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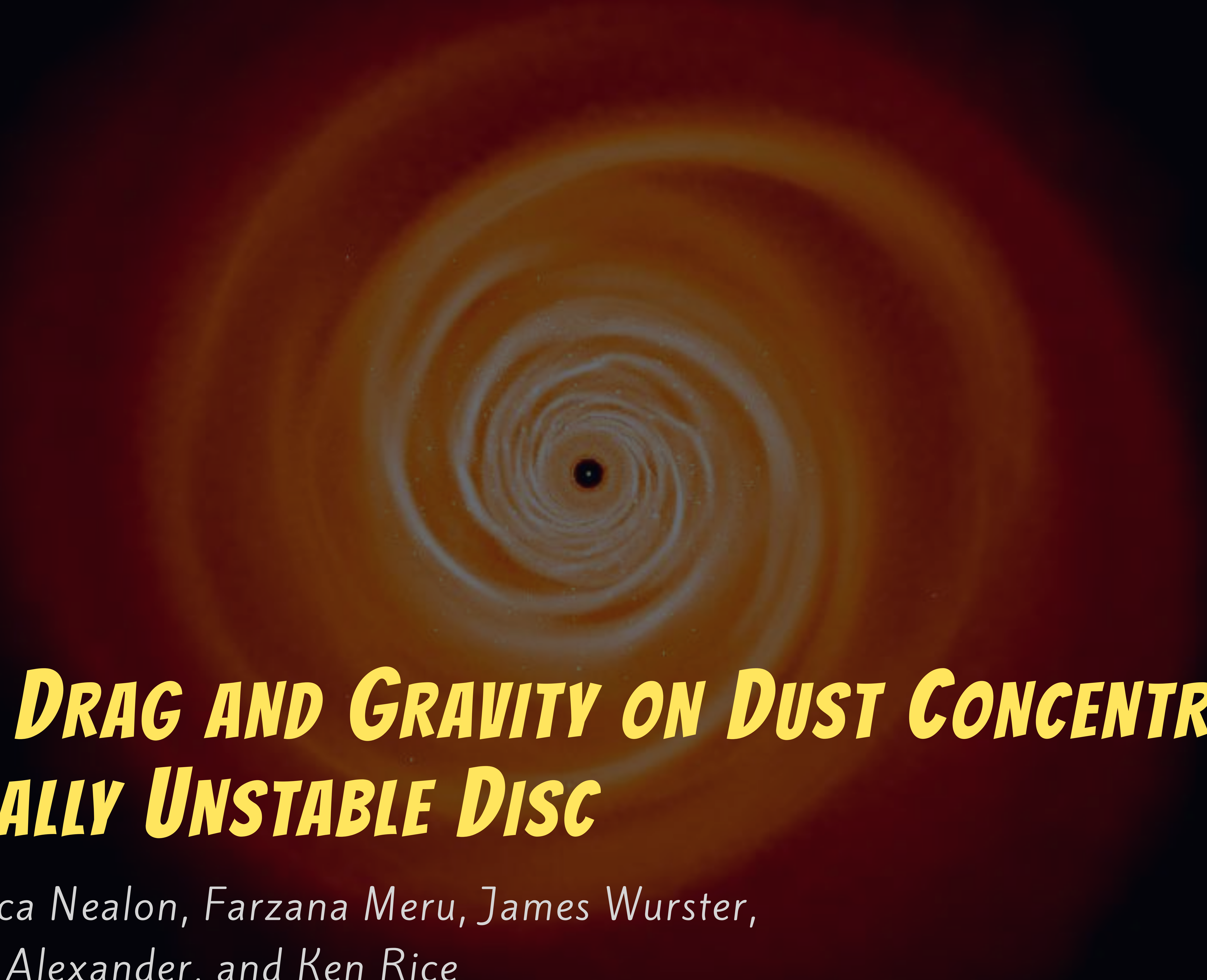
Science and Technology Facilities Council



The Role of Drag and Gravity on Dust Concentration in a Gravitationally Unstable Disc

Sahl Rowther, Rebecca Nealon, Farzana Meru, James Wurster, Hossam Aly, Richard Alexander, and Ken Rice

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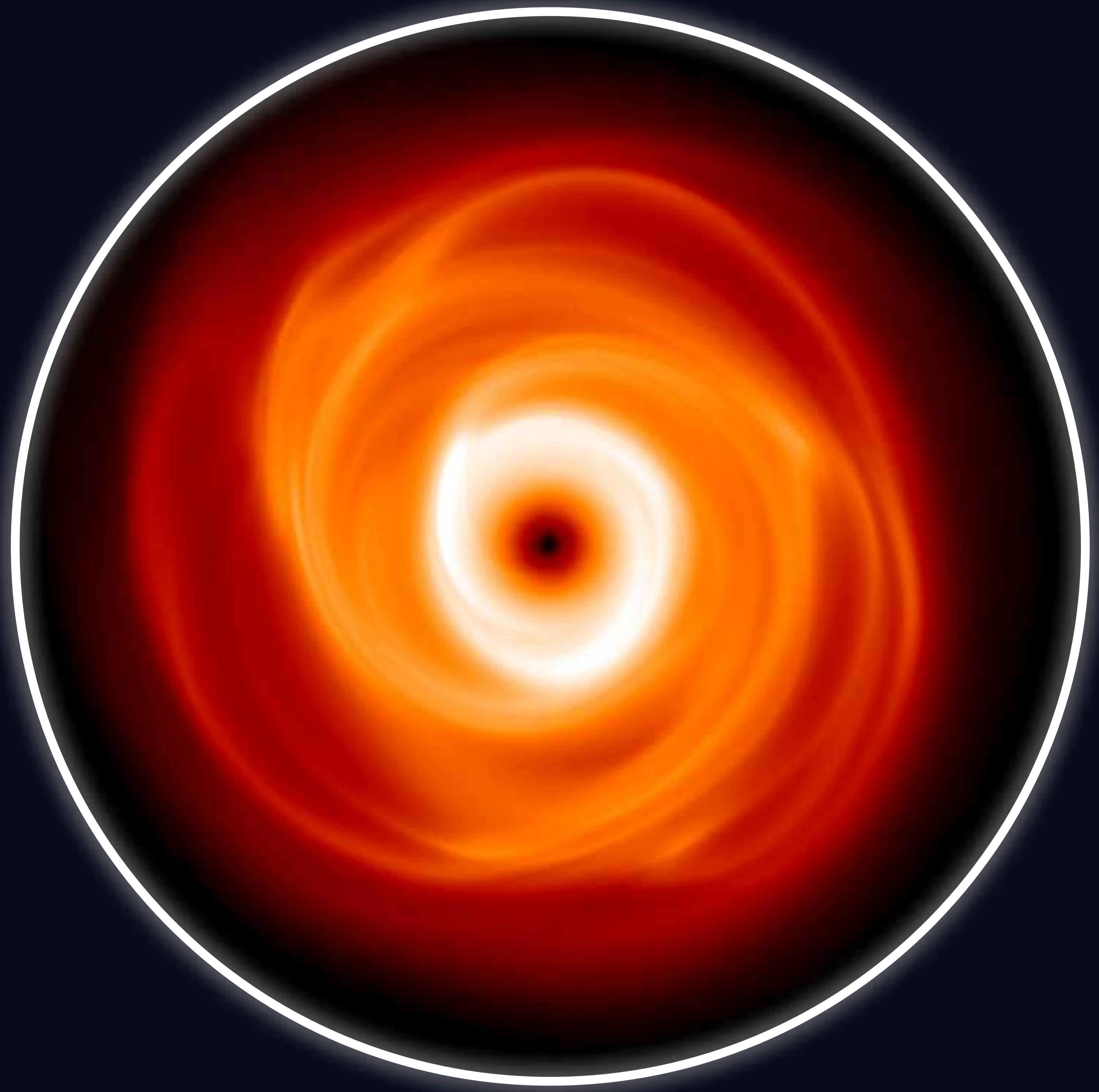
When are Discs Gravitationally Unstable?

- *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.*



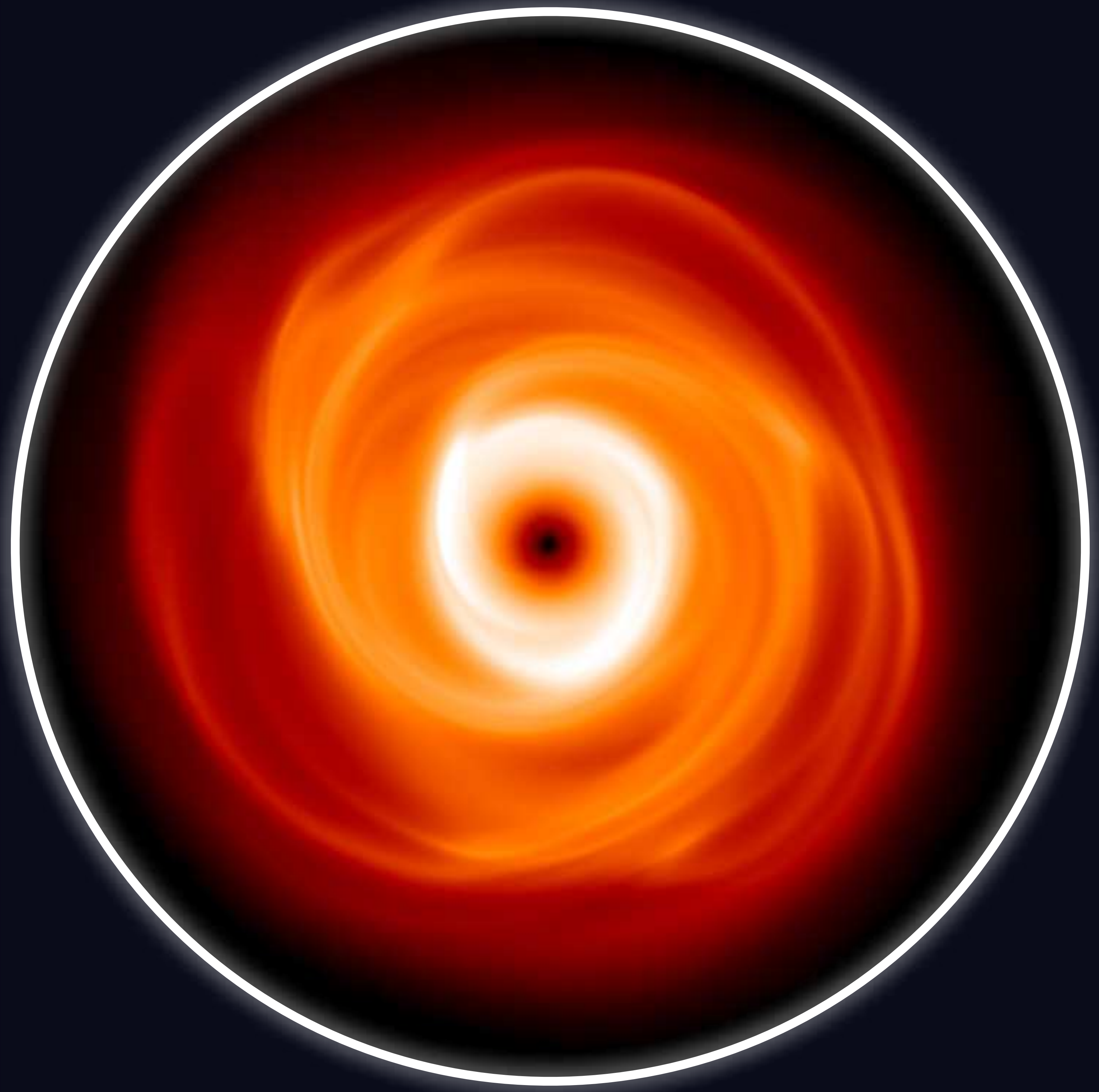
When are Discs Gravitationally Unstable?

Sound speed

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

Surface Density

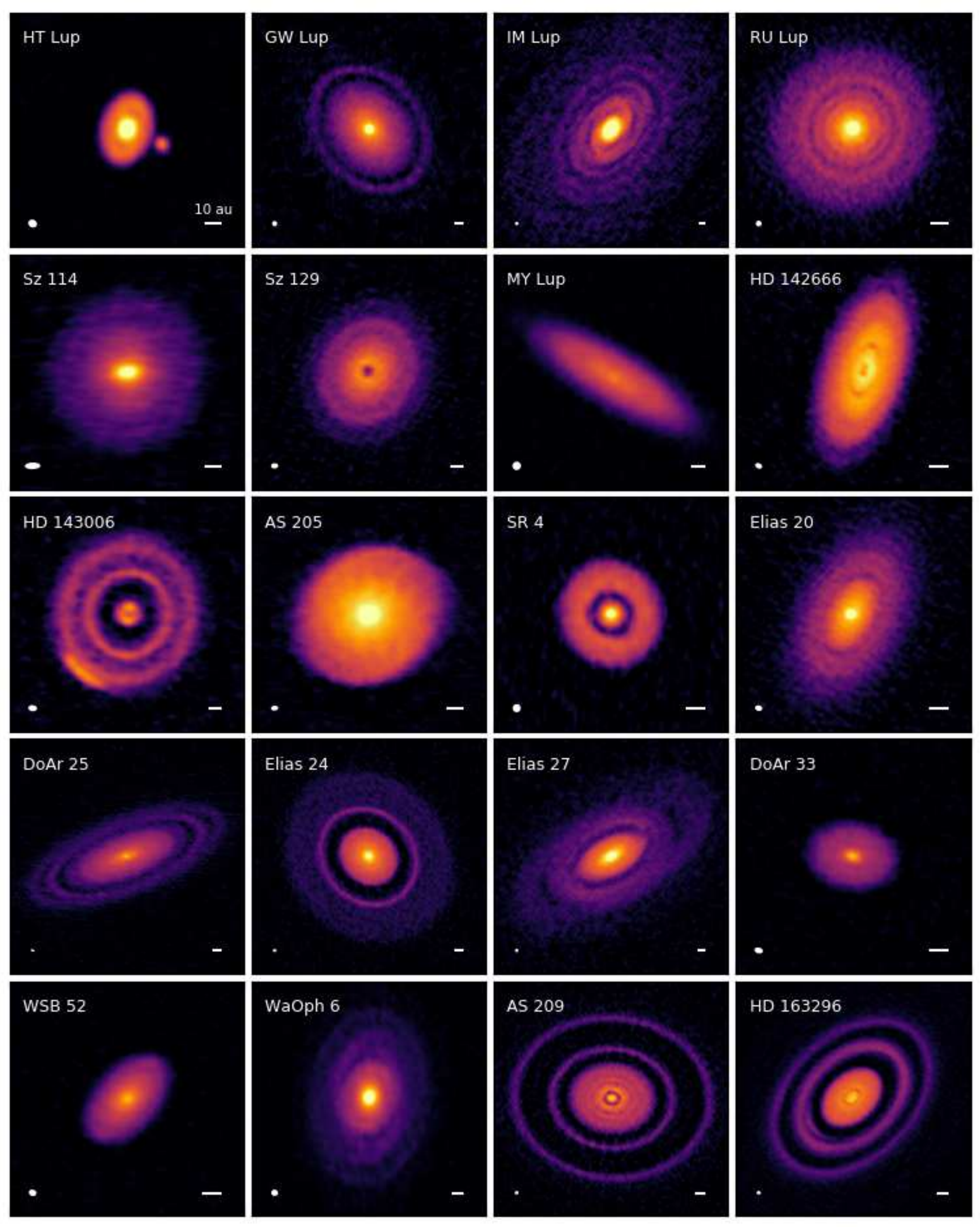
Toomre 1964



ALMA Observations

Observed substructures

- Rings & gaps (axisymmetric) are very common.
- Spiral (non-axisymmetric) features are rare.



Andrews+ 2018

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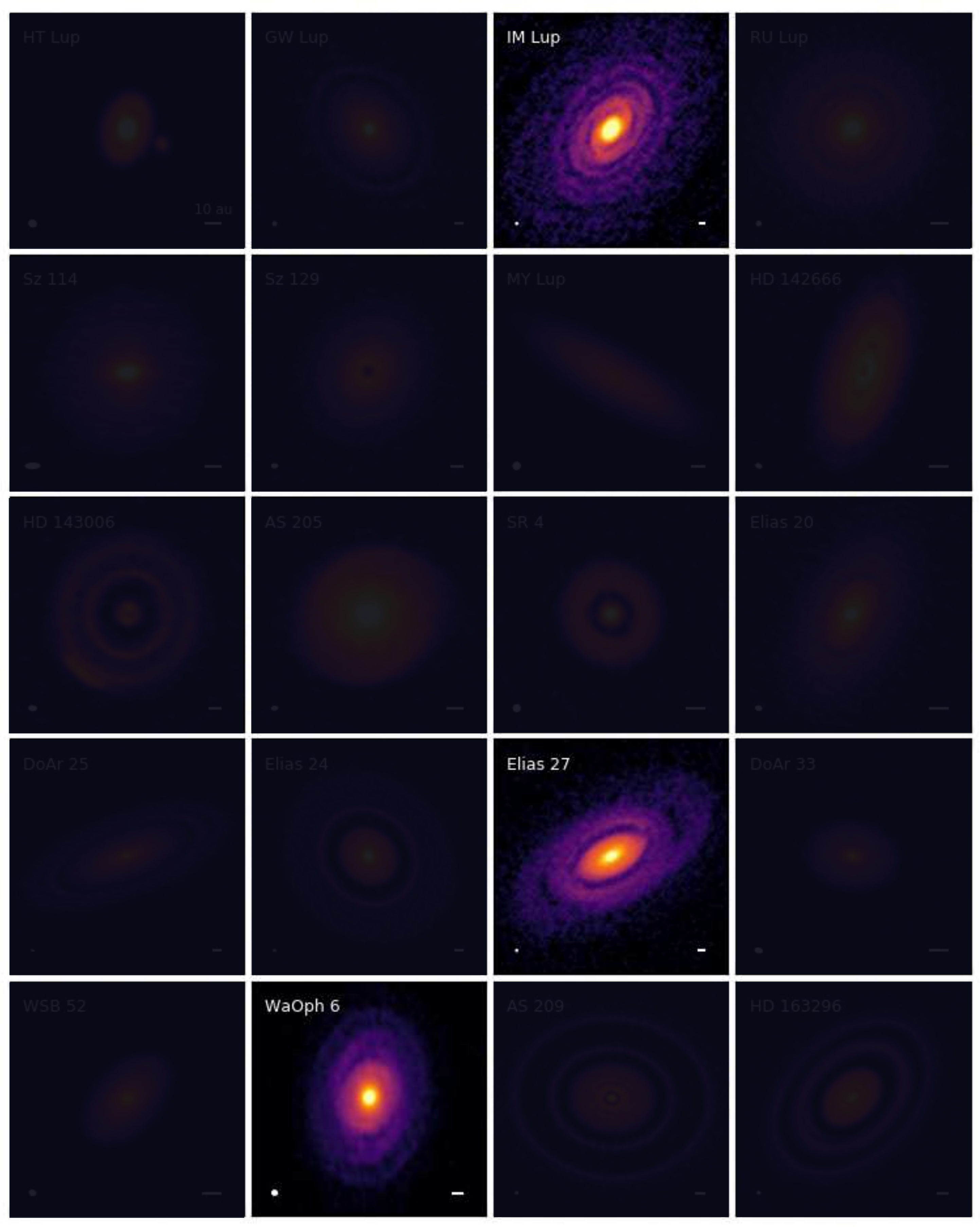
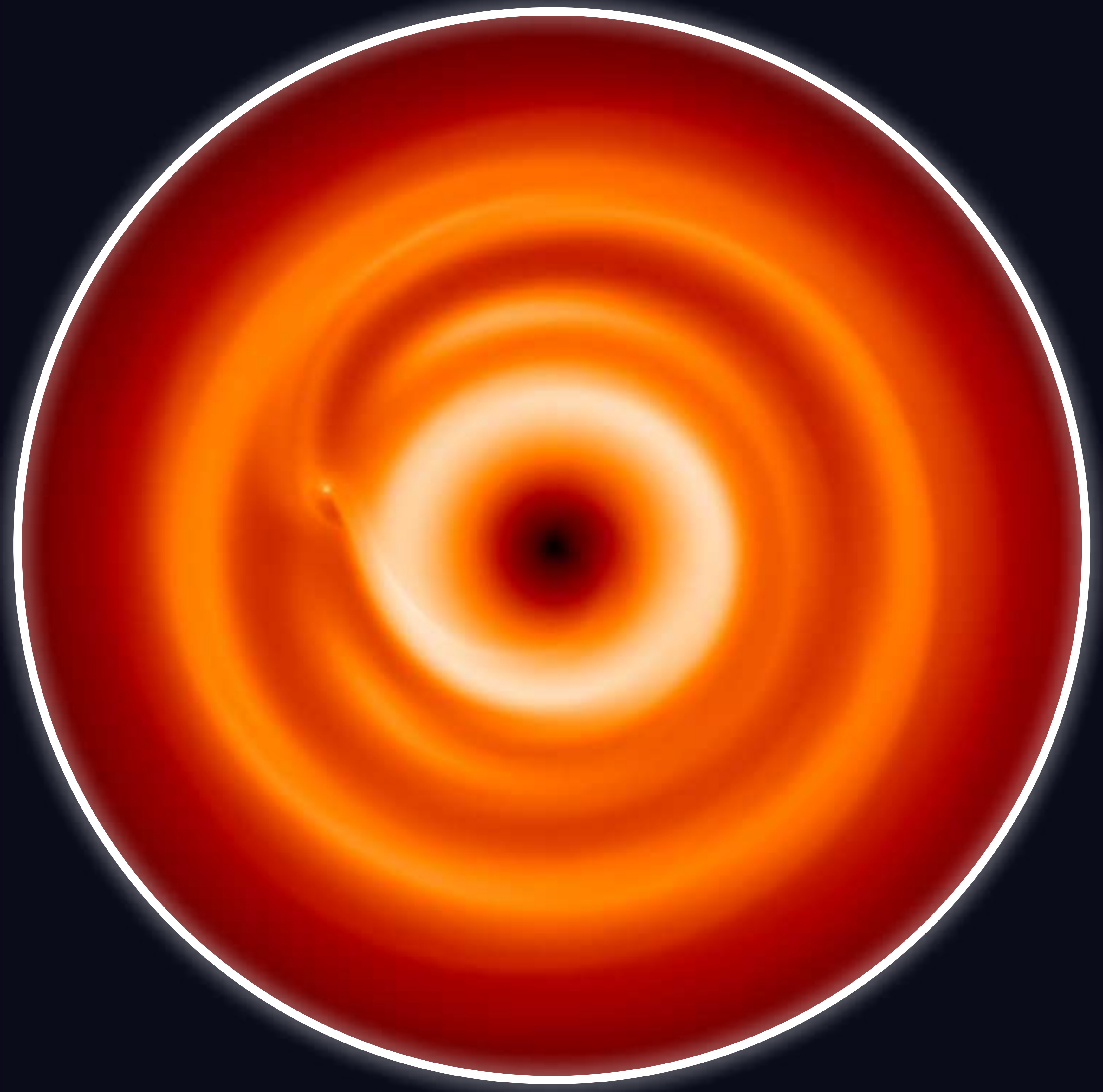


