Self-gravitating discs with radiative transfer - their role in giant planet formation

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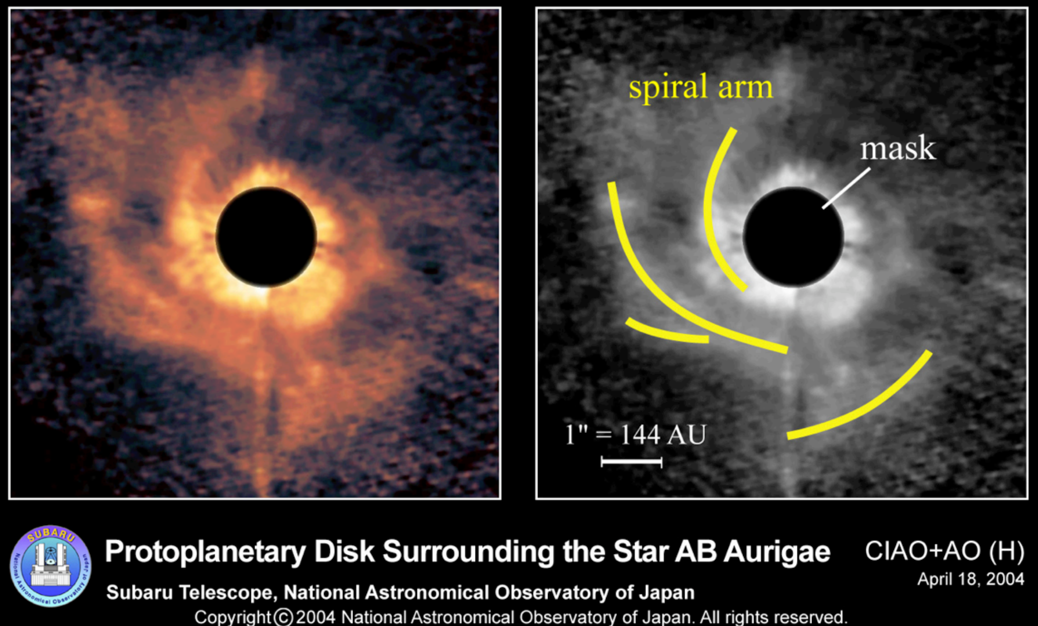
Background

- Gravitational Instability (Cameron 1978, Boss 1997)
  - Giant planet formation model - alternative to Core Accretion (Hubickyj et al 1995)

- Jupiter may not have a solid core (Saumon & Guillot 2004)

- ALMA
  - May be able to image gravitationally unstable discs



Background: fragmentation criterion

- Toomre stability parameter (Toomre 1964)

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

$$Q_{crit}$$

$$Q > 1 \equiv stable$$

$$Q < 1 \equiv unstable$$

- Cooling rate (Gammie 2001)
  - high cooling rate $\longrightarrow$ fragmentation

Background: past simulations

- Energetics
  - without radiative transfer
    e.g. Lodato & Rice 2004; Rice et al 2003; Mayer et al 2004; Mayer et al 2005
    - compression
    - viscosity
    - shocks
    - cooling: $t_{cool} = \beta\Omega^{-1}$
  - with radiative transfer
    e.g. Boss 2001, Mejia 2004, Cai et al 2006, Boley et al 2006, Durisen et al 2007, Mayer et al 2007, Stamatellos 2008, Forgan et al 2009

Radiative Transfer

- Smoothed Particle Hydrodynamics (Benz 1990; Monaghan 1992; Whitehouse, Bate & Monaghan 2005)
- Flux-limited diffusion method
- Optically thick region - solves radiation energy equation
- Optically thin region - particles defined as “boundary particles”
- Interstellar opacity tables of Alexander (1975) and Pollack et al (1985)

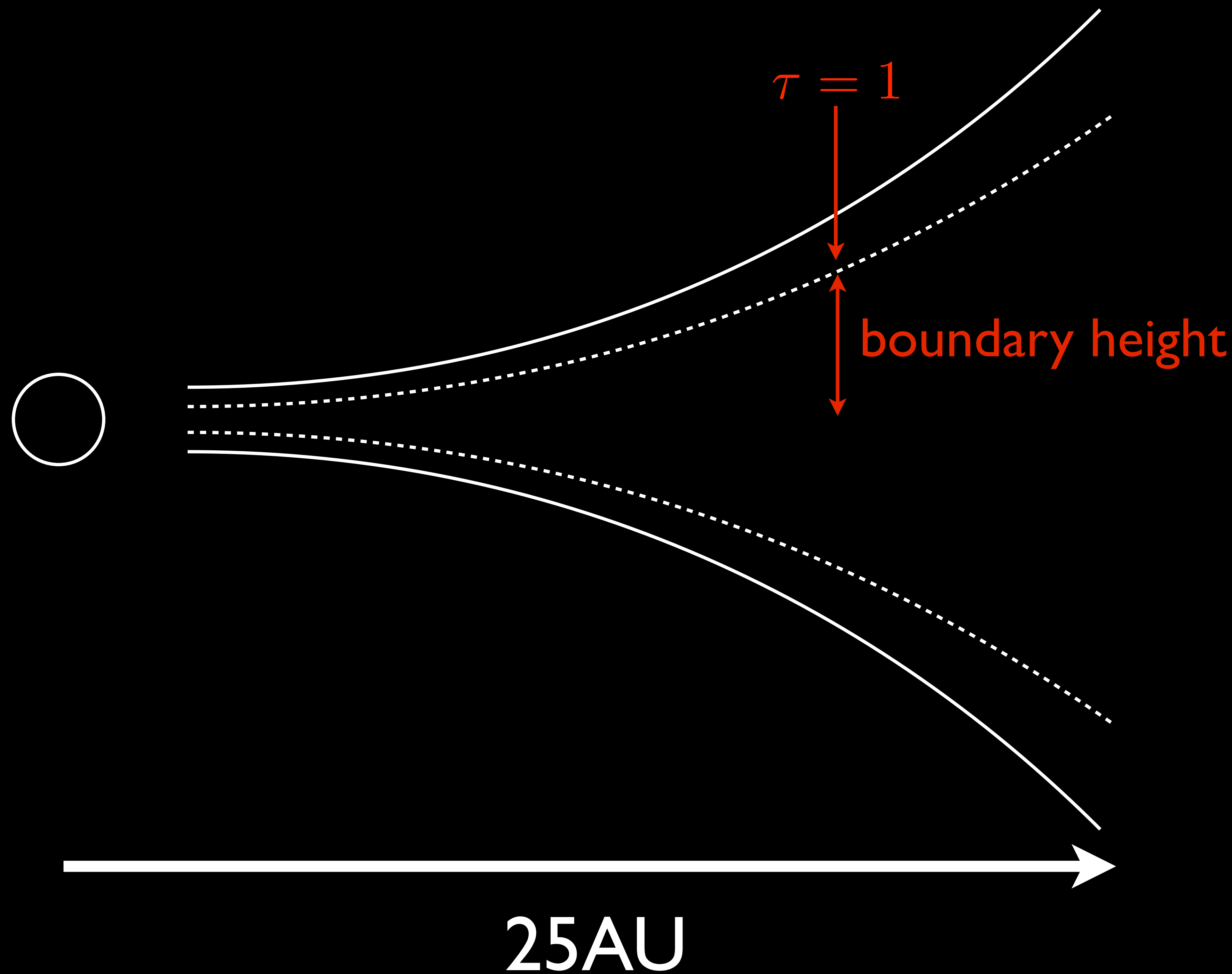
Reference disc setup

- Simulating Lodato & Rice (2004) disc
  - $0.1M_\odot$ disc around $1.0M_\odot$ mass star
  - 250,000 particle disc, sink particle for central star
  - 25AU disc
  - $\Sigma \propto R^{-1}$
  - $T \propto R^{-\frac{1}{2}}$
  - $Q_{out} = 2$

