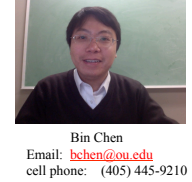


Parallel Computing in High Energy Astrophysics: Combining Microlensing and Black Hole Ray-Tracing

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Motivation

Gravitational lensing is an important probe in modern cosmology and astrophysics. In particular, quasar microlensing strongly constrains the geometry of the high-energy X-ray emitting regions of active galactic nuclei (AGNs) which are very close to the central supermassive black hole powering the AGNs. The X-ray emission of a microlensed quasar is lensed by both the background supermassive black hole and the thousands to millions of random stars in the foreground lens galaxy.

Parallel ray-tracing is an ideal tool to simulate the observed image and light curve of an accretion disk lensed by both the spinning massive black hole and the microlensing magnification patterns caused by foreground random stars. We present two parallel ray-tracing codes recently developed by our group to study strong lensing of AGN X-ray emission by Kerr black holes and microlensing by foreground lens galaxies, and a numerical scheme to combine microlensing with black hole lensing. We discuss the unique constraints on AGN X-ray emission geometry obtained by our computer programs.

Gravitational Lensing and Microlensing

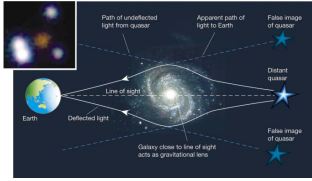


Fig. 1. **Gravitational lensing.** Light from a distant quasar is deflected/lensed by the gravitational field of a foreground galaxy lying close to the line of sight from Earth to the quasar. As a result, the quasar appears brighter, and multiple images of the quasar may be seen. The inset on the top left shows the 4 images of the source in the sky (Edwin L. Turner, 2002, *Nature*, 417, 905).

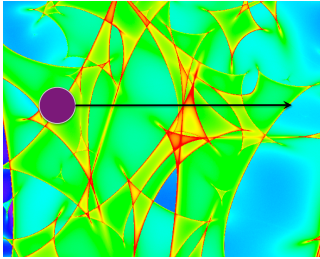


Fig. 2. **Microlensing Magnification pattern** (a 2D high resolution image) shows the magnification of a point source as a function of its position in the source plane. Cold and warm colors show the low and high magnification regions. The diamond like lines show the microlensing caustics where the magnification diverges for point source.

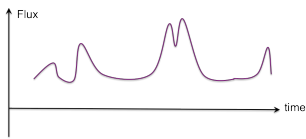


Fig. 3. **Microlensing light curve** for the source moving in the magnification pattern (see Fig. 2)

Gravitational lensing: Refer to Fig. 1 to the left.

Microlensing: a photon traverses the interior of a galaxy will be lensed by thousands to millions of stars in the lens galaxy, with the total bending angle a linear sum of the individual bending caused by each star, i.e.,

$$\alpha = \sum_{i=1}^n \frac{4GM_i}{r_i} \quad \text{Eq. (1)}$$

Microlensing Equation (ray-tracing equation) is used to find the source position given its image position on the sky:

$$\theta_s = \theta_l - \frac{D_s}{D_l} \alpha(\theta_l) \quad \text{Eq. (2)}$$

However, this equation can not be solved analytically. Backward ray-tracing is used in practice. To compute the bending angle caused by many stars in the lens galaxy is computationally costly (see Fig. 1).

Magnification Image Matrix: the observed flux of a microlensed source (e.g., a quasar) will be magnified or de-magnified depends on position of the source on the sky. Consequently, for an assumed distribution of microlensing stars, the magnification matrix—a 2D high resolution image—is generated by numerical ray-tracing, for each pixel of the image matrix, thousands of rays need be traced (see Fig. 2).

Microlensing Light Curve: when the source is moving in the magnification pattern, the observed flux varies with time (the light curve). At each time, the observed flux is a *convolution* of the intrinsic brightness profile of the source with the magnification pattern covered by the extended source (see Fig. 3).

