Precision cosmology with gravitational lensing

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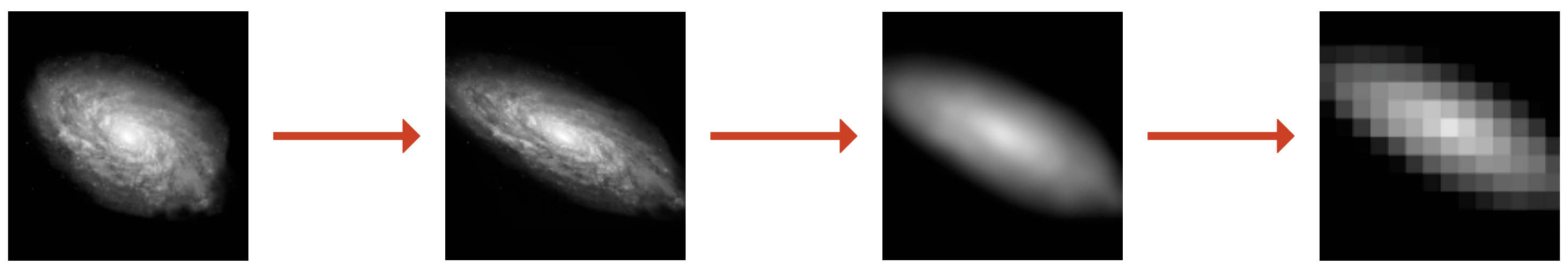
Future surveys like LSST will deliver images to usher in the era of precision cosmology. Thanks to these images, it will be possible to carry out unprecedented weak gravitational lensing analysis in order to better understand dark energy. However, the weak lensing measurement is complex and associated with biases that can have multiple sources, including a poorly calibrated estimator. Here we describe the development of an unbiased cosmic shear estimator measured on galaxies, based on a self-calibrated algorithm using the second moments method.



e^i → e^i + **shear** → e^i + **shear** + PSF → e^i + **shear** + PSF + pixels

Method :

First step : How to measure the shape ?

$$M = \int XX^T W(X) I(X)\, dX^2 \longrightarrow \mathbf{e} = \begin{pmatrix} e_1 \\ e_2 \end{pmatrix} = F^{-1}\begin{pmatrix} M_{xx} - M_{yy} \\ 2M_{xy} \end{pmatrix}$$

