Critical Cooling Parameter in Self-Gravitating Disks

HANS BAEHR - PENCIL CODE 2015

NTNU - 14 MAY 2015

Overview

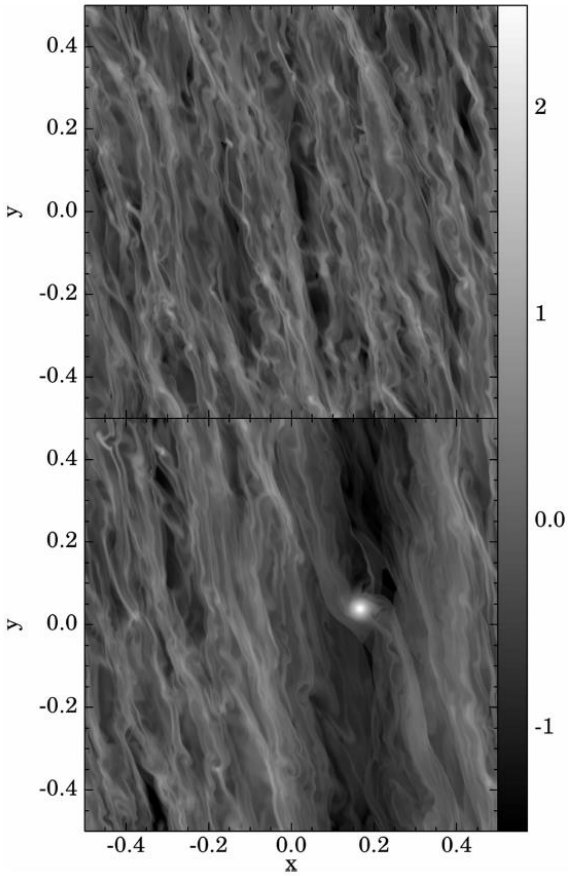
Introduction
- Gravitational Instability
- Motivation

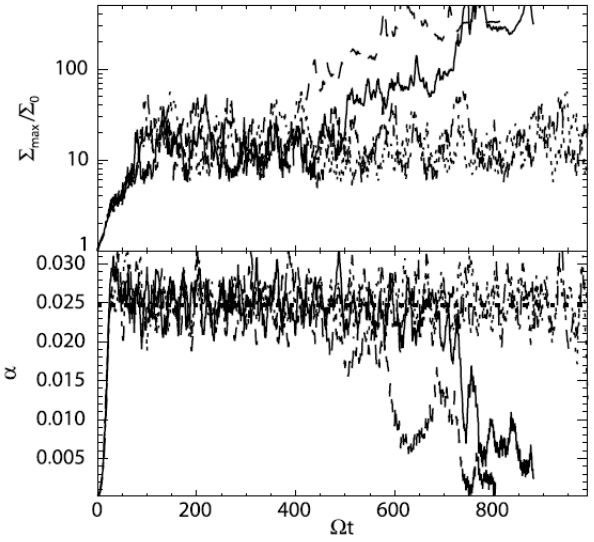
Conditions for Planet Formation
- Adjusting the Cooling Timescale
- Results

What Happens Next?
- Additional Adjustments
- Radiative Transfer

Conclusion

Intro: Gravitational Instability





Paardekooper (2012)

Massive enough?

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

Cools fast enough?

$$t_c = \beta \Omega^{-1}$$

Intro: Cooling Criterion

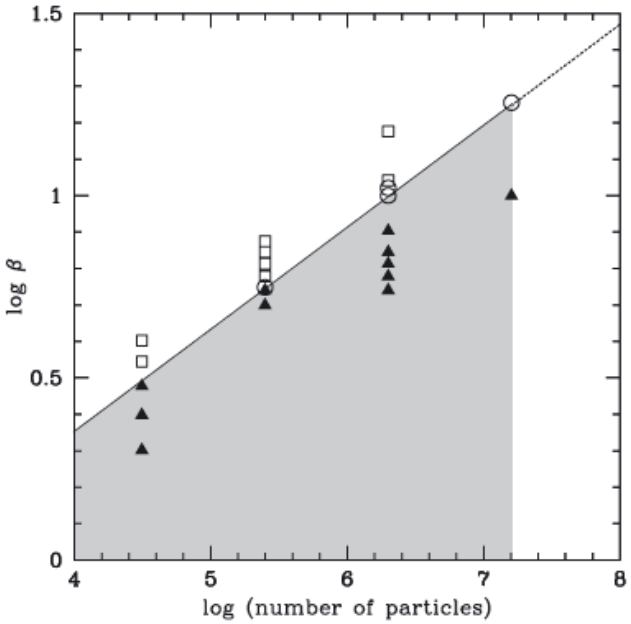
$$t_c = \beta \Omega^{-1}$$

Thermal relaxation times too long at short radii

$$\beta_{crit} = 3$$ Gammie (2001)

