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DE LYON

✚ POLITECNICO DI MILANO



INSA

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✚ Time-resolved wavelet- based acquisitions using a single pixel camera



Introduction

- 1 – Single pixel camera
- 2 – Motivation
- 3 – Problem
- 4 – State of the art

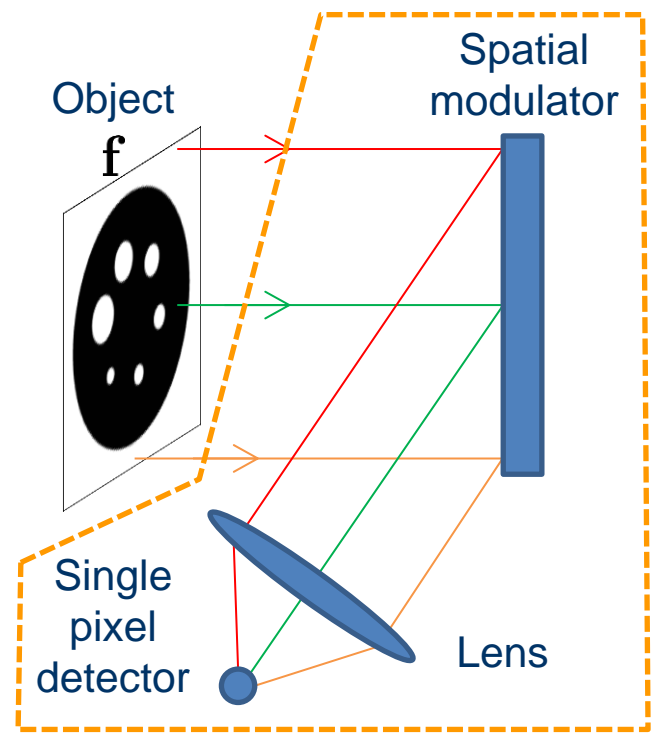
Materials and methods

- 1 – Experimental setup
- 2 – Wavelet decomposition
- 3 – ABS-WP strategy
- 4 – Extension to TR measurements

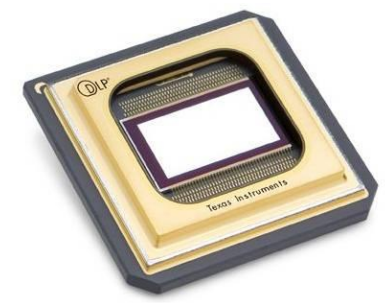
Results

- 1 – Temporal resolution
- 2 – Application to FLIM
- 3 – Multispectral TR measurements

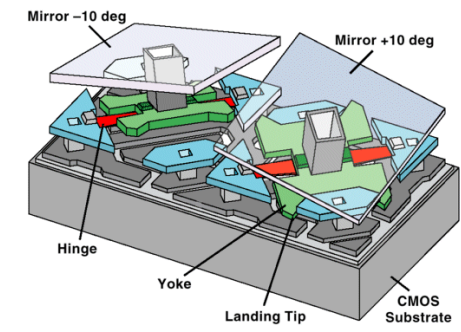
Conclusion



Single-pixel camera (SPC)



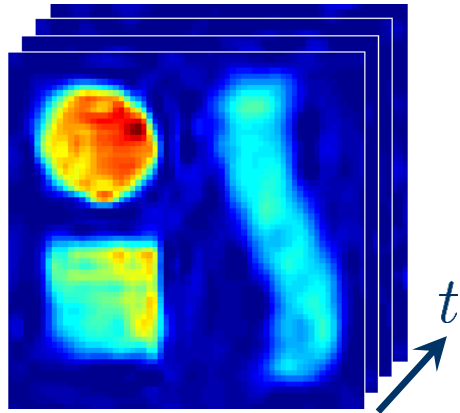
Digital micro-mirror device (DMD)



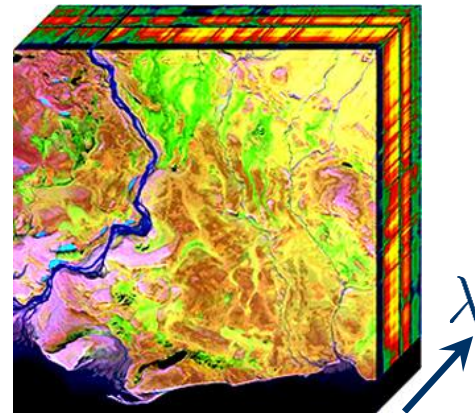
Two mirrors of 13.7 μm (Texas Instruments)

- Spatial modulator: SLM, LCD, **DMD** (Digital Micro-mirror Device)
- DMD: array mirrors that can **independently** be tilted in two states

- **Multi-dimensional acquisitions** → management of **huge datasets**



Stack of time images



Stack of spectral images (Wikipedia)

- Single pixel camera (SPC) → partial **compression** at the hardware level
 - **Infrared** or **multispectral** imaging [Edgar et al., *Scientific Reports*, 5, 2015]
 - **Low cost** time-resolved system [Pian et al., *Biomedical Optics*, 2016]

COUPLE COMPRESSION TECHNIQUES (SOFTWARE LEVEL)

WITH THE SPC (HARDWARE LEVEL)

