A 1.349 Tflops simulation of black holes in a galactic center on GRAPE-6

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Summary

- For simulation of triple BH system in the core of a galaxy, we achieved 1.349 Tflops for long simulation, and 1.64 Tflops for large but short simulation.
- System used is a 6-board GRAPE-6 with the peak speed of 2.889 Tflops, developed by our group.
- Direct summation with individual timestep is used to achieve required accuracy.
- Full GRAPE-6 system will deliver $>$ 100 Tflops. soon.

Talk overview

- Introduction — Why consider multiple black holes in a galactic center?
- Numerical challenge
- GRAPE Project
- GRAPE-6
- Present simulation
- Conclusion

Introduction

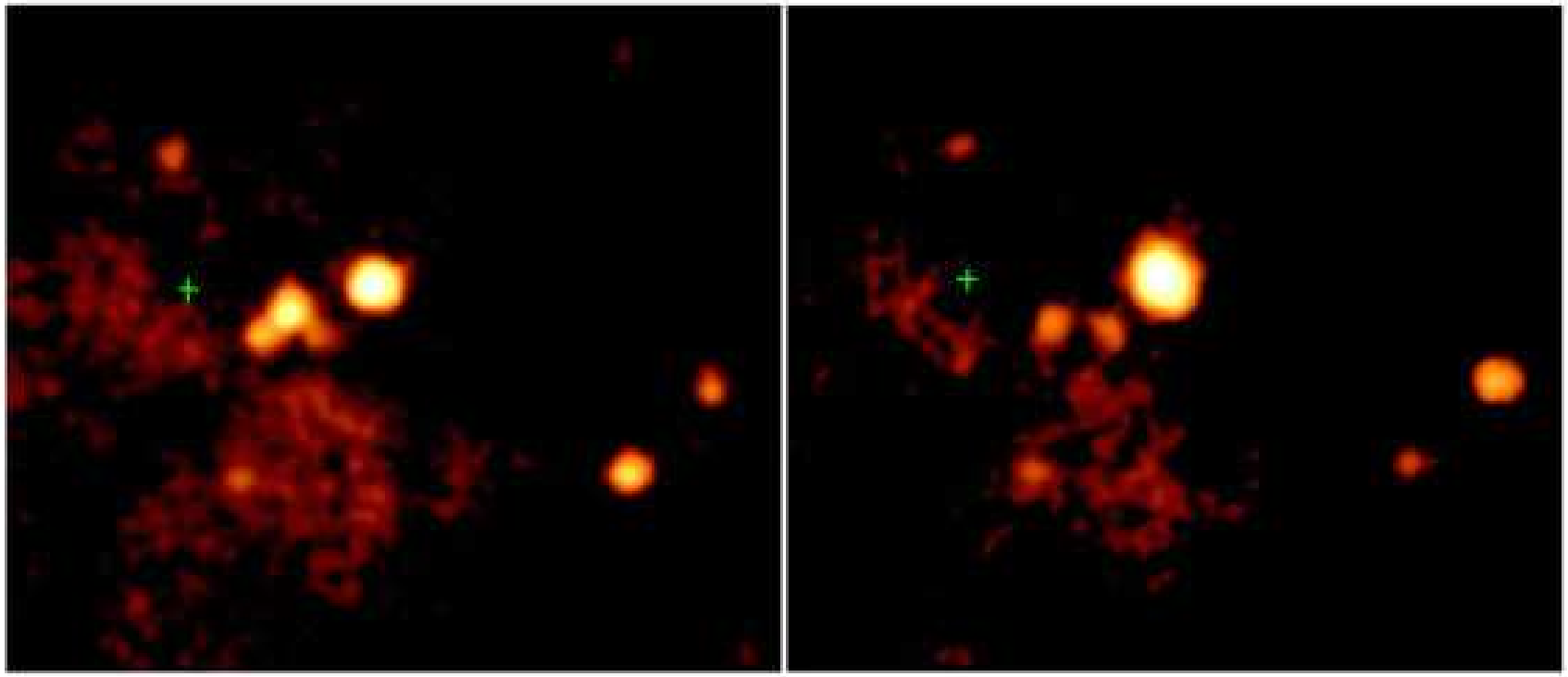
Massive black holes in galactic centers.

Central 8 arcsecs of an E4 galaxy NGC 7052 (distance = 58 Mpc), by HST WFPC2 (van der Marel and van den Bosch 1998)

Estimated BH mass $\sim 3 \times 10^8 M\odot$ (300 million times the mass of our sun)

And there may be more than one...

Two Chandra X-ray views of central 30 arcsecs of M82 (distance 17Mpc) with 2 months interval



M82 interpretation

- There are several bright sources (most likely 100–1000 $M_\odot$black holes)
- Time variation suggests that most of them are single objects.
- These sources roughly match with bright star clusters found by Subaru telescope.

Question

- How massive central black holes observed in many ellipticals are formed?
- How multiple black holes like the one observed in M82 are formed?
- Are they related? If so, how?
- ...

Need to understand how a multiple black hole system evolves.

