CIRCUMBINARY DISKS

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STScI
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THANK YOU!

BRIDGING THE GAP: ACCRETION AND ORBITAL EVOLUTION IN STELLAR AND BLACK HOLE BINARIES

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Scientific Justification

Binary systems are ubiquitous in nature, from binary stars in our Galaxy to the supermassive black hole binaries (SBHBs) expected to reside in distant galactic nuclei. In many circumstances, the binary system is expected to be enveloped by external circumbinary gas: binary stars form in shared molecular cores or even disks, and SBHBs, produced in galaxy mergers, are expected to initially reside in the newly formed, gas-rich nucleus. The proposed workshop will bring together researchers working on circumbinary accretion in the two distinct fields of stellar binary and black hole binary accretion, with the goal of combining the distinct observational and theoretical tools across both fields towards mutually enhanced progress on the problem of binary accretion.

OUTLINE

- Early History:
  - decretion disk model
  - binary eccentricity evolution
  - inflow for eccentric orbit binaries
  - inflow for circular orbit binaries

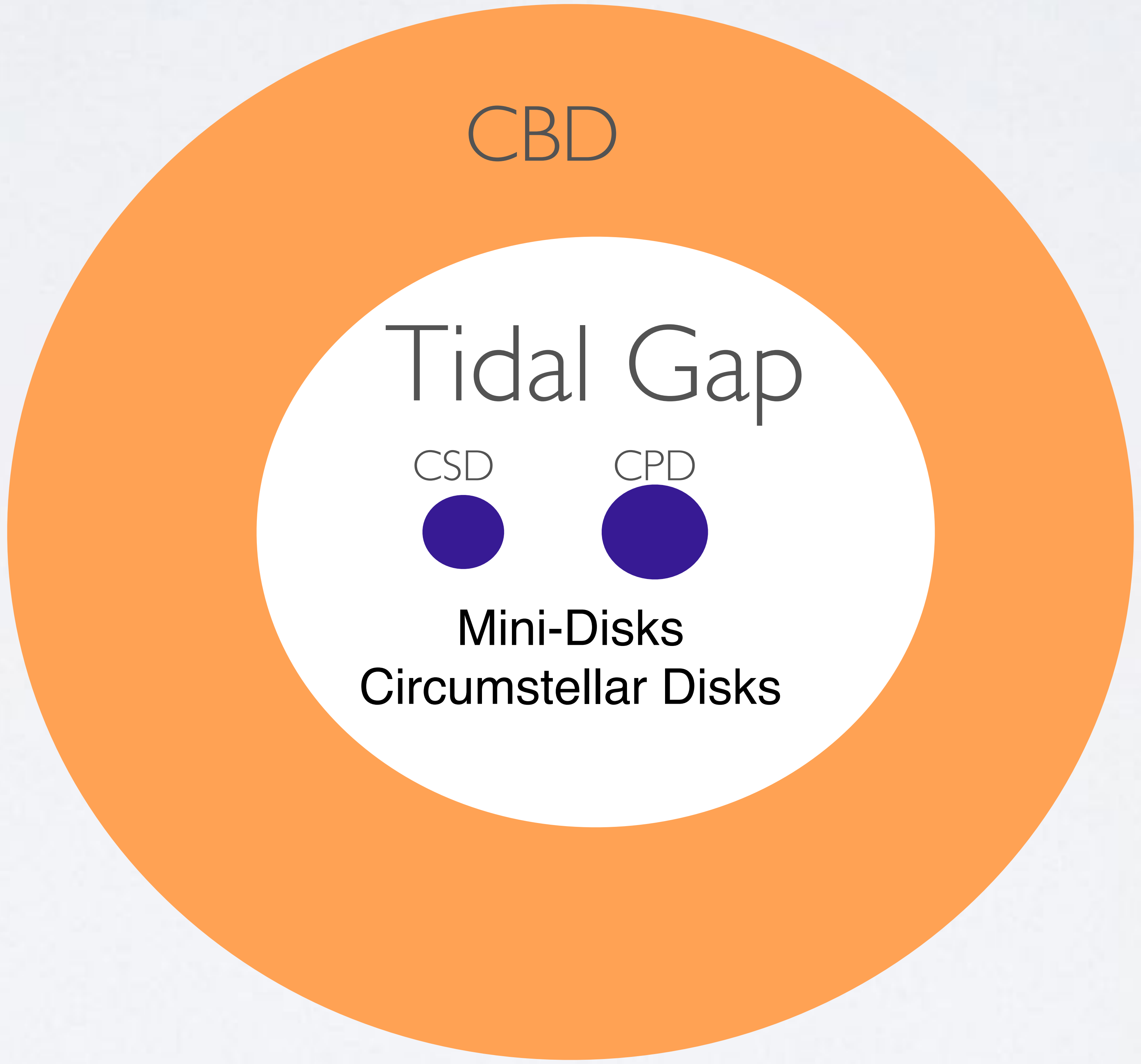
- Disks around SMBH versus young binaries

- Some open questions

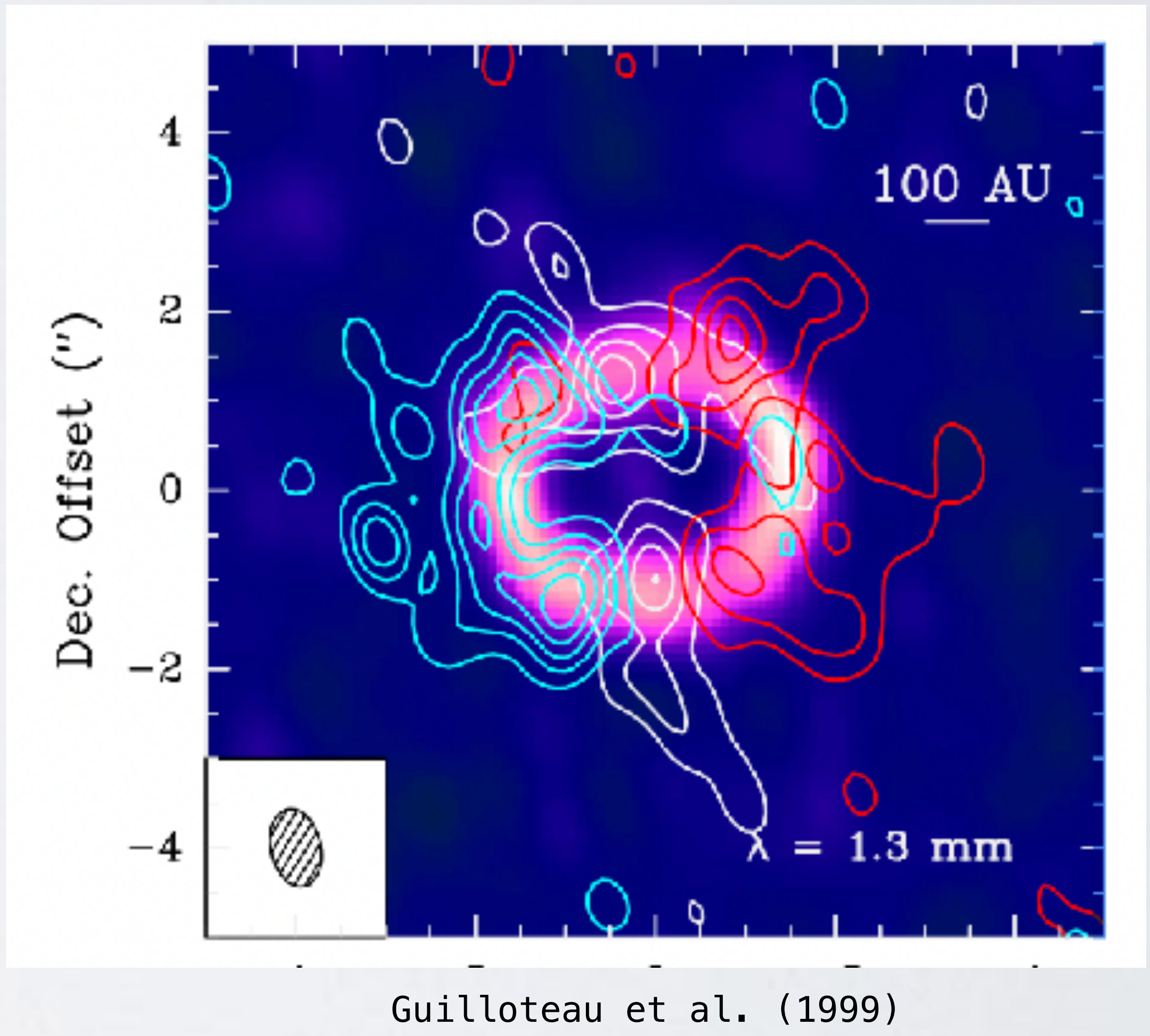
Disclaimer: Not a full review

BINARY DISKS

- 3 Disks
  - circumsecondary (CSD)
  - circumprimary (CPD)
  - circumbinary (CBD)

