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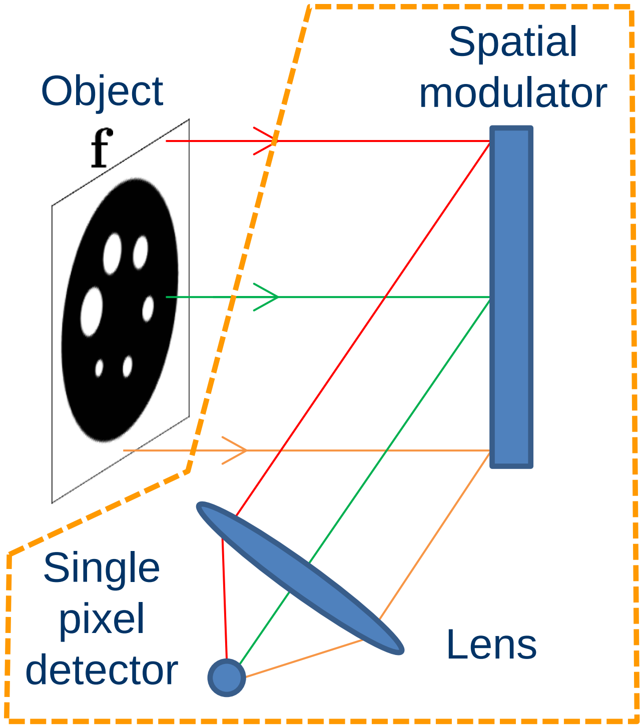
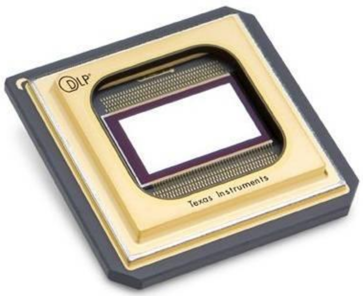
Time-resolved wavelet-based acquisitions using a single pixel camera

SPIE Photonics West – BIOS 2017 | February 1st, 2017

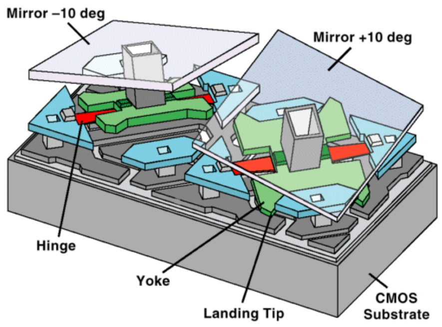
Overview



Single-pixel camera (SPC)



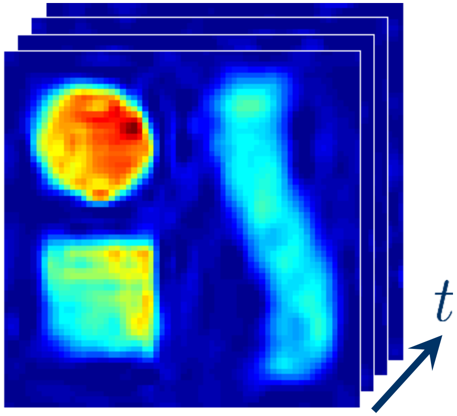
Digital micro-mirror device (DMD)



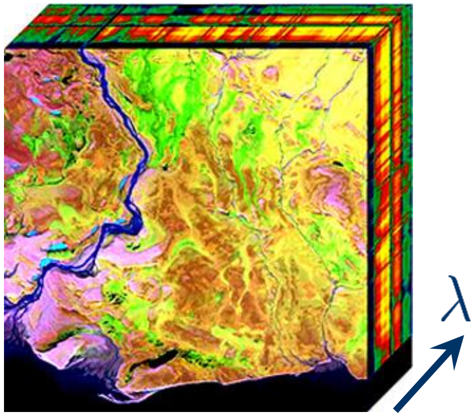
Two mirrors of 13.7 µm (Texas Instruments)

- 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)

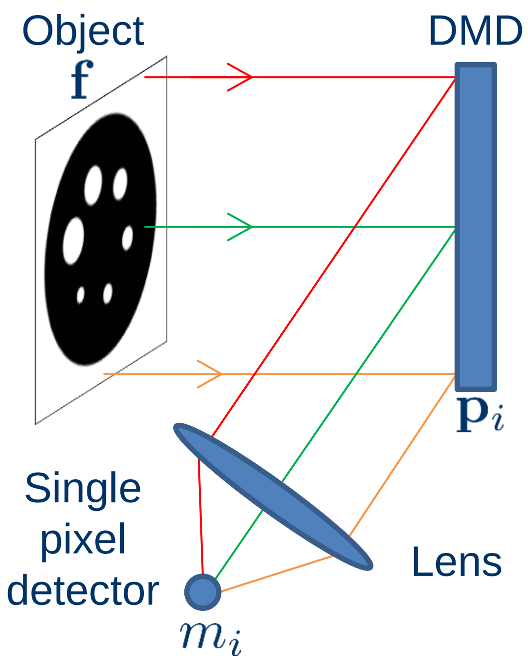


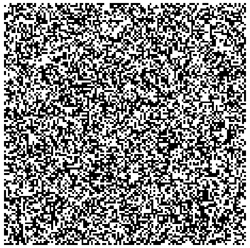
Image of size $N \times N$: $\mathbf{f}$

