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Image reconstruction from in-line holograms using inverse problems recipes: tutorial

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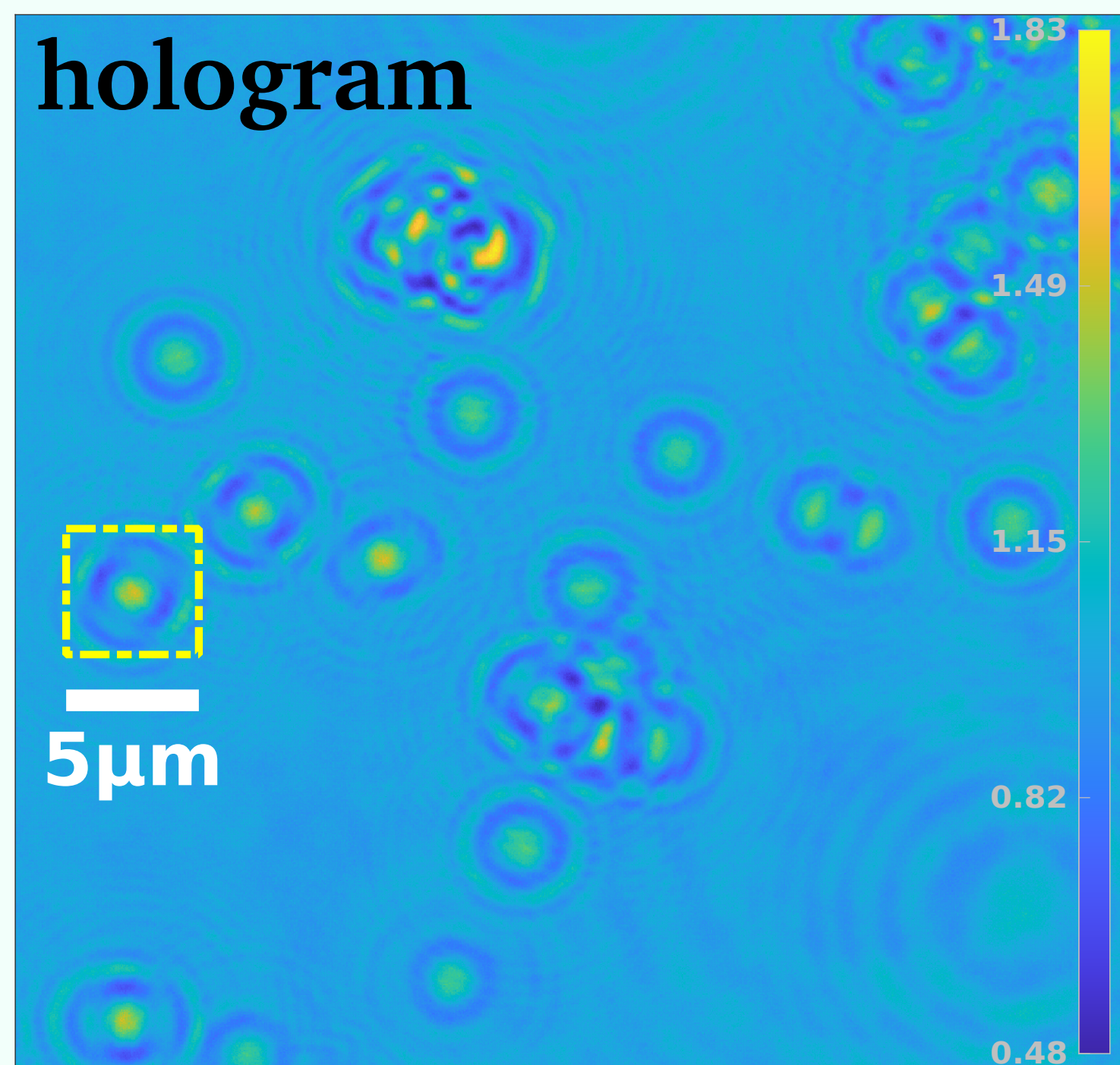
