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Orbital Evolution of S Stars Due to Resonant Relaxation

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Summary

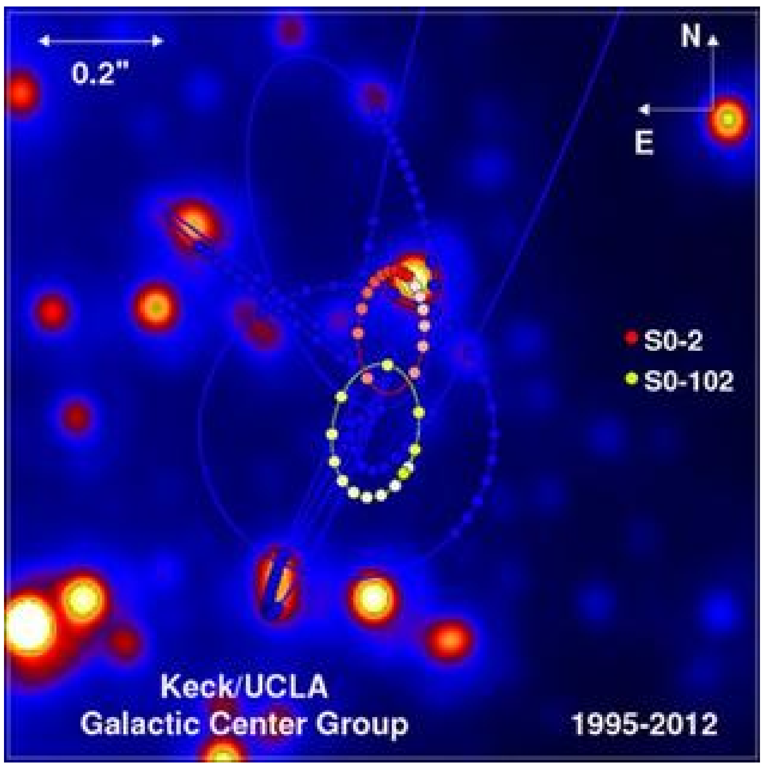
- We performed N-body simulations of dynamical evolution of the stellar system around the MBH at the Center of the Galaxy.
- Orbits of S stars evolve from their initial Kepler orbits
- Precession and inclination evolution take place.
- The evolution of inclination is due to RR only.
- We find dependence of the evolution of inclination on cluster properties such as its mass and N.
- Further observation of inclination evolution of S stars will be a clue to above properties.

Contents

1. Introduction

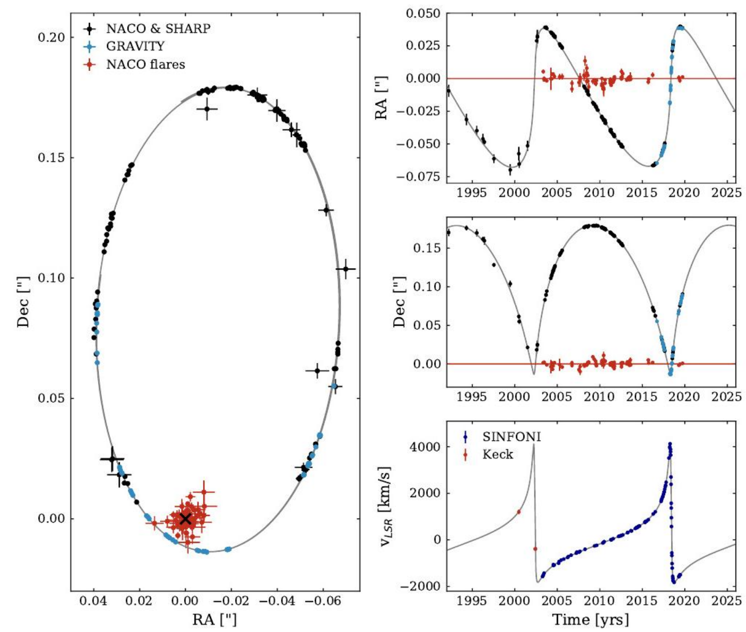
Center of the Galaxy and Orbit of S2 star

Galactic Center



(c)Andrea Ghez

Orbit of S2



GRAVITY Colab. 2020 A&A

$\Delta\phi = 0.003$ **[rad/P]**

Table E.1. Best-fit orbit parameters.

Parameter	Value	Fit error	MCMC error	Unit
f_{SP}	1.10	0.19	0.21	
f_{RS}	1	Fixed	Fixed	
$M_\bullet$	4.261	0.012	0.012	$10^6\ M_\odot$
R_0	8246.7	9.3	9.3	pc
a	125.058	0.041	0.044	mas
e	0.884649	0.000066	0.000079	
i	134.567	0.033	0.033	°
ω	66.263	0.031	0.030	°
Ω	228.171	0.031	0.031	°
P	16.0455	0.0013	0.0013	yr
t_{peri}	2018.37900	0.00016	0.00017	yr
x_0	−0.90	0.14	0.15	mas
y_0	0.07	0.12	0.11	mas
vx_0	0.080	0.010	0.010	mas yr^{-1}
vy_0	0.0341	0.0096	0.0096	mas yr^{-1}
vz_0	−1.6	1.4	1.4	km s^{-1}

Notes. The orbital parameters are to be interpreted as the osculating orbital parameters. The argument of periapsis ω and the time of pericentre passage t_{peri} are given for the epoch of last apocentre in 2010.

$$\boldsymbol{a} = -\frac{GM}{r^3}\boldsymbol{r} + f_{SP}\frac{GM}{c^2 r^2}\left[\left(4\frac{GM}{r} - v^2\right)\frac{\boldsymbol{r}}{r} + 4\dot{r}\boldsymbol{v}\right] + O[J] + O[Q_2]. \tag{C.1}$$

