I am interested in the coevolution of the supermassive black hole (SMBH) and its host galaxy, in particular in terms of galaxy dynamics: How does the SMBH form? How does it effect the structure and evolution of its host galaxy? How does SMBH binaries evolve and transform the galaxy?

To address these questions, I use massively parallel N-body simulations to evolve stellar models of a galaxy with one or two SMBHs embedded in, then analyze the orbital content, the time-dependent structure, the density profile, as well as the dynamical properties of the SMBH binaries such as the orbital eccentricity and the hardening rate. I have outlined a few of my recent projects below.

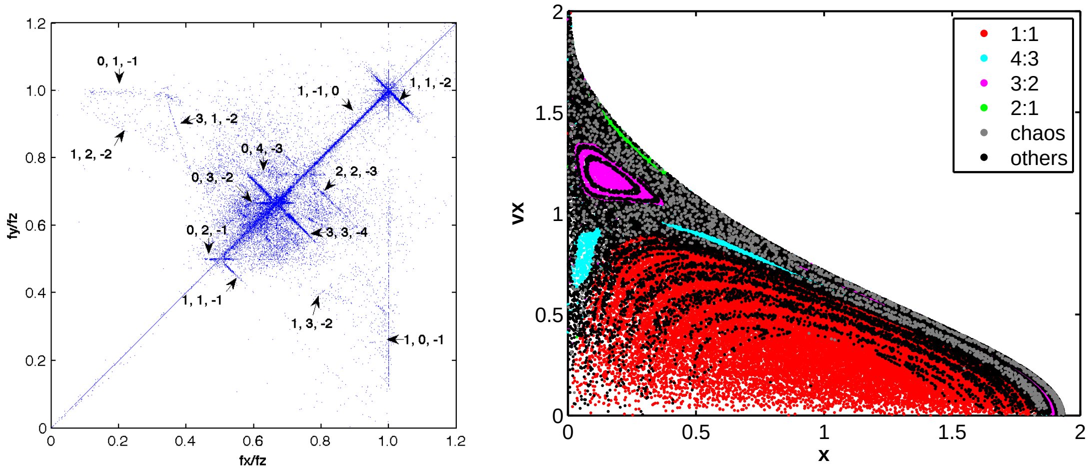

Figure 1: ***Left****: fy/fz versus fx/fz for the axisymmetric galaxy model. This model has a rich variety of resonant orbits such as (1, 1, -2), (3, 3, -4), (0, 3, -2), (0, 2, -1), (1,1,-1), (1, 2, -2) and (3, 1, -2) etc., marked in the figure, where the integers (u,v,w) are the coefficients of the equation* $u \cdot fx + v \cdot fy + w \cdot fz = 0$*. While for the spherical galaxy model, 88% particles are lying at the point (1,1), which means they have fx=fy=fz and are 1:1:1 tubes, and nearly all of the rest particles lying on lines fx=fy, fx=fz and fy=fz. There is no complex orbit types in the spherical galaxy model.* ***Right****: Surface of section of particles with the same given energy from the 2D axisymmetric galaxy model. In order to check the orbit type distribution in phase space, we make a 2D axisymmetric galaxy model, in which we randomly generate particles with the same given energy and make them run in the x-z plane by setting the initial condition of particles y=0, vy=0. This figure is colored by orbit type denoted by fz/fx, in which 1:1 loops are showed by red dots, 4:3 pretzels by cyan dots, 3:2 fishes by magenta dots, 2:1 bananas by green dots, chaos by grey dots and other resonances by black dots. It is seen from the area that each type of orbit occupies that the 1:1 loop is dominant. The chaos always occupy the lower angular momentum part of the figure.*

I. Classification of Stellar Orbits in Axisymmetric Galaxies.

Authors:* *Li*, Holley-Bockelmann and Khan*

Project status: Submitted to Astrophysical Journal.

