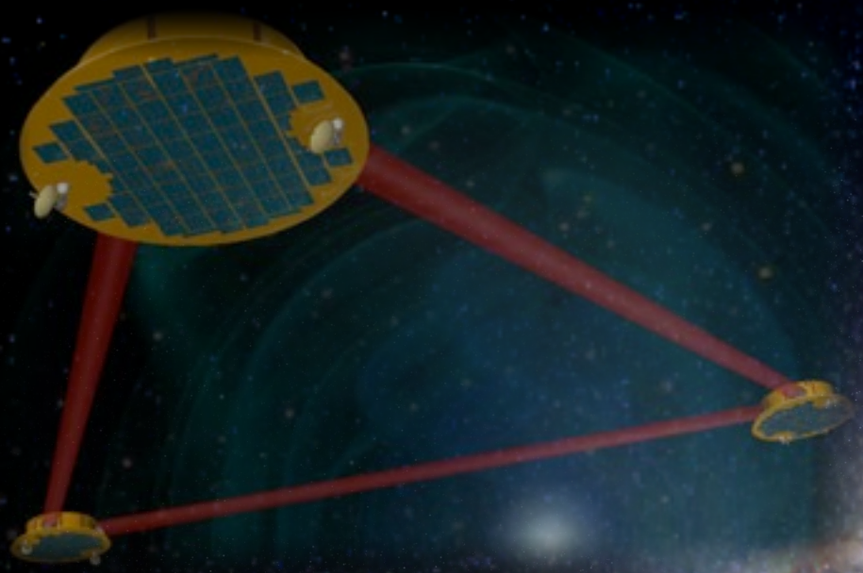

# Black Holes with Spin in Star Cluster Simulations with NBODY6++

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*5th China-Korea Workshop*

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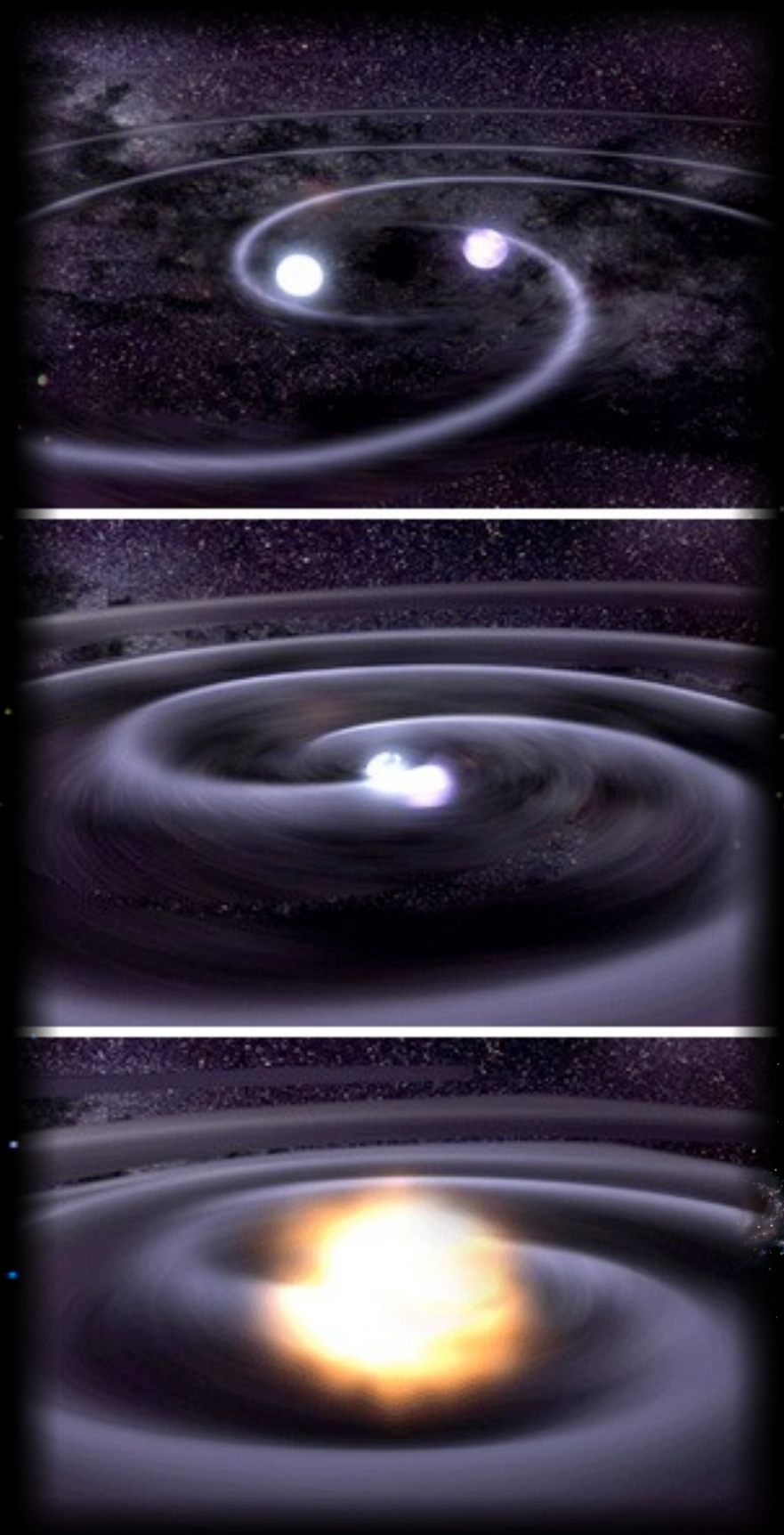
# Objectives and Context

Understand the role of binary black holes in the evolution of the globular cluster, as well as in the emission of gravitational waves.

- Templates of the grav. wave form
- Relativistic merger rates

# Why Globular Clusters?

The large number of stars, and their old nature leads that GCs be harbor of a large over density of compact stellar remnants due to their high density and the mass segregation of the compact remnants towards the cluster core. The formation of the compact stars, neutron stars (NS) and black holes (BH), are the result of the stellar evolution of the most massive stars in the cluster.



