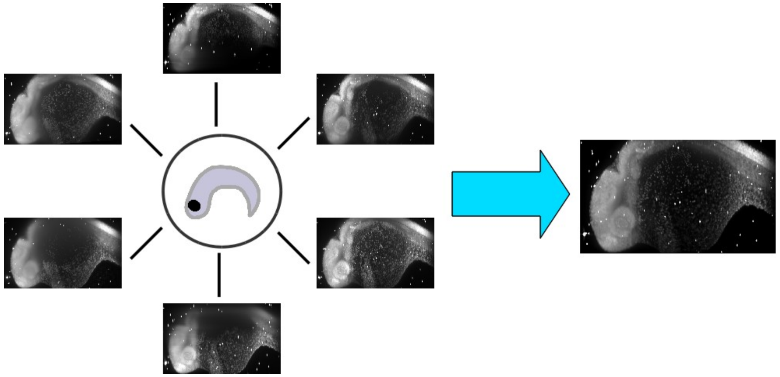
SPATIALLY-VARIANT LUCY-RICHARDSON DECONVOLUTION FOR MULTIVIEW FUSION OF MICROSCOPICAL 3D IMAGES



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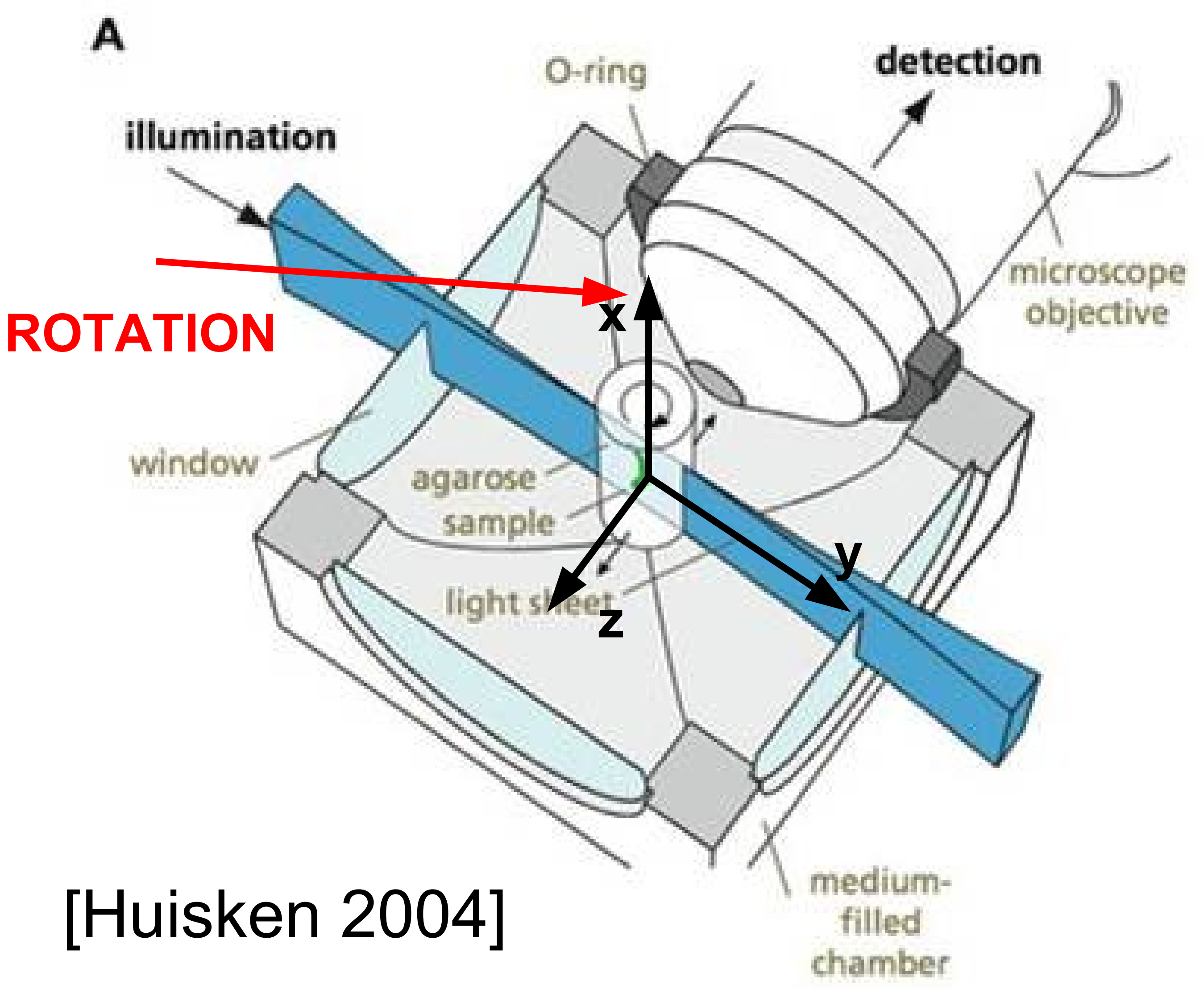
CENTRE FOR BIOLOGICAL SIGNALLING STUDIES

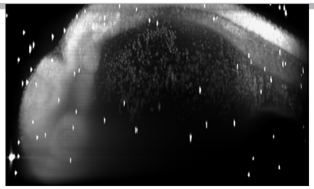
SFB 592
Sonderforschungsbereich 592

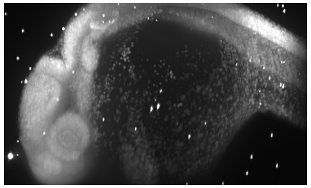
The Third LSM Workshop, Toulouse, October 13th-14th, 2011

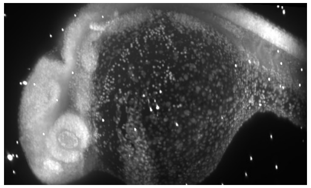
SPIM =
Single Plane Illumination Microscopy



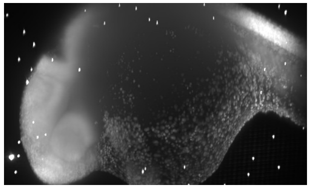
[Huisken 2004]