$$\beta > 3$$

$$\beta < 3$$



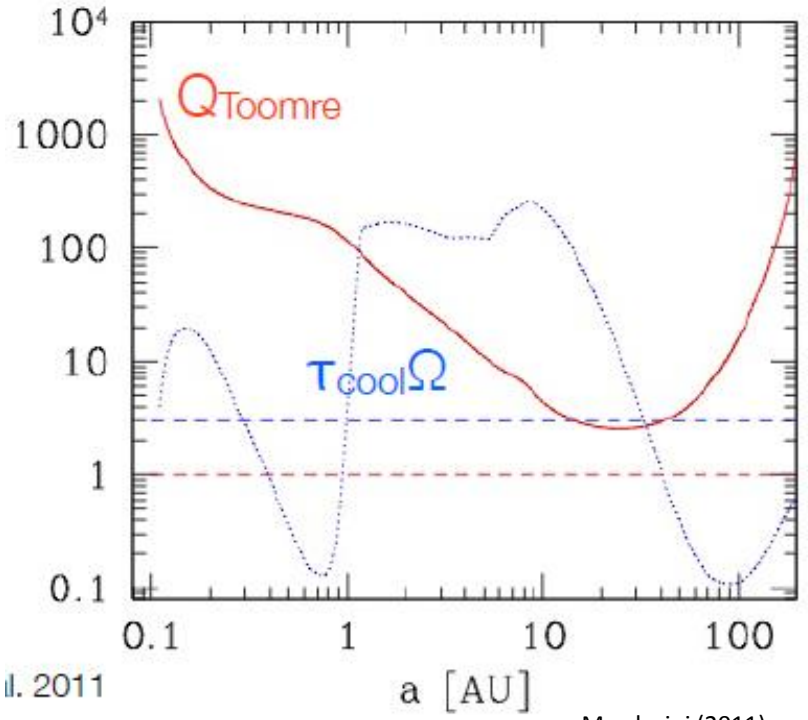
Meru & Bate 2011

Intro: Toomre Parameter

