the SILK ROAD PROJECT at NAOC

丝绸之路 计划

Astron. Rechen-Inst.
ZENTRUM FÜR ASTRONOMIE
University of Heidelberg

Experimental Stellar Dynamics
Dense Star Clusters – Silk Road Project

Rainer Spurzem, and Silk Road Team

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

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

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https://www.astro-silkroad.eu

1) **Introduction – People**
2) Main Project Topics
3) Sketches of Future Projects
4) Summary

Our Team Re-Union at MODEST-15s in Kobe, Dec. 2015
(ARI Heidelberg around 2000)

Team Members, collaborators, former students

- Introduction
  - GC + NSC
  - Multi-messenger
- Method
- Dragon 1, 2, 3
- Dragon 3 ic
- Pre-results
  - Form compact obj.
  - Binary

Group Introduction

Globular cluster simulations


Albrecht Kamlah

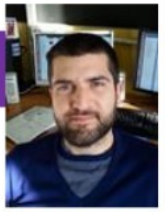

Kai Wu


Long Wang


Peter Berczik


Mirek Giersz


Abbas Askar


Manuel Arca Sedda

Planetary systems in star clusters


Francesco Flammini Dotti


Rainer Spurzem
Tan Yi, Maria Rah
Ambreesh Khurana

Rotating cluster

Xiaoying Pang
Abylay Bissekenov
(talk on Mon.)


Vahid Amiri

Stellar evolution updates
(talk today and tomorrow)


Jarrod Hurley


Yuzhe Song (Robert)

Very massive star formation
(talk by Abbas on Mon.)


Marcelo Vergara

Nuclear cluster
(talk on Wed.)


Philip Cho

Taras Panamarev
Shuo Li, Shiyan Zhong

Original Slide by Kai Wu, for IAU398

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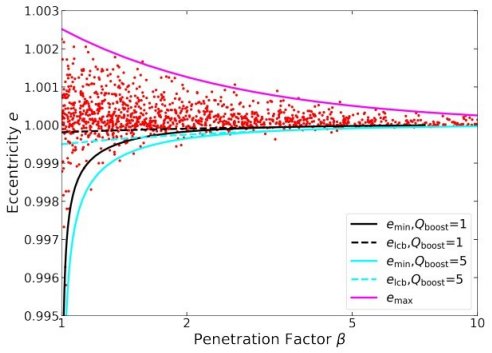
Core Team Silk Road

Rainer Spurzem, Kai Wu, Francesco Flammini Dotti, Vahid Amiri, Marcelo Vergara, Philip Cho, Shuo Li, Shiyan Zhong, Peter Berczik

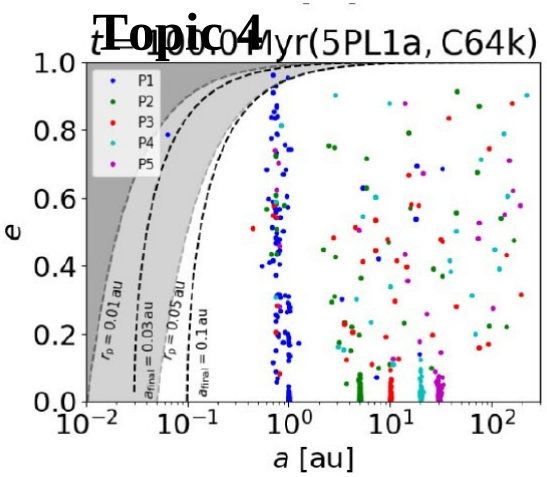
- Topic 1: DRAGON Simulations, Globular and young dense star clusters, Special Objects, Multiple Pop.; Galactic and Extragalactic; Kai, Francesco, Rainer, Marcelo, Peter, Abbas, Mirek
- Topic 2: Open Star Clusters, Fractal Structure, Rotation, … Vahid, Francesco, Abylay, Xiaoying
- Topic 3: Evolution and Formation of Nuclear Star Clusters, Star Accretion on SMBH and IMBH, EMRIs, Black Holes, Relativistic Dynamics, Galaxy Mergers Philip, Shuo, Shiyan, Peter
- Topic 4: Planets, massless particles in Star Clusters Kai, Francesco
- Topics X, see below

