NAOC 中国科学院国家天文台 NATIONAL ASTRONOMICAL OBSERVATORIES, CAS

Mapping the cosmic large scale structure using deep learning

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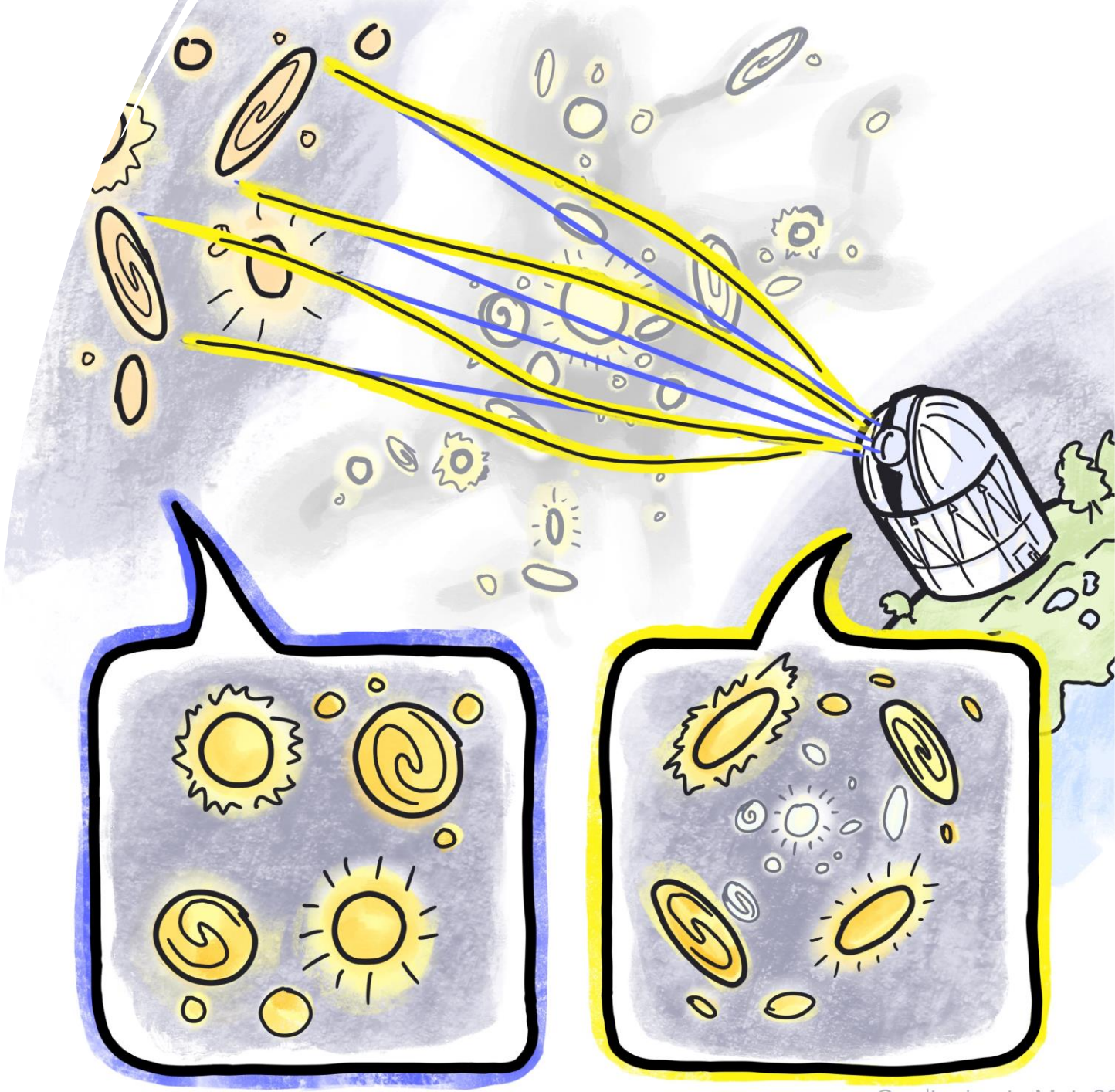
Collaborators: Wenhan Guo, Rui Li, Xiangkun Liu, and An Zhao

What is Weak Lensing (WL)?

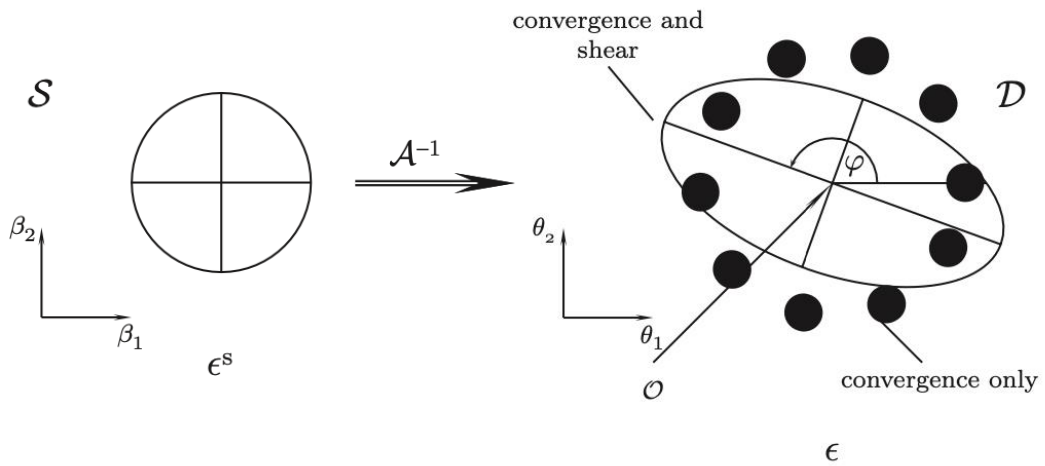
- small distortions (background galaxies)

- A direct way to trace the projected mass distribution

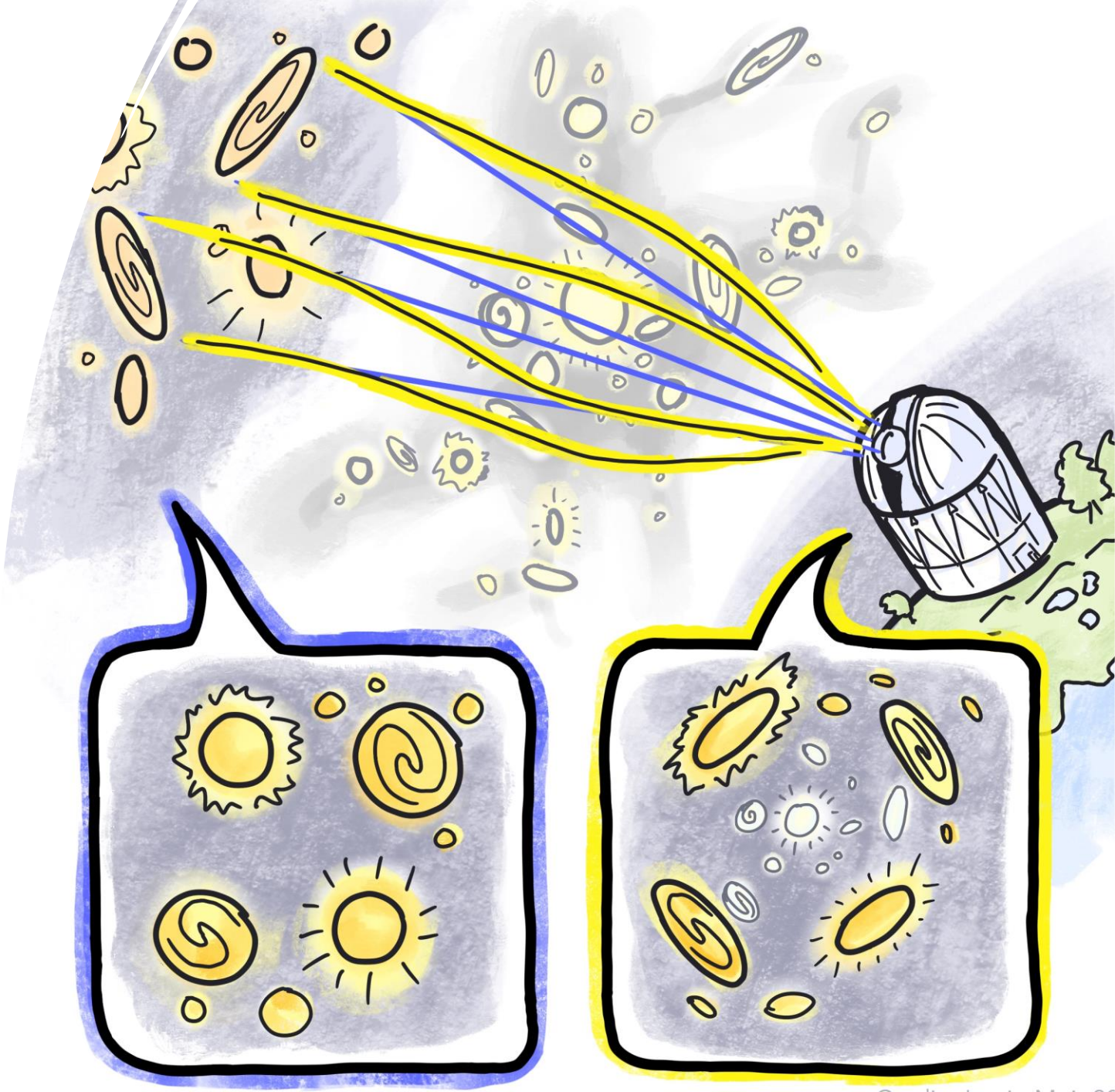


Shear (γ)
Convergence (κ)

