Compressive sensing: how to sample data from what you know!

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First Part:

- Sparsity, low-rankness and relatives:
  "From information to structures"

- Compress while you sample:
  "From structure to scrambled sensing"

- and Reconstruct!
  "From scrambled sensing to information"

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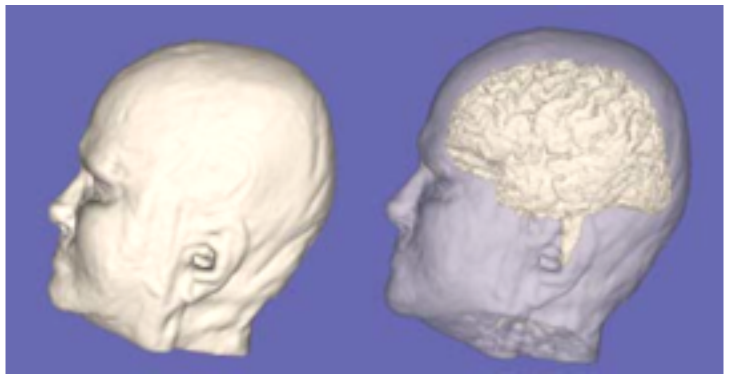
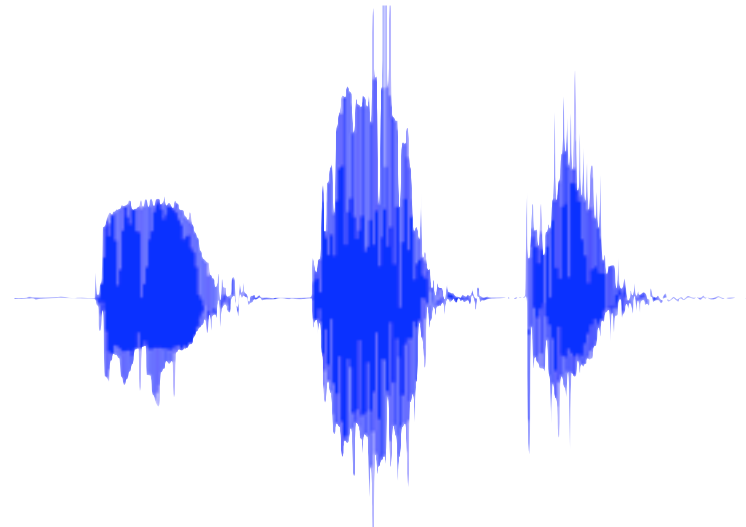
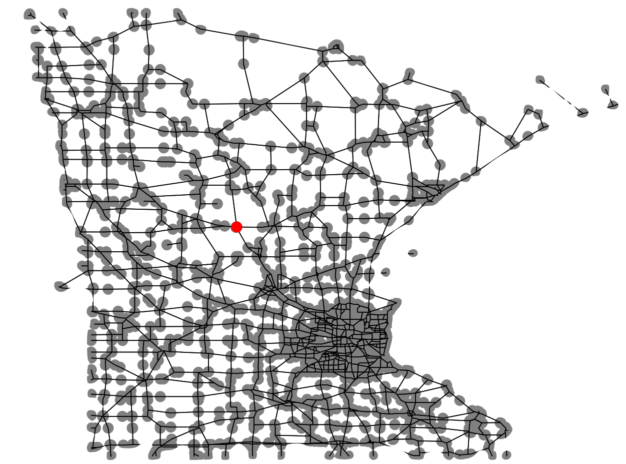
Informative signals are composed of structures ...



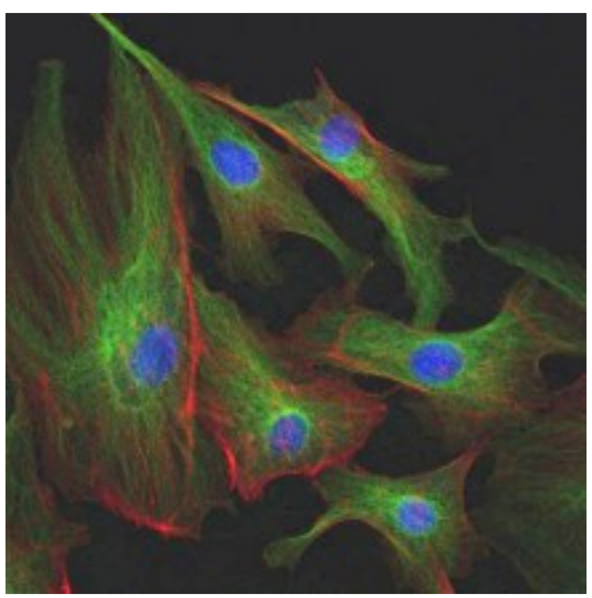
3-D data



Speech signal



Data on Graph



Biology

Video

Astronomy

2-D Example: Using Wavelets!

Representing this image ...

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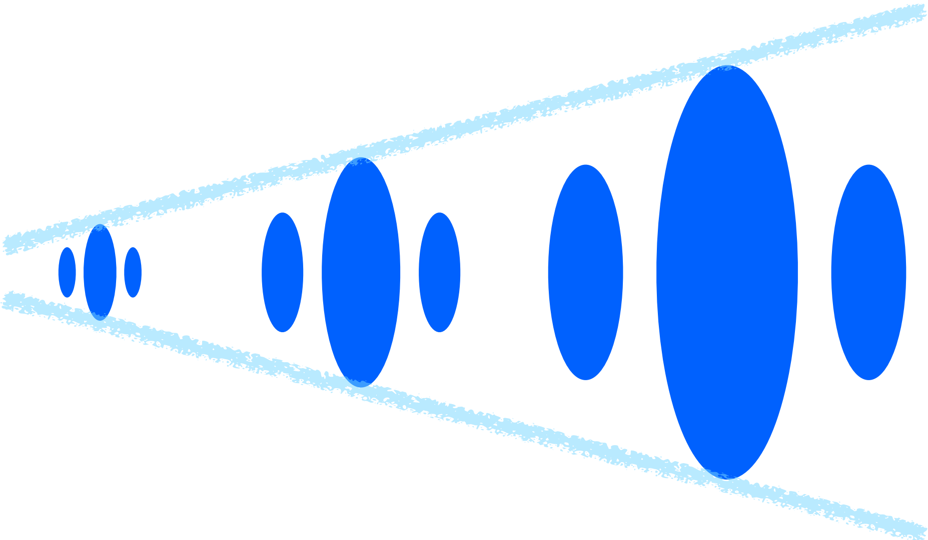
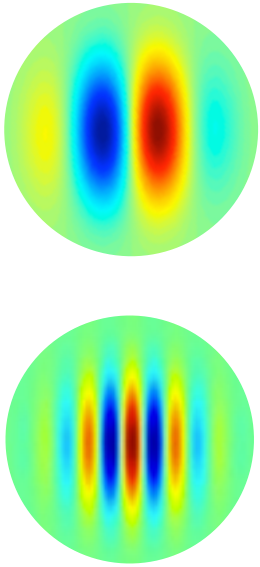
Representing this image ...

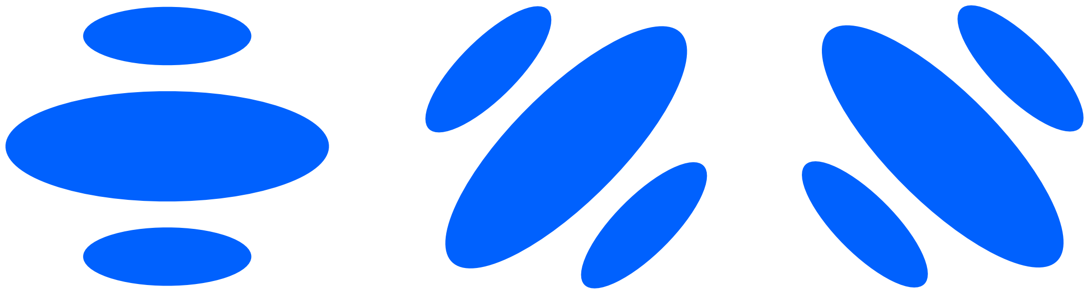
...with those "wavelets"



different sizes, scales

e.g.,





different orientations

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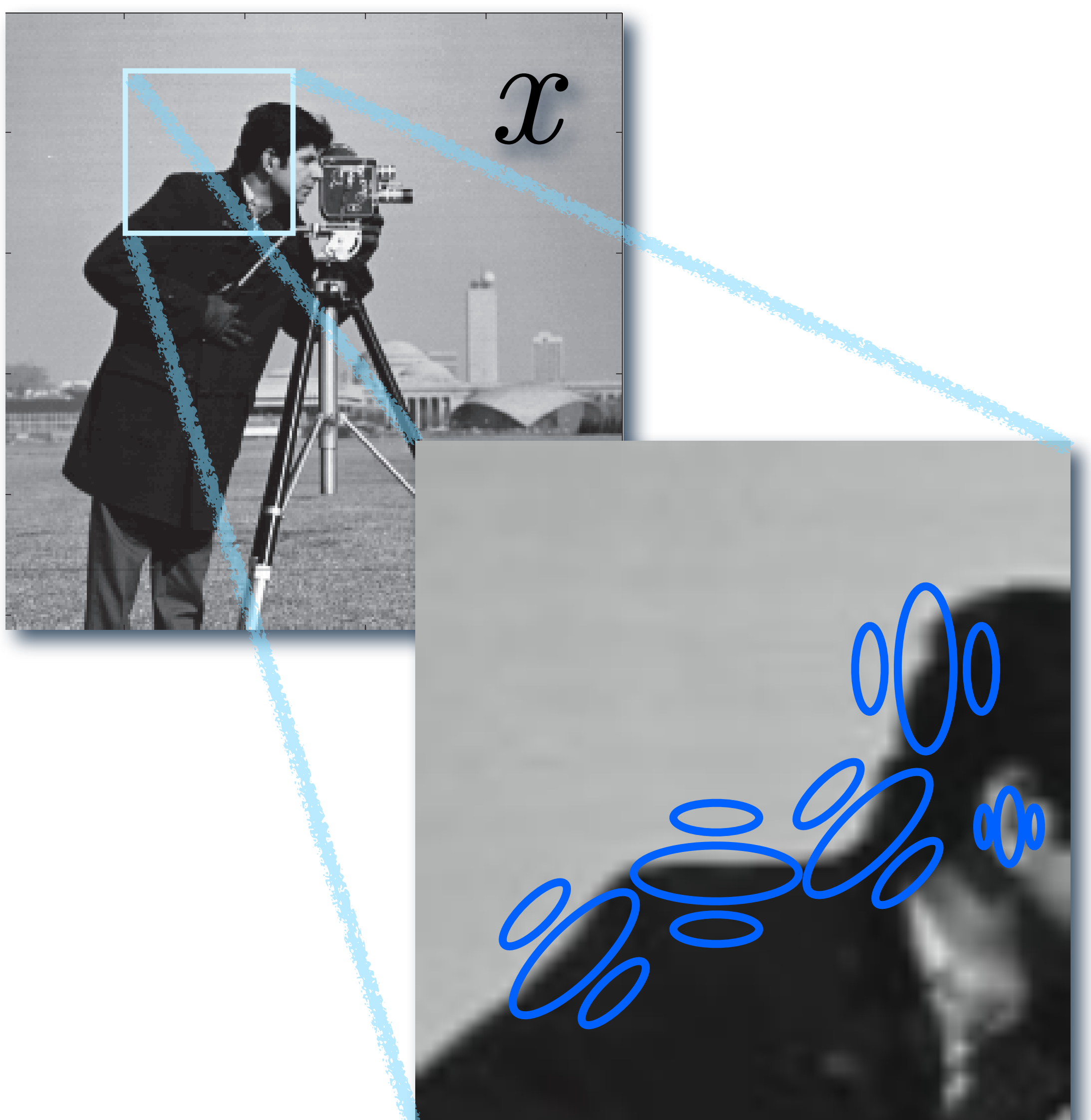

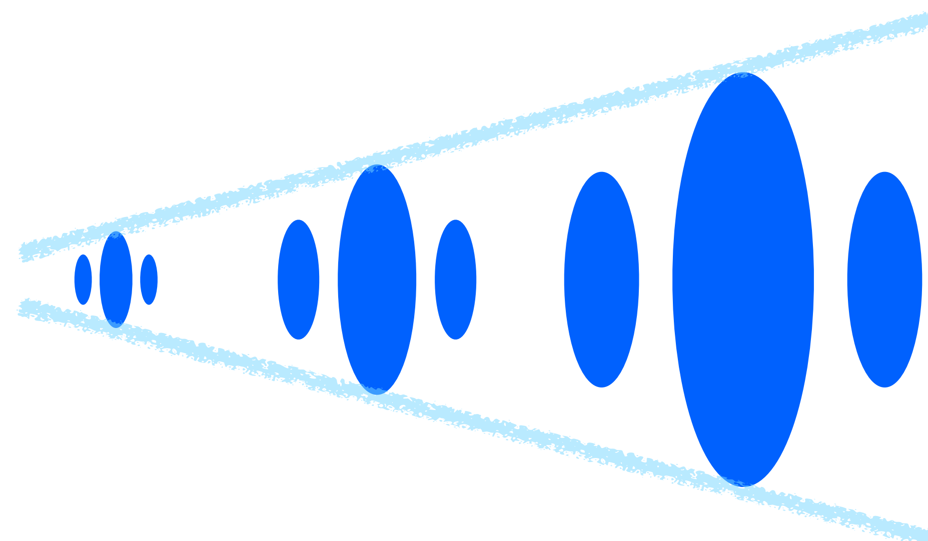

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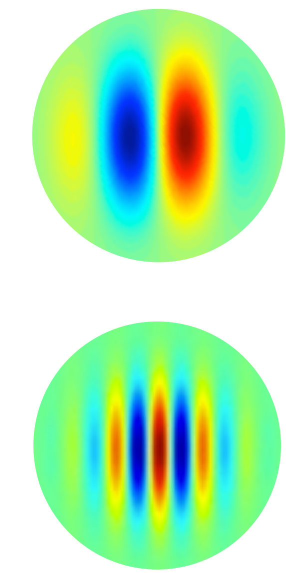

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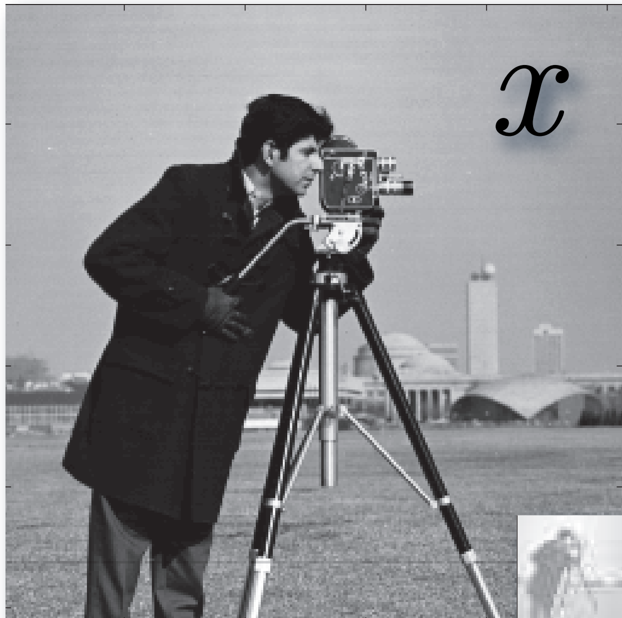
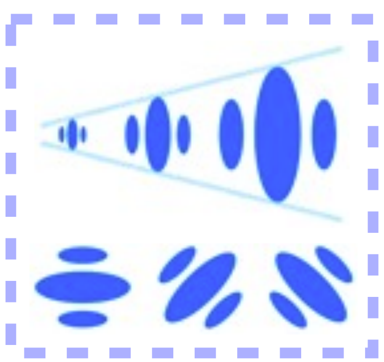
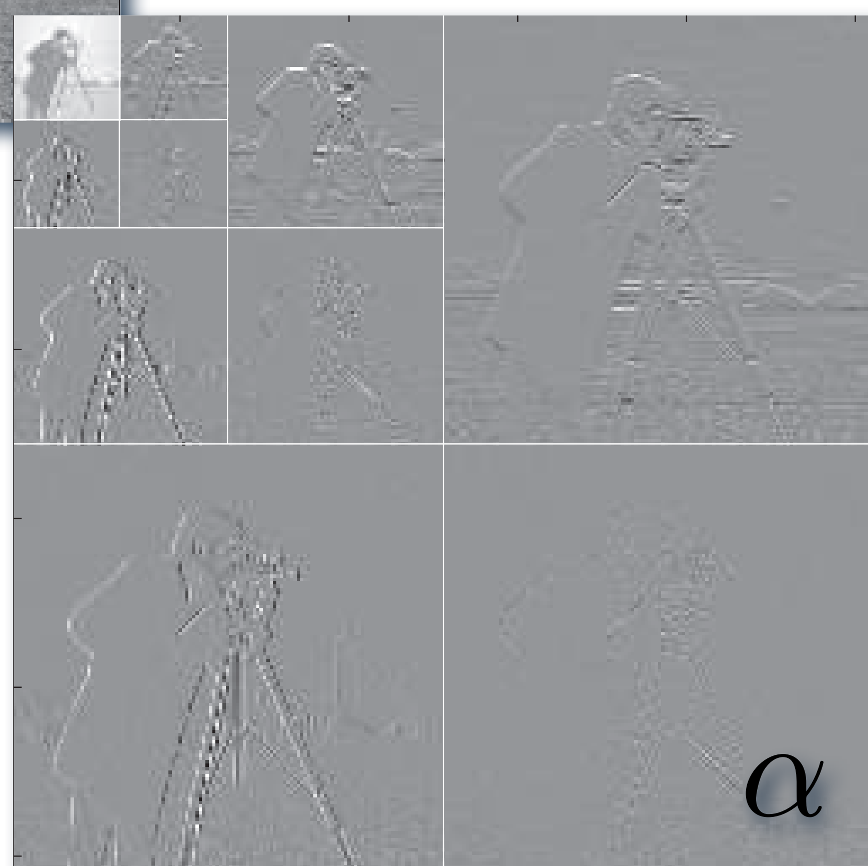


Set of coefficients in Ψ
(gray=0)

Wavelet
basis Ψ





$$\alpha \text{ s.t. } x = \sum_i \alpha_i \Psi_i$$

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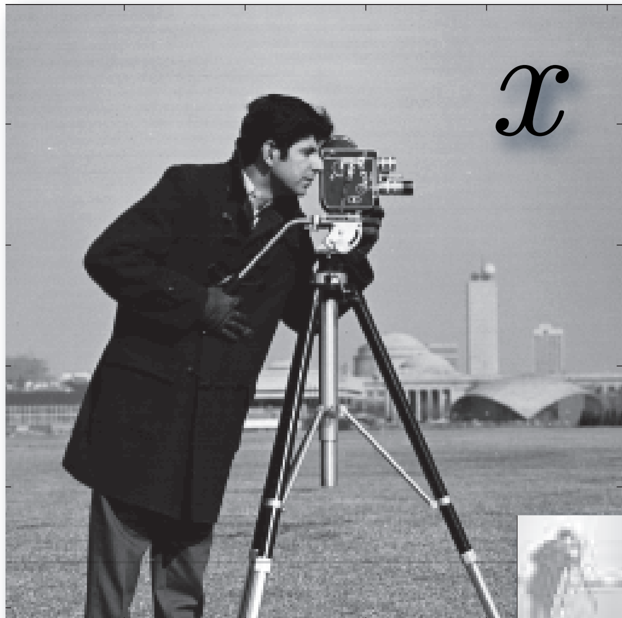

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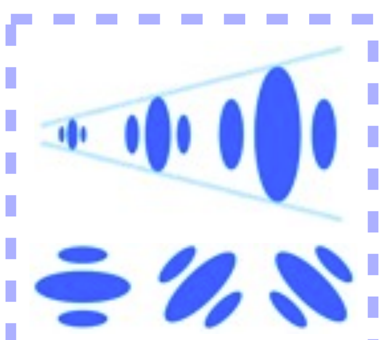

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α_K

Thresholding =
Keep K first values

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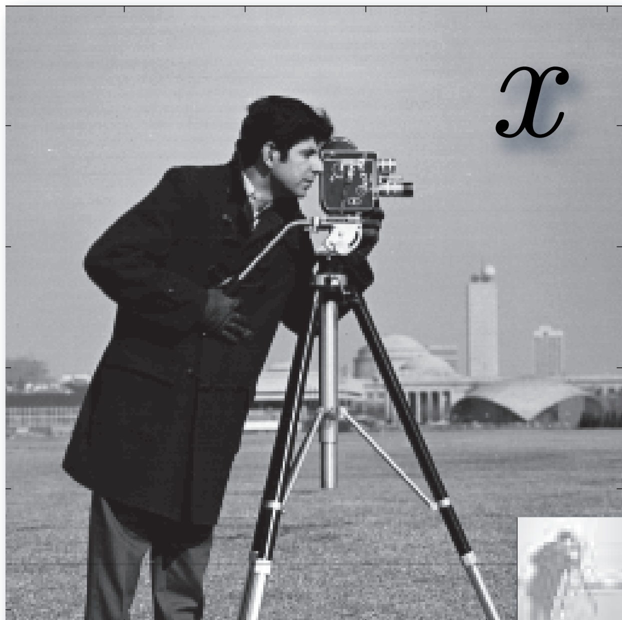

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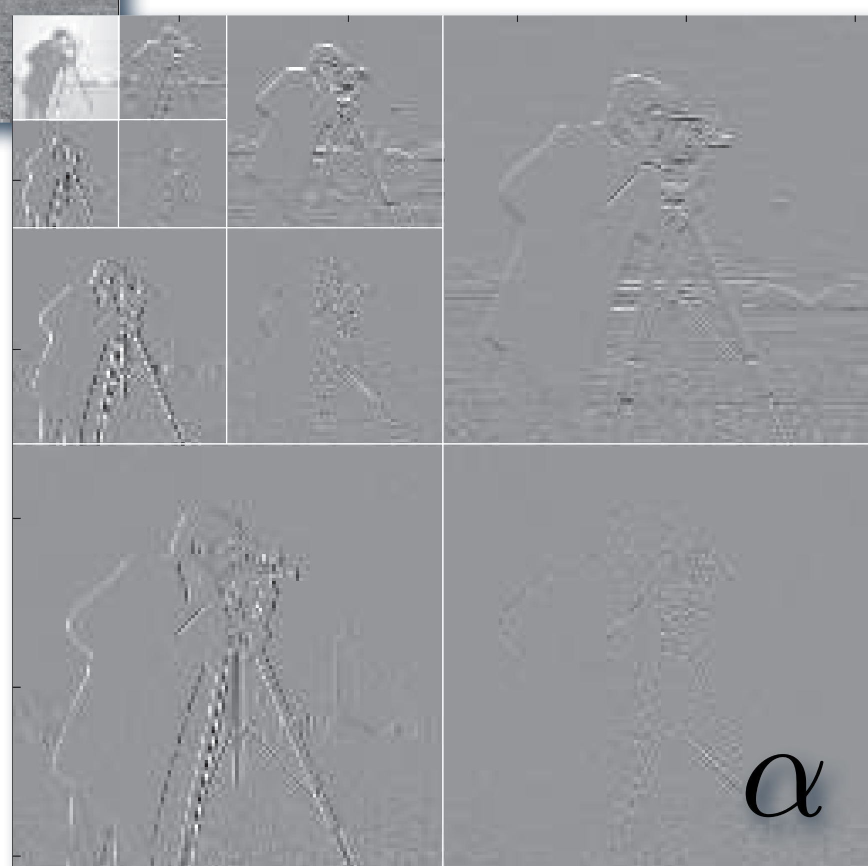

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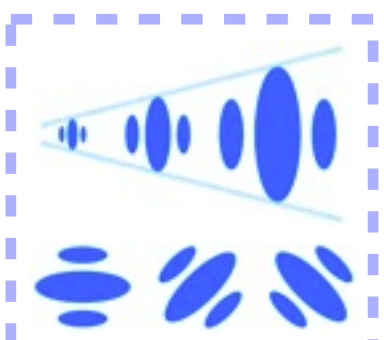

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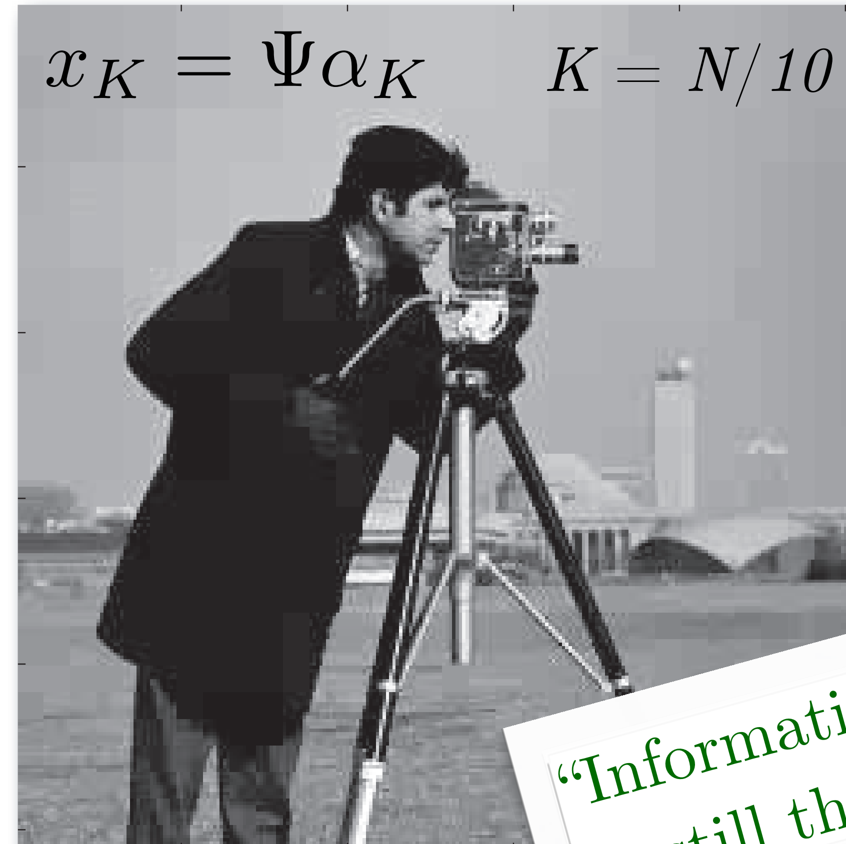

"Information" is still there!

α_K

Thresholding =
Keep K first values

Generalization: Sparsity principle

- Hypothesis: an image (or any signal) can be decomposed in a "sparsity basis" Ψ with few non-zero elements α :

$$x = \sum_{j=1}^{D} \alpha_j \Psi_j = \Psi\alpha\,, \qquad \Psi = (\Psi_1, \cdots, \Psi_D) \in \mathbb{R}^{N \times D}$$

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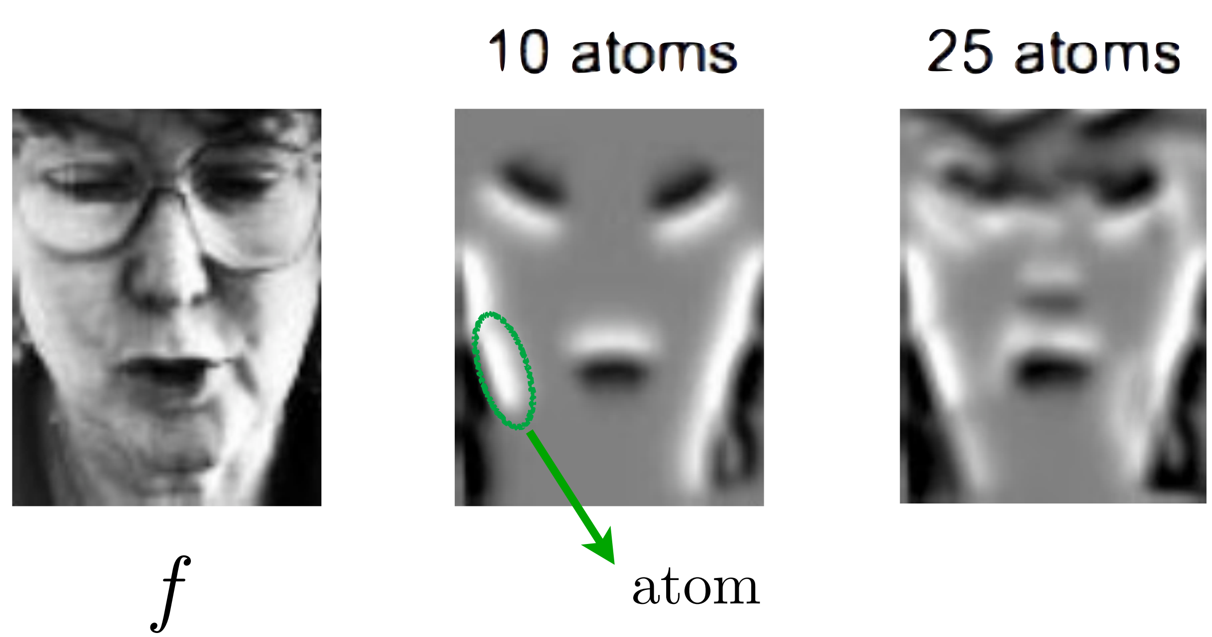

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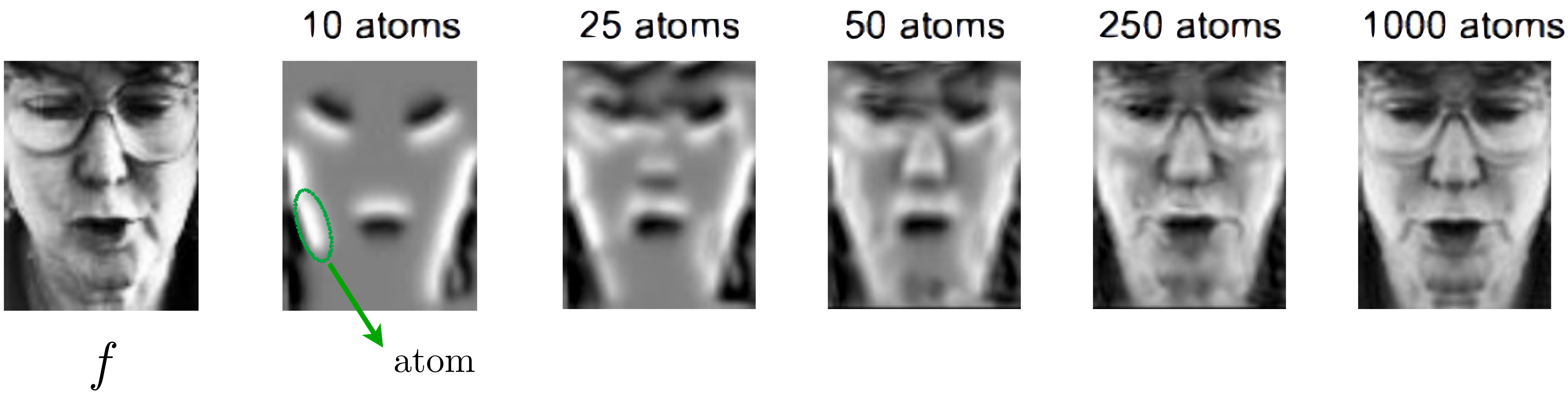

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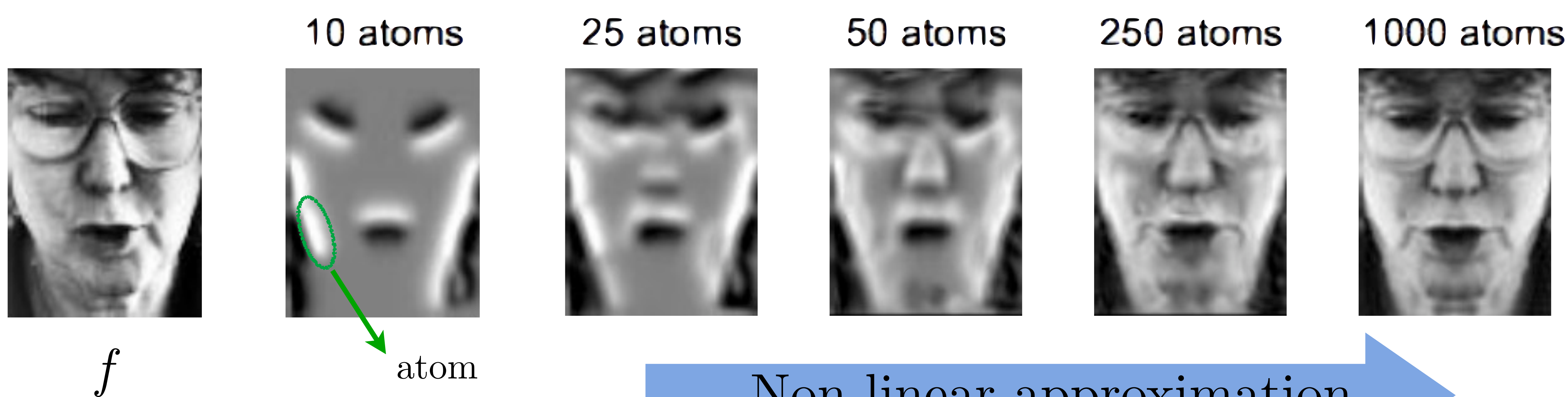


Non-linear approximation

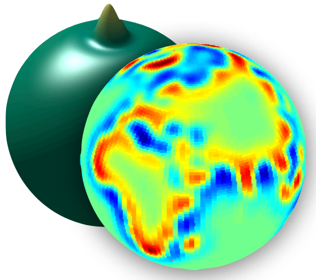
\# "atoms" ⇔ improved quality

In summary: if "information" ...

