Extended Depth-of-Field with Speckle Based Super-resolution

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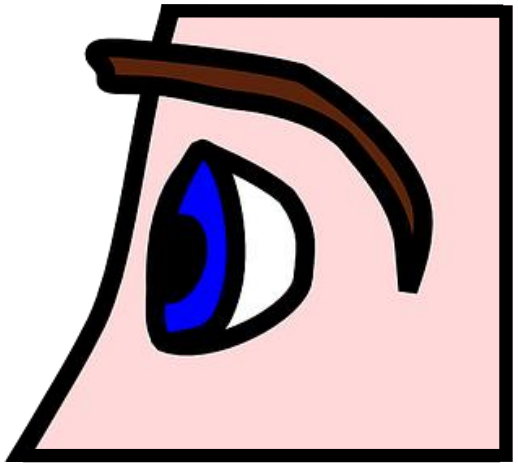
Challenge: HR-Biometrics with large DoF

$$\delta x \leq 20\ \mu m$$

$$\delta t \leq 0.5\ sec$$



Depth-of-Field: 50 cm

f/16 f/11 f/8 f/5.6 f/4 f/2.8

Small aperture
Stopped down

More Depth-of-Field
Less Light

Less Depth-of-Field
More Light

Large aperture
Wide open

http://www.photoskop.com/player.html?l=all&ch=3&sec=0#

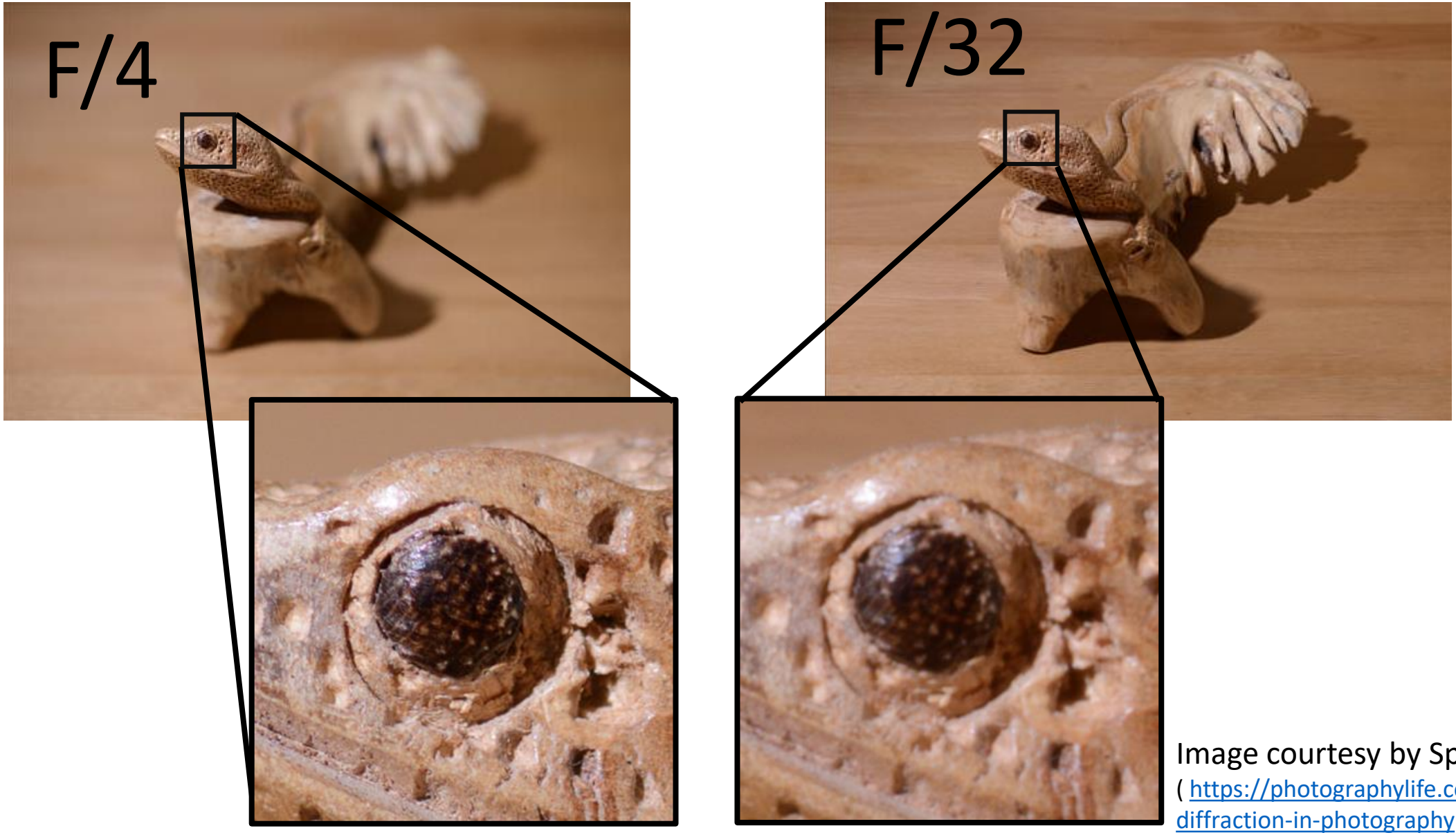
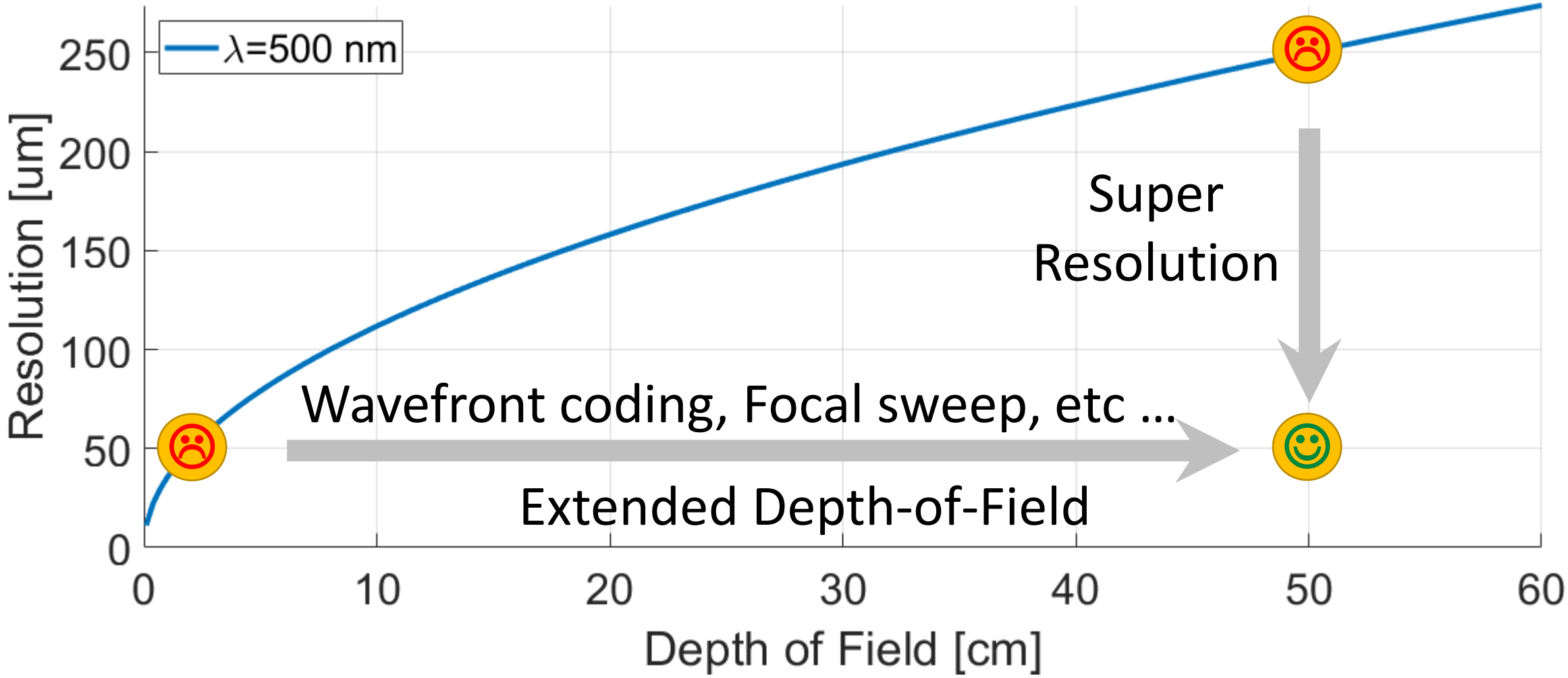