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

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

- 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

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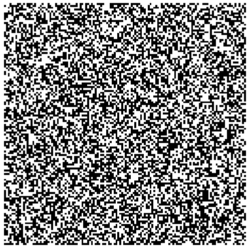
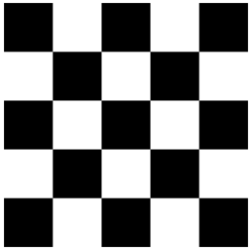


Random pattern

- 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

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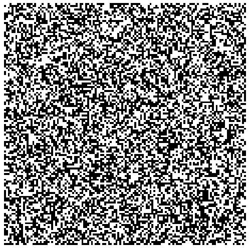

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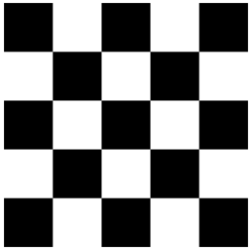
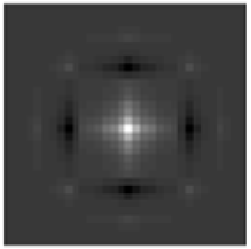


Hadamard pattern

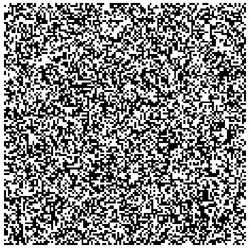
- Adaptive basis scan *[Dai et al., Applied Optics, 53 (29), 2014]*
  - P1 – ***$I \ll N^2$* patterns** in a chosen basis ☺
  - P2 – Chosen basis inverse transform ☺

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



Wavelet pattern

- Compressive sensing *[Duarte et al., IEEE SPM, 25, 2008]*
  - P1 – Random ±1 Bernoulli variables ☺
  - P2 – Restoration by **l_1-minimization** ☹



Random pattern

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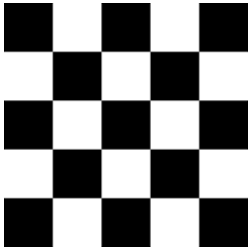

Hadamard pattern

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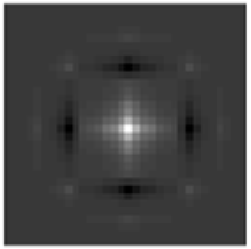
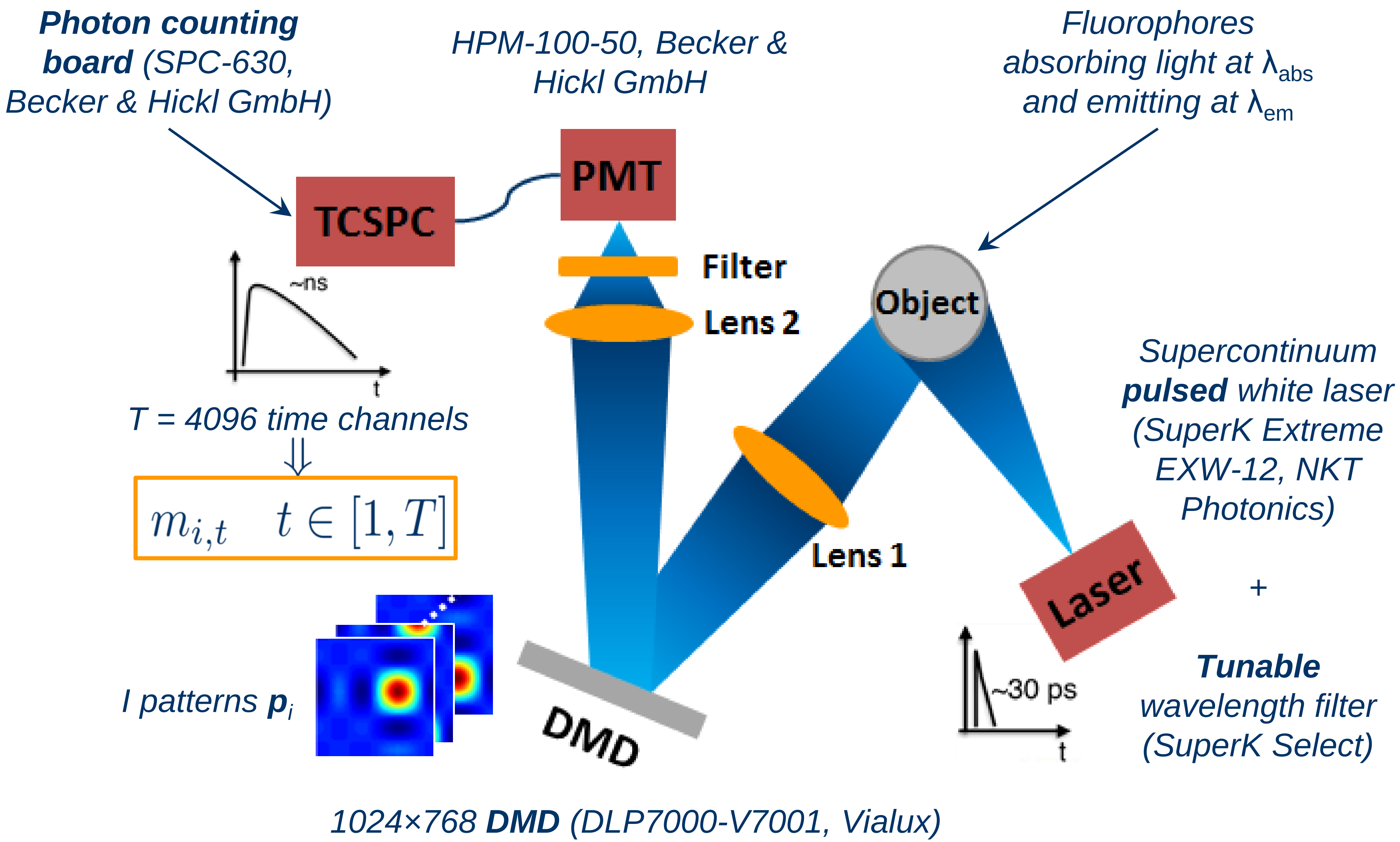
  → **Prediction** of the *I* patterns based on previous measures