... in a signal $x \in \mathbb{R}^N$ (e.g. N = pixel number, voxels, graph nodes, ...)

there exists a "sparsity" basis (e.g. wavelets, Fourier, ...)

$$\Psi = (\Psi_1, \cdots, \Psi_D) \in \mathbb{R}^{N \times D}$$

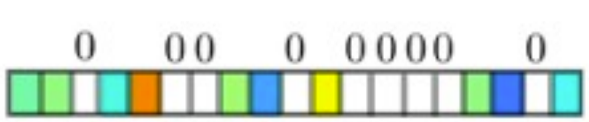


where x has a linear representation

$$x = \sum_{j=1}^{D} \alpha_j \Psi_j = \Psi \alpha$$

and

$\|\alpha\|_0 := \#\{i : \alpha_i \neq 0\} \ll N$ $\|\alpha - \alpha_K\| \ll \|\alpha\|$

$\alpha =$ 

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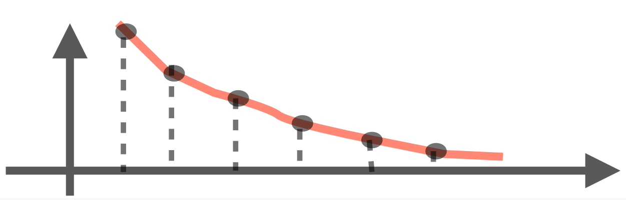

Counterexample: Noise!

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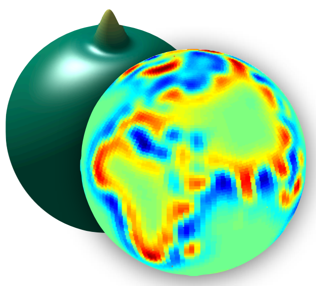

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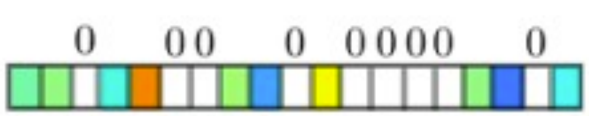
$\alpha =$ 

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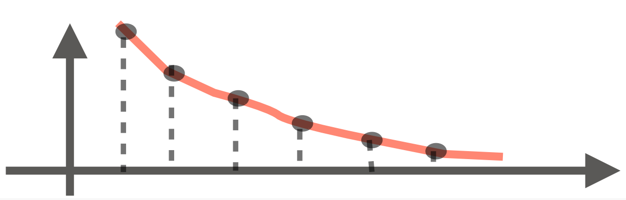

or

Small ℓ_1-norm

$\|\alpha\|_1 = \sum_i |\alpha_i|$

Counterexample: Noise!

Convex! (see after)

Other "informative" models

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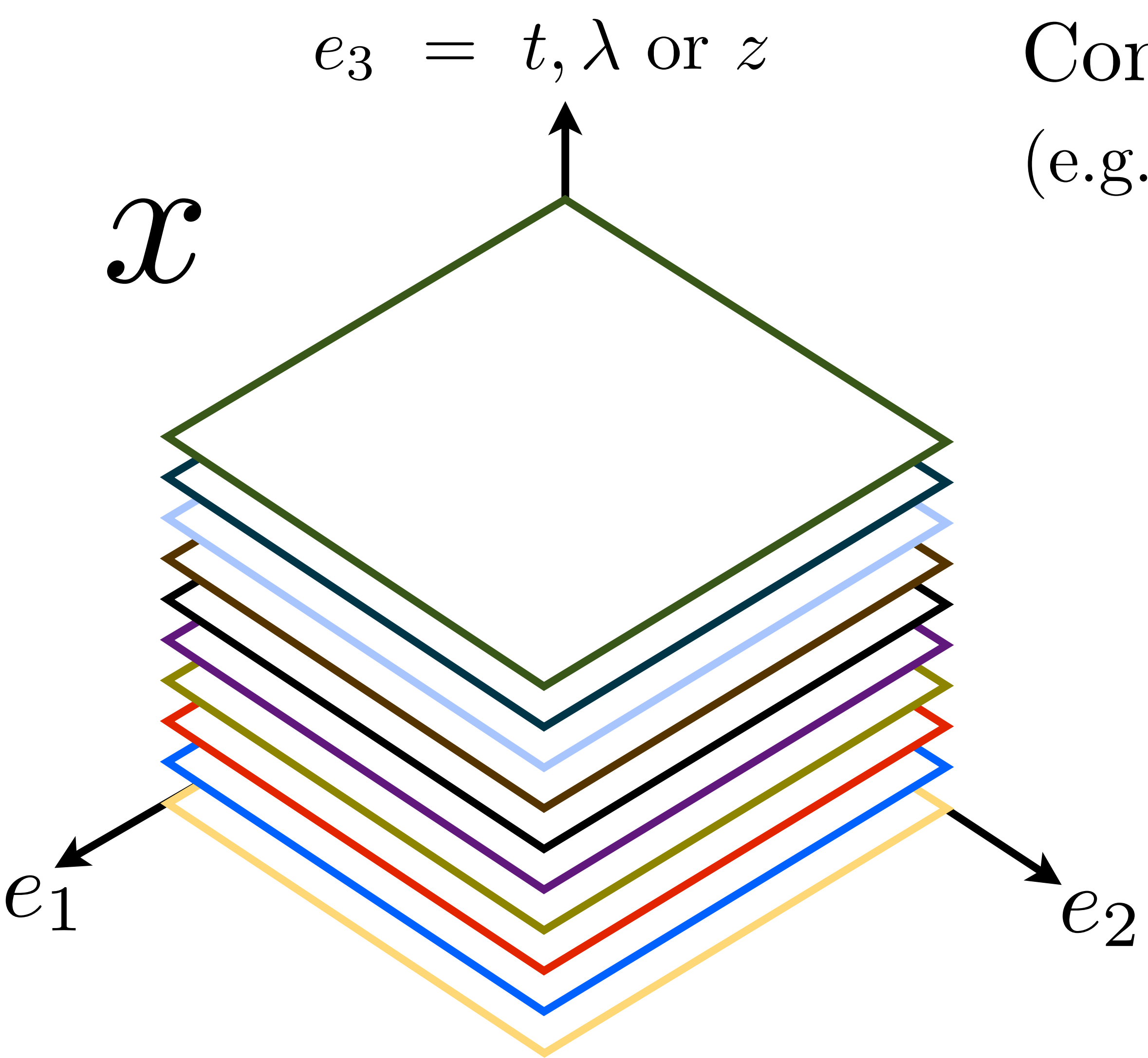
- Structured sparsity for high-dimensional data



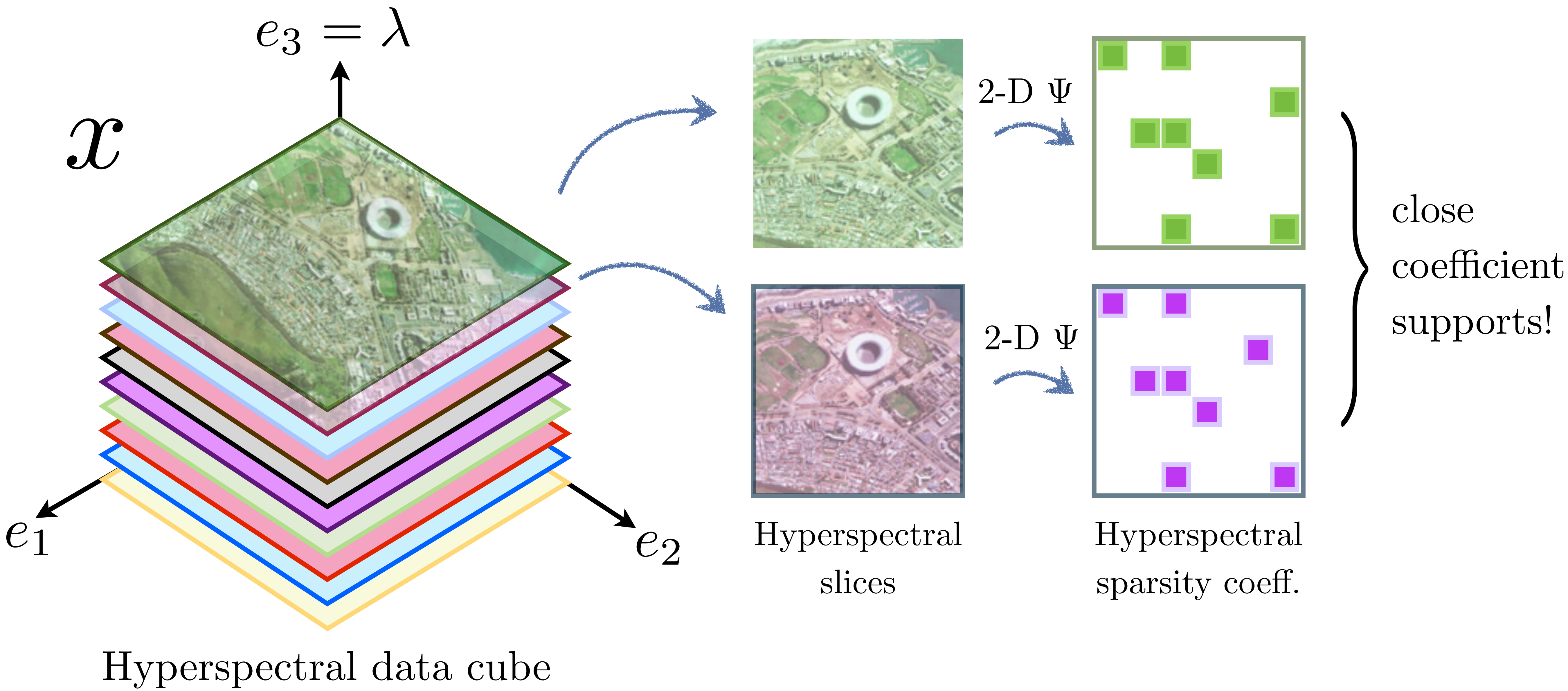
Consider a data volume (3-D or more)
(e.g. video, hyperspectral data, medical data)

Possible models:

- 3-D sparsity basis (see before)
  (sometimes costly, sometimes $\nexists$)
- or *structured sparsity*
  idea: consecutive "slices" vary "slowly"

Other "informative" models

- Structured sparsity for high-dimensional data



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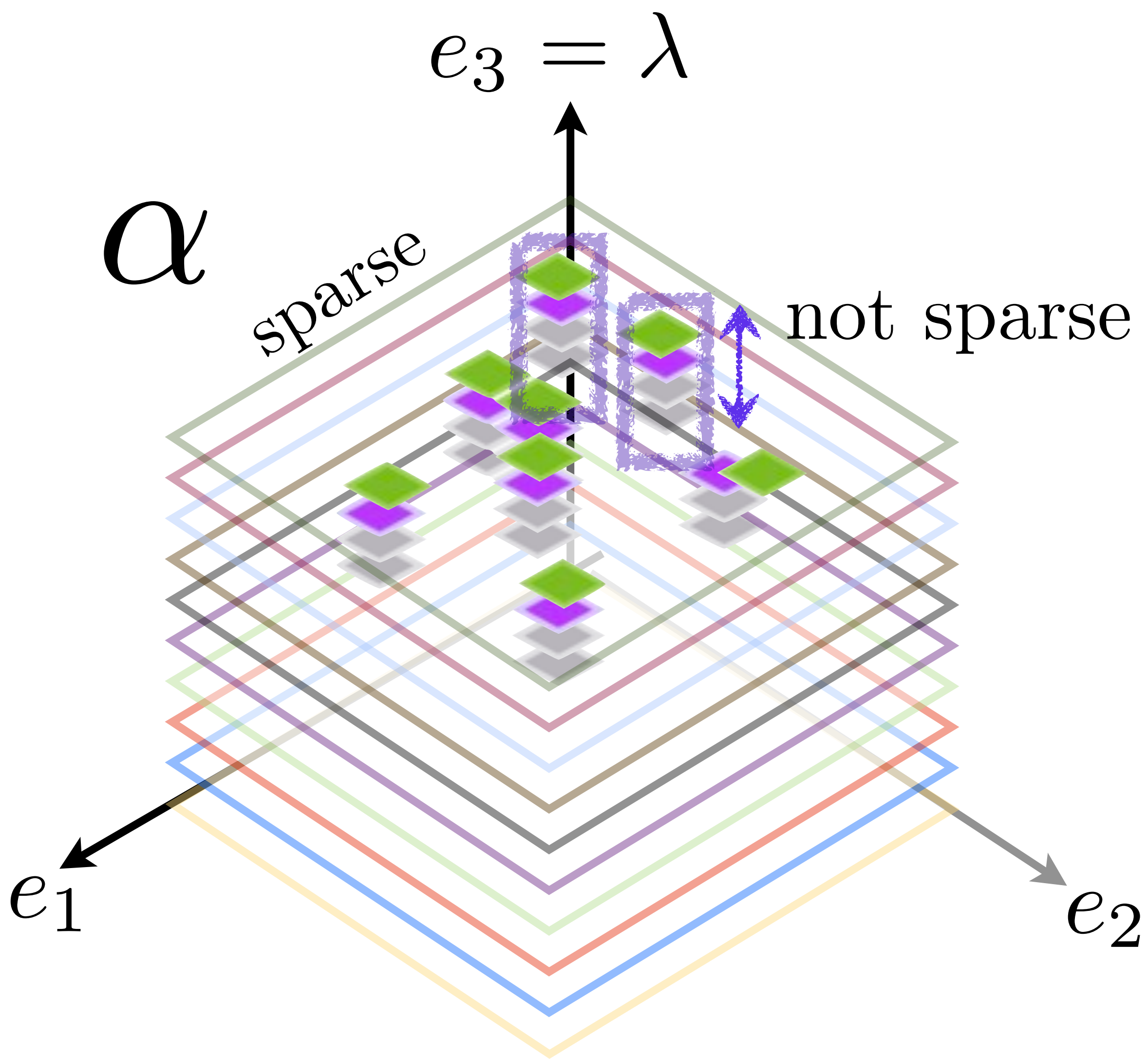
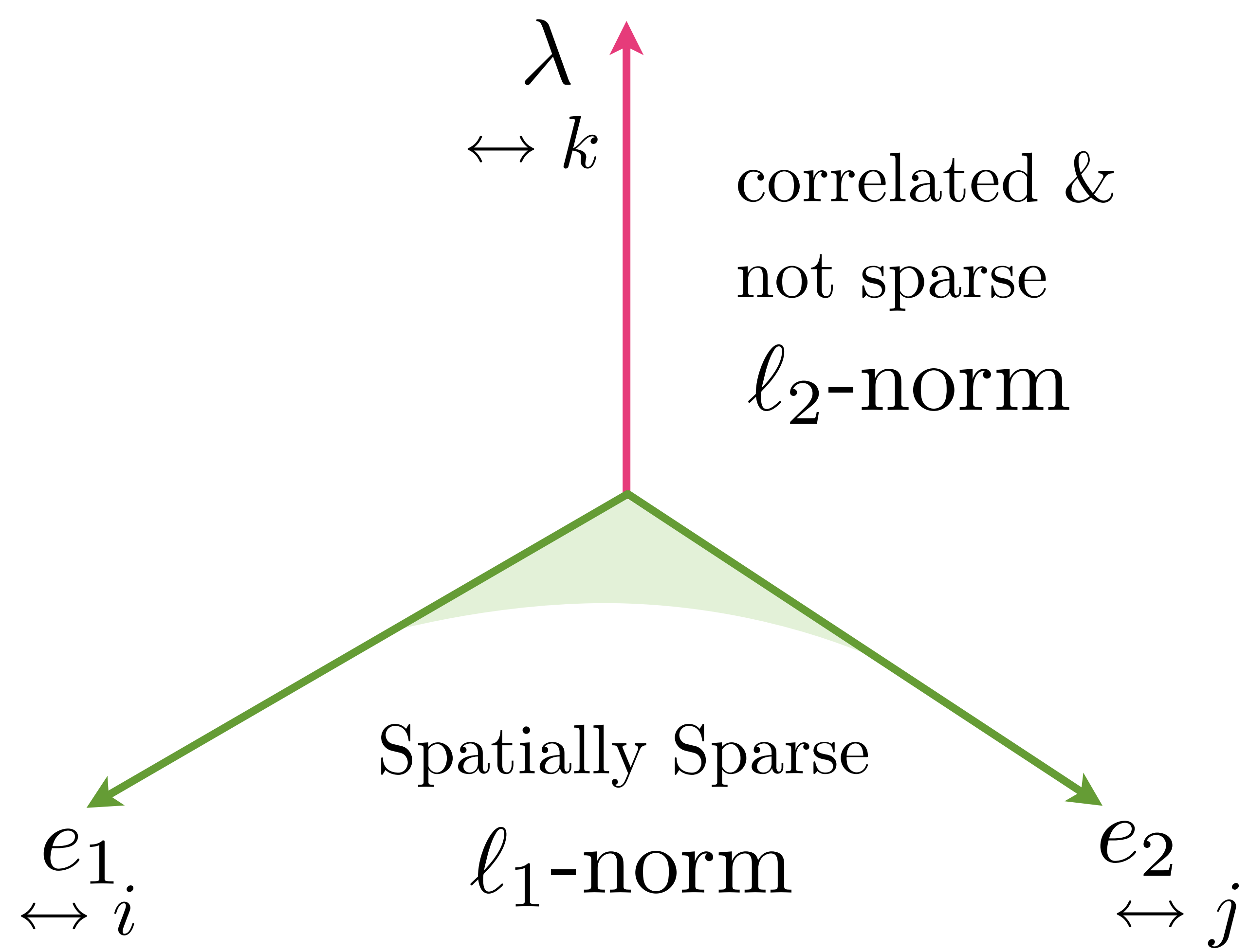


Hyperspectral sparsity coeff.



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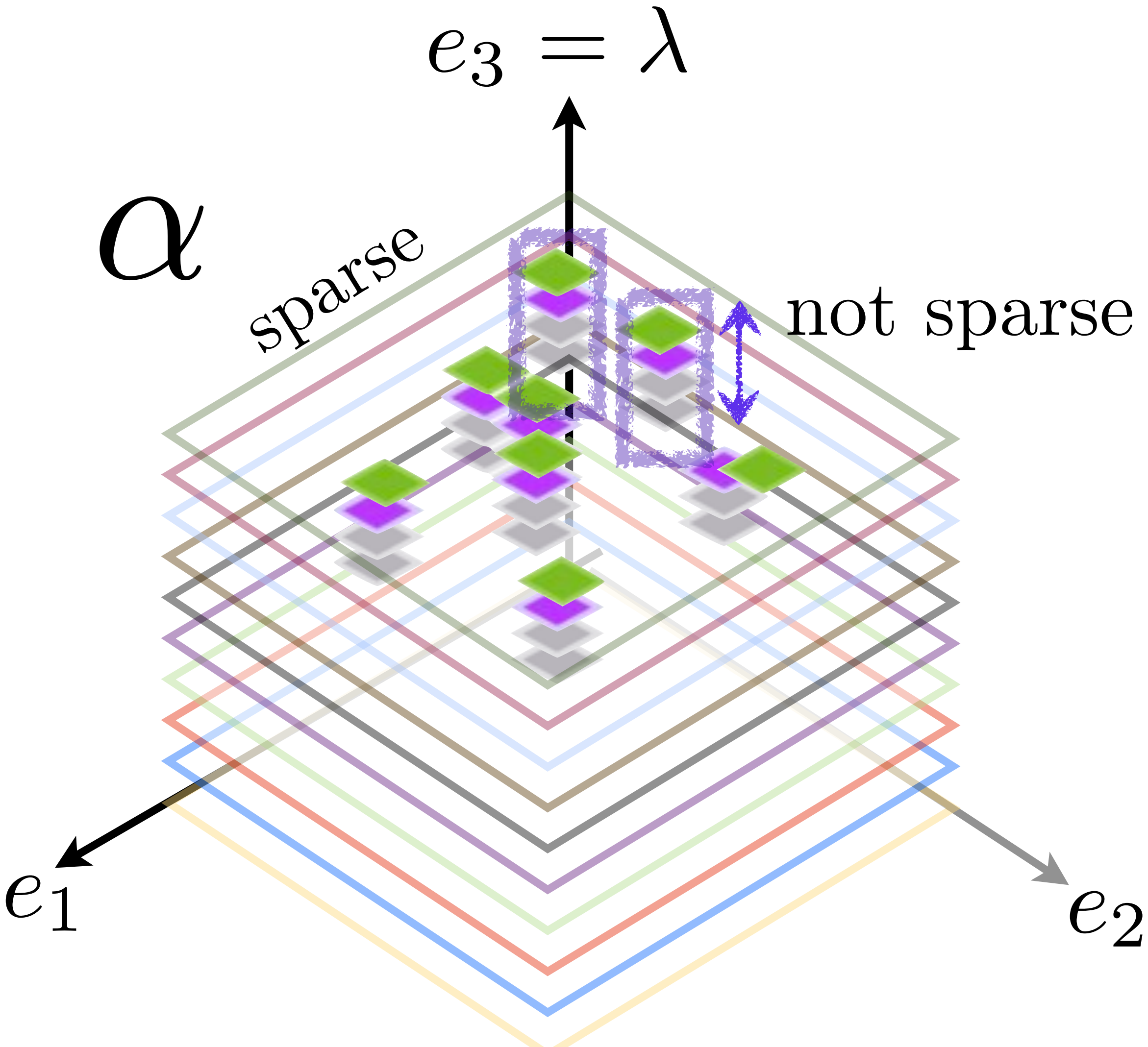

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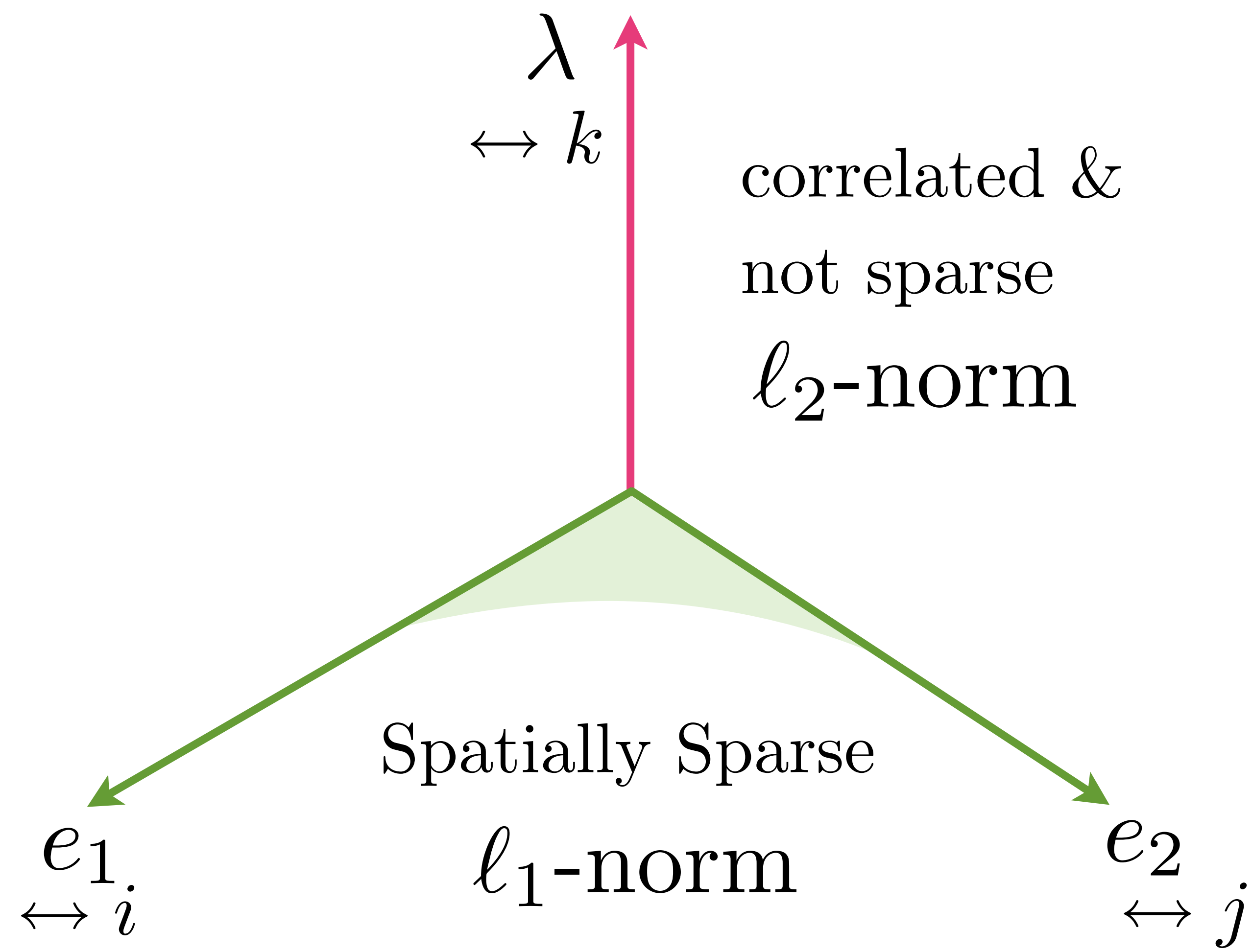


$\Rightarrow$ small $\ell_{2,1}$-norm

$$\|\alpha\|_{2,1} = \sum_{ij} \left(\sum_k |\alpha_{i,j,k}|^2\right)^{1/2}$$

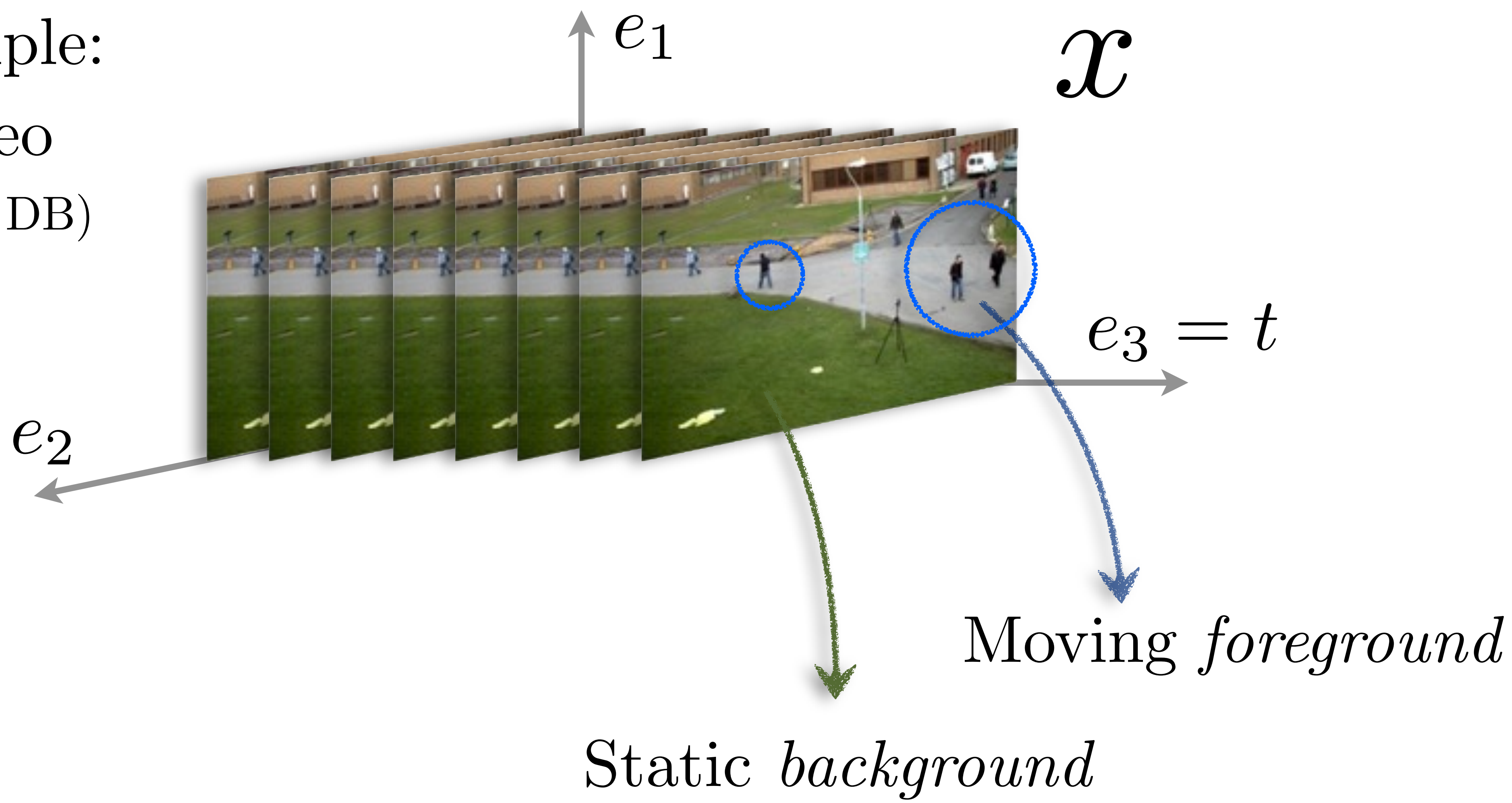
Other "informative" models

- Low-rank models in high dimensions

Example:

