Pebble Accretion in Protoplanetary Disks

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OTHER WORLDS LABORATORY

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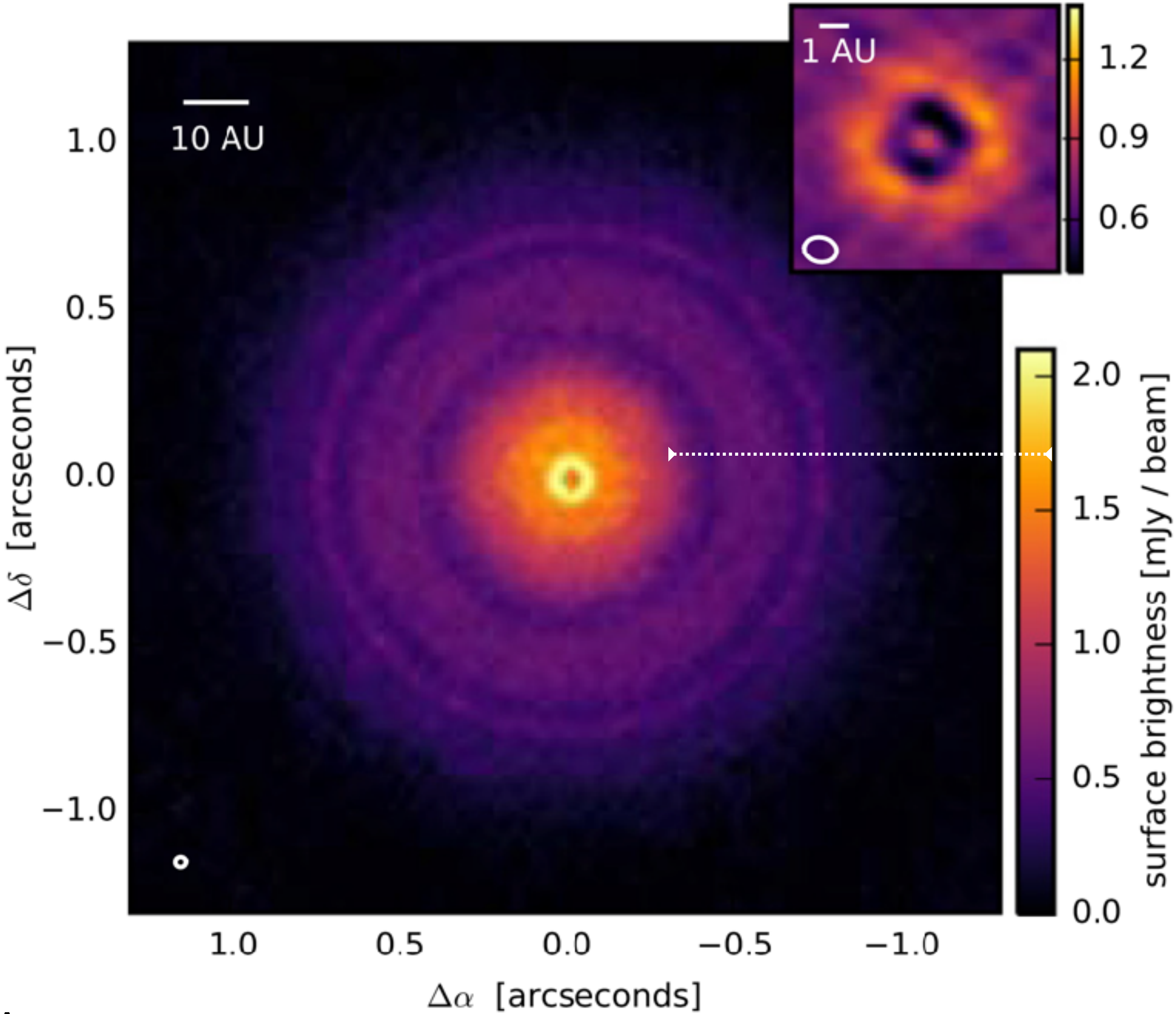
Image Credit: NASA

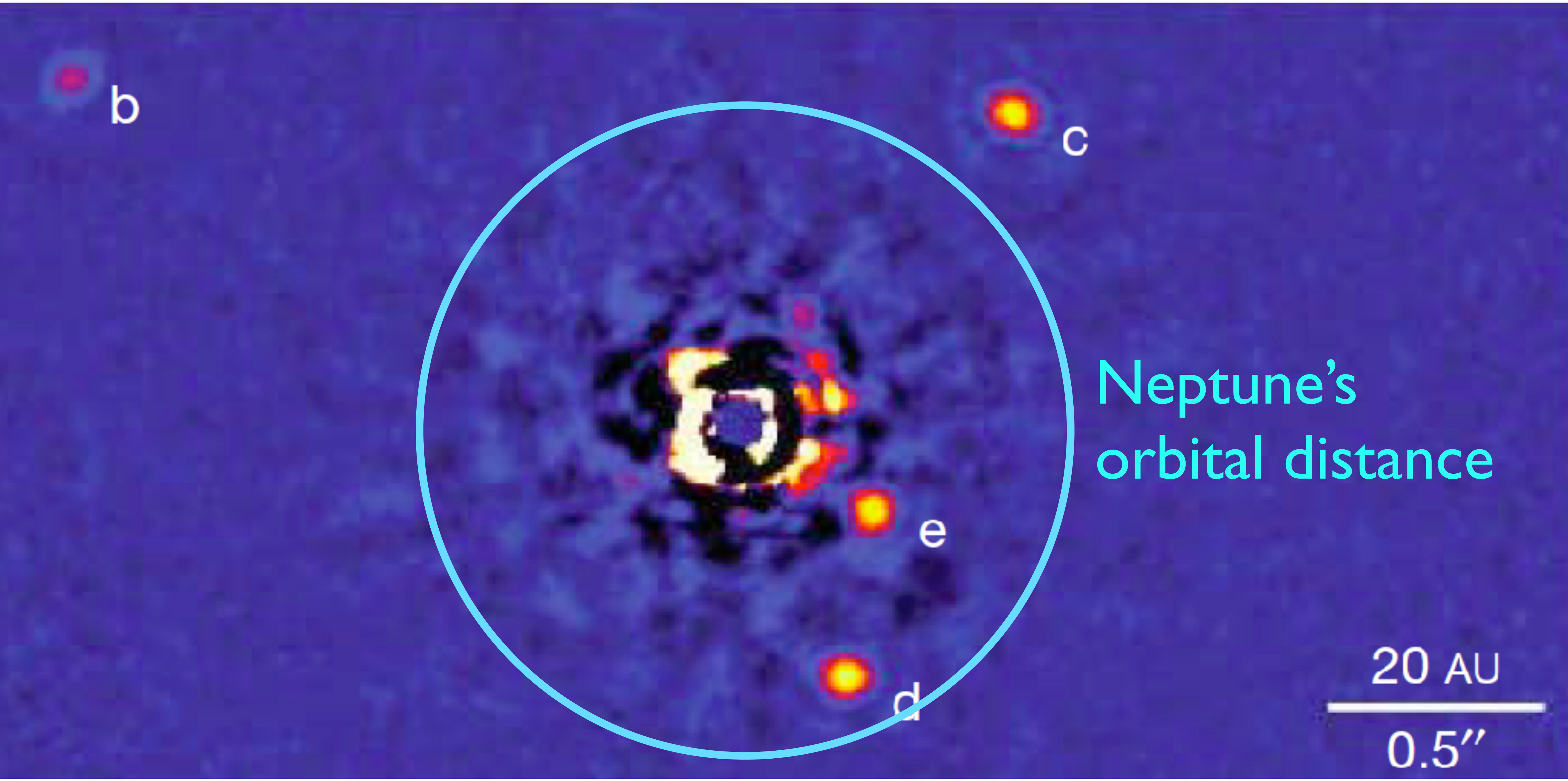
TW Hydra



ALMA

Andrews et al. 2016

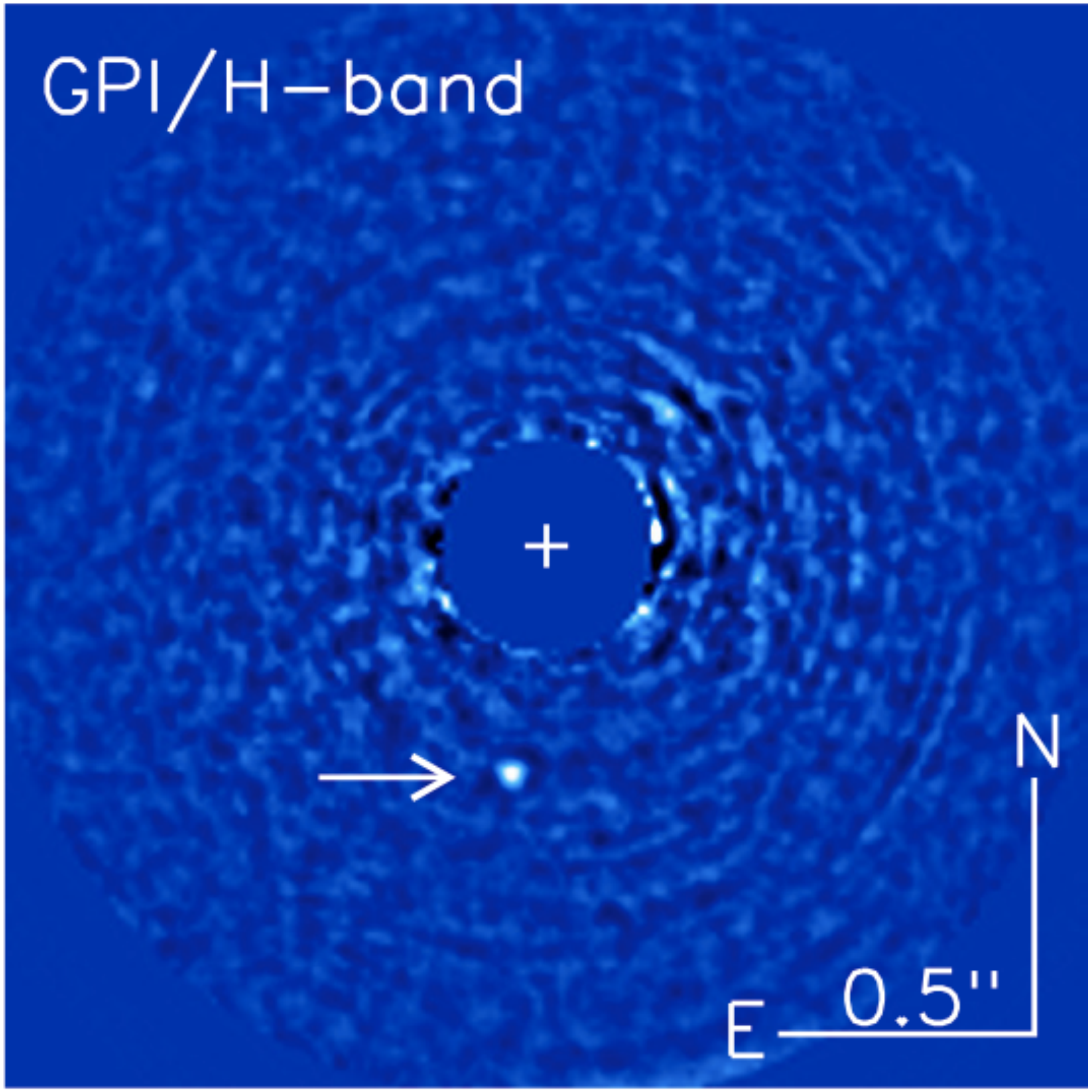
HR 8799: A testbed for planet formation theories



Marois et al. 2010

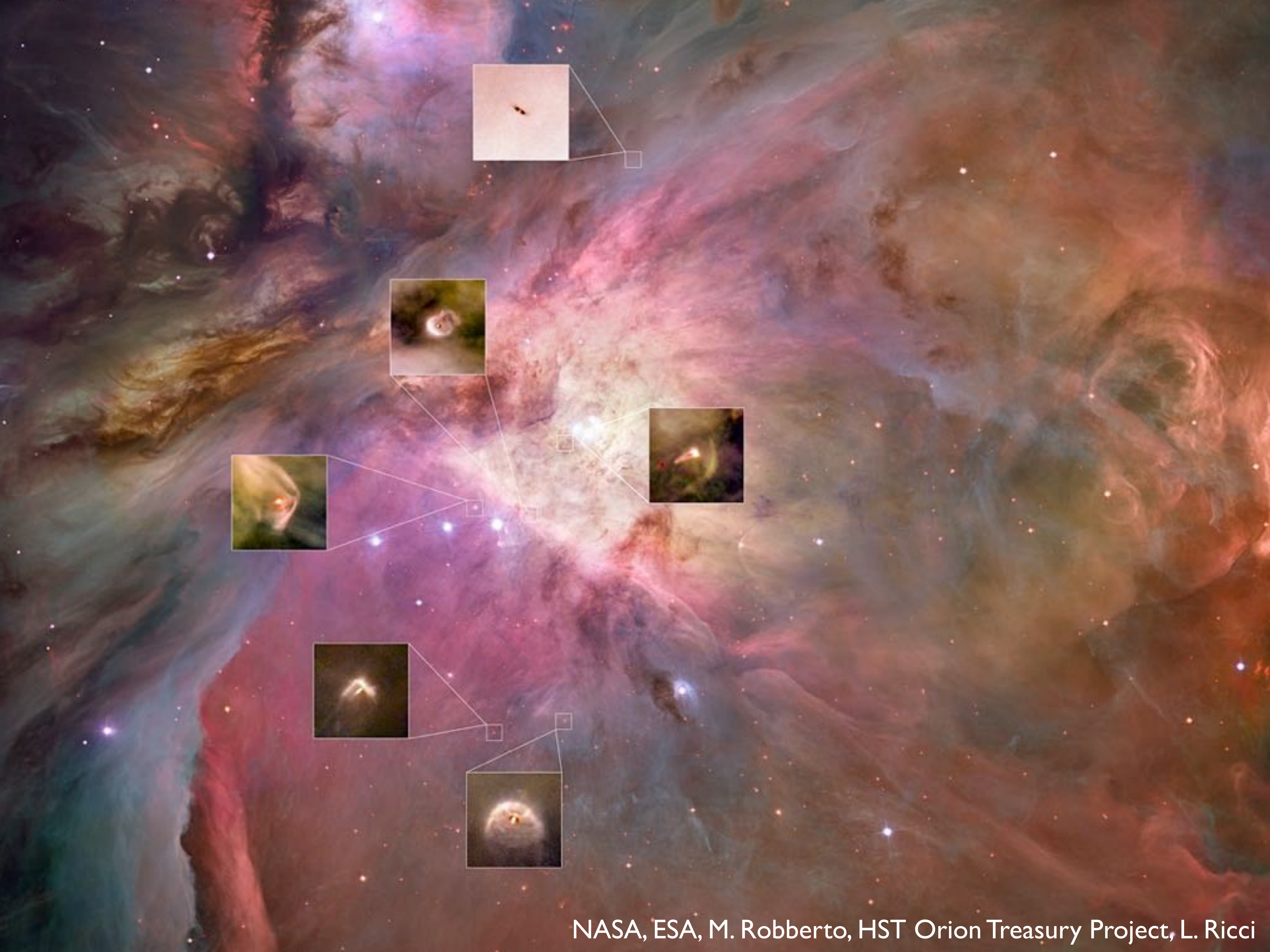
51 Eridani b

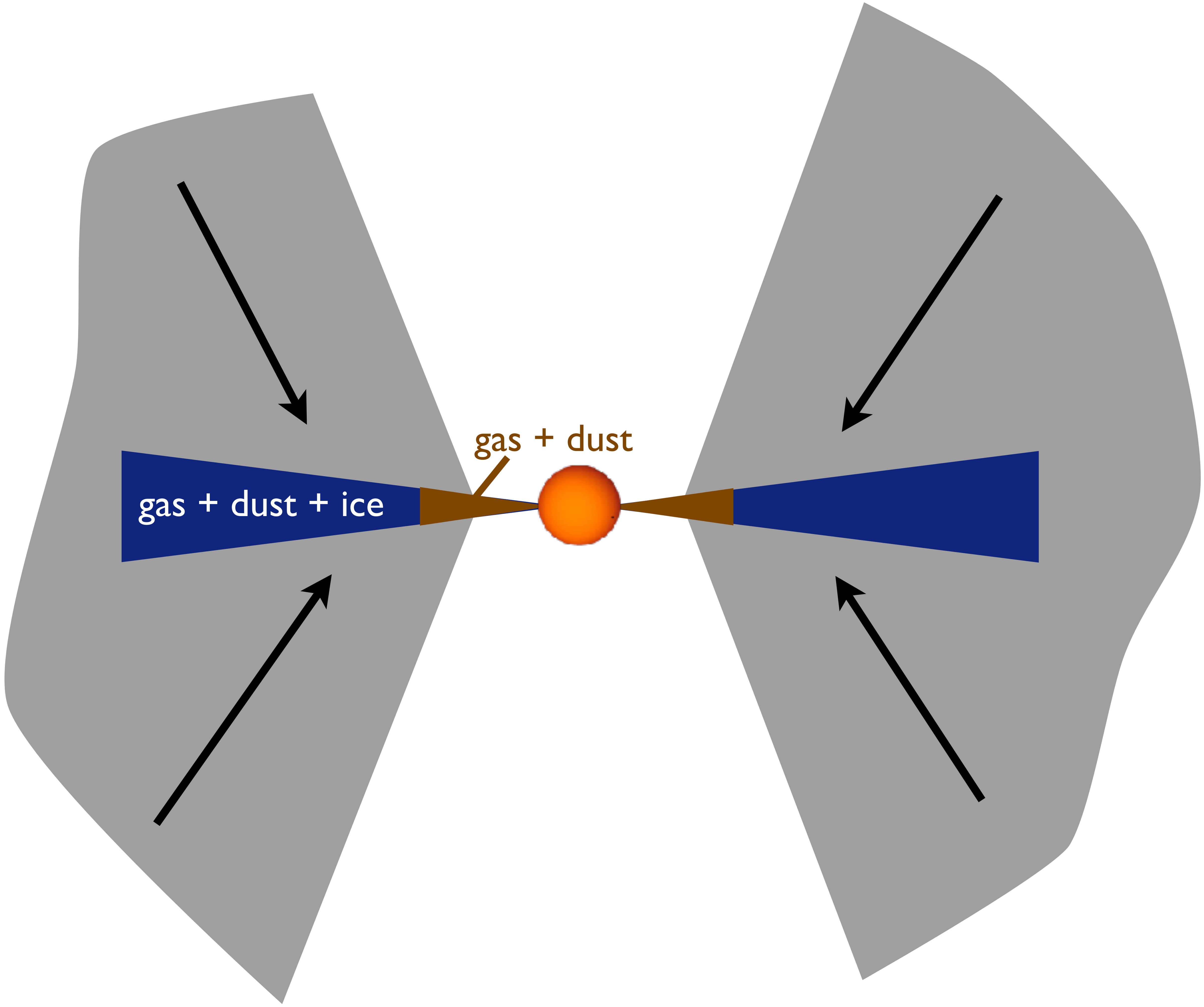
Only a few giant planets or brown dwarfs have been found at wide separations, despite extensive searches.



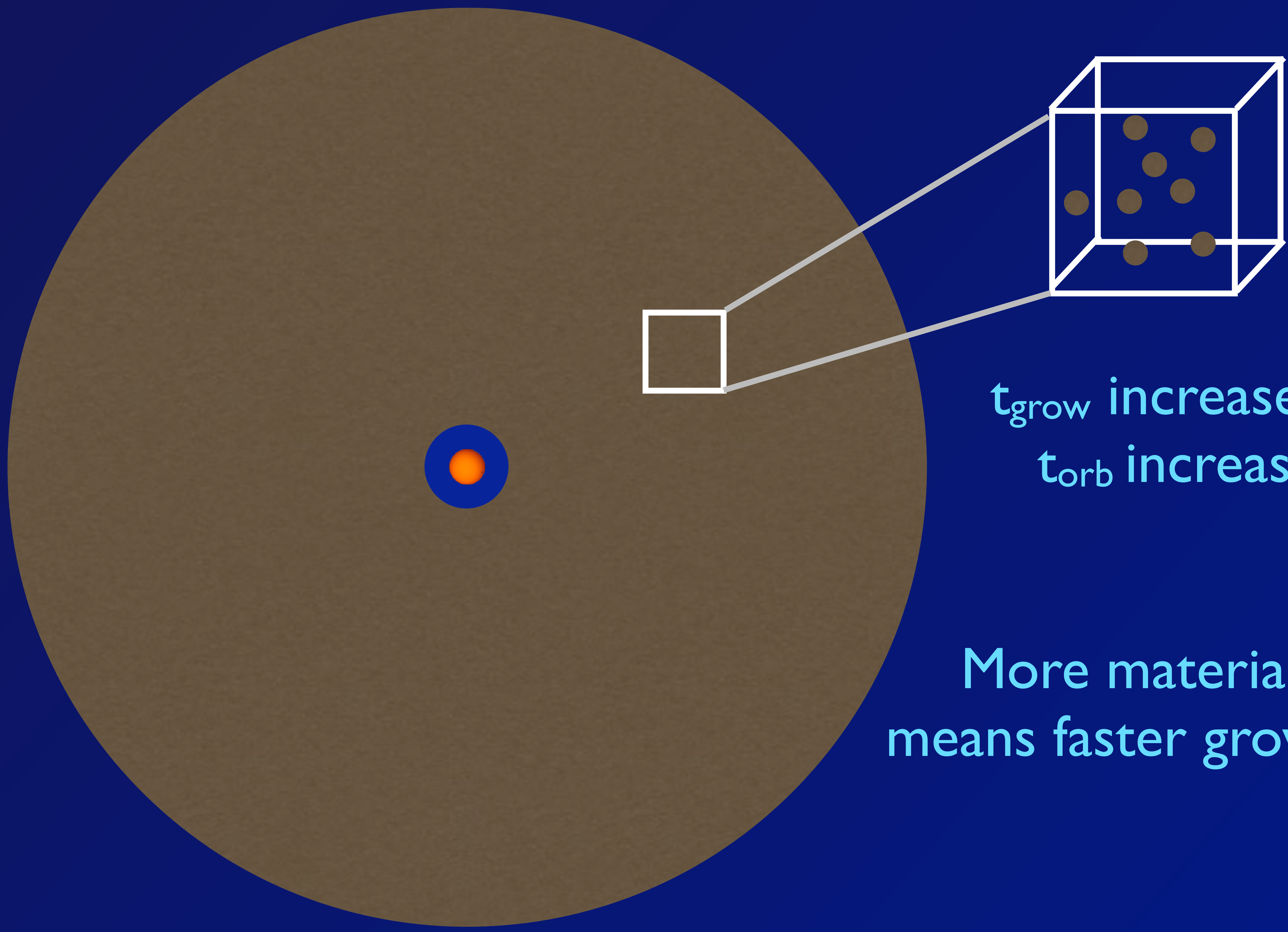
2-12 M_{Jup}
13 AU

Macintosh et al. (2015)


