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

Dense Star Clusters
Binary Black Holes
Gravitational Waves

Uni Heidelberg

Rainer Spurzem with Silk Road Team

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

Here main collaborators:

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M.B.N. Kouwenhoven (now Suzhou XJTLU-former KIAA/PKU)
Sverre Aarseth (Inst. Of Astron. U Cambridge, UK)
T. Naab, R. Schadow (MPA Garching),
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VolkswagenStiftung

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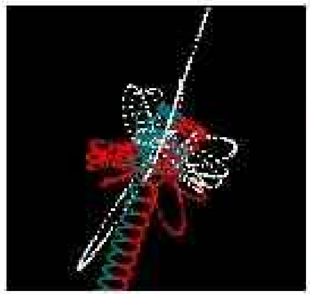
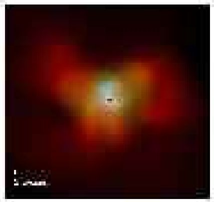
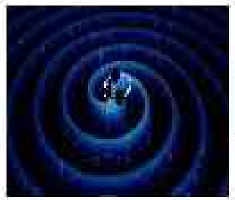
http://silkroad.bao.ac.cn

Our Main Research Projects are:

- Binary Supermassive Black Holes and Gravitational Waves in Quiet and Active Galactic Nuclei

- Dynamical Evolution of Stars and Gas in Galactic Nuclei and Dense Star Clusters
- How are planetary systems forming and evolving (in star clusters)?
- How can we design supercomputers which are faster and consume less energy?

ICCS
International Center for Computational Science


千人計畫
RECRUITMENT
PROGRAM OF GLOBAL EXPERTS

Support and Collaboration by CNIC @ NAOC (Chenzhou CUI and team)

- Education and Workshops in Computational and Theoretical Astrophysics, Parallel Programming and Accelerated Computing

Chinese President Xi Jinping welcomes “Foreign Experts”

the SILK ROAD PROJECT at NAOC/KIAA

丝绸之路 计划

千人計劃

RECRUITMENT
PROGRAM OF GLOBAL EXPERTS

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

http://silkroad.bao.ac.cn

National Astronomical Observatory of Chinese Academy of Sciences, Beijing Ch
Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing, Chin
Fesenkov Astrophysical Institute, Space Institute, Almaty, Kazakhstan
Institute of Space Technology, Islamabad, Pakistan (NEW)
Main Astronomical Observatory of Ukrainian Academy of Sciences, Kiev, Ukrain
Astronomisches Rechen-Institut,Zentrum f. Astronomie (ZAH) and
Computer Engineering and Architecture (ZITI), Univ. Of Heidelberg, Germany
Max-Planck Institute for Astrophysics (MPA), Garching/Munich, Germany

- Instruments (Hardware/Software)
- Dragon Simulations of Star Clusters
- Black Holes / Gravitational Waves
- Link to Cosmology

GPU Computing

General Purpose
GPU Supercomputing (GPGPU)

http://www.nvidia.com

http://www.astrogpu.org

http://gpgpu.org

PCI Express 2.0

NVIDIA TESLA with CUDA

GPU

- Number of processor cores: 240
- Processor core clock: 1.296 GHz
- Voltage: 1.1875 V
- Package size: 45.0 mm × 45.0 mm 2236-pin flip-chip ball grid array (FCBGA)

Board

- Fourteen layer printed circuit board (PCB)
- PCI Express 2.0 ×16 system interface
- Physical dimensions: 4.376 inches × 10.50 inches, dual slot
- Board power dissipation: 187.8 W

External Connectors

- None

Internal Connectors and Headers

- One 6-pin PCI Express power connector
- One 8-pin PCI Express power connector
- 4-pin fan connector

NVIDIA Tesla C1060
in kolob cluster Heidelberg Univ.

Computational Science...

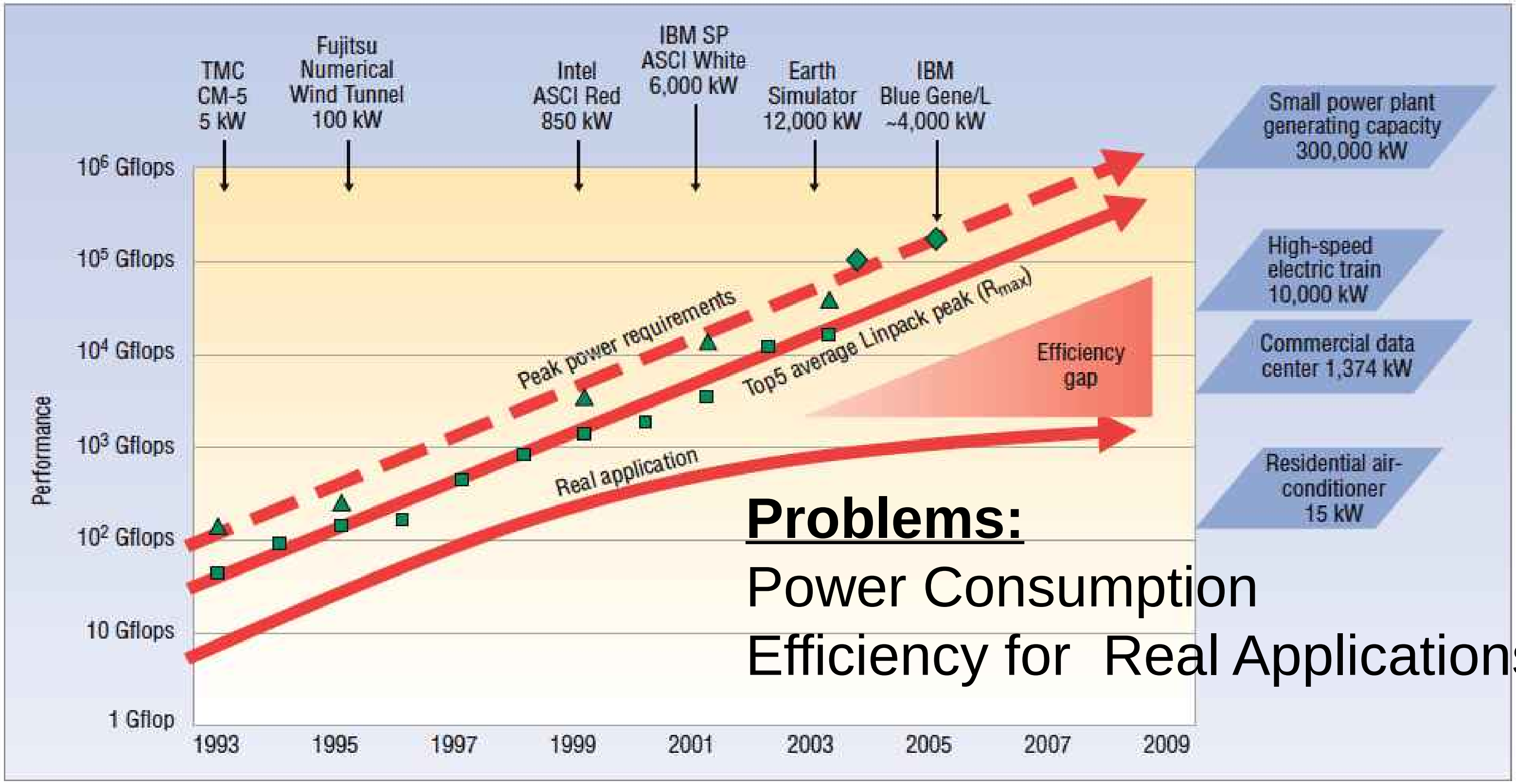
...after von Neumann...

Exaflop/s?

Petaflop/s

Teraflop/s

Gigaflop/s



Problems:

Power Consumption

Efficiency for Real Applications

Figure 1. Rising power requirements. Peak power consumption of the top supercomputers has steadily increased over the past 15 years.

Thanks to Horst Simon, LBNL/NERSC for this diagram.

NAOC laohu cluster

64 Kepler K20

Request:
New and/or upgrade of laohu

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

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

Compare:
AEI Hannover B. Allen

MPG Garching Hydra

Our Green Grid: GPU Clusters used:

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

85 Nodes, 64 Kepler K2

Max-Planck MPCDF GPU cluster (400 Kepler K20 GPUs)

Golowood cluster, Main Astron. Observatory, Kiev, Ukraine

Kepler cluster Heidelberg, Germany (12x Kepler GPU)

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

Tianhe-2 (MilkyWay-2) - TH-IV
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

