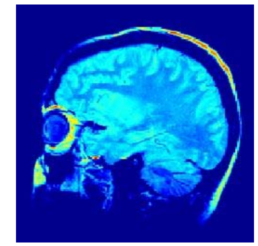
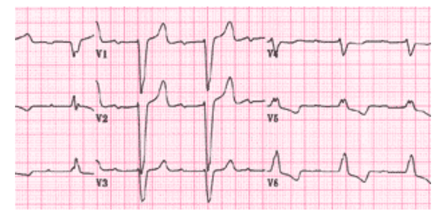
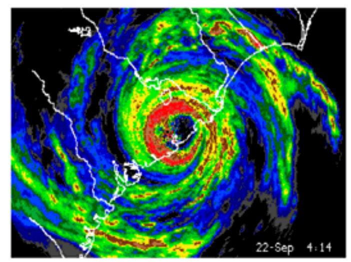
# DMD Implementation of a Single Pixel Camera Based on Compressed Sensing

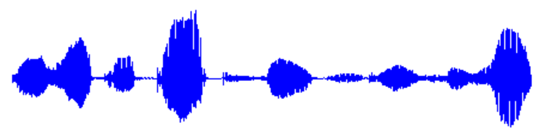
*Dharmpal Takhar*

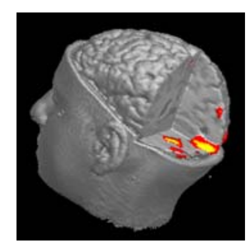
ECE Department
Rice University
dsp.rice.edu/cs