NASA, ESA, M. Robberto, HST Orion Treasury Project, L. Ricci

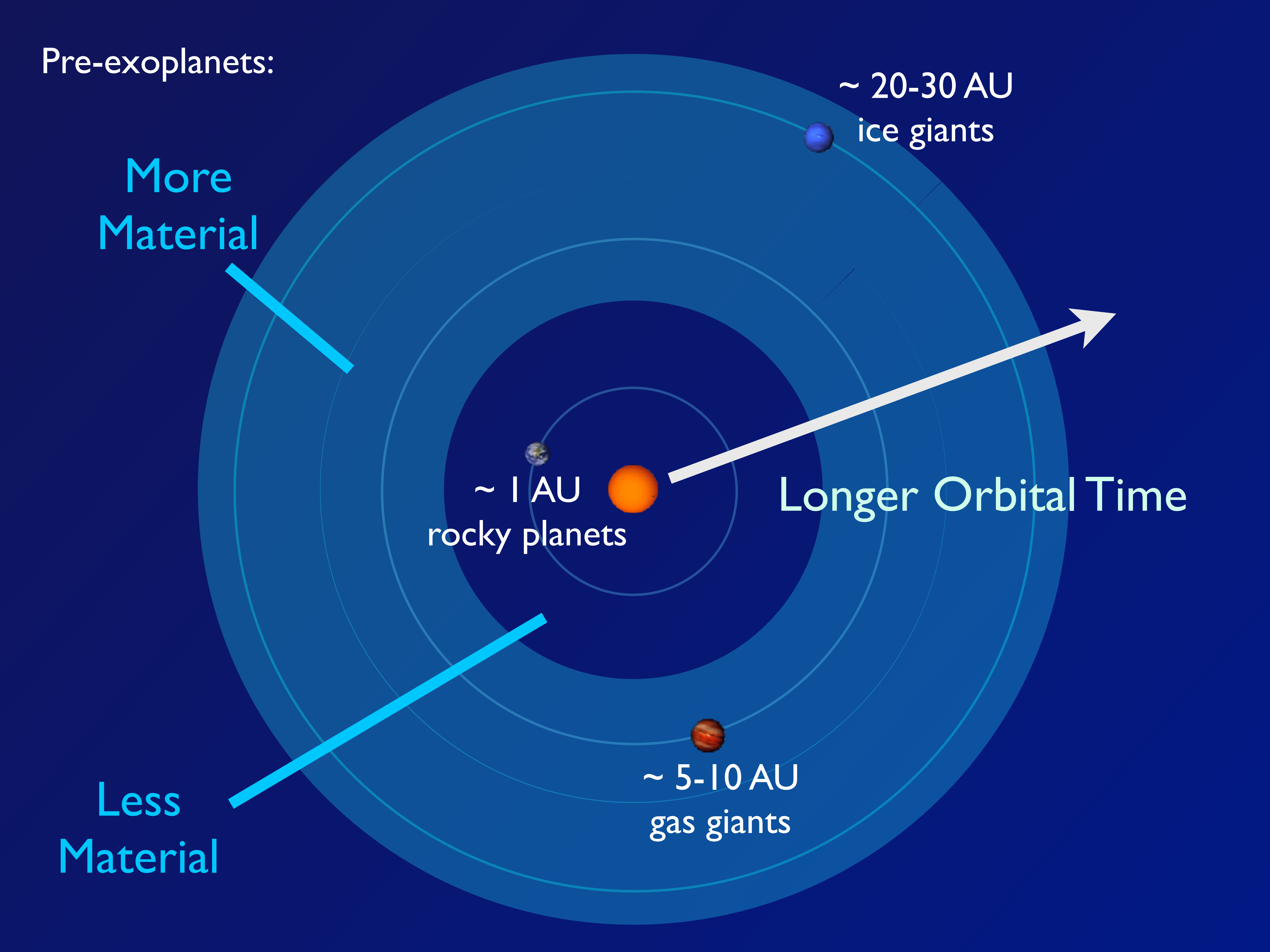

gas + dust
gas + dust + ice

Solids grow through collisions in the disk

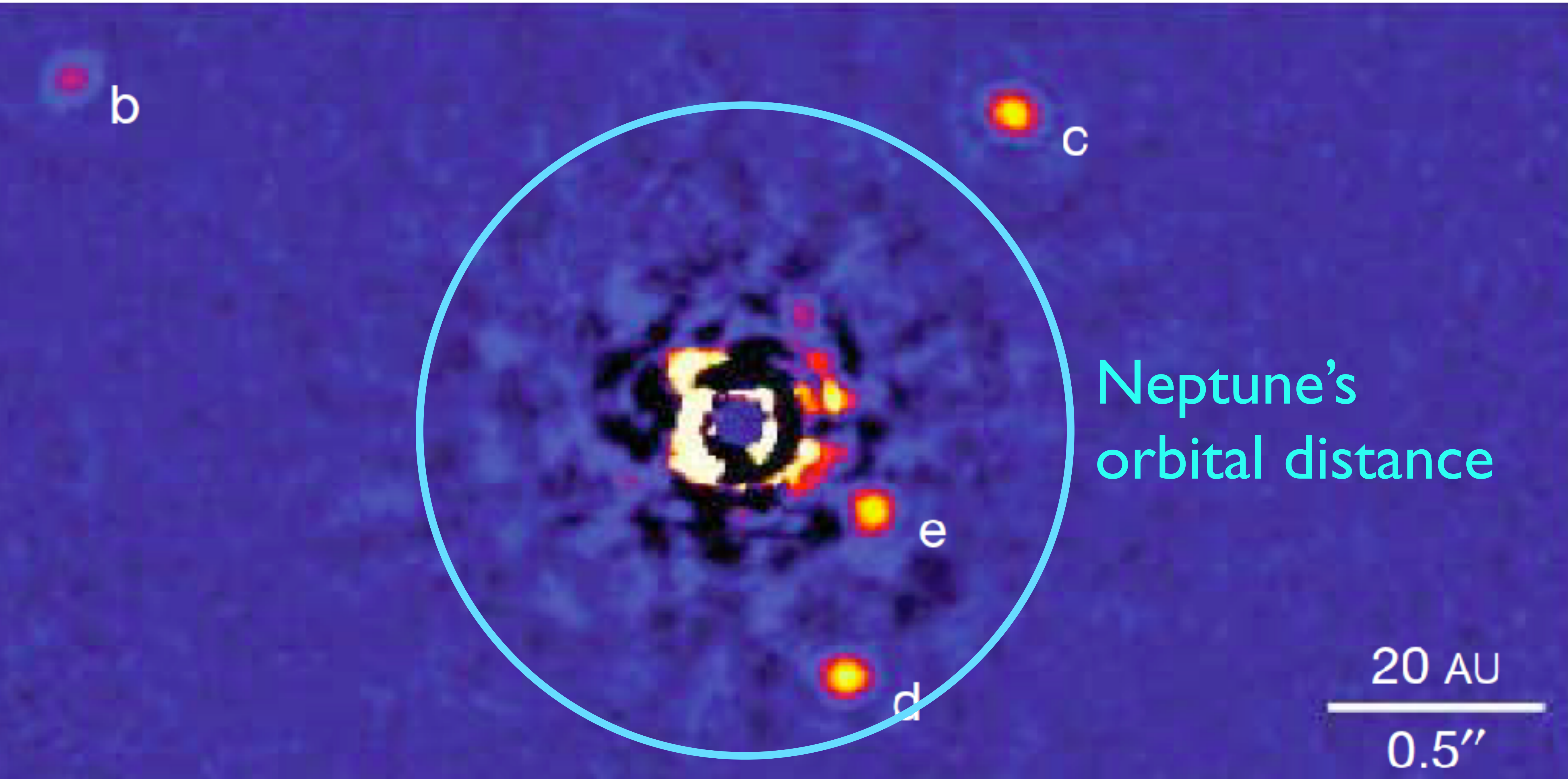


t_{grow} increases as t_{orb} increases

More material means faster growth


Pre-exoplanets:
~ 20-30 AU
ice giants
More
Material
~ 1 AU
rocky planets
Longer Orbital Time
Less
Material
~ 5-10 AU
gas giants

HR 8799: A testbed for planet formation theories

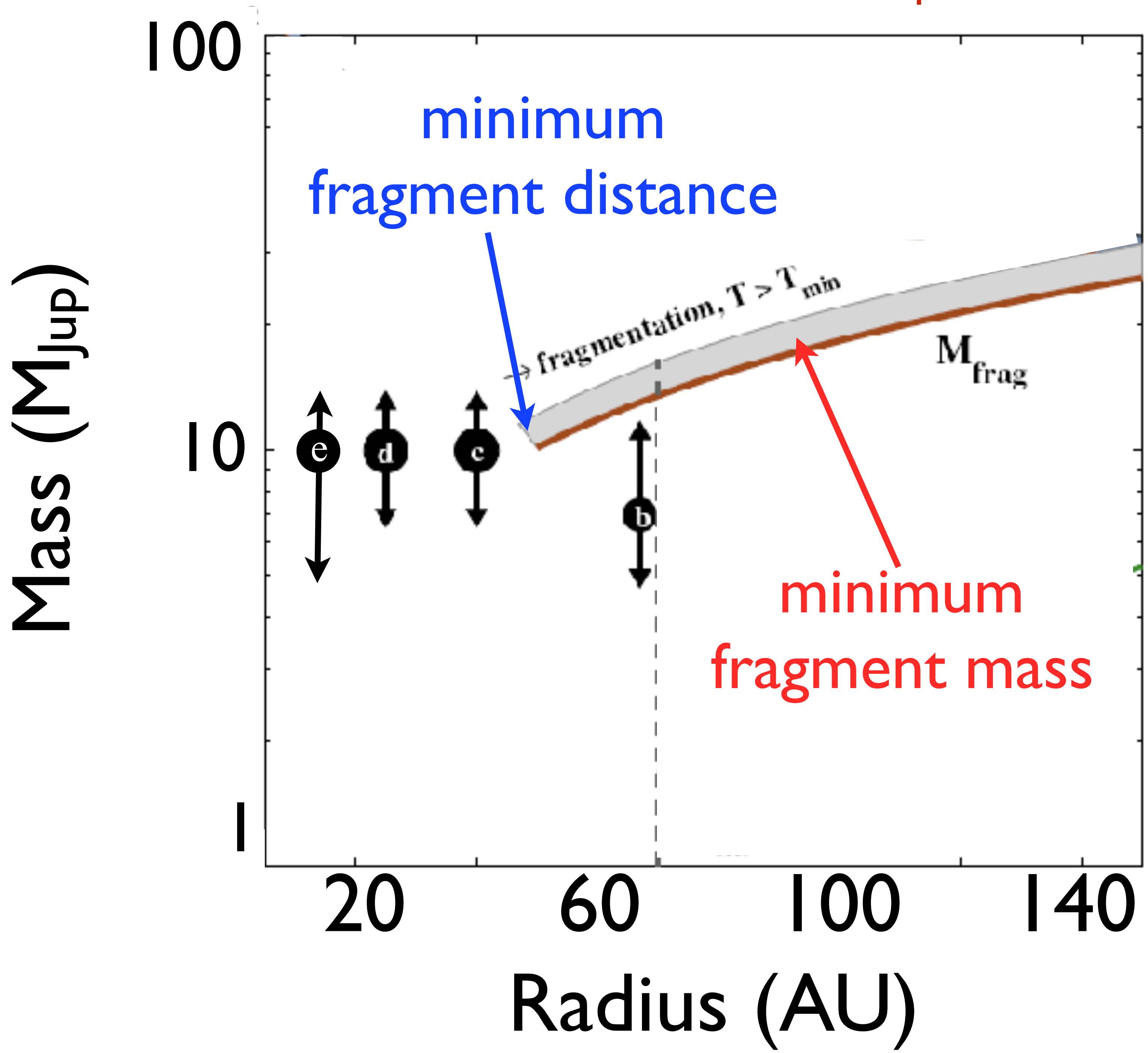


Marois et al. 2010

Gravitational Instability?

Planets cannot grow after fragmentation and they must migrate in

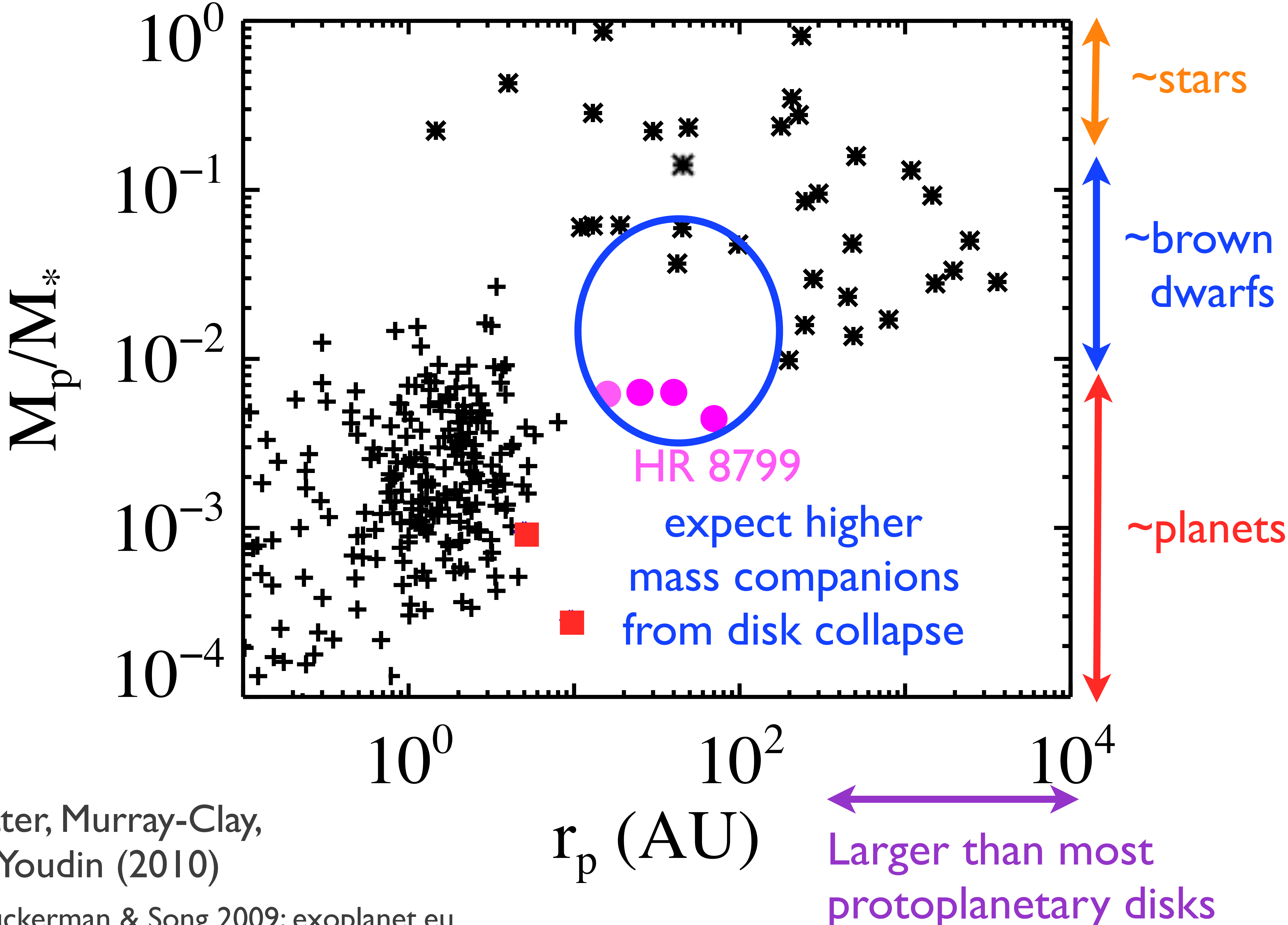
Problem because GI requires strong accretion



HR8799

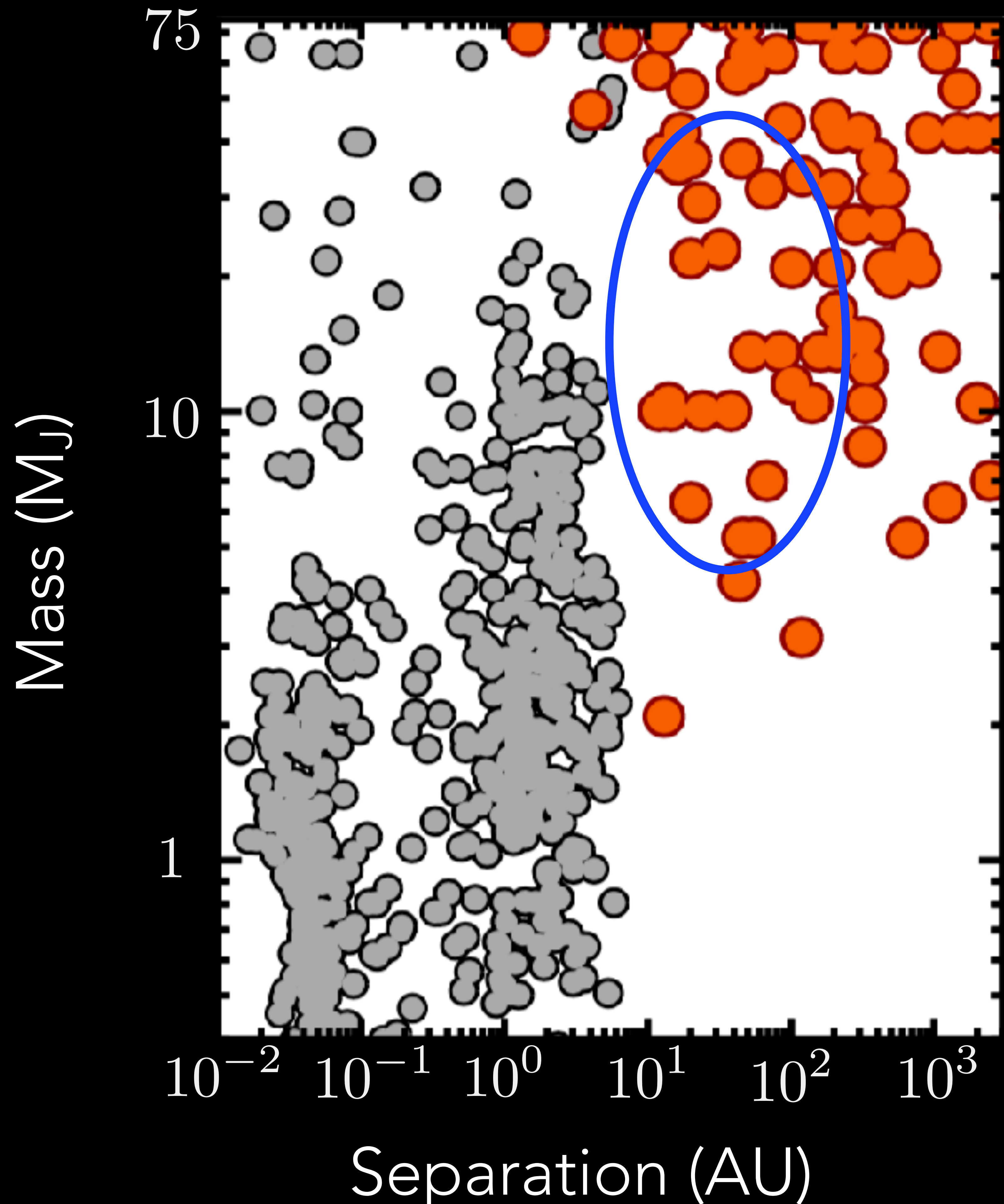
Kratter, Murray-Clay, & Youdin, ApJ 2010

Gravitational instability planets can only be failed binary stars



Kratter, Murray-Clay, & Youdin (2010)

Data: Zuckerman & Song 2009; exoplanet.eu



The possibility of a third Gravitational Instability population isn't dead.

Bowler (2016)

Wide separation giants:

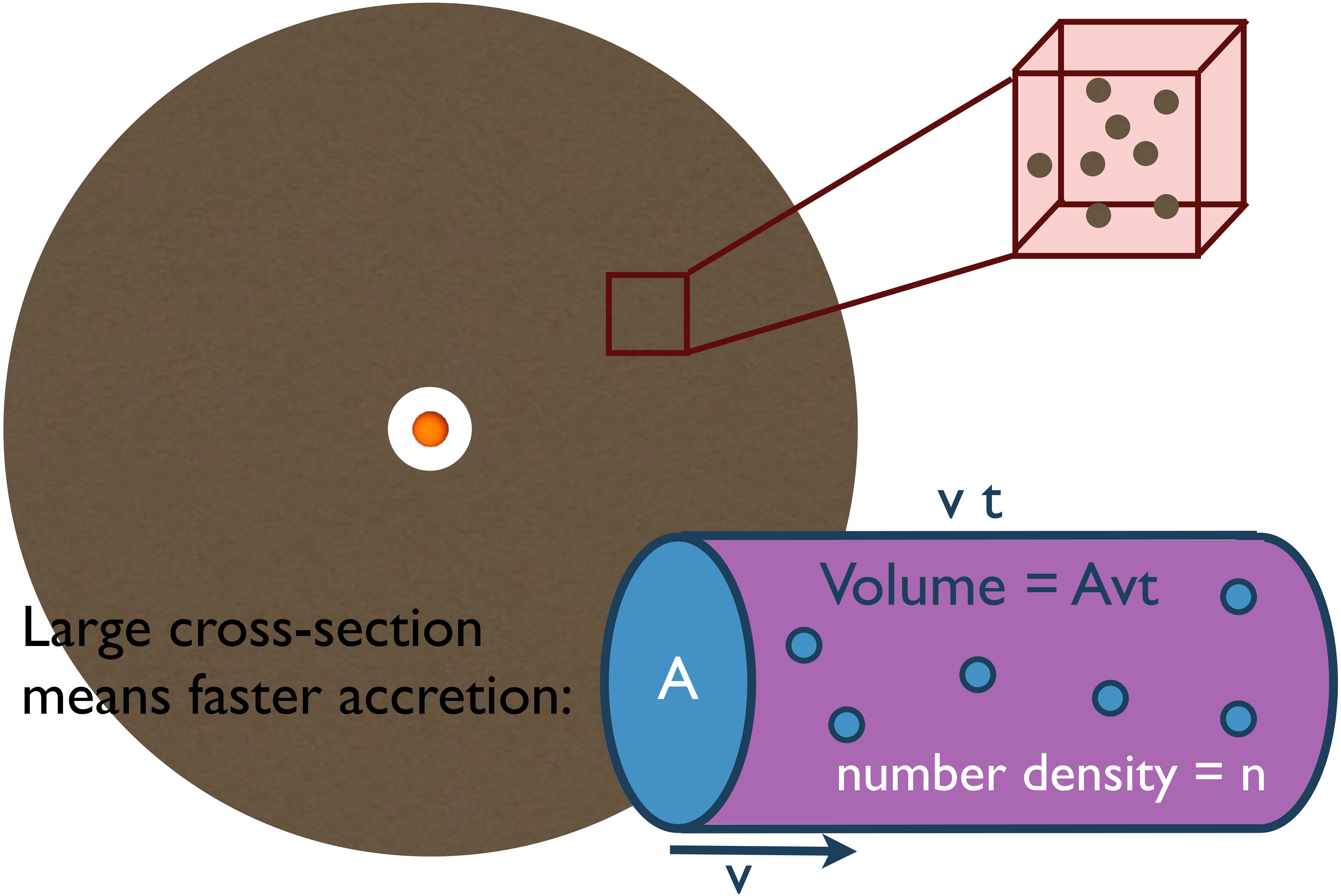
How far out can core accretion produce giants?

Should we have seen them?

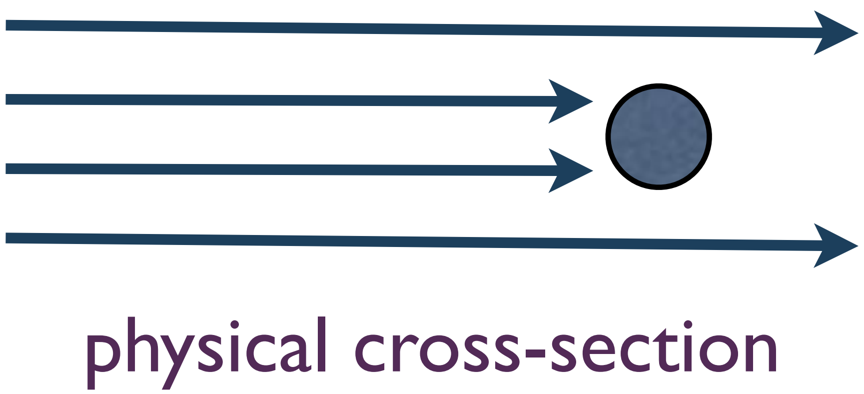
Core accretion:

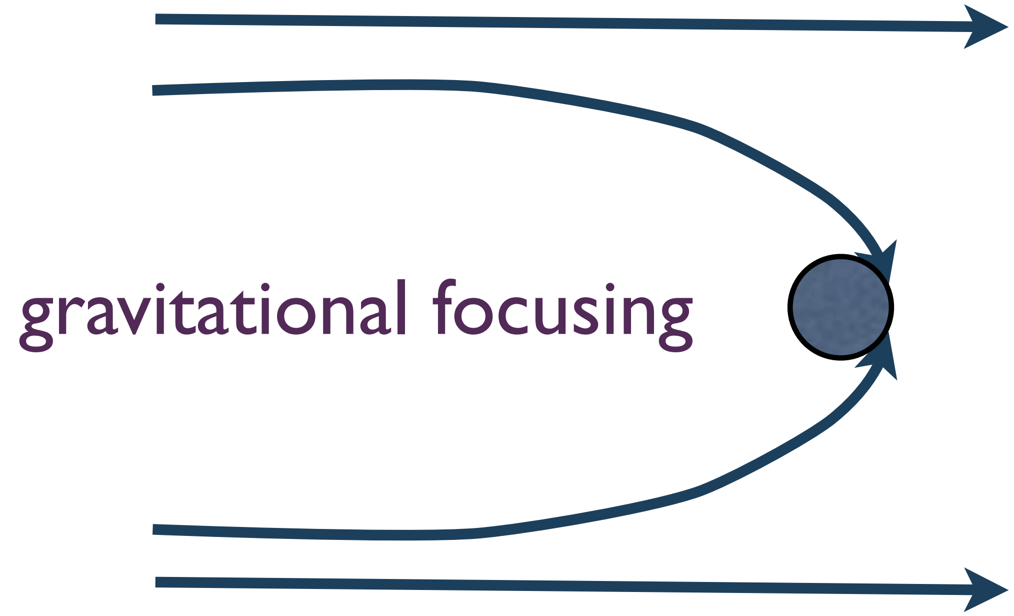
Need to grow a massive solid core through collisions

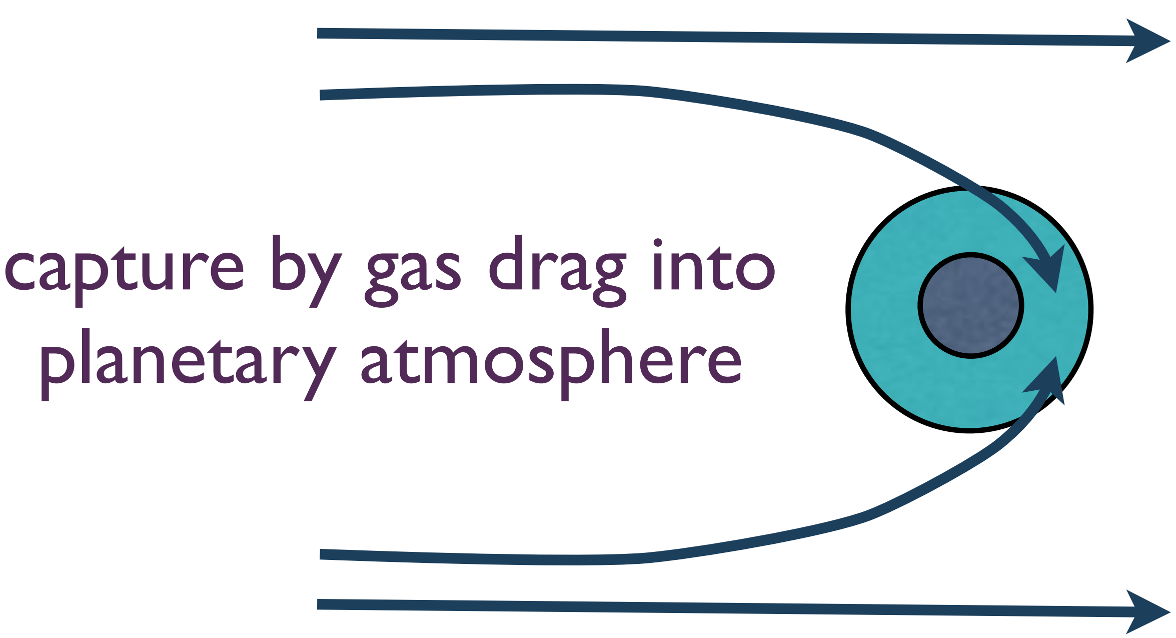
Longstanding problem: The last doubling time.



