

中国科学院国家天文台

National Astronomical Observatories, CAS



the SILK ROAD PROJECT at NAOC

丝绸之路计划



National Natural Science Foundation of China

Deutsche Forschungsgemeinschaft

DFG



Astrophysical GPU Supercomputing
in China and elsewhere
Galaxies - Black Holes
& Gravitational Waves

Rainer Spurzem

National Astronomical Observatories (NAOC), Chinese Academy of Sciences
Kavli Institute for Astronomy and Astrophysics (KIAA), Peking University
Astronomisches Rechen-Inst., ZAH, Univ. of Heidelberg, Germany

spurzem@bao.ac.cn

<http://ilibrary.las.ac.cn/web/silkroad>



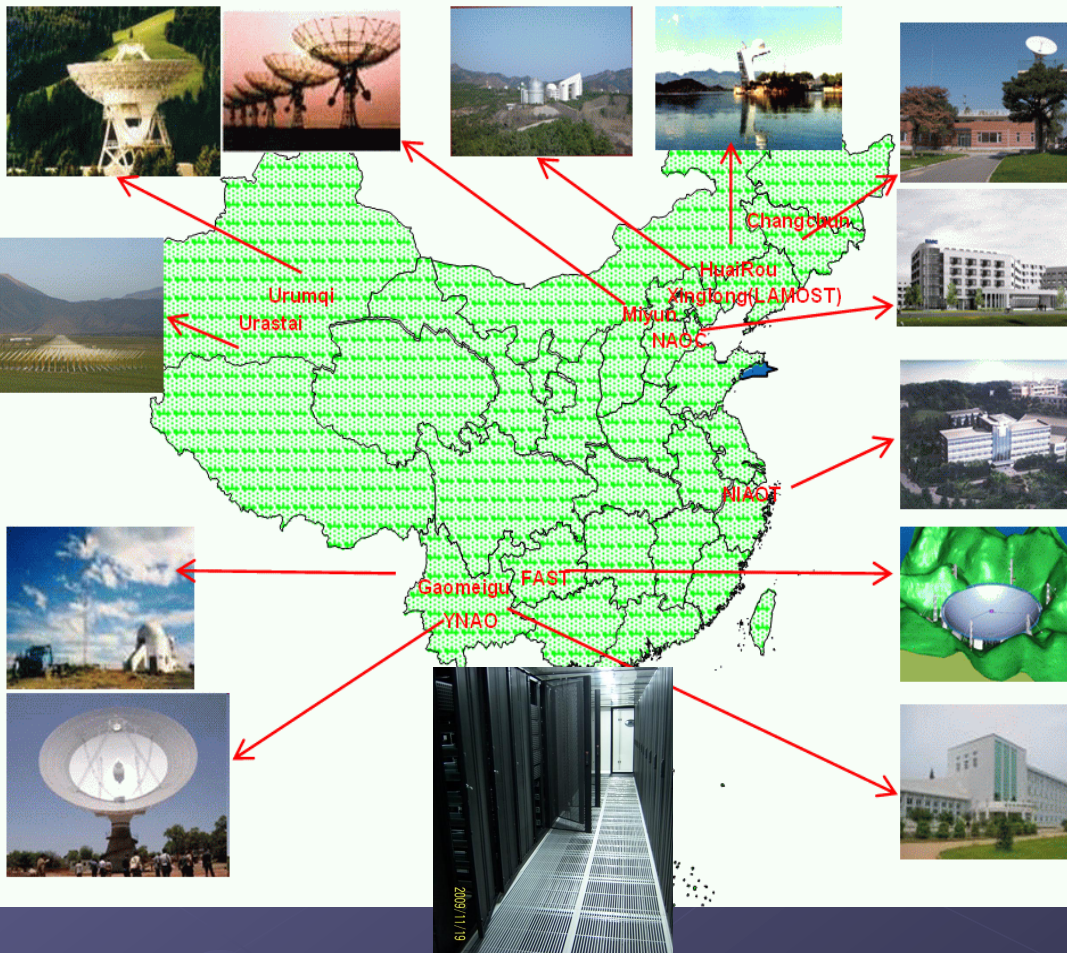
VolkswagenStiftung



中国科学院国家天文台

NATIONAL ASTRONOMICAL OBSERVATORIES, CHINESE ACADEMY OF SCIENCES

NAOC/ CAS



Top: NAOC Headquarter Beijing
Bottom: LAMOST Site



Computational Science Projects...

GTC 2011

(Astro)-physical GPU Supercomputing in China...



Pictures from: <http://www.chinatourselect.com/>

<http://ilibrary.las.ac.cn/web/silkroad>

New Instrument @ NAOC: GPU Supercomputer...

Core Team @ NAOC: R. Spurzem, P. Berczik, Li Shuo, Zhong Shiyan, Liu Lei, ...

Germany: Univ. Heidelberg, Excellence Program, Global Mobility Funds
Astronomisches Rechen-Institut, Inst. Theoretical Astrophysics (ZAH)
Computer Engineering and Architecture (ZITI)

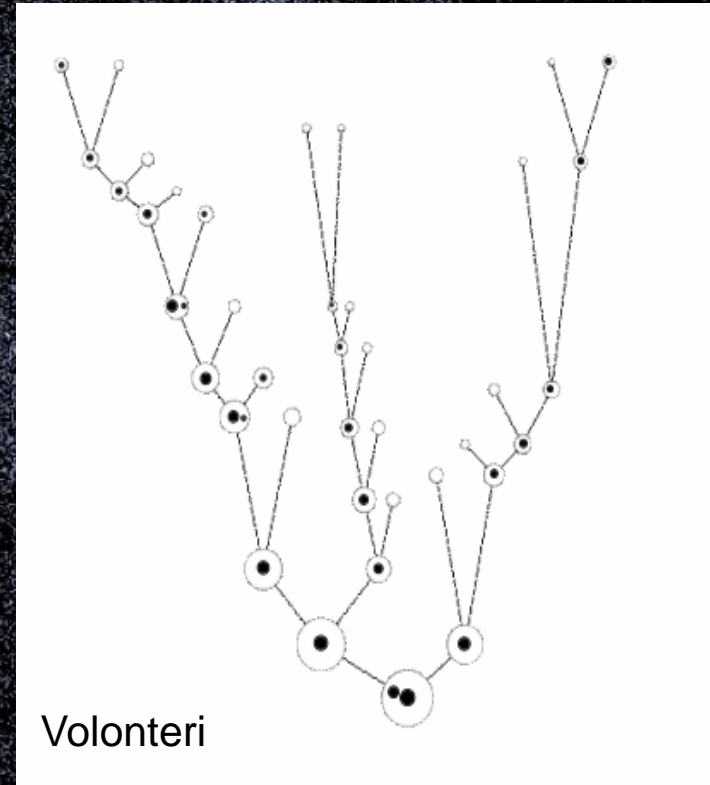
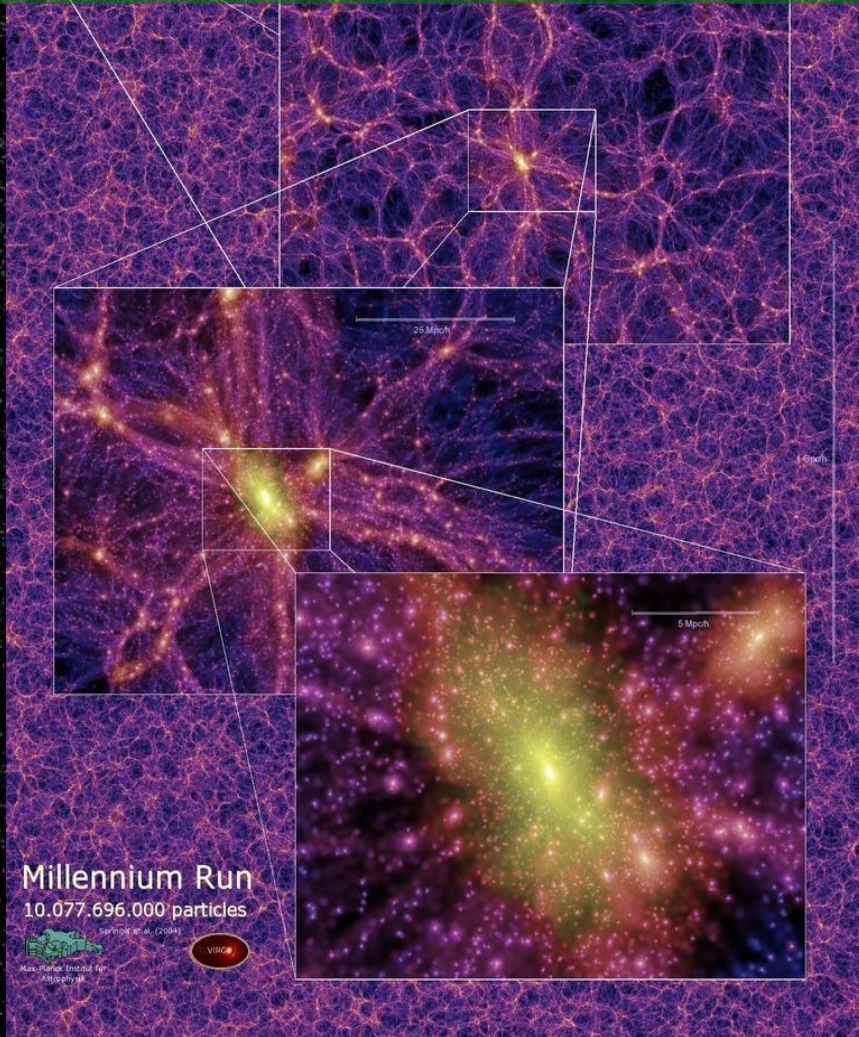
the SILK ROAD PROJECT at NAOC/KIAA

丝绸之路计划

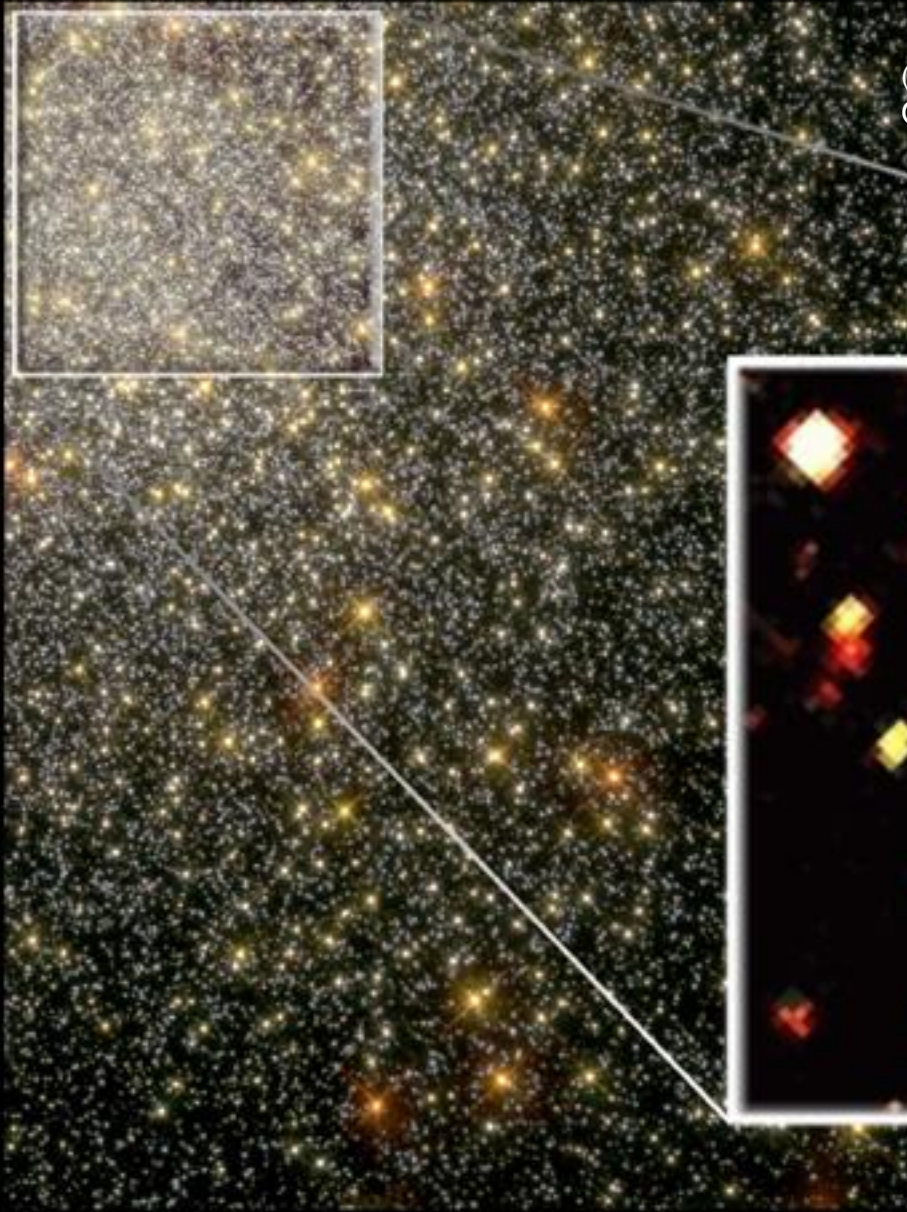
(Astro)-physical GPU Supercomputing in China...