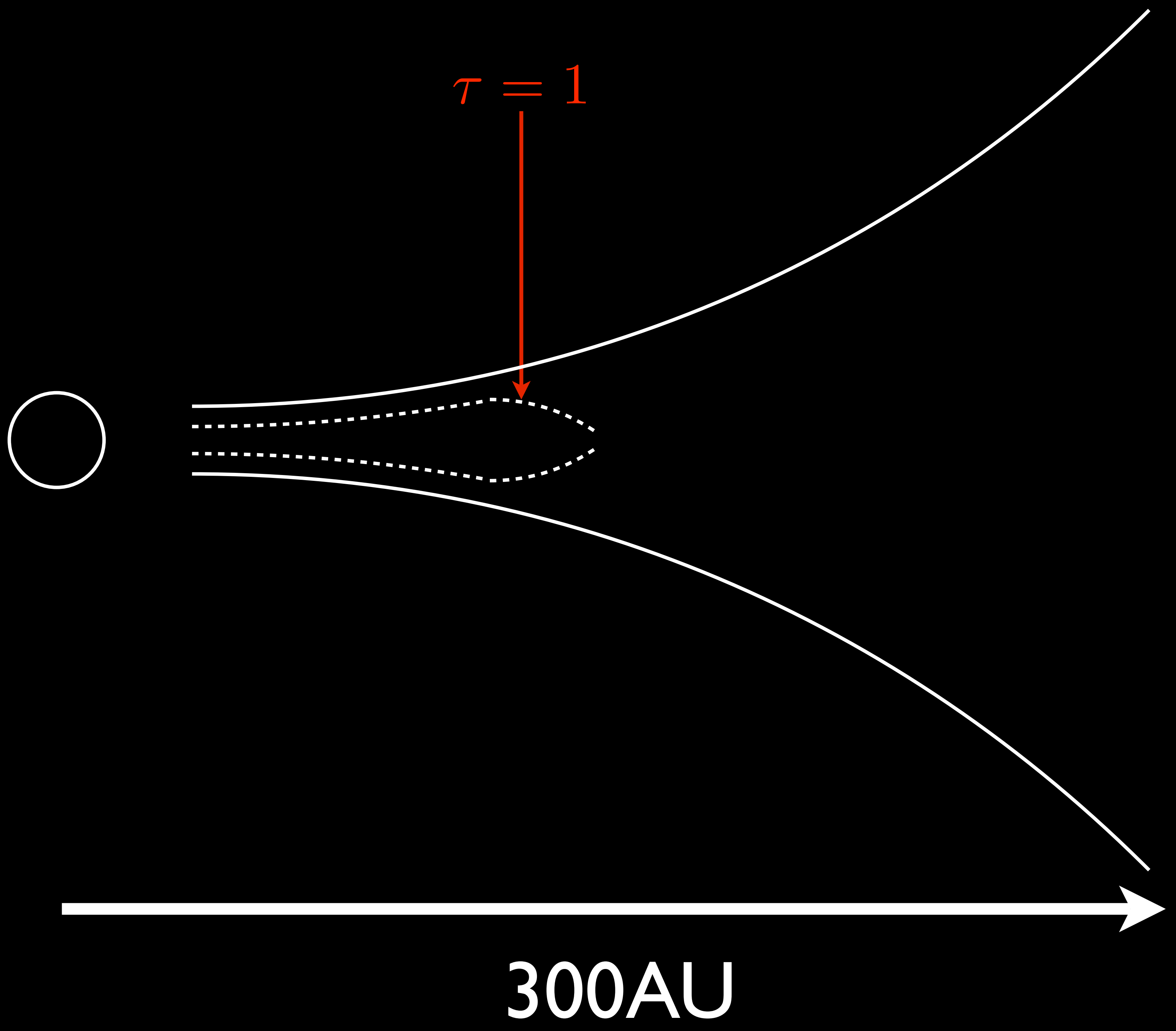
Parameter space

- opacity
- disc size (Rafikov 2005, Matzner & Levin 2005)
- initial and boundary absolute temperatures
- orthohydrogen : parahydrogen ratio
  (Black & Bodenheimer 1975, Boley et al 2007)