+TR



Wavelet pattern

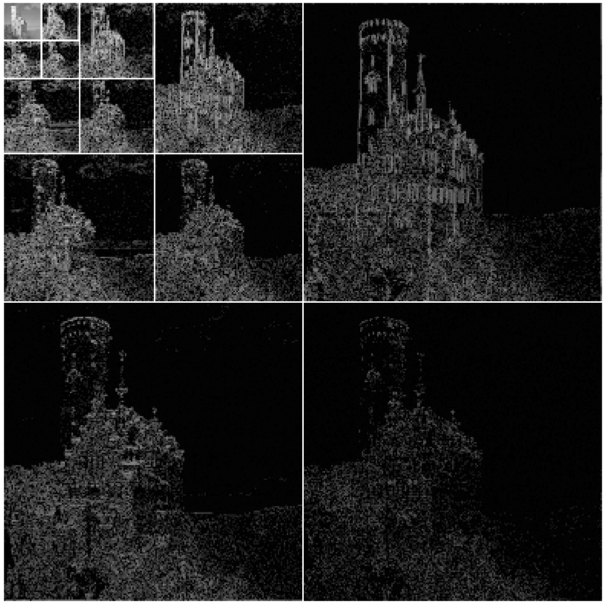
Overview



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}
TCSPC
PMT
Filter
Lens 2
Object
~ns
t
T = 4096 time channels
⇓
$m_{i,t} \quad t \in [1,T]$
Lens 1
Supercontinuum **pulsed** white laser (SuperK Extreme EXW-12, NKT Photonics)
Laser
+
I patterns $\mathbf{p}_i$
DMD
~30 ps
t
Tunable wavelength filter (SuperK Select)
1024×768 **DMD** (DLP7000-V7001, Vialux)

- **Adaptive** approach in the wavelet domain
- One wavelet coefficient: $\boxed{c = \mathbf{f}^\top \mathbf{p}}$ $\Leftrightarrow$ 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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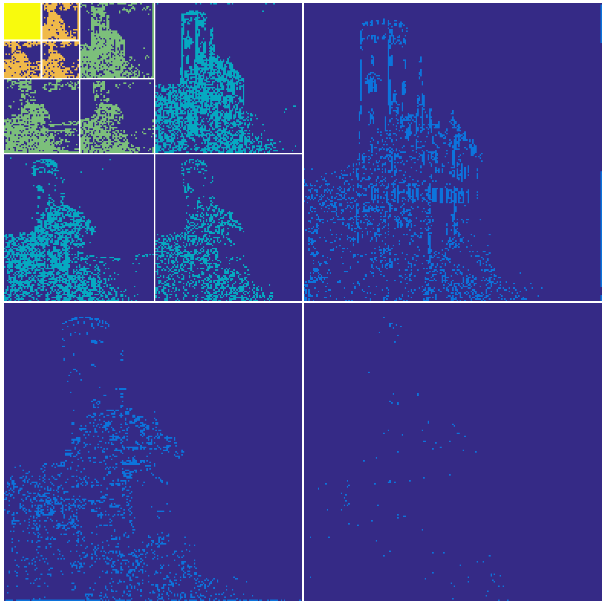
Ground truth 512 x 512 *image*



10% of the strongest coefficients

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- One wavelet coefficient: $\boxed{c = \mathbf{f}^{\top}\mathbf{p}}$ $\Leftrightarrow$ one SPC measurement
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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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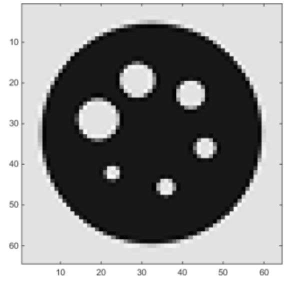
  1 – Approximation image acquisition



