From NBODY1 to NBODY7: the growth of Sverre's industry

Univ. Heidelberg

IAUS 298/MODEST 25 Seoul

Rainer Spurzem

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

National Astronomical Observatories (NAOC), Chinese Academy of Sciences, Beijing, China

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

Picture:

Xi Shuang Banna, Yunnan, SW China (R.Sp.)

spurzem@ari.uni-heidelberg.de

spurzem@nao.cas.cn

https://astro-silkroad.eu

the SILK ROAD PROJECT at NAOC

丝绸之路 计划

ARI ITA LSW

- **Start and Growth**
- Code(s) and Science
- The future

Publications of the Astronomical Society of the Pacific, **111**:1333–1346, 1999 November

Invited Review

From NBODY1 to NBODY6: The Growth of an Industry[1]

Sverre J. Aarseth

Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, England, UK; sverre@ast.cam.ac.uk

Received 1999 July 30; accepted 1999 July 30

ABSTRACT. I review the development of direct N-body codes at Cambridge over nearly 40 years, highlighting the main stepping stones. The first code (NBODY1) was based on the simple concepts of a force polynomial combined with individual time steps, where numerical problems due to close encounters were avoided by a softened potential. Fortuitously, the elegant Kustaanheimo-Stiefel two-body regularization soon permitted small star clusters to be studied (NBODY3). Subsequent extensions to unperturbed three-body and four-body regularization proved beneficial in dealing with multiple interactions. Investigations of larger systems became possible with the Ahmad-Cohen neighbor scheme which was used more than 20 years ago for expanding universe models of 4000 galaxies (NBODY2). Combining the neighbor scheme with the regularization procedures enabled more realistic star clusters to be considered (NBODY5). After a period of simulations with no apparent technical progress, chain regularization replaced the treatment of compact subsystems (NBODY3, NBODY5). More recently, the Hermite integration method provided a major advance and has been implemented on the special-purpose HARP computers (NBODY4) together with an alternative version for workstations and supercomputers (NBODY6). These codes also include a variety of algorithms for stellar evolution based on fast lookup functions. The treatment of primordial binaries contains efficient procedures for chaotic two-body motion as well as tidal circularization, and special attention is paid to hierarchical systems and their stability. This family of N-body codes constitutes a powerful tool for dynamical simulations which is freely available to the astronomical community, and the massive effort owes much to collaborators.

Aarseth, Henon, Wielen, 1974, A&A:
A comparison of numerical methods for the study of star cluster dynamics

N-body Codes:

Wielen
Aarseth

Monte Carlo:
Hénon

Fluid Model:
Larson

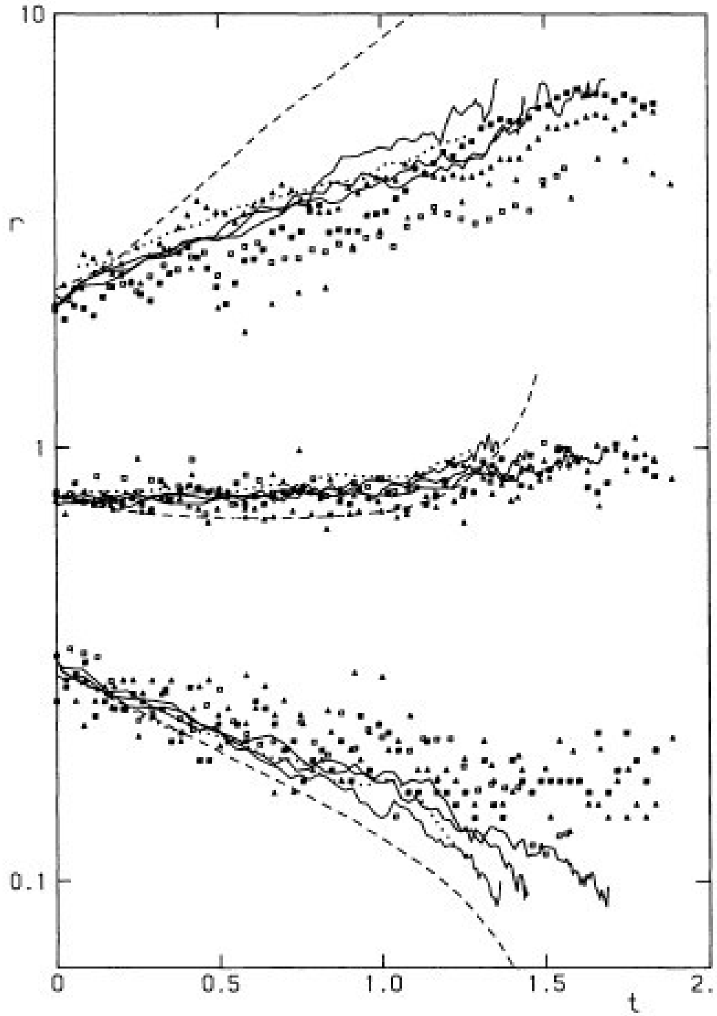


Fig. 1. Radii containing 10%, 50%, 90% of the mass, plotted versus time for a cluster with stars of equal masses. Open triangles and squares: N-body integrations with $N=100$ and $N=250$ (Wielen). Filled triangles and squares: N-body integrations with $N=250$ (Aarseth). Full lines: Monte Carlo models (Hénon). Dotted lines: Monte Carlo model (Shull and Spitzer). Dashed lines: fluid-dynamical model (Larson)

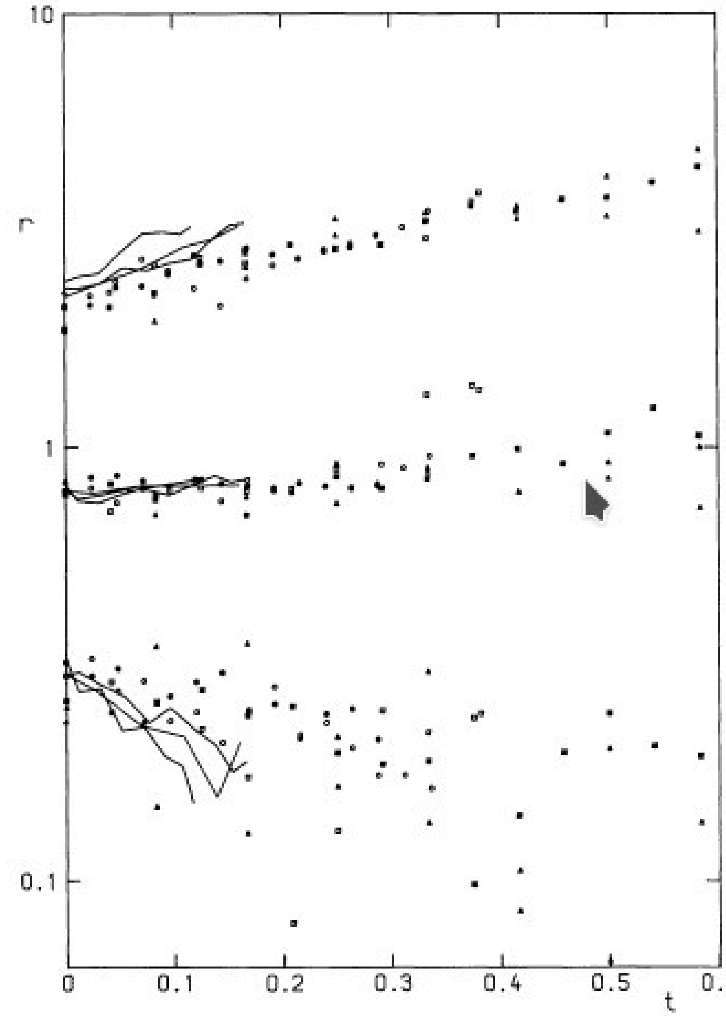
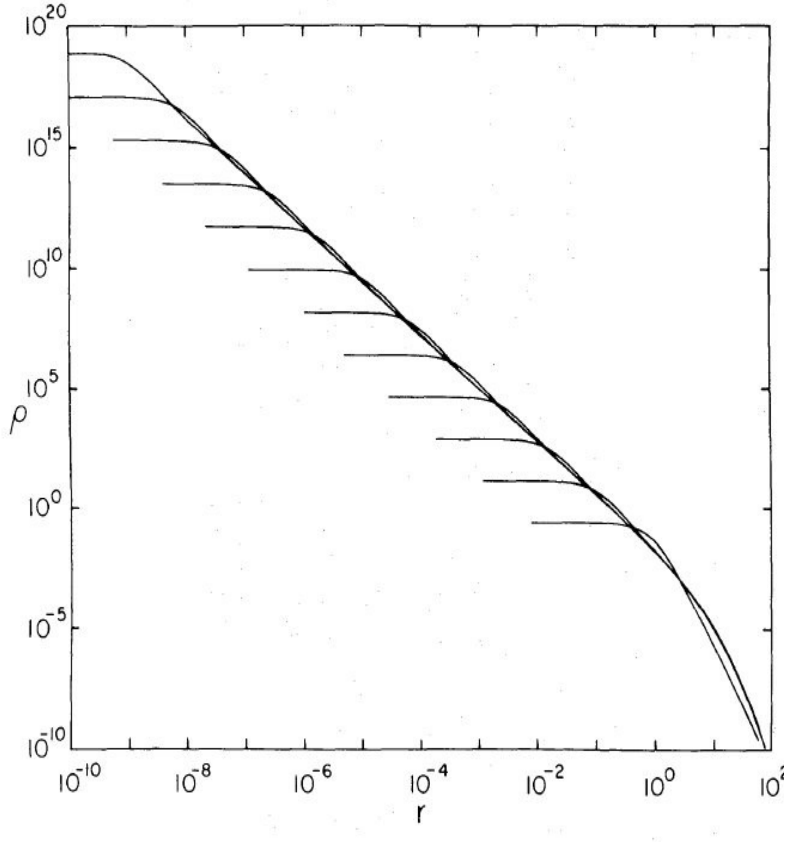


Fig. 2. Radii containing 10%, 50%, 90% of the mass, plotted versus time for a cluster with stars of different masses. Open and filled symbols: N-body integrations with $N=100$ (triangles), $N=250$ (squares), $N=500$ (circles) (Wielen). Full lines: Monte Carlo models (Hénon)

