the SILK ROAD PROJECT at NAOC
丝绸之路 计划

ZAH ZENTRUM FÜR ASTRONOMIE
ARI ITA LSW Univ. Heidelberg

Deutsche Forschungsgemeinschaft DFG

Direct N-Body
Gravothermal Systems

Rainer Spurzem, and Silk Road Team

(mainly: M. Arca Sedda, GSSI; A. Kamlah, F. Flammini Dotti, J. Hurley, Shuo Li, P. Berczik)

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

National Astronomical Observatories (NAOC), Univ. of Chinese Academy of Sciences

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

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

KITP kinetics24
June 2024

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https://silkroad.zah.uni-heidelberg.de

VolkswagenStiftung

1) **<u>Introduction – History and Theory</u>**

2) Code(s)* and Supercomputers

3) Star Clusters/Black Holes/Grav. Waves

4) Wrap-Up and References

*mainly Nbody6++GPU

Kavli Institute for Astronomy and Astrophysics, Peking Univ..

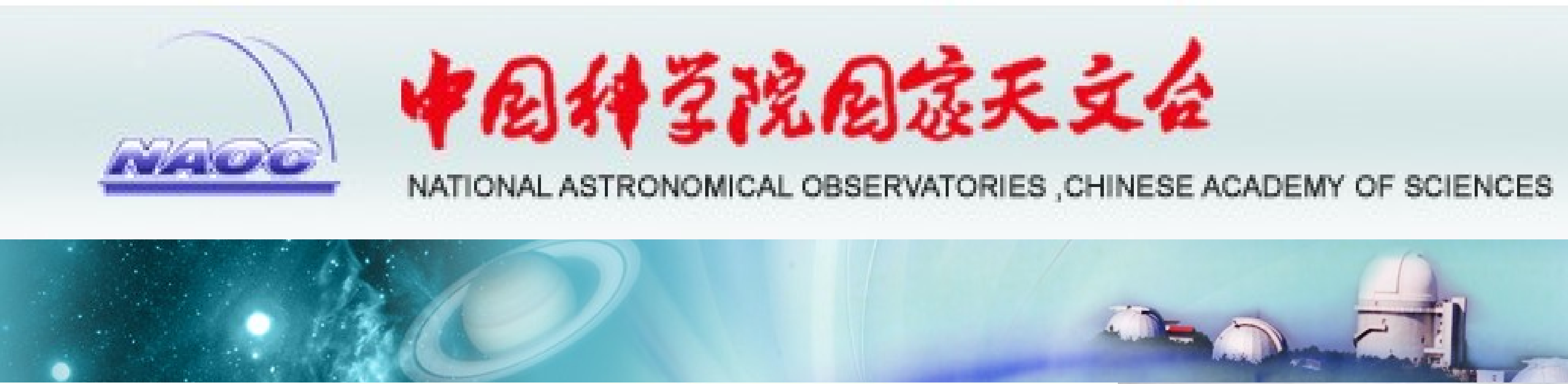
北京大學
PEKING UNIVERSITY

Founded 2008

Astronomisches Rechen-Institut (ARI)
Univ. of Heidelberg, Germany

Founded May 10, 1700

Star2000 Conference Heidelberg: 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.
San Francisco: Astronomical Society of the Pacific.



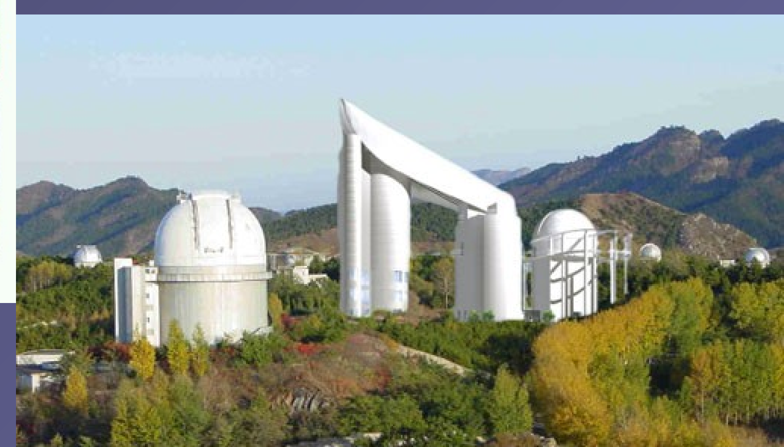
NAOC/ CAS

Silk Road Project =

Computational Science Project...

Top: NAOC Headquarter Beijing

Bottom: LAMOST Site



Kazakhstan - China - Korea (KCK) becomes Silk Road Conference

Kazakhstan-China-Korea meeting becomes Silk Road Conference

13th Silk Road Conference: Dali, China, June 23-27, 2025 (just after the IAU Symposium Compact Objects and Binaries in Dense Star Clusters to be held in Seoul, Korea, June 16-20, 2025)

14th Silk Road Conference: Samarkand, Uzbekistan, June 2026 (to be confirmed)

Exploring the Frontiers of Dynamical Astronomy with High-Performance Computing, Artificial Intelligence, and Leading-Edge Observational Techniques.

We continue the numbering of these conferences, which started as Korea-China meeting in 2009; later it became Kazakhstan-China-Korea meeting, and due to increasing interest and participation of colleagues from all over central and east Asia we decided now to rename it to Silk Road Conference.

Last Conference: 12th Kazakhstan-China-Korea meeting in Astana, Kazakhstan, May 20-24, 2024

IAU Symp. No. 312: Star Clusters and Black Holes in Galaxies across Cosmic Time, August 2014, National Library Beijing

On the Evolution of Stellar Systems

V. A. Ambartsumian

(George Darwin Lecture, delivered on 1960 May 13)

IN THIS lecture we shall consider some aspects of the problem of the evolution of stellar systems. We shall concentrate chiefly on *galaxies*. However, at the same time we shall treat here some questions connected with star *clusters* as component members of galaxies.

Concepts discussed:

Total Energy of grav. star clusters NOT additive

No thermodynamical equilibrium

Statistical Theory of Gases to be used with care

(large mean free path)

Locally truncated Maxwellian distribution.

Physical and Numerical Methods: Modelling the Dynamics

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

- $N = \infty$

negative specific Heat

gravothermal Collapse

gravothermal Oscillations

- $N = 3 \ (N = 2, \ldots, \approx 100)$

History

Exponential Instability

Chaos and Resonance

Regularisation

- $N = 10^6 \ (N = 10^4, 10^5)$

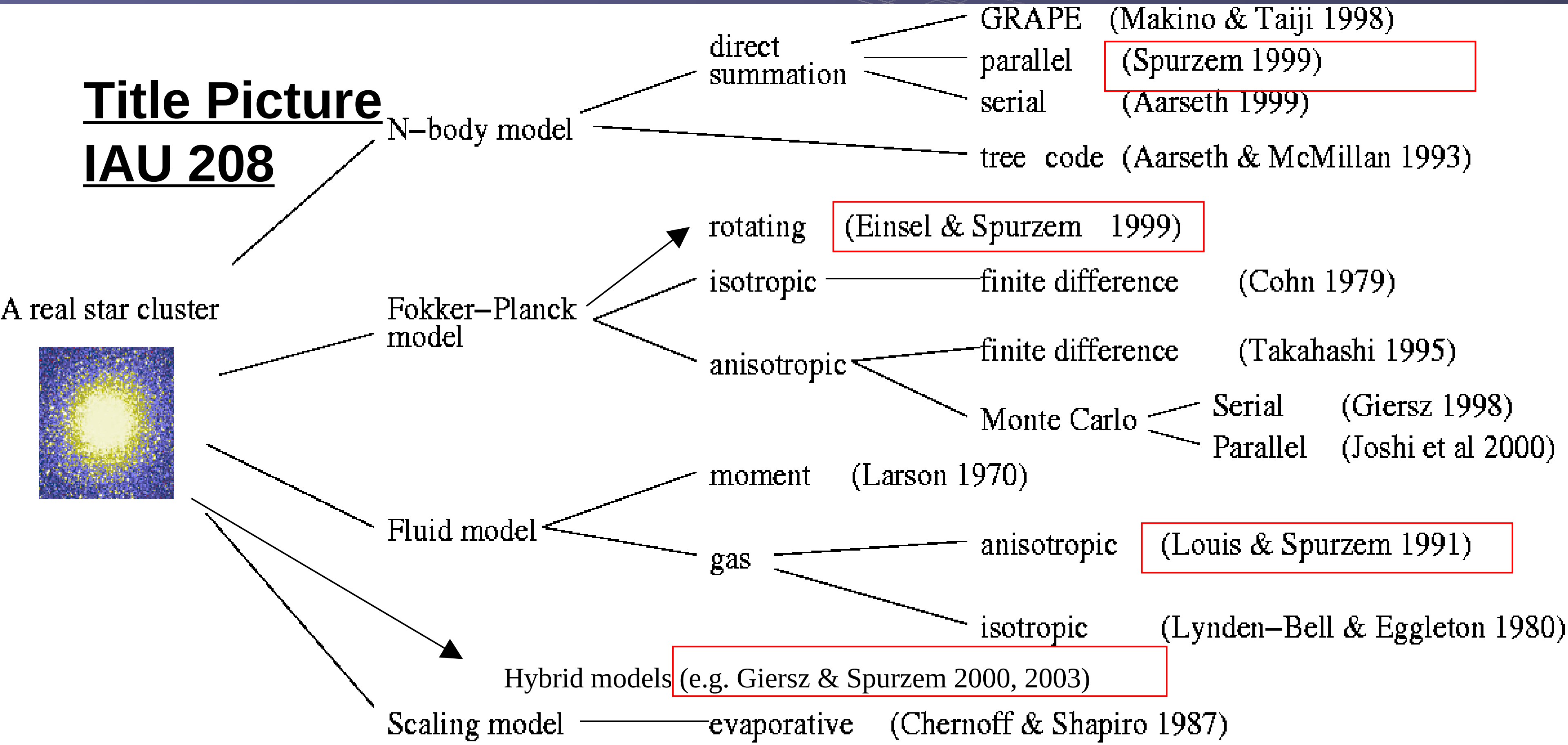
Post-Kollaps-Evolution

Binaries

Globular Clusters

Numerical Stellar Dynamics

Some methods for studying the evolution of globular clusters (by D.C.Heggie)



(citations are not complete for 2006)

Mon. Not. R. astr. Soc. (1980) 191, 483–498

1980

On the consequences of the gravothermal catastrophe

D. Lynden-Bell and P. P. Eggleton *Institute of Astronomy, The Observatories, Cambridge CB3 0HA*

Received 1979 October 9; in original form 1979 July 11

between encounters. In such a stellar system a typical star at any radius moves in and out by about a local Jeans length $\lambda = 1/k_J$ where $k_J^2 v^2 = 4\pi G\rho$. This gives a typical radial distance between encounters. However, the time between those encounters is not λ/v but rather a relaxation time T_r. Hence the energy flux is given by equation (3.5) with $\lambda = k_J^{-1}$ and with τ replaced by T_r

$$\frac{L}{4\pi r^2} = -\frac{C\rho}{k_J^2 T_r}\frac{\partial}{\partial r}\left(\frac{3}{2}v^2\right) \quad (3.7)$$

$$= -3GmC(\log N)\frac{\rho}{v}\frac{\partial v^2}{\partial r} \quad (3.8)$$

- Conductivity ∝ ρ/v
- Based on Jeans Length
- Anisotropic generalization

(Louis & Spurzem 1991)

where C is a dimensionless constant of order unity. As Lecar pointed out, this implies a conductivity K proportional to $\rho T^{-1/2}$ or an opacity κ proportional to $T^{3.5}\rho^{-2}$. Notice that the details of the argument are unimportant, for the use of dimensions, coupled with the fact that the heat flux must be proportional to the relaxation rate (T_r^{-1}) gives the same dependence of conductivity on ρ, v. The detailed computation of Hachisu *et al.* (1978) was

