# PROTOPLANETARY DISC THEORY IN THE ALMA ERA

GIUSEPPE LODATO - UNIVERSITÀ DEGLI STUDI DI MILANO

# SUMMARY

- A few things that we thought we knew, but we do not
  - Angular momentum transport mechanism
  - Disc substructures
  - Planet formation timescale
  - Planet migration

# ANGULAR MOMENTUM TRANSPORT: IS THE DISC VISCOUS OR NOT?

- ALMA allows to measure disc turbulence constraining it to a low level, with $\alpha <\sim 10^{-3}$ (Flaherty et al., 2017)

$$t_\nu = \frac{4}{9}\frac{R_\mathrm{d}^2}{\nu} = \frac{2}{9\pi\alpha}\left(\frac{H}{R}\right)^{-2} T(R_\mathrm{d}) \approx 1.5\ 10^6 \left(\frac{R_\mathrm{d}}{50\mathrm{au}}\right)^{3/2} \mathrm{yr}$$

- An $\alpha \sim 10^{-3}$ is just enough to allow reasonable disc lifetimes but it cannot be much smaller than that.

# DO VISCOUS MODELS WORK? POPULATION SYNTHESIS STUDIES

- A nice way to probe global disc evolution is to test global properties against surveys
- Surveys have shown interesting correlations:
  - $M_{dot}$ vs $M_{disc}$ (Ansdell et al 2016, Pascucci et al. 2016, Manara et al 2016)
  - mm-flux vs disc radius (Tripathi et al 2017, Andrews et al 2018)

Lodato et al 2017

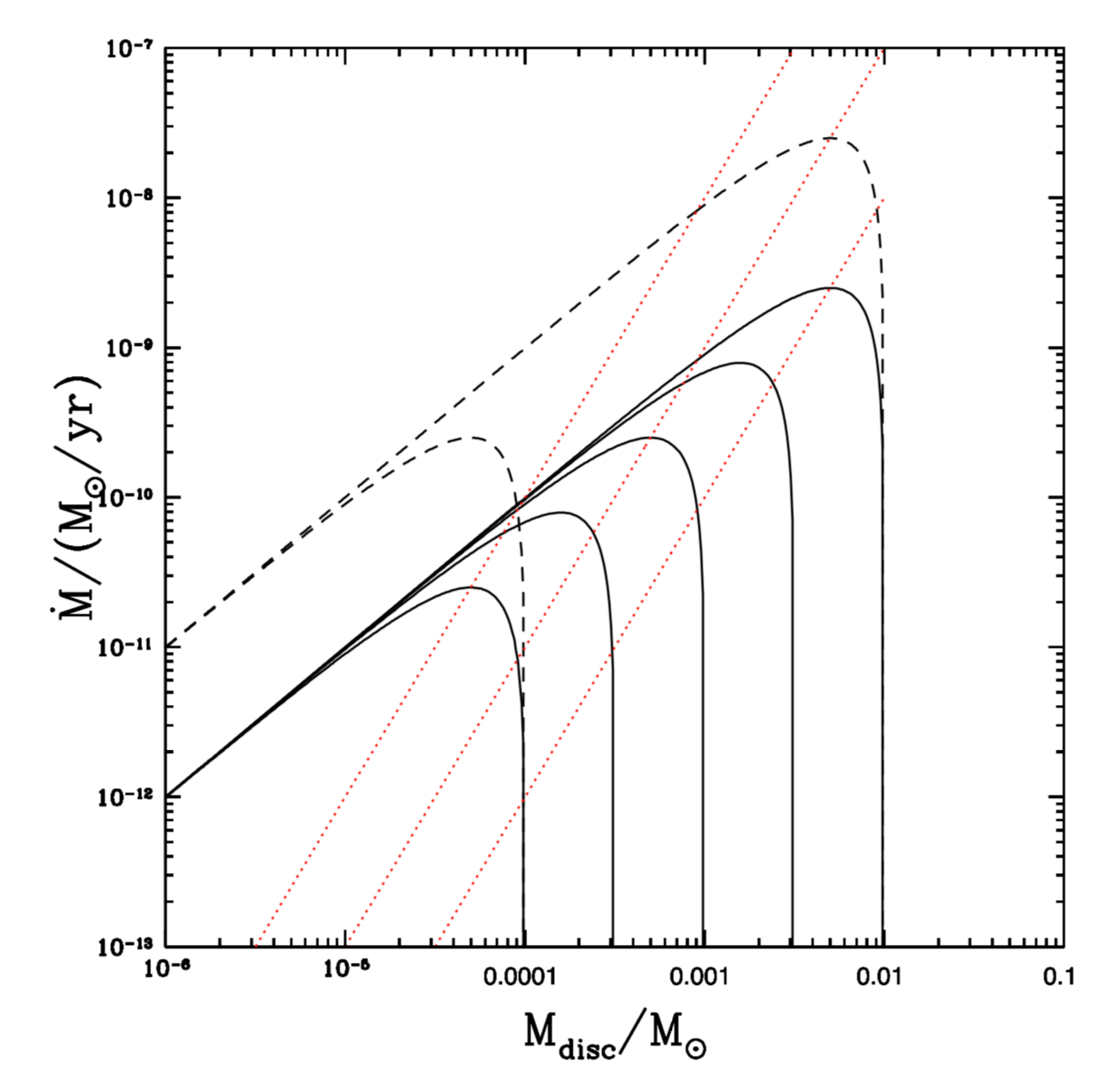
# DISC 'ISOCHRONES'

- Locus of points for a population with different viscous times but same age
- Use self-similar solutions

$$\Sigma(R,t) = \frac{M_0}{2\pi R_0^2}(2-\gamma)\left(\frac{R}{R_0}\right)^{-\gamma} T^{-\eta}\exp\left(-\frac{(R/R_0)^{(2-\gamma)}}{T}\right)$$

$$\dot{M} = \frac{M_\mathrm{d}}{2(2-\gamma)t}\left[1-\left(\frac{M_\mathrm{d}}{M_0}\right)^{2(2-\gamma)}\right]$$

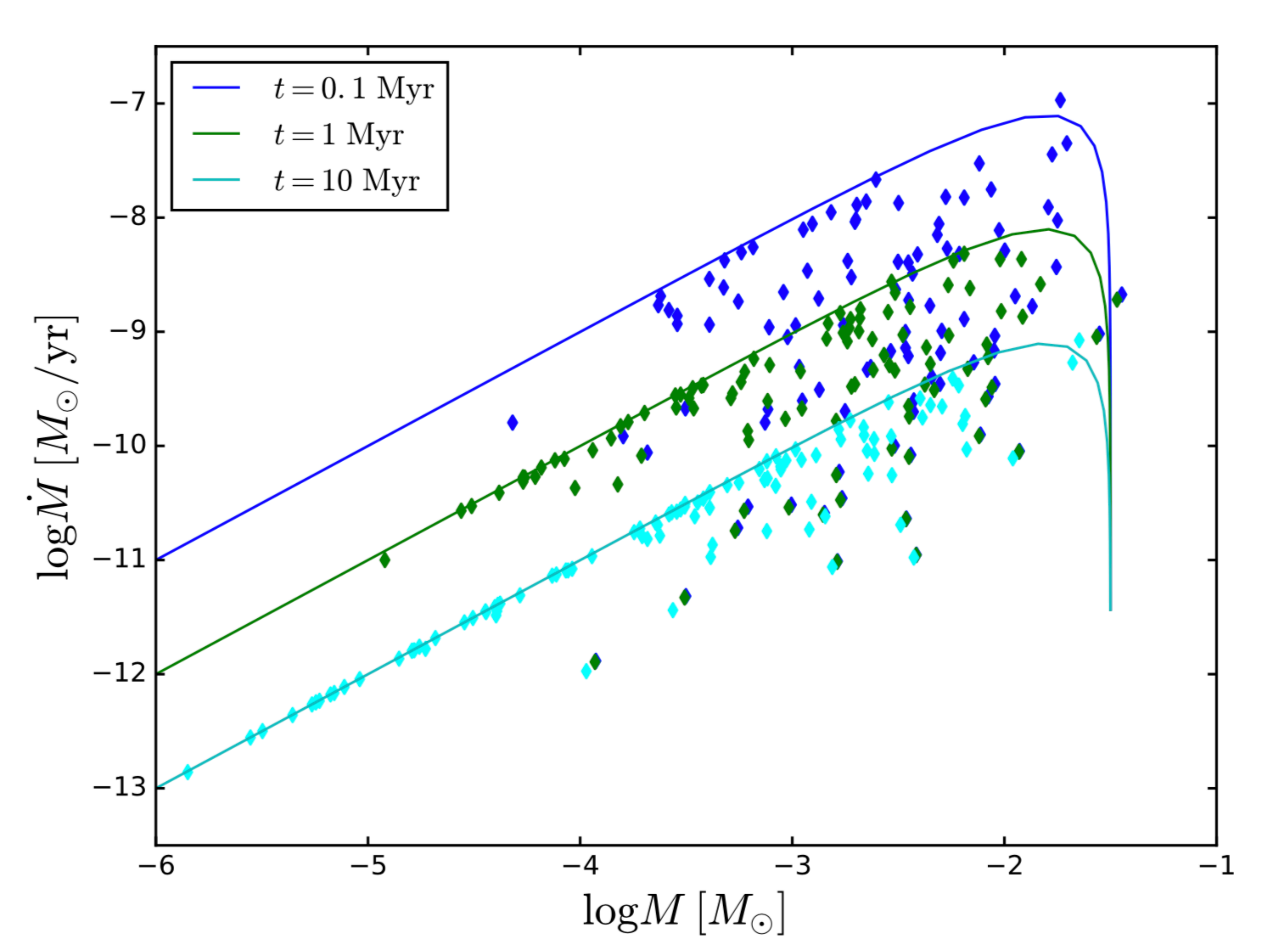
A linear correlation arises for evolved discs



Lodato et al 2017

# DISC 'ISOCHRONES'

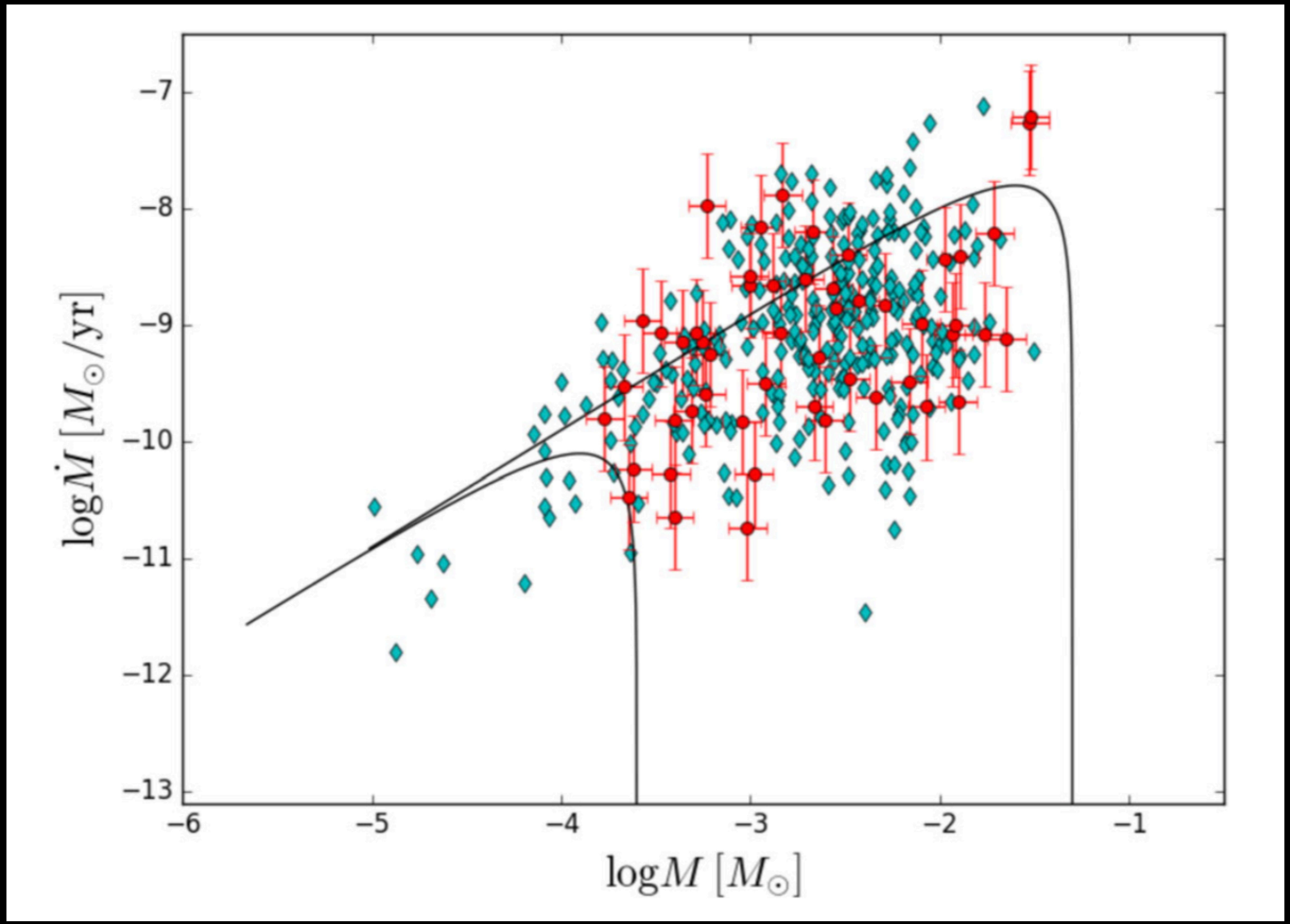
- Montecarlo realization of such similarity solutions however show the following:
  - If the population is young, large scatter around the correlation
  - Correlation shallower than linear
  - A tight, linear correlation is only found if age >> average viscous time



Lodato et al 2017

# DISC 'ISOCHRONES'

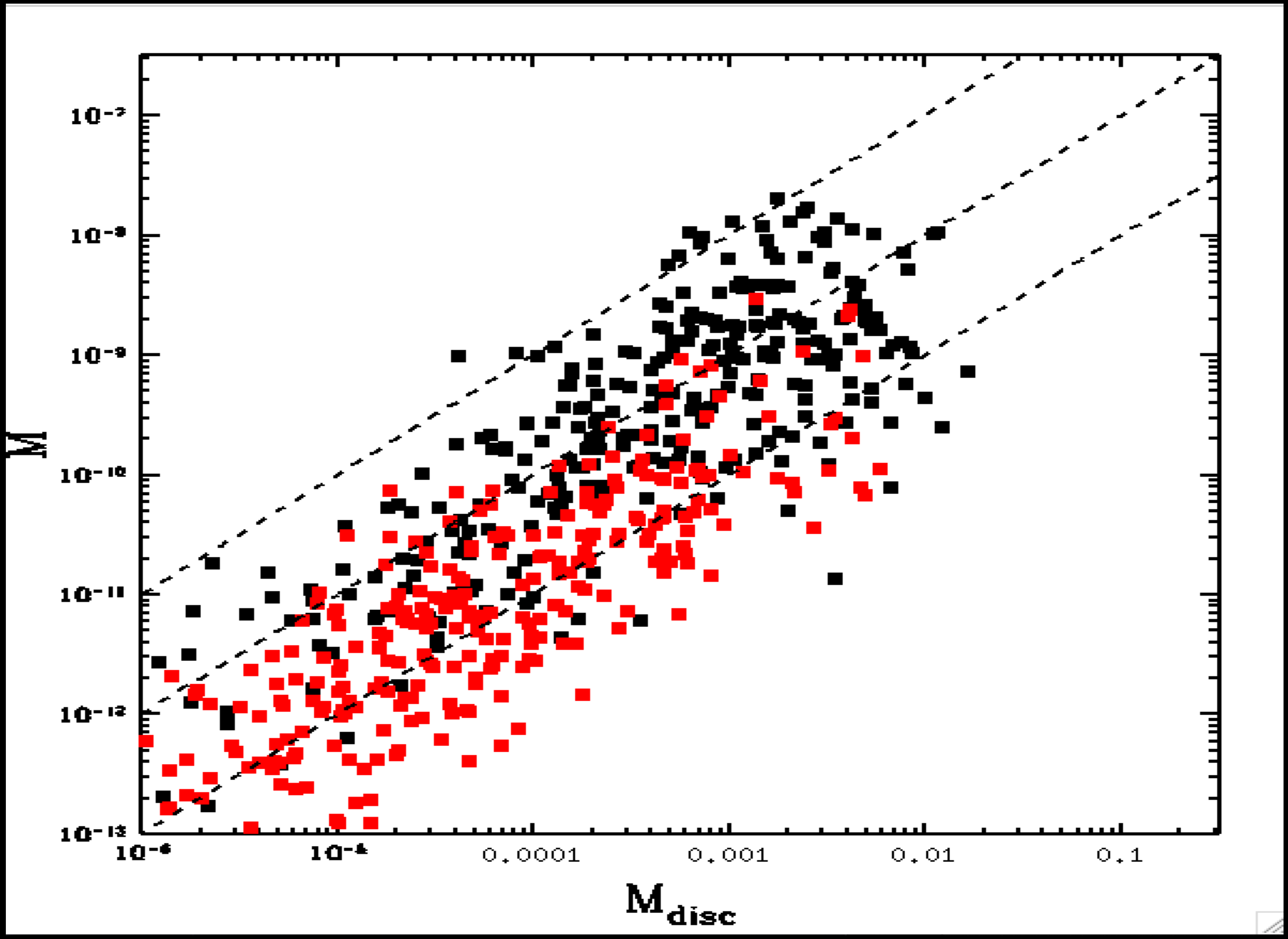
- The correlation observed in Lupus and Chamaleon is well fitted by viscous models if:
  - Age ~ 1Myr
  - Average viscous time ~ 1Myr
  - Initial disc radii have to be on average <~ 50 au



Lodato et al 2017

# DISC 'ISOCHRONES'

- Is there a way to test further these models for older regions (i.e. Upper Sco)?
- Theoretically, one expects a tighter correlation
- However, given the current uncertainties in disc masses, accretion rates and ages, such tightening is not possible to measure