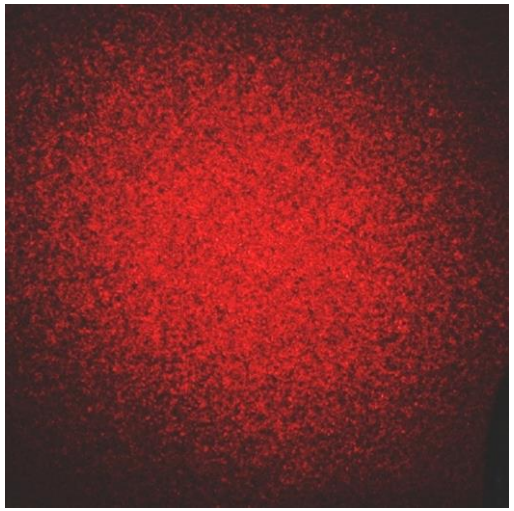
Image courtesy by Spencer Cox
(https://photographylife.com/what-is-diffraction-in-photography)

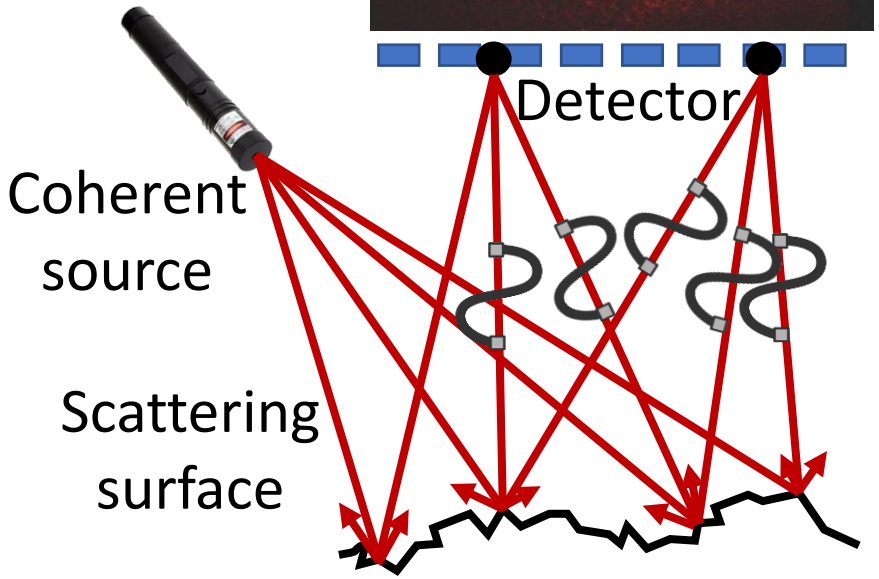
Lateral Resolution $\delta x \sim \frac{\lambda}{\mathbf{NA}}$ Depth-of-Field: $\delta z \sim \frac{\lambda}{\mathbf{NA}^2}$