When two galaxies merge, the SMBHs at each center will also merge and become a bound binary black hole that shrinks its orbit by three-body scattering the stars passing by. The stars that can interact with the black hole binary occupy a part of phase space called "the loss cone". In a perfect spherical galaxy model, the stars in the loss cone will be depleted very soon and cannot be supplemented within a Hubble time, so that the binary black hole will stop stalling at a separation of about 1 pc. This is called "the final-parsec problem". However, if the galaxy is mildly flattened, the SMBHs coalesce within a few billion years, bypassing the stalling seen in spherical systems. To understand what specifically causes the SMBHs to merge, we want to analyze the orbits within the axisymmetric galaxies. In this project, with my collaborators Kelly Holley-Bockelmann and Fazeel Khan I classified the stellar orbits in a SMBH-embedded axisymmetric galaxy with axes ratio c/a=0.75. I adapted the self-consistent field (SCF) code to run each orbit. In an SCF code the particles do not interact with each other directly, but are accelerated by the global potential of the system. We then analyze each orbit in the model using fast fourier transform (FFT) and Laskar's frequency mapping (see left panel of Figure 1). According to the frequency ratio, we classified the orbits into regular orbits and chaotic orbits. Using the same classification method, we also classified the stellar orbits in an otherwise identical spherical galaxy as a comparison group. We directly discovered a rich variety of resonances in the axisymmetric model (see both panels of Figure 1), such as saucers (see Figure 2) and other type of centrophilic orbits. The stellar mass included in the centrophilic orbits is roughly twice of that of the SMBH and 1% of the total stellar mass. Those centrophilic orbits are indeed the ones that interact most with the SMBH. We suspect that these orbits are the reason that the SMBH binary can coalesce efficiently. We also found pyramid orbits (see Figure 3) among the centrophilic orbits since we have a slightly non-axisymmetric nuclear center including 1% mass of the total stellar mass.

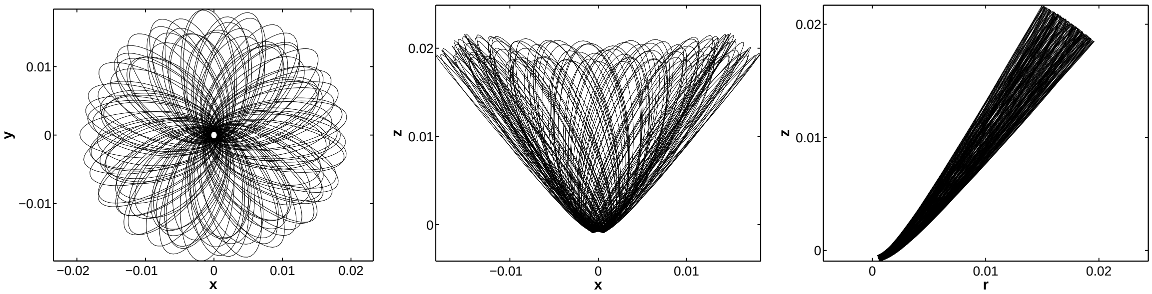

Figure 2: A typical saucer orbit emerged in the axisymmetric galaxy models. The three panels from left to right show the projection of the saucer orbit in the x-y, x-z and r-z plane respectively, where $r = \sqrt{x^2 + y^2}$.

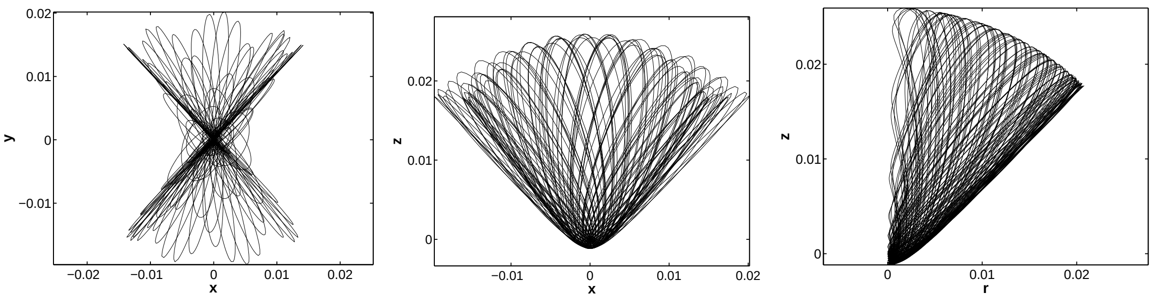

Figure 3: A typical pyramid orbit emerged at the non-axisymmetric central part of the axisymmetric galaxy models. The three panels from left to right show the projection of the pyramid orbit in the x-y, x-z and r-z plane respectively, where $r = \sqrt{x^2 + y^2}$. *There is a hole in the x-y plane projection of the saucer orbit, while there is not in the pyramid orbit.*

II. Supermassive Black Hole Binary Mergers within Axisymmetric Galaxies.

Authors: ***Li****, Holley-Bockelmann and Khan*

Project status: in progress.

