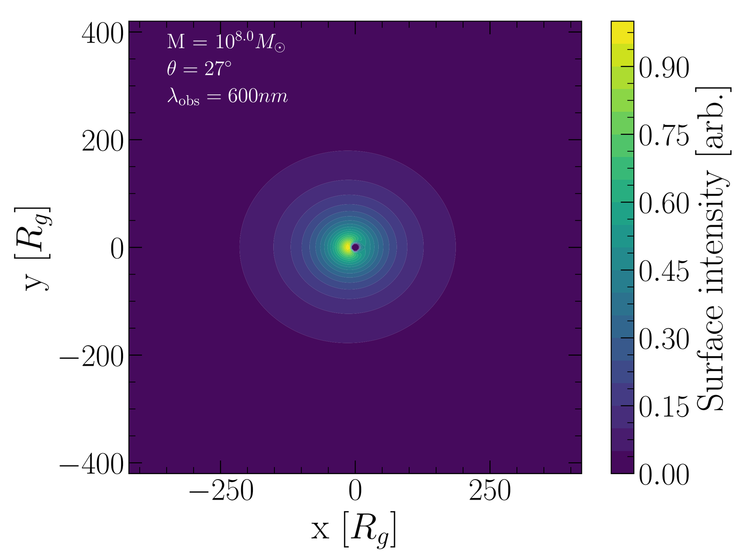
Self-Consistent Modeling of Variable AGN

Henry Best (hbest@gradcenter.cuny.edu), Matt O'Dowd, James Chan, Joshua Fagin, Bridget Ierace

The City University of New York · Lehman College · American Museum of Natural History

We present Amoeba, a new code that enables simultaneous, self-consistent modeling of intrinsic and microlensing variability. Strongly lensed quasars exhibit variability from both source fluctuations (intrinsic) and microlensing (extrinsic). Measurement of time lags from intrinsic fluctuations across multiple lensed images enables time-delay cosmography, while both the intrinsic and extrinsic variability encode quasar structure through the reverberation signal and differential microlensing respectively. Most studies will isolate either intrinsic or extrinsic variability depending on their science case, however there is good reason to treat these together. For example, it's been shown that microlensing induces a significant offset in time delay measurements (Tie + Kochanek 2018) and so should be carefully modeled, while quasar structure studies can benefit from simultaneous modeling of the reverberation and microlensing signal. Amoeba enables this self-consistent modeling by producing physically-motivated quasar light curves that incorporate flexible analytic models for accretion disk and broad-line flows, full relativistic effects on the inner accretion disk, and intrinsic variability via propagation of arbitrary variability sources through the quasar structure. In this poster we focus on one example application: calculating the deviation in time lag measurements due to microlensing.

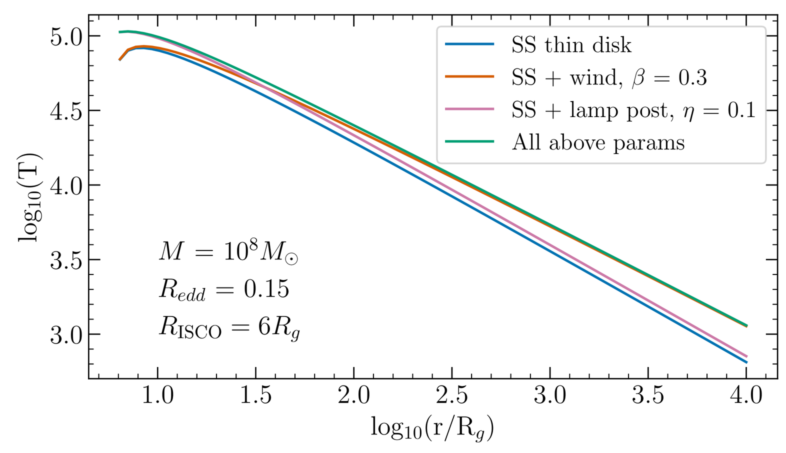
Surface Intensity Maps



Surface intensity maps: We convolve surface intensity maps along a track on a simulated microlensing magnification map to derive microlensing light curves. These encode details of disk structure, such as the innermost stable circular orbit (ISCO) and temperature gradient. Due to spatially-dependent intrinsic variability, the surface intensity map varies along these tracks, necessitating the calculation of a microlensed transfer function.