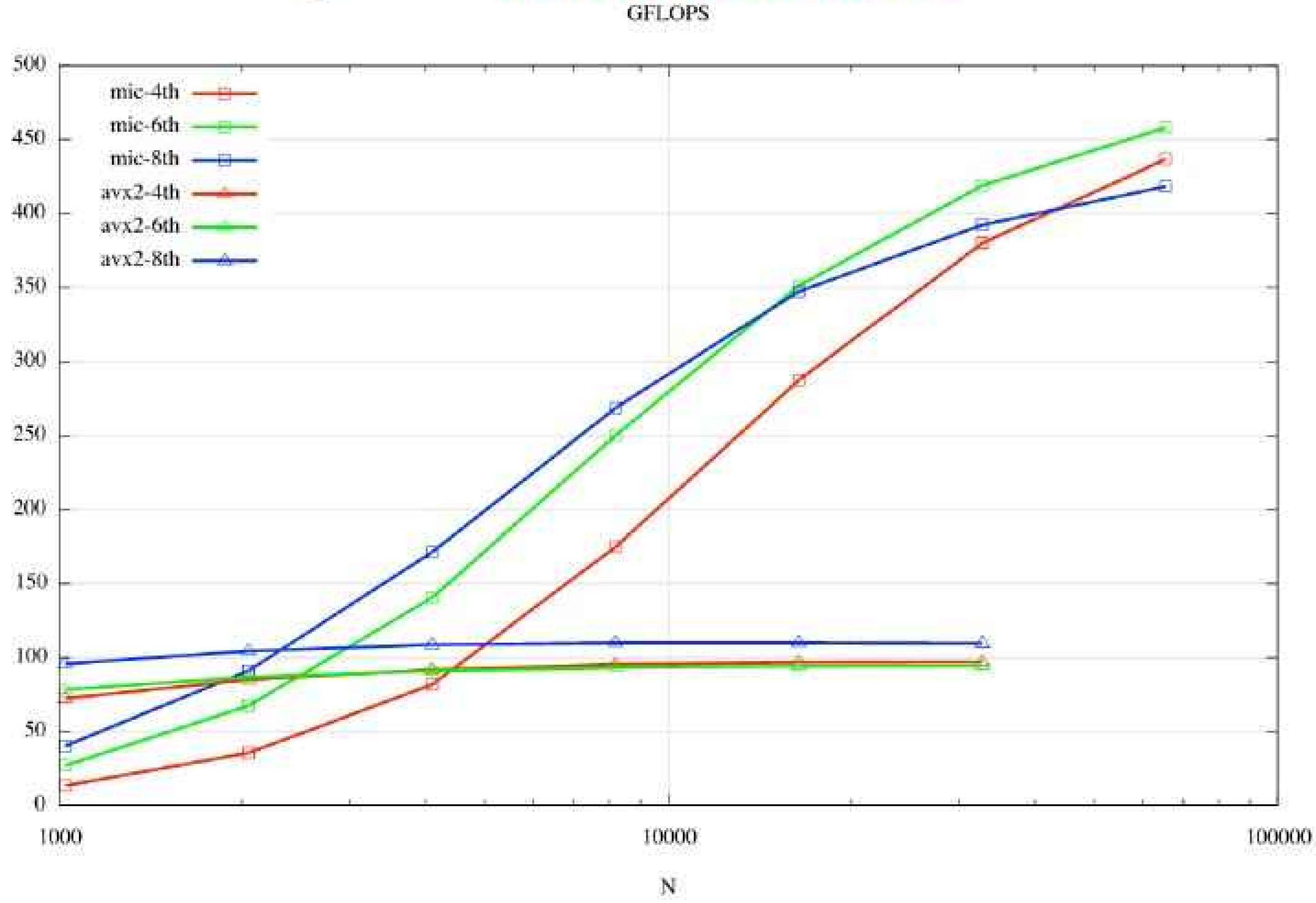
Intel MIC Hardware

INSPUR, NAOC - 2013.XI.26

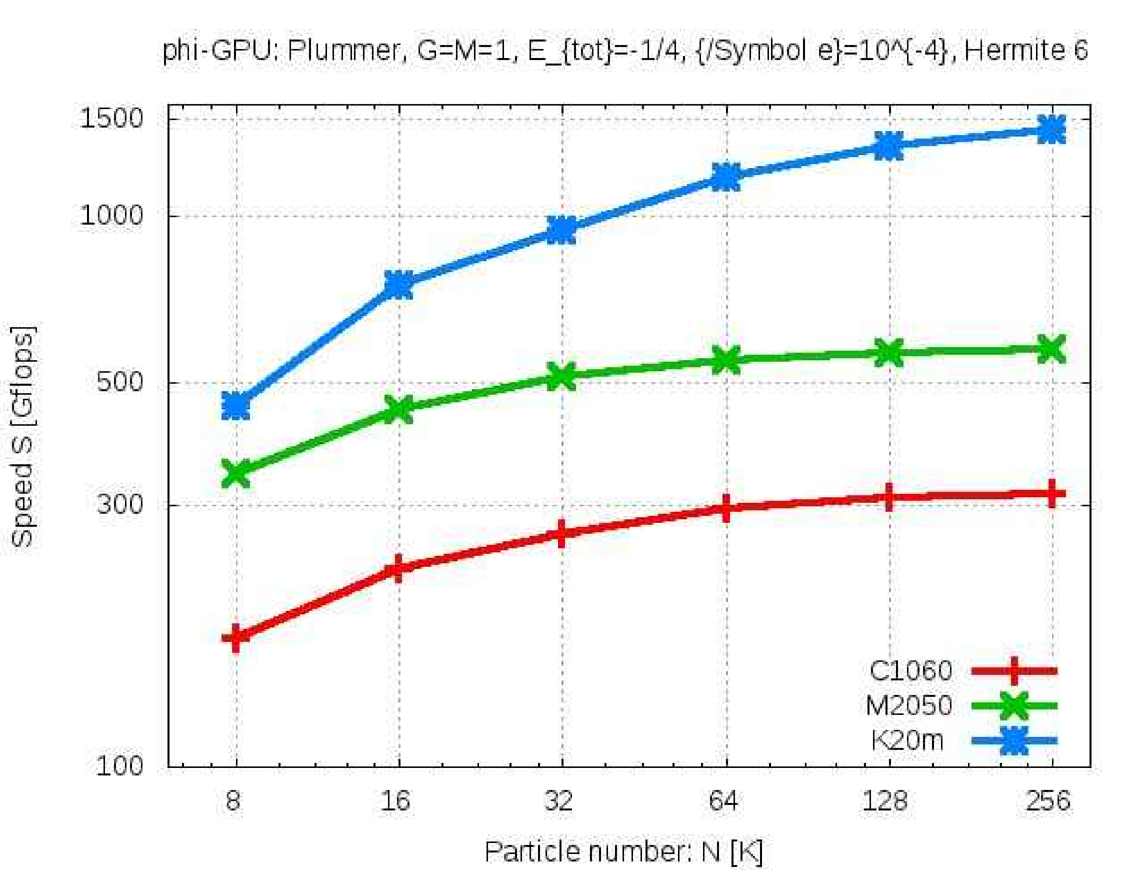
icpc ... "-mmic" ... 61 x 4 = 244 x 1.1 GHz omp cores !!!

Full fp64 !!!

φGPU Hermite results



Kepler Scaling, it works...



Spurzem, Berczik, et al., 2013, LNCS Supercomputi 2013, pp. 13-25, Springer publisher.

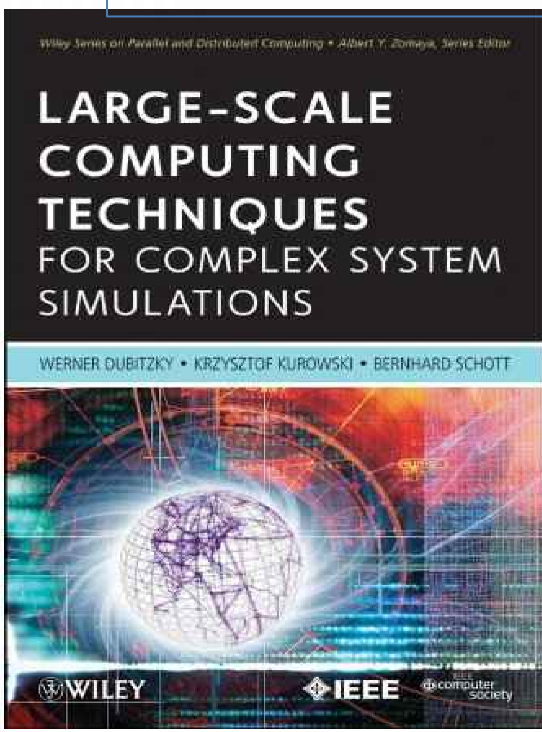
Fig. 4. Here we report a preliminary result from a benchmark test of our code on one Kepler K20 card; we compare with the performance on Fermi C2050 (used in the Mole-8.5 cluster), and the oldest Tesla C1060 GPU (used in the laohu cluster of 2009) - the latter is used as a normalization reference. We plot the speed ratio of our usual benchmarking simulation used in the previous figures, as a function of particle number. From this we see the sustained performance of a Kepler K20 would be about 1.4 - 1.5 Tflop/s.

PRACE

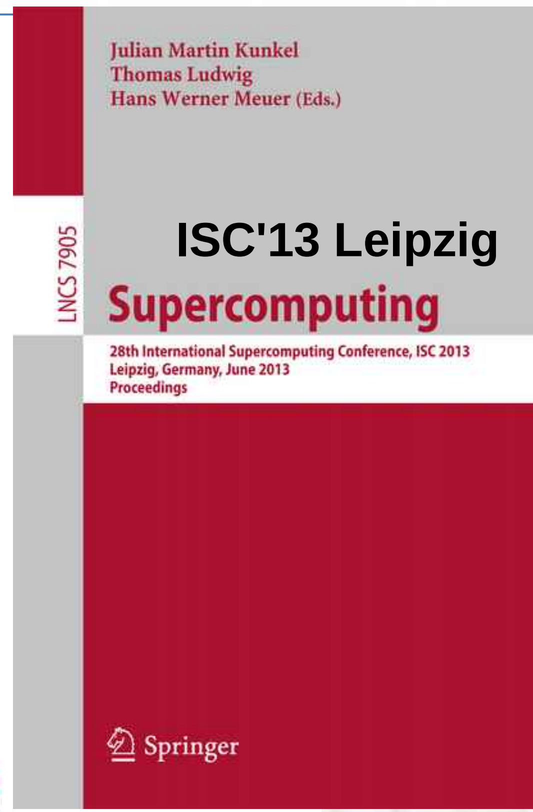
PRACE Award - 2011

Astrophysical Particle Simulations with Large Custom GPU Clusters on Three Continents

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



ISC'13 Leipzig



中国科学院国家天文台
NATIONAL ASTRONOMICAL OBSERVATORIES ,CHINESE ACADEMY OF SCIENCES

北京大學
PEKING UNIVERSITY

Software

NBODY4, NBODY6, S.J.Aarseth, S. Mikkola, ...

(ca. 20.000 lines, since 1963):

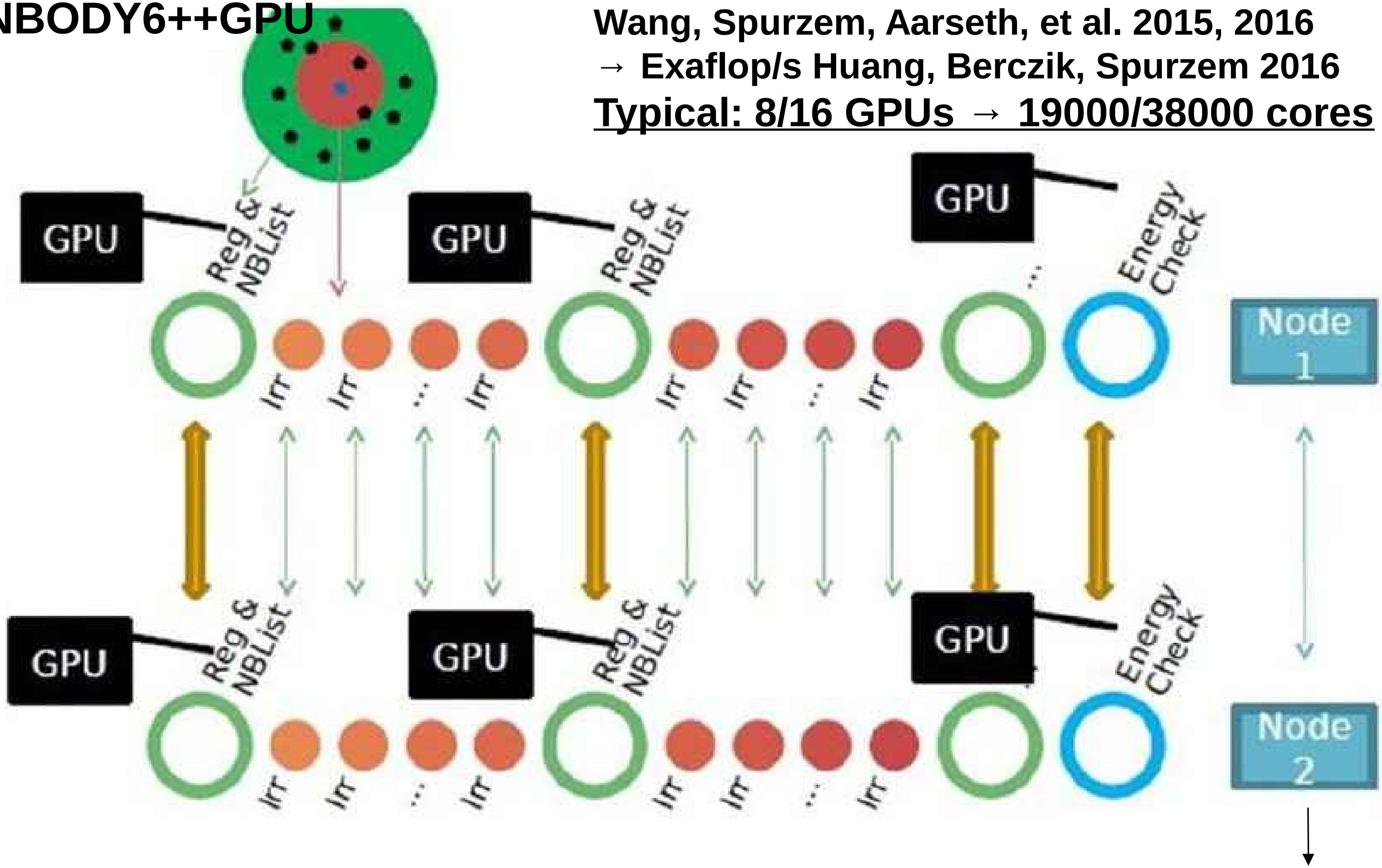
- **Hierarchical Individual Time Steps (HITS)**
- **Ahmad-Cohen Neighbour Scheme (ACS)**
- **Kustaanheimo-Stiefel and Chain-Regular. (KSREG) for bound subsystems of N<6 (Quaternions!)**
- **4th order Hermite scheme (pred/corr), Bulirsch-Stoer (for Chain)**
- **Stellar Evolution (single/binary) (w Hurley)**

- ***NBODY6++GPU, φGPU, L. Wang, R. Spurzem, P. Berczik, K. Nitadori,...***
- ***(massively parallel codes, since 1999, recent paper Wang, Spurzem, Aarseth, et al. 2015):***
- **NBODY6++ (Spurzem 1999) using MPI**
- **Parallel φGRAPE / φGPU (Harfst et al. 2006, Spurzem et al. 2009)**
- **NBODY6++/GPU-MPI (Wang, Spurzem, Aarseth, et al. 2015)**
- **Parallel Binary Integration in Progress (KSREG)**

Our CPU/GPU N-body (AC) code

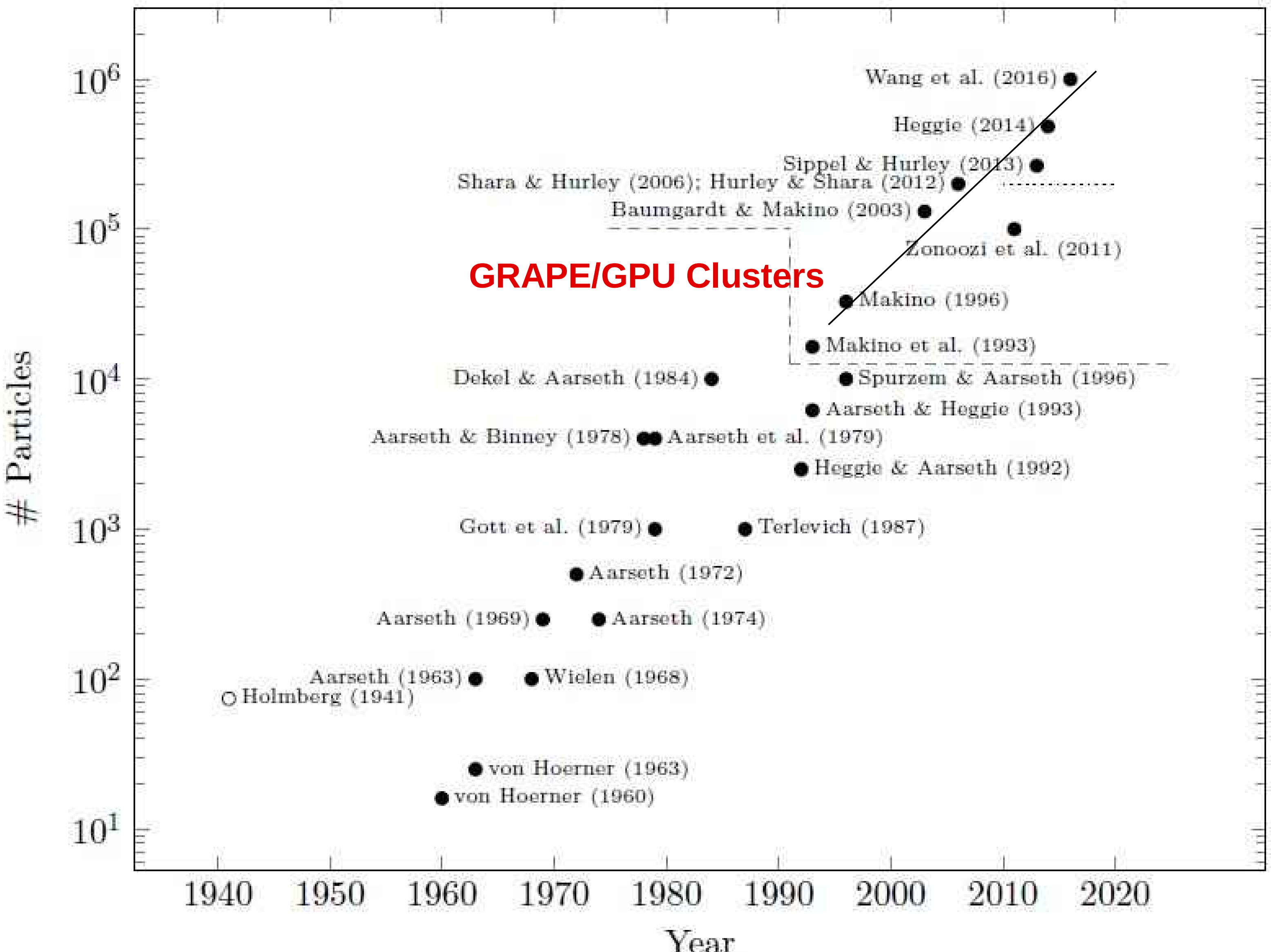
NBODY6++GPU

Wang, Spurzem, Aarseth, et al. 2015, 2016
→ Exaflop/s Huang, Berczik, Spurzem 2016
<u>Typical: 8/16 GPUs → 19000/38000 cores</u>