Cross-section regimes:

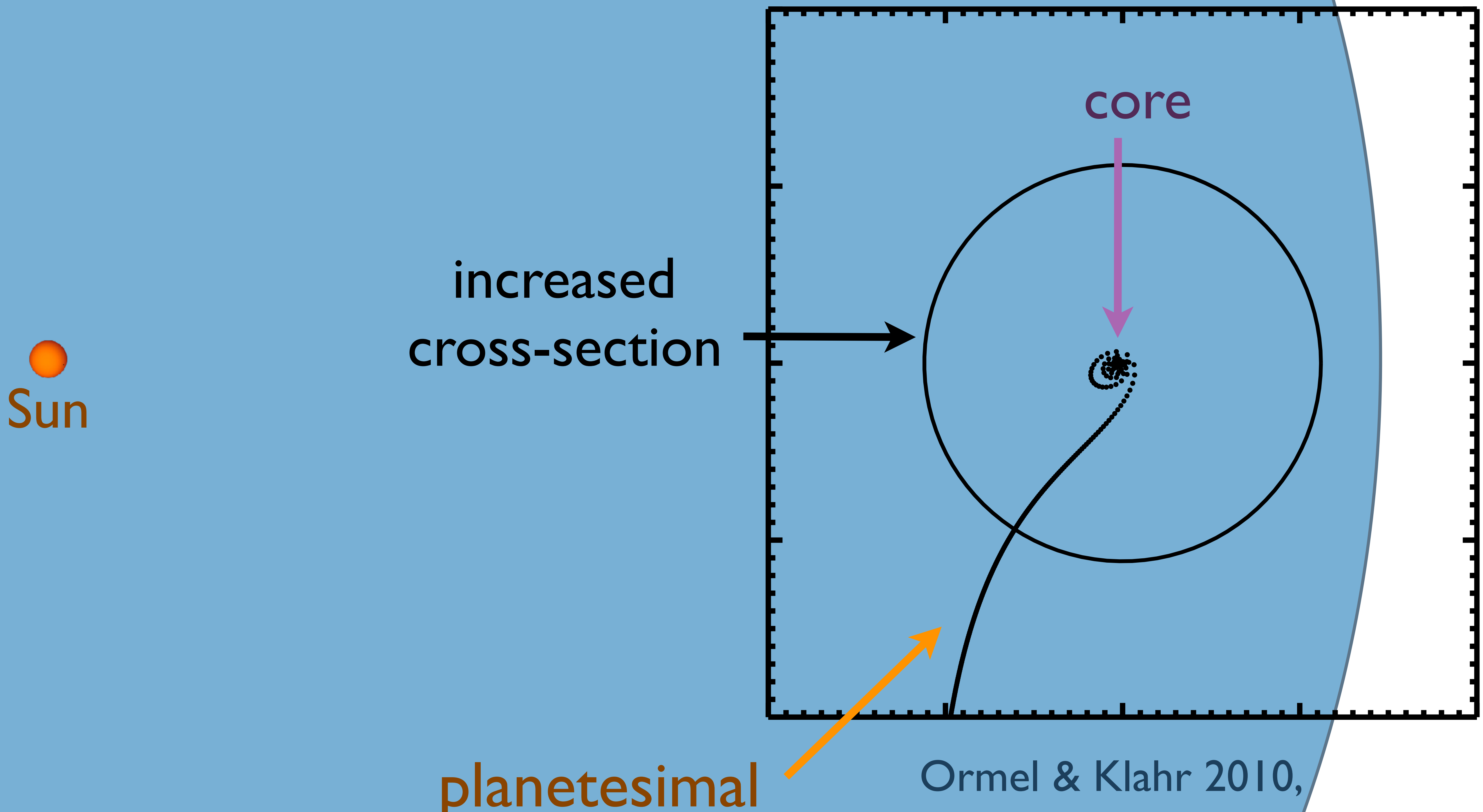






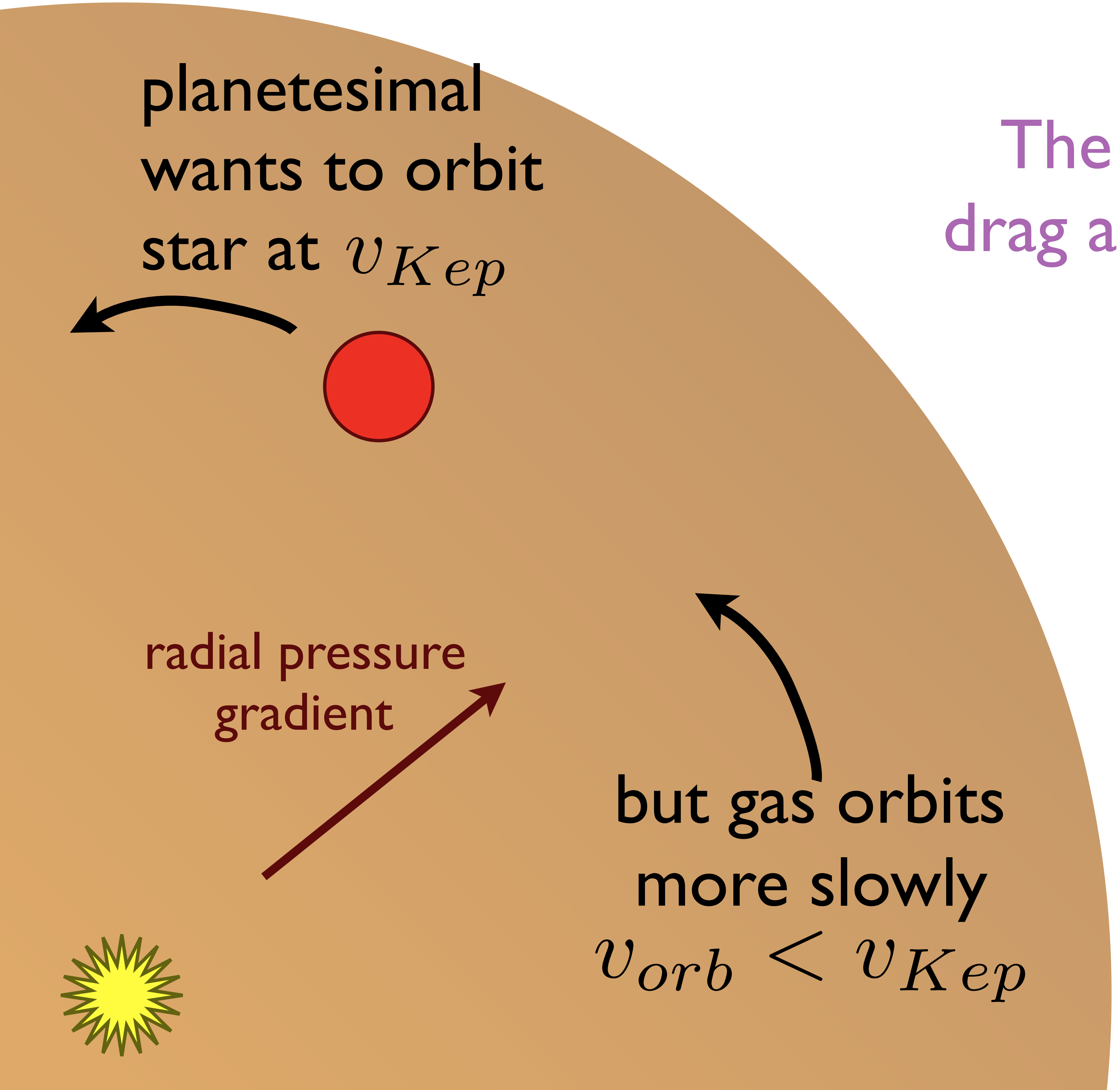
Final stage of core growth too slow at distance of HR 8799 outer planet given standard theory

Capture by gas drag allows fast enough growth to nucleate a massive atmosphere

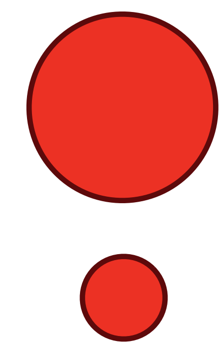


Ormel & Klahr 2010,
Lambrechts & Johansen 2012
Rosenthal, Murray-Clay, Perets,
& Wolansky, subm.

Gas Alters the Orbits of Single Planetesimals

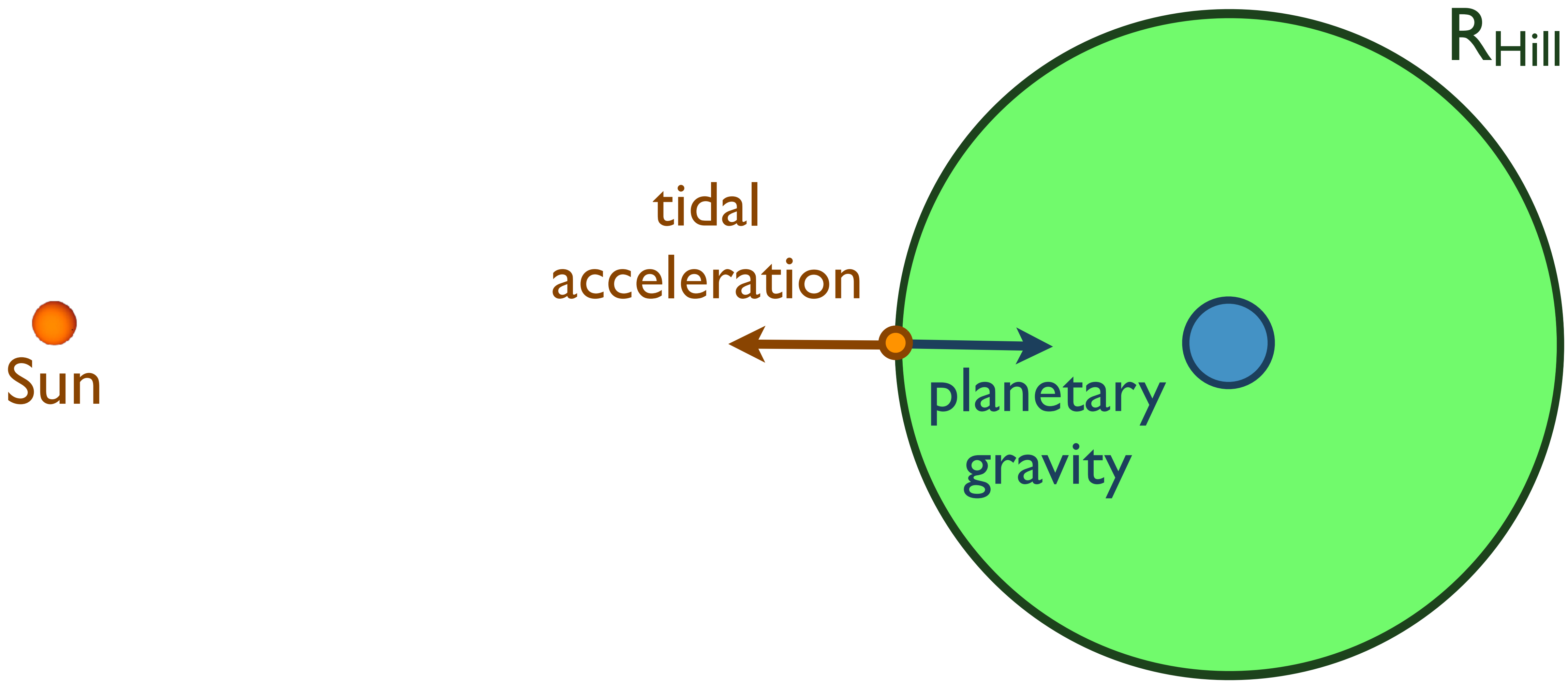


The resulting drag acceleration $\frac{F_D}{m}$ is



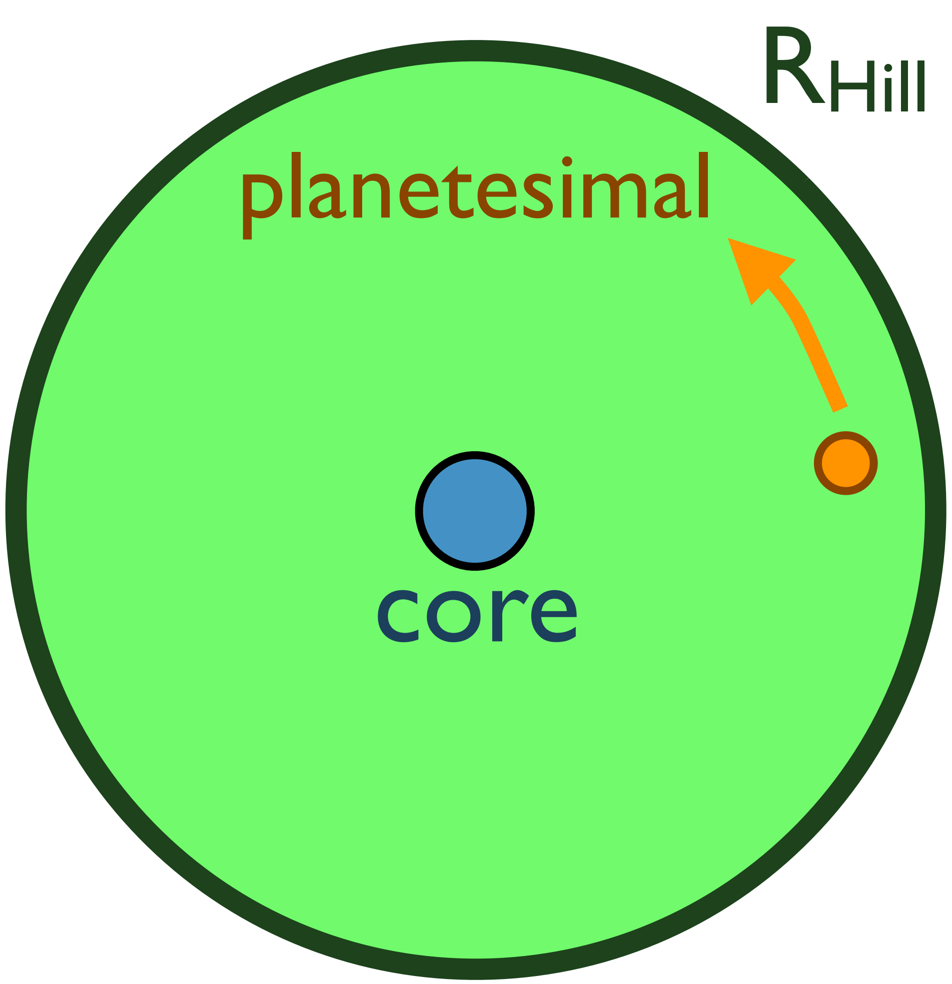
$$\frac{v_{orb}^2}{r} = \frac{GM_*}{r^2} + \frac{1}{\rho}\frac{dP}{dr}$$

In the absence of gas, satellites can orbit within the Hill radius



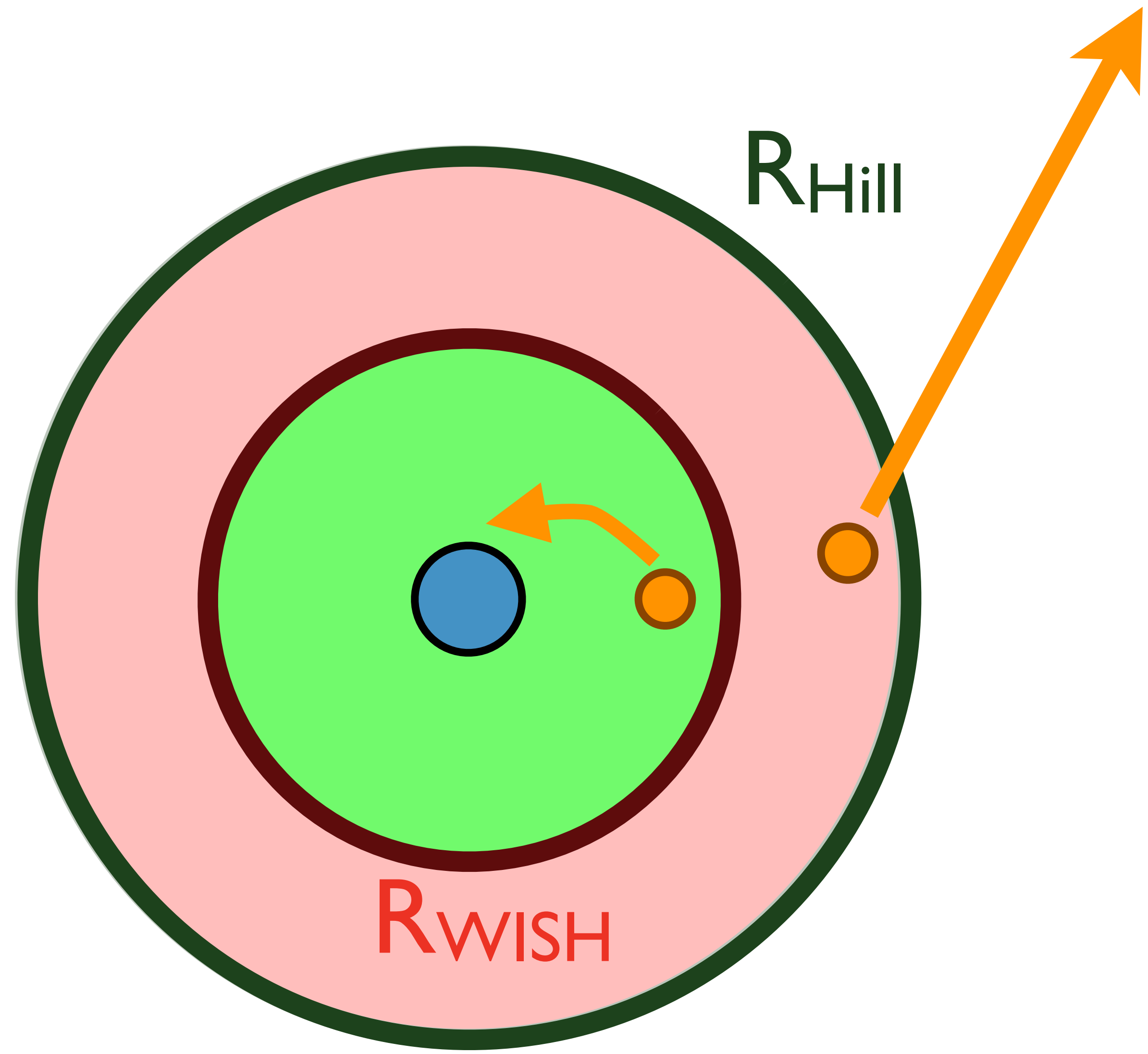
No gas:

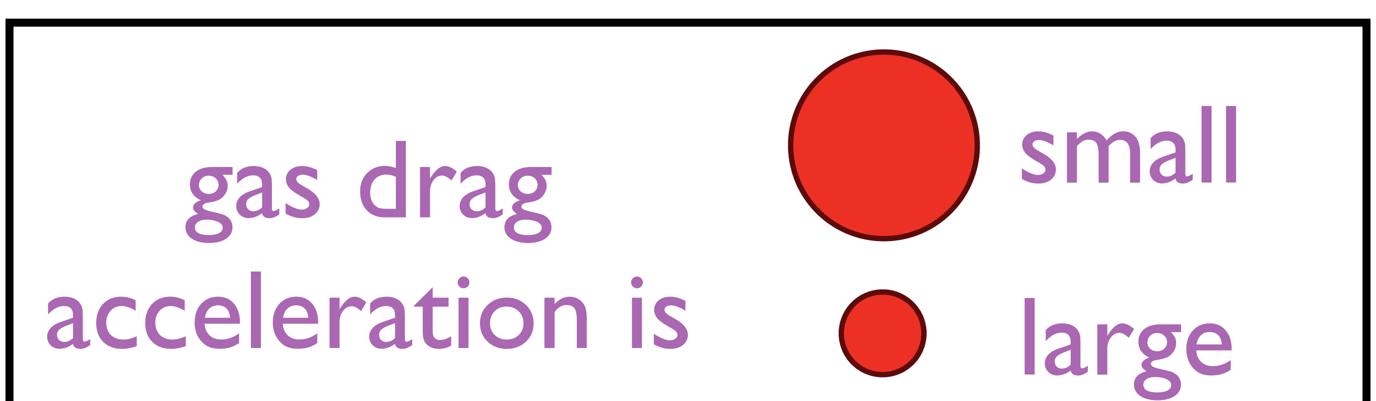
Satellites can orbit within the “Hill radius”



Gas:

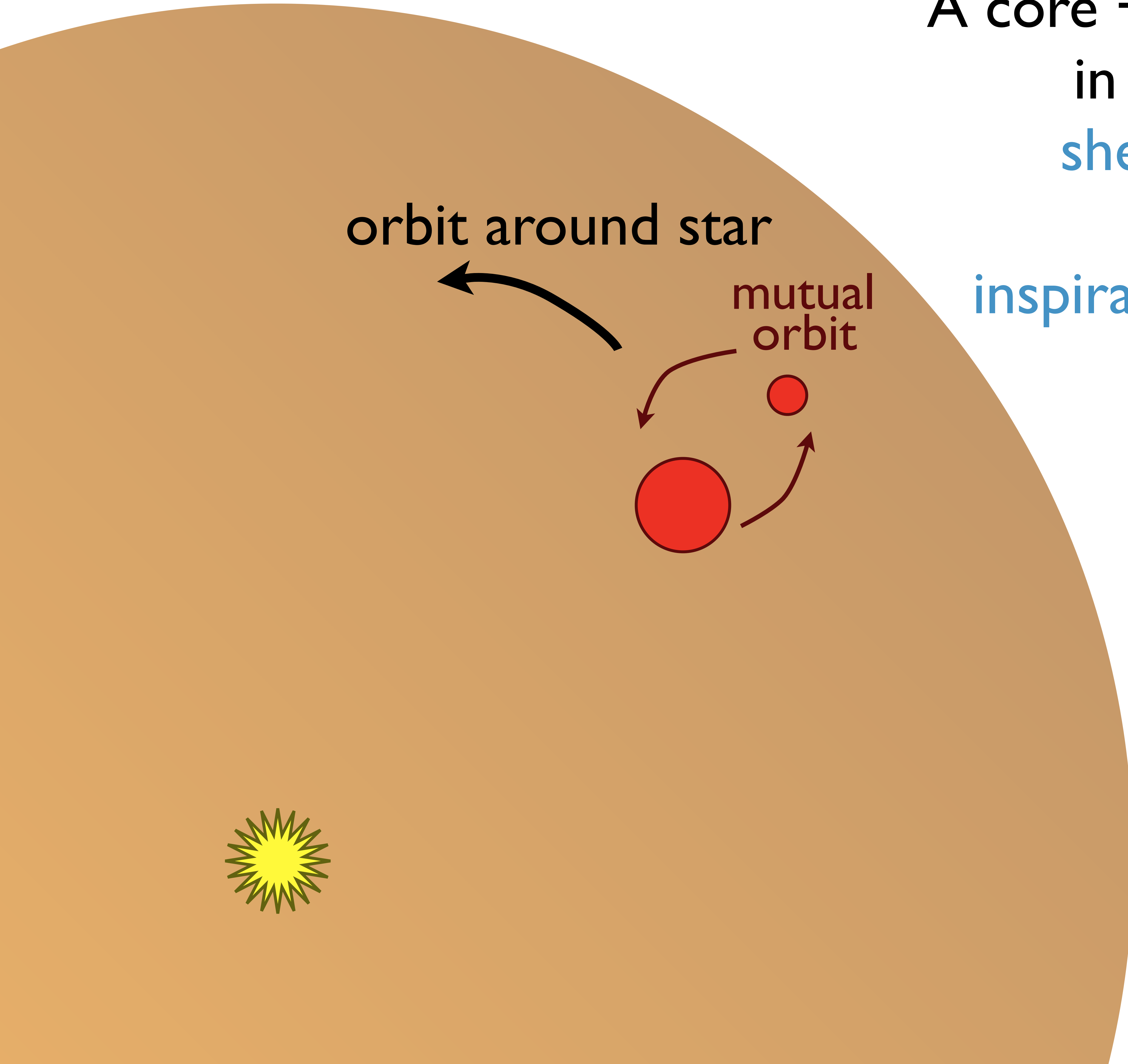
Wind Shearing (WISH)





Perets & Murray-Clay (2011)

A core + planetesimal in gas can:
shear apart
or
inspiral and merge



A core + planetesimal in gas can:
shear apart
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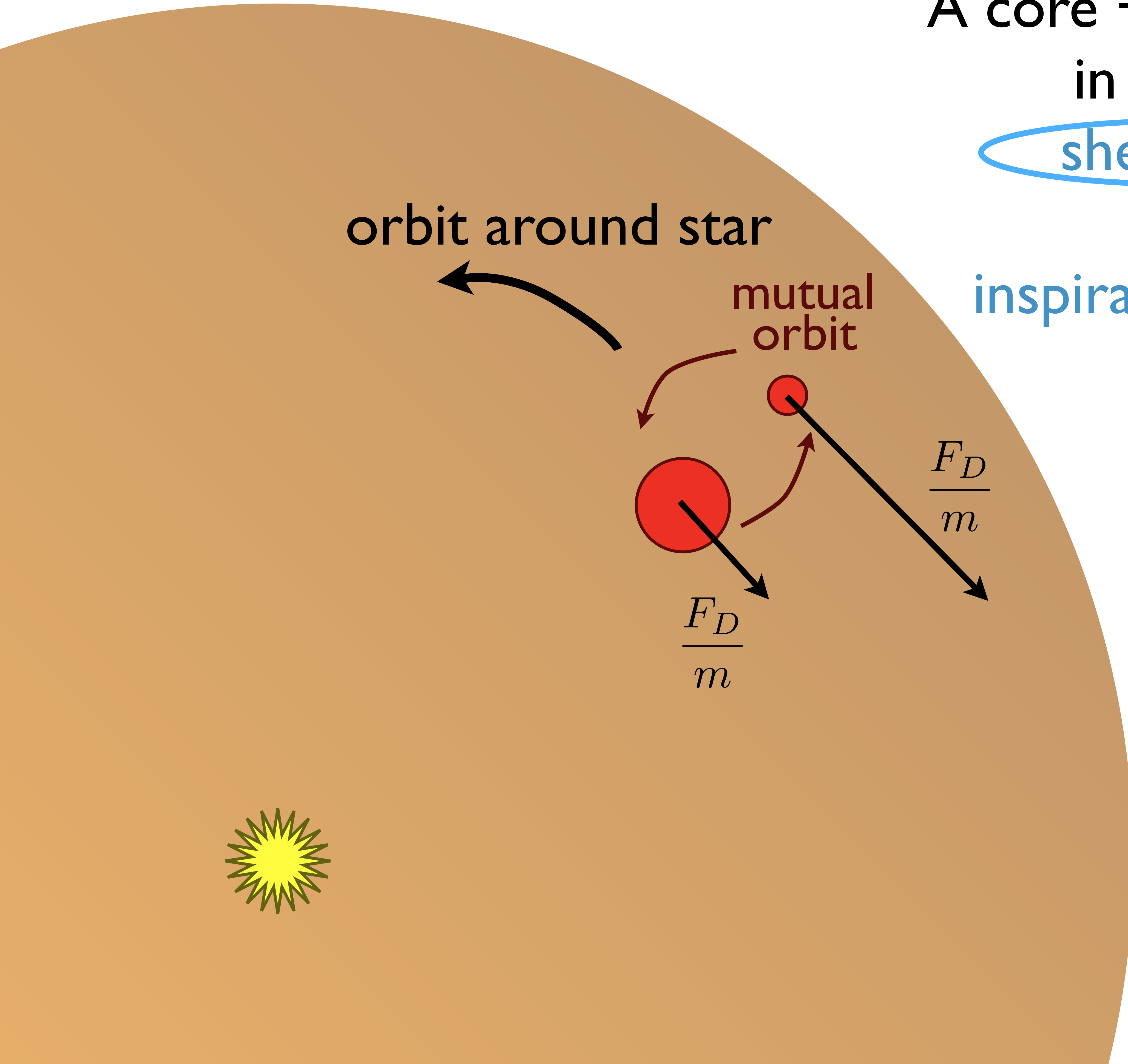

