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

Deutsche Forschungsgemeinschaft
SFB881 DFG

Uni Heidelberg

Binary Black Holes in star clusters

Rainer Spurzem with Silk Road Team
Long Wang, Peter Berczik, Paulina Assmann, Andreas Just, Taras Panamarev...
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

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http://silkroad.bao.ac.cn

VolkswagenStiftung

- <u>Introduction</u>
- Excursion Galactic Nuclei
- Black Holes in Star Clusters
- Gravitational Wave Observations
- Computational Instruments/ Galactic Center/Summary

Kavli Institute for Astronomy and Astrophysics, Peking Univ..

Regular Openings:

Postdoc
Faculty
Visitors
(see AAS Job Reg, search KIAA)

Total 25 faculty; 1/3 are non-Chinese

中国科学院国家天文台

NATIONAL ASTRONOMICAL OBSERVATORIES ,CHINESE ACADEMY OF SCIENCES

NAOC/ CAS

Silk Road Project =
Computational Science Project...

Top: NAOC Headquarter Beijing
Bottom: LAMOST Site

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

Picture: Luca Naso

Rainer Spurzem
CAS Visiting Professor, Senior International Scientists
Professor at Heidelberg University (on partial leave)

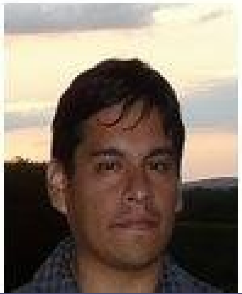
Peter Berczik
Senior Silk Road Project Postdoc

Thijs Kouwenhoven
Bairen research professor at KIAA

Gareth Kennedy
Postdoc (CAS Fellow)

Shuo Li
Postdoc (NAOC)

Yohai Meiron
Postdoc (KIAA-PKU)



Jose Fiestas
Postdoc at NAOC

Xiaoying Pang
Postdoc at NAOC

Shiyan Zhong
Ph. D. Student (NAOC)

Long Wang
Ph. D. Student (Peking University)

Maxwell Tsai (aka. Xu CAI)
Ph. D. Student (NAOC)

Siyi Huang
Graduate student

Changhua Li
Engineer

Hazel Wei
Administrative staff

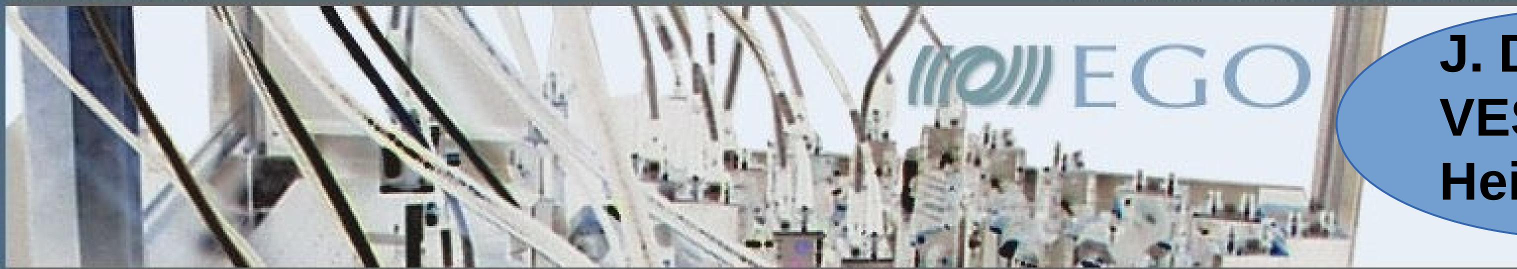
Lei Liu
Graduate student at:
(1) Astronomisches Rechen-Institut, Zentrum fuer Astronomie, Heidelberg University
and (2) National Astronomical Observatories, CAS)

Pakistan: Fazeel Khan
Kazakhstan: Chingis Omarov, Mukhagaly Kalambay
Germany: Andreas Just, Taras Panamarev, Bekdaulet Shukirgaliev
Ukraine: Margaryta Sobolenko, Alexander Veles

RECRUITMENT PROGRAM OF GLOBAL EXPERTS

EUROPEAN GRAVITATIONAL OBSERVATORY

Home Reserved Area Safety Privacy Contacts **Job Opportunities**



Ego Virgo Organization... Events EU Projects R&D VESF VIRGO Missions

J. Downing
VESF Fellow
Heidelberg

VESF - The Virgo-EGO Scientific Forum

Compact Binaries in Star Clusters I - Black Hole Binaries Inside Globular Clusters

MNRAS 2010

J. M. B. Downing[3⋆], M. Benacquista[4], R. Spurzem[1,2,3], and M. Giersz[5]

[1] National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Ln. Chaoyang District, 100012, China

...lberg, Germany

Compact Binaries in Star Clusters II - Escapers and Detection Rates

MNRAS 2011

J. M. B. Downing[1,2⋆], M. J. Benacquista[3], M. Giersz[4], and R. Spurzem[5,6,1]

[1] Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Monchhofsraße 12-14, D-69120 Heidelberg, Germany

[2] Fellow of the International Max-Planck Research School for Astronomy and Cosmic Physics at the University of Heidelberg, Heidelberg, Germany

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[4] Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, ul. Bartycka 18, 00-716 Warsaw, Poland

[5] National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Rd., Chaoyang District, 100012, China

[6] Kavli Institute of Astronomy and Astrophysics, Peking University, Beijing, China

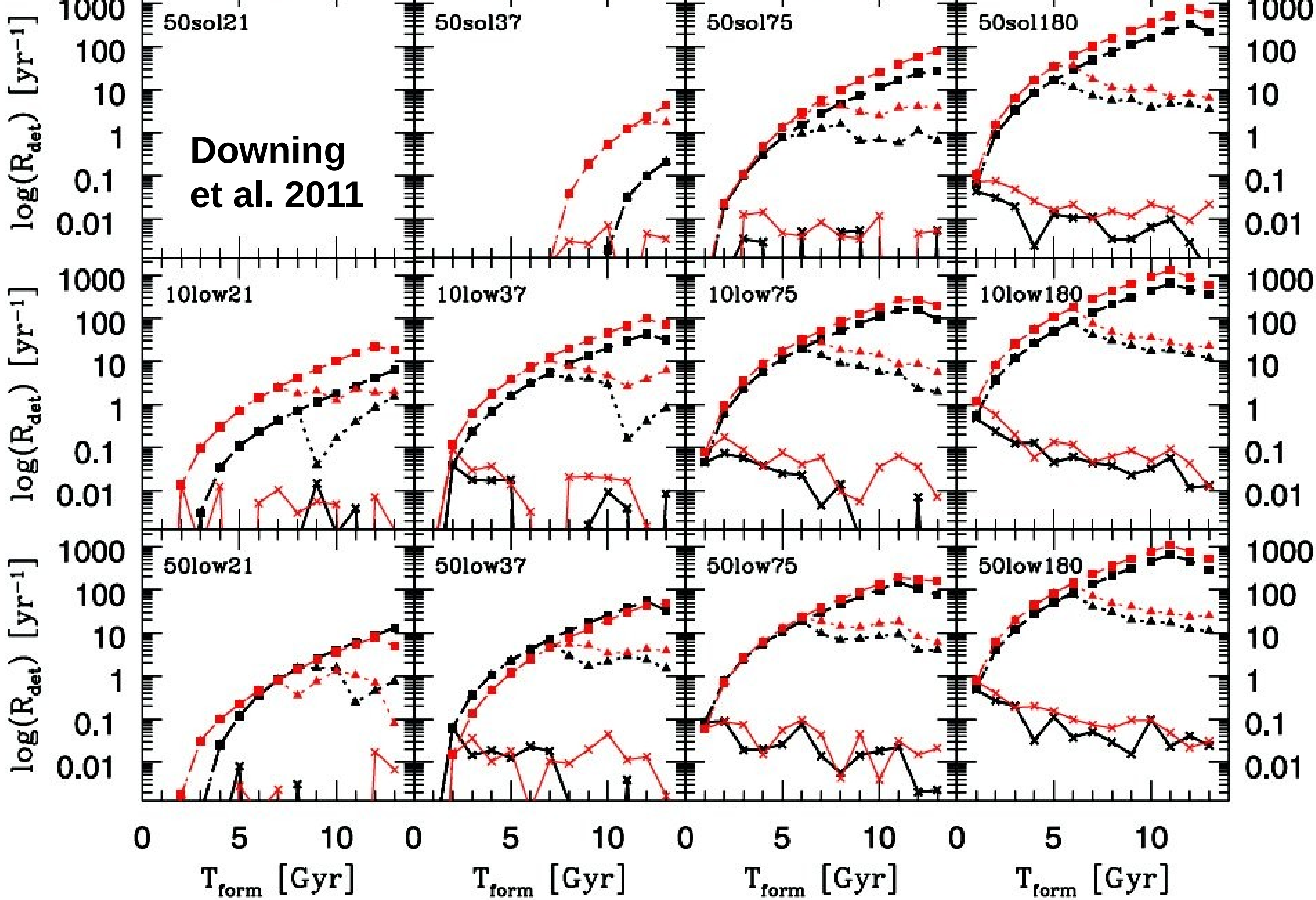

Figure 9. Detection rates by cluster type. Each panel gives the expected detection rate if the entire cluster population in the Universe was composed of identical clusters, each with the corresponding initial conditions. The *x*-axis gives the look-back time to $T_{\rm form}$ in Gyr. The solid line with crosses is for $D_{\rm L,0} = 19.1$ Mpc, the dotted line with triangles is for $D_{\rm L,0} = 191.0$ Mpc and the dashed line with squares is for $D_{\rm L,0} = 1910.0$ Mpc. Black lines give the detection rates if the binaries have the eccentricities produced by the Monte Carlo code, while the red lines give the rate if the binaries have eccentricities drawn from a thermal distribution.

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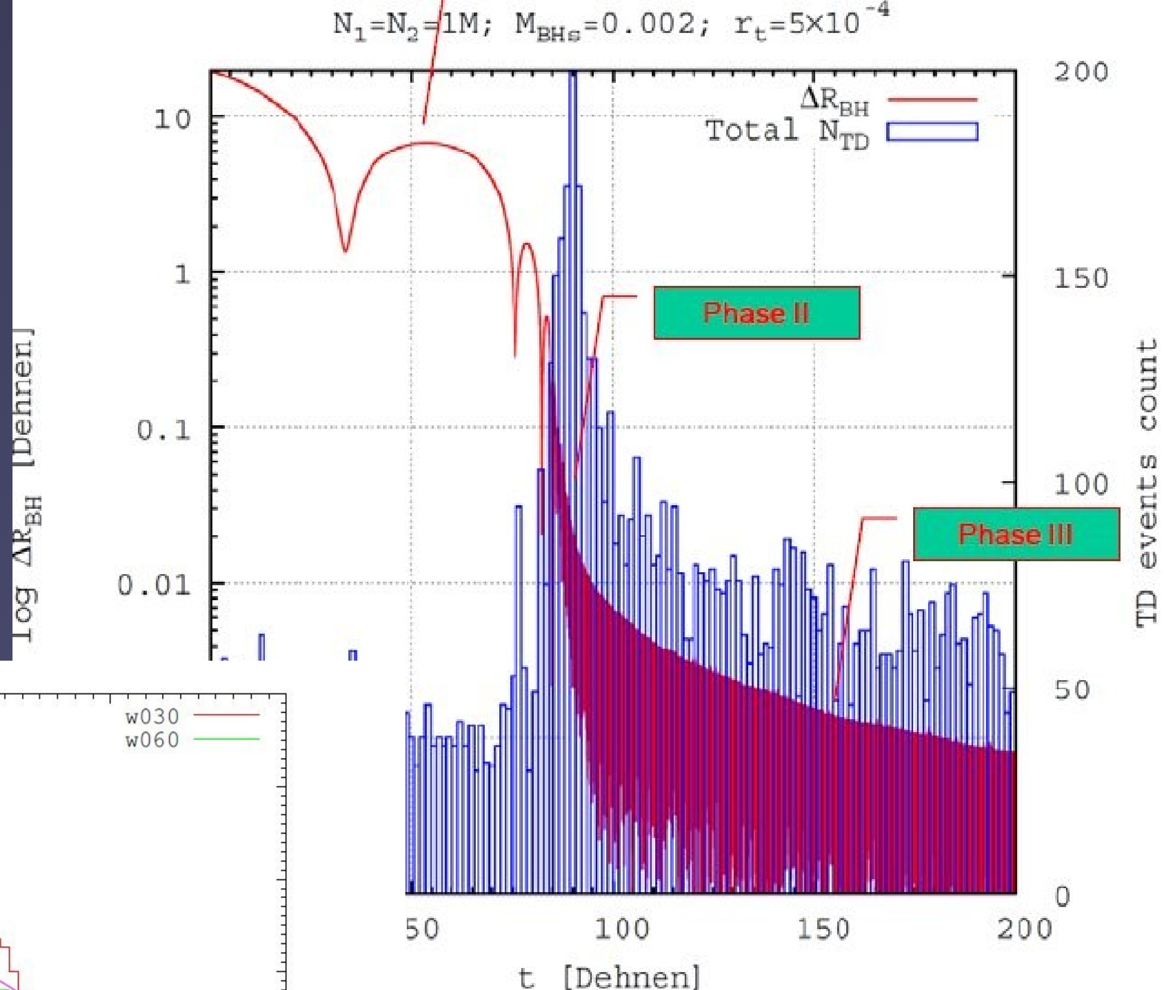
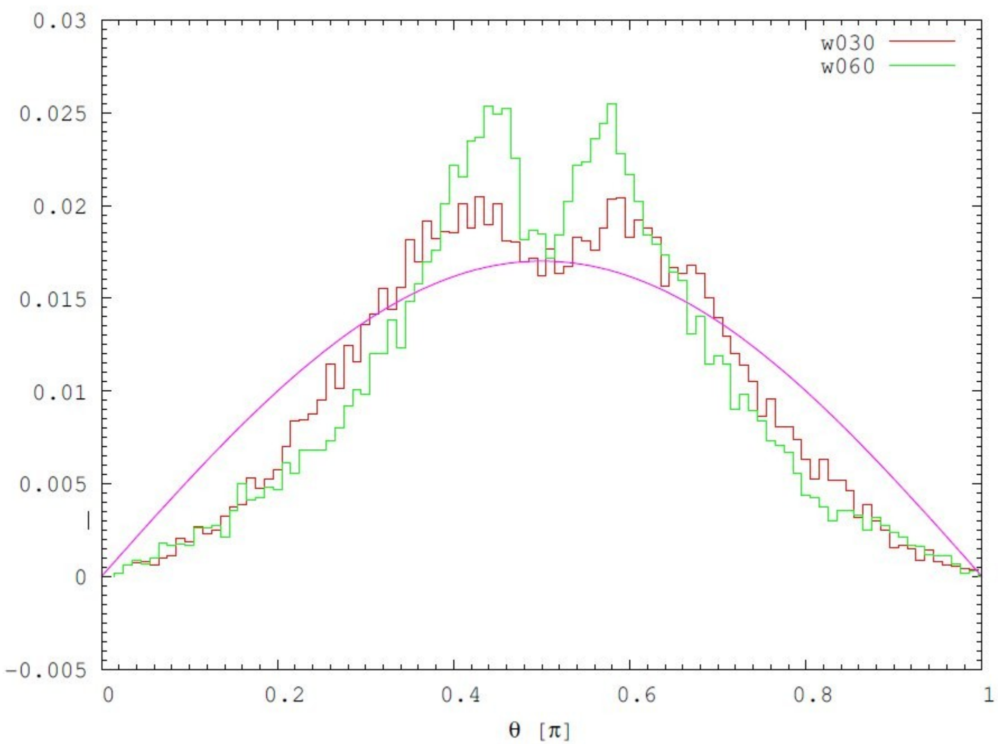
Tidal Disruption
Merging Galaxies
Li et al. subm. MNRAS