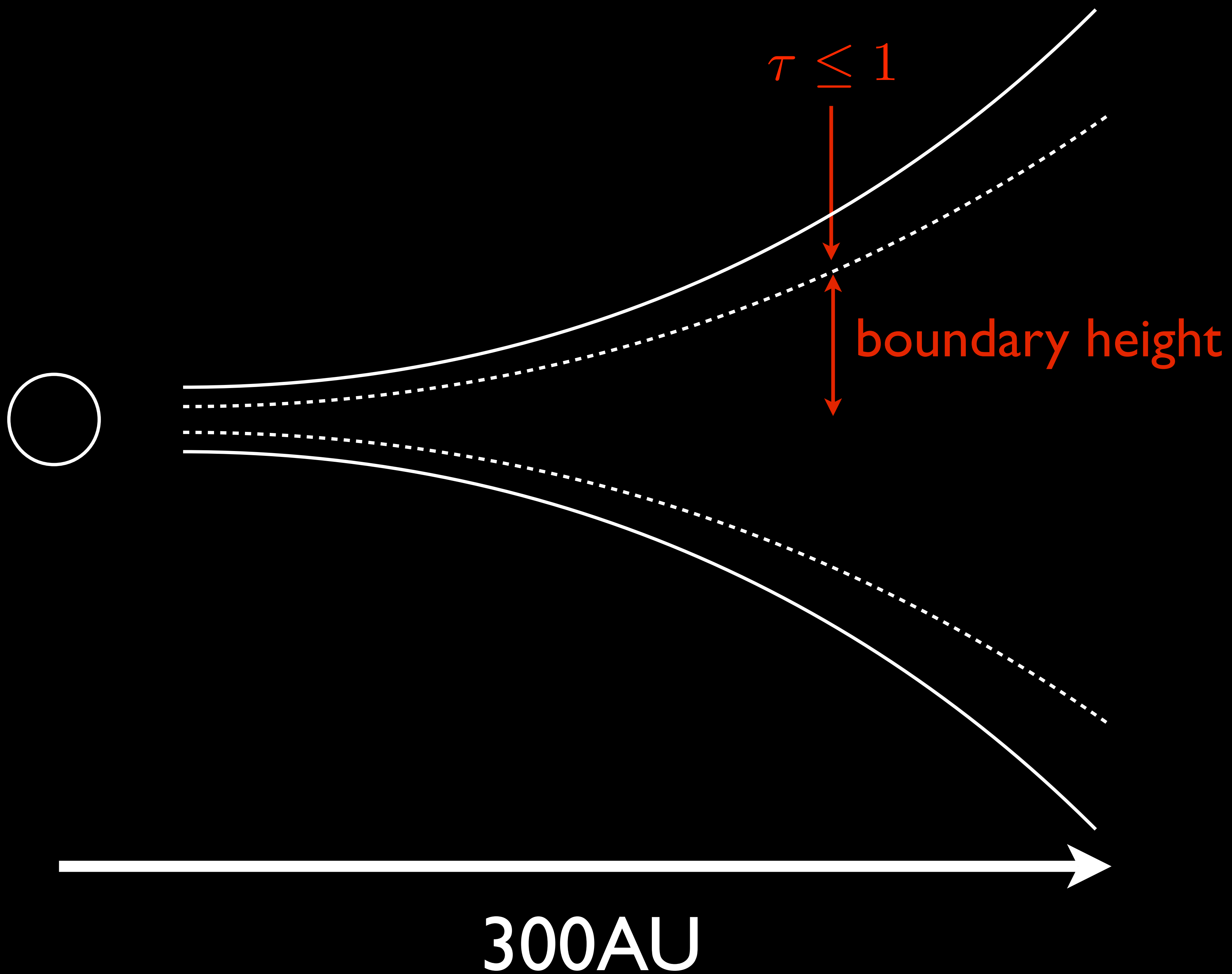
Vertical boundary for 25AU discs



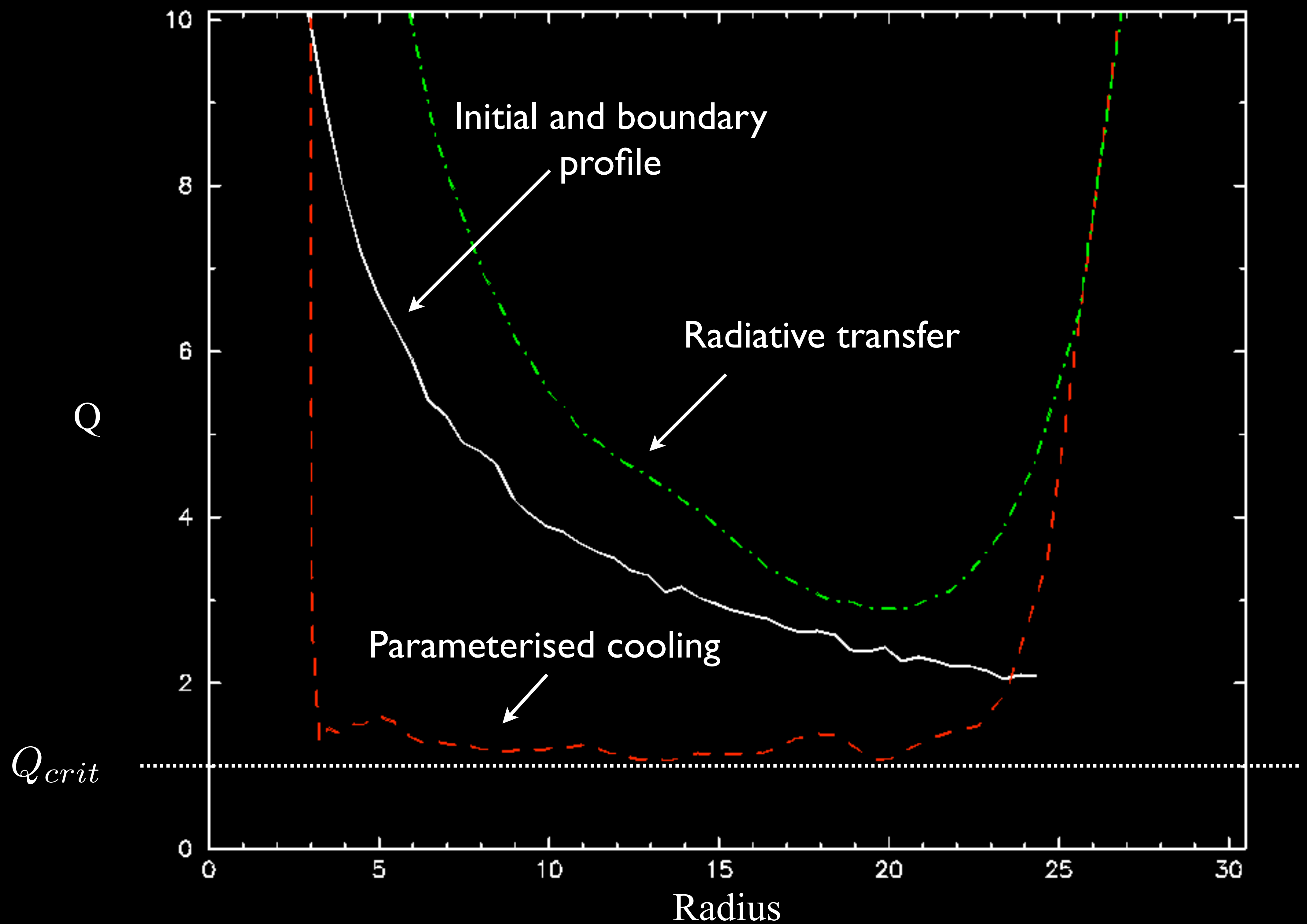
Vertical boundary for 300AU discs



Vertical boundary for 300AU discs

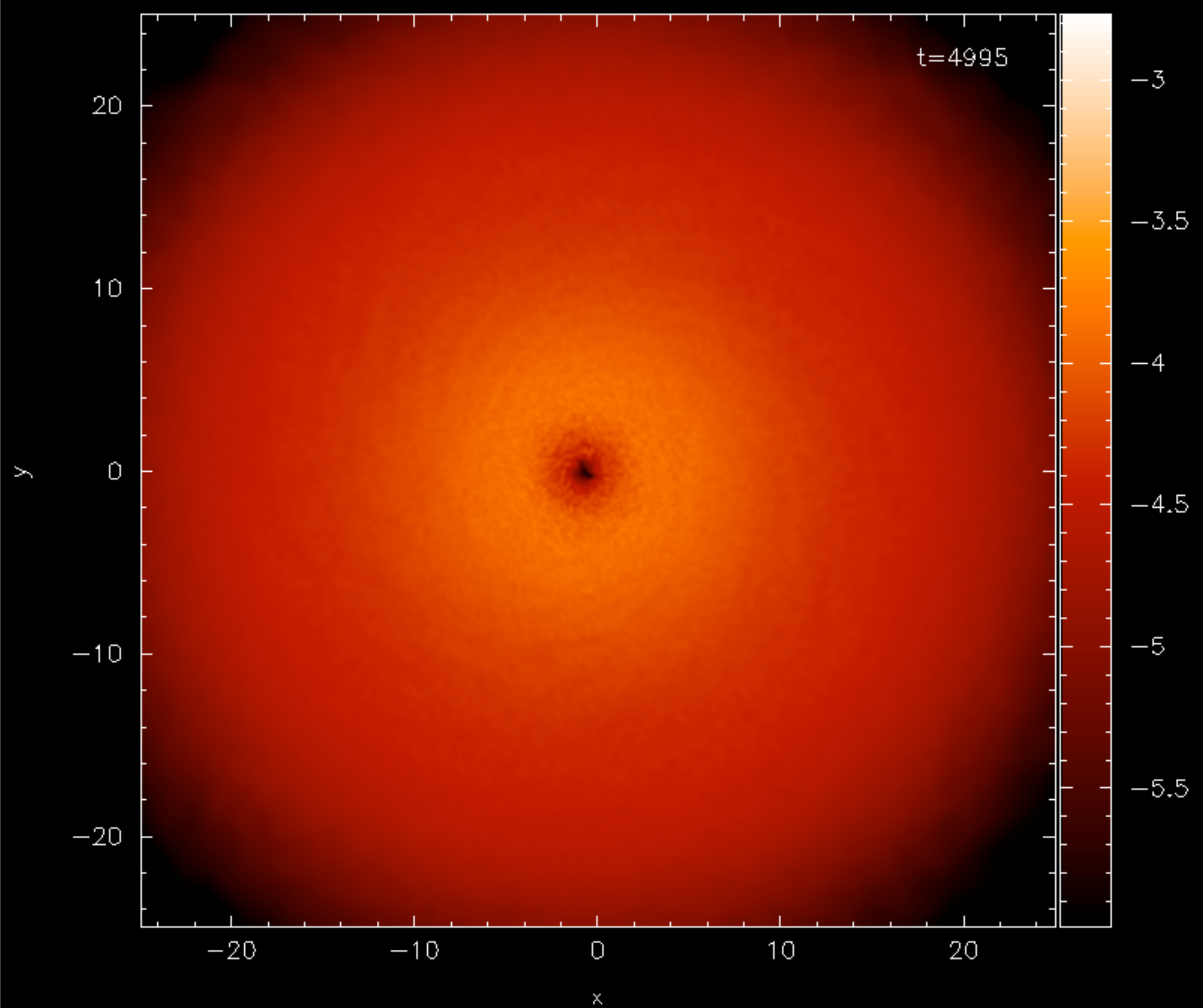


Results: inclusion of radiative transfer

