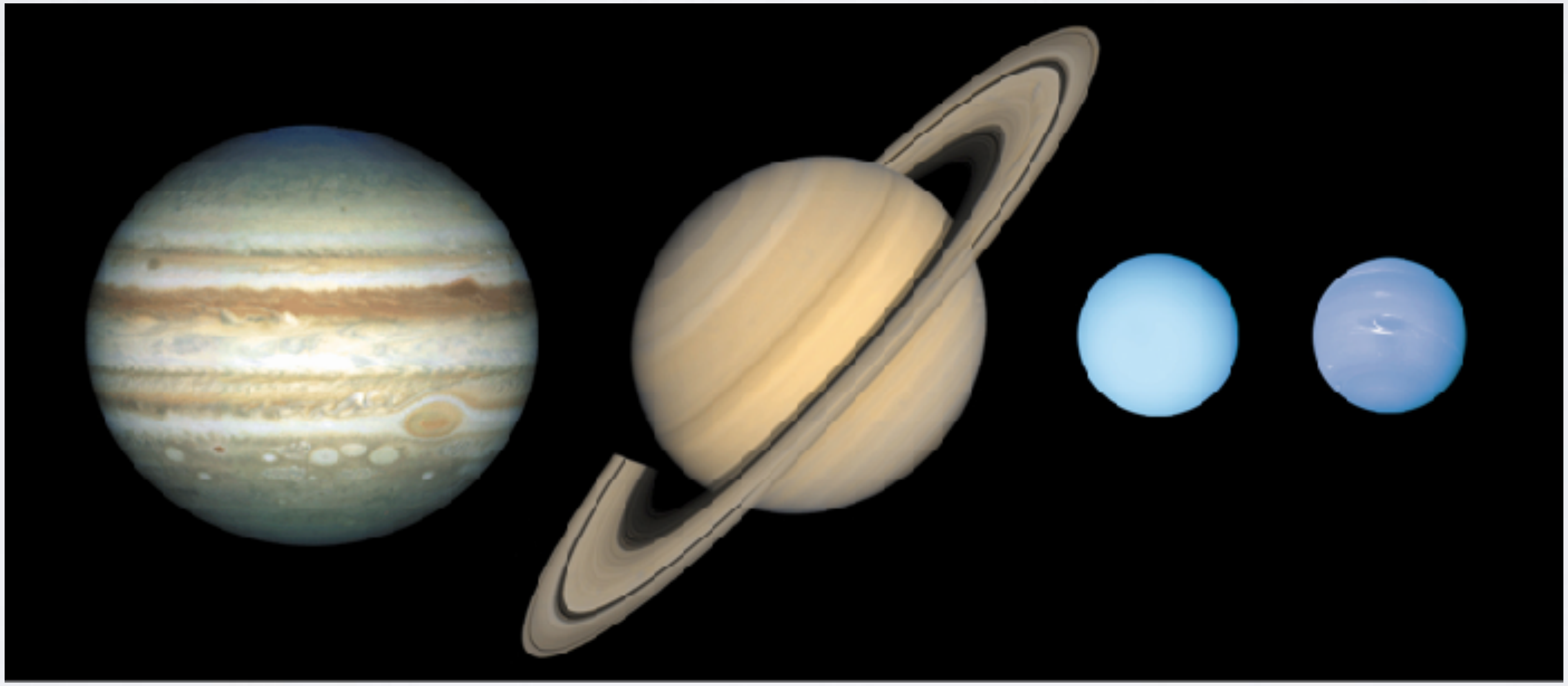
PLANET FORMATION (FOR MICROLENSING HUNTERS)

Kaitlin Kratter

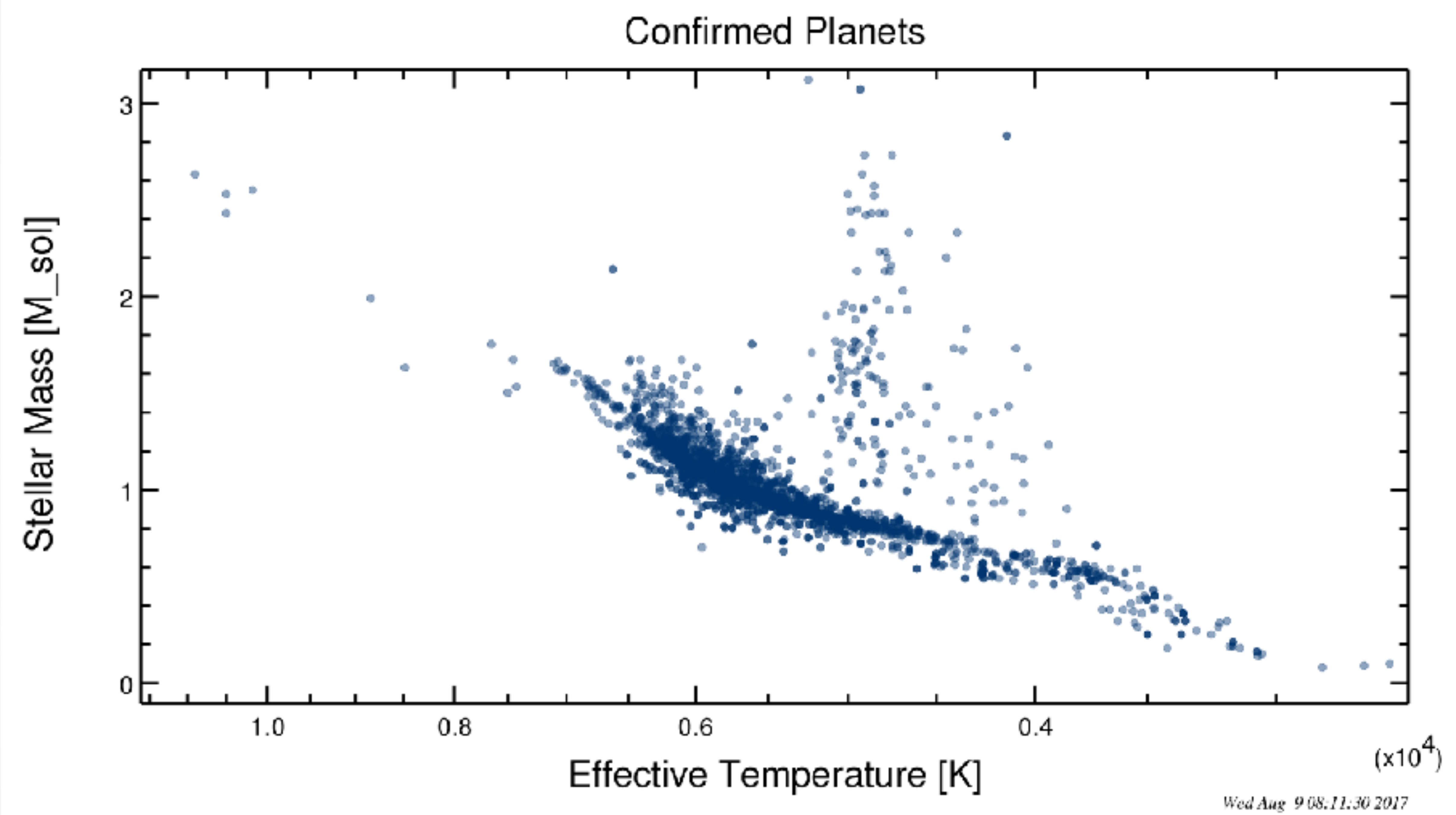


THE UNIVERSITY OF ARIZONA
COLLEGE OF SCIENCE
Astronomy
& Steward Observatory

BIG CHALLENGES IN PLANET FORMATION MODELING + OBSERVATIONS

- planets form from small (by mass) component of the disk — think metallicity. ISM has gas-to-dust ratio 100:1
- we can't see particles at the crucial building block stages
- solids / planet-gas interactions are complicated
- planets don't live where they were born

SOME CAUTION REQUIRED FOR MICROLENSING HOSTS:



NASA Exoplanet Archive

els

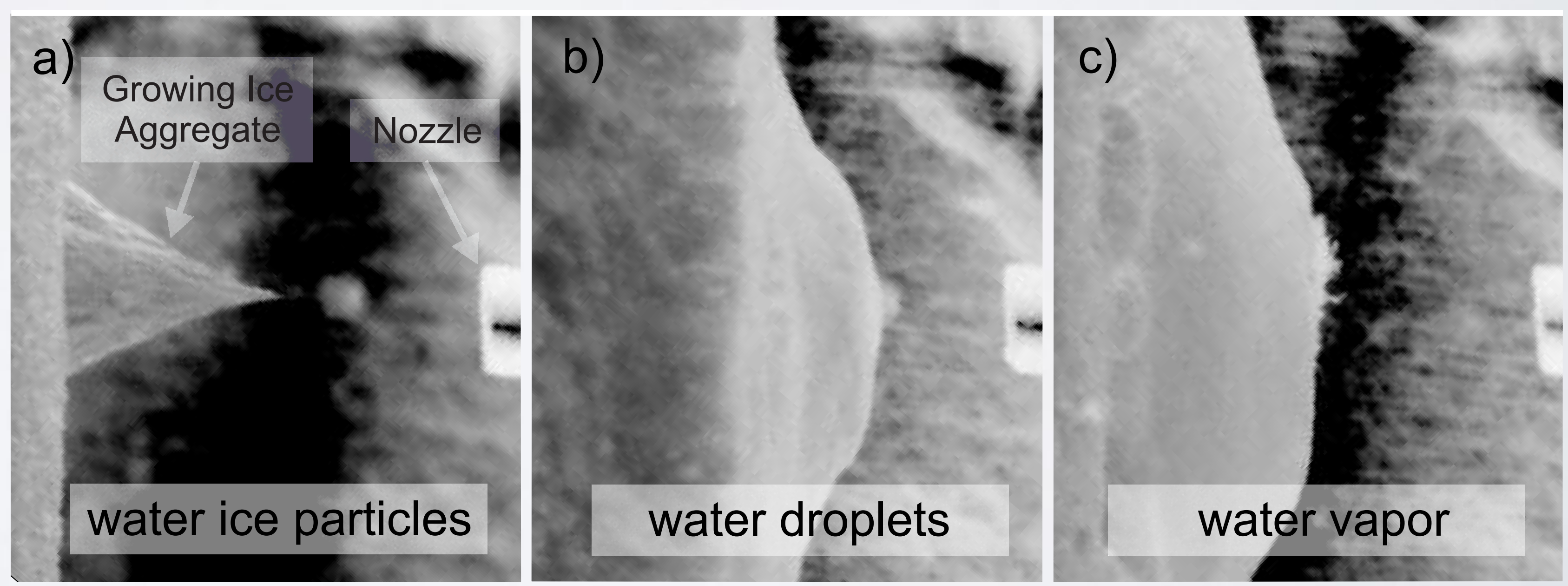
OUTLINE

- The (old) standard model for planet formation: Core Accretion
- Newer developments that address "textbook problems" in Core Accretion
- Unsolved problems
- The role of gravitational instability

CORE ACCRETION, "CLASSICALLY"

- Basic parts of core accretion:
  - Dust grains coagulate to sizes larger than the ISM (mm, cm, m?)

Gundlach & Blum 2014



Stevenson+ 1986, Pollack+1996

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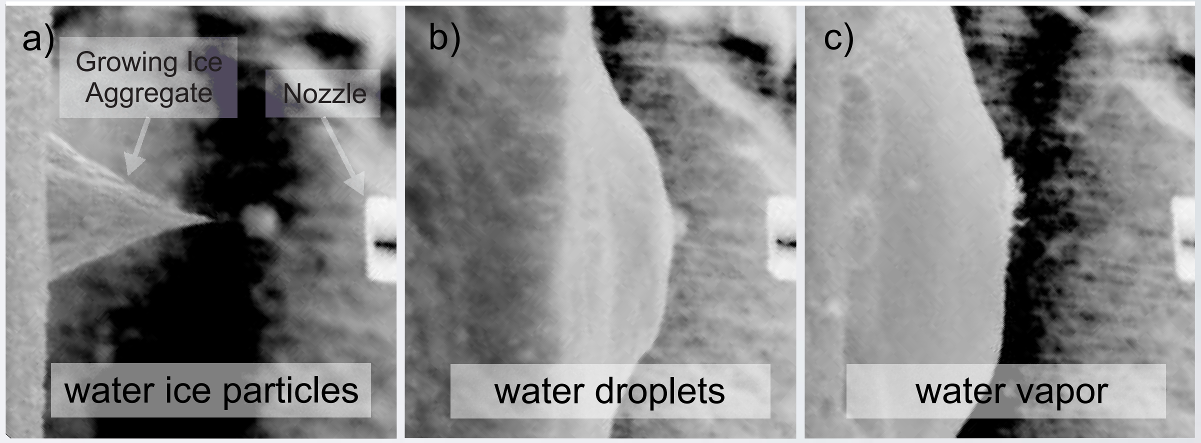

- Basic parts of core accretion:
  - Dust grains coagulate to sizes larger than the ISM (mm, cm, m?)
  - Planetesimals (km+) form via continued coagulation of small bodies

F. Sulehria

Stevenson+ 1986, Pollack+1996

CORE ACCRETION, "CLASSICALLY"

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  - Planetesimals (km+) form via growth of small bodies (aka magic?, "meter-size" barrier)
  - Planetesimals grow into planet-cores via gravity-assisted collisions