Tidal Disruption
Recoiling Black Hole
Li, Liu, Berczik, Chen,
Spurzem ApJ 2012



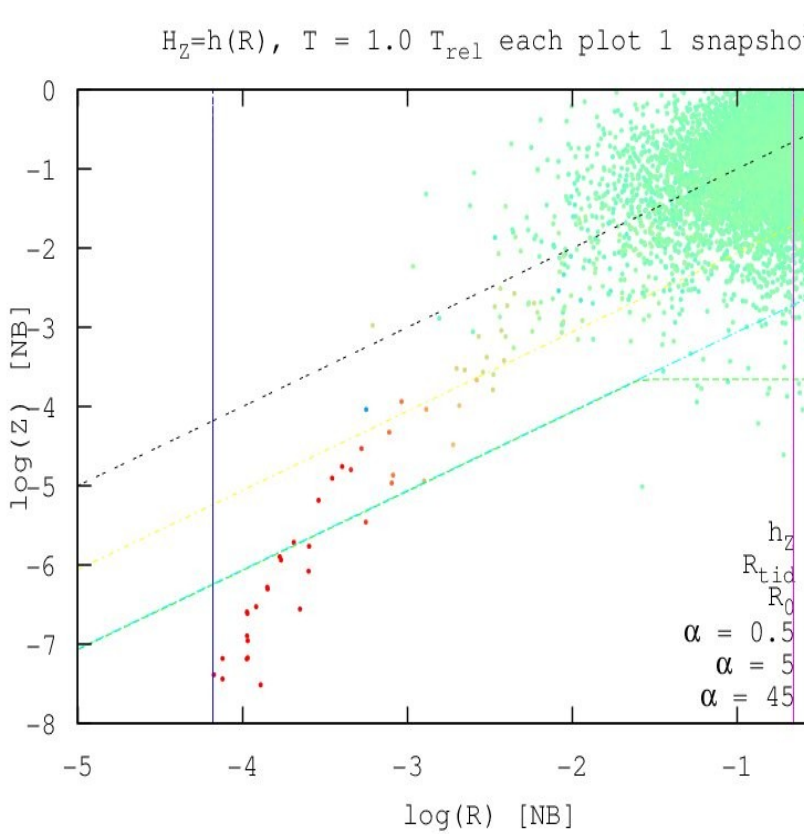


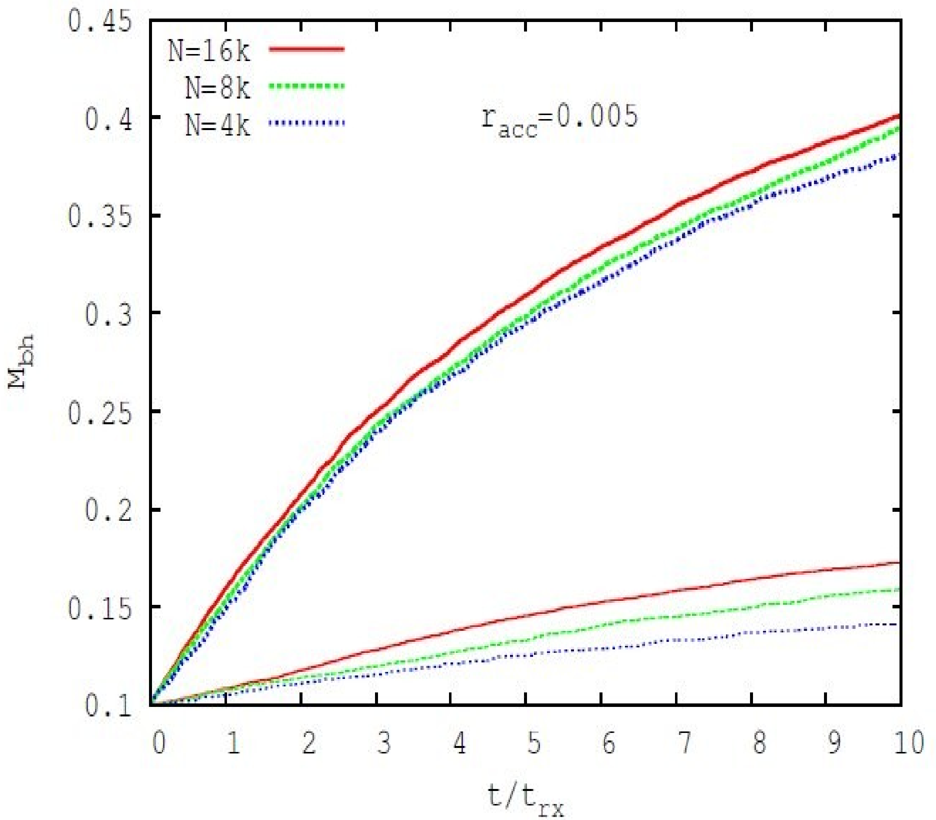
Tidal Disruption
Rotating Galaxies
Zhong, Berczik, Spurzem,
ApJ 2014 (Paper I)
ApJ 2015 (Paper II)

Stardisk Project – Beijing – Almaty – Kiev - Heidelberg

Just, ... Berczik, Spurzem, et a, 2012, ApJ (Paper I)
Kennedy, Meiron et al. 2016 MNRAS (Paper II)
Shukirgaliev et al. 2016 in prep. (Paper III)

The presence of a gaseous accretion disk near an SMBH enhances the mass growth rate of SMBH and forms a compact stellar disk.





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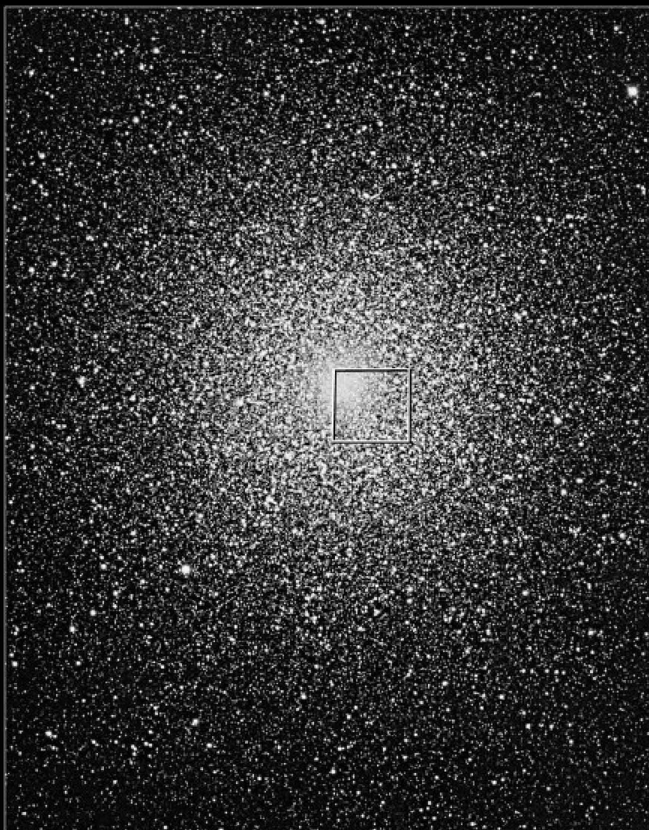
$$\vec{a}_0 = \sum_j G m_j \frac{\vec{R}_j}{R_j^3} \quad ; \quad \dot{\vec{a}}_0 = \sum_j G m_j \left[\frac{\vec{V}_j}{R_j^3} - \frac{3(\vec{V}_j \cdot \vec{R}_j)\vec{R}_j}{R_j^5} \right]$$

Globular Cluster 47 Tucanae

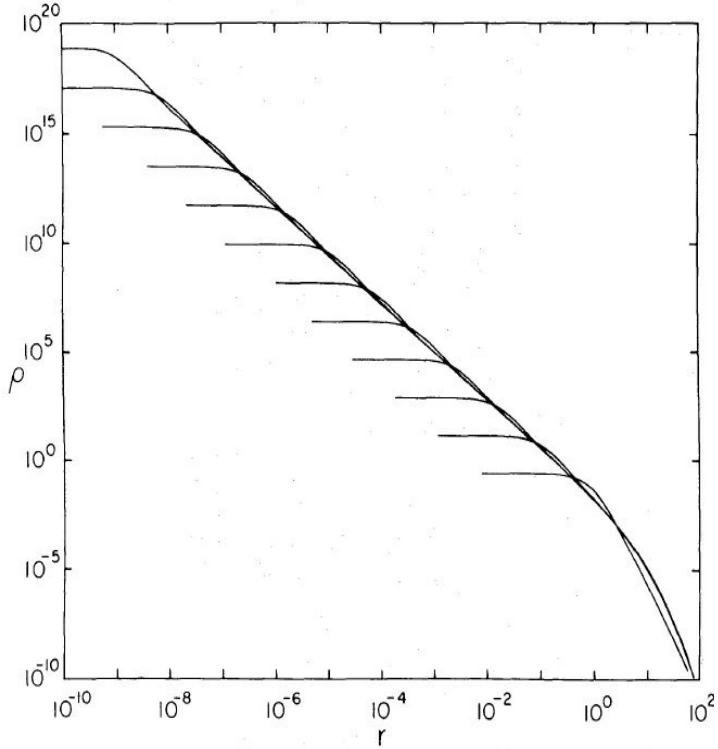


Ground • AAT

Hubble Space Telescope • WFPC2

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

Binary Heating was detected before 2000...



Cohn (1980): Direct Fokker-Planck model

Core Collapse

Gravothermal Catastrophe

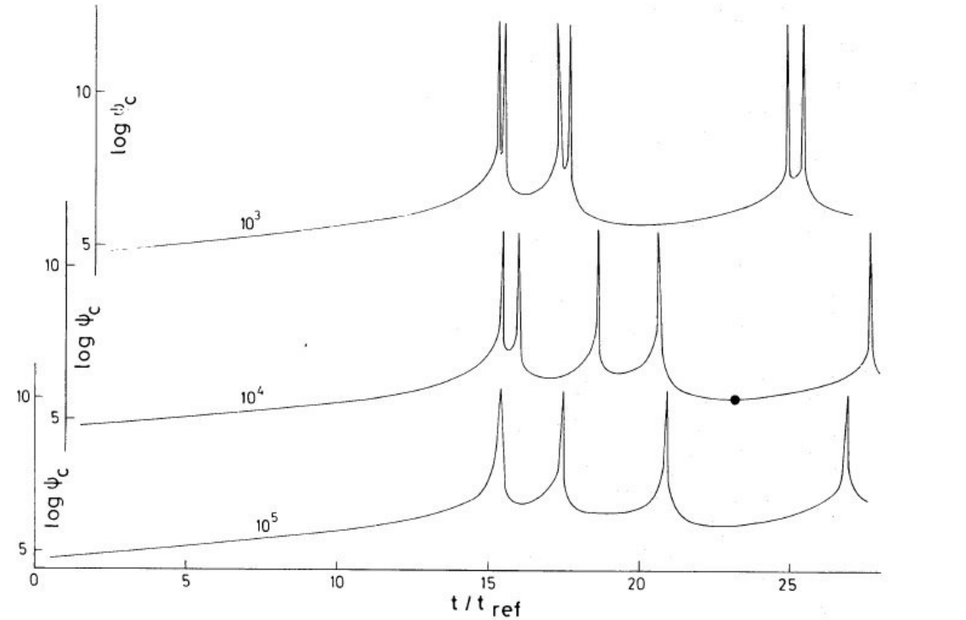


Figure 1. The 'central' density ψ_c is plotted against the non-dimensional time t/t_{ref} for $k = 2$ models with three different values of C as attached to each curve. Note, that if they were plotted with the same ordinate they would be close to each other despite the great differences in C. The model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

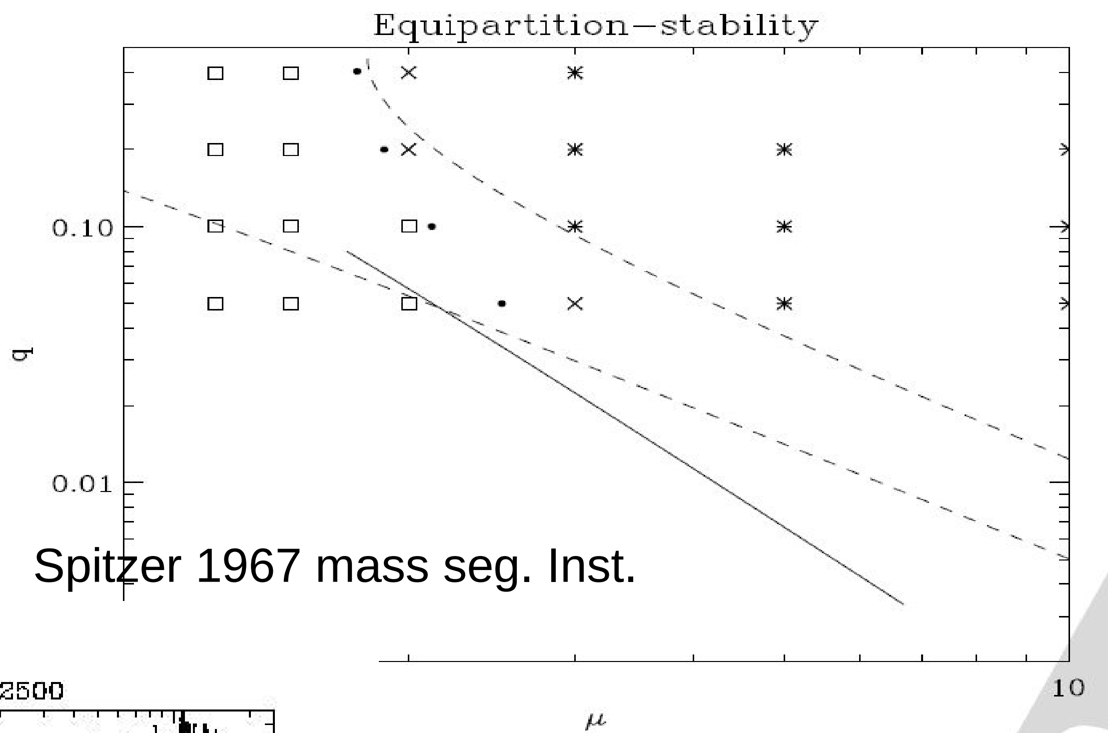
Bettwieser & Sugimoto 1984:

Gravothermal Oscillations by energy generation from binaries (cf. nuclear stellar energy generation), later also Heggie, Hut, Goodman...