A core + planetesimal in gas can:
shear apart
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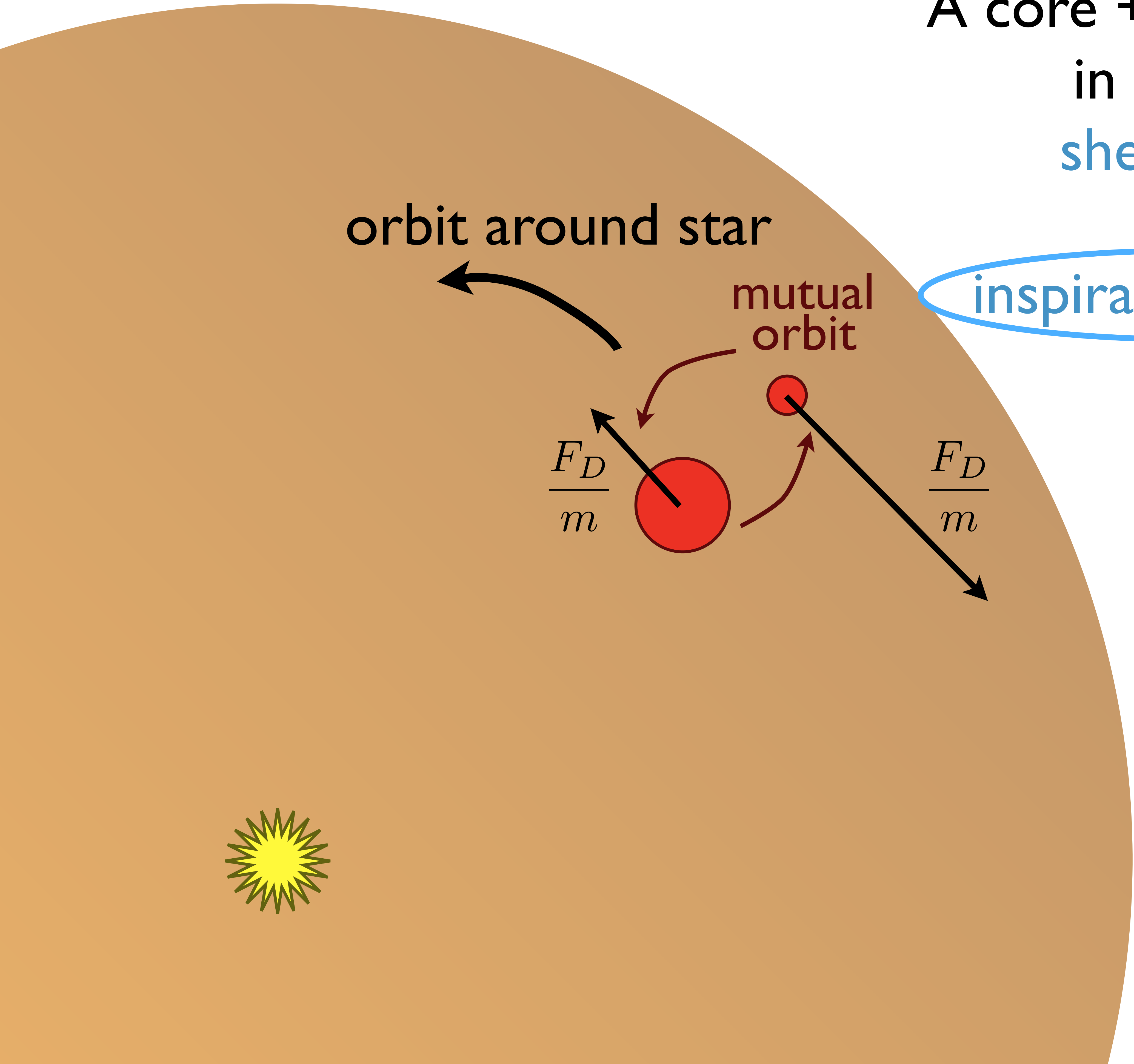
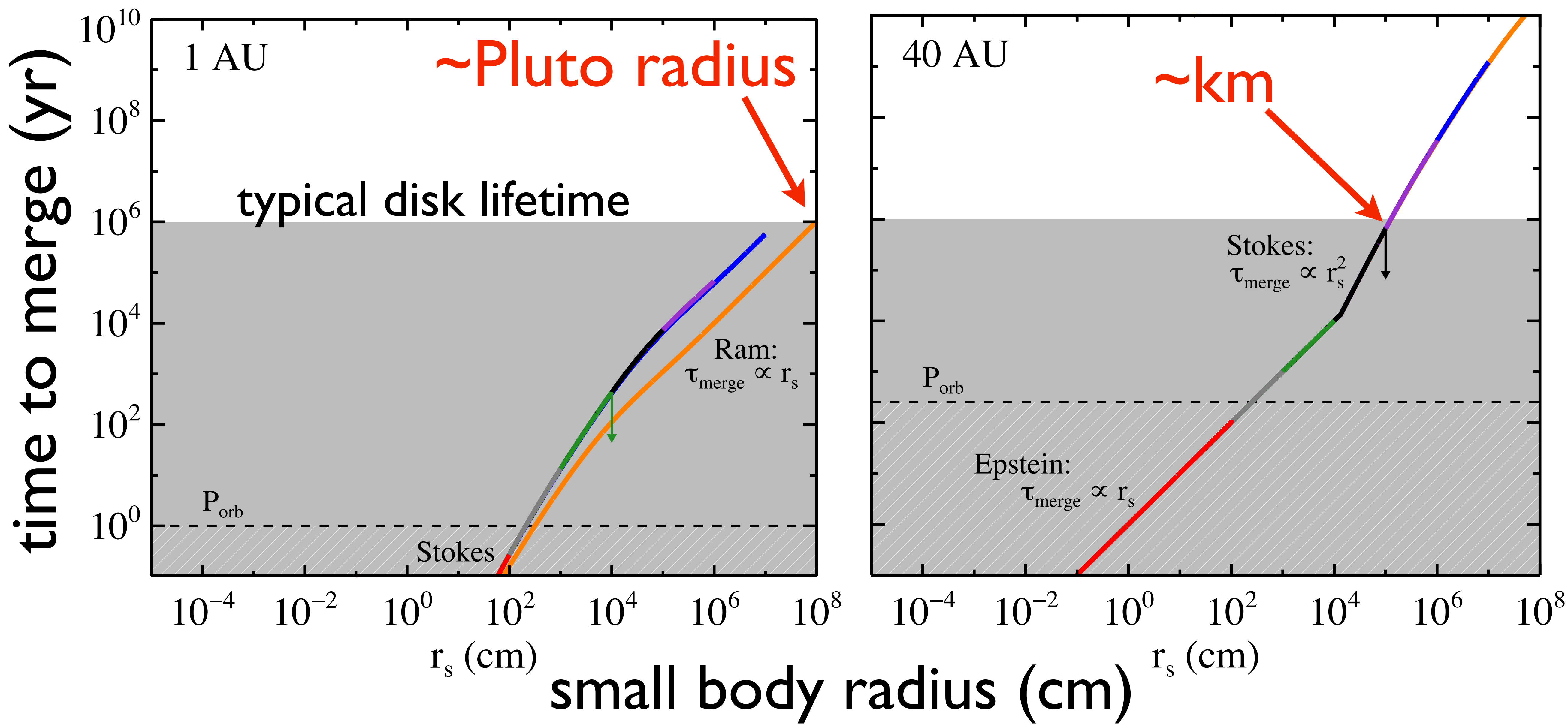
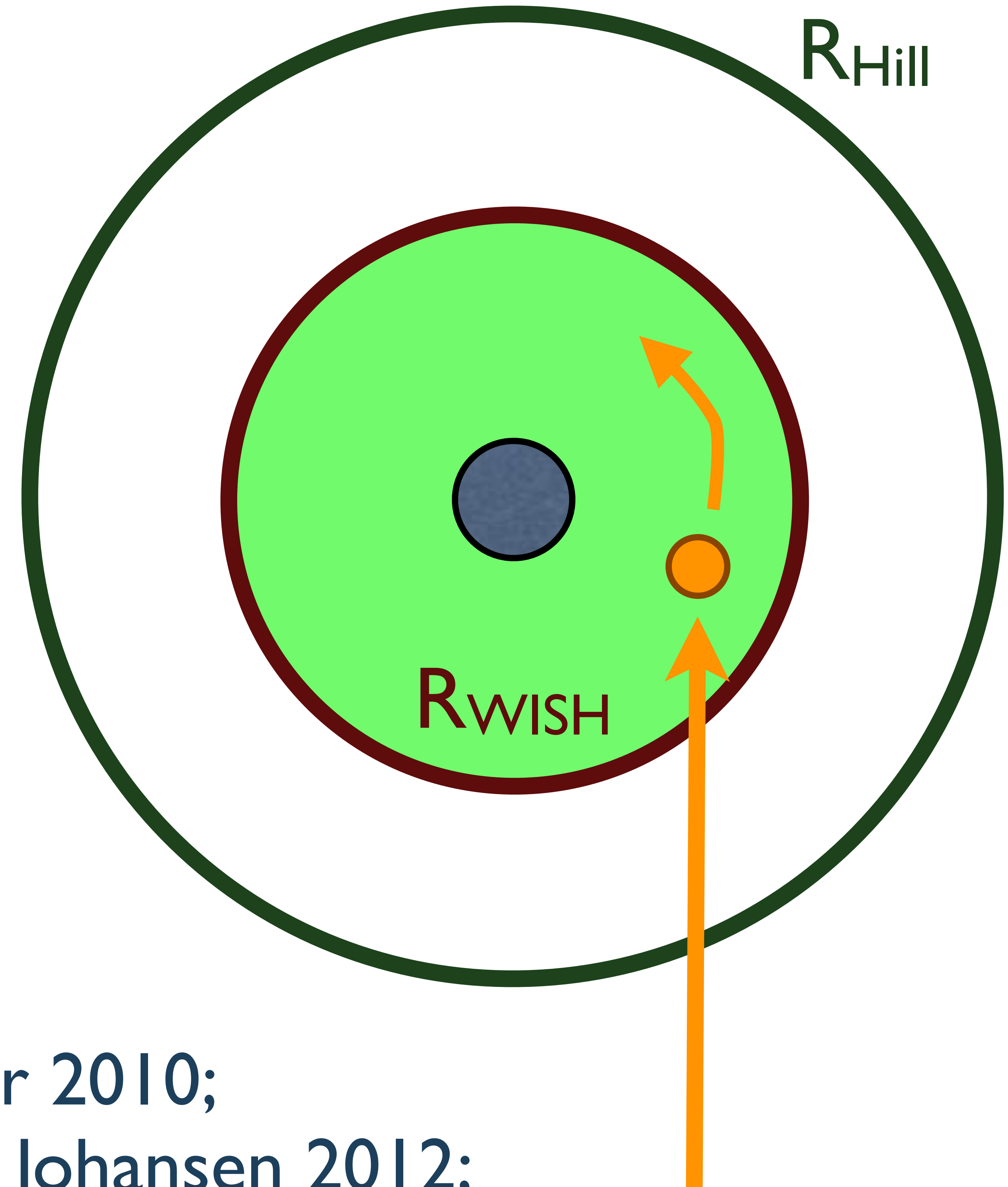


For Small Planetesimals, Merger Times < Disk Lifetimes



Perets & Murray-Clay (2011)

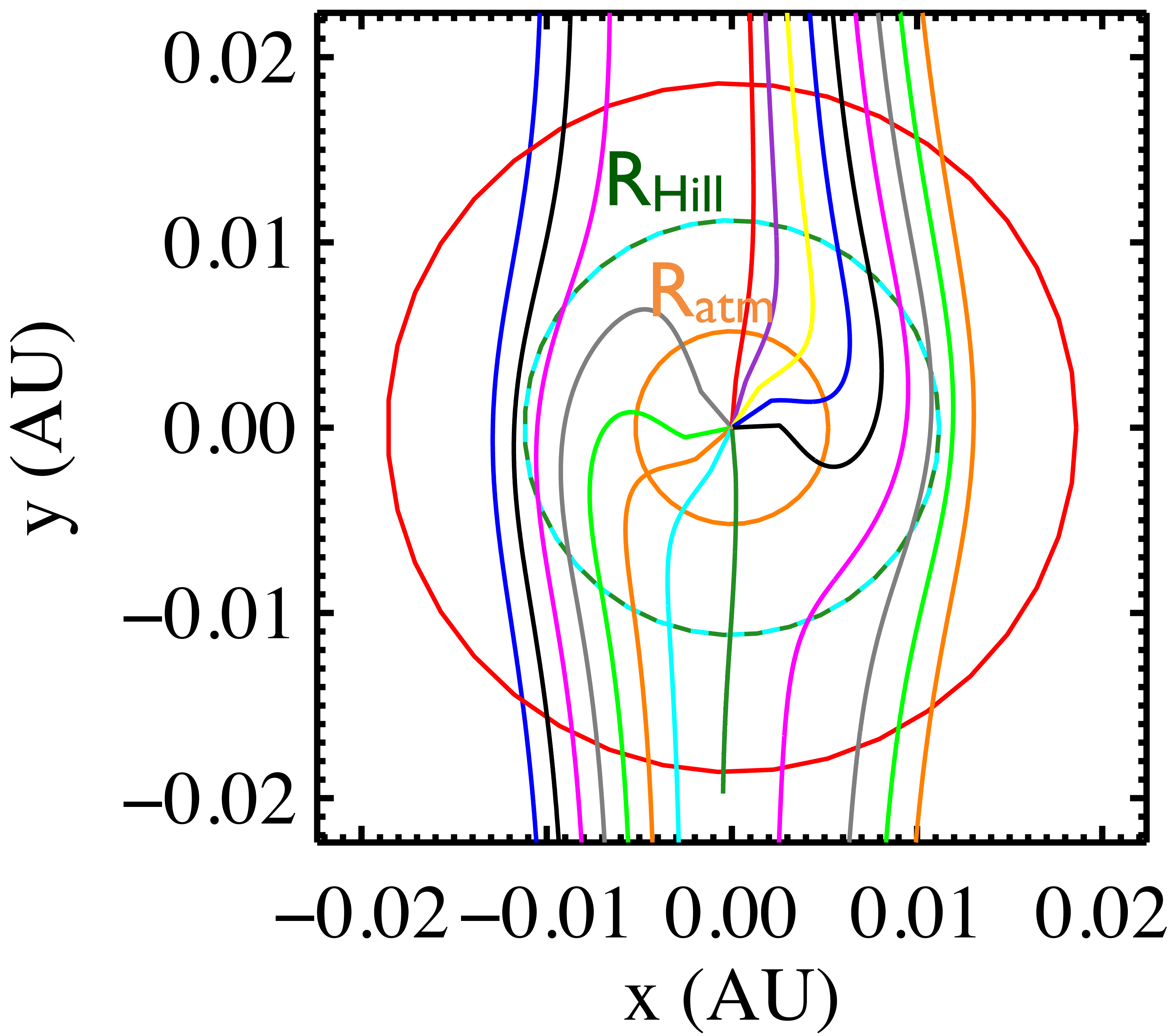
"Binary Capture"



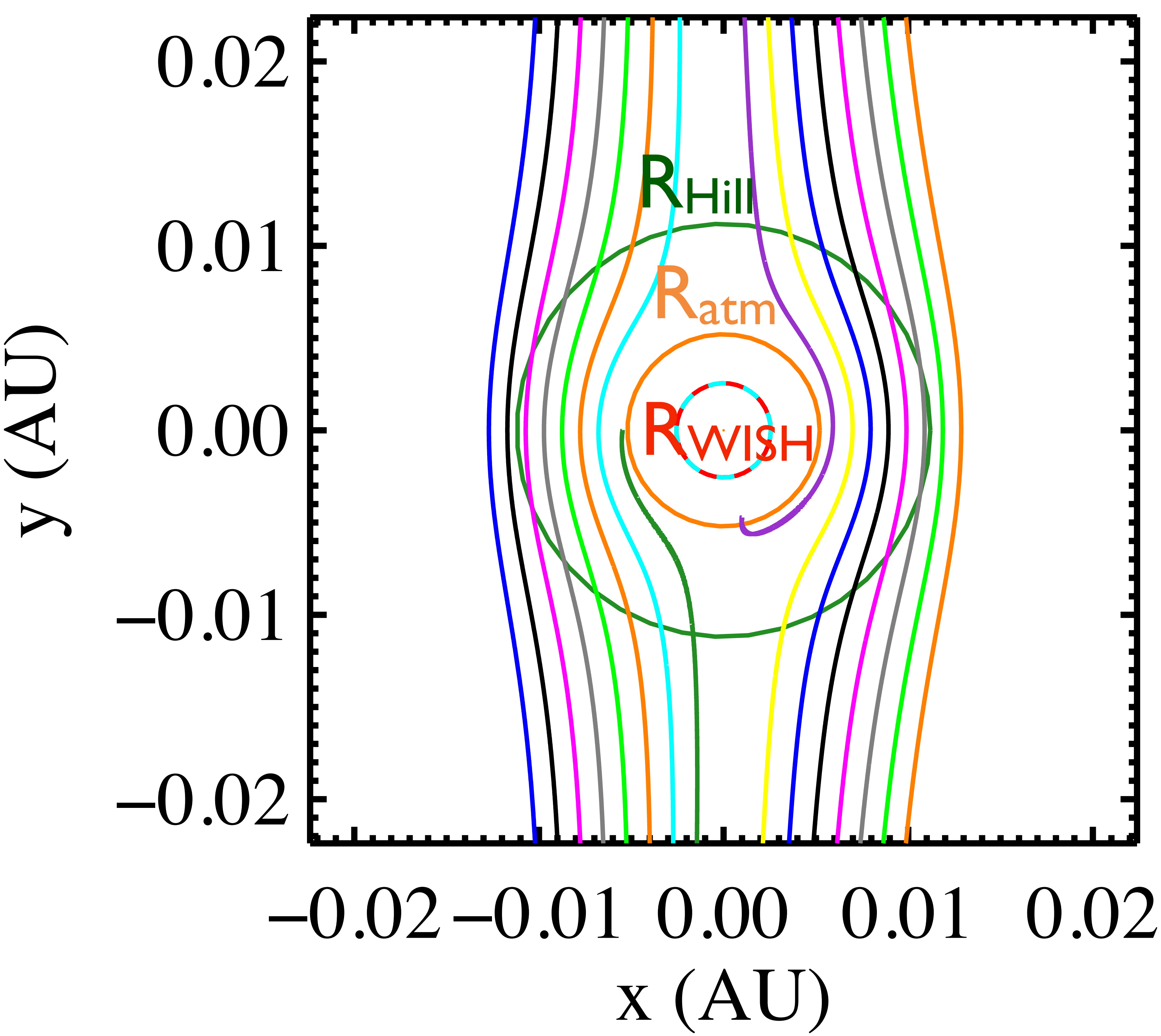
dissipation due to interaction with gas

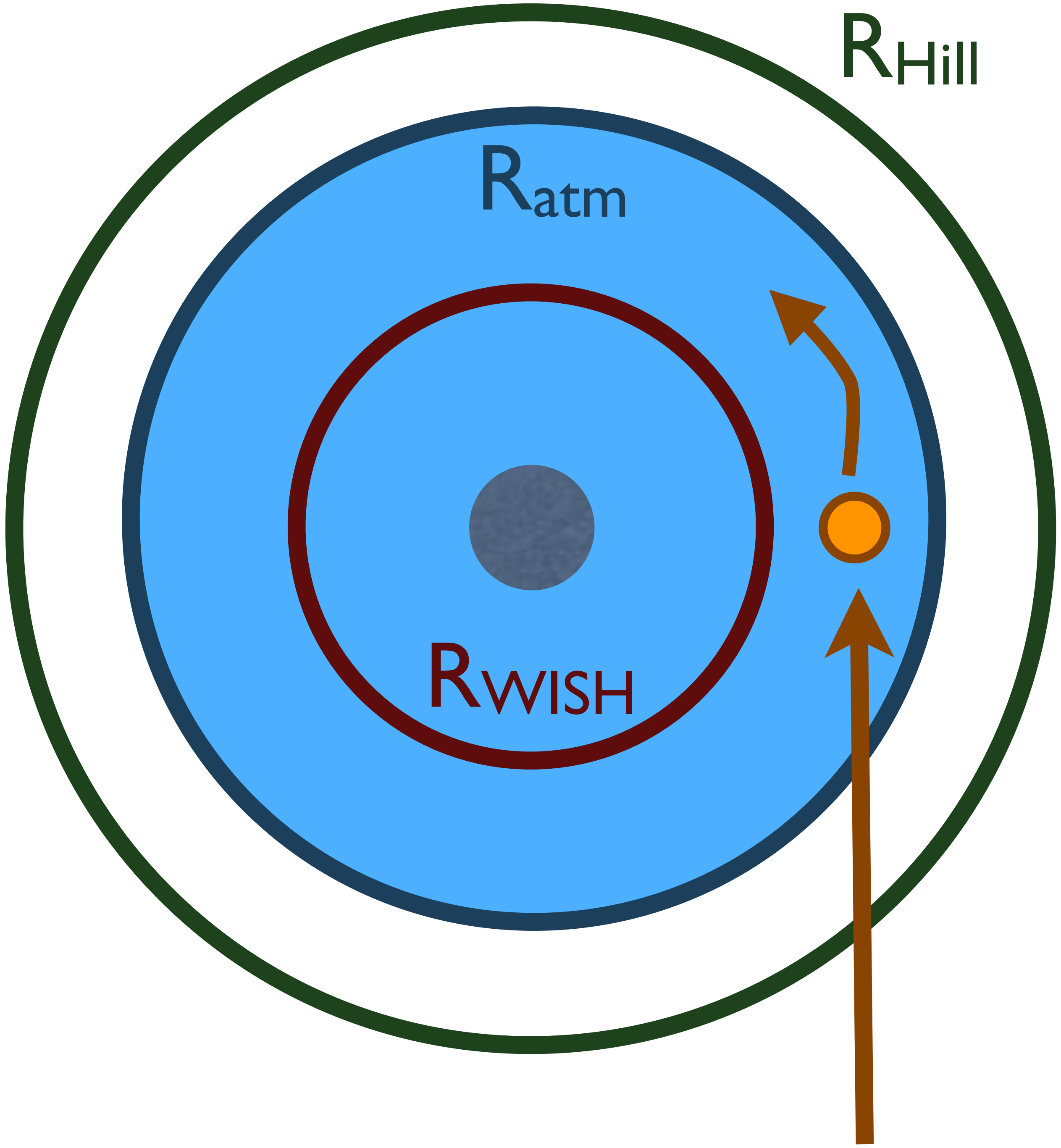
Ormel & Klahr 2010;
Lambrechts & Johansen 2012;
Rosenthal, Murray-Clay, Perets, & Wolansky subm.

Capture can happen with a cross-section as large as the Hill radius



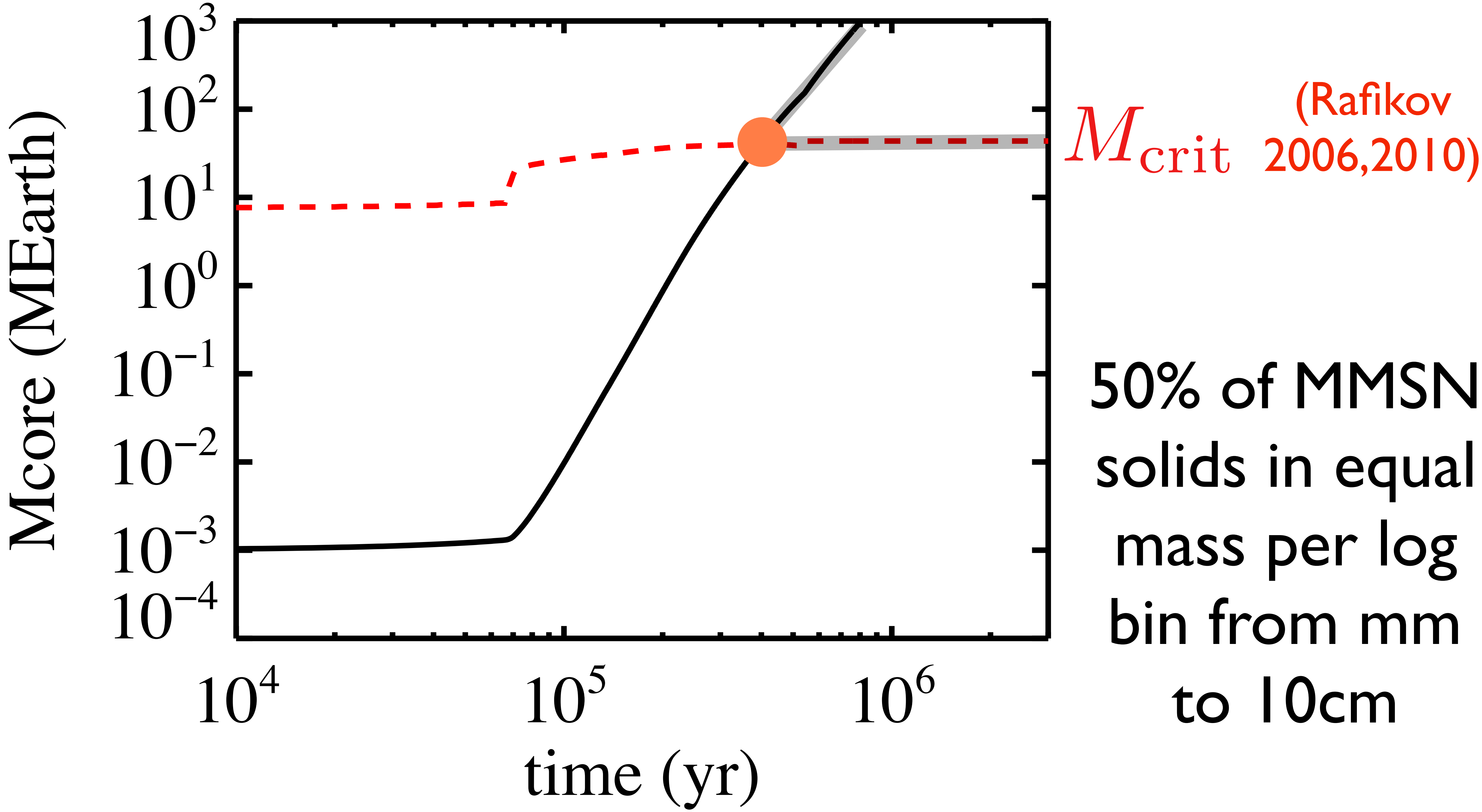
Well-entrained particles can be swept around the core, preventing accretion





Capture by the atmosphere is only possible if the small particle can decouple from the exterior gas.