- Galaxies and Black Holes
- Gravitational Waves
- Cluster Hardware
- Applications and Performance
- Future

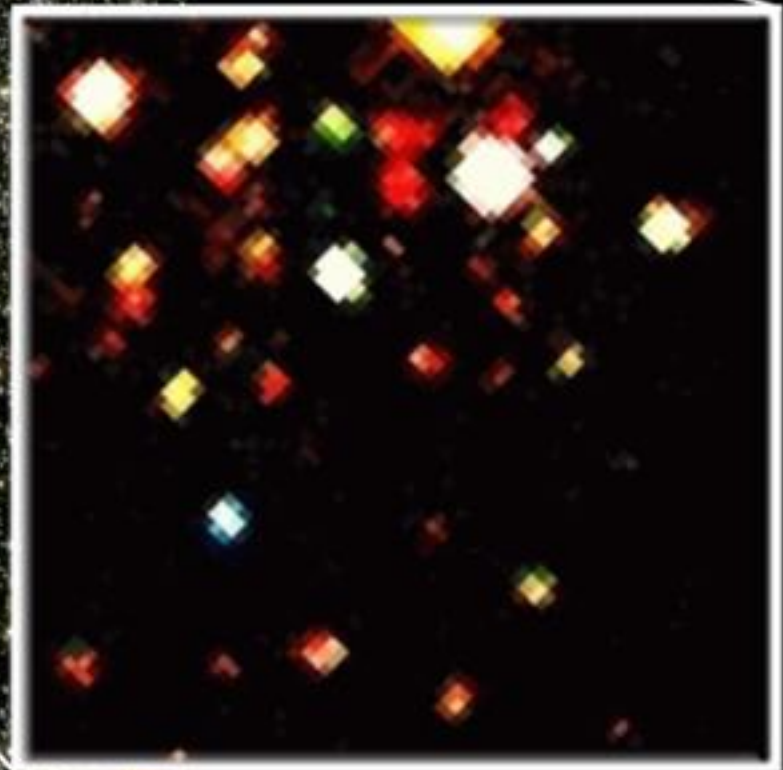
Galaxies merge, hierarchical Structure formation, their centres? Black Holes in Nuclei?



Slide:
Ingo
Berentzen



(Credit: X-ray: NASA/CfA/J. Grindlay et al.,
Optical: NASA/STScI/R. Gilliland et al.)



Globular Cluster 47 Tucanae

$$\vec{a}_0 = \sum_j Gm_j \frac{\vec{R}_j}{R_j^3} ; \quad \vec{\dot{a}}_0 = \sum_j Gm_j \left[\frac{\vec{V}_j}{R_j^3} - \frac{3(\vec{V}_j \cdot \vec{R}_j)\vec{R}_j}{R_j^5} \right]$$



Ground • AAT

NASA and R. Gilliland (STScI)
STScI-PRC00-33



Hubble Space Telescope • WFPC2

Galaxies and Black Holes

Left:

double-double radio galaxies, clear out of inner disk, milliparsec, small mass ratio

Right:

Jet Flipping, large mass ratio, depend on viscous time scales (Liu 2004, Liu et al. 2006)

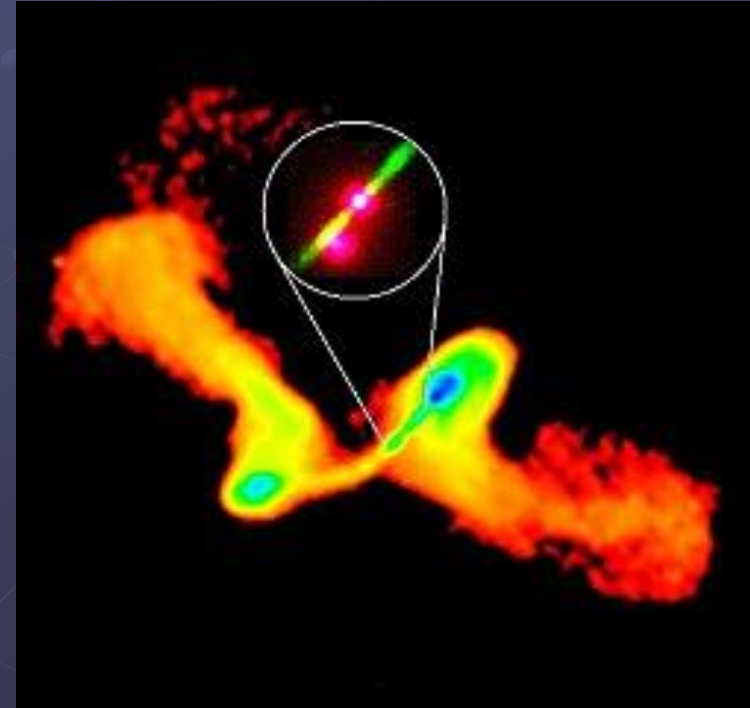
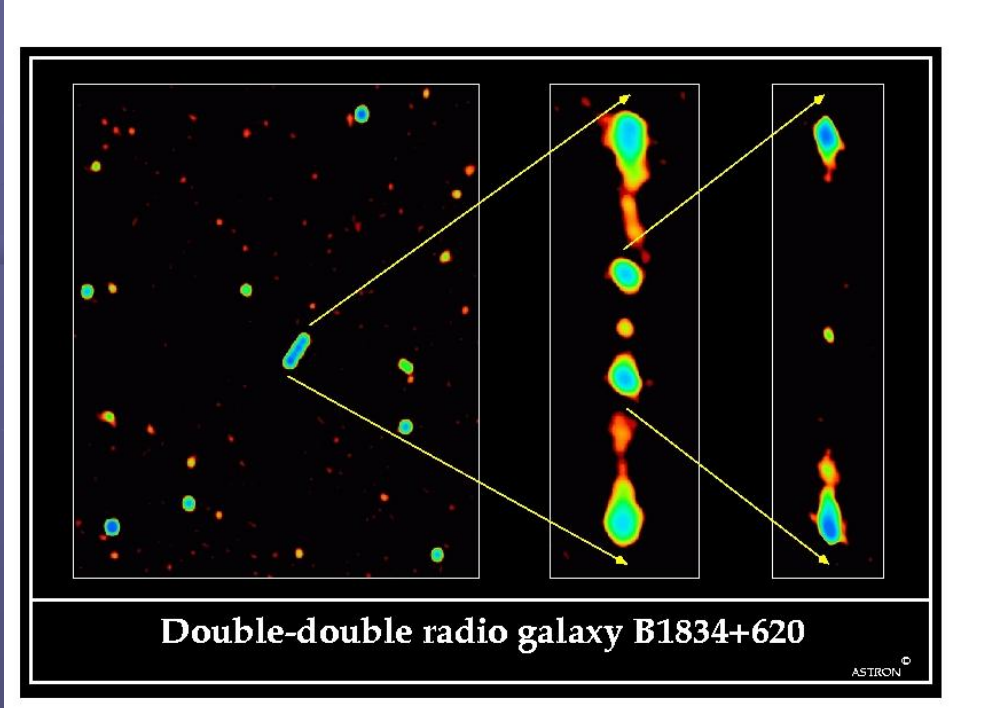
No Picture:

Interruption of Tidal Flares by Binary Black Holes,

Liu, Li, Chen, 2009 The Astrophysical Journal 706, L133

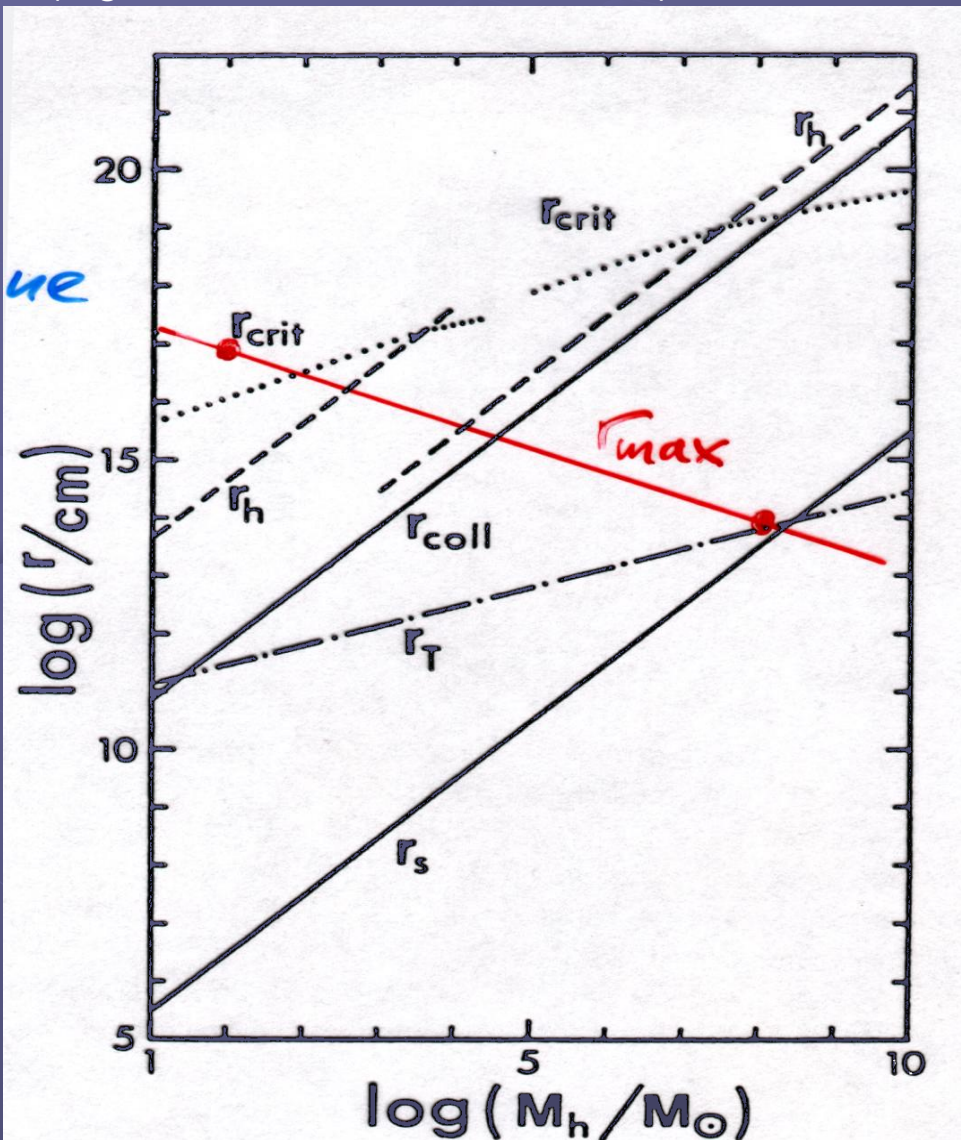
Enhances Tidal Disruptions from Binary Black Holes:

Chen, Madau, Sesana, Liu, 2009, The Astrophysical Journal 697, L149



One or more black holes...

