Triggered fragmentation in gravitationally unstable discs: forming fragments at small radii

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Instabilities & Structures in Protoplanetary Discs
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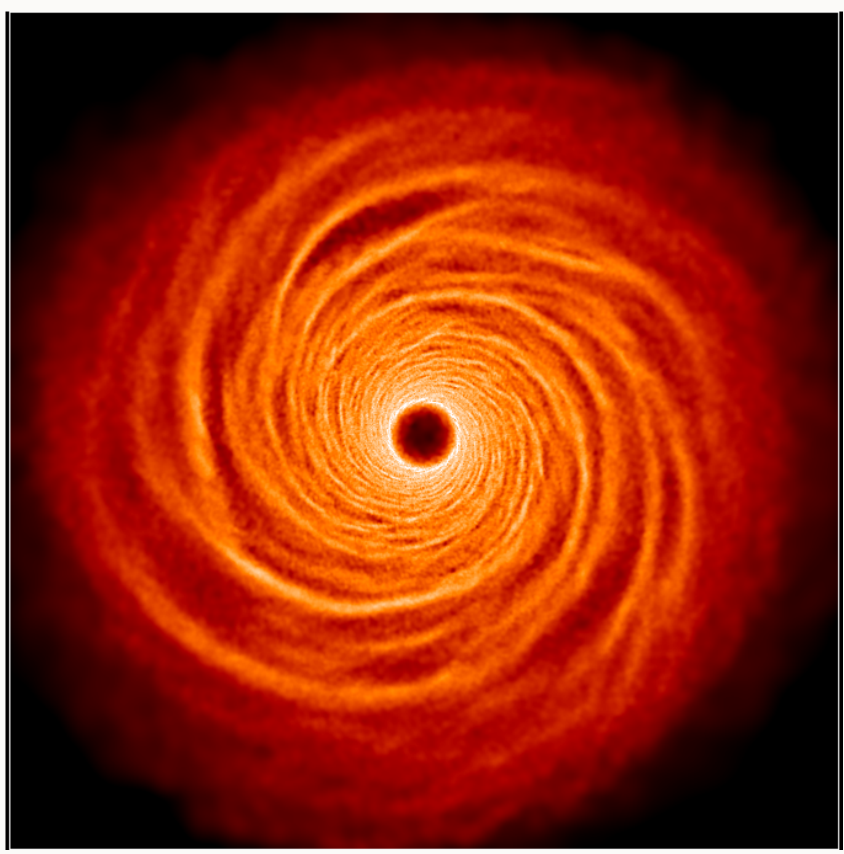
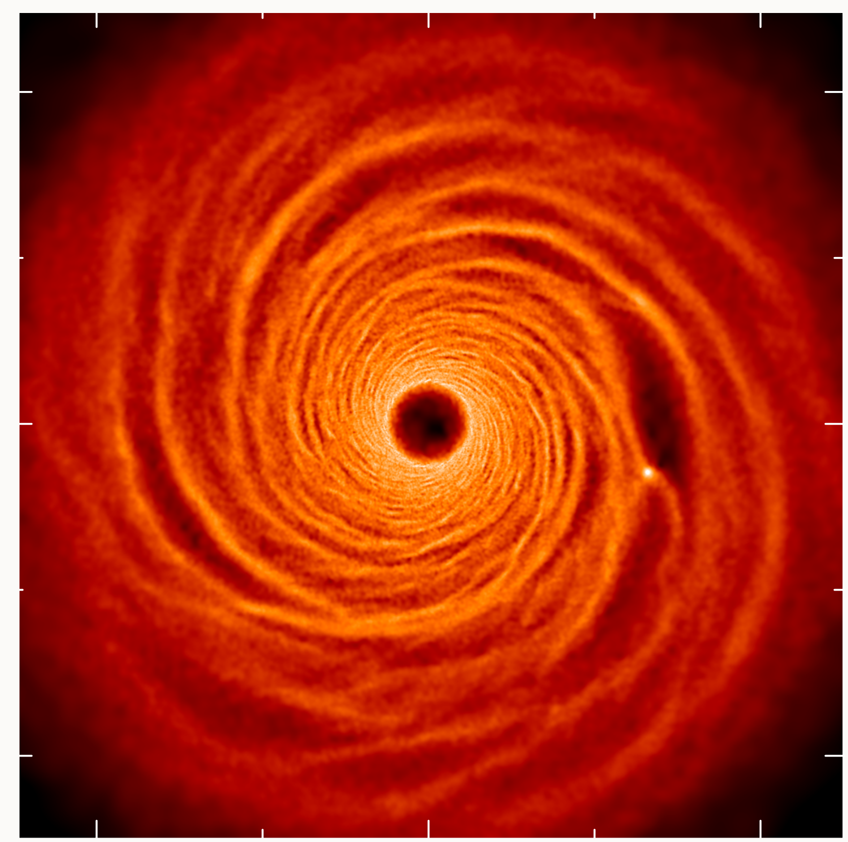
GRAVITATIONAL INSTABILITY

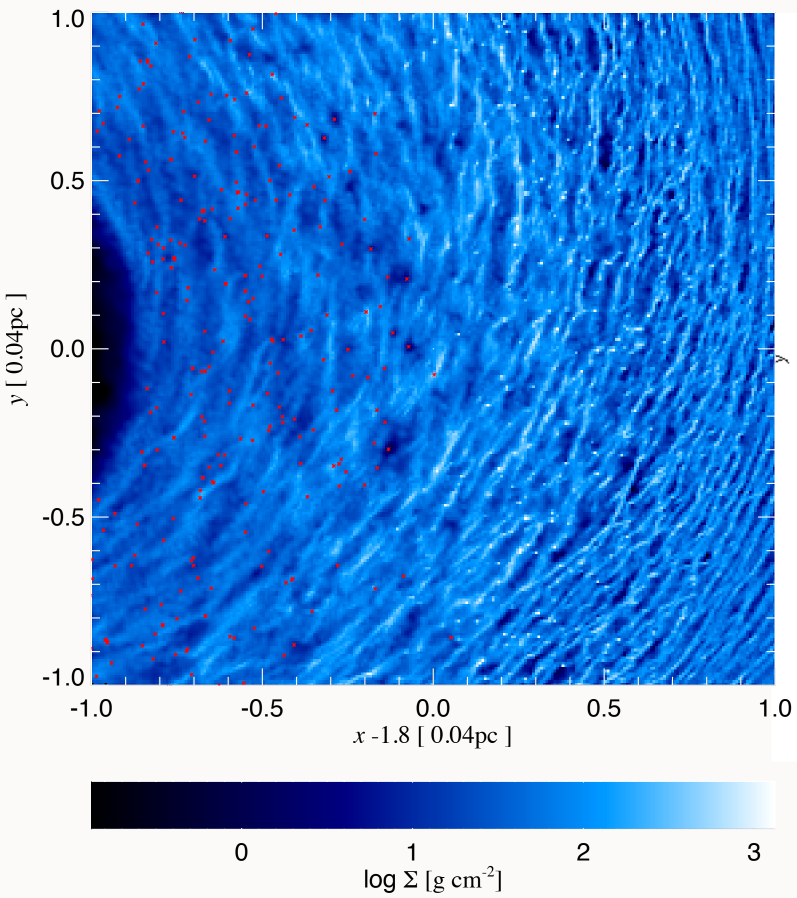
- Fragmentation into bound objects is a fast process
- Occurs at large radii in a disc