<u>https://github.com/lwang-astro/betanb6pp</u>

“Moore's” Law for Direct N-Body

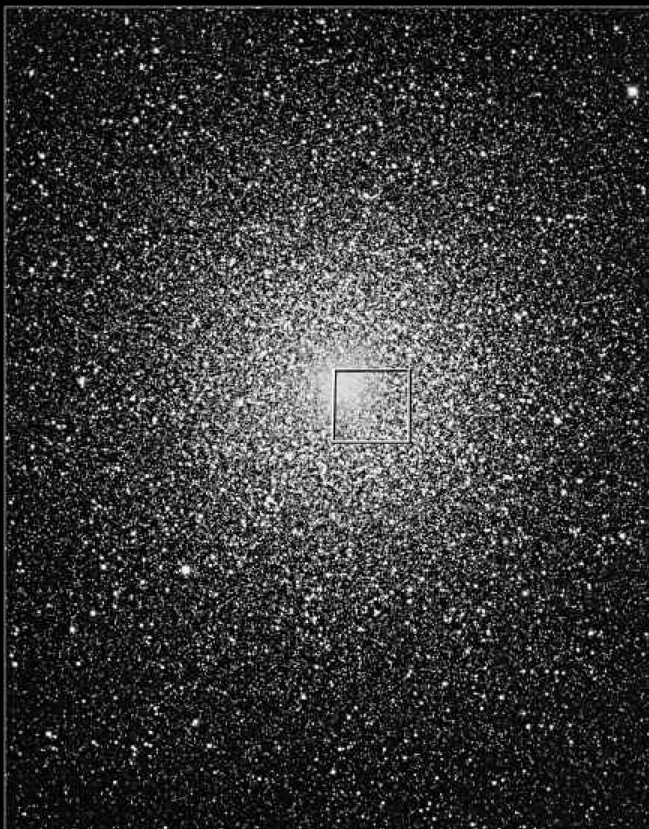


Originally by D.C. Heggie
Extended by Anna Sippel

- Instruments (Hardware/Software)
- Dragon Simulations of Star Clusters
- Black Holes / Gravitational Waves
- Link to Cosmology

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

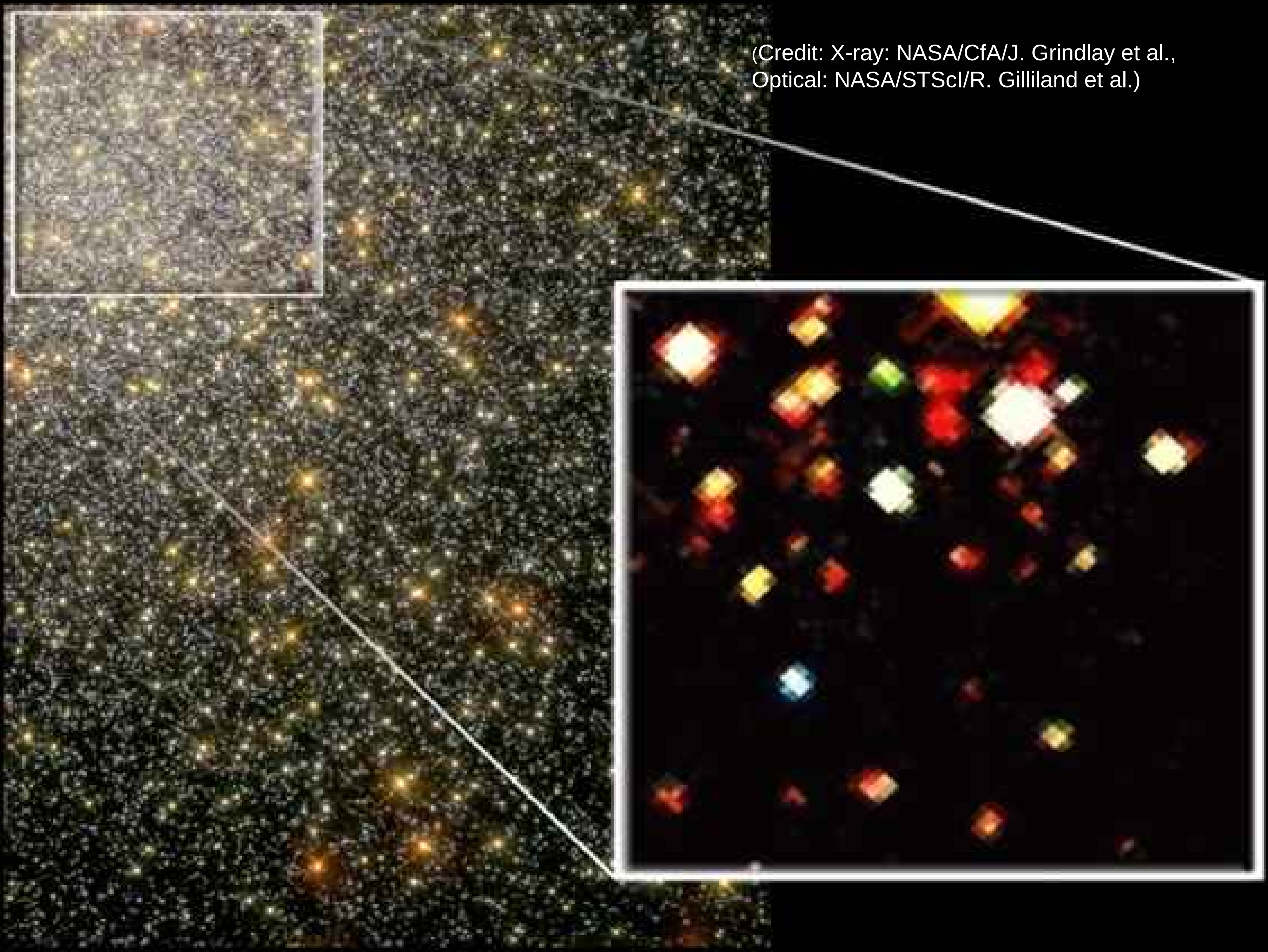
Globular Cluster 47 Tucanae



Ground • AAT

Hubble Space Telescope • WFPC2

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



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

From: Quarterly Journal of the Royal Astron. Soc., 1, p. 152, 1960

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.

Globular Clusters – Tracers of Galaxy Formation (e.g. Brodie & Strader 2006 ARAA)

...also...

Laboratories for Stellar Dynamics

...for single and binary stellar evolution... ..multiple Populations...

Neutron stars (FAST!) and black holes (LIGO/VIRGO)

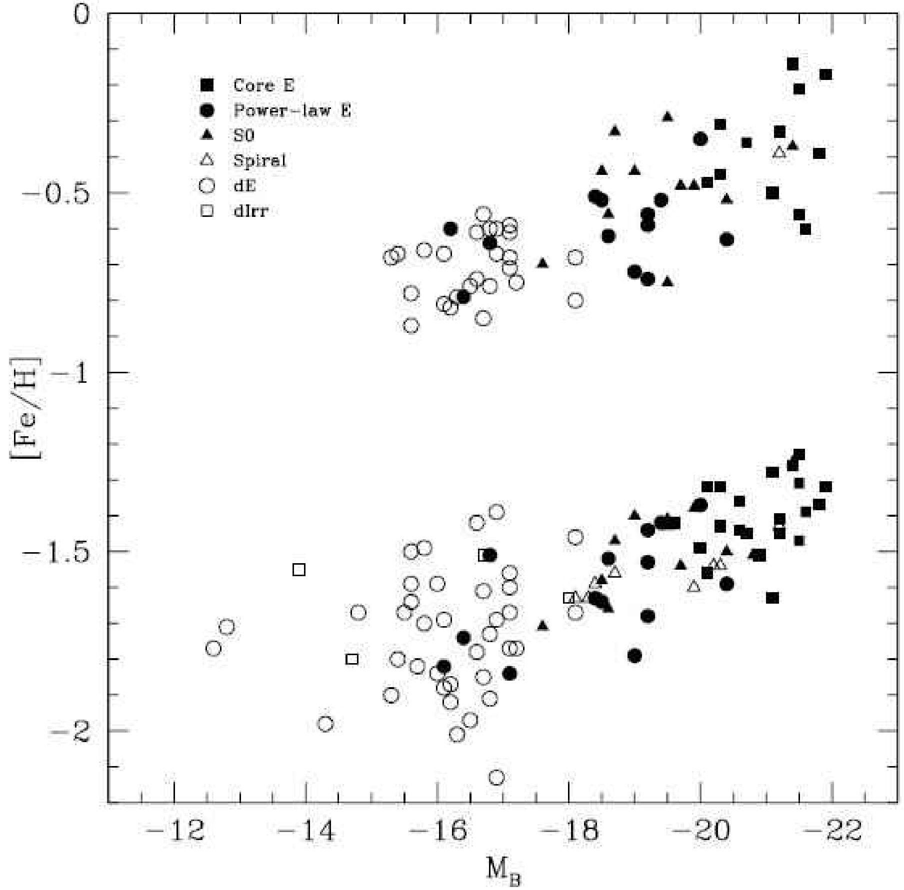


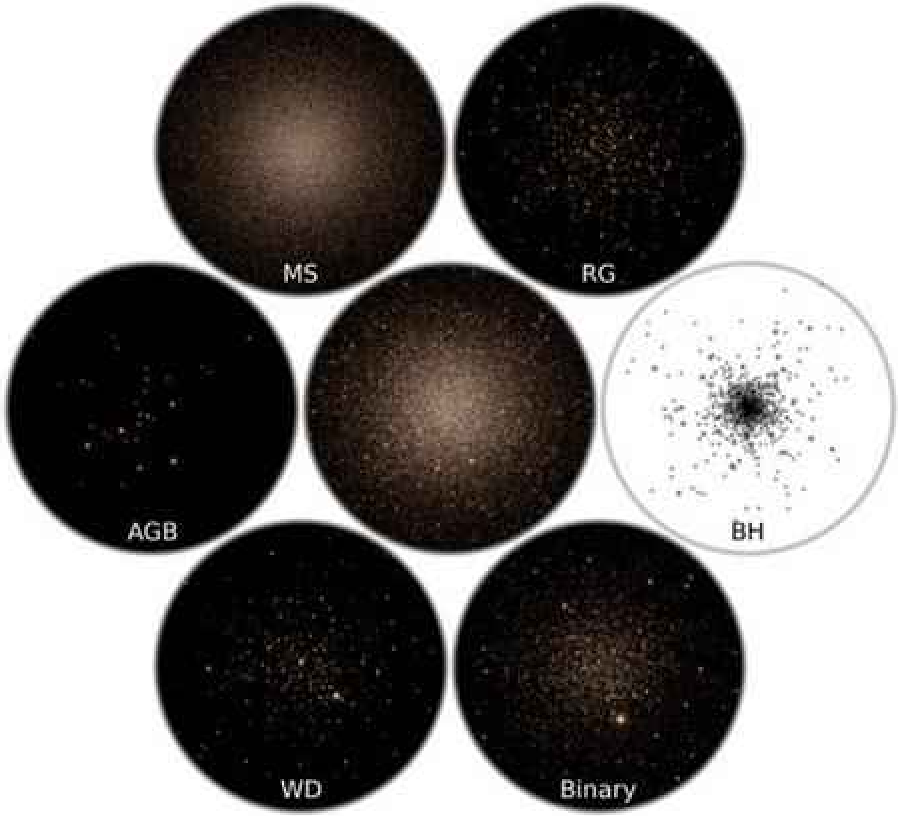
Figure 2: Peak GC metallicity vs. galaxy luminosity (M_B) for metal-poor and metal-rich GCs in a range of galaxies. The points are from Strader *et al.* (2004a) and Strader *et al.* (2006) and have been converted from $V-I$ and $g-z$ to [Fe/H] using the relations of Barmby *et al.* (2000) and Peng *et al.* (2006), respectively. Galaxy types are indicated in the figure key; classifications are in Table 1. Linear relations exist for both subpopulations down to the limit of available data.