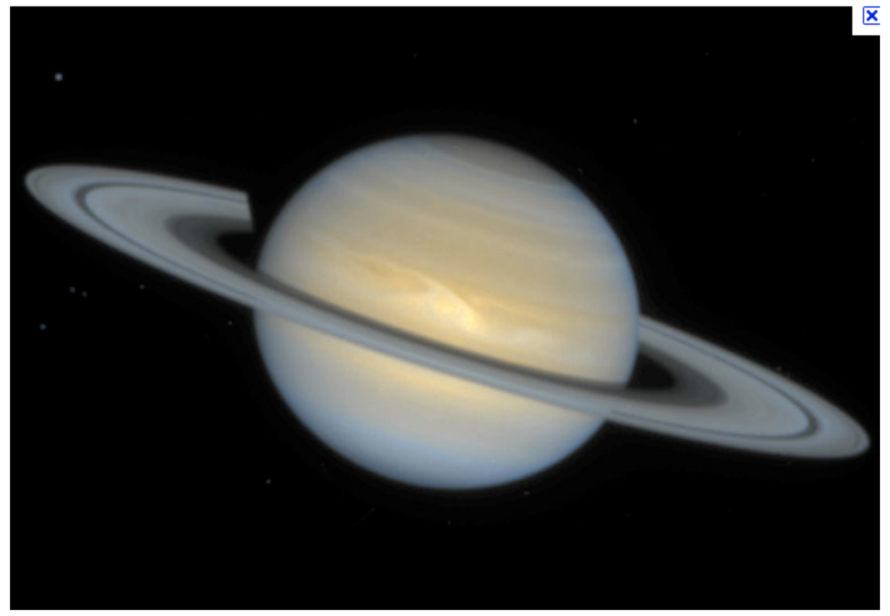


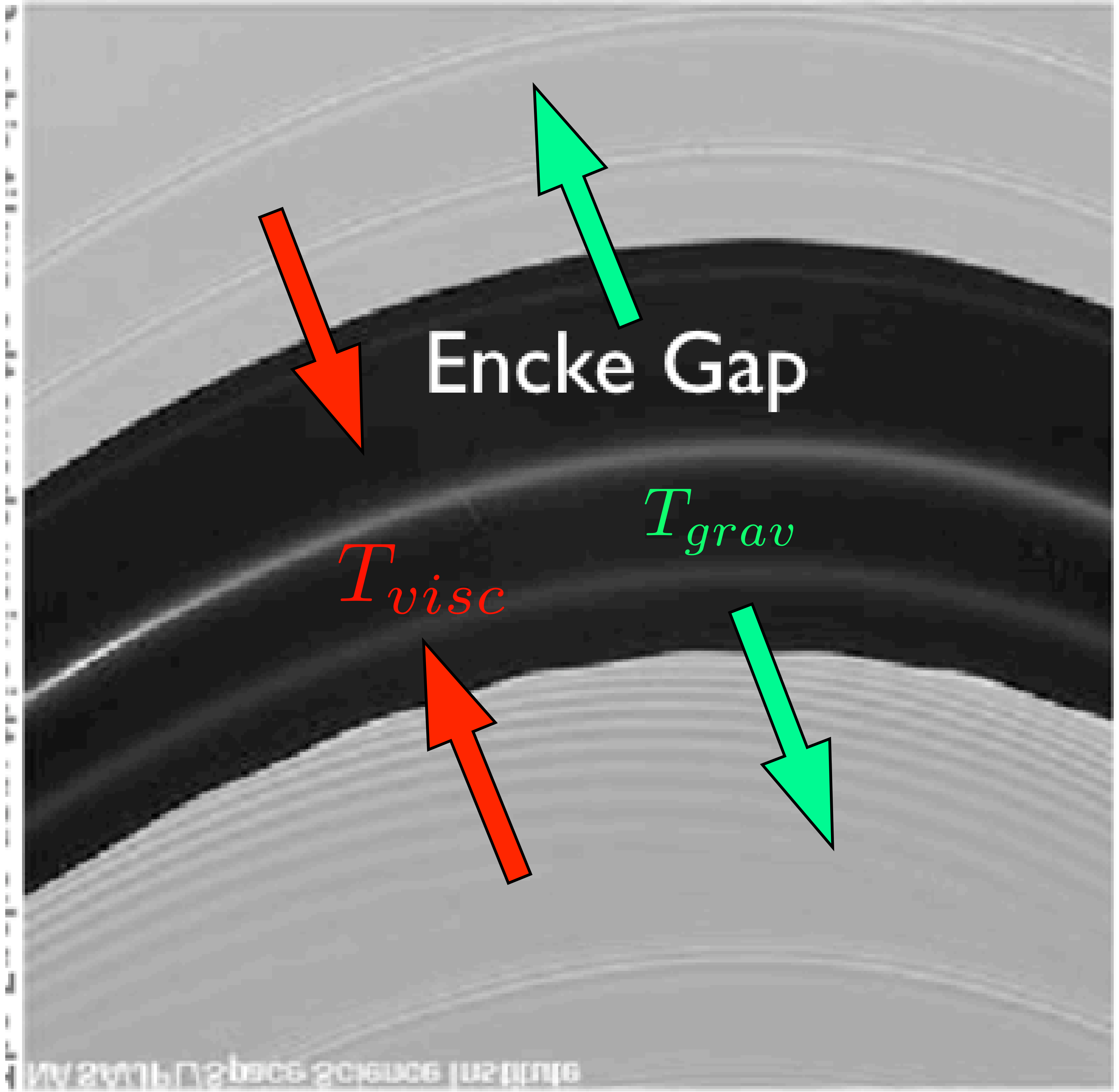
GG Tau



Dutrey et al. 2016

Gap Opening





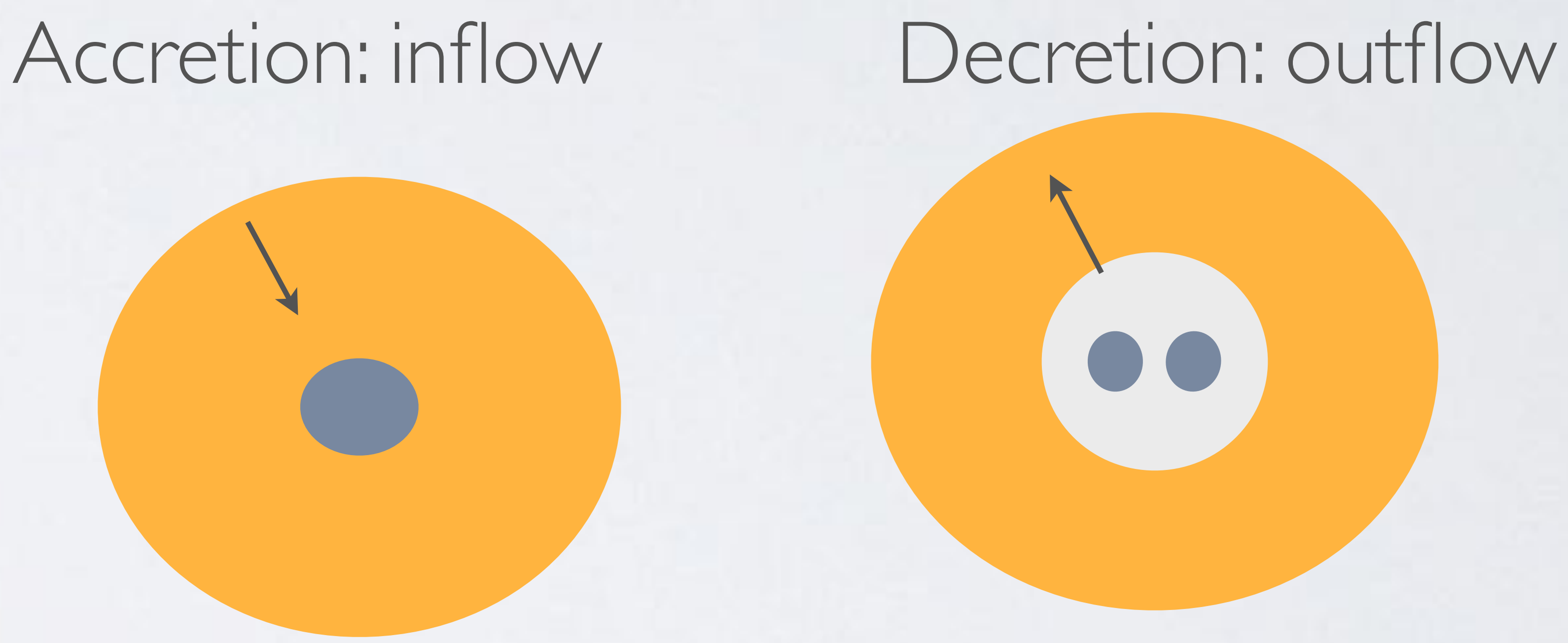
Pan

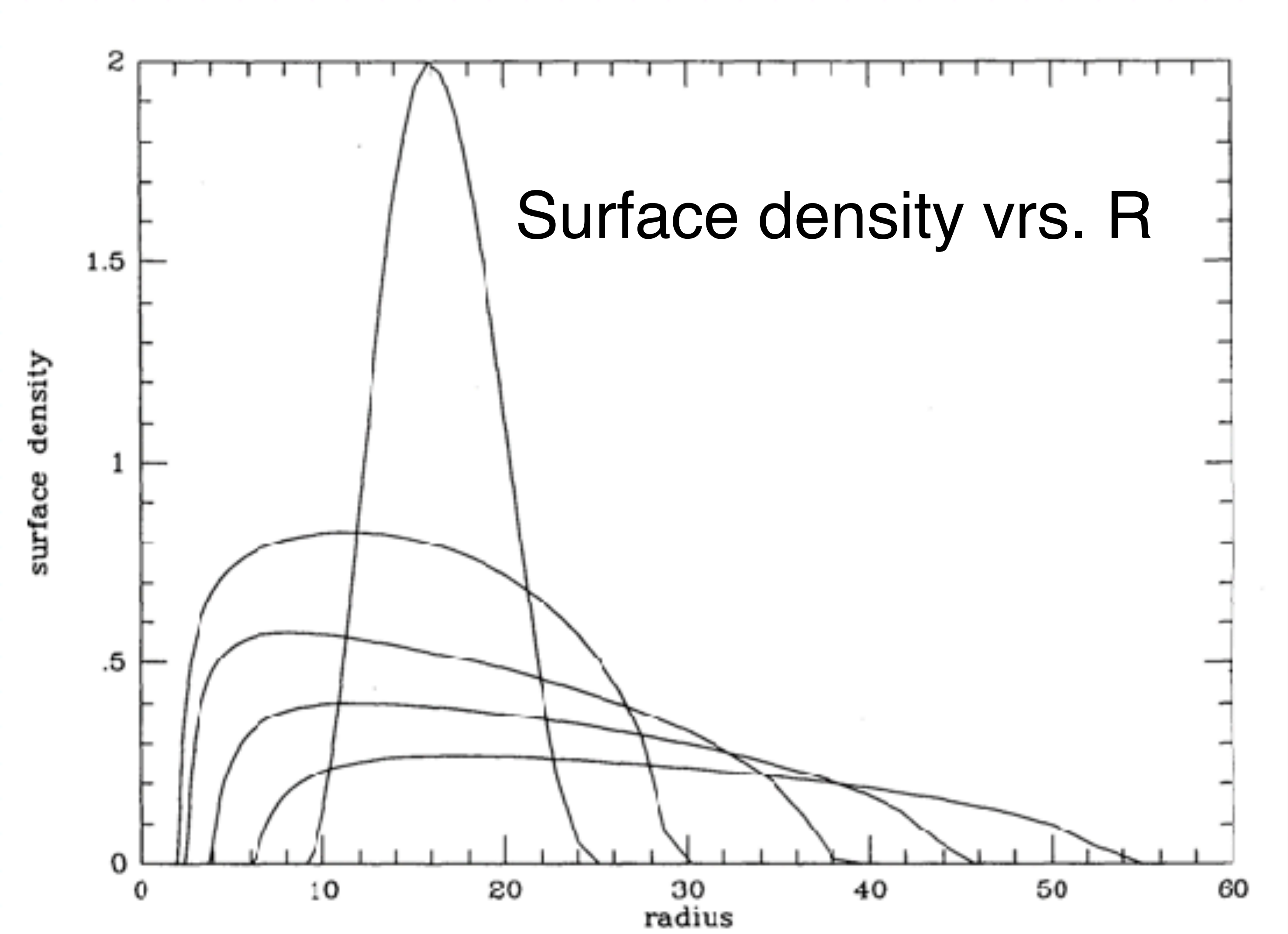
Gap width 300 km

Pan radius 10 km

CBD AS A DECRETION DISK

- 2D axisymmetric: r, t
- Two types of disk similarity solutions involving a central point mass (Lynden-Bell & Pringle 1974)
- Accretion disk: $\dot{M}(r=0) > 0 \quad \dot{J}(r=0) = 0$
- Decretion disk: $\dot{M}(r=0) = 0 \quad \dot{J}(r=0) > 0$
- CBD disk is a decretion disk, zero mass flux at some radius, circular orbit binary (Pringle 1991)

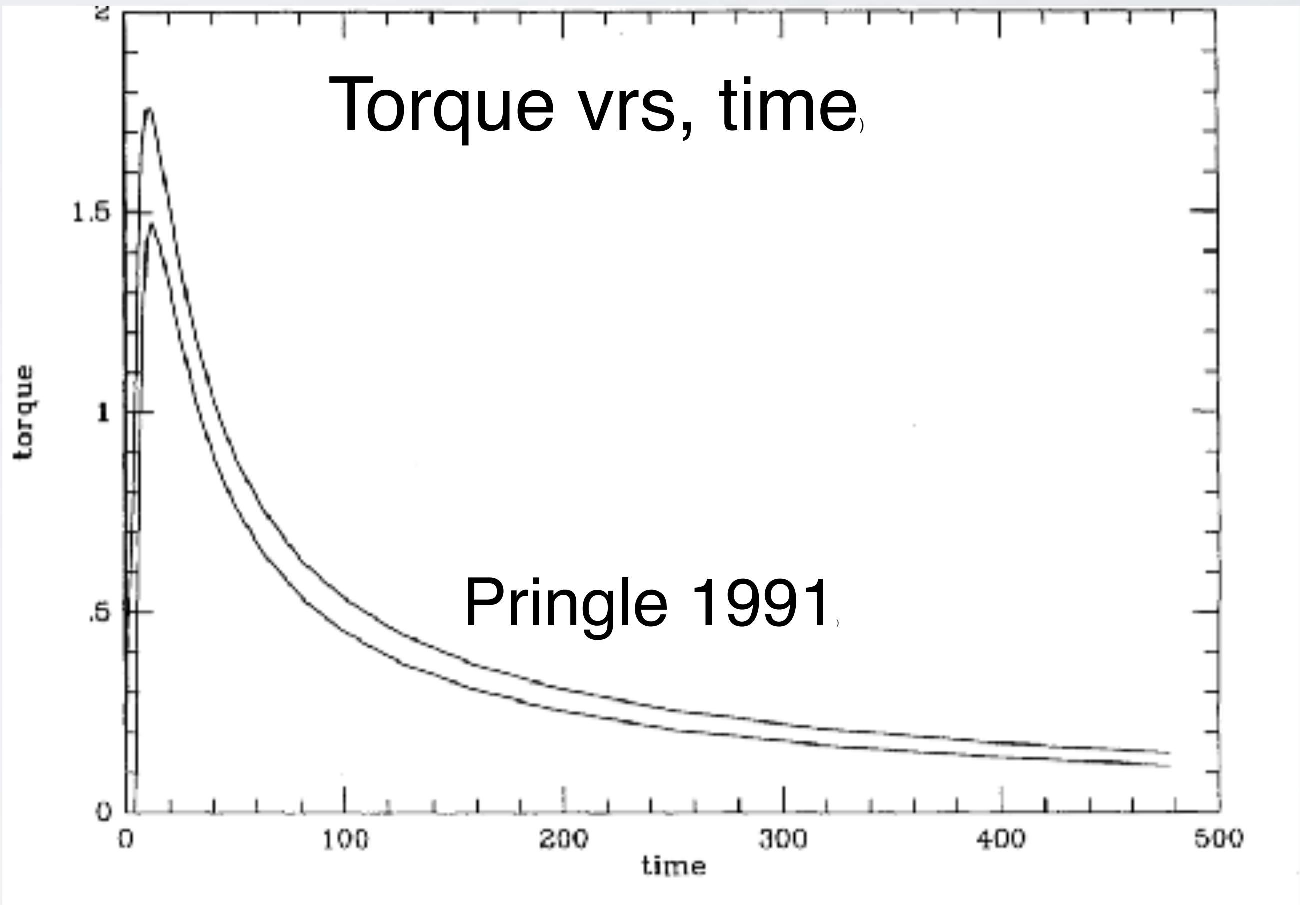




Pringle 1991

CBD AS A DECRETION DISK

- Accretion: mass in and J goes out
- Decretion: mass and J go out
- CBD gains E and J from binary
- Torque applied decreases in time as disk expands
- Mixed accretion/decretion disks (Rafikov 2013, 2016; Nixon & Pringle 2020)



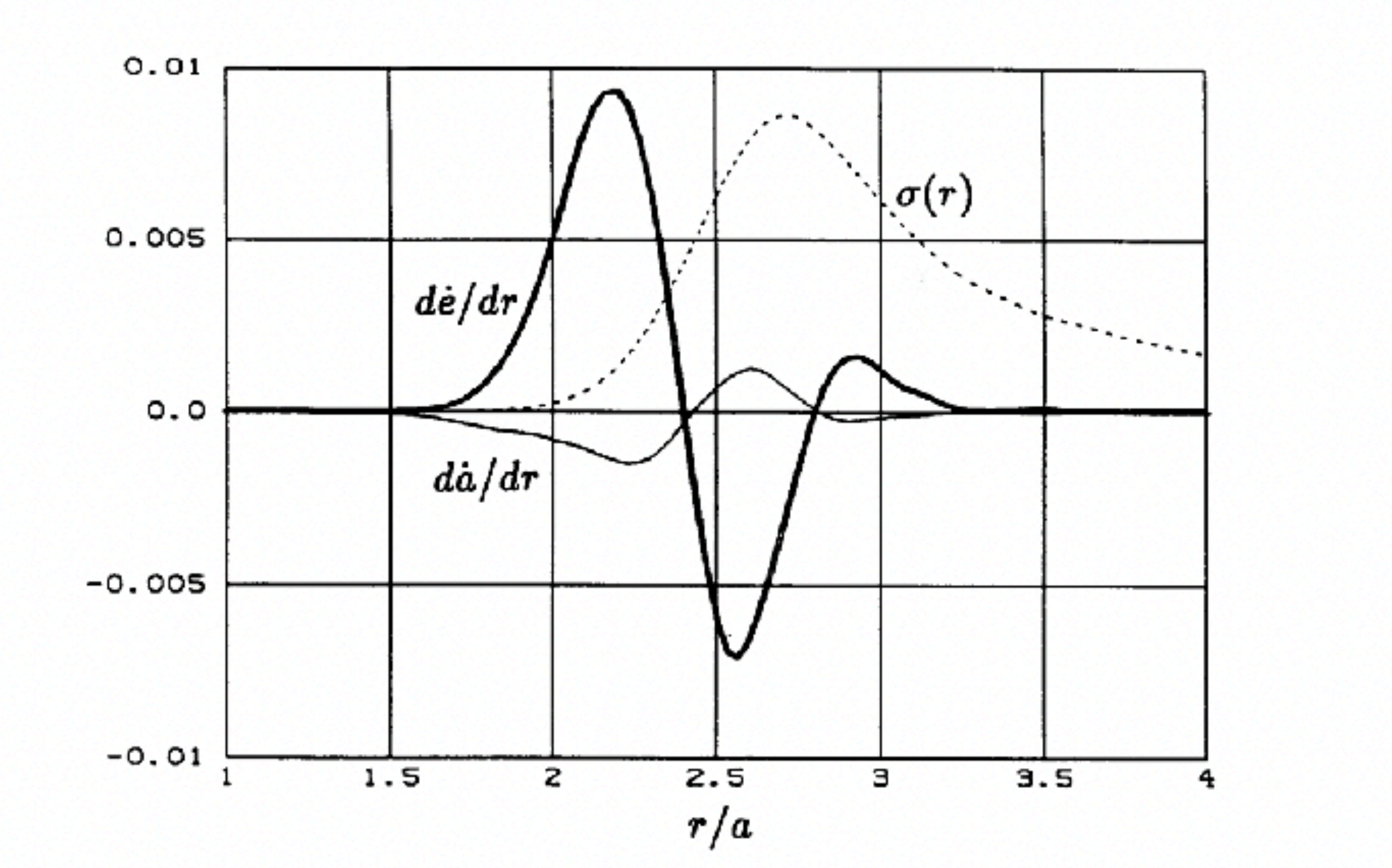
EARLY SPH SIMULATIONS

- 1990s, Sun sparc workstation 1, 25 MHz (iphone 13: 2.4 GHz)
- up to 64 MB RAM (iphone 13: 4 GB standard)
- ~ 2 weeks per run for 50 to few 100 binary orbits
- ~ 20K particles

Sun SPARCstation 1+ "pizzabox", 25 MHz SPARC processor, early 1990s

BINARY ECCENTRICITY

- Might expect that disks damp binary eccentricity
- CBD can increase the eccentricity of the low eccentricity binary (Artymowicz et al. 1991)
- Simulation $e_b = 0.1,\ H/R = 0.03$.
- No gas in gap (decretion disk)
- $\dot{e}_b$ in agreement with resonance theory at 20% level (Goldreich & Tremaine 1980)

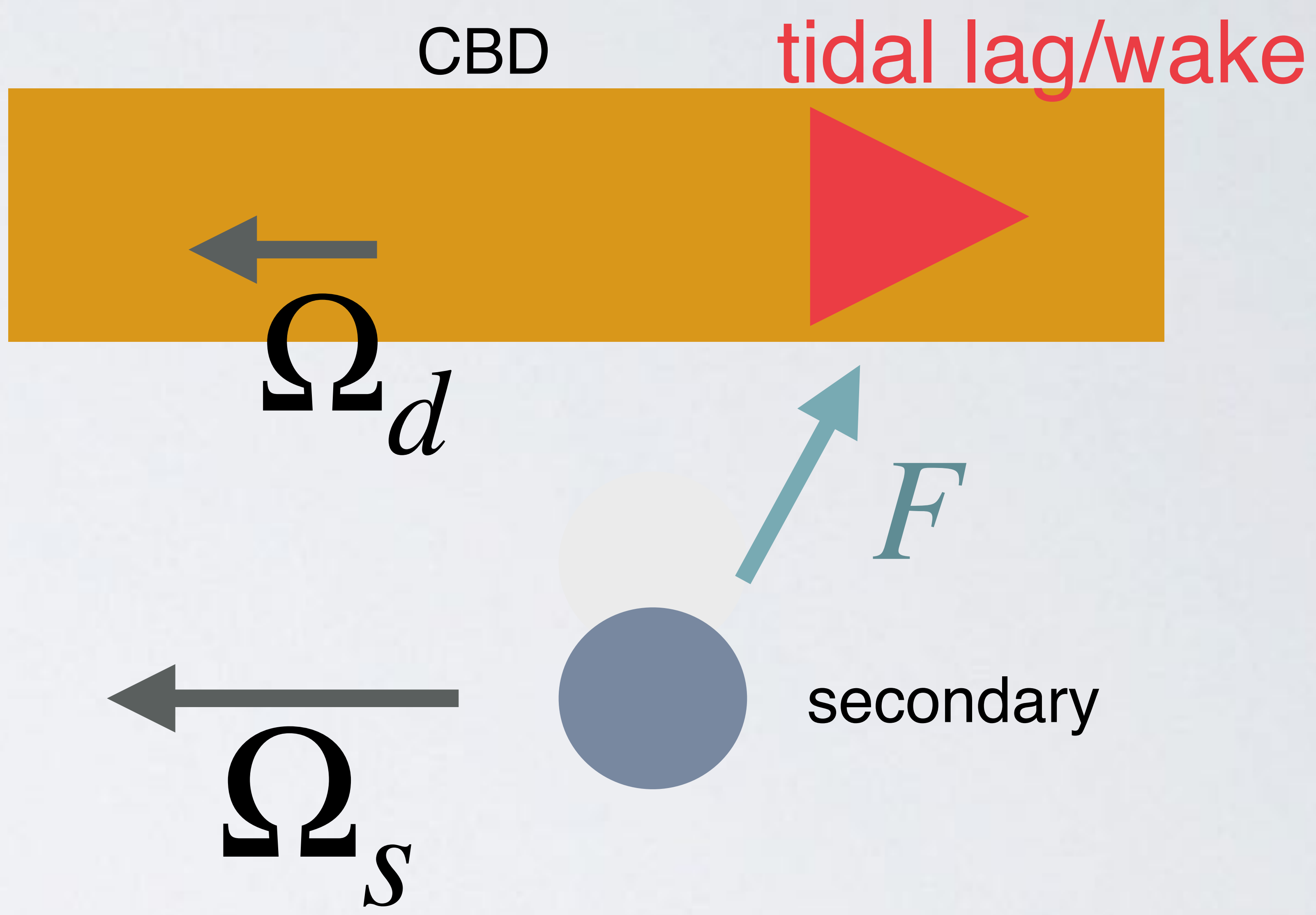


Artymowicz et al. 1991

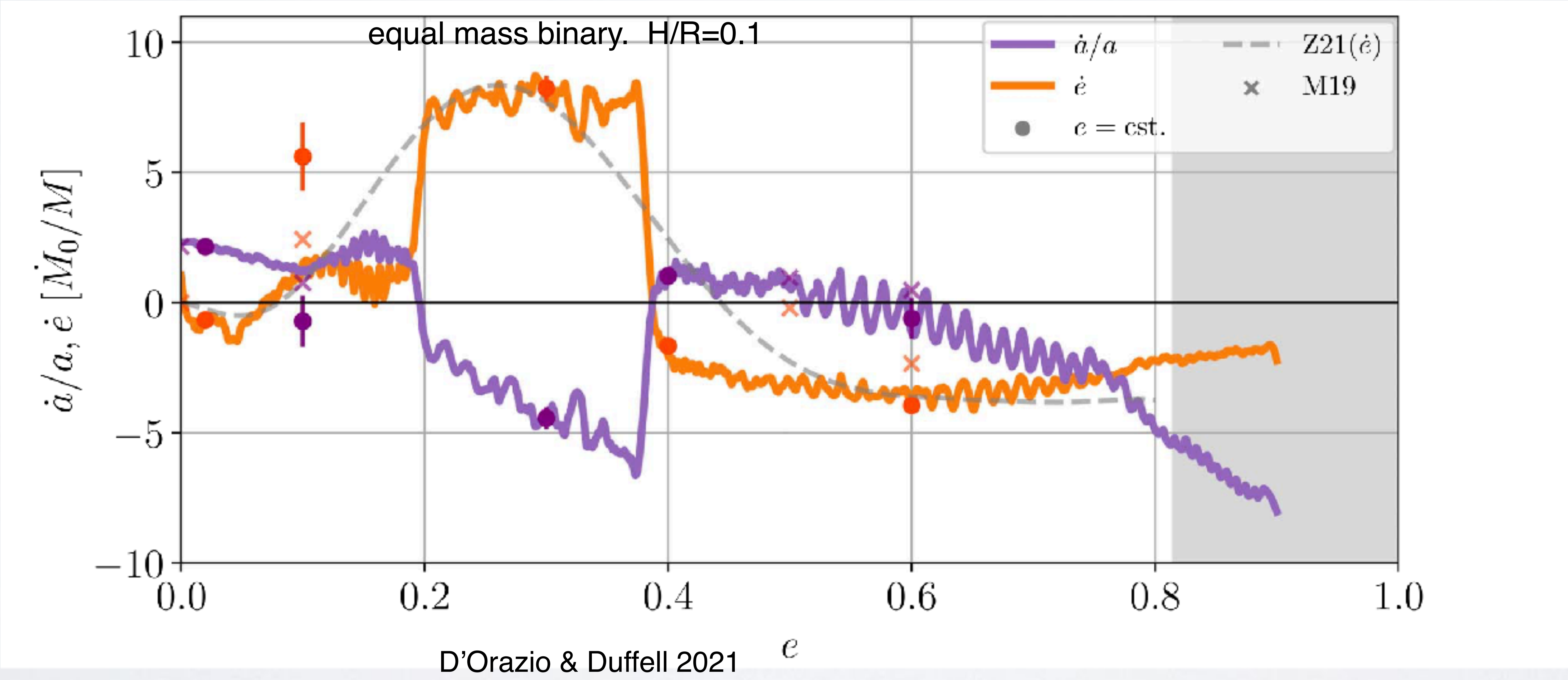
TOY MODEL FOR $\dot{e}_b$

- Eccentric orbit secondary gravitationally interacts with circular CBD at apastron only
  - impulse at apastron: $a_b(1+e_b)$ is constant
  - for small e_b, secondary moves faster than disk: binary loses E and J to disk, $\dot{a}_b < 0$
  - then $\dot{e}_b > 0$

