

# Creating Eccentric Nuclear Disks with Two Black Holes

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# Andromeda/M31

Tremaine (1995):

- M31's double nucleus could be explained by eccentric nuclear disk
- Unusual galactic center!

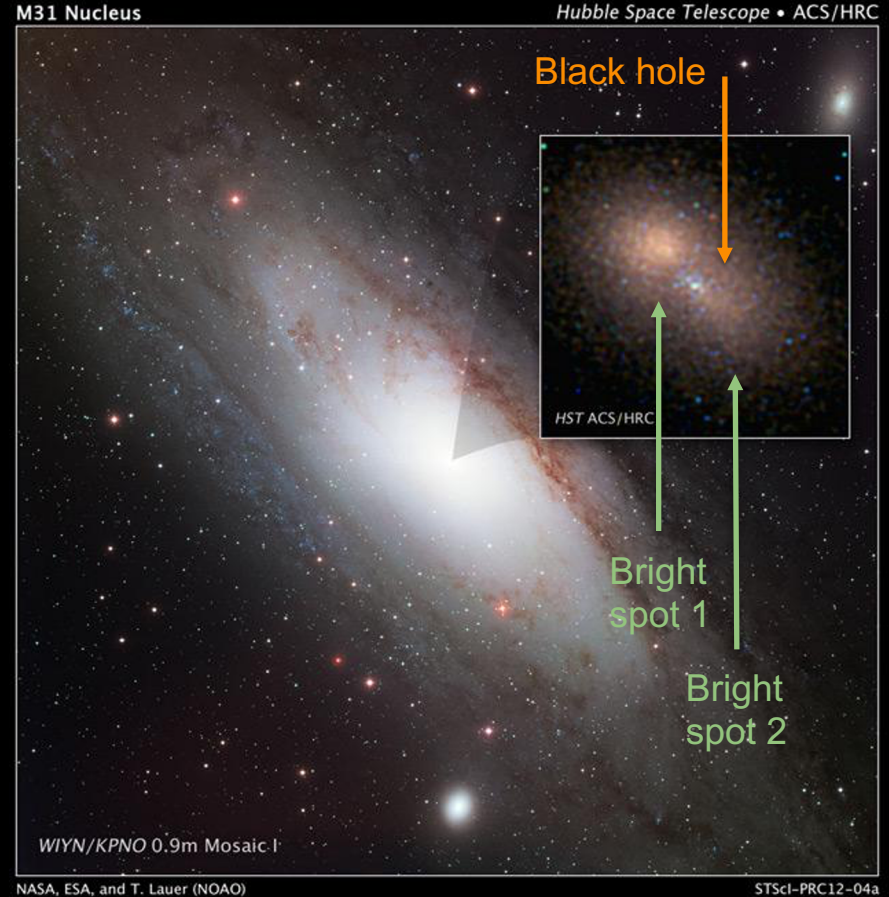
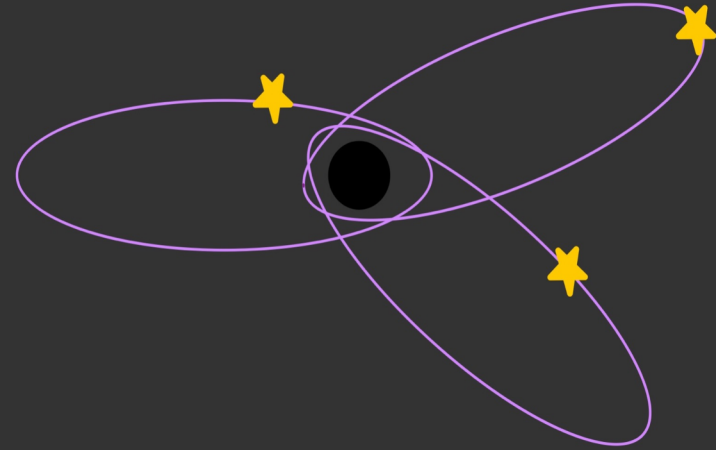


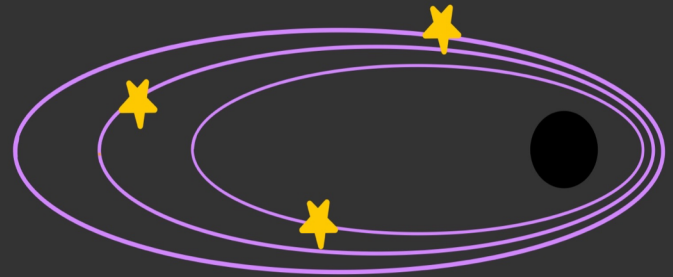
Figure 1 - Lauer et. al. (1993): Hubble image of M31's lopsided, "double", nucleus

# Galactic centers

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Usually = random, axisymmetric