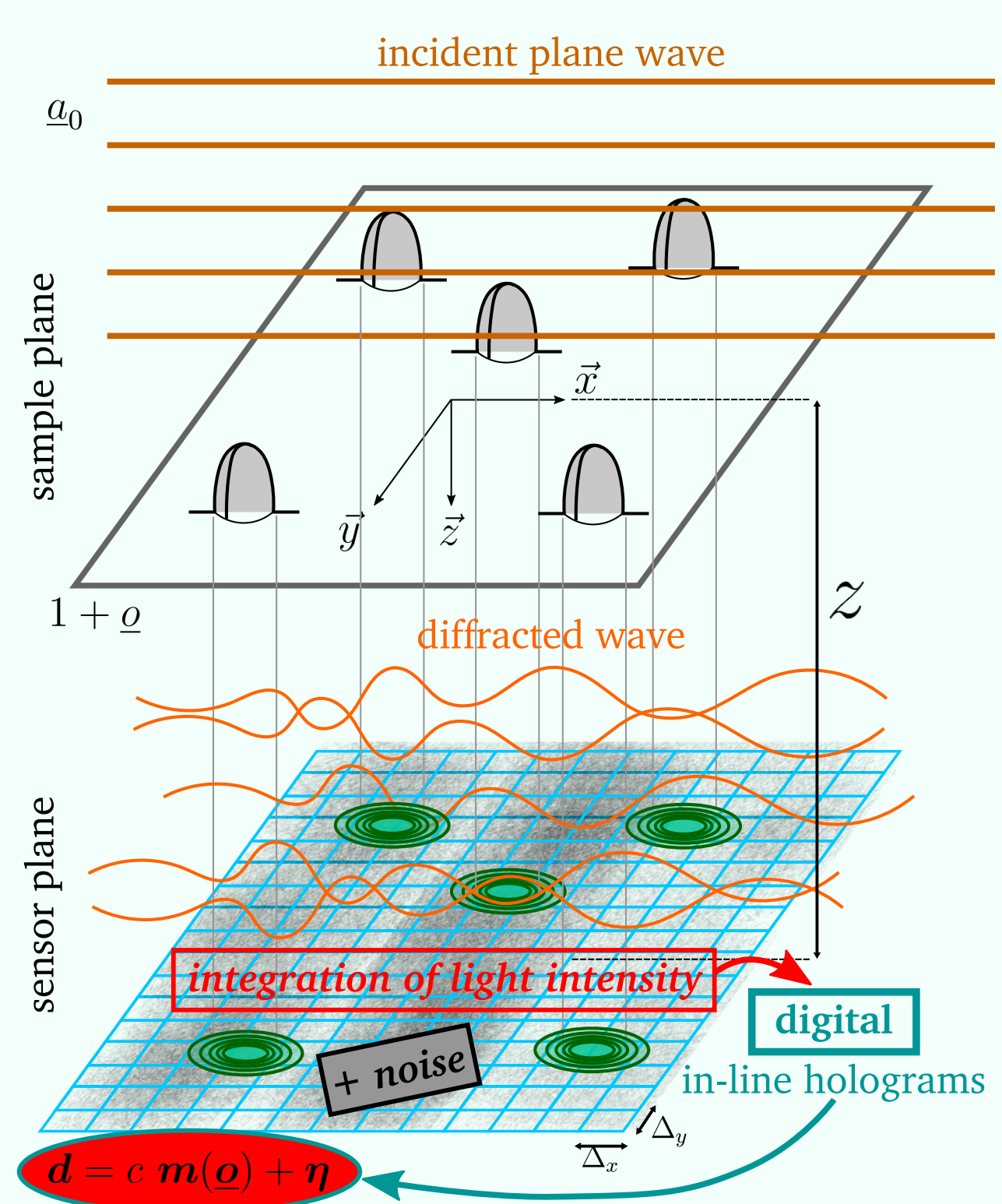
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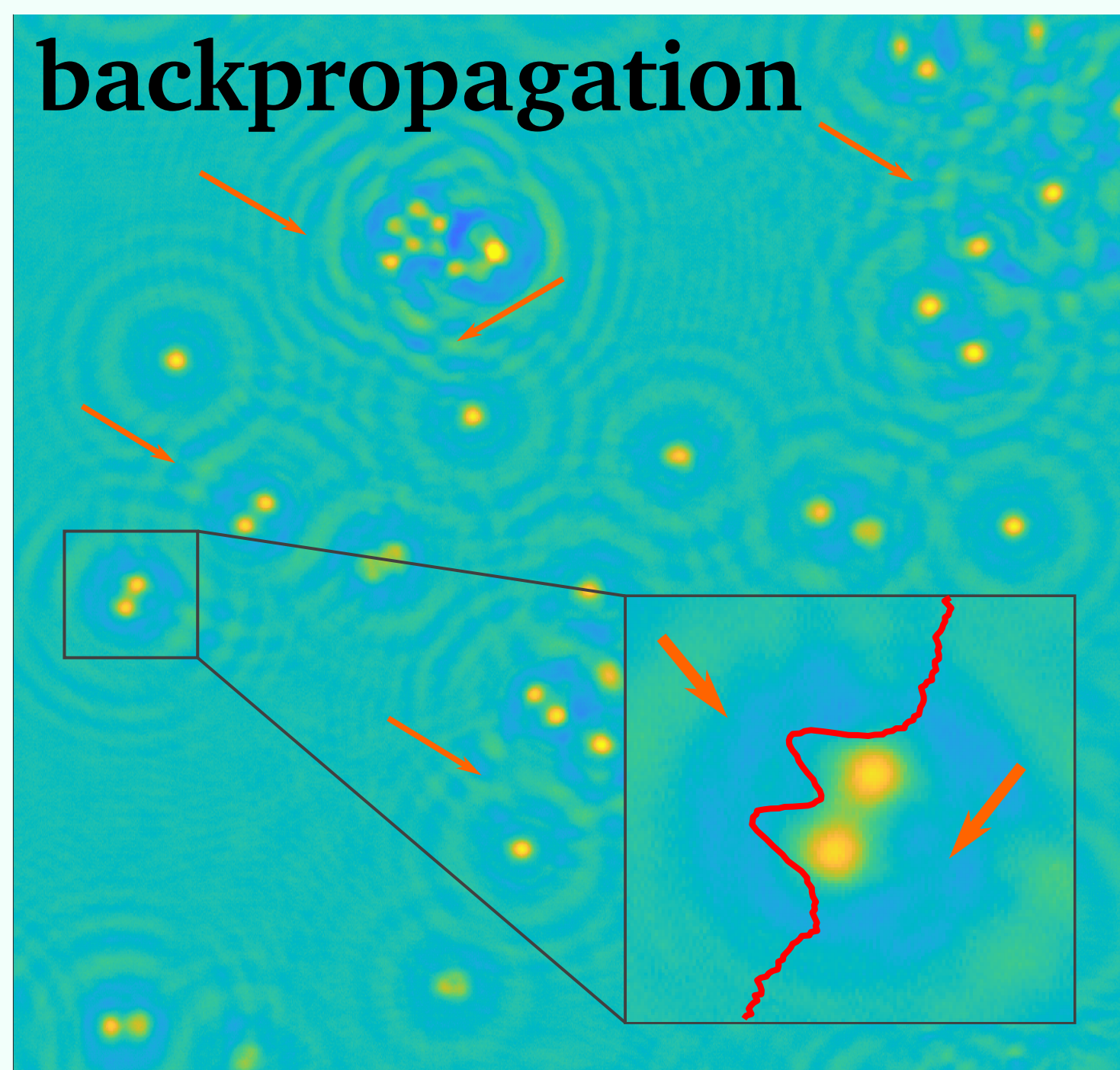
Abstract