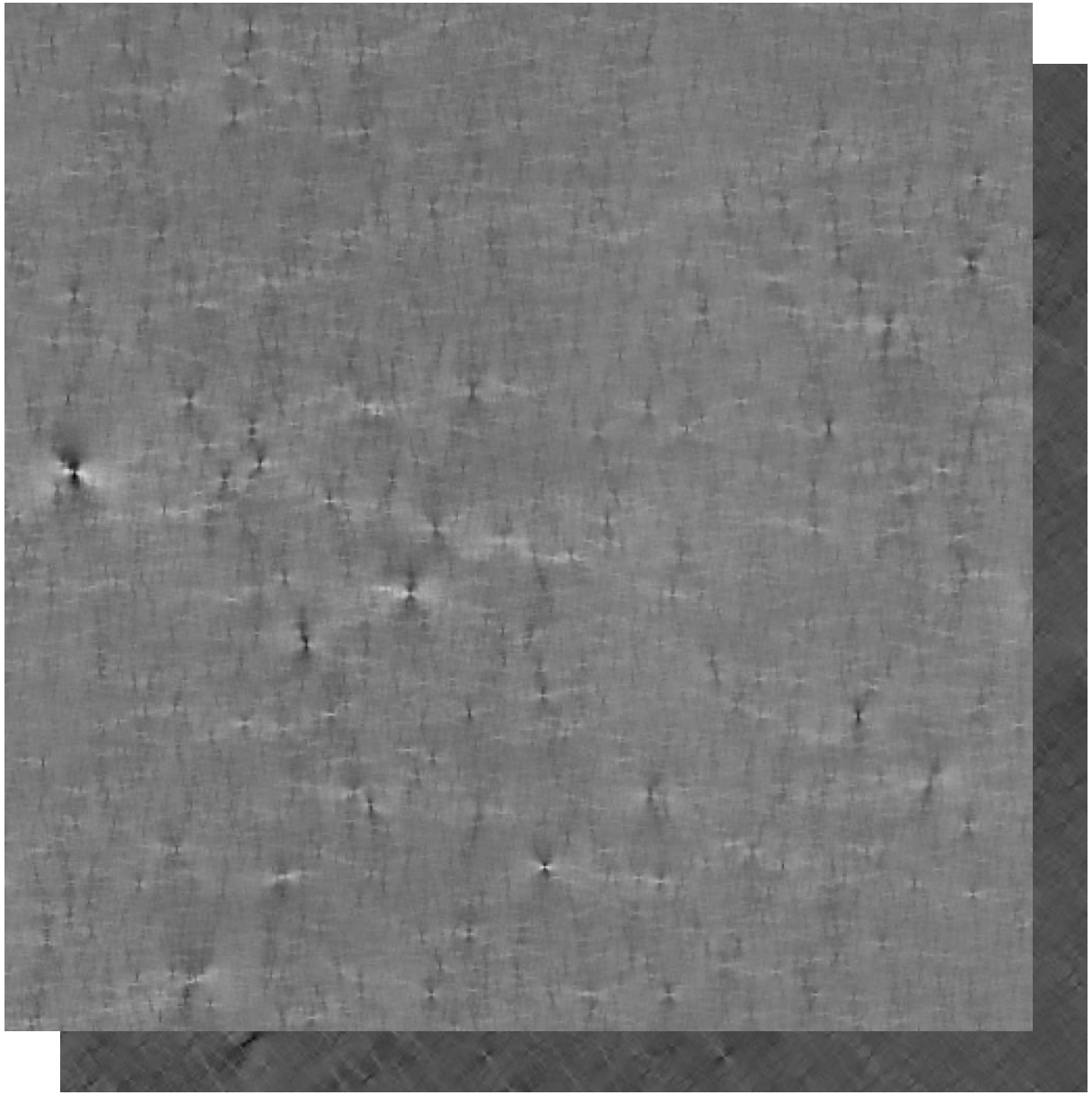
$$\mathcal{A}(\boldsymbol{\theta}) = (1-\kappa)\begin{pmatrix} 1-g_1 & -g_2 \\ -g_2 & 1+g_1 \end{pmatrix}, \text{ where } g(\boldsymbol{\theta}) = \frac{\gamma(\boldsymbol{\theta})}{[1-\kappa(\boldsymbol{\theta})]}$$



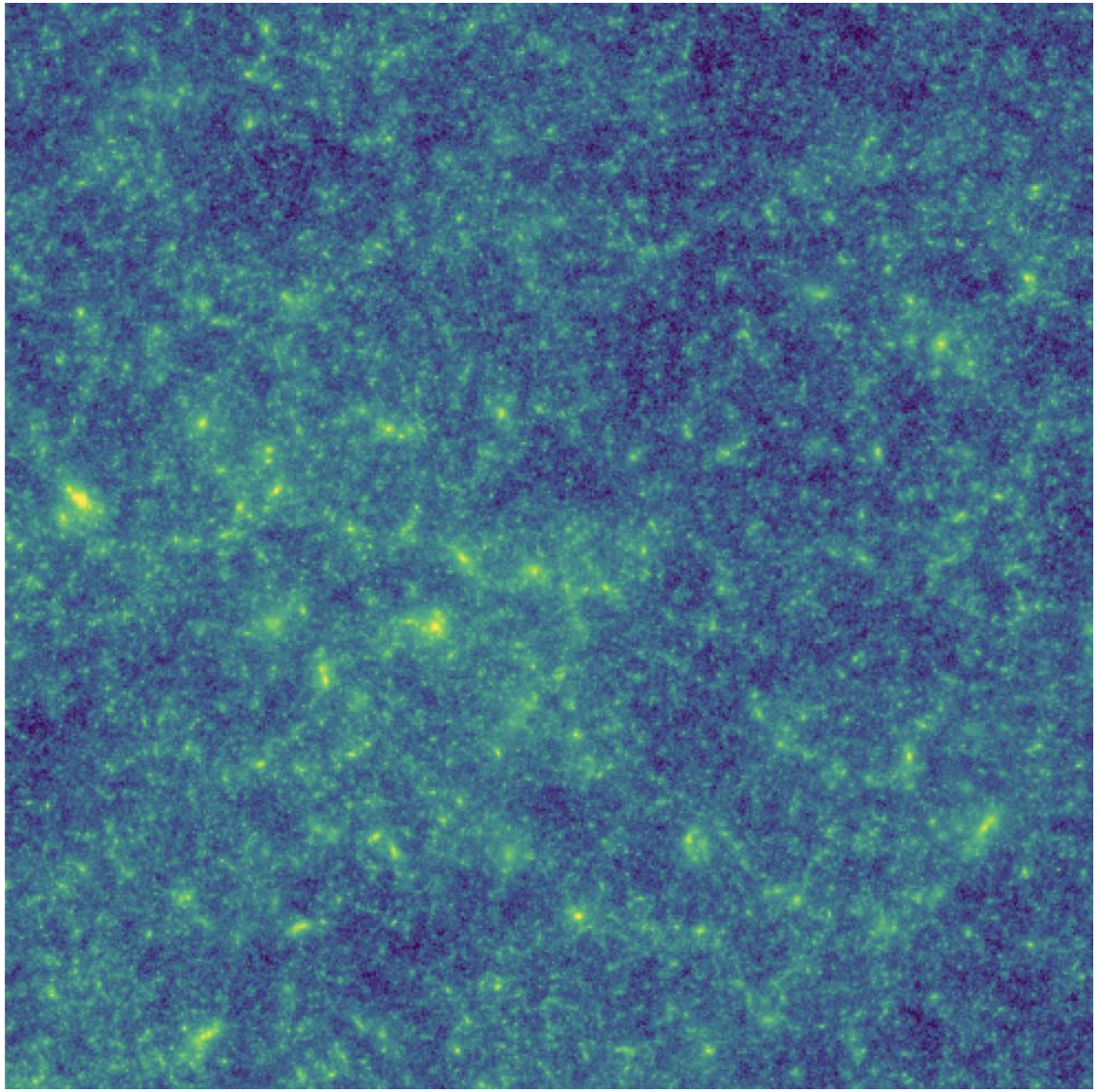
M. Bradac



Credit: Jessie Muir 20

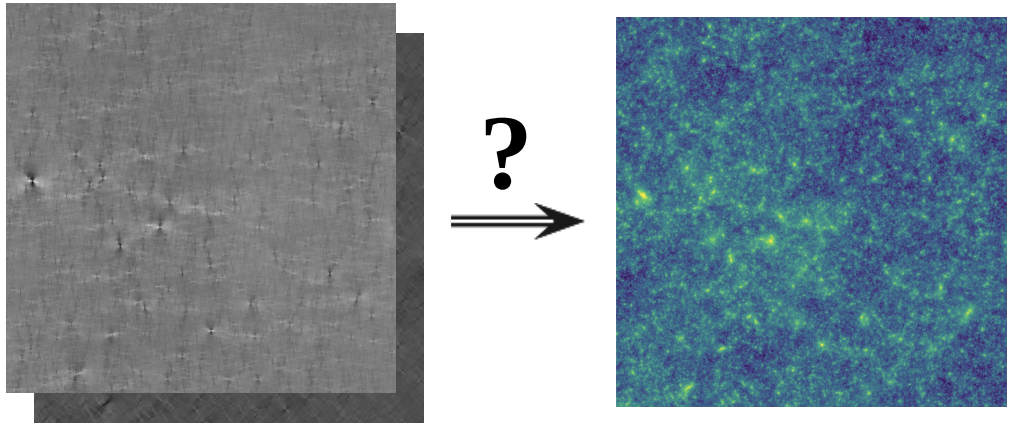


Shear (γ)

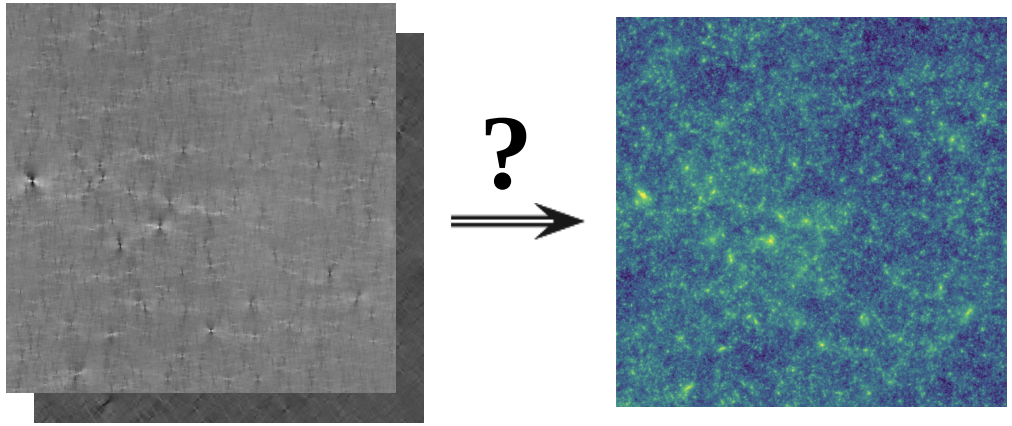


Convergence (κ)

Shear → Convergence



Shear → Convergence



$$\gamma(\boldsymbol{\theta}) = \frac{1}{\pi}\int_{\mathbb{R}^2} \mathrm{d}^2\theta'\, \mathcal{D}(\boldsymbol{\theta}-\boldsymbol{\theta}')\,\kappa(\boldsymbol{\theta}')\,, \quad \text{with}$$