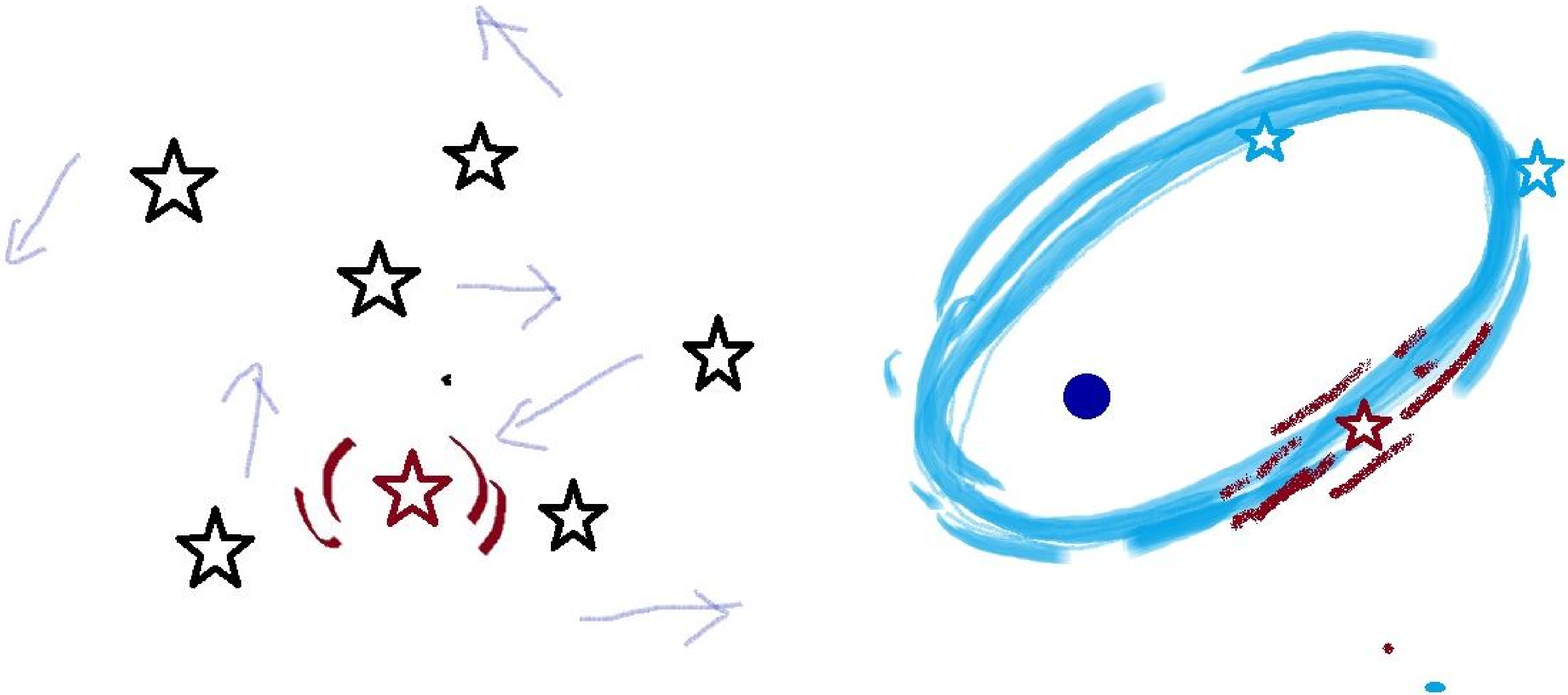
the (first-order) parameterized post-Newtonian (PPN) expansion of GR

Resonant Relaxation (RR)

- **theoretically predicted by Rauch & Tremaine 1996**
  - **relaxation in angular momentum space**
  - **different relaxation from two-body relaxation**
  - **takes place in N-body systems which contains a massive object at the center and its gravitation dominates the system.**

    ex.1: planetary system with a host star

    ex.2: central region of a nuclear star cluster containing an SMBH



characteristic properties of RR

Timescale :

- $t_{\rm rr} \sim \frac{m_{\rm B\mathit{H}}}{m_*} t_{\rm o\mathit{rb}}$

each star **:**

- $\Delta E \sim 0$
- $\Delta L \sim t$

consequently

* $\Delta\phi \sim t$

* $\Delta i \sim t$

characteristic properties of RR

Timescale :

- $t_{\rm rr} \sim \frac{m_{\rm B}H}{m_*} t_{\rm o}rb$

each star :

- $\Delta E \sim 0$
- $\Delta L \sim t$

consequently

* $\Delta\phi \sim t$

* $\Delta i \sim t$

statistical behavior :

- $\sqrt{< |\Delta E|^2 >} \sim 0$
- $< \Delta L > \sim 0$
- $\sqrt{< |\Delta L|^2 >} \sim t$

