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

RECRUITMENT
PROGRAM OF GLOBAL EXPERTS

Deutsche Forschungsgemeinschaft
SFB881 DFG

# Direct N-Body Simulations


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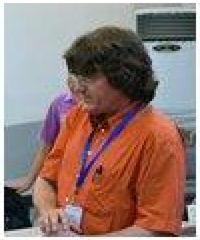
中国科学院国家天文台

National Astronomical Observatories, CAS

# the SILK ROAD PROJECT at NAOC

# 丝绸之路 计划



Picture: Luca Naso

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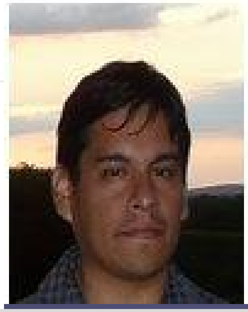
Postdoc (KIAA-PKU)



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Engineer

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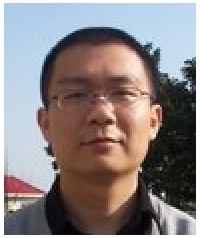
Administrative staff



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北京大學 PEKING UNIVERSITY

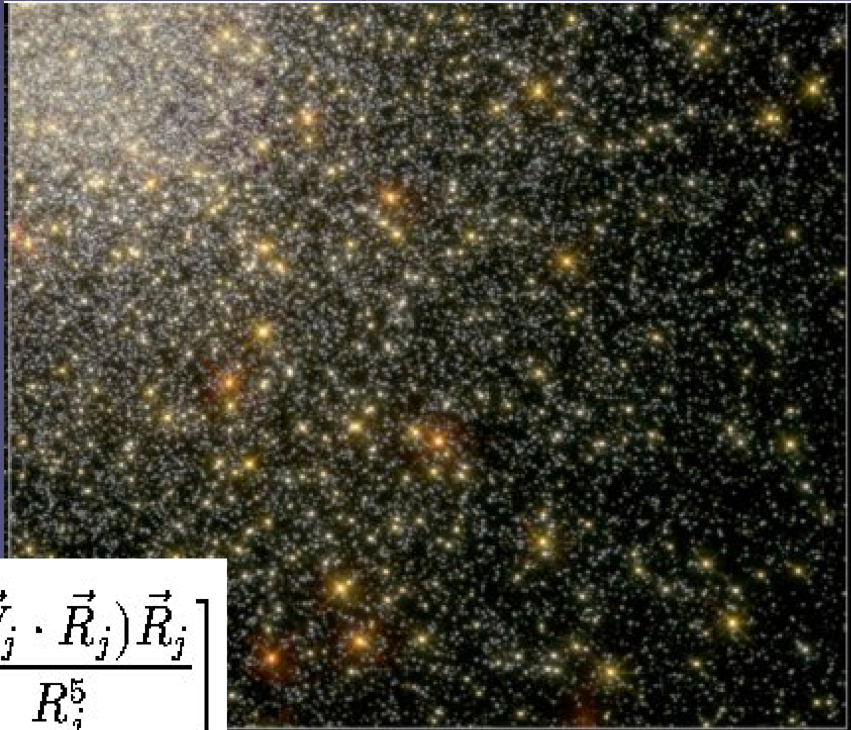
Aspen Jan. 2015

千人計劃

RECRUITMENT PROGRAM OF GLOBAL EXPERTS

# Star Cluster Simulations – Key Issues

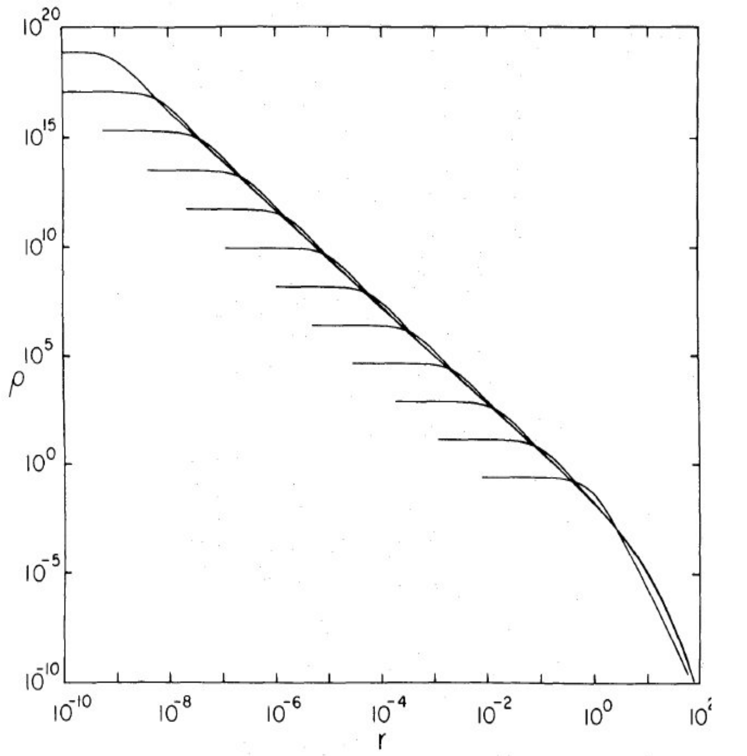
- Theoretical Models / Large N-Body Models
- Black Holes and Tidal Disruption/Star Accretion
- Accelerated Computing (GPU)



Hubble Space Telescope • WFPC2

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

# Theoretical Modelling: Gas Sphere
## Gravothermal Expansion!




Cohn (1980): Direct Fokker-Planckj model

Core Collapse

Gravothermal Catastrophe

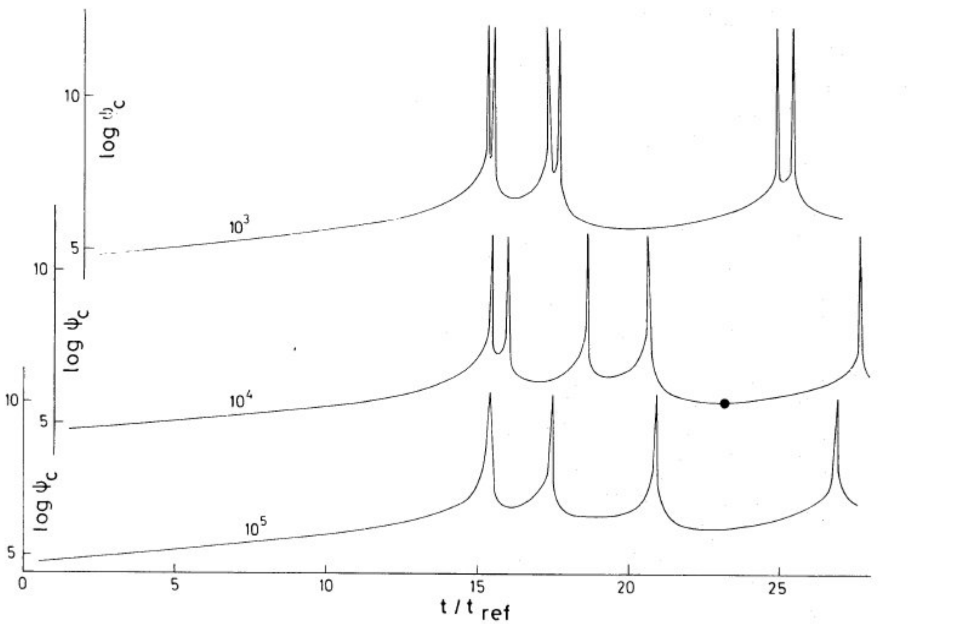



**Figure 1.** The 'central' density $\psi_c$ is plotted against the non-dimensional time $t/t_{ref}$ for $k = 2$ models with three different values of $C$ as attached to each curve. Note, that if they were plotted with the same ordinate they would be close to each other despite the great differences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

