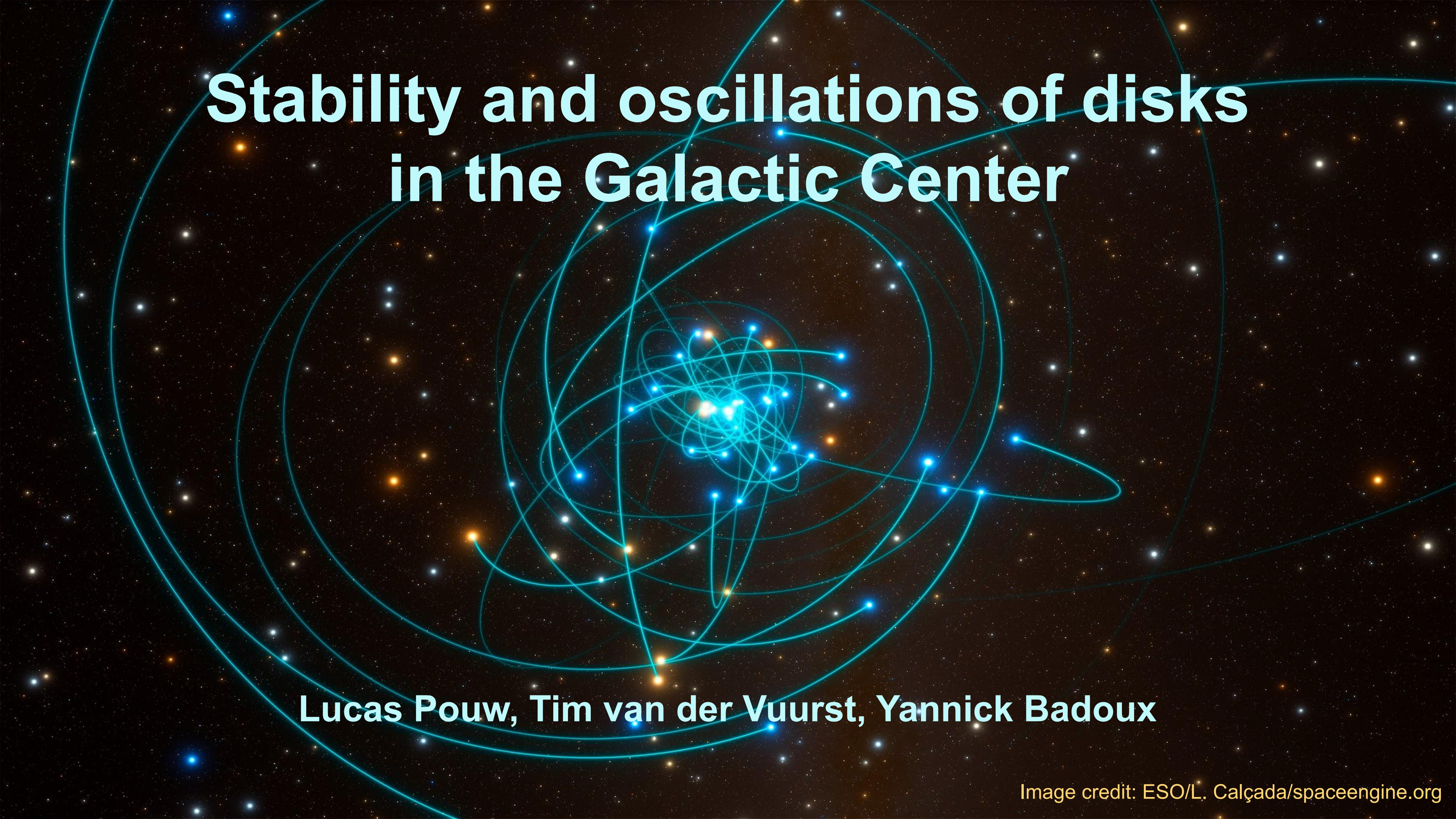
Stability and oscillations of disks in the Galactic Center



Lucas Pouw, Tim van der Vuurst, Yannick Badoux

Image credit: ESO/L. Calçada/spaceengine.org

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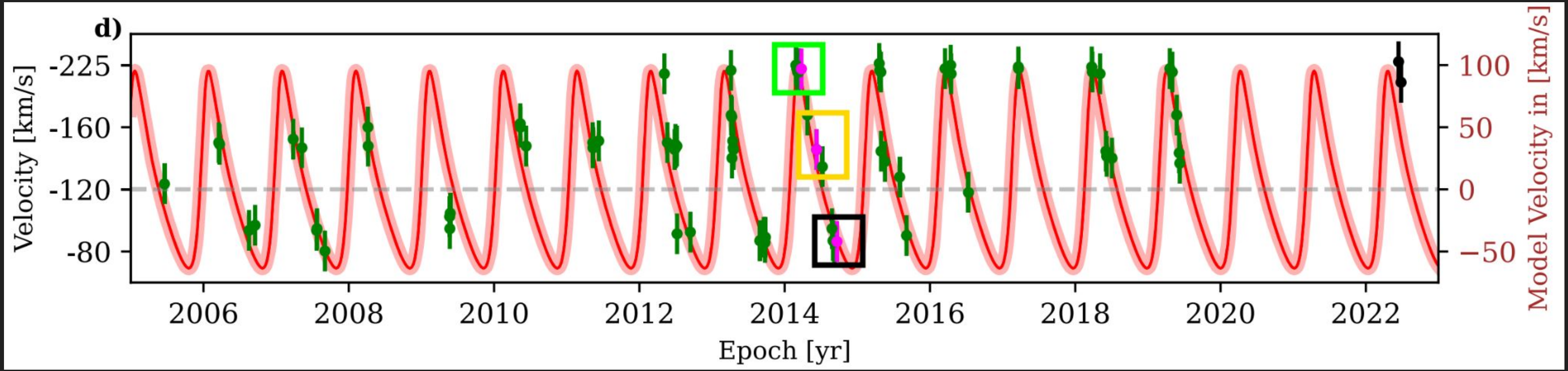

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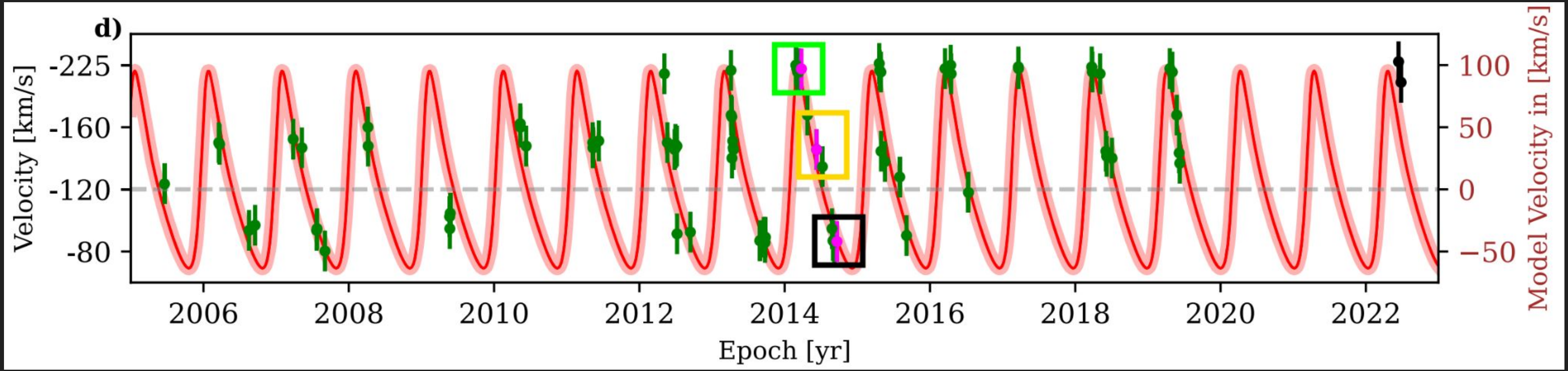
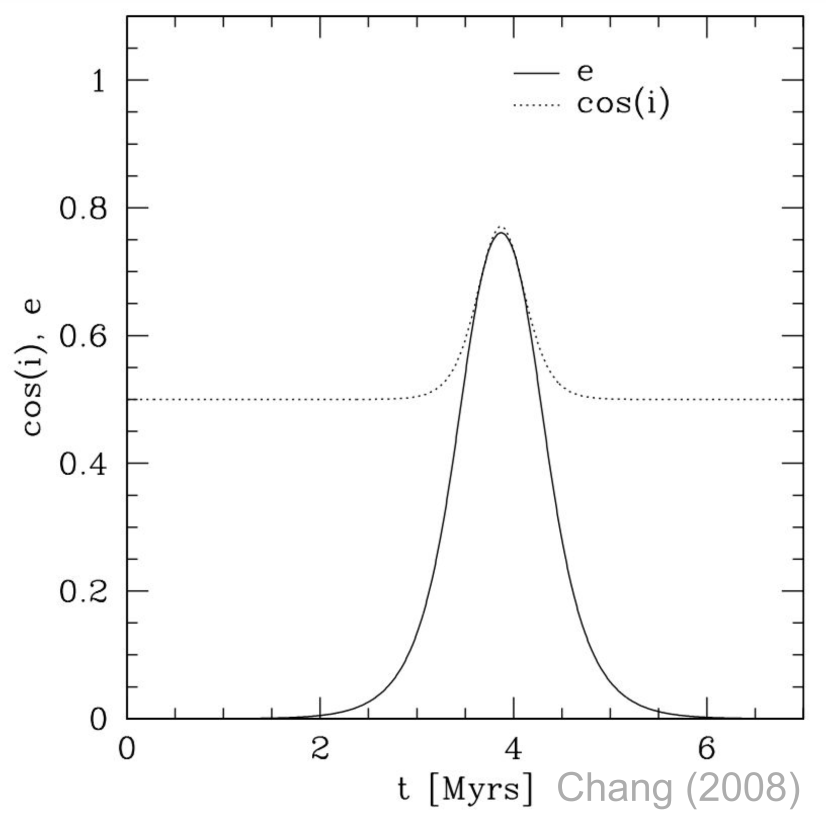


Circumprimary? Circumbinary?