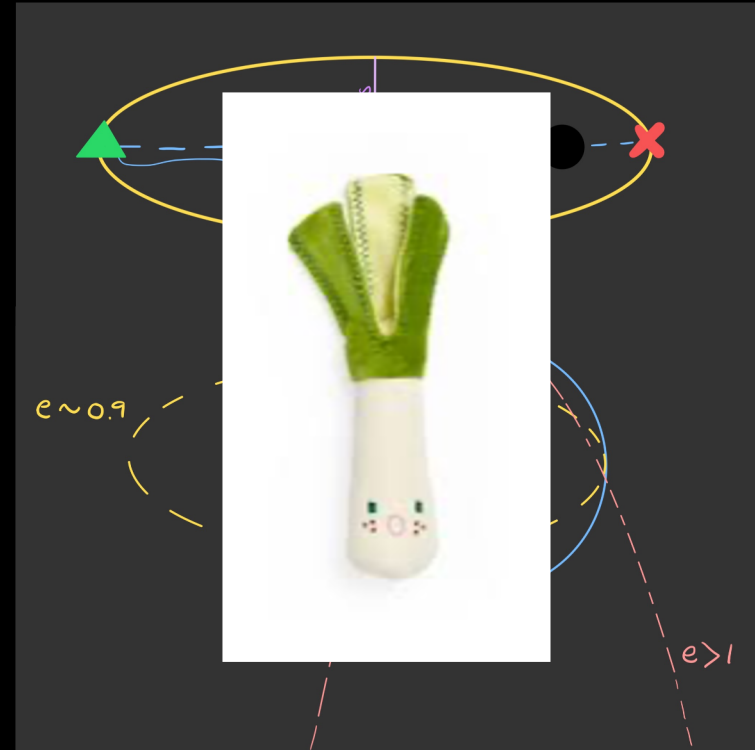
Unusual = eccentric nuclear disk

Figure 2

# Orbits

- Apoapsis ( $\Delta$ ) – spend most of their time near here
  - Periapsis (X) – spend least of their time here
  - Semi-Major axis (a)
  - Eccentricity (e)
- 
- Inclination (i)
  - Orientation of orbit in physical space
    - Longitude of ascending node ( $\Omega$ )
    - Argument of periapsis ( $\omega$ )
  - Longitude of periapsis,  $\varpi$ 
    - $\varpi = \Omega + \omega$
    - Direction of the eccentricity vector

Figure 2



# Vectors - explain with demo

- Position ('r')
- Velocity ('v')
- Angular Momentum ('J')

$$\vec{J} = |m \vec{r} \times \vec{v}|$$

- Eccentricity Vector
  - Apoapsis ( $\Delta$ )  $\rightarrow$  Periapsis(X)
  - Length = Eccentricity
  - Longitude of periapsis,  $\varpi$ 
    - Direction of eccentricity vector

$$\vec{e} = \frac{\vec{v} \times \vec{j}}{GM} - \hat{r}$$

**Angular momentum and eccentricity vectors conserved for Keplerian (unperturbed) orbits**

# Apsidal Precession

- In systems with  $+1$  orbiting objects around the central body (diagram shows a leek's precession)
- Due to inter-orbit gravitational forces (star-star, leek-leek, etc.)
- Precession rate depends on distance (semi-major axis,  $a$ ), from central object = differential precession
- Swinging (oscillations in the longitude of periapsis,  $\varpi$ ) of stellar eccentricity vectors around central object

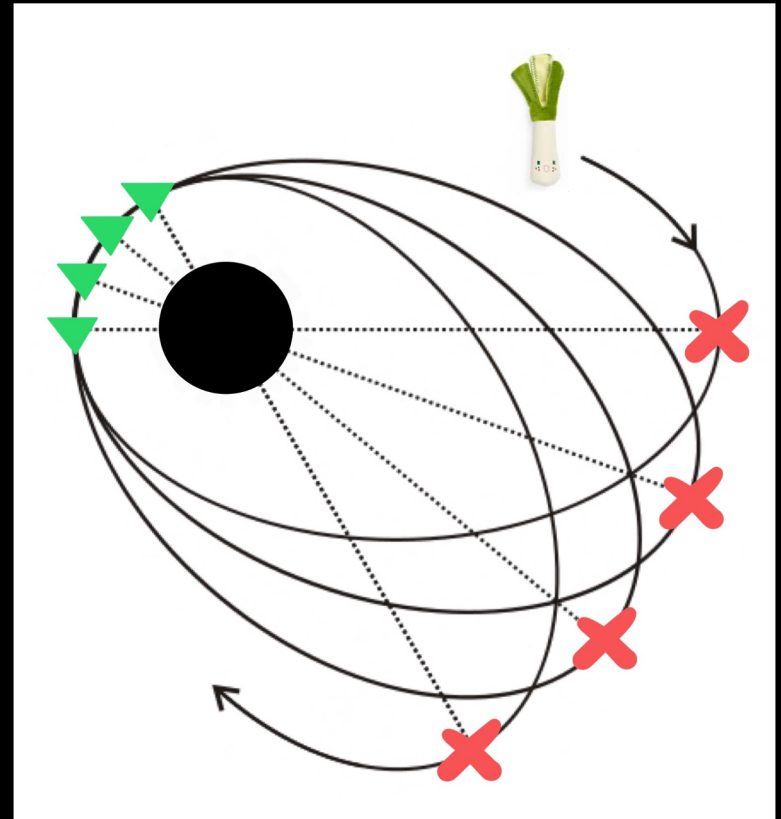
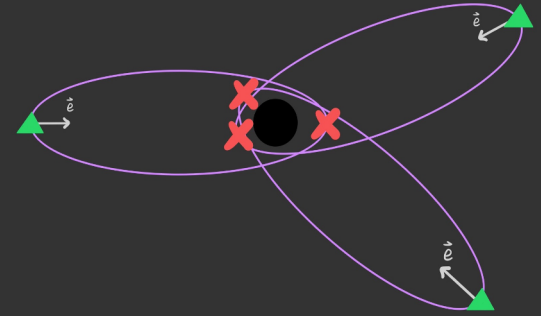
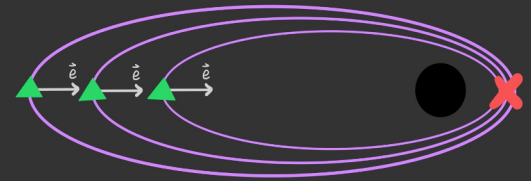