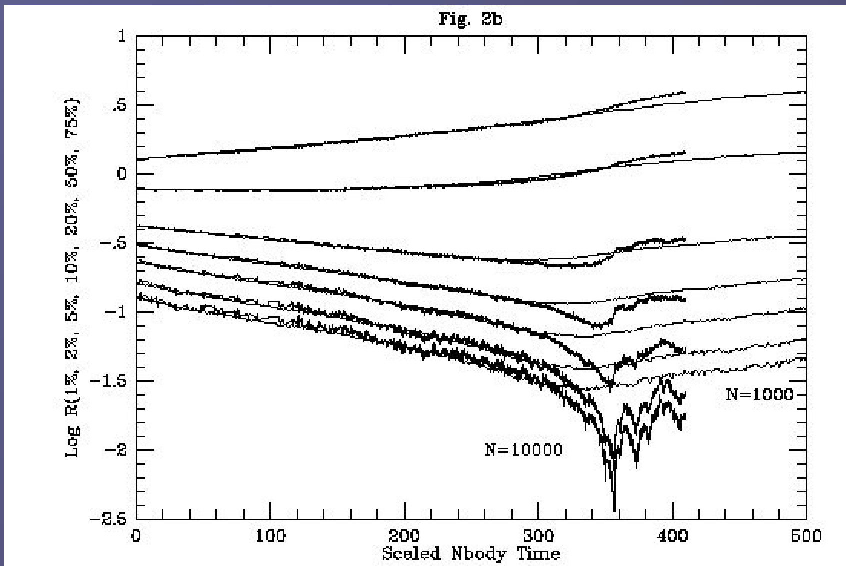
Star Clusters: Modelling the Dynamics

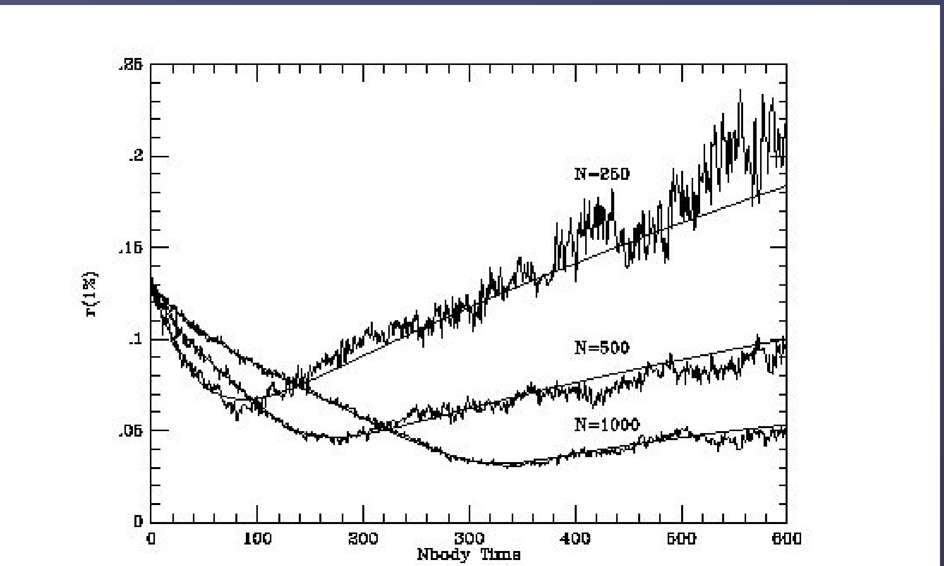
(compare gaseous model with direct N-body integration)

(Spurzem & Aarseth 1996)

(Giersz & Spurzem 1994)

(now in Binney/Tremaine)





N-Body / N-Body

N-Body / Fokker-Planck

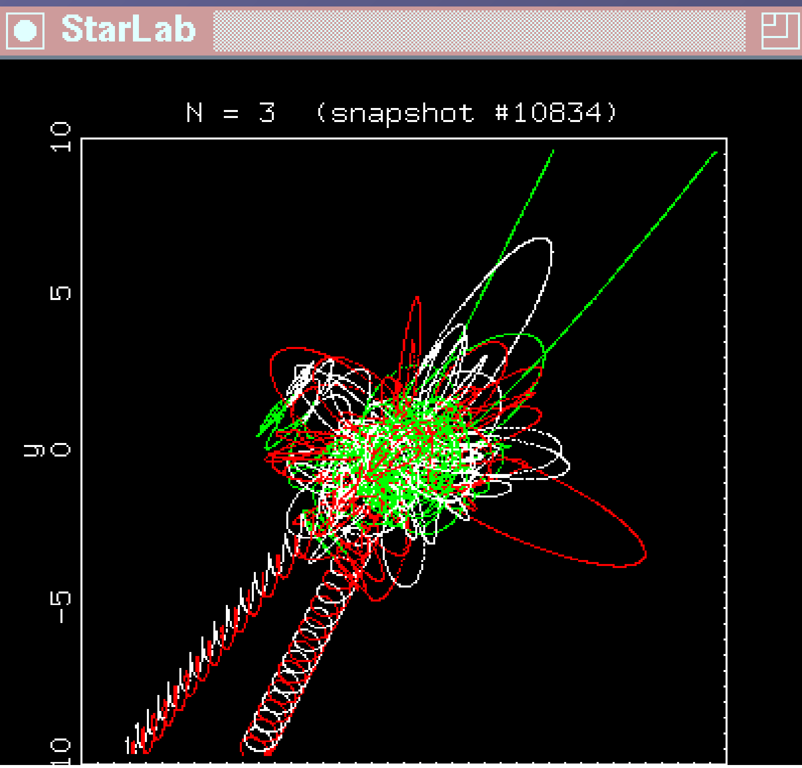
→ Blackboard Talk Week 4 gives more (Tue June 25):

- Fluid and orbit averaged Fokker-Planck models
- central supermassive black hole, rotation
- Anisotropic heat transport, aniso TOV generalization
- Ultracold plasma and self-interacting dark matter

3-body Encounters Starlab Simulation (S.L.W. McMillan)

http://www.physics.drexel.edu/~steve/

-> Three-Body-Problem



Gravothermal Oscillations - Attractor in Phase Space

Spurzem 1994, Giersz & Spurzem 1994

Amaro-Seoane, Freitag & Sp. 2004

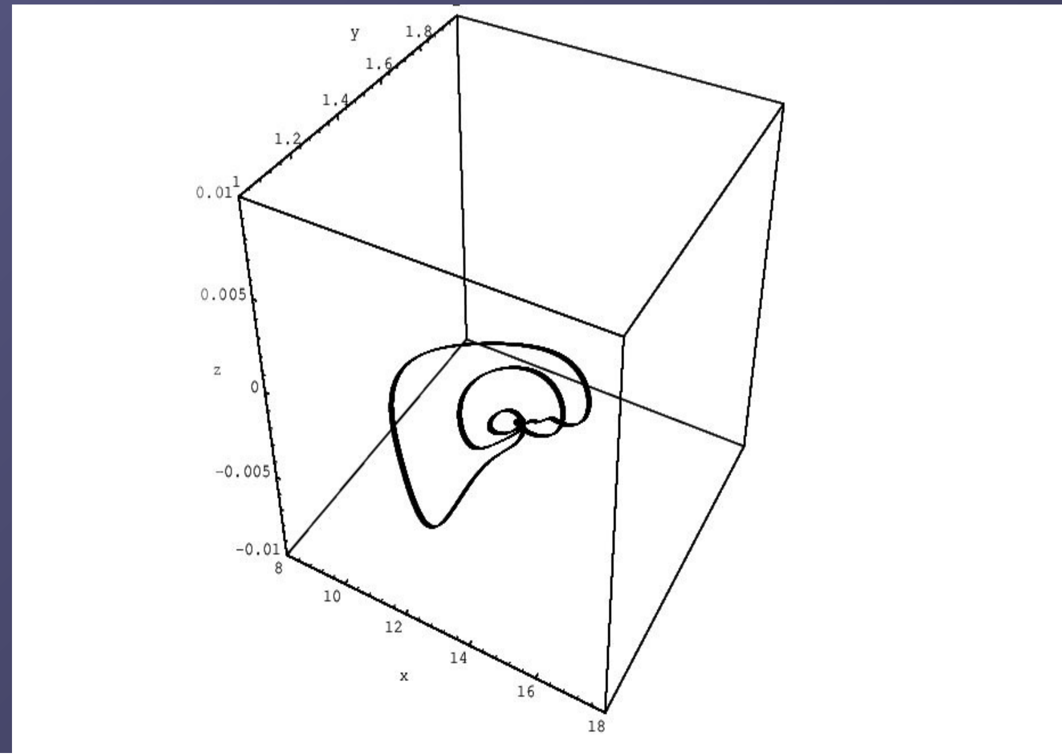


Fig. 3:

-dimensional attractor for $N = 100.000$ system, $x =$ σ'_c, $z = \xi$.

Mon. Not. R. astr. Soc. (1991) **252**, 177–189

Gravothermal instability of anisotropic self-gravitating gas spheres: singular equilibrium solution

R. Spurzem[1,2,3]

[1] *Institut für Theoretische Physik und Sternwarte, University of Kiel, Olshausenstraße 40, D-2300 Kiel, Germany*
[2] *Institut für Astronomie und Astrophysik, University of Würzburg, Am Hubland, D-8700 Würzburg, Germany*
[3] *Universitätssternwarte Göttingen, Geismarlandstraße 11, D-3400 Göttingen, Germany*

Follow-Up of Angeletti & Giannone and Larson

Numerical Stellar Dynamics B: Fokker-Planck

$$\frac{\partial f}{\partial t} + \frac{\partial \phi}{\partial t}\frac{\partial f}{\partial E} = \left(\frac{\partial f}{\partial t}\right)_{\rm enc},$$

with the potential ϕ advanced according to the Poisson equa

$$\nabla^2 \phi = 4\pi G n,$$

and the collisional term on the right-hand side of equatio expressed under the Fokker–Planck assumption of small scatterings:

$$\left(\frac{\partial f}{\partial t}\right)_{\rm enc} = \frac{1}{V}\left[-\frac{\partial}{\partial E}(<\Delta E> fV) - \frac{\partial}{\partial J_z}(<\Delta J_z> fV)\right.$$

$$+\frac{1}{2}\frac{\partial^2}{\partial E^2}(<(\Delta E)^2> fV) + \frac{\partial^2}{\partial E \partial J_z}(<\Delta E \Delta J_z> fV)$$

$$\left.+\frac{1}{2}\frac{\partial^2}{\partial J_z^2}(<(\Delta J_z)^2> fV)\right],$$