Binary system (D9) + perturber (Sgr A*) = Oscillations

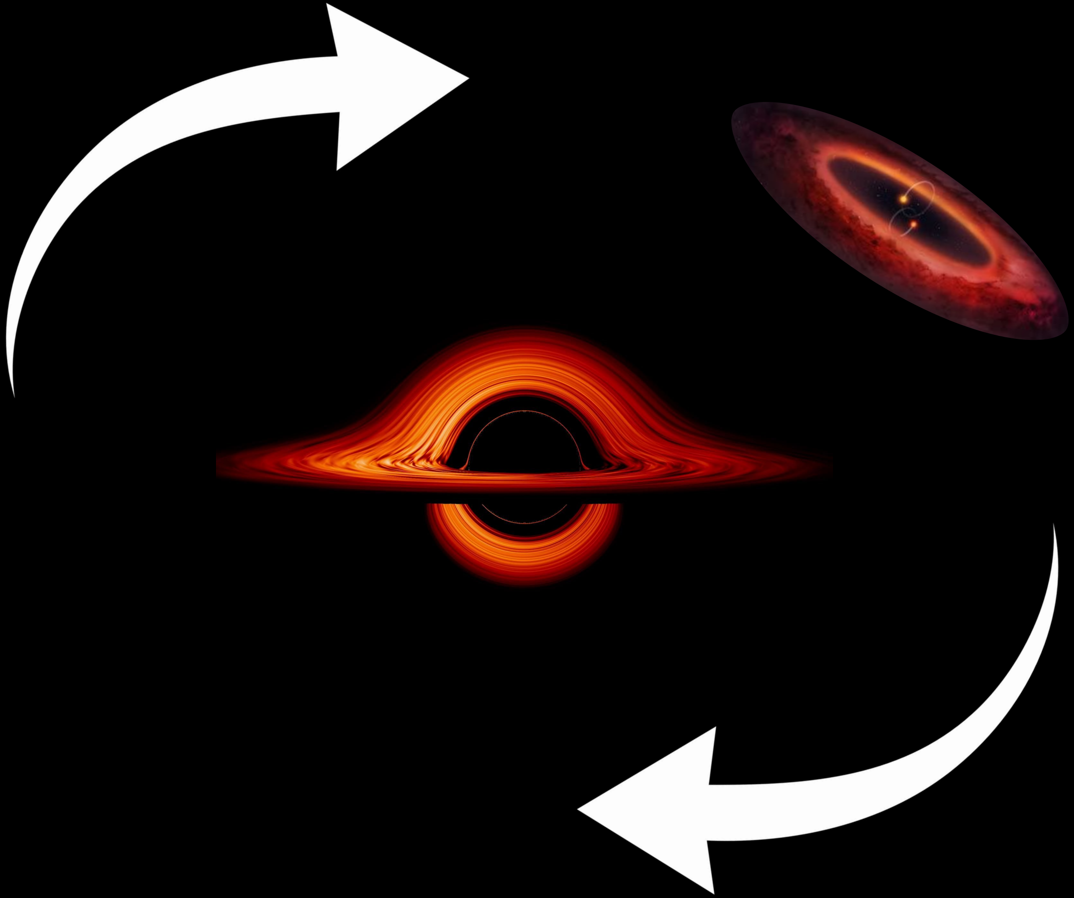


Chang (2008)

Special moment!

- No merger
- No full evaporation
- Survived the GC
- Survived the Kozai oscillations
- Survived Sgr A*

How stable is this system?



Implementation

- Gravity N-body integrator: Huayno (Jänes et al., 2014)

- Hydrodynamics code: Fi (Hernquist and Katz, 1989; Gerritsen and Icke, 1997; Pelupessy et al., 2004)

- Bridge: AMUSE’s classical 2nd-order bridge integrator

Initial conditions

- Values in the table taken from Peißker et al. (2024) and GRAVITY Collaboration et al. (2023)

- Missing: inner and outer radii of the disk

Variable	Value
$M_{\mathrm{SgrA^*}}$	$4.30 \cdot 10^6\ M_\odot$
M_{D9a}	$2.80\ M_\odot$
M_{D9b}	$0.73\ M_\odot$
M_{disk}	$1.6 \cdot 10^{-6}\ M_\odot$
a_{out}	$9.1 \cdot 10^3$ AU
e_{out}	0.32
a_{in}	1.59 AU
e_{in}	0.45
i_{mut}	$102.55°$
ω_{in}	$311.75°$

Disk radii

- Inner radius: 4.5 AU, from Mardling & Aarseth (2001):

$$a_{\rm out} > 2.8 \cdot \frac{a_{\rm in}}{1 - e_{\rm out}} \cdot \left(1 - 0.3\frac{i_{\rm mut}}{180^\circ}\right) \cdot \left[\left(1 + \frac{m_3}{m_{\rm bin}}\right) \cdot \frac{1 + e_{\rm out}}{\sqrt{1 - e_{\rm out}}}\right]^{2/5}$$

- Outer radius: 13.4 AU, which is ⅓ of the Hill Radius:

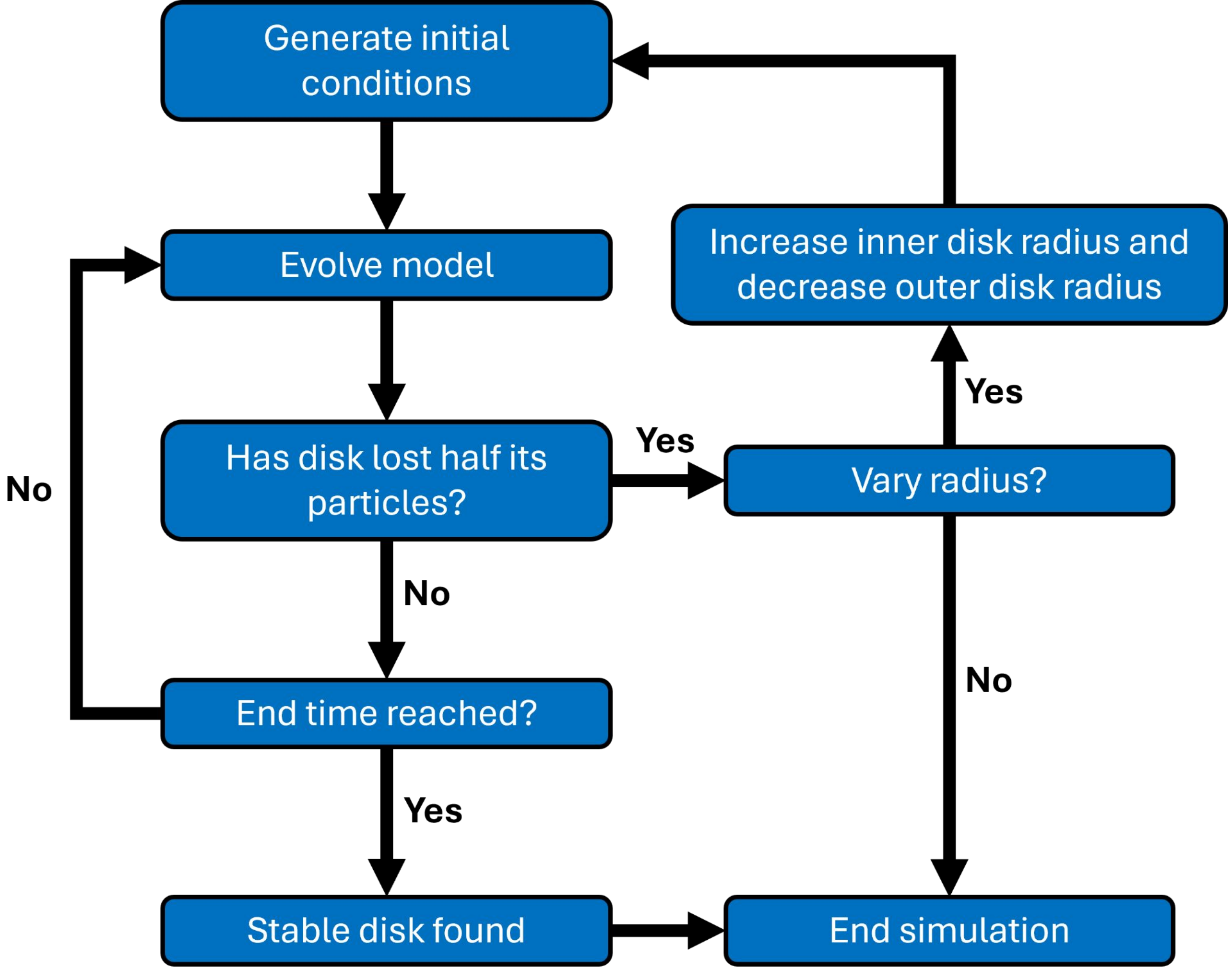
$$R_{\rm H} = a(1 - e)\left(\frac{m_{\rm bin}}{m_{\rm bin} + M_{\rm SMBH}}\right)^{1/3}$$