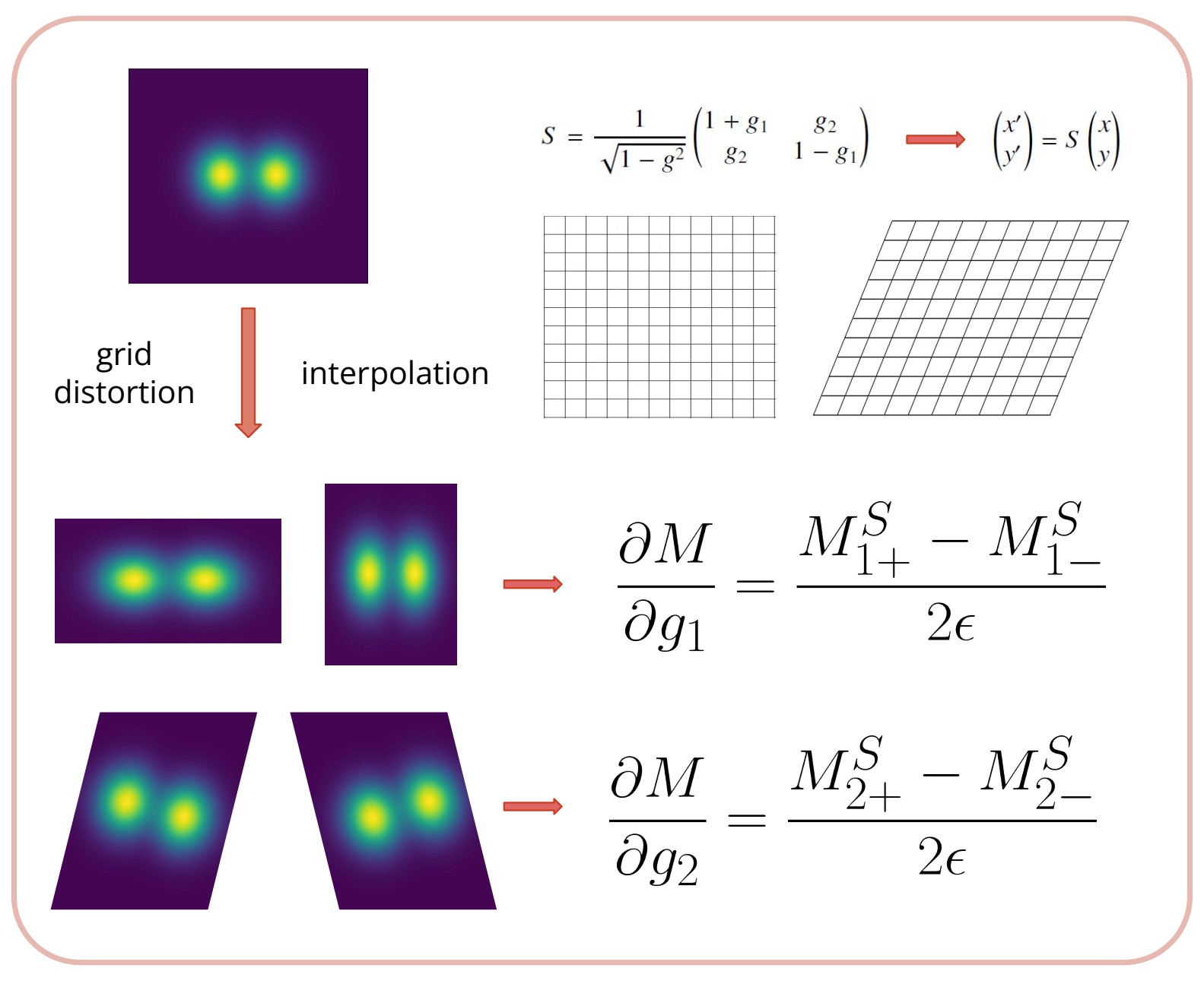
Ellipticity

$$\downarrow$$

$$I_0 \circledast \psi$$

Second step : Ellipticity only is not sufficient to estimate shear → Calibration is needed !

$$\boxed{\frac{dM}{d\gamma}} = \int \boxed{\frac{dG(S(\gamma), X)}{d\gamma}} I(X)\, dX^2$$



$$S = \frac{1}{\sqrt{1-g^2}}\begin{pmatrix} 1+g_1 & g_2 \\ g_2 & 1-g_1 \end{pmatrix} \rightarrow \begin{pmatrix} x' \\ y' \end{pmatrix} = S\begin{pmatrix} x \\ y \end{pmatrix}$$

$$\frac{\partial M}{\partial g_1} = \frac{M^S_{1+} - M^S_{1-}}{2\epsilon}$$

$$\frac{\partial M}{\partial g_2} = \frac{M^S_{2+} - M^S_{2-}}{2\epsilon}$$

$$M(S) = \int (XX^T W(X)) \psi \circledast I_0(SX) dX^2$$

$$M(S) = \int \underbrace{(XX^T W(X) \circledast \psi_-)}_{F(X)} I_0(SX) dX^2$$

$$= \int F(S^{-1}X) I_0(X)\, dX^2$$

$$= \int G(S, X) I(X)\, dX^2$$

$$\mathbf{R} = \begin{pmatrix} \frac{\partial e_1}{\partial g_1} & \frac{\partial e_2}{\partial g_1} \\ \frac{\partial e_1}{\partial g_2} & \frac{\partial e_2}{\partial g_2} \end{pmatrix} = \begin{pmatrix} \frac{\partial M_{xx}}{\partial g_1} - \frac{\partial M_{yy}}{\partial g_1} & \frac{2\partial M_{xy}}{\partial g_1} \\ \frac{\partial M_{xx}}{\partial g_2} - \frac{\partial M_{yy}}{\partial g_2} & \frac{2\partial M_{xy}}{\partial g_2} \end{pmatrix}$$

Auto-calibration factor

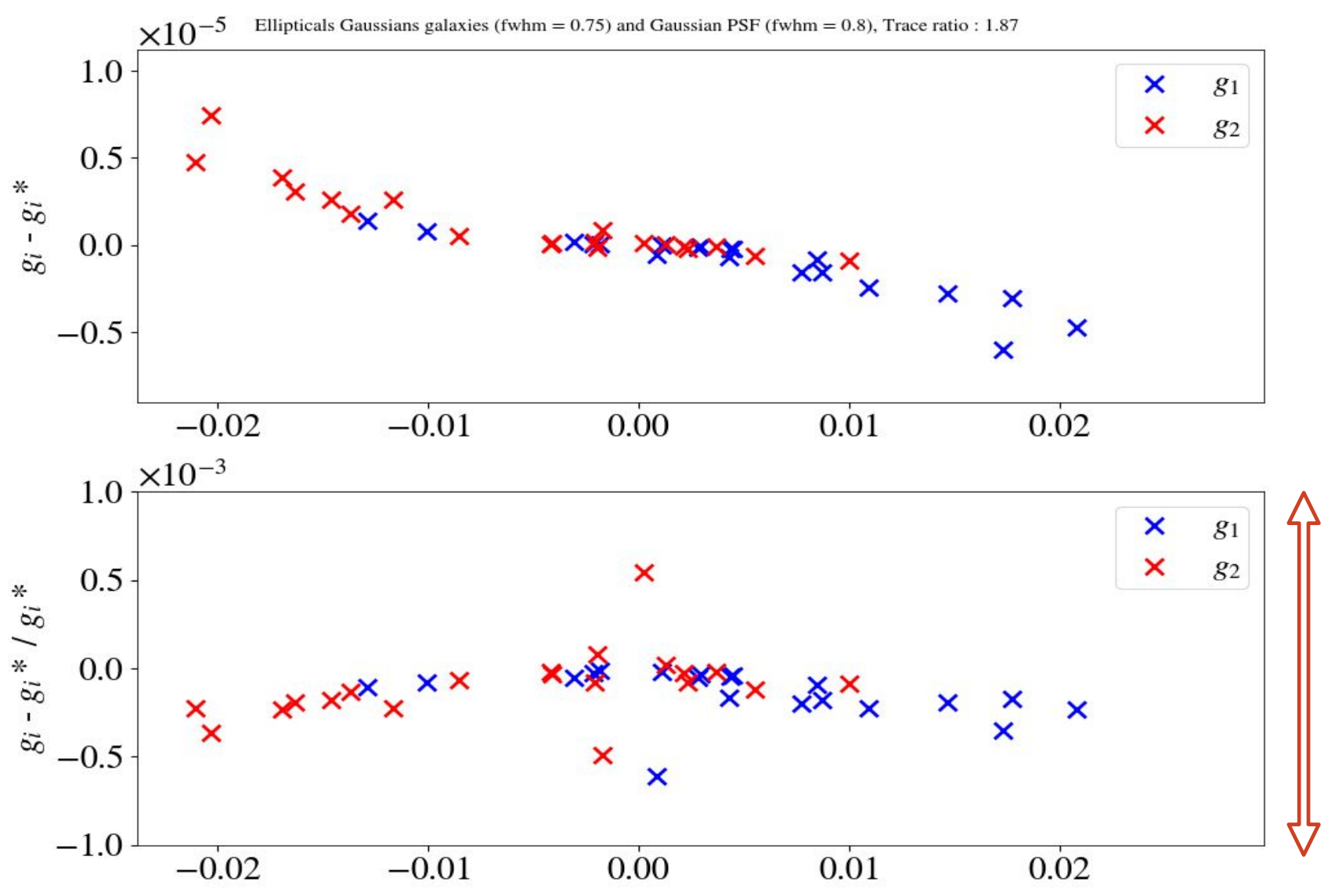
Third step : Shear estimation :