Approx. Models I: Gas Sphere



Cohn (1980): Direct Fokker-Planck model

Core Collapse

Gravothermal Catastrophe

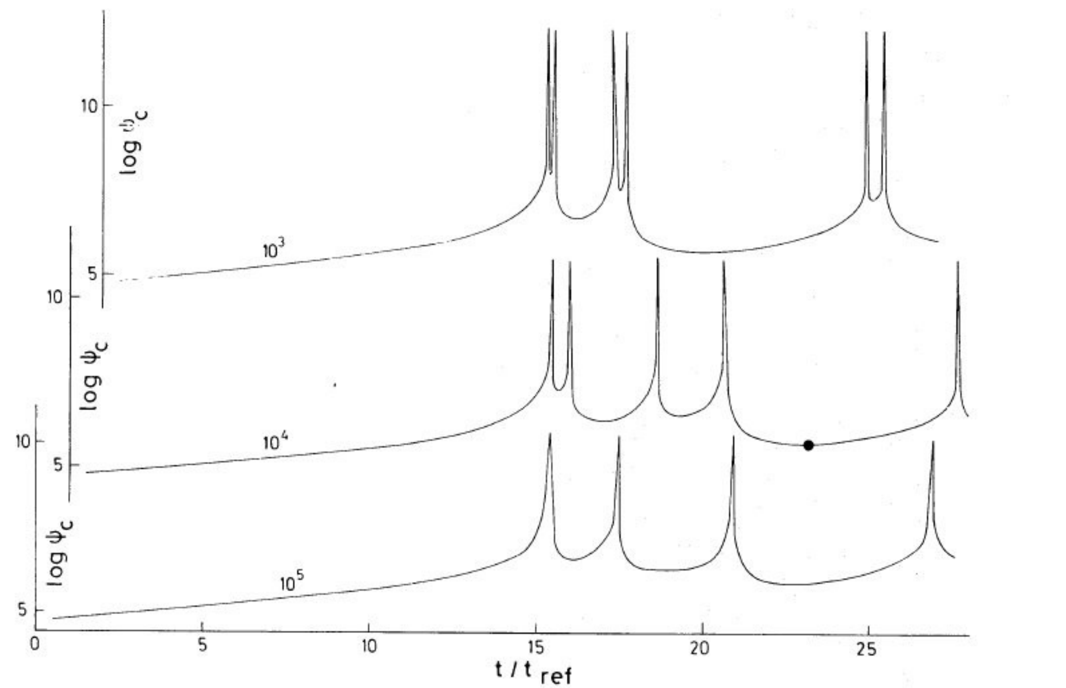


Figure 1. The 'central' density ψ_c is plotted against the non-dimensional time $t/t_{\mathbf{ref}}$ for $k = 2$ models with three different values of C as attached to each curve. Note, that if they were plotted with the same ordinate they would be close to each other despite the great differences in C. The model indicated with a filled circle will be compared with King's model in Section 4.2.

Bettwieser & Sugimoto 1984:

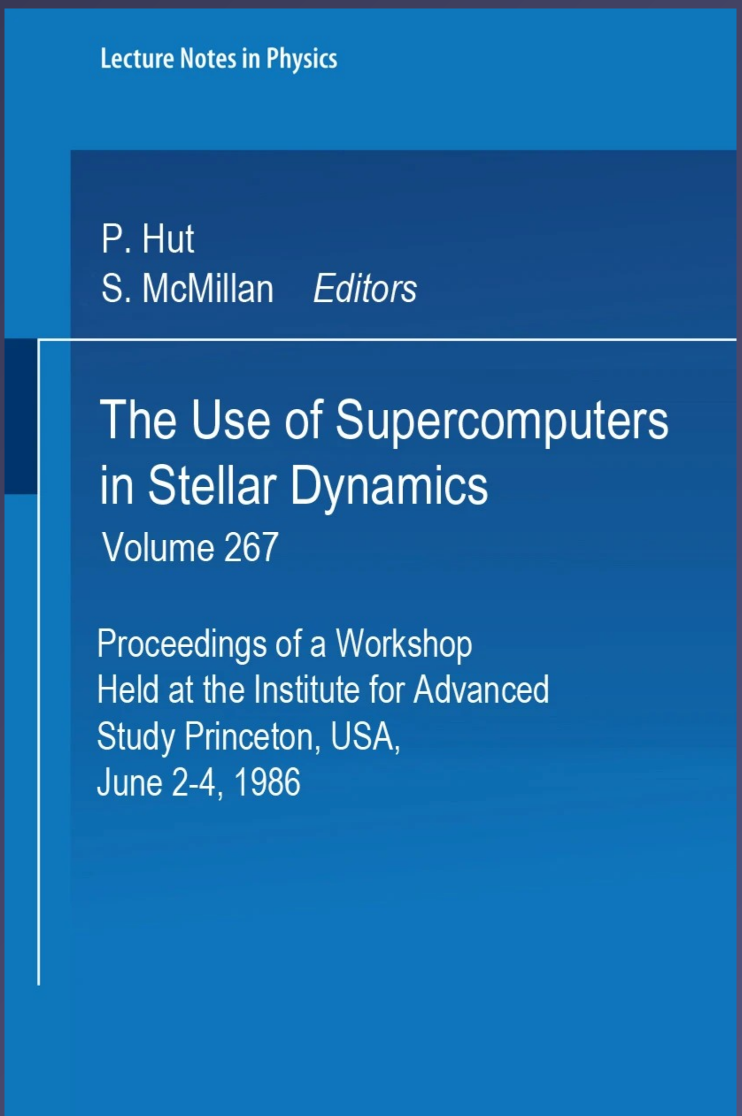
Gravothermal Oscillations by

energy generation from binaries

(cf. nuclear stellar energy generation)

New fluid (gaseous) model

Some Innovations 80’s to 90’s

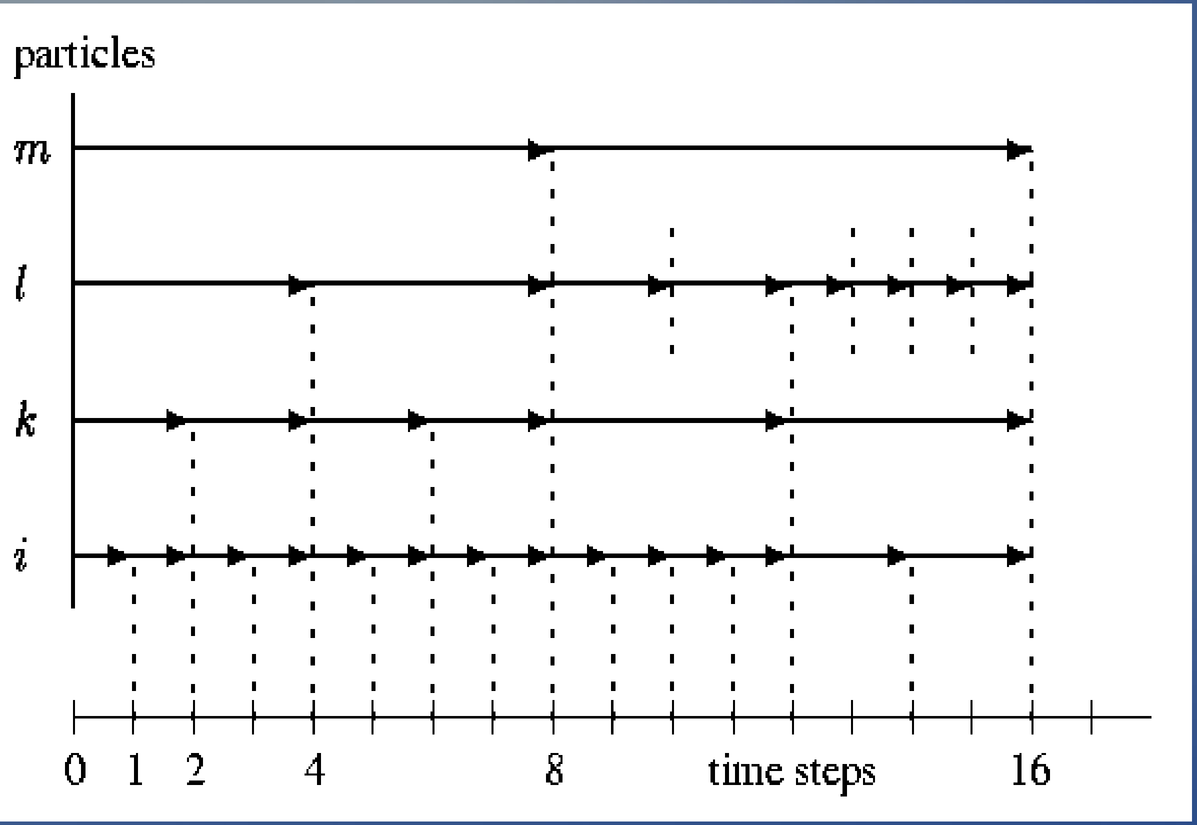


NBODY5 → NBODY6

- Individual → Hierarchical Block Time Steps (McMillan 1986)
- Divided Differences → Hermite Scheme (Makino & Aarseth 1992)

Vector / Parallel Computers
GRAPE

Some Innovations 80’s to 90’s



S.J.Aarseth, S. Mikkola
(ca. 20.000 lines):

- Hierarchical Block Time Steps
- Ahmad-Cohen Scheme
- Regularisations
- 4th order Hermite scheme

- NBODY6 (Aarseth 1999)
- NBODY6++ (Spurzem 1999) MPI
- NBODY6++GPU (Wang, Spurzem, Aarseth et al. 2015, Kamlah & Spurzem 2023)

Hierarchical Block Time Steps

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

A special-purpose computer for gravitational many-body problems

Nature 1990

Daiichiro Sugimoto*, Yoshihiro Chikada†, Junichiro Makino*, Tomoyoshi Ito*, Toshikazu Ebisuzaki* & Masayuki Umemura‡

* Department of Earth Science and Astronomy, College of Arts and Sciences, University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo 153, Japan
† Nobeyama Radio Observatory, Minamimaki-mura, Minamisaku-gun, Nagano 384-13, Japan
‡ National Astronomical Observatory, Mitaka, Tokyo 181, Japan

A processor has been constructed using a 'pipeline' architecture to simulate many-body systems with long-range forces. It has a speed equivalent to 120 megaflops, and the architecture can be readily parallelized to make teraflop machines a feasible possibility. The machine can be adapted to study molecular dynamics, plasma dynamics and astrophysical hydrodynamics with only minor modifications.