Theoretical possibilities

Two black holes eventually form a binary system, which might

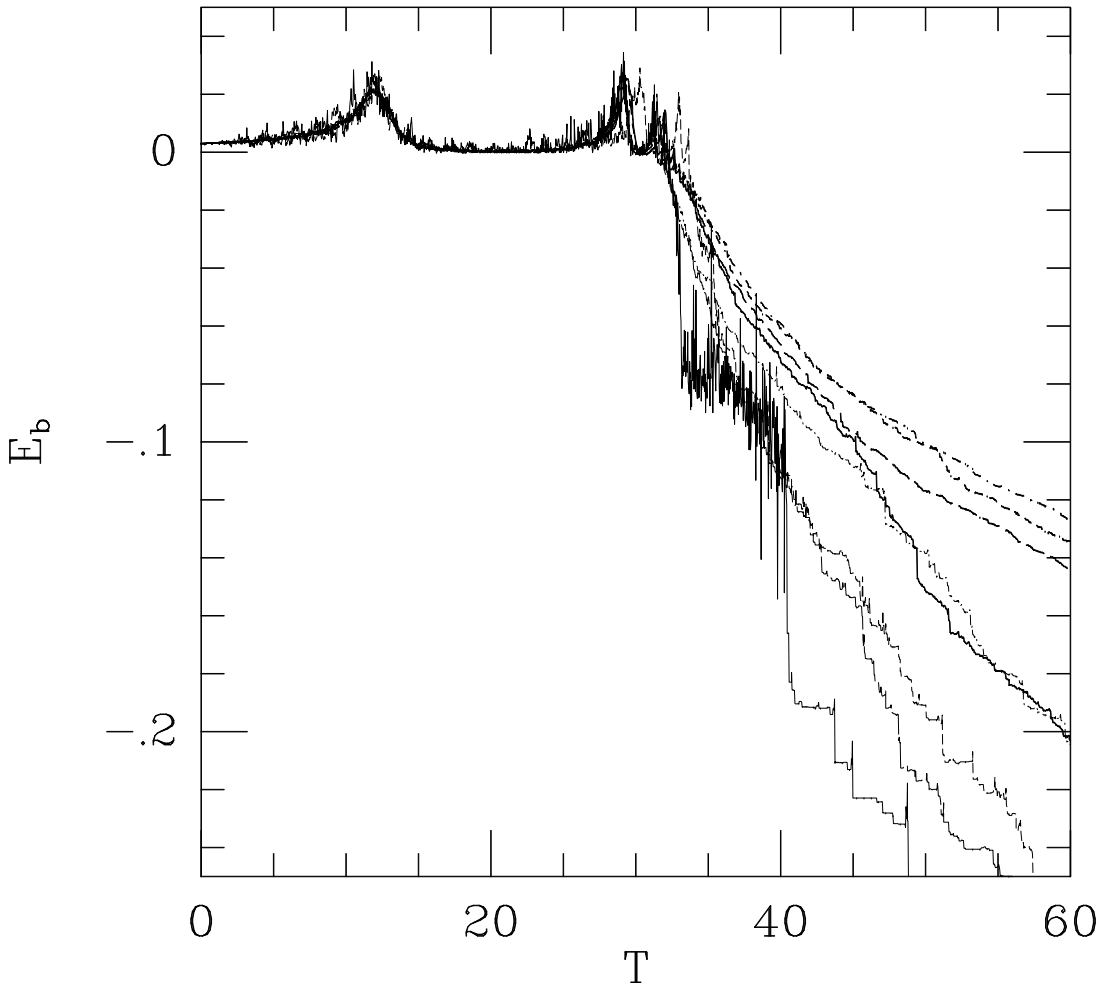
- merge through dynamical friction and gravitational wave radiation,
- or survive over the age of the Universe.

Numerical simulations (large N-body simulations by JM as well as Quinlan et al.): Not really conclusive.
Reason: insufficient particle number (mass resolution)