Topic 3



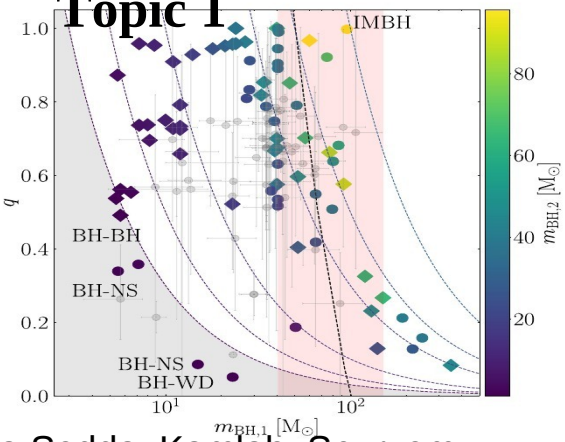
Zhong, Hayasaki, Li, Berczik, Spurzem, ApJ 2023

Topic 4



Benkendorff, Flammini Dotti, Stock, Cai, Spurzem, MNRAS, 2024

Topic 1



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

Topic 1: DRAGON Dynamical Evolution of Globular Star Clusters

- DRAGON III simulations; wide binaries (Wu et al. 2026); future: next goal about 1 Gyr? Wait for jupiter computing time grant, data analysis, triples?
- More Future Issues: Triples and Multiples, MSE, TSE? New pulsar treatment

(Yuzhe Robert Song, Debatri Chattopadhyay, Maria Rah)

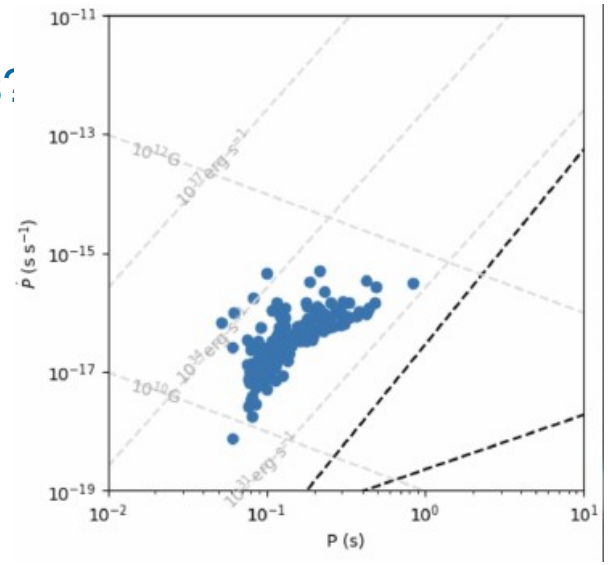
- Full Black Hole Spin Model, Stellar Rotation? Cluster Rotation?
- 47 Tuc, CMC and Nbody? (Ambreesh)
- Multiple Populations (Peter, Margaryta, Abbas, Mirek, …)
- Improved CE and Mass Transfer

(Yunnan Group)

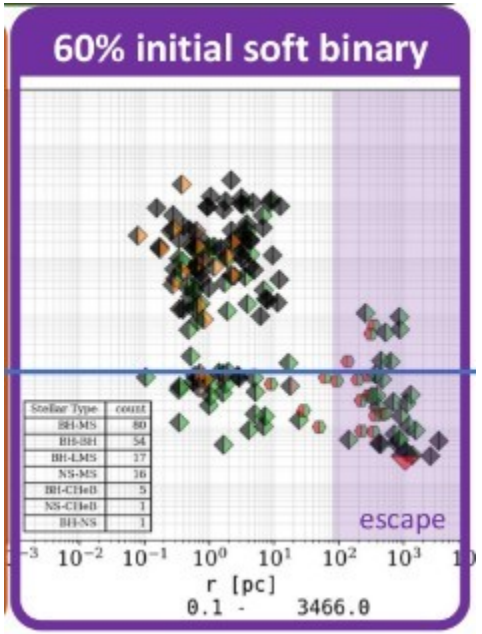
- High Energy Sources?