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construction and
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GRAPE-1 achie
XMP/1 at a cost

The pipeline a

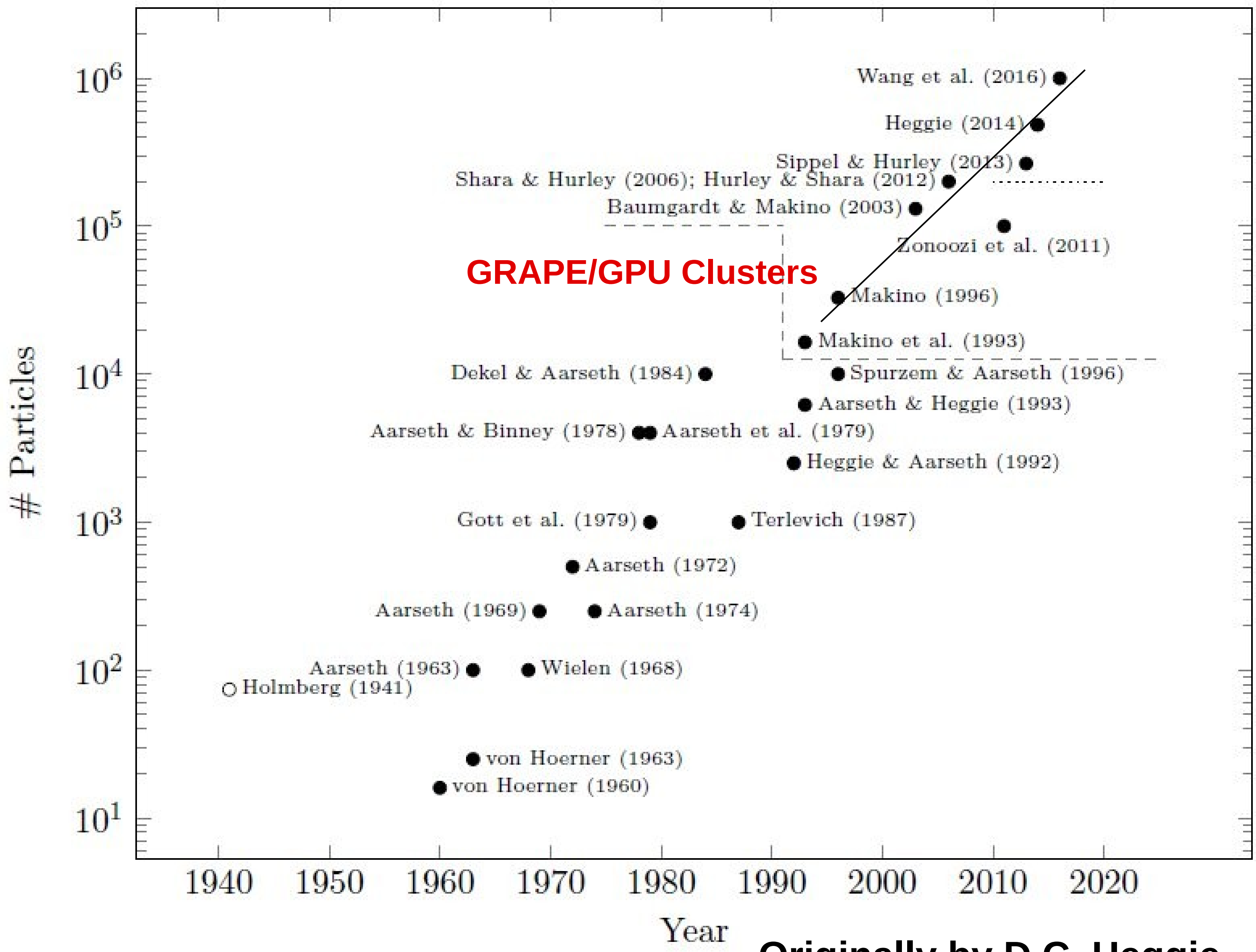
The N-body pro

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..

Jun Makino
with GRAPE6 →
(2002)

"Moore's" Law for Direct N-Body



Originally by D.C. Heggie
Extended by Anna Sippel

90’s at Institute of Astronomy, Cambridge, UK

Left: Emanuel Vilkoviski, Pavel Kroupa, Sverre Aarseth, R.Sp.

Below: Chris Tout, E. Vilkoviski, Sverre Aarseth

Star2000 Conference Heidelberg
ARI 300 year anniversary

Dynamics of Star Clusters and the Milky Way, ASP Conference Series, Vol. 228. Edited by S. Deiters, B. Fuchs, R. Spurzem, A. Just, and R. Wielen. 2001.

some history

Astronomisches Rechen-Institut in Heidelberg
Mitteilungen Serie A Nr. 14

Die numerische Integration des n-Körper-Problemes für Sternhaufen I

Von

SEBASTIAN VON HOERNER

Mit 3 Textabbildungen

(Eingegangen am 10. Mai 1960)

Astronomisches Rechen-Institut in Heidelberg
Mitteilungen Serie A Nr. 19

Die numerische Integration des n-Körper-Problems für Sternhaufen, II.

Von

SEBASTIAN VON HOERNER

Mit 10 Textabbildungen

(Eingegangen am 19. November 1962)

Sebastian von Hoerner
(1919 – 2003)

Dynamics of Star Clusters and the Milky Way
ASP Conference Series, Vol. 228, 2001
S. Deiters, B. Fuchs, A. Just, R. Spurzem, and R. Wielen, eds.

How it All Started

Sebastian von Hoerner

Krummenackerstraße 186, 73733 Esslingen, Germany

After having worked for turbulence and shock fronts, I changed 1956 to the structure and dynamics of star clusters, but soon I found this somewhat frustrating. Before starting a theoretical treatment, one had to make so many assumptions and approximations, that I did not know how much of the final results one really could believe. I would have loved to try it a completely different way, by "Experimental Mathematics", so to say. Just make a little cluster of stars, with random locations and random velocities, put it on a computer, integrate Newton's gravity in small time steps, and just look and see what the little thing really does. Without any assumptions or approximations to start with. Well, one assumption: that treating a small number will already make sense.

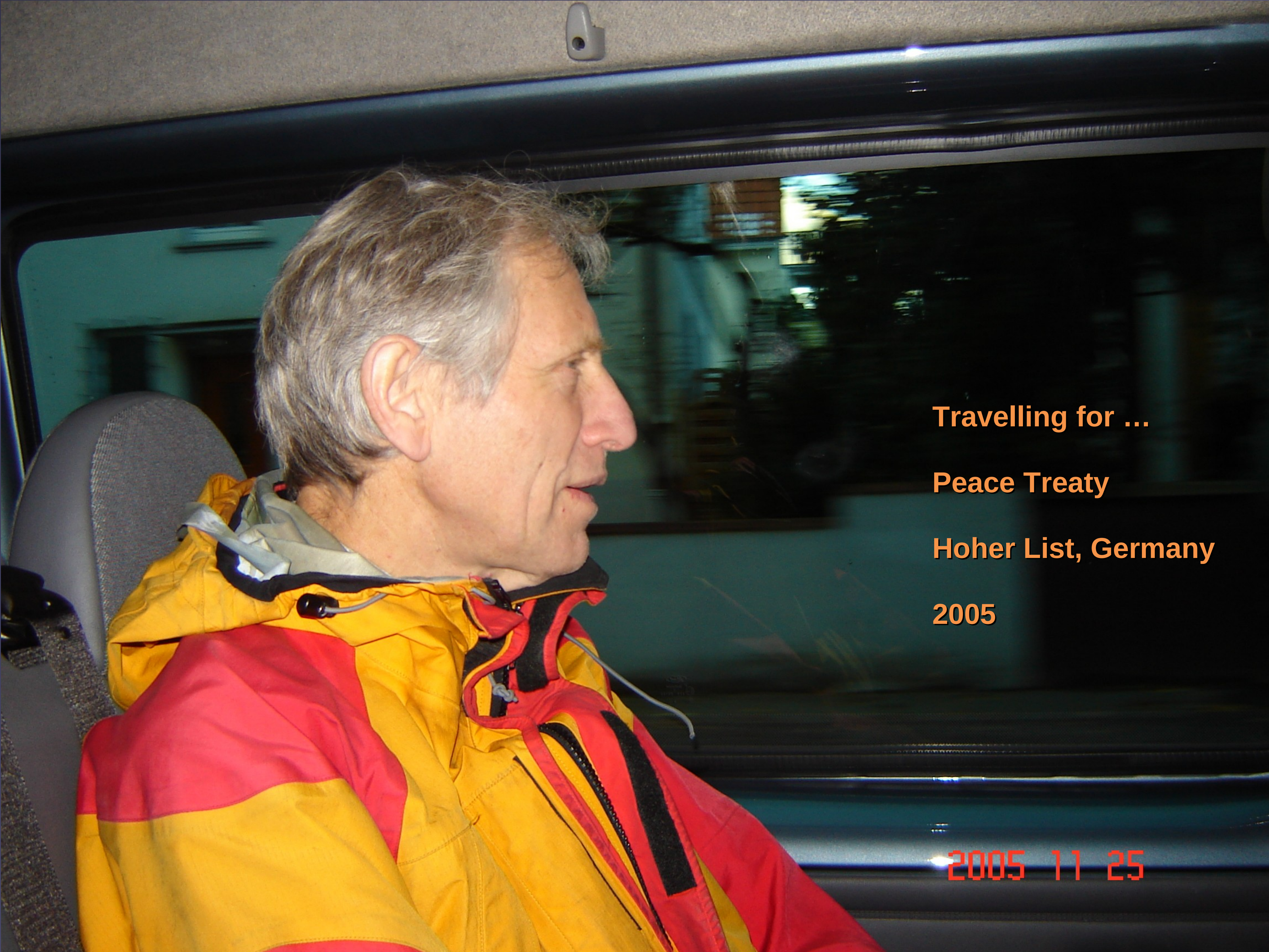
This would need two new things: random numbers, and a fast computer. The first one did exist: in 1956 I had invented a method to create fairly good random numbers, which stayed in general use for some years. But the second one did not. Our first electronic computer, finished 1952 by the Max-Planck-Institut at Göttingen, G1, made 5 operations/sec (fixed point), and had a memory of 26 numbers. It used 476 vacuum tubes (and 101 relays). And with a lifetime of, say 4 years per tube, this gives every three days a breakdown (of computer and user). Nevertheless, we gladly used it day and night. The next one, the G2 in 1955, hat about ten times the speed and the memory. Good progress; but a square root still took 0.6 seconds. – Integrating a little cluster, of only $N = 10$ stars, would mean to handle $6 \times N = 60$ coupled partial differential equations of second order, and that was completely out of question. Also, each small time step would need $N(N\text{-}1)/2 = 45$ square roots, or 27 seconds for just those roots. – Thus, the whole method wound up in my drawer of "great impossible ideas".

