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

Manycore Supercomputing (GPU) in China and Germany - Dynamics of Black Holes in Galactic Nuclei

Rainer Spurzem

National Astronomical Observatories (NAOC), Chinese Academy of Sciences

Kavli Institute for Astronomy and Astrophysics (KIAA), Peking University

3 Astronomisches Rechen-Inst., ZAH, Univ. of Heidelberg, Germany

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

NVIDIA

World Leader in Visual Computing Technologies

VolkswagenStiftung

Manycore Computing in China and Germany
Dynamics of Galactic Nuclei with Black Holes

@ NAOC Beijing and Univ. of Peking & Heidelberg:
Peter Berczik, Ingo Berentzen, Jose Fiestas, Justus Schneider, ...
Jonathan Downing, Christoph Olczak… (ARI-ZAH)
LIU Fukun, LI Shuo, ZHONG Shiyan, ... (Dep. Of Astronomy, PKU & NAOC)
Reinhard Männer, Andreas Kugel, Guillermo Marcus (ZITI-CE)

@ICCS: H. Shukla, J. Shalf, H. Simon

Further Important collaborators:
K. Nitadori, T. Hamada (Japan), S. Aarseth (UK)
G. Schäfer (U Jena, Germany), A. Gopakumar (TIFR Mumbai, India)
B. Schutz, P. Amaro-Seoane (LISA Germany, MPIG-Albert-Einstein-Inst.)

@ other CAS Institutes
LIN Weipeng (Shanghai Astron. Obs. SHAO)
GE Wei, WANG Xiaowei, CHEN Feiguo (Inst. For Process Engineering), ...
LIU Runqiu, CAO Zhoujian (Academy of Mathematics and Systems Sciences,Numerical Relativity Group)

Manycore Computing in China and Germany
Dynamics of Galactic Nuclei with Black Holes

- Manycore (GPU) Research at
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- GRACE-2 Project
- ICCS and Green Grid
- Parallel Direct N-Body Codes with MPI and CUDA
- Galactic Nuclei, Black Holes, Gravitational Waves

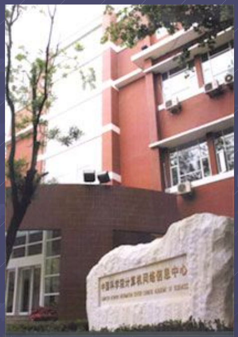
Chinese Academy of Sciences
— a comprehensive R&D system in China

Institute: ~100

Staff members: ~50,000

Graduated Students: ~35,000

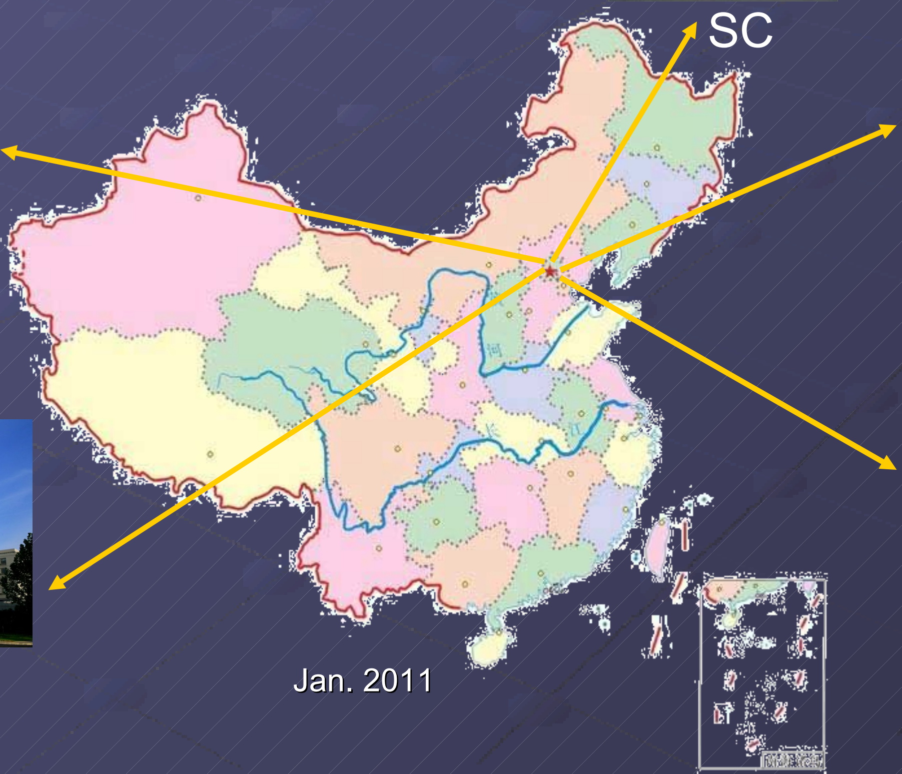
R&D revenue: ~10B RMB (1.5B USD)



SC

CAS HQ

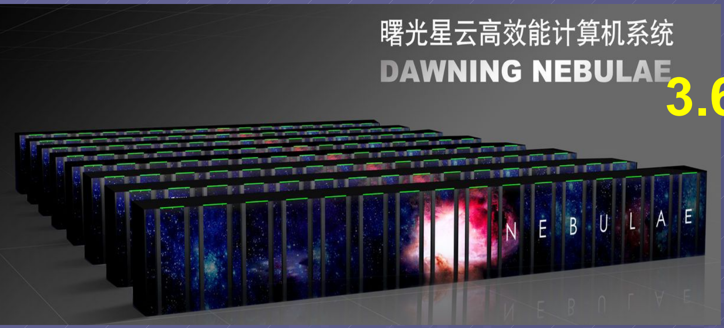
IPE



IS

NAOC

Slide by GE Wei



No. 1, Top500

3.6Pflops Linpack

5 Cities 10 Institutes
Each 100~200Tflops SP

Distributed System Collective capacity：

4.907Pflops SP

1.300Plops DP

3 GPU SC in Top500 from China (Pos. 1,3,28)

2010
Mole-8.5
1Pflops DP

No. 19, Top500, 2010.6
207Tflops Linpack

2009
Mole-8.7
1Pflops SP

2008
Mole-9.7
100Tflops SP

Jan. 2011

Application defines the value of SC systems

Slide by GE Wei

Towards Peta-Scale Green Computation

— applications of the GPU supercomputers in CAS

Wei Ge
Xiaowei Wang
Inst. of Proc. Eng.

Yunquan Zhang
Inst. of Software

Rainer Spurzem
Nat. Astro. Obs. Chn.

Long Wang
SC Center

ICCS Berkeley Jan. 2011

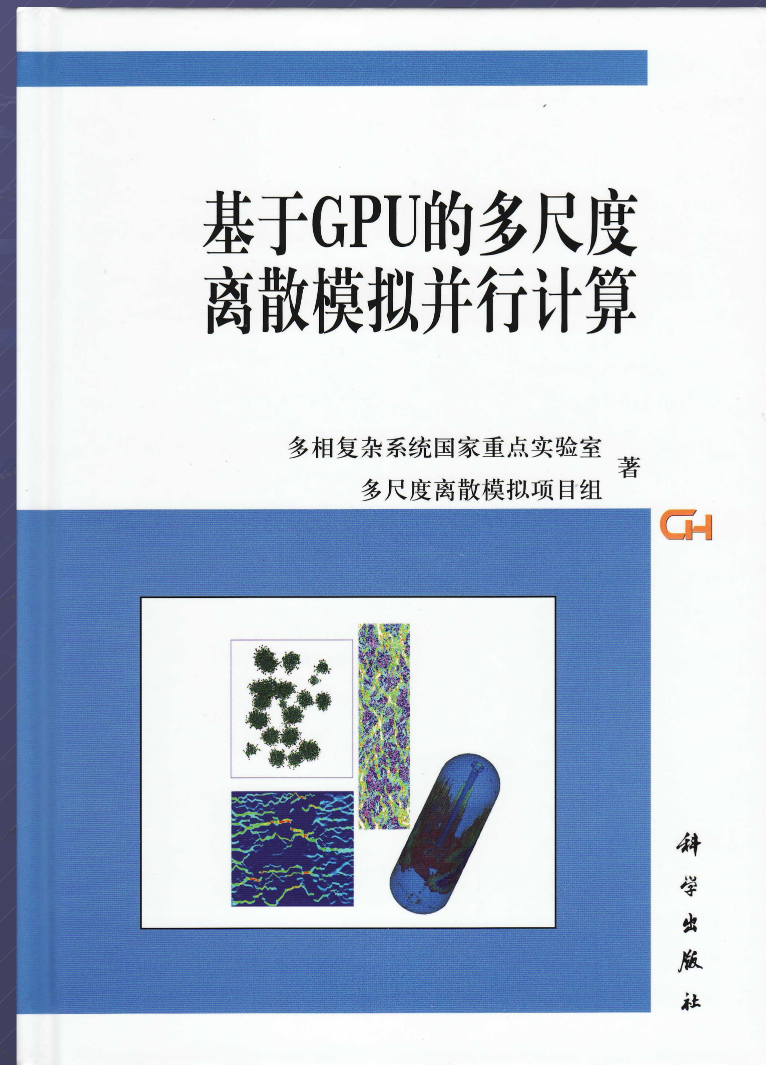
中国科学院过程工程研究所

Institute Of Process Engineering, Chinese Academy Of Sciences

The booming GPUs in China mainland

2 of 8 CCOEs worldwide:

IPE, CAS & Tsinghua Univ.

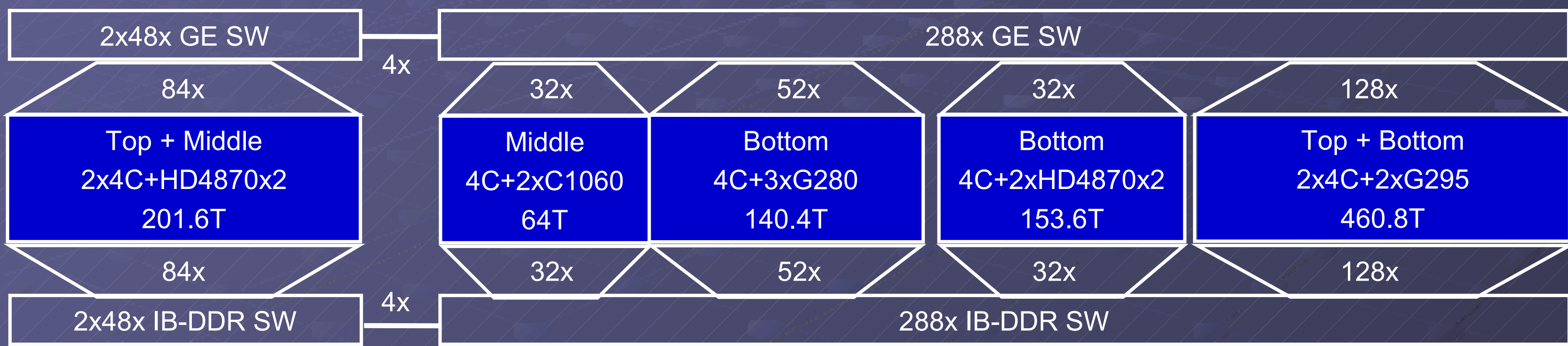


Monographs on CUDA:

IPE, CAS 2000 sold

Slide by GE Wei

China's first HPC system with 1.0 Petaflops peak performance in single precision (2009.03.19)



200T(IPE/Dawning)

200T(IPE/Lenovo)

150T(IPE)

450T(IPE)

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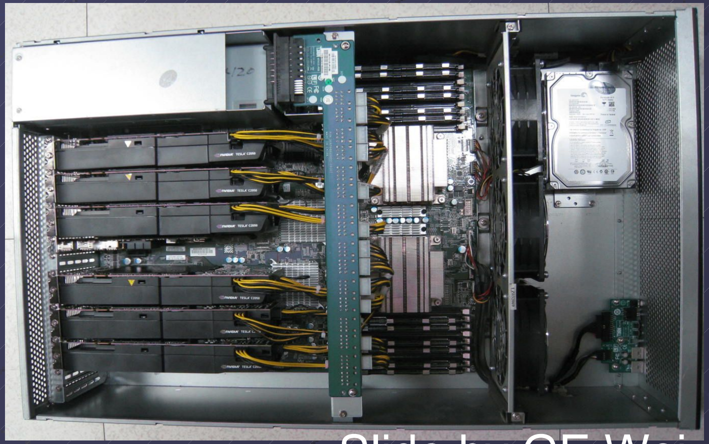
Mole-8.7 (<300kW)

Fermi-based GPU supercomputer IPE (2010.04.24)

Rpeak SP：	2Pflops
Rpeak DP：	1Pflops
Linpack:	207.3T (Top500 19th)
Mflops/Watt:	431 (Green500 8th)
Total RAM：	17.2TB
Total VRAM：	6.6TB
Total HD：	360TB
Inst. Comm.：	H3C GE
Data Comm.：	Mellanox QDR IB
Occupied area：	150 sq.m.
Weight：	12.6 tons
Max Power：	600kW(computing) 200kW(cooling)
System：	CentOS 5.4, PBS
Monitor：	Ganglia, GPU monitor
Languages：	C, C++, CUDA 3.1 , OpenCL

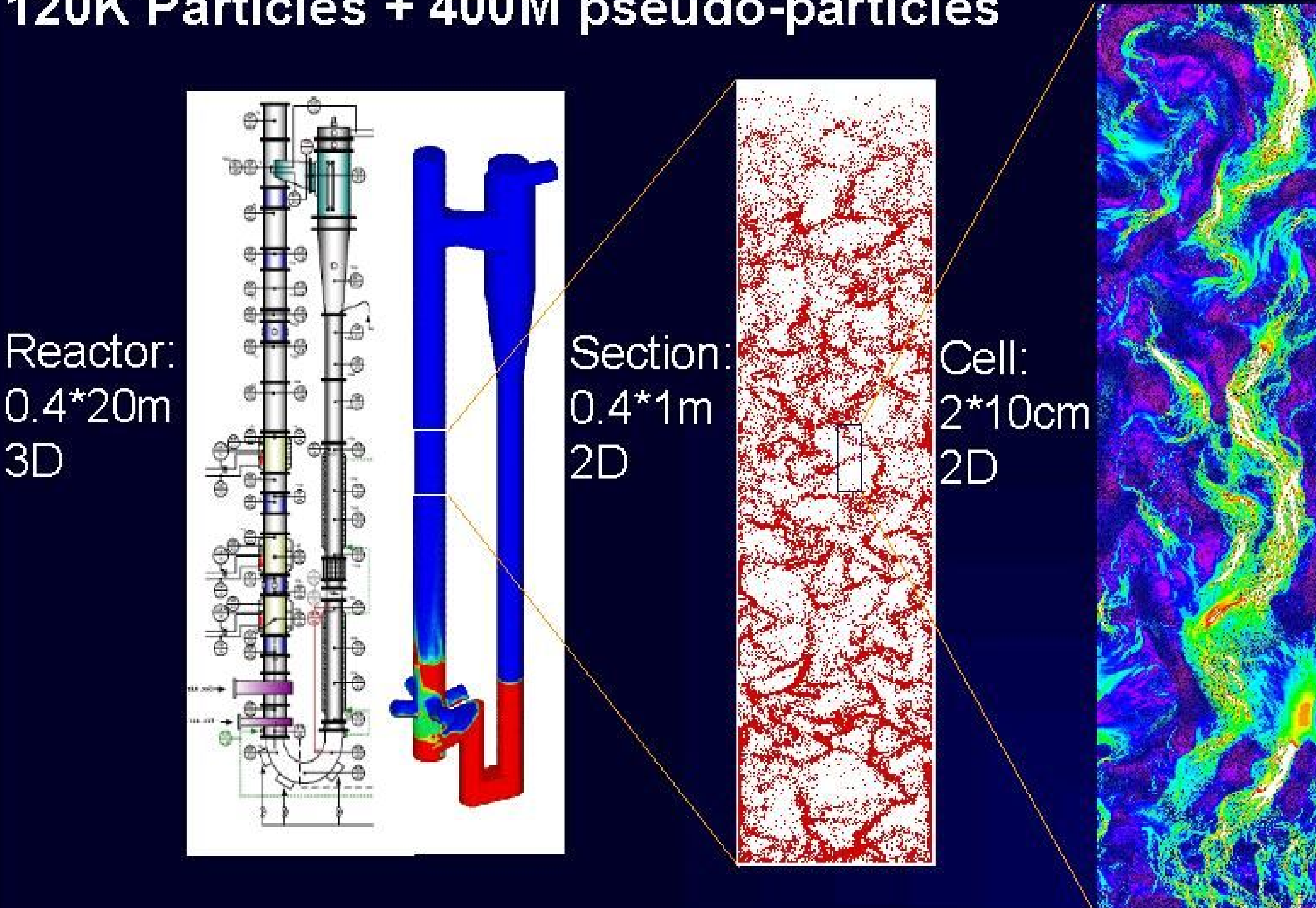


中国科学院过程工程研究所
Institute Of Process Engineering, Chinese Academy Of Sciences

Slide by GE Wei

DNS of gas-solid flow : >20x speedup (1C1060/1E5430 core)

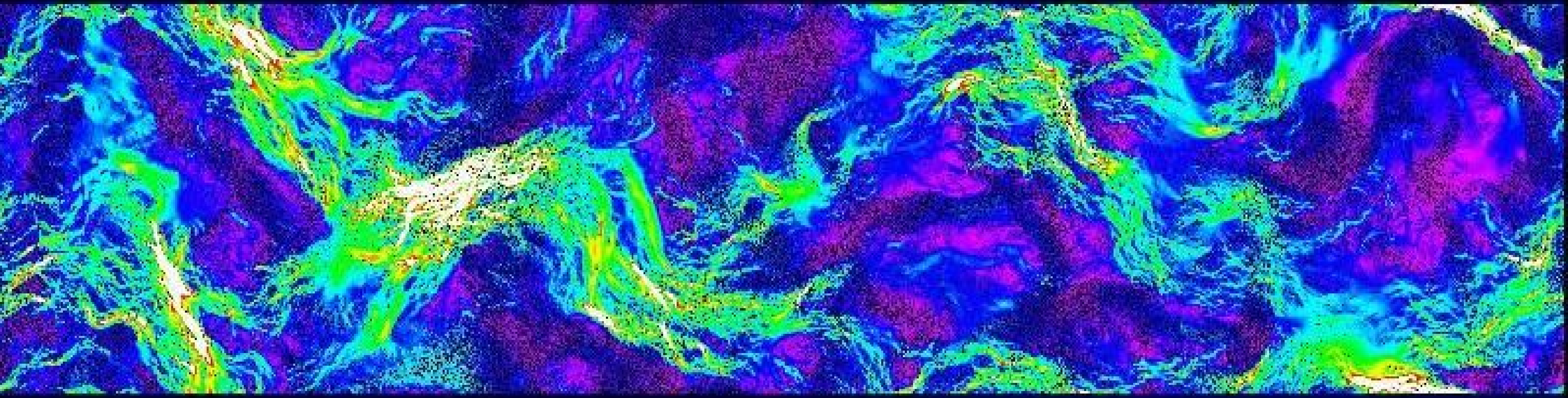
120K Particles + 400M pseudo-particles



Animation Challenge:

9600x2400 → 1200x300 pixels

1000 → 17 frames



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ICCS Growth

LBNL Projects

ISAAC
Astrophysics

FPGA Hybrid-core
Geophysics, Bio-informatics, Astrophysics

Smart Grid
Energy Efficiency

Cloud Modeling
Climate science

ALS Software HUB
Advanced Light Source

International Projects

GRACE II
Astrophysics

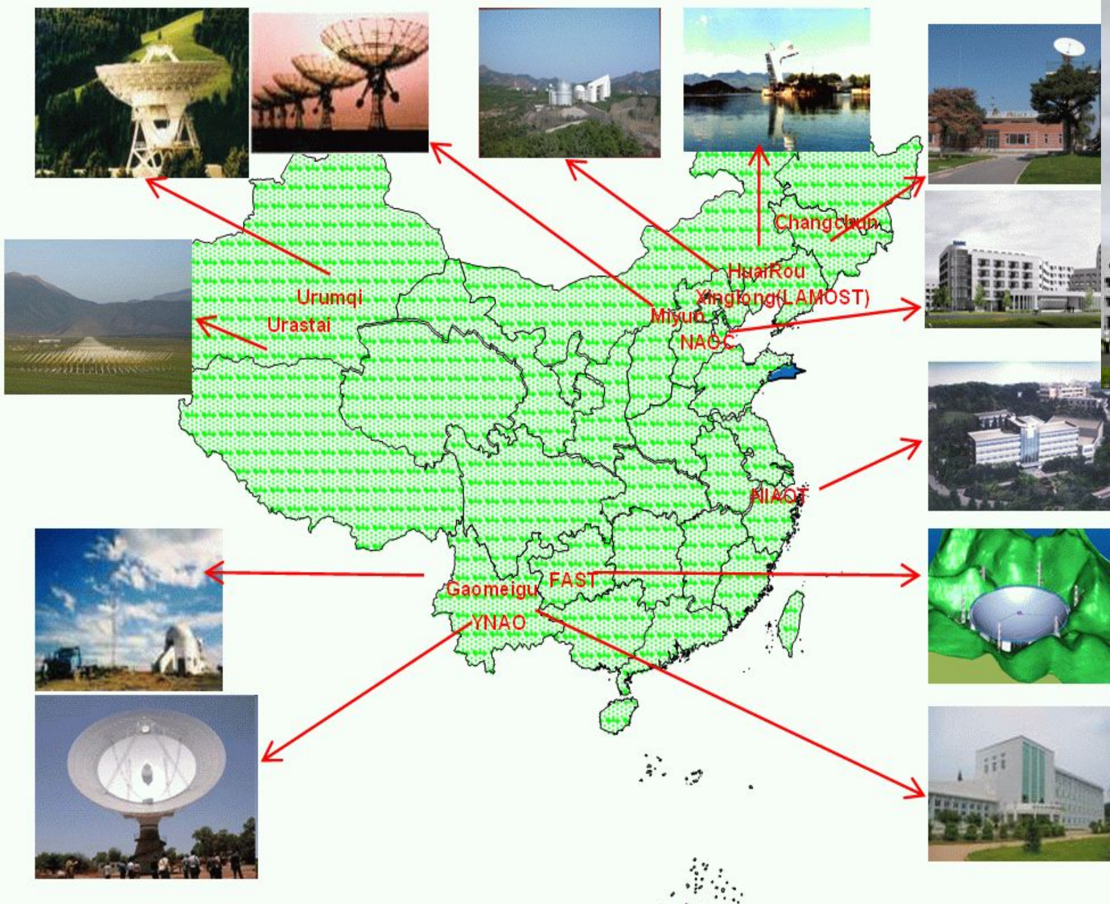
SILK ROAD
Astrophysics

Slide: Hemant Shukla

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

北京大学
PEKING UNIVERSITY

Chinese Academy of Sciences &
Peking University form
Beijing Astrophysical Centre (BAC)

Top and Right: (Nov. 11, 2009)
Kavli Institute for Astronomy and Astrophysics.
Bottom: Dept. of Astronomy at Peking Univ.

Jan. 2011

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

http://silkroad.bao.ac.cn

New Instrument @ NAOC: GPU Supercomputer...

Core Teams @ NAOC: R. Spurzem, P. Berczik, ...

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

hARDWARE

GPU Clusters used in Silk Road Project:

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

86x8 Cores, 170 Tesla C1060

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

Univ. Heidelberg, Germany

titan: 32 GeForce GPU + 10 FPGA,

kolob: 40 Tesla C860 GPU

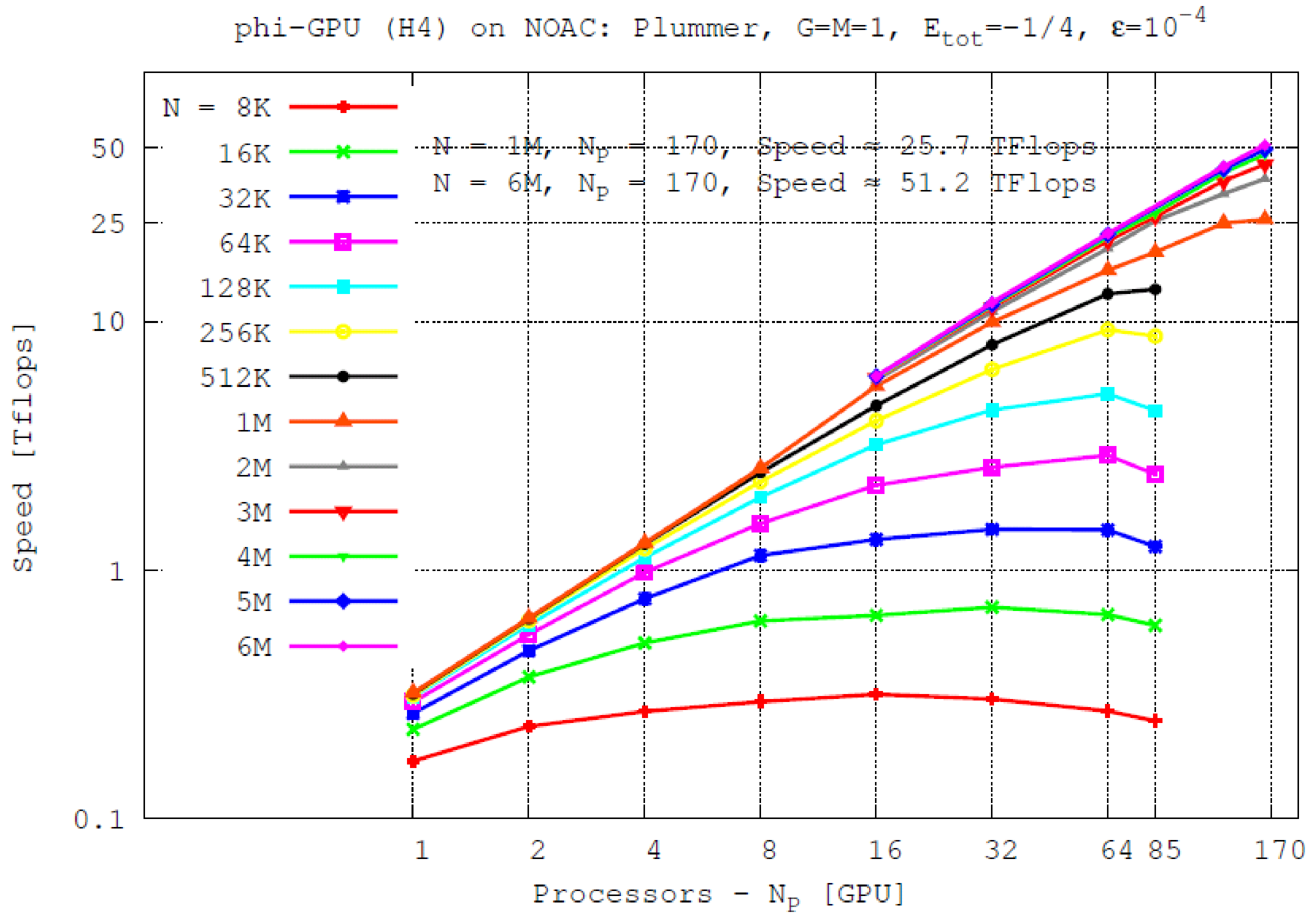
soon: new cluster 100 Fermi GPU

Titan (right)

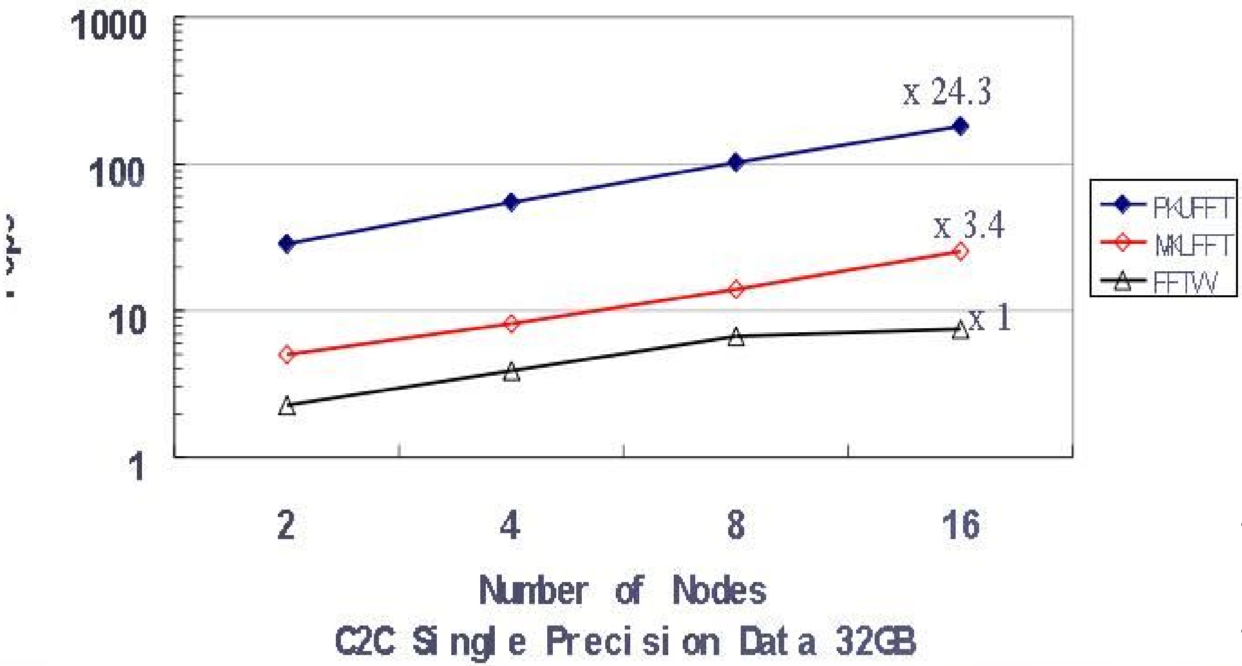
Kiev, Ukraine (left)

ΦGPU - NBODY

Result on NAOC cluster, 170 GPUs, N = 6 mill., 51.2 Tflop/s

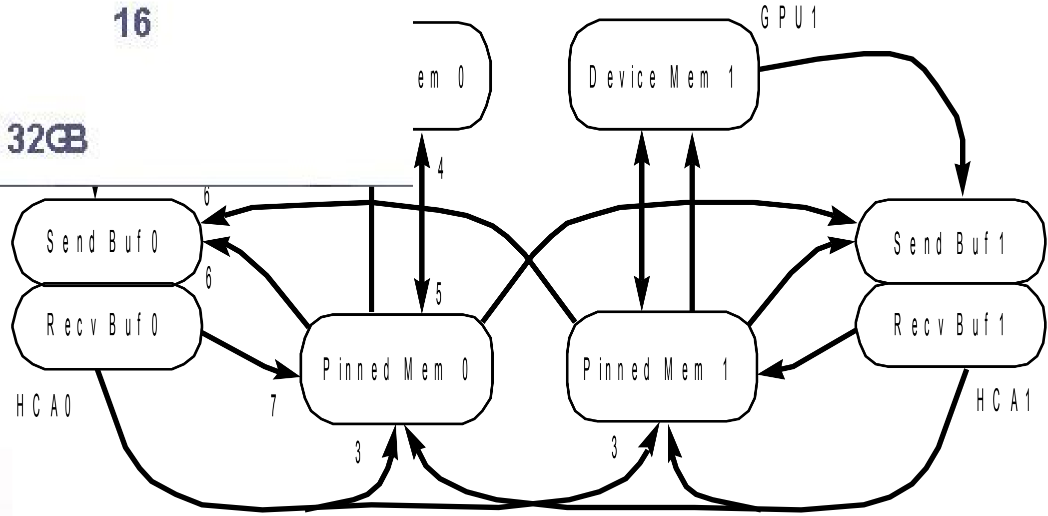


Speedup of Fast Fourier Transform



FFT

On GPU Clusters



Y. Chen, X. Cui and H. Mei.
Large-scale FFT on GPU clusters. 24th International Conference on Supercomputing (ICS'10), ACM 2010.

Y. Chen and J. W. Sanders,
Logic of global synchrony, ACM Transactions on Programming Languages and Systems, Vol.26, No.2, pp.221-262, 2004.

北京大學 PEKING UNIVERSITY

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

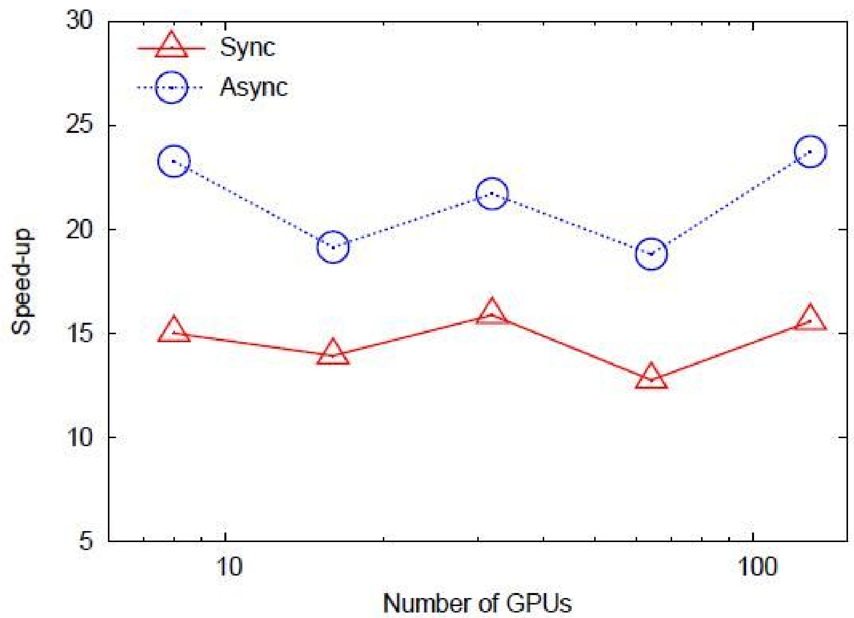


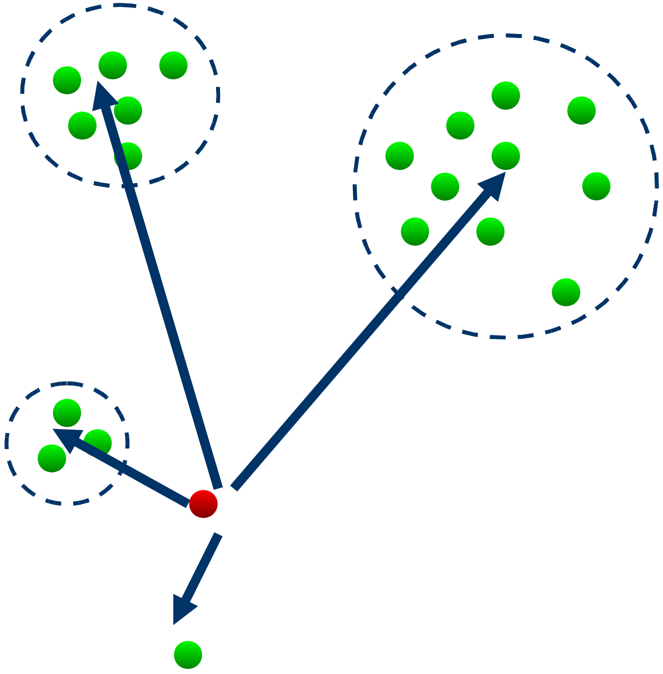
Fig. 1.— Performance speed-up as a function of the number of GPUs/CPUs. For each data point, we compare the performance by using the same number of GPUs and CPU cores. The blue circles and red triangles show the timing results with and without the concurrent execution between CPUs and GPUs, respectively.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

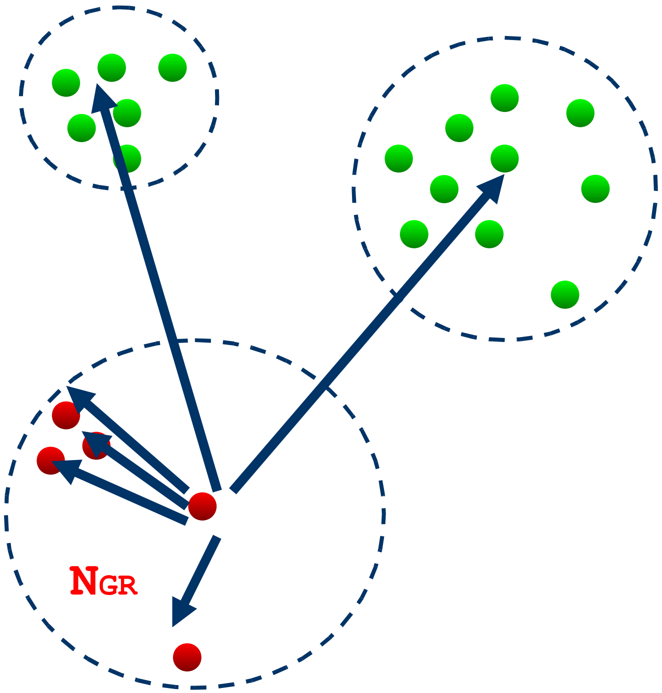
Some simulation details:

(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

Parallel TREE GPU gravity

Jun Makino (pC++): TREE+GRAPE/GPU code





Makino, PASJ, 43, 621 (1991)

Inter. list on host ~N
Inter. list length -> short…

Makino, PASJ, 56, 521 (2004)
Fukushige, Makino & Kawai, PASJ, 57, 1009 (2005)
One interaction list is shared among
NGR particles!
Inter. list on host ~N/NGR
Inter. list length -> larger…

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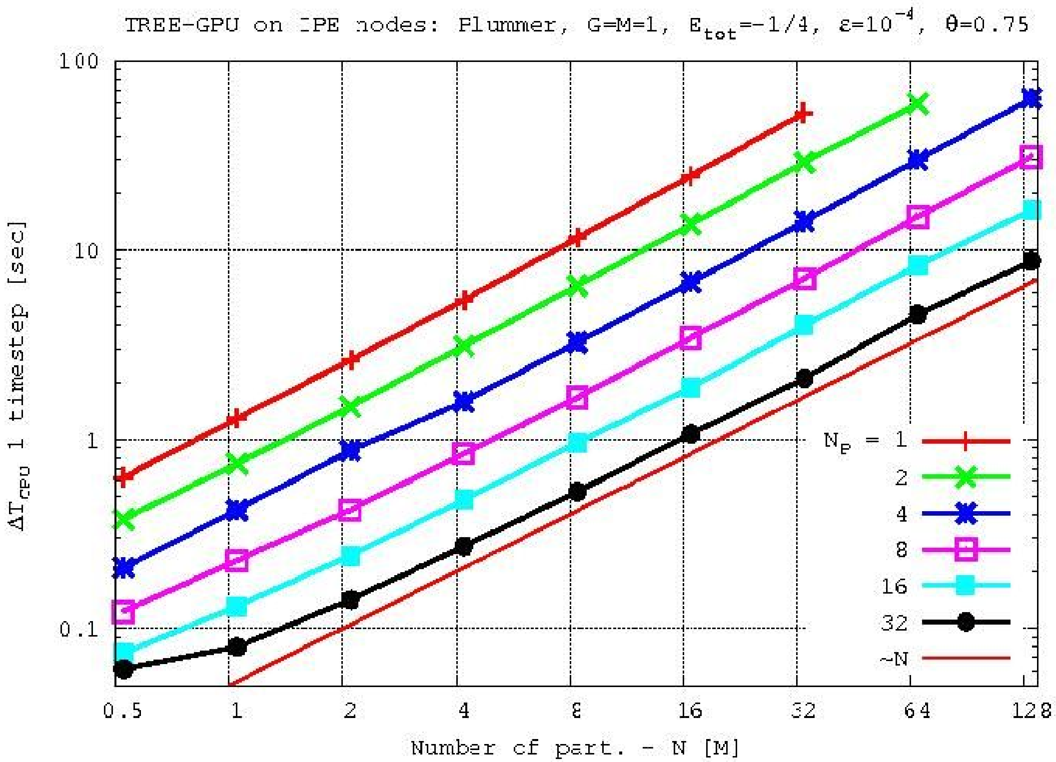
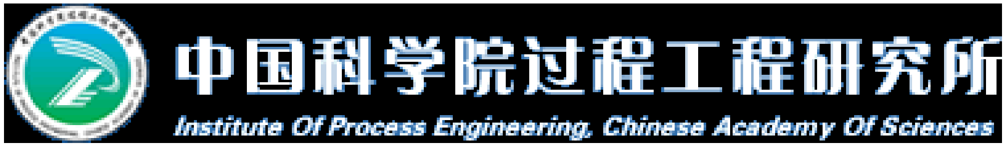
TREE-GPU - NBODY

2010 – China, Beijing, IPE (CAS) Lenovo cluster testing,
P. Berczik, T. Hamada, K. Nitadori. R. Spurzem in prep.
(rewritten Makino-GRAPE code)



<u>**Near ideal scaling!**</u>



the SILK ROAD PROJECT at NAOC/KIAA
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Green Supercomputing...

