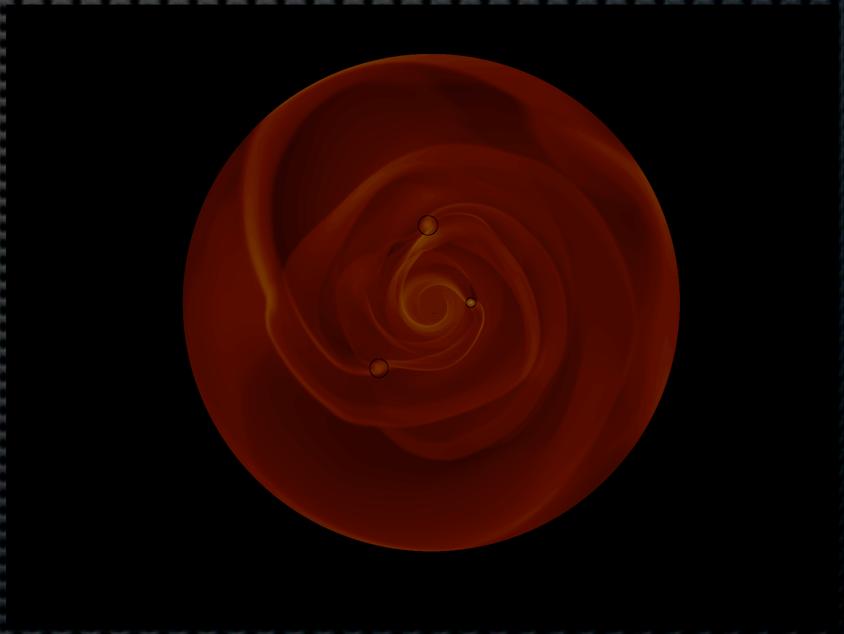
# Do Wide Orbit Planets Form via Gravitational Instability?

**Kaitlin Kratter** (CfA)

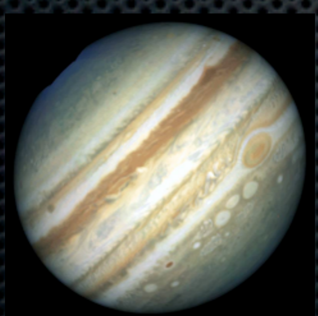
Ruth Murray-Clay (CfA)

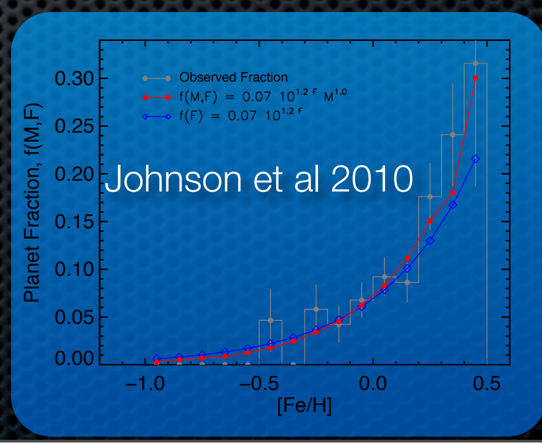
Andrew Youdin (CfA)

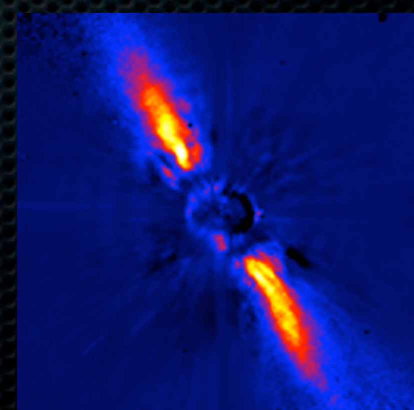


# *Observational* Support for Core Accretion

- ✓ **Planet-Metallicity Correlation**
- ✓ Debris Disks
- ✓ Kuiper / Asteroid Belts
- ✓ Abundance of small planets
- ✓ Solar System Giants are metal rich
- ✓ Continuous population distribution







# What can Core Accretion

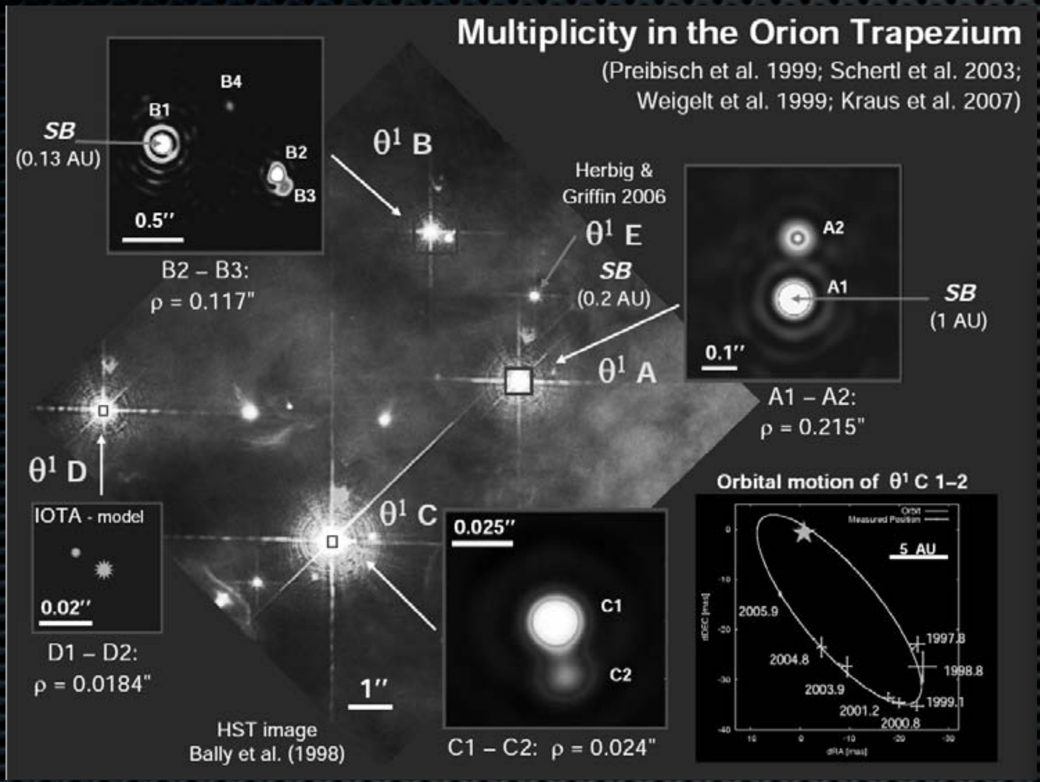
(+ Migration / Scattering)

# do for *you* ?

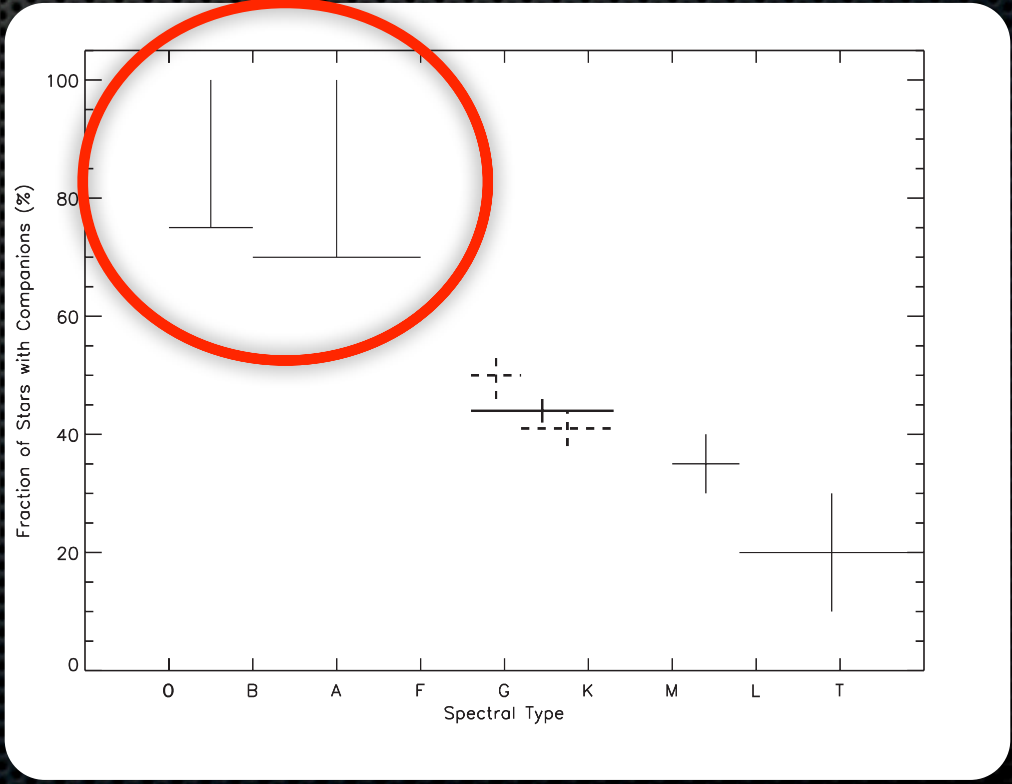
- ✓ Solar System
- ✓ Hot Jupiters
- ✓ Super Earths / Ice Giants
- ✓ Big Planetesimals
- ✓ Single planets on wide orbits
- ? Massive multi-planet systems on wide orbits

# **Observational** support for GI?

# **Observational** support for GI?




e.g. Kratter & Matzner 2006, Kratter et al 2008



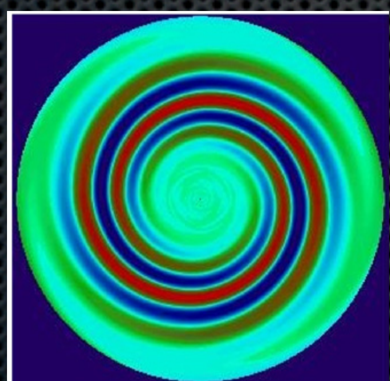

Raghavan et al 2010

# **Theoretical** Motivation for GI?

- Standard Core Accretion is slow at large radii
- Disk fragmentation is more likely far from the star