# Post -Newtonian Terms

*General Relativity & Newton's theory of gravity lead to very similar predictions for the motion of bodies and the propagation of light.*

$$\mathbf{a} = \mathbf{a}_N + \mathbf{a}_{1\mathrm{PN}} + \mathbf{a}_{2\mathrm{PN}} + \mathbf{a}_{2.5\mathrm{PN}} + \mathbf{a}_{3\mathrm{PN}} + \mathbf{a}_{3.5\mathrm{PN}}$$

The expansion is in terms of c $(v/c)^{2n}$

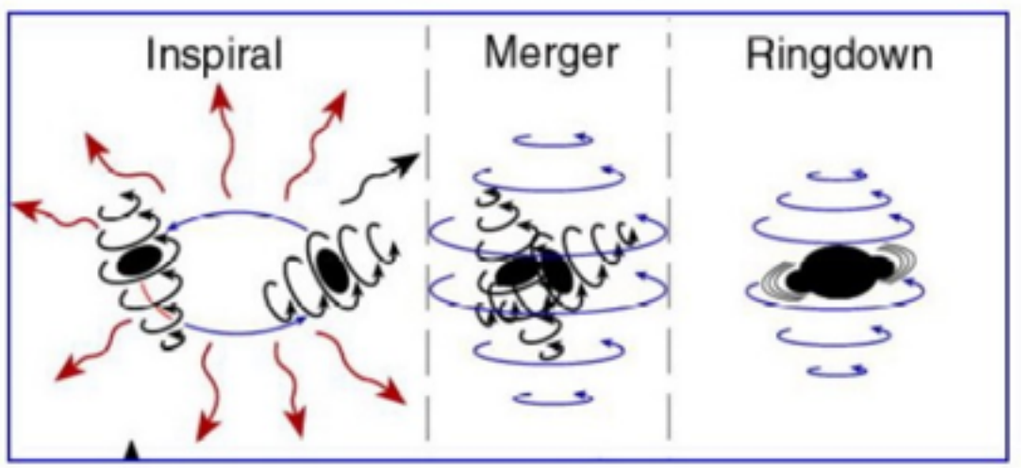
- valid only in a weak field of gravity

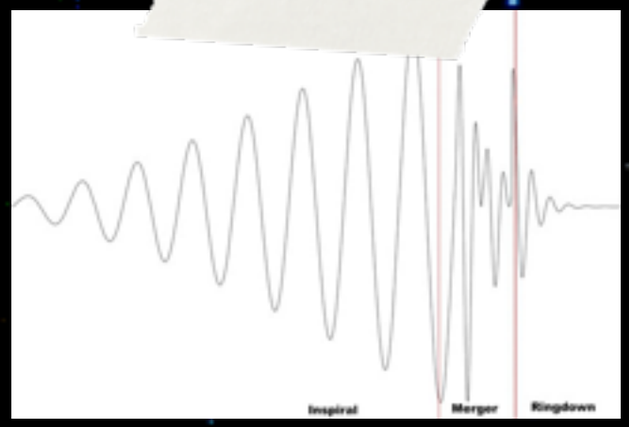
# Why add the Spin term?

effect of spin in BHs dynamics is that the direction of the orbital angular momentum is NOT longer conserver.

Non-Spinning BHs bin → shrinking of the modulus of the AM due to 2.5 PN order.

Spinning BH bin → spins + OAM precess around total AM vector J=S +L




$$\mathrm{a} = \mathrm{a}_N + \mathrm{a}_{1\mathrm{PN}} + \mathrm{a}_{2\mathrm{PN}} + \mathrm{a}_{2.5\mathrm{PN}} + \mathrm{a}_{3\mathrm{PN}} + \mathrm{a}_{3.5\mathrm{PN}} + \mathrm{a}_{1.5\mathrm{PN,SO}} + \mathrm{a}_{2\mathrm{PN,SS}} + \mathrm{a}_{2.5\mathrm{PN,SO}},$$

# Post-Newtonian terms in NBODY6++

Kupi et al. 2006
Brem et al. 2013

If the KS pair satisfy

$$v > \beta c$$

$$v > \frac{\beta}{5} c, \text{ and } \frac{g_{\rm PN}}{g} > \gamma_{\rm rel}$$

$\beta = 0.02$ and $\gamma = 0.01$

```
1 1000000.0 1.E6 40 40
500000 1 10 4300 100 1
0.02 0.02 0.1 1.0 1.0 100.0 10.0 10.0 0.7
1 2 1 0 1 1 4 1 0 2
1 1 0 0 2 1 0 0 3 2
1 0 2 0 0 2 0 0 0 2
0 0 2 0 1 0 1 1 0 1
0 0 0 0 1 1 8 0 0 0
0.02 100.0 7000.0 5.0E-3 0.7
1.0E-04 0.01 0.1 1.0 1.0E-06 0.01 0.5
2.35 100.0 0.08 50000 0 0.02 -70.0 0.0
0.5 0.0 0.0 0.0
0.005 -1.0 1.0 5.0 5 0
```

PN terms turn on

```
KSTART, TCOMP, TCRITp, isernb,iserreg                    (nbody6.F)
N, NFIX, NCRIT, NRAND, NNBOPT, NRUN                      (input.F)
ETAI, ETAR, RS0, DTADJ, DELTAT, TCRIT, QE, RBAR, ZMBAR   (input.F)
(KZ(J),J=1,50)                                           (input.F)
BETAREL, DTUPN,CLIGHTIN,GAMMAREL,SPN                     (input.F)
DTMIN, RMIN, ETAU, ECLOSE, GMIN, GMAX                    (input.F)
ALPHA, BODY1, BODYN, NBIN0, NHI0, ZMET, EPOCH0, DTPLOT   (data.F)
Q, VXROT, VZROT, RSPH2, SMAX                             (scale.F)
SEMI0, ECC0, RATIO,RANGE, NSKIP, IDORM                   (binpop.f)
```

Threshold for $v/c$ given in the input file.

Threshold for $a_{\rm PN}/a_{\rm Newton}$ given in the input file.

What are the physical processes involved during the formation of compact binaries in a dense cluster and their contribution to the gravitational wave detection rate by ground-based detectors?

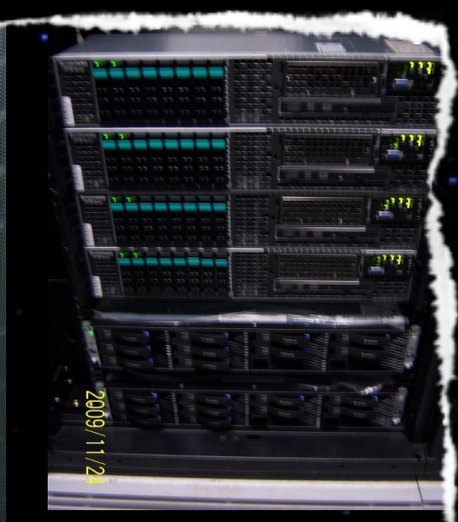
1) investigate numerically the spin distribution and evolution in a dense stellar cluster with a "realistic number of stars", considering also the process of stellar evolution and primordial binaries

2) run Monte Carlo simulations for compare the results of our N-body simulations

3) find observables signatures in our simulations that we can compare with observations.

# Supercomputers

The Silk Road project is operating the GPU accelerated supercomputer LAOHU, which has 85 nodes, 59 of them with a Kepler K20 GPU (each 3.0 Tflop/s), and 26 of them with three Tesla C1060 GPUs (each with 1.0 Tflop/s); in total 255 Tflop/s (in single precision, for double precision we reach about half of that). This clusters is located at NAOC, China.