$$\boxed{\langle g \rangle = \langle \mathbf{R} \rangle^{-1} \langle e \rangle}$$

Advantages of this method :

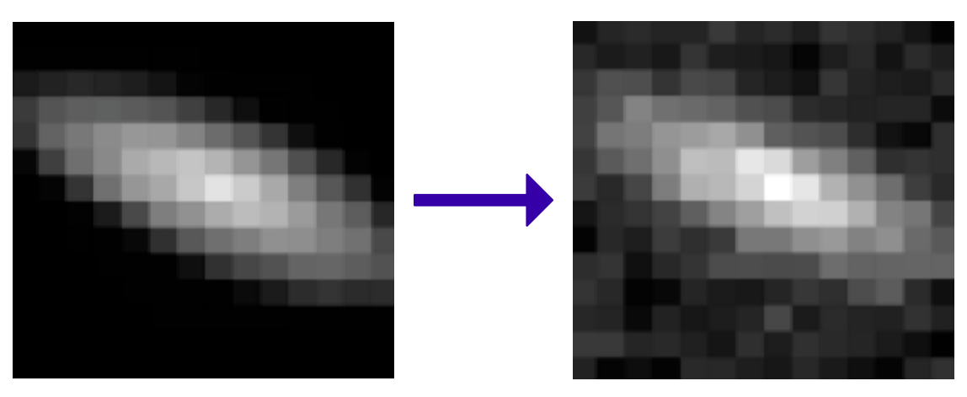
- Calculations based on second moments → no assumption about galaxy profile
- *F* function more extensive than I_0 → therefore better to apply shear distortion on it :
  - distorting I_0 introduces correlated noise
  - allows shear estimations on undersampled images

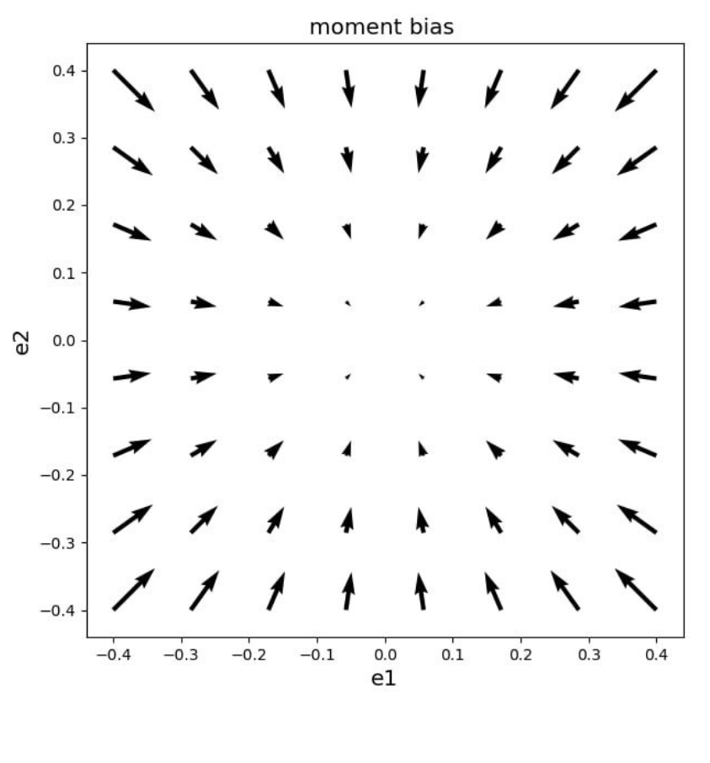
Results noise-free :