Later used: Siemens 2002 at ARI in Heidelberg...

Binary Parallelization in Norway 2001 – not yet successful

Binary Parallelization in Norway 2001 – not yet successful


MODEST-3, Monash/Melbourne, 2003


Travelling for …
Peace Treaty
Hoher List, Germany
2005
2005 11 25

Peace Treaty

Hoher List, Germany

2005

Top:
Simon Portegies Zwart
Sverre Aarseth

Right:
Holger Baumgardt, Sverre Aarseth,
Pavel Kroupa, Rainer Spurzem

Top:
Andrea Borch
Gopakumar Achamveedu
Sverre Aarseth

Right:
Gopu, Sverre, Peter Berczik,
Jose Fiestas

Sambaran Banerjee, Ann-Marie Madigan, Sverre Aarseth, Alexei Minz, Oliver Porth, R.Spurzem
Avetis Sadoyan, Matthew Benacquista

MODEST 8a
Heidelberg 2008

Further Development of
Chain Regularization

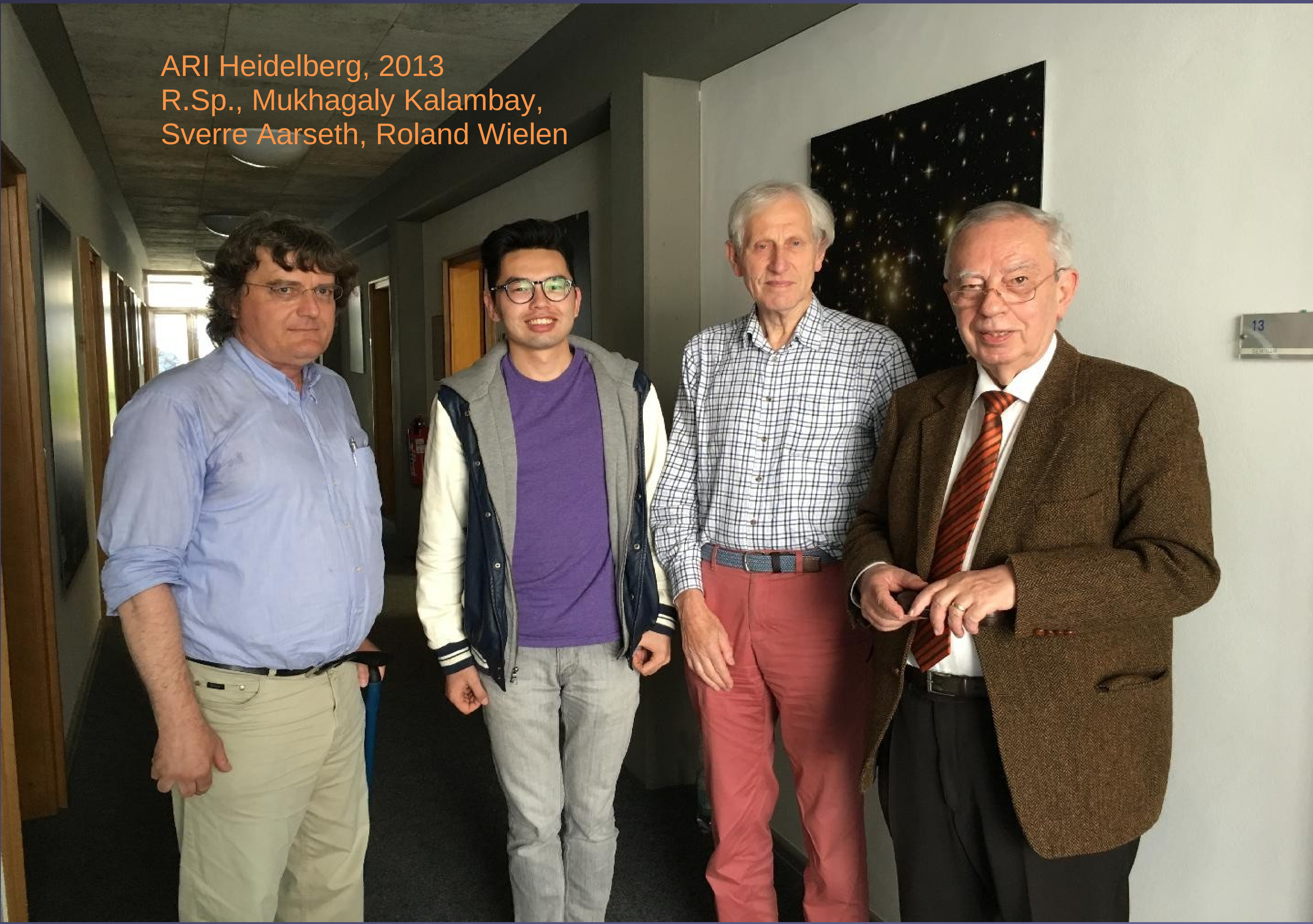
IAU Symp. No. 246
Capri, Italy, 2007

Top:
Sverre Aarseth,
Seppo Mikkola

Right:
Sverre Aarseth
Pavel Kroupa
Paulina Assmann

Pfalz Region near Heidelberg
2008

For the Silk Road Project: MODEST-13, 2013
Almaty, Kazakhstan - Mountaineering



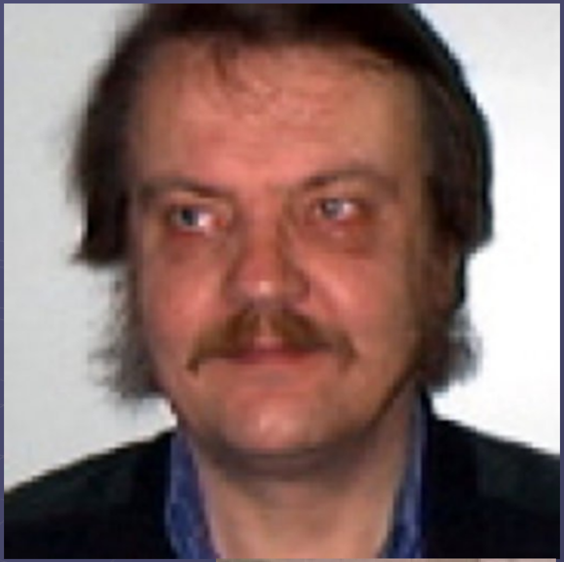
ARI Heidelberg, 2013
R.Sp., Mukhagaly Kalambay,
Sverre Aarseth, Roland Wielen

Heidelberg 2018 with
Thijs M.B.N. Kouwenhoven


Heidelberg 2018
Work Life Balance

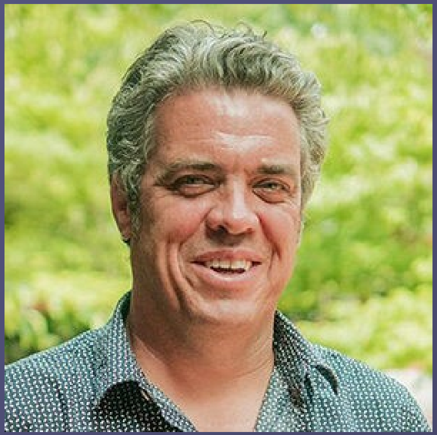
- Start and Growth
- **Code(s) and science**
- The future

Last but not least: Nbody-X History



After Holmberg and von Hoerner:

Sverre Aarseth, Roland Wielen, Seppo Mikkola



Jarrod Hurley, Steve McMillan, Jun Makino

Later see: Keigo Nitadori, Long Wang, Peter Berczik…

and more: Sambaran Banerjee, Albrecht Kamlah,

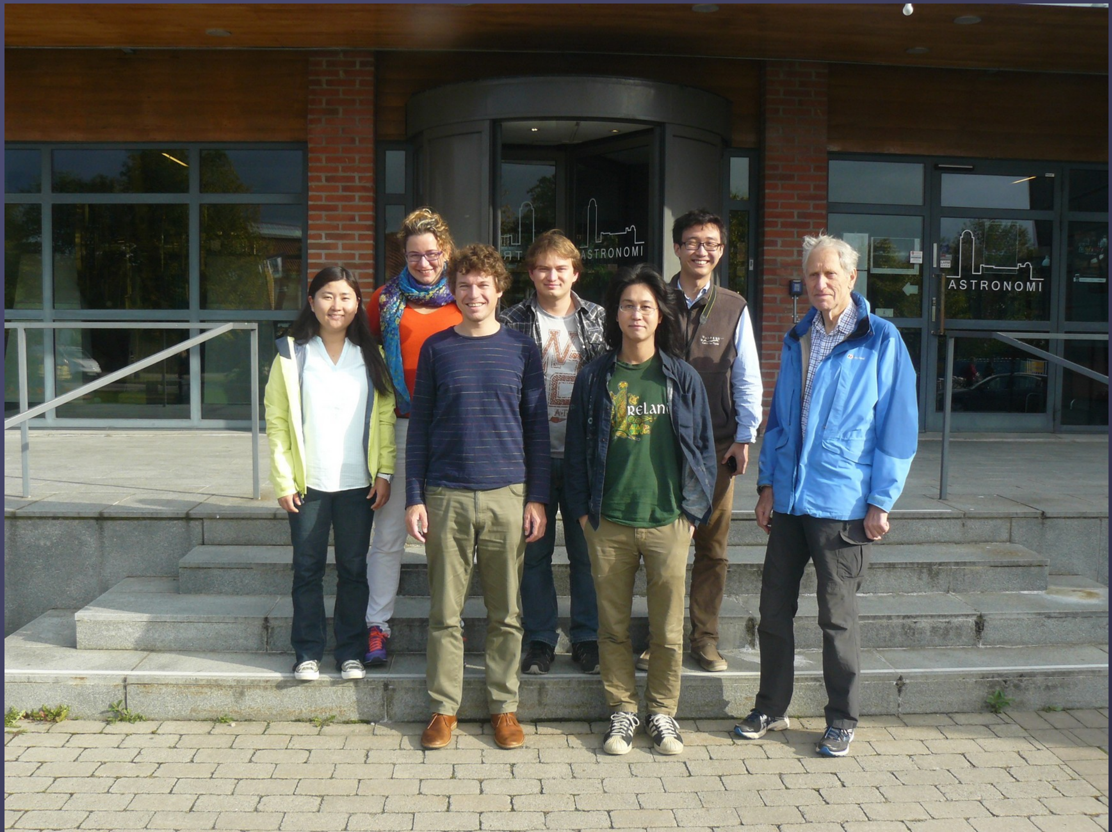
Manuel Arca Sedda, ...

Direct N-Body Simulations

So we need (among others):

- 2-body Regularization (Kustaanheimo & Stiefel 1965)
- 3-body Regularization (Aarseth & Zare 1974)
- Hierarchical Subsystems (Chain, Aarseth & Mikkola)
- Our GPU implementation: Keigo (Nitadori & Aarseth 2012)

Quaternions....



18 September 2015: some participants at the N-body workshop in Lund

From the left: Seungkyung Oh, Anna Sippel, Mark Gieles, ***Taras Panamarev, Keigo Nitadori, Long Wang, Sverre Aarseth***

Keigo: RIKEN Inst. Japan (→ Fugaku)

NBODY1 – NBODY7: "The Further Growth of the Industry"
Spurzem & Kamlah, 2023, Liv. Rev. Comp. Astrophysics

Table 3 Comparison of the code versions

	ITS	ACS	KS	HITS	PN	AR	CC	MPI	GPU
NBODY1	✓								
NBODY2		✓		✓					
NBODY3	✓		✓						
NBODY4			✓	✓			✓		
NBODY5	✓	✓	✓		(✓)		✓		
NBODY6		✓	✓	✓	r		✓		
NBODY6GPU		✓	✓	✓	✓		✓		✓
NBODY6++		✓	✓	✓			✓	✓	
NBODY6++GPU		✓	✓	✓	r		✓	✓	✓
NBODY7		✓	✓	✓	✓	✓			✓

✓: Included in standard version of that level
ITS: Individual time-steps (Aarseth 1985a)
ACS: Ahmad–Cohen neighbour scheme (Ahmad and Cohen 1973)
KS: KS–regularization of few-body subsystems (Kustaanheimo and Stiefel 1965)
HITS: Hermite scheme integration method combined with hierarchical block time-steps (Makino and Aarseth 1992)
PN: Post-Newtonian (Kupi et al. 2006; Mikkola and Merritt 2008a; Aarseth 2012)
r: restricted PN, only orbit-averaged energy loss by gravitational radiation (Rizzuto et al. 2021, 2022; Arca-Sedda et al. 2021)
(✓): only included in special version of the code (Kupi et al. 2006)
AR: Algorithmic regularization (Mikkola and Merritt 2008a)
CC: Classical chain regularization (Mikkola and Aarseth 1998)
MPI: Message Passing Interface, multi-node multi-CPU parallelization (Spurzem 1999)
GPU: use of GPU acceleration (Nitadori and Aarseth 2012) (if also MPI: multi-node many GPU, Berczik et al. 2013)

Table 5.1: Table showing important algorithmic, hardware and software development stepping stones in the development of direct N-body codes. The table is adapted from Aarseth (1999a), corrected in some places, but expanded to more recent developments.

Year	Keyword	Reference
1961	Force polynomial	(Aarseth, 1963)
	Individual time steps	(Aarseth, 1963)
	Gravitaitonal softening	(Aarseth, 1963)
1966	Spherical harmonics	(Aarseth, 1967)
1969	Two-body regularization	(Kustaanheimo & Stiefel, 1965)
1972	Three-body regularization	(Aarseth & Zare, 1974)
1973	Global regularization	(Heggie, 1974)
	Neighbor scheme	(Ahmad & Cohen, 1973)
1978	Co-moving coordinates	(Aarseth, 1979)
1979	Regularized AC	(Aarseth, 1985)
1980	Planetary formation	(Lecar & Aarseth, 1986)
1986	Hierarchical block-time steps	(McMillan, 1986)
1989	Chain regularization	(Mikkola & Aarseth, 1990)
1990	Particle in box scheme	(Aarseth, Lin, & Palmer, 1993)
1991	Collisional tree code	(McMillan & Aarseth, 1993)
1992	Chain N-body interface	(Aarseth, 1994)
1993	Hermite integration	(Makino, 1991)
1995	Synthetic stellar evolution	(Tout et al., 1997)
	Tidal circularization	(Mardling, 1995a, 1995b)
	Slow chain regularization	(Mikkola & Aarseth, 1998)
1996	Hierarchical stability	(Mardling & Aarseth, 1999)
1998	Evolution of hierarchies	(Mardling & Aarseth, 1999)
	Stumpff KS method	(Mikkola & Aarseth, 1998)
1999	HARP-6 procedures	(Aarseth, 1999a)
	Sympletic integrators	(Mikkola & Tanikawa, 1999b, 1999a)
	NBODY6++ SPMD / MPI acceleration	(Spurzem, 1999)
2000	Single stellar evolution - SSE	(Hurley, Pols, & Tout, 2000)
2002	Binary stellar evolution - BSE	(Hurley, Tout, & Pols, 2002)
2003	GRAPE-6 procedures	(Makino et al., 2003)
2006	2.5PN in NBODY5	(Kupi, Amaro-Seoane, & Spurzem, 2006)
2007	direct N-body GPU acceleration	(Portegies Zwart, Belleman, & Geldof, 2007)
2008	AR with Post-Newtonian terms	(Mikkola & Merritt, 2008)
2010	Updated AR for few-body problems	(Hellström & Mikkola, 2010)
2012	NBODY codes GPU acceleration	(Nitadori & Aarseth, 2012)
2013	MPI acceleration on GPU clusters / PHIGPU	(Berczik et al., 2013)
	3.5PN in NBODY6	(Brem, Amaro-Seoane, & Spurzem, 2013)
2015	SSE/AVX acceleration on GPU clusters	(Wang et al., 2015)
2017	Sympletic integrators (FSI)	(Dehnen & Hernandez, 2017)
2020	P^3T with SDAR in PETAR	(Wang, Nitadori, & Makino, 2020a; Wang et al., 2020a)
2021	Minimum spanning tree MSTAR/BIFROST	(Rantala, Naab, & Springel, 2021)

From: Spurzem, Kamlah, Living Review Computational Astrophysics Vol. 9, pp. 3-109 2023

Parameterized stellar evolution tracks (IFMR for neutron stars and white dwarfs)

(SSE++/BSE++ from Kamlah et al. 2022 and Spurzem & Kamlah, Living Reviews Comp. Astroph. 2023)

- updated metallicity dependent core-collapse SNe, their remnant masses and fallback (Fryer et al. 2012; Banerjee et al. 2020),
- updated electron-capture supernovae (ECSNe), accretion-induced collapse (AIC) and merger-induced collapse (MIC) remnant masses and natal kicks (Nomoto 1984, 1987; Nomoto & Kondo 1991; Saio & Nomoto 1985, 2004; Kiel et al. 2008; Gessner & Janka 2018)
- (P)PISNe remnant masses (Belczynski et al. 2010, 2016; Woosley 2017),
- updated fallback-scaled natal kicks for NSs and BHs (Fuller et al. 2003; Scheck et al. 2004; Fryer 2004; Fryer & Kusenko 2006; Meakin & Arnett 2006, 2007; Fryer & Young 2007; Scheck et al. 2008; Fryer et al. 2012; Banerjee et al. 2020),
- and BH natal spins (see also Belczynski et al. (2020); Belczynski & Banerjee (2020)) from
  - Geneva model (Eggenberger et al. 2008; Ekström et al. 2012; Banerjee et al. 2020; Banerjee 2021b),
  - MESA model (Spruit 2002; Paxton et al. 2011, 2015; Banerjee et al. 2020; Banerjee 2021b),
  - and the Fuller model (Fuller & Ma 2019; Fuller et al. 2019; Banerjee et al. 2020; Banerjee 2021b).