Figure 4

# Galactic centers



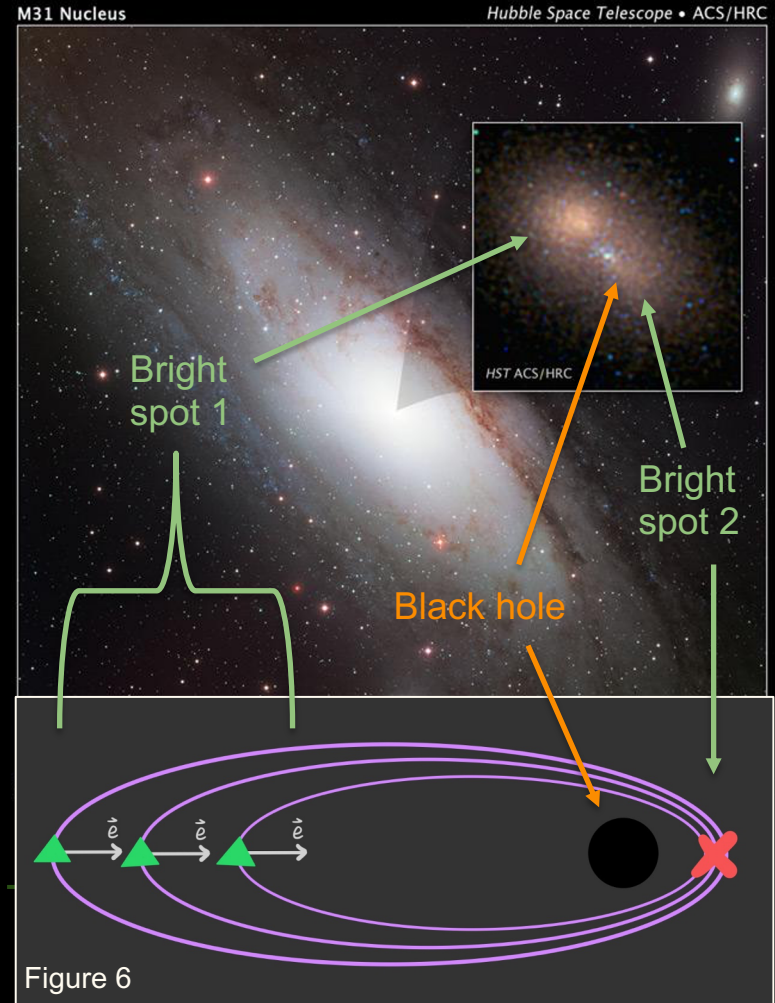
Usually = random, axisymmetric



Unusual = eccentric nuclear disk  
(apsidal alignment, alignment of the  
eccentricity vectors)

# Double nuclei explained

- Lauer et. al. (2005): ~20% of galactic nuclei show features suggestive of eccentric nuclear disks
- Madigan et. al. (2018): eccentric nuclear disks = stable through star-star gravitational torques
- Gruzinov et. al. (2010): eccentric nuclear disks = thermodynamic equilibrium configuration for galactic nuclei
- How do eccentric nuclear disks form?!



# Retrograde Galaxy Mergers

Thomasson et. al. (1989):

- Resonance and gravitational torques during encounter creates asymmetries in galaxy

