

GRAVITATIONAL LENSING

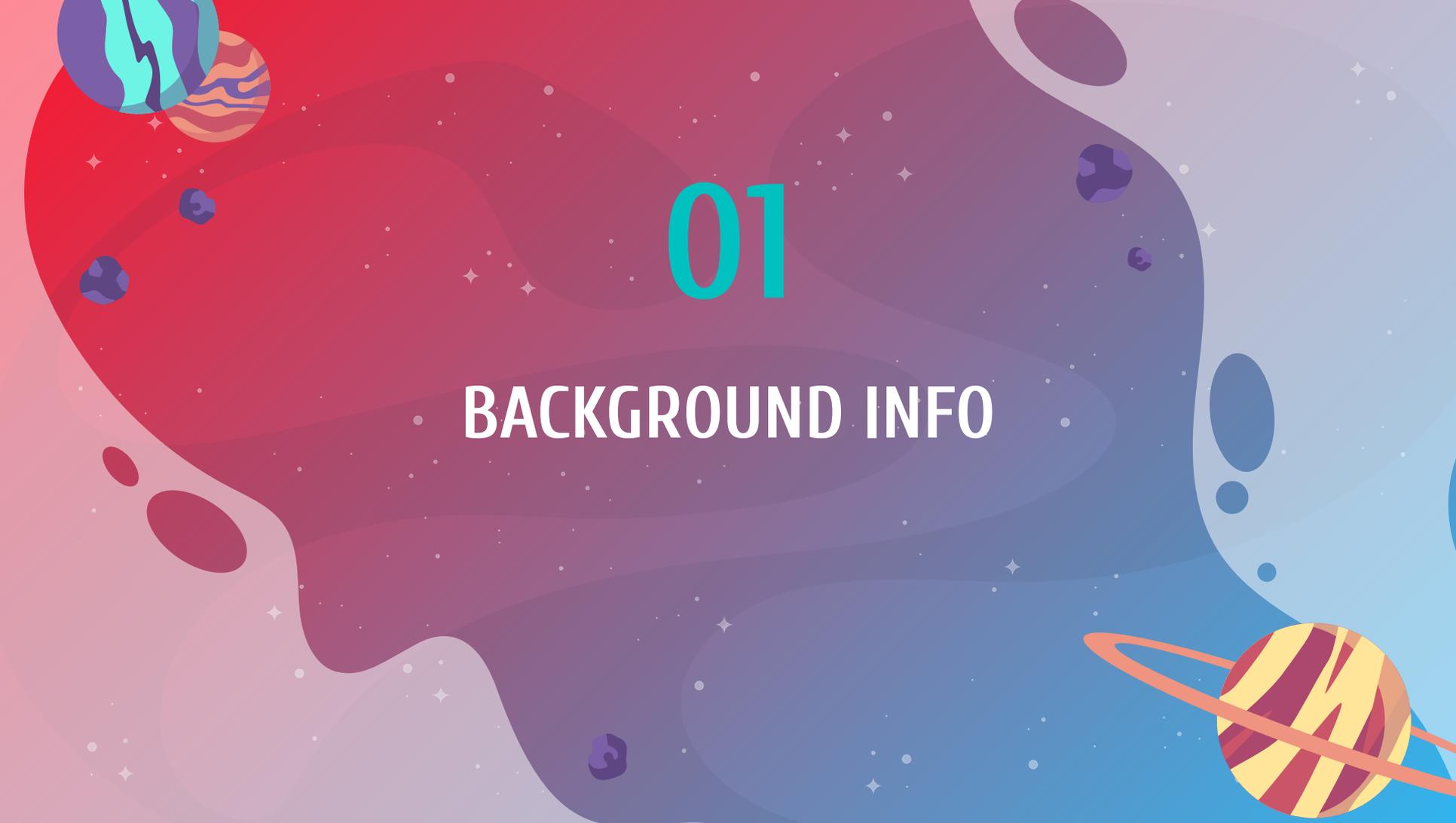
Diego Bonilla, Kate Bostow, Annie
McCutcheon, and Edgar Vidal