DRAGON Simulation

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

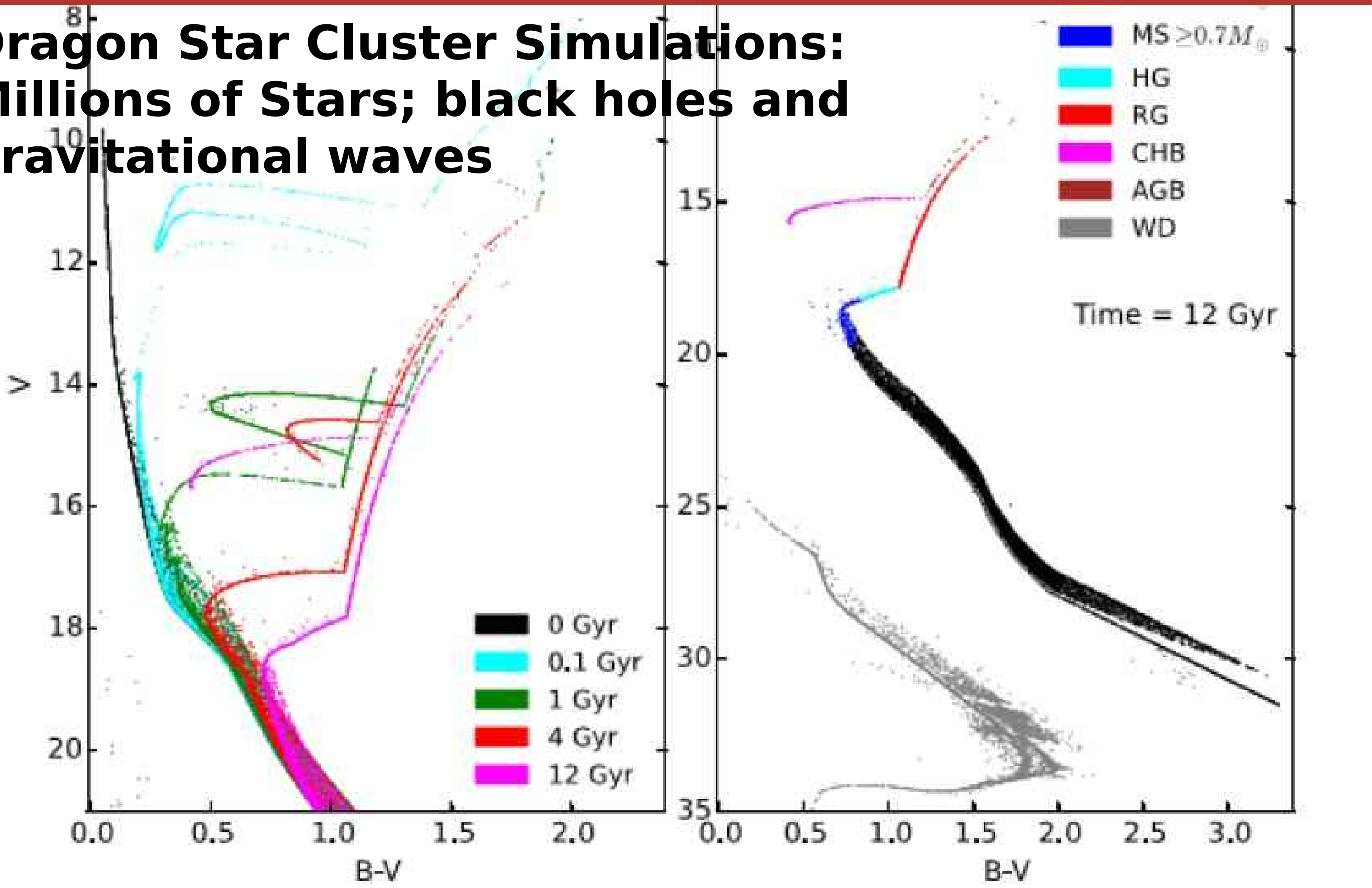
One million stars direct simulation,

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, Aarseth Naab, et al. re-subm. 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



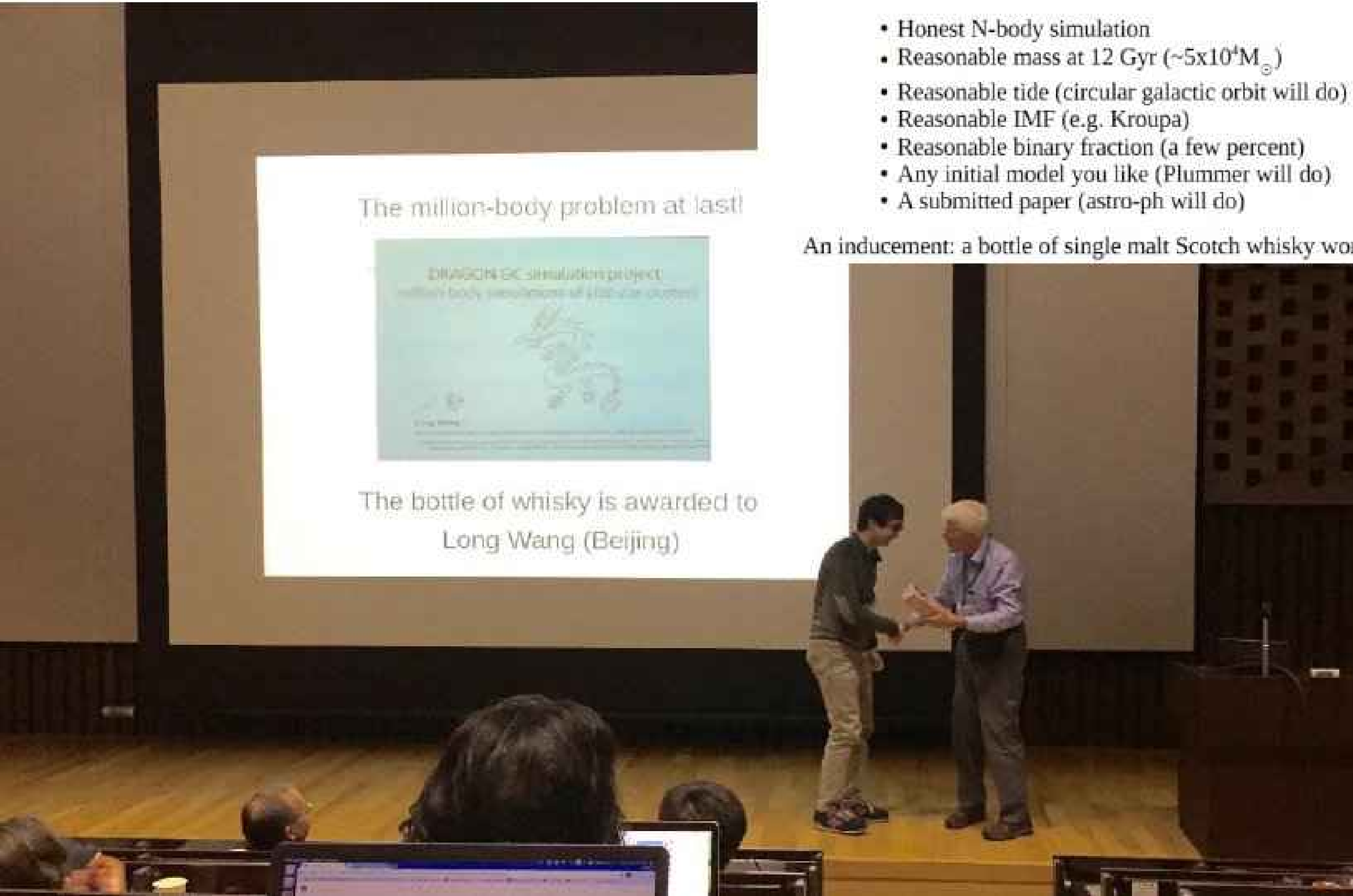
Leiden

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



MPA Garching Highlight March 2016

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

The Kavli Institute for Astronomy and Astrophysics at Peking University
北京大学科维理天文与天体物理研究所

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http://kiaa.pku.edu.cn **News...**

Home » The DRAGON globular cluster simulations: a million stars, black holes and gravitational waves

HIGHLIGHT: MARCH 2016

The DRAGON globular cluster simulations: a million stars, black holes and gravitational waves

March 01, 2016

An international team of experts from Europe and China has performed the first simulations of globular clusters with a million stars on the high-performance GPU cluster of the Max Planck Computing and Data Facility. These – up to now - largest and most realistic simulations can not only reproduce observed properties of stars in globular clusters at unprecedented detail but also shed light into the dark world of black holes. The computer models produce high quality synthetic data comparable to Hubble Space Telescope observations. They also predict nuclear clusters of single and binary black holes. The recently detected gravitational wave signal might have originated from a binary black hole merger in the center of a globular cluster.

RGB image of a simulated globular cluster

© MPA

Globular clusters are truly enigmatic objects. They consist of hundreds of thousands luminous stars and their remnants, which are confined to a few tens of parsecs (up to 100 lightyears) – they are the densest and oldest gravitationally bound stellar systems in the Universe. Their central star densities can reach a million times the stellar density near our Sun. About 150 globular clusters orbit the Milky Way but more massive galaxies can have over 10,000 gravitationally bound globular clusters. As their stars have mostly formed at the same time but with different masses, globular clusters are ideal laboratories for studies of stellar dynamics and stellar evolution.

The dynamical evolution of globular clusters, however, is very complex. Unlike in galaxies, the stellar densities are so high that stars can interact in close gravitational encounters or might even physically collide with each other. Because of these interactions there are more tightly bound binary stars than for normal galactic field stars. Moreover, in a process called mass-segregation more massive stars sink to the center of the system.

Search @ KIAA-PKU

Search

Upcoming Events

Pulsars and FRBs: Recent Developments
Speaker: Richard N. Manchester (CSIRO Astronomy and Space Science, Australia)
3 Nov 2016 - 4:00pm
KIAA-PKU Auditorium

The role of vortices in multi-dimensional protoplanetary disks
Speaker: Hui Li
7 Nov 2016 - 12:00pm
DoA, Rm 2907

TBD
Speaker: Jessy Jose
8 Nov 2016 - 12:00pm
KIAA-PKU

more

Navigation

Biblio

The DRAGON globular cluster simulations: a million stars, black holes and gravitational waves

By shuyan on Mon, 2016-06-27 08:55

An international team of experts from China and Europe has performed the first simulations of globular clusters with a million stars on the high-performance GPU

1. ***Wang, Long; Spurzem, Rainer; Aarseth, Sverre; Nitadori, Keigo; Berczik, Peter; Kouwenhoven, M. B. N.; Naab, Thorsten***
NBODY6++GPU: ready for the gravitational million-body problem
2015, MNRAS, 450, 4070
Source

2. ***Wang, Long; Spurzem, Rainer; Aarseth, Sverre; Giersz, Mirek; Askar, Abbas; Berczik, Peter; Naab, Thorsten; M. B. N. Kouwenhoven, Riko Schadow***
The DRAGON simulations: globular cluster evolution with a million stars

Kavli Roundtable expected Dec 2016

北京大學 PEKING UNIVERSITY

- Instruments (Hardware/Software)
- Dragon Simulations of Star Clusters
- <u>Black Holes / Gravitational Waves</u>
- Link to Cosmology

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/c5), higher order gauge functions appear.**

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

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

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

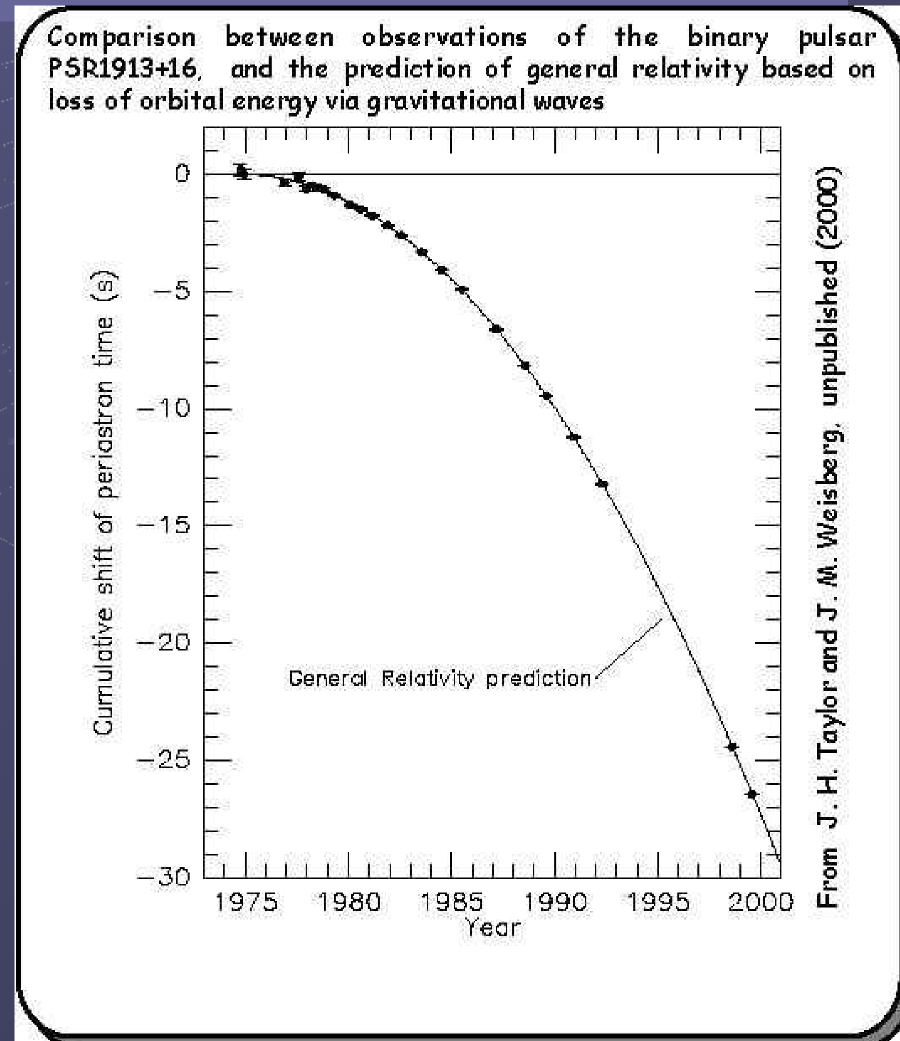
... higher order...