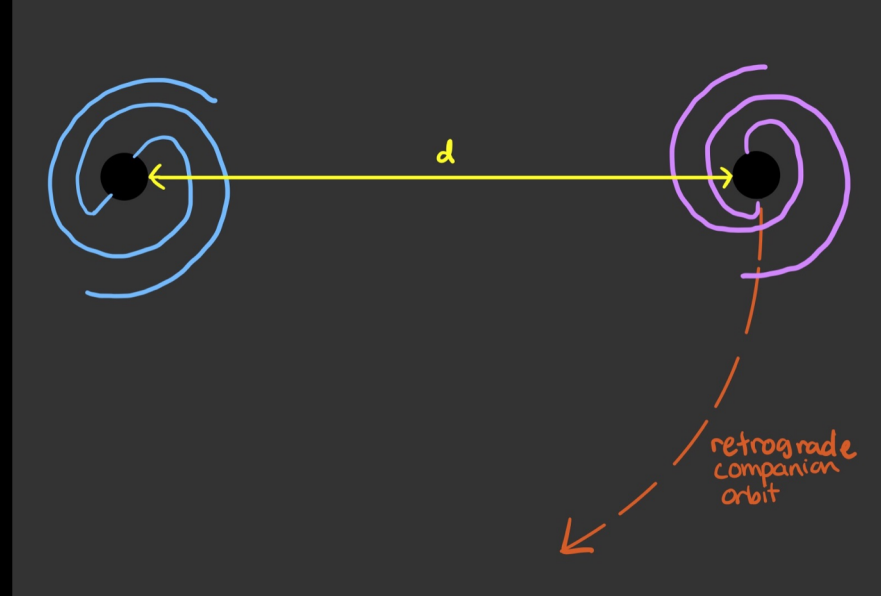


Figure 7

# Our setup

- Two black holes (BH1 and BH2), BH1 has a circular, flat stellar disk orbiting it
- Stars orbit BH1 counter-clockwise (prograde)
- Disk precession and BH2 orbits clockwise (retrograde around BH1)

## Want:

- a. Surface density profile, so... uniform disk precession period
- b. Resonance between disk precession period and companion orbital period
- c. Faster timescale for significant change in angular momentum from sufficient torque by BH2

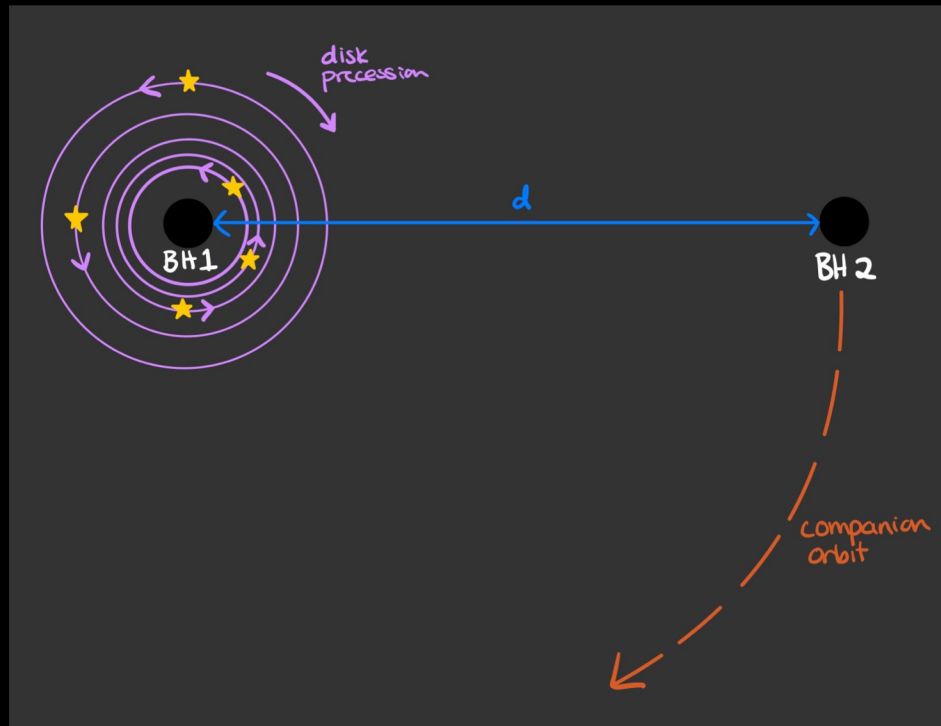


Figure 8

# Analytical Theory

Conditions:

1. *Resonance*: Set orbital period of companion equal to disk precession period.
2. *Torque*: Choose number of stellar orbital periods in which orbit should be significantly affected by companion's gravitational torque

Simulations:

Table 1

| Simulation | Resonance | Torque | $M_1$ | $M_{\text{disk}}$ | $N$ | $m$  | $M_2$ | $d$   |
|------------|-----------|--------|-------|-------------------|-----|------|-------|-------|
| RT         | ✓         | ✓      | 1     | 1/100             | 200 | 5e-5 | 27.7  | 132   |
| T          |           | ✓      | 1     | 1/500             | 200 | 1e-5 | 27.7  | 132   |
| R          | ✓         |        | 1     | 1/500             | 200 | 1e-5 | 1     | 25.07 |

- Primary black hole mass is  $M_1$
- Disk mass,  $M_{\text{disk}}$
- Number of particles,  $N$
- Star mass,  $m$
- Companion black hole mass is  $M_2$
- Orbital separation,  $d$ , between the black holes