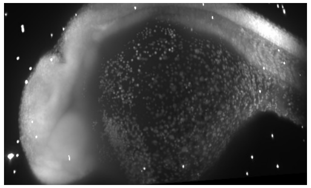

view 0°


view 60°

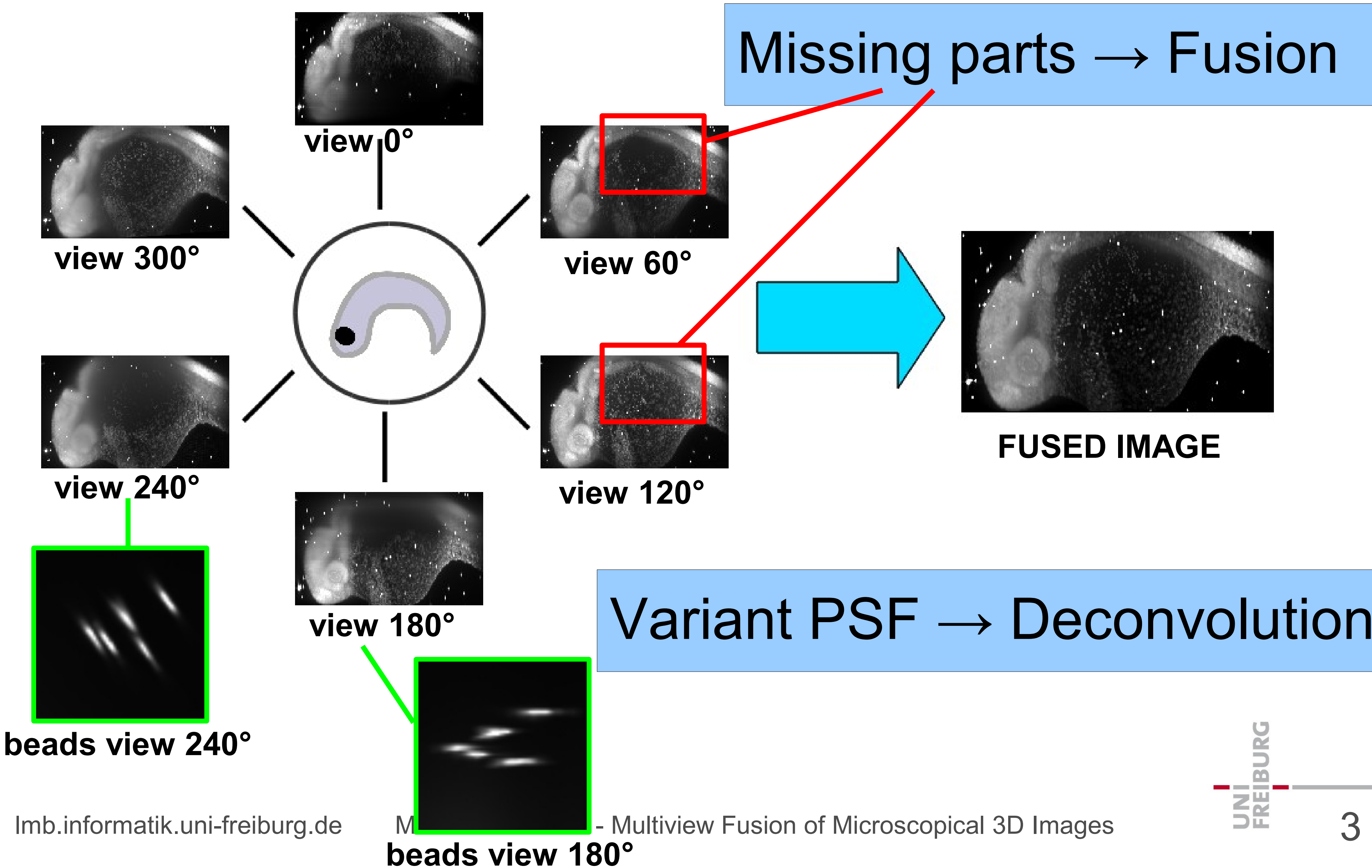

view 120°


view 180°

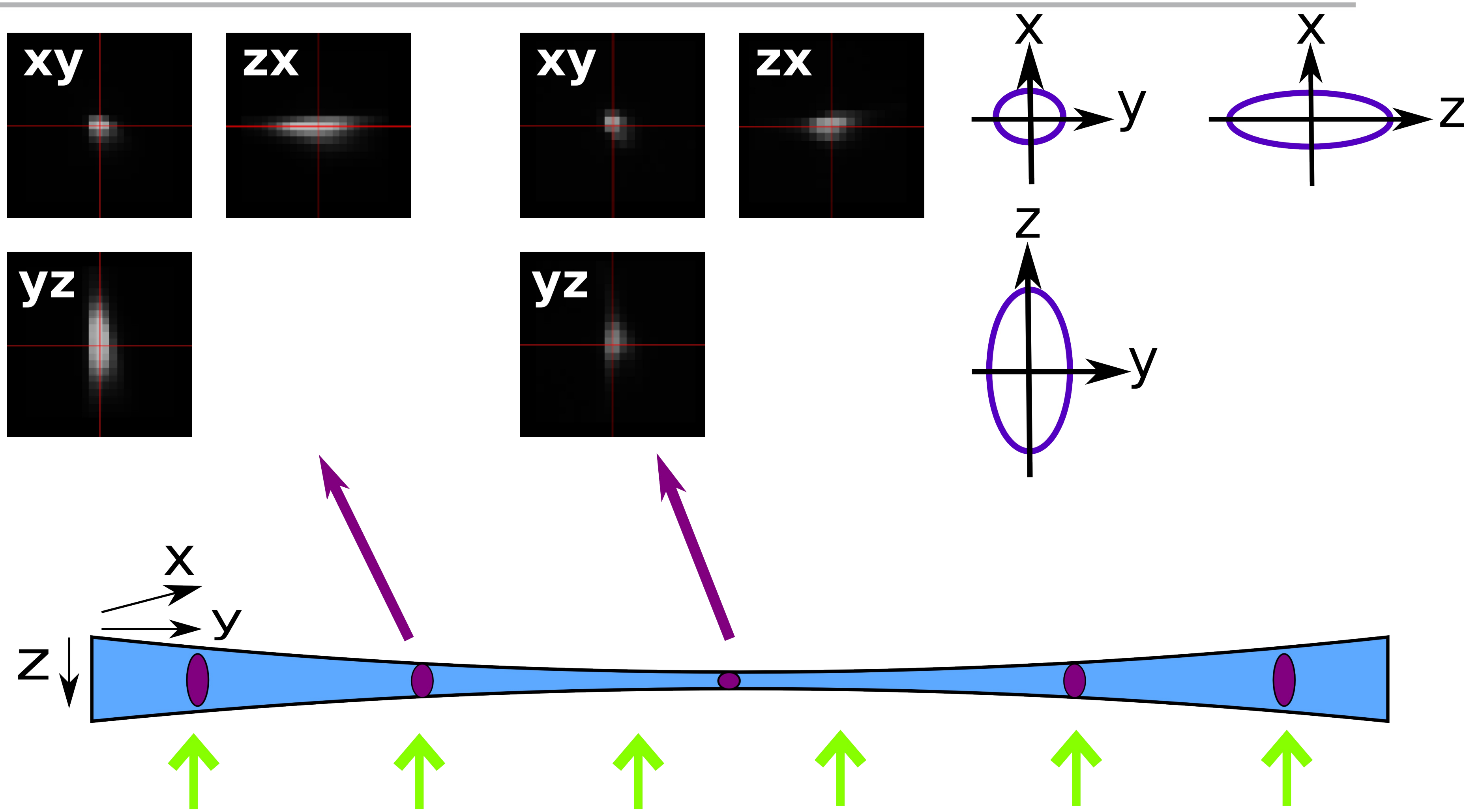

view 240°


view 300°

Goal: Joint Fusion and Deconvolution



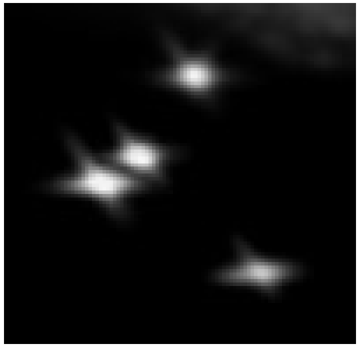
Estimation of the PSF at Bead Positions



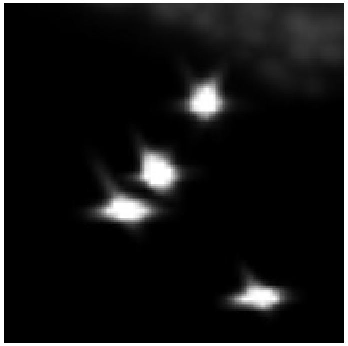
- Variation of the PSF along y-axis

Related Work

- Blending [Preibisch 2010]
  - Combines Gray values without a prior model
    - Fast Computation
    - Smearing of the points + blur



- Average PSF for Multiview Deconvolution [Krzic 2009]
  - Assumes constant PSF
    - Good in the center
    - Bad at the corners of the image



Contribution

- Location **variant PSF estimation** for joint deconvolution and fusion
- Approach:
  - PSF Estimation
  - Overlap-Save Deconvolution
  - Lucy-Richardson Algorithm
  - Multiview deconvolution
  - TV Regularization