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

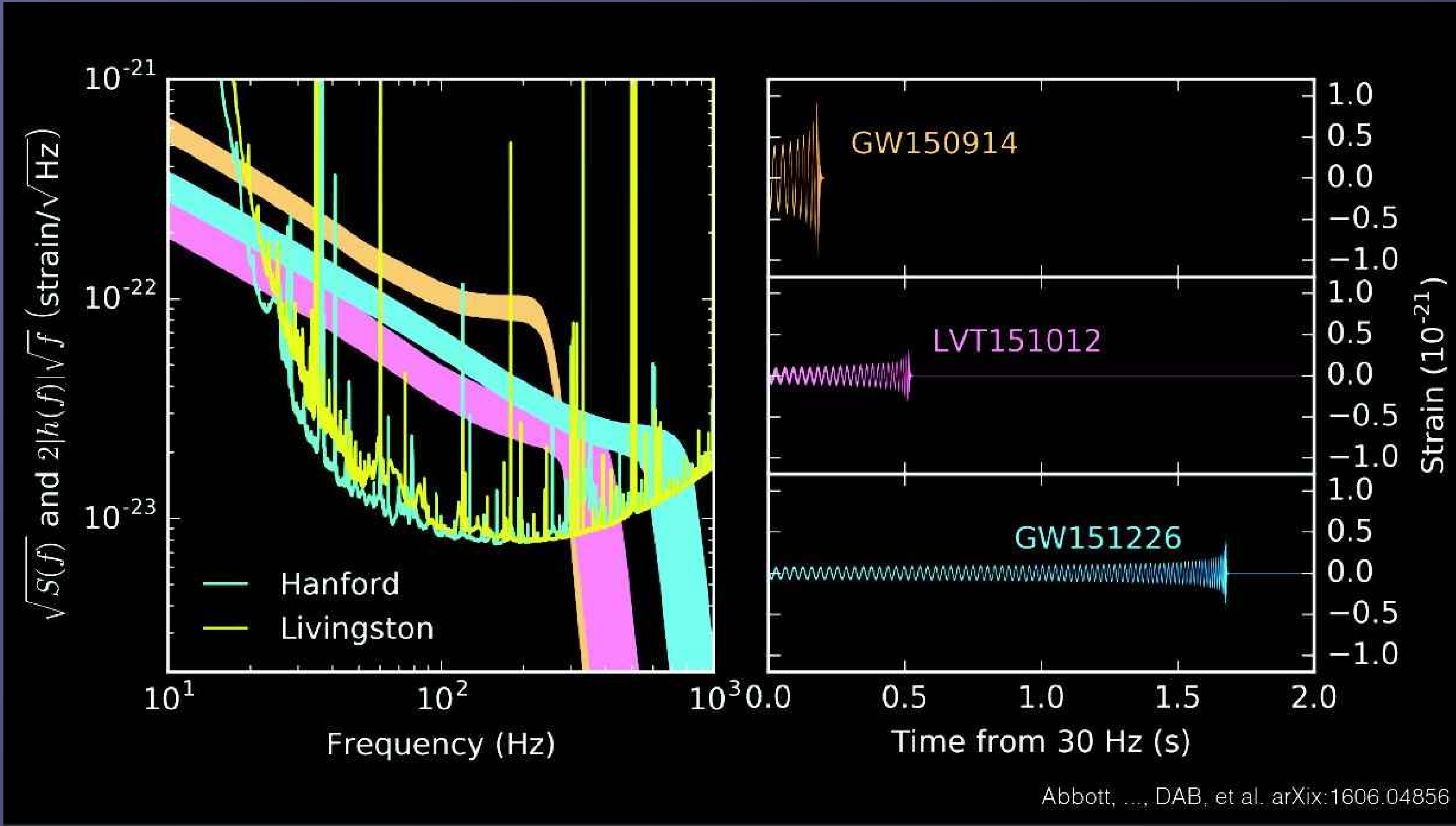
Grav. Radiation

Post-Newtonian Dynamics

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



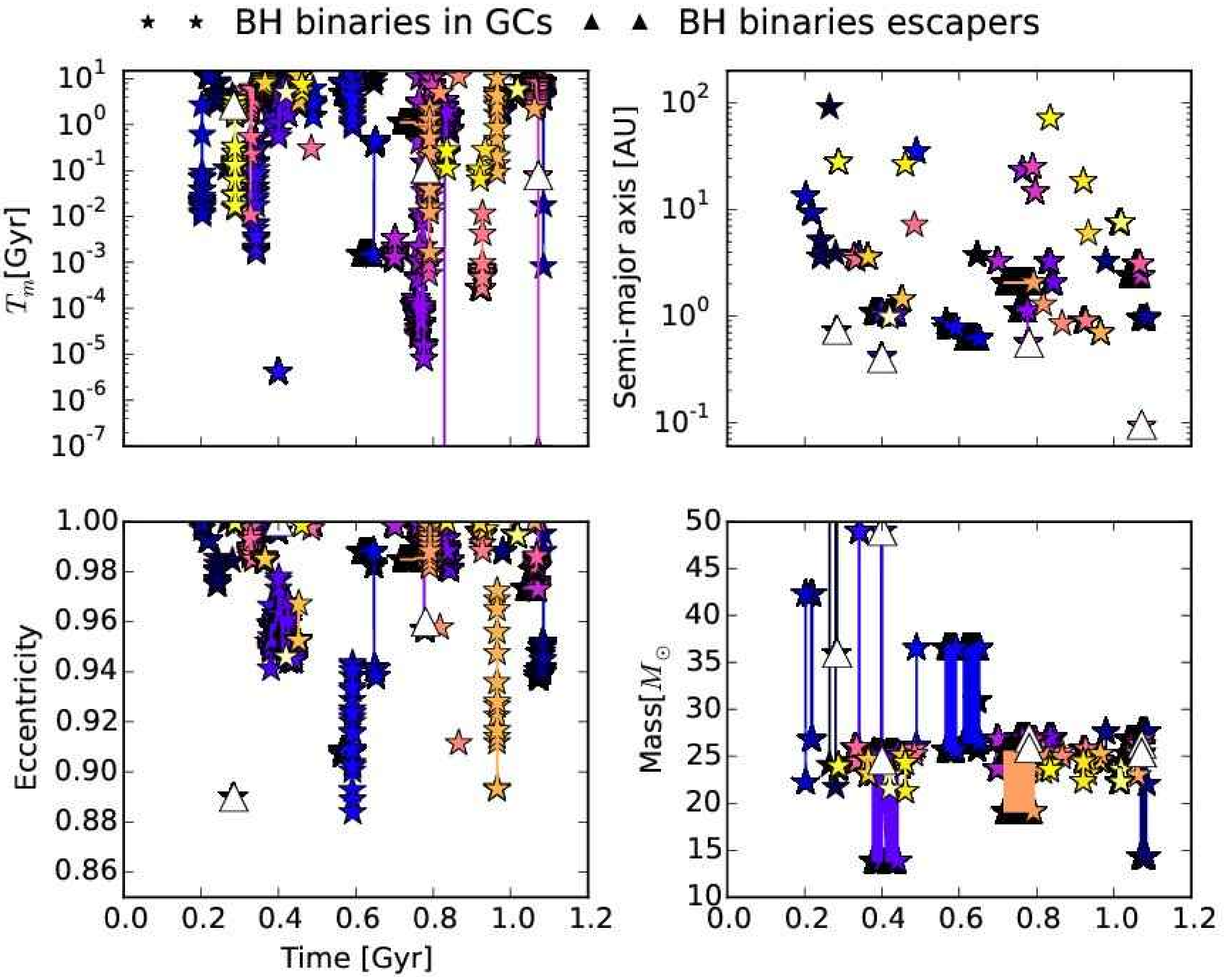
The Observed LIGO Events – Slide from Brown's Talk at KITP (1)



The Observed LIGO Events – Slide from Brown's Talk at KITP (2)

	GW150914	GW151226	LVT151012
Source Mass 1	$36.2^{+5.2}_{-3.8}\ M_\odot$	$14.2^{+8.3}_{-3.7}\ M_\odot$	$23^{+18}_{-6}\ M_\odot$
Source Mass 2	$29.1^{+3.7}_{-4.4}\ M_\odot$	$7.5^{+2.3}_{-2.3}\ M_\odot$	$13^{+4}_{-5}\ M_\odot$
Luminosity Distance	420^{+150}_{-180} Mpc	440^{+180}_{-190} Mpc	1000^{+500}_{-500} Mpc

Abbott, ..., DAB, et al. arXix:1606.04856



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)

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)

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

GW Detection Frequency Time Diagram

Top: Our simulation (Sobolenko , Berczik, Spurzem, et al. In prep.)