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01

BACKGROUND INFO

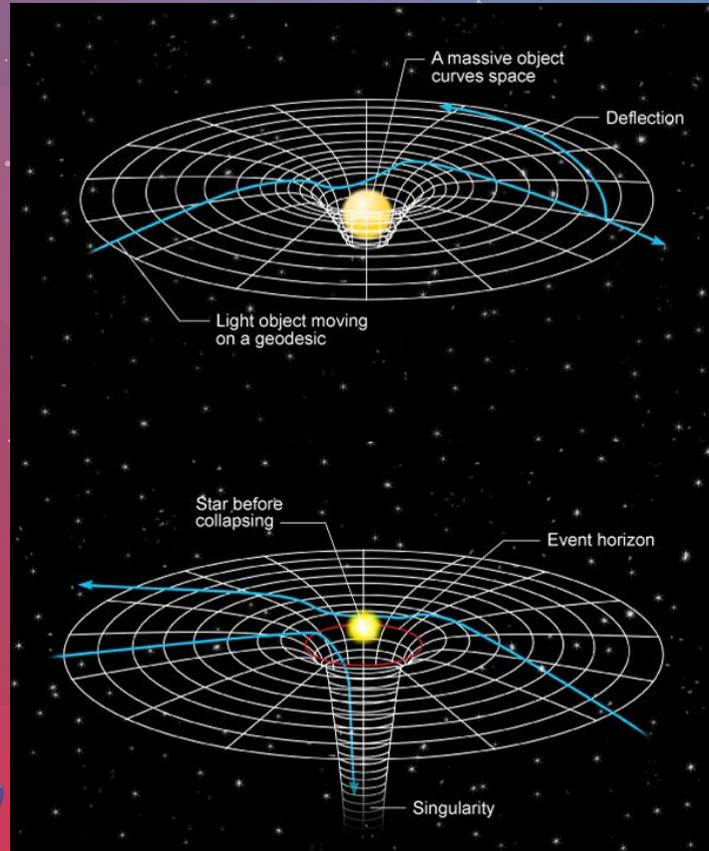


BACKGROUND INFO

- General Relativity: mass warps space-time
 - Think of space-time as a 2D blanket
- When an object is placed on it, the blanket stretches out