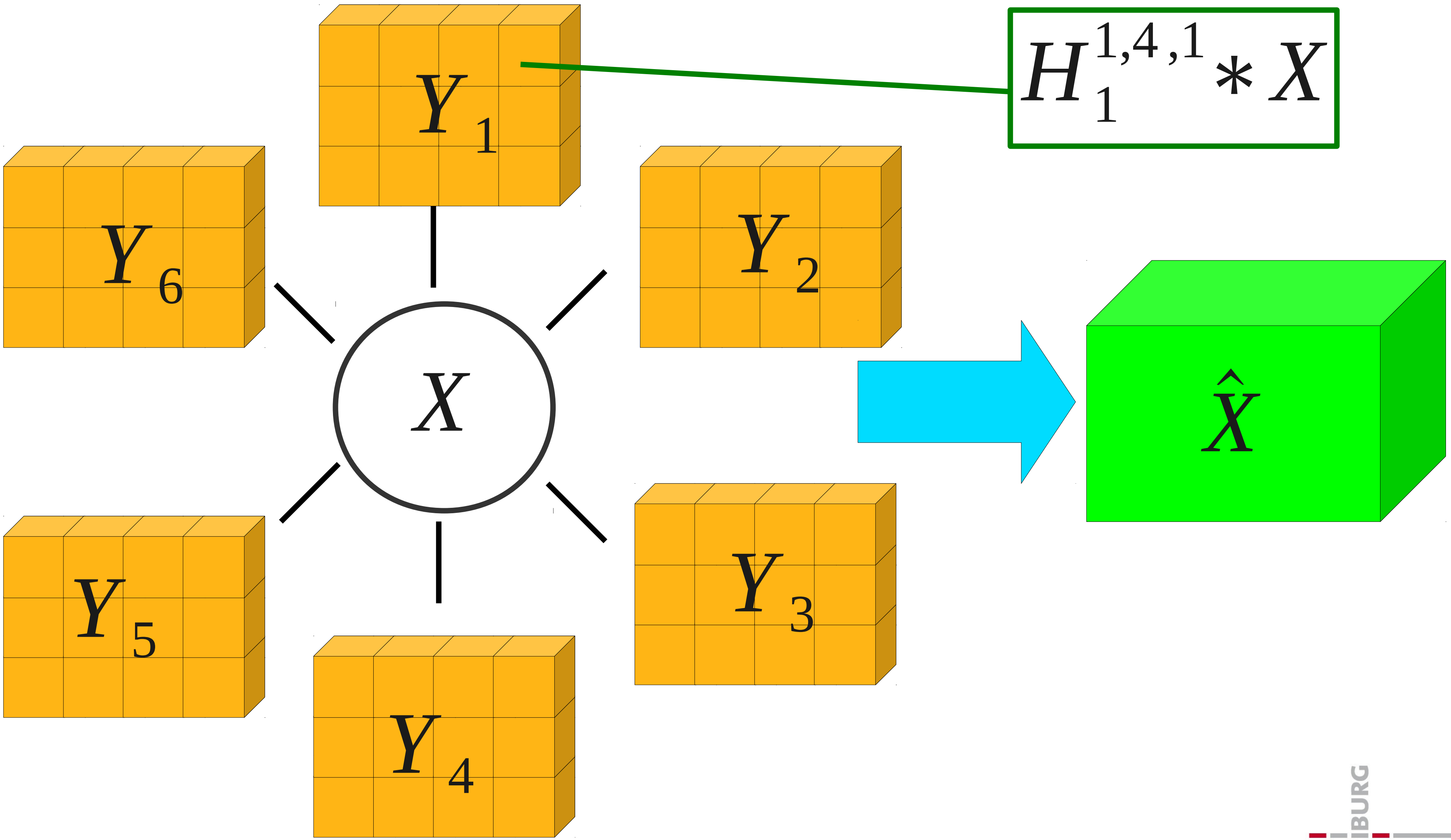
➡ **LRMOS-TV**

Problem Formulation: Multiview Fusion

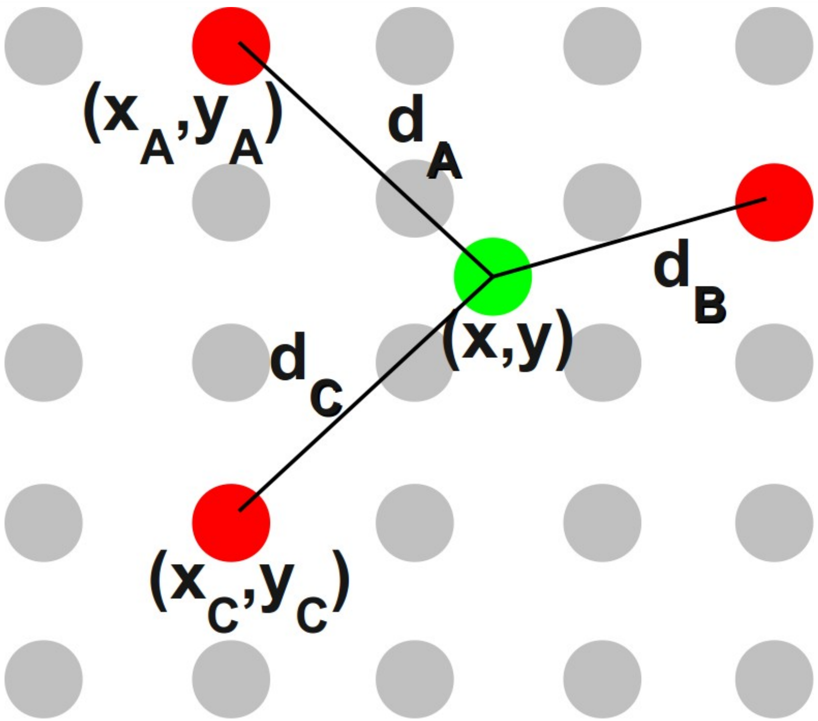
- Given:
  - **Recorded images** $Y_1, \ldots, Y_N$
  - **PSF** at bead positions $H_1, \ldots, H_N$
- Goal:
  - Find **true image** X
    that maximizes

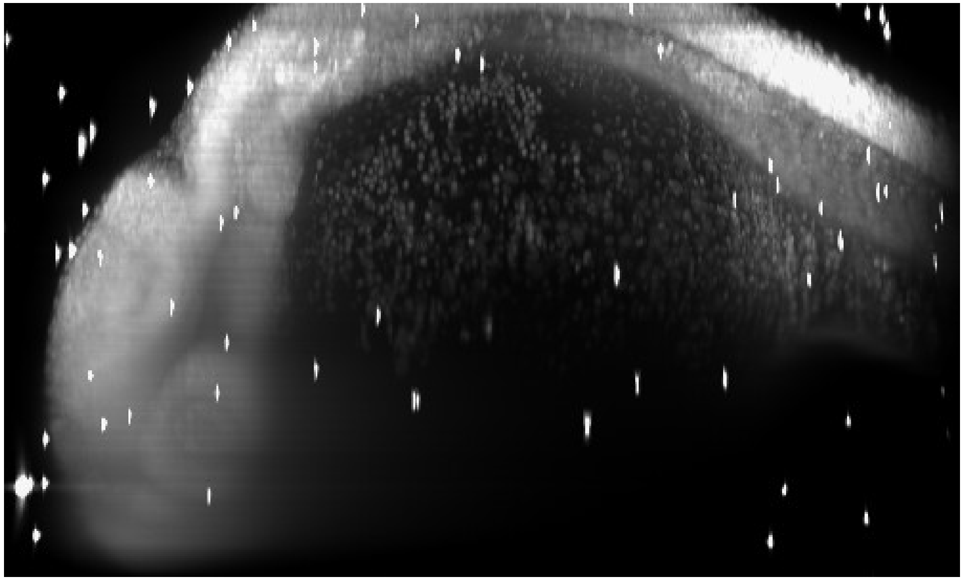
$$p(X|Y_{1,\ldots}, Y_N, H_{1,\ldots}, H_N) = \prod_{i=1}^{N} p(X|Y_i)$$

Solution: Regionwise Multiview Fusion



PSF Estimation





$$H(x,y)=\frac{d_B d_C H_A + d_A d_C H_B + d_A d_B H_C}{d_B d_C + d_A d_C + d_A d_B}$$

$$d_A=\sqrt{(x-x_A)^2+(y-y_A)^2}$$

Overlap-Save Deconvolution

- Model spatially-variant PSF by blockwise constant PSFs
- Consider large overlapping regions to overcome boundary artifacts

$$\begin{bmatrix} Y_{11} & Y_{12} & \dots & Y_{1n} \\ Y_{21} & Y_{22} & \dots & Y_{2n} \\ \vdots & \vdots & & \vdots \\ Y_{n1} & Y_{n2} & \dots & Y_{nn} \end{bmatrix}$$

$$Y_{ij}^{(r+s)} = \begin{bmatrix} \times & \times & \times \\ \times & Y_{ij} & \times \\ \times & \times & \times \end{bmatrix}$$

Size of the blocks:
s x s

Size of the padded blocks:
(s+r) x (s+r)

Image Formation Model

- Convolution with the PSF of the system:

$$Y = P(H * X)$$

Recorded Image

Noise Model

PSF

“True” Image

Deconvolution: MLE Estimation

- Image Statistics Modeled by Poisson Process [Herbert 1989]:

$$p(X|Y) = \prod_{\mathbf{v}} \frac{[(H*X)(\mathbf{v})]^{Y(\mathbf{v})} \exp(-(H*X)(\mathbf{v}))}{Y(\mathbf{v})!}$$