Stevenson+ 1986, Pollack+1996

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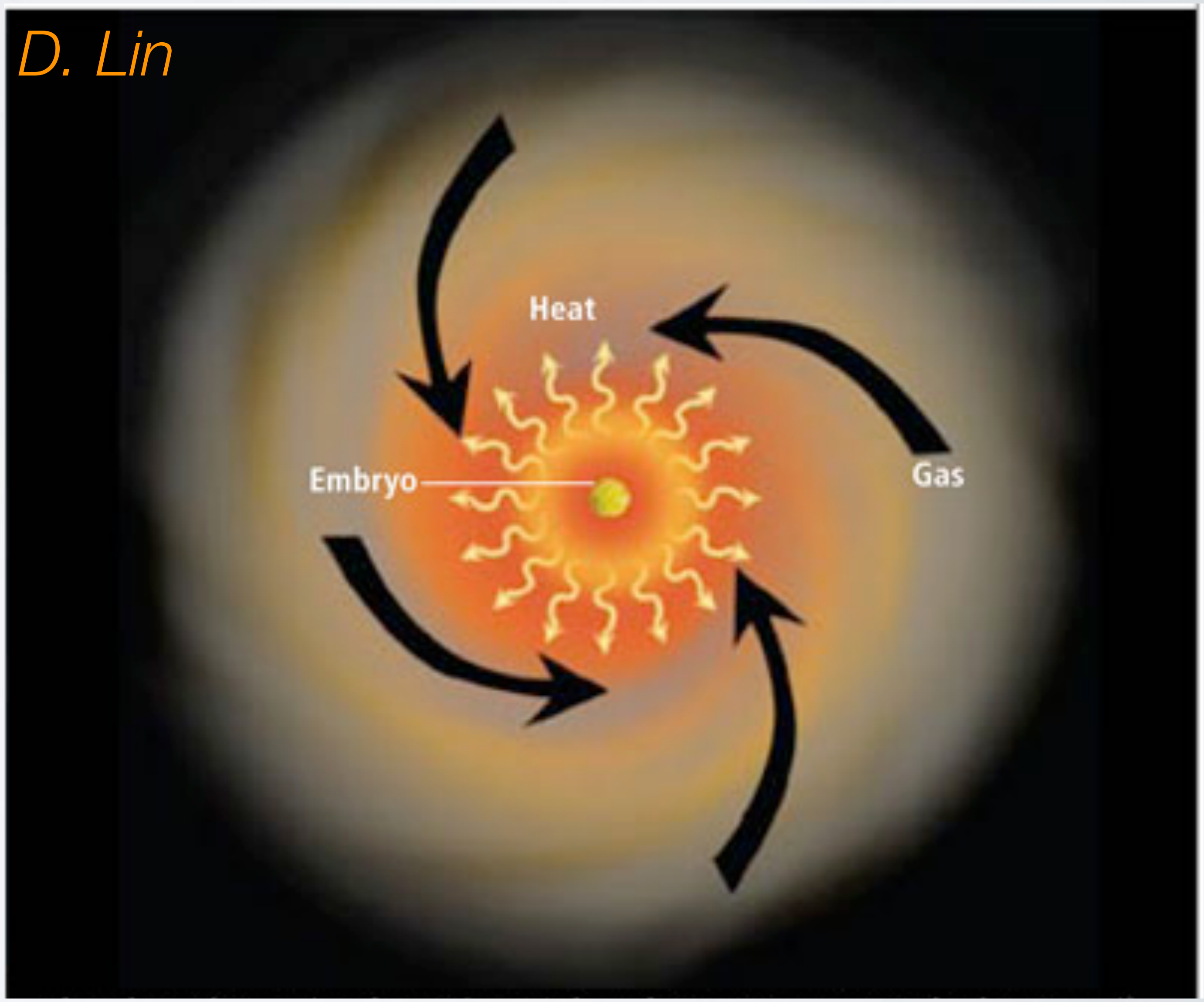
  - Planetary cores can undergo runaway atmospheric growth



Stevenson+ 1986, Pollack+1996

WHAT'S SO HARD ABOUT PLANET FORMATION (ESP. IN THE OUTER DISK?)

- Classic Problems:
  - growing up to meter size bodies via coagulation is difficult
  - growing through the "meter size" barrier is an extreme challenge due to radial drift
  - It takes longer than the disk lifetime (few Myr) to build a big enough solid core mass to trigger runaway atmospheric growth to make a gas giant

CORE ACCRETION IN THIS CENTURY…

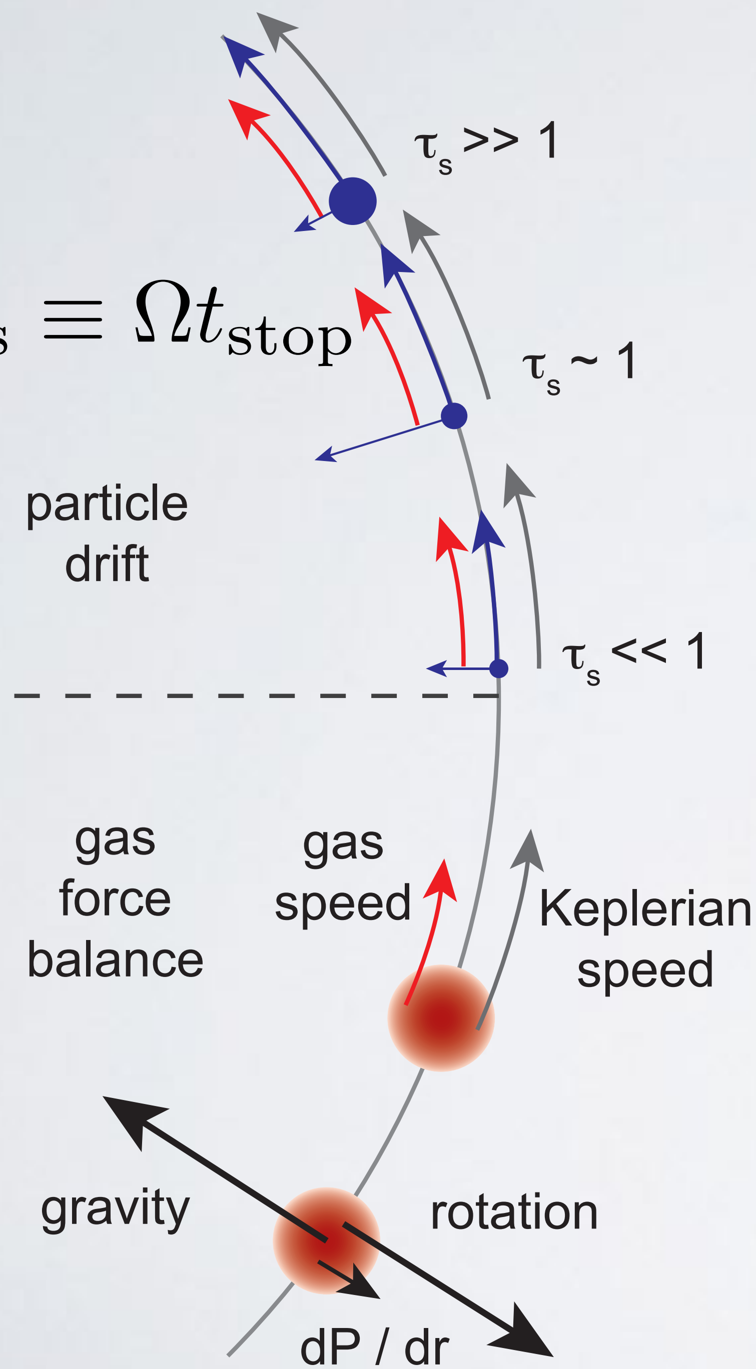
- Basic parts of classic core accretion:
  - Dust grains coagulate to sizes larger than the ISM (mm, cm, m?)
  - Planetesimals form with some size distribution (km-500km)
  - Planetesimals grow into planet-cores via gravity-assisted collisions
  - Planetary cores sometimes accrete gaseous atmospheres

- Updated parts of core accretion:
  - Dust grains grow early (Najita & Kenyon 2014, Andsell+ 2016) to at least cm sizes aided by pressure traps
  - Planetesimals form via Streaming Instability with range of sizes (up to ~500km) (Youdin & Goodman 2005, Simon et al 2016)
  - Planetesimals accrete substantial mass from "pebbles," not just other planetesimals (Ormel & Klahr 2010, Lambrechts & Johansen 2012)
  - Planetary cores sometimes undergo gas accretion, fed by circumplanetary disk (Zhu 2016)