Growth times at 70 AU can be short enough to nucleate an atmosphere



50% of MMSN solids in equal mass per log bin from mm to 10cm

SURFACE DENSITY IN 0.1 - 1 MM SIZED PARTICLES

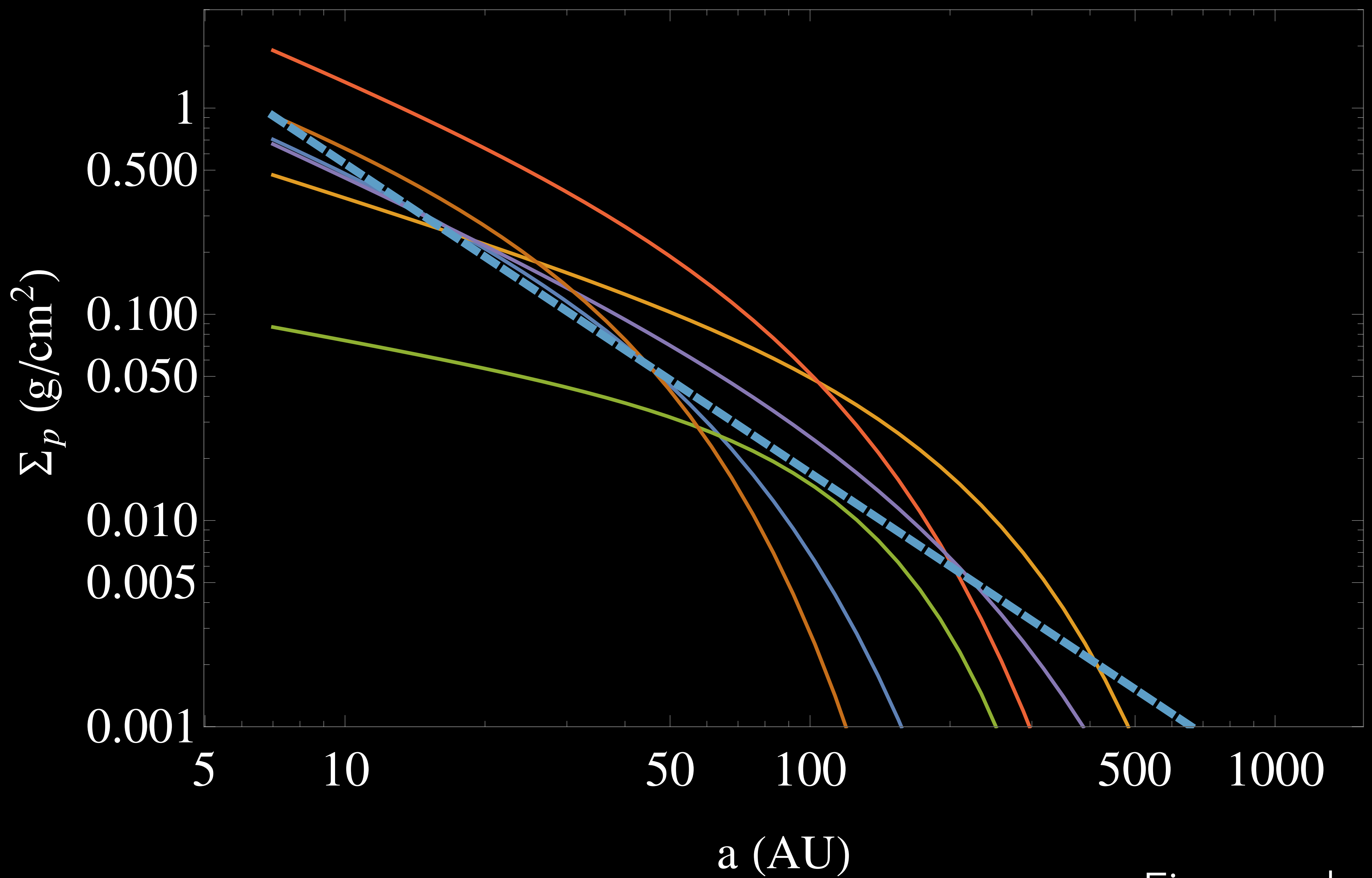
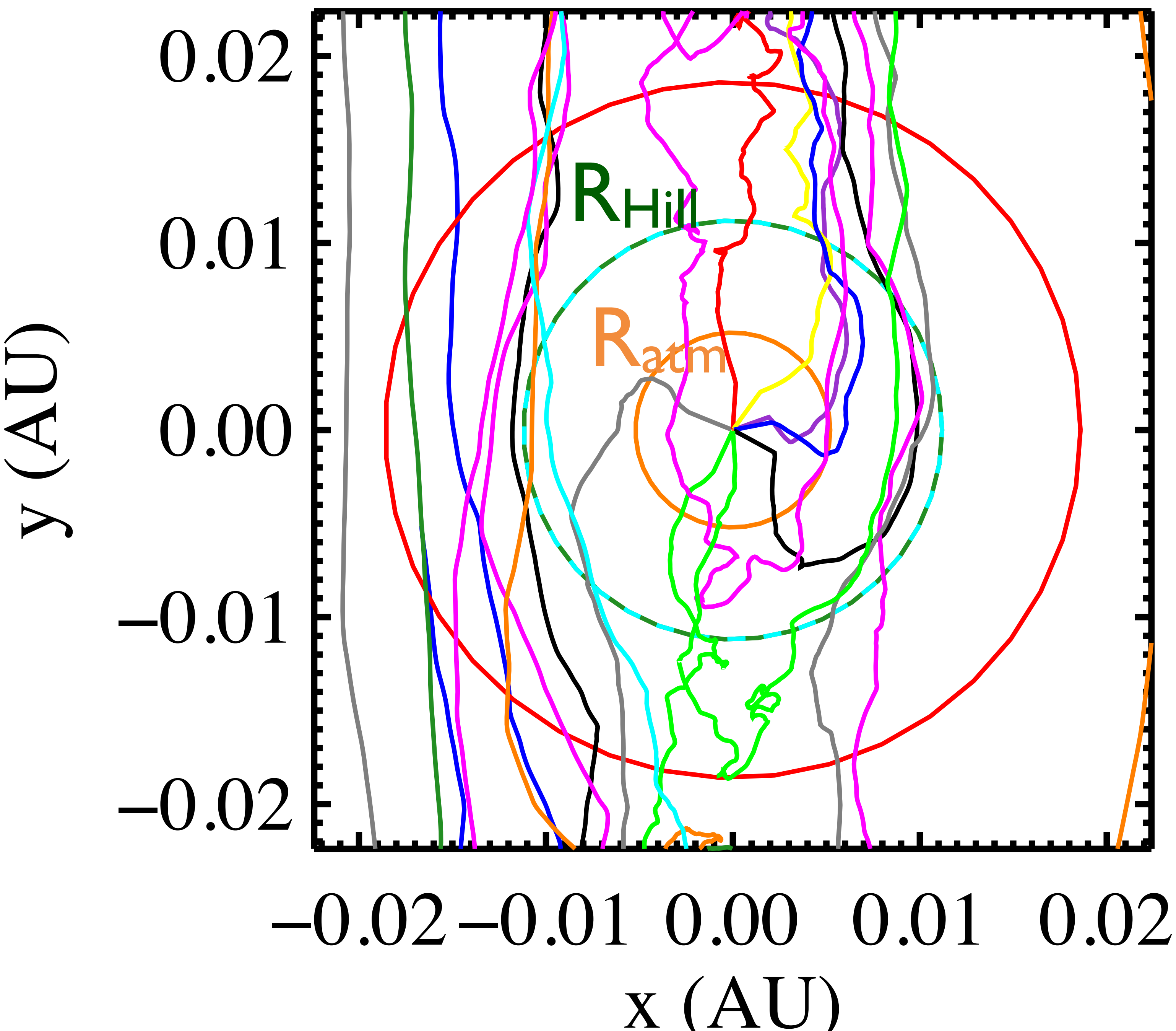


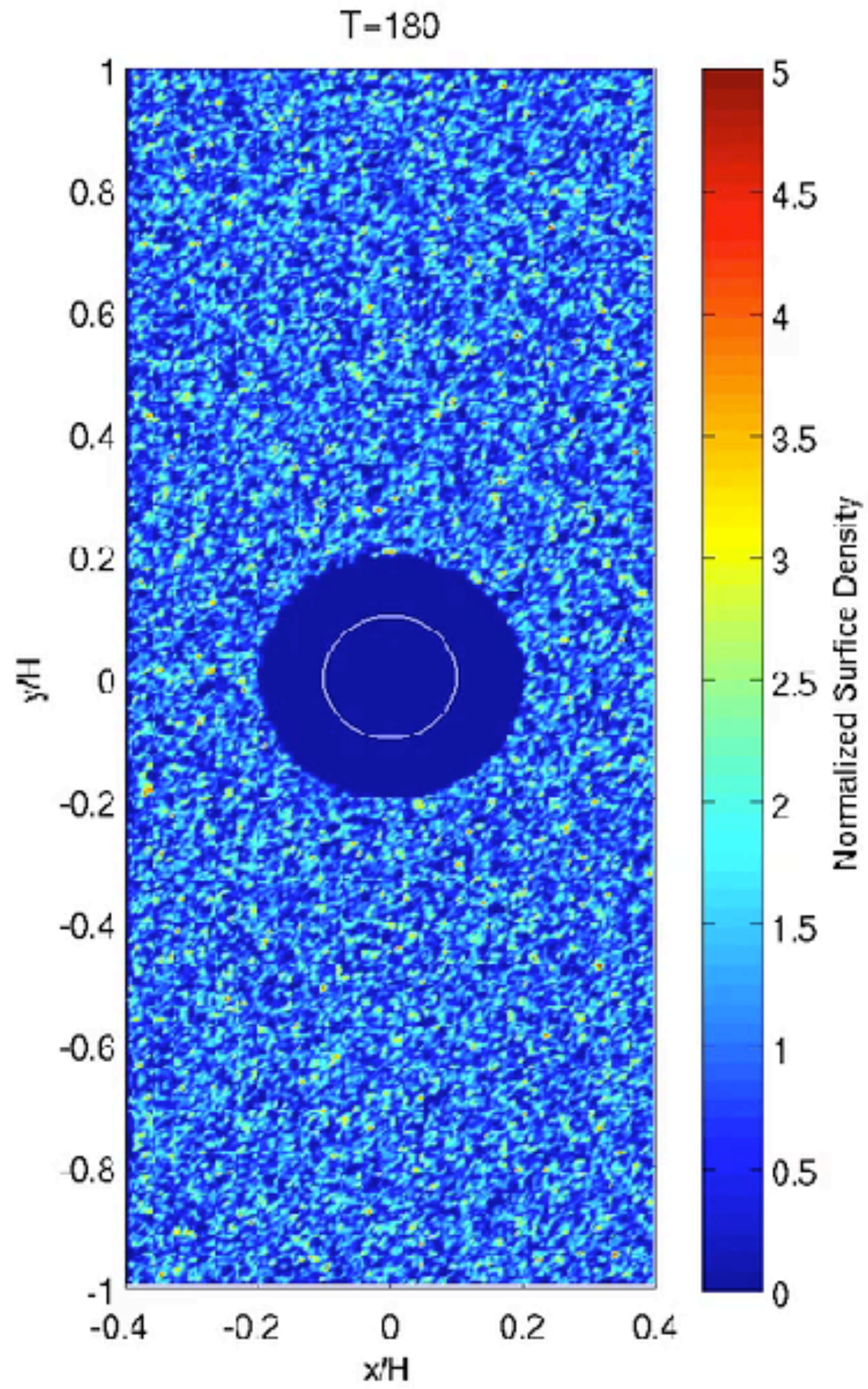
Figure adapted by Rosenthal from Andrews et al. (2009)

Turbulence doesn't prevent the final stage of core growth by capture of planetesimals



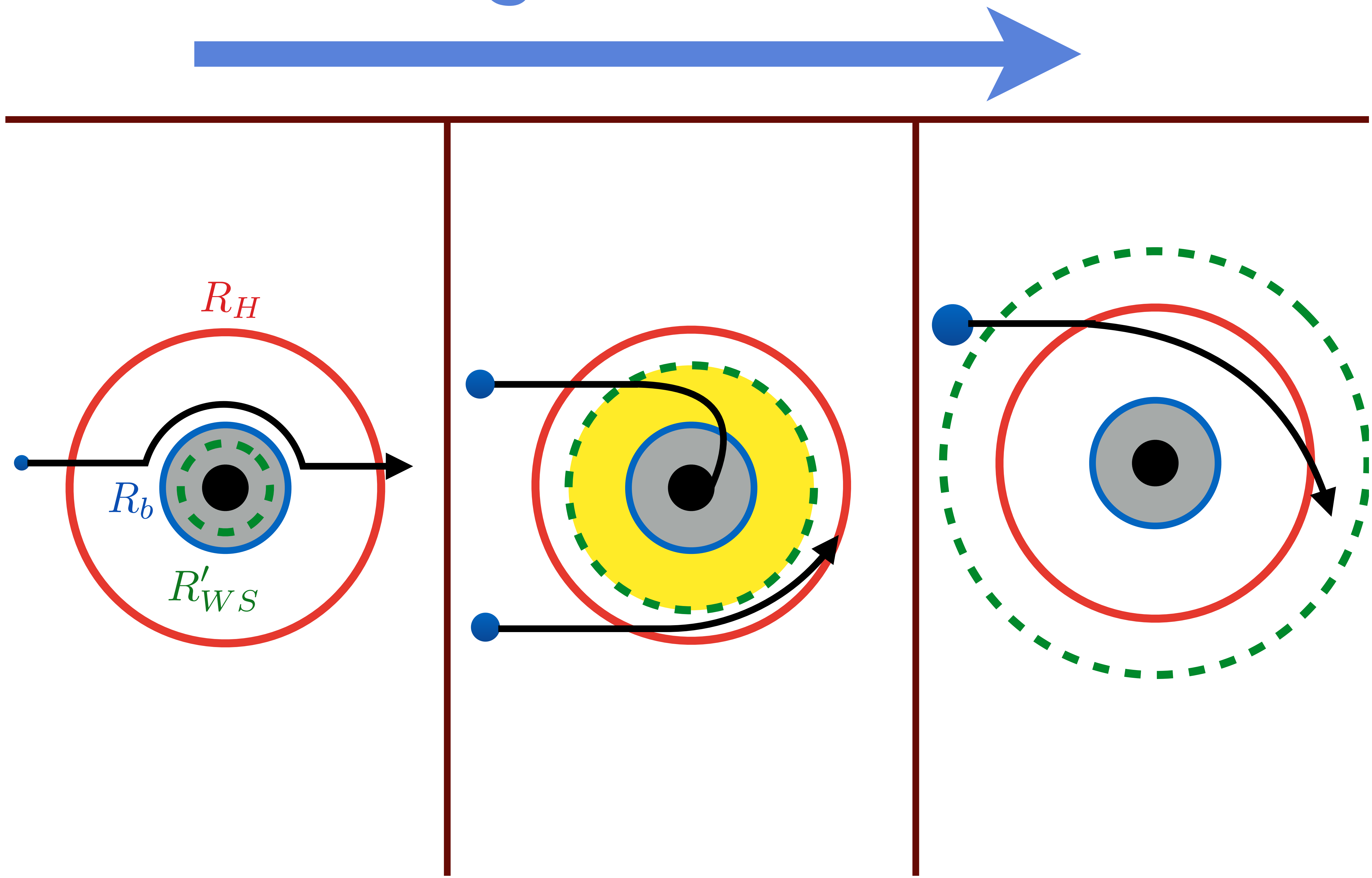
$\alpha = 0.01$

Turbulence doesn't prevent the final stage of core growth



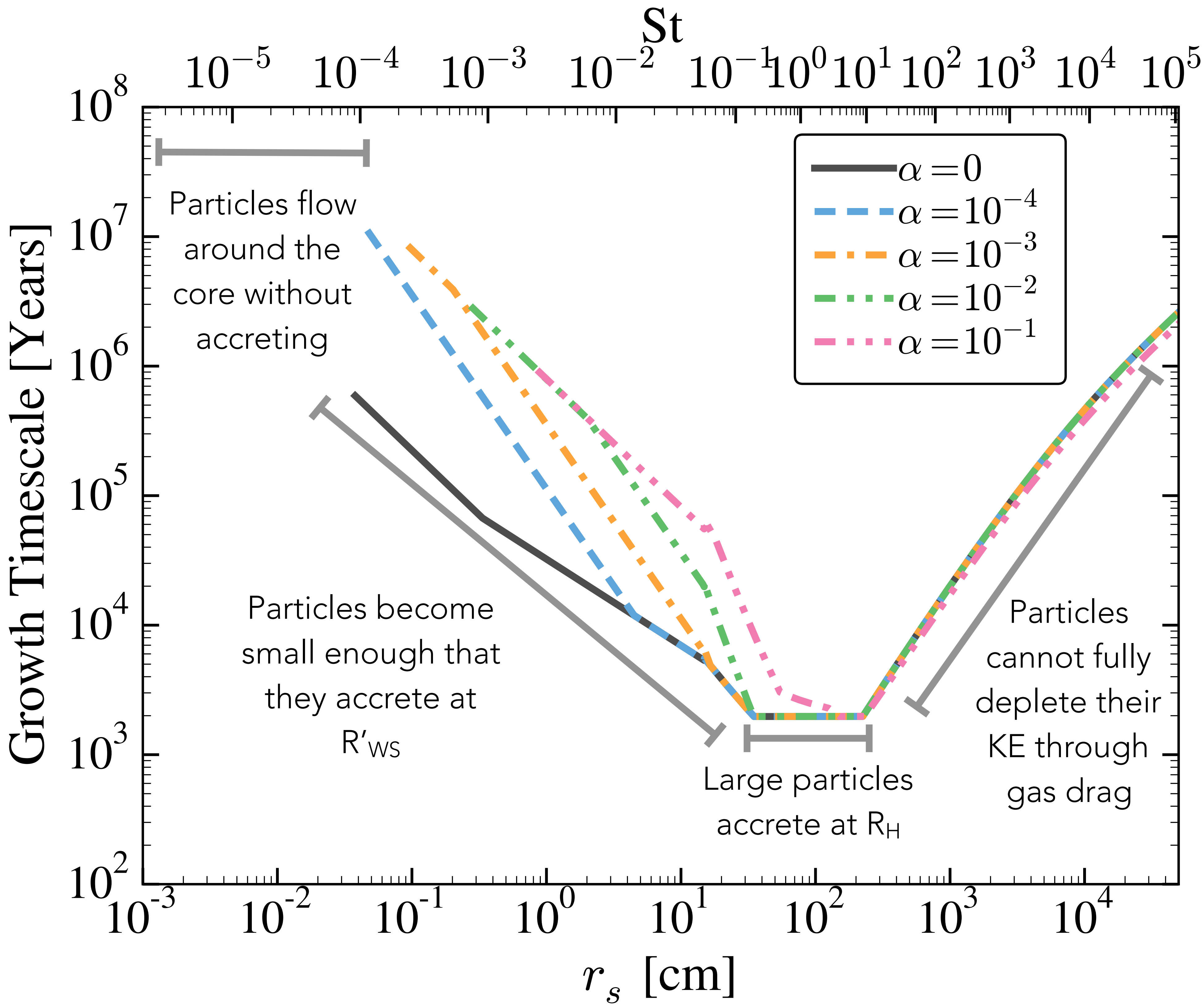
Xu, Bai, & Murray-Clay 2017

Larger Particles

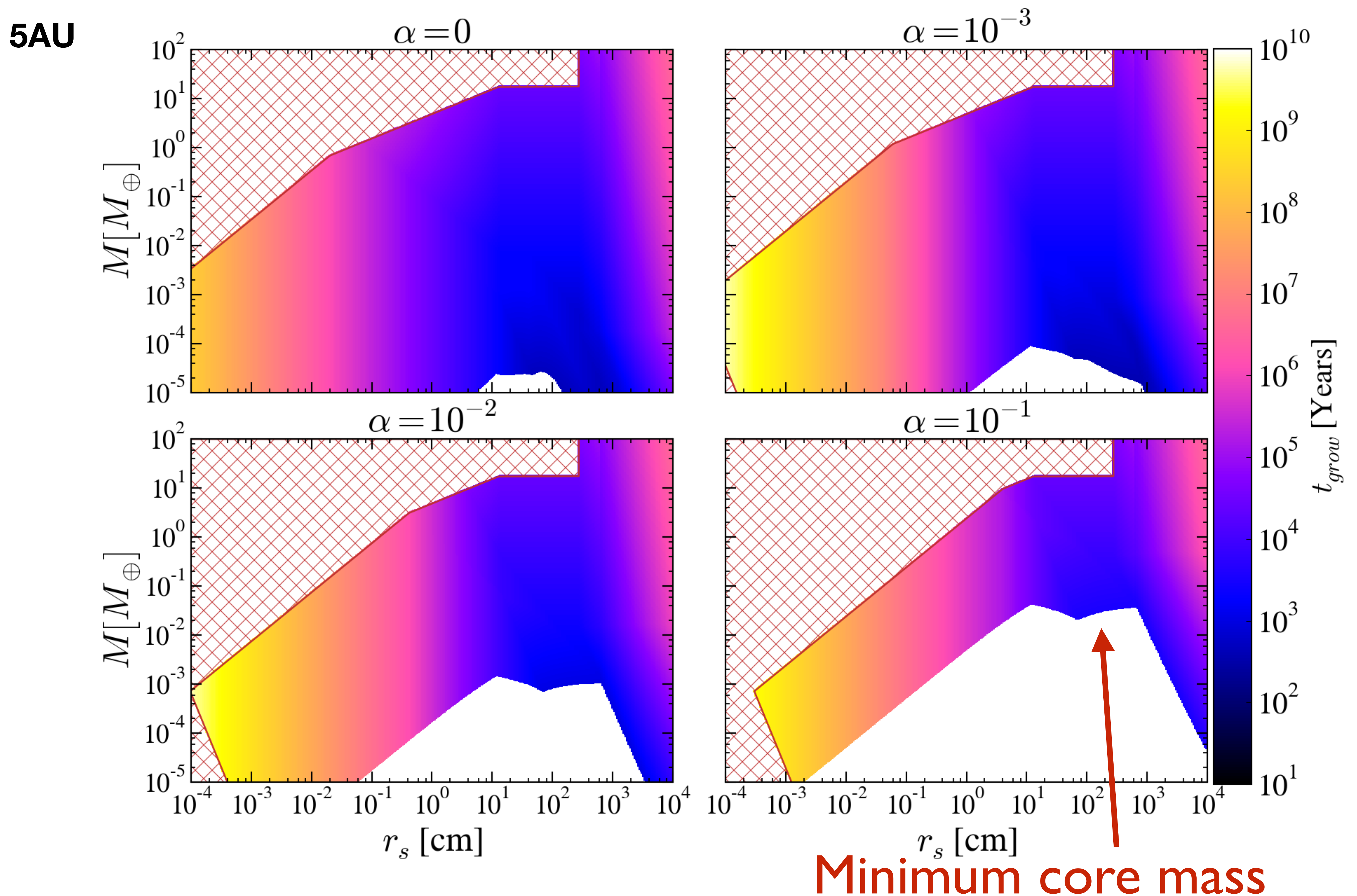


Rosenthal, Murray-Clay, Perets, & Wolansky subm.

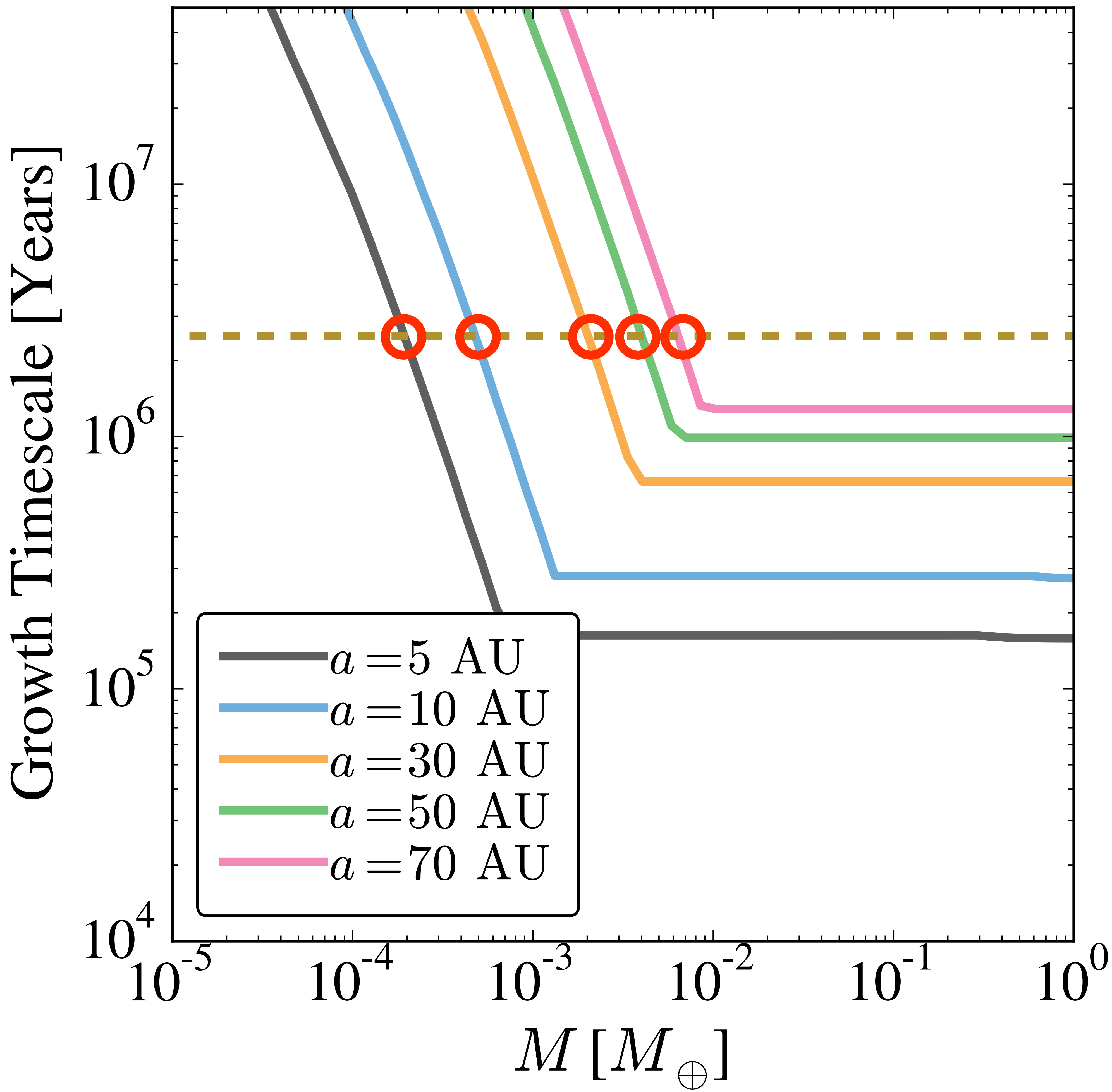
Gas-assisted growth depends strongly on planetesimal size. Turbulence impedes growth for smaller planetesimals.



