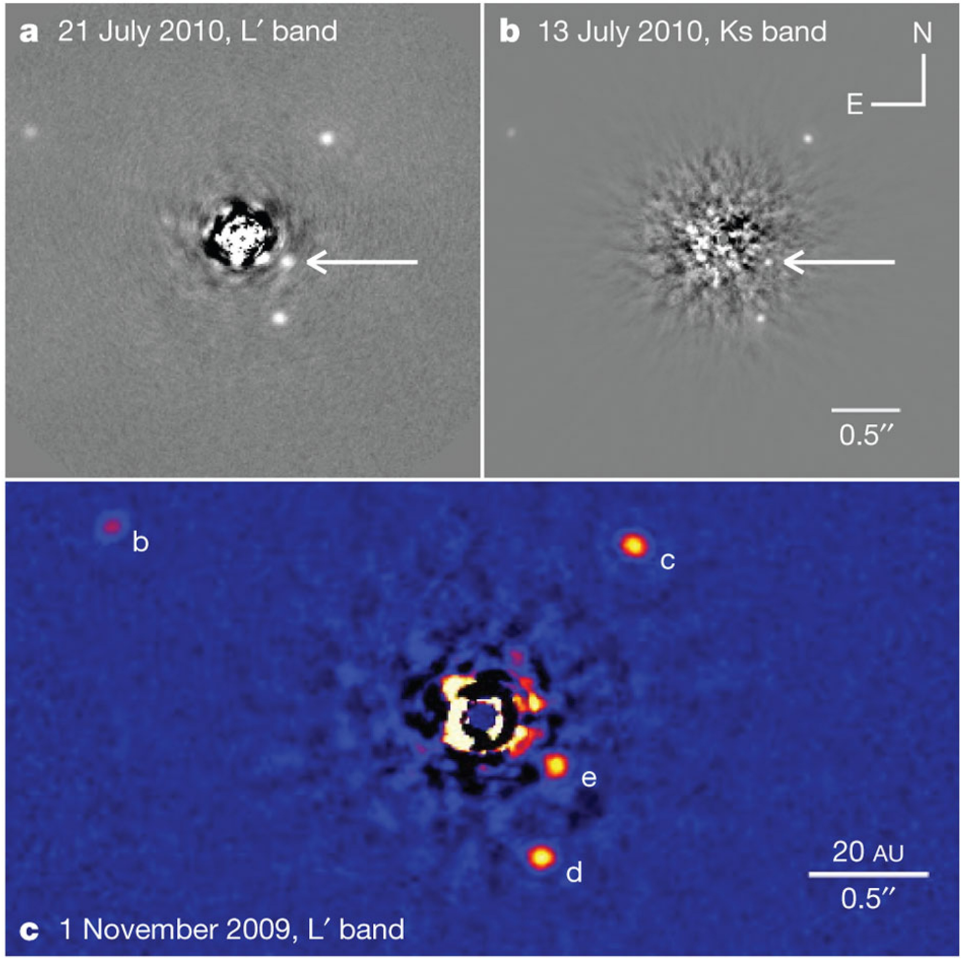
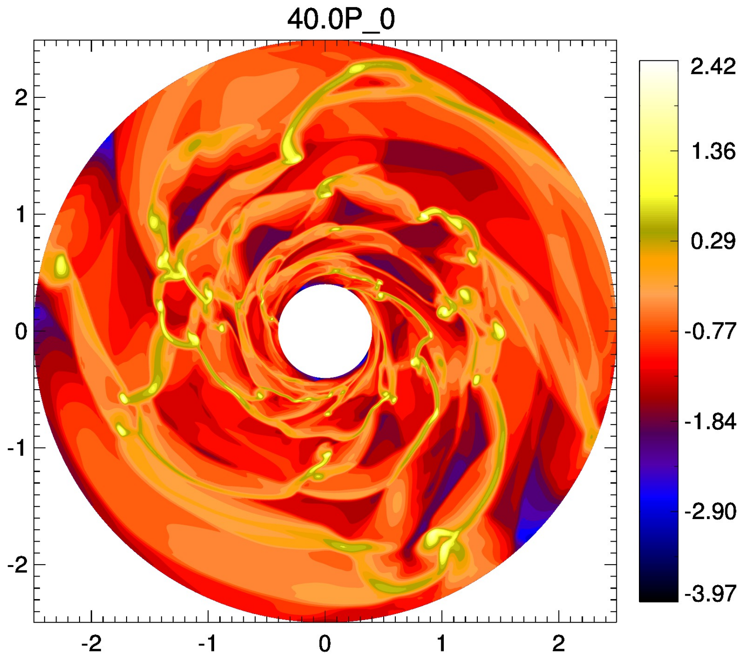
Directly imaged wide orbit planets/brown dwarfs