RADIAL DRIFT

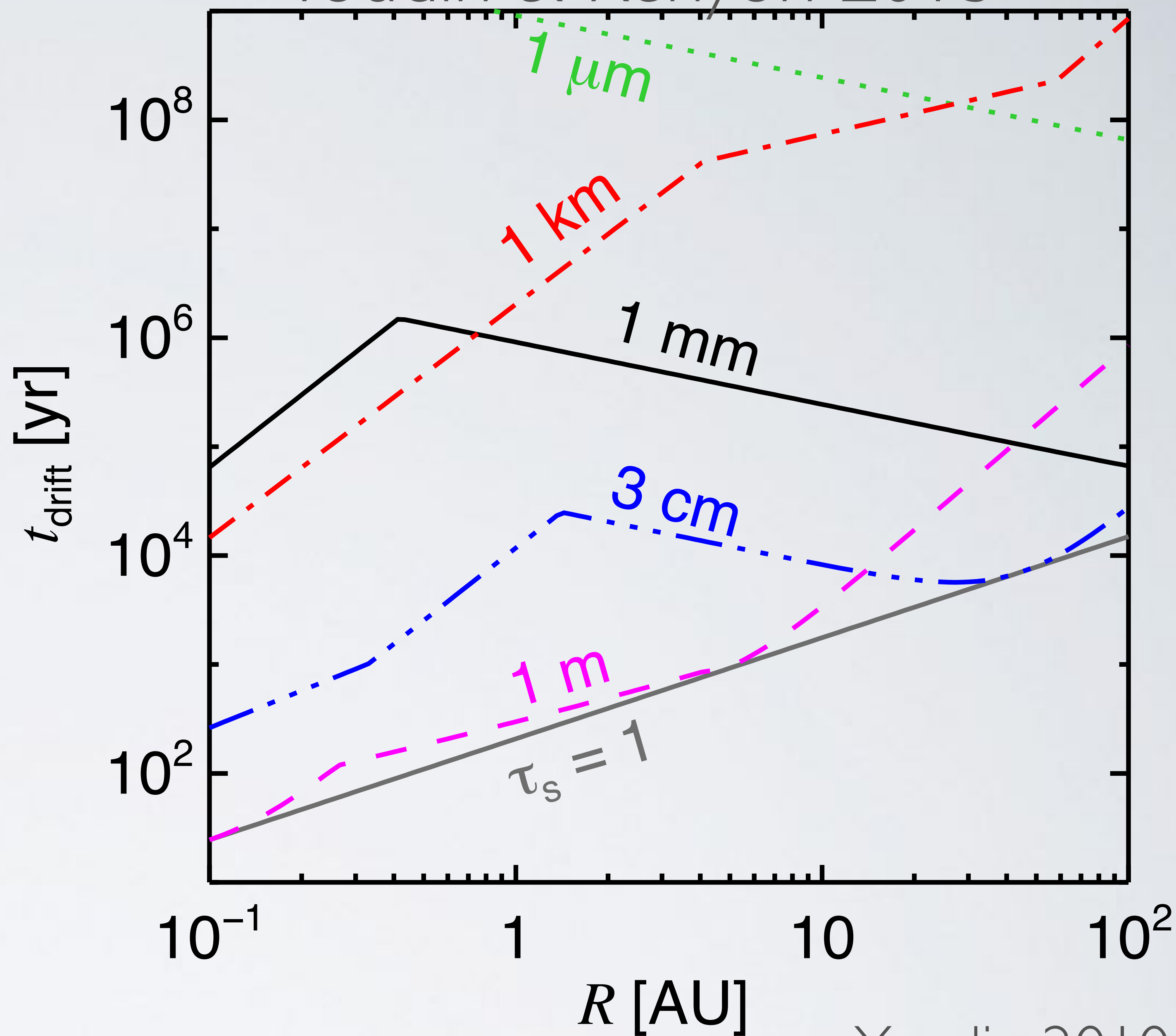
gas feels pressure, dust doesn't

$$\tau_s \equiv \Omega t_{stop}$$



Armitage 2015

Youdin & Kenyon 2013



Youdin 2010

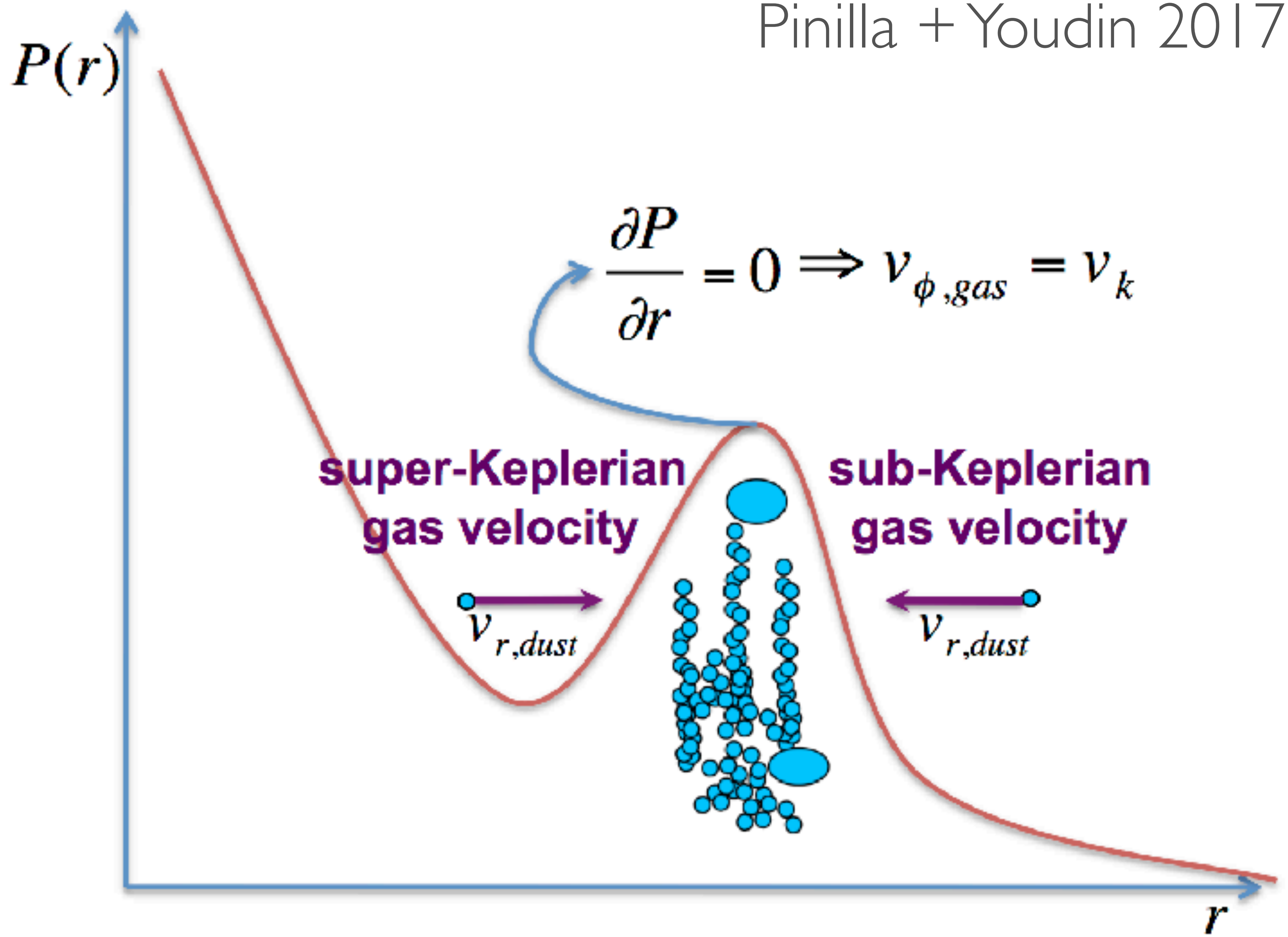
$$t_{stop} = \begin{cases} t^{Ep}_{stop} \equiv \rho_s a/(\rho_g c_s) & \text{if } a < 9\lambda/4 \\ t^{Stokes}_{stop} \equiv t^{Ep}_{stop} \cdot 4a/(9\lambda) & \text{if } 9\lambda/4 < a < \lambda/(4\mathrm{Ma}) \\ t^{Ep}_{stop} \cdot (a/\lambda)^{3/5}\,\mathrm{Ma}^{-2/5}/4 & \text{if } \lambda/(4\mathrm{Ma}) < a < 200\lambda/\mathrm{Ma} \\ t^{turb}_{stop} \equiv t^{Ep}_{stop} \cdot 6/\mathrm{Ma} & \text{if } a > 200\lambda/\mathrm{Ma} \end{cases}$$

$\mathrm{Ma} \equiv |\Delta \boldsymbol{v}|/c_s,\ \lambda \propto 1/\rho_g$

PRESSURE BUMPS CAN TRAP PARTICLES

changes in radial pressure profile can aid in particle concentration and thus coagulation

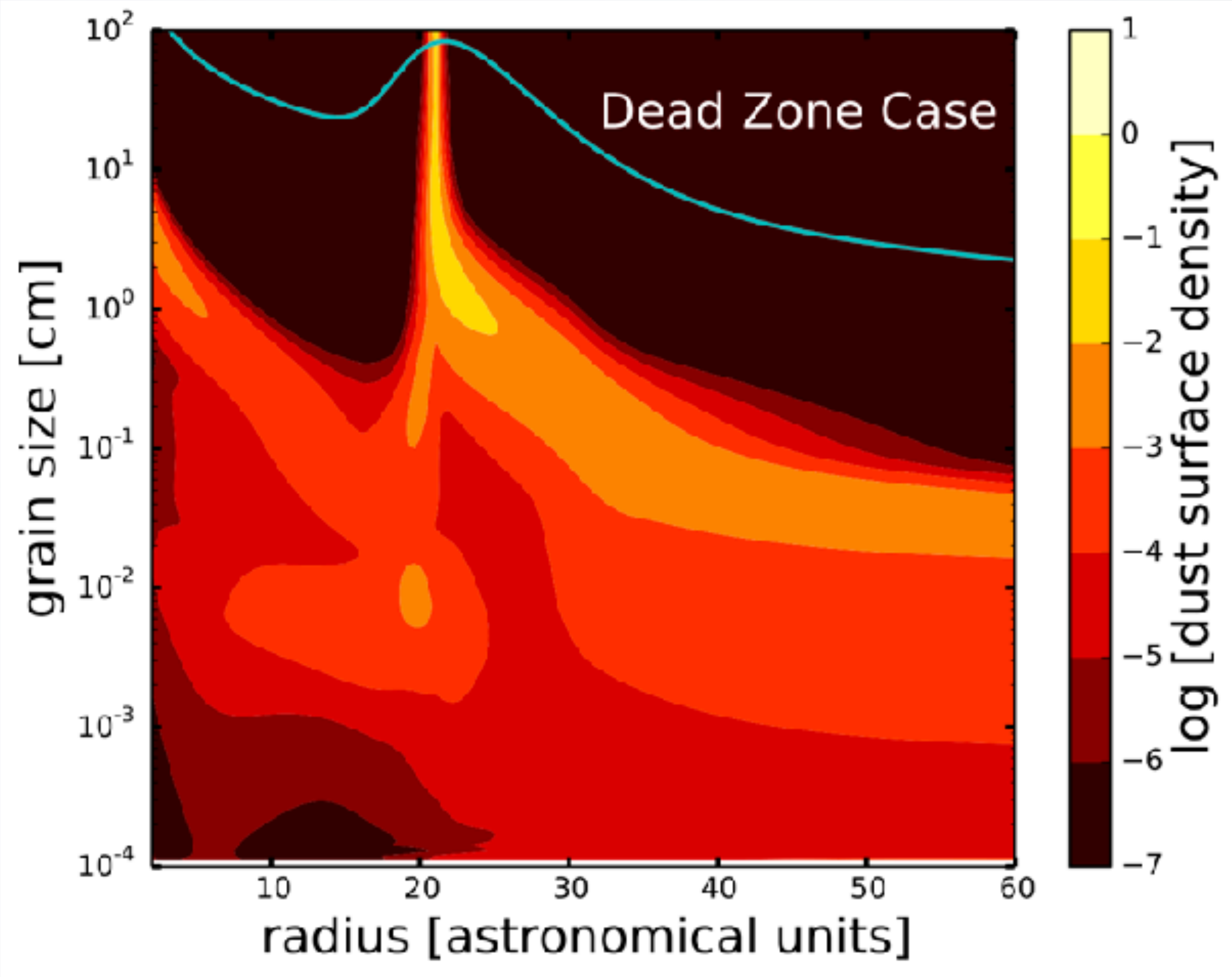
Pinilla + Youdin 2017



GRAIN GROWTH SIMULATIONS

Pinilla+ 2016

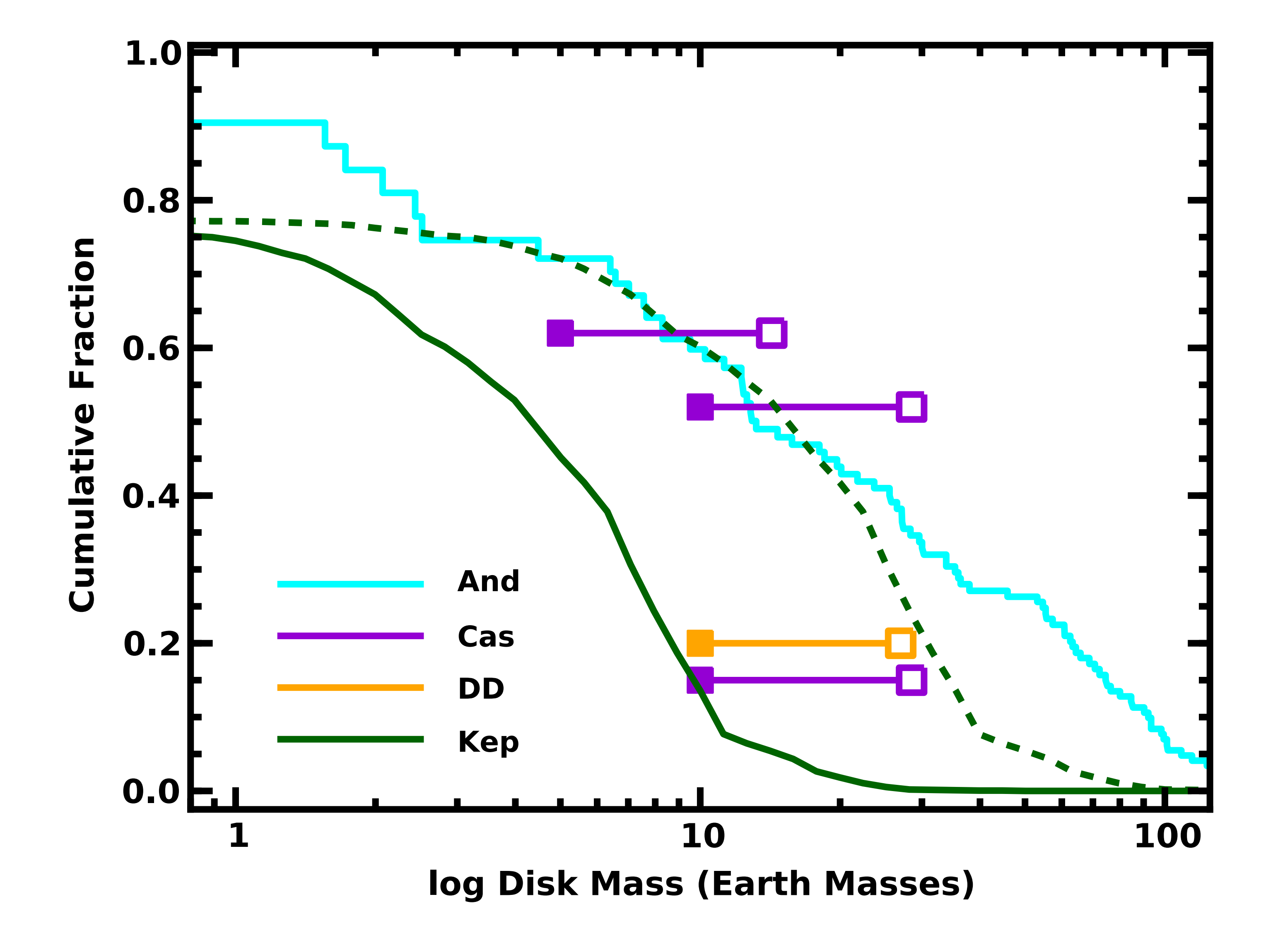
pressure traps facilitate growth to larger sizes
these larger particles (>few cm) are better participants in subsequent growth phases of planetesimal formation and pebble accretion



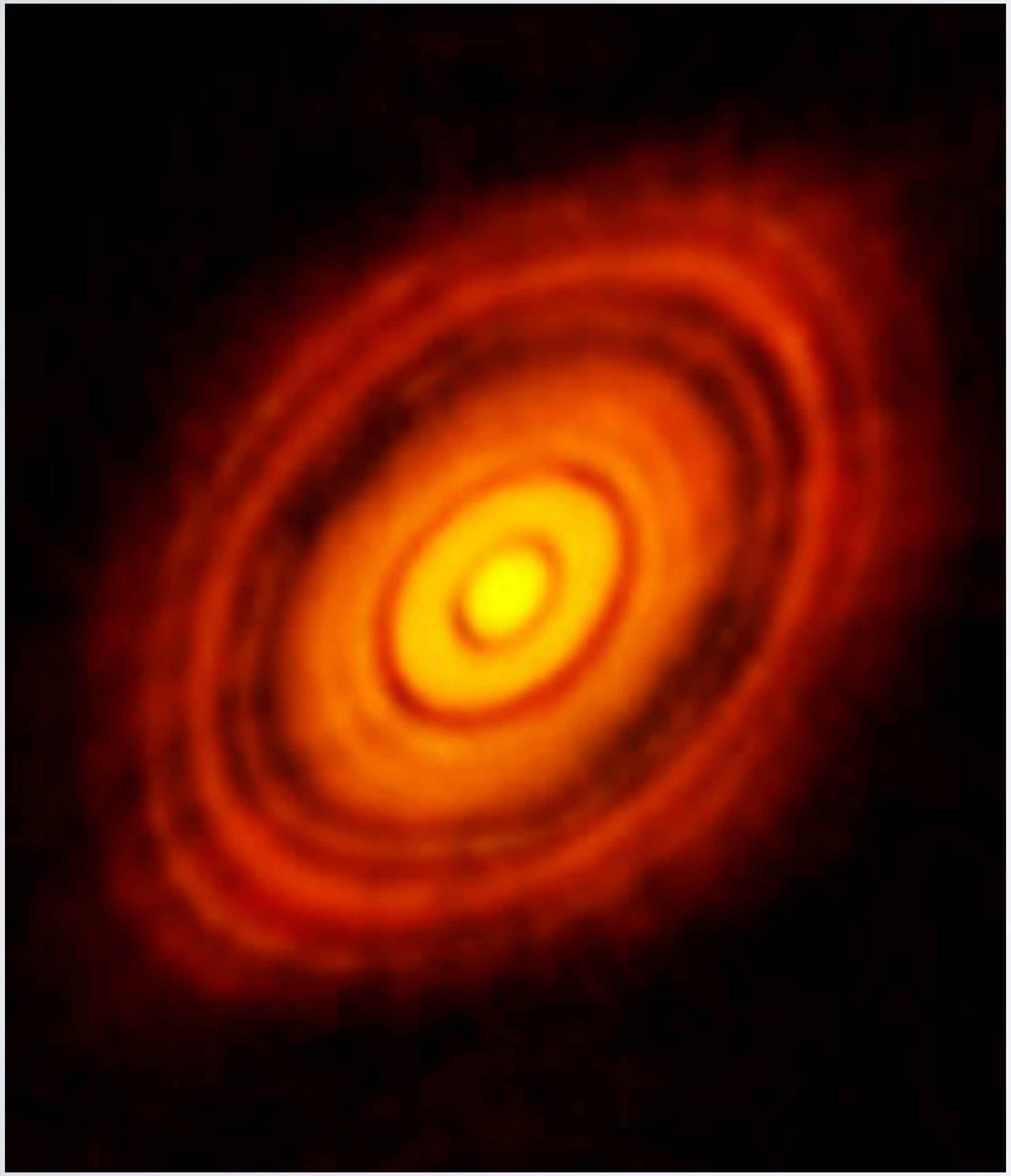
Grains are observed to grow

Najita & Kenyon 2014

- observations indicate that dust must grow quickly beyond mm-cm sizes —otherwise disks simply don't have enough mass to account for observed exoplanets.
- recall that grains emit efficiently at size near wavelength



CONSEQUENCES OF RADIAL DRIFT?