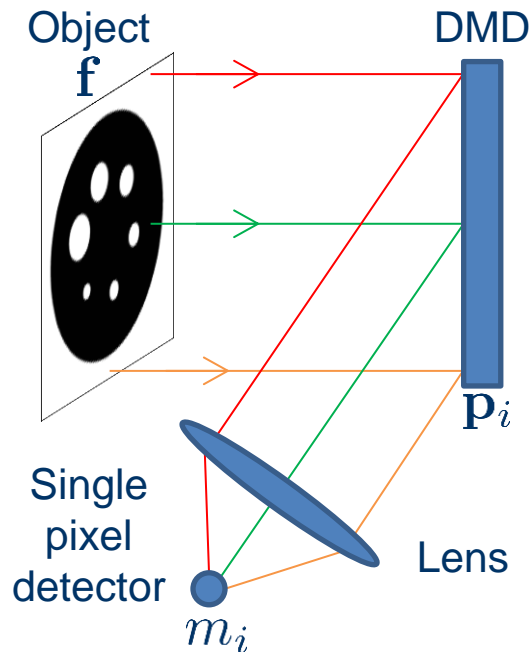


Image of size $N \times N$: \mathbf{f}

I patterns of size $N \times N$: \mathbf{p}_i

$\Rightarrow I$ measurements: $m_i = \mathbf{f}^\top \mathbf{p}_i$

➤ Sequential measurements m_i for different patterns \mathbf{p}_i

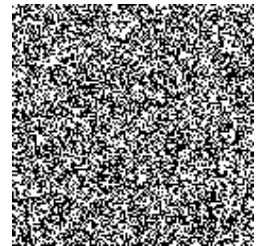
➤ **Problems**

- P1 – Choice / design of the patterns \mathbf{p}_i
- P2 – Restoration of the image \mathbf{f} from the measures m_i knowing \mathbf{p}_i



➤ Compressive sensing [Duarte et al., IEEE SPM, 25, 2008]

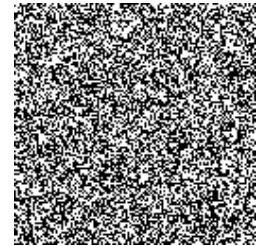
- P1 – Random ± 1 Bernoulli variables 😊
- P2 – Restoration by l_1 -minimization 😞



Random pattern

➤ Compressive sensing [*Duarte et al., IEEE SPM, 25, 2008*]

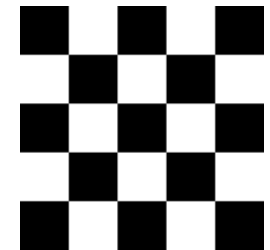
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Random pattern

➤ Basis scan [*Zhang et al., Nature Comm., 6, 2015*]

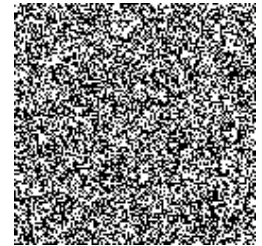
- P1 – N^2 patterns in a basis (Hadamard, Fourier, etc.) 😞
- P2 – Chosen basis inverse transform 😊



Hadamard pattern

➤ Compressive sensing [Duarte et al., IEEE SPM, 25, 2008]

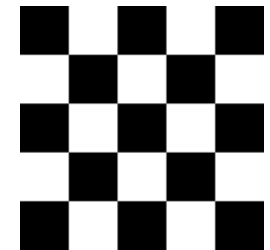
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Random pattern

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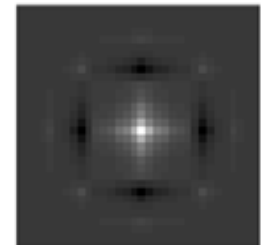
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Hadamard pattern

➤ Adaptive basis scan [Dai et al., Applied Optics, 53 (29), 2014]

- P1 – $l \ll N^2$ patterns in a chosen basis 😊
- P2 – Chosen basis inverse transform 😊



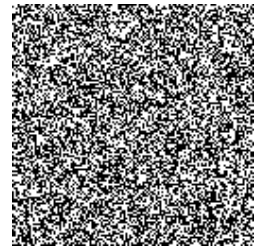
Wavelet pattern

→ **Prediction** of the l patterns based on previous measures



➤ Compressive sensing [Duarte et al., IEEE SPM, 25, 2008]

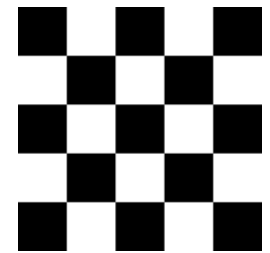
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Random pattern

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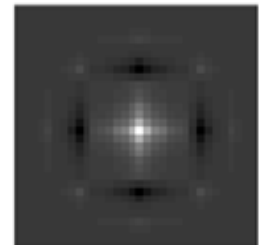
Hadamard pattern

➤ Adaptive basis scan [Dai et al., Applied Optics, 53 (29), 2014]

- P1 – $l \ll N^2$ patterns in a chosen basis 😊
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+TR