# Setup in NBODY6++

GOAL

Globular Cluster :

N=10^6

Plummer profile

Kroupa IMF 0.08 <m<100

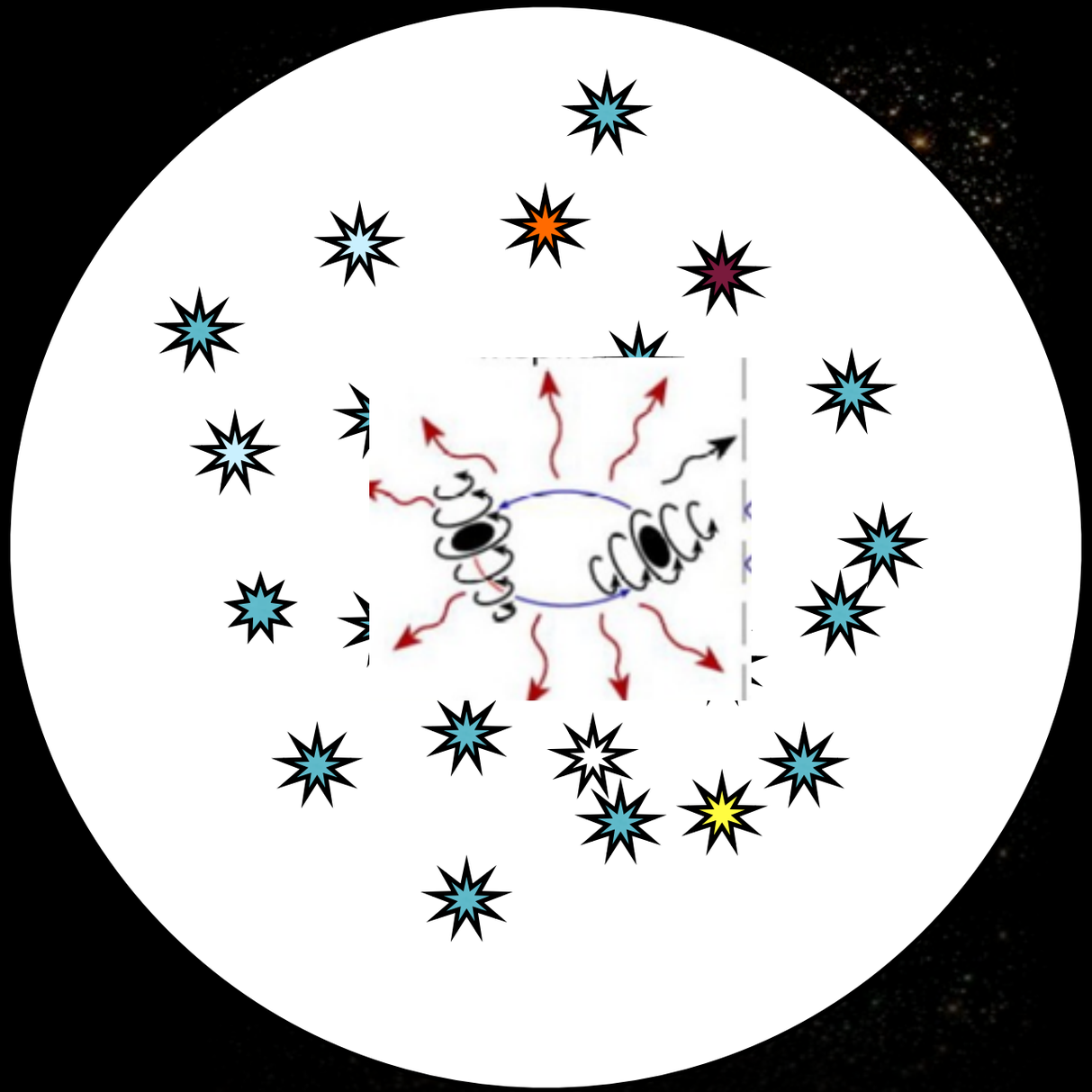
\alpha=2.35

Primordial Binaries

NBIN= 100k

CLIGHT=10000 ???

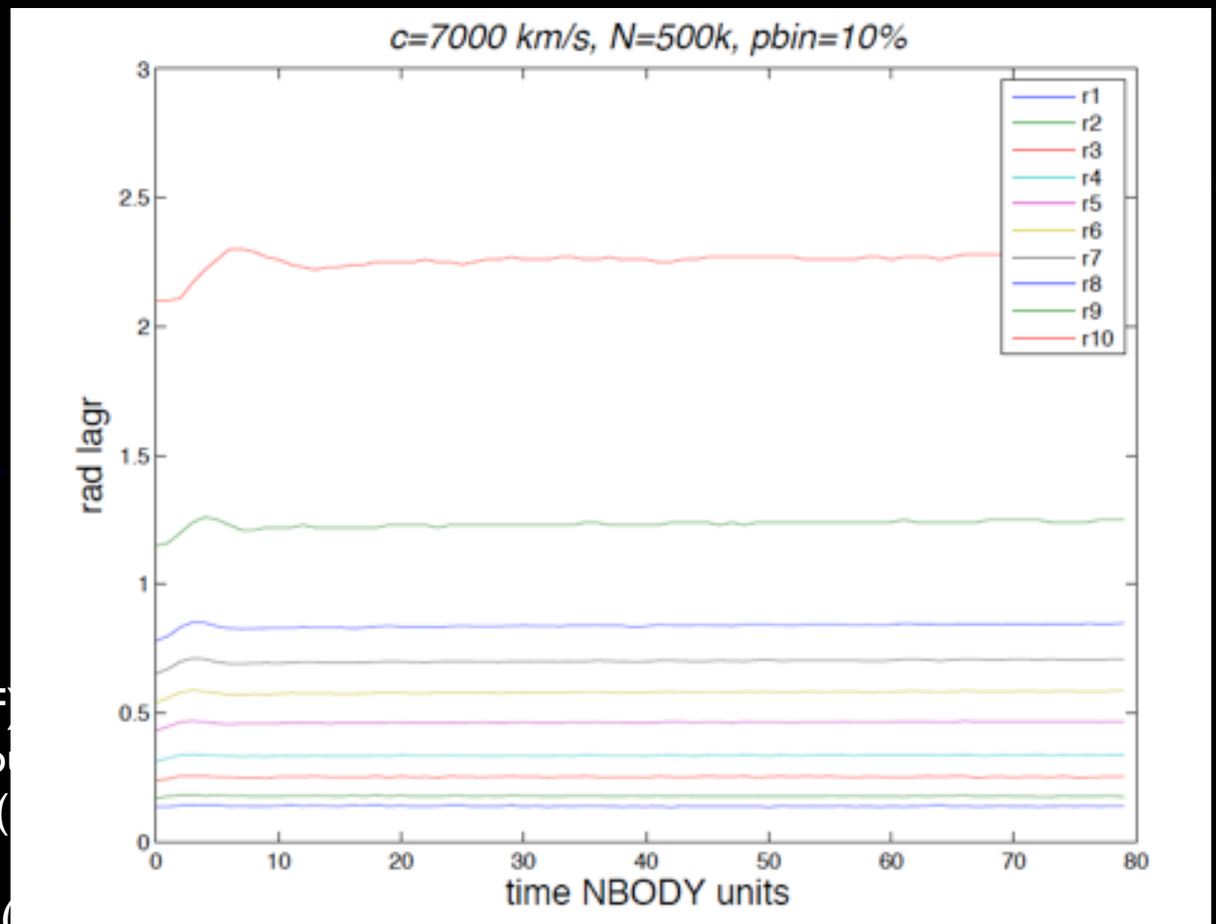
SPIN = 0, 0.7, 1 and Random



# Test

1 1000000.0 1.E6 40 40
500000 1 10 4300 100 1
0.02 0.02 0.1 1.0 1.0 100.0 10.0 10.0 0.7
1 2 1 0 1 1 4 1 0 2
1 1 0 1 2 1 0 0 3 2
1 0 2 0 0 2 0 0 0 2
0 0 2 0 1 0 1 1 0 1
0 0 0 0 1 1 2 0 0 0