(Figure from Frank & Rees 1976)



Theory of ONE BLACK HOLE (fixed):

Formation:

- Spitzer & Saslaw 1965, 1966
- Spitzer & Stone 1967
- Sanders 1970
- Hara 1978
- Duncan & Shapiro 1982, 1983
- Langbein, Spurzem et al. 1990
- Quinlan & Shapiro 1990

Evolution:

- Frank & Rees 1976
- Shapiro & Lightman 1976
- Marchant & Shapiro 1980
- Murphy, Cohn, Hut, 1990
- Amaro-Seoane & Spurzem 2001, 2004

Post-Newtonian Dynamics Gravitational Wave Templates

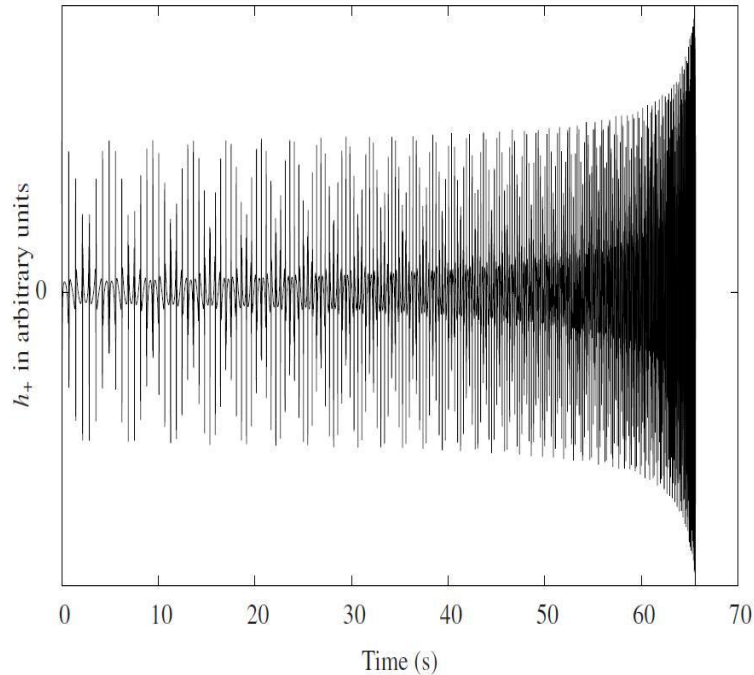


Figure 3.11: Waveform for two equal mass objects on an orbit with $e = 0.5$.

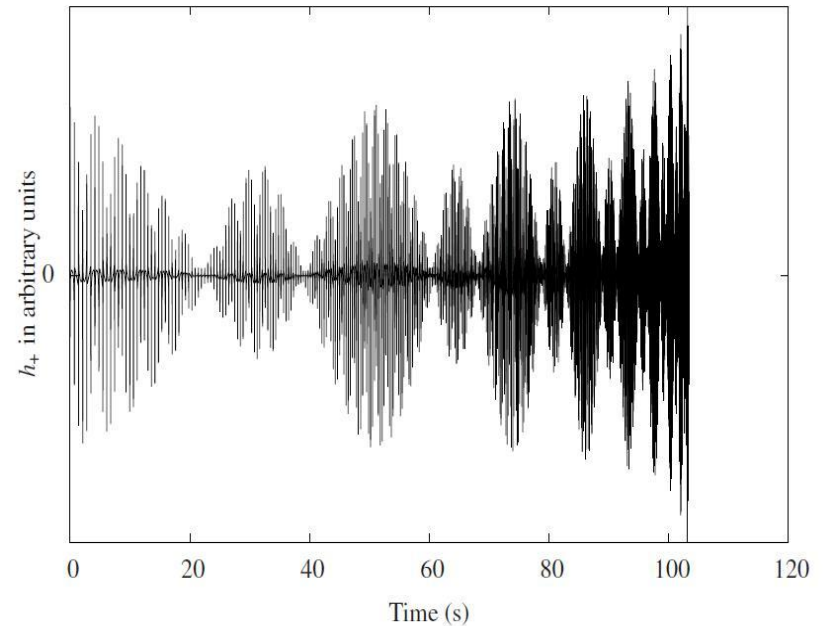


Figure 3.12: Waveform for two objects with a mass ratio of $q = 1/10$ on an orbit with $e = 0.5$ and spins $a_{1,x} = 1.0$, $a_{2,y} = 1.0$.

Plots of $h_+(t)$ showing 3 relevant time scales

Orbital evolution is NOT adiabatic (fully 3.5PN accurate)

Handle arbitrary eccentricities (P.Brem, R. Spurzem, Univ. Heidelberg)

Right side: include spin-orbit coupling...

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VIRGO – Pisa 3km

LIGO – Livingston, LA
Hanford, WA
4km

GEO600 – Hannover
600m

AIGO or Australian LIGO
(planned, 5 km)

<http://www.ligo-la.caltech.edu/>

<http://www.ego-gw.it>

<http://www.geo600.uni-hannover.de>

Advanced:
Outreach to 50 Millionen
light years (Neutron Stars)

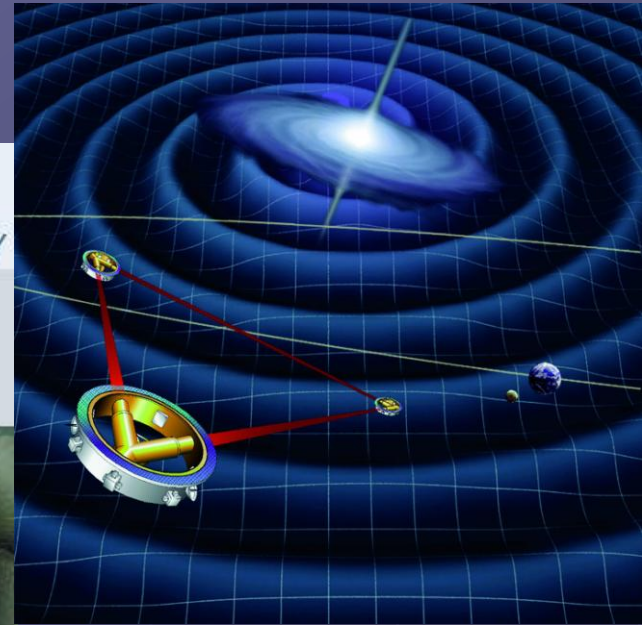
EUROPEAN GRAVITATIONAL OBSERVATORY

EGO



Consortium of

VIRGO Detector in Cascina near Pisa, Italy



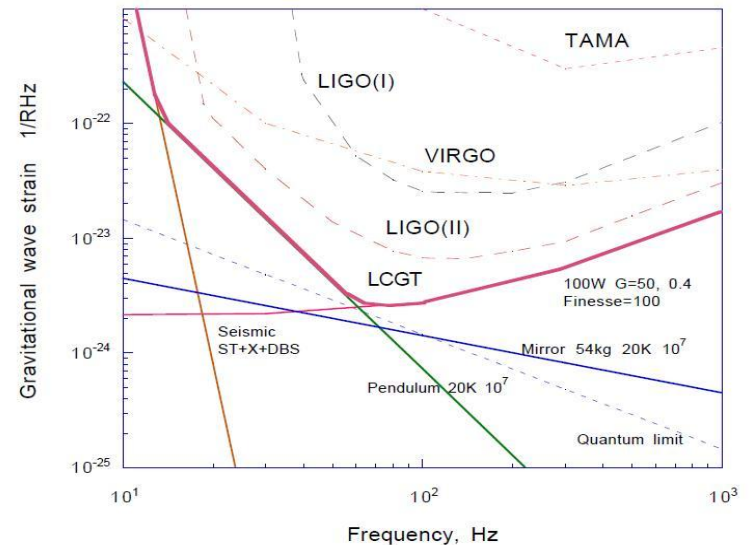
LISA =
Laser Space
Interferometer Antenna

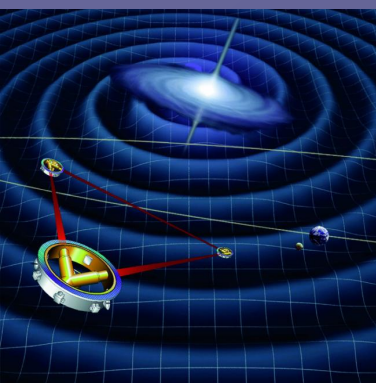


Underground Gravitational Wave Detector — LCGT —



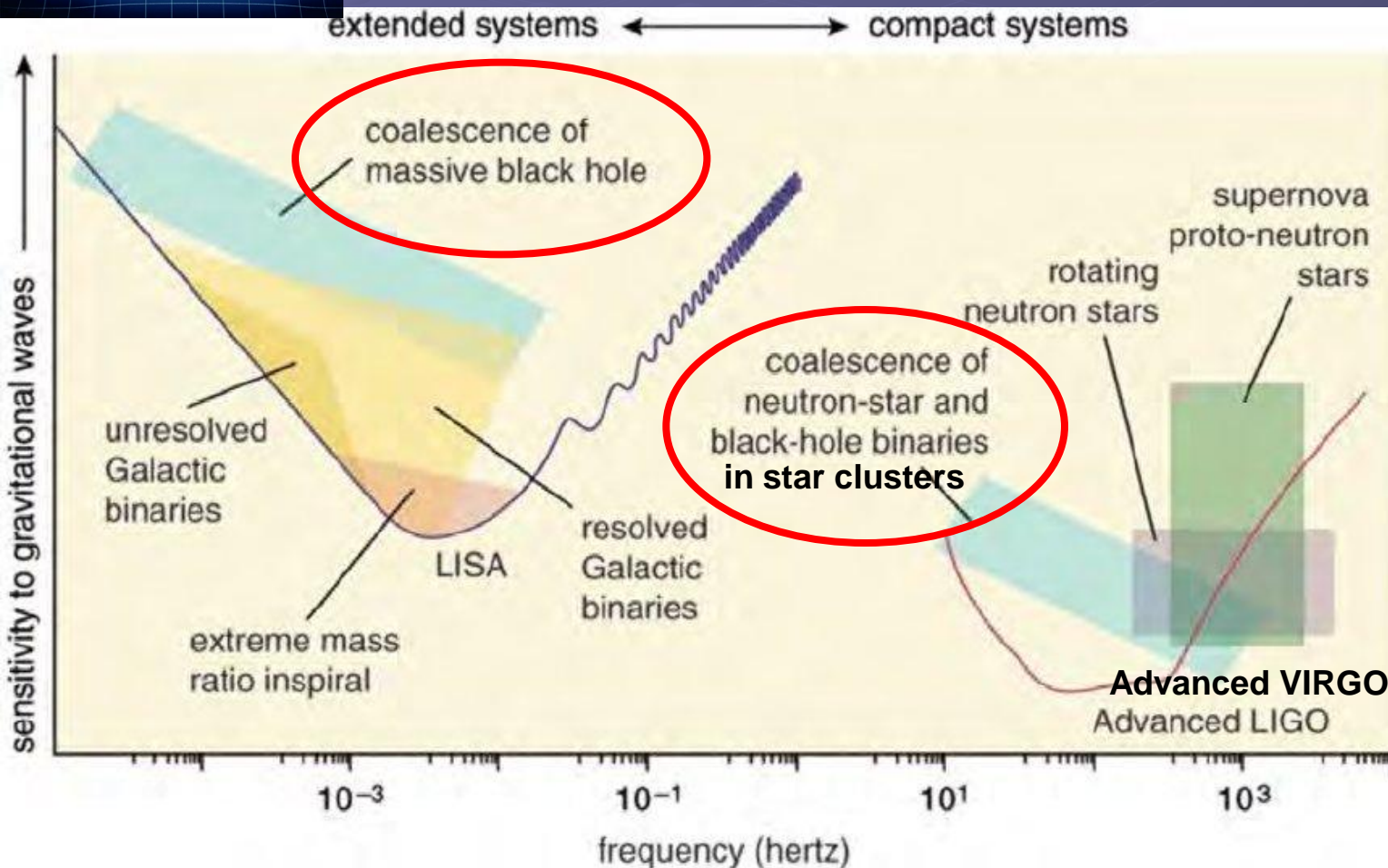
Kazuaki Kuroda
On behalf of LCGT





Gravitational Wave Prediction from Black Holes in Galactic Nuclei and Star Clusters

Astrophysical Objects in the realm of LISA (left) and VIRGO or LIGO (right)
= activities with Nbody Simulations



Proposed Gravitational Wave Instrument of China and Collaboration (ALIA)

