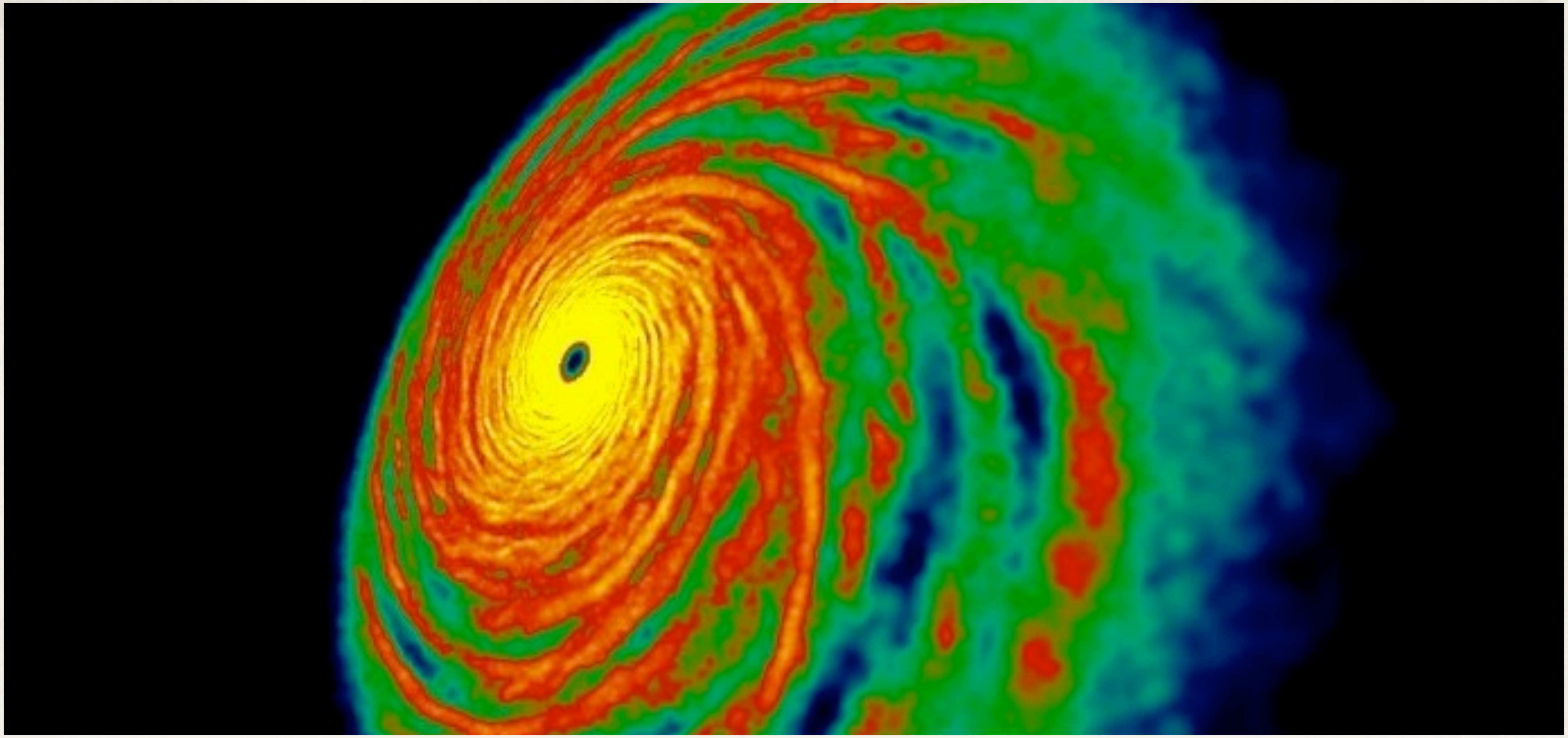

The dynamics of solids in self-gravitating protostellar discs

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5 November 2009 - From circumstellar disks to planetary systems

Gravitational instabilities in protostellar discs

- Conditions for instability
- Dynamics of self-gravitating discs:
  - Conditions for fragmentation/self-regulation
- Planetesimal formation and evolution in spiral arms
- Self-regulated disc models and their application to planetesimal formation

Linear stability criterion

- Well known axisymmetric instability criterion:

$$Q = \frac{c_{\rm s}\Omega}{\pi G \Sigma} < \bar{Q} \approx 1$$

- Equivalent form of the instability criterion

$$\frac{M_{\rm disc}(R)}{M_\star} \gtrsim \frac{H}{R}$$

- Need the disc to be cold and/or massive

- What are the masses and aspect ratio in actual protostellar discs?

Are protostellar discs linearly unstable?

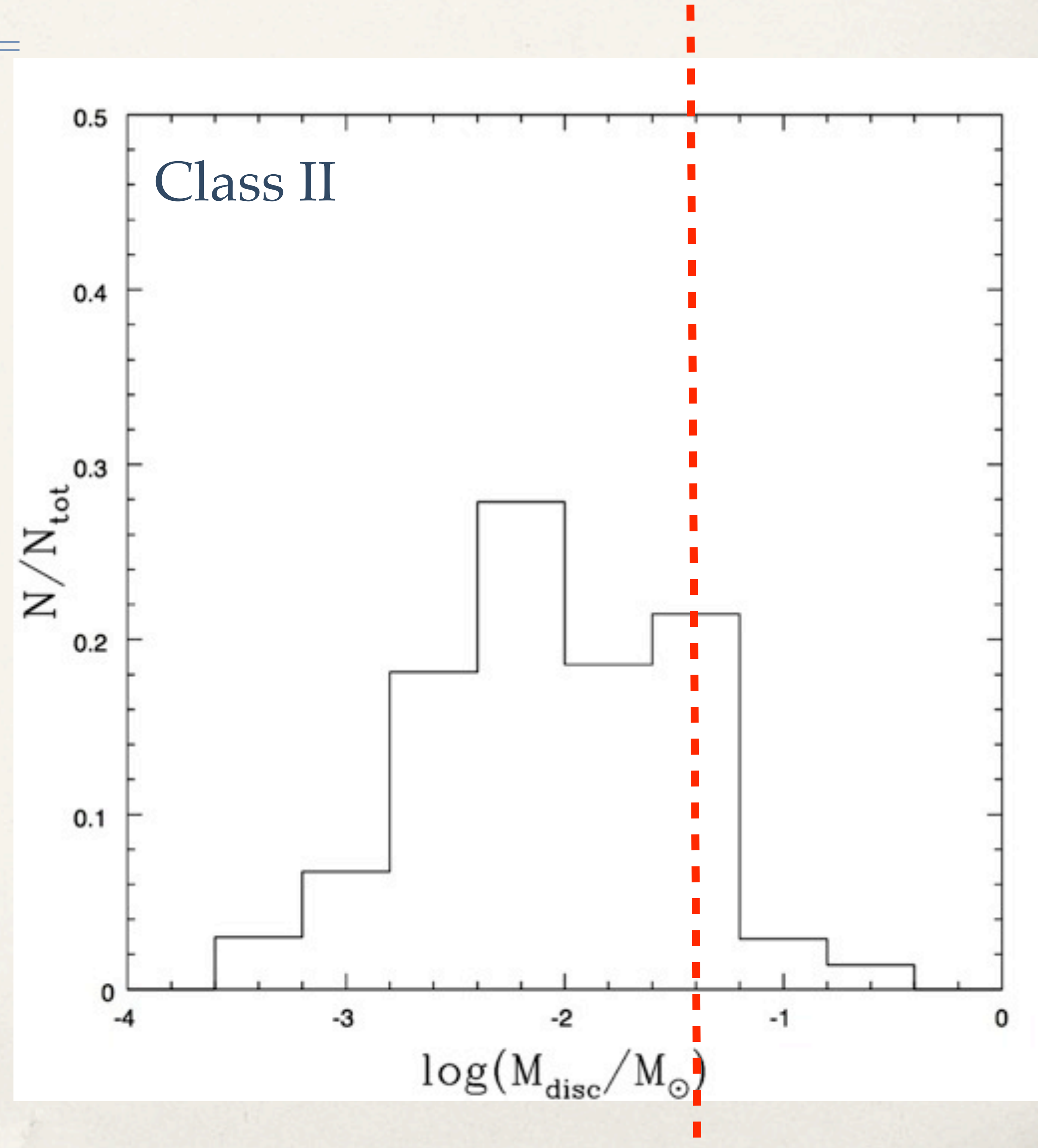
- Midplane temperature for irradiated discs (Chiang & Goldreich 1997, Chiang & Youdin 2009) gives:

$$\frac{H}{R} \simeq 0.02 \left(\frac{R}{\mathrm{AU}} \right)^{2/7}$$

- Therefore H/R varies from **0.02** at 1AU to **0.06** at 100 AU
- Need disc masses of order 5% of the stellar mass to be unstable
- Protostellar disc masses difficult to measure (see Hartmann et al 2006)

Are protostellar discs linearly unstable?

- Disc masses in Taurus and Ophiucus by Andrews and Williams (2005, 2007)
- Clear trend to have smaller masses at later stages of evolution
- A substantial fraction of Class I (and even some Class II) objects expected to be unstable
- Disc masses might be underestimated significantly (Hartmann et al 2006)
- Uncertainties in dust opacities



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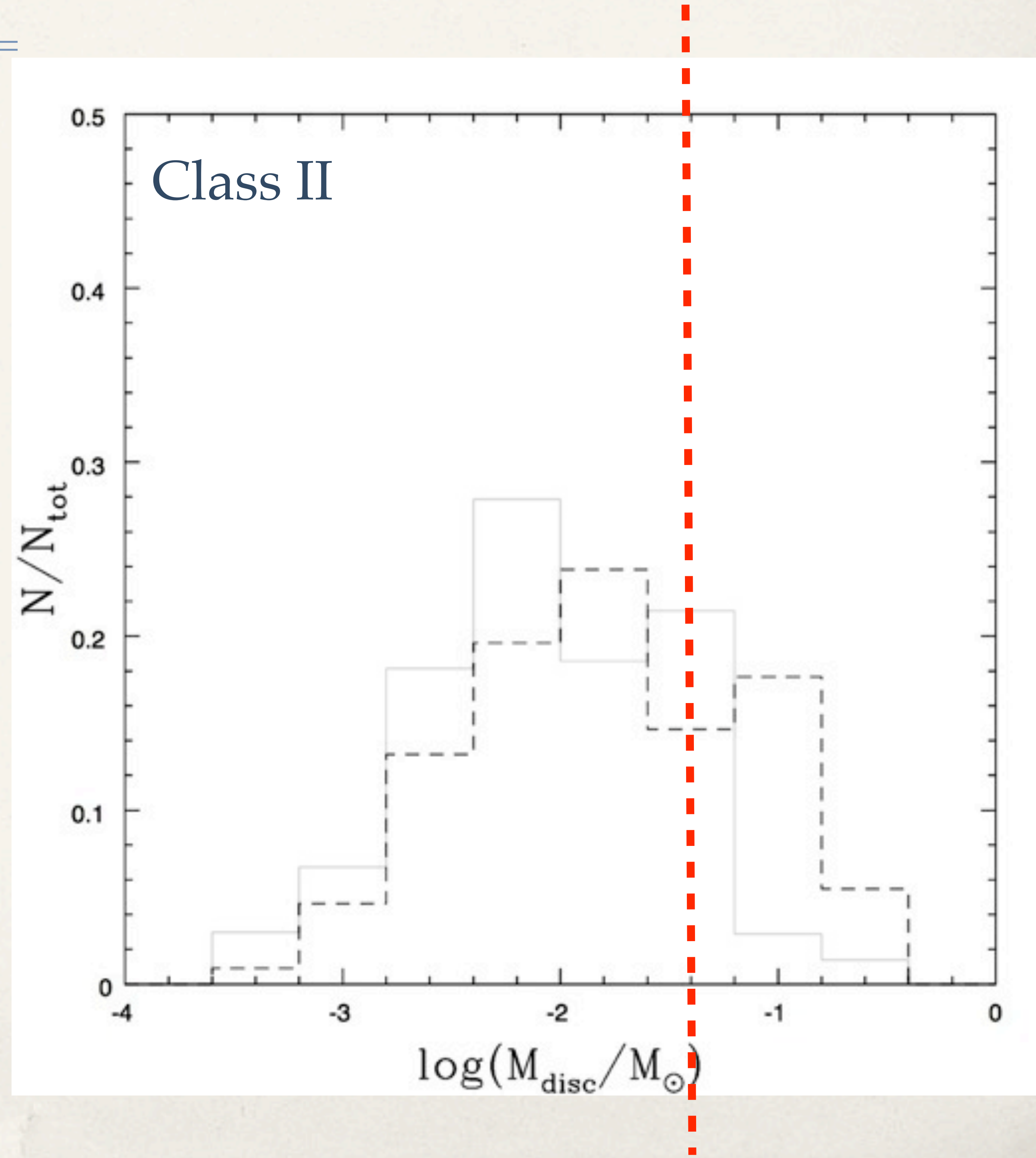