Speckle

Speckle image



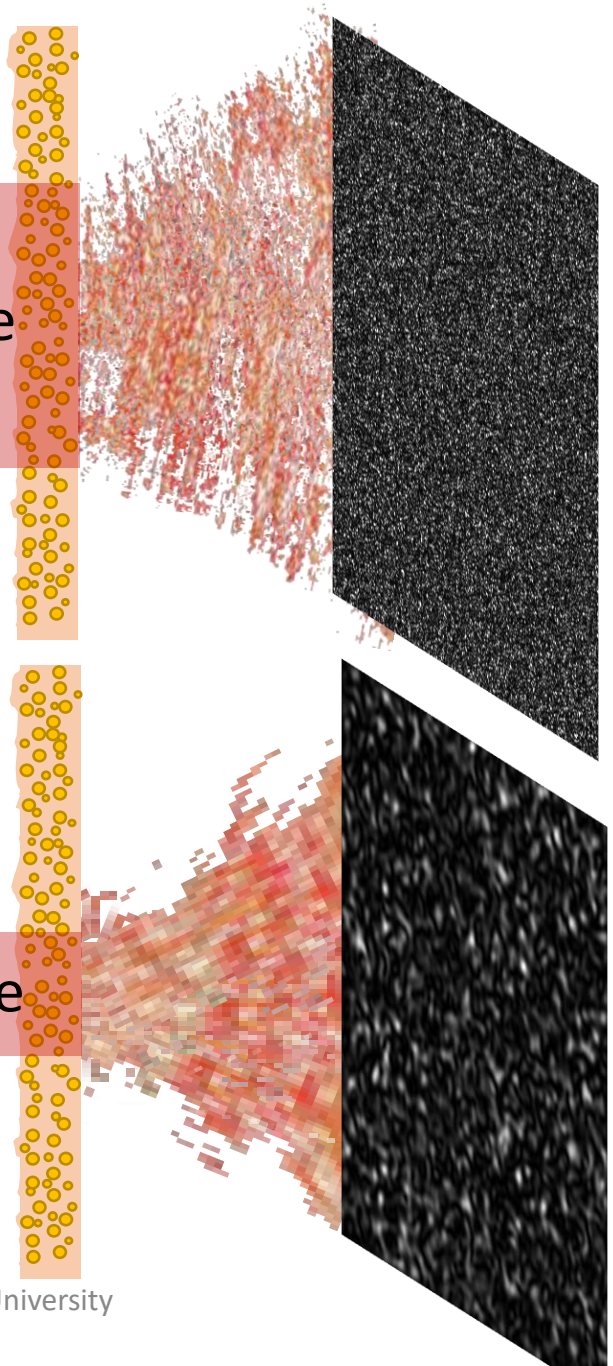


Large Aperture

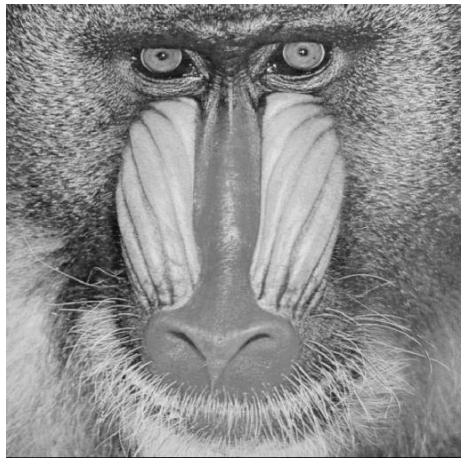
$$\delta z \sim \frac{\lambda}{u^2}$$

$$\delta x \sim \frac{\lambda}{u}$$

Small Aperture



$\mathbf{o}(\mathbf{x})$ $\mathbf{p}(\mathbf{x})$ $\mathbf{m}(\mathbf{x})$



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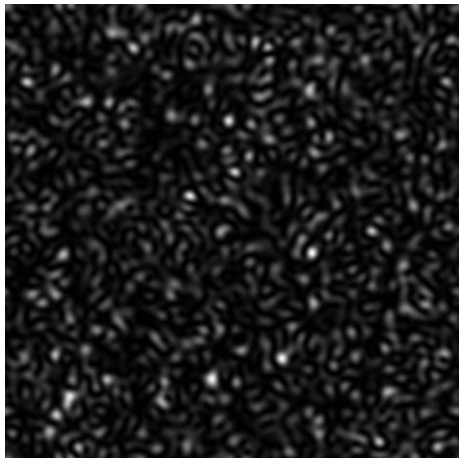

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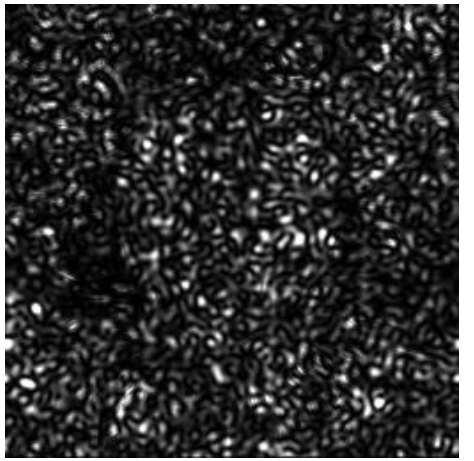
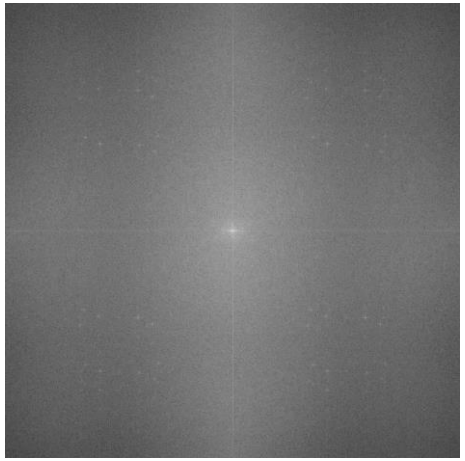