Andrews+ 2018

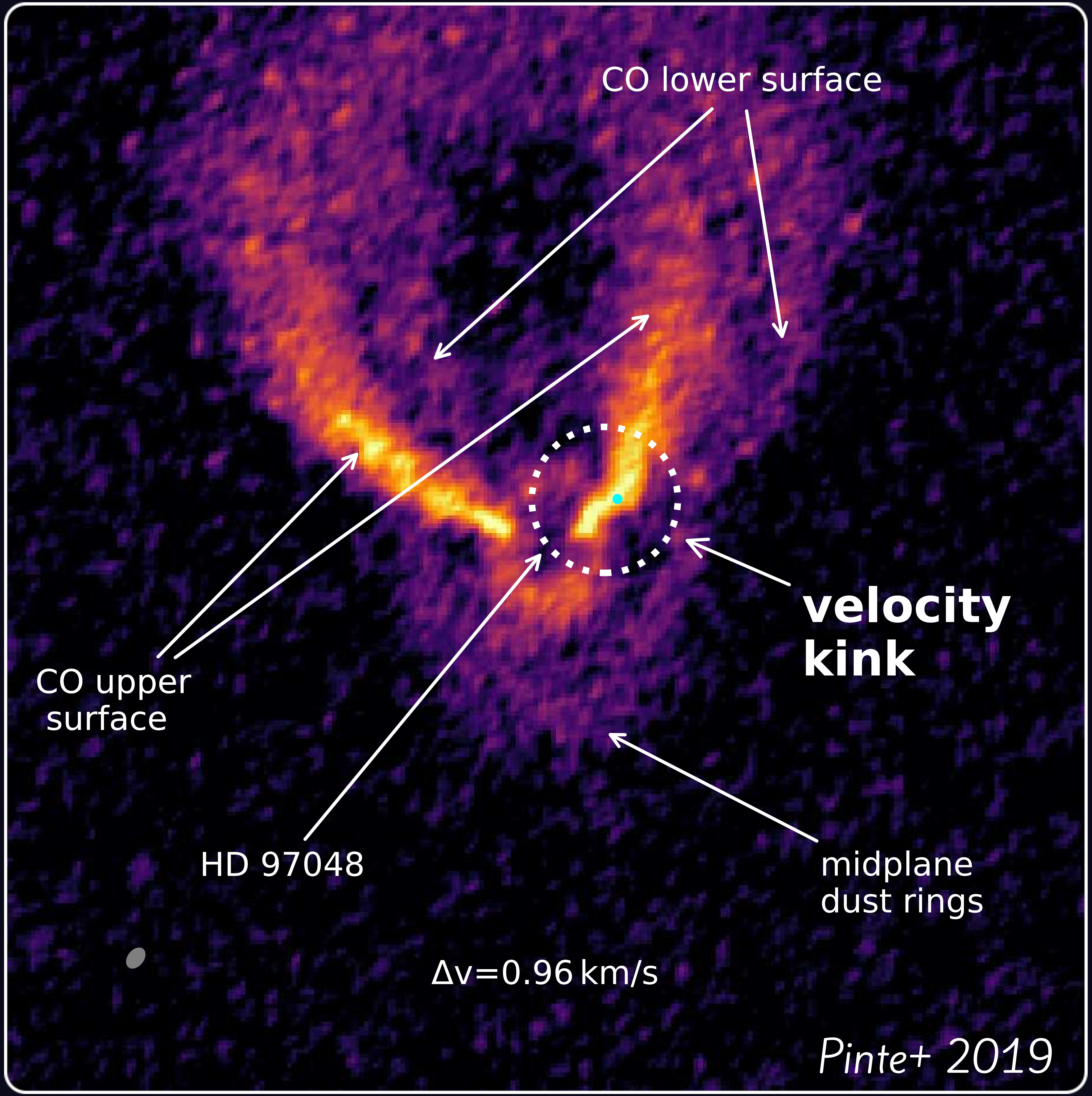
Planet-Disc Interactions

- The planet and disc exert a force on each other.
- The exchange of angular momentum between the planet and the disc can lead to migration of the planet.
- If the planet is massive enough, it can carve open a gap in the disc.



Substructures in the Gas

An embedded planet can leave its imprint in the disc kinematics. This is seen here by a kink at the planet's location.



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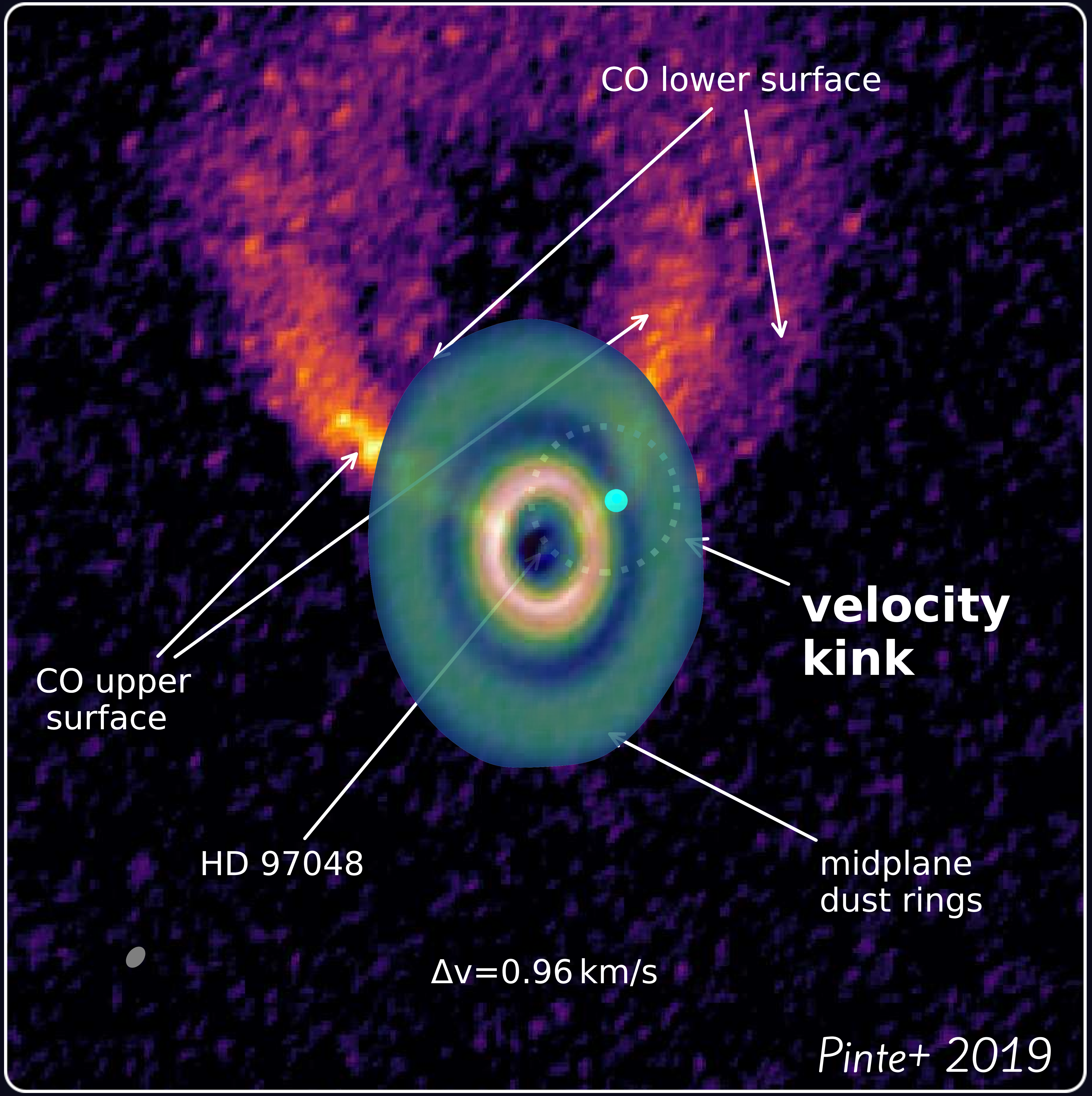

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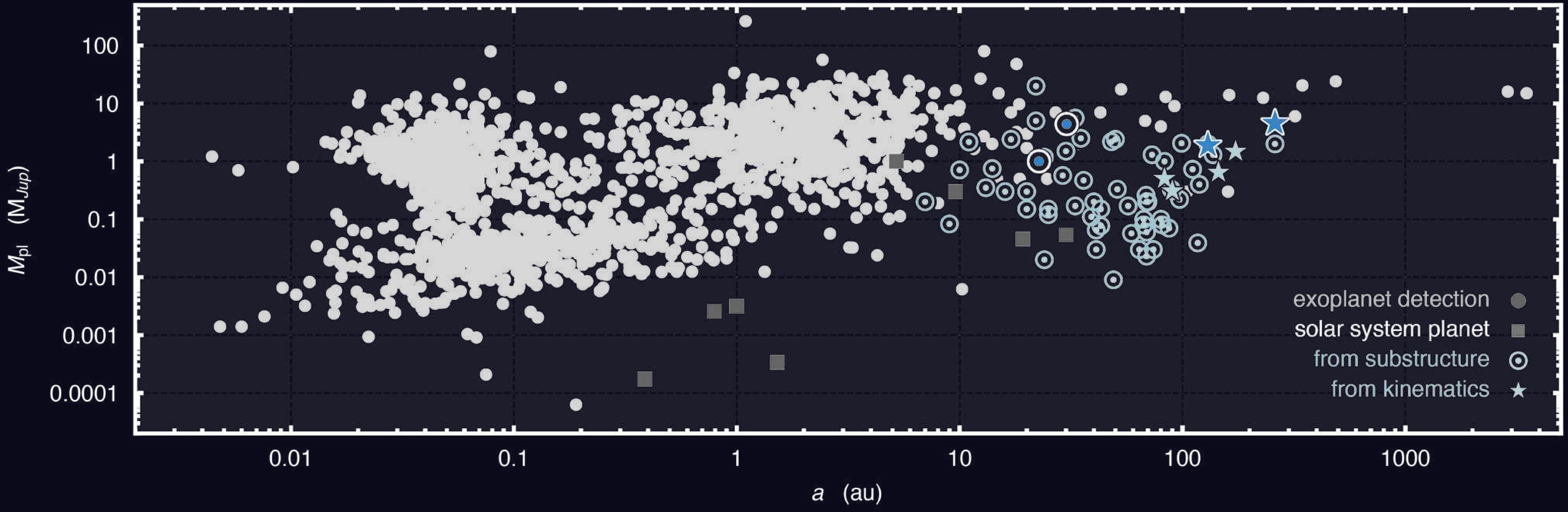
Planets Inferred from Disc Sub-Structures & Kinematics

Pinte+ 2022



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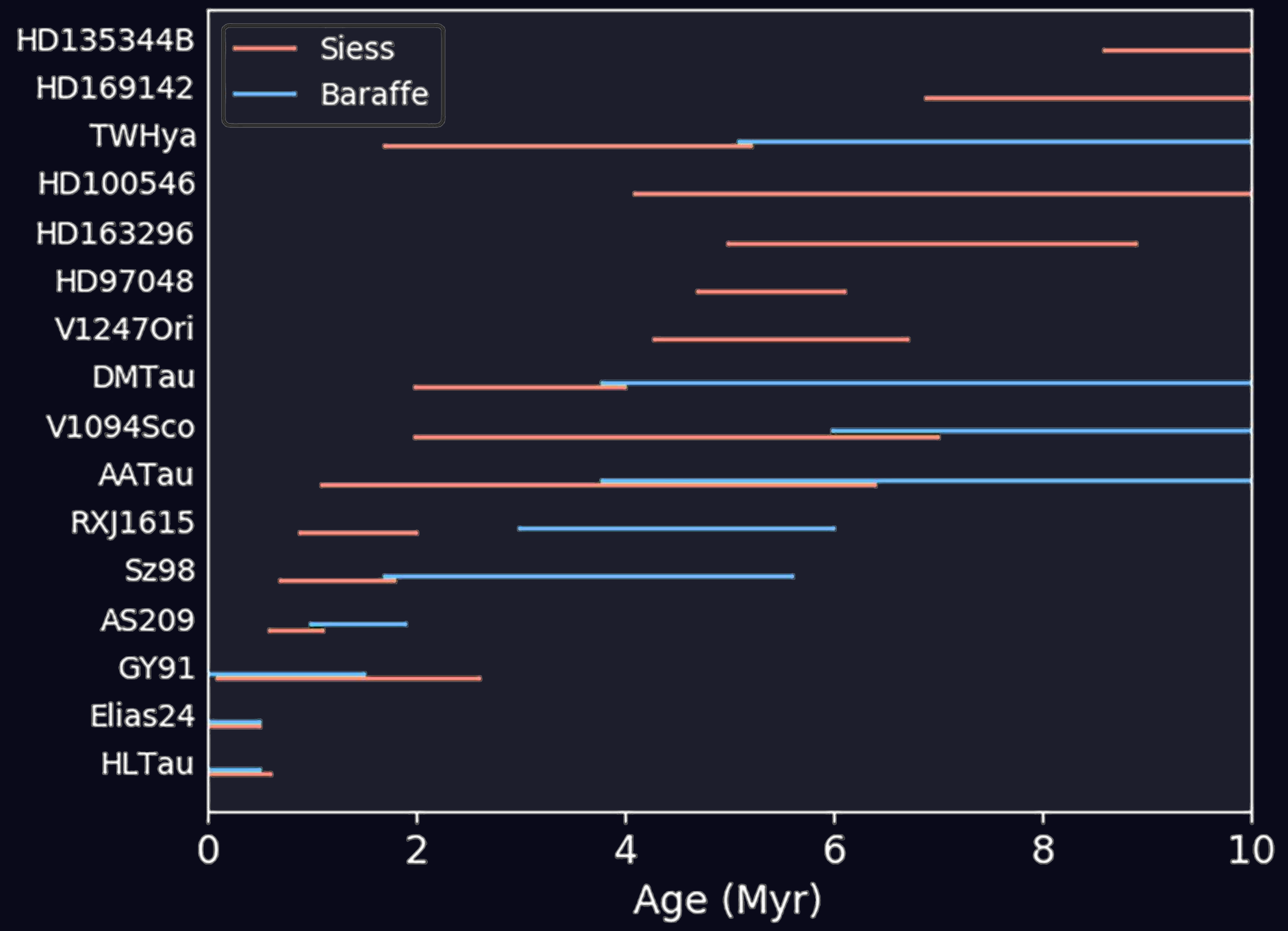
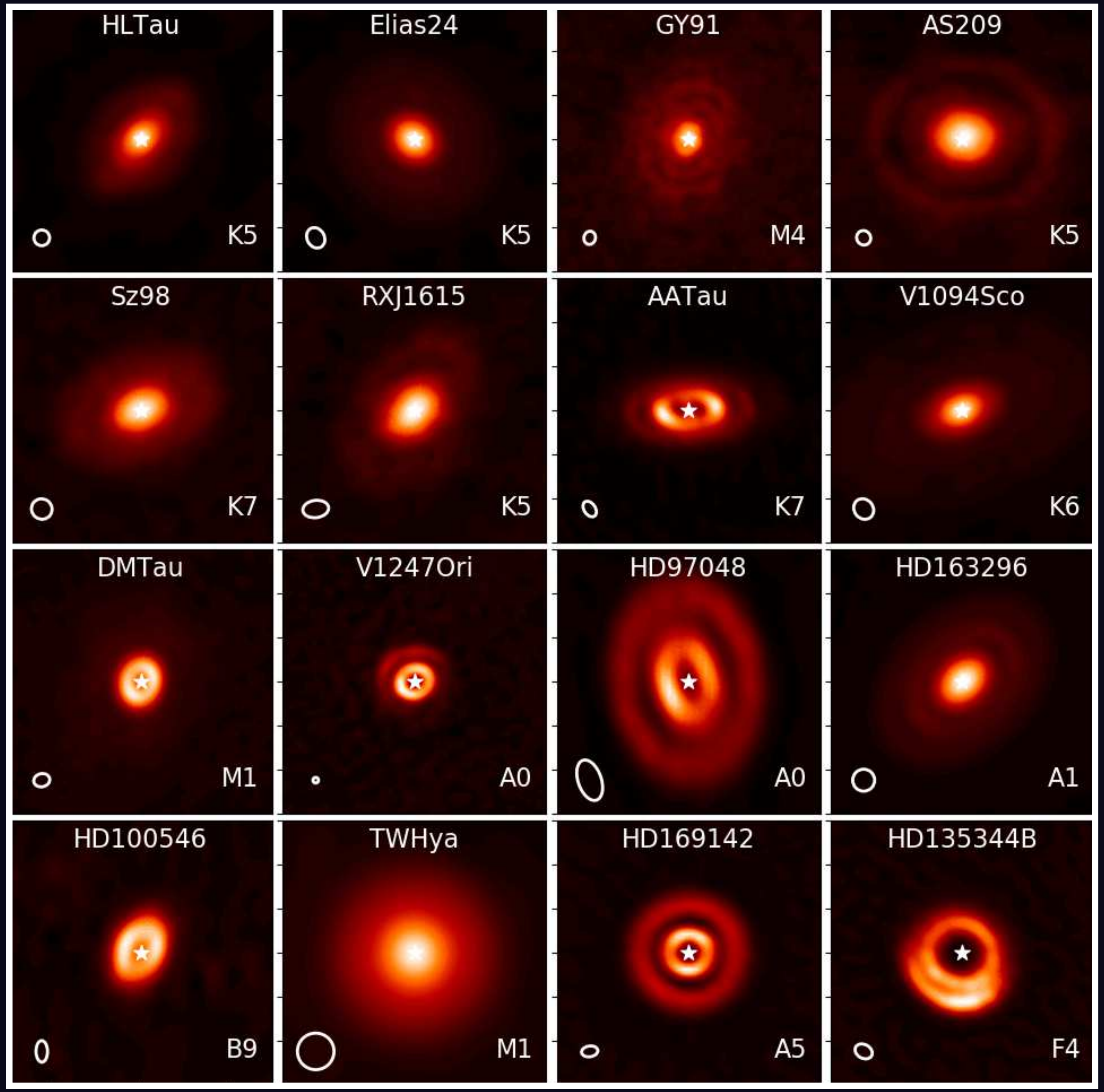
Ages of Discs

van der Marel+ 2019

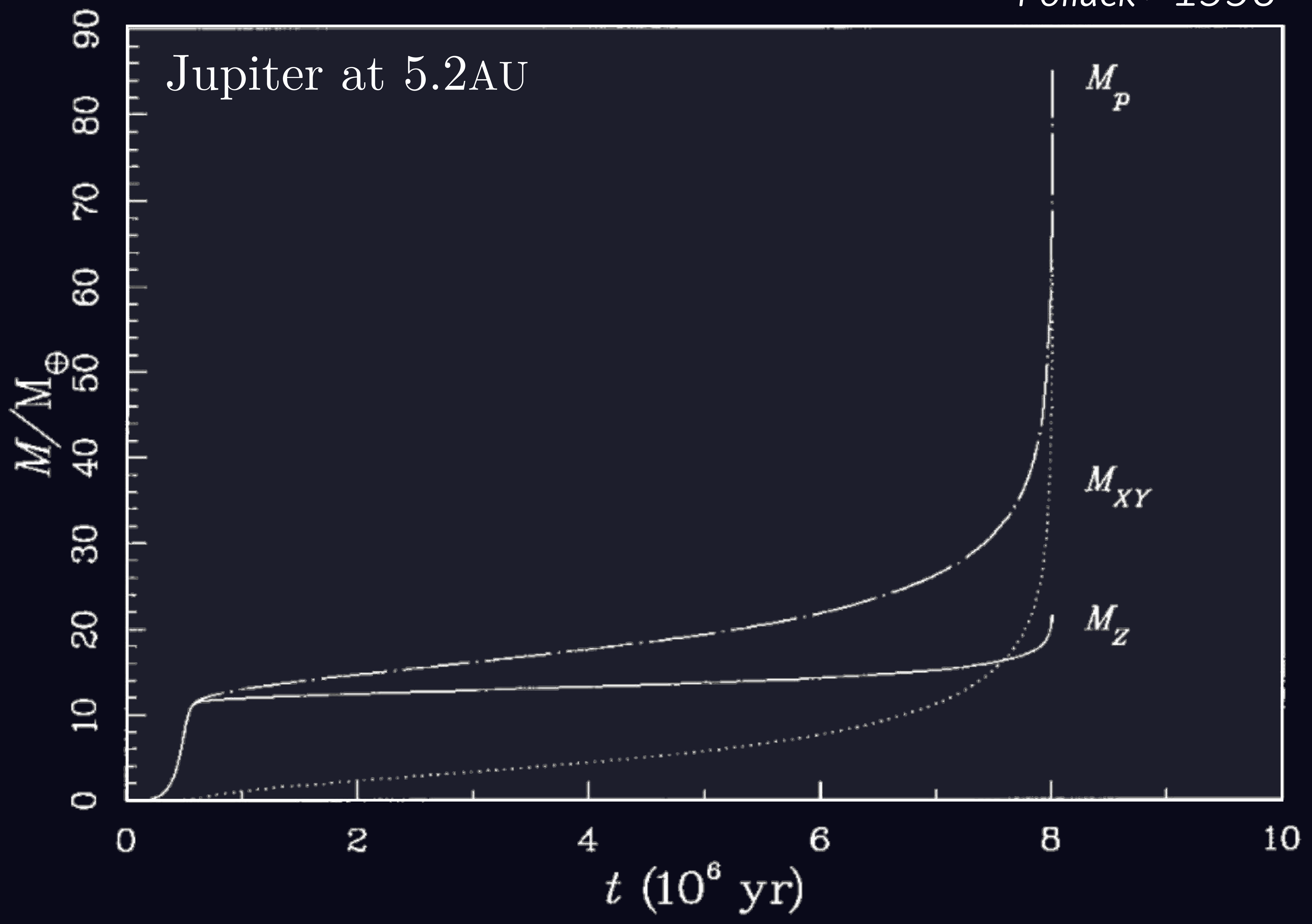




Pollack+ 1996

Core Accretion Timescale

- *Forming planets takes a long time.*
- *Issue becomes worse the further out the planet is located.*