- Extended model
  - for larger e_b, secondary moves slower than disk: binary gains E and J from disk, $\dot{a}_b > 0$ (migration reversal)
  - then $\dot{e}_b < 0$



ECCENTRICITY EVOLUTION

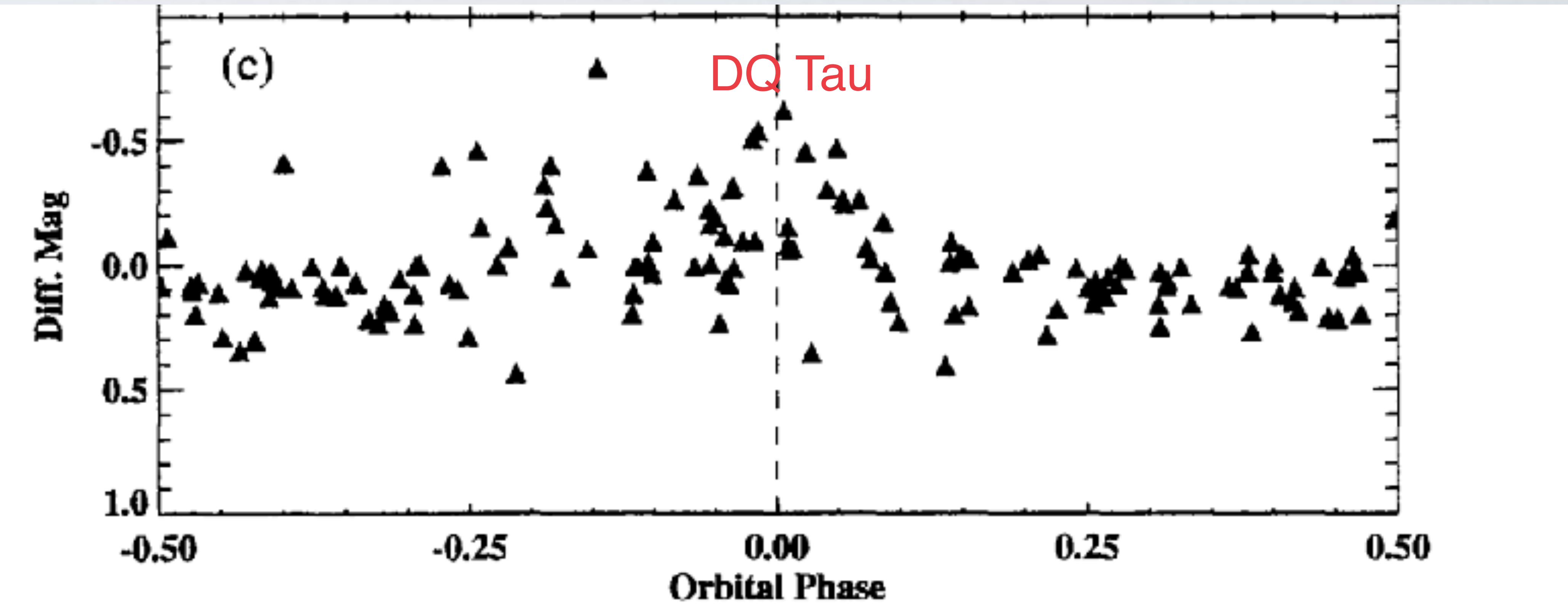


- Toy model roughly right. Situation more complicated: binary mass gain, additional torques in gap, eccentric disk (Zrake et al. 2021; D'Orazio & Duffell 2021)

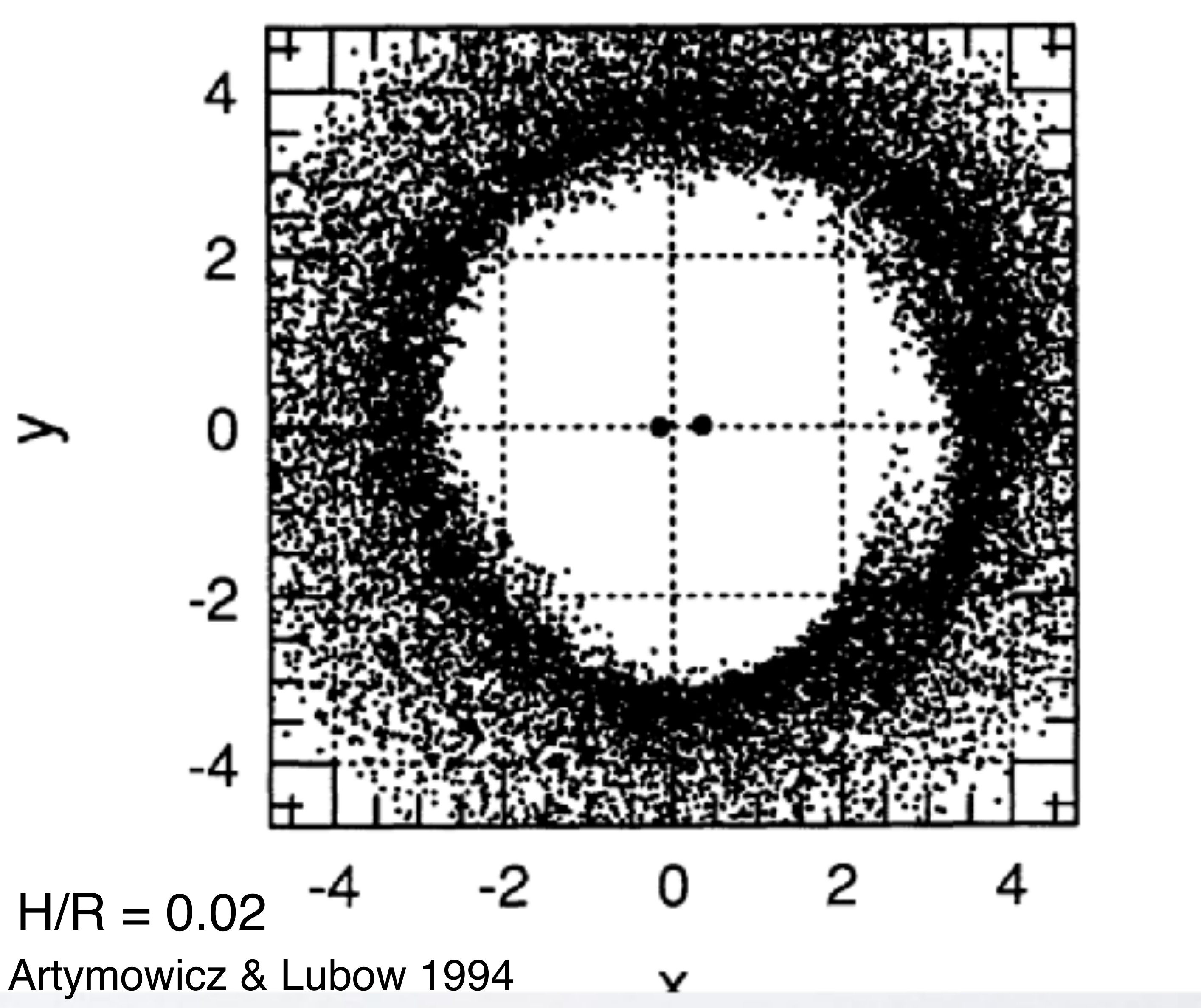
FLOW THROUGH GAPS

- Observations of DQ Tau suggested periodic brightening at periastron (Hint from Bob Mathieu ~ 1995)

- Simulations did not show accretion onto binary for H/R < 0.05.



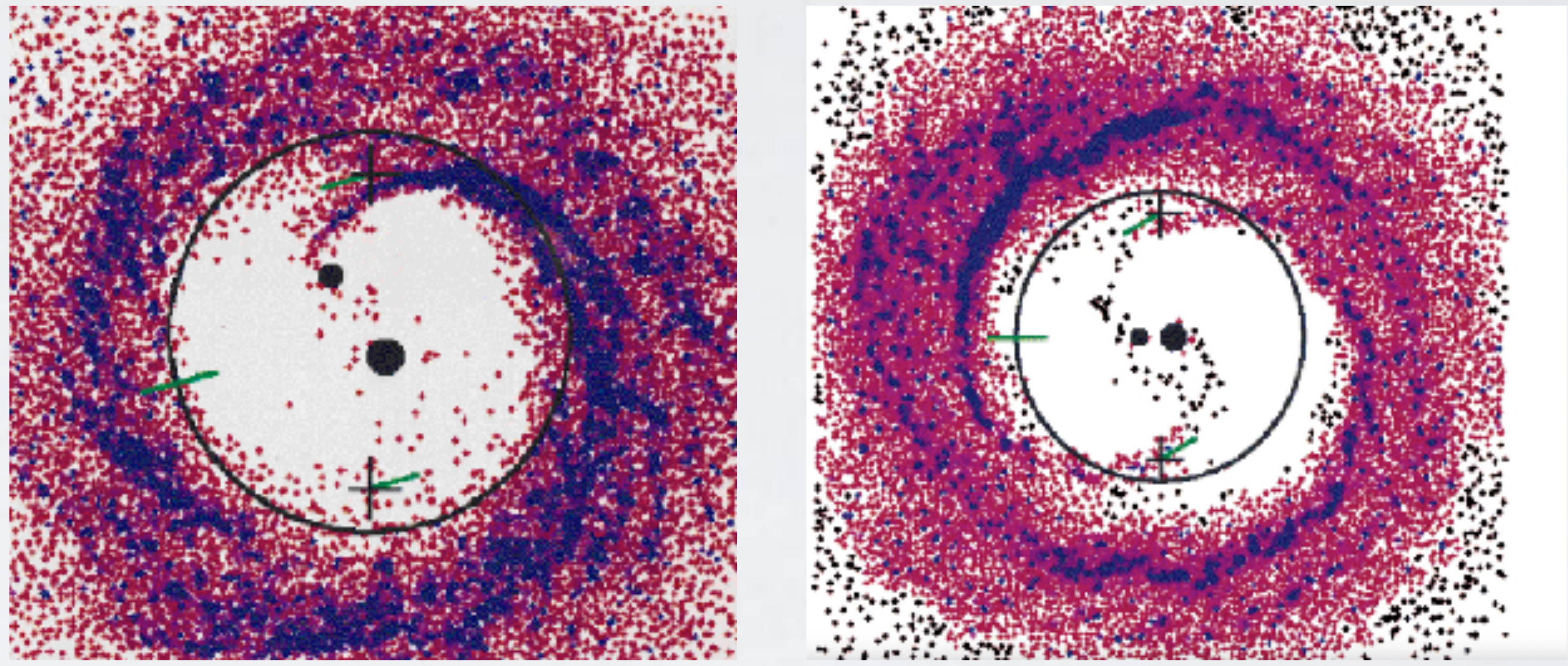
Mathieu el al. 1997



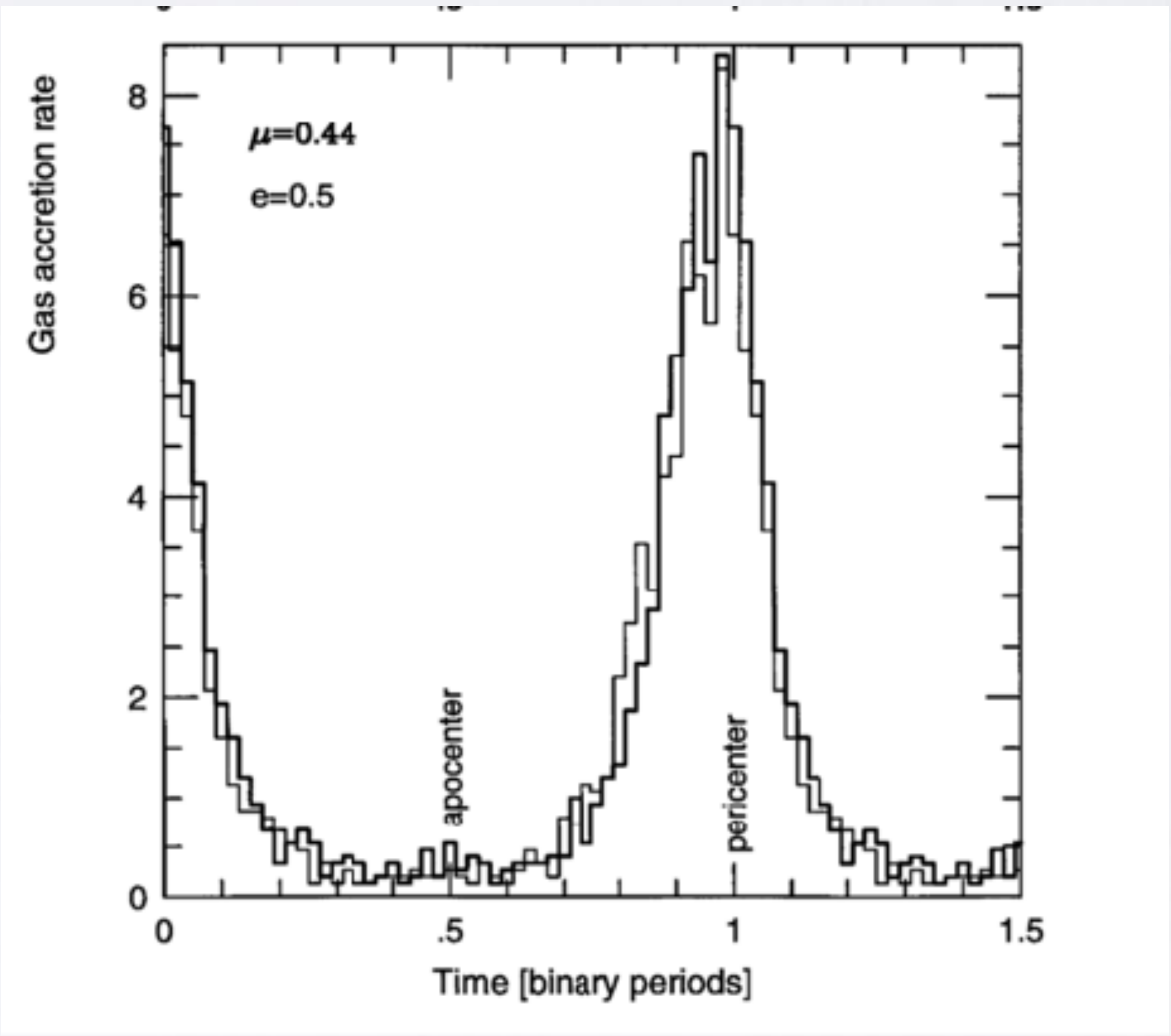
H/R = 0.02
Artymowicz & Lubow 1994

FLOW THROUGH GAPS

- Mass flow through gaps occurs in binaries (stars, black holes, and planets) for $H/R > 0.05$, $e_b = 0.3,0.5$ (Artymowicz & Lubow 1996)
- Flow in gas streams, preferentially onto secondary (mass equalization) (also Bate 1997)
- Mass flux in gap ~ CBD accretion rate
- Pulsed accretion on orbital period of binary
- Model based on flow through eccentric corotation points



