Evolution of Disk-like Structures in the Galactic Centre

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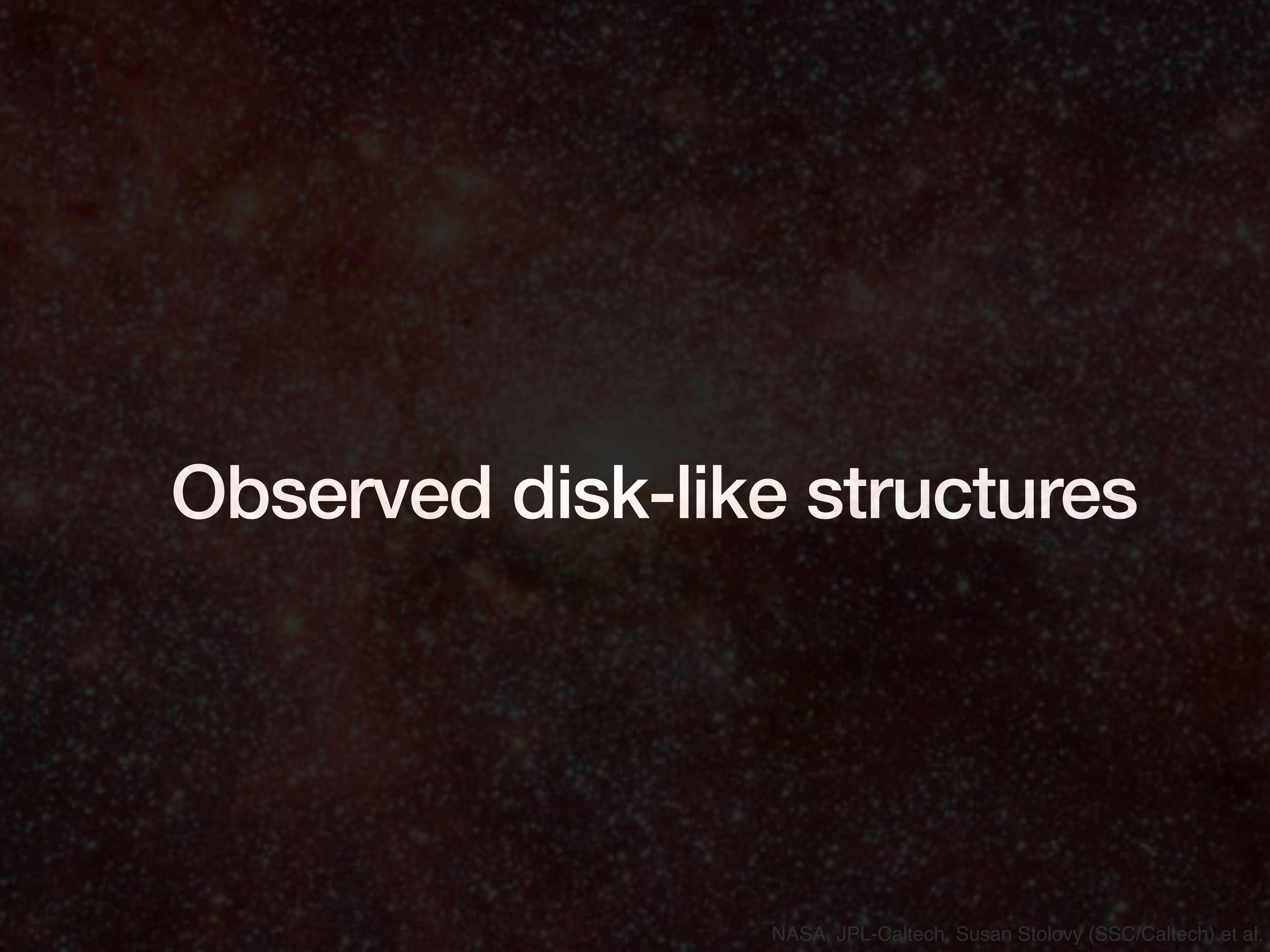
This work was funded by the Grant Agency of Charles University (179123)

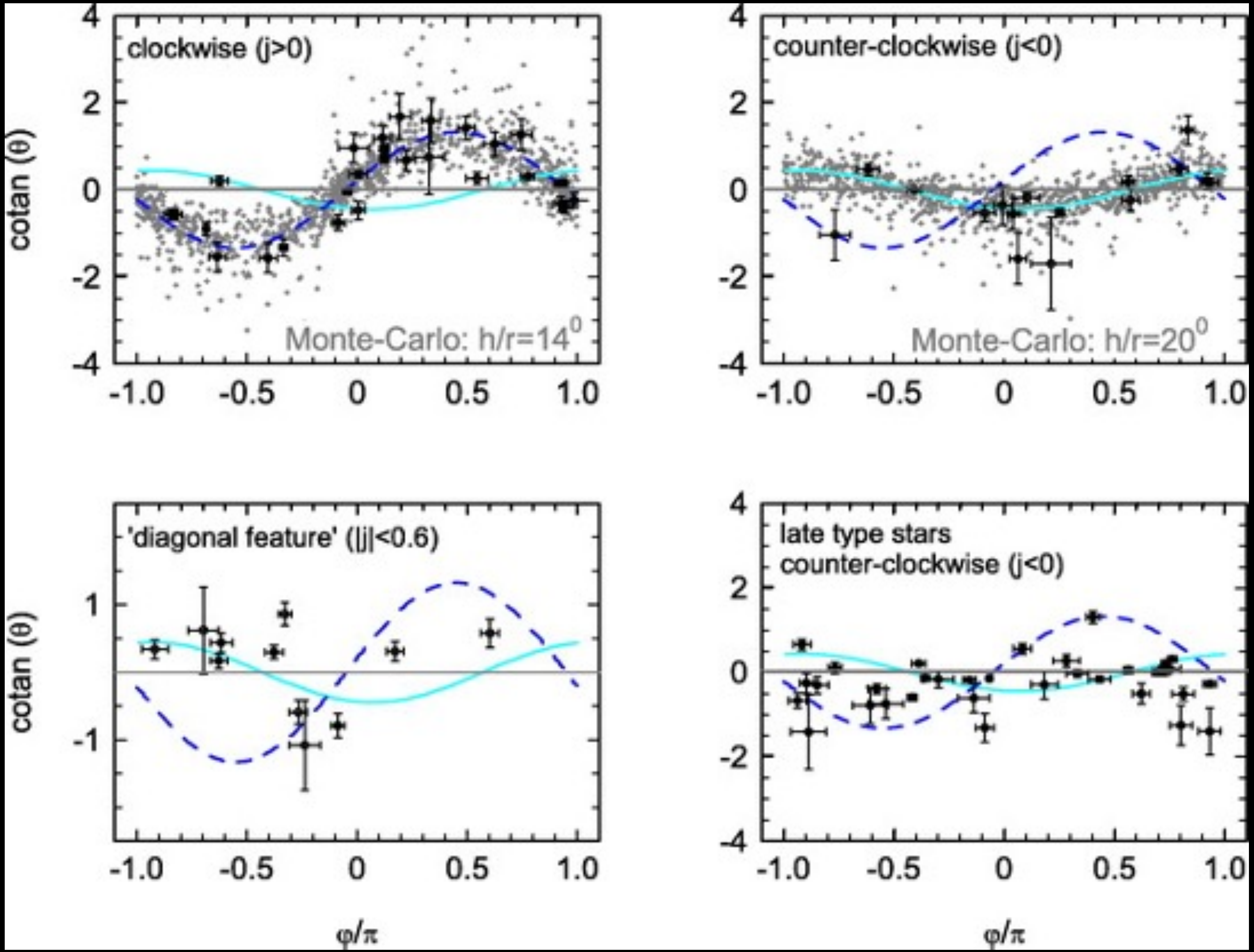
Goals

- Observed structures in the Galactic Centre.
- Simulation of a disk of stars in the GC.
- Understanding the fundamental mechanism.


Observed disk-like structures
NASA, JPL-Caltech, Susan Stolovy (SSC/Caltech) et al.

Young Stellar Disks

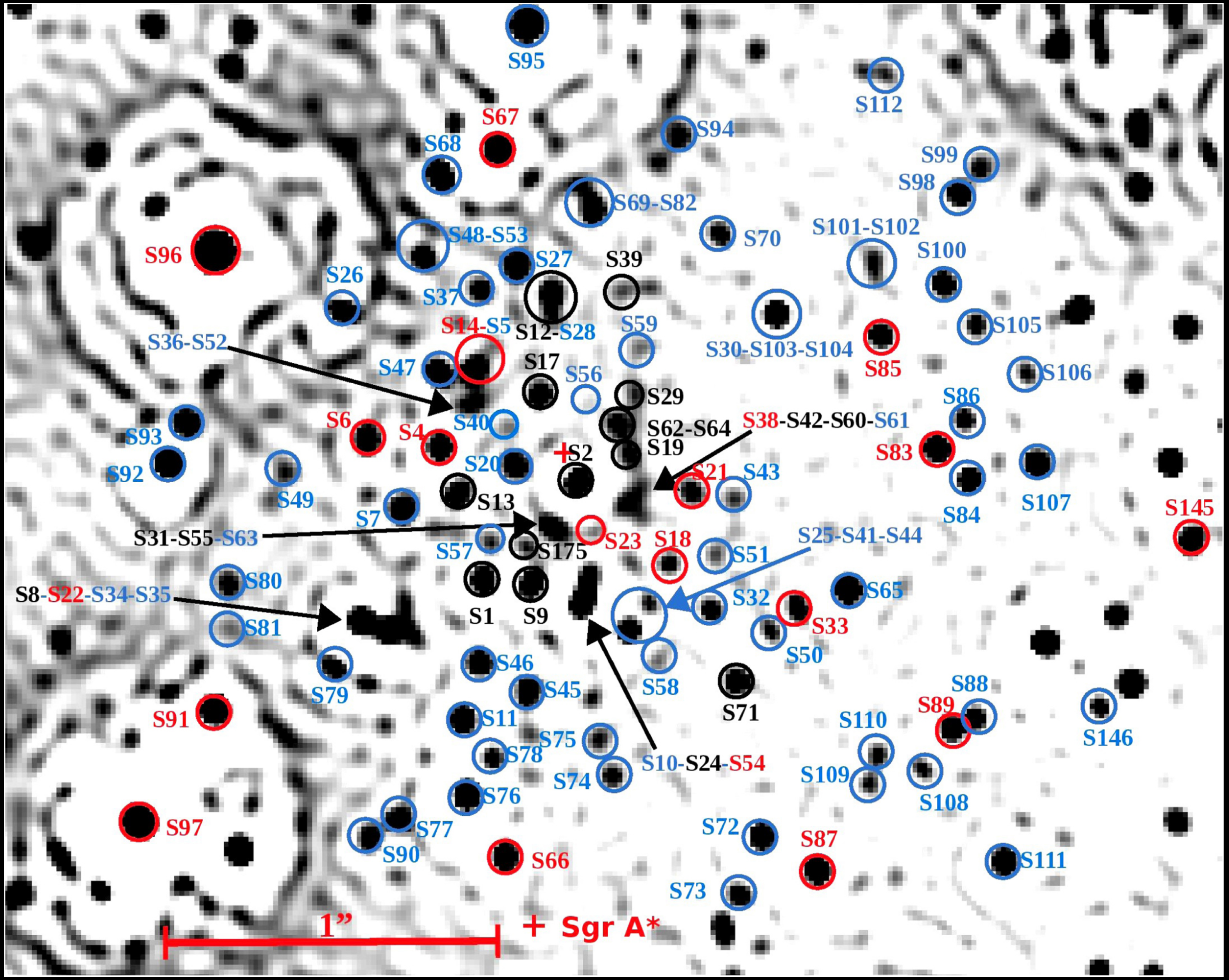
- Primarily OB type stars.
- Situated within distances of 0.04-0.4 pc.
- Levin & Beloborodov (2003), Paumard et al. (2006), Bartko et al. (2009, 2010)



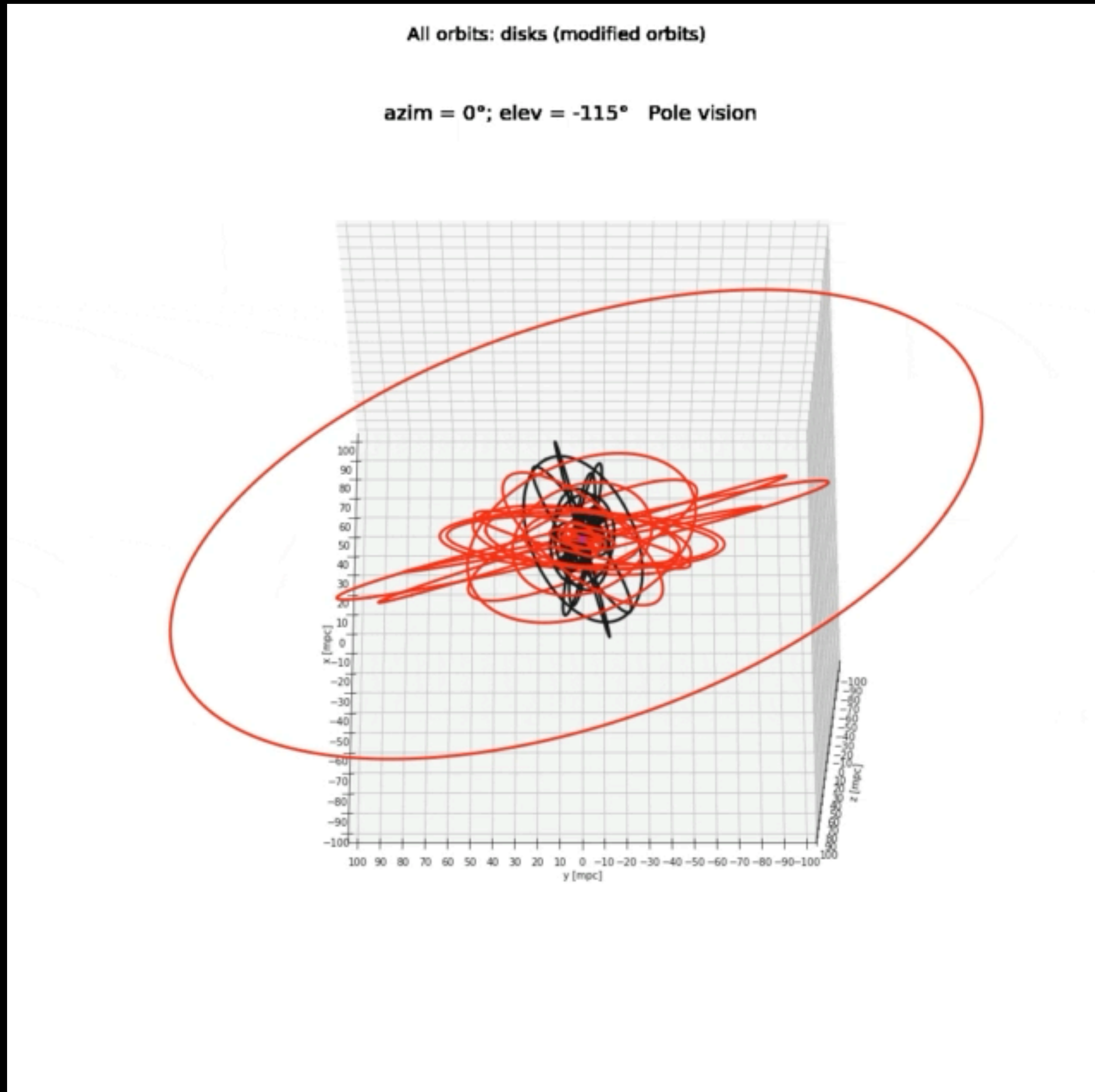
Paumard et al. (2006)

S-stars

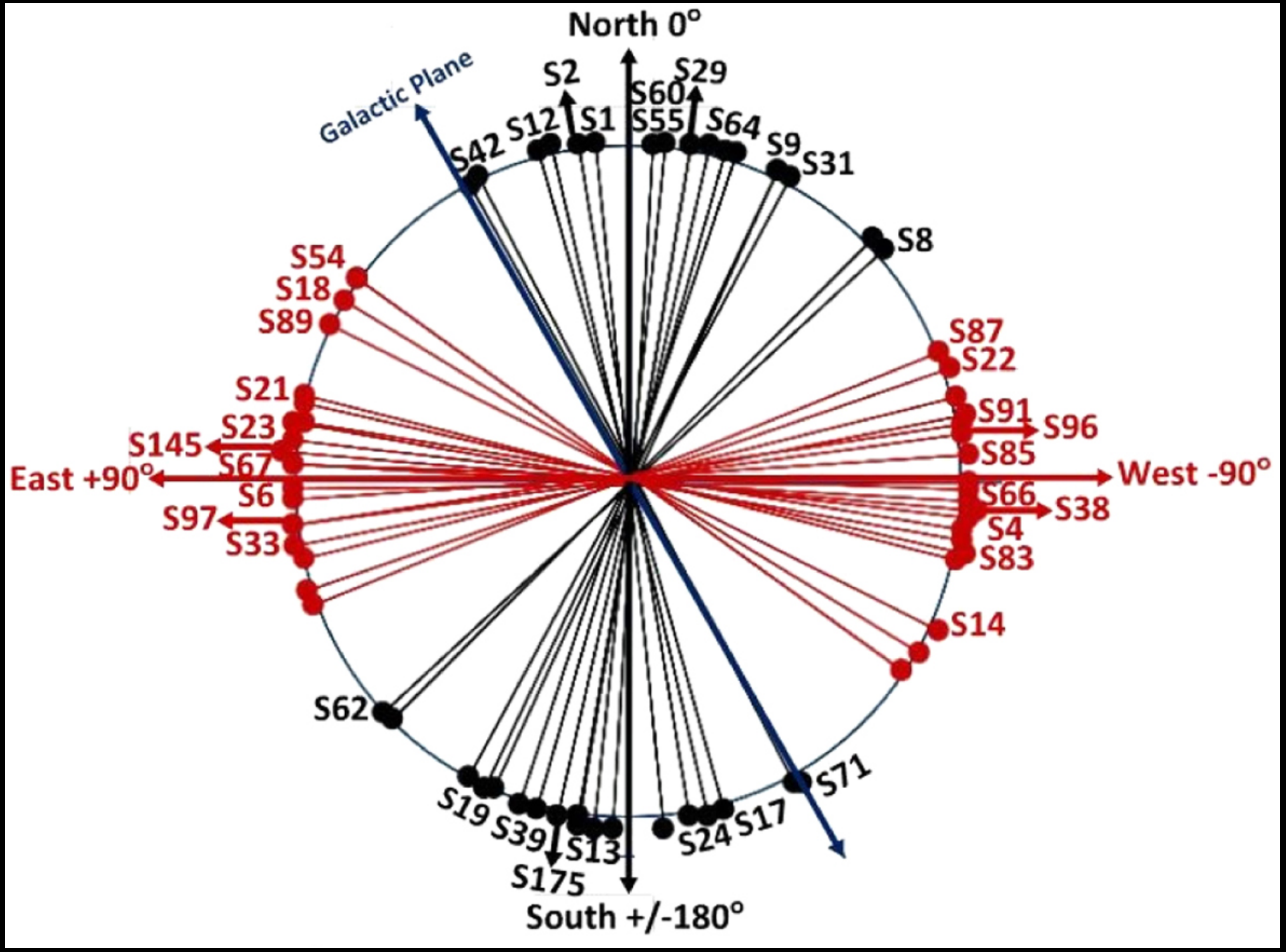
- Young stars that closely orbit Sag A*.
- S2 orbit agrees with Schwarzschild geodesics.
- Their origin is currently not well understood.
- GRAVITY Collaboration. (2020), Do et al. (2009)