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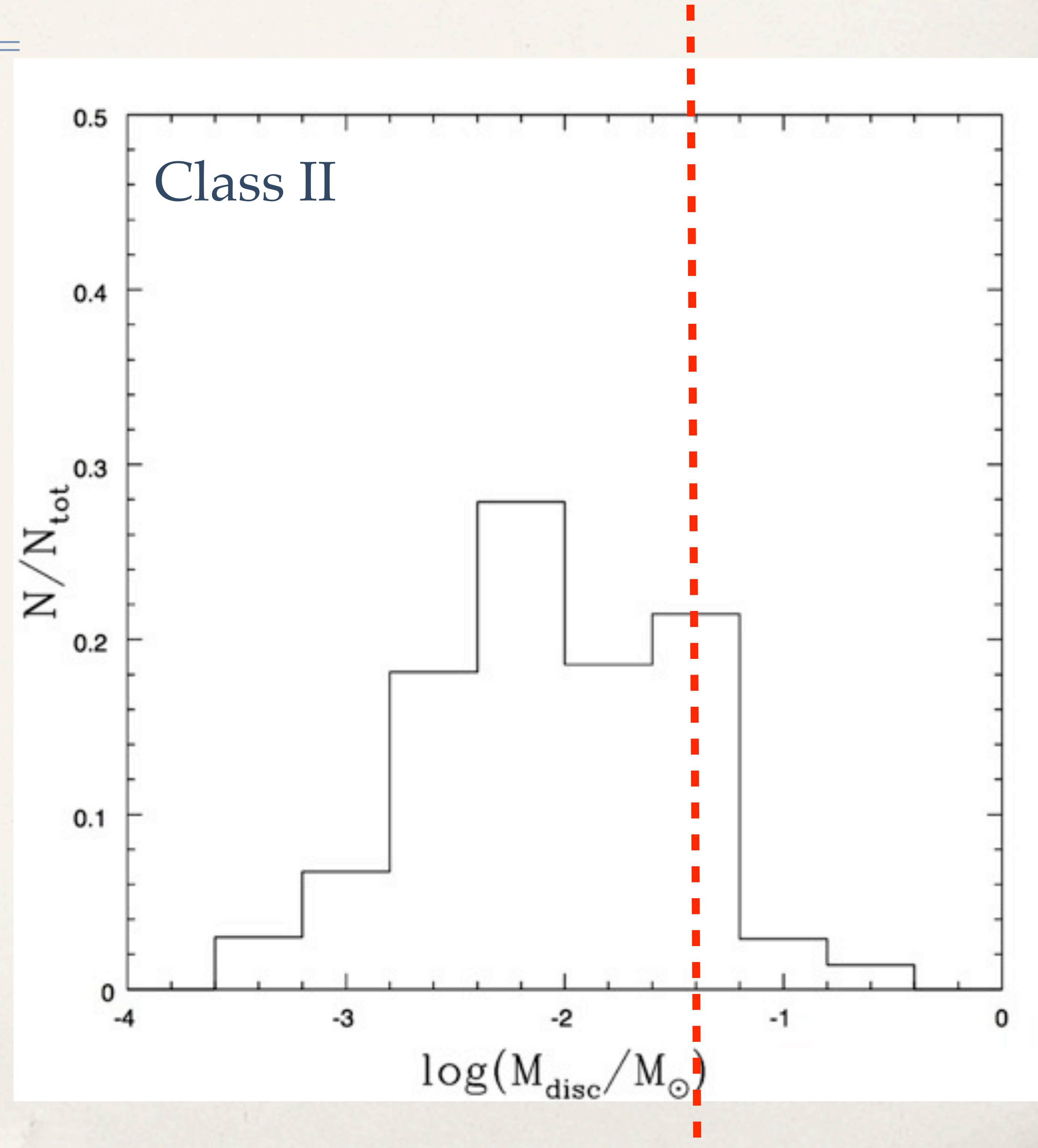