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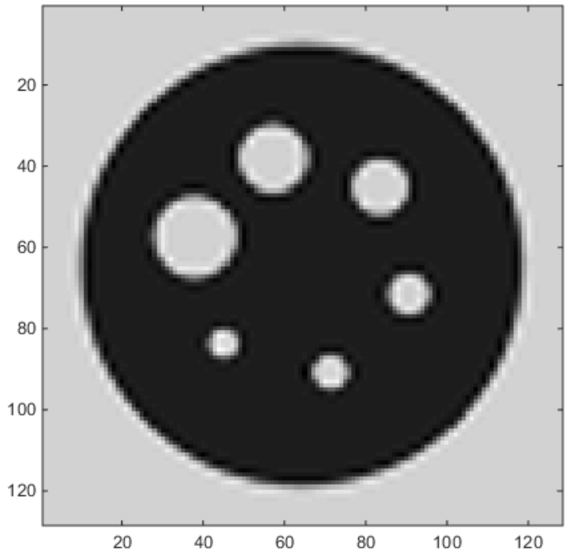

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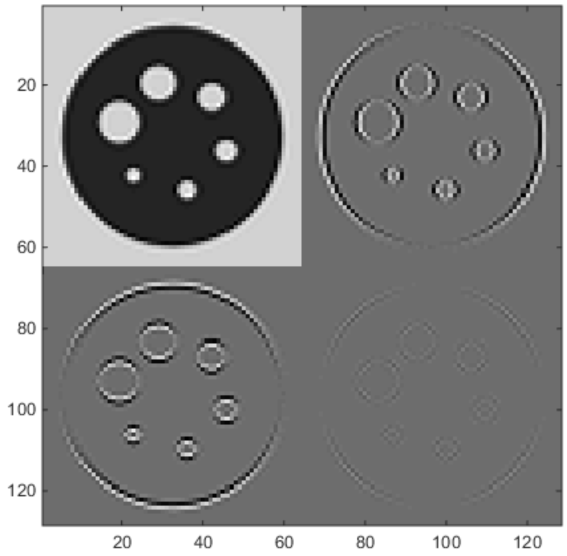

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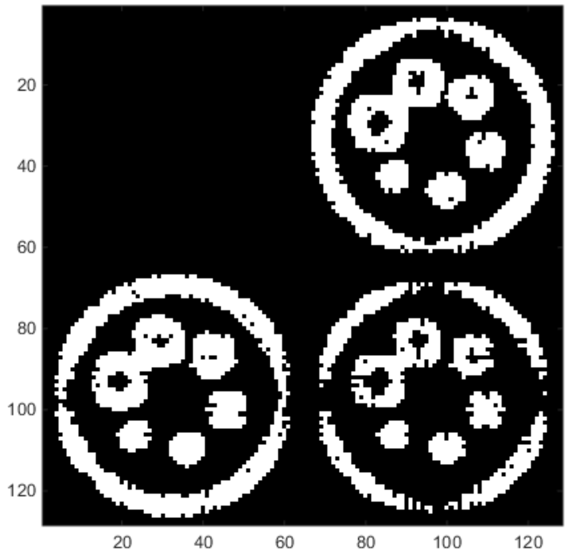
  4 – A percentage p_j of the strongest detail wavelet coefficients is retained



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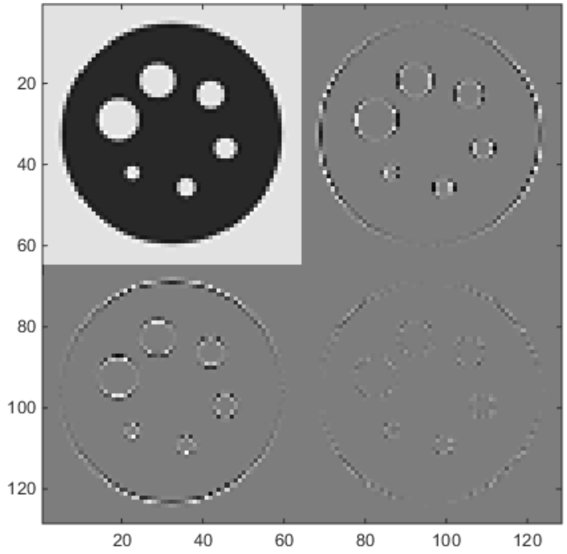
  5 – The "predicted" significant coefficients are experimentally acquired