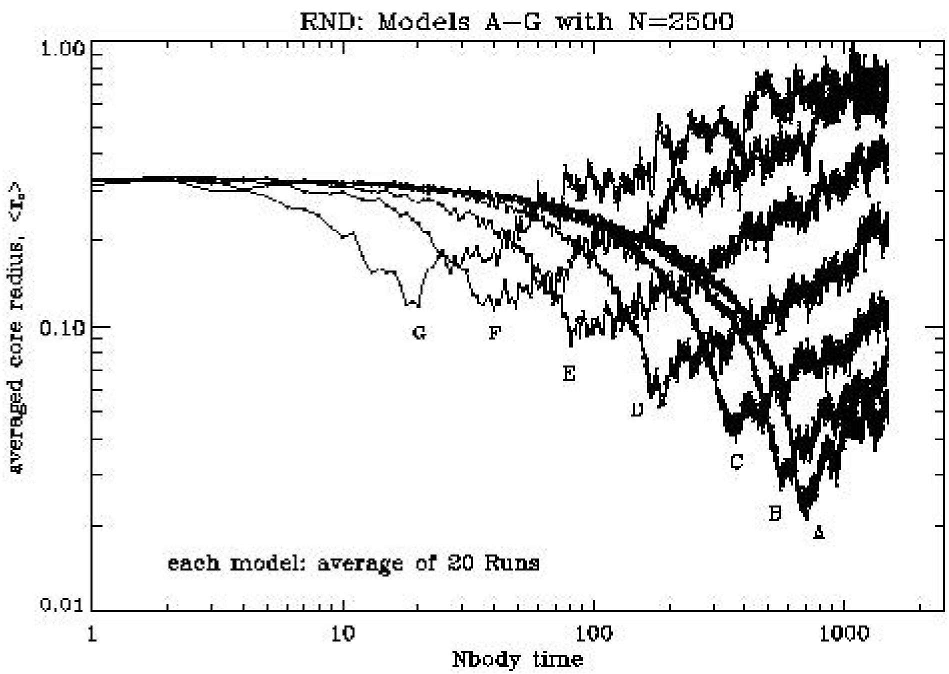
earlier: Henon

Black Hole Subsystems
Due to mass segregation:

Phinney + Sigurdsson 91
Kulkarni, Hut, McMillan 93
Sigurdsson, Hernquist 93
Portegies Zw., McMillan 2000



Spitzer 1967 mass seg. Inst.



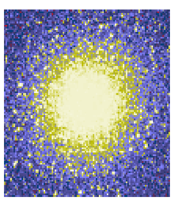
Mass Segregation
N-Body

Khalisi, Amaro-Seoane,
Spurzem, MNRAS, 2007

Methods for studying the evolution of globular clusters (adopted from D.C.Heggie)

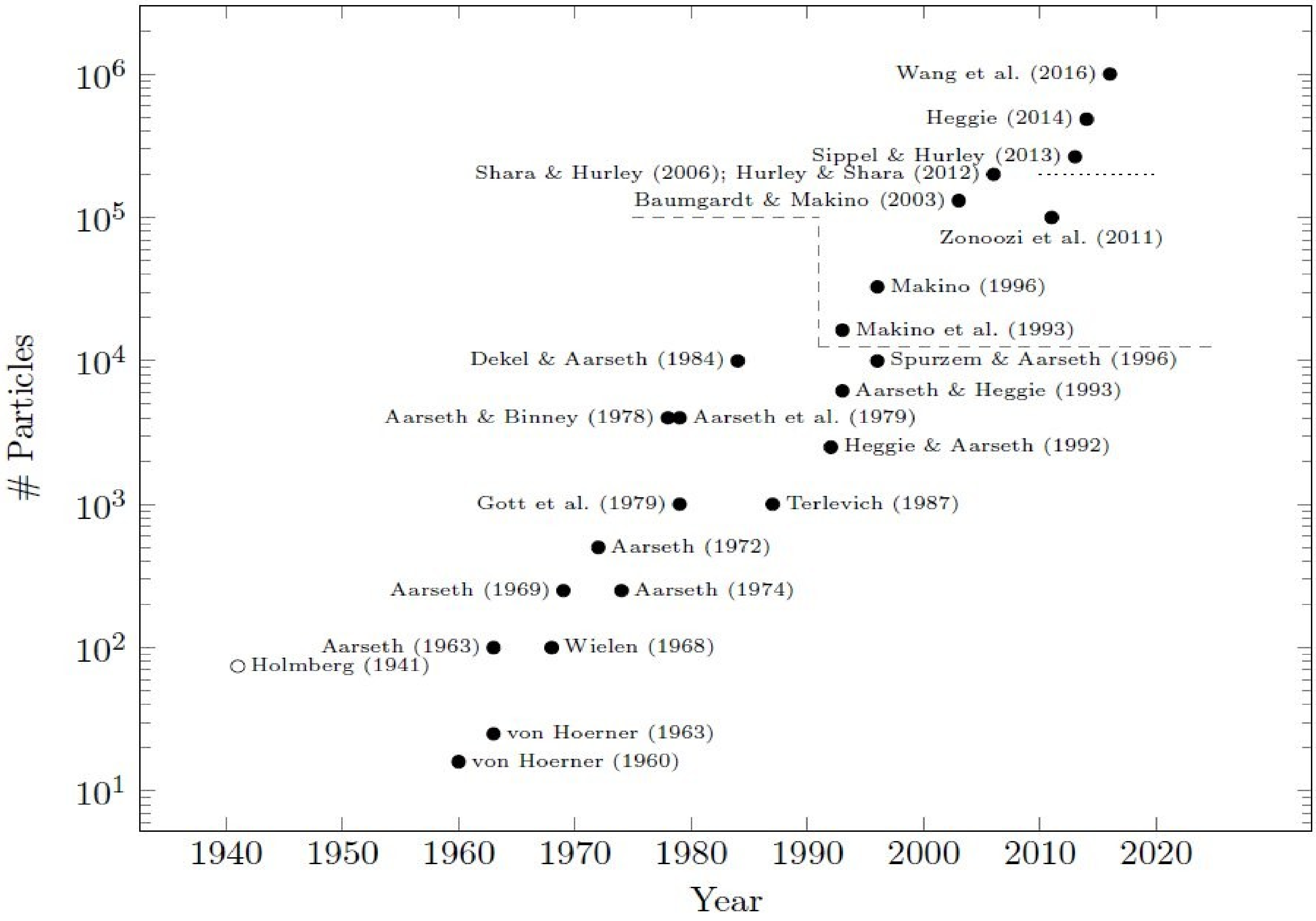
Title Picture IAU 208

A real star cluster



- N–body model
  - direct summation
    - GRAPE (Makino & Taiji 1998)
    - parallel (Spurzem 1999)
    - serial (Aarseth 1999)
  - tree code (Aarseth & McMillan 1993)
- Fokker–Planck model
  - rotating (Einsel & Spurzem 1999) Kim, Lee & Spurzem (2004) Fiestas & Spurzem (2006)
  - isotropic
    - finite difference (Cohn 1979) Cohn (1980)
  - anisotropic
    - finite difference (Takahashi 1995)
    - Monte Carlo
      - Henon, Giersz, Freitag Joshi, Rasio…
      - Spitzer, Shapiro, Marchant
- Fluid model
  - moment (Larson 1970)
  - gas
    - anisotropic (Louis & Spurzem 1991) Amaro-Seoane et al. (2004)
    - isotropic (Lynden–Bell & Eggleton 1980)
- **Hybrid models (Giersz & Spurzem 2000, 2003)**

“Moore's” Law for Direct N-Body



GRAPE/
GPU Clusters

GRAPE

Vector Computers

by D.C. Heggie Via added new cits. Sippel

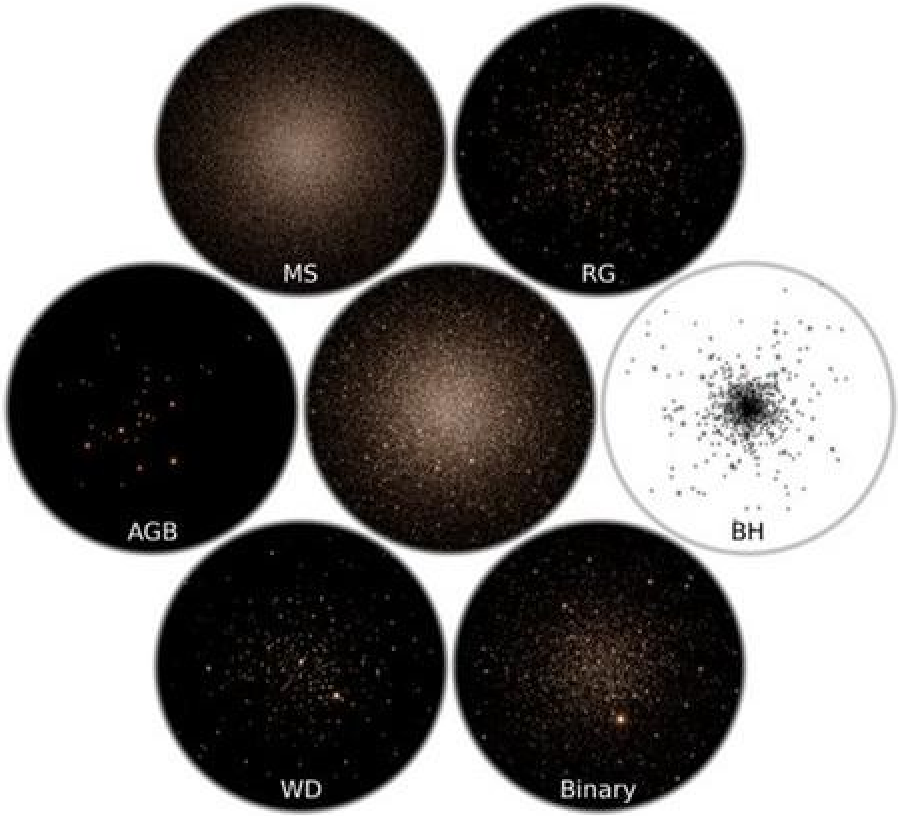
DRAGON Simulation

http://silkroad.bao.ac.cn/dragon/

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).

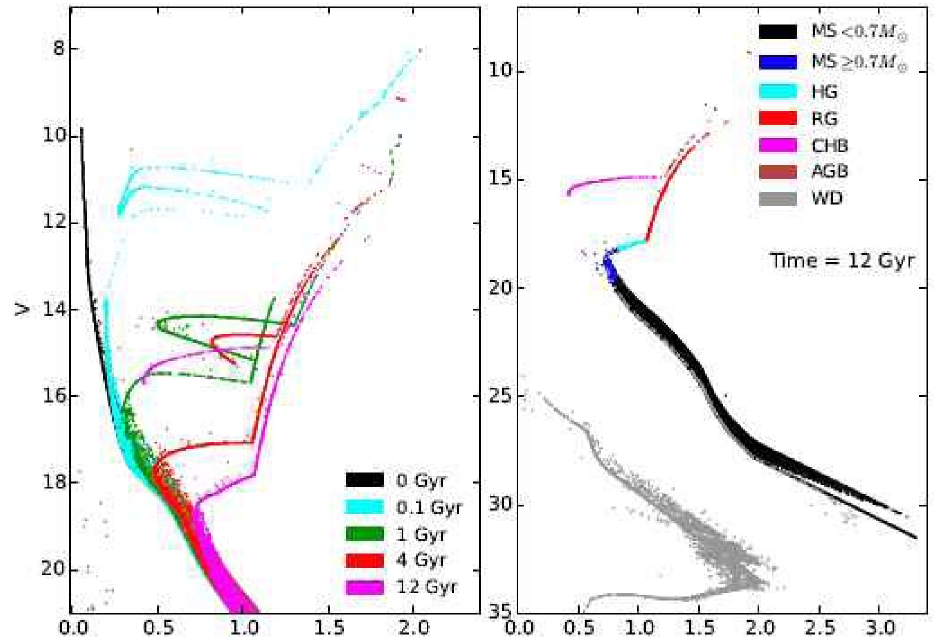
Wang, Spurzem, Aarseth, Naab et al.
MNRAS, 2015
Wang, Spurzem, Aarsteh Naab, et al.
MNRAS 2016

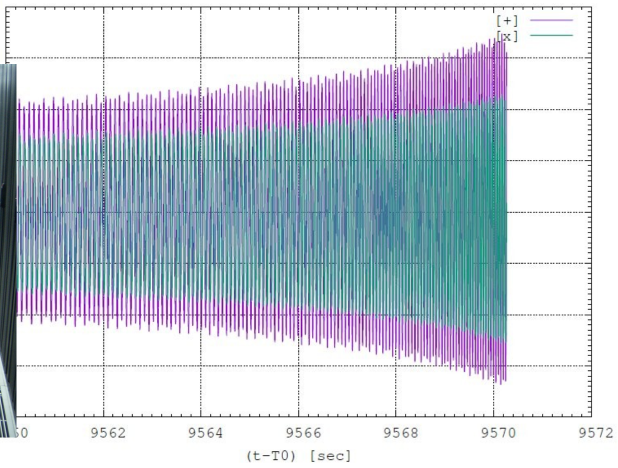


天龙星团模拟：百万数量级恒星、黑洞和引力波

Dragon Star Cluster Simulations: Millions of Stars; black holes and gravitational waves

