Dynamical Evolution of Dense Star Clusters with and without central black holes

(NIC project chhd28, using Juwels GPU)

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DRAGON Simulations – million bodies with black holes – LIGO-like detection of gravitational waves:

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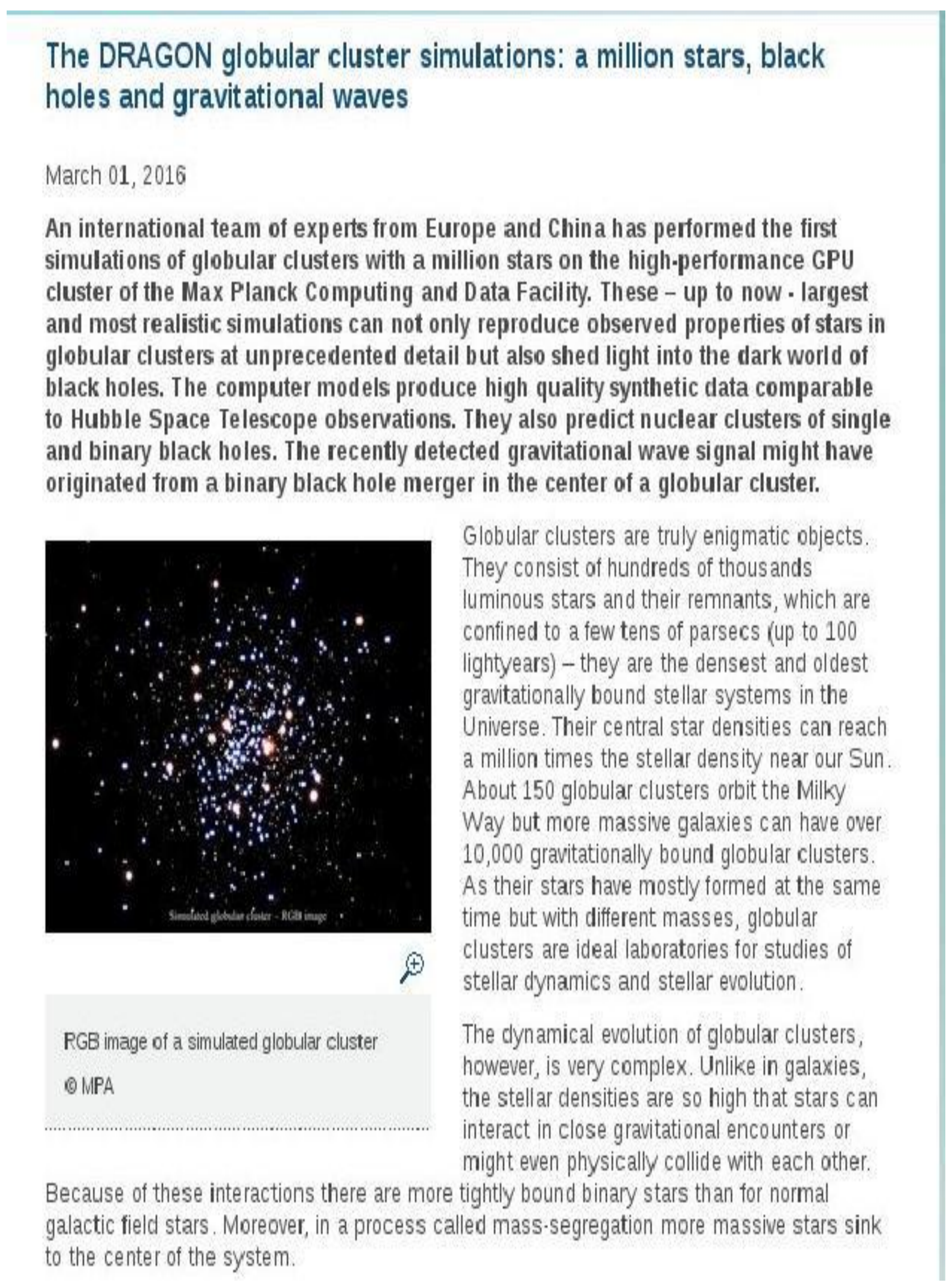

The DRAGON globular cluster simulations: a million stars, black holes and gravitational waves

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

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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.

We have analyzed the formation and evolution of stellar mass black hole subsystems in the DRAGON and further simulations done on the JUWELS system. The figures below show the spatial distribution of black holes, and the gravitational wave emission of one merger event. These merger events would show up as signals in the LIGO/Virgo gravitational wave detectors.

