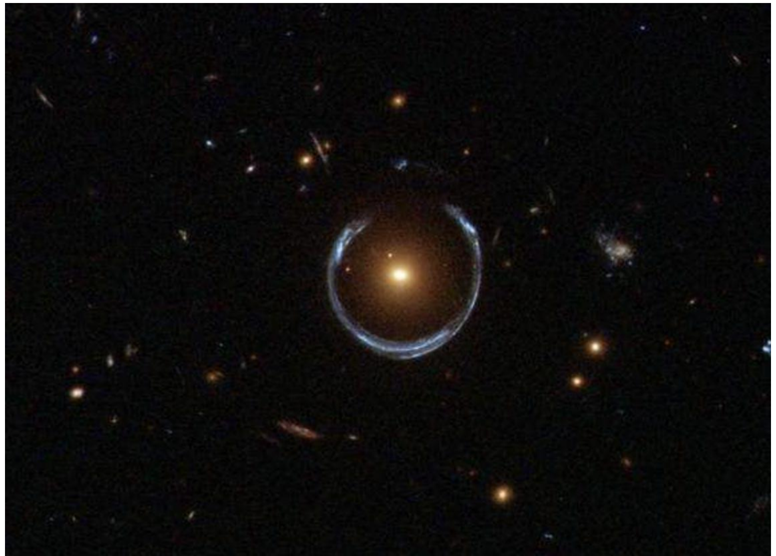
Microlensing by Galactic Center Supermassive BH

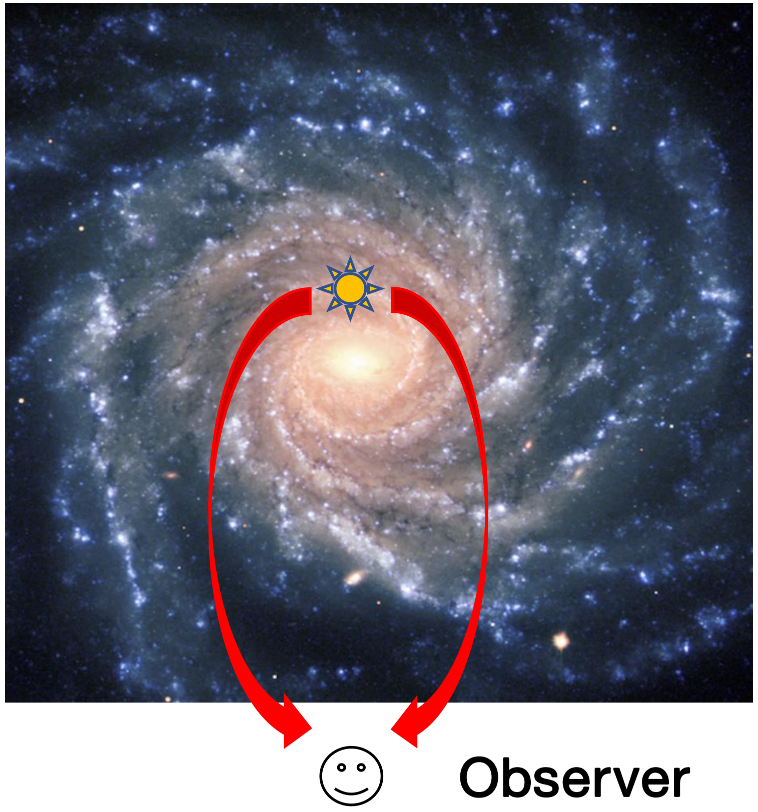
Yixian Chen
Instructor: Jessica Lu

Dep of Astronomy, UC Berkeley
Dep of Physics, Tsinghua University

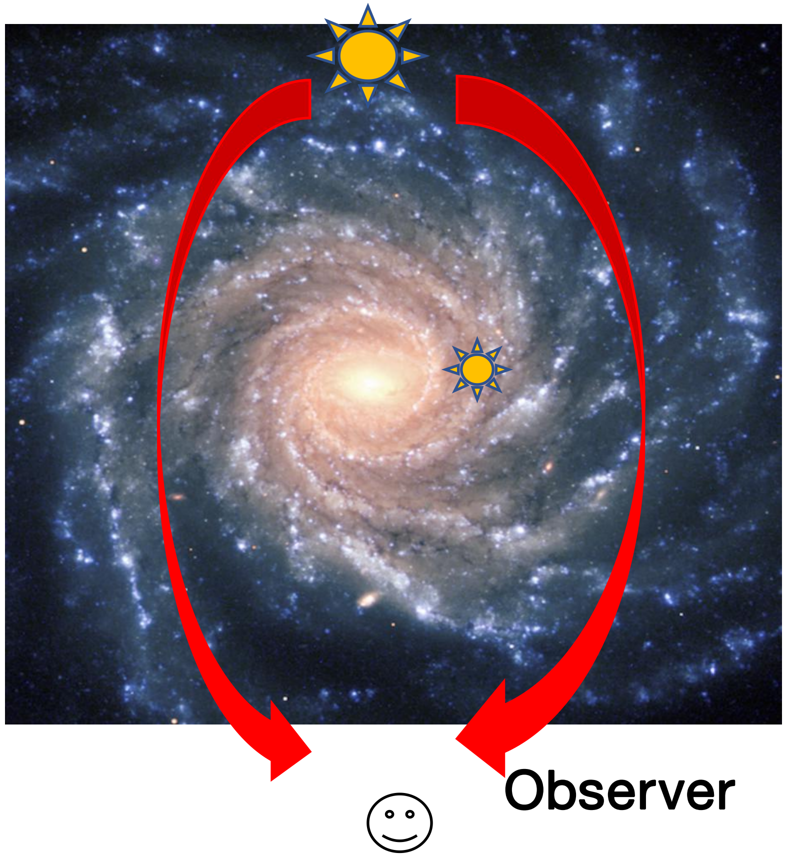


Two Cases

Alexander & Sternberg 1999: lensing of GC stellar population by the SMBH



Alexander & Loeb 2001: lensing of distant stars by SMBH perturbed by GC stars as secondary lenses