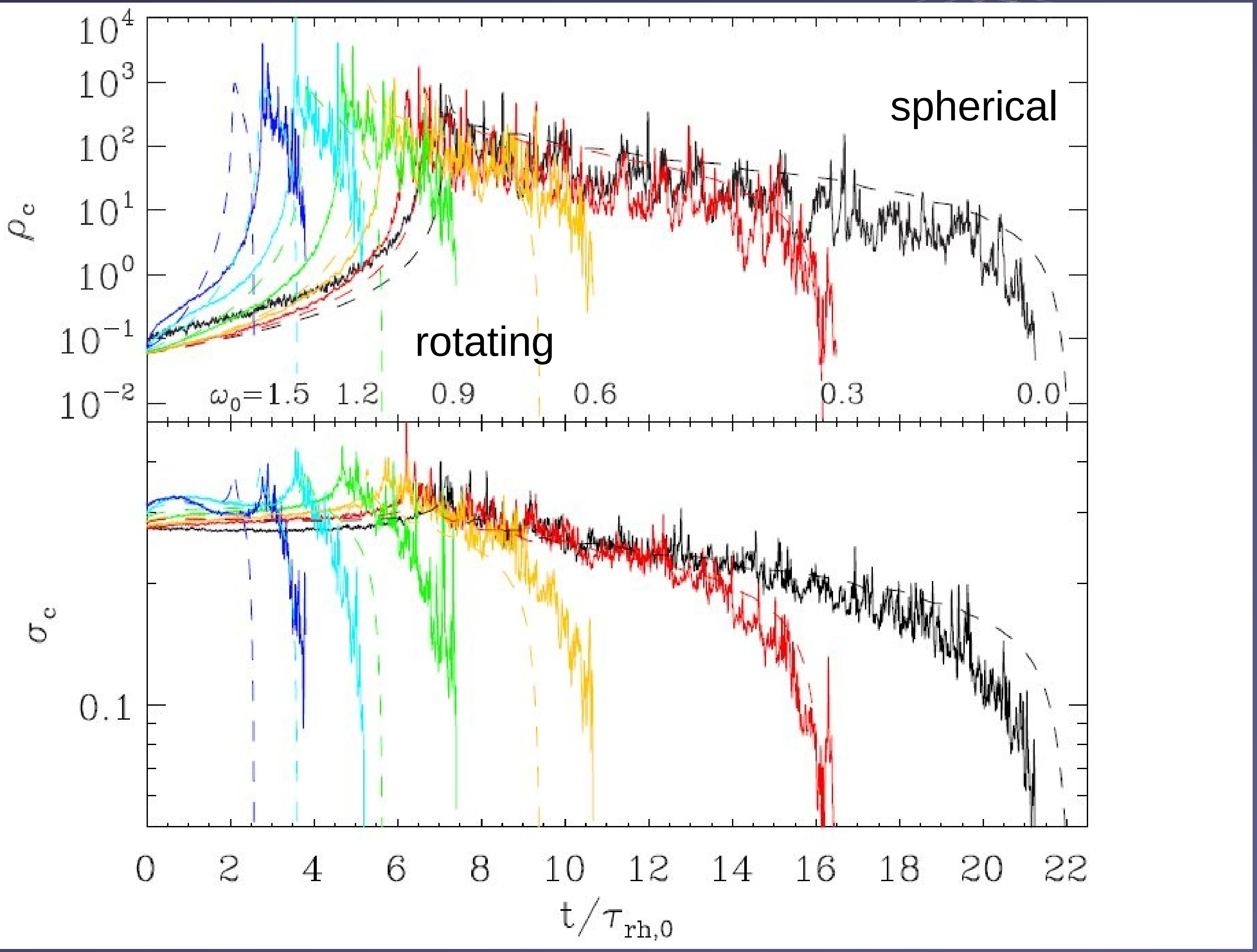
Orbit averaged Fokker-Planck Equation

(here in the 2D form for axisymm. systems, Einsel & Spurzem 1999) (unpubl.Ph.D. thesis by J. Goodman 1983)

Rotating Star Clusters

(compare Fokker-Planck model with direct N-body integration)

Dissolution of Star Cluster in Tidal Field



Kim, Yoon, Lee, Spurzem, 2008, MNRAS

Hong, Kim, Lee, Spurzem, 2013, MNRAS

Three Phases in Cluster Dissolution:

1) Core Collapse (Encounters)

2) Post-Collapse Steady Evaporation (Encount)

3) Dynamic final dissolution

1) Introduction – History and Theory

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*mainly Nbody6++GPU

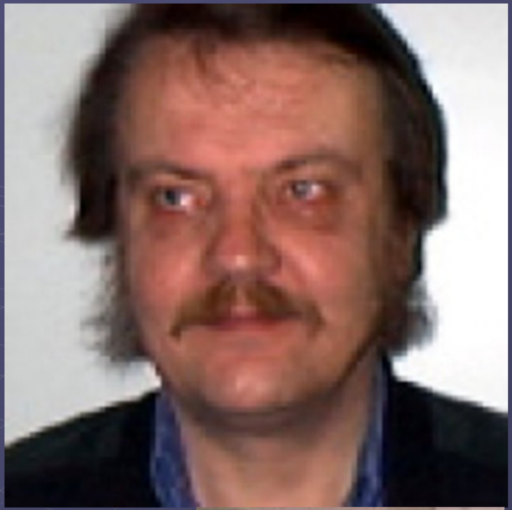
Code(s)

(mainly Nbody6++GPU)

https://github.com/nbody6ppgpu

https://github.com/nbody6ppgpu/Nbody6PPGPU-beijing

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…

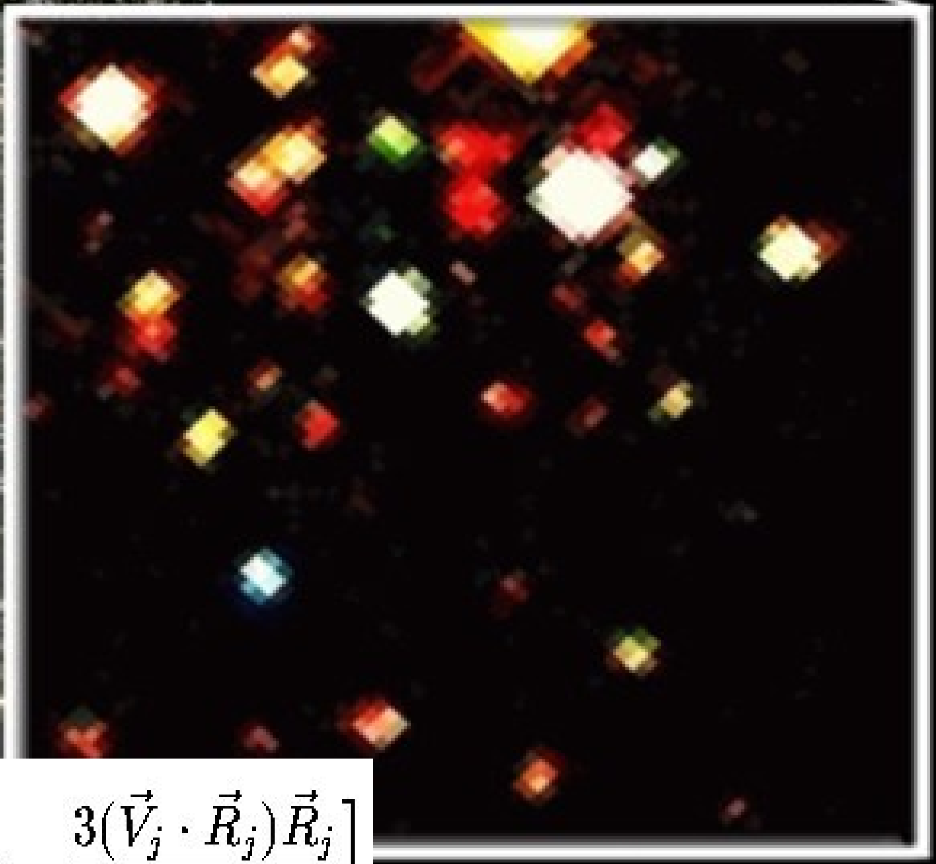
and more: Sambaran Banerjee, Albrecht Kamlah,

Manuel Arca Sedda, ...

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

X-ray binaries

with neutron stars and black holes



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

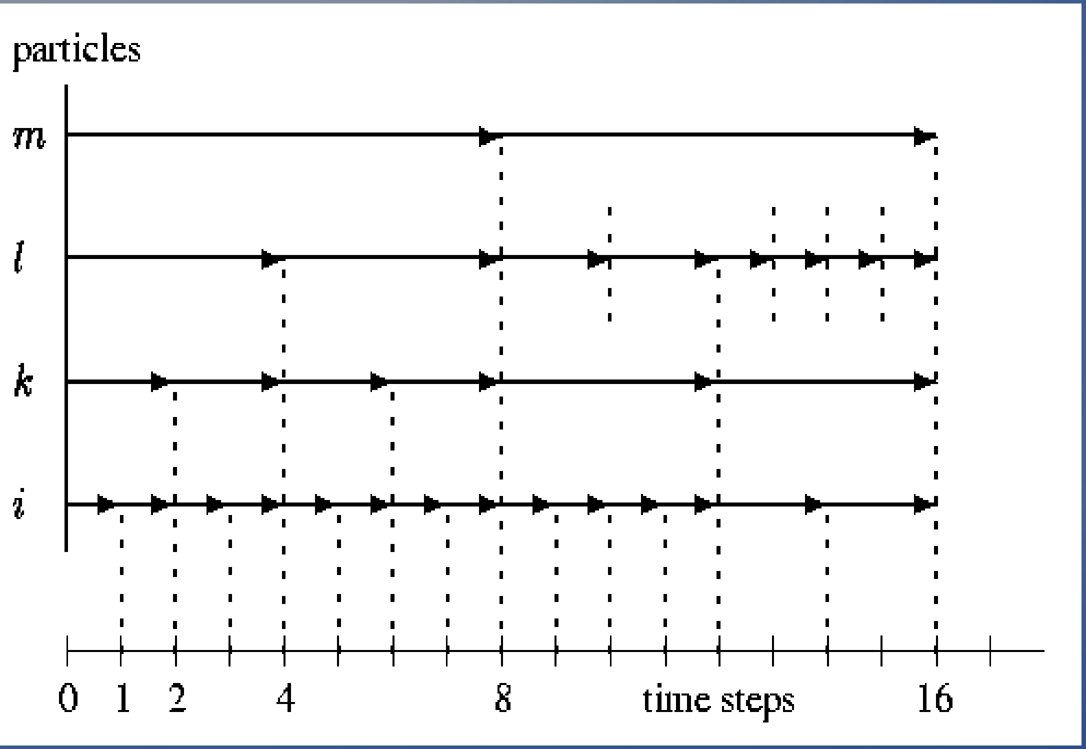
Code(s) – mainly Nbody6++GPU

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, Sp, et al. 2022A, Spurzem & Kamlah LRCA 2023)

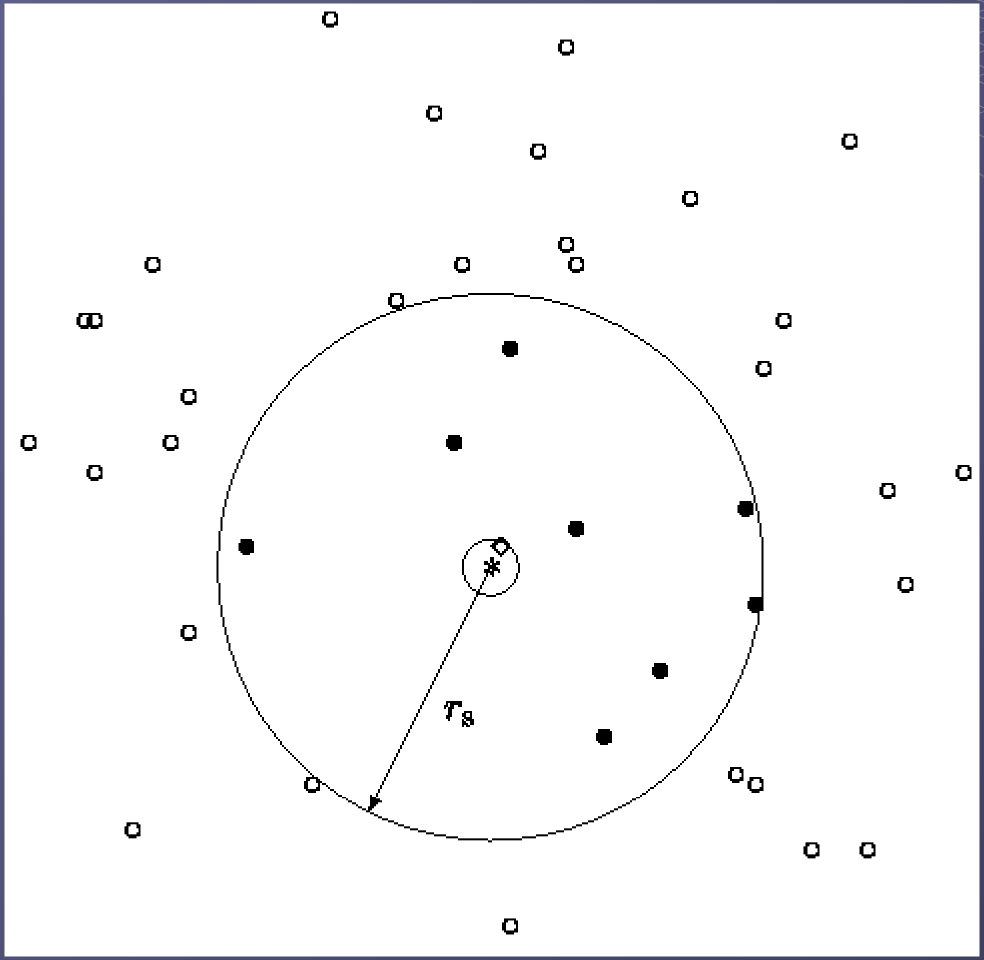


Hierarchical Block Time Steps

"Aarseth step" →

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

Code(s) – mainly Nbody6++GPU



Ahmad-Cohen Neighbour Scheme

(Double Volume for Incoming Particles)