Video

(PETS DB)



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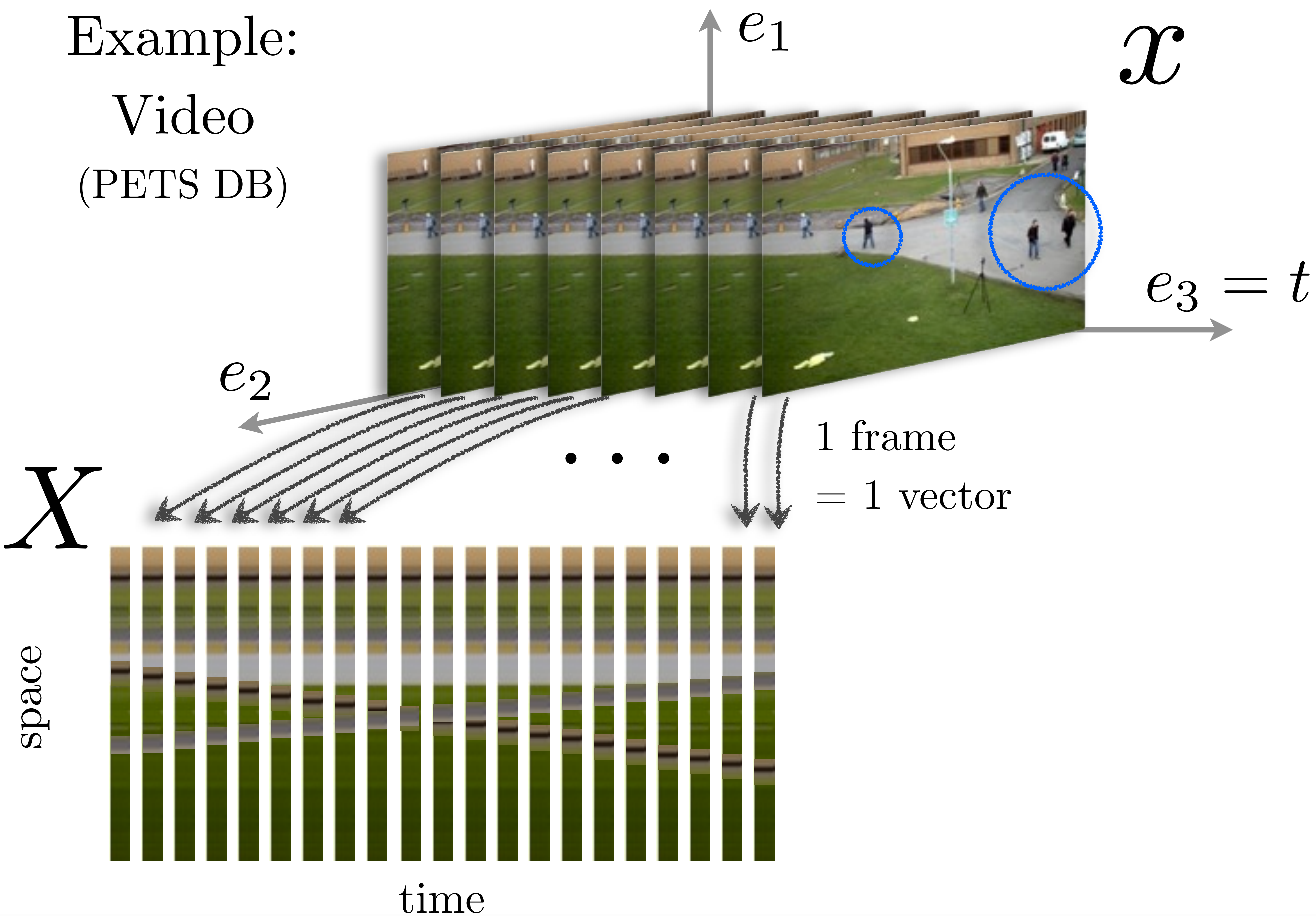

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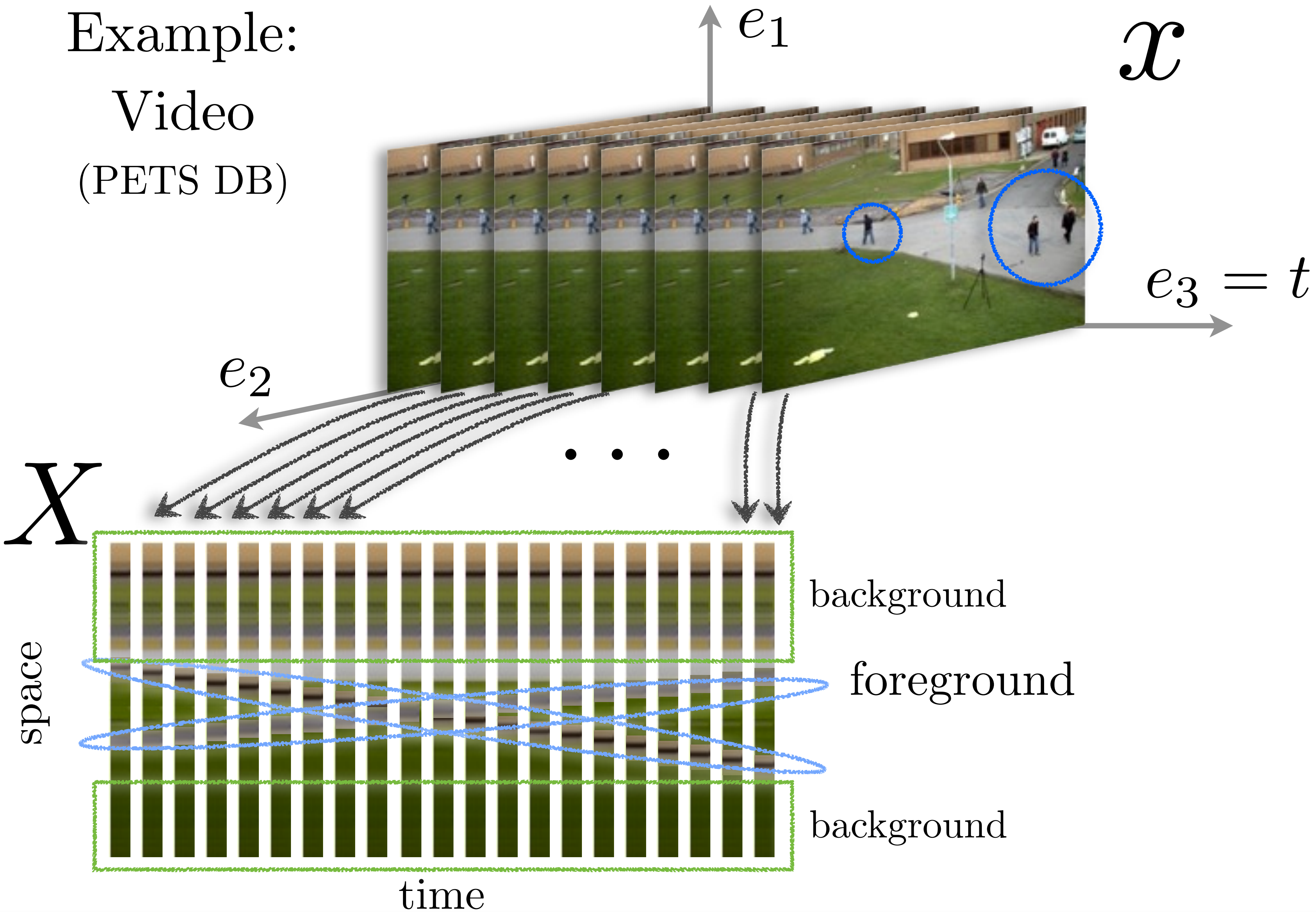

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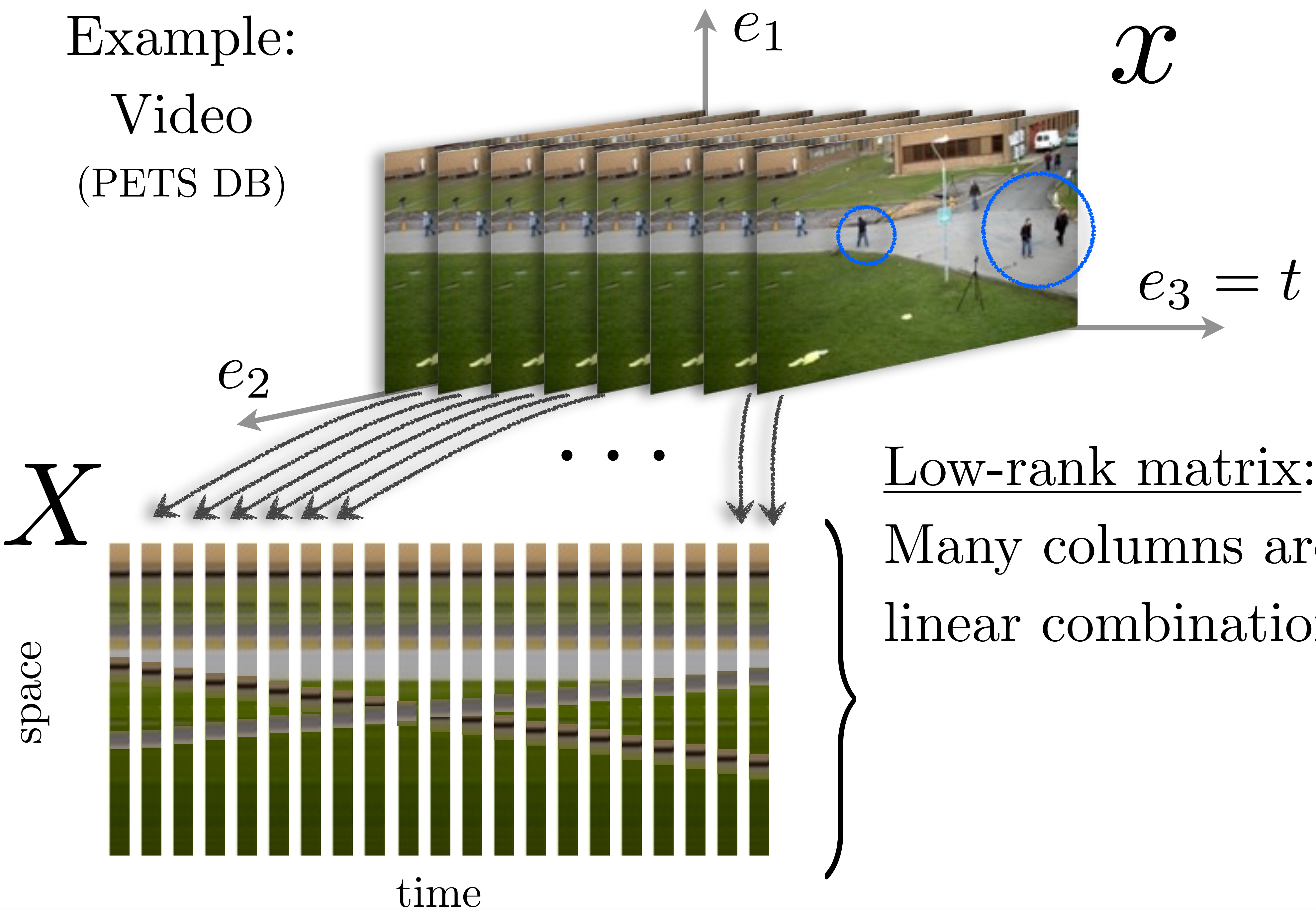

Low-rank matrix:

Many columns are (almost) linear combination of others

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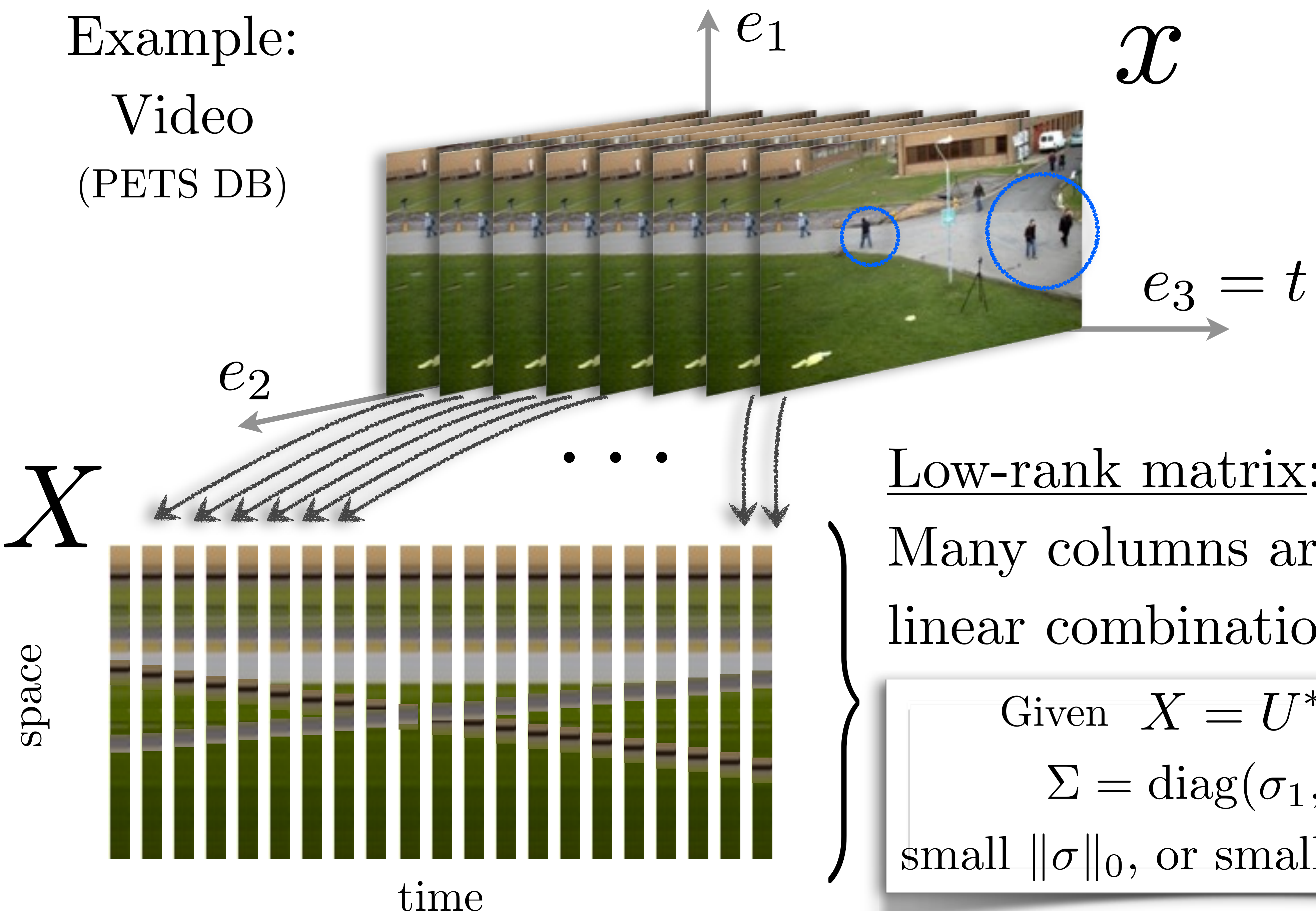


<u>Low-rank matrix</u>:

Many columns are (almost) linear combination of others

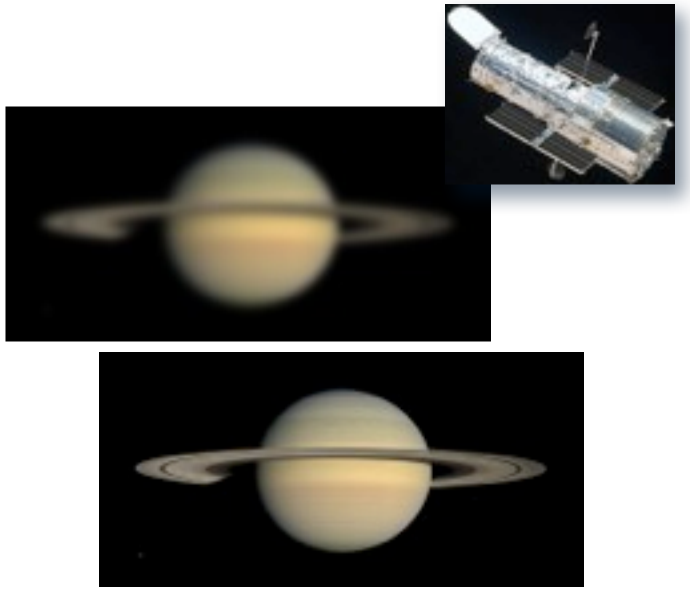
Given $X = U^* \Sigma V$ (SVD)

$$\Sigma = \mathrm{diag}(\sigma_1, \cdots, \sigma_N)$$

small $\|\sigma\|_0$, or small $\|\sigma\|_1 = \|X\|_*$

General Sparsity Applications

1. Data Compression/Transmission (by definition);
2. Data restoration :
   - Denoising,
   - Debluring,
   - Inpainting, ...



3. Simplified model and interpretation (*e.g.*, in ML)

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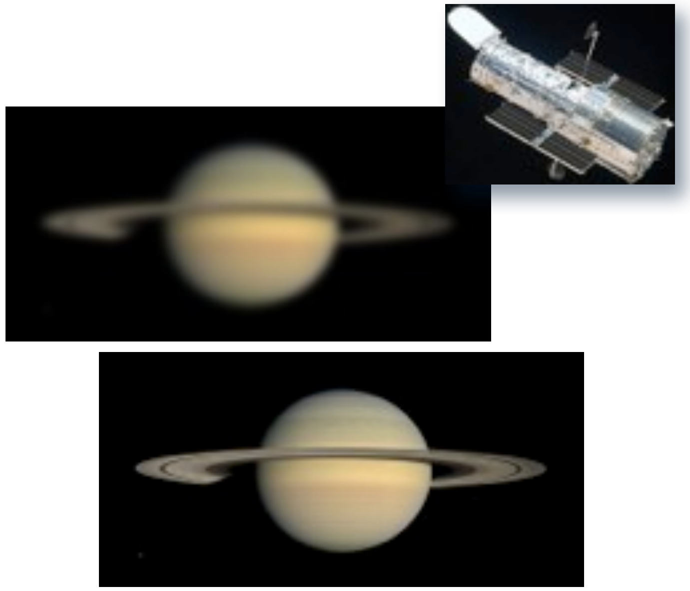


3. Simplified model and interpretation (*e.g.*, in ML)

More generally,
For regularizing (stabilizing) inverse problems
+ Impact on data sampling philosophy ! (see after)

e.g., in Ivo's talk

First Part:

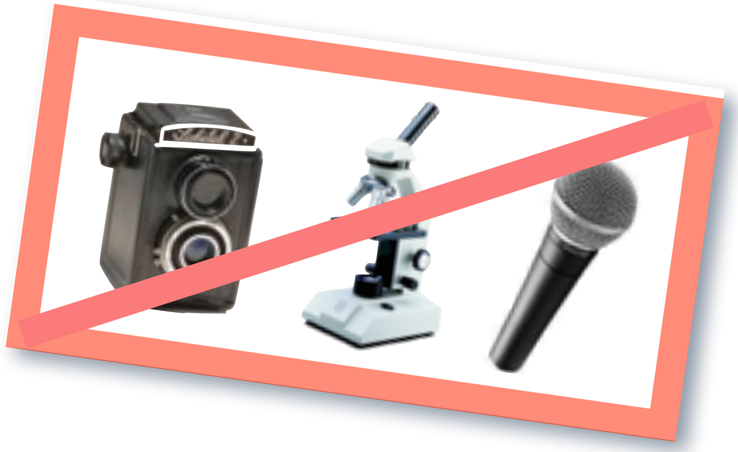
- Sparsity, low-rankness and relatives:
  "From information to structures"

- Compress while you sample:
  "From structure to scrambled sensing"

- and Reconstruct!
  "From scrambled sensing to information"

Sampling with Sparsity

- Paradigm shift:
  "Computer readable" sensing
  + prior information (structures)

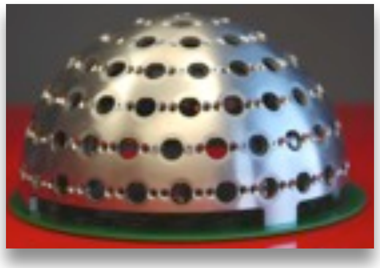


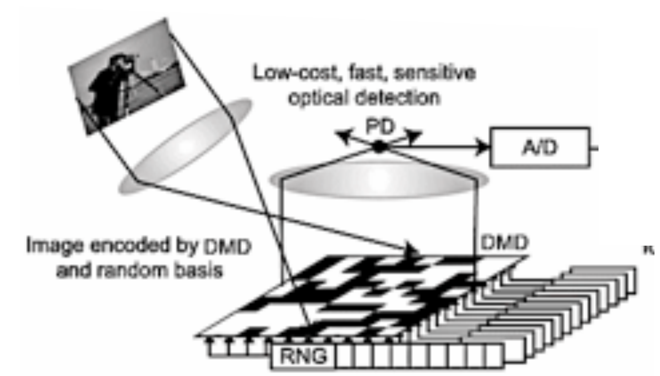
Sampling with Sparsity

- Paradigm shift:
  "Computer readable" sensing
  + prior information (structures)

World → Signal → Sensing Device → Sensing →  → Signal → Human

Optimized setup: sampling rate $\propto$ information





- Examples:
  Radio-Interferometry, Compressed Sensing, MRI, Deflectometry, Seismology, ...

Sampling with Sparsity

but ... non-linear reconstruction schemes!

Regularized inverse problems:

Reconstruct $x \in \mathbb{R}^N$ from $y = \text{Sensing}(x) \in \mathbb{R}^M$ given a sparse model on x.

Examples: Tomography, frequency/partial observations, ...

$$x^* = \underset{u \in \mathbb{R}^N}{\text{argmin}}\ \mathcal{S}(u) \text{ s.t. } \text{Sensing}(u) \approx \text{Sensing}(x)$$

Sparsity metric:

e.g., small $\mathcal{S}(\alpha) = \|\alpha\|_1$ if $u = \Psi\alpha$,
small Total Variation $\mathcal{S}(u) = \|\nabla u\|$

Noise: Gaussian, Poisson, ...

Compressed Sensing

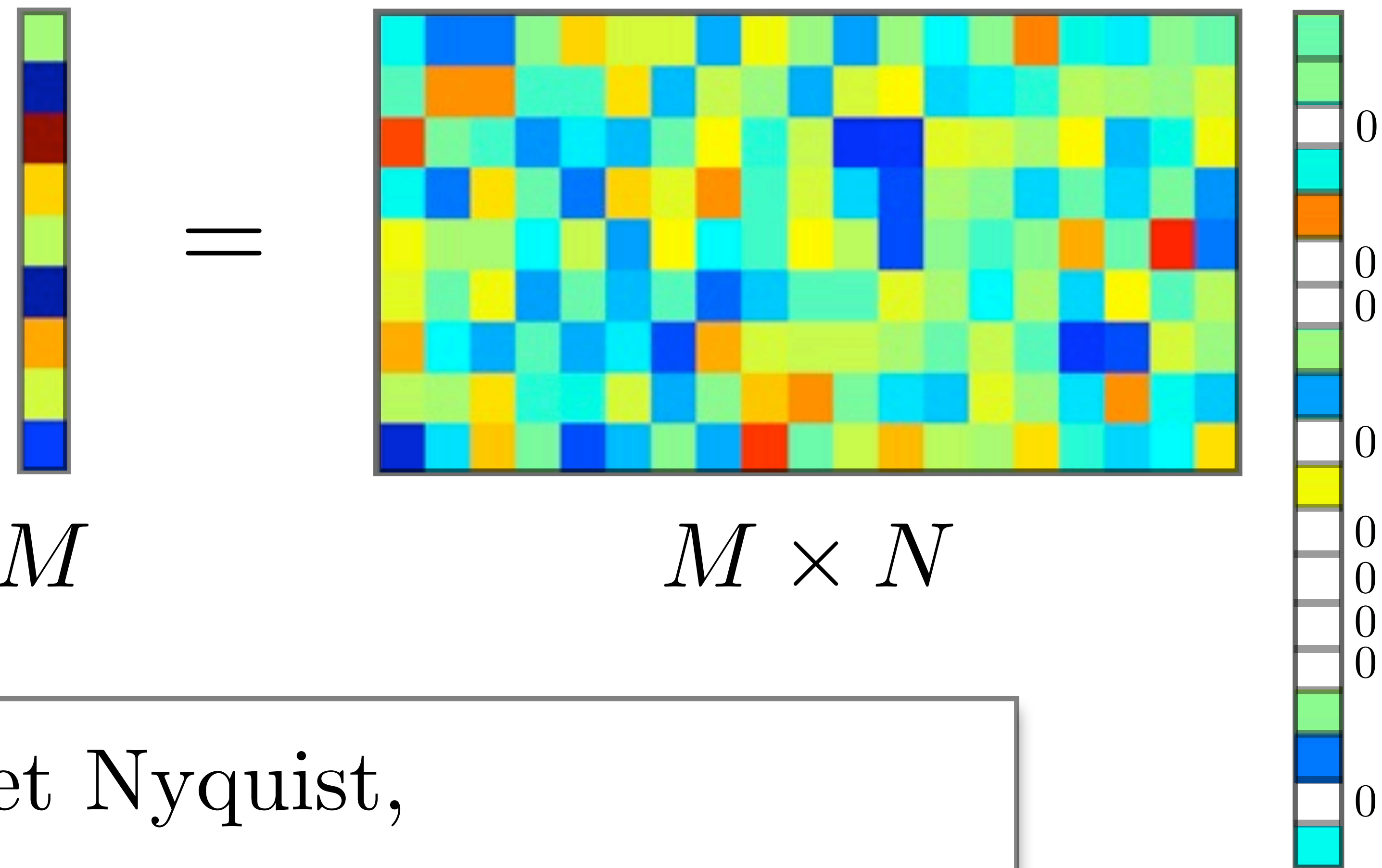
CS in a nutshell:

"Forget" Dirac, forget Nyquist,
ask *few* (linear) *questions*
about your informative (sparse) signal,
and recover it *differently* (non-linearly)"

Compressed Sensing

M questions — Sensing method — Signal

$\boldsymbol{y}$ — $\boldsymbol{\Phi}$ — $\boldsymbol{x}$



M — $M \times N$ — N

Sparsity Prior ($\Psi = \mathrm{Id}$)

