Delensing With Physics-Informed Neural Networks

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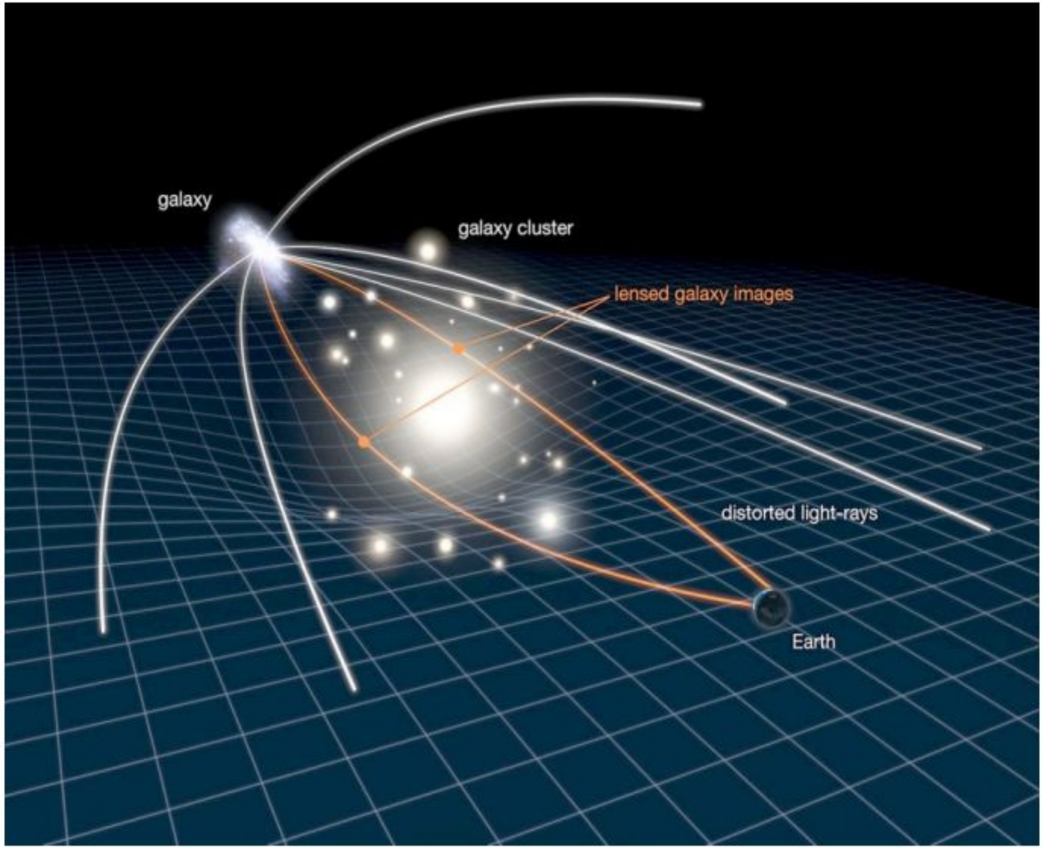
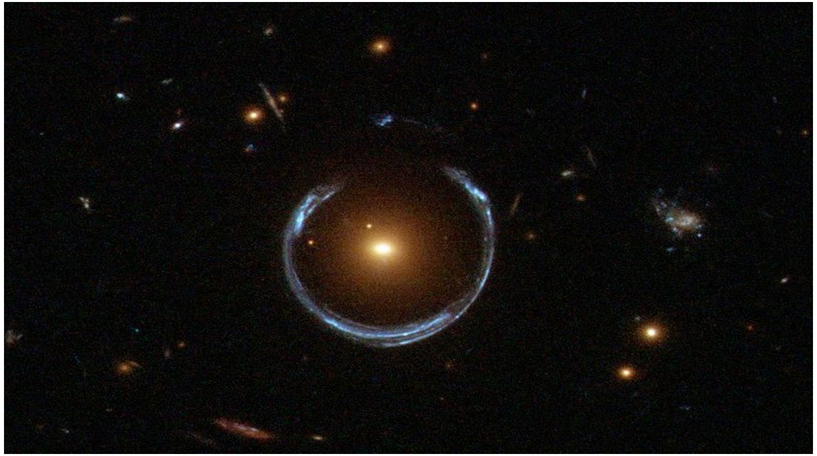
Gravitational Lensing Phenomenon