General Goal:

"Digital Twins" of GCs across cosmic time; multi-messenger and multi-wavelength predictions



Song et al. 2026



Wu et al. 2026, IAU398

Main Code used : Nbody6++GPU/Mcluster

Topic 2: Dynamical Evolution of Open Star Clusters

- Galactic Open Star Cluster Evolution; influence of binaries, rotation, mass segregation, fractal initial structure on life time and escapers; compare with observations (Amiri et al. 2026 a,b; see also Bissekenov et al. 2025, 2026)
- Future: wide binaries, triples, tidal tails...

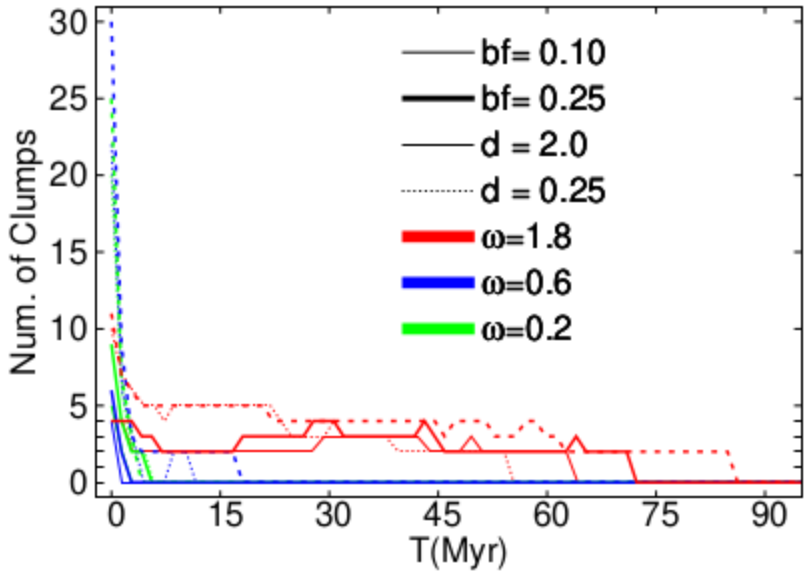


Fig. 12. Time evolution of the number of clumps for all models.

General Goal:

Predictions for Gaia, CSST, JWST?

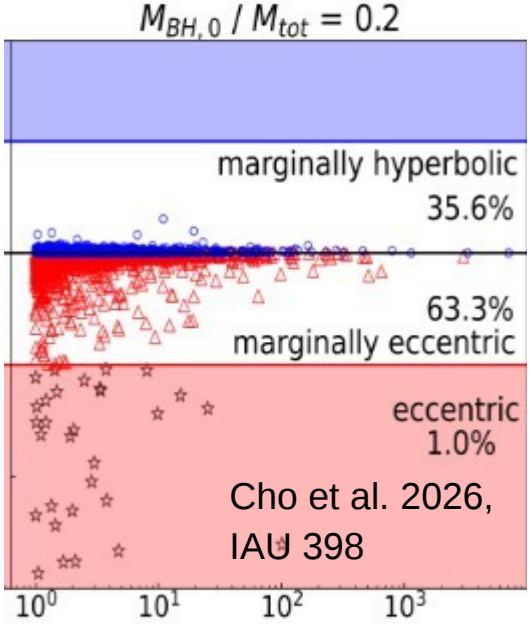
Main Code used :
Nbody6++GPU/Mcluster
fopax rotating initial model

Amiri et al., 2026 Paper I; and in prep. Paper II

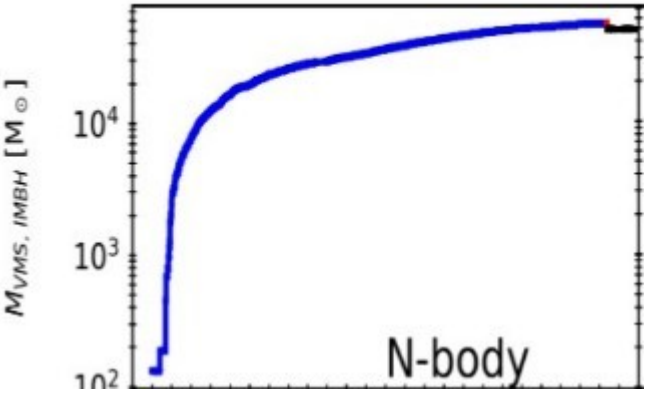
Topic 3: Formation and Evolution of Nuclear Star Clusters, Star Accretion on SMBH, IMBH, EMRIs, Black Holes, Relativistic Dynamics, Gal. Mergers