# Two Key Questions for GI

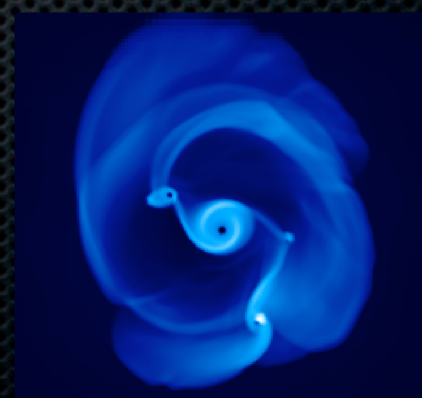
1. **Does the disk fragment?** Depends on star formation history (KMCY 2010), accretion rates are typically low (Offner, Kratter et al 2010), cooling times prohibit inner disk fragmentation
2. **Do fragments make planets? *Fragments grow!*** Need a thin (cold) disk to fragment into low mass objects (KMCY 2010). Need low viscosity post-fragmentation to control growth (e.g. Lissauer et al 2009). Needs to happen late in disk timescales, but we don't see massive disks (Andrews et al 2009), inward migration, resonant configuration



Dodson-Robinson et al 2009

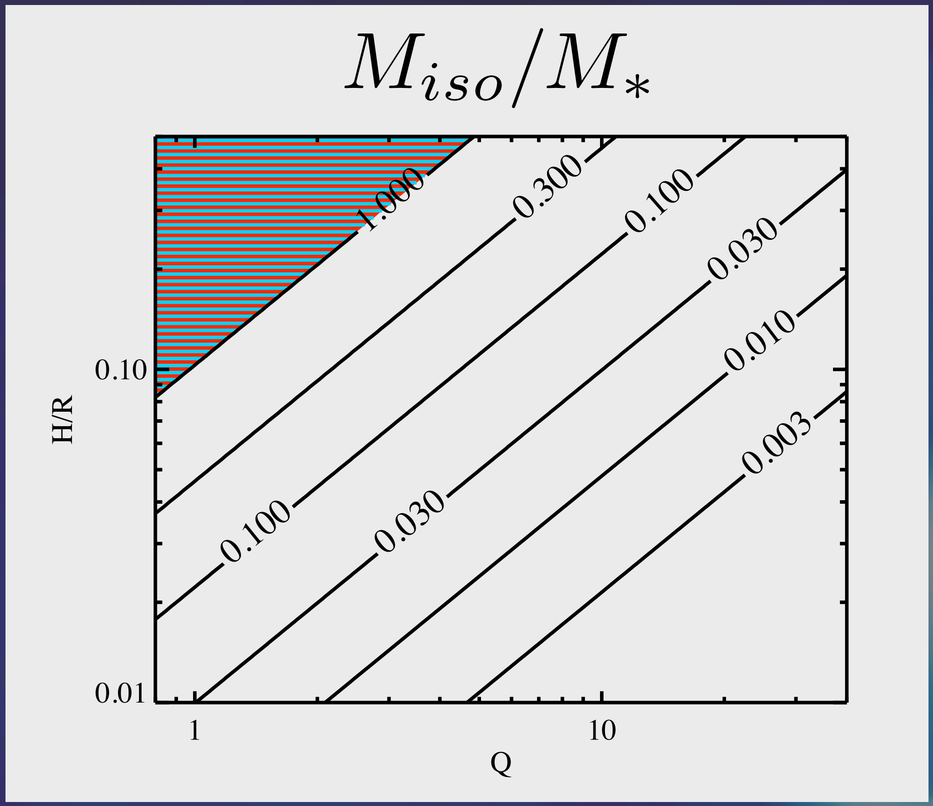
**Growing spiral modes are not equivalent to fragmentation**