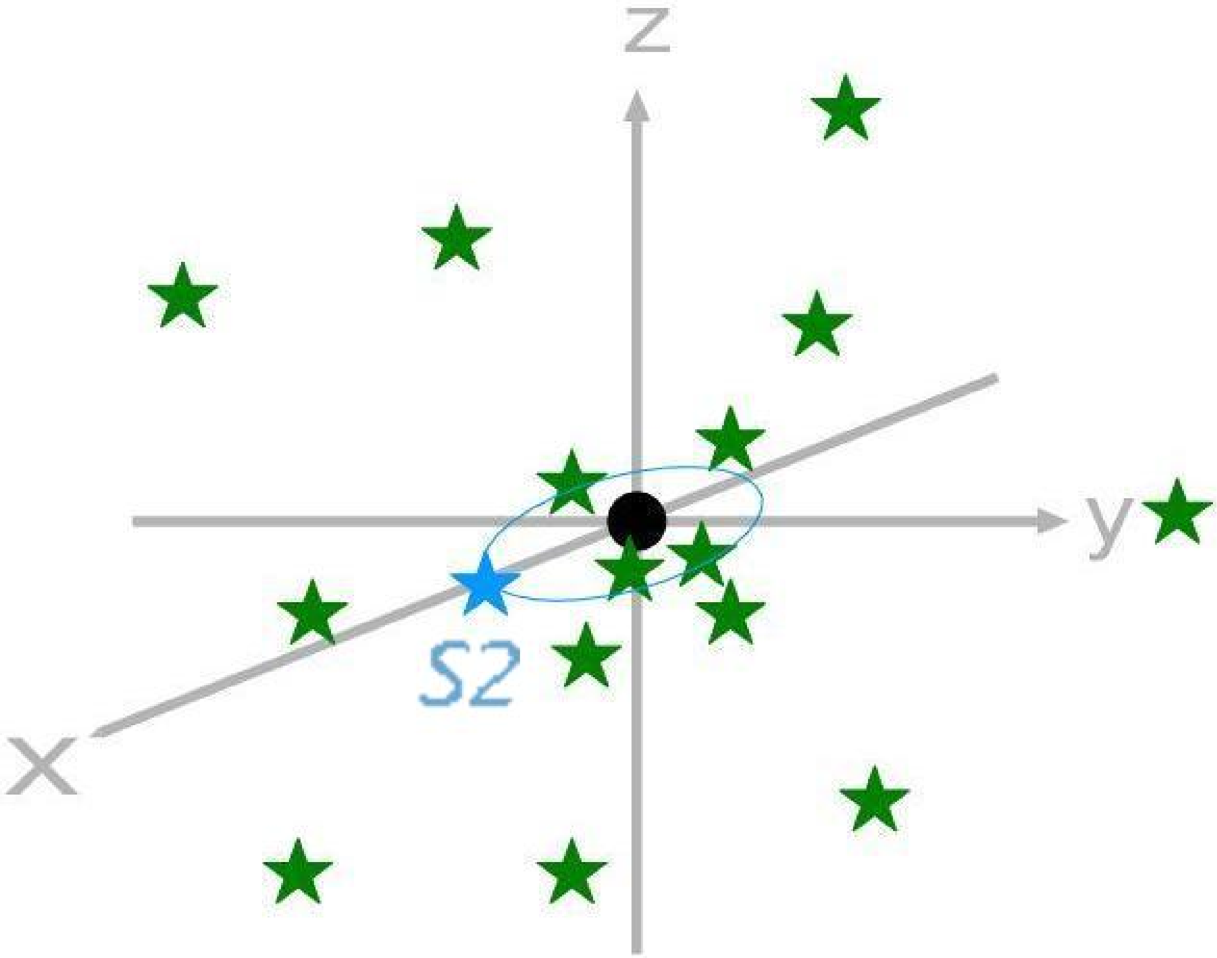
consequently

* $\sqrt{|\Delta\phi|^2} \sim t$

* $\sqrt{|\Delta i|^2} \sim t$

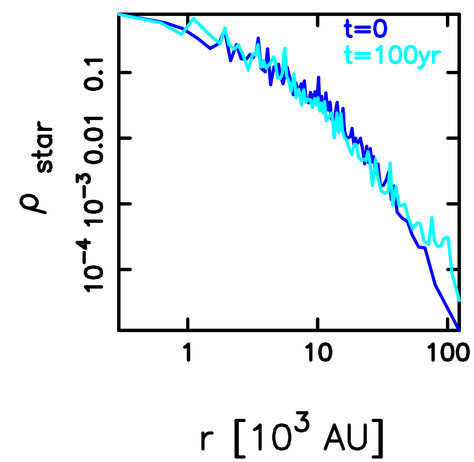
$<>$ ... *average of particles*

2.1 Model& Initial Condition



density profile

(T.Matsubayashi+ 2007)



Model parameters

- $M_{\rm SMBH}$ **: fix**
- r_0 *(scale length)* **: fix**
- $M_{\rm cluster}$**: changing**

  max: **observational upper limit (Abuter+ 2020)**

  min: **theoretical prediction (Alexander+ 2009)**
- N **: changing (i.e.mass ratio :** $M_{\rm SMBH} : M_{\rm star}$**)**
- GR **: w/wo**
- **20 different seed run/model**

2.2 Numerical Method

GPLUM

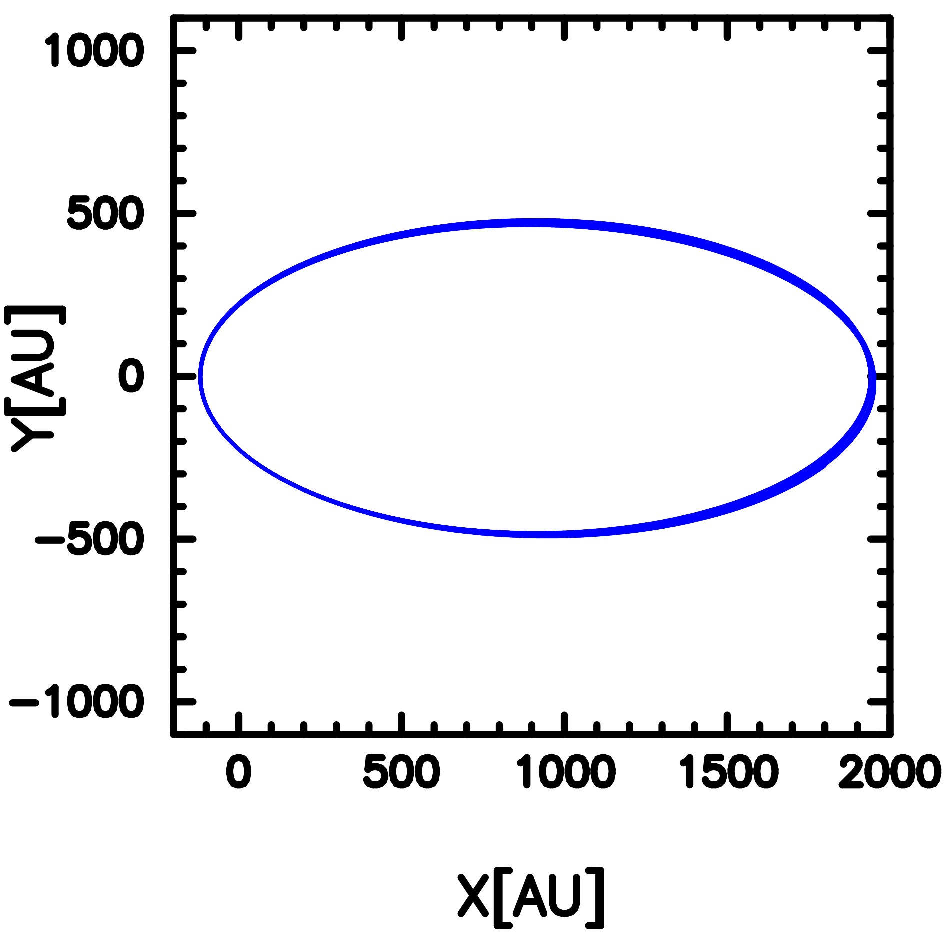
(Y.Ishigaki+ 2020)

- **a massive body (the Sun, a BH) at the origin**
- **P^{3}T method** *(S.Oshino, Y.Funato, J.Makino, 2011)*
- **FDPS** *(M.Iwasawa+ 2019)*
- *w/wo PN term*