- Formation: Massive high density star clusters, collisional run-away, IMBH seed formation (Vergara et al. 2024, 2025, 2026); future: rotation, binaries, PopIII, fractal initial structure, collision and PMS model, long term model.
- Evolution: Philip Cho, based on Taras Panamarev et al. 2019, IAU conf. Paper. In progress: final state of TDE/EMRI depending on stellar parameters; future: new pulsar models, full Post-Newtonian with spins, partial TDEs (Zhong et al. 2022)
- Evolution: Nuclear Star Cluster with Galaxy Merger (Li et al. 2023); In progress: improved TDE/EMRI model for binary SMBH
- Main Code used : Nbody6++GPU stardisk version (standard for moving IMBH?)

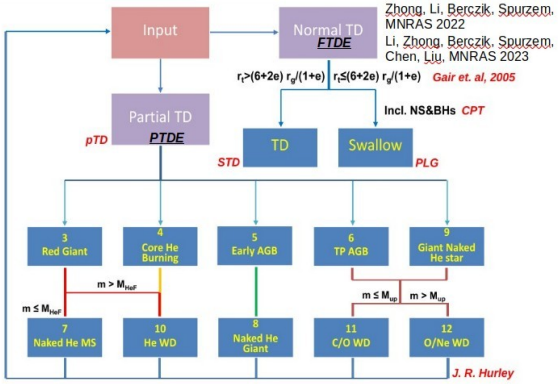
General Goal: TDE/EMRI rates, light curves, SMBH seed formation



Cho et al. 2026, IAU 398



Vergara et al. 2026



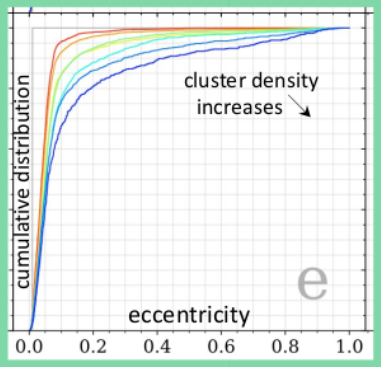
Zhong, Li, Berczik, Spurzem, MNRAS 2022
Li, Zhong, Berczik, Spurzem, Chen, Liu, MNRAS 2023
Li et al. 2023

Topic 4a: Planets, massless particles in star clusters

Kai Wu (吴开)
kaiwu.astro@gmail.com

Planetary systems in star clusters

- **LPS+ (LonelyPlanetS+)**
  - Nbody6++GPU
  - REBOUND
  - C language interface
- **Star cluster + planet + disk**

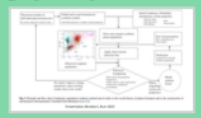


Rotating Pop III star cluster

- **Rotating + massive (100k stars)**
- **10^{-8} of solar metallicity**

Upcoming DFG application

- **Improve planetary population synthesis prescriptions with N-body results**
- **PPS connect theory to obs. , but systematically ignored star cluster dynamics**
- **Preparing proposal, welcome to join**



Dragon III globular cluster simulations

- **5% hard binary + 0 / 20% / 60% soft binary**
- **No escaper removal**
- **In progress: 265 / 337 / 88 Myr**

chore: admin of NBODY6++GPU GitHub repo, Silkroad webpage, Silk server, conference calendar

nbody6ppgpu.github.io/conference-calendar

Past — PhD finish 2024 June — Now 2026 April 28 — Future

Topic 4b: Planets, massless particles in star clusters

See separate file linked same place
by Francesco Flammini Dotti

Topic X: Statistical Models Of Star Clusters and SIDM

KITP UC Santa Barbara Program:
Interconnections between the Physics of Plasmas and Self-gravitating Systems

- Gaseous/Momentum and Fokker-Planck Models
- Main Code used : fopax + spedi
- Self-Interacting Dark Matter Models (SIDM)
- Pure Black Hole Clusters, Collapse and Mergers
- High Energy Emission from star clusters? (MODEST26)

Bottom right: Schneider, Amaro-Seoane, Spurzem, MNRAS 2011:
Anisotropic Gaseous Model, post-Gaussian velocity distribution;
Bottom: Einsel, Spurzem, MNRAS 1999:
2D Fokker-Planck model, accelerated core collapse?