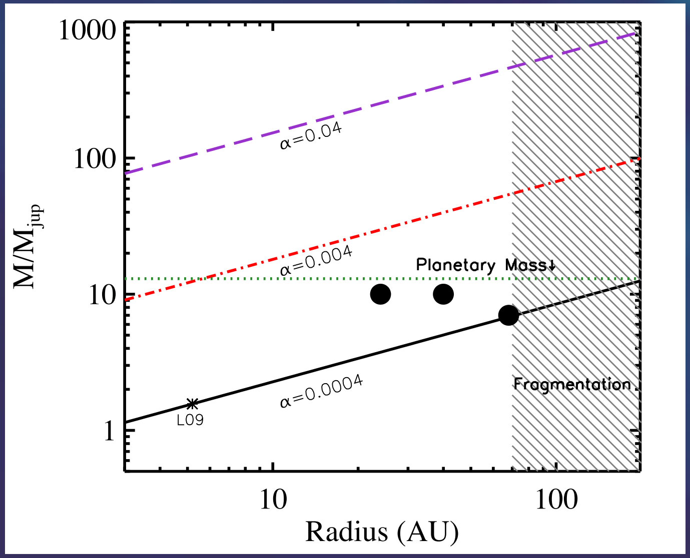
$\neq$

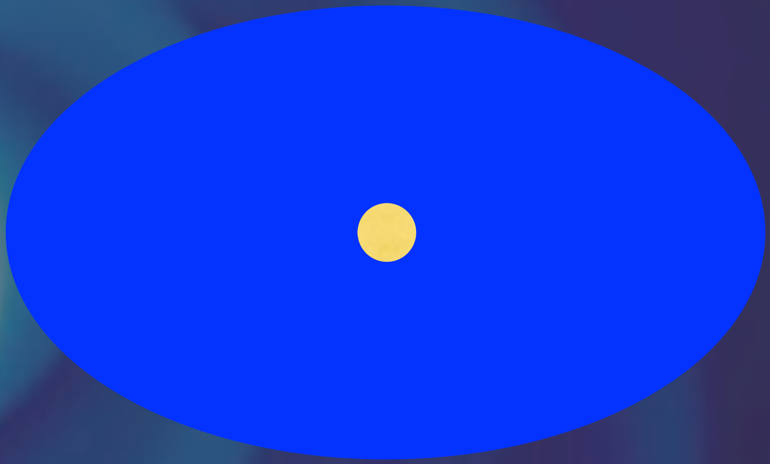


Kratter et al 2010

# Fragments like to grow!

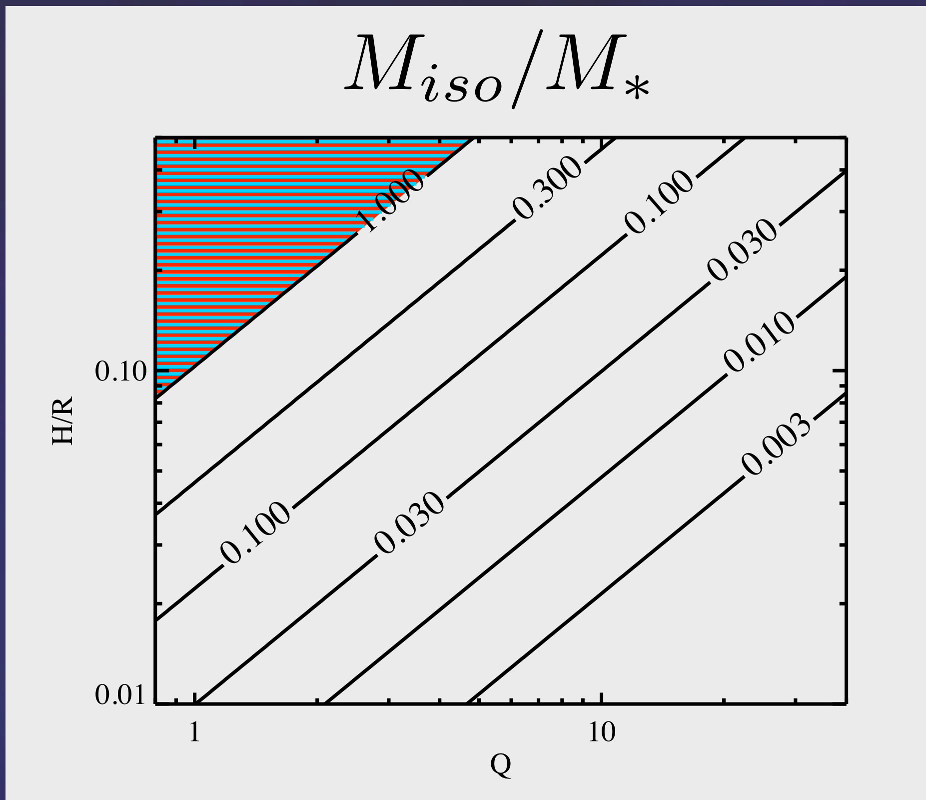


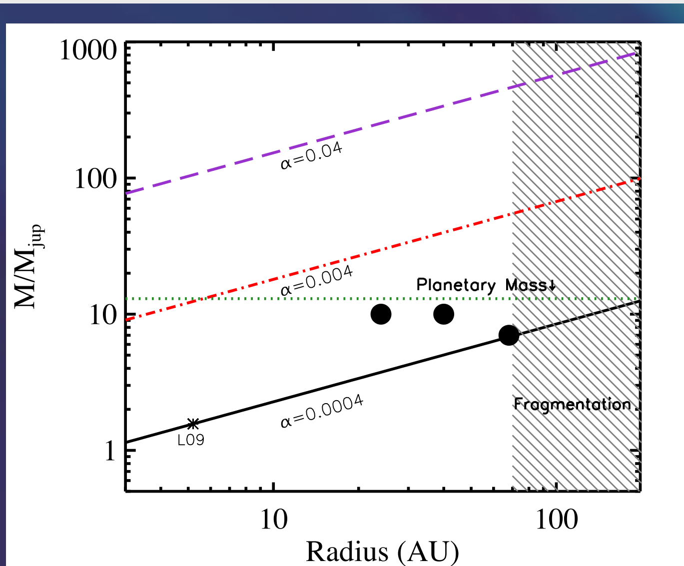



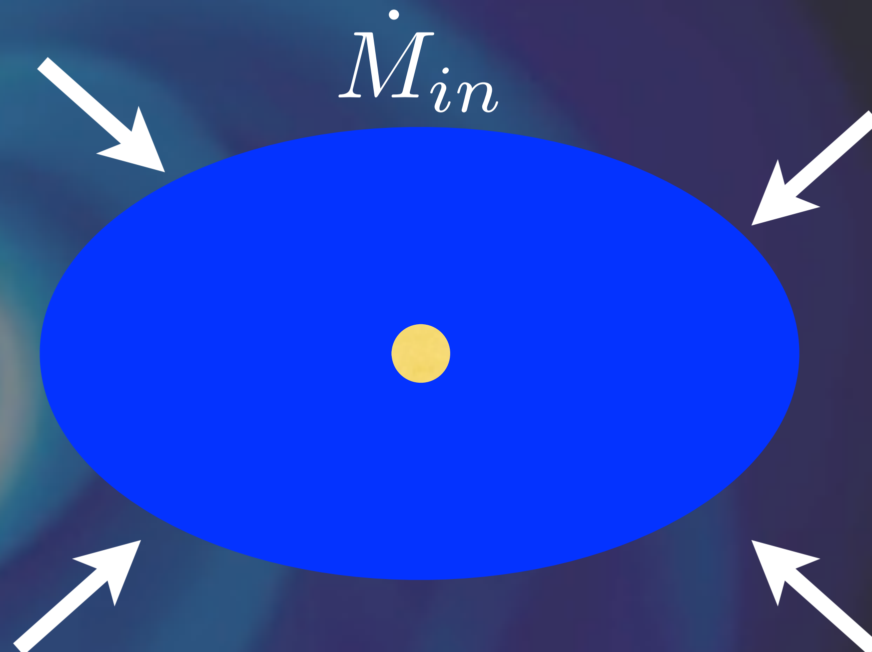



Kratter et al, 2008, 2010,
KMCY, 2010

# Fragments like to grow!

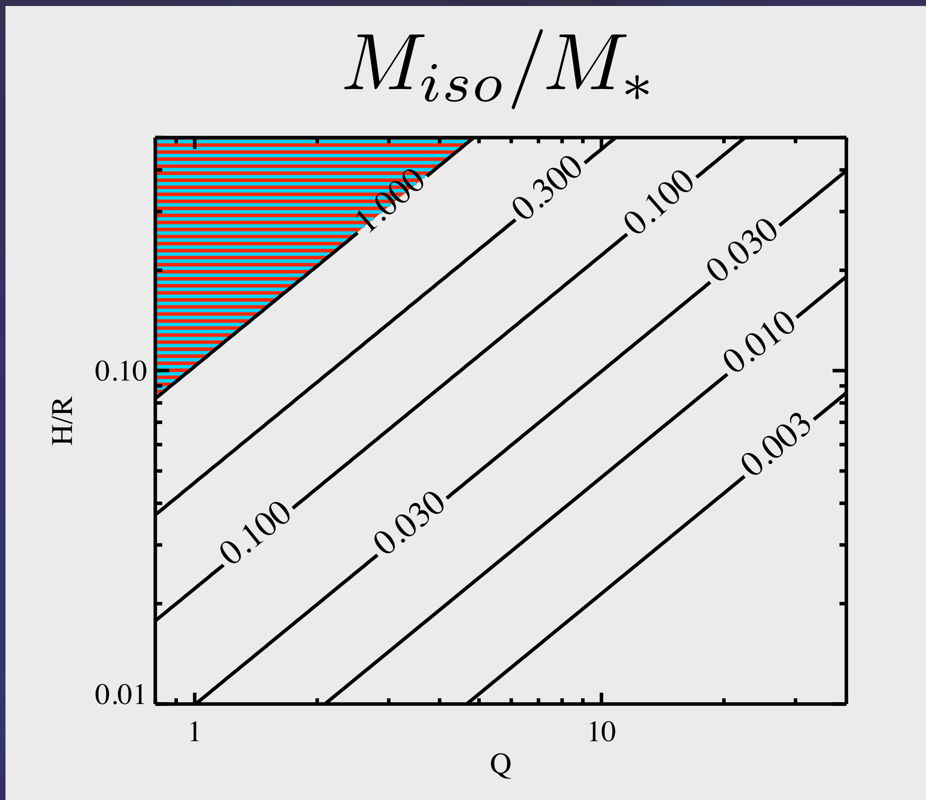


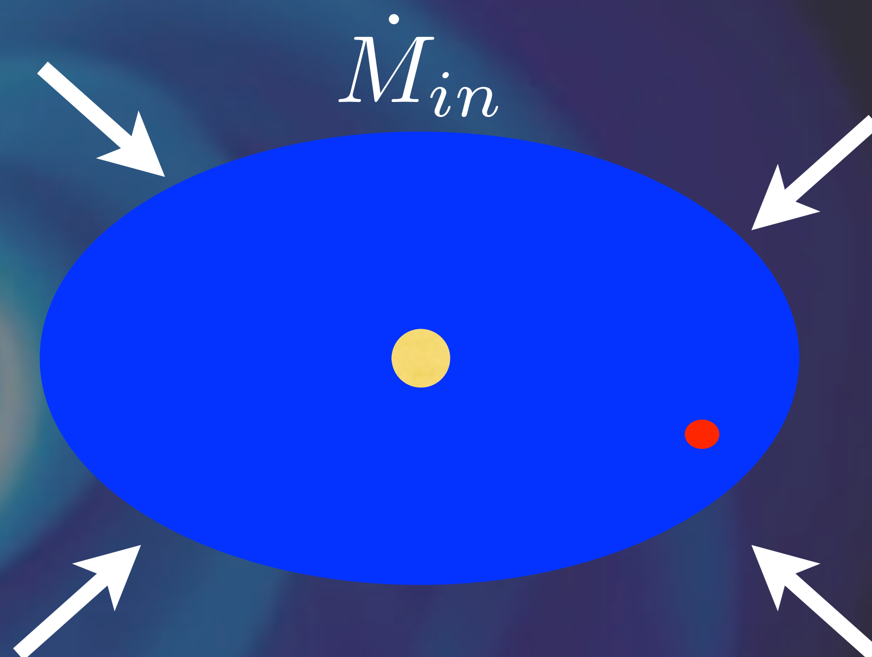



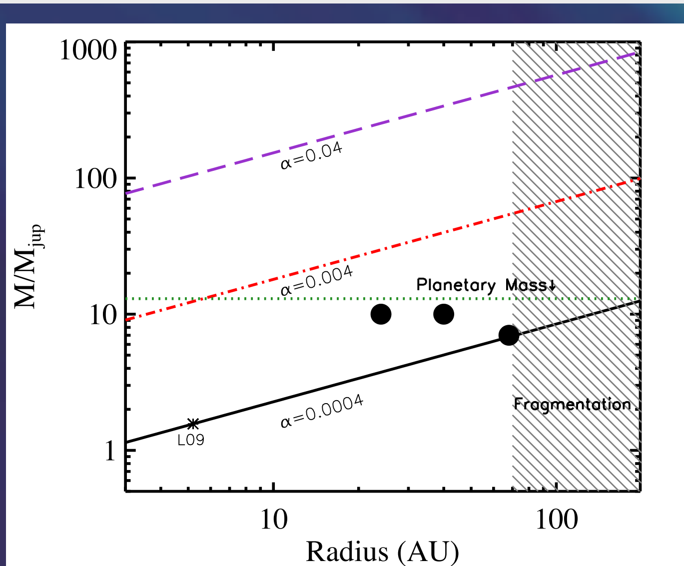