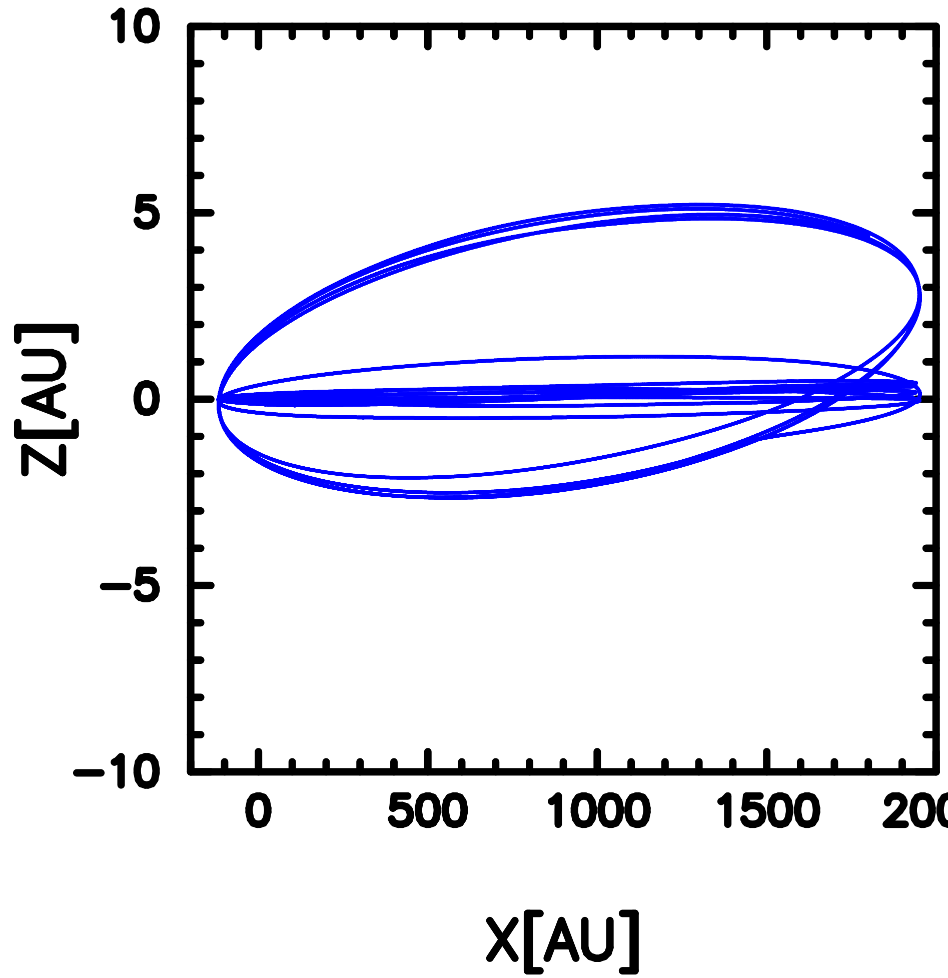
3. Result

an example of orbital evolution

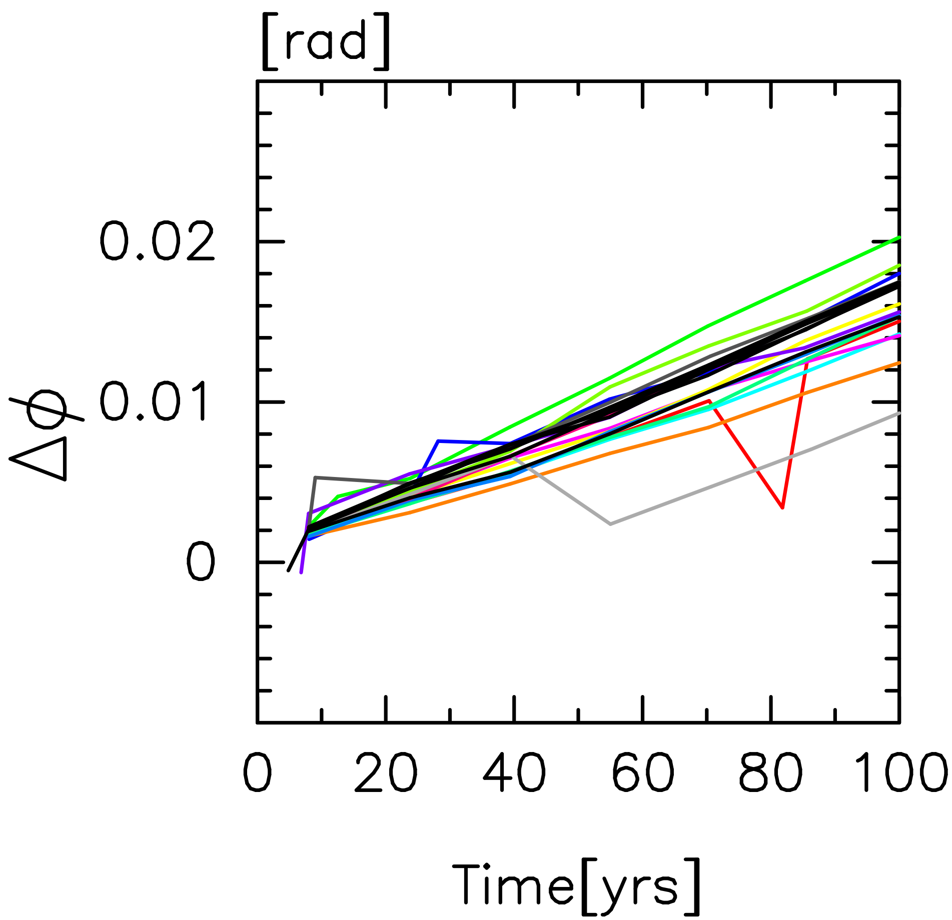
x-y



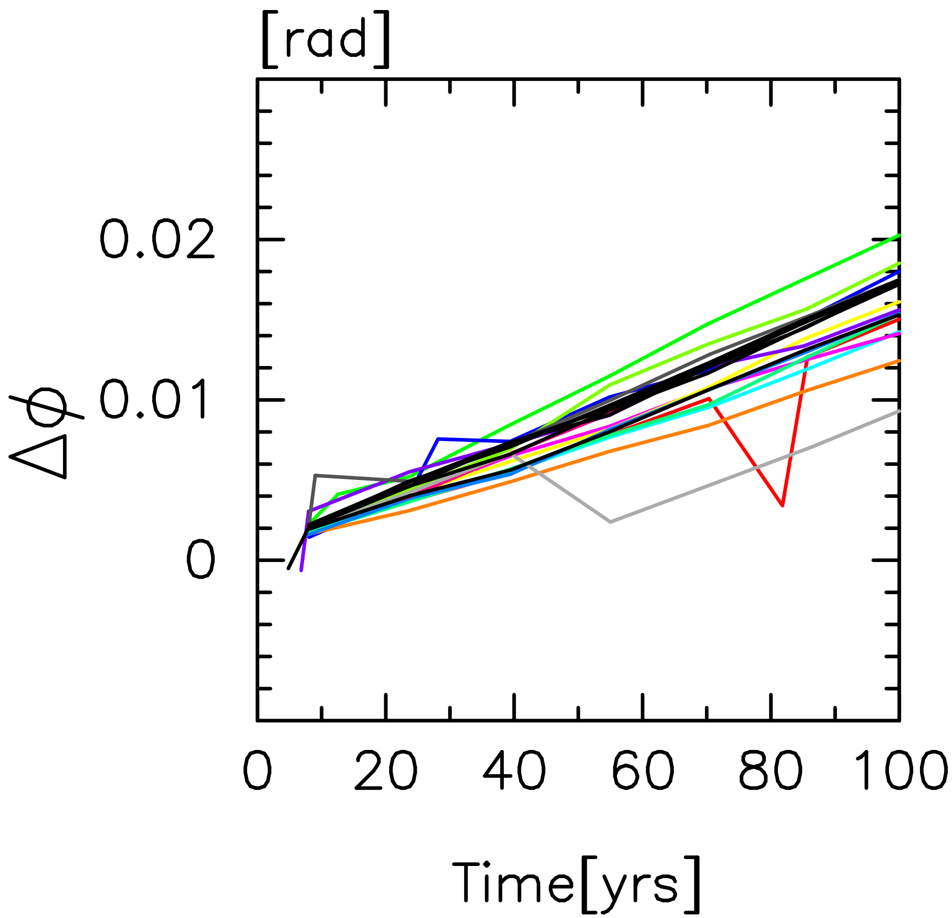
x-z



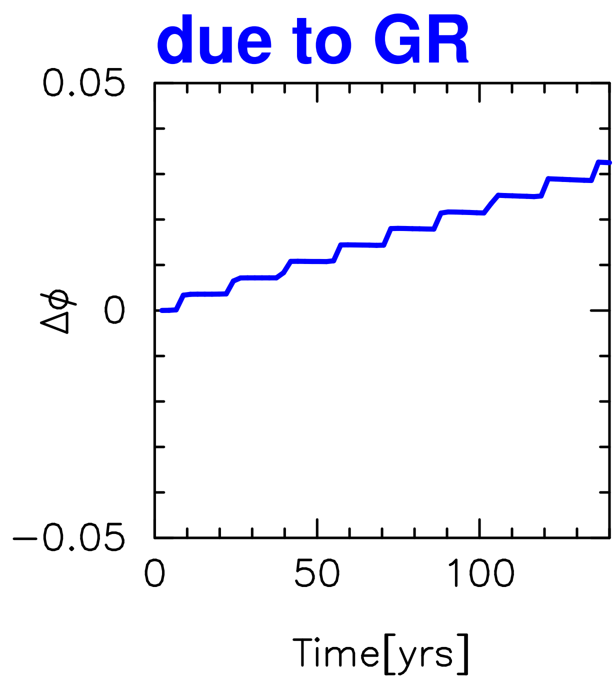