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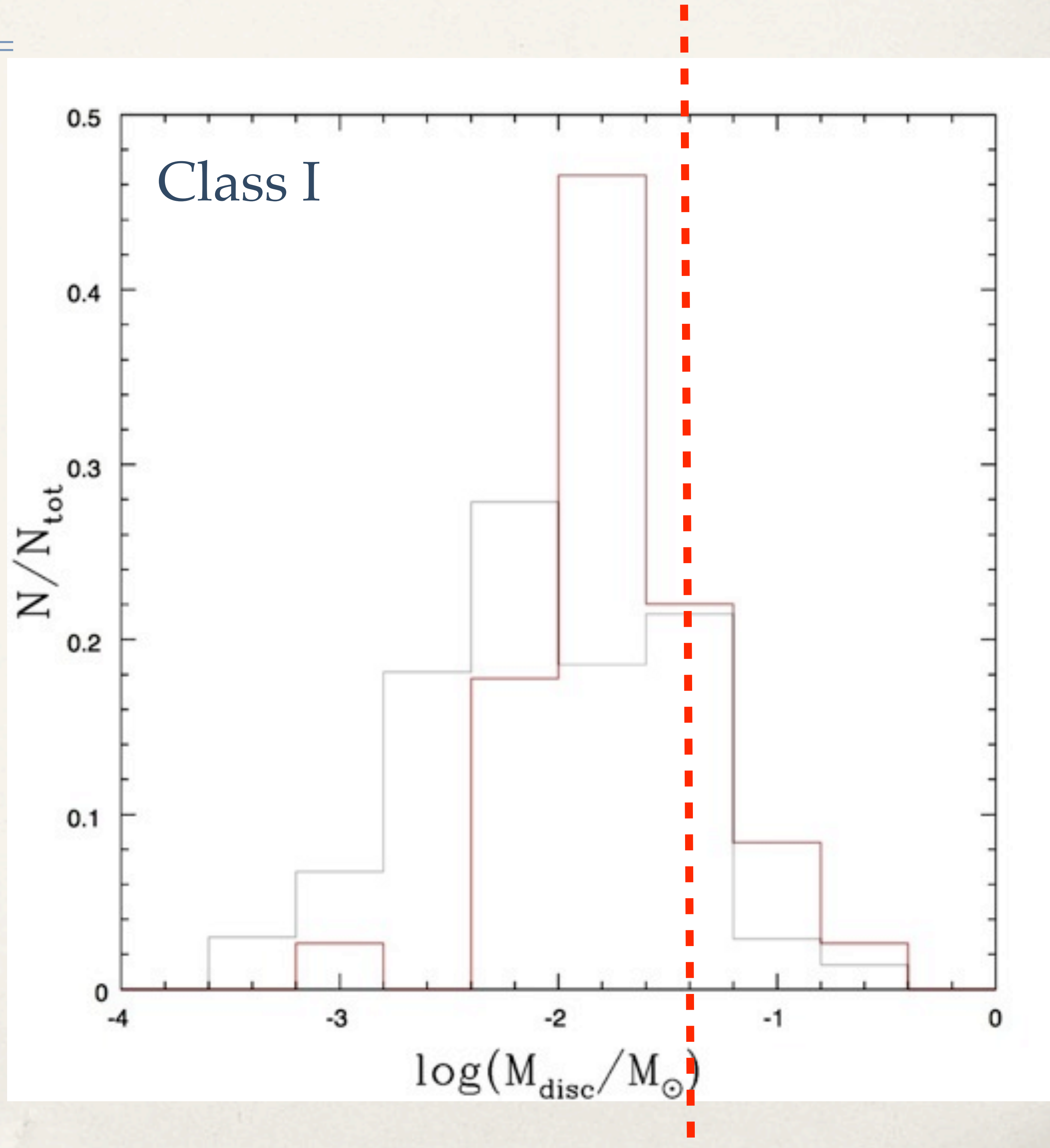
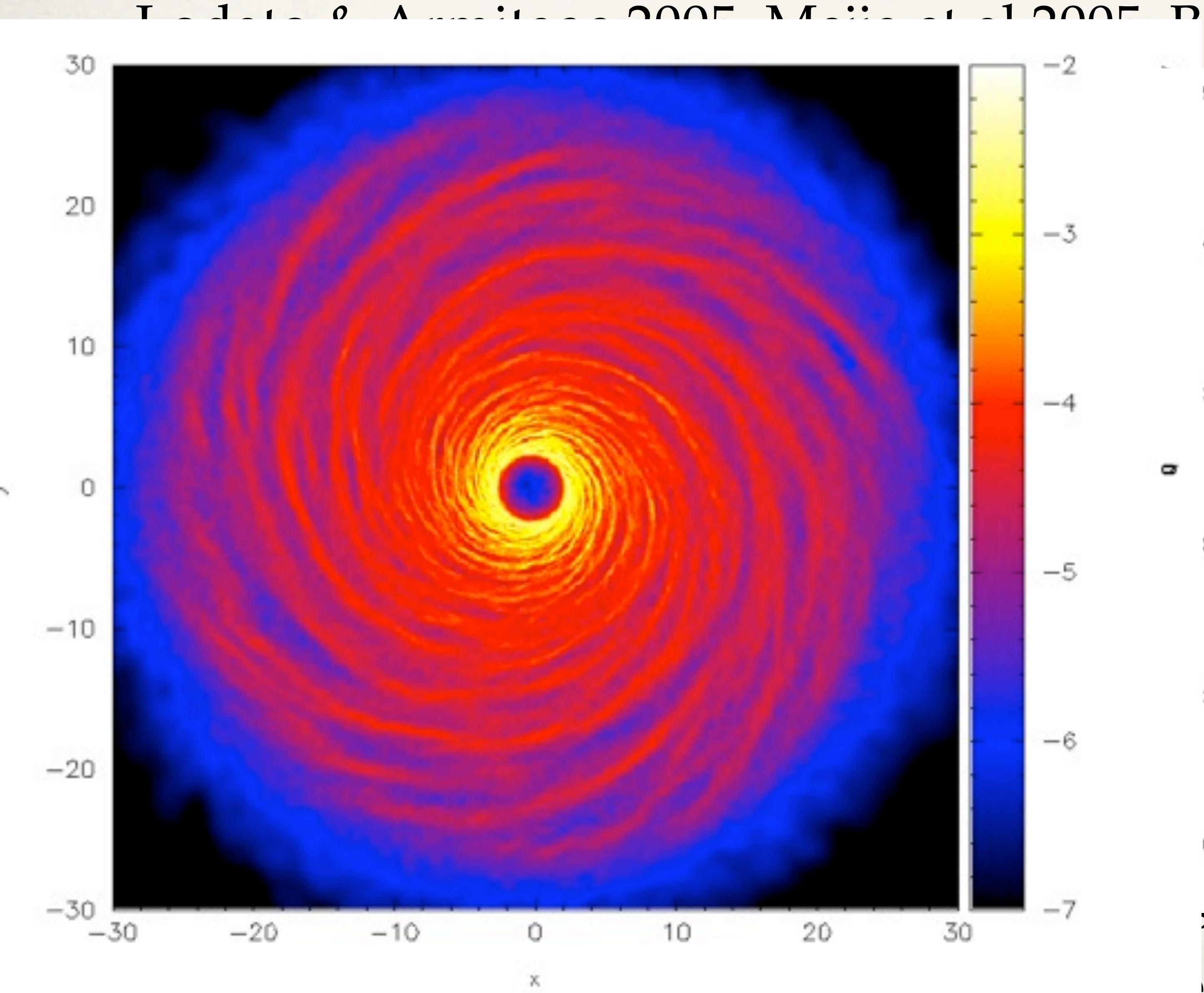
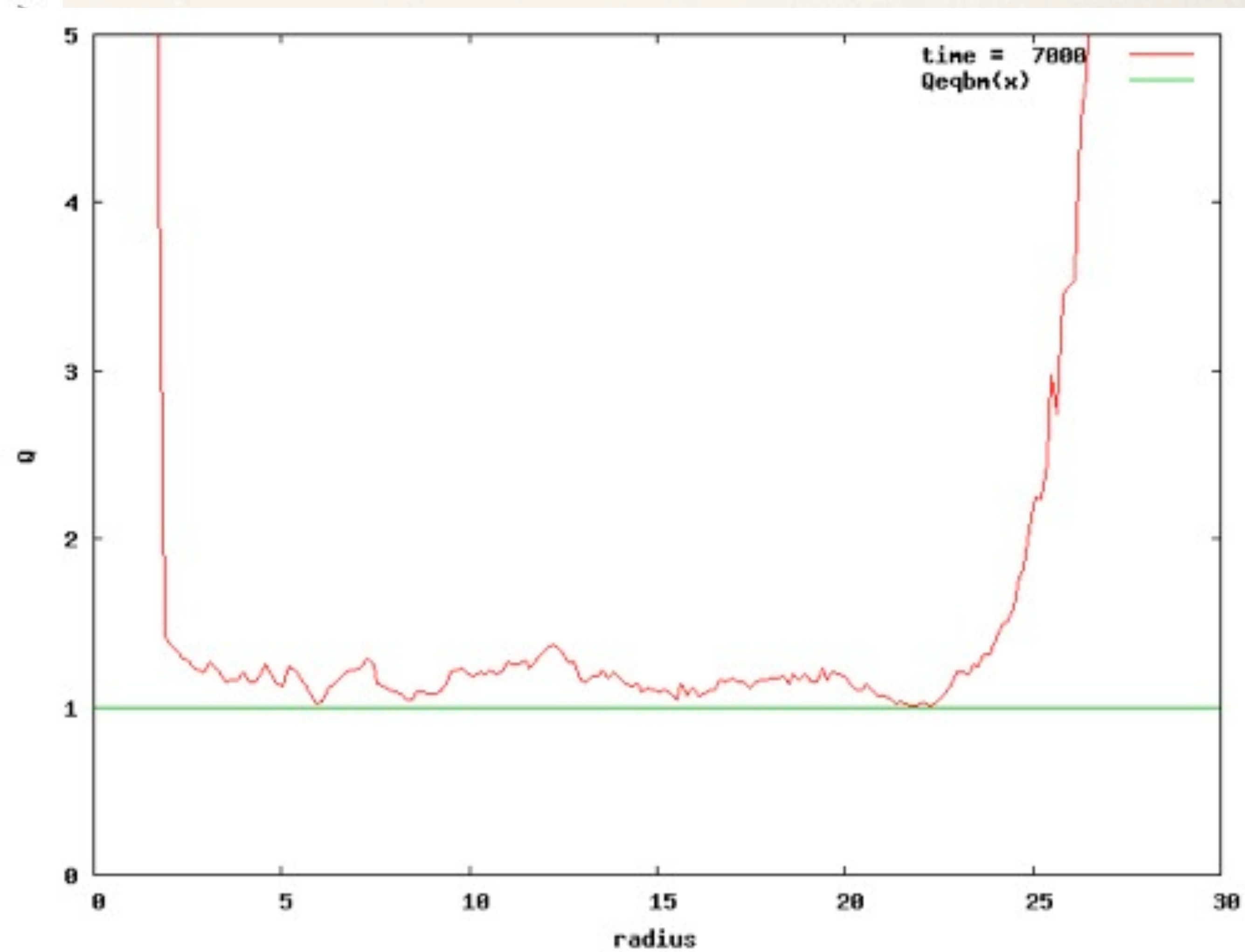


Non linear evolution of GI

- Investigated in several papers (Gammie 2001, Lodato & Rice 2004, 2005, Rice, ... oley et al. 2006)





...sport induced by spiral can be ...tion disc models (Lodato & Rice 2004, 2005, Cossins et al. 2009a)