A scientific case study of an advanced LISA mission

Xuefei Gong¹, Shengnian Xu², Shan Bai^{3,4}, Zhoujian Cao^{3,4},
 Gerui Chen⁵, Yanbei Chen⁶, Xiaokai He^{3,7}, Gerhard Heinzel^{8,9},
 Yun-Kau Lau^{3,4}, Chenzhou Liu^{3,7}, Jun Luo¹⁰, Ziren Luo¹¹,
 Antonio Pulido Patón¹², Albrecht Rüdiger⁸, Mingxue Shao³,
 Rainer Spurzem^{13,14,15}, Yan Wang^{8,9,16}, Dong Xu³, Hejun Xu¹⁰,
 Yefei Yuan² and Zebing Zhang⁷

Class. Quantum Grav. 28 (2011) 094012

X Gong et al

¹ Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, People's Republic of China

² Center for Astrophysics, Department of Physics, University of Science and Technology of China, 96 Jinzhai Road, Hefei 230026, China

³ Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Beijing 100049, People's Republic of China

⁴ State Key Laboratory of Scientific and Technical Instruments, Beijing 100190, People's Republic of China

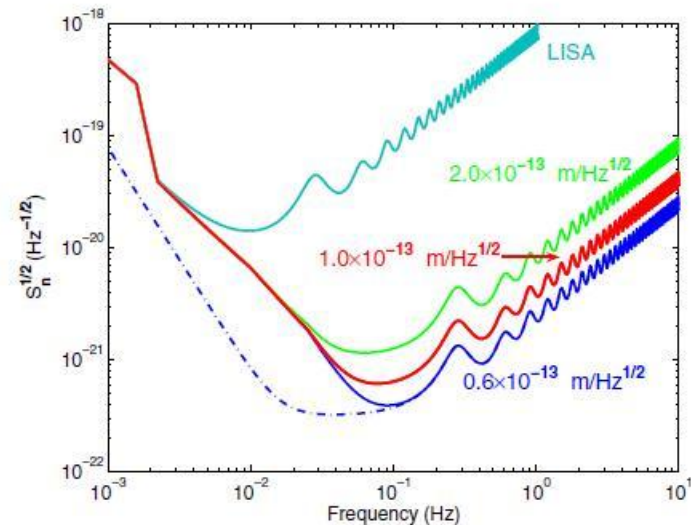


Figure 1. Sensitivity of a few representative mission options whose sensitivity curves are labeled by their corresponding total position noise budget levels. Also shown is the standard single Michelson sensitivity of LISA for comparison [20]. The optimistic confusion noise level generated by both galactic and extra-galactic cosmological compact binaries (mainly WD-WD) given in [17] is adopted in drawing the solid lines, and the dash-dotted curve stands for the pure instrumental noise for the most ambitious design.

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HARDWARE

Custom PC Clusters

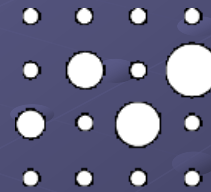
with manycore accelerator hardware

Since 2005:

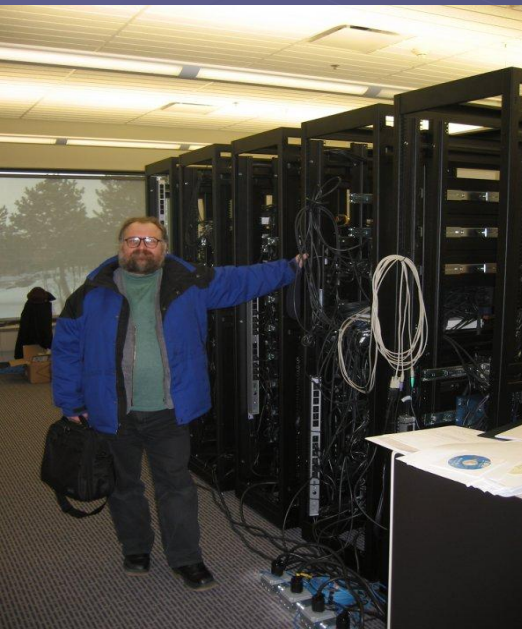
Heidelberg (2x, GRAPE, FPGA, GPU)

Rochester, NY (only GRAPE)

Kiev, Ukraine (2x, GRAPE, GPU)



VolkswagenStiftung



Top: GRAPE/FPGA Cluster

Univ. Heidelberg, Germany

2005 (32 nodes)

Bottom: GRAPE Cluster

Main Astronomical Obs.

Kiev, Ukraine





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the SILK ROAD PROJECT at NAOC

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GPU Clusters used for the project:

Beijing **(NAOC/CAS and Silk Road Project)**

86x8 Cores, 170 Tesla C1060

Mole-8.5 **(IPE/CAS)** 33000 Cores, 2200 Tesla C2070

Heidelberg, Germany (2x, FPGA, GPU)



Heidelberg
Germany



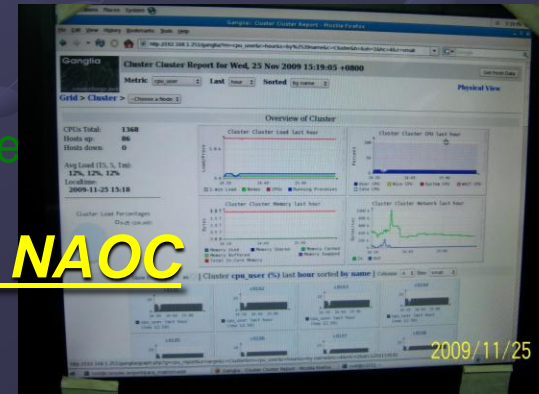
Mole-8.5
System

yesky
天极网



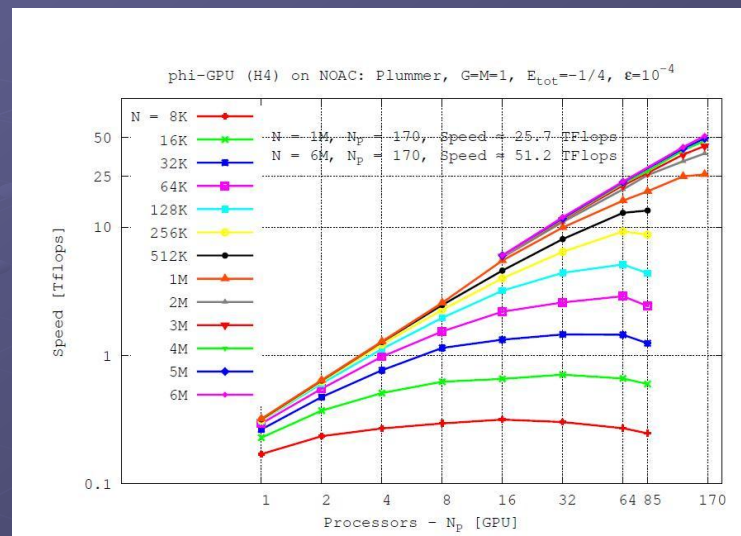
2009/11/19

老虎 NAOC



2009/11/25

国家天文台GPU超级计算机



85
 Infiniband
 2 4 Xeon E5520
 24GB CPU
 1.5
 2 Nvidia C1060
 160

GPU

ϕ GPU

6

GPU

50

Our next GPU Cluster... Milky Way + Judge

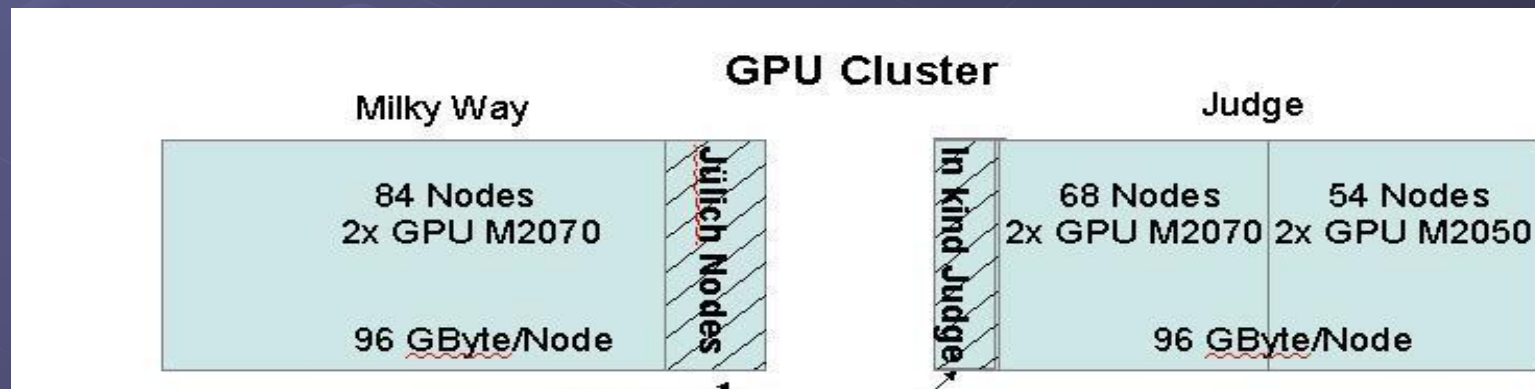
*At Research Center
FZ Jülich, Germany*

204 nodes ~ 2448 CPU cores

408 GPUs M2070/M2050

~ 200.000 GPU threads

*Spring 2012... jointly built and
Operated with Univ. Of Heidelberg....*

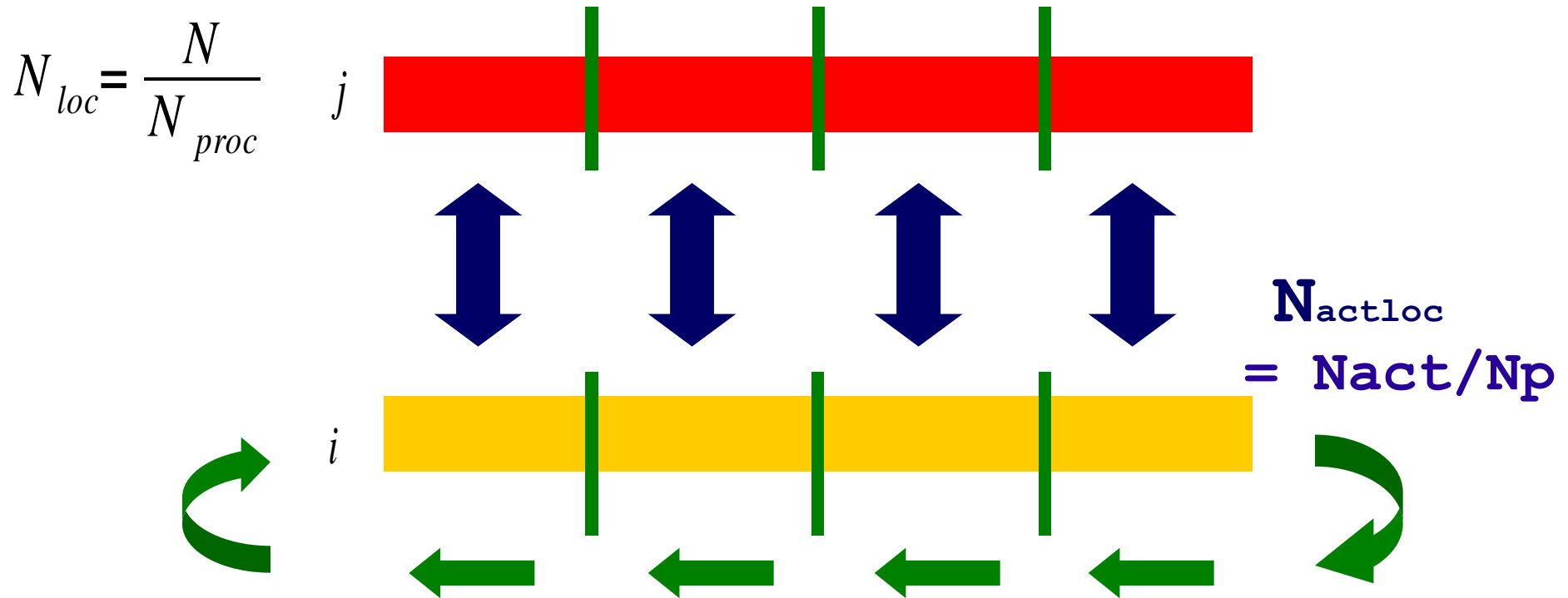


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Basic idea of parallel N-body code