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The Drag Force

$$-\frac{K}{\rho_{\mathrm{d}}}(\boldsymbol{v}_{\mathrm{d}} - \boldsymbol{v}_{\mathrm{g}})$$

Stopping Time

$$t_{\mathrm{s}} = \frac{\rho_{\mathrm{g}}\rho_{\mathrm{d}}}{K\rho}$$

$$t_{\mathrm{s}} = \frac{\rho_{\mathrm{grain}} s_{\mathrm{grain}}}{\rho c_{\mathrm{s}} f}\sqrt{\frac{\pi\gamma}{8}}$$

Stokes Number

$$\mathrm{St} = t_{\mathrm{s}}\Omega$$

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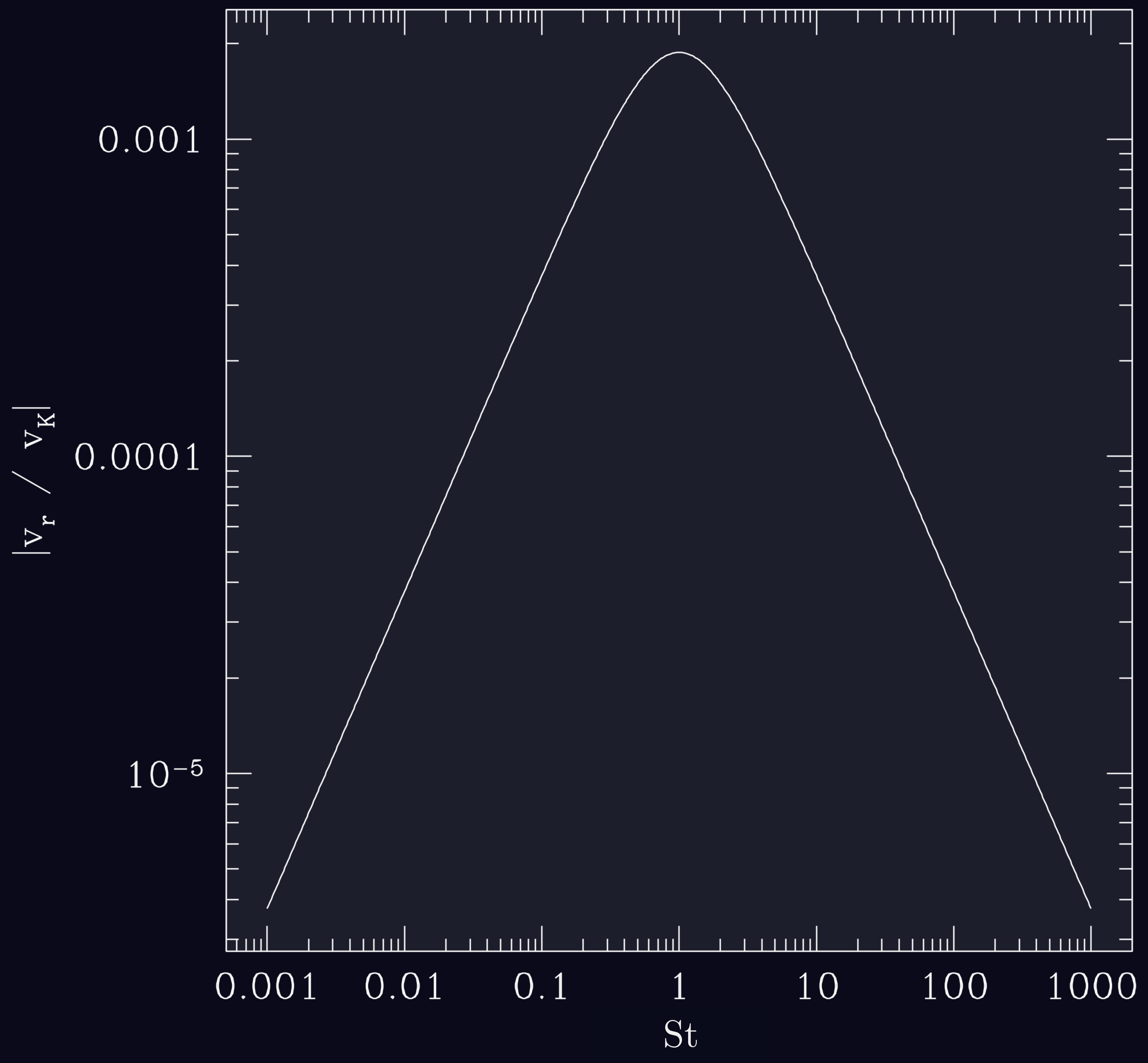
Radial Drift

- *Maximum for St = 1 (grain sizes from cm to m).*
- *Drives particles towards regions of highest pressure.*
- *In a smooth disc, motion is inwards as pressure declines smoothly.*

Armitage 2007



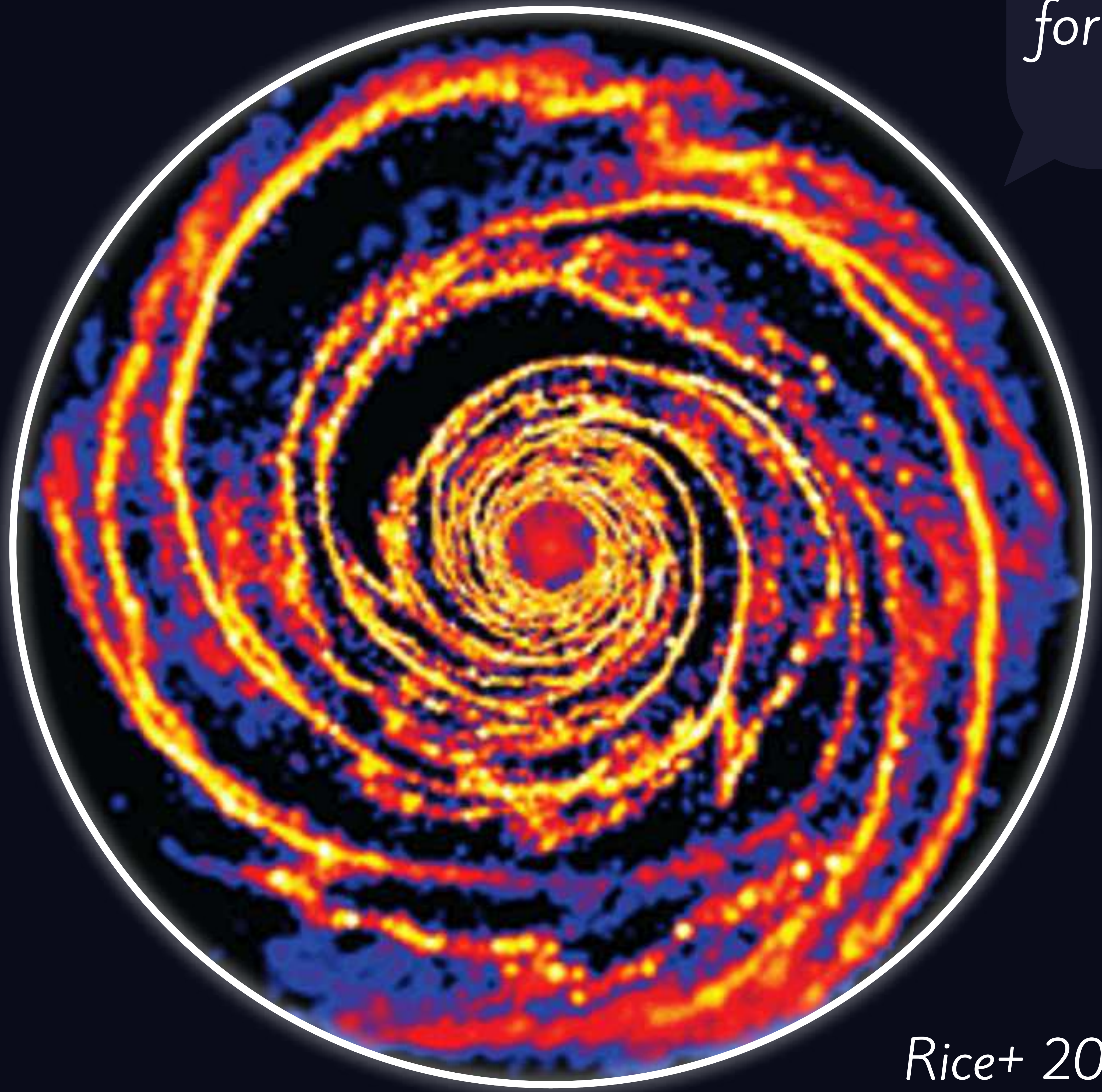
Velocity Dispersion of Dust

- Will be used to measure how gravitationally unstable (Toomre Q) the dust becomes.
- And will be compared to the gas sound speed. If $c_d = c_g$, the dust is very well coupled to the gas.

$$c_{\mathrm{d},i}^2 = \sum_{j=1}^{N_{\mathrm{neigh}}} m_j \frac{(v_{\mathrm{d},i} - v_{\mathrm{d},j})^2}{\rho_{\mathrm{d},j}} W_{ij}(h_i)$$

Past Studies of Dusty GI Discs

- Global 3D simulations (Rice+ 2004, 2006)
- Global 2D simulations with test particles (Booth & Clarke 2016)



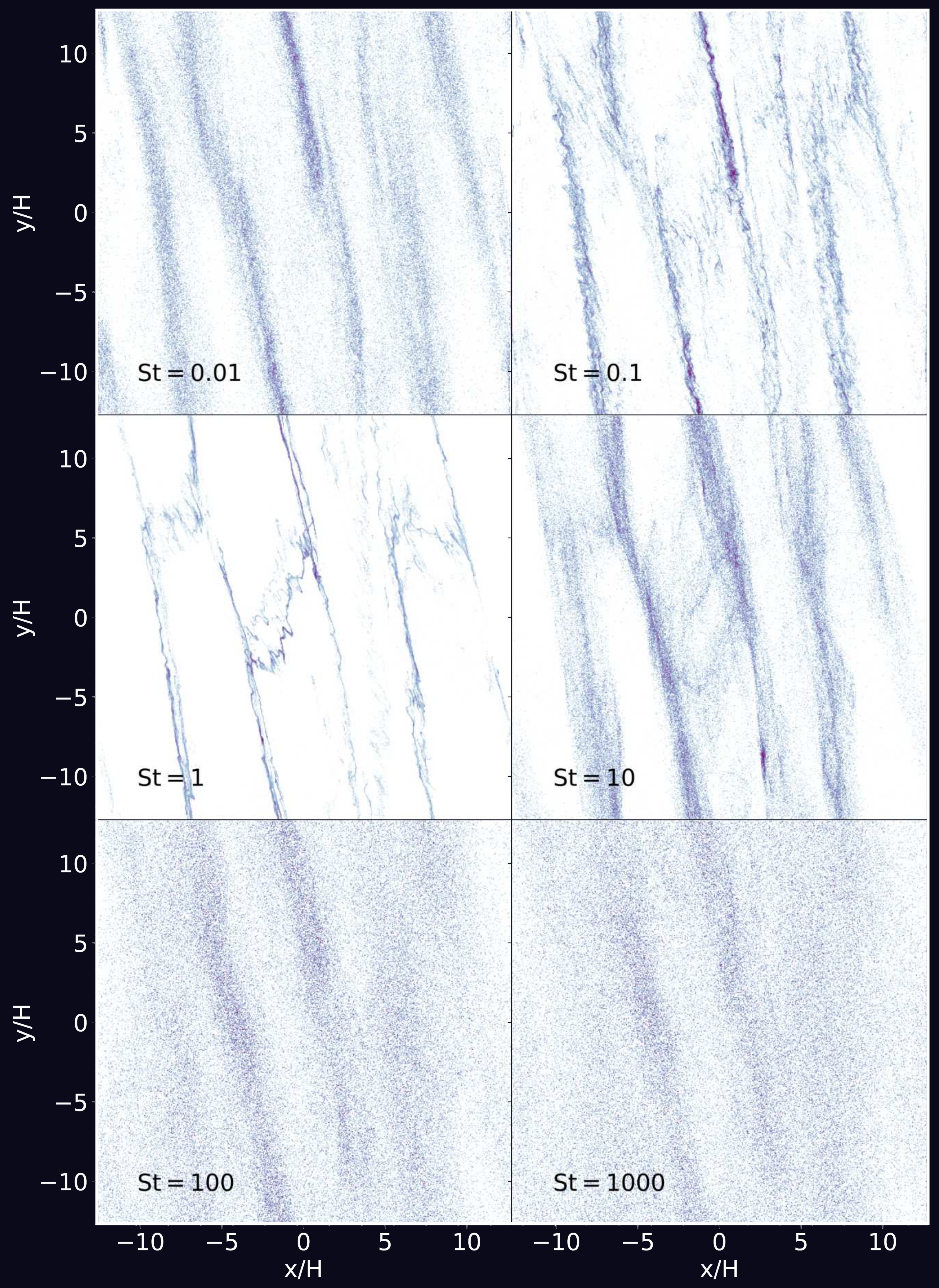
Dust disc has fragmented forming bound clumps

Rice+ 2006

Past Studies of Dusty GI Discs

- 2D shearing box simulations (Gibbons+ 2012, 2014, Shi+ 2016)
- 3D shearing box simulations (Baehr & Zhu 2021a,b, Baehr+ 2022)

Baehr & Zhu 2021a



Current Studies

See Cristiano's Talk on Thursday!

What Drives the Dust Dynamics?

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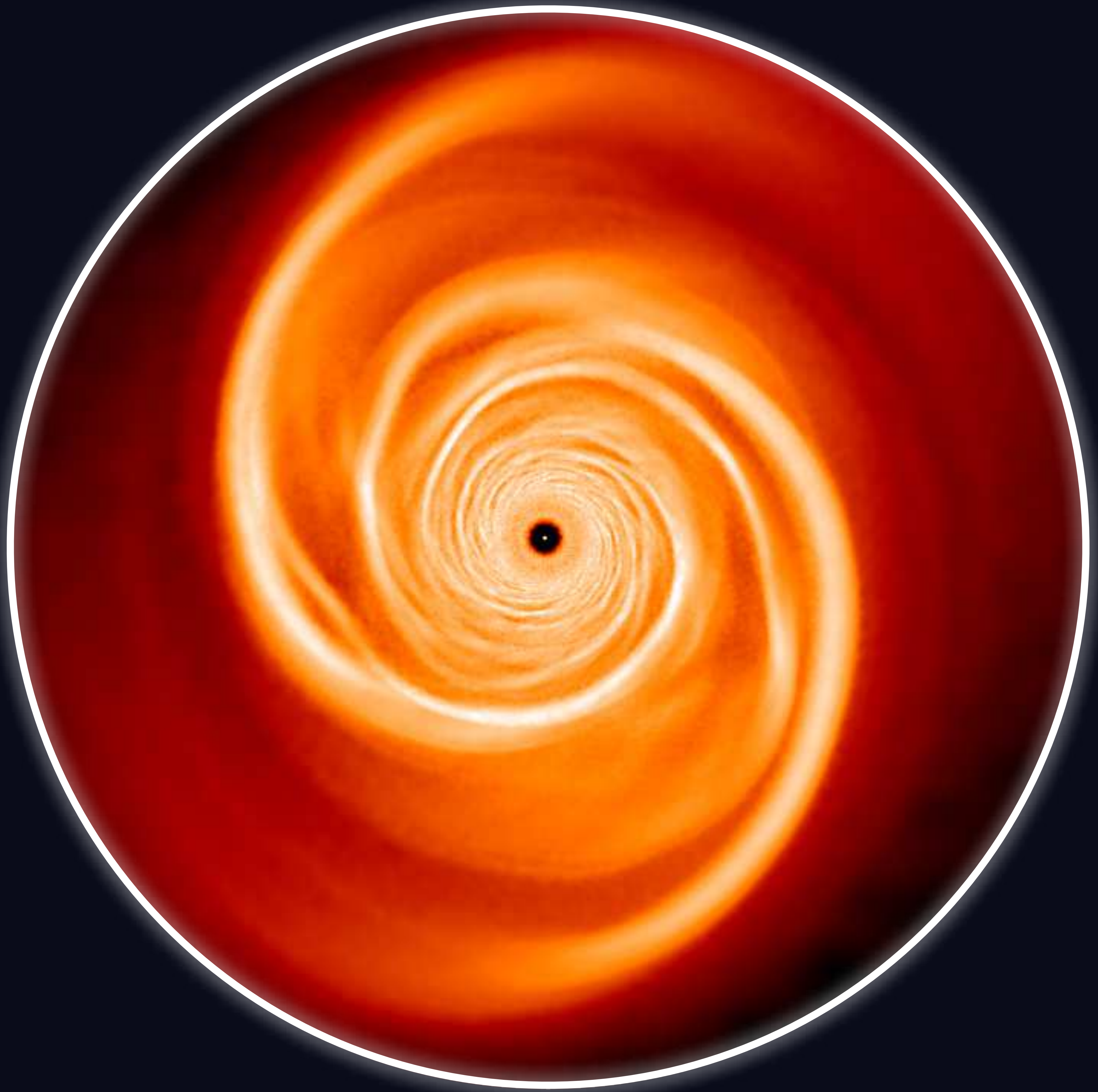
The Drag Force or Gravity?



Rowther+ (in prep)

Evolving a $0.2M_\odot$ gas only disc until spiral structures have formed

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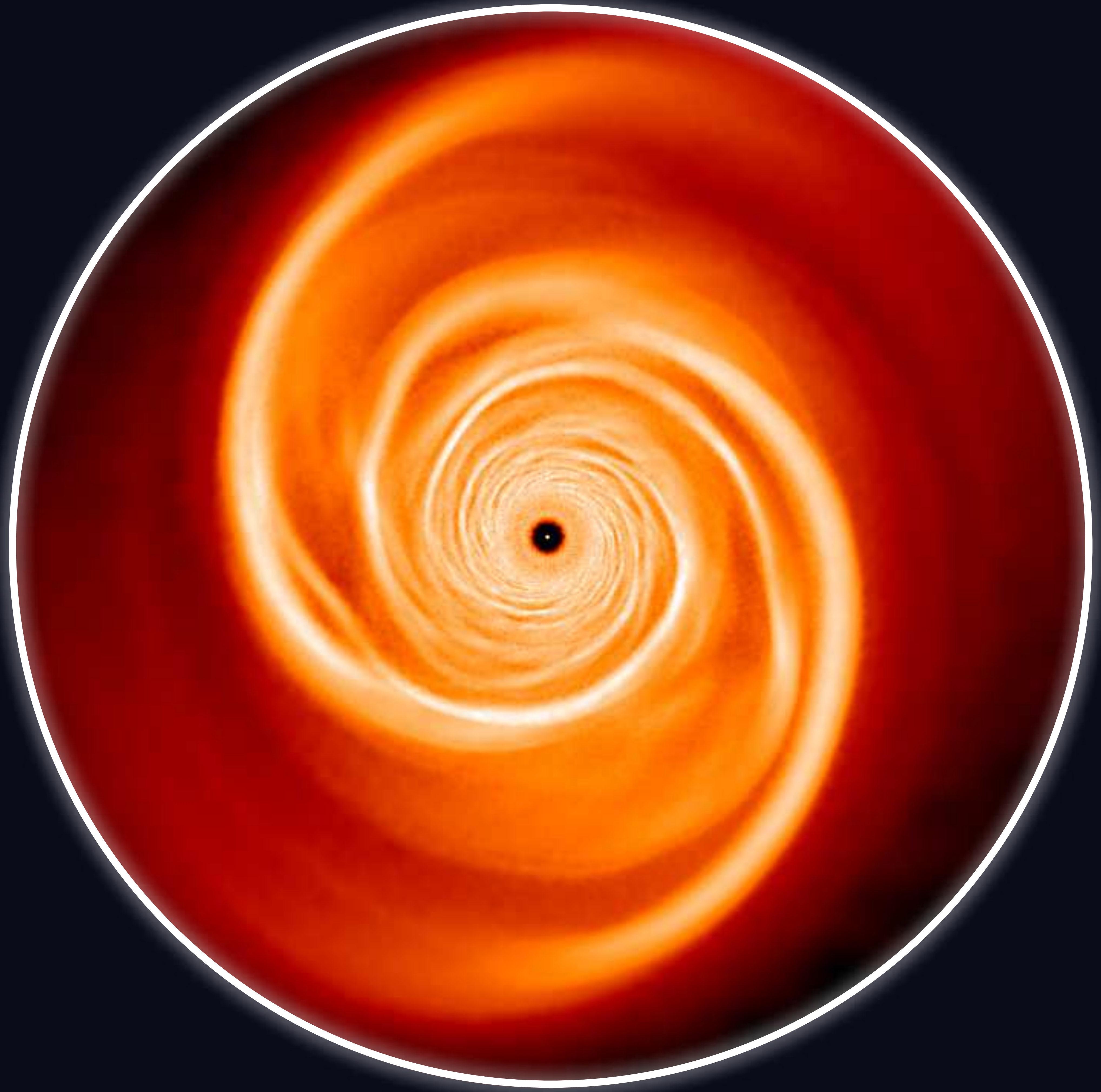
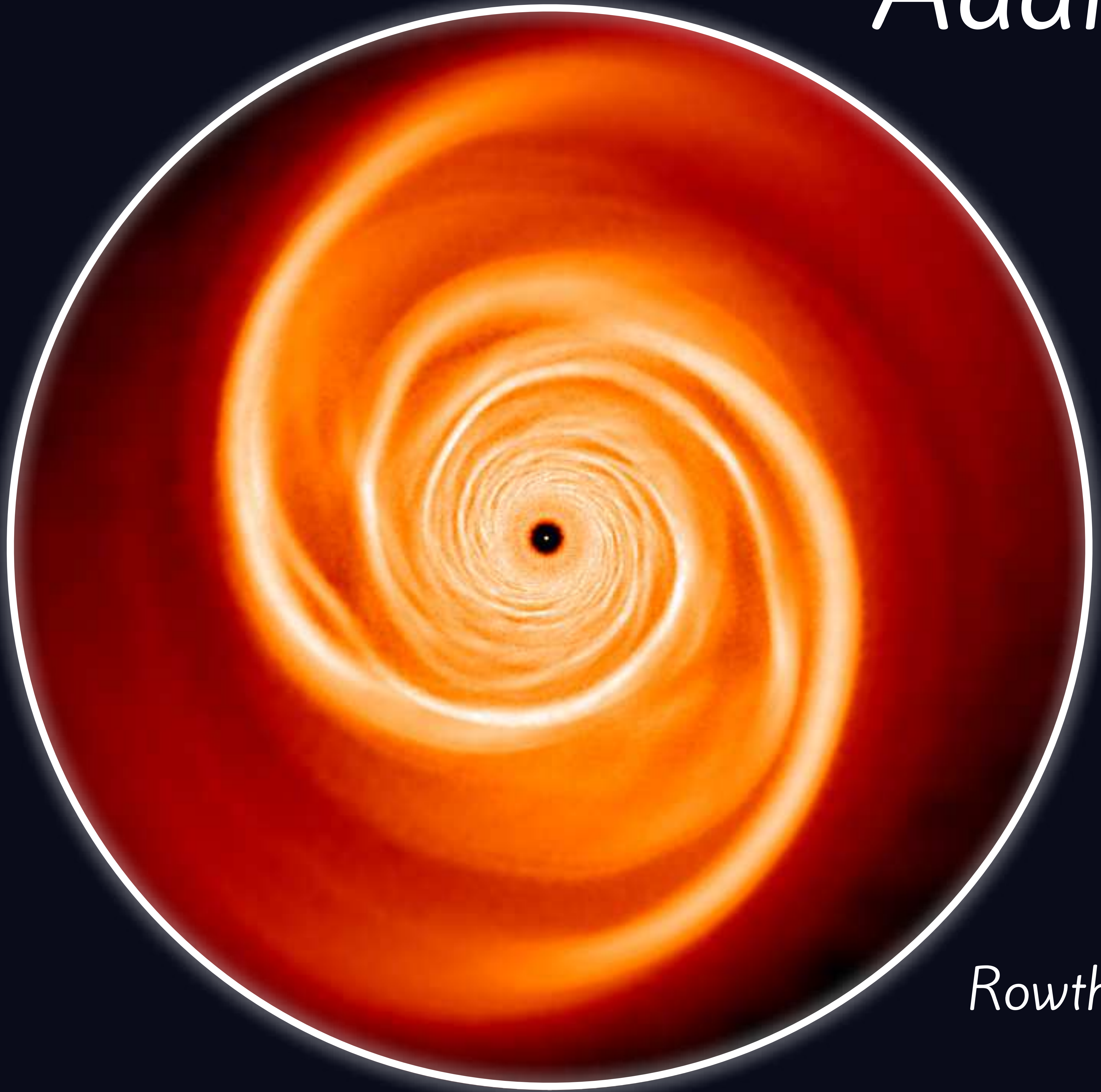

