GRAVITATIONAL LENSING

LECTURE 5

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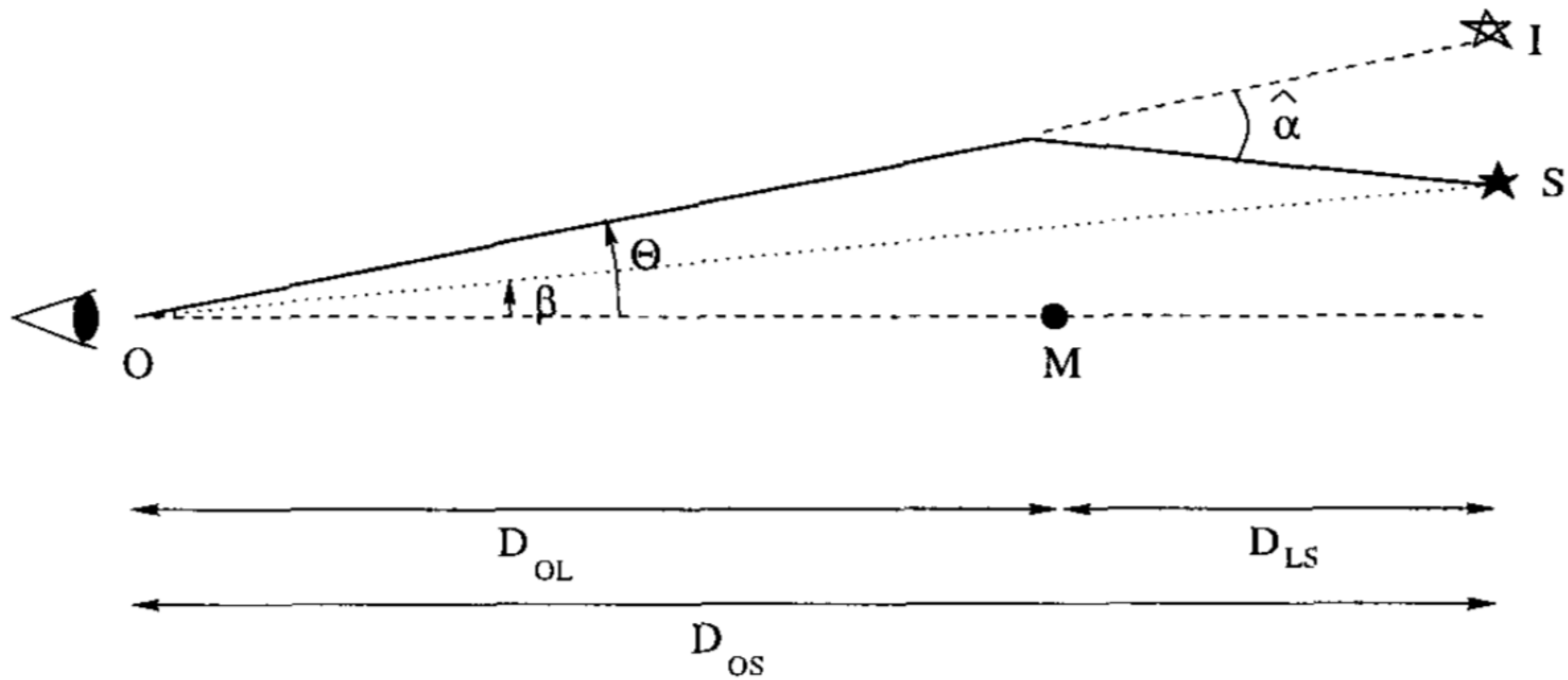
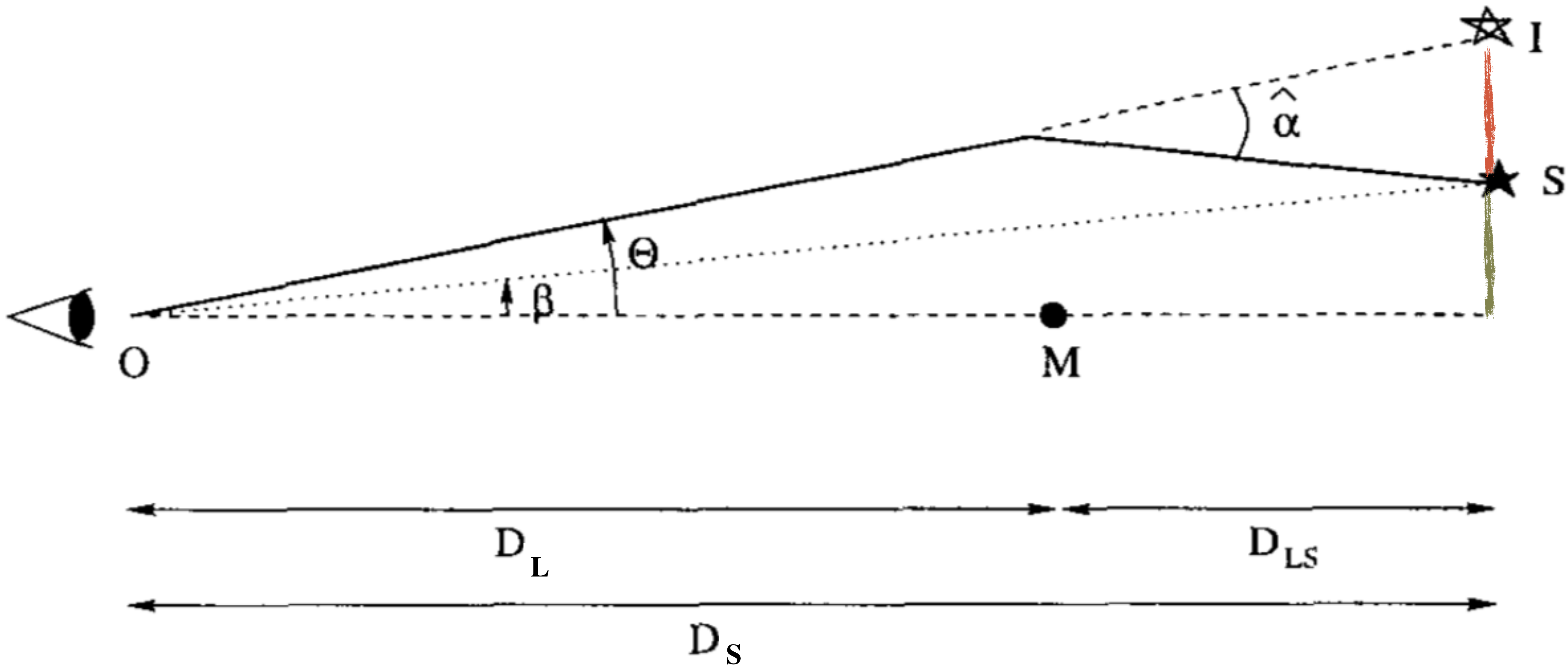
- the lens equation
- lensing potential