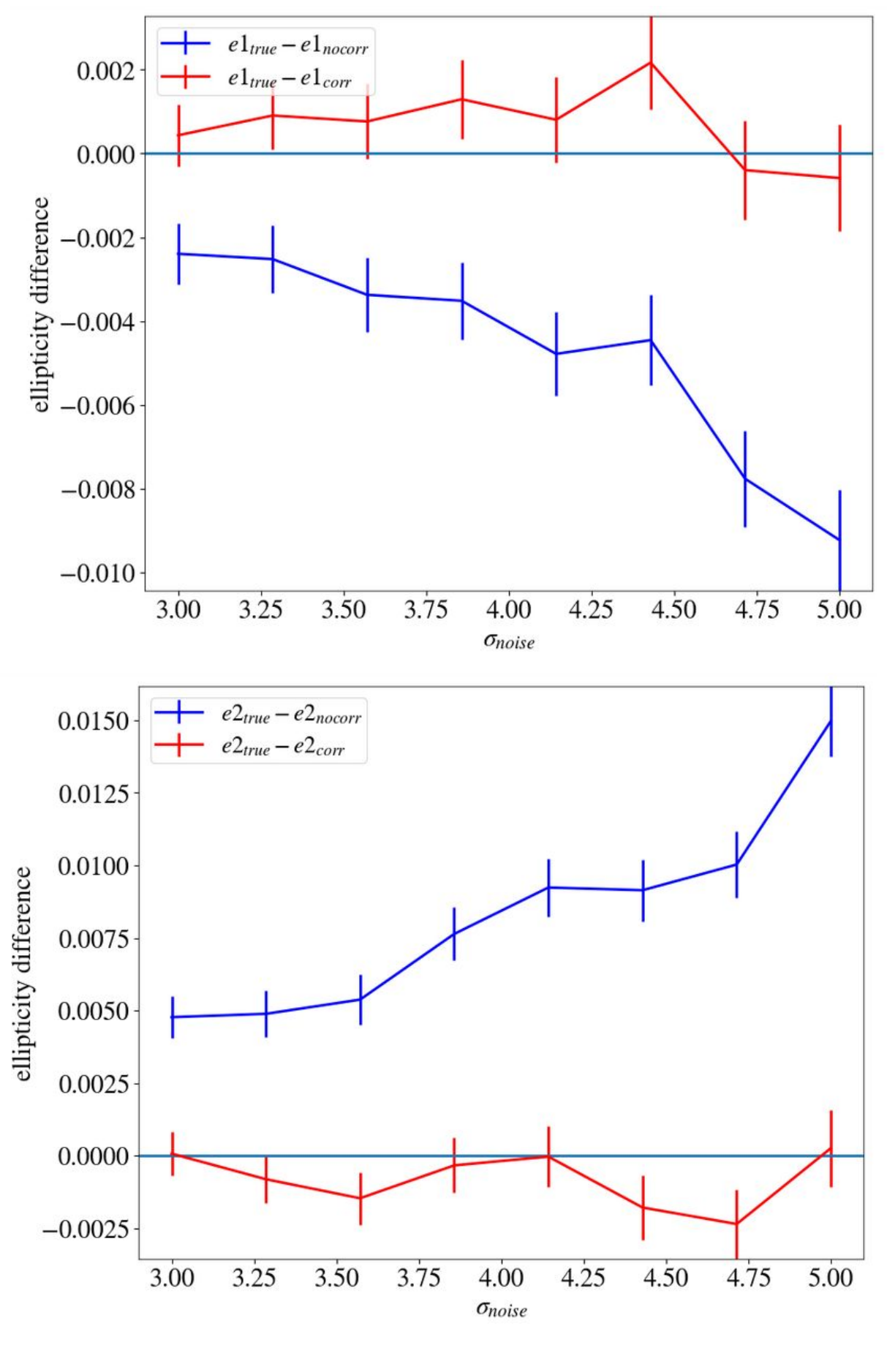


bias < 10^{-3} !

Results noisy :



