The Link Between Ejected Stars, Hardening and Eccentricity Growth of Super Massive Black Holes in Galactic Nuclei

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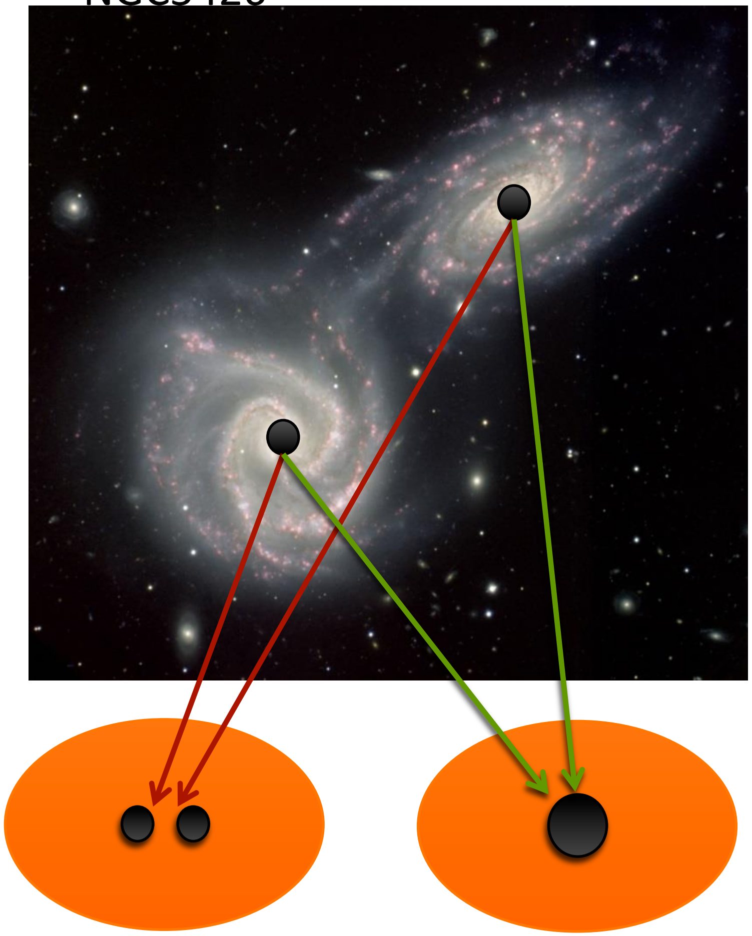
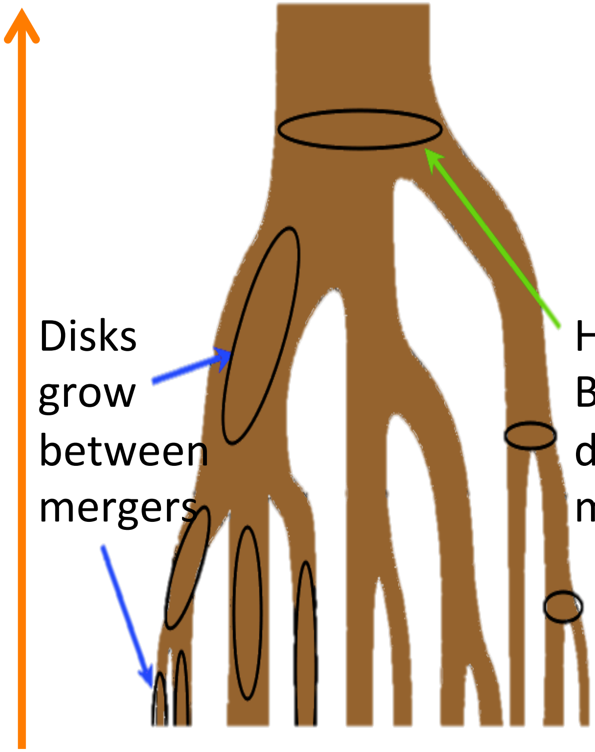
Galaxy Mergers

NGC5426





Merger Tree

Time

Disks grow between mergers

Halos & Bulges grow during mergers

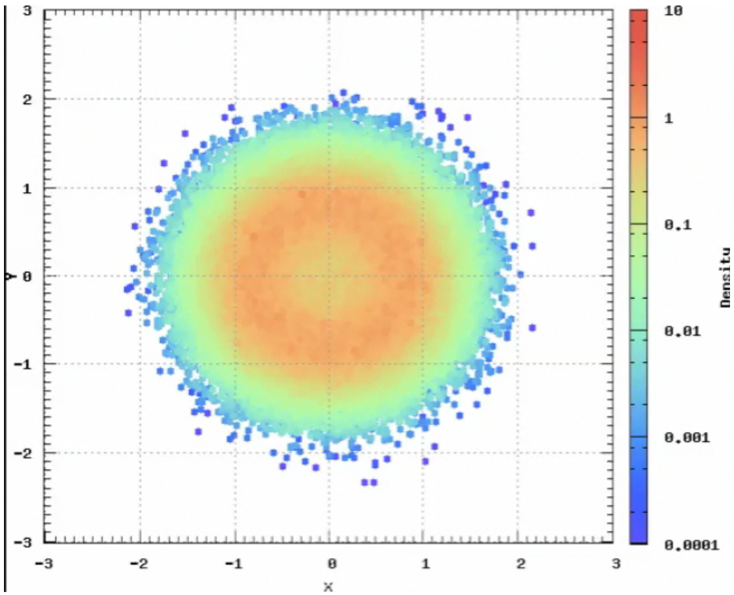
http://www.astro.virginia.edu/class/whittle/astr553/Topic02/Lecture_2.html

Three Phases Evolution

- Three Phases (Begelman et al. 1980).
  - Dynamical friction (Merritt 2001; Yu 2002)

$$t_{df} \sim \frac{4\times10^{6}}{\log N}\left(\frac{\sigma_*}{200km/s}\right)\left(\frac{r_*}{100pc}\right)^{2}\left(\frac{10^{8}M_{sun}}{m_{BH}}\right)yr$$

  - Three body interactions (Quinlan 1996)
  - Gravitational Waves Radiation (Peters 1964)



$$a_h \approx G\mu/4\sigma_*^2 \approx 10^{-3} - 0.1pc$$

$$t_{merge} \sim \frac{3}{85}\frac{c^5a^4}{G^3\mu M_{BH1,2}^2}\left(1-e^2\right)^{7/2} \sim 10^7\left(\frac{a}{0.01pc}\right)^4\left(\frac{10^8M_{sun}}{m_{BH1}}\right)^3\left(1-e^2\right)^{7/2}\frac{m_{BH1}^2}{m_{BH2}M_{BH1,2}}yr$$

Final Parsec Problem

- Low efficient three body interaction
  - In merger of gas-poor galaxies
  - Spherical stellar environment

- Solution:
  - Axisymmetry(rotation) & triaxiality of galactic nuclei
    - (Yu 2002; Merritt & Poon 2004; Berczik et al. 2006; Preto et al. 2011; Fiestas et al. 2012; Gualandris & Merritt 2012; Khan et al. 2012b, 2013)
  - High initial eccentricity of Massive black hole binary (MBHB)
    - (Aarseth 2003; Berentzen et al. 2008, 2009a; Preto et al. 2009, 2011; Khan et al. 2011; Li et al. 2012)
    - Co-rotating and counter-rotating stars around MBHB (Zier & Biermann 2001, 2002; Iwasawa et al. 2011; Sesana et al.2011; Meiron & Laor 2013)

Ejecting stars in large N-body simulations

- Ejecting stars carry away energy and angular momentum of MBHB during three body interaction phase.