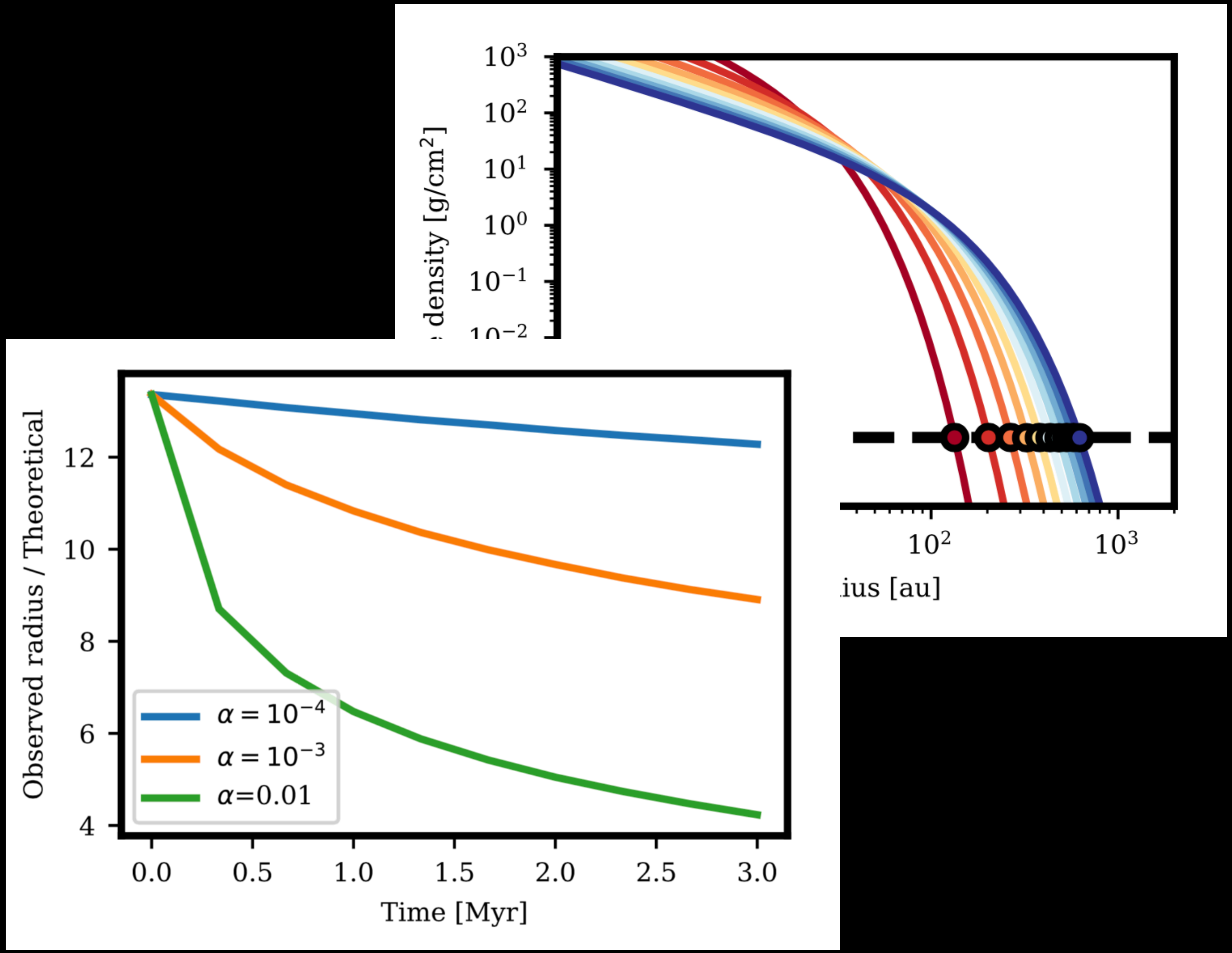


Rosotti et al 2019a,b

# EVOLUTION OF DISC RADIUS

- Is it possible to observe disc spreading?
- Case 1: disc spreading in the gas (e.g. by optically thick CO lines)
- It all depends on how sensitive observations are
- If we assume minimum detectable Sigma to be the CO dissociation threshold, disc radii increase with time, but slower than theoretically predicted

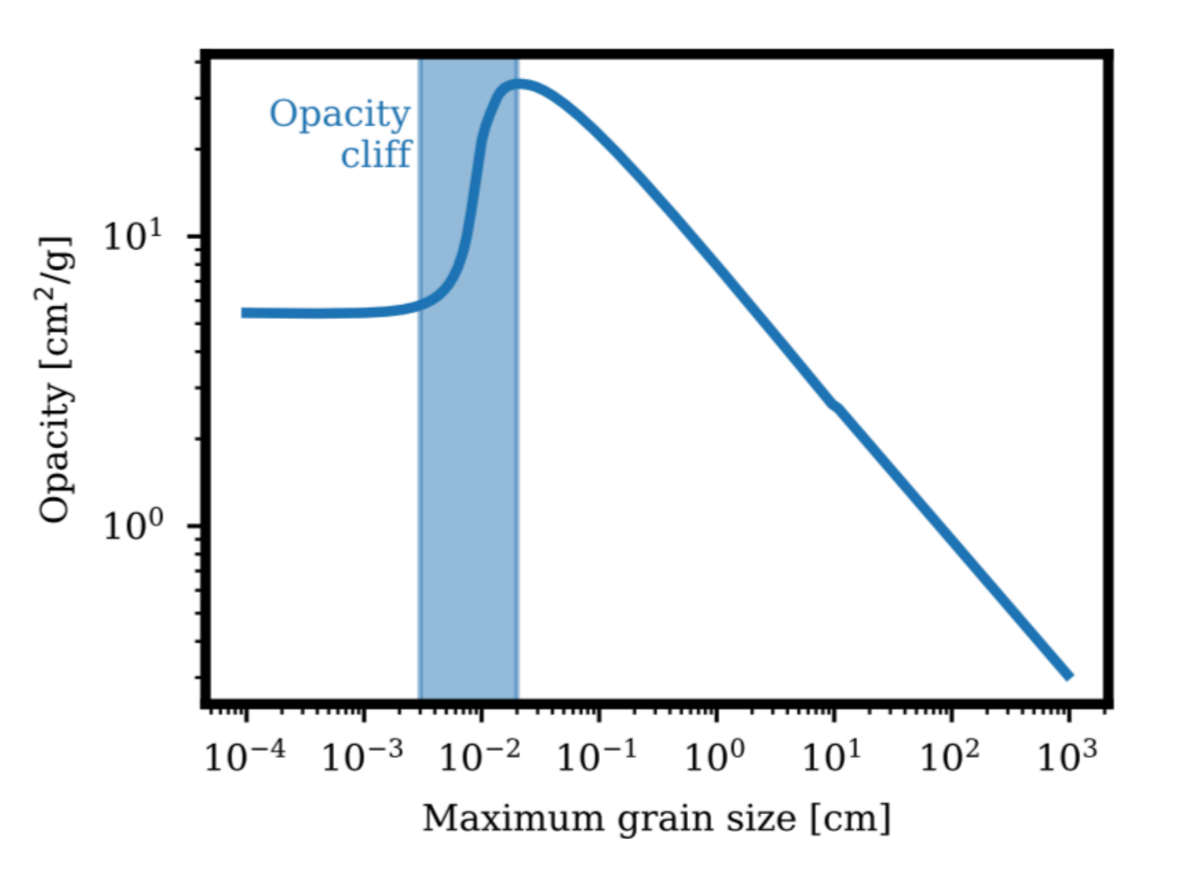
$M_{disc,0}$=0.1, $R_{disc,0}$=10 au

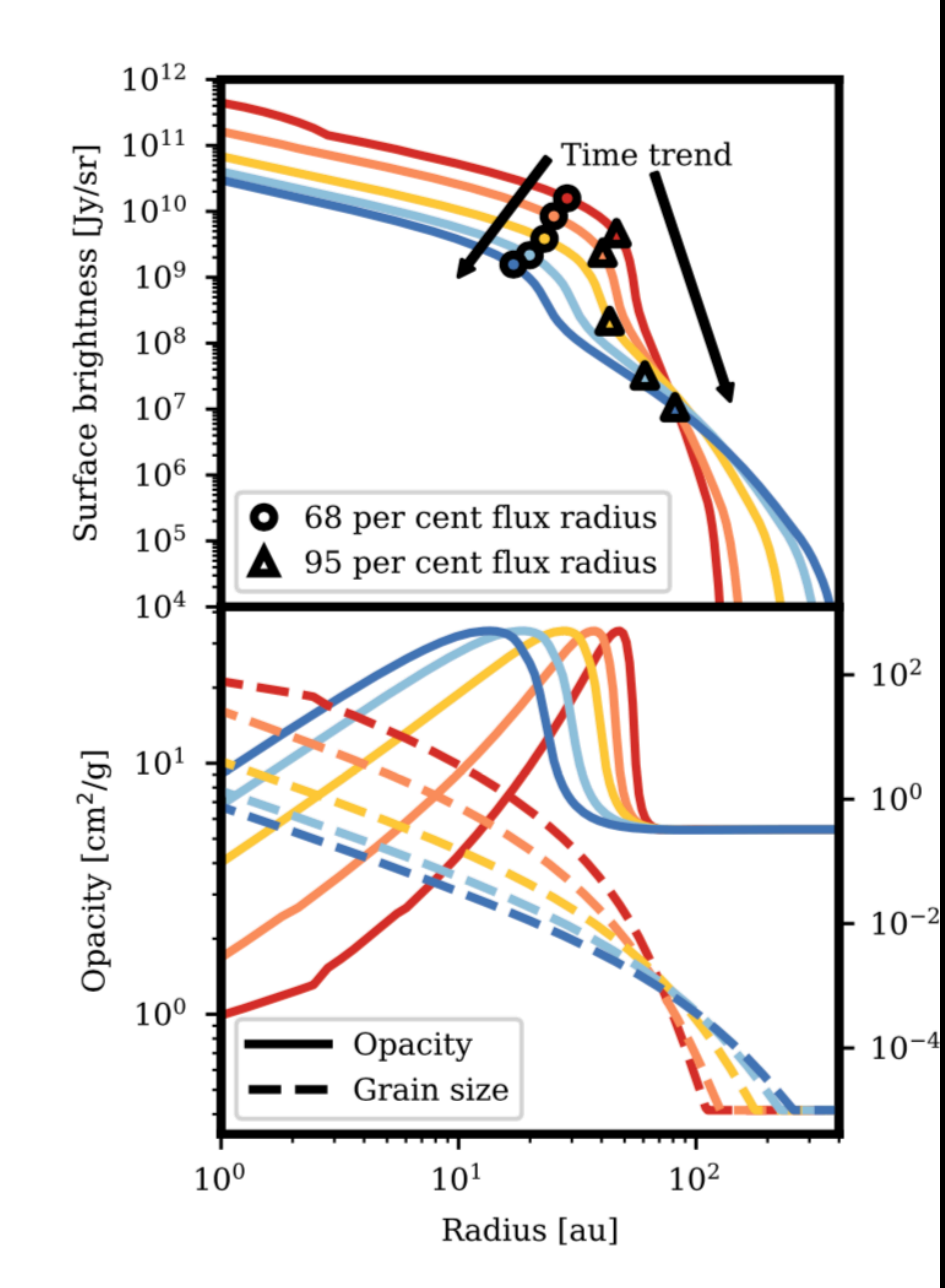


Rosotti et al 2019a,b

# EVOLUTION OF DISC RADIUS

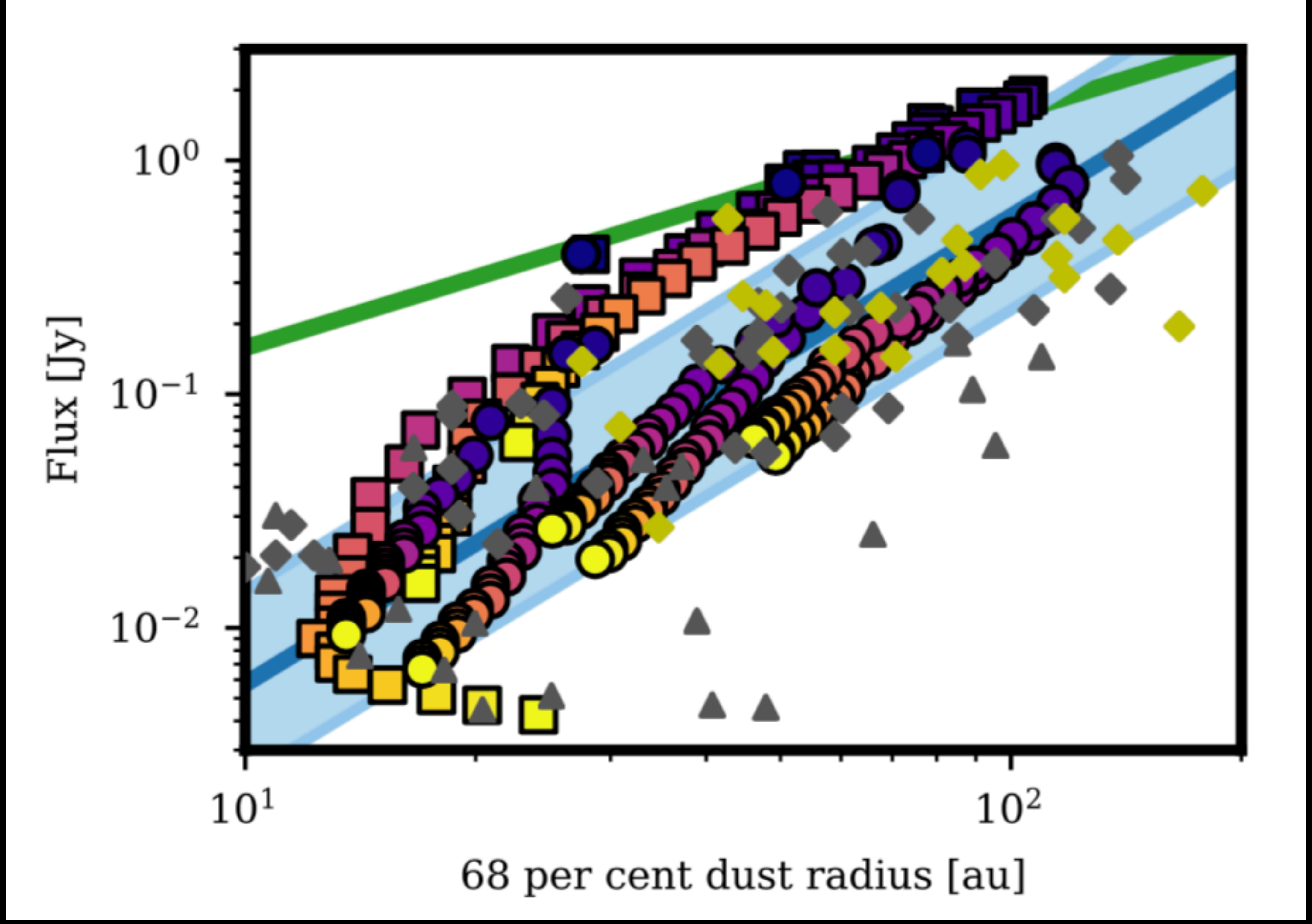
- Is it possible to observe disc spreading?
- Case 2: The dust radius
- Situations more complex because of:
  - Radial drift and dust growth
  - Opacity 'cliff'



# FLUX-RADIUS CORRELATION

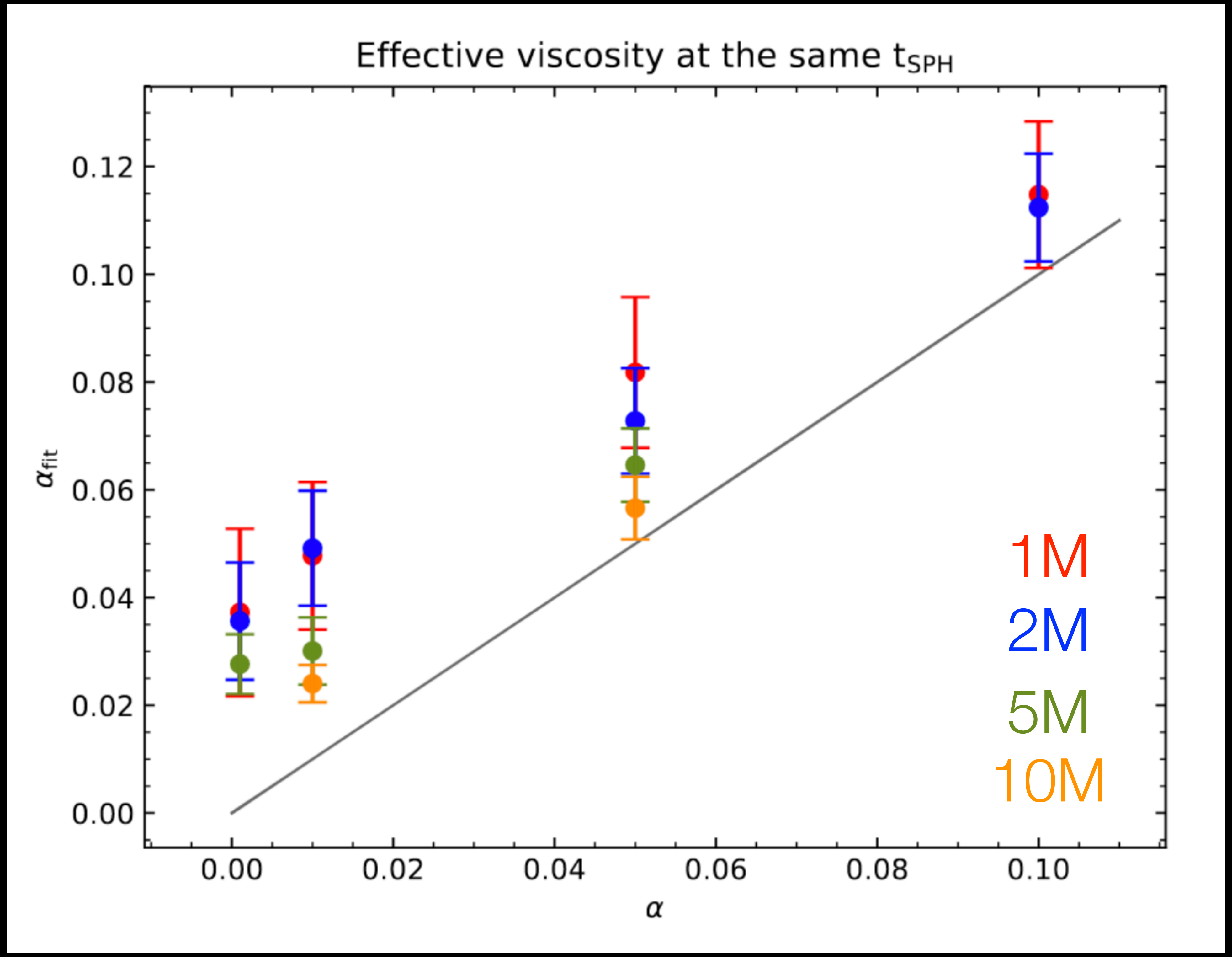
- Tripathi et al (2017) and Andres et al (2018) report a correlation between disc flux and radius
- A natural explanation is that the disc is optically thick in the mm —> Discs are very massive
- Another explanation may arise even in the optically thin regime if dust evolution is dominated by drift rather than by fragmentation
  - Either is small ($\alpha$ <~10$^{-3}$), or the fragmentation velocity is high ($v_f$>~ 10 m/s)



# A NOTE TO US SPH MODELERS

Zagaria, Lodato & Aly (2019)

- If really $\alpha <\sim 10^{-3}$, we should be careful when modeling discs with SPH
- Lodato & Price (2010) show a very good match between expected and measured $\alpha$ from artificial viscosity in SPH, for moderately high values of $\alpha$.
- What happens in the very low viscosity case?
  - Even using ~ 10M particles, hard to go below $\alpha \sim 0.01$
  - Using the quadratic term in artificial viscosity makes the disc significantly more viscous
  - Using Wendland kernels improves but not much



# WHAT CAUSES ANGULAR MOMENTUM TRANSPORT?

- MRI transport is inefficient when non-ideal effects are included (several recent MHD simulations)
  - Not a novelty in itself (see the layered disc models by Gammie 1996)
- Most likely, the MRI is not relevant for protostellar discs
- Hydrodynamical instabilities (VSI) can provide $\alpha \sim 10^{-4}$
- For early discs, gravitational instabilities are the most likely cause of transport (Cossins et al 2009, Kratter & Lodato 2016)
- For more evolved discs, magnetic winds can be effective (Bai 2017)
- Need specific, global evolutionary models for disc wind evolution, or for a mix of wind and viscosity driven evolution