The crucial similarity in plasma physics and self-gravitating systems arises from the fact that inter-particle interactions in both systems are primarily governed by coherent forces from distant particles, as opposed to quasi-random forces from violent collisions with nearby particles.

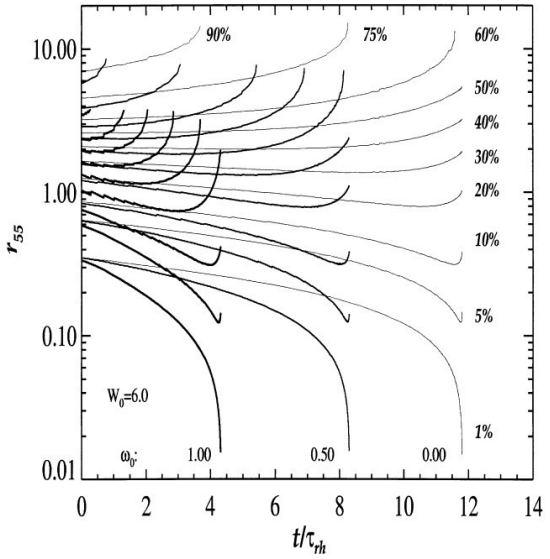
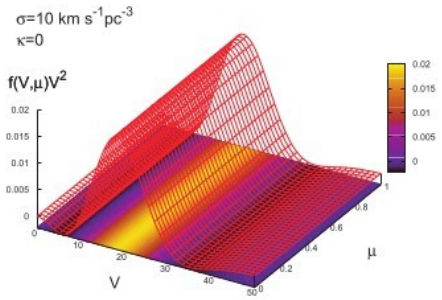
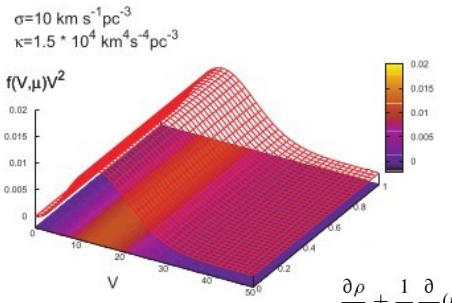


Figure 1. Evolution of mass shells (Lagrange radii r_{55}) for models with $(W_0, \omega_0) = (6.0, 0.00$: light lines), $(6.0, 0.50)$, $(6.0, 1.00$: heavy lines). Shown are the radii for mass columns containing the indicated percentage of total initial mass in the direction of the $\theta = 54.^{\circ}74$ angle.





$$\left(\frac{\partial f}{\partial t}\right)_{\rm enc} = \frac{1}{V}\left[-\frac{\partial}{\partial E}(<\Delta E>fV) - \frac{\partial}{\partial J_z}(<\Delta J_z>fV) + \frac{1}{2}\frac{\partial^2}{\partial E^2}(<(\Delta E)^2>fV) + \frac{\partial^2}{\partial E \partial J_z}(<\Delta E \Delta J_z>fV) + \frac{1}{2}\frac{\partial^2}{\partial J_z^2}(<(\Delta J_z)^2>fV)\right],$$

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 u\rho) = 0$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + \frac{GM_r}{r^2} + \frac{1}{\rho}\frac{\partial p_r}{\partial r} + 2\frac{p_r - p_t}{\rho r} = 0$$

$$\frac{\partial p_r}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 u p_r\right) + 2p_r\frac{\partial u}{\partial r} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 F_r\right) - \frac{2F_t}{r} = -\frac{3}{5}\frac{p_r - p_t}{\lambda_A t_{rx}} + \left(\frac{\delta p_r}{\delta t}\right)_{\rm bin3}$$

$$\frac{\partial p_t}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 u p_t\right) + \frac{2p_r u}{r} + \frac{1}{2r^2}\frac{\partial}{\partial r}(r^2 F_t) + \frac{F_t}{r} = \frac{3}{10}\frac{p_r - p_t}{\lambda_A t_{rx}} + \left(\frac{\delta p_t}{\delta t}\right)_{\rm bin3}.$$