Likelihood Probability

$$J(X) = \int_{\mathbf{v}} Y(\mathbf{v}) \log[(H*X)(\mathbf{v})] - (H*X)(\mathbf{v})\, d\mathbf{v}$$

log likelihood

Lucy-Richardson Algorithm

$$\hat{X}^{p+1}(\boldsymbol{v}) = \hat{X}^{p}(\boldsymbol{v}) \cdot C^{p}(\boldsymbol{v})$$

Correction Factor: $$C^{p}(\boldsymbol{v}) = \left(H^{s} * \frac{Y}{S^{p}}\right)(\boldsymbol{v})$$

Simulated Image

$$H^{s}(\boldsymbol{v}) = H(-\boldsymbol{v}) \qquad S^{p} = (H * \hat{X}^{p})(\boldsymbol{v})$$

Multiview Deconvolution

- Total Correction Factor (CF) as average of the individual correction factors [Krzic 2009]:

$$C^p = \frac{1}{N} \sum_{i=1}^{N} C_i^p$$

- Computation of the individual CF:

$$C_i^p(\boldsymbol{v}) = \left(H_i^s * \frac{Y_i}{S_i^p}\right)(\boldsymbol{v})$$

$$S_i^p = (H_i * \hat{X}^p)(\boldsymbol{v})$$

TV Regularization

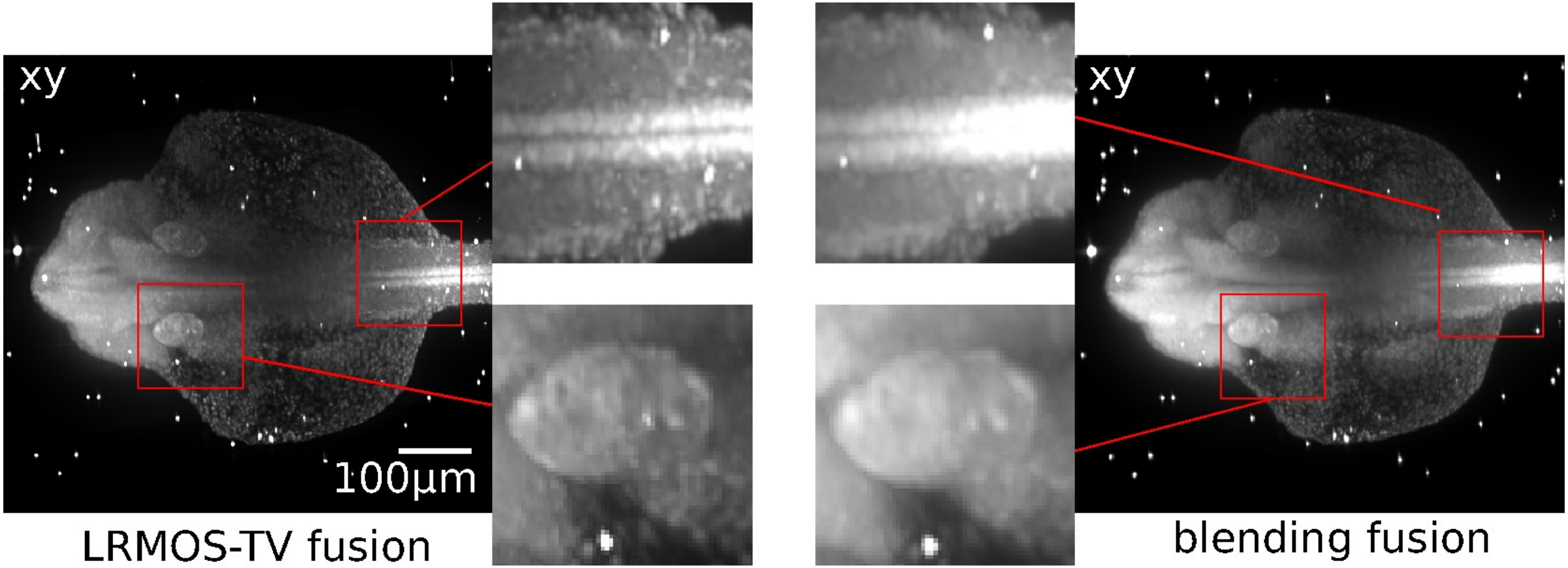
- Regularization of the initial energy by Total Variation [Dey 2004] :

$$J_{TV}(X) = J(X) + \lambda \int_{\boldsymbol{v}} |\nabla X(\boldsymbol{v})| d\boldsymbol{v}$$

- Resulting iteration using Green's one-step-late (OSL) algorithm:

$$\hat{X}^{p+1}(\boldsymbol{v}) = \frac{\hat{X}^{p}(\boldsymbol{v})}{1 - \lambda \, div\left(\frac{\nabla(\hat{X})^{p}(\boldsymbol{v})}{|\nabla(\hat{X})^{p}(\boldsymbol{v})|}\right)} \cdot C^{p}(\boldsymbol{v})$$