ECSN = electron capture Supernova

AIC = accretion induced collapse

MIC = merger induced Collapse

PISN = pair instability Supernova

PPISN = pulsating PISN

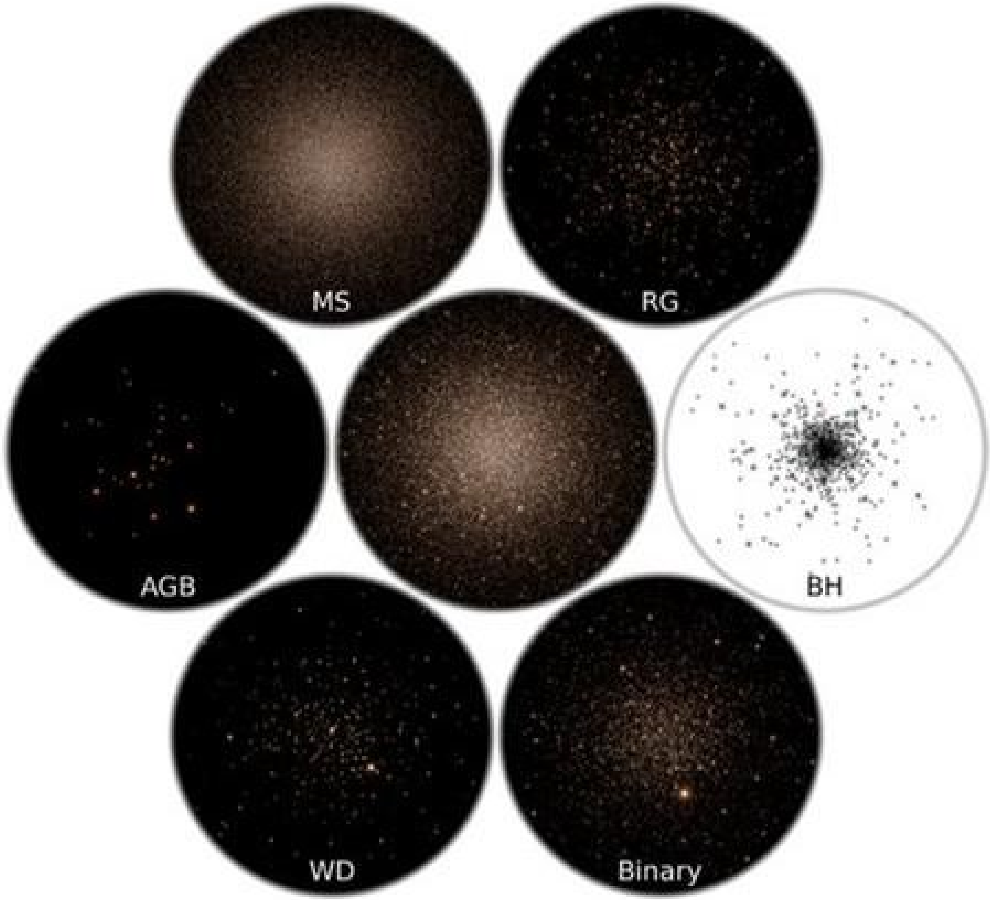
NS = neutron star

BH = black hole

MESA = recent stellar evolution model

One million stars direct simulation,
biggest and most realistic direct N-Body simulation of globular star clusters.
With stellar mass function, single and binary stellar evolution, regularization of close encounters, tidal field (NBODY6++GPU).
(NAOC/Silk Road/MPA collaboration).

Wang, Spurzem, Aarseth, Naab et al.
MNRAS, 2015
Wang, Spurzem, Aarseth Naab, et al.
MNRAS 2016



CPU/GPU N-body6++

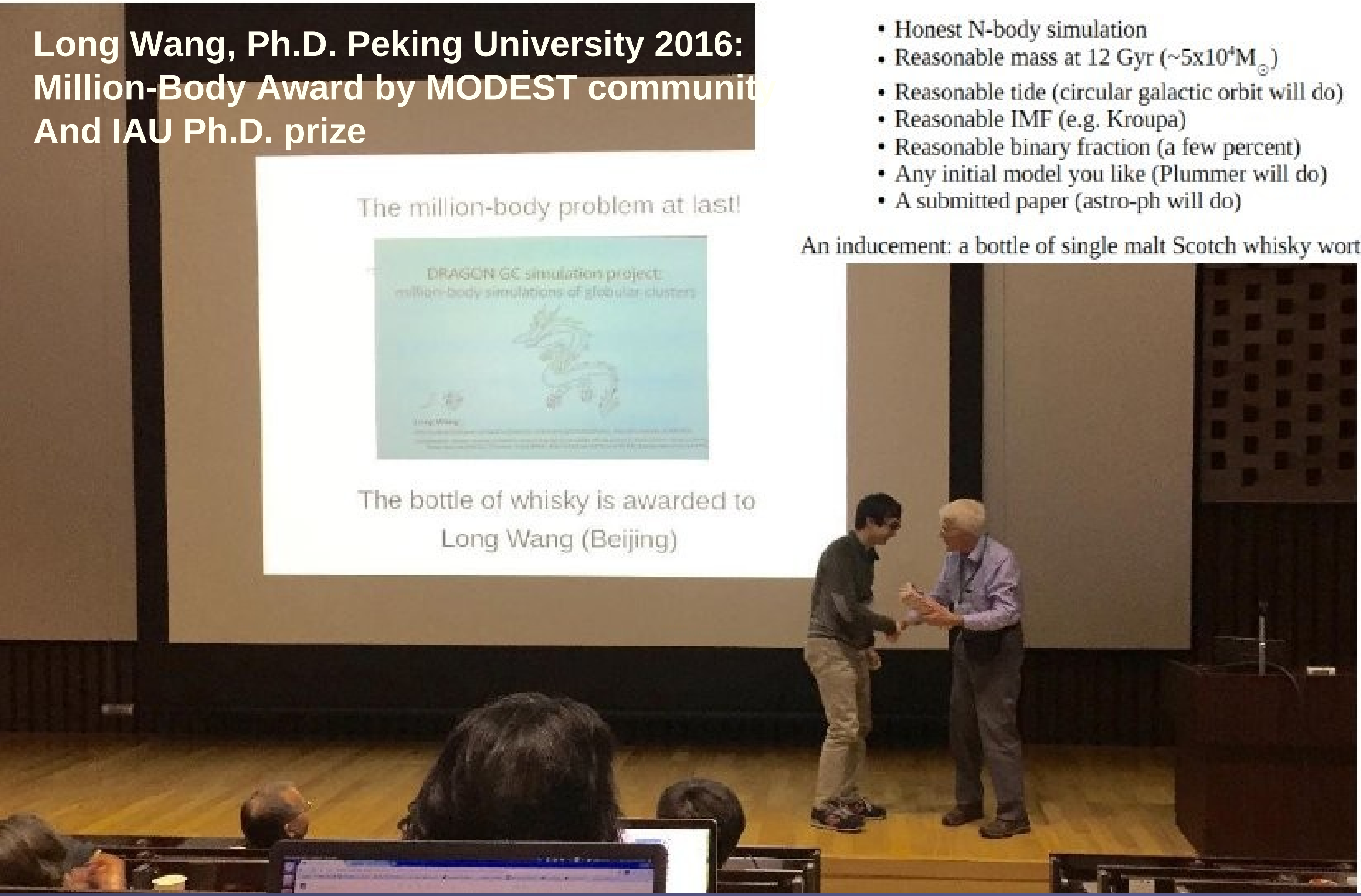
Leiden

Key Question 1. When will we see the first star-by-star *N*-body model of a globular cluster?

- Honest N-body simulation
- Reasonable mass at 12 Gyr (~$5\times10^4 M_\odot$)
- Reasonable tide (circular galactic orbit will do)
- Reasonable IMF (e.g. Kroupa)
- Reasonable binary fraction (a few percent)
- Any initial model you like (Plummer will do)
- A submitted paper (astro-ph will do)

An inducement: a bottle of single malt Scotch whisky worth €50

Long Wang, Ph.D. Peking University 2016:
Million-Body Award by MODEST community
And IAU Ph.D. prize



Long Wang gets award for first globular cluster simulation with Nbody6++GPU (2016 PhD student of R. Spurzem; now professor at Zhongshan Univ., Zhuhai)

DRAGON I Galactic Center Simulations

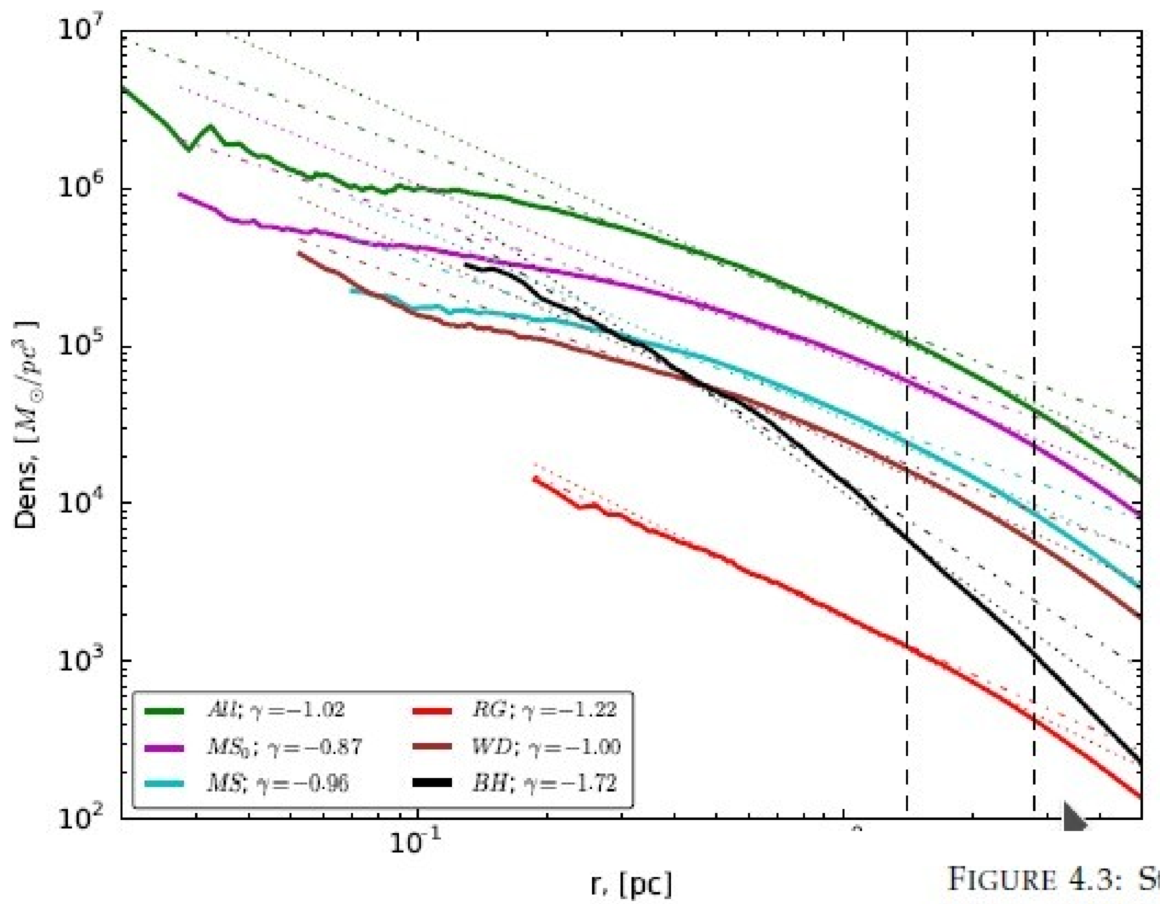


FIGURE 4.3: Stellar density profiles at t = 5 Gyr for different stellar types. Thick solid lines correspond to: All - all stars, MS_{low} - low mass main sequence stars, MS - main sequence, RG - red giants, WD - white dwarfs, BH - black holes. Corresponding power-law slopes fitted inside the initial and final influence radii of the SMBH are shown as dash-dotted and dotted lines of the same colour. The dashed vertical lines denote the initial influence radius ($r = 1.4pc$) and the influence radius at $t = 5Gyr$ ($r \sim 2.8pc$) of the SMBH. The power-law indices fitted inside $r = 1.4pc$ are shown in the legend.