Special Care for fast Particles

Complexity

$\alpha N^2 + \beta N \cdot N_n$

α small, $N_n \sim 50\text{-}200$

Physical and Numerical Methods: Direct Simulations
Direct: high accuracy / active-inactive particles

The Hermite Scheme: 4th Order on two time points

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

$$\vec{x}_p(t) = \frac{1}{6}(t-t_0)^3 \dot{\vec{a}}_0 + \frac{1}{2}(t-t_0)^2 \vec{a}_0 + (t-t_0)\vec{v} + \vec{x} ,$$

$$\vec{v}_p(t) = \frac{1}{2}(t-t_0)^2 \dot{\vec{a}}_0 + (t-t_0)\vec{a}_0 + \vec{v} ,$$

Repeat Step 1 at t_1 using predicted x,v → a_1, å$_1$

NBODY6++GPU: https://github.com/nbody6ppgpu/

Physical and Numerical Methods: Direct Simulations

$$\frac{1}{2}\vec{a}^{(2)} = -3\frac{\vec{a}_0 - \vec{a}_1}{(t-t_0)^2} - \frac{2\dot{\vec{a}}_0 + \dot{\vec{a}}_1}{(t-t_0)}$$

$$\frac{1}{6}\vec{a}^{(3)} = 2\frac{\vec{a}_0 - \vec{a}_1}{(t-t_0)^3} - \frac{\dot{\vec{a}}_0 + \dot{\vec{a}}_1}{(t-t_0)^2} \, ,$$

The Hermite Step

Get Higher Derivatives

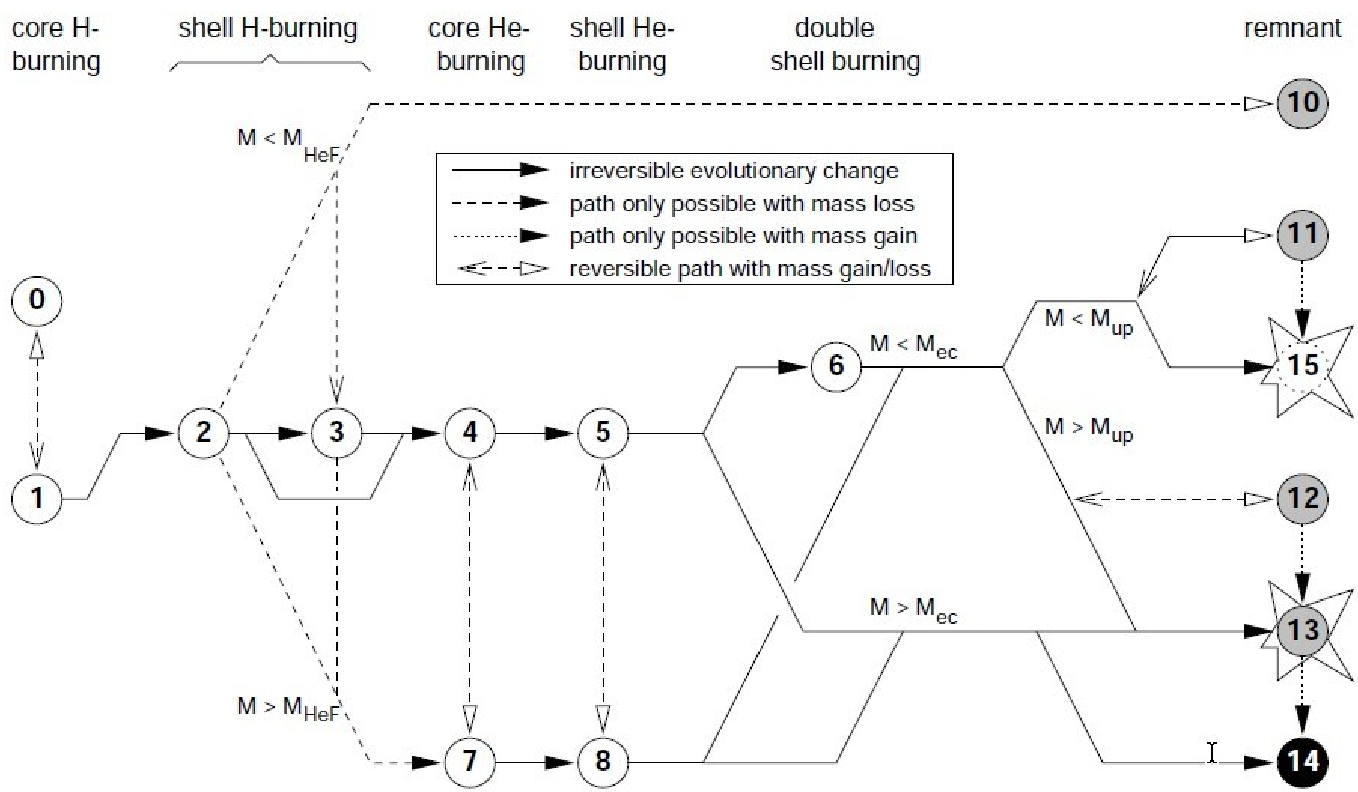
$$\vec{x}(t) = \vec{x}_p(t) + \frac{1}{24}(t-t_0)^4\vec{a}_0^{(2)} + \frac{1}{120}(t-t_0)^5\vec{a}^{(3)} \, ,$$

$$\vec{v}(t) = \vec{v}_p(t) + \frac{1}{6}(t-t_0)^3\vec{a}_0^{(2)} + \frac{1}{24}(t-t_0)^4\vec{a}_0^{(3)} \, .$$

The Corrector Step – this is not time symmetric!

Most NBODY Codes ...

Hurley, 2001
Ph.D. thesis
and many papers
Following...

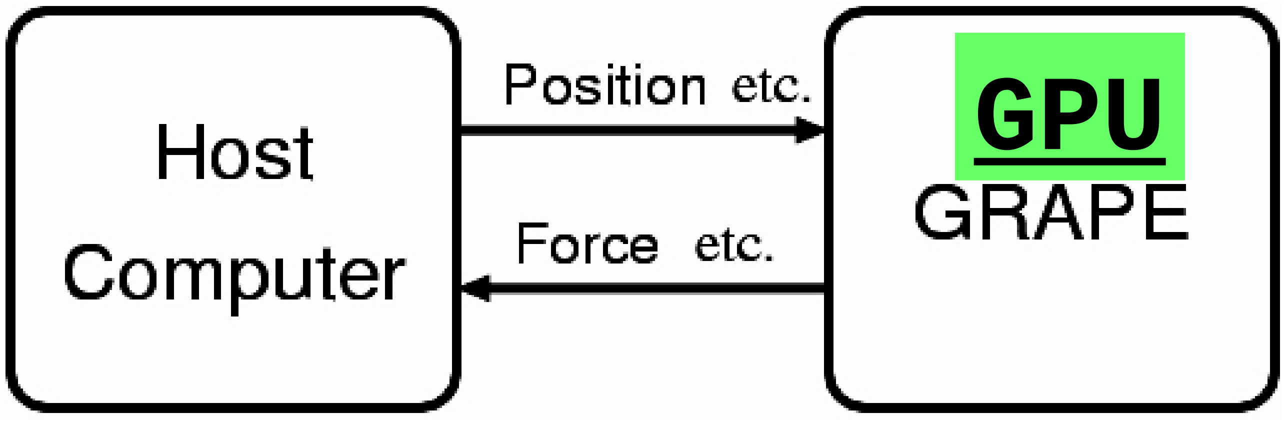


0 = main sequence $M < 0.7 M_\odot$
1 = main sequence $M > 0.7 M_\odot$
2 = Hertzsprung gap / subgiant
3 = first-ascent red giant
4 = horizontal branch / helium-burning giant
5 = early asymptotic giant / red supergiant
6 = thermally pulsating asymptotic giant
7 = naked helium main sequence
8 = naked helium (sub) giant
10 = helium white dwarf
11 = carbon/oxygen white dwarf
12 = oxygen/neon white dwarf
13 = neutron star
14 = black hole
15 = no stellar remnant

Code(s) - mainly Nbody6++GPU

(note also φGRAPE/φGPU, Berczik et al. 2013)

~N



~N^2

$$\vec{a}_i = \sum_{j=1;j\neq i}^{N} \vec{f}_{ij} \qquad \vec{f}_{ij} = -\frac{G \cdot m_j}{\left(r_{ij}^2 + \varepsilon^2\right)^{3/2}} \vec{r}_{ij}$$

(Here: ε=0 !)

