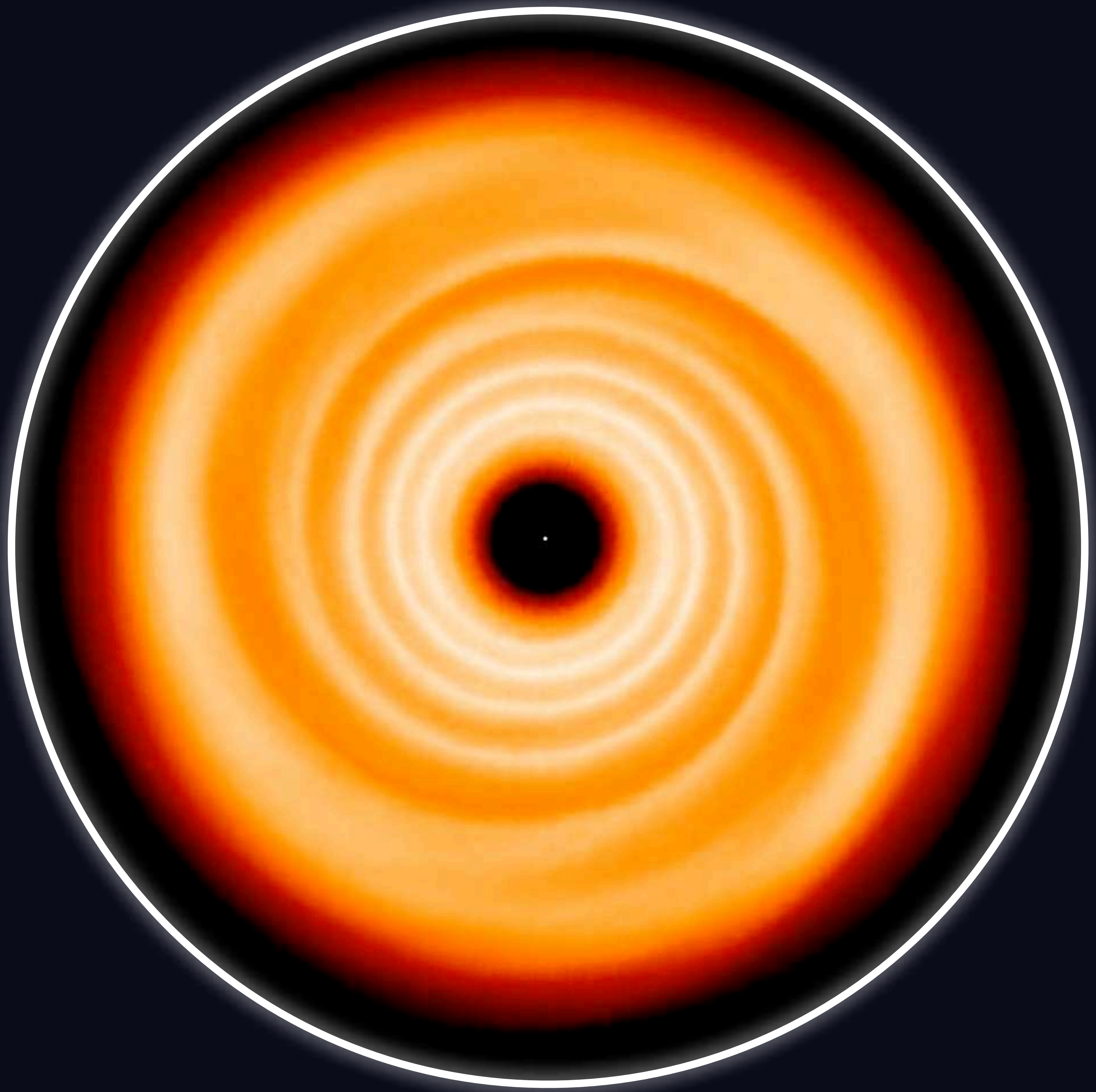
How Many Photons?

- Previous works (Nealon+ 2020, Borchert+ 2022a,b) have used 100 photons for every SPH particle. However, those discs were not as massive.
- Gravitationally unstable discs are much more massive, and hence very optically thick.
- Need a much higher number of photons to ensure every SPH particle is reached. If no photons reach, the temperature of the particle. is set to 2.73K. This results in a negative feedback loop resulting in artificial fragmentation.
- We use 5000 photons for every SPH particle.

Evolution of a $0.1M_{\odot}$ disc with Radiative Transfer



Rowther+ (in prep)

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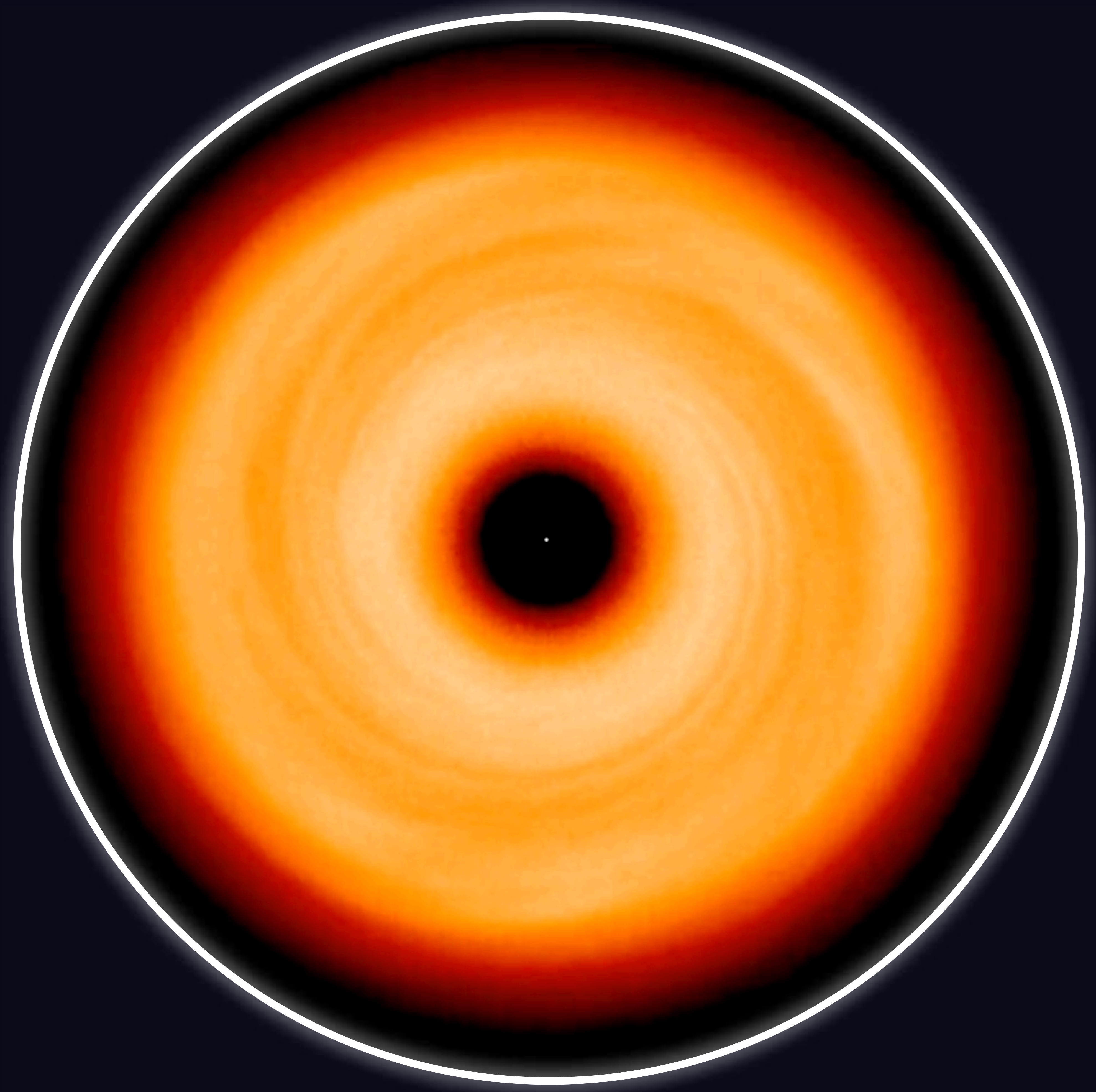
Evolution of a $0.1M_{\odot}$ disc with Radiative Transfer



Gravitational instabilities become weaker over time.

Rowther+ (in prep)

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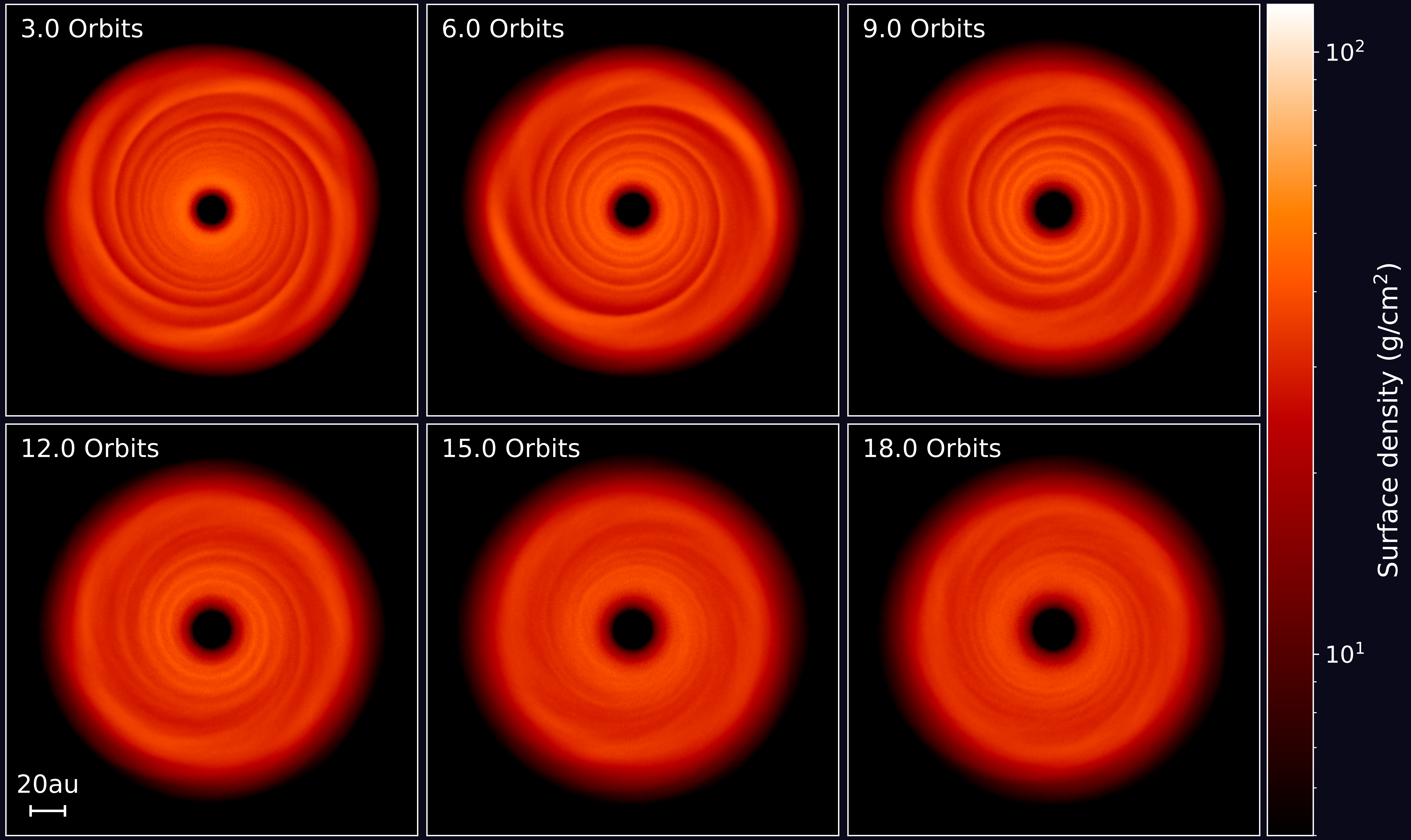
Radiative Transfer

