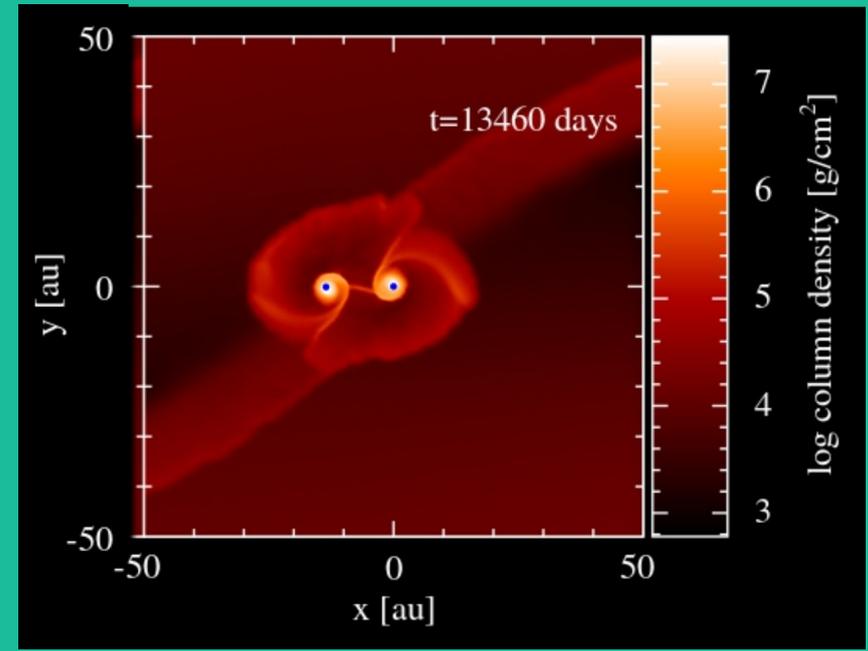


Singer 1968



Rowan+ In prep.

## Jacobi captures:

# *close encounters in astrophysical disks*

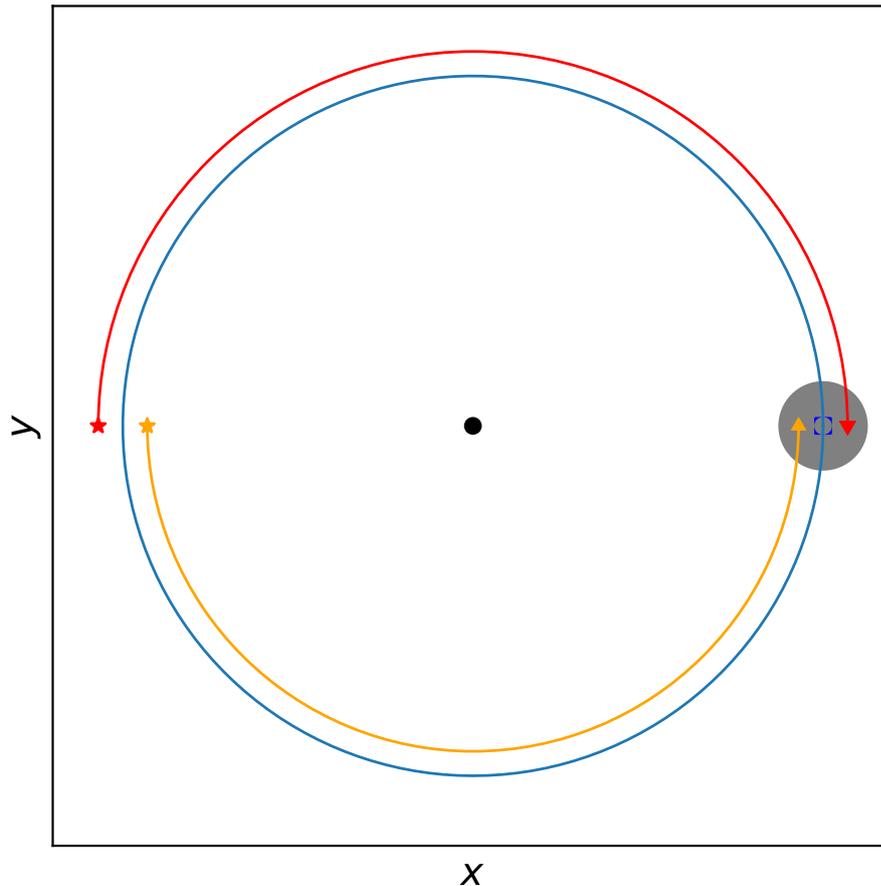
Tjarda Boekholt  
Connor Rowan  
Bence Kocsis



Copenhagen  
01-06-22

References: Boekholt+ arXiv:2203.09646  
Rowan+In Prep.

