Non-ideal gravitational instabilities in protoplanetary disks [2016, ApJ, 824, 94]

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Introduction

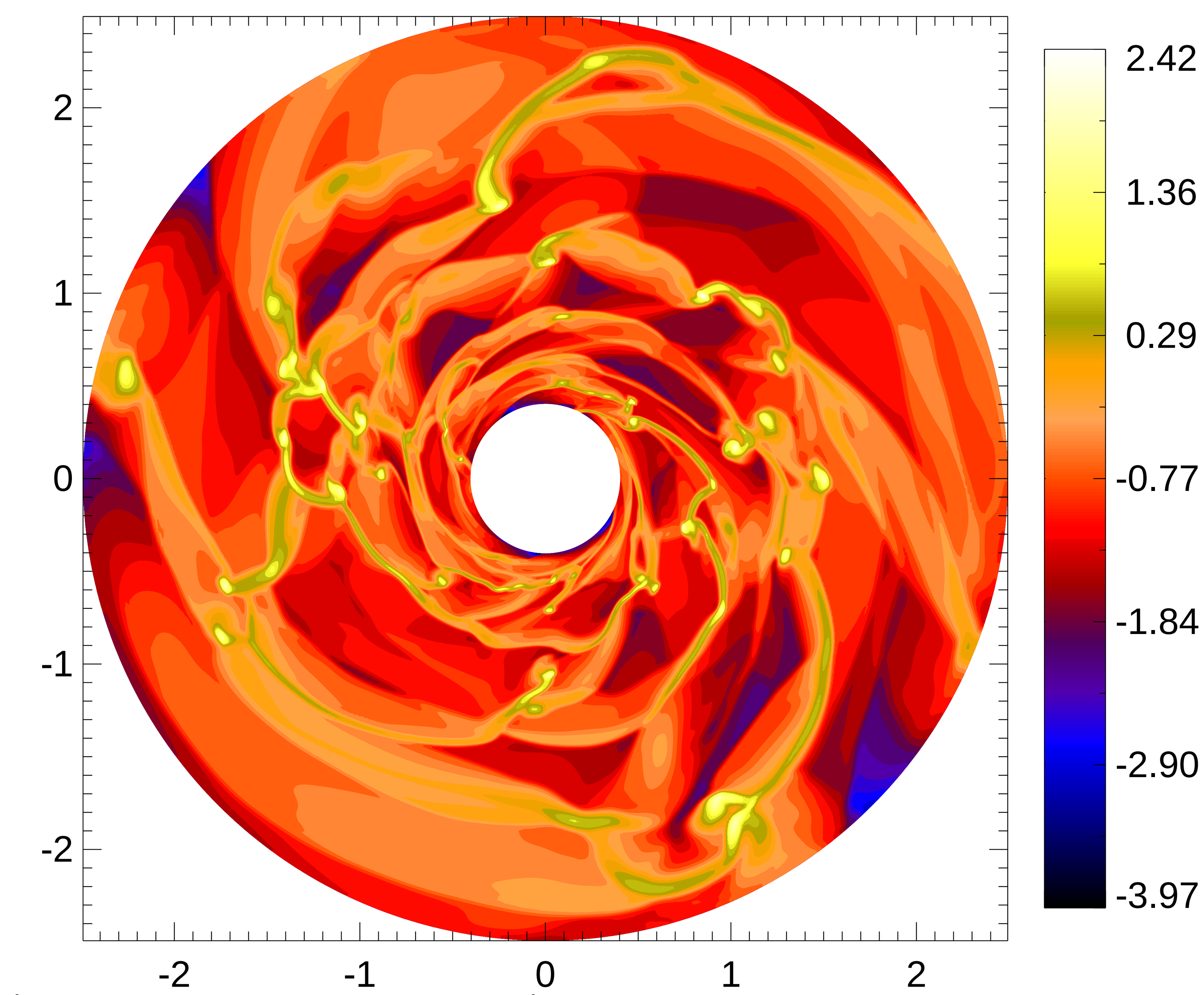
The self-gravitational fragmentaion of massive proto-planetary/stellar disks is a potential route to the formation of giant planets, brown dwarfs or sub-stellar companions on wide orbits. This phenomenon is usually studied via direct numerical simulations, which may include a range of physical effects such as cooling, turbulence and irradiation. However, these simulations are also subject to uncertainties associated with their numerical setups. We circumvent this difficulty by extending the analytic treatment of gravitational instabilities to include the above non-ideal physics, thereby predict disk fragmentation without input from previous numerical simulations.