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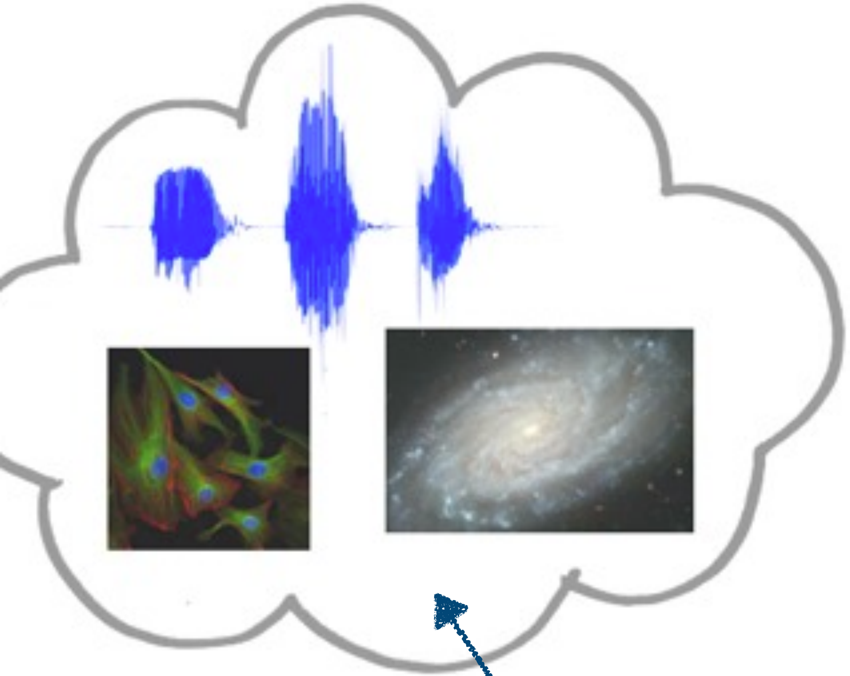
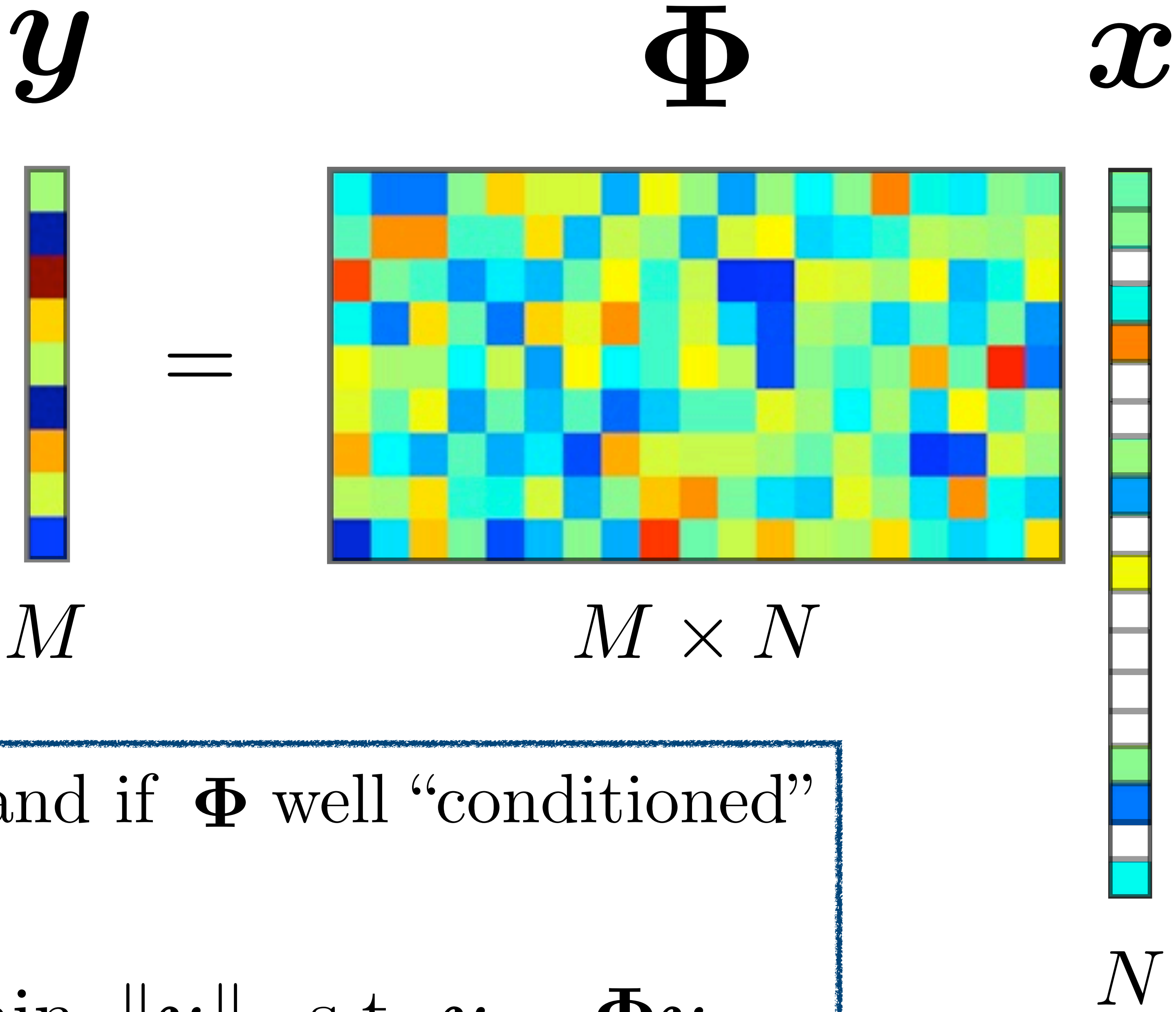
Low complexity signal



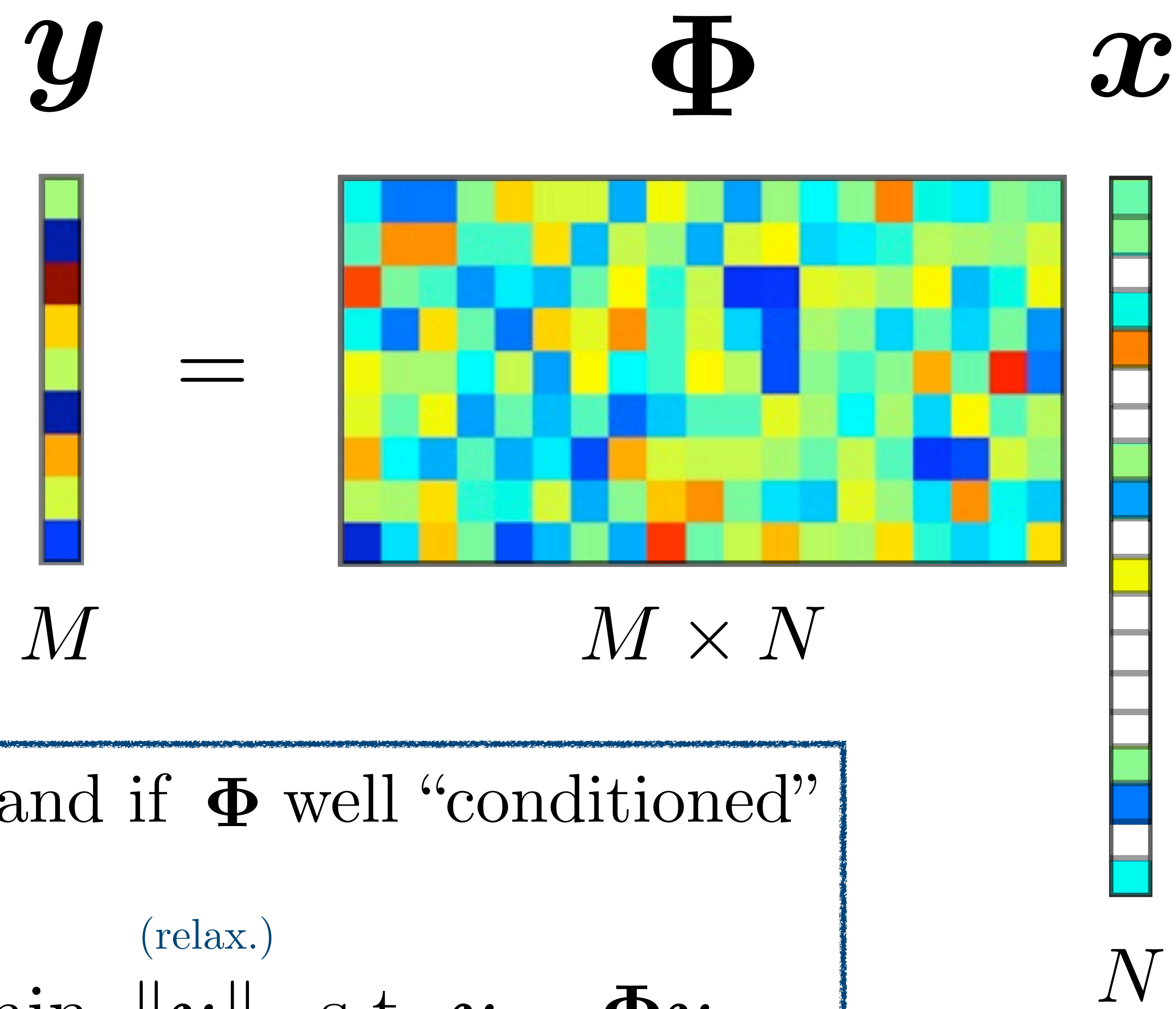


If $\boldsymbol{x}$ is K-sparse and if $\boldsymbol{\Phi}$ well "conditioned" then:

$$\boldsymbol{x}^* = \underset{\boldsymbol{u} \in \mathbb{R}^N}{\arg\min} \; \|\boldsymbol{u}\|_0 \text{ s.t. } \boldsymbol{y} = \boldsymbol{\Phi u}$$

$\|\boldsymbol{u}\|_0 = \#\{j : u_j \neq 0\}$ **Non-linear reconstruction**

Compressed Sensing



If $\boldsymbol{x}$ is K-sparse and if $\boldsymbol{\Phi}$ well "conditioned" then:

(relax.)

$$\boldsymbol{x}^* = \mathop{\arg\min}_{\boldsymbol{u}\in\mathbb{R}^N} \|\boldsymbol{u}\|_{\not{0}\;1} \ \text{s.t.}\ \boldsymbol{y} = \boldsymbol{\Phi}\boldsymbol{u}$$

$\|\boldsymbol{u}\|_1 = \sum_j |u_j|$

(Basis Pursuit) [Chen, Donoho, Saunders, 1998]

Compressed Sensing

$\exists\, \delta \in (0,1)$ Restricted Isometry Property

$$\sqrt{1-\delta}\,\|\boldsymbol{v}\|_2 \;\leqslant\; \|\boldsymbol{\Phi v}\|_2 \;\leqslant\; \sqrt{1+\delta}\,\|\boldsymbol{v}\|_2$$

for all $2K$ sparse signals $\boldsymbol{v}$.

any subset of $2K$ columns is an *isometry*

If $\boldsymbol{x}$ is K-sparse and if $\boldsymbol{\Phi}$ well "conditioned"

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(relax.)

$$\boldsymbol{x}^* = \underset{\boldsymbol{u}\in\mathbb{R}^N}{\arg\min}\; \|\boldsymbol{u}\|_{\cancel{0}\,1} \text{ s.t. } \boldsymbol{y} = \boldsymbol{\Phi u}$$

if $\delta < \sqrt{2}-1$ [Candes 08]

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for all $2K$ sparse signals $\boldsymbol{v}$.

any subset of $2K$ columns is an *isometry*

Examples:

+ Gaussian
+ Bernoulli
+ Random Fourier
+ ....

$M = O(K \ln N/K) \ll N$

$\boldsymbol{\Phi} \in \mathbb{R}^{M\times N}$, $\Phi_{ij} \sim_{\rm iid} \mathcal{N}(0,1)$

If $\boldsymbol{x}$ is K-sparse and if $\boldsymbol{\Phi}$ well "conditioned" then:

(relax.)

$$\boldsymbol{x}^* = \underset{\boldsymbol{u}\in\mathbb{R}^N}{\arg\min}\ \|\boldsymbol{u}\|_{\cancel{0}\,1} \ \text{s.t.}\ \boldsymbol{y} = \boldsymbol{\Phi u}$$

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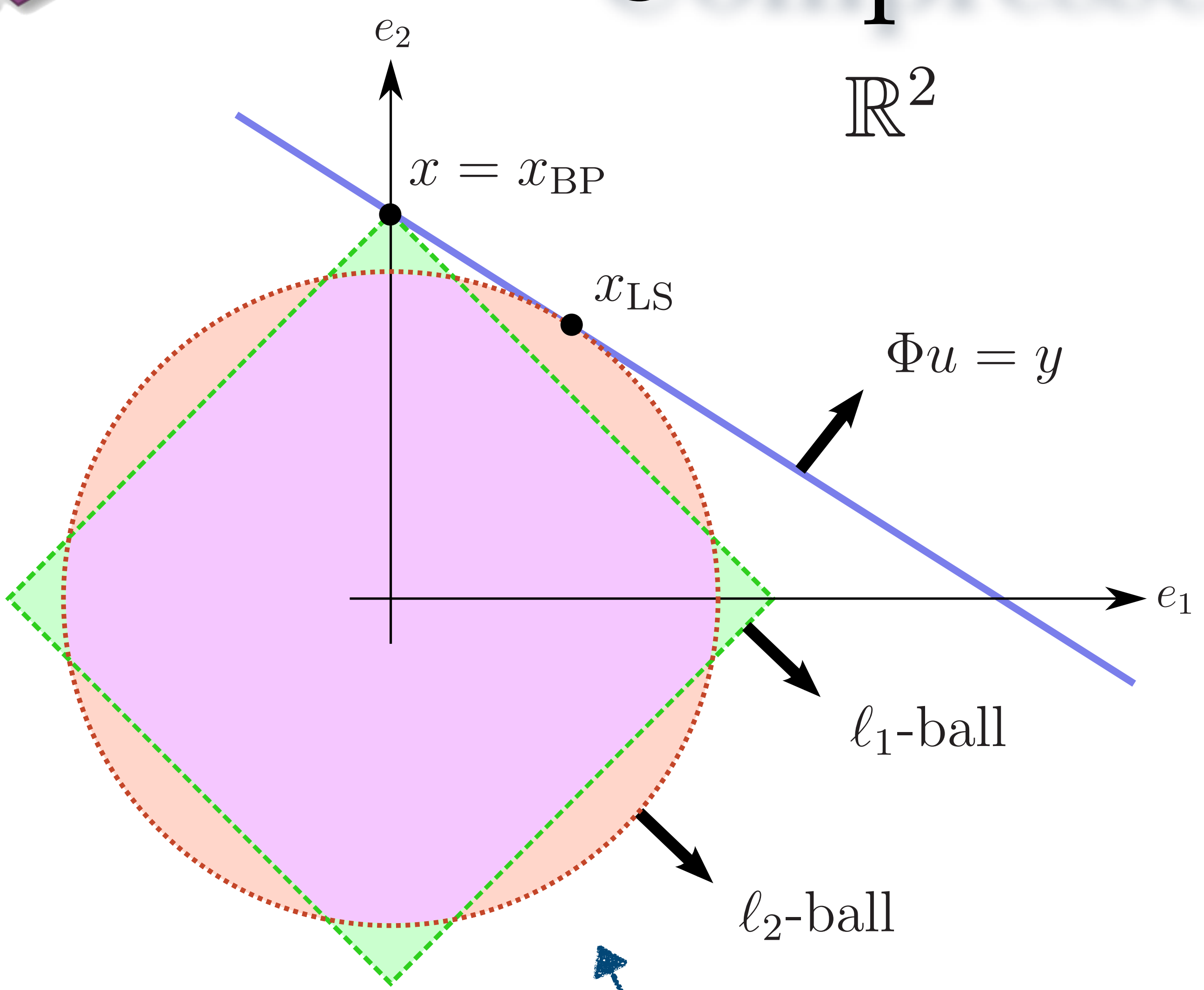

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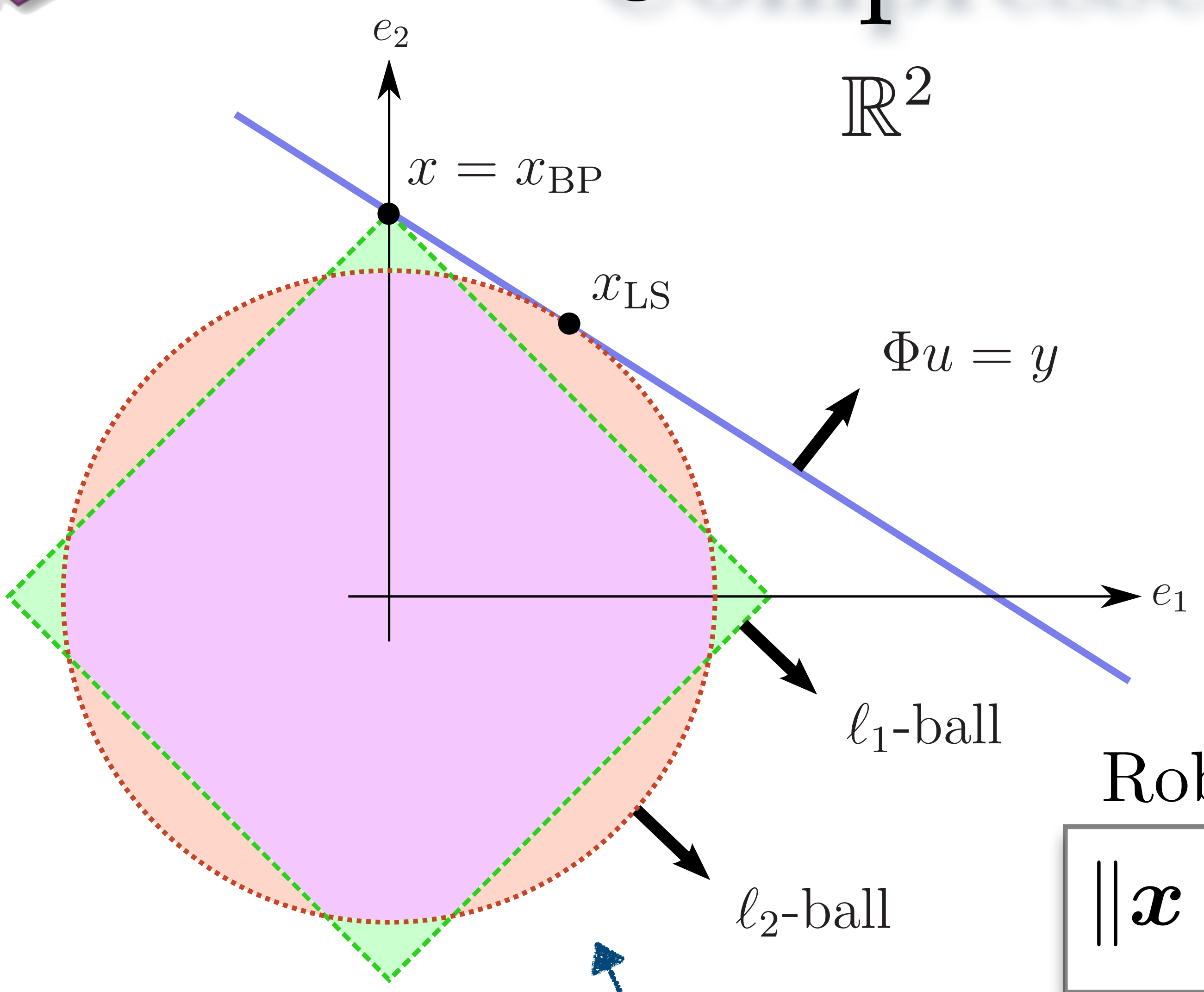
(Basis Pursuit) [Chen, Donoho, Saunders, 1998]

Solvers:

Linear Programming,
Interior Point Method,
Proximal Methods,
... **Tons** of toolboxes ...

Compressed Sensing



Robustness: *vs* sparse deviation + noise.

$$\|\boldsymbol{x} - \boldsymbol{x}^*\| \leqslant C \frac{1}{\sqrt{K}} \|\boldsymbol{x} - \boldsymbol{x}_K\|_1 + D\epsilon$$

If $\boldsymbol{x}$ is K-sparse and if $\boldsymbol{\Phi}$ well "conditioned" then:

$\|\boldsymbol{y} - \boldsymbol{\Phi u}\| \leqslant \epsilon$

(relax.)

$$\boldsymbol{x}^* = \underset{\boldsymbol{u} \in \mathbb{R}^N}{\arg\min} \ \|\boldsymbol{u}\|_{\not 0 \; 1} \ \text{s.t.} \ \boldsymbol{y} = \boldsymbol{\Phi u}$$

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(Basis Pursuit) [Chen, Donoho, Saunders, 1998]

Solvers:

Linear Programming,
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Proximal Methods,
... **Tons** of toolboxes ...

... in summary, CS is

$M = O(K \log N/K)$

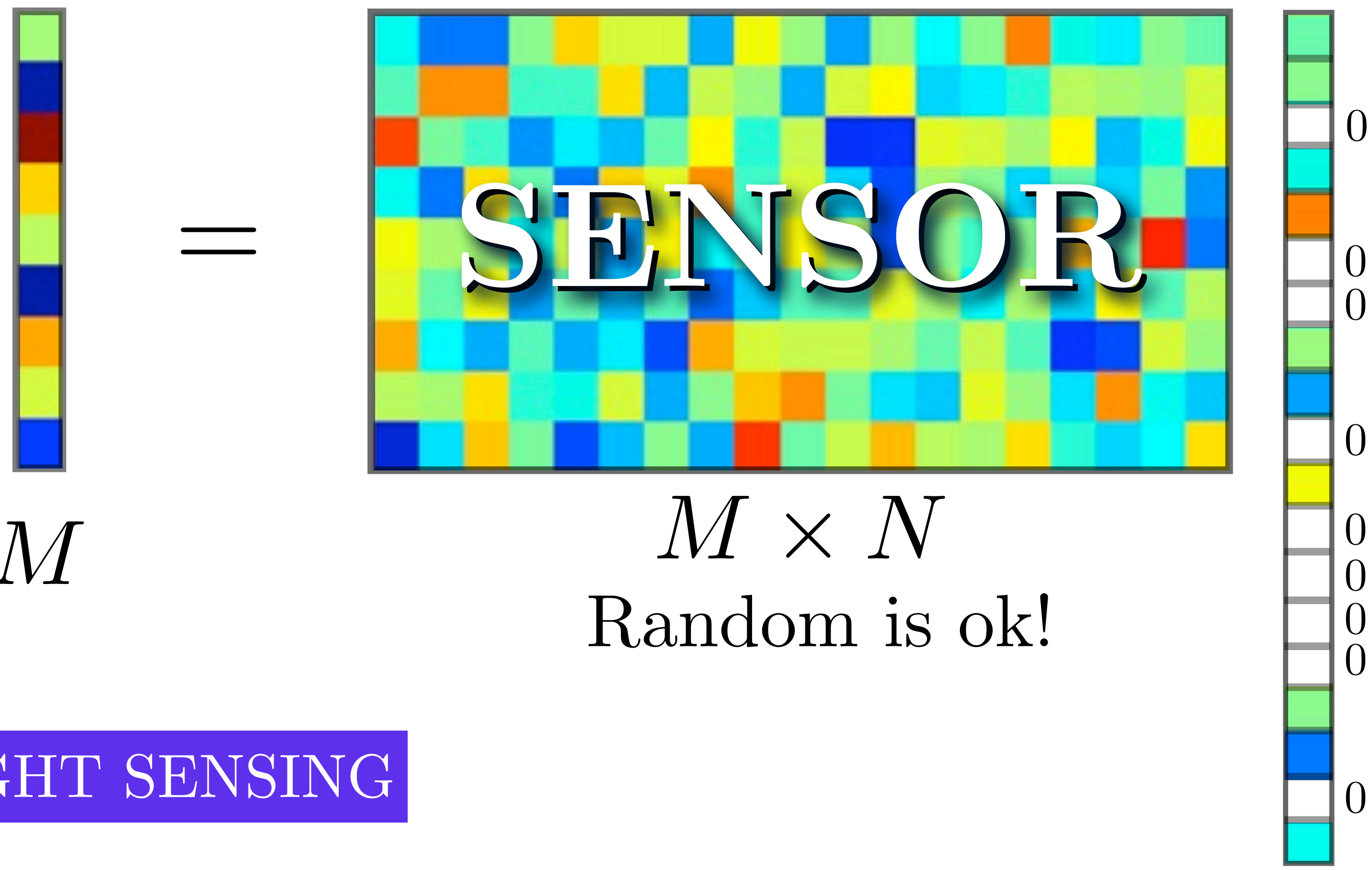
$\boldsymbol{x}$

or $\boldsymbol{x}^* \simeq \boldsymbol{x}$

if noise, quantization, non-linearities

M questions — Sensing method — Signal

$\boldsymbol{y} = \boldsymbol{\Phi} \boldsymbol{x}$



M

$M \times N$

Random is ok!

N

HEAVY RECONSTRUCTION

LIGHT SENSING

Ask *few* (linear) *questions*
about your informative (sparse) signal,
and recover it *differently* (non-linearly)”

Candès, Romberg, Tao, 2006
Donoho, 2006
1-Pixel Camera, Wakin et al., 2006

First Part:

- Sparsity, low-rankness and relatives:
  "From information to structures"

- Compress while you sample:
  "From structure to scrambled sensing"

- and Reconstruct!
  "From scrambled sensing to information"

(very broad and active field ... just one slide)

Reconstruct? (just one slide)

- For solving:

e.g., sparsity, low-rank, TV, ...

e.g., L2/L1 distance, robust to Gaussian/Poisson noise, ...

$$x^* = \operatorname*{argmin}_{u \in \mathbb{R}^N} \ \mathcal{S}(u) \text{ s.t. } \mathrm{Sensing}(u) \approx \mathrm{Sensing}(x)$$

many possibilities/solvers ...

Reconstruct?

- For solving:

e.g., sparsity, low-rank, TV, …

e.g., L2/L1 distance, robust to Gaussian/Poisson noise, …

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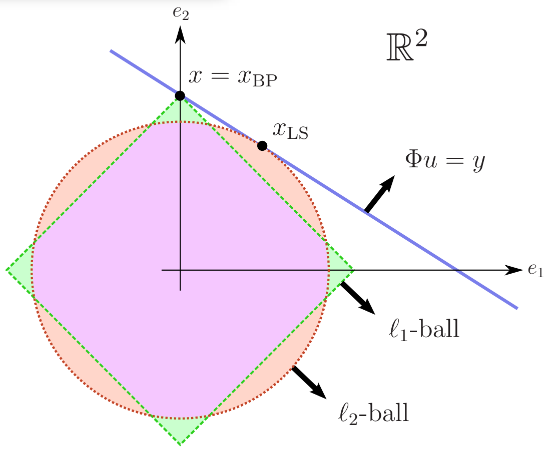

- Convex optimization: tons of toolboxes
  - SPGL1, L1Magic, (F)ISTA, ADMM, …
  - Proximal algorithms (see also B. Goldluecke's part)
- Iterative (*greedy*) methods:
  - matching pursuit and relatives (OMP)
  - iterative hard thresholding, CoSAMP, SP, smoothed L0, …
  - Approximate Message Passing Algorithms, Bayesian, …

Second Part:

- Compressive imaging appetizer:
  The Rice single pixel camera
- Other case studies:
  - Radio-interferometry and aperture synthesis
  - Hyperspectral CASSI imaging
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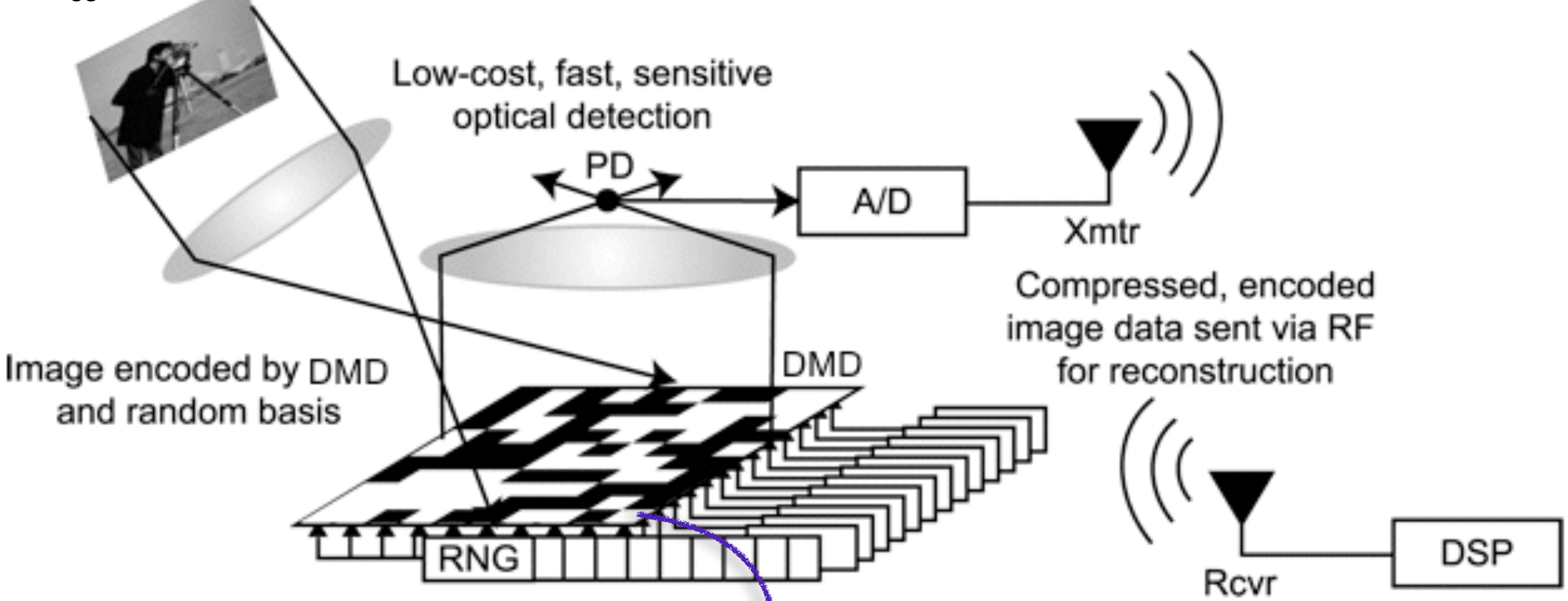
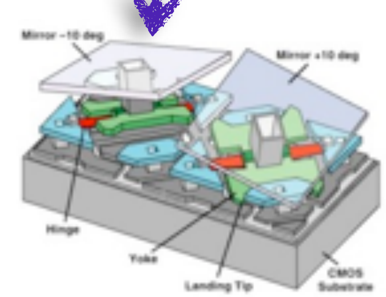
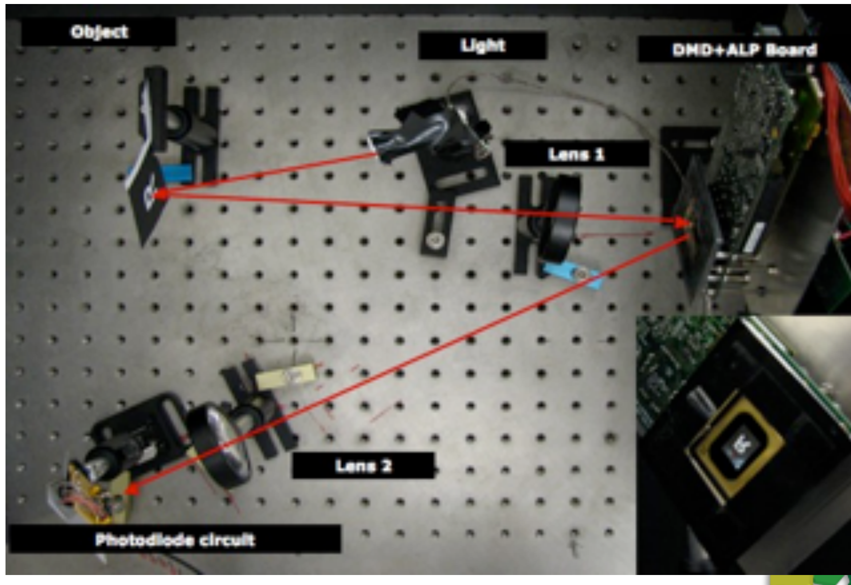
Rice Single-pixel Camera

x

[Duarte, Davenport, Takbar, Laska, Sun, Kelly, Baraniuk, 2008]