Parallel Computing in Microlensing Ray-Tracing

- Goal: to generate the high resolution microlensing magnification matrix ($\geq 10^8$ pixels in general).
- Method: backward ray-tracing (backward: from observer to the source).
- Difficulty: for each pixel, $\sim 10^3$ rays needed be traced, and for each ray, the gravitational bending of $\sim 10^3$ to $\sim 10^4$ stars needs to be added.
- Further complication: if we allow the stars in the lens galaxy to move, then at each point of the time grid, a new magnification image need be simulated.
- Good news: microlensing ray-tracing is therefore an *embarrassingly parallel* computing problem.
- Remark. GPU ray-tracing is a very promising new tool to study microlensing phenomena (e.g., Vernardos & Fluke 2013).

Progress of Our Group:

- We have developed a parallel ray-tracing code based on Fortran OpenMP+MPI techniques, and have used this code to study the X-ray microlensing of quasars (Chen et al. 2013a, *Astrophys. J.*).
- Performance:** to generate a microlensing magnification pattern of resolution 10000x10000 produced by ~ 500 stars (~ 1000 rays were traced for each pixel), takes about ~ 23 hours on a single node with 8 cores

Strong Lensing by Spinning Supermassive Black Hole

Background knowledge: The high-energy X-ray emission of AGNs comes from regions very close to the central supermassive black hole (10^9 solar mass), and is therefore strongly lensed by the black hole. Consequently the image and intrinsic surface brightness profile are strongly distorted by the central black hole (Fig. 4).

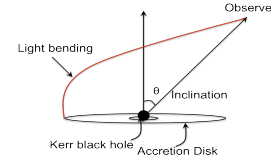


Fig. 4. Extreme Black Hole Lensing

A Few Facts about Extreme Black Hole lensing:

- Black hole lensing strongly distorts the shape of the image.
- Doppler/Gravity redshift significantly changes the photon frequency and the intensity profile.
- Both image distortion and redshift depends on inclination angle θ .

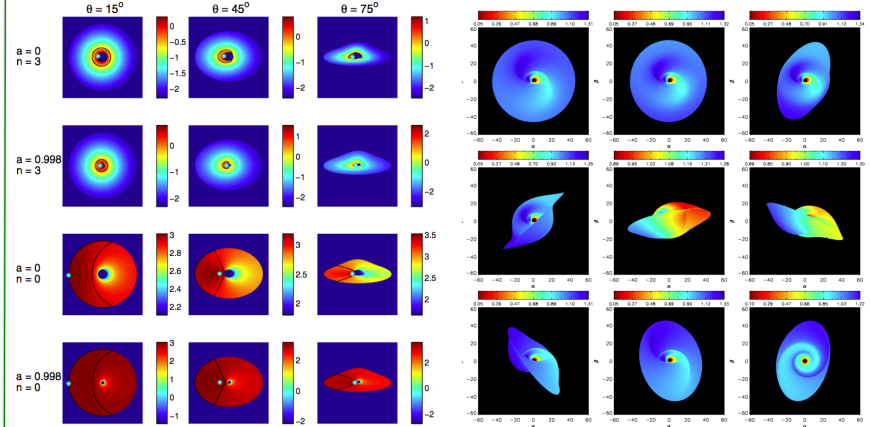


Fig. 5. Images of an accretion disk lensed by Kerr black holes. The three columns are for three inclination angles; whereas the four rows corresponds to different black hole angular momentum and intrinsic profile of the X-ray emission. Image resolution 1000x1000 (Chen et al. 2013b, *Astrophys. J.*)

Fig. 6. Image of warped AGN accretion disks lensed by Kerr black holes. The accretion disk has more complex geometry than the thin disk model on the left (Yang & Wang, 2013, *Astrophys. J. Supp. Ser.*).