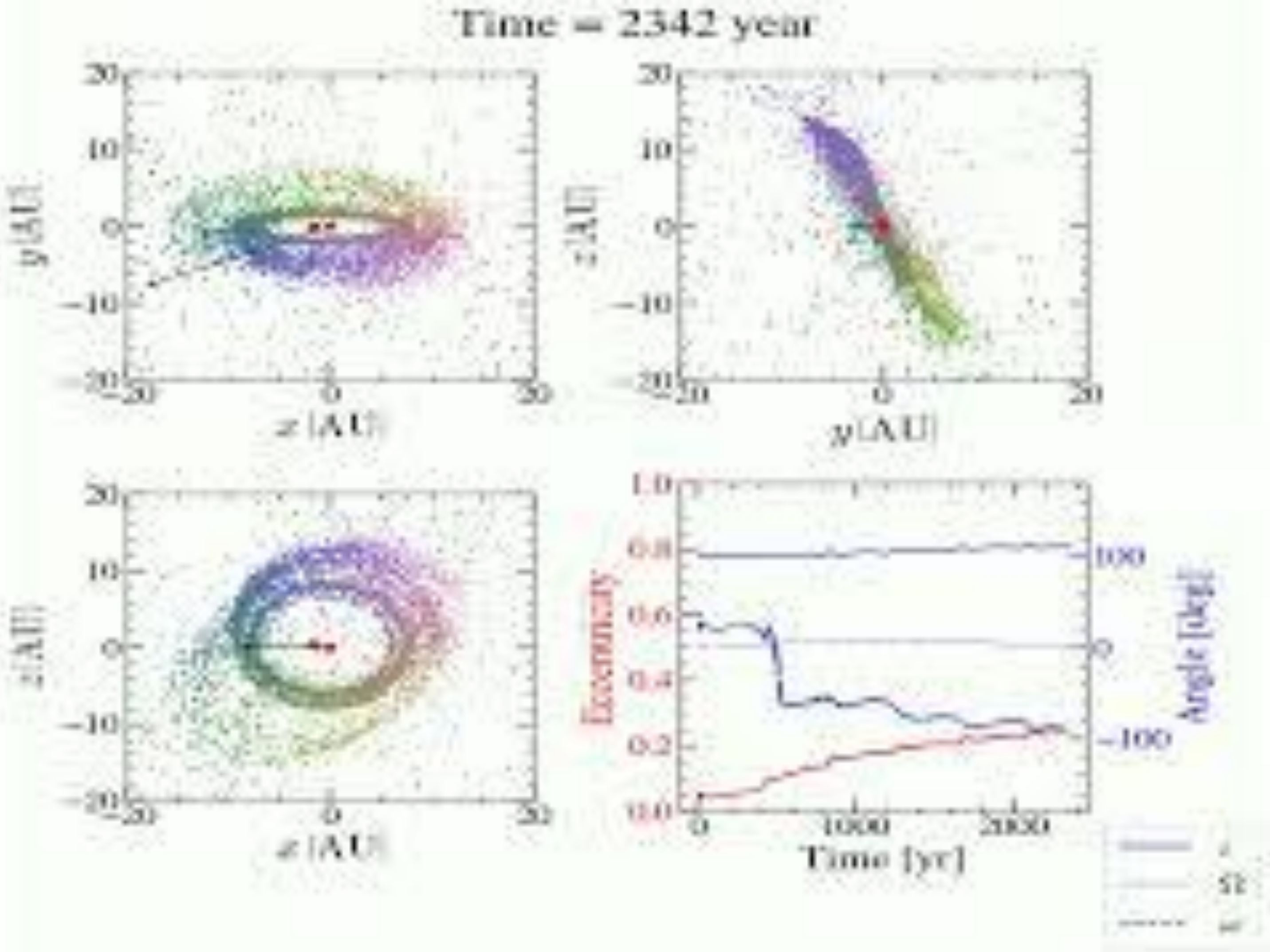
Particle loss in the disk

- Particles lost both at the inner and outer edge of the disk

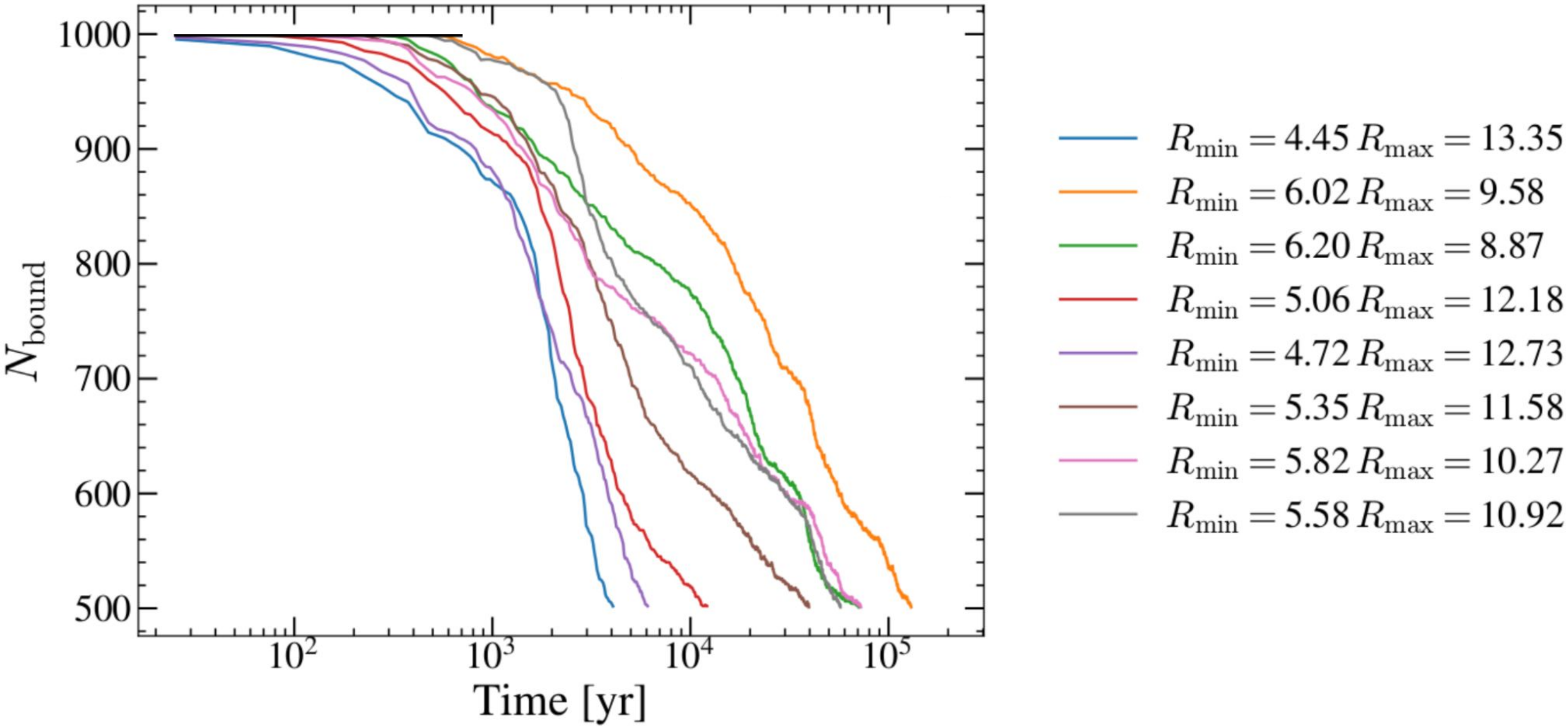
- Idea: iteratively scale the disk based on the inner and outer particle loss (if so desired)

- Stopping conditions: at most 250,000 years or when half the disk particles lost

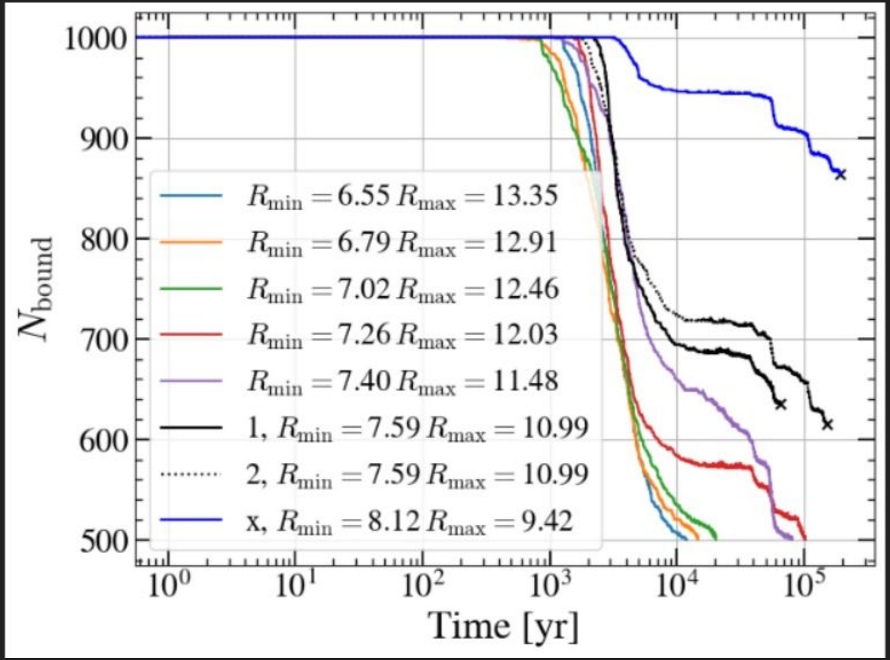

Generate initial conditions
Evolve model
Has disk lost half its particles?
Yes
Vary radius?
Yes
Increase inner disk radius and decrease outer disk radius
No
No
End time reached?
Yes
Stable disk found
No
End simulation