- One million N-body simulation of galactic nuclei with MBHB
  - Phi-GPU code (Berczik et al. 2011) in laohu (NAOC) & Milkyway (Juelich SC)

- Rotating King Model (Einsel et al 1999)
  - $f(E,J_z) \sim (e^{\beta E}-1)e^{-\beta\Omega_0 J_z}$

$$\omega_0 = \sqrt{9/4\pi G n_c}\,\Omega_0 \qquad W_0 = -\beta m(\phi - \phi_t)$$

Initial conditions

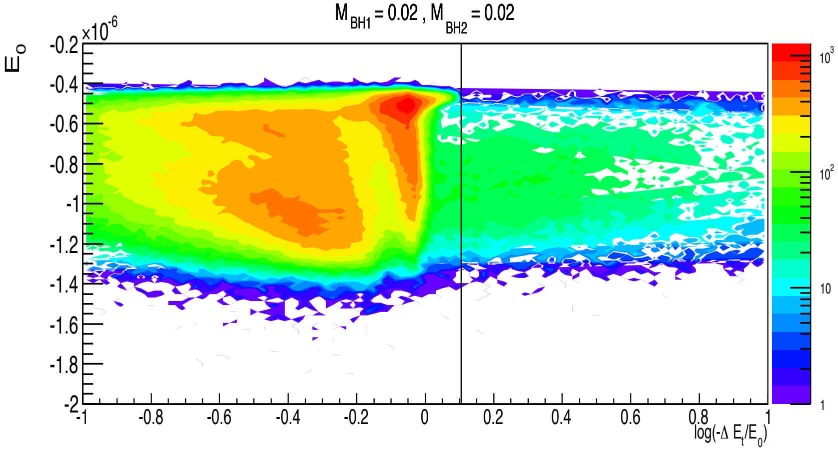
- King parameters: W0 = 0.6 ω0 = 1.8 / 0.0
- Scaling Free: E = -1/4; G = 1; Mtot = 1
- Initial MBHB: vcirc = 0.7; seperation: 0.6 at the center

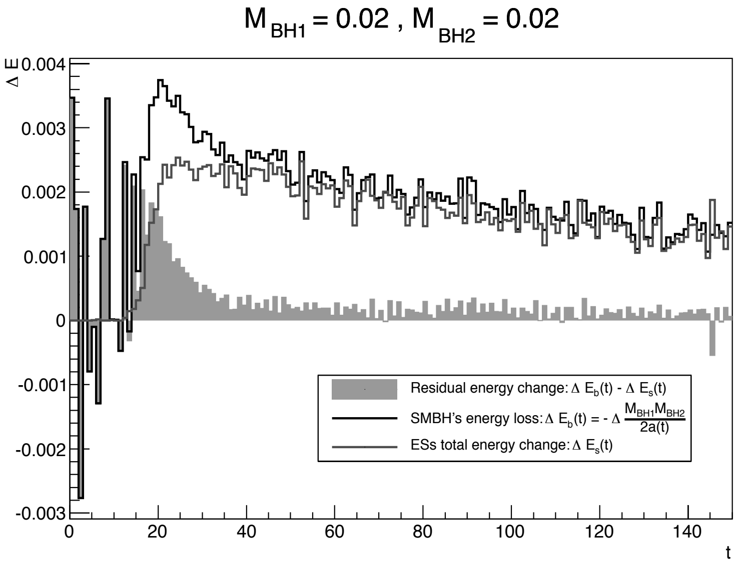
Model	**0110**	**0210**	**0510**	**1010**	**2020**	**4020**	**4040**
M_{BH1}	0.01	0.01	0.01	0.01	0.02	0.04	0.04
M_{BH2}	0.001	0.002	0.005	0.01	0.02	0.02	0.04

- End time: 150

Example:	$\mathbf{M_{BH}}$	**R**	**T**	**V**
Nbody Unit	0.01	0.6	150	0.7
Astro. Unit	$10^7 M_\odot$	600 pc	2.25 Gyr	46 km/s

Ejected star selection

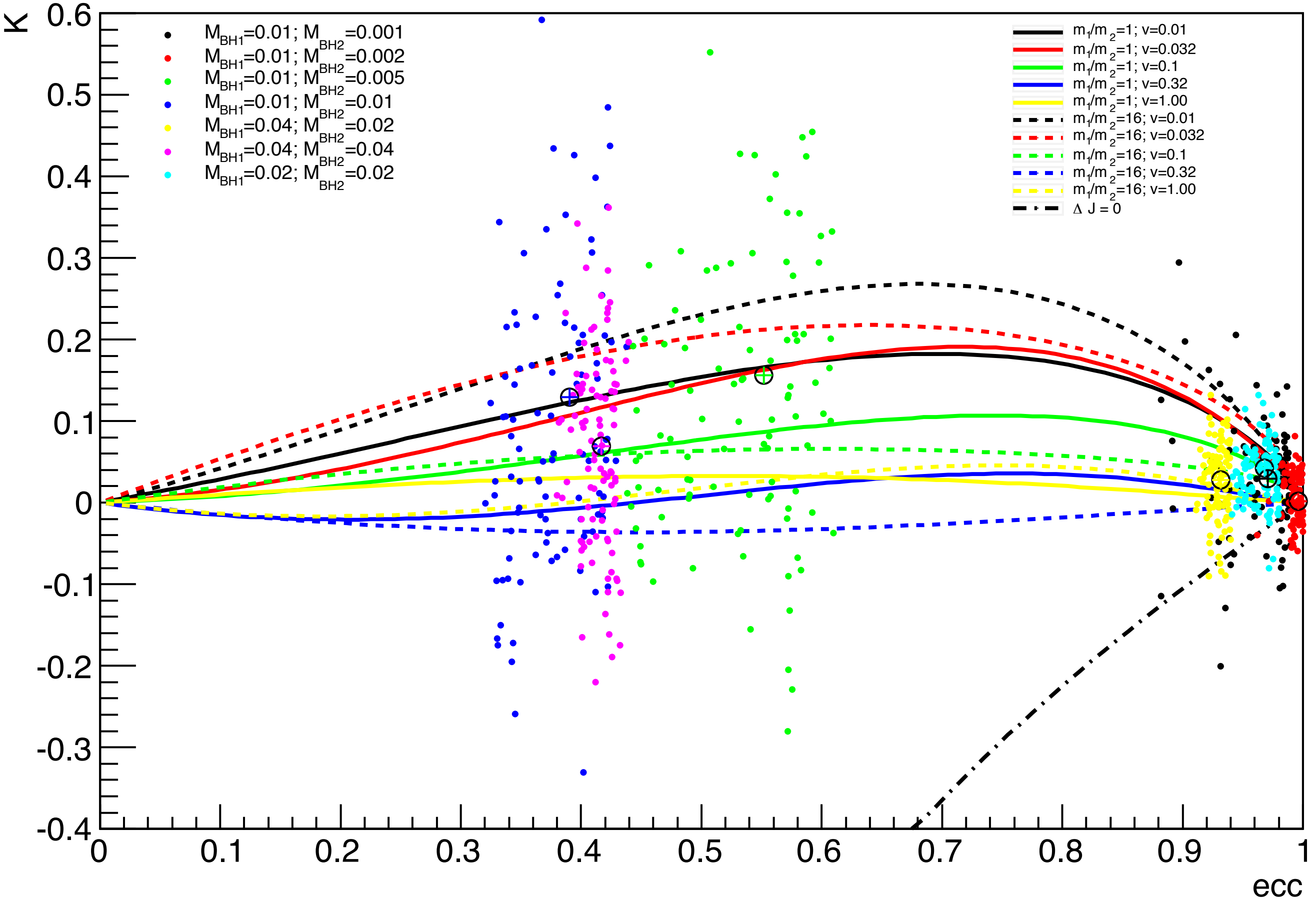




Ejected star samples

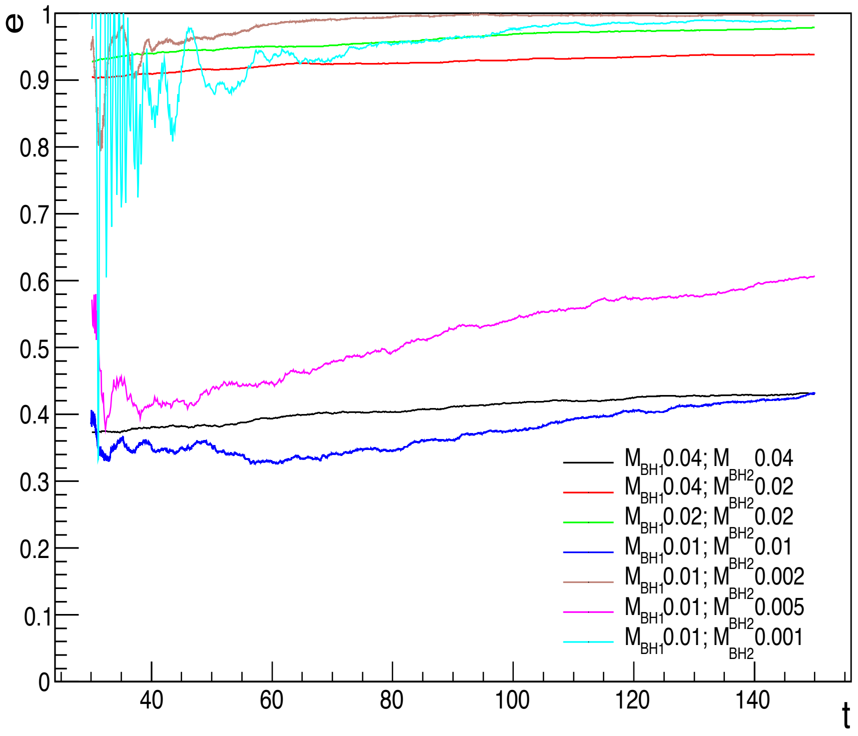
Model	**0110**	**0210**	**0510**	**1010**	**2020**	**4020**	**4040**
N_{EJ}	863	3457	10203	16656	40288	57596	83367
N_{EJ}/N_{TOT}(%)	0.086	0.34	1.02	1.67	4.03	5.76	8.34