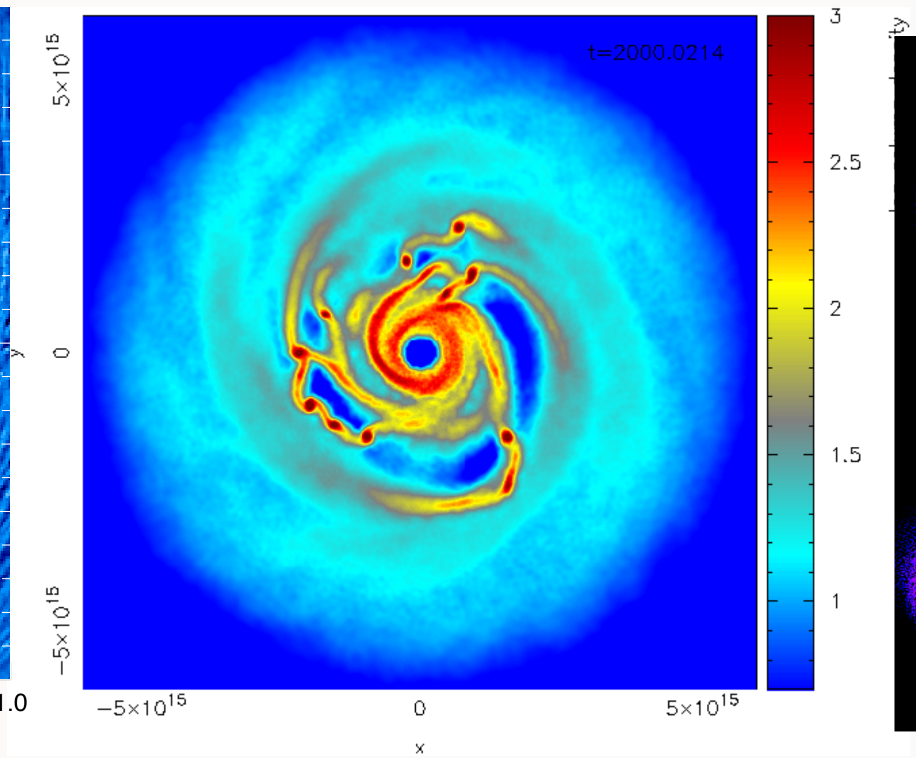


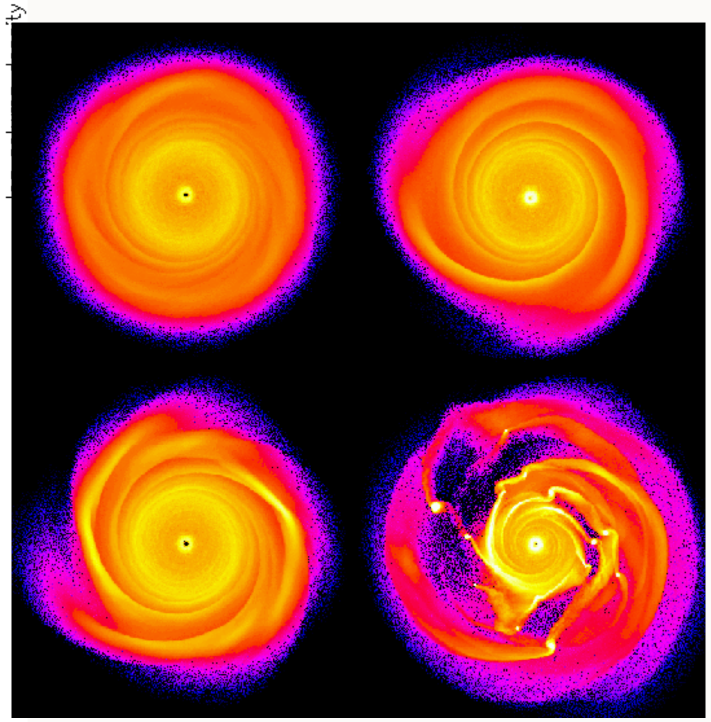


Meru & Bate 2011b

GRAVITATIONAL INSTABILITY ON MANY SCALES





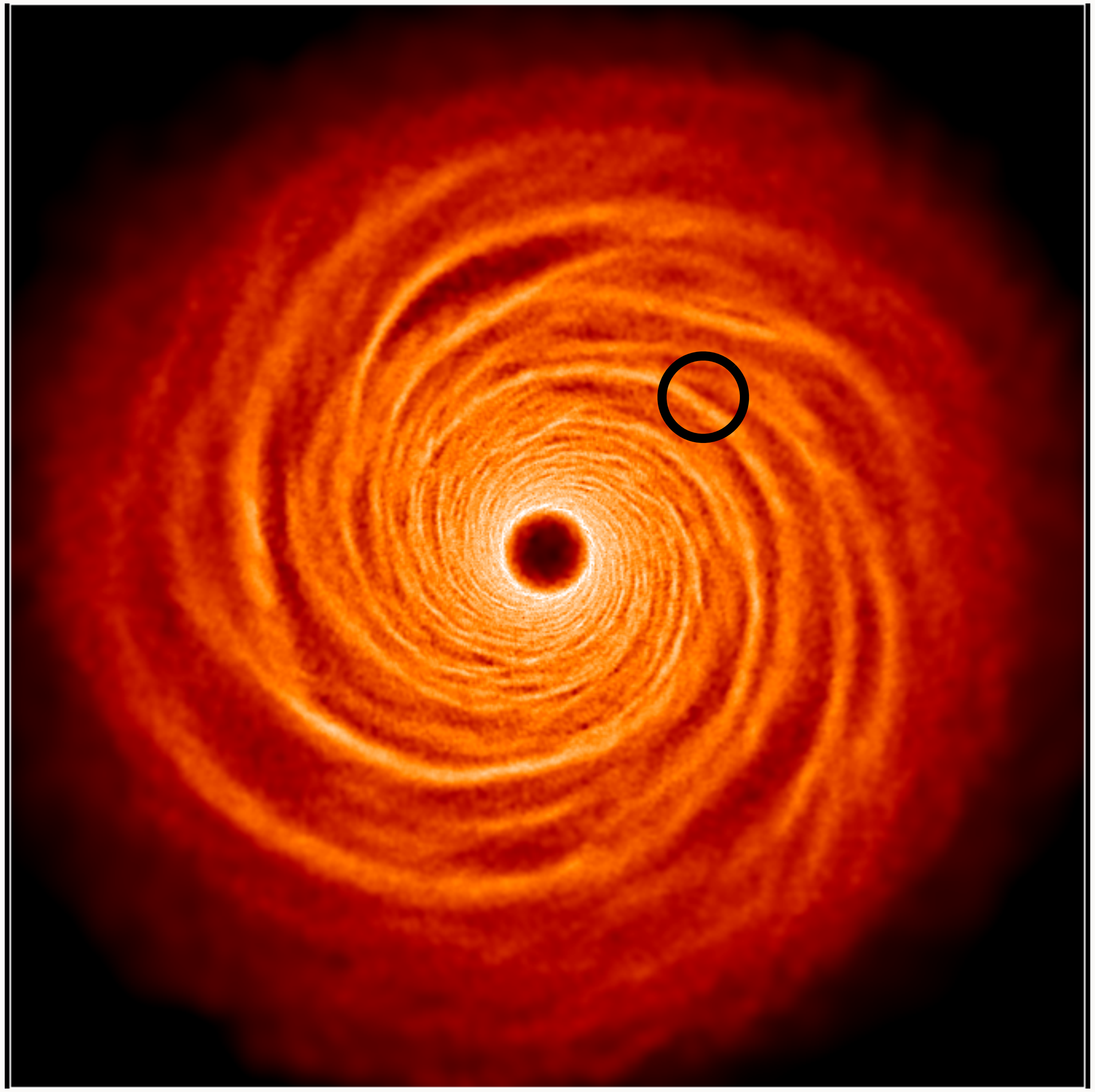


AGN discs: star formation
Nayakshin, Cuadra & Springel 2007

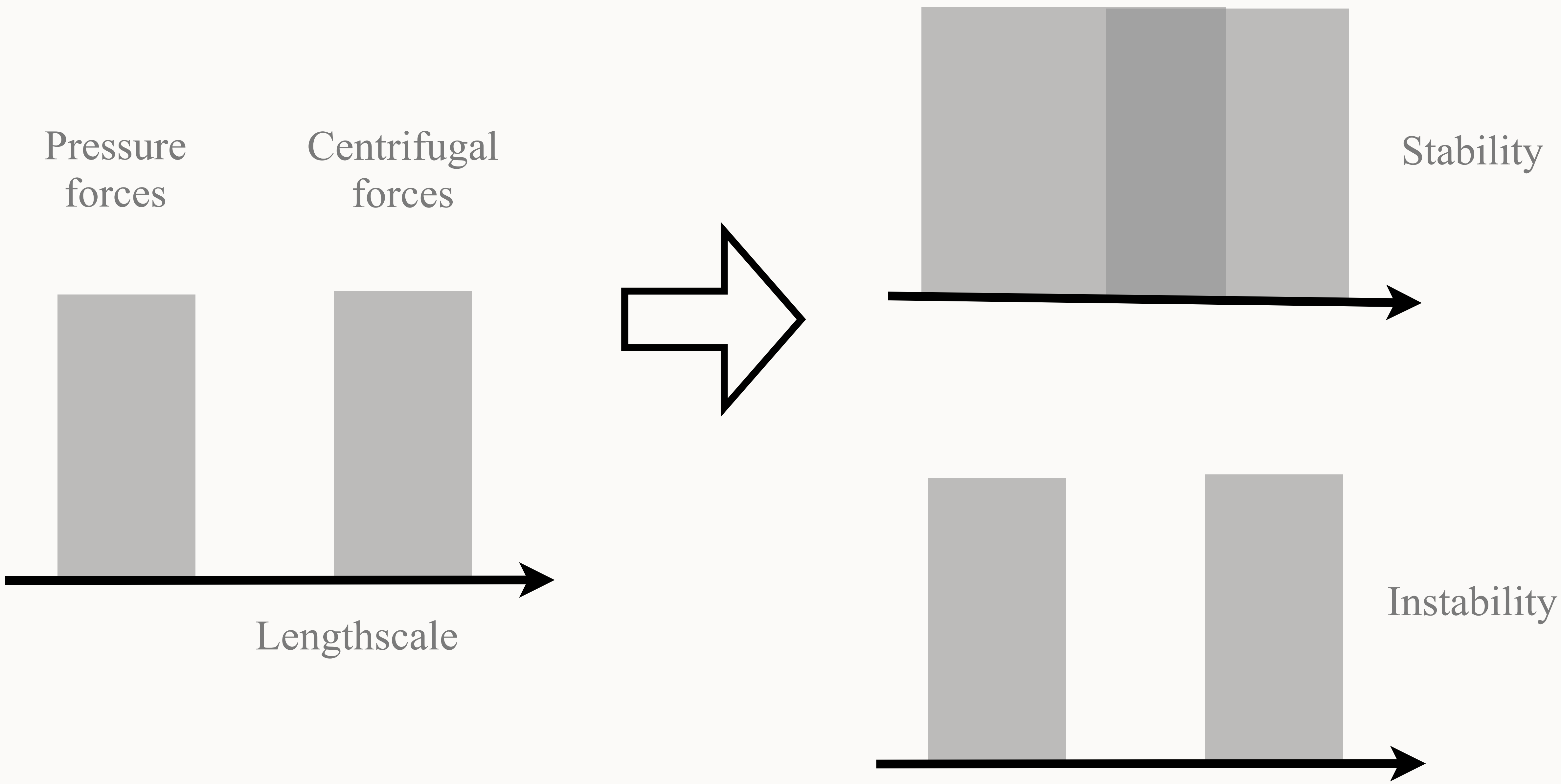
Brown dwarf formation
Stamatellos et al 2007