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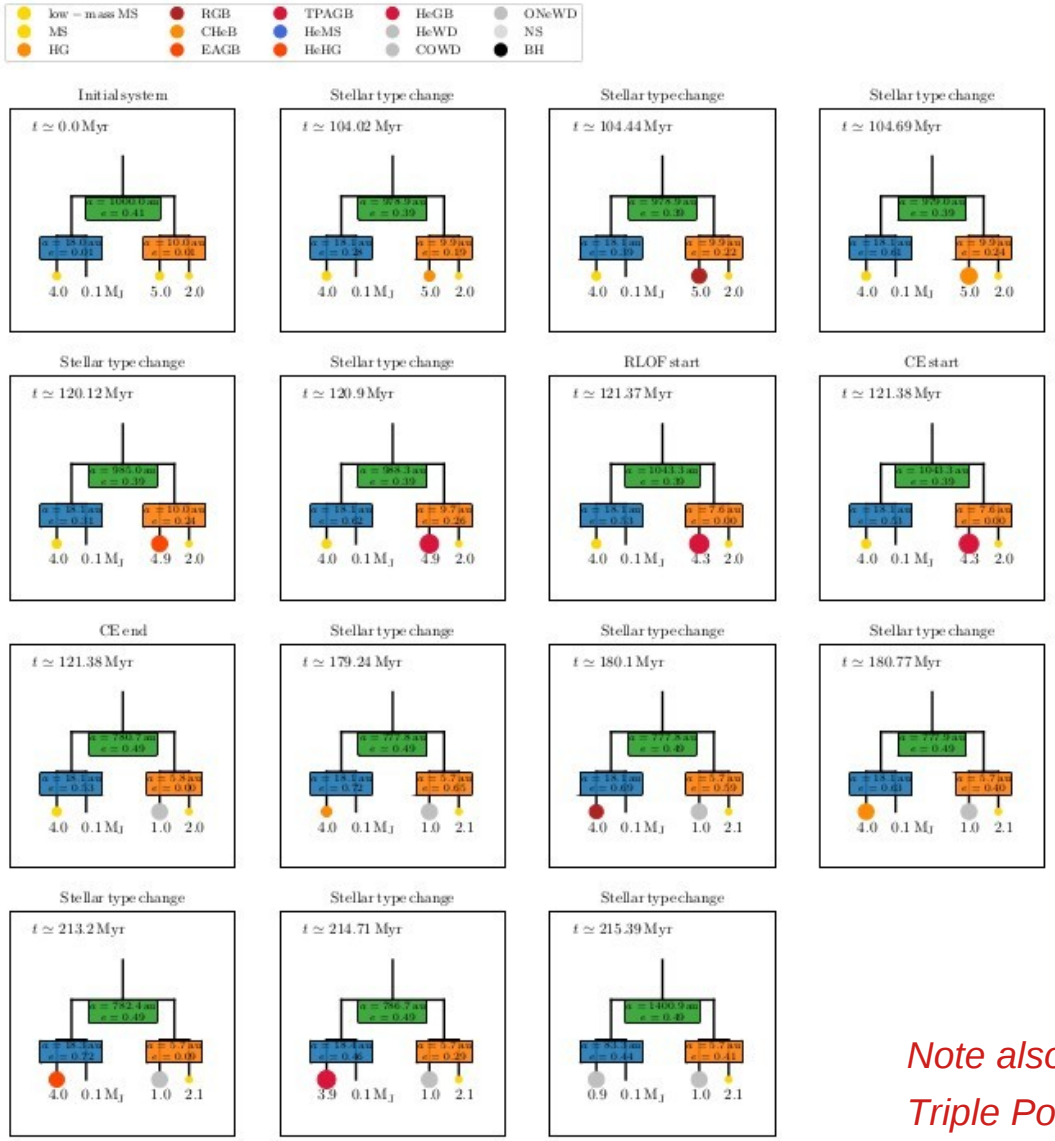
MSE/TSE Triple/Multiple Stellar Evolution

(Hamers et al. 2021, Stegmann et al. 2022, Stegmann & Antonini 2024)



New features of MSE/TSE:

Evolution of planet

In Triple System

See also further work by Holly Preece and Jakob Stegmann (TSE)