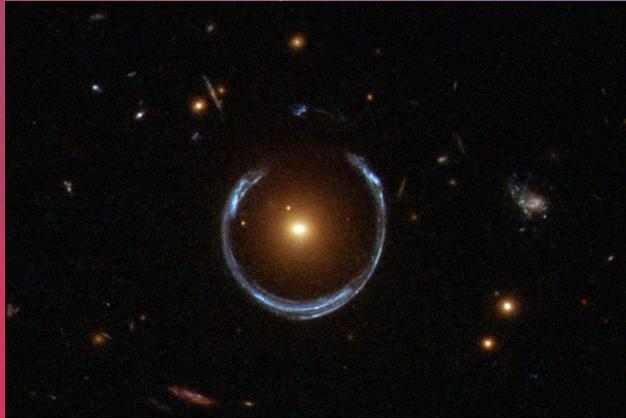


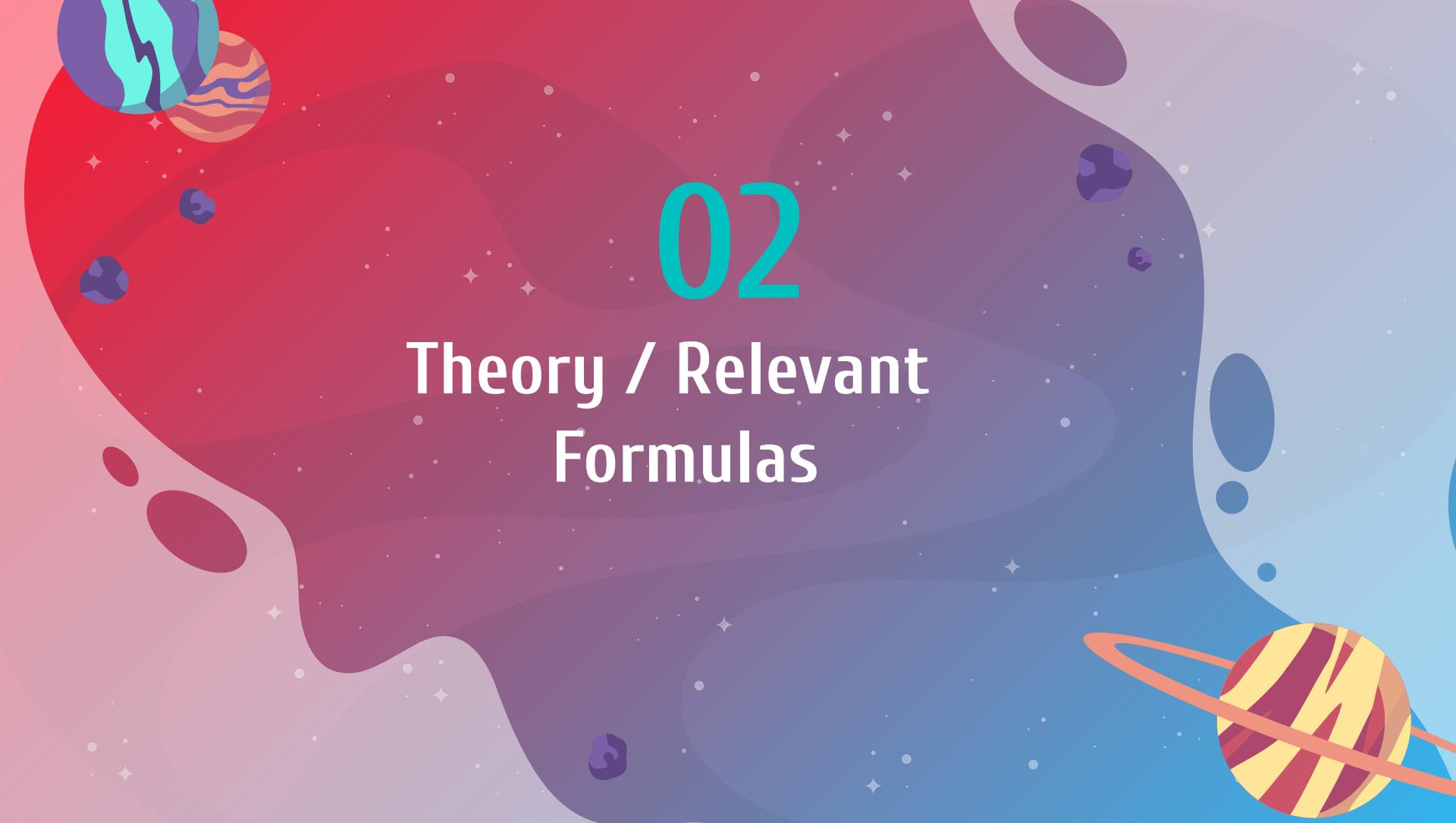
MORE MASS = MORE STRETCHING!



WHAT IS GRAVITATIONAL LENSING?

- The effect of the massive object curves traveling light!
- This causes objects to appear in different places than they actually are
- Can also change object's appearance entirely with enough curvature!



The background is a vibrant, abstract space scene. It features a gradient from deep red on the left to light blue on the right. Scattered throughout are various celestial bodies: a planet with blue and red stripes in the top left, a ringed planet with yellow and red stripes in the bottom right, and several smaller planets with blue and purple patterns. Numerous small white stars and sparkles are scattered across the background, creating a sense of depth and movement.

02

Theory / Relevant Formulas

1 Gravitational Lensing Formula Special Case

The deflection is defined by $\tilde{\alpha}$ where $M(\xi)$ is the mass within the distance of closest approach, ξ

$$\tilde{\alpha} = \frac{4GM(\xi)}{c^2} \frac{1}{\xi^2}$$

For the sun, $\tilde{\alpha} = \frac{4GM_{\odot}}{c^2} \frac{1}{R_{\odot}^2} = 1.74$ arcseconds

**1 arcsecond = 1/3600 degree

$$\alpha(\theta) = \frac{D_{ls}}{D_{os}} \tilde{\alpha}(\theta)$$

$$\beta(\theta) = \theta - \alpha(\theta)$$

$$\beta(\theta) = \theta - \frac{D_{ls}}{D_{os}D_{ol}} \frac{4GM}{c^2\theta}$$

If we set $\beta(\theta) = 0$ such that the source is just behind the lense, then we get,