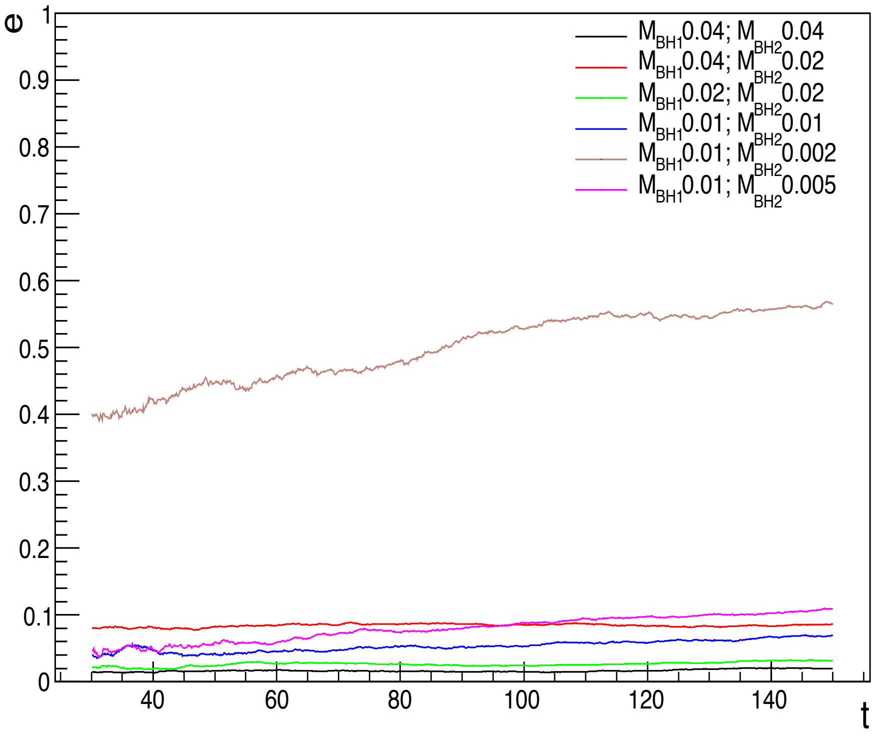
Results – eccentricity evolution



$$K = \frac{\Delta e}{\Delta \ln(1/a)}$$

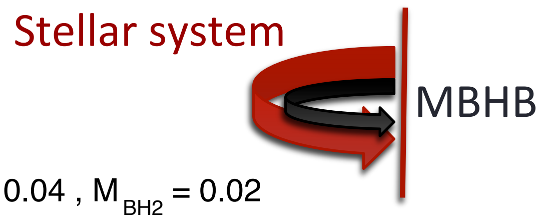
Results – eccentricity evolution


Rotating models

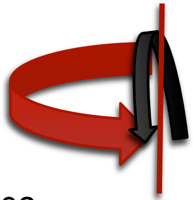

Non-rotating models

MBHB angular momentum evolution

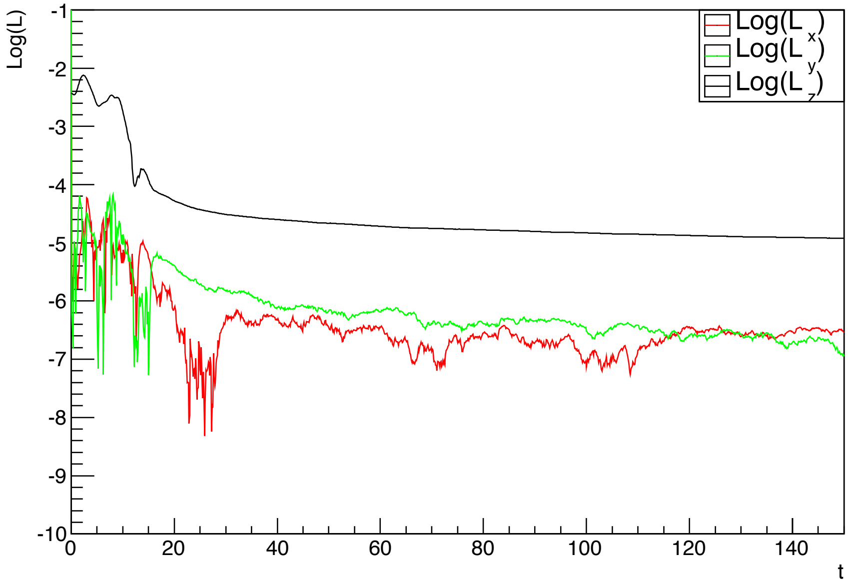
β ~ 0°



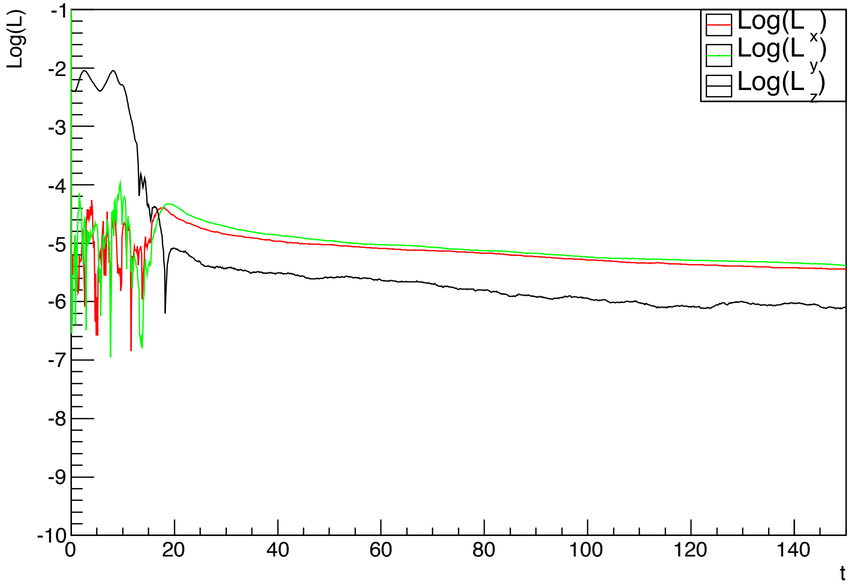
β >> 0°



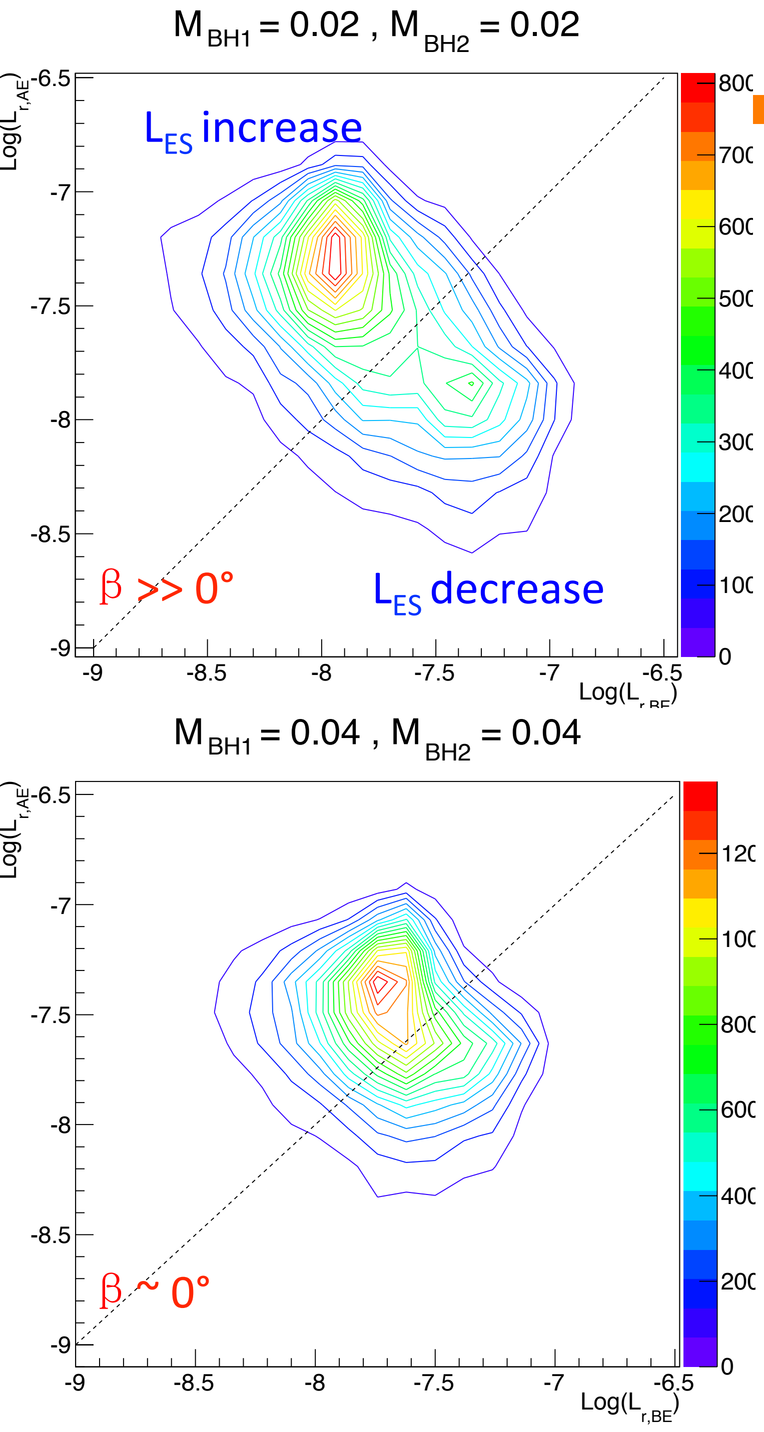
$M_{BH1} = 0.04$, $M_{BH2} = 0.02$