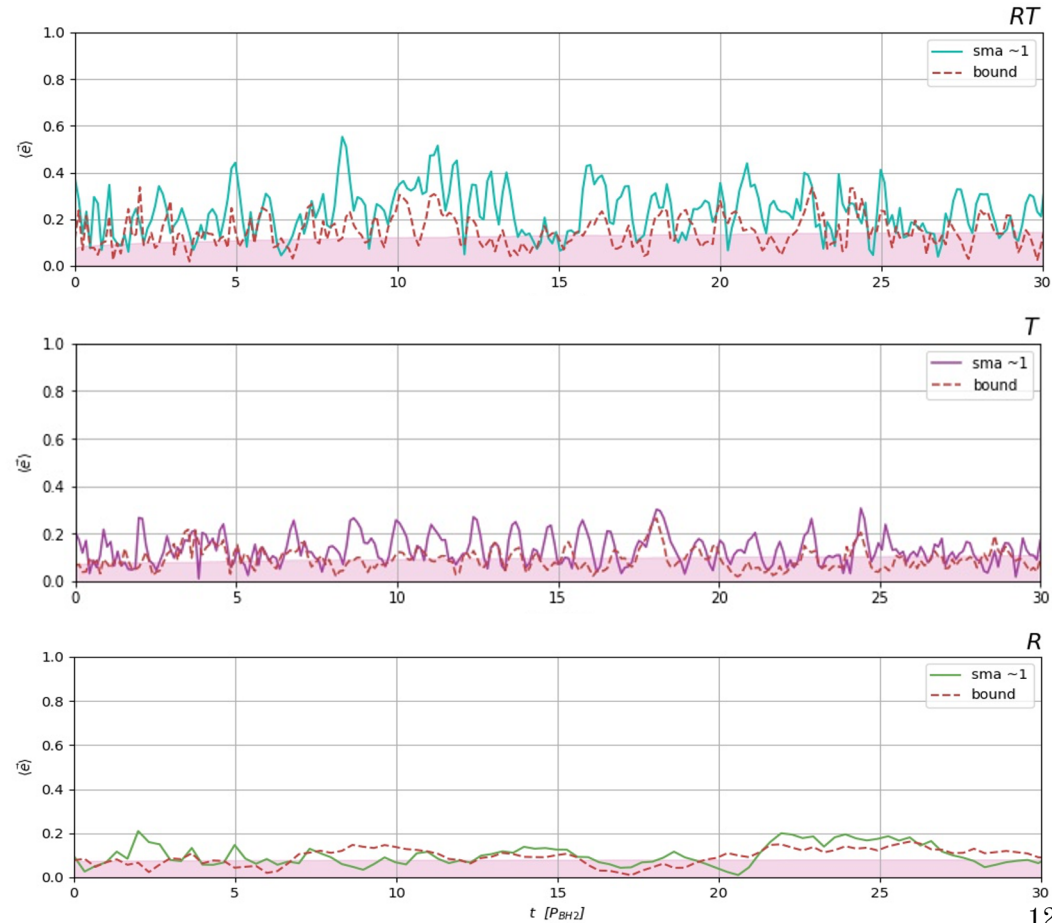
# Average unit eccentricity vector

$$\langle \hat{e} \rangle = \sum_{n=1}^{N_{bound}} \frac{\hat{e}_n}{N}$$

- No obvious apsidal alignment in Torqued (T) and Resonating (R) disks
- Apsidal alignment in Resonating & Torqued (RT) disk?
- Resonating & Torqued (RT) and Torqued (T) disks = noisy data