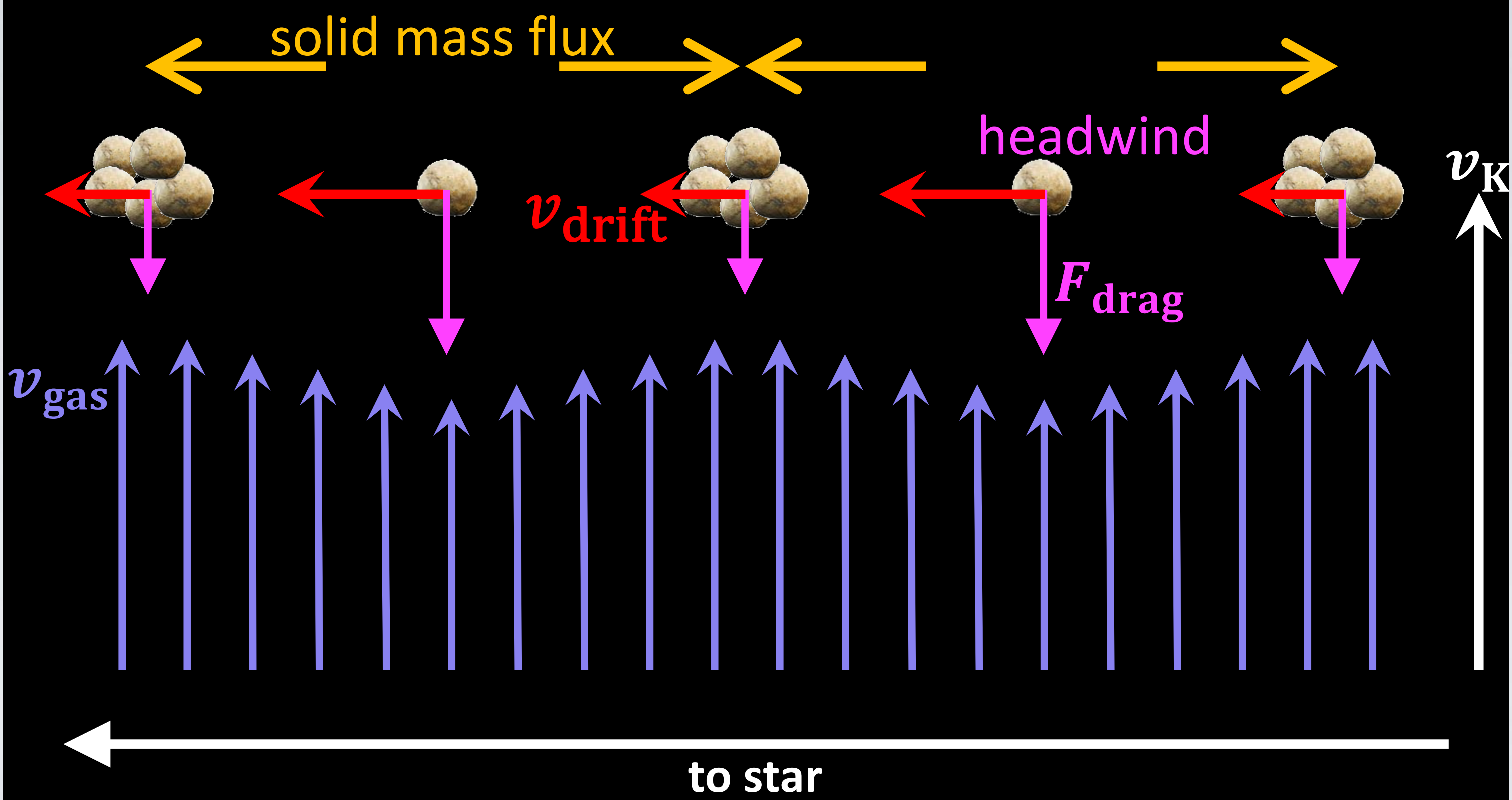
- ring structures could simply be particles, not planets

- radial drift also serves to trigger planetesimal formation!

Credit: Rixin Li

The Streaming Instability (SI)

Particles trigger their own concentration while interacting with gas

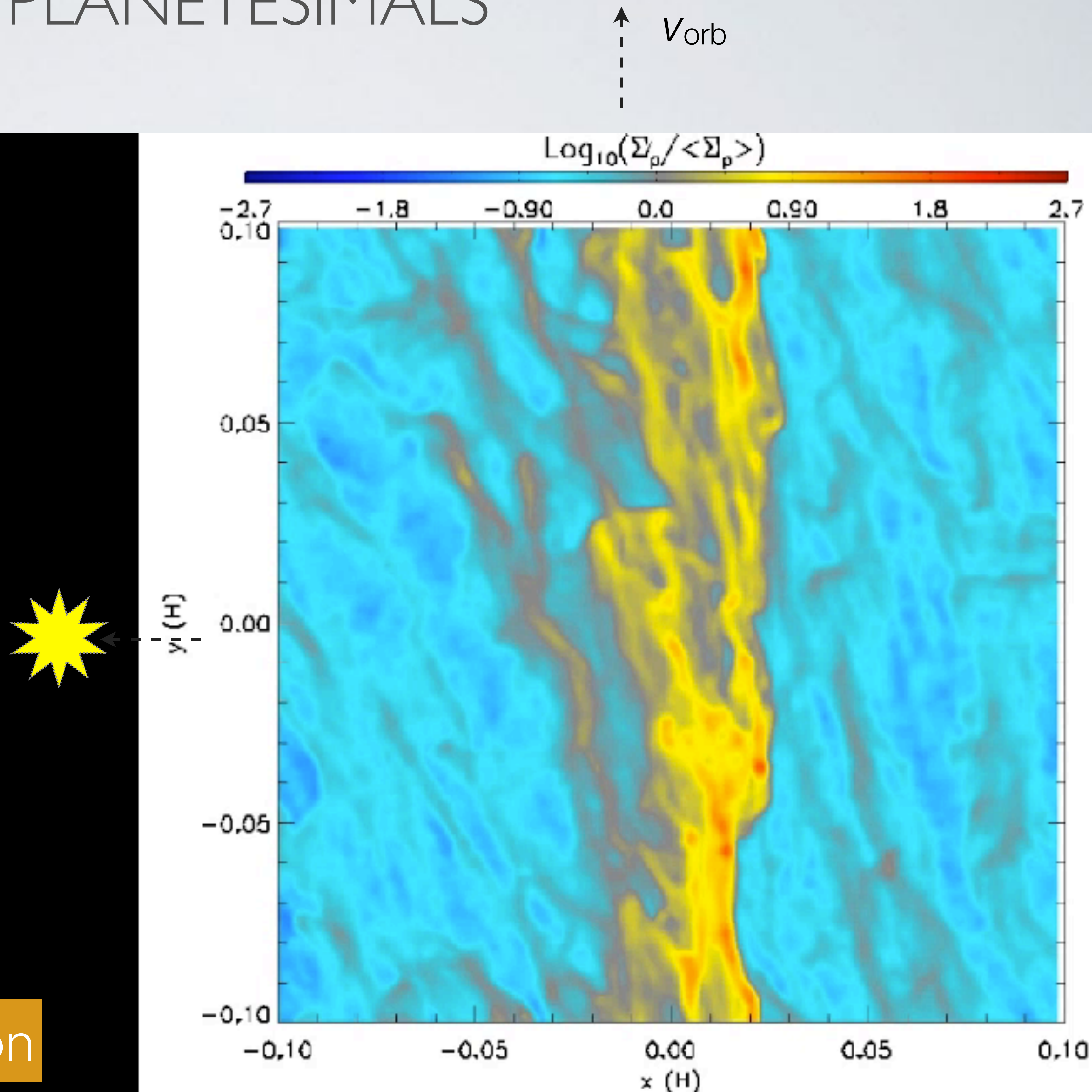


Youdin & Goodman 2005; Johansen & Youdin 2007; Bai & Stone 2010, etc.

SI: FROM DUST GRAINS TO >100KM ASTEROIDS / PLANETESIMALS

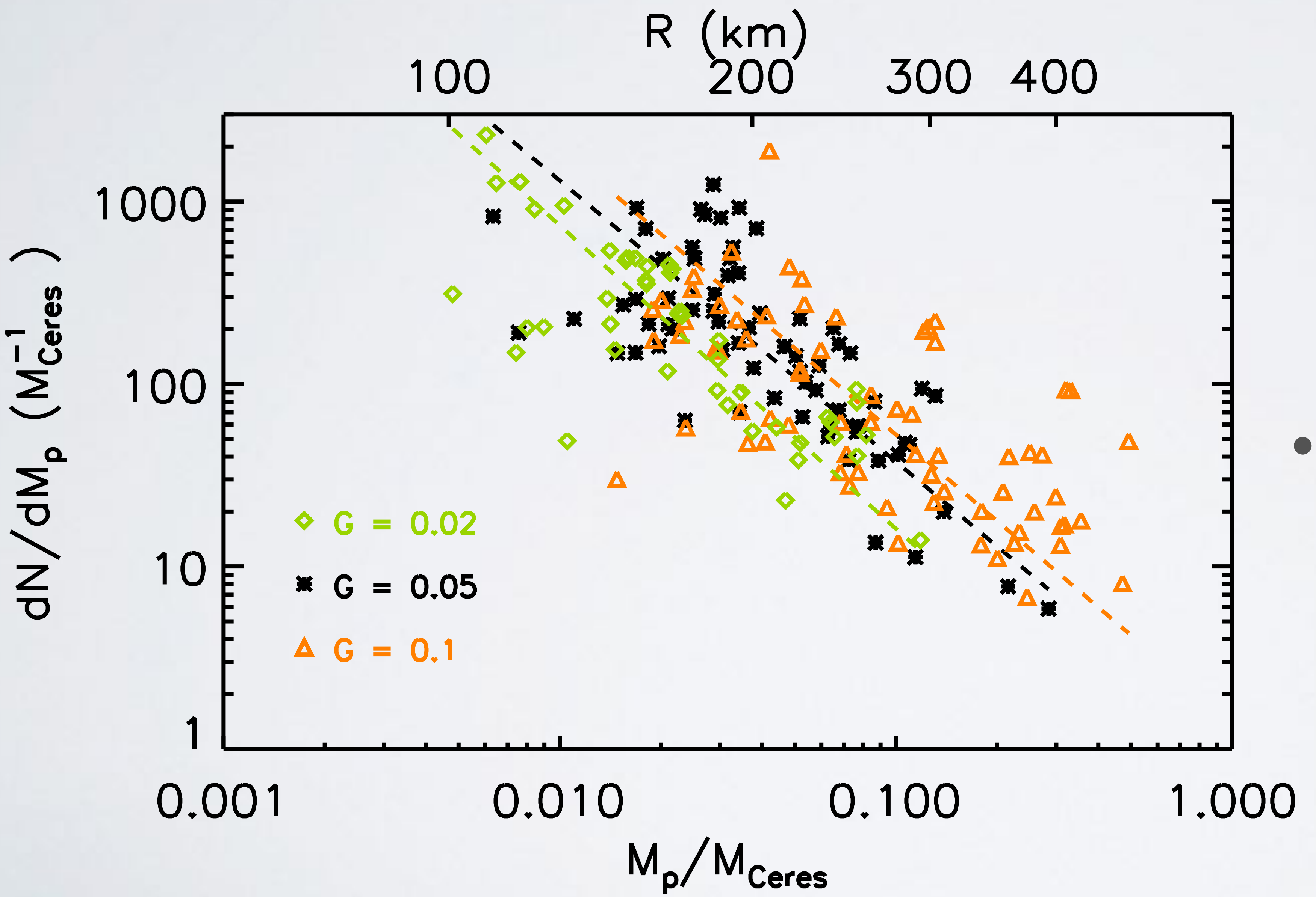
Shearing box simulation of dust particles interacting with gas