We present our tutorial [1] for building **inverse problems** based image reconstruction strategies in **digital in-line holography (DH)**, starting from the identification of the connections with the well known **alternated projections** strategies. **In-line DH is of great interest for optical microscopy dedicated to biology, as it constitutes a robust, efficient and label-free tool for imaging transparent living samples.**

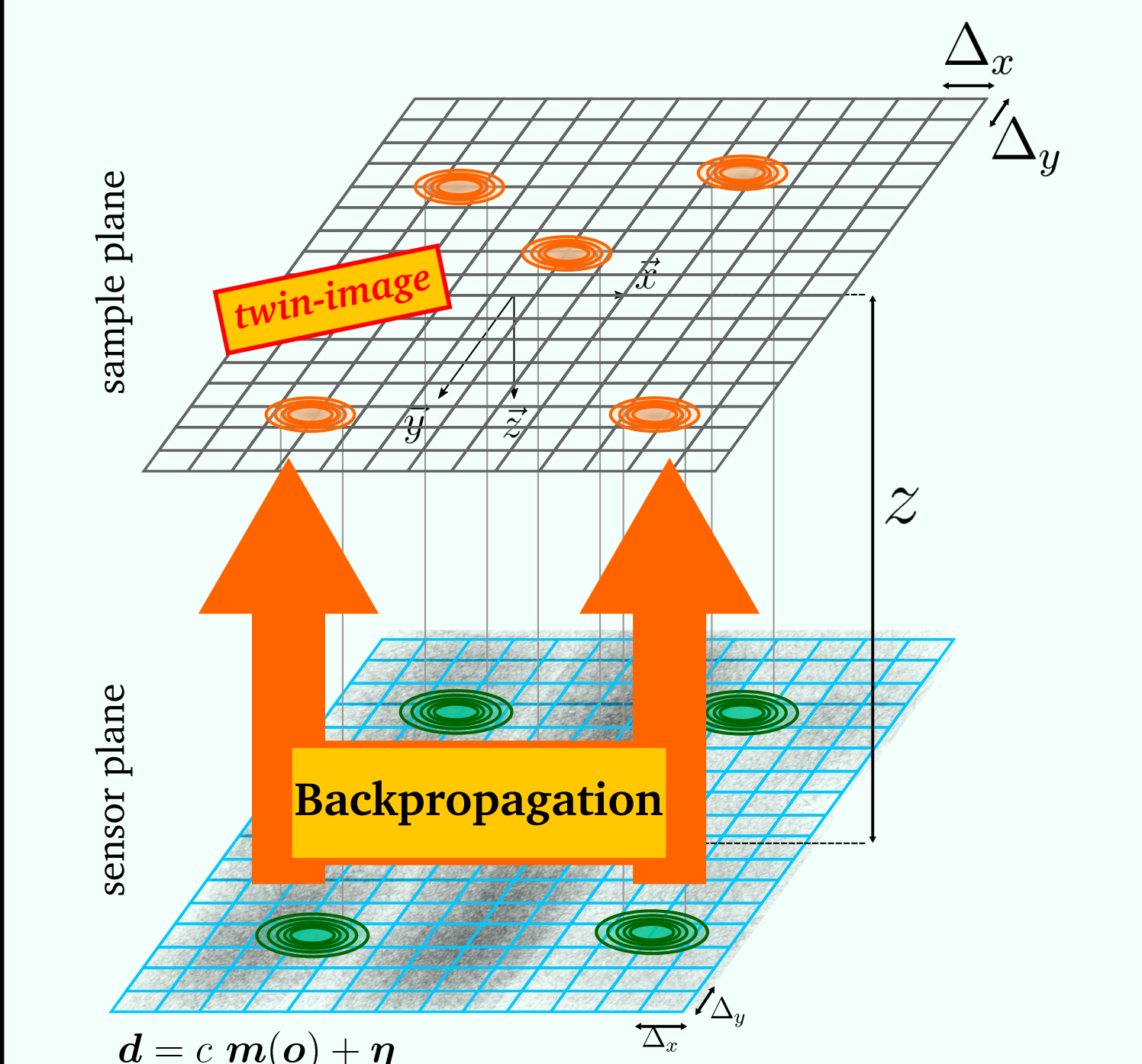
Digital Holography (DH) and the phase retrieval problem



polystyrene beads in immersion oil
- illumination wavelength: $\lambda = 532\text{nm}$
- refractive index of the medium: $n_0 = 1.52$
- pixel size: $\Delta_x = \Delta_y = 2.2\mu\text{m}$