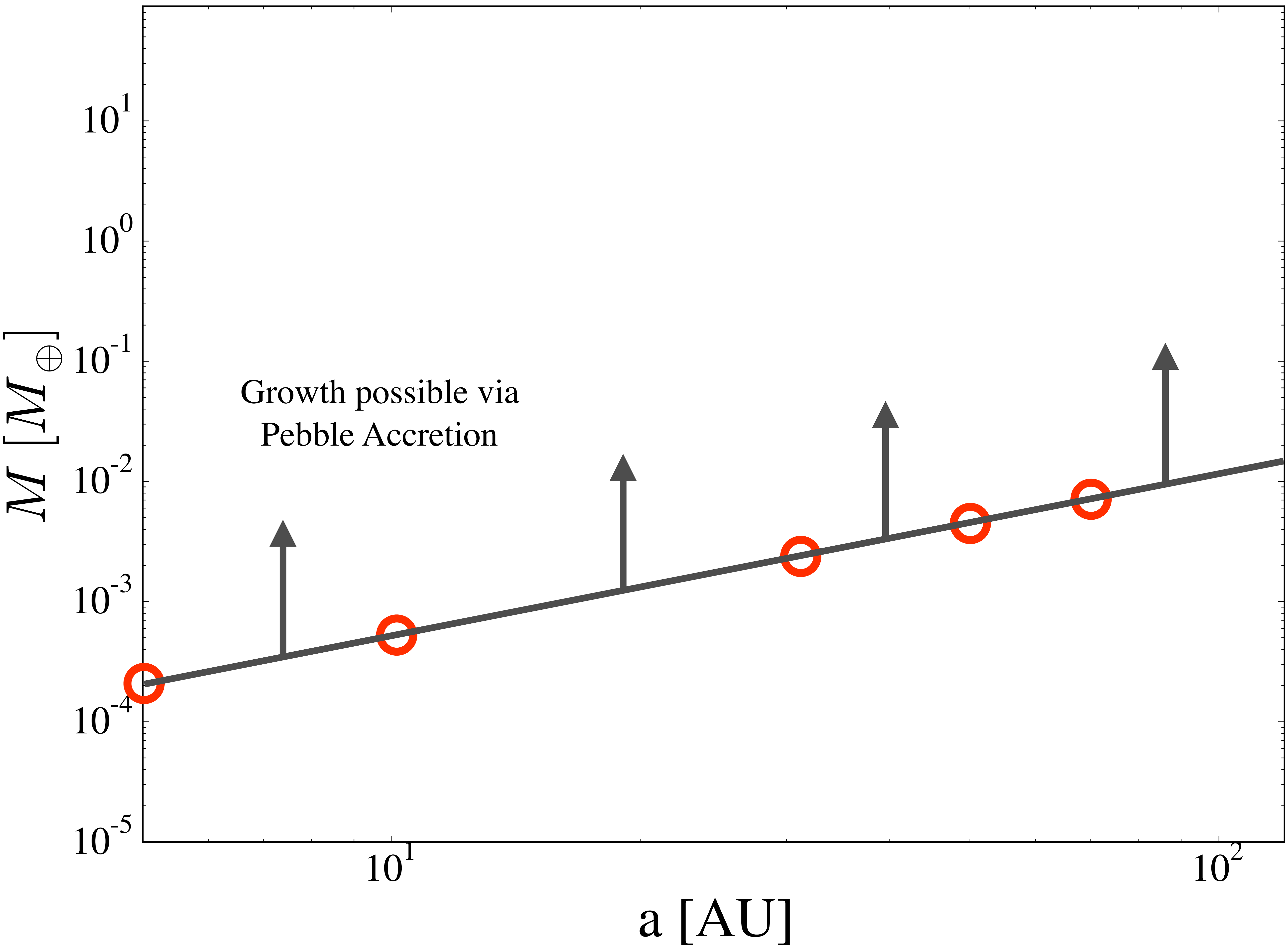
Rosenthal, Murray-Clay, Perets, & Wolansky subm.



Rosenthal, Murray-Clay, Perets, & Wolansky subm.



Growth Timescale [Years]
10^4
10^5
10^6
10^7
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
$M\ [M_\oplus]$
$a = 5$ AU
$a = 10$ AU
$a = 30$ AU
$a = 50$ AU
$a = 70$ AU

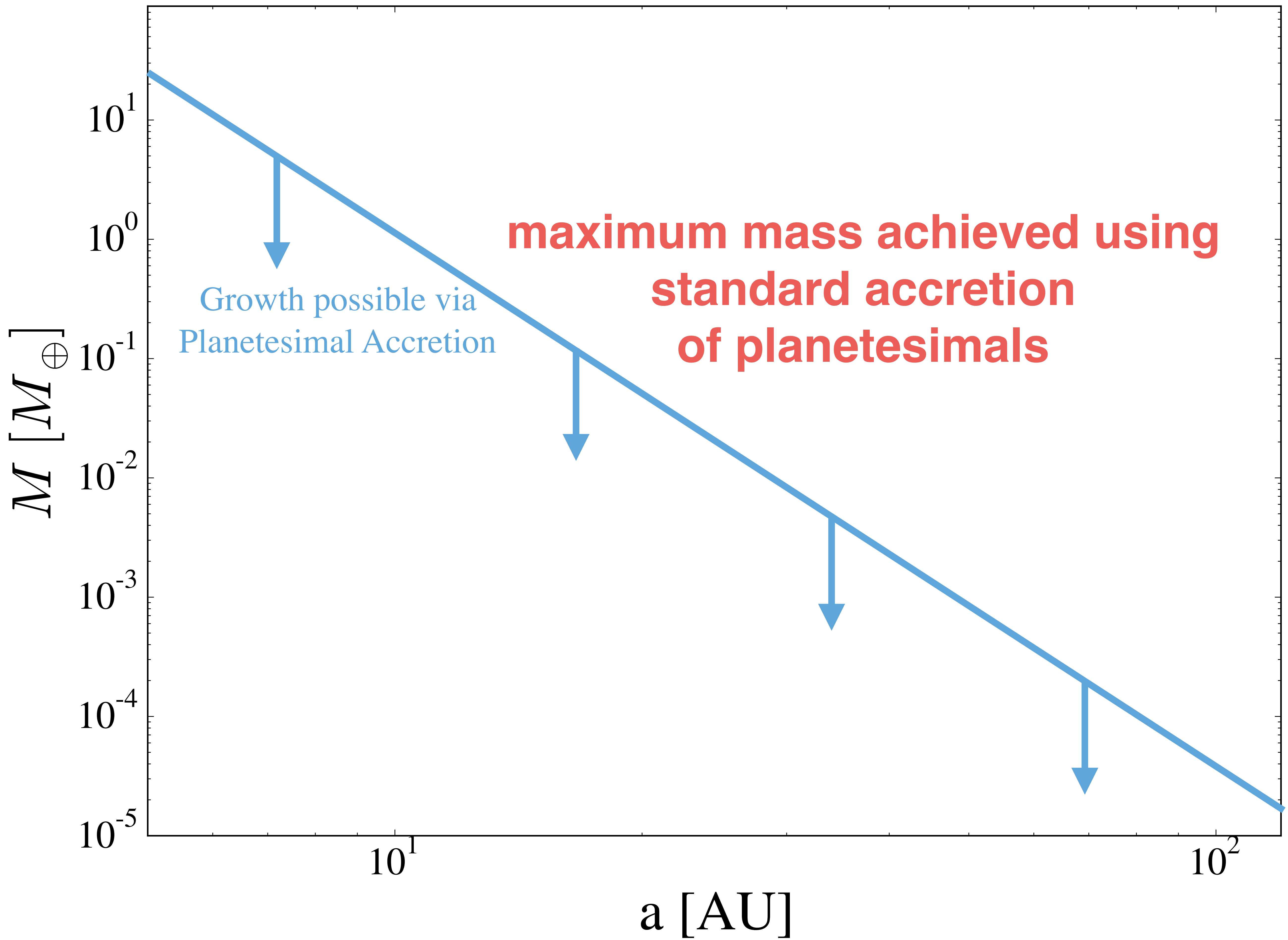


Growth possible via
Pebble Accretion
M [$M_\oplus$]
a [AU]
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{1}
10^{2}

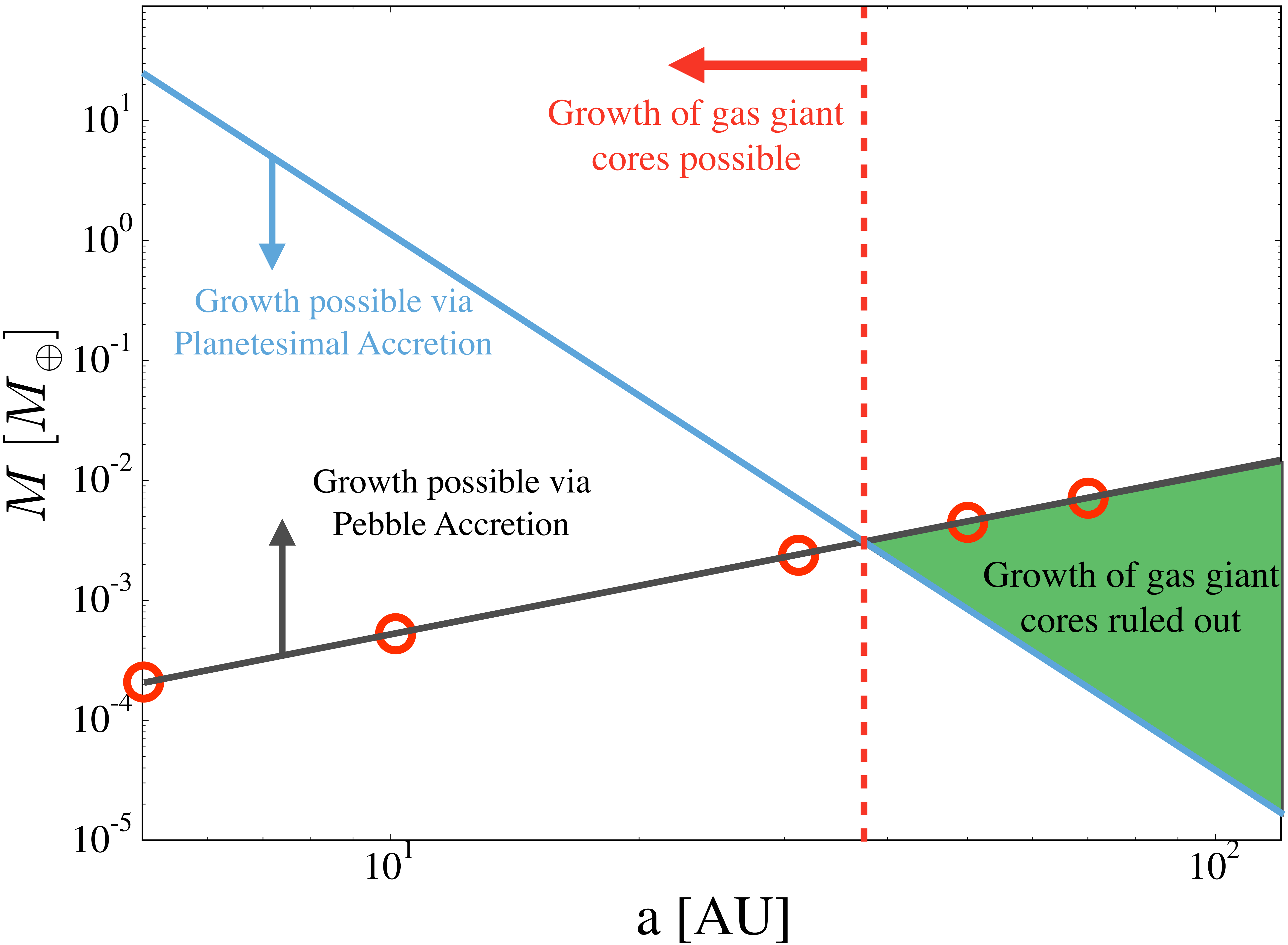
How do cores get big enough for pebble accretion to begin?

Scattering from the interior is a possibility

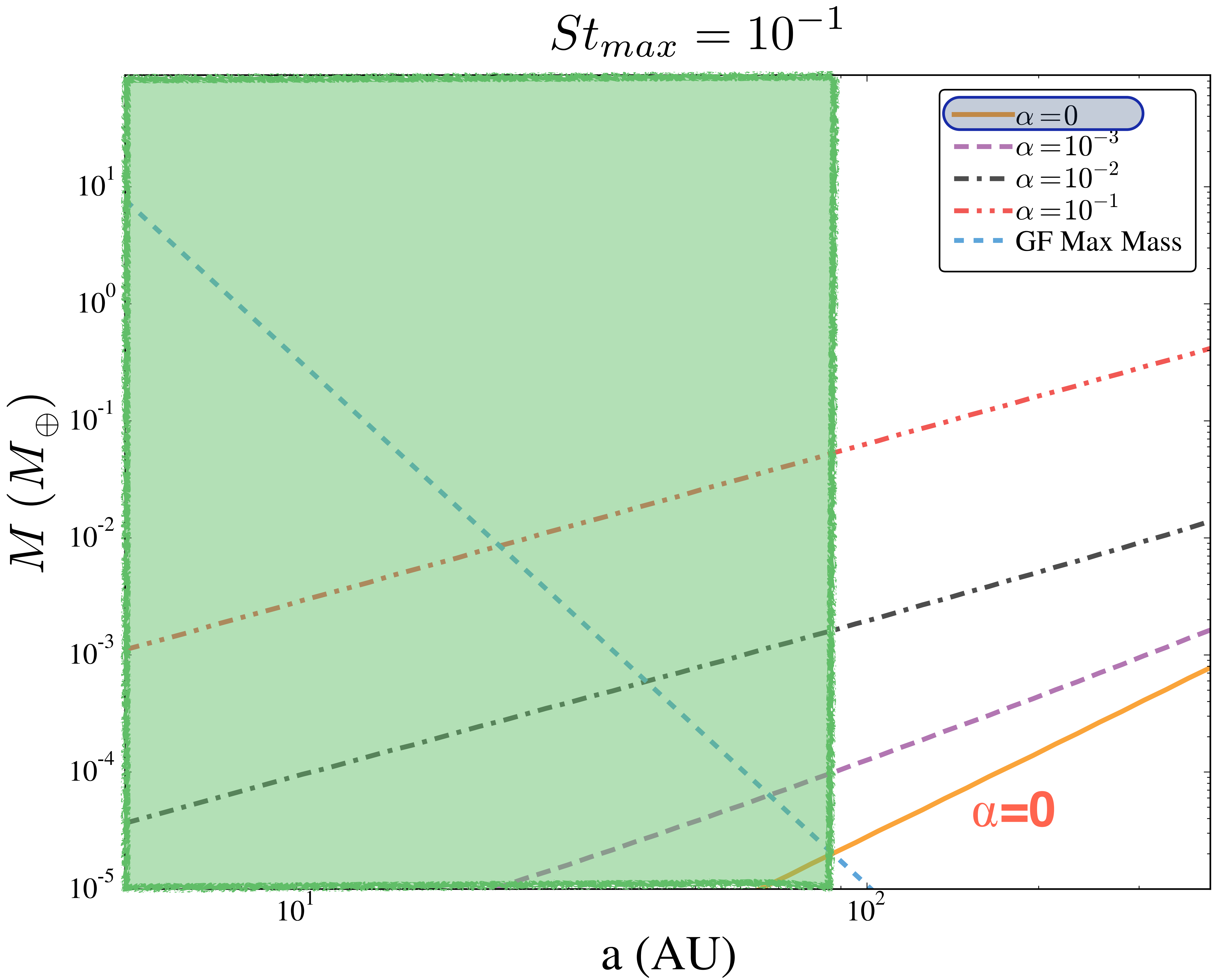
Standard planetesimal growth is another



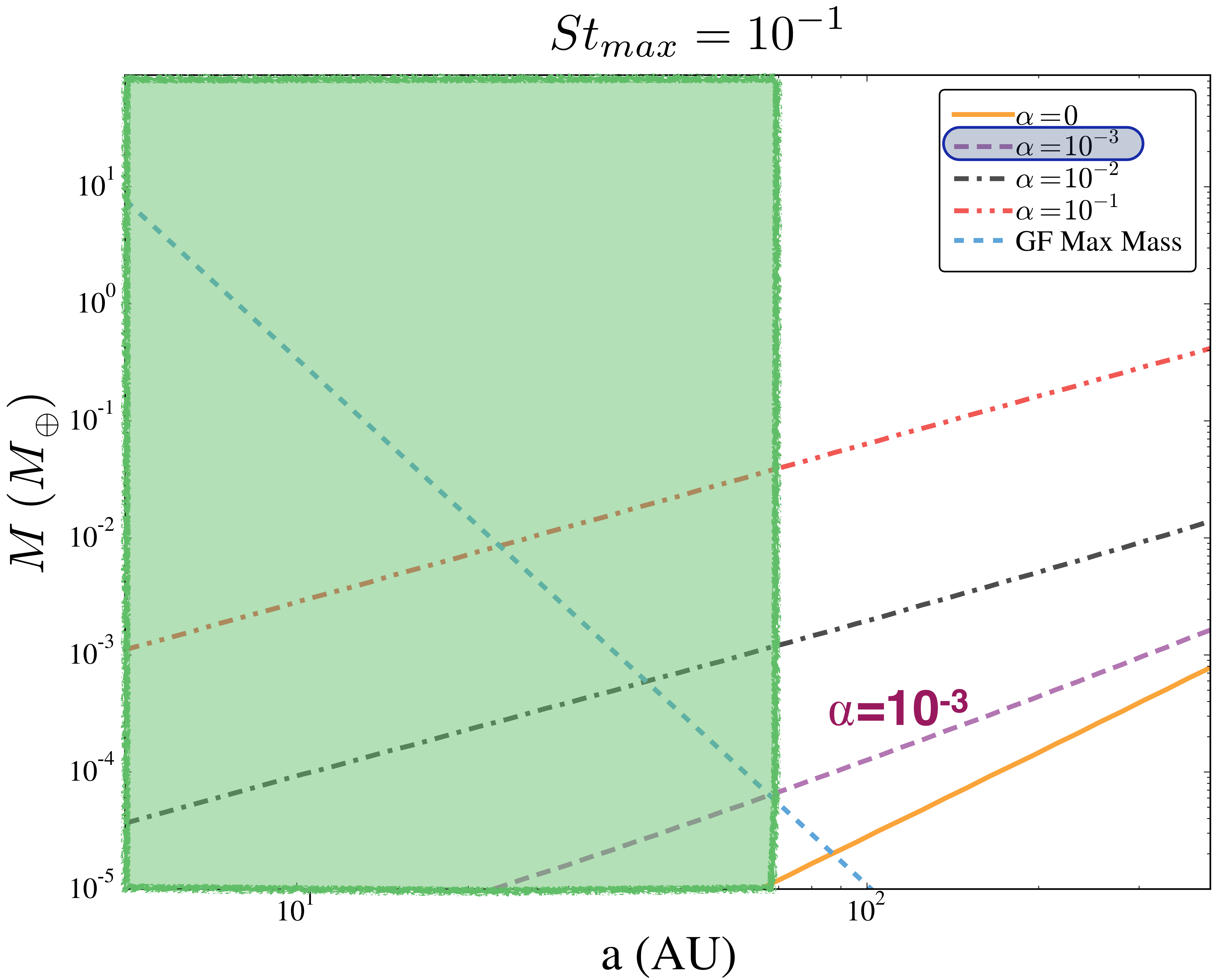
maximum mass achieved using
standard accretion
of planetesimals
Growth possible via
Planetesimal Accretion
$M\ [M_\oplus]$
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{1}
10^{2}
a [AU]



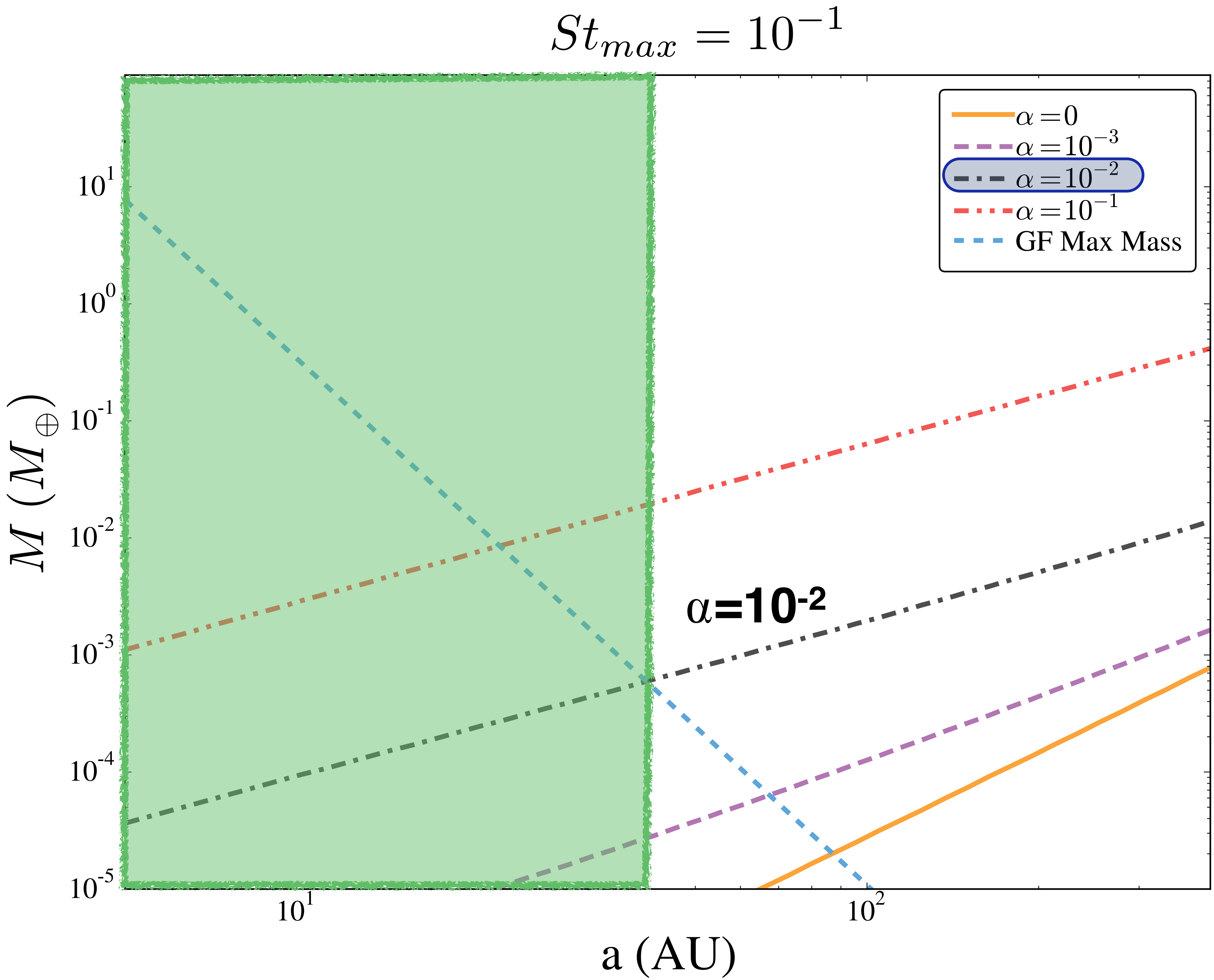
Growth of gas giant
cores possible
Growth possible via
Planetesimal Accretion
Growth possible via
Pebble Accretion
Growth of gas giant
cores ruled out
$M\ [M_\oplus]$
a [AU]
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{1}
10^{2}



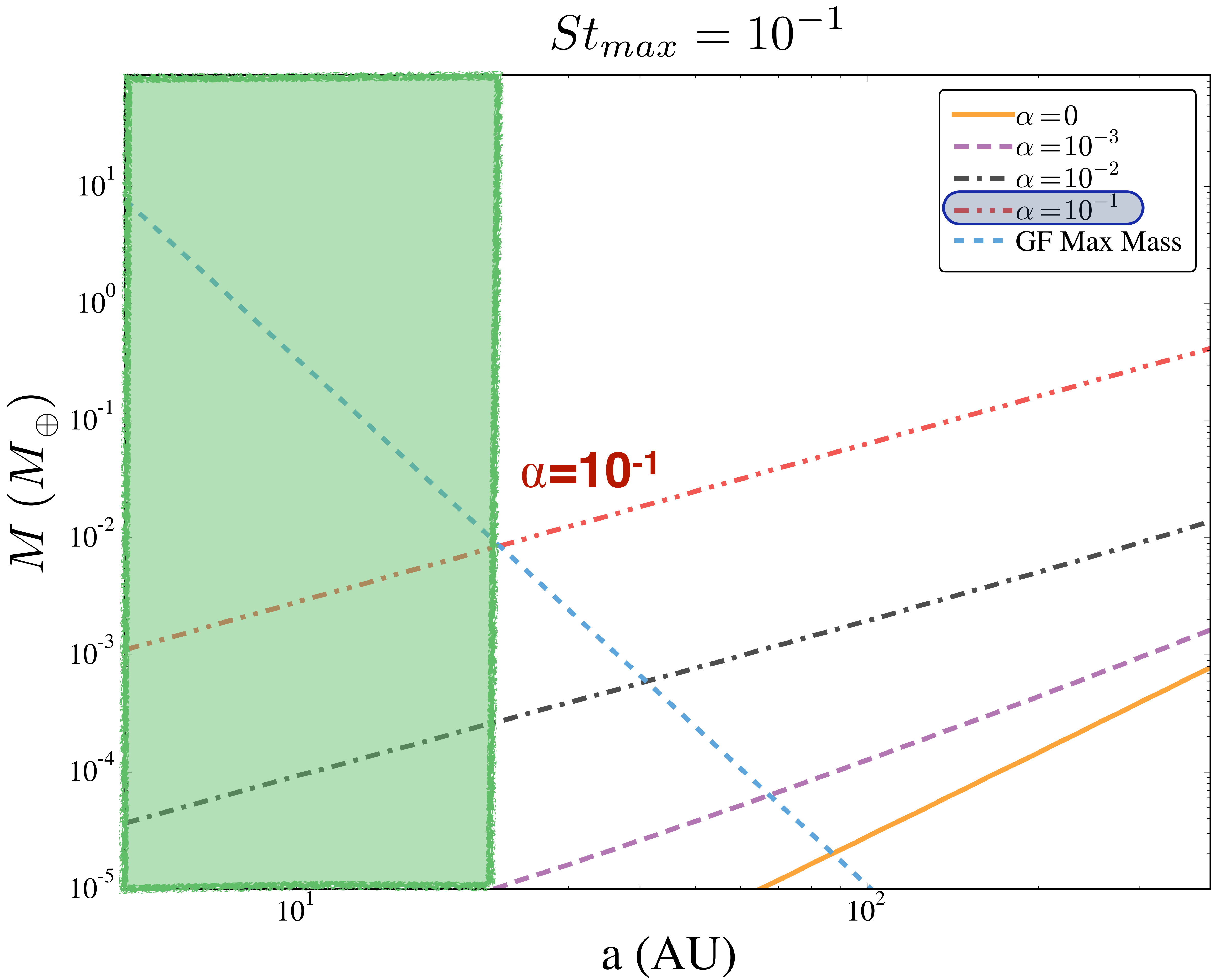
$St_{max} = 10^{-1}$
$\alpha = 0$
$\alpha = 10^{-3}$
$\alpha = 10^{-2}$
$\alpha = 10^{-1}$
GF Max Mass
α=0
$M\ (M_\oplus)$
a (AU)