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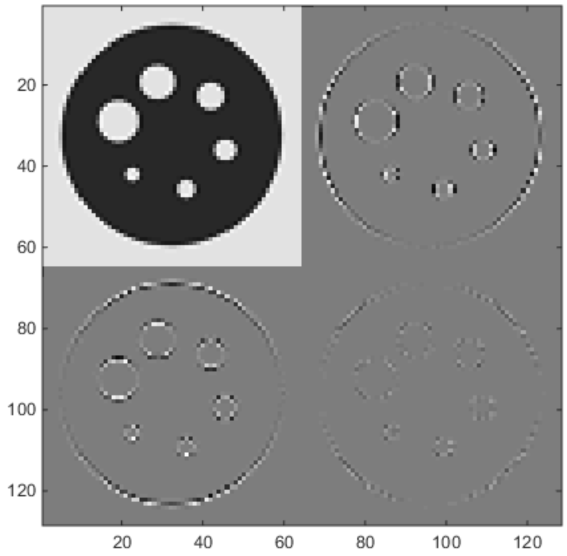
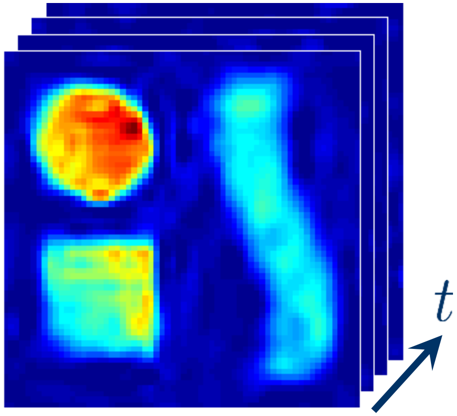


- Set of percentages $\mathcal{P} = \{p_J, \ldots, p_1\}$ to control the compression rate (CR)

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



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

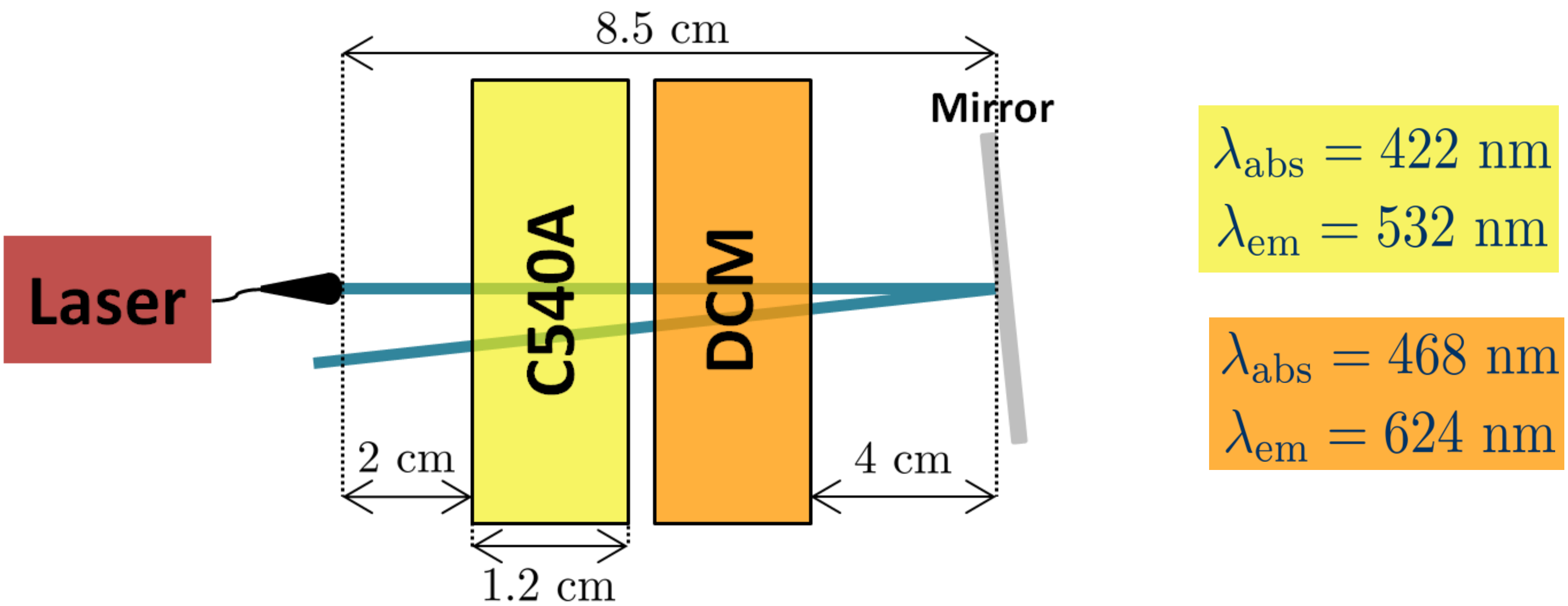
- **Vector of time measurements** directly obtained by the TR-SPC

$$\boxed{\mathbf{m}_i^\top = \mathbf{p}_i^\top \mathbf{F}_{1\ldots T}} \qquad \mathbf{m}_i = (m_{i,1}, \ldots, m_{i,T})^\top \in \mathbb{R}^{T \times 1}$$