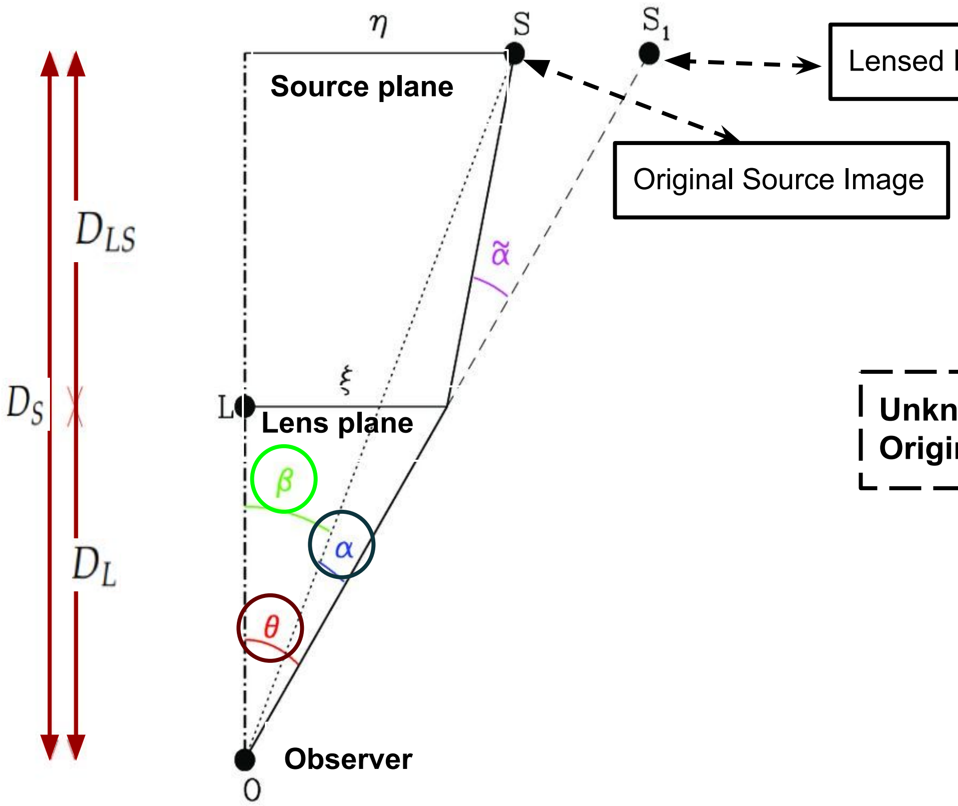


- Foreground mass → **distorts space-time**

- Lensed image distorted
  - Einstein ring
  - Multiple images



Gravitational Lensing Phenomenon



Lensing equation :

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

Unknown position of **Original** source (delensed)

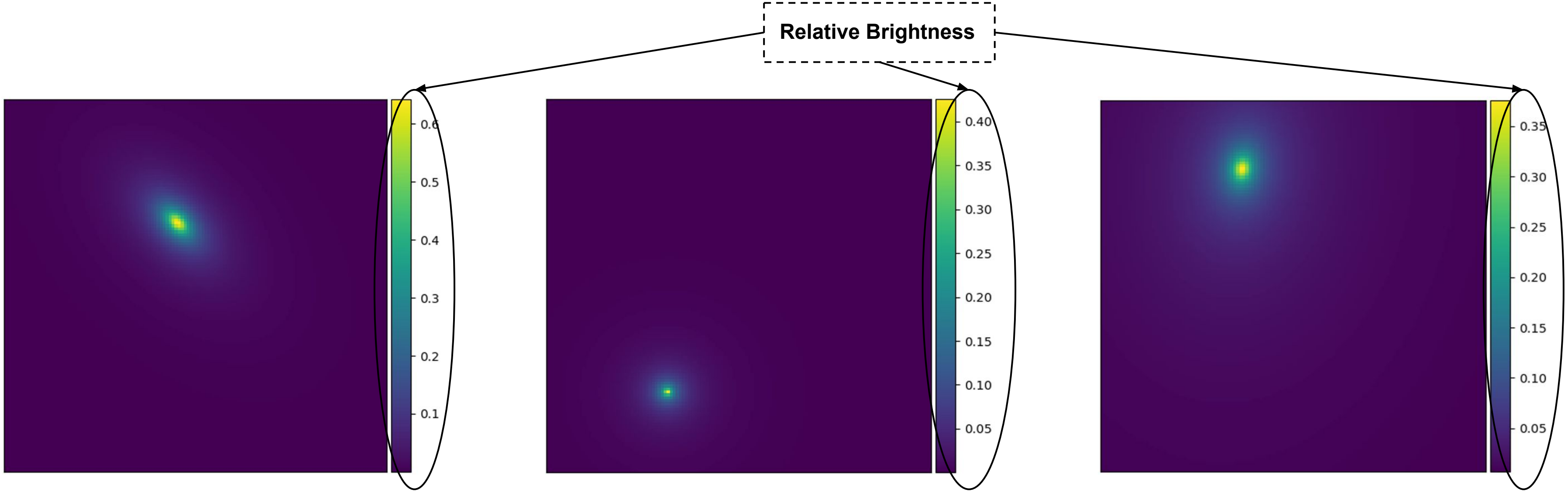
Known position of **lensed** source

Unknown deflection angle given by **gradient** of lensing potential : $\alpha = \nabla\Phi$

Dataset Generation

Birrer et al. 2021

- Use of **Lenstronomy** Python Package
- 3 different type of original sources used : **NIE, Chameleon, Hernquist**
- Different parameters to be fixed (amplitude, position)



Chameleon **Hernquist** **NIE**

Lens Model

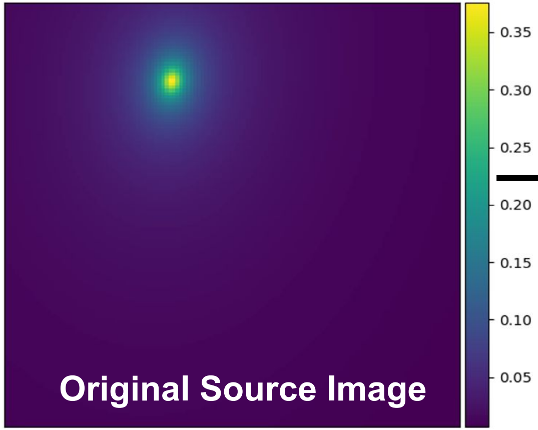
Grid

$$\kappa(x, y) = \frac{3-\gamma}{2}\left(\frac{\theta_E}{\sqrt{qx^2 + y^2/q}}\right)^{\gamma-1}$$