- propagation distance: $z = 12.5\mu\text{m}$
- refractive index of the beads: $n_b = 1.59$
- magnification factor: $\text{mag} = 56.7$

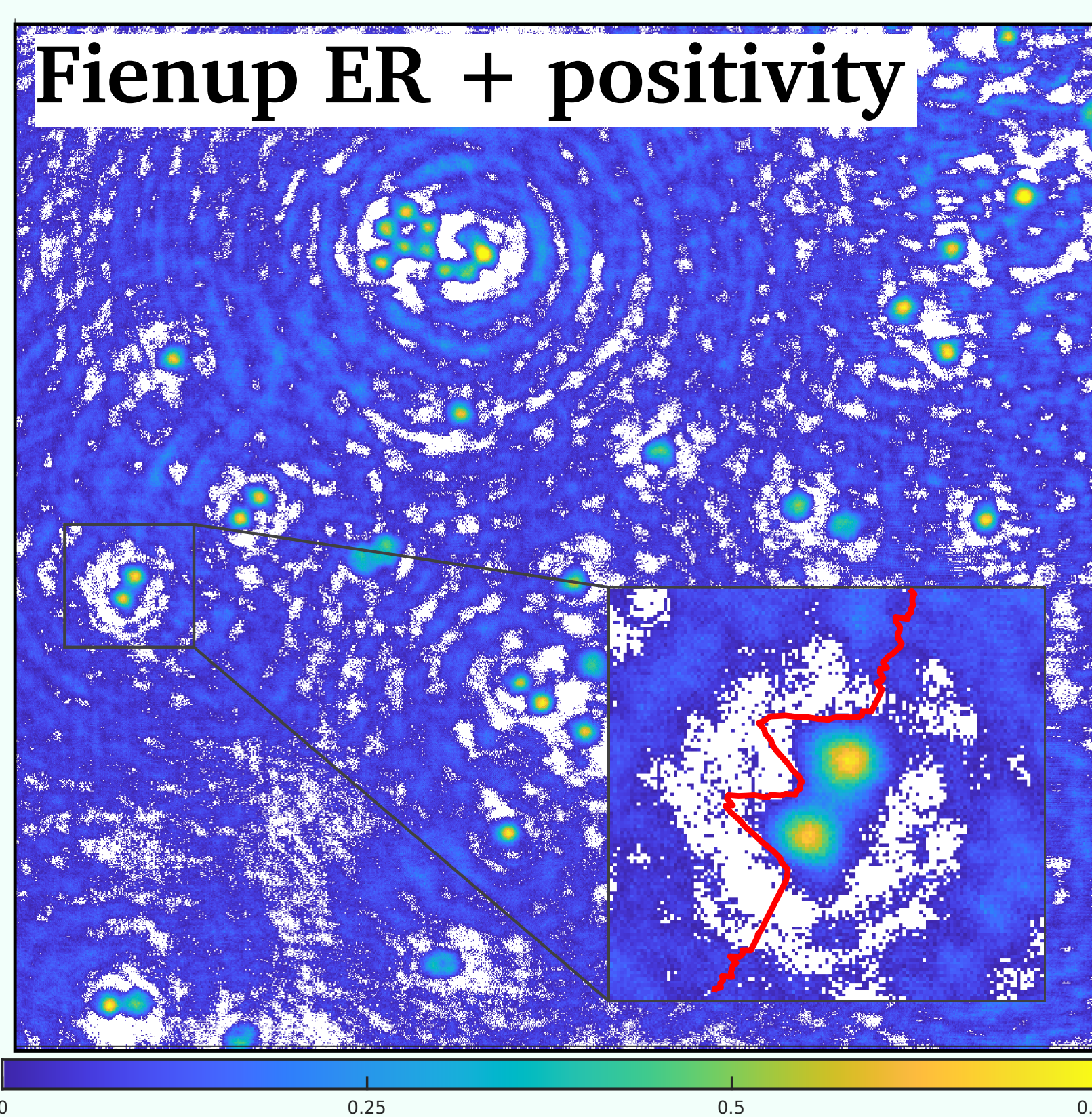


$$\underline{o}_{\text{backprop}} = \underline{H}_{-z} (\underline{\bar{d}} - 1) \text{ s.t. } \underline{H}_{-z} \underline{H}_{-z} \approx \underline{I}$$

Alternated projections

→ Iterative procedure involving a projection step on a feasible domain $\underline{o} \in \mathbb{O}$ (e.g. positive values of the phase-shift / support constraint) to reduce/suppress twin-image artifacts [2].