... is application driven:

- Star Cluster Dynamics *(KIAA/NAOC, with Sverre Aarseth,...)*
- Binary Black Holes, Galactic Centres, Gravitational Waves *(NAOC, KIAA/PKU, UHD, APHI: Rainer Spurzem, Peter Berczik, Fukun Liu Chingis Omarov, Emmanuil Vilkoviski, ...)*
- Galaxy Formation and Evolution *(SHAO: Lin Weipeng, Vienna, G. Hensler)*
- *Adaptive Mesh Hydrodynamics (Star Formation, Galactic Nuclei, ...)*
- Data Processing, Instrument Development, e.g. LOFAR, Tsinghua/LIGO, ICRAR...
- 21 cm Radio Astronomy Signal and Data Processing (Chen Xuelei, NAOC)
- Numerical Relativity (Acad. of Maths. and Systems Sciences/CAS & AEI Potsdam)
- Molecular Dynamics / Chemical Processes *(IPE/CAS)*

Invitation to interested teams to join ICCS!

Benchmarks on different hardwares!

Send message R. Spurzem / spurzem@bao.ac.cn

Or Hemant Shukla hshukla@lbl.gov

中国科学院国家天文台
National Astronomical Observatories, CAS

Jan. 2011

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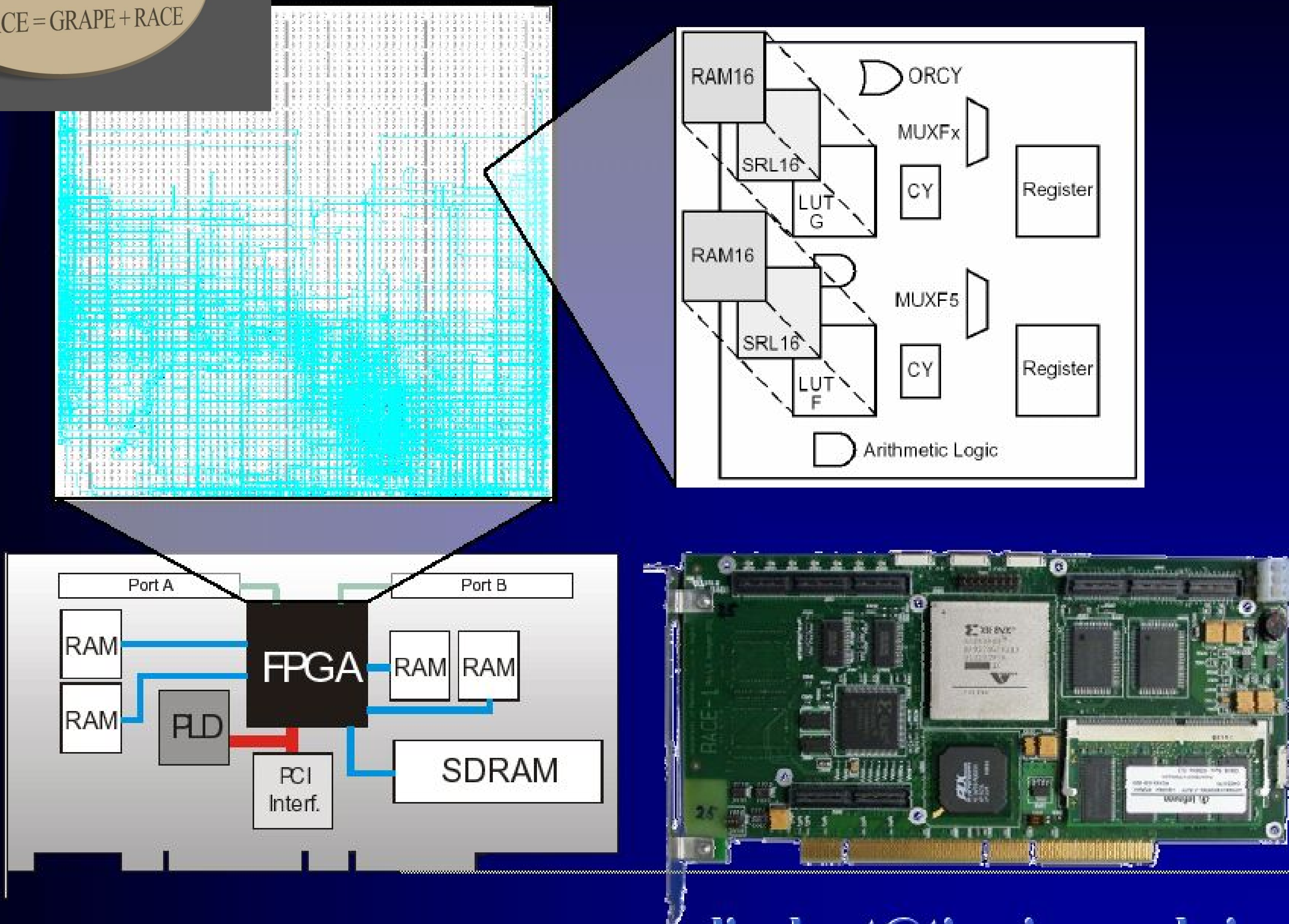
GRACE

GRACE = GRAPE + RACE

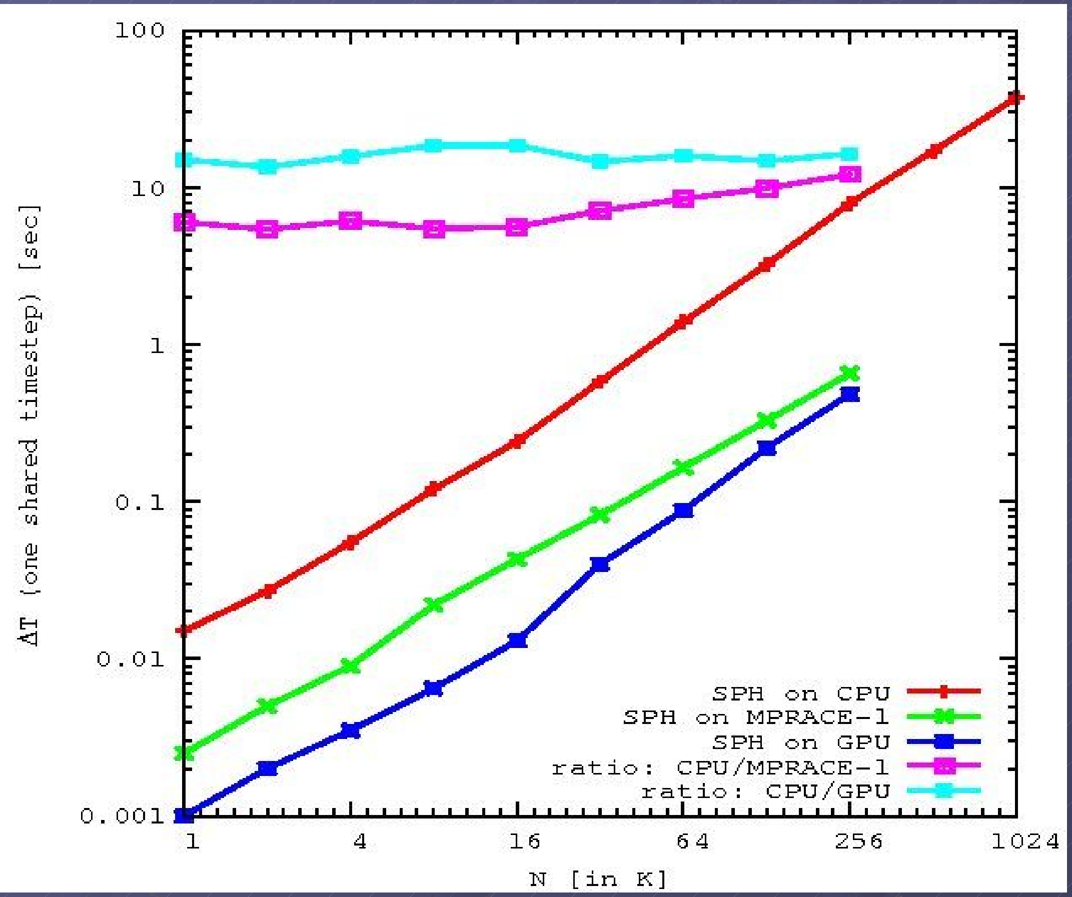
FPGA-Plattform MPRACE



lienhart@ti.uni-mannheim.de

FPGA...

Versus GPU for SPH:



GeForce 8800 GTX (NVIDIA)
Using CUDA Library
Special Interfaces and API from GRACE project ported.

Spurzem et al. 2007,
Jl.Phys.Conf.Ser.
Berczik et al. 2008,
Marcus et al. 2008
(SPHERIC)
Spurzem et al. 2009
(ISC 09 Procs., Springer)

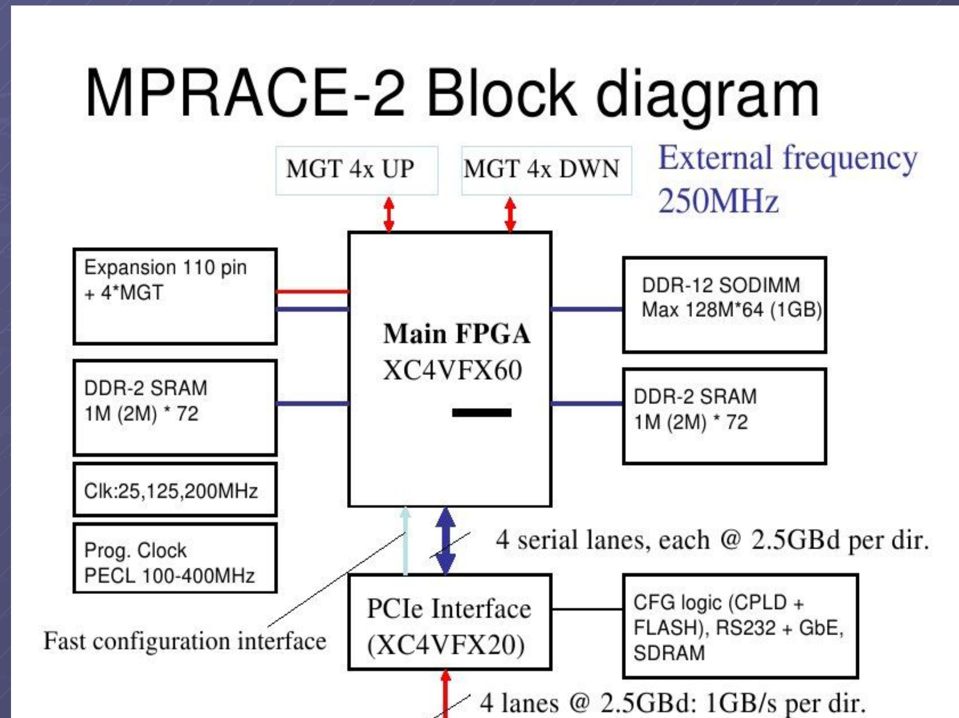
GRACE

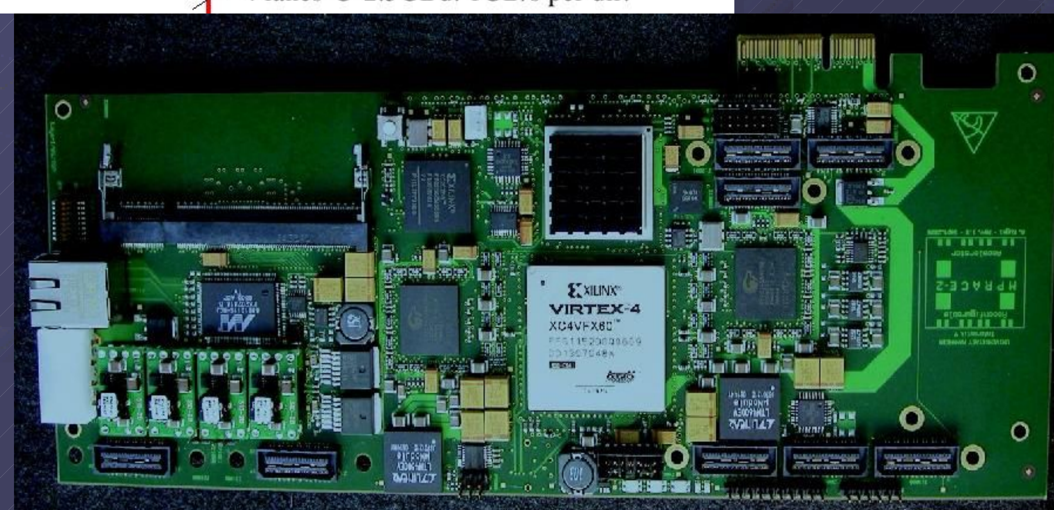
GRACE = GRAPE + RACE

FPGA...

Computer Engineering
R. Männer
G. Marcus
A. Kugel

Univ. Heidelberg
(Mannheim)





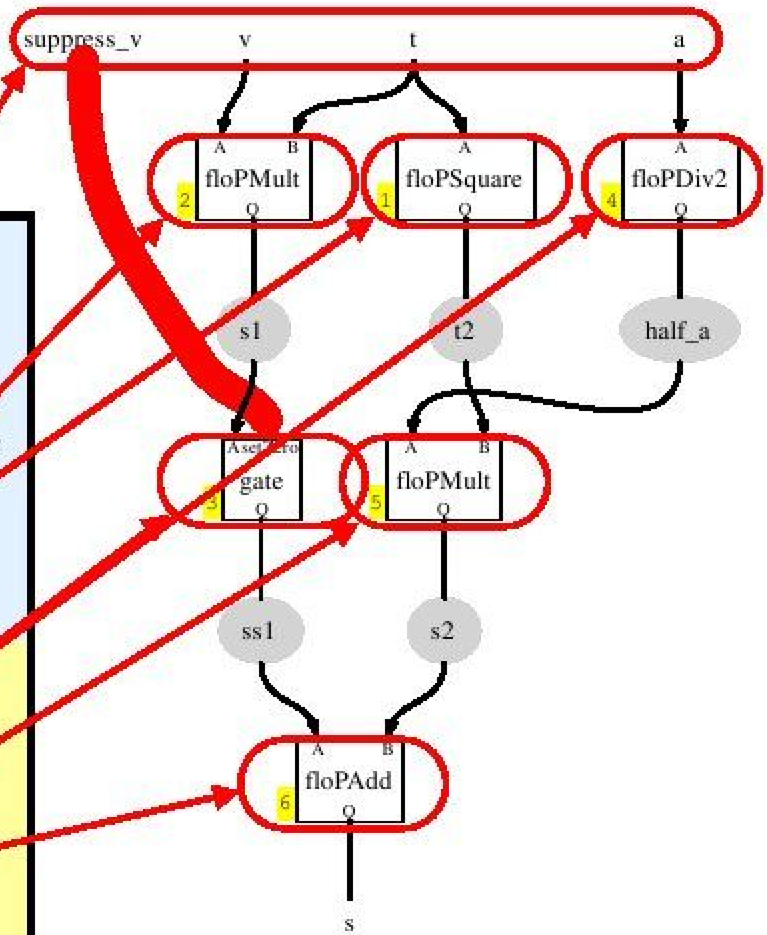
ICCS Berkeley

FPGA...