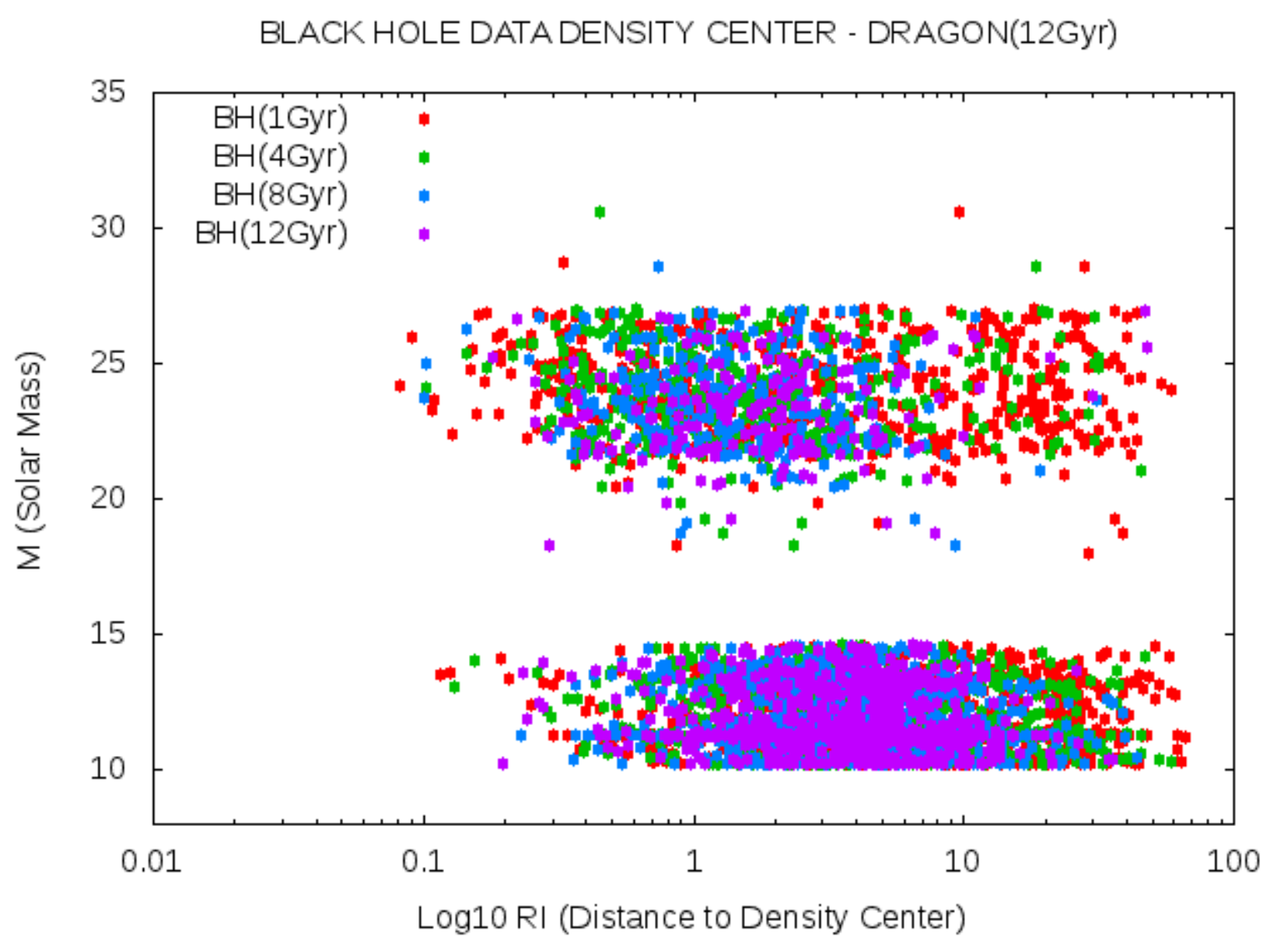

Figure: Position of the Black Holes from the density center in the DRAGON models up to 12 Gyr.