# The experimental setup

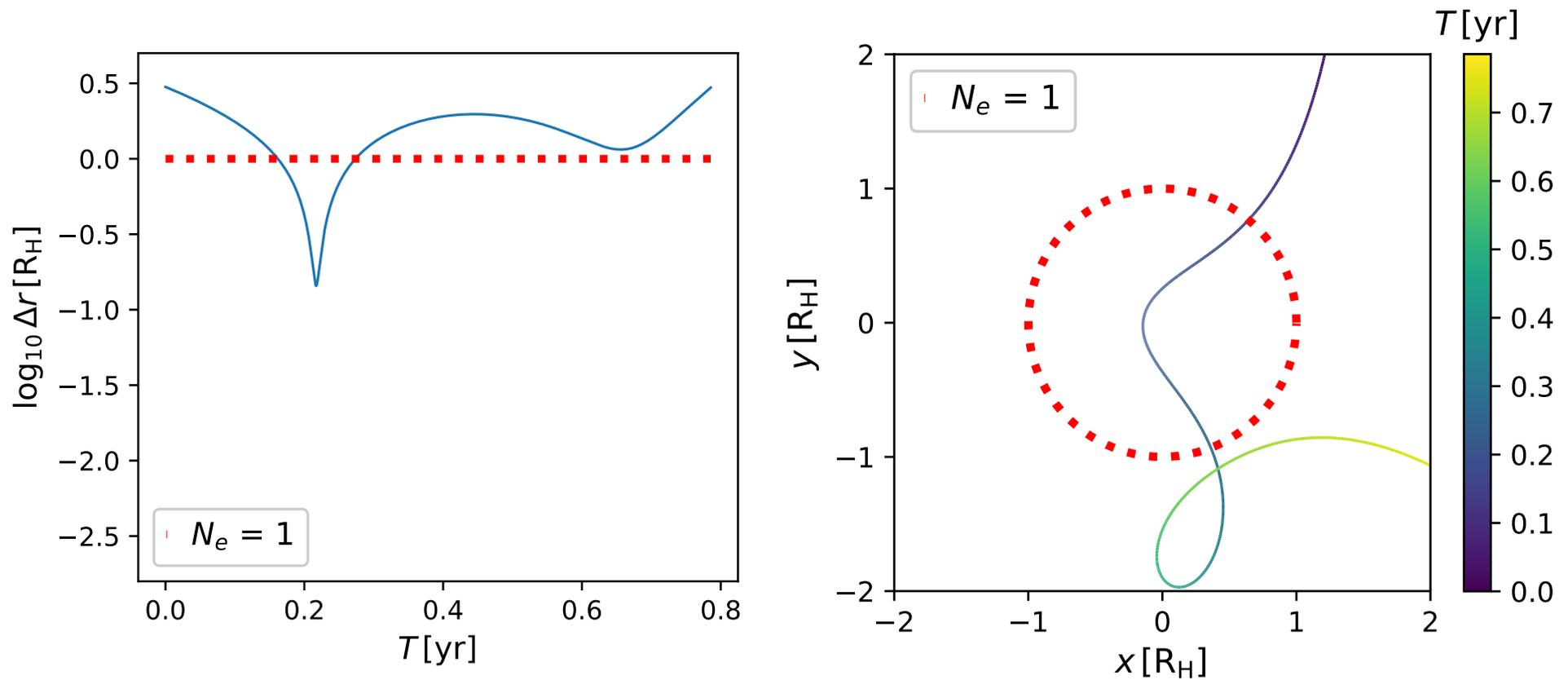


●	$M$
■	$m_t$
●	$R_H \approx a \sqrt[3]{\frac{m}{3M}}$
★	$m_p$
★	$m_p$

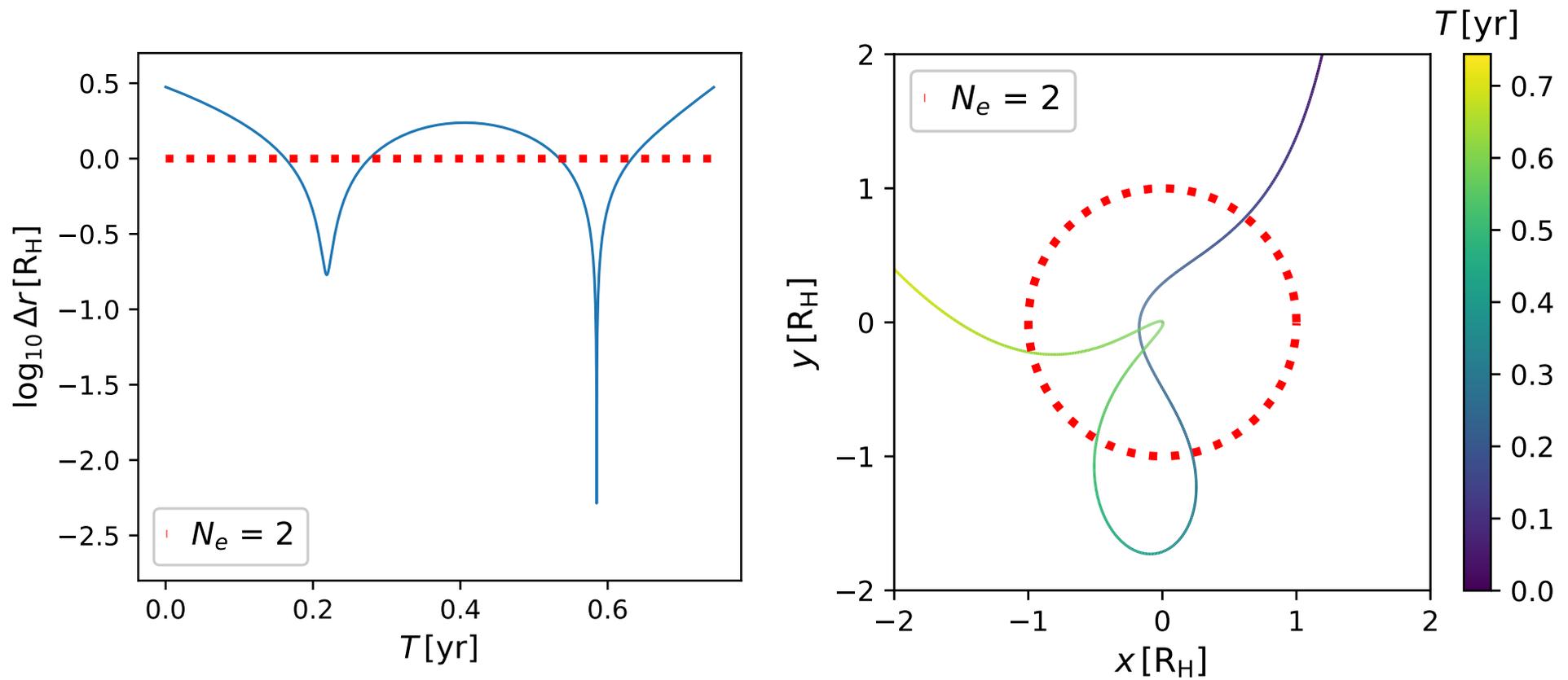
- Circular/planar orbits initially  
(see also Dong Lai, Amy Secunda and Hagai Perets)
- Vary “impact parameter”  $p$
- “What happens in the grey area?”

# Close encounters of the Jacobi kind

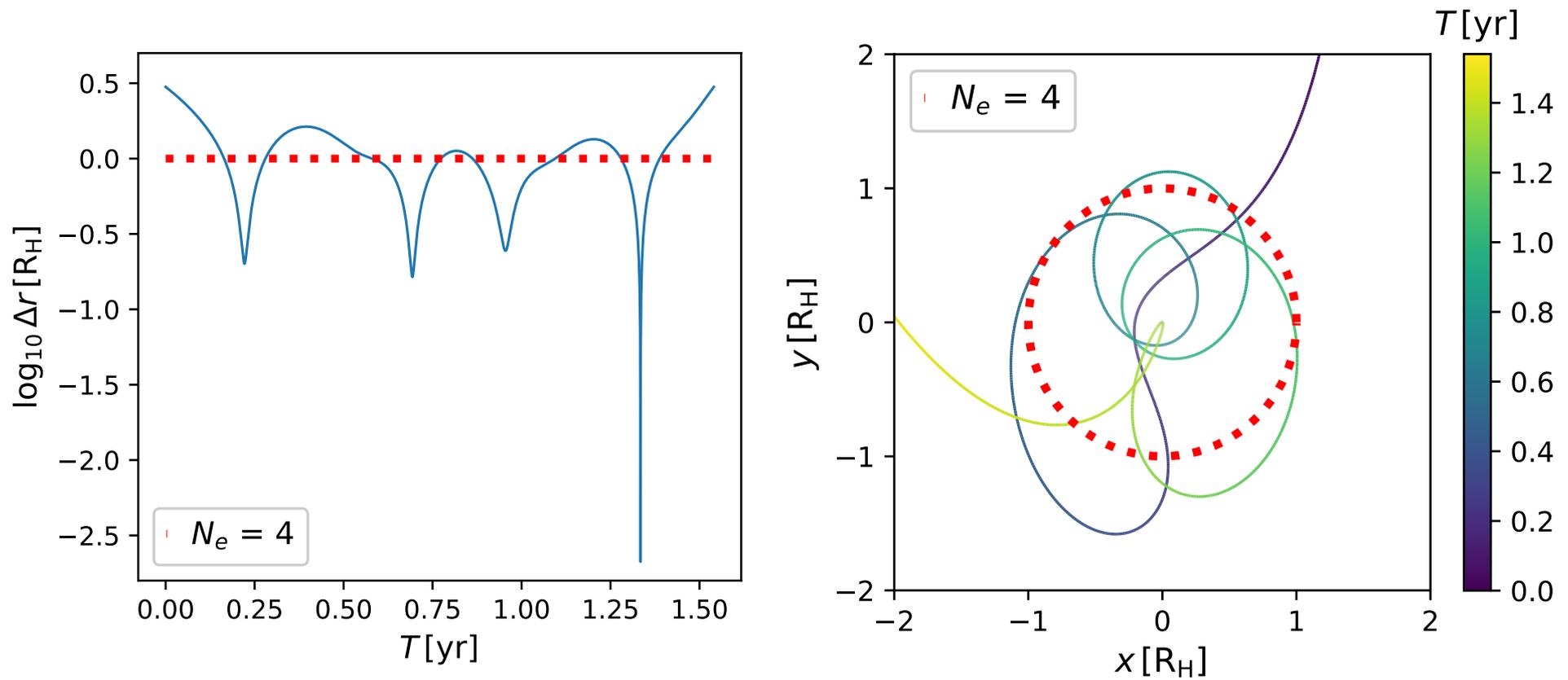
For the Sun-Earth-Moon, but similar for black hole case