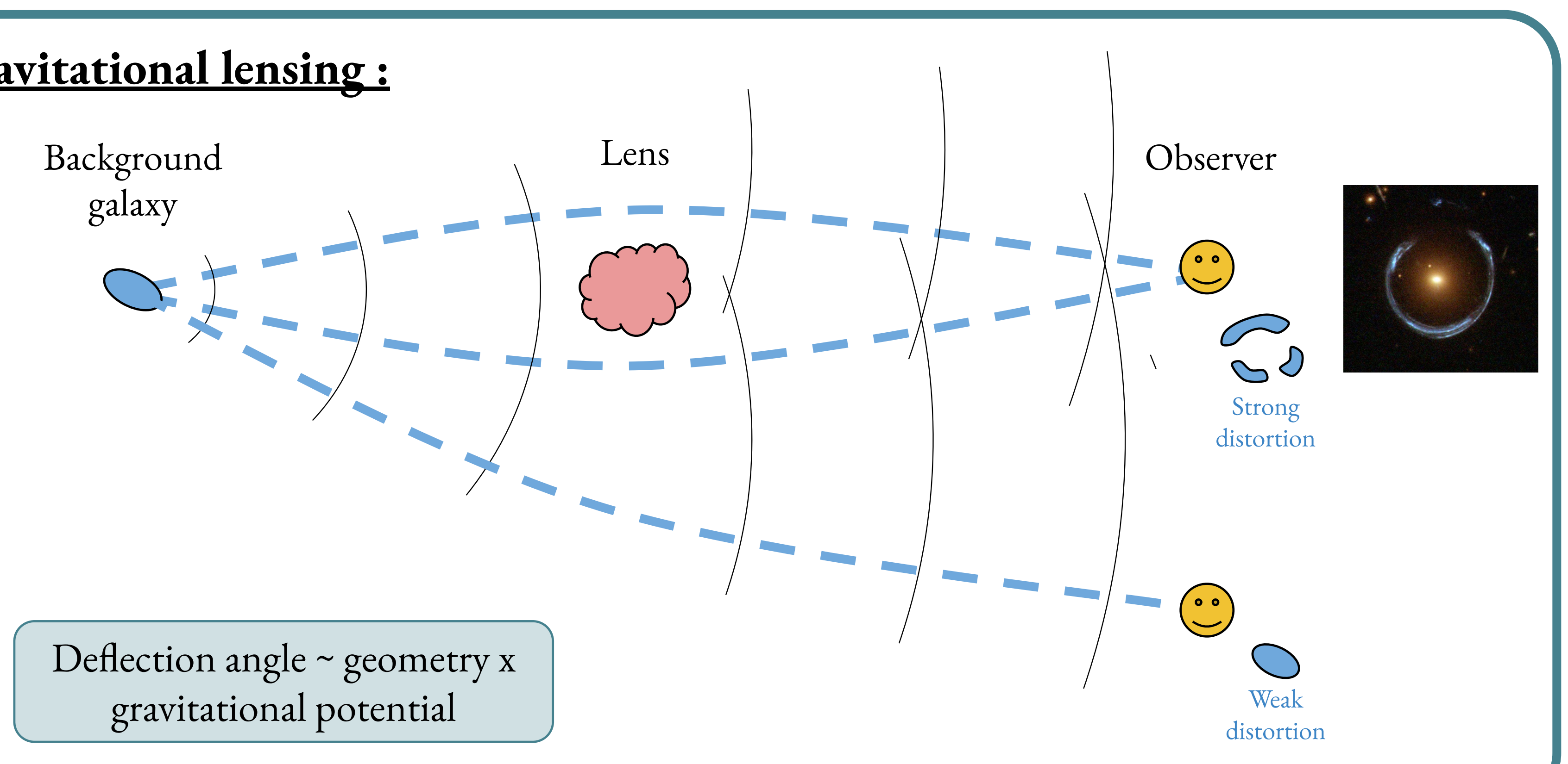




Idea → Calculate analytical formulas to correct the noise bias :

$$m_I(I+n) = m_I(I) + \sum_k \frac{dm_I}{dI_k} n_k + \frac{1}{2}\sum_{kl} \boxed{\frac{d^2 m_I}{dI_k dI_l}} n_k n_l$$

Gravitational lensing :