Motivation: Discovery of IR variable sources in the direction of the SMBH

Basics of Micro-lensing

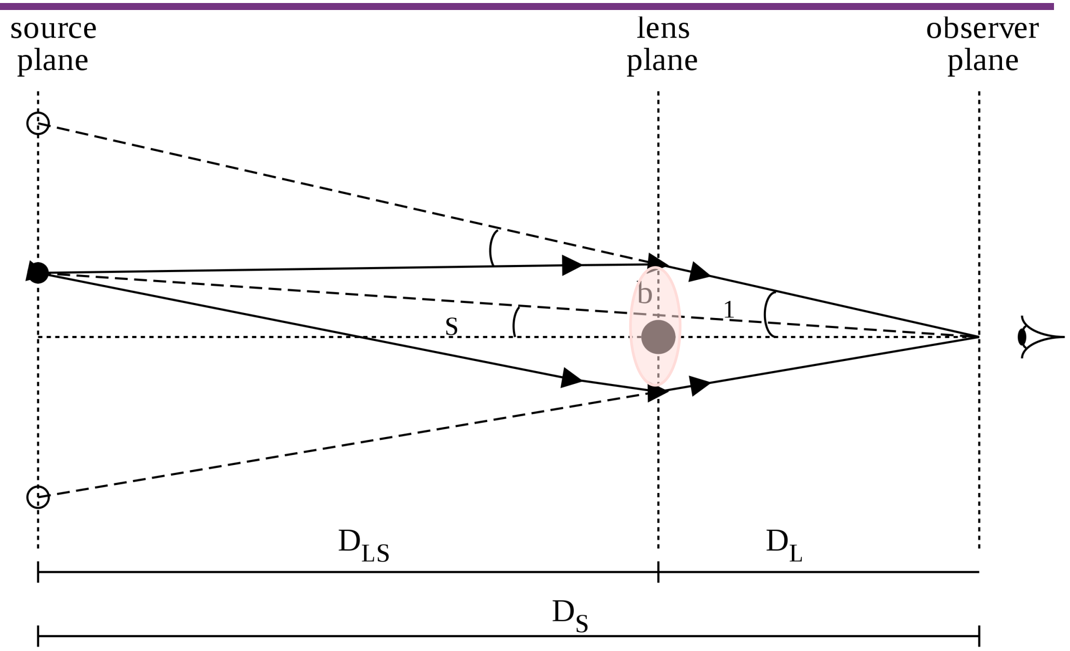
General Setup

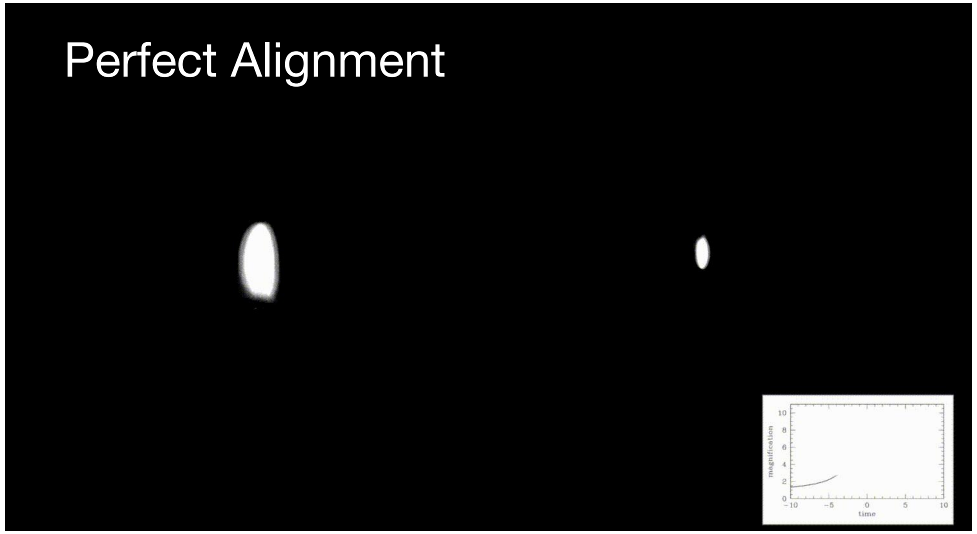
Einstein Angle

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{d_S - d_L}{d_S d_L}}$$

Einstein Radius

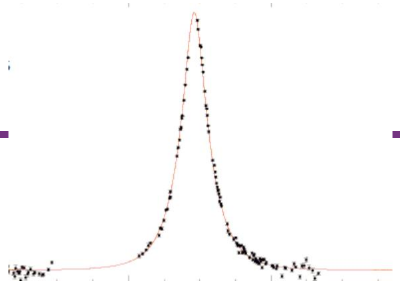
$$R_E = \theta_E D$$





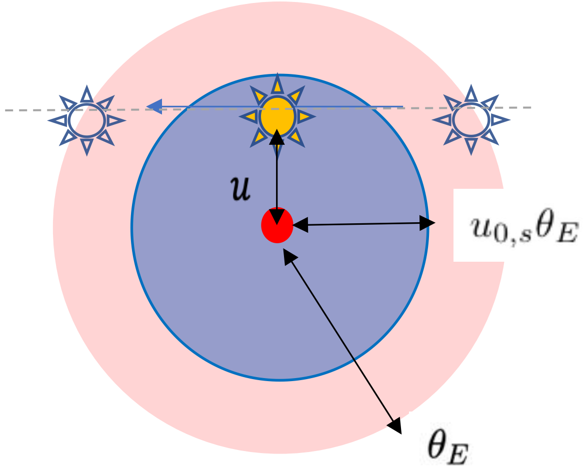
https://www.youtube.com/watch?v=emNAxv8_aXU

Basics of Micro-lensing



Impact parameter and Magnification

$$\vec{u} = \frac{\vec{\theta}_S - \vec{\theta}_L}{\theta_E} \qquad A(u) = \frac{u^2+2}{u\sqrt{u^2+4}}$$



Faint-star lensing $K_s \gtrsim K_0$

Need extra amplification to be detected within a timescale

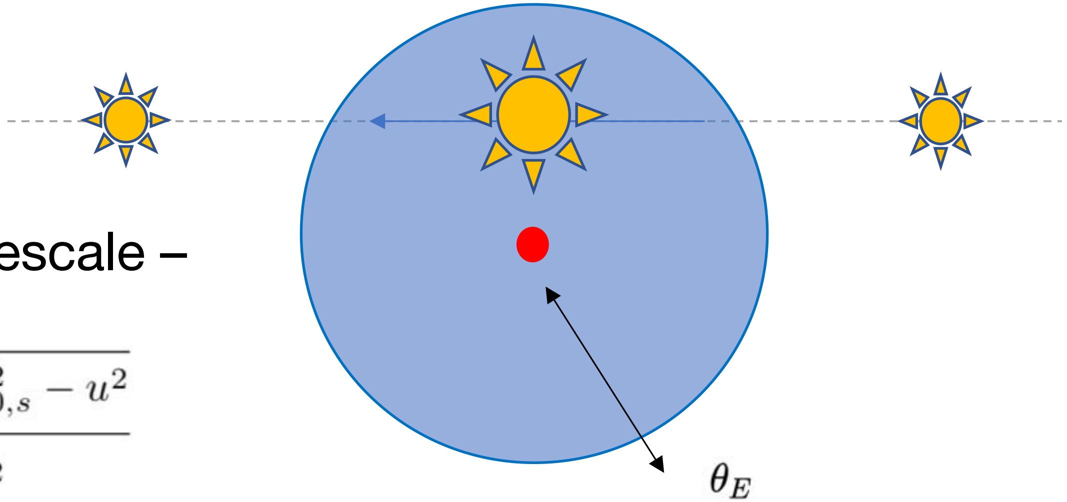
$$A_s(K_s;K_0) = 10^{-0.4(K_0 - K_{s,ab} - \Delta - A_K)} = 10^{-0.4(K_0 - K_s)}$$

$$\Rightarrow \quad u_{0,s}^2 = 2A(K_s;K_0)/\sqrt{A(K_s;K_0)^2 - 1} - 2$$

Bright-star lensing $K_s \lesssim K_0$

Can always be detected, care about amplification timescale – Nearly exactly the time for source to pass the ER!

$$u_{0,s} \approx 1 \qquad \tau = \frac{2R_S\sqrt{u_{0,s}^2 - u^2}}{v_2}$$



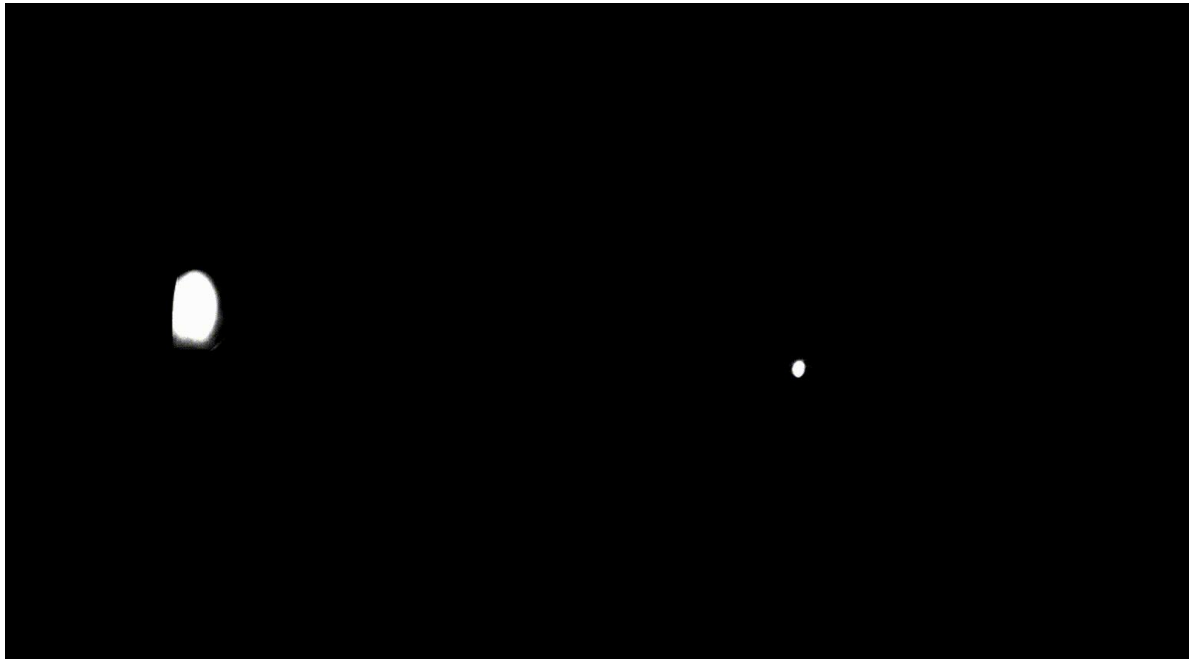
Basics of Micro-lensing

Resolved Lensing

Requirement:

Angular separation between central stars bigger than between two images

$$\Sigma_{center}(K_0)^{-1/2} \gtrsim \theta_E$$



Effect: effective amplification halved

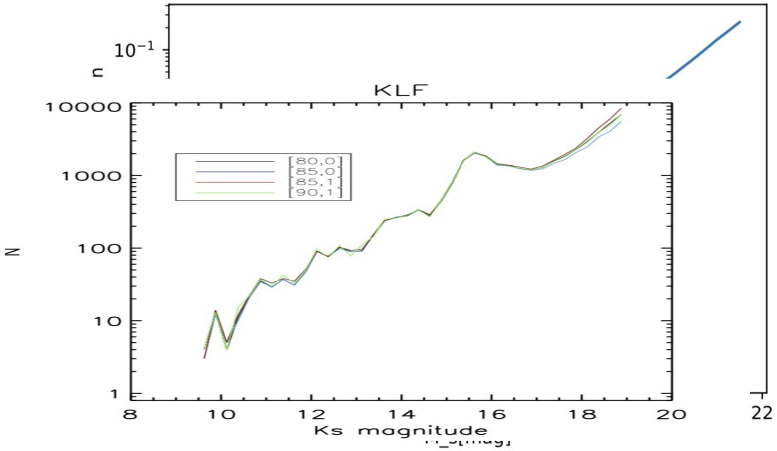
$$A' = A/2$$

These are all models for ONE lensing event.
How about for a population of stars in the galactic center?

Model of Galactic Center NSC

KLF:

Luminosity
probability distribution

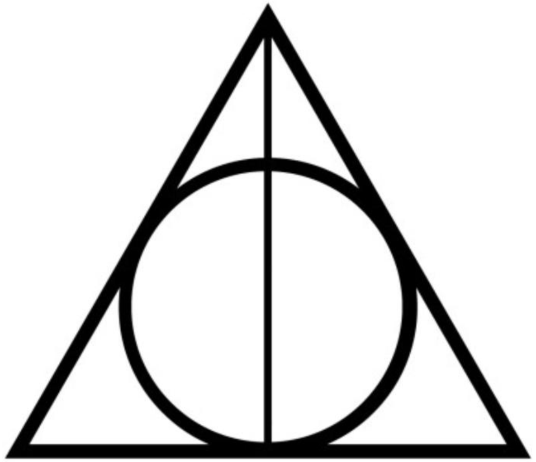


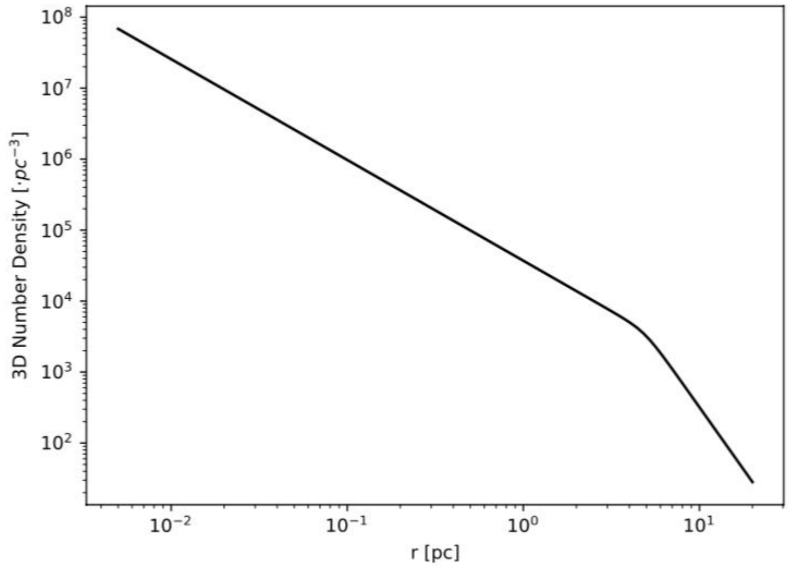
Gallego-Cano + 18

Number density:

Gallego-Cano + 18

$$n_*(r)$$



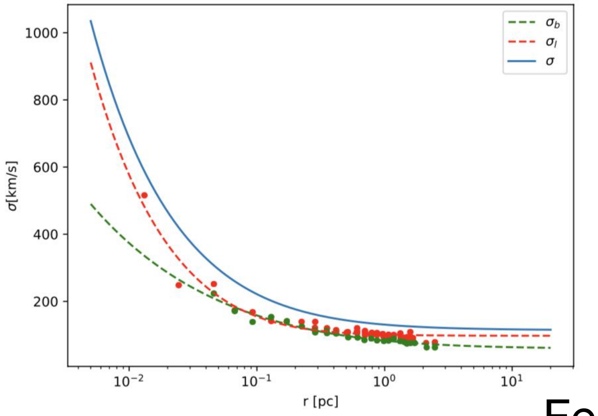


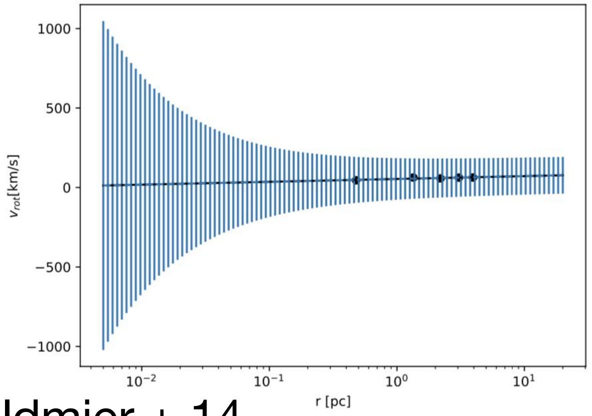
Velocity Distribution:

Transverse
Gaussian dispersion

$$v_{\rm rot}(r)$$

$$\sigma^2 = \sigma_l^2 + \sigma_b^2$$



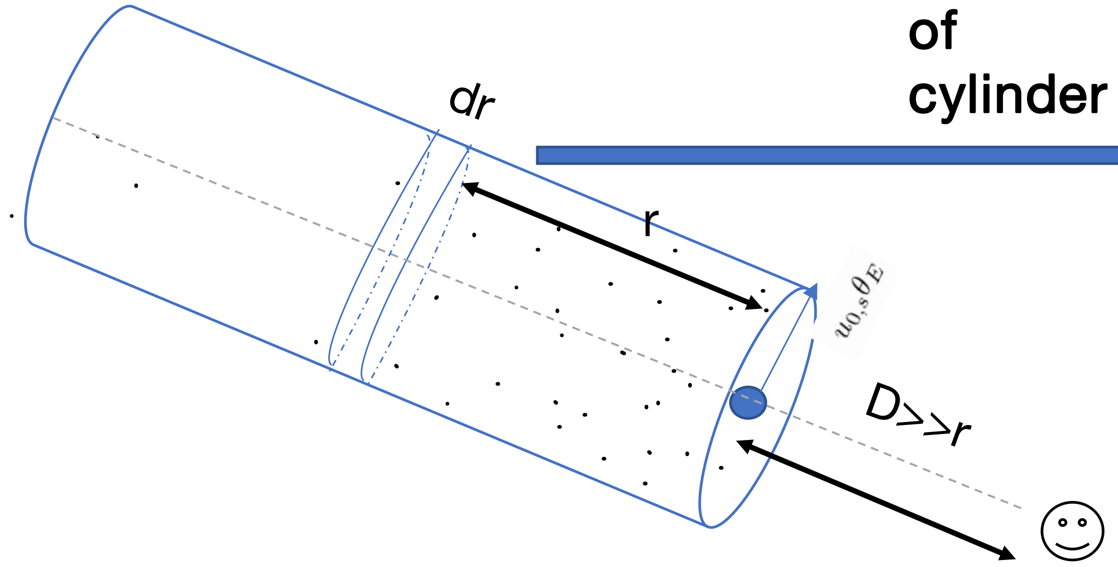


Feldmier + 14

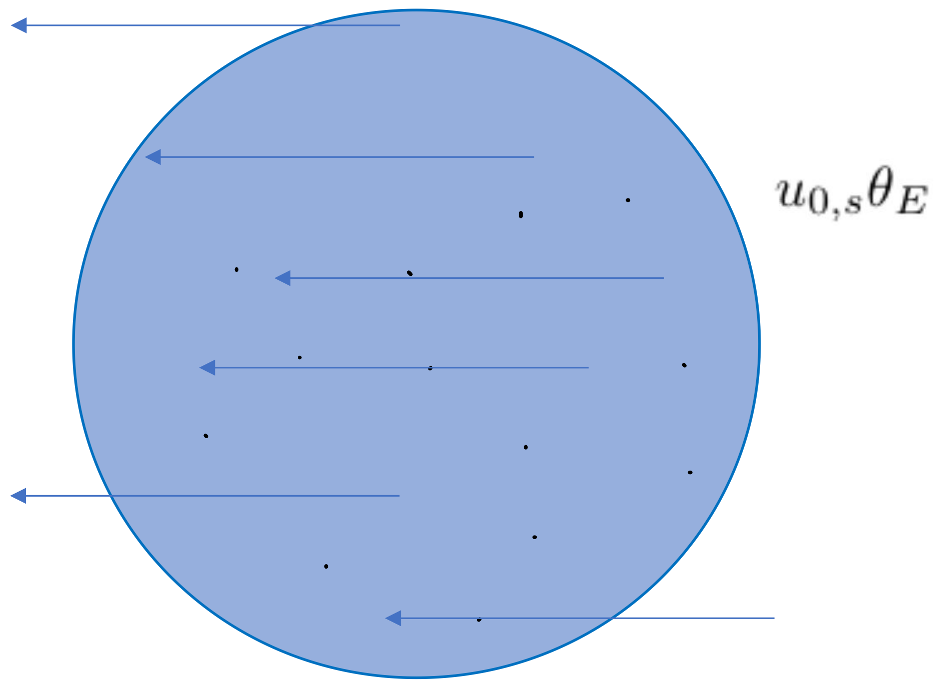
Event Rates

$$R_{\rm E} = \left(\frac{4GM_\bullet}{c^2}\cdot\frac{Dr}{D+r}\right)^{1/2} \sim 2.73\times10^{15}\left(\frac{r}{1\ {\rm pc}}M_{4.0}\right)^{1/2}\ {\rm cm}$$

Given luminosity and distance:



A slice of cylinder



For every dr :

$$d\Gamma = \frac{d\tau_*}{\bar{\tau}} = \frac{n_*\pi(R_E u_{0,s})^2 dr}{\bar{\tau}}$$

$$= 2u_{0,s}R_E\bar{v_2}dr$$

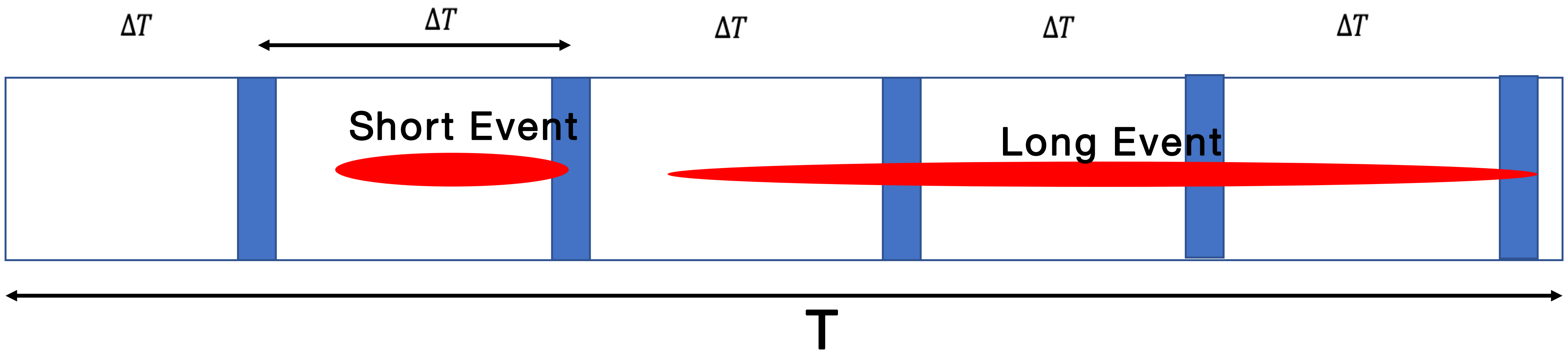
Kiraga & Paczynski 1994

Total Rate

$$\Gamma(K_0) = 2\langle u_{0,s}\rangle\int_{r_1}^{r_2} R_{\rm E}(r)\overline{v_2}(r)n_*(r)dr$$

0.005-20pc

For Specific Observation Campaign



Long Events

$$\tau = \frac{2R_S\sqrt{u_{0,s}^2 - u^2}}{v_2} > \Delta T$$

Short Events

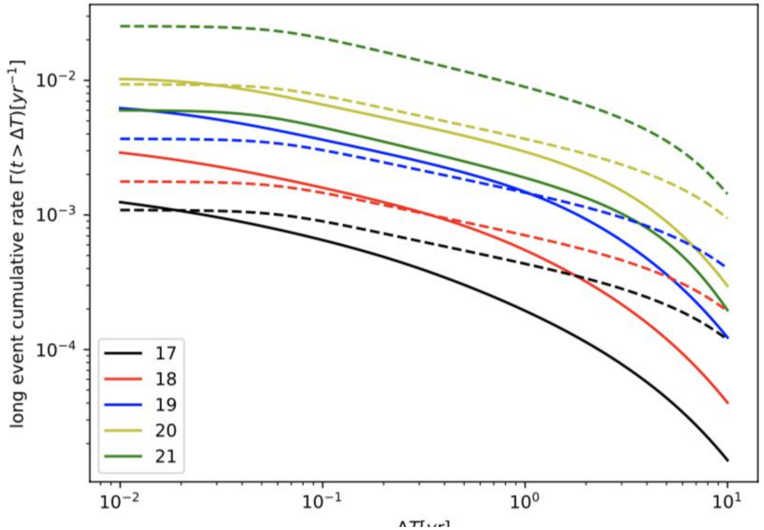
$$\tau < \Delta T, P_{short}/P_{long} = \tau_{short}/\Delta T$$

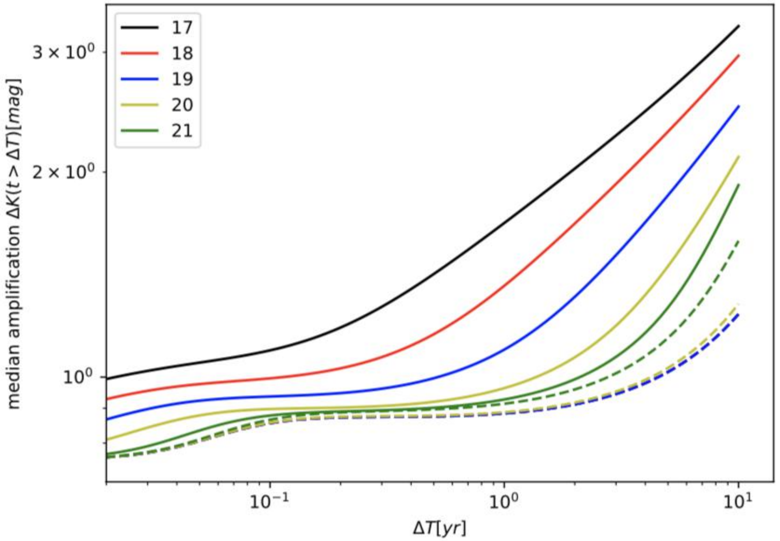
$$P = P_{\text{short}} + P_{\text{long}} = n\bar{\tau}_{\text{short}}\,\Gamma_{\text{short}} + T\Gamma_{\text{long}}\,, \Gamma_{\text{short}} + \Gamma_{\text{long}} = \Gamma_{\text{total}}$$