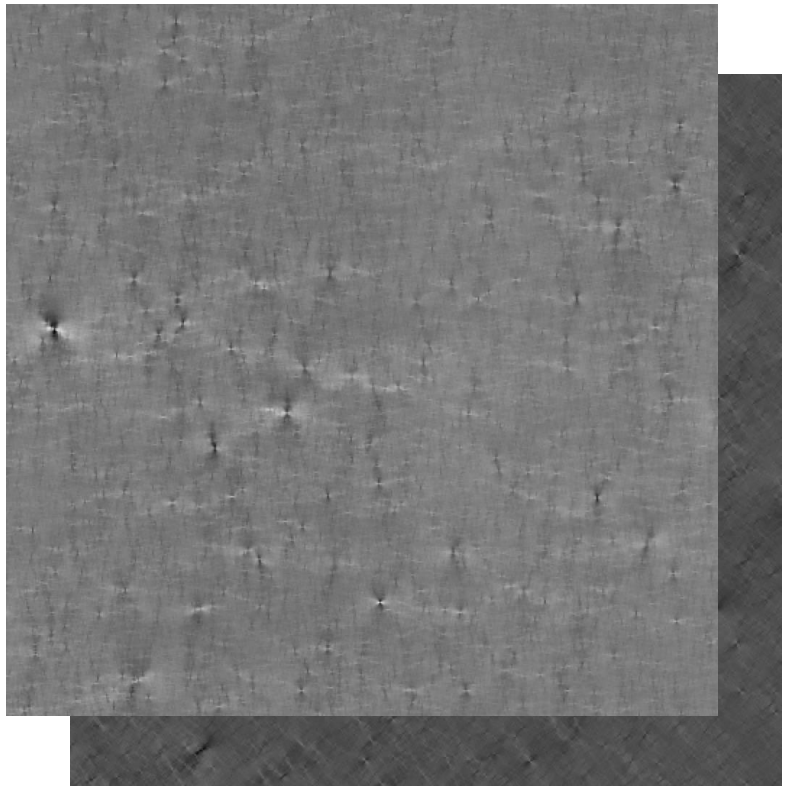
$$\mathcal{D}(\boldsymbol{\theta}) \equiv -\frac{\theta_1^2-\theta_2^2+2\mathrm{i}\theta_1\theta_2}{|\boldsymbol{\theta}|^4} = \frac{-1}{(\theta_1-\mathrm{i}\theta_2)^2}\,.$$

$$\hat{\gamma}(\boldsymbol{\ell}) = \pi^{-1}\hat{\mathcal{D}}(\boldsymbol{\ell})\,\hat{\kappa}(\boldsymbol{\ell}) \quad \text{for} \quad \boldsymbol{\ell}\neq\mathbf{0}\,, \quad \hat{\mathcal{D}}(\boldsymbol{\ell}) = \pi\frac{\left(\ell_1^2-\ell_2^2+2\mathrm{i}\ell_1\ell_2\right)}{|\boldsymbol{\ell}|^2}$$

$$\hat{\kappa}(\boldsymbol{\ell}) = \pi^{-1}\hat{\gamma}(\boldsymbol{\ell})\,\hat{\mathcal{D}}^*(\boldsymbol{\ell}) \quad \text{for} \quad \boldsymbol{\ell}\neq\mathbf{0}\,, \quad \hat{\mathcal{D}}(\boldsymbol{\ell})\hat{\mathcal{D}}^*(\boldsymbol{\ell}) = \pi^2$$

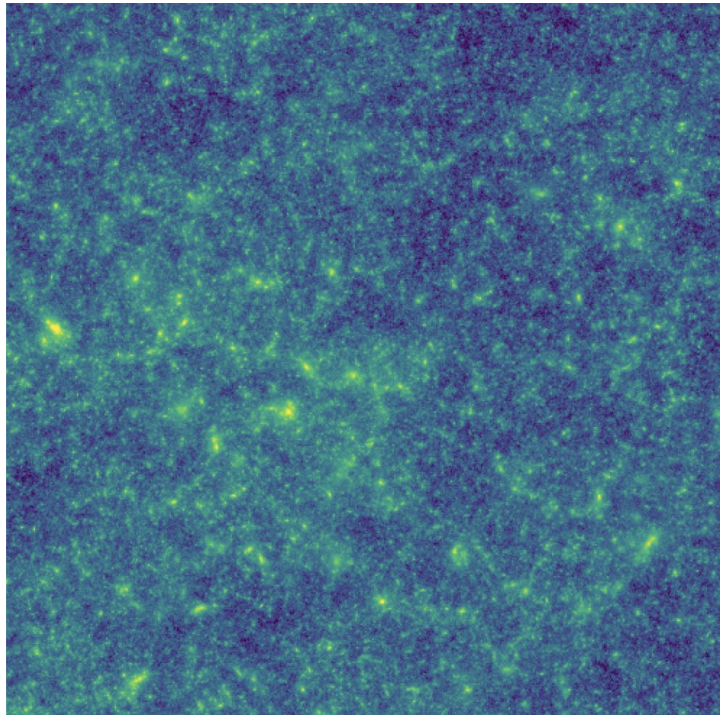
$$\kappa(\boldsymbol{\theta}) - \kappa_0 = \frac{1}{\pi}\int_{\mathbb{R}^2} \mathrm{d}^2\theta'\, \mathcal{D}^*(\boldsymbol{\theta}-\boldsymbol{\theta}')\,\gamma(\boldsymbol{\theta}')$$

KS Deconvolution

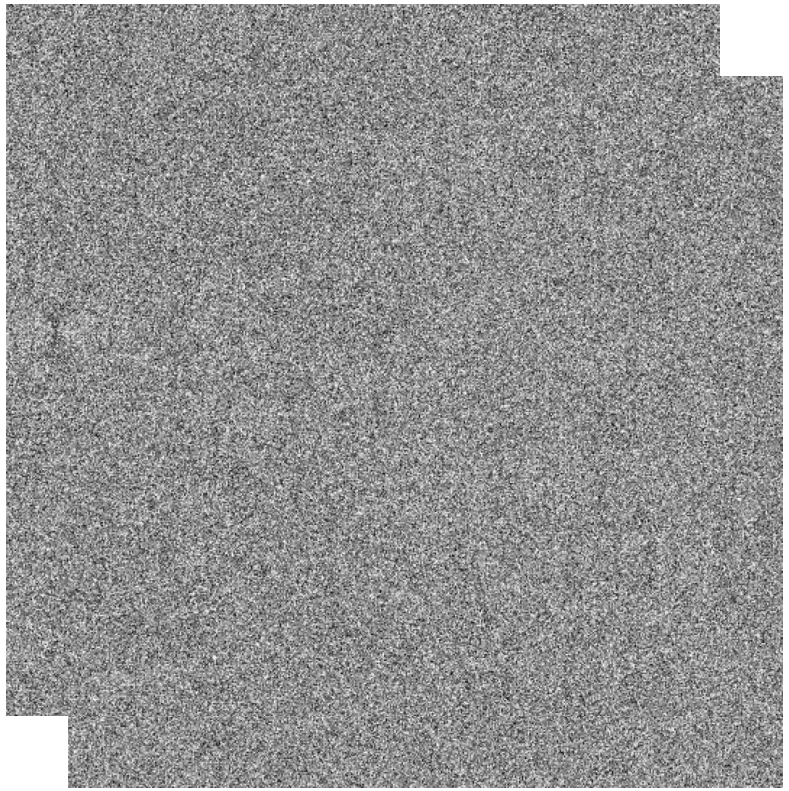


$$\frac{1}{\pi}\int_{\mathbb{R}^2} \mathrm{d}^2\theta'\, \mathcal{D}^*(\boldsymbol{\theta}-\boldsymbol{\theta}')\,\gamma(\boldsymbol{\theta}')$$

KS Deconvolution

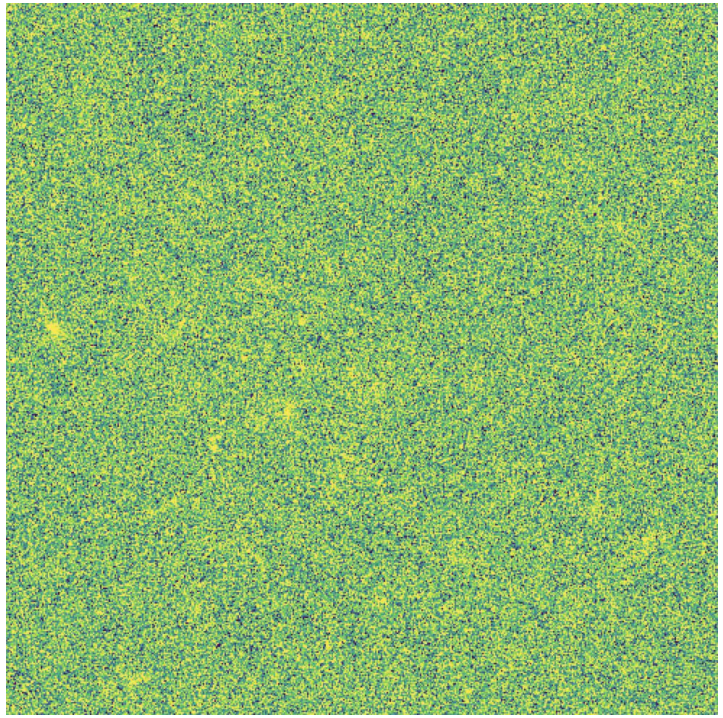


+ noise = 50 galaxies / arcmin^2



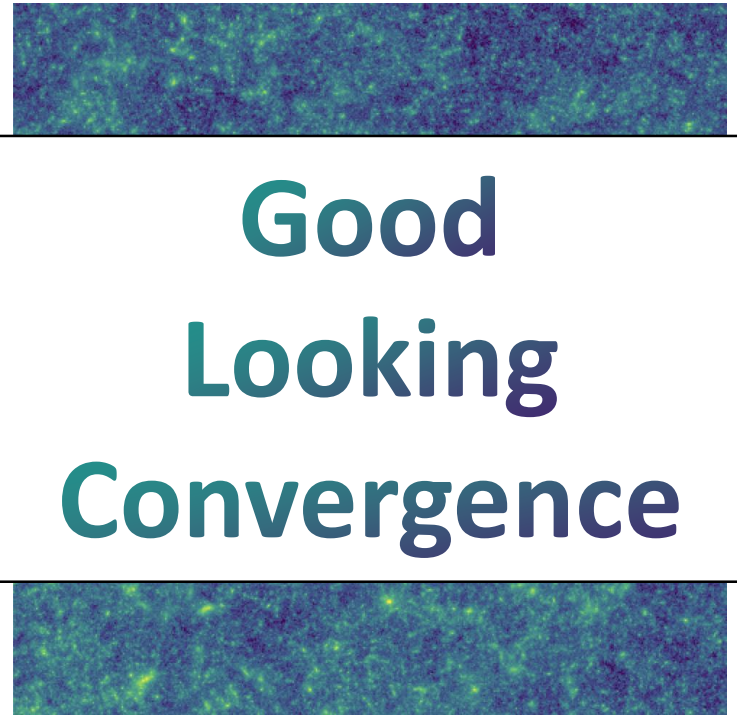
$$\frac{1}{\pi}\int_{\mathbb{R}^2} \mathrm{d}^2\theta'\, \mathcal{D}^*(\boldsymbol{\theta}-\boldsymbol{\theta}')\,\gamma(\boldsymbol{\theta}')$$

KS Deconvolution




Noisy Shear

?