Down: Abott et al. 2016 LIGO measurement

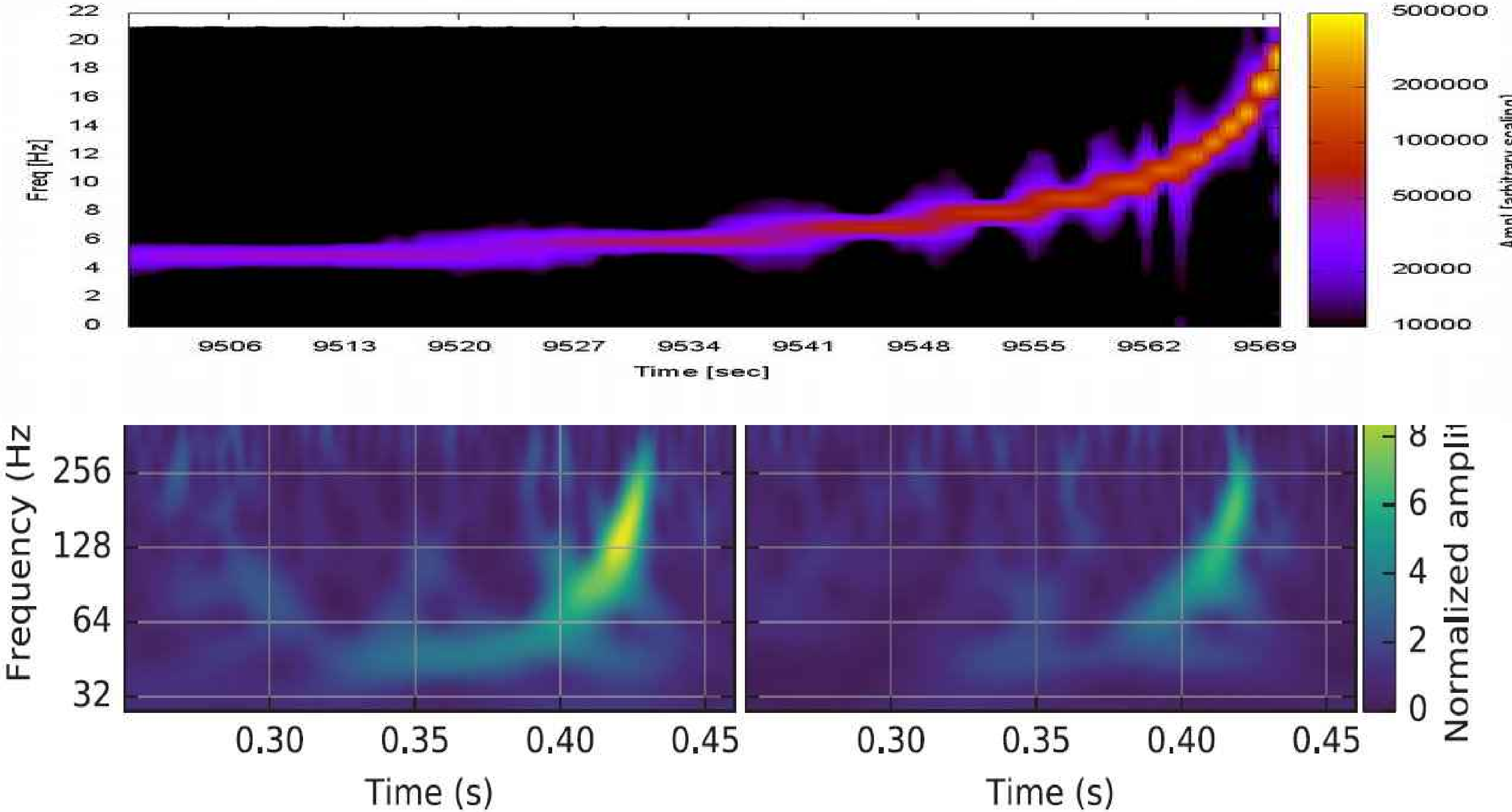


FIG. 1. The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right

- Instruments (Hardware/Software)
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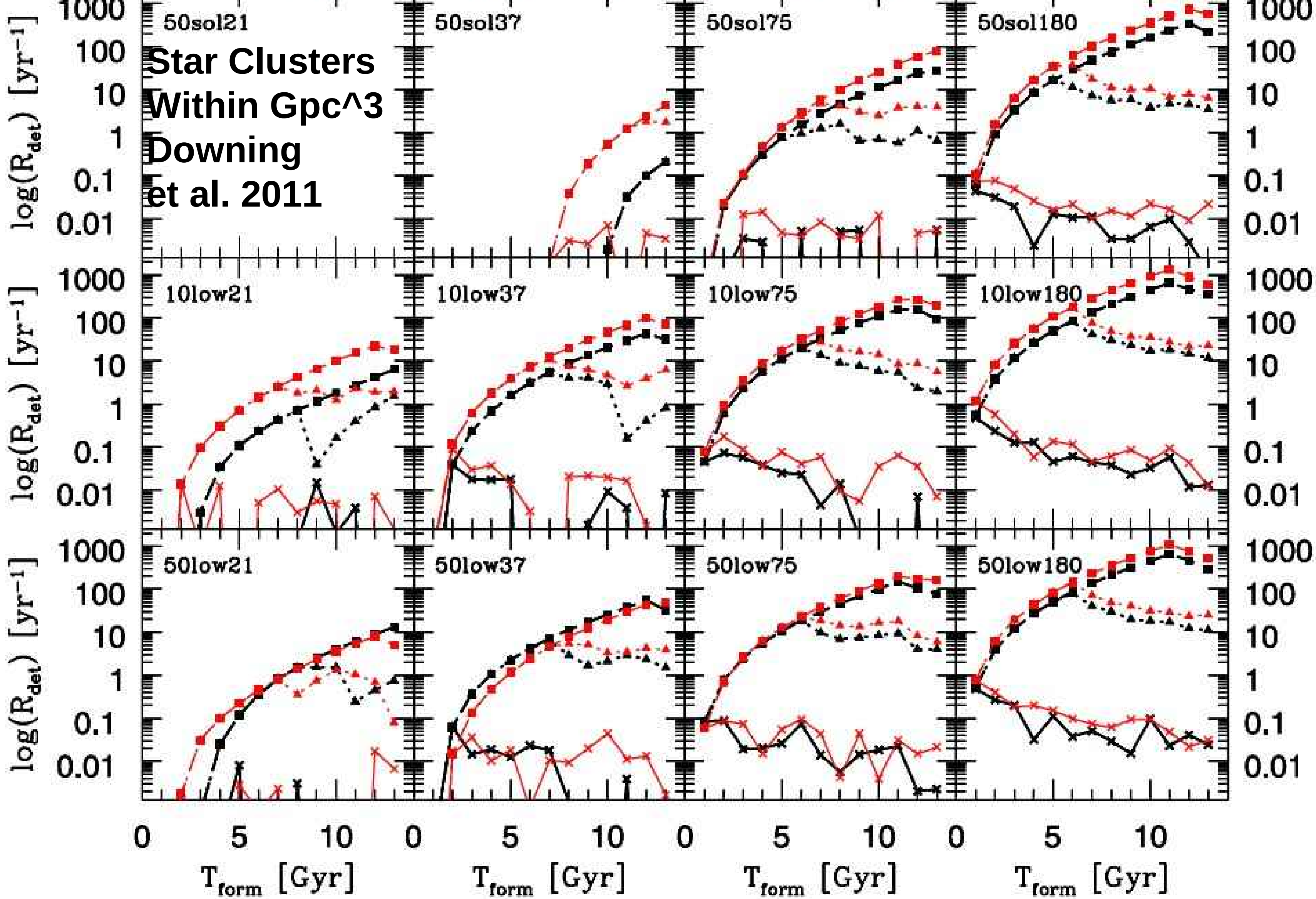
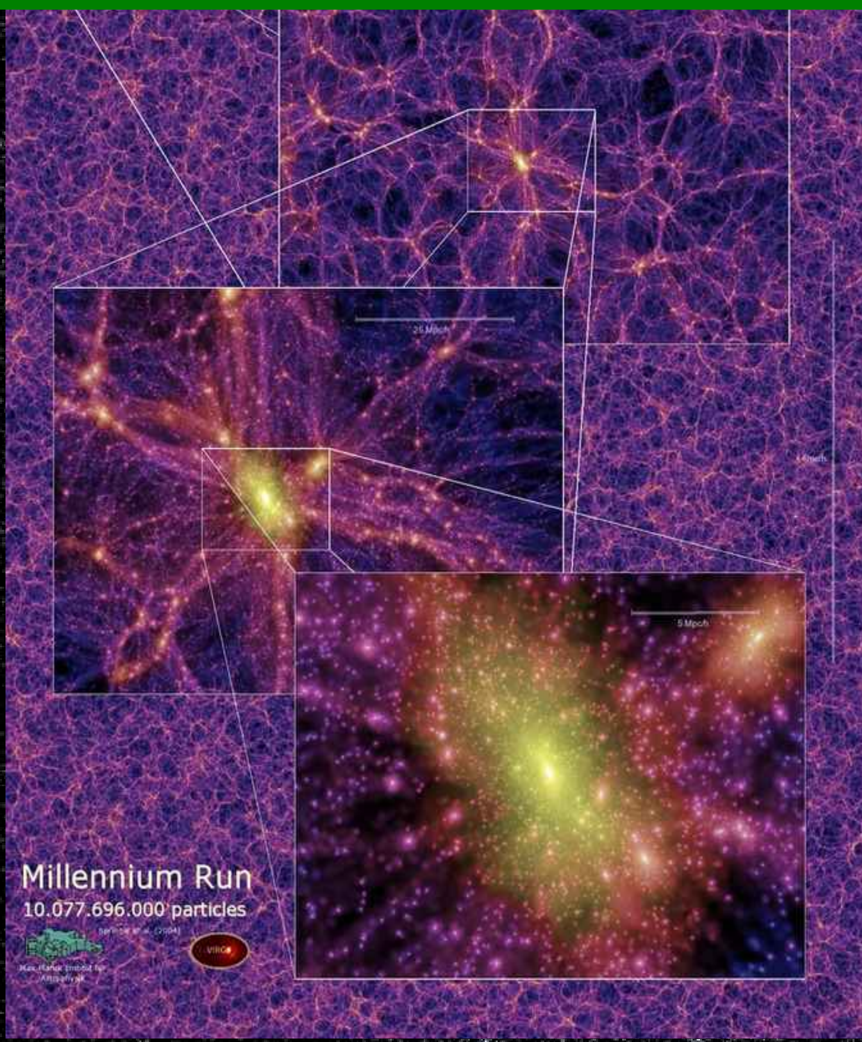
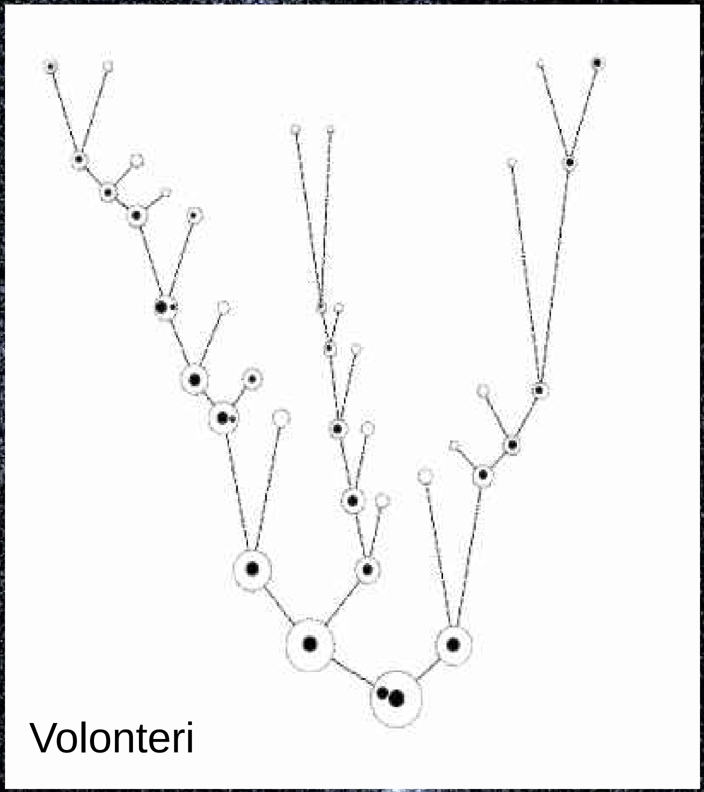
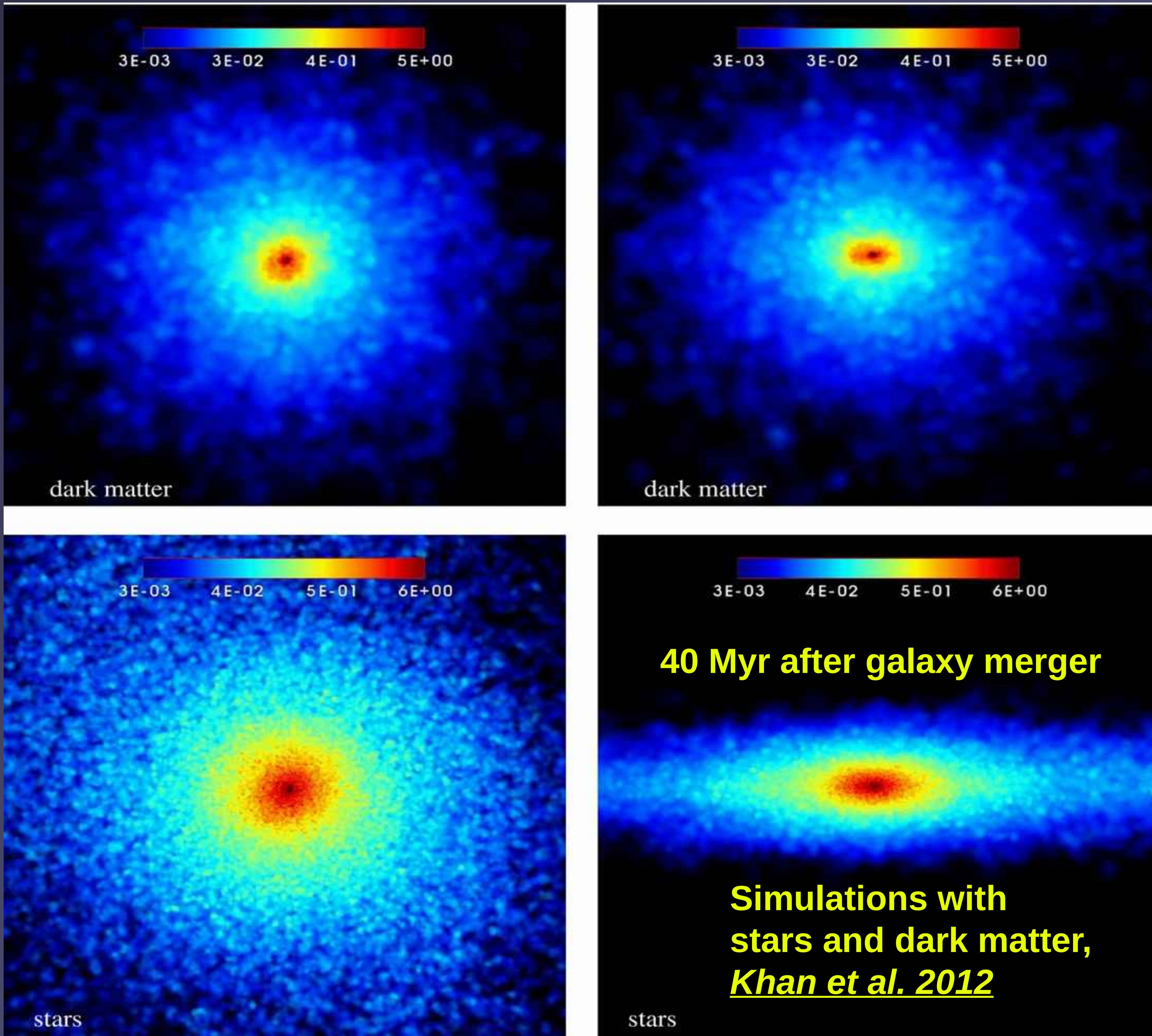


Figure 9. Detection rates by cluster type. Each panel gives the expected detection rate if the entire cluster population in the Universe was composed of identical clusters, each with the corresponding initial conditions. The *x*-axis gives the look-back time to $T_{\rm form}$ in Gyr. The solid line with 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.