LENS EQUATION



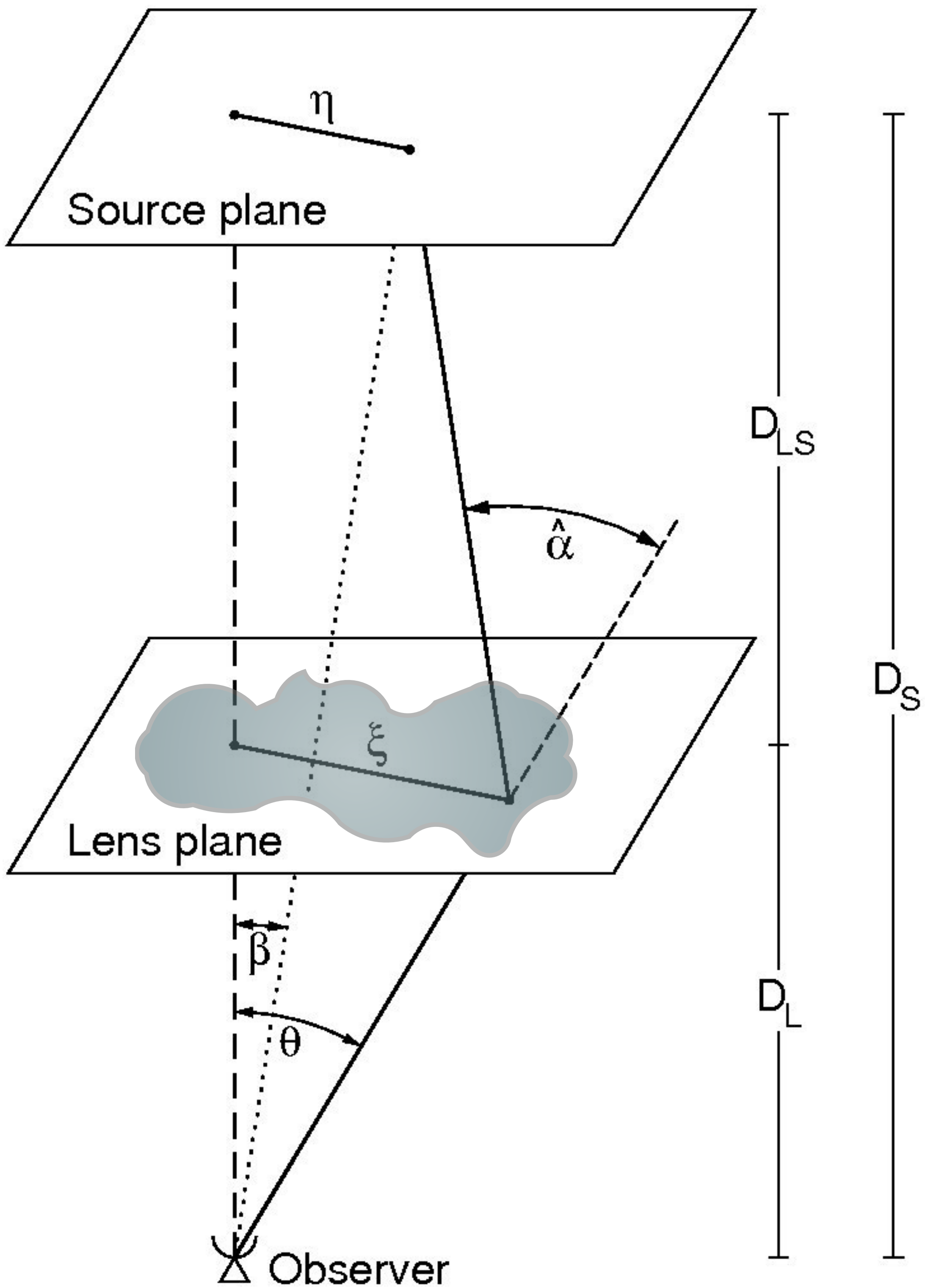
- We seek a relationship between observed and intrinsic positions of a source in a gravitational lensing event
- In absence of the lens, the light emitted by a distant source reaches the observer along a line-of-sight, which identifies the ***source' intrinsic position*** on the sky
- If there is a deflector, the source won't appear at the same position anymore: photons originally emitted in a different direction are deflected such to reach the observer, who will see the source at a different position, called the ***observed position of the image***

LENS EQUATION



$$D_S\theta = D_S\beta + D_{LS}\hat{\alpha} \Rightarrow \beta = \theta - \frac{D_{LS}}{D_S}\hat{\alpha}(\theta)$$

LENS EQUATION



Remember that:

1) *we are using the "Thin Screen Approximation"*
2) *positions on the lens and source planes are defined by vectors*
3) *the deflection angle itself is a vector*

$$\vec{\beta} = \vec{\theta} - \frac{D_{LS}}{D_S}\hat{\vec{\alpha}}(\vec{\theta})$$

$$\vec{\theta} = \frac{\vec{\xi}}{D_L} \qquad \vec{\beta} = \frac{\vec{\eta}}{D_S}$$

$$\vec{\beta} = \vec{\theta} - \vec{\alpha} \qquad \vec{\alpha}(\vec{\theta}) = \frac{D_{LS}}{D_S}\hat{\vec{\alpha}}(\vec{\theta})$$

OTHER NOTATIONS

Quite often, an alternative way is chosen to write the lens equation: the so called "adimensional" notation.