Fragmentation criteria for PPDs

$$\boxed{Q \equiv \frac{c_s\Omega}{\pi G\Sigma} \lesssim 2} \quad \text{and} \quad \boxed{t_{\mathrm{cool}}\Omega \lesssim 3}$$

The *cooling criterion* ($\leftrightarrow$ a viscosity criterion) is

- **Empirical** — observed in numerical simulations, no analytical basis
- Possibly dependent on numerical setup of the simulation!



(Fargo simulation, $\log \boldsymbol{\Sigma}$ shown)

Simulations v.s. classic analyses

Modern sims. (c. 2010)

- Have cooling physics,

$$\frac{\partial E}{\partial t} = -\frac{E}{t_{\mathrm{cool}}}$$

- Are turbulent/viscous,

$$\nu = \alpha\frac{c_s^2}{\Omega}$$

Analytic toolbox (c. 1960)

- No cooling

$$\frac{\partial E}{\partial t} = 0$$

- Laminar

$$\nu = 0$$

- $\omega^2 = \Omega^2 - 2\pi G\Sigma|k| + c_s^2k^2$

Classic $\omega^2(k, Q)$ cannot capture cooling/viscous effects!

Beyond classic theory

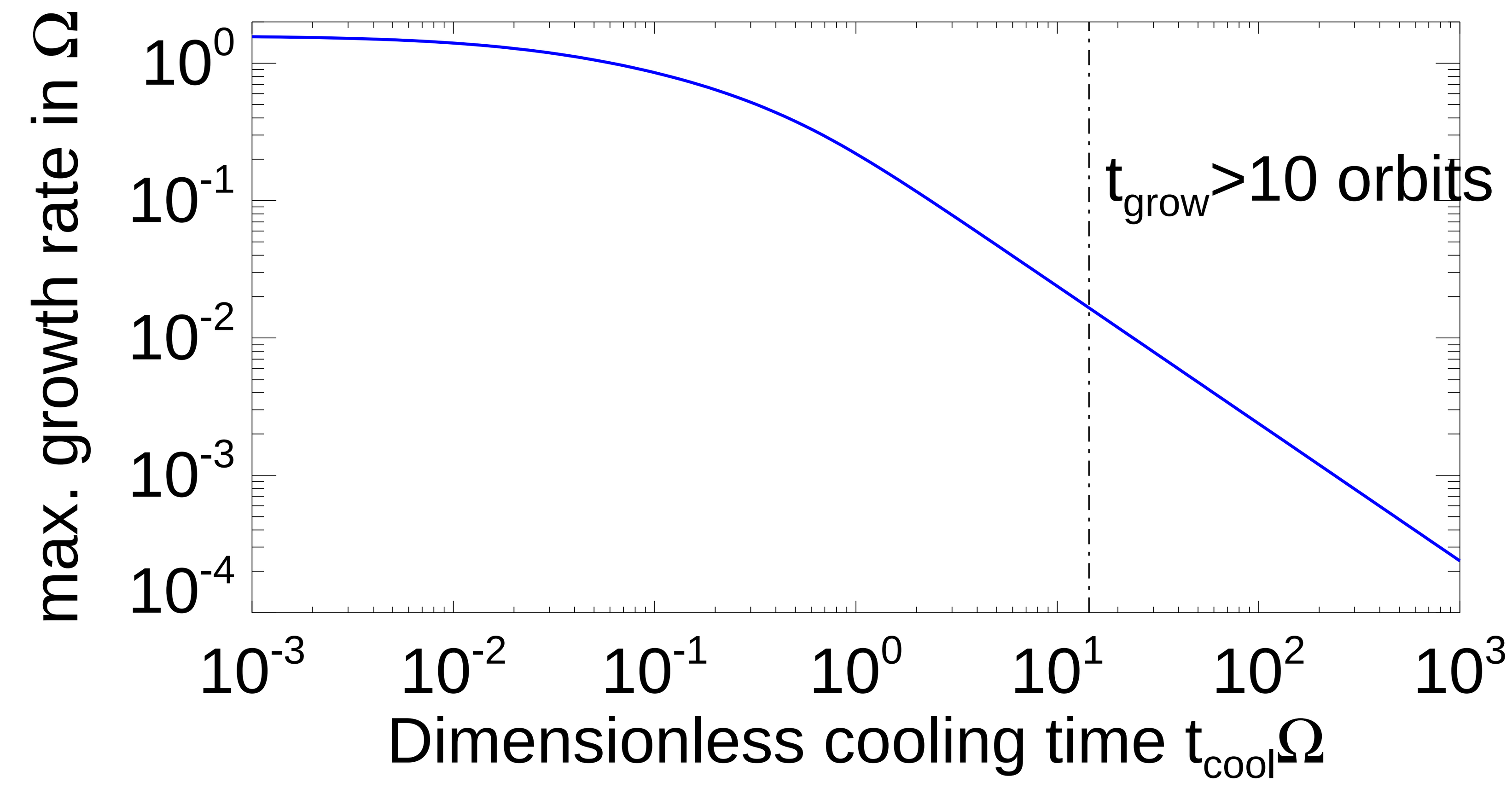
- Local, axisymmetric linear stability analysis of 2D/3D disks, 'gravito-turbulent' basic state
- Include **cooling**/radiative diff., **viscous** forces/heating, **irradiation**