Precession



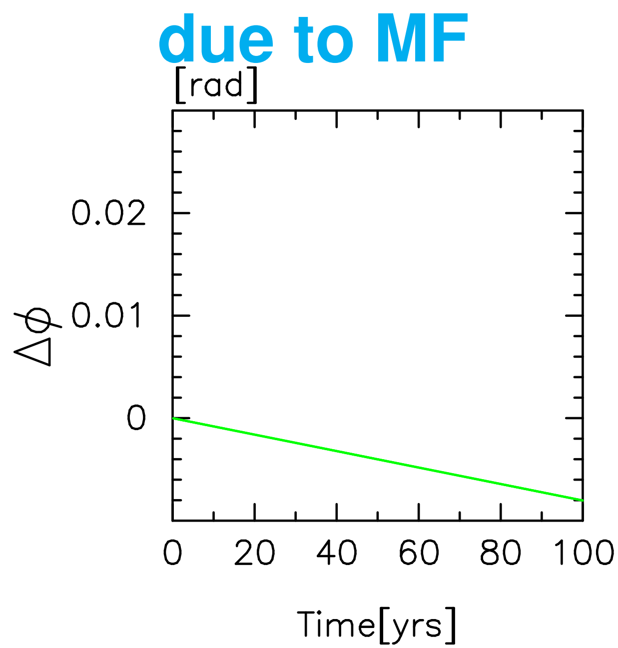
Precession



[rad]
0.02
0.01
0
Δφ
0
20
40
60
80
100
Time[yrs]

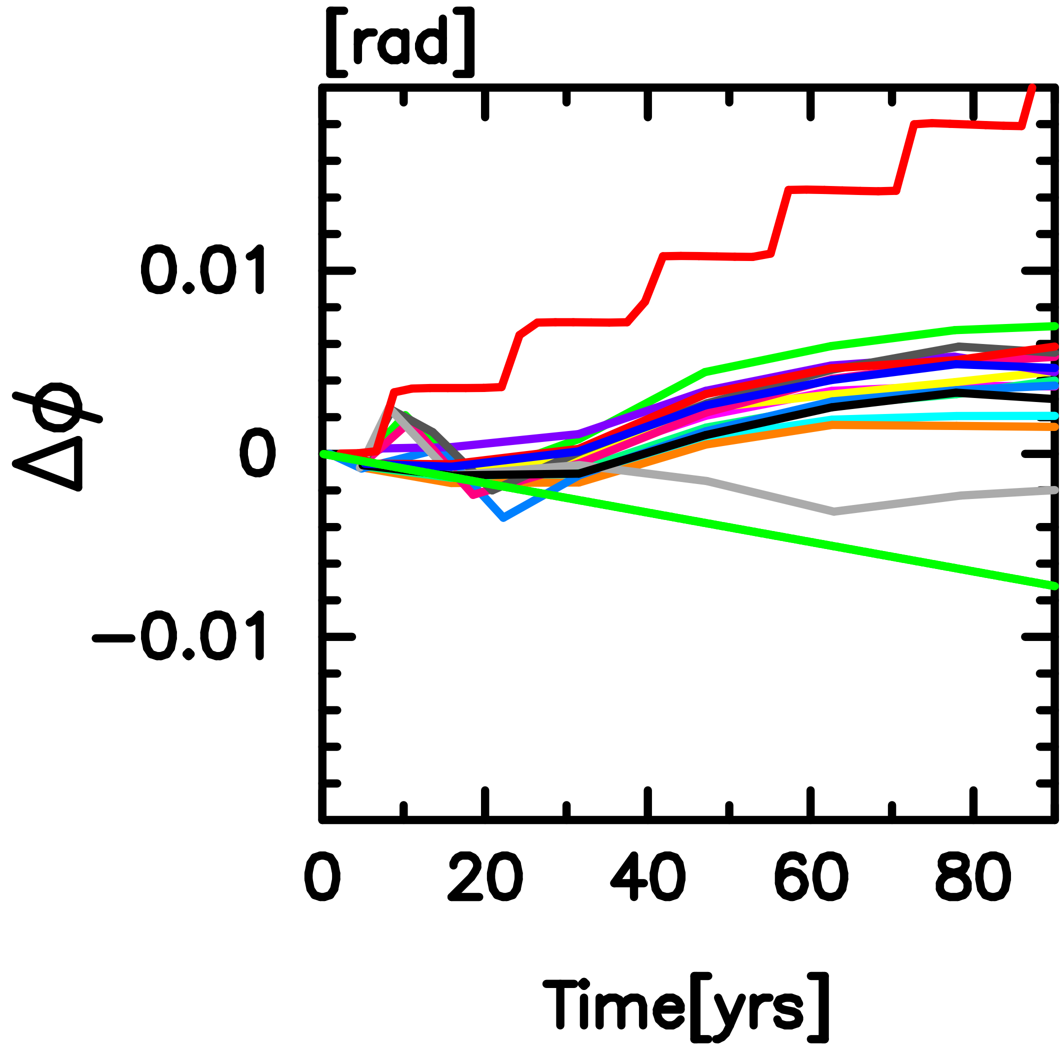


due to GR
0.05
0
−0.05
Δφ
0
50
100
Time[yrs]