Rowther+ (in prep)

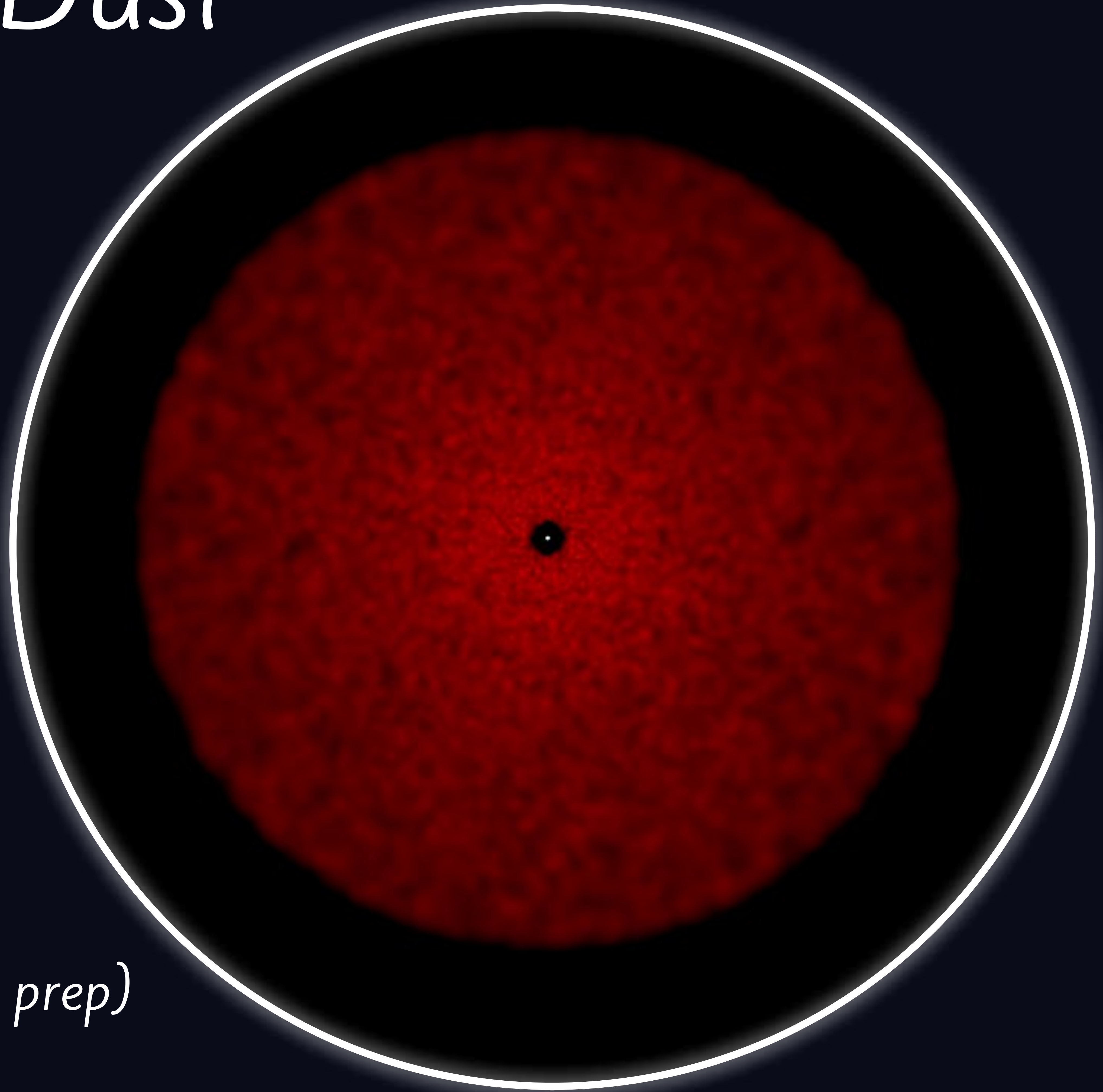
Add 50cm (St ~ 4) sized dust grains

Initial dust-to-gas mass ratio = 0.01

Adding Dust


Gas

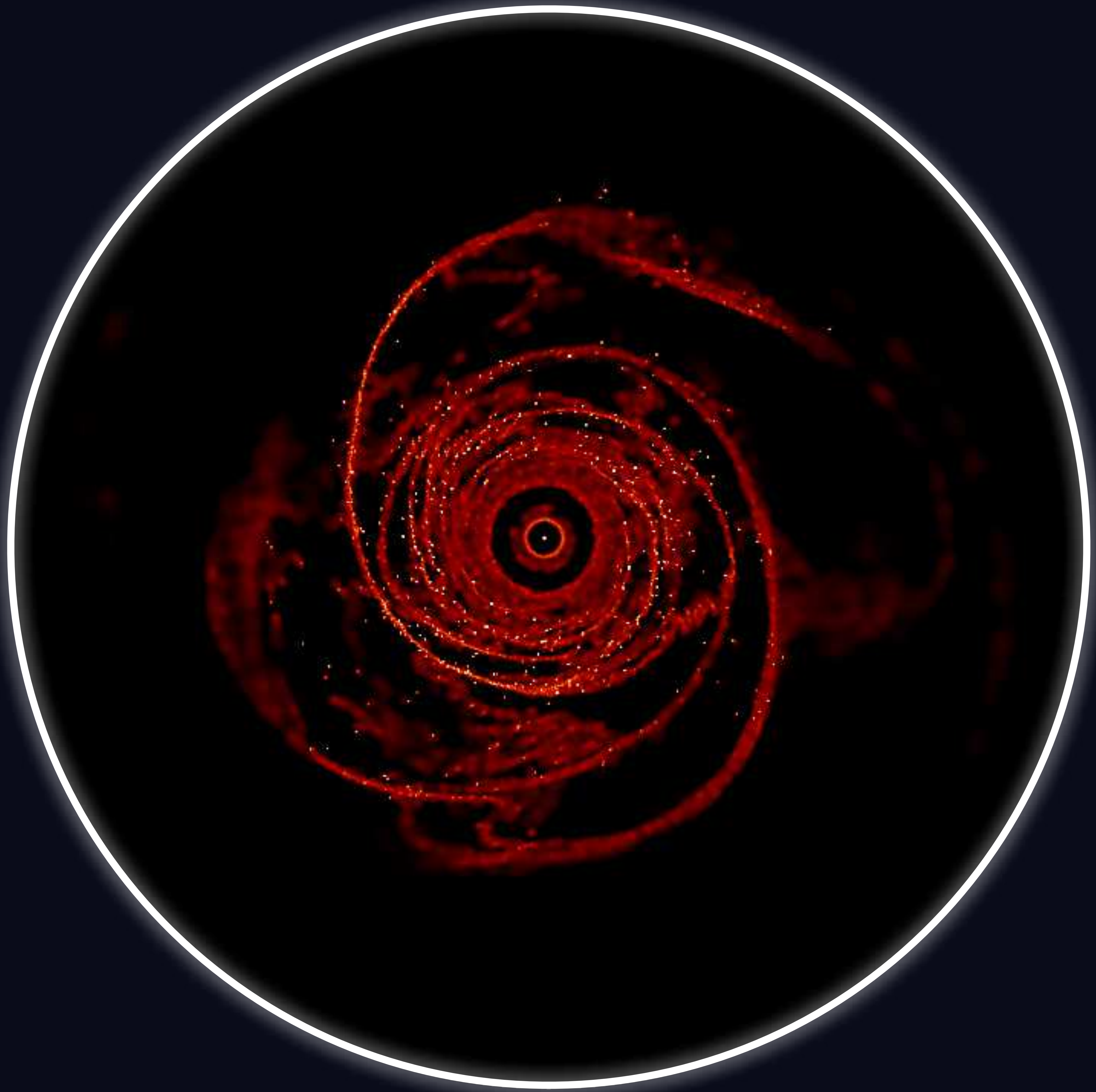
+


Dust

Rowther+ (in prep)

Evolution of 50cm (St ~ 4) sized dust grains

- Dust drifts towards the gas spirals.
- Dust disc becomes gravitationally unstable forming bound clumps.



Rowther+ (in prep)

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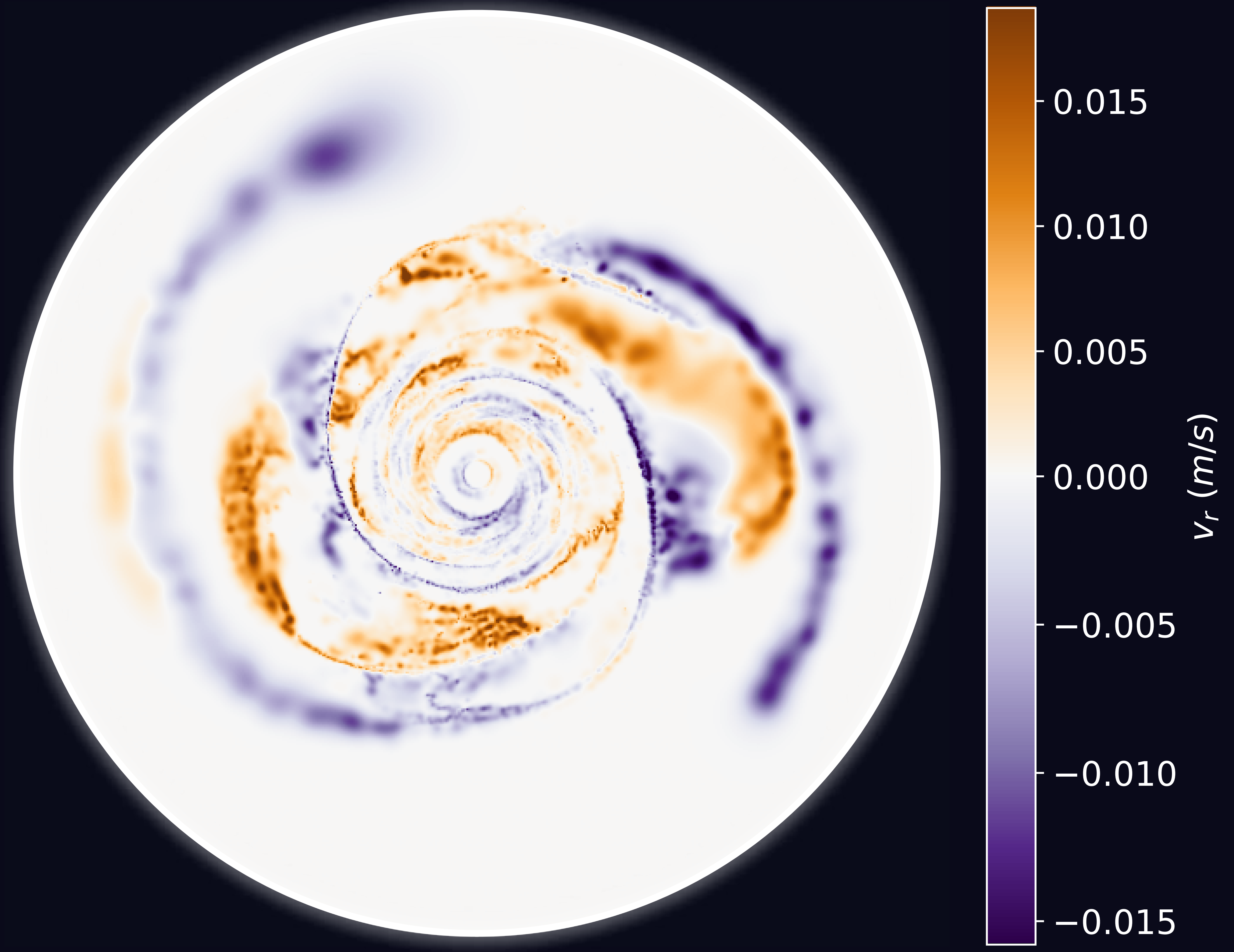
Radial Drift

- Spirals due to gravitational instabilities are regions of pressure maxima.
- Dust drifts towards spirals rather than primarily inwards.



Rowther+ (in prep)

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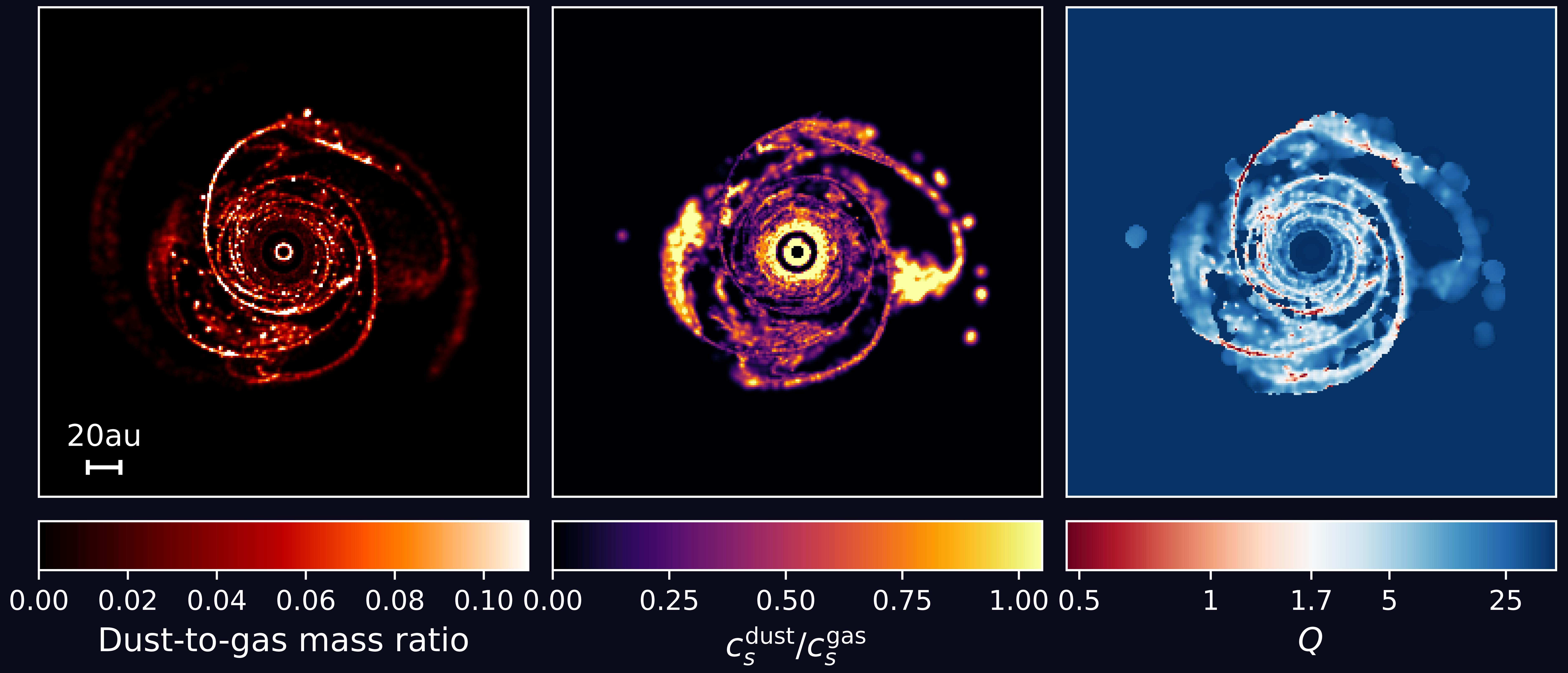
Why does the dust form clumps?

Toomre Stability Parameter

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

Rowther+ (in prep)



University of Leicester

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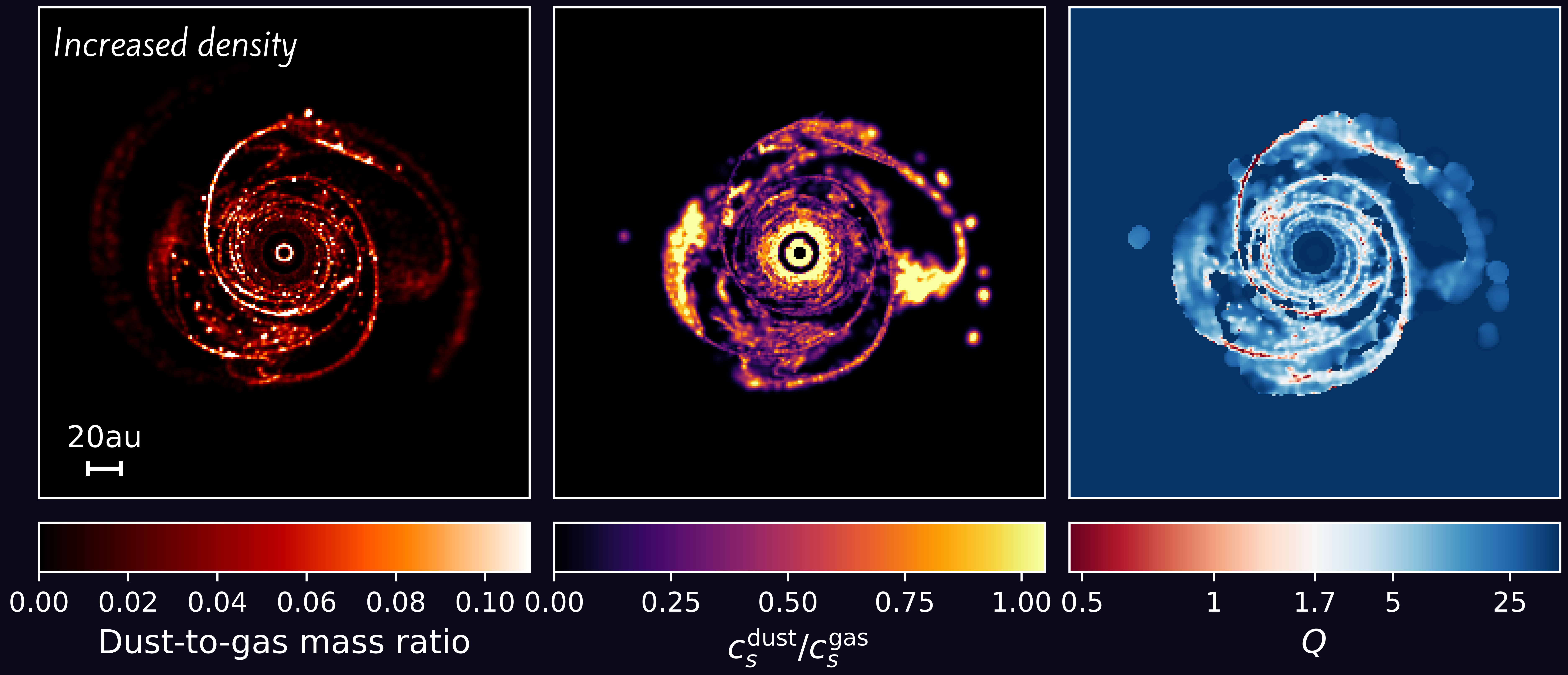
Rowther+ (in prep)