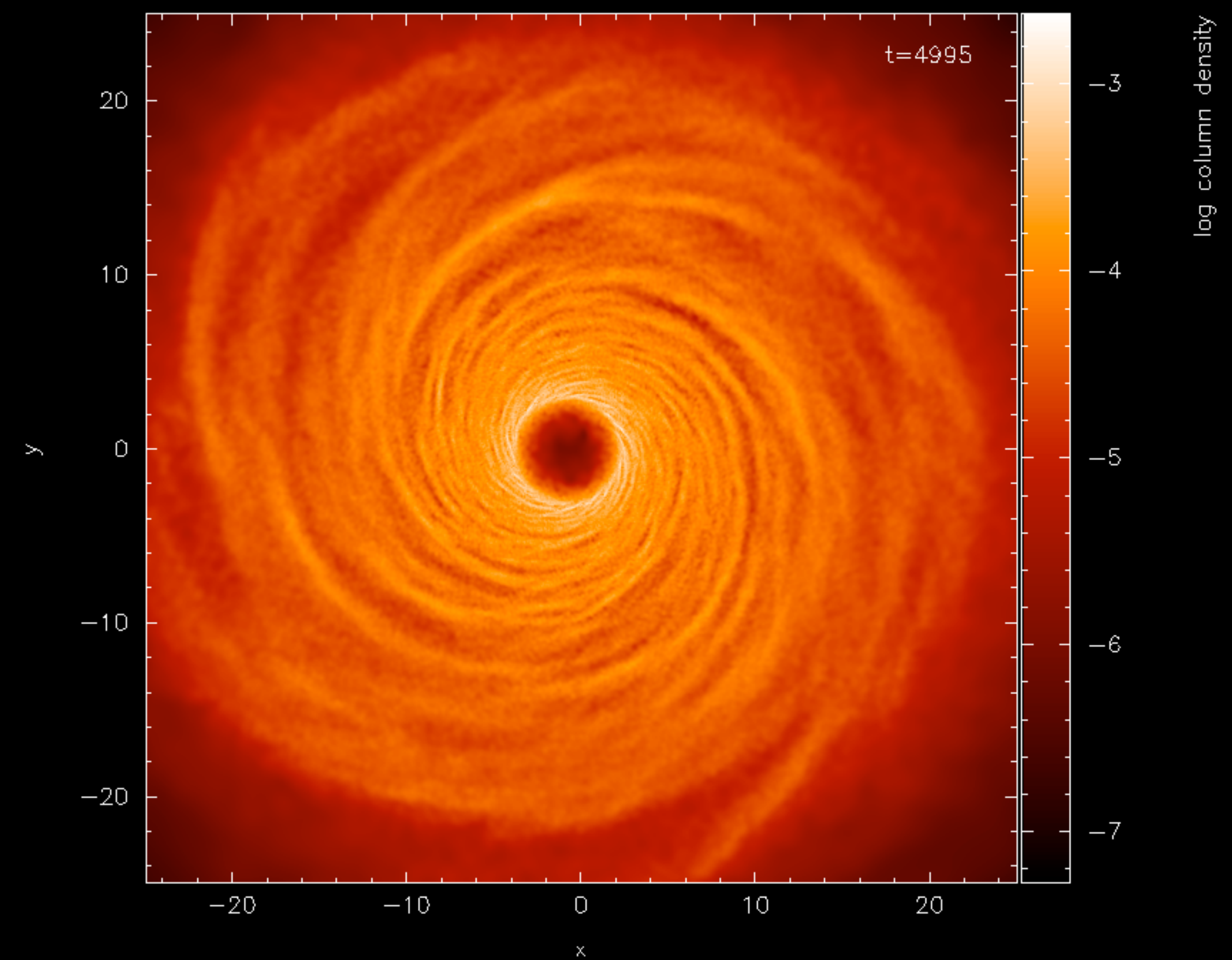


Results: inclusion of radiative transfer

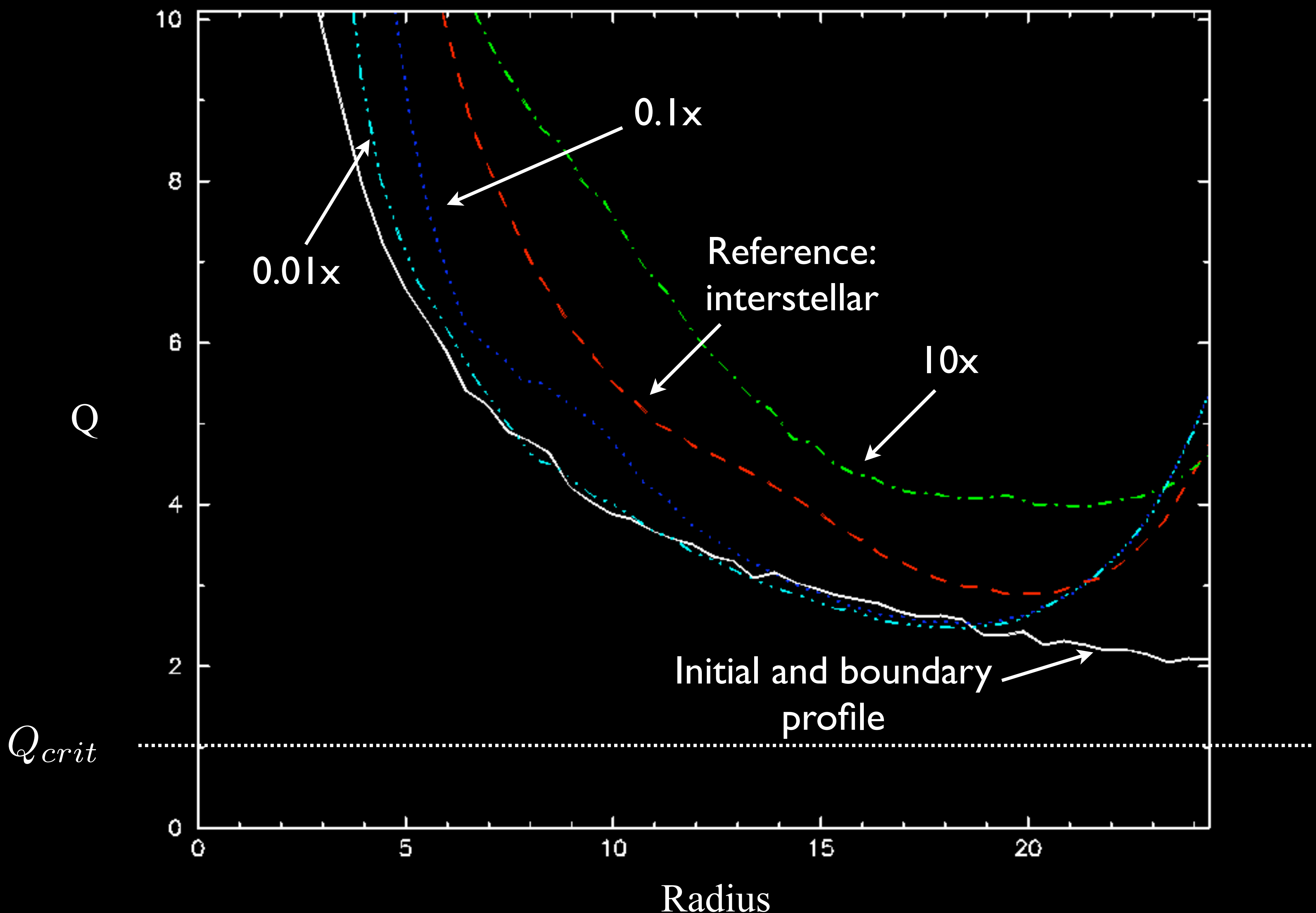
Radiative Transfer



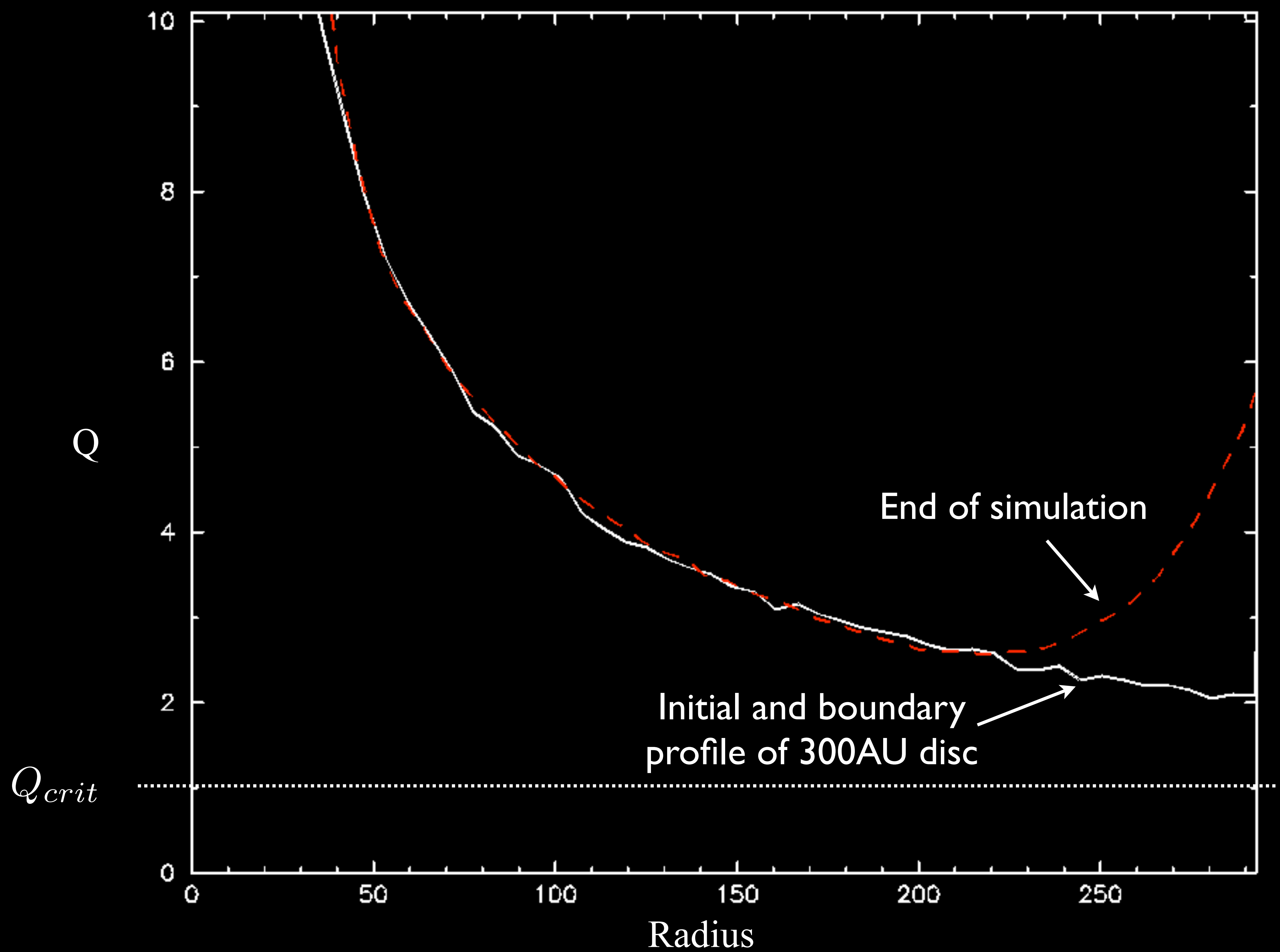
Parameterised cooling



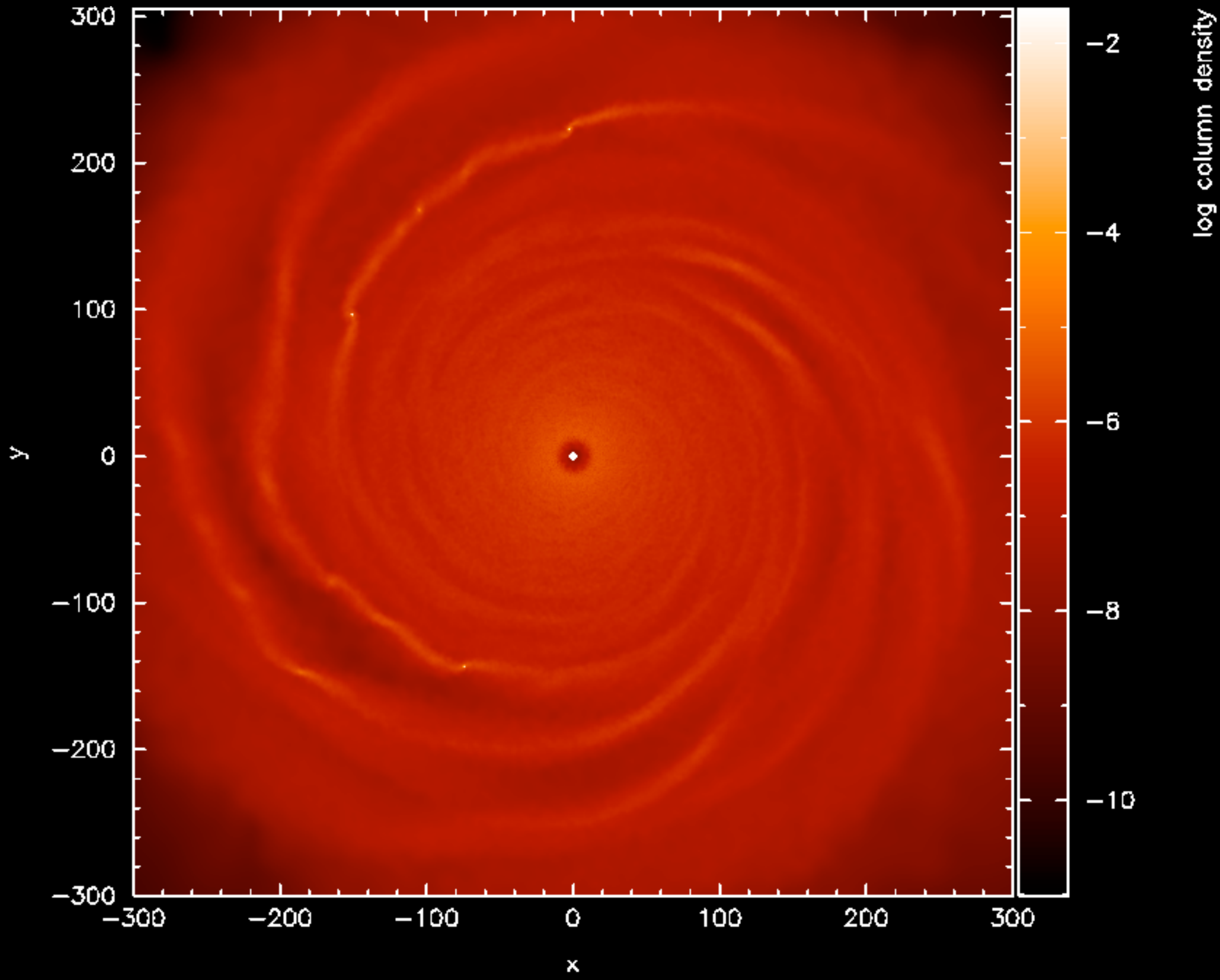