(Marois et al., 2010)

Disk instability theory

- Young, massive protoplanetary disks can fragment under its own gravity



(Lin, Fargo sims., log density)

Fragmentation conditions

- **Massive disk**

$$Q \equiv \frac{c_s\Omega}{\pi G\Sigma} \lesssim 2 \text{ or } M_{\rm disk} \gtrsim 0.1M_*$$

- **Fast cooling**

$$t_{\rm cool}\Omega \lesssim 3$$

The cooling criterion is empirical!

When do realistic protostellar disks fragment?

Work out $\Sigma(R)$, $T(R)$..etc., then ask

1. Where/when is Toomre $Q \lesssim 2$?
2. Where/when is $t_{\mathrm{cool}}\Omega \lesssim 3$?

WARNING

Critical cooling depends on the numerical simulation!

(resolution, 2D/3D, local/global, particle-based or grid-based simulations)

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Motivation 1:

Assess disk fragmentation <u>without</u> input from hydrodynamic simulations

Beyond classical gravitational instability

Modern simulations (c. 2010)

- Cooling physics, e.g.

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

- Turbulent/viscous, e.g.

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

Analytic toolbox (c. 1960)

Lin-Shu dispersion relation, Toomre Q

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

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

- Isothermal/adiabatic (no cooling)
- Laminar (inviscid)

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Motivation 2:

Generalize analytic treatment of GI to include cooling, irradiation and viscosity