$$\theta = \theta_E = \sqrt{\frac{4GM}{c^2} \frac{D_{ls}}{D_{os}D_{ol}}}$$

D_{ij} = distance from plane i to plane j

l= lens

o=observer

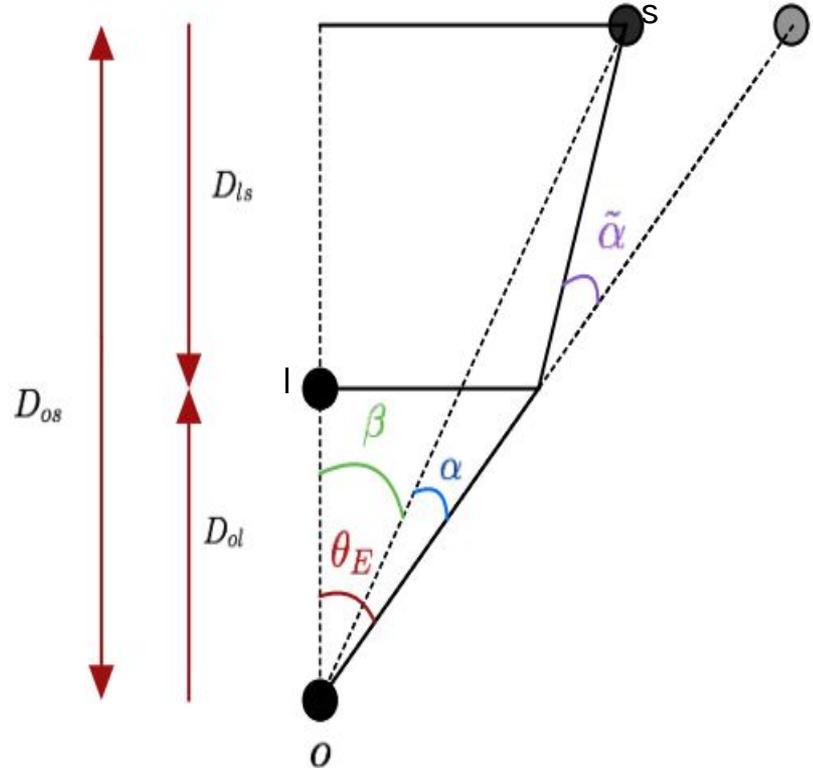
s= source

assuming that $D_{ls} \approx D_{ol}$

$$\theta = \theta_E = \sqrt{\frac{4GM}{c^2 D_{os}}}$$

I will write a function that can give us the angle for the various parameters

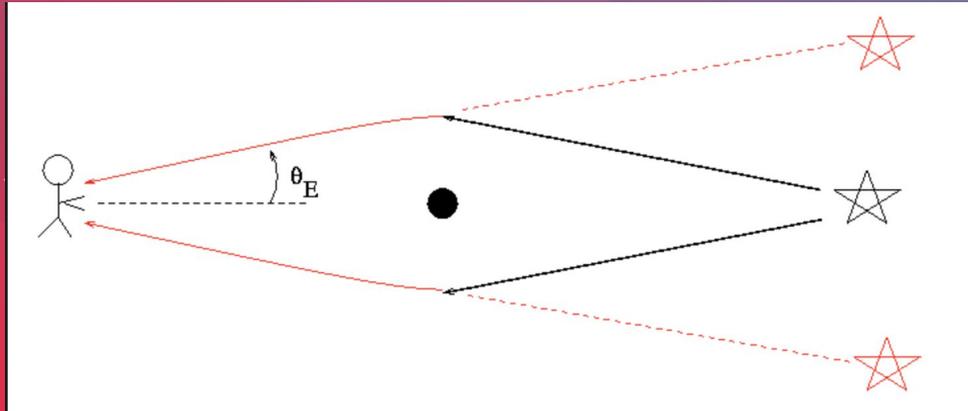
LATEX



RELEVANT EQUATION

$$\theta_E = \sqrt{\frac{4GM}{Dc^2}}$$

- As mass increases, the angle of deflection increases
- Larger distance creates a smaller angle