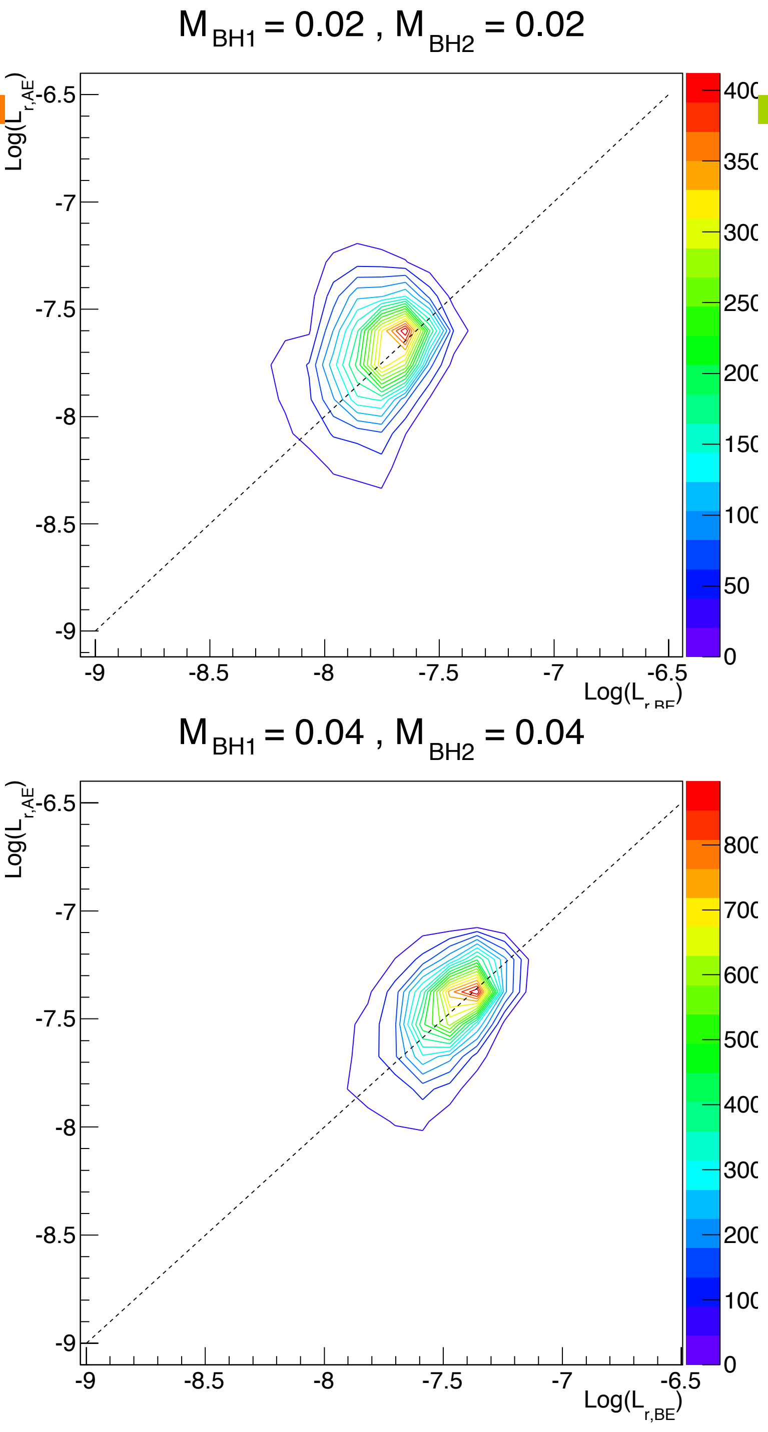
$M_{BH1} = 0.02$, $M_{BH2} = 0.02$



β: Inclination angle between MBHB orbit plane and stellar rotating plane



Rotating models

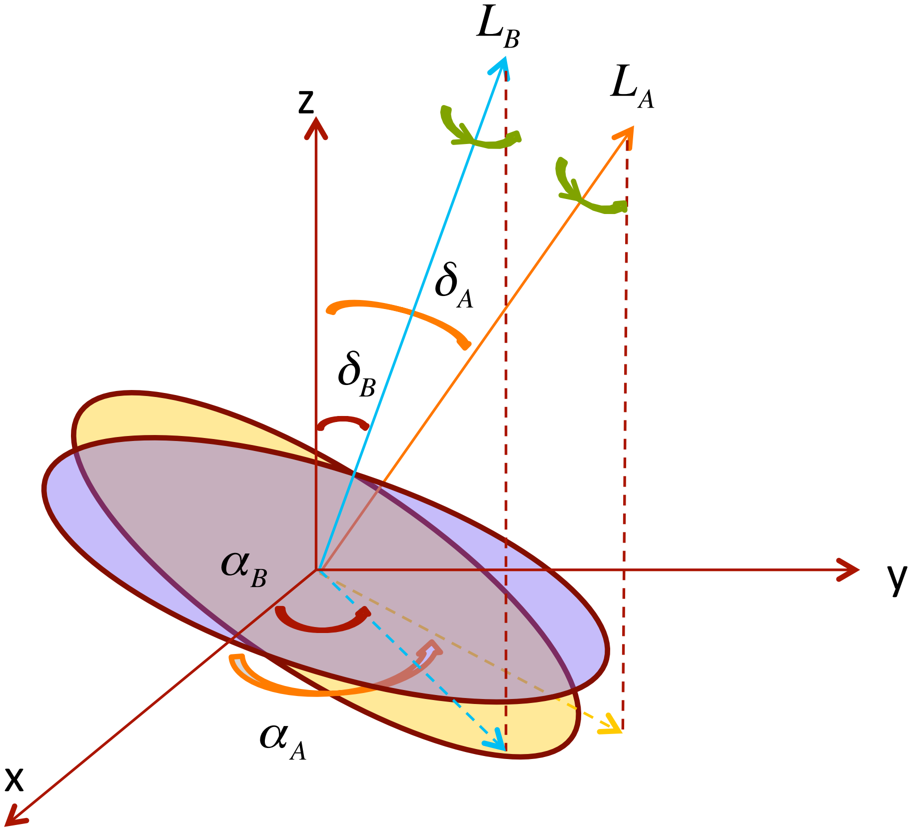


Non-rotating models

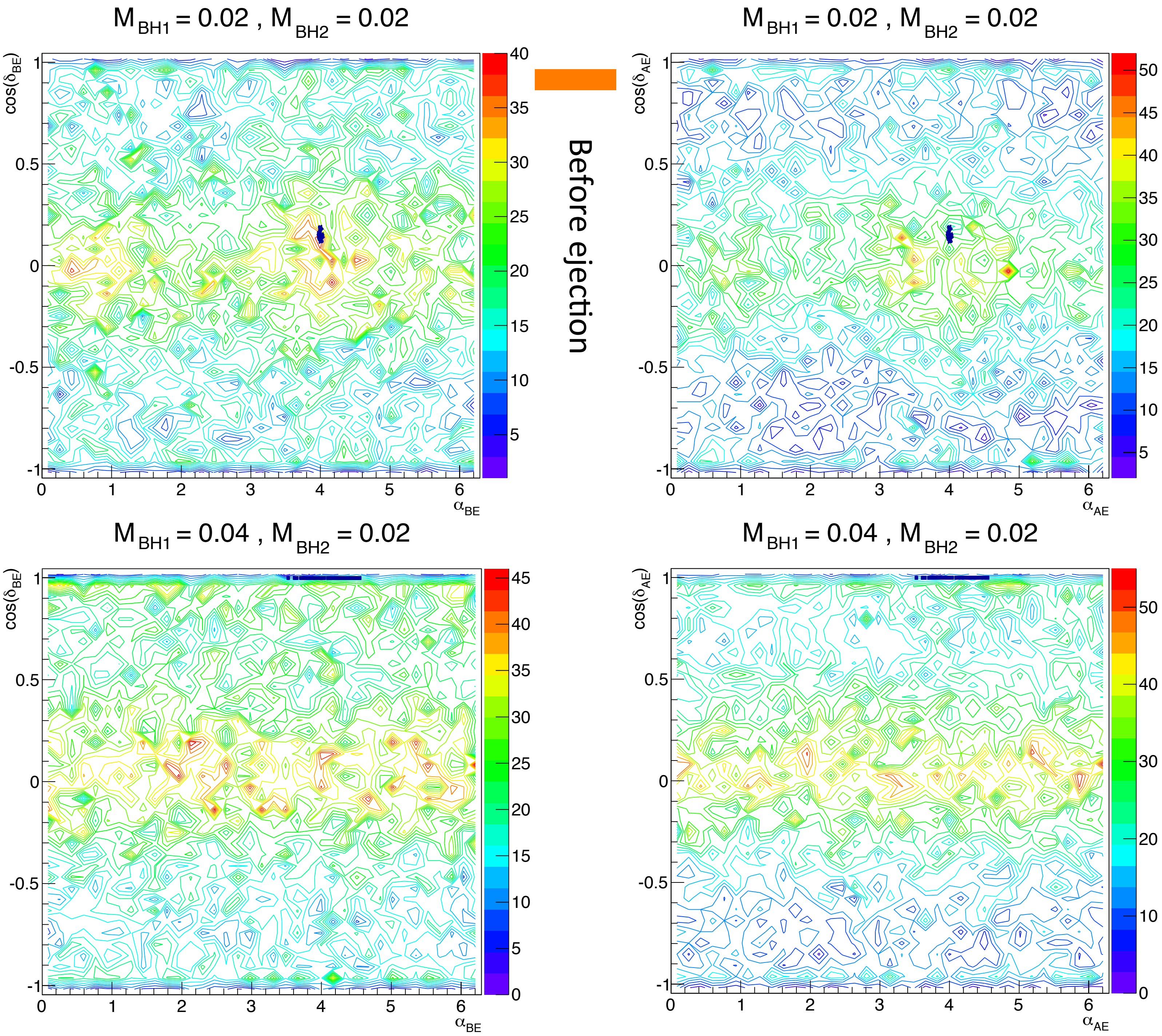
Ejected star angular momentum change

Angular momentum angle distribution

- Spherical coordinate
  - Stellar disk plane: plane
  - Two angles denotes directions of Angular momentum
    - : in plane