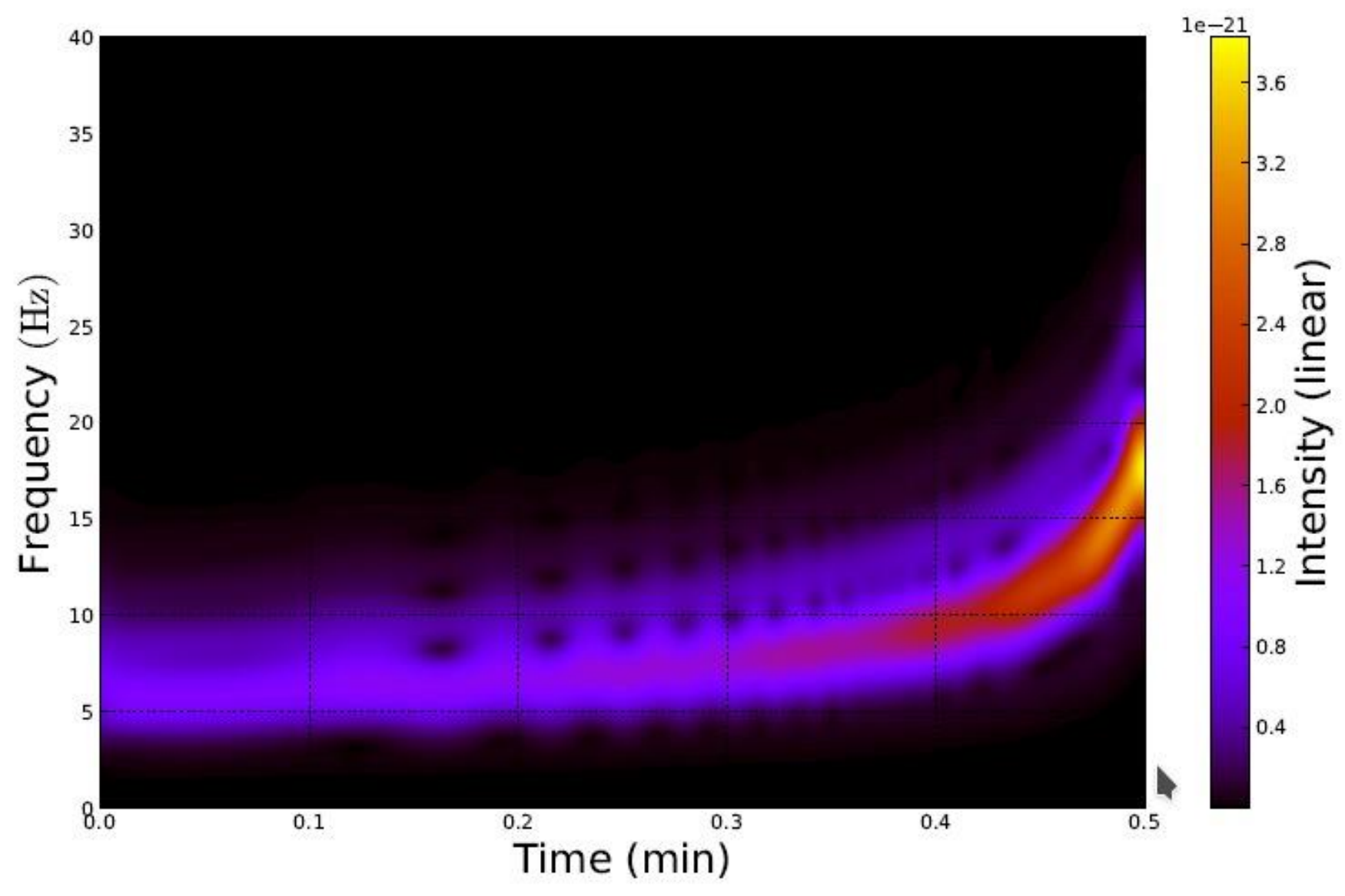

Figure: Spectrogram of Gravitational Waves emitted from a merging binary black hole in one of our star cluster simulations; to be compared with LIGO observations (Assmann et al. 2018).

Direct N-body6++GPU code, scaling and facilities:

Computing Facilities used: FZ Jülich JUWELS/JURECA, and also Max-Planck Hydra Cluster, and Laohu cluster at NAOC/CAS in Beijing, right picture down

Figure: JUWELS GPU accelerated Supercomputer of NIC/RZG **(left);** Laohu GPU accelerated Supercomputer at NAOC Beijing **(right)**