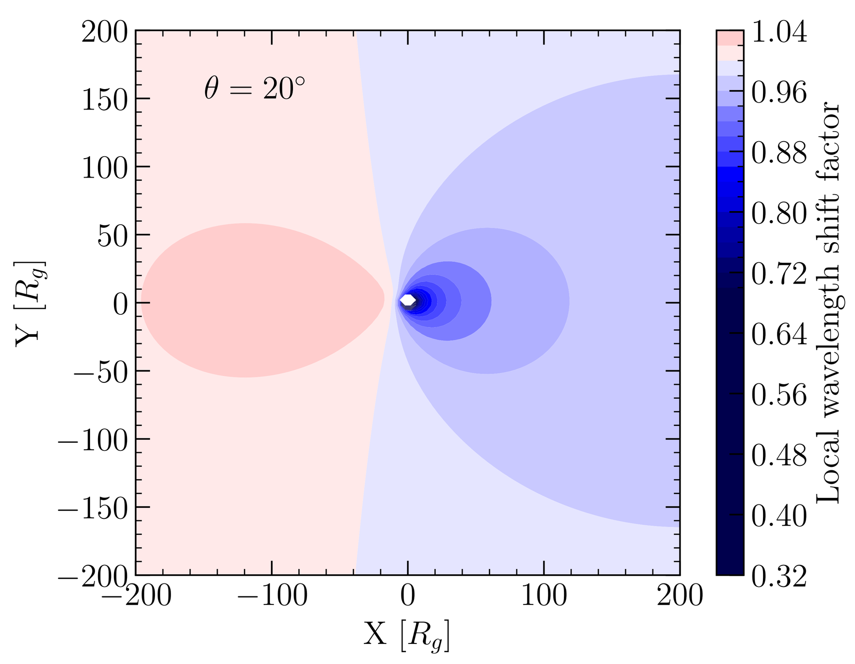
Flexible Temperature Profile

$$T^4(r) = \left(\frac{3GM\dot{M}_0\left(1-\sqrt{R_{in}/r}\right)}{8\pi\sigma(2R_g)^3}\right)\left(\frac{r}{2R_g}\right)^{(\beta-3)} + \left(\frac{(1-A)L_x}{4\pi\sigma R_*^2}\right)\cos\theta_x$$



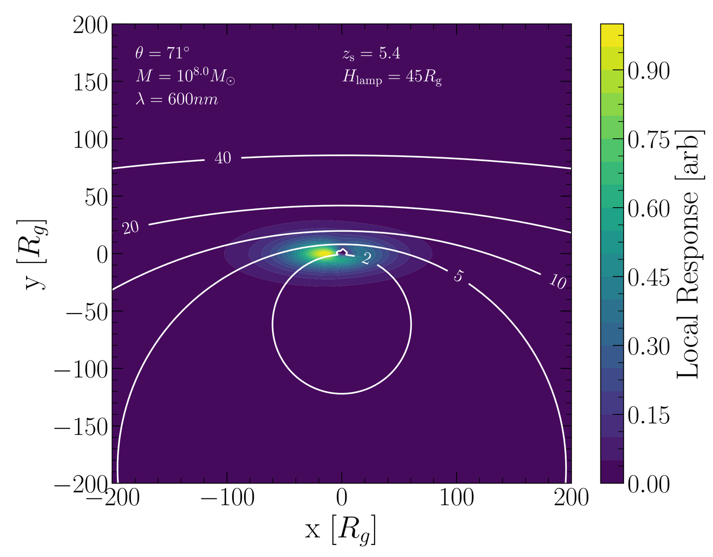
Flexible temperature profiles: Heating by a variable source above the disk and radially varying accretion rates can be accounted for with a modified analytic temperature profile. This analytic form enables fast generation of the raw surface brightness map at each time step. T(r) converges smoothly to the thin disk profile as $\beta \to 0,\ L_x \to 0$ where β controls the asymptotic temperature slope and L_x controls the corona heating.