- First realistic globular star cluster model with million stars *(Wang, Spurzem, Aarseth, …, Berczik, Kouwenhoven, … MNRAS 2015, 2016)*
- Synthetic CMD (right side) with zero photometric errors, different ages shown
- Black hole binary mergers occur as observed by LIGO. Our grav. waveforms computed from simulation (right side). (Only inspiral plotted not ringdown.)
- GPU accelerated supercomputers laohu in NAOC and hydra of Max-Planck (MPCDF) in Germany needed!





http://www.mpa-garching.mpg.de/328833/hl201603

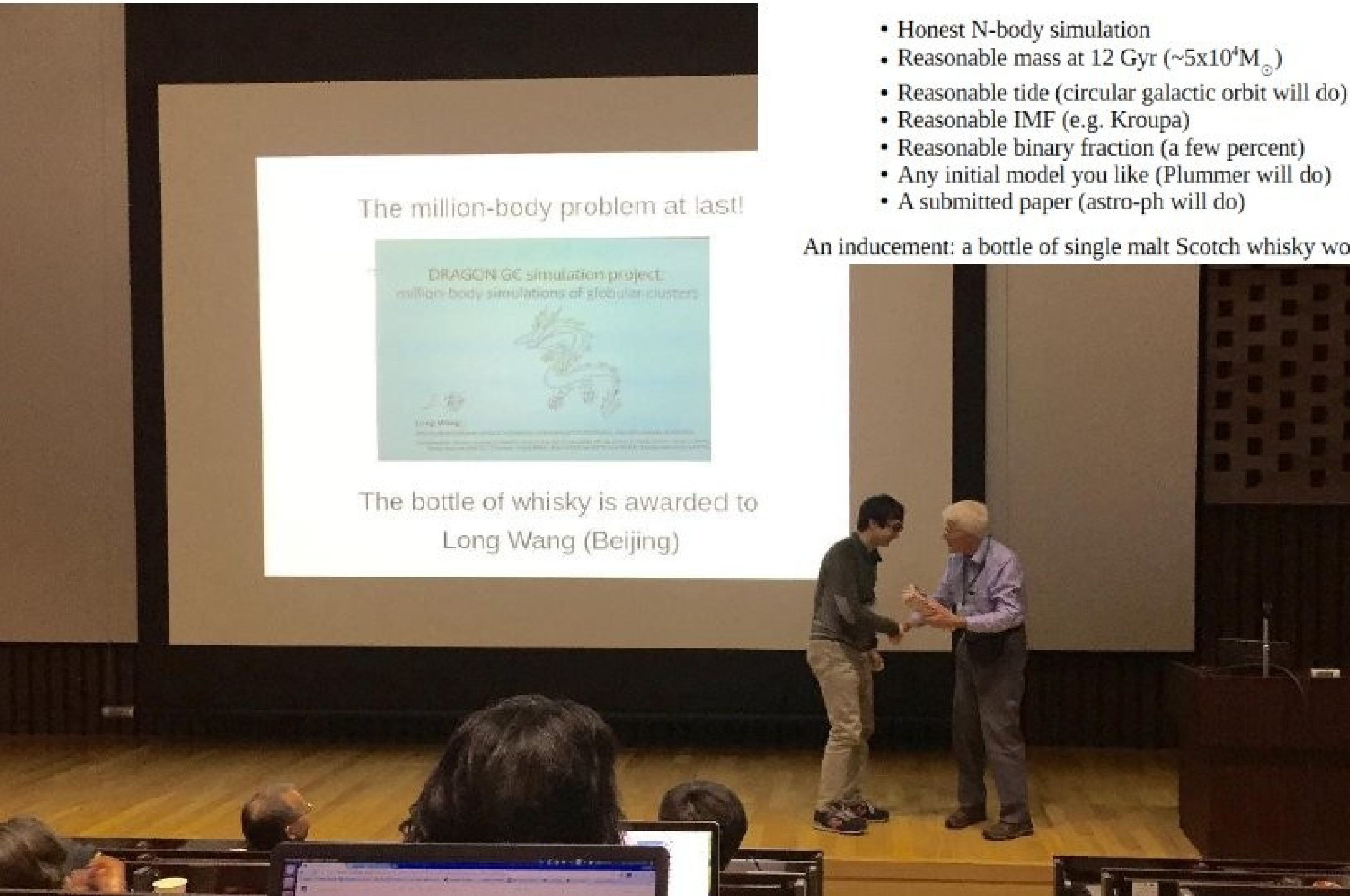
Leiden

CPU/GPU N-body6++

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



THE INITIAL CONDITIONS

DRAGON Simulations

- N_{single} = 950K; N_{binary} = 50K
- **Plummer** + point mass potential (MakeHalo, Dehnen 2005) (XX)
- **IMF**: Kroupa, 2001; 0.08 – 100 $M_\odot$ Or KTG 1993

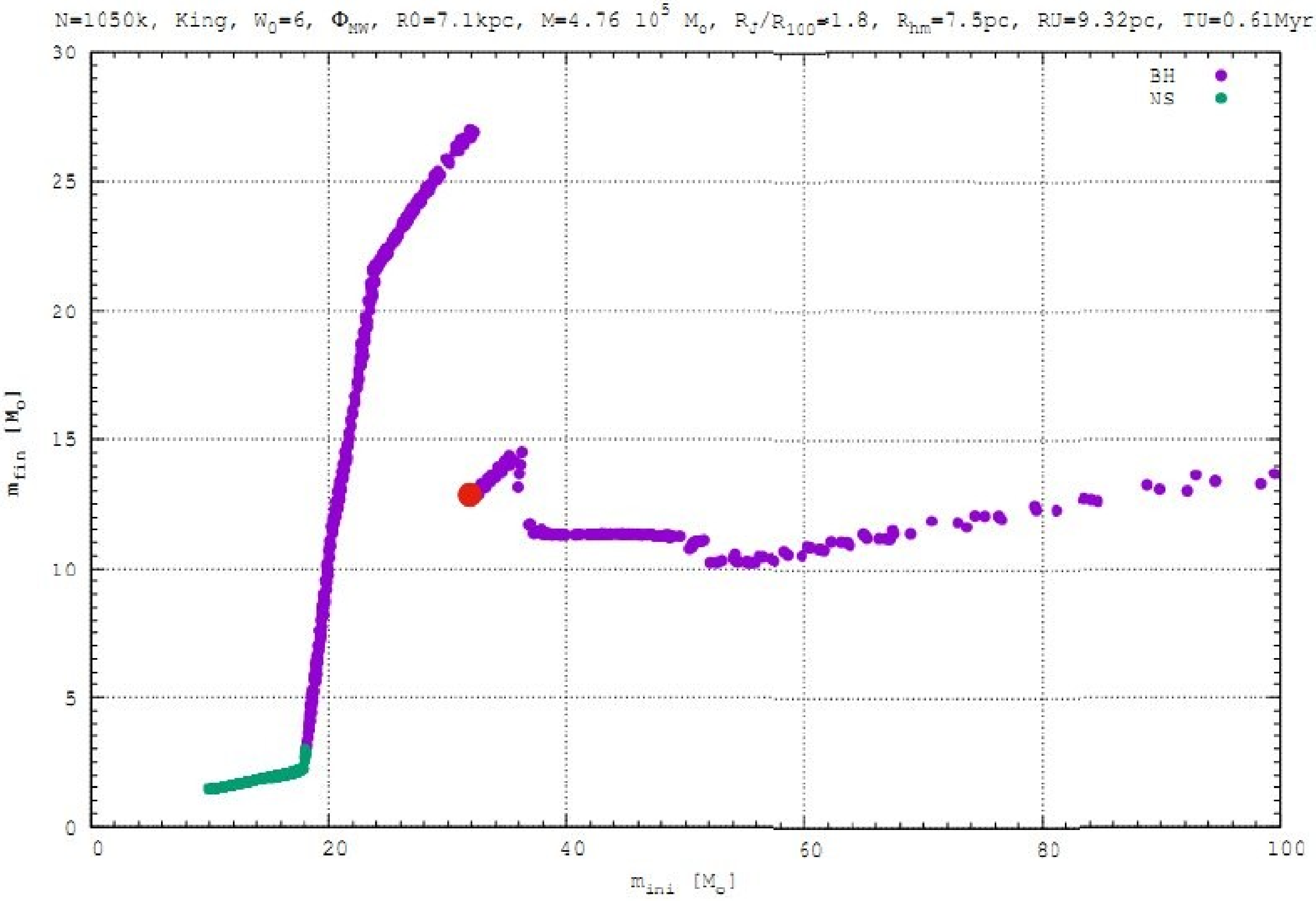
$$M_{tot} = 0.574 \times 10^8 M_\odot = 10 M_{smbh}$$ (XX)

- SSE/BSE: Mass Loss, Common Envelope?
- **Binaries**:
  - Uniform in log(a)
  - Thermal eccentricity distribution f(e) = 2e
  - Mass ratios: $f(q) \propto q^{-0.4}$ (Kouwenhowen+2007)
- **Kick**: 265 km/s (Hobbs+2005)

(XX) Only in case of central SMBH

Original Slide by
Taras Panamarev

Initial – Final Mass Relation in simulations for neutr. stars/black holes



Hurley, Pols, Tout et al. 2000, 2002; Belczynski et al. 2007

N-Body – Monte Carlo Comparison I

Rodriguez, Morscher, Wang, Chatterjee, Wang, Rasio, Spurzem, 2016

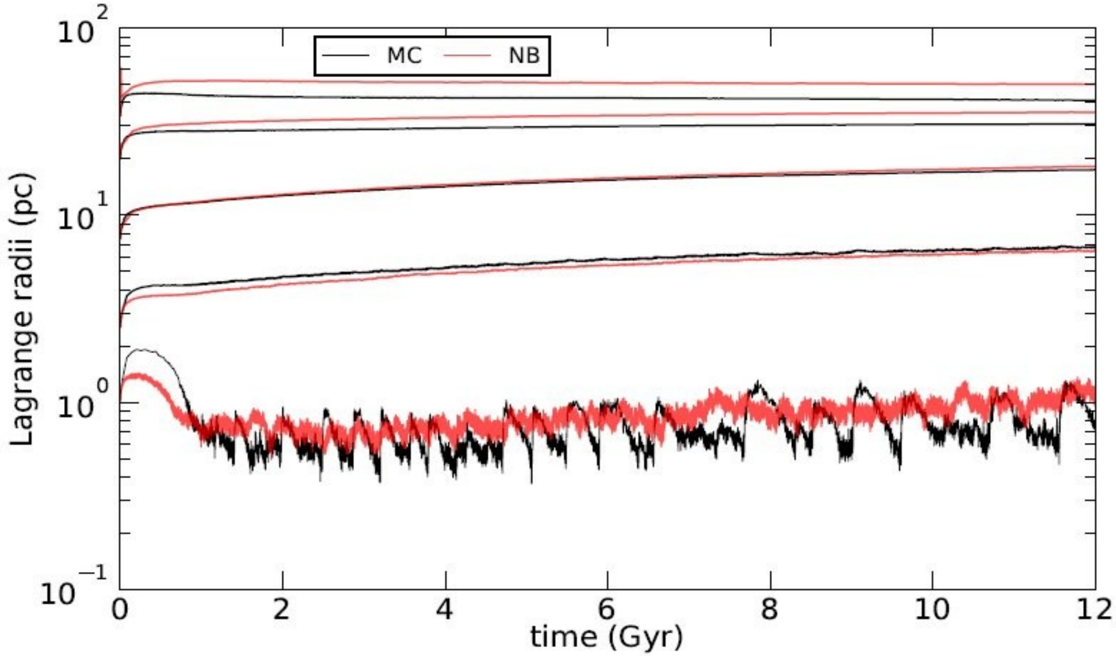


Figure 6. Comparison of the Lagrange radii for models MC (black) and NB (red). The pairs of black and red curves show the radii enclosing 1%, 10%, 50%, 90% and 99% (bottom to top) of the total cluster mass for the two respective models over the entire simulation.

Are there gravothermal oscillations?

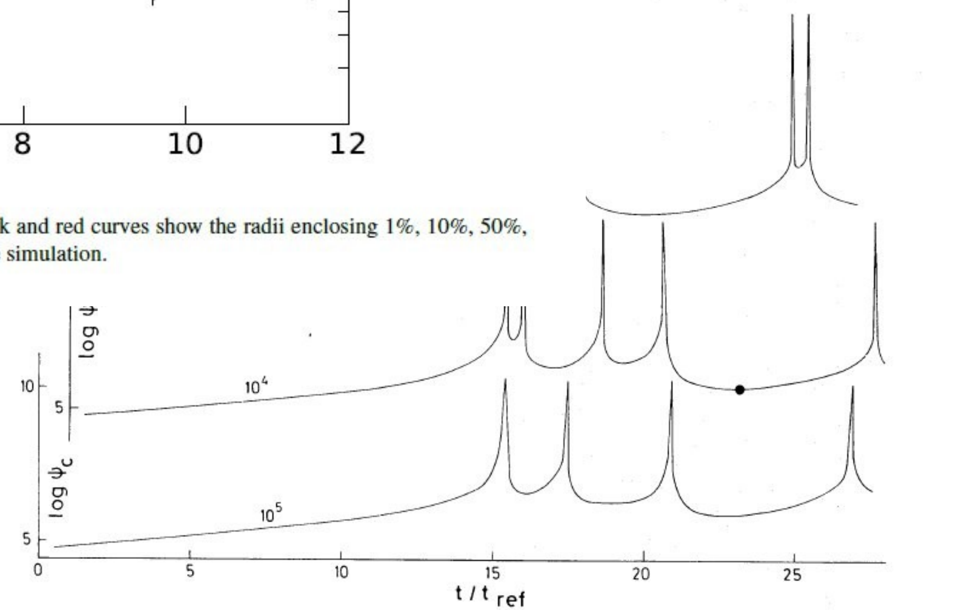


Figure 1. The 'central' density ψ_c is plotted against the non-dimensional time t/t_{ref} for $k = 2$ models with three different values of C as attached to each curve. Note, that if they were plotted with the same ordinate they would be close to each other despite the great differences in C. The model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

N-Body – Monte Carlo Comparison II
Wang, Askar, Giersz, Spurzem, 2016, in prep.