Results: opacity



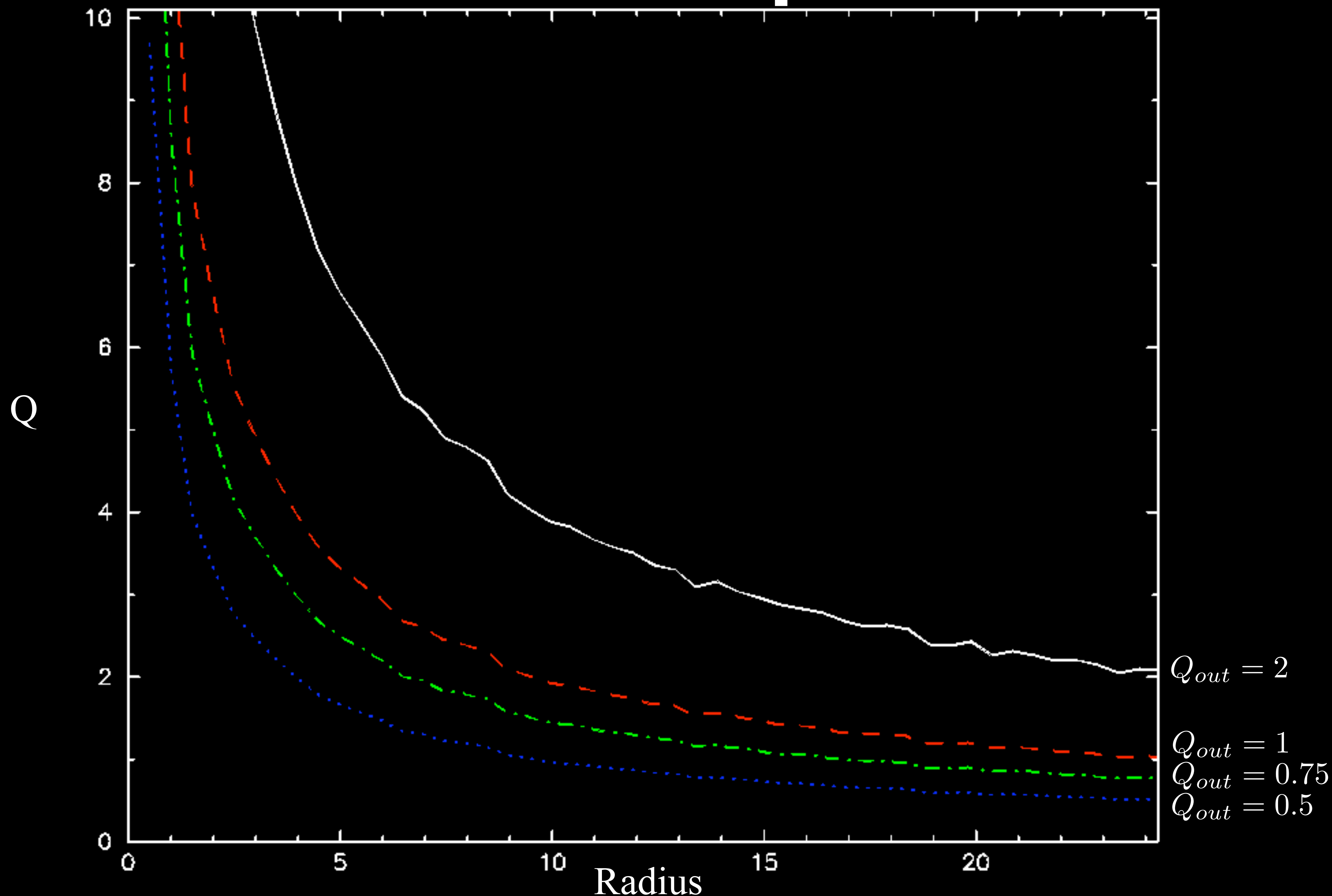
Results: disc size



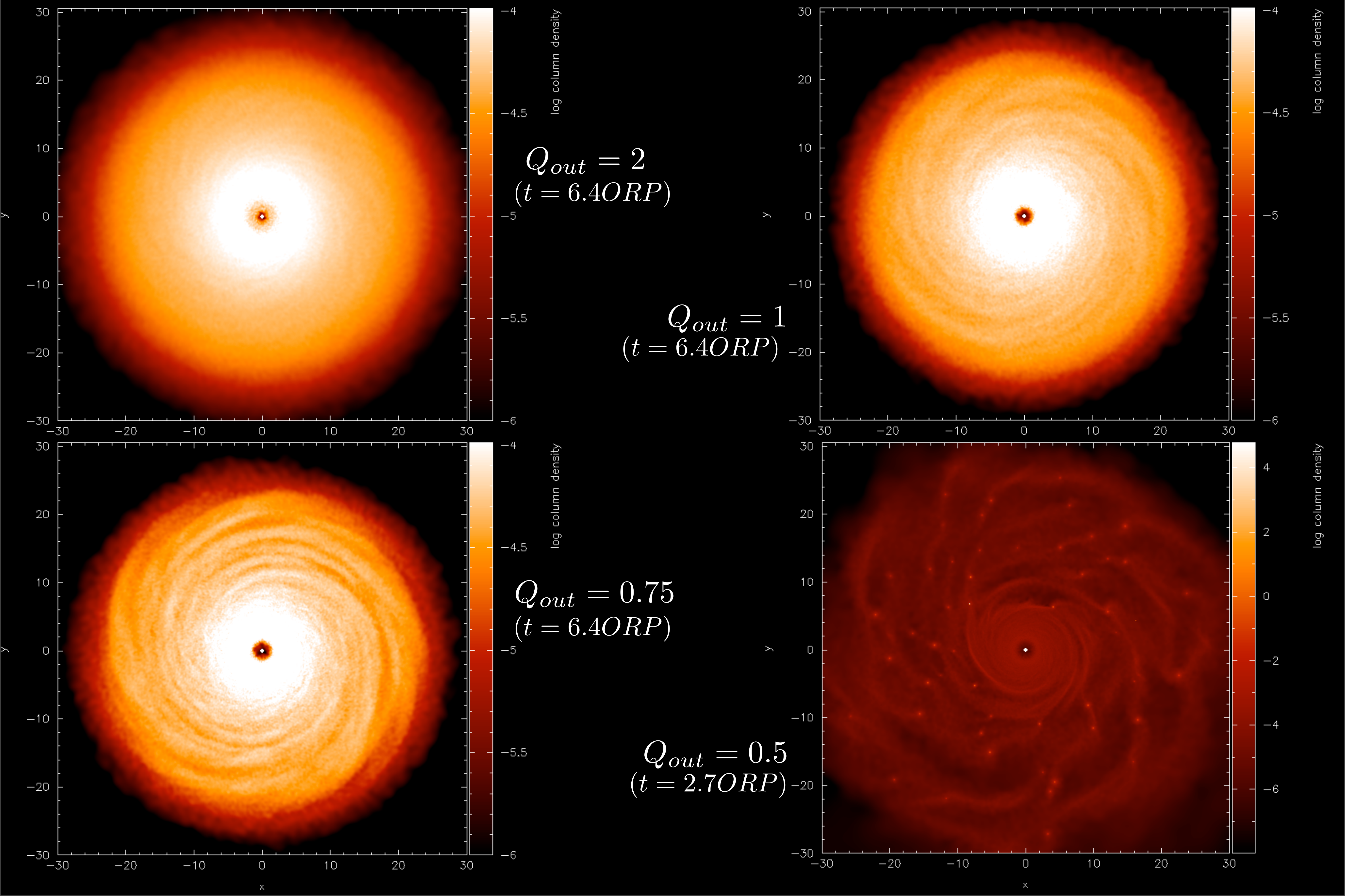
Results: large disc, low opacity, low temperature



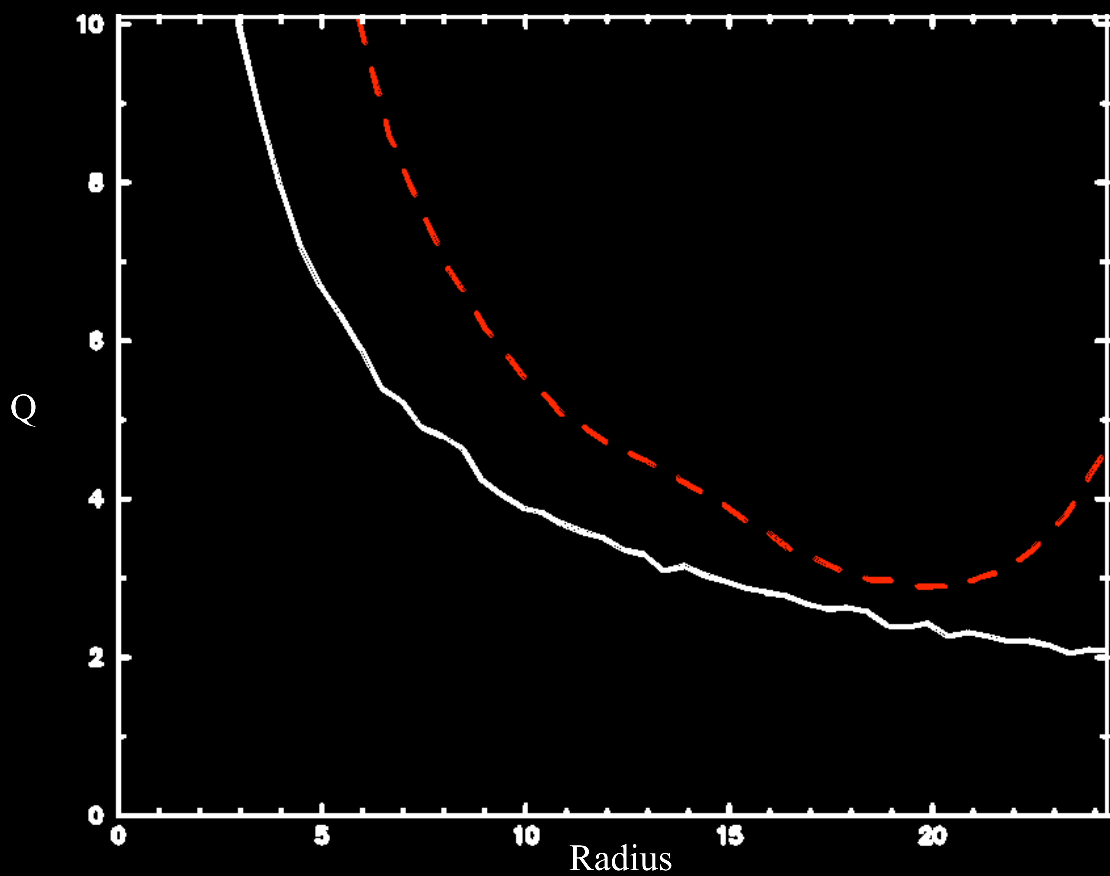
Results: initial/boundary absolute temperature