Planet formation
Mayer et al 2003

GRAVITATIONAL INSTABILITY



CONDITIONS FOR FRAGMENTATION: TOOMRE CRITERION



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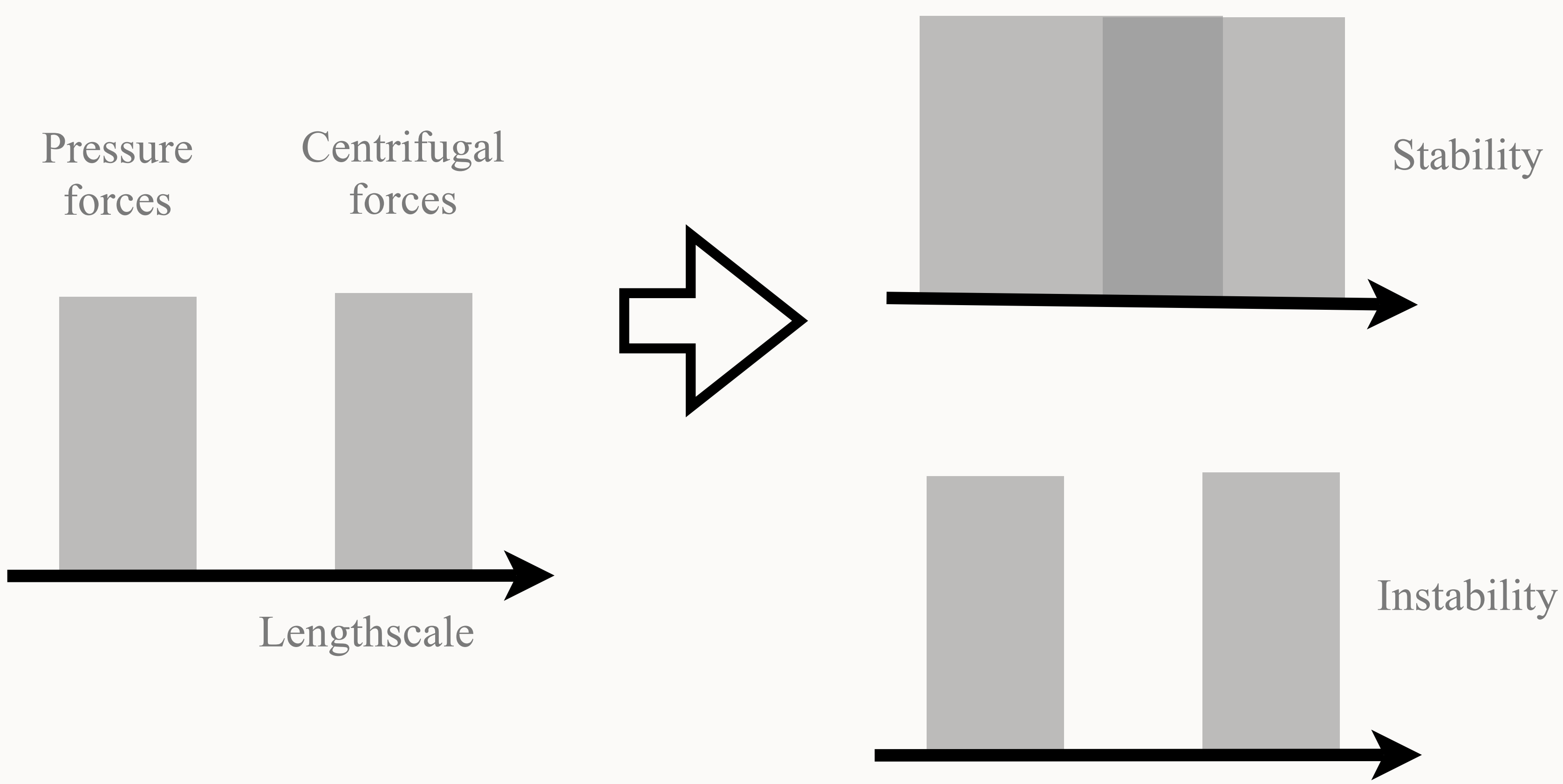


Stability determined by (Toomre 1964):

$$Q = \frac{c_{\mathrm{s}} \kappa}{\pi \Sigma G}$$

For an infinitesimally thin disc:

$$Q > 1 \equiv \text{stable}$$

$$Q < 1 \equiv \text{unstable}$$

CONDITIONS FOR FRAGMENTATION: COOLING RATE

- Fast cooling rate $\longrightarrow$ fragmentation
  Gammie 2001

$$\beta = t_{\mathrm{cool}}\Omega \qquad t_{\mathrm{cool}} = u\left(\frac{\mathrm{d}u}{\mathrm{d}t}\right)^{-1}$$

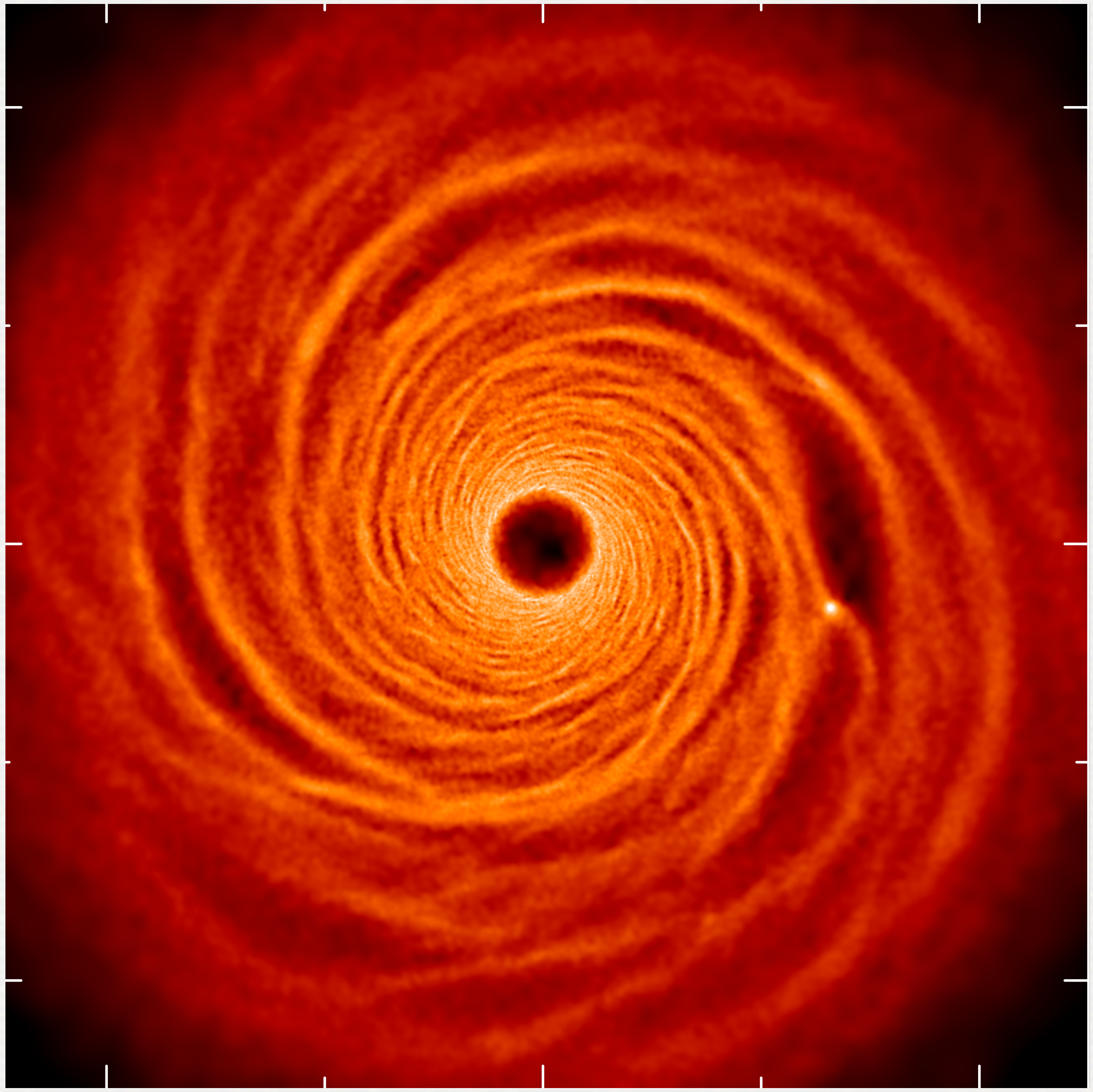
$$\beta_{\mathrm{crit}} \approx 3 \qquad \gamma = 2$$