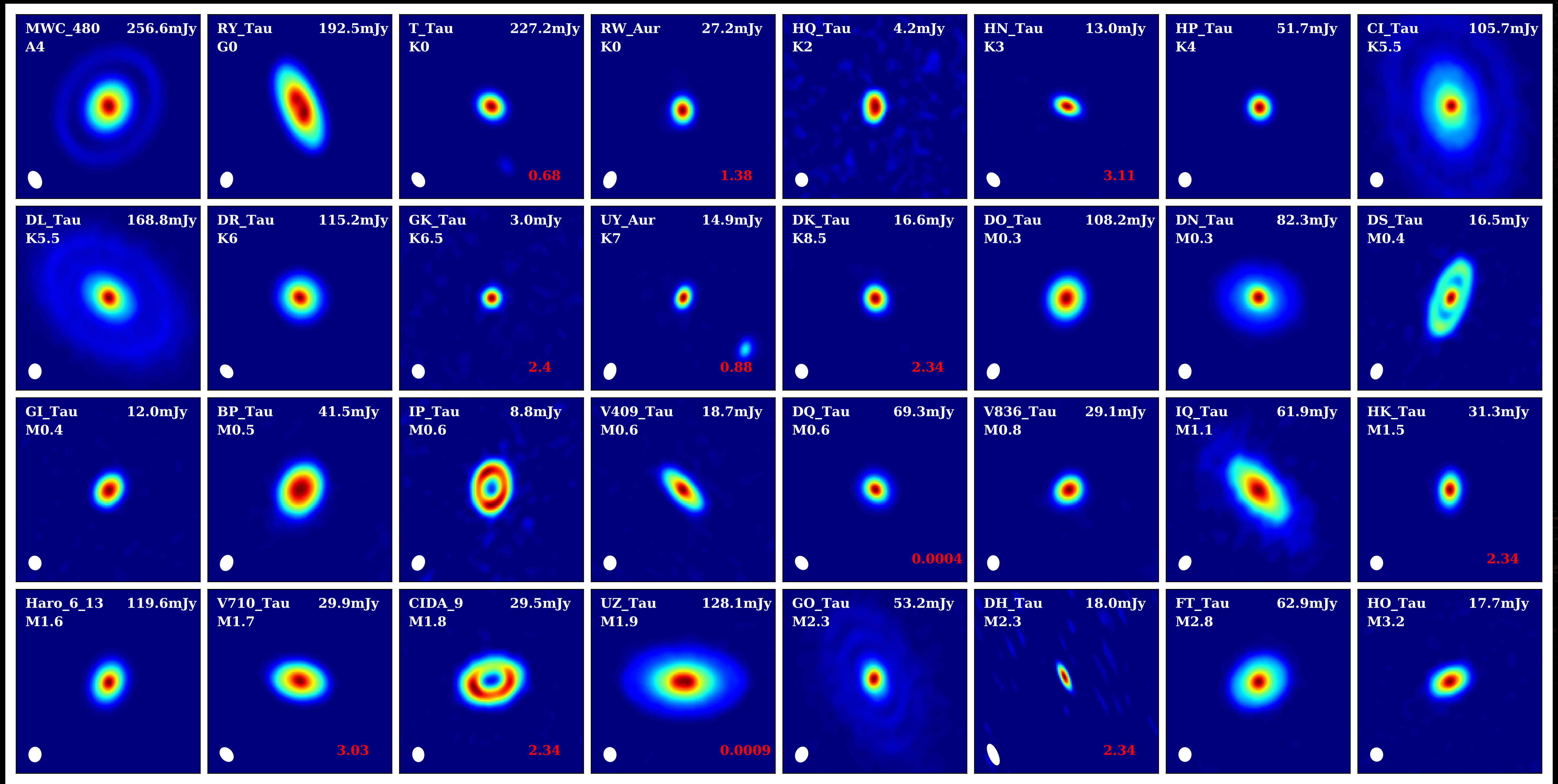
# CONCLUSIONS ON VISCOUS DISC EVOLUTION

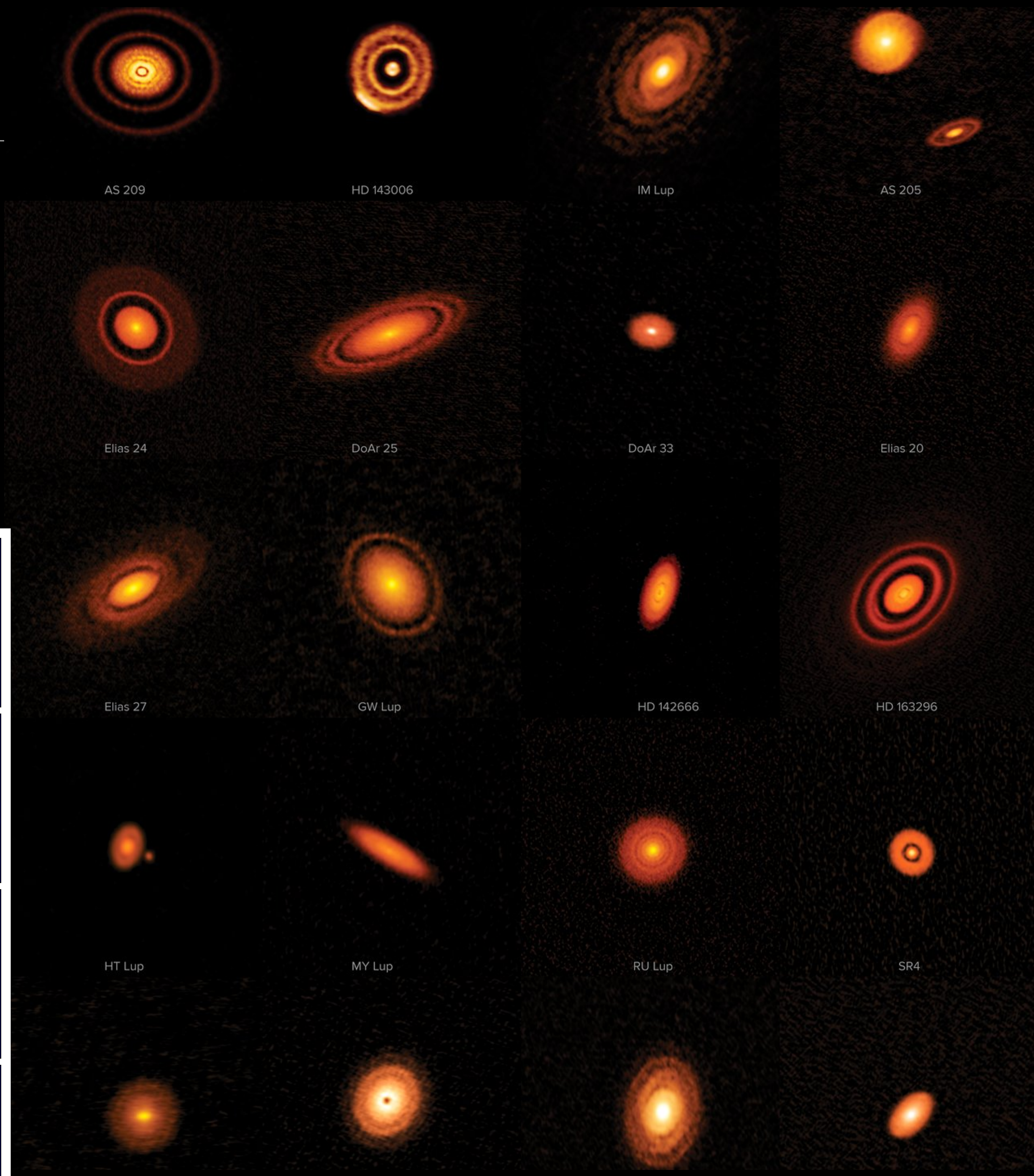
- Evidences for limited viscous transport
  - **Observations**: mostly from turbulence measurements (Flaherti et al 2017). Only available for a small number of discs, need more statistics
  - **Theory**: MHD simulations show that the MRI does not work
- Magnetic winds?
  - Predict outflow rates comparable to accretion rates: is this observed?
  - Global evolutionary models would be very much needed (Bai 2017)
  - Combine viscous and wind driven angular momentum evolution
- Viscous models very well developed and tested: not obvious that they do not reproduce observed populations

# SUBSTRUCTURES IN DISCS

- We now all know that discs show substructures (DSHARP survey, Andrews et al 2018, Taurus survey, Long et al 2018)

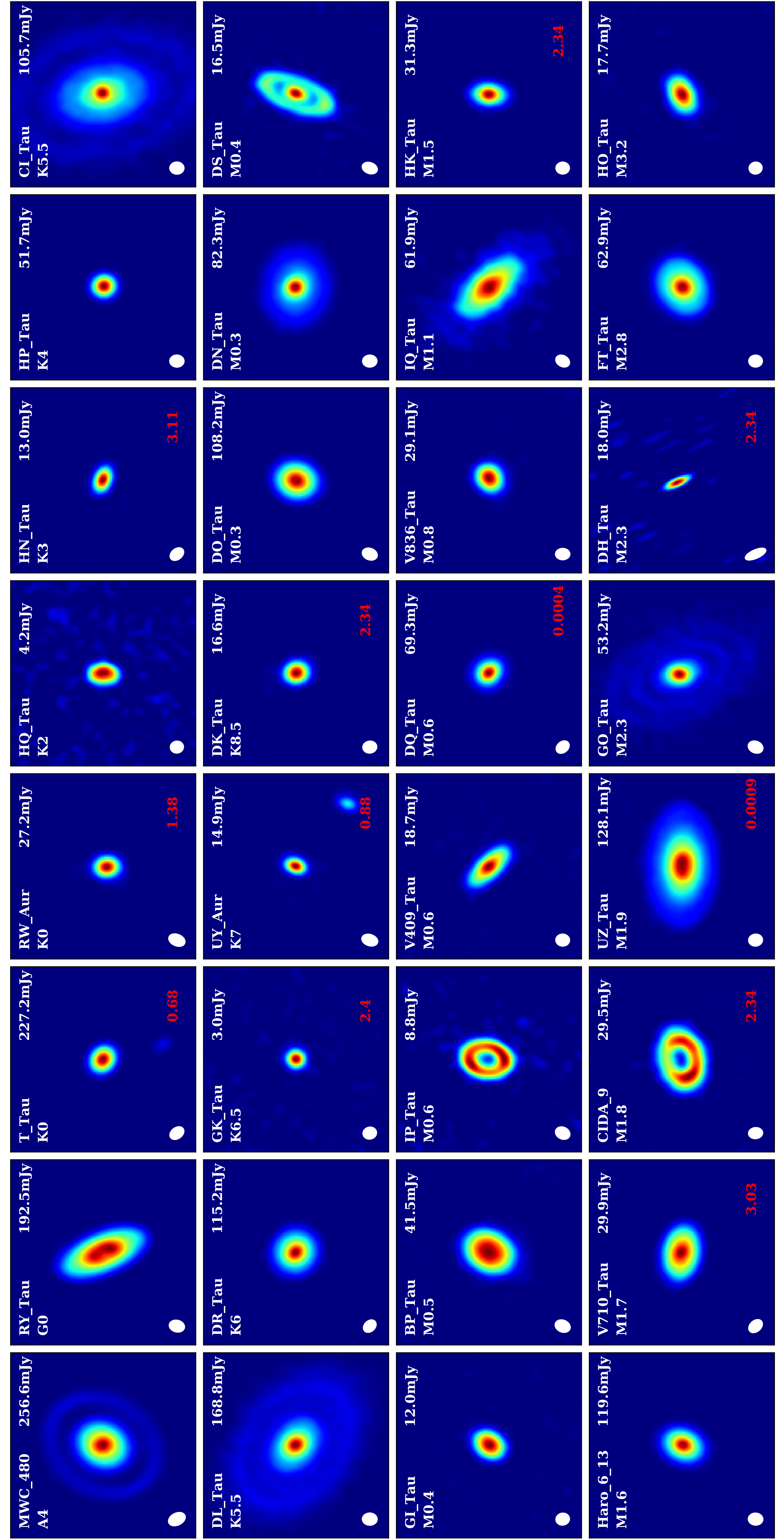
- Rings are by far the most common type of structure



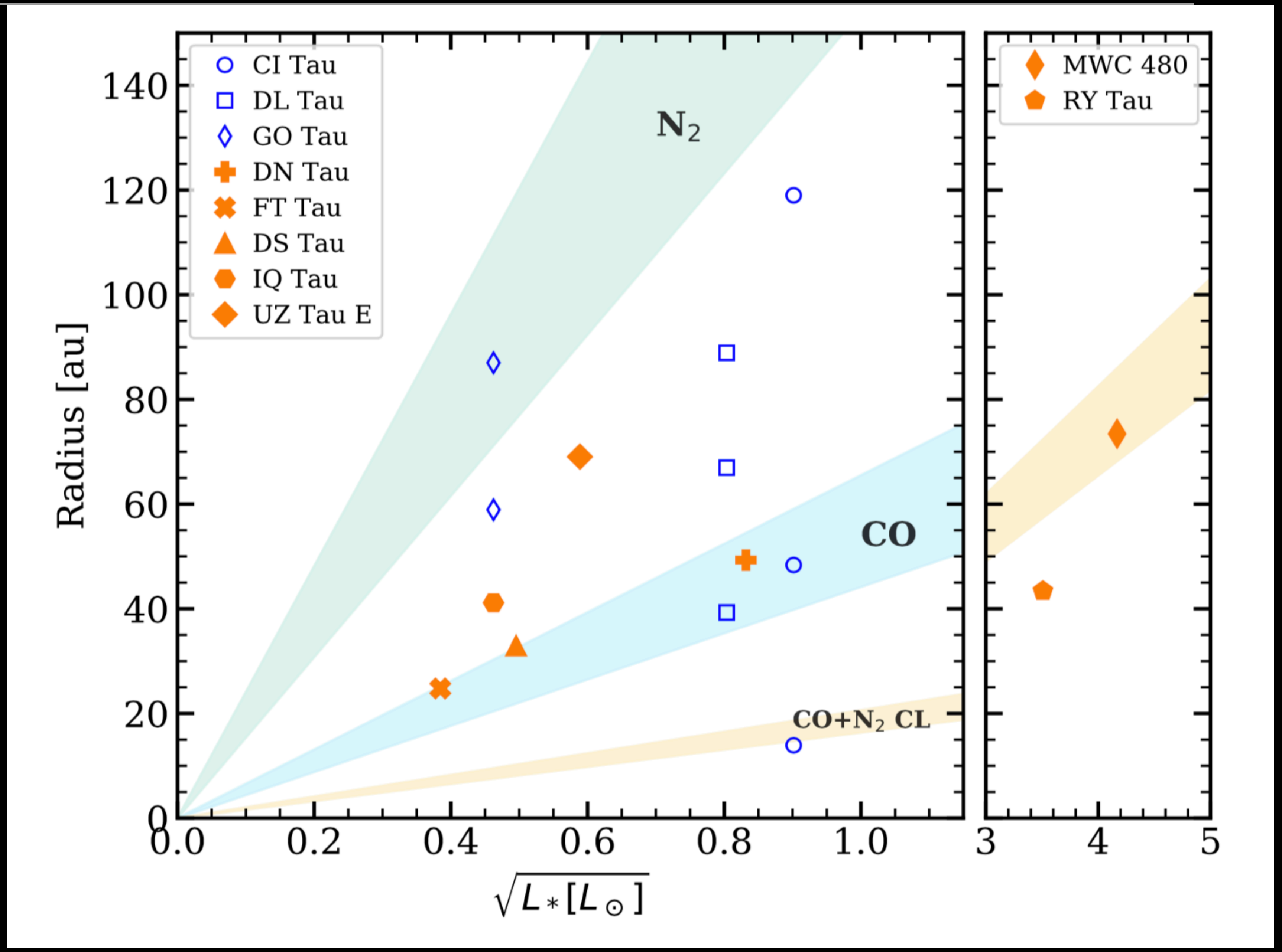
# SUBSTRUCTURES IN DISCS

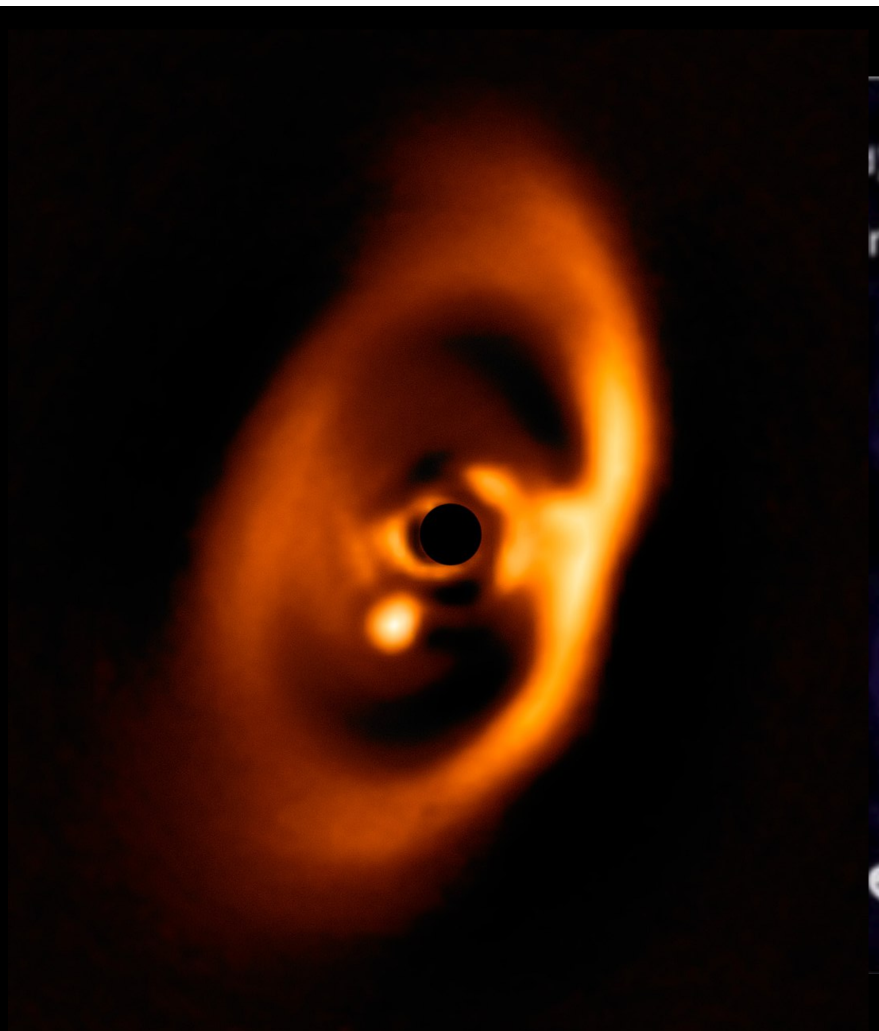
- We now all know that discs show substructures (DSHARP survey, Andrews et al 2018, Taurus survey, Long et al 2018)
- Rings are by far the most common type of structure
- The unbiased long et al sample offers a way to determine the incidence of ring structures in discs. Out of 32 discs in total:
    - 8 in binaries
    - 12 single without substructures
    - 12 singles with rings
- Rings incidence is 50% for singles, or ~37% for the whole sample.