Results (E.g. Unresolved lensing)

Chen+ 19 in prep

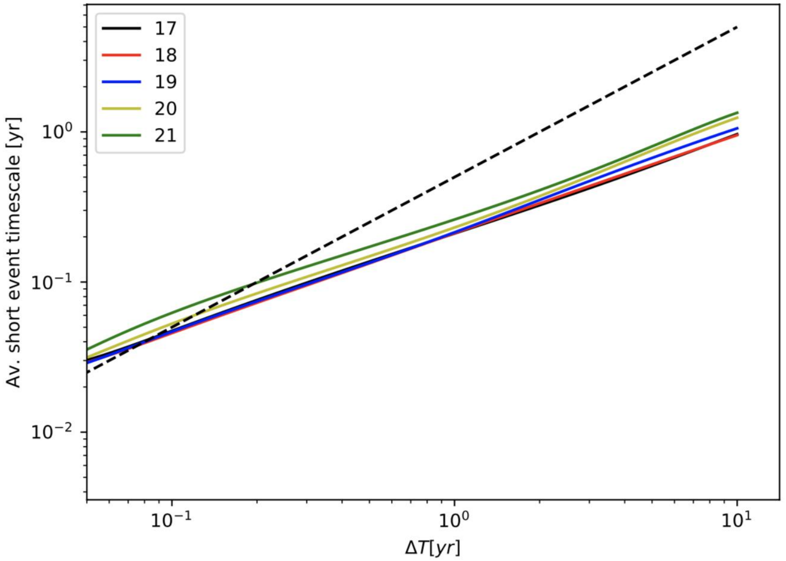
Long event rate with respect to detection interval





Long event average amplification with respect to detection interval

Short event average timescale with respect to detection interval



$$n\bar{\tau}_{\rm short}\,\Gamma_{\rm short} + T\Gamma_{\rm long}$$

E.g. 10 yrs, 10 runs, 19 mag

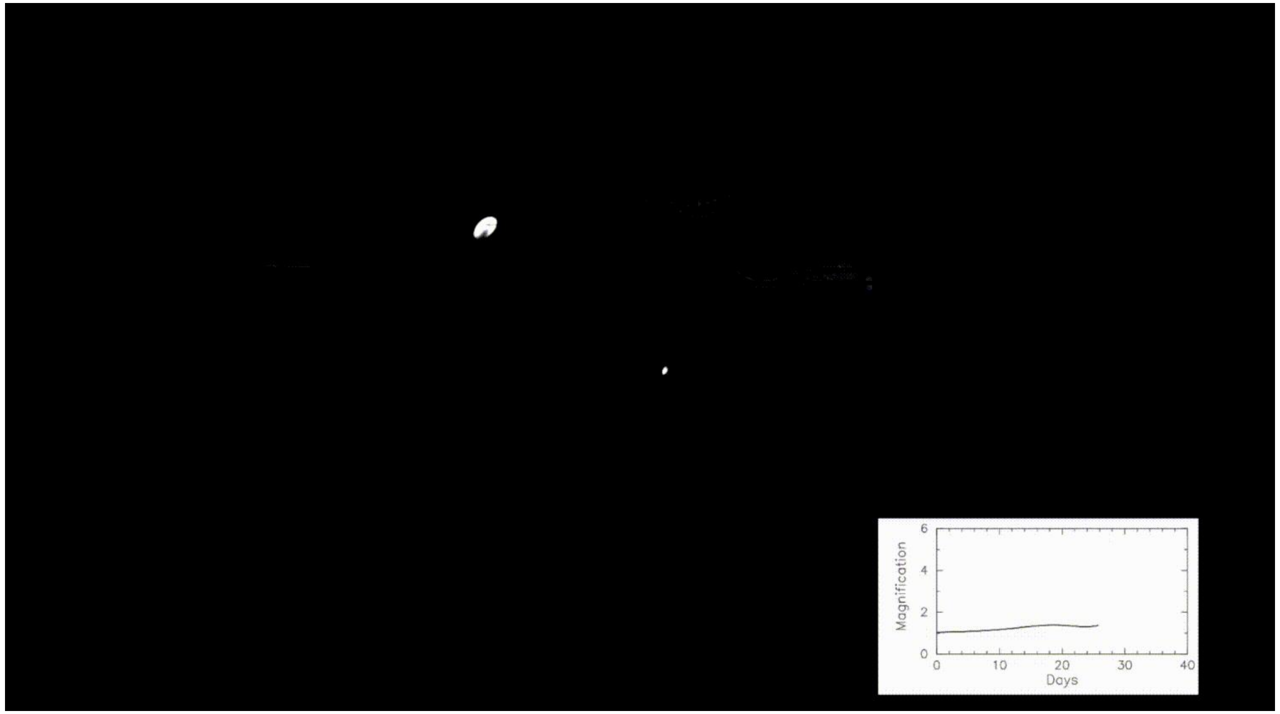
10*0.2*0.004+10*0.005=0.06 times

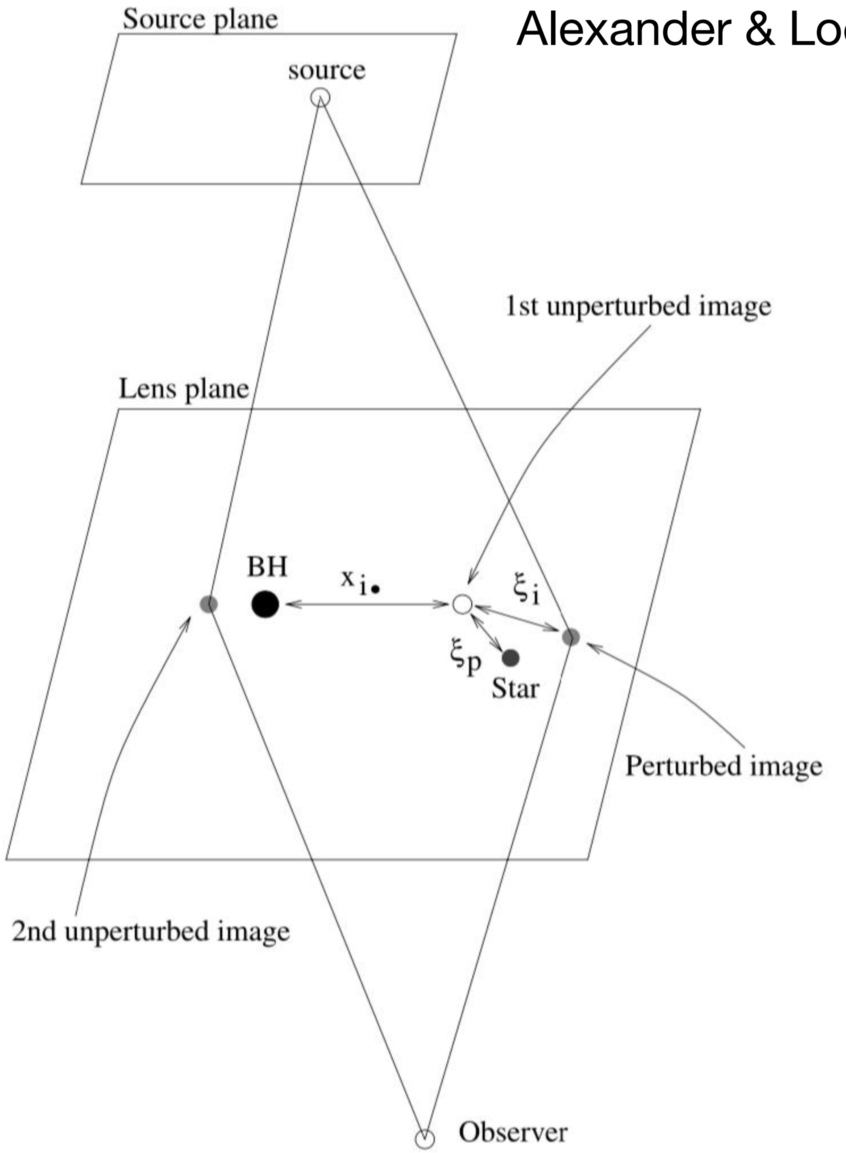
Average 1 magnitude amplification

Secondary lens

Alexander & Loeb 2001

$$R_{\mathrm{E}} = \left(\frac{4GM_\bullet}{c^2} \cdot \frac{Dr}{D+r} \right)^{1/2}$$