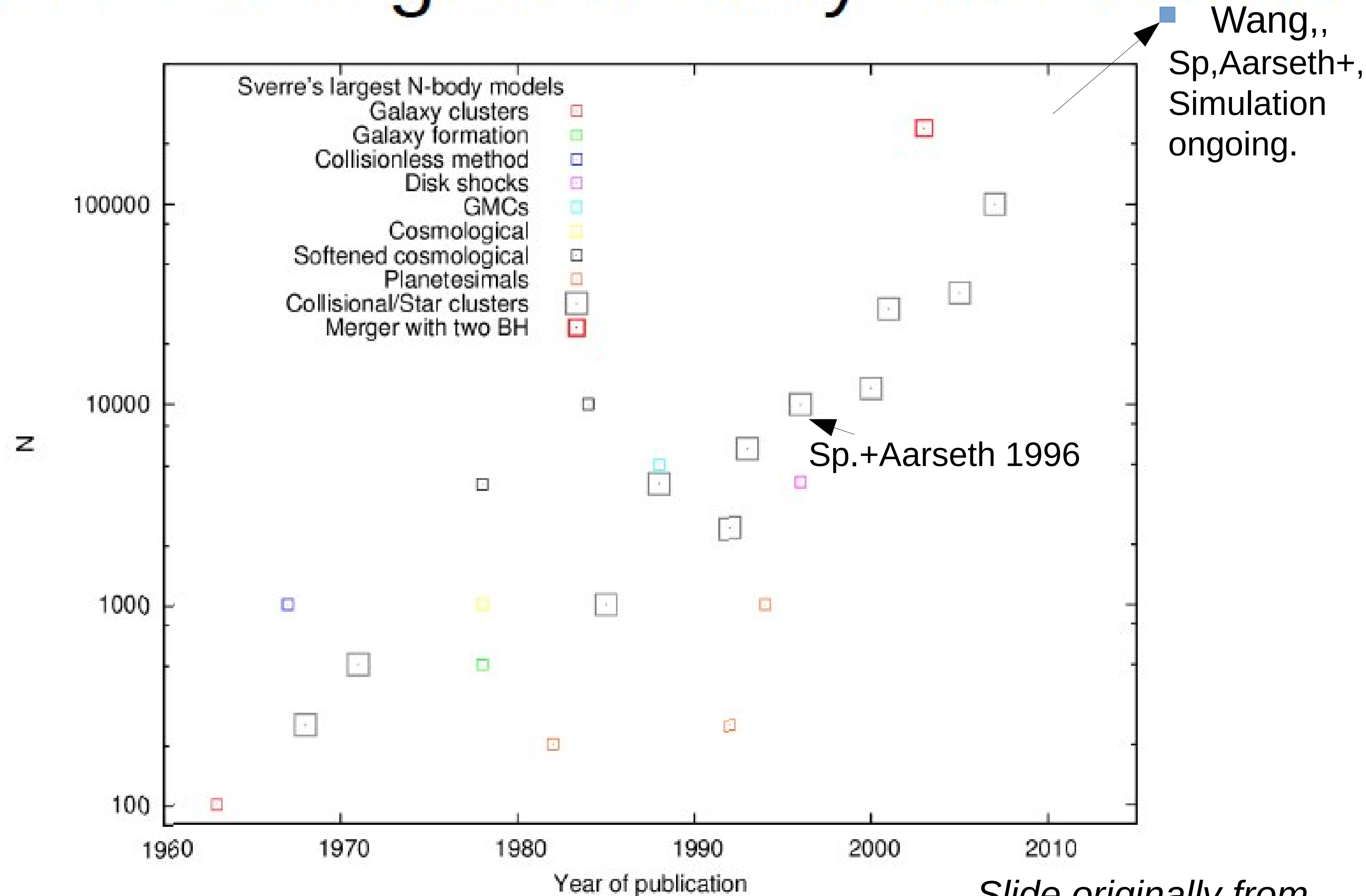
Bettwieser & Sugimoto 1984:

Gravothermal Oscillations by

energy generation from binaries

(cf. nuclear stellar energy generation)

# Sverre's largest N-body simulations

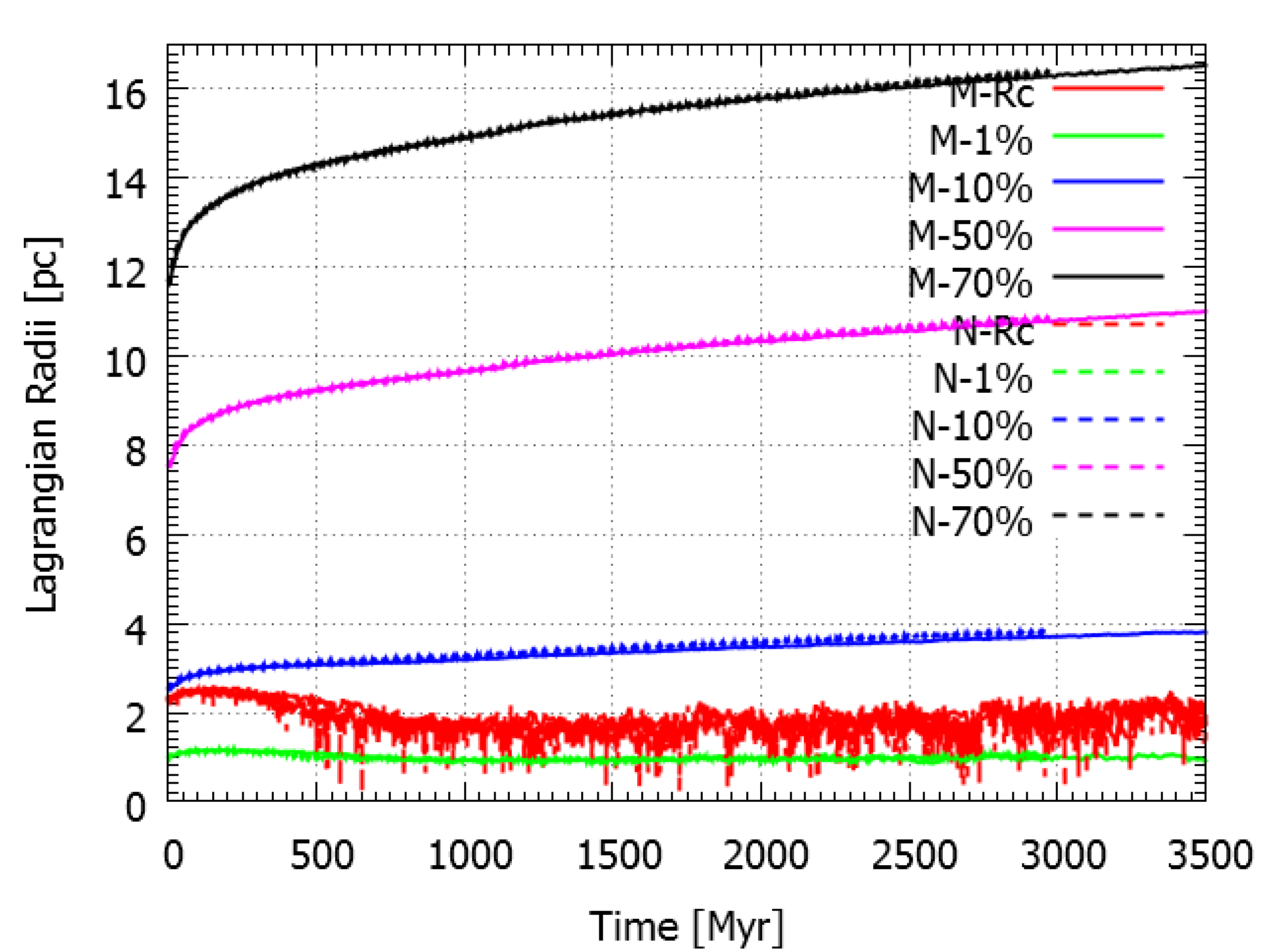



Criteria: published results, evolution well advanced

*Slide originally from Douglas C. Heggie, citations added by RS*

# Direct Simulation (Poster Long Wang)

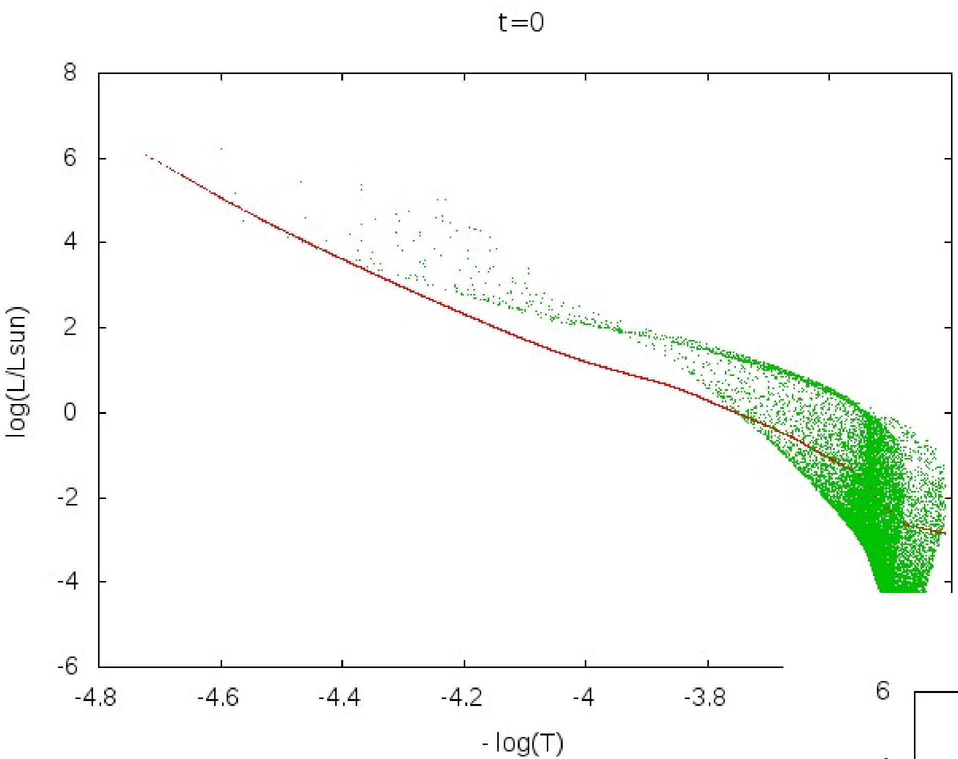
## NBODY6++GPU 1 Million Bodies




Wang, Spurzem, Aarseth, Berczik, Nitadori, Kouwenhoven, Naab 2015a subm. MNRAS, Wang et al. 2015b, in prep.