$$\omega = \omega(k; Q, t_{\rm cool}, \alpha)$$

Quantifying cooling

Dispersion relation with cooling

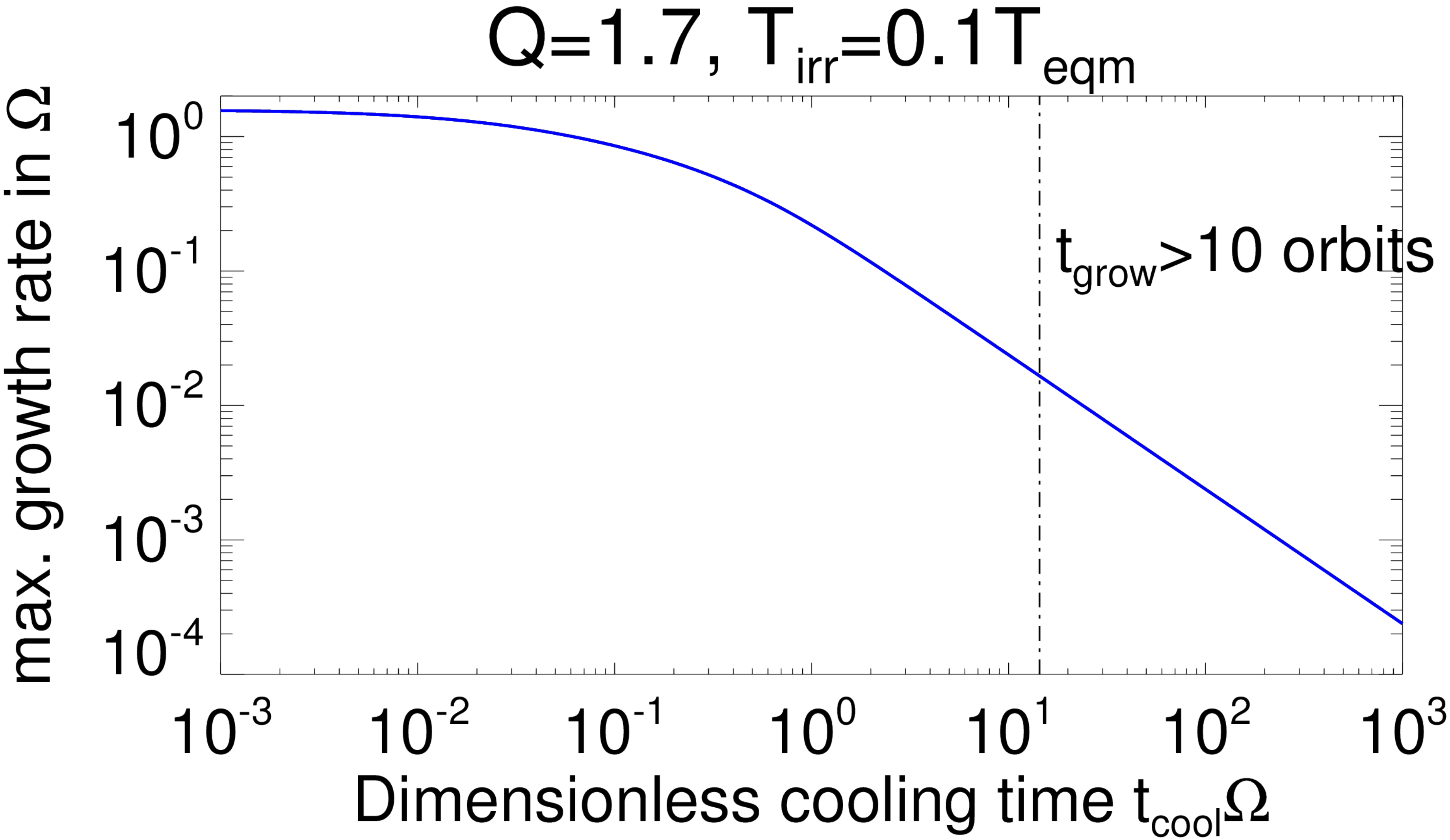
$$\underbrace{s^2}_{\text{growth}} = \underbrace{2\pi G\Sigma|k|}_{+\text{gravity}} \underbrace{-\Omega^2}_{-\text{rotation}} \underbrace{-\left(\frac{T_{\rm irr}/T + \gamma t_{\rm cool} s}{1 + t_{\rm cool} s}\right) c_s^2 k^2}_{-\text{modified pressure}}$$

(Lin & Kratter, 2016, arXiv:1603.01613)

- $T_{\rm irr}$: irradiation or floor temperature
- Can be unstable even for $Q > 1$ (cf. $Q < 1$ for classic GI)