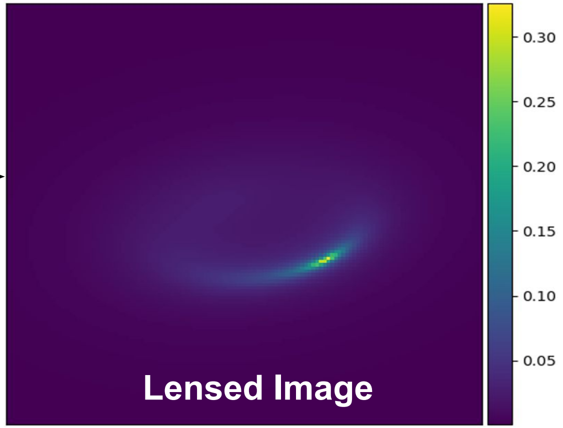
<u>Elliptical Power Law (EPL) mass profile :</u>

$$q = \frac{1-\sqrt{e_1^2+e_2^2}}{1+\sqrt{e_1^2+e_2^2}}$$

4 parameters : e_1 , e_2 , θ_E , γ

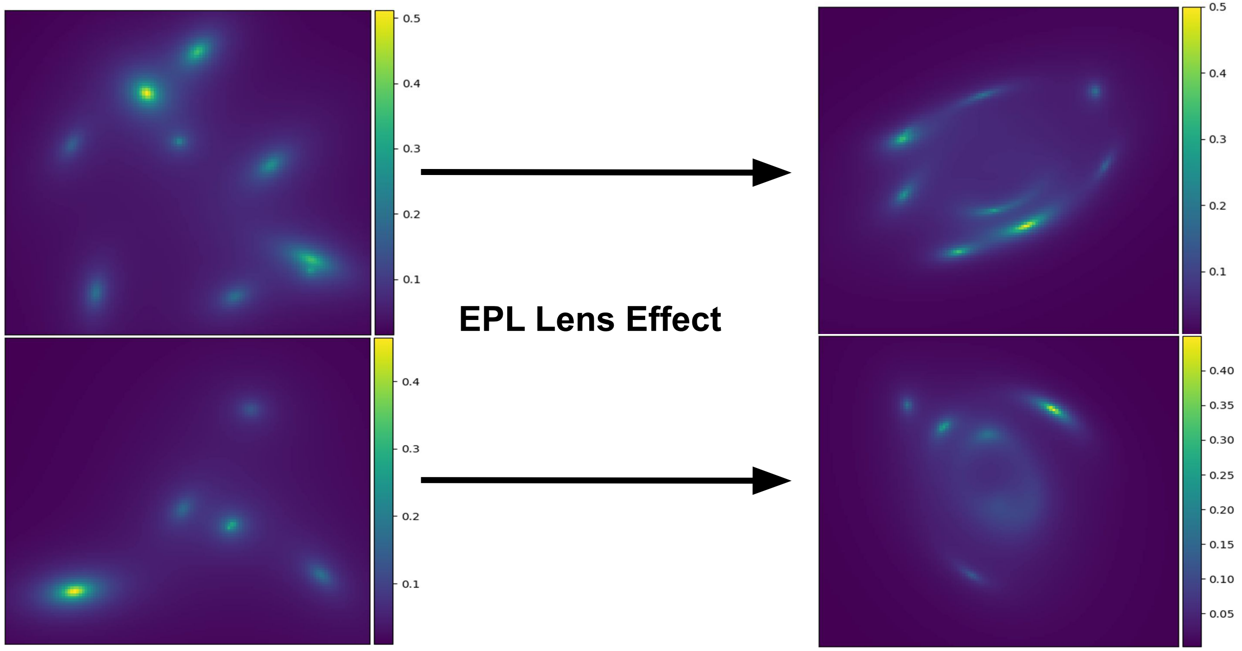


Lens Model Effect



Final Dataset

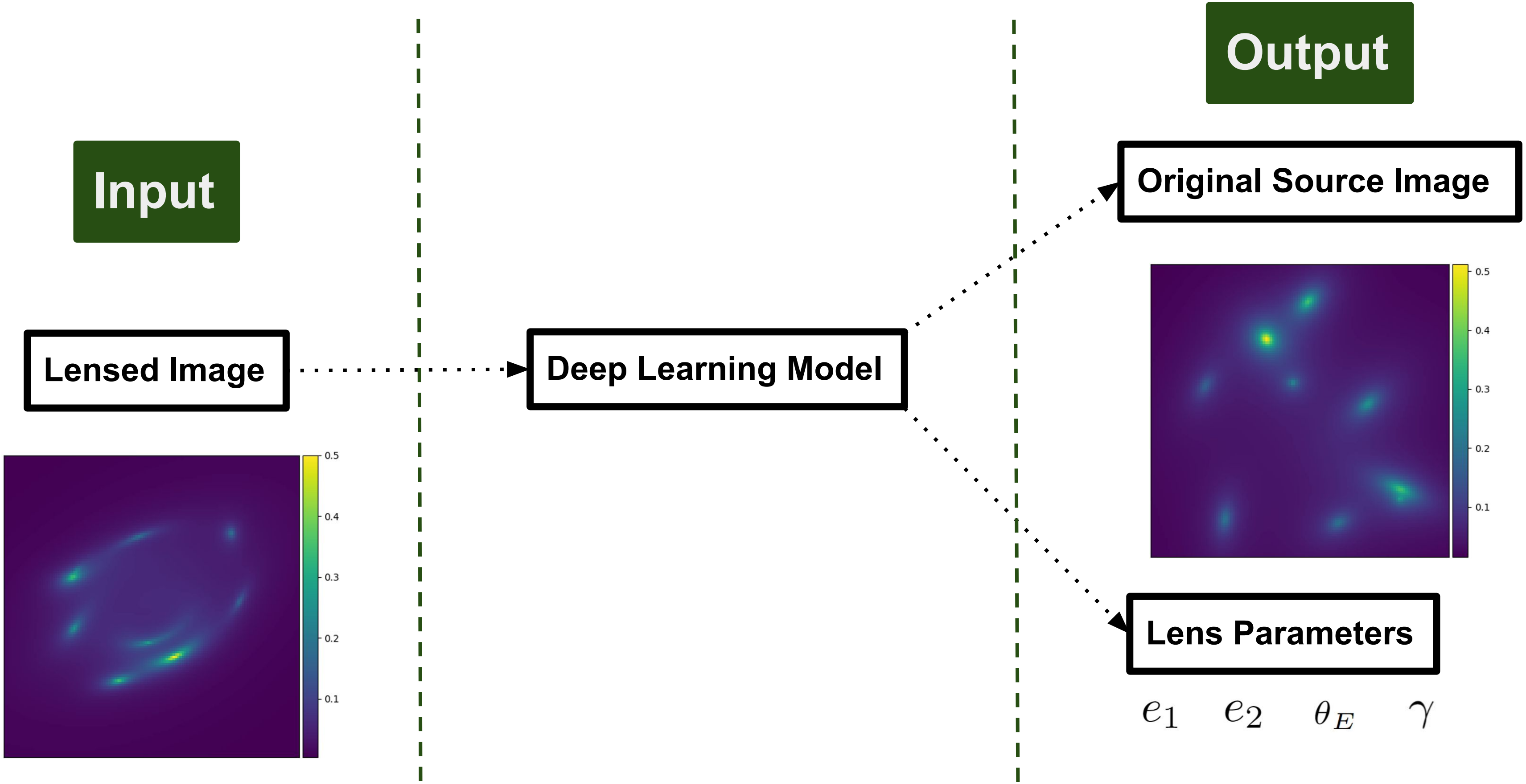
- Final Dataset → Between **5** and **10** sources per original source image
- Number of sources ← **random choice** between 5 and 10