This implies the choice of a reference angle (or length) to scale the source and image positions and the deflection angle:

$$\vec{\theta} = \frac{\vec{\xi}}{D_L} \qquad \vec{\beta} = \frac{\vec{\eta}}{D_S} \qquad \vec{\alpha}(\vec{\theta}) = \frac{D_{LS}}{D_S}\hat{\vec{\alpha}}(\vec{\theta}) \qquad \vec{\beta} = \vec{\theta} - \vec{\alpha}$$

$$\theta_0 = \frac{\xi_0}{D_L} = \frac{\eta_0}{D_S}$$

the reference angle subtends the reference scales on the lens and on the source planes

dividing both members of the lens equation by the reference angle…

$$\vec{y} = \vec{x} - \vec{\alpha}(\vec{x})$$

$$\vec{\alpha}(\vec{x}) = \frac{\vec{\alpha}(\theta)}{\theta_0} = \frac{D_L}{\xi_0}\frac{D_{LS}}{D_S}\hat{\vec{\alpha}}(\vec{\theta})$$

LENSING POTENTIAL

$$\hat{\vec{\alpha}} = \frac{2}{c^2}\int_{-\infty}^{+\infty}\vec{\nabla}_\perp \Phi dz$$

This formula tells us that the deflection is caused by the projection of the Newtonian gravitational potential on the lens plane.

$$\hat{\Psi}(\vec{\theta}) = \frac{D_{\mathrm{LS}}}{D_{\mathrm{L}} D_{\mathrm{S}}}\frac{2}{c^2}\int \Phi(D_{\mathrm{L}}\vec{\theta}, z)\mathrm{d}z$$

*We introduce the **effective lensing potential***

1 *the lensing potential is the projection of the 3D potential*

2 *the lensing potential scales with distances*

OTHER PROPERTIES OF THE LENSING POTENTIAL

$$\vec{\nabla}_\theta \hat{\Psi}(\vec{\theta}) = \vec{\alpha}(\vec{\theta})$$

The reduced deflection angle is the gradient of the lensing potential

$$\begin{aligned}
\vec{\nabla}_\theta \hat{\Psi}(\vec{\theta}) &= D_\mathrm{L} \vec{\nabla}_\perp \hat{\Psi} = \vec{\nabla}_\perp \left(\frac{D_\mathrm{LS}}{D_\mathrm{S}} \frac{2}{c^2} \int \hat{\Phi}(\vec{\theta}, z) \mathrm{d}z \right) \\
&= \frac{D_\mathrm{LS}}{D_\mathrm{S}} \frac{2}{c^2} \int \vec{\nabla}_\perp \Phi(\vec{\theta}, z) \mathrm{d}z \\
&= \vec{\alpha}(\vec{\theta})
\end{aligned}$$

NOTE THAT...

... the same result holds if we use the adimensional notation:

$$\vec{\nabla}_x = \frac{\xi_0}{D_L}\vec{\nabla}_\theta$$

$$\Downarrow$$

$$\vec{\nabla}_x\hat{\Psi} = \frac{\xi_0}{D_L}\vec{\nabla}_\theta\hat{\Psi} = \frac{\xi_0}{D_L}\vec{\alpha}$$

By multiplying both sides of the equation by D_L^2/ξ_0^2 *we obtain:*

$$\frac{D_L^2}{\xi_0^2}\vec{\nabla}_x\hat{\Psi} = \frac{D_L}{\xi_0}\vec{\alpha} \quad \Rightarrow \quad \Psi = \frac{D_L^2}{\xi_0^2}\hat{\Psi} \quad \Rightarrow \quad \vec{\nabla}_x\Psi(\vec{x}) = \vec{\alpha}(\vec{x})$$

We have introduced the ***adimensional counter-part of the lensing potential!***

OTHER PROPERTIES OF THE LENSING POTENTIAL

$$\triangle_\theta \Psi(\vec{\theta}) = 2\kappa(\vec{\theta})$$

The laplacian of the lensing potential is twice the ***convergence:***

$$\kappa(\vec{\theta}) \equiv \frac{\Sigma(\vec{\theta})}{\Sigma_{\rm cr}} \quad \text{with} \quad \Sigma_{\rm cr} = \frac{c^2}{4\pi G} \frac{D_{\rm S}}{D_{\rm L} D_{\rm LS}}$$

$[G] = L^3/M/T^2$

$[c^2] = L^2/T^2$

$[D_X] = L$

The critical surface density is a characteristic density to distinguish between strong and weak gravitational lenses!