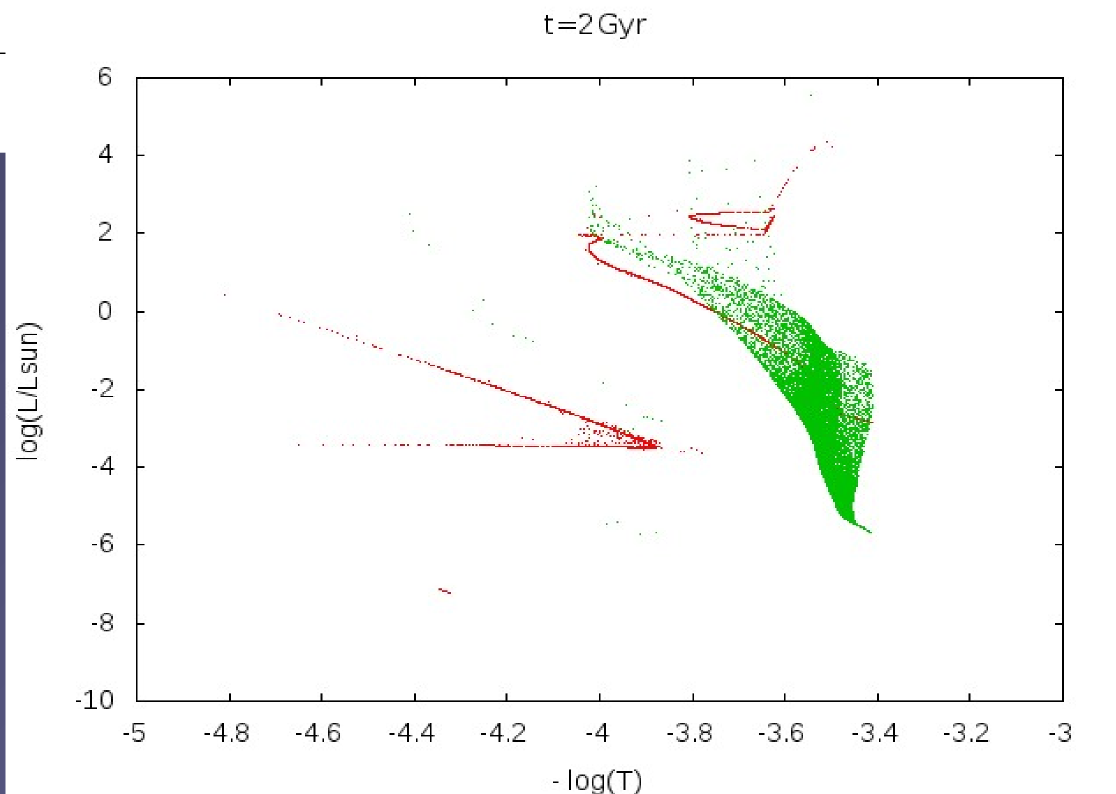
***Used RZG Garching hydra GPU cluster (400 Kepler GPUs)***

Aspen Jan. 2015




Preliminary Results
N=256k star cluster
10% initial binaries
Wang, Spurzem, Aarseth, Berczik,+

Left: initial HR diagram
Right: after 2 Gyrs
...ongoing 1M ...




Sorry!
Problem with Plot of Binaries.

.. work ongoing …

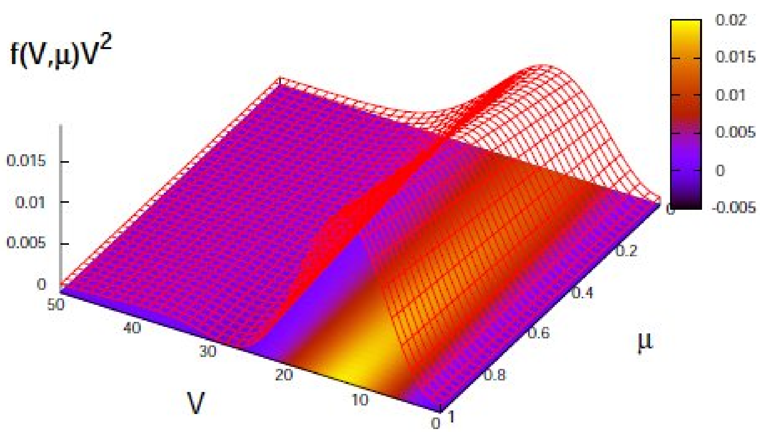
Long Wang et al.

# Theoretical Modelling: Moment Models

16 *Schneider, Amaro-Seoane & Spurzem* 2011

| | | $a_p$ $\left[\frac{\mathrm{km}^2}{\mathrm{s}^2\mathrm{pc}^3}\right]$ | $F$ $\left[\frac{\mathrm{km}^3}{\mathrm{s}^3\mathrm{pc}^3}\right]$ | $a_F$ $\left[\frac{\mathrm{km}^3}{\mathrm{s}^3\mathrm{pc}^3}\right]$ | $\kappa$ $\left[\frac{\mathrm{km}^4}{\mathrm{s}^4\mathrm{pc}^3}\right]$ | $a_{\kappa 1}$ $\left[\frac{\mathrm{km}^4}{\mathrm{s}^4\mathrm{pc}^3}\right]$ | $a_{\kappa 2}$ $\left[\frac{\mathrm{km}^4}{\mathrm{s}^4\mathrm{pc}^3}\right]$ | $G$ $\left[\frac{\mathrm{km}^5}{\mathrm{s}^5\mathrm{pc}^3}\right]$ | $a_{G1}$ $\left[\frac{\mathrm{km}^5}{\mathrm{s}^5\mathrm{pc}^3}\right]$ | $a_{G2}$ $\left[\frac{\mathrm{km}^5}{\mathrm{s}^5\mathrm{pc}^3}\right]$ |
|---|---|---|---|---|---|---|---|---|---|---|
| FIG. 2. | *left* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | *right* | 0 | 0 | 0 | $1.5 \cdot 10^5$ | 0 | 0 | 0 | 0 | 0 |
| FIG. 3. | *left* | $-5$ | 0 | 0 | $1.5 \cdot 10^5$ | 0 | 0 | 0 | 0 | 0 |
| | *right* | 3.3 | 0 | 0 | $1.5 \cdot 10^5$ | 0 | 0 | 0 | 0 | 0 |
| FIG. 4. | *left* | 0 | $-2.5 \cdot 10^2$ | 0 | $1.5 \cdot 10^5$ | 0 | 0 | 0 | 0 | 0 |
| | *right* | 0 | $3.5 \cdot 10^2$ | 0 | $1.5 \cdot 10^5$ | 0 | 0 | 0 | 0 | 0 |

$F = -2.5 * 10^2\ \mathrm{km}^3\mathrm{s}^{-3}\mathrm{pc}^{-3}$




$F = 3.5 * 10^2\ \mathrm{km}^3\mathrm{s}^{-3}\mathrm{pc}^{-3}$

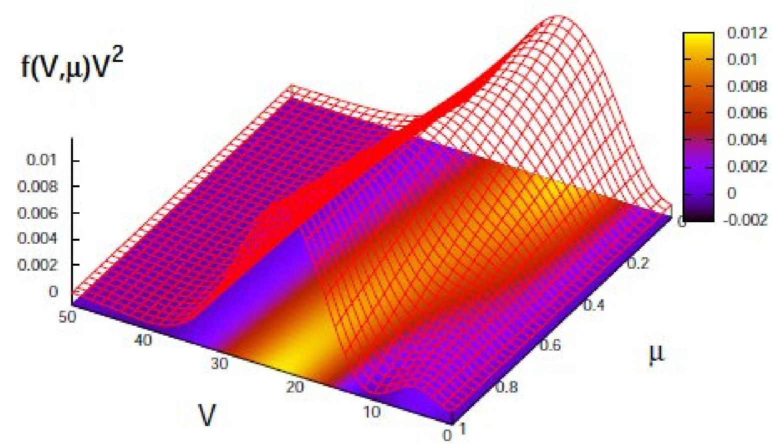



**Figure 4.** VDF with two different values for the third order total moment $F$ corresponding to energy flux. *left:* Shows the effect of negative $F$ on a MB distribution. *right:* The effect of positive $F$ on a MB distribution

## 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*
[2] *Kavli Institute of Astronomy and Astrophysics, Peking University, Beijing, China*
[3] *Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Monchhofsraße 12-14, D-69120 Heidelberg, Germany*
[4] *Center for Gravitational Wave Astronomy, University of Texas at Brownsville, Brownsville, TX 78520, USA*
[5] *Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, ul. Bartycka 18, 00-716 Warsaw, Poland*