→ a popular instance is the **Fienup's Error Reduction algorithm (Fienup ER)**:



$$\underline{o}^{(i+1)} \approx \mathcal{P}_{\mathbb{O}} \left[\underline{o}^{(i)} - \underline{H}_z^\dagger \left(\frac{\underline{a}_z^{(i+1/2)}}{|\underline{a}_z^{(i+1/2)}|} \odot \left(|\underline{a}_z^{(i+1/2)}| - \sqrt{\underline{\bar{d}}} \right) \right) \right]$$

→ **gradient descent step** of the data-fidelity criterion \mathcal{G} at current point $\underline{o}^{(i)}$.

→ **projection step** $\mathcal{P}_{\mathbb{O}}$ on the domain \mathbb{O} , called **proximal mapping** of the indicator function $\iota_{\mathbb{O}}$ at point $\underline{o}^{(i+1/2)}$.

This resolution method is an instance of the **ISTA algorithm (Iterative Shrinkage Thresholding Algorithm)**, a proximal gradient method.

→ **Fienup ER** is an **Inverse Problems** approach that uses a particular optimization strategy for minimizing the following criterion:

$$\underline{o}^* = \arg \min_{\underline{o}} \underbrace{\| |1 + \underline{H}_z \underline{o}| - \sqrt{\underline{\bar{d}}} \|_2^2}_{\text{data-fidelity } \mathcal{G}(\underline{o}) \text{ (smooth)}} + \underbrace{\iota_{\mathbb{O}}(\underline{o})}_{\mathcal{H}(\underline{o}) \text{ (non smooth)}}$$

Towards inverse approaches

Alternating projections methods such Fienup ER can then benefit from the Inverse Problems framework to gain flexibility and reconstruction quality.

→ More appropriate **direct image formation model** $m(\underline{o})$.