Ali et al. (2020)



Ali et al. (2020)

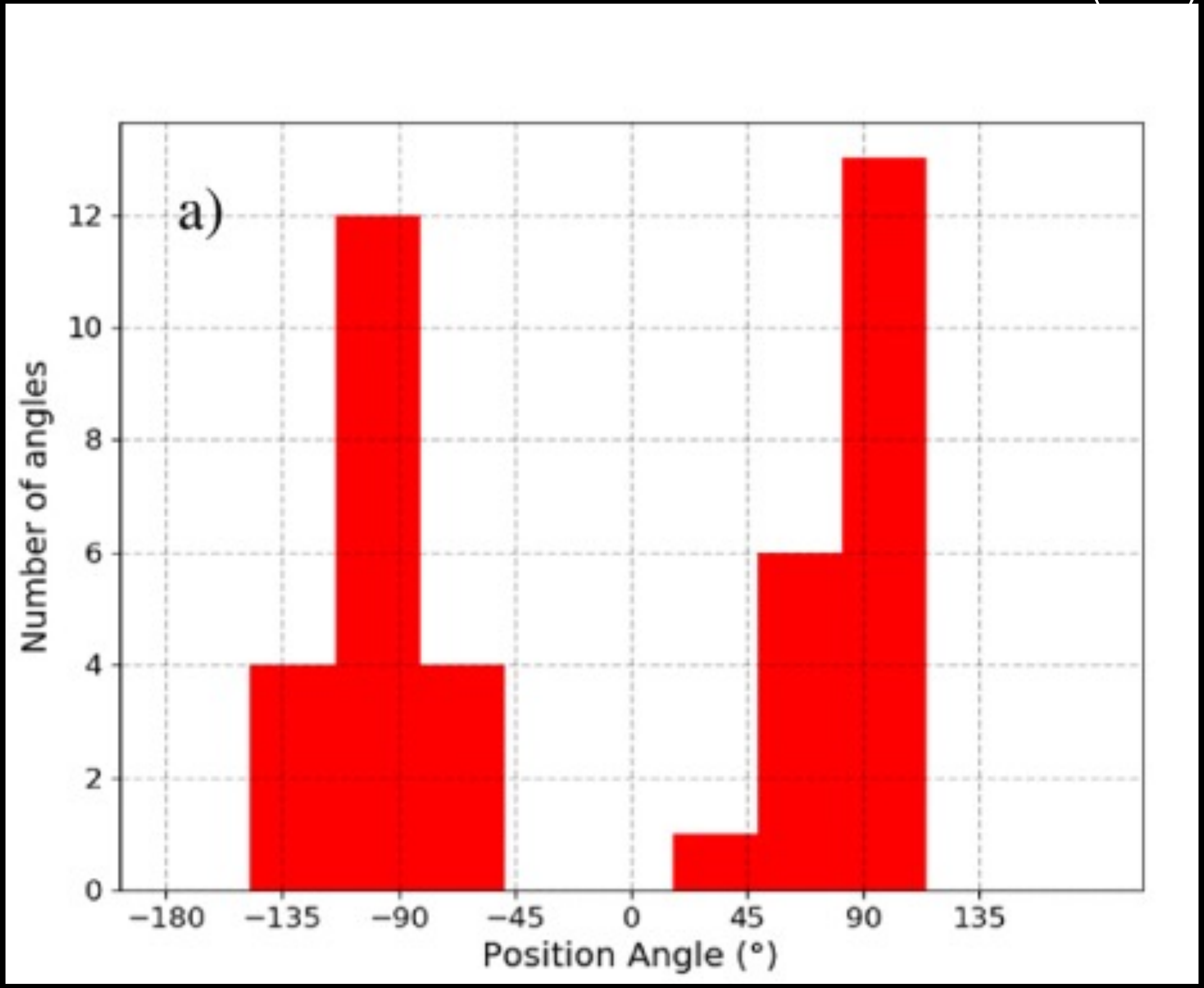


Ali et al. (2020)

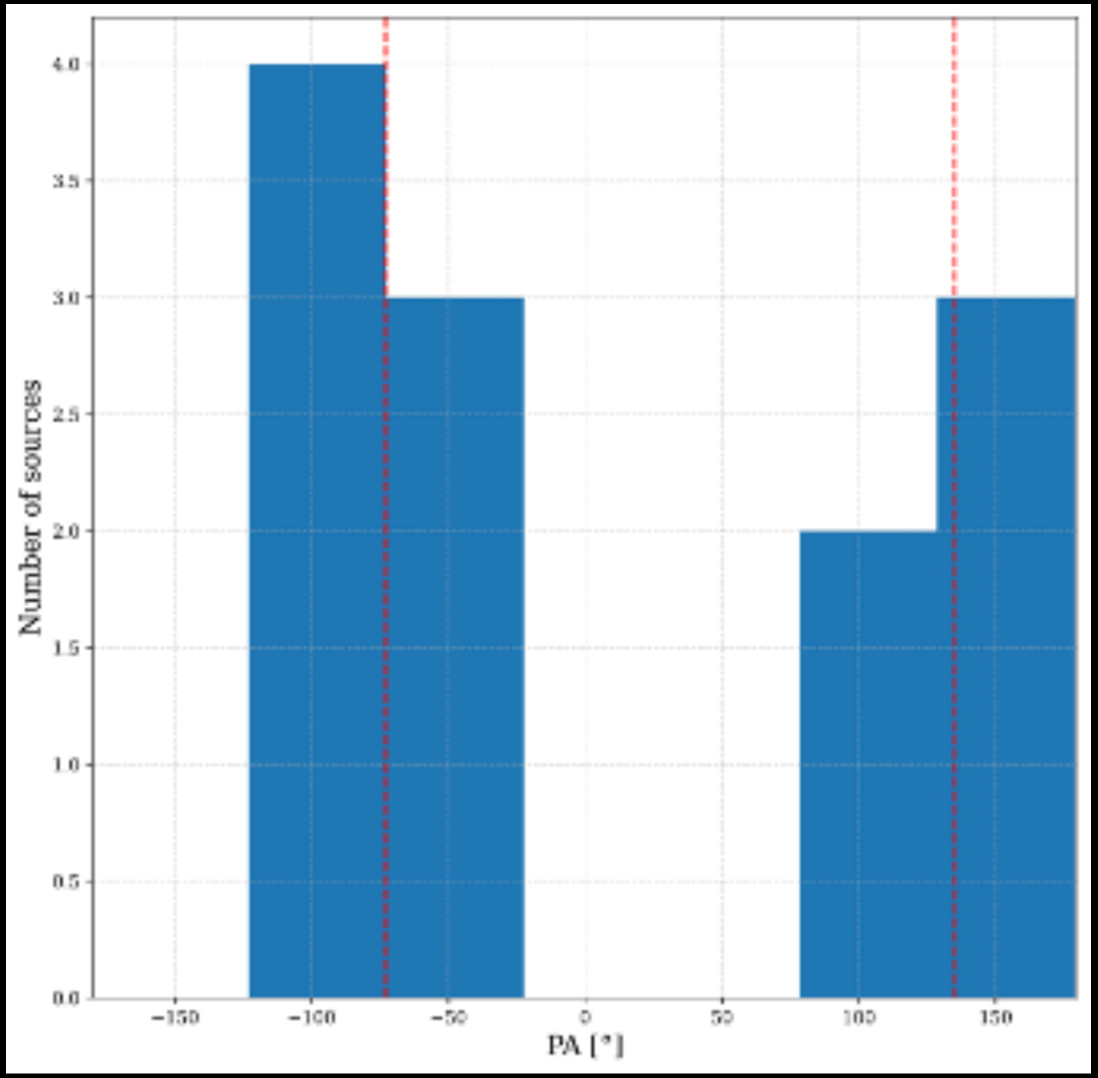
Dusty Objects

- Seem to align with the disks formed with the S-stars.

Ali et al. (2020)



Peißker et al. (Accepted in A&A)



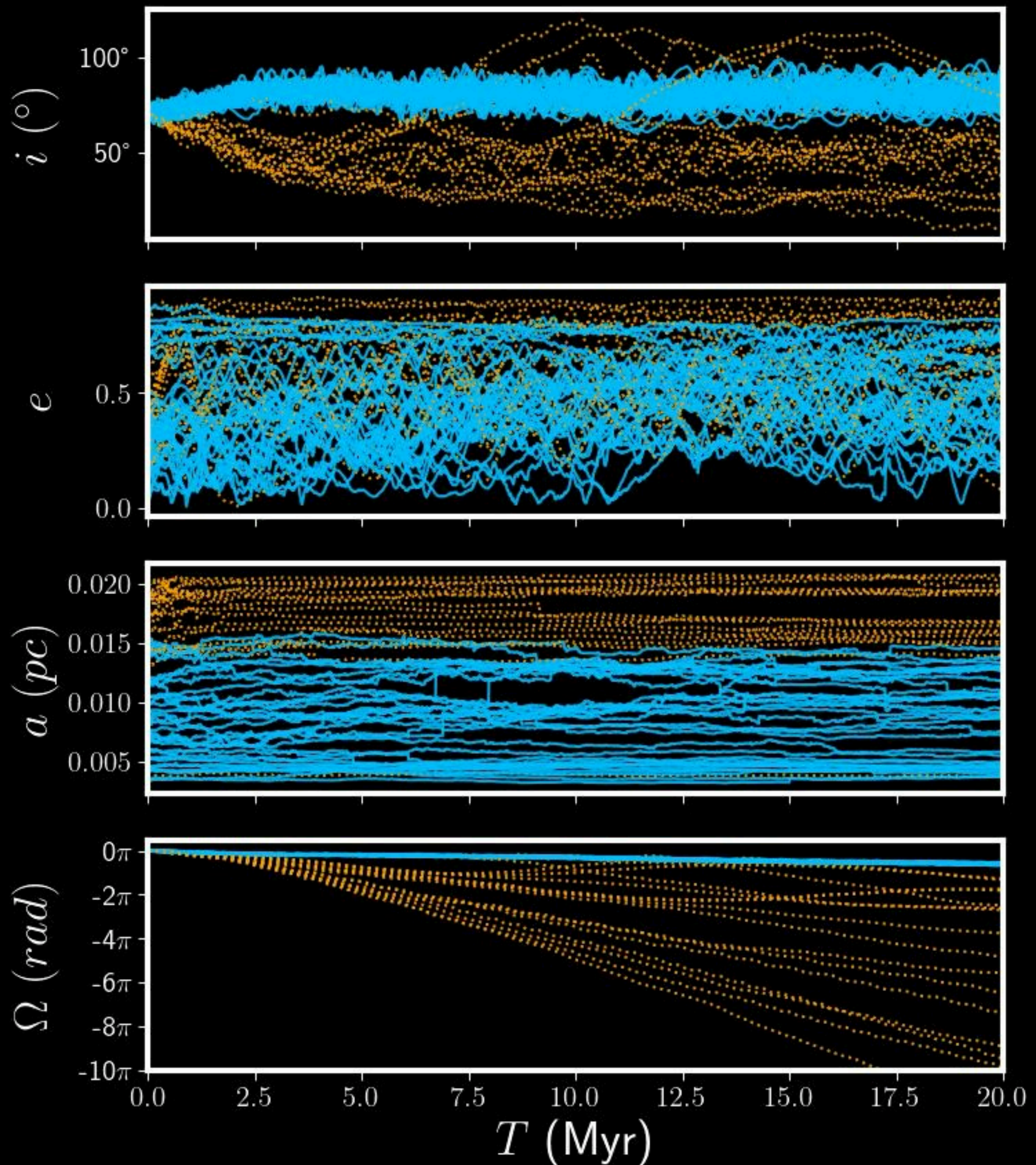
Simulations of disk of stars

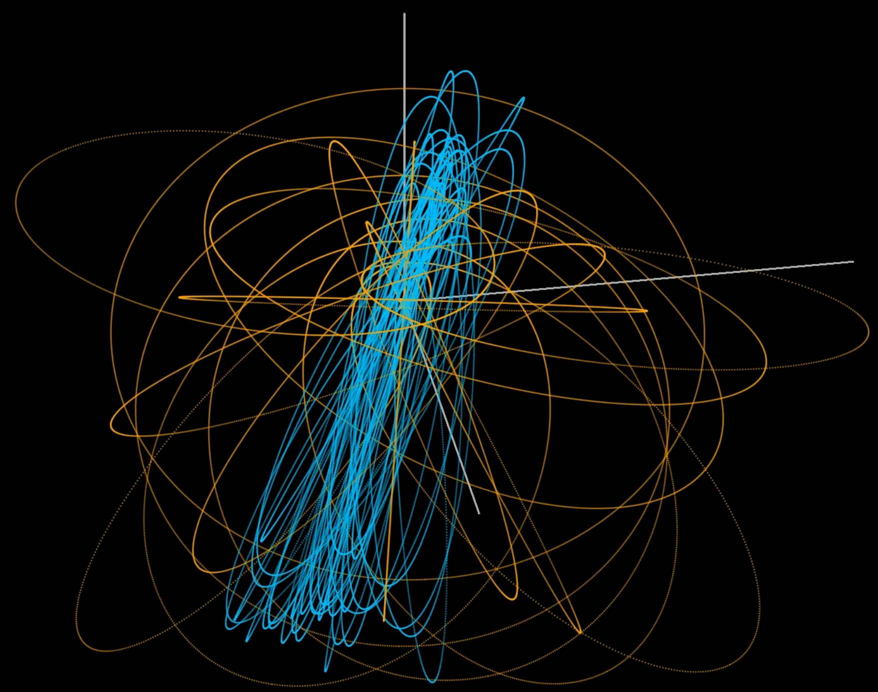
Evolution of a disk of stars
Setup

- Central massive body ($M_{SMBH} = 4 \cdot 10^6 M_\odot$)
- 1 massive perturber on a circular orbit. ($M_p = 10^4 M_\odot, R_p = 0.1 pc$)
- Disk of 50 stars:
  - Salpeter mass distribution function $\xi(m) \propto m^{-2.35}$, $m \in [1,15)$ $\mathrm{M}_\odot$
  - $e \in [0,1)$
  - $a \in [0.0035, 0.02)$ pc
  - $i \in [65°, 75°)$
  - $\Omega = 0°$
  - $\omega = 0°$
  - $\nu \in [0, 2\pi)$