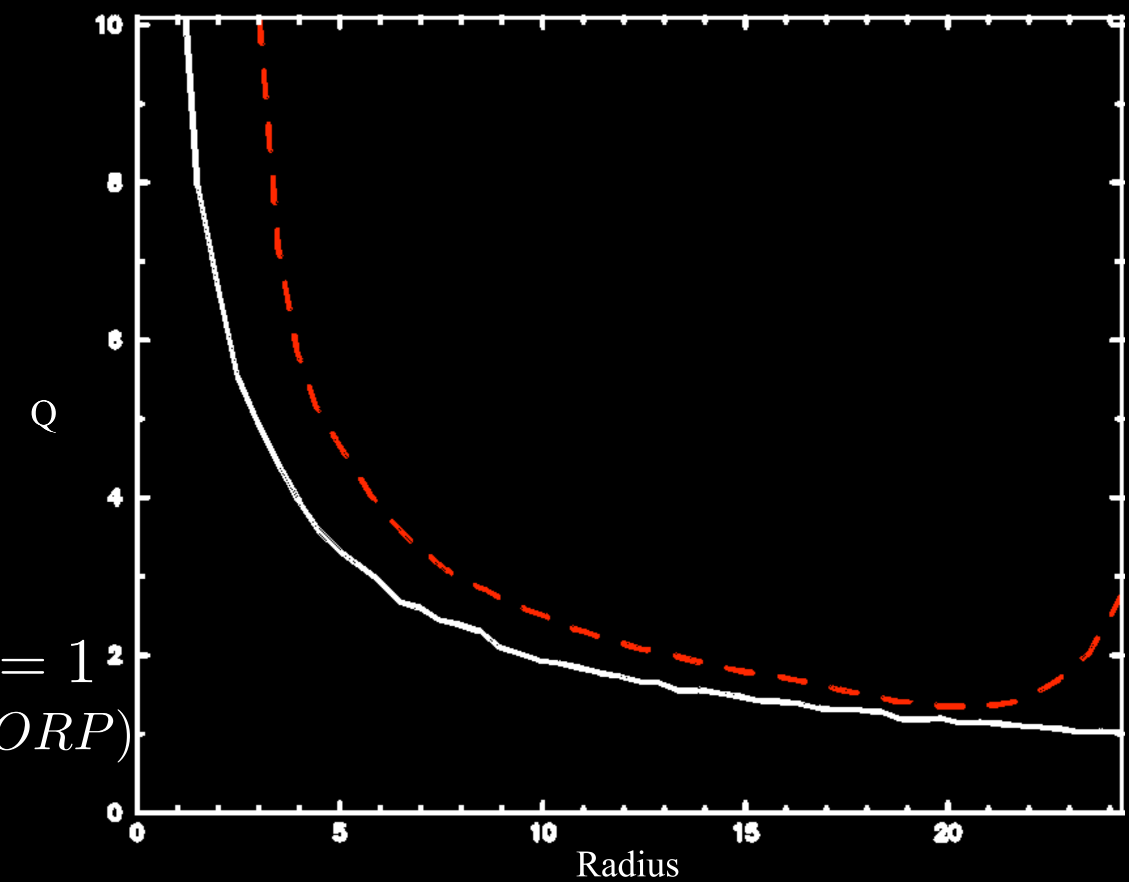
Results: initial/boundary absolute temperature



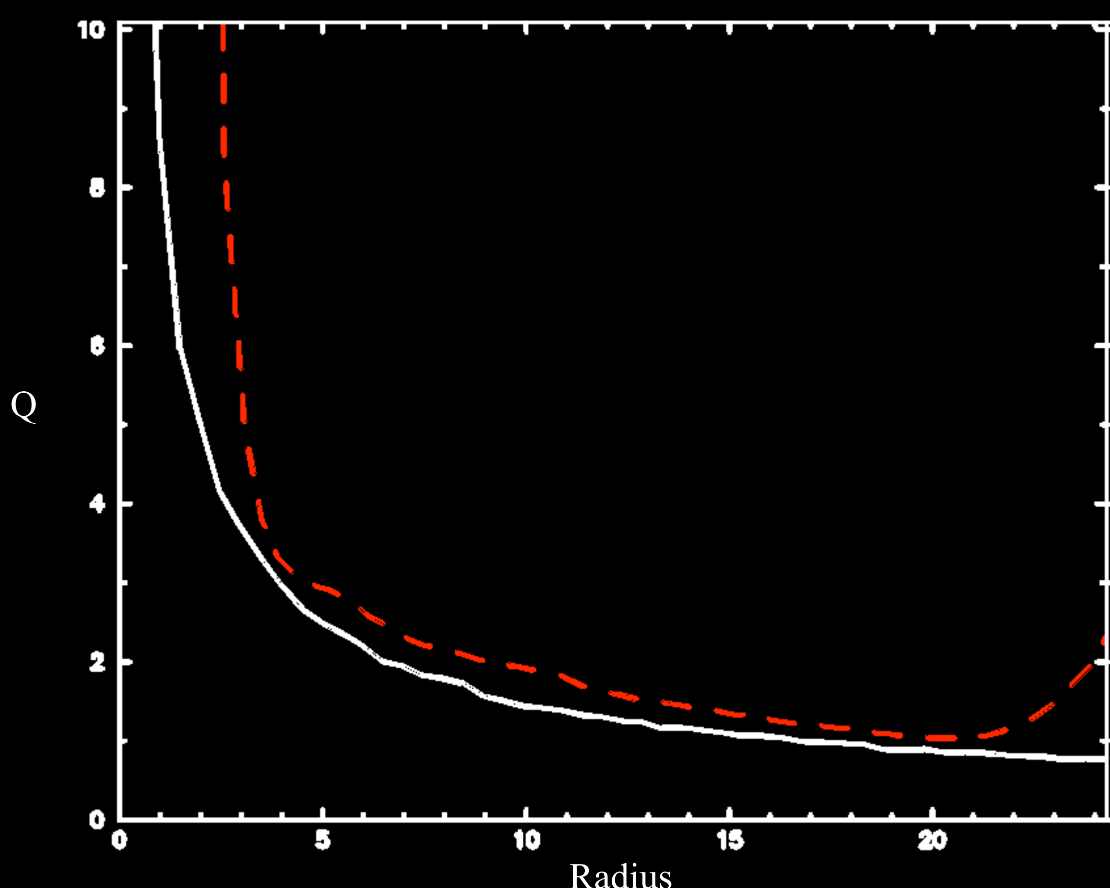
Results: initial/boundary absolute temperature