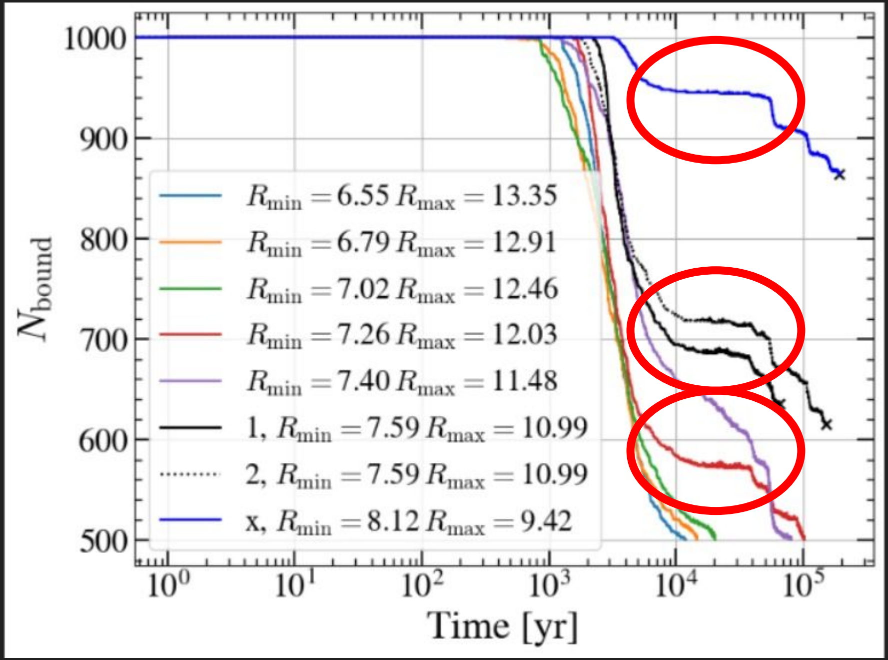


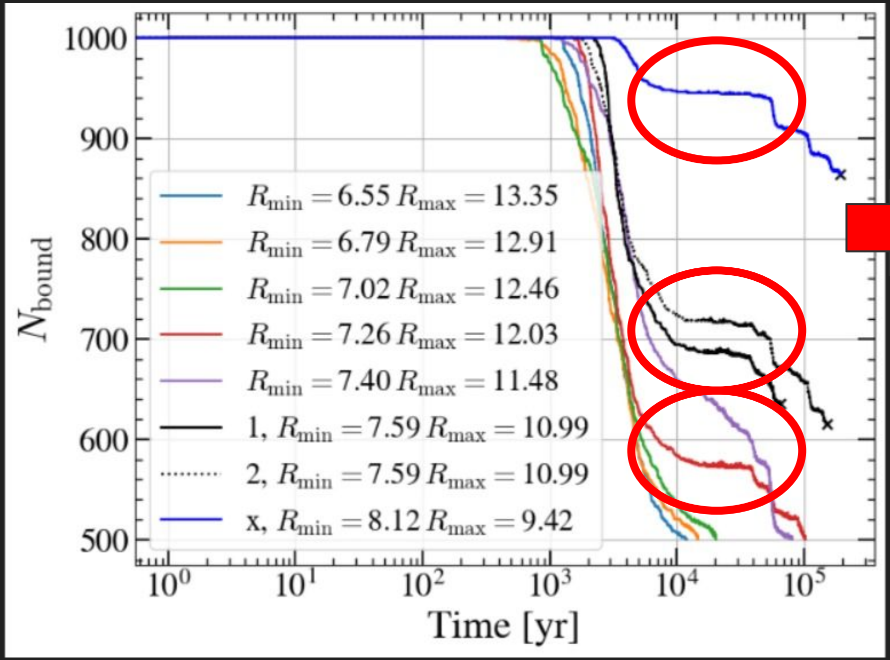
Time = 2342 year
x [AU]
y [AU]
y [AU]
z [AU]
x [AU]
z [AU]
Eccentricity
Angle [deg]
Time [yr]
e
Ω
ω



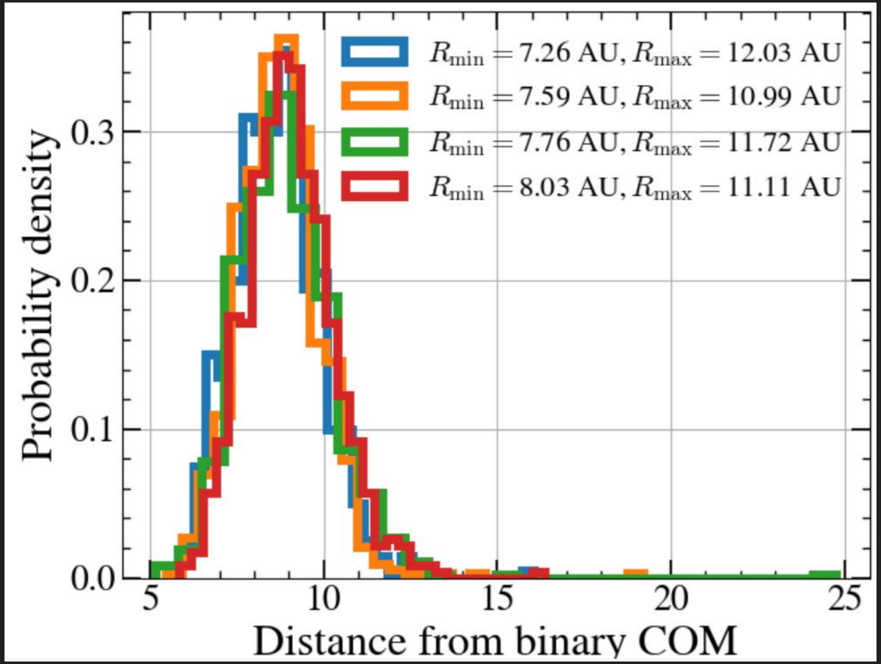
N_{bound}
1000
900
800
700
600
500
10^2
10^3
10^4
10^5
Time [yr]
$R_{\min} = 4.45\, R_{\max} = 13.35$
$R_{\min} = 6.02\, R_{\max} = 9.58$
$R_{\min} = 6.20\, R_{\max} = 8.87$
$R_{\min} = 5.06\, R_{\max} = 12.18$
$R_{\min} = 4.72\, R_{\max} = 12.73$
$R_{\min} = 5.35\, R_{\max} = 11.58$
$R_{\min} = 5.82\, R_{\max} = 10.27$
$R_{\min} = 5.58\, R_{\max} = 10.92$


1000
900
800
700
600
500
N_{bound}
10^0
10^1
10^2
10^3
10^4
10^5
Time [yr]
$R_{\min} = 6.55\ R_{\max} = 13.35$
$R_{\min} = 6.79\ R_{\max} = 12.91$
$R_{\min} = 7.02\ R_{\max} = 12.46$
$R_{\min} = 7.26\ R_{\max} = 12.03$
$R_{\min} = 7.40\ R_{\max} = 11.48$
1, $R_{\min} = 7.59\ R_{\max} = 10.99$
2, $R_{\min} = 7.59\ R_{\max} = 10.99$
x, $R_{\min} = 8.12\ R_{\max} = 9.42$

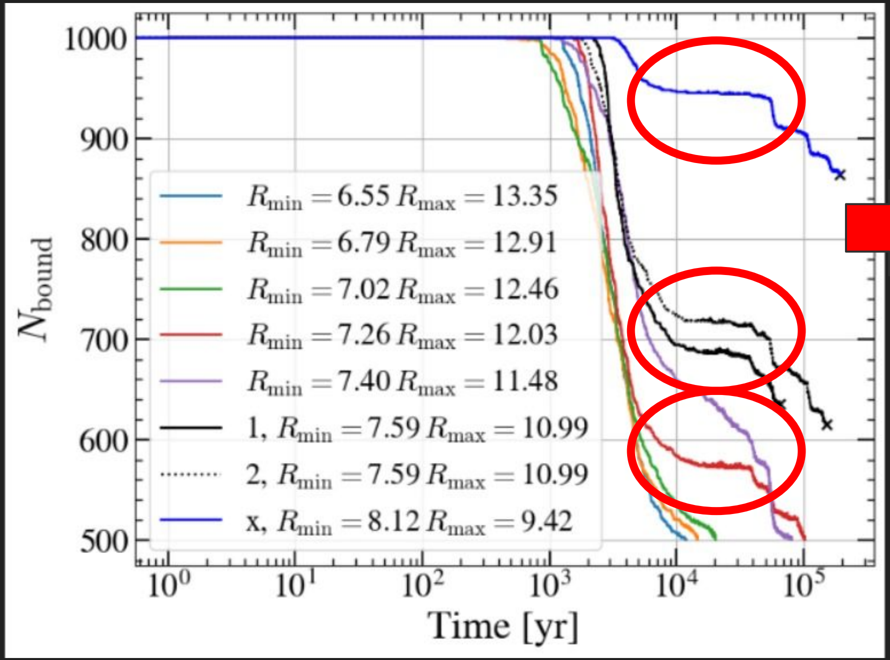

$N_{\rm bound}$
1000
900
800
700
600
500
$R_{\rm min} = 6.55\ R_{\rm max} = 13.35$
$R_{\rm min} = 6.79\ R_{\rm max} = 12.91$
$R_{\rm min} = 7.02\ R_{\rm max} = 12.46$
$R_{\rm min} = 7.26\ R_{\rm max} = 12.03$
$R_{\rm min} = 7.40\ R_{\rm max} = 11.48$
1, $R_{\rm min} = 7.59\ R_{\rm max} = 10.99$
2, $R_{\rm min} = 7.59\ R_{\rm max} = 10.99$
x, $R_{\rm min} = 8.12\ R_{\rm max} = 9.42$
10^0
10^1
10^2
10^3
10^4
10^5
Time [yr]