Results: Visual Comparison to Blending

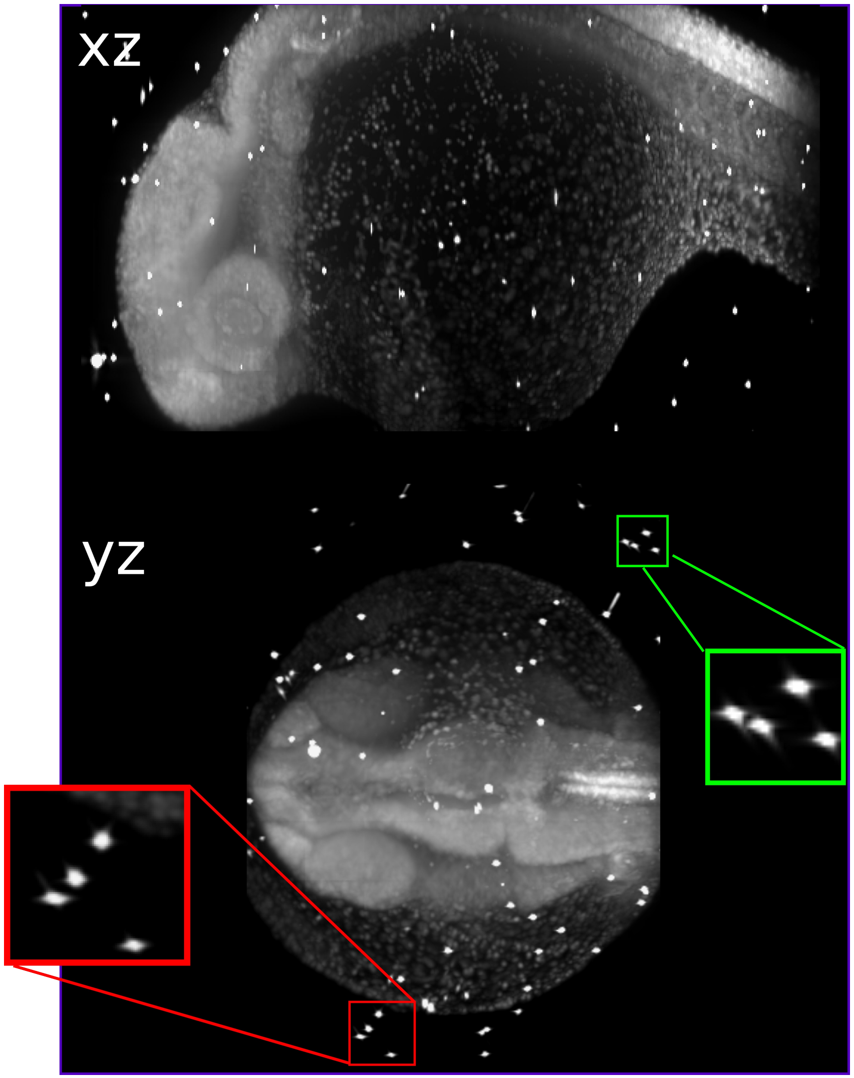


Parameters:
r = 11, p =4,
s+r = 64
Computation Time: 40 min

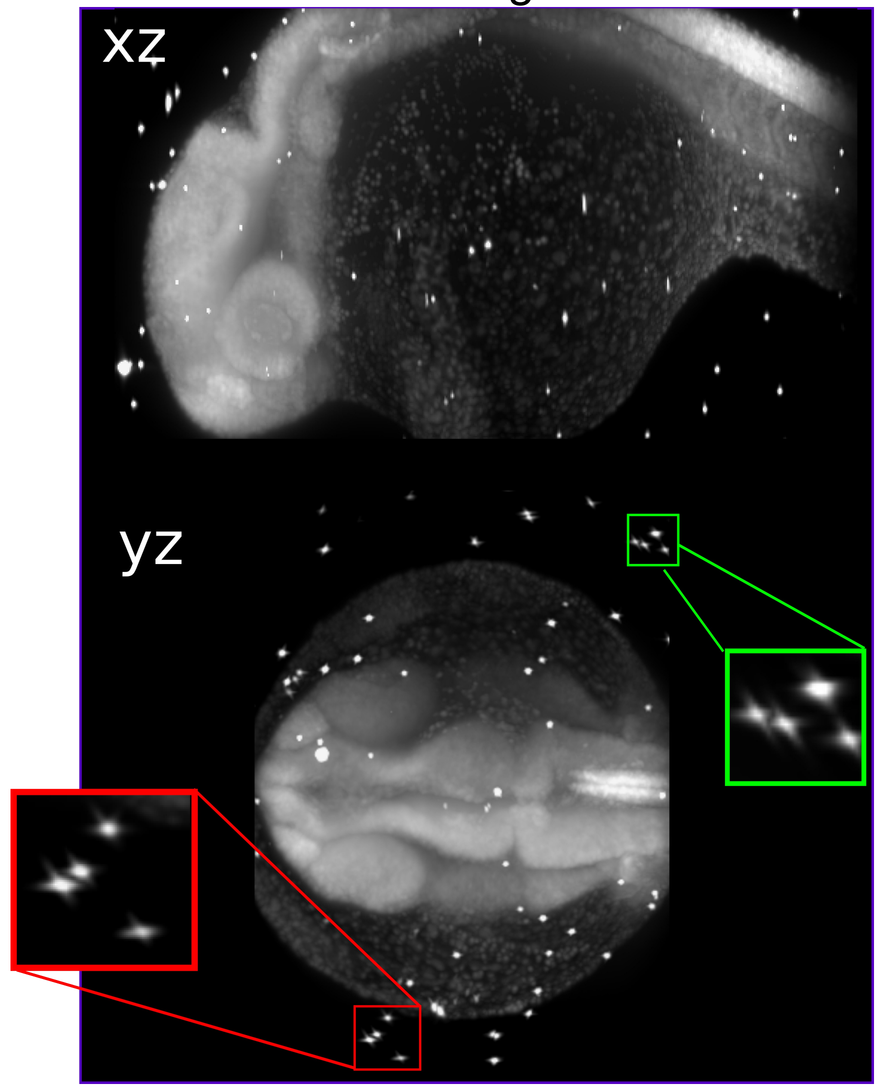
[Preibisch 2010]
Computation Time: 20 min