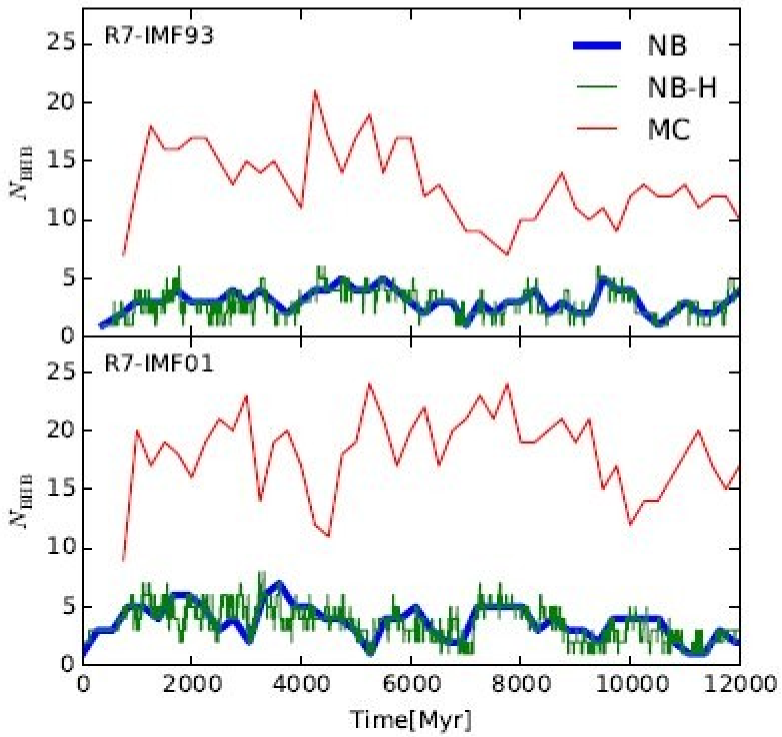


Figure 2. The evolution of hard BHB ($\tilde{a} < 100$ AU) numbers within core radii in R7-IMF93 ($R_c = 2pc$) and R7-IMF01 ($R_c = 3pc$). The blue curves show direct N-body (NBODY6++GPU) results and red curves show Monte-Carlo (MOCCA) results. These two curves have a same time resolution. The green curves show the same direct N-body result but higher time resolution.

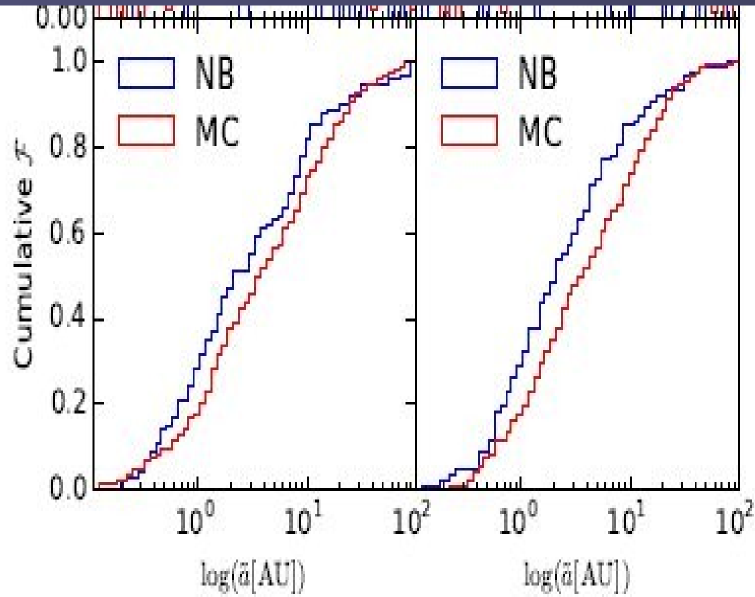
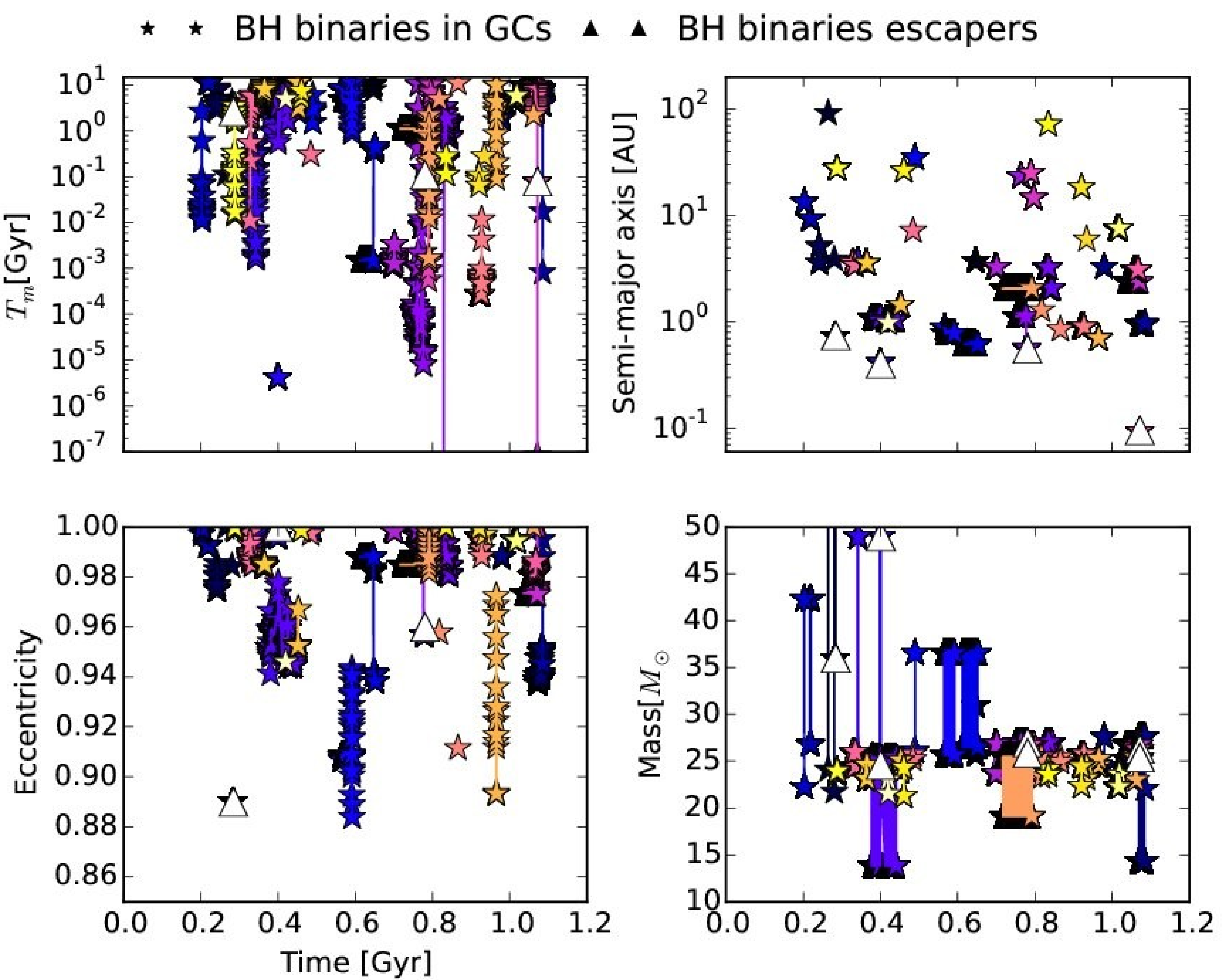


Figure 3. The normalized distribution of hard BHB scaled-semi-major axises $\tilde{a}$ ($\tilde{a} < 100$ AU) within core radii in R7-IMF93 and R7-IMF01 models. The upper panels show the histograms and the lower panels show the cumulative distributions. To obtain better statistics, BHB data from snapshots of every 250 Myr between the ages of 1 Gyr and 12 Gyr are collected (totally 45 snapshots). The blue color indicates the direct N-body results and the red color indicates the Monte-Carlo results.



BH binaries in GCs
BH binaries escapers
T_m[Gyr]
Semi-major axis [AU]
Eccentricity
Mass[$M_\odot$]
Time [Gyr]

Example Detections in one of the Dragon models....

Table header:

Status T[Gyr] Name1 Name2 M1[M_sun] M2[M_sun] a[AU] ecc Tm[Gyr] Tme[Gyr]

R7-IMF93 model

2 mergers in GC, 4 escapers:

1. There are two mergers in GCs [P] (merging time scale is very short)

Status	T[Gyr]	Name1	Name2	M1[M_sun]	M2[M_sun]	a[AU]	ecc	Tm[Gyr]	Tme[Gyr]
P	2.32566	49	100229	25.6495	26.3923	12.51693	0.999867	6.18E-05	0.000124
P	1.54318	100237	100373	26.1701	21.932	8.93532	0.99996	3.06E-07	6.13E-07

2. There are two escaped mergers [E]: ('L' means the parameter before ejection)

Status	T[Gyr]	Name1	Name2	M1[M_sun]	M2[M_sun]	a[AU]	ecc	Tm[Gyr]	Tme[Gyr]
L	1.3261	100246	37	25.7717	27.5506	1.088842	0.96292	1.19077	2.239183
E	1.32673	100246	37	25.8	27.6	1.092031	0.96	1.563829	2.925774
L	1.24649	100217	100291	26.9635	24.2528	2.375981	0.987629	0.655226	1.286116
E	1.24711	100217	100291	27	24.3	2.404434	0.99	0.3247471	0.640051

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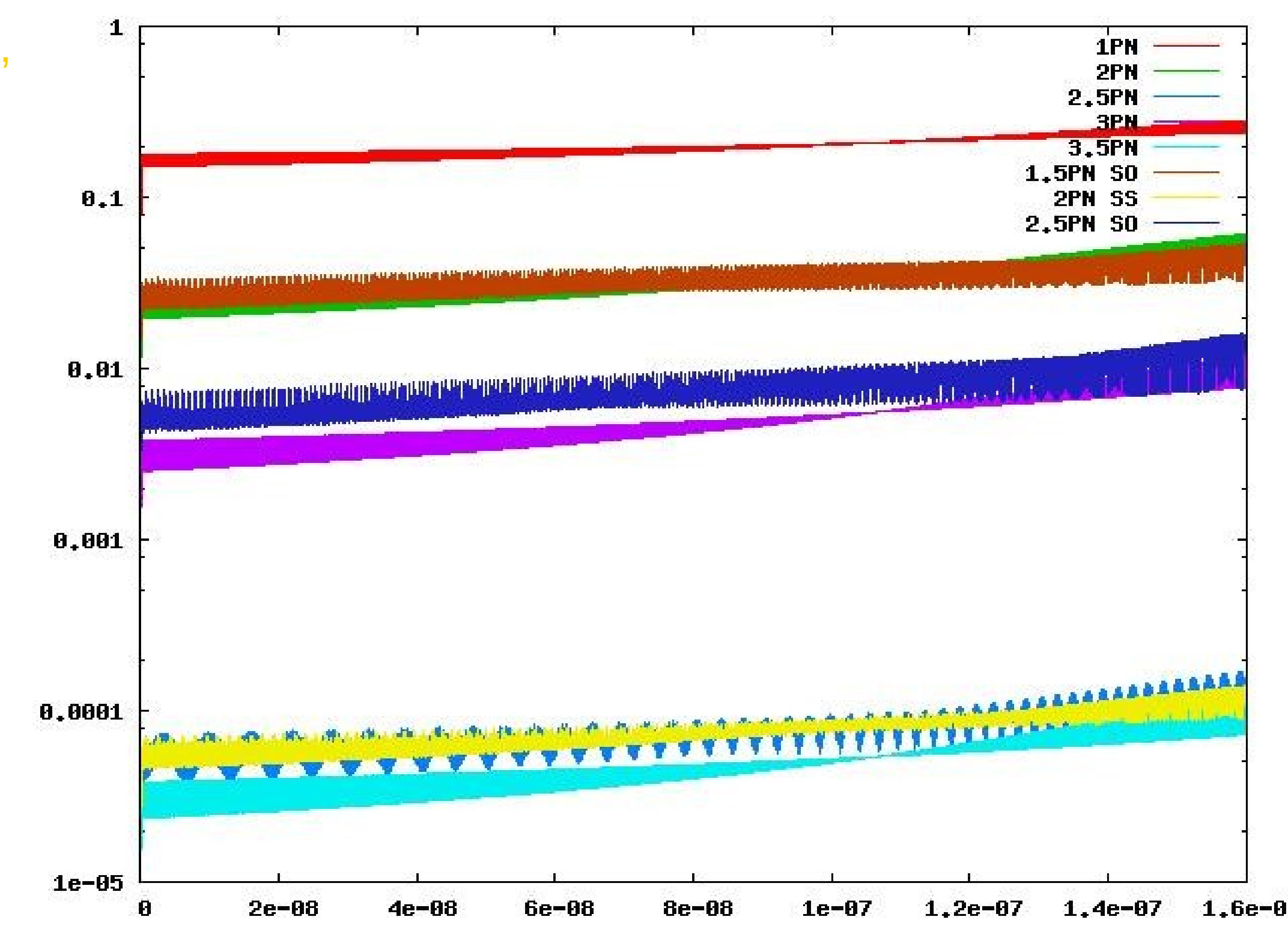
Post-Newtonian Dynamics

Brem, Amaro-Seoane, Spurzem, MNRAS 2013

Include
Spin-Orbit
Spin-Spin
PN3, PN3.5
Spin Dynamics

By Patrick Brem
(Diploma Thesis
Univ. Heidelberg)

1PN
2PN + 1.5PN SO
3PN + 2.5PN SO
2.5PN + 2PN SS
3.5PN



PN dynamics from Blanchet, Spins Faye et al. 2006

Rezzolla
Final Spin
Formula

Brem,
Amaro-SeoaneS,
Spurzem,
MNRAS 2013

$$|\mathbf{a}_{\rm fin}| = \frac{1}{(1+q)^2}\Big[|\mathbf{a}_1|^2 + |\mathbf{a}_2|^2 q^4 + 2|\mathbf{a}_2||\mathbf{a}_1|q^2 \cos\alpha + 2(|\mathbf{a}_1|\cos\beta + |\mathbf{a}_2|q^2\cos\gamma)|\mathbf{l}|q + |\mathbf{l}|^2 q^2\Big]^{1/2},$$

where $q = M_2/M_1$ is the mass ratio and the angles are defined as

$$\cos\alpha = \hat{a}_1 \cdot \hat{a}_2, \qquad \cos\beta = \hat{a}_1 \cdot \hat{l}, \qquad \cos\gamma = \hat{a}_2 \cdot \hat{l}.$$