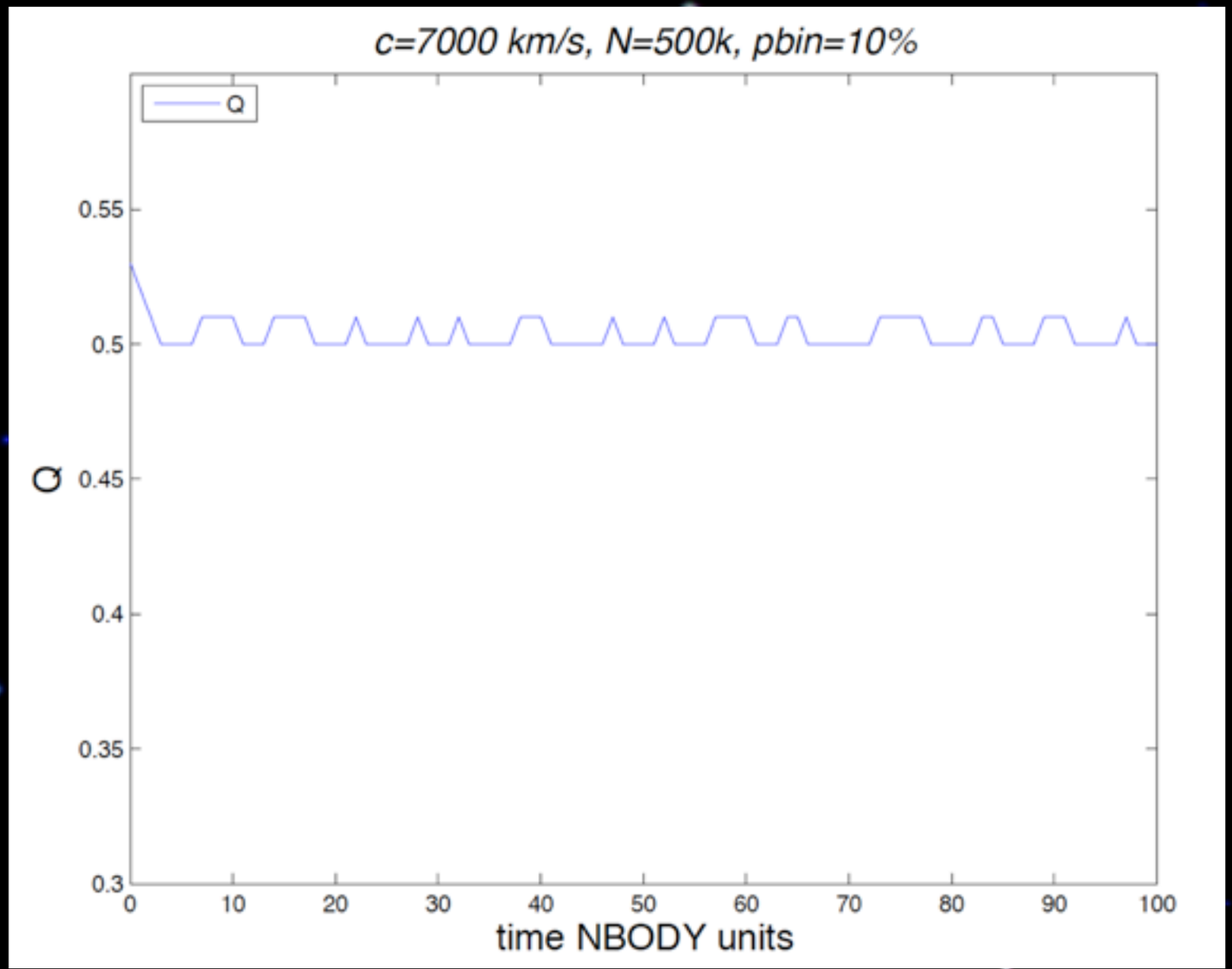
1.0E-04 0.01 0.1 1.0 1.0E-06 0.01 0.5
2.35 100.0 0.08 50000 0 0.02 -70.0 0.0
0.5 0.0 0.0 0.0
0.005 -1.0 1.0 5.0 5 0
KSTART,TCOMP,TCRITp, isernb,iserreg (nbody6.F)
N, NFIX, NCRIT, NRAND, NNBOPT, NRUN (inp
ETAI, ETAR, RS0, DTADJ, DELTAT,TCRIT, QE, RBAR, ZMBAR (
(KZ(J),J=1,50) (input.F)
BETAREL, DTUPN,CLIGHTIN,GAMMAREL,SPN (
DTMIN, RMIN, ETAU, ECLOSE, GMIN, GMAX (input.F)
ALPHA, BODY1, BODYN, NBIN0, NHI0, ZMET, EPOCH0, DTPLOT
Q,VXROT,VZROT, RSPH2, SMAX (scale.F)
SEMI0, ECC0, RATIO,RANGE, NSKIP, IDORM (binpop.f)