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

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

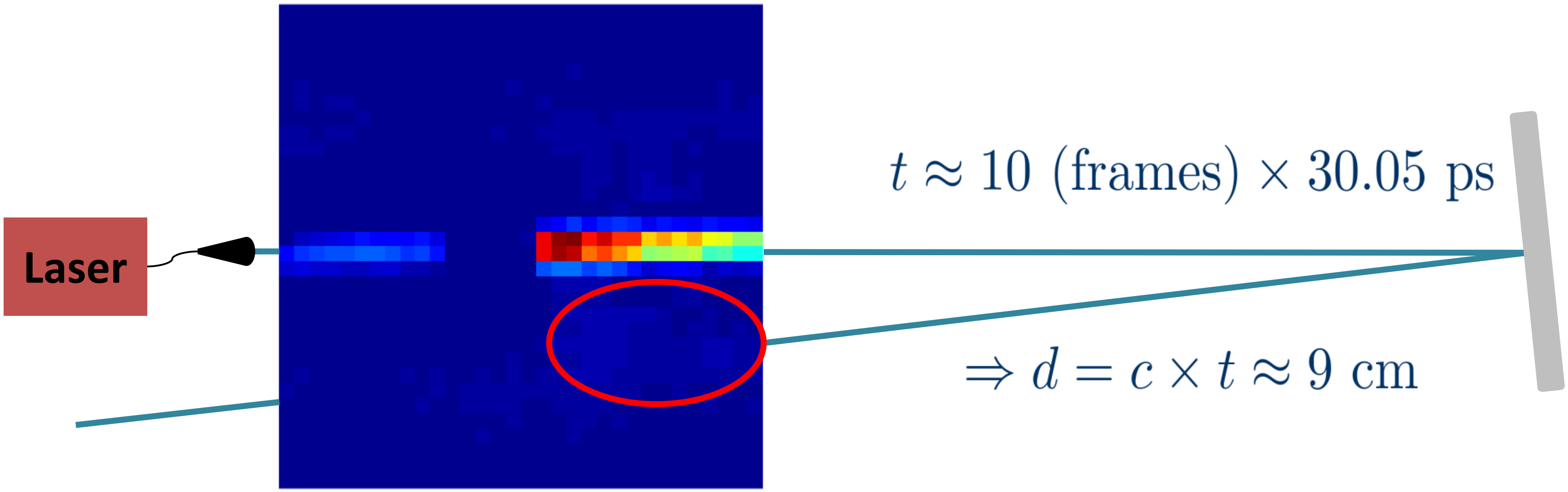
- Cuvettes with different solutions of dyes (Coumarin 540A or DCM) in ethanol



- 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):

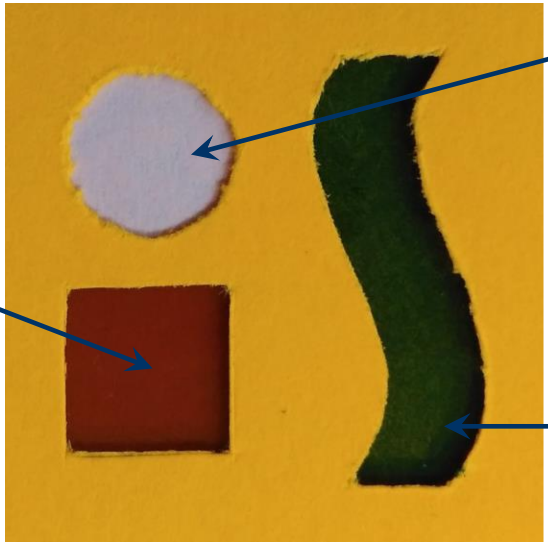


- Ability to detect the laser beam travelling at the speed of light

- 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:

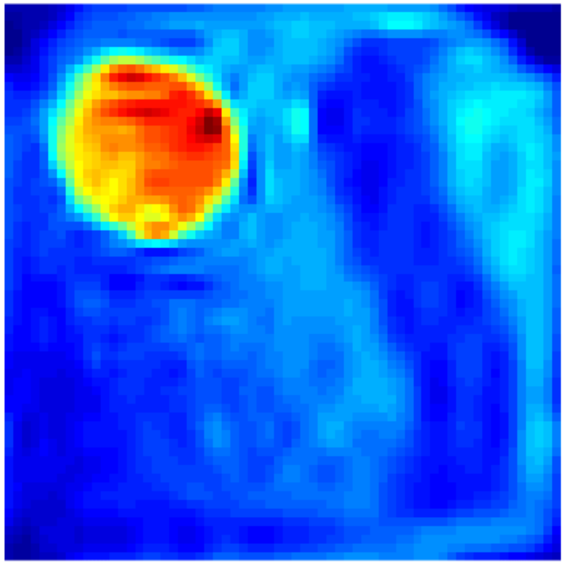
$$\lambda_{\text{abs}} = 468 \text{ nm}$$
$$\lambda_{\text{em}} = 624 \text{ nm}$$

Green autofluorescent plastic slide (CHROMA):