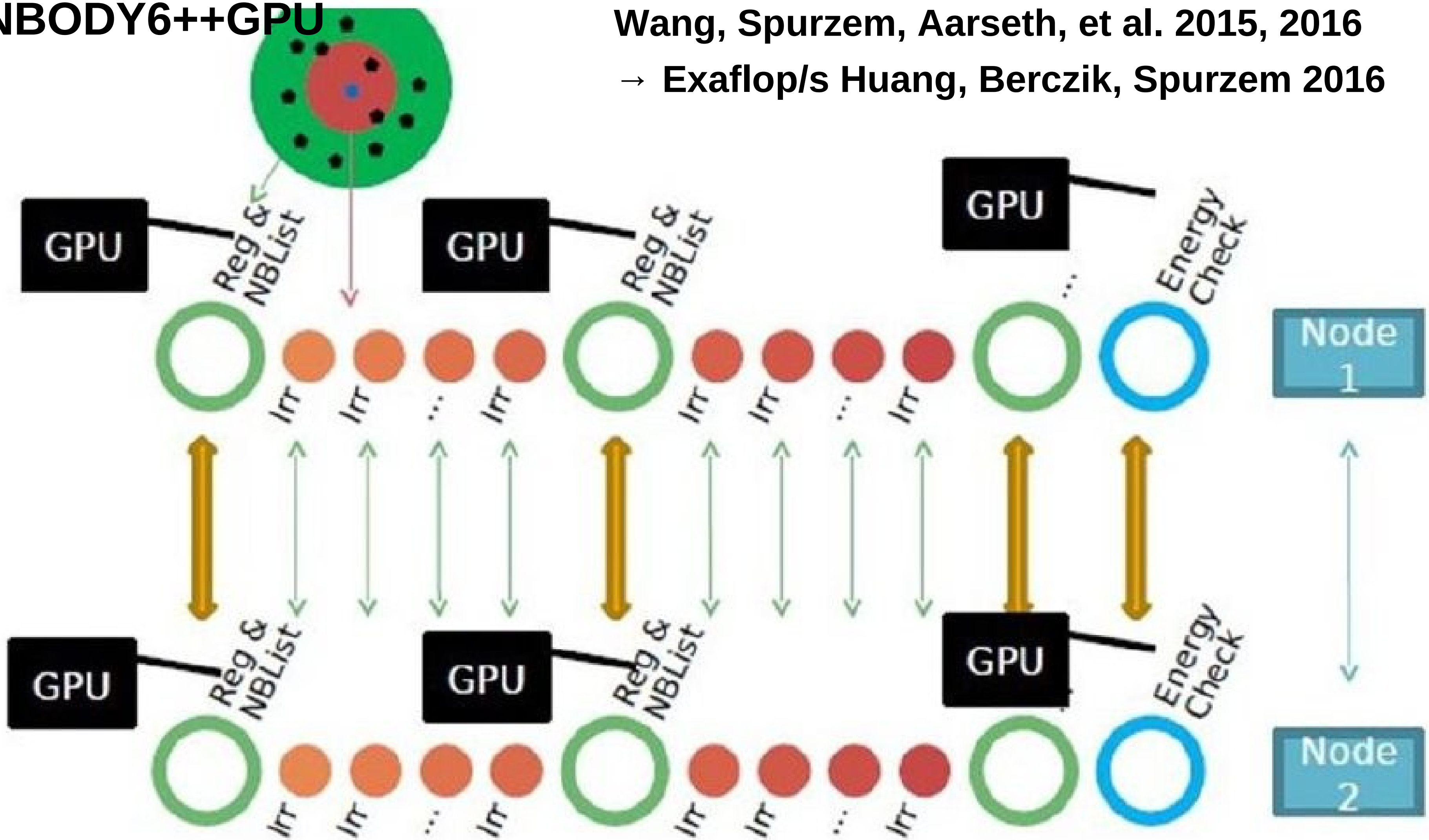
Slide: Peter Berczik

Our CPU/GPU N-body (AC) code

NBODY6++GPU

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

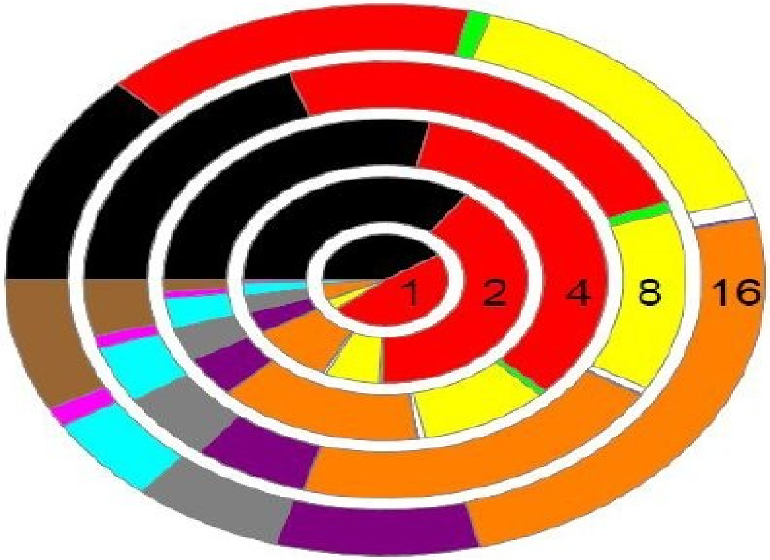
→ Exaflop/s Huang, Berczik, Spurzem 2016



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

Huang, Spurzem. Berczik, 2016, RAA

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



A timing model of Nbody6++GPU

Table 1 Main components of NBODY6++

Description	Timing variable	Expected scaling N	Expected scaling N_p	Fitting value [sec]
Regular force computation	$T_{\rm reg}$	$\mathcal{O}(N_{\rm reg} \cdot N)$	$\mathcal{O}(N_p^{-1})$	$(2.2 \cdot 10^{-9} \cdot N^{2.11} + 10.43) \cdot N_p^{-1}$
Irregular force computation	$T_{\rm irr}$	$\mathcal{O}(N_{\rm irr} \cdot \langle N_{nb} \rangle)$	$\mathcal{O}(N_p^{-1})$	$(3.9 \cdot 10^{-7} \cdot N^{1.76} - 16.47) \cdot N_p^{-1}$
Prediction	$T_{\rm pre}$	$\mathcal{O}(N^{kn_p})$	$\mathcal{O}(N_p^{-kp_p})$	$(1.2 \cdot 10^{-6} \cdot N^{1.51} - 3.58) \cdot N_p^{-0.5}$
Data moving	$T_{\rm mov}$	$\mathcal{O}(N^{kn_{m1}})$	$\mathcal{O}(1)$	$2.5 \cdot 10^{-6} \cdot N^{1.29} - 0.28$
MPI communication (regular)	$T_{\rm mcr}$	$\mathcal{O}(N^{kn_{cr}})$	$\mathcal{O}(kp_{cr} \cdot \frac{N_p-1}{N_p})$	$(3.3 \cdot 10^{-6} \cdot N^{1.18} + 0.12)(1.5 \cdot \frac{N_p-1}{N_p})$
MPI communication (irregular)	$T_{\rm mci}$	$\mathcal{O}(N^{kn_{ci}})$	$\mathcal{O}(kp_{ci} \cdot \frac{N_p-1}{N_p})$	$(3.6 \cdot 10^{-7} \cdot N^{1.40} + 0.56)(1.5 \cdot \frac{N_p-1}{N_p})$
Synchronization	$T_{\rm syn}$	$\mathcal{O}(N^{kn_s})$	$\mathcal{O}(N_p^{kp_s})$	$(4.1 \cdot 10^{-8} \cdot N^{1.34} + 0.07) \cdot N_p$
Sequential parts on host	$T_{\rm host}$	$\mathcal{O}(N^{kn_h})$	$\mathcal{O}(1)$	$4.4 \cdot 10^{-7} \cdot N^{1.49} + 1.23$

NBODY6++GPU with up to 16M particles

(Benchmarks on raven at MPCDF)

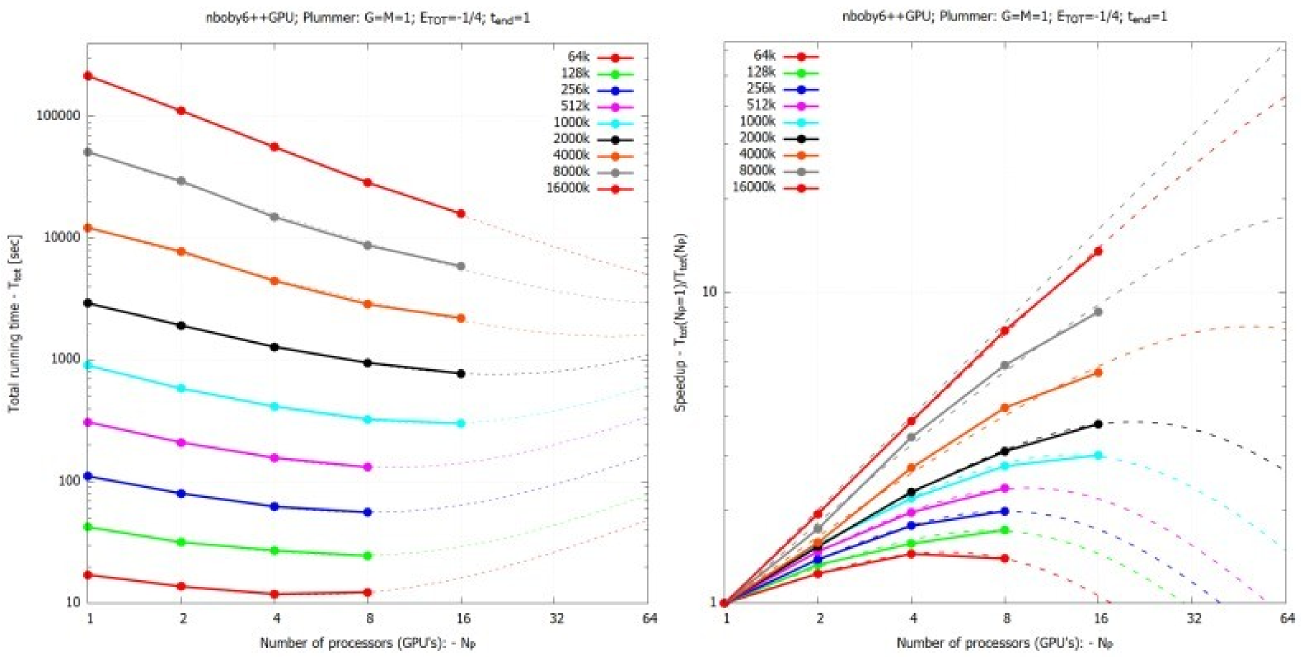
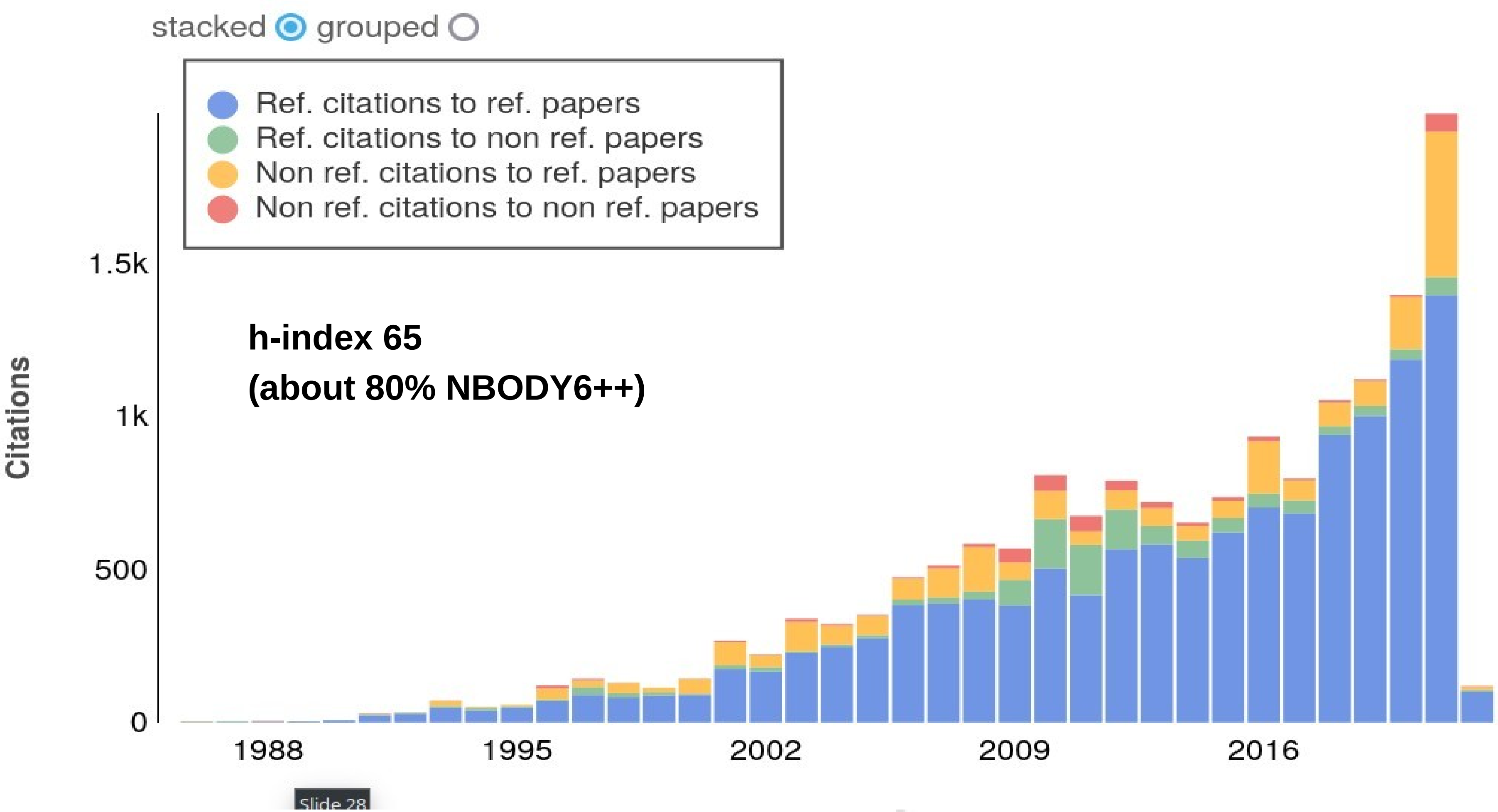


Figure 6: Benchmark results and extrapolated scaling for NBODY6++GPU, initial Plummer model, on the raven cluster at MPCDF, see main text. **Left:** Total time for one NBODY model unit in secs; **Right:** Speed-Up compared to using one GPU only. In both cases different curves for particle numbers from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

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.