Full Relativistic Modeling



Relativistic modeling: At the inner accretion disk, large orbital velocities result in significant relativistic boosting and Doppler shifts, and these photons are also subject to substantial lensing in the potential well of the SMBH. These relativistic effects lead to large asymmetries in the surface brightness distribution at the inner accretion disk, and accurate modeling of this is critical for high-magnification microlensing events.

Surface Reprocessing Maps With Time Delays

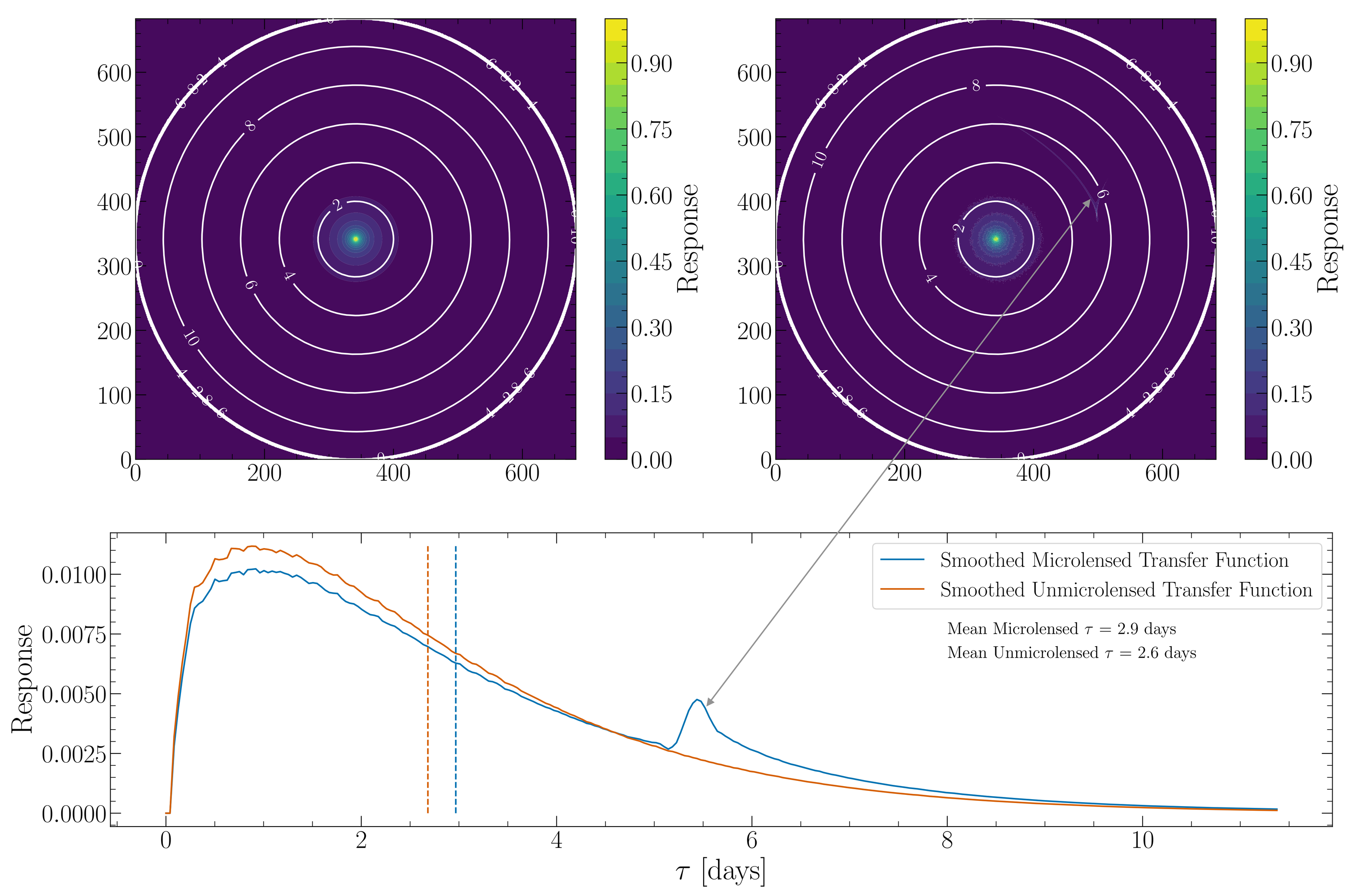


*All time delay contours are in units of days

Surface reprocessing maps: The increase in apparent flux due to the heating of an accretion disk by some external source (e.g. a corona) is how we define reprocessing within this model. Inclined relativistic disks show there is asymmetry between