→ **Prediction** of the l patterns based on previous measures



Wavelet pattern



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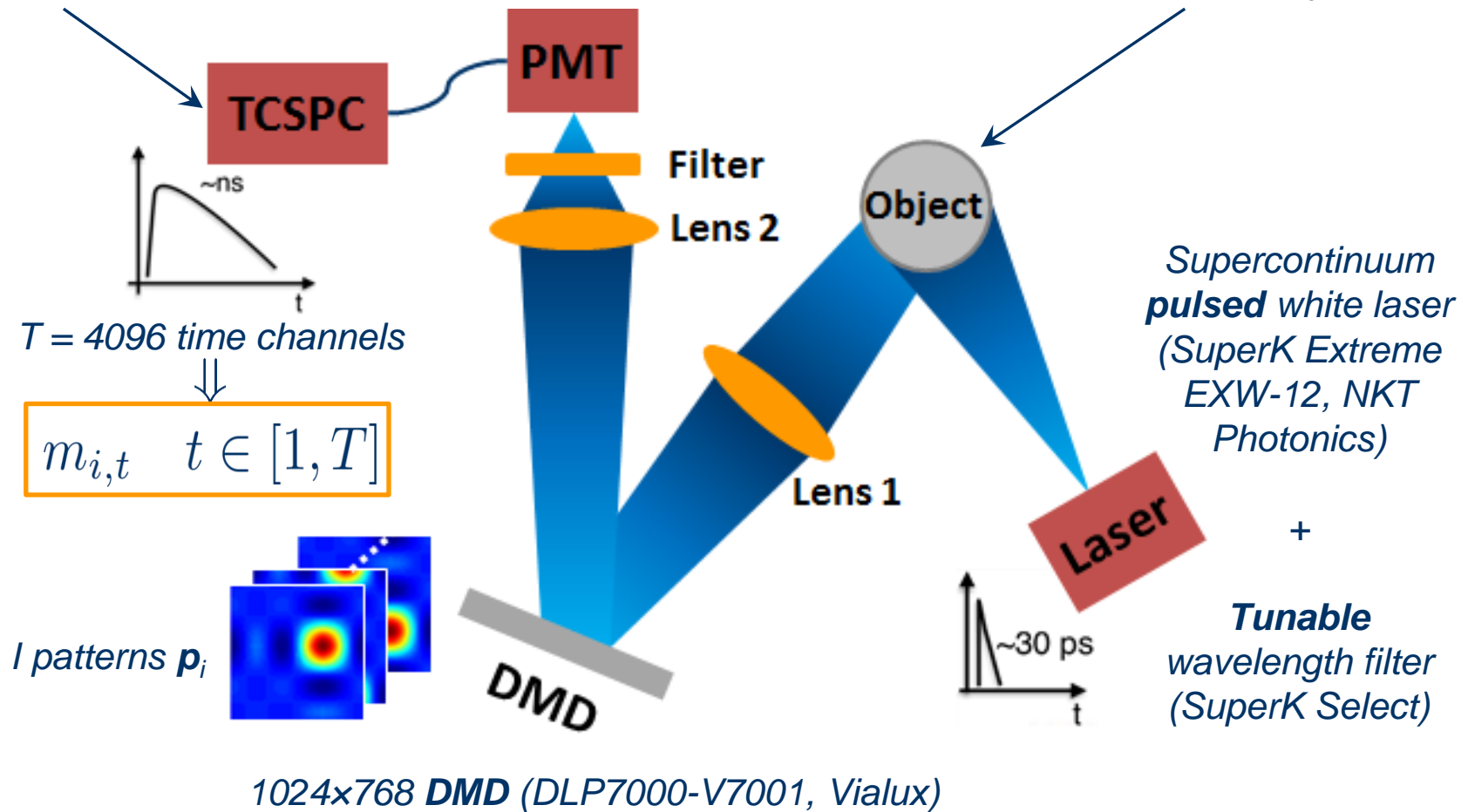
Conclusion



Photon counting board (SPC-630, Becker & Hickl GmbH)

HPM-100-50, Becker & Hickl GmbH

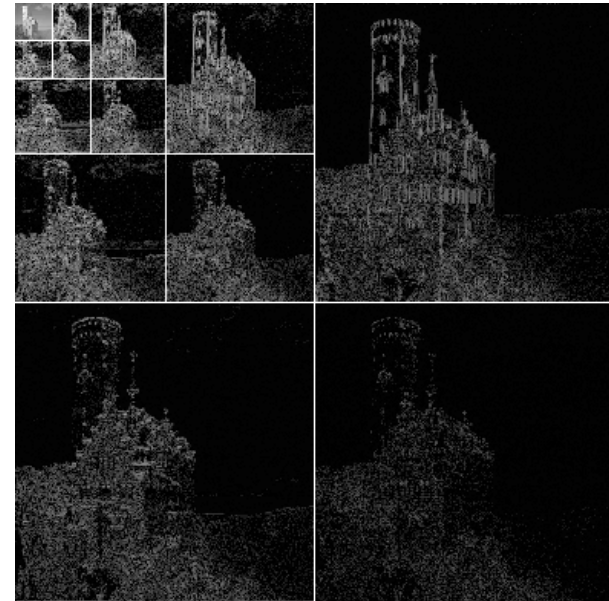
Fluorophores absorbing light at λ_{abs} and emitting at λ_{em}



- **Adaptive** approach in the wavelet domain
- One wavelet coefficient: $c = \mathbf{f}^T \mathbf{p}$ \Leftrightarrow one SPC measurement
- **Non-linear approximation**: retains a percentage of the **strongest wavelet coefficients** and shows excellent image recovery [Mallat, Academic Press, 2008]



Ground truth 512 x 512 image

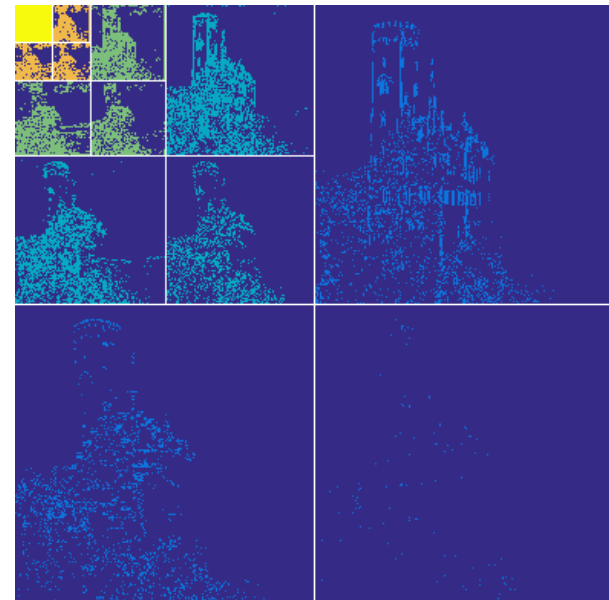


4-level wavelet decomposition 512 x 512

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Ground truth 512 x 512 image