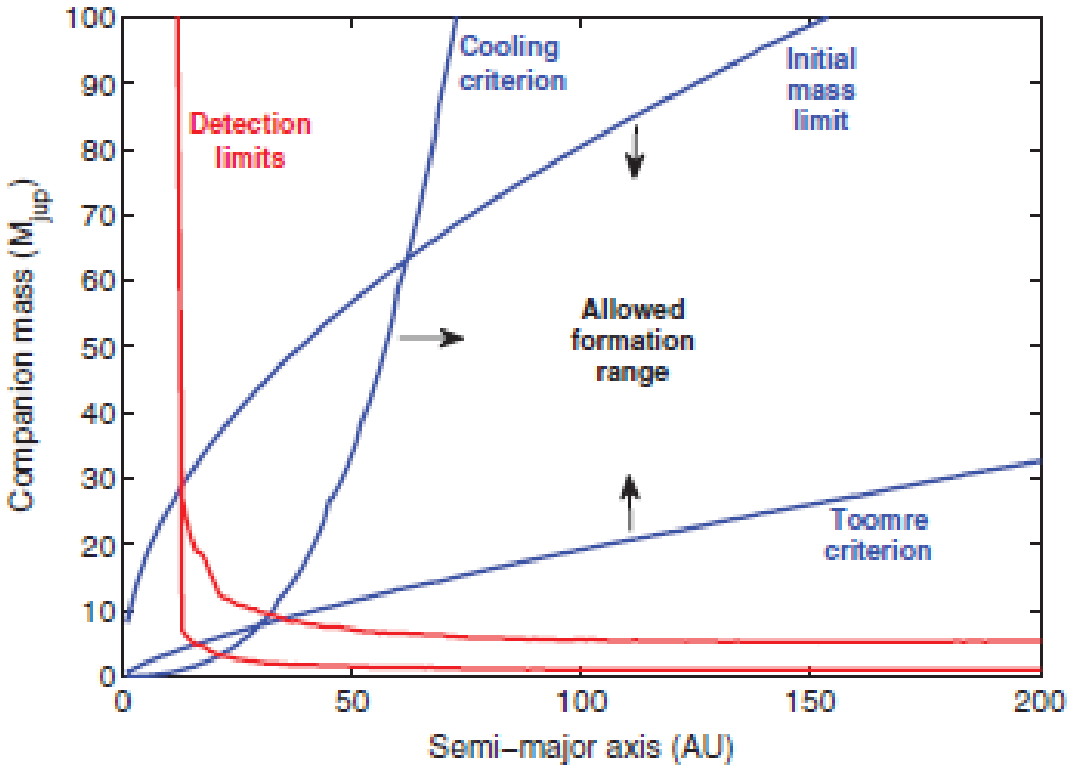
$$Q = \frac{c_s \Omega}{\pi G \Sigma}$$

Axisymmetric perturbations