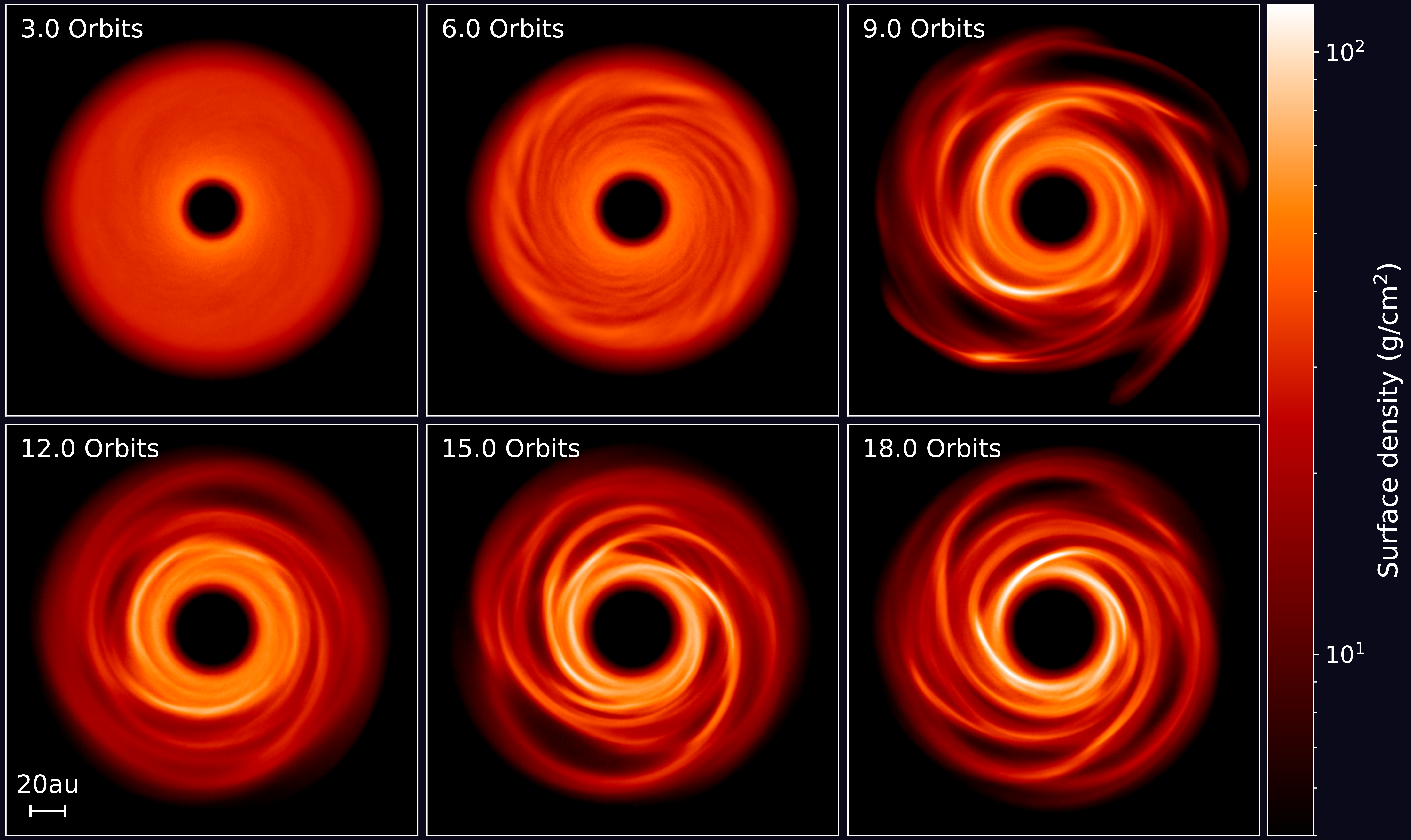


Rowther+ (in prep)

- *Spiral structures are weaker.*
- *Disc becomes more stable over time.*

β cooling

- Spiral structures are stronger.
- Disc is in a steady state with spiral structures.



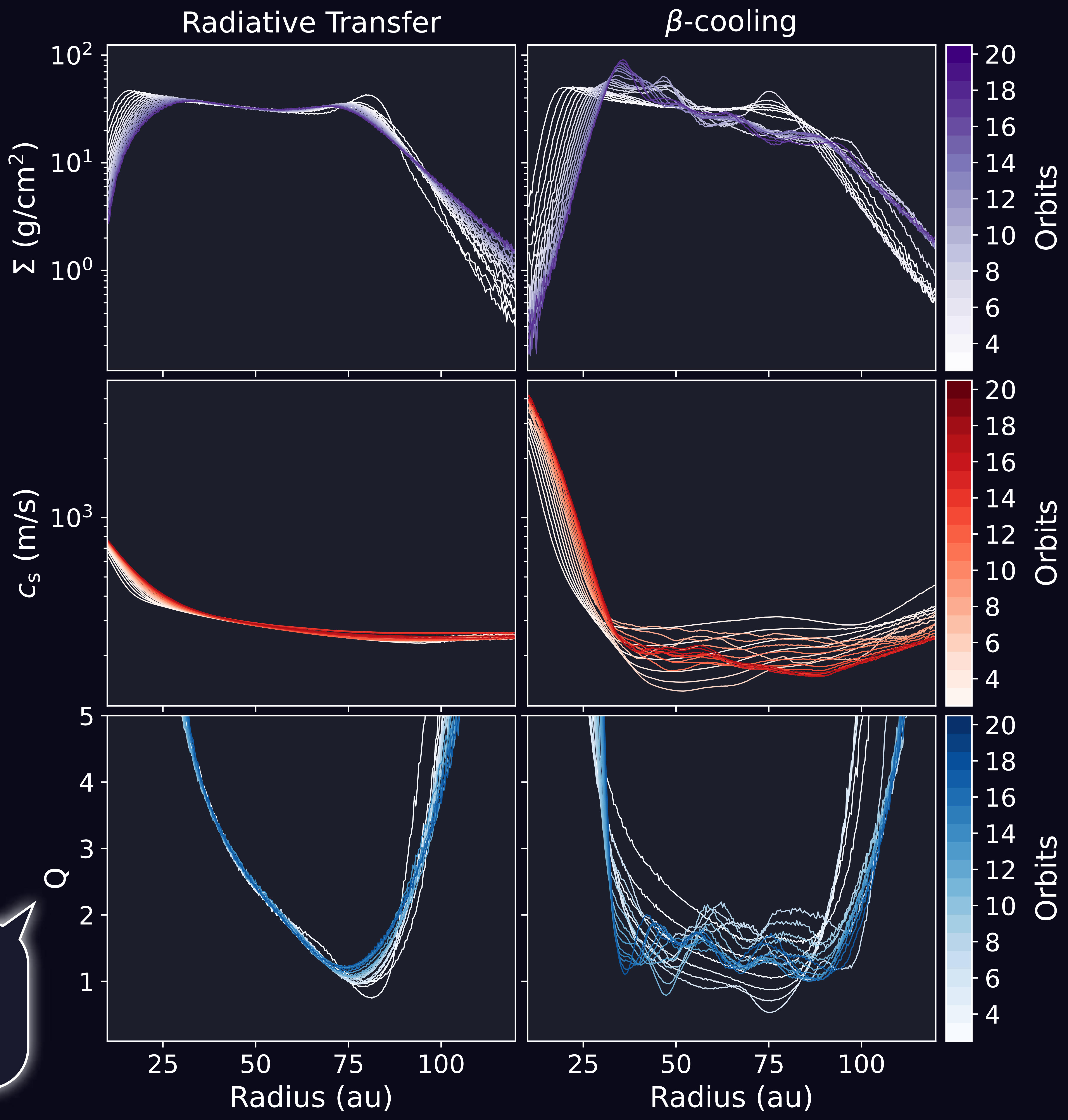
Rowther+ (in prep)

Evolution of Disc Instability

Radiative Transfer

- Disc is warmer.
- Temperature is fairly constant.
- Q has a steady increase.