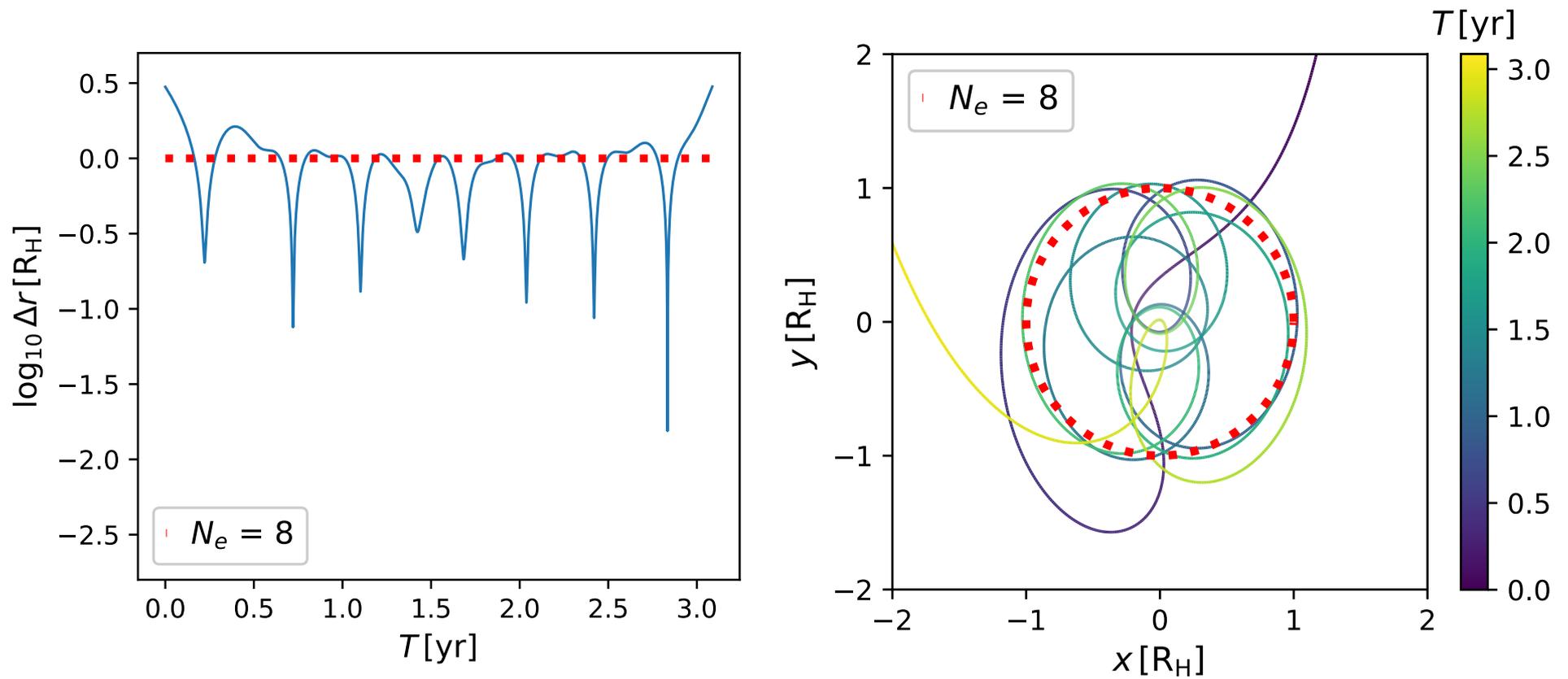
# Close encounters of the Jacobi kind



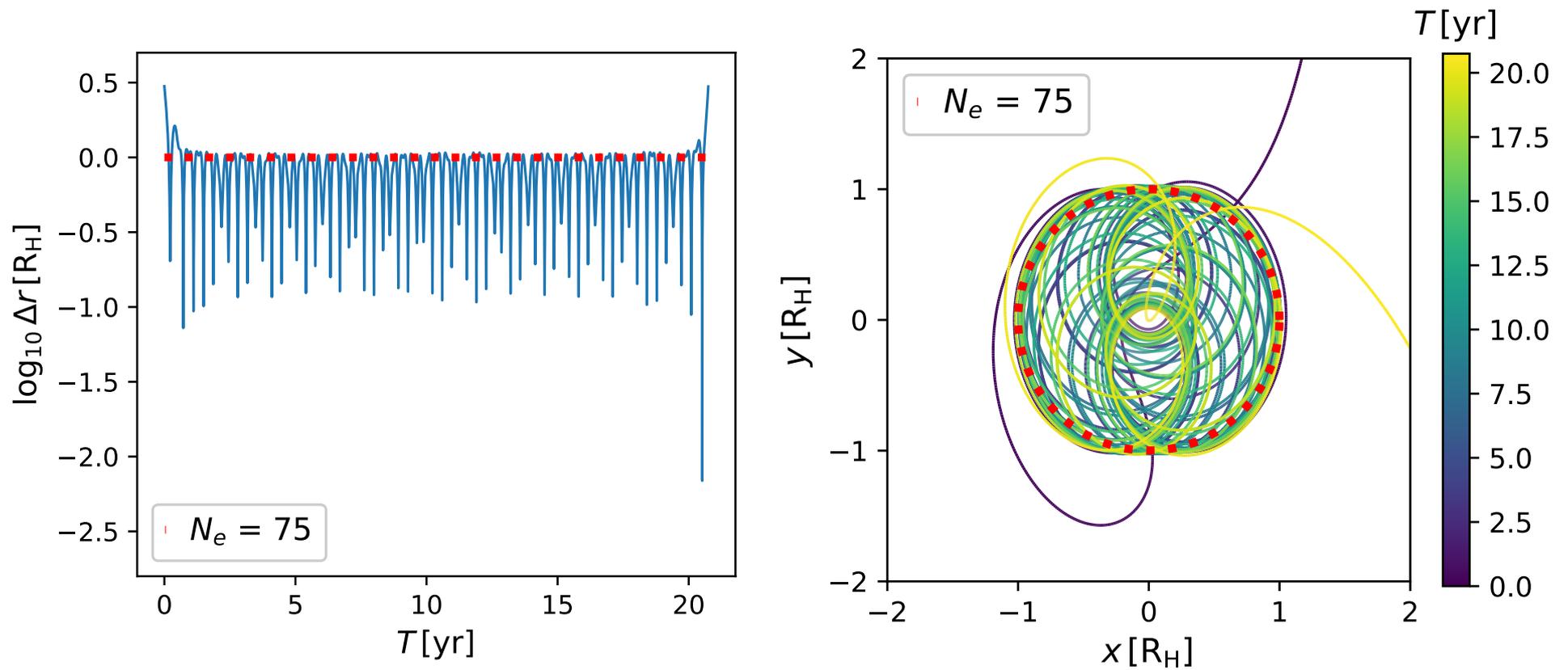
# Close encounters of the Jacobi kind



# Close encounters of the Jacobi kind



# Close encounters of the Jacobi kind



# What is a Jacobi capture?

*“...transient binary when two large bodies penetrate each other’s Hill spheres.”*

- Goldreich+2002

*“... (Jacobi) capture can be thought of as a competition between two primary masses for the possession of the third particle ...”*

*“... gravitational capture is intimately associated with chaotic motion.”*

- Murison 1989

- What are some examples of (potential) Jacobi captures from the literature?

# Jacobi capture of the Moon

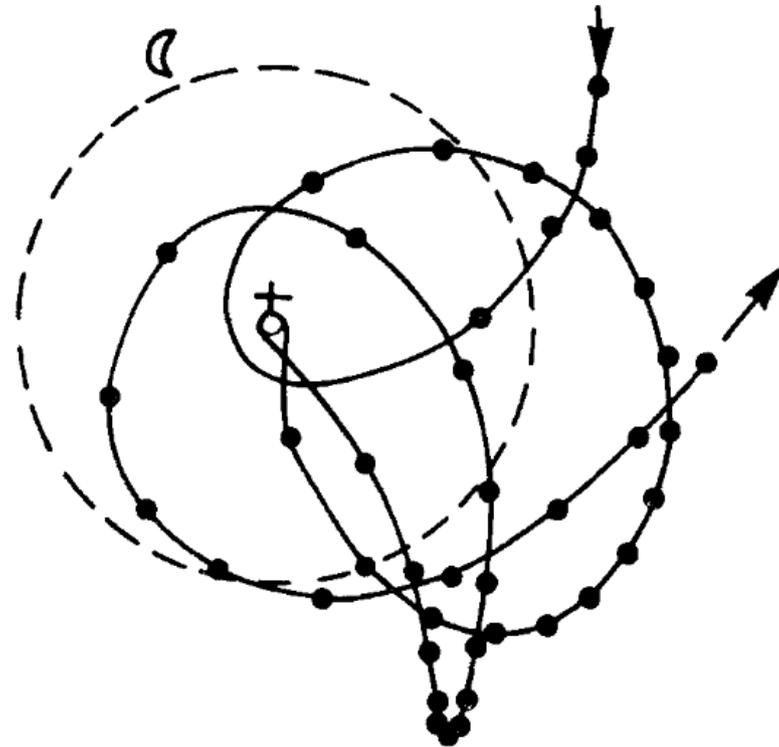
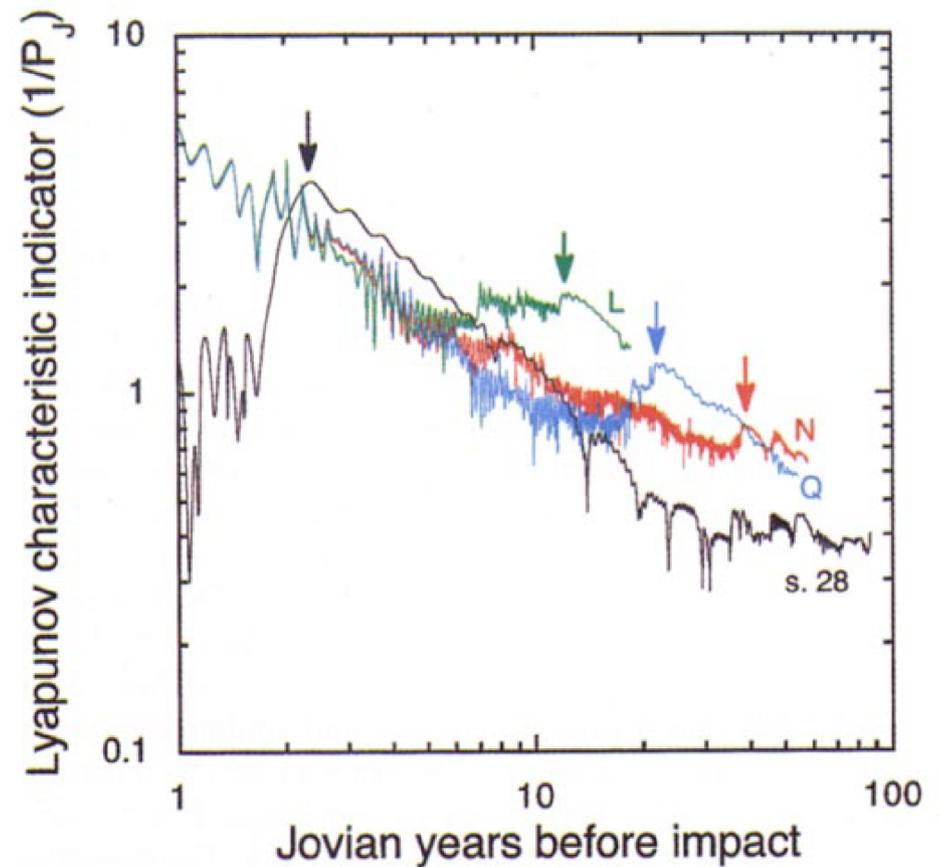
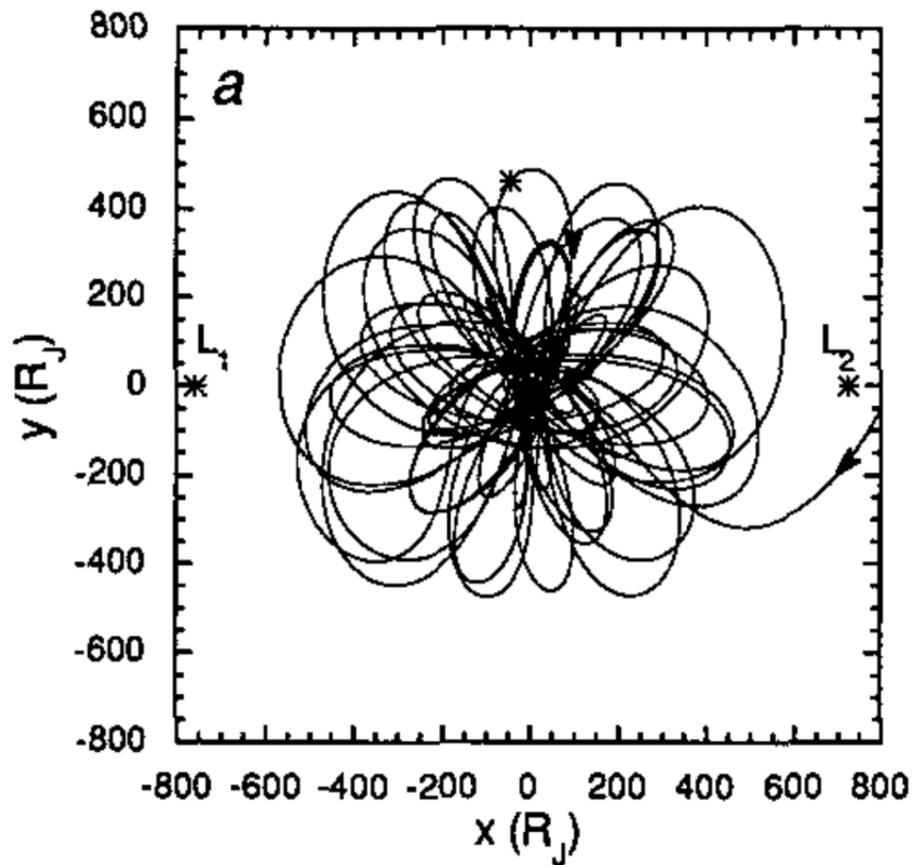
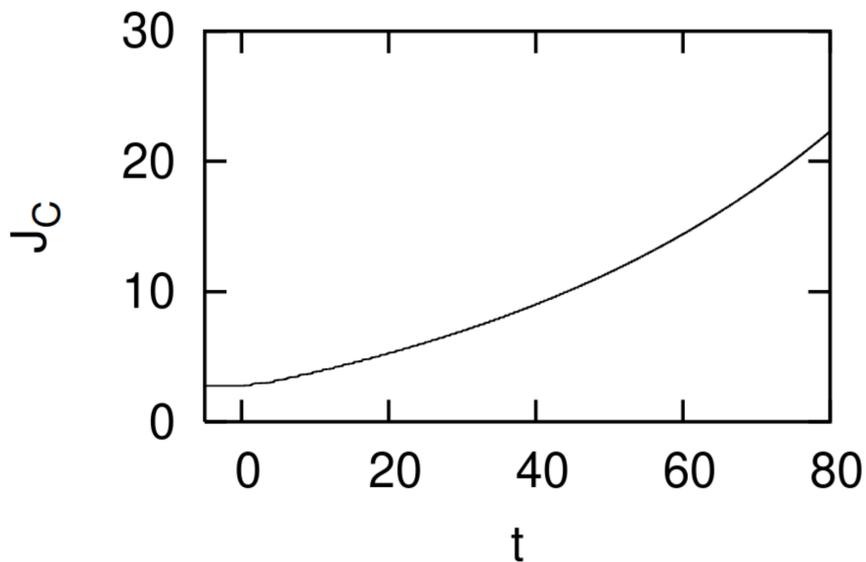
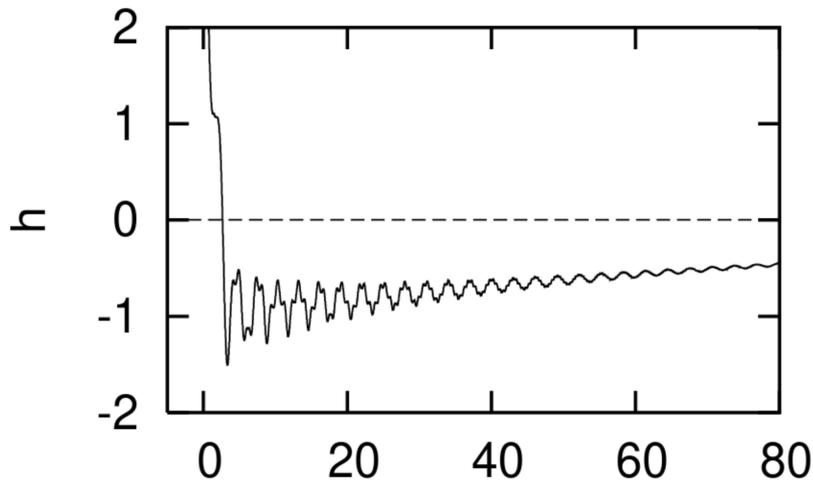