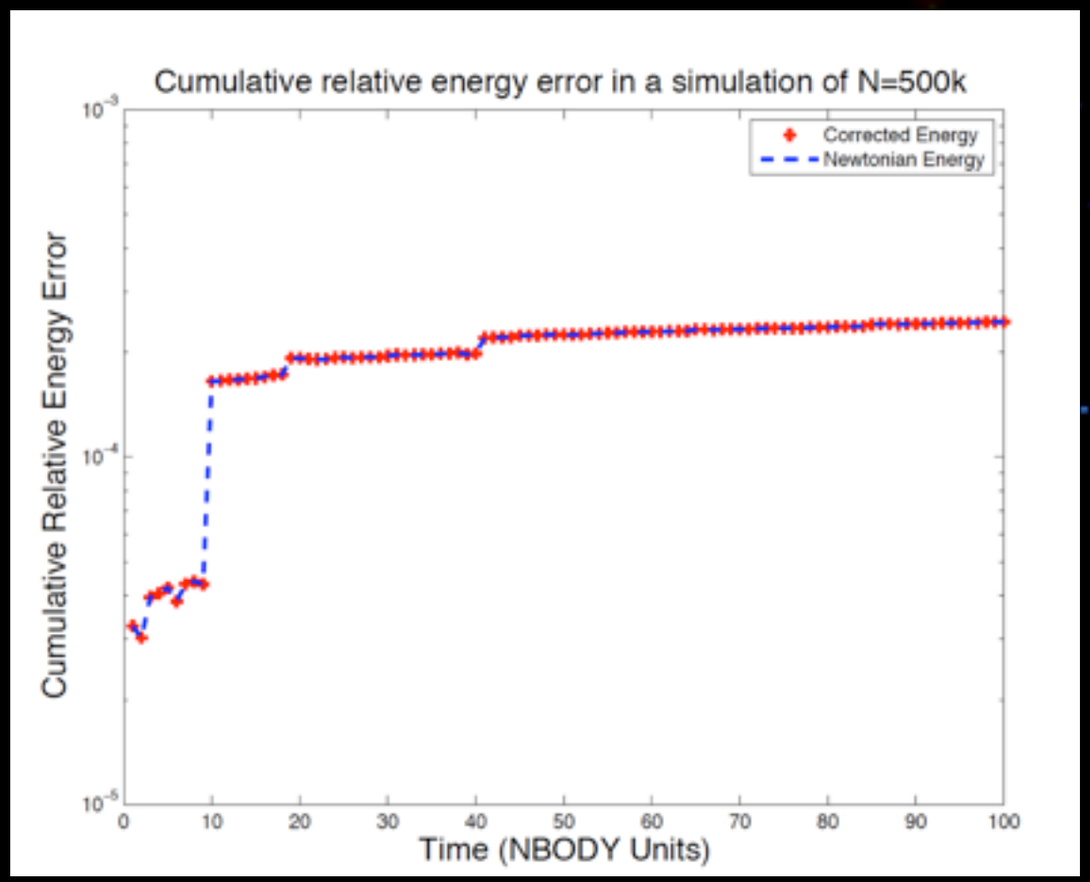

PHYSICAL SCALING: R* =10.00 M* =247454.0 V* =10.316 T* = 0.950
<M> = 0.49 SU = 4.4E+08

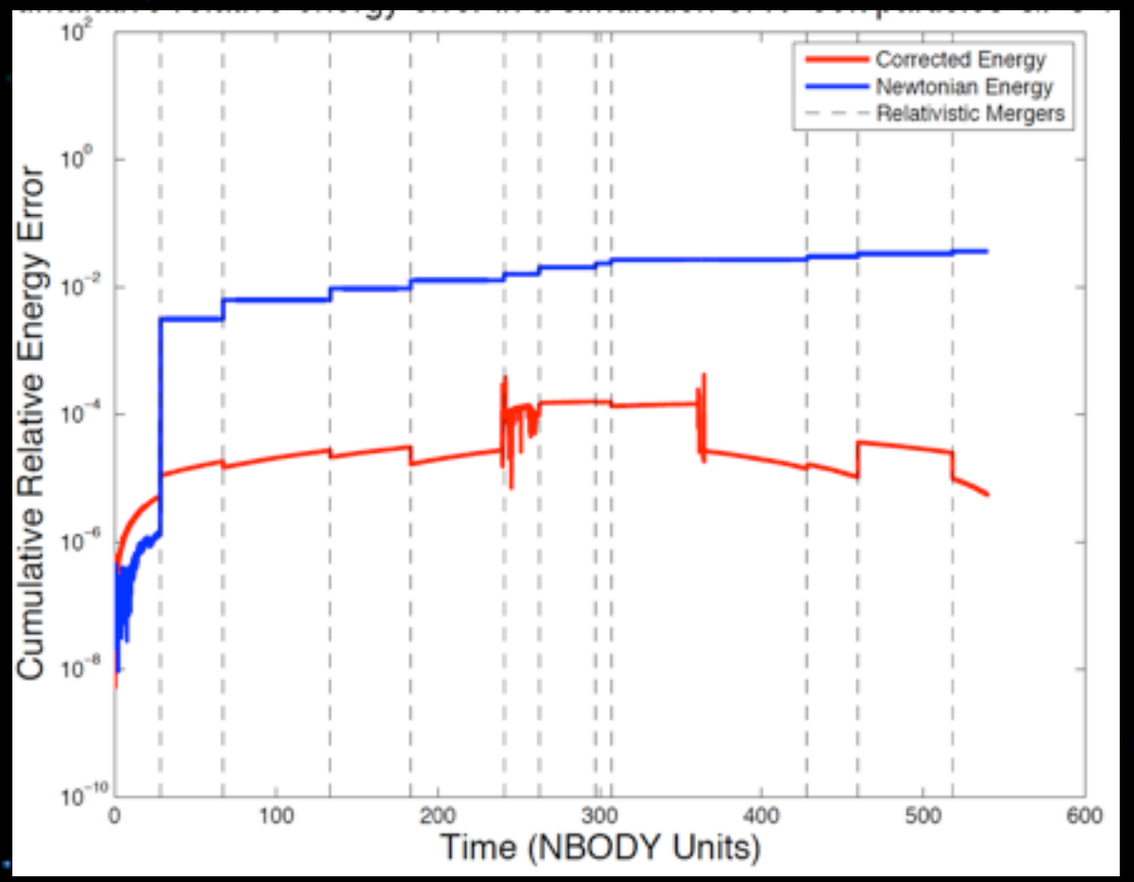
TOTAL MASS =247454.0 TIDAL(1&3) = 1.52E-03 -6.07E-03 PC/
GM = 2.33E-08