approaching/receding sides similar to surface intensity maps. Therefore, it is important to have a flexible model which can take this into account.

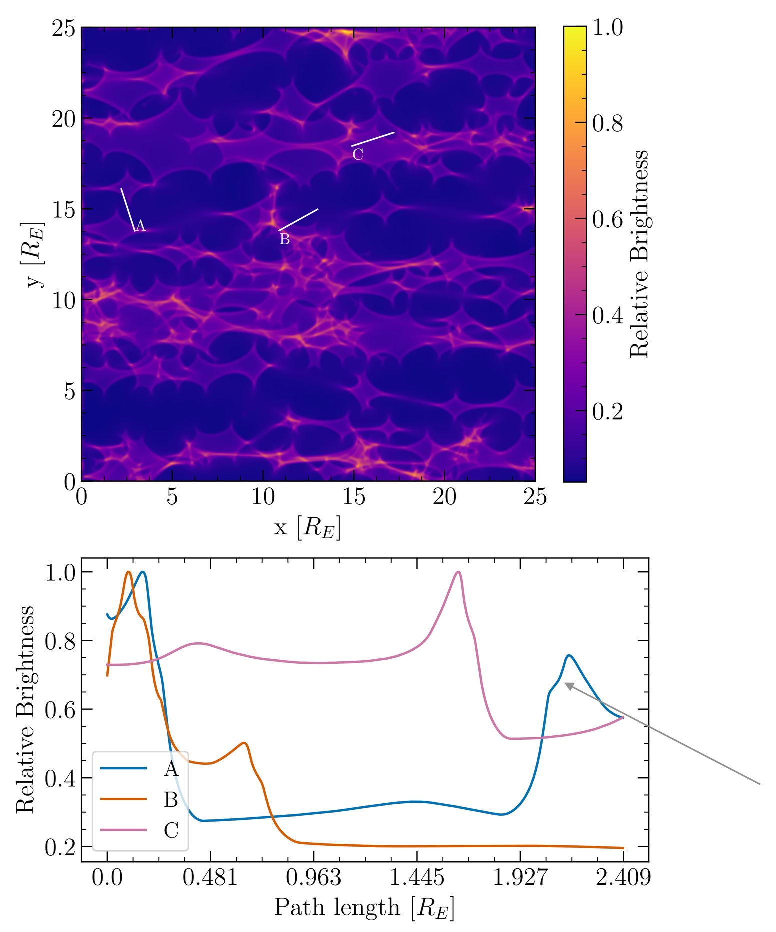
Time delays in the source plane are used to construct the transfer functions of these non-analytic disks for any orientation and configuration of driving source(s).

Microlensed Transfer Functions



Microlensed Transfer Functions: Transfer functions derived from pixelated face-on accretion disks. Top left: The unmicrolensed accretion disk produces the transfer function in orange on bottom. Top right: Microlensing amplifies a small region of the response leading to higher response at time lags of ~5 days evident in the blue transfer function on bottom. Amplifications of various regions may impact expected response functions and shift mean time lags (Best et. al in prep).