Kratter et al, 2008, 2010,
KMCY, 2010

# Fragments like to grow!

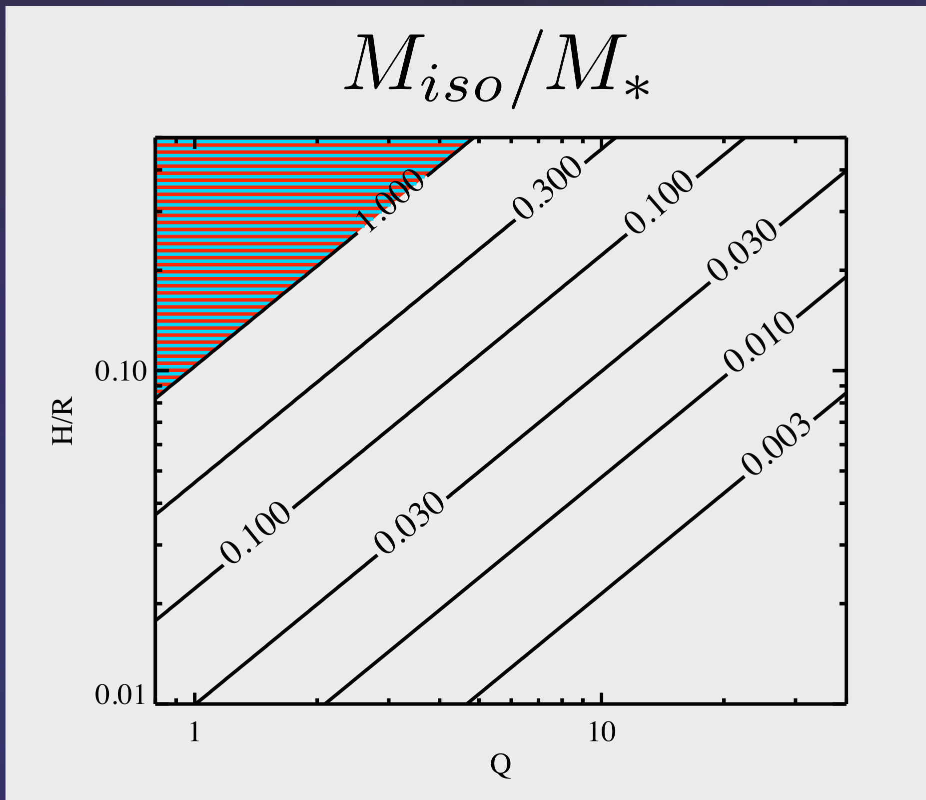


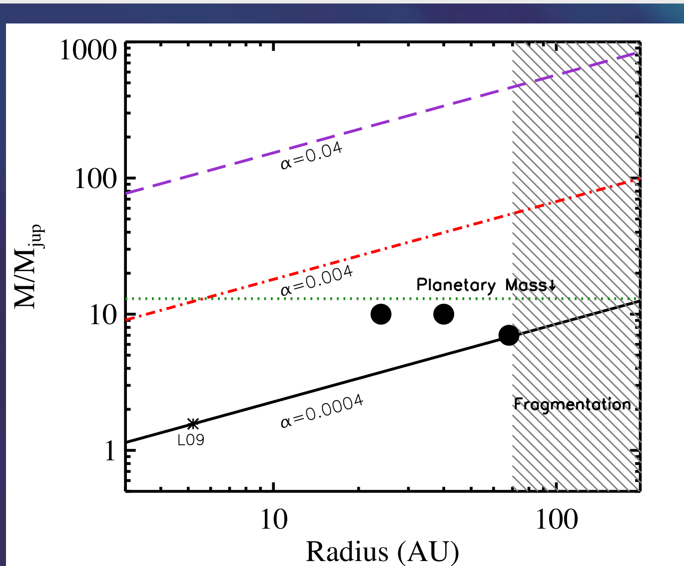



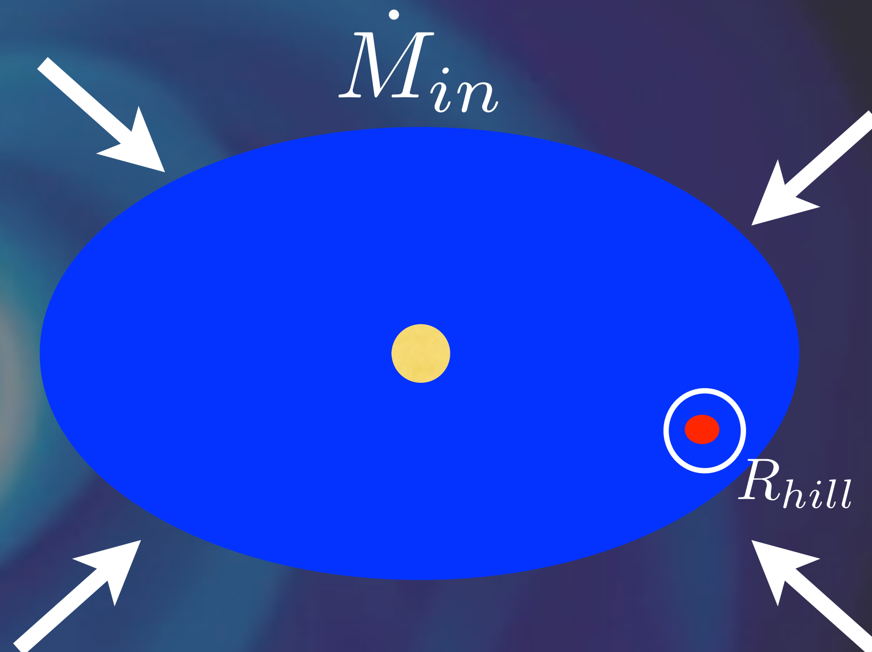




Kratter et al, 2008, 2010,
KMCY, 2010

# Fragments like to grow!

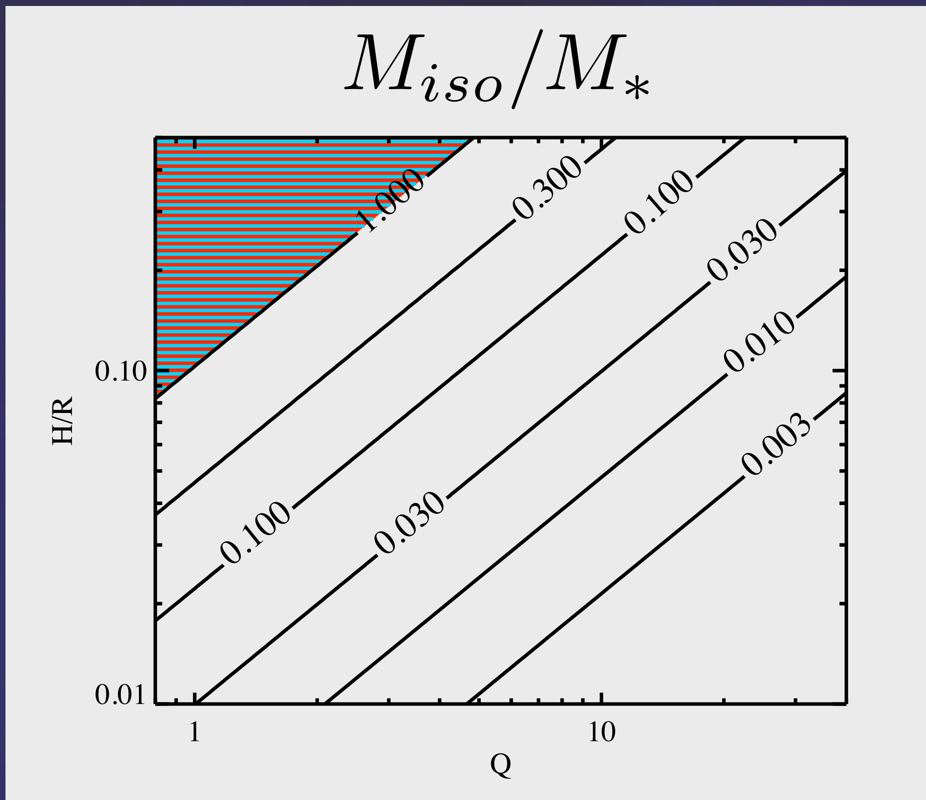


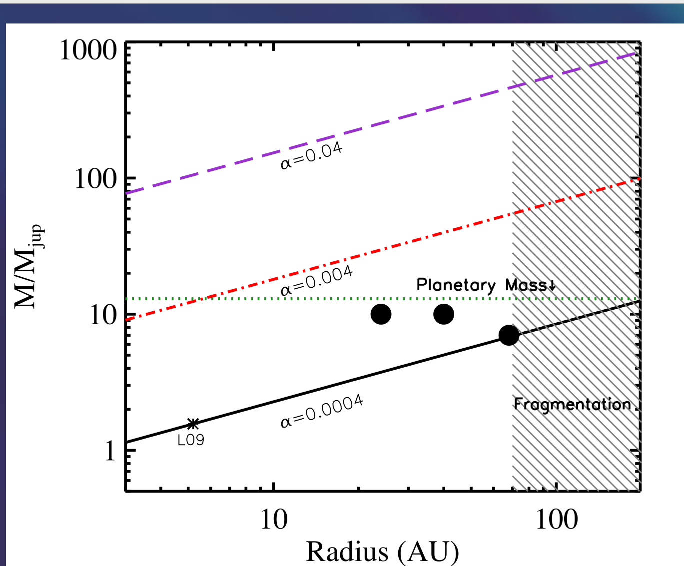



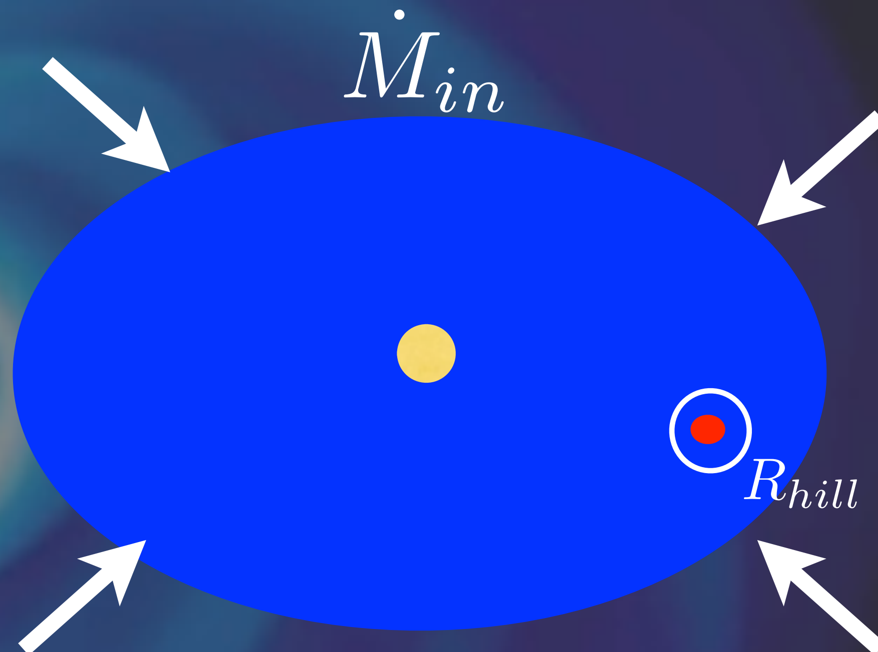




Kratter et al, 2008, 2010,