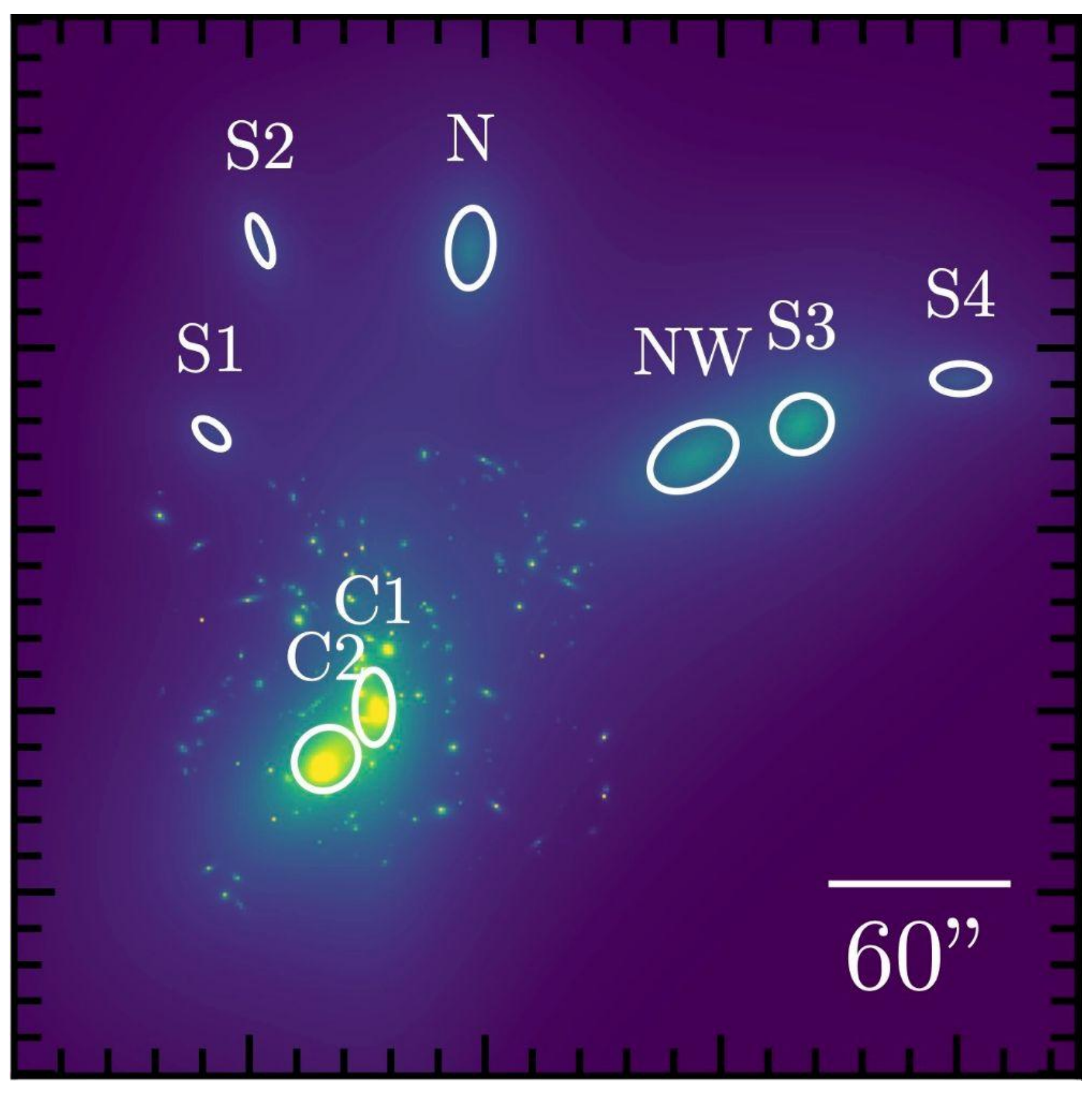


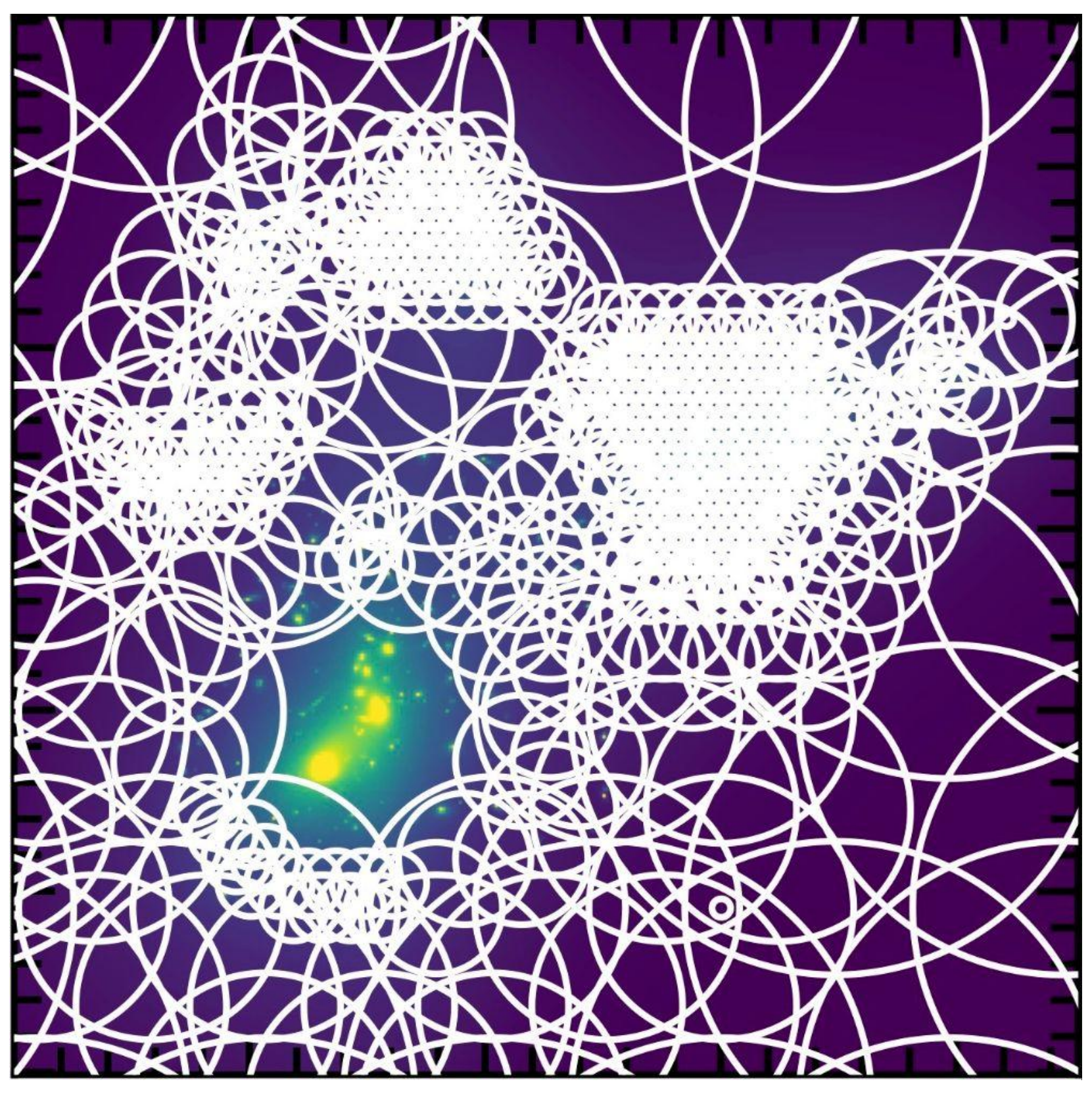
Deflection angle ~ geometry x gravitational potential

Mass mapping galaxy clusters with lensing :

Measure total mass distribution (dark matter + baryons)

First step : set up structure of the projected mass distribution model → hybrid model