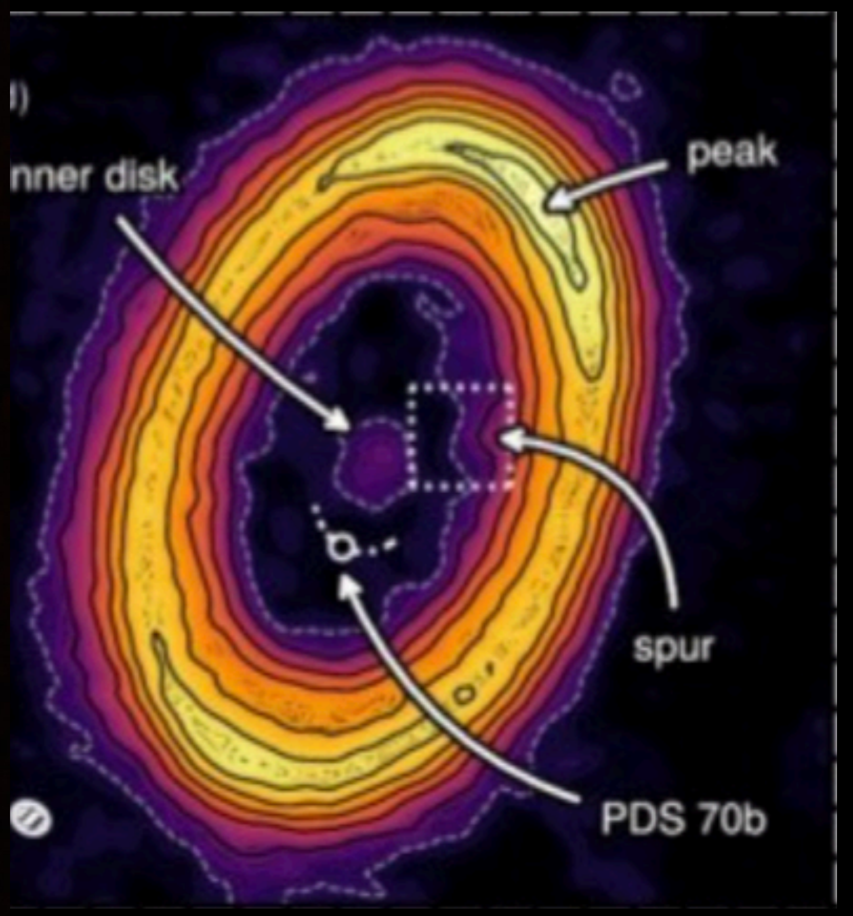


# PLANETS AND GAPS IN PLANET FORMING DISCS

- Origin of rings debated
  - Long et al (2018), Huang et al (2018): no obvious correlation between gap location and expected snowlines
  - Planets are a natural explanation, recently confirmed in PDS70
- **We are not observing planet formation, but planet-disc interaction**





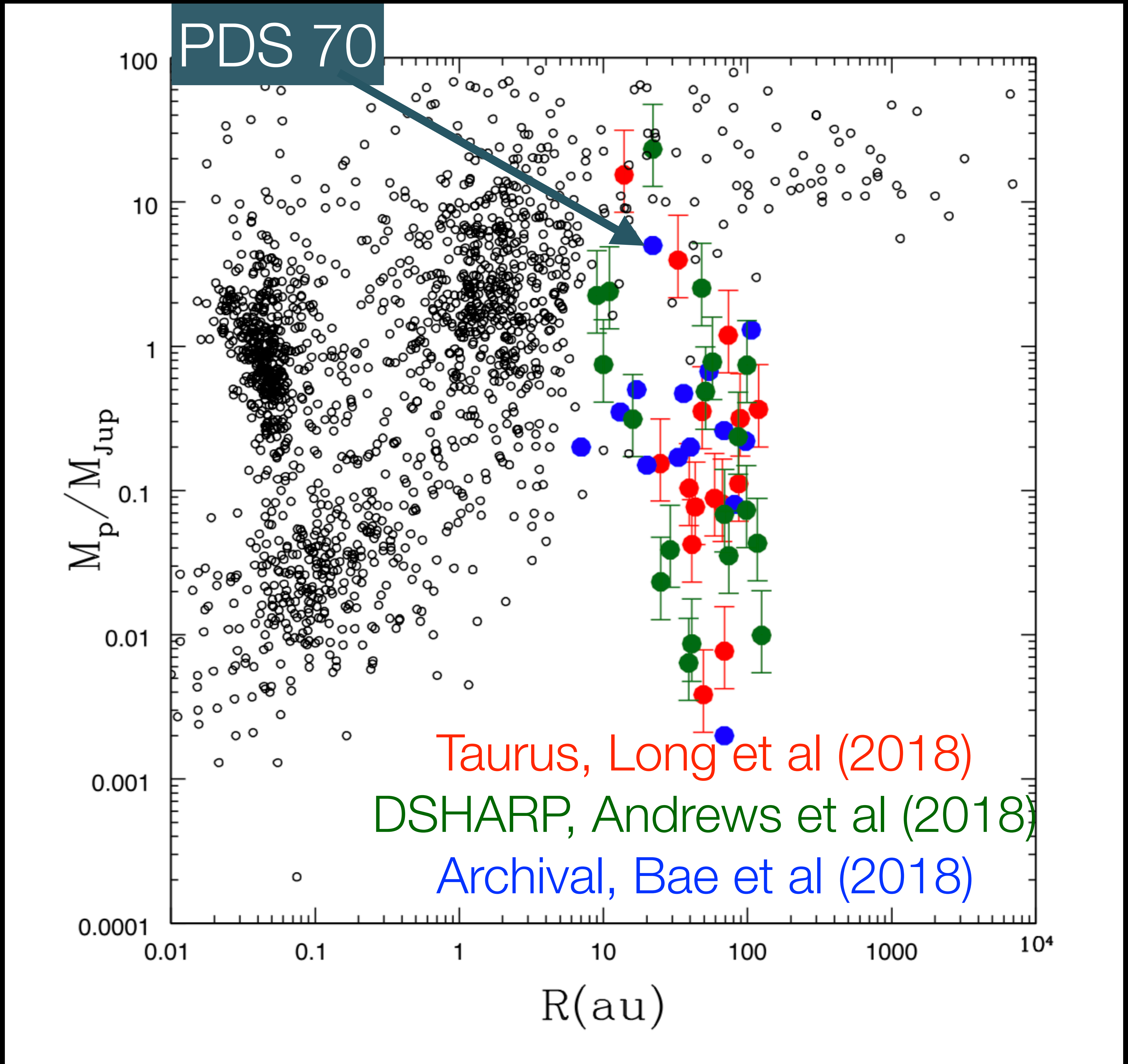

PDS 70
Keppler et al (2018, 2019)

# THE NEWBORN PLANET POPULATION FROM GAPS

- Take a simple recipe to derive the planet mass from ring width (Rosotti et al 2016)

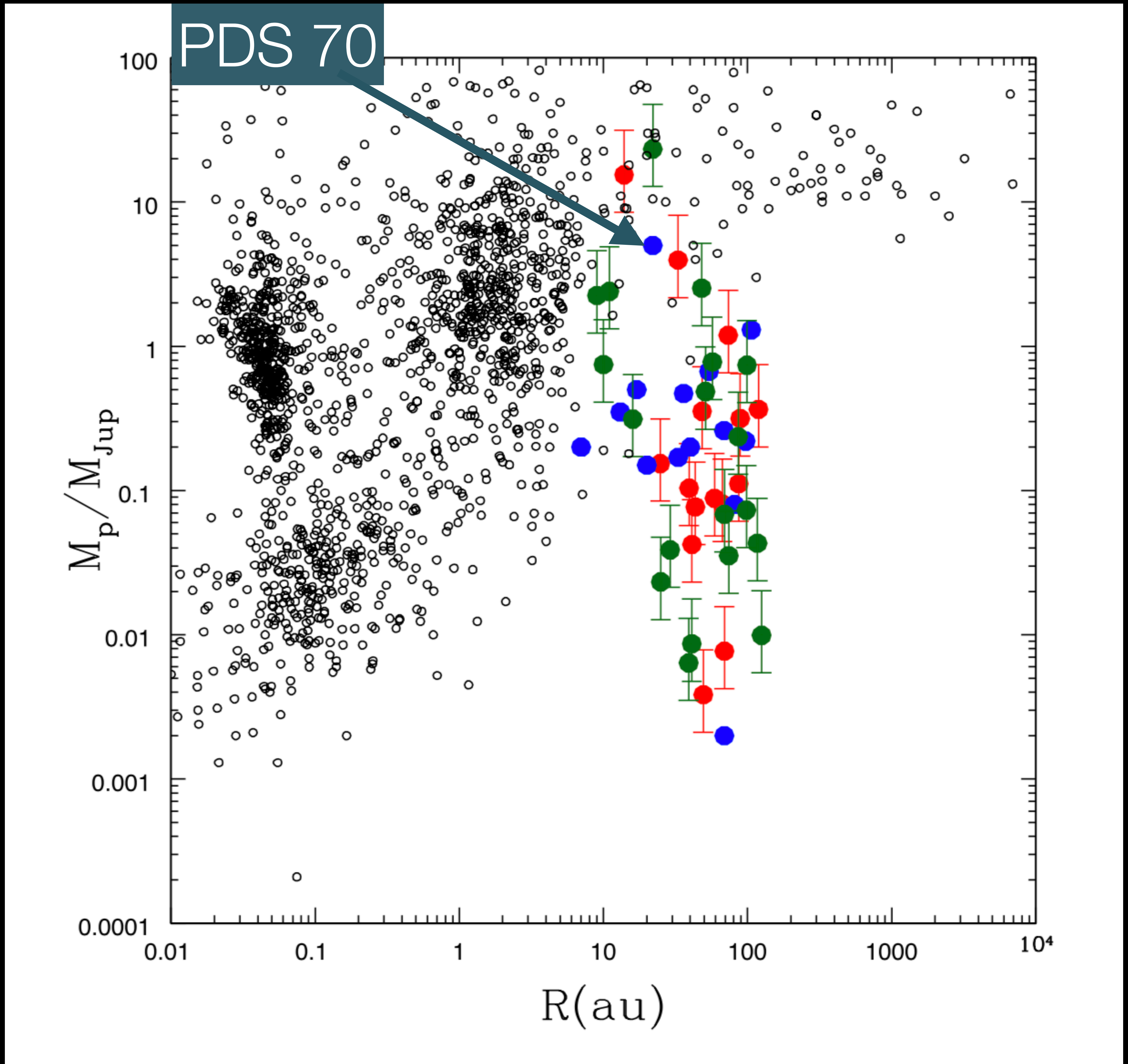
$$\Delta = f R_{\rm Hill}$$

- f is calibrated from numerical simulations of selected rings (CI Tau: Clarke et al, 2018, MWC 480: Liu et al 2018)



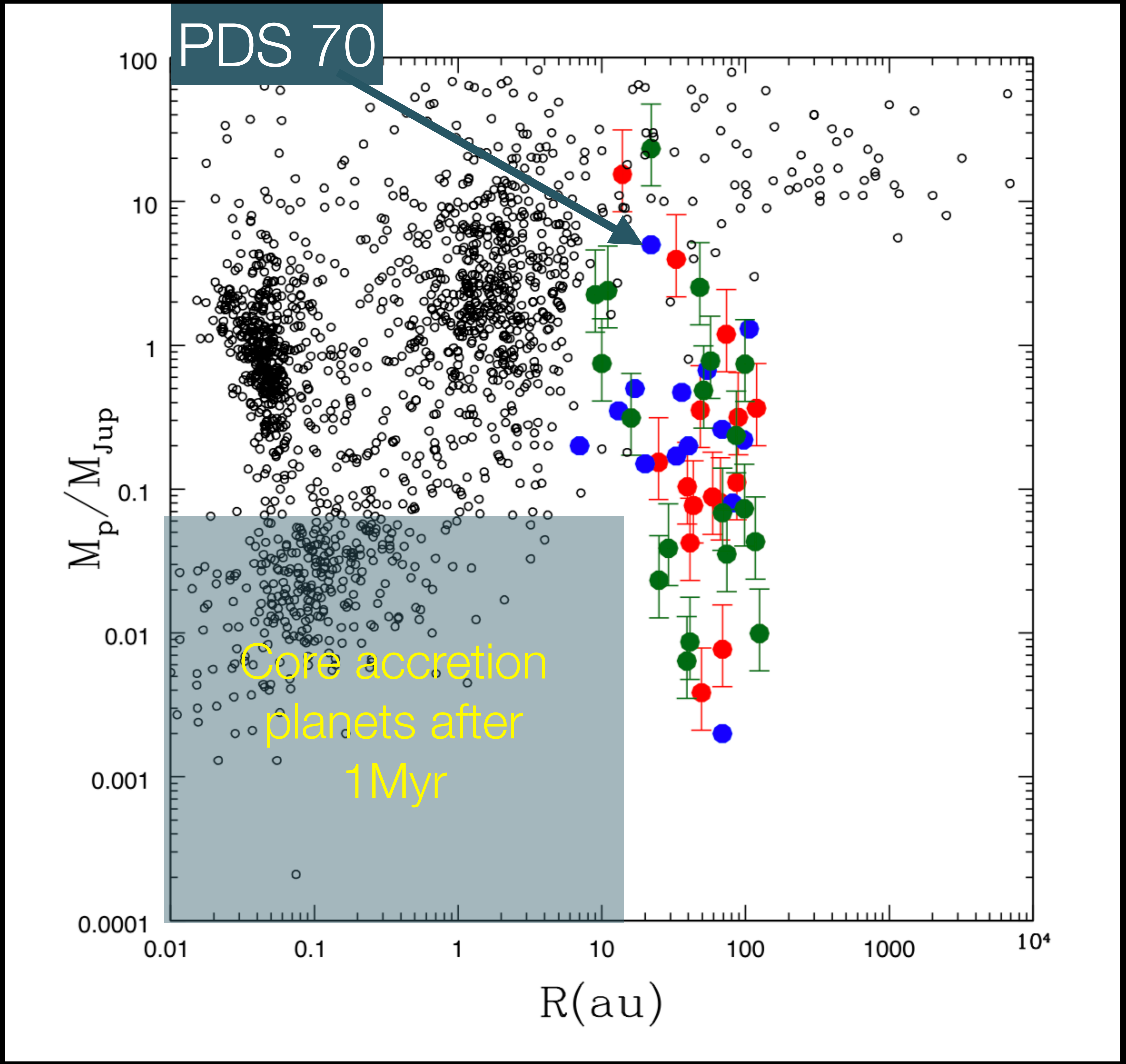
# THE NEWBORN PLANET POPULATION FROM GAPS

- Planets occupy a region in the parameter space not accessible from direct imaging
- Very hard to explain the presence of such planets at ~ 1Myr in all current planet formation models
- Planet formation is much faster than we use to think!



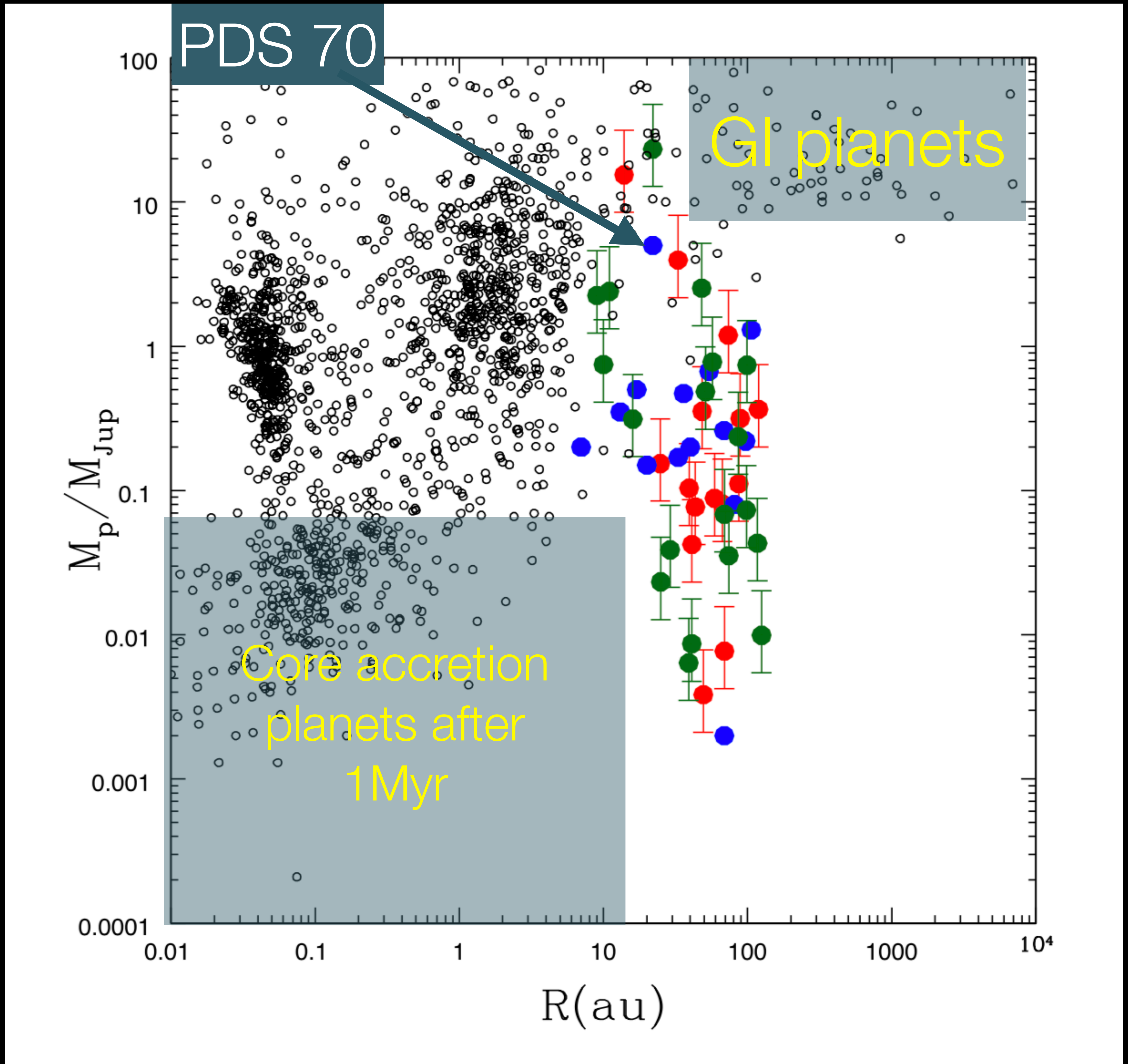
# THE NEWBORN PLANET POPULATION FROM GAPS

- Planets occupy a region in the parameter space not accessible from direct imaging
- Very hard to explain the presence of such planets at ~ 1Myr in all current planet formation models
- Planet formation is much faster than we use to think!



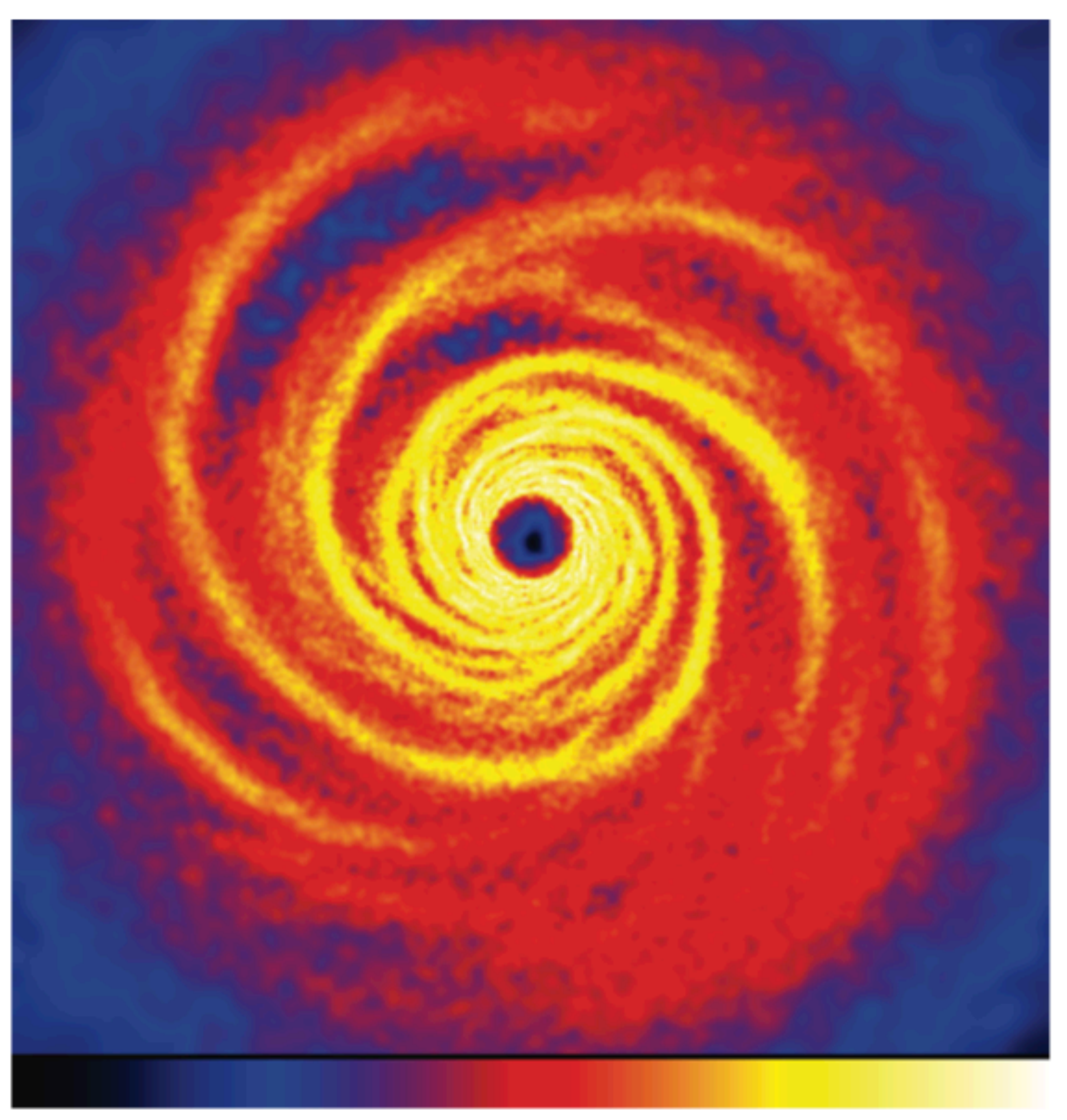
# THE NEWBORN PLANET POPULATION FROM GAPS

- Planets occupy a region in the parameter space not accessible from direct imaging
- Very hard to explain the presence of such planets at ~ 1Myr in all current planet formation models
- Planet formation is much faster than we use to think!