$St_{max} = 10^{-1}$
$\alpha = 0$
$\alpha = 10^{-3}$
$\alpha = 10^{-2}$
$\alpha = 10^{-1}$
GF Max Mass
α=10-3
$M\ (M_\oplus)$
a (AU)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{1}
10^{2}

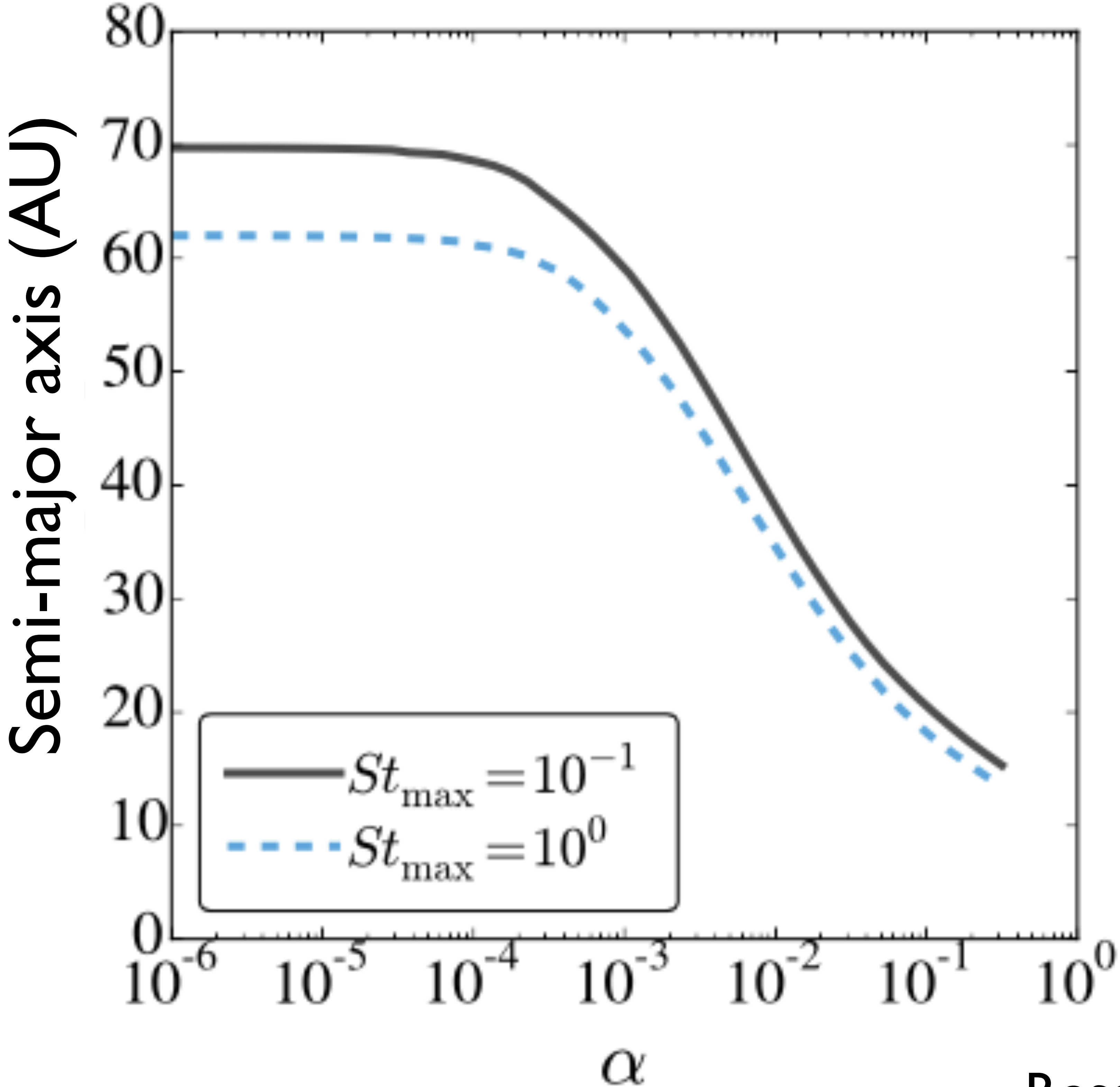


$St_{max} = 10^{-1}$
$\alpha = 0$
$\alpha = 10^{-3}$
$\alpha = 10^{-2}$
$\alpha = 10^{-1}$
GF Max Mass
α=10-2
$M\ (M_\oplus)$
a (AU)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{1}
10^{2}



$St_{max} = 10^{-1}$
$\alpha = 0$
$\alpha = 10^{-3}$
$\alpha = 10^{-2}$
$\alpha = 10^{-1}$
GF Max Mass
α=10-1
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$M\ (M_\oplus)$
10^{1}
10^{2}
a (AU)

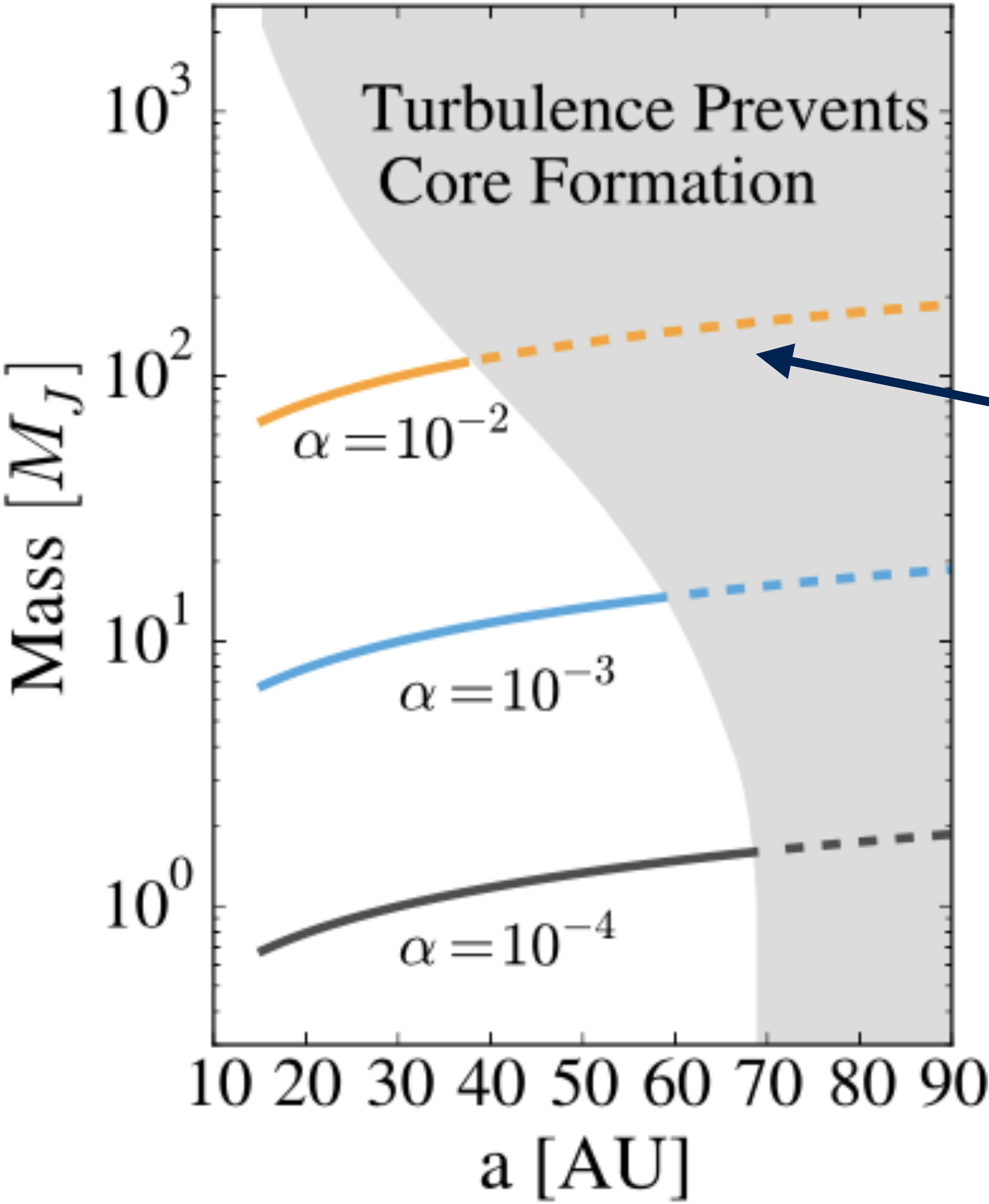
Predicted distance at which giant planets can form as a function of turbulence strength.



Upshot:
Disk turbulence may set the outer scale of giant planet formation.

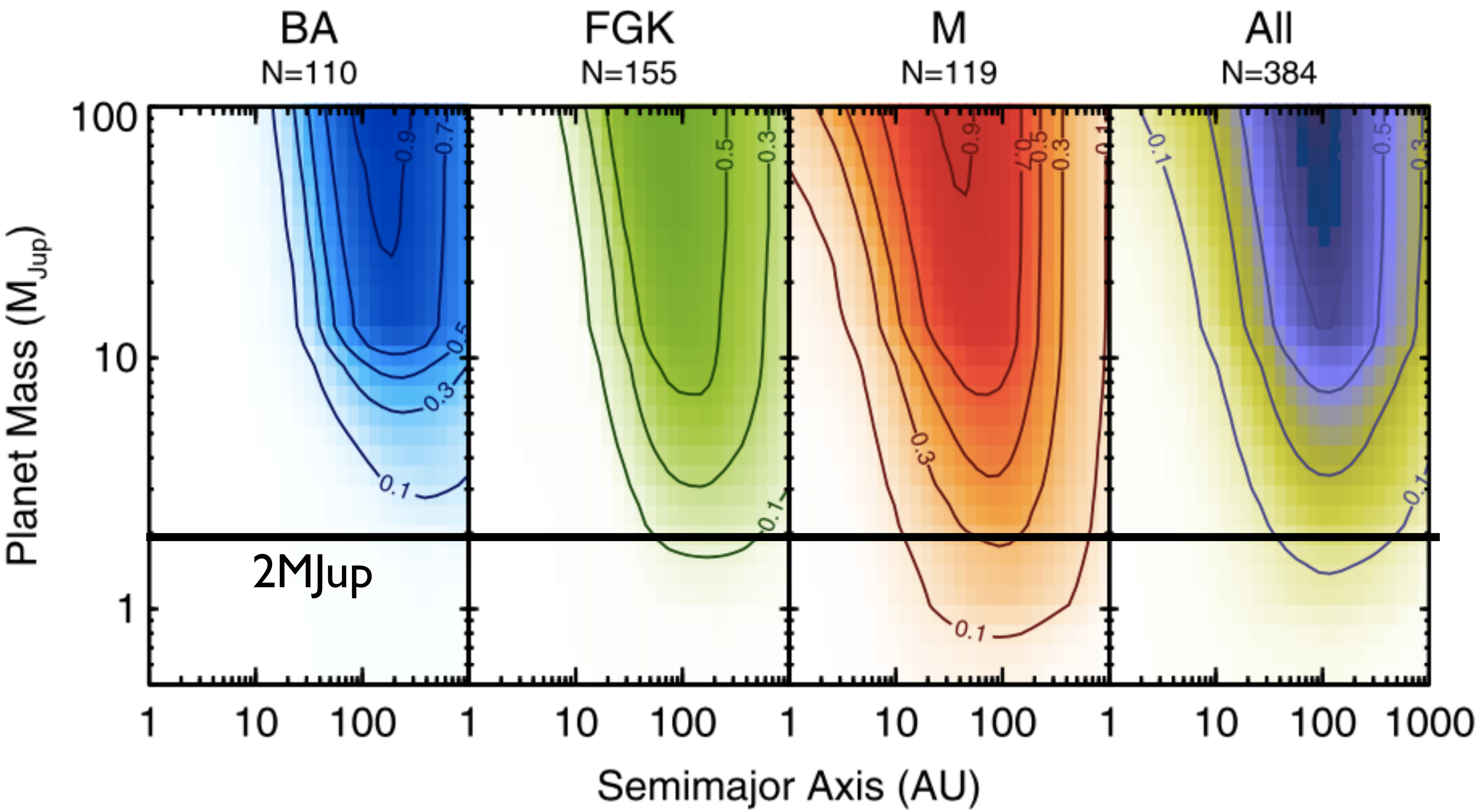
Rosenthal & Murray-Clay, subm.

Gap starvation may determine final masses

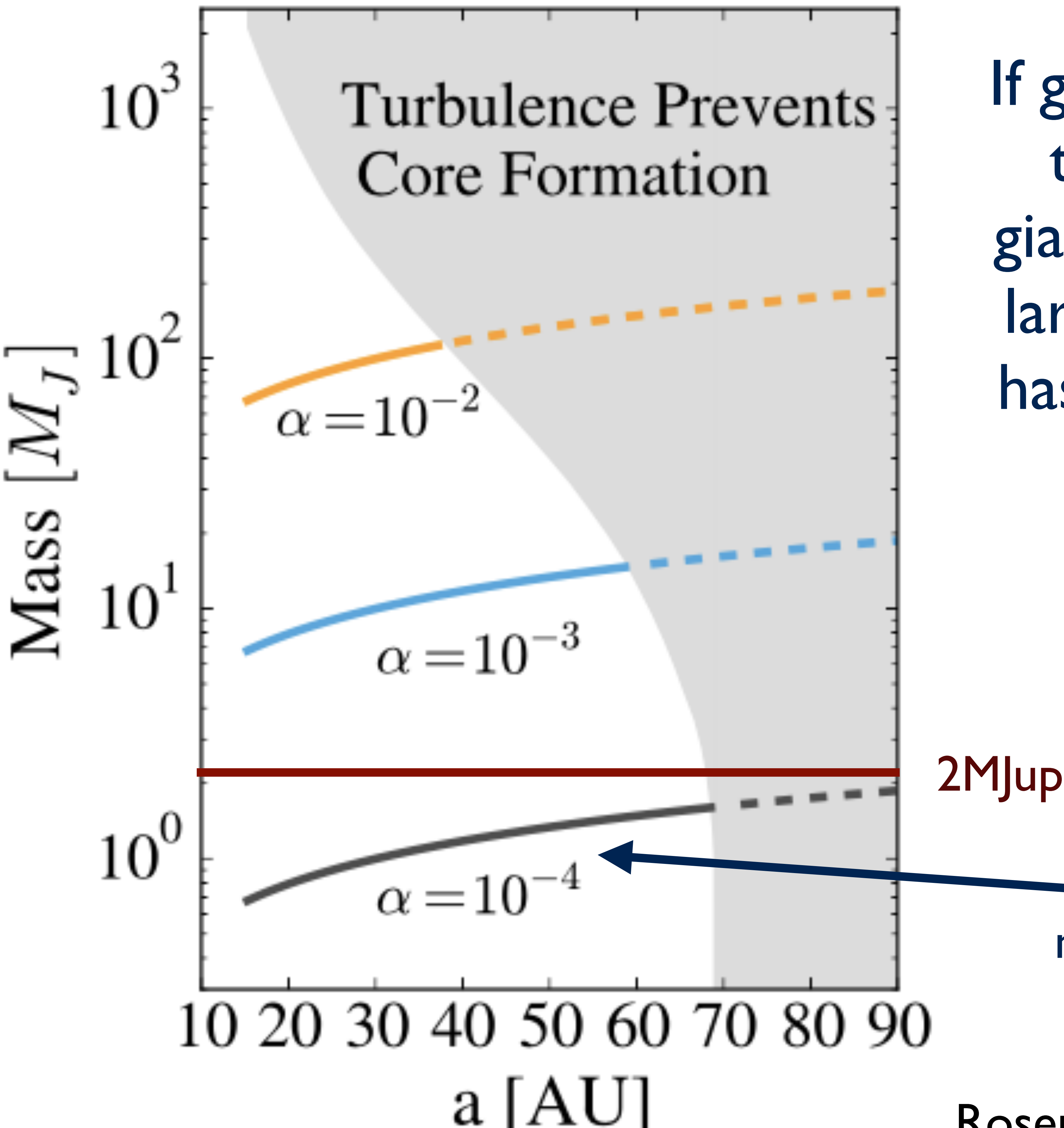


In high-viscosity disks, planets must be large to open a gap

Rosenthal & Murray-Clay, subm.


BA
N=110
FGK
N=155
M
N=119
All
N=384
Planet Mass (M_{Jup})
Semimajor Axis (AU)
2MJup
100
10
1
1
10
100
1000
0.9
0.7
0.5
0.3
0.1

Bowler (2016)



If gap starvation limits the masses of gas giants, there may be a large population that hasn't been observed

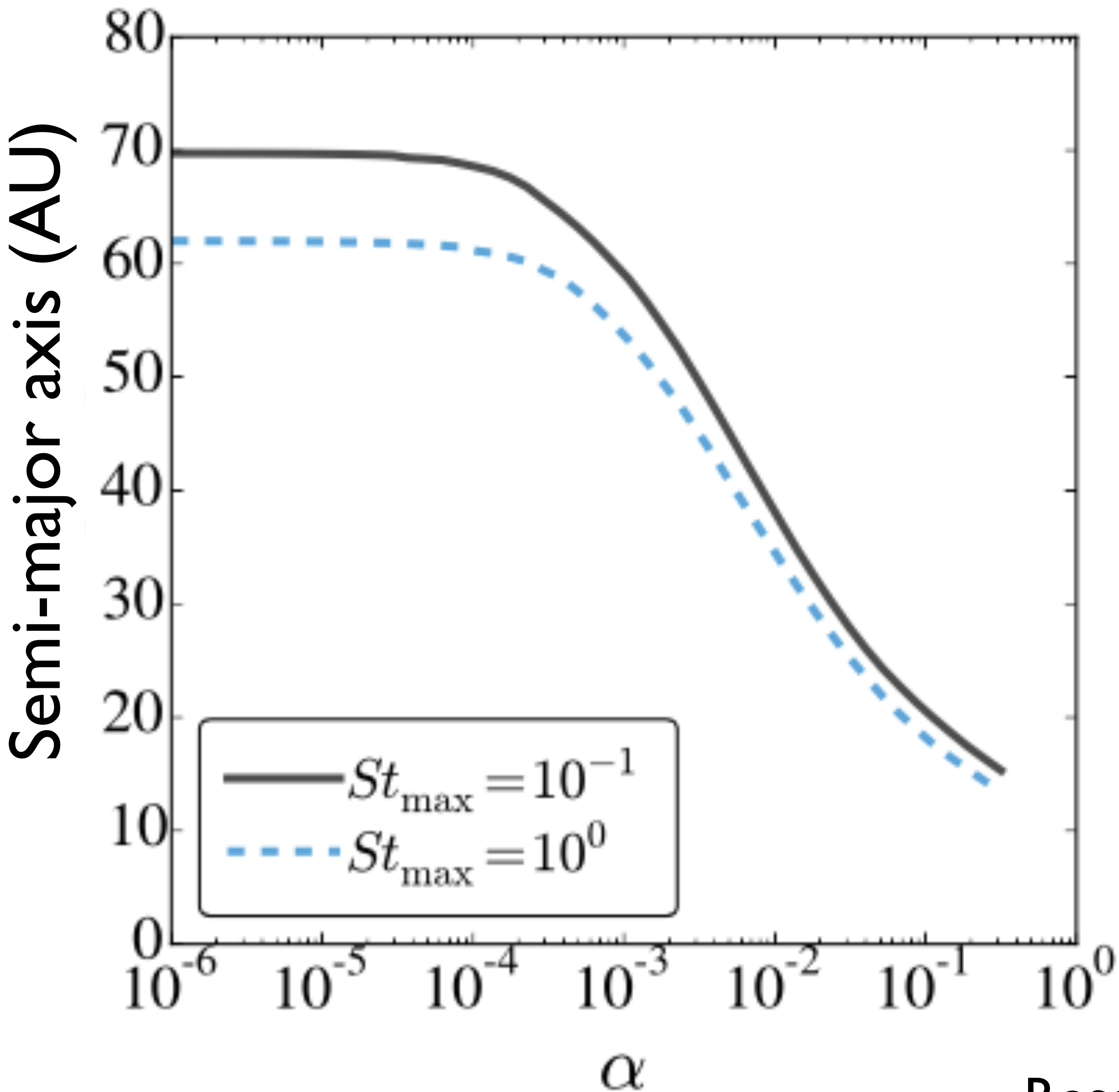
Maybe G stars make lower-mass giants

Rosenthal & Murray-Clay, subm.

Hypothesis:

Perhaps gas giants are more common than we think, just less massive than direct imaging limits.

Predicted distance at which giant planets can form as a function of turbulence strength.



Depends strongly on size distribution of small bodies

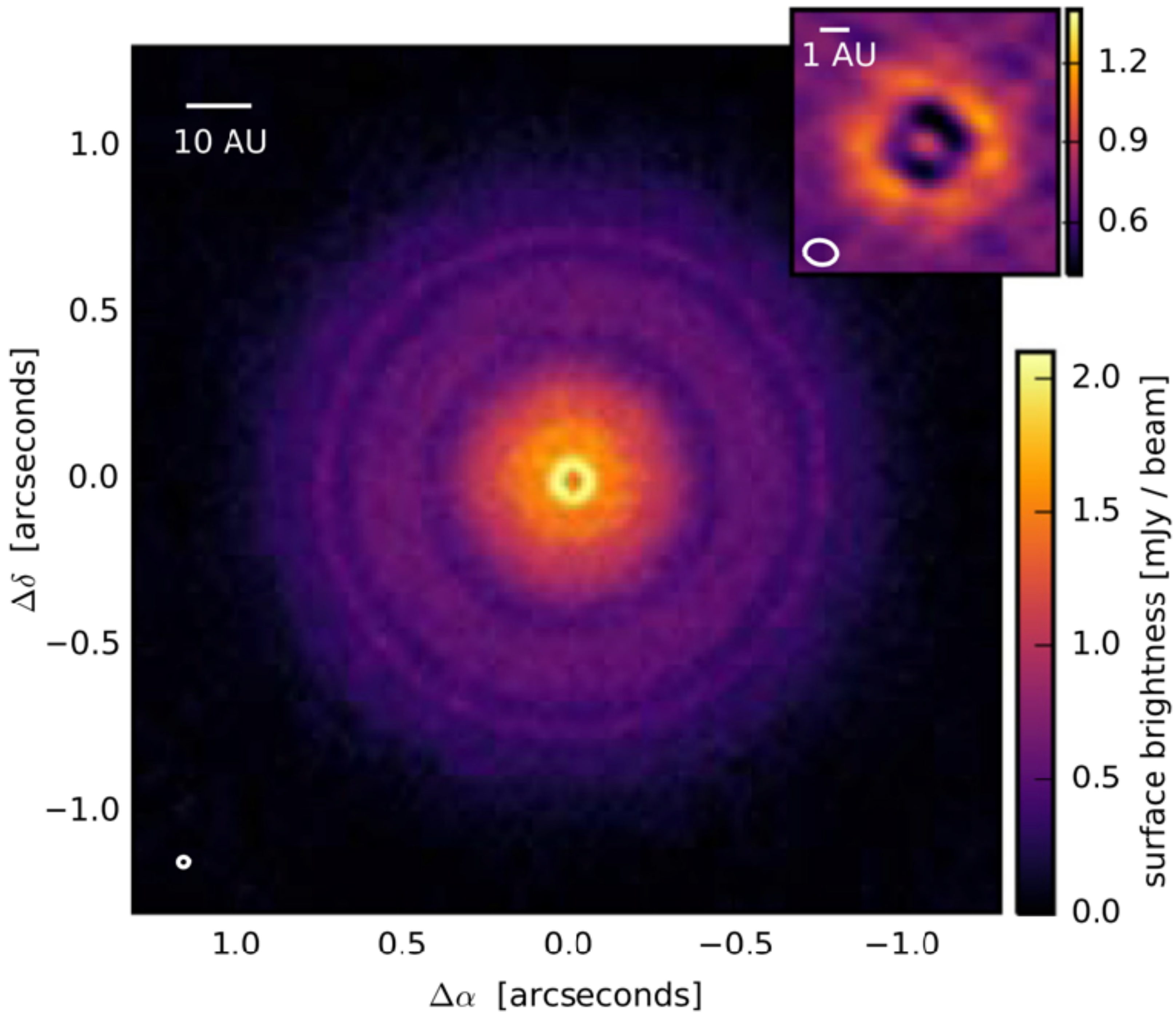
Rosenthal & Murray-Clay, subm.