- β_{crit} may depend on:
  - Equation of state
    Rice et al (2005)
  - Disc's thermal history
    Clarke et al (2007)
  - Temperature dependence of the cooling law
    Cossins et al (2005)
  - Star & disc properties
    Meru & Bate (2011a)
  - Numerical: resolution
    Meru & Bate (2011b)
    Lodato & Clarke (2011)
    Pardekooper, Baruteau & Meru (2011)
    Paardekooper (2012)
  - Numerical: artificial viscosity
    Meru & Bate, MNRAS accepted $\beta_{\mathrm{crit}} > 20$

DISC-FRAGMENT INTERACTION AFTER FRAGMENTATION

- Migration of fragment
  Mayer et al 2002; Boss 2005; Cha & Nayakshin 2010; Machida et al 2011; Baruteau, Meru & Paardekooper, 2011; Vorobyov & Basu 2010; Vorobyov 2010; Michael et al 2011

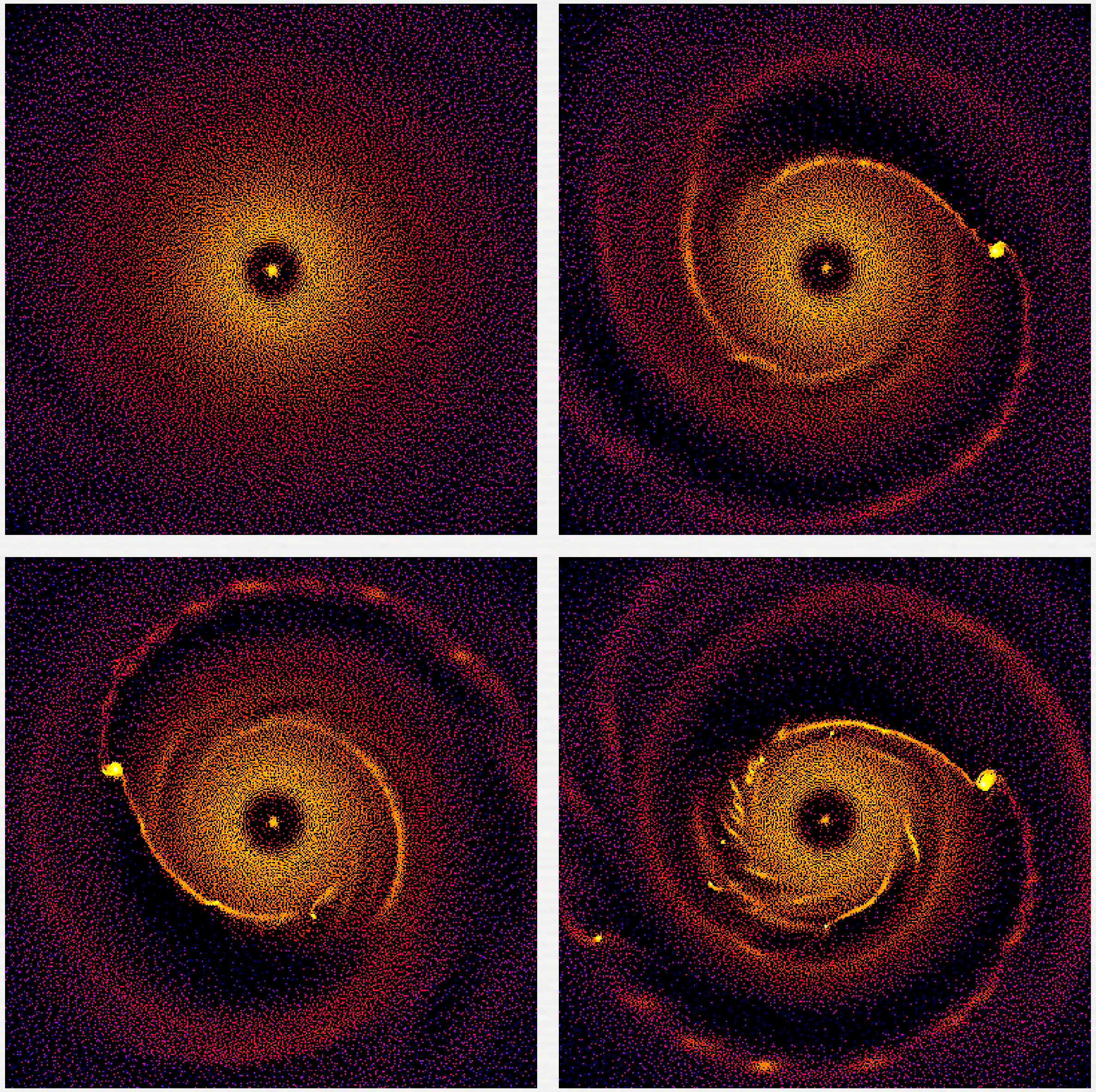
- Effect on the disc
  e.g. Stamatellos & Whitworth 2009



Meru & Bate 2011b

TRIGGERED FRAGMENTATION

- Presence of a planet can trigger the gravitational collapse of the disc
  Armitage & Hansen 1999
- Isothermal equation of state - favourable for fragmentation