10% of the strongest coefficients

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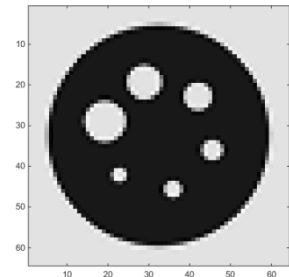
Ground truth 512 x 512 image



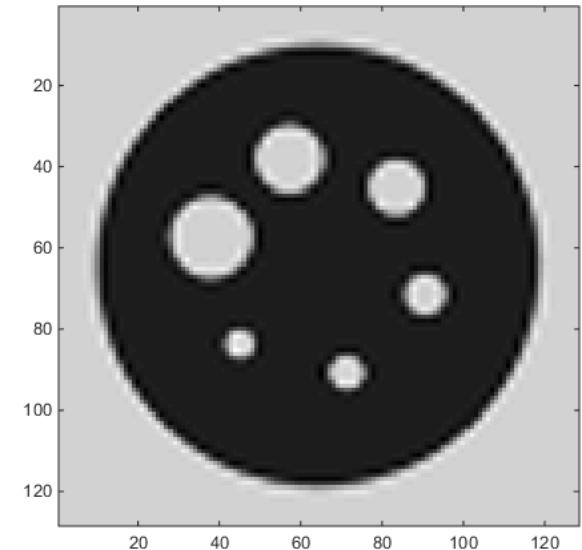
Restored image with 10% of the coefficients

- **ABS-WP:** Adaptive Basis Scan by Wavelet Prediction [*Rousset et al., IEEE TCI, in press, 2017*]
- **Multiresolution** approach: non-linear approximation idea applied on each of the $j = 1 \dots J$ scales of the J -level wavelet decomposition
- **Steps:** example for a 128 x 128 pixel image for $J = 1$

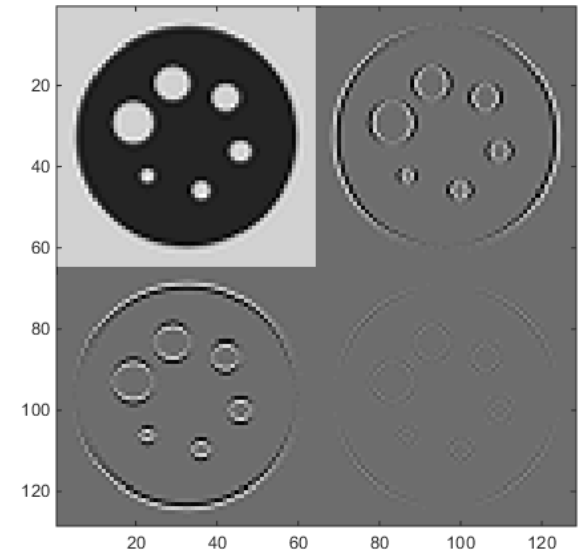
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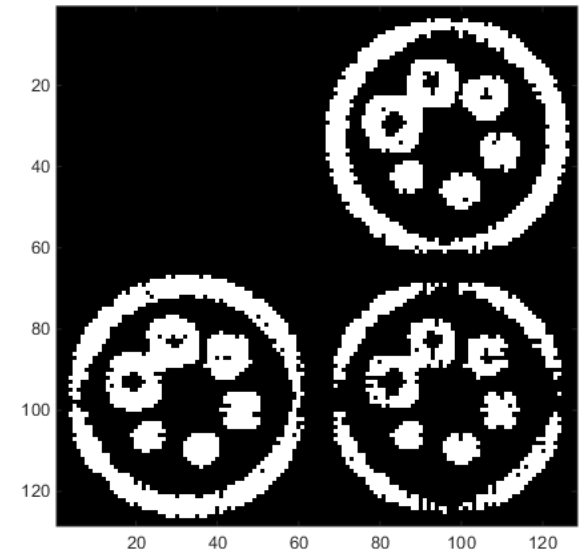
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 - 2 – Over-sampling by a factor 2 by a bi-cubic interpolation



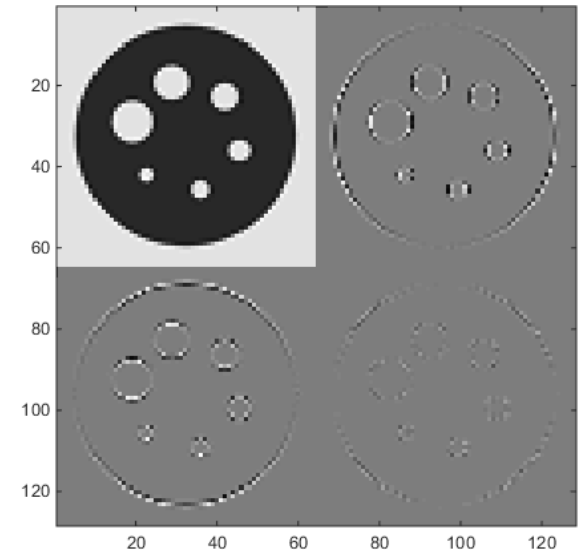
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 - 3 – 1-level wavelet transform