Original Source Image

Lensed Image

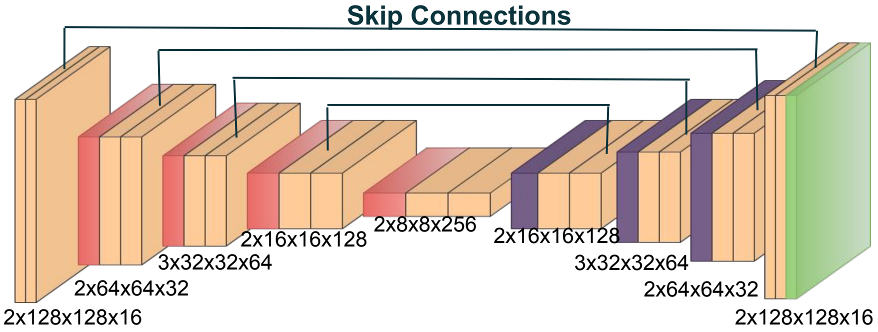
Expectations



Deep Learning Model

Predict Original
Sources (unlensed)

Encoder Decoder
(U-Net) Architecture

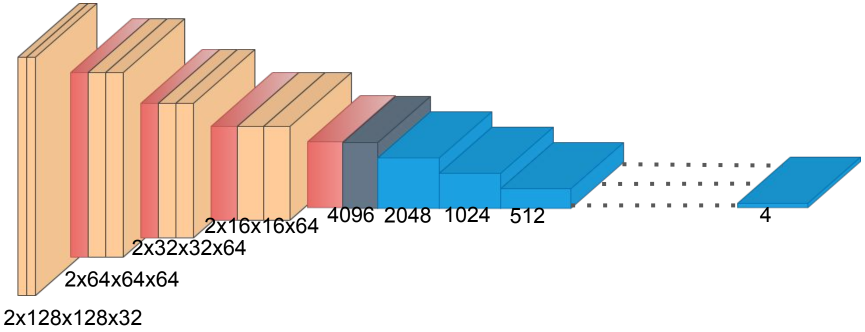


Optimizer : Adam

Loss : Mean(MSE - SSIM)

Predict the **4**
Lens parameters

CNN + FCN



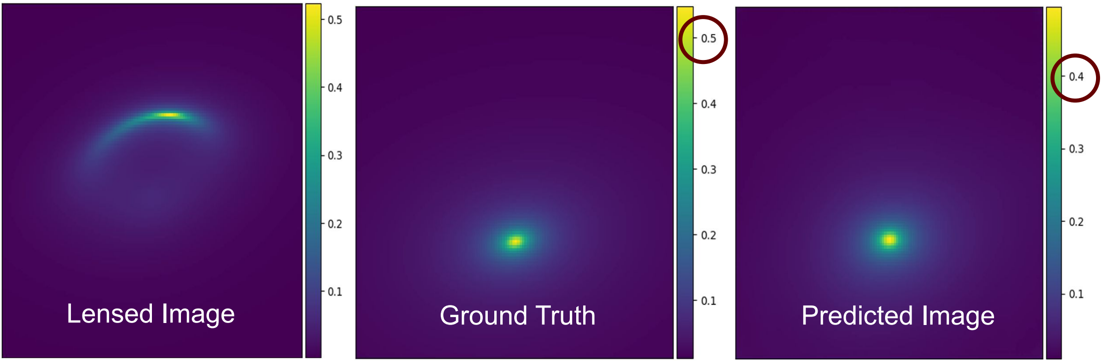
Optimizer : Adam

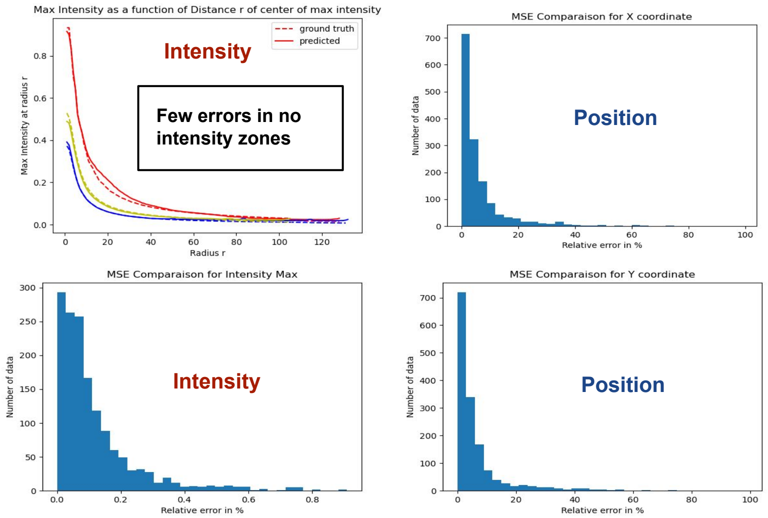
Loss : MSE

Convolutional + Batch_Norm + ReLu
Convolutional + Batch_Norm + Linear
Convolutional Transpose
Max Pooling
Flatten
Fully Connected + Relu