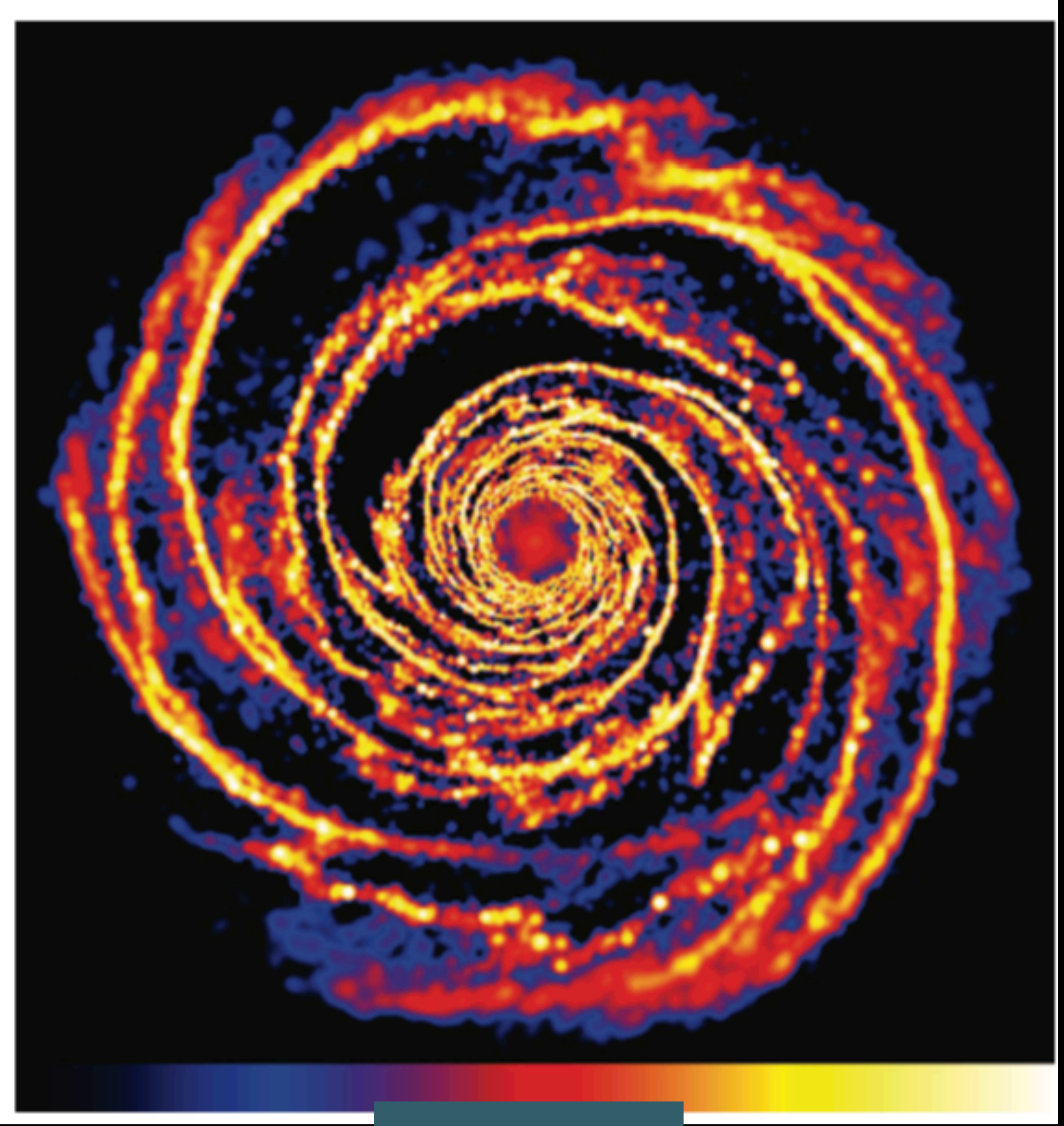
# PLANETESIMAL/CORE FORMATION IN SELF-GRAVITATING DISCS

- Spirals in self-gravitating discs are efficient dust traps (Rice et al, 2005)
- Can lead to direct collapse in the solid component (Rice et al, 2006)
- Rice et al (2006): solid fragment mass ~ $1M_{Earth}$ —> need to re-evaluate at higher resolution



Gas

from Rice et al 2006

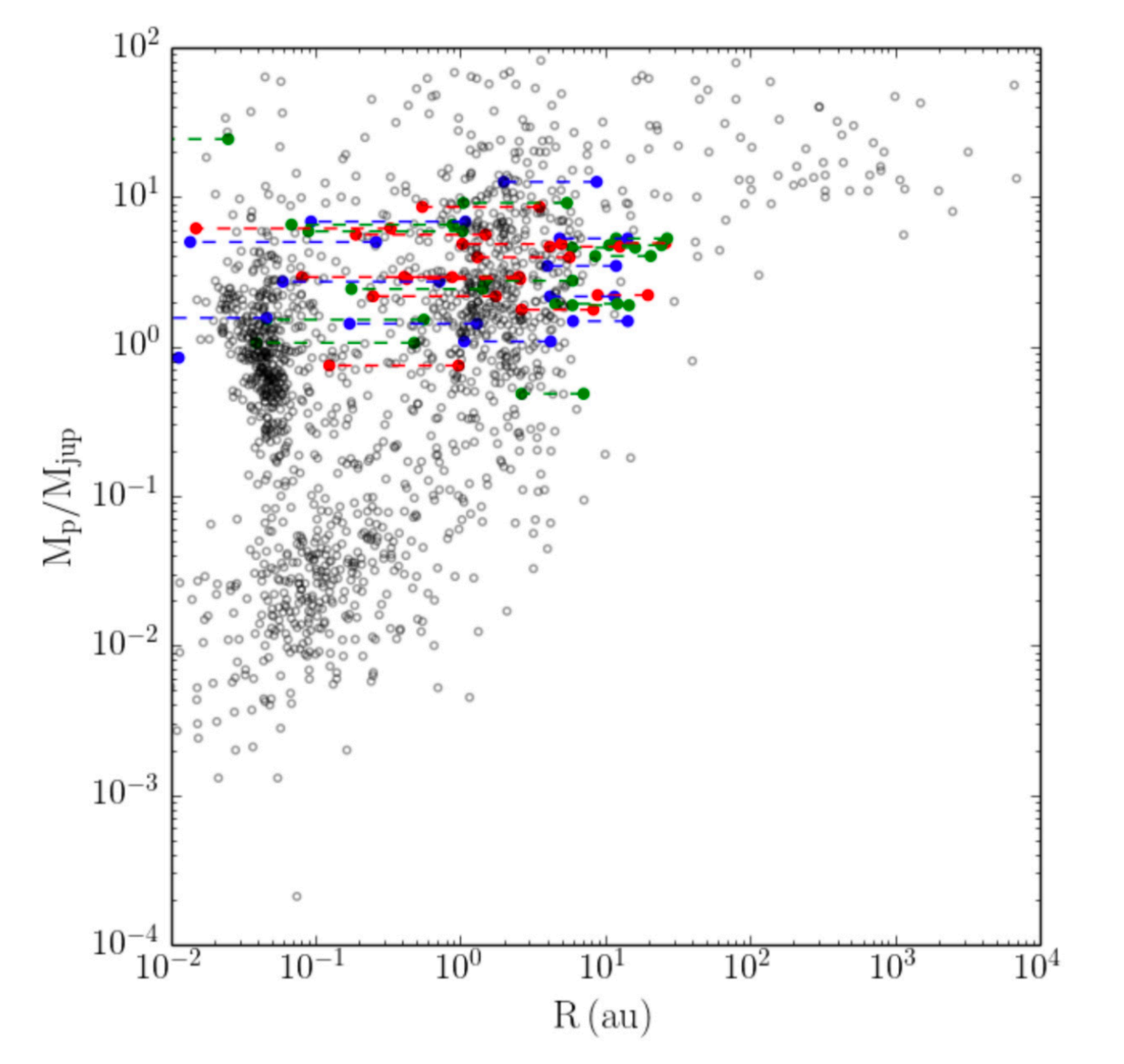


Solids

# THE NEWBORN PLANET POPULATION FROM GAPS

Lodato et al (2019)

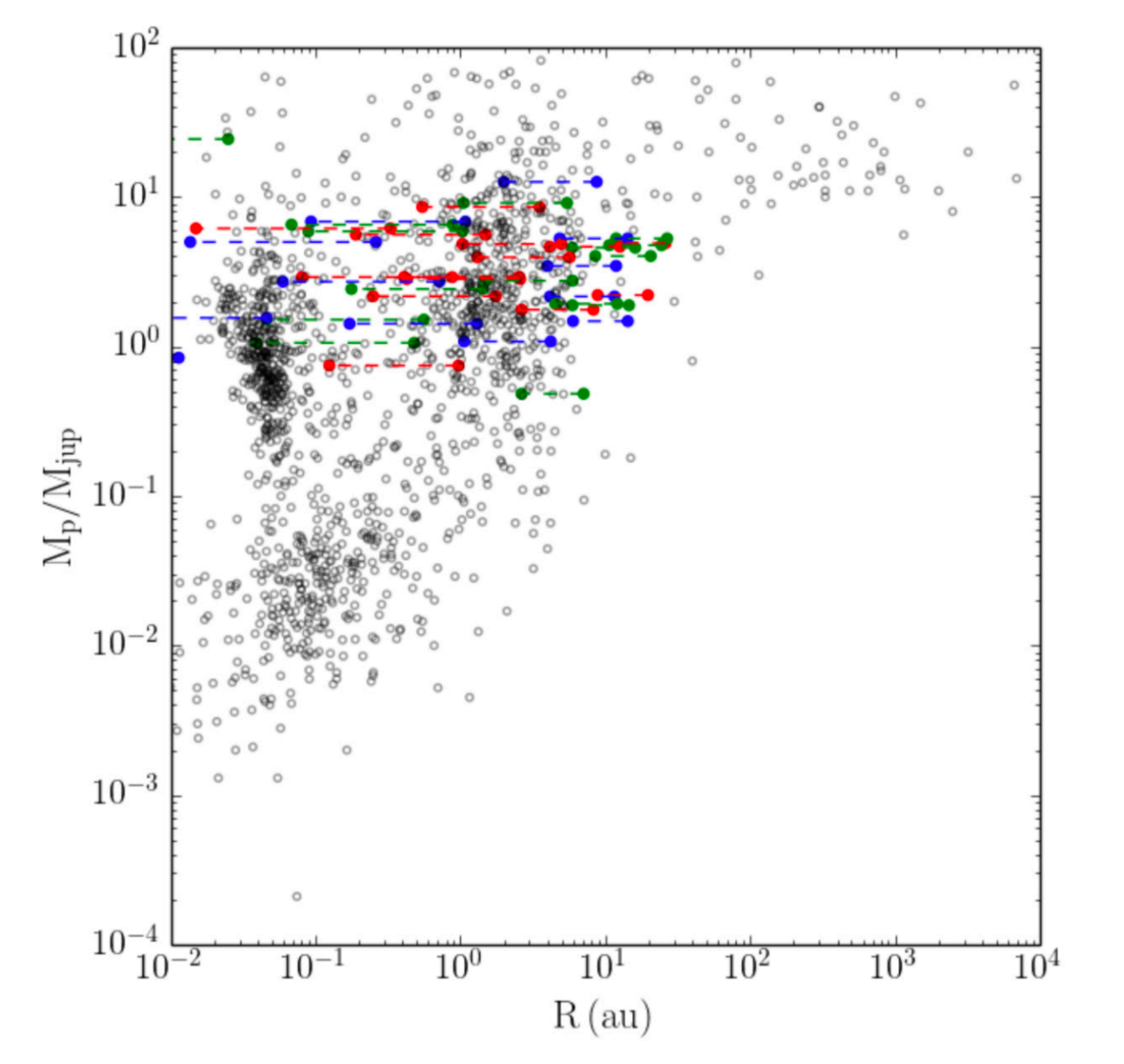
- Planet evolution after 3-5 Myrs
- When planets are below the Crida et al (2006) criterion for gas gap opening: they **migrate according to Type I and accrete mass** (see Dipierro et al 2018).
- When a gas gap is opened, we stop accretion and **continue migration at the nominal Type II rate** (i.e. the viscous rate)



# THE NEWBORN PLANET POPULATION FROM GAPS

- Occurrence rates
  - From Long et al., occurrence rate of "planets" would be in the range of 1/3 (for $M_{planet} > 1\ M_{Jupiter}$)
  - Fernandes et al (2019) suggest an occurrence rate of giant planets extrapolating results from RV surveys to be ~ 26% for $M_{planet} > 0.1\ M_{Jupiter}$

Lodato et al (2019)



# CONCLUSIONS ON RINGS AND PLANET FORMATION

- Rings are due to planets!
  - Is it a one-to-one relation or not? (multiple planets can form a single ring, single planets can form multiple rings)
- There are NOT too many rings compared to planets!
  - "Ring" planets are generally smaller than could be directly detected
  - "Ring" planets end up as Jupiter planets when they become adults
- Serious question is how to produce those planets that early
  - Planet formation is much faster than we previously thought

# TYPE II MIGRATION

- We know everything about Type II migration, don't we?
- Well known since Lin & Papaloizou (1986)
- The planet behaves as a fluid element in the disc

$$\frac{M_\mathrm{p}}{2}\Omega_\mathrm{p} a\dot{a} + 2\pi\Sigma\Omega_\mathrm{p} a^3\dot{a} = -3\pi\nu\Sigma\Omega_\mathrm{p} a^2$$

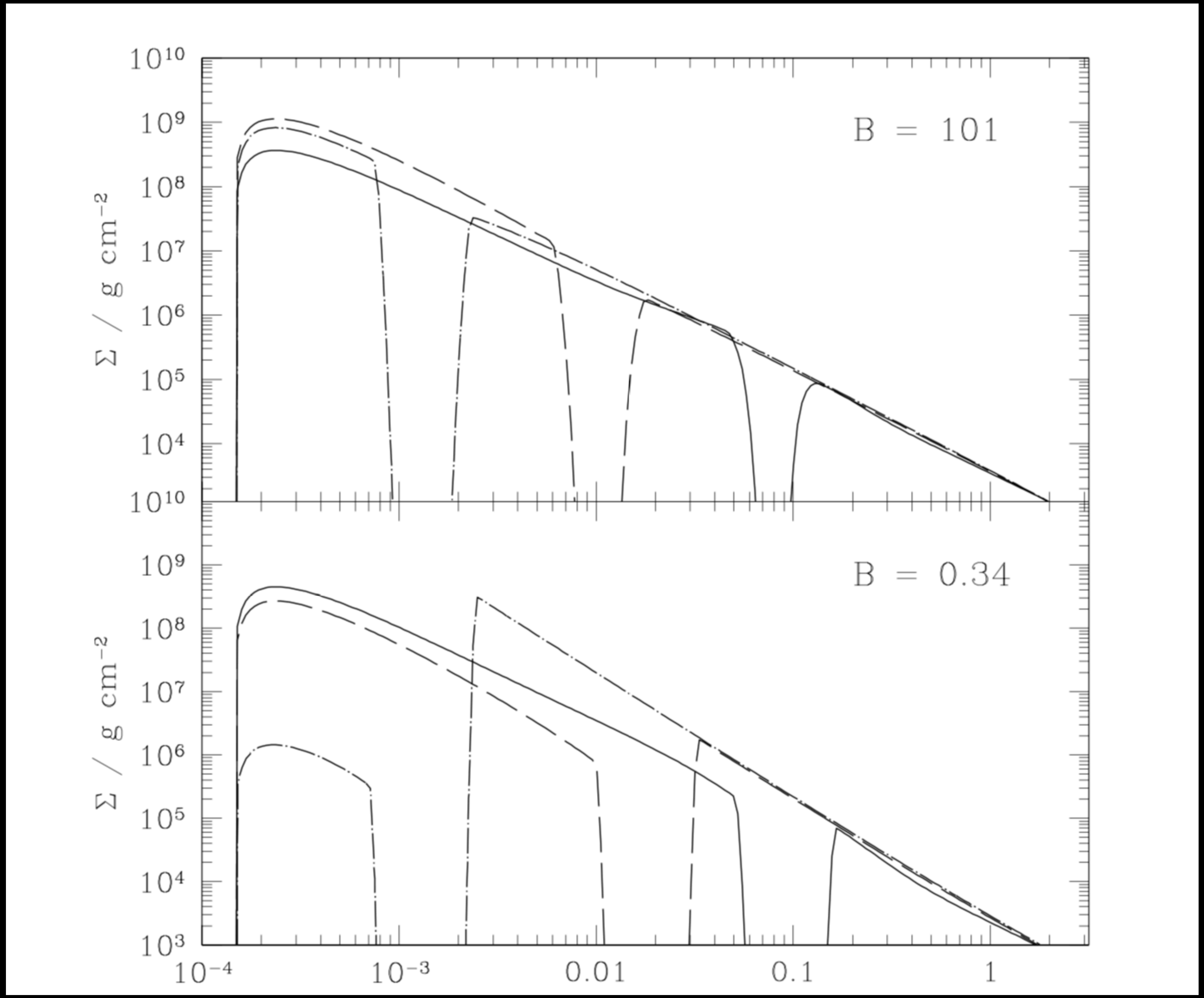
$$\dot{a} = -\frac{3\nu}{2a}\frac{B}{B+1}$$

$$B = \frac{4\pi a^2\Sigma}{M_\mathrm{p}}$$

Traditional Type II migration rate

Syer & Clarke (1995), Ivanov et al (1999)