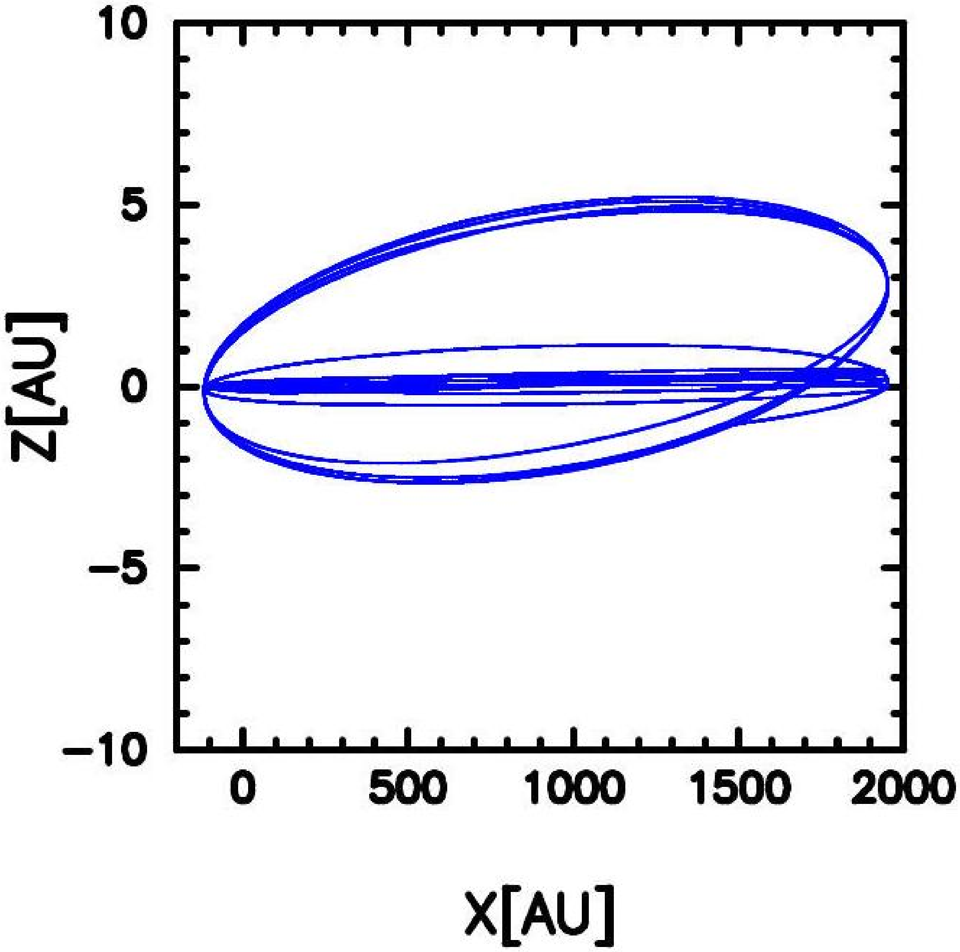
due to MF
[rad]
0.02
0.01
0
Δφ
0
20
40
60
80
100
Time[yrs]