$$\omega^2 = \omega^2(k; Q, t_{\mathrm{cool}}, \alpha, T_{\mathrm{irr}})$$

Can now have instability ($\omega^2 < 0$) even when $Q > 1$!

- Cooling reduces thermal support $\longrightarrow$ destabilize small scales
- Viscous forces reduce rotational support $\longrightarrow$ destabilize large scales

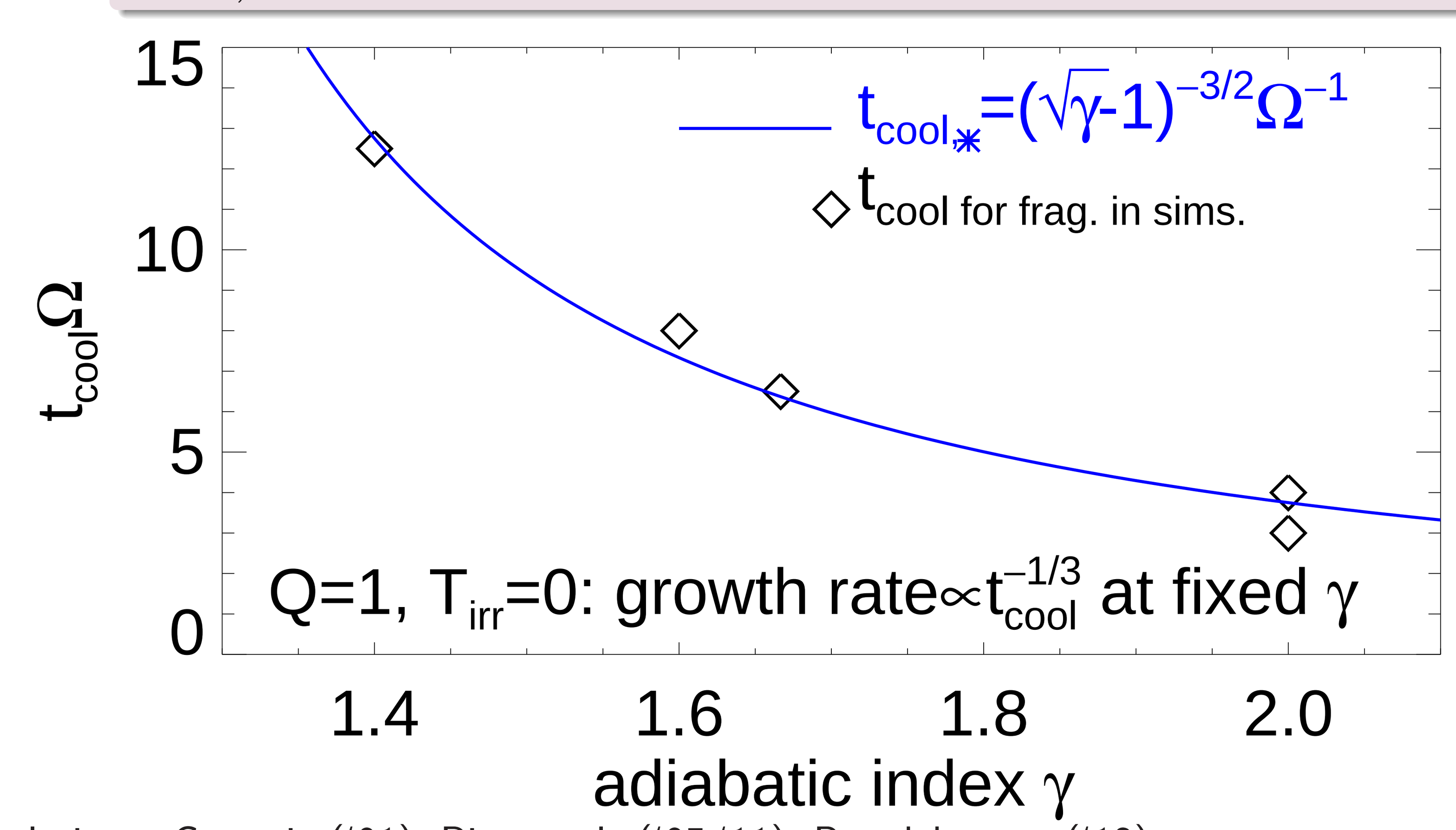