Parametric model for main components

Cluster and galaxy scale haloes

→ position, shape, density profiles

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Free-form model for substructures

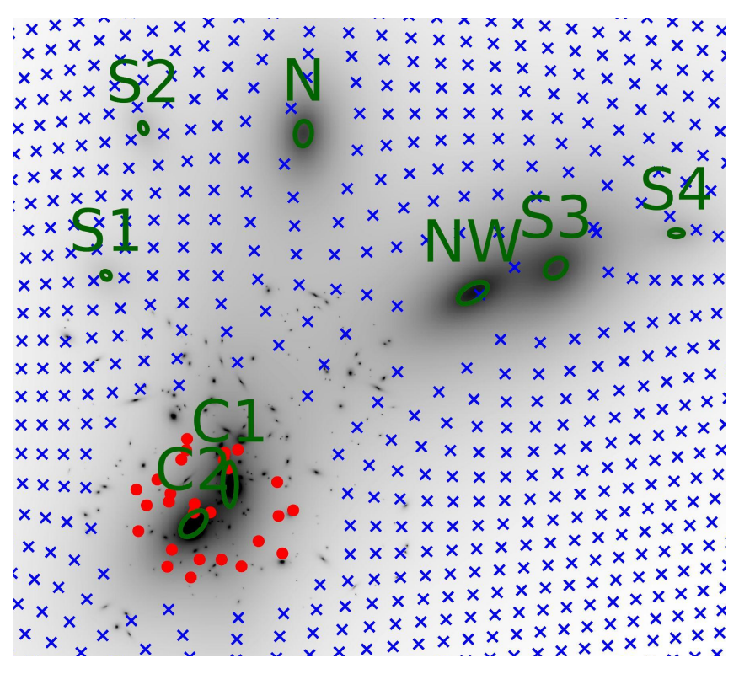
Grid of Radial Basis Functions

→ amplitude of “mass pixels”