Evolution of a disk of stars

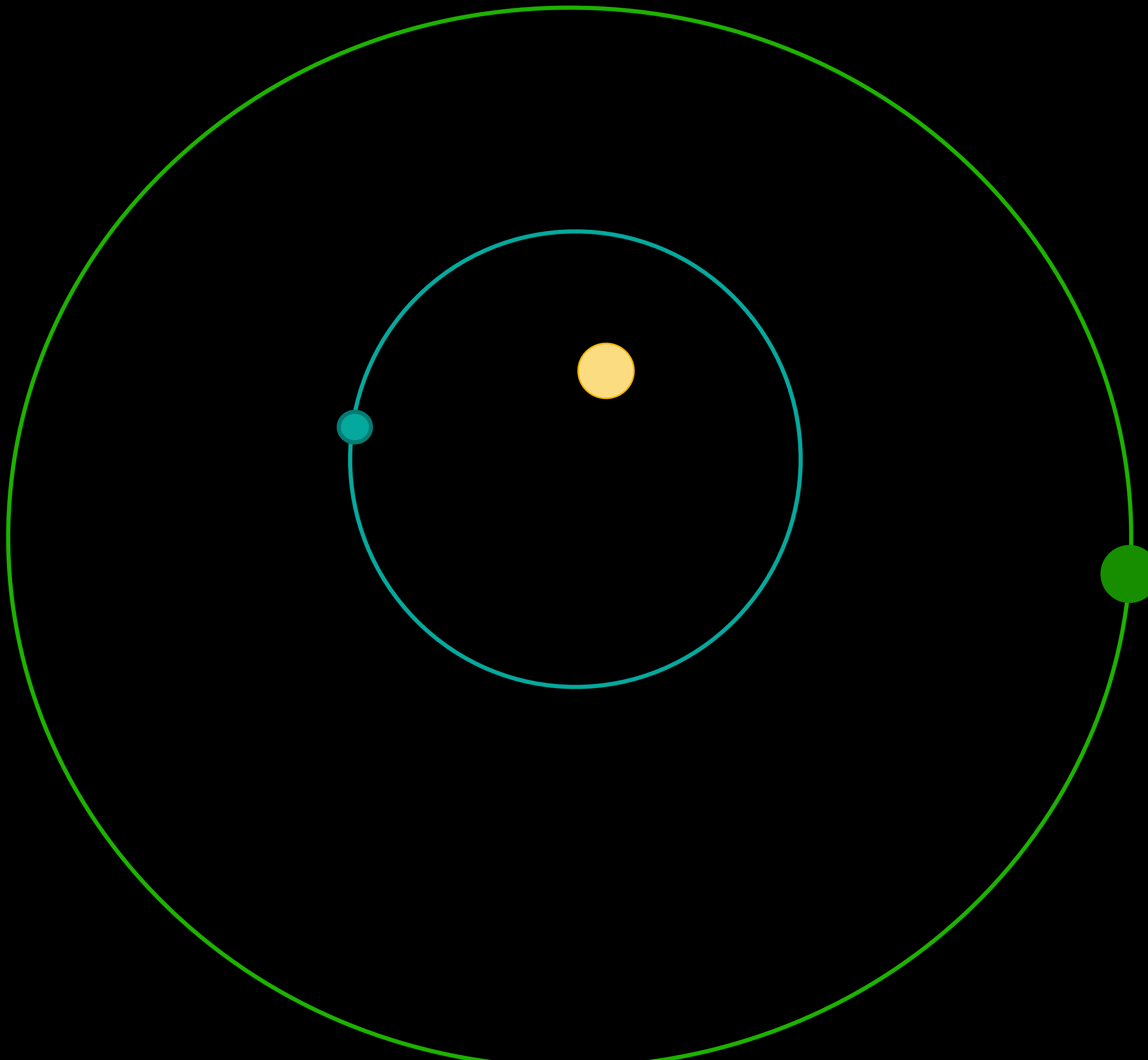
Evolution



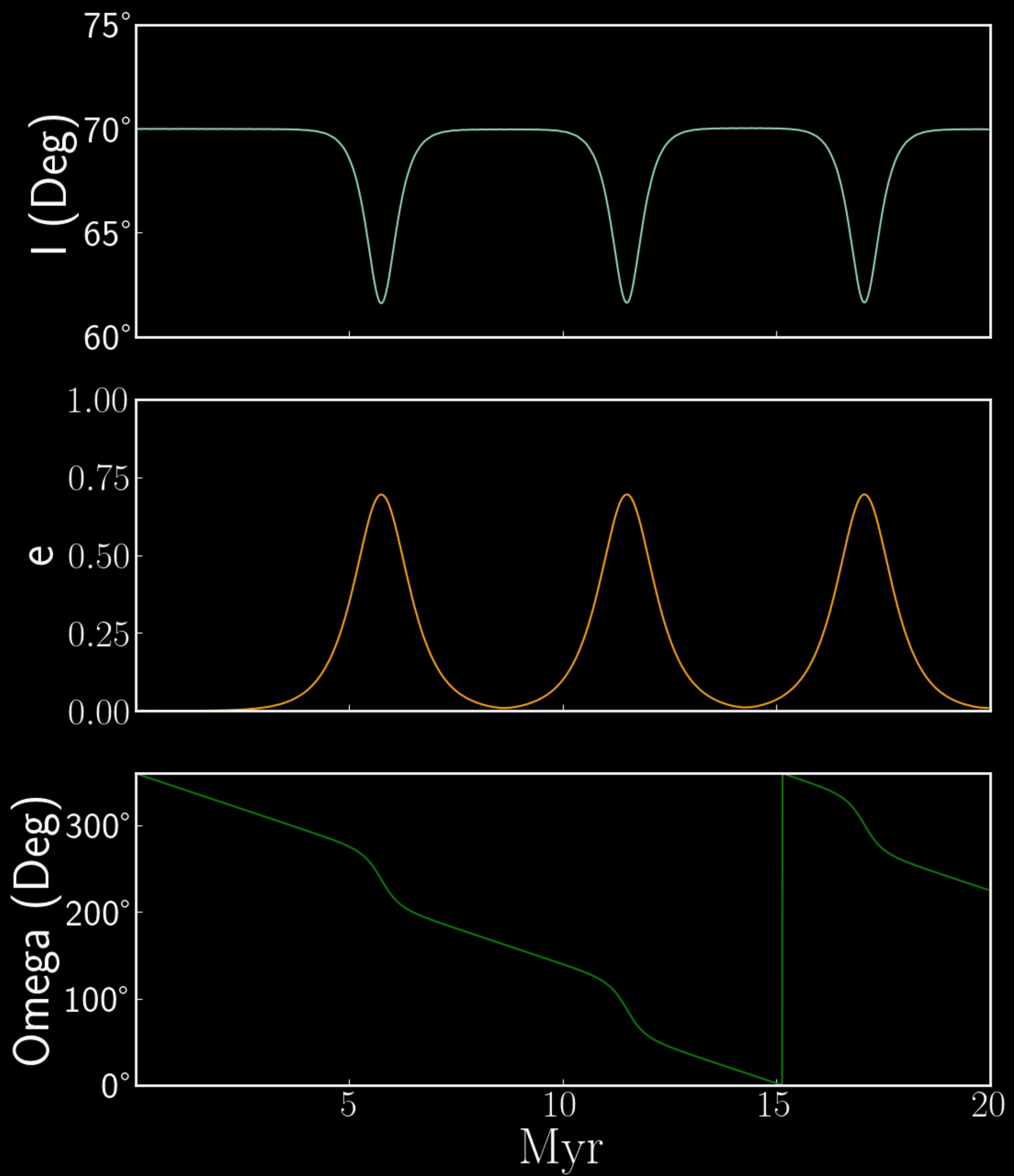


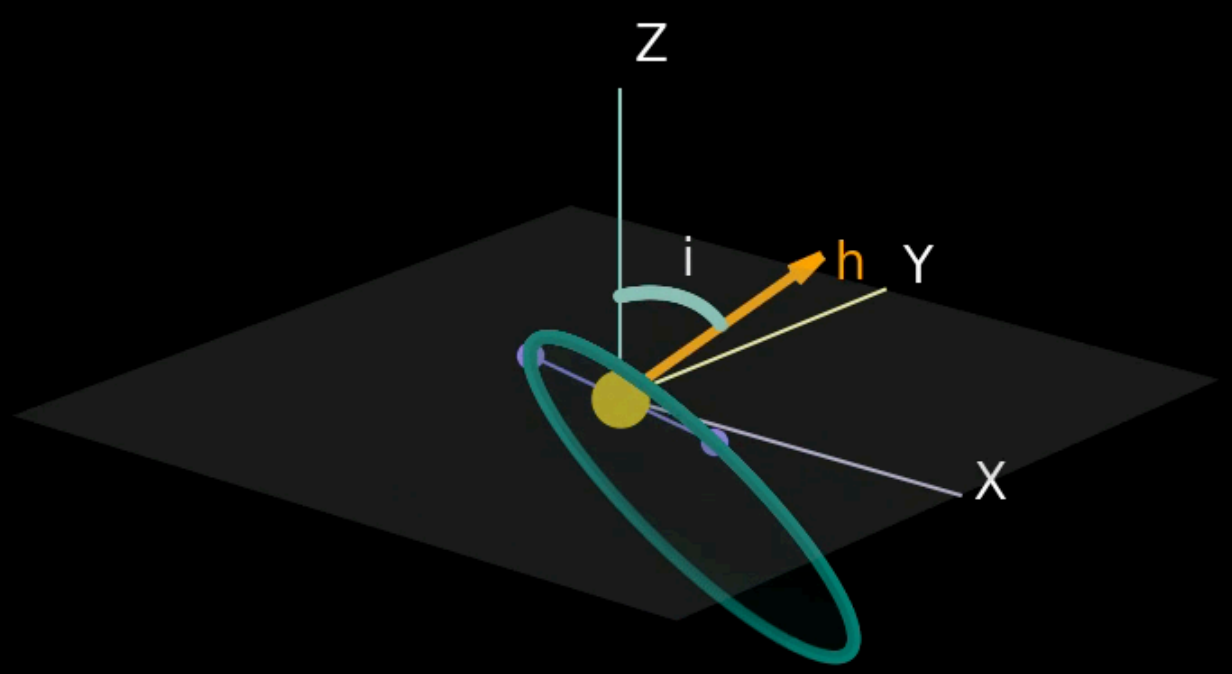
3-body
Hierarchical Setup

3-body
Hierarchical Setup



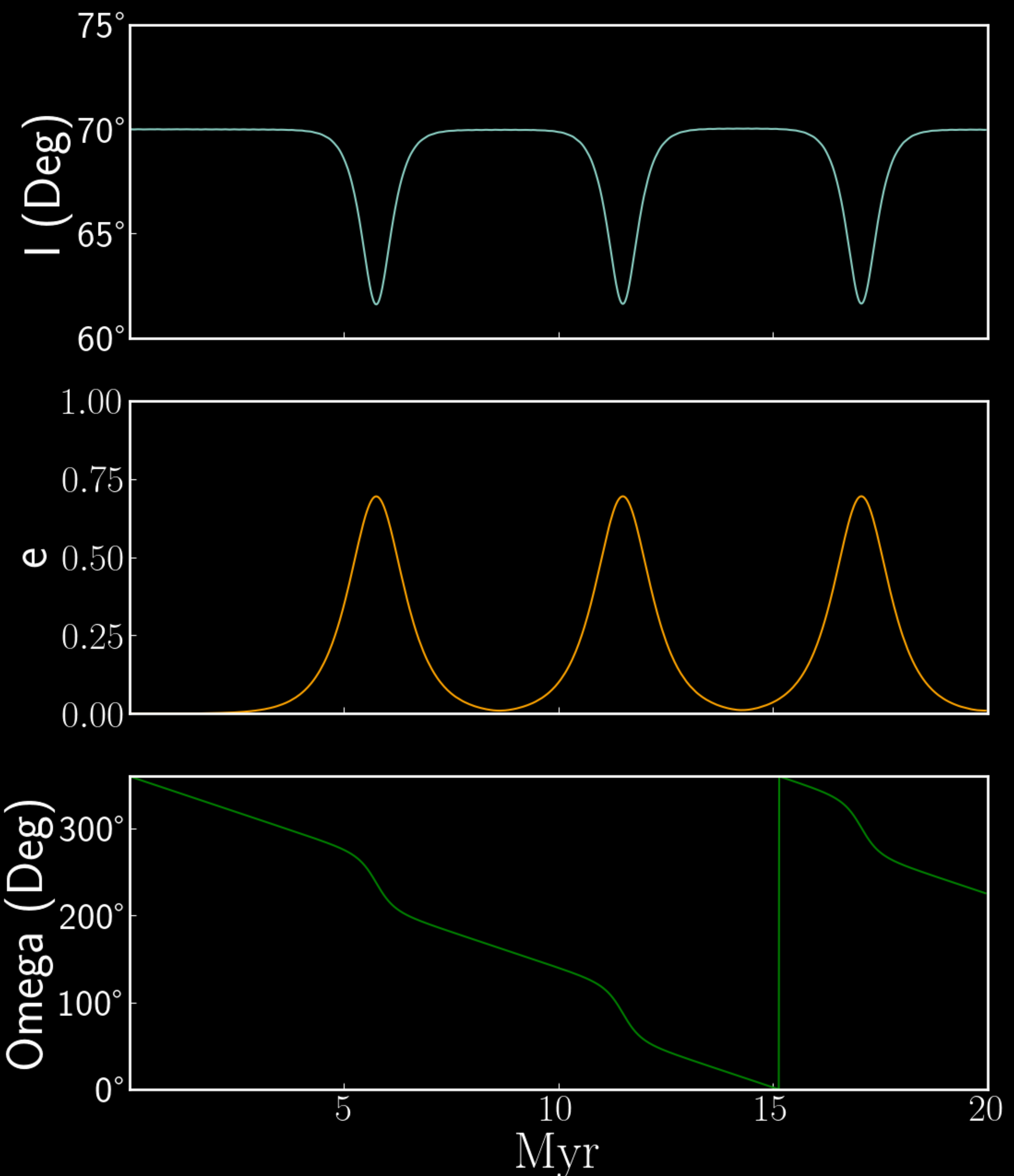
Kozai—Lidov Oscillations





Kozai—Lidov Oscillations

- A binary system perturbed by a massive body.
- Angular momentum of inner binary is no longer conserved.
- $M_{SMBH} = 4 \cdot 10^6 M_\odot$
  $M_p = 10^4 M_\odot$
  $R_p = 0.1pc$
  $M_{test} = 10M_\odot$
  $R_{test} = 2.2 \cdot 10^{-2}pc$



Kozai—Lidov Oscillations

- The Kozai constant is conserved: $C \equiv \sqrt{1 - e^2} \cos i$.
- $C = \sqrt{3/5} \approx 0.77$ sets the critical value.
- $C < \sqrt{3/5}$ results in a separatrix at $e = 0$.

Kozai—Lidov Oscillations

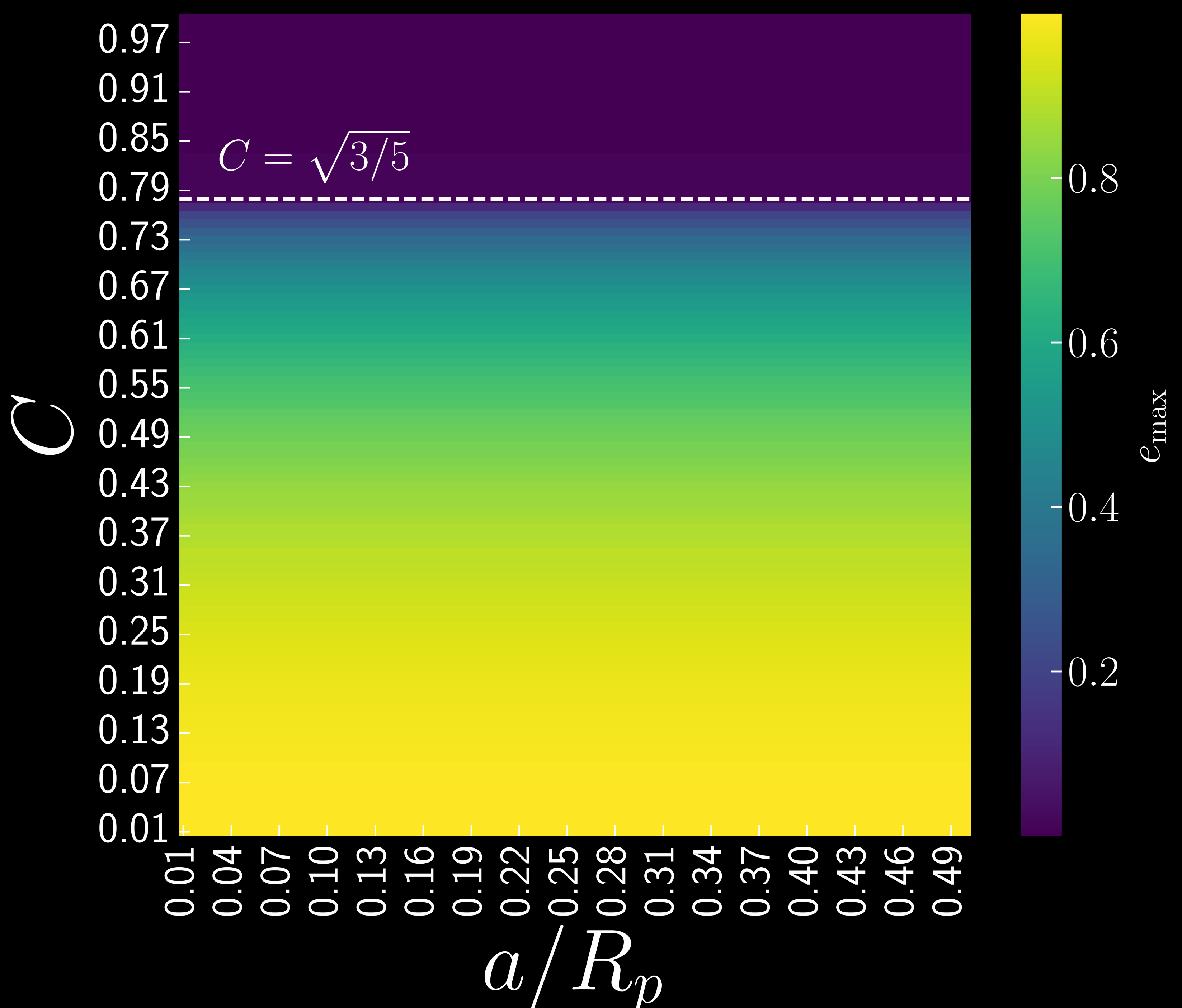
$M_{SMBH} = 4 \cdot 10^6 M_\odot$

$M_{test} = 1 M_\odot$

$M_p = 10^4 M_\odot$

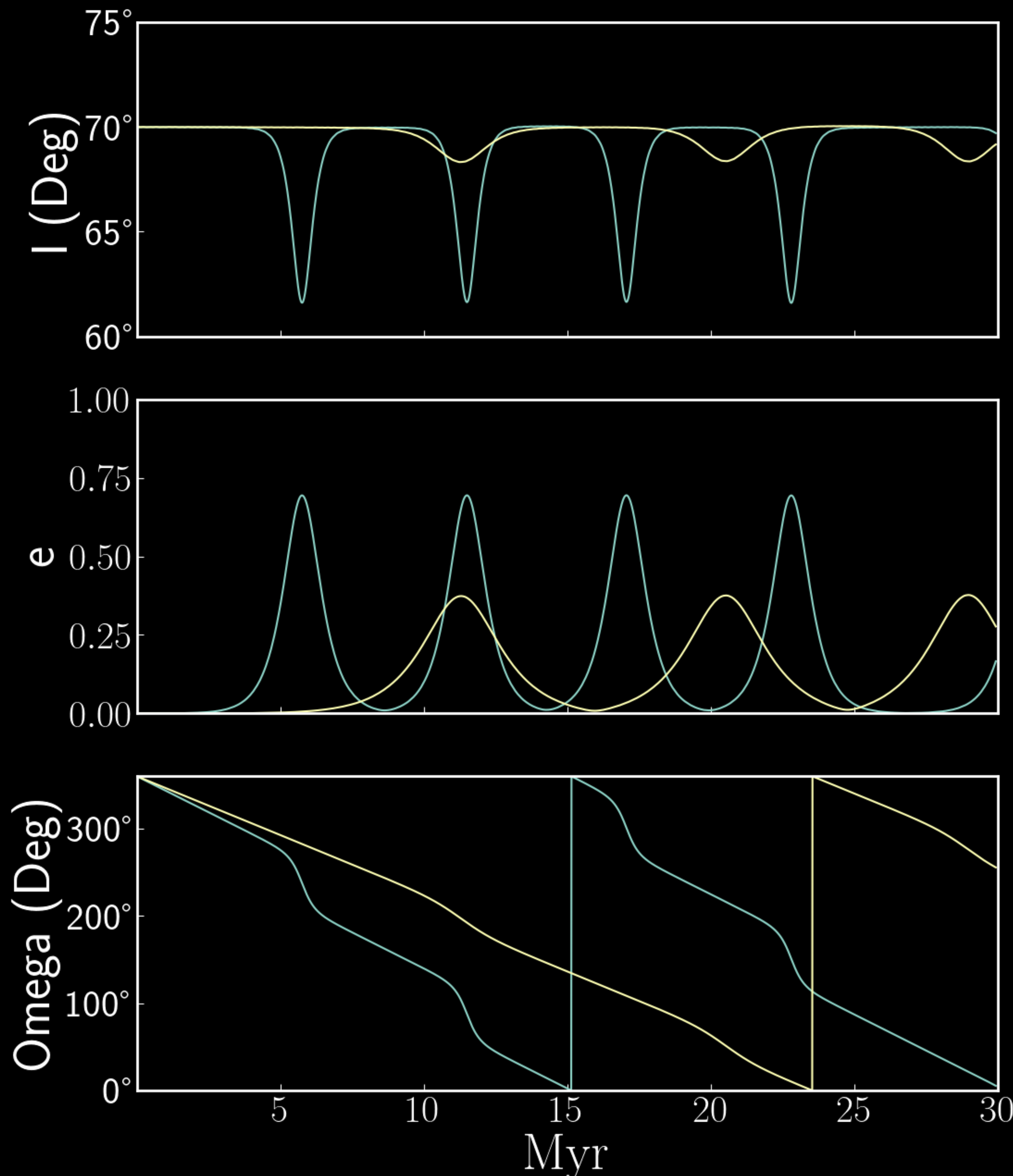
$R_p = 0.1 pc$

$e_{ini} = 10^{-4}$



Kozai—Lidov Oscillations

- Oscillations damped due to spherically symmetric external potential.
- External potential can be due to:
  - extended stellar cusp.
  - relativistic corrections to newtonian dynamics.
- $M_{SMBH} = 4 \cdot 10^6 M_\odot$
  $M_{test} = 10 M_\odot$
  $R_{test} = 1.5 \cdot 10^{-2} pc$
  $M_p = 10^4 M_\odot$
  $R_p = 0.1 pc$