FFT FFT FFT



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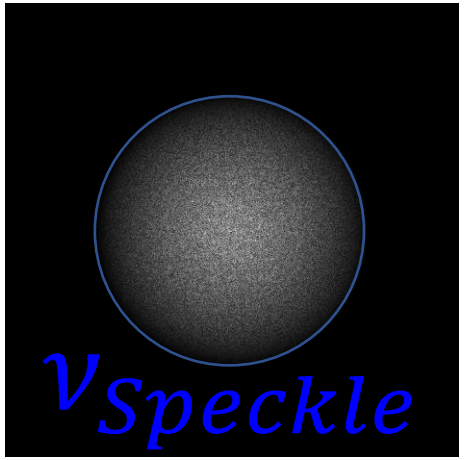

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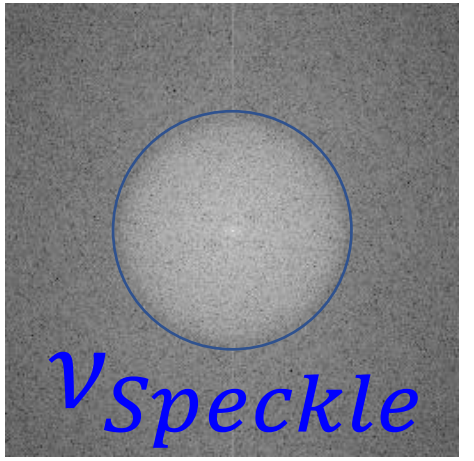
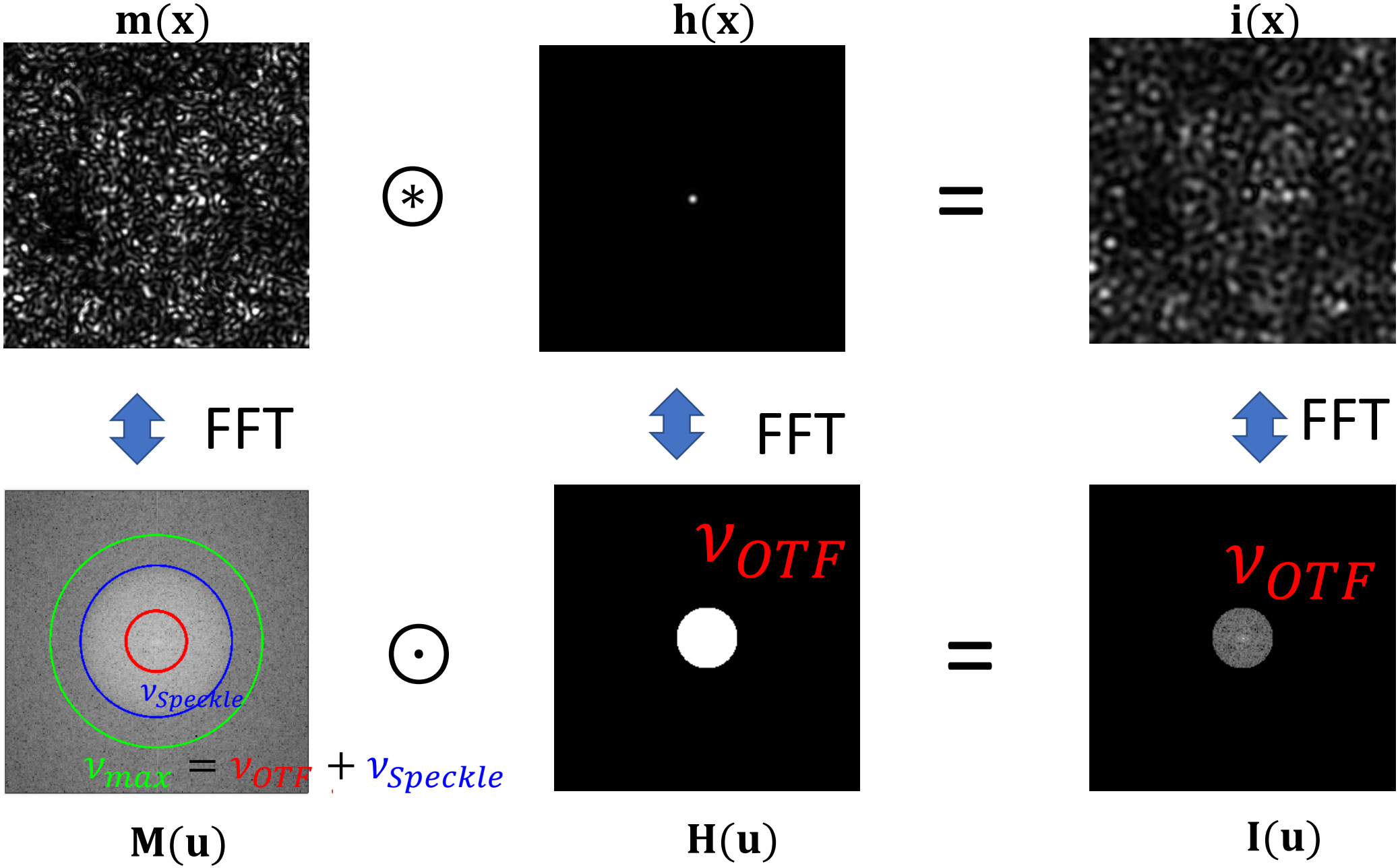
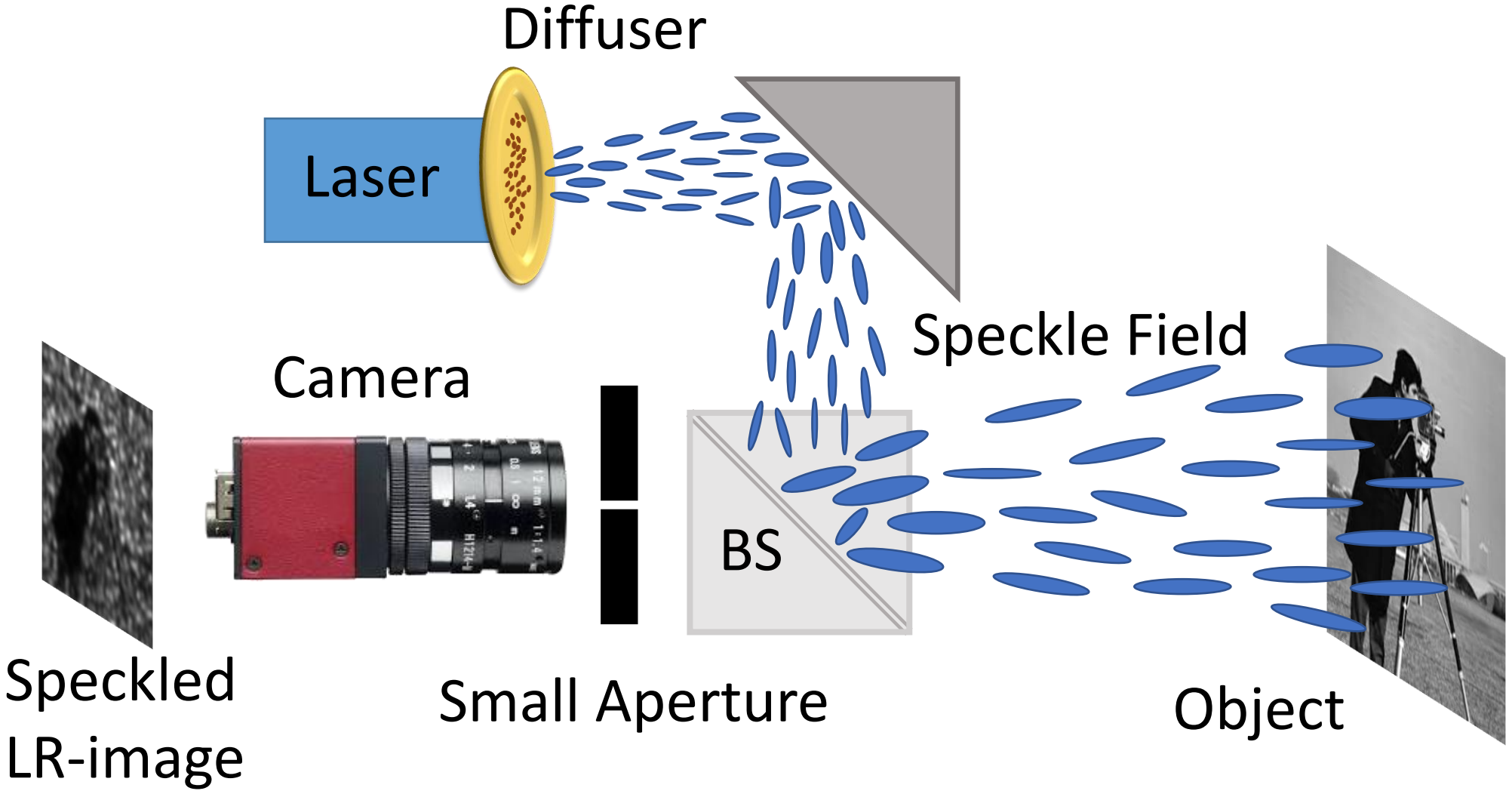