Pipeline Generation

$$s = \begin{cases} \frac{1}{2} a\, t^2 + v\, t & : \quad \text{suppress\_v} = 0 \\ \frac{1}{2} a\, t^2 & : \quad \text{suppress\_v} = 1 \end{cases}$$

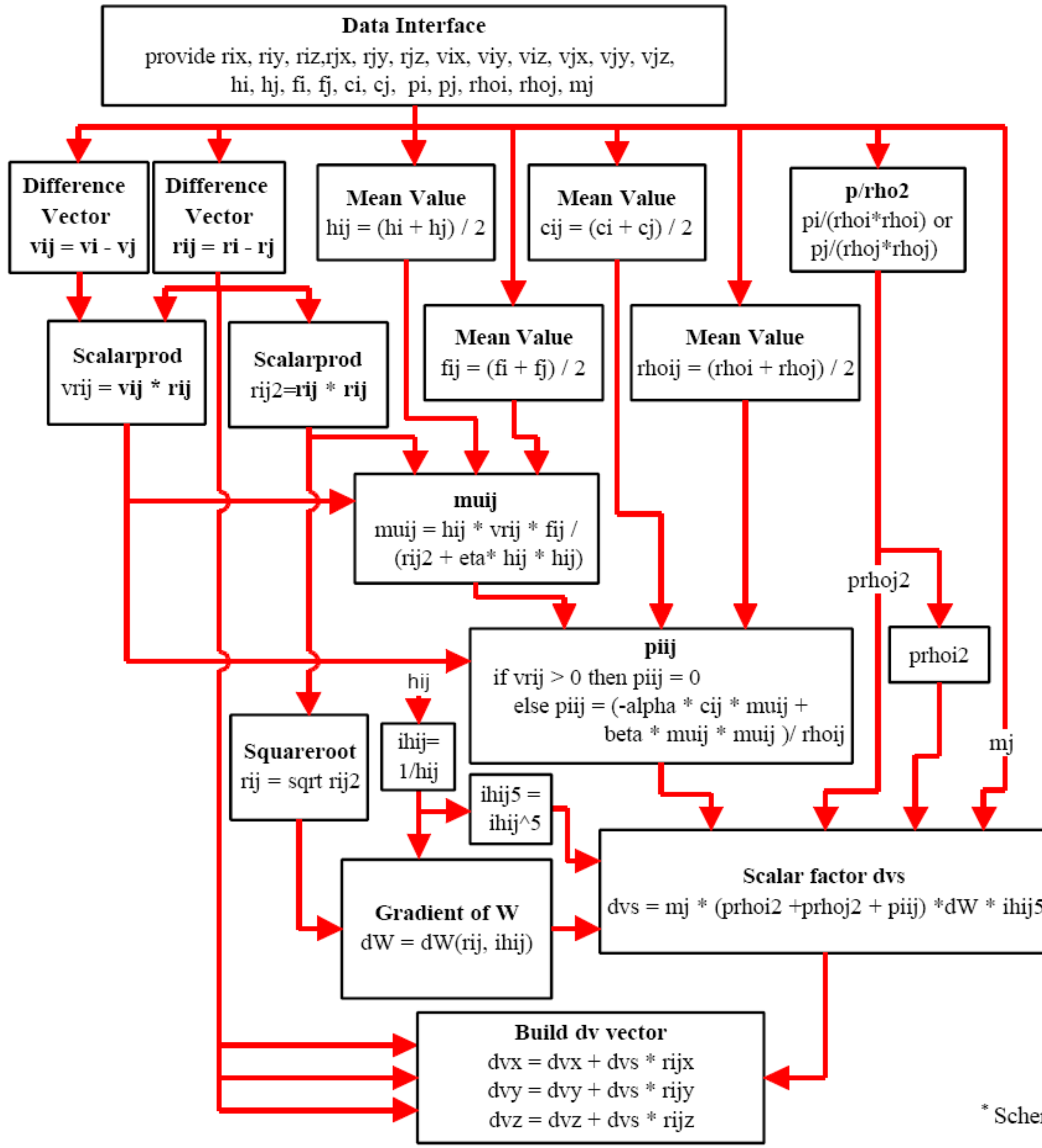
```
entity distance;
clock clk;

# parameters
floPValDef fpDef(signifLength=>24,
 expLength=>8,useSign=>1,useIsZero=>0);

# inputs
signal (suppress_v);
floPVal (v,a,t)(fpDef);

# calculate
t2 = <floPSquare> t;
s1 = v <floPMult> t;
ss1 = gated(s1,suppress_v);
half_a = <floPDiv2> a;
s2 = half_a <floPMult> t2;
s = ss1 <floPAdd> s2;
```



GRACE
GRACE = GRAPE + RACE

FPGA...

Pressure force pipeline:



* Scheme doesn't show energy term

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ICCS Vision

R&D of Scientific HPC Solutions

Deliver Science Driven Solutions in Hardware, Programming Models, Algorithms, Infrastructure

Enabling Scientific Growth

Simulations, Remote Location Real-time Feedback, Energy Efficiency

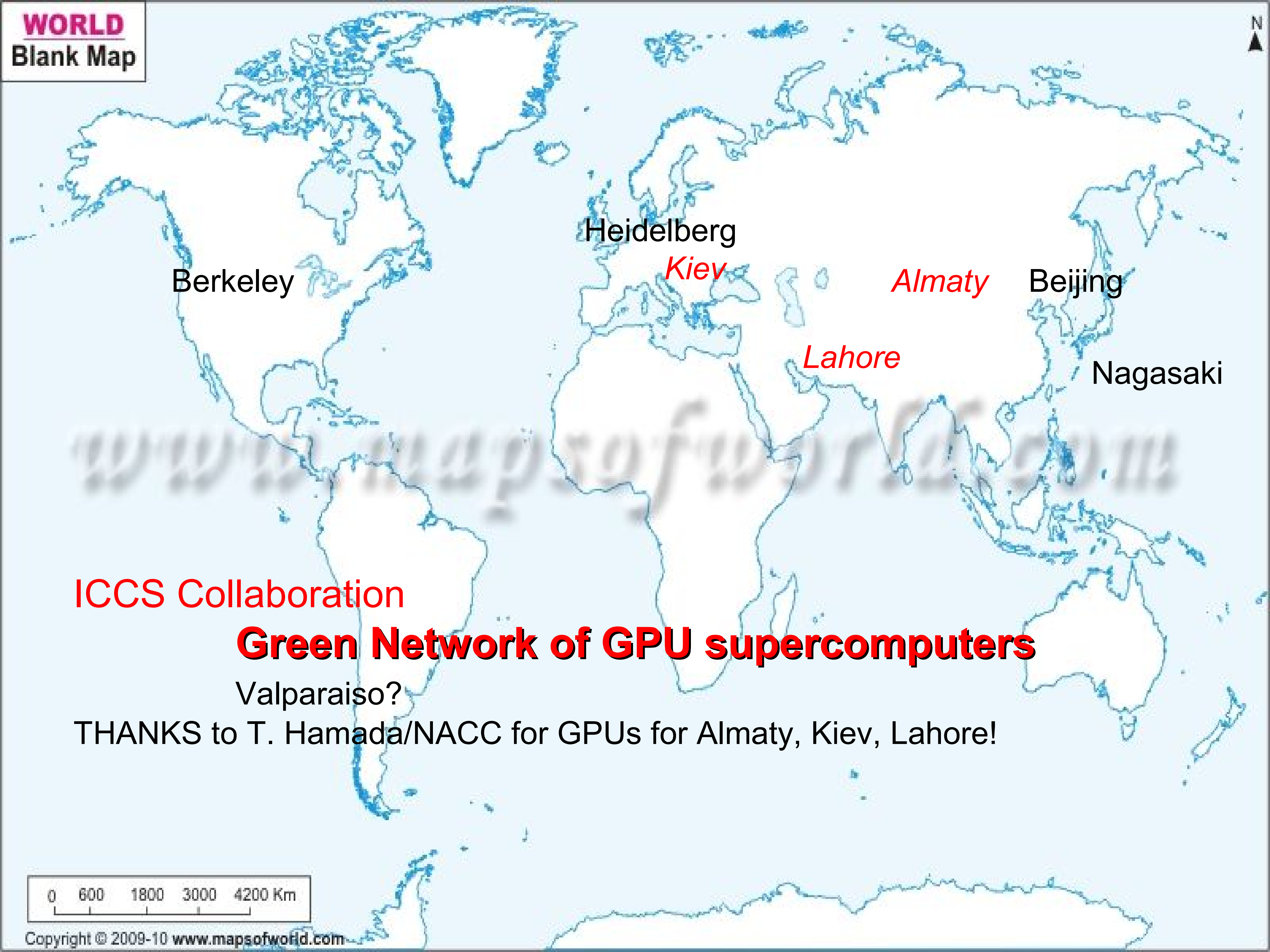
Building International Community

Multi-discipline Scientific Communities, Industry Leaders, International Partnerships

Education and Outreach

Curriculum, Training, Publications, Software/Hardware Dissemination, Workshops, Conferences

Slide: Hemant Shukla



ICCS Collaboration

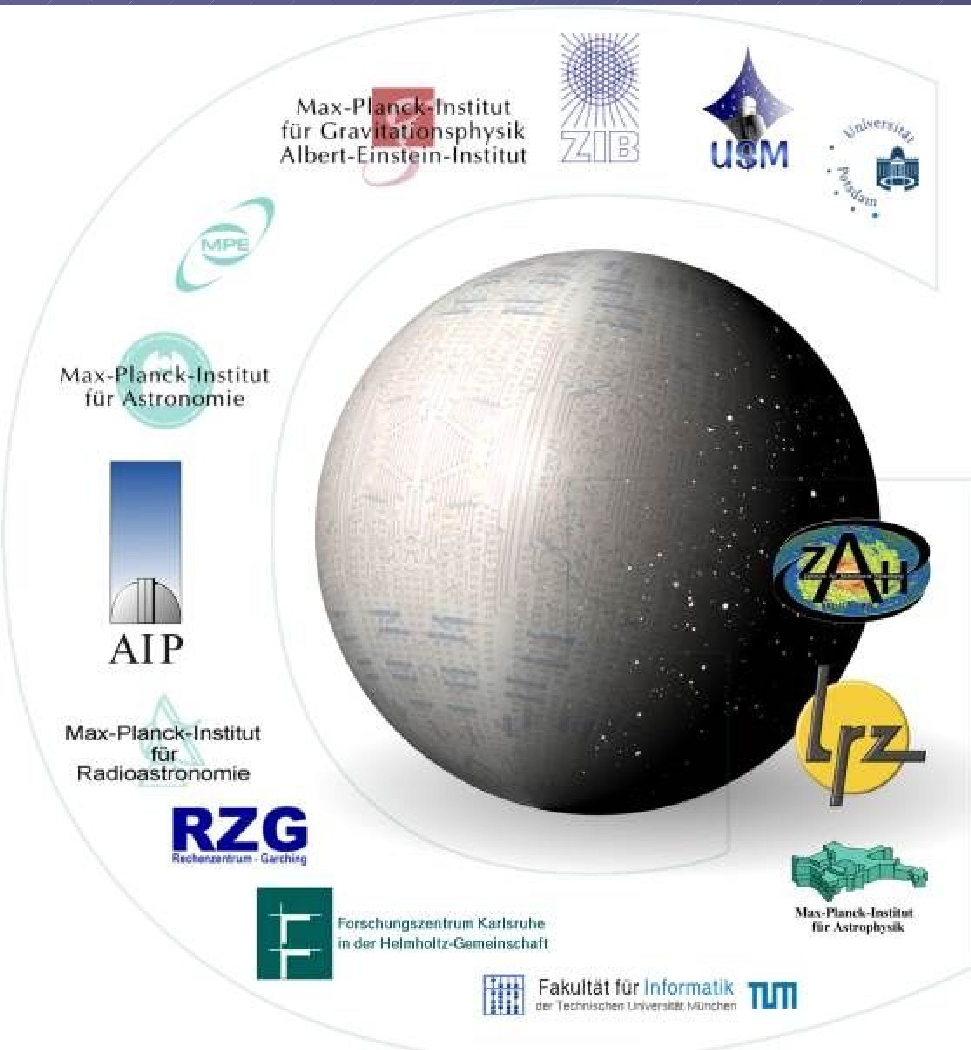
Green Network of GPU supercomputers

Valparaiso?

THANKS to T. Hamada/NACC for GPUs for Almaty, Kiev, Lahore!

Bundesministerium
für Bildung
und Forschung

Green Network



GACG =
German Astronomy
Community Grid

http://www.gac-grid.org

Including support for
large N-body, SPH, GRAPE
and other special
hardware jobs

technology supplied for new
grids:

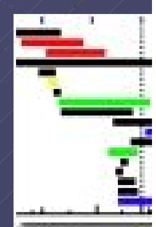
Green Network – Overview

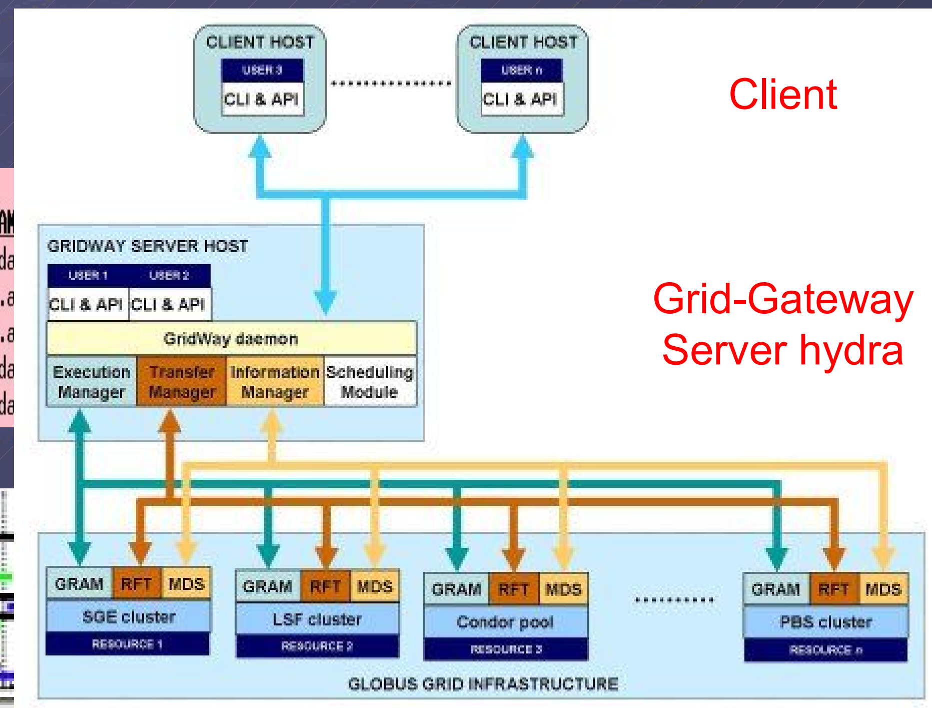
The Astrogrid-D currently offers: software to access the grid:

- Web Portal to access the grid for common applications
- Gridway / Grid-Gateway for classical job submission
- (Enke et al. 2010, New Astronomy)

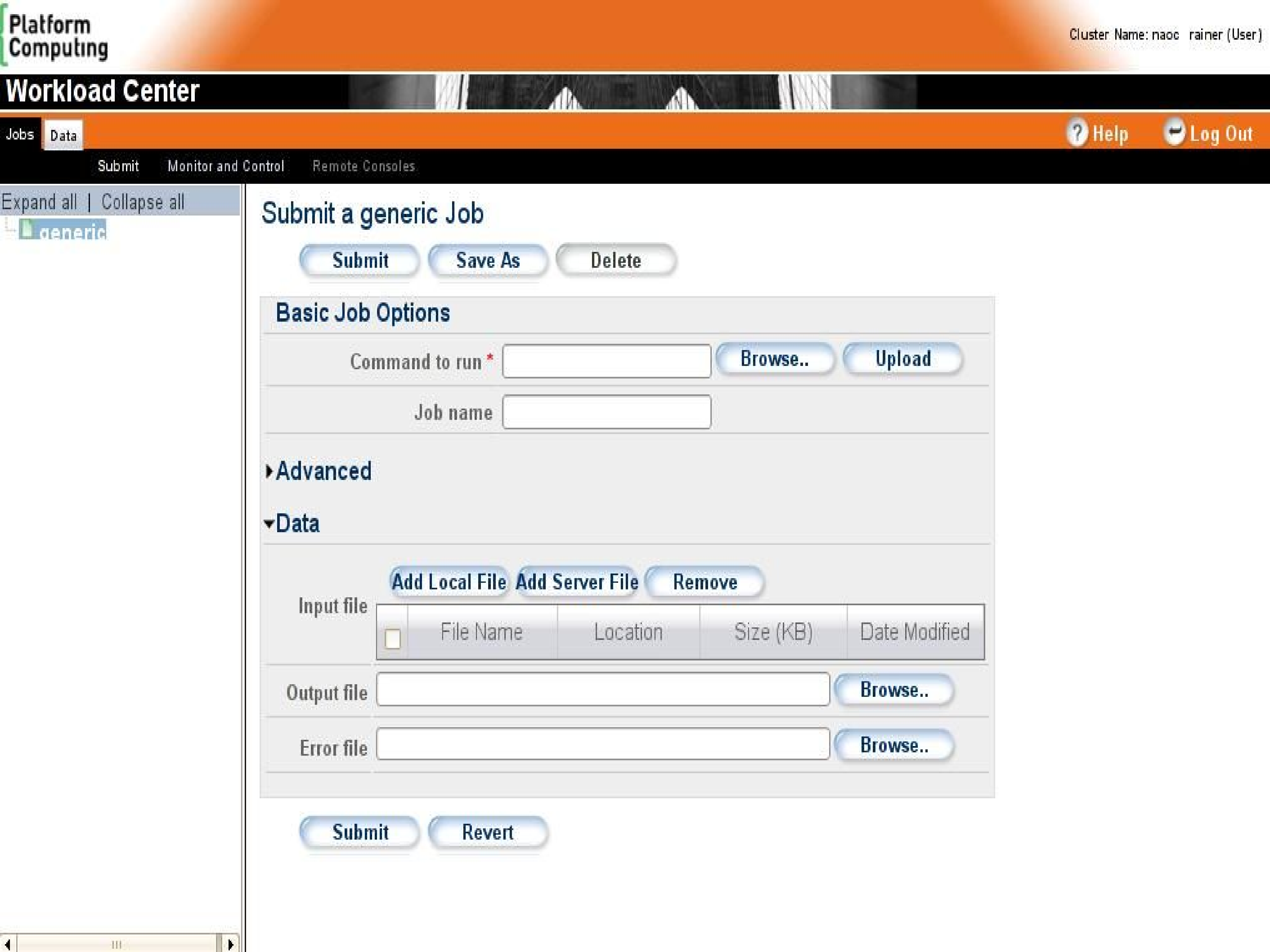
```
spurzem@hydra:~> gwhost
HID PRIO  OS              ARCH   MHZ %CPU  MEM(F/T)     DISK(F/T)      N(U/F/T) LRMS        HOSTNAM
0   1     Linux2.6.16.33- x86_6 2411  200 3076/7939 197805/220515    0/2/2 Fork        astroda
1   1     Linux2.6.11.4-2 x86_6 3200  300  866/3974   67177/79742    0/3/4 Fork        titan.a
2   1     Linux2.4.27-2-3 x86    996   99     6/502    7150/19366    0/1/2 Fork        buran.a
3   1     Linux2.6.9-42.0 x86_6 2411   98 1399/7970 289588/311777    0/1/2 Fork        astroda
4   1                              0    0       0/0           0/0    0/0/0             astroda
```

Stellaris





Information Systems Gridmap Grid Timeline Astrogrid-D Resources


Platform Computing
Cluster Name: naoc rainer (User)
Workload Center
Jobs
Data
Help
Log Out
Submit
Monitor and Control
Remote Consoles
Expand all | Collapse all
generic
Submit a generic Job
Submit
Save As
Delete
Basic Job Options
Command to run *
Browse..
Upload
Job name
Advanced
Data
Add Local File
Add Server File
Remove
Input file
File Name
Location
Size (KB)
Date Modified
Output file
Browse..
Error file
Browse..
Submit
Revert

ICCS Invitation

Building International Community

Invitation to join at different level:

See also H. Simon's talk today!