Accretion of small (e.g. mm) solid material by planets depends strongly on particle size (really aerodynamic properties)

So

Variation in the particle size distribution across the disk affects where planetary cores can grow quickly

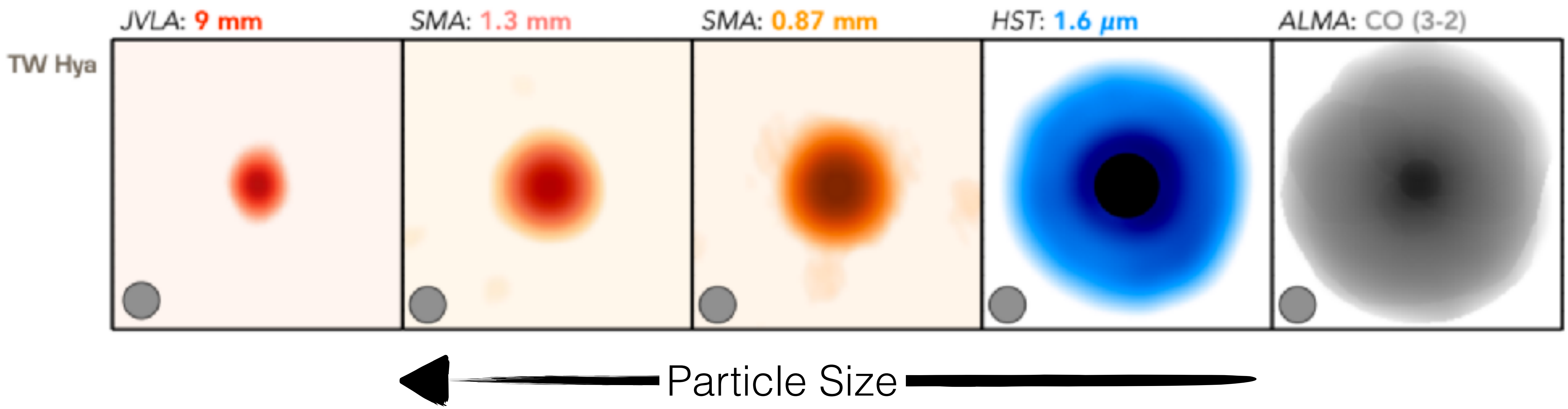
TW Hydra

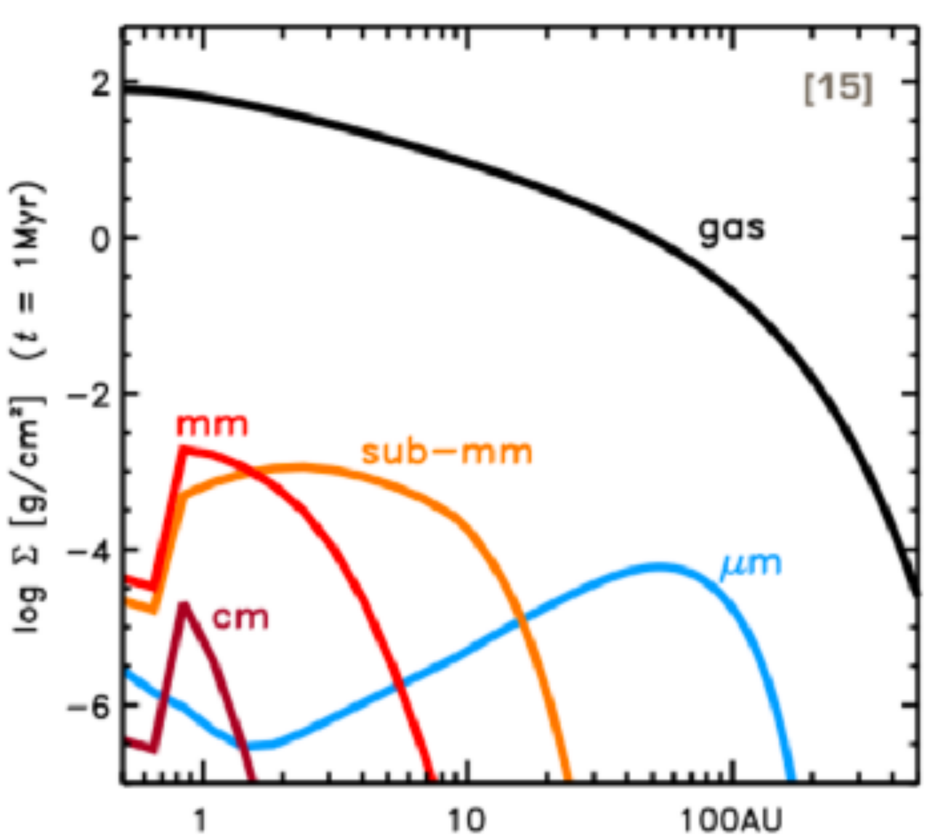


ALMA

Andrews et al. 2016

Protoplanetary disks appear smaller at longer wavelengths

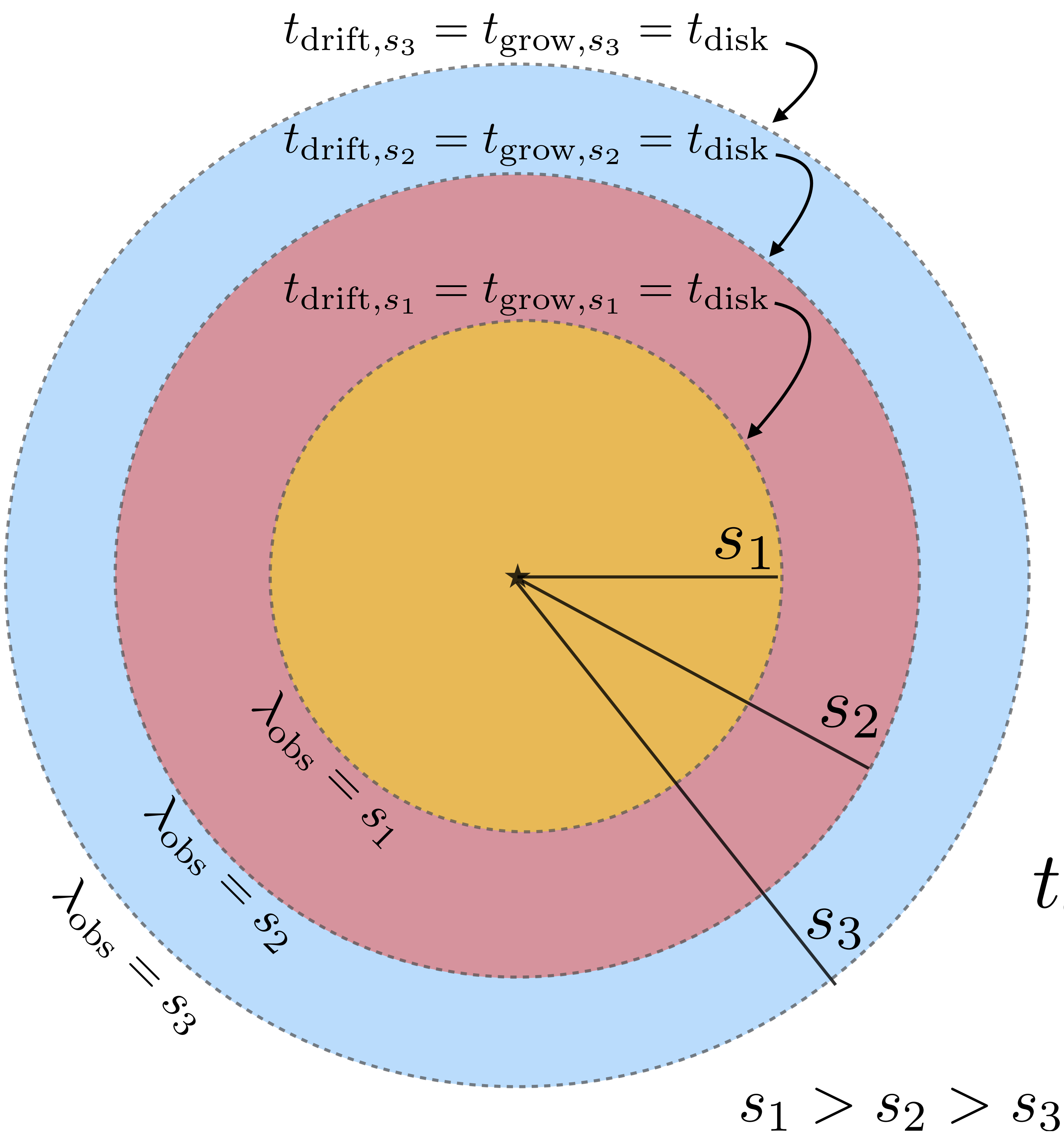




for well-coupled dust, larger particles drift inward more quickly

Birnstiel & Andrews 2015, Menu et al. 2014, L.I. Cleeves, Andrews et al. 2012, Debes et al. 2013,
images from presentation by
Sean Andrews May 2016

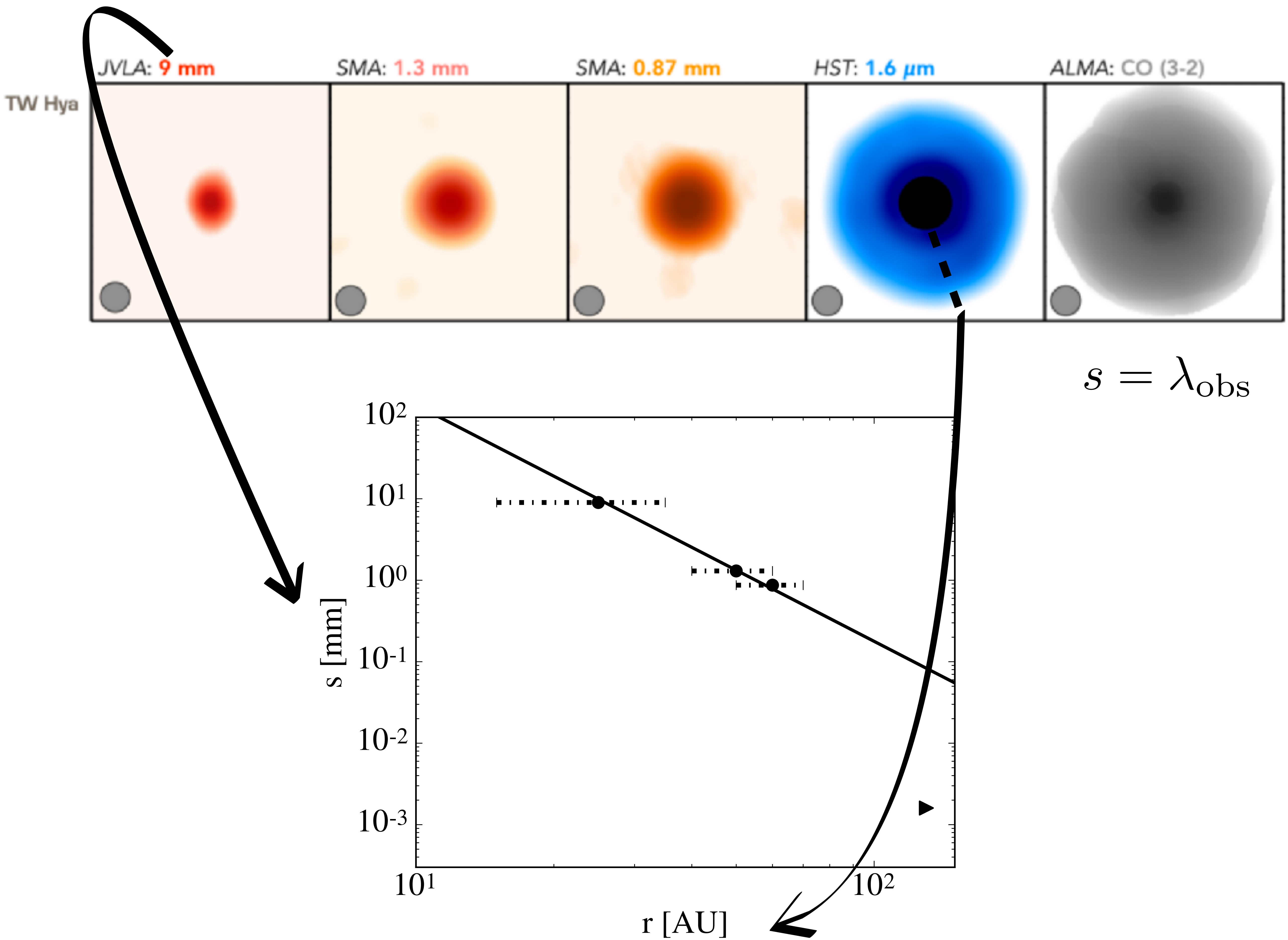
A new way to derive surface density



outer disk:
particle growth ends
due to drift

$$t_{\mathrm{drift}} \sim \frac{\Sigma r}{v_0 \rho_{\mathrm{part}} s} \sim t_{\mathrm{disk}}$$

Powell, Murray-Clay, & Schlichting 2017

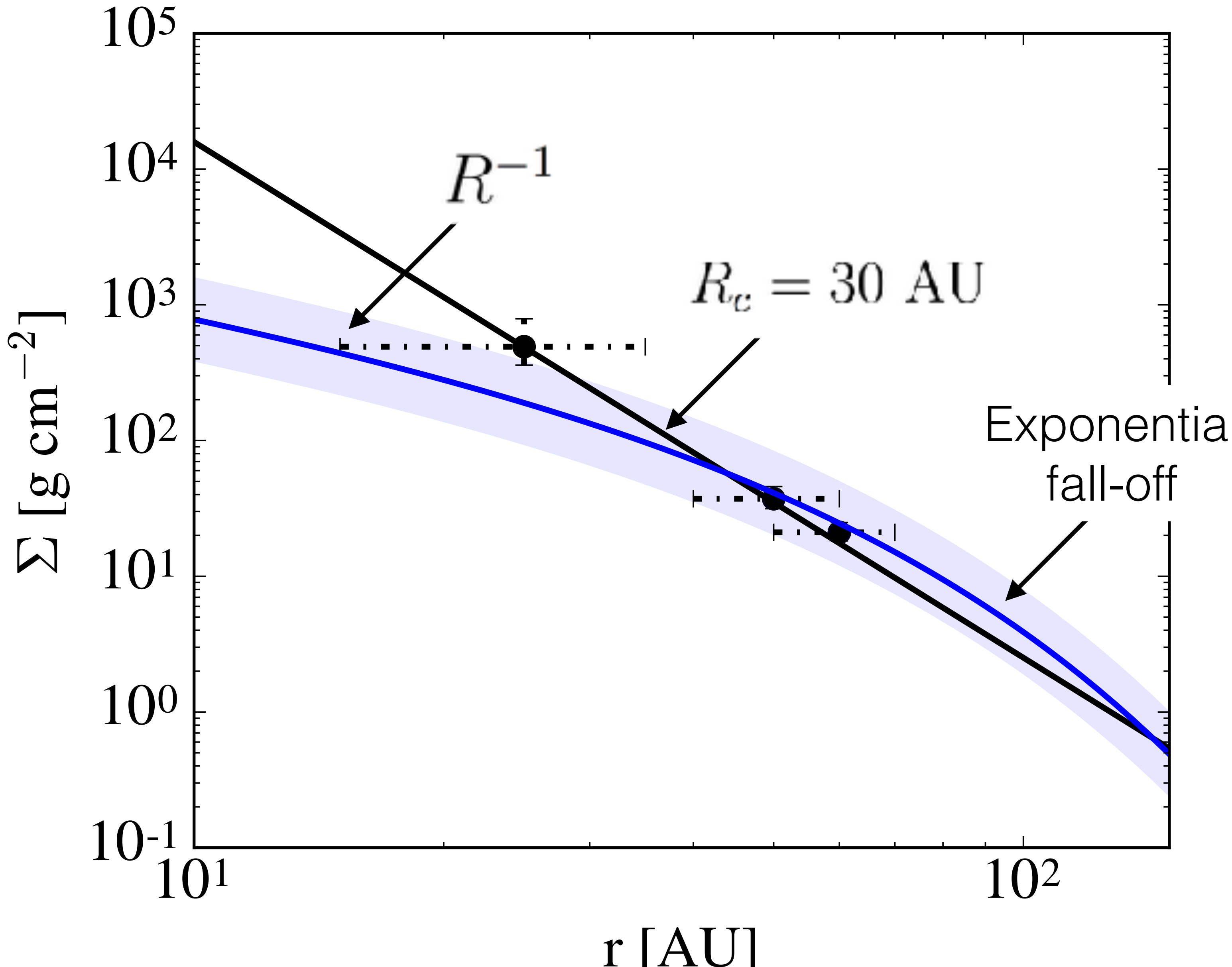


$$s = \lambda_{\rm obs}$$

Powell, Murray-Clay, & Schlichting 2017

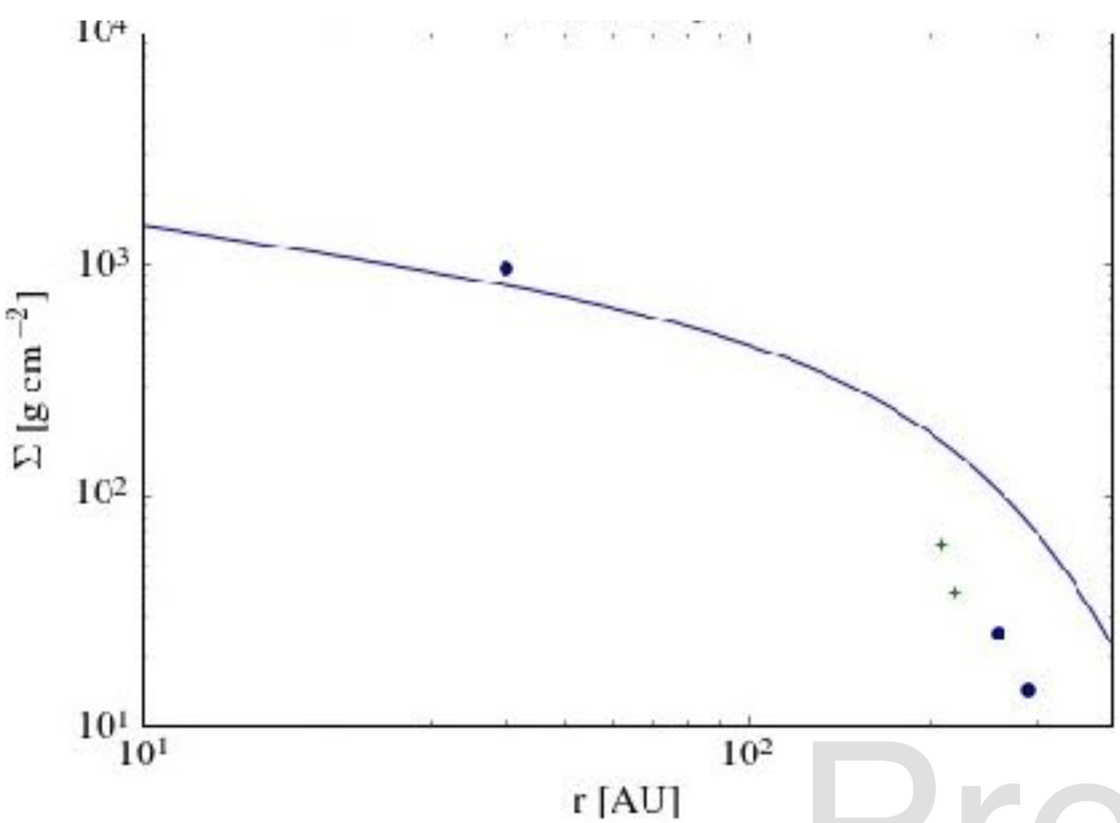
Normalized CO Surface Density Profile

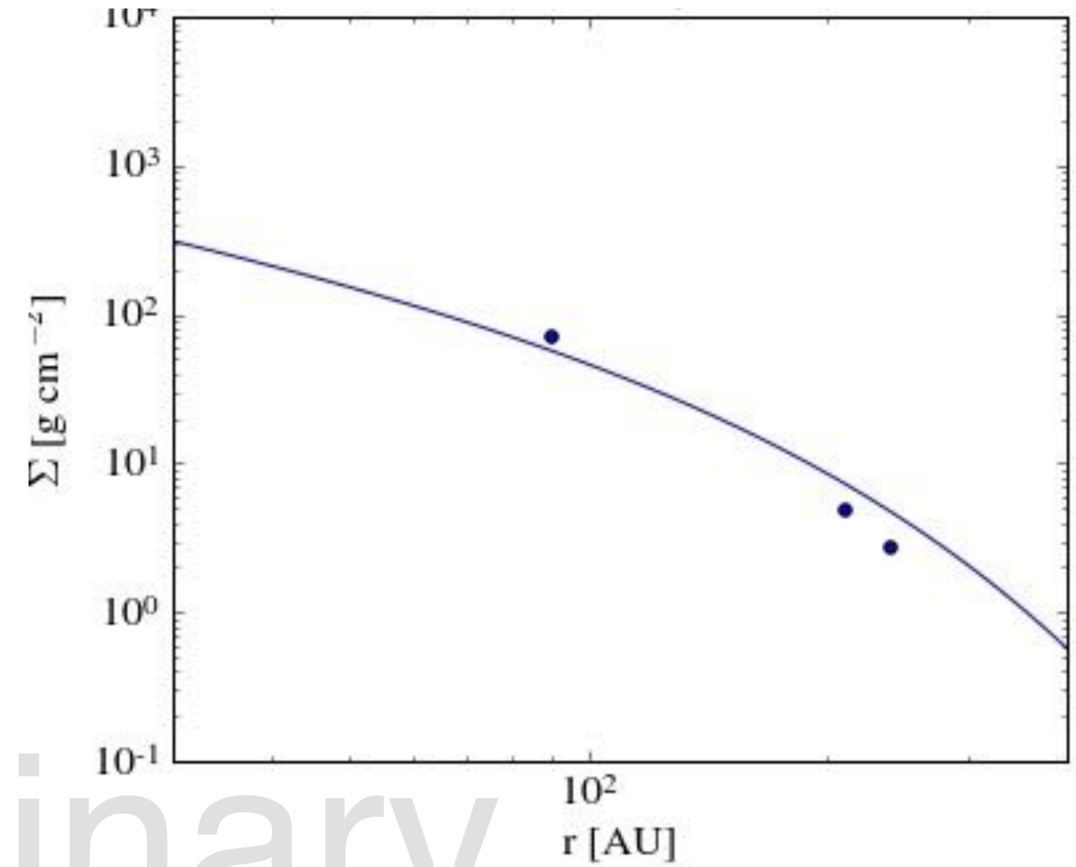
$$\Sigma_{\rm c} \sim 300\ {\rm g\ cm^{-2}}$$
$$X_{\rm CO} \sim 3 \times 10^{-7}$$



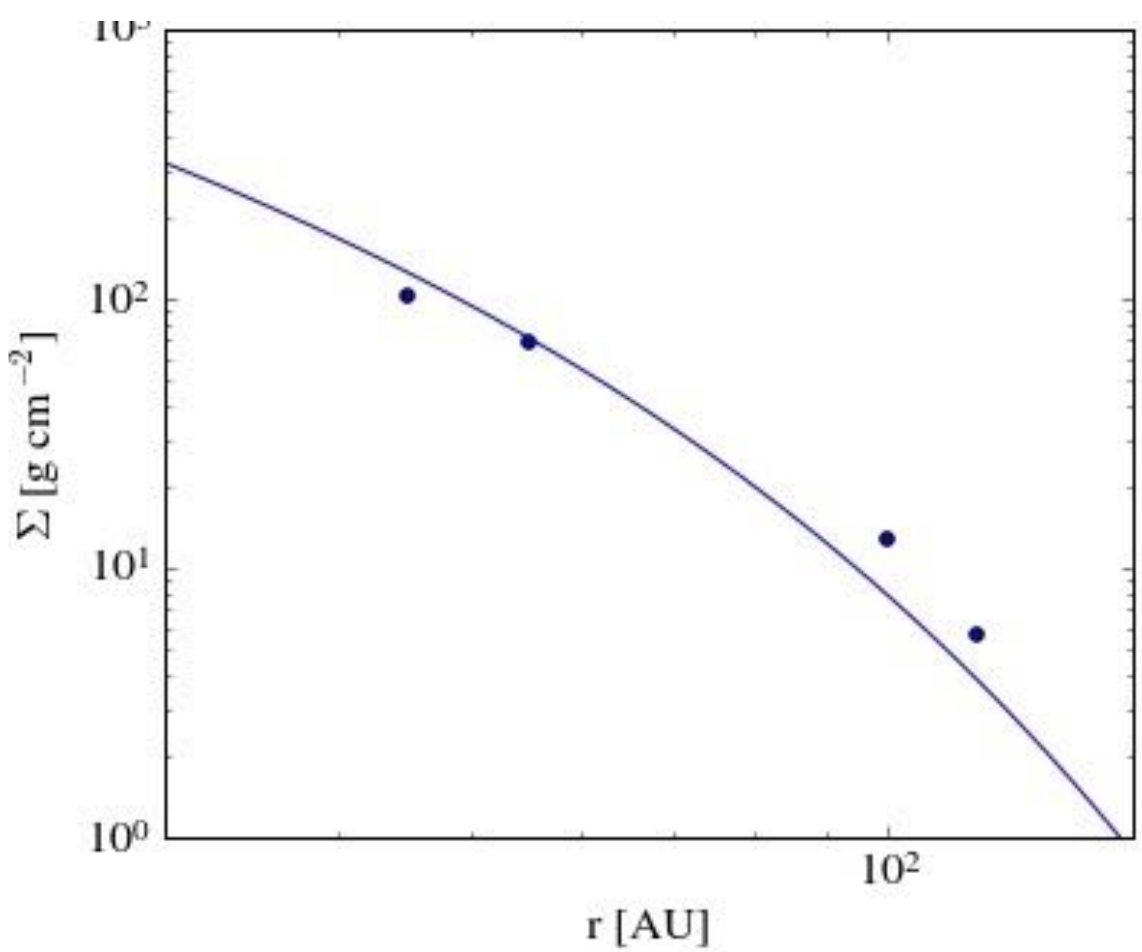
$$t_{\rm drift} \sim \frac{\Sigma r}{v_0 \rho_{\rm part} s} \sim t_{\rm disk}$$

Powell, Murray-Clay, & Schlichting 2017





Preliminary



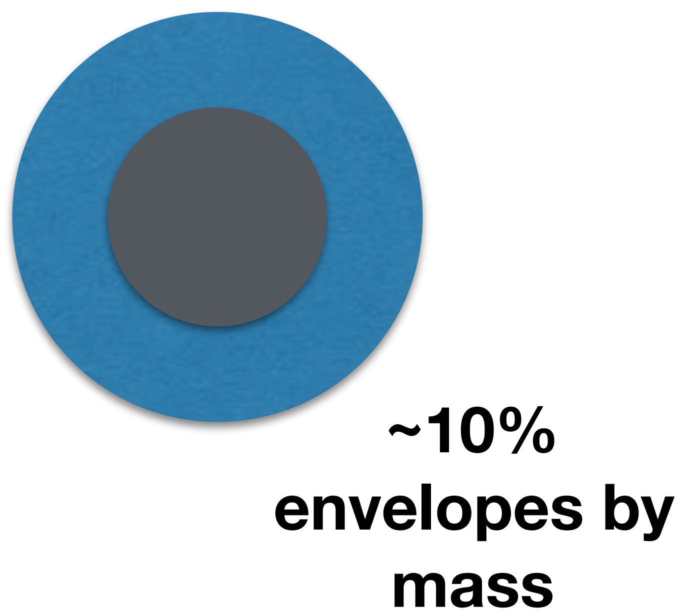
Powell et al. (in prep)

Upshot:
Observed disks may be orders of magnitude more massive than previously thought.

At least some close to Q=1 gravitational stability limit
(though the images of symmetric disks can't quite be at Q=1)

See Powell et al. (2017) for the additional tests that we propose to validate our model.

Pebble accretion poses a fine-tuning problem for the intermediate-mass atmospheres of Uranus and Neptune.



Frelikh & Murray-Clay 2017

Gas-assisted growth (pebble accretion) is a size-dependent dynamical capture process that likely has important implications for planet formation

(Imperfect) Analogies:

Formation of Kuiper belt binaries by dynamical friction with a sea of small bodies

Accretion of dwarf galaxies by dynamical friction

Hardening of stellar binaries

Stellar binary formation in the galactic center (Doug's talk)