github.com/madhumitadange

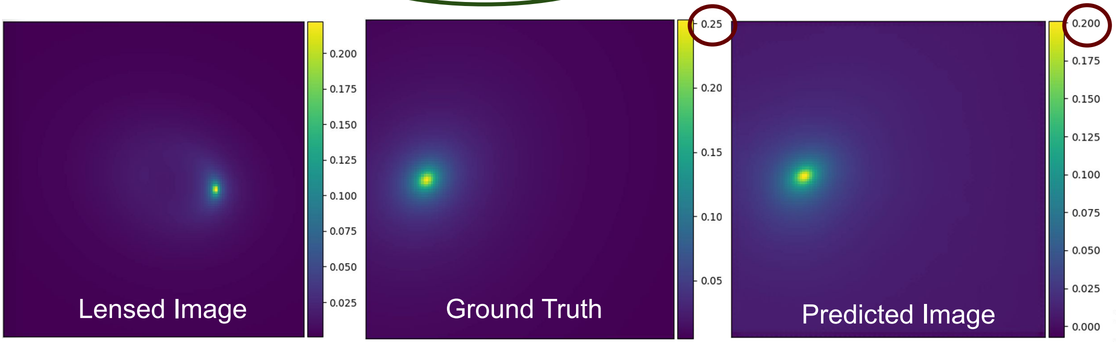
1 Source per Image : NIE type

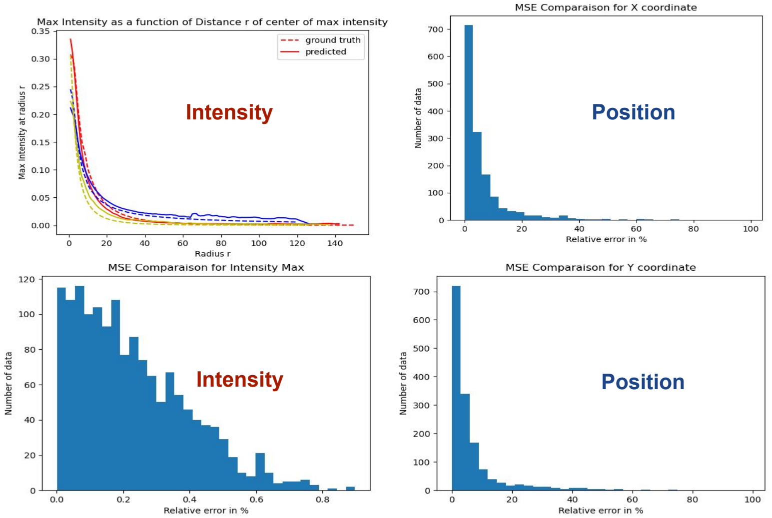




Few influence

1 Source per Image : Random choice NIE, Chameleon, Hernquist

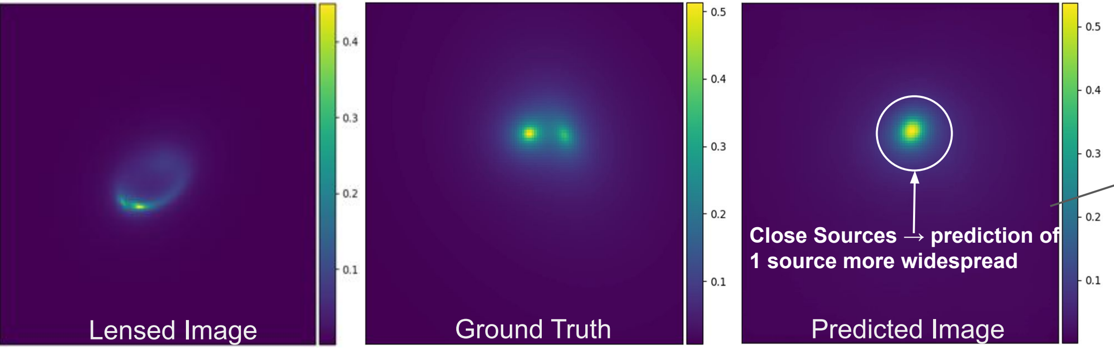


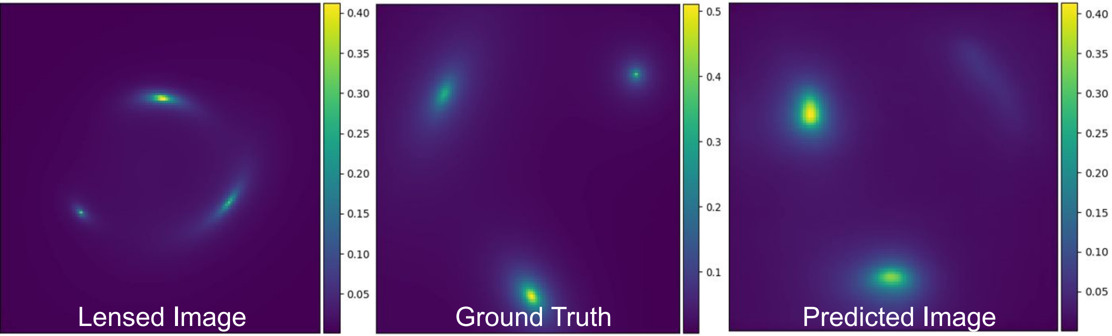


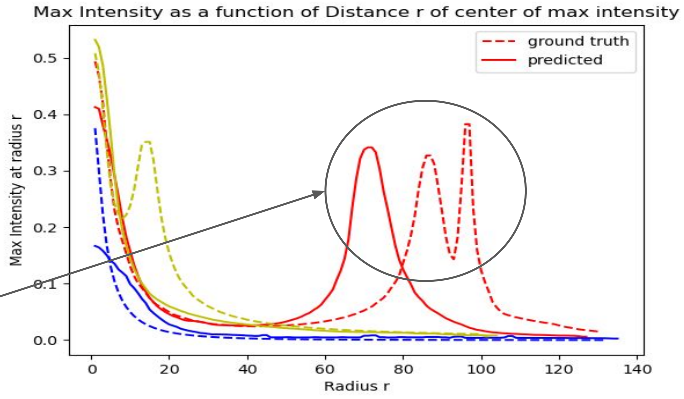
More Difficulties with **intensity** than with **position**

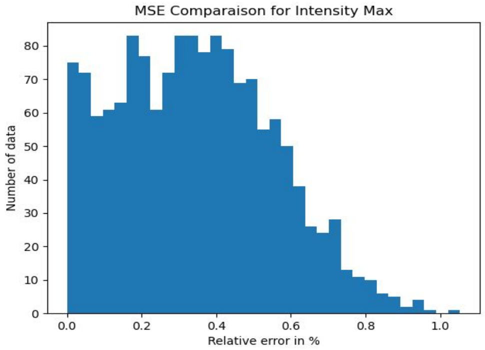
Small sources → Prediction more **widespread**

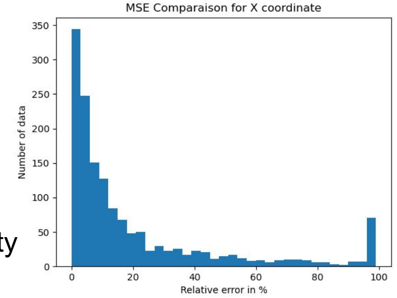
Random Number from 1 to 3 Sources per Image : Random choice NIE, Chameleon, Hernquist