Precession due to RR, GR, MF

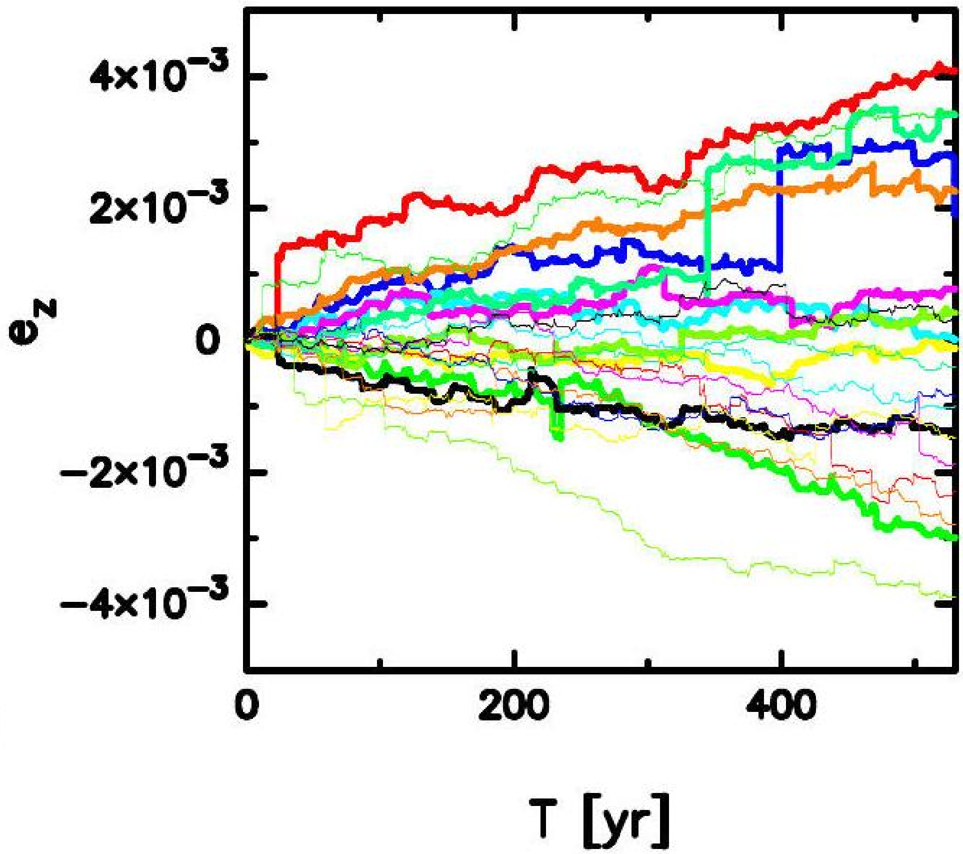


z evolution: examples

X-Z

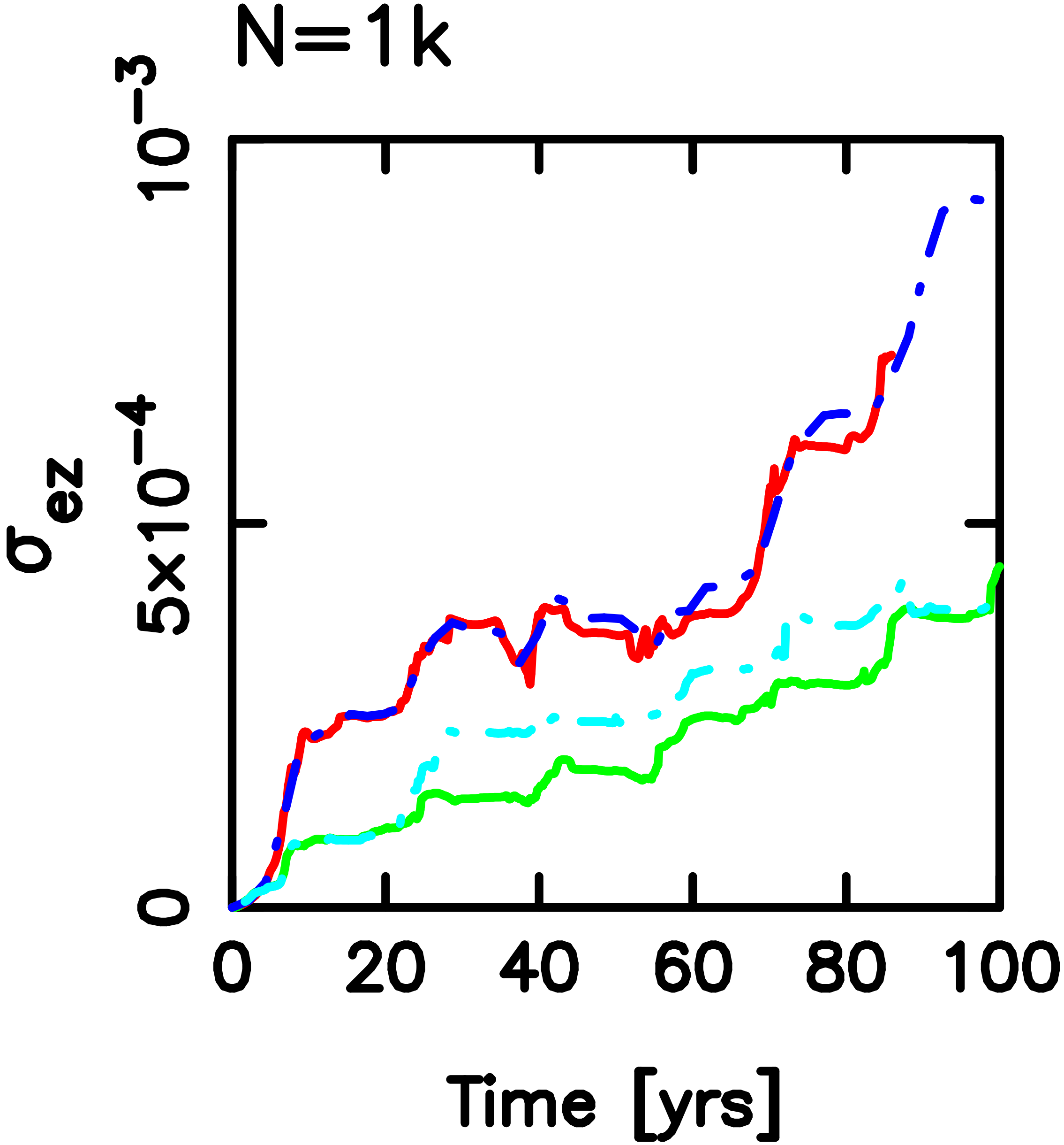


t-$e_z \doteqdot \Delta i$



Here $e_z = \sin(\Delta i) \doteqdot \Delta i$

variance $\sigma_{\rm ez}^2 = (1/n_{\rm run}) \sum^{\rm nrun} (e_z - < e_z >)^2$



$M_{\rm cl,enc} \fallingdotseq 10^4 M_\odot$

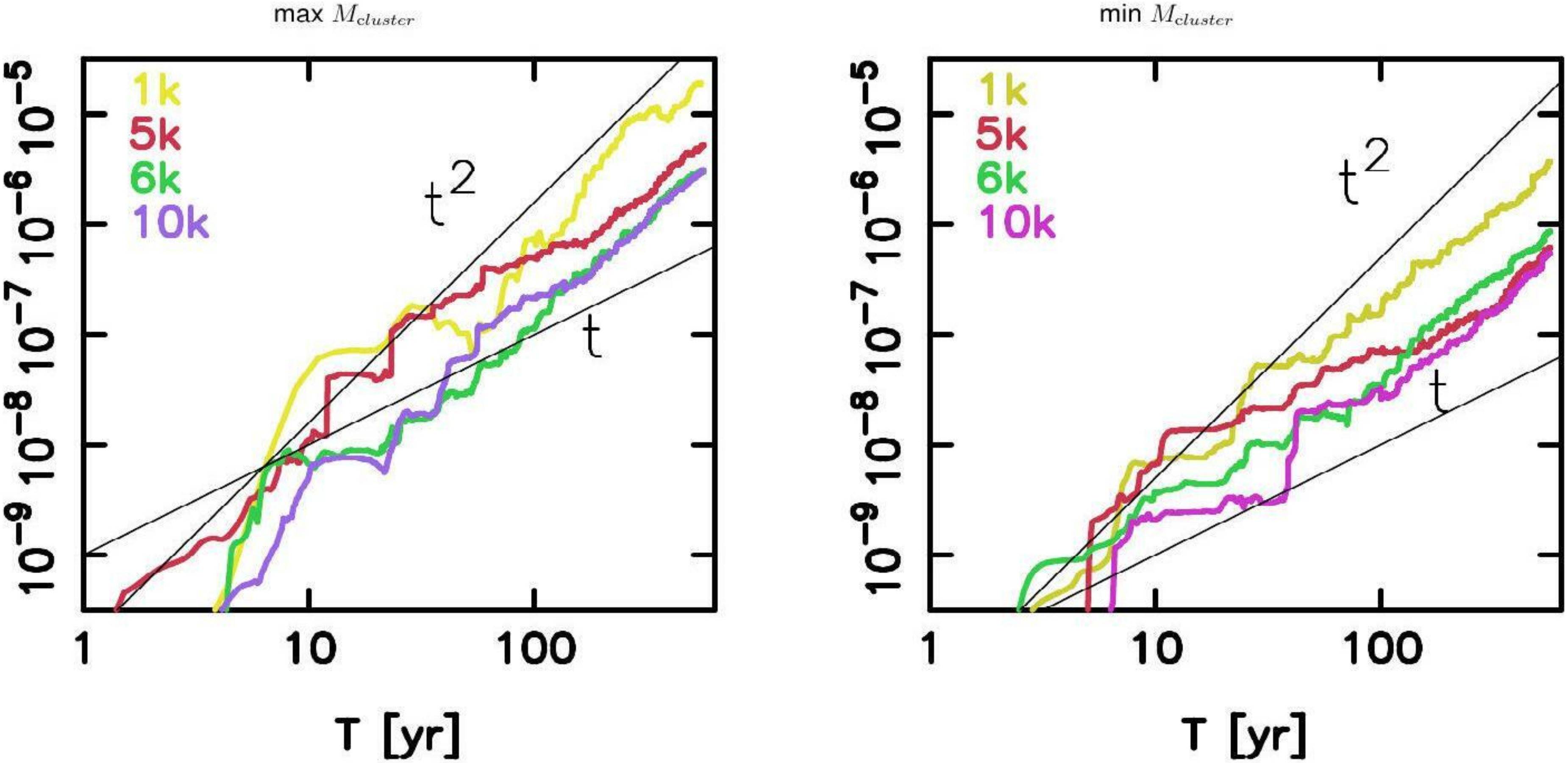
$M_{\rm cl,enc} \fallingdotseq 5 \times 10^3 M_\odot$