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

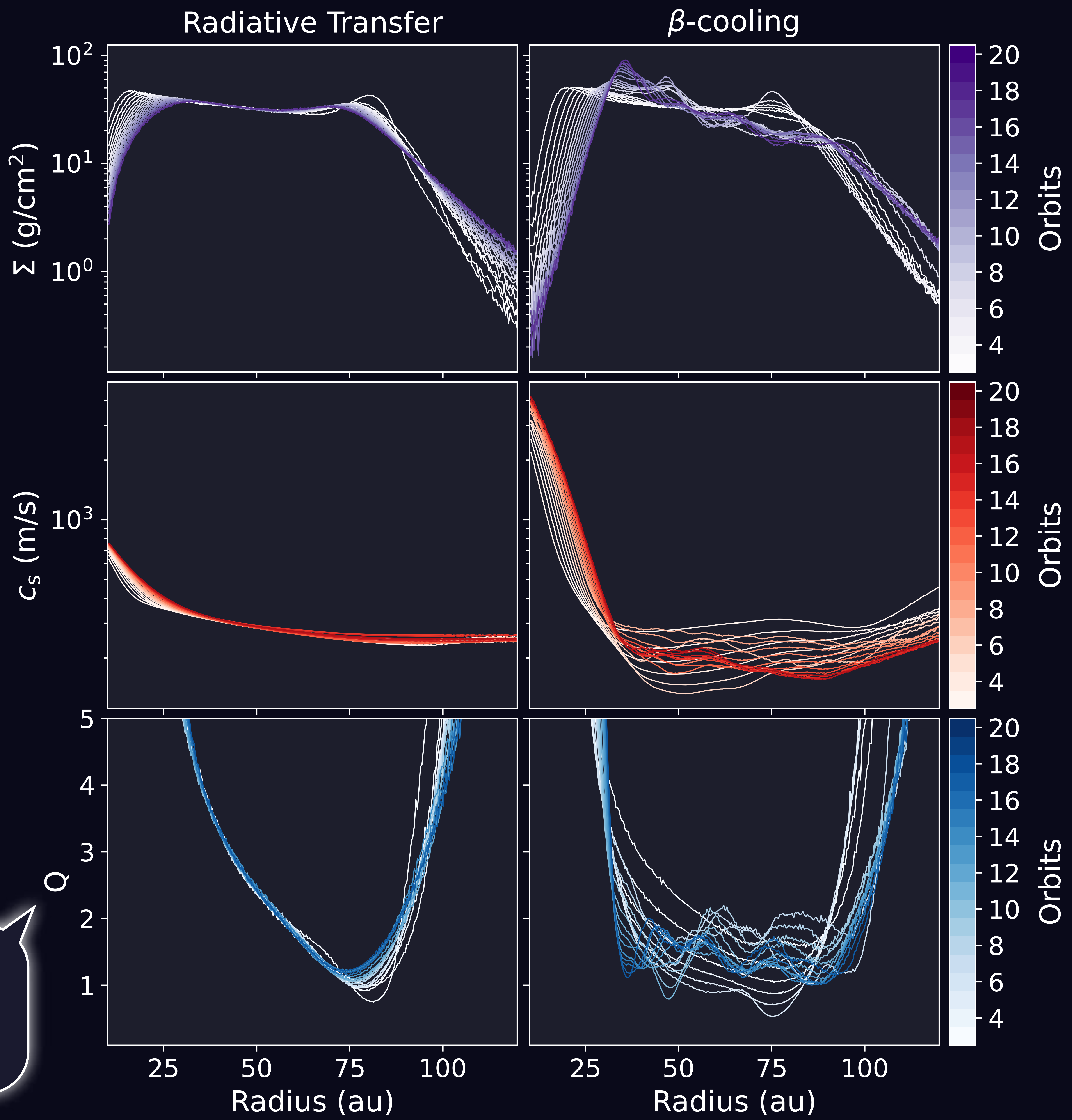


Evolution of Disc Instability

β cooling

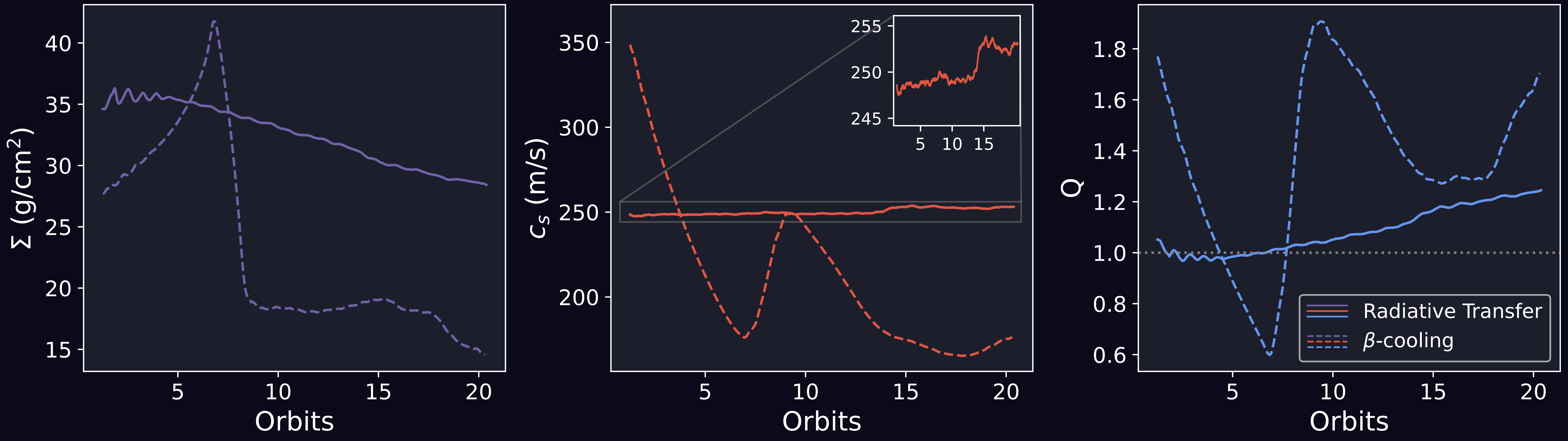
- Both surface density and sound speed evolve.
- Q eventually stabilises when heating and cooling are in balance.

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



Evolution of Disc Instability (At R=77AU)

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



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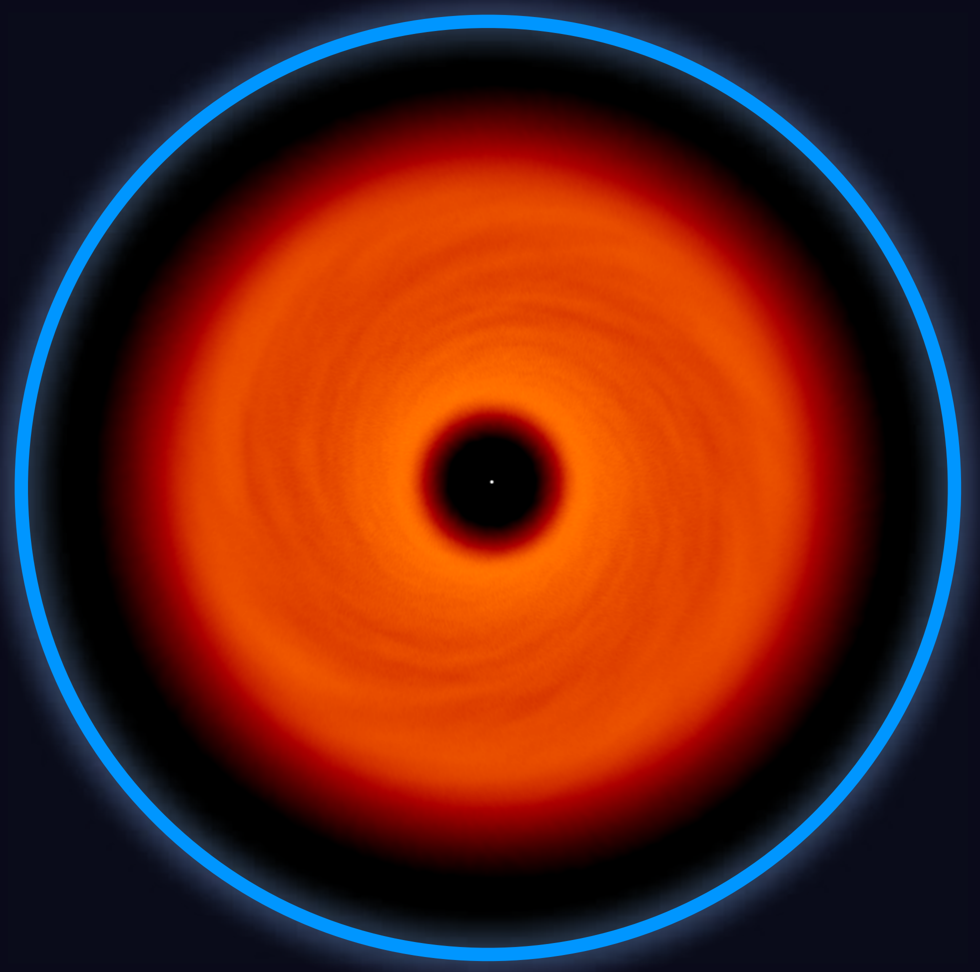
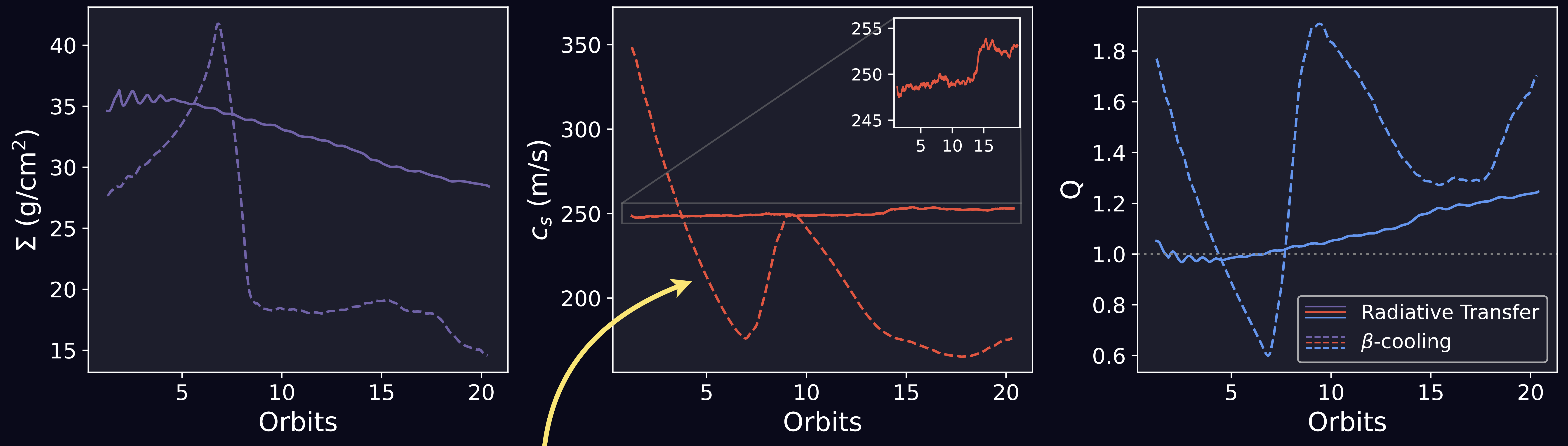
Evolution of Disc Instability (At R=77AU)