## 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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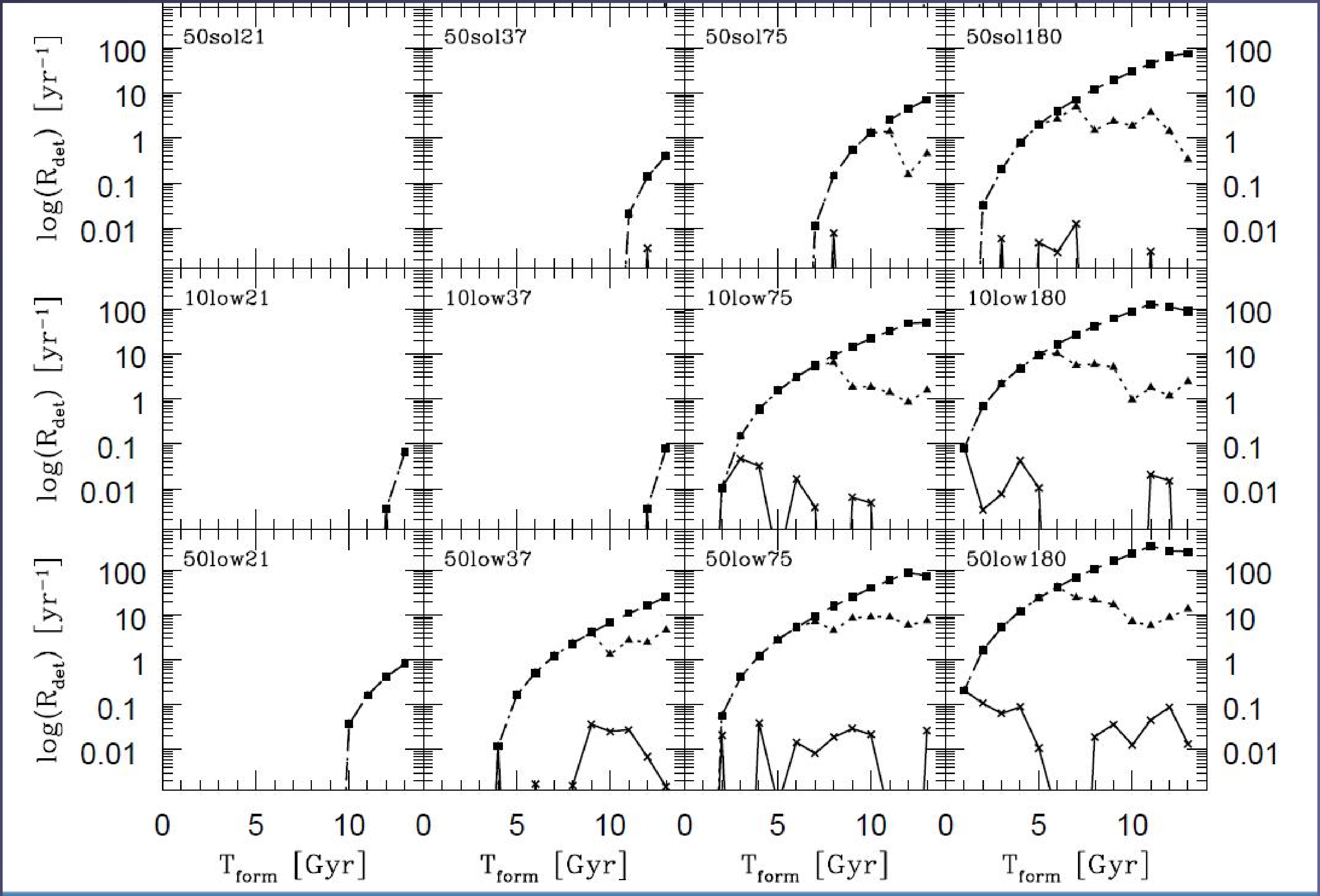
[4] *Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, ul. Bartycka 18, 00-716 Warsaw, Poland*
[5] *National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Rd., Chaoyang District, 100012, China*
[6] *Kavli Institute of Astronomy and Astrophysics, Peking University, Beijing, China*

# Downing et al. 2011



# Theoretical Models II: 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 $\phi$ advanced according to the Poisson equa

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

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

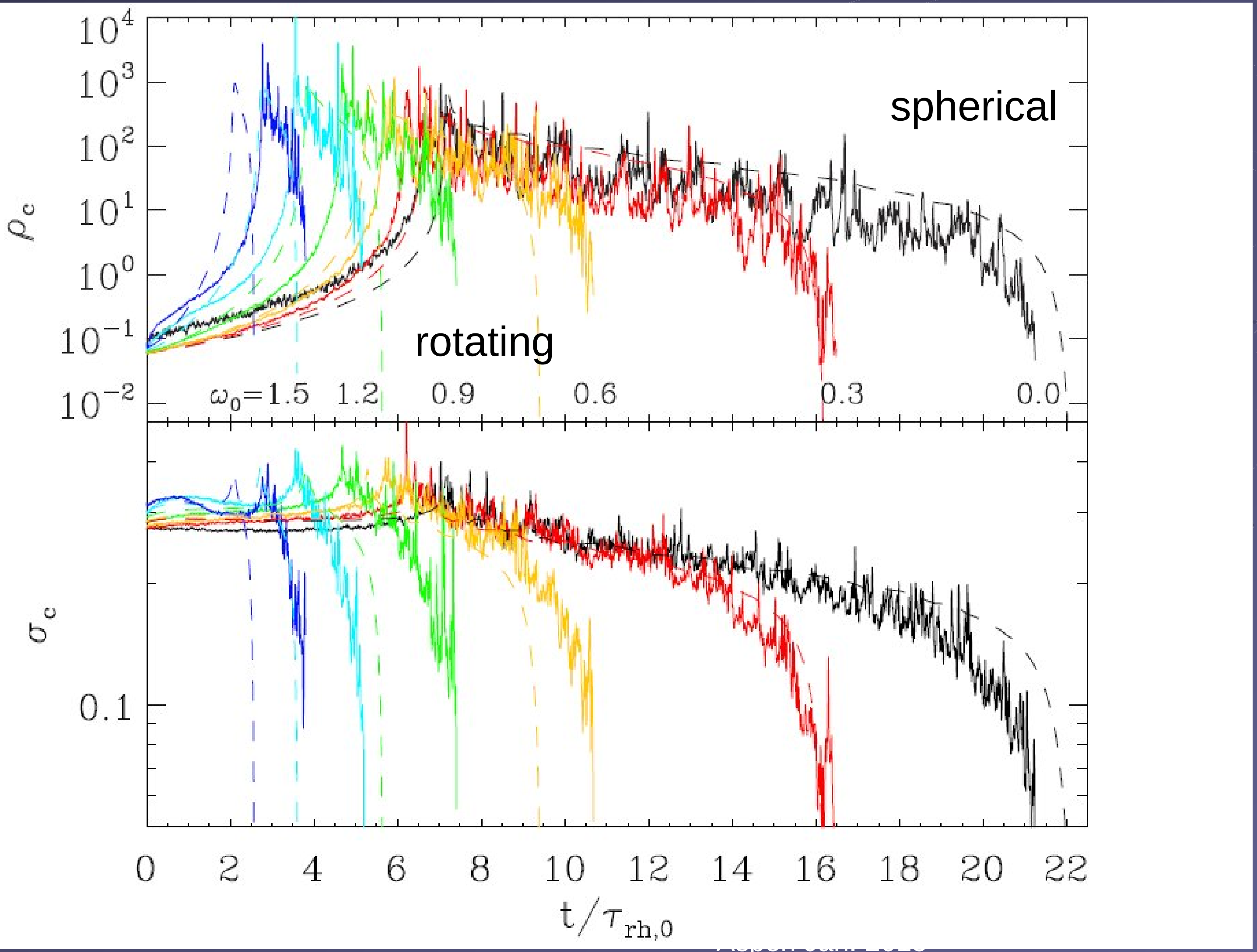
$$\left(\frac{\partial f}{\partial t}\right)_{\rm enc} = \frac{1}{V}\left[-\frac{\partial}{\partial E}(<\Delta E> fV) - \frac{\partial}{\partial J_z}(<\Delta J_z> fV)\right.$$
$$+\frac{1}{2}\frac{\partial^2}{\partial E^2}(<(\Delta E)^2> fV) + \frac{\partial^2}{\partial E \partial J_z}(<\Delta E \Delta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

Orbit averaged Fokker-Planck Equation

(here in the 2D form for axisymm. systems,
Einsel & Spurzem 1999)

# Theoretical Models II: Fokker-Planck

Dissolution of Star Cluster in Tidal Field




Kim, Yoon, Lee, Spurzem, 2008, MNRAS

Hong, Kim, Lee, Spurzem, 2013, MNRAS

Three Phases in Cluster Dissolution:

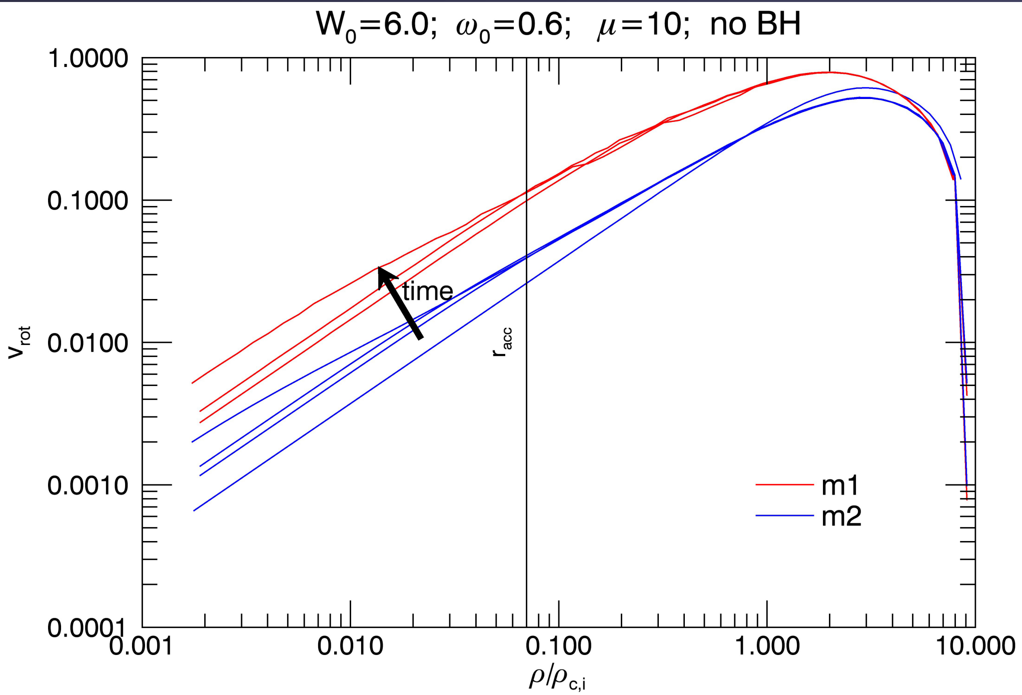
1) Core Collapse (Encounters)

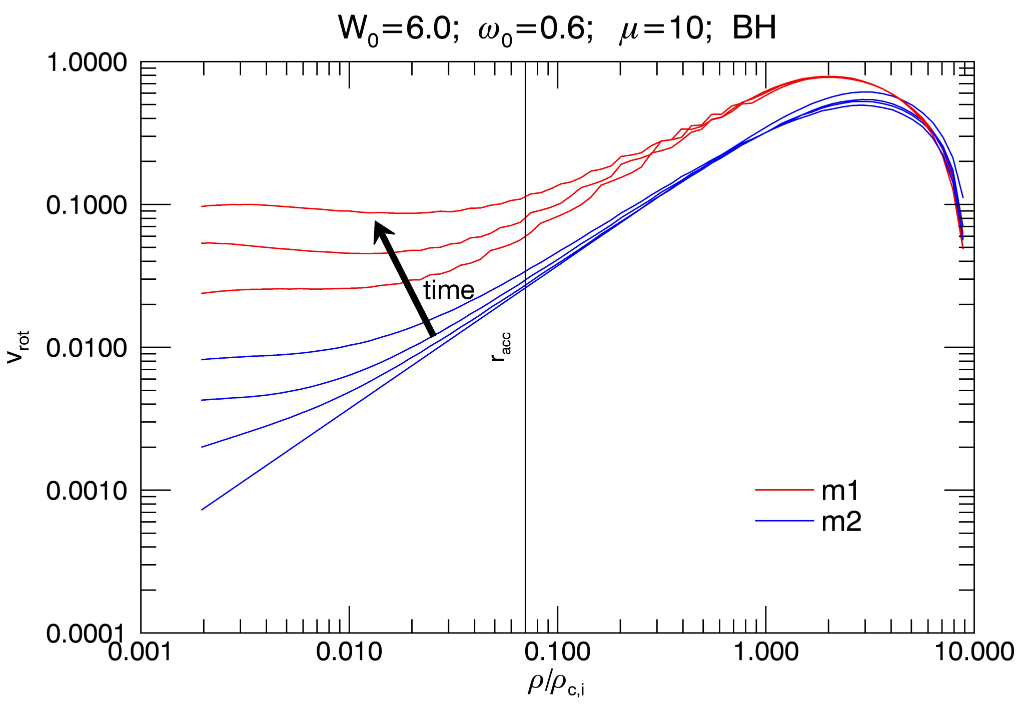
2) Post-Collapse Steady Evaporation (Encount)

3) Dynamic final dissolution

# Star Cluster Simulations – Key Issues

- Theoretical Models / Large N-Body Models
- Black Holes and Tidal Disruption/Star Accretion
- Accelerated Computing (GPU)



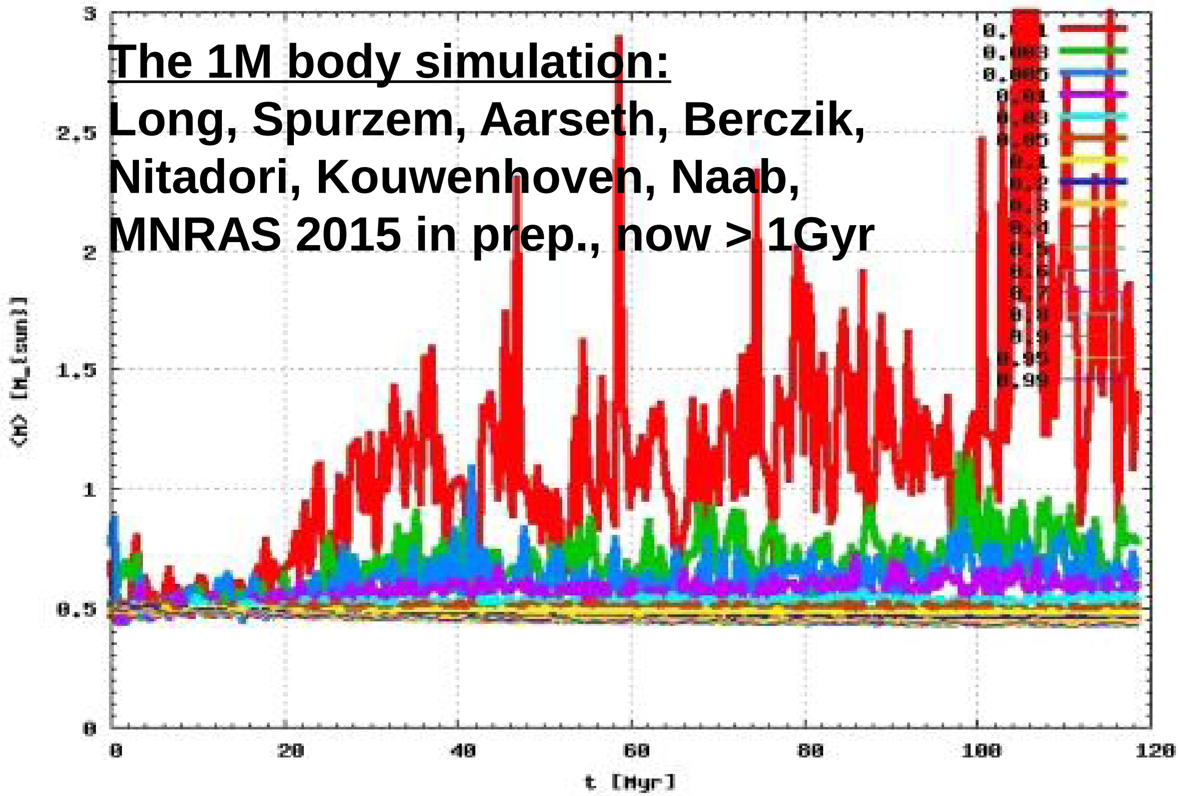

# Theoretical Models II: Fokker-Planck

Fiestas, Preto, Berczik, Spurzem, Lee, 2015 in prep.

**Two Masses, Rotation, with and without black hole**

**N-Body?**

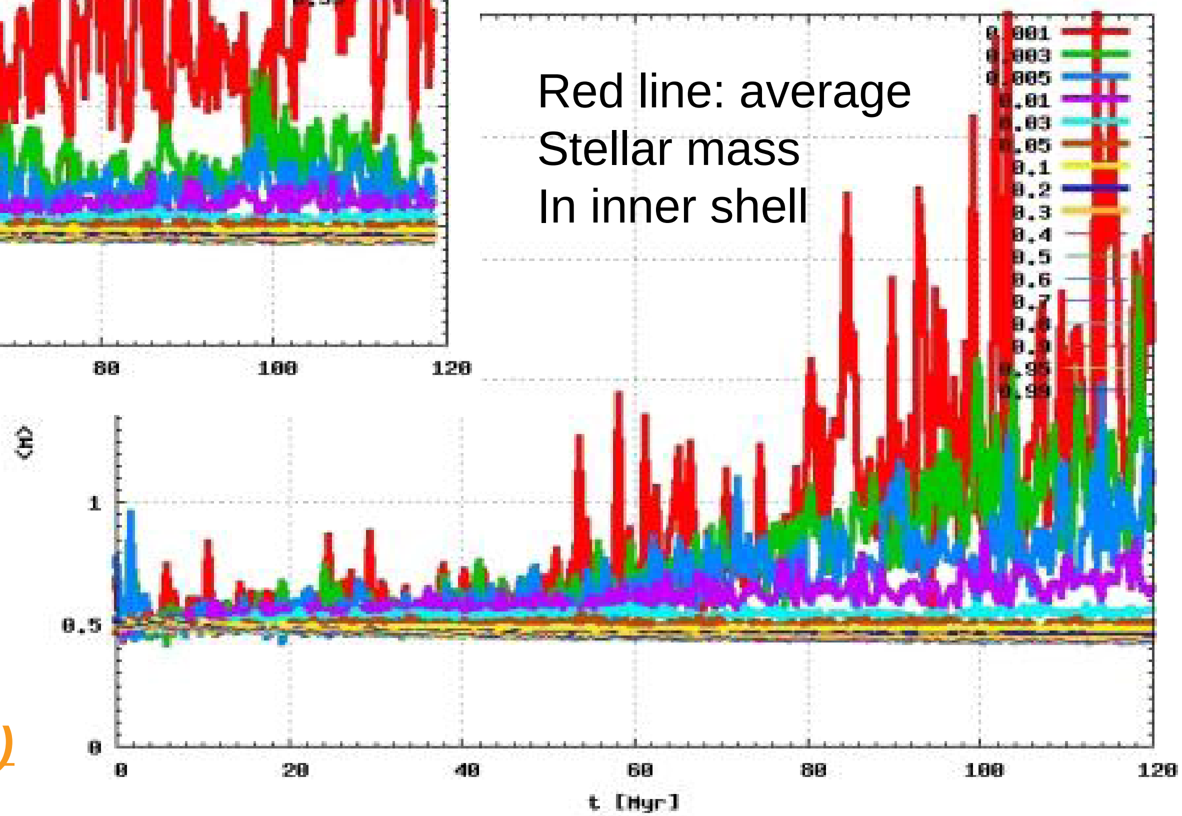
# Intermediate Mass Black Hole?