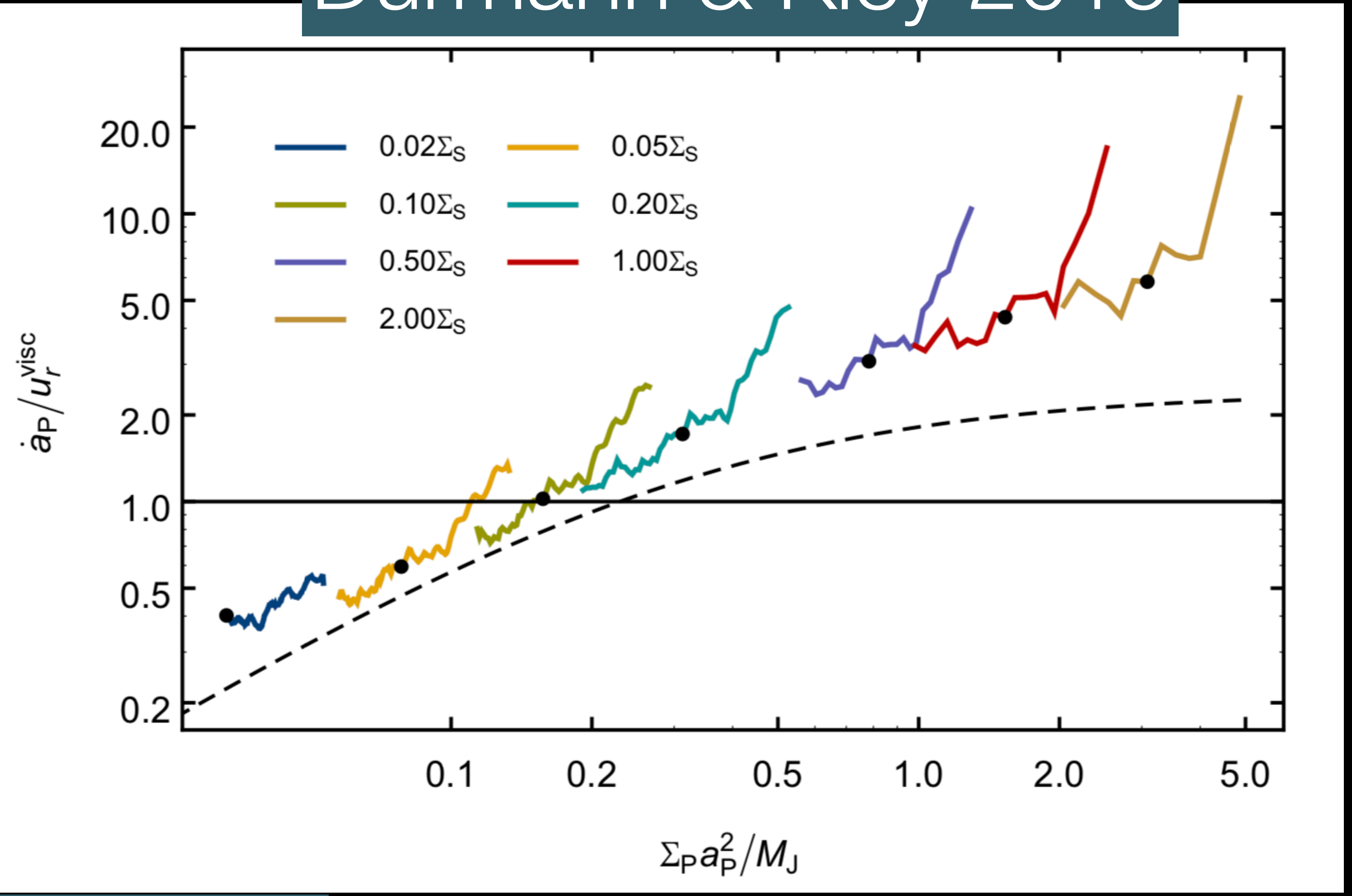
Tazzari's Master Thesis



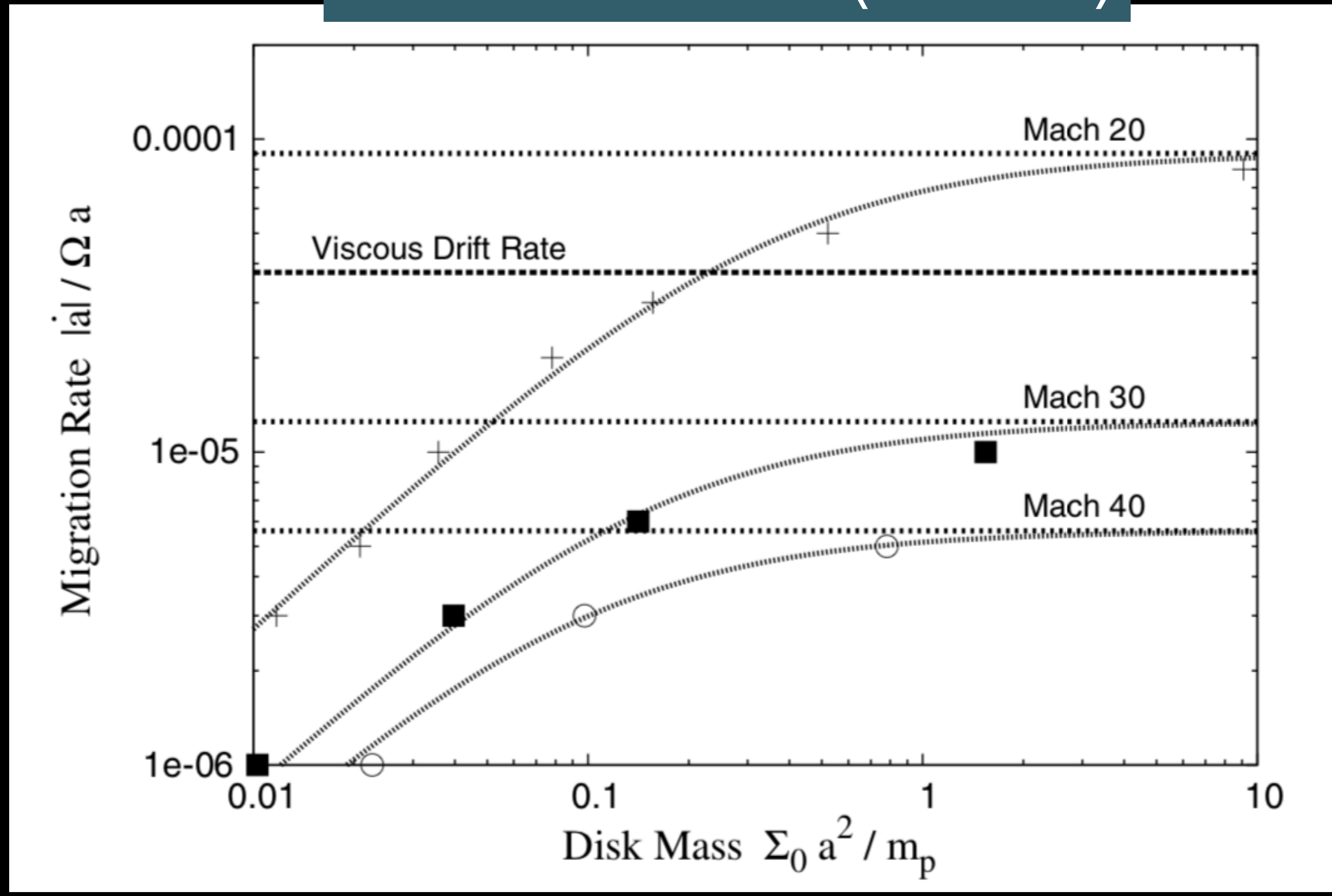
# IS TYPE II REALLY LOCKED TO THE VISCOUS RATE?

- Duffell et al (2014) and Durmann & Kley (2015) measure migration rates in 2D simulations of migrating planets, finding significant departures from Type II regime (see also Kanagawa et al. 2018, Robert et al 2018).
- Duffell et al use DISCO (but prescribe the migration rate of the planet), for various choices of H/R, and $\alpha$ =0.01
- Durmann & Kley use NIRVANA, q=0.001, $\alpha$ =0.003 and H/R = 0.05
- Typical integration time: up to ~ $10^3$ orbits ~ 0.05 viscous timescales

Durmann & Kley 2015




Duffell et al (2014)




H/R=0.05

H/R=0.03

H/R=0.025

# IS TYPE II REALLY LOCKED TO THE VISCOUS RATE?

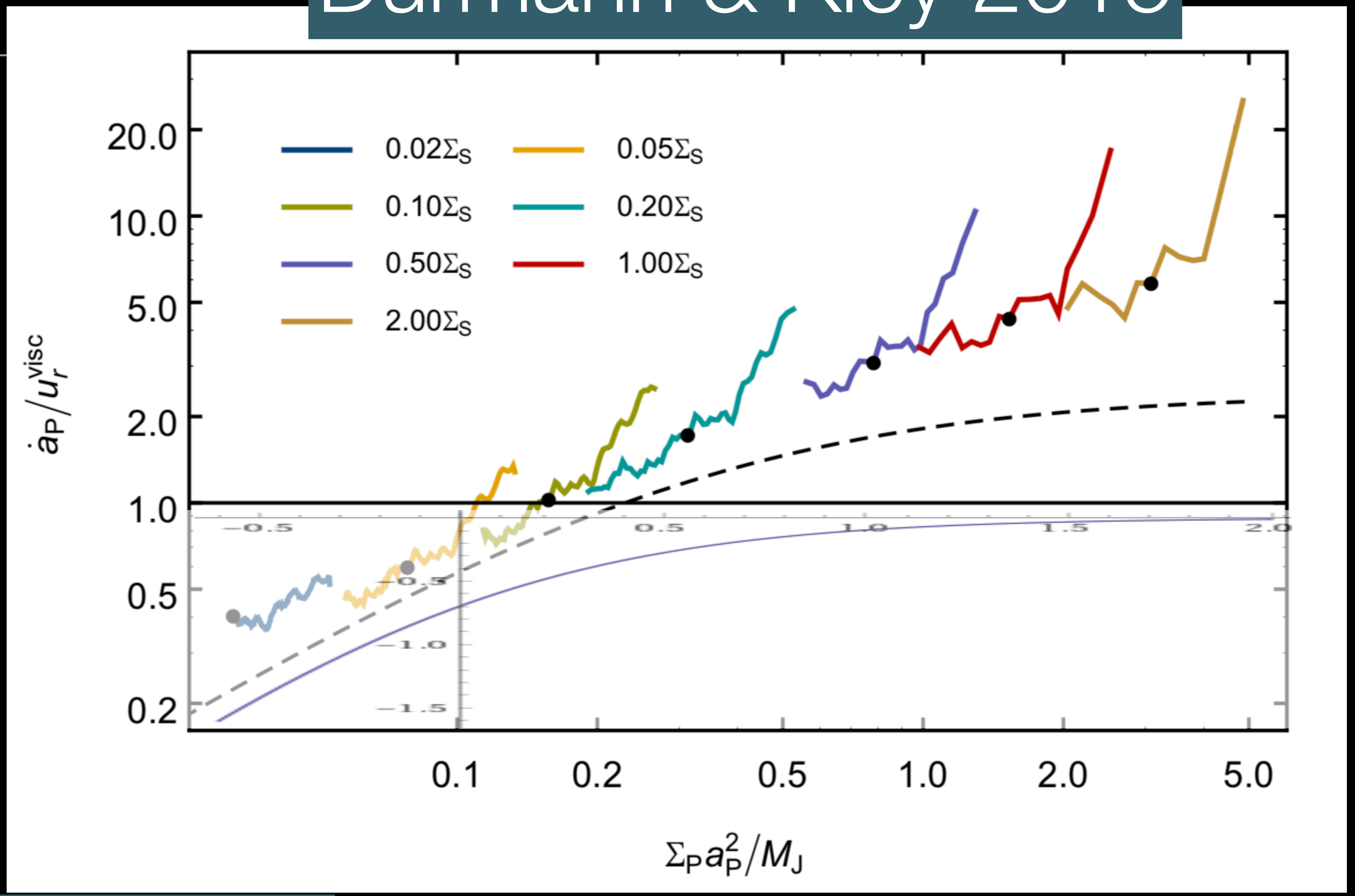
- Duffell et al (2014) and Durmann & Kley (2015) measure migration rates in 2D simulations of migrating planets, finding significant departures from Type II regime (see also Kanagawa et al. 2018, Robert et al 2018).

- Duffell et al use DISCO (but prescribe the migration rate of the planet), for various choices of H/R, and $\alpha = 0.01$

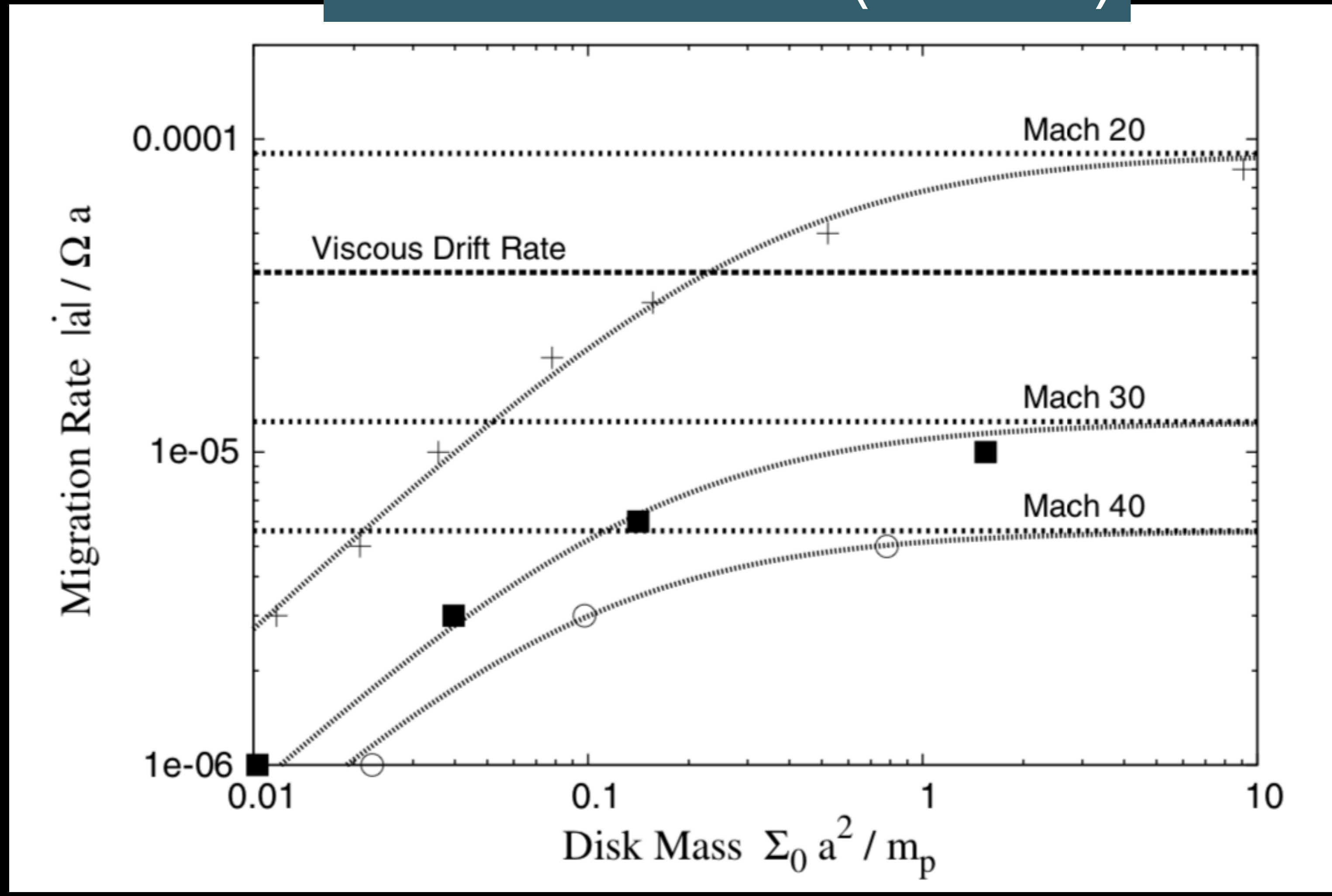
- Durmann & Kley use NIRVANA, q=0.001, $\alpha = 0.003$ and H/R = 0.05

- Typical integration time: up to ~ $10^3$ orbits ~ 0.05 viscous timescales

Durmann & Kley 2015




Duffell et al (2014)