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



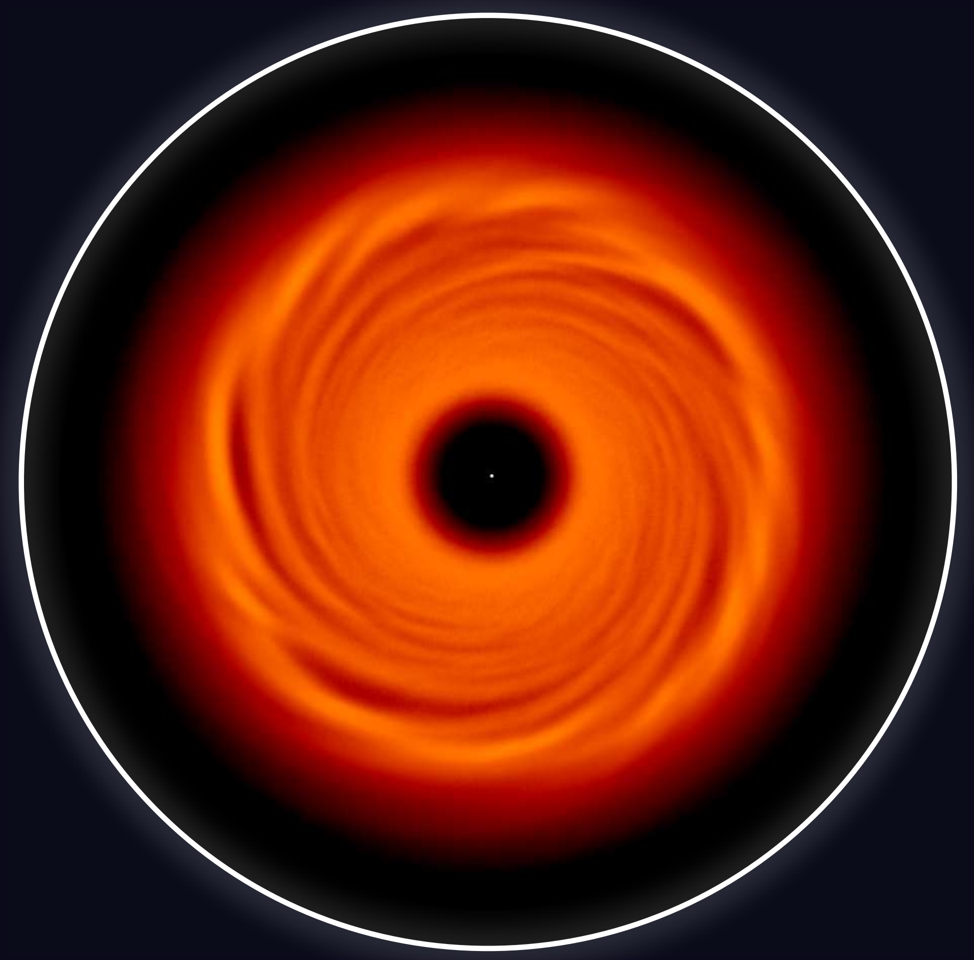


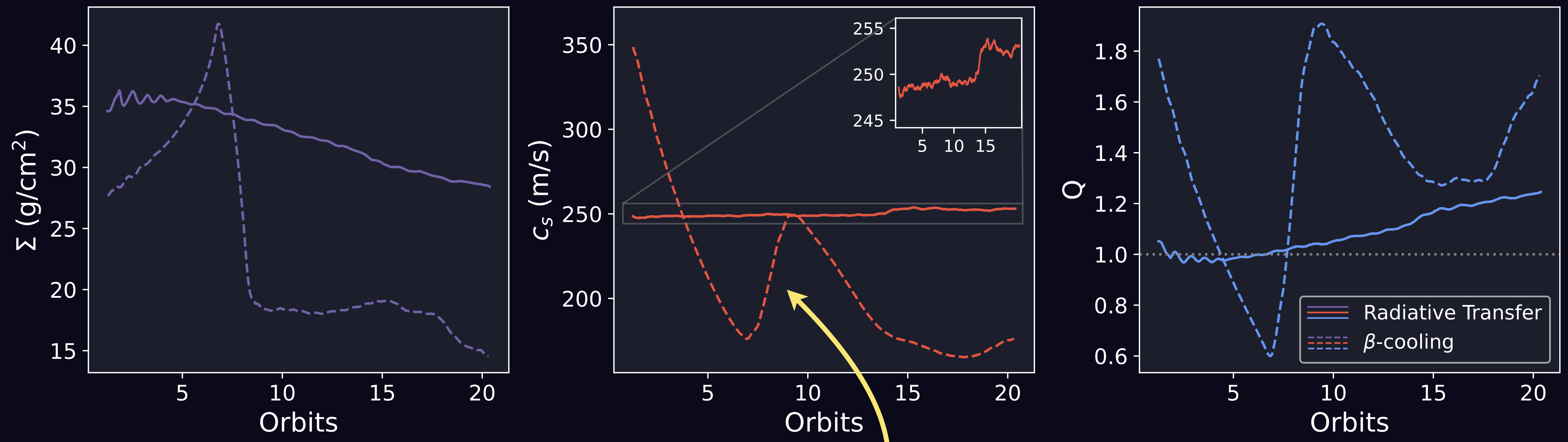
Initially, very little PdV and shock heating, so the disc just cools.

Evolution of Disc Instability (At R=77AU)

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

Disc has cooled enough to form dense spirals.



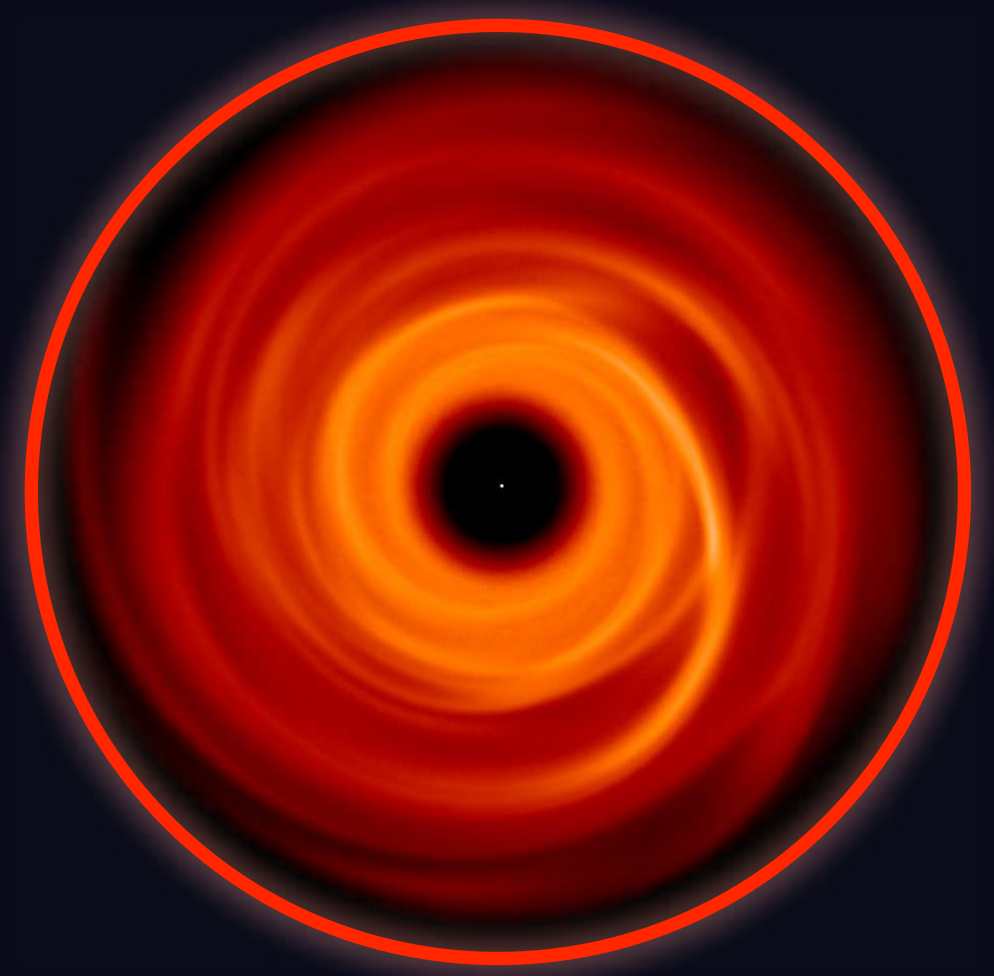


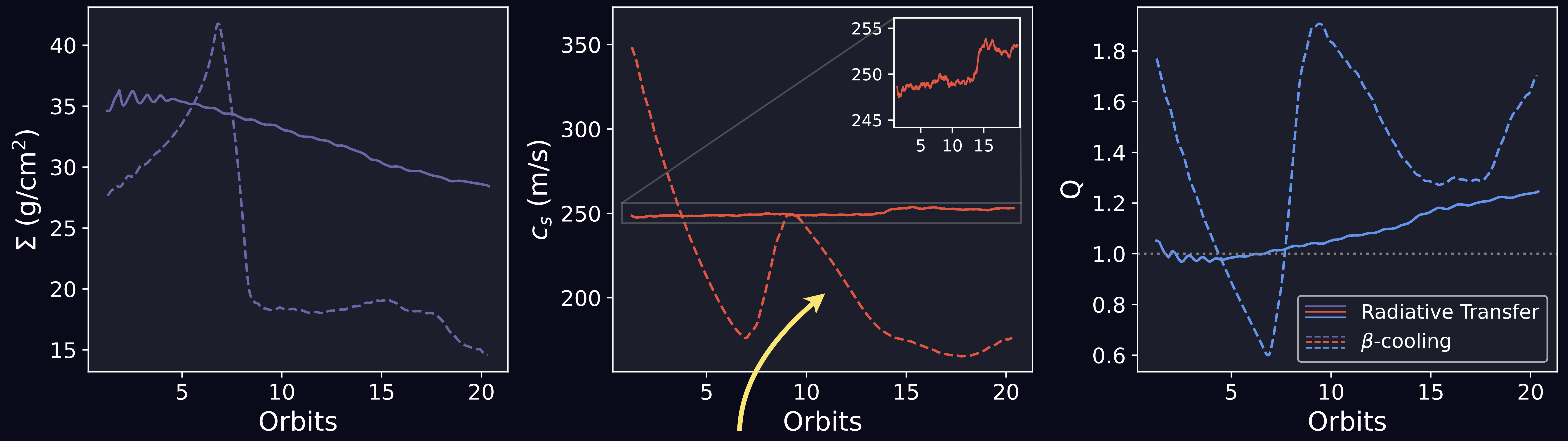
Spirals are strong enough to stabilise the disc through PdV and shock heating

Evolution of Disc Instability (At R=77AU)

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

Spirals weaken as the disc heats up.



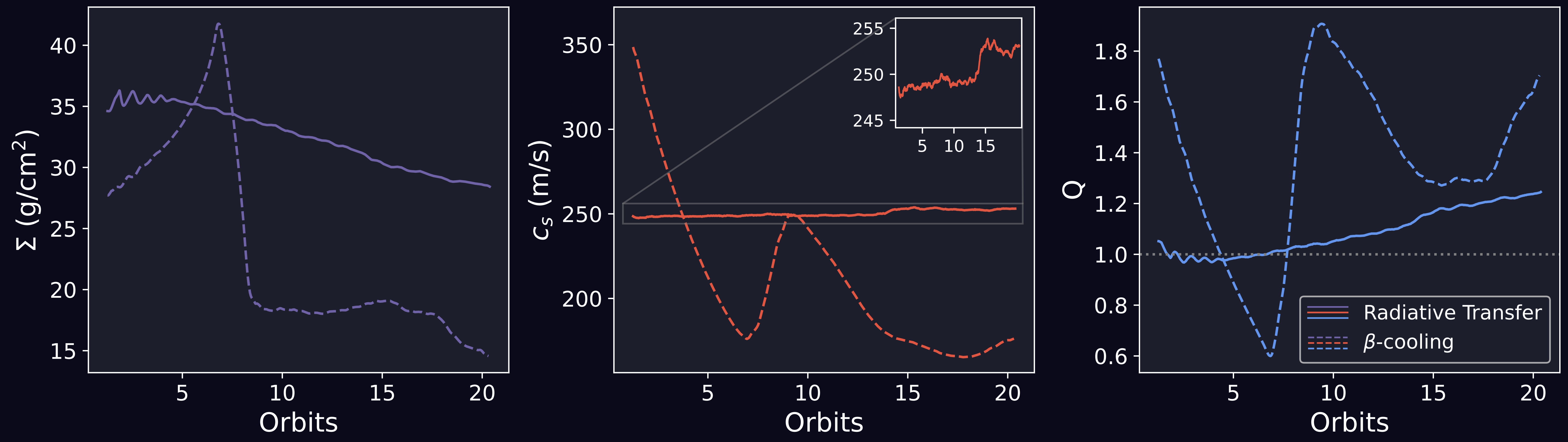


Cooling takes over once more as PdV and shock heating lessen

Evolution of Disc Instability (At R=77AU)