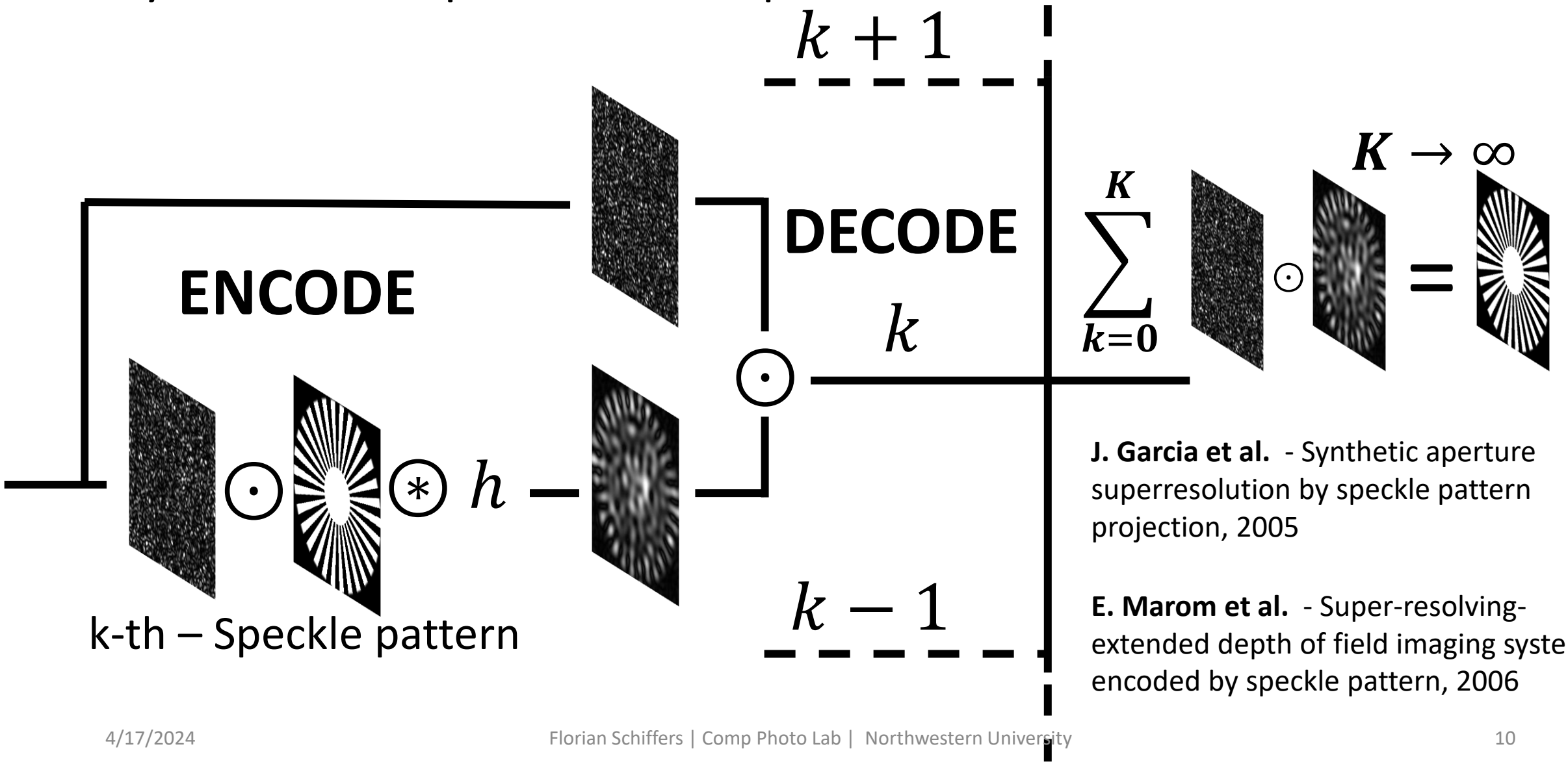
$\mathbf{O}(\boldsymbol{\nu})$ $\mathbf{P}(\boldsymbol{\nu})$ $\mathbf{M}(\boldsymbol{\nu})$