FIG. 14. Orbit of a particle in the Sun–Earth system, illustrating Jacobi capture. Calculated by Th. Schmidt (Heidelberg). The present orbit of the Moon is shown for comparison purposes. Note that the orbit of the particle is initially a retrograde orbit, but may change into a direct orbit. For a massive particle, the tidal perturbation would modify the orbit substantially after the period of closest approach.

# Comet Shoemaker-Levy 9



# Jacobi captures in the Kuiper belt



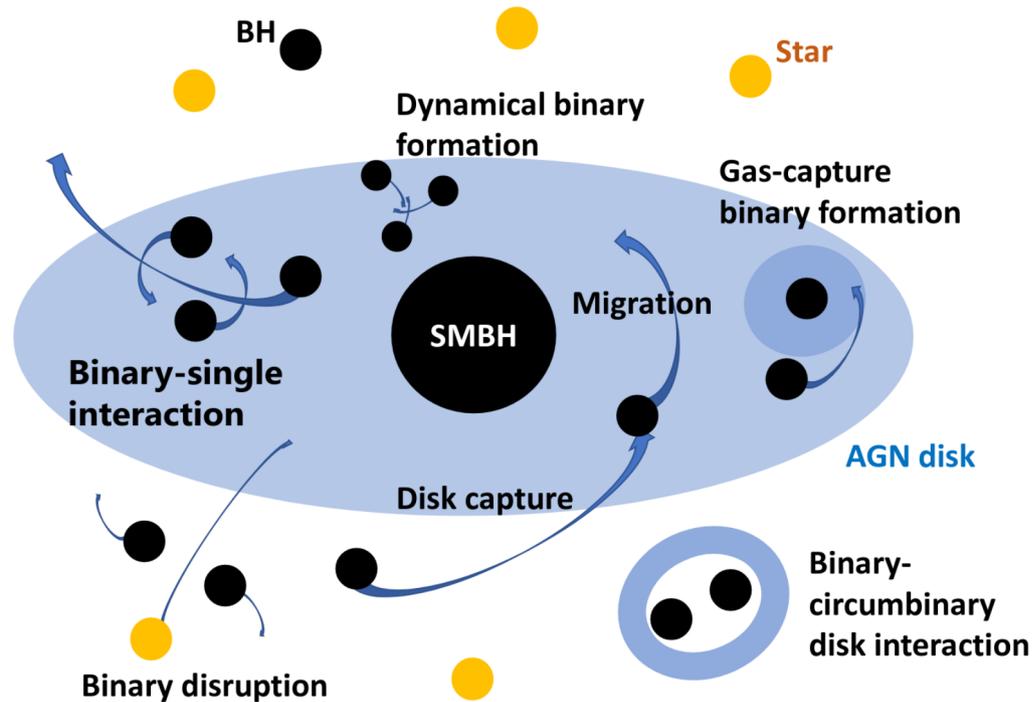
- **Origin of equal mass, wide binaries**
  - e.g. Pluto & Charon
- **Step 1: Capture**
  - Occurrence of a Jacobi capture
- **Step 2: Dissipation**
  - **L2s**: dynamical friction by a sea of planetesimals
    - Retrograde binaries
  - **L3**: interaction with a third large body
    - Prograde & Retrograde

Goldreich+ 2002, Schlichting+ 2008

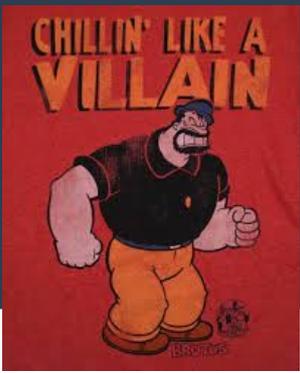
- Majority of the literature considers small bodies in the Solar System
- But...are Jacobi captures not universal?

# How about compact objects in AGN?

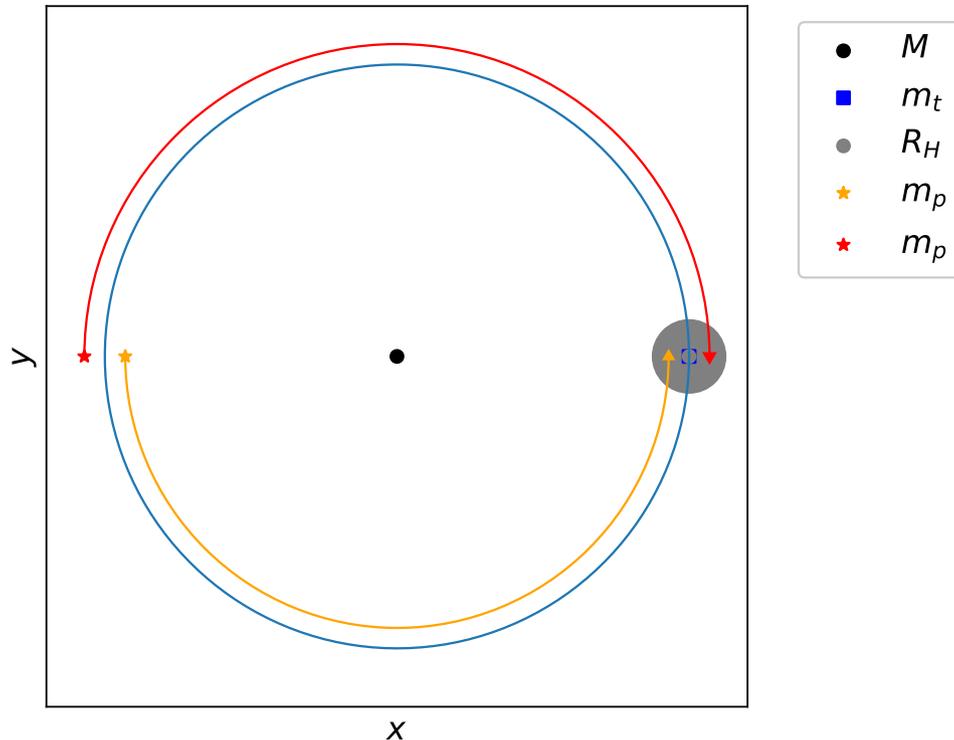
## Formation of gravitational wave sources



**Figure 3.** Schematic diagram illustrating the mechanisms affecting the BH population and driving binary formation and evolution. See § 2 and Fig. 2 for an overview and § 3 for numerical details.