TIDAL PARAMETERS: 1.43E-03 0.00E+00 -5.71E-03 5.12E-02
TSCALE = 9.50E-01 RTIDE = 8.88

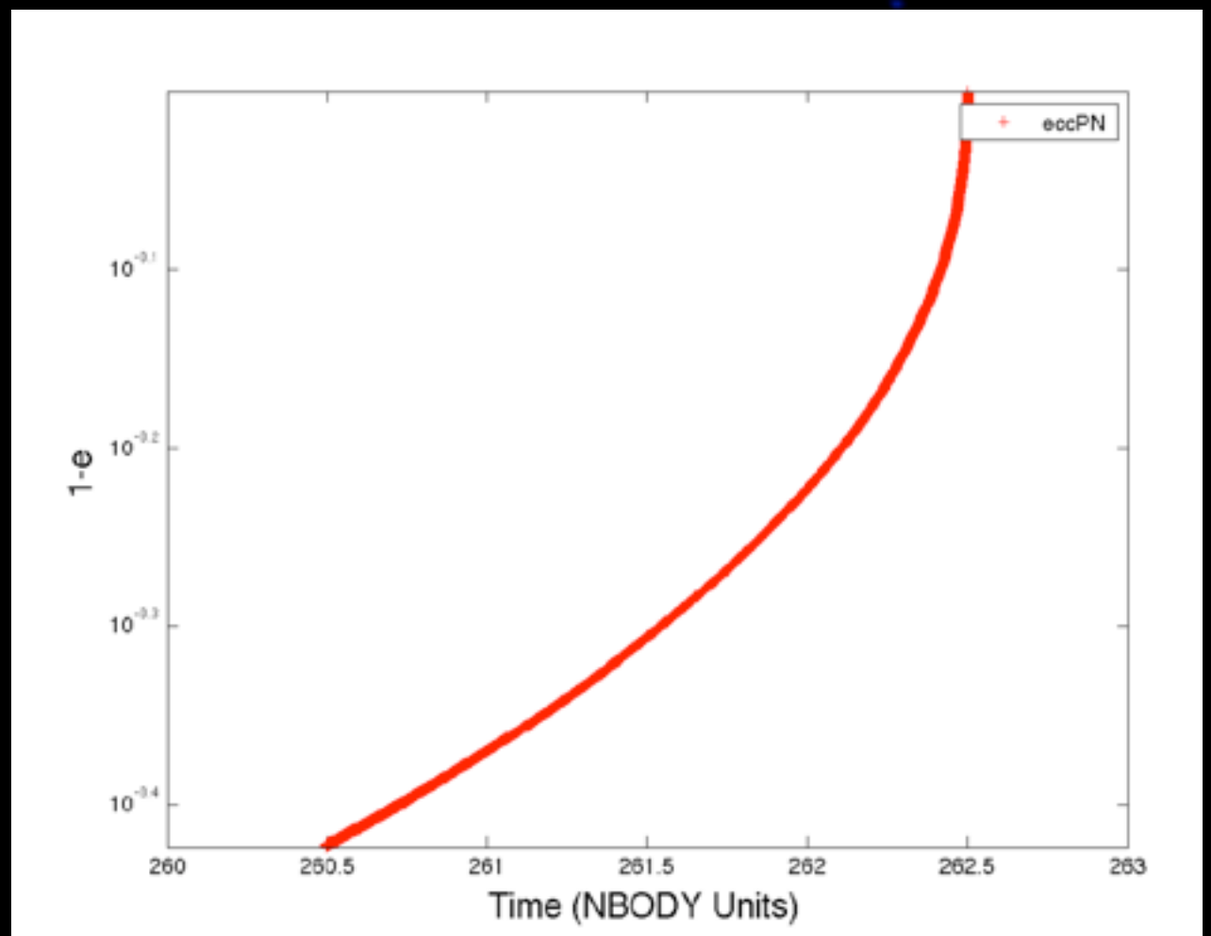

c=7000 km/s, N=500k, pbin=10%
Q
0.55
0.5
0.45
0.4
0.35
0.3
Q
0
10
20
30
40
50
60
70
80
90
100
time NBODY units