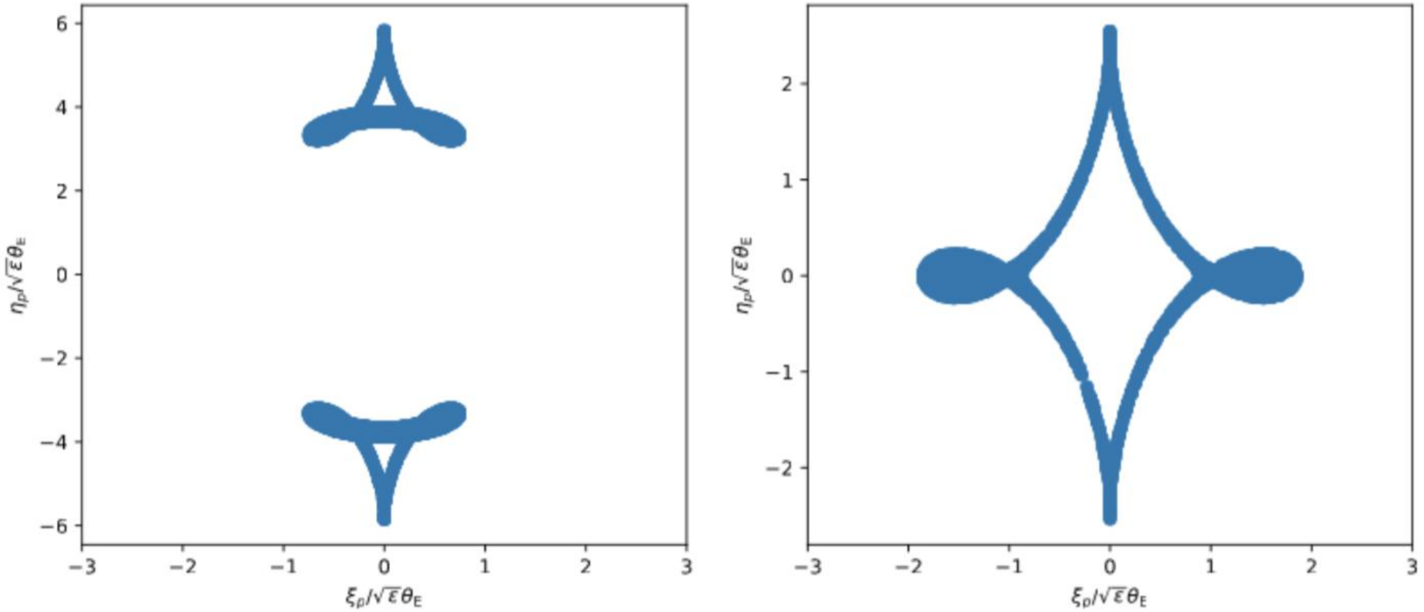


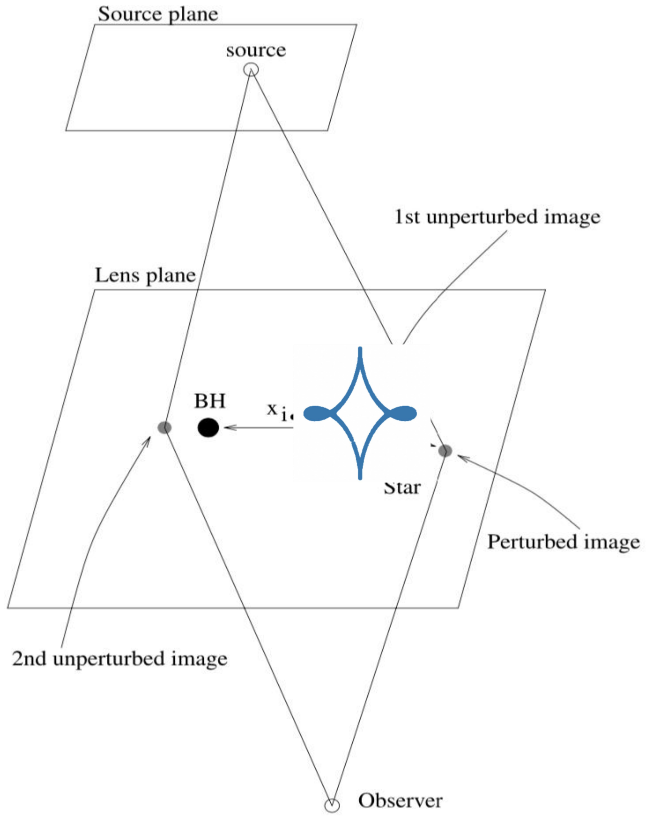


Secondary lens

$$\epsilon = m_* / M_{\rm SMBH}$$

Assume $\epsilon_* = 2.5 \times 10^{-7}$





Chen+ 19 in prep

Figure 8. Areas in the (ξ_p, η_p) plane that satisfy the constraint of $A > 300\%$ (for *any* of the perturbed images generated), left panel: $\gamma = 1.3$; right panel: $\gamma = 0.6$. The intrinsic shapes differ for γ larger and smaller than 1, and approaches infinity for γ approaching 1, these images are consistent with (Gould & Loeb 1992)

Optical Depth (Lens)

$$\Sigma_*(r) = 2\int_r^\infty \frac{x n_*(x)\mathrm{d}x}{\sqrt{x^2 - r^2}}$$

$$\tau_*(>A, x_{BH}) = \sigma_*(>A, x_{BH})\Sigma_*(x_{BH}) \ll 1$$

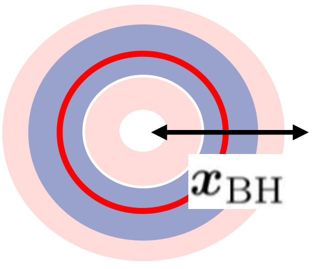
Higher order terms are neglected (lower probability for TWO secondary lenses)

Cross Section in Source Plane

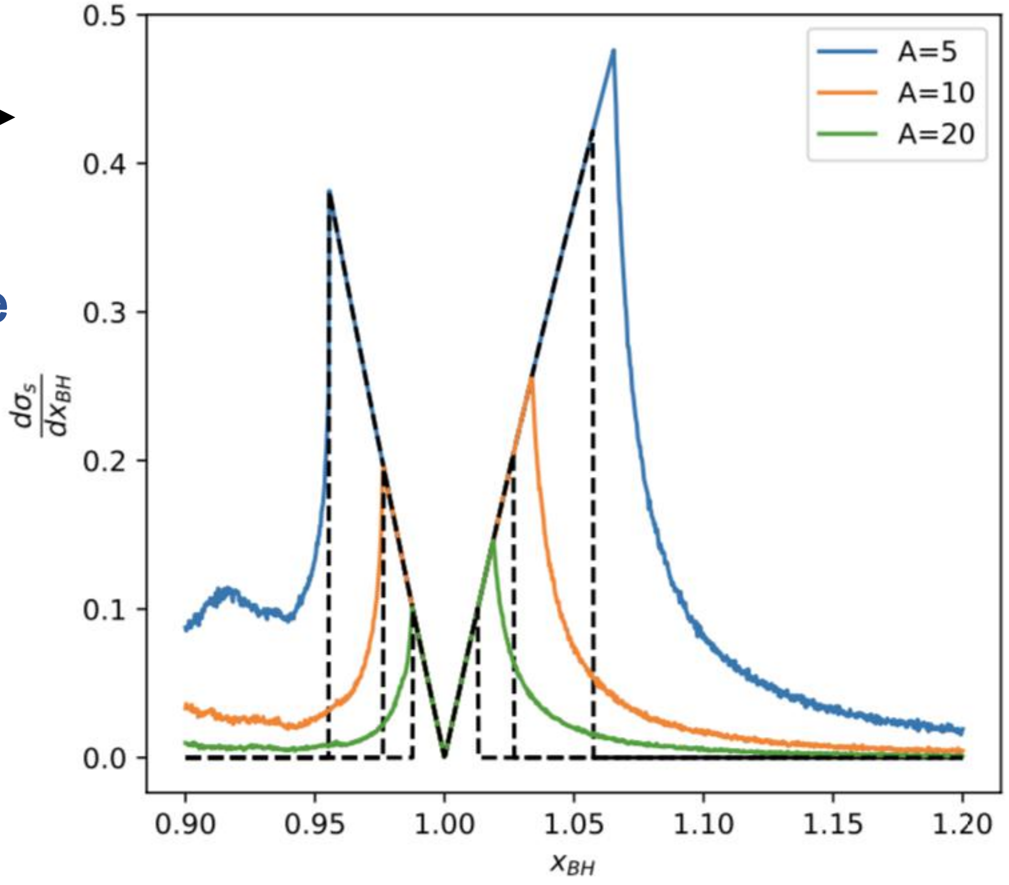
$$P\left(>A, \boldsymbol{x}_{\mathrm{BH}}\right) \simeq \tau_*\left(>A, x_{\mathrm{BH}}\right)+\Theta\left(A_{\mathrm{BH}}-A\right)$$