Results: Visual Comparison to Blending

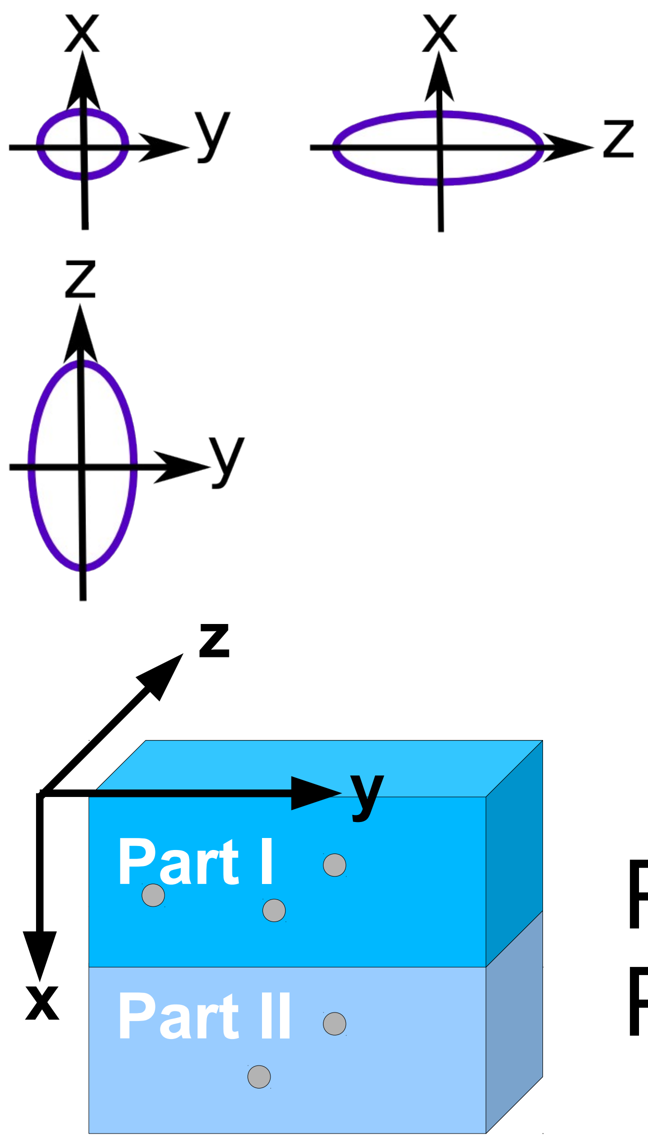
LRMOS-TV fusion

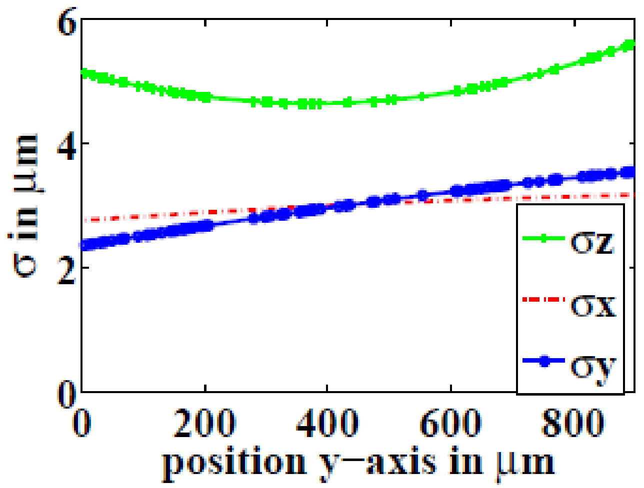


Blending fusion



Quantitative Evaluation





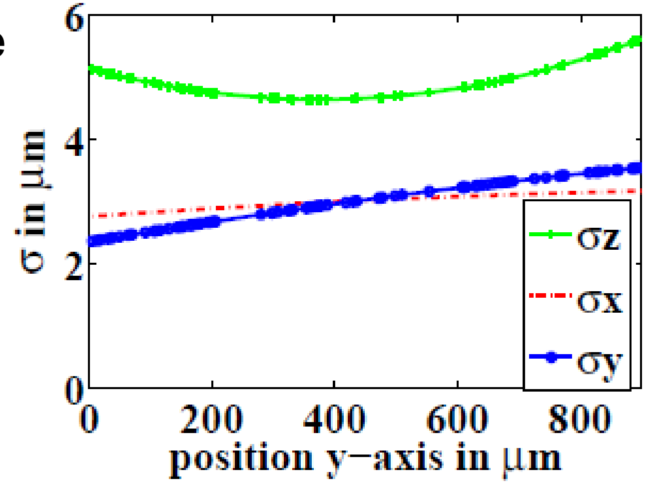
Original bead shape (single view)

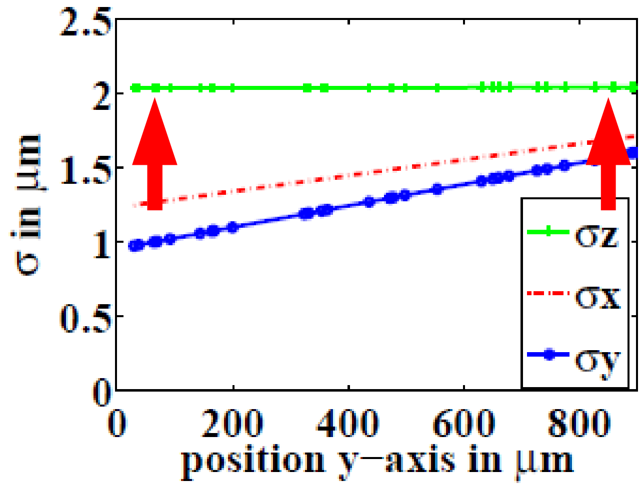
Part I: PSF Estimation

Part II: Multiview Fusion

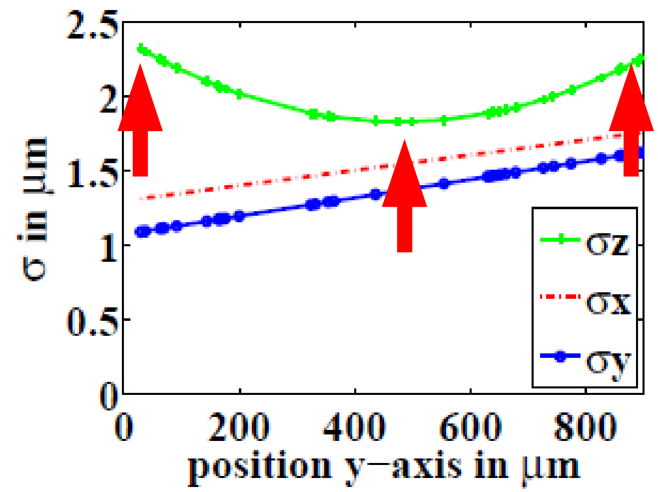
Results: Comparison to Average PSF

Original bead shape
(single view)



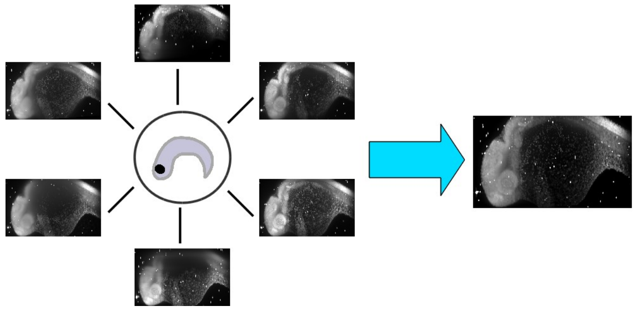


Deconvolved with variant PSF
(fused image, upper)

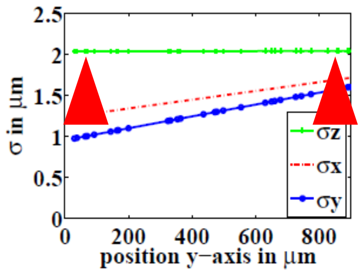


Deconvolved with average PSF
(fused image, upper)