$$Noise\ Floor = \frac{1}{\sqrt{N_{bound}}}$$

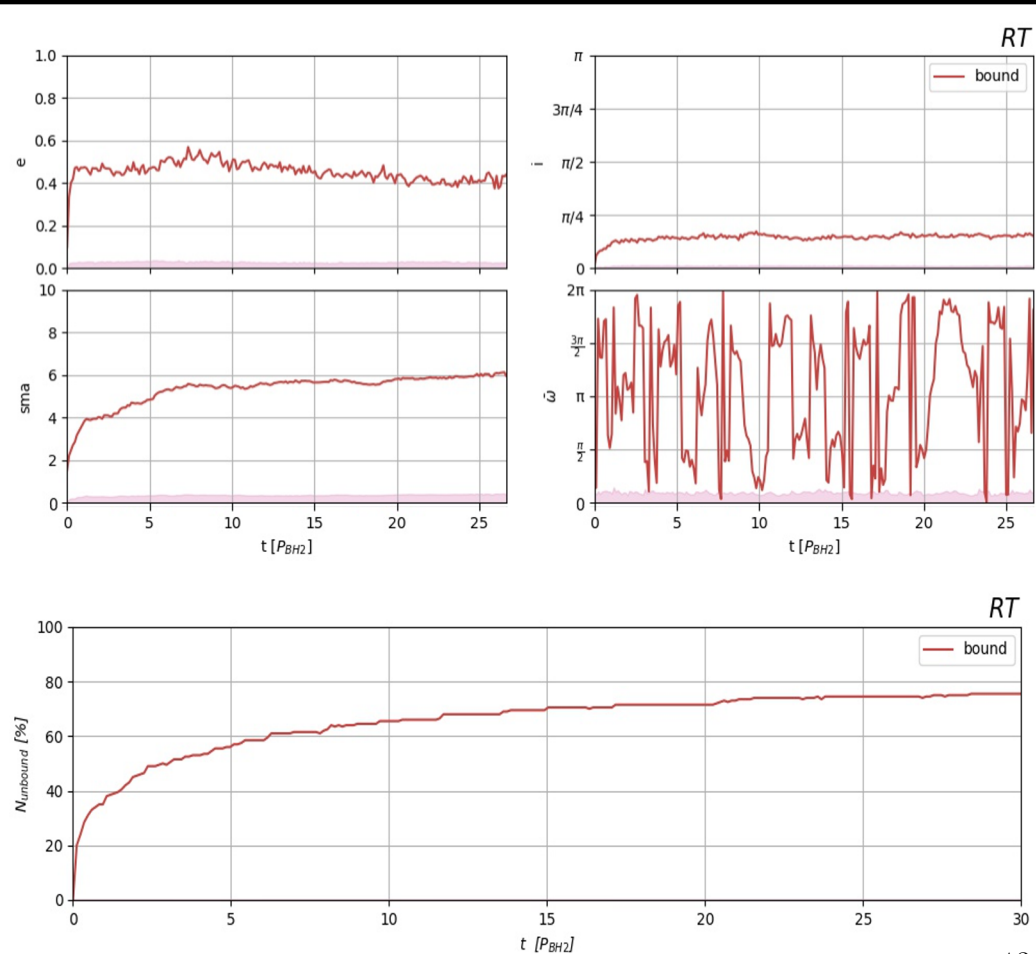
Figure 8



# Resonating & Torqued Disk (RT): Mean kepler elements

- Eccentricities, inclinations, and semi-major axes  $\uparrow$  on average
- Precession? Longitude of periapsis,  $\varpi \rightarrow$  Noisy!
- Disk  $\rightarrow$   $\sim 80\%$  of stars become unbound
- Disk drops out of resonance

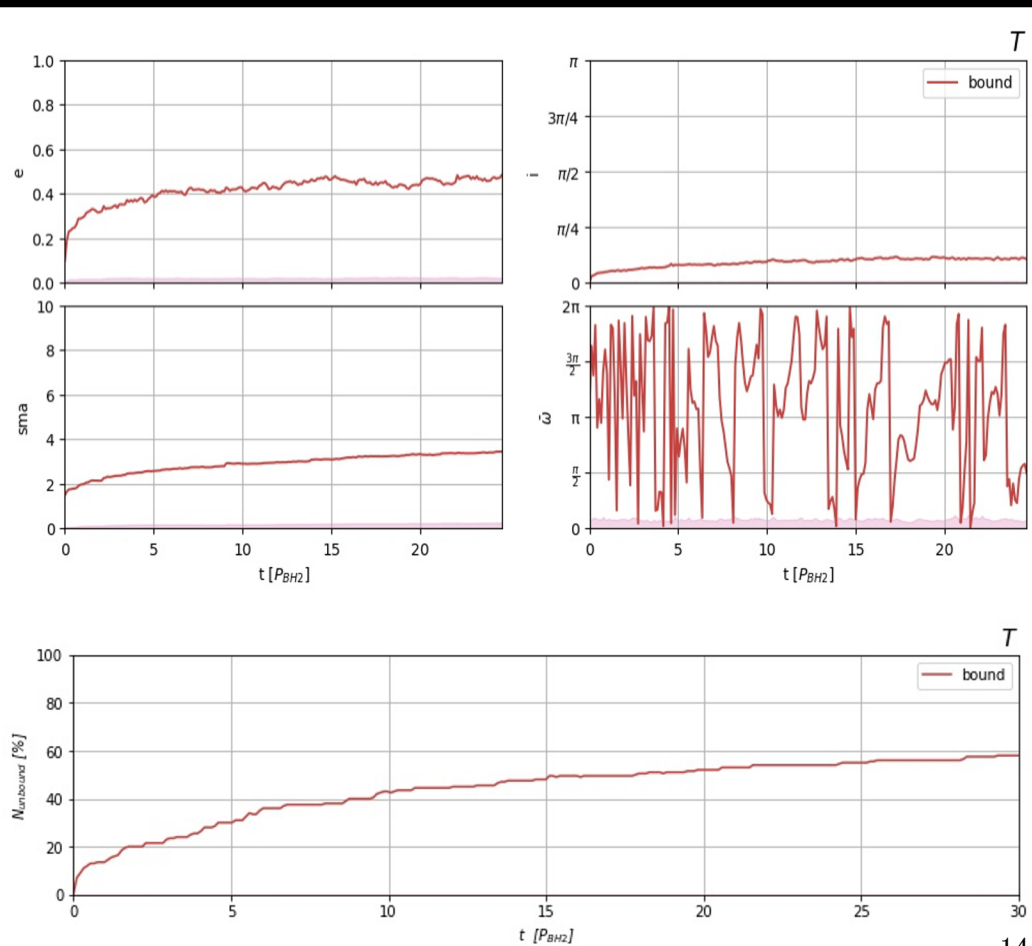
Figure 9



# Torqued disk (T): Mean kepler elements

- Eccentricity, inclination, and semi-major axes  $\uparrow$  on average, not as extreme as RT
- Precession?  $\rightarrow$  Longitude of periapsis,  $\varpi$   
 $\rightarrow$  Noisy!
- Disk  $\rightarrow$   $\sim 60\%$  of stars become unbound