H/R=0.05

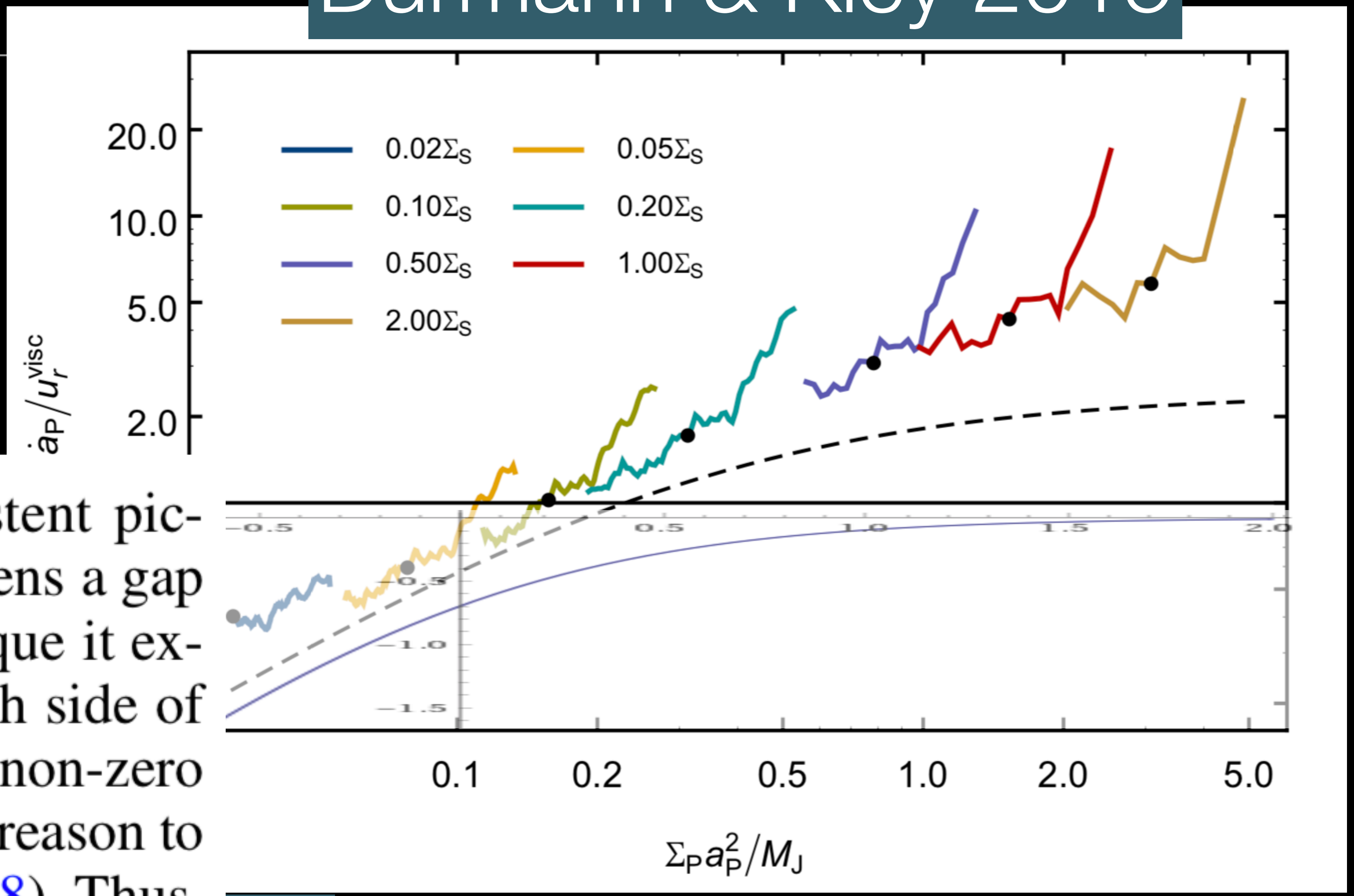
H/R=0.03

H/R=0.025

# IS TYPE II REALLY LOCKED TO THE VISCOUS RATE?

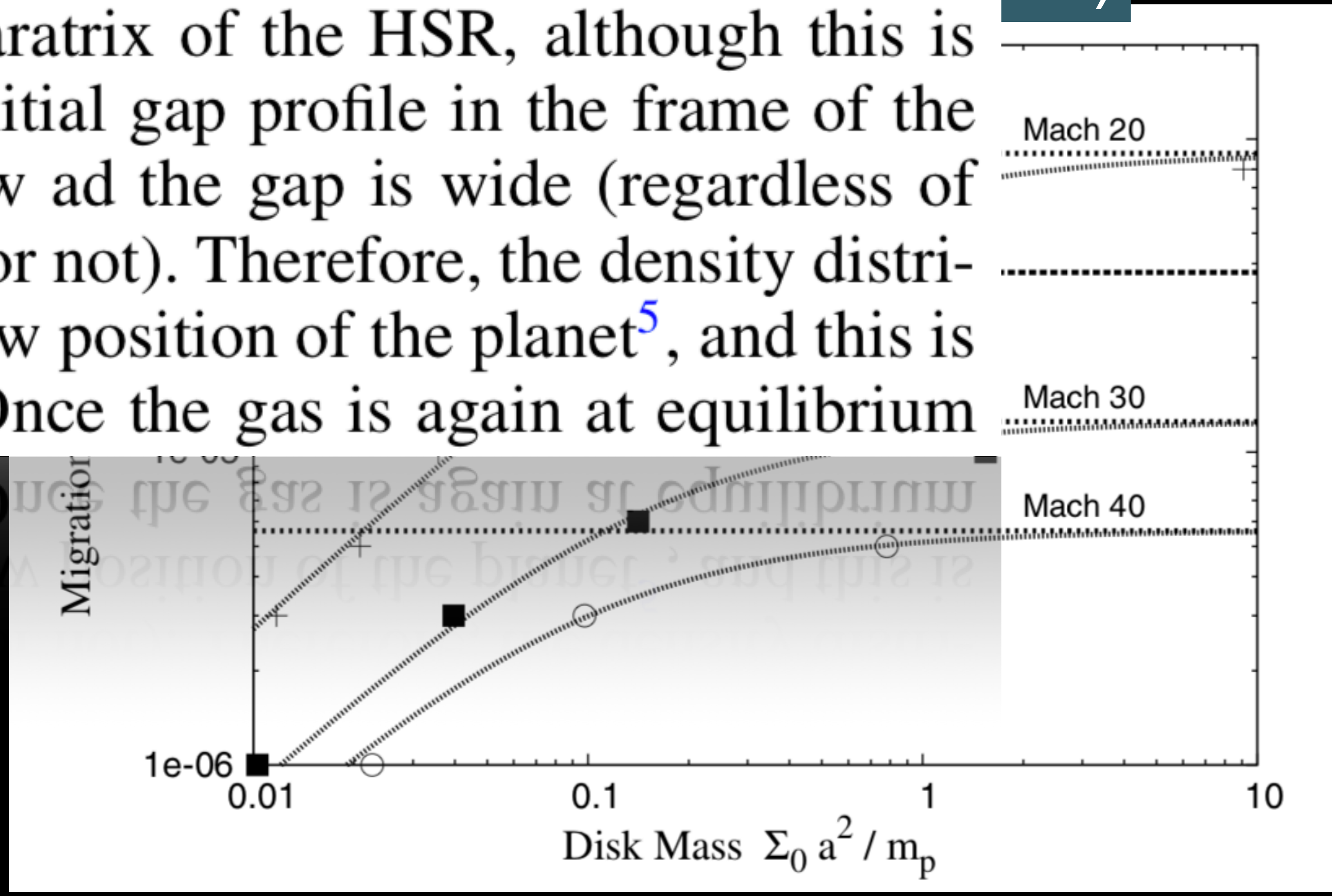
- Duffell et al (2014) and Durmann & Kley (2015) measure migration rates in 2D simulations of migrating planets, finding significant departures from Type II regime (see also Kanagawa et al. 2018, R
- Duffell et al use DISCO (bu migration rate of the planet choices of H/R, and $\alpha$ =0.0
- Durmann & Kley use NIRVA $\alpha$ =0.003 and H/R = 0.05
- Typical integration time: up 0.05 viscous timescales

Durmann & Kley 2015




These two results allow to us draw a new, consistent picture of type II migration. As a giant planet forms, it opens a gap by perturbing the gas profile with the gravitational torque it exerts. The gas reaches a new equilibrium profile on each side of the gap. Nonetheless, the planet inside its gap feels a non-zero torque, because the inner and the outer torques have no reason to balance out (as recently studied by Kanagawa et al. 2018). Thus, the planet has to migrate inwards. As it does so, some gas may cross the gap from the separatrix of the HSR, although this is not enough to restore the initial gap profile in the frame of the planet if the viscosity is low ad the gap is wide (regardless of whether the planet accretes or not). Therefore, the density distribution has to adapt to the new position of the planet[5], and this is done over a viscous time. Once the gas is again at equilibrium

14)




H/R=0.05

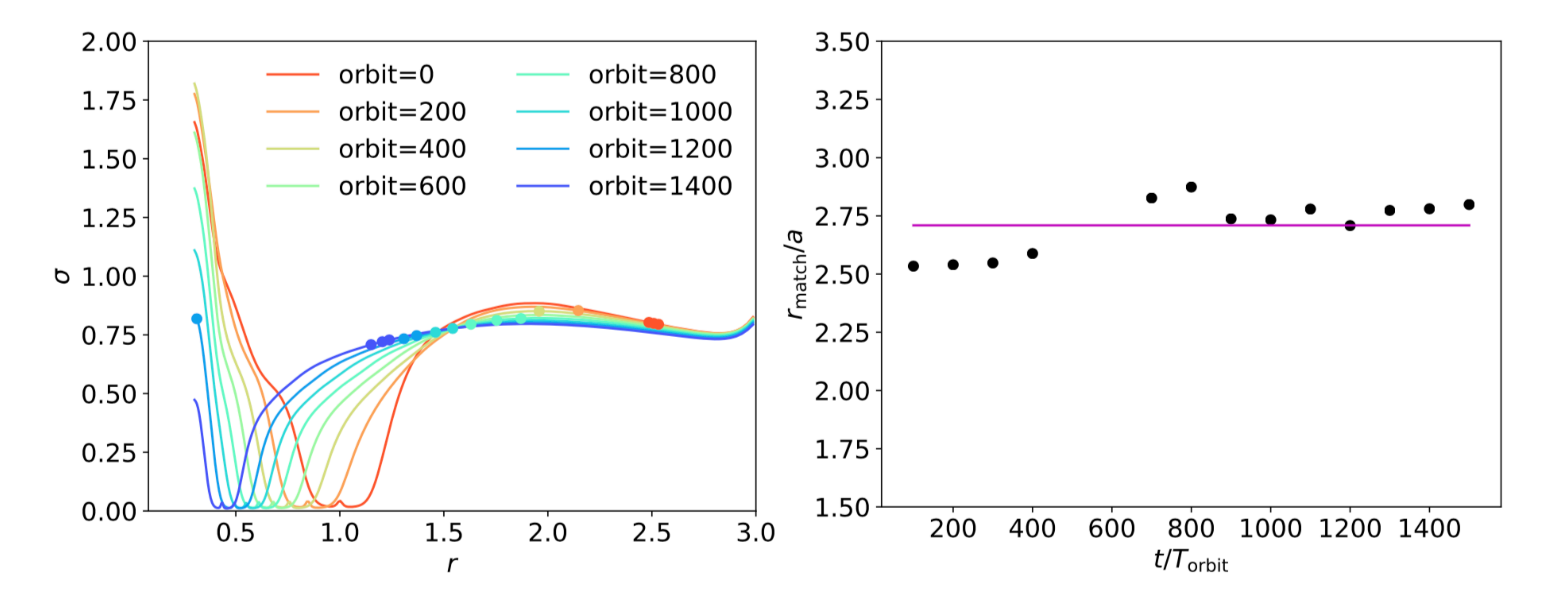
H/R=0.03

H/R=0.025

# NEW SIMULATIONS - Scardoni et al (in prep)

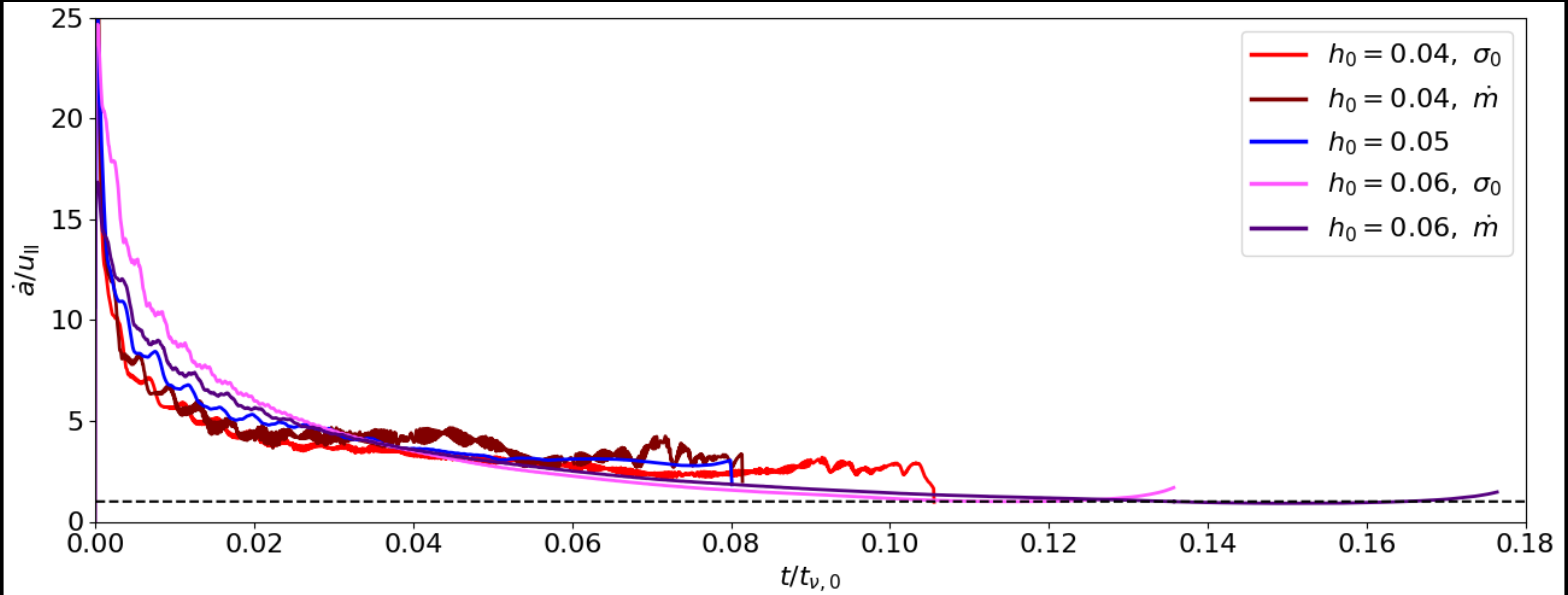
- Use FARGO3D in 2D. Same parameters as Durmann and Kley, but vary H/R = 0.04, 0.05, 0.06 and two values of the disc mass.

- Resolution is such that **Δ**$\varphi$=**Δ**r/r=0.2H/R ($N_\varphi$~500-700)



# NEW SIMULATIONS - Scardoni et al (in prep)

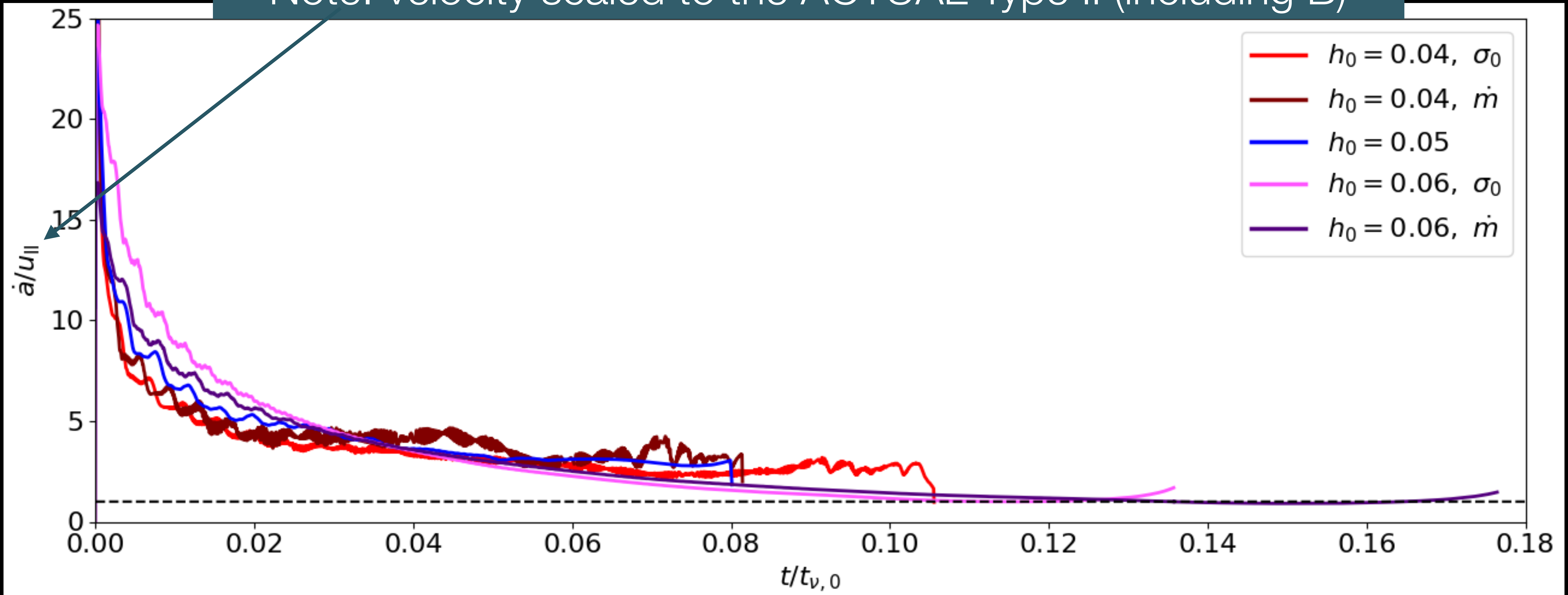
- Use FARGO3D in 2D. Same parameters as Durmann and Kley, but vary H/R = 0.04, 0.05, 0.06 and two values of the disc mass.



# NEW SIMULATIONS - Scardoni et al (in prep)

- Use FARGO3D in 2D. Same parameters as Durmann and Kley, but vary H/R = 0.04, 0.05, 0.06 and two values of the disc mass.

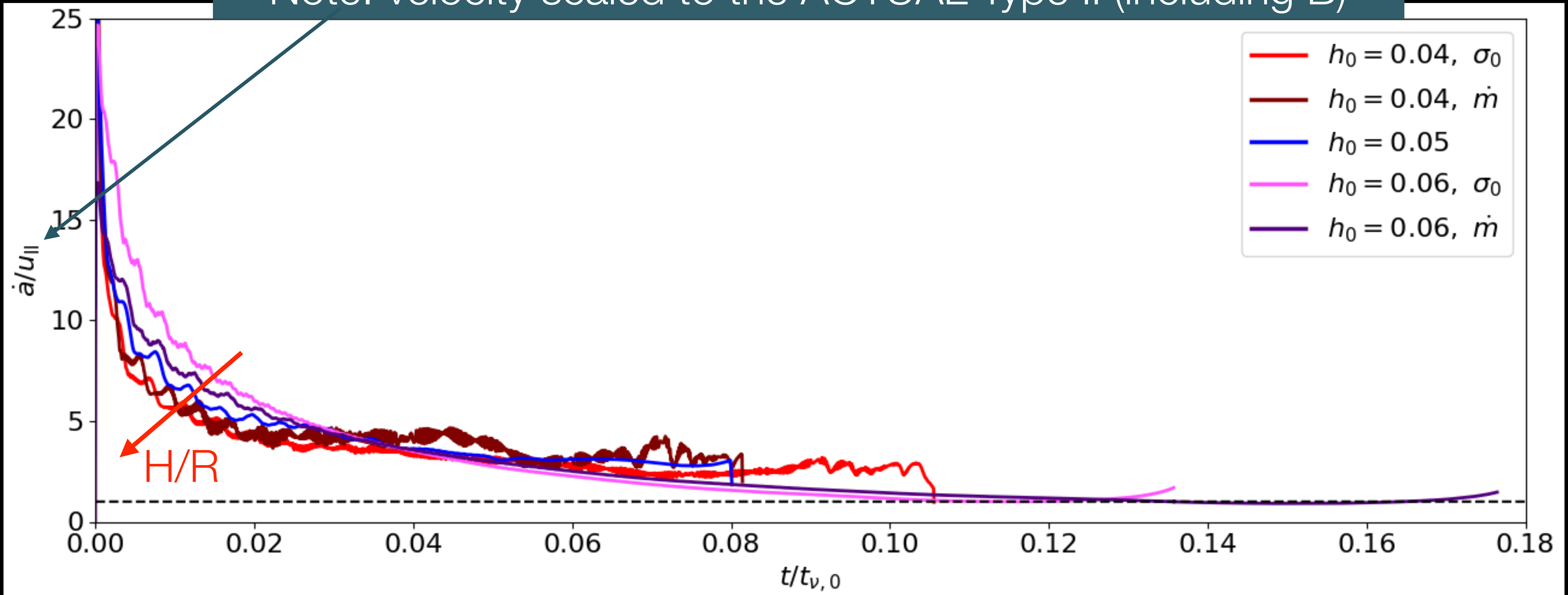
Note: velocity scaled to the ACTUAL Type II (including B)



# NEW SIMULATIONS - Scardoni et al (in prep)

- Use FARGO3D in 2D. Same parameters as Durmann and Kley, but vary H/R = 0.04, 0.05, 0.06 and two values of the disc mass.