Steady spiral structures as cooling is balanced by PdV and shock heating

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



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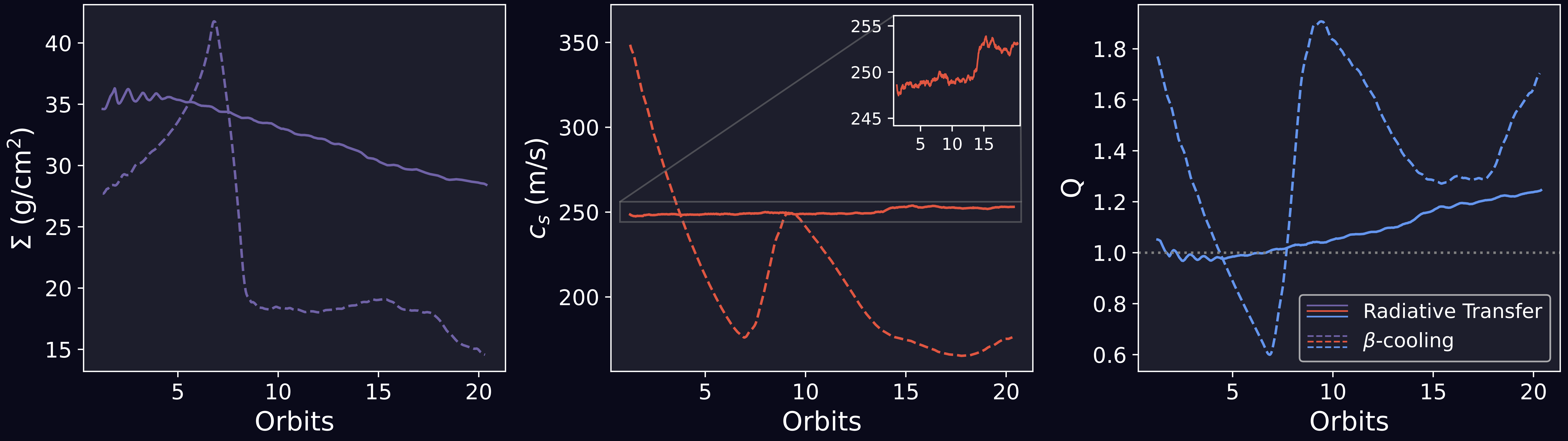
Evolution of Disc Instability (At R=77AU)

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



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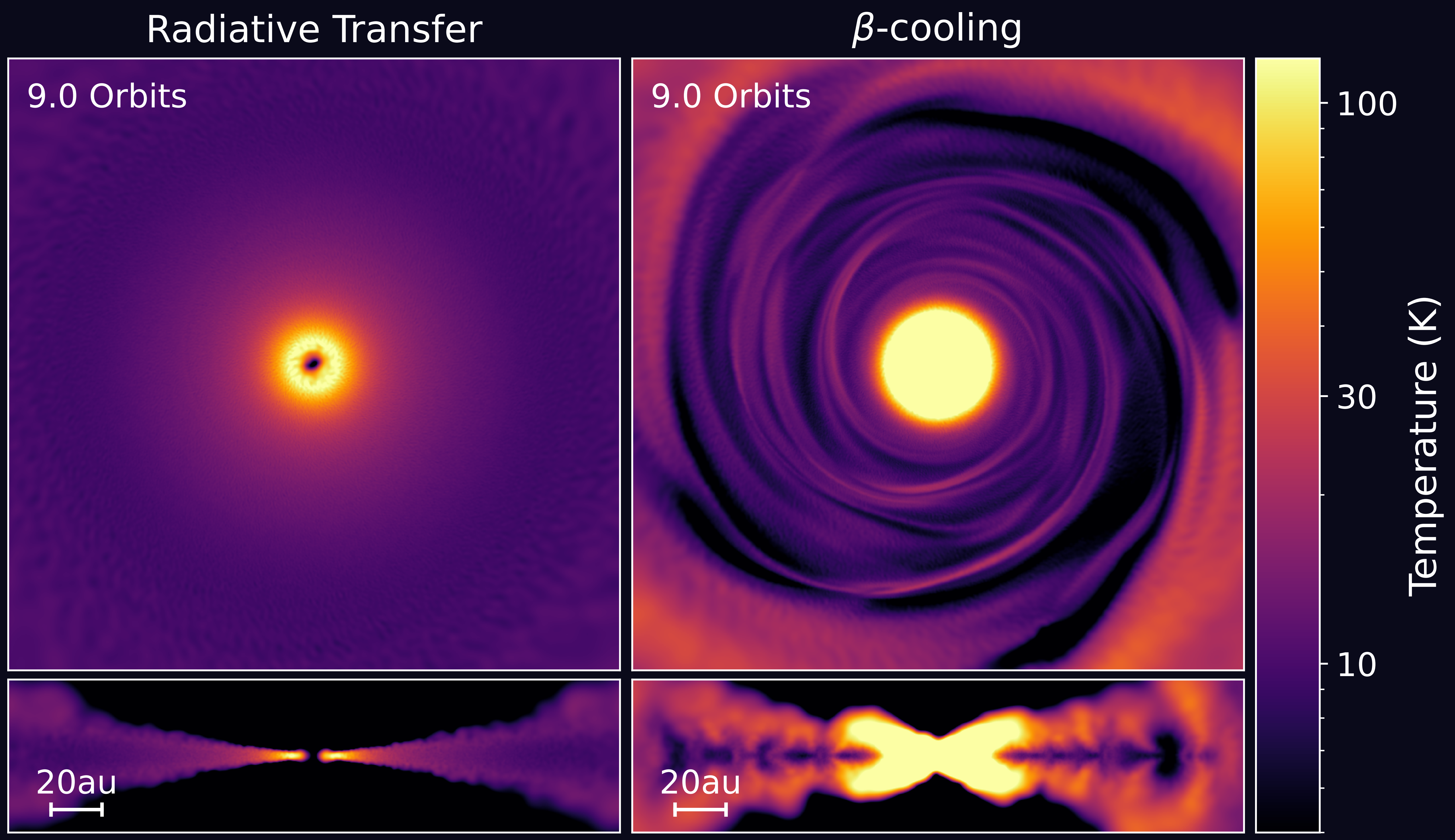
Why is PdV and Shock heating more important for β cooling?

Temperature Structure

β cooling

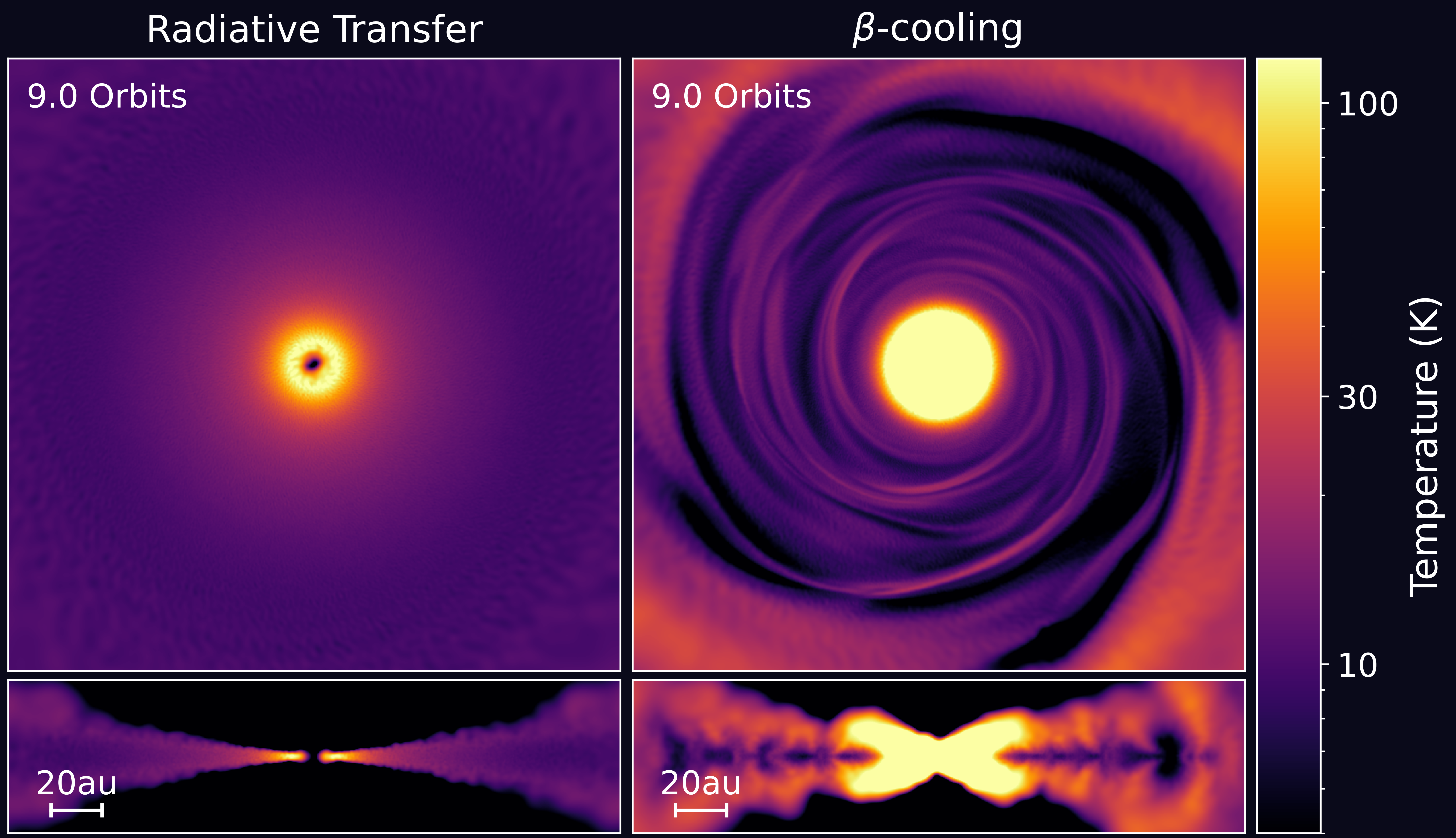
- A colder disc.
- PdV and shock heating from the spirals are the source of heating.