- (I) Provide hardware access and support for green network of GPU clusters (currently Berkeley dirac, Heidelberg titan, Beijing laohu, Nagasaki dejima invited)
- (II) Take part in individual collaborations, community building by bridging the disciplines, contribute to database of benchmarks and tools, workshops, publications

Education and Outreach

Invitation to 3rd ICCS School and Workshop

Beijing, Dec. 5-9 2011 or Jan. 9-13, 2012

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

Globular Cluster
47 Tucanae

Ground • AAT

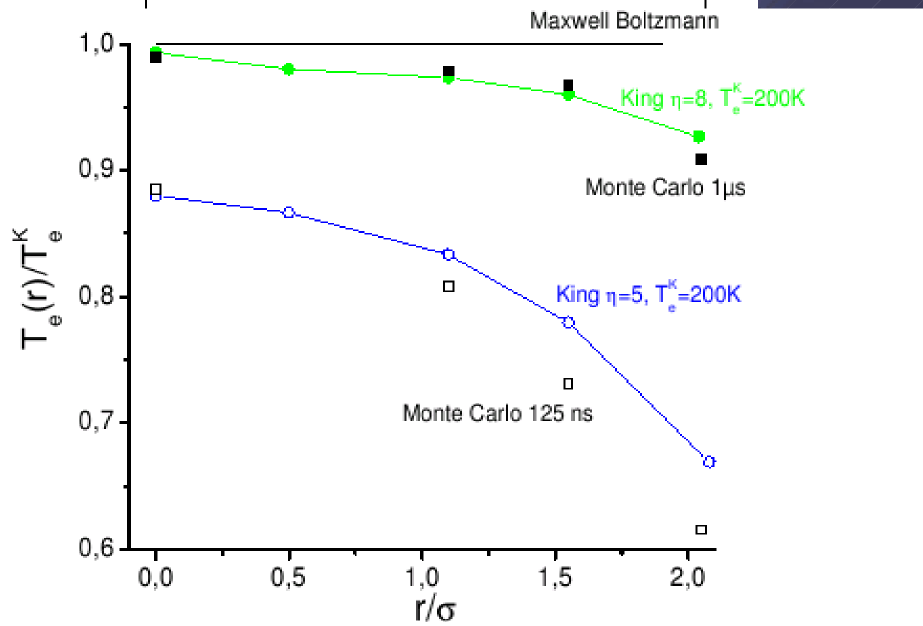
Hubble Space Telescope • WFPC2

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

Star Cluster Dynamics

	Star Cluster	Ultracold Plasma
Number of particles	$5 \cdot 10^5$	10^6
Peak Density	$10^6 M_\odot pc^{-3}$	$10^{10} cm^{-3}$
Size/Core Radius r	1 pc $\approx 3 \cdot 10^{18}$ cm	200 $\mu m = 2 \cdot 10^{-2}$ cm
d/r	0.01	$10^{-5.33}$
mass range M/m	100 (1000)	1800 (m_i/m_e)
Γ_e (e-e)	0.01	0.1
Γ_i (i-i)	$(M/m)\Gamma_e$	$(m_i/m_e)\Gamma_e$
t_{e-e}/t_{dyn}	100	0.01
t_{e_i}/t_{dyn}	1.0	1.0

A



Plasma Physics and
Stellar Dynamics ...

How do they compare?
(Table inspired by Comparat et al. 2004)

Complexity asympt. N**2!

Star Cluster Dynamics

Three-Body – Million Body - Continuum

- o Secular Instability
- o Exponential Divergence
- o Deterministic Chaos
- o Weak and Strong Correlations (Binaries/Multiples)
  coupling to global dynamics (no shielding)
  multi-scale problem
  (e.g. different to galaxy dynamics)
- o Strong Mixing – (many) thousands of crossing times
  (e.g. different to cosmological N-body)

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++, φGPU, R. Spurzem, P. Berczik, T. Hamada, K. Nitadori,...*
- *(massively parallel codes, since 1999):*

- NBODY6++ (Spurzem 1999) using MPI
- Parallel Binary Integration in Progress (KSREG)
- Parallel φGRAPE / φGPU Use in Progress (Harfst et al. 2006,
- Spurzem et al. 2009)

Software

•**Copy Algorithm**: parallelize work over block members
replicate all data on all processors
(Example: NBODY6++)

•**Ring Algorithm:** domain decomposition
partial forces shifted
blocking or non-blocking, systolic or hyper-systolic
(Gualandris et al. 2005, Dorband et al. 2003)

Our present workhorse:

•**Mixed Algorithm**: φGPU – domain decomposition on GPU memories, copy algorithm for active particles
(Harfst el al. 2007, Spurzem et al. 2009)

Note: Special hypersystolic quadratic algorithm (Makino 2002):

$$O(N/\sqrt{p}) + O(N/p)$$

hARDWARE

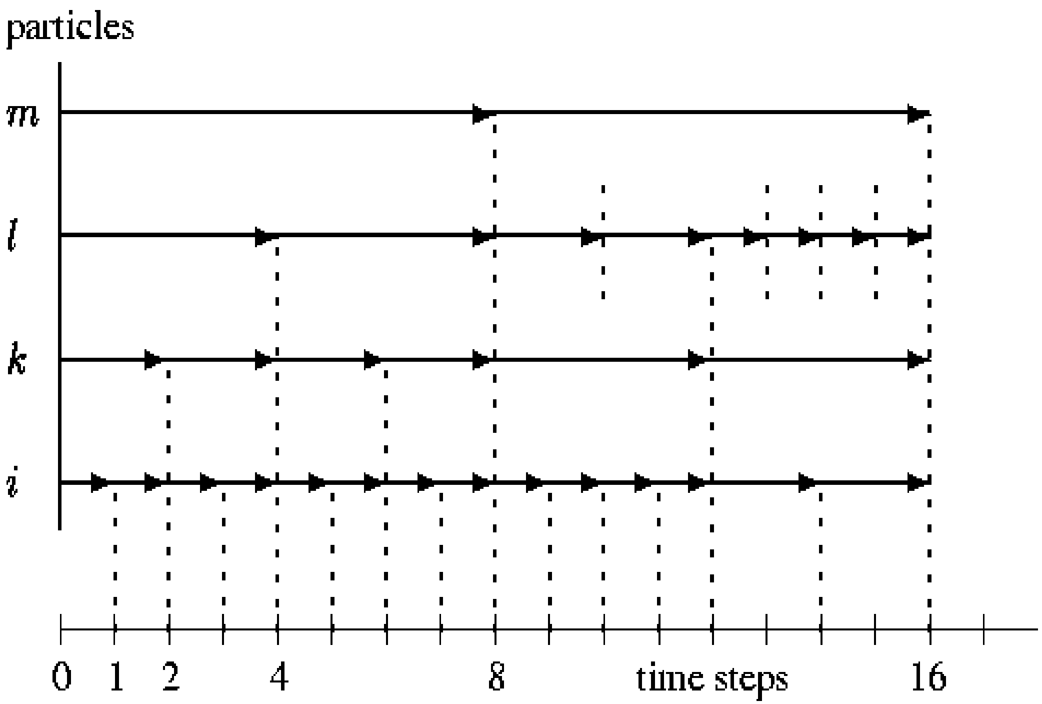
GRAPE-6 Gravity/Coulomb Part

- G6 Chip: 0.25μ 2MGate ASIC, 6 Pipelines
- at 90MHz, 31Gflops/chip
- 48Tflops full system (March 2002)
- Plan up to 72Tflops full system (in 2002)
- Installed in Cambridge, Marseille, Drexel, Amsterdam, New York (AMNH), Mitaka (NAO), Tokyo, etc..
  New Jersey, Indiana, Heidelberg

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



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

4th order Hermite scheme

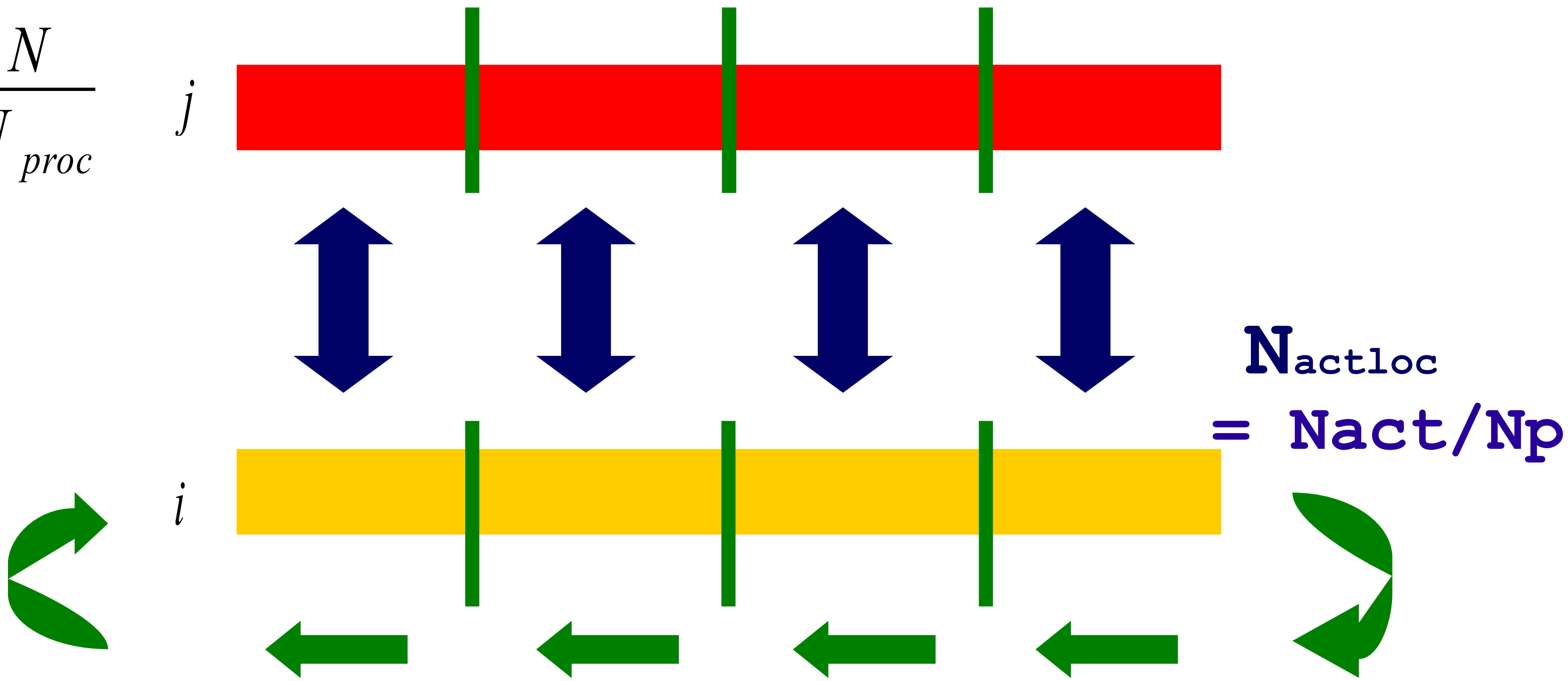
$$\frac{d^2 \vec{r}_i}{dt^2} = \vec{a}_i$$

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

Basic idea of parallel N-body code

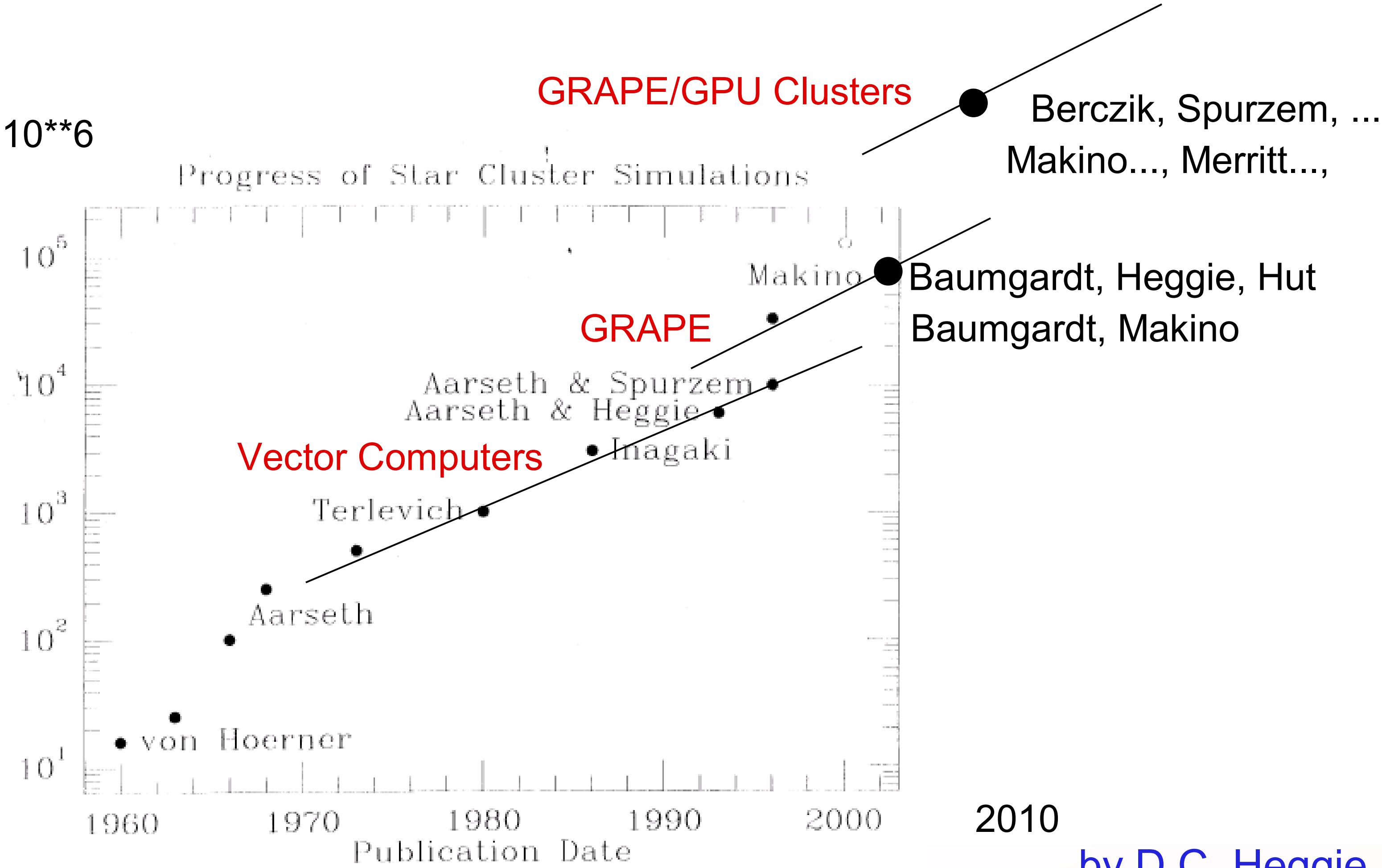
$$i,j - particle$$

$$N_{loc} = \frac{N}{N_{proc}}$$



Some communication scheme...

"Moore's" Law for Direct N-Body

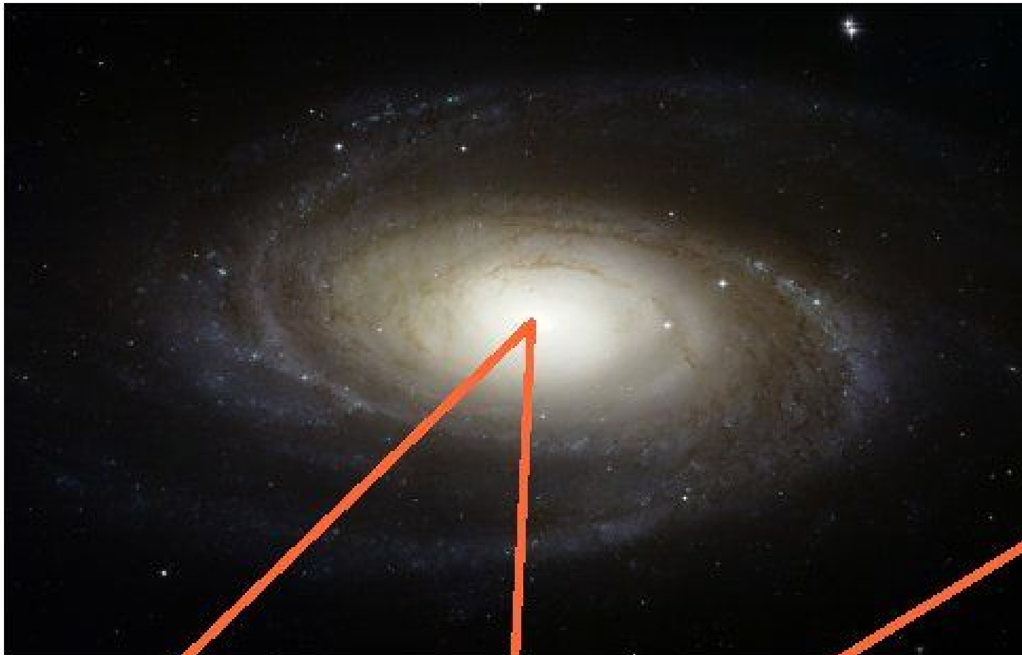


by D.C. Heggie
Via www.maths.ed.ac.uk

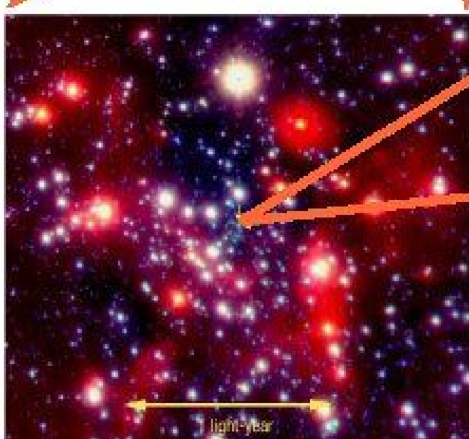
Manycore Computing in China and Germany
Dynamics of Galactic Nuclei with Black Holes

- Manycore (GPU) Research at
- Chinese Academy of Sciences
- Silk Road Project
- GRACE-2 Project
- ICCS and Green Grid
- Parallel Direct N-Body Codes with MPI and CUDA
- Galactic Nuclei, Black Holes, Gravitational Waves

Setting the stage: the galactic nucleus



Size ~ 10 Kpc
Density ~ 0.05 M_{sun} pc^{-3}
Vel. Disp. ~ 40 Km/s
Relaxation time ~ 10^{15} yrs.