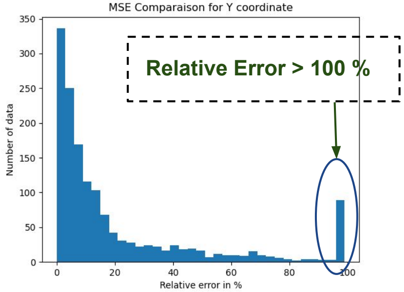








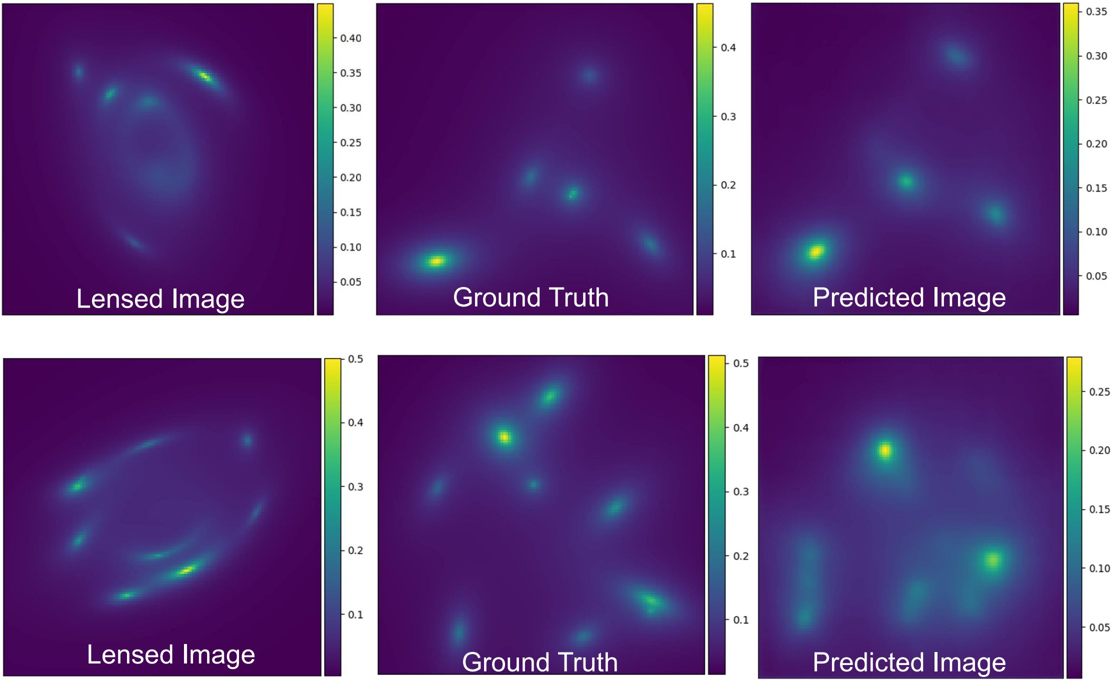


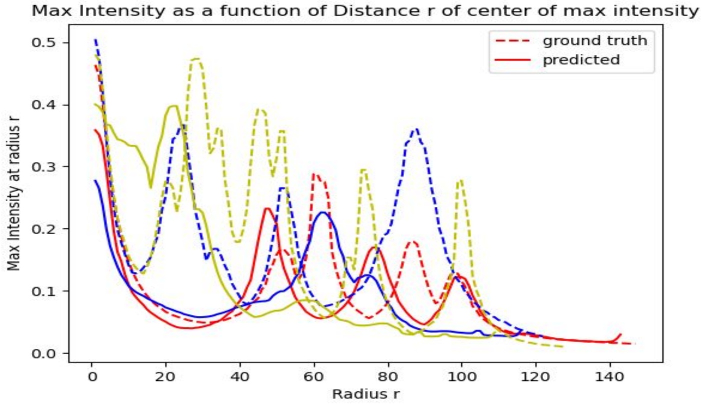


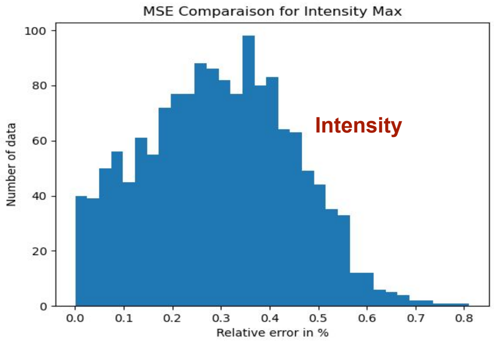
Number of sources → less reconstruction accuracy

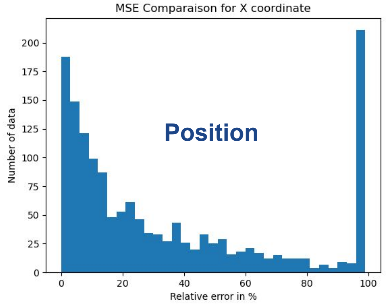
Difficult to reconstruct the good number of sources → Close sources issue + Low intensity

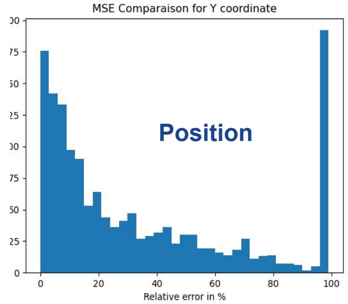
Random Number from 5 to 10 Sources per Image : Random choice NIE, Chameleon, Hernquist







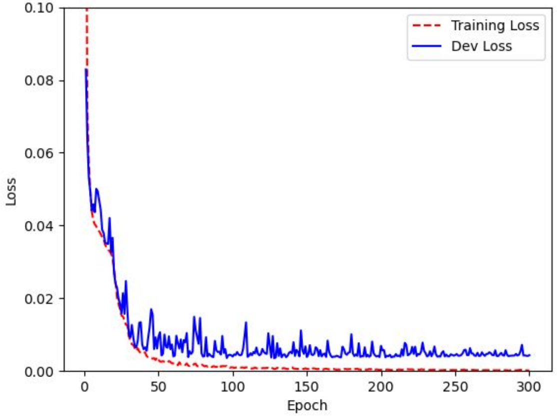