Non-axisymmetric perturbations

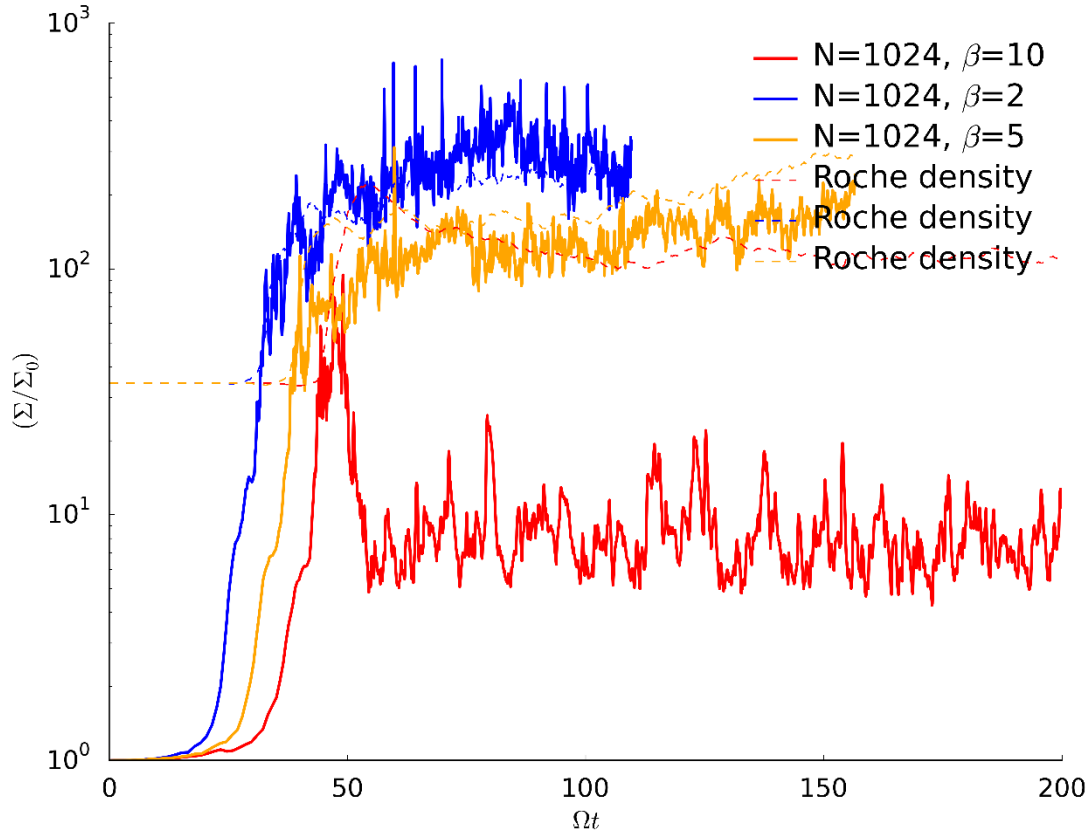


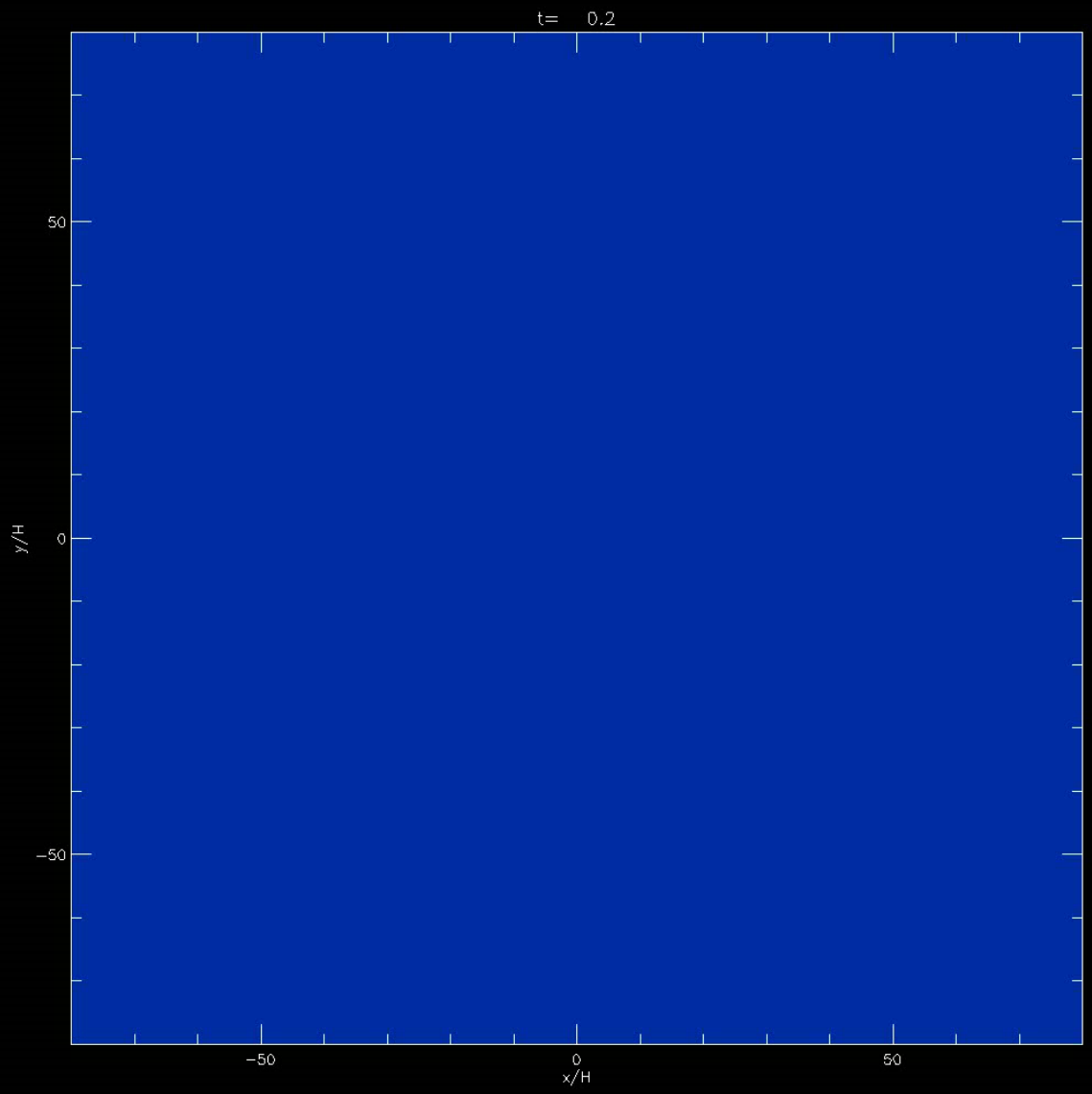
So What?