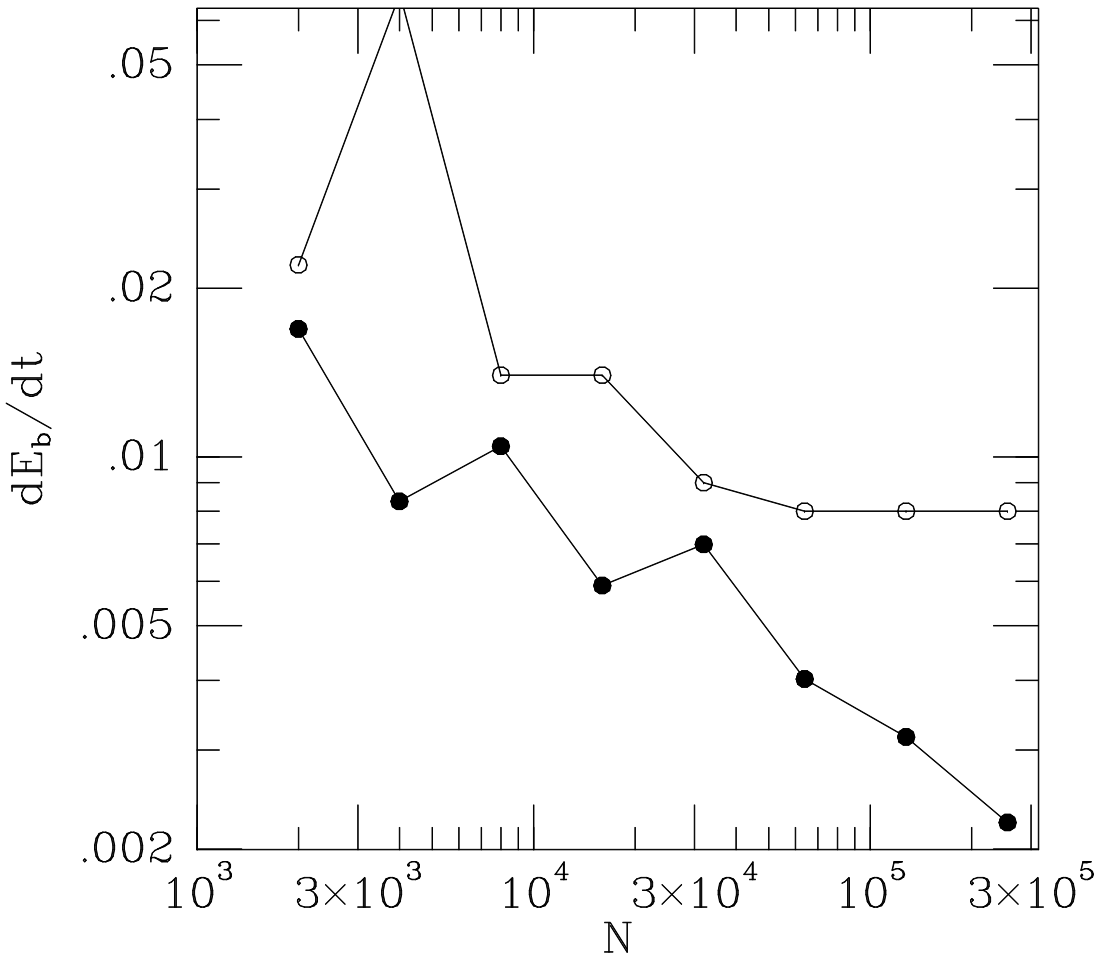
BH binary evolution — JM 1997 result

N is too small — tried to see the *N*-dependence.

Result for N=2k — 256k (Makino 1997, GRAPE-4)



Growth rate



Open: early
Filled: late

Timescale:

Early phase: converges?
Late phase: $\propto N^{1/3}$?

BH binary simulation summary

- Evolution timescale depends on N (number of particles used)
  - However, the dependence is much weaker ($t \sim N^{1/3}$) than theoretical prediction ($t \sim N$).
- Extrapolation to large N: BHs do not merge within Hubble time

What about three BHs?

If binary BHs have long lifetimes, systems of three (or more) massive BH must be common.

- Merging of two galaxies, one with a central BH and the other with binary BH would form triple BHs in the center.
- Merging of galaxies is common — galaxies are formed "bottom-up", through merging of smaller objects.

Numerical Simulation necessary....

Difficulty with simulations of galaxy with central BH(s)

- Wide range in the distance scale — from 100kpc to 0.001 pc
- Wide range in the orbital timescale — from 100Myr to days or less
- High accuracy required for short-timescale orbits

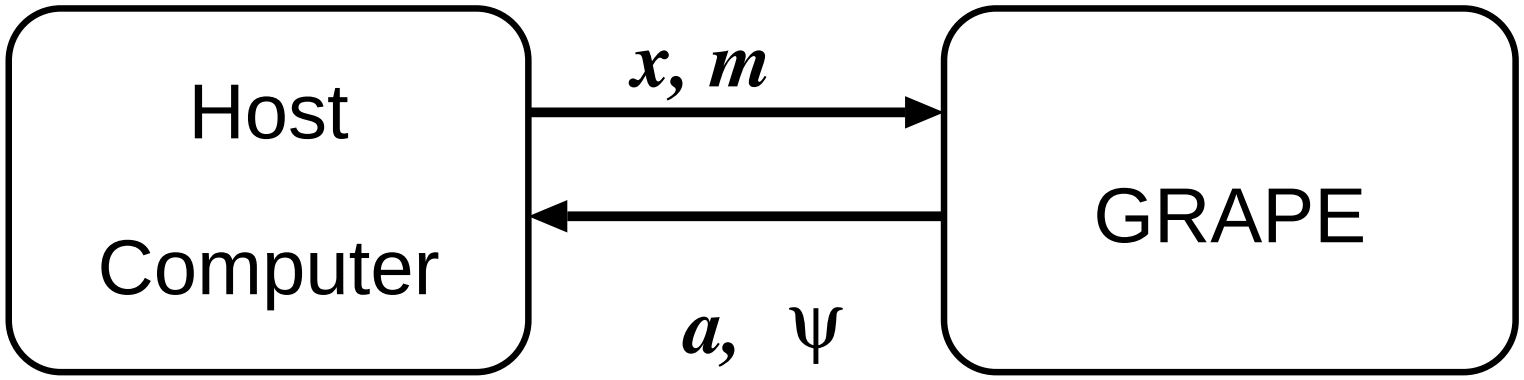
↓

Direct summation algorithm + Individual timestep is the only viable tool.

GRAPE: specialized hardware for this kind of problems (can be used for treecode etc, though)