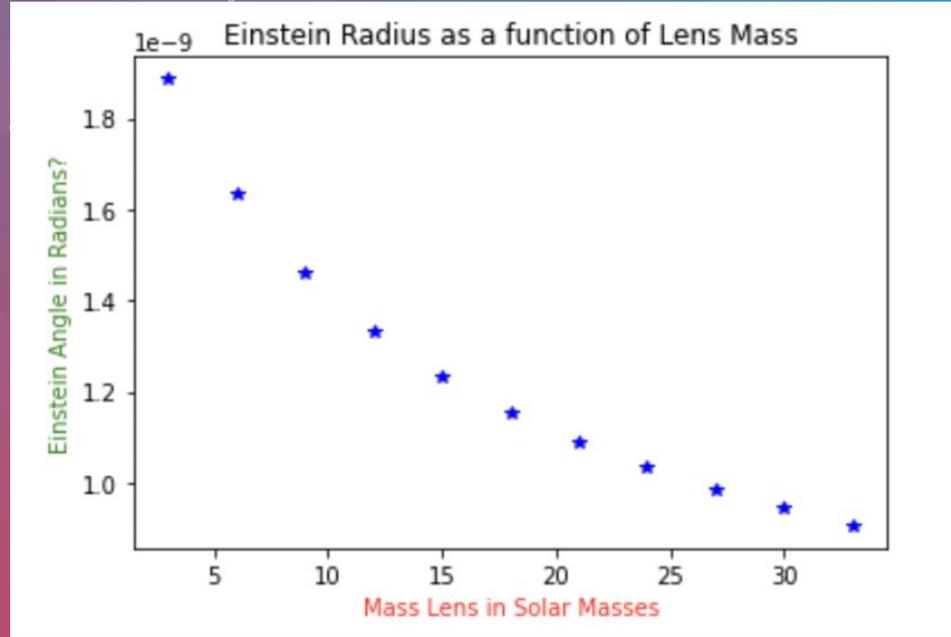


The background is a vibrant, stylized space scene. It features a gradient from deep red on the left to light blue on the right. Scattered throughout are various celestial bodies: a large yellow and orange sun in the top right, a planet with blue and white stripes, several smaller purple and blue planets, and numerous white stars of varying sizes. The overall aesthetic is modern and illustrative.

03

METHODS/TECHNIQUES

INITIAL PLOT OF ANGLE VS. MASS



Einstein Angle Python Function

```
# Einstein Angle Function theta_E
constant = 4 * con.G / con.c**2

Mass = input('Mass in Solar Masses = ') * u.solMass
D_ol = input('D_ol in parsec = ') * u.parsec

def theta_e(Mass, D_ol):

    E = np.sqrt(constant * Mass / D_ol) * u.rad

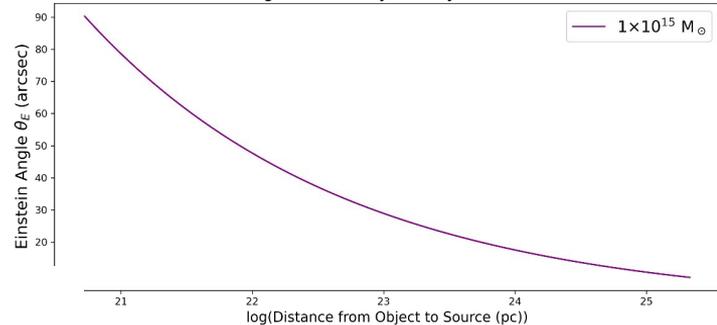
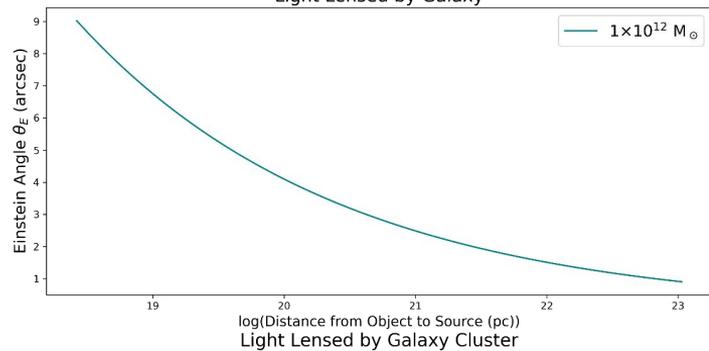
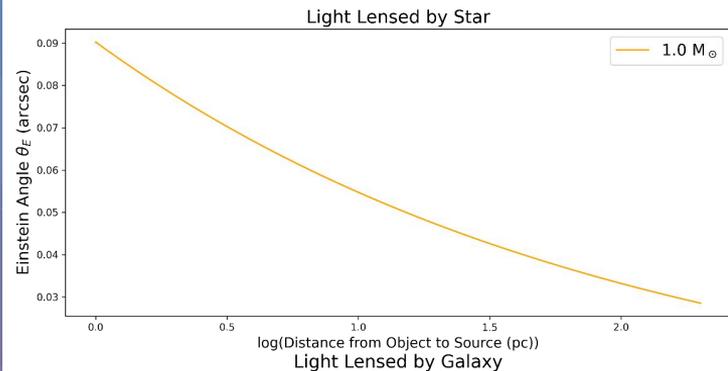
    return E.to(u.arcsec)

#E is in radians and 1 rad is 206265 arcseconds
print('\nthe Einstein Angle of Sagittarius A* (black hole at the center of the milky way galaxy)')
print('\ntheta_e = ',theta_e(Mass, D_ol))
```