Parallel Computing in Kerr Black Hole Ray-Tracing

- Goal: to generate high resolution images of accretion disks strongly lensed by Kerr black holes powering AGNs.
- Method: Solve the geodesic equations for Kerr metric by backward ray-tracing using the 5th order Runge-Kutta algorithm with adaptive step-size control.
- Parallel computing: for each ray shot from the observer (backward to the black hole), the geodesic equations (a groups of first order ODEs) can be solved independently. Consequently, to generate the image of a source (e.g., the black hole accretion disk) strongly lensed by a Kerr black hole, is an *embarrassingly parallel* computing problem.
- Further complication: the image depends strongly on the black hole spin (angular momentum) and the disk inclination angle (see Fig. 4). It also depends on the geometry assumed for the X-ray source. This increases the dimension of the parameter space needs to be explored.
- Remark. GPU ray-tracing is again applicable and highly desired for Kerr black hole ray-tracing.

Progress of Our Group:

- We have developed a parallel ray-tracing code based on 5th order Runge-Kutta algorithm and Fortran OpenMP+MPI techniques, and have used this code to study the strong lensing by Kerr black holes (Chen et al. 2013b, *Astrophys. J.*).
- Performance:** It takes ~ 450 seconds to generate a single image of a Kerr-lensed accretion disk of very simple geometries with resolution 2000x2000 using a single node with 8 cores (see Table 1 on the next page).

New Results: Combining Kerr Black Hole Ray-Tracing with Stellar-Mass Microlensing Ray-Tracing

Background: The X-ray emission of a microlensed quasar is lensed by both the supermassive black hole powering the AGN and the random stars in the foreground lens galaxy.

Outstanding Problem: current quasar microlensing technique ignores black hole lensing, and gives biased estimates on the size of the AGN X-ray emission.

Contribution: Our essential contribution is inventing a novel scheme to combine black hole lensing with standard microlensing, and improving the accuracy of quasar microlensing techniques significantly.

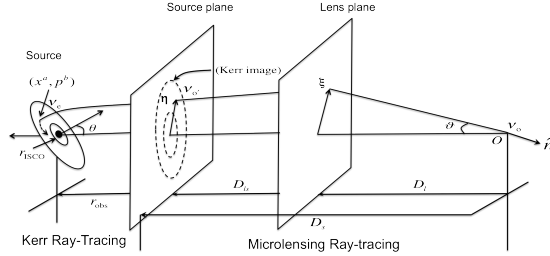


Fig. 7 Combining black hole lensing with standard microlensing (Chen et al. 2013b *Astrophys. J.*).

A Novel Scheme Combining Kerr Lensing with Microlensing (see Fig. 7):

- A source plane between the background quasar and the foreground lens plane can be conveniently defined as an **interface** between microlensing ray-tracing and Kerr ray-tracing;
- Microlensing magnification patterns are computed in this **flat** source plane by backward parallel ray-tracing;
- The image of a Kerr-lensed accretion disk in this source plane is generated by backward Kerr ray-tracing;
- The 2D Kerr image is treated as the source for the foreground microlensing analysis (see the following figures).