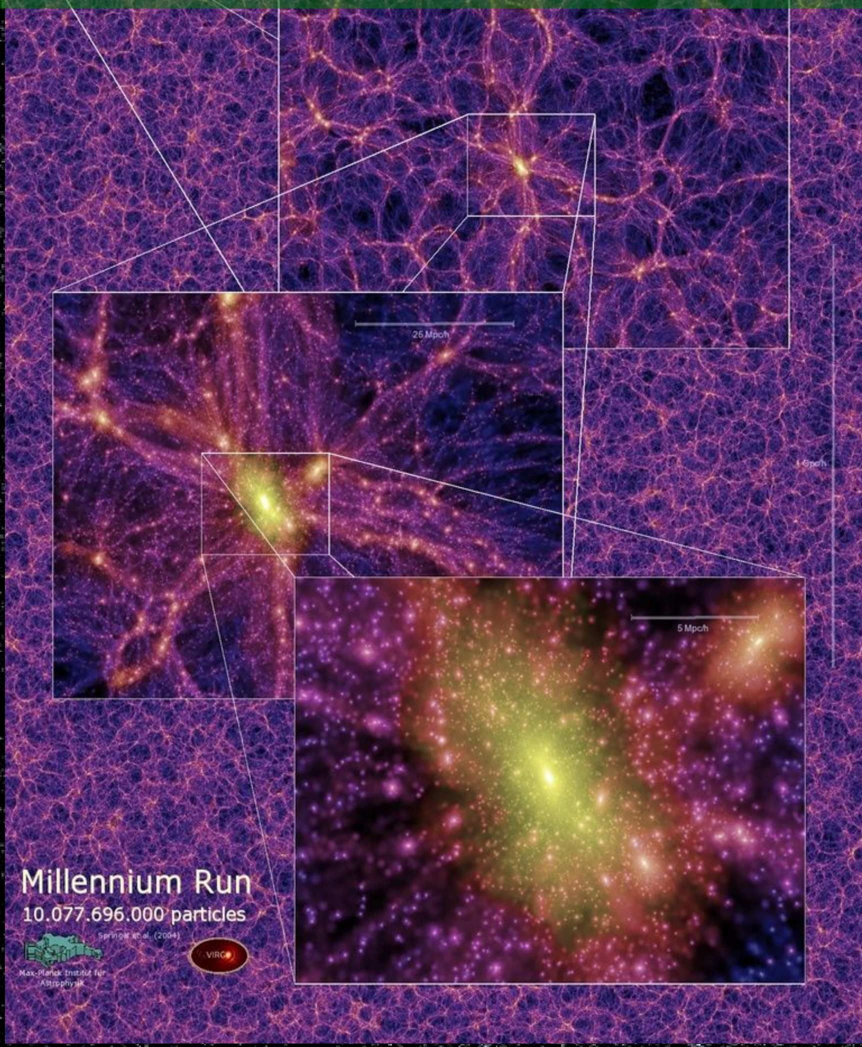


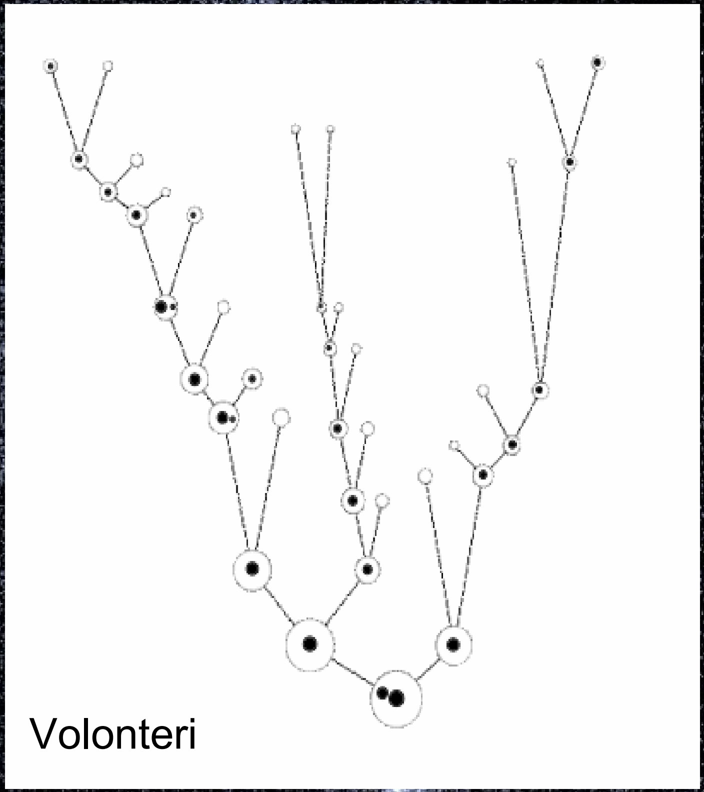
Size ~ 1-10 pc
Density ~ $10^{6\text{-}8}$ M_{sun} pc^{-3}
Vel. Disp. ~ $10^{2\text{-}3}$ Km/s
Relaxation time ~ $10^{8\text{-}9}$ yrs.

Size ~ 10^{-7}-10^{-4} pc
$R_s = 2G\,M_{BH}/c^2$
$R_t \sim (\alpha\, M_{BH}/m_*)^{1/3}\, R_*$
Loss cone aperture: θ

Slide: Miguel Preto

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

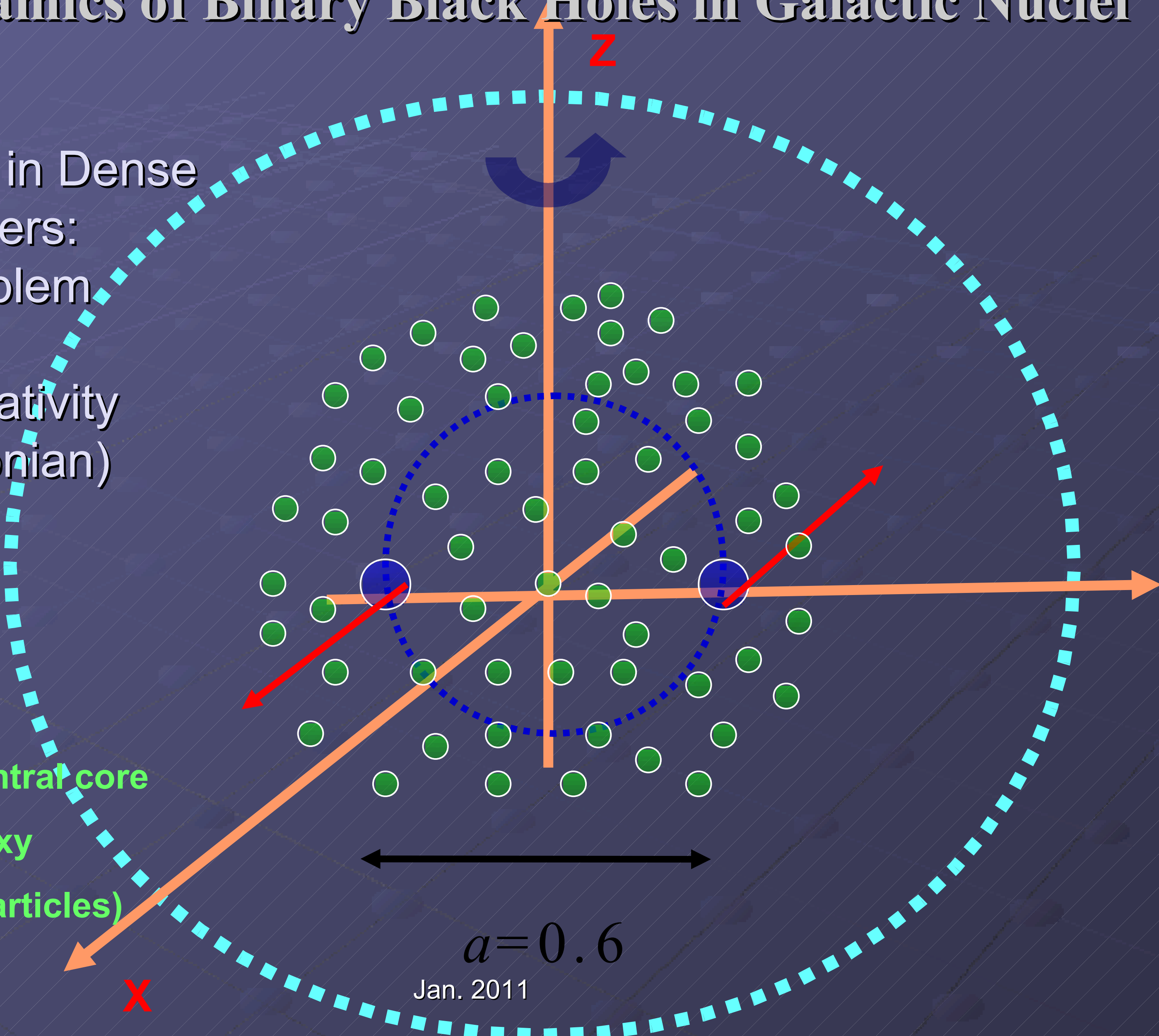




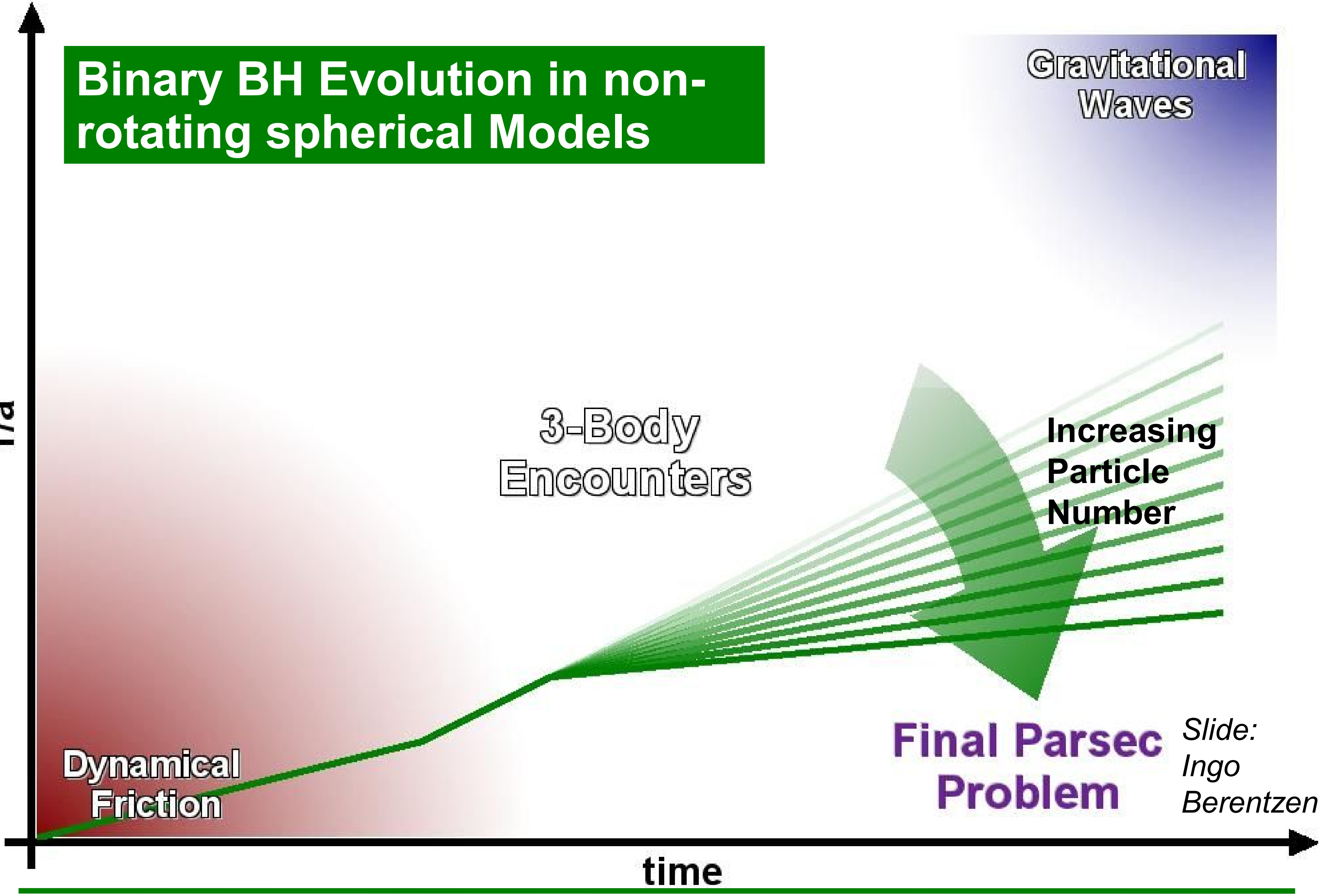
Slide: Ingo Berentzen

Dynamics of Binary Black Holes in Galactic Nuclei

Black Holes in Dense Stellar Clusters:
N-Body Problem with General Relativity (Post-Newtonian)



Two equal-mass black holes in central core of simplified galaxy (up to 4 million particles)

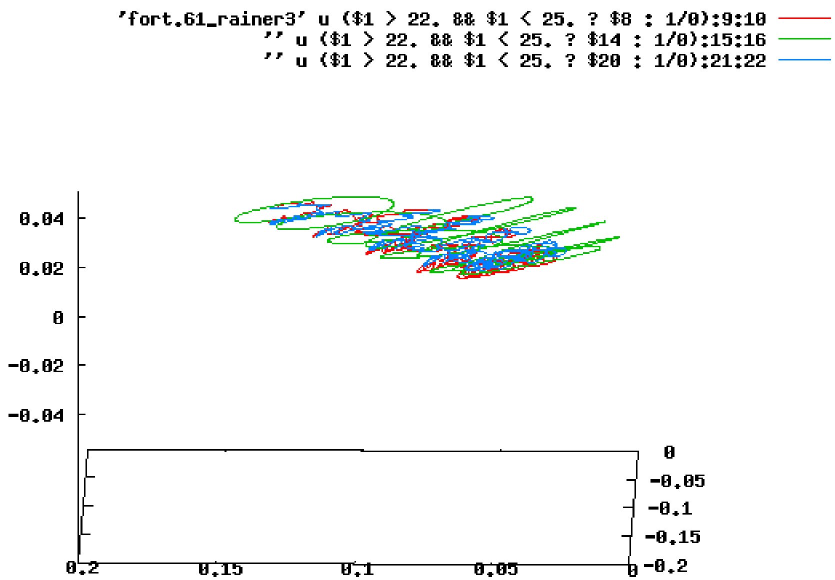


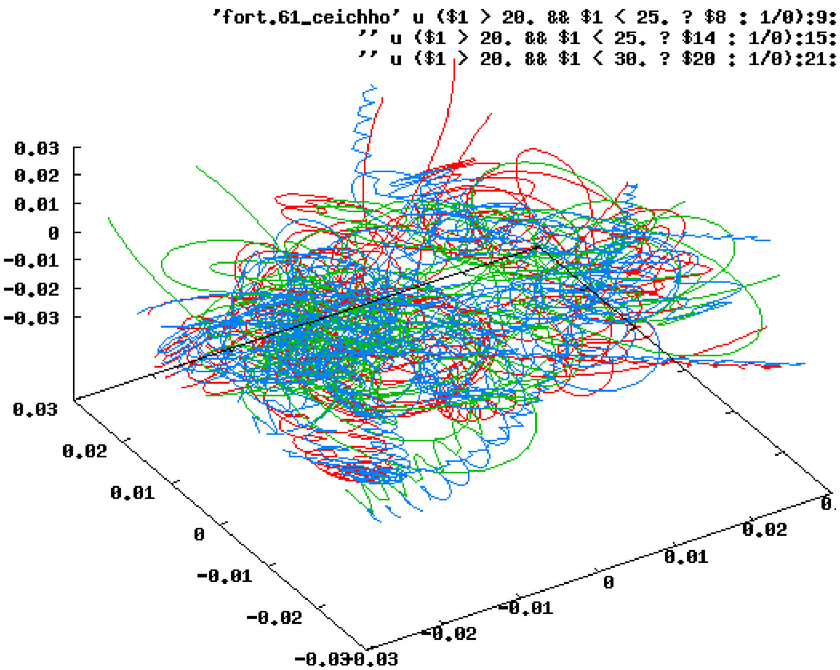
Binary BH Evolution in non-rotating spherical Models
Gravitational Waves
1/a
3-Body Encounters
Increasing Particle Number
Dynamical Friction
Final Parsec Problem
Slide: Ingo Berentzen
time

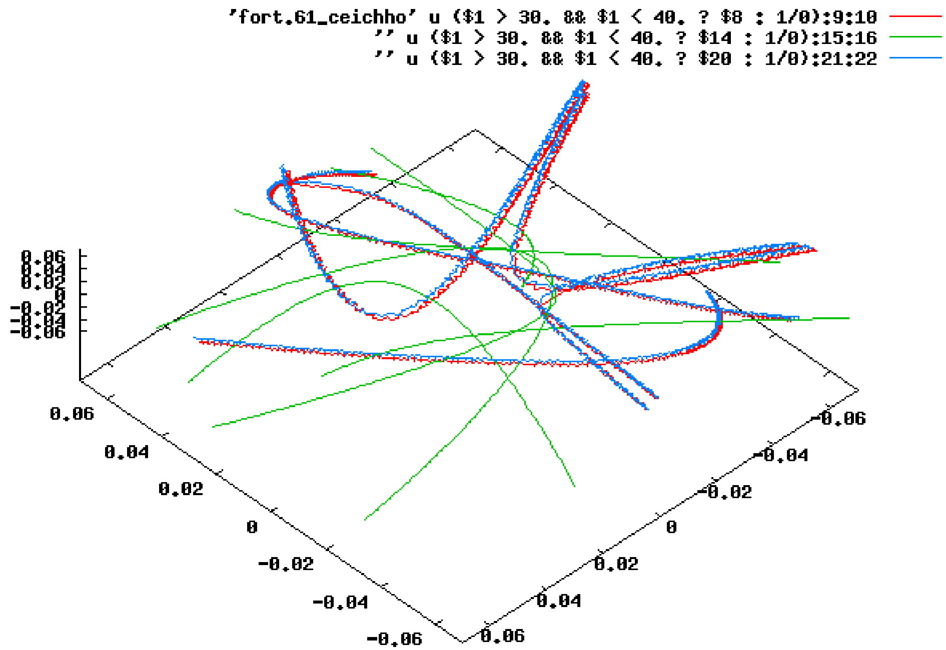
Triple Black Holes

Left: Triple initially coplanar
Bottom: Triple initially nonplanar

We see hierarchical triples,
chaotic three-body,
binary plus single...

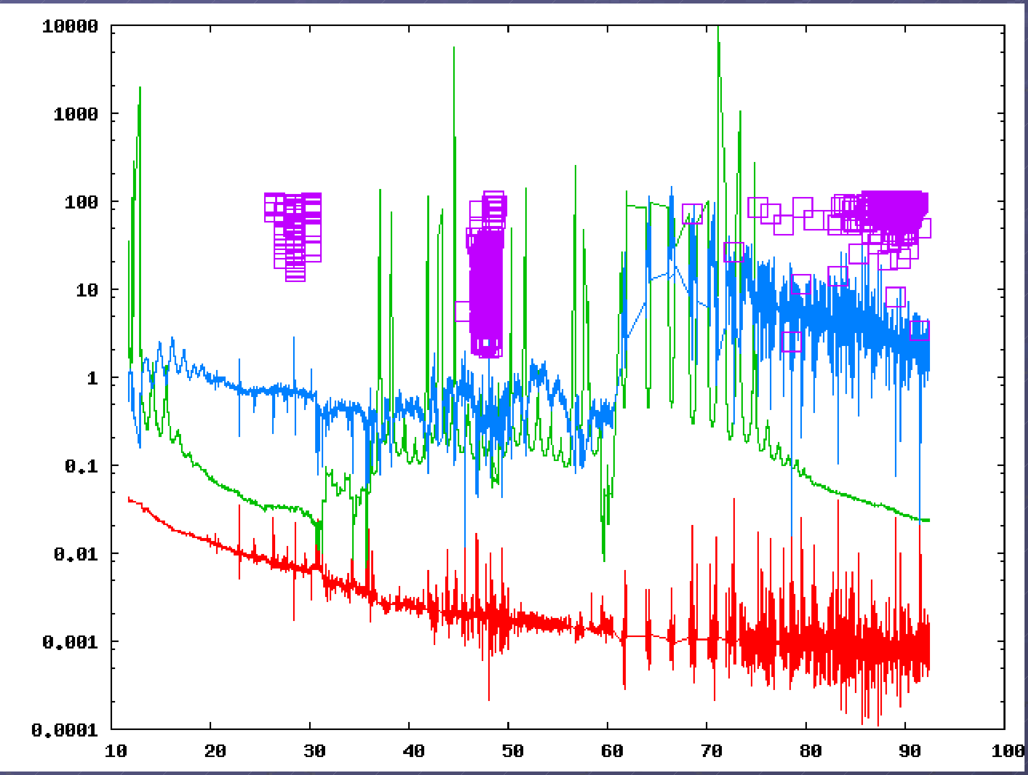






Triple Black Holes

Three SM Black Holes, another case study, dynamics Newtonian...