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



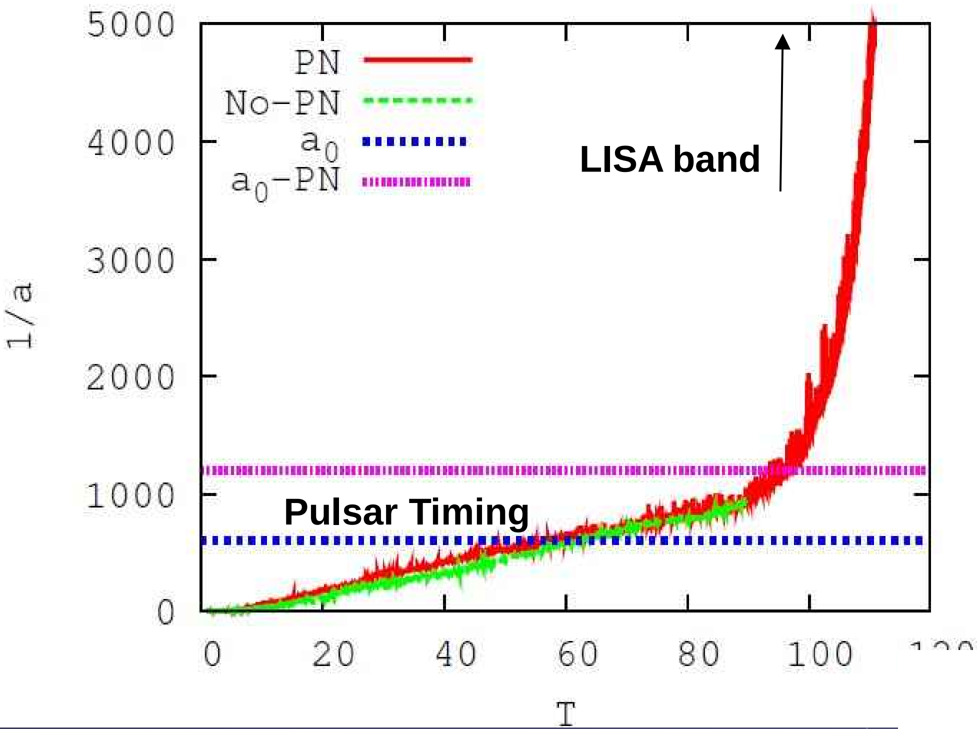




40 Myr after galaxy merger

Simulations with stars and dark matter, *Khan et al. 2012*

Box Size 4 kpc



1 / SMBH Bin. Separation

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

GW Emission from
Pulsar Timing to
LISA band modelled

Also Worked on SMBH Triples!
Amaro-Seoane, Sesana,Benacquista,
… Spurzem MNRAS 2010

Khan, Berentzen, Berczik,
Just, Mayer, Nitadori,
Callegari, ApJ 756, 30 (2012)

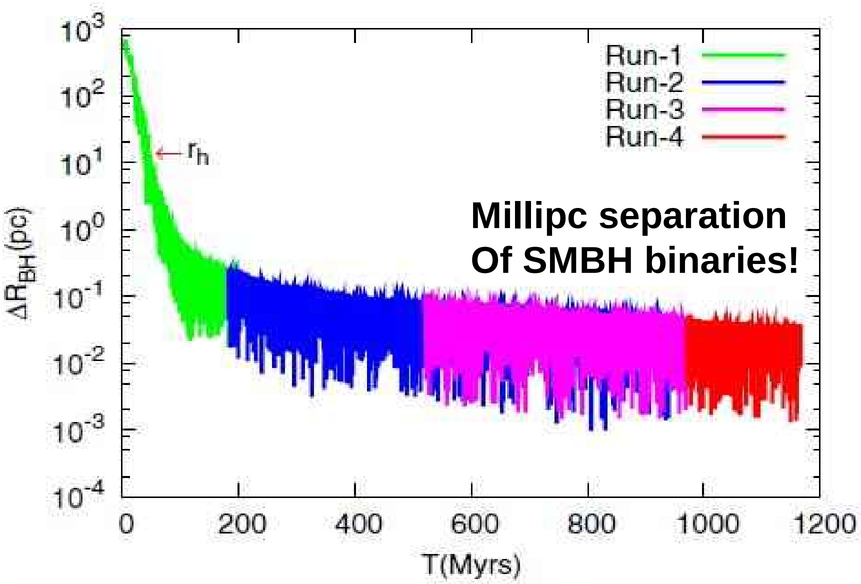


Figure 4. Relative separation between the two SMBHs as a function of time. The red arrow shows the estimated value of the influence radius r_h.
(A color version of this figure is available in the online journal.)

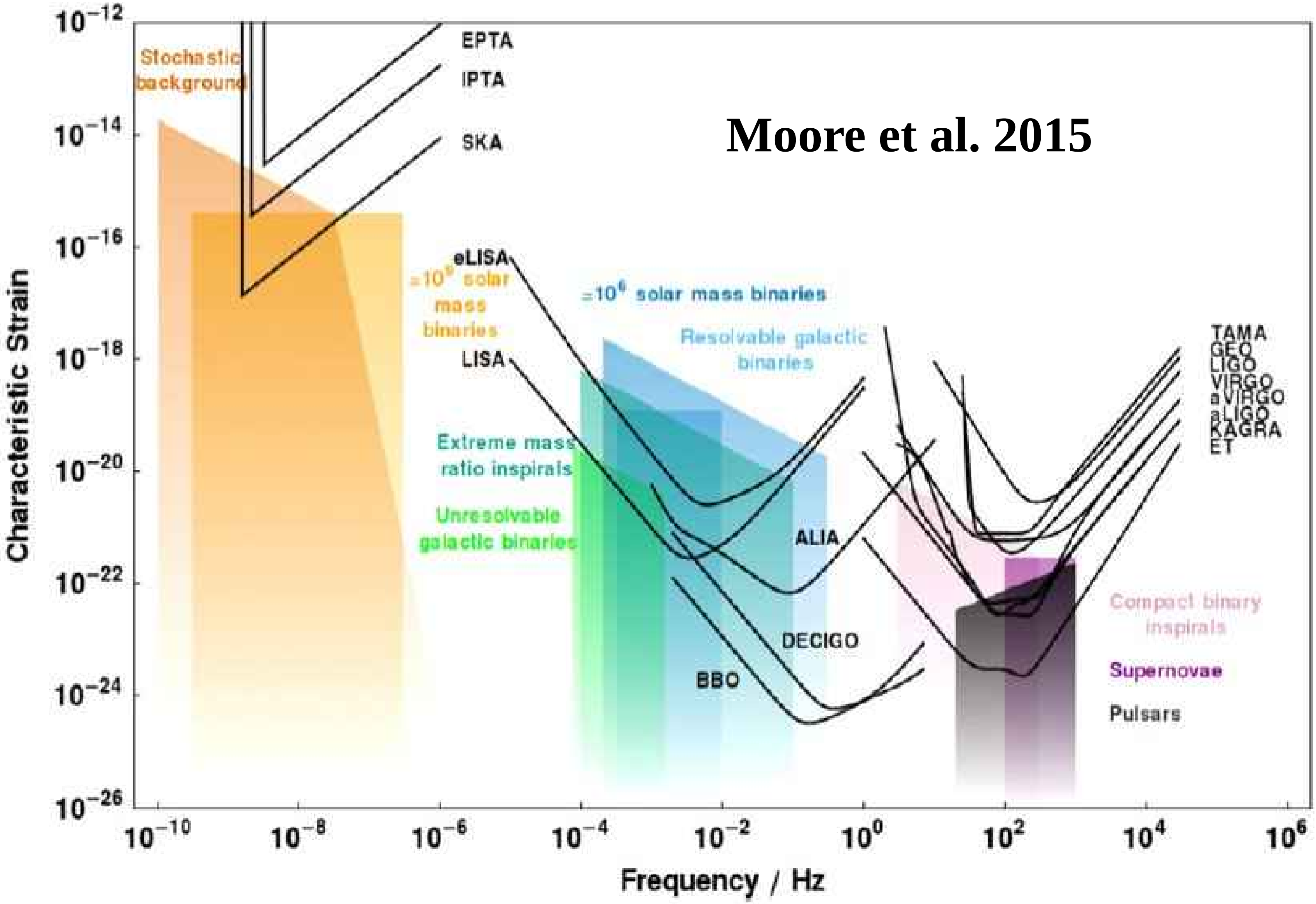
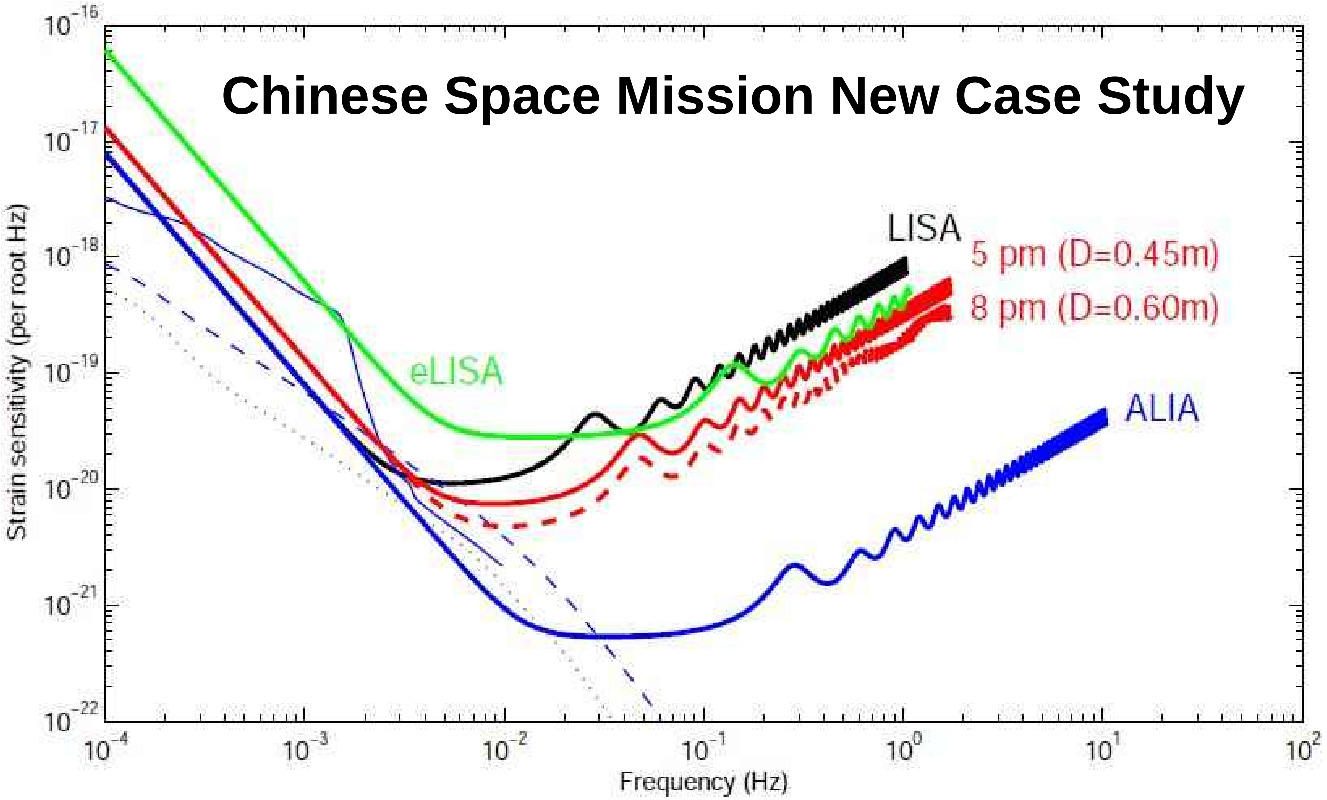


Figure A1. A plot of characteristic strain against frequency for a variety of detectors and sources.