    - : from to
  - Two pairs of for ESs & MBHs
    - Before ejection
    - After ejection



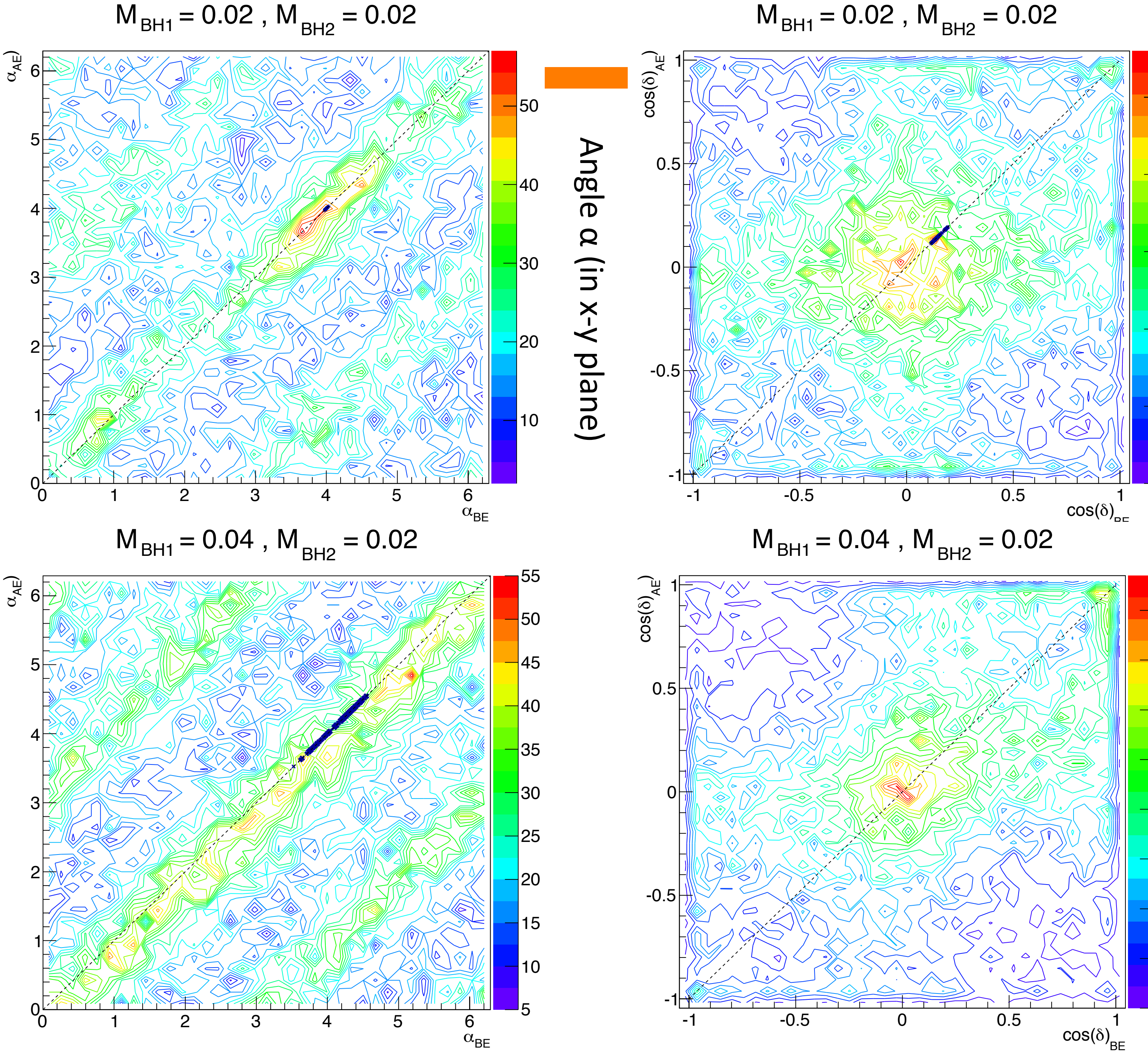
Ejecting star angular momentum angle distribution



Before ejection

after ejection

Ejecting star angular momentum angle distribution



$M_{BH1} = 0.02$, $M_{BH2} = 0.02$

$M_{BH1} = 0.02$, $M_{BH2} = 0.02$

$M_{BH1} = 0.04$, $M_{BH2} = 0.02$

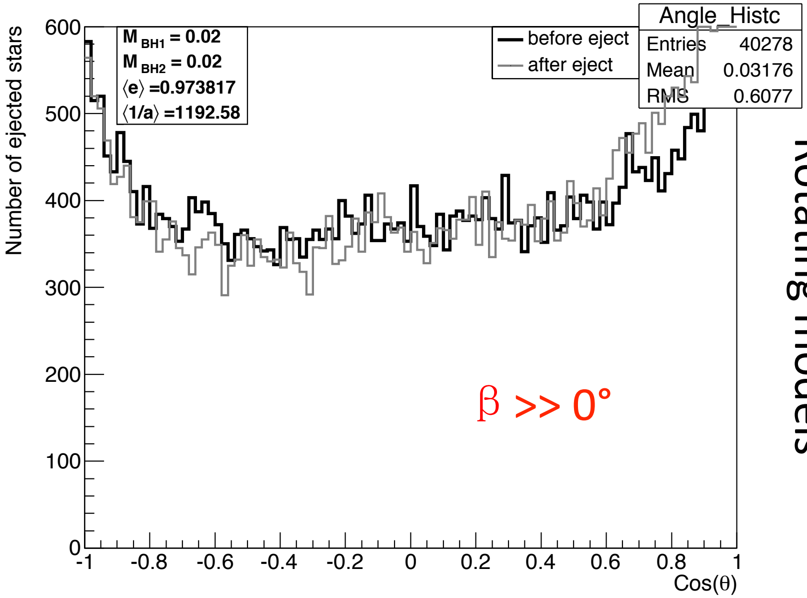
$M_{BH1} = 0.04$, $M_{BH2} = 0.02$

🟧 Angle α (in x-y plane)