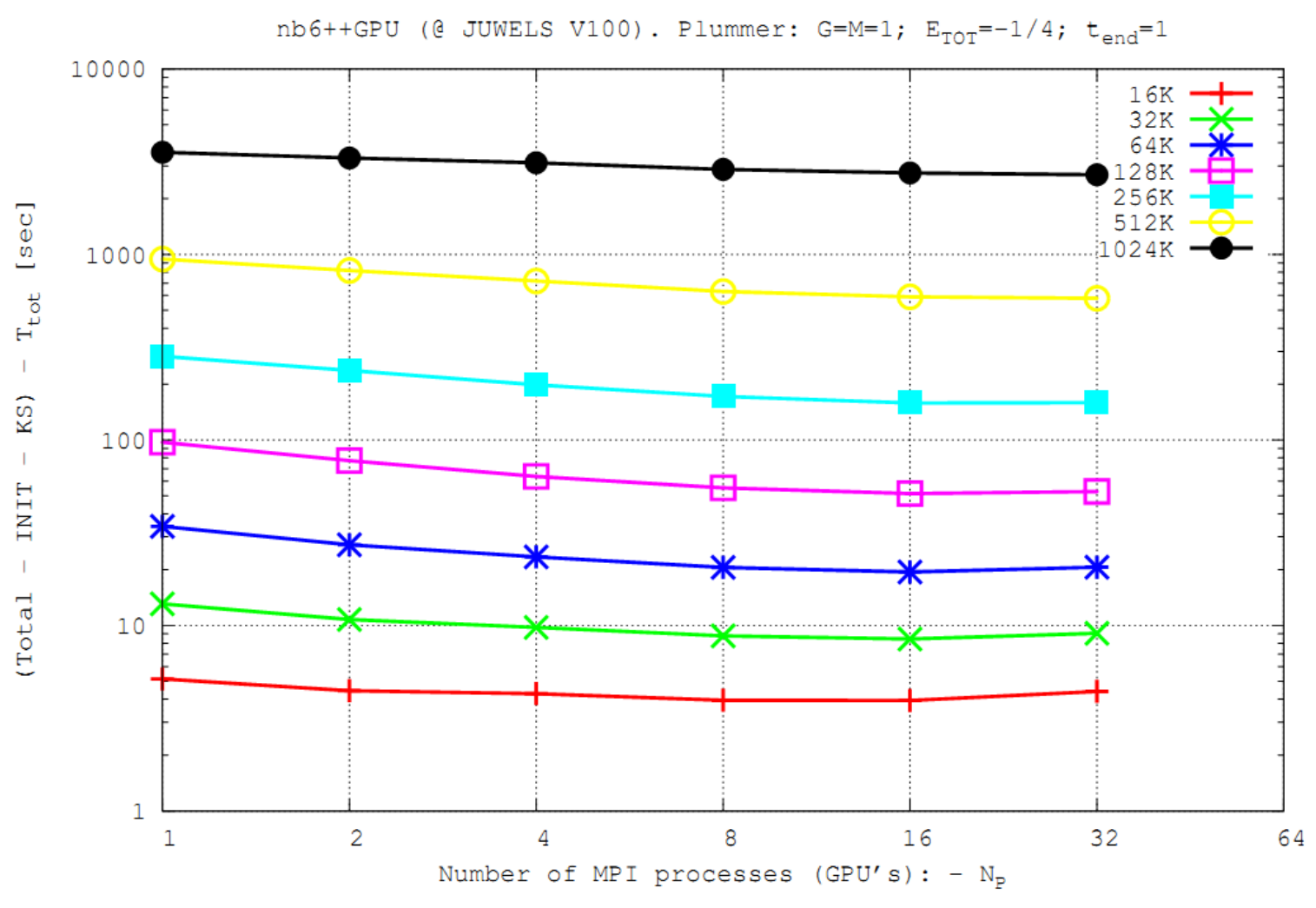

Figure: The current **nbody6++gpu** performance results on the JUWELS clusters. The computing nodes of the cluster are equipped with the recent NVIDIA Tesla V100 GPU accelerators. The initial conditions was a test Plummer sphere, without any primordial binaries. The plot shows the so call "hard" scaling of the simulations. Running time versus MPI process (=GPU's) numbers for different fixed particles numbers.