Artymowicz & Lubow 1996



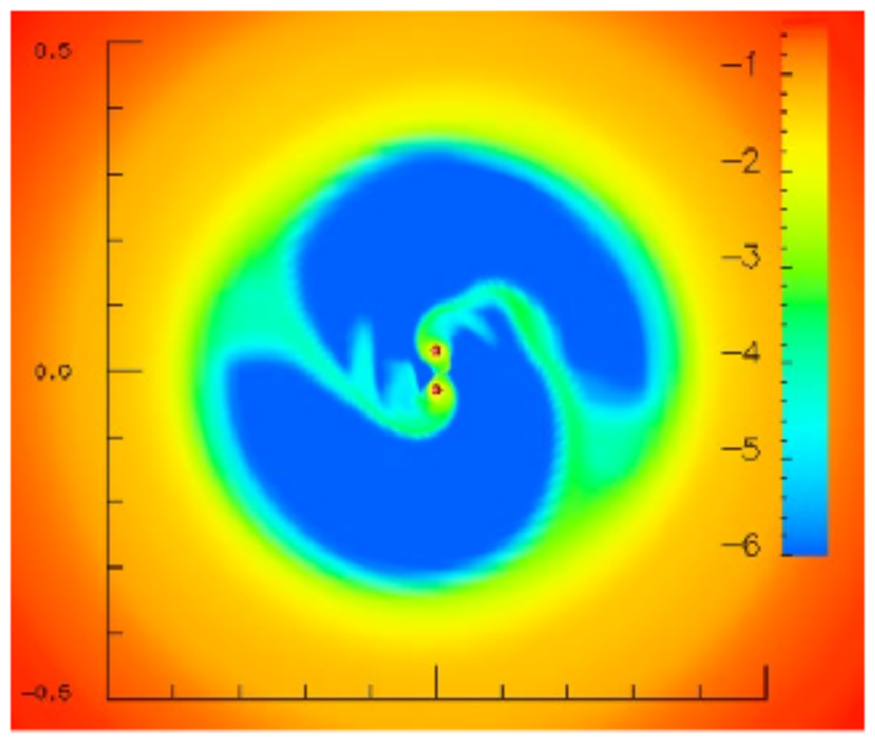
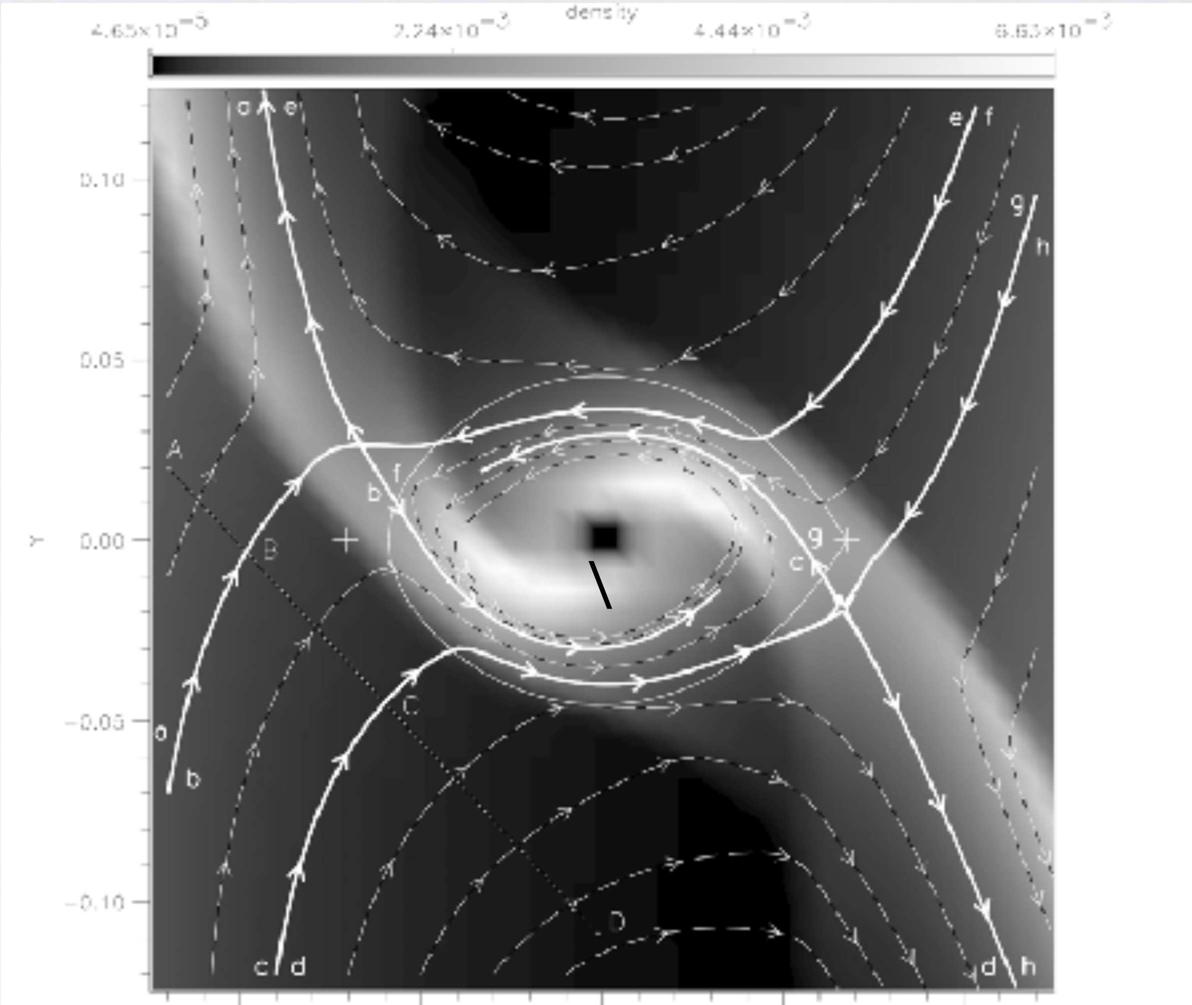


Fig. 10. DQ Tau circumbinary disk after 85.5 orbital periods in periastron. Color coding is log(Σ), the size of the stars reflects the actual stellar radii, the length scales are in AU.

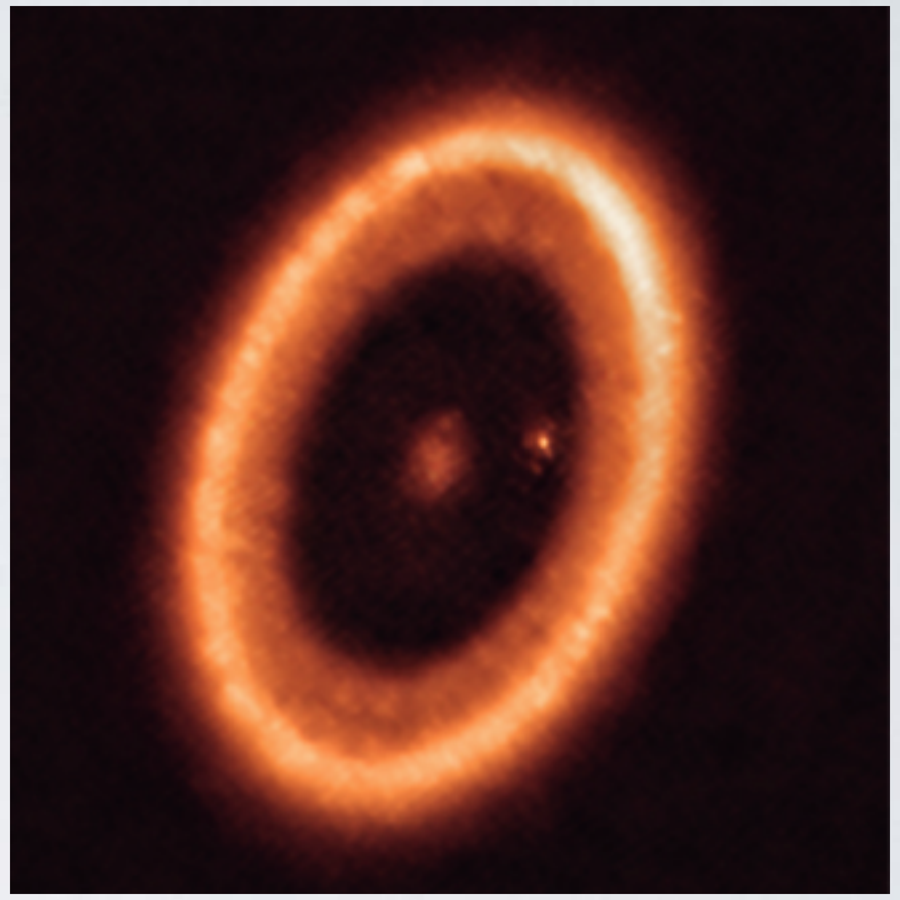
Gunther & Kley 2002

FLOW THROUGH GAPS TO PLANETS

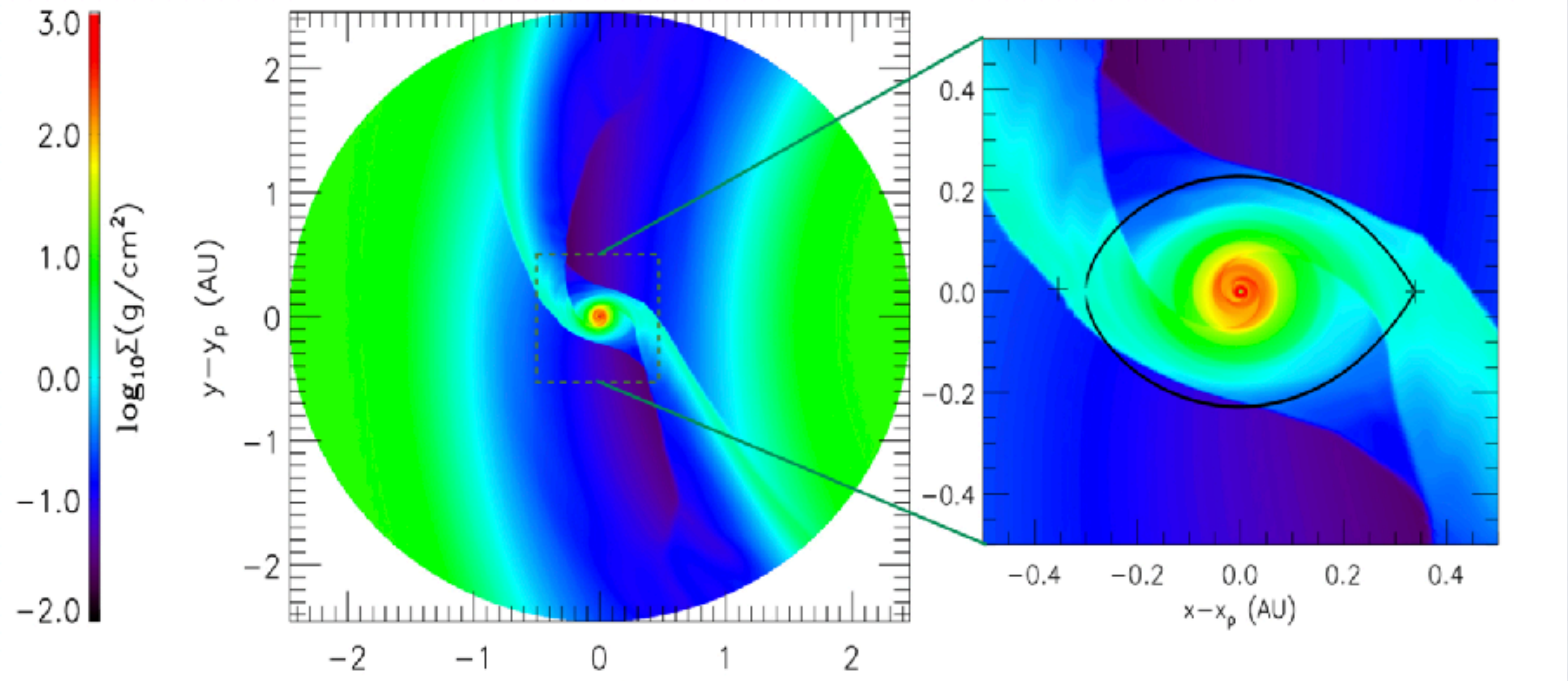
- Flow into gap around high mass planet
- Steady accretion for circular orbit planets: circumplanetary disks (Lubow et al. 1999; Chen et al. 2021)
- Form satellites in circumplanetary disks (Canup & Ward 2002, Mosqueira & Estrada 2003)
- Eccentric orbit planets undergo pulsed accretion onto circumplanetary disks (D'Angelo et al. 2006, Tanaka et al. 2021)
- PDS 70 More should be found (Zhu 2015, Zurlo et al. 2020)



Lubow et al. 1999



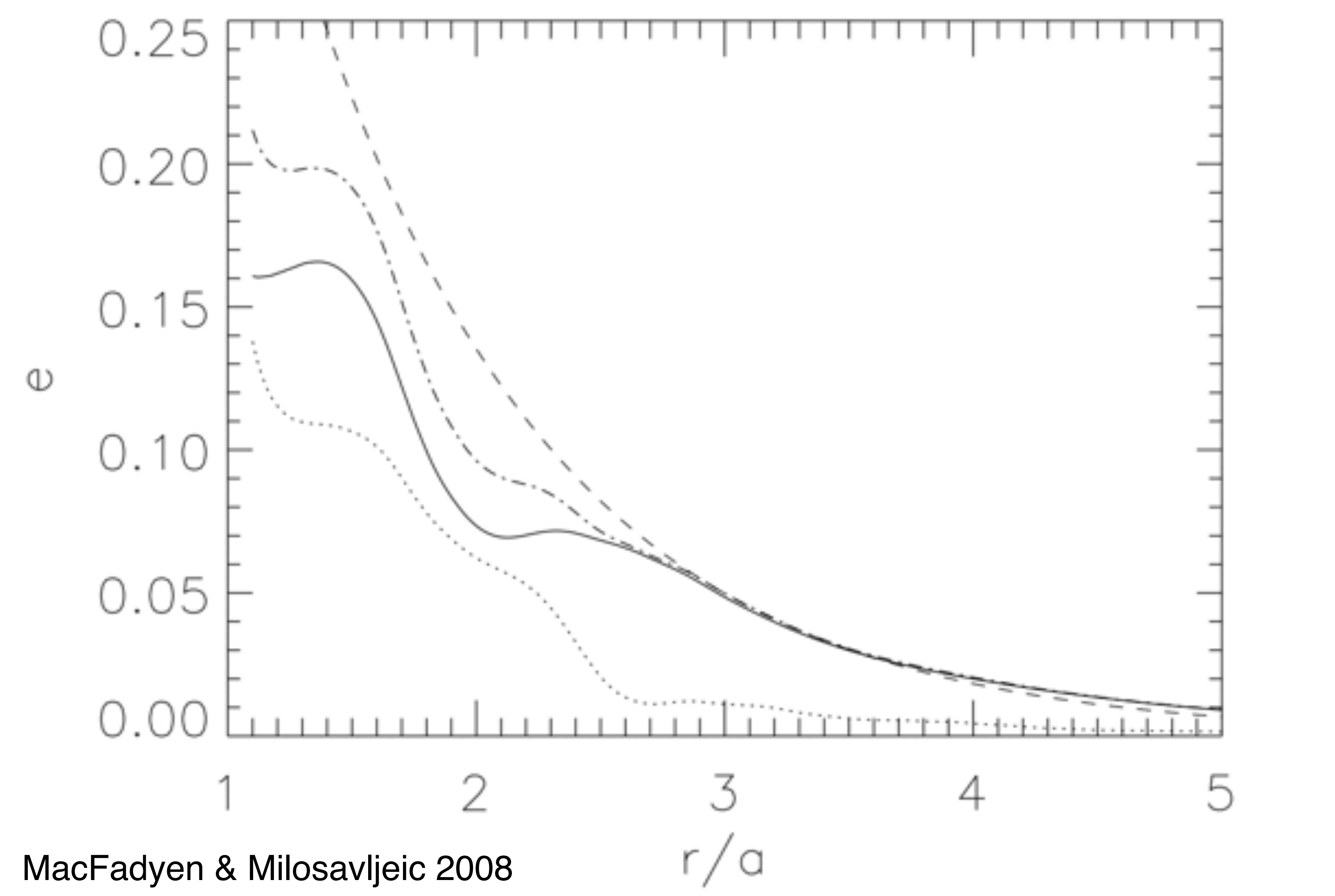
ALMA 2021



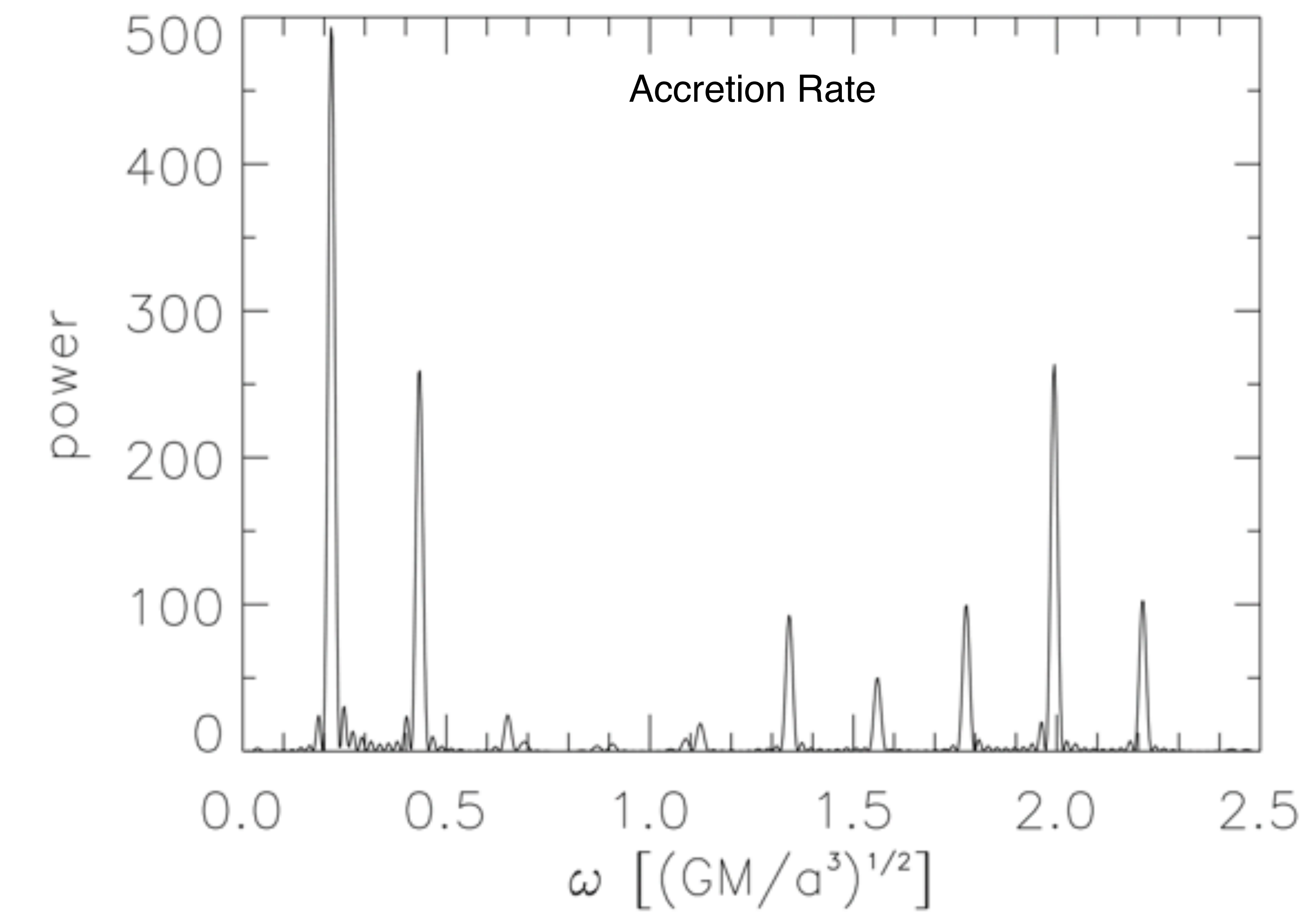
Zhu et al. 2016

CIRCULAR ORBIT BINARIES

- Circular orbit equal mass binaries do interesting things too! (MacFadyen & Milosavljevic´ 2008)
- CBD eccentricity driven by stream impacts with inner edge
- Accretion modulation on longer than binary orbital period timescales. Later found due to a lump at inner CBD (Shi et al. 2012, D'Orazio 2013, Farris et al. 2014).