Basic idea of GRAPE

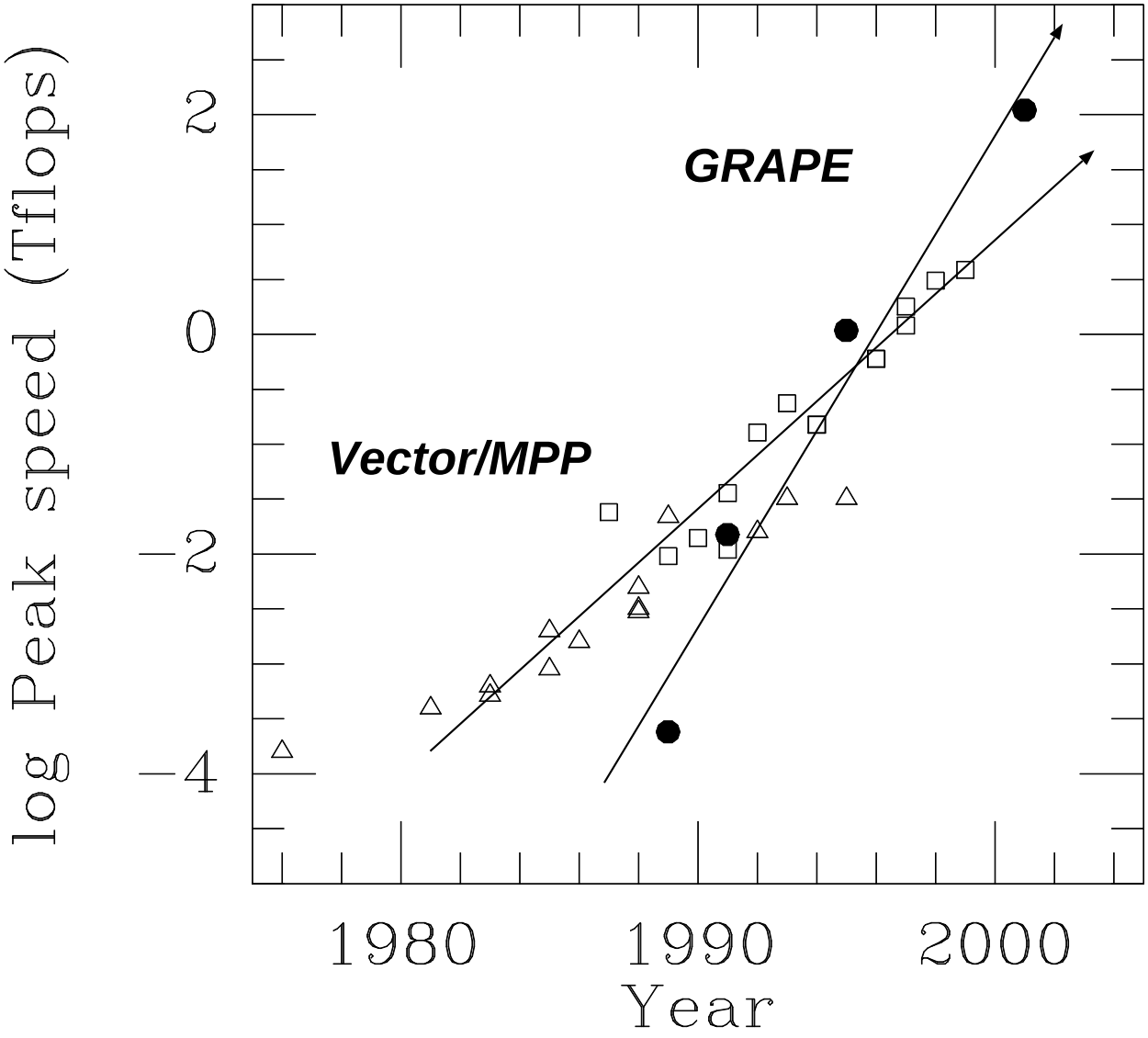
Special-purpose hardware for force calculation
General-purpose host for all other calculation



Advantages of GRAPE

- Special-purpose hardware
  - Hardwired logic → No software needed
  - Pipelined processor → High performance
- General-purpose host
  - Programmable in high-level languages
  - existing programs can be used with "small" modifications
  - can be used with Barnes-Hut tree/Aarseth scheme

Evolution of GRAPE systems



GRAPE-4

Features:

- Predictor pipeline in hardware (for individual timesteps)
- Massively parallel system with 1692 pipeline chips
- 36 processor boards each with 47 processor chips
- calculates force on 94 particles
- Peak speed: 1.08 Tflops

Project goals for GRAPE-6

- Peak speed $>$ 100Tflops (We've got somewhat more money...)
- Improved communication speed ($>$ 2GB/s)
- Minor fixes for some "features" of GRAPE-4...

Overall structure

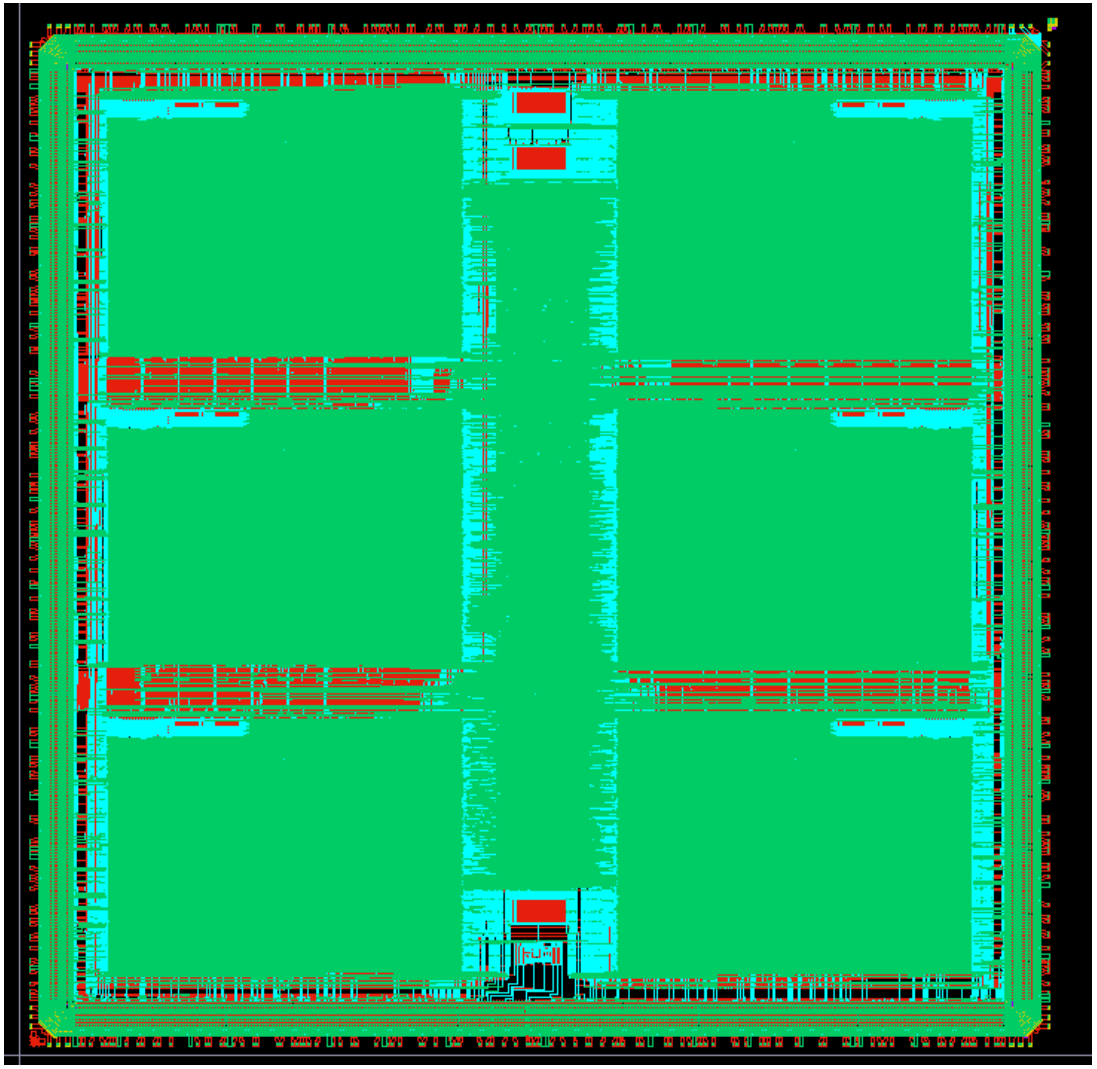
- 16 (or somewhat less...) clusters
- 16 processor boards per cluster
- 8 processor modules per board
- 2 chips per modules
- 6 pipelines per chip
- 60 arithmetic units per pipeline