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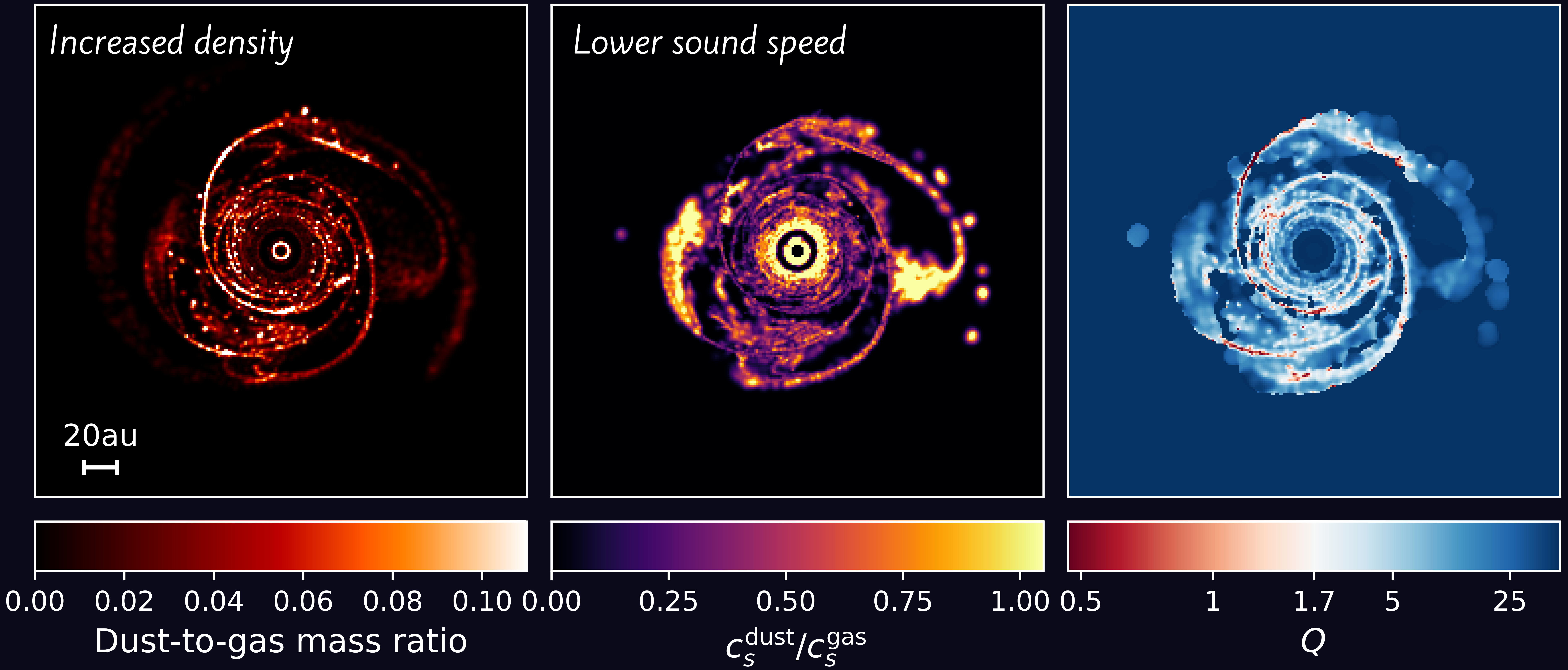

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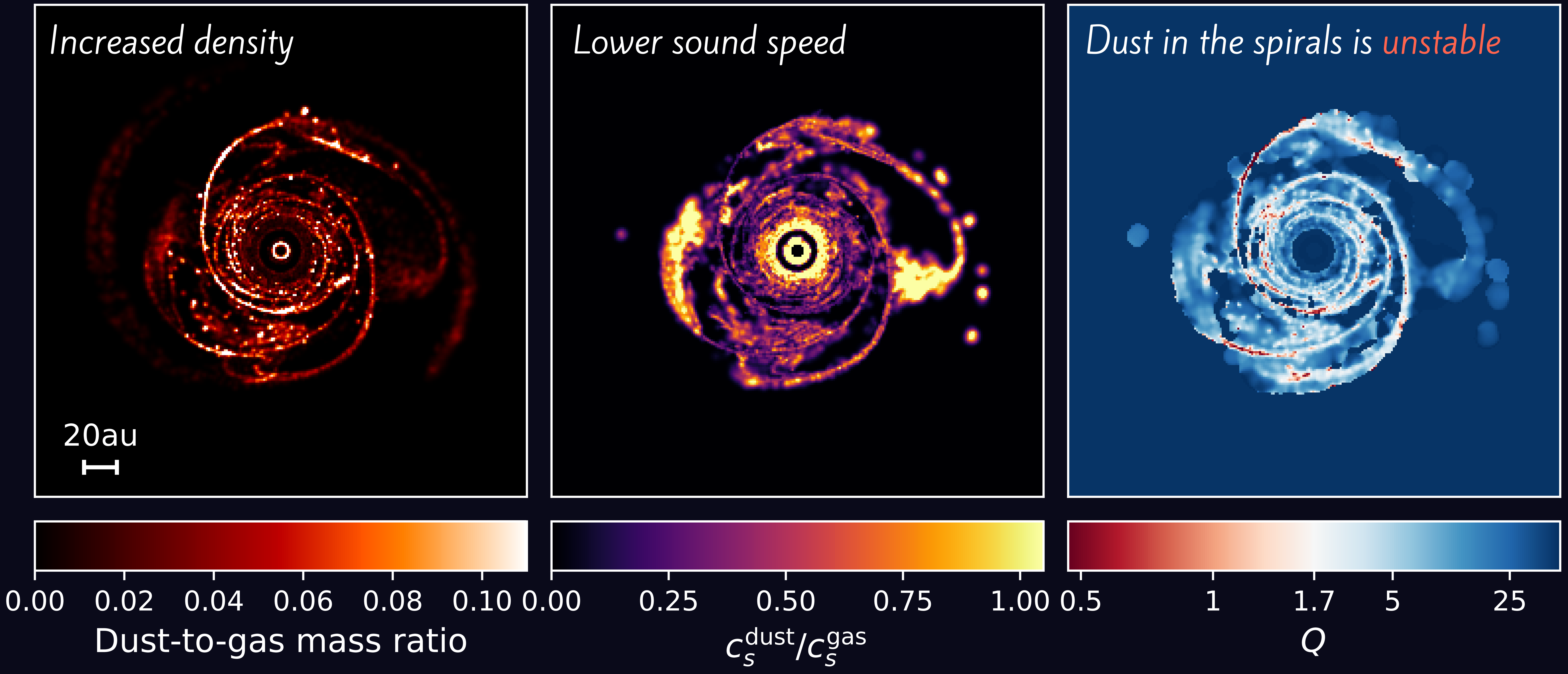
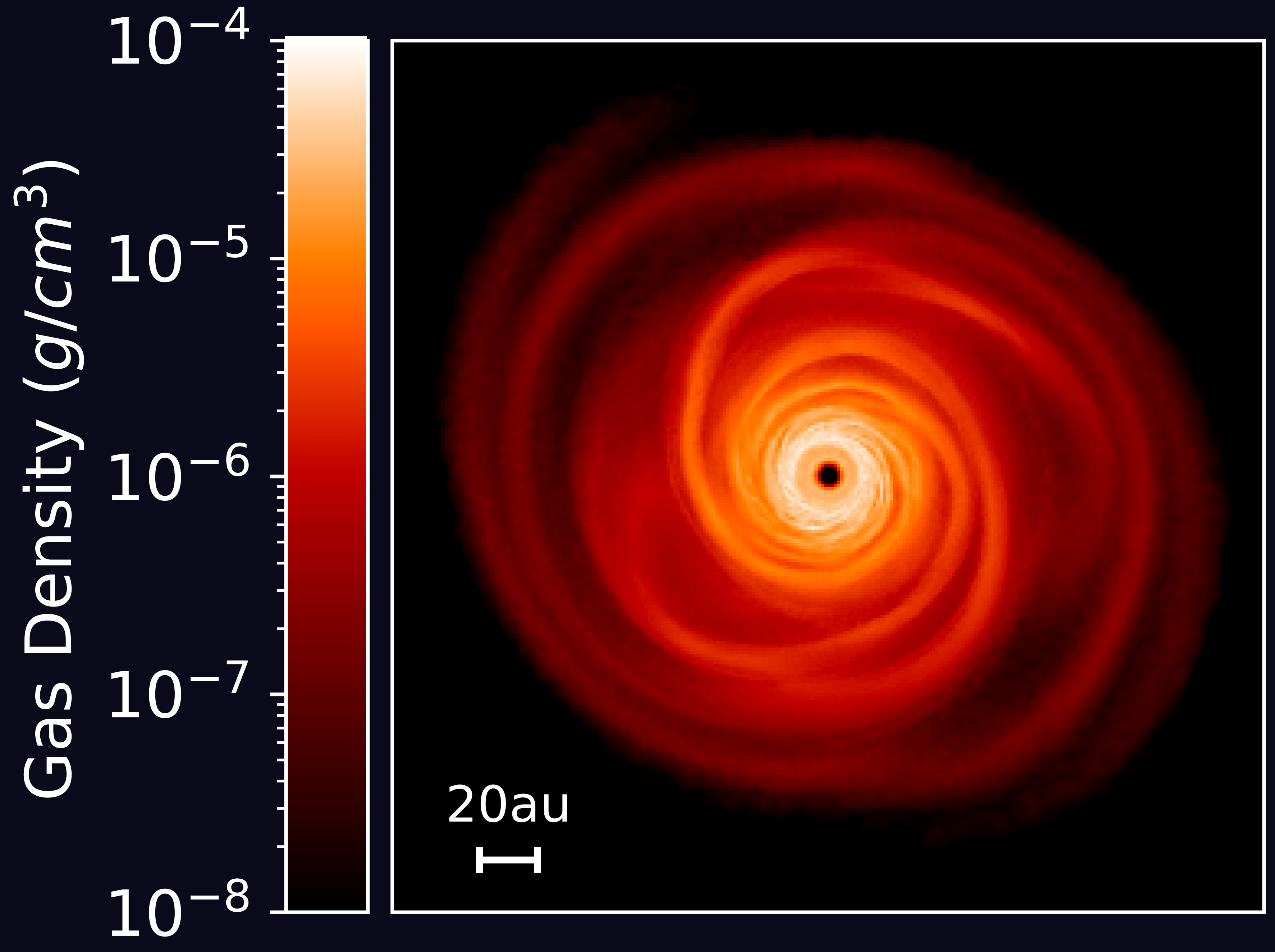
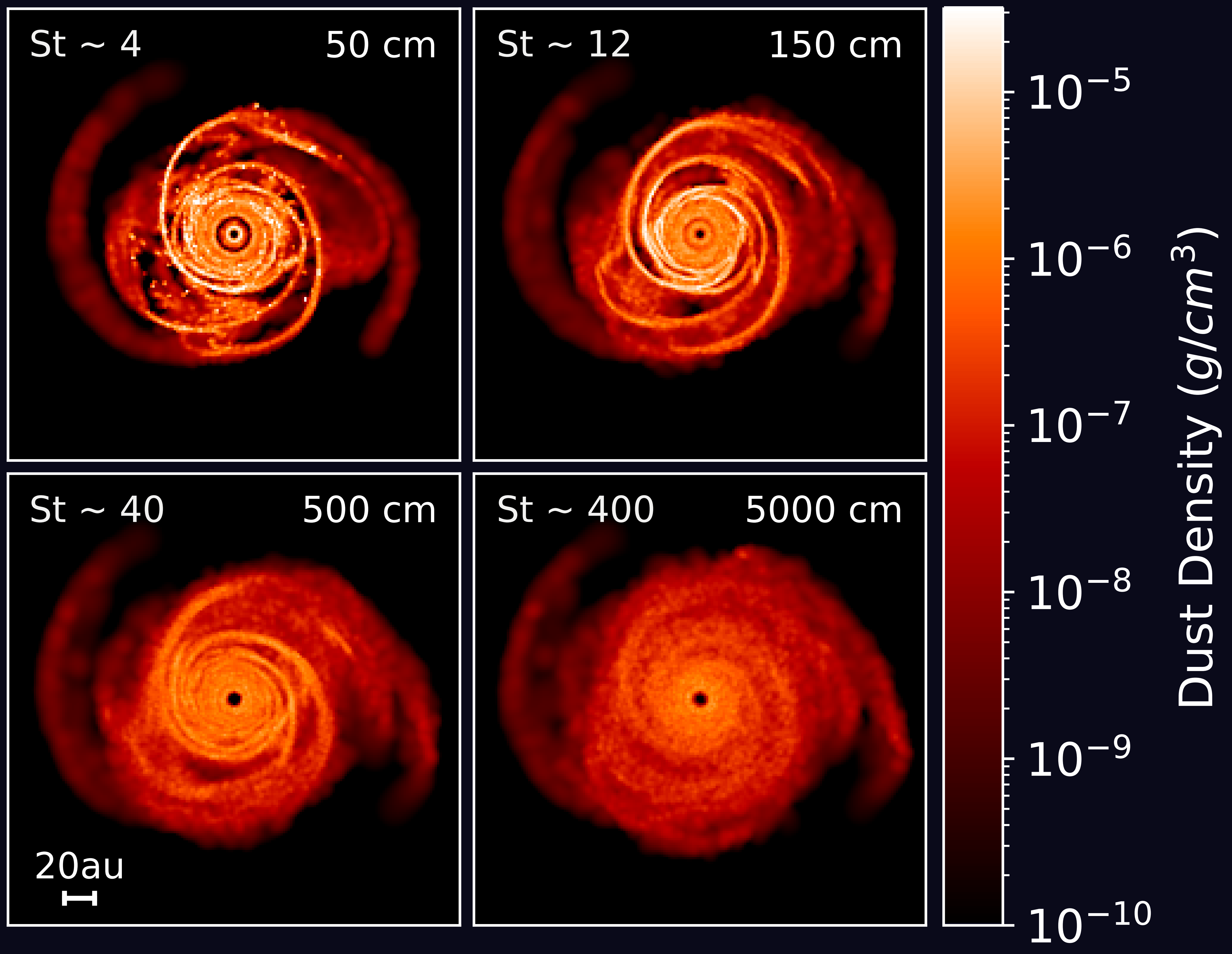


Different Dust Sizes

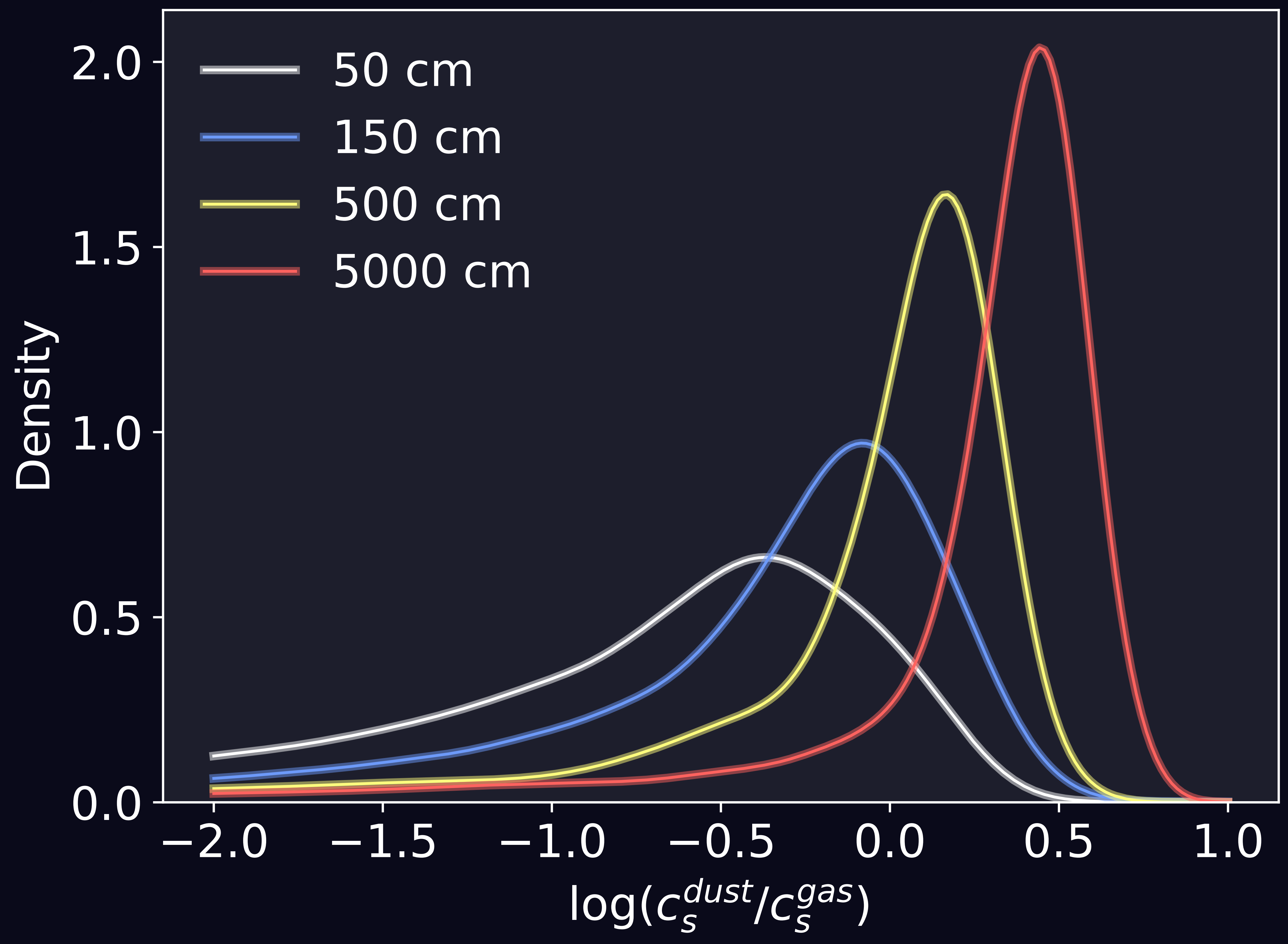


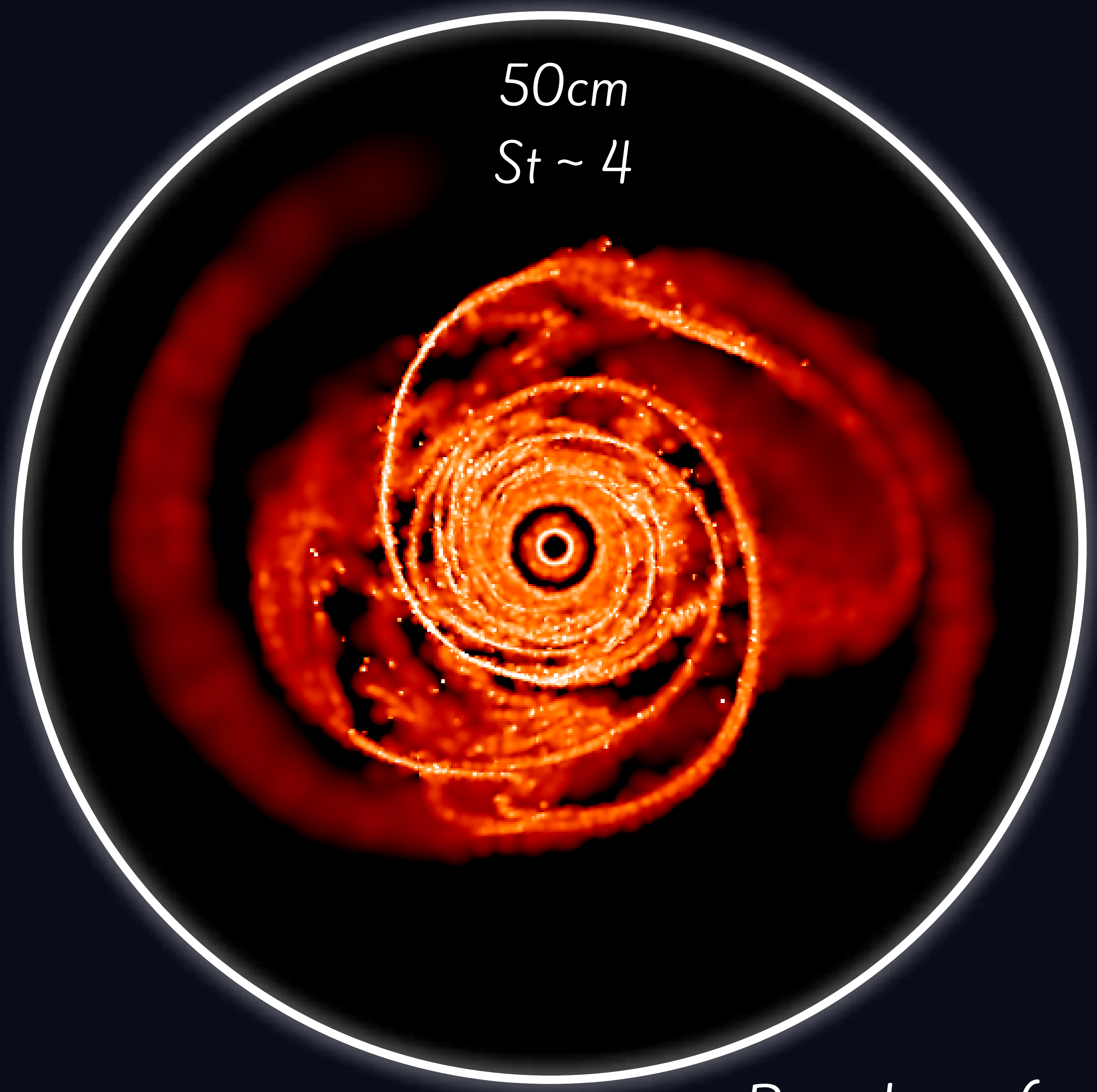
Rowther+ (in prep)