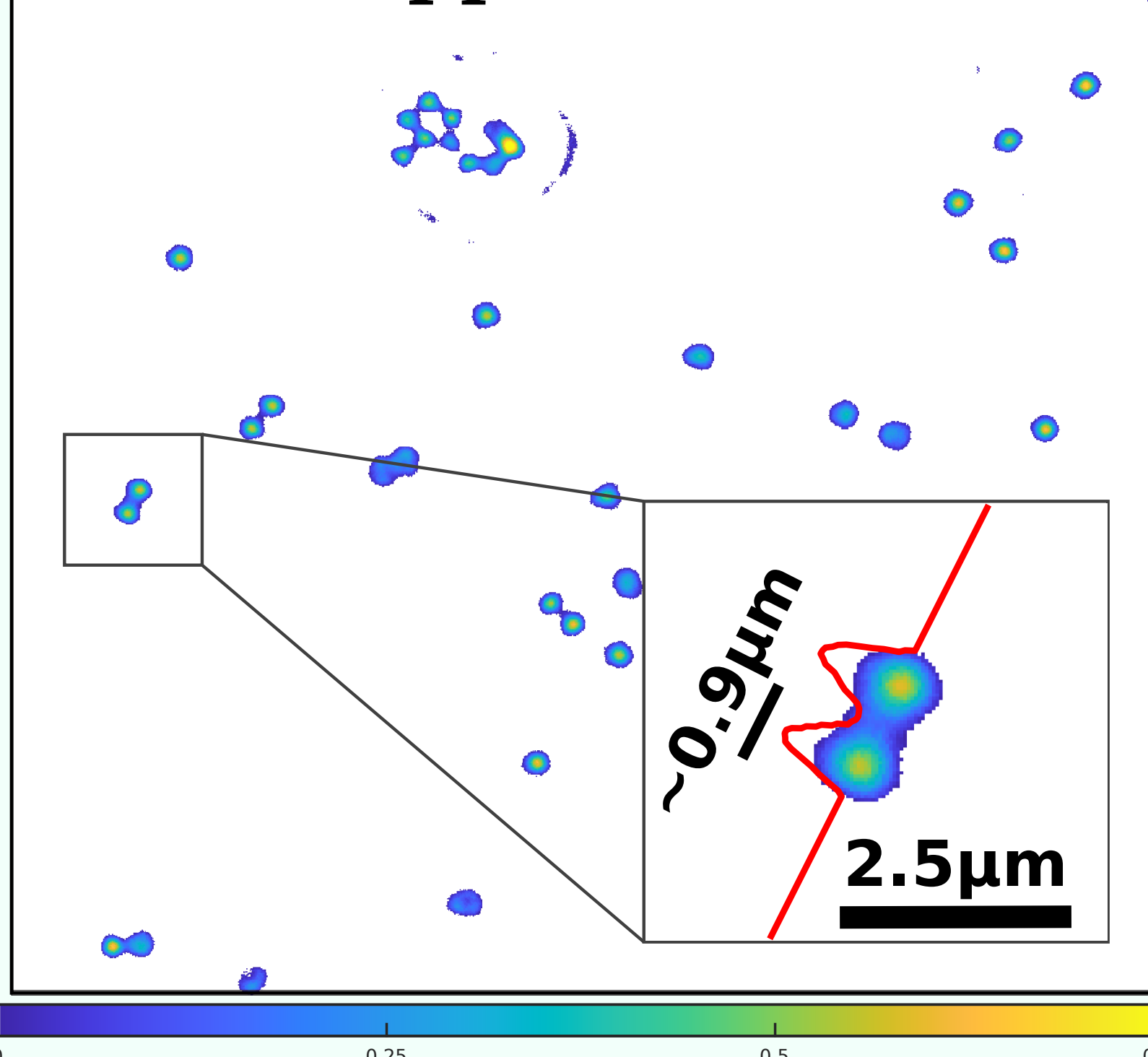
→ **auto-calibration** of model parameters made possible.

→ Taking into account **data uncertainties** (statistical considerations about the **noise** η in the criterion).

→ Inclusion of **more sophisticated non smooth and smooth regularizers**: sparsity constraints (ℓ_1 , TV / non smooth), image gradient smoothing (Tikhonov, edge-preserving / smooth).

$$\underline{o}^* = \arg \min_{\underline{o} \geq 0} \underbrace{\| c^* m(\underline{o}) - \underline{d} \|_W^2 + \mu_{\text{TV}} \sum_q \sqrt{\|\nabla_q \underline{o}\|_2^2 + \epsilon^2}}_{\mathcal{G}(\underline{o}) \text{ (smooth)}} + \underbrace{\mu_{\ell_1} \|\underline{o}\|_1}_{\mathcal{H}(\underline{o}) \text{ (non smooth)}}$$

Inverse approach



→ Others optimization methods than **ISTA** are possible: **FISTA** ("accelerated" ISTA), **L-BFGS-B** (smooth criterions), etc.

Conclusion & perspectives

→ **Inverse problems** constitute a rigorous framework for solving image reconstruction and/or parameter estimation tasks in **Digital Holography (DH)**.

→ **Inverse problems** make possible the extension of classical **2D DH** to deal with **multi-dimensional** and **multi-variate data**: fully-3D (diffractive tomography), multi-spectral, polarimetric data, etc.

A **Matlab™** code for **2D DH reconstruction** is available for download at this link:
https://github.com/fabienmomey/Inline_Hologram_Reconstruction_by_Regularized_Inversion.git

References

[1] Momey, F., Denis, L., Olivier, T., and Fournier, C., "From Fienup's phase retrieval techniques to regularized inversion for in-line holography: tutorial," J. Opt. Soc. Am. A 36, D62-D80 (2019).

[2] Fienup, J. R., "Phase retrieval algorithms: a comparison," Appl. Opt., 21, 2758-2769 (1982).