KMCY, 2010

# Fragments like to grow!

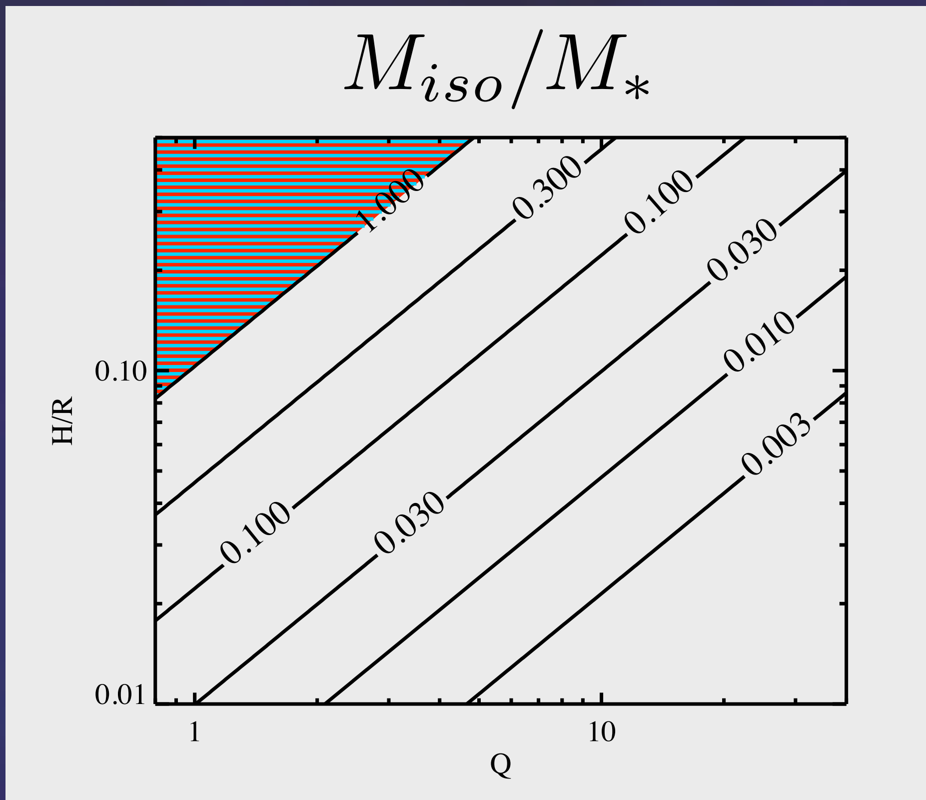


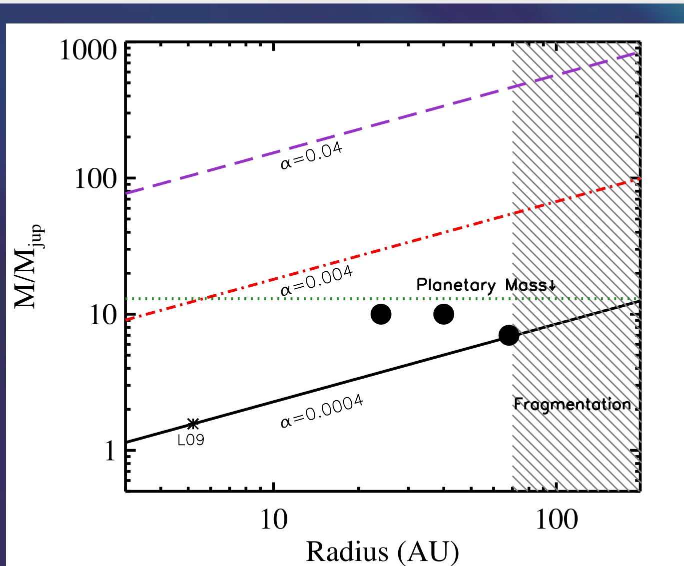



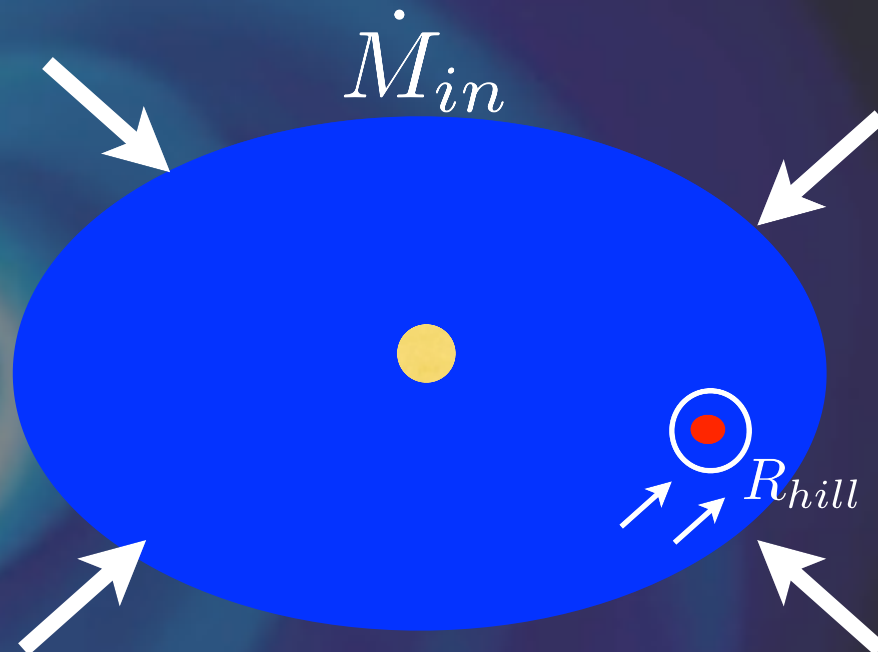




Kratter et al, 2008, 2010,
KMCY, 2010

# Fragments like to grow!

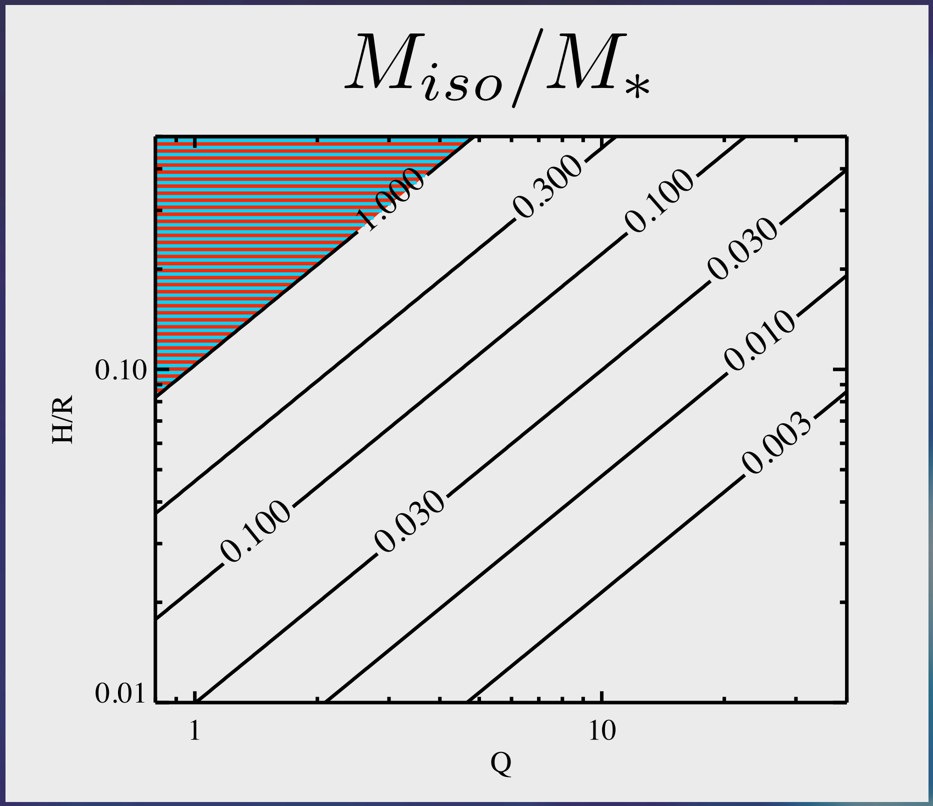


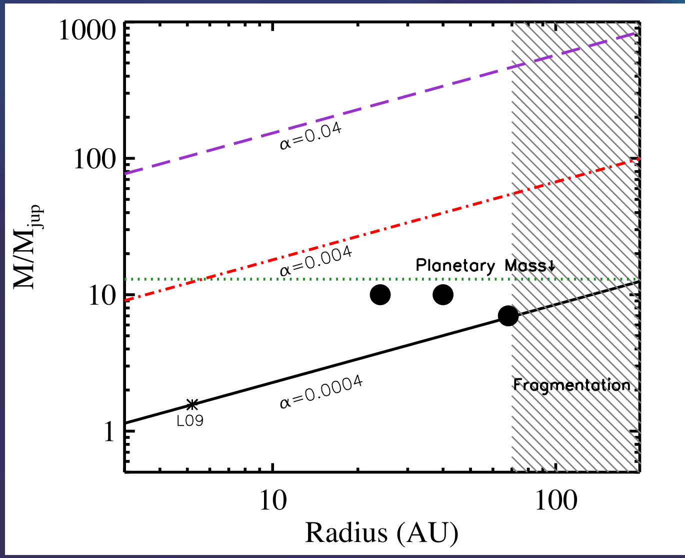



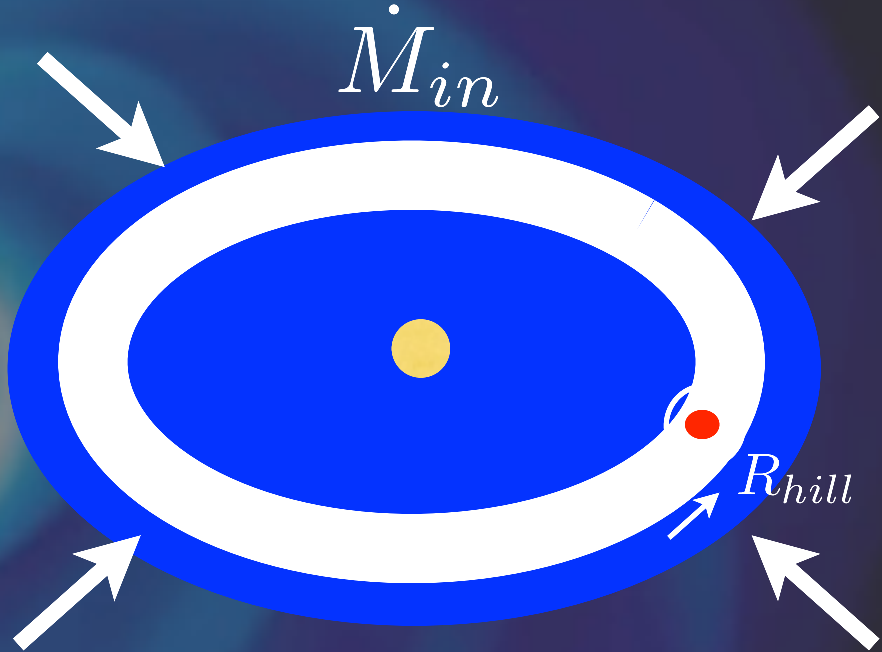




Kratter et al, 2008, 2010,
KMCY, 2010

# Fragments like to grow!

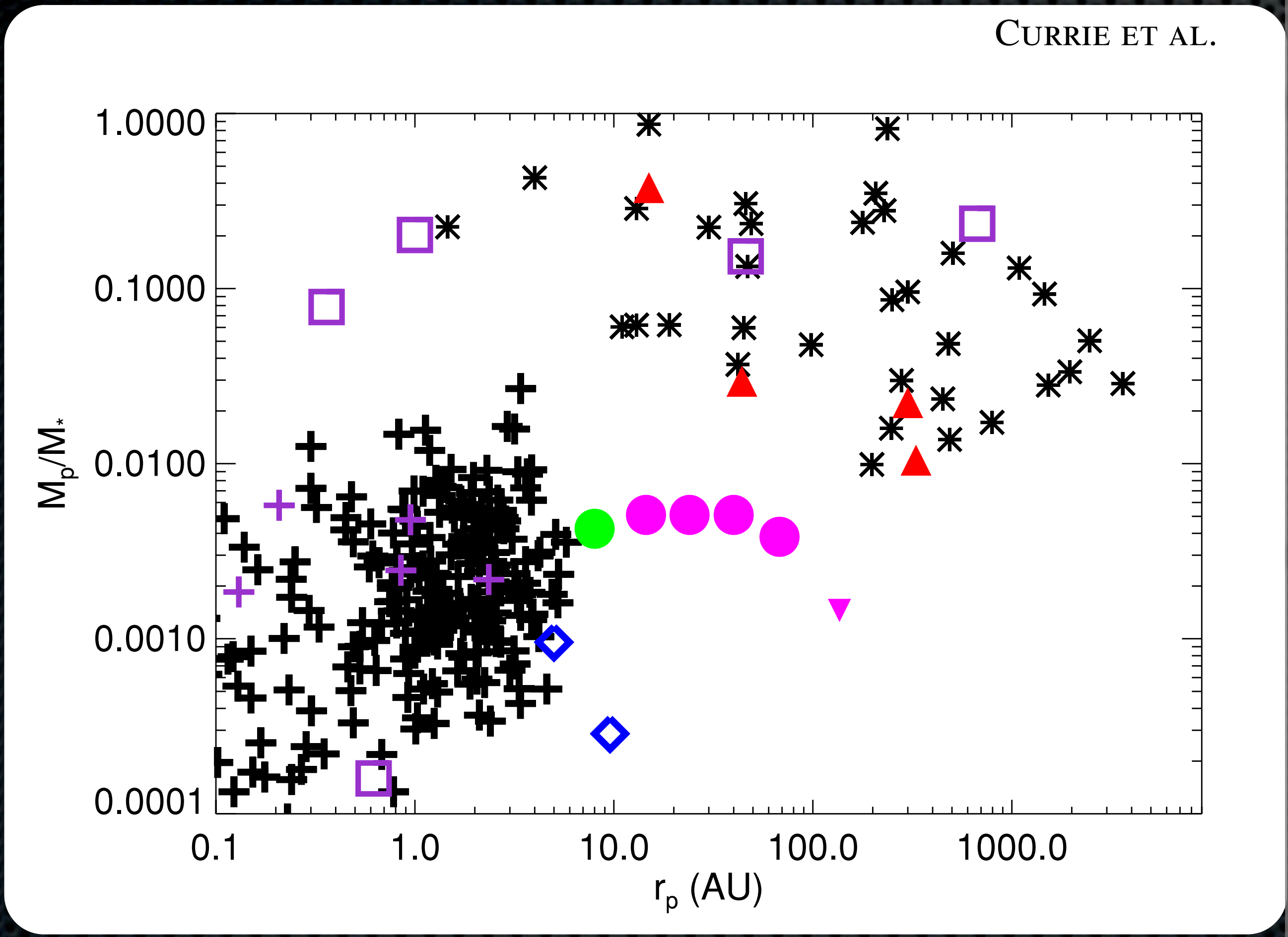