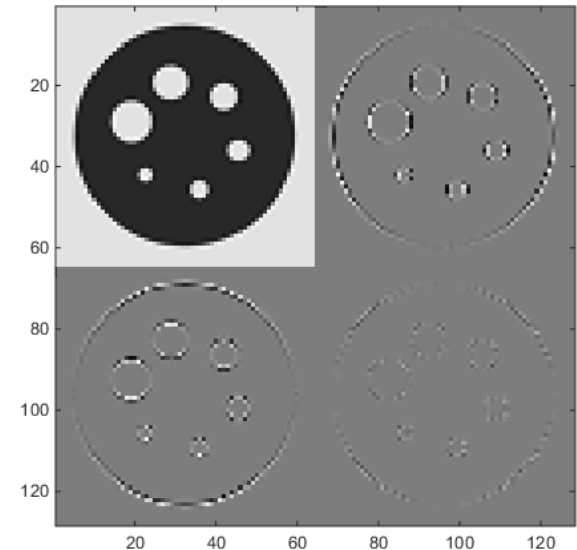
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 - 4 – A percentage p_j of the strongest detail wavelet coefficients is retained



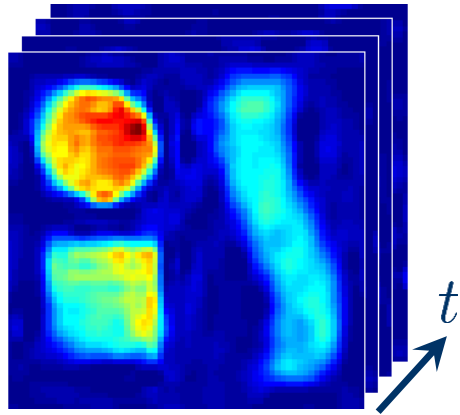
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 - 5 – The “predicted” significant coefficients are experimentally acquired



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 - 5 – The “predicted” significant coefficients are experimentally acquired
- Set of percentages $\mathcal{P} = \{p_J, \dots, p_1\}$ to control the compression rate (CR)



- $N \times N$ single image \mathbf{f} → 2D+t stack of T images $\mathbf{f}_1, \dots, \mathbf{f}_T$ of size $N \times N$



$$\mathbf{F}_{1\dots T} = (\mathbf{f}_1, \dots, \mathbf{f}_T) \in \mathbb{R}^{N^2 \times T}$$

- **Vector of time measurements** directly obtained by the TR-SPC

$$\mathbf{m}_i^\top = \mathbf{p}_i^\top \mathbf{F}_{1\dots T}$$

$$\mathbf{m}_i = (m_{i,1}, \dots, m_{i,T})^\top \in \mathbb{R}^{T \times 1}$$

- Prediction performed on the continuous-wave (CW) measures

$$m_i = \sum_{t=1}^T m_{i,t}$$



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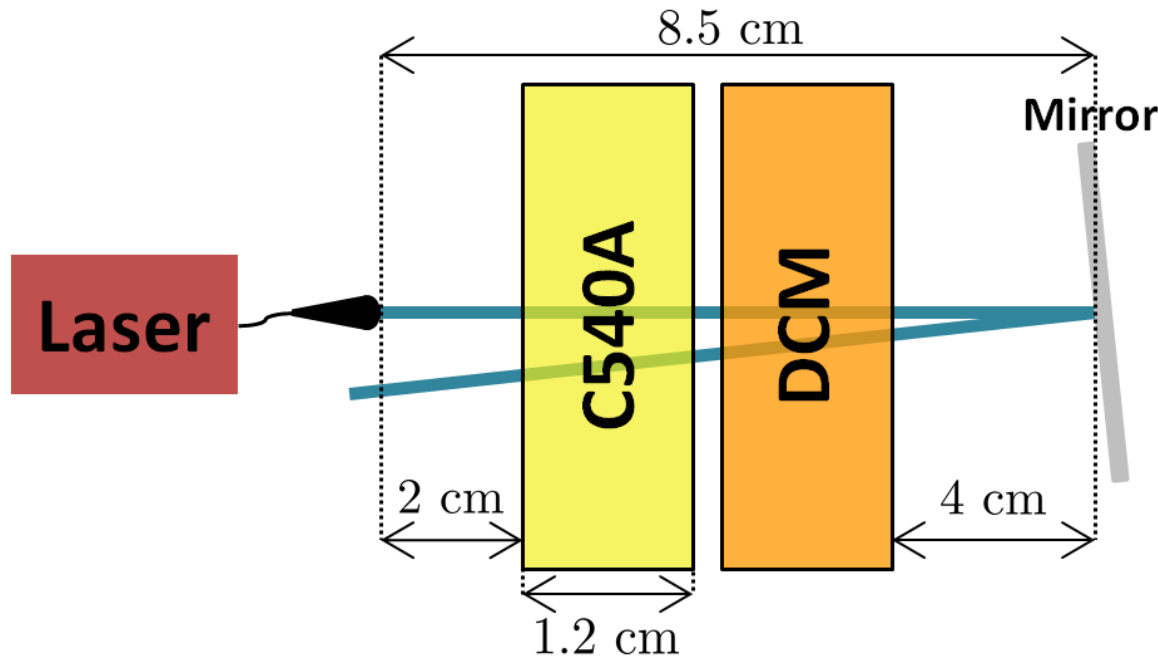
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Conclusion