Preece, H. P., Hamers, A., et al., Forming hot subluminous stars from hierarchical triples - I. The role of an outer tertiary on formation channels, 2022, MNRAS, 517, 2111

Preece, H. P., Hamers, A., et al., The Equilibrium Tide: An Updated Prescription for Population Synthesis Codes, 2022, ApJ, 933, 25

Note also: Bonetti et al 2016, 2018ab, 2019: Triple Post-Newtonian

Work of Yunnan BSE group

(Han Zhanwen & Team)

Formation of millisecond pulsars with helium white dwarfs, ultra-compact X-ray binaries and gravitational wave sources

Hai-Liang Chen,[1,2,3]★ Thomas M. Tauris,[3,4] Zhanwen Han,[1,2,5,6] Xuefei Chen,[1,2,5,6]†

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[2] *Key Laboratory for the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, Kunming 650011, China*
[3] *Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, 8000 Aarhus C, Denmark*
[4] *Aarhus Institute of Advanced Studies (AIAS), Aarhus University, Høegh-Guldbergs Gade 6B, 8000 Aarhus C, Denmark*
[5] *University of the Chinese Academy of Sciences, Yuquan Road 19, Shijingshan Block, 100049, Beijing, China*
[6] *Center for Astronomical Mega-Science, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Bejing 100012, China*

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Linking LMXBs, MSPs, UCXBs and GW sources 11

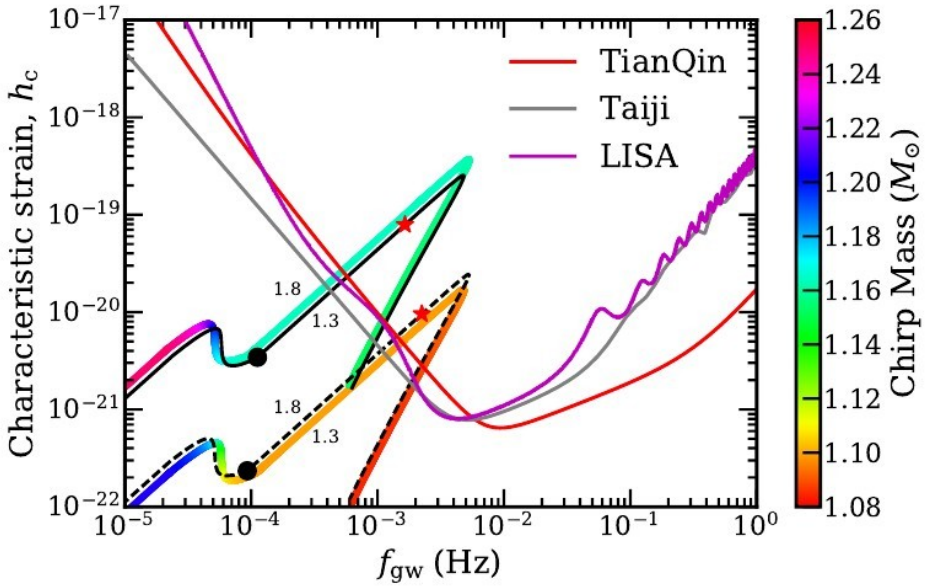

Figure 13. Characteristic GW strain produced by UCXBs as a function of GW frequency. The black line, and also the thick coloured line below the black dashed line (marked "1.3"), are for binaries with initial binary parameters of M_{NS} = 1.30 $M_\odot$, M_2 = 1.25 $M_\odot$, P_{orb} = 7.94 d. The black dashed line, and also the thick coloured line above the black solid line (marked "1.8"), are for similar binaries with M_{NS} = 1.80 $M_\odot$. The upper and lower pairs of evolutionary tracks are for UCXBs at distances of d = 1 kpc and d = 15 kpc, respectively. Their peak SNR are above 100 and 10, respectively. The black circles represent the end of the first mass-transfer phase (LMXB) and the red stars indicate the onset of mass transfer in the UCXB phase. The colors on the two thick evolutionary tracks represent chirp masses (cf. vertical colour bar on the right). The red and grey solid lines are the sensitive curves for TianQin and Taiji with an observing time, T = 5 yr, and the magenta line shows the sensitive curve for LISA with an observing time, T = 4 yr.