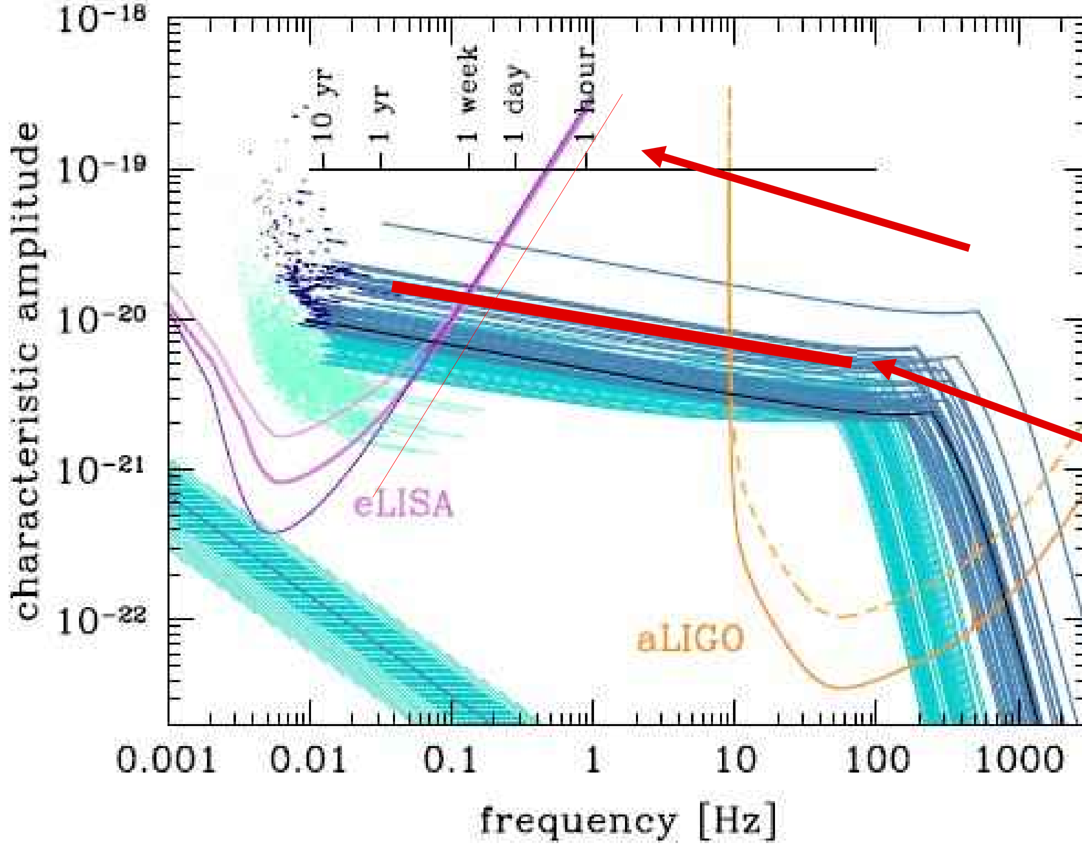


Gong, Lau, … Amaro-Seoane, … Spurzem et al. 2015

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	$3 \times 10^{-15}(> 0.1\text{mHz})$

Gong, Lau, …
Amaro-Seoane,
…Spurzem + 2015
Taiji Chinese
Space Based
GW Detector
Proposal



“Our”
DRAGON
Black Hole
Binary

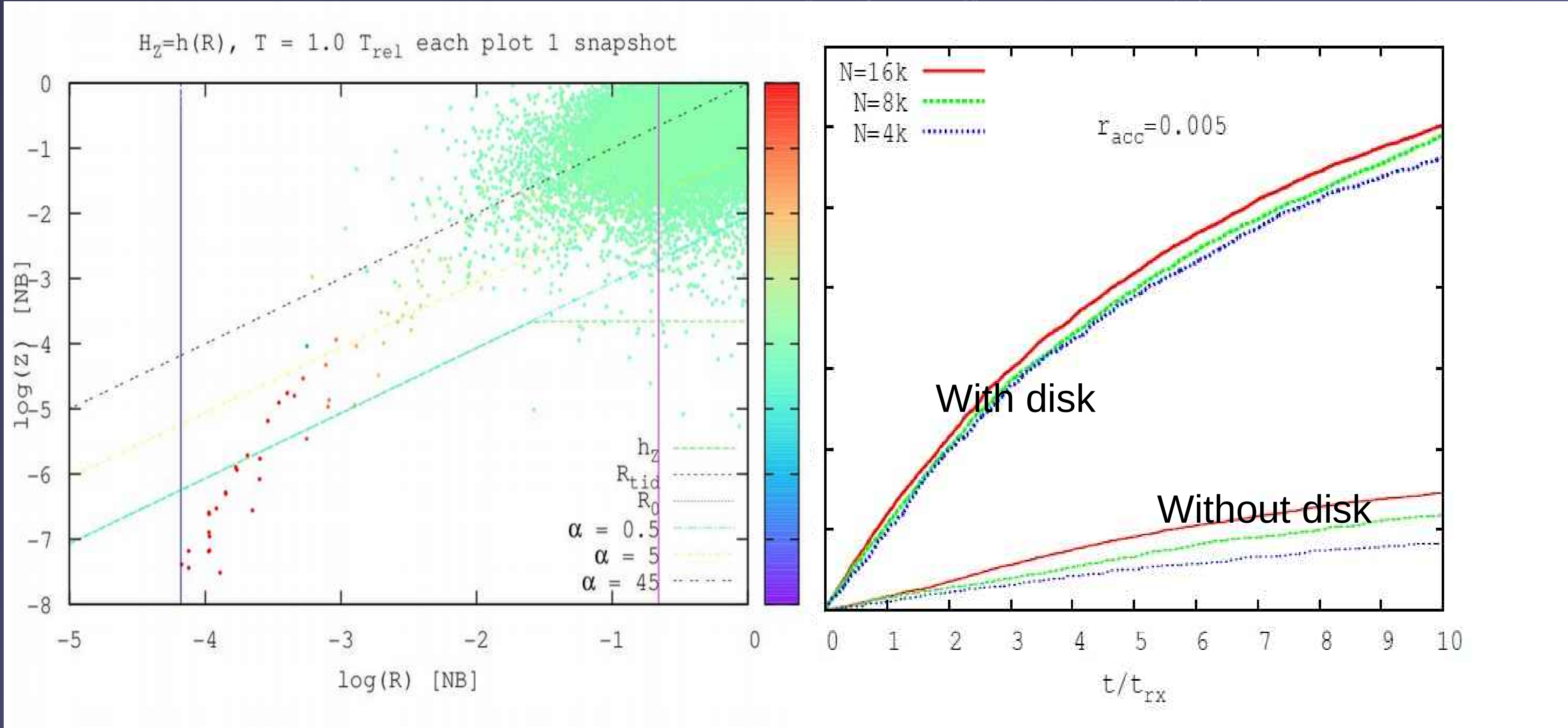
Sesana 2016

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.

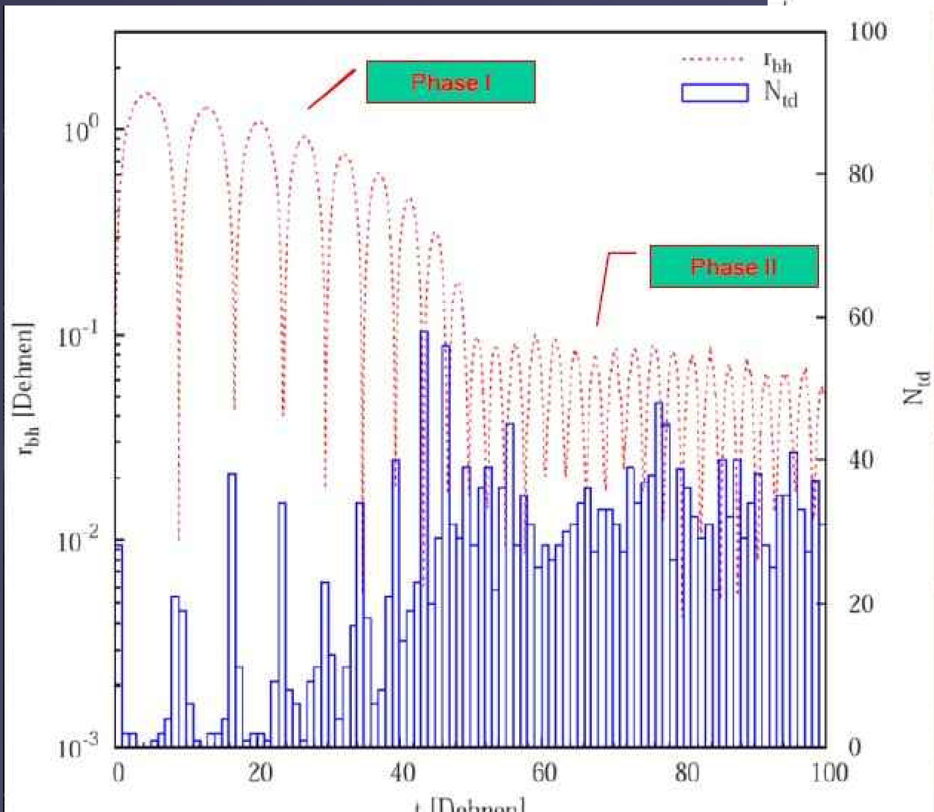
Stardisk Project – Beijing – Almaty – Kiev - Heidelberg

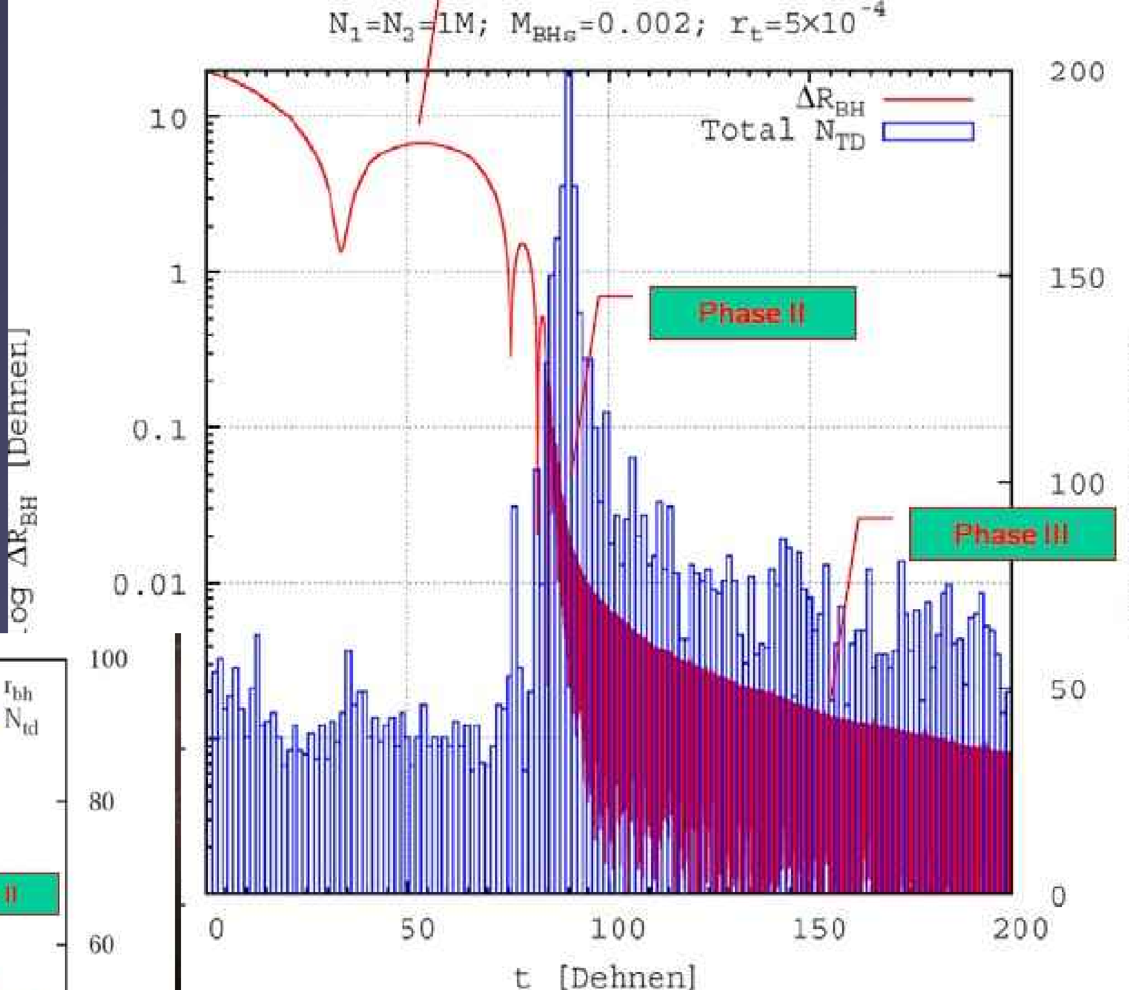
Just, ... Berczik, Spurzem, et a, 2012, ApJ (Paper I)
Kennedy, Meiron et al. 2016 MNRAS (Paper II)
Shukirgaliev, Panamarev, et al. 2017 in prep. (Paper III)

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



Tidal Disruption
Merging Galaxies
Li et al. in prep. 2014





Tidal Disruption
Recoiling Black Hole
Li, Liu, Berczik, Chen,
Spurzem ApJ 2012
(40 ~ 1.E-05 Msol/yr)

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 → see

(Zhong et al. 2014, 2015, ApJ. Li et al. 2012 ApJ, 2015 subm. ApJ Khan et al. 2012, 2014 ApJ, Sobolenko et al. 2015, Berczik et al. 2016)

- **Further Astrophysical Science Drivers:**
  - **Extragalactic and Massive Star Clusters**
  - **IMBH Formation? Multiple Generations?**
  - **Gravitational Waves in Pulsar Timing/eLISA/LIGO**
  - **Radio Pulsars**
  - **Accretion to central black holes**

INVITATION/DISCUSSION

- Building National and International Community on on Astrophysical Supercomputing in China and South Africa also with international partner institutes – like here.

- Training and Teaching – come to Beijing (NAOC) for testing and developing, or remote testing/running, or invite our experts for talks and hardware/software cooperation (regular schools and training workshops http://kiaa.pku.edu.cn/~kouwenhoven/nbody.html And GPU lectures.

- Relation to 'big data' – common platforms for pathfinding/testing with simulations?