Kozai—Lidov Oscillations

With 1st-Order PN Corrections

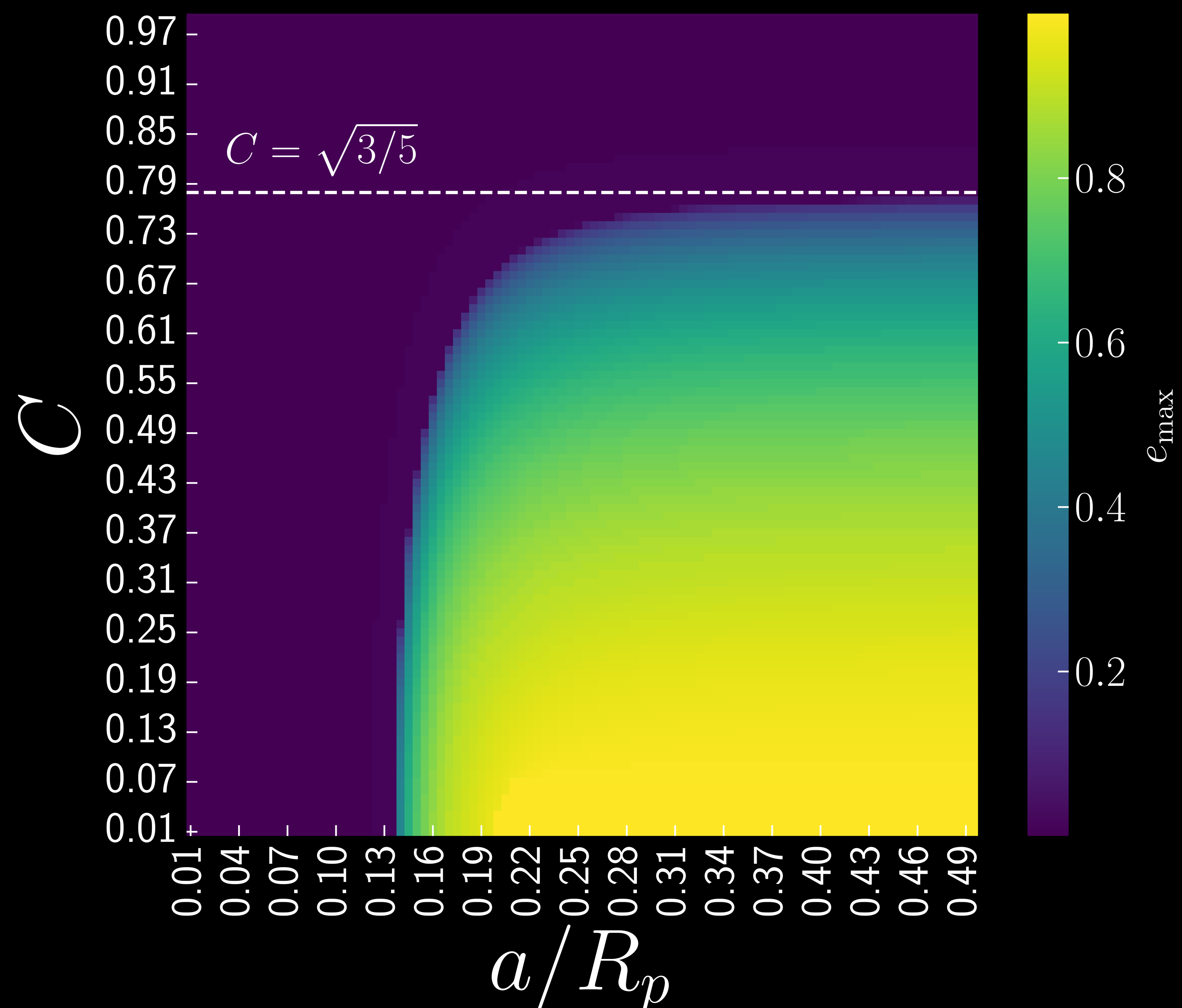
$M_{SMBH} = 4 \cdot 10^6 M_\odot$

$M_{test} = 1 M_\odot$

$M_p = 10^4 M_\odot$

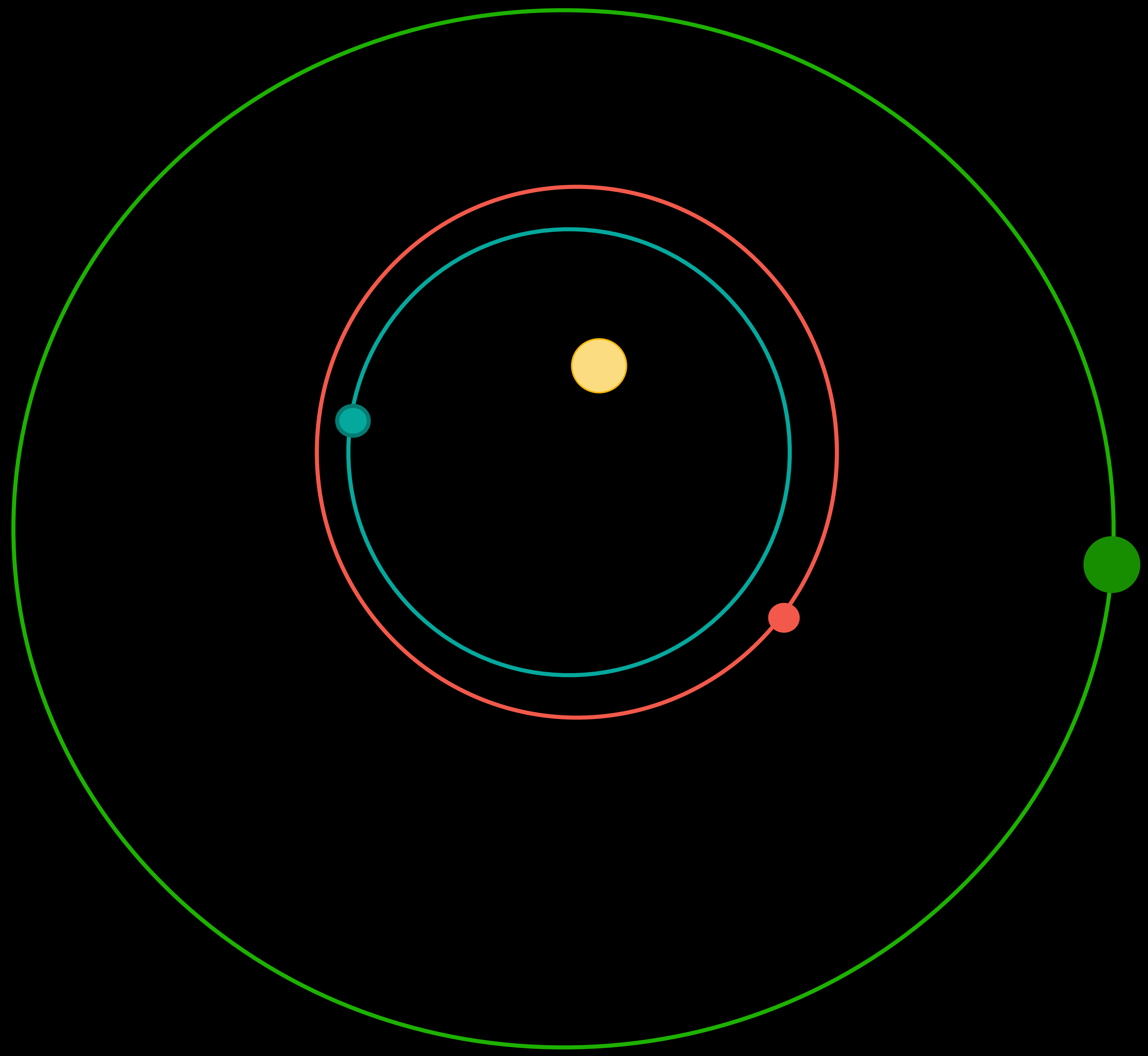
$R_p = 0.1 pc$

$e_{ini} = 10^{-4}$



4-body
Hierarchical Setup

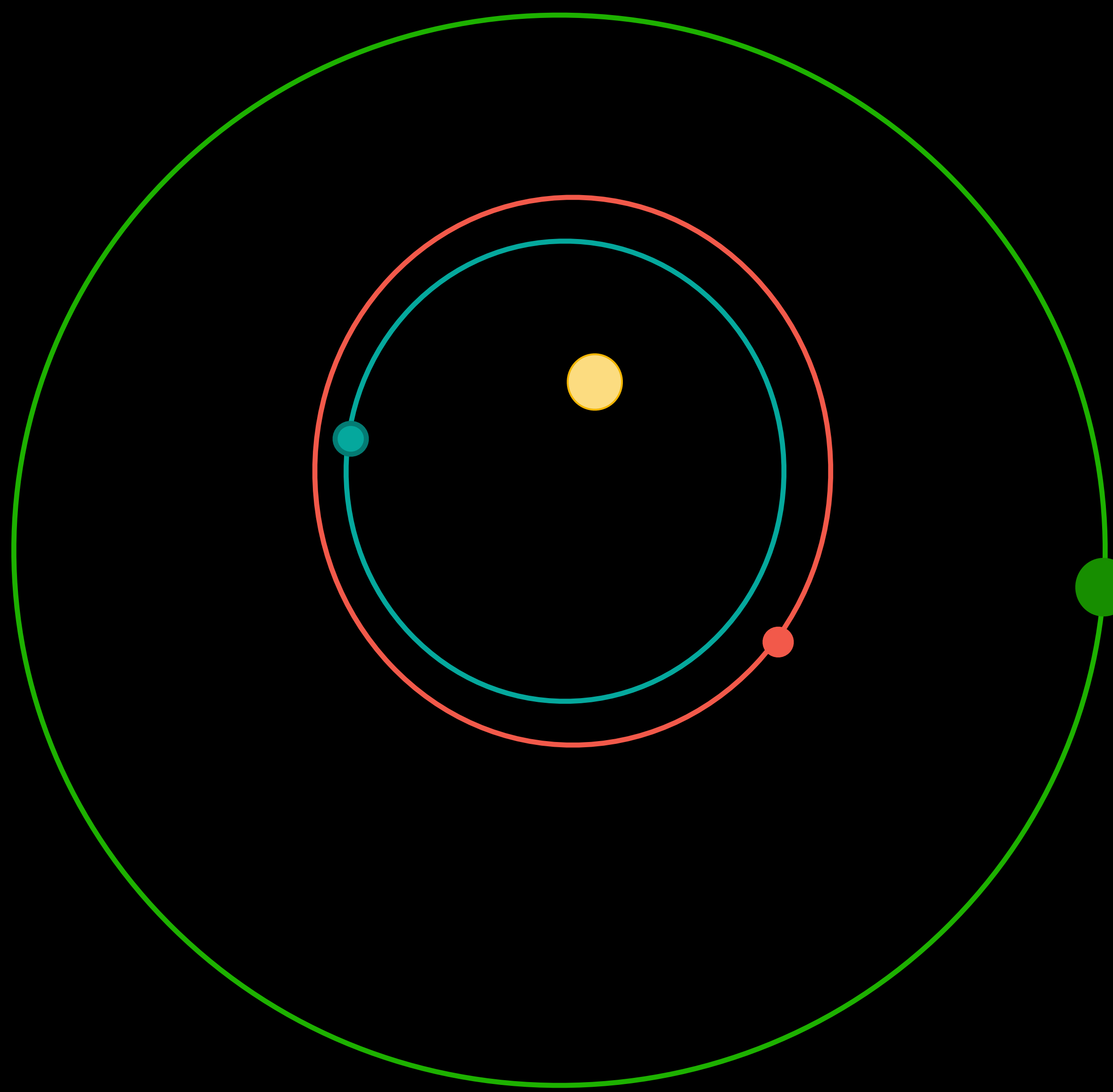
4-body
Hierarchical Setup



VHS Mechanism

Haas, Šubr & Vokrouhlický (2011)

- Four-body system
  - Central massive body
  - 1 massive perturber on circular orbit.
  - 2 light bodies on circular orbits:
- Spherical external potential from stellar cusp to damp KL oscillations.



VHS Mechanism

Haas, Šubr & Vokrouhlický (2011)

- Four body system
  - Central massive body ($M_{SMBH} = 3.5 \cdot 10^6 M_\odot$)
  - 1 massive perturber on circular orbit. ($M_{CND} = 0.3 M_{SMBH}, R_{CND} = 1.5pc$)
  - 2 light bodies on circular orbits:
    - $a_1 = 0.04 R_{CND}, a_2 = 0.05 R_{CND}$
    - $e_1 = e_2 = 0, i_1 = i_2 = 70^\circ$

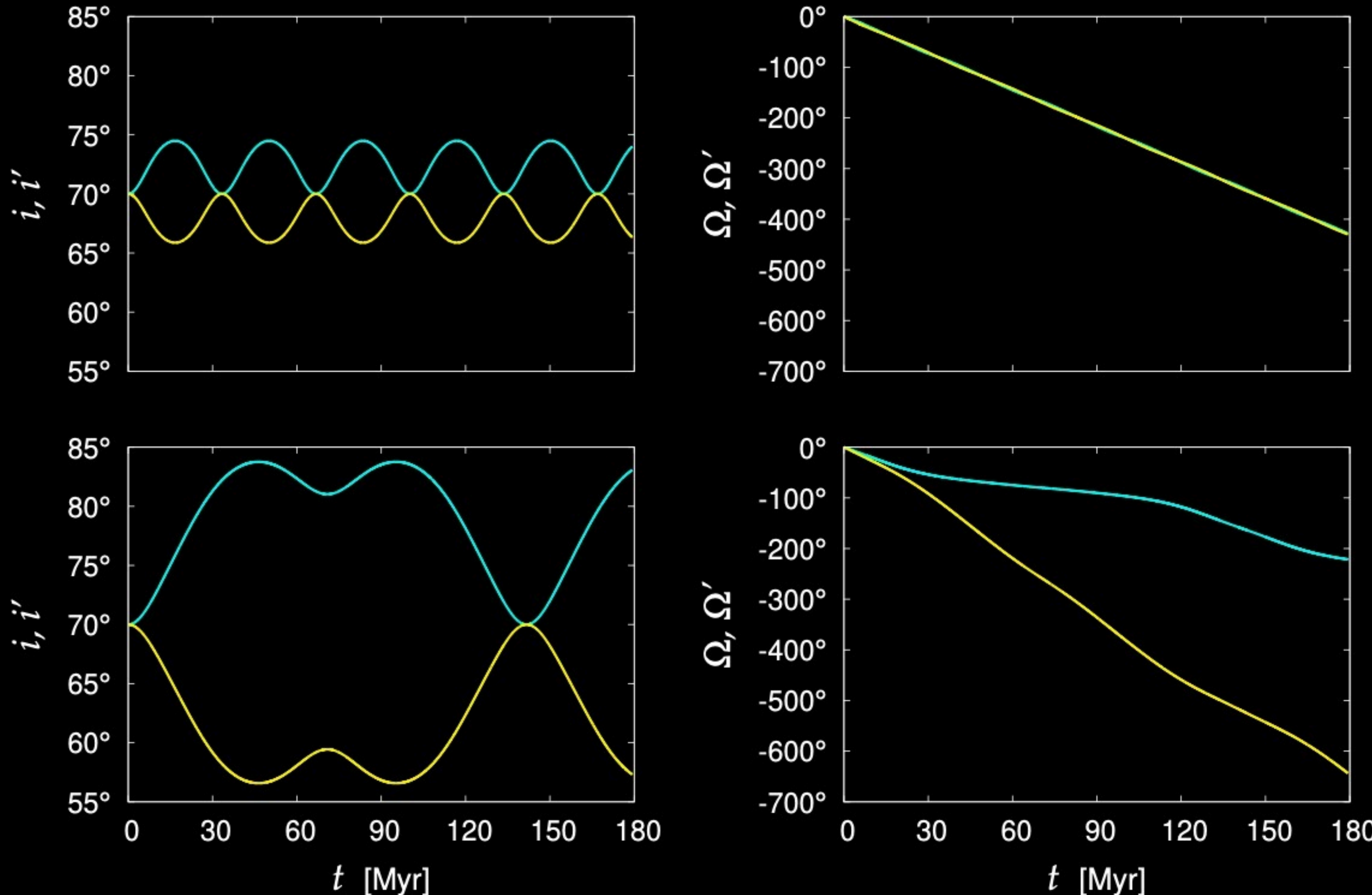
	Strong Interaction	**Weak Interaction**
m_1	$9 \cdot 10^{-6} M_{SMBH}$	$5 \cdot 10^{-6} M_{SMBH}$
m_2	$9 \cdot 10^{-6} M_{SMBH}$	$5 \cdot 10^{-6} M_{SMBH}$

- Spherical external potential from stellar cusp to damp KL oscillations.