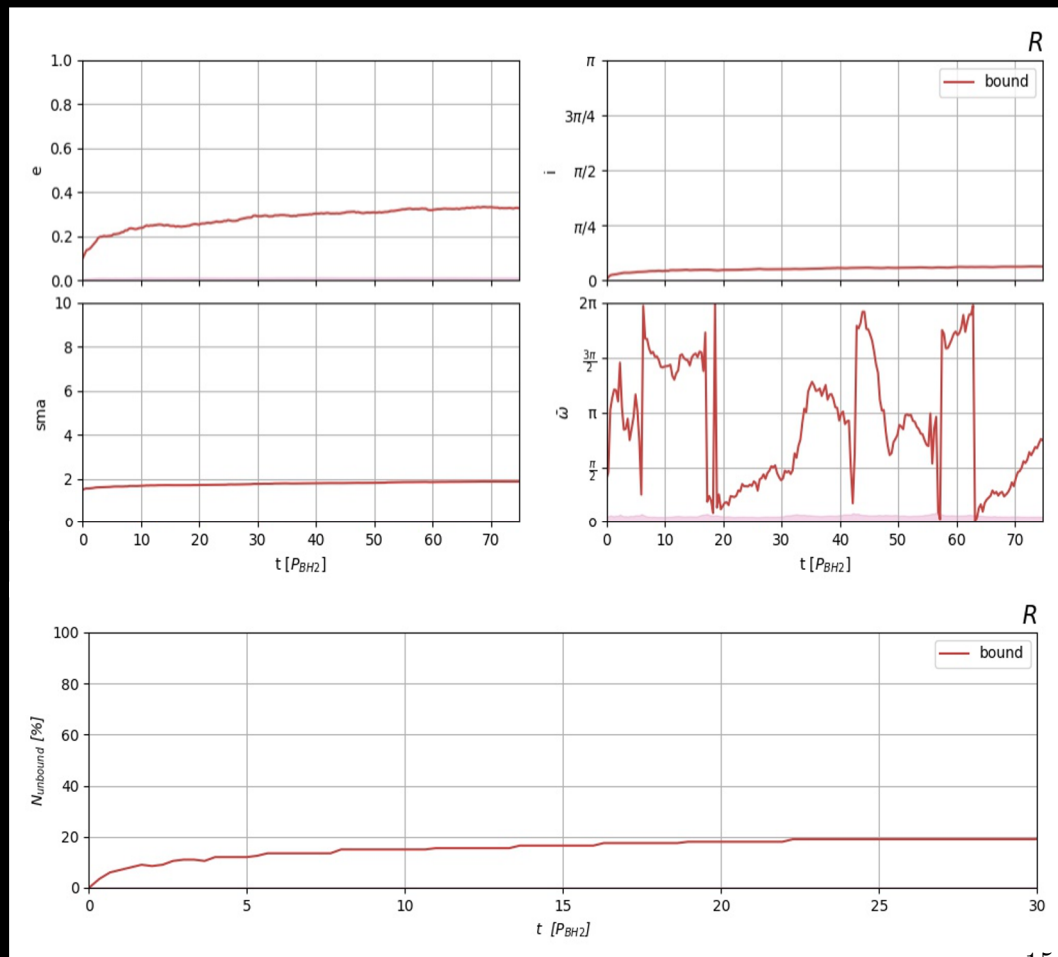
Figure 10



# Resonating Disk (R): Mean kepler elements

- Eccentricity  $\uparrow$  on average
- Disk stays pretty flat and small
- Precession?  $\rightarrow$  Longitude of periapsis,  $\varpi$   
 $\rightarrow$  eccentric nuclear disk!
- Disk  $\rightarrow$  Only  $\sim 20\%$  of stars become unbound