In total,1.5×10^6 Arithmetic units operating at 90 MHz = 135 Tflops

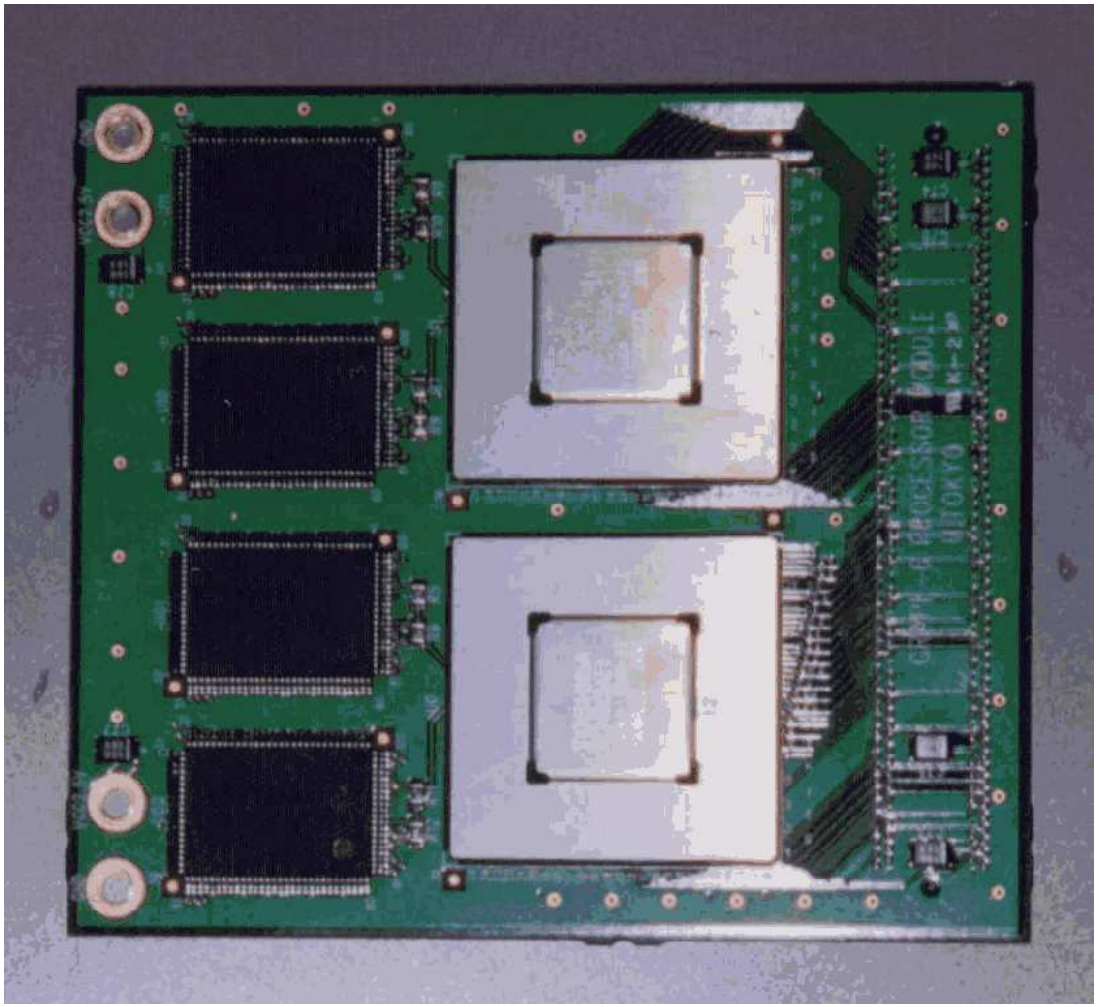
GRAPE-6 Processor Chip

- 0.25 μm custom design (Toshiba TC240E, 1.8M gates)
- 2.5 V power supply, 100 MHz operation (design goal)
- 6 pipelines in a chip
- $>$ 30 Gflops (equivalent) per chip
- system clock: 25 MHz
- Single chip equivalent to single GRAPE-4 board