Also new models of ns-ns, ns-bh binaries:

Chattopadhyay et al. 2020, 2021, 2022

Ye et al. 2019, 2022 (Rasio Northwestern Team)

Rah et al. 2024, 2025ab

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Example Summary Message from talk this month

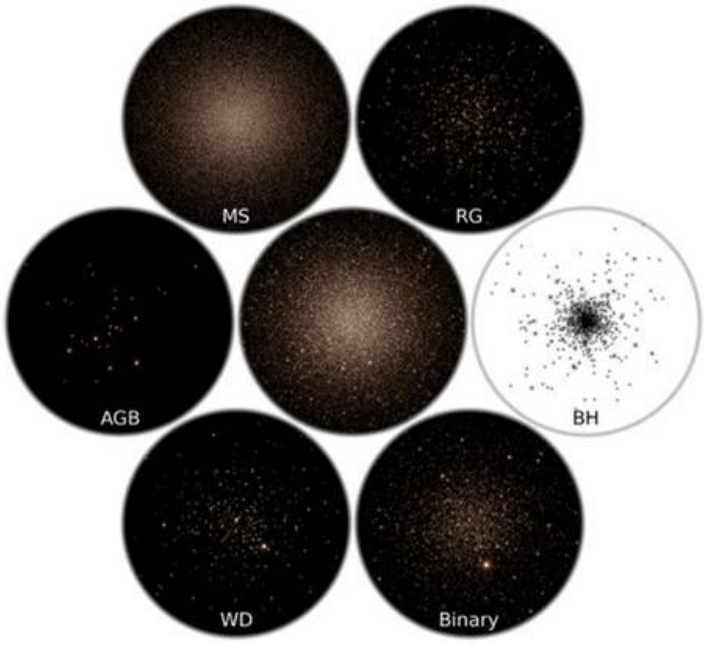
Massive Star Clusters:

- 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)
- Soft Binaries, Tidal Tails in DRAGON-III , future work rotation
- Necessary Input: single/binary stellar evolution / relativistic (PN) dynamics
- Still very long computing time for few models (in spite of GPU, Lumi, DCU…)

- **Monte Carlo Models (MOCCA, Warsaw, M. Giersz, CMC, Northwestern, F. Rasio) needed to get good sweep of parameter space, comparison with N-Body**

Nuclear Star Clusters:

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



ARI ITA LSW

Relevant References

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.) **Paper I,II,III (MNRAS 2023, 2024)**
- **DRAGON-III, in prep.,** Wu, K., Spurzem, R., Flammini Dotti, F., et al. ; prel. Conf. Paper IAU398: arxiv:2510.03933

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)
- Vergara, M., et al., Rapid formation of a very massive star (>50000 $M_\odot$), and subsequently, of an IMBH, from runaway collisions: Direct N-body and Monte Carlo simulations of dense star clusters, 2026, Astron. Astroph., 704, A321

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., ApJ 933, 96 (2022)
- **Tracing the Evolution of SMBHs and Stellar Objects in Galaxy Mergers: A Multi-mass Direct N-body Model,** Li, Zhong, Berczik, Spurzem, Chen, Liu 2023, ApJ 944, 109, TDE improved
- Simulating Tidal Disruption Events in Nuclear Star Clusters, Philip Cho, et al., A&A, 2026, in prep.

Summary / Project Plans

Current Project List and Future Plan

- **DFG Star Clusters Across Cosmic Time: until 2026 (Kai)**
- **DFG Planets in Star Clusters (in prep., Kai, Francesco, Rainer)**
- **DFG Koselleck: Nuclear and Globular Star Clusters with GPU and DPU (to be subm. Soon, 5 years, with local GPU/DPU supercomputer? Rainer)**
- **Chinese Academy of Sciences International Collaboration Fund for Creative Research Teams (ICFCRT), Title Dense young and nuclear star clusters as multi-messenger sources with tidal disruption events and gravitational wave inspirals (TDE and EMRI), 2027-2029**
- **Research Unit DFG on Star Clusters (1.5 years from application)**

with Hamburg, Cologne/Bonn, Heidelberg, Garching

- **Collaboration programs China-Italy, China-Kazakhstan, China-Armenia**