Cooling-driven GI



- $Q = 1.7$, $T_{\mathrm{irr}} = 0.1T_{\mathrm{steady}}$, only consider effect of cooling
- Disk is unstable at *all* t_{cool}, irradiation is stabilizing

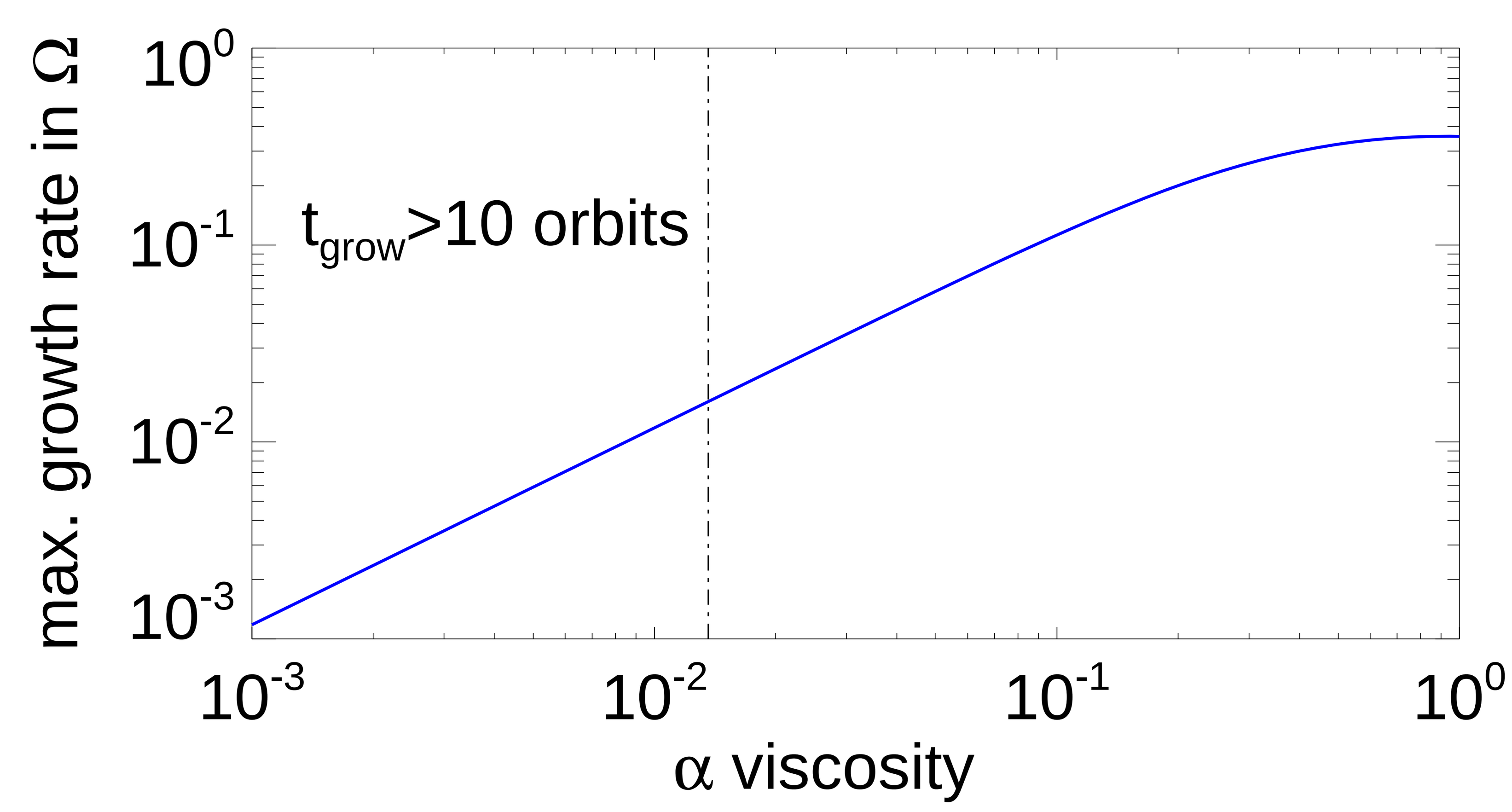
Understanding (some) simulations

Define $t_{\mathrm{cool},*}$: removes pressure support over radial lengthscales $\sim H$