OTHER PROPERTIES OF THE LENSING POTENTIAL

$$\triangle_\theta \Psi(\vec{\theta}) = 2\kappa(\vec{\theta})$$

The laplacian of the lensing potential is twice the ***convergence:***

We start from the poisson equation

$$\triangle \Phi = 4\pi G \rho$$

The surface mass density is then:

$$\Sigma(\vec{\theta}) = \frac{1}{4\pi G}\int_{-\infty}^{+\infty} \triangle \Phi \mathrm{d}z$$

$$\kappa(\vec{\theta}) = \frac{1}{c^2}\frac{D_\mathrm{L} D_\mathrm{LS}}{D_\mathrm{S}}\int_{-\infty}^{+\infty} \triangle \Phi \mathrm{d}z$$

Let's introduce the Laplacian operator on the lens plane:

$$\triangle_\theta = \frac{\partial^2}{\partial\theta_1^2} + \frac{\partial^2}{\partial\theta_2^2} = D_\mathrm{L}^2\left(\frac{\partial^2}{\partial\xi_1^2} + \frac{\partial^2}{\partial\xi_2^2}\right) = D_\mathrm{L}^2\left(\triangle - \frac{\partial^2}{\partial z^2}\right)$$

Then:

$$\triangle \Phi = \frac{1}{D_\mathrm{L}^2}\triangle_\theta \Phi + \frac{\partial^2 \Phi}{\partial z^2}$$

OTHER PROPERTIES OF THE LENSING POTENTIAL

With this substitution:

$$\kappa(\vec{\theta}) = \frac{1}{c^2}\frac{D_{\rm LS}}{D_{\rm S}D_{\rm L}}\left[\triangle_\theta \int_{-\infty}^{+\infty} \Phi {\rm d}z + D_{\rm L}^2 \int_{-\infty}^{+\infty} \frac{\partial^2 \Phi}{\partial z^2} {\rm d}z\right]$$

where the second term in the sum is zero, if the lens if gravitationally bound!

Given the definition of lensing potential:

$$\kappa(\theta) = \frac{1}{2}\triangle_\theta \hat{\Psi}$$

Note that:

$$\triangle_\theta = D_{\rm L}^2 \triangle_\xi = \frac{D_{\rm L}^2}{\xi_0^2}\triangle_x \qquad \kappa(\theta) = \frac{1}{2}\triangle_\theta \hat{\Psi} = \frac{1}{2}\frac{\xi_0^2}{D_{\rm L}^2}\triangle_\theta \Psi$$

$$\Rightarrow \quad \kappa(\vec{x}) = \frac{1}{2}\triangle_x \Psi(\vec{x})$$

ADIMENSIONAL NOTATION

From

$$\vec{\hat{\alpha}}(\vec{\xi}) = \frac{4G}{c^2} \int \frac{(\vec{\xi} - \vec{\xi}')\Sigma(\vec{\xi}')}{|\vec{\xi} - \vec{\xi}'|^2} \, \mathrm{d}^2\xi'$$

we obtain

$$\vec{\alpha}(\vec{x}) = \frac{1}{\pi} \int_{\mathbf{R}^2} \mathrm{d}^2x' \kappa(\vec{x}') \frac{\vec{x} - \vec{x}'}{|\vec{x} - \vec{x}'|}$$

Using

$$\vec{\nabla}_x \Psi(\vec{x}) = \vec{\alpha}(\vec{x})$$

Convolution kernels

$$\Psi(\vec{x}) = \frac{1}{\pi} \int_{\mathbf{R}^2} \kappa(\vec{x}') \ln|\vec{x} - \vec{x}'| \mathrm{d}^2x'$$