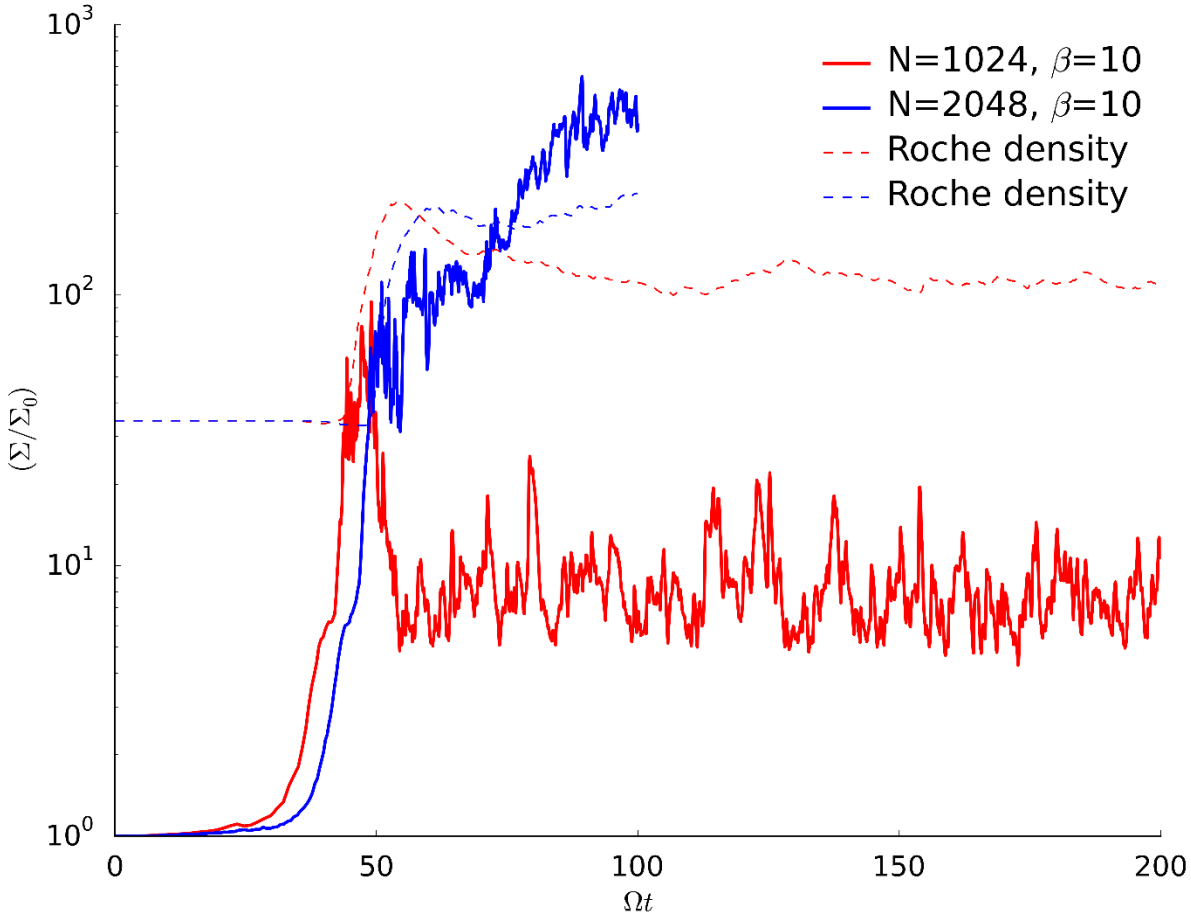
Janson et al. 2012

Current Cooling Criterion




t= 0.2
50
0
−50
y/H
−50
0
50
x/H

Cooling Timescale: Non-convergence



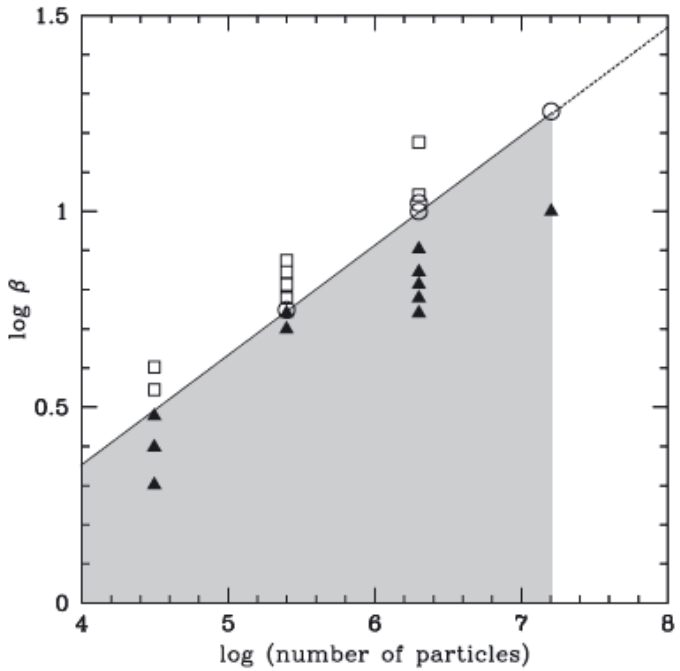
Cooling Timescale

Critical cooling criterion depends on resolution

Alter the cooling so that:

- Criterion is more or less constant with resolution
- It still makes sense physically

How does this change the expected formation regime of gas giant planets?



Meru & Bate 2011

Change the Cooling Timescale

Cooling timescale is not so simple

$$\frac{t_c}{\Omega^{-1}} \approx 1$$

Optical depth depends on density

$$\tau \approx \Sigma\kappa$$

$$\kappa \sim \rho^a T^b$$

FREQUENCY-AVERAGED OPACITY LAW OVER EIGHT REGIONS IN ORDER OF ASCENDING TEMPERATURE

Region	κ_i	a	b
Ice grains	2×10^{-4}	0	2
Evaporation of ice grains	2×10^{16}	0	−7
Metal grains	0.1	0	1/2
Evaporation of metal grains	2×10^{81}	1	−24
Molecules	10^{-8}	2/3	3
H-scattering	10^{-36}	1/3	10
Bound-free and free-free	1.5×10^{20}	1	−5/2
Electron scattering	0.348	0	0

$$t_c = \beta\left(\frac{\Sigma}{\Sigma_0}\right)\Omega^{-1}$$

Bell & Lin (1994)

Change the Cooling Timescale

Why might this lead to convergence?