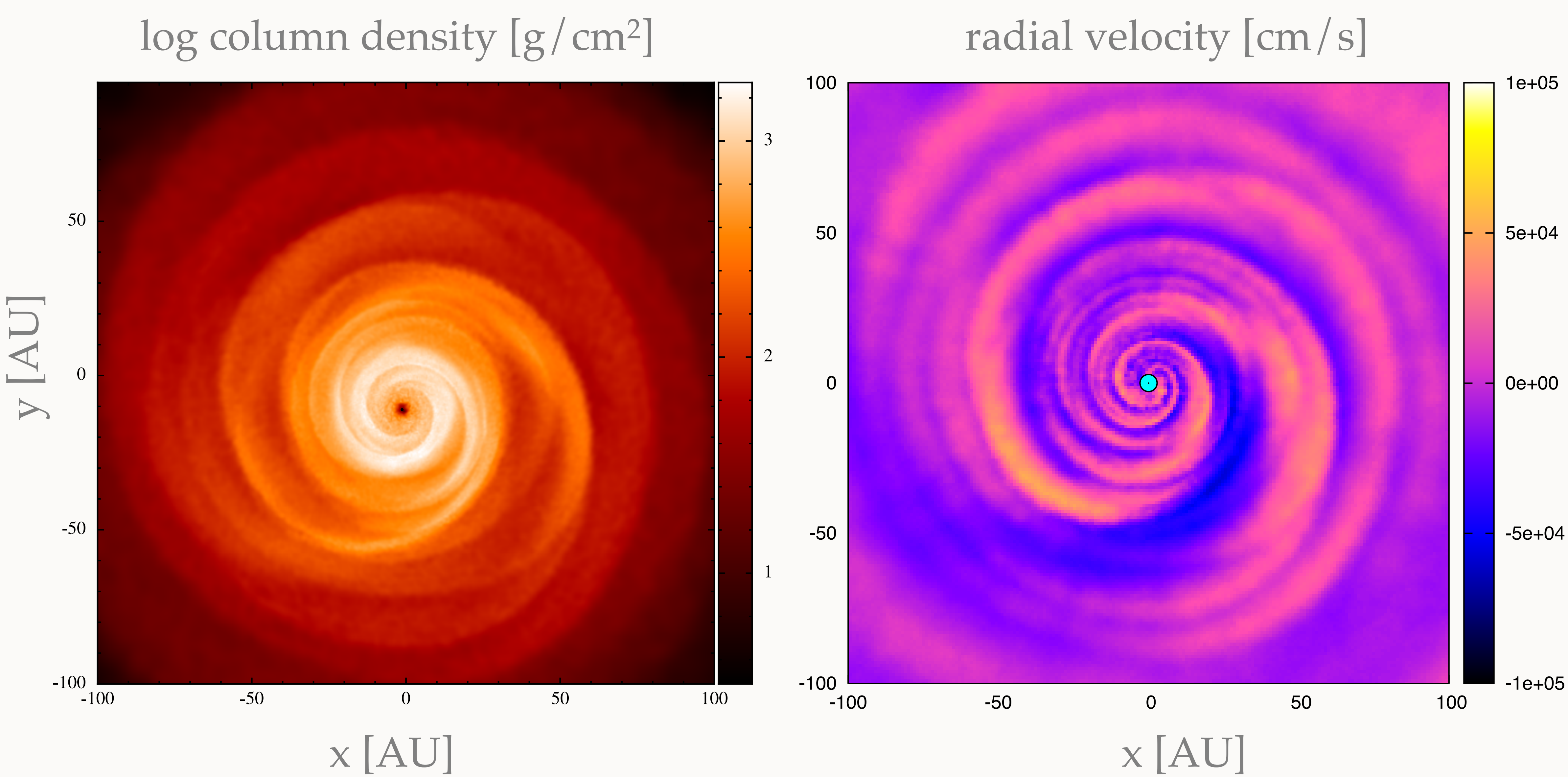


Armitage & Hansen, 1999

TRIGGERED FRAGMENTATION

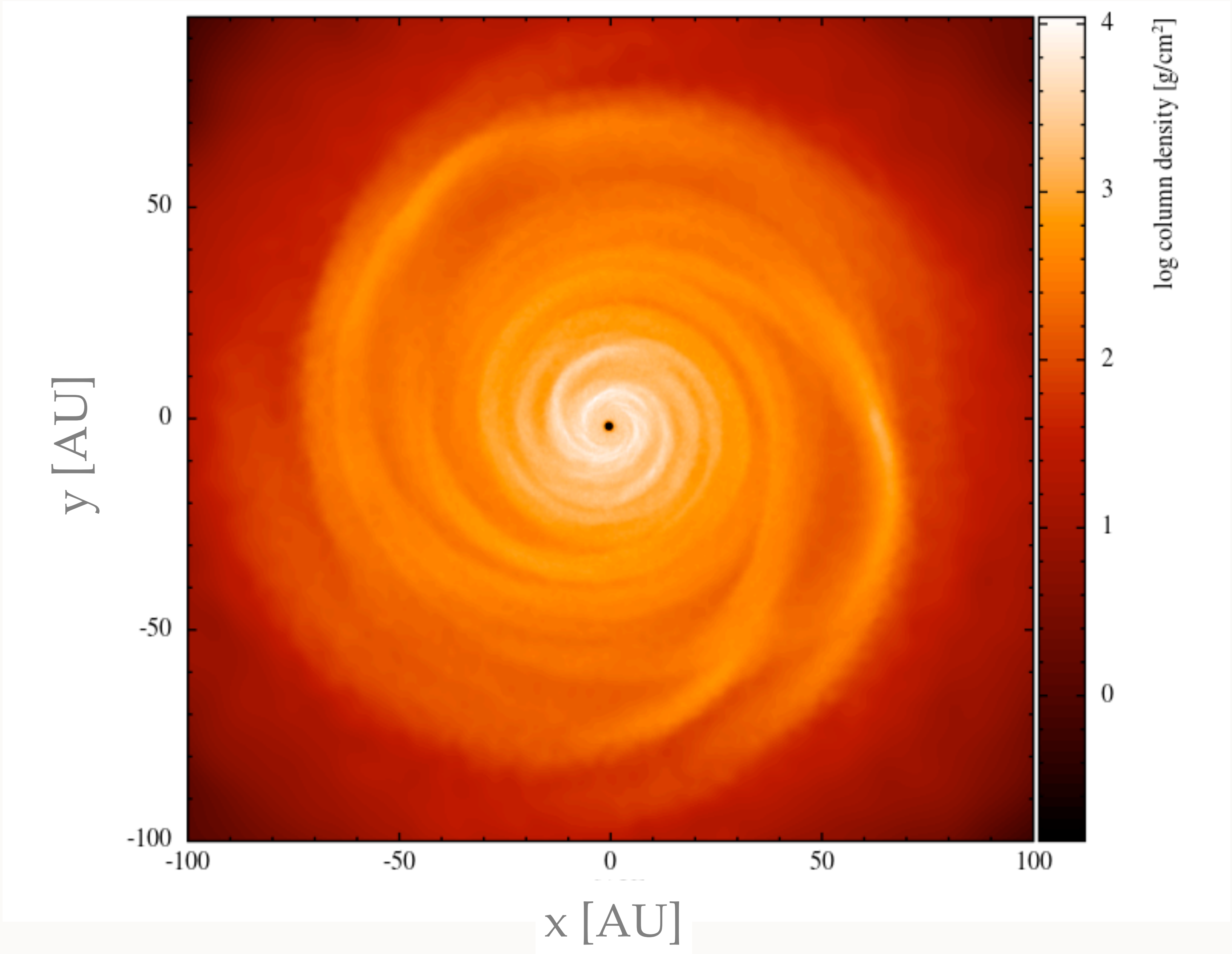
- 3D SPH radiative transfer simulations of gravitationally unstable discs $1 < R < 100AU$
- Self-consistently understand the effect of first fragmentation on the disc
- Initial Toomre profile decreases with radius:
  - Outer disc can fragment
  - Inner disc has Q > 1 such that it is not expected to fragment

DISC WITHOUT FRAGMENTATION



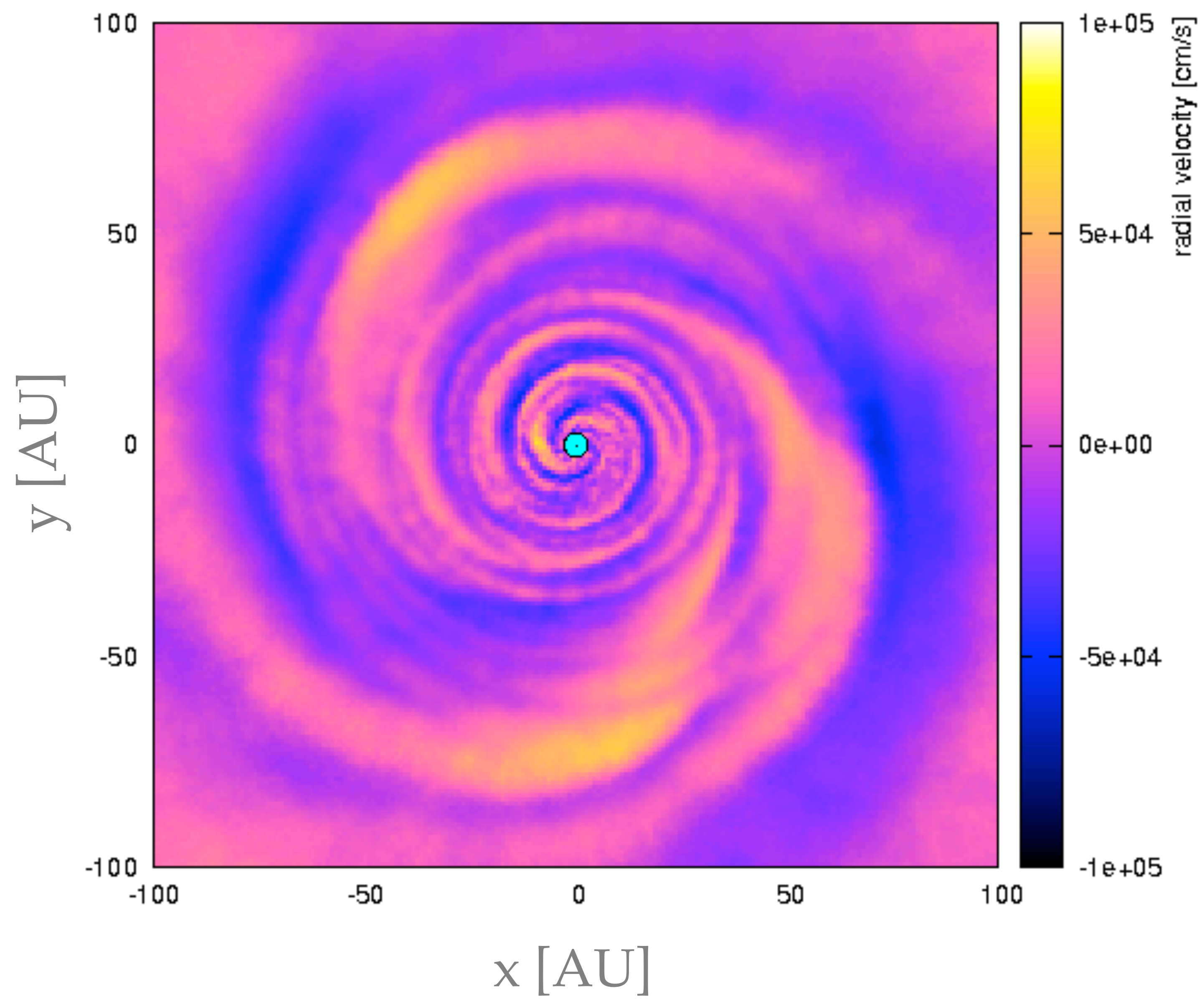
$M_\star = 0.8M_\odot, M_{\rm disc} = 0.8M_\odot, \kappa = 0.1$ x interstellar Rosseland mean

SEQUENTIAL FRAGMENTATION



$M_\star = 1.5 M_\odot, M_{\rm disc} = 1.2 M_\odot, \kappa = 0.3$ x interstellar Rosseland mean