**<u>The 1M body simulation:</u>**
**Long, Spurzem, Aarseth, Berczik, Nitadori, Kouwenhoven, Naab, MNRAS 2015 in prep., now > 1Gyr**

← without IMBH
Fast mass segregation

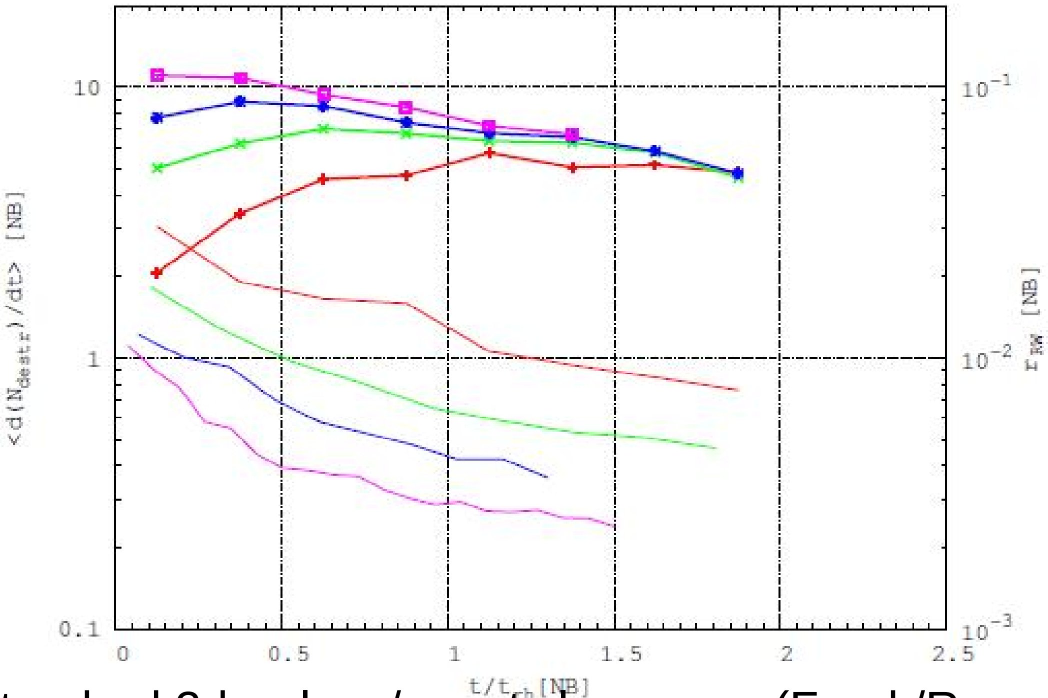
Red line: average
Stellar mass
In inner shell




With IMBH →
Slow mass segregation

***<u>Used RZG Garching hydra GPU cluster (400 Kepler GPUs)</u>***

# Tidal Disruption of Stars in Nuclear Star Clusters around SMBH
# Paper I: Spherical Models




Standard 2-b relax. / empty loss cone (Frank/Rees 76)
works extremely well, in spherical systems...

FIG. 2.— $x$ axis is time expressed in unit of initial half-mass relaxation time($t_{rh}$), left $y$ axis is the averaged disruption rate in a given time range( i.e. 1/4 $t_{rh}$). The unit for disruption rate is number of disrupted stars per unit time. Right $y$ axis is the Brownian motion amplitude. Curves with symbols are TD rate for $r_t = 10^{-3}$, from bottom to top, respond for N=16k,32k,64k and 128k. Curves without symbols shows black hole's Brownian motion amplitude for N=16k,32k,64k and 128k(from top to bottom)