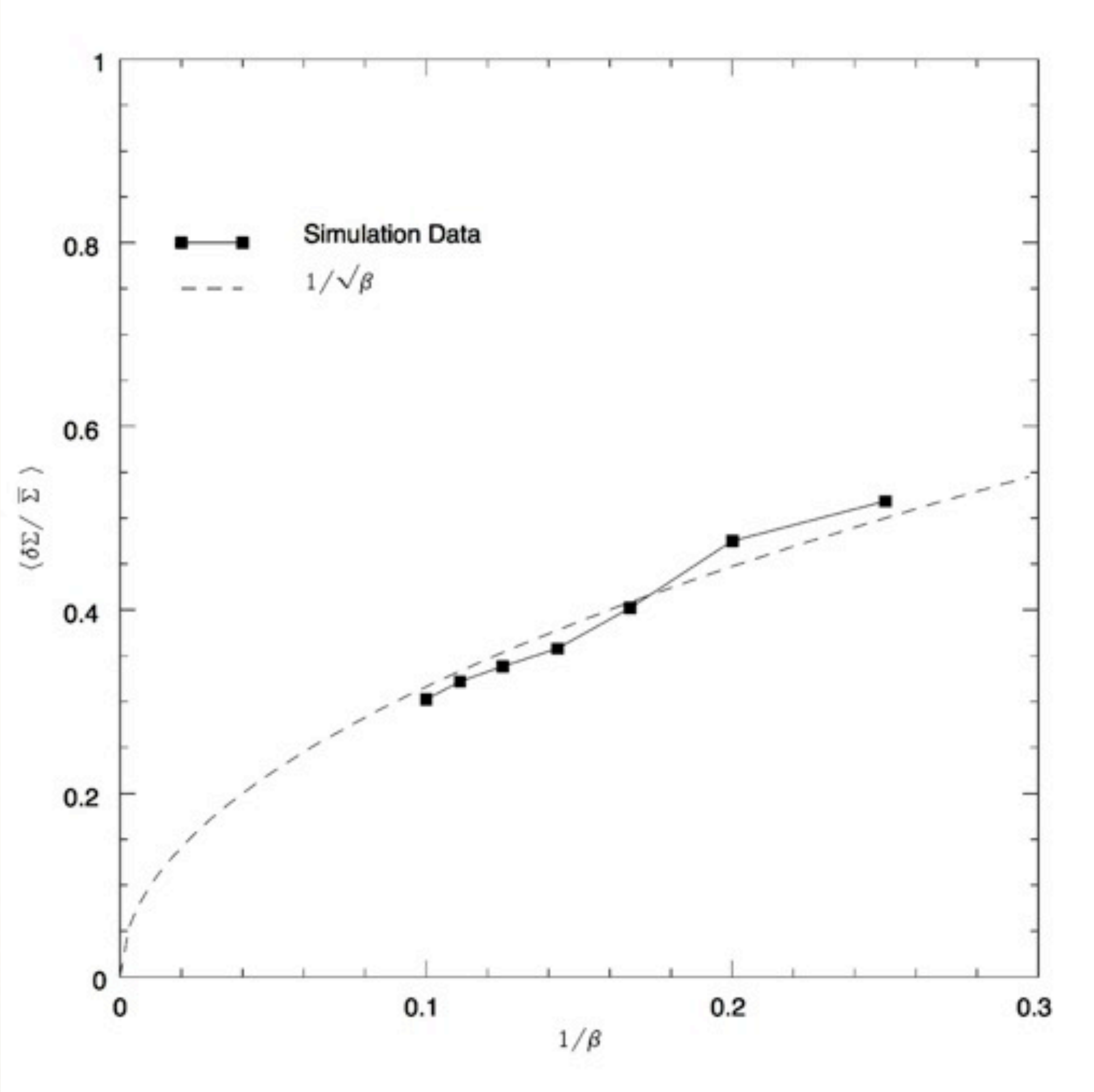
Thermal saturation of GI

Cossins, Lodato & Clarke 2009a

- Self-regulation is established through thermal saturation of the spiral waves.
- **IMPORTANT**: Amplitude of density perturbation must be related to cooling rate
- We find that:

$$\frac{\Delta\Sigma}{\Sigma} \approx \frac{1}{\sqrt{\Omega t_{\rm cool}}}$$

- Naturally predicts a radially varying value of α



Evolution of solids in self-gravitating discs

(Rice, Lodato et al 2004, 2006)

- Effects of gas drag on solid particles is to induce fast migration towards pressure maxima.
- In a laminar disc this produces a fast inward migration of meter-sized particles (Weidenschilling 1977)

Radial velocity of solids

Stopping time

Difference between gas velocity and keplerian

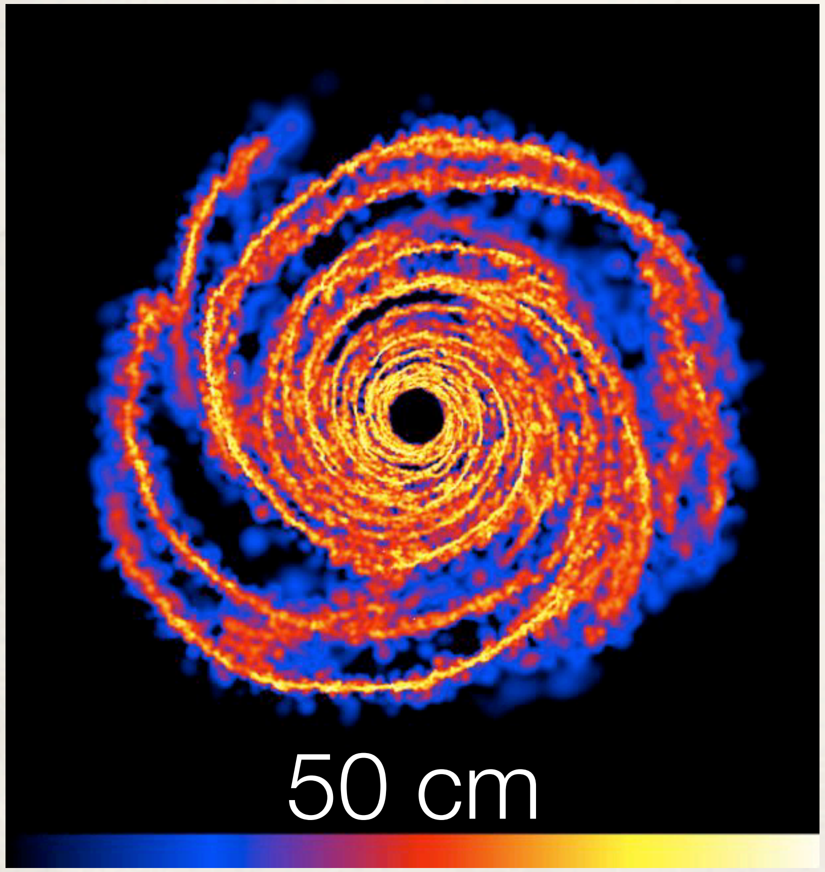
$$v_r = \frac{\Delta v}{\Omega t_{\rm s} + 1/\Omega t_{\rm s}}$$