Good
Looking
Convergence

Noisy Shear

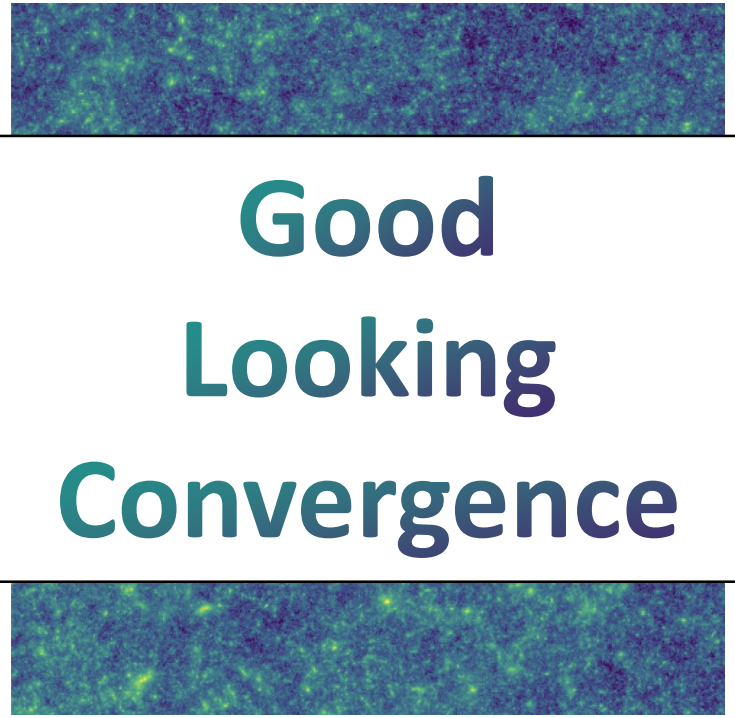
$$\mathcal{F}(\gamma)$$

KS++

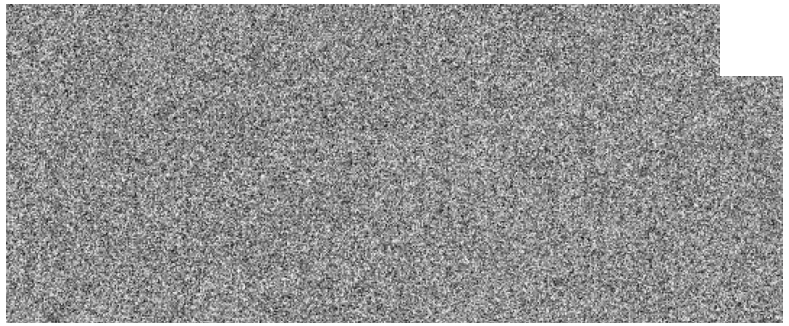
Wiener Filtering

Sparse Reconstruction

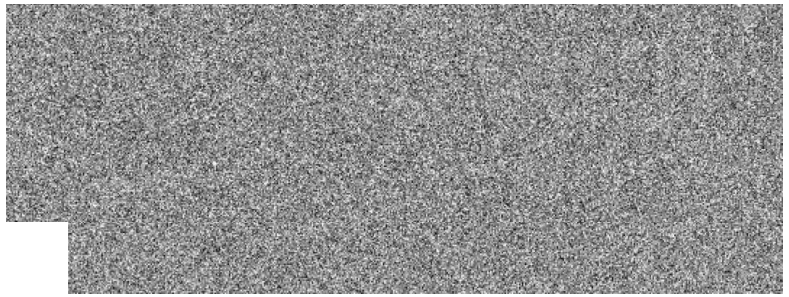
...



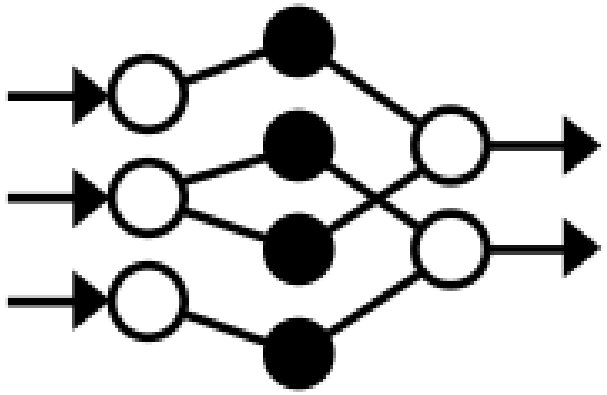
What is ML?

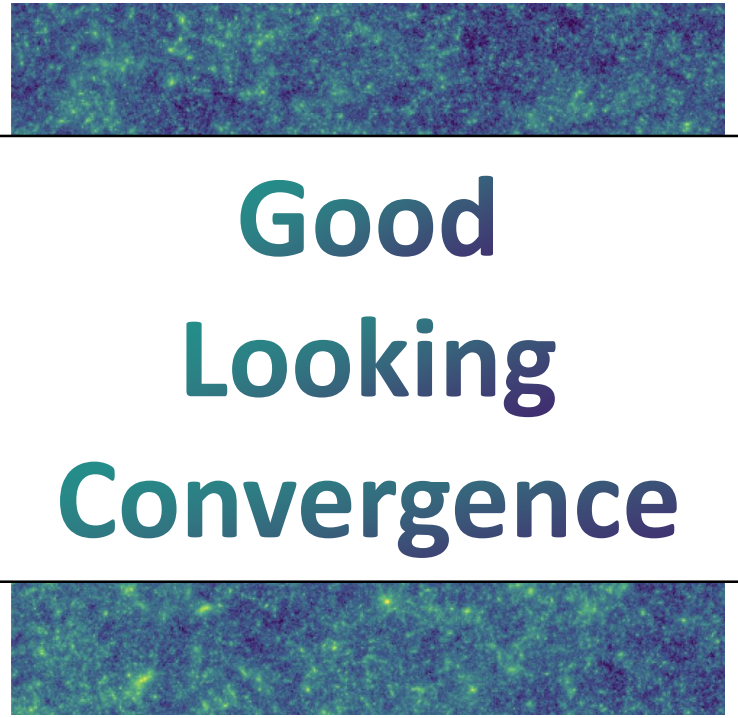


Noisy Shear

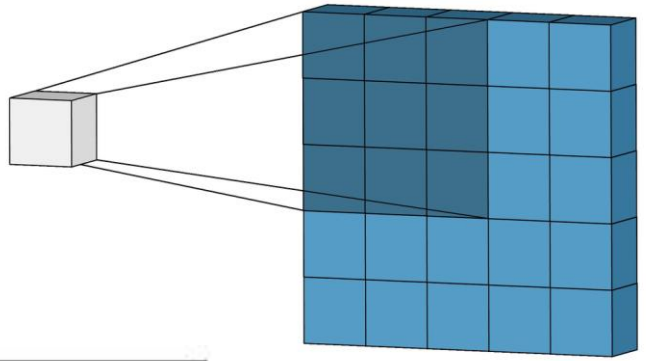


$\boldsymbol{\mathcal{F}}(\gamma)$





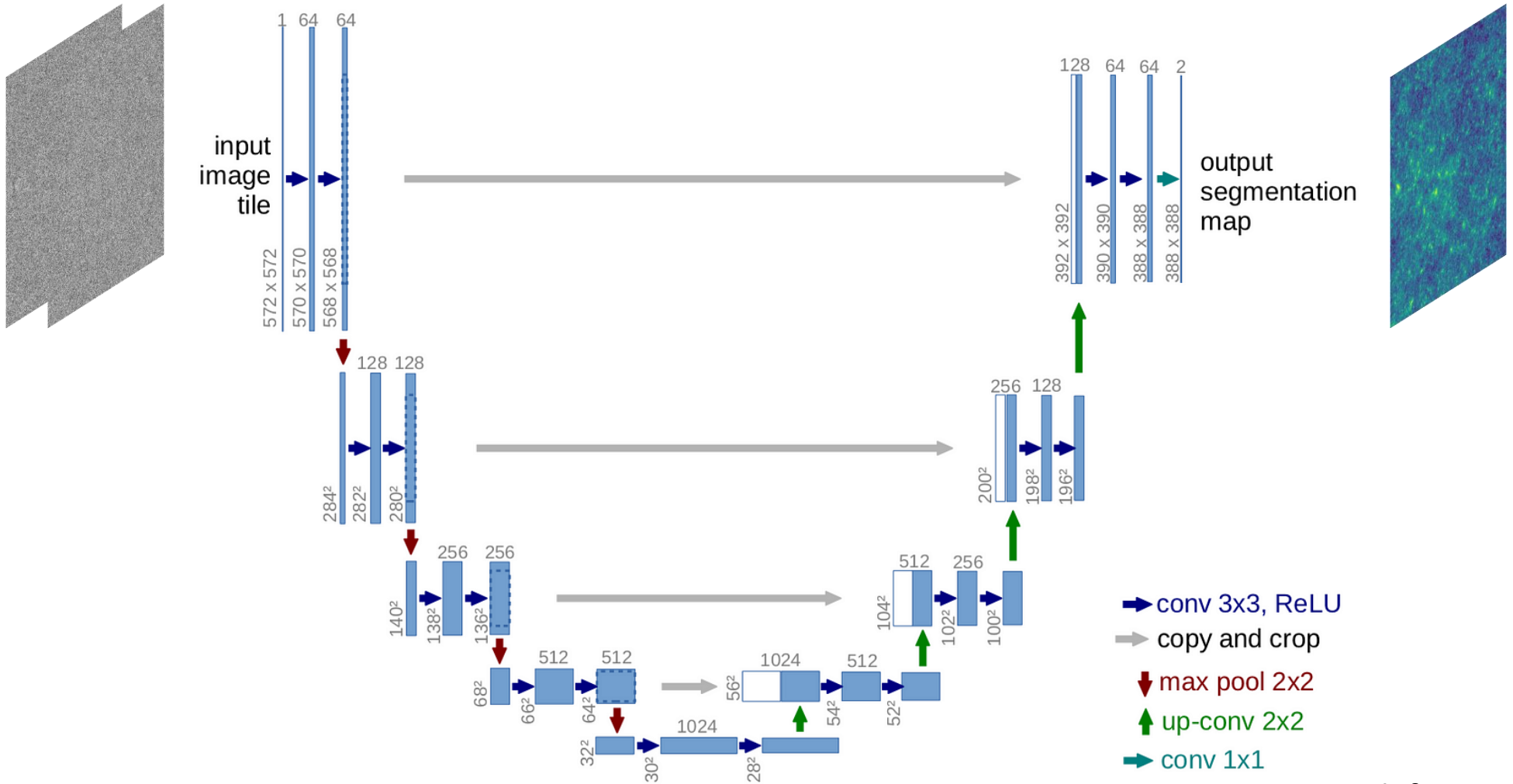
Convolution



Original	*Gaussian Blur*	*Sharpen*	*Edge Detection*
$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$	$\frac{1}{16}\begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix}$	$\begin{bmatrix} 0 & -1 & 0 \\ -1 & 5 & -1 \\ 0 & -1 & 0 \end{bmatrix}$	$\begin{bmatrix} -1 & -1 & -1 \\ -1 & 8 & -1 \\ -1 & -1 & -1 \end{bmatrix}$
			