m(x)
h(x)
i(x)
FFT
FFT
FFT
$\nu_{Speckle}$
$\nu_{max} = \nu_{OTF} + \nu_{Speckle}$
ν_{OTF}
ν_{OTF}
M(u)
H(u)
I(u)

Experimental Setup – 2D case



Synthetic aperture super resolution

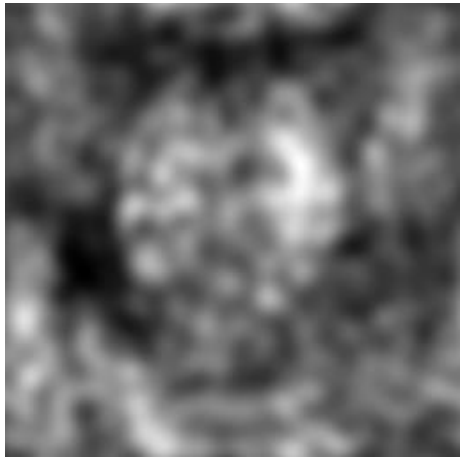


J. Garcia et al. - Synthetic aperture superresolution by speckle pattern projection, 2005

E. Marom et al. - Super-resolving-extended depth of field imaging system encoded by speckle pattern, 2006

Forward-Model

$$\mathbf{I_k(x)} = \mathbf{h(x)} * [\, \mathbf{p_k(x)} \cdot \mathbf{o(x)} \,]$$



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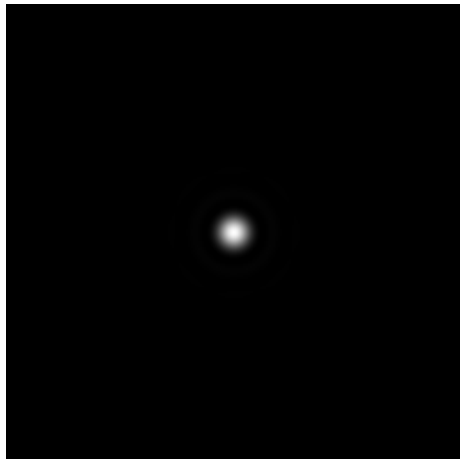

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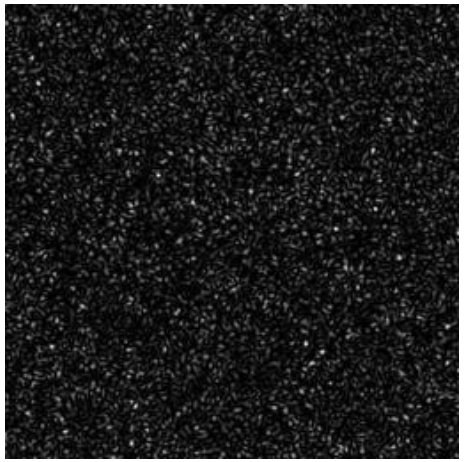

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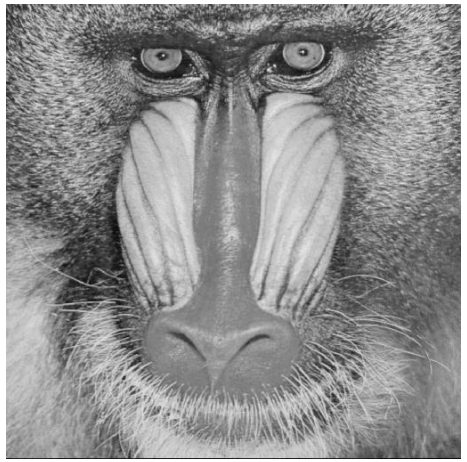

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Measurement

PSF

Speckle #K

Object

Forward-Model – Inverse Problem

Continuous: $$\mathbf{I_k(x) = h(x) * [p_k(x) \cdot o(x)]}$$

Discretized: $$\mathbf{I_k = C \cdot D_k \cdot o}$$

$$\mathbf{o^* = \arg\min_o \sum_k \|I_k - CD_k o\|^2}$$

$$\mathbf{= \left[\sum_k D_k^T C^T C D_k\right]^{-1} \sum_k D_k^T C^T I_k}$$

No Speckle: $\mathbf{C^T C}$ → Non-invertible

Speckle: $\sum_{\mathbf{k}} \mathbf{D_k^T C^T C D_k}$

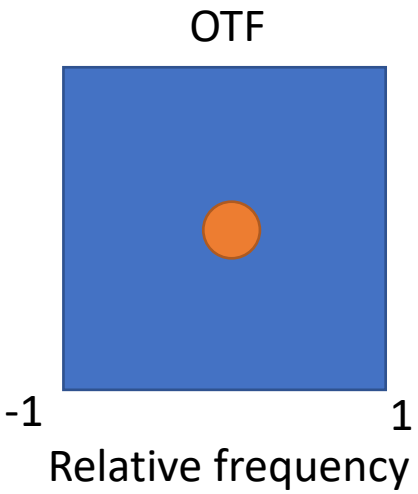
Full rank ? How many speckle images?