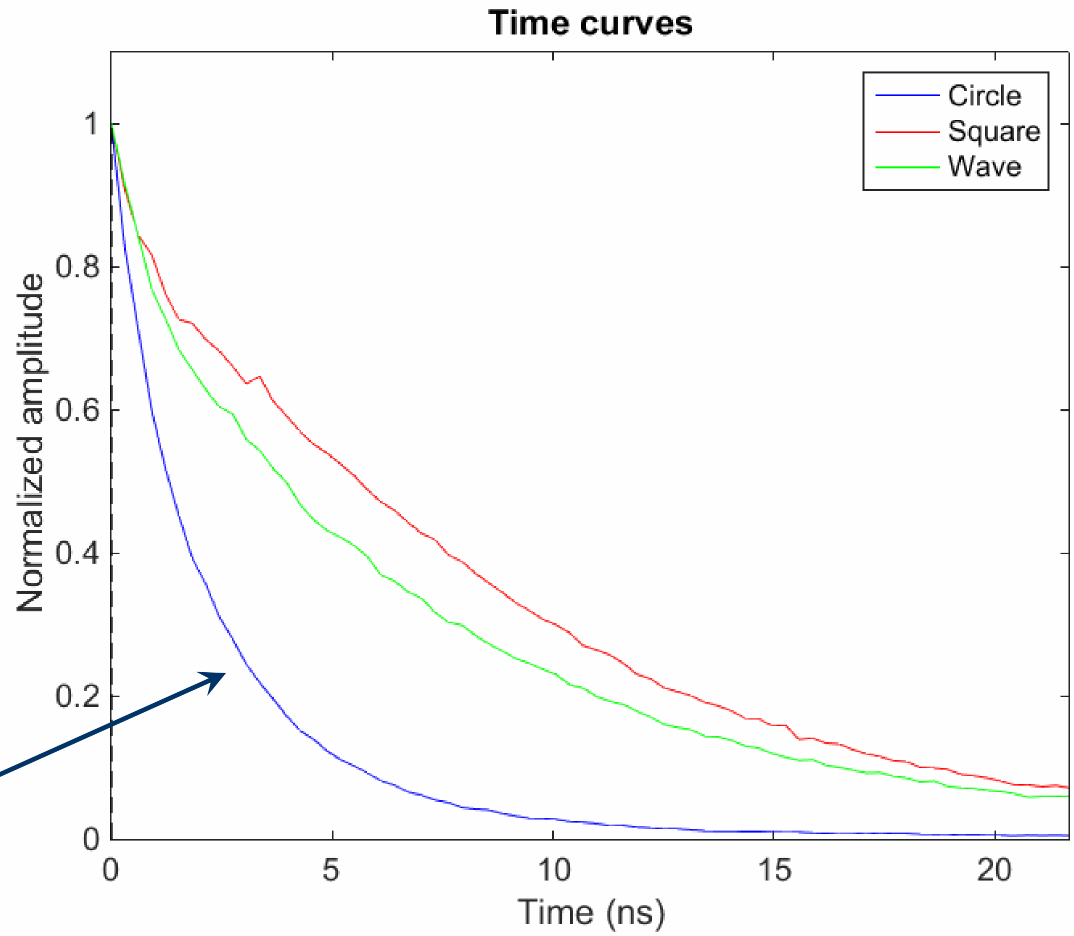
$$\lambda_{\text{abs}} = 464 \text{ nm}$$
$$\lambda_{\text{em}} = 525 \text{ nm}$$