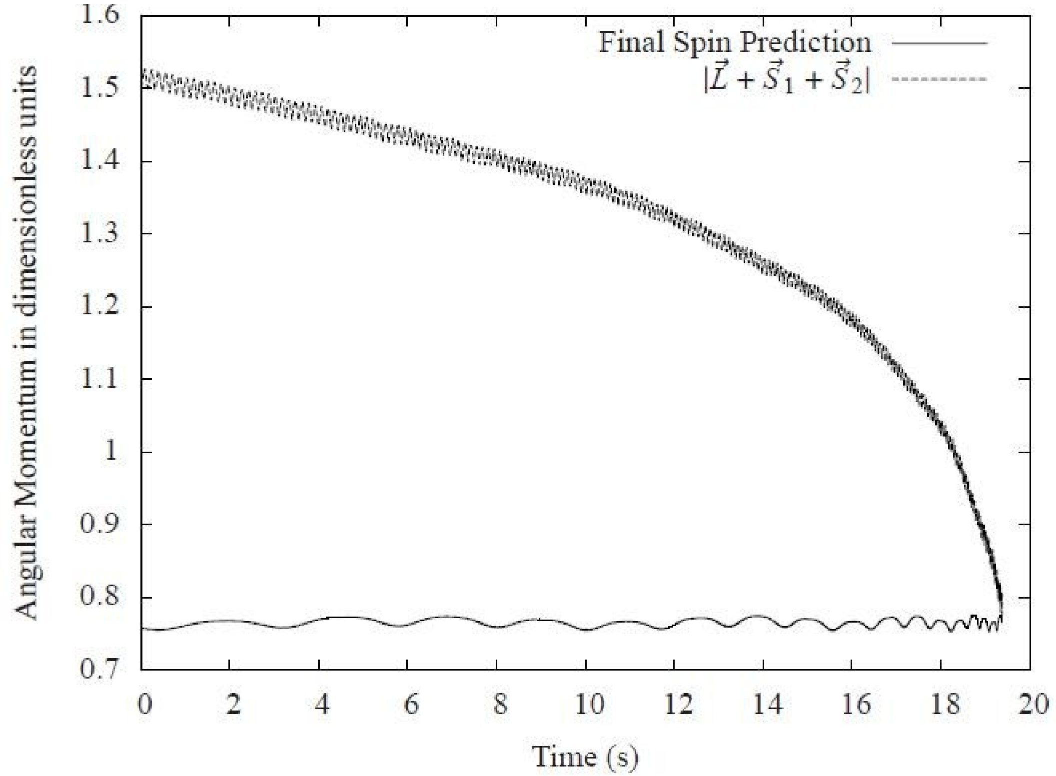


Figure 3.7: Comparison between the current final spin prediction and the actual total angular momentum of the binary system.

Post-Newtonian Dynamics Gravitational Wave Templates

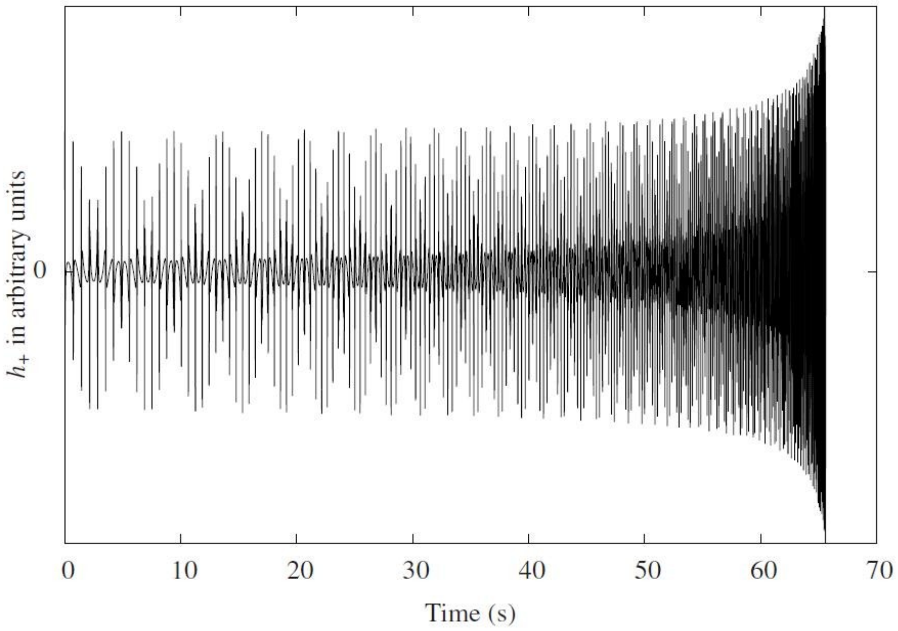


Figure 3.11: Waveform for two equal mass objects on a an orbit with $e = 0.5$.

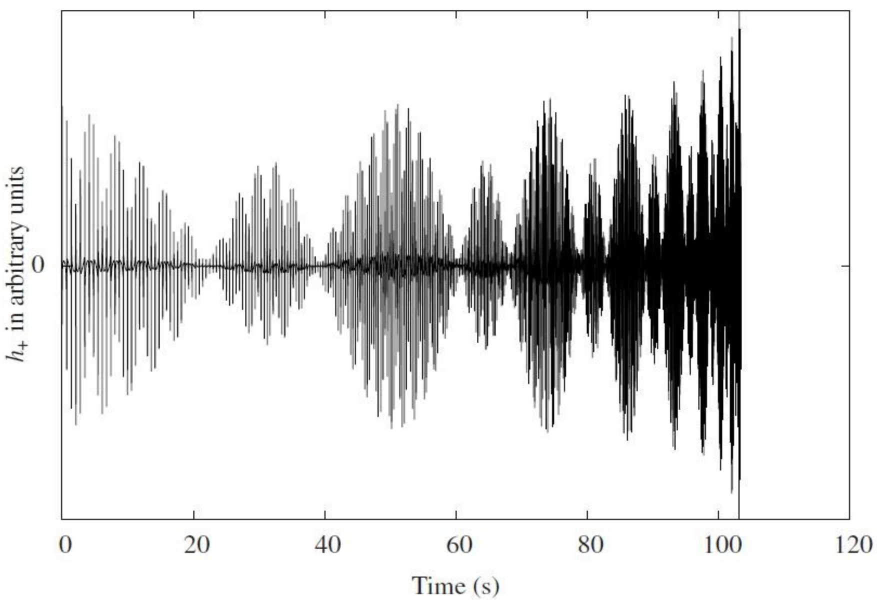


Figure 3.12: Waveform for two objects with a mass ratio of $q = 1/10$ on an orbit with $e = 0.5$ and spins $a_{1,x} = 1.0$, $a_{2,y} = 1.0$.

Handle spin-orbit and spin-spin coupling
(P.Brem, R. Spurzem, Univ. Heidelberg)

Brem, Amaro-Seoane, Spurzem, MNRAS, 2013

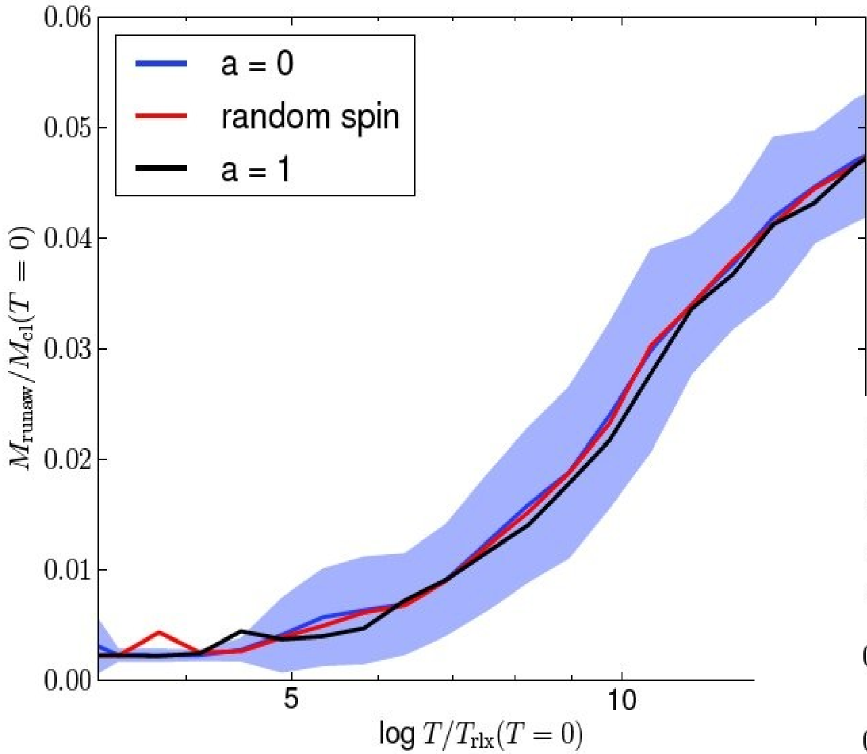
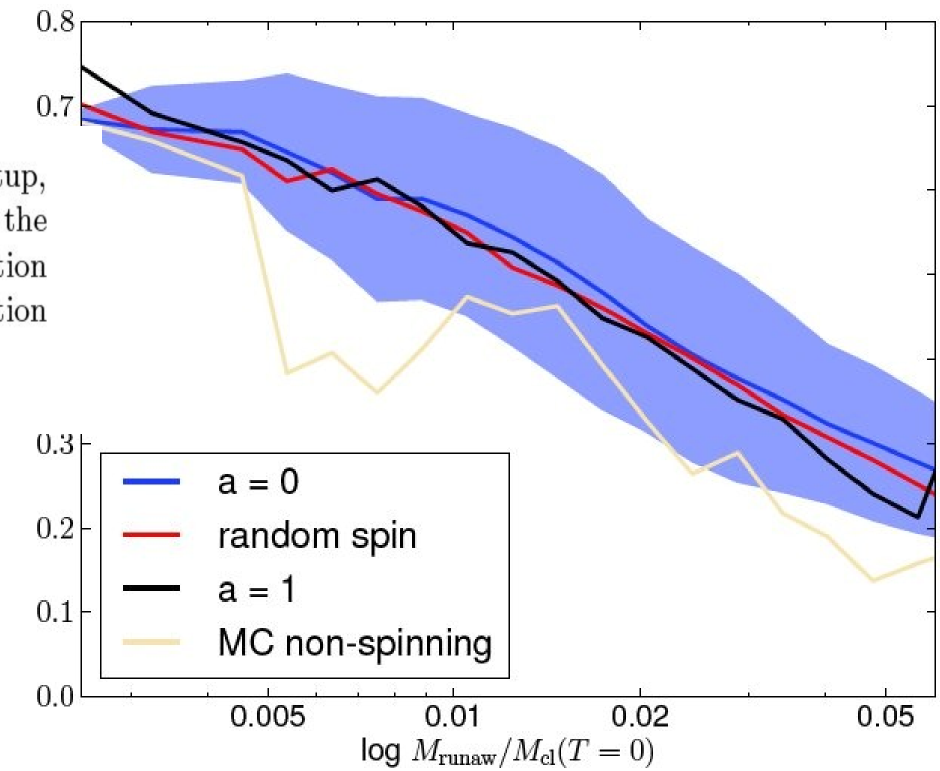


Figure 8. Mass of the runaway body, M_{runaw}, for each setup, averaged over 500 runs. $M_{cl}(T = 0)$ is the total mass of the cluster at the time $T = 0$ and $T_{rlx}(T = 0)$ the initial relaxation time of the cluster. The shaded area shows the standard deviation for the $a = 0$ case.

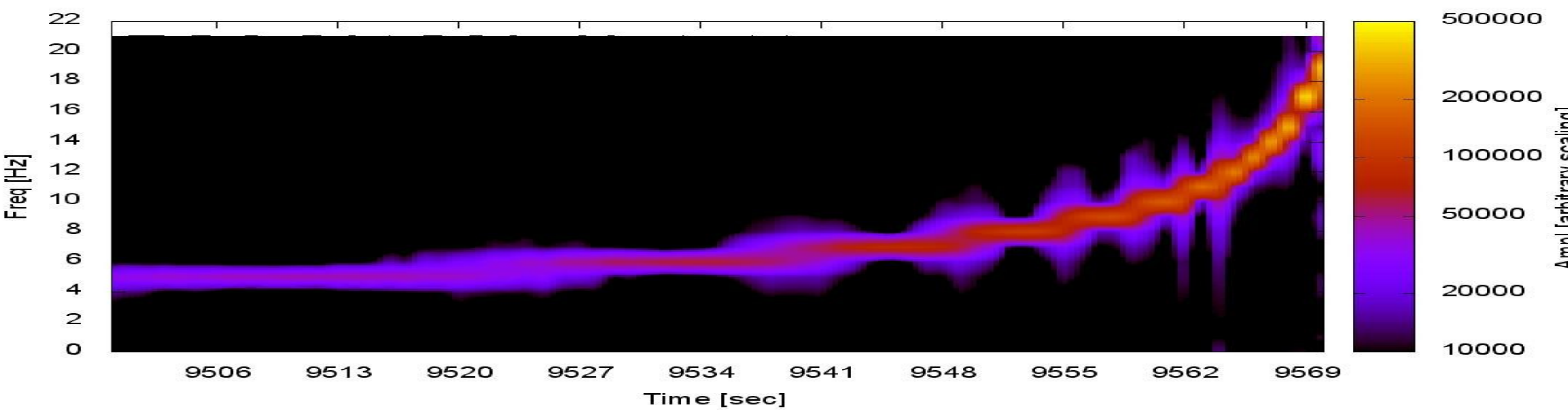
Figure 9. Spin of the runaway body in each simulation, averaged over 500 runs. The shaded area shows the standard deviation for the $a = 0$ case. All initial spin setups lead to a similar evolution, except for the very first data point which is slightly higher for the maximally spinning initial conditions.



GW Detection Frequency Time Diagram

Top: Our simulation (Wang et al. 2016, Berczik et al. In prep.)