Cooling changes the fundamental nature of disk GI

Cooling-driven gravitational instability

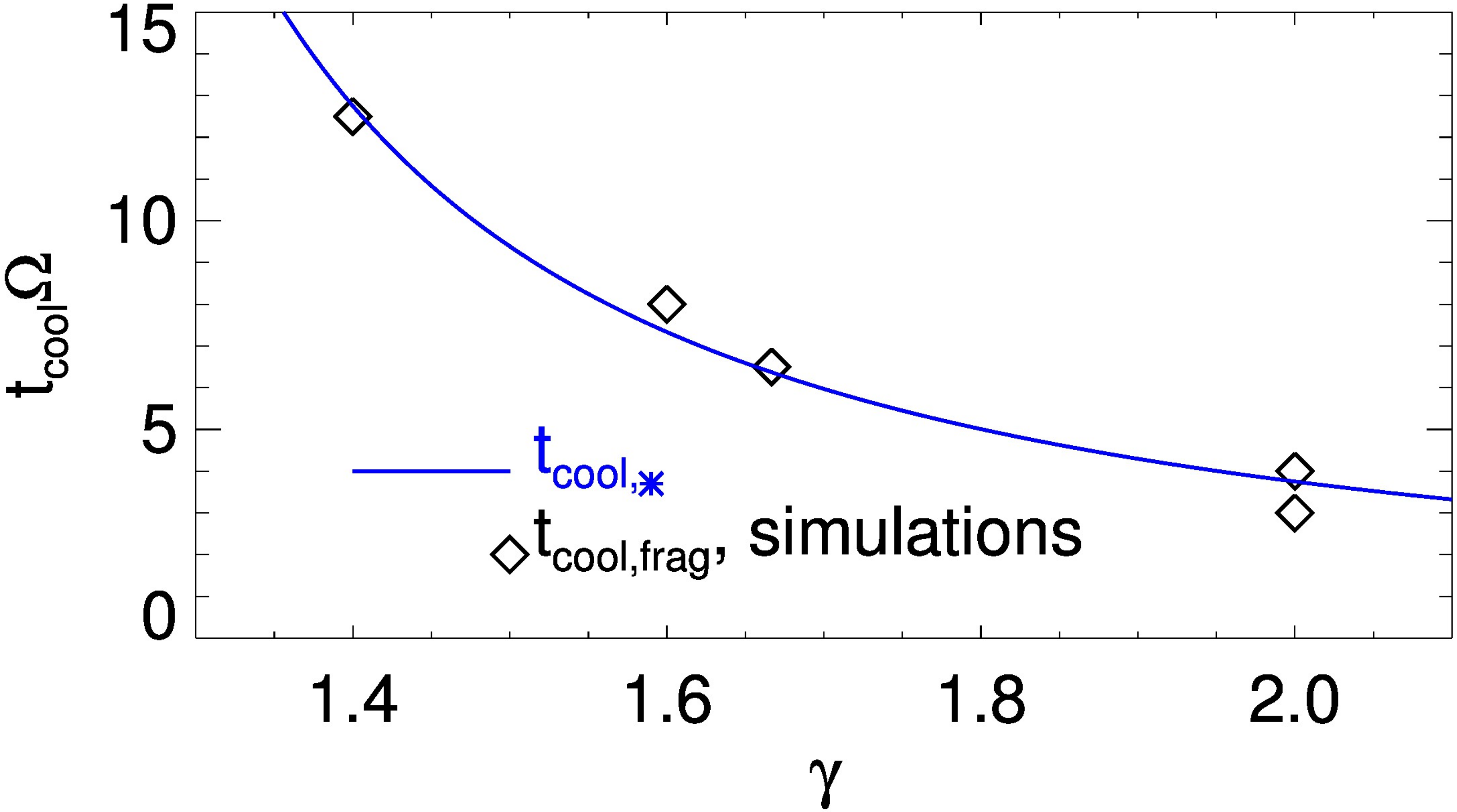


(Lin & Kratter, 2016, arXiv:1603.01613)