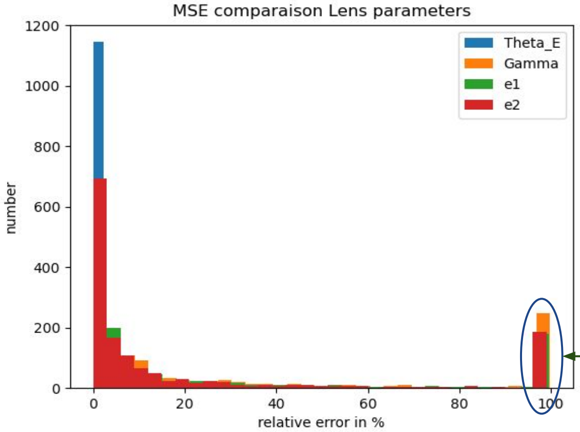


5 to 10 → Huge number of sources + very wide range of choices
→ need of **more priors**

For 1 image : the **fewer** the number of sources is → the **better** the prediction is

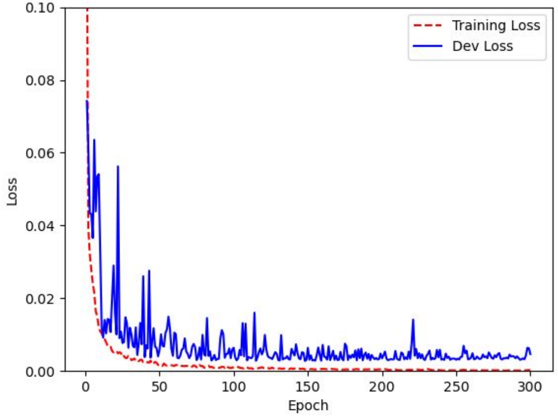
Random Number from 1 to 3 Sources per Image : Random choice NIE, Chameleon, Hernquist

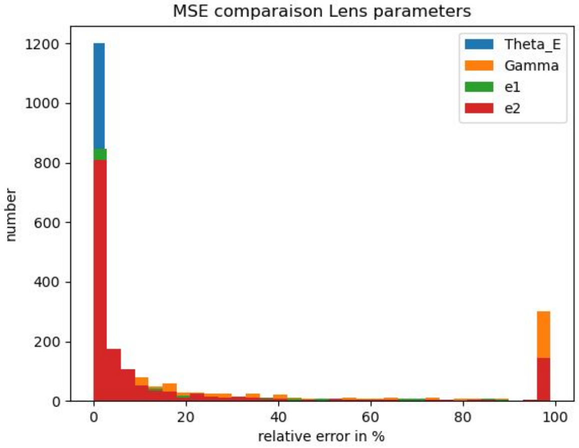




Relative Error > 100 %

Random Number from 5 to 10 Sources per Image : Random choice NIE, Chameleon, Hernquist