MacFadyen & Milosavljeic 2008

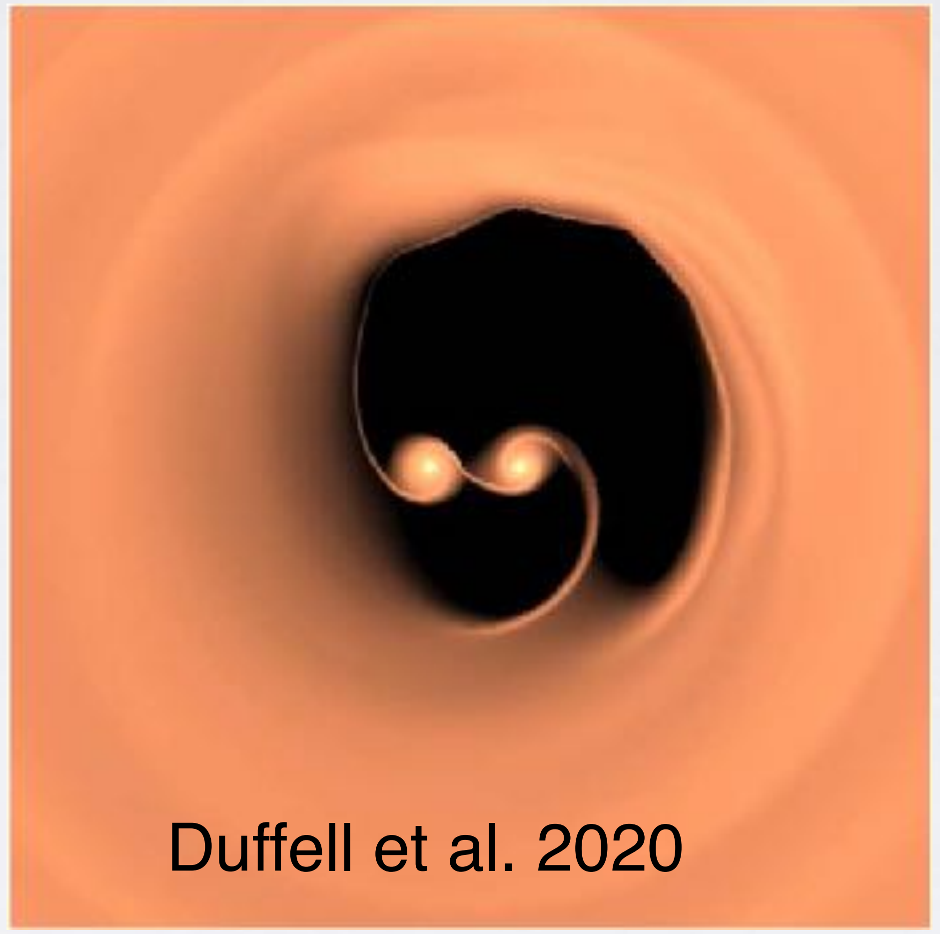


MUCH PROGRESS

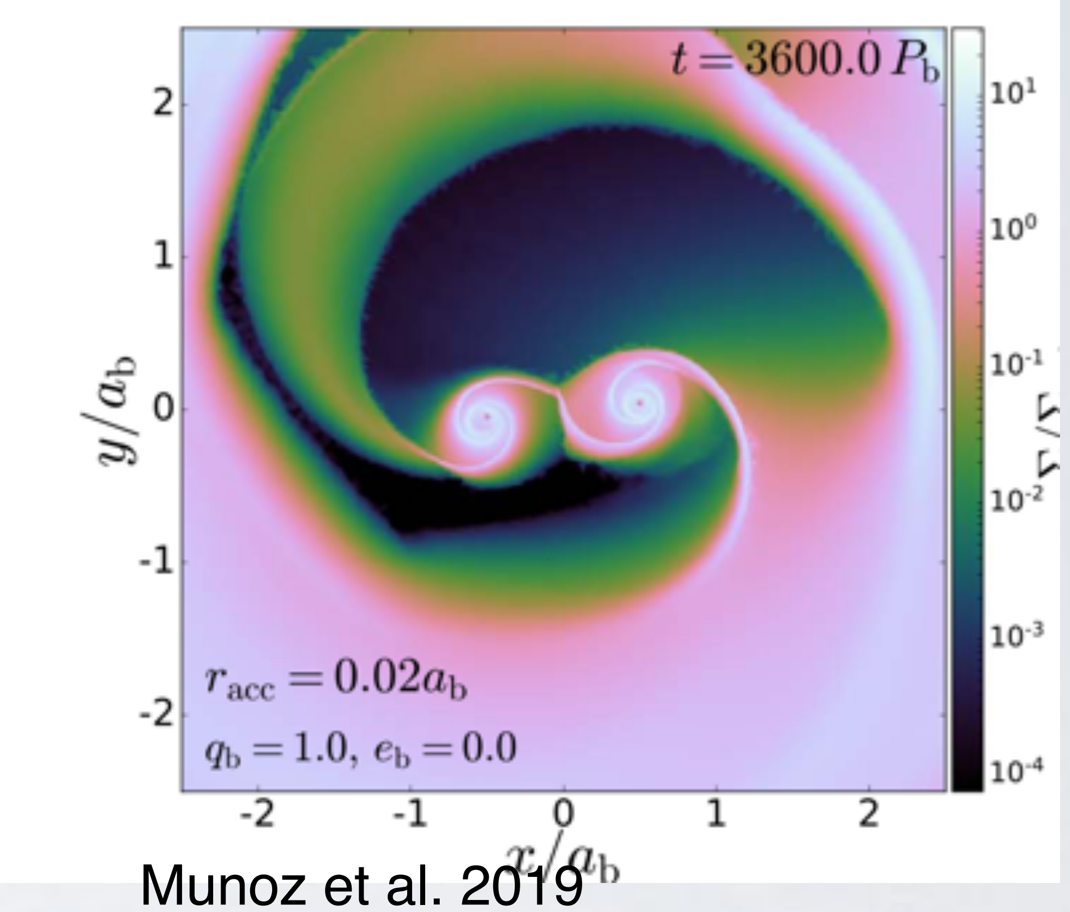
- Better codes and theory

- More complete analysis
  - binary and disk parameters
  - disk inclination (including retrograde)
  - run longer
  - alpha and MRI
  - thermal effects (radial entropy gradient)

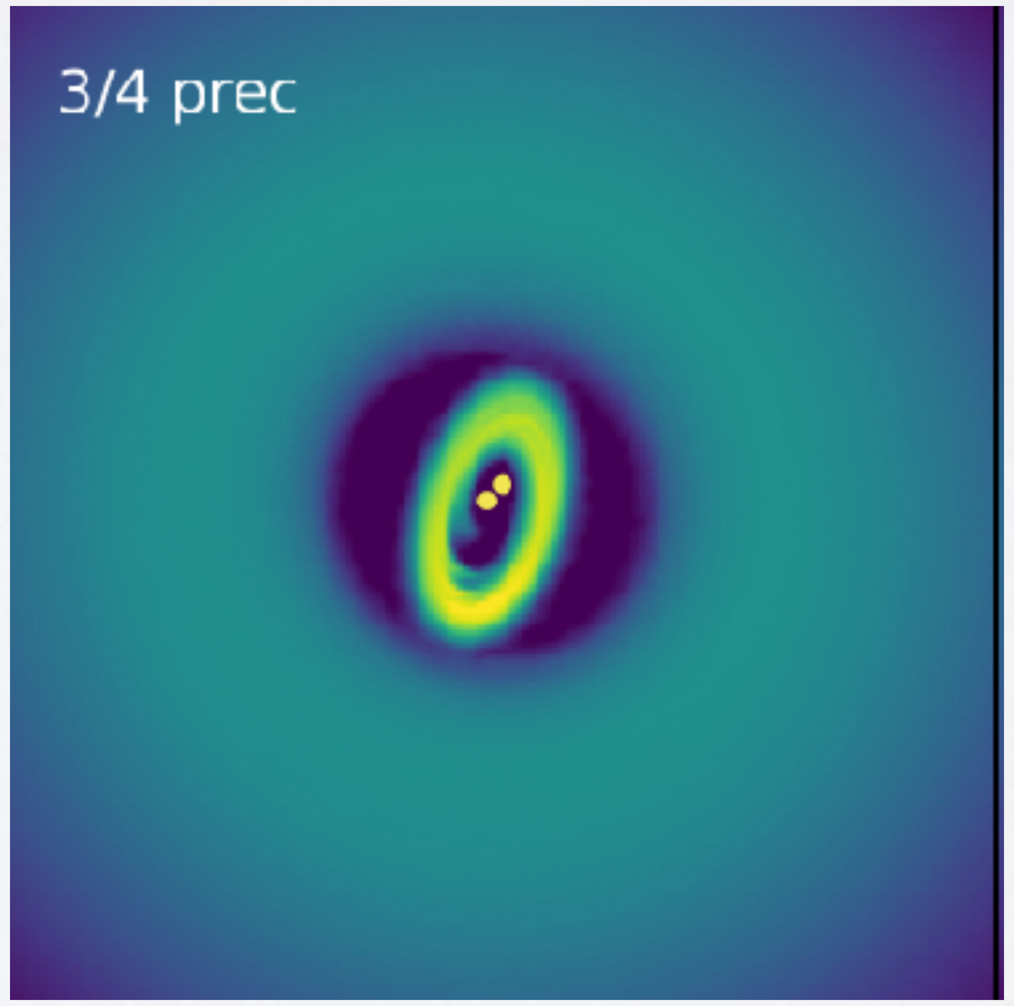
- Increased knowledge:
  - effects of binary orbit and mass ratio
  - disk density (lump) and eccentricity
  - accretion signatures, variability



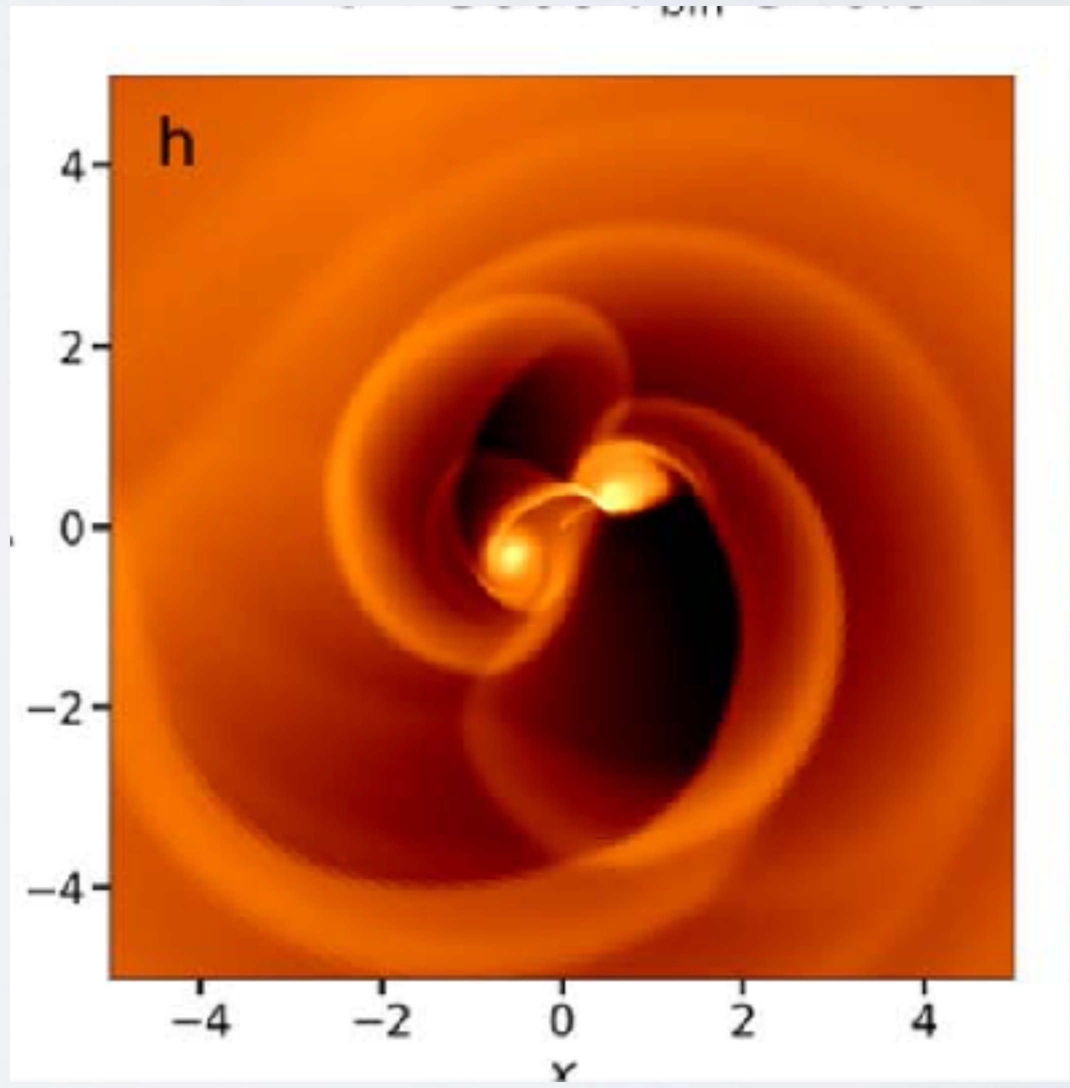
Duffell et al. 2020



Munoz et al. 2019



Nealon et al. 2020



Moesta al al. 2019

SMBH AND YOUNG STAR CBD

- Focus - black holes, GW counterparts; star and planet formation, about 12 CBP found

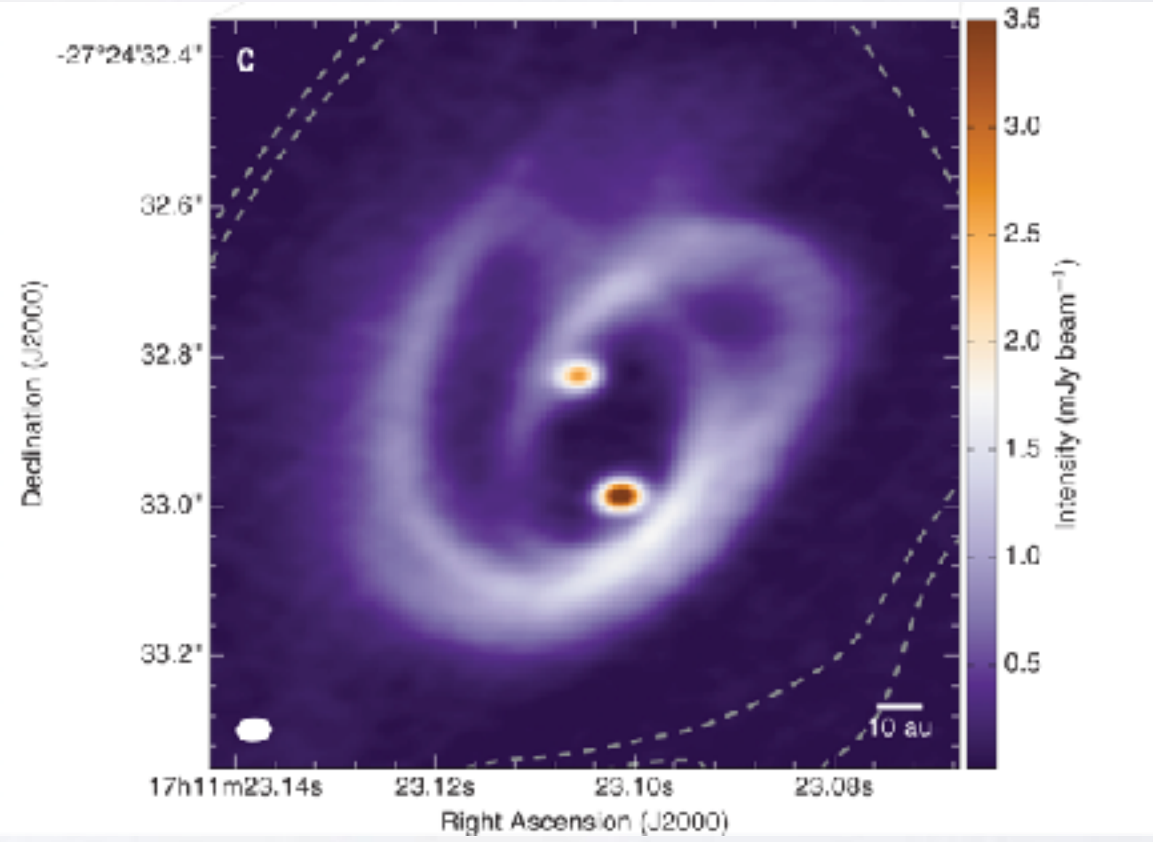
- Observability - indirect, one candidate; SED evidence of gap opening; resolved imaging and spectra several systems; systems showing pulsed accretion signatures