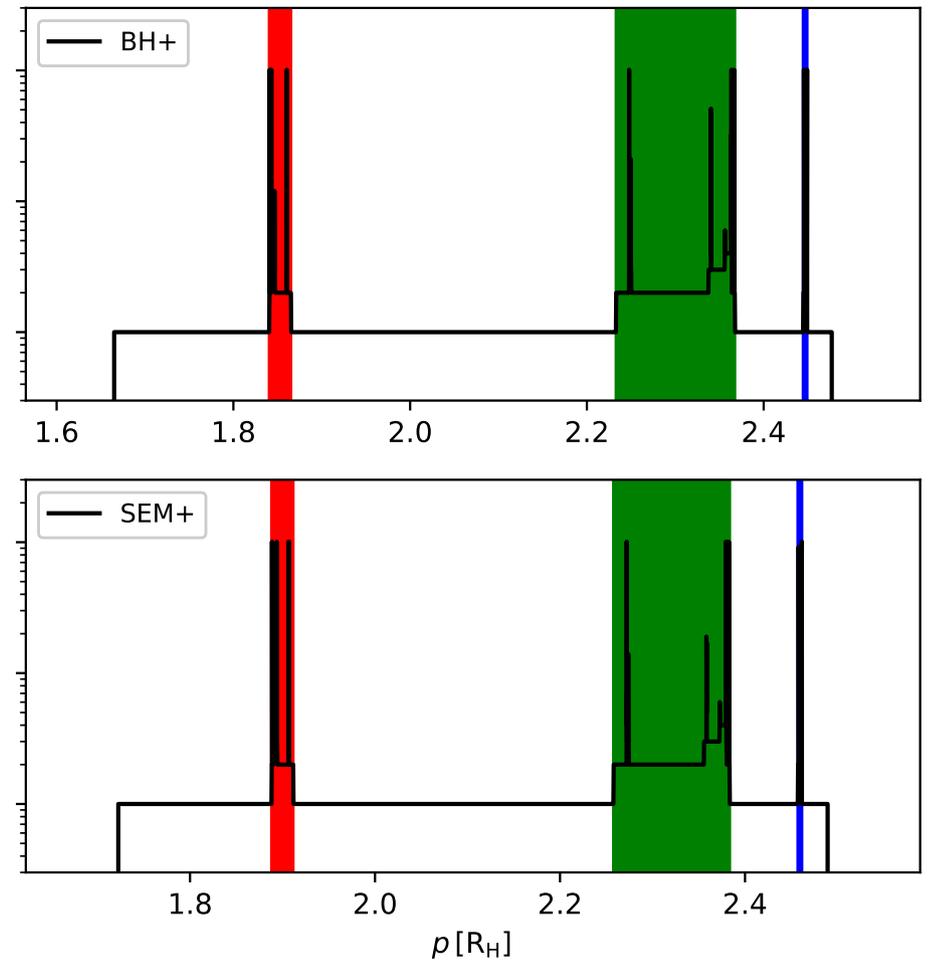
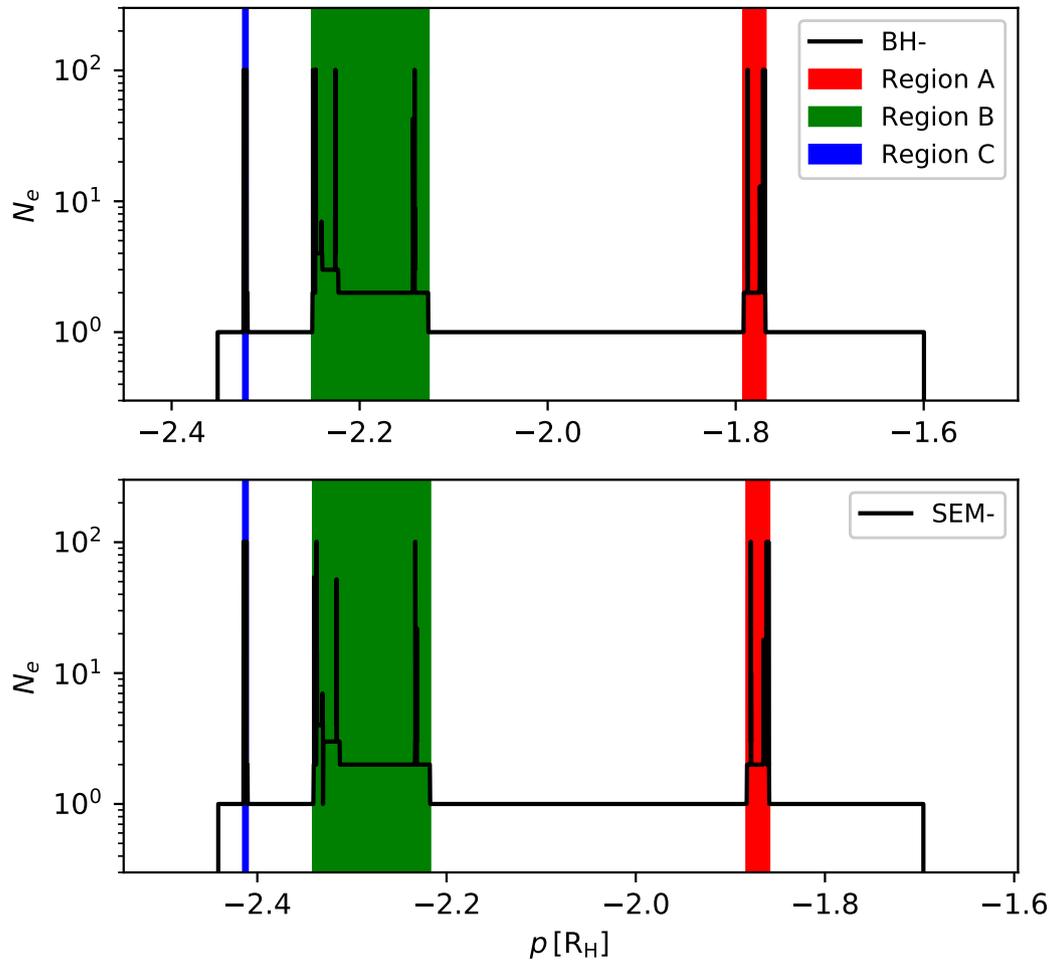
# Experimental setup



- Sun-Earth-Moon (SEM)
  - $Q=3e-6$ ,  $q=1.2e-2$
- SgA\* + GW190521 (BH)
  - $Q=2e-5$ ,  $q=7.8e-1$
  - $(m_t, m_p) = (85, 66) M_{\text{Sun}}$
- Sample “impact parameter” with high resolution
- Measure various encounter properties

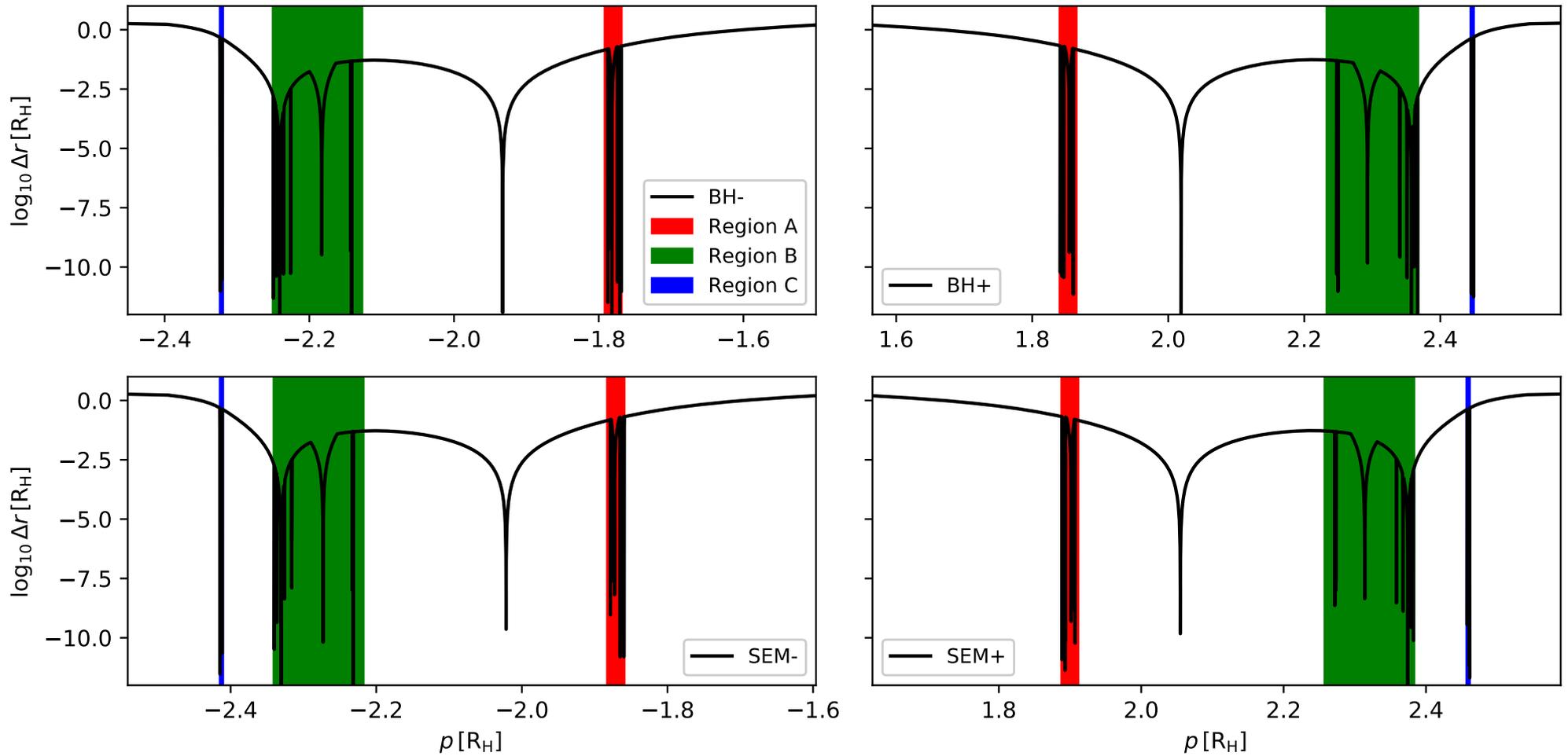
# "Jacobi spectra"