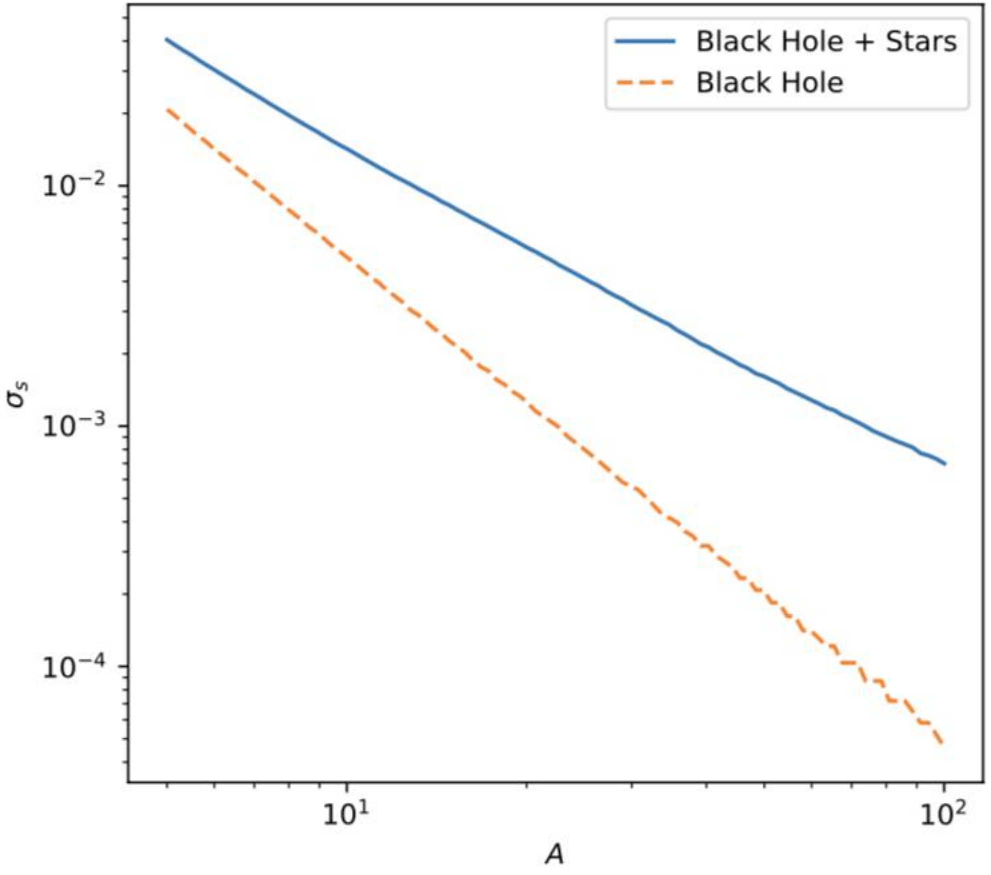
$$\sigma_s(>A)=2 \int P\left(>A, x_{i\mathrm{BH}}\right) A_{\mathrm{BH}}^{-1}\left(x_{i\mathrm{BH}}\right) x_{i\mathrm{BH}} d x_{i\mathrm{BH}}$$

Heaviside step function:
Only when the BH isn't enough to give the amplification needed does secondary lens optical depth play a role in putting a probability weight <<1



Lens Plane

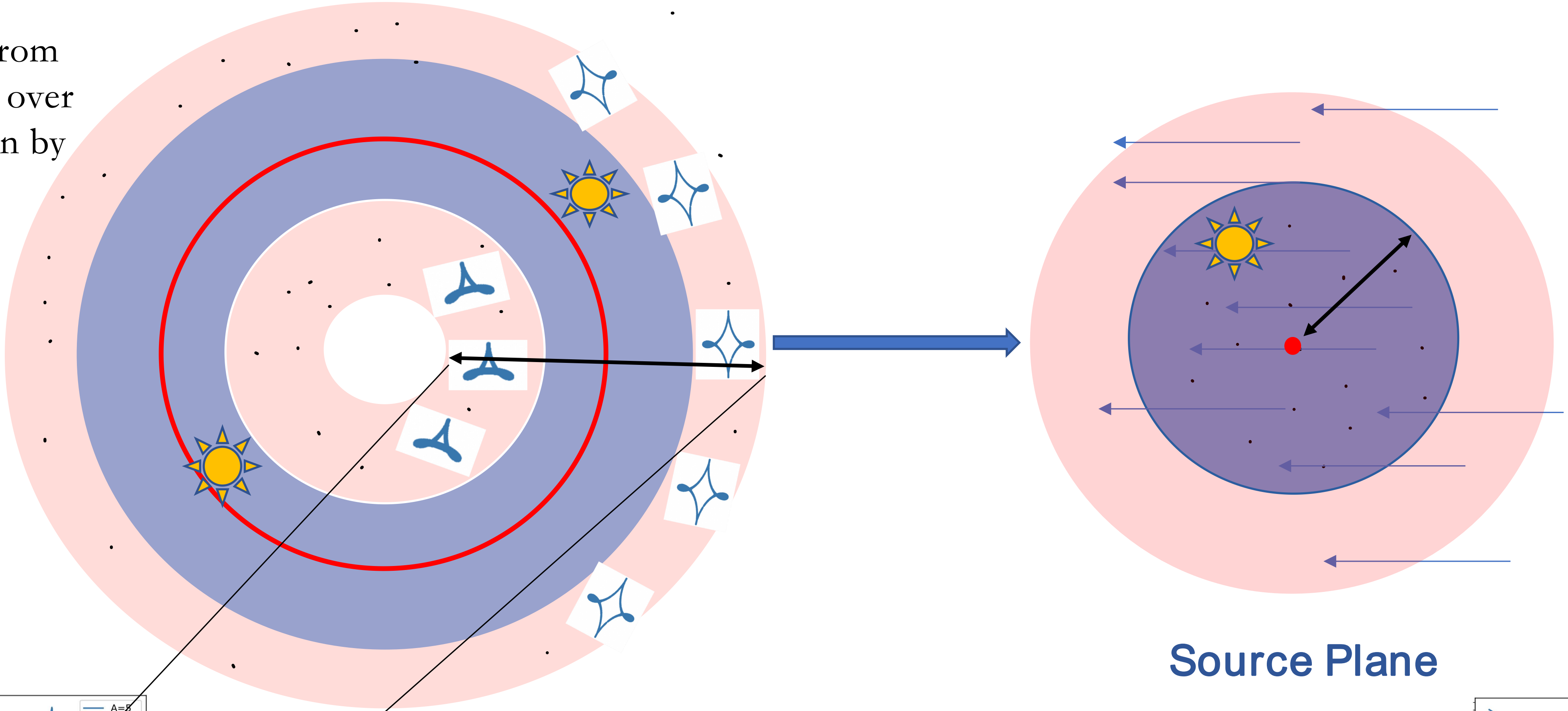




Cross Section in Source Plane

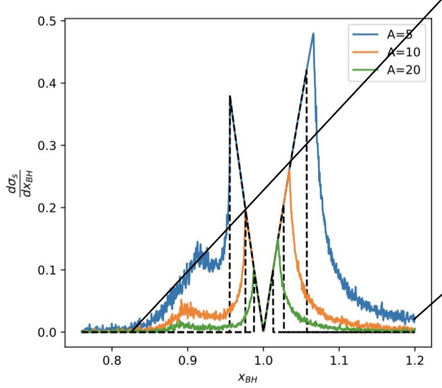
$$\sigma_s(>A) = 2\int P(>A, x_{i\mathrm{BH}})\, A_{\mathrm{BH}}^{-1}(x_{i\mathrm{BH}})\, x_{i\mathrm{BH}} dx_{i\mathrm{BH}}$$