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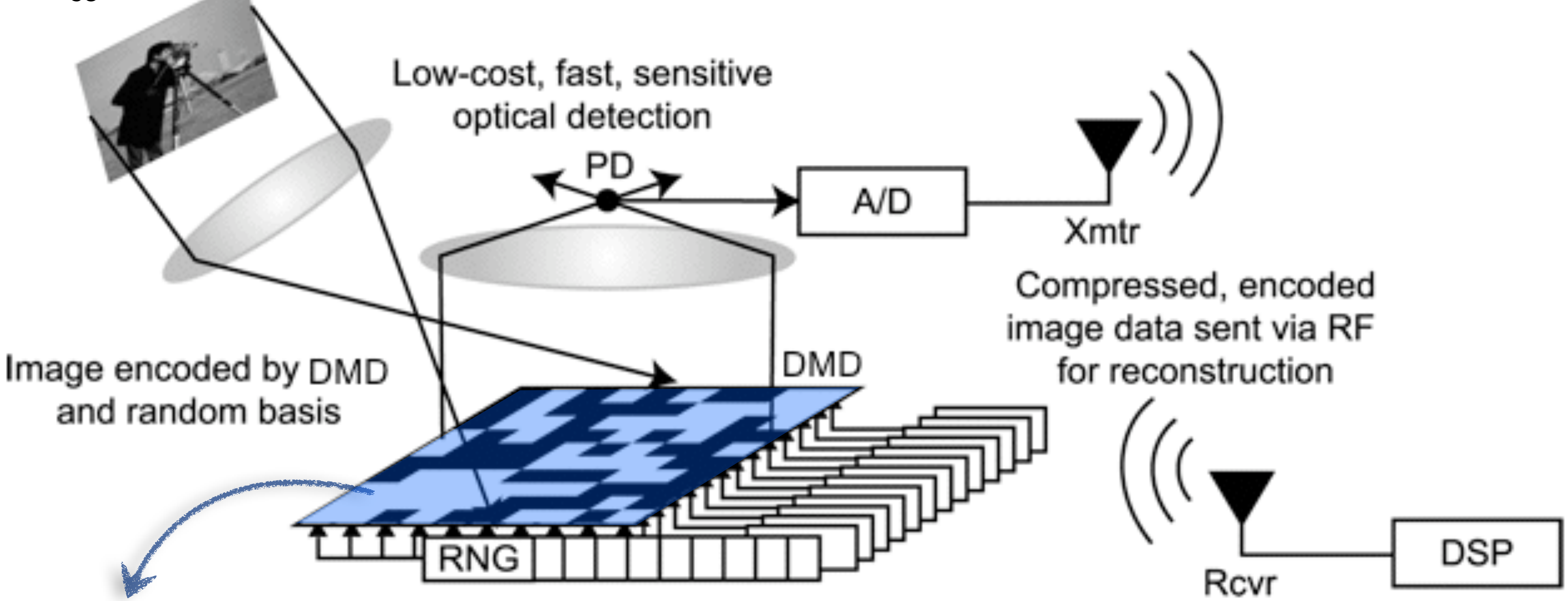
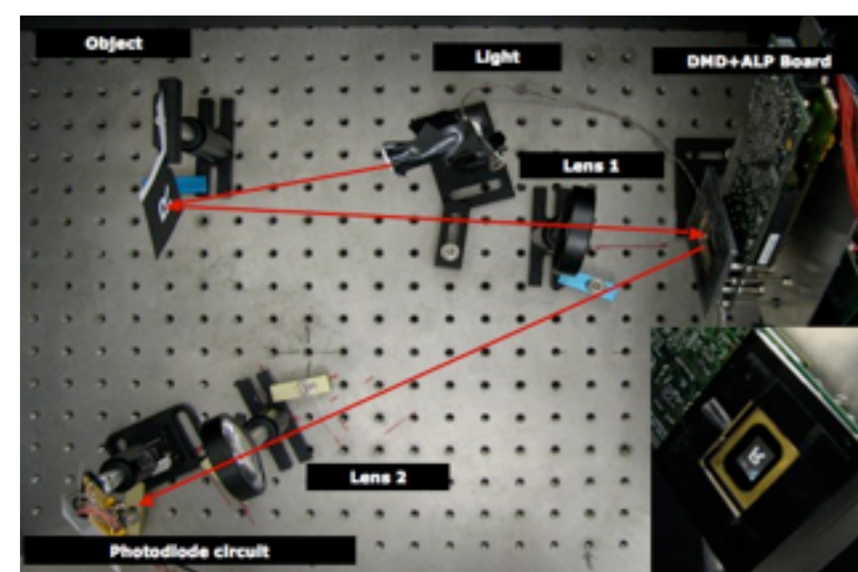


$$\varphi_{ji}\, x_i, \quad \varphi_{ji} \in \{0, 1\}$$

j^{th} random pattern $\varphi_j \in \mathbb{R}^N$



Rice Single-pixel Camera

[Duarte, Davenport, Takbar, Laska, Sun, Kelly, Baraniuk, 2008]

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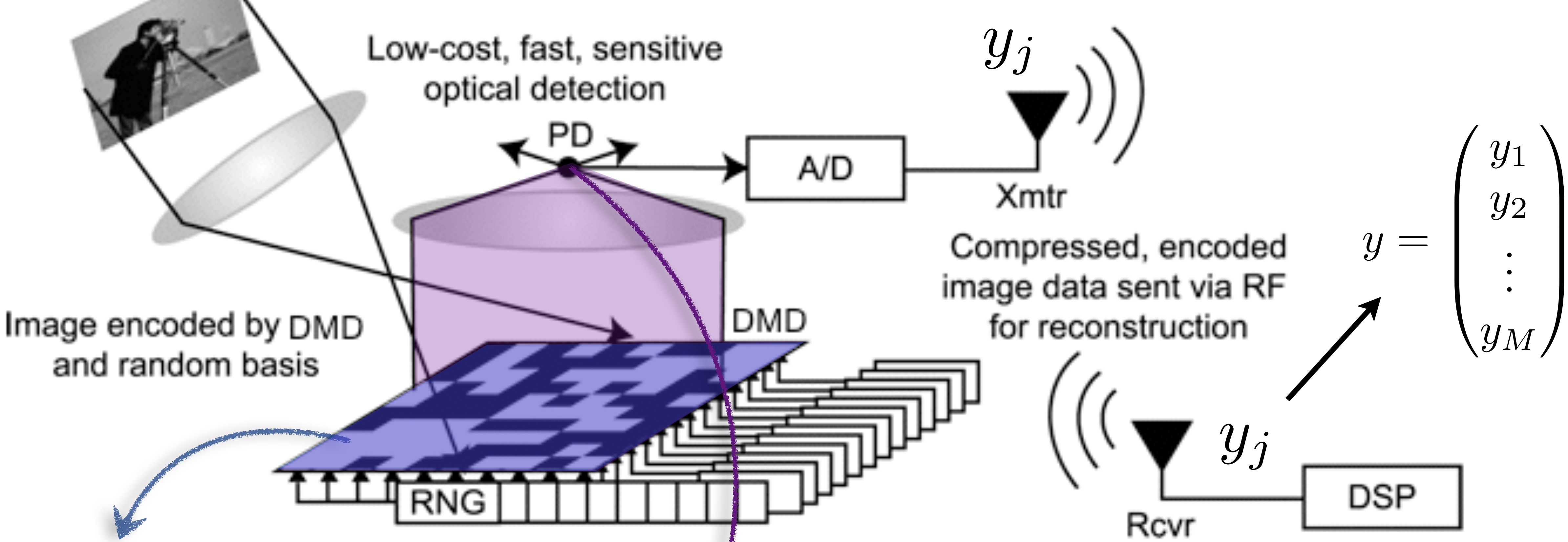
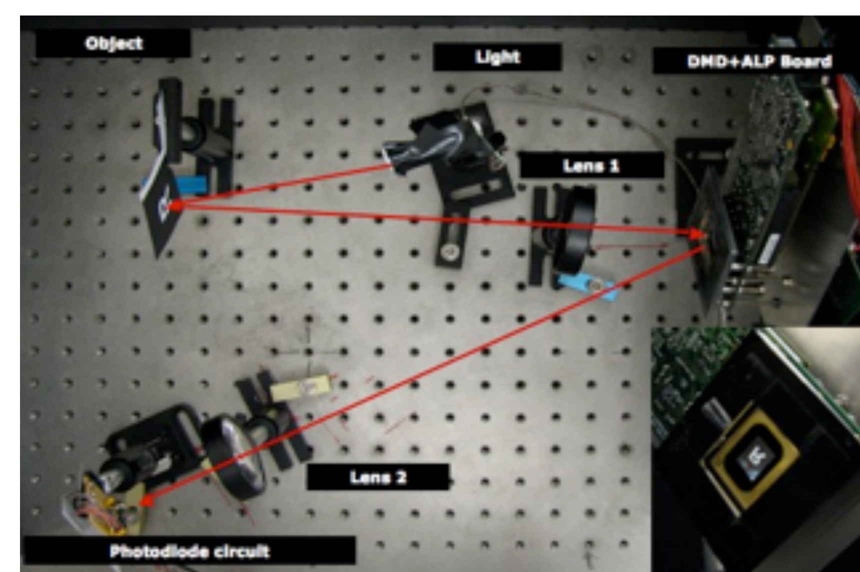


$\varphi_{ji}\, x_i, \quad \varphi_{ji} \in \{0, 1\}$

j^{th} random pattern $\varphi_j \in \mathbb{R}^N$

Optical sum

$$y_j = \sum_i \varphi_{ji}\, x_i$$



Rice Single-pixel Camera

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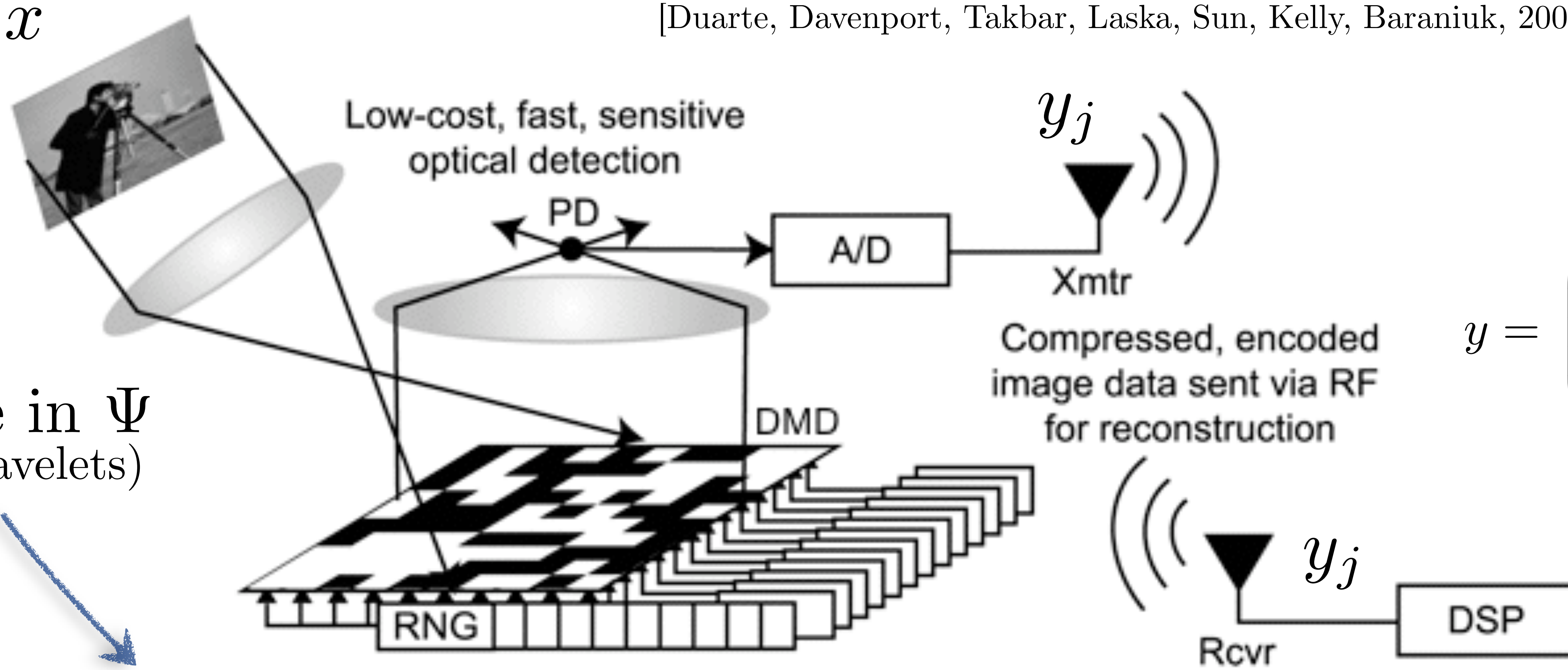
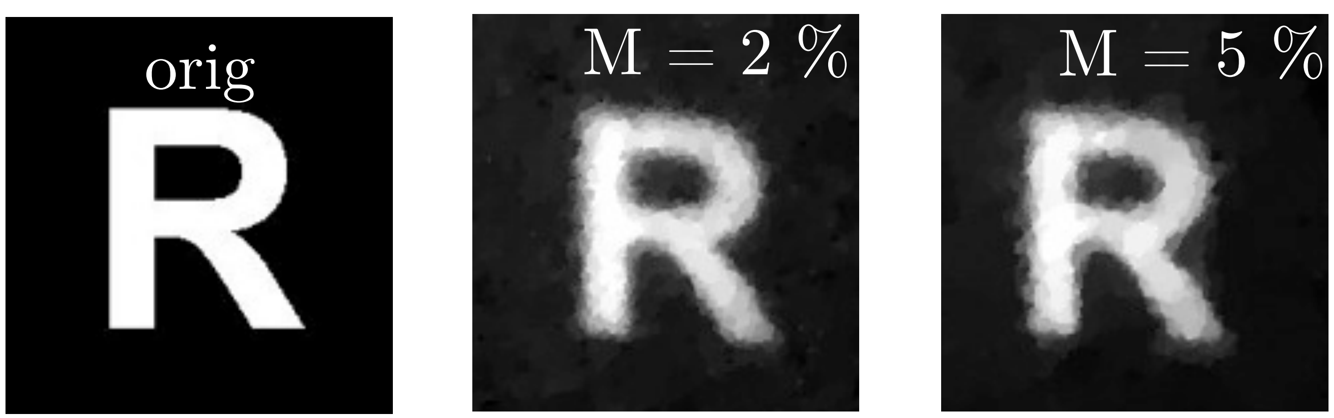
[Duarte, Davenport, Takbar, Laska, Sun, Kelly, Baraniuk, 2008]



$$y = \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_M \end{pmatrix}$$

sparse in Ψ
(e.g., wavelets)

$$x^* = \operatorname{argmin} \|\alpha\|_1 \text{ s.t. } \Phi\Psi\alpha = y$$



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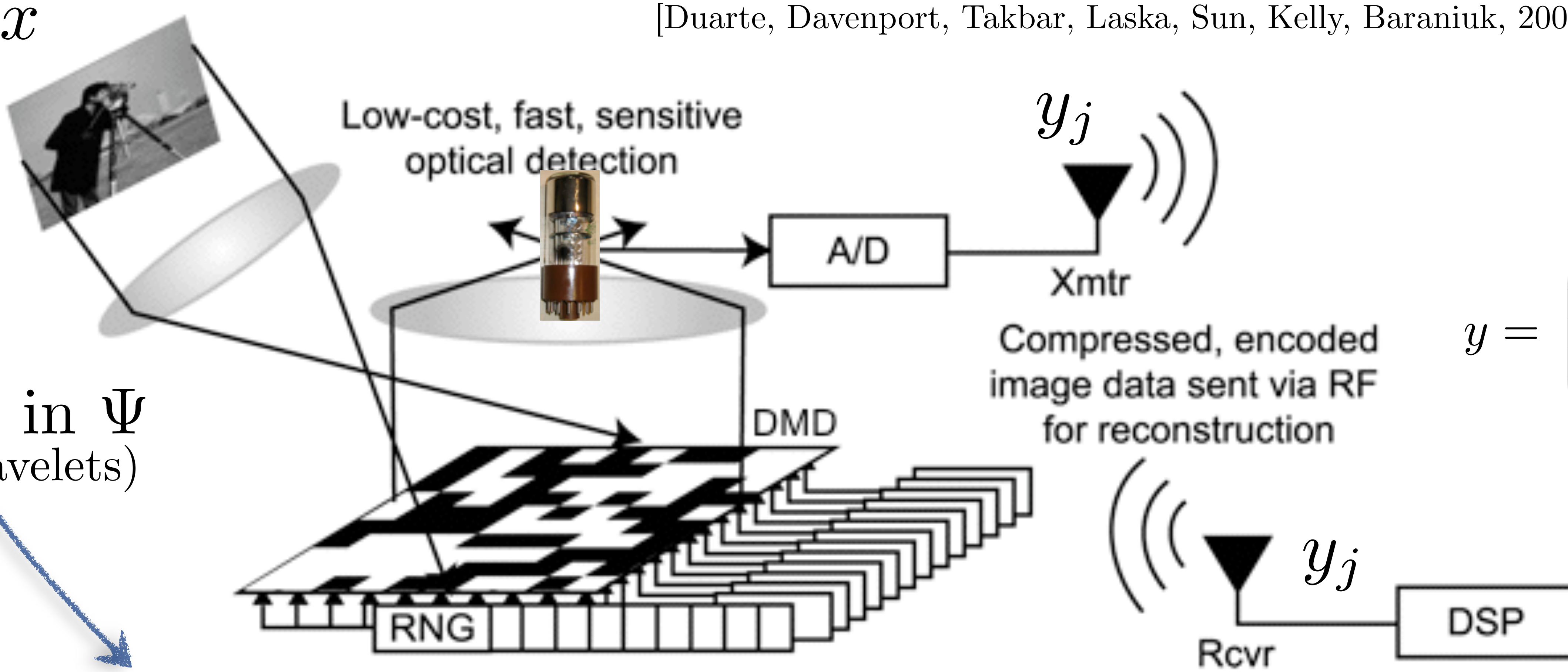

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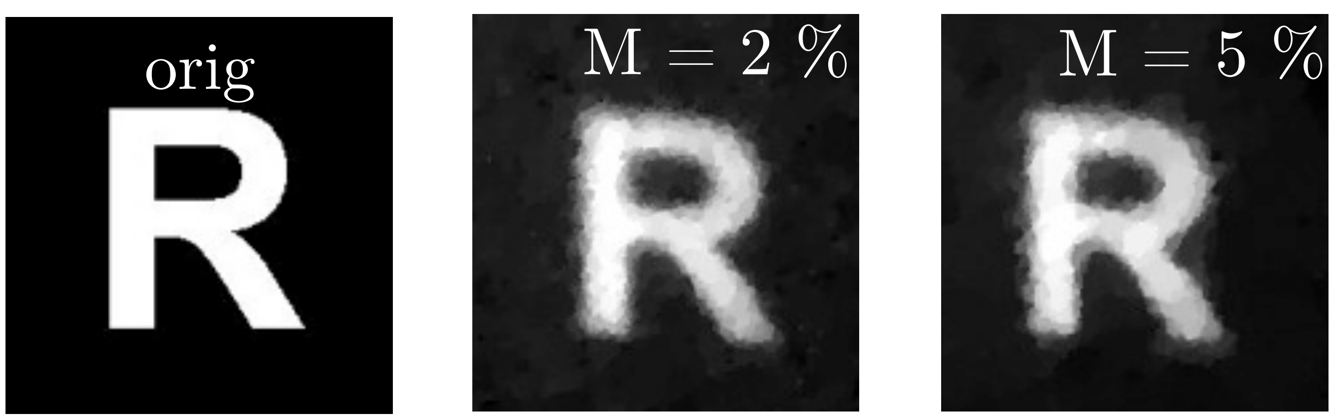

Proof of concept **but** PD is unique!

<u>Specific imaging application</u>:

high energy photons with
single costly photomultiplier

Second Part:

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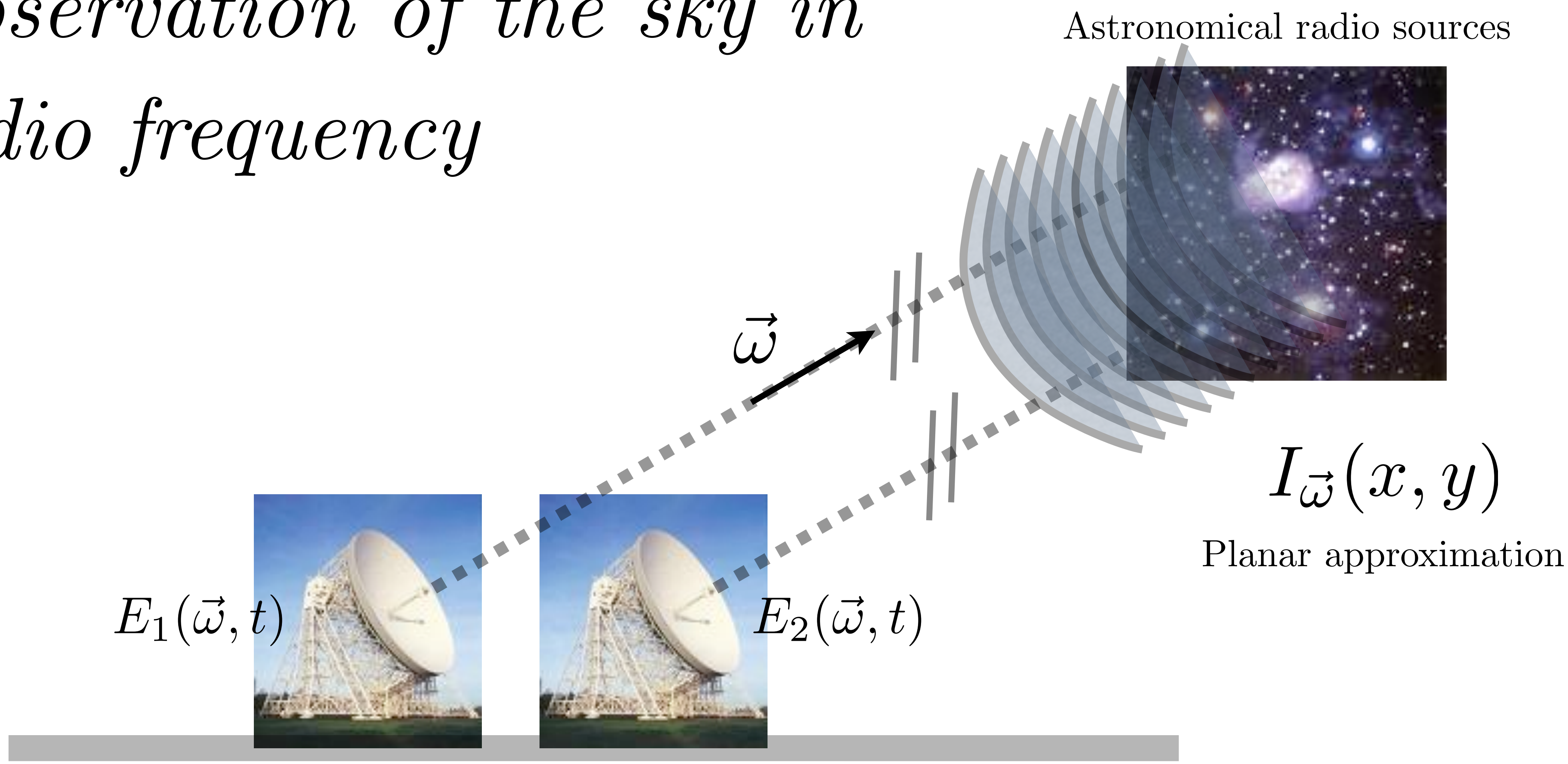
Aperture Synthesis in Radio-Astronomy

Observation of the sky in radio frequency



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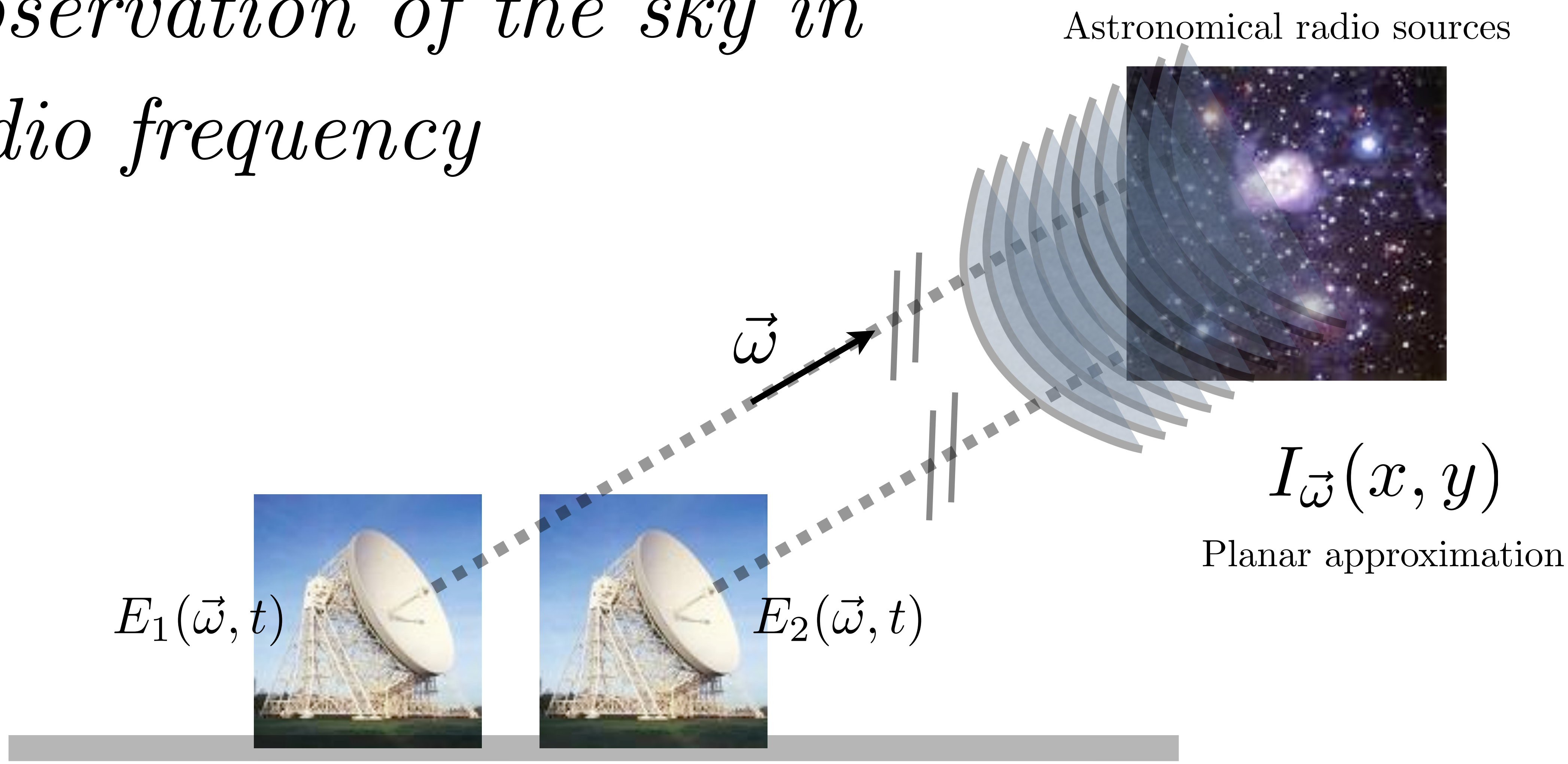
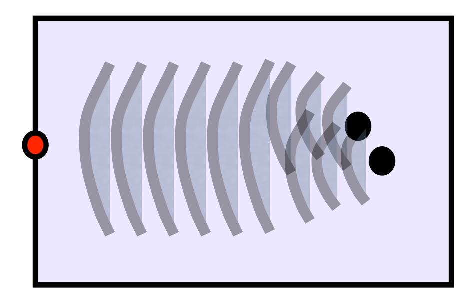


“ Imagine a swimming pool with two swimmers, and you want to detect their positions from the waves they produce ... ”



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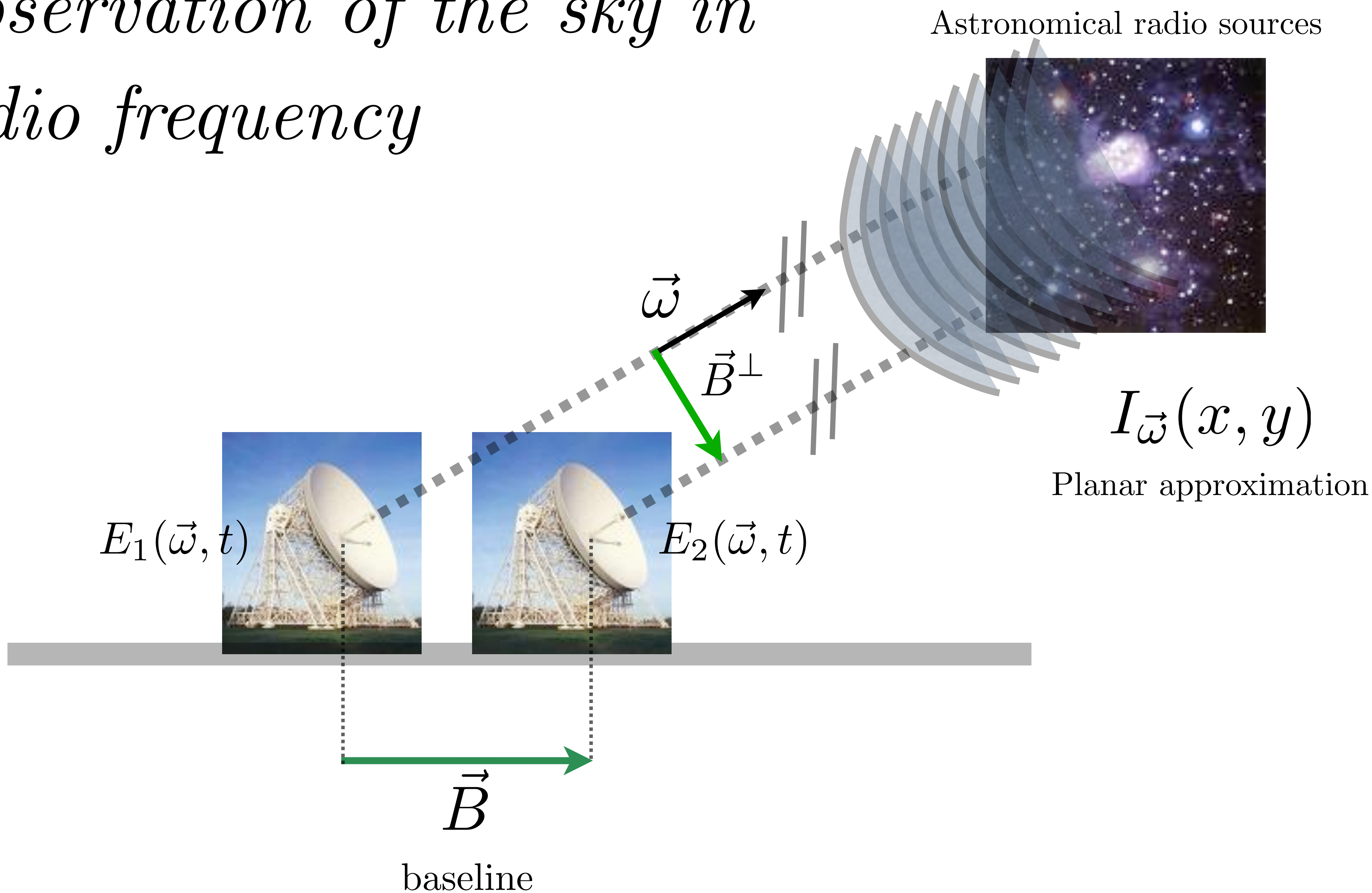