Analysis of Velocity Dispersion

Dust forms bound clumps

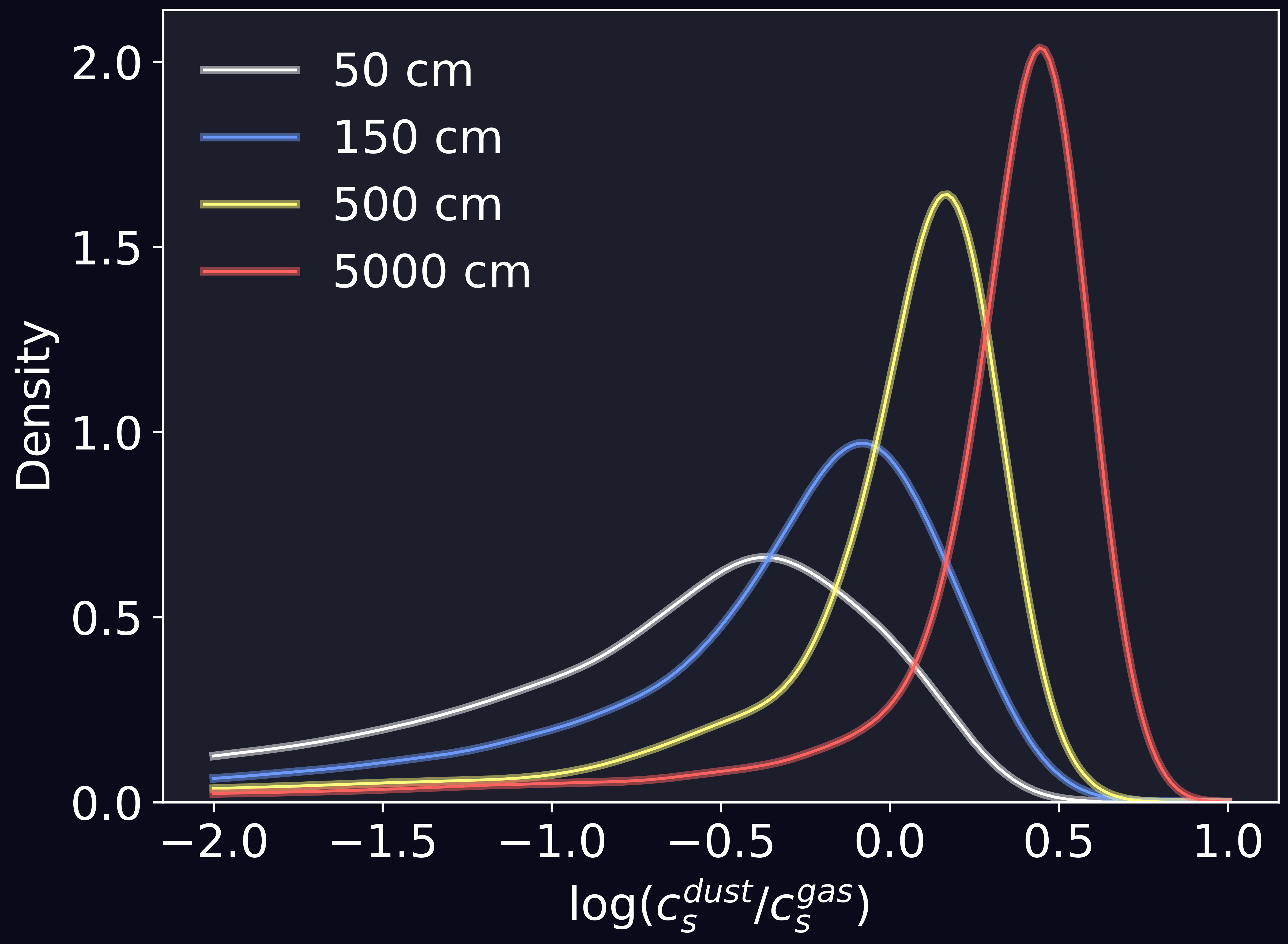


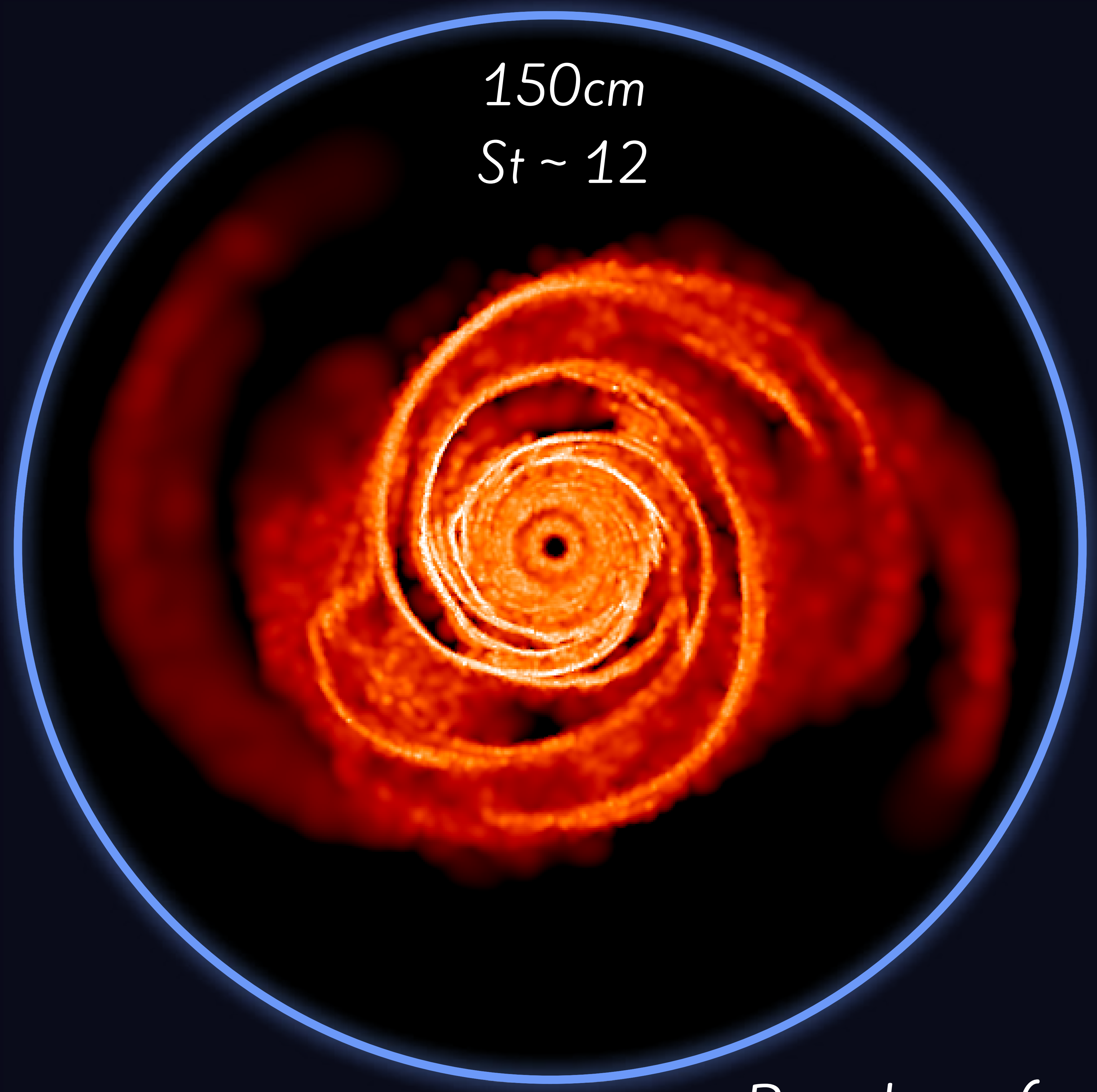


Rowther+ (in prep)

Analysis of Velocity Dispersion

Dust spirals well coupled to gas

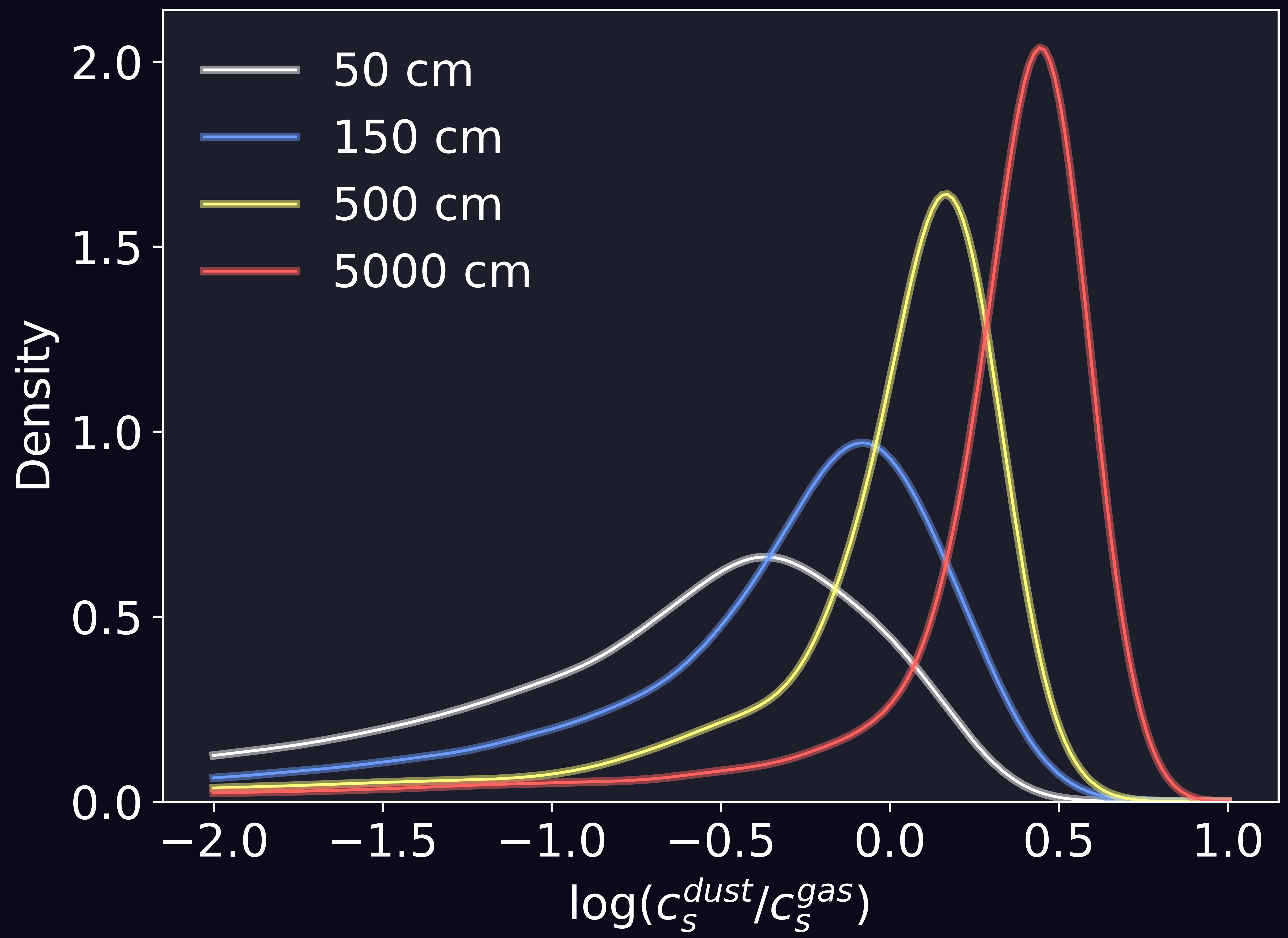


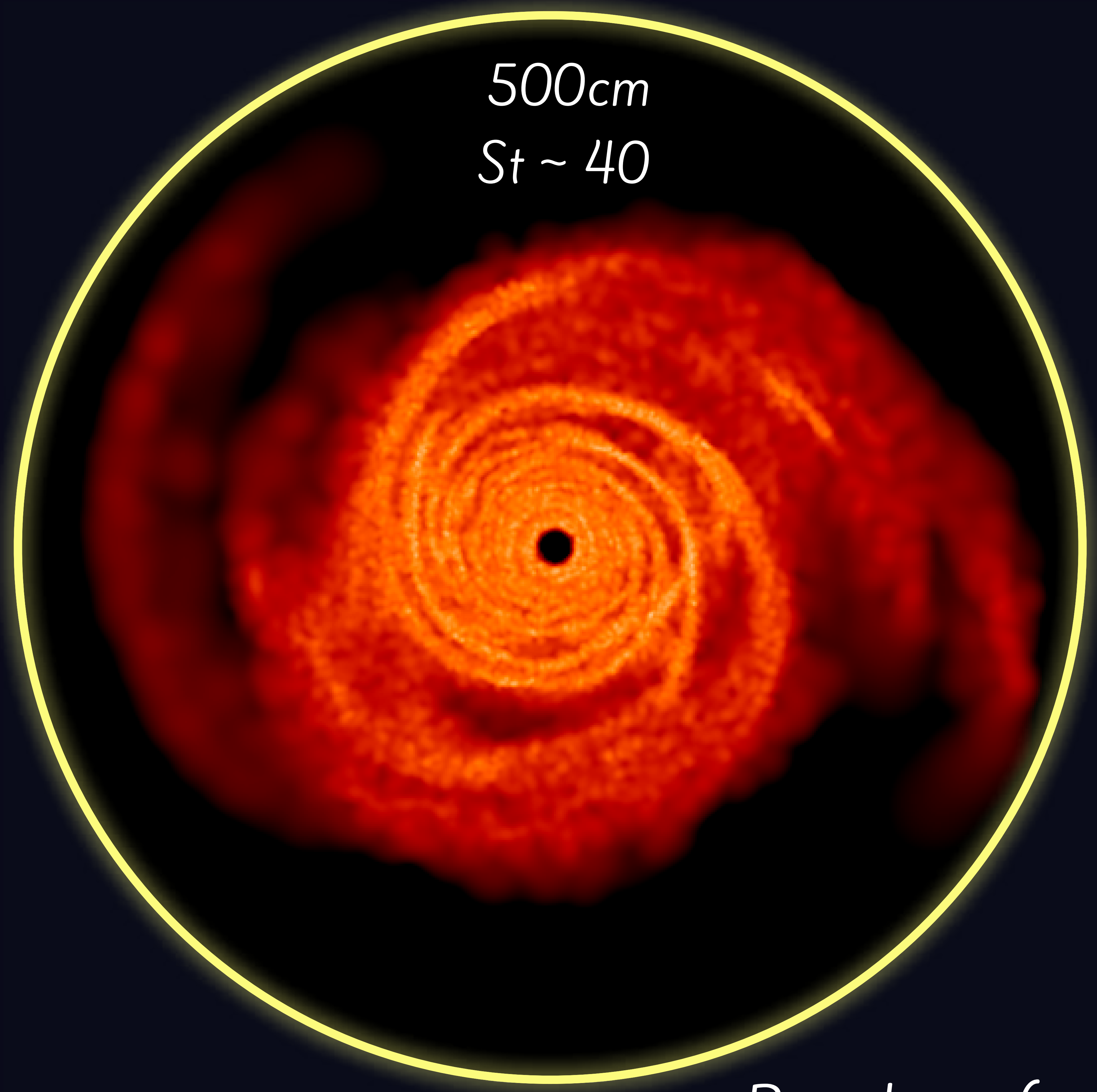


Rowther+ (in prep)

Analysis of Velocity Dispersion

Dust decoupling from gas





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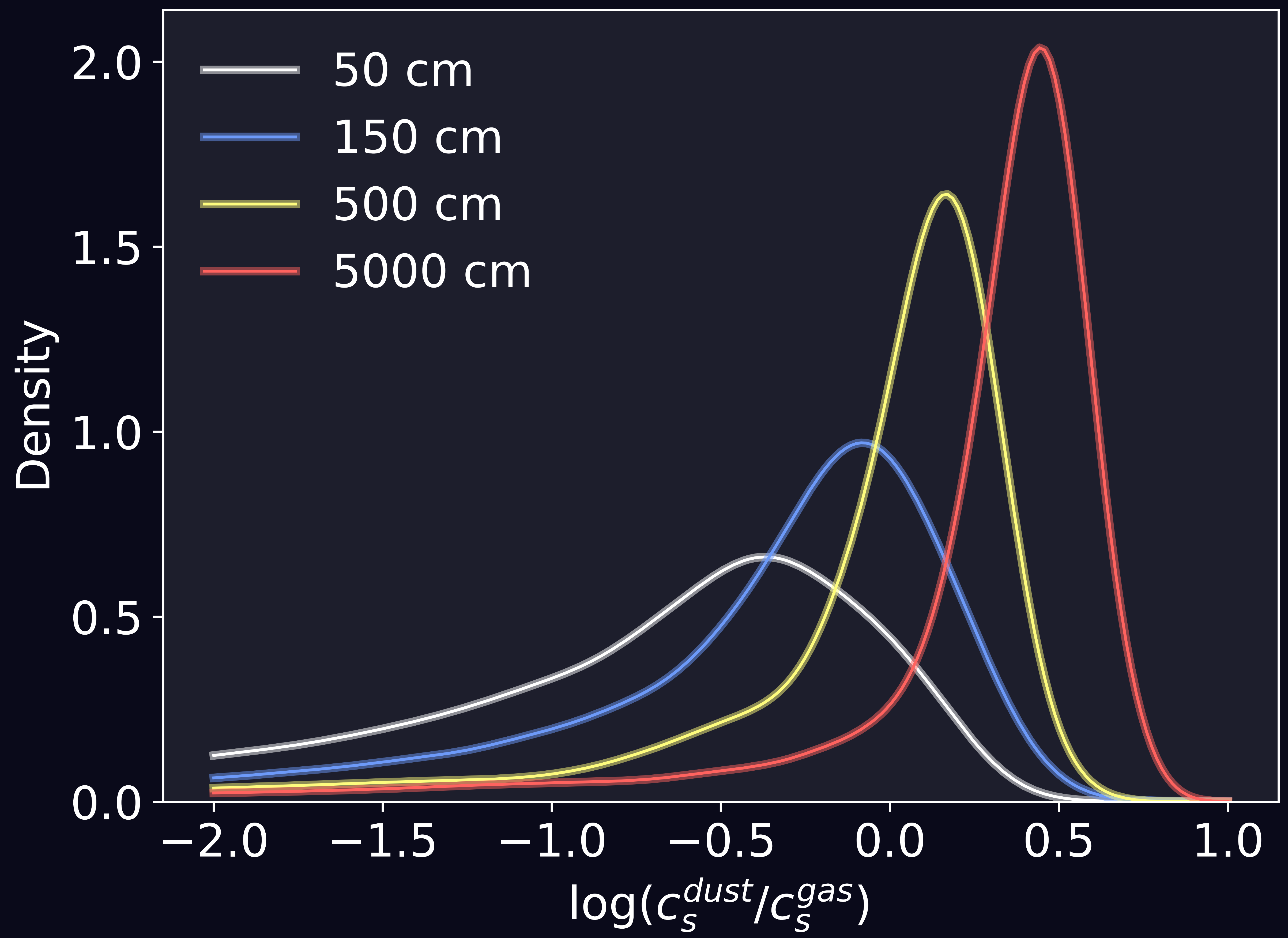
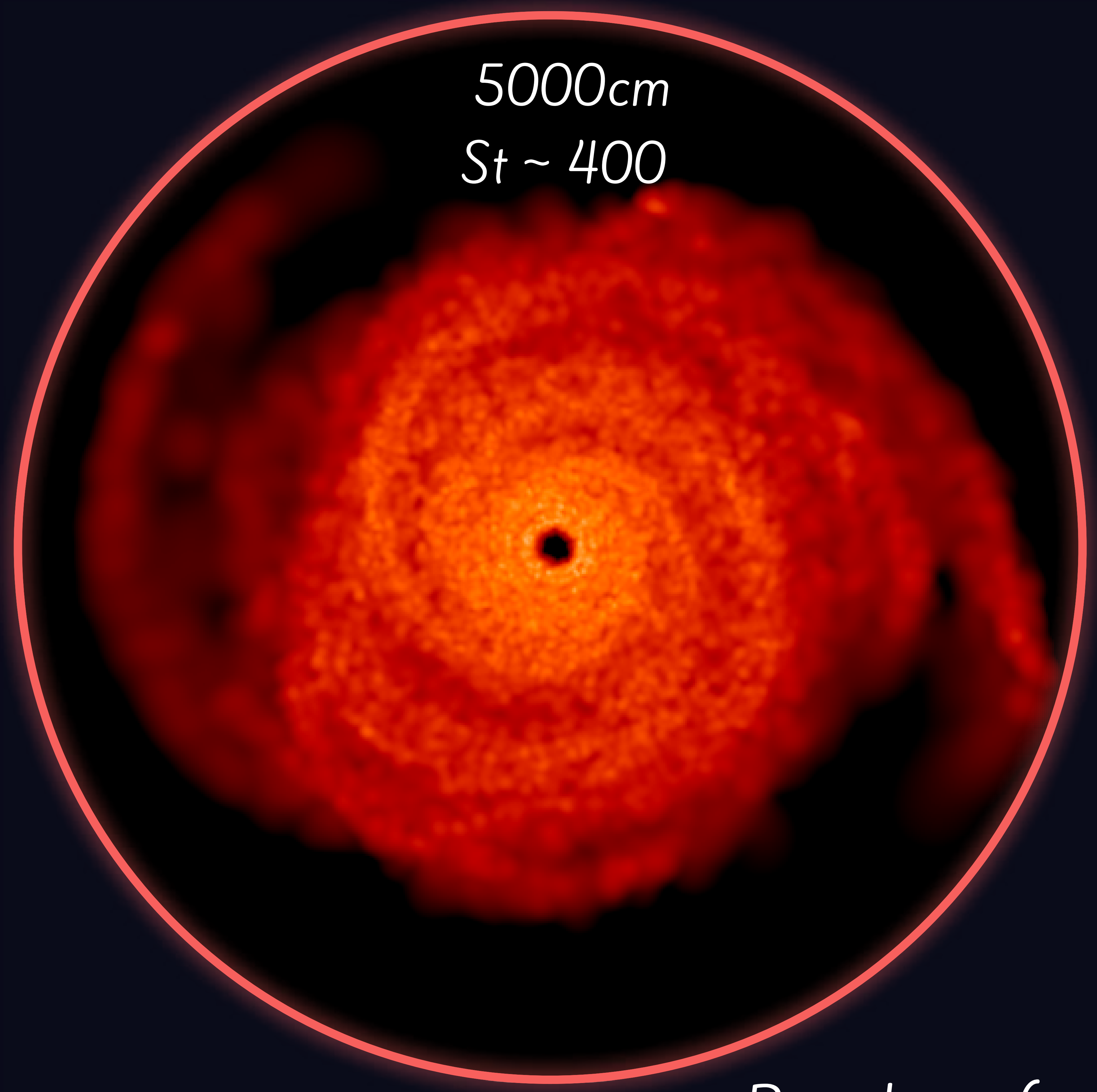
Analysis of Velocity Dispersion