- Binary eccentricity - ?. damping via GW; low for $P < 10$ d

- Alpha - > 0.01 (ionized MRI); small (MRI?); winds

- H/R - very small 0.001 to 0.01; higher 0.05 to 0.1

Star Wars 1977

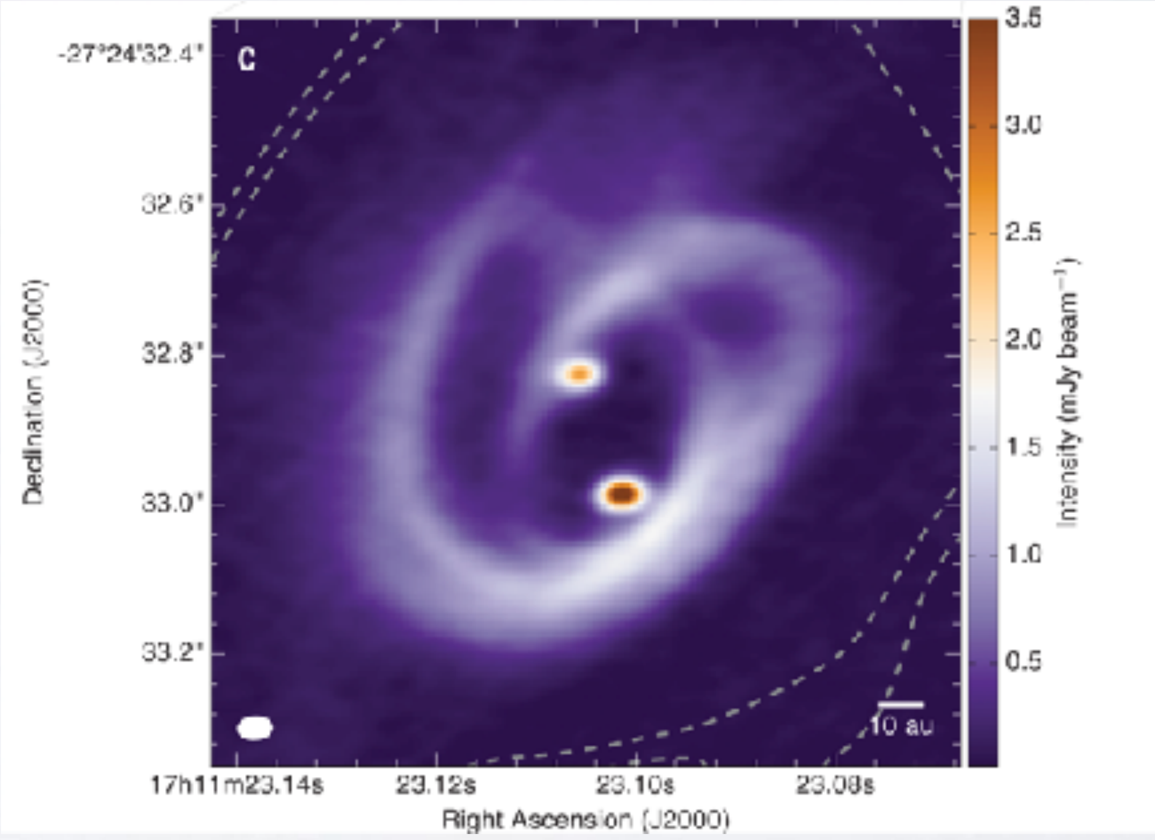


Alves et al. 2019

BBH AND YOUNG STAR CBD

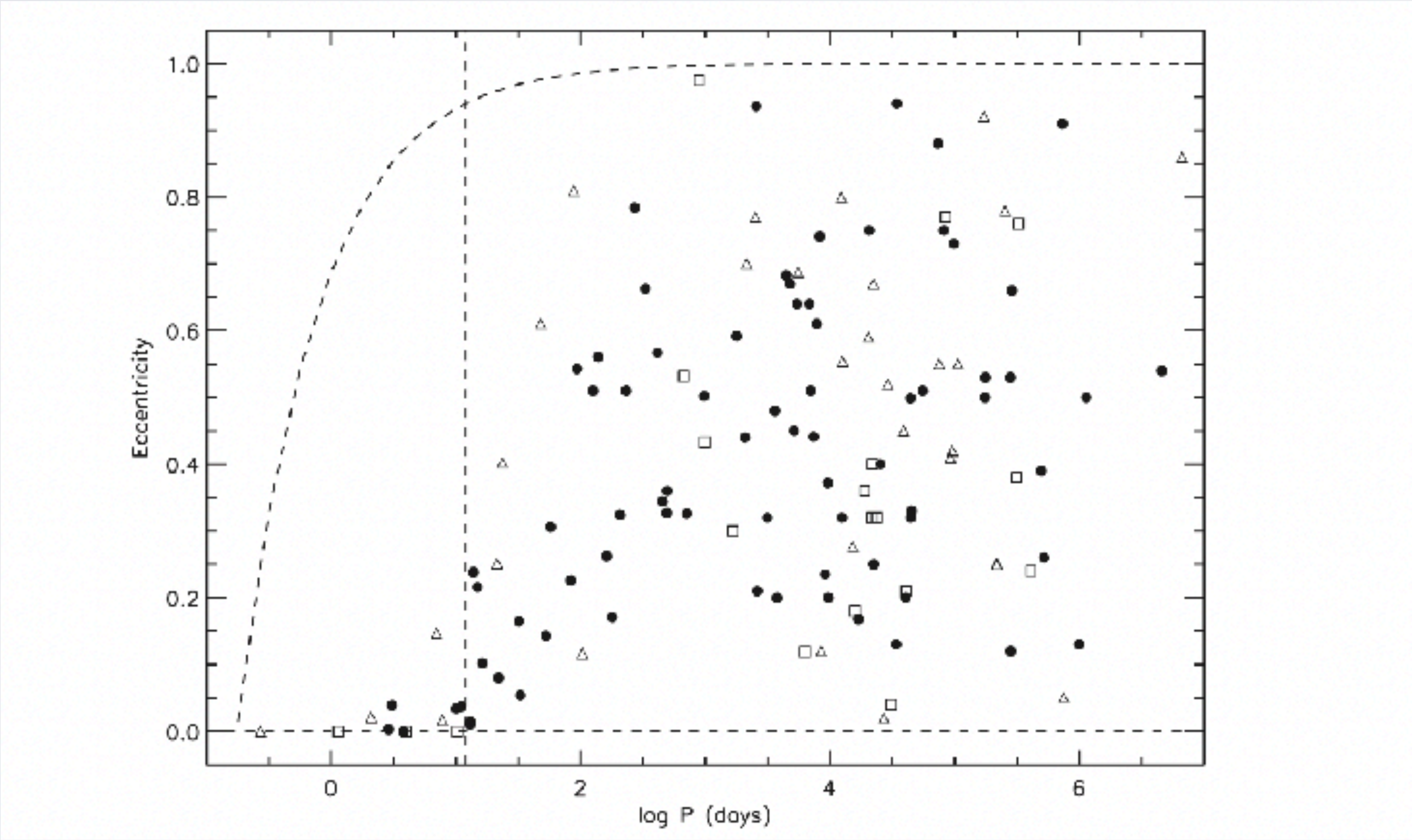
- B-Disk Alignment - wide range, could be counter aligned; aligned for P < 30 d
- Mass Ratio - wide range, order unity and extreme (planets)
- Triple+ systems - maybe ; frequent (CBP)

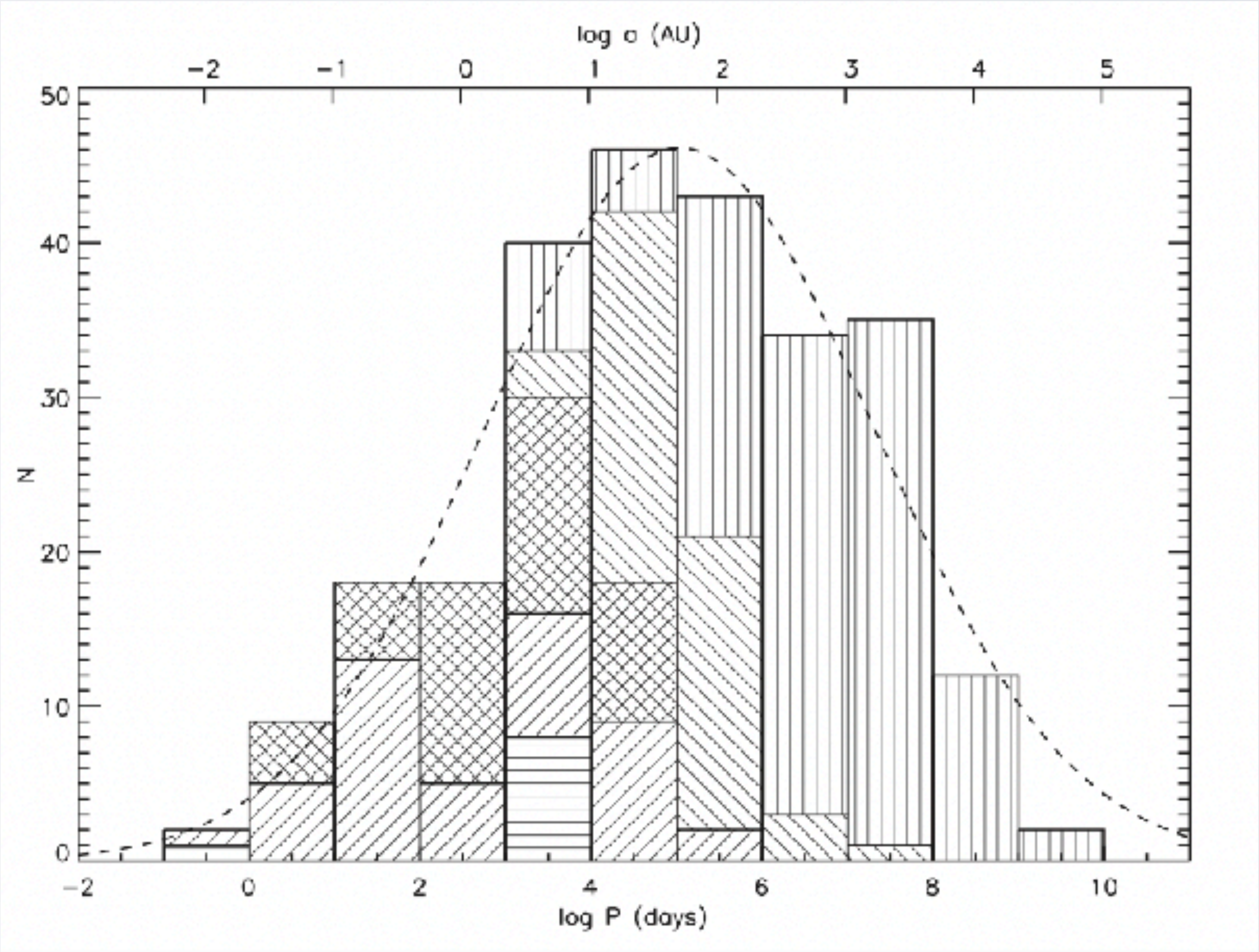
Star Wars



Alves et al. 2019

PROPERTIES OF LOCAL BINARIES

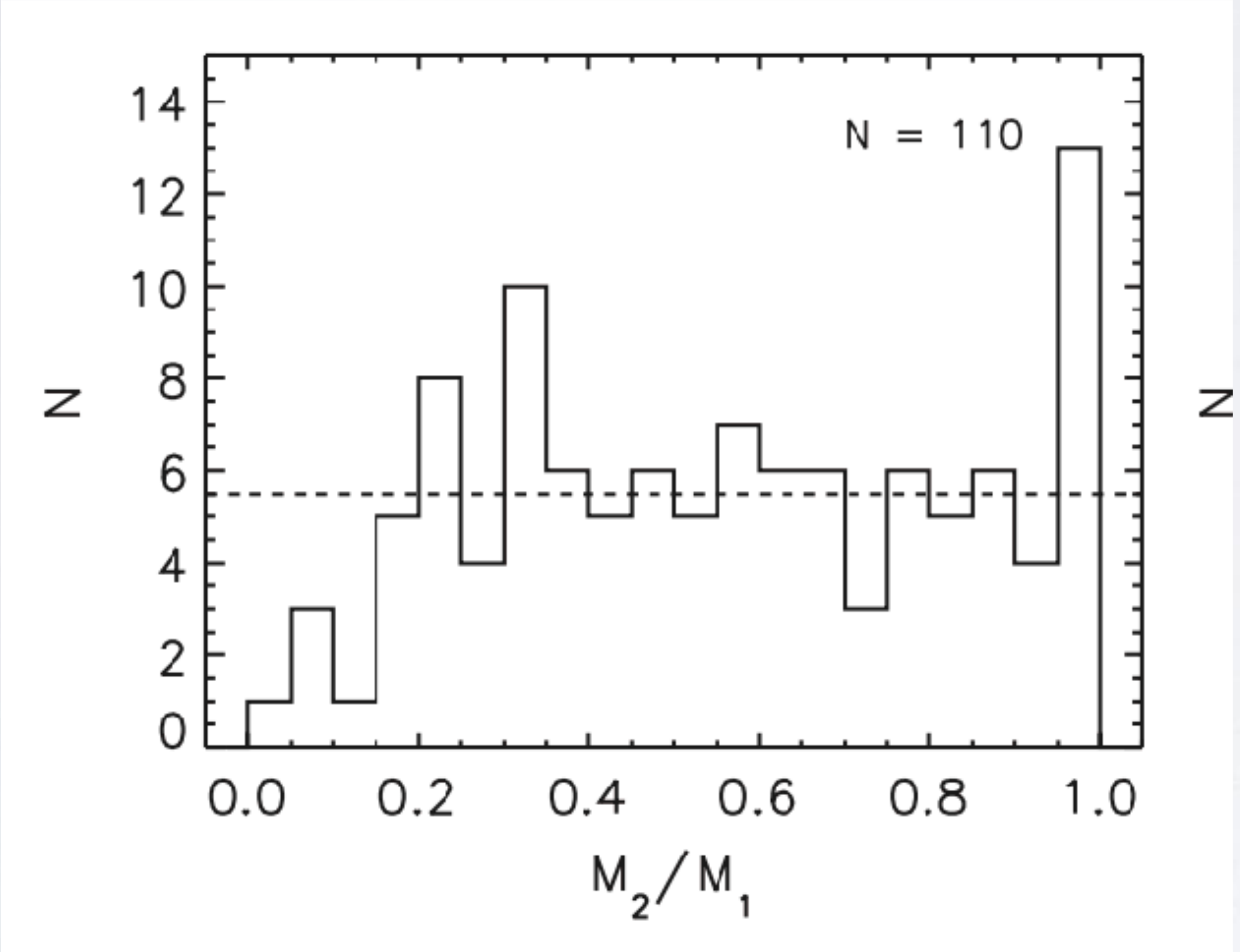




Raghavan et al. 2010

- Solar type stars within 25 pc

PROPERTIES OF LOCAL BINARIES



Raghavan et al. 2010

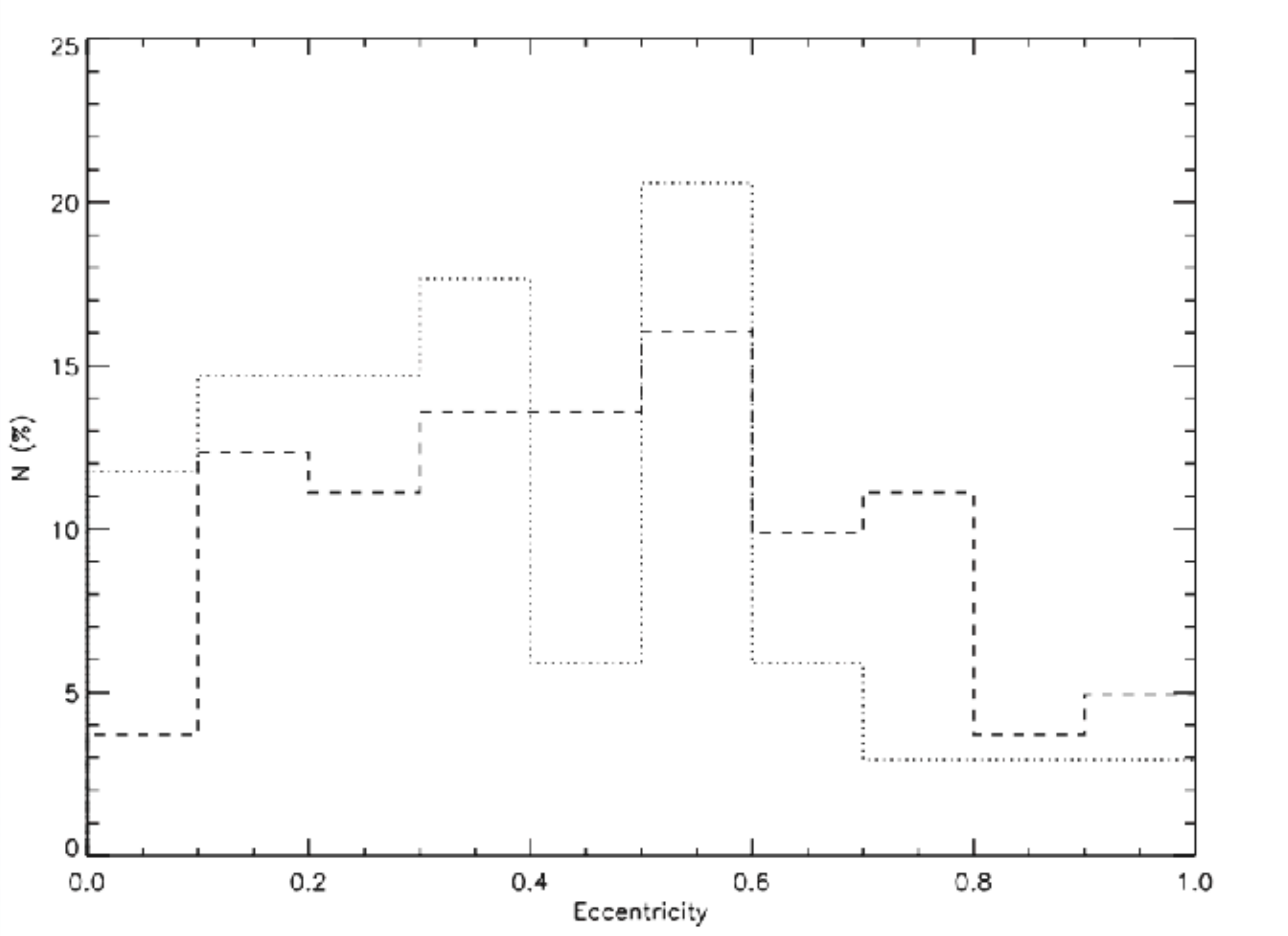
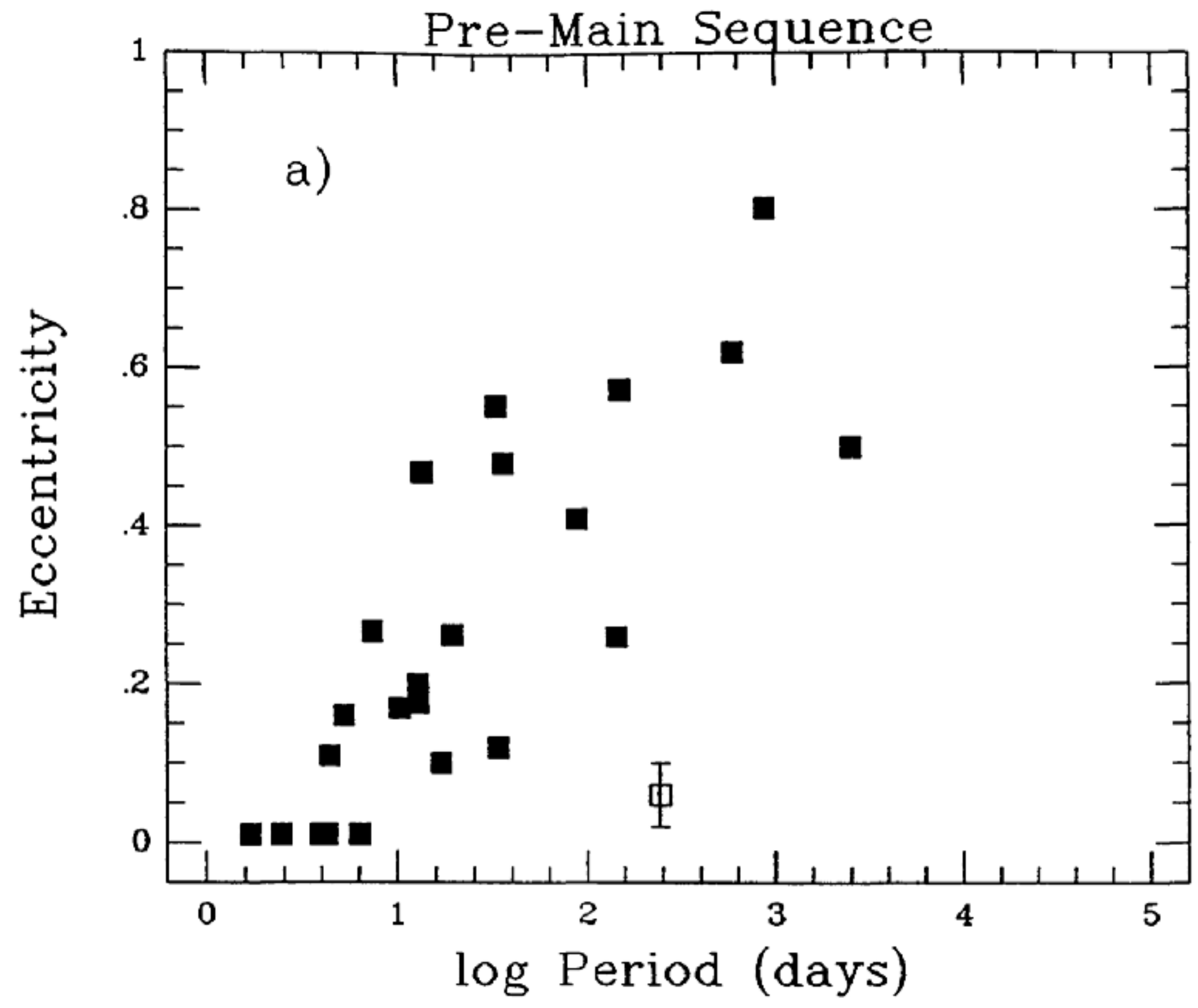