NBODY1 – NBODY7: “The Growth of an Industry” (Aarseth 1999)

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

ITS: Individual time–steps [107] Aarseth 1985

ACS: Ahmad-Cohen neighbour scheme [109] Ahmad, Cohen 1973

KS: KS–regularization of few-body subsystems [104] Kustaanheimo, Stiefel 1965

HITS: Hermite scheme integration method combined with hierarchical block time-steps [111]

PN: Post-Newtonian [150, 125, 151] Kupi, Amaro-Seoane, Sp. 2006, \ Makino, Aarseth 1992

AR: Algorithmic regularization [125] Mikkola, Merritt 2008, Aarseth 2012, Banerjee et al. 2020

CC: Classical chain regularization [114] Mikkola, Aarseth 1998

MPI: Message Passing Interface, multi-node multi-CPU parallelization [139]

GPU: use of GPU acceleration [138] (if also MPI: multi-node many GPU [148]) Spurzem 1999

Berczik, Spurzem, et al., LNCS 2013; Table from: Spurzem, Kamlah 2023, LRCA

NBODY6++GPU: https://github.com/nbody6ppgpu/

Part of https://www.punch4nfdi.de/ PUNCH4NFDI Consortium w. Jülich

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* Slide 50 *ho, Nada-ku, Kobe, Hyogo 657-8501, Japan*

Accepted XXX. Received YYY; in original form ZZZ

New competition 1:

PeTar: MNRAS 2020

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

Slide 50

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-

Supercomputers

A special-purpose computer for gravitational many-body problems

Nature 1990

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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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The pipeline a

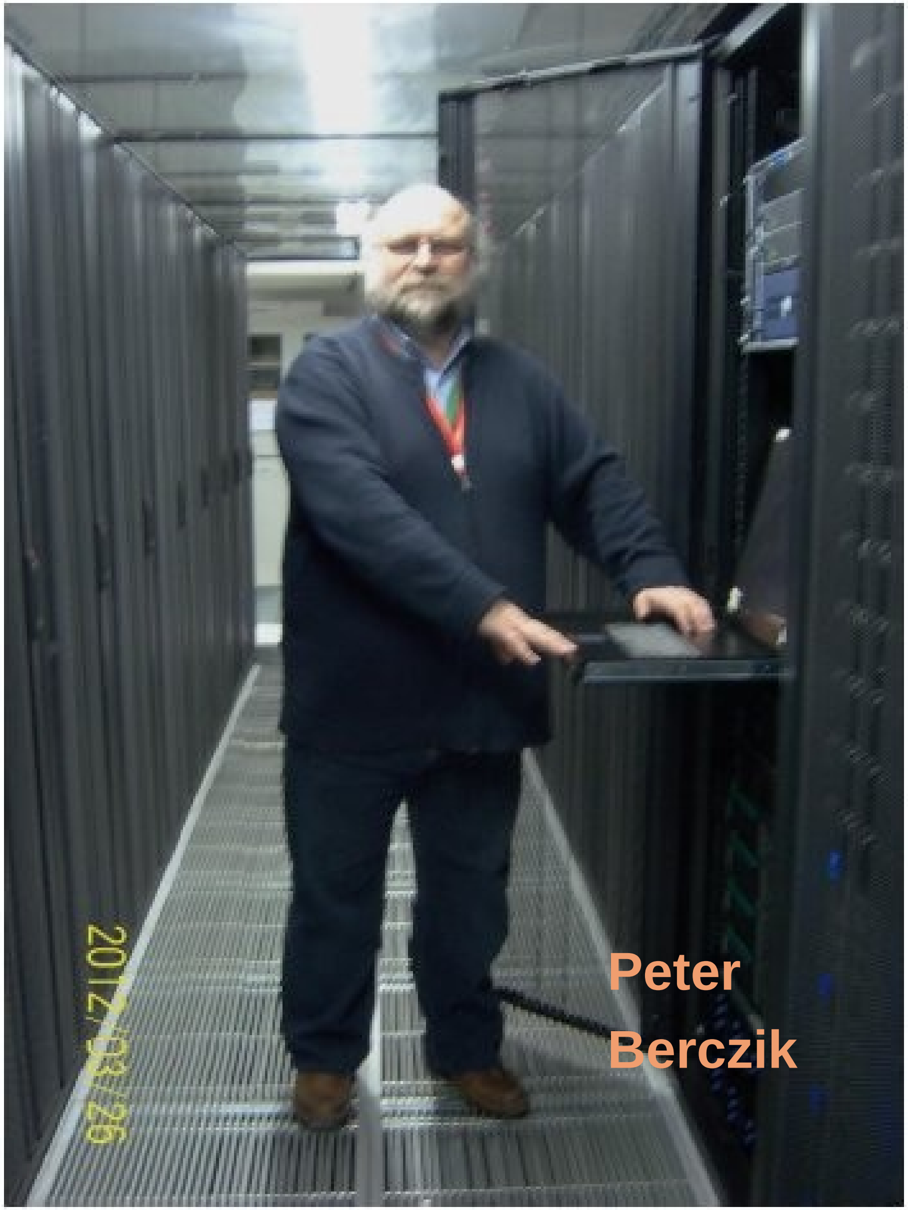
The N-body pro

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..

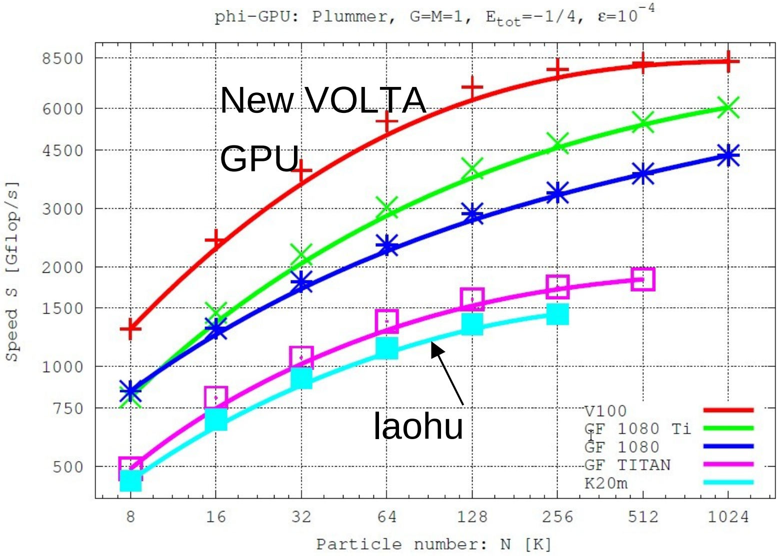
Jun Makino
with GRAPE6 →
(2002)

2010 Beijing: NAOC laohu cluster 2015: 64 Kepler K20



Laohu: 2009/2015
(Kepler GPU)
100 Tflop/s 150k cores

New GPUs 5-6 times faster… (see below)



JUWELS Booster 936 nodes (AMD CPU, 4x Ampere GPU)

~450.000 AMD cores, 25 million NVIDIA Ampere GPU cores

~ 70 Pflop/s SP ~ 44 Pflop/s DP

No. 12 in top500 list, No. 25 in green500 list

Jülich Wizard for European Leadership Science

LUMI

Supercomputer, Kajaani, Finland

Using only

Hydroelectric

Power and its

Heat used for heating buildings.

No. 3 in top500

No. 7 in green500

2.2 million cores

10.000 AMD GPUs

EuroHPC and LUMI consortium:

Finland, Belgium, Czech Republic, Denmark, Estonia, Iceland, Norway, Poland, Sweden, and Switzerland.

1) Introduction – History and Theory

2) Code(s) and Supercomputers

3) <u>Star Clusters/Black Holes/Grav. Waves</u>

4) Wrap-Up and References

DRAGON I Simulation

http://silkroad.zah.uni-heidelberg.de/dragon/

https://github.com/nbody6ppgpu

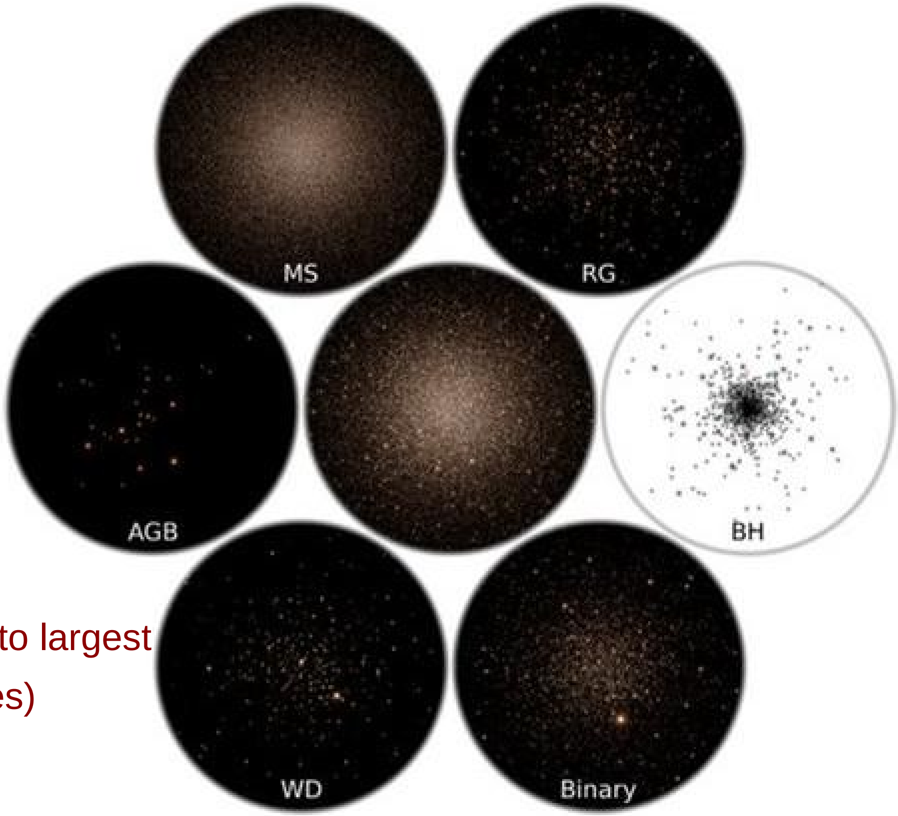
Also in: https://www.punch4nfdi.de/

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).