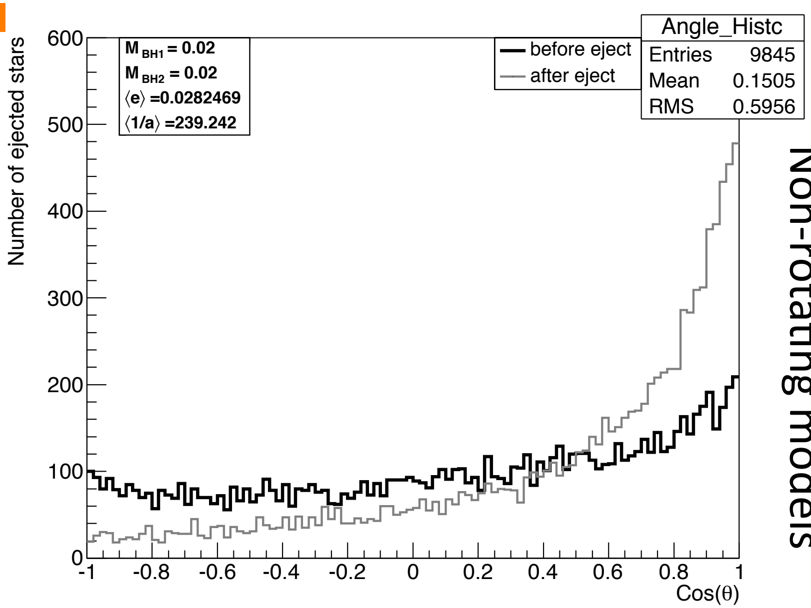
🟩 Angle δ (from z to x-y plane)

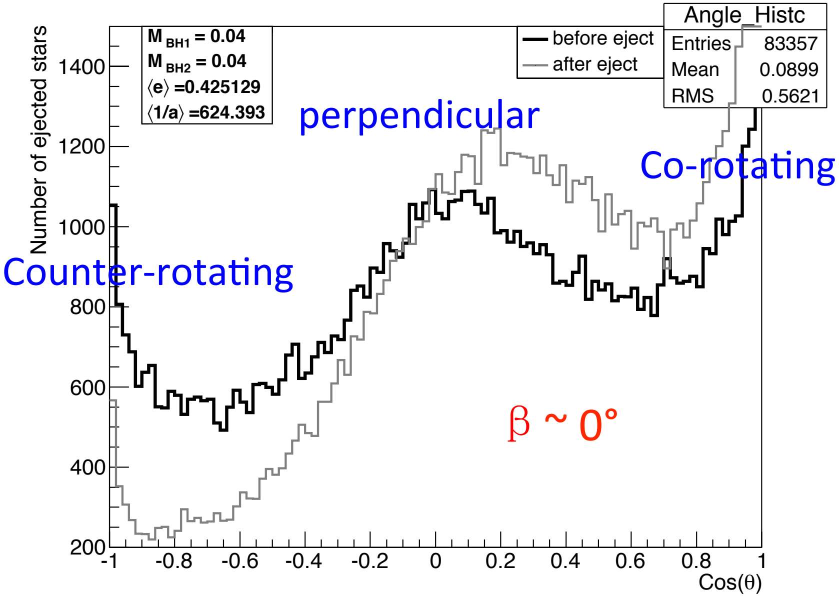
Ejecting star angular momentum angle distribution

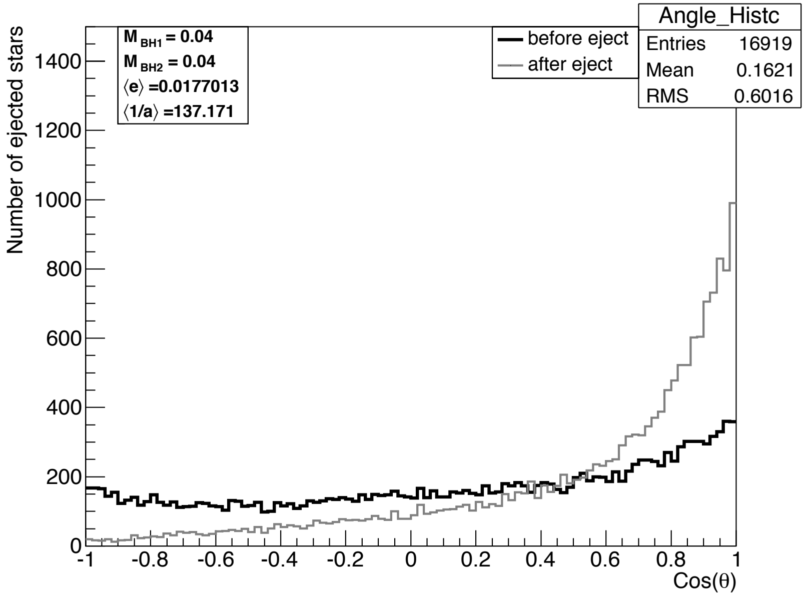
Rotating models



Non-rotating models







Conclusion

- 0.08% - 8% of stars are ejected by MBHBs in 1M N-body simulations with 150 N-body time unit (~2Gyr).
- Eccentricity of MBHB grows in a stochastic way, where positive and negative K occur all the time, but there is an average trend towards higher eccentricity.
- In rotating model:
  - The angular momentum of ejected stars tend to whether increase or decrease after interaction.
  - the ejected stars tend to have co/counter-rotating orbit with MBHB or perpendicular orbit to stellar system.
- In non-rotating model
  - The angular momentum of ejected stars tend to be constant after interaction.
  - there is only the trend that ejected stars prefer co-rotating orbit with MBHB.
- MBHBs tend to switch stars with counter-rotating orbits into co-rotating orbits during their interactions.

Star cluster simulations with Nbody6++ & GPU

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Star cluster dynamics

Observations (Simon F. 2010)

Cluster	**Age**	**M**	**R_{vir}**	**ρ_c**	**Z**	**Location**	**t_{dyn}**	**t_{rh}**
Unit	Gyr	$M_\odot$	pc	$M_\odot/pc^3$	$Z_\odot$		Myr	Myr
OC	≤ 0.3	$\leq 10^3$	1	$\leq 10^3$	~ 1	disk	~ 1	≤ 100
GC	≥ 10	$\geq 10^5$	10	$\geq 10^3$	< 1	halo	≥ 1	≥ 1000
YMC	≤ 0.1	$\geq 10^4$	1	$\geq 10^3$	≥ 1	Galaxy	≤ 1	≤ 100

$$t_{dyn} = \left(\frac{GM}{r_{vir}^{3}}\right)^{-1/2} \qquad t_{rh} = 0.138\frac{N^{1/2} r_h^{3/2}}{\langle m\rangle^{1/2} G^{1/2} \ln\Lambda}$$

$\Lambda \sim 0.11N$ for equal mass system

Λ smaller for large mass range

(Spitzer, 1987)

Galaxies: collisionless system; Star cluster: collisional system

Star cluster dynamics

- **Star cluster**
  - Galaxy formation
  - Star formation
  - Massive star/ Compact objects
  - Distance measurement

Observations (Simon F. 2010)

Cluster	**Age**	**M**	R_{vir}	ρ_c	**Z**	**Location**	t_{dyn}	t_{rh}
Unit	Gyr	$M_\odot$	pc	$M_\odot/pc^3$	$Z_\odot$		Myr	Myr
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GC	≥ 10	$\geq 10^5$	10	$\geq 10^3$	< 1	halo	≥ 1	≥ 1000
YMC	≤ 0.1	$\geq 10^4$	1	$\geq 10^3$	≥ 1	Galaxy	≤ 1	≤ 100