VHS Mechanism

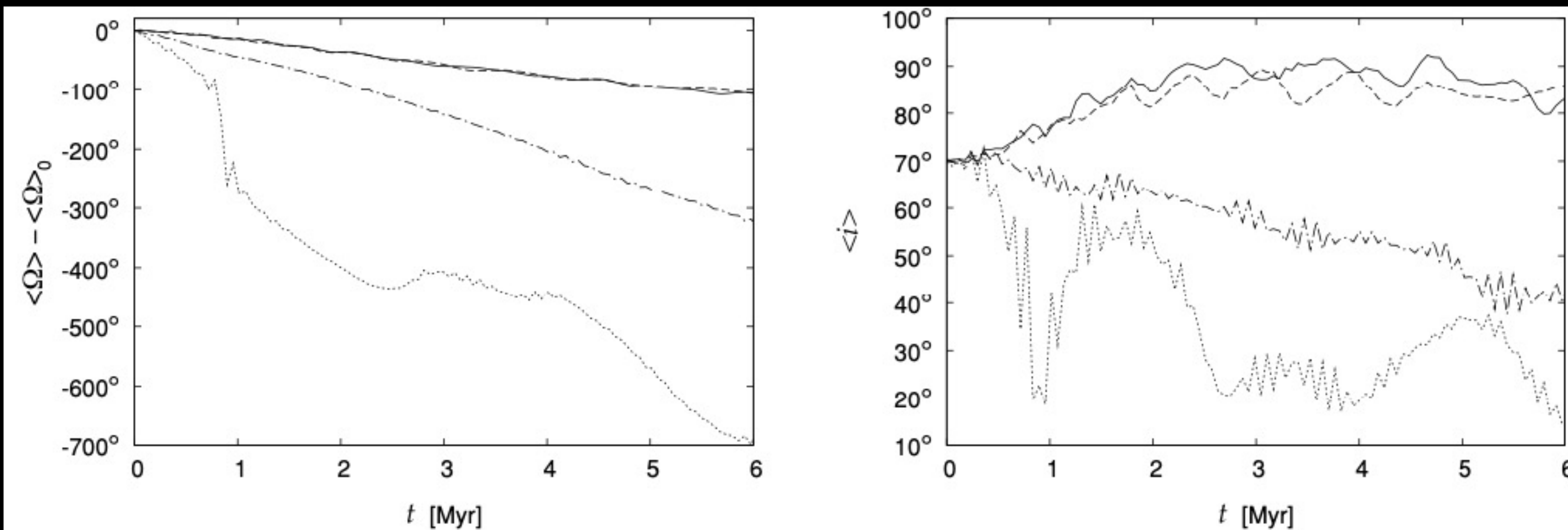
Strong Interaction

Weak Interaction



Haas, Šubr & Vokrouhlický (2011)

VHS Mechanism



Haas, Šubr & Kroupa (2011)

VHS Mechanism with relativistic corrections

Code

- We use *ARWV*, a N-body integration code which calculates PN corrections upto 2.5 orders (Chassonnery et al. 2019).
- It uses the *ARCHAIN* algorithm developed by Mikkola and Merritt (2006, 2008) to calculate velocity dependent forces.

Setup

- Four-body system
  - Central massive body ($M_{SMBH} = 4 \cdot 10^6 M_\odot$)
  - 1 massive perturber on circular orbit. ($M_p = 10^4 M_\odot, R_p = 0.1pc$)
  - 2 light bodies

VHS Mechanism with relativistic corrections

Strong Interaction - Zero eccentricity

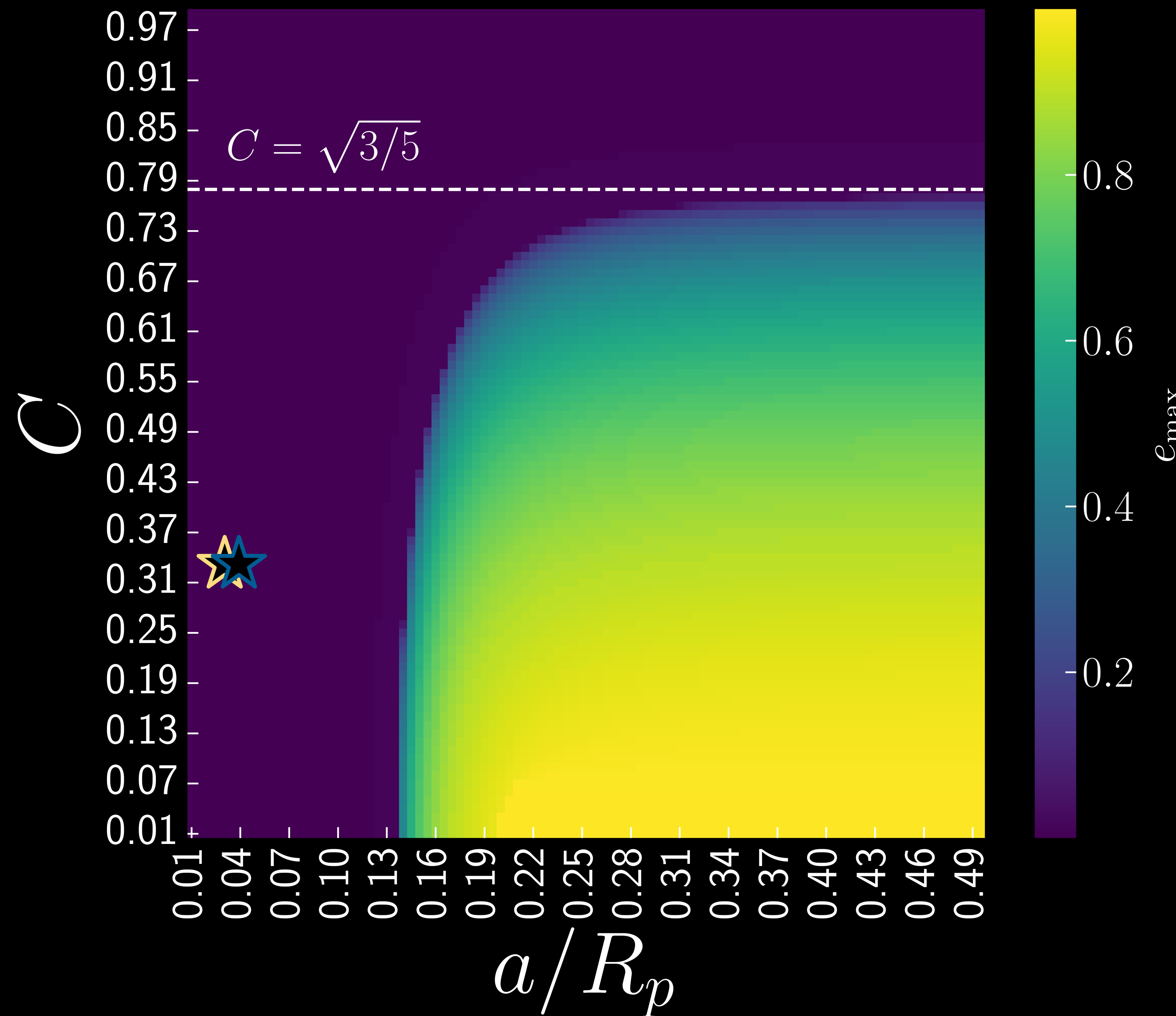
$m = m' = 10\ M_\odot$

$a = 0.0035\ pc$

$a' = 0.0045\ pc$

$i_{ini} = i'_{ini} = 70°$

$e = e' = 0$



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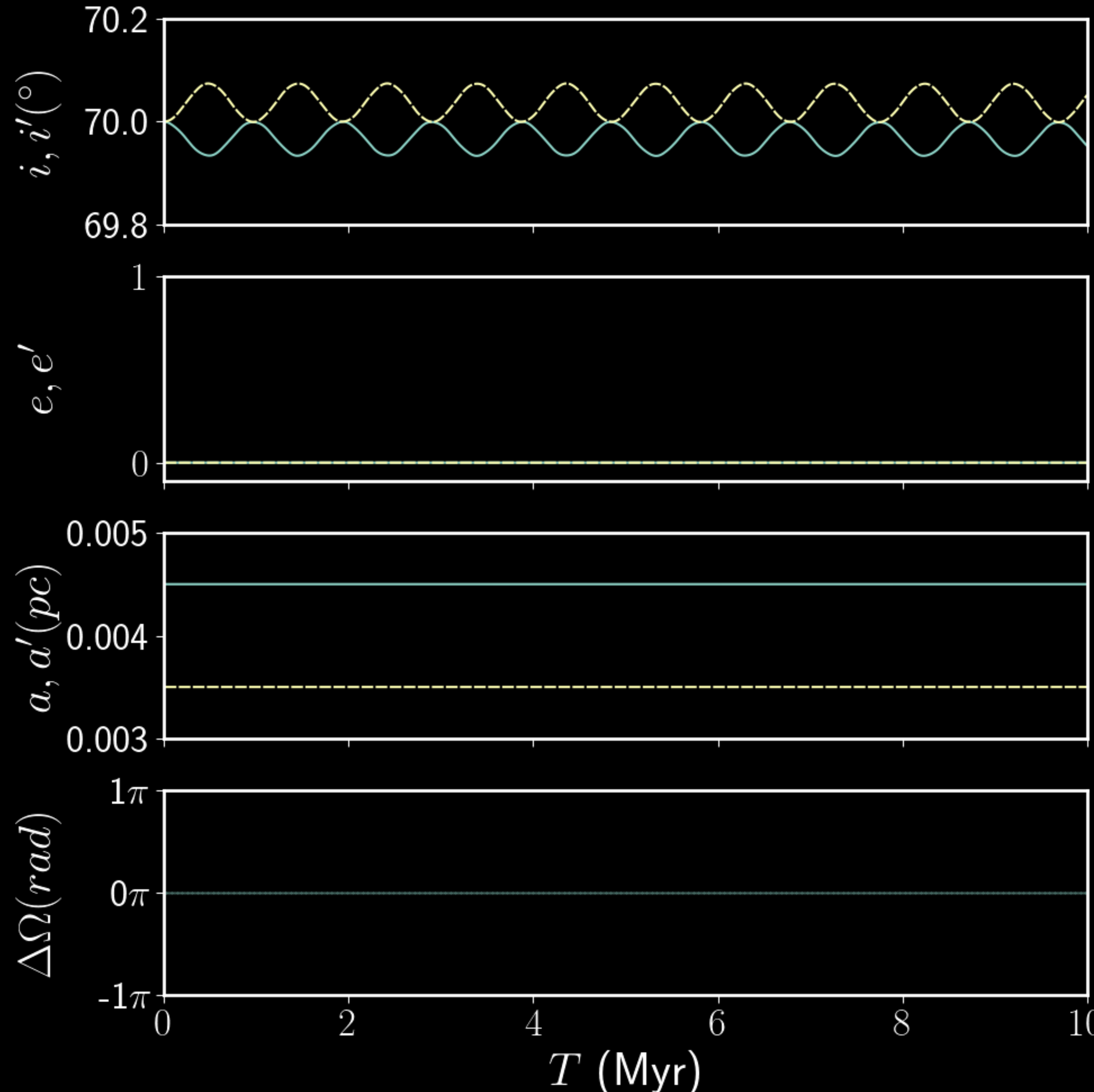

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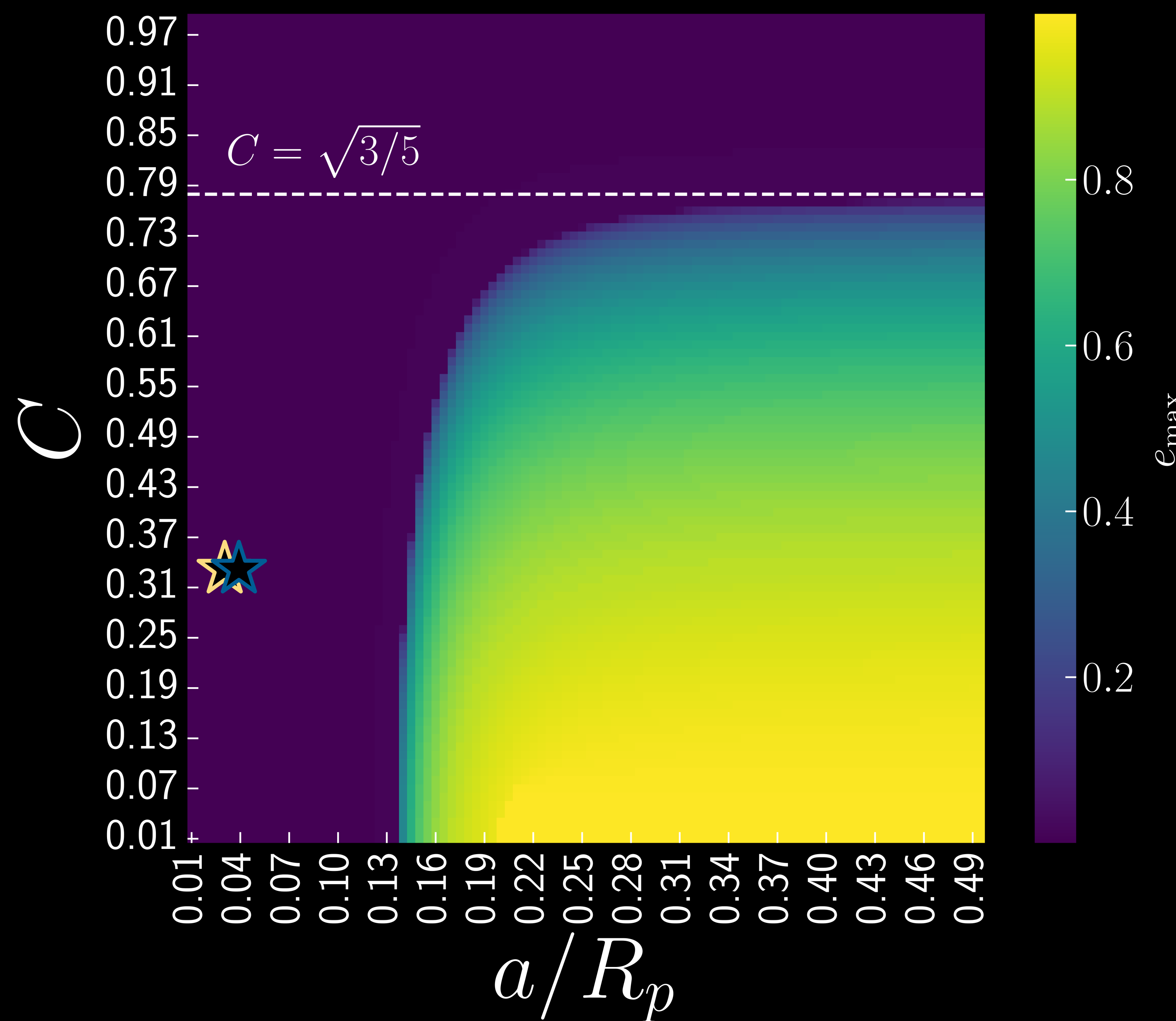


VHS Mechanism with relativistic corrections

Strong Interaction - Non-zero eccentricity

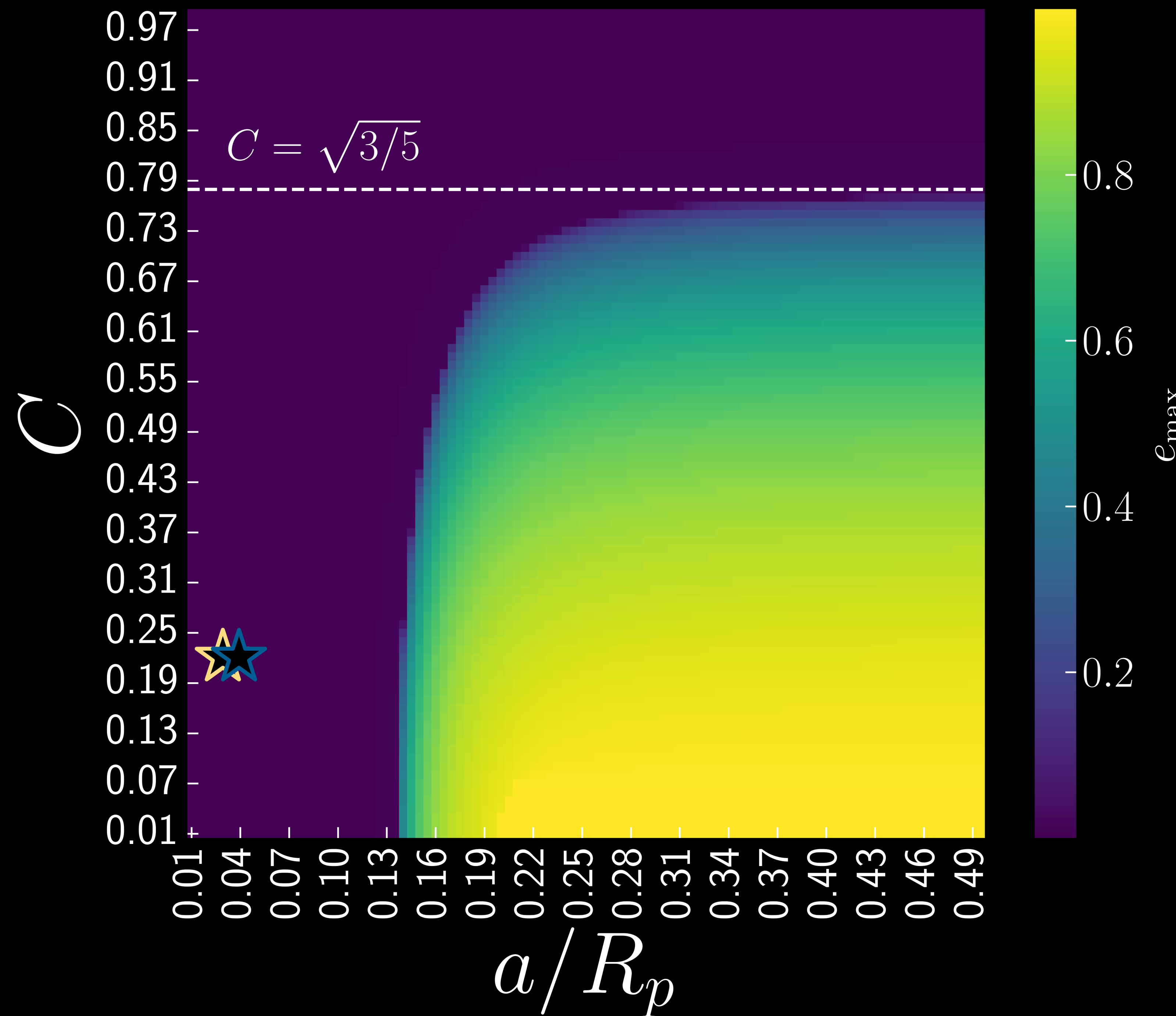
$m = m' = 10\ M_\odot$

$a = 0.0035\ pc$

$a' = 0.0045\ pc$

$i_{ini} = i'_{ini} = 70°$

$e = e' = 0.77$



VHS Mechanism with relativistic corrections

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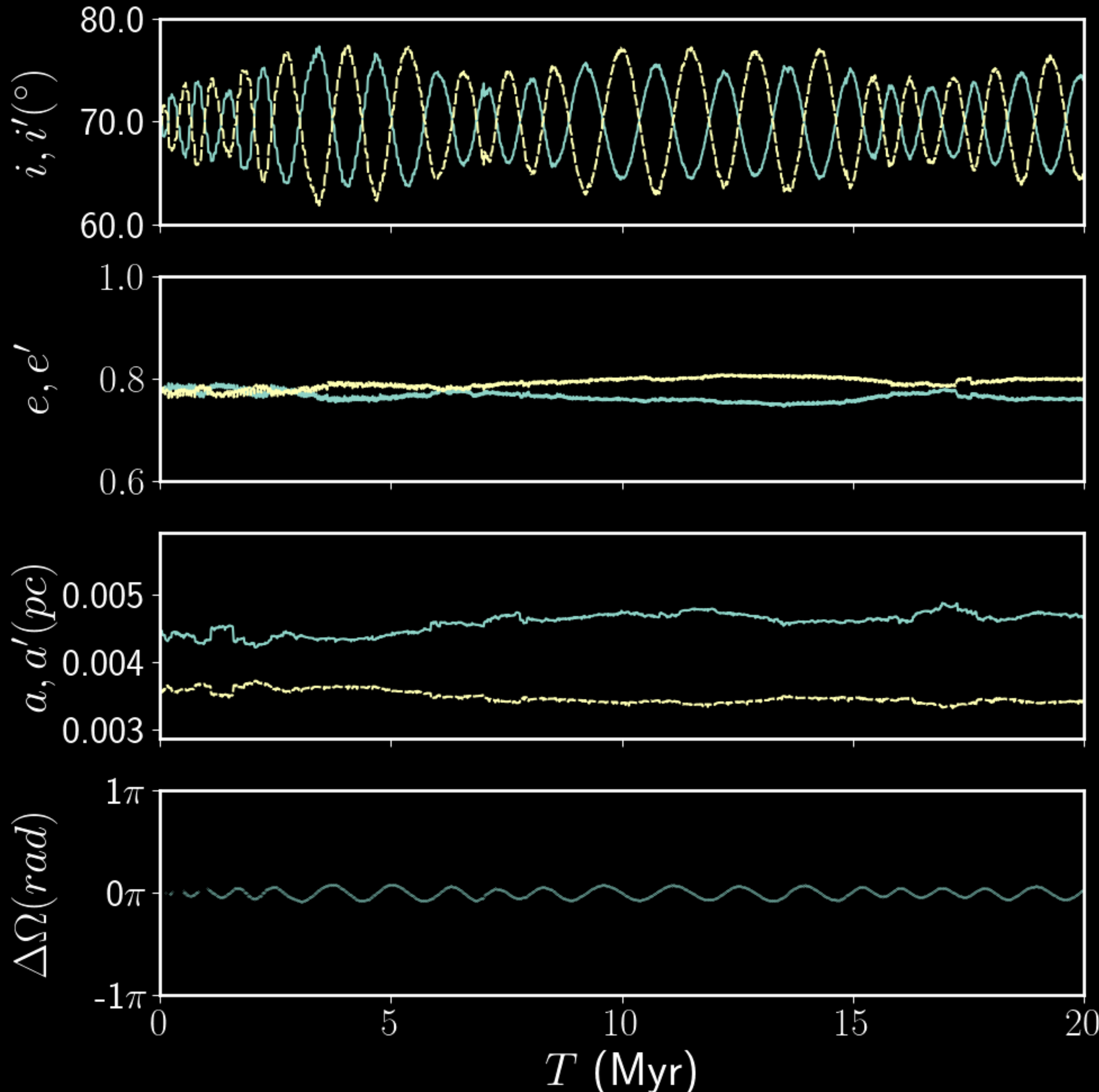