Kratter et al, 2008, 2010,
KMCY, 2010

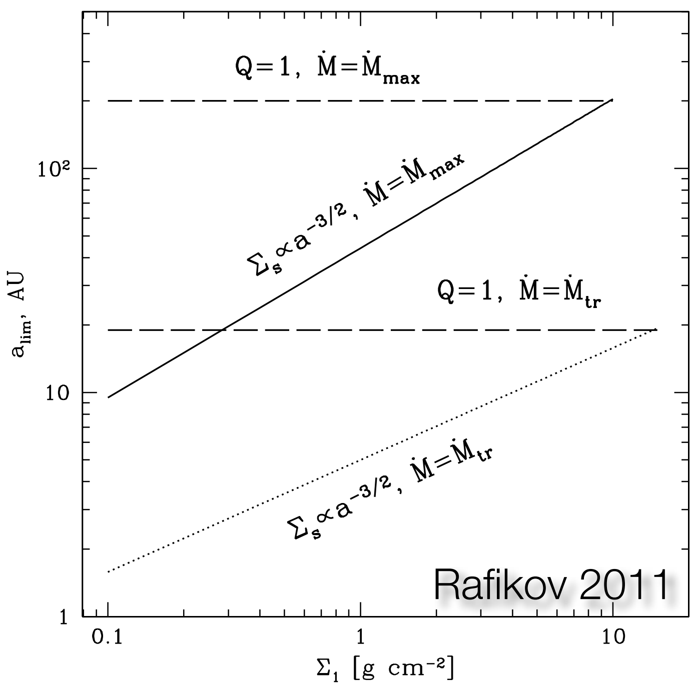
# GI predicts a population of **more massive** objects!

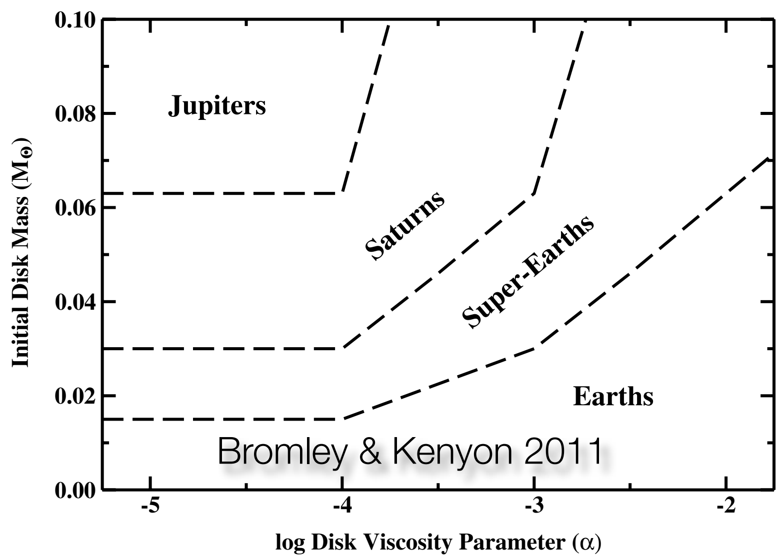



- Brown Dwarf (and massive planet) Desert is real (Nielsen & Close 2009, Lafreniere et al 2007, Quanz et al 2011)
- More massive stars do not have frequent similar (or higher) mass companions either (Leconte et al 2010, Hinkley et al 2010)