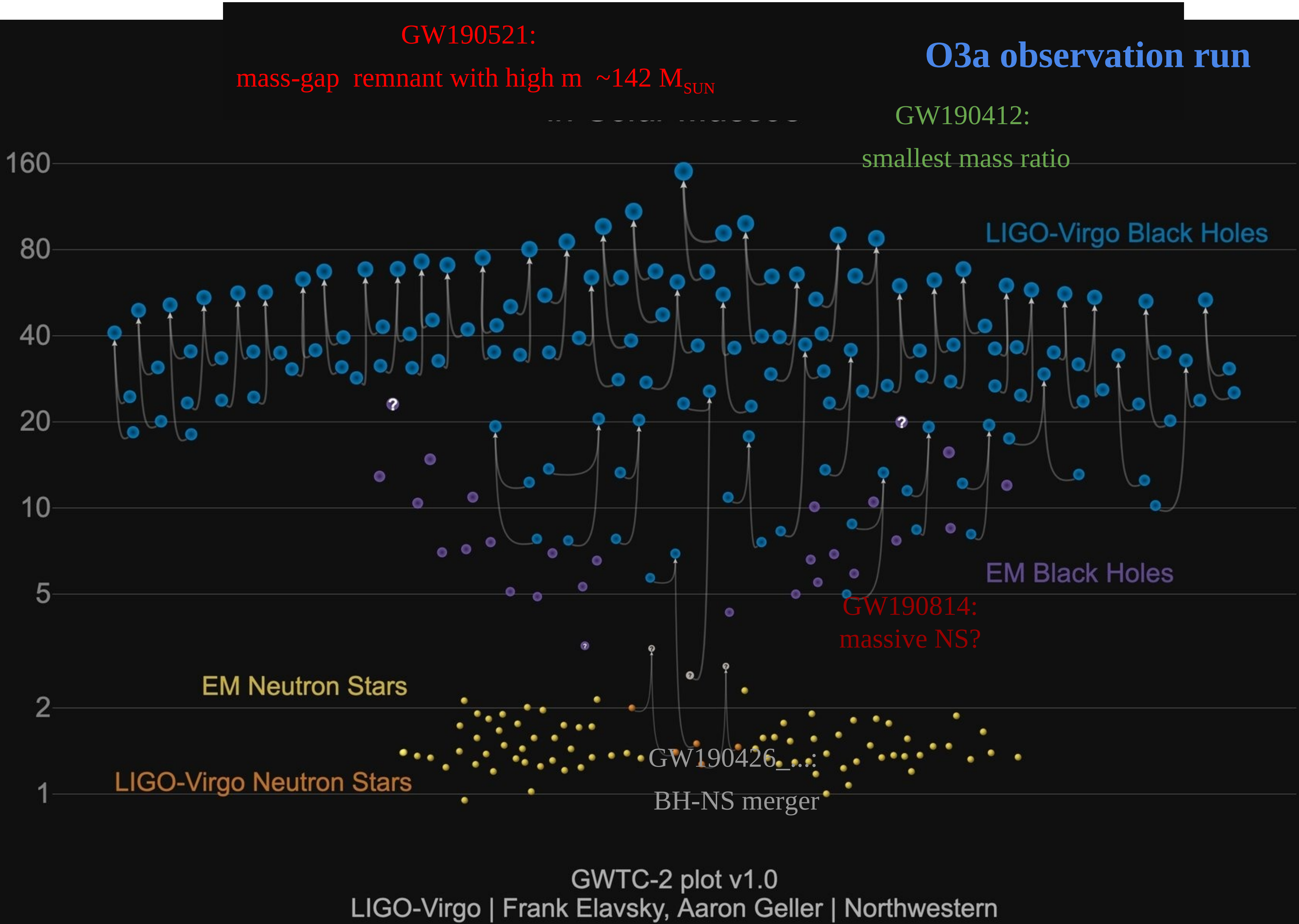


Wang, Spurzem, Aarseth, Naab et al. MNRAS, 2015

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

Number of Floating Point Operations (~1M bodies) similar to largest Cosmological simulations (Millennium, Illustris, ~10^{10} bodies)

What about black holes?
Black Hole Binaries?
DRAGON II Models


GW190521:
mass-gap remnant with high m ~142 M_{SUN}
O3a observation run
GW190412:
smallest mass ratio
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
GW190814:
massive NS?
EM Neutron Stars
LIGO-Virgo Neutron Stars
GW190426_...:
BH-NS merger
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Binary Evolution Relativistic – current

(taken from Rizzuto et al. 2021, 2022, Arca Sedda et al. 2021, 2022,

and DRAGONII Papers I,II,III, In preparation, using citations given here and cited in papers)

$$\left\langle\frac{da}{dt}\right\rangle = -\frac{64}{5}\frac{G^3 m_1 m_2 (m_1+m_2)}{c^5 a^3 (1-e^2)^{7/2}}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right),$$

$$\left\langle\frac{de}{dt}\right\rangle = -\frac{304}{15}e\frac{G^3 m_1 m_2 (m_1+m_2)}{c^5 a^4 (1-e^2)^{5/2}}\left(1+\frac{121}{304}e^2\right).$$

Orbit Averaged

Post-Newtonian

(Peters & Mathews 1963,

Peters 1964)

semi-major axis a,

Eccentricity a

(Rizzuto et al. 2021, 2022)

$$\begin{aligned}
\vec{v}_{\rm GW} &= v_m \hat{e}_{\perp,1} + v_\perp(\cos\xi\,\hat{e}_{\perp,1} + \sin\xi\,\hat{e}_{\perp,2}) + v_\parallel \hat{e}_\parallel,\\
v_m &= A\eta^2\sqrt{1-4\eta}(1+B\eta),\\
v_\perp &= \frac{H\eta^2}{1+q_{\rm BBH}}\left(S_{2,\parallel} - q_{\rm BBH}S_{1,\parallel}\right),\\
v_\parallel &= \frac{16\eta^2}{1+q_{\rm BBH}}\left[V_{11} + V_A\Xi_\parallel + V_B\Xi_\parallel^2 + V_C\Xi_\parallel^3\right]\times\\
&\quad \times\left|\vec{S}_{2,\perp} - q_{\rm BBH}\vec{S}_{1,\perp}\right|\cos(\phi_\Delta - \phi_1).
\end{aligned}$$

Implementation of

relativistic kick after

gravitational wave

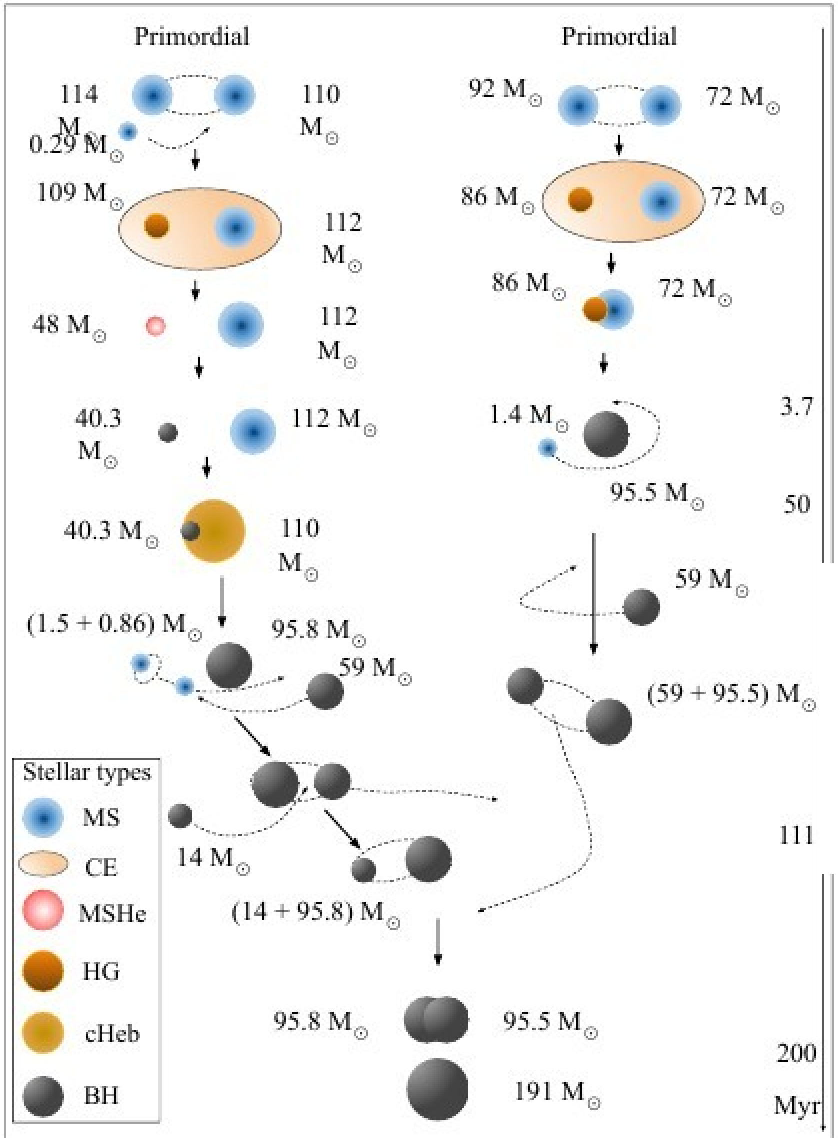
Induced coalescence

(Arca Sedda et al. 2023abc,

following papers cited therein)

DRAGON-II Simulations – Paper II

using NBODY6++GPU



Arca Sedda et al. 2023abc: MNRAS:

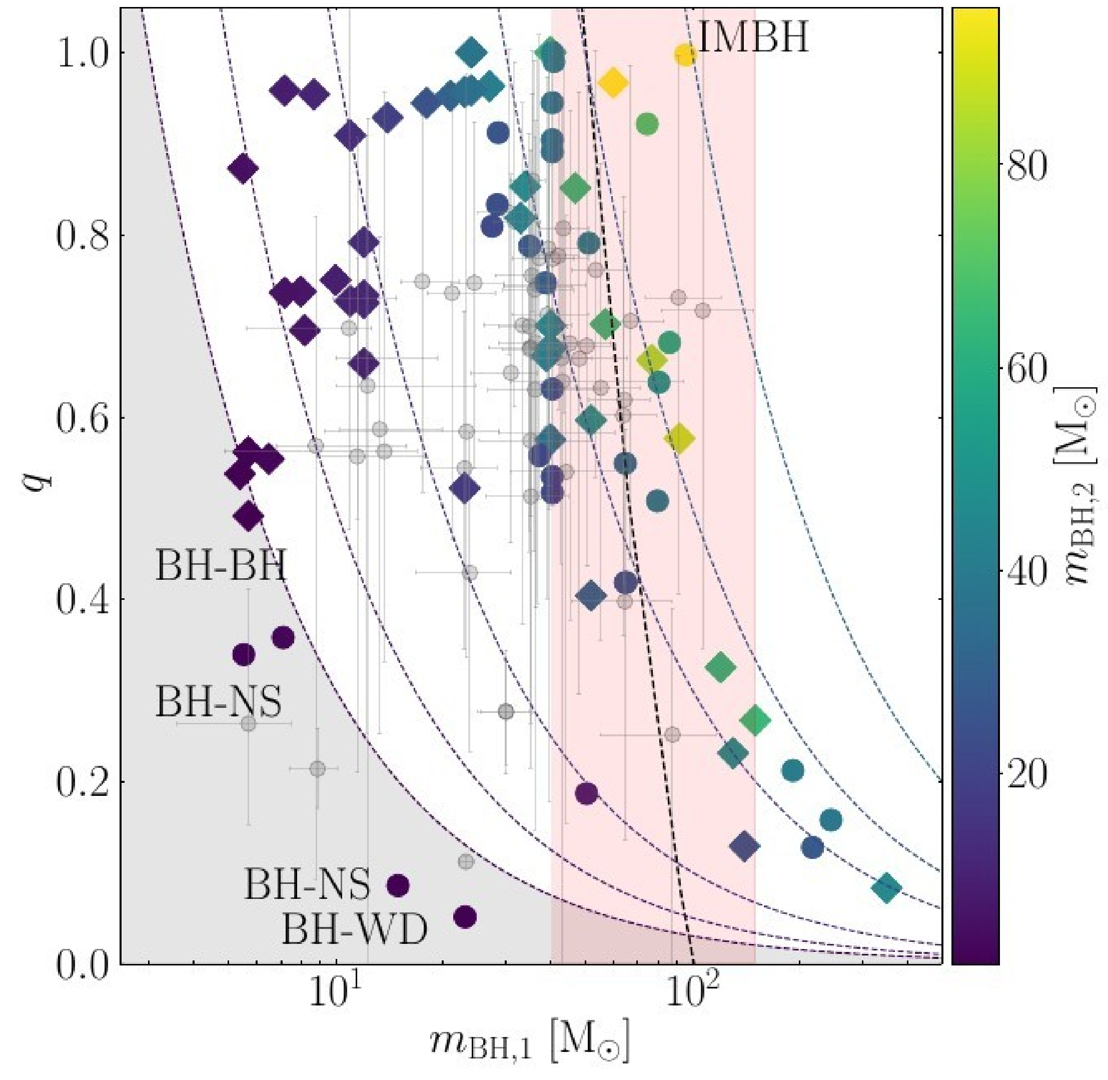
19 models, up to 1 million stars, up to 33% initial hard binaries