Initial Data:

1 million stars

10% fixed SMBH mass

Zero age pop, 0.8 – 100

Spherical

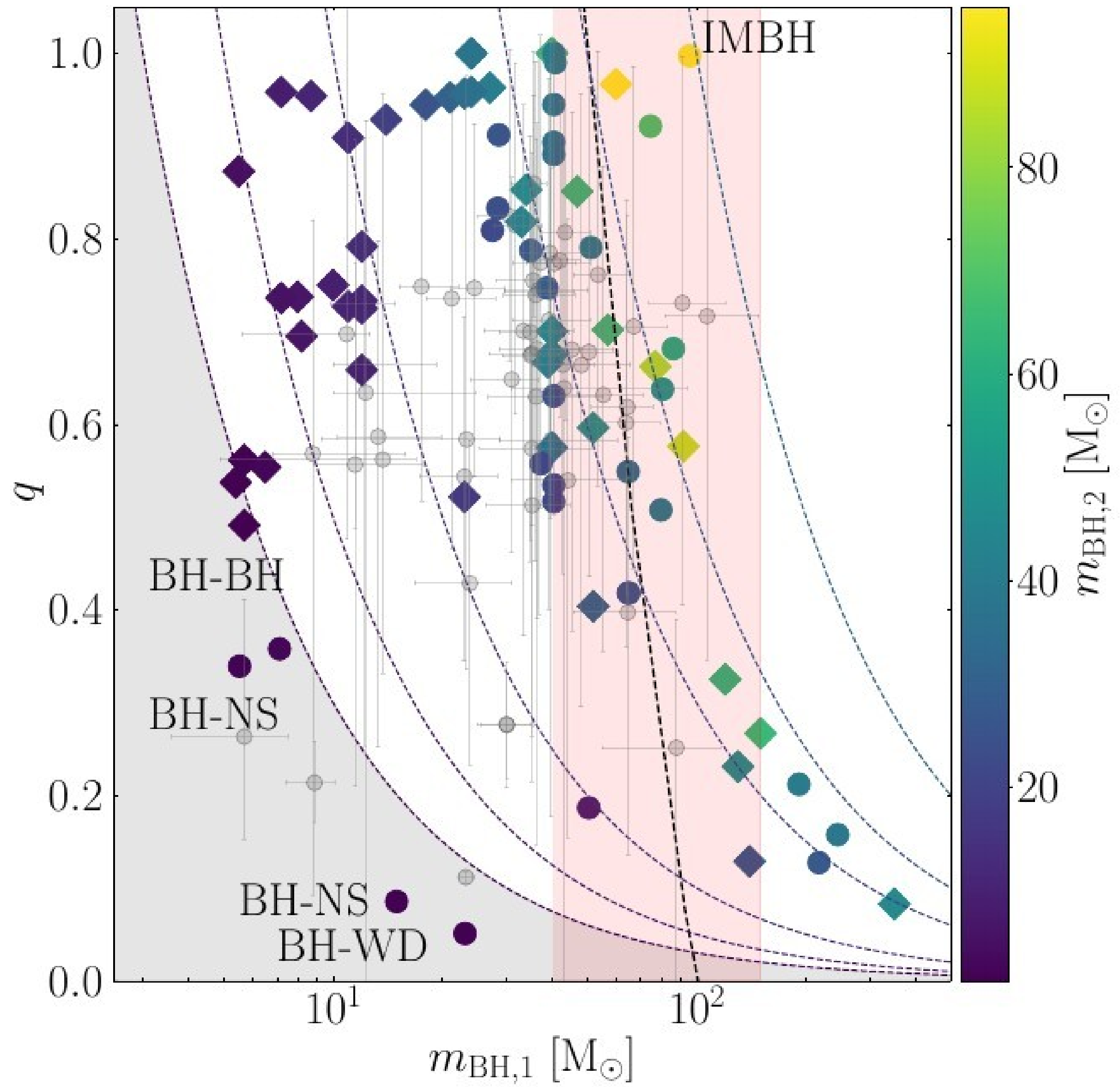
Density Profiles of stars and *-mass Black Holes in the Galactic Center after 5 Gyr

Extremely simple "accretion radius" For ALL objects.

Panamarev, Just, Spurzem, et al. 2019

Panamarev, …, Just, Spurzem, 2018, MNRAS

Simulation of Gravitational Wave Sources of LIGO/Virgo
using NBODY6++GPU



Arca Sedda et al. 2023ab, 2024: MNRAS

Colored Points:
Nbody6++GPU

Gray Points:
Gravirational Wave Observations
By LIGO/Virgo

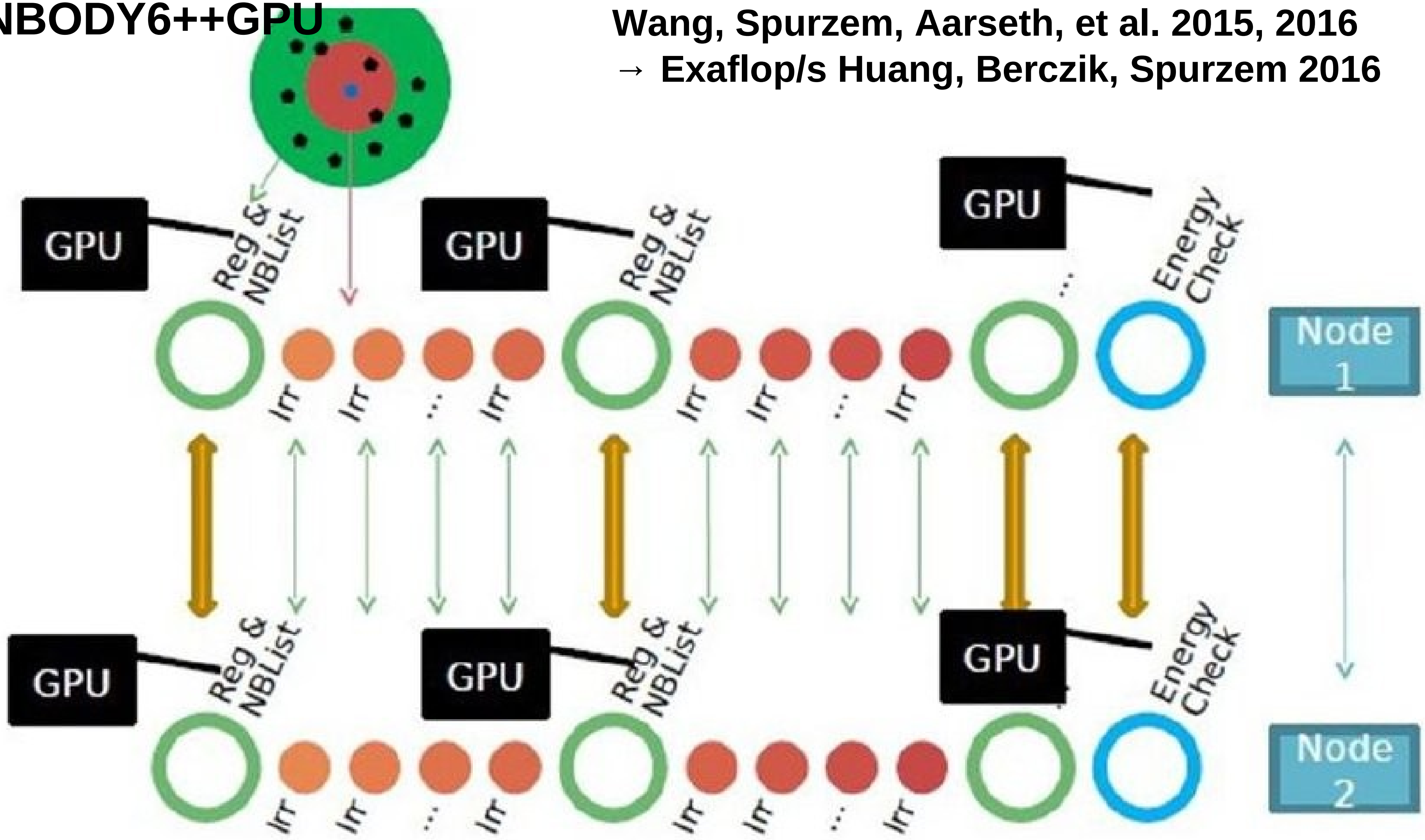
Left Corner:
Black Hole – Neutron Star Binary Detected

Will be observed by FAST
(next slide)

Our CPU/GPU N-body (AC) code

NBODY6++GPU

Wang, Spurzem, Aarseth, et al. 2015, 2016
→ Exaflop/s Huang, Berczik, Spurzem 2016