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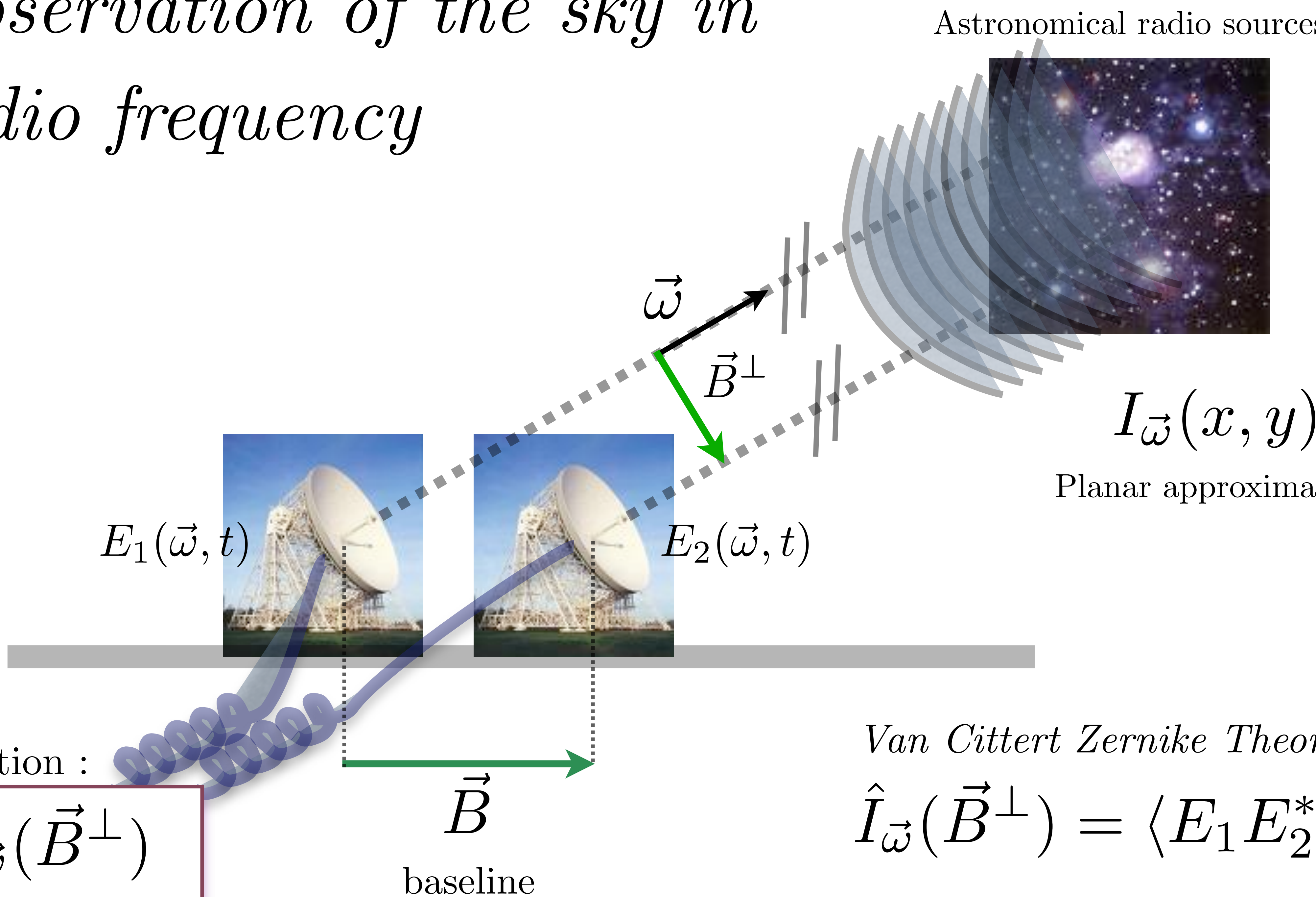


Time correlation :

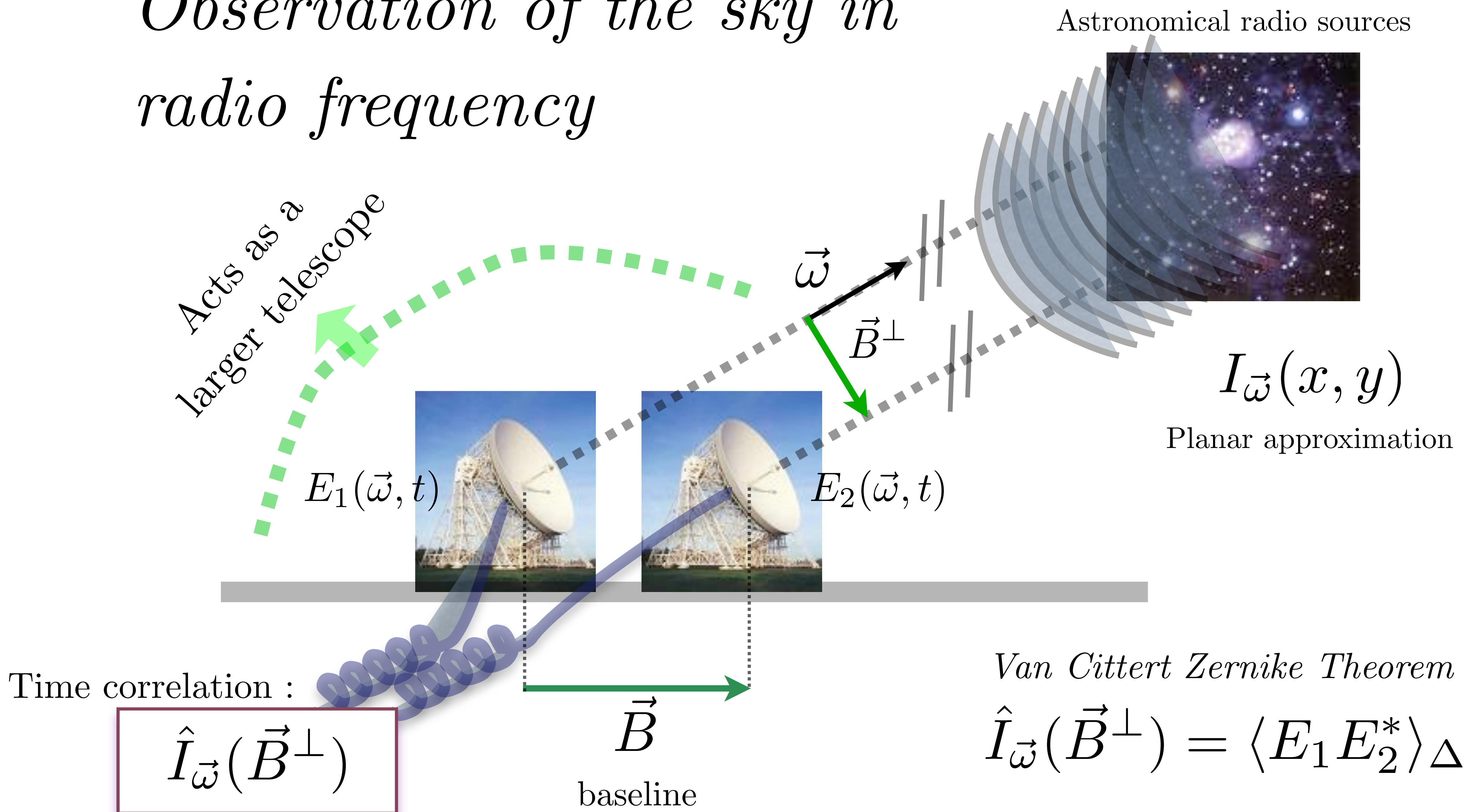
$$\hat{I}_{\vec{\omega}}(\vec{B}^{\perp})$$

Van Cittert Zernike Theorem :

$$\hat{I}_{\vec{\omega}}(\vec{B}^{\perp}) = \langle E_1 E_2^* \rangle_{\Delta t}$$

Aperture Synthesis in Radio-Astronomy

Observation of the sky in radio frequency



Van Cittert Zernike Theorem :

$$\hat{I}_{\vec{\omega}}(\vec{B}^{\perp}) = \langle E_1 E_2^* \rangle_{\Delta t}$$

Fourier transform

E pur si muove! "And yet it moves!"

- using N telescopes, $\binom{N}{2}$ possible Fourier observations
- and baselines undergo Earth rotation !

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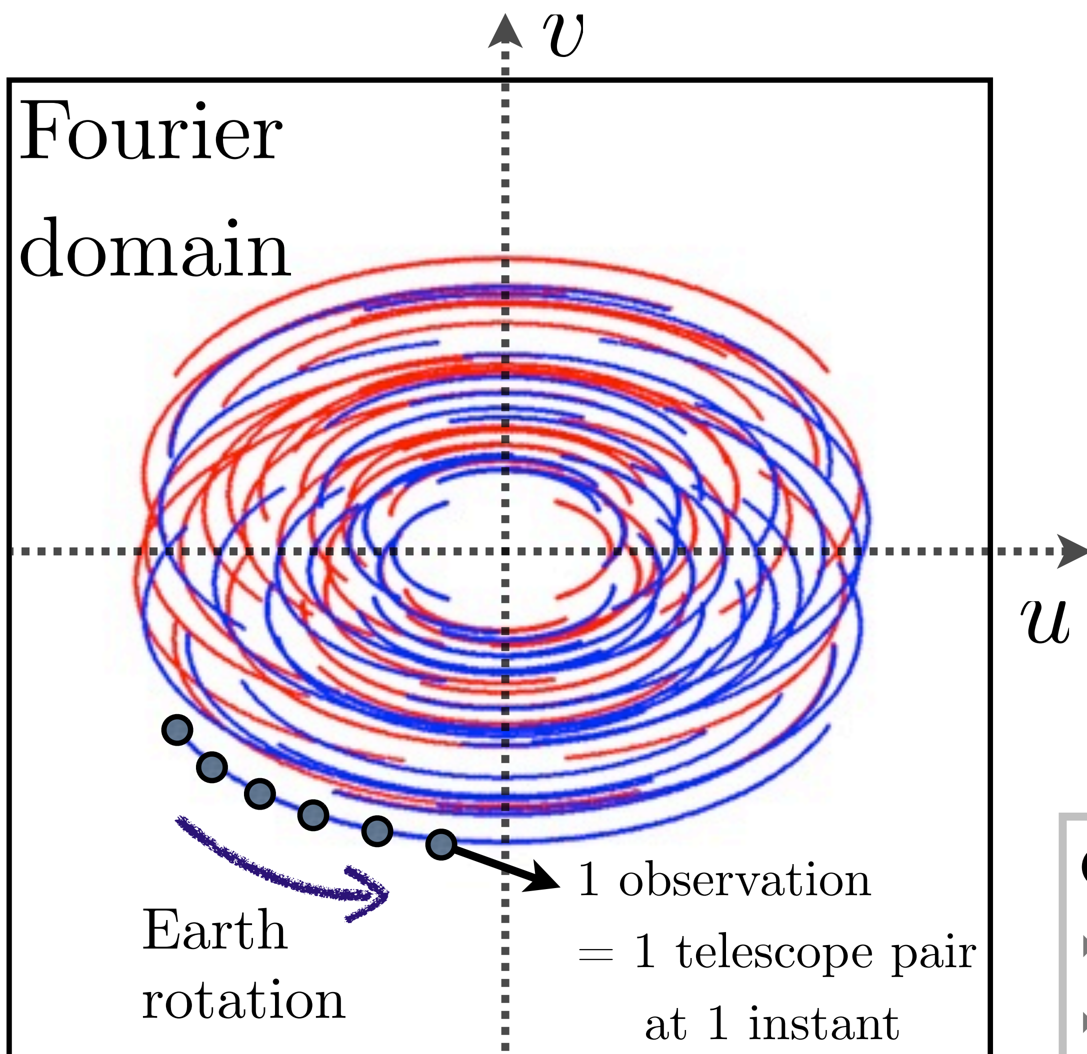
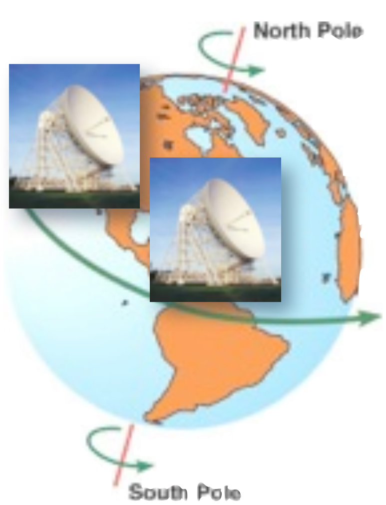
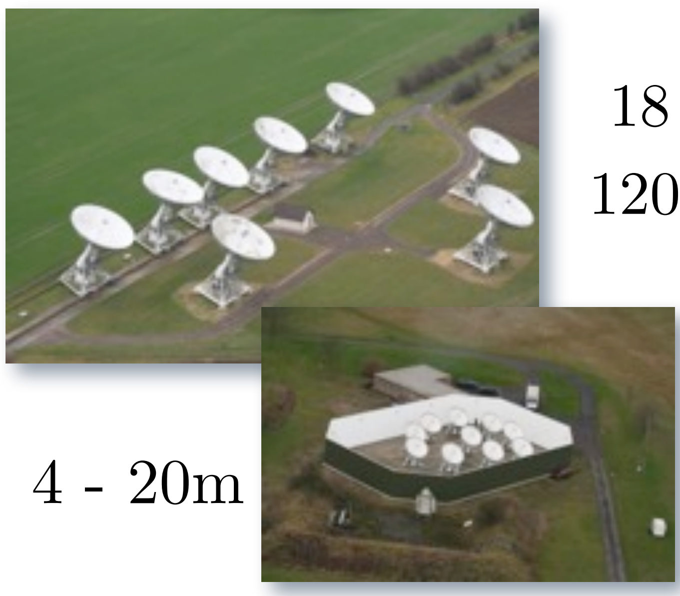
- Example :



Each telescope pair
=
1 elliptic path



Arcminute Microkelvin Imager
AMI



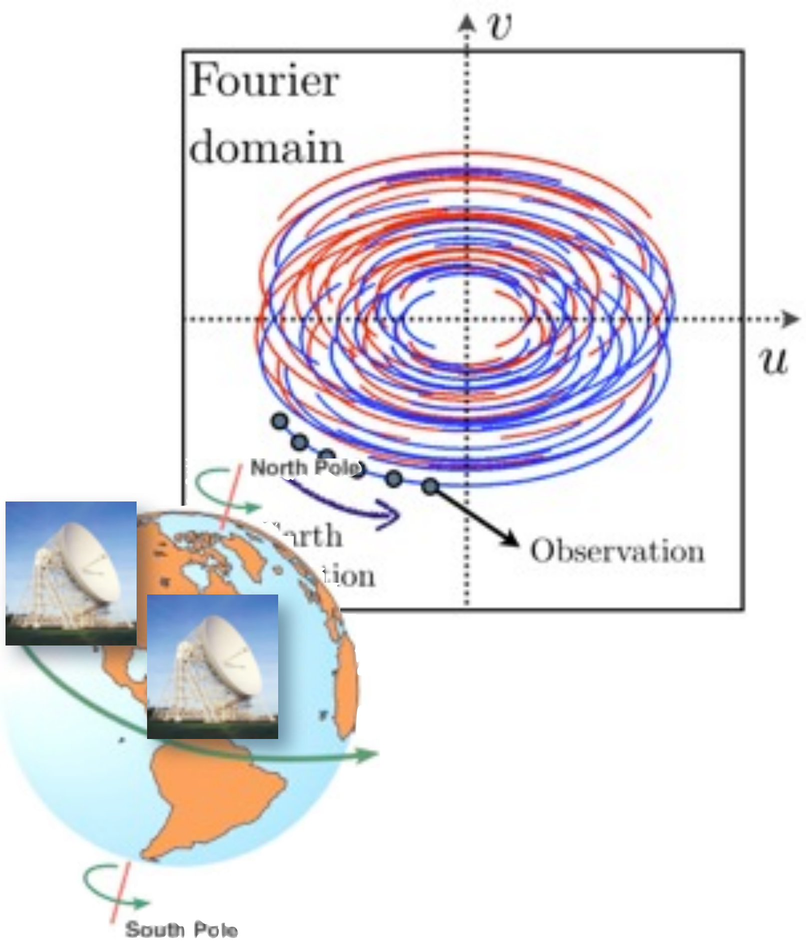
18 - 120m

4 - 20m

Other configurations :
- Very Large Array VLA
- Square Kilometer Array SKA

E pur si muove! "And yet it moves!"

- using N telescopes, $\binom{N}{2}$ possible Fourier observations
- and baselines undergo Earth rotation !
- Example :



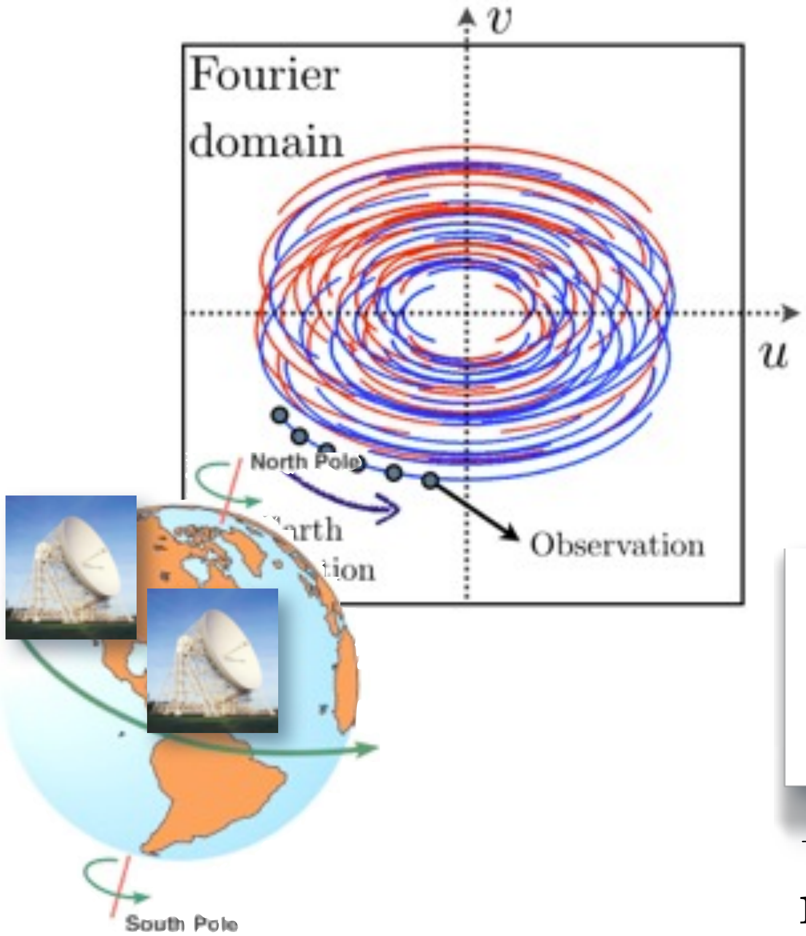
Partial Fourier Sampling Problem!

$$y = SFx + n$$

- S: Selection of a few frequencies
- F: 2-D Fourier Transform

E pur si muove! "And yet it moves!"

- using N telescopes, $\binom{N}{2}$ possible Fourier observations
- and baselines undergo Earth rotation !
- Example :



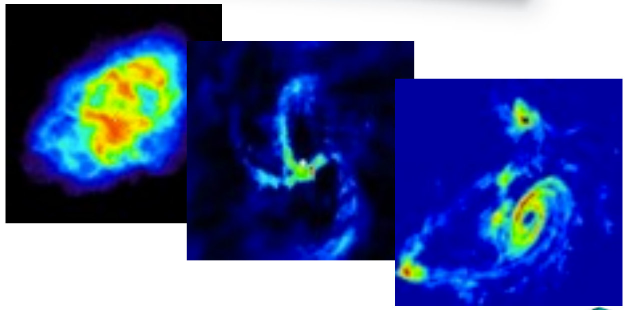
Partial Fourier Sampling Problem!

$$y = SFx + n$$

Selection of a few frequencies

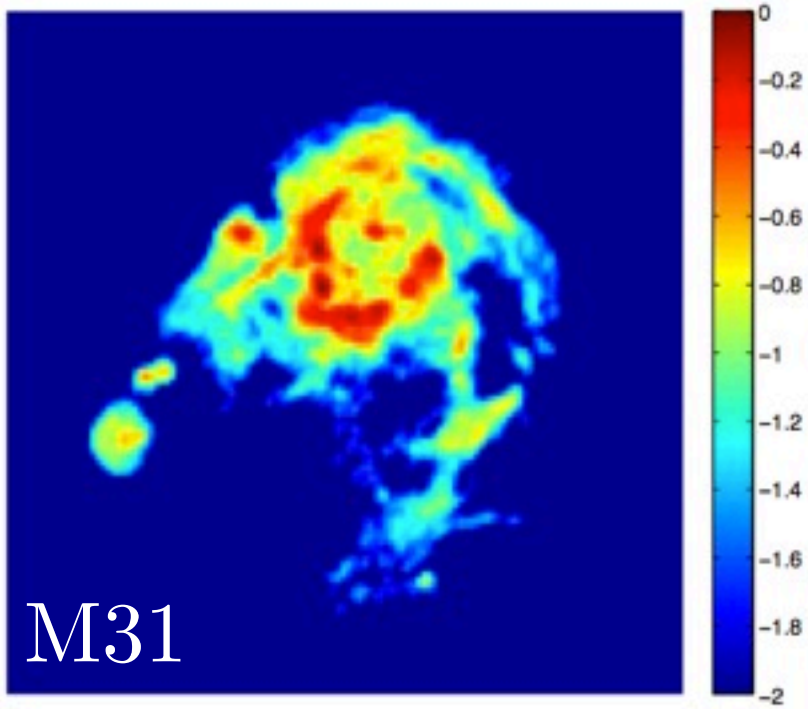
2-D Fourier Transform

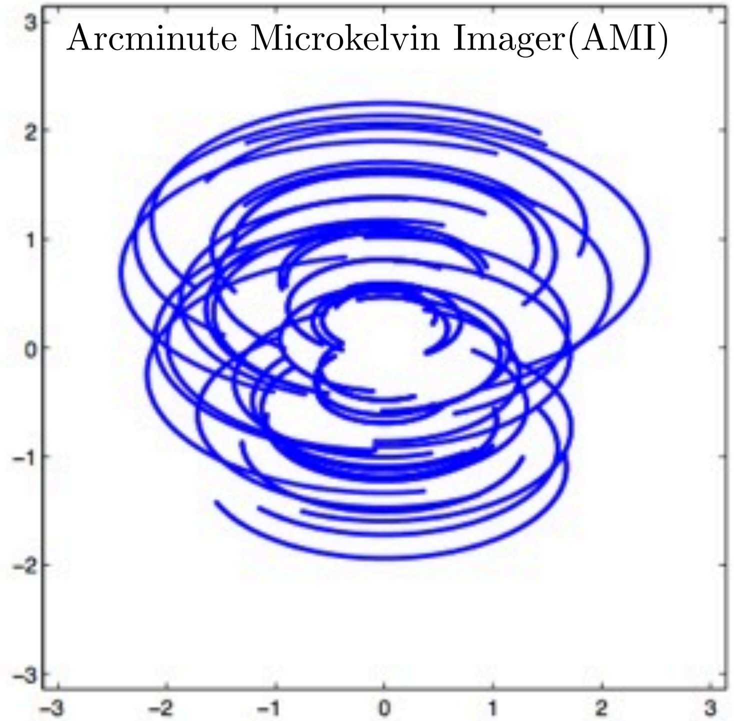
Image prior: SPARSITY!

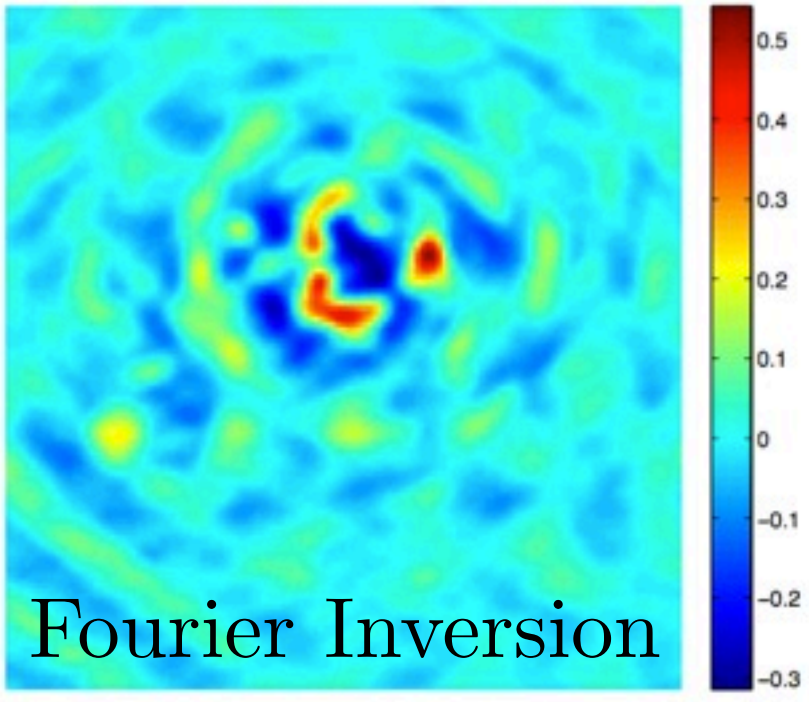


+ Additional improvements:
multiple sparsity basis, reweighted L1, ...