Currie et al, 2011,
Kratter, Murray-Clay & Youdin, 2010

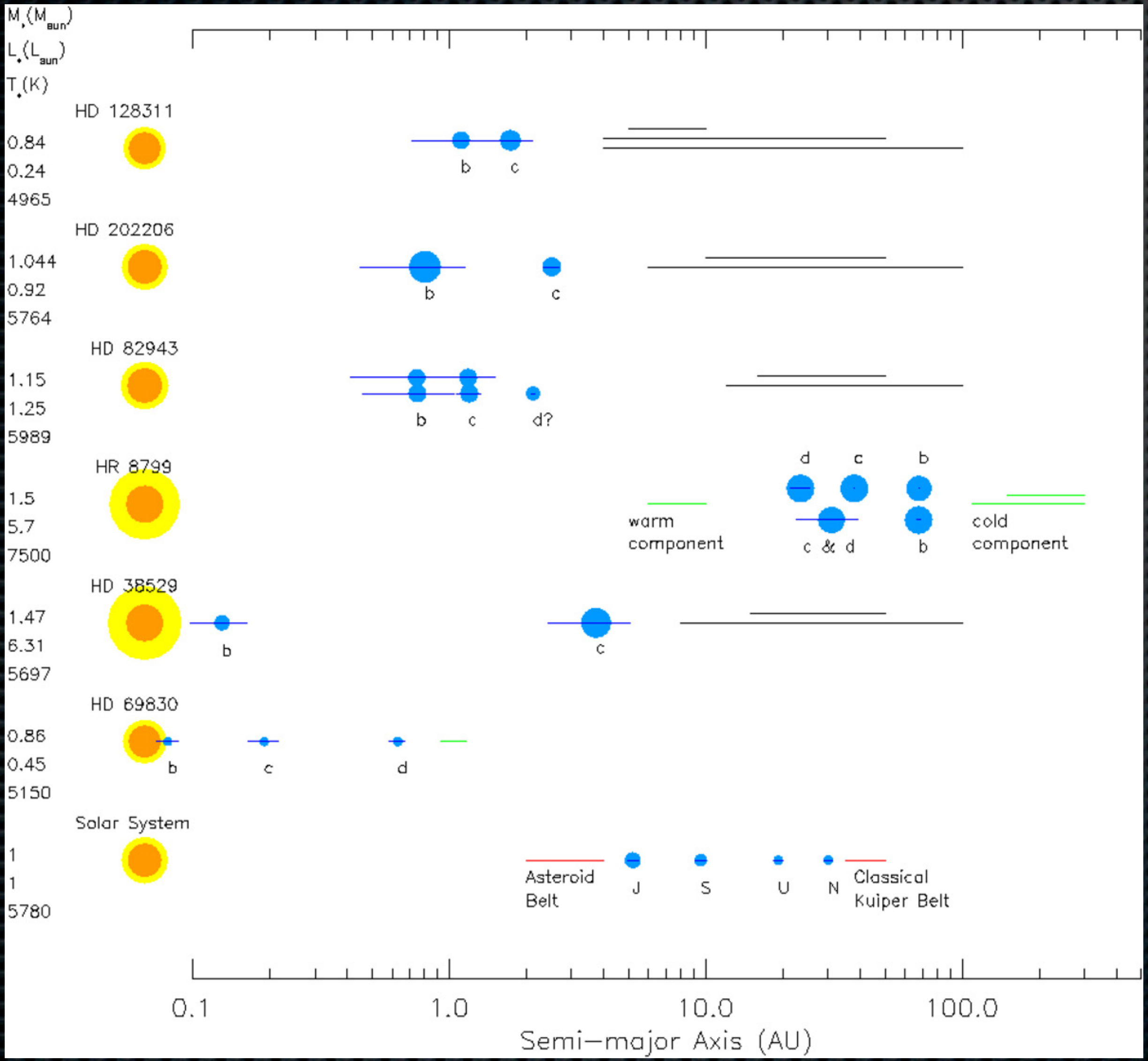
# Is core accretion *too slow?*




- **Planetesimal** formation can get a **head start** (Chiang & Youdin 2010, Youdin 2010)
- Critical core **mass** gets **smaller** (not always 10 Me, Rafikov 2011)
- **Faster accretion** rates are possible (Dones & Tremaine 1993, Goldreich Lithwick & Sari 2004, Rafikov 2003,2006,2011, Kenyon & Bromley 2009, 2011, Inaba & Ikoma 2003)

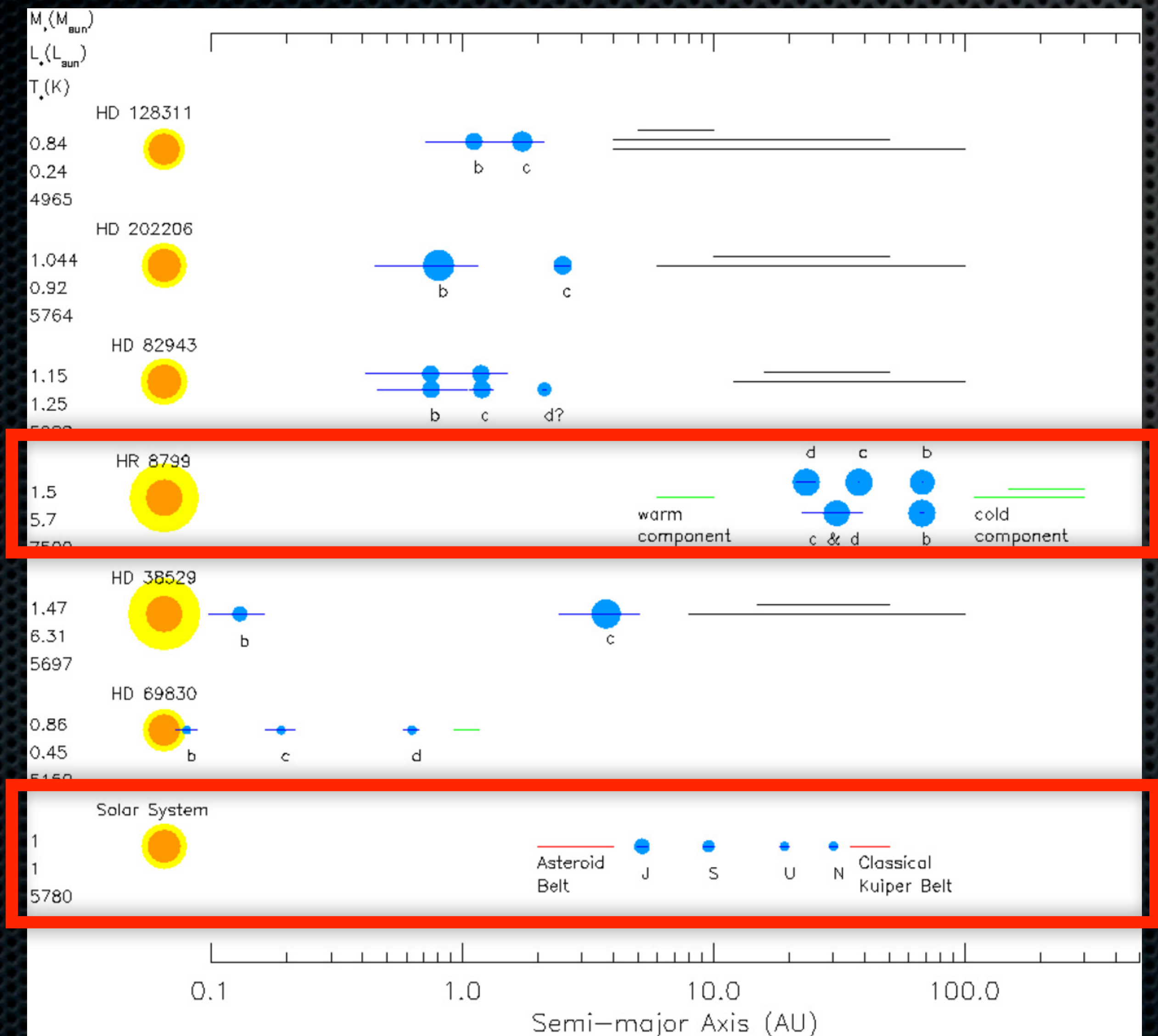
# Evidence for core accretion in HR 8799




- Only strong "counter" observation to standard planet formation has a debris disk
- Massive Stars form more planets at wider separations (Johnson 2010, **Crepp & Johnson 2011**)

Moro-Martin et al, 2010 & Kate Su's talk

# Evidence for core accretion in HR 8799




- Only strong "counter" observation to standard planet formation has a debris disk
- Massive Stars form more planets at wider separations (Johnson 2010, **Crepp & Johnson 2011**)

Moro-Martin et al, 2010 & Kate Su's talk

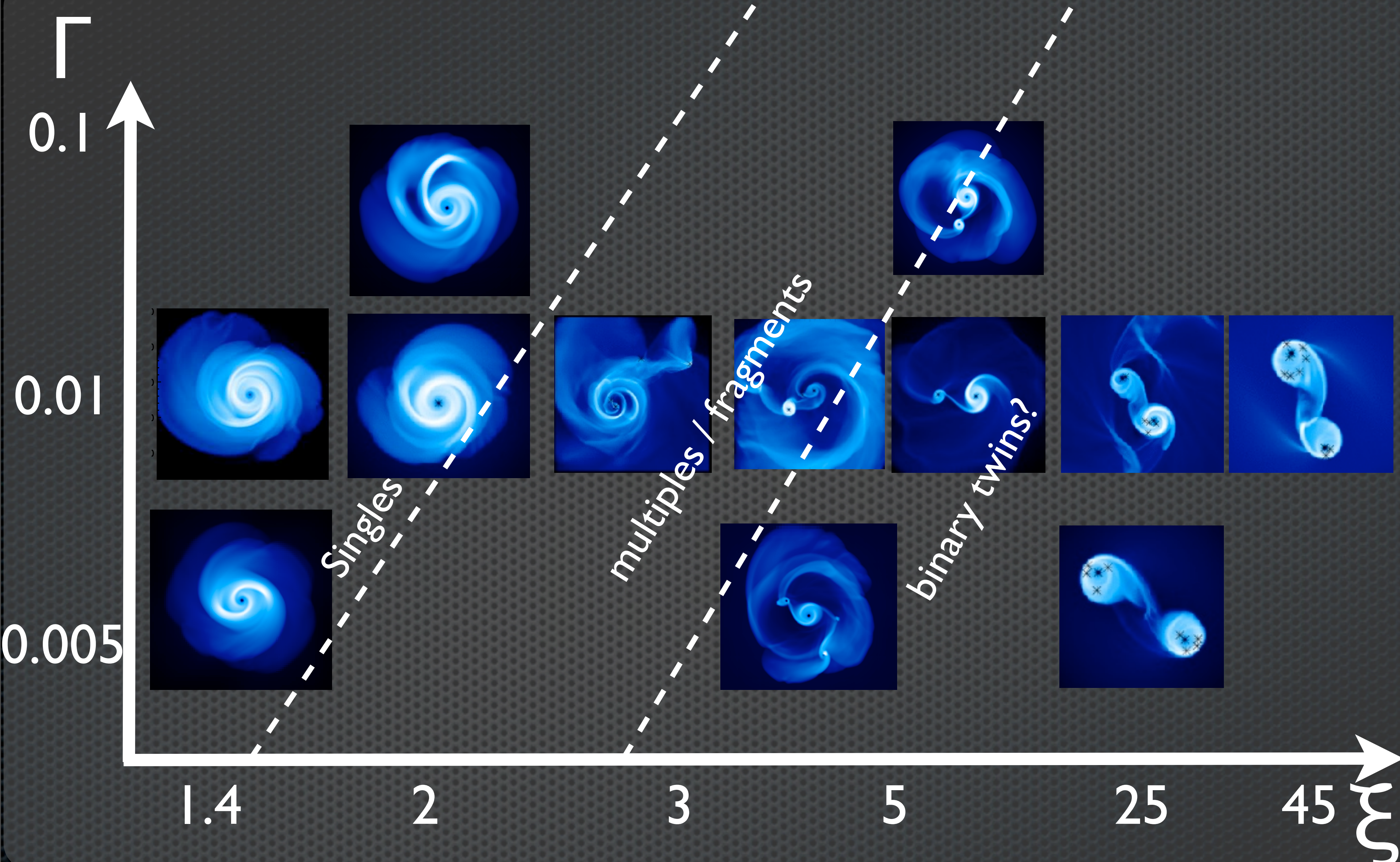
# Summary

- **Observations support core accretion** for a wide range of planets
- GI is proposed to account for “hard” to form planets, but suffers from similar, if not more extreme theoretical difficulties. It predicts a population of more massive objects