VHS Mechanism with relativistic corrections

Weak Interaction - Zero eccentricity

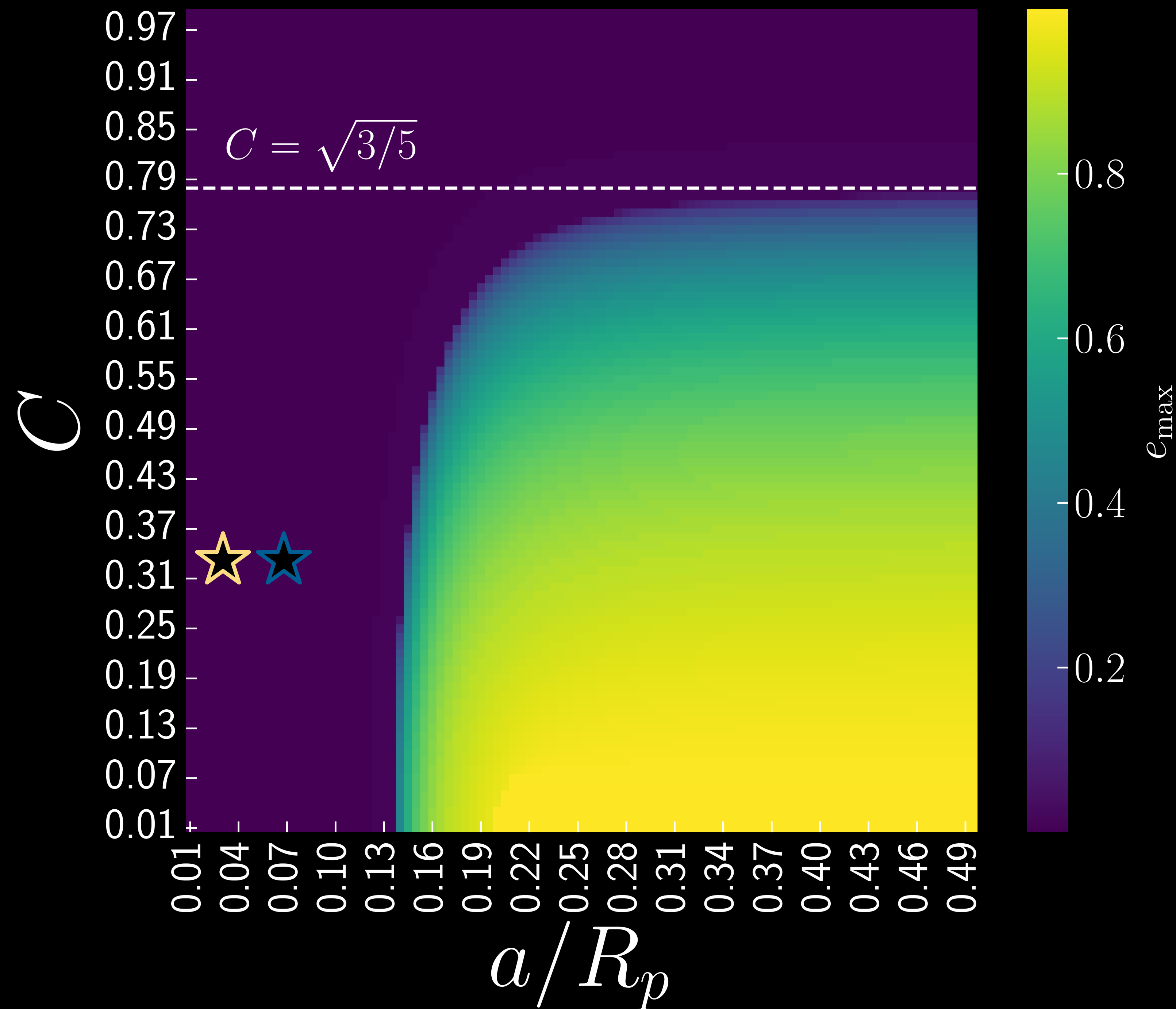
$m = m' = 1\ M_\odot$

$a = 0.0035\ pc$

$a' = 0.007\ pc$

$i_{ini} = i'_{ini} = 70°$

$e = e' = 0$



VHS Mechanism with relativistic corrections

Weak Interaction - Zero eccentricity

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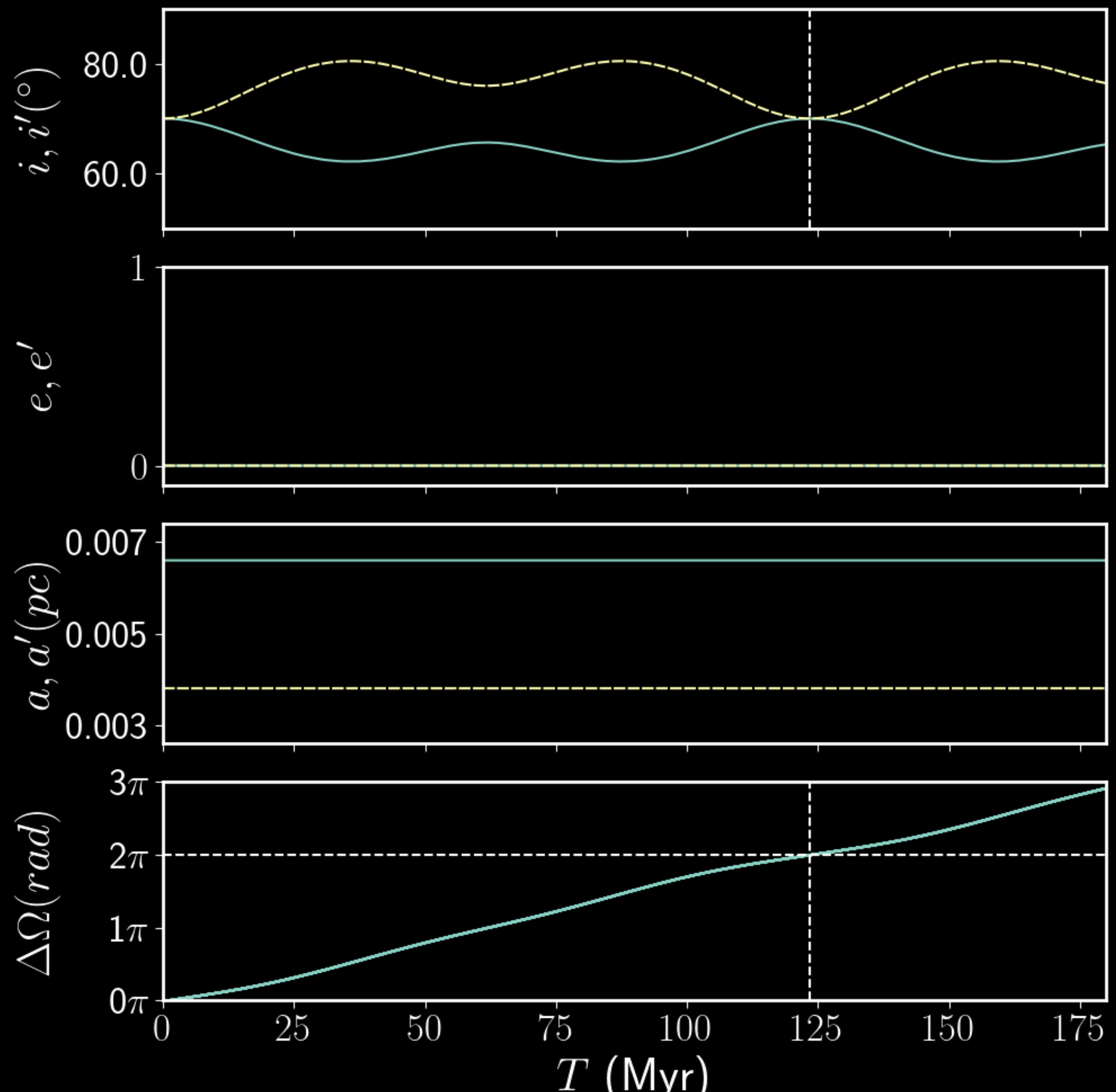

VHS Mechanism with relativistic corrections

Weak Interaction - Zero eccentricity

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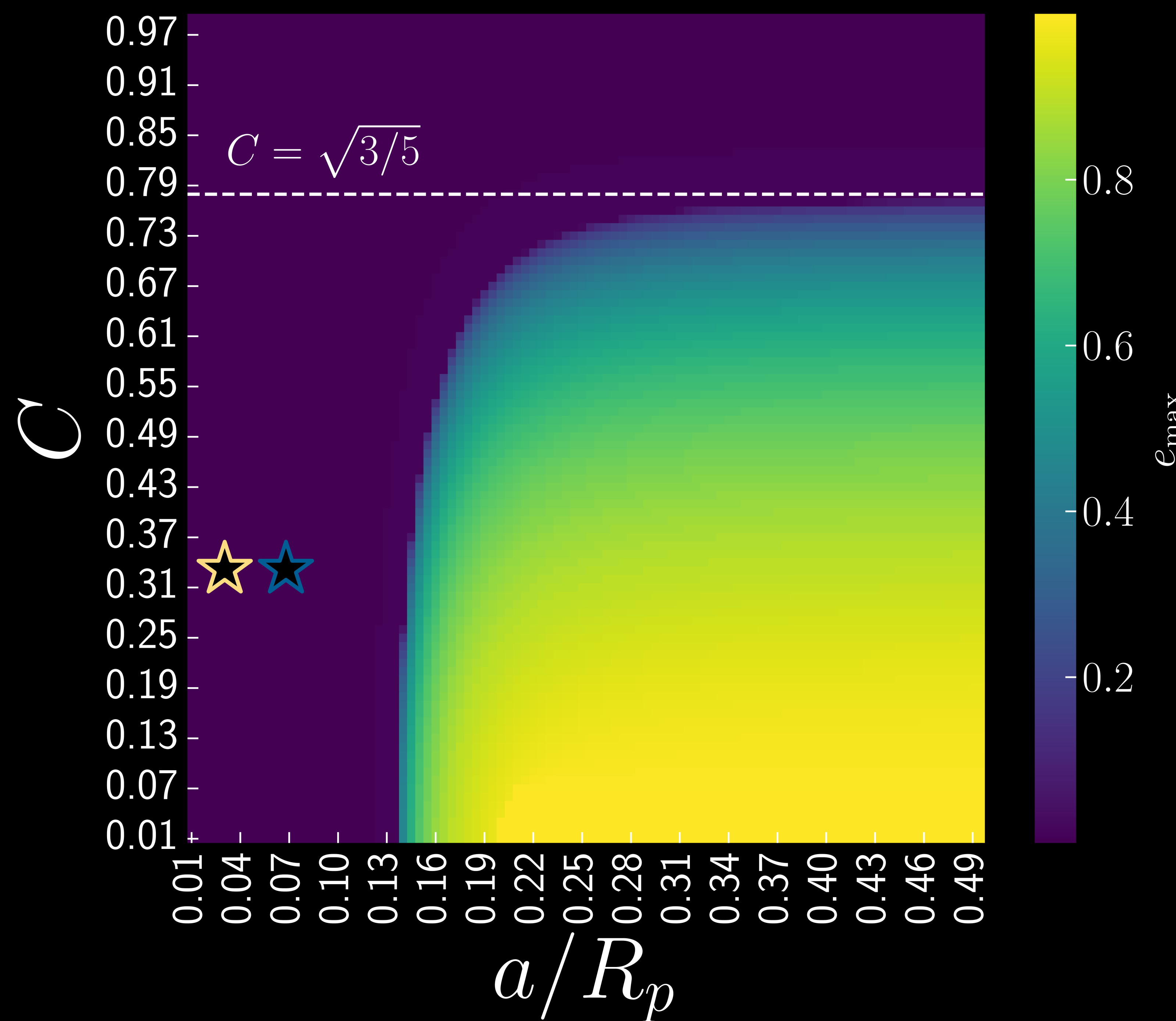