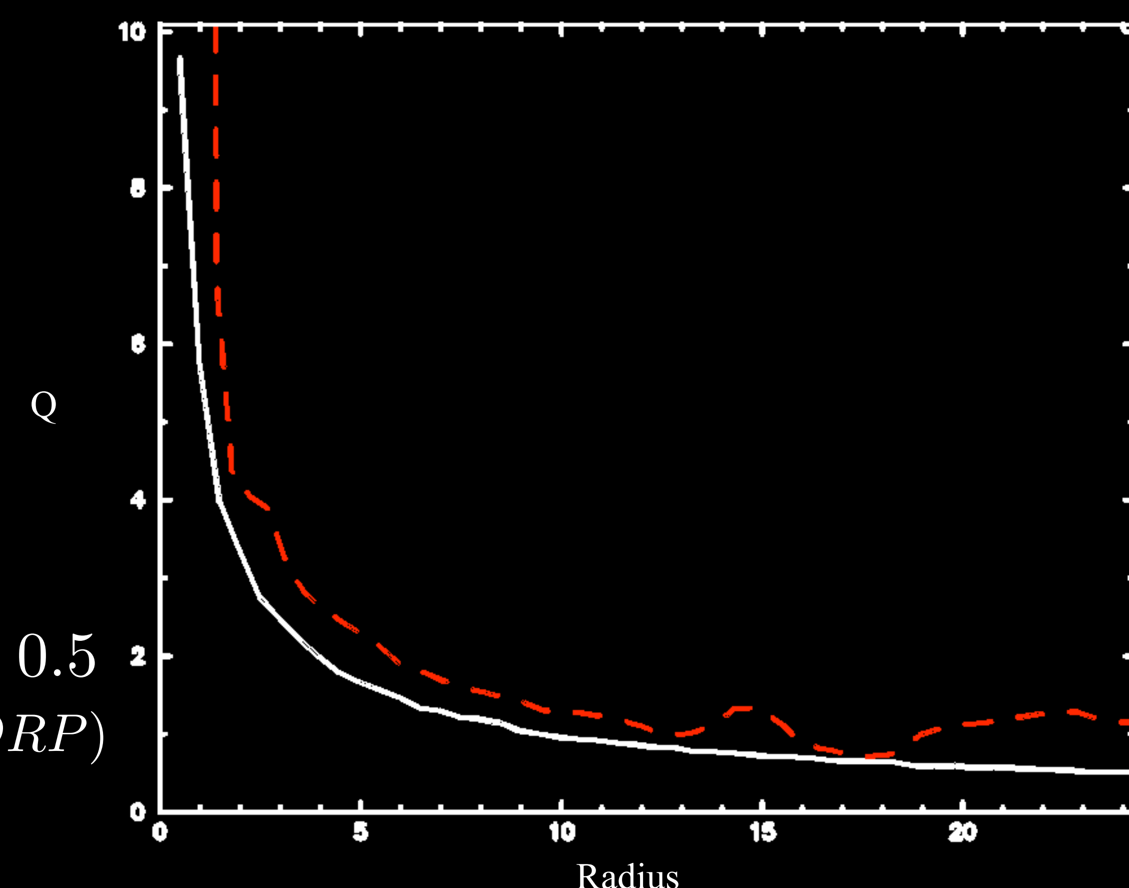
$Q_{out} = 2$
$(t = 6.4ORP)$



$Q_{out} = 1$
$(t = 6.4ORP)$

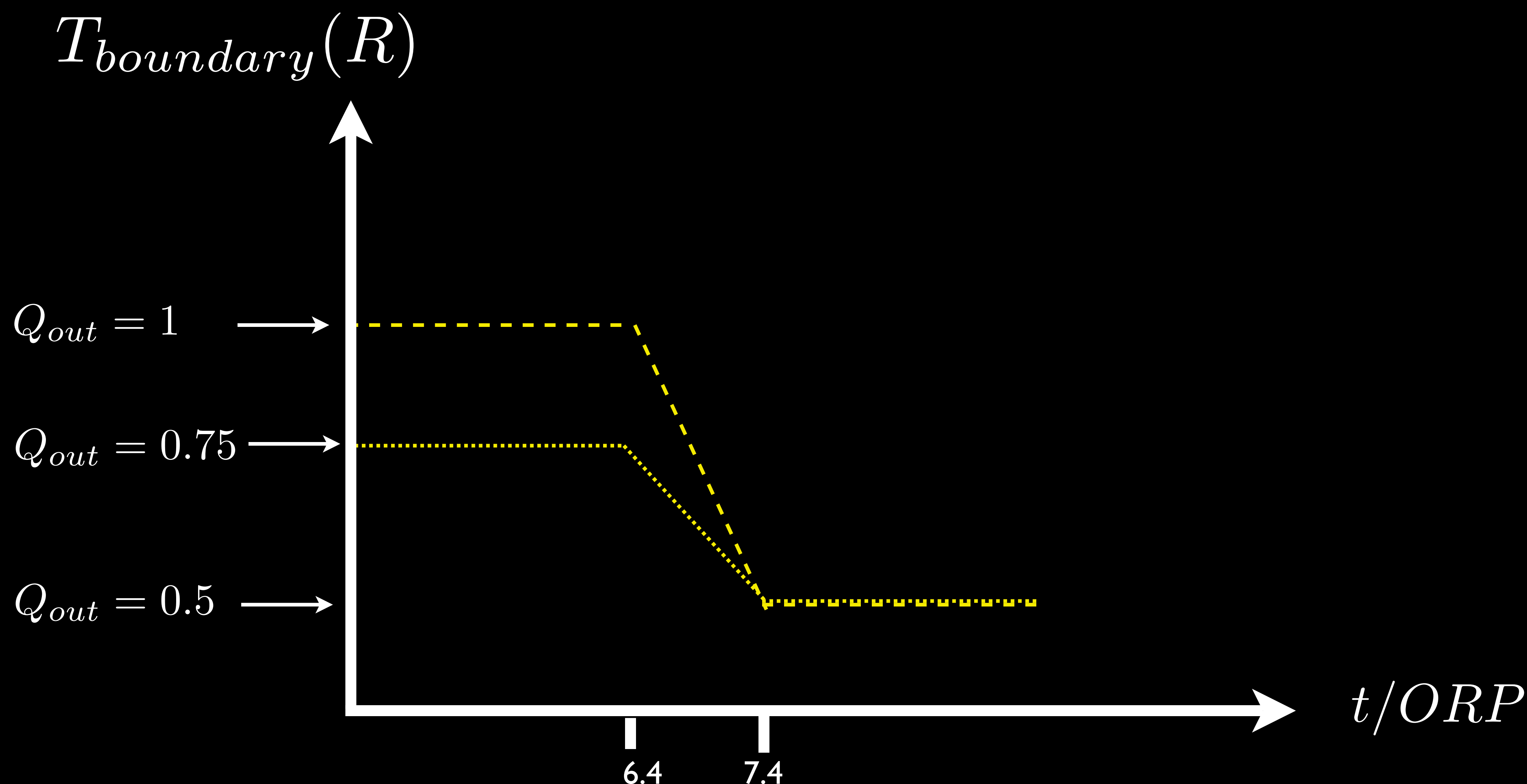


$Q_{out} = 0.75$
$(t = 6.4ORP)$

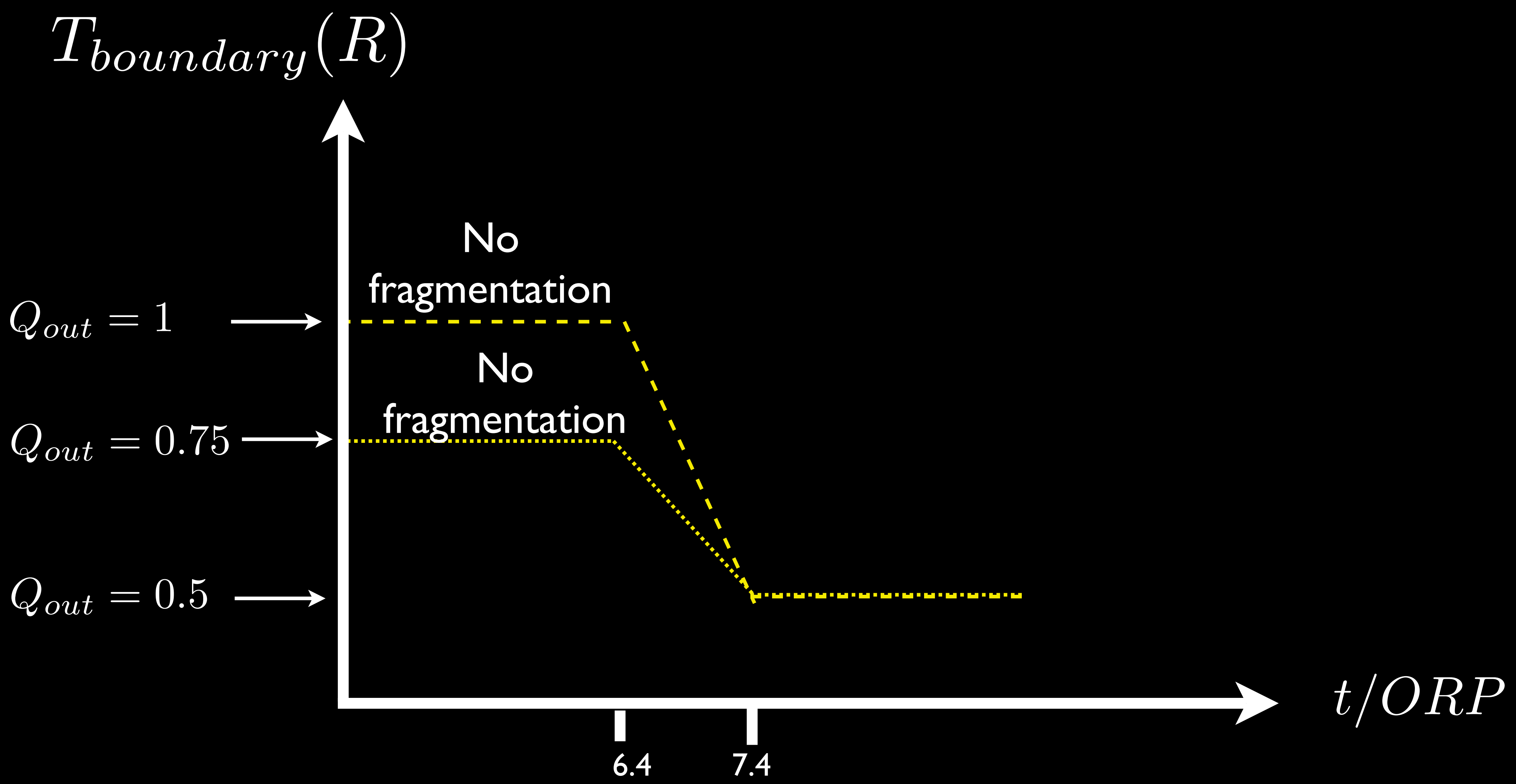


$Q_{out} = 0.5$
$(t = 1.2ORP)$

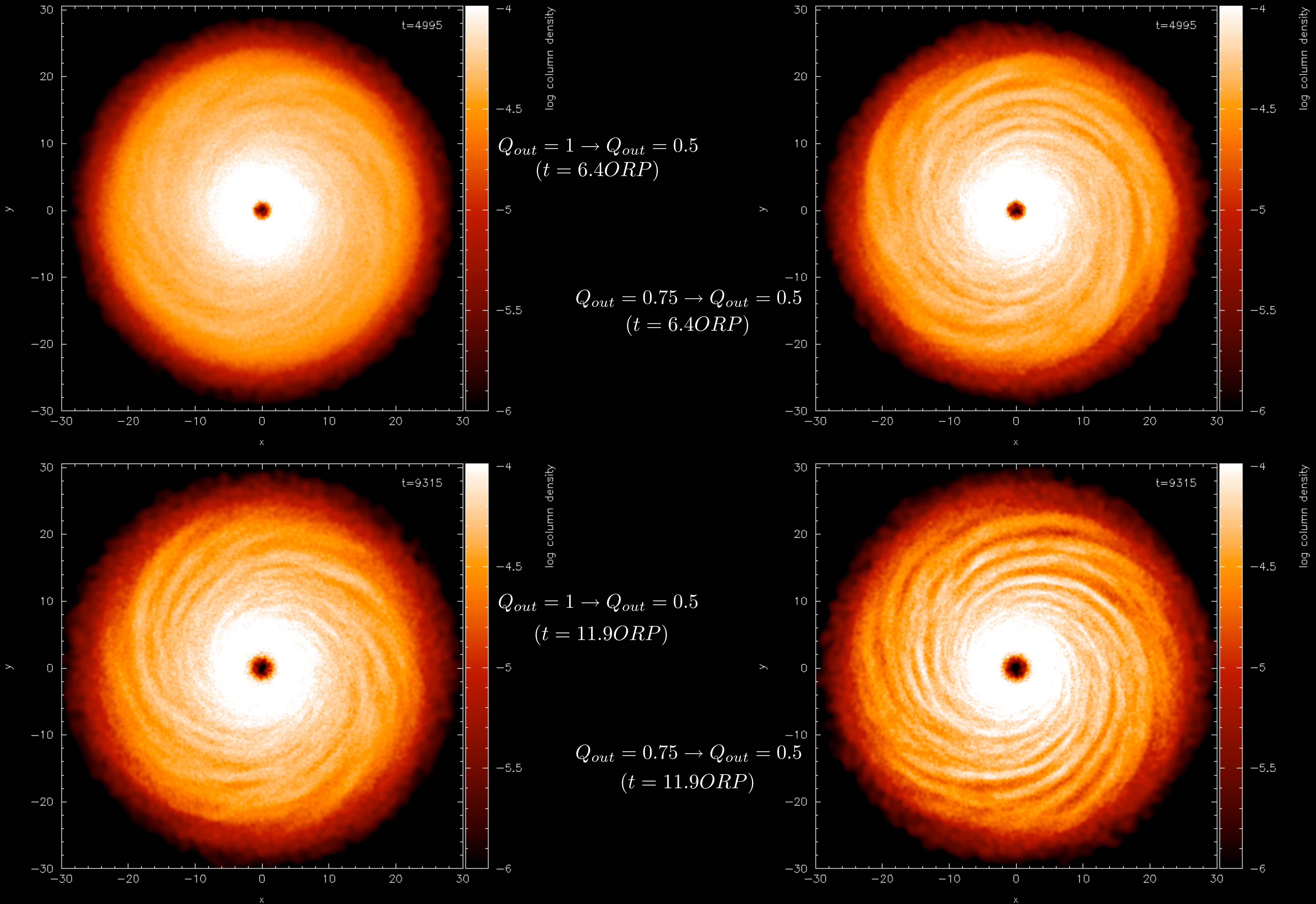
Results: boundary temperature conditions