# Cumulative Absolute Energy Error

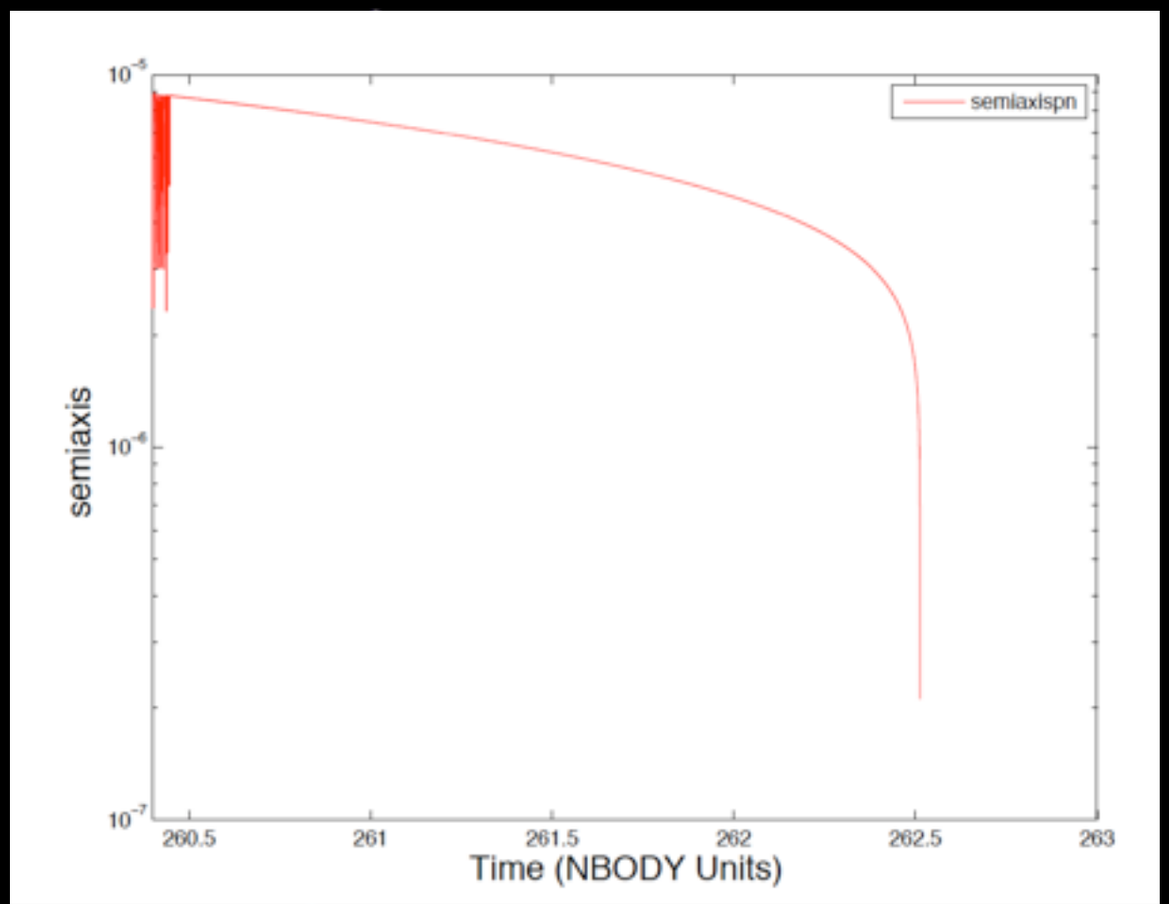


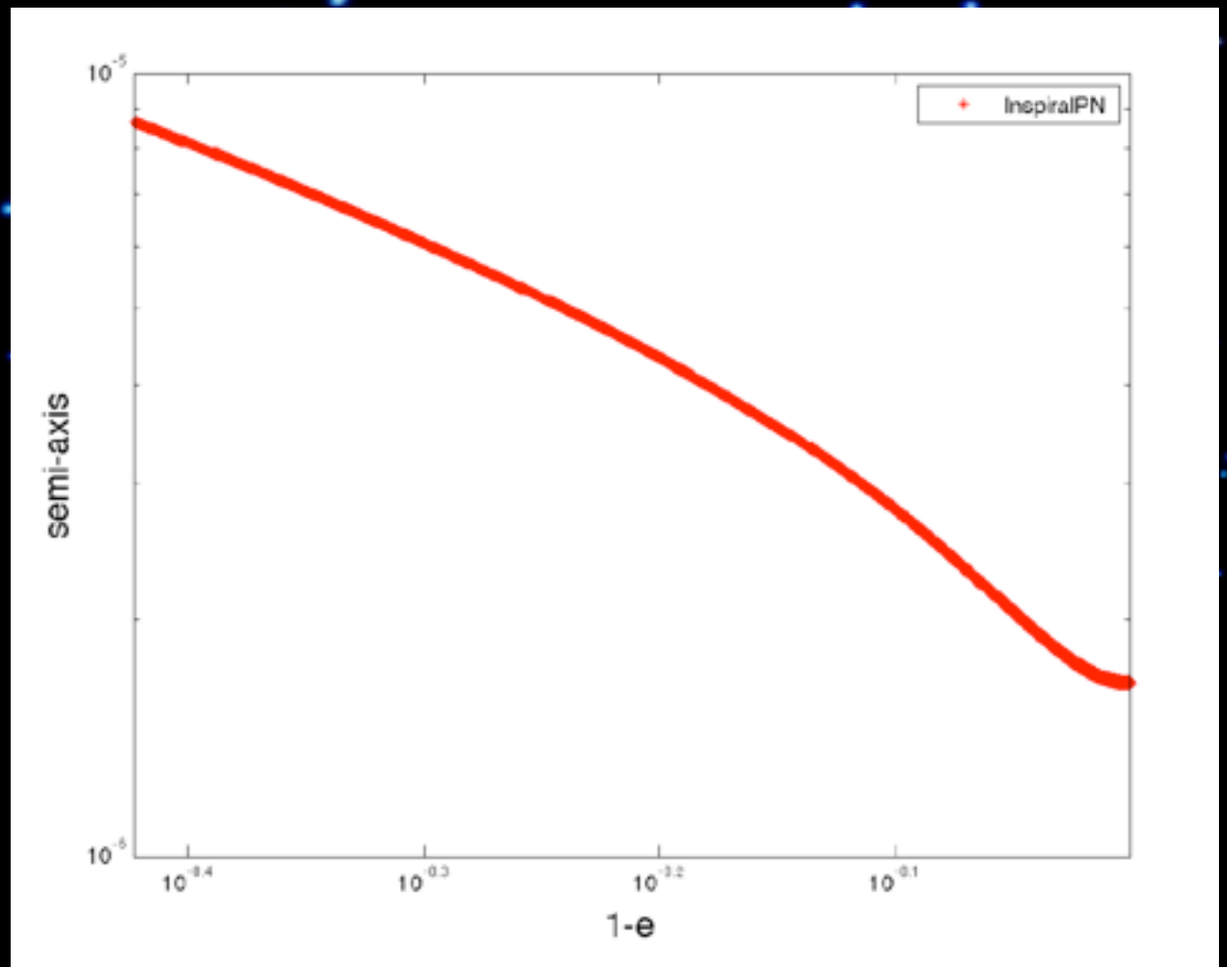
# Eccentricity

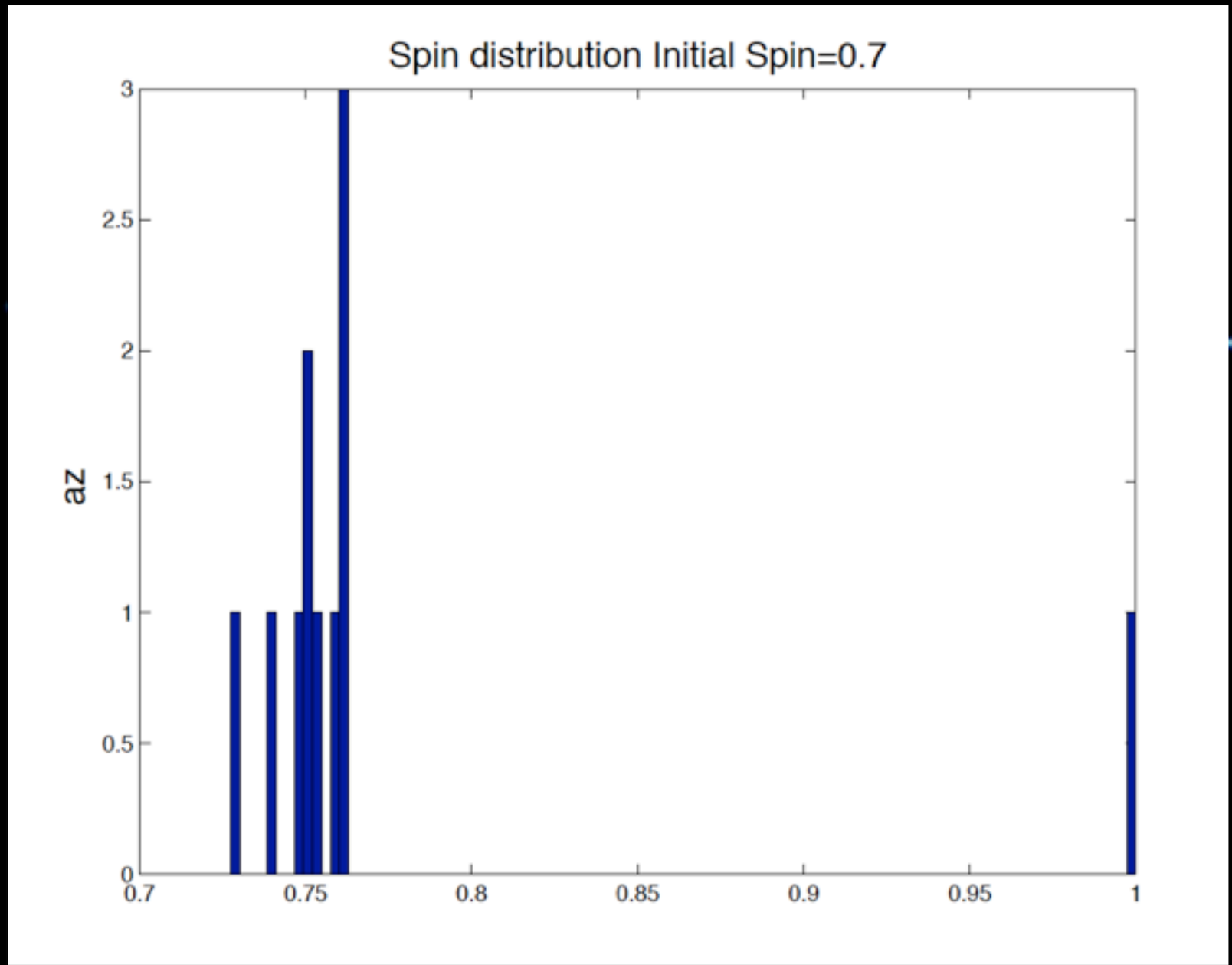


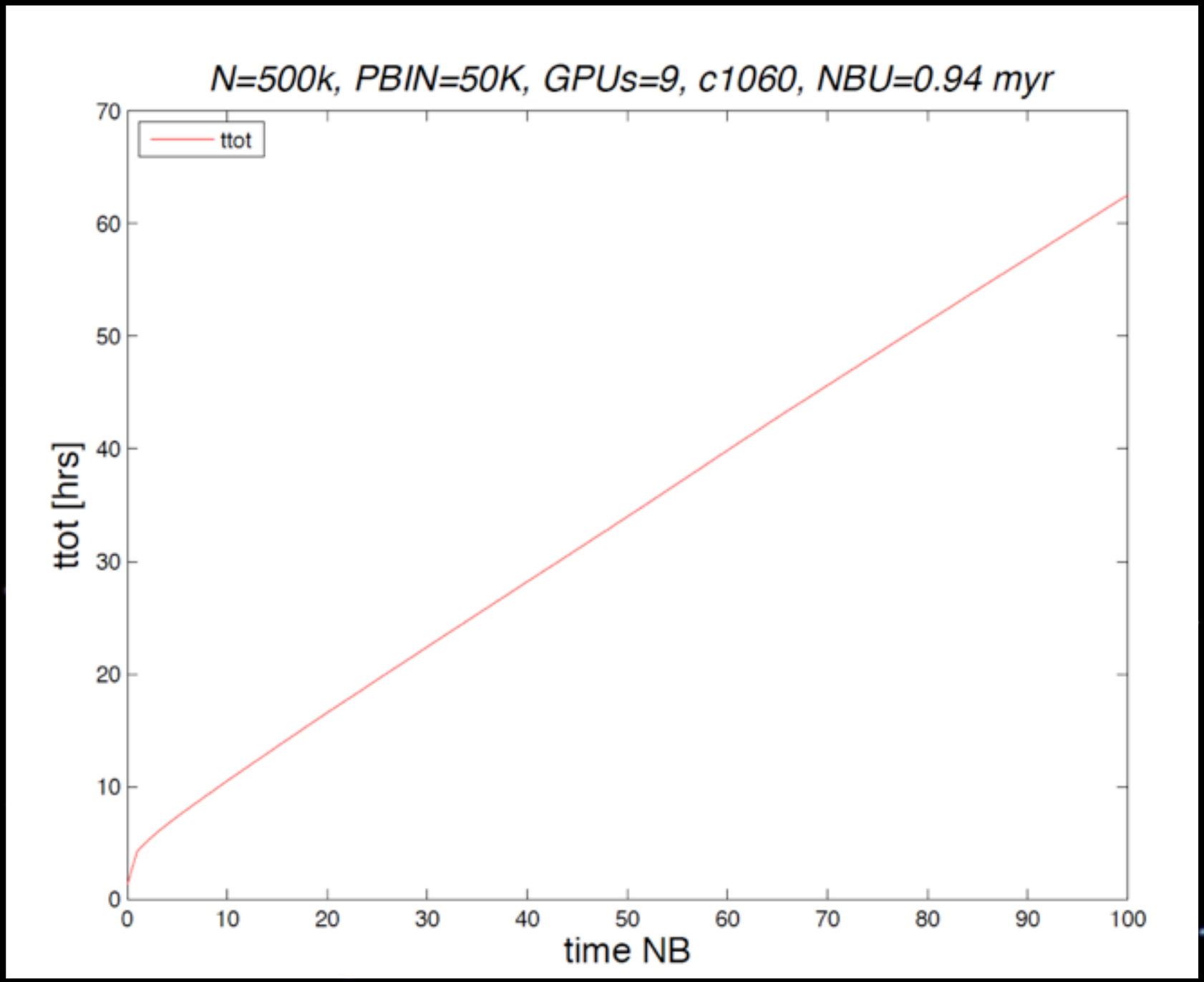

# Semi-Axis



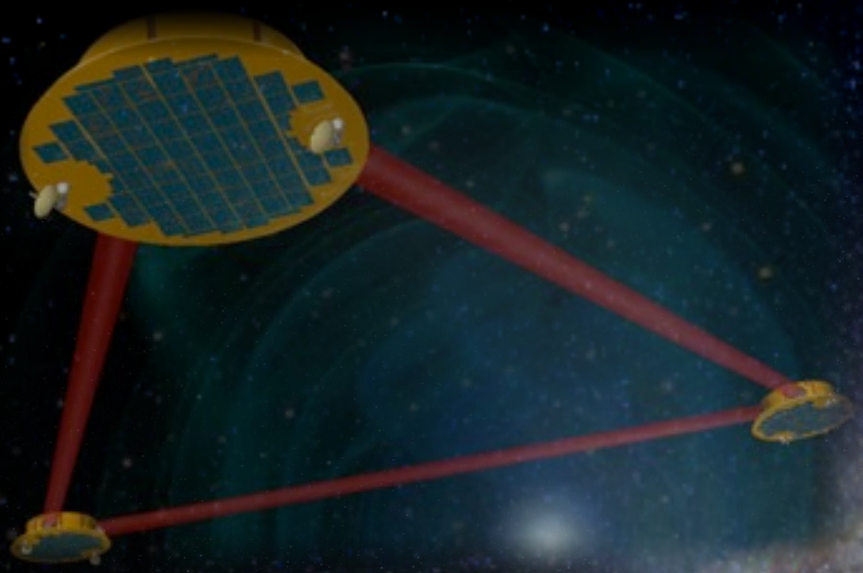
# The inspiral of the binary




Spin distribution Initial Spin=0.7