Microlensing Imprints Details of Disk



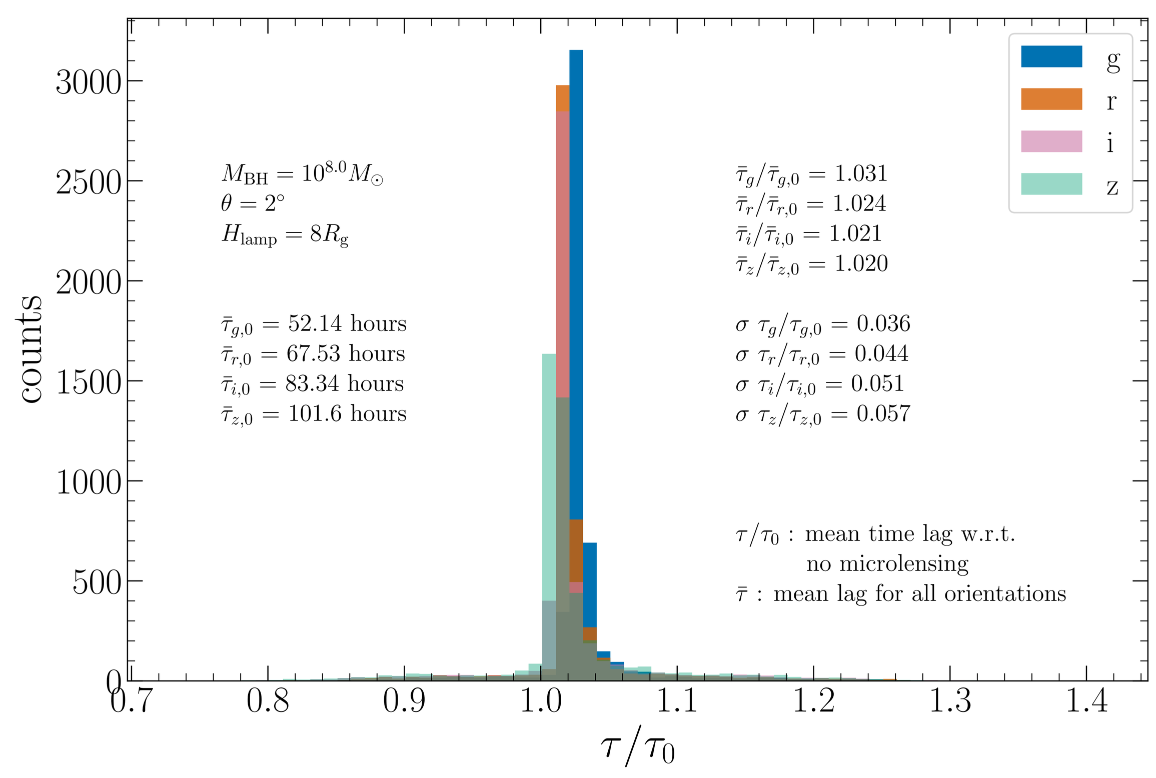
Microlensing light curves with high R_g/R_E ratios reveal details relating to ISCO crossing events as the surface brightness map sweeps over regions of high magnification.

Most simulated microlensing light curves typically do not contain any intrinsic variability.