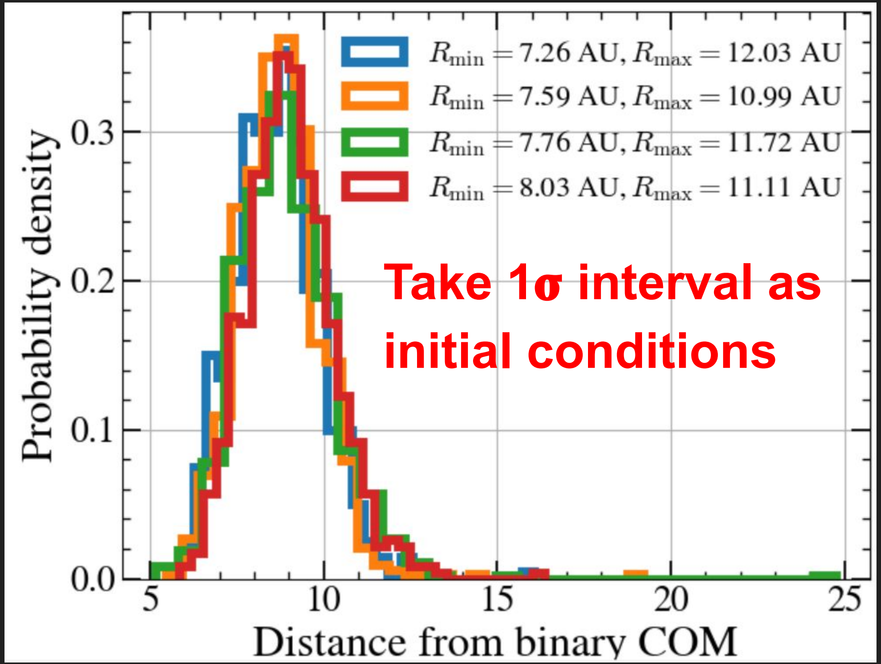


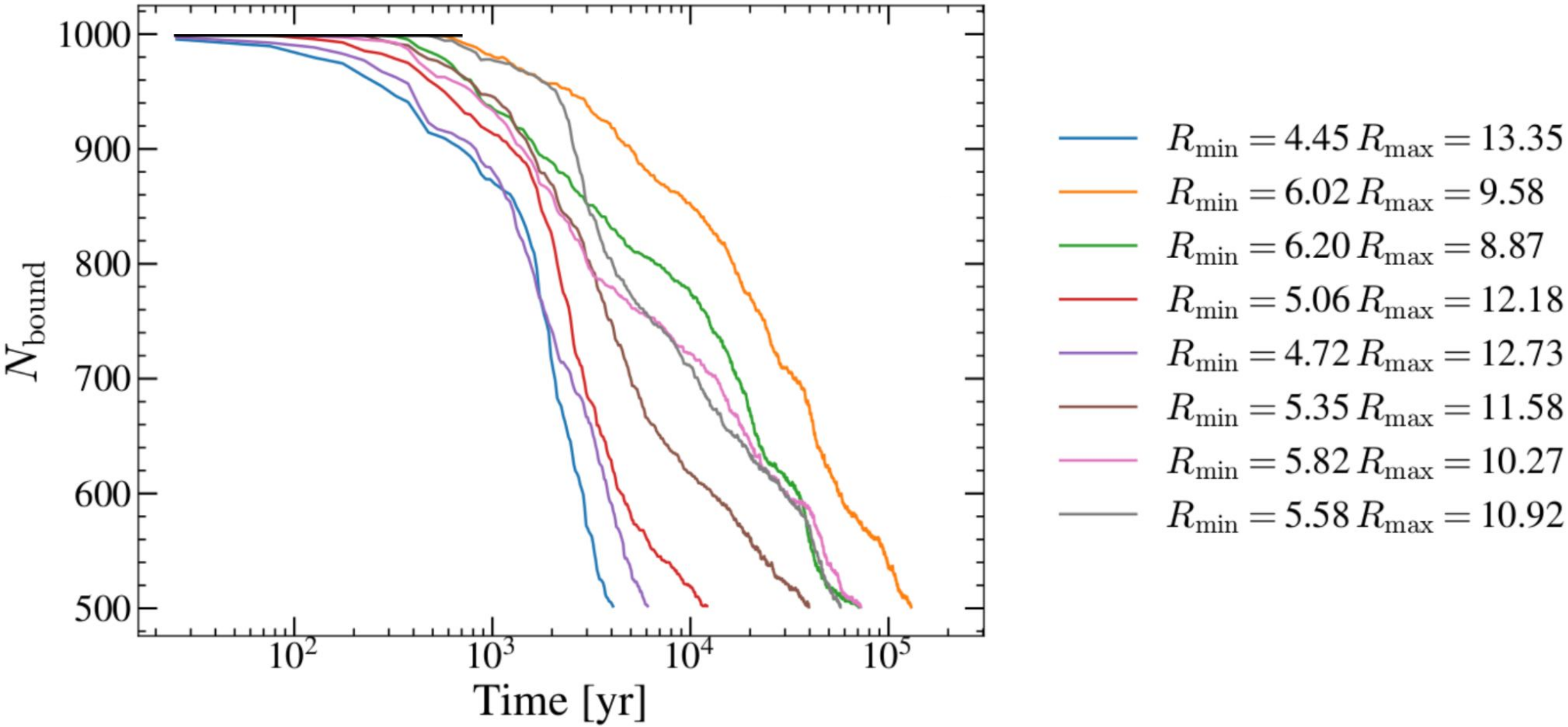
1000
900
800
700
600
500
N_{bound}
10^0 10^1 10^2 10^3 10^4 10^5
Time [yr]
$R_{\min} = 6.55\ R_{\max} = 13.35$
$R_{\min} = 6.79\ R_{\max} = 12.91$
$R_{\min} = 7.02\ R_{\max} = 12.46$
$R_{\min} = 7.26\ R_{\max} = 12.03$
$R_{\min} = 7.40\ R_{\max} = 11.48$
1, $R_{\min} = 7.59\ R_{\max} = 10.99$
2, $R_{\min} = 7.59\ R_{\max} = 10.99$
x, $R_{\min} = 8.12\ R_{\max} = 9.42$



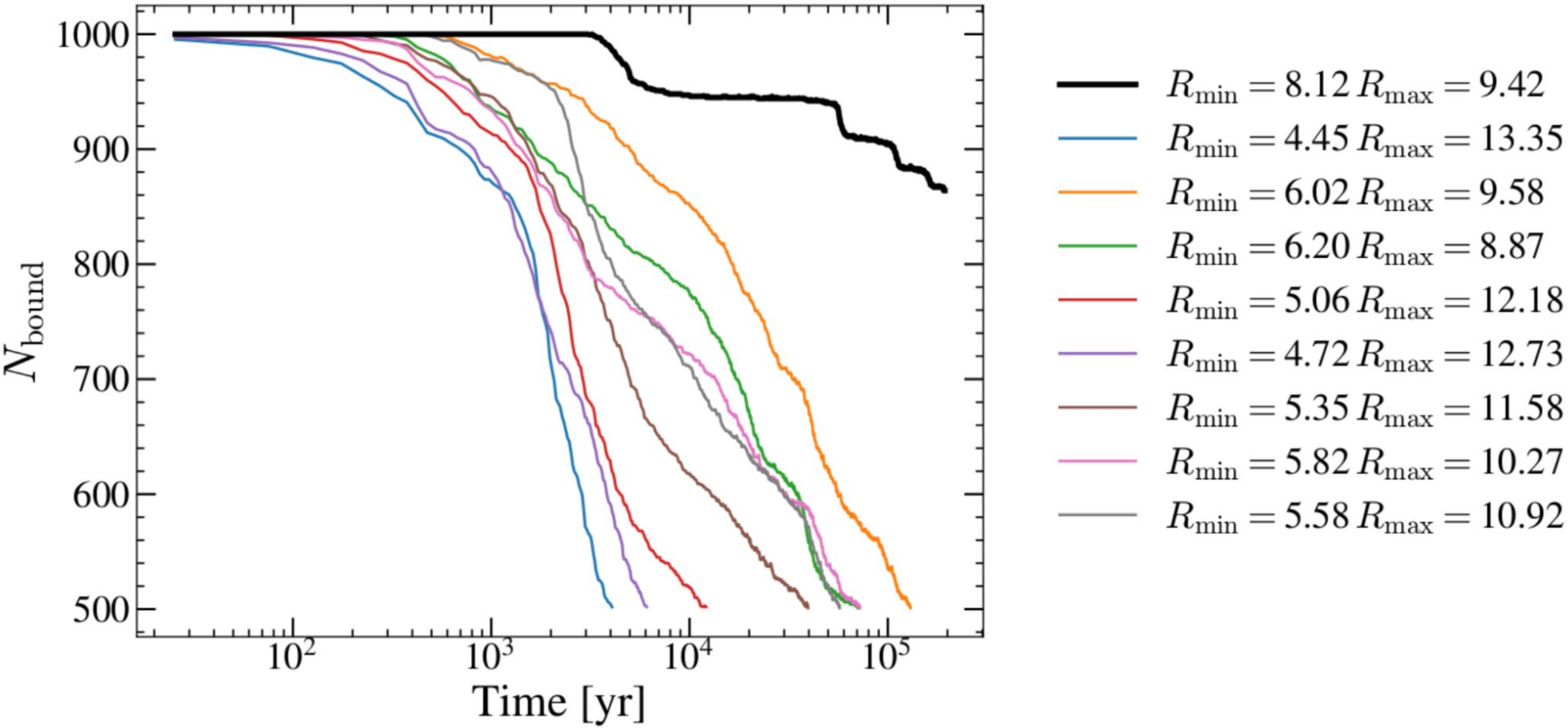
$R_{\min} = 7.26$ AU, $R_{\max} = 12.03$ AU
$R_{\min} = 7.59$ AU, $R_{\max} = 10.99$ AU
$R_{\min} = 7.76$ AU, $R_{\max} = 11.72$ AU
$R_{\min} = 8.03$ AU, $R_{\max} = 11.11$ AU
Probability density
0.0 0.1 0.2 0.3
5 10 15 20 25
Distance from binary COM


N_{bound}
Time [yr]
$R_{\min} = 6.55$ $R_{\max} = 13.35$
$R_{\min} = 6.79$ $R_{\max} = 12.91$
$R_{\min} = 7.02$ $R_{\max} = 12.46$
$R_{\min} = 7.26$ $R_{\max} = 12.03$
$R_{\min} = 7.40$ $R_{\max} = 11.48$
1, $R_{\min} = 7.59$ $R_{\max} = 10.99$
2, $R_{\min} = 7.59$ $R_{\max} = 10.99$
x, $R_{\min} = 8.12$ $R_{\max} = 9.42$


Probability density
Distance from binary COM
$R_{\min} = 7.26$ AU, $R_{\max} = 12.03$ AU
$R_{\min} = 7.59$ AU, $R_{\max} = 10.99$ AU
$R_{\min} = 7.76$ AU, $R_{\max} = 11.72$ AU
$R_{\min} = 8.03$ AU, $R_{\max} = 11.11$ AU
Take 1σ interval as initial conditions



1000
900
800
700
600
500
N_{bound}
10^2
10^3
10^4
10^5
Time [yr]
$R_{\mathrm{min}} = 4.45\, R_{\mathrm{max}} = 13.35$
$R_{\mathrm{min}} = 6.02\, R_{\mathrm{max}} = 9.58$
$R_{\mathrm{min}} = 6.20\, R_{\mathrm{max}} = 8.87$
$R_{\mathrm{min}} = 5.06\, R_{\mathrm{max}} = 12.18$
$R_{\mathrm{min}} = 4.72\, R_{\mathrm{max}} = 12.73$
$R_{\mathrm{min}} = 5.35\, R_{\mathrm{max}} = 11.58$
$R_{\mathrm{min}} = 5.82\, R_{\mathrm{max}} = 10.27$
$R_{\mathrm{min}} = 5.58\, R_{\mathrm{max}} = 10.92$