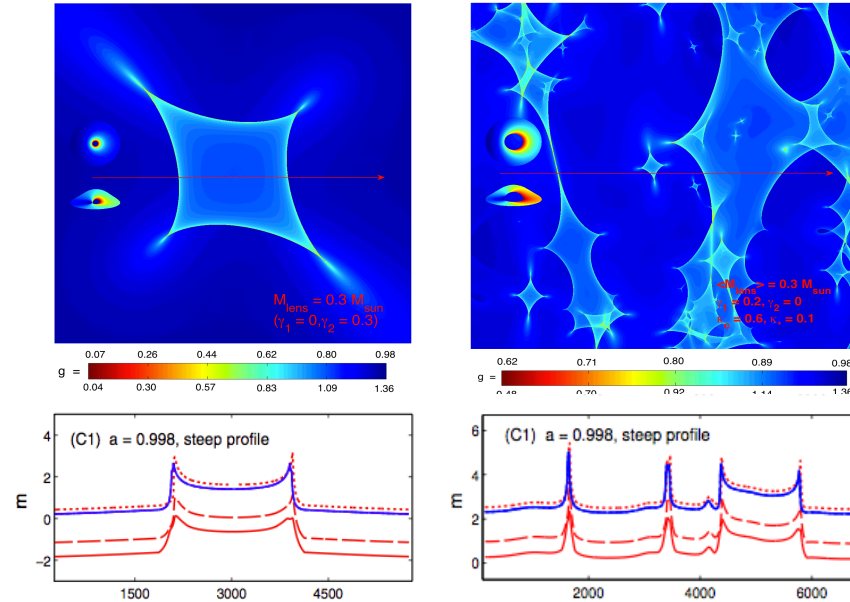


Fig. 8. (Top row). Microlensing magnification pattern in the source plane caused by a single star (left panel) and a random star field (right panel). Image resolution 10000x10000. The insets are images of an accretion disk lensed by a Kerr black hole seen by observers at two different inclination angles (15 deg and 75 deg, respectively).

(Bottom row). The X-ray light curves for a Kerr-lensed accretion disk moving in the magnification pattern. The solid, dashed, and dotted curves are for accretion disk inclination angle 15, 45, and 75 degree respectively. The blue curves show results of microlensing without black hole lensing, and the red curves show the results combining black hole lensing and microlensing. **The Kerr+Micro lensing light curves differ significantly from standard microlensing light curves** (Chen et al. 2013a, b, *Astrophys. J.*).

Scalability of the Kerr black hole ray-tracing code. In Table 1 we show the performance of ray-tracing an accretion disk of radius $20r_g$ with resolution 2000×2000 . The scaling is not perfectly linear mainly because of the cost of saving a large array of data needed for our analysis, in particular, diagnosing data for those rays falling into the horizon of the black hole.

No. Processors	1	2	4	8	16	32
Speed ($\times 3200$ rays/s)	1	1.8	3.5	7.0	13.6	27

Tab. 1. Performance of the Parallel Kerr ray-tracing code.

Conclusions and Discussions

Conclusions and Discussions:

- High resolution images of black hole accretion disks and microlensing magnification patterns are needed to study quasar X-ray microlensing. Parallel ray-tracing is the ideal tool to study microlensing by random stars, as well as extreme lensing by supermassive black holes powering AGNs.
- The current quasar X-ray microlensing simulations ignore the effect of black hole lensing and gives biased estimates on the size of the quasar X-ray emitting regions.
- We have developed parallel ray-tracing codes based on hybrid OpenMP+MPI techniques for both microlensing and Kerr black hole lensing, and have invented a novel scheme to combine microlensing and black hole ray-tracing.
- Our results indicate that significant bias (up to $\sim 50\%$) on the size estimate of quasar X-ray emission regions can happen if the black hole lensing is ignored.
- Regarding Parallel Computing:** the ability for astronomers to acquire a large number of simulated microlensing magnification patterns spanning a high dimension parameter space as well as a large number of Kerr-lensed accretion disk images for different black hole parameters and X-ray corona geometries, is critical for using microlensing techniques to probe either quasar accretion disks or cosmological parameters, given that thousands of new lenses are expected to be discovered by next generation all-sky surveys such as LSST. Consequently, high performance parallel computing and GPU ray-tracing will play an important role in high energy astrophysics in the next two decades.

Future Works:

- Combine our Kerr lensing code with the Bayesian Monte Carlo simulation code (Kochanek, 2004 *Astrophys. J.* 605, 58)
- Apply Kerr+Micro lensing simulation techniques to observed light curves of lensed quasars such as Q2237+0305, and obtain more accurate size estimates of AGN X-ray emission.
- Measure important black hole parameters such as black hole spin, and disk inclination using Kerr+Micro lensing techniques.
- Realize our ray-tracing codes on GPU (speed up by a factor of at least of 10 is expected).

Acknowledgement:

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