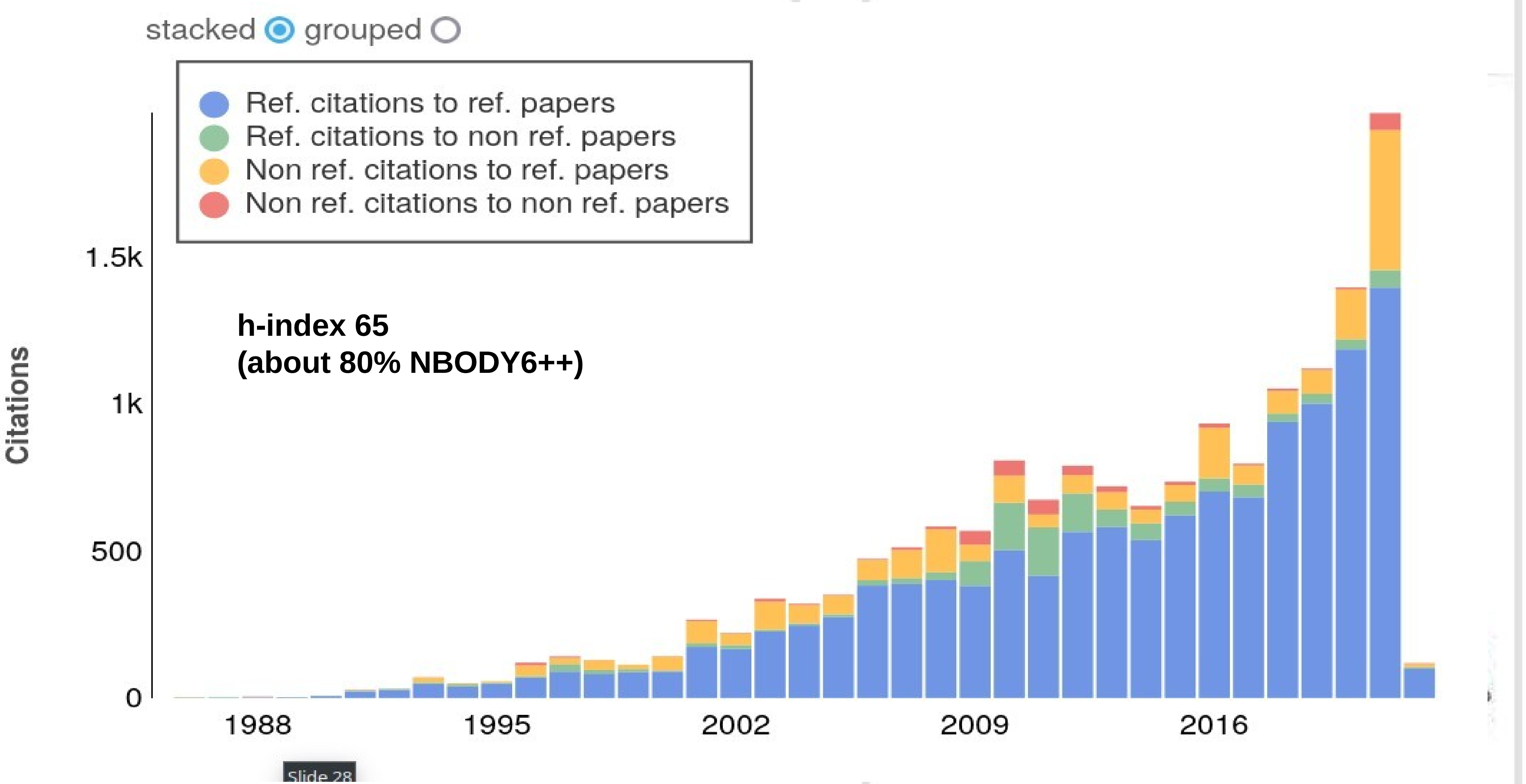


https://github.com/lwang-astro/betanb6pp

To demonstrate how successful the direct NBODY codes are in our field we have collected the following three figures from the ADS Bumblebee (full text search) facility. The search string

full:NBODY5 OR full:NBODY6 OR full:"NBODY6++" OR full:NBODY7 OR full:NBODY4

has been used to catch all publications using or citing the different variants of the code.



- Start and Growth
- Code(s) and Science
- **The future**

PeTar: a high-performance N-body code for modeling massive collisional stellar systems

Long Wang,[1,2★] Masaki Iwasawa,[2,3] Keigo Nitadori[2] and Junichiro Makino[2,4]
[1]Department of Astronomy, School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan
[2]RIKEN Center for Computational Science, 7-1-26 Minatojima-minami-machi, Chuo-ku, Kobe, Hyogo 650-0047, Japan
[3]National Institute of Technology, Matsue College, 14-4, Nishi-ikuma-cho, Matsue, Shimane 690-8518, Japan
[4]Graduate School of Science, Kobe University, 1-1 Roki...ho, Nada-ku, Kobe, Hyogo 657-8501, Japan

Accepted XXX. Received YYY; in original form ZZZ

New competition 1:
PeTar: MNRAS 2020
Many more papers...

ABSTRACT
The numerical simulations of massive collisional stellar systems, such as globular clusters (GCs), are very time-consuming. Until now, only a few realistic million-body simulations of GCs with a small fraction of binaries (5%) have been performed by using the NBODY6++GPU code. Such models took half a year computational time on a GPU based super-

FROST: a momentum-conserving CUDA implementation of a hierarchical fourth-order forward symplectic integrator

Antti Rantala[1★], Thorsten Naab[1], Volker Springel[1]
[1]Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85748, Garching, Germany

New competition 2:
FROST: MNRAS 2021
BIFROST: MNRAS 2022

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT
We present a novel hierarchical formulation of the fourth-order forward symplectic integrator and its numerical implementation in the GPU-accelerated direct-summation N-body code FROST. The new integrator is especially suitable for simulations with a large dynamical range due to its hierarchical nature. The strictly positive integrator sub-steps in a fourth-

NBODY6++GPU with up to 16M particles

(Benchmarks on raven at MPCDF)

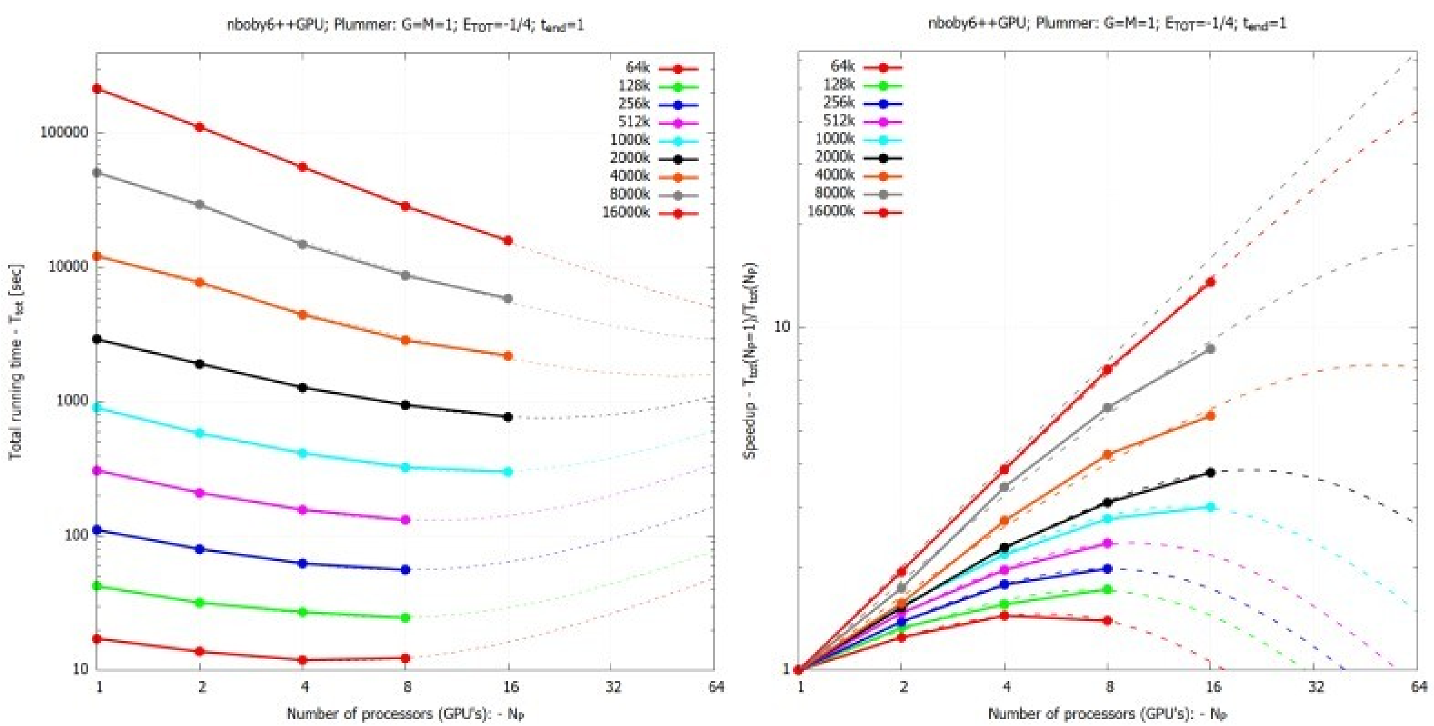


Figure 6: Benchmark results and extrapolated scaling for NBODY6++GPU, initial Plummer model, on the raven cluster at MPCDF, see main text. **Left:** Total time for one NBODY model unit in secs; **Right:** Speed-Up compared to using one GPU only. In both cases different curves for particle numbers from 64k to 16m. Ideal Speedup is the diagonal dashed lines, other dashed lines extrapolations from the timing model.

DRAGON I Simulation

Wang, Spurzem, Aarseth, et al. 2015, 2016

DRAGON II Simulation

Arca Sedda, Kamlah, Spurzem, et al. 2023, 2024ab

https://github.com/nbody6ppgpu

Also in: https://www.punch4nfdi.de/

Sverre Aarseth (1934-2024)

The Future - DRAGON III 1m – 8m (16m?)

- Following talks of Kai Wu, Seungjae Lee and more in other sessions here using NBODY6++GPU
- Talks about using PeTar and BiFrost
- Globular Cluster (GC) next issues: Rotation, Populations, Tides and Tails, …
- Nuclear Star Cluster (NSC) Simulations: TDE, EMRI, direct capture, partial TDE, partial accretion to SMBH.
- Will legacy codes survive with good support? (Ease of use, data releases, interfaces…)
- AI assisted coding, how far will it go?