- Cuvettes with different solutions of dyes (Coumarin 540A or DCM) in ethanol



$$\lambda_{\text{abs}} = 422 \text{ nm}$$

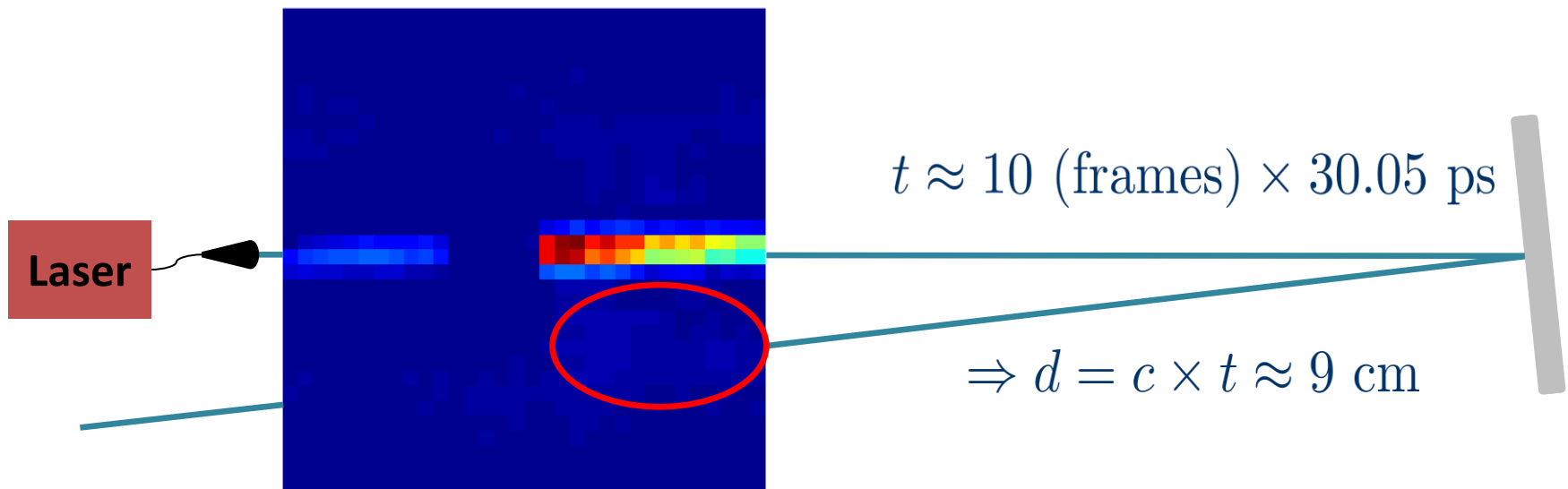
$$\lambda_{\text{em}} = 532 \text{ nm}$$

$$\lambda_{\text{abs}} = 468 \text{ nm}$$

$$\lambda_{\text{em}} = 624 \text{ nm}$$

- Illumination: wavelengths ranging from 455 to 485 nm with a 5 nm step
- Detection: long-pass filter at 500 nm (*FEL0500, ThorLabs*)

- **High temporal resolution** with a minimum of 3.05 ps per time channel
- In practice → **binning** of the time channels to reduce the noise influence
- Acquisition of the cuvettes with a binning of 10 (30.05 ps per time channel):



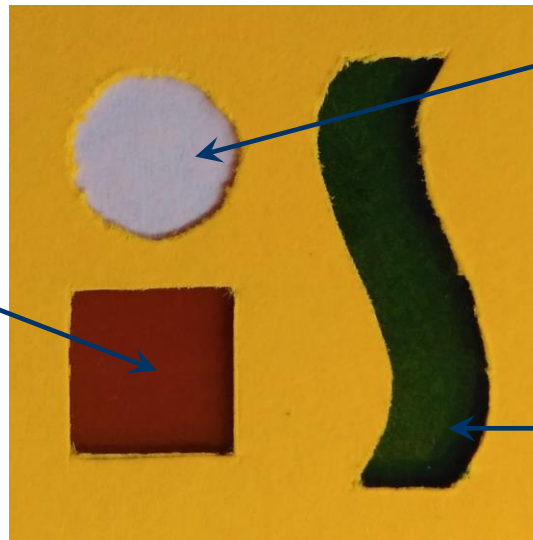
- Ability to detect the laser beam travelling at the speed of light

- Phantom with different fluorophores

Red autofluorescent plastic slide (CHROMA):

$$\lambda_{\text{abs}} = 520 \text{ nm}$$

$$\lambda_{\text{em}} = 625 \text{ nm}$$



Solution of DCM in ethanol:

$$\lambda_{\text{abs}} = 468 \text{ nm}$$

$$\lambda_{\text{em}} = 624 \text{ nm}$$

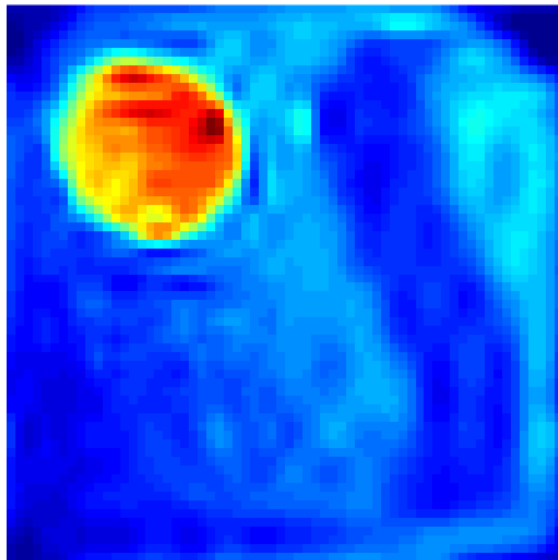
Green autofluorescent plastic slide (CHROMA):

$$\lambda_{\text{abs}} = 464 \text{ nm}$$

$$\lambda_{\text{em}} = 525 \text{ nm}$$

- Illumination: 455 to 485 nm with a 5 nm step
- Detection: long-pass filter at 500 nm (*FEL0500, ThorLabs*)
- $T = 72$ time channels: 0 to 21.66 ns (0.305 ns time step)