VHS Mechanism with relativistic corrections

Weak Interaction - Non-zero eccentricity

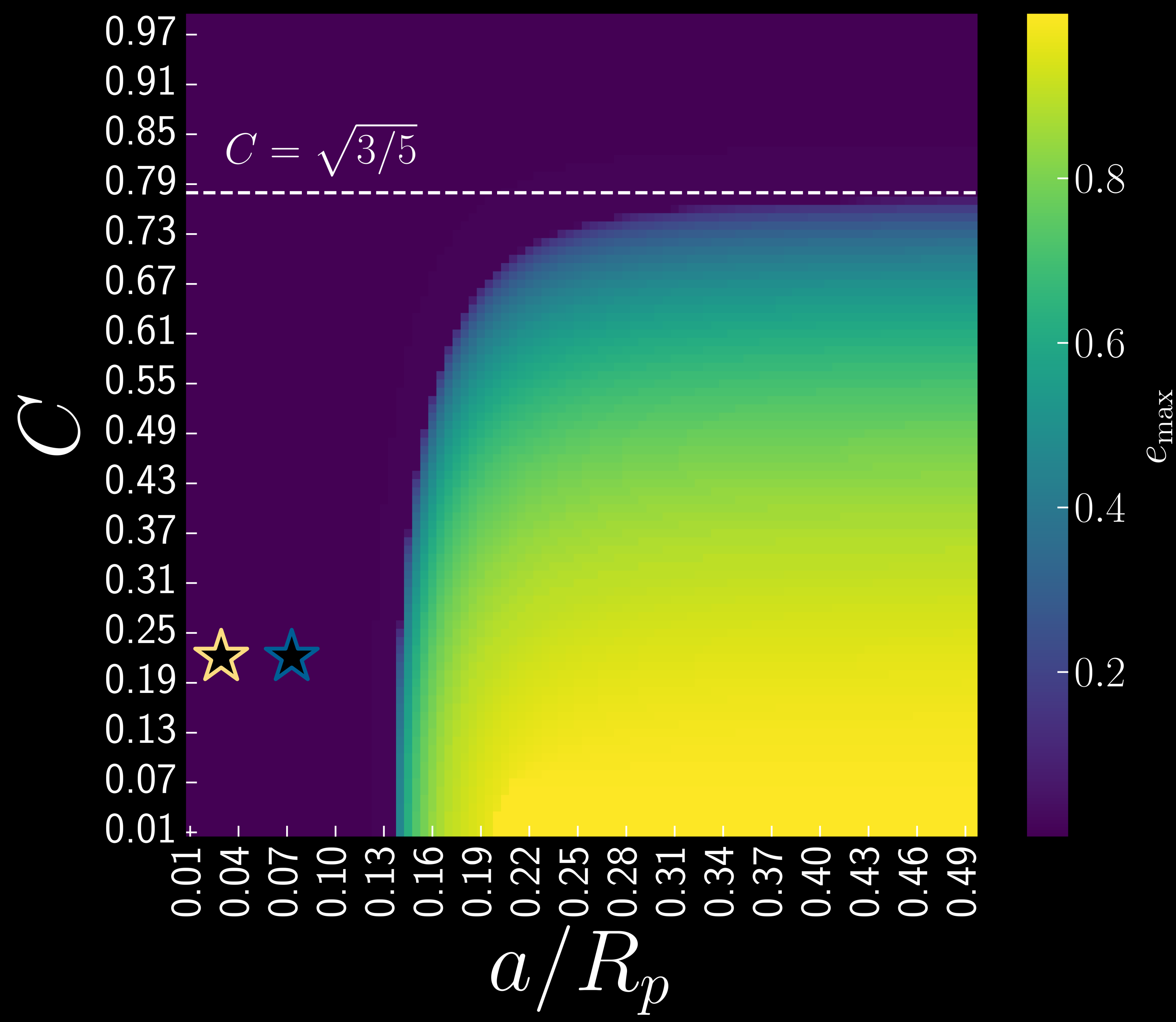
$m = m' = 1\ M_\odot$

$a = 0.0035\ pc$

$a' = 0.007\ pc$

$i_{ini} = i'_{ini} = 70°$

$e = e' = 0.72$



VHS Mechanism with relativistic corrections

Weak Interaction - Non-zero eccentricity

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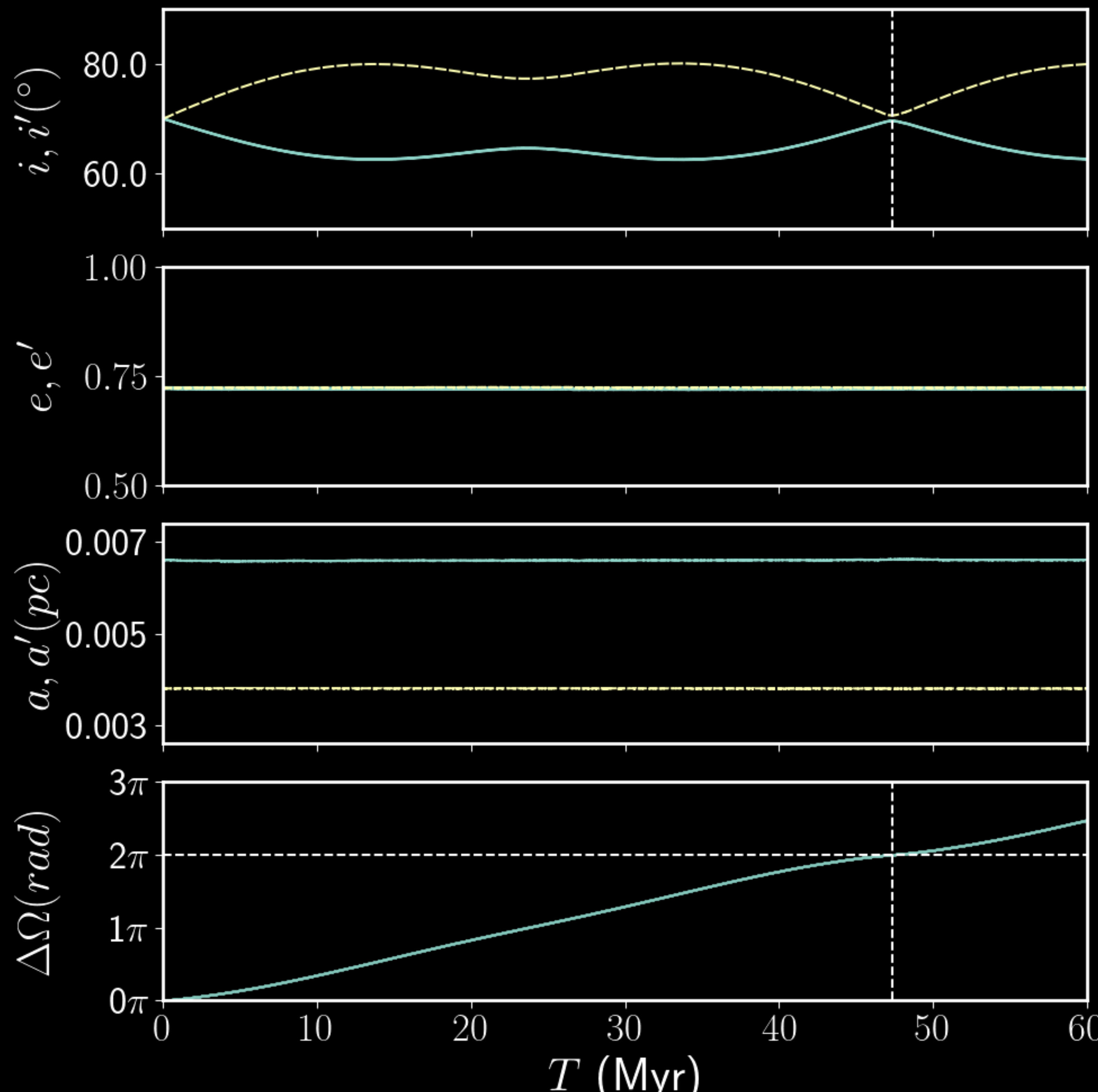


VHS Mechanism with relativistic corrections

With Kozai—Lidov oscillations

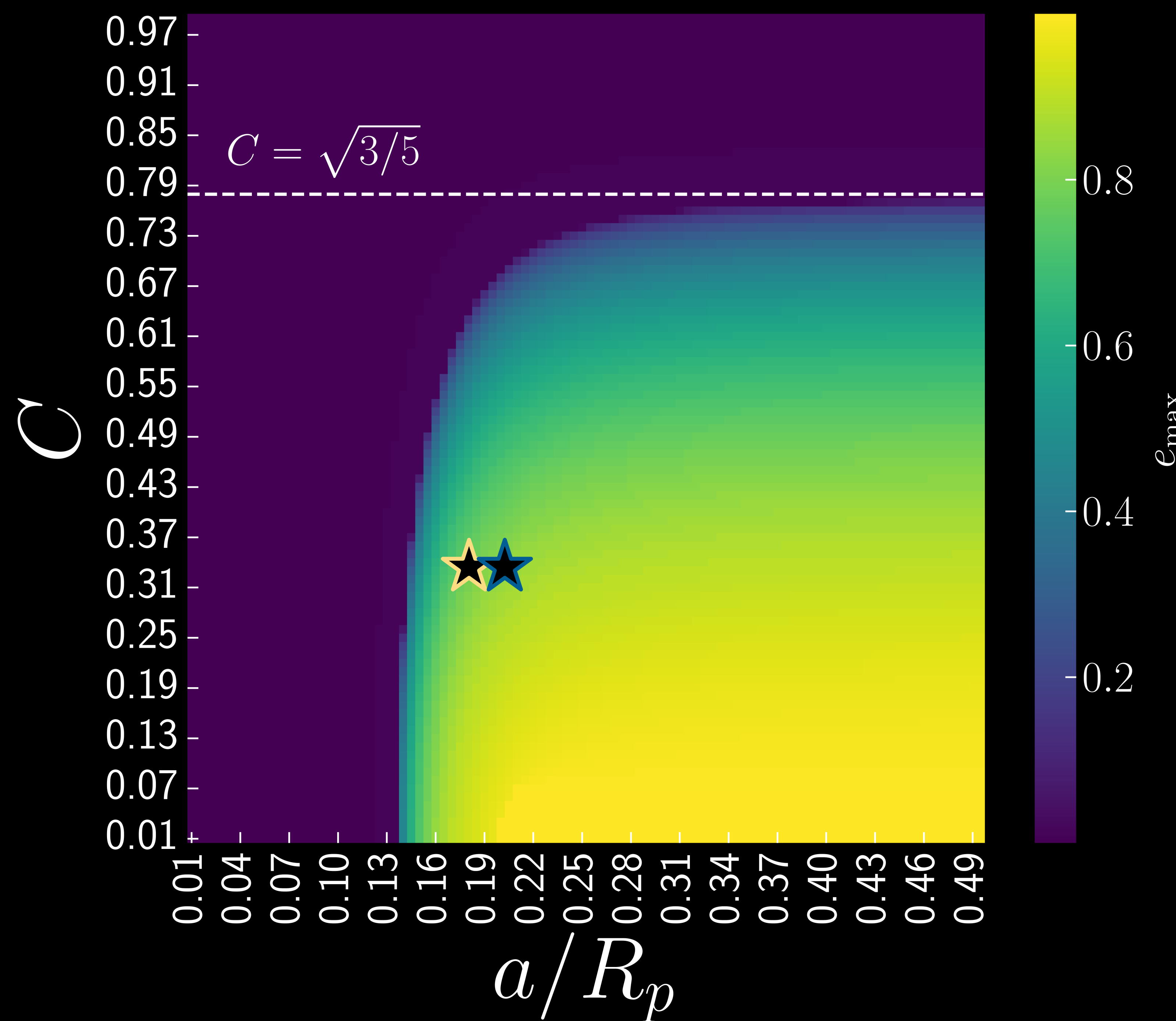
$m = m' = 10\ M_\odot$

$a = 0.0196\ pc$

$a' = 0.0218\ pc$

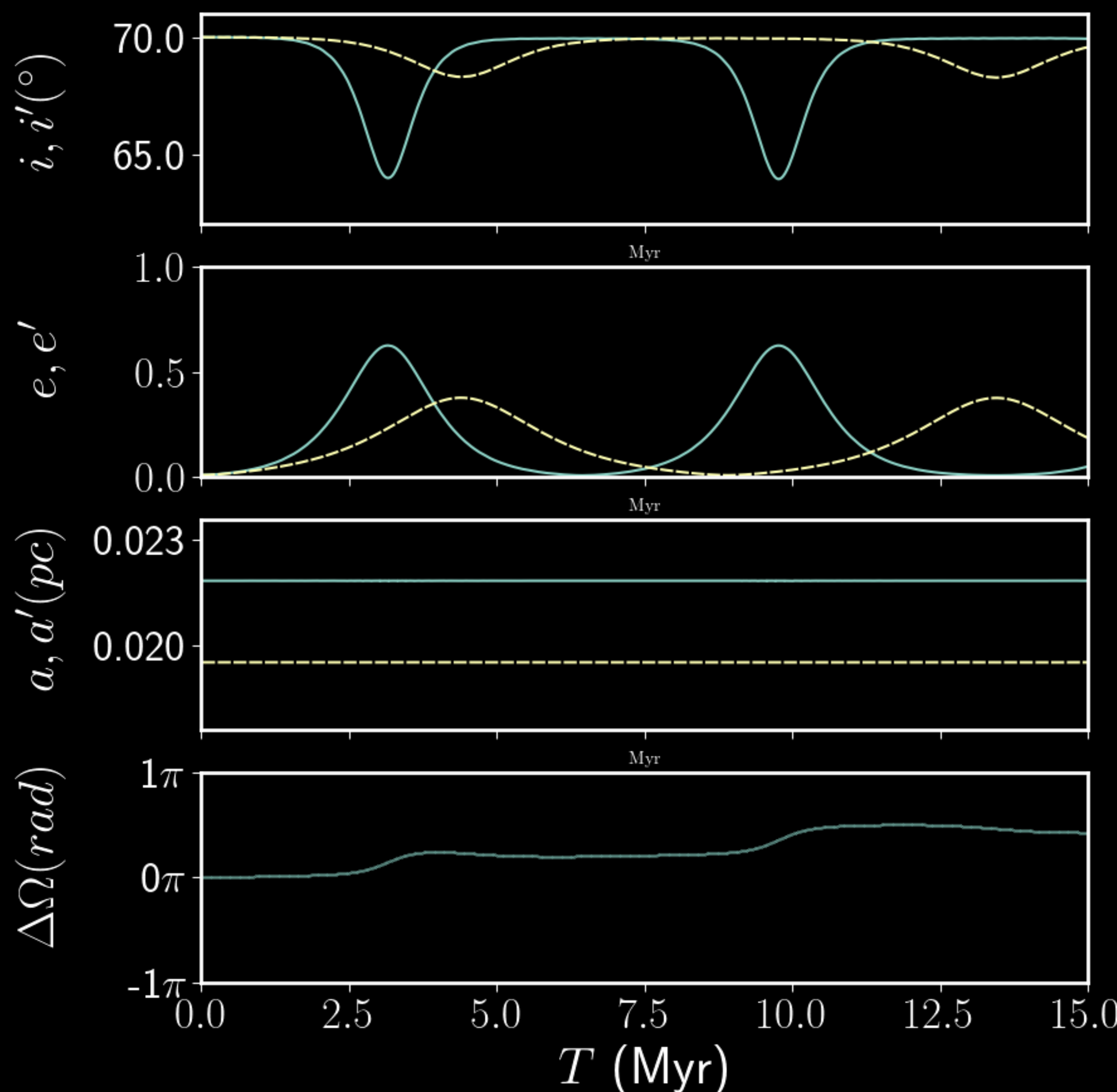
$i_{ini} = i'_{ini} = 70°$

$e = e' = 0.01$



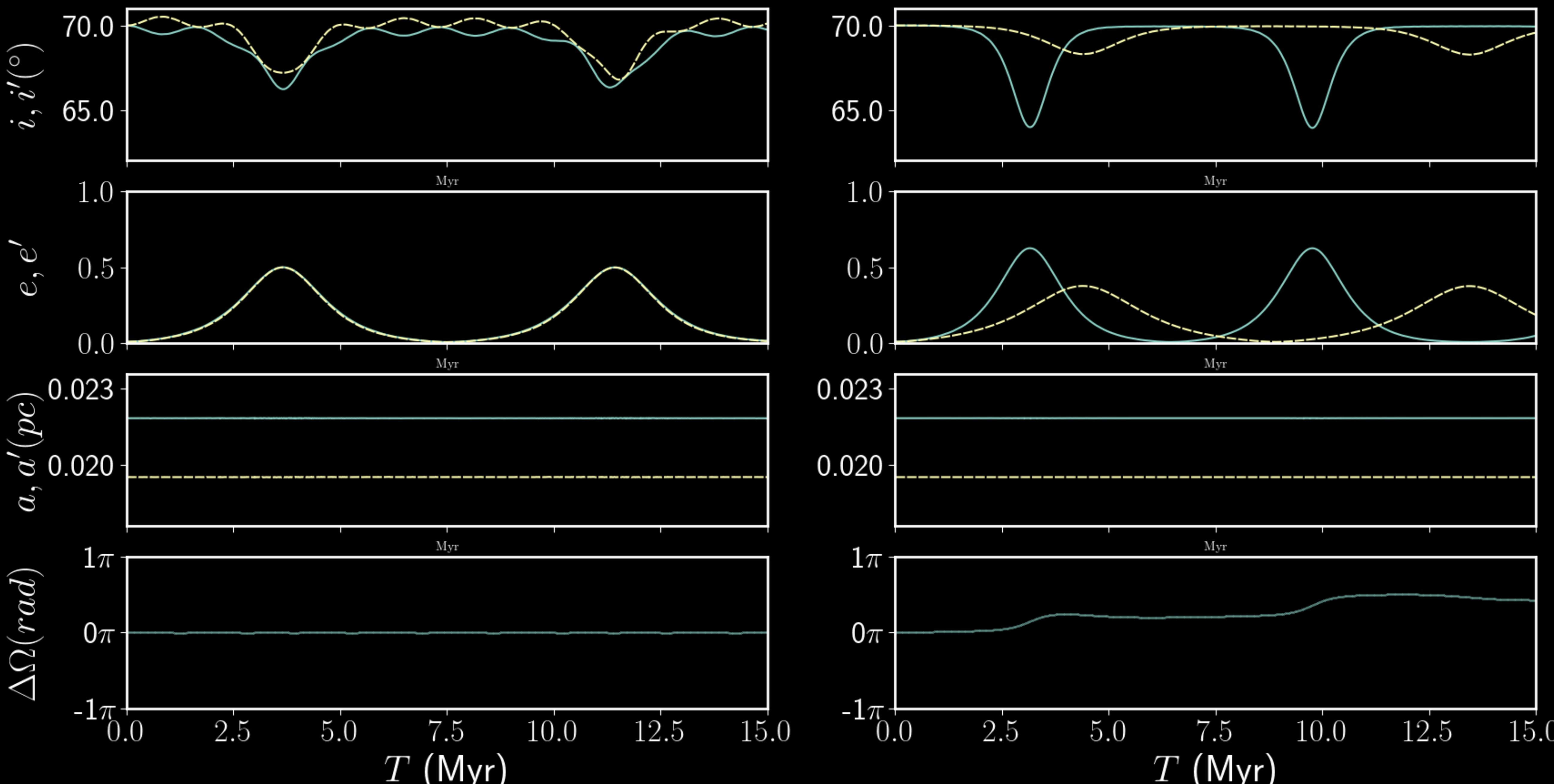
VHS Mechanism with relativistic corrections