solid: *w PN*

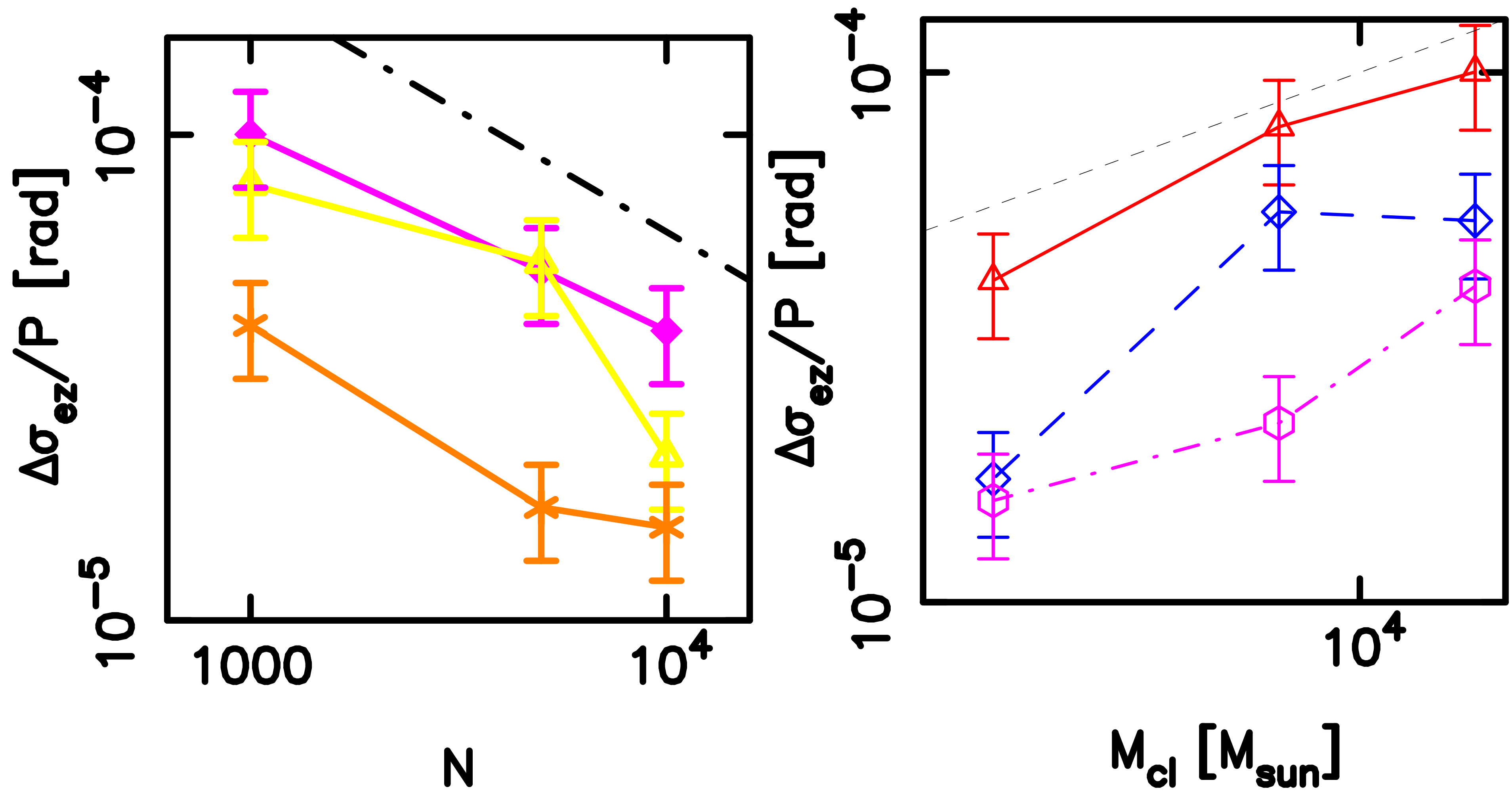
dashed: *wo PN*

Comparison between cluster models (wo PN)

$$\sigma_{\rm ez}^2 \equiv (1/n_{\rm run}) \sum^{\rm nrun} \Delta i^2$$



Dependence on Cluster Properties



$$\propto M_{CL} N^{-1/2}$$

consistent with theoretical prediction by RT96

$\rightarrow$ *RR*

Summary & Discussion (1)

- We performed N-body simulations of dynamical evolution of the star cluster at the GC.
- The orbit of S2 evolves from its initial Kepler orbit.
- Its precession is due to GR, MF and RR.
- Precession due to RR is $0.01 \sim 0.1$ times of that due to GR.

Summary & Discussion (2)

- **The evolution of inclination is driven by RR.**
- **The increasing/decreasing rate of inclination, amplitude of its fluctuation depend on cluster properties: the mass, number of objects.**
- **... composition of stellar and compact objects...**
- **Further observation of S2 may be a clue to N.**
- **Observation of inclination evolution of S stars may be a clue to understand the above properties.**

N-body simulations of the cases of mass function including IMBH is in progress.