Temperature Structure

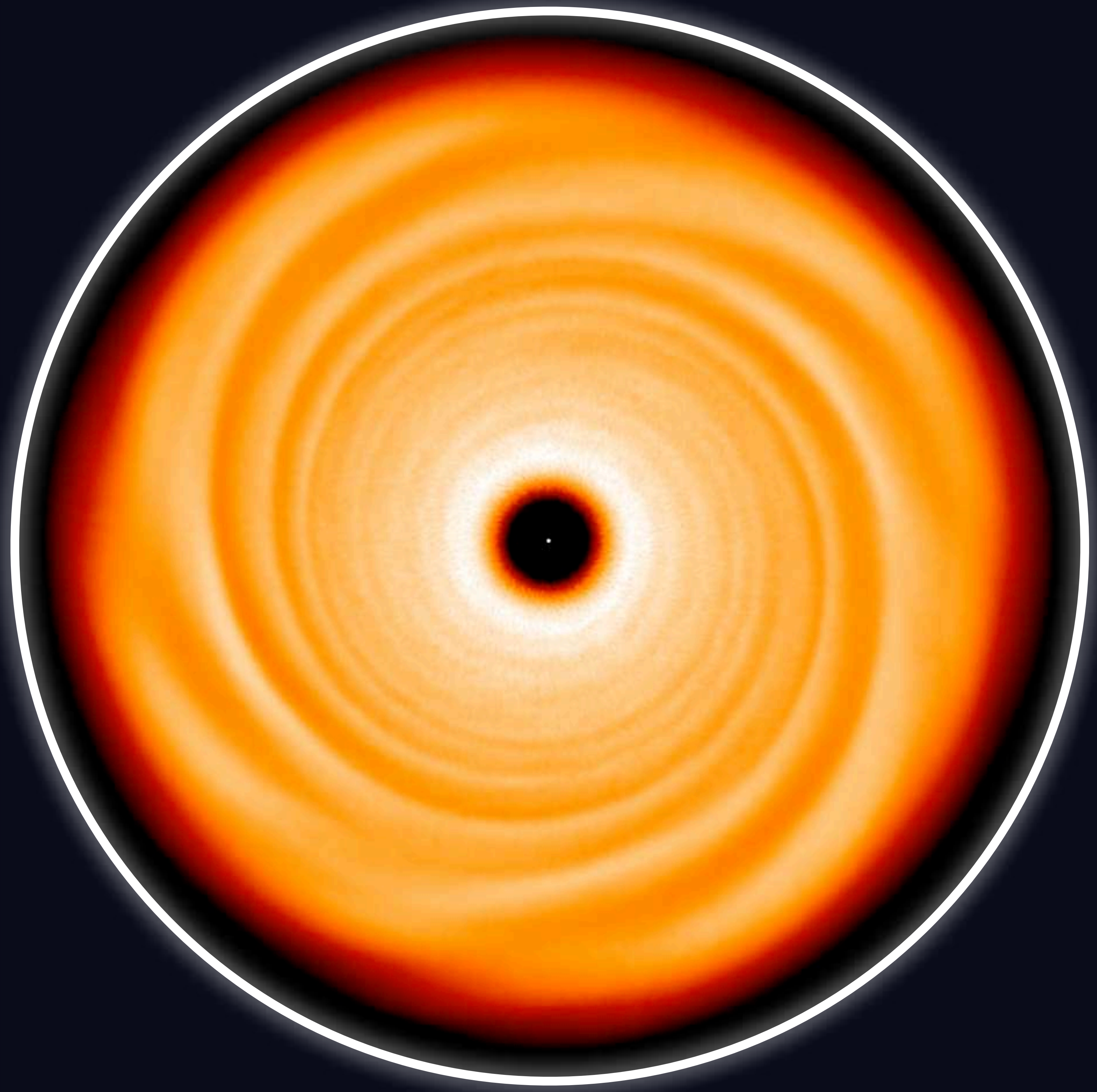
Radiative Transfer

- Disc is warmer.
- Stellar irradiation is the dominant source of heating.



The Computational Cost

Radiative Transfer - 3e8 CPU seconds

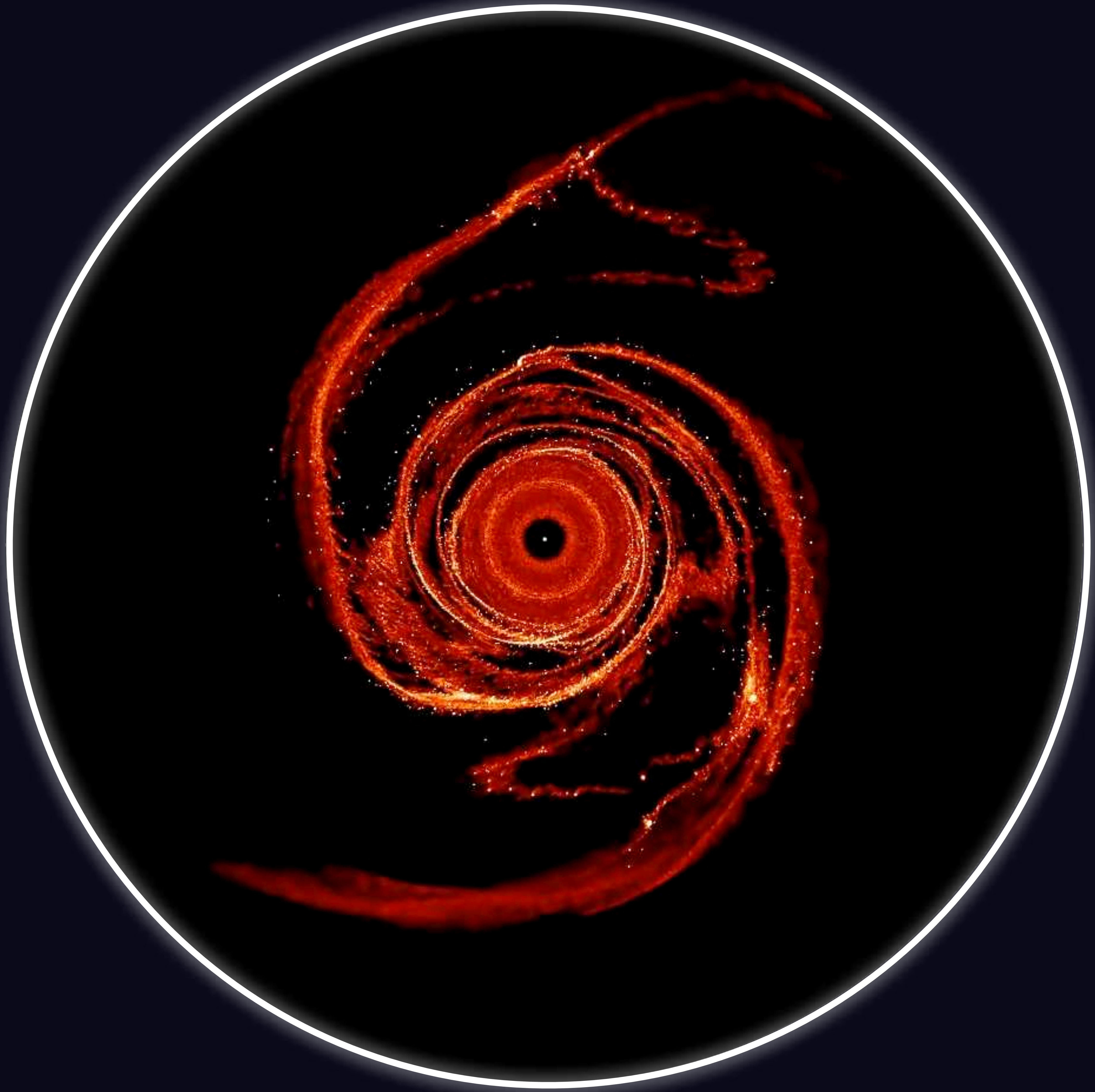


β cooling - 3e6 CPU seconds

Why bother simulating for months?

Dust Dynamics

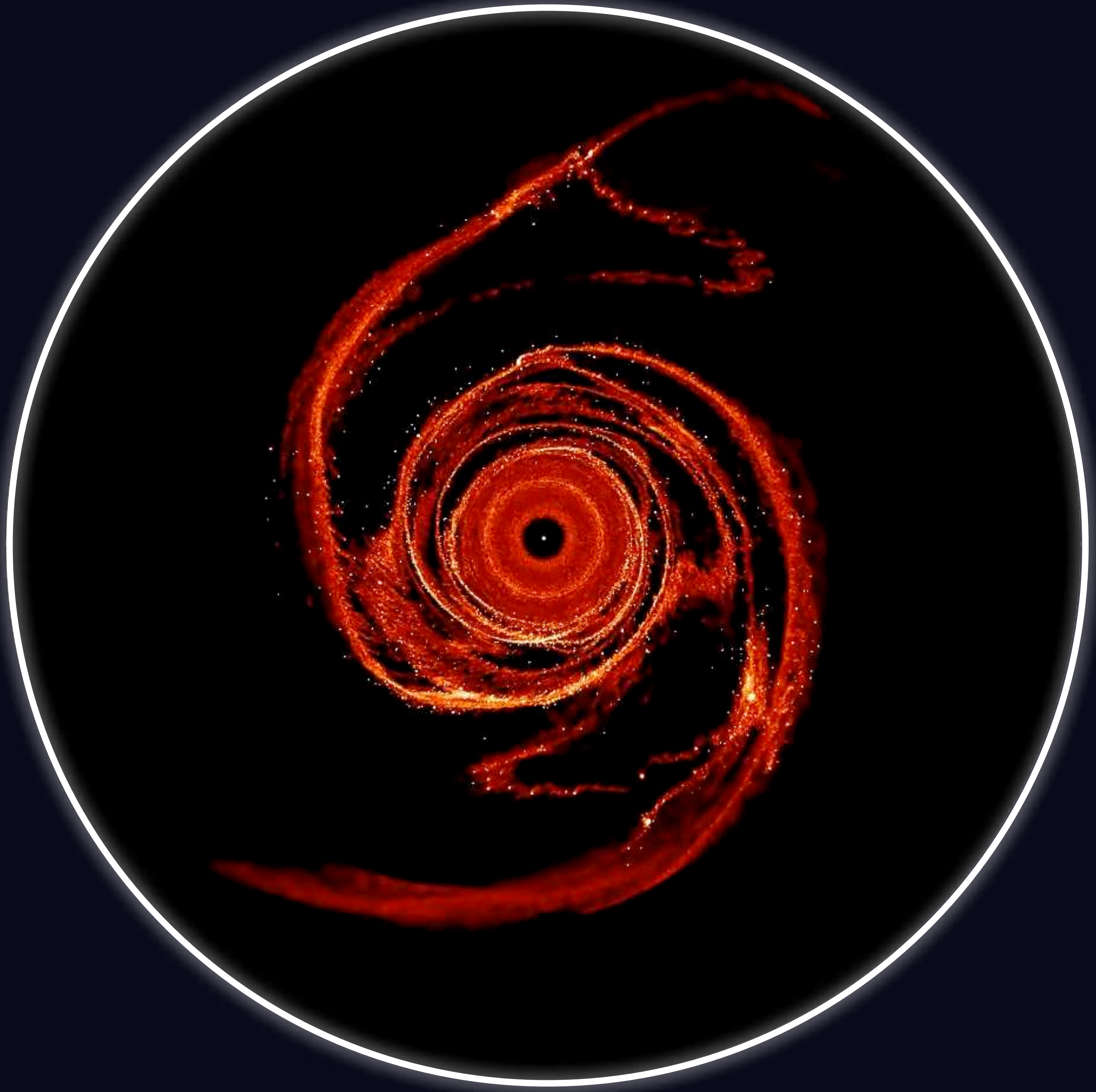
- *The spirals are regions of pressure maxima where dust can be efficiently trapped and grow to form planetesimals.*