Including GR kicks for mergers!

Figure 2. Formation of an IMBH in simulation with $N = 120$k, $R_{\rm HM} = 1.75$ pc, and $f_b = 0.2$, realization ID 0. Two massive primordial binaries undergo common envelope that eventually lead to the formation of two nearly equal mass BHs ($m_{\rm BH} \sim 95$ M$_\odot$) that eventually find each other via a complex series of binary-binary interactions. The binary eventually merge and builds-up an IMBH with mass $m_{\rm IMBH} \simeq 191$ M$_\odot$. The color-coded legend is ent colors correspond to different evolutionary stages: main sequence (MS), common envelope (CE), naked main sequence He star (MSHe), Hertzsprung gap (HG), core He burning (cHeb), and black hole (BH).

DRAGON-II Simulations – Paper III

using NBODY6++GPU



Arca Sedda et al. 2023c:

Submitted to MNRAS:

19 models, up to 1 million stars, up to 33% initial hard binaries

Compact Object Mergers

Compared with LIGO-Virgo GWTC-3 catalogue (grey symbols)

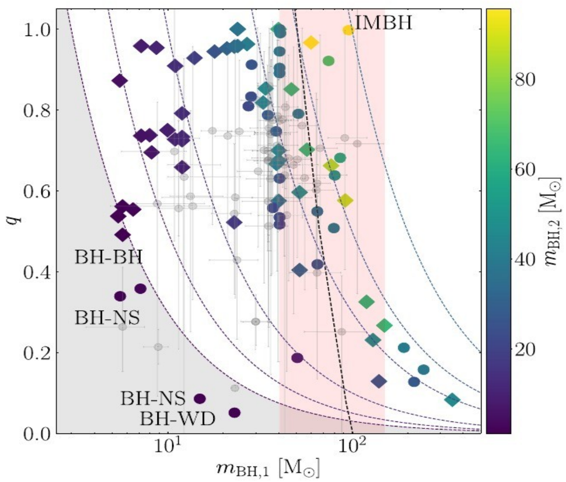
Mass ratio q vs. primary mass m1; colour code:

secondary mass m2

grey shade: neutron star involved

Work in Progress: Very Massive Stars, ... Black Holes, Relativistic Dynamics

- DRAGON-II simulations: approximate Post-Newtonian, max. 1 Gyr or shorter, need longer simulations, currently waiting: PopIII clusters (with Ataru Tanikawa)
- Pure Black Hole Clusters: check effect of spins and recoil kicks (Ricarda)
- Growth of Massive Stars: Albrecht Kamlah with Rainer, Marcelo, Francesco, Peter, and many collaborators (e.g. Renyue Cen, Nadine Neumayer)
- Full Post-Newtonian up to PN3.5 with spins in large cluster models



Arca Sedda, Kamlah, Spurzem, Rizzuto, Giersz, Naab, Berczik, DRAGON-II, MNRAS, 2023/24 Paper I,II,III

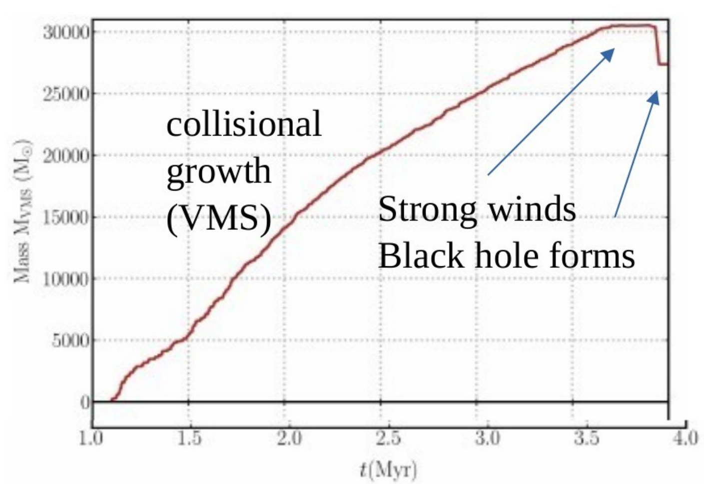


Figure 8. Figure showing temporal evolution of the mass M_{VMS} ($M_\odot$) of the VMS (and IMBH thereafter), the logarithm

Kamlah, Spurzem, et al. (incl. Jarrod Hurley) to be subm. ASAP

Issues:

- Rejuvenation
- He ageing
- Massive star evolution

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Summary Message

Massive Star Clusters:

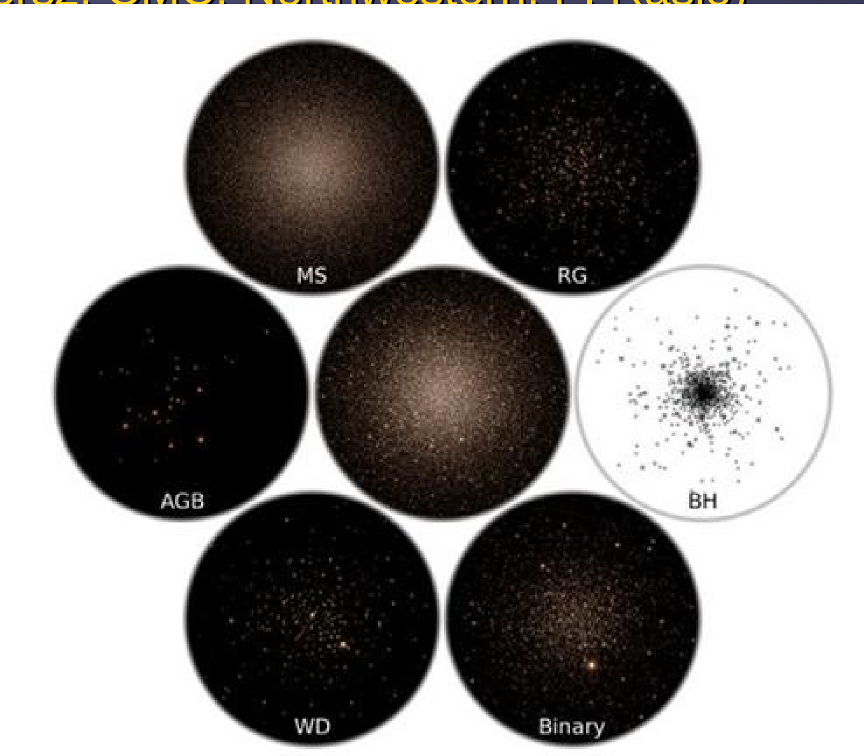
- Direct N-Body Simulations of star clusters give LIGO/Virgo Sources (are consistent with them, it does not mean all sources are from star clusters)
- Necessary Input: single/binary stellar evolution / relativistic (PN) dynamics
- Still very long computing time for few models (in spite of GPU, Lumi, …)

Monte Carlo Models (MOCCA, Warsaw, M. Giersz, CMC, Northwestern, F. Rasio) needed to get good sweep of parameter space

Nuclear Star Clusters

(not covered in this talk):

- Observable Tidal Disruption Events (TDE)
- Light Curves correspond to dynamics of TDE
- Future Work: relativistic inspirals
- Future Work: pulsars
- Future Work: star disk



Stars, Stellar Dynamics, Black Holes, and Gravitational Waves at UNC

The Cluster Monte Carlo (CMC) Code

January 12, 2022 By carlrodr

After **several** years of work that started before I was an assistant prof, we have the first public release of the Cluster Monte Carlo code, CMC. The **paper** is available here while the **code itself** is available here. CMC is a Monte Carlo technique for stellar dynamics, based on an aproach developed by Hénon in 1971. Instead of integrating the force of every particle on every other particle, Hénon's approach was to model the effect of many two-body encounters as single "effective" encounters.

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Warsaw PL: MOCCA team:
M. Giersz, A. Hypki, A. Askar et al.

Team & Collaborators as below and further:

Thorsten Naab (MPA), Mirek Giersz (CAMK),
Ataru Tanikawa (Tokyo U), Nadine Neumayer (MPIA)

ARI ITA LSW

DRAGON simulations – globular and nuclear star clusters

- **DRAGON simulation: PhD thesis Long Wang, KIAA/PKU,** awarded for first realistic globular cluster simulation using **NBODY6++GPU** with one million stars and many binaries (Wang, Spurzem, Aarseth, et al., MNRAS 2016).
- **The Dragon-II simulations – Paper III. Compact binary mergers in clusters with up to 1 million stars: mass, spin, eccentricity, merger rate and pair instability supernovae rate** (Arca Sedda, M., Kamlah, A. W. H., Spurzem, R., et al.) arXiv e-prints arXiv:2307.04807, **Paper II:** MNRAS 525, 429 (2023), **Paper I:** arXiv e-prints arXiv:2307.04805

NBODY6++GPU and more, current state:

- **Spurzem, R., Kamlah A.W.H. Direct N-body simulations, in Living Rev. in Comp. Astrophysics 9, id.3 (2023) (NBODY7 see also Banerjee, Sambaran papers)**

Direct Nuclear Star Cluster Models with SMBH and TDE:

- **DRAGON simulation of the Galactic Center**, PhD thesis of Taras Panamarev, ARI/ZAH Univ. of Heidelberg (Panamarev, Just, Spurzem, Berczik, Wang, Arca Sedda, MNRAS 2019), simple TDE
- **Revisit the Rate of Tidal Disruption Events: The Role of the Partial Tidal Disruption Event** (Zhong, S., Li, S., Berczik, P., Spurzem, R.) 933, 96 (2022), TDE improved 1
- Marija Minzburg, Philip Cho: Master Thesises Heidelberg 2023, publication in progress, TDE improved 2 and 3.

Some other papers and collaborators may be mentioned:

- Rizzuto, Naab, Spurzem et al. (2021, 2022) precursor of DRAGON II but no GW kicks, no TDE
- Li, Zhong, Berczik, Spurzem, Chen, Liu (MNRAS 2023 and earlier): merging nuclei with TDE