SEQUENTIAL FRAGMENTATION



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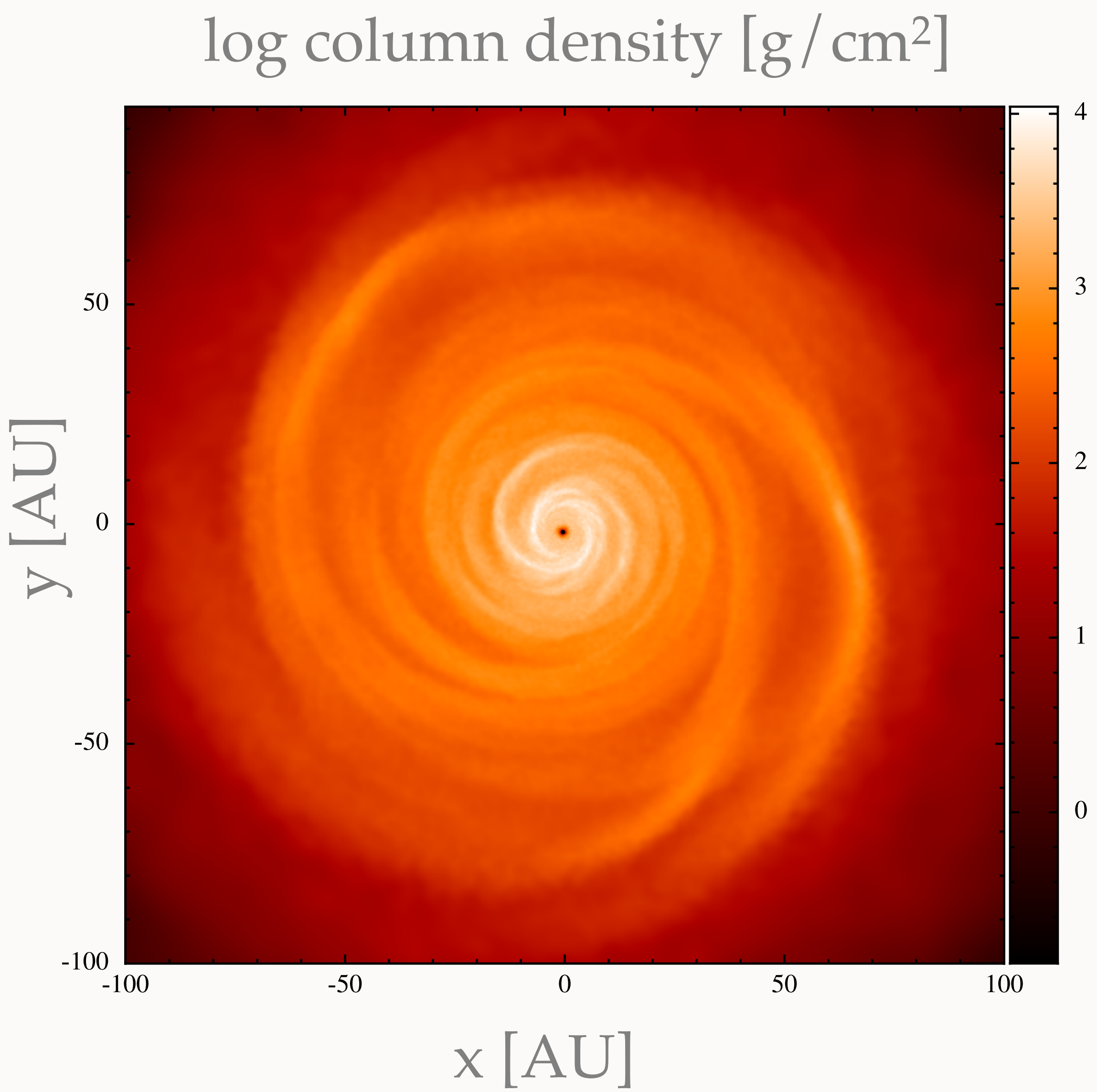

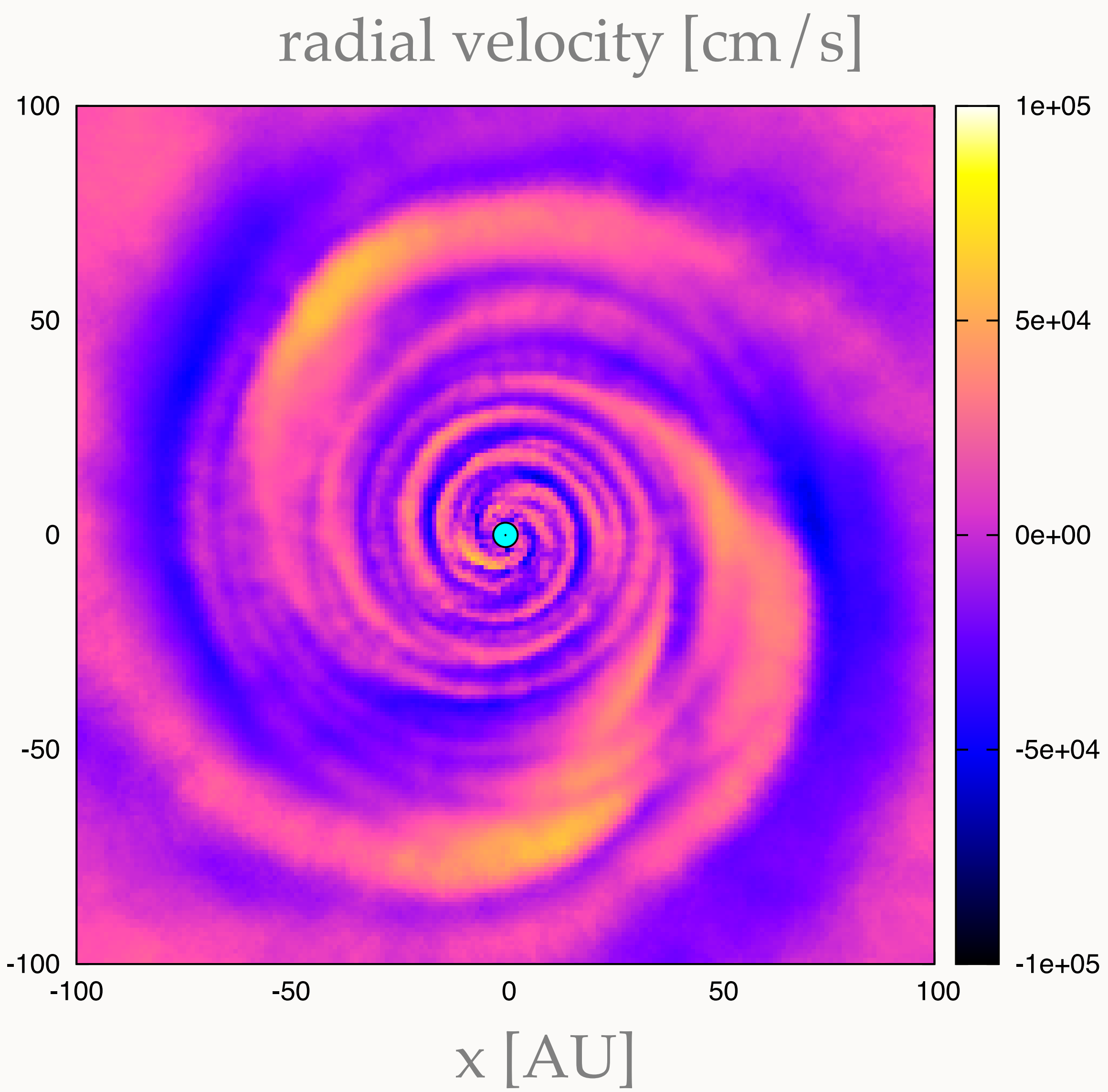

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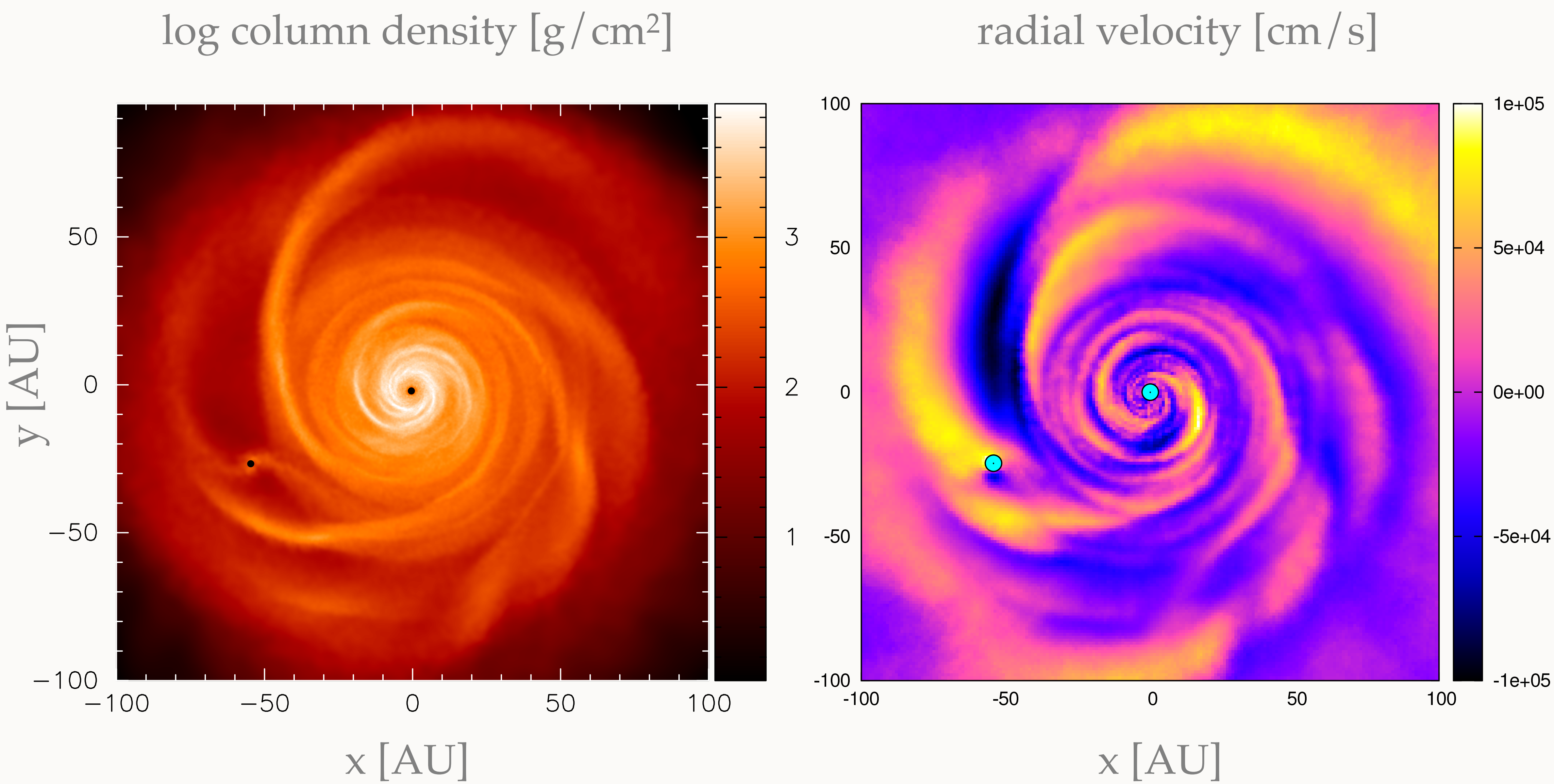