i,j- particle

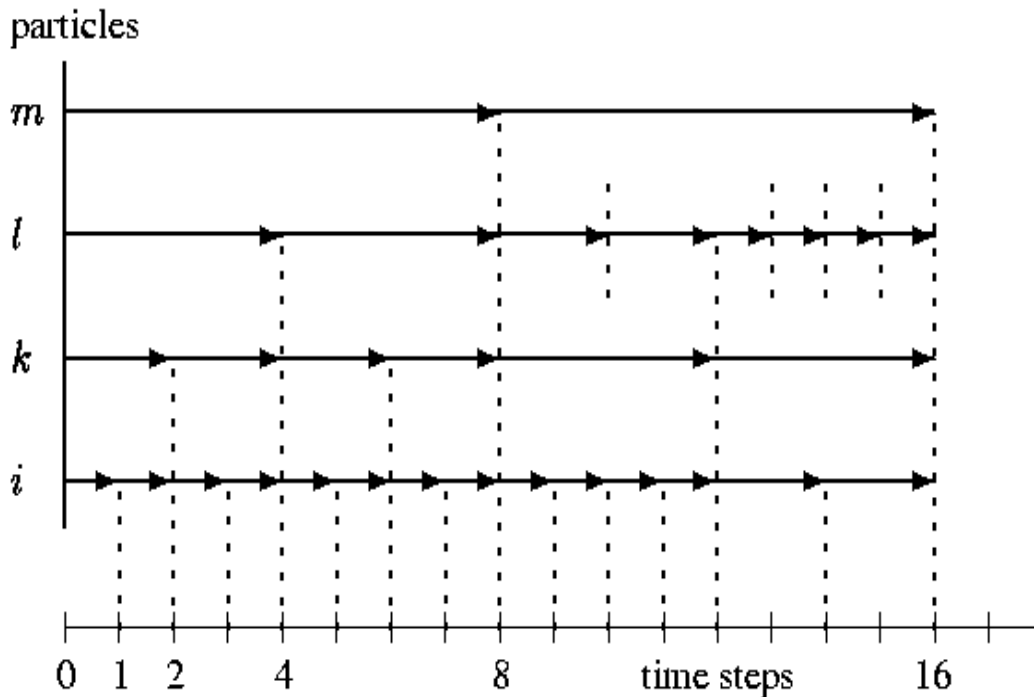


Some communication scheme...

Presently used GPU (GRAPE) N-body code

Harfst, Berczik, Merritt, Spurzem et al, *NewA*, 12, 357 (2007)
Spurzem et al., *Comp. Science Res. & Dev.* 23, 231 (2009)

Hierarchical Individual Block Time Steps



$$\Delta t = \sqrt{\eta \frac{|\vec{a}| |\vec{a}^{(2)}| + |\vec{a}|^2}{|\vec{a}| |\vec{a}^{(3)}| + |\vec{a}^{(2)}|^2}}$$

4th_{th} order Hermite scheme

$$\frac{d^2 \boxed{r}_i}{dt^2} = \boxed{a}_i$$

<ftp://ftp.ari.uni-heidelberg.de/pub/staff/berczik/phi-GRAPE/>

Software

NBODY4, NBODY6, S.J.Aarseth, S. Mikkola, ...
(ca. 20.000 lines, since 1963):

- Hierarchical Individual Time Steps (HITS)
- Ahmad-Cohen Neighbour Scheme (ACS)
- Kustaanheimo-Stiefel and Chain-Regular. (KSREG)
for bound subsystems of $N < 6$ (Quaternions!)
- 4th order Hermite scheme (pred/corr), Bulirsch-Stoer (for Chain)
- Stellar Evolution (single/binary) (w Hurley)
- NBODY6++, ϕ GPU, R. Spurzem, P. Berczik, T. Hamada, K. Nitadori,...
(massively parallel codes, since 1999):
- NBODY6++ (Spurzem 1999) using MPI
- Parallel ϕ GRAPE / ϕ GPU (Harfst et al. 2006, Spurzem et al. 2009, Berczik, Hamada et al. 2011 in prep.)
- NBODY6++/GPU-MPI (Spurzem, Aarseth, Berczik 2011 in progress...)
- Parallel Binary Integration in Progress (KSREG)

Φ GPU - NBODY

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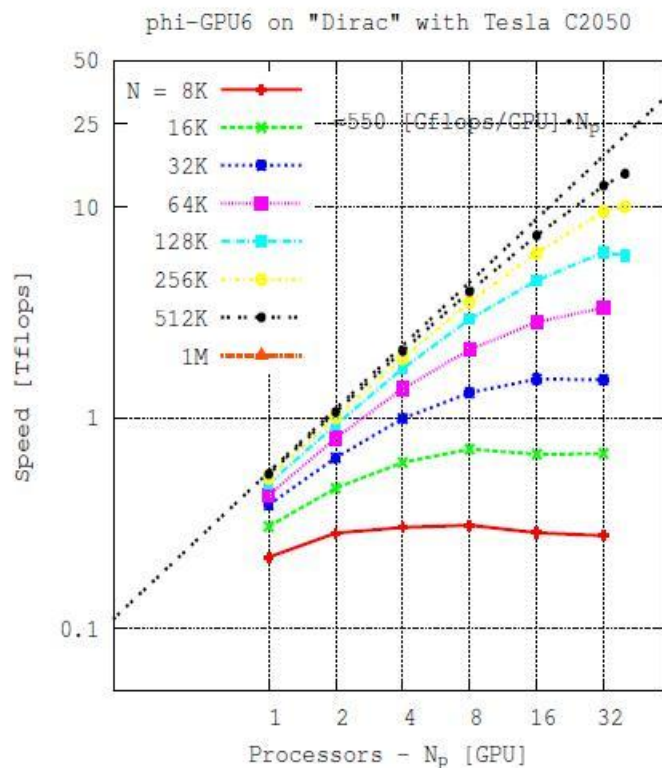
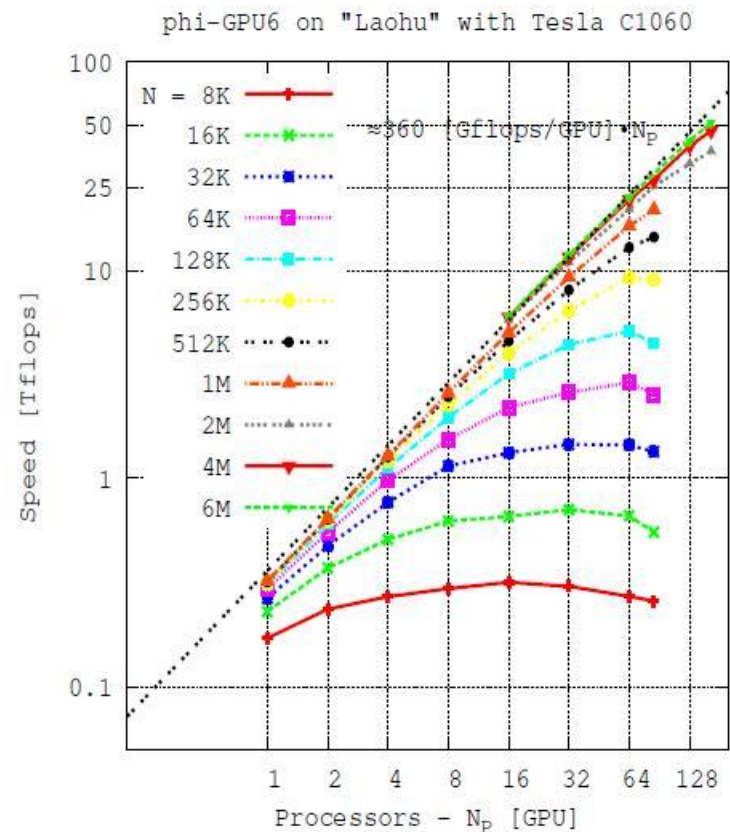
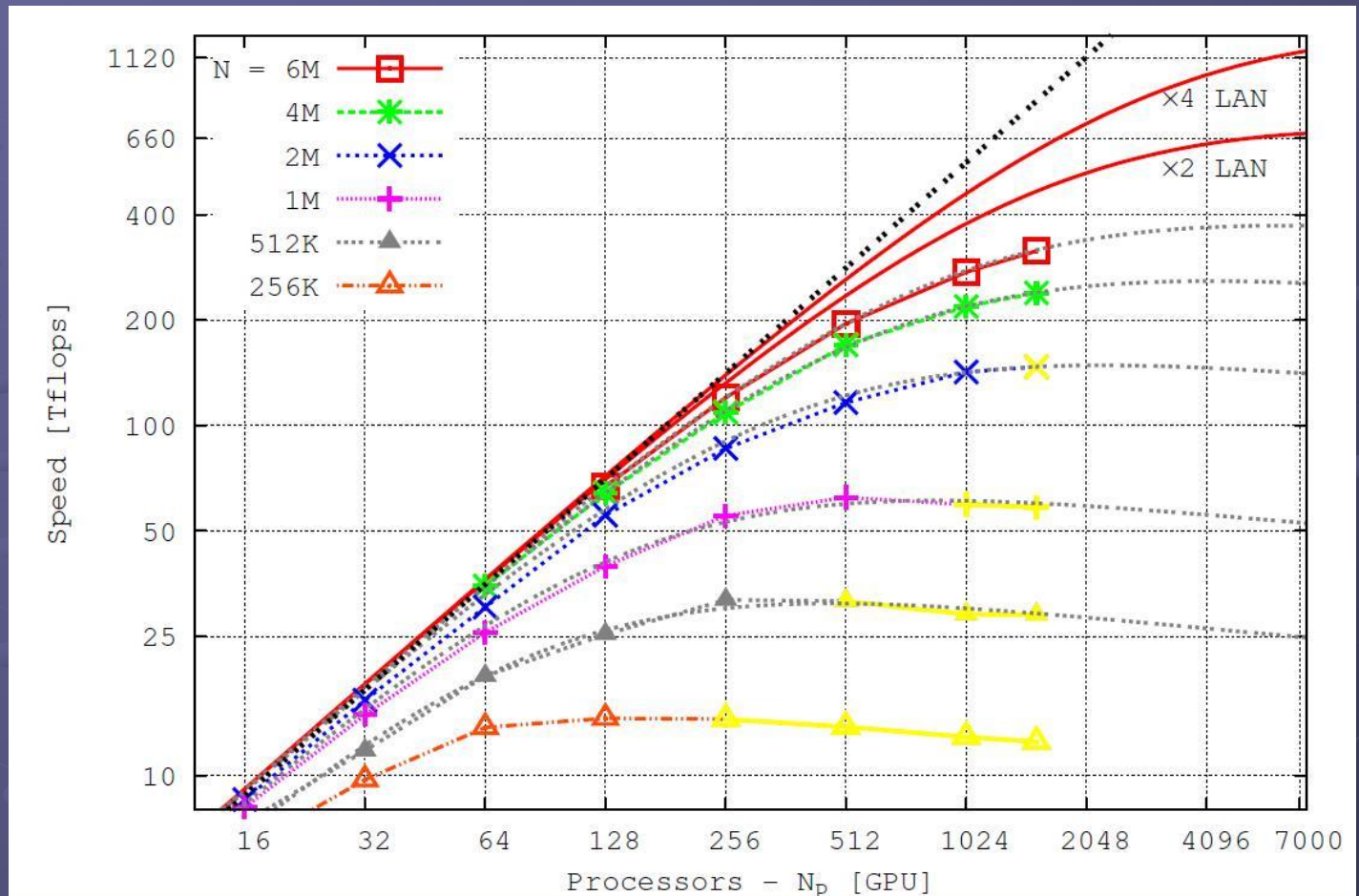


Fig. 3 The performance of φ GPU on Fermi C2050 (dirac cluster in Berkeley) accelerated nodes; speed in Teraflop/s reached as a function of number of processes, each process with one GPU; limit to 40 GPU's as this is the maximum on the dirac cluster. Each line corresponds to a different problem size (particle number), which is given in the key.