Numerical Analysis

$$\mathbf{I_k} = \mathbf{C} \cdot \mathbf{D_k} \cdot \mathbf{S}$$

$$\mathrm{N} = 32 \times 32 = 1024 \text{ Pixel}$$

$$\mathbf{C} \in \mathbb{R}^{32^2 \times 32^2} = \mathbb{R}^{1024 \times 1024}$$

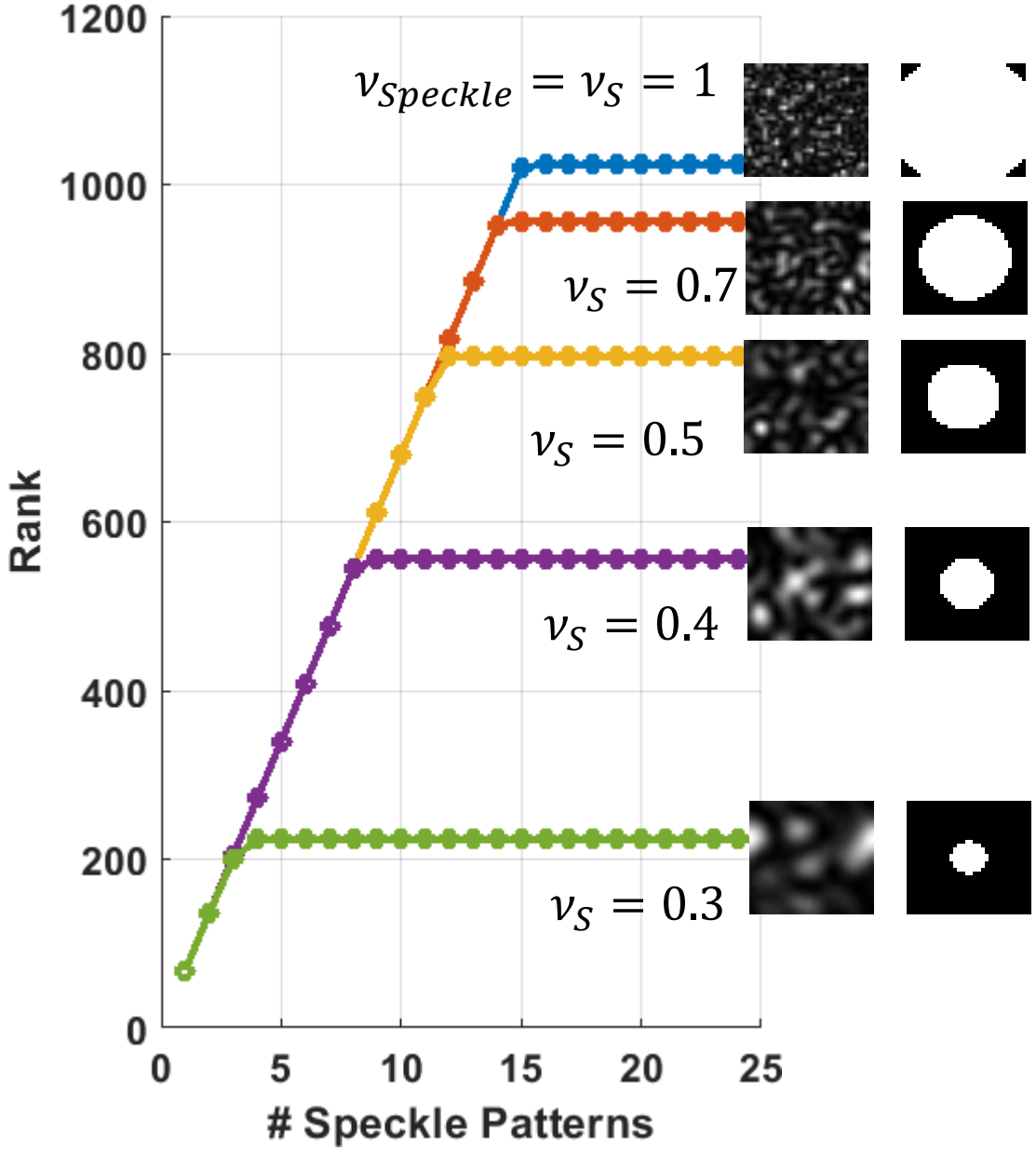


$$\nu_{OTF} = 0.15$$

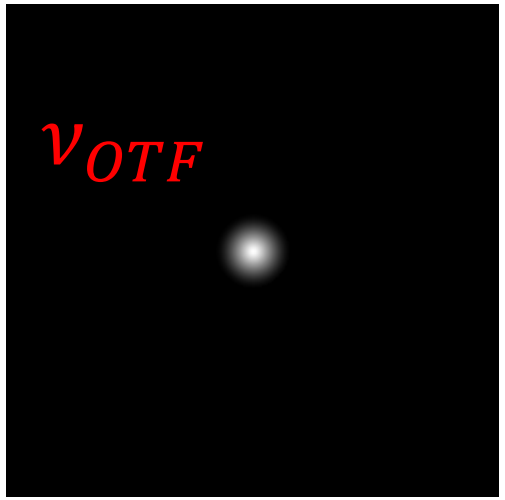
$$\mathbf{rank(C)} = 68$$

$$\approx \mathrm{N} \cdot \pi \cdot (\nu_{OTF})^2$$

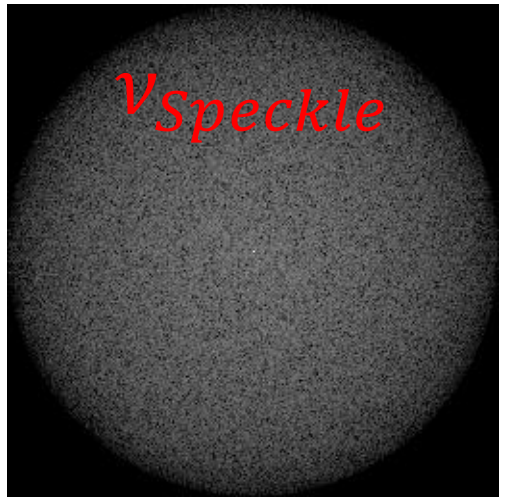
$$\#\mathbf{K_{min}} = \frac{\mathrm{N}}{\mathbf{rank(C)}} = \frac{1024}{68} \approx 15$$



OTF

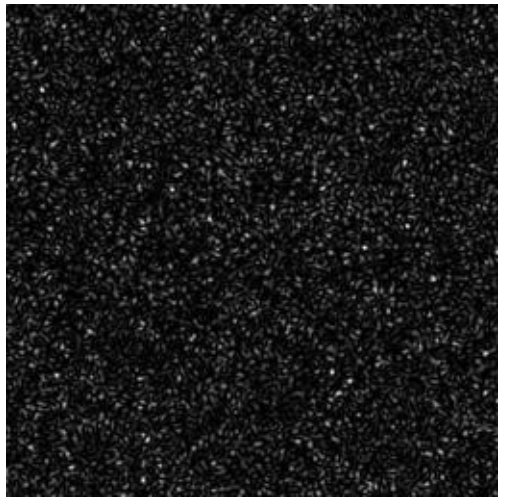