Mass in Solar Masses = 4.154e6
D_ol in parsec = 26673

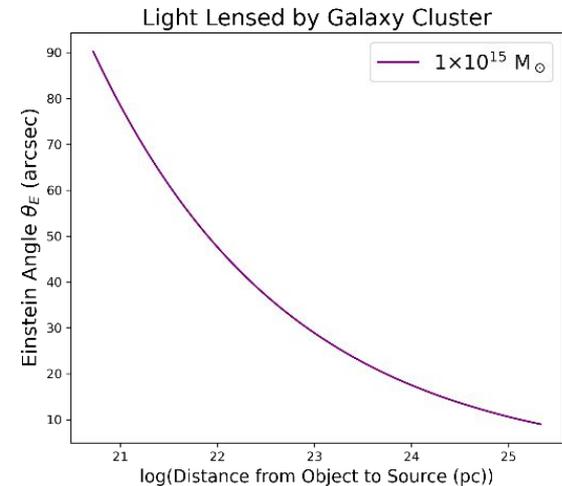
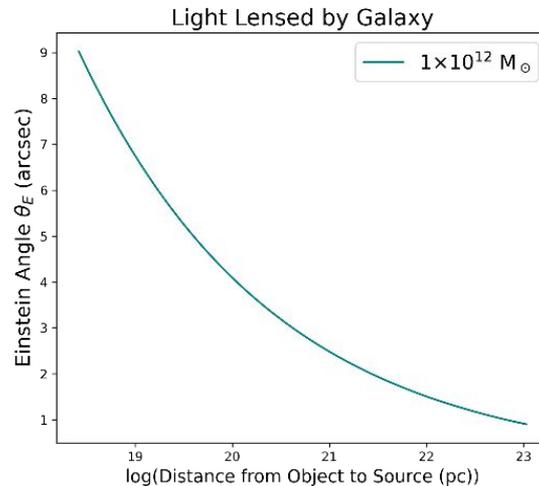
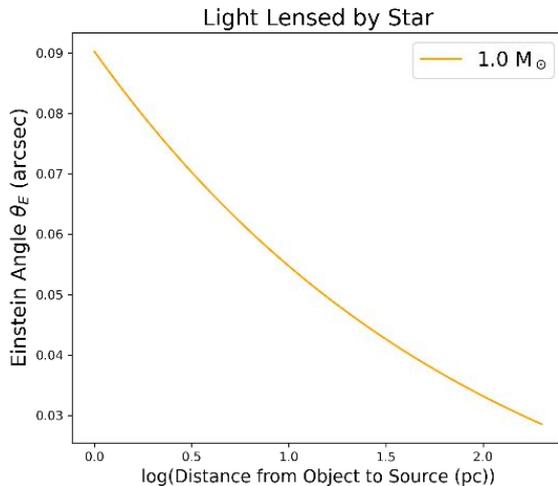
the Einstein Angle of Sagittarius A* (black hole at the center of the milky way galaxy)