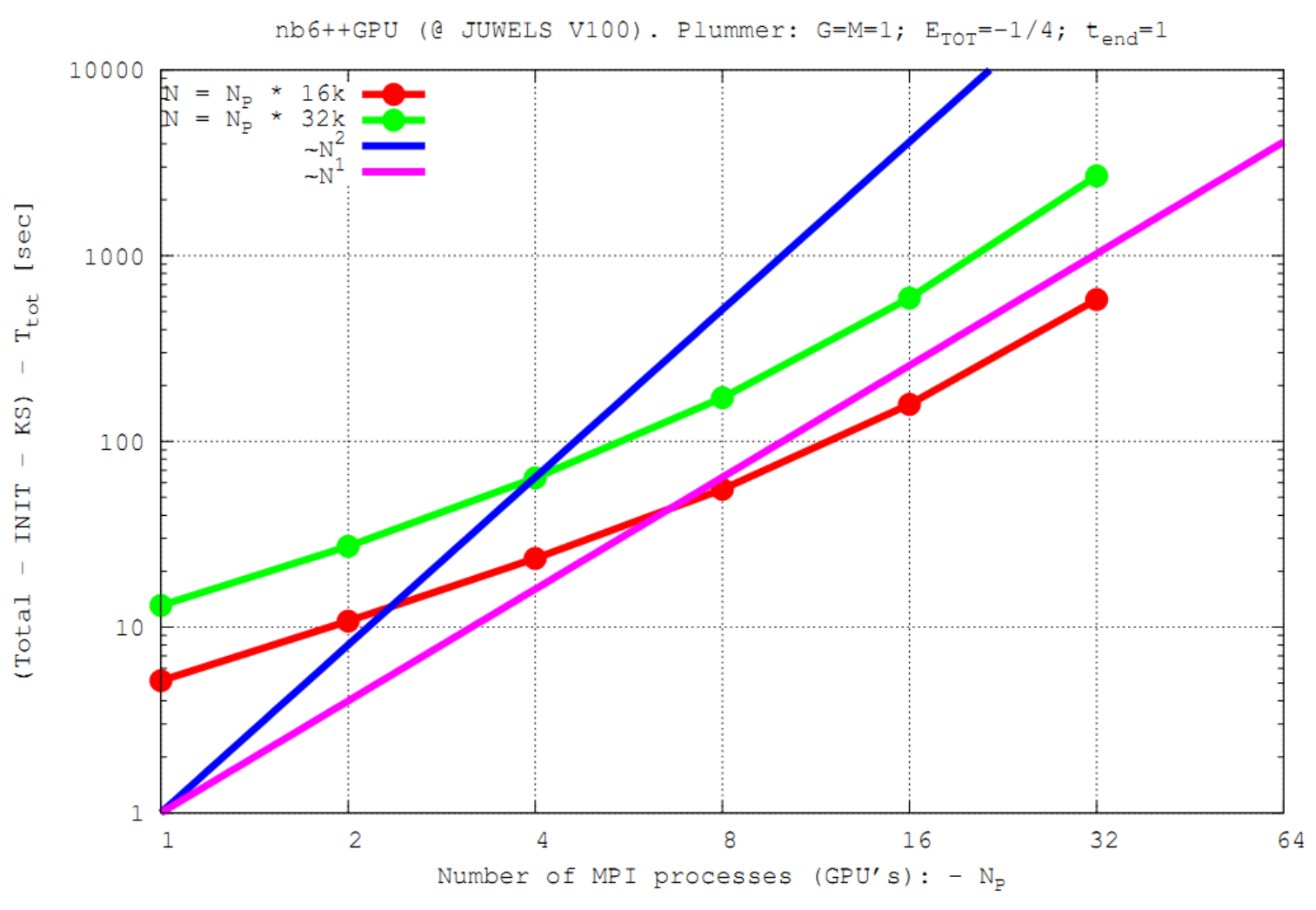

Figure: Our test model "soft" scaling. Here we also plot the ~N and ~N² dependences. As we can see our model data for larger N are asymptotically come to the ~N "ideal" soft scaling line.