Streaming Instability + gravity turns cm size pebbles directly into asteroid size planetesimals



Movie Credit: Jake Simon

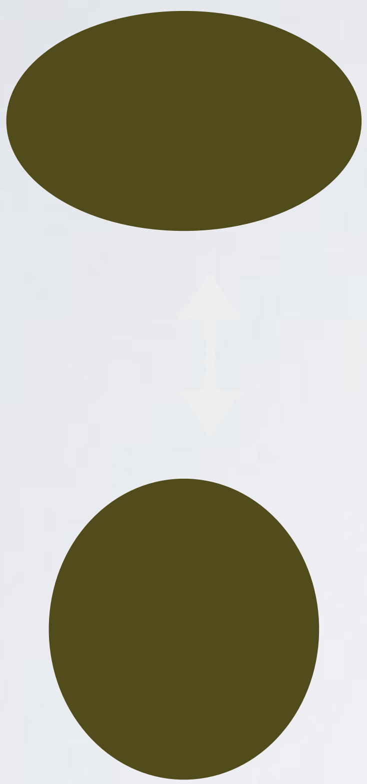
Planetesimals from SI span a wide range of sizes

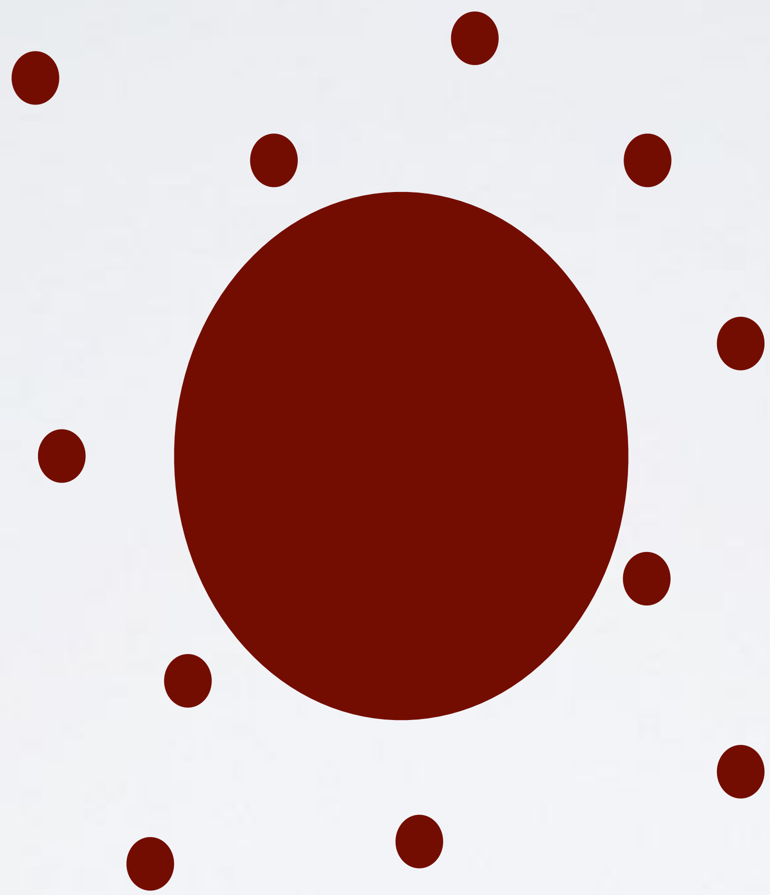


Simon et al 2016

- broad, large, initial planetesimal distribution seems consistent with Kuiper Belt objects
- not all pebbles / dust turns into planetesimals

FROM 100KM TO EARTH MASS CORES



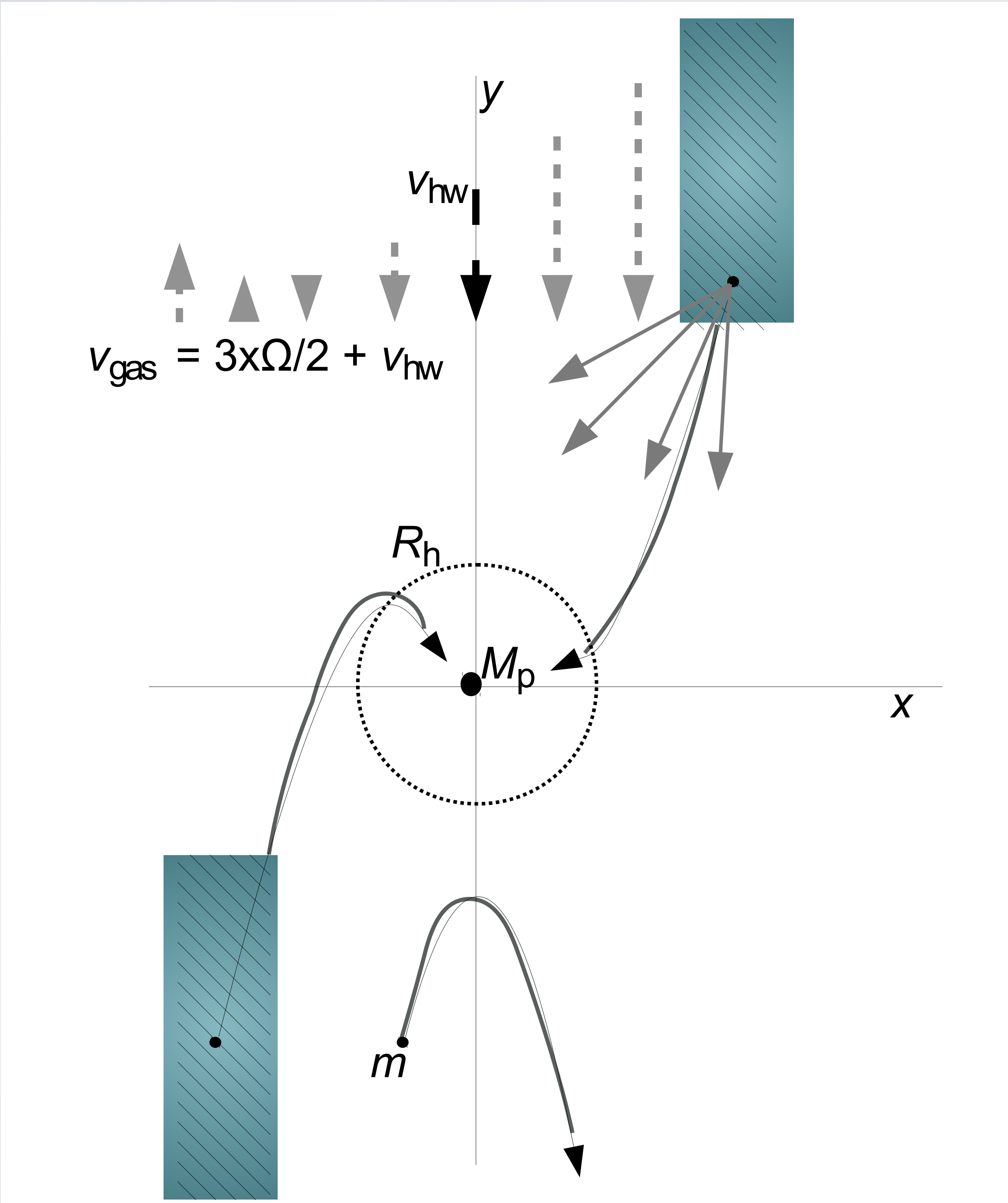


asteroid size bodies are gravitationally attracted to each other

when they collide, a lot of the mass goes into one bigger body, but smaller debris is produced as well

this, plus SI, keep a lot of mass around in "pebbles"

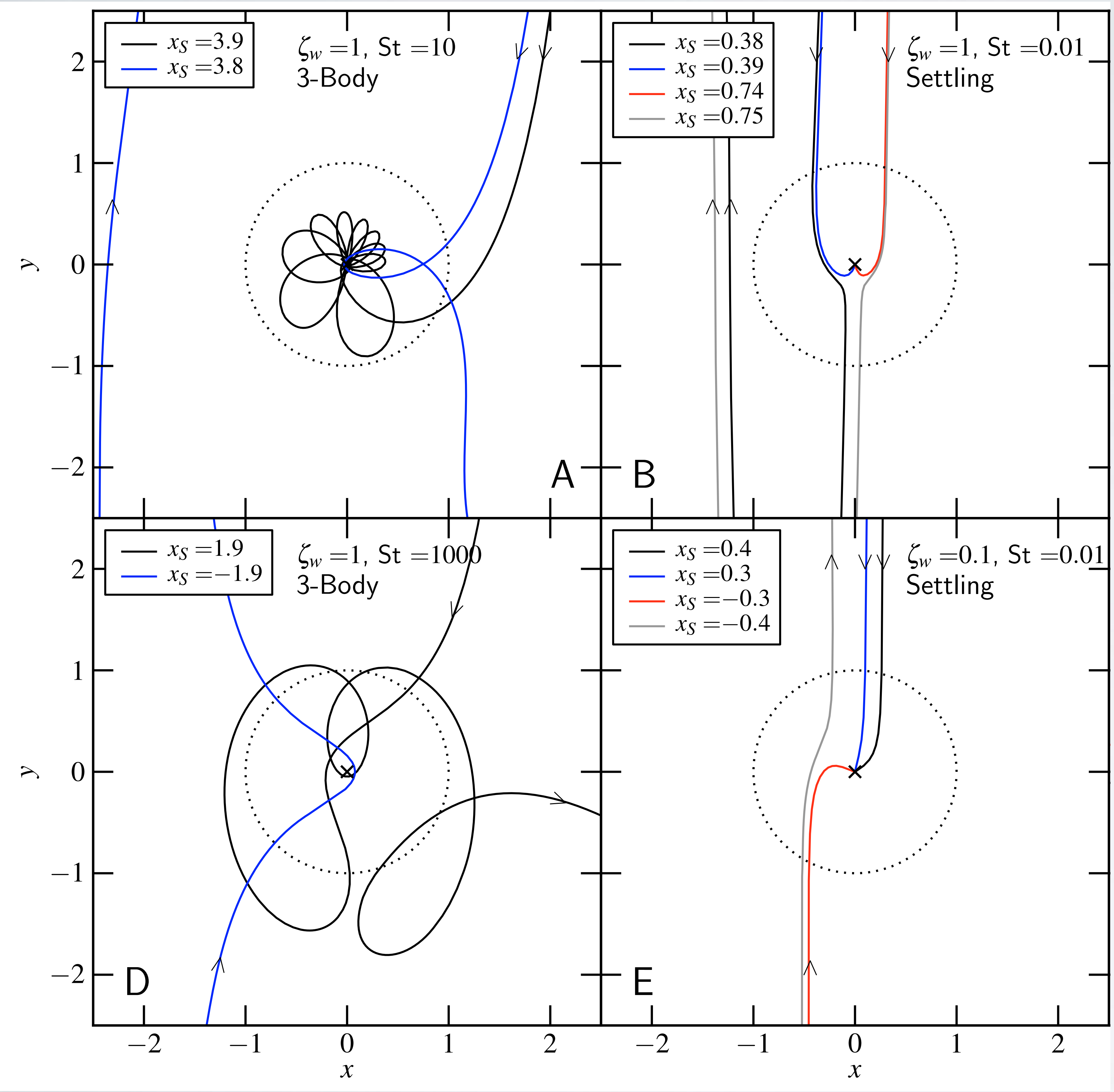
core growth via pebble accretion



Ormel & Klahr, 2010

- ignoring gas drag, only particles with just the right velocity get trapped in the Hill sphere
- including gas drag allows a wider range of particles to accrete