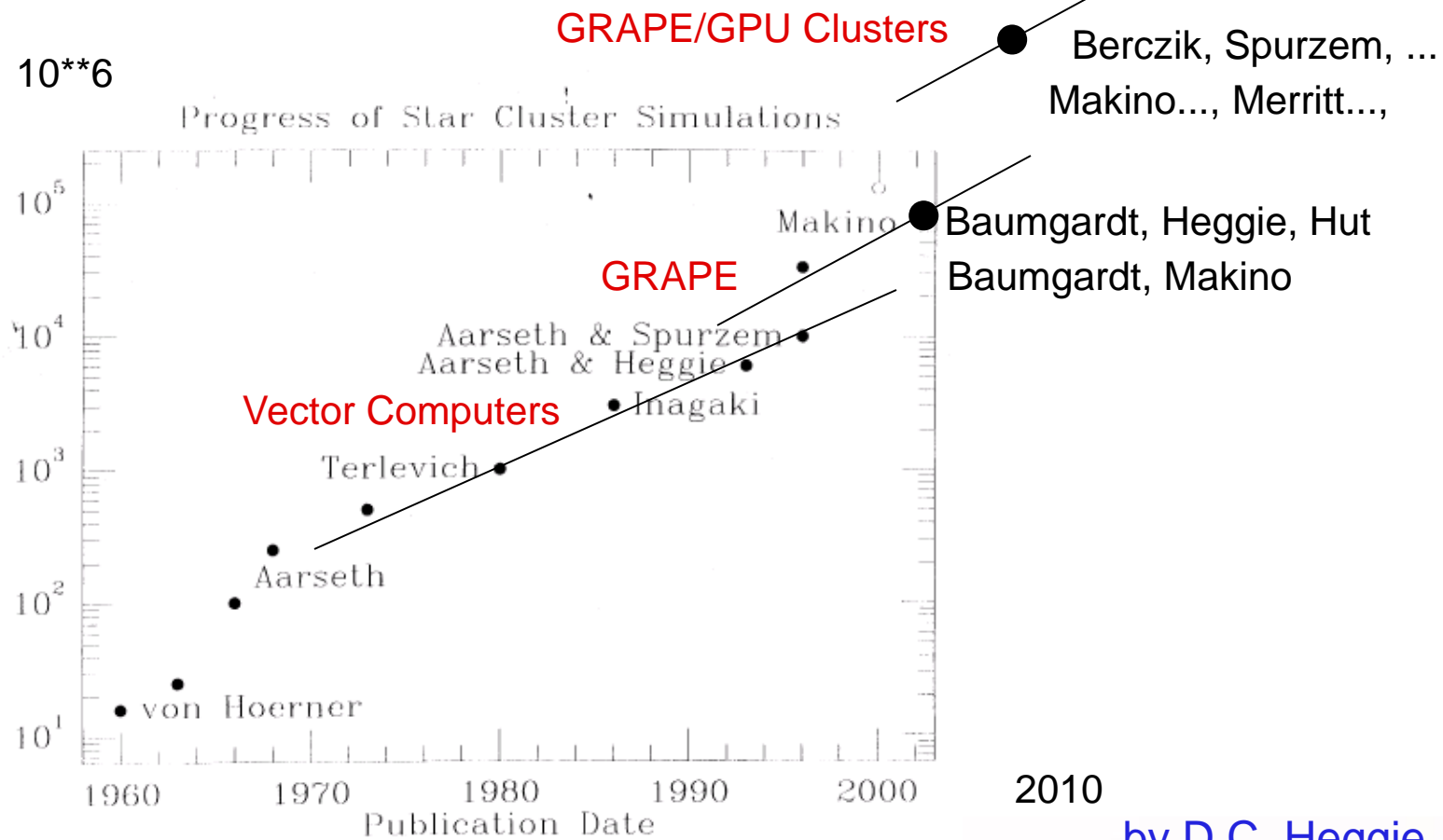
Berczik, Nitadori, Spurzem, et al. 2010, in pre
Spurzem et al. 2011, Computer Science -
Research and Development (CSR D), 26, 145

Φ GPU - NBODY



Results on Mole-8.5 cluster, 2000 GPUs, $N = 6$ mill., 350 Tflop/s
Extrapolation to Tianhe System
Berczik et al. 2011, subm. to SC11
GTC 2011

“Moore's” Law for Direct N-Body



by D.C. Heggie

Via www.maths.ed.ac.uk



北京大學
PEKING UNIVERSITY

GAMER – Adaptive Mesh Refinement with many GPU's on Beijing GPU cluster, Schive et al. 2010, Schive, Shukla et al. SC11 In pre

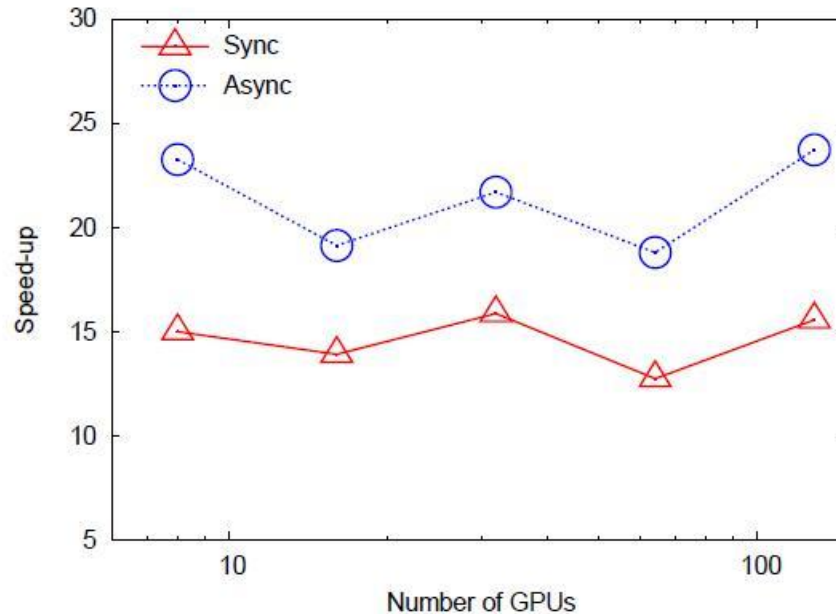


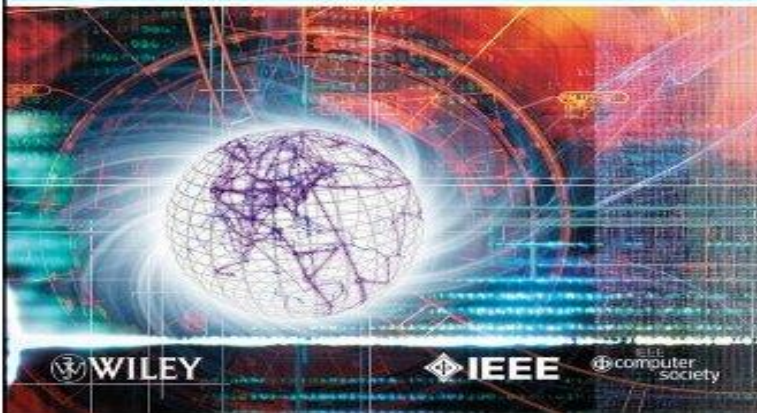
Fig. 1.— Performance speed-up as a function of the number of GPUs/CPU's. For each data point, we compare the performance by using the same number of GPUs and CPU cores. The blue circles and red triangles show the timing results with and without the concurrent execution between CPUs and GPUs, respectively. The speed-up achieved in the 128-GPU run is 23.7x.

Some simulation details:

- (1) Root-level resolution : 256^3
- (2) Number of refinement levels : 7
- (3) Highest effective resolution : $32,768^3$
- (4) Total memory consumption : ~ 100 GB
- (5) Total number of grids : $\sim 1.8 * 10^9$
- (6) Number of GPUs/CPU cores : 8, 16, 32, 64, 128

LARGE-SCALE COMPUTING TECHNIQUES FOR COMPLEX SYSTEM SIMULATIONS

WERNER DUBITZKY • KRZYSZTOF KUROWSKI • BERNHARD SCHOTT



Edited Volume
To appear November 22

With Paper

Spurzem, et al.,
Accelerated Many-Core
GPU Computing for
Physics and Astrophysics
on Three Continents



PRACE Award - 2011

**Astrophysical Particle Simulations with Large Custom GPU Clusters
on Three Continents**

Rainer Spurzem, *et al*, Chinese Academy of Sciences & University of Heidelberg

Black Holes in Galactic Nuclei simulated with large GPU clusters at Chinese Academy of Sciences

Rainer Spurzem, Peter Berczik, Shiyun Zhong (钟诗言)

National Astronomical Observatories, Chinese Academy of Sciences (NAOC/CAS), 20A Datun China Rd., Chaoyang Distr., Beijing 100012

地址: 北京市朝阳区大屯路甲 20 号 中国科学院国家天文台 邮编: 100012

Astronomisches Rechen-Institut, Zentrum für Astronomie, Universität Heidelberg, Mönchhofstr. 12-14, 69120 Heidelberg, Germany (德国)

1. Supermassive Black Holes in Galactic Nuclei

Many, if not all galaxies harbour supermassive black holes. If galaxies merge, which is quite common in the process of hierarchical structure formation in the universe, their black holes sink to the centre of the merger remnant and form a tight binary. Depending on initial conditions and time supermassive black hole binaries are prominent gravitational wave sources, if they ultimately come close together and coalesce. We model such systems as gravitating N-body systems (stars) with two or more massive bodies (black holes), including if necessary relativistic corrections to the classical Newtonian gravitational forces, and model their gravitational radiation emission directly from the simulation.

Some References:

- Baranton, J., Prieto, M., Berczik, P., Spurzem, R., Binary Black Hole Merger in Galactic Nuclei: Post-Newtonian Simulations, 2009, *The Astrophysical Journal* 695, 455
- Fiaschi, J., Poth, O., Berczik, P., and Spurzem, R., Evolution of growing black holes in asymmetric galaxy cores, 2011, *Monthly Notices of the Royal Astronomical Society* 1894
- Prieto, Miguel, Baranton, Ingo, Berczik, Peter, and Spurzem, Rainer, Fast Coalescence of Massive Black Hole Binaries from Mergers of Galactic Nuclei: Implications for Low-Frequency Gravitational-wave Astrophysics, 2011, *The Astrophysical Journal* 730, L28

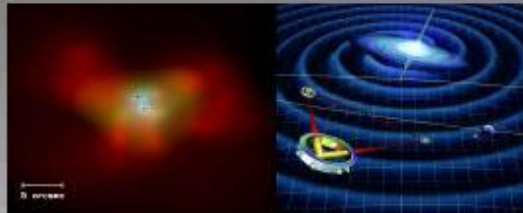


Figure 1 Left: X-Ray observation of two nuclei of a galaxy after merging, both bright spots are interpreted as hot gas around a supermassive black hole, which cannot be directly resolved. The distance between both black holes is 3000 light years (Picture from S. Komossa, Max-Planck-Institute for Extraterrestrial Physics in Garching near Munich, Germany).

Figure 1 Right: Artist's impression of the space-based LISA laser interferometer satellites, designed to detect gravitational waves from massive black hole coalescences in the entire universe (Picture: ESA, China (ALIA) and Europe (LISA) are currently planning space missions with laser interferometer satellites to detect gravitational waves, see Gong, Xuefei, ..., Spurzem, R., ..., et al., A scientific case study of an advanced LISA mission, 2011, *Classical and Quantum Gravity* 28, 044012

Other teams, interested students and postdocs from NAOC, or from other Chinese institutions are invited to test their own, develop new and use their codes on the NAOC/CAS GPU supercomputer. International Collaborations are also possible.

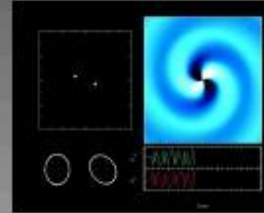
Please contact spurzem@bao.ac.cn and look at the Silk Road Project Webpage <http://library.las.ac.cn/web/silkroad>

2. Gravitational Waves from Black Holes in Galactic Centres

Supermassive black hole binaries (SMBHBs) are products of galaxy mergers, and are important sources of gravitational wave (GW) radiation. For this reason, it will be important to detect electromagnetic counterparts of GW radiation sources. In this work we focus on stars being disrupted by tidal forces in the vicinity of supermassive black holes, they generate an X-ray flare, which is observable. We are also interested in supermassive black holes which are kicked out of galactic nuclei due to recoil after a gravitational radiation induced merger.