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SEQUENTIAL FRAGMENTATION

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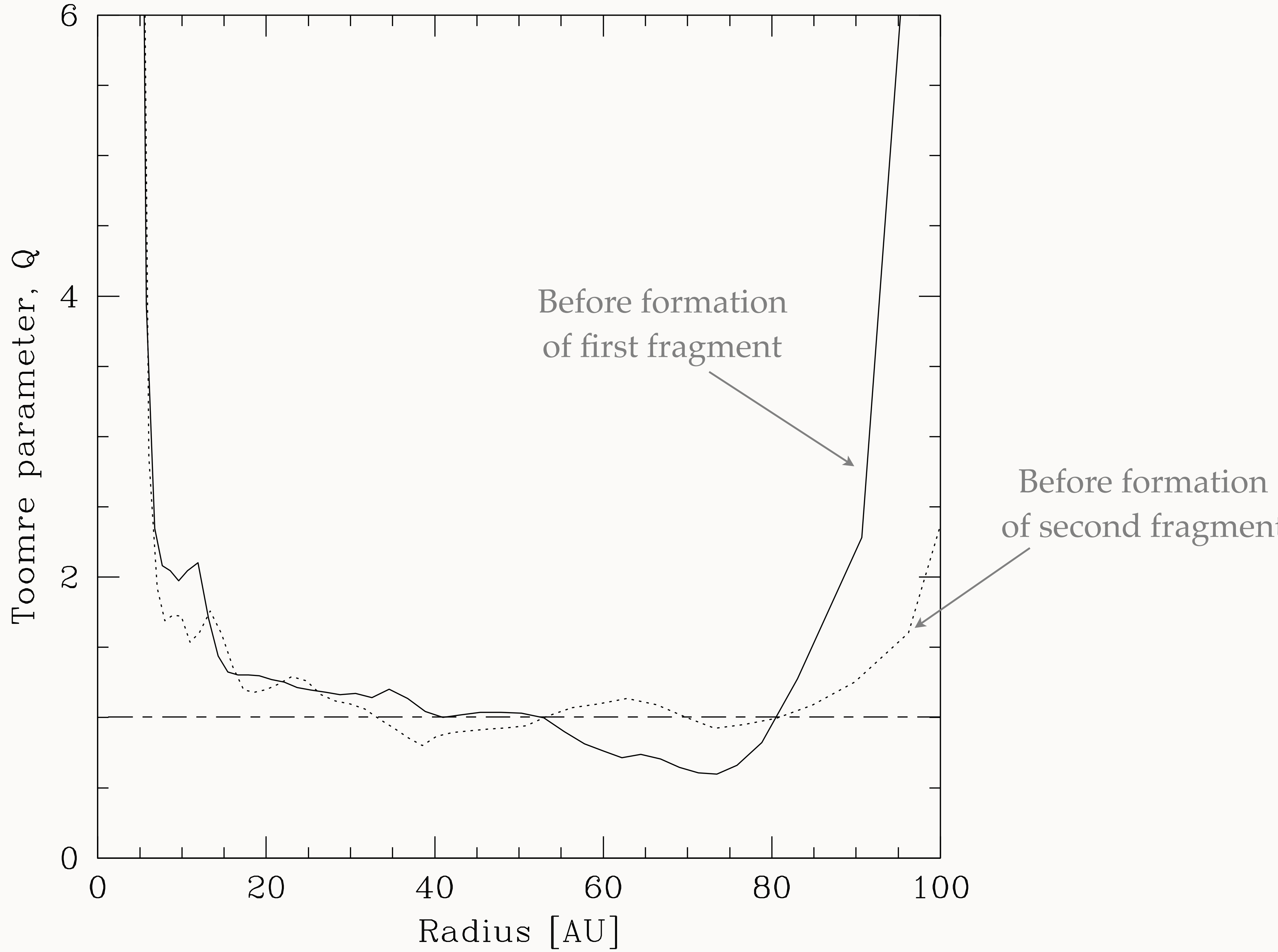

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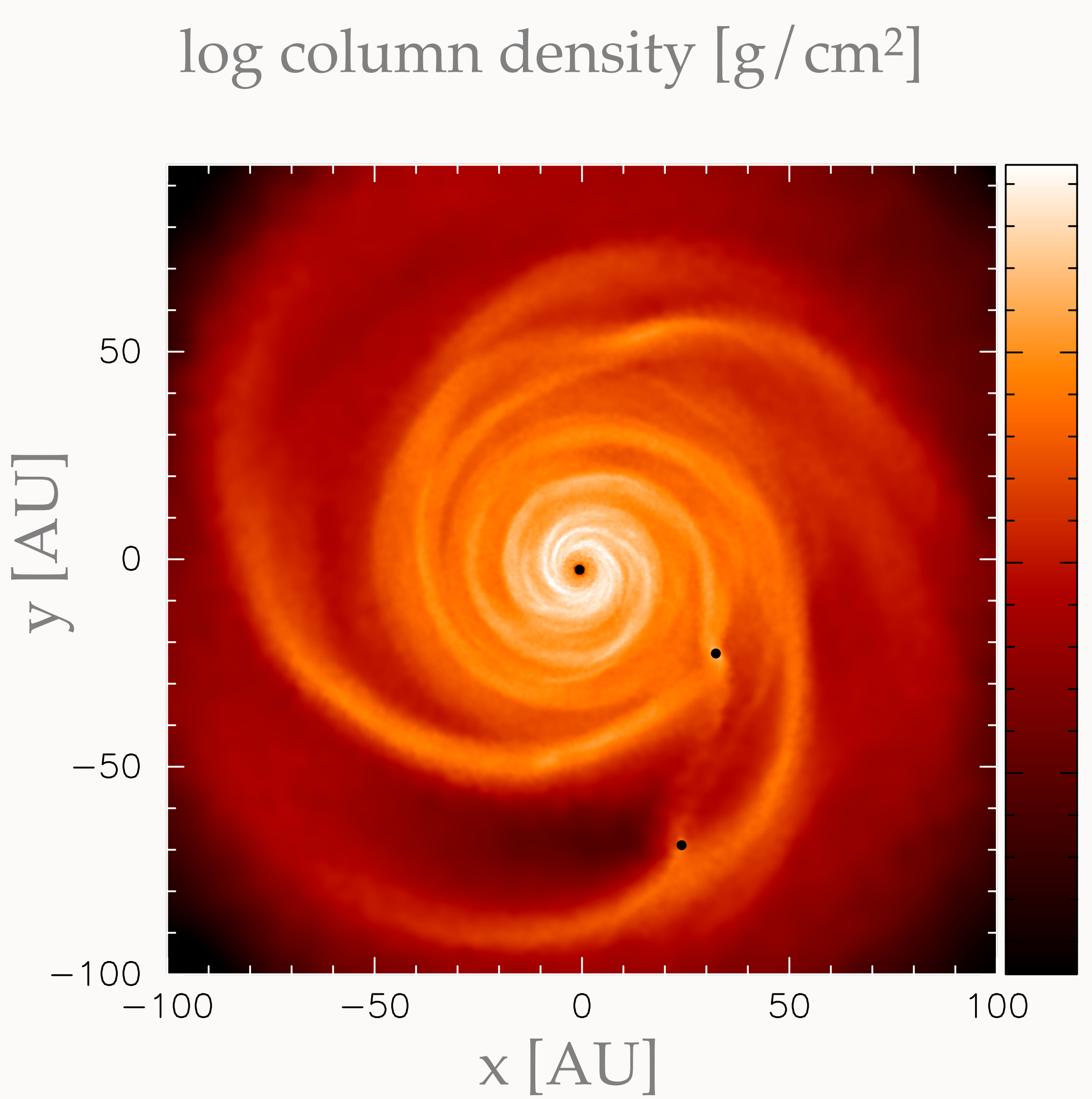