Rowther+ 2024

Dust Dynamics

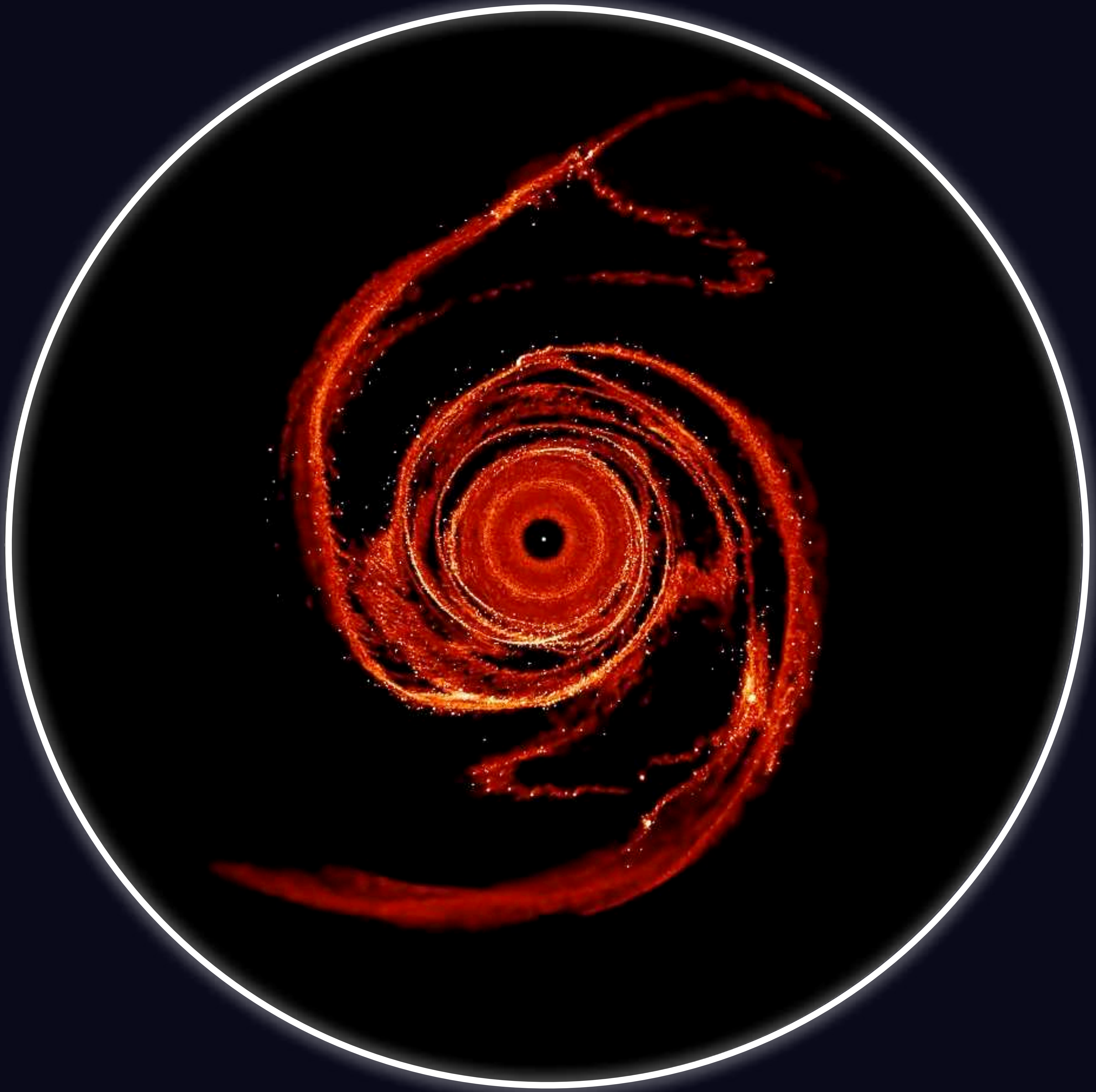
- *Dust is kicked around by high amplitude spirals (Longarini+ 2023b).*



Rowther+ 2024

Dust Dynamics

- The weaker spirals with radiative transfer could be more favourable to forming planetesimals.



Rowther+ 2024

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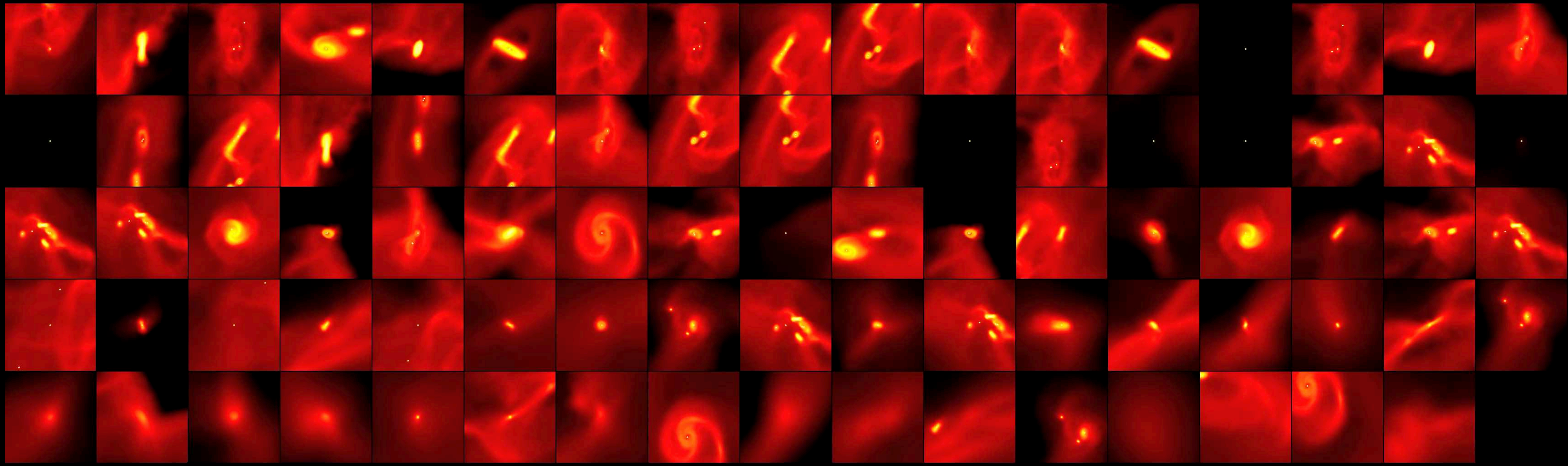