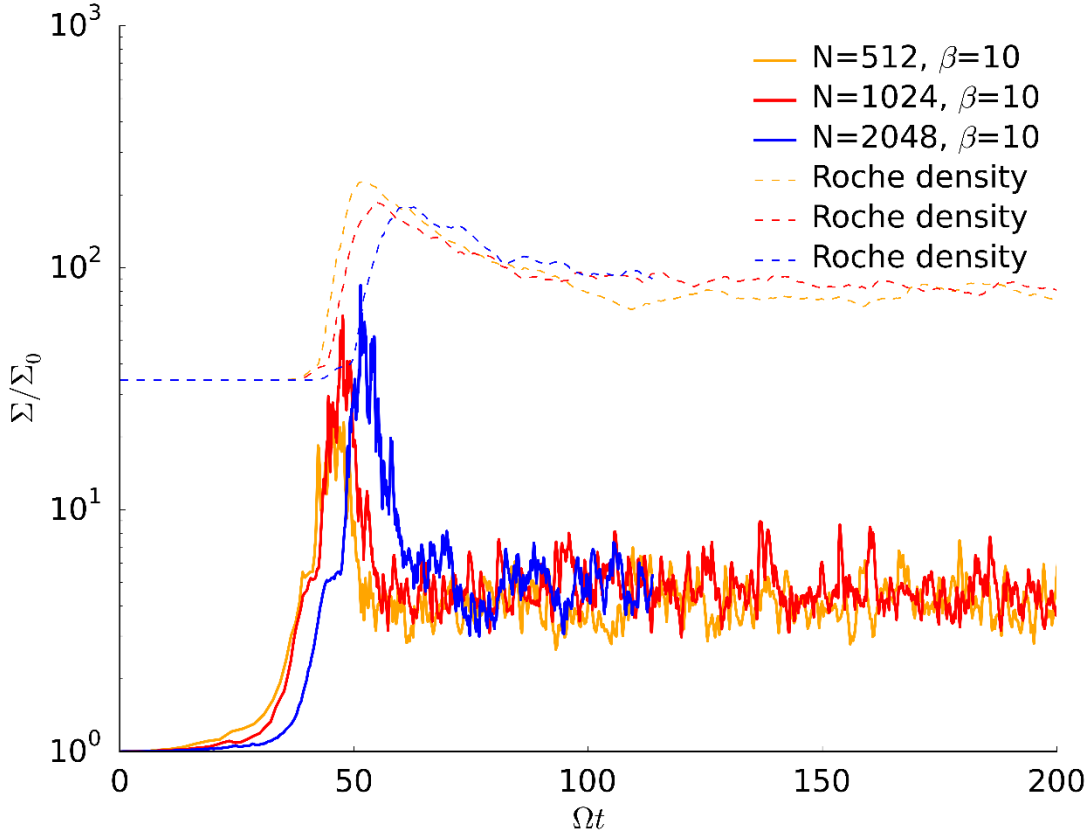
Increased resolution → Larger density perturbations at the same cooling timescale

Consequences?