- Numerical simulation need to consider encounter and primordial binary effects

Encounters & Binaries

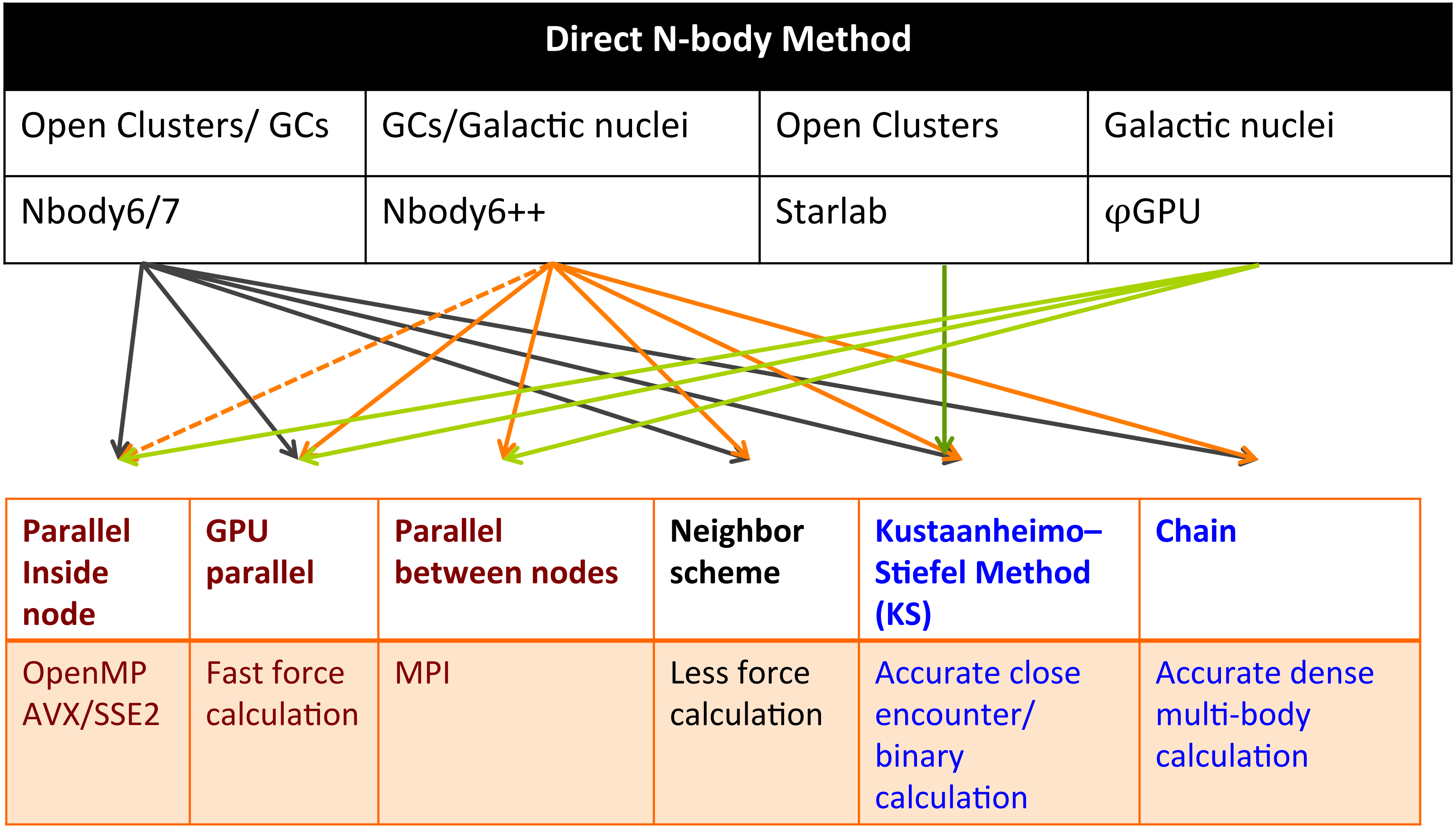
Binney & Tremaine 2008

- Relaxation: loss memory
- Equipartition: mass segregation
- Escape: disruption of clusters
- Inelastic encounters: massive stars (Blue stragglers) formation
- Triple encounters: binary formation
- Interactions with primordial binaries: high binding energy of binaries transform to energy of cluster

Numerical methods

	Fluid Dynamics	Monte Carlo/Fokker-Planck	Direct N-body
Advantages	Easy to use methods from fluid dynamics	1. Very Fast 2. Include encounter effects	1. Very accurate 2. No assumption of dynamical process 3. All dynamical information
Disadvantages	Ignore the free path difference	1. Assume spherical symmetry 2. Assume velocity distribution for perturbations 3. Cannot resolve individual objects	

N-body Method



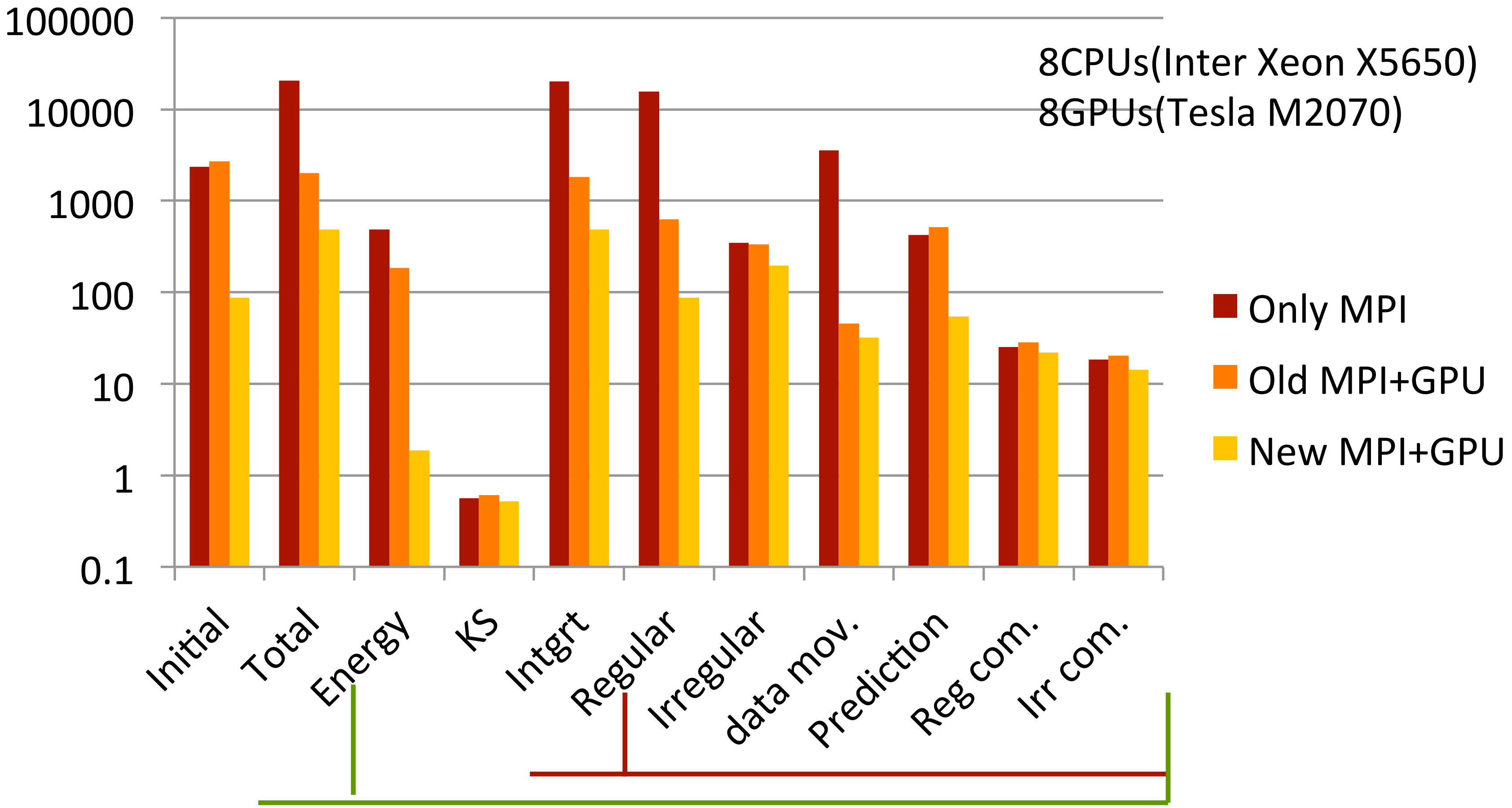
Direct N-body Method			
Open Clusters/ GCs	GCs/Galactic nuclei	Open Clusters	Galactic nuclei
Nbody6/7	Nbody6++	Starlab	φGPU

Parallel Inside node	**GPU parallel**	**Parallel between nodes**	**Neighbor scheme**	**Kustaanheimo–Stiefel Method (KS)**	**Chain**
OpenMP AVX/SSE2	Fast force calculation	MPI	Less force calculation	Accurate close encounter/ binary calculation	Accurate dense multi-body calculation

Speed challenge

- Time requirement for Long-term 1M particle simulation
  - Typical scale factor (G=M=1, E=-0.25)
    - Plummer model, R_{vir}=1pc
    - Salpeter IMF a=2.3, $M_{max}=10M_\odot$, $M_{max}=0.1M_\odot$
    - 1Myr ~ 50 N-body time unit
  - 10Gyr simulation within one Month:
    - $\langle T_{1NB} \rangle = 5s$