1000
900
800
700
600
500
N_{bound}
10^2
10^3
10^4
10^5
Time [yr]
$R_{\min} = 8.12\, R_{\max} = 9.42$
$R_{\min} = 4.45\, R_{\max} = 13.35$
$R_{\min} = 6.02\, R_{\max} = 9.58$
$R_{\min} = 6.20\, R_{\max} = 8.87$
$R_{\min} = 5.06\, R_{\max} = 12.18$
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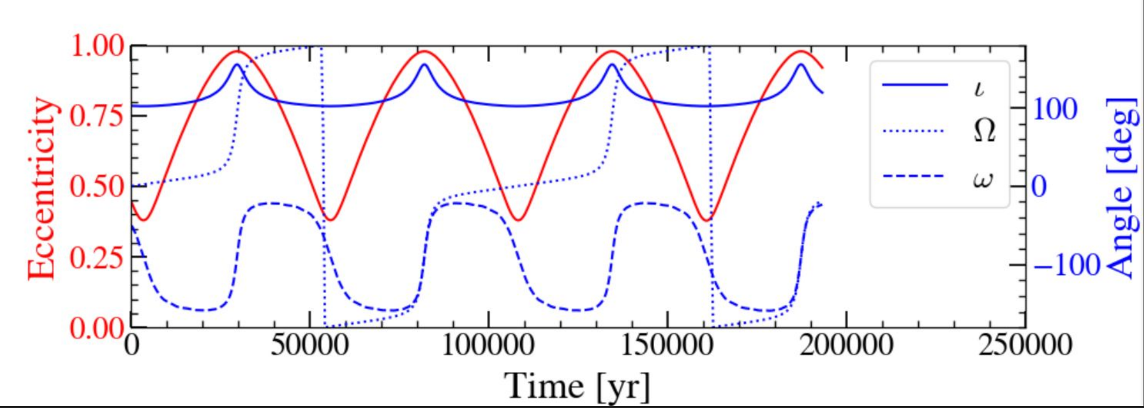
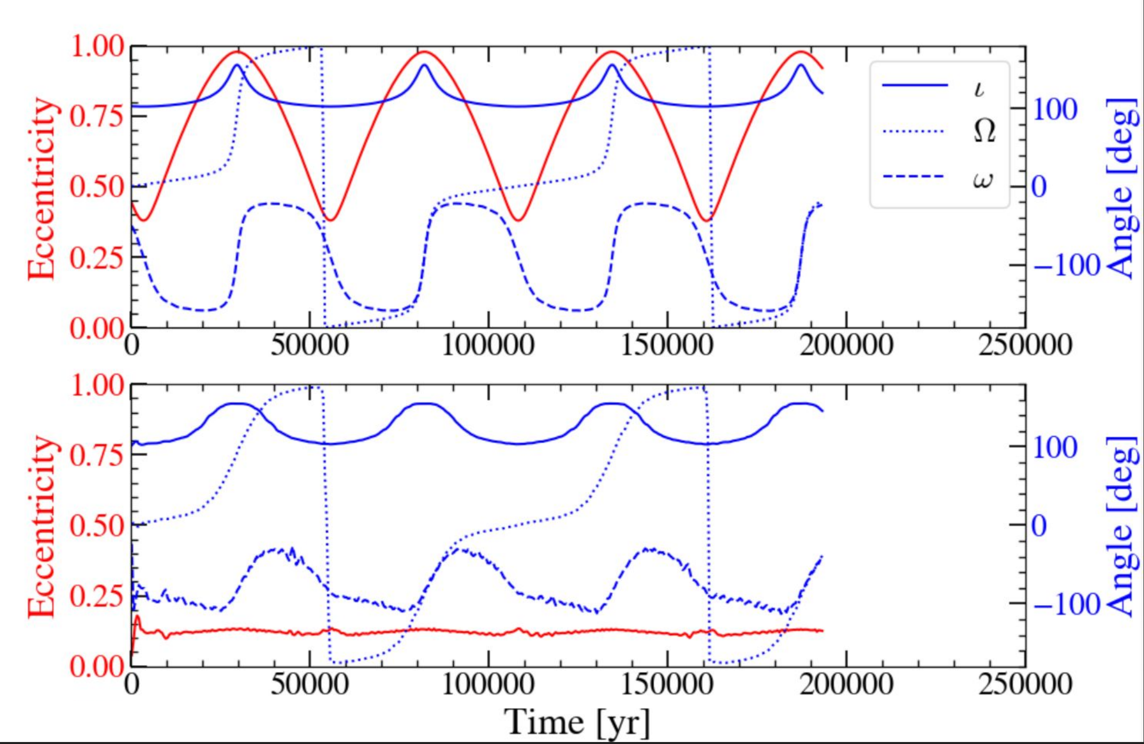
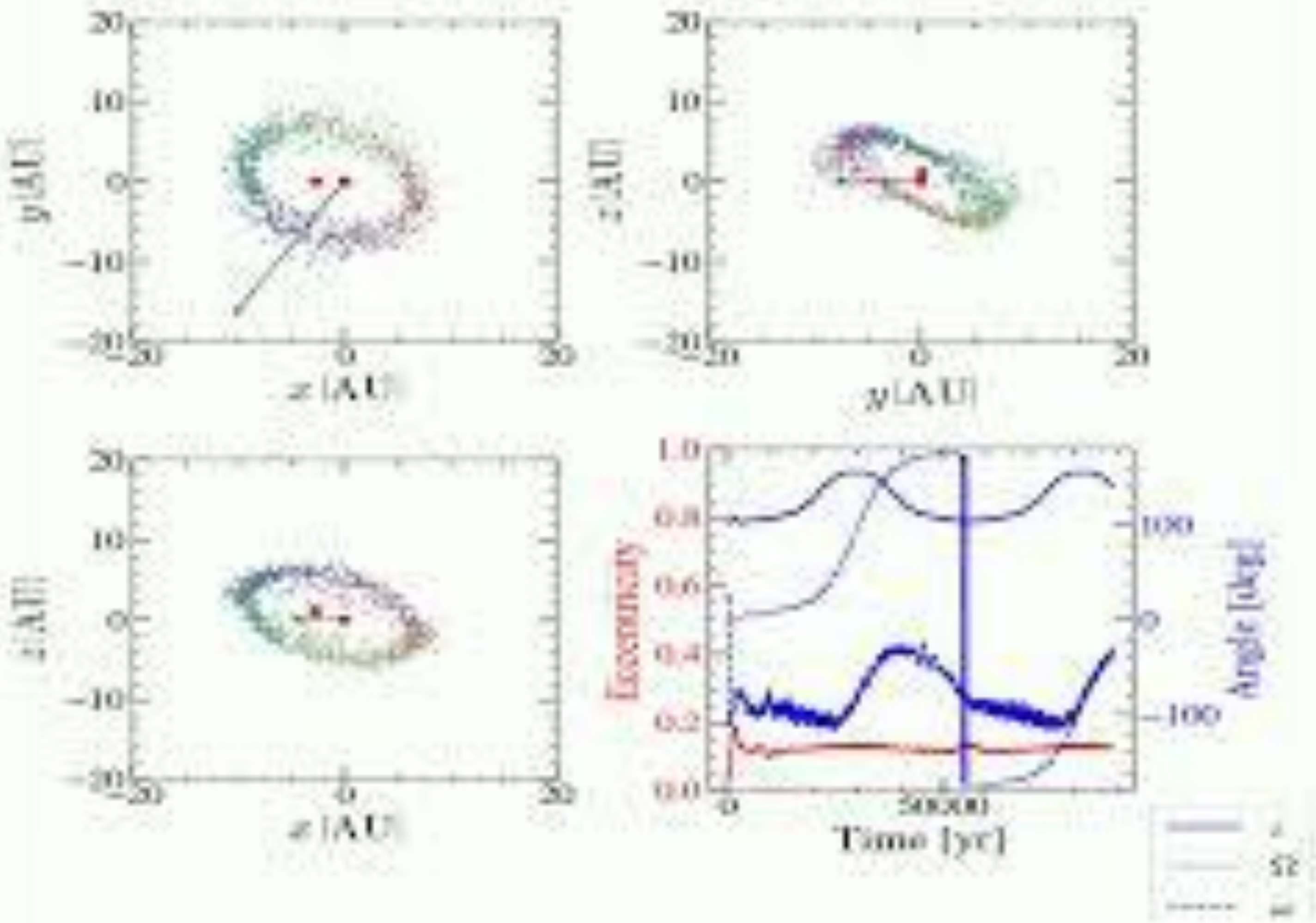
$R_{\min} = 5.35\, R_{\max} = 11.58$
$R_{\min} = 5.82\, R_{\max} = 10.27$
$R_{\min} = 5.58\, R_{\max} = 10.92$