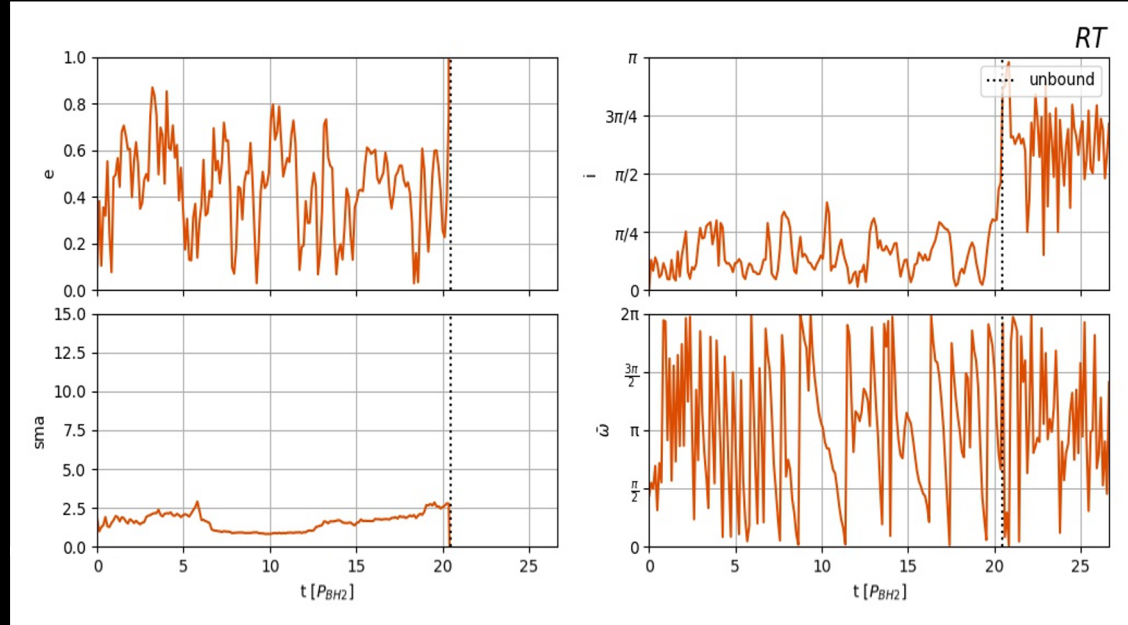
Figure 11



# Unbound star's kepler elements - Resonating & Torqued Disk (RT)

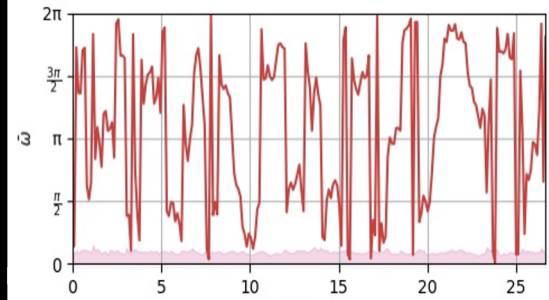
- Oscillations in eccentricity ( $e$ ) and inclination ( $i$ ) then, eccentricity  $\rightarrow \infty$   
 $\rightarrow$  Extreme torque
- Semi-major axis ( $a$ )  $\rightarrow$  zero  
 $\rightarrow$  Star ejected by gravitational scattering encounter

Figure 12

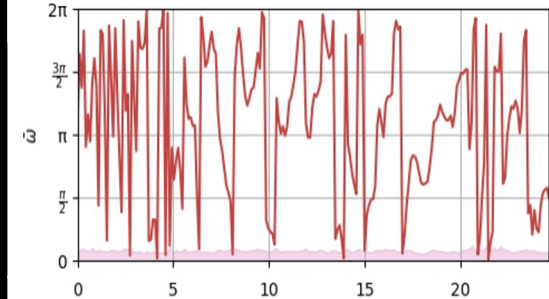


# Eccentric Nuclear Disk?

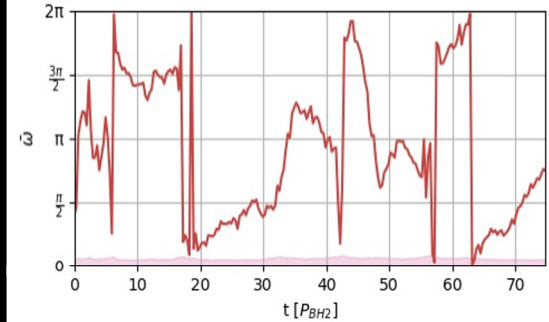
Resonating &  
Torqued Disk



Torqued Disk



Resonating Disk



# Conclusion

The Resonating & Torqued (RT) and Torqued (T) disk's massive companions unbind most of their stars. No eccentric nuclear disk forms.

- Resonating & Torqued (RT) disk drops out of resonance with its companion
- Does not rule out that sufficiently torqued disk could form eccentric nuclear disk

Resonating disk forms an eccentric nuclear disk!

- Need 4x the integration time to see full clustering of the stellar eccentricity vectors



# Future Work

- Account for massive companion where the sufficient torque condition is met
- Longer times for resonating disks
- Different Kepler element distributions
  - Not just a flat circular disk
- Look into tidal disruption events

Gruzinov, A., Levin, Y., & Zhu, J. 2020, arXiv e-prints, arXiv:2007.08471.  
<https://arxiv.org/abs/2007.08471>

Lauer, T. R., Faber, S. M., Groth, E. J., et al. 1993, AJ, 106, 1436, doi: 10.1086/116737

Lauer, T. R., Faber, S. M., Gebhardt, K., et al. 2005, AJ, 129, 2138, doi: 10.1086/429565

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Madigan, A.-M., Halle, A., Moody, M., et al. 2018, ApJ, 853, 141, doi: 10.3847/1538-4357/aaa714

# References

Rauch, K. P., & Tremaine, S. 1996, *New Astronomy*, 1, 149

Rein, H., & Liu, S.-F. 2012, *A&A*, 537, A128, doi: 10.1051/0004-6361/201118085

Rein, H., & Spiegel, D. S. 2015, *MNRAS*, 446, 1424, doi: 10.1093/mnras/stu2164

Thomasson, M., Donner, K. J., Sundelius, B., et al. 1989, *A&A*, 211, 25

Tremaine, S. 1995, AJ, 110, 628, doi: 10.1086/117548

Figure 1 - Lauer, T. R., Faber, S. M., Groth, E. J., et al. 1993, AJ, 106, 1436, doi:  
10.1086/116737

Figure 2, 5, 7 – Drawing by Allie Christensen

Figure 3 – Drawing by Allie Christensen, and image of presenter’s dog toy

Figure 4 - Adapted from Wikipedia’s “Apsidal precession”

# Figures/Tables

Figure 6 – Lauer, T. R., Faber, S. M., Groth, E. J., et al. 1993, AJ, 106, 1436, doi:  
10.1086/116737 and drawing by Allie Christensen

Figure 8-11 – Figures from Honors Thesis

Table 1 - Table from Honors Thesis