With Kozai—Lidov oscillations



VHS Mechanism with relativistic corrections

With Kozai—Lidov oscillations



VHS Mechanism with relativistic corrections

Chaotic Evolution

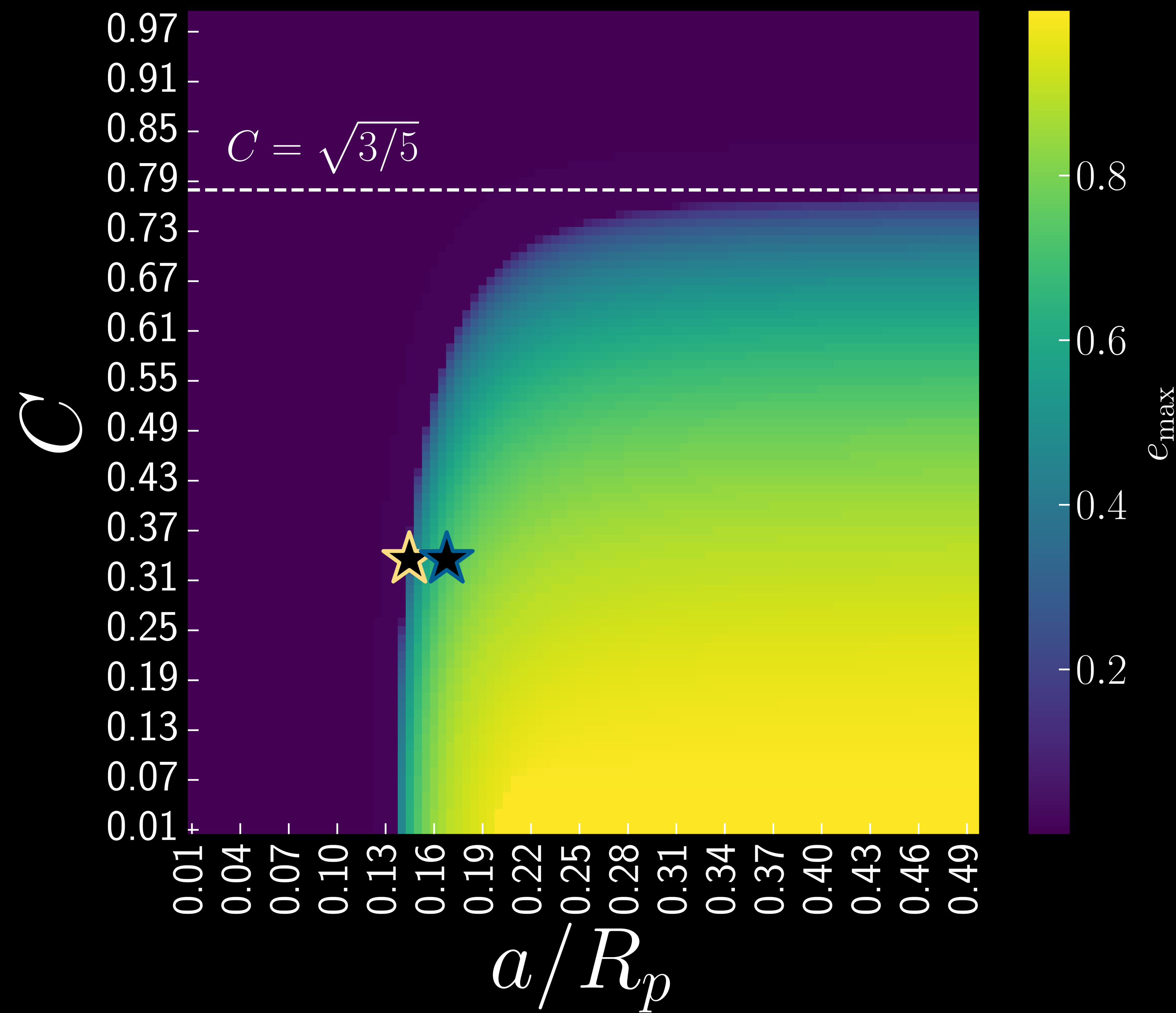
$m = m' = 10\ M_\odot$

$a = 0.015\ pc$

$a' = 0.0168\ pc$

$i_{ini} = i'_{ini} = 70°$

$e = e' = 0.03$



VHS Mechanism with relativistic corrections

Chaotic Evolution

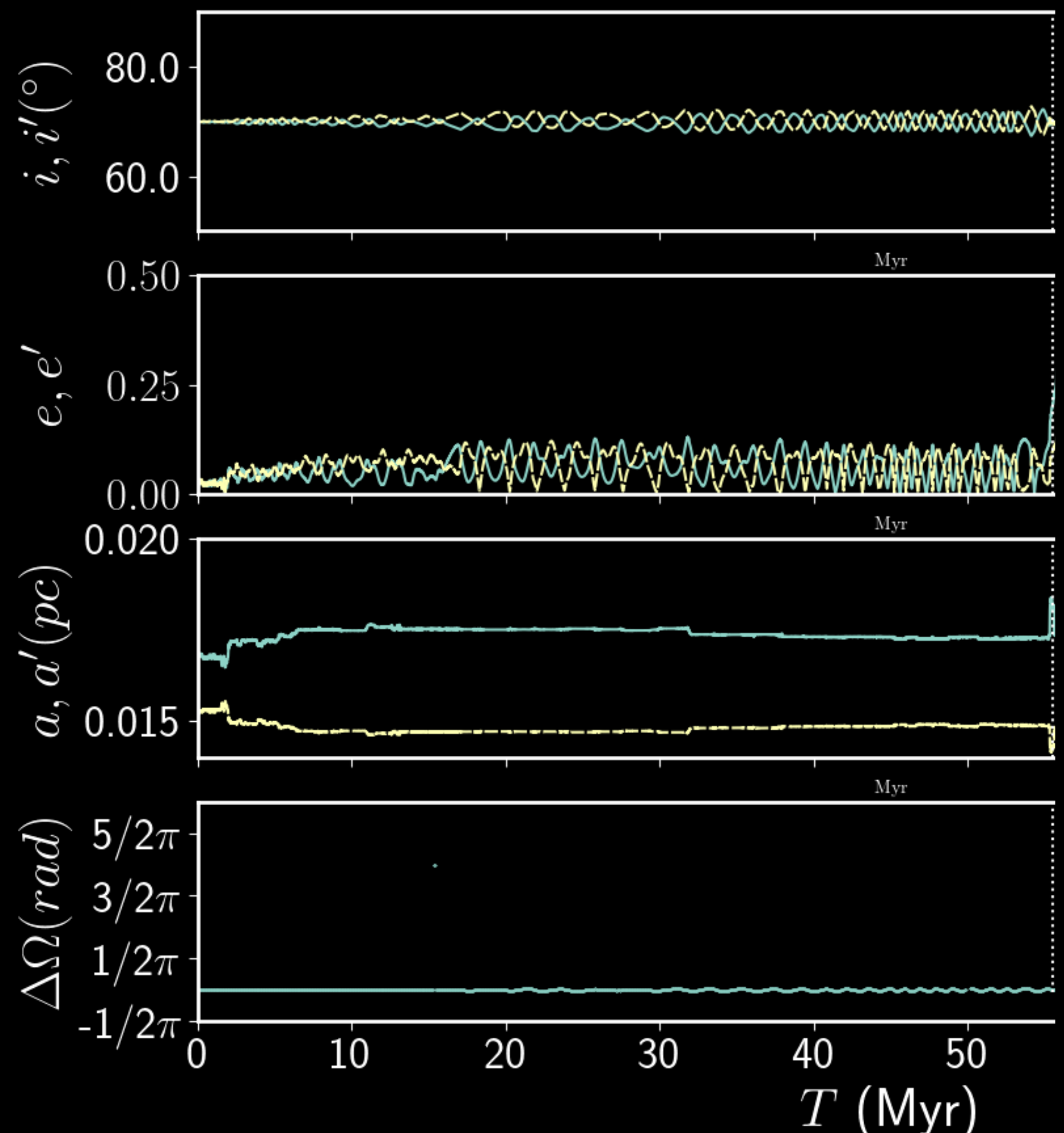
$m = m' = 10\ M_\odot$

$a = 0.015\ pc$

$a' = 0.0168\ pc$

$i_{ini} = i'_{ini} = 70^\circ$

$e = e' = 0.03$



VHS Mechanism with relativistic corrections

Chaotic Evolution

$m = m' = 10\ M_\odot$

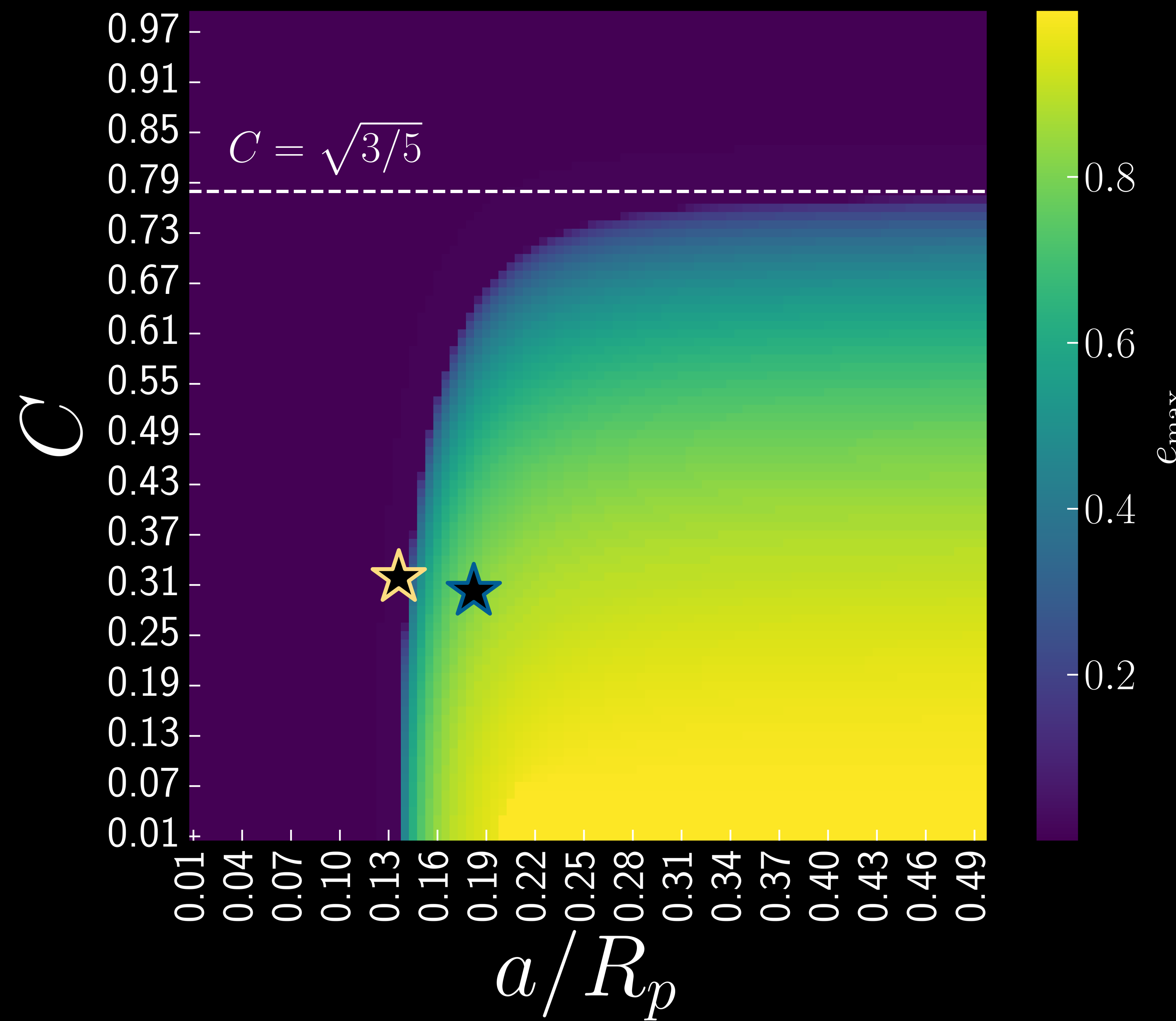
$a = 0.0146\ pc$

$a' = 0.0183\ pc$

$i_{ini} = i'_{ini} = 70°$

$e = 0.11$

$e' = 0.21$



VHS Mechanism with relativistic corrections

Chaotic Evolution

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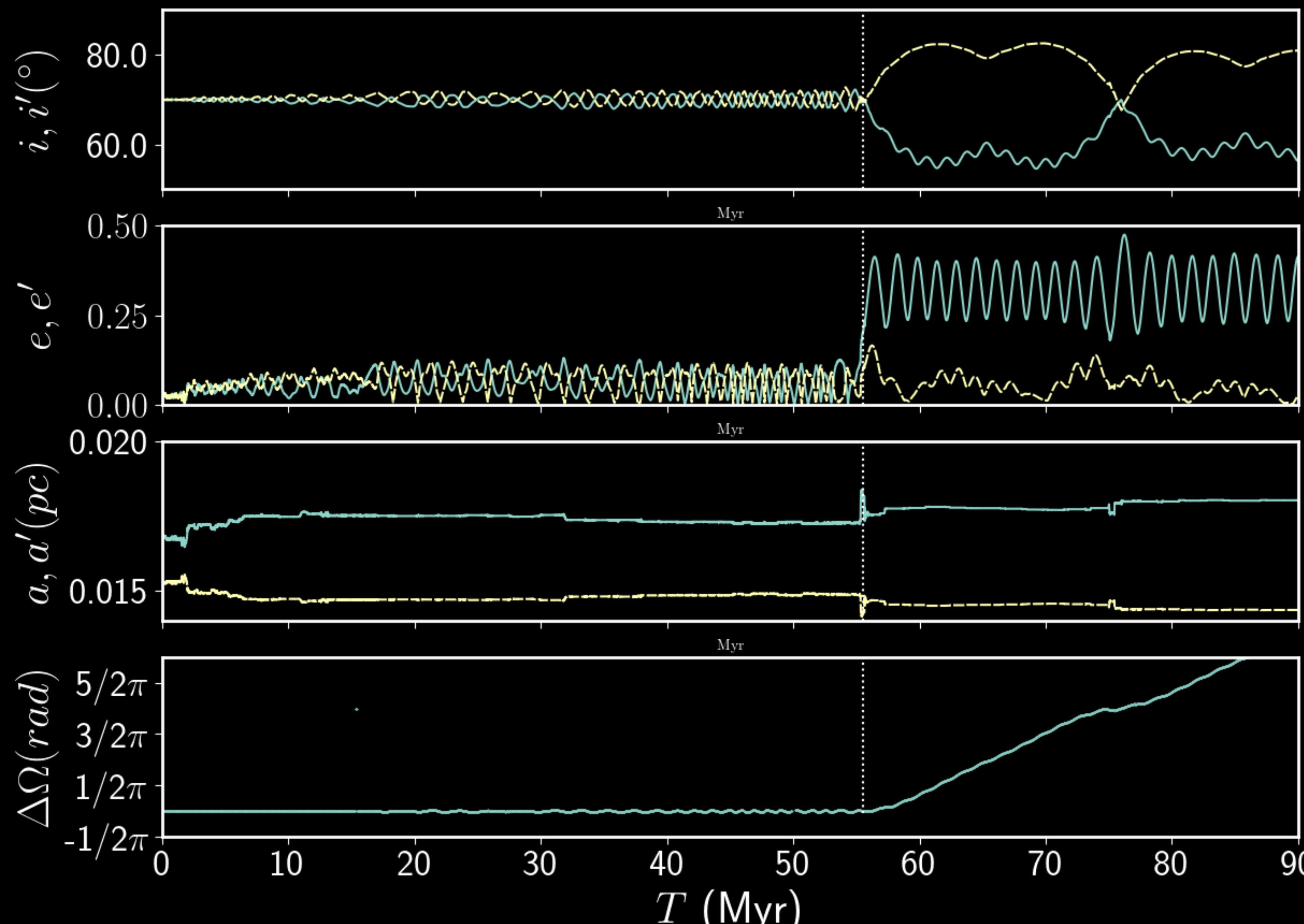
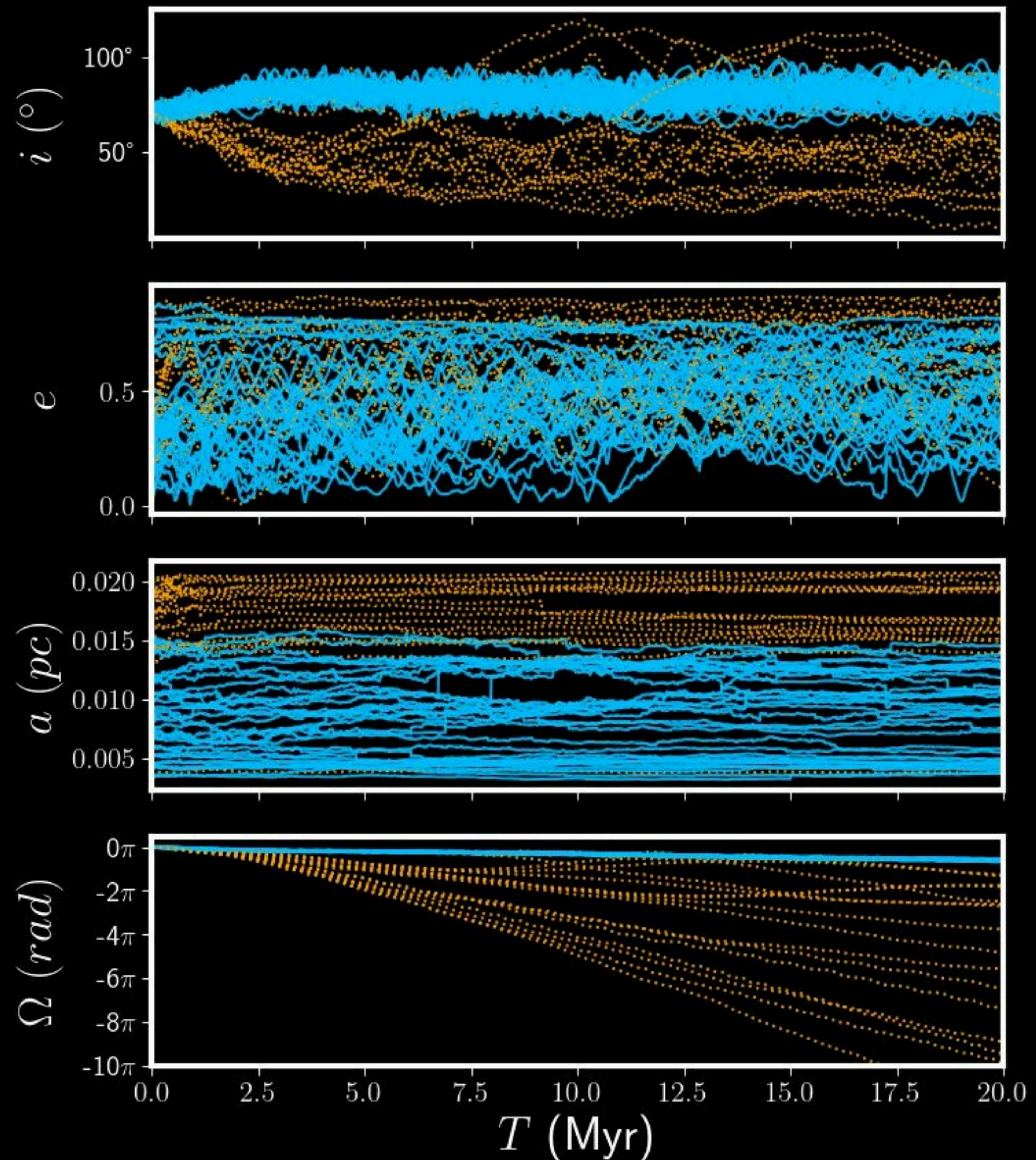
$i_{ini} = i'_{ini} = 70°$

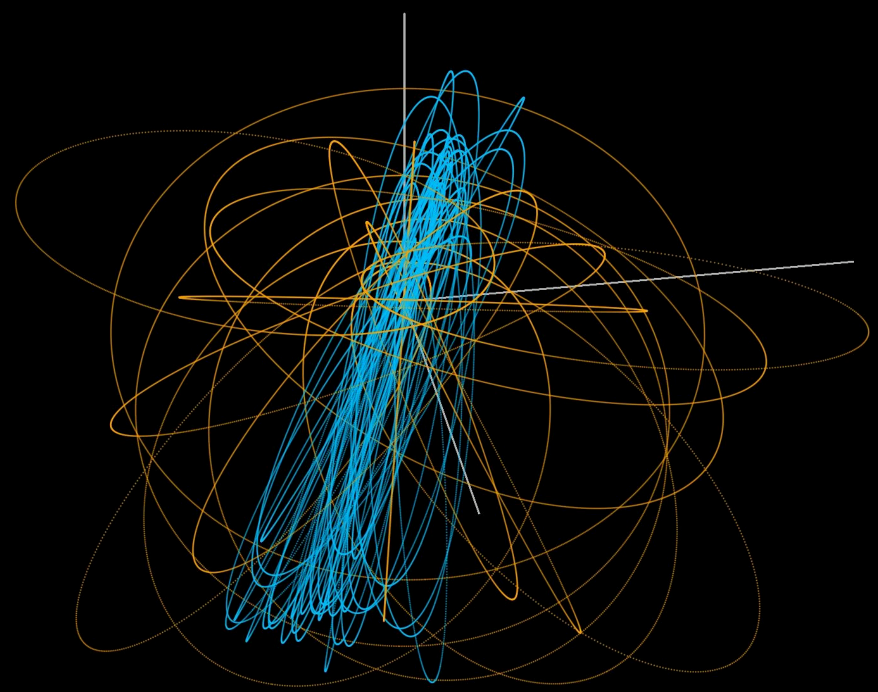
$e = e' = 0.03$



Evolution of a disk of stars

Evolution





Summary

- The four body dynamics of VHS mechanism are applicable in relativistic regime.
- These dynamics are not only applicable in secular system with damped KL oscillations but
  - can exist in non-eccentric orbits with slight changes.
  - can co-exist with KL oscillations and bind the oscillation together in case of strong interaction.
- These relativistic corrections are applicable to stars in close orbit around Sagittarius A* and these dynamics could be present in that system.

This work was funded by the Grant Agency of Charles University (179123)