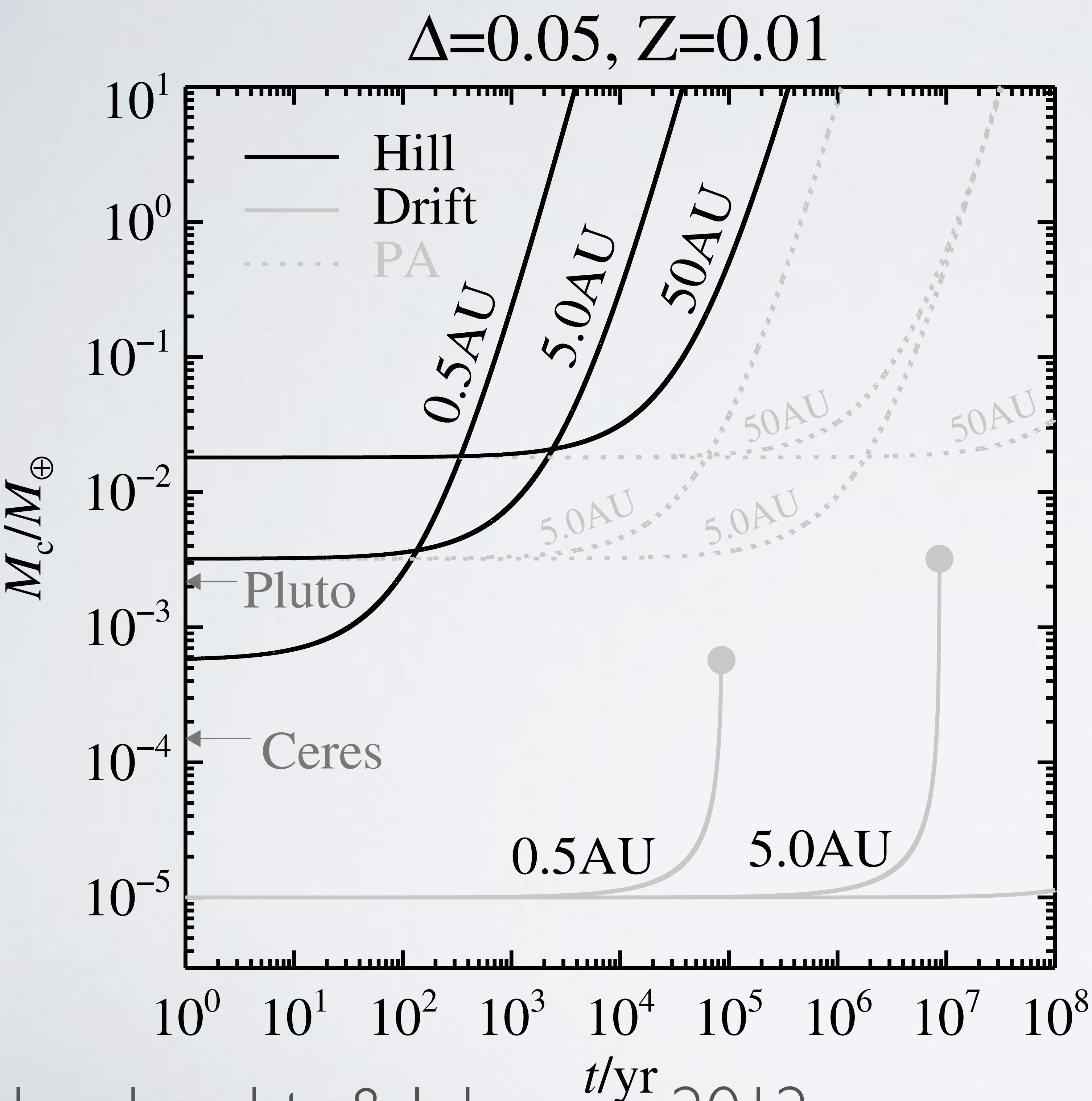
core growth via pebble accretion



- "pebbles", brought in by radial drift from the disk feel the right amount of gas drag to accrete very efficiently

Ormel & Klahr, 2010

Growth timescales change when including aerodynamic pebble capture

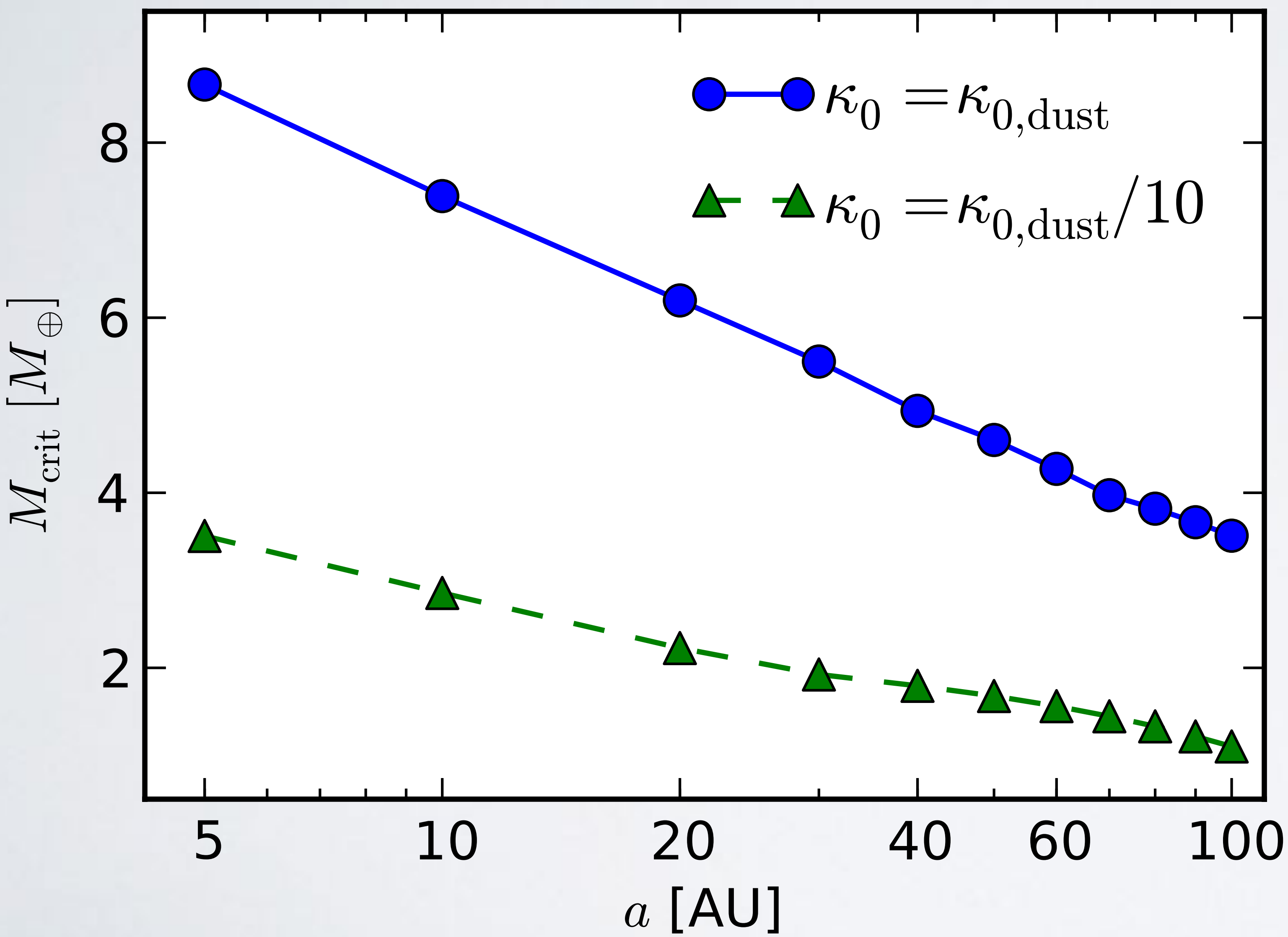


Lambrechts & Johansen 2012

- Gas giants can in principal form even at 50 AU in disk lifetime
- Problem is first mass doubling time, not the last

BUT: need initial ~pluto mass cores…

The critical core mass to trigger runaway growth declines with semi-major axis



- Even though growth times are slower, less core growth is required
- Temperature goes down, Bondi radius goes up, and opacity declines

Piso & Youdin 2014

WHAT'S SO ~~HARD~~ EASY! ABOUT PLANET FORMATION (ESP. IN THE OUTER DISK?)

- ~~Classic~~ Modern Problems:
  - ~~growing up to meter size bodies via coagulation is difficult~~

    particle traps!
  - ~~growing through the "meter size" barrier is an extreme challenge due to radial drift~~

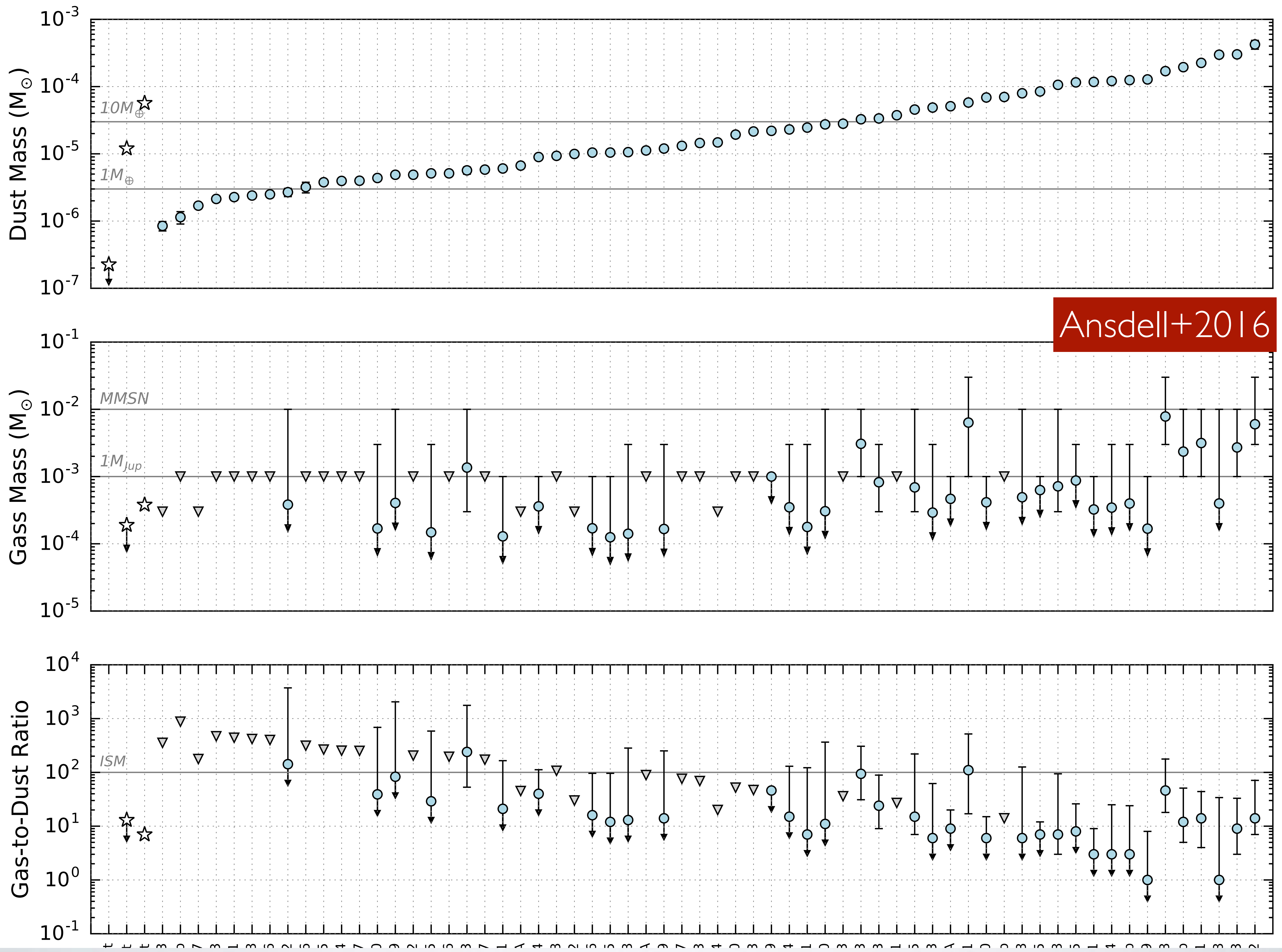
    planetesimals from SI!
  - ~~It takes longer than the disk lifetime (few Myr) to build a big enough solid core mass to trigger runaway atmospheric growth to make a gas giant~~

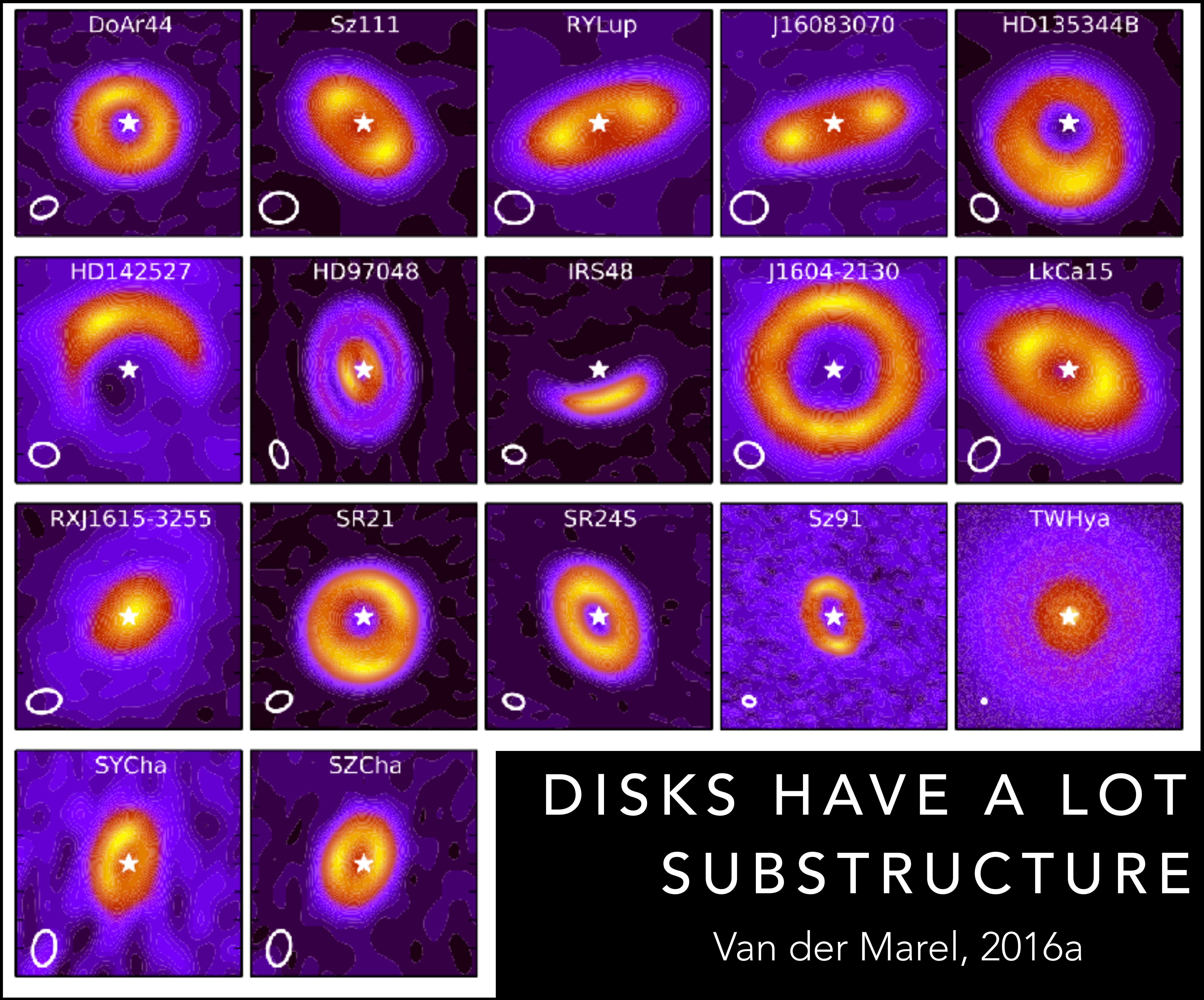
    pebble accretion!