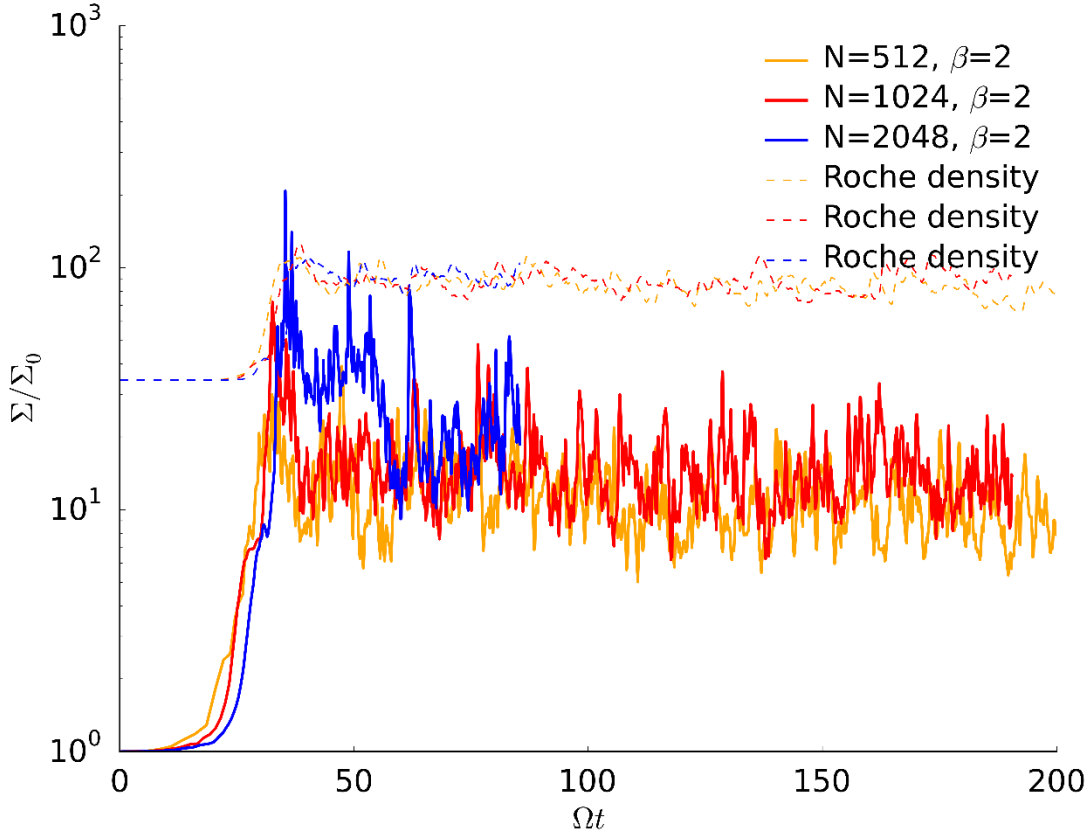
Suppression of surface density perturbations

Change in the critical cooling parameter altogether

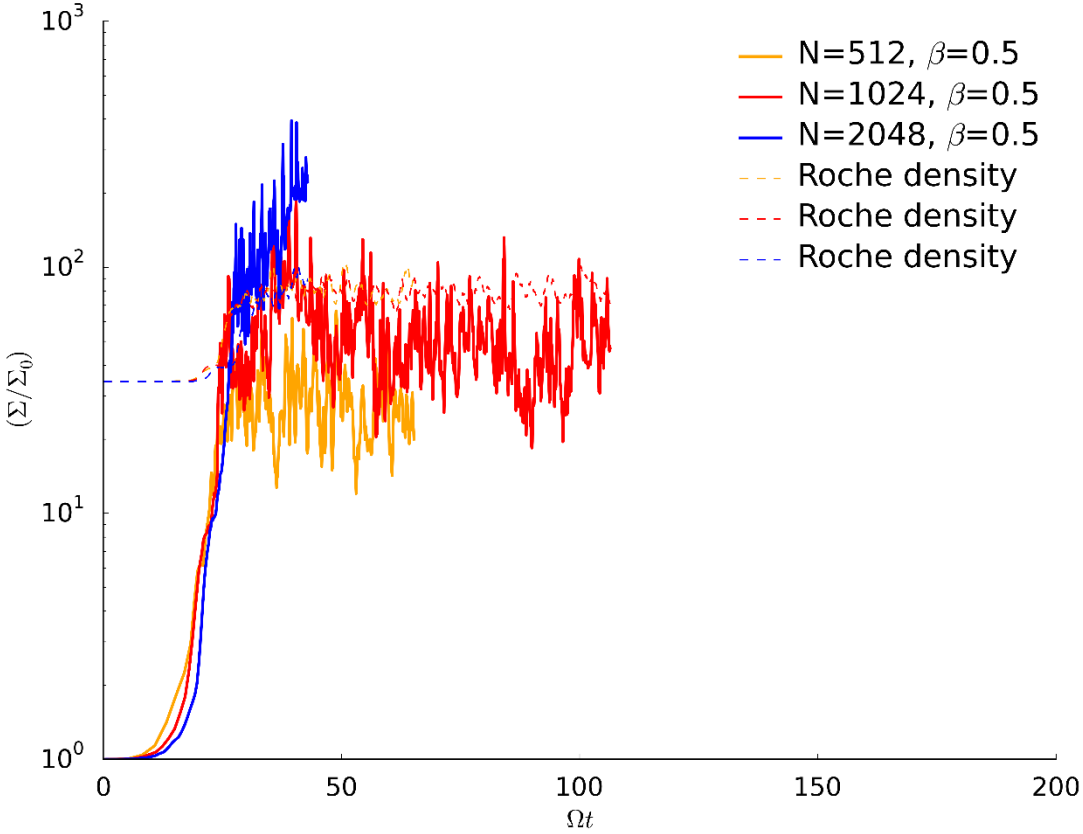
Results: convergence?