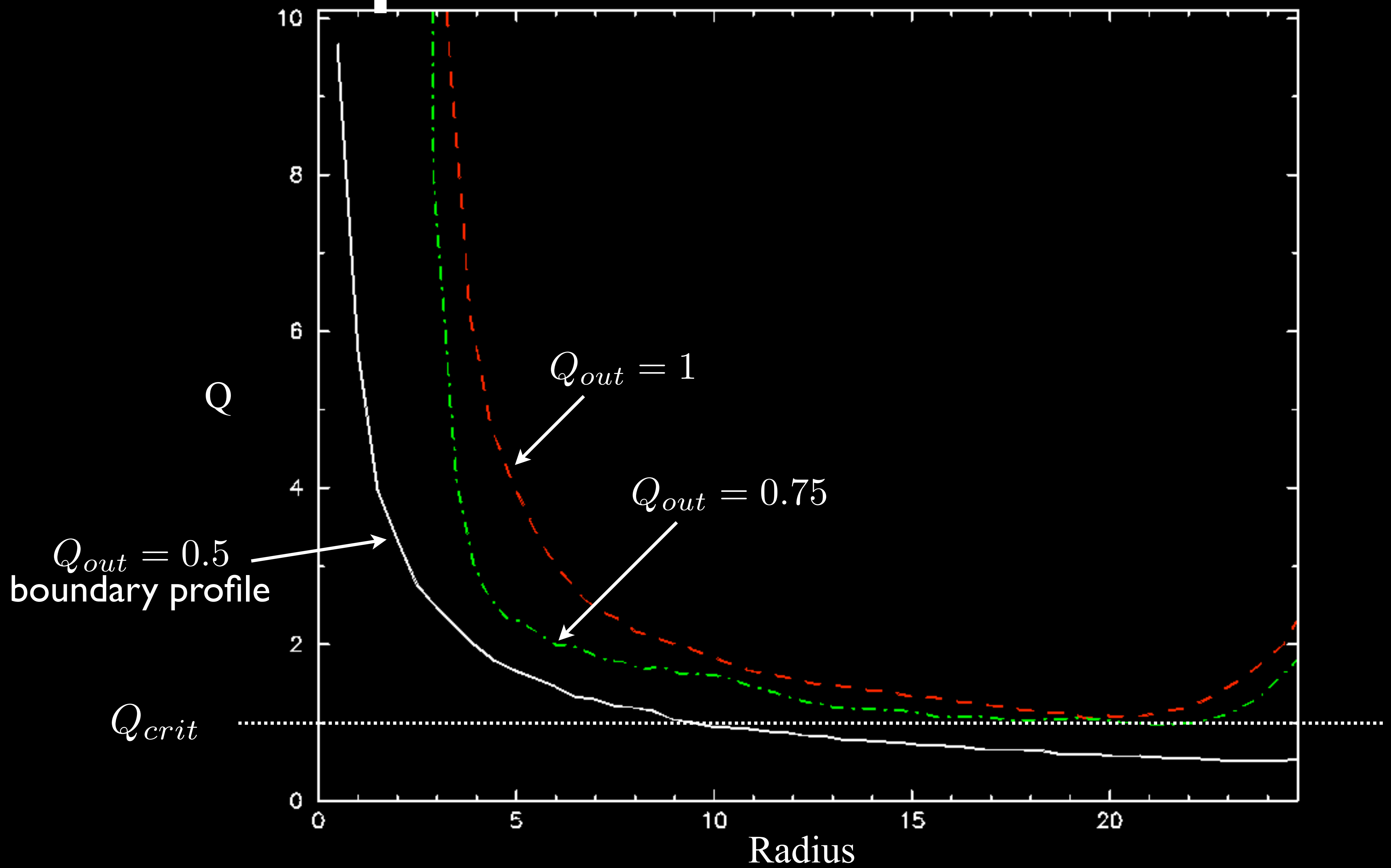
Results: boundary temperature conditions



Results: boundary temperature conditions



Results: boundary temperature conditions



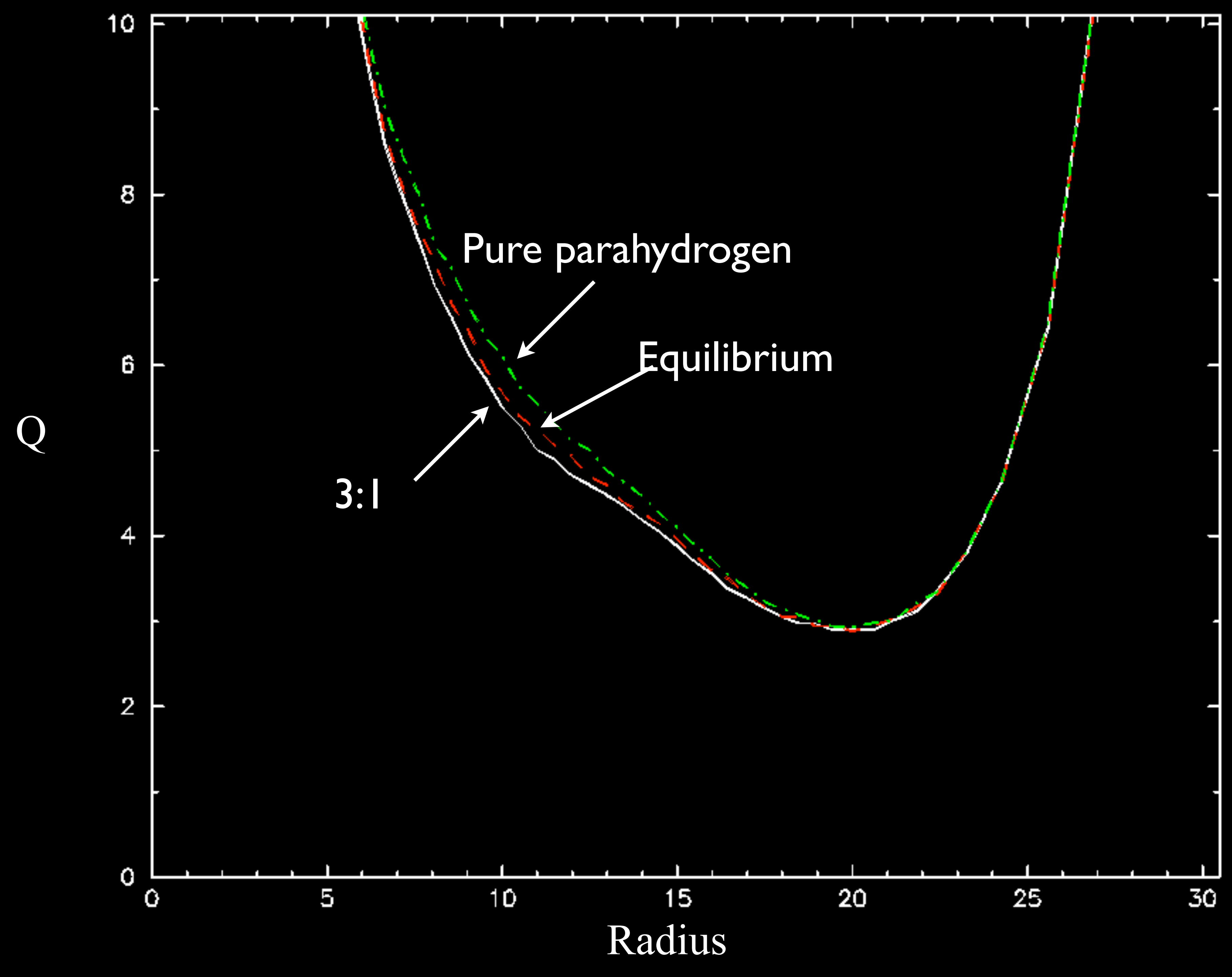
Summary

- Radiative transfer calculations with realistic opacities
- Radiative transfer discs resistant to fragmentation - cooling rates not fast enough for it to reach thermal equilibrium with the boundary
- Low opacity & larger discs reach thermal equilibrium - more likely avenues to follow for giant planet formation
- Can get fragmentation if go to extreme cases (very low Q_{out}) BUT large initial increase in temperature implies an unrealistic situation
- Taking a stable disc and cooling its boundary suggests the disc is resistant to fragmentation

Ortho-para H ratio

- Molecular hydrogen has 2 spin isomers
  - parallel = orthohydrogen
  - anti-parallel = parahydrogen
- 3:1
  - H_2 formation on cold dust grains (Flower et al 2006)

Results: ortho-para H ratio



Results: boundary temperature conditions