Down: Abott et al. 2016 LIGO measurement



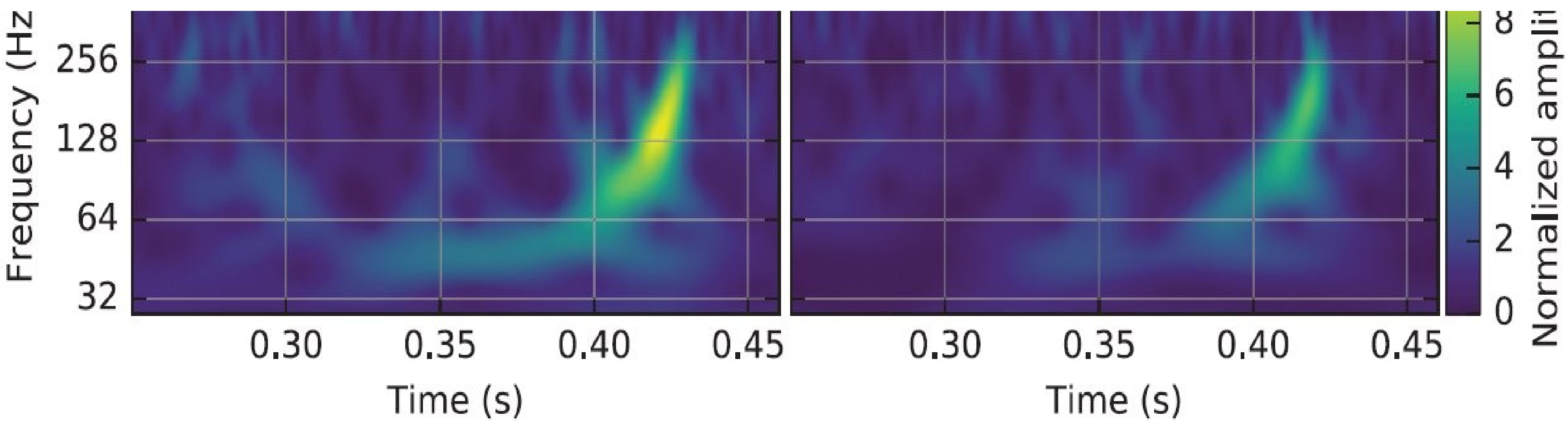
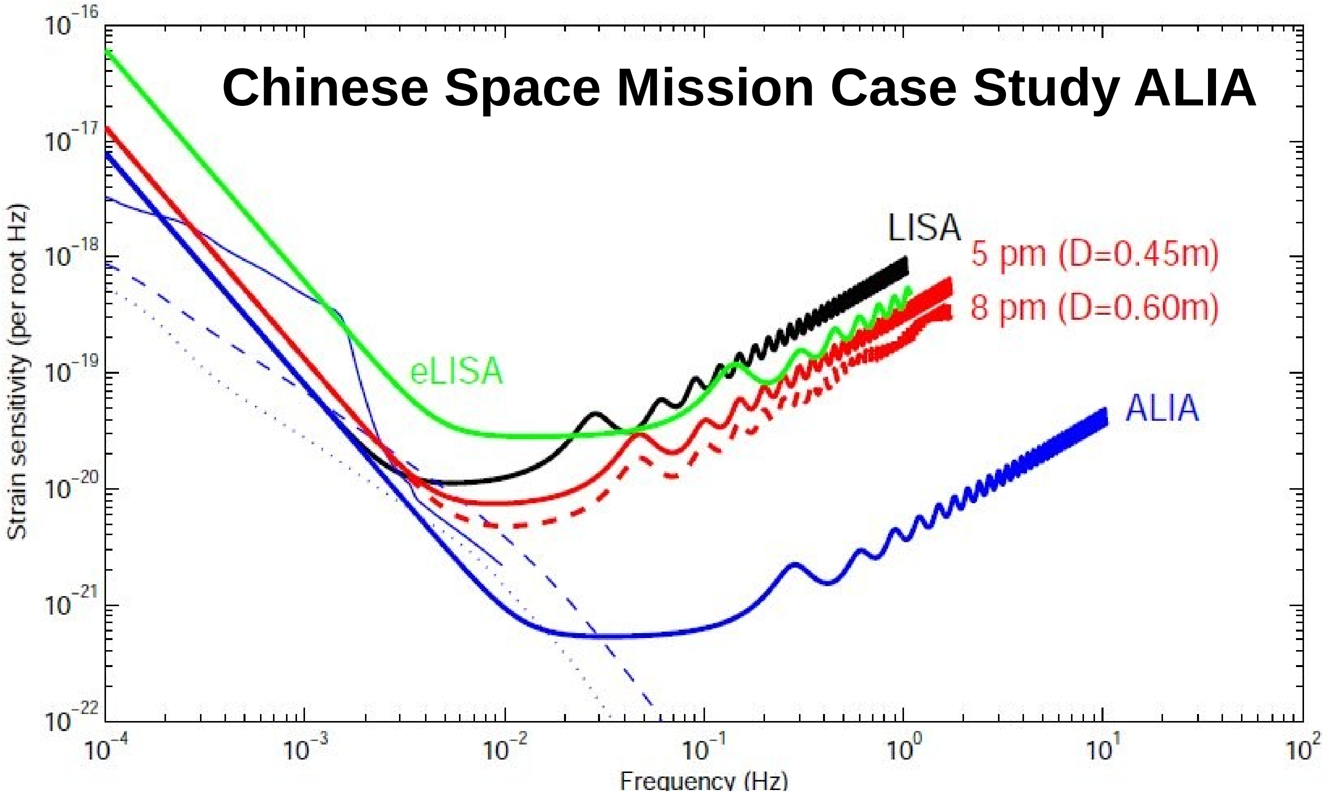


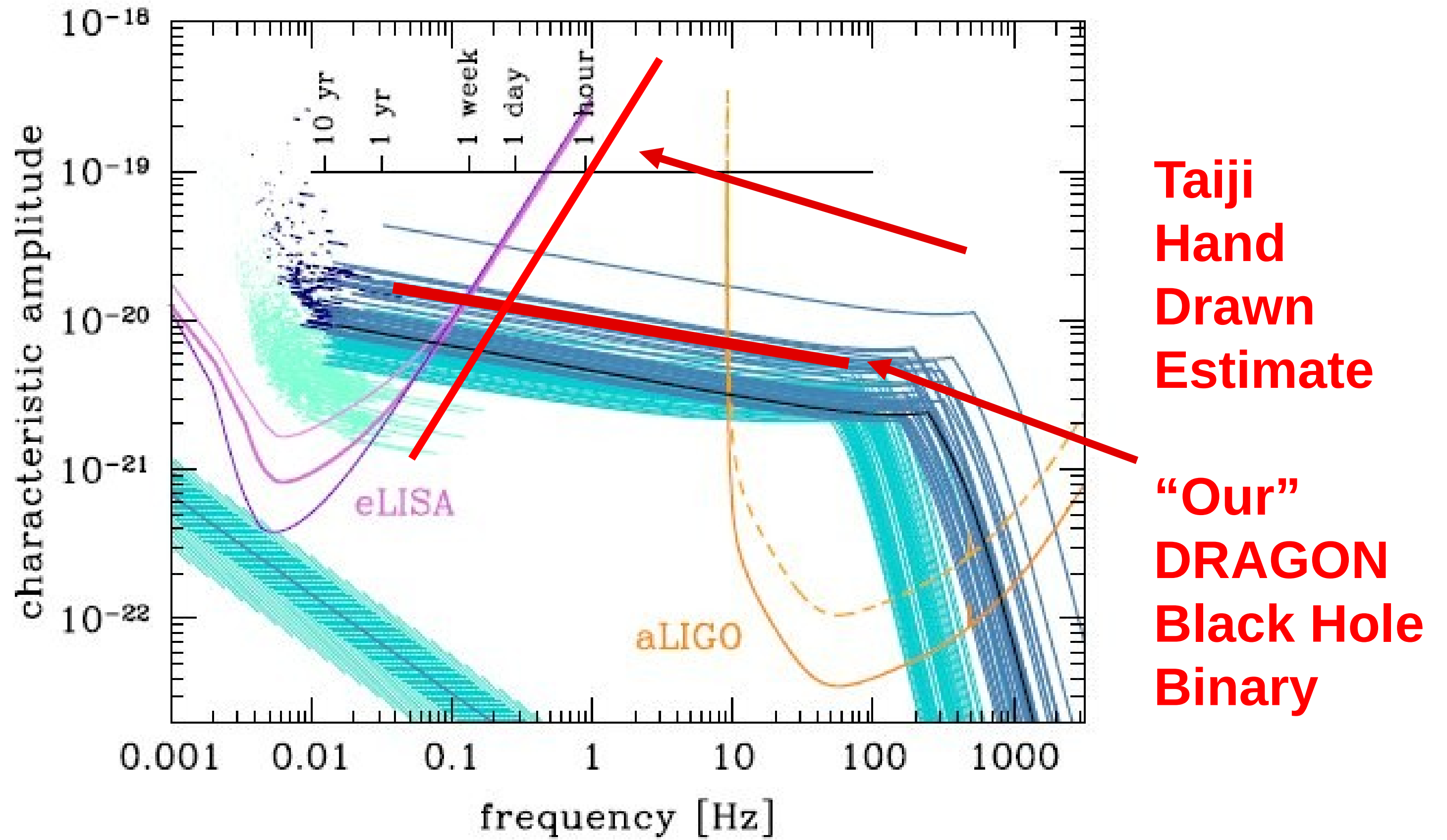
FIG. 1. The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right



**Gong, Lau, …
Amaro-Seoane, …
Spurzem et al. 2015**

Table 1.

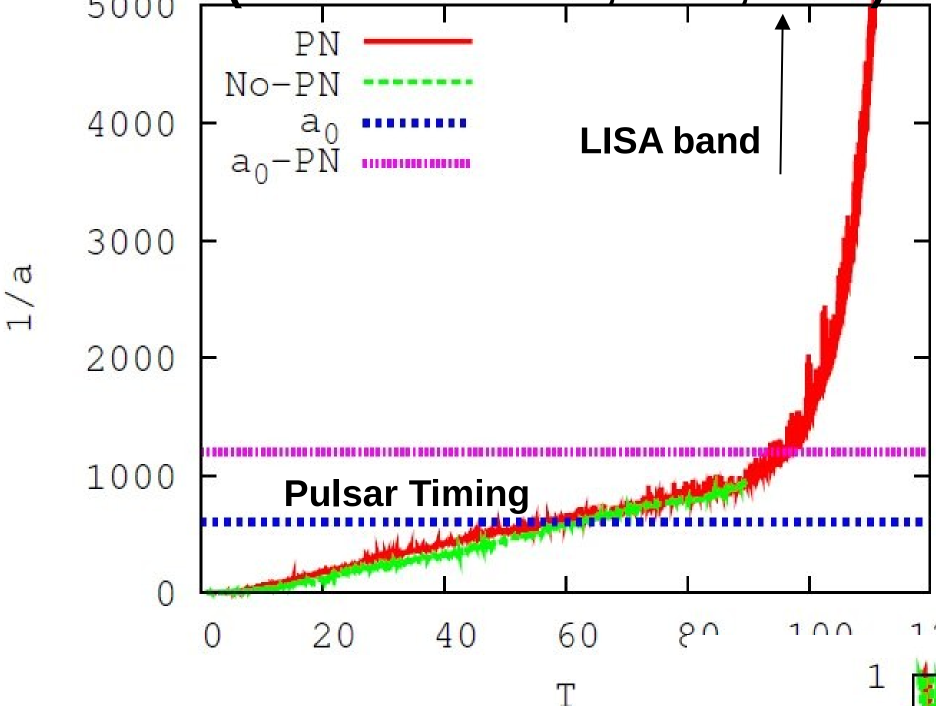
Armlength (m)	Telescope diameter (m)	Laser power(W)	1-way position noise ($\frac{\text{pm}}{\sqrt{\text{Hz}}}$)	Acceleration ($\frac{\text{m s}^{-2}}{\sqrt{\text{Hz}}}$)
3×10^9	0.45-0.6	2	5-8	$3 \times 10^{-15}(> 0.1\text{mHz})$
5×10^8 (ALIA)	1.0	30	0.1	$3 \times 10^{-16}(> 1\text{mHz})$
5×10^9 (LISA)	0.4	2	18	$3 \times 10^{-15}(> 0.1\text{mHz})$
1×10^9 (eLISA)	0.2	2	11	$3 \times 10^{-15}(> 0.1\text{mHz})$



Sesana 2016

FIG. 1: The multi-band GW astronomy concept. The violet lines are the total sensitivity curves (assuming two Michelson) of three eLISA configurations; from top to bottom N2A1, N2A2, N2A5 (from [11]). The orange lines are the current (dashed) and design (solid) aLIGO sensitivity curves. The lines in different blue flavours represent characteristic amplitude tracks of BHB sources for a realization of the *flat* population model (see main text) seen with S/N> 1 in the N2A2 configuration (highlighted as the thick eLISA middle curve), integrated assuming a five year mission lifetime. The light turquoise lines clustering around 0.01Hz are sources seen in eLISA with S/N< 5 (for clarity, we down-sampled them by a factor of 20 and we removed sources extending to the aLIGO band); the light and dark blue curves crossing to the aLIGO band are sources with S/N> 5 and S/N> 8 respectively in eLISA; the dark blue marks in the upper left corner are other sources with S/N> 8 in eLISA but not crossing to the aLIGO band within the mission lifetime. For comparison, the characteristic amplitude track completed by GW150914 is shown as a black solid line, and the chart at the top of the figure indicates the frequency progression of this particular source in the last 10 years before coalescence. The shaded area at the bottom left marks the expected confusion noise level produced by the same population model (median, 68% and 95% intervals are shown). The waveforms shown are second order post-Newtonian inspirals phenomenologically adjusted with a Lorentzian function to describe the ringdown.

(Khan et al. 2012, 2013, 2016)

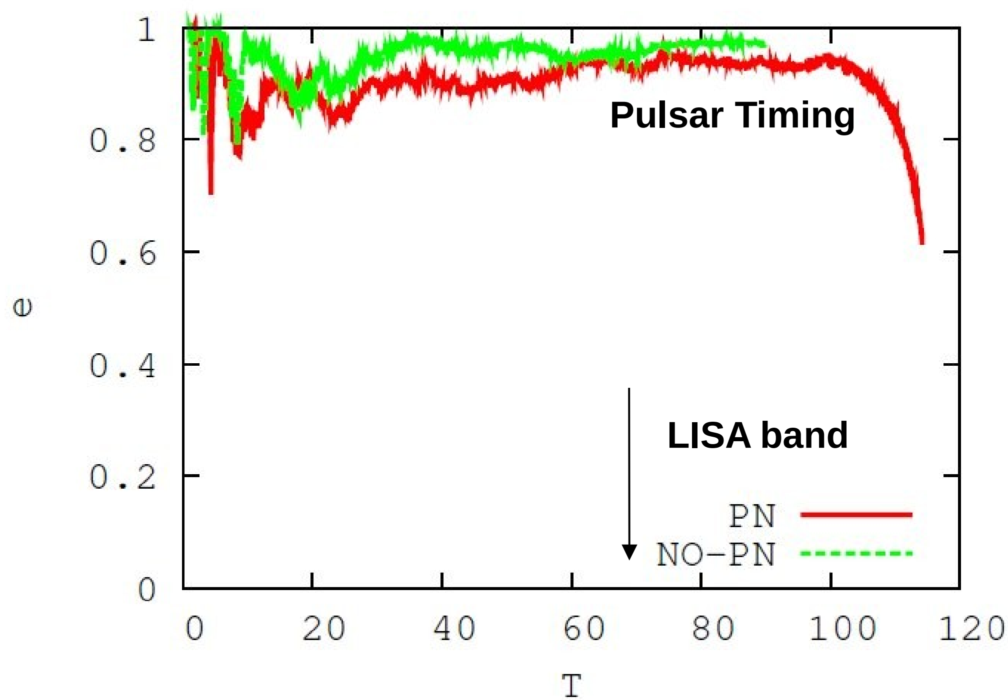


1 / SMBH Bin. Separation

Full Model from Merger
To
SMBH coalescence
6 orders in separation!