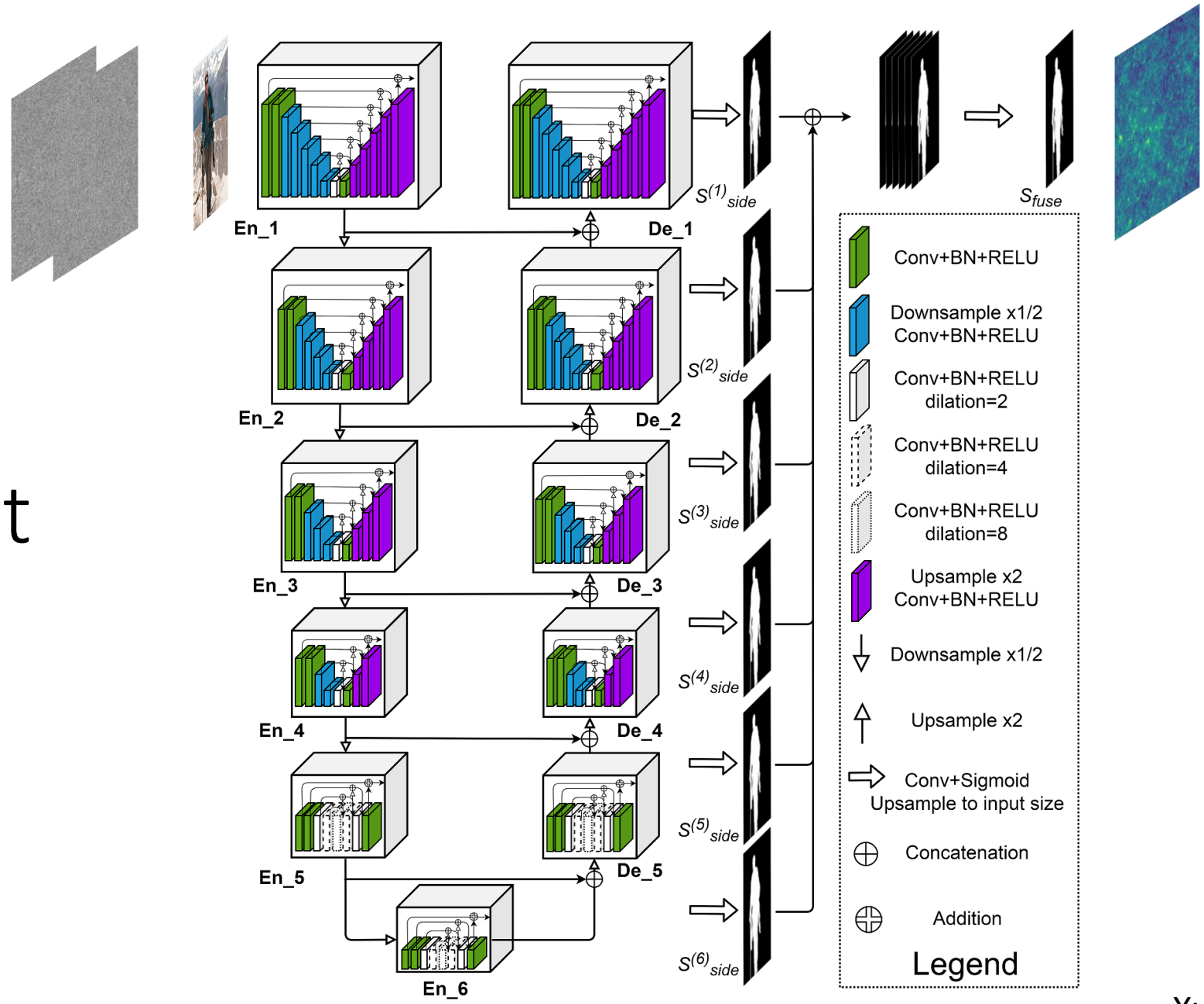
← Feature Maps

UNet (Encoder-Decoder)



Olaf Ronneberger 2015

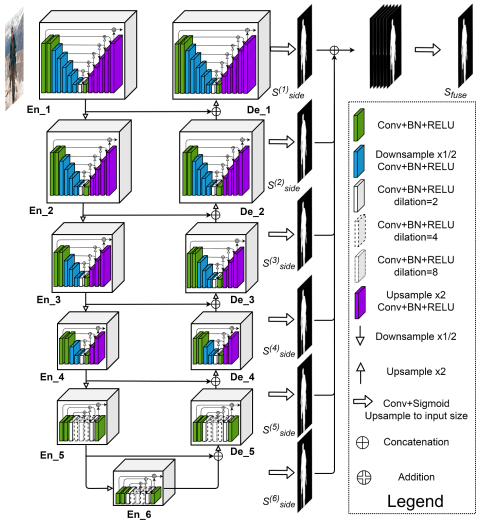
U2Net



Xuebin Qin 2020

Noisy Shear

$$\mathcal{F}(\gamma)$$



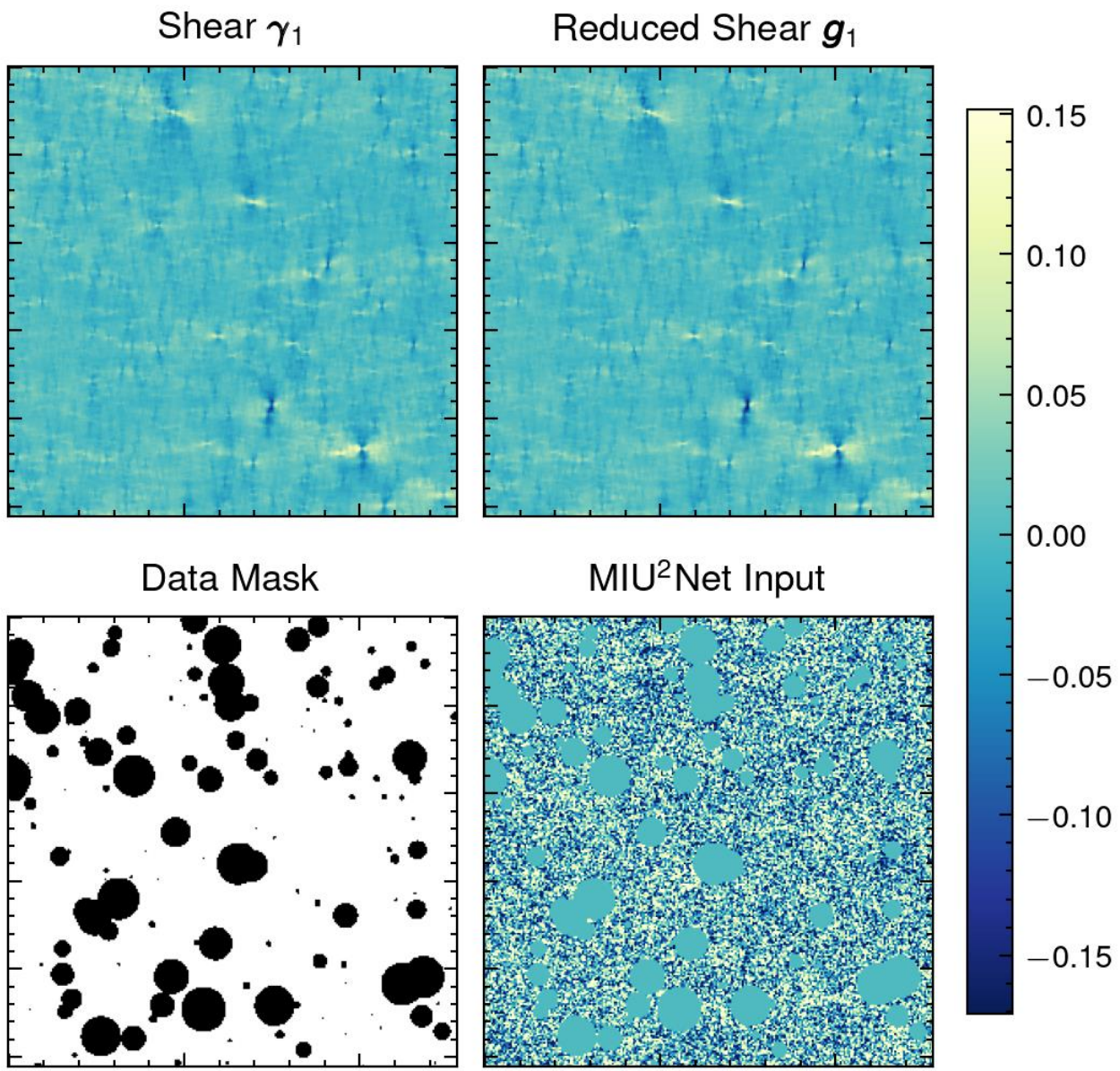
Good Looking Convergence

MIU^{2}Net Input:

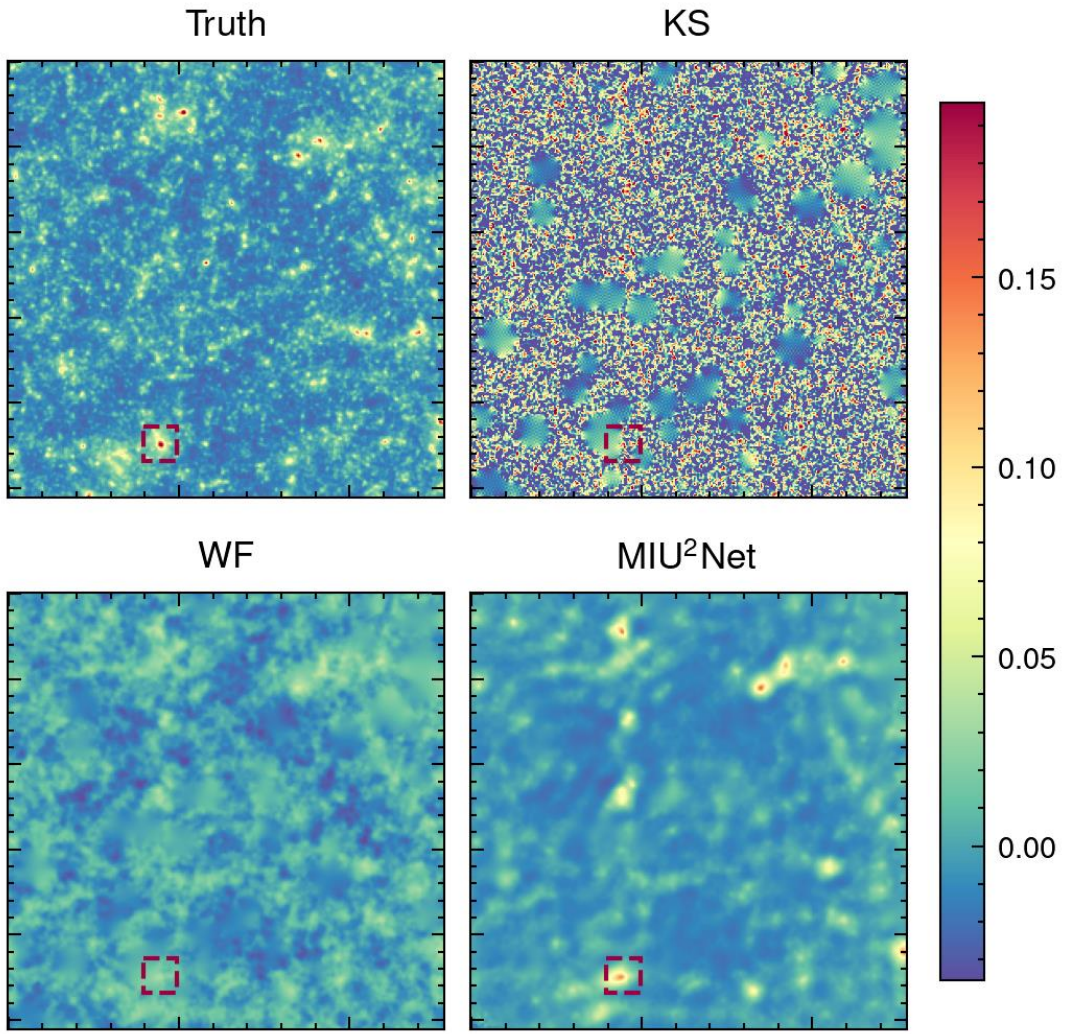
Masked, Noisy Reduced γ – clear κ pairs

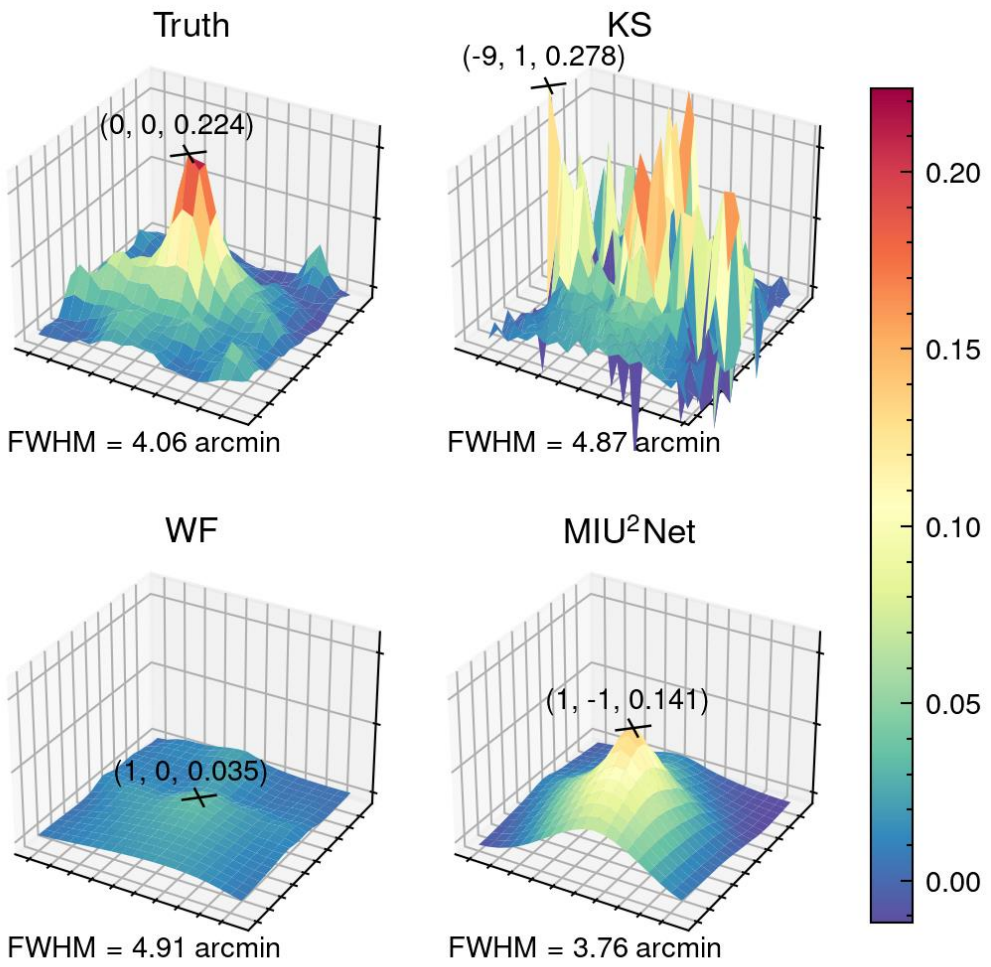
Training set : Validation set=5:1

training epochs=2000



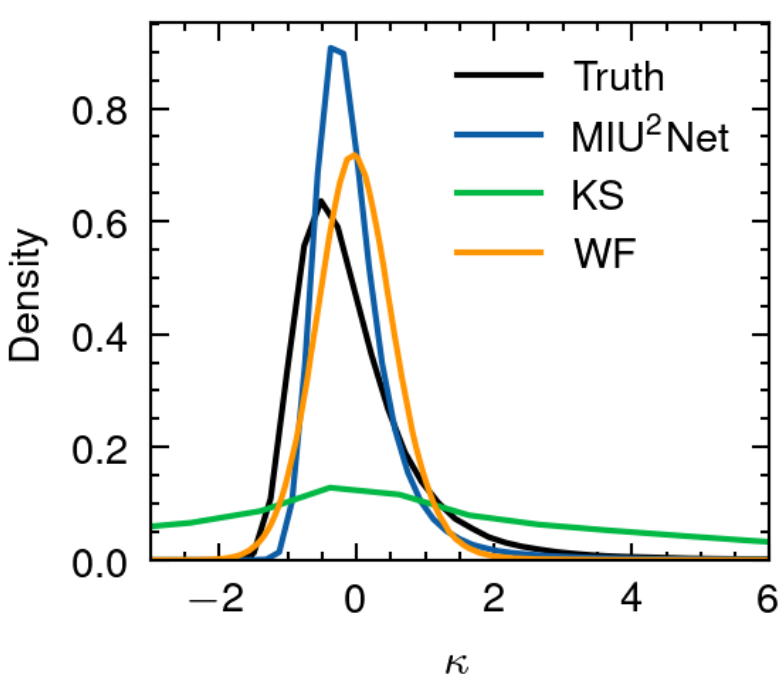
Results

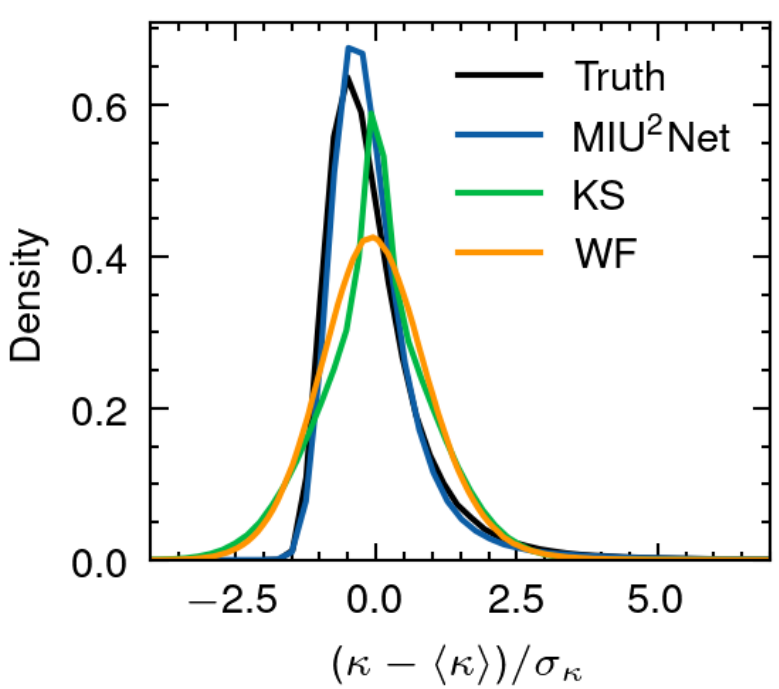


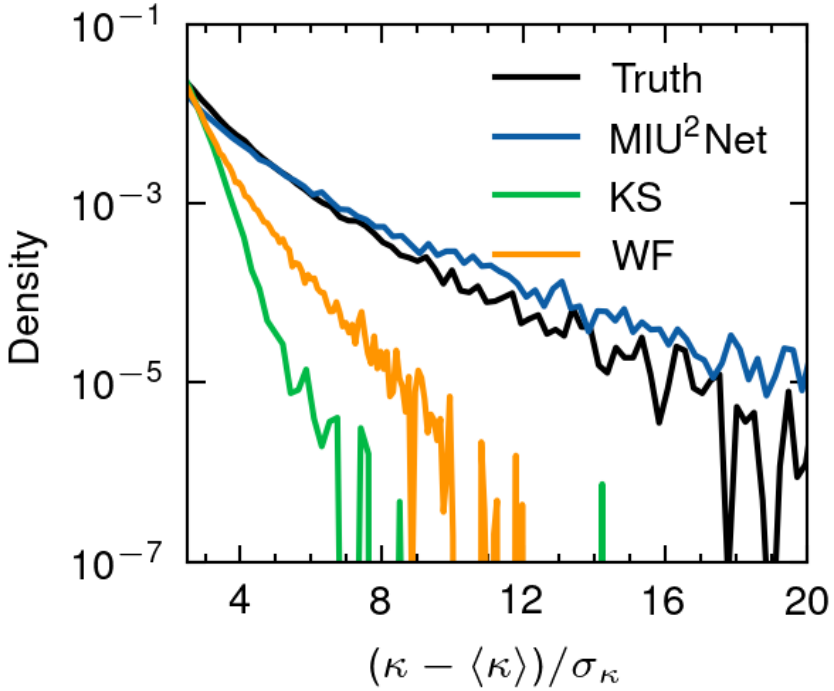


Wenhan Guo

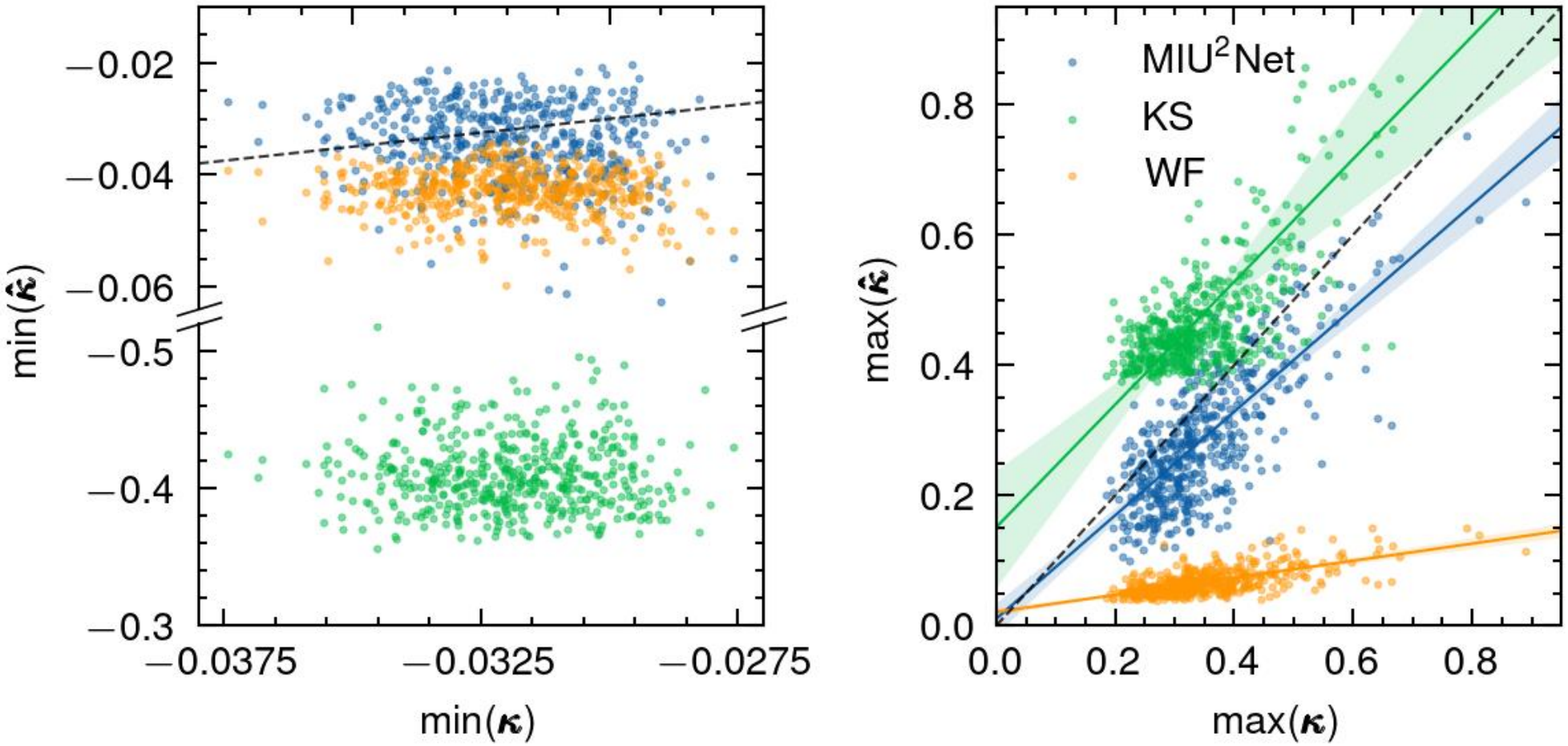
Convergence Distribution







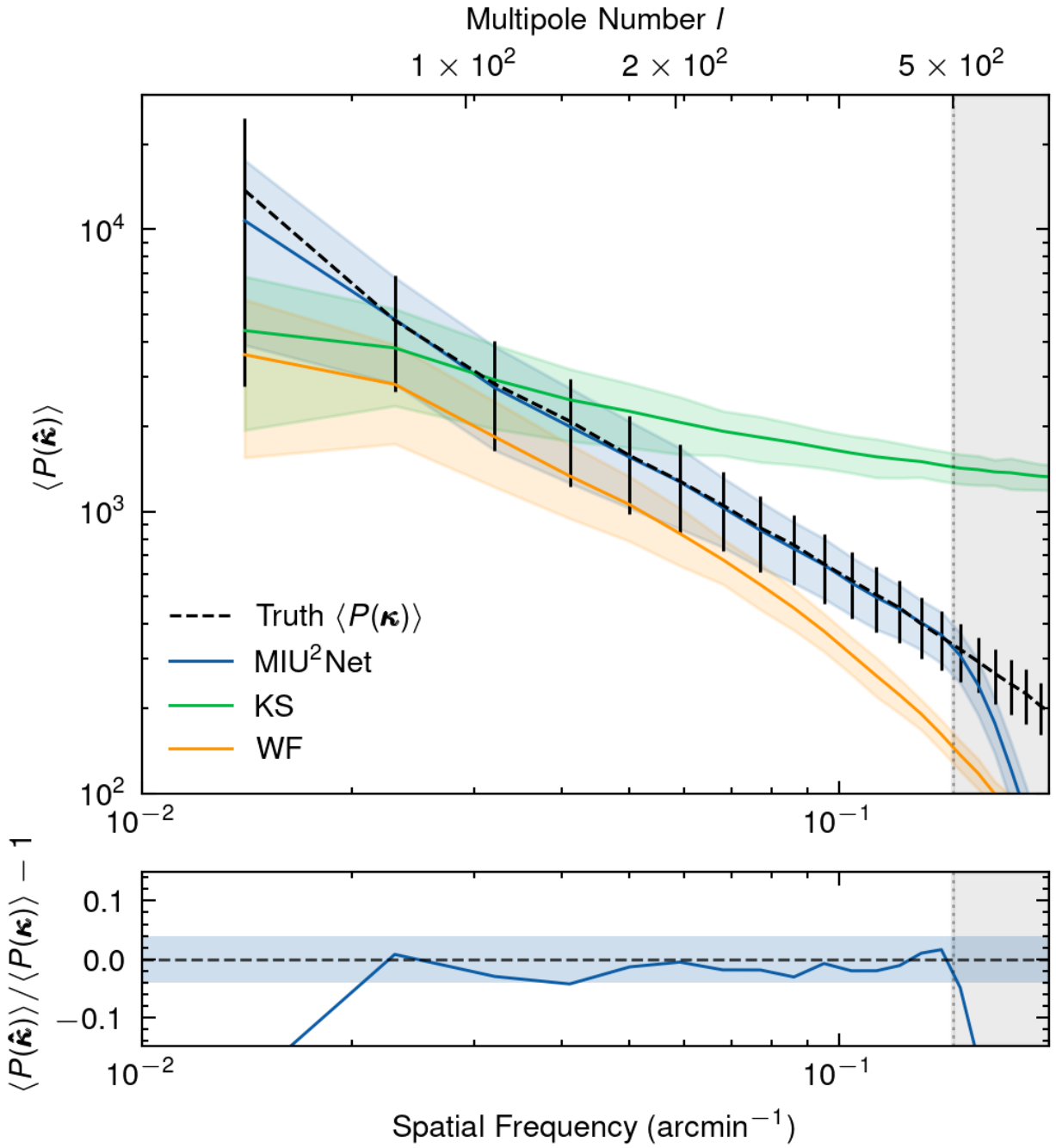
Dynamic Range Recovery