Reconstruction results







R. Carrillo, J. McEwen, Y. Wiaux, "PURIFY: a new approach to radio-interferometric imaging", Accepted MNRAS, 2014

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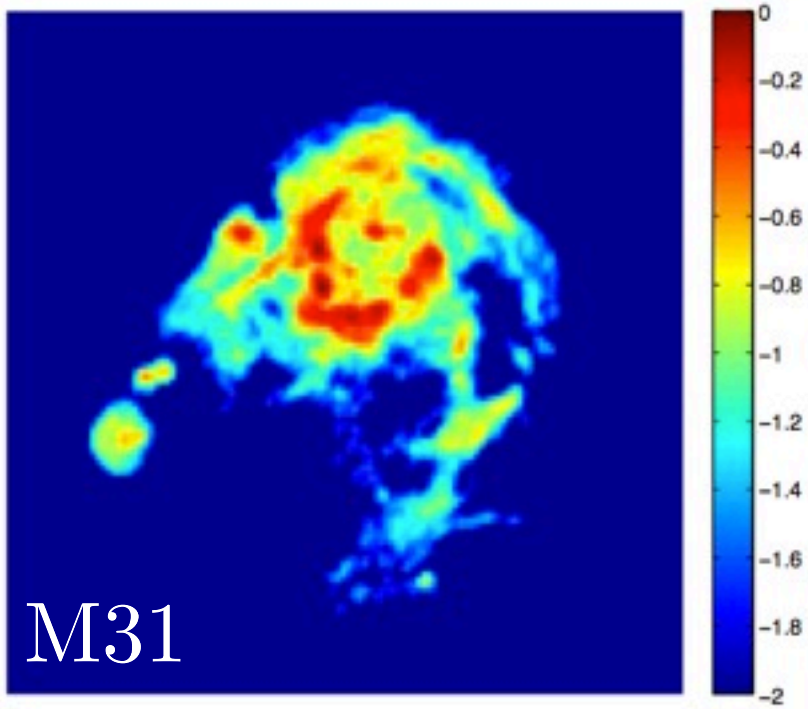
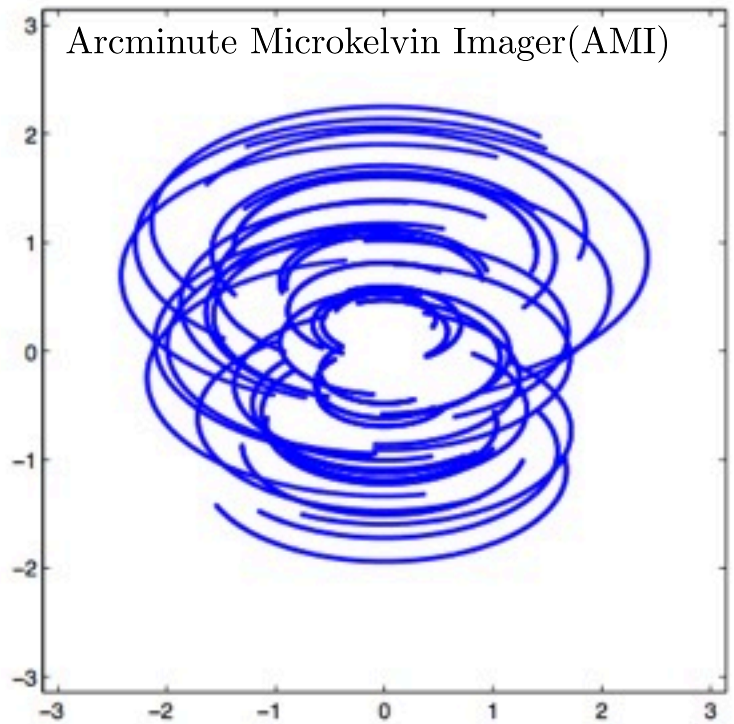
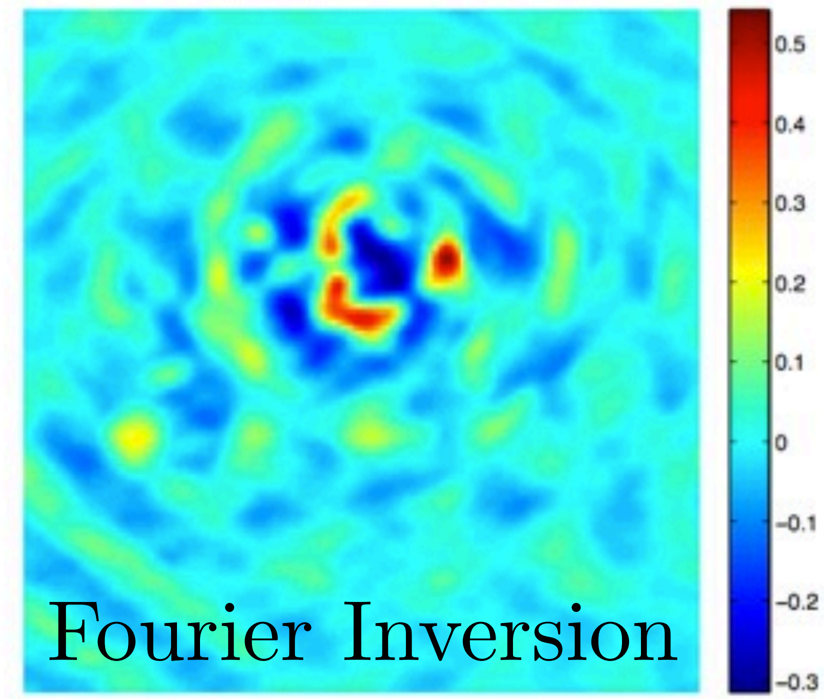
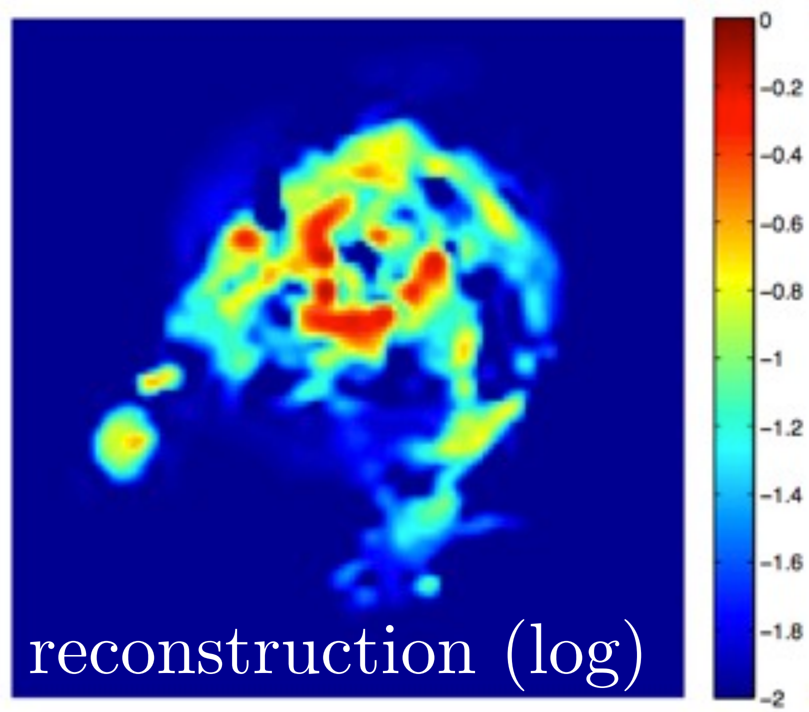
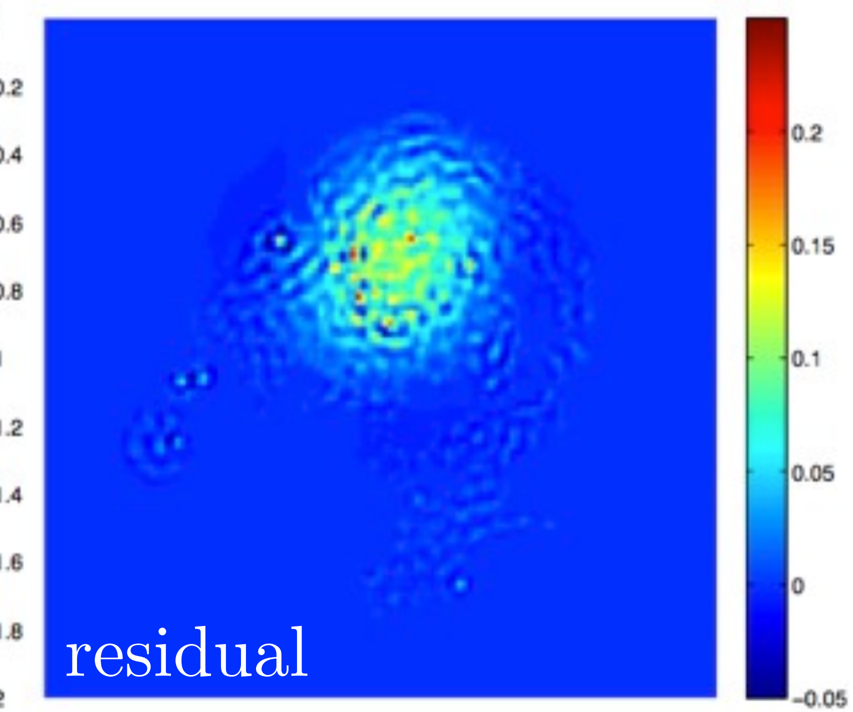






Sparsity
Averaging
Reweighted
Analysis
(SARA)





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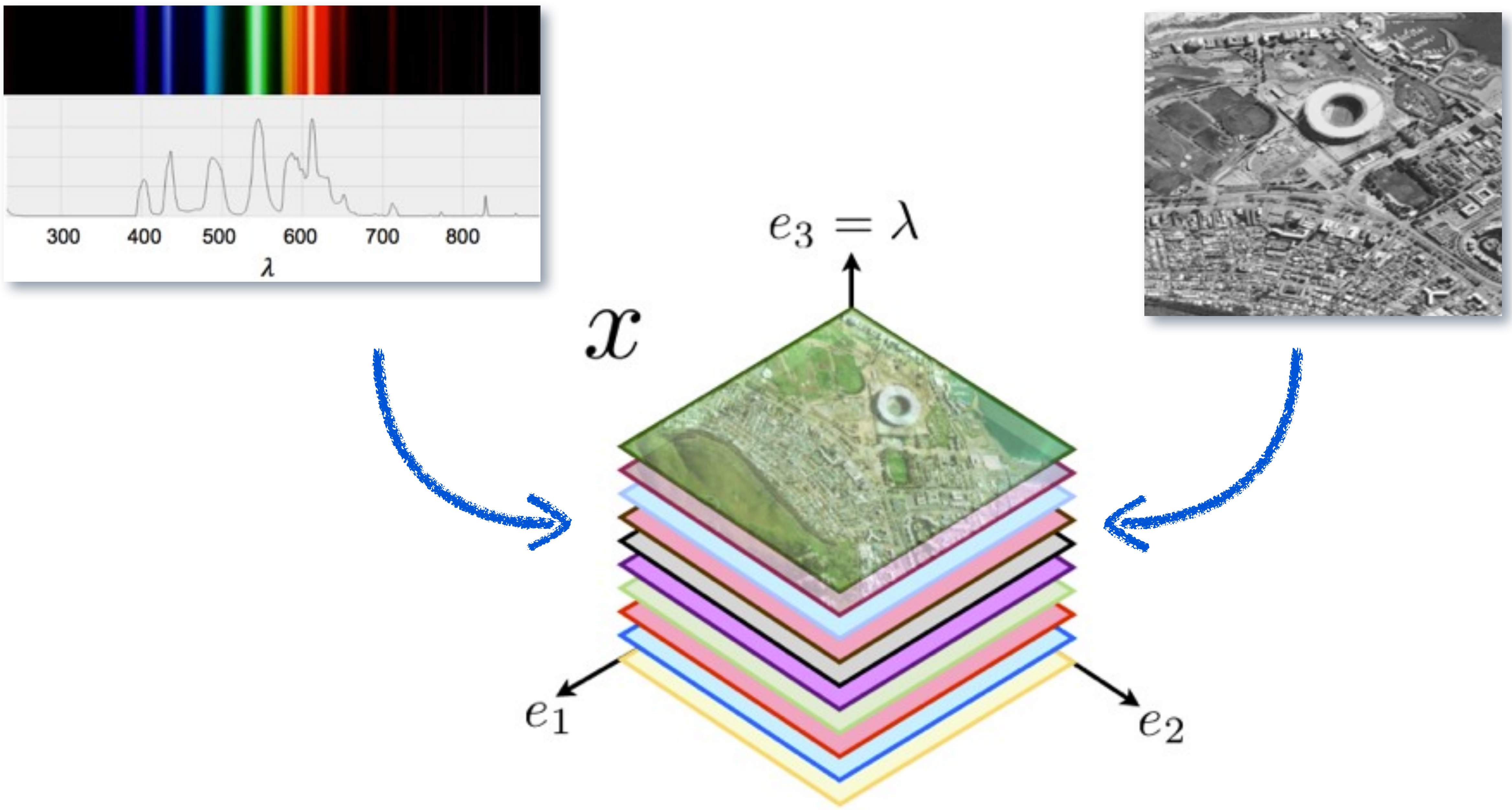
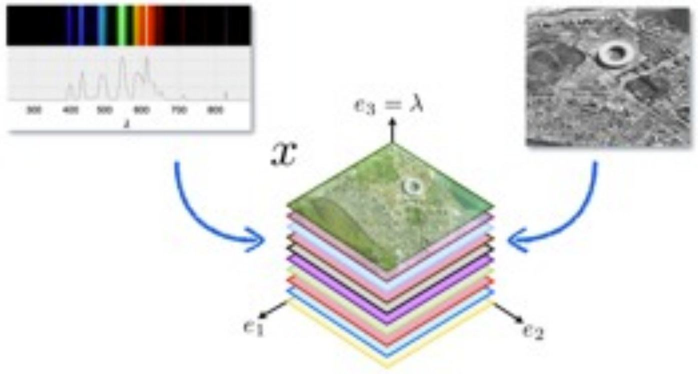
Hyperspectral imaging

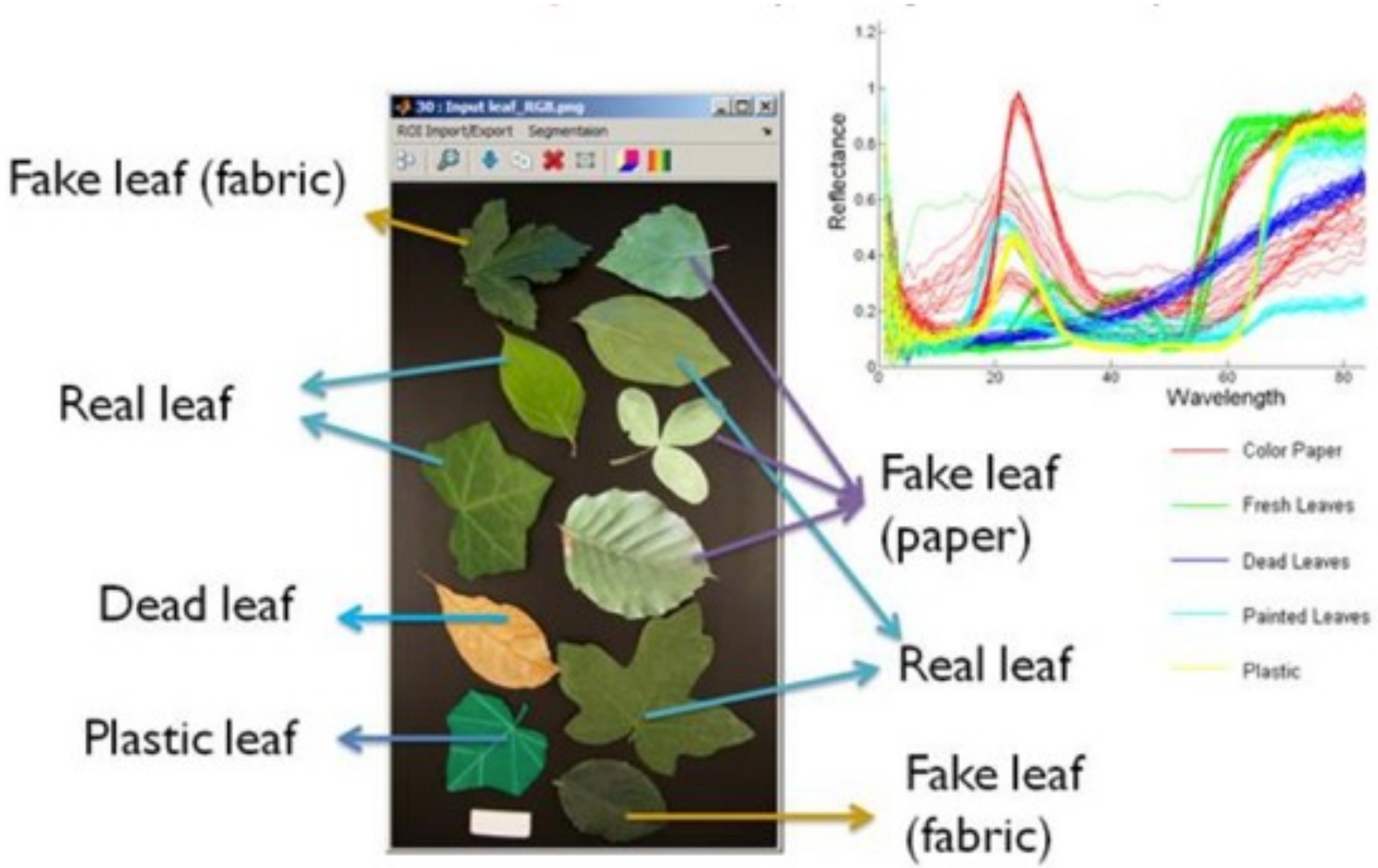
- Fusion of spectrometry and imaging



Hyperspectral imaging

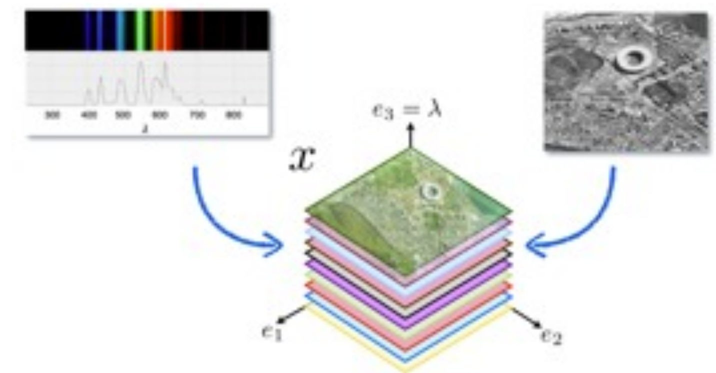
- Fusion of spectrometry and imaging
- Applications:
  - material classification/segmentation

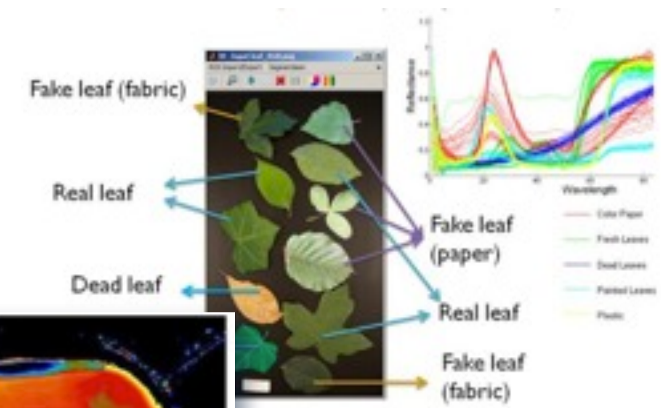


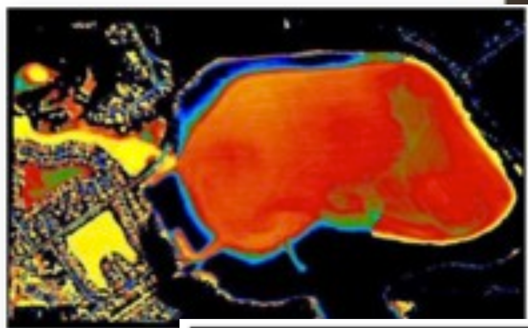


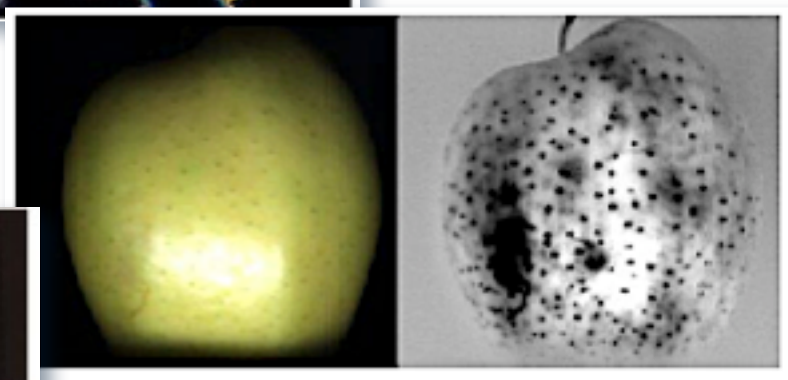
Hyperspectral imaging

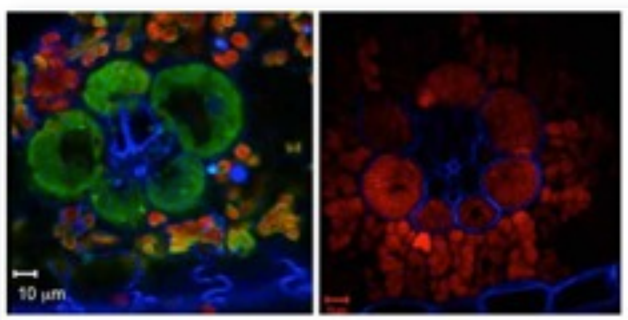
- Fusion of spectrometry and imaging
- Applications:
  - material classification/segmentation
  - microscopy/spectroscopy
  - counterfeit detection
  - environmental monitoring
  - skin decease detection
  - …



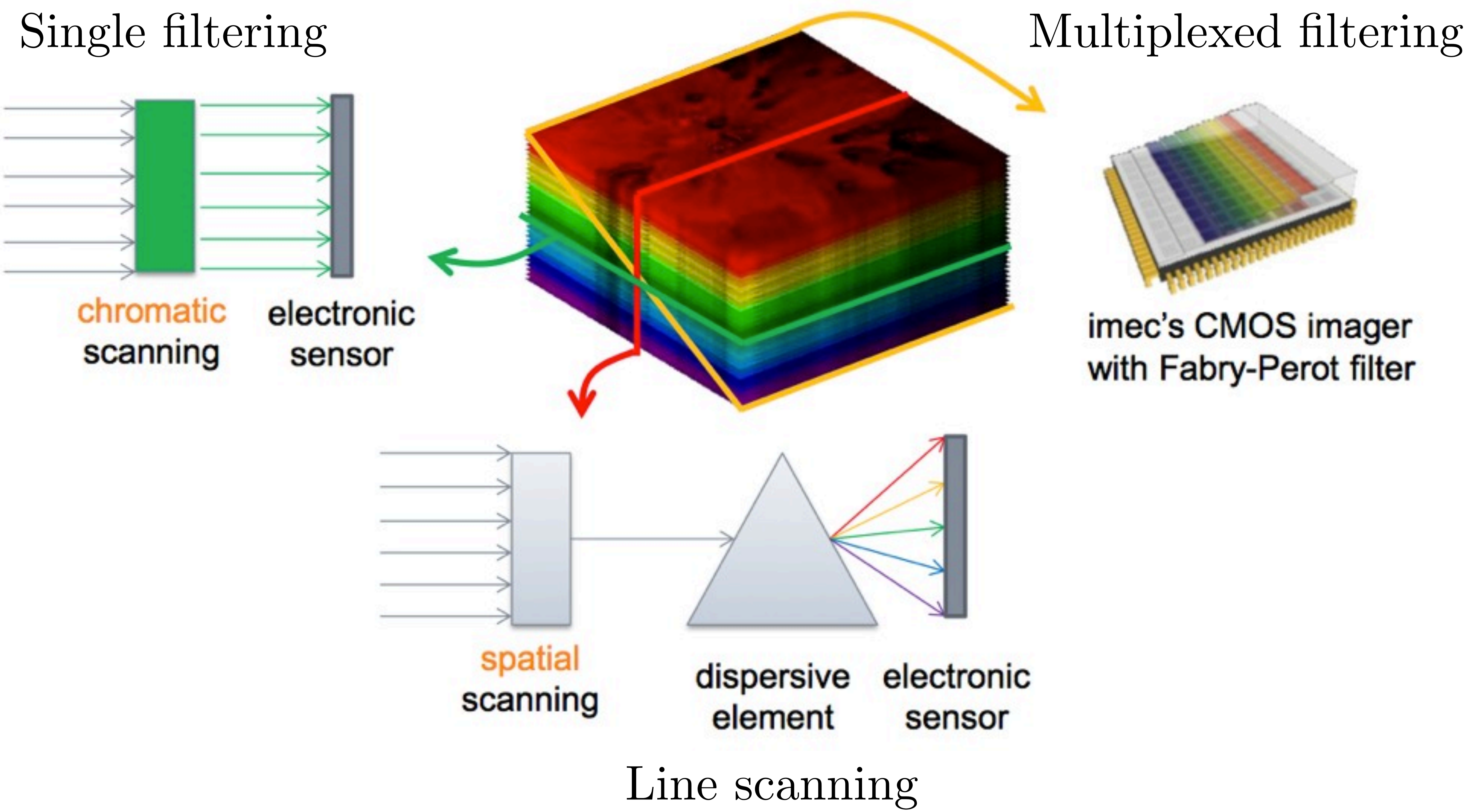








How is it usually done?



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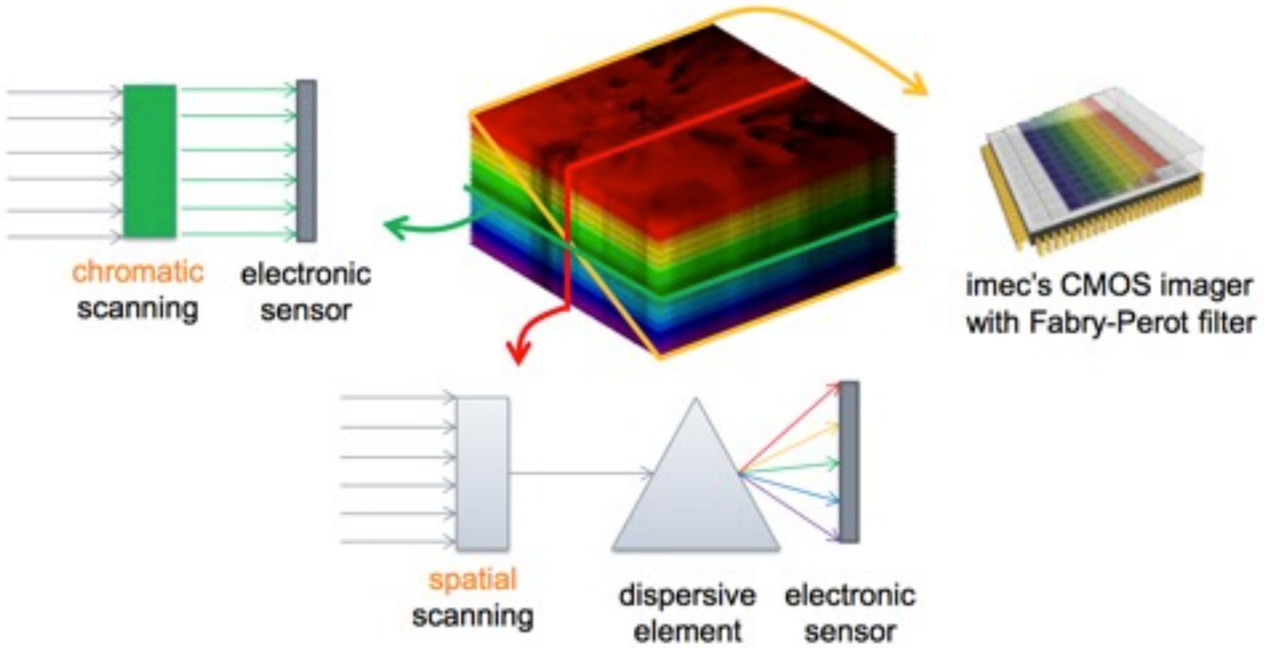


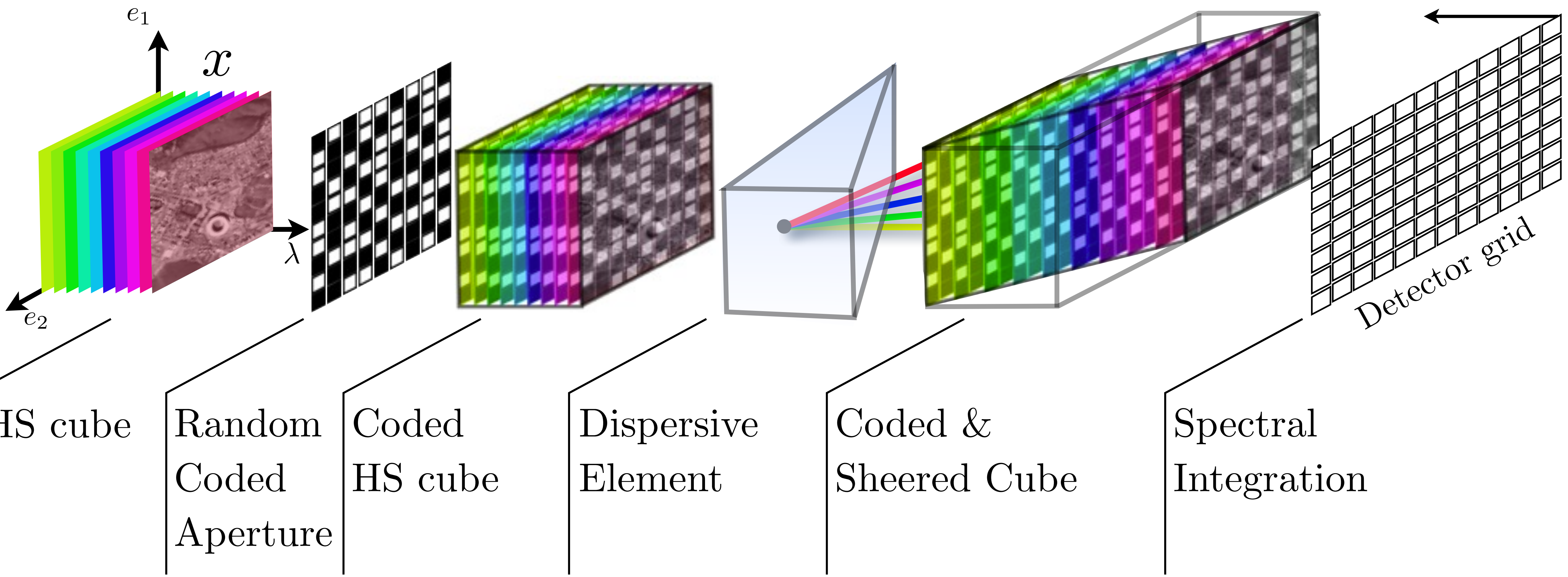
Issues:

- acquisition time is slow
- low spatial/spectral/temporal resolution

  (depending on selected sensing)
- Huge amount of data at sensing
- But "low complexity" (sparse/low-rank) signals

Compressive HS imaging

- high-dimensional data = natural field for CS!
- Coded Aperture Snapshot Spectral Imaging (CASSI)
  - Mixing dispersive element + coded aperture



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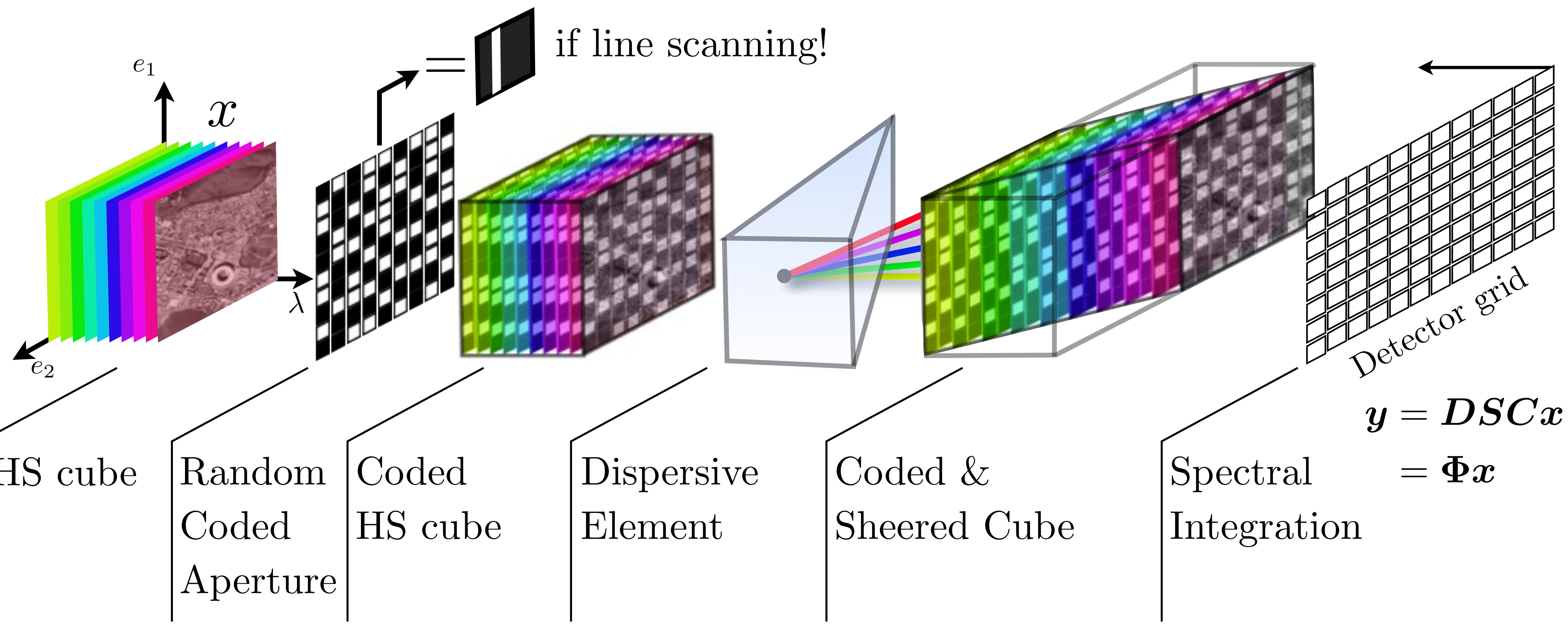