REMAINING CHALLENGES (ABRIDGED)

- Planet migration is too fast
- We haven't found enough massive disks
- Disk substructure indicates more giant planets than we observe

where is all the mass?

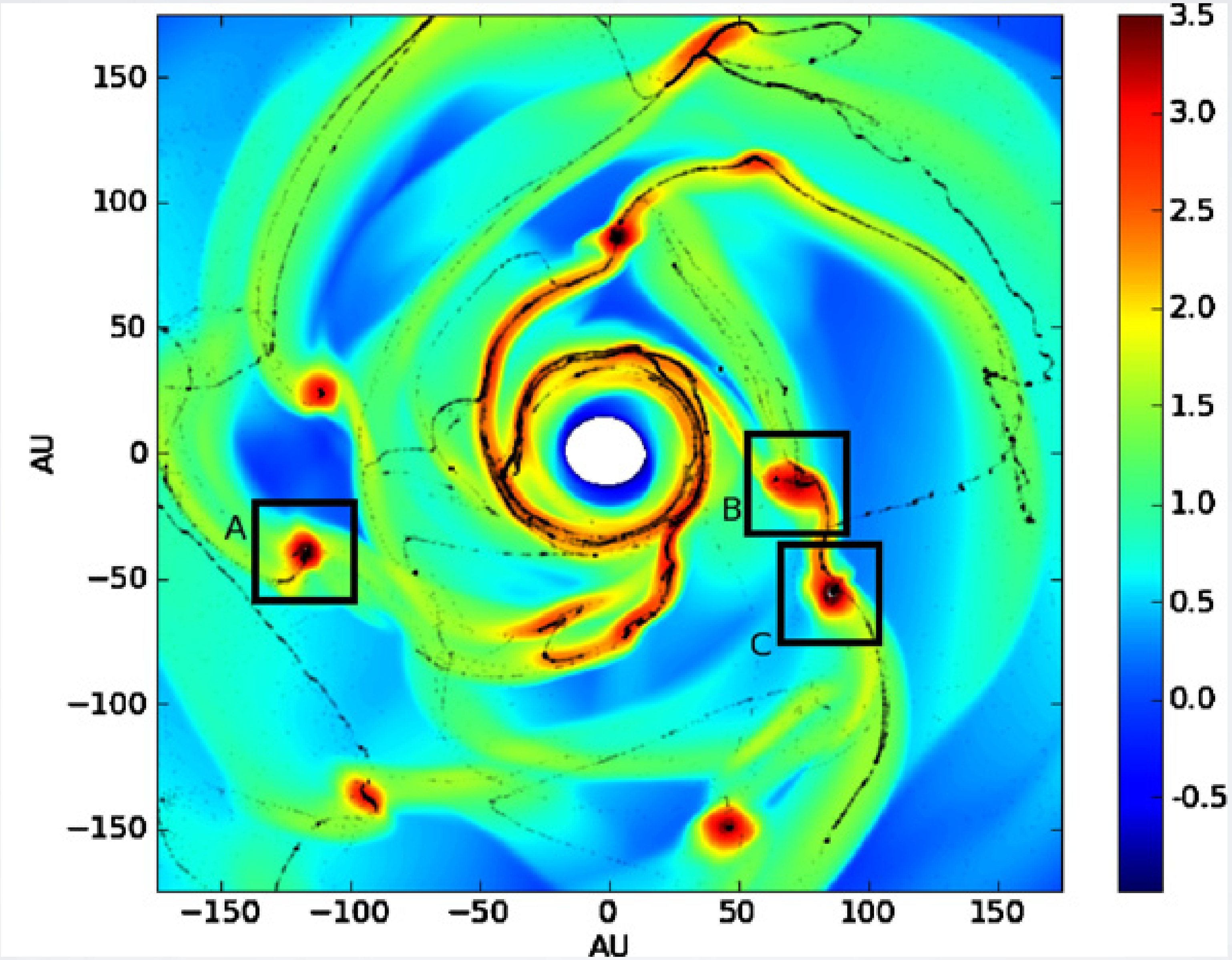




DISKS HAVE A LOT OF SUBSTRUCTURE

Van der Marel, 2016a

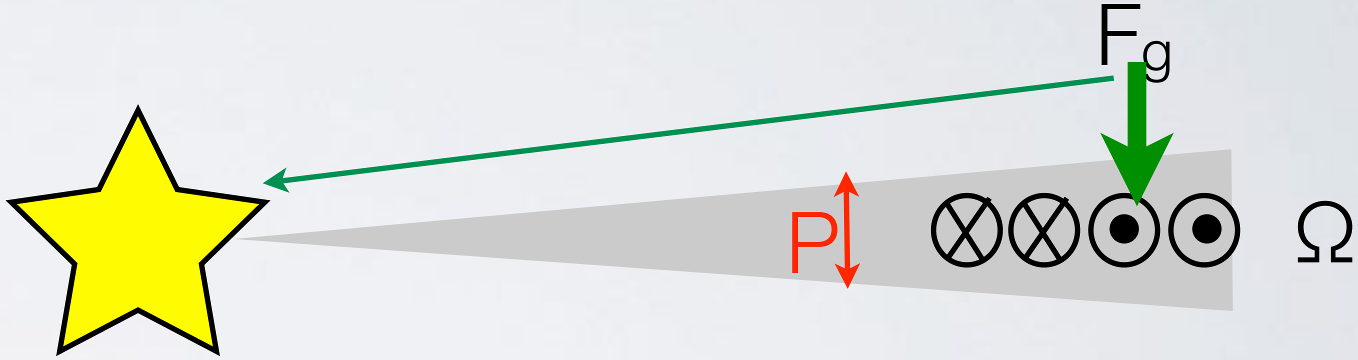
WHAT ABOUT PLANETS FROM GRAVITATIONAL INSTABILITY?



Boley+2011

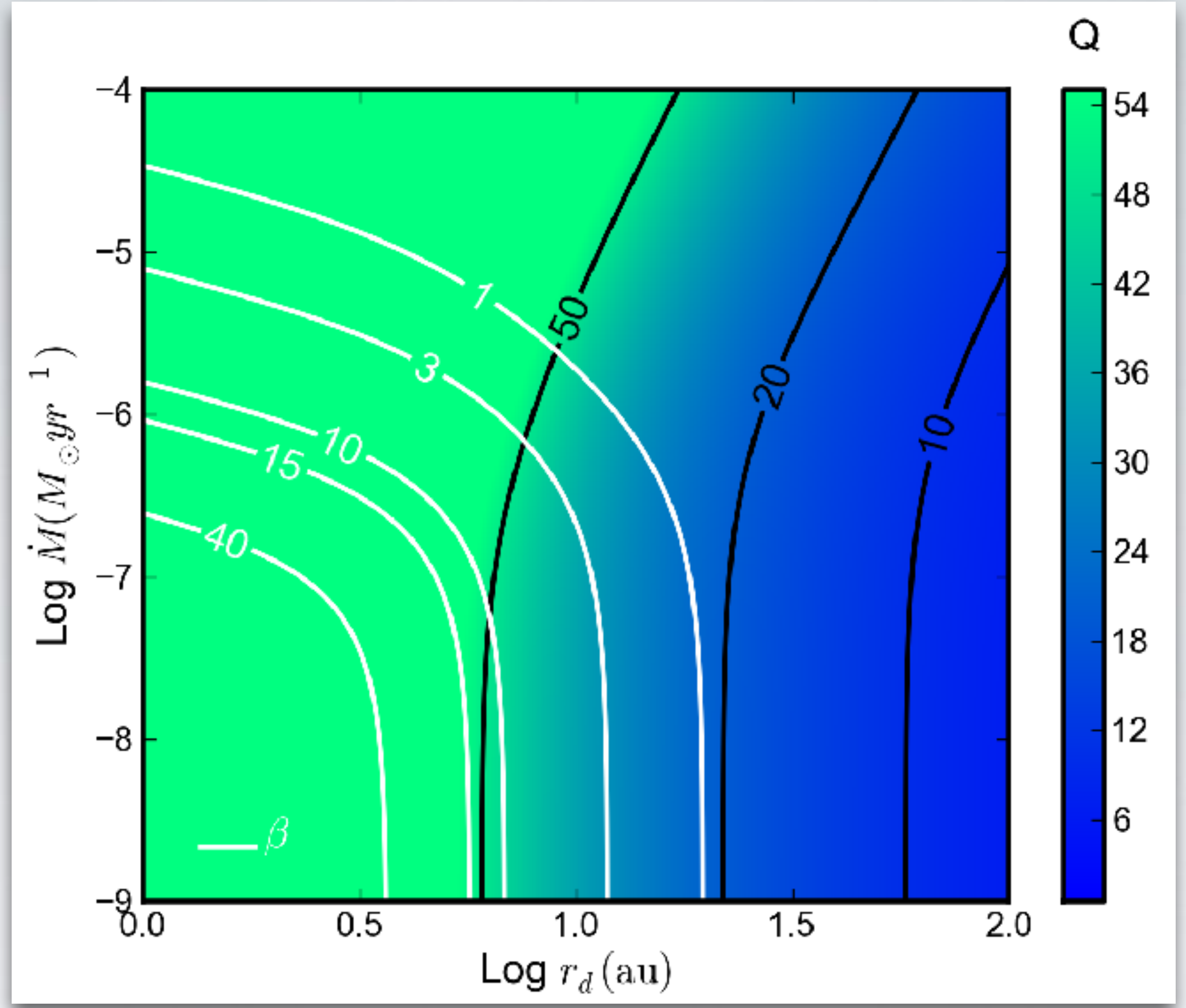
WHAT IS GRAVITATIONAL INSTABILITY?

- A hydrodynamic instability that arises in rotationally supported disks when **self-gravity** wins out over **pressure** support on small scales, and stabilization due to **shear** on large scales



$$Q = \frac{c_s \Omega}{\pi G \Sigma} = f \frac{M_*}{M_D} \frac{H}{r}$$

Fragmentation is the non-linear outcome of this instability



Conditions for measured Class I disks around sun-like stars are typically too low in mass and too hot to be unstable

Kratter & Lodato, 2016

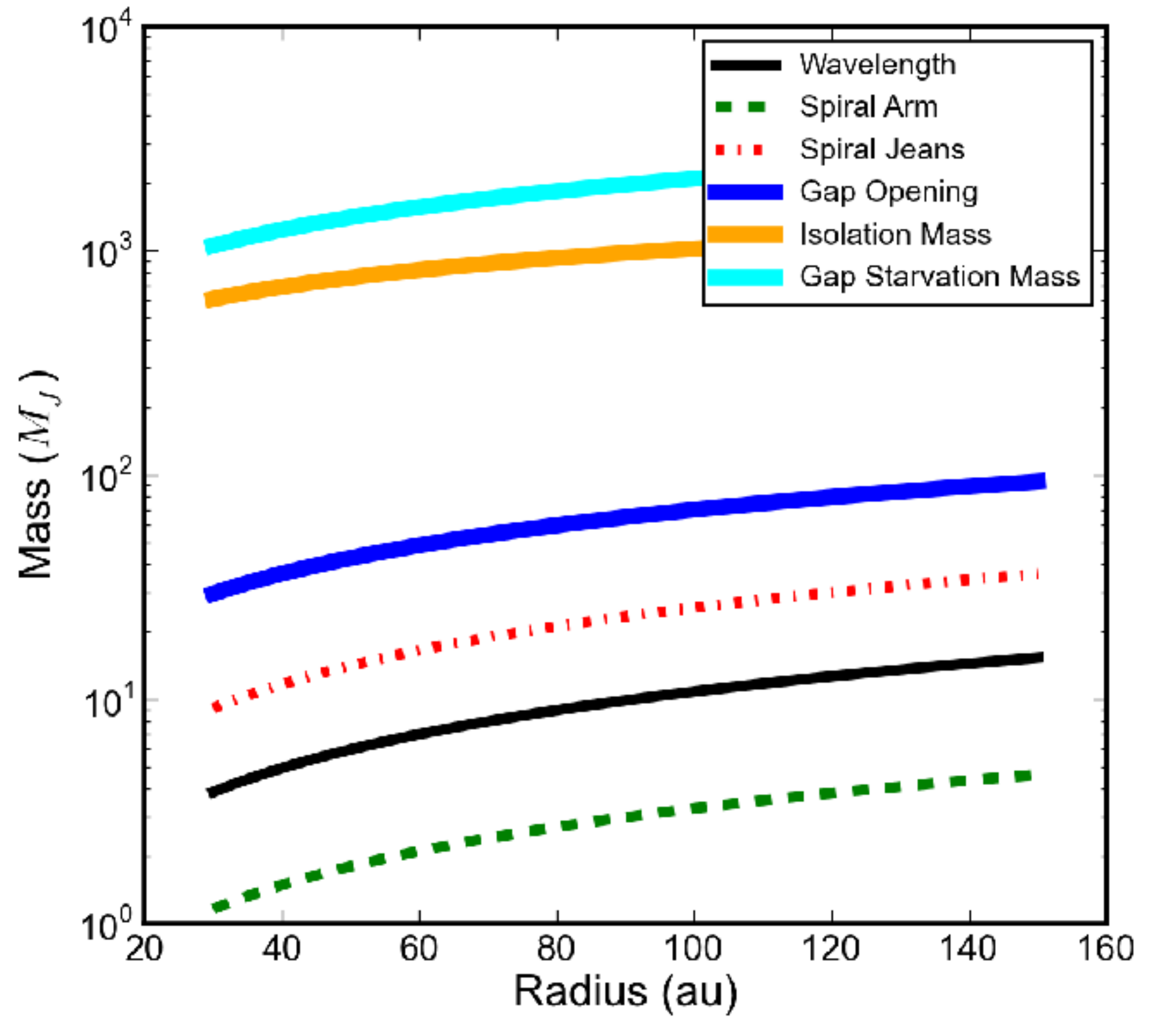
How big are objects that form via GI?