Large N-Body Simulations
phiGPU
**(Zhong, Berczik, Spurzem 2014, ApJ)**

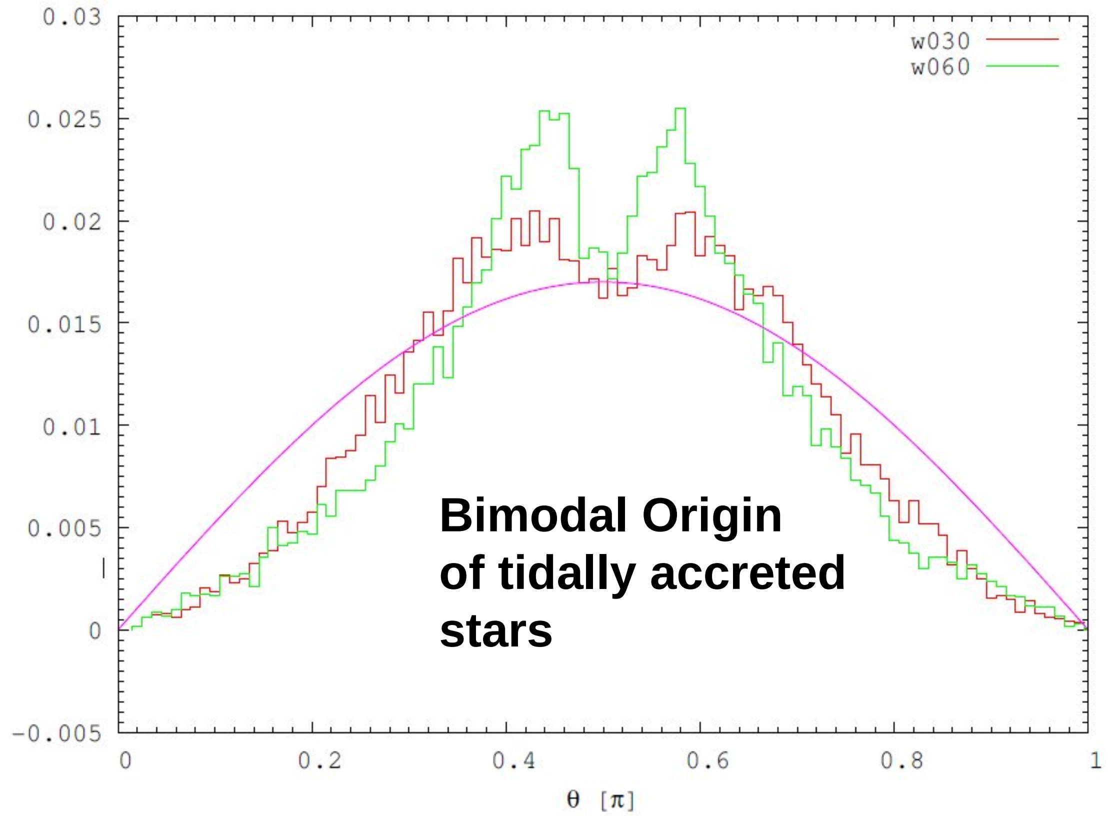
Using

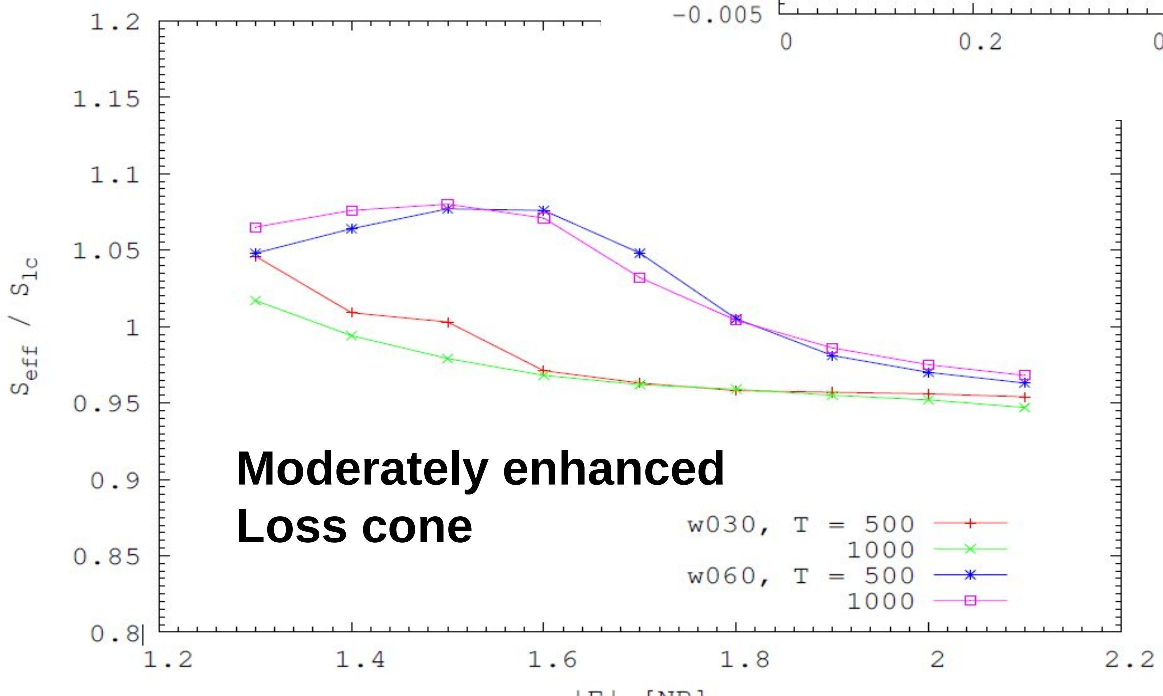
NAOC GPU Cluster

(See also
Li, Liu, Berczik, Chen, Spurzem, 2012)

# Tidal Disruption of Stars in Nuclear Star Clusters around SMBH Paper II: Rotating Axisymmetric Models

Zhong, Berczik, Spurzem, to be subm. MNRAS Feb 2015

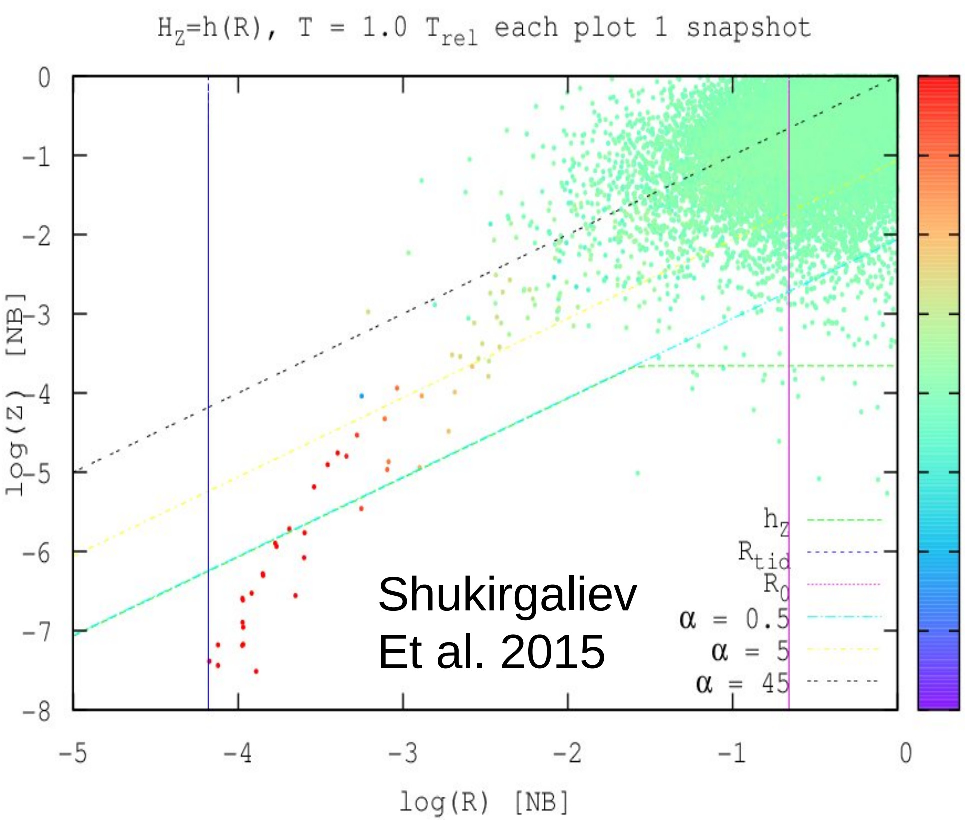


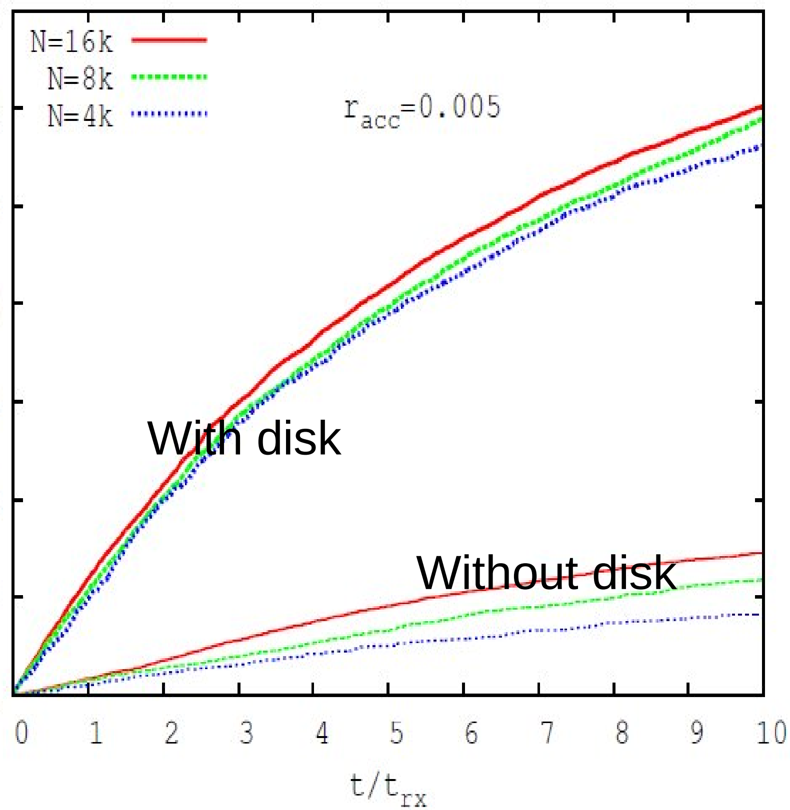



## Star-Disk Interactions enhance tidal accretion rate in star clusters with BH

Just, ... Berczik, Spurzem, ..., 2012, ApJ (Paper I)
Kennedy et al. 2015 in prep. (Paper II)
Shukirgaliev et al. 2015 in prep. (Paper III)

**The presence of an accretion disk near an SMBH enhances the mass growth rate of SMBH by factor 3 and creates a stellar disk.**

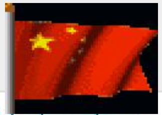
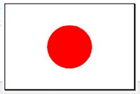


# Star Cluster Simulations – Key Issues

- Theoretical Models / Large N-Body Models
- Black Holes and Tidal Disruption/Star Accretion
- Accelerated Computing (GPU)