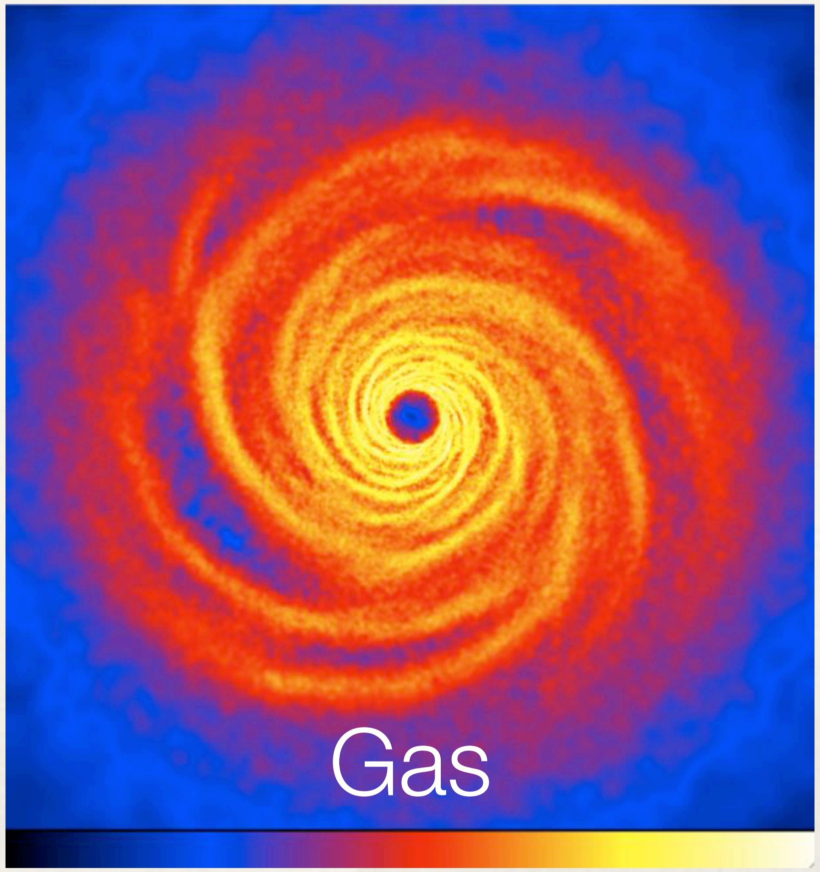
$$\Delta v \approx \frac{c_{\rm s}^2}{v_{\rm K}} \frac{\partial \ln \rho}{\partial \ln R}$$

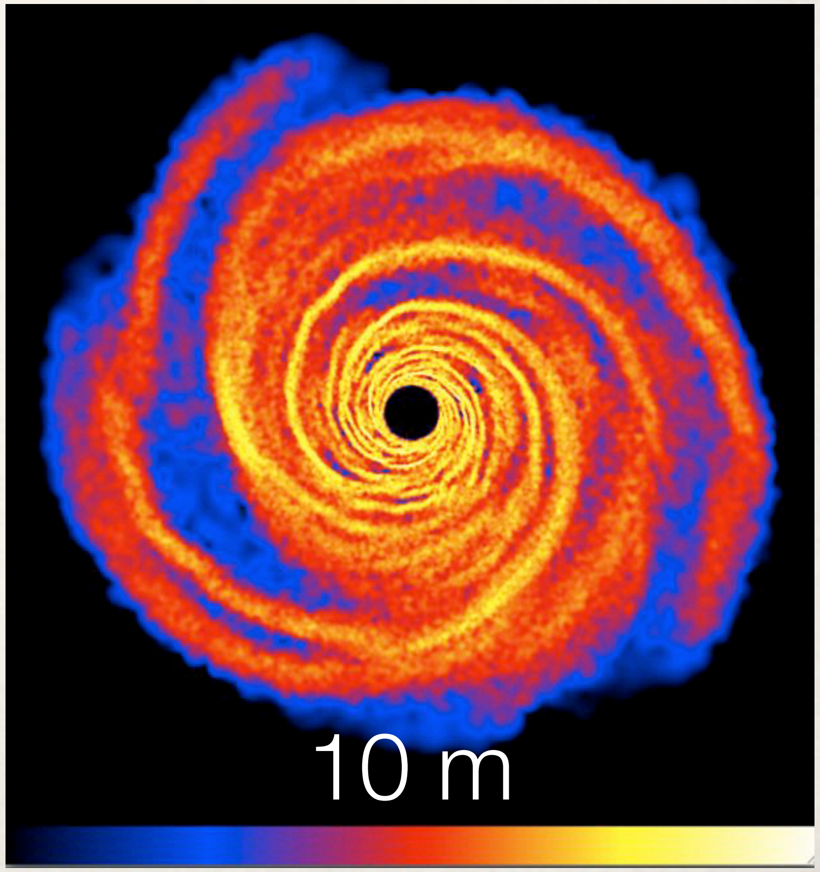
Evolution of solids in self-gravitating discs

(Rice, Lodato et al 2004, 2006)

- Pressure maxima in spiral structure efficient trap for meter sized objects (see also Haghighipour & Boss 2003, Durisen et al 2005).
- Run SPH simulations of a two component system (gas + solids)



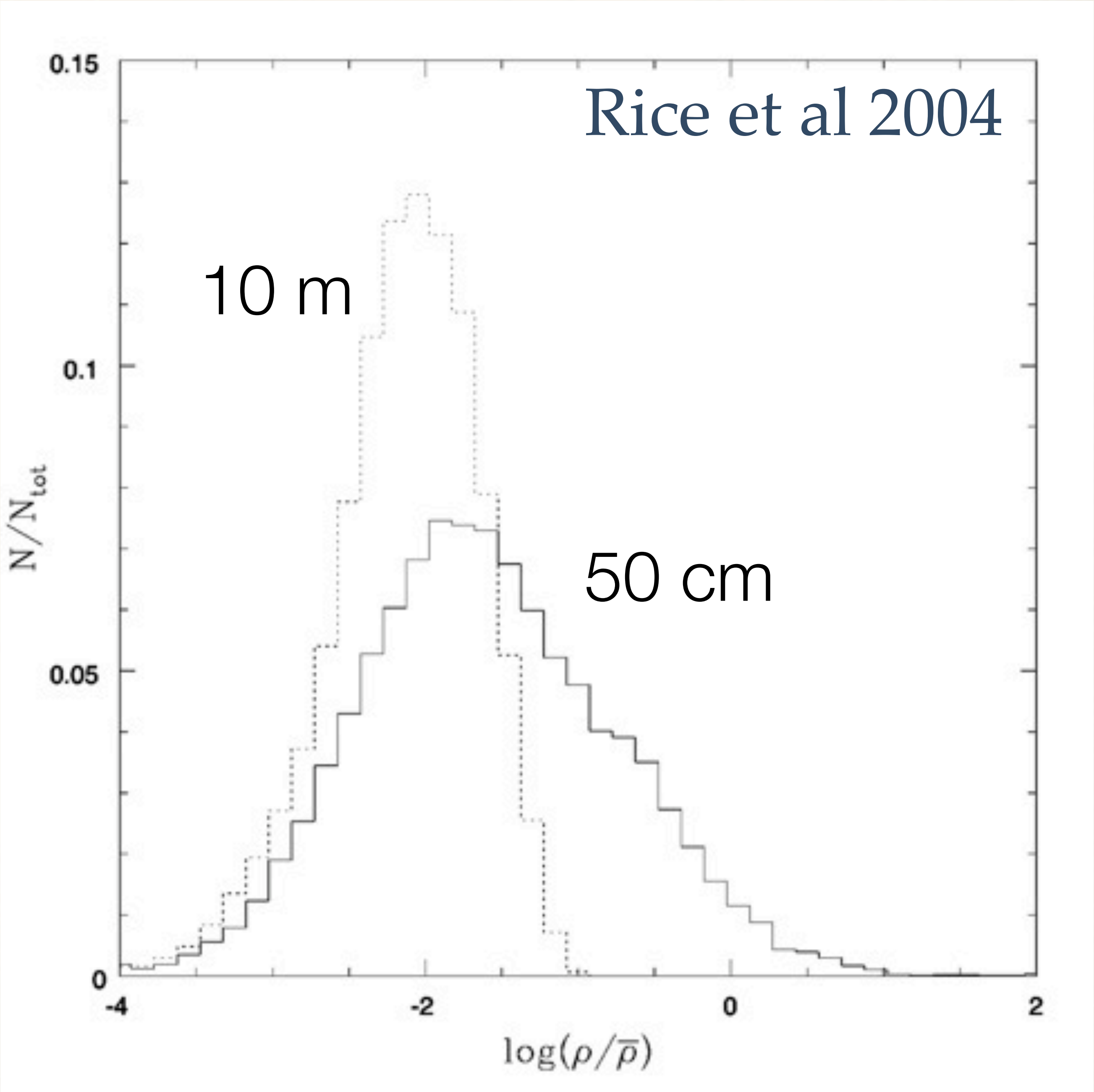




Solid agglomeration in pressure maxima

(Rice, Lodato et al 2004, 2006)