az
3
2.5
2
1.5
1
0.5
0
0.7
0.75
0.8
0.85
0.9
0.95
1


N=500k, PBIN=50K, GPUs=9, c1060, NBU=0.94 myr
ttot
ttot [hrs]
time NB
0
10
20
30
40
50
60
70
80
90
100

# VIDEO



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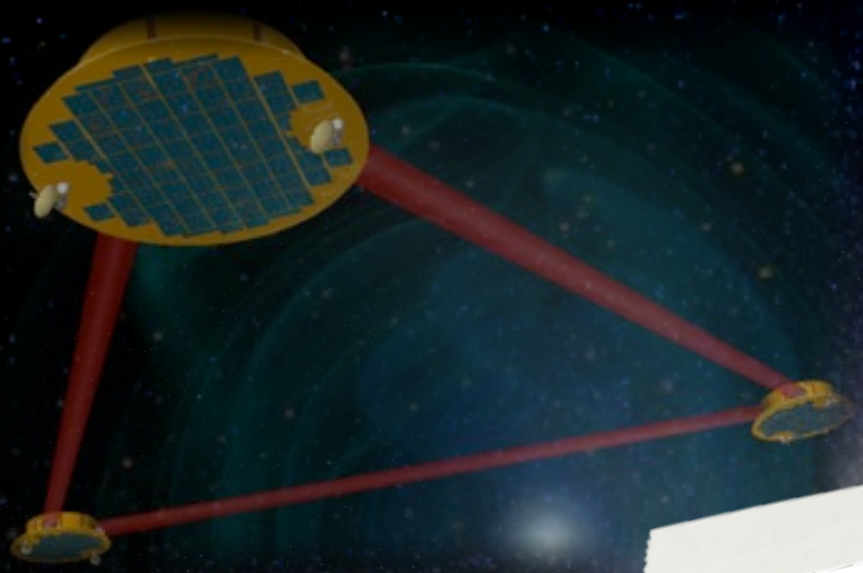

Thank you!

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