theta_e = 1.1261916005486818 arcsec



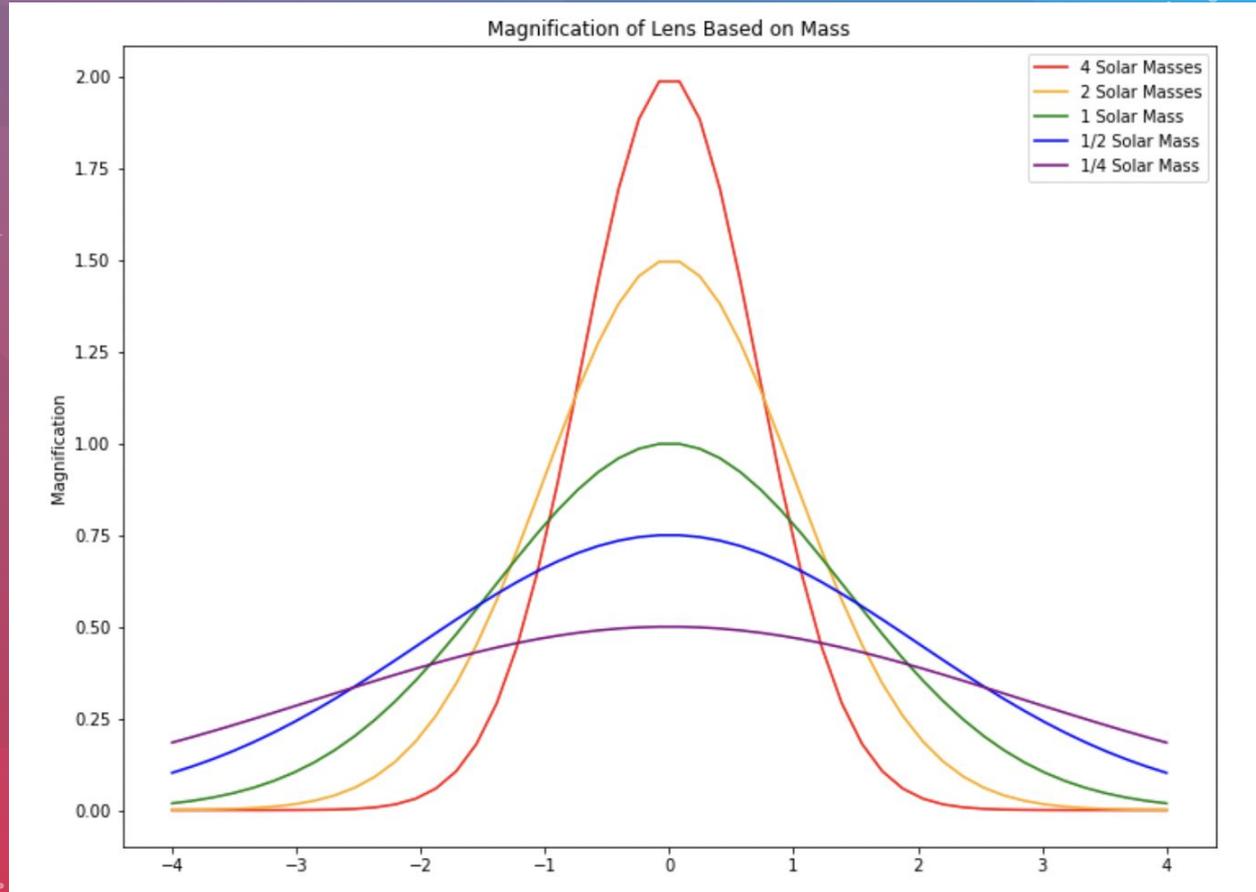
Need a Massive Object, some stars just do not deflect light enough, but blackholes, galaxies, galaxy clusters do!

Lens Mass M_{\odot}	D_{os}	θ_E
solMass	pc	arcsec
float64	float64	float64
1.0	100.0	0.009024330045344293
1.0	1000.0	0.0028537437300378554
1.0	10000.0	0.0009024330045344293
4154000.0	26673.0	1.1261916005486818
10000000000000.0	100000000.0	9.024330045344295
10000000000000.0	1000000000.0	2.8537437300378556
10000000000000.0	10000000000.0	0.9024330045344293
10000000000000000.0	10000000000.0	90.24330045344293
10000000000000000.0	100000000000.0	28.537437300378553
10000000000000000.0	1000000000000.0	9.024330045344295



If the black hole/star is more massive, the magnification increases!

$$\mu = \frac{u^2 + 2}{u\sqrt{u^2 + 2}}$$



RESOURCES

LECTURES

- Astro 7B Lecture 25 (Spring 2020)

Academic Papers

Abdo, A. "Department of Physics and
Astronomy Michigan State
University East Lansing, Michigan
48823."