Discs do not evolve in isolation

Matthew Bate
University of Exeter

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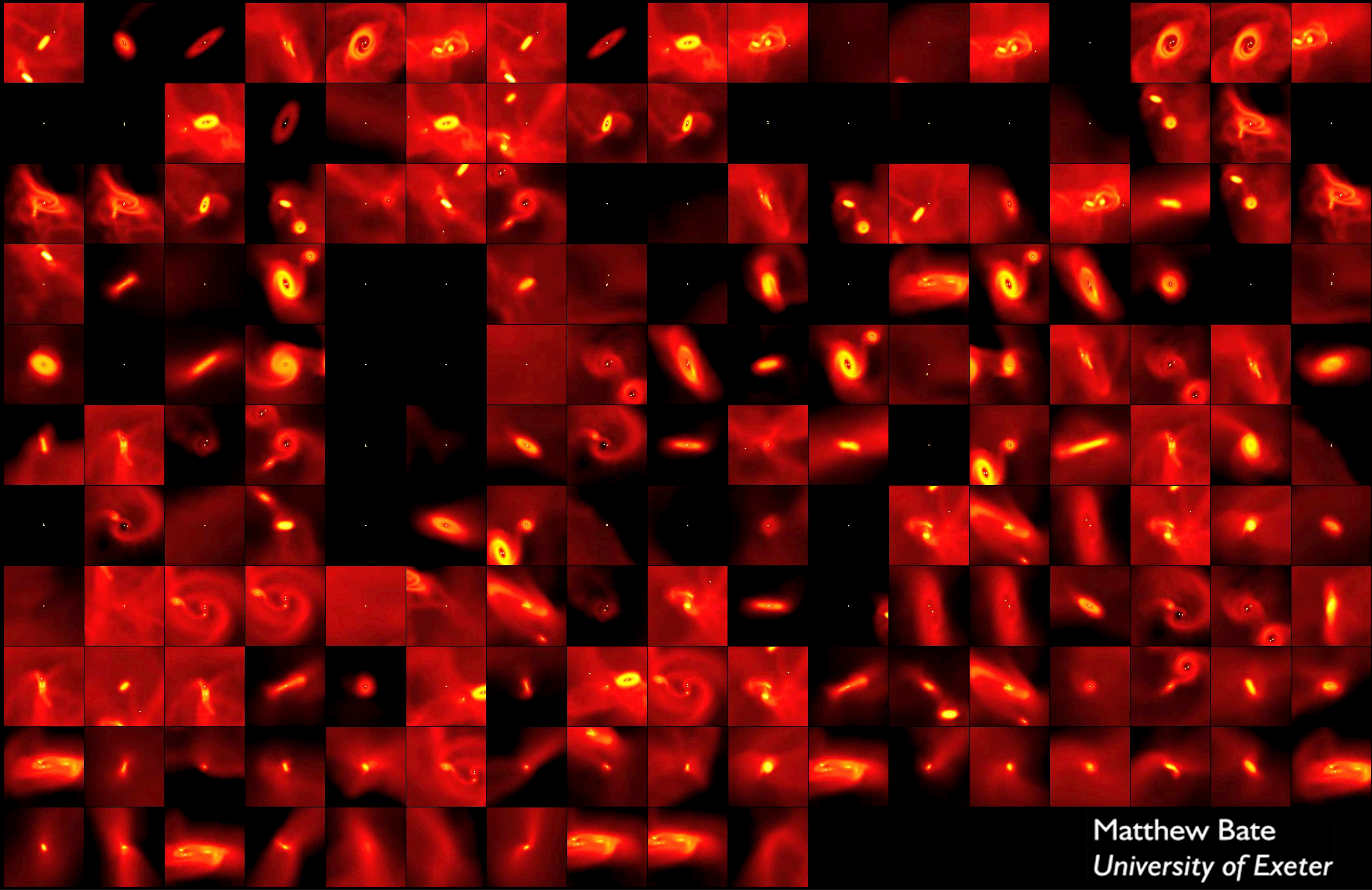
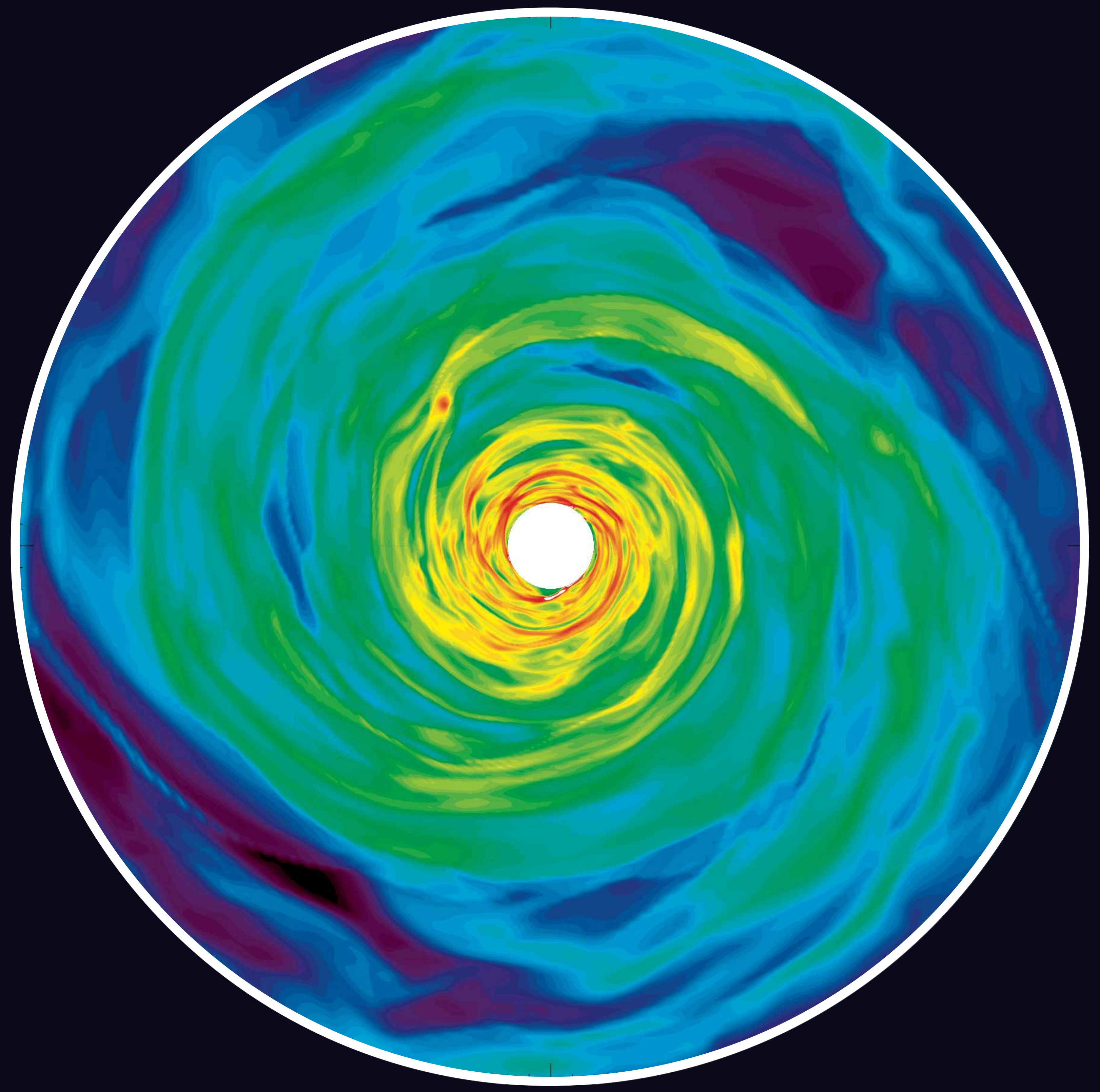
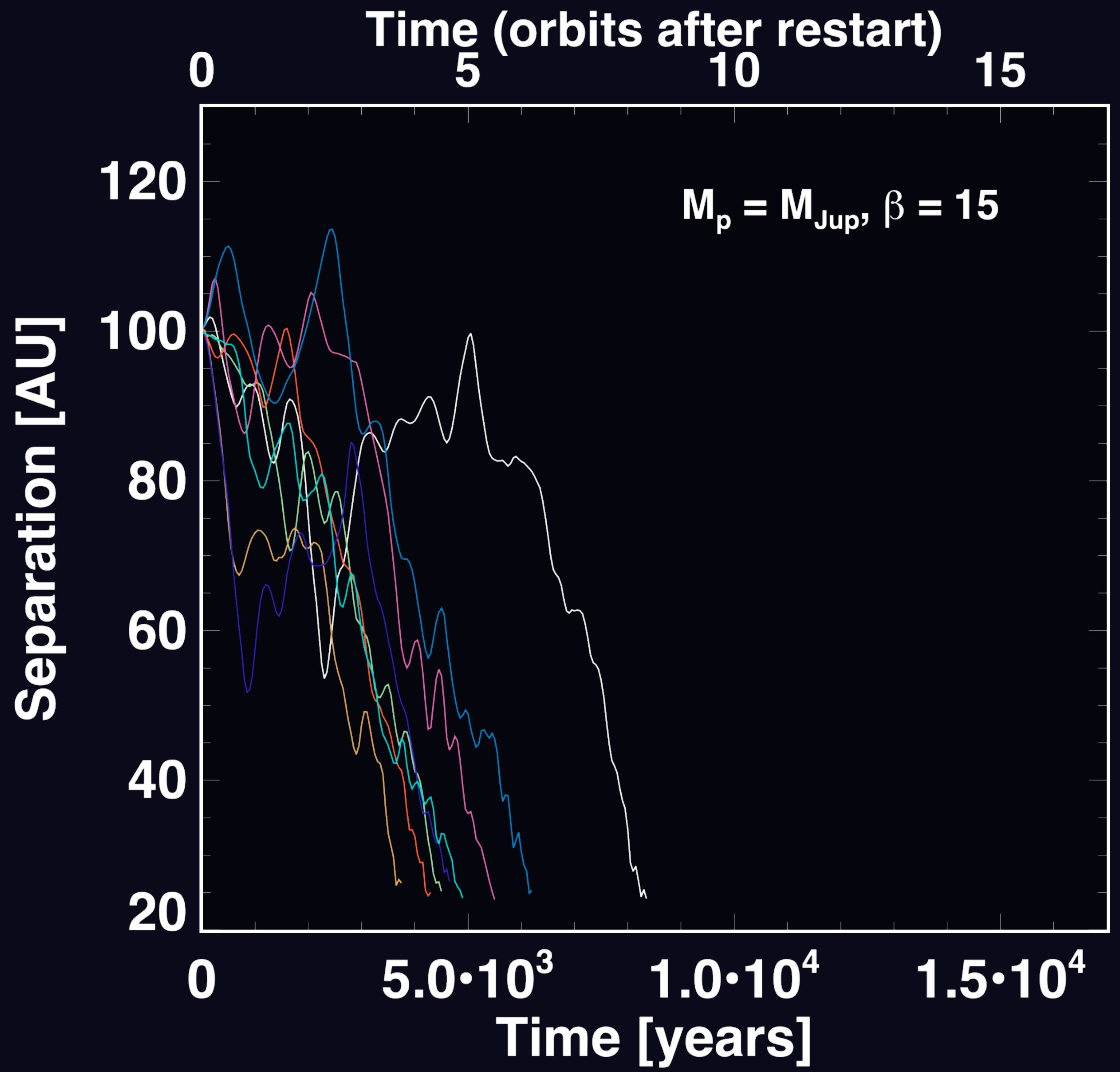
Neighbours, companions, and chaotic accretion episodes all can alter the evolution of the disc



The Doom of Giant Planets



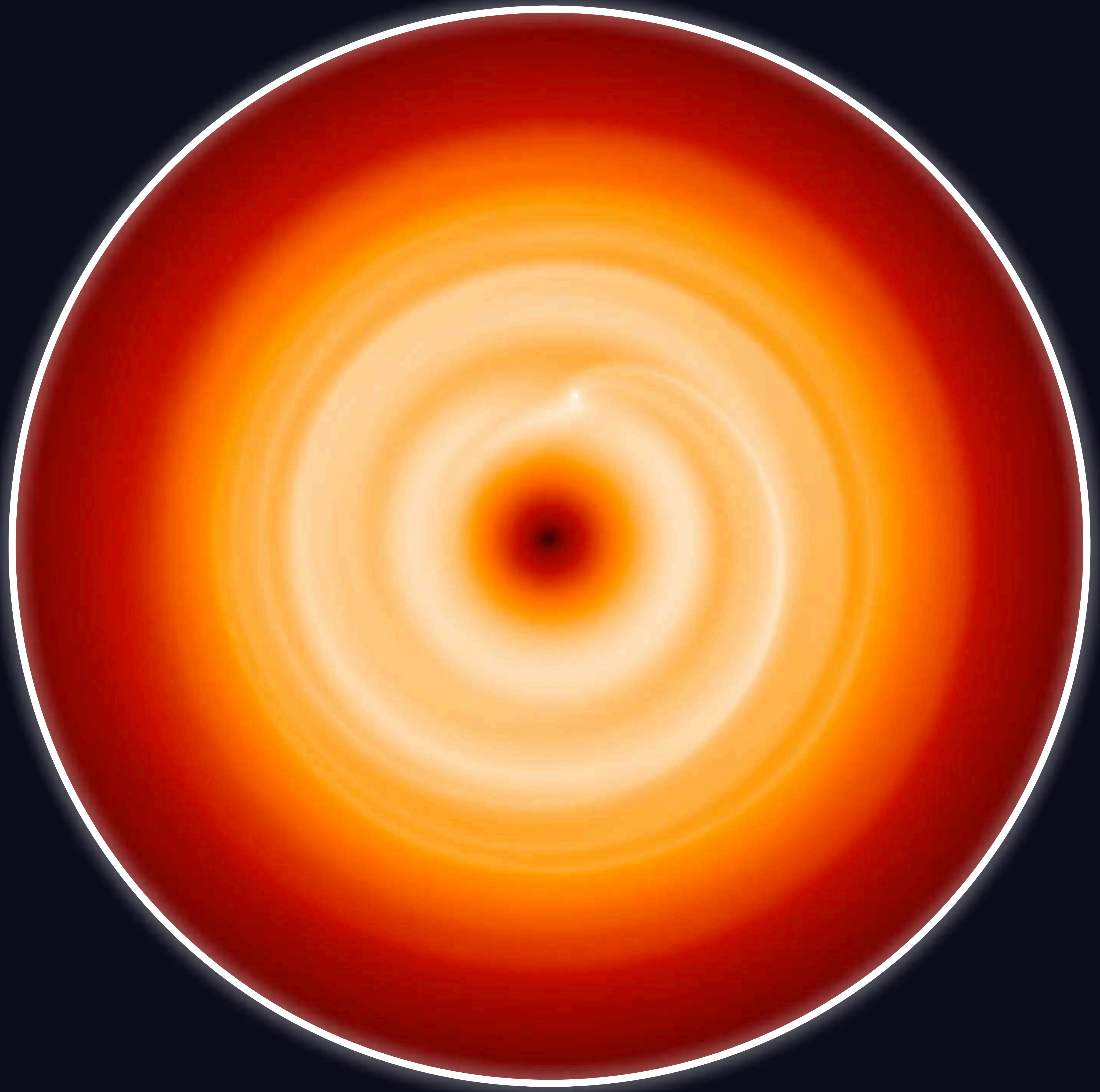


Planets migrate inwards rapidly within a few orbits in discs modelled with simple thermodynamics (Baruteau+ 2011)

Slightly better β cooling

Survival of Giant Planets

- Spirals with radiative transfer are weaker.
- Could be easier for planets to open up gaps, slowing their migration.



Rowther+ 2020, 2023

Conclusions

- Discs can become gravitationally unstable with stellar irradiation.
- The contribution from PdV and shock heating is tiny. the temperature of the disc is instead set by the star, and is fairly constant. This is in contrast to β-cooling where disc is very cold and the spirals set the temperature.
- Hence, the morphology of the spiral structures is different. They are weaker, and less numerous. Additionally, the disc becomes more stable over time as the surface density of the disc decreases.