## *Number of close encounters*

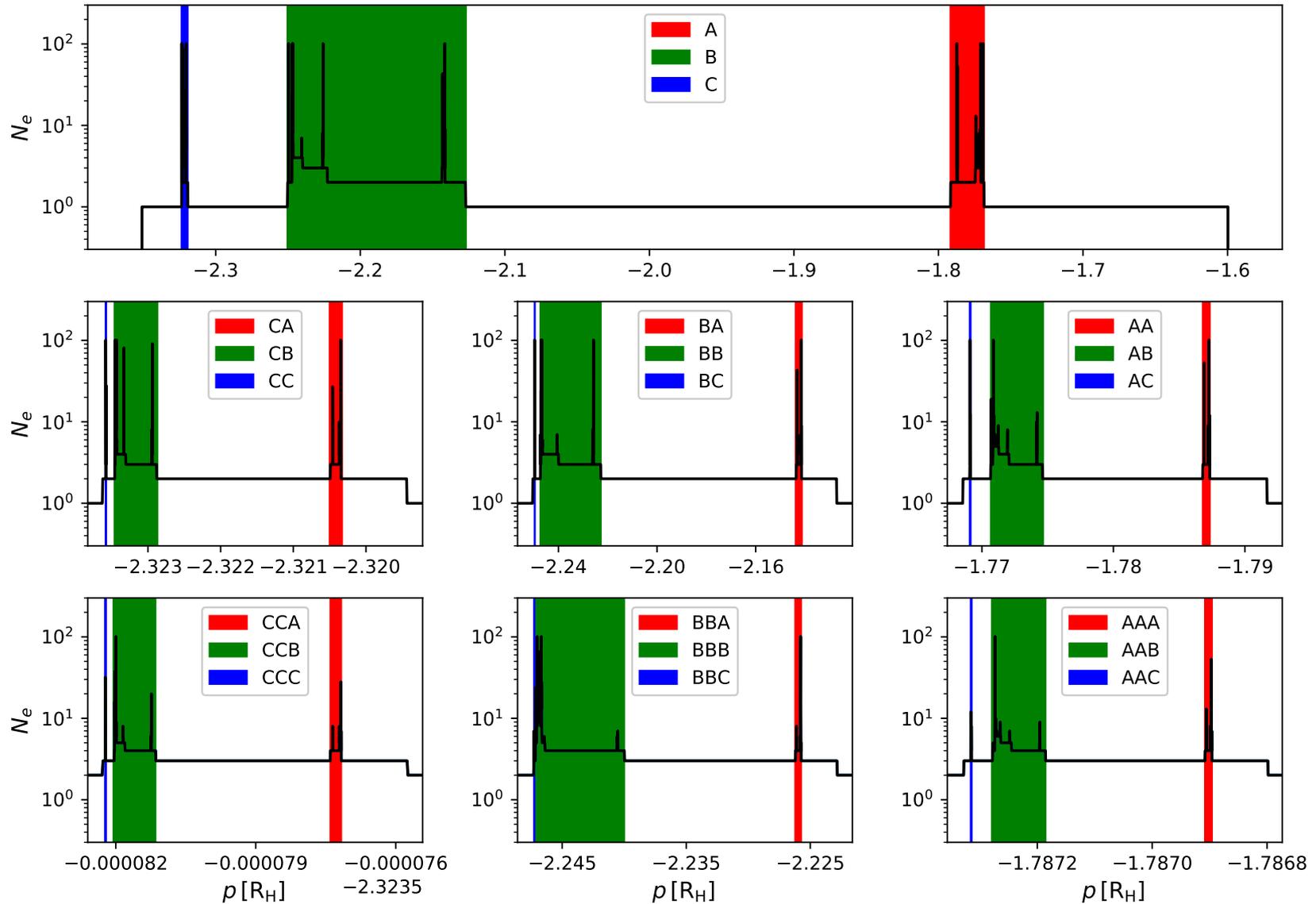


# "Jacobi spectra"

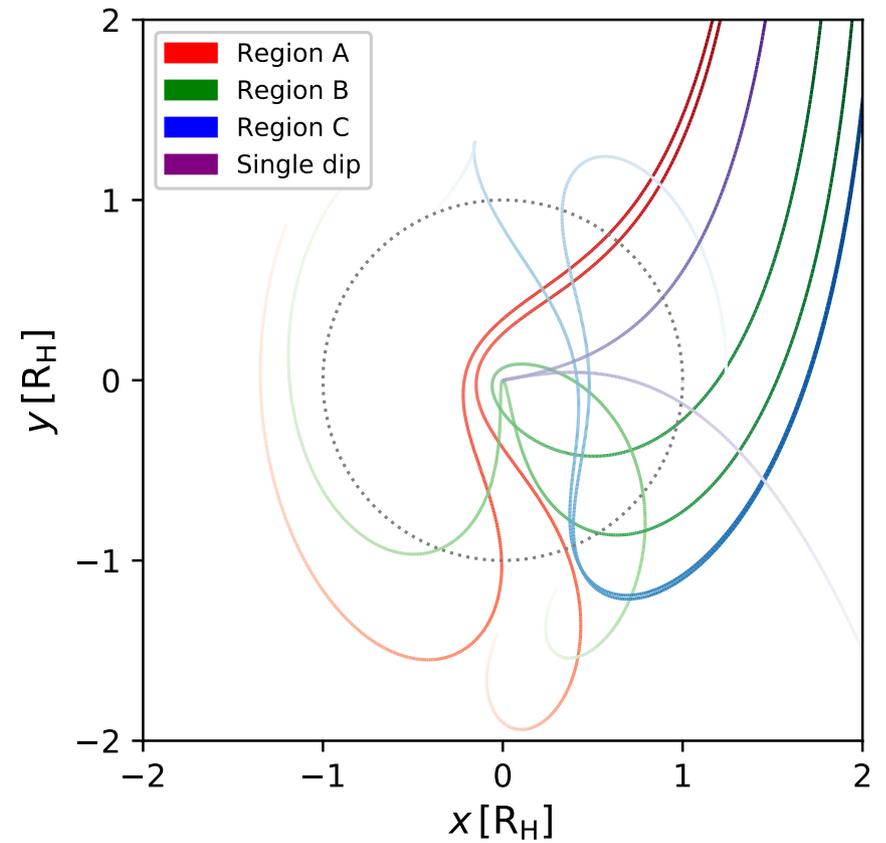
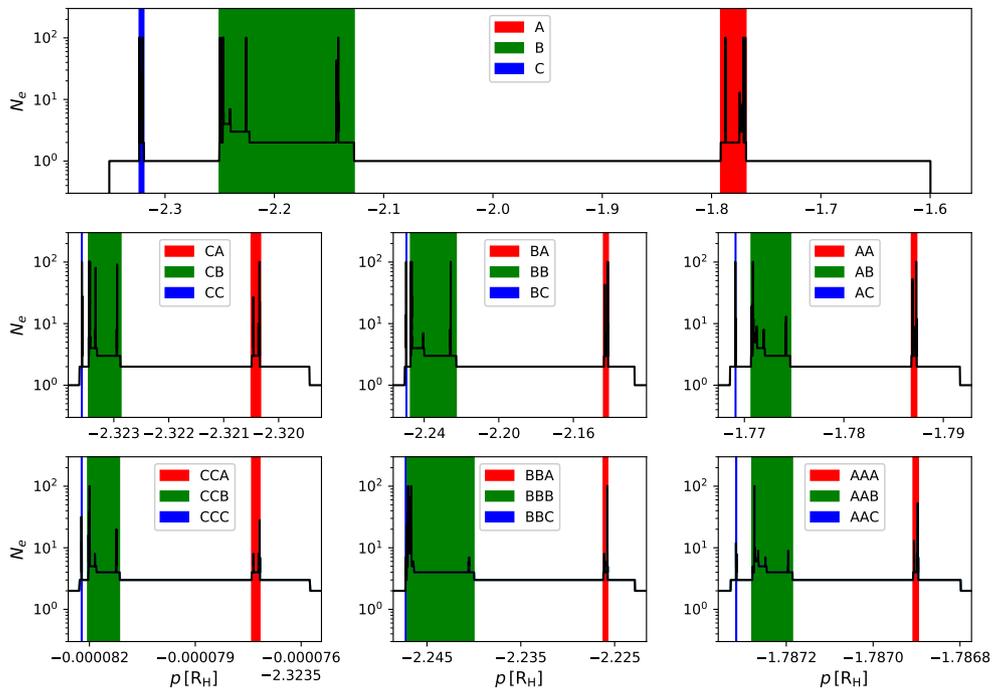
## *Separation during closest encounter*