- Initial mass estimates all scale with

$$\Sigma H^2$$

- Fragments that are not disrupted can also easily grow from the parent disk

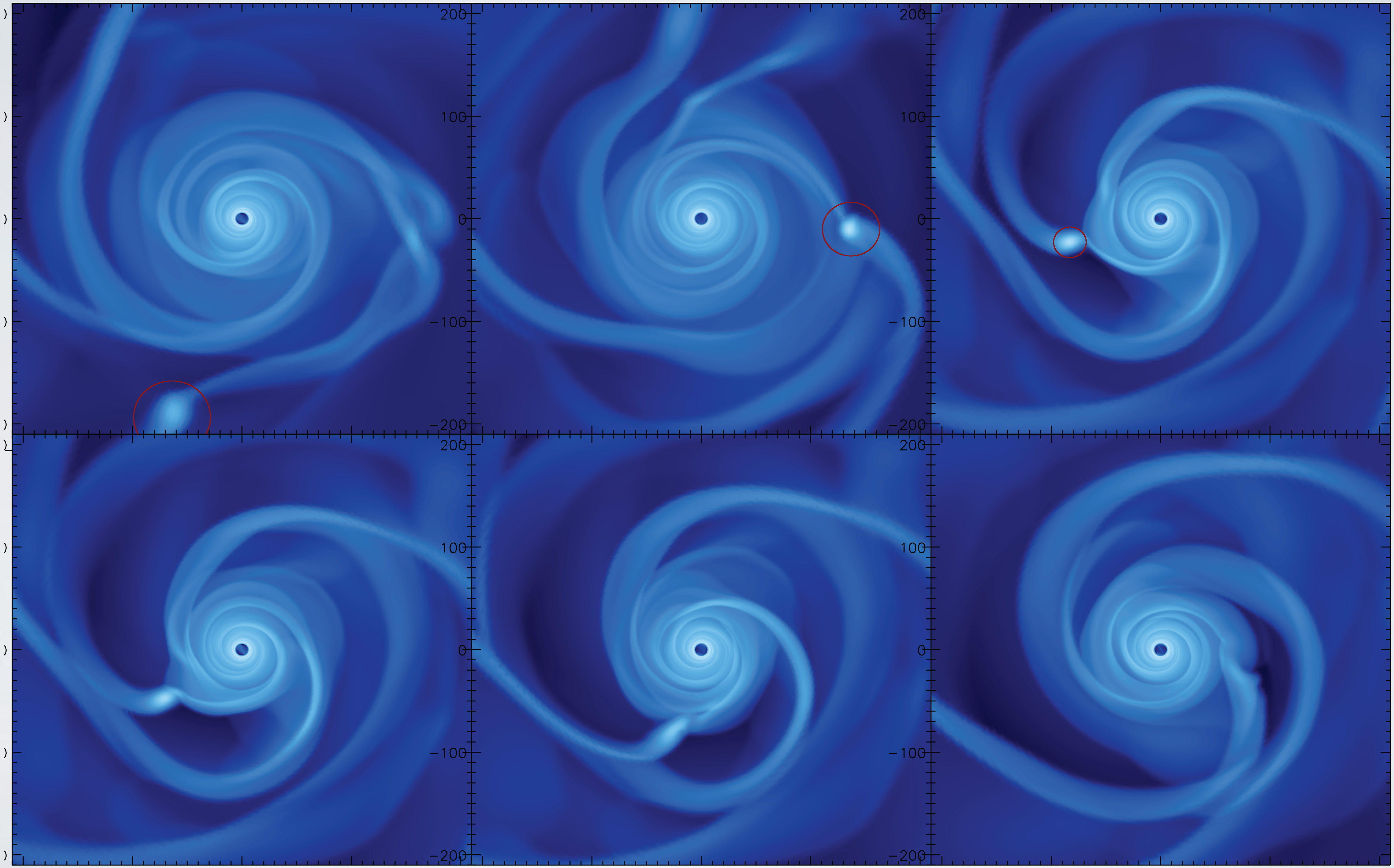
Kratter+2010, Boley+2010, Forgan & Rice 2013, Young & Clarke 2015



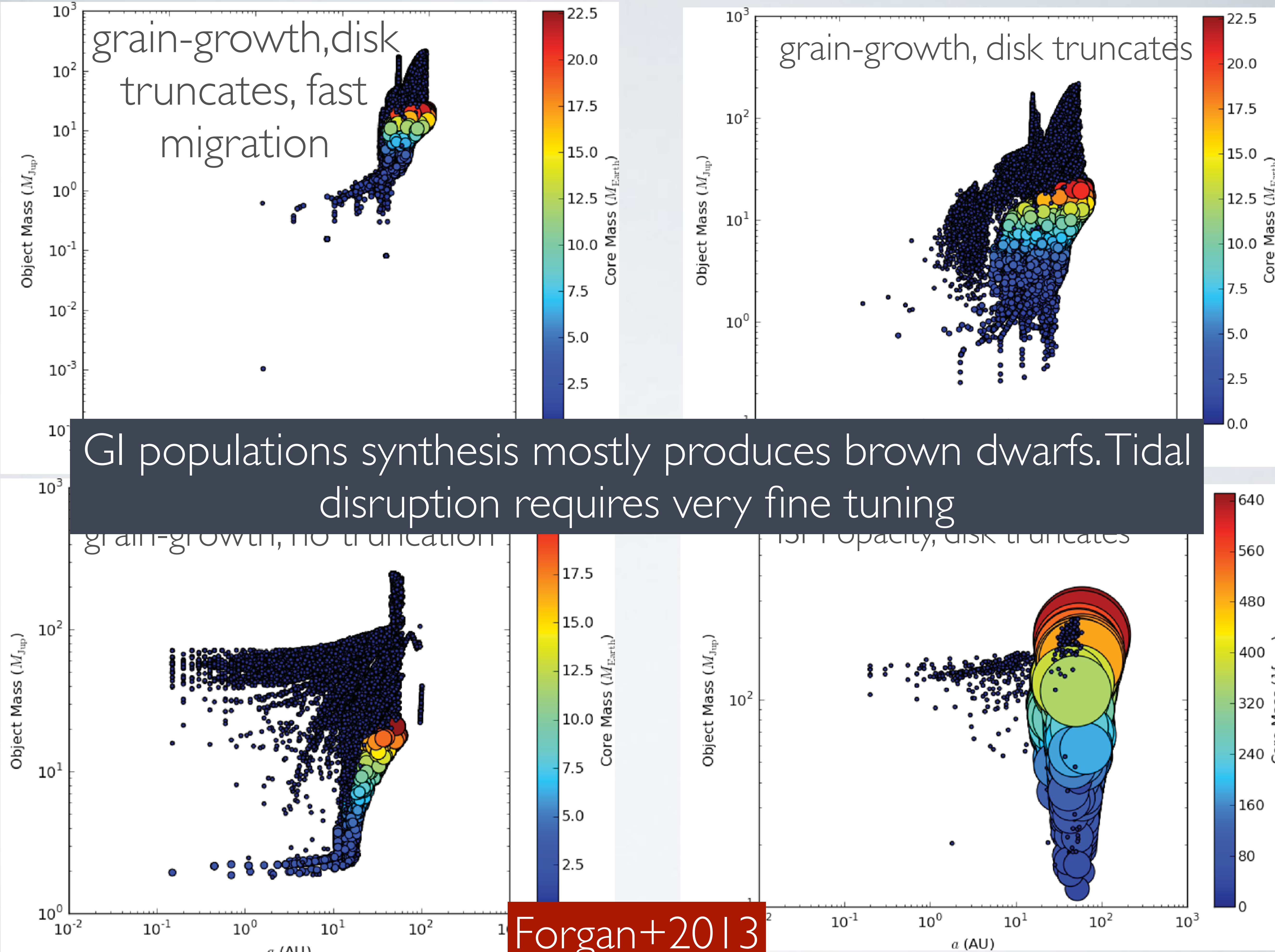
Growth, Migration, Disruption

Fragments migrate inwards on ~10 outer dynamical timescales.

$$\tau_{mig} = 784 \left(\frac{M_c}{0.01 M_\odot}\right)^{-1} \left(\frac{R}{100 AU}\right)^{1.75} yr$$



Zhu et al 2012

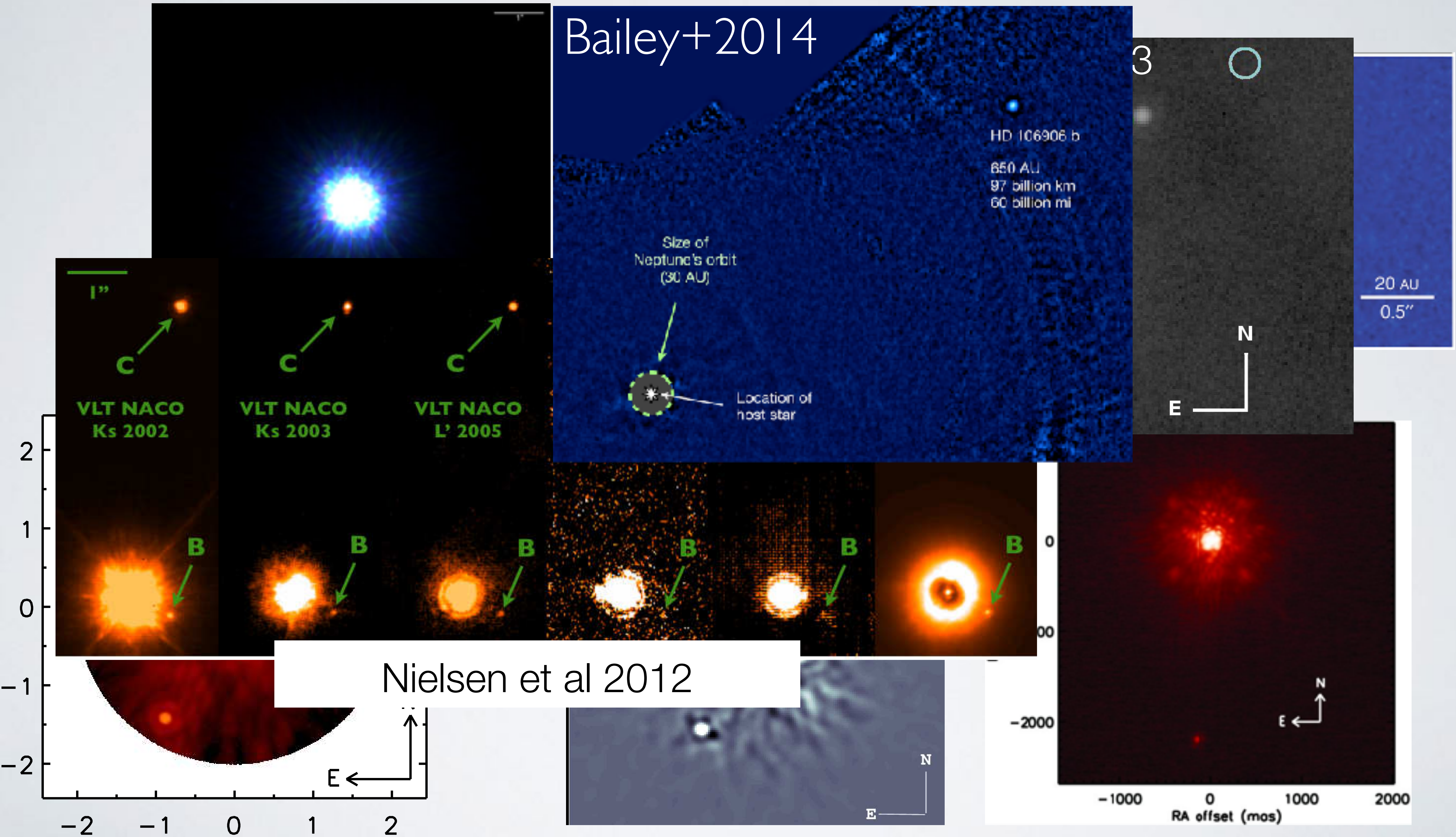


GI populations synthesis mostly produces brown dwarfs. Tidal disruption requires very fine tuning

Forgan+2013

THE RUNTS OF THE LITTER?

(KRATTER ET AL, 2010B)



Hinkley + 10, Marois+ 10,Lafrieniere +11, Janson+11, Ireland+11, Crepp+12

THANKS FOR YOUR ATTENTION

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