GW Emission from
Pulsar Timing to
LISA band modelled

SMBH Bin. Eccentricity



- Introduction
- Excursion Galactic Nuclei
- Black Holes in Star Clusters
- Gravitational Wave Observations
- Computational Instruments

NAOC laohu cluster

64 Kepler K20

Request:
New Supercomputer

Laohu: 2009/2013
(Kepler GPU)
100 Tflop/s 150k cores

Need:
~100 Pascal GPU
1.5 Pflop/s 300k cores

Compare:
AEI Hannover B. Allen

MPG Garching Hydra

Nr. 1,2 Supercomputer from China: 96/33 Pflop/s Linpack
Wuxi/Guangzhou/Tianjin National Supercomputing Center
Taihu 10 mill. cores

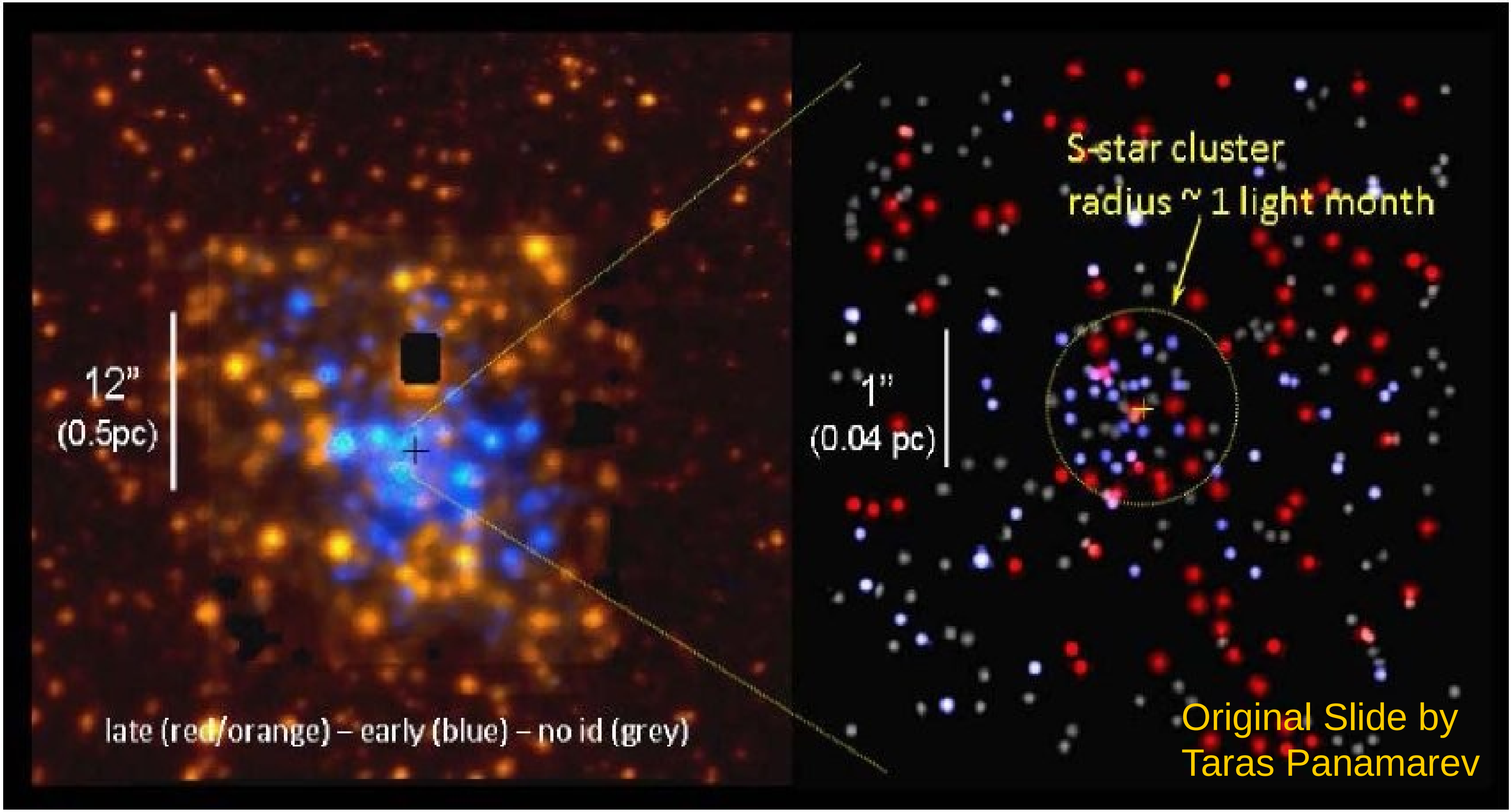
Tianhe-2 (MilkyWay-2) - TH-IVI
E5-2692 12C 2.200GHz, TH Ex
31S1P

32000 Intel Xeon 12 core,
48000 Intel Phi Accelerators 57 Core

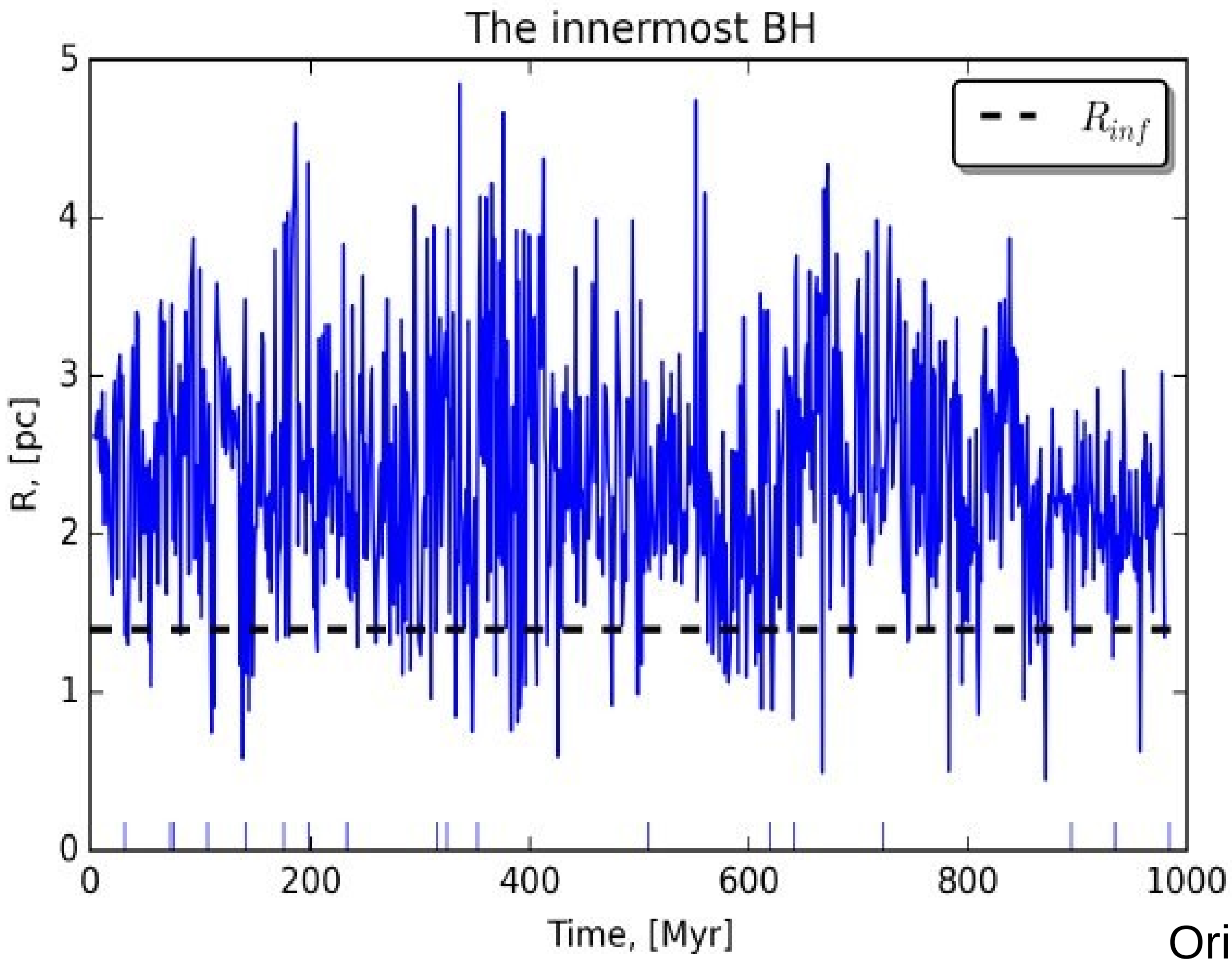
Test of Taihu planned;
But:
Local cluster with new GPUs at NAOC gives much more resources.

Distribution of stars

Galactic Center



Compact Objects Galactic Center

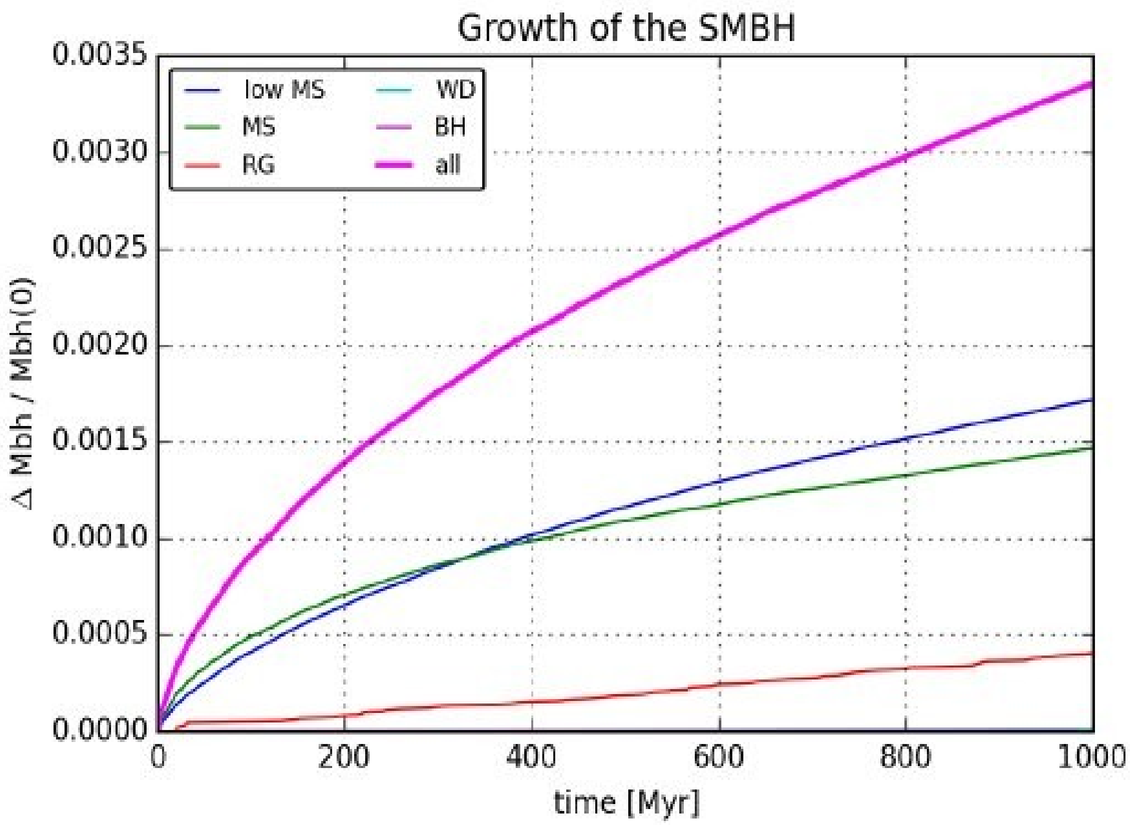


Original Slide by
Taras Panamarev

Distance to the nearest black hole as a function of time.

Tidal disruption

Galactic Center



MS_{low}	43114
MS	6518
RG	870
WD	68
BH	1,8

$R_{RG} \sim 10^{-5}\ pc$ $\quad R_{MS} \sim 10^{-6}\ pc$ $\quad R_{WDBH} < R_S$

Accretion rate grows linearly with racc (Just+2012)

Original Slide by
Taras Panamarev

Conclusions

Galactic Center

- Black holes survive and segregate to the centre
- RGs envelope stripping ~600 /Gyr/galaxy
- GW: BH – SMBH 1-2 /Gyr/Galaxy

  WD – SMBH 60-70 /Gyr/Galaxy
- Millisecond pulsars:

  Accretion induced collapse – likely to present in the GC

Original Slide by
Taras Panamarev

Summary

- **Astrophysical High Precision N-Body – Star Clusters**
  DRAGON simulations of low-density star cluster
  Need more Dragon simulations to study physics of rotation, binaries, high density, nuclear star clusters

(Wang et al. 2015a, ApJ, 2015b, Cai et al. 2015, ApJS, Pang et al. 2015 RAA, Huang et al. 2015, RAA)

- **Black Holes in Galactic Nuclei**
  No stalling problem – robust result with rotation
  STARDISK project – disk, stars and black hole...
  Enhanced tidal disruption rates due to:
  galaxy mergers / black hole kicks / rotation

(Zhong et al. 2014, 2015, ApJ. Li et al. 2012 ApJ, 2015 subm. ApJ Khan et al. 2012, 2014 ApJ, Sobolenko et al. 2015 ApJ subm.)

- **Further Astrophysical Science Drivers:**
  Gravitational Waves in Pulsar Timing/eLISA/LIGO
  more work on spins needed
  Coordinated update of SSE/BSE needed...