PN1 becomes important

Mardling & Aarseth stability parameter > 1 stable

outer semi-major axis

inner semi-major axis

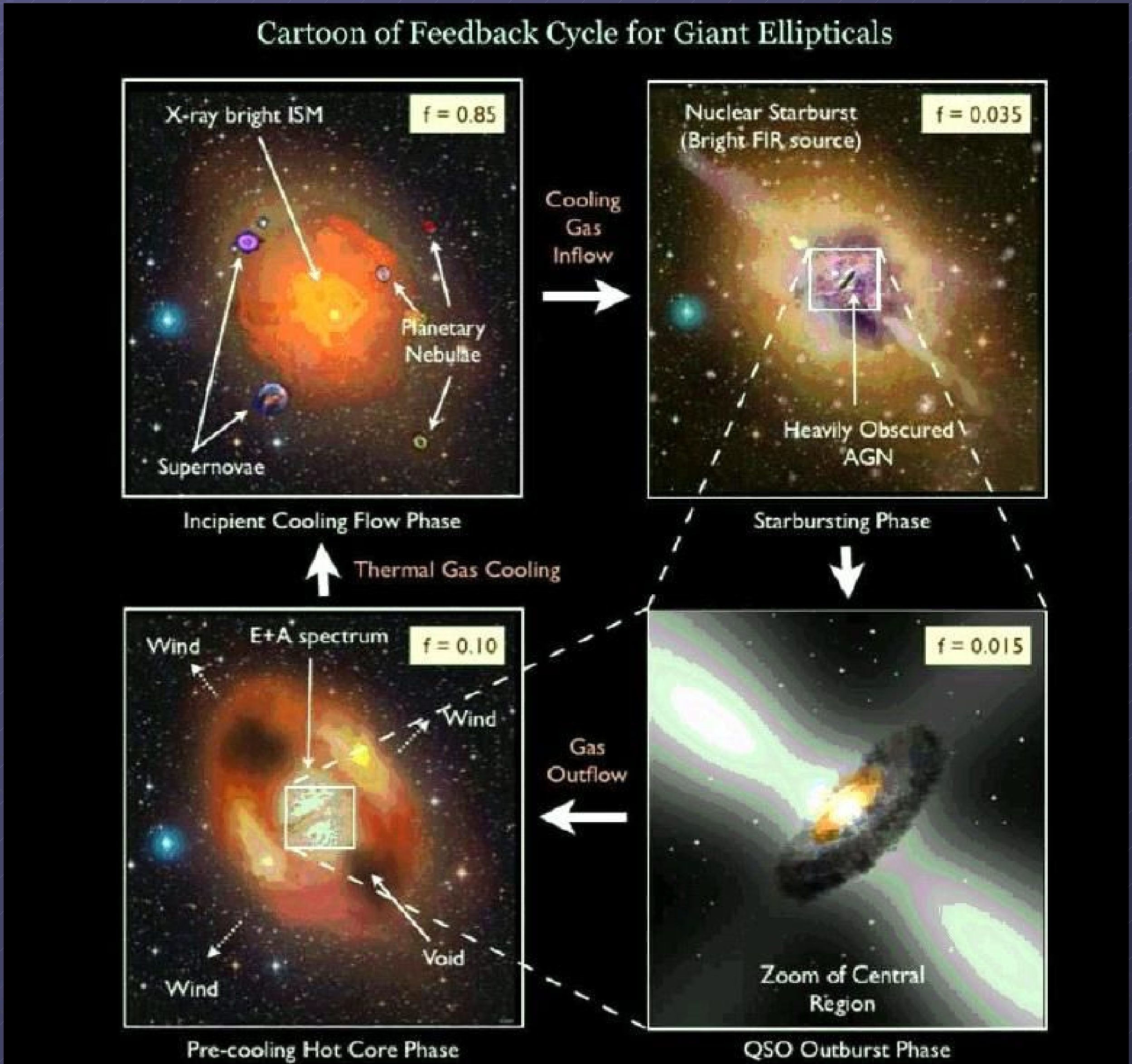
Gopakumar, Mardling, Spurzem, in prep.

Gas Dynamics and Black Holes

Feedback And
Chemodynamical
Duty Cycles
In Galactic Nuclei

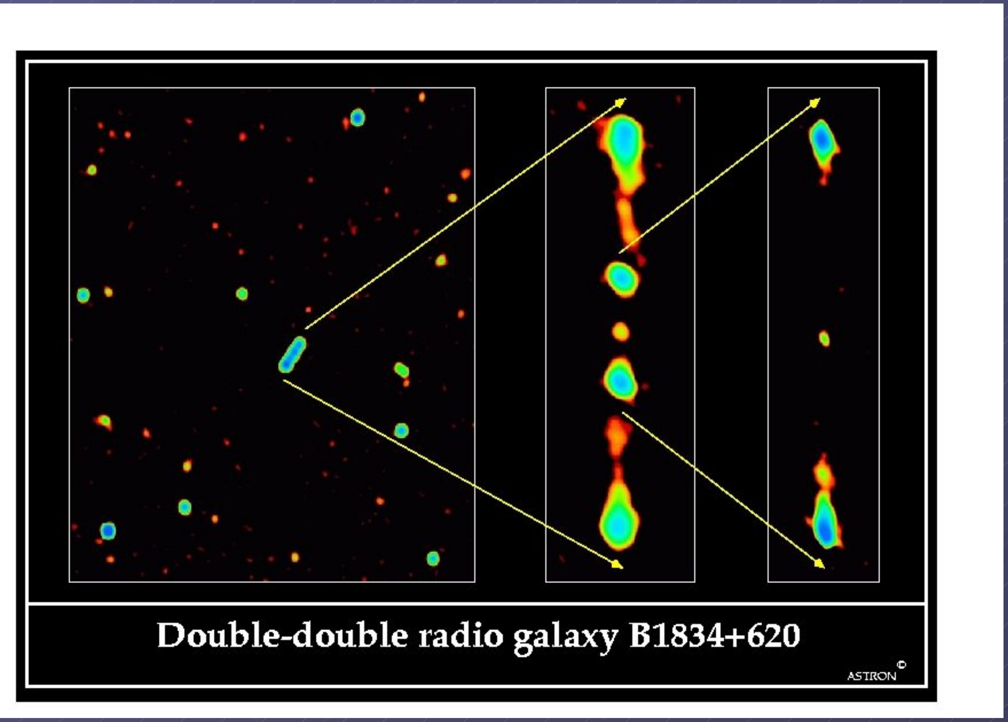
From 1D-Models
Of Shin, Ciotti,
Ostriker

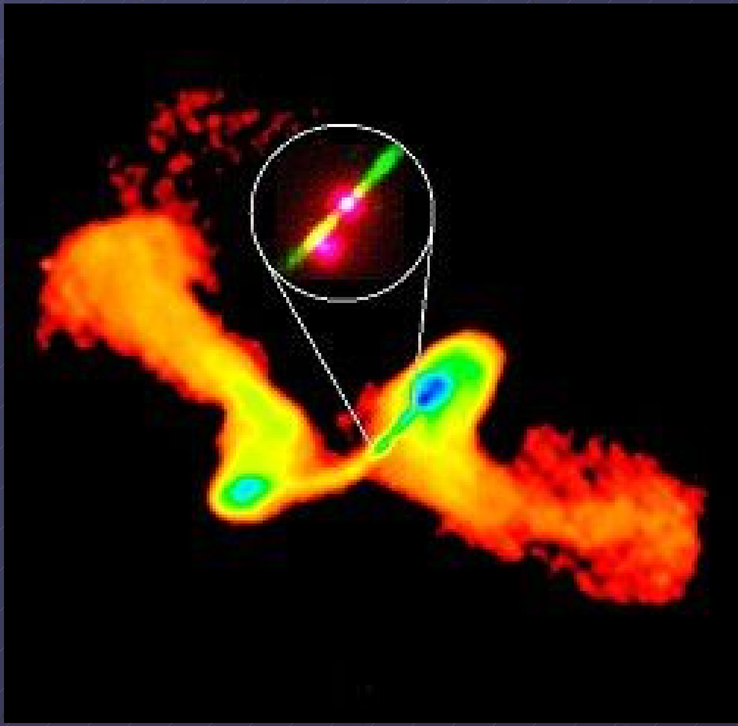
Need resolution
Comparable to
Stellar dynamics
(1 mpc or less)



Gas Dynamics 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 (Theory: Liu 2004, Liu et al. 2006)



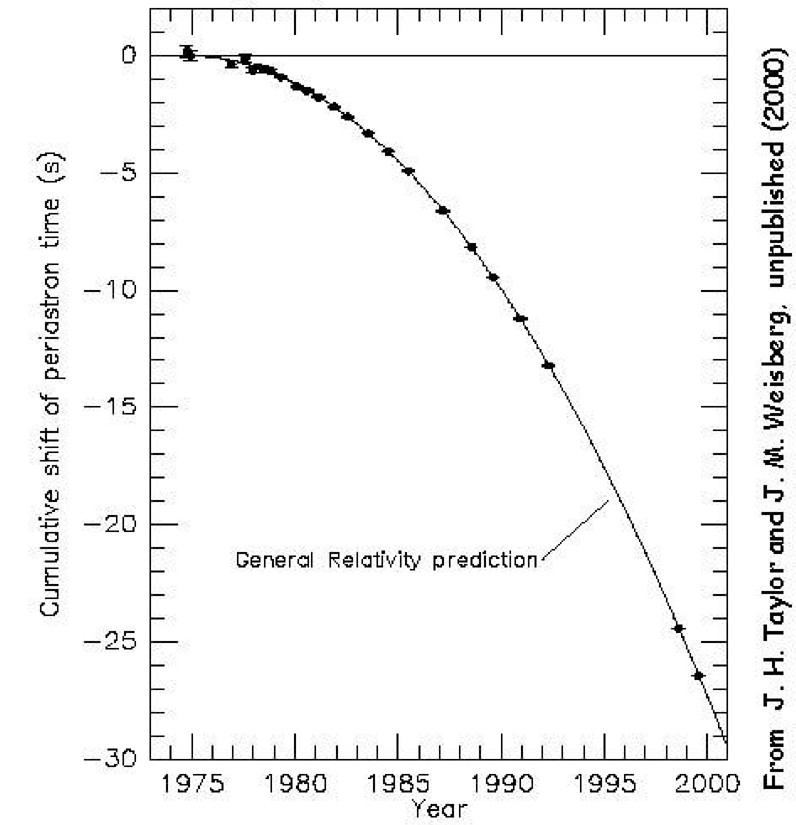


Post-Newtonian Dynamics

Indirect Proof by Hulse and Taylor, binary pulsar (Nobel prize 1993)

"for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"

Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves



Post-Newtonian Dynamics

Method A: use geodetic equations, harmonic gauge, directly obtain eqs. of motion (Blanchet et al.)
Method B: Hamiltonian approach using ADM gauge (Schaefer et al.)

A and B equivalent till PN2.5 (1/c**5), higher order gauge functions appear.

$$\frac{dv^i}{dt} = -\frac{Gm}{r^2}\left[(1+\mathcal{A})\,n^i + \mathcal{B}\,v^i\right] + \mathcal{O}\left(\frac{1}{c^8}\right), \tag{181}$$

and find [43] that the coefficients $\mathcal{A}$ and $\mathcal{B}$ are

$$\mathcal{A} = \frac{1}{c^2}\left\{-\frac{3\dot{r}^2\nu}{2} + v^2 + 3\nu v^2 - \frac{Gm}{r}(4+2\nu)\right\}$$

Perihel shift

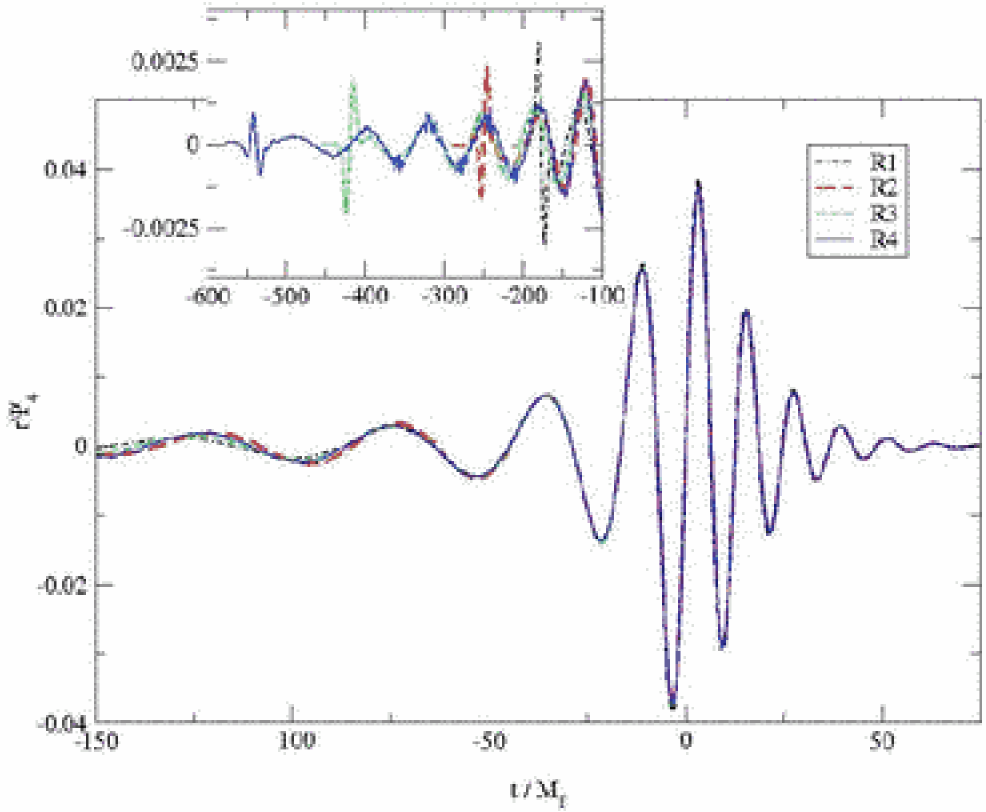
$$+\frac{1}{c^4}\left\{\frac{15\dot{r}^4\nu}{8} - \frac{45\dot{r}^4\nu^2}{8} - \frac{9\dot{r}^2\nu v^2}{2} + 6\dot{r}^2\nu^2 v^2 + 3\nu v^4 - 4\nu^2 v^4 + \frac{Gm}{r}\left(-2\dot{r}^2 - 25\dot{r}^2\nu - 2\dot{r}^2\nu^2 - \frac{13\nu v^2}{2} + 2\nu^2 v^2\right) + \frac{G^2m^2}{r^2}\left(9 + \frac{87\nu}{4}\right)\right\}$$

... higher order...

$$+\frac{1}{c^5}\left\{-\frac{24\dot{r}\nu v^2}{5}\frac{Gm}{r} - \frac{136\dot{r}\nu}{15}\frac{G^2m^2}{r^2}\right\}$$

Grav. Radiation

So far, it seems not!



Initial separations:

R1 = 6.5 M

R2 = 7.6 M

R3 = 8.5 M

R4 = 9.6 M

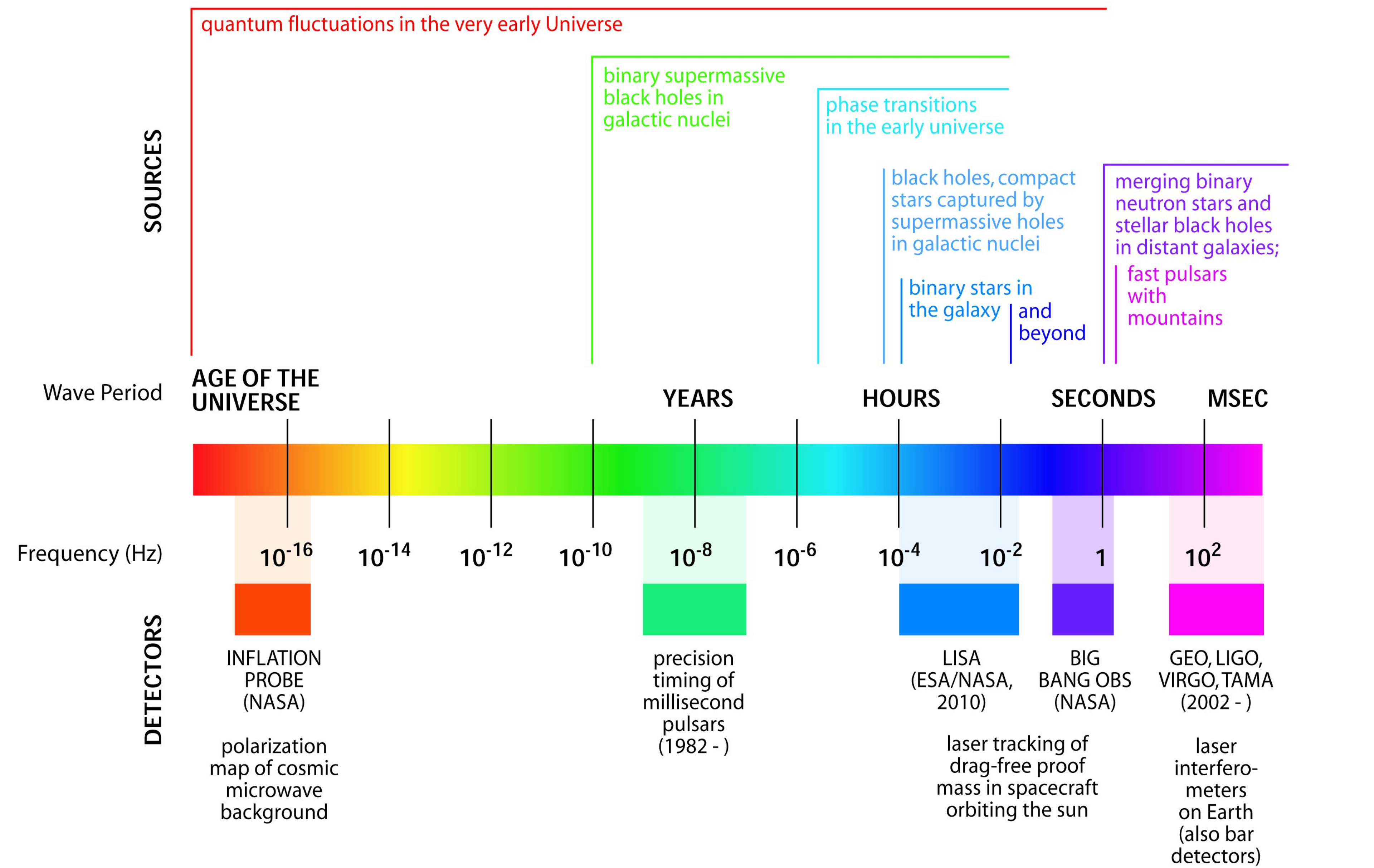
NASA-GSFC

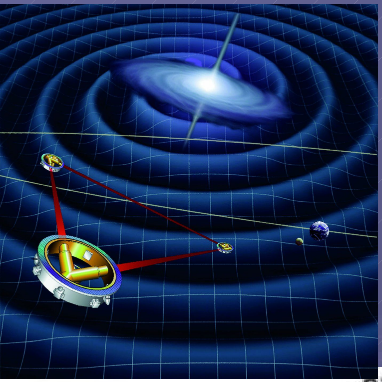
Baker, Centrella, Choi, Koppitz, van Meter