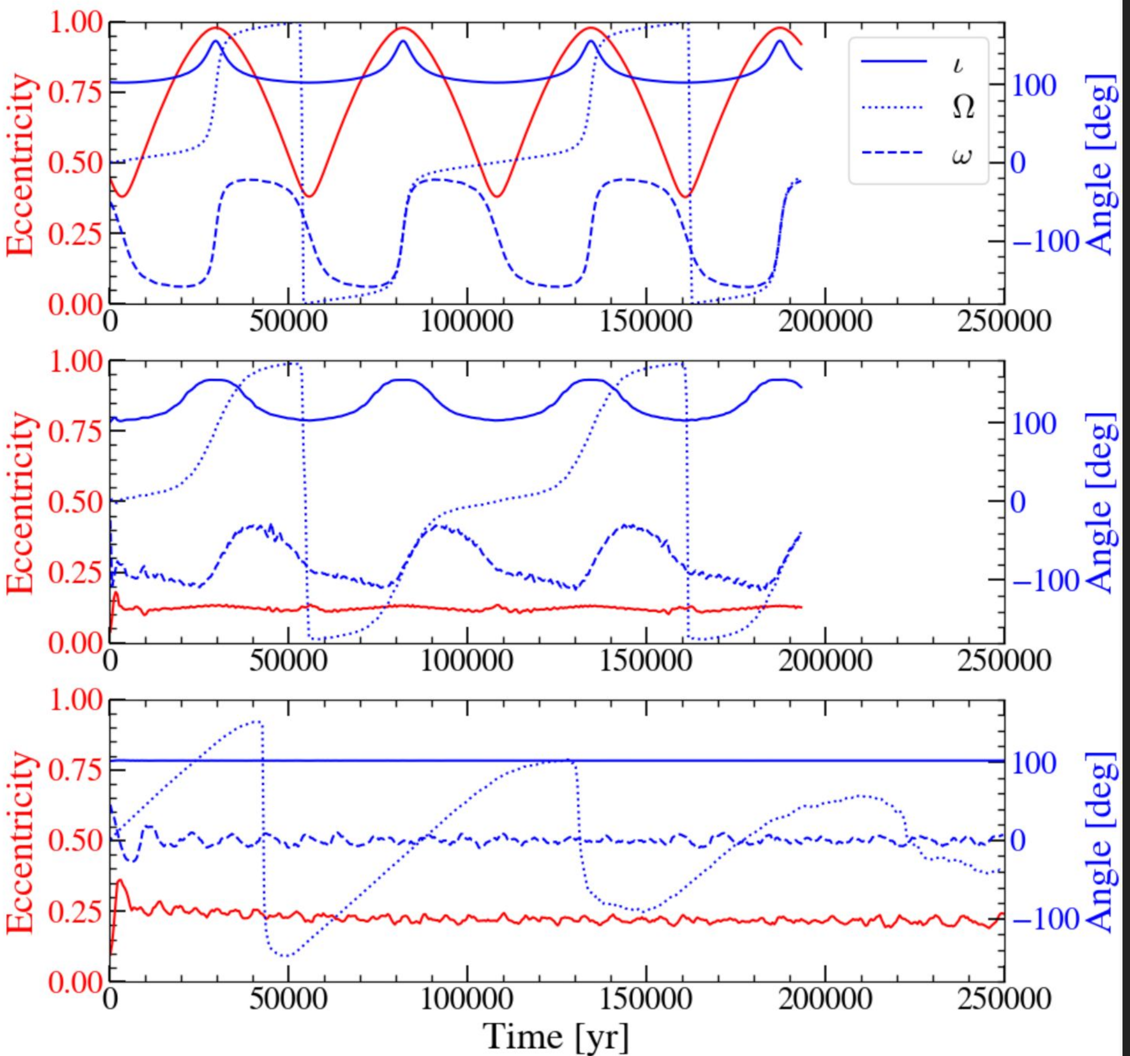

1.00
0.75
0.50
0.25
0.00
Eccentricity
0
50000
100000
150000
200000
250000
Time [yr]
100
0
−100
Angle [deg]
ι
Ω
ω



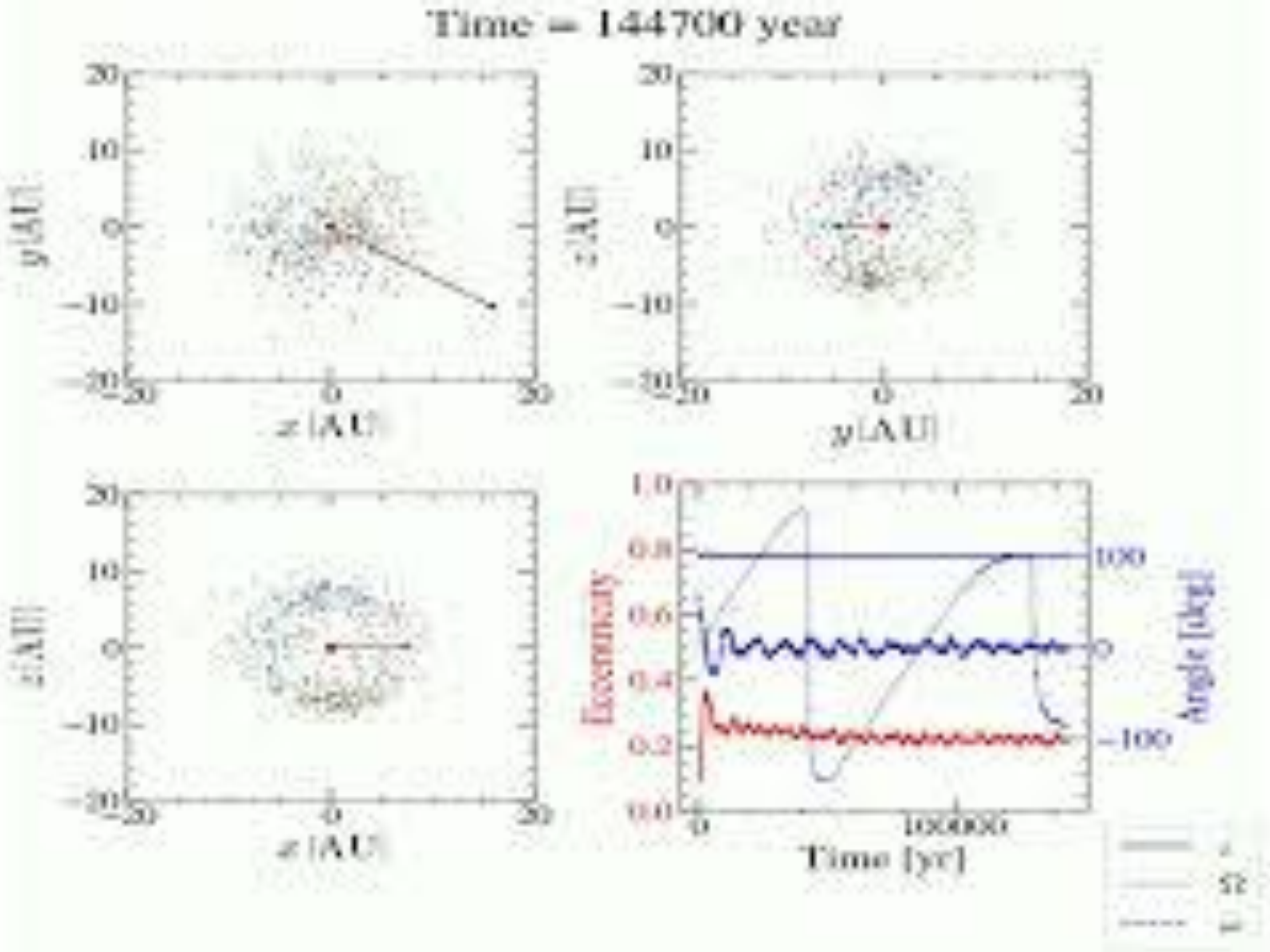
Eccentricity
Angle [deg]
ι
Ω
ω
Time [yr]

Time = 89150 year



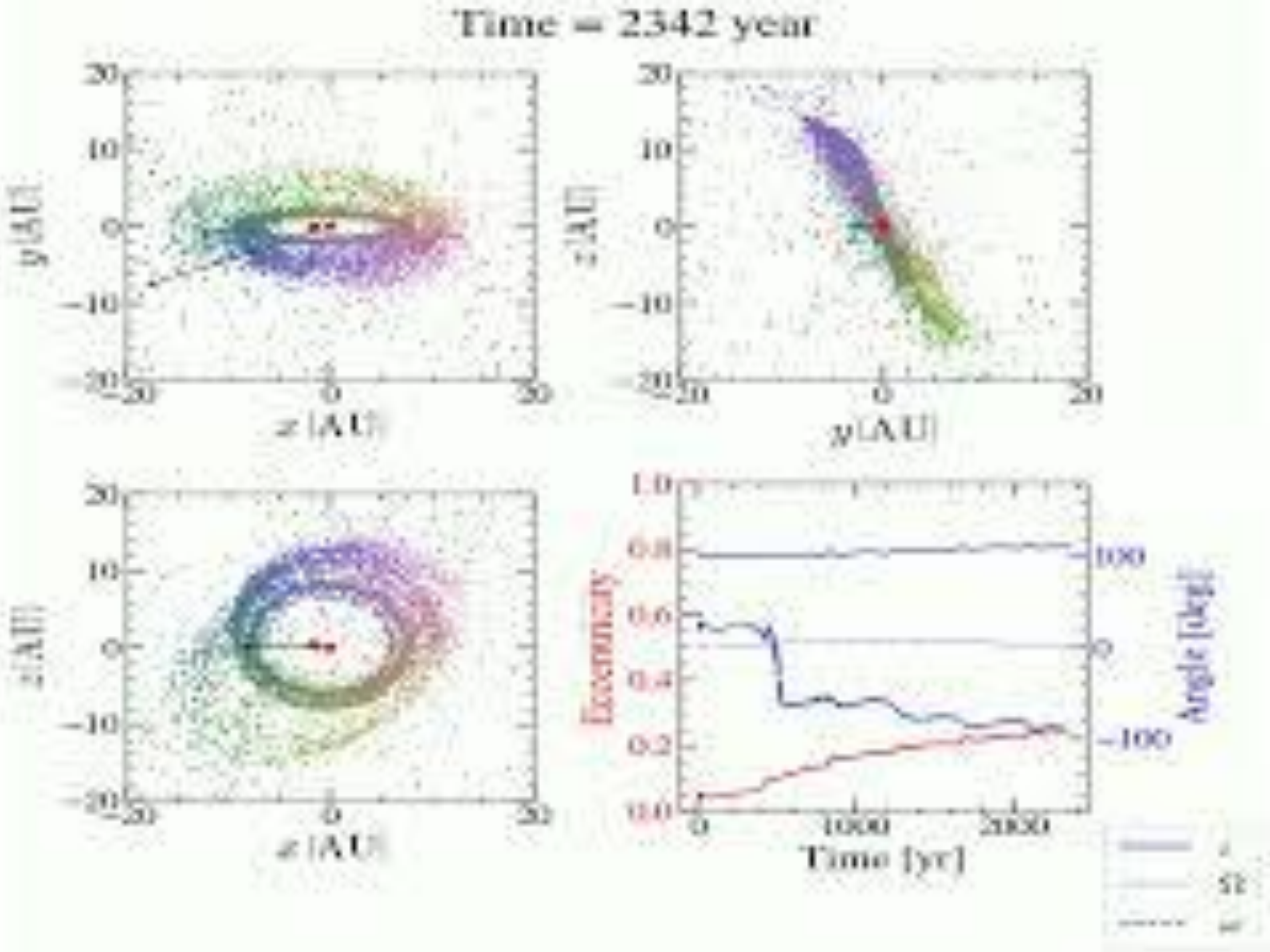


ι
Ω
ω
Eccentricity
Angle [deg]
Time [yr]
0.00
0.25
0.50
0.75
1.00
−100
0
100
0
50000
100000
150000
200000
250000