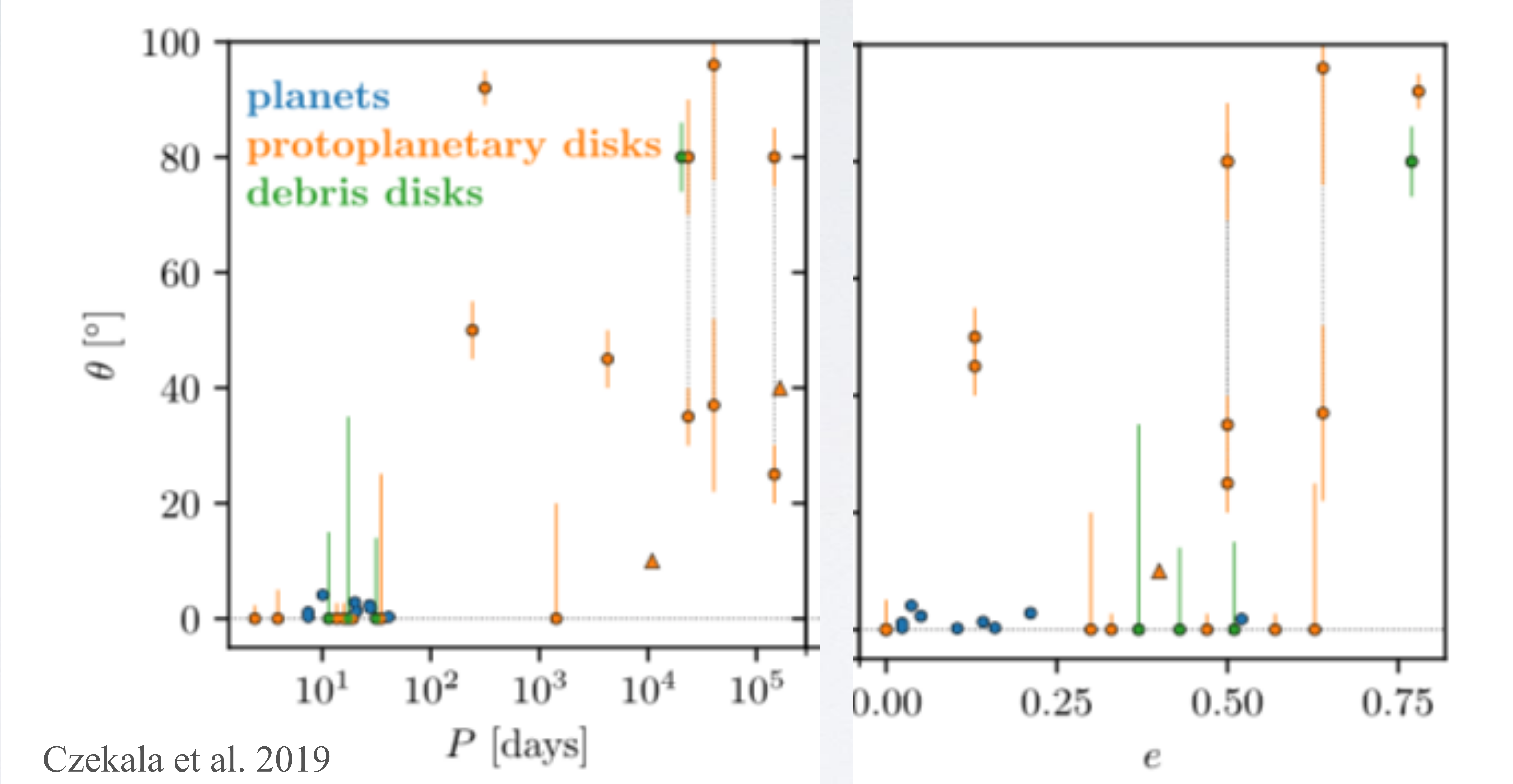
Figure 15. Eccentricity distribution for the 117 systems with periods longer than the 12 day circularization limit with estimated eccentricities from visual or spectroscopic solutions. The dotted line represents the 35 systems with periods below 1000 days, and the dashed line represents the 82 systems with periods longer than 1000 days.

PROPERTIES OF YOUNG BINARIES



Mathieu 1994

BINARY/PLANET/CB DISK ALIGNMENT OBSERVATIONS



Czekala et al. 2019

- CB disk alignments for P < 30d ; Correlated with binary eccentricity

SOME OPEN QUESTIONS

- Under what conditions do coplanar binary orbits expand/contract (final parsec problem) (Munoz, Miranda, and Lai)
  - H/R and alpha
  - simulations and dynamical models

- What controls disk eccentricity growth for eccentric orbit binaries?

- Does decretion play any role?

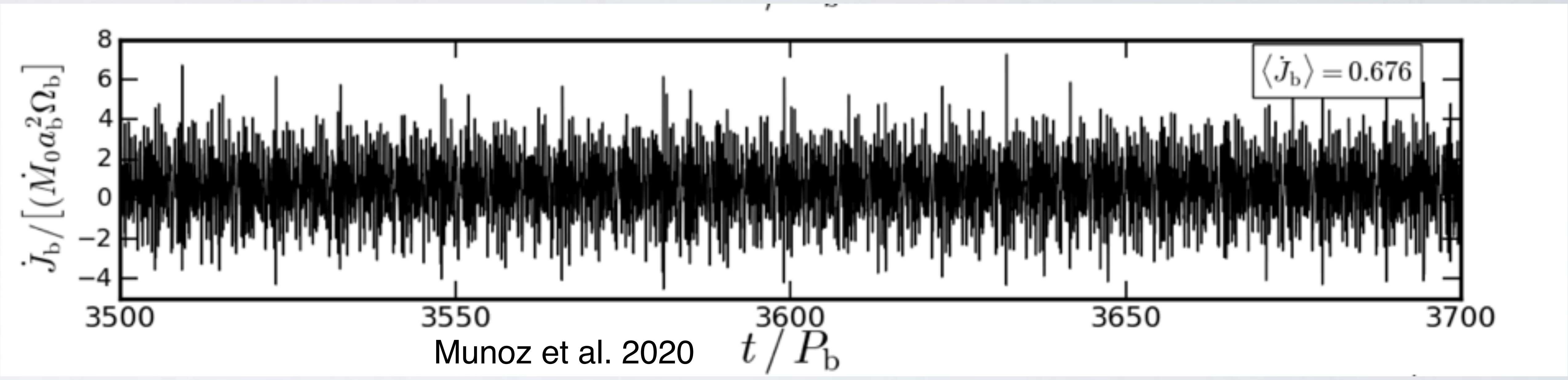
- Accretion variability/mini-disk buffering

- Gap size: Role of disk eccentricity

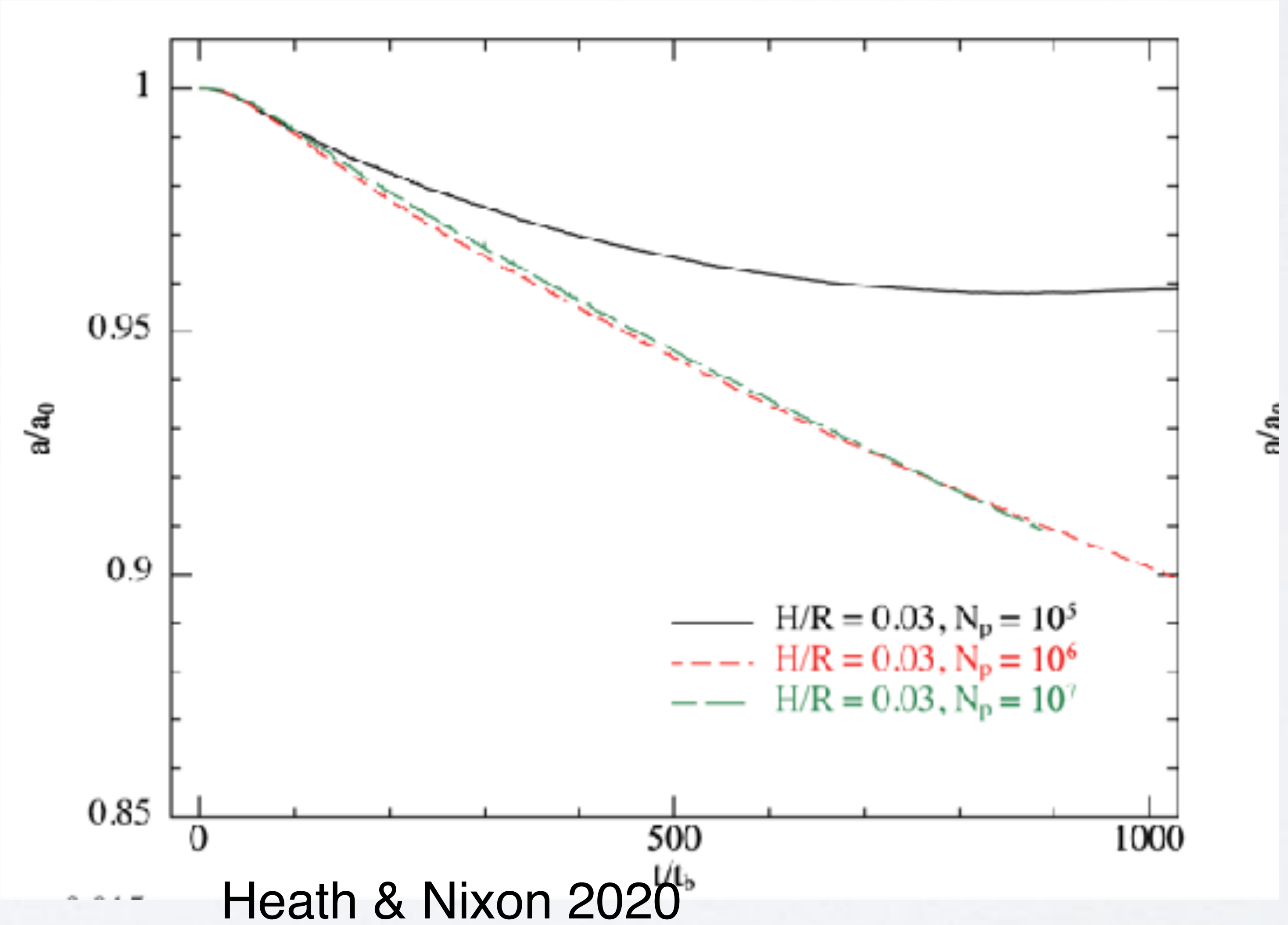
- 3D inclined disks

BINARY ORBIT EVOLUTION

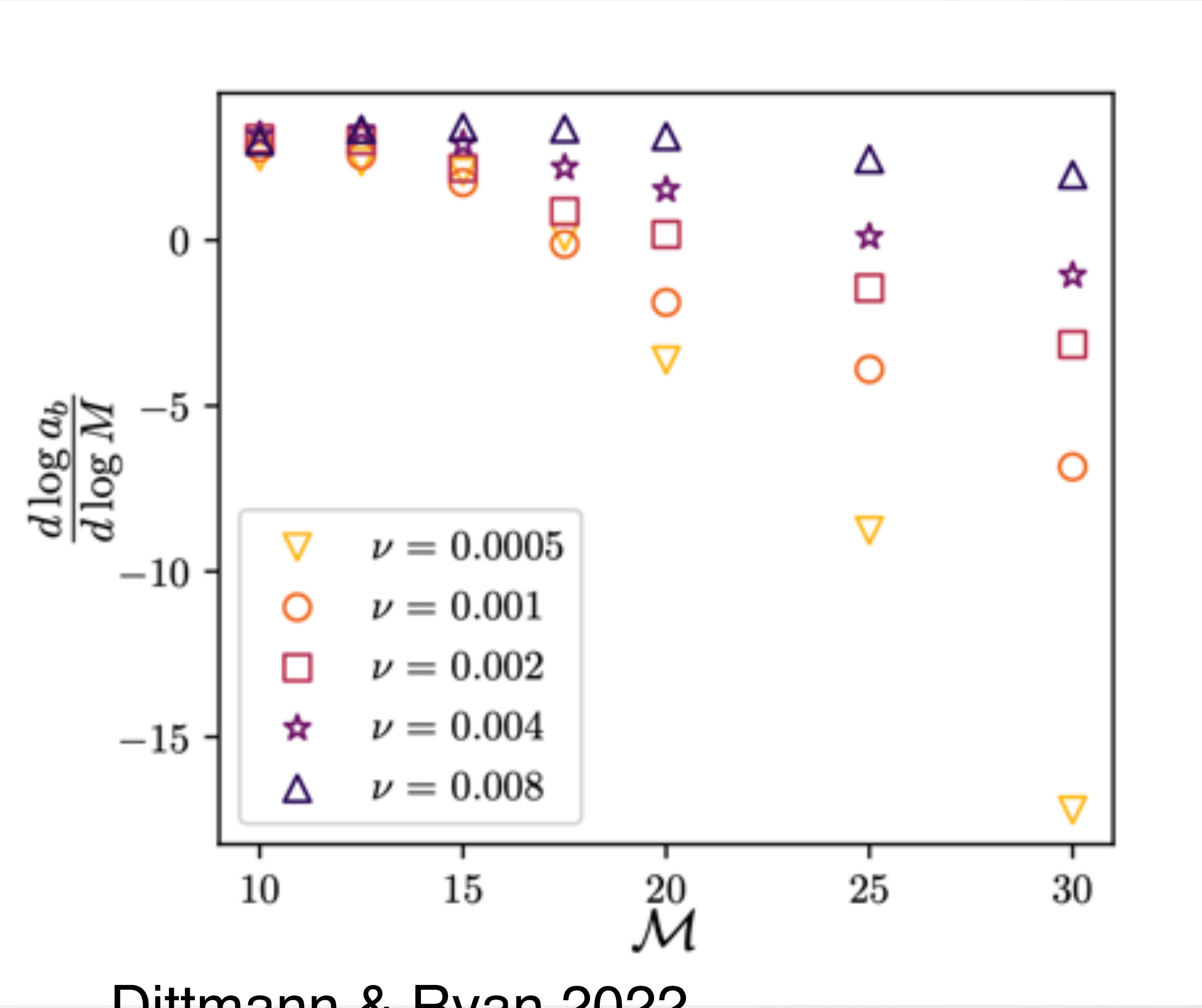
- Orbit expansion for larger H/R ?
- Orbit contraction for small H/R and alpha?
- Does $\dot{M}/\dot{M}_a$ decrease with decreasing H/R? (Ragusa et al. 2016)
- accretion to decretion parameter f. Do disk torques dominate at small H/R (Heath & Nixon 2020)? Is f(H/R)?