Understanding simulations

Cooling timescale to remove pressure over a lengthscale $\sim H$

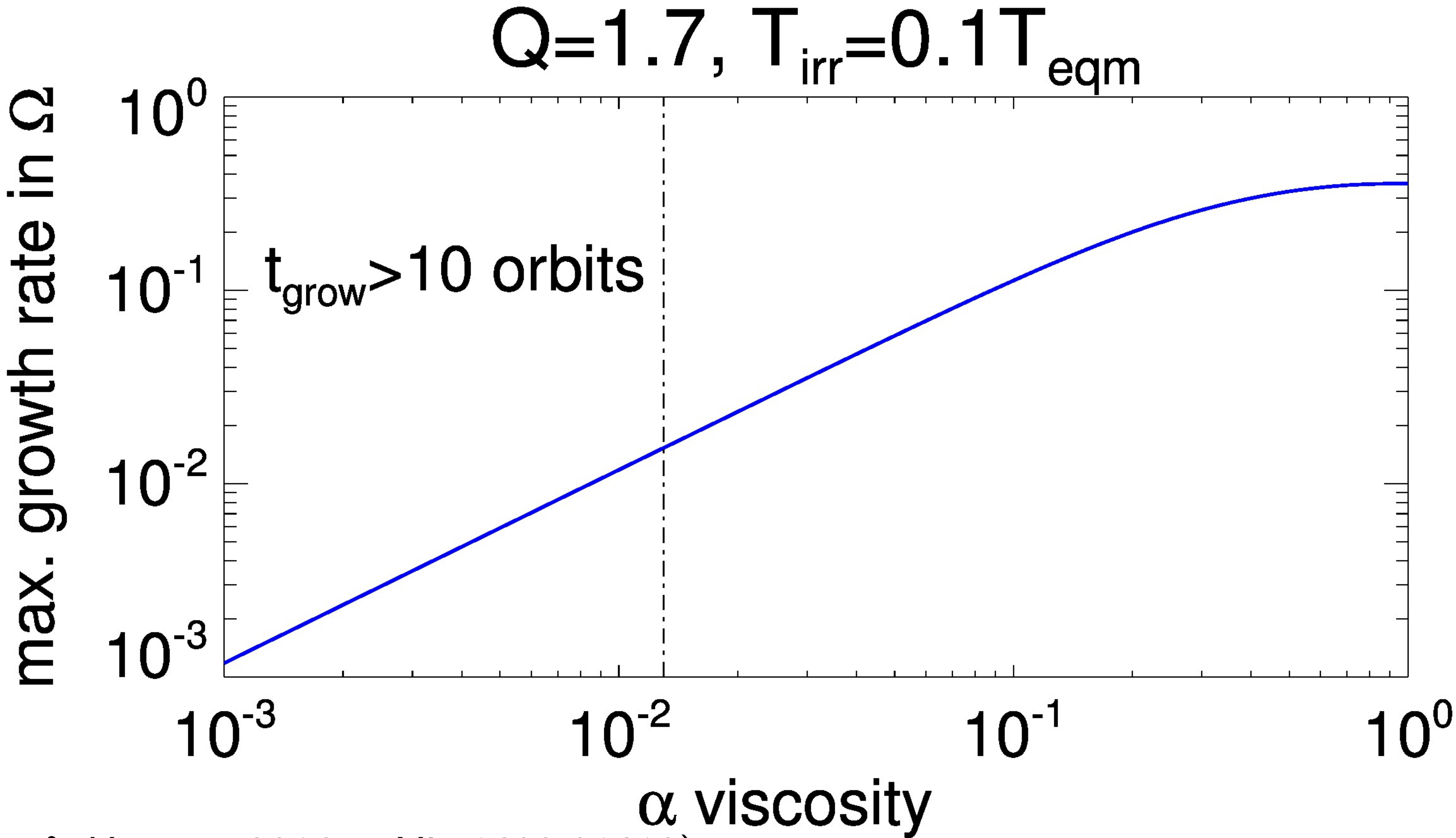
$t_{\mathrm{cool},*} = (\sqrt{\gamma} - 1)^{-3/2}\,\Omega^{-1}$ (Lin & Kratter, 2016, arXiv:1603.01613)



Simulations: Gammie (2001); Rice et al. (2005, 2011); Paardekooper (2012)