Results: convergence?

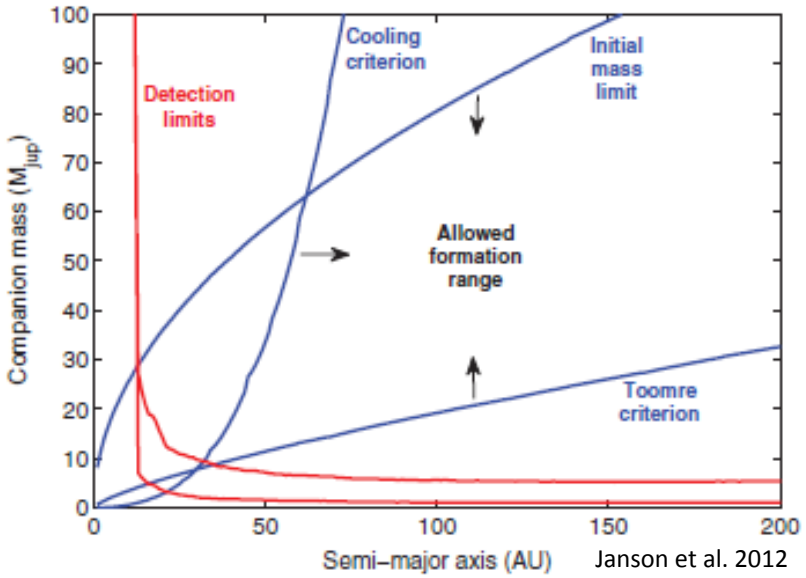


Results: convergence?



Impact on Planet Formation

Gas giant formation is less likely



Janson et al. 2012

Core accretion remains the primary way to form most planets

What Next?

Further adjustments to the cooling timescale:

$$t_c = \frac{U}{\Lambda} \approx \frac{3}{16} \frac{U \Sigma \kappa}{\sigma T^4}$$

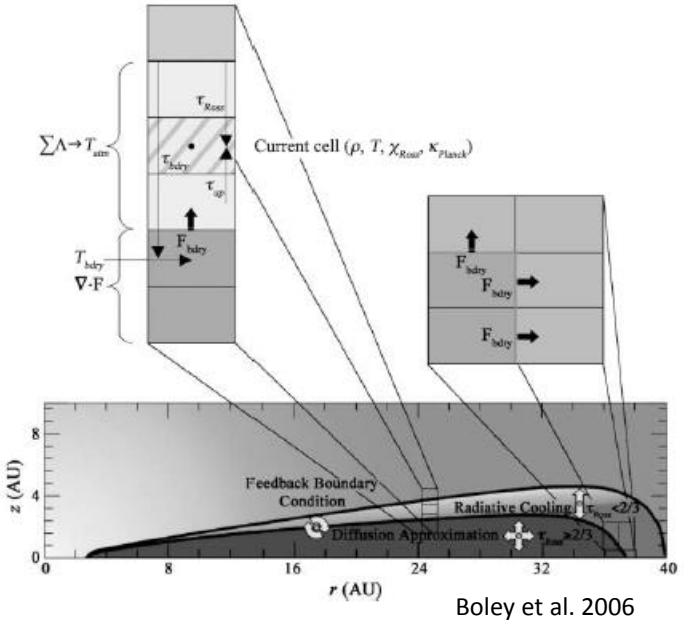
Possible convergence? Or just more shifting around?

Coming soon ...

What Next?

Use radiative transfer instead

- 2D to 3D
- More expensive, but more realistic



Boley et al. 2006

Conclusion

- Newtonian cooling does not account for the increasing density refinement with resolution

- Incorporating more physics may be a realistic solution

- GI may still form planets, but it seems less likely

References

Bell K. R., Lin D. N. C., 1994, ApJ, 427, 987

Boley A. C., Hayfield T. Mayer L., Durisen R. H., 2010, Icarus, 207, 509

Gammie C. F., 2001, ApJ, 553, 174

Janson M., Bonavita M., Klahr H., Lafreniére D., 2012, ApJ, 745, 4

Meru F., Bate M. R., 2011, MNRAS, 411, L1

Mordasini C. et al., 2011, *Astronomy and Astrophysics Review*

Paardekooper S.-J., 2012, MNRAS, 421, 3286

Stone J. M., Norman M. L., 1992, ApJS, 80, 753