Dust fully decouples from gas





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Drag Force is Important, Even for Large ($St > 1$) Grains

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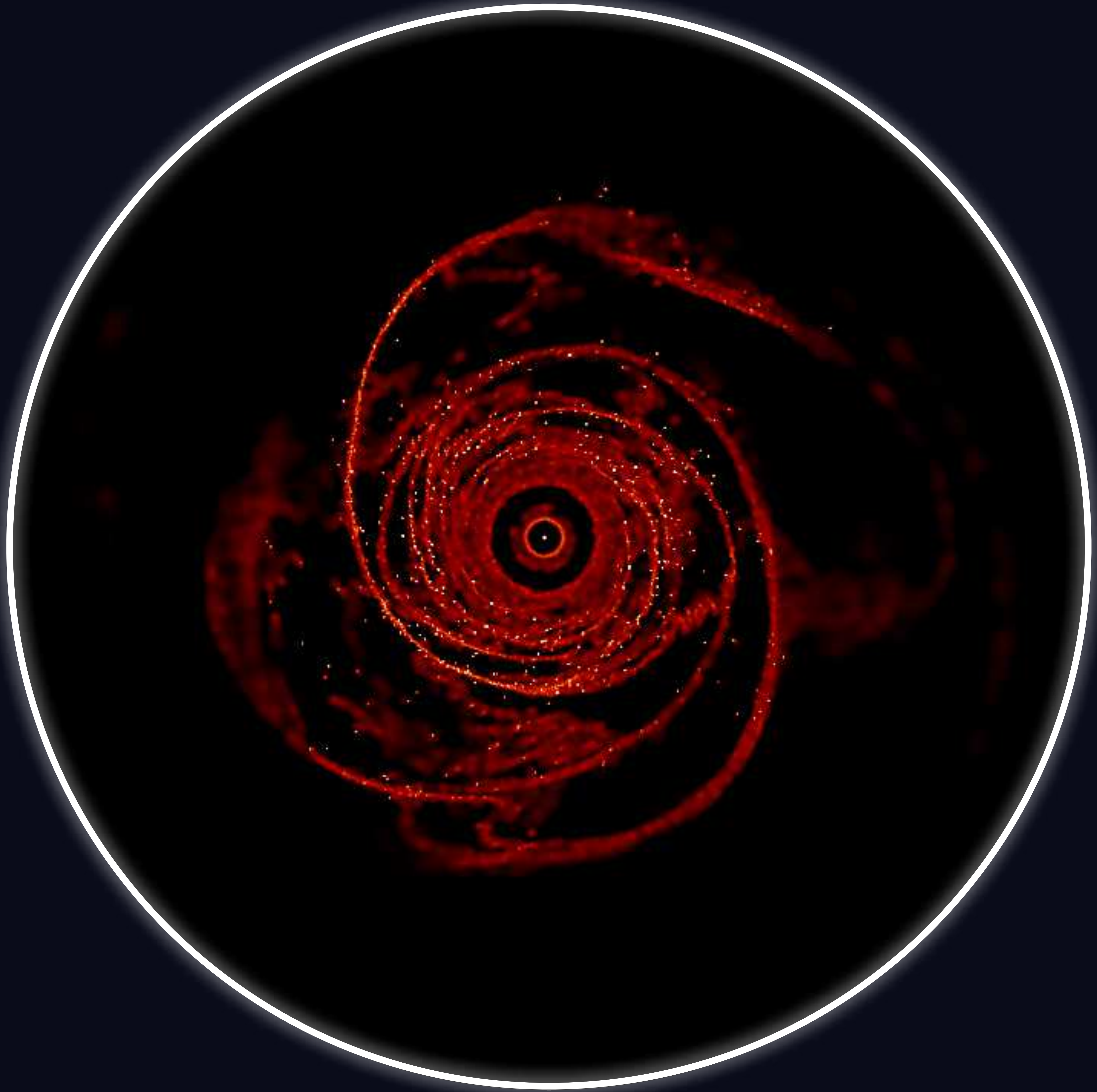
How Important is Gravity?

Is the Coupling Purely Due to Drag?

Modifying the Physics

1. Full Physics
2. No Dust Self-Gravity
3. Drag Only
4. Gravity Only



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Forces Acting on the Dust

Full Physics

$$\frac{\mathrm{d}\boldsymbol{v}_{\mathrm{d}}}{\mathrm{d}t} = -\frac{K}{\rho_{\mathrm{d}}}(\boldsymbol{v}_{\mathrm{d}} - \boldsymbol{v}_{\mathrm{g}}) + \boldsymbol{a}_{\mathrm{dust-gas}} + \boldsymbol{a}_{\mathrm{selfgrav}} + \boldsymbol{a}_{\mathrm{dust-star}}$$

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Forces Acting on the Dust

No Dust Self-Gravity

$$\frac{\mathrm{d}\boldsymbol{v}_\mathrm{d}}{\mathrm{d}t} = -\frac{K}{\rho_\mathrm{d}}(\boldsymbol{v}_\mathrm{d} - \boldsymbol{v}_\mathrm{g}) + \boldsymbol{a}_\mathrm{dust-gas} + \boldsymbol{a}_\mathrm{selfgrav} + \boldsymbol{a}_\mathrm{dust-star}$$

Forces Acting on the Dust

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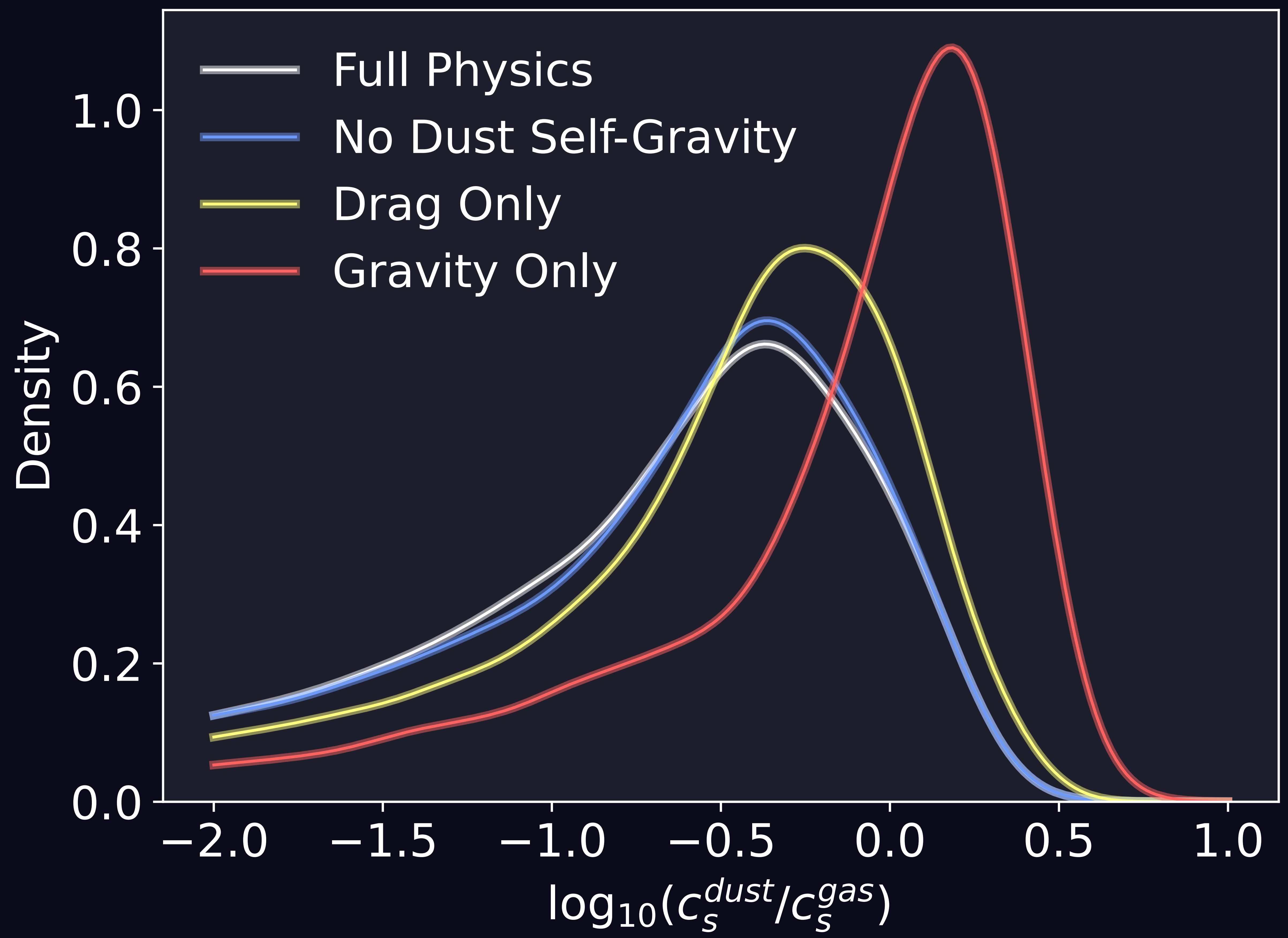
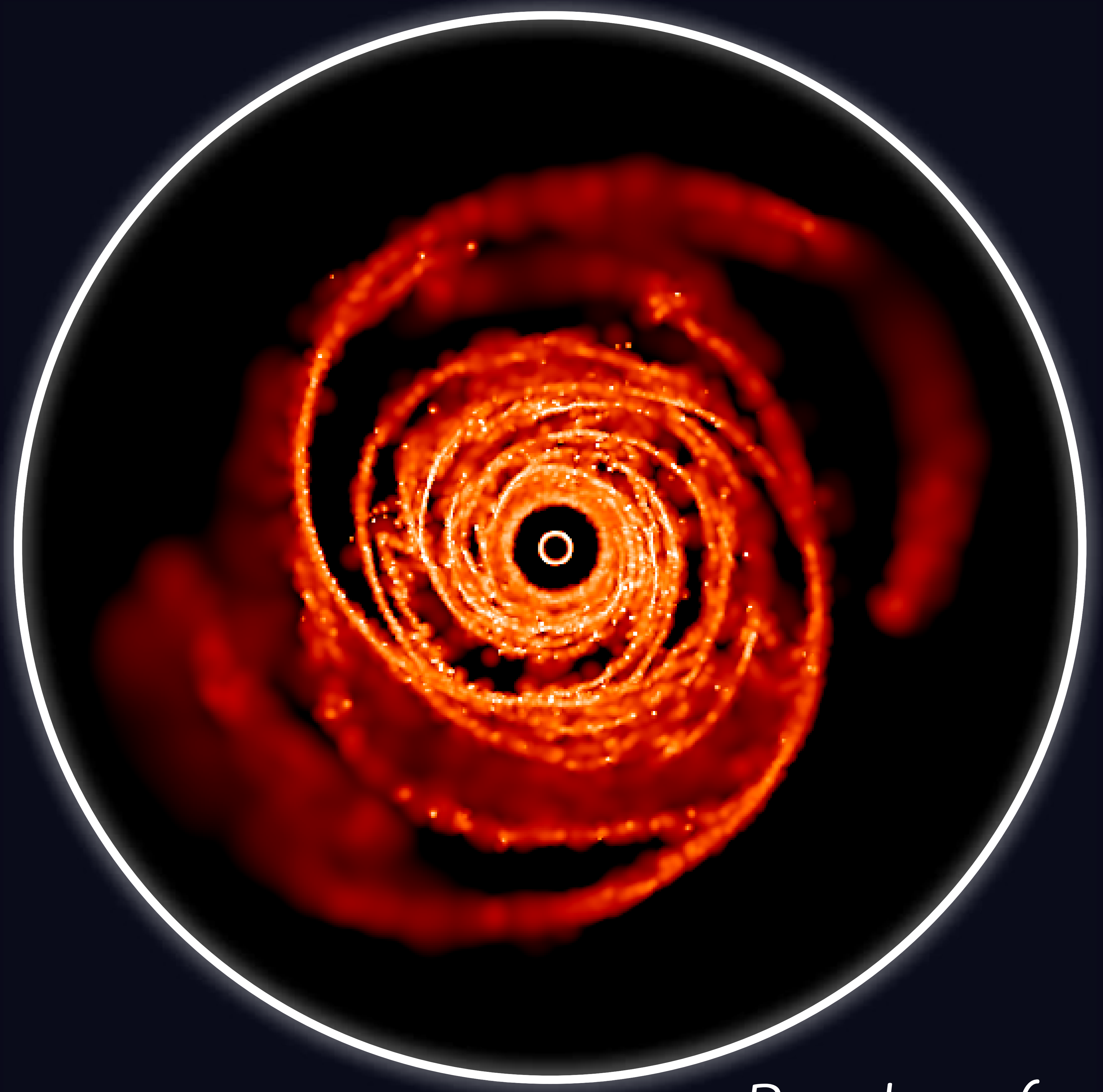
Full Physics





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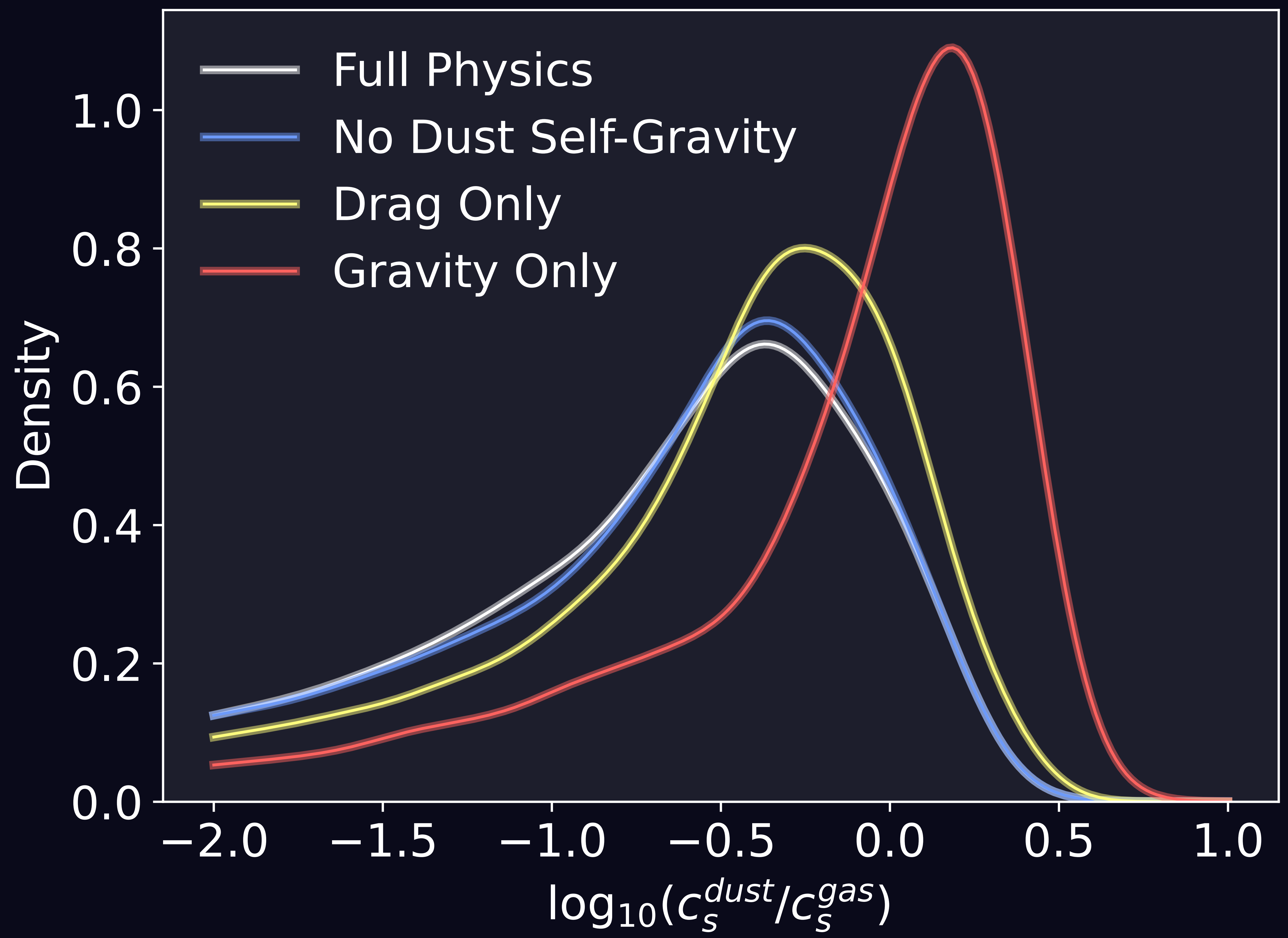
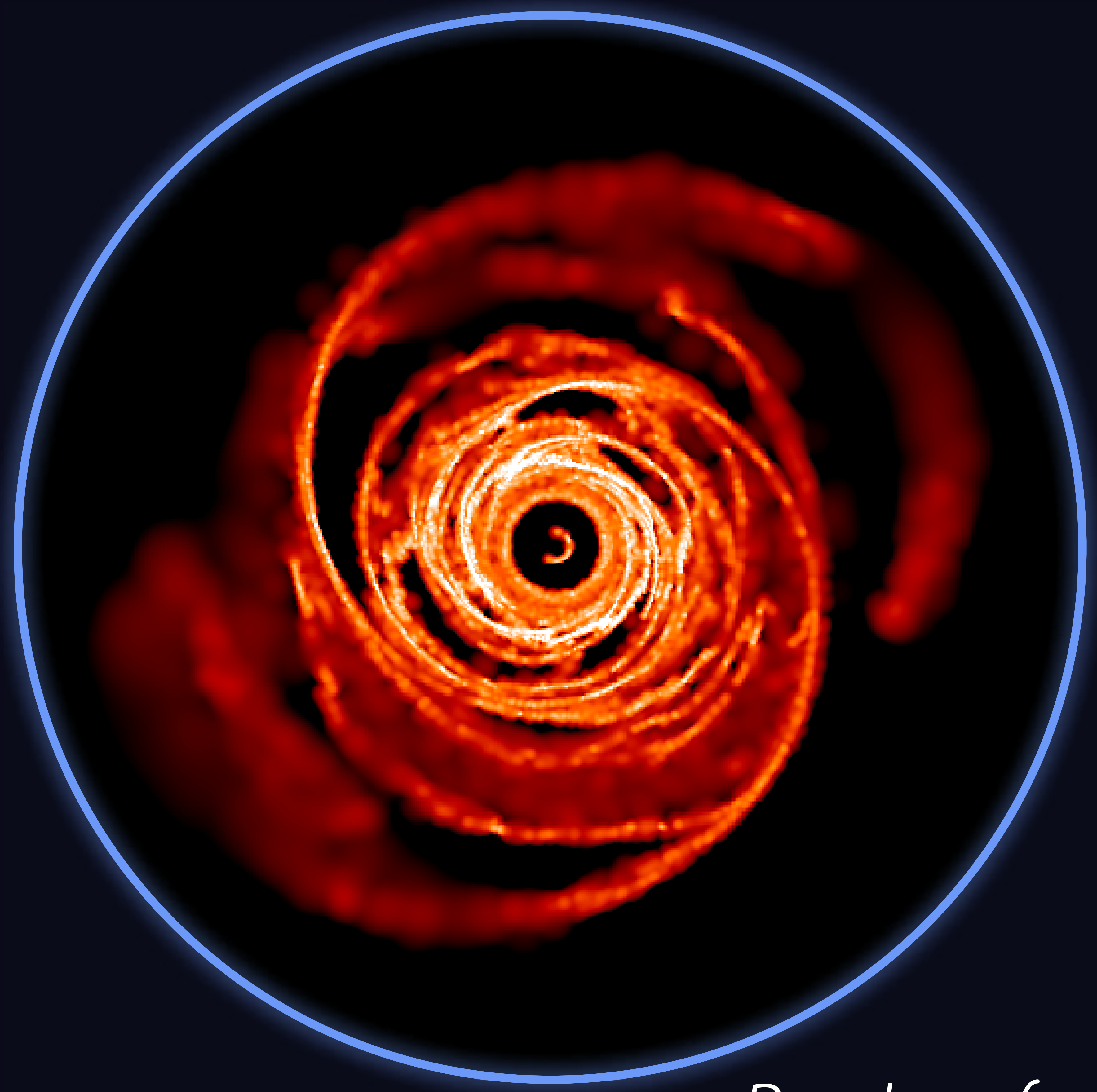
No Dust Self-Gravity