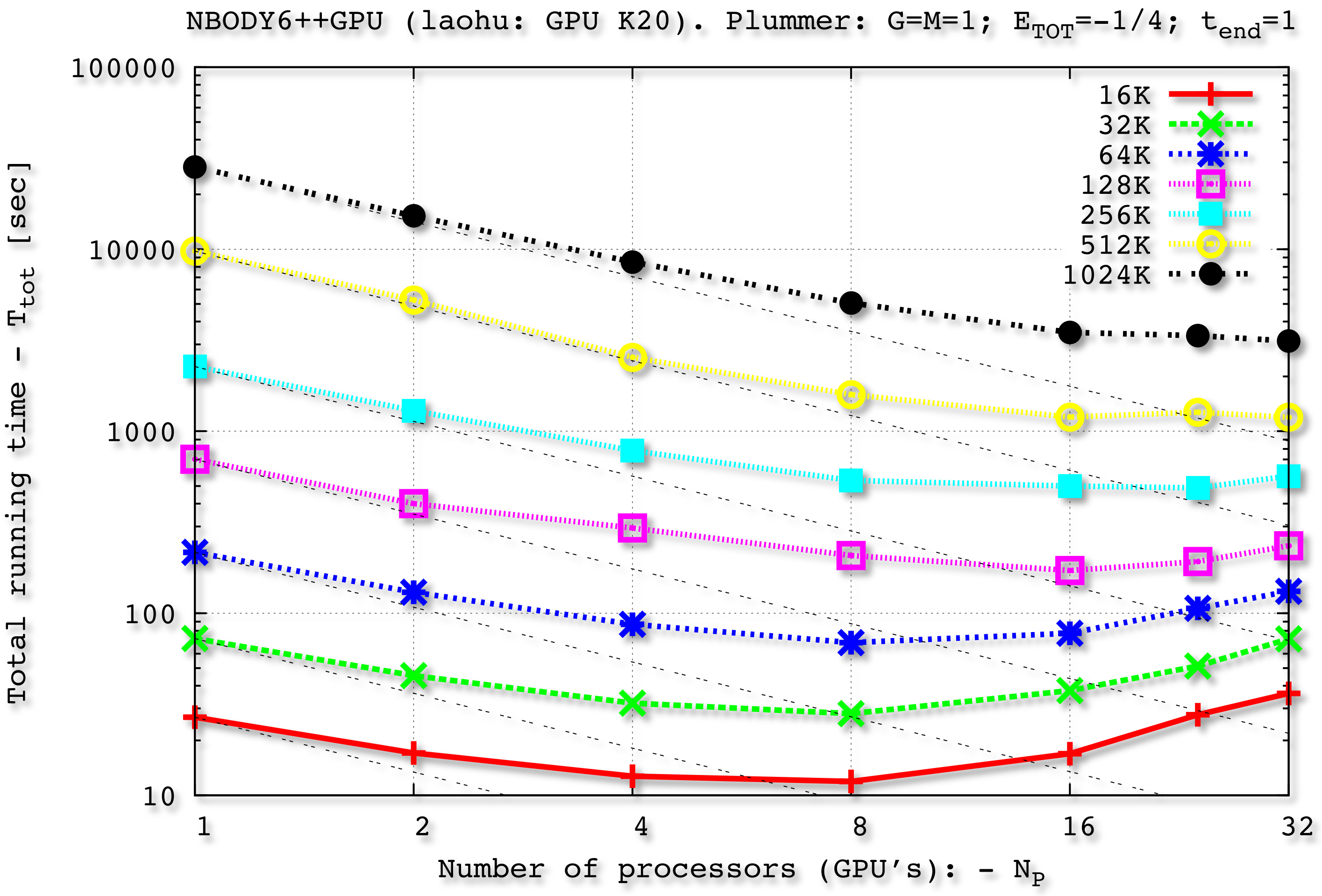
Recent Improvements for MPI+GPU



256k single star, 1 NB time unit, in Milkyway computer cluster

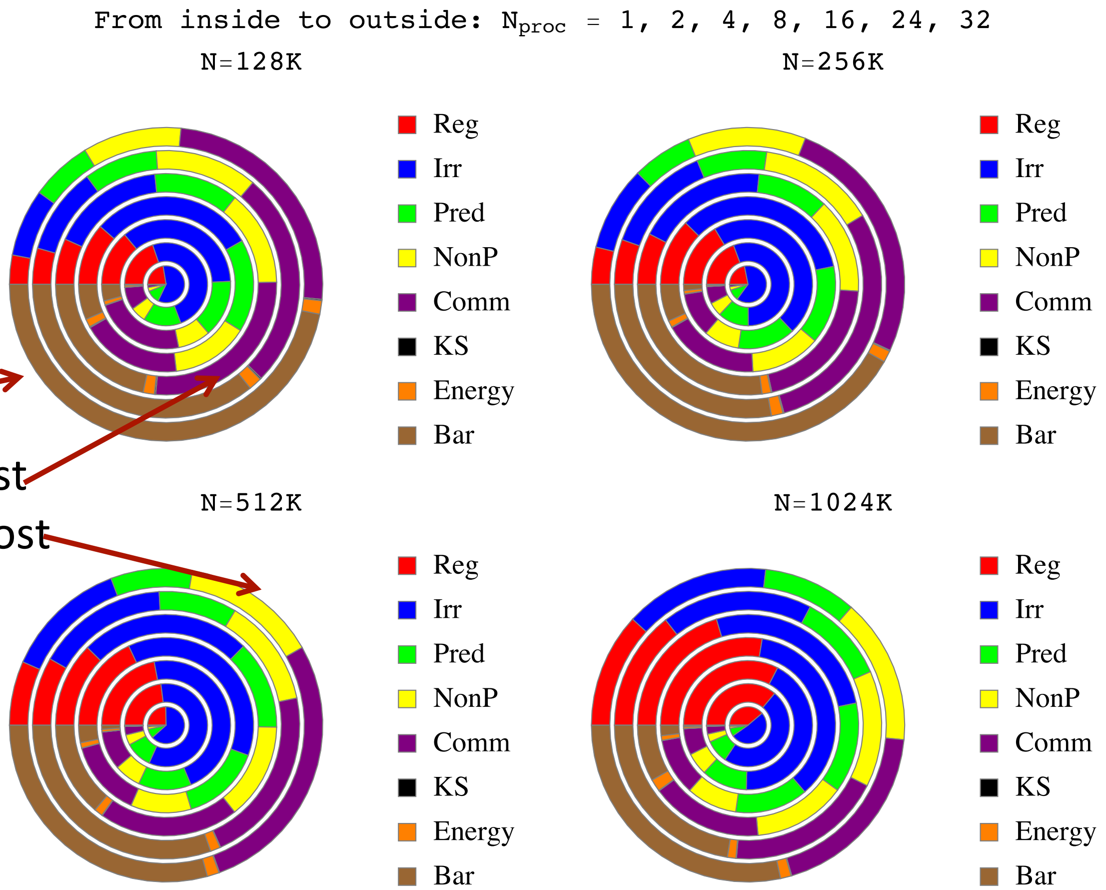
8CPUs(Inter Xeon X5650)
8GPUs(Tesla M2070)

Benchmark of NBODY6++



Time fraction

- Very fast GPU part
- CPU dominated



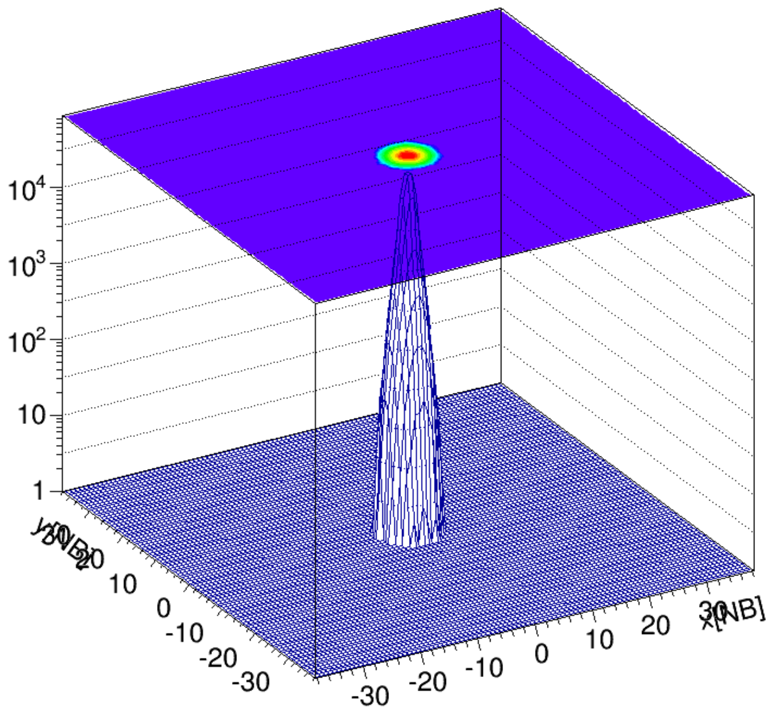
From inside to outside: N_{proc} = 1, 2, 4, 8, 16, 24, 32

1. Imbalance
2. Communication cost
3. Non-parallel part cost

Strong mass loss by tidal field

$N = 10^6$
$M = 574000.0M_\odot$
$R_{vir} = 30.67$pc
Solar neighbor tidal field

Density T = 0 Myr



Summary

- Direct N-body simulations are important for accurately understanding the dynamical evolution of star clusters.
- The speed of direct N-body simulation is still a big challenge for long-term evolution of massive star clusters.
- Nbody6++ speed up a lot recently
- KS parallelization will be done in the future