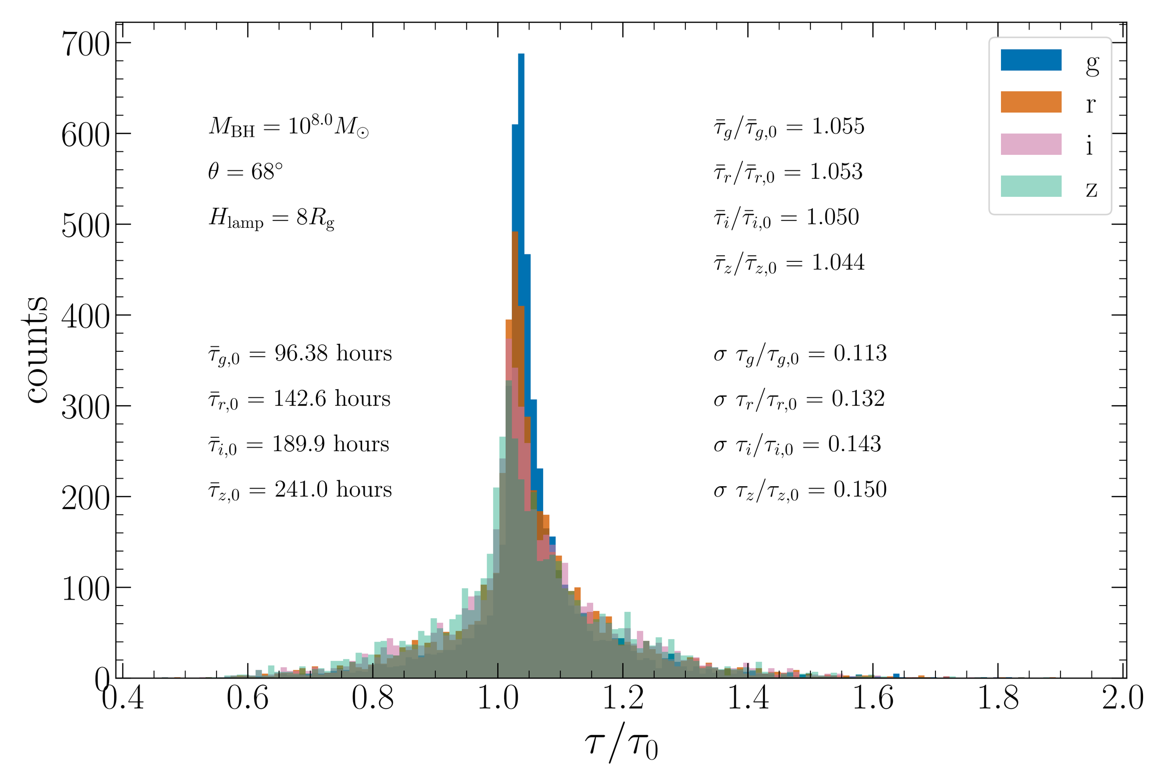
Some studies apply correlated noise to these light curves to model the intrinsic variability, but this does not include microlensing of a reprocessed signal.

Visible ISCO crossing feature observable in simulated light curve: (Best et. al 2023) https://arxiv.org/abs/2210.10500