Snapshot of gravitational wave emission by our simulated binary black holes. (Picture thanks to Ingo Baranton, Univ. of Heidelberg)

Figure 2 top left: position of black holes
 Figure 2 top right: gravitational wave pattern in coordinate plane
 Figure 2 bottom left: polarisations of gravitational waves
 Figure 2 bottom right: amplitudes of the two polarisations as a function of time at hypothetical earth observer's point (black dot in upper right picture).



3. Direct N-Body Code ϕ GPU

The application code which we use for benchmarking here is a direct N-body simulation code for astrophysics, using a high order Hermite integration scheme and hierarchical block time steps (the code supports time integration of particle orbits with 4_s, 6_s, and 8_s order schemes). The code is called ϕ GPU, it has been developed from our earlier published version ϕ GRAPE (using GRAPE hardware instead of GPU, Hacht et al. 2007). It is parallelised using MPI (Message Passing Interface), and on each node using many cores of the special GPU hardware to compute gravitational forces between particles. The code was developed in cooperation with Keigo Nitadori (RIKEN Japan) and Tsuyoshi Hamada (Nagasaki Univ. Japan). It is written in C++ with MPI and CUDA, and it is based on Nitadori & Makino (2003) earlier CPU serial code (ybsim). It runs on single (Tesla C1060) or double precision (Fermi C2050) GPUs; higher than single precision is emulated, where needed (Nitadori & Makino, 2008).

Some References:

- Hacht, S., Gualandri, A., Manfrot, D., Spurzem, R., Portegiese Zwart, S., Berczik, P., Performance analysis of direct N-body algorithms on special-purpose supercomputers, 2007, *New Astronomy* 12, 357
- Nitadori, K., Makino, J., Sixth- and eighth-order Hermite integrator for N-body simulations, 2008, *New Astronomy* 13, 498
- Spurzem, R., Berczik, P., Baranton, I., Nitadori, K., Hamada, T., Marcus, G., Kugel, A., Manfrot, R., Fiaschi, J., and Banerjee, R., Astrophysical particle simulations with large custom GPU clusters on three continents, *Computer Science - Research and Development*, Volume 26, Numbers 3-4, 145-151
- Spurzem, R., Berczik, P., Baranton, I., De, W., Wang, X., Schölk, H.-Y., Nitadori, K., Hamada, T., Fiaschi, J., Accelerated Many-Core GPU computing for astrophysics and astrophysics on three continents, in *Large-Scale Computing Techniques for Cosmological System Simulations (Wiley Series on Parallel and Distributed Computing)*, eds. Marcin Dubitzky, Krzysztof Kuroszek, Bernard Schölk, Wiley/IEEE Computer Society, 1st edition (to appear November 22, 2011).

4. Performance on GPU Supercomputer at NAOC

We report results obtained with our parallel direct N-body code on the CAS GPU clusters at our Institute (NAOC/CAS) and at the IPE/CAS. The NAOC cluster Lachy (龙) is running with 85 nodes, each with 4x NVIDIA Tesla C1060 GPUs. The PE cluster Mole-3.5 is running with 372 nodes, each with 4x NVIDIA Fermi C2050 GPUs.

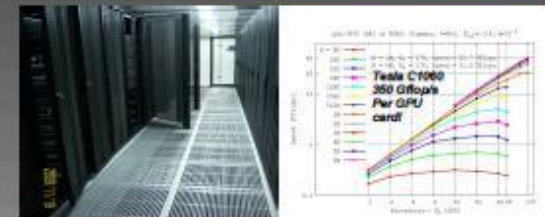


Figure 3 Left: NAOC GPU Cluster Lachy (170 Tesla C1060); Right: Sustained Speed in TeraFlops of astrophysical N-body Simulation for different particle numbers, as a function of number of GPU multiprocessors used. Near ideal speed-up is reached for large N, approaching the diagonal.

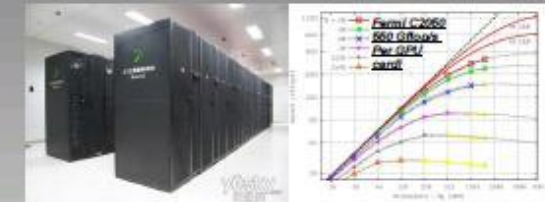


Figure 4 Left: 2 PetaFlop GPU cluster of the Institute of Process Engineering in Beijing (IPE/CAS) featuring 2000 Fermi C2050 GPU accelerator boards (Mole-3.5); Right: Measured sustained peak performance of our code on Mole-3.5, using up to 1600 C2050 Fermi GPUs in one run in parallel (up to 360 TeraFlop sustained total performance); gray lines: our performance model fitted to the measurements; top solid red lines: expected speed on Tianhe-1 supercomputer from our performance model using up to 7000 C2050 Fermi GPUs, expected to break the 1 PetaFlop barrier for sustained code speed.

ACKNOWLEDGMENTS: Chinese Academy of Sciences has supported this work by a Young Professional for Senior International Scientists, Grant Number 2009-1-4 (P.S.), and National Astronomical Observatory of China (NAOC) of CAS by the Silk Road Project (P.S. and R.S.). We thank the Institute of Process Engineering of Chinese Academy of Sciences for generous provision of computing time on their 100k-S GPU cluster, and especially Prof. Dr. Wu and Dr. Wang. Thanks for constructive help and support. The special supercomputer Lachy (龙) at the High Performance Computing Center at National Astronomical Observatories of China, funded by Ministry of Science under the grant ZDZ2009-5, has been used. Simulations were also performed on the GRAPE supercomputer (grants No. 04-044) and 01 361 of the Volkswagen Foundation and 031213-4/04-06 and 04 of the Ministry of Science, Research and the Arts of Baden-Württemberg, Germany.

Recoiling SMBH

The hierarchical galaxy formation model in Λ CDM cosmology predicts that supermassive black holes (SMBHs) in merging galaxies can produce SMBH binaries. Recoiling SMBHs are the production of anisotropic gravitational wave (GW) emission during the coalescence of SMBH binaries. That recoil velocity can achieve to several thousands km/s for some cases, which means the recoiling SMBH can escape from the host galaxy or simply oscillate around the galactic center. Thus the interactions between recoiling SMBH and stellar background can give us many observational evidences. One of them is for recoiling SMBH tidally disrupting stars. A star getting close to a SMBH within tidal radius r_t will be tidally disrupted, followed by a tidal flare (TD) which can be easily observed.

We focus on the dynamical co-evolution between recoiling SMBH and stellar background, especially the evolution of tidal disruption rate on recoiling SMBH. Since there are many complicated processes in such kind of systems, which bring troubles for analytical calculation, we need do series of direct N -body numerical simulations.

Simulation Method

Limited by hardware capability, it is impossible to modeling a galaxy with 10^1 stars in N -body simulation. We instead use 1M particles to represent the whole galaxy. By extrapolating particle number to real galactic condition, we can achieve convincing results. Here we adopt a special high-accuracy, parallel direct N -body code with high order Hermite integration scheme and hierarchical block time steps (Harfst et al. 2007).



To obtain higher performance, the code has been developed to φ -GPU version, which can be accelerated by GPU devices when computing gravitational forces between particles. By using the NAOC cluster (with a picture below, which has 85 nodes and two Tesla C1060 GPUs/node), we are the first one investigate the evolution of recoiling SMBH with TD scheme in direct N -body simulation.

Galaxy Model

We use 1M particles to represent the whole galaxy with stellar distribution followed Dehnen Model (Dehnen, 1993). Since the particle number N we adopted here is far more less than the real condition in galactic center, we set both N and r_1 as free parameters. The results with these varying parameters can be extrapolated to physical conclusions with real galactic conditions.

The SMBH is initially put in galactic center, and then added a recoil velocity. To follow the co-evolution between SMBH and surrounding stars, we integrate whole system using our φ -GPU code with a simplified TD scheme included.

Results

Dynamical Evolution

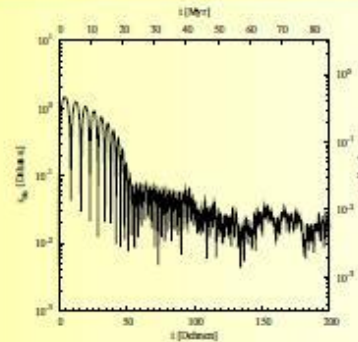
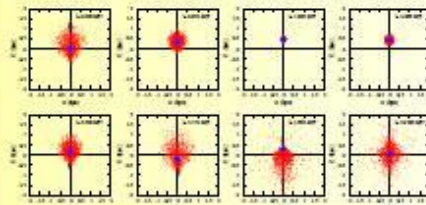


Figure above gives the time evolution of recoiling SMBH trajectory. r_{gal} is the distance from recoiling SMBH to galactic center. The evolution can be easily divided into phase I and phase II, which are similar to the results in Gualandris & Merritt (2008) without TD scheme. That means the TD do not impact the dynamical evolution of recoiling SMBH.

Compact Star Cluster

Our calculation show that there are only few particles bound to recoiling SMBH, which corresponding to $\sim 0.1\% - 1\% M_{\text{HBH}}$. This result confirms the prediction of hypercompact stellar system (HCSS) around escaping SMBH by Merritt et al. (2009). Besides, we also find that the oscillating SMBH can capture stars when it pass through galactic center, which may increase the HCSS.



Furthermore, we find that an oscillating SMBH can influence more stars than HCSS. The figure above shows the co-evolution of an oscillating SMBH and those impacted stars. We make several time snapshot to trace the evolution of those stars which are strongly influenced by the recoiling SMBH when the latter arrives at its first apocenter ($t \approx 1.863$ Myr). Blue circle marks the position of recoiling SMBH and black arrow gives the velocity vector of it. Those influenced stars, mostly unbound to SMBH, form a polarization cloud with mass comparable to the SMBH. That is a vivid example for the influence of dynamical friction.

Tidal Disruption

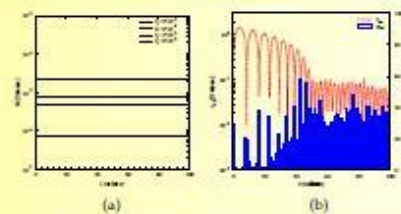
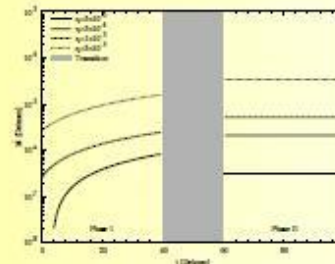
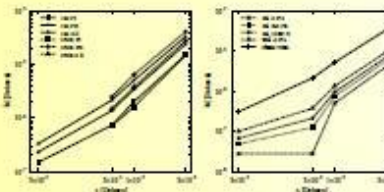


FIG (a) gives TD rates for SMBH without recoil within different r_t . All of TD rates seems keep constant. The extrapolation gives TD rate $\sim 10^{-5} M_{\odot} \text{ yr}^{-1}$ in real galaxy condition. FIG (b) gives TD events evolution for recoiling SMBH. The red dotted line is the SMBH trajectory, and blue boxes represent the TD events count. Most of stellar TDs are happened when the oscillating SMBH passing through galactic center, which means TD events are dominated by unbound stars instead of bound stars.



This figure gives the averaged TD rates for recoiling SMBH with different TD radius in our simulation unit. Left and right side are corresponding to phase I and II respectively. The increasing TD rates in phase I is because of the oscillation of recoiling SMBH.



The left panel shows the dependence of average TD rates on r_1 and N , for phase I, II and entire process. Right panel shows TD rate - r_1 dependence for several special snapshot during the evolution of recoiling SMBH. The figure above shows that there is a good correlation between TD rates and r_1 , and the N do not strongly impacts the results. The extrapolated TD rate in phase I is $\sim 10^{-6} M_{\odot} \text{ yr}^{-1}$ or $10^{-7} - 10^{-8} M_{\odot} \text{ yr}^{-1}$ corresponding to the galactic center or off-center region respectively.

Conclusion

- The TD scheme does not significantly change the dynamical evolution of recoiling SMBH.
- The recoiling SMBH do not only keep a hypercompact bound stellar system but also impact unbound stars to form a polarization massive stellar cloud, which can be seen as an echo of dynamical friction.
- The TD rate of oscillating SMBH is $\sim 10^{-6} M_{\odot} \text{ yr}^{-1}$ or $10^{-7} - 10^{-8} M_{\odot} \text{ yr}^{-1}$, which depends on whether the oscillating SMBH is passing through galactic center or apart from it with a large distance.
- The use of GPU acceleration enhanced the performance of our simulations dramatically (Spurzem et al. 2011).