- Density of meter sized objects enhanced by up to two orders of magnitude
- Density becomes high enough to become comparable to Roche density
- Gravitational collapse of solids is possible
- Confirmed through additional simulations including the solids self-gravity (Rice et al. 2005)
- Resulting planetesimals mass expected to be high (but difficult to measure from simulations)

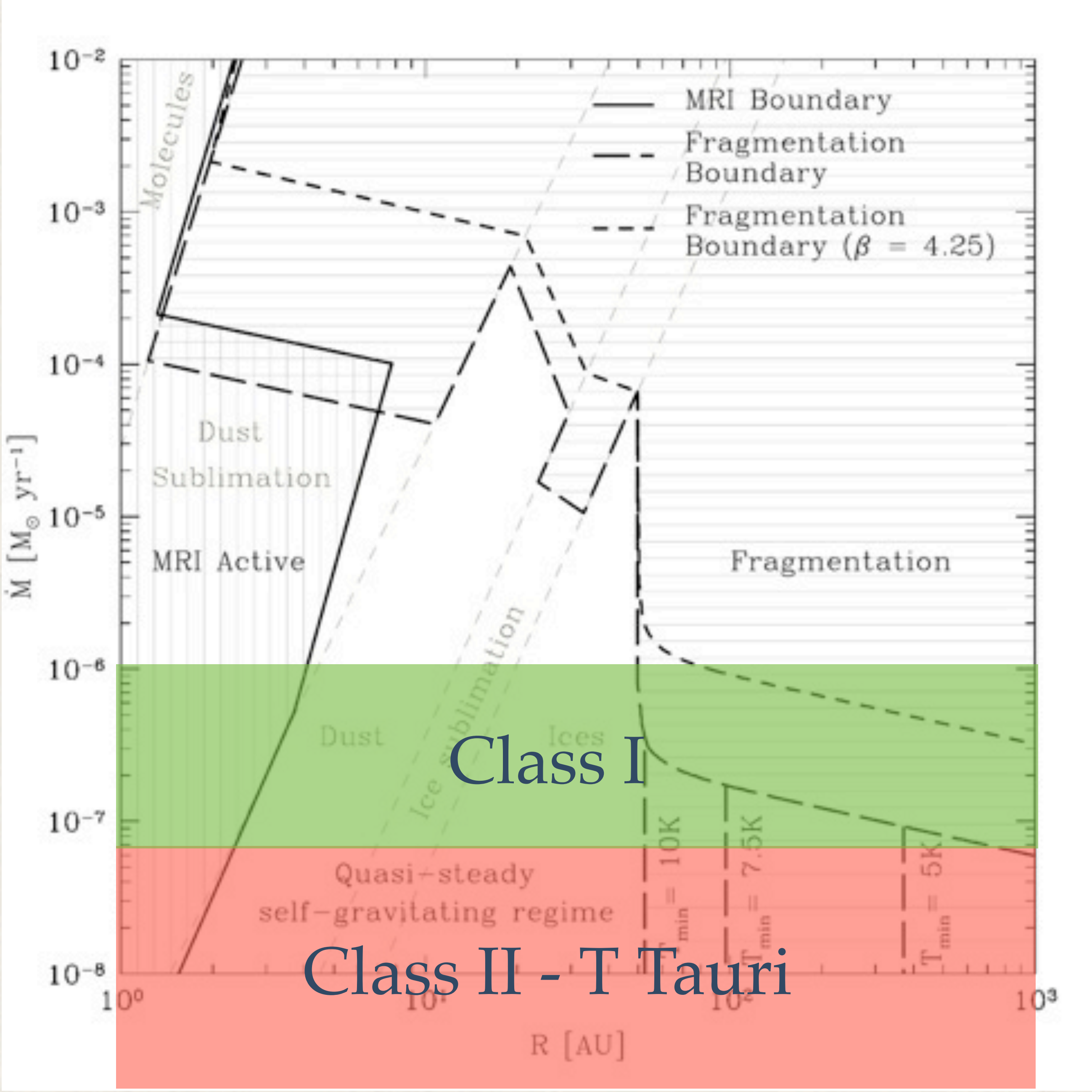


Planetesimals in self-gravitating discs

- Particle traps in spiral arms are an effective way of producing large solid bodies in the disc:
  - Resulting planetesimal mass quite large
  - Dynamically stirred population of planetesimals (Britsch, Lodato & Clarke 2008)
  - Expected to occur in early phases of star formation (<~ 1Myr)
  - **Is this process limited to some specific radial range in the disc?**
    - Note: Rice et al. used an idealized cooling function leading to a rather large amplitude spiral $\Delta\Sigma/\Sigma \approx 0.1$
    - Need a detailed model of self-gravitating discs with realistic cooling

Local models of self-regulated protostellar discs

Clarke 2009, Cossins, Lodato & Clarke 2009, Rafikov 2009



- If transport is local (cf. Cossins et al 2009), then in thermal equilibrium (and absent other sources of heating, e.g. irradiation):