Viscous gravitational instability

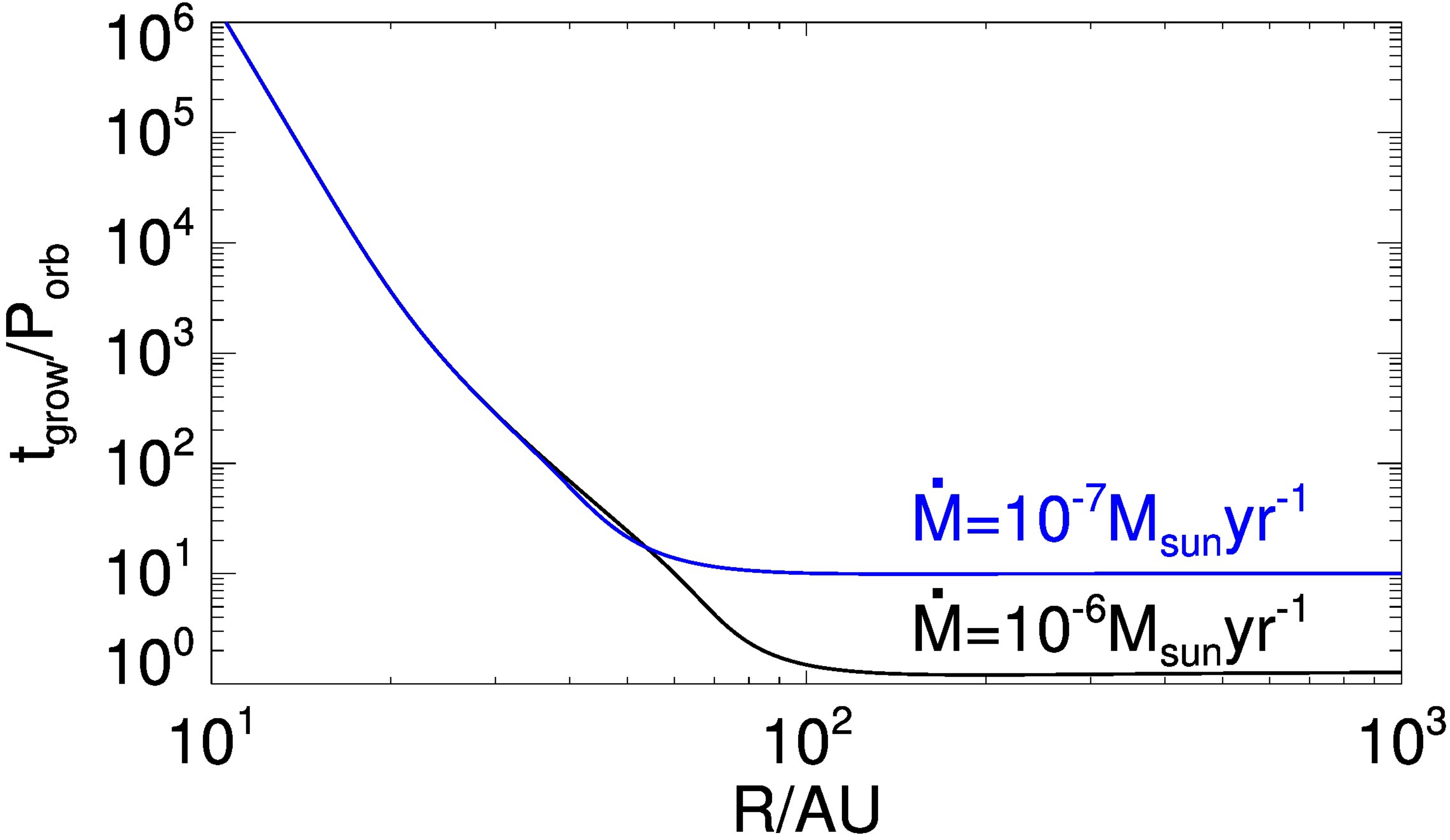
- Viscosity/friction can remove rotational stabilization (Lynden-Bell & Pringle, 1974)



(Lin & Kratter, 2016, arXiv:1603.01613)

Putting it all together: application to protoplanetary disks

- Input physical disk model with cooling and viscosity — get growth timescales



(Lin & Kratter, 2016, arXiv:1603.01613)

- High $\dot{M}$ disk fragments $\gtrsim$ 60AU, growth times $\sim$ one orbit

What's next for disk GI theory?

- Global effects with cooling and viscosity
  - Mass infall
  - Disks with radial structure
  - Large-scale spiral instabilities
- Magnetic effects: good or bad for stability?
  - Extend Lin (2014) to include cooling/viscosity