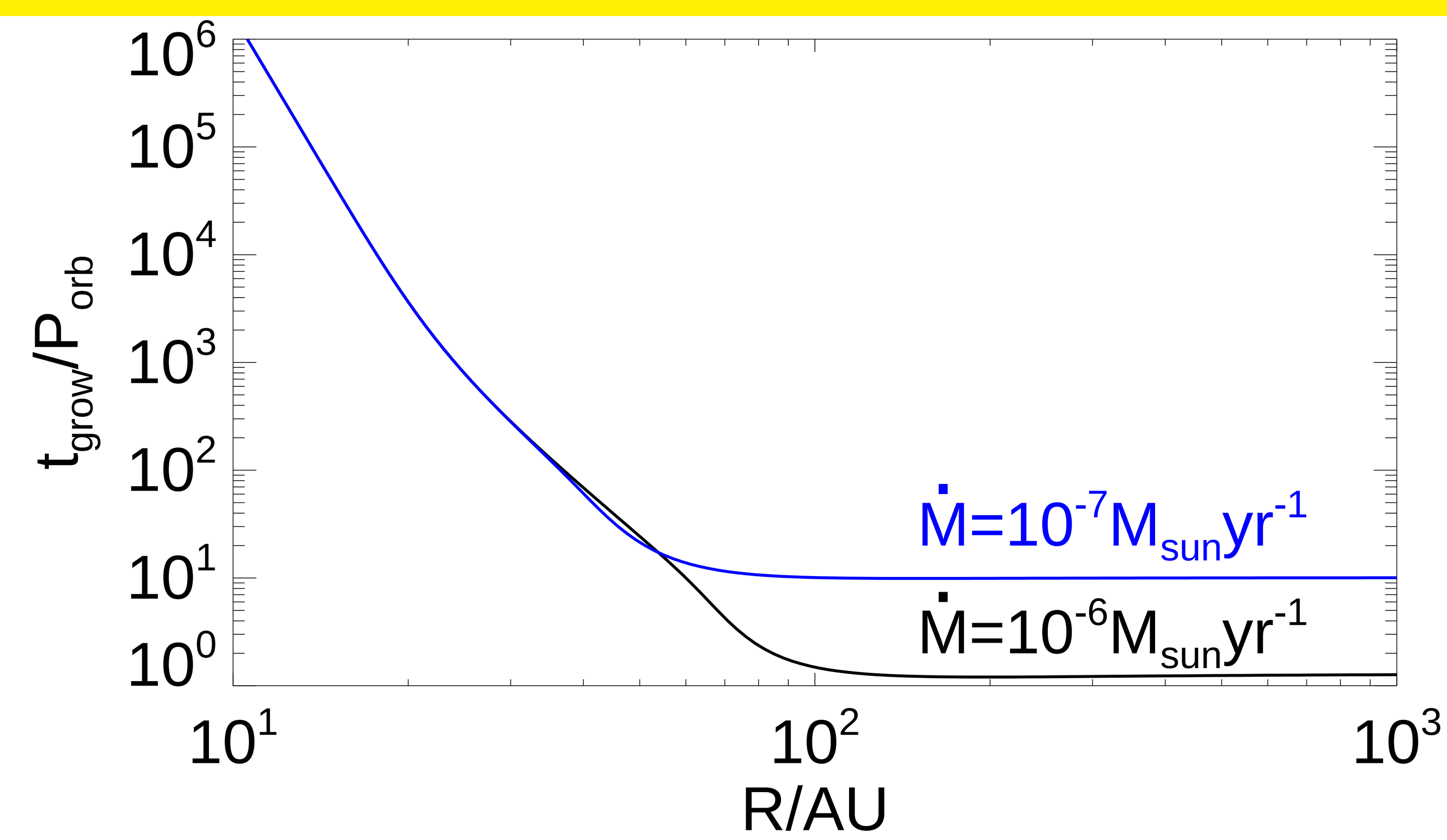
Simulations: Gammie ('01), Rice et al. ('05,'11), Paardekooper ('12)

Viscosity-driven GI



- $Q = 1.7$, $T_{\mathrm{irr}} = 0.1T_{\mathrm{steady}}$, $\alpha = \alpha(t_{\mathrm{cool}})$ from thermal eqm.

Application to protoplanetary disks



- High $\dot{M}$ disk fragments $\gtrsim$ **100**AU