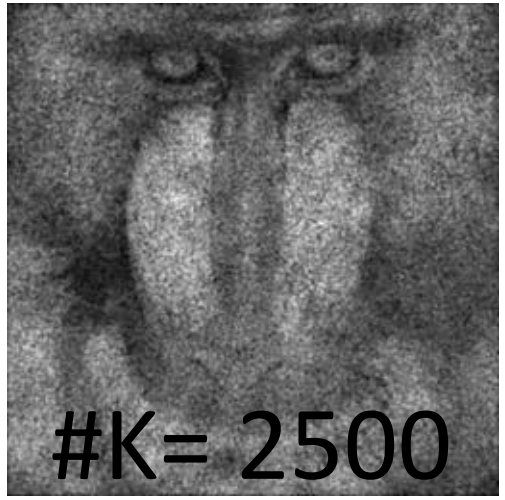
FFT(speckle)

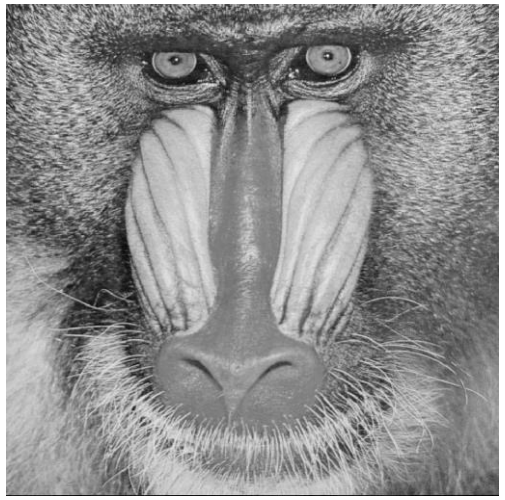


FFT

speckle

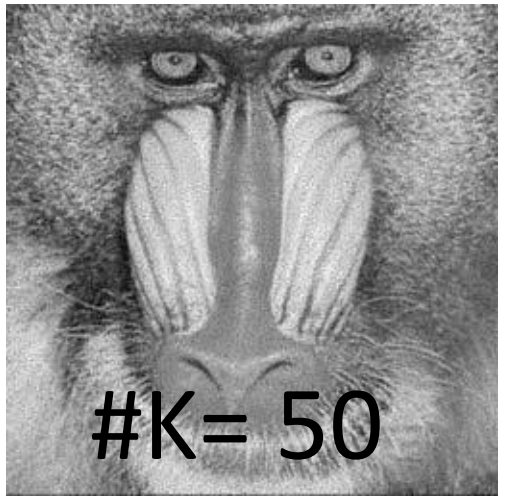




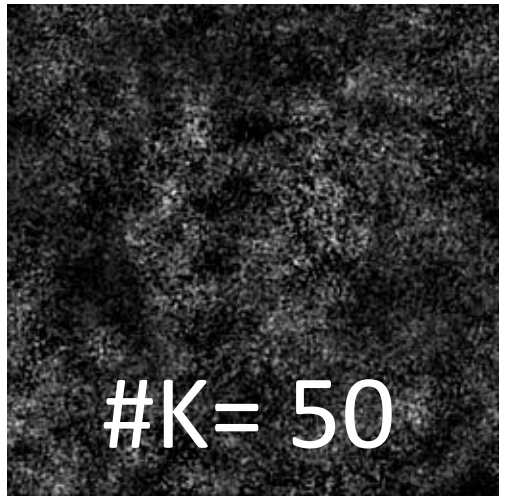


ground truth

low resolution



proposed



Garcia et. al.

Summary

- Small aperture:
  - ➔ Large Depth-of-Field
  - ➔ Low Optical Resolution
    - ➔ Super-resolution
- Simulation experiments
- **Prior knowledge** of projected speckle pattern

Outlook

- **Coherent** projection but **incoherent** imaging ?
  - ➔ Subjective speckle ?
- **Joint estimation** of **pattern** and **object**
- **Comparison** to other eDoF methods