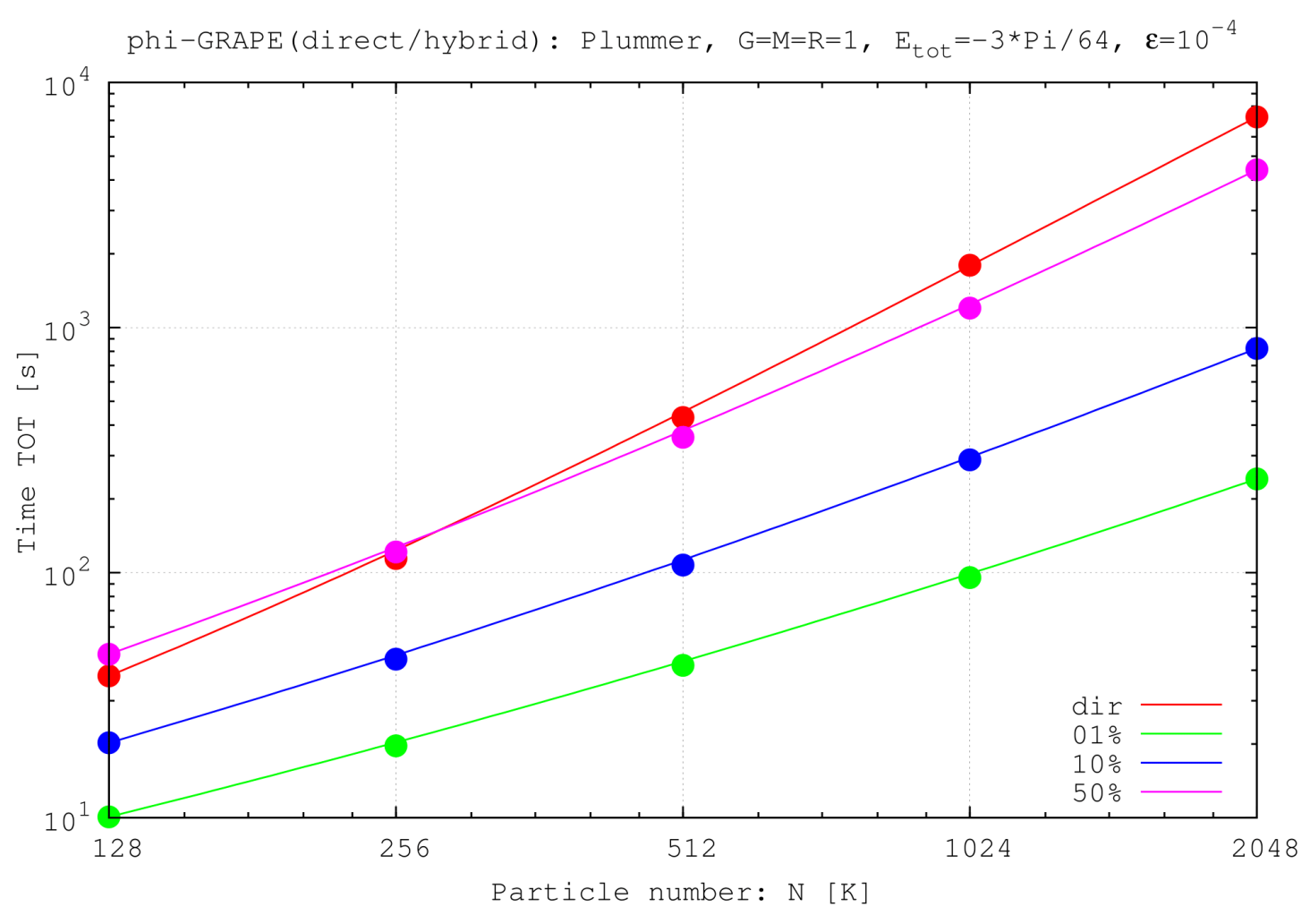

Figure : Performance results of the hybrid version of **φ-GRAPE** (see right column, method section) as a function of particle number, using 2 NVIDIA GeForce 2080 Ti devices. Different lines correspond to different percentage of particles integrated in a direct way.

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Identifying Hypervelocity Stars in an N-body Massive Black Hole Merger Scenario:

Introduction

It is well established that Supermassive black holes (SMBH) are present in the centers of the vast majority of galaxies. During galaxy mergers, SMBHs are brought close together to form gravitationally bound binary systems, which can result in a merger event and gravitational wave emission. During such a merger, the SMBH pair dynamically interacts with incoming stars and as a result, loses orbital energy. However, the nature of these interactions and the properties of these stars are still not well known

Method

We utilize a novel, fully GPU-parallelized hybrid integration approach which combines direct summation with the self-consistent field (SCF) method (Hernquist & Ostriker, 1992) in order to efficiently represent the galaxy merger remnant potential, while significantly reducing computational time. The hybrid code consists of the **φ-GRAPE** code (Harfst et al., 2007), combined with **ETICS** (Meiron et al., 2015) and **GRAPite** (Meiron et al., 2020, in prep.). We simulate a system of N= 6x 10⁶ particles, including 2 SMBH particles. Only about **3%** of the particles are integrated in a direct way, leading to a speed-up of a factor of **5**, over the direct-only approach.