GRAPE-6 Processor Chip

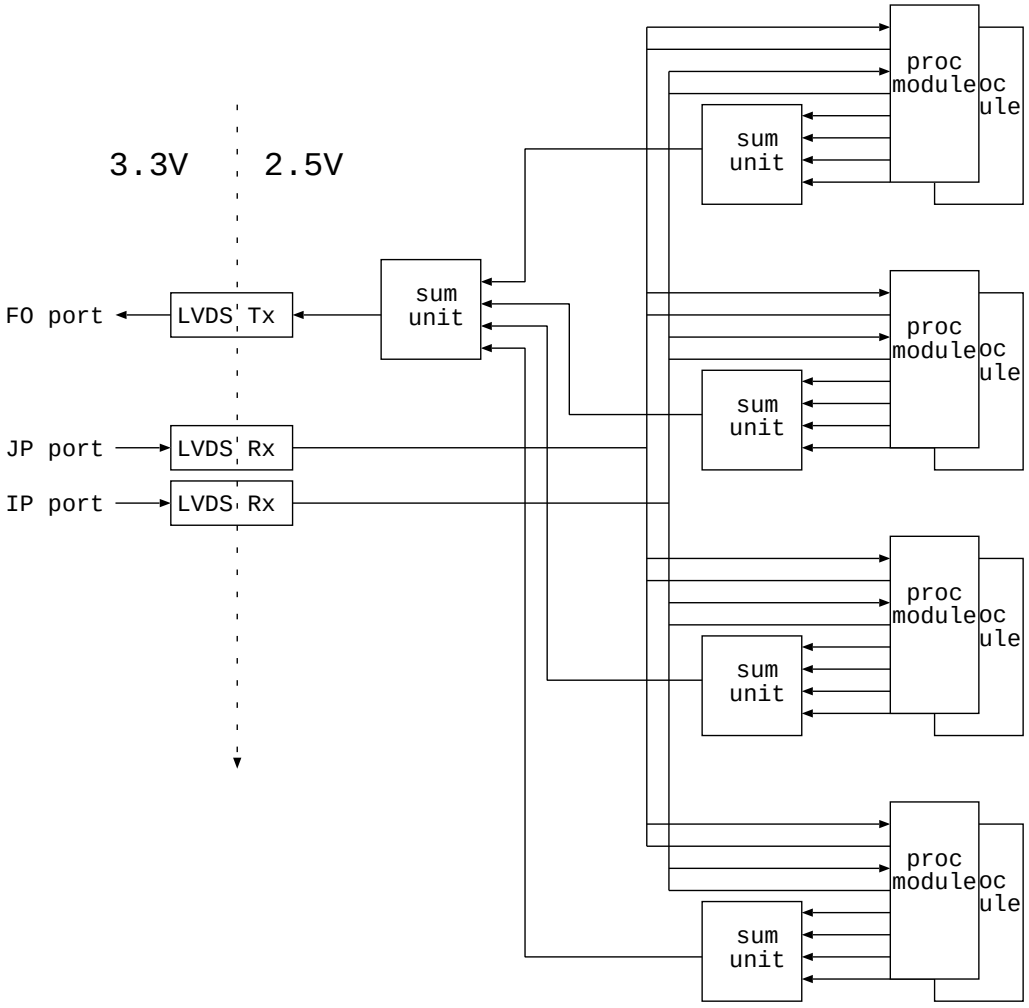


GRAPE-6 processor module



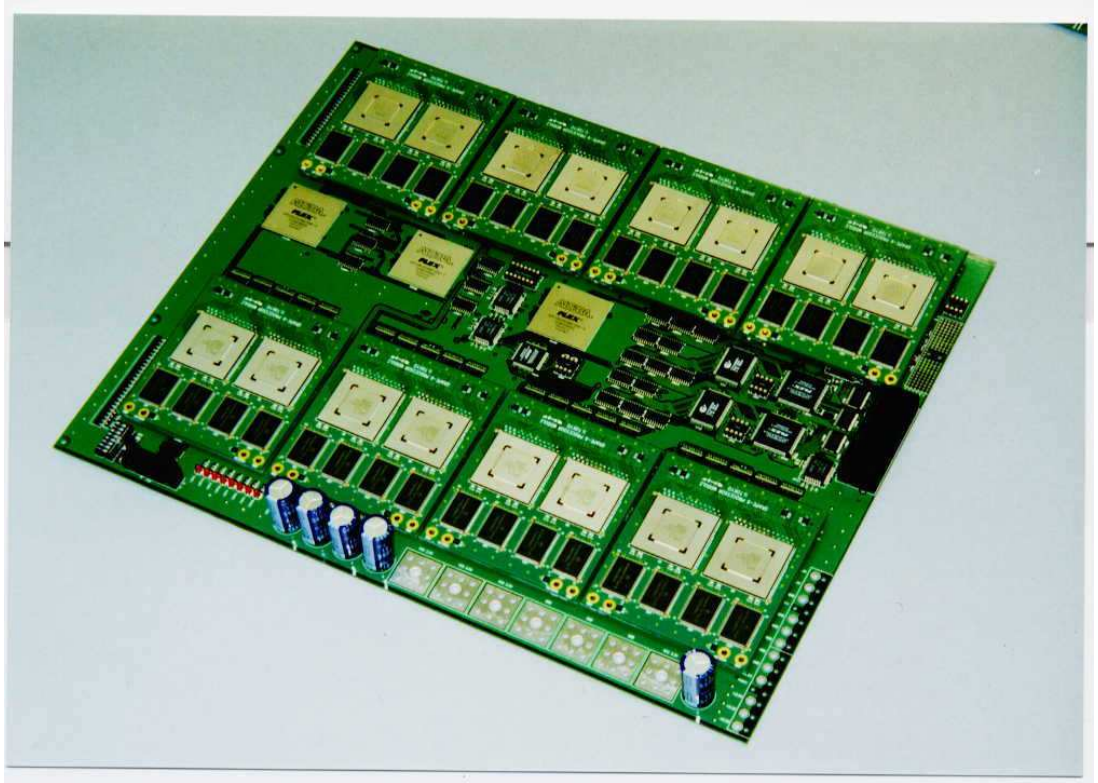
- Two processor chips + Memory chips.
- Integrates all functions of GRAPE-4 processor board.