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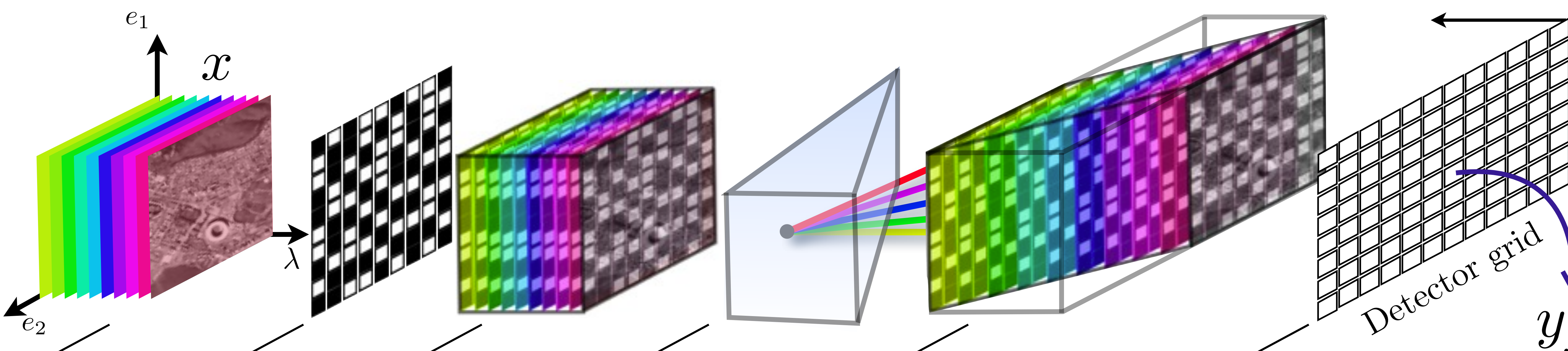

$\boldsymbol{x} \rightarrow \boldsymbol{C} = \mathrm{diag}(\boldsymbol{c}) \rightarrow \boldsymbol{S} \rightarrow \rightarrow \boldsymbol{D} \rightarrow \boldsymbol{y}$

Sensing model: $\boldsymbol{y} = \boldsymbol{DSCx} = \boldsymbol{\Phi x}$

+ with multiple $\boldsymbol{c}$

Compressive HS imaging

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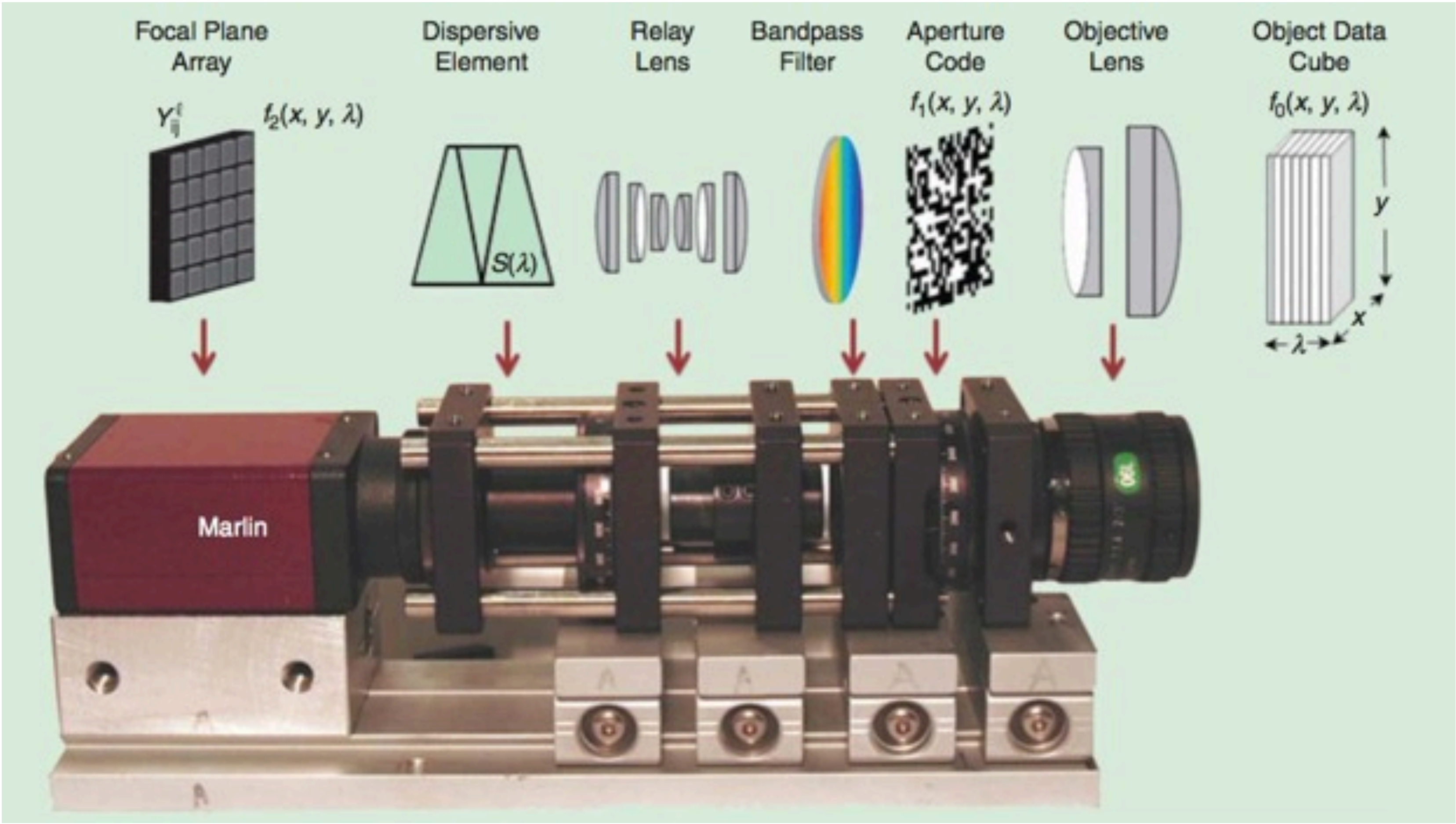
Optically:



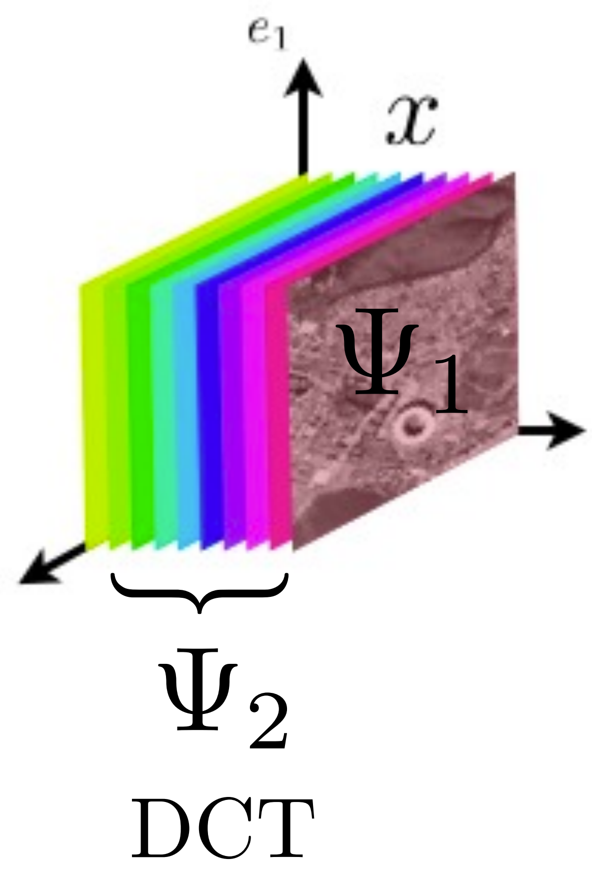
Gonzalo R. Arce, David J. Brady, Lawrence Carin, Henry Arguello, and David S. Kittle, "Compressive Coded Aperture Spectral Imaging", IEEE Sig. Proc, vol. 1, 2014

Compressive HS imaging

- Reconstruction: solving

$$x^* = \Psi^T \big(\arg\min_{\alpha} \tau \|\alpha\|_1 + \tfrac{1}{2} \|y - DSC\Psi\alpha\|^2\big)$$

$$\Psi = \Psi_1 \otimes \Psi_2$$

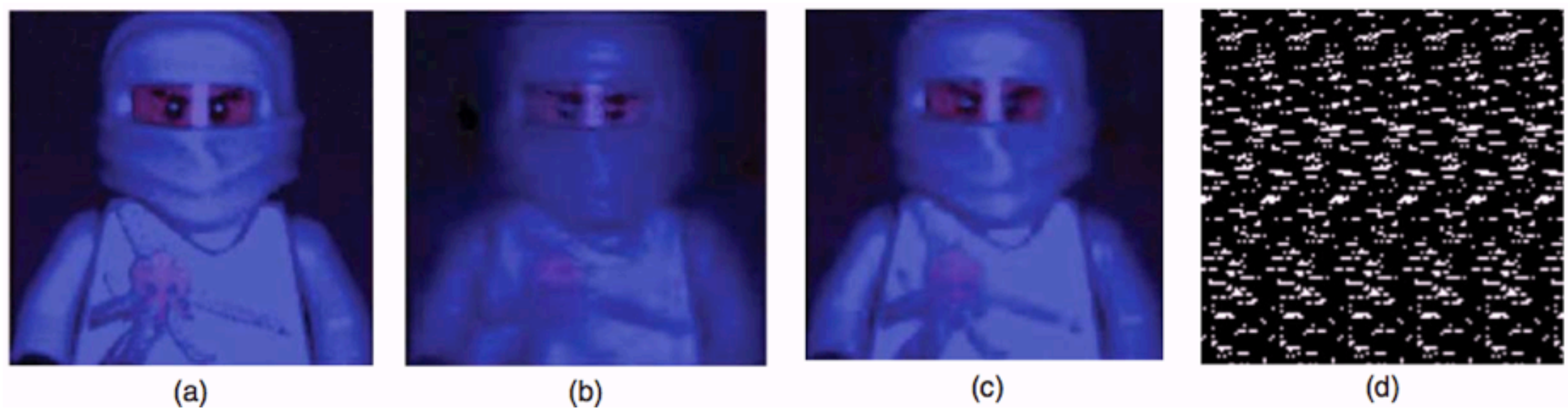


2-D wavelet
Symmlet-8

Gonzalo R. Arce, David J. Brady, Lawrence Carin, Henry Arguello, and David S. Kittle, "Compressive Coded Aperture Spectral Imaging", IEEE Sig. Proc, vol. 1, 2014

Compressive HS imaging

- Reconstruction:



Original (several wav.)	With 12 shots and random $\boldsymbol{c}$	With 12 shots and optimized $\boldsymbol{c}$	example of optimized $\boldsymbol{c}$

Gonzalo R. Arce, David J. Brady, Lawrence Carin, Henry Arguello, and David S. Kittle, "Compressive Coded Aperture Spectral Imaging", IEEE Sig. Proc, vol. 1, 2014

Second Part:

- Compressive imaging appetizer:
  The Rice single pixel camera
- Other case studies:
  - Radio-interferometry and aperture synthesis
  - Hyperspectral CASSI imaging
  - Highspeed Coded Strobing Imaging

High Speed Imaging

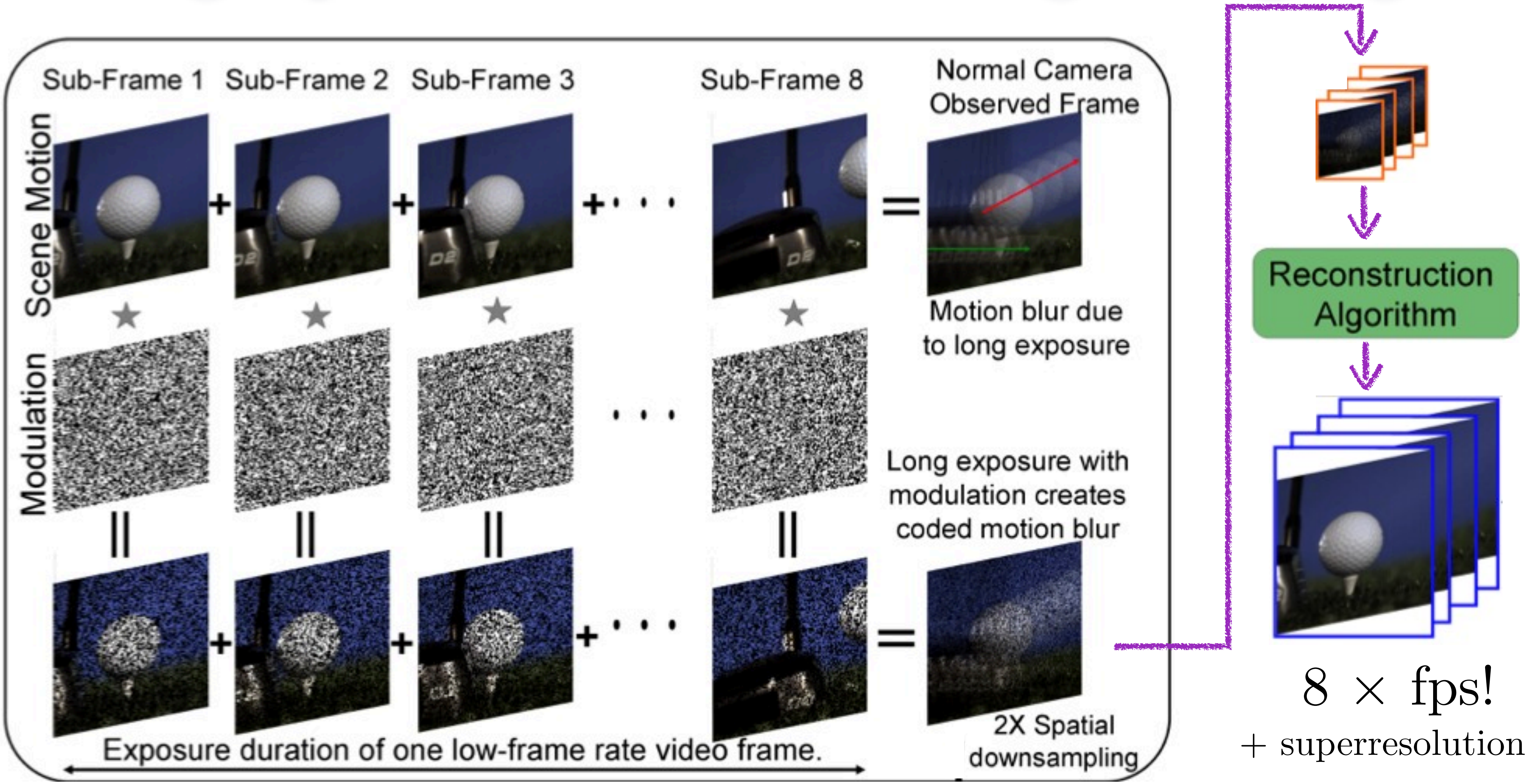
- Imaging high speed object
  lead to blurry image
  if low shutter frequency

(source: wikipedia)

- But hardware limitation in # fps (e.g., O(20fps))
- <u>Solution</u>: “Highspeed Coded Strobing Imaging”
  - keep the detector fps rate unchanged
  - and add high rate *coding* of the shutter!

(Reddy, Veeraraghavan, Chellappa, ...)

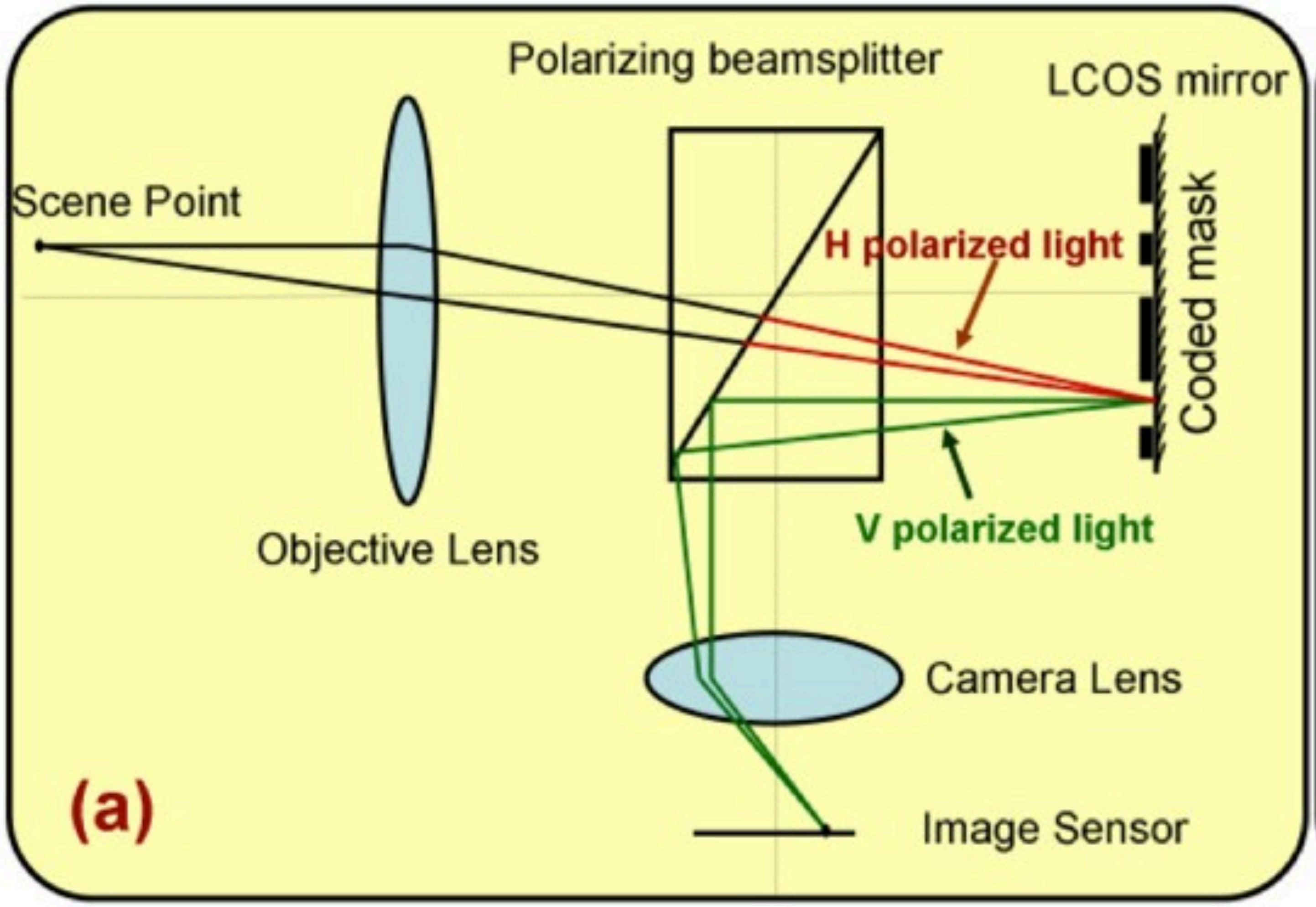
Highspeed Coded Strobing Imaging

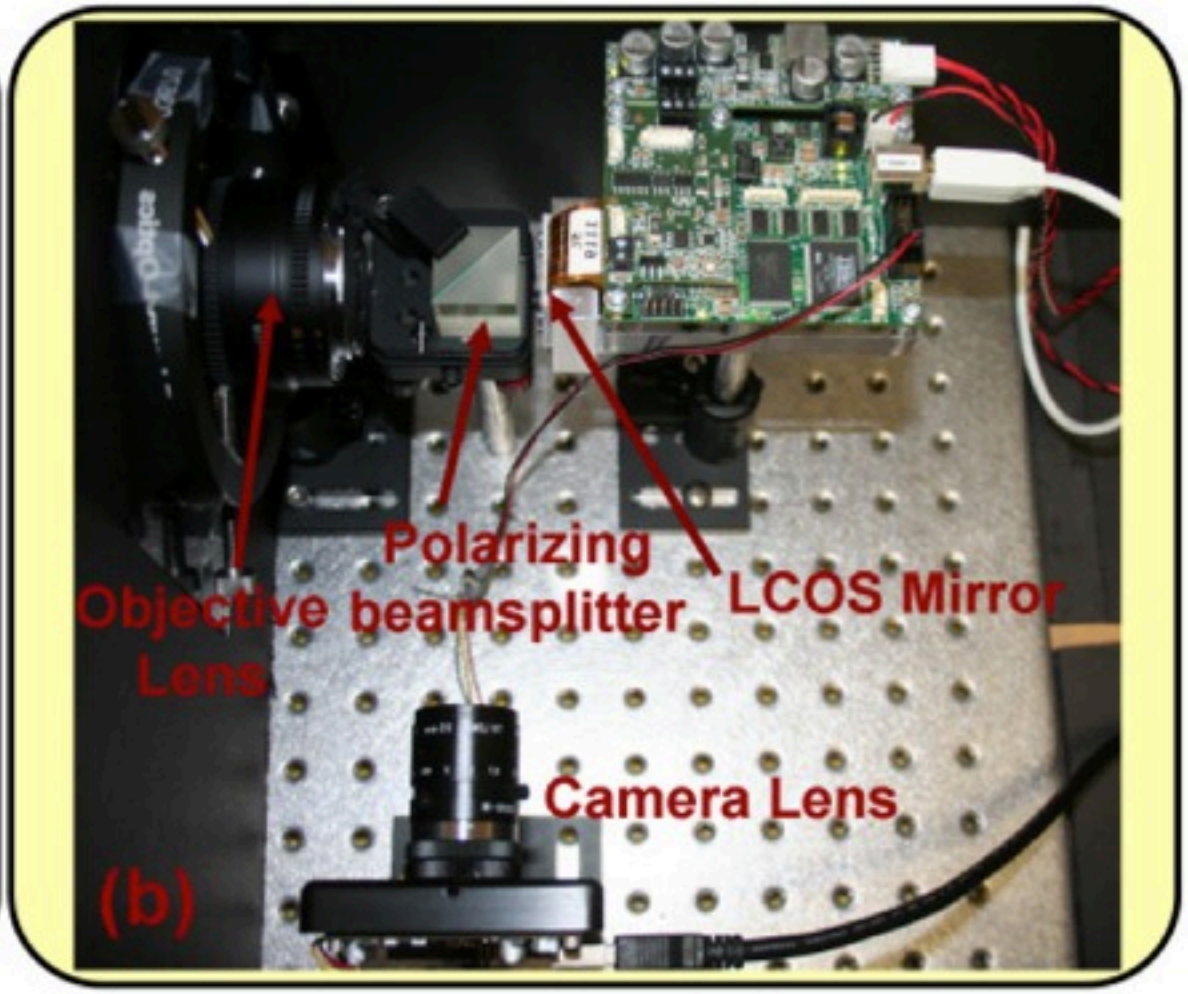


R. Dikpal, A. Veeraraghavan, and R. Chellappa. "P2C2: Programmable pixel compressive camera for high speed imaging" Computer Vision and Pattern Recognition (CVPR), 2011 IEEE Conference on. IEEE, 2011.

Highspeed Coded Strobing Imaging

Optically:

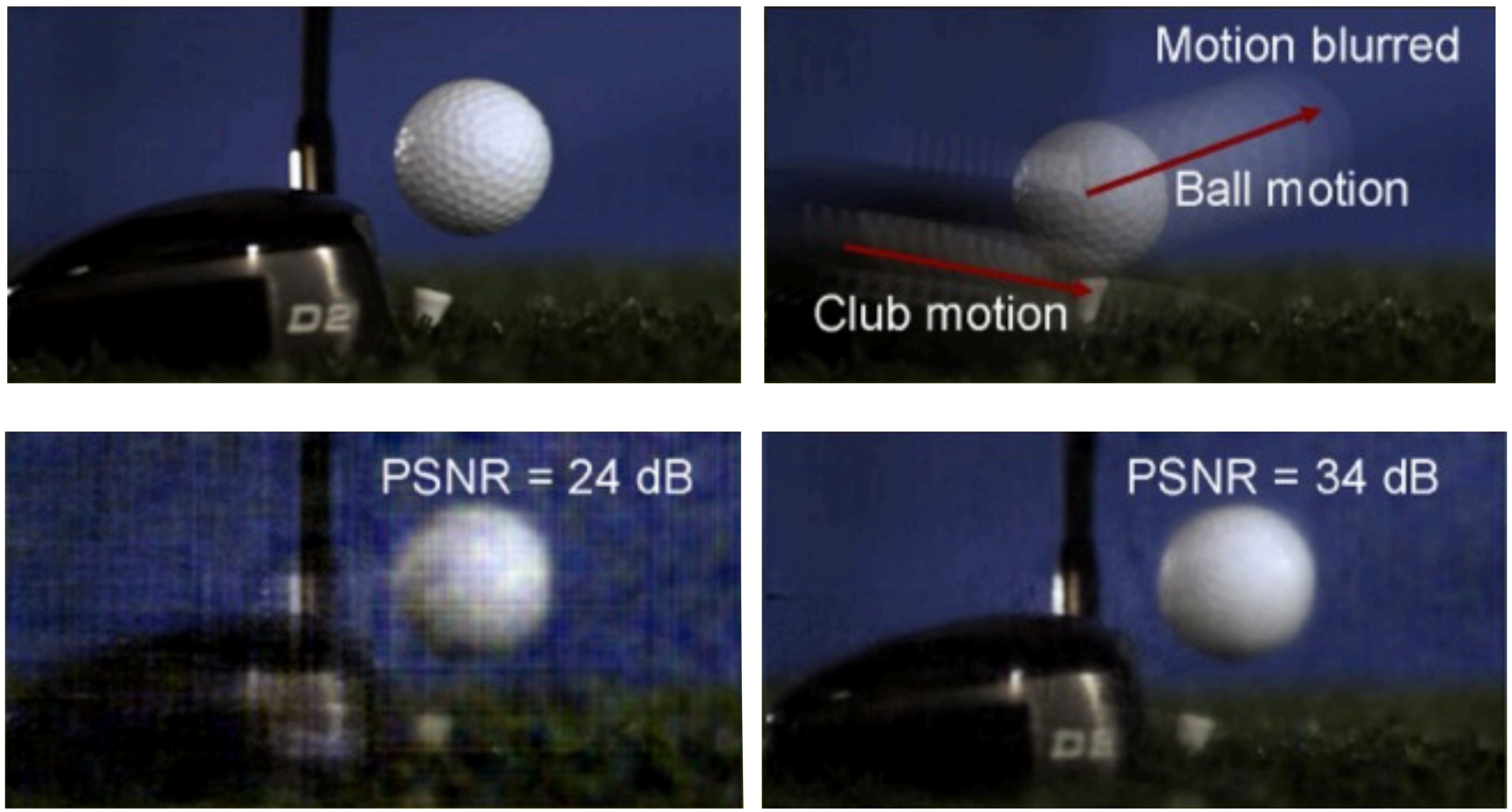




R. Dikpal, A. Veeraraghavan, and R. Chellappa. "P2C2: Programmable pixel compressive camera for high speed imaging" Computer Vision and Pattern Recognition (CVPR), 2011 IEEE Conference on. IEEE, 2011.

Highspeed Coded Strobing Imaging

- Reconstruction: regularized with optical flow



with wavelet prior | + optical flow reg.

R. Dikpal, A. Veeraraghavan, and R. Chellappa. "P2C2: Programmable pixel compressive camera for high speed imaging" Computer Vision and Pattern Recognition (CVPR), 2011 IEEE Conference on. IEEE, 2011.

Conclusions

Conclusion

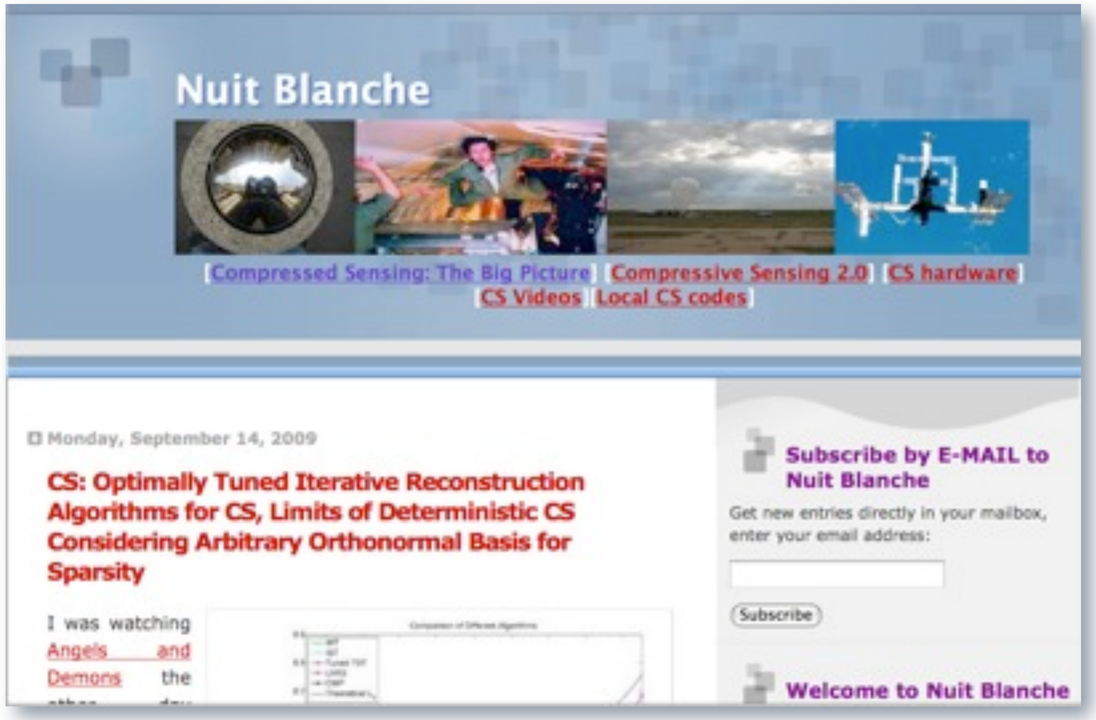
- Sparsity prior involves new sensing methods:
  e.g., Compressed Sensing, Compressive Imaging.
- Future:
  - More sensing examples: http://nuit-blanche.blogspot.com
    hyperspectral, network, GPR, Lidar, ... (explosion)
  - Better sparsity prior:
    structured, model-based, mixed-norm (Cevher, Bach, ...)
    co-sparsity/analysis model (Gribonval, Nam, Davies, Elad, Candes)
  - Non-linear sensing models ?
    1-bit CS is one instance, phase recovery (Candès),
    polychromatic CT, ...

Links (Science 2.0.)

- Rice CS Resources page:
  http://www-dsp.rice.edu/cs

- Igor Carron's
  "*Nuit Blanche*" blog:
  http://nuit-blanche.blogspot.com

  1 CS post/day!



Thank you!