# Top 10 List June 2012

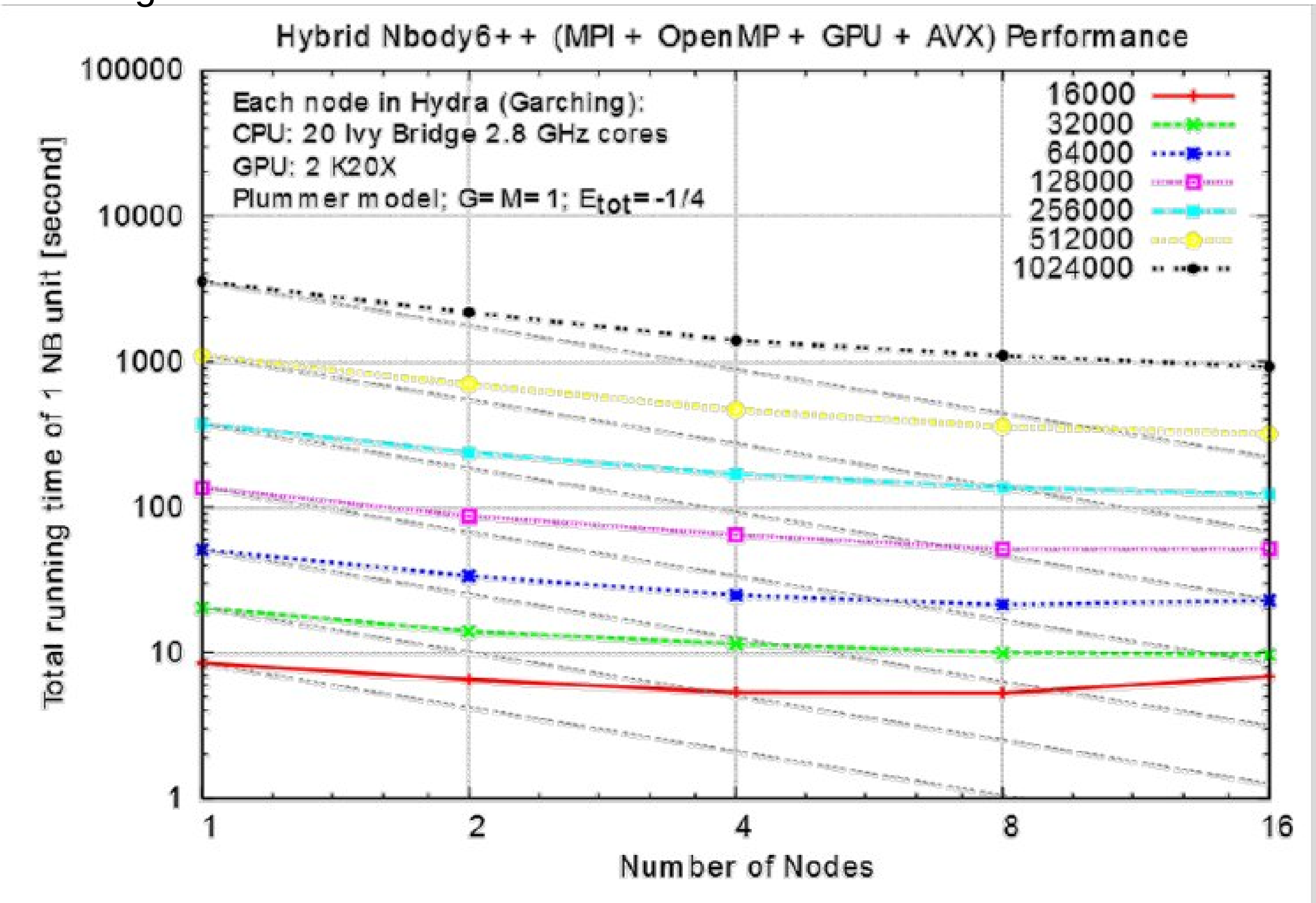
| Rank | Site | System | Cores | Rmax (TFlop/s) | Rpeak (TFlop/s) | Power (kW) |
|---|---|---|---|---|---|---|
| 1 | National University of Defense Technology<br>China  | **Tianhe-2 (MilkyWay-2)** - TH-IVB-FEP Cluster, Intel Xeon E5-2692 12C 2.200GHz, TH Express-2, Intel Xeon Phi 31S1P<br>NUDT<br>***Xeonϕ*** | 3120000 | 33862.7 | 54902.4 | 17808 |
| 2 | DOE/SC/Oak Ridge National Laboratory<br>United States | **Titan** - Cray XK7 , Opteron 6274 16C 2.200GHz, Cray Gemini interconnect, NVIDIA K20x<br>Cray Inc.<br>***GPU*** | 560640 | 17590.0 | 27112.5 | 8209 |
| 3 | DOE/NNSA/LLNL<br>United States | **Sequoia** - BlueGene/Q, Power BQC 16C 1.60 GHz, Custom<br>IBM | 1572864 | 17173.2 | 20132.7 | 7890 |
| 4 | RIKEN Advanced Institute for Computational Science (AICS)<br>Japan  | K computer, SPARC64 VIIIfx 2.0GHz, Tofu interconnect<br>Fujitsu | 705024 | 10510.0 | 11280.4 | 12660 |
| 5 | DOE/SC/Argonne National Laboratory<br>United States | **Mira** - BlueGene/Q, Power BQC 16C 1.60GHz, Custom<br>IBM | 786432 | 8586.6 | 10066.3 | 3945 |
| 6 | Texas Advanced Computing Center/Univ. of Texas<br>United States | **Stampede** - PowerEdge C8220, Xeon E5-2680 8C 2.700GHz, Infiniband FDR, Intel Xeon Phi SE10P<br>Dell<br>***Xeonϕ*** | 462462 | 5168.1 | 8520.1 | 4510 |
| 7 | Forschungszentrum Juelich (FZJ)<br>Germany  | **JUQUEEN** - BlueGene/Q, Power BQC 16C 1.600GHz, Custom Interconnect<br>IBM | 458752 | 5008.9 | 5872.0 | 2301 |
| 8 | DOE/NNSA/LLNL<br>United States | **Vulcan** - BlueGene/Q, Power BQC 16C 1.600GHz, Custom Interconnect<br>IBM | 393216 | 4293.3 | 5033.2 | 1972 |
| 9 | Leibniz Rechenzentrum<br>Germany  | **SuperMUC** - iDataPlex DX360M4, Xeon E5-2680 8C 2.70GHz, Infiniband FDR | 147456 | 2897.0 | 3185.1 | 3423 |

# NAOC laohu cluster


# NBODY6++GPU (Poster Long Wang)

## PERFORMANCE OF HYBRID MPI

Wang et al. subm. MNRAS 2015



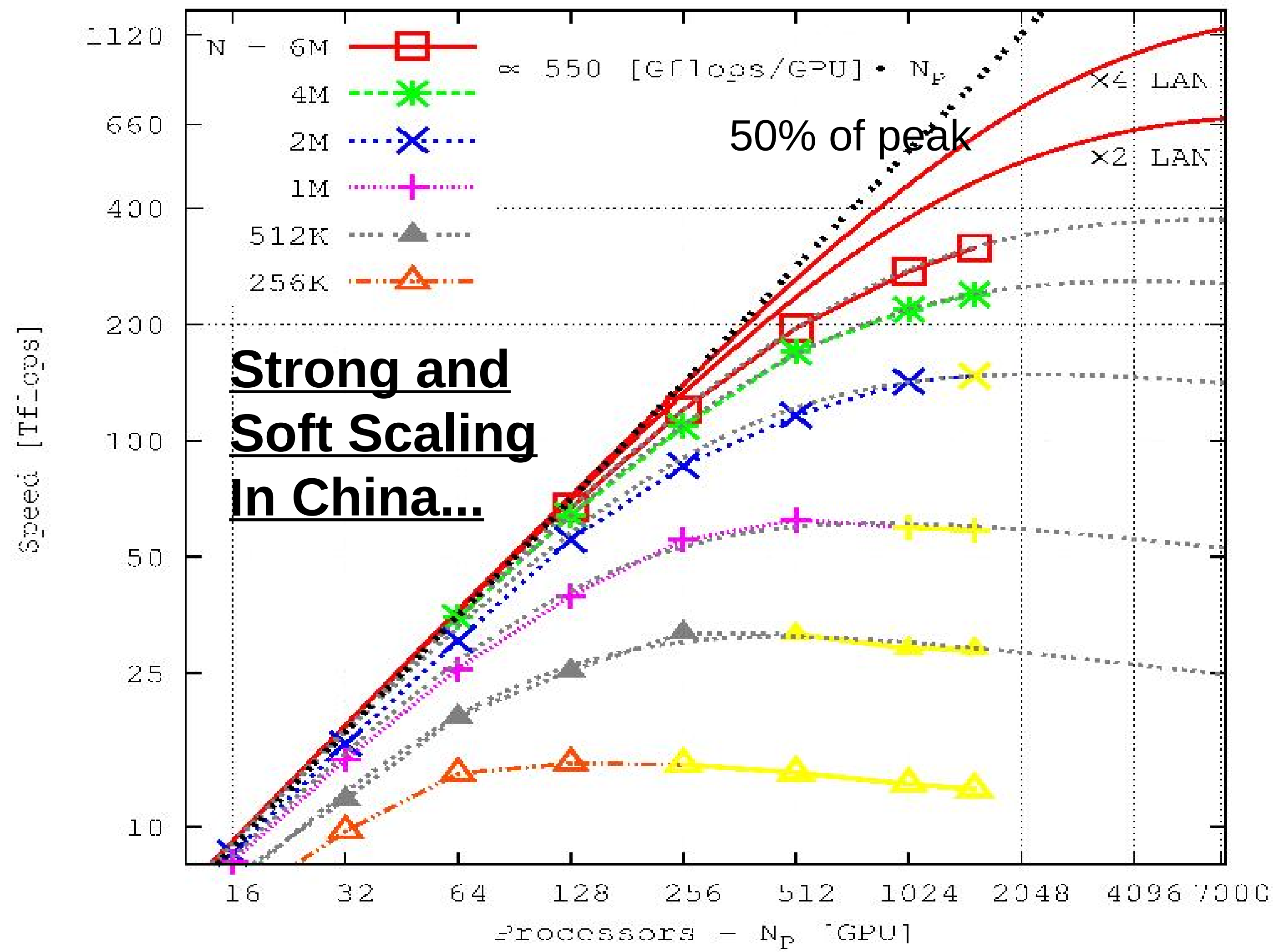
# ΦGPU – NBODY Code

中国科学院国家天文台
National Astronomical Observatories, CAS

350 Teraflop/s
1600 GPUs .
440 cores
= 704.000
GPU-Cores

Using
Mole-8.5
of
IPE/CAS
Beijing

Spurzem et al.
2013, Lect.
Notes Comp.
Phys., Springer






中国科学院过程工程研究所
Institute Of Process Engineering, Chinese Academy Of Sciences

# Summary/Future

- **Astrophysical High Precision N-Body -**
- **Data Mining for million body simulations**
- **Rotation compare with theory**
- **Binaries, Collision Products**
- **Tidal Star Accretion with Black Hole**

- **Some More Astrophysical Science Drivers:**

**GW Sources in Star Clusters / Gal. Nuclei**
**No Evidence of Stalling of Binary Black Holes -**
**Coalescence in 0.1 – 1.0 Gyrs in full simulation**