$$\alpha = \frac{4}{9}\frac{1}{\gamma(\gamma-1)}\frac{1}{\Omega t_{\rm cool}}$$

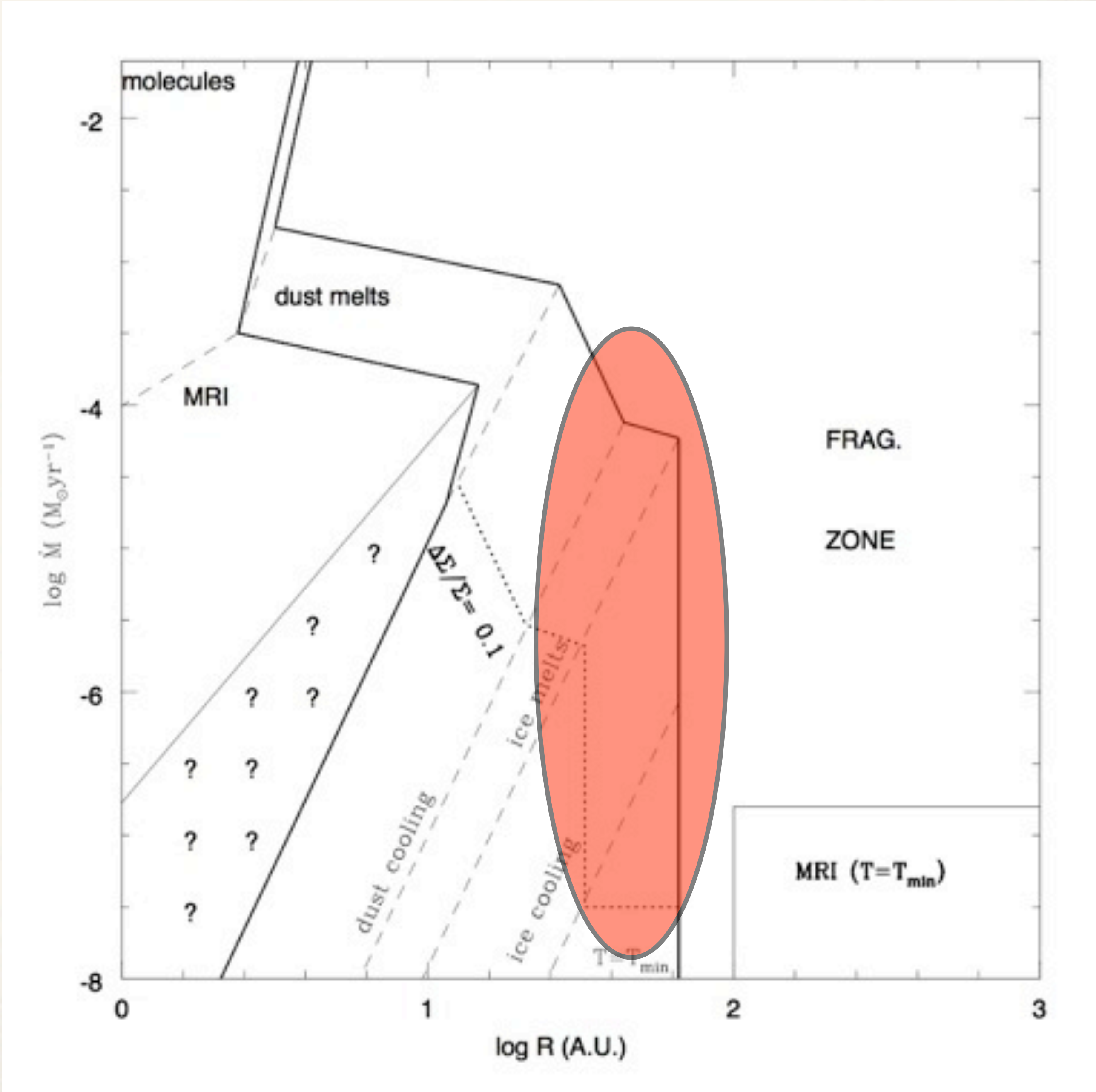
- Possible to construct models of self-regulated discs (Q~1), where viscosity is related to cooling time (Clarke 2009, Rafikov 2009)

- Identify various possible regimes for self-gravitating protostellar discs

Where do planetesimals form?

Clarke & Lodato (2009)

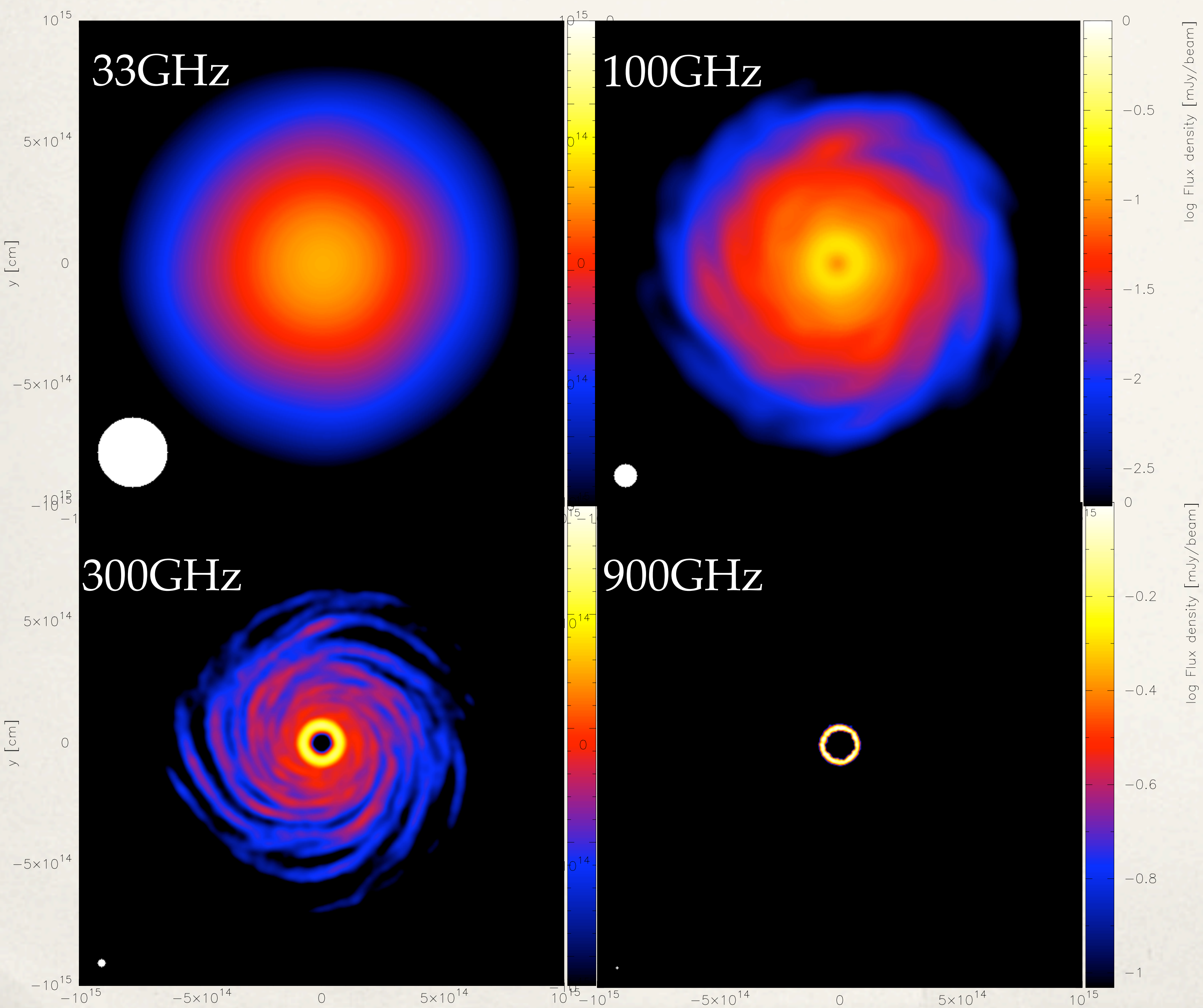
- Planetesimal formation through this process occurs at ***30AU < R < 50 AU***
- Roughly coincident with the location of the Kuiper belt
- Some evidence for a large inner hole in debris disc systems (Currie et al. 2008), based on the apparent increase of debris disc brightness at late ages ~ 10 Myrs (Meyer's talk)
- Rapid production of large bodies in the outer disc may preserve sub-mm emission in the T Tauri phase (Takeuchi, Clarke & Lin 2005)



Spiral structure with ALMA

Cossins & Lodato, in prep.

- Will we be able to observe a spiral structure at ~ 50 AU with ALMA?



$M_{disc} / M_* = 0.1$

$M_* = 2M_{Sun}$

$R_{disc} = 50AU$

$D = 140pc$

10h integration

Conclusions

- Class I discs are likely to be gravitationally unstable
- Self-regulated evolution of GI leads to sustained angular momentum transport for ~ 1 Myr, bringing the disc into the T Tauri phase
- Spiral arms where the first sites to be identified as optimal particle traps for the formation of planetesimals
- Such process works only in the outer disc, between 30 AU and 50 AU
- Leads to the rapid formation of solid in an annular region at large distances: possibly consistent with observations of debris discs and the Kuiper belt