Munoz et al. 2020



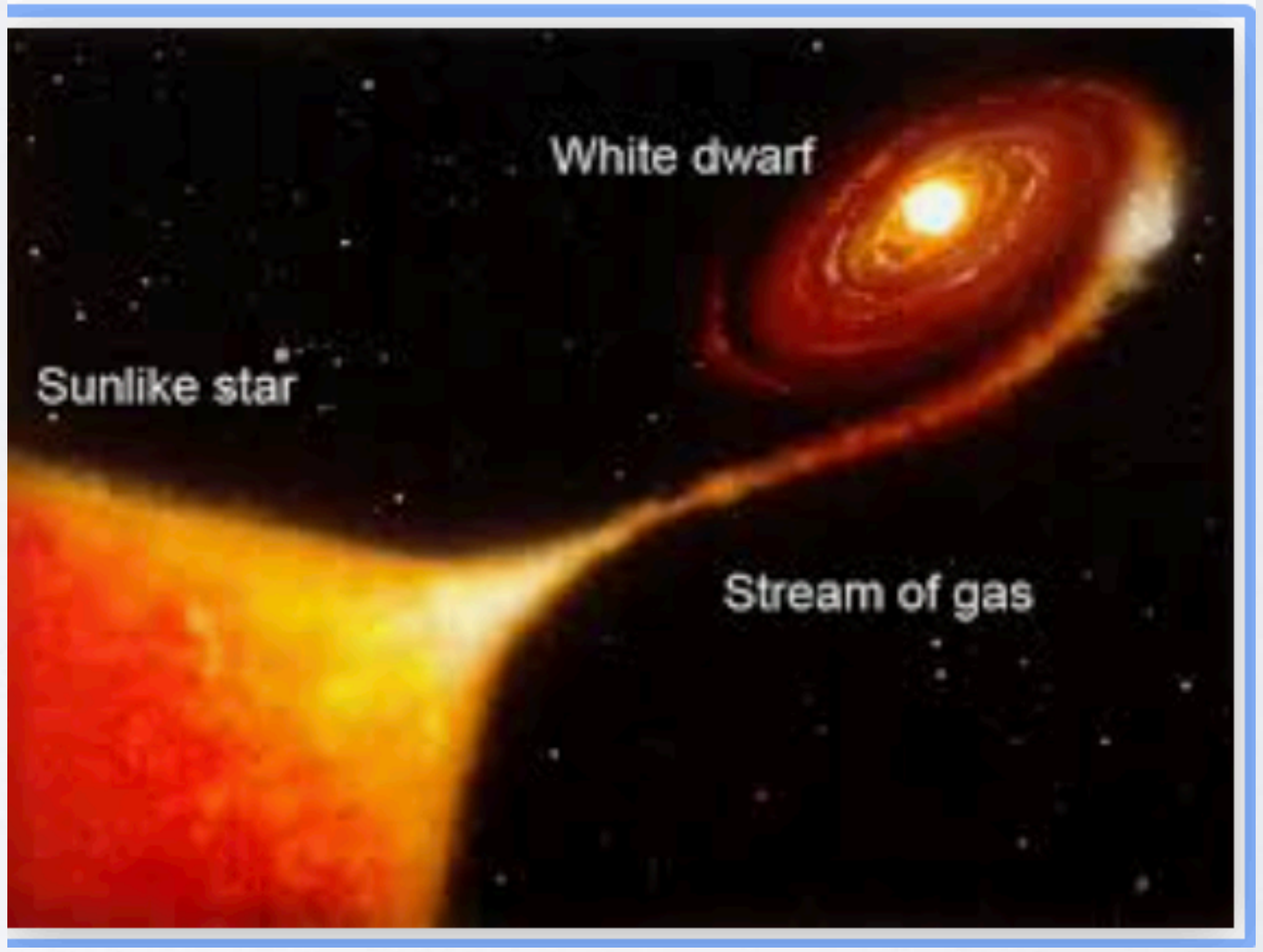
Heath & Nixon 2020



Dittmann & Ryan 2022

GAS STREAMS

- Best understood example of gas streams: mass exchange binaries
- CBD streams flow through Lagrange (corotation?) point analogs?



universetoday.com

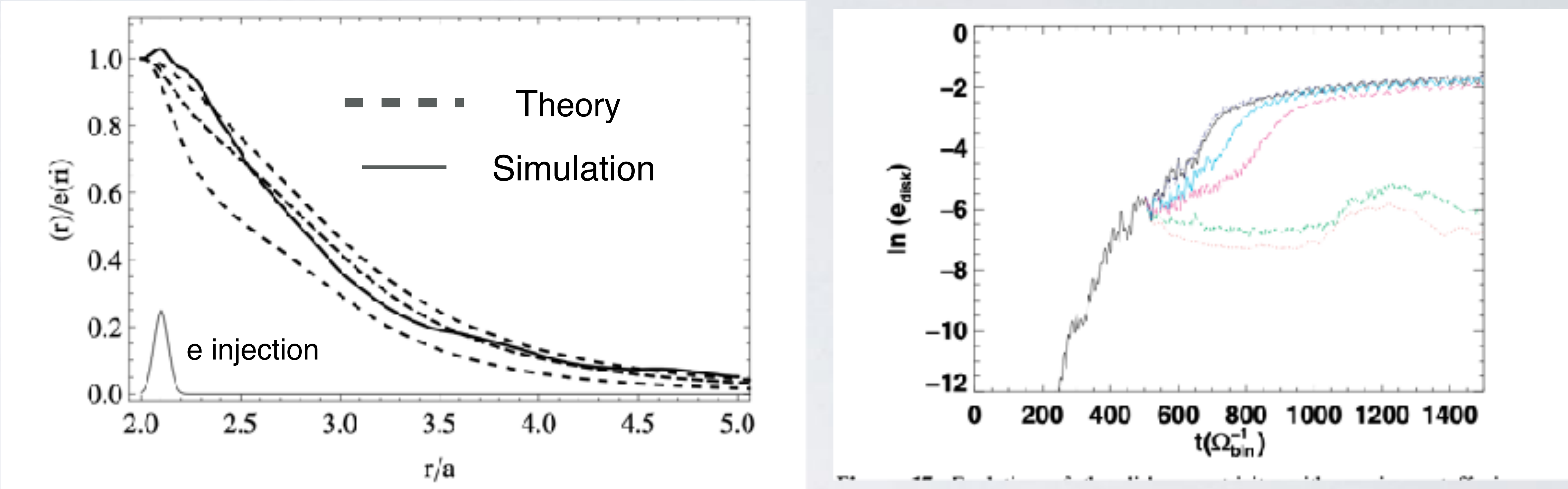
BINARY ORBIT EVOLUTION

- Current simulations H/R > 0.02
- How to get to H/R~ 0.003?
- Need to understand flow transition from outward Lindblad torque zone to supersonic inflow. Tunneling through Lindblad resonance?
- Tracer particle dynamics/flow regimes (e.g., Tiede et al. 2021)
- Key question: How does this transition flow depend on H/R and alpha?

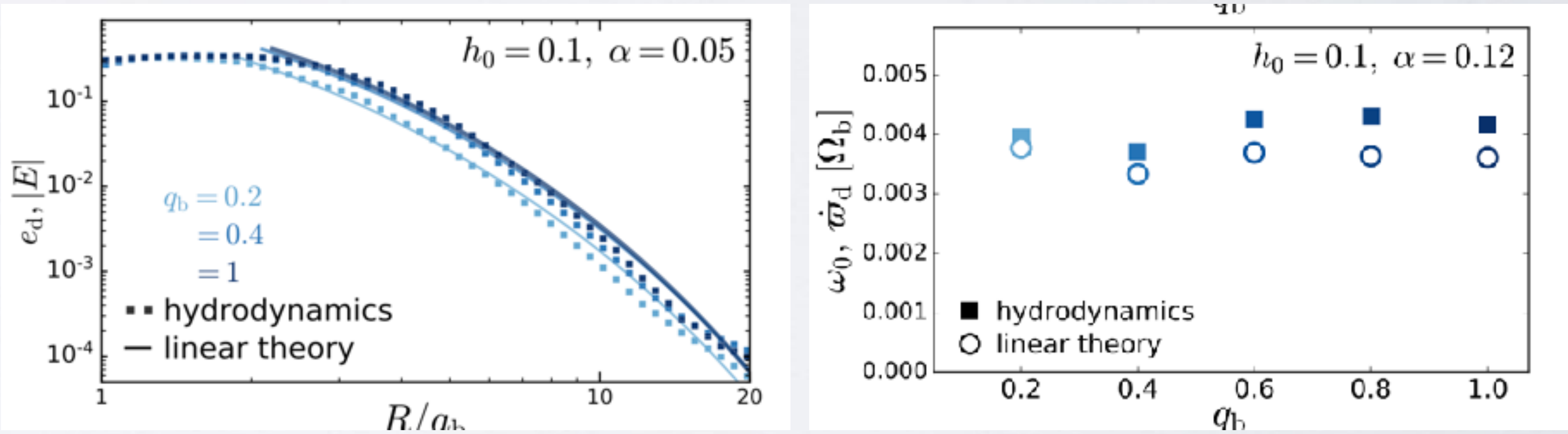
DISK ECCENTRICITY

- low eccentricity binaries: stream impact model well understood; agrees with linear model of Goodchild & Ogilvie (2006) + (Shi et al. 2012; Munoz & Lithwick 2020) and secular theory for effects of stream impact

- higher eccentricity binaries more complicated



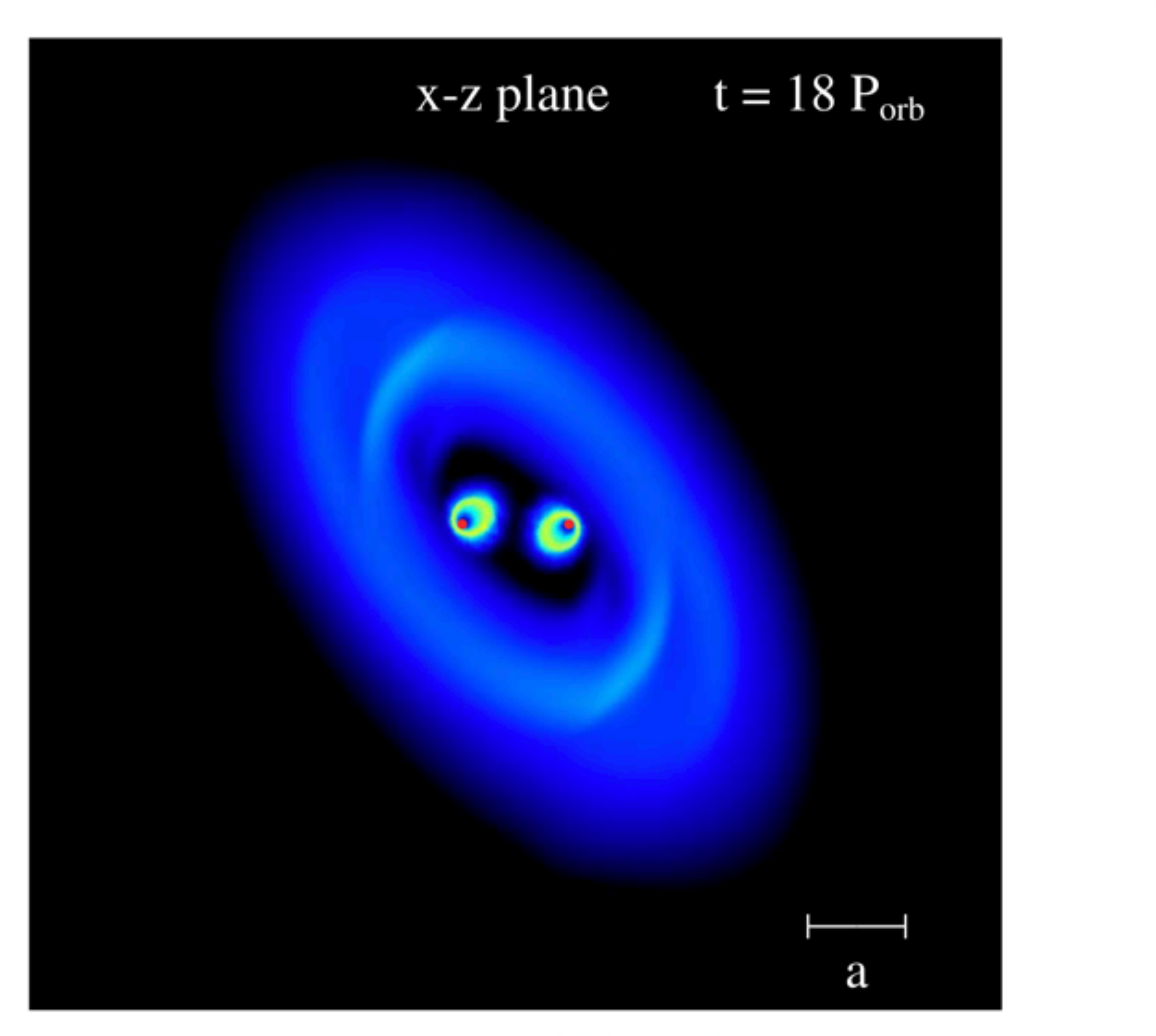
Shi et al. 2012



Munoz & Ltthwick 2020

CODES AND 3D

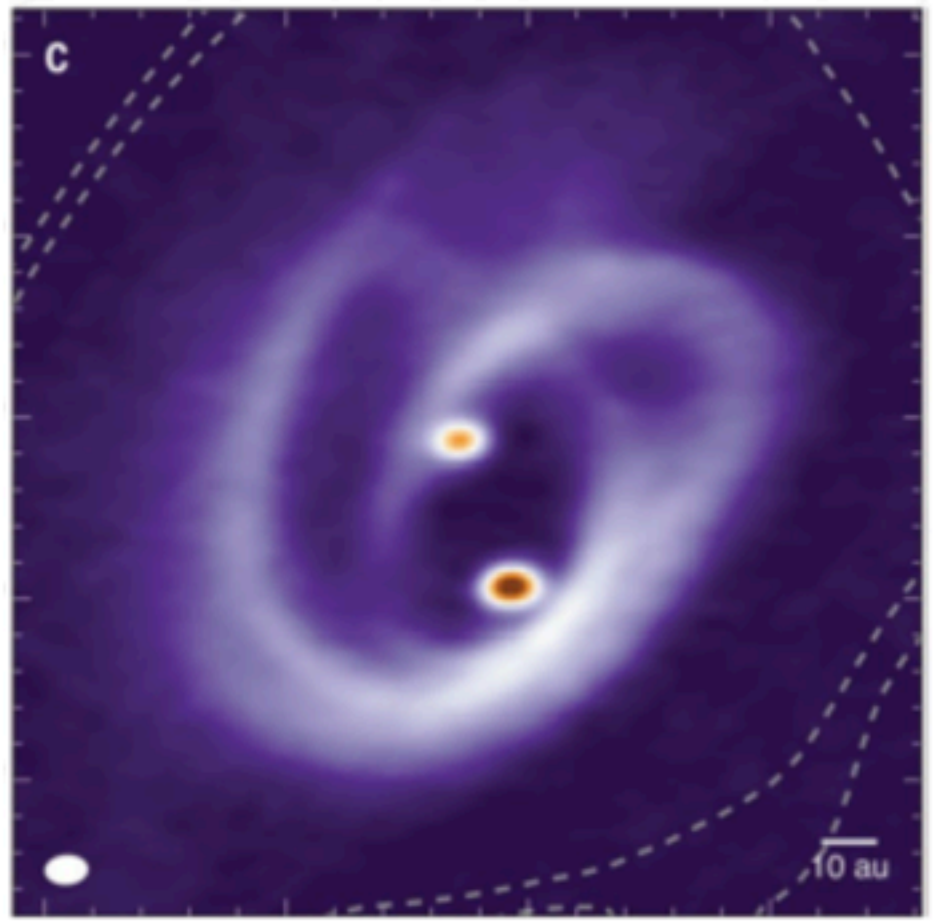
- 2D codes have provided high quality results
- Want fully 3D models: highly misaligned disks likely in SMBH case
- Most codes have not handled full 3D dynamics
- Not a problem for SPH that has sometimes led to finding new effects, but limited resolution and alpha ~ 0.01 or larger.
- Ongoing 3D work with Athena++ by Rabago and Zhu



Smallwood et al. 2021

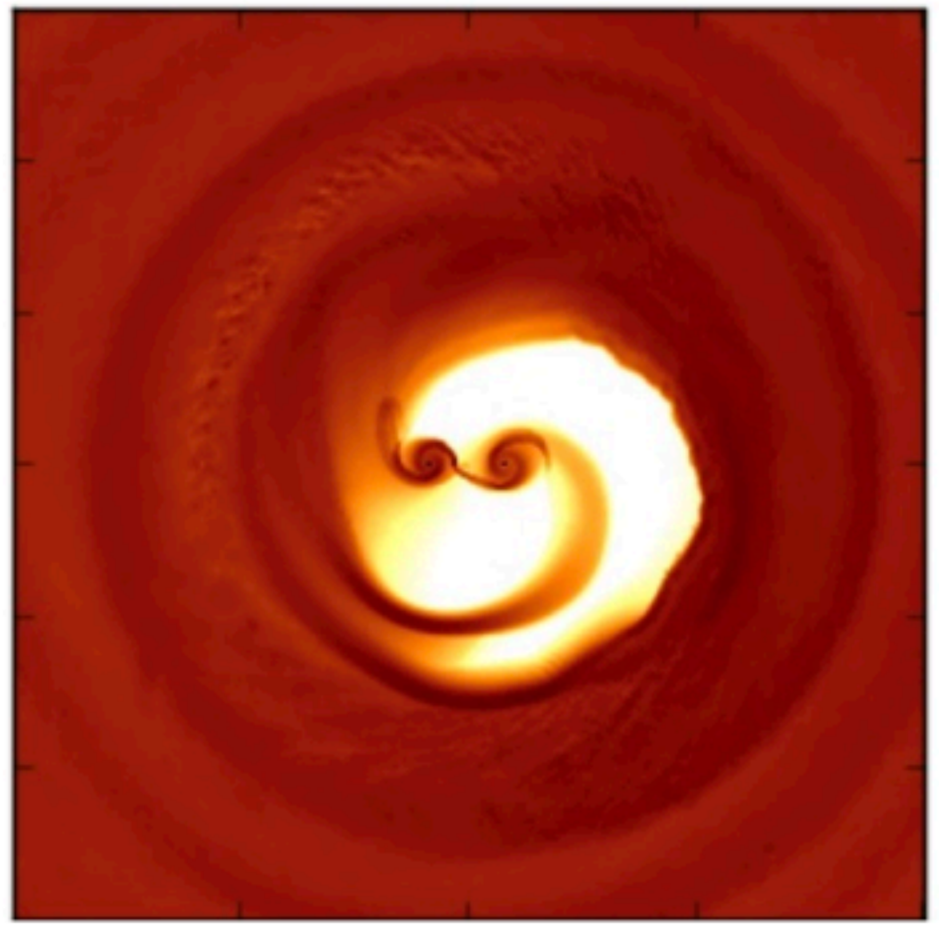
FINAL THOUGHTS

- Lots of ongoing work to understand circumbinary disks for a variety of disk and binary parameters.
- Many computational, analytical, and observational challenges.
- Need to better understand simulation results.
- SMBH and young star differences: H/R and α
- Observations in young star case provide model checks. Can help validate SMBH case.
- Surprising complexity! CBD are much more challenging than conventional accretion disks.



ALMA image of the young binary protostar BHB2007

Alves et al. 2019



Simulated image of a massive black hole binary with a disk

Farris et al. 2014