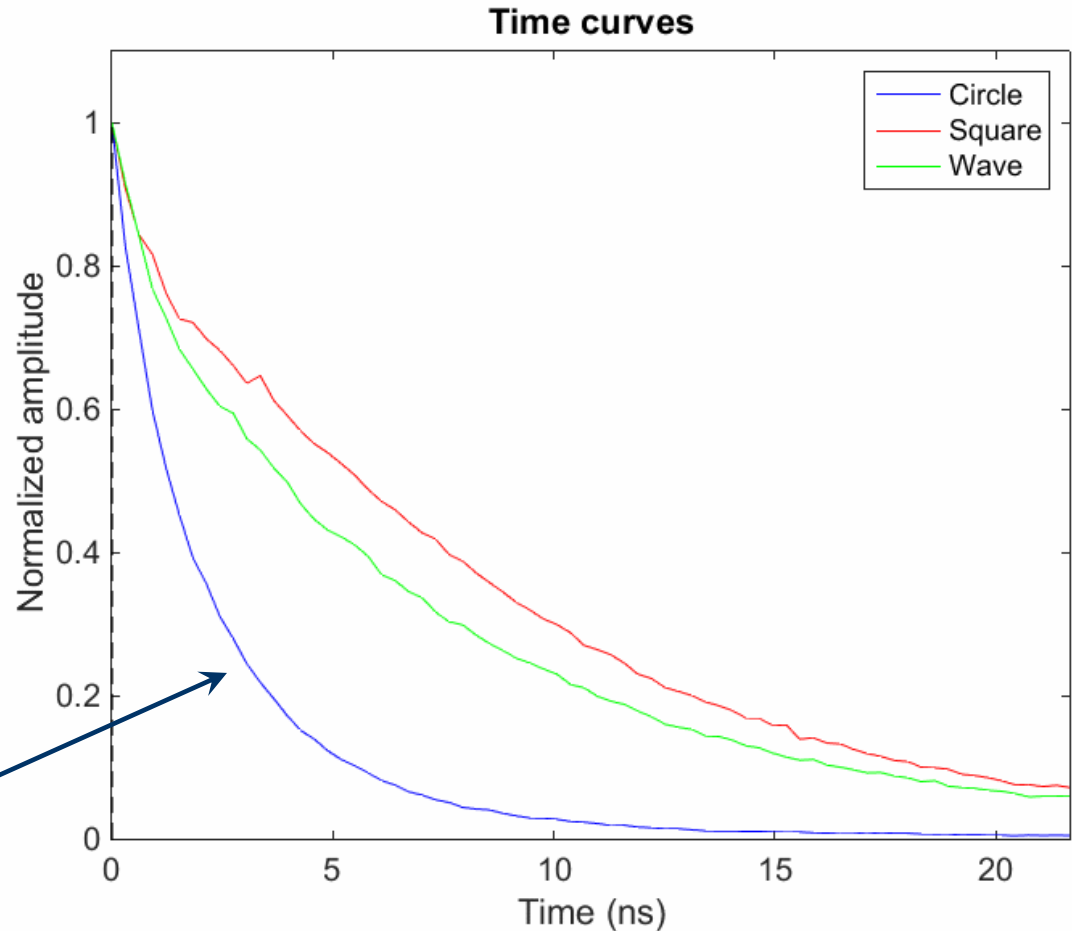
- Total of 72 images of size 64×64 acquired and restored with ABS-WP using Daubechies wavelet (Db5) with a **CR of 93 %**:



SPC recovered stack

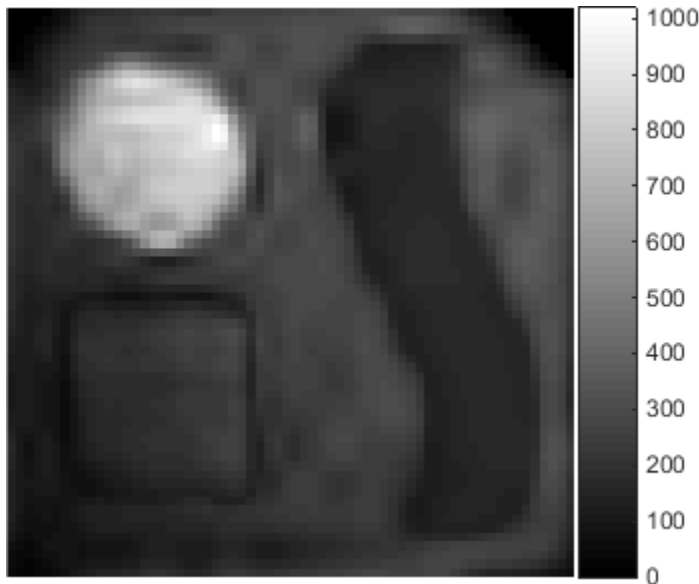
- **Fluorescence decay**

$$I(t) = Ae^{\frac{-t}{\tau}}$$

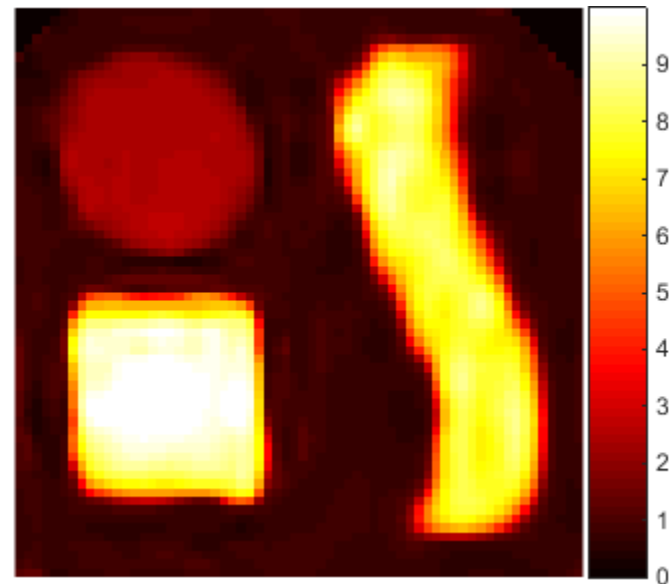


- $I(t) = Ae^{-\frac{t}{\tau}}$ depicted by experimental curves $\hat{I}(t)$ for each pixel of the image
- Fitting of the model for each pixel \rightarrow amplitude and **lifetime** maps

$$(A^*, \tau^*) = \arg \min \| \hat{I}(\mathbf{t}) - Ae^{-\frac{t}{\tau}} \|_2^2$$