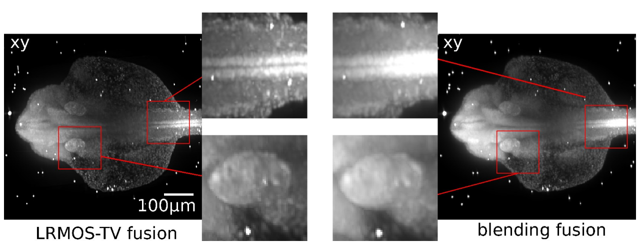
Conclusions



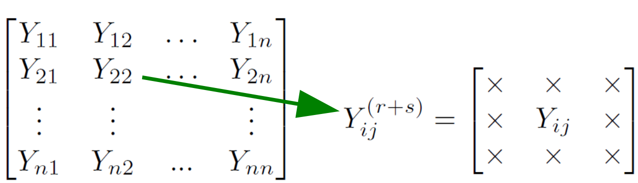
- A **new framework** for the fusion of the SPIM images was presented



- Spatially-variant Deconvolution better **models the optical properties** of the system than existing methods



- The structure **borders are well preserved** due to the TV regularization



- The algorithm is **fast** and can be easily parallelized

Thank you for your attention!

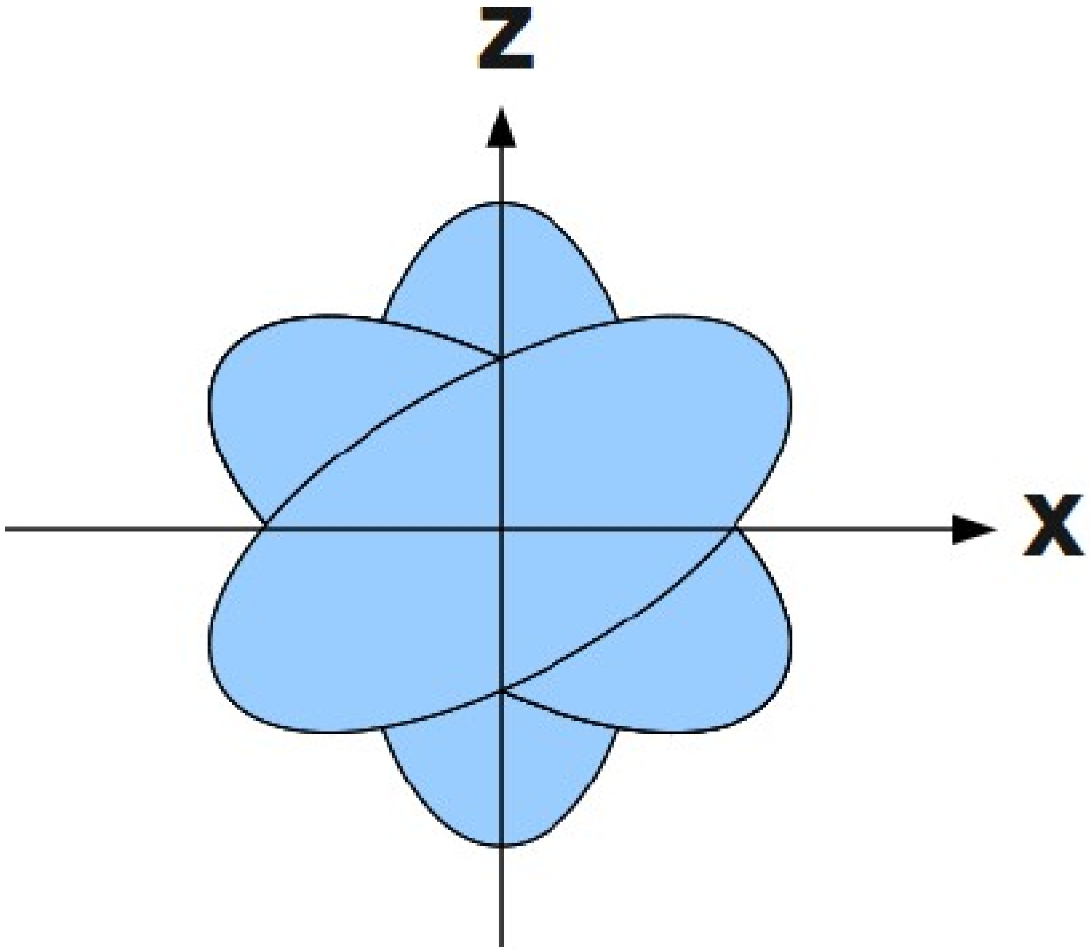
Proposed Algorithm ("LRMOS-TV")

for $m = 1$ to T_1 **do**
  for $n = 1$ to T_2 **do**
    for $k = 1$ to T_3 **do**
      1. Extract extended region $R_i = Y_{mnk}^{(r+s)}$ from Y_i for each view i.
      2. Obtain $H_i = H_{m,n,k}^{(r+s)}$ by padding with zeros for each view i.
      3. Compute the initial estimate: $\hat{X}^0 = \frac{1}{N} \sum_{i=1}^{N} R_i^p$
      4. Iterate: $\hat{X}_{m,n,k}^{p+1}(\mathbf{v}) = \frac{\hat{X}_{m,n,k}^{p}(\mathbf{v})}{1-\lambda \mathrm{div}\left(\frac{\nabla \hat{X}_{m,n,k}^{p}(\mathbf{v})}{|\nabla \hat{X}_{m,n,k}^{p}(\mathbf{v})|}\right)} \cdot C^p(\mathbf{v})$
      5. Extract $\hat{X}_{mnk}$ from $\hat{X}_{mnk}^{(r+s)}$ and save into $\hat{X}$.
    end for
  end for
end for

Outlook

- Algorithm:
  - Additional regularization strategies
  - Optimal number of iteration steps
  - A parametric model of the PSF along the lightsheet
- Microscopy:
  - Insert and record beads inside the sample for better PSF modeling inside the tissue
  - Automatic centering of the sample

Coverage of the Beads in xz



Average PSF vs Variant PSF

	deconvolved with average PSF	deconvolved with variant PSF
σ_x	1.5375 (max 1.6409)	1.4835 (max 1.6179)
σ_y	1.3598 (max 1.7707)	1.2937 (max 1.7233)
σ_z	2.0252 (max 2.4188)	2.0354 (max 2.038)