Obtained from integrating over contribution by annulus

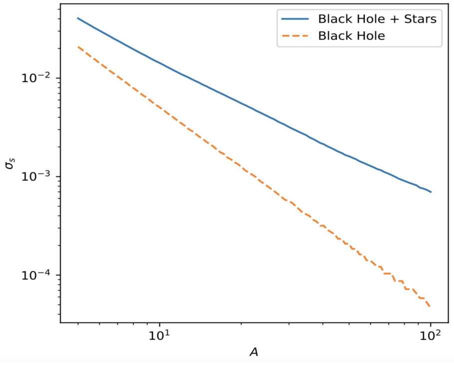


Lens Plane

Source Plane



- Annulus around ER on lens plane = one point behind lens the source plane
- Contribution by BH alone – projected back with weight 1
- Contribution by secondary lenses – projected back with weight optical depth



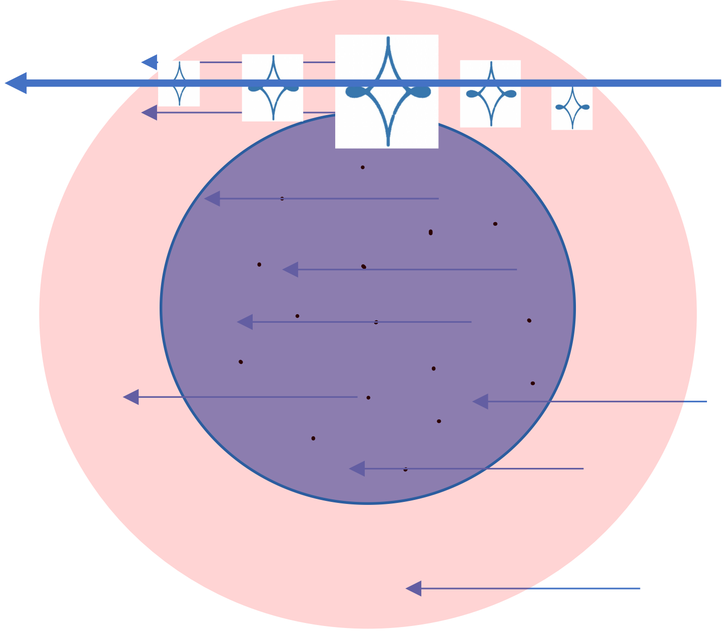
Results

Background star surface density (in KLF form)

$$\Sigma_s(< K) = \hat{\Sigma}_s 10^{bK}$$

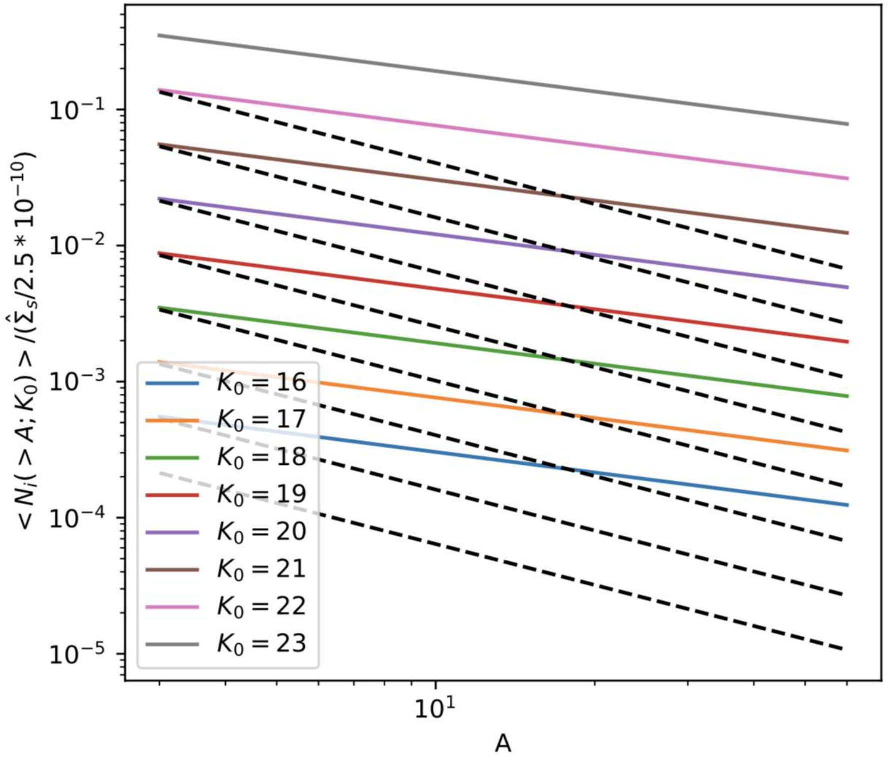
$$\langle N_i\,(> A; K_0)\rangle = \int_A^{\infty} dA' \int_{-\infty}^{K_0} dK \left|\frac{d\sigma_s}{dA}\right|_{A'} \left|\frac{d\Sigma_s}{dK}\right|_{K+K_{A'}}$$

Alexander & Loeb 2001



$$\Gamma = N_i/\bar{\tau}?$$

Velocity brings too much complication into RATE and timescale calculation

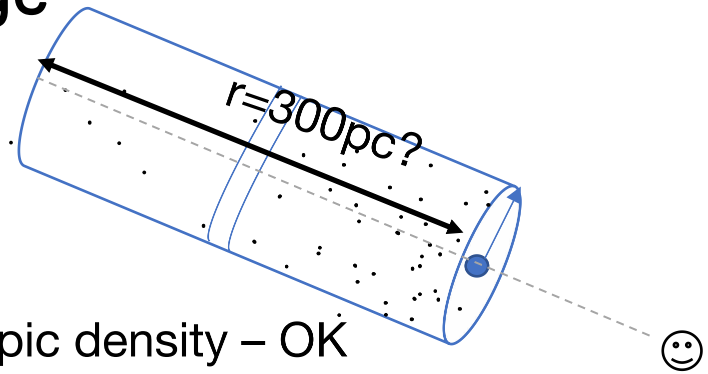


Snapshot of the Source Plane

How many events can we see looking at the GC 2’’ ANY TIME?

Future Prospects

- **Density profiles for GC Disk and Bulge**



Anisotropic density – OK
Anisotropic velocity - complicated

- **Distribution of Secondary lens mass**

Assumed uniformly solar-mass
Different $\epsilon = m_*/M_{\rm SMBH}$ might have different probability weight at different annulus.

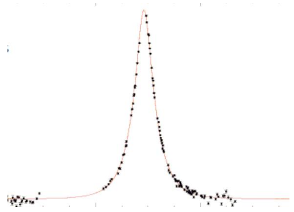
This has potentials to solve problems for microlensing in other galaxies and asteroid in planetary systems

- **Background stellar density calls for better model**

$$\Sigma_s(<K) = \hat{\Sigma}_s 10^{bK}$$

Uncertainty in velocity, density, extinction……

- **Analysis of survey-data: Hypothesis test**



Non periodic variable K-band source with predicted typical magnification and timescale in direction of SMBH (0.01-0.1’’)?

Microlensing events from campaigns Within central 2’’? VVV, OGLE…