- 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



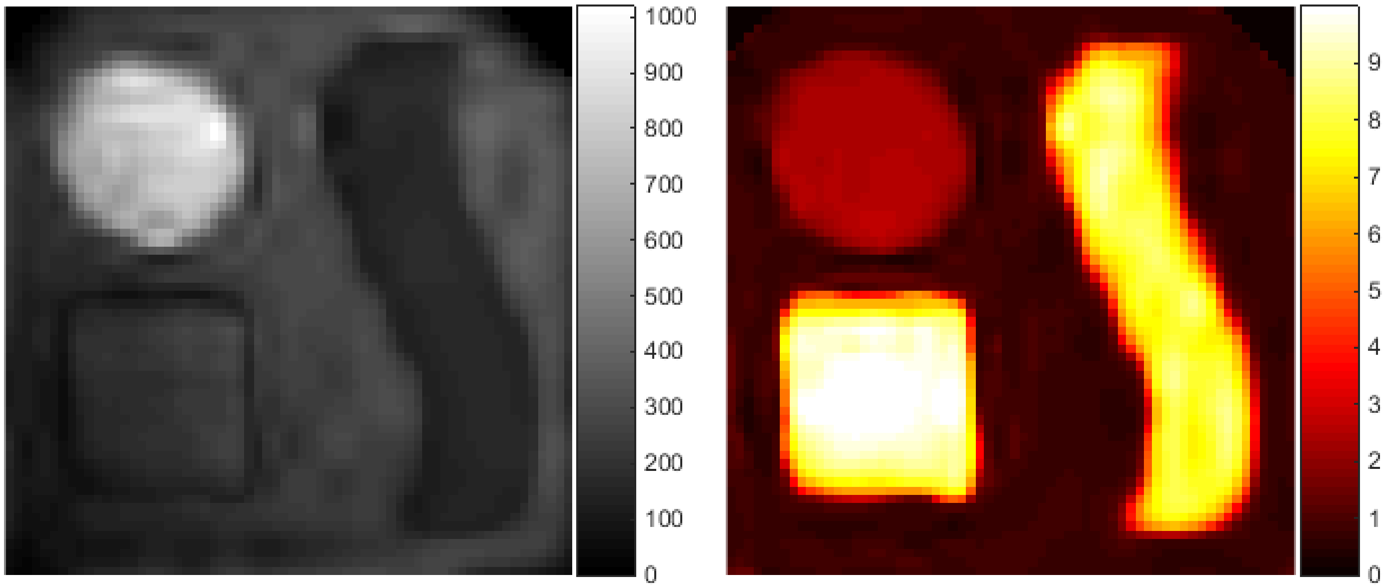
- **Fluorescence decay**

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

- $I(t) = Ae^{\frac{-t}{\tau}}$ depicted by experimental curves $\hat{I}(t)$ for each pixel of the image

- Fitting of the model for each pixel → amplitude and **lifetime** maps

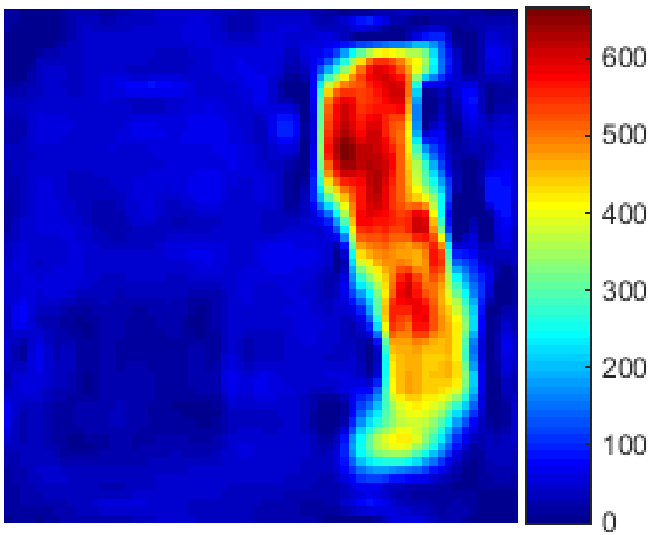
$$\boxed{(A^*, \tau^*) = \arg\min \|\hat{I}(\mathbf{t}) - Ae^{\frac{-\mathbf{t}}{\tau}}\|_2^2}$$



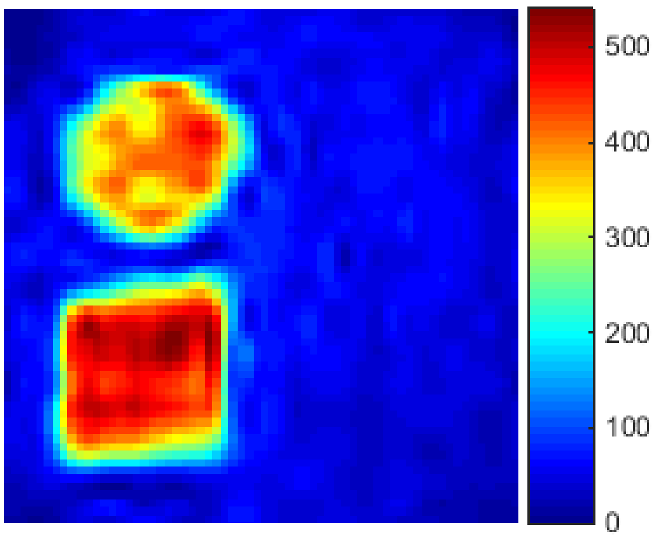
Amplitude (photons) *Lifetime (ns)*

- New experimental setup: addition of a **grating** with ***Λ* = 16 parallel detectors** (*PML-16-1, Becker & Hickl GmbH*) → possibility to obtain *Λ*×*T* images

- Images obtained with ABS-WP with the same parameters:



CW image for λ = 525 nm



CW image for λ = 625 nm

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

Introduction

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

Materials and methods

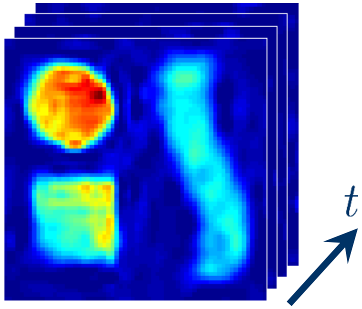
1 – Experimental setup
2 – Wavelet decomposition
3 – ABS-WP strategy
4 – Extension to TR measurements

Results

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

Conclusion

- Proposed system to acquire 2D + t + λ 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

Acknowledgments

CREATIS

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Wavelet pattern creation

- We note **W** an orthonormal operator so that one wavelet pattern **p** can be obtained as

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

with 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:

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

Computation times

- **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