Improve Deep Learning Model : PINN

Use of **Physics Constraints as Priors → Change the Loss**

Tessore & Metcalf 2015

EPL surface mass density profile : $\kappa(x,y) = \frac{3-\gamma}{2}\left(\frac{\theta_E}{\sqrt{qx^2+y^2/q}}\right)^{\gamma-1}$ ← Depends only on the 4 Lens parameters

$$\text{Loss} = \text{MSE} + c||k - \hat{k}||_2^2$$

Ground Truth (k)

Depends only on the 4 **predicted** lens parameters ($\hat{k}$)

Other Physical Quantities :

All quantities depend only on the 4 Lens parameters

$$\alpha^*(z) = 2\,\frac{\sqrt{z^2}}{z}\int_0^{R(z)} \mathrm{d}r\,\frac{\kappa(r)\,r}{\sqrt{q^2\,z^2 - (1-q^2)\,r^2}}$$

$$\psi(z) = \frac{1}{2-t}\,\frac{z\,\alpha^*(z) + z^*\,\alpha(z)}{2}$$

Conjugate of **Deflection angle** ($\alpha^*(z)$)

Lensing Potential ($\psi(z)$)

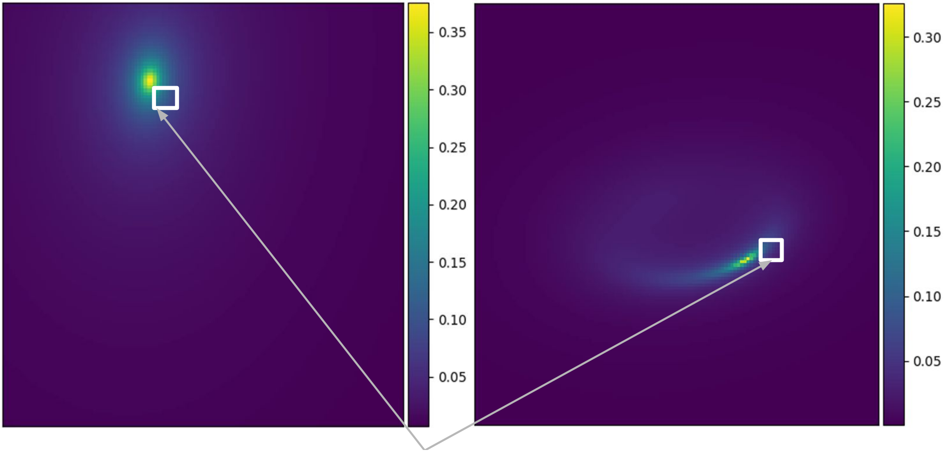
Improve Deep Learning Model : PINN

Lensing equation : $\beta = \theta - \alpha(\theta)$

Deflection angle depends only on the **4 Lens parameters**

Unknown Position of **Original** source

Position of **lensed** source **(Input)**



$$Original[\beta(i)][\beta(j)] = Lensed[\theta(i)][\theta(j)]$$

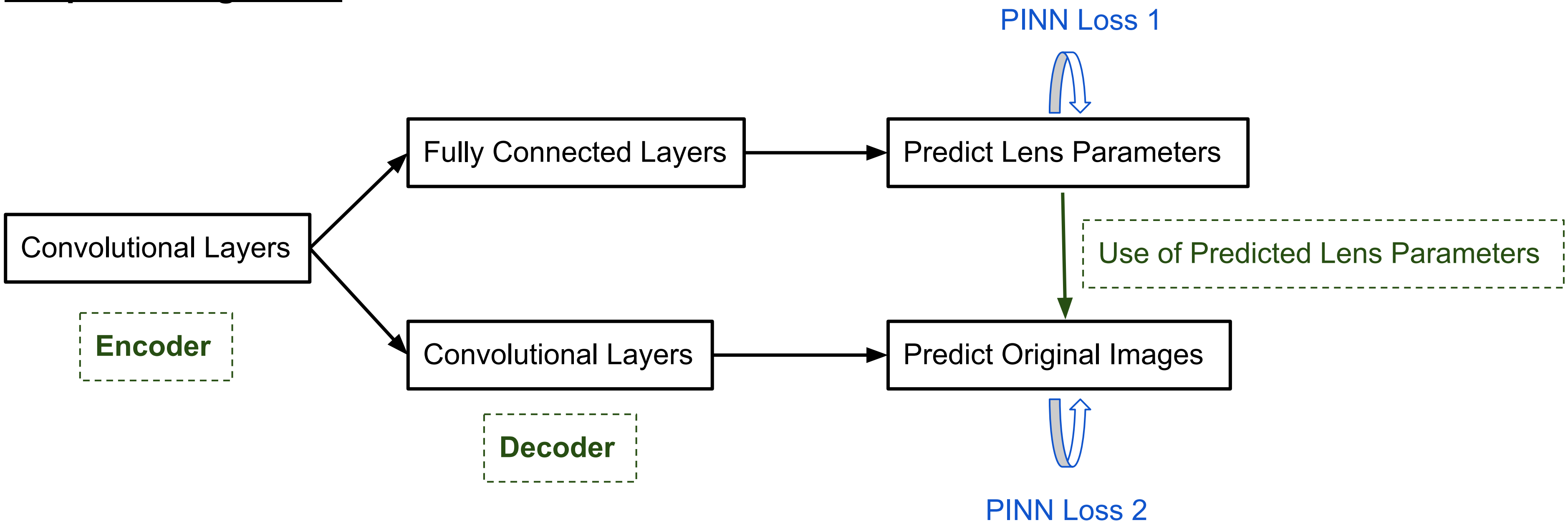
Need to have the Lens Model (from the first network)

Change the Loss → PINN

$$\text{Loss} = \text{Mean}(\text{MSE} - \text{SSIM}) + c||O[\beta[i]][\beta[j]] - L[\theta[i]][\theta[j]]||_2^2$$

Future Perspective

Deep Learning Model



Thank you for listening !

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