Face-on Disk



Inclined Disk

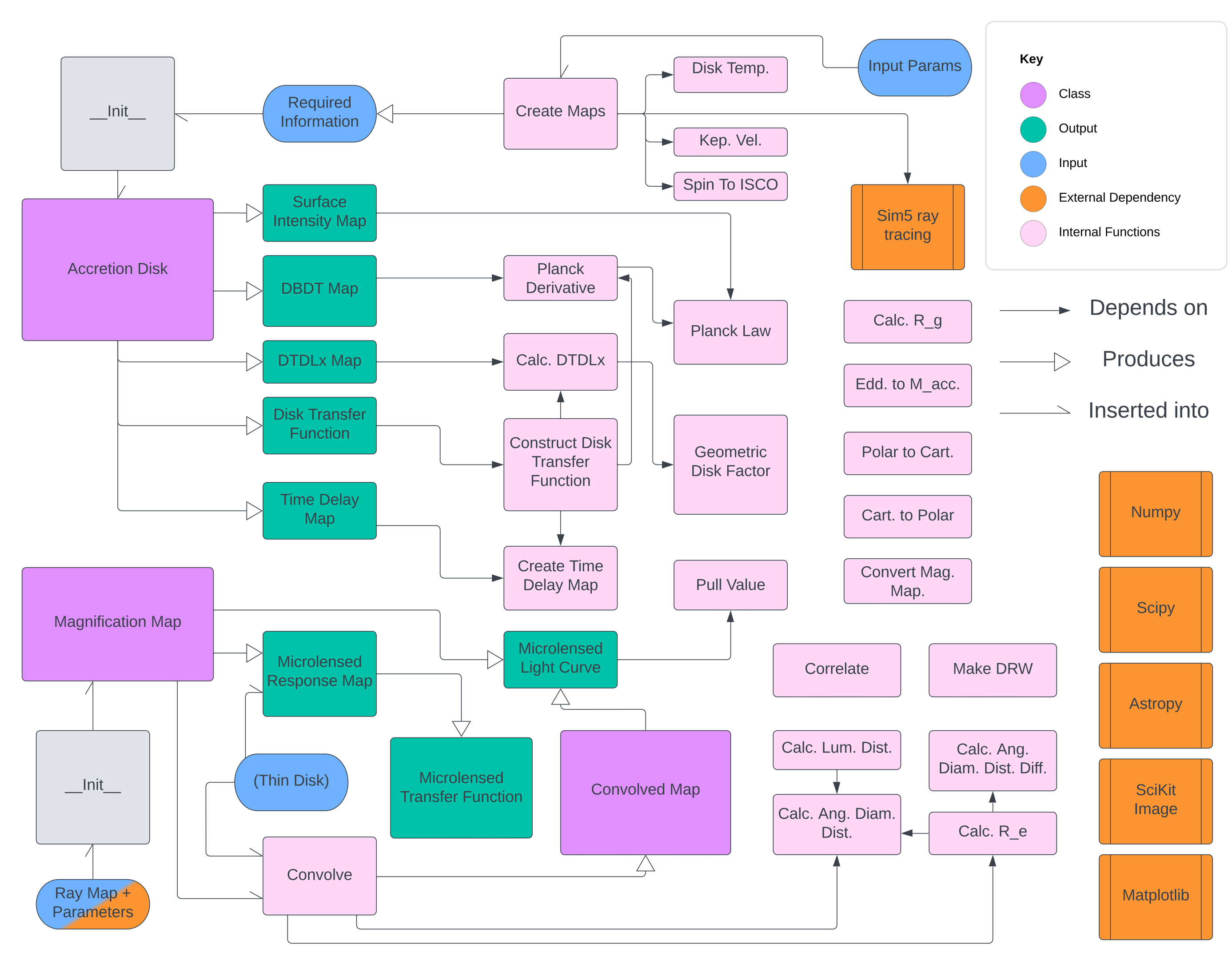


Basic statistics of stationary microlensed transfer functions: Accretion disks were positioned at 5000 random locations and orientations on a magnification map and simulated in multiple wavebands. The ratio between mean microlensed and unmicrolensed time lags ($\bar{\tau}/\bar{\tau}_0$) is found to increase by an order of 1-5%. A significantly greater dispersion in τ/τ_0 is found for inclined disks at all wavelengths with respect to a face-on disk. Dispersion also increases significantly with accretion disk size for constant orientation, supporting the need for fully self-consistent models.

By accounting for relativistic corrections within our model, we find that we can recover the known result that microlensing can impact continuum time lags. We aim to accurately predict these time delays as it is important for time-delay cosmography. These pixelated sources can be combined into individual time varying signals. Each pixel may be treated as a response to some driving source, from which a "movie" of the accretion disk may be derived. **These may be used with MOLET to create self-consistent intrinsically varying microlensing light curves.**

Amoeba Code Map

(Best et. al in prep.)



Amoeba currently aims to model continuum emissions from an accretion disk. Extensions to include BLR emission contributions are planned for the near future. We remain flexible in order to allow a wide range of modeling and can self-consistently treat any pixelated surface temperature map, even beyond the temperature profile provided. Parameters not explicitly related to GR ray tracing (e.g. $T(r), M_{BH}, \lambda, z_s$) can be adjusted rapidly to facilitate MCMC optimization.