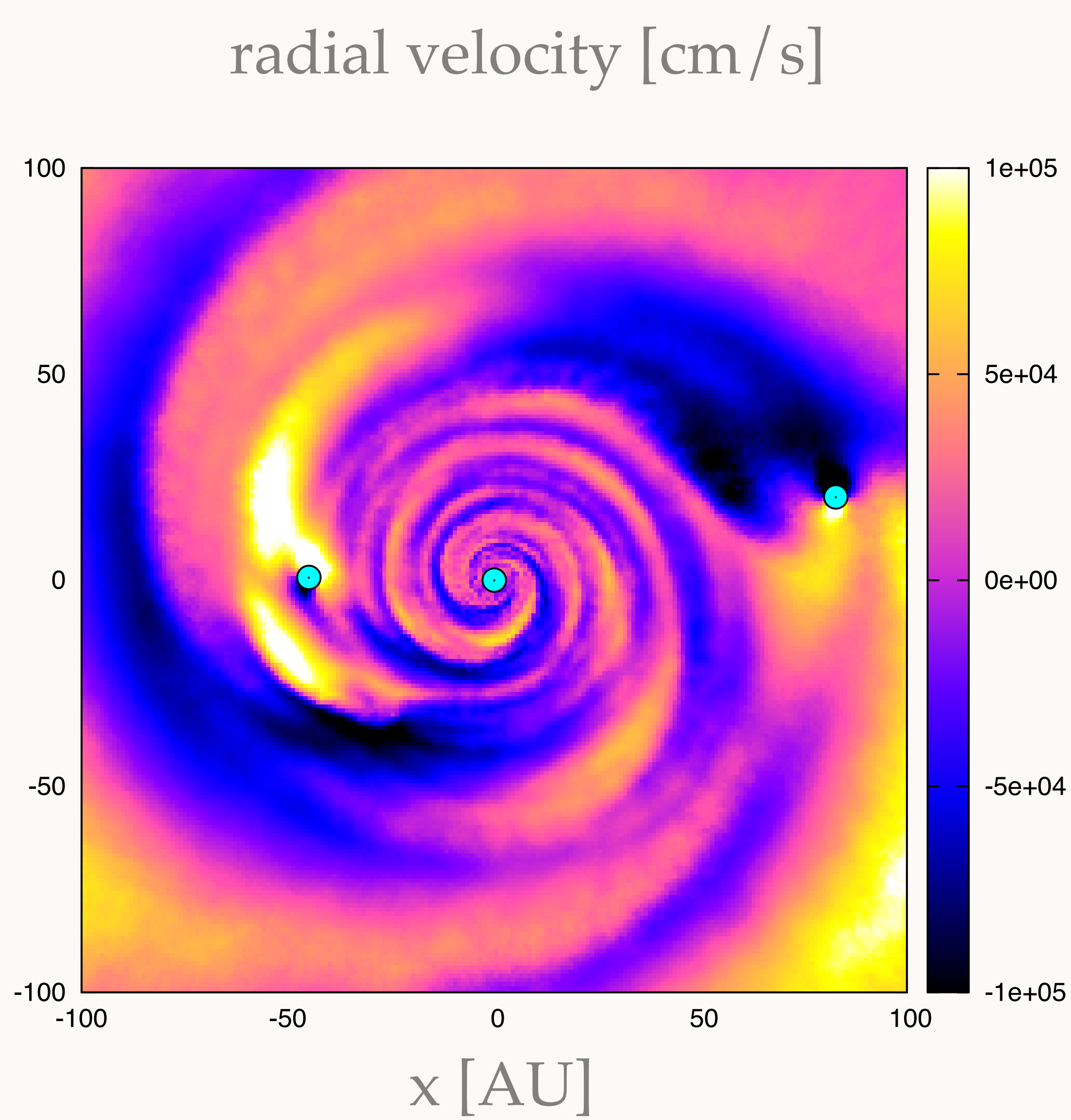

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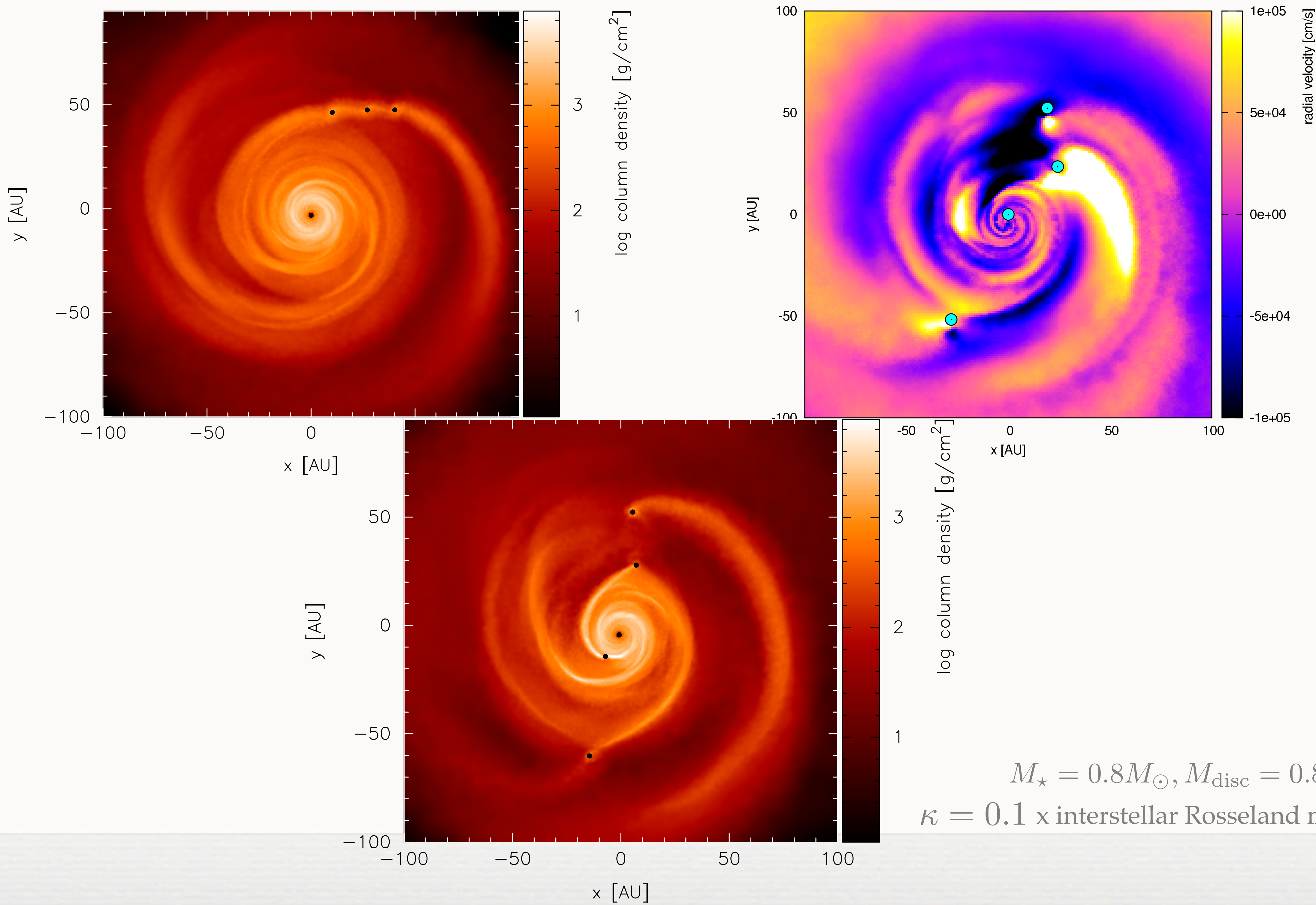
MULTIPLE FRAGMENTS



$M_\star = 0.8 M_\odot, M_{\rm disc} = 0.8 M_\odot$

$\kappa = 0.1$ x interstellar Rosseland mean

IN THE CONTEXT OF PROTOPLANETARY DISCS

- Core accretion is a likely formation mechanism at small radii (≈5-10AU): $\frac{\mathrm{d}M_\mathrm{p}}{\mathrm{d}t} \propto \Sigma\Omega$
- Gravitational instability can occur outside ≈50AU
- Intermediate radial range where no one in situ formation mechanism known to operate
- Triggered fragmentation may bridge this gap

SUMMARY

- 3D radiative transfer simulations of gravitationally unstable discs to look at the mass movement in a disc following the formation of the first fragment
- Model the formation of the first fragment and subsequent disc evolution self-consistently
- Radial velocities increase by factor of ≈2-3
- If an inner disc is reasonably close to marginal stability, then this can push that region into a state of instability where further fragmentation may occur

Meru, in prep