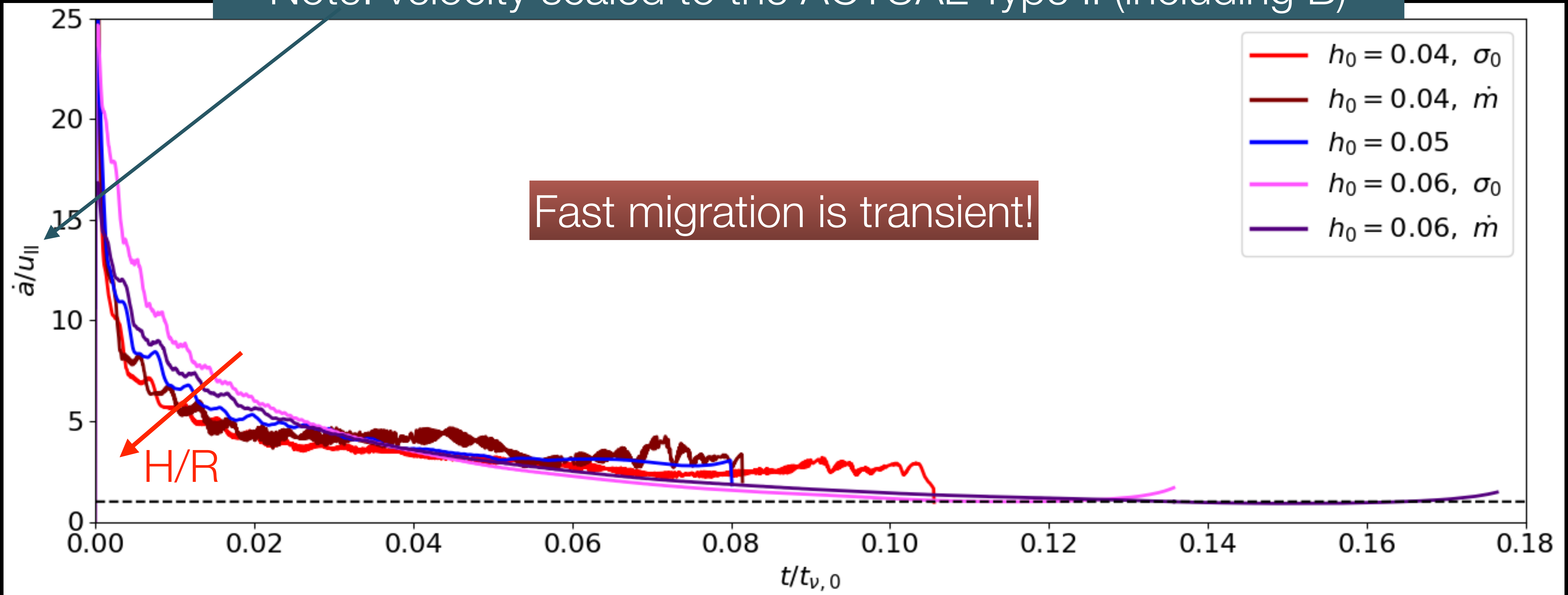
Note: velocity scaled to the ACTUAL Type II (including B)



# NEW SIMULATIONS - Scardoni et al (in prep)

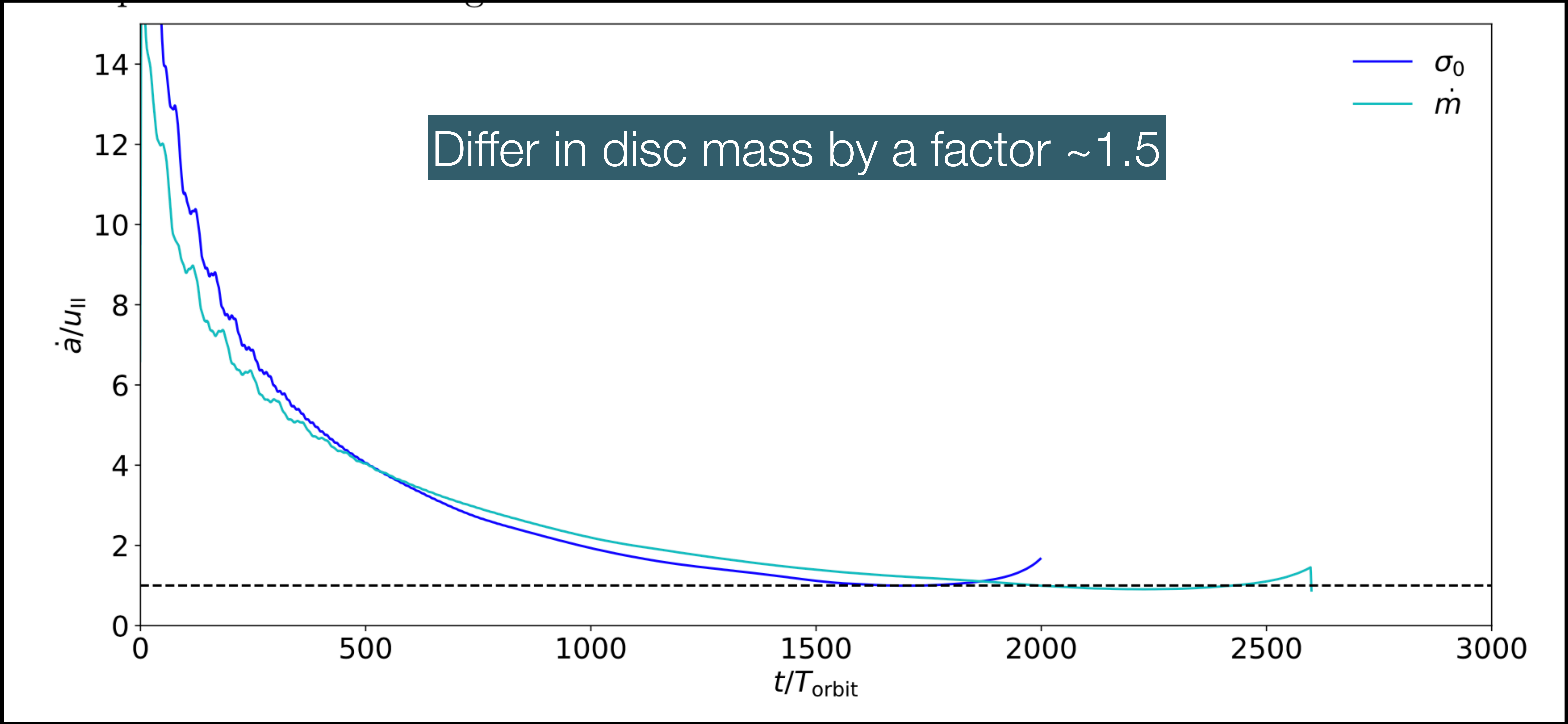
- Use FARGO3D in 2D. Same parameters as Durmann and Kley, but vary H/R = 0.04, 0.05, 0.06 and two values of the disc mass.

Note: velocity scaled to the ACTUAL Type II (including B)



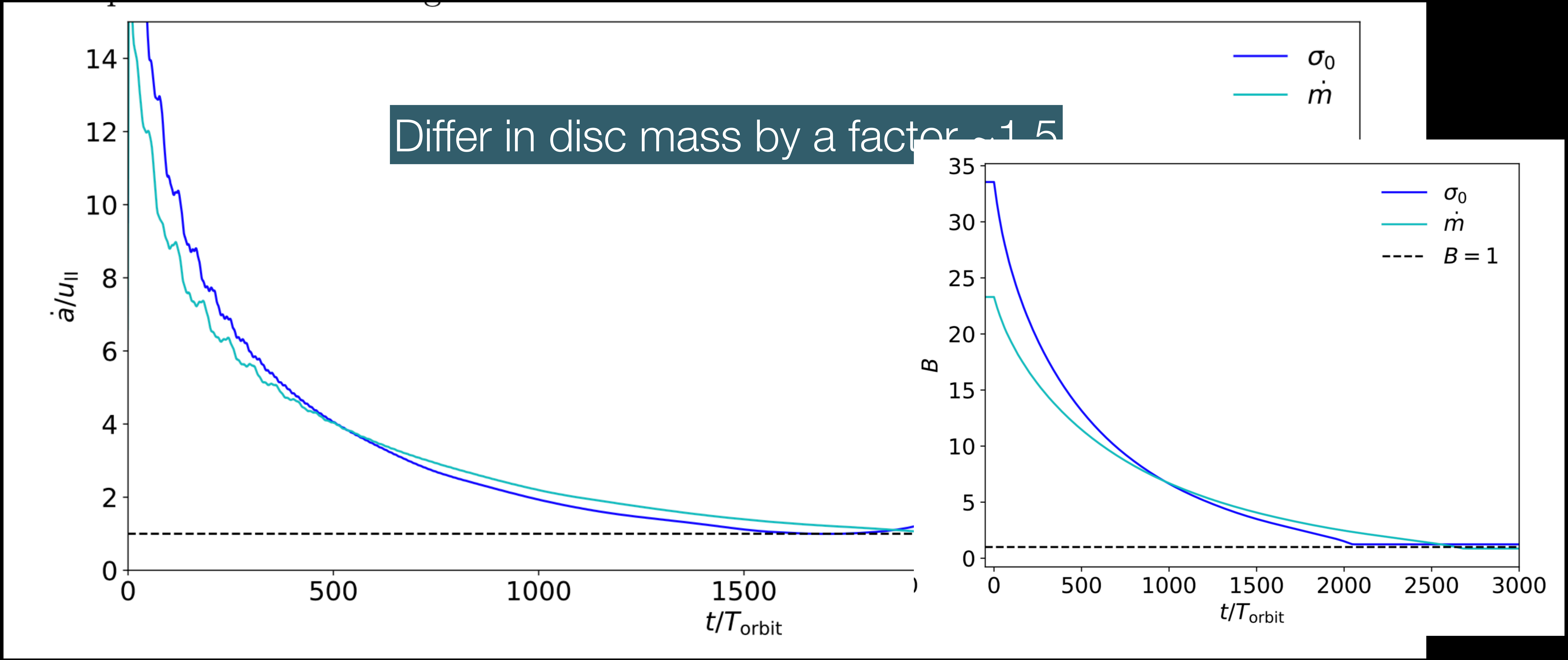
# DEPENDENCE ON DISC MASS?

- We do not find significant dependence on disc mass



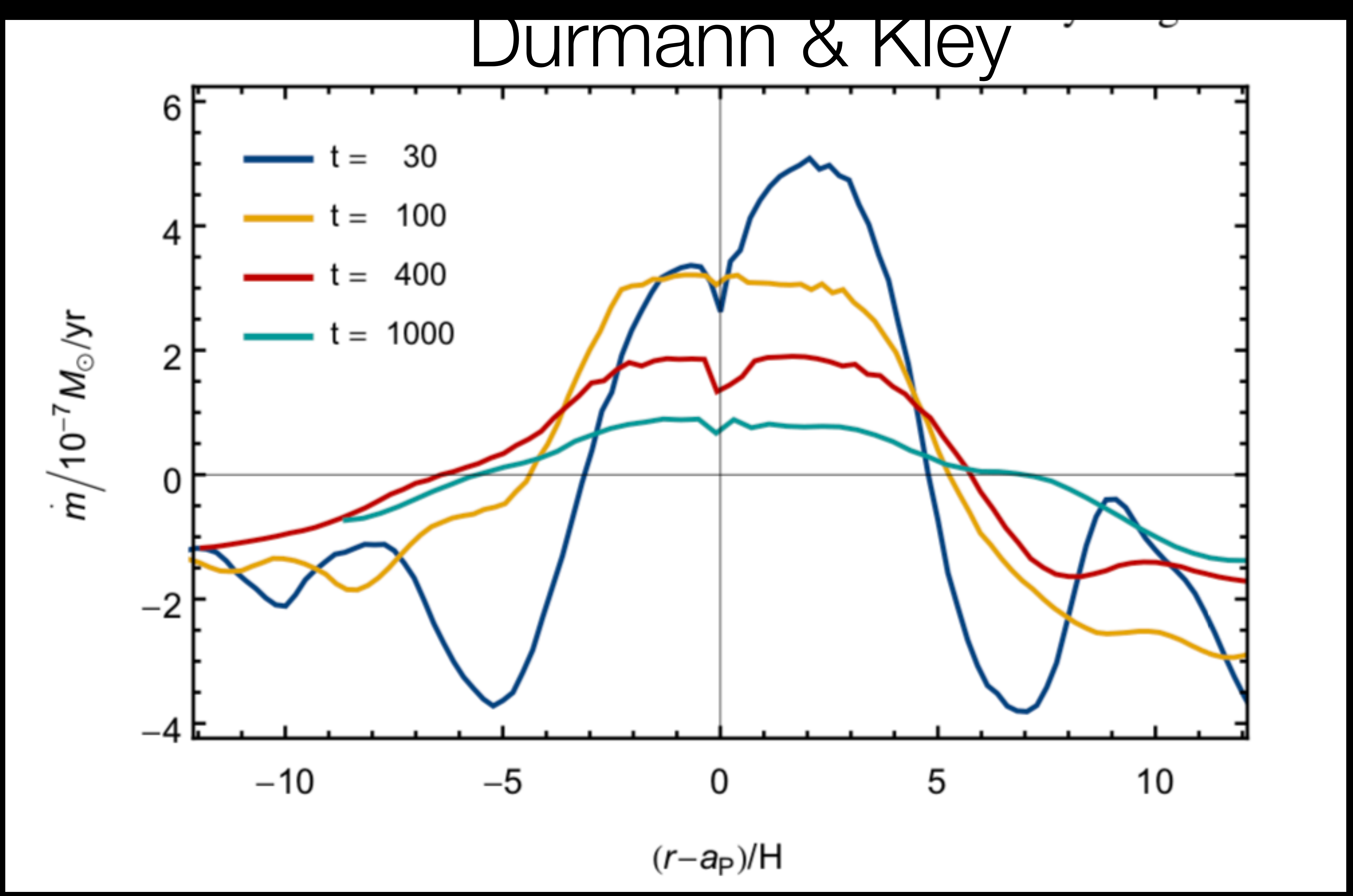
# DEPENDENCE ON DISC MASS?

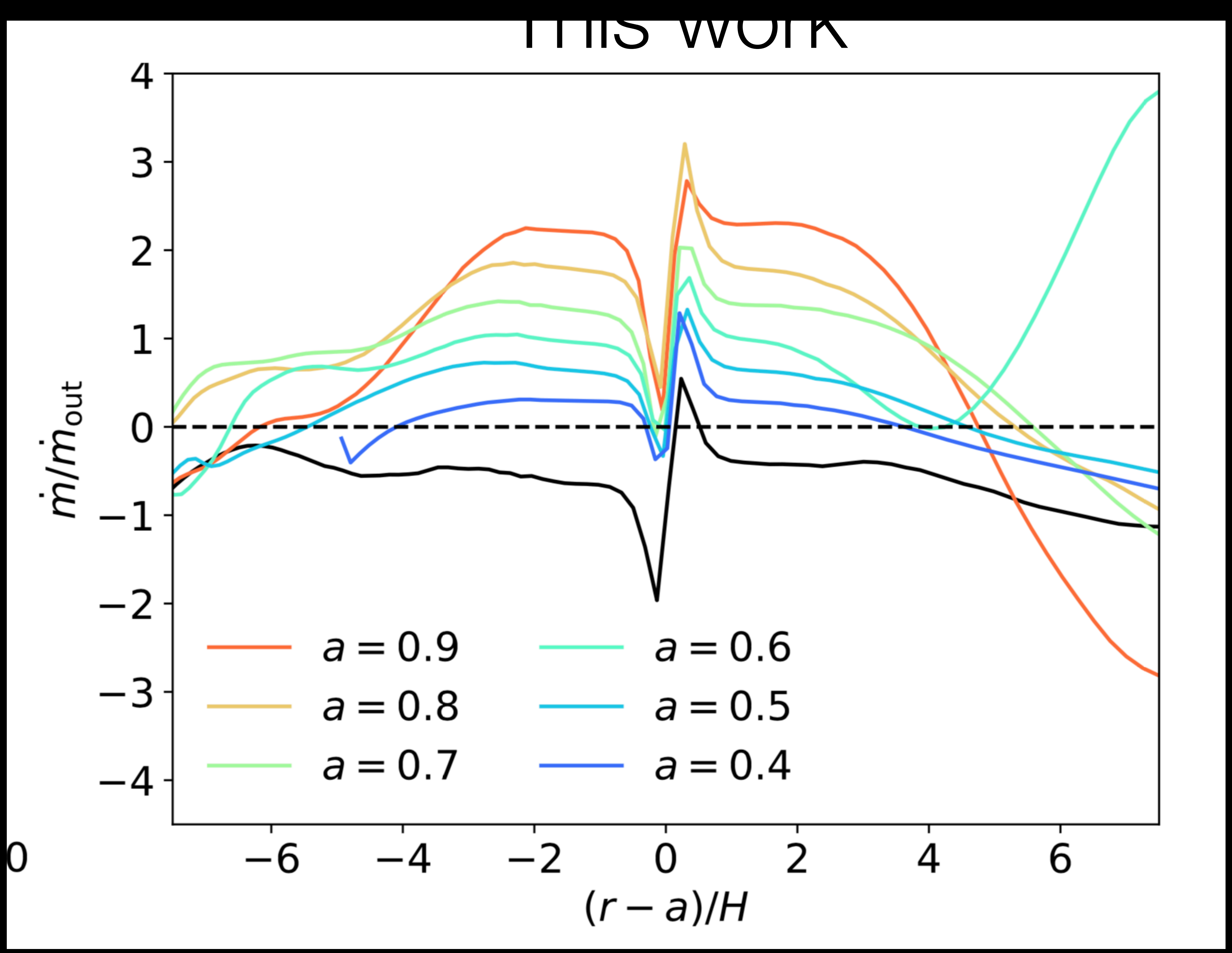
- We do not find significant dependence on disc mass



# MASS FLOW THROUGH THE GAP

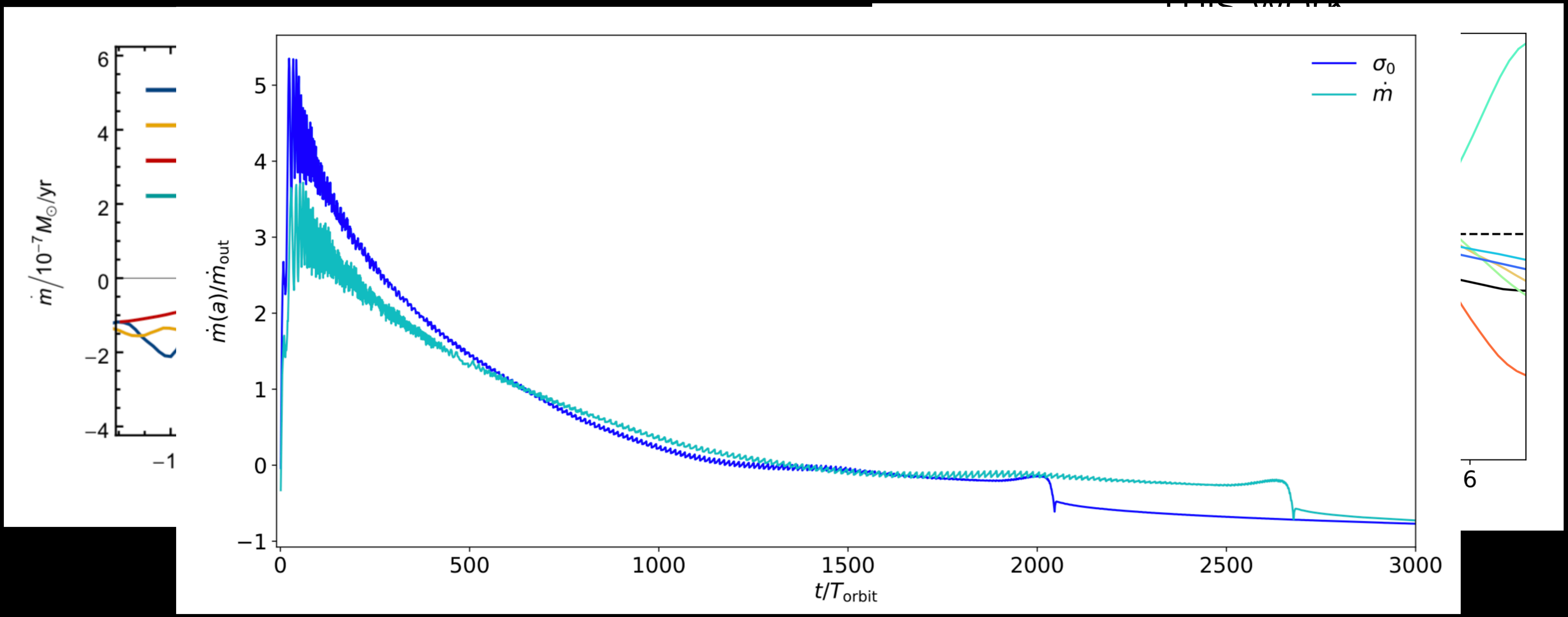
- Initially, there is indeed mass flow through the gap, as required by having a faster migrartion rate



# MASS FLOW THROUGH THE GAP

- Initially, there is indeed mass flow through the gap, as required by having a faster migrartion rate



# CONCLUSIONS ON TYPE II MIGRATION

- Is Type II migration locked to the viscous rate?
  - Duffel et al (2014) and Durmann & Kley (2015): **NO** Robert et al "A new paradigm of Type II migration"
  - Actually, this result appears to be just a transient, and after ~ 0.1 viscous time migration attains its canonical value **(Scardoni et al, in prep)**
- Choice of parameters:
  - Obviously, as the gap gets filled in (i.e. lower planet mass, higher H/R) discrepancies are more severe
  - Need to understand better the role of disc mass in this results, we only explored a limited range of disc masses.