With my collaborators Kelly Holley-Bockelmann and Fazeel Khan I am currently analyzing the time-dependent structure of an axisymmetric galaxy with an initially wide SMBH binary at the center. As the SMBH binary coalesces, we are investigating the orbits and origin of stars that are three-body scattered by the binary, and exploring the effect of the binary merger on the orbital content of the host galaxy.

III. Expansion Techniques for Collisionless Stellar Dynamical Simulations.

Authors*: Meiron,* ***Li****, Holley-Bockelmann and Spurzem*

Project status: Published on Astrophysical Journal, 2014, 792, 98

This work focused on generating GPU versions of particle field codes. We created a new type of expansion code called multipole expansion (MEX), and discussed its advantages and uses compared to the traditional SCF code. I helped port the SCF code to CUDA and was responsible for benchmarking the SCF code. We found that when the number of particles in the system, N, is over 10^4, the running time of the GPU version code of both MEX and SCF running on a GPU is less than that of the CPU version code of SCF running on a CPU with the same expansion parameter, e.g. nmax=10, lmax=6. When N=10^7, the GPU codes are 50 times faster than the CPU code of SCF (see Figure 4).

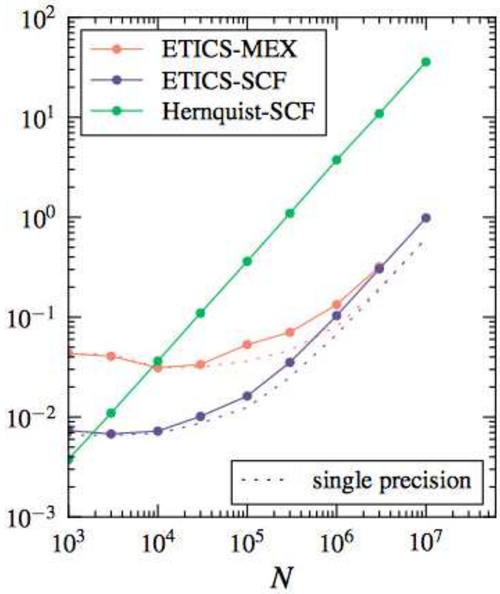

Figure 4: Hernquist's SCF code (in green) is a CPU code and was tested on an Intel Xeon E5520 CPU (one core). ETICS is a GPU code with both MEX (red) and SCF (blue) methods, and was tested with an Nvidia Tesla K20 GPU; for the GPU codes, dotted lines show the performance in single-precision mode. For the scaling with N, we set lmax = 6, and for the SCF codes nmax = 10. The scaling is theoretically linear with N for SCF and N logN for MEX, but the theoretical behavior is only seen asymptotically for the GPU codes since the GPU is not fully loaded at low N. Both methods scale quadratically with lmax (the tests were performed with N = 10^6 and nmax = 10 for SCF).

IV. Supermassive Black Hole Spin Evolution in Spherical galaxies.

Authors: Li *and Holley-Bockelmann*

Project status: in progress.

With my collaborator Kelly Holley-Bockelmann I am investigating the spin evolution of a SMBH in a non-rotating spherical galaxy model with non-zero net orbital angular momentum. When the particles pass by the SMBH, the orbital angular momentum of the particles couples with the spin angular momentum of the SMBH. To model this, I wrote a post-Newtonian (PN) SCF code, adding up to 3.5 PN terms in order to capture the effect of the particle motion on the SMBH spin.

In the future I plan to continue my research on the interaction between the SMBH binary and its host galaxy. I am going to investigate the effect of the SMBH binary with different mass ratios and different spin orientations on the time-dependent structure of its host rotating galaxy with different initial density profiles and different shapes, and also study the effect of the host galaxy on the coalescence time and final spin of the coalesced black hole. Although I have been doing simulations during my PhD time, I am also interested in observing the phenomena caused by or related to the SMBHs.