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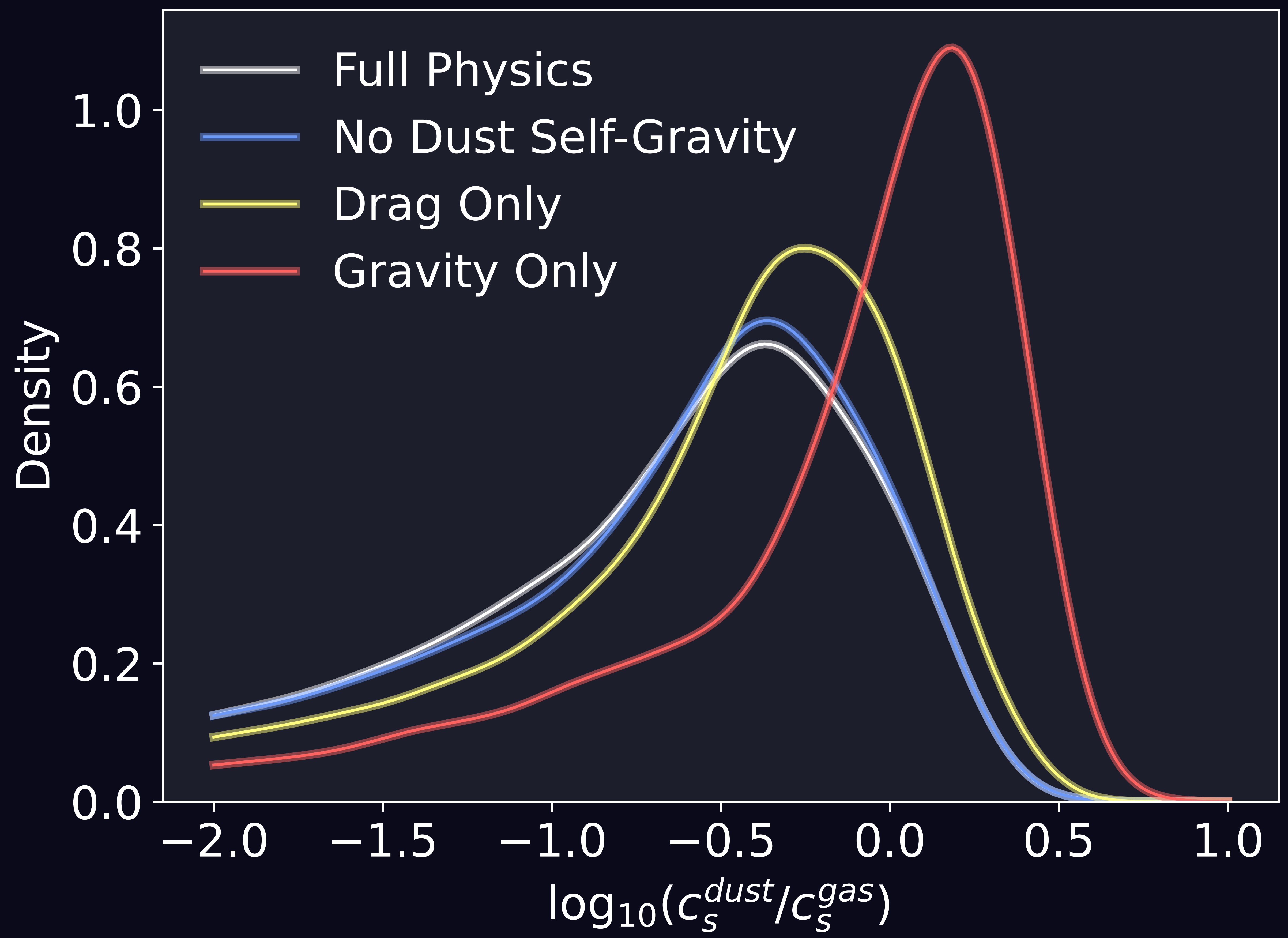
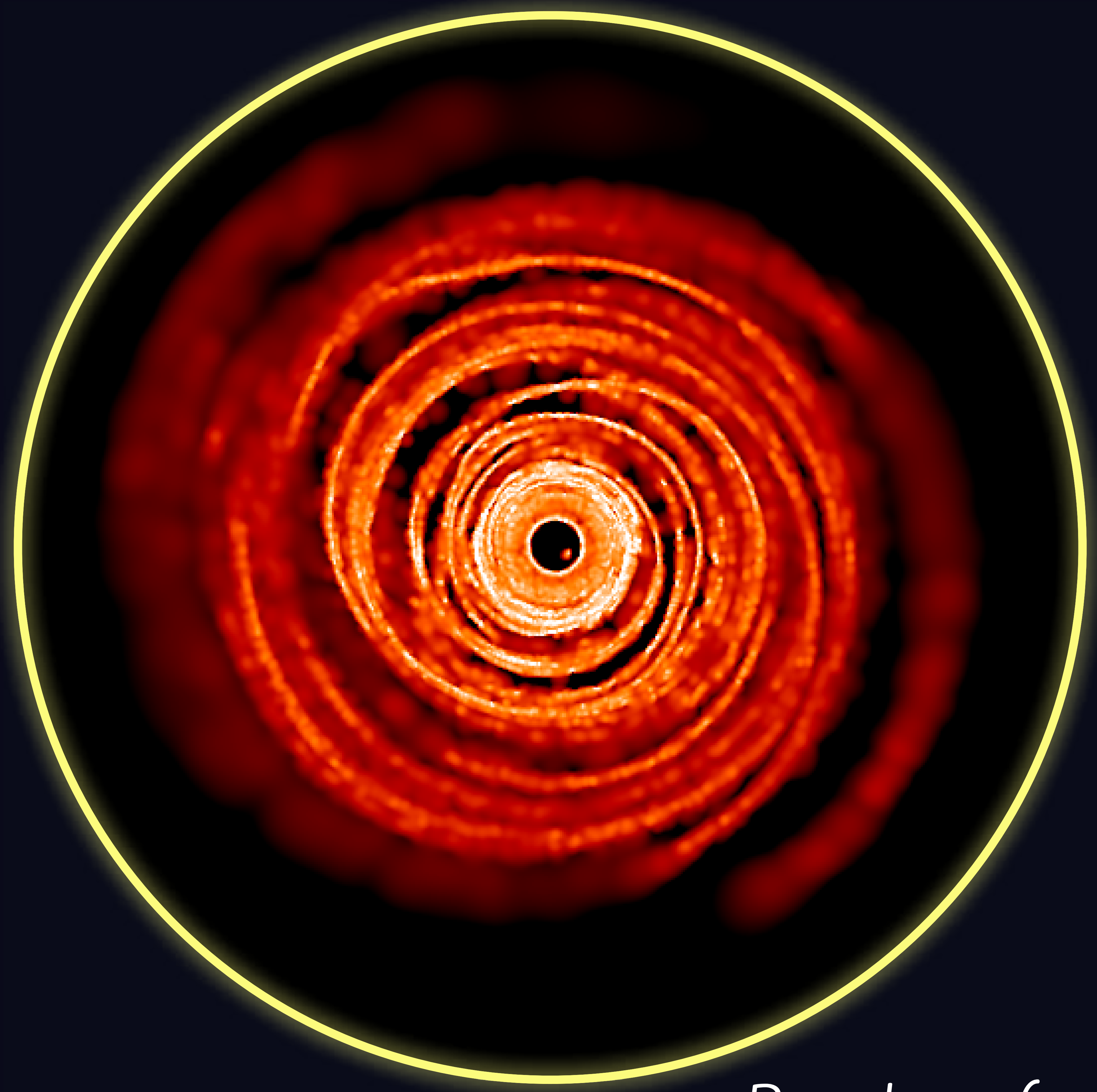
Drag Only





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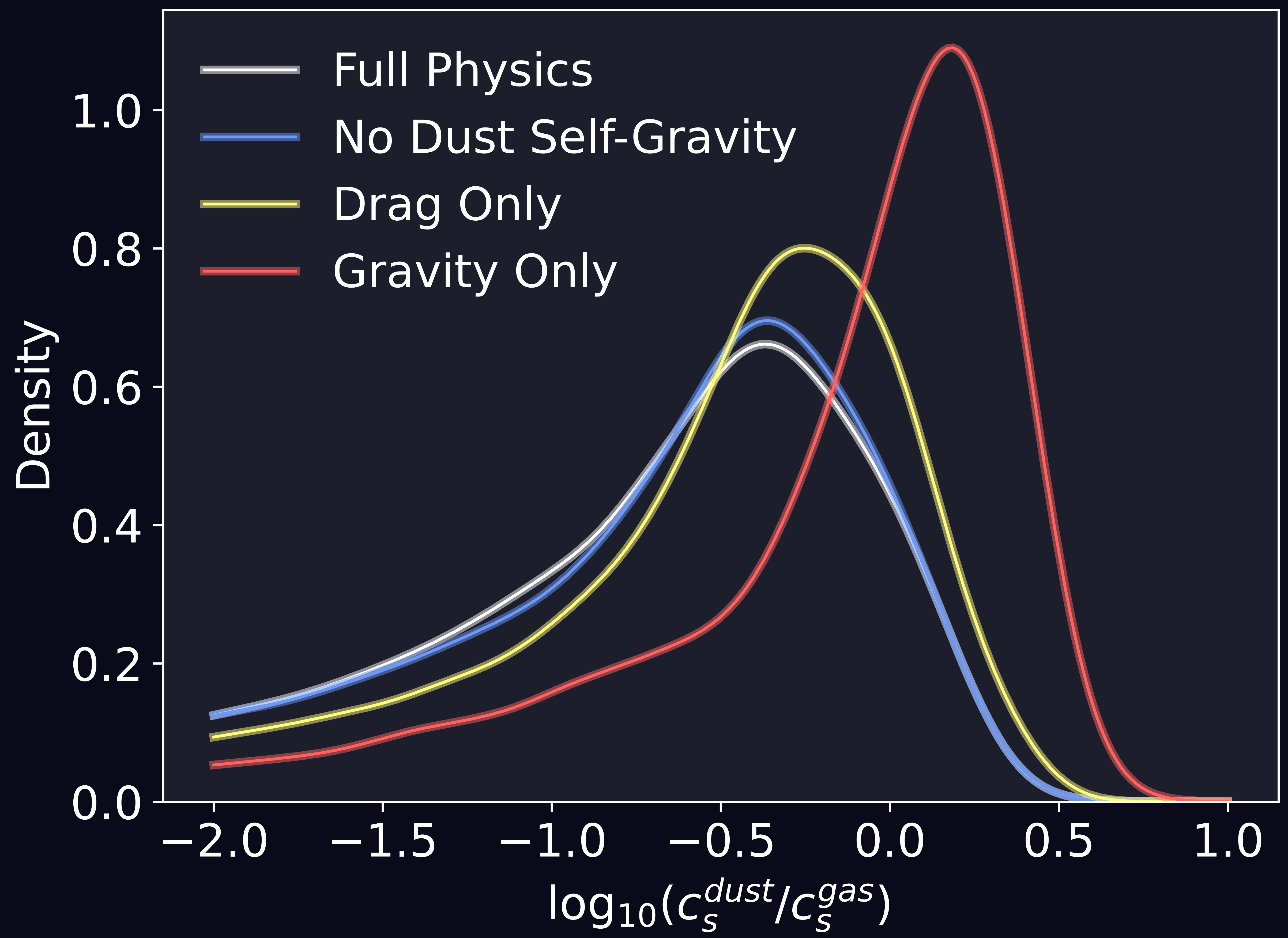
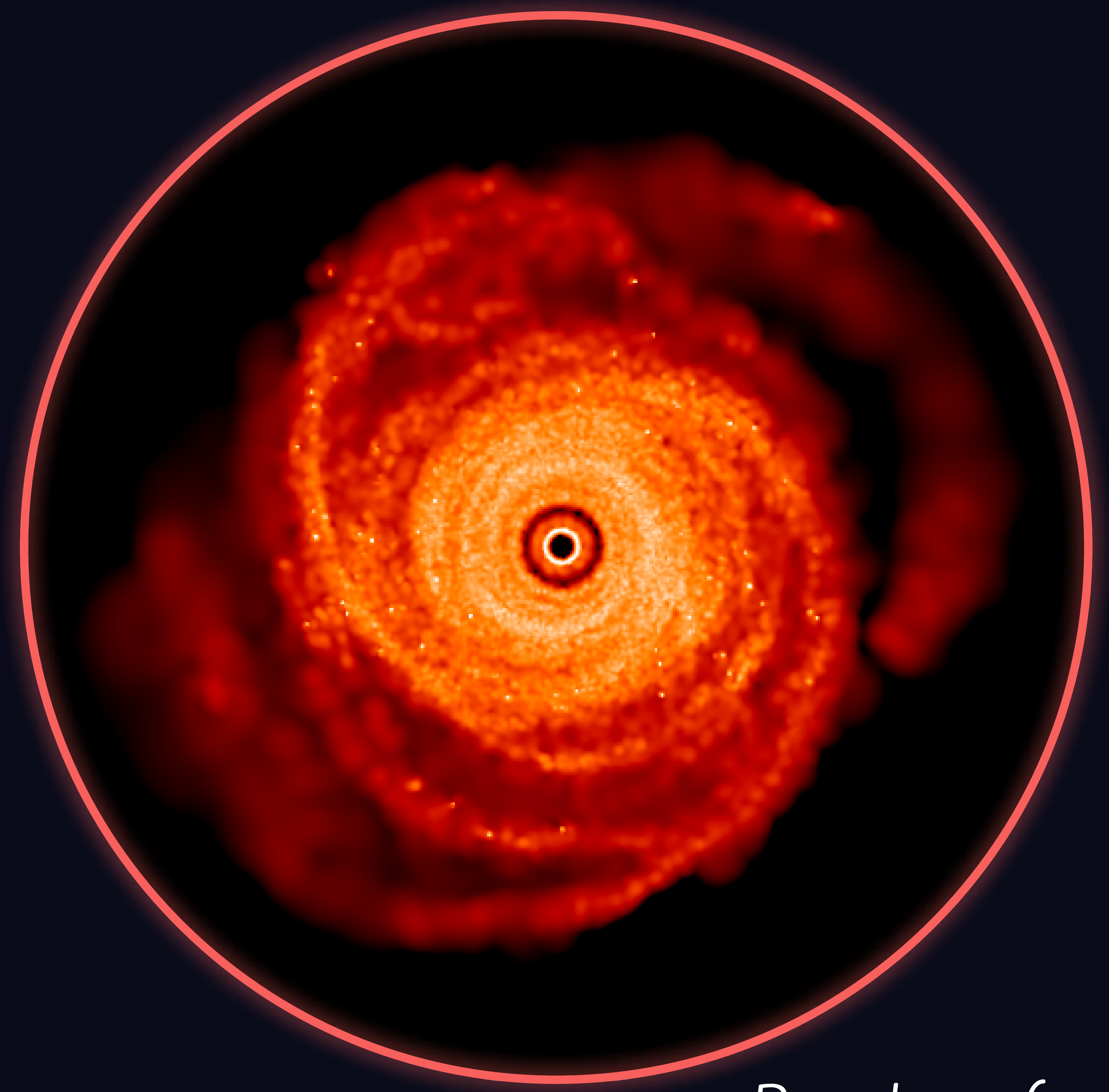
Gravity Only





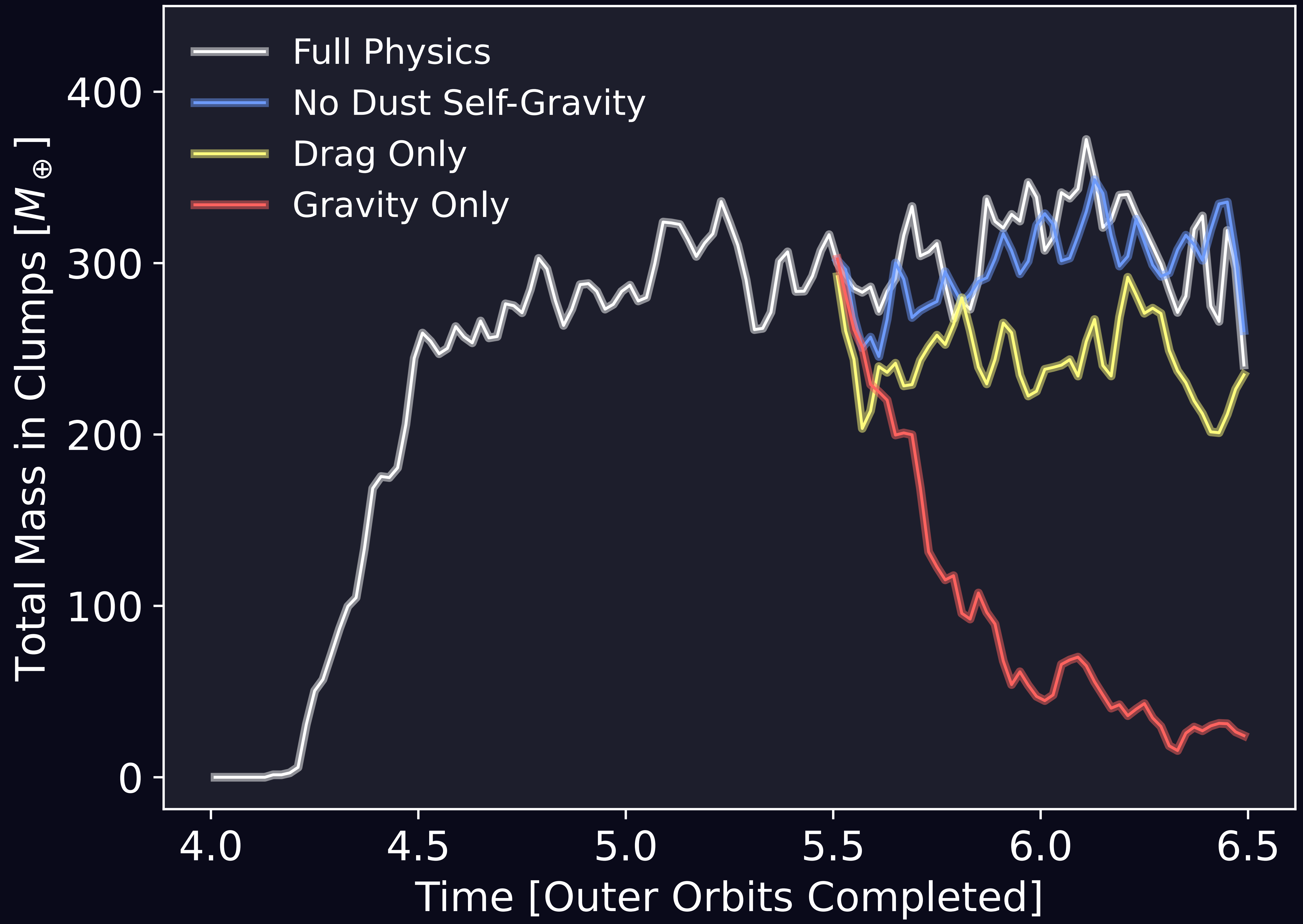
Rowther+ (in prep)

Both Gravity and Drag are Necessary for Large Grains to Couple to the Gas

Rowther+ (in prep)

Total Mass in Clumps

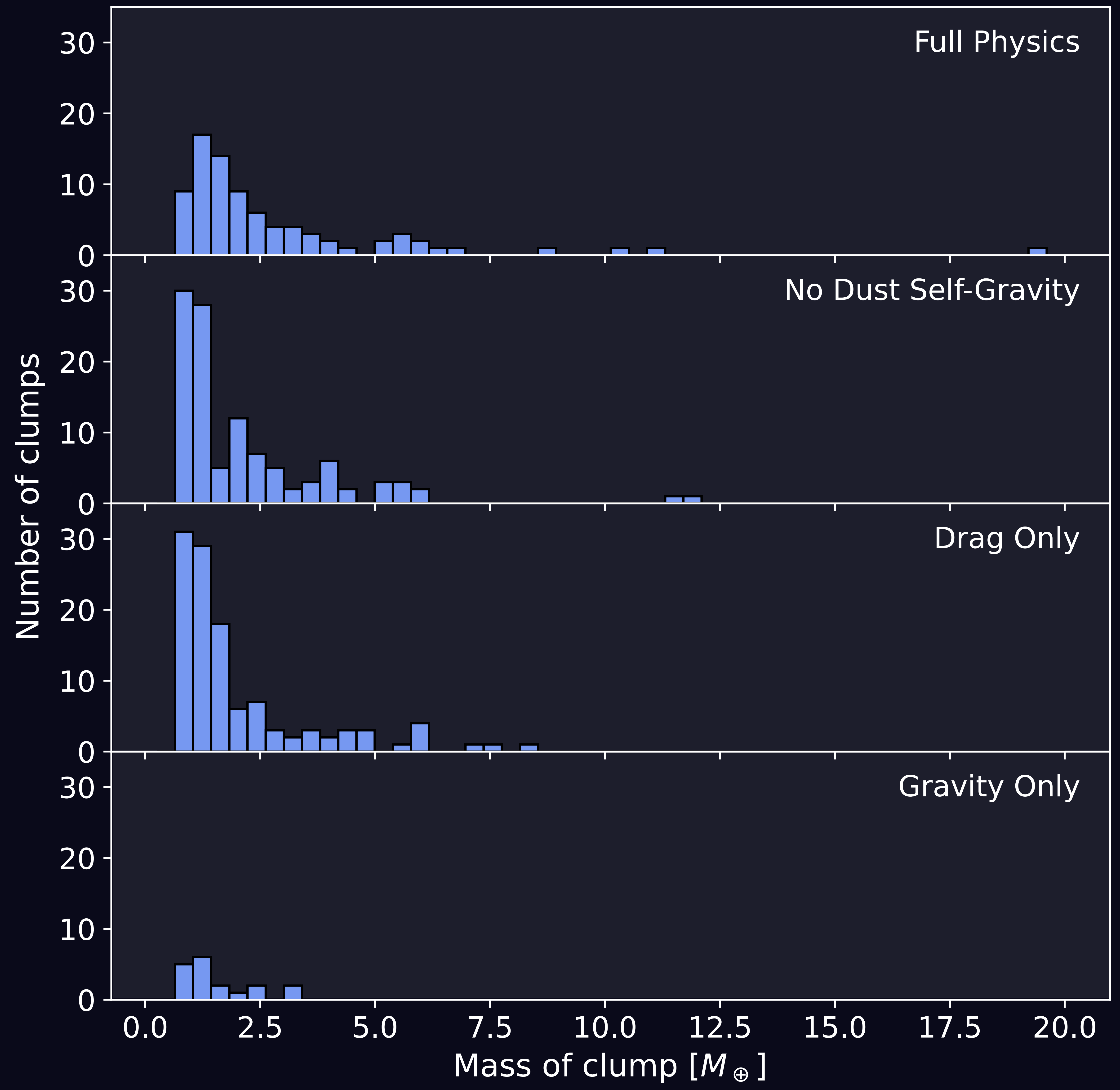
- Clump finding algorithm (Wurster & Bonnell, in prep)
- Clumps are formed very quickly.
- Until 40% of the dust disc is in clumps.



Rowther+ (in prep)

Impact of Physics on Clump Masses

- *Loss of gravity results in clumps falling apart into smaller clumps.*
- *Loss of drag results in clumps falling apart almost as fast as they initially formed.*



Implications on Planet Formation

- Clumps can form extremely rapidly.
- Clump masses can reach the threshold at which runaway accretion can occur.
- Dust does not primarily drift inward, potentially prolonging the dust disc's lifetime.

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Conclusions

- The gas spirals are able to efficiently trap dust.
- For Stokes numbers near unity, the dust can become gravitationally unstable forming bound clumps.
- These clumps are mostly in the 1-3$M_\oplus$ range, but a few are bigger than 10$M_\oplus$.
- Both drag and gravity are necessary to trap dust in the gas spirals.