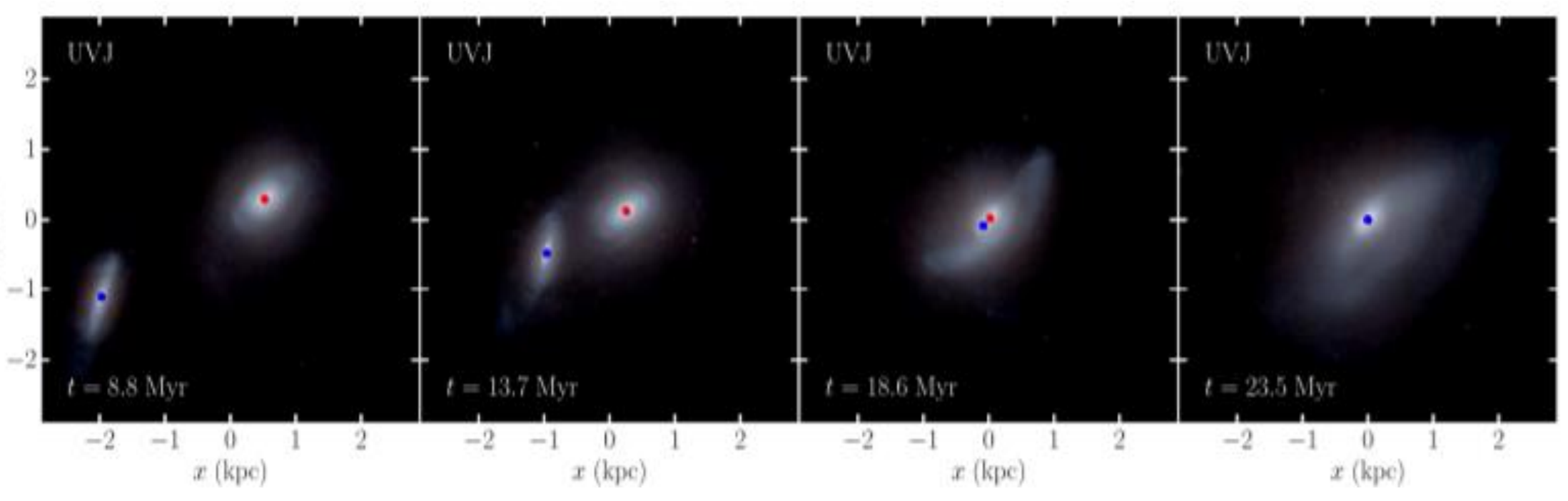

Figure : Time evolution of the galaxy merger used as initial data (Khan et al., 2016). Each galaxy contains a SMBH particle, with masses m_1 = 3x 10⁸ and m_2 = 8x 10⁷ solar masses, respectively.

Results

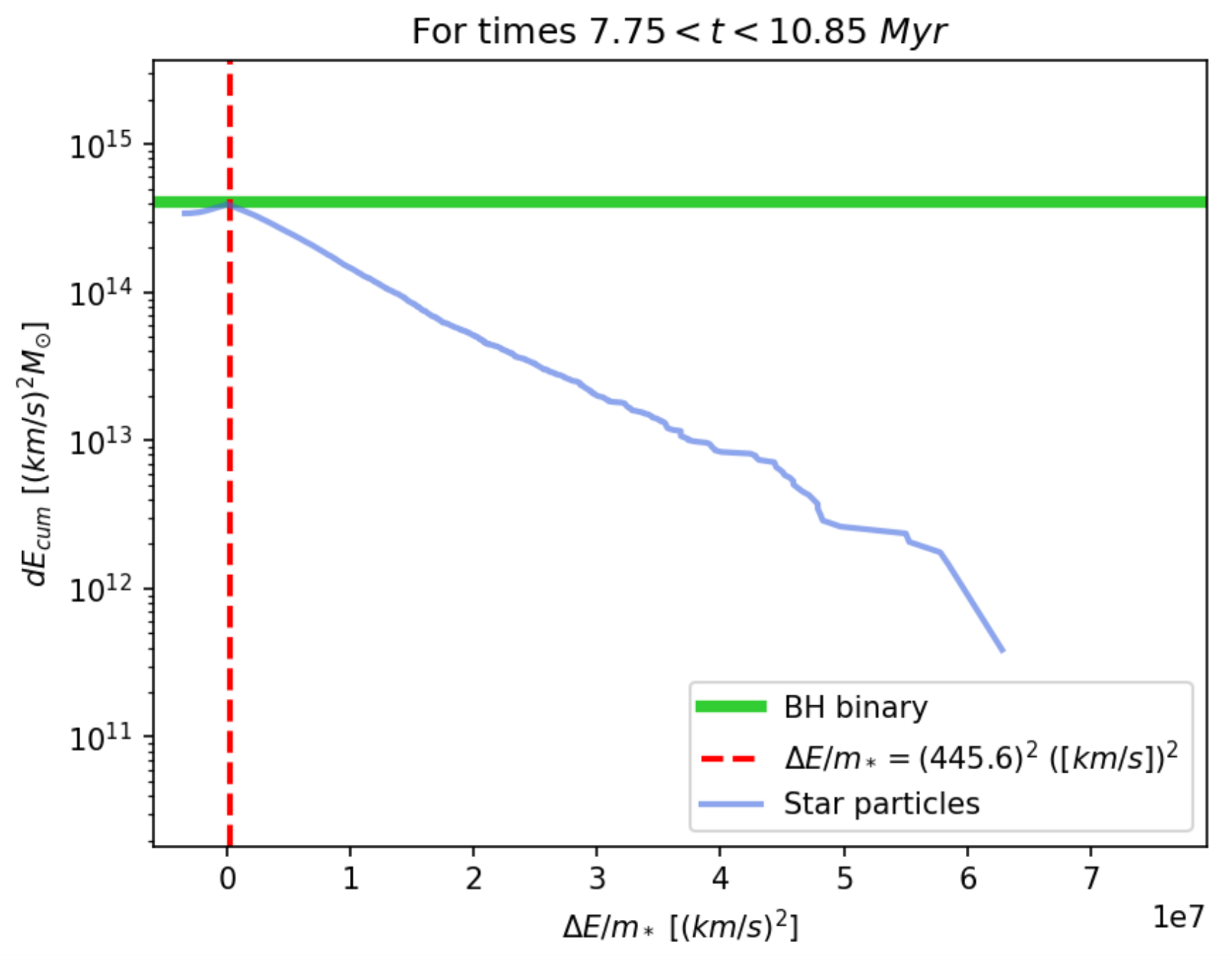

Figure : Cumulative energy change as a function of specific energy change of the interacting stars. The energy change of the stars we identify completely accounts for the total energy change of the SMBH binary, given in green (Avramov et al., 2020, in prep.)