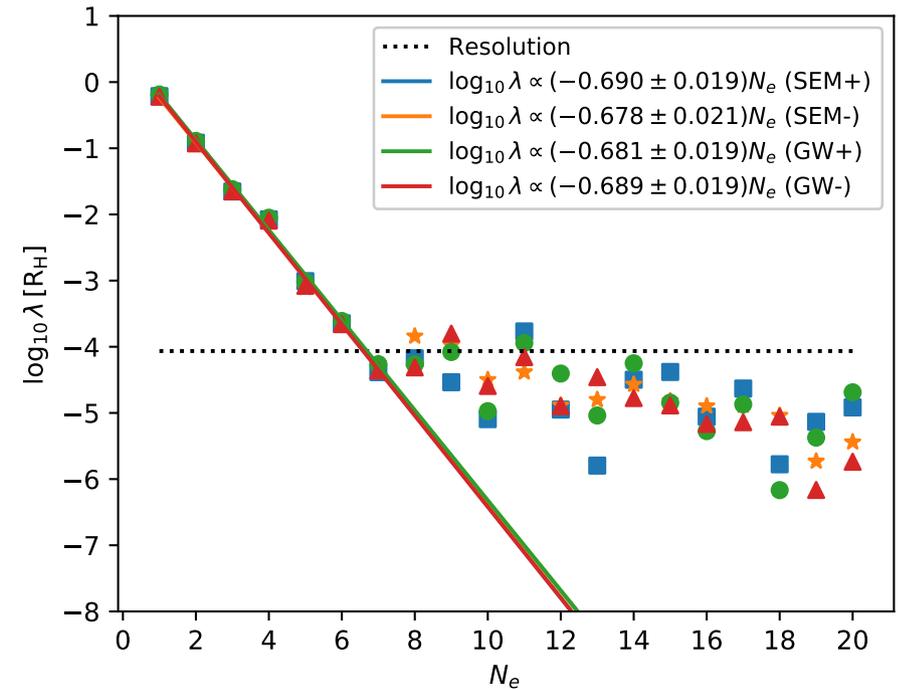
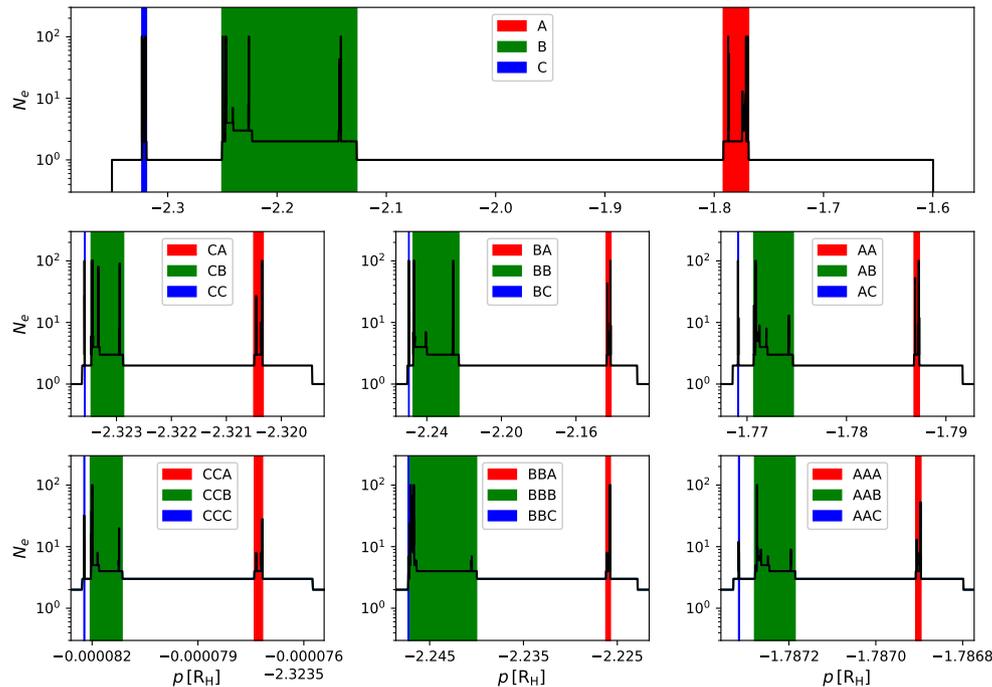
# Zooming in... self-similarity!



# Types of encounters



# Line section for number of encounters

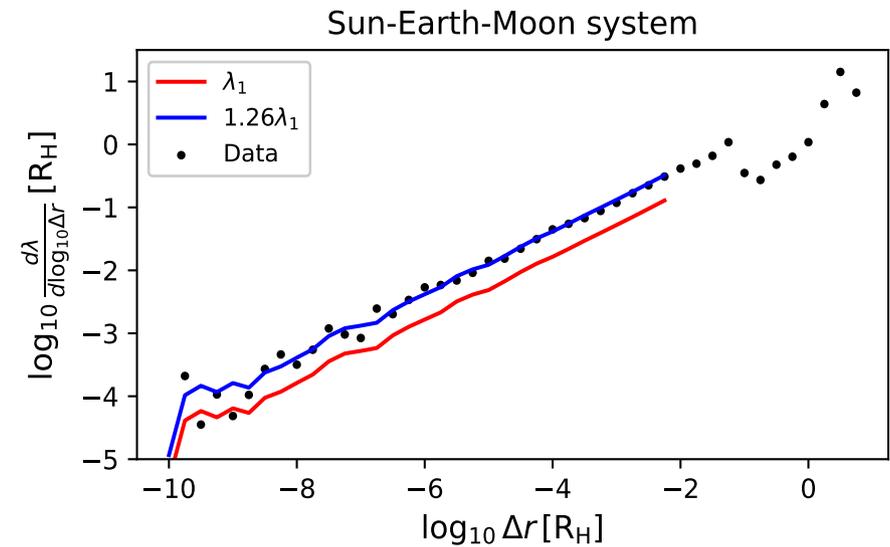
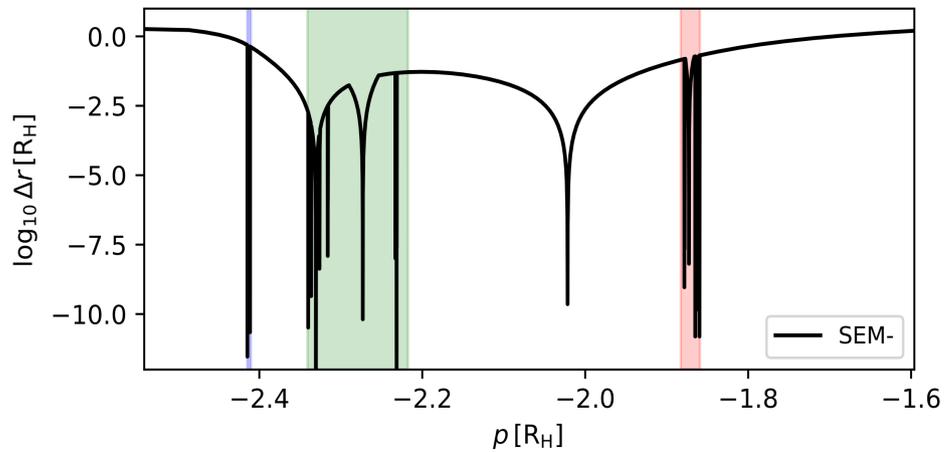


$L(n+1) = L(n) * 3 * s$ , with  $s$  the scaling factor

$s \sim 0.068 \pm 0.006$

$L(n+1) / L(n) \sim 0.2 \rightarrow 20\%$  of impact parameter space leads to Jacobi captures