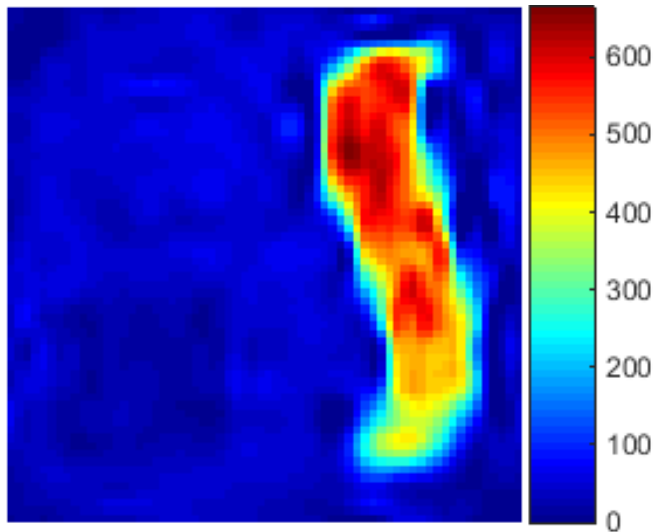


Amplitude (photons)

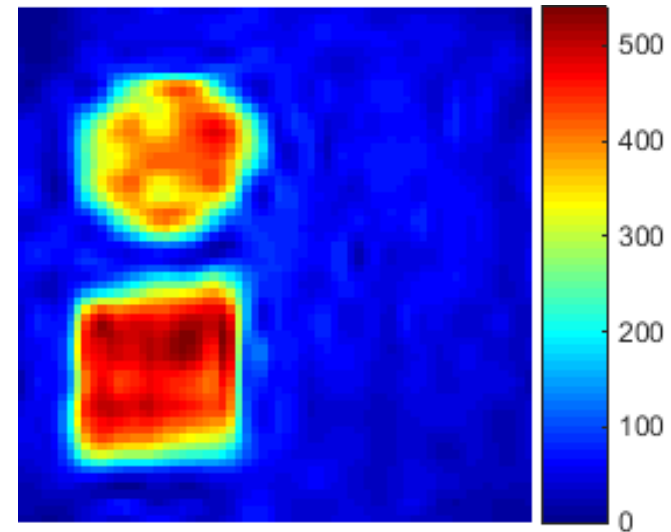


Lifetime (ns)

- New experimental setup: addition of a **grating** with $\Lambda = 16$ **parallel detectors** (*PML-16-1, Becker & Hickl GmbH*) → possibility to obtain $\Lambda \times T$ images
- Images obtained with ABS-WP with the same parameters:



CW image for $\lambda = 525$ nm



CW image for $\lambda = 625$ nm

- Ability to discern the 3 fluorophores using the **time and spectral information**



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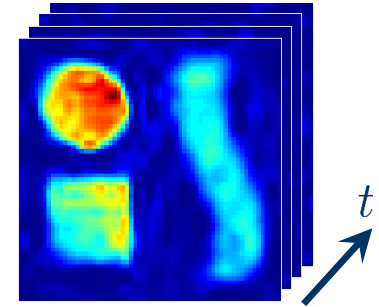
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➤ Proposed system to acquire $2D + t + \lambda$ images by a SPC:

- **Adaptive** technique
- **Wavelet** patterns
- Bi-cubic interpolation **prediction**
- **Multiresolution** approach



➤ **Faster** than CS for equivalent image quality [Rousset et al., IEEE TCI, in press, 2017]

www.creatis.insa-lyon.fr/~ducros/single_pixel_imaging

➤ Efficient yet **low cost** (multispectral) **time-resolved system, transposable on a microscope**

➤ **Perspectives**

- Investigate prediction based only in certain time channels
- Method to divide the acquisition time by 2



CREATIS

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- We note \mathbf{W} an orthonormal operator so that one wavelet pattern \mathbf{p} can be obtained as

$$\mathbf{p} = \mathbf{W}^{-1}\mathbf{e} \quad \mathbf{W} \in \mathbb{R}^{P \times P}$$

with \mathbf{e} a unit vector chosen from the canonic basis :



- Obtained patterns have real positive and negative values. The DMD can only receive b-bits patterns

→ **uniform quantization** of the patterns and positive/negative separation:

$$q_f = \frac{\max(|\mathbf{p}|)}{2^b - 1} \quad \hat{\mathbf{p}} = \left\lfloor \frac{1}{q_f} \mathbf{p} \right\rfloor \quad c \approx q_f \mathbf{f}^\top \hat{\mathbf{p}} = q_f (\mathbf{f}^\top \hat{\mathbf{p}}^+ - \mathbf{f}^\top \hat{\mathbf{p}}^-)$$



- **Average computation times** (acquisition time excluded), includes TV-minimization for CS and the prediction step + restoration for ABS-WP

Image size	Time (s)	
	CS	ABS-WP
128 x 128	13.18	0.18
256 x 256	213.62	0.42

- **TV-minimization** demands **expensive computations**, time increases quickly with the number of measures and the image size
- For ABS-WP, **bi-cubic interpolation** and the **wavelet transform** are **optimized** and **fast** operations
- **Real time** possible for our technique