# Summary

- **Observations support core accretion** for a wide range of planets
- GI is proposed to account for "hard" to form planets, but suffers from similar, if not more extreme theoretical difficulties. It predicts a population of more massive objects

> Researchers are "trapped in the mindset of the disk-instability deniers" who believe that the inner part of a planet-forming disk, because it lies closer to the parent star, would be too hot to fragment, Boss says. "This really is more of a religious split than a scientific one," he adds. (ScienceNews, Dec. 2010)




$$\xi = \frac{\dot{M}G}{c_s^3}$$

$$\Gamma = \frac{\dot{M}_{in}}{M_{*d}\Omega}$$

Kratter et al 2010

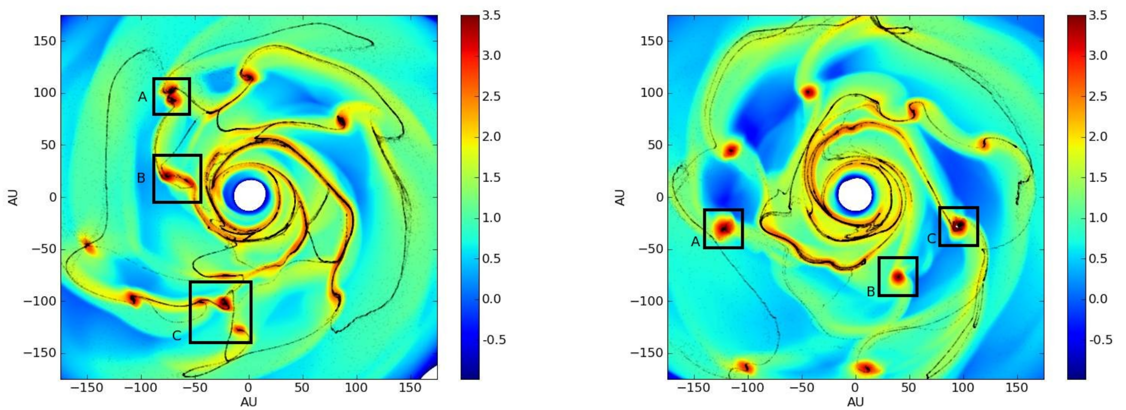



Fig. 2.— Similar to Figure 1, but for later in the disk's evolution after additional fragmentation has occurred. Left: There are three regions of interest that are highlighted by boxes A, B, and C. Box A shows to clumps that are about to merge and become one object. Box B shows two clumps that just missed merging. One is becoming disrupted, and releasing its gas solids back into the disk. In Box C, a three clumps are about to merge. Right: The boxes represent the same objects 200 yr later. Boxes A and C show that the clumps have completed their mergers. The clump in Box C is now 32 $M_J$ with 270 $M_\oplus$ of total heavy elements. In contrast, one of the clumps in Box B has survived, while the other was tidally disrupted. The clump is 11 $M_J$ with $\sim$ 100 $M_\oplus$ of heavy elements.

Boley et al, 2011

# What is the GI mechanism

$$Q = \frac{c_s \Omega}{\pi G \Sigma} \sim 1$$

criterion for disk unstable to GI

$$t_{cool} \sim \frac{\Sigma c_s^2 \tau}{\sigma T^4} \sim \Omega^{-1}$$

allow disk to dissipate energy / fragments to collapse on free-fall time

$$\tau = \frac{\kappa \Sigma}{2} \sim 1$$

$$M_{frag} = \Sigma \lambda^2 \sim \Sigma H^2$$

fragment mass consistent with fastest growing mode

$$q > \alpha \frac{\pi}{f_g} \frac{H^2}{r^2} \left( \frac{\Delta}{R_H} \right)^3$$

criterion for fragment to stop accreting (gap opening)

# What is the GI mechanism

$$Q = \frac{c_s \Omega}{\pi G \Sigma} \sim 1$$

criterion for disk unstable to GI

$$t_{cool} \sim \frac{\Sigma c_s^2 \tau}{\sigma T^4} \sim \Omega^{-1}$$

allow disk to dissipate energy / fragments to collapse on free-fall time

$$\tau = \frac{\kappa \Sigma}{2} \sim 1$$

$$M_{frag} = \Sigma \lambda^2 \sim \Sigma H^2$$

fragment mass consistent with fastest growing mode

$$q > \alpha \frac{\pi}{f_g} \frac{H^2}{r^2} \left( \frac{\Delta}{R_H} \right)^3$$

criterion for fragment to stop accreting (gap opening)

# What is the GI mechanism

$$Q = \frac{c_s \Omega}{\pi G \Sigma} \sim 1$$

criterion for disk unstable to GI

$$t_{cool} \sim \frac{\Sigma c_s^2 \tau}{\sigma T^4} \sim \Omega^{-1}$$

$$\tau = \frac{\kappa \Sigma}{2} \sim 1$$

allow disk to dissipate energy / fragments to collapse on free-fall time

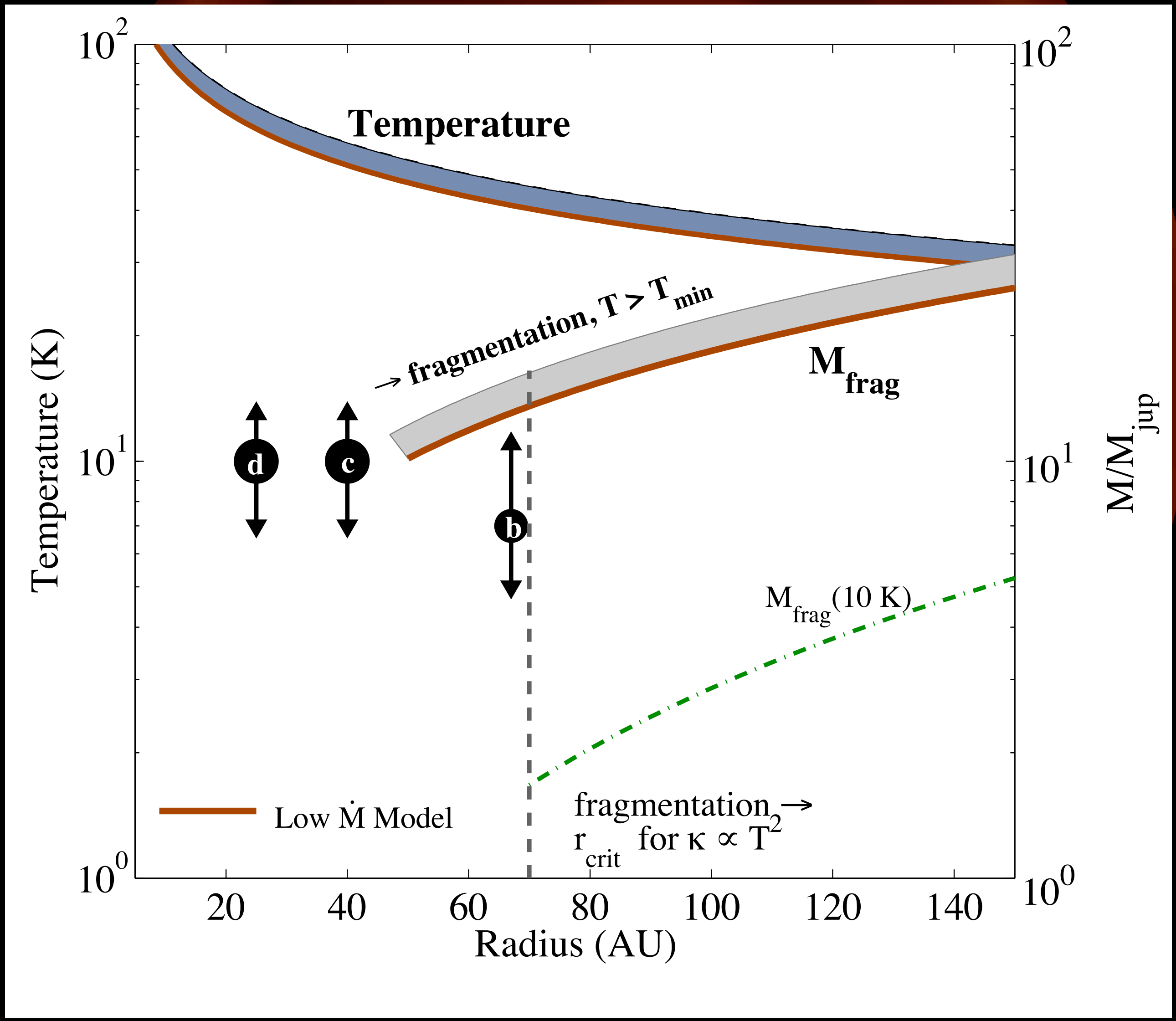
$$M_{frag} = \Sigma \lambda^2 \sim \Sigma H^2$$

fragment mass consistent with fastest growing mode

$$q > \alpha \frac{\pi}{f_g} \frac{H^2}{r^2} \left( \frac{\Delta}{R_H} \right)^3$$

criterion for fragment to stop accreting (gap opening)

# let there be planets?




Kratter, Murray-Clay, Youdin, 2010