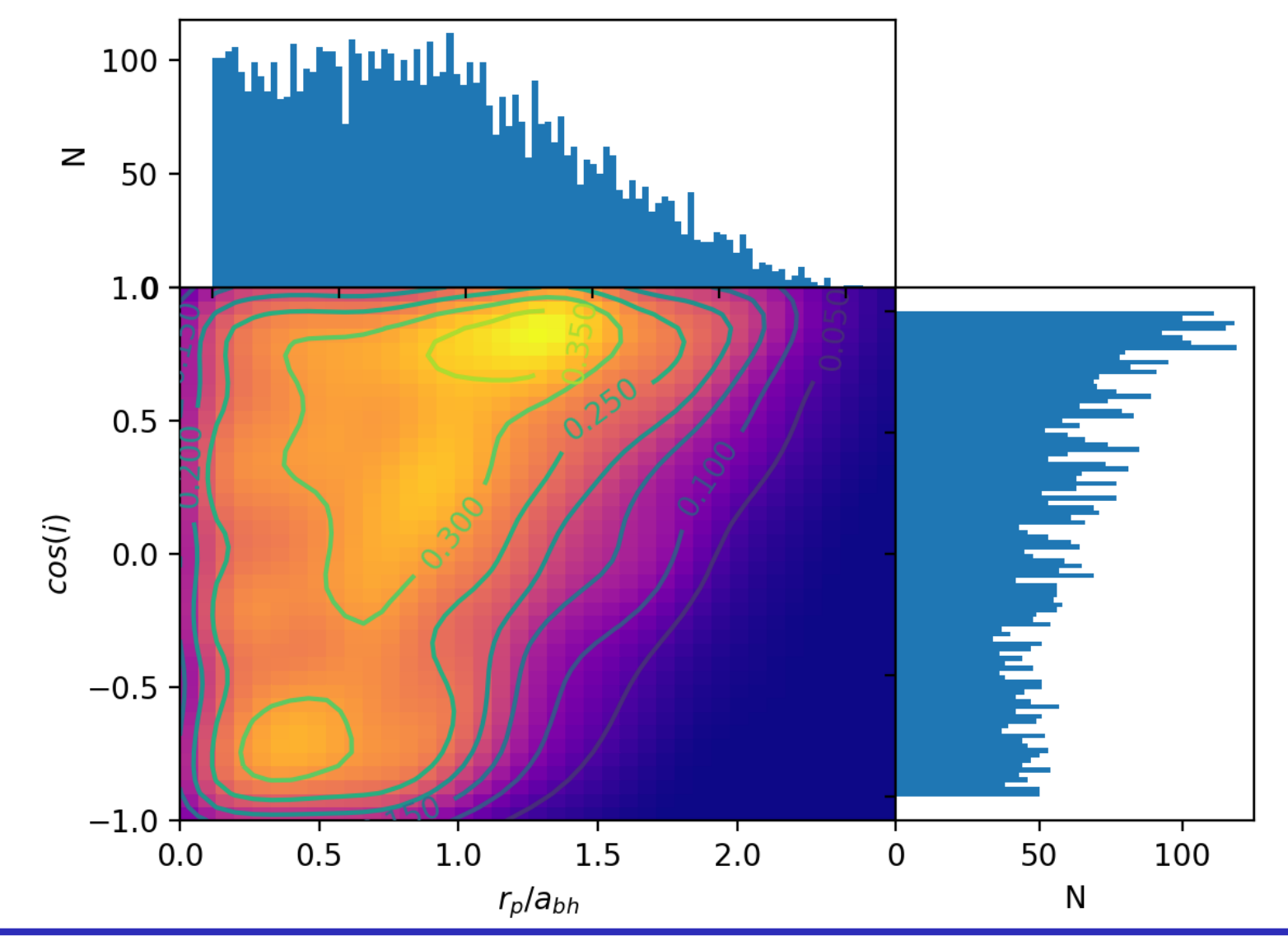

Figure : Distribution of the orbital inclination of the stars, as a function of pericenter normalized to the SMBH binary semi-major axis. The stellar orbits are mostly prograde, while the retrograde interactions need to come much closer to the SMBH binary (Avramov et al., 2020, in prep.).

Acknowledgements: This work has been partly supported by the "Landengraduiertenstipendium" from Heidelberg University, by Volkswagen Foundation (Trilateral Collaboration Scheme, Grants No. 90411 and 97778), and by the Strategic Priority Research Program (Pilot B) Multiwavelength gravitational wave universe of Chinese Academy of Sciences (No.XDB23040100).