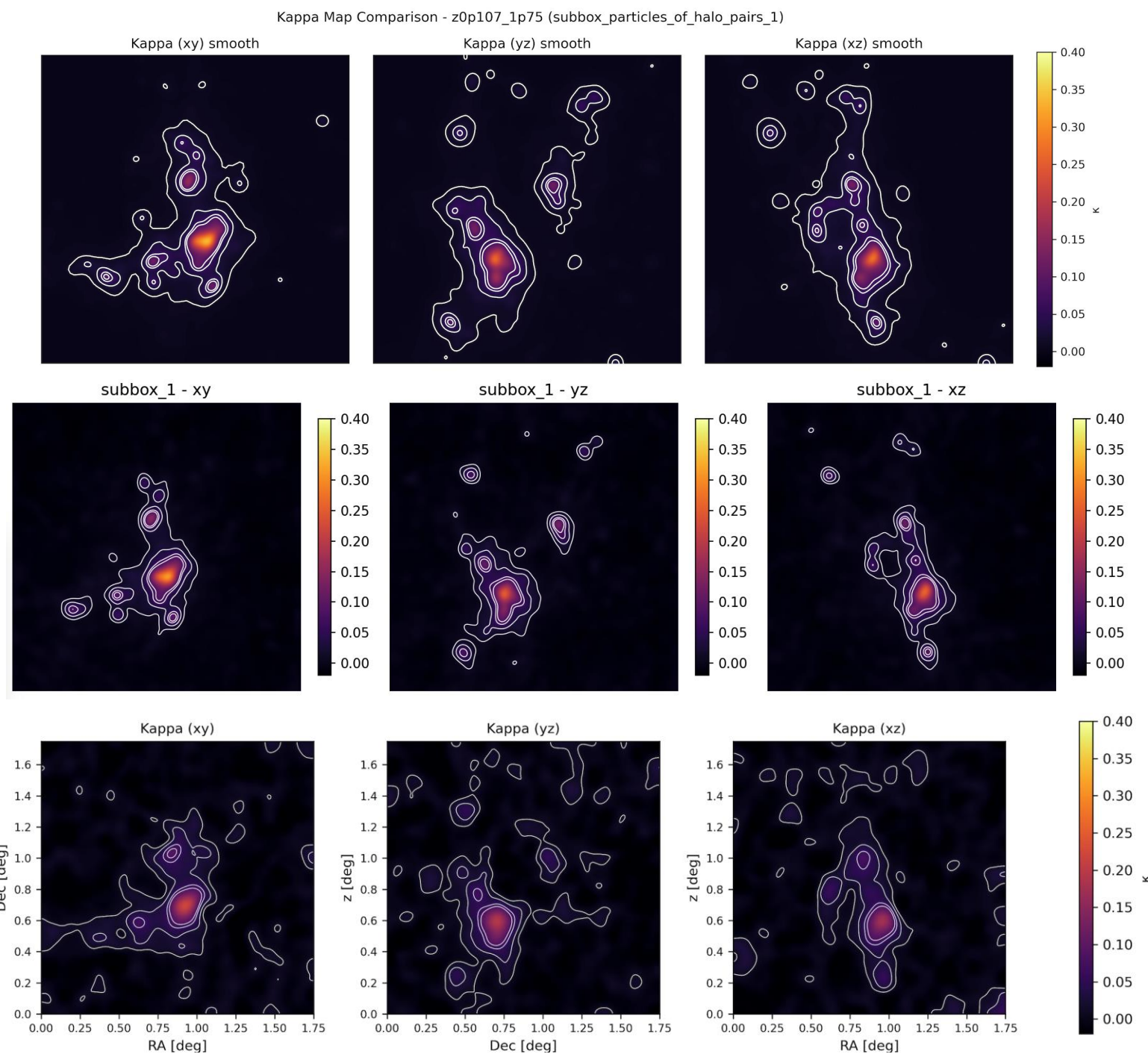
500 convergence reconstructions

Power Spectrum

within 4% accuracy up to ℓ ≈ 500



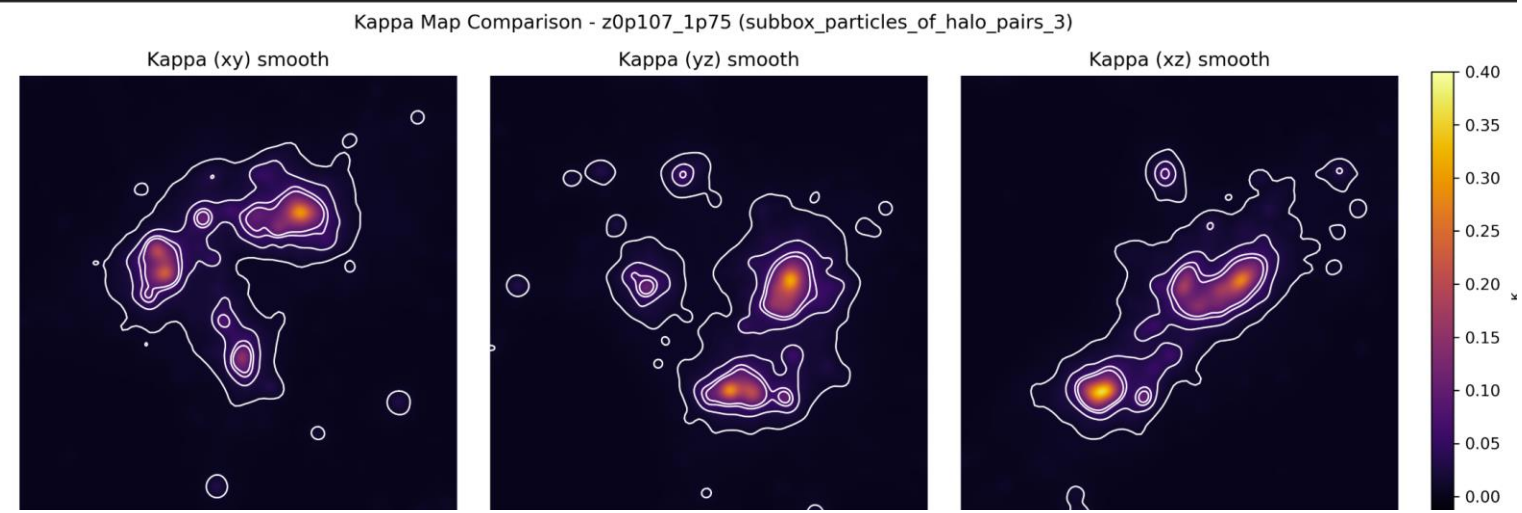
Halo pair/ Merging cluster



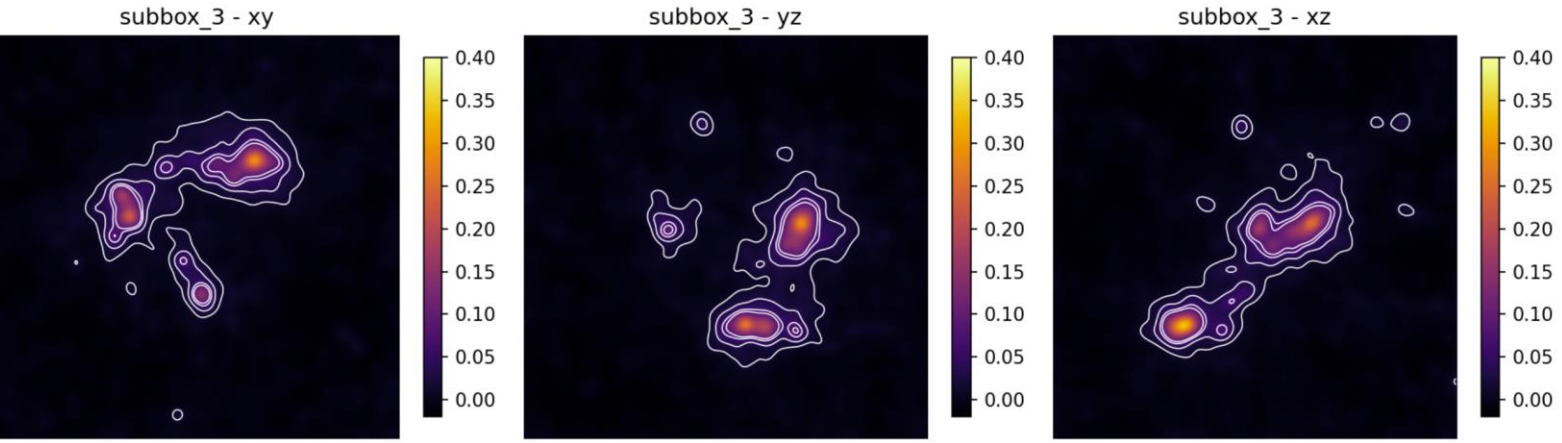
True

MIU2NET

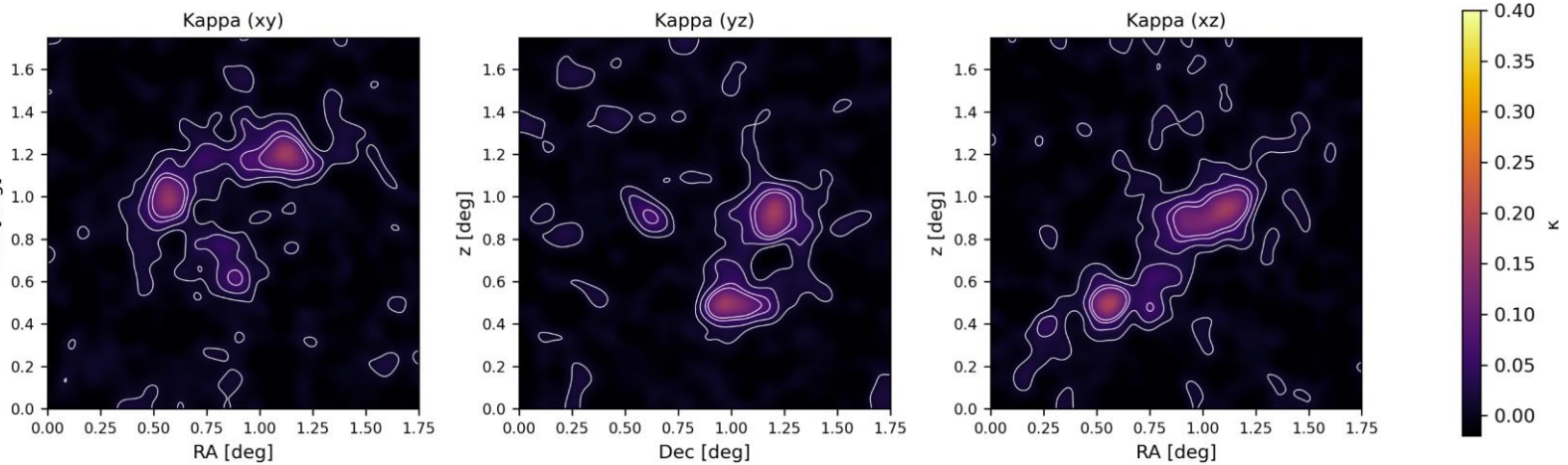
KS



True



MIU2NET



KS

Summary

- We propose Mass-Inversion-U2Net (MIU2NET), a general deep learning framework for weak lensing mass inversion.

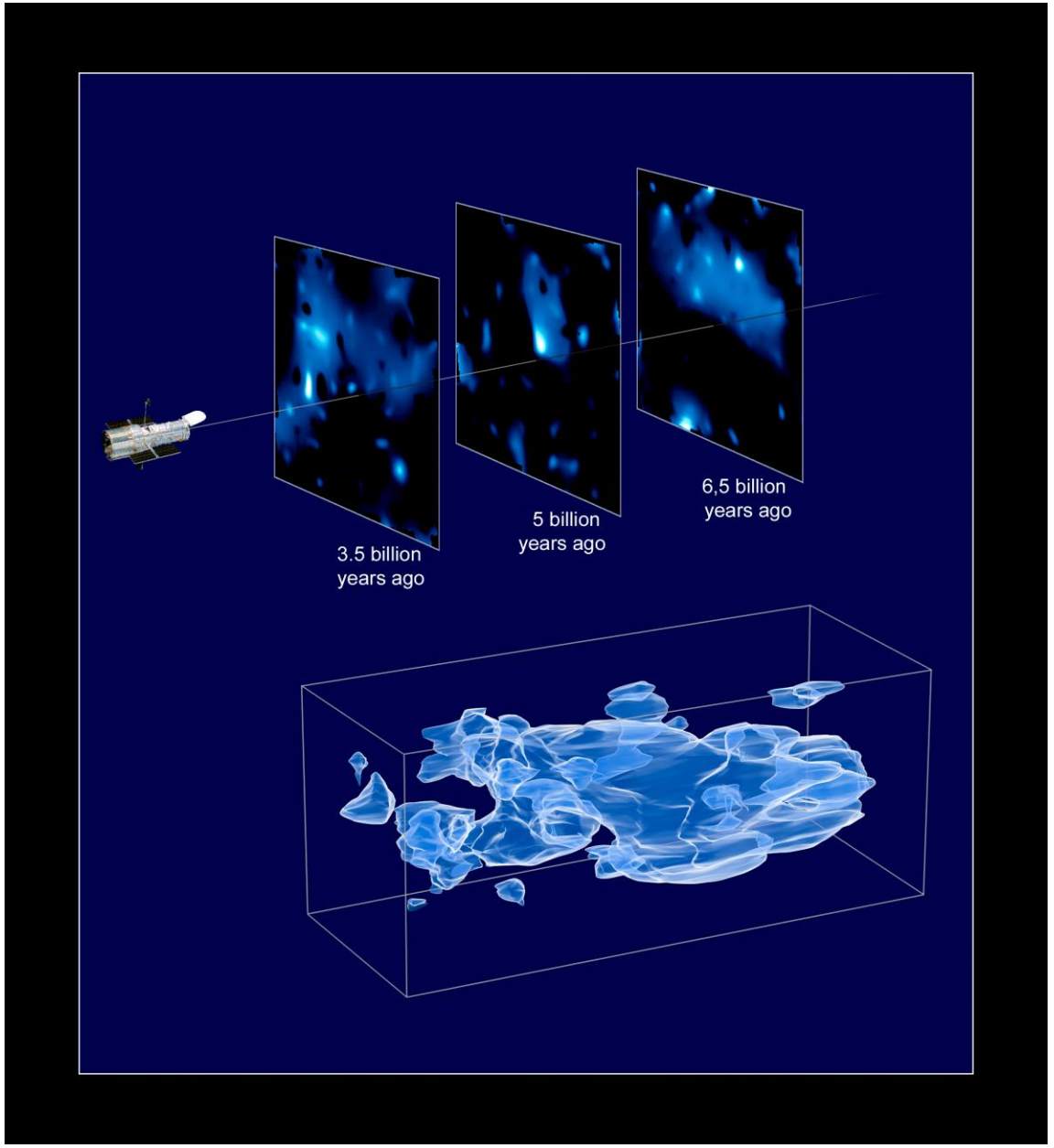
- MIU2NET has superior reconstruction quality from large-scale, filament-like structures to well-defined, non-Gaussian peaks.

- In the era of large, deep surveys like CSST, MIU2NET serves as a deep learning framework completely independent of traditional pipelines

Future Directions

- Large-scale structure (filament between merging clusters)
- Information integration: DM halo & Galaxy position
- 3D weak lensing

3D Weak Lensing



Thank you for your attention!