The GRAPE-6 Processor board



- Single board with 16-chips
- Semi-serial (LVDS) interface (350MHz clock, 4 wires)
- Two input ports and one output port
- Result from 16 chips are summed by a reduction tree

The GRAPE-6 processor board

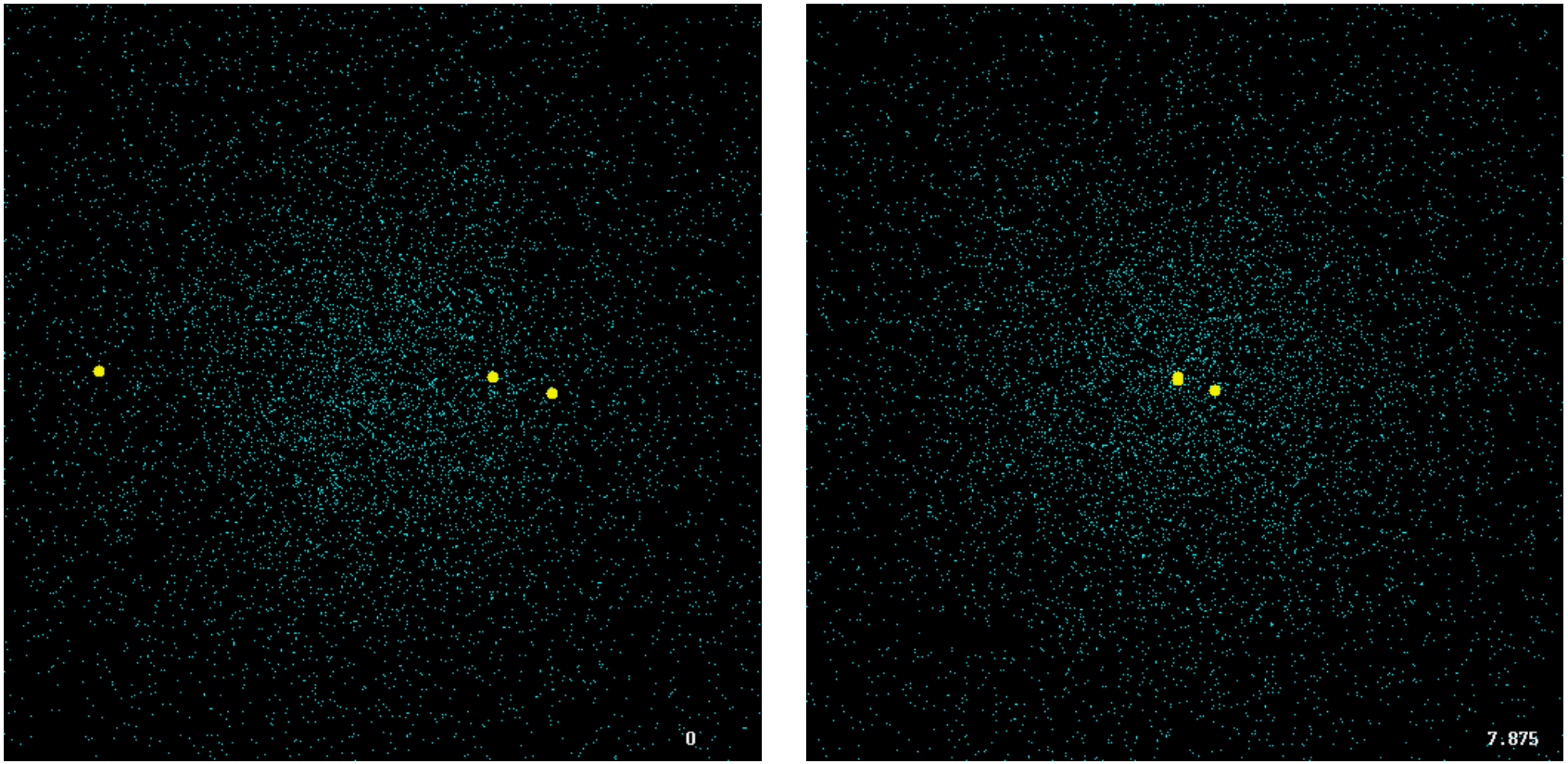


GRAPE-6 cabinet and 4-board system

Triple BH simulation

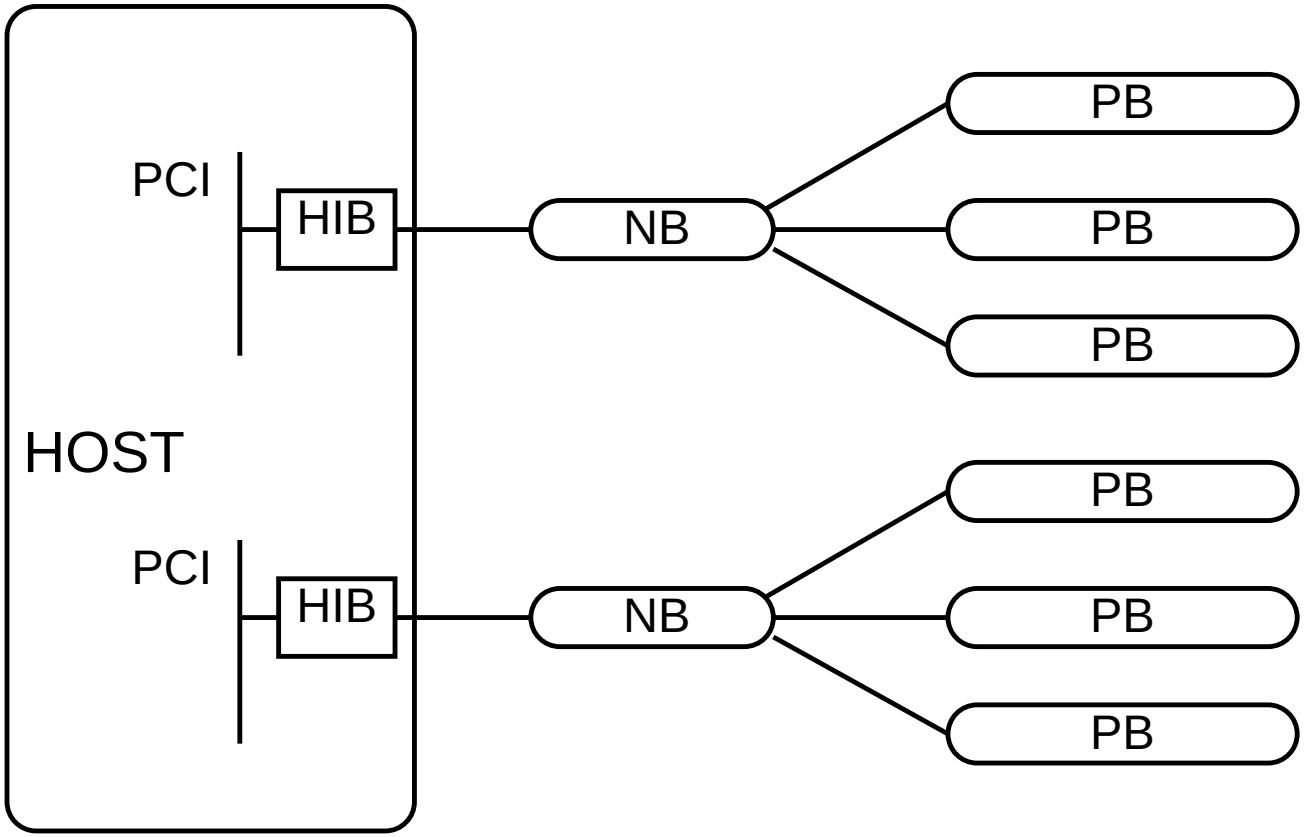
- Host Galaxy modeled by 786,432 equal-mass stars
- BHs have 1% of the mass of the host galaxy
- gravitational wave radiation ignored
- BHs placed "randomly" around the center

Initial and final snapshots



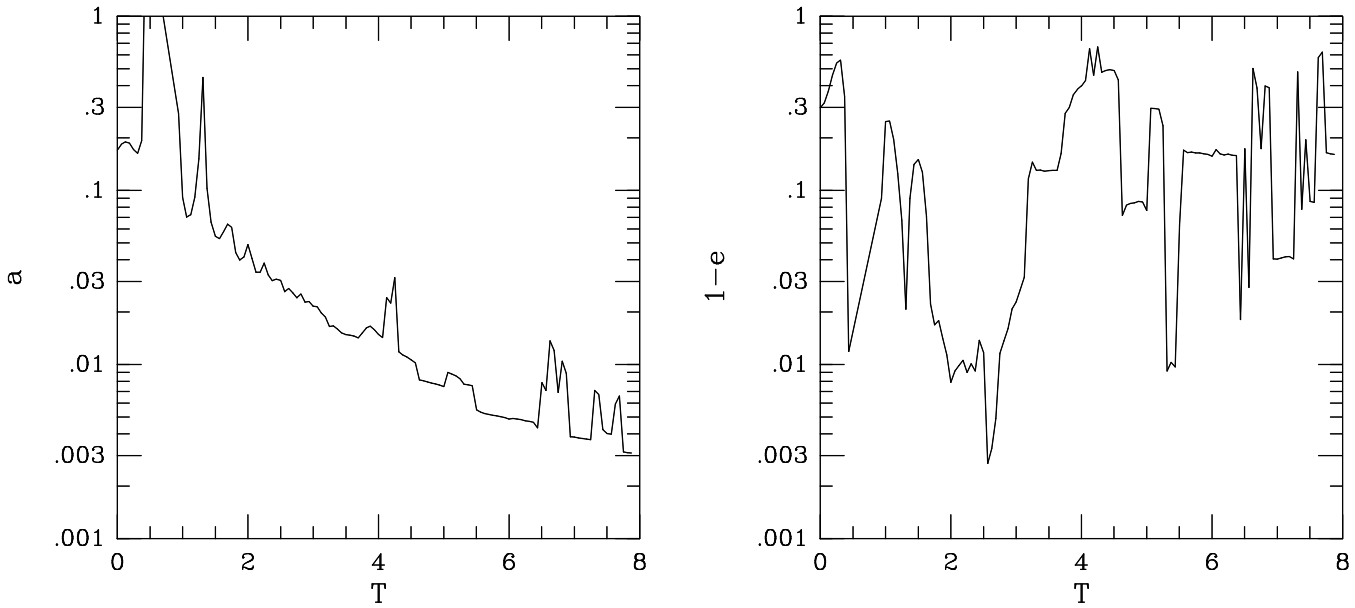
Hardware used

6-board GRAPE-6 system Peak speed: 2.889 Tflops



Host: EV-6 Alpha box (UP-2000 motherboard) with Tru64 UNIX

Result



Left: separation, right: eccentricity of the most strongly bound pair.

Eccentricity can go very close to one — gravitational wave would quickly let the bound pair merge.

Performance

Total number of (individual) timesteps: 3.238×10^9

Floating point operations per timestep: $786,434 \times 57$

Total floating point operations: 1.451×10^{17}

Wallclock execution time: 29.88 hours

The average speed during the run: **1.349 Tflops**

Short run with 1.4M particles: **1.64 Tflops**

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