Phys.Rev. D73 (2006) 104002

Slide by P. Laguna

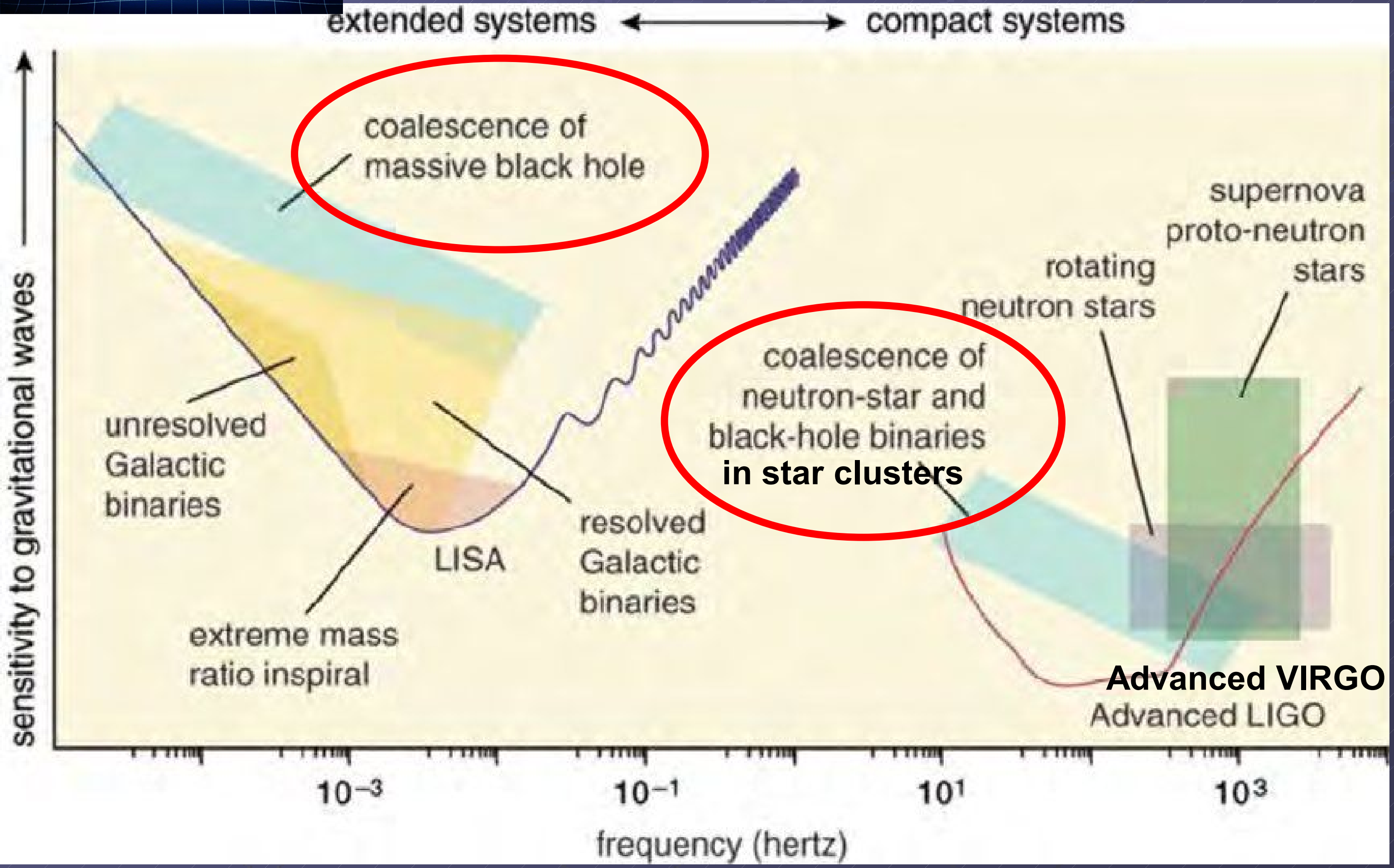
THE GRAVITATIONAL WAVE SPECTRUM



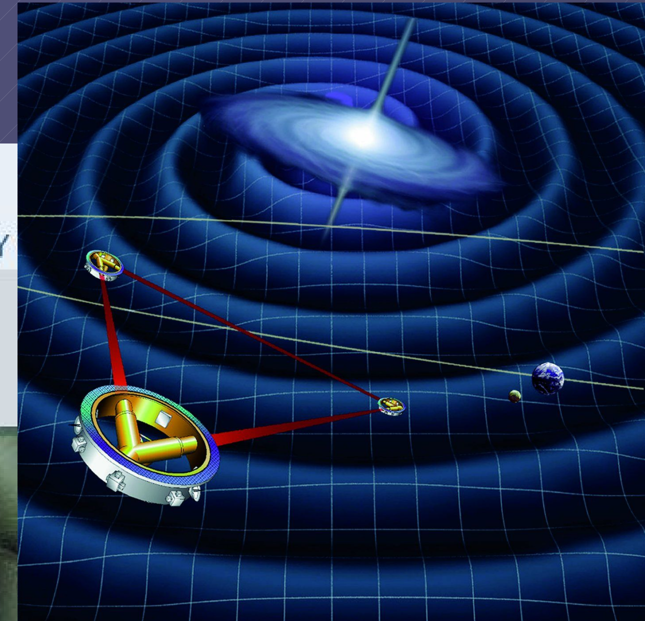


Gravitational Wave Prediction from Black Holes in Galactic Nuclei and Star Clusters

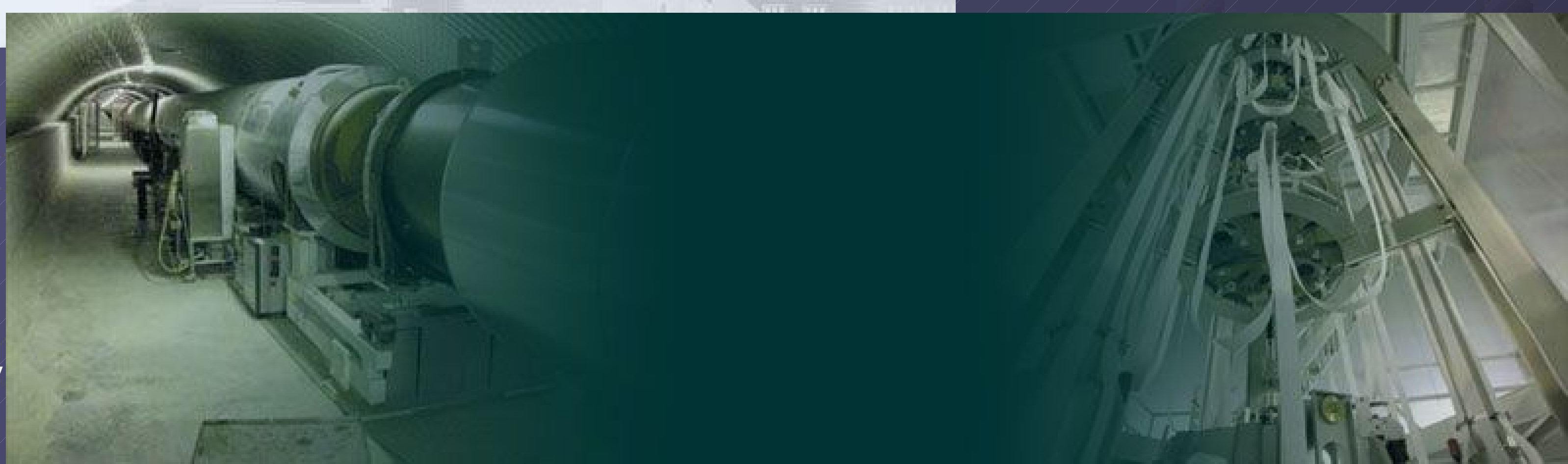
Astrophysical Objects in the realm of LISA (left)
and VIRGO or LIGO (right)
= activities with Nbody Simulations



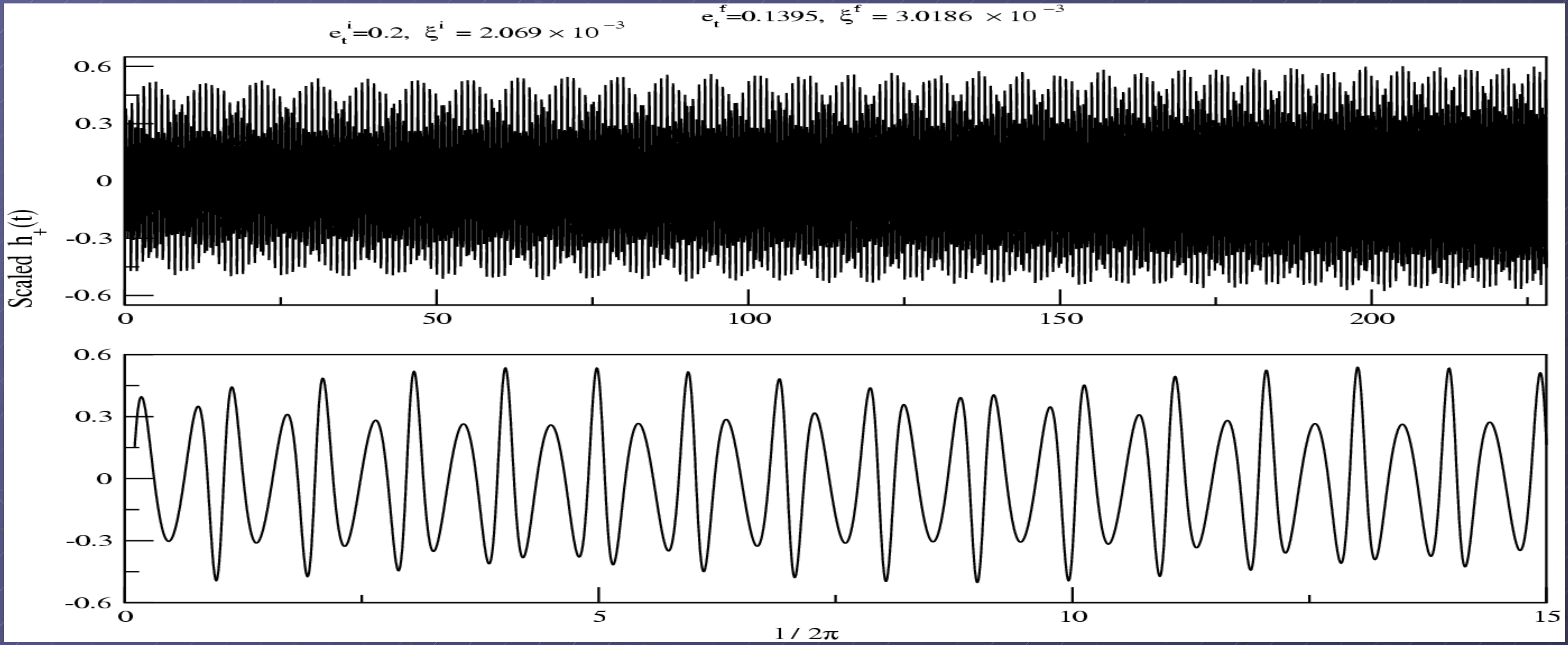
VIRGO Detector in Cascina near Pisa, Italy



LISA =
Laser Space
Interferometer Antenna



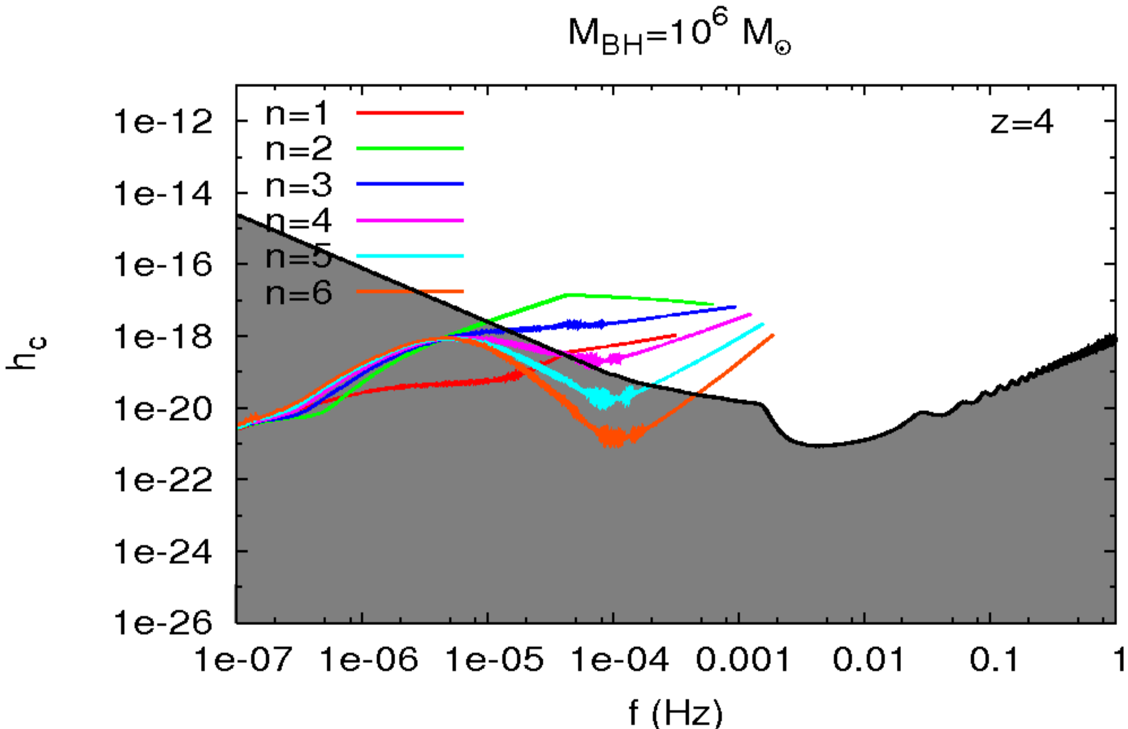
Post-Newtonian Dynamics
Gravitational Wave Templates



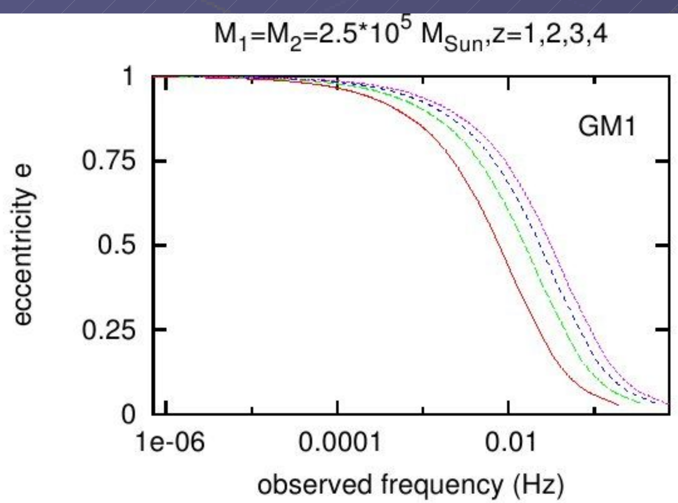
Plots of h+(t) showing 3 relevant time scales

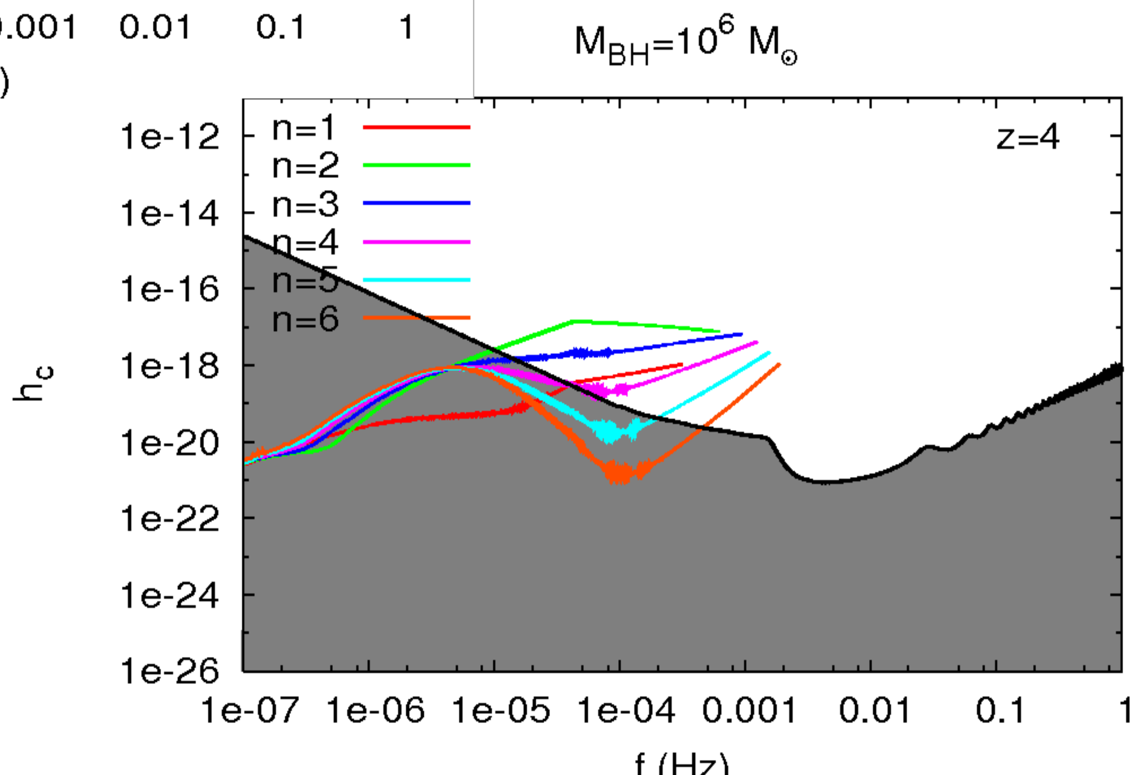
Orbital evolution is NOT adiabatic (fully 3.5PN accurate)

Handle arbitrary eccentricities (Gopakumar, Schäfer, et al.)



Berentzen, Preto, Berczik, Merritt, Spurzem 2009 (ApJ)





ICCS Invitation

Building International Community

Invitation to join at different level:

See also H. Simon's talk today!

- (I) Provide hardware access and support for green network of GPU clusters (currently Berkeley dirac, Heidelberg titan, Beijing laohu, Nagasaki dejima invited)
- (II) Take part in individual collaborations, community building by bridging the disciplines, contribute to database of benchmarks and tools, workshops, publications

Education and Outreach

Invitation to 3rd ICCS School and Workshop

Beijing, Dec. 5-9 2011 or Jan. 9-13, 2012