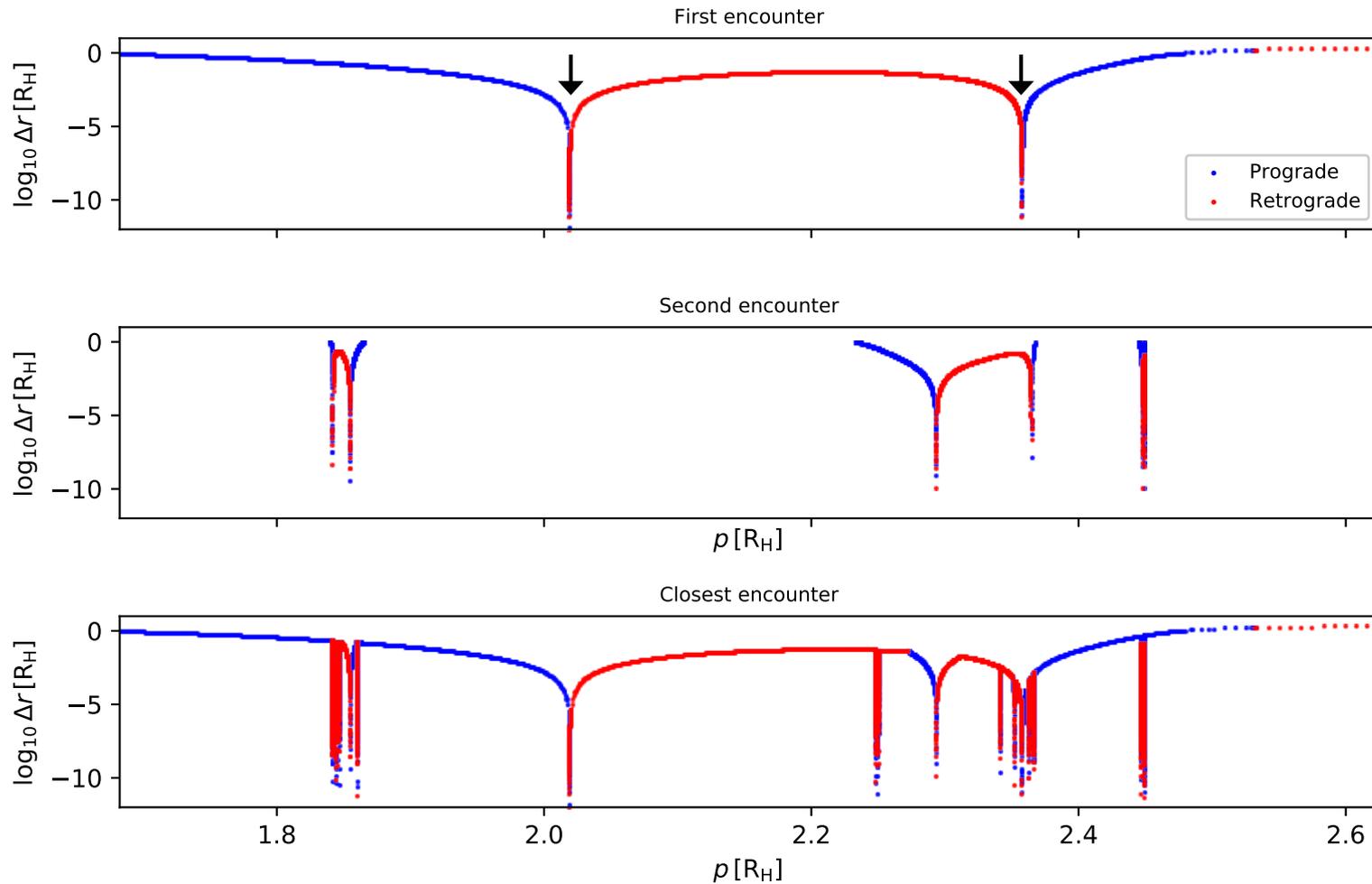
# Line section for closest separation



$$\lambda_{\infty}(\Delta r) = \lambda_1(\Delta r) \sum_{i=0}^{\infty} (3s)^i,$$

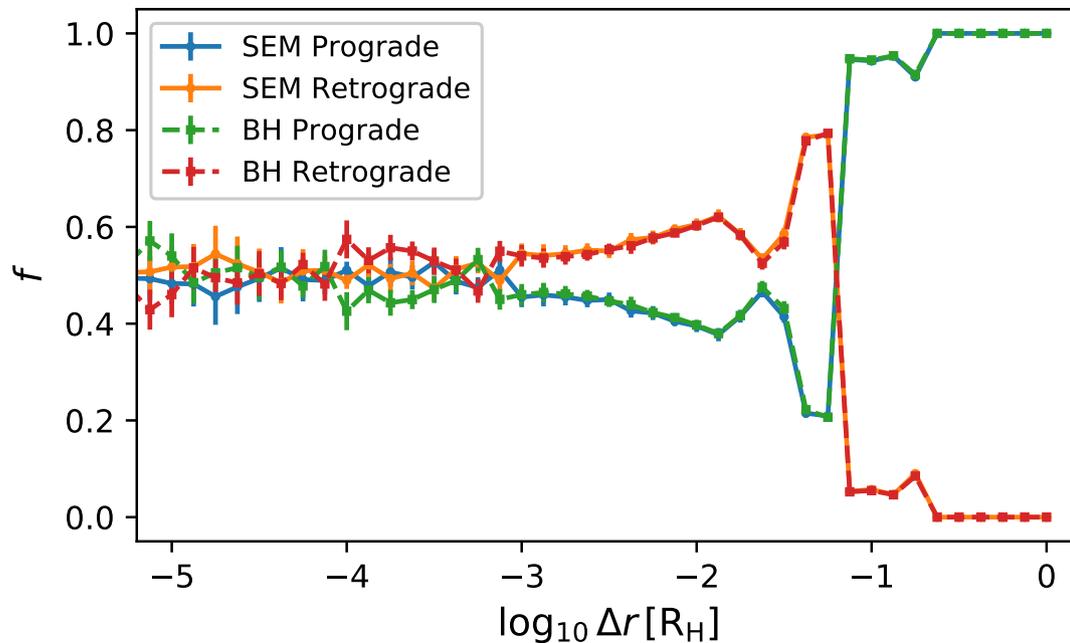
$$\lambda_{\infty}(\Delta r) = \frac{1}{1-3s} \lambda_1(\Delta r) = 1.26\lambda_1(\Delta r)$$

# Prograde vs. Retrograde Dependence on impact parameter



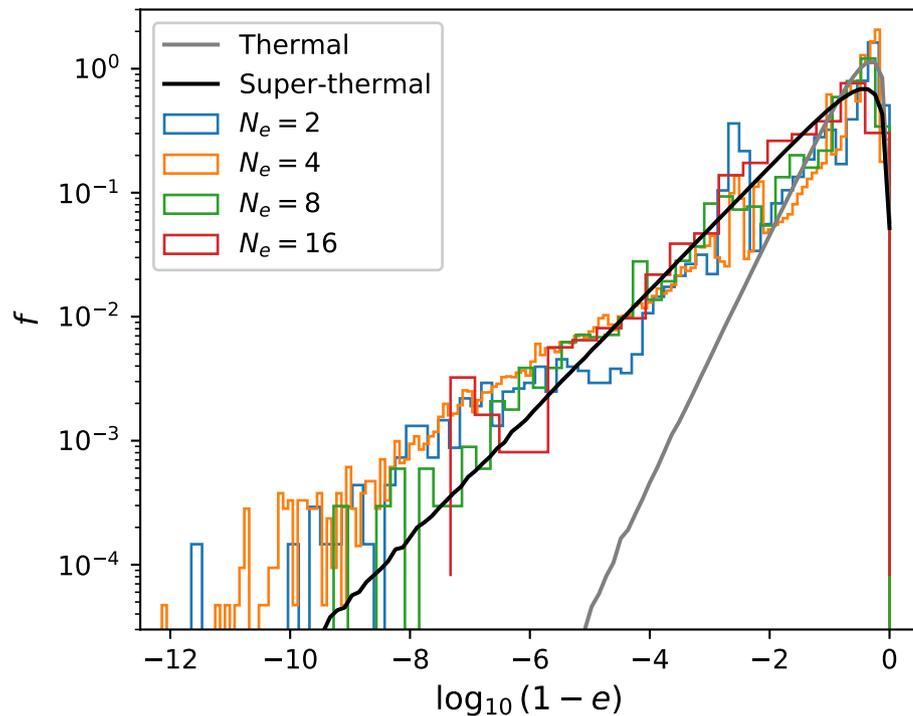
# Prograde vs. Retrograde

## Correlation with separation



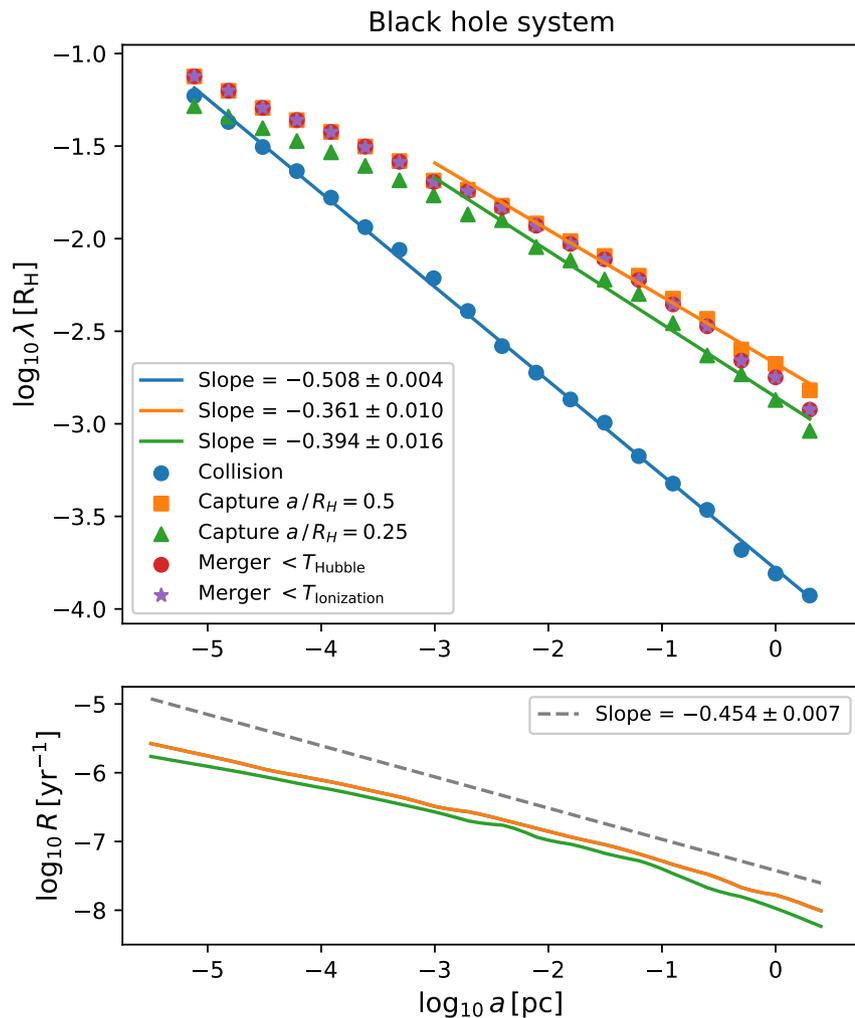
- **Earth-Moon impact:**
  - $(R_E + R_M)/R_H \sim 0.005$
- **Black holes in AGN**
  - $R_{BH}/R_H < 10^{-4}$

# Eccentricity during close encounters



- Approximately super-thermal
- Expected:
  - Planar setup
  - Large difference between  $r_p$  and  $r_a$

# Line section for GW capture



$$\Delta E = \frac{8}{15} \frac{G^7}{c^5} (m_t + m_p)^{\frac{1}{2}} (m_t m_p)^2 r_p^{-\frac{7}{2}} g(e)$$

Turner 1977

Implement energy loss during closest approach

Calculate new apocenter distance

- GW capture dominates throughout
- Merger time is relatively short

# What happens inside the Hill radius?

- Jacobi capture = prolonged, chaotic encounter between 2 bodies in a disk
- Not sensitive to mass ratio
- Approximately super-thermal eccentricities
- Dissipation by gravitational waves can lead to binary capture and mergers
- See Connar's talk (Thursday) for the effects of gas