Second step : constraints from gravitational lensing

Strong lensing

Position of background galaxies

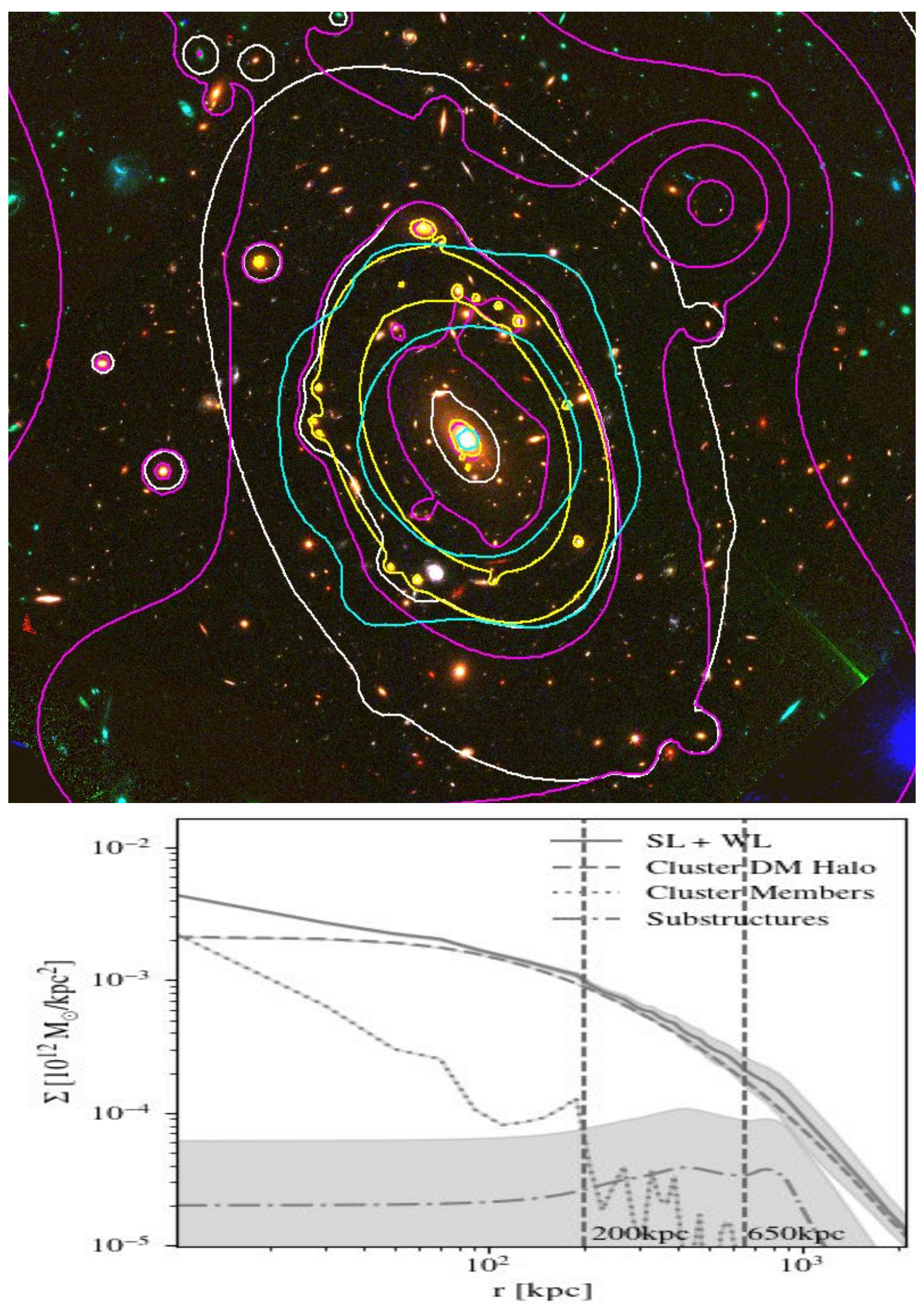


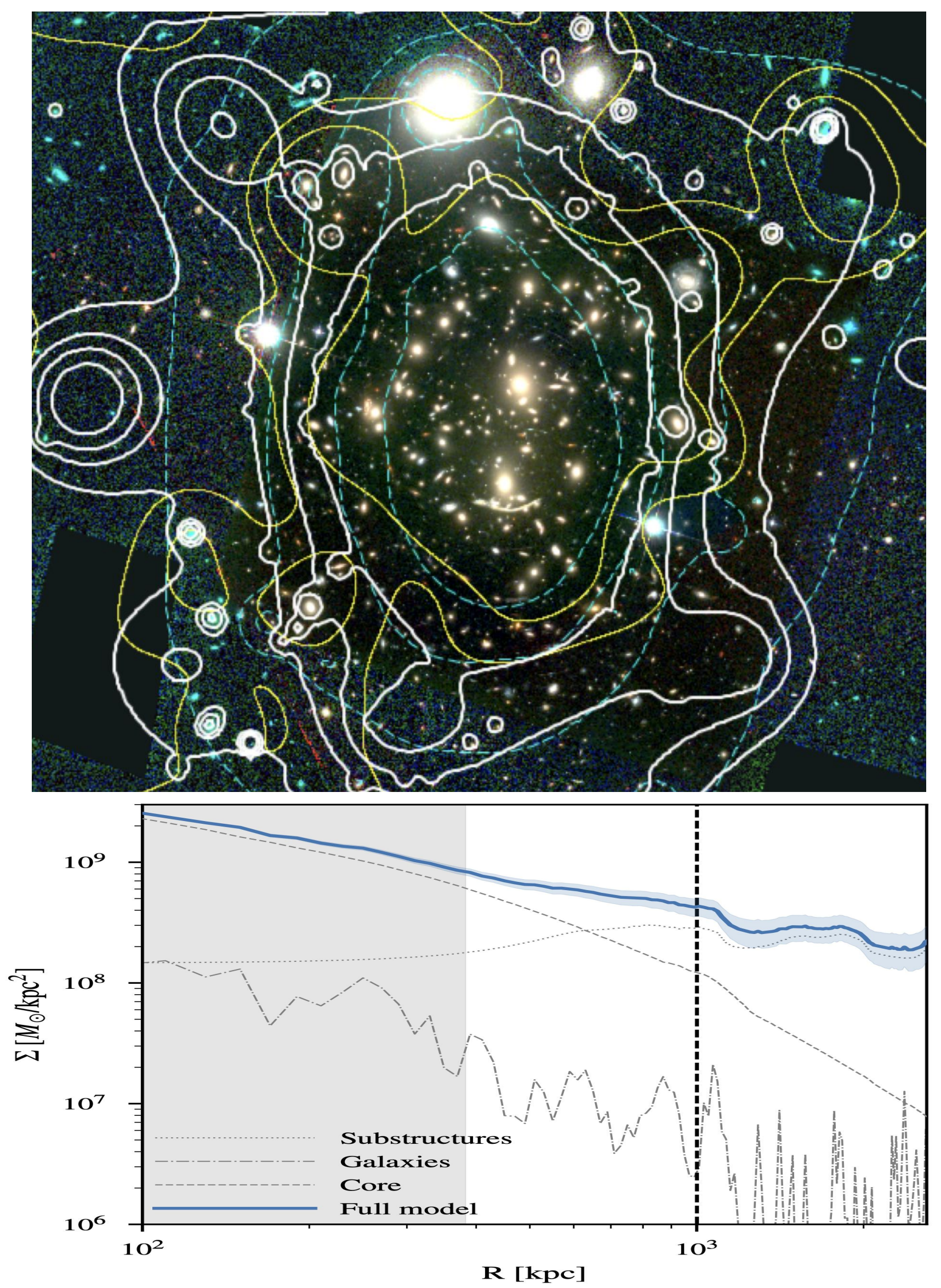
Weak lensing

Shear of background galaxies

Third step : optimise model in bayesian framework (*hybrid*-Lenstool, *Niemiec+2020*)

Application for two clusters at opposite evolutionary stages :





Macs1423 (*Patel+submitted*)

Dynamically relaxed cluster, low ratio of substructures to main components

Abell370 (*Niemiec+2023*)

Post-merger cluster, complex mass distribution, high substructure contribution

Galaxy clusters are complex structures, presenting a range of morphologies and dynamical states. The degree of relaxation of a cluster impact the complexity of its matter distribution, as well as the relative distribution of its different components (dark matter, hot ionized gas, stars). Combining gravitational lensing analyses and multi-wavelength observations (X-rays, optical, etc.) allows to trace these components, and thus establish precise mass models. These models are a key tool for a range of cosmological applications (cluster abundance to measure σ_8 and Ω_m, baryon fraction, constrain nature of dark matter, ...).