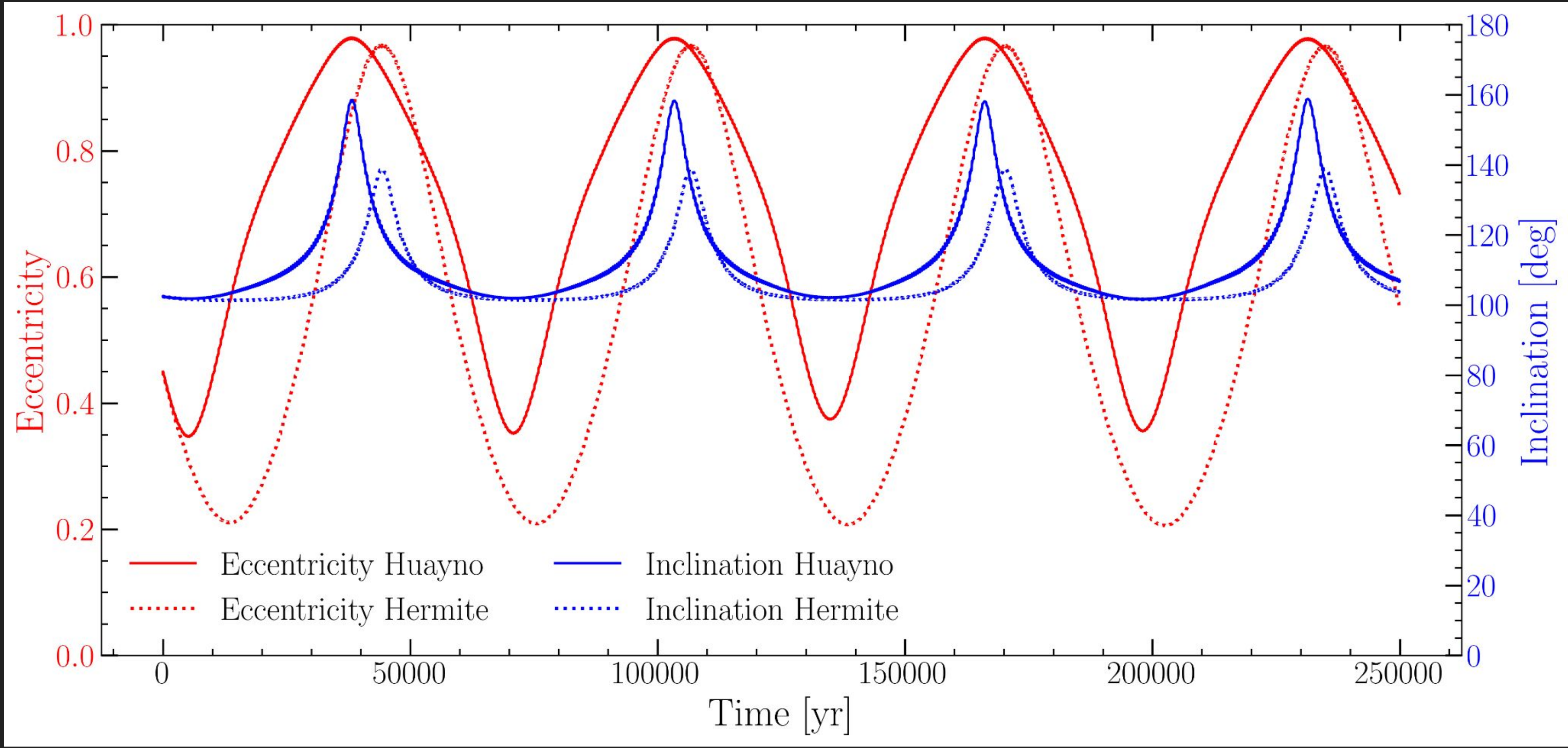

Time = 144700 year
y [AU]
x [AU]
z [AU]
y [AU]
z [AU]
x [AU]
Eccentricity
Angle [deg]
Time [yr]
Ω

Conclusions

- In the absence of the S-star cluster, there is a quasi-stable configuration for a circumbinary disk close to Sgr. A* on timescales of ~10^5 years.
- The Kozai oscillations of the disk trace those of the binary
- The binary is necessary in order to keep a flat disk.

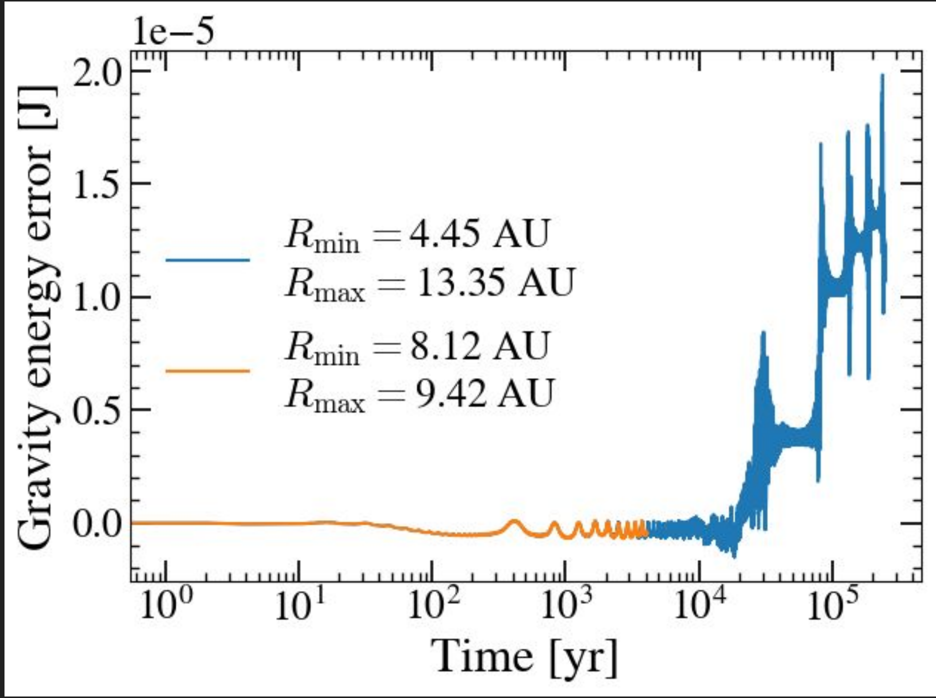

Time = 2342 year
x [AU]
y [AU]
y [AU]
z [AU]
x [AU]
z [AU]
Eccentricity
Angle [deg]
Time [yr]
e
Ω
ω

Huayno vs. Hermite



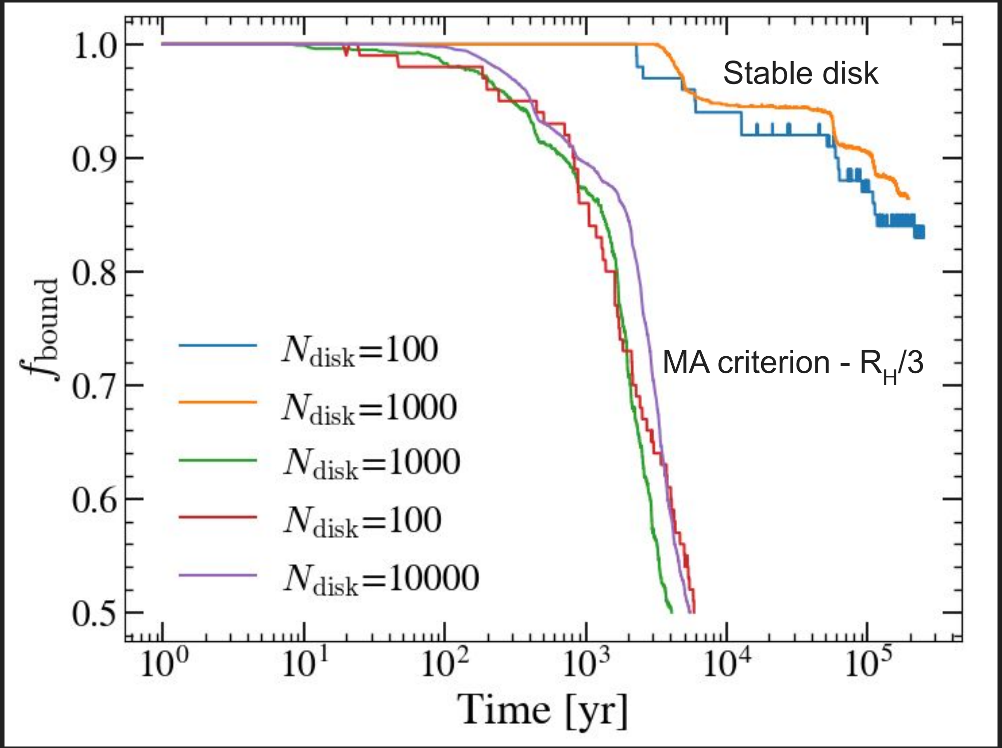
Validation: Energy Error

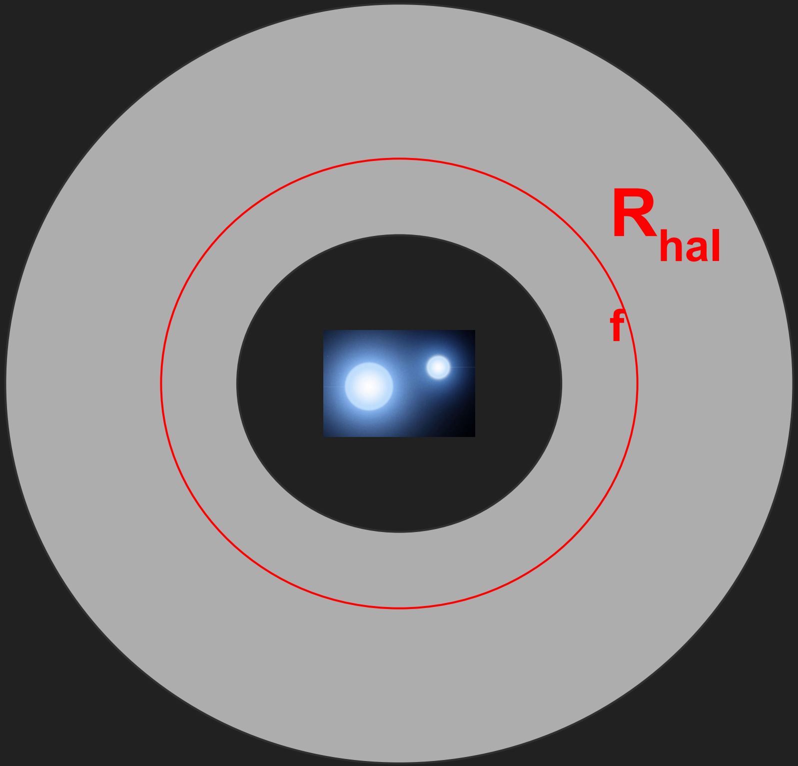
- Gravity energy error
- Disk mass low, negligible



Validation: Convergence tests

- Two disk sizes
  - MA criterion - $R_H/3$
  - Stable disk




R_{hal}
f