Future Plan

- Investigate the observational properties of polarization cloud.
- Consider the influences of stellar evolution.
- Consider the evolution of tidal disruption rates for SMBHB.

Acknowledgement

This work was supported by the Chinese national 973 program, the National Natural Science Foundation of China, the Research Fund for the Doctoral Program of Higher Education, the China Scholarship Council, Silk Road Project and Global Networks and Mobility Program of the University of Heidelberg. The special supercomputer Luchu at the High Performance Computing Center at National Astronomical Observatories of China, funded by Ministry of Finance under the grant ZDYZ2008-2, has been used.

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(Astro)-physical GPU Supercomputing in China...

- Galaxies and Black Holes
- Gravitational Waves
- Cluster Hardware
- Applications and Performance
- **Future**

Astrophysical SPH Simulations with raceSPH Library

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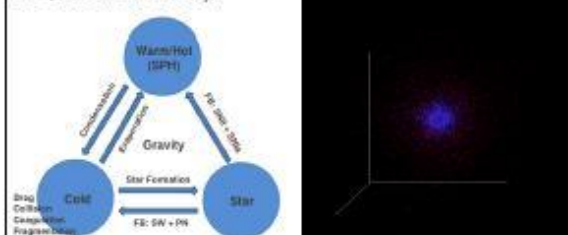
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1. SPH simulations in Astrophysics

There is no doubt that gravitation plays the most important role in the study of astrophysical simulation, however, in many cases we are more concerned with the behavior of gas, such as the study of galaxy formation. Gravity in this case only provides the necessary potential profile that pulls the gas in the center and prevents them from escaping. Smoothed Particle Hydrodynamics (SPH) is often used for the modeling of gas in astrophysical hydrodynamical simulation. One reason is its ability to deal with huge density contrast in the universe by means of interaction forces between neighbouring particles, without the need for any grid or mesh that defines the resolution of the system at any particular moment. Therefore, the gas behavior can be well described by the SPH formulations.

2. SPH Based Galaxy Formation Model

We (Lei Liu et al.) newly developed a multi-phase chemodynamic SPH galaxy formation model, which will be used for the simulation of dwarf galaxy. In this model, various physical processes are implemented based on an N-body/SPH program, such as various star formation recipes, condensation and evaporation between hot gas and cold cloud, coagulation and fragmentation of cold cloud, gas cooling, stellar feedback and so on. SPH method are used to describe the behavior of hot gas ($10^4\text{K} \sim 10^7\text{K}$) (Berczik et al. 2003, Spurzem et al. 2004, Pasetto et al. 2010).



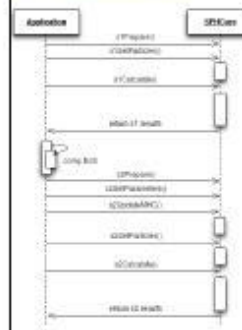
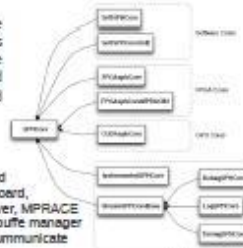
For SPH calculation, interactions between target particle and its neighbors are calculated one by one. When gravity computation is accelerated by special hardware (GRAPE, GPU), which becomes more and more popular in recent years, SPH calculation will become the most time consuming part. We use raceSPH library (Guillermo et al.) to accelerate this part by using different hardware resources (CPU, SSE, GPU, FPGA based MPRACE board)

3. The raceSPH Library

The raceSPH library focuses on the acceleration of SPH calculation accelerators used range from vectorizing units on the microprocessors (SSE instruction) to Field Programmable Gate Arrays (FPGAs) and Graphics Processing Units (GPUs).



FPGA based MPRACE board, use PCI driver, MPRACE library and buffer manager library to communicate



This library is mainly developed by Guillermo Marcus from Institute of Computer Engineering (ZITI) of Heidelberg University. It implements a generic interface to compute 2-step SPH process, such that the hardware accelerators can be easily integrated into existing astrophysical applications.

In step 1, particle position, velocity, mass, smoothing length, sound speed and neighbour lists of target particles are loaded. After calculation, density, divergence and curl of velocity for this particles are returned. Applications need to calculate pressure and Balsara factor themselves since the equation of state varies greatly from one application to another.

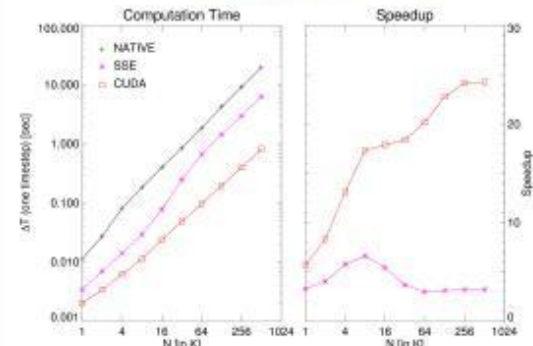
In step 2, density, pressure and force are loaded, final results are returned after calculation, including acceleration and internal energy change rate.

4. Hardware

The benchmark is mainly carried out on the GPU cluster Titan of Astronomisches Rechen-Institut (ARI), which is part of the Centre for Astronomy of Heidelberg University (ZAH). The cluster consists of 32 dual CPU, single core Xeon 3.2GHz (family 14, model 4, 1MB cache) nodes, with each node featuring an NVIDIA GeForce 8800 GTS 512 graphics card (128 cores, 1.8GHz) and 4GB memory. Nodes are interconnected with 20 Gbit Infiniband links. We use 4 of the 32 nodes for the benchmark of raceSPH library of different hardware accelerators.

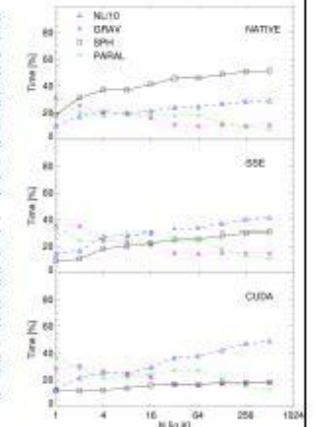


5. Benchmark Result



We present our benchmark results of an astrophysical run for a dwarf galaxy of 4×10^5 solar mass with Burkert profile (Burkert 1995). We will mainly focus on the time consumption of the most time consuming parts of the code, namely gravity, SPH calculation and neighbour lists construction. Other physical processes will be switched off since they are not related with SPH calculation directly.

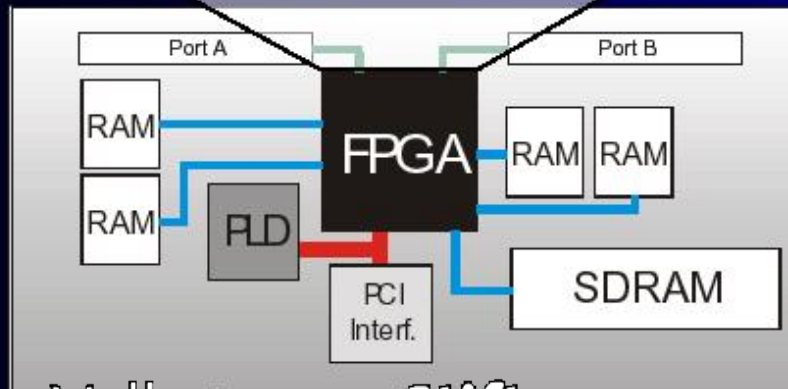
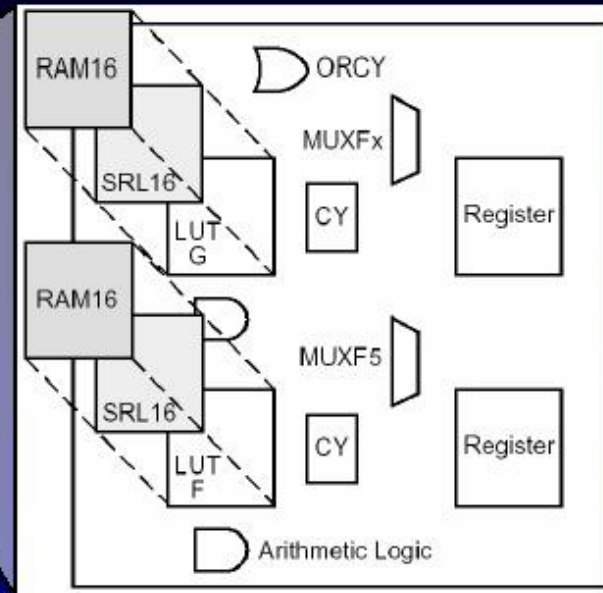
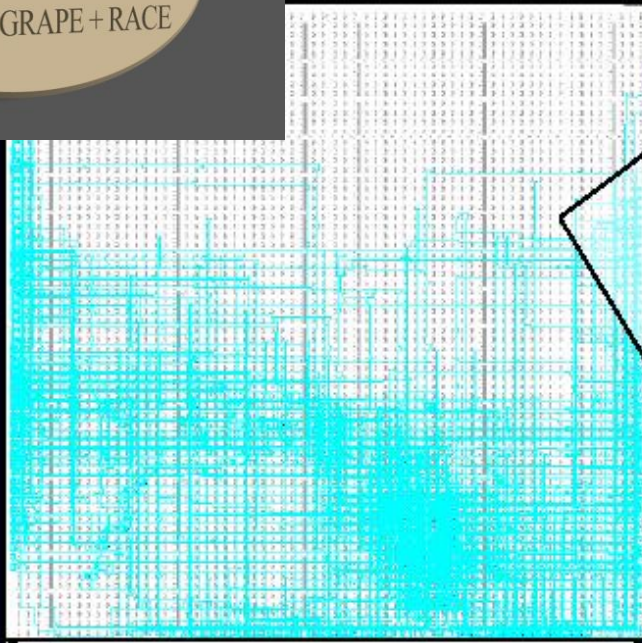
A maximum speedup of 24x is achieved in the single node run with the raceSPH using the GPU (CUDA core). As is shown on the right figure, after gravity computation is accelerated by GPU on 4 nodes of Titan in the parallel run, SPH calculation consumes most of the time. When SPH calculation is also accelerated by SSE and GPU core of raceSPH library, neighbour search becomes the bottleneck, even if it has been averaged over 10 steps. In the 512K particles case, if both gravity and SPH are calculated on GPU, almost half of the time is spent on neighbour list construction. Therefore our next step work is to speedup this part, such as use construct the neighbour lists parallel on GPU (currently we ANN library on one CPU for each node).



FPGA-Plattform MPRACE

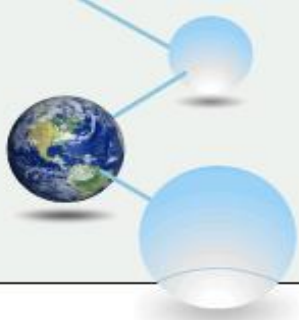
GRACE

GRACE = GRAPE + RACE



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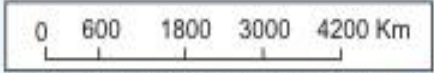
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On the path to Exascale?

Black: existing GPU clusters in our network

Red: clusters in construction or planned



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- (II) Take part in individual collaborations, community building by bridging the disciplines, contribute to database of benchmarks and tools, workshops, publications
- * (III) Take part in Technical Working Groups

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Future Work – with collaborators...

- How does SMBH (-binary) interact with interstellar central gas disk? Circum-binary, individual, exchange of torques between 0.1 and 10^{-3} pc? (L. Mayer, U. Zürich, CH)

Stellar Dynamical Shrinking Time Scale

Viscous Timescale of Disk (Thin/Thick)

Migration of Black Holes / Star Formation in Disk

Spin-Orbit Interaction (A. Gopakumar, Tata IFR, Mumbai)
(L. Rezzolla, P. Amaro-Seoane, AEI)

Spin Alignment BH-Disk Bardeen-Petterson Effect

Spin Alignment due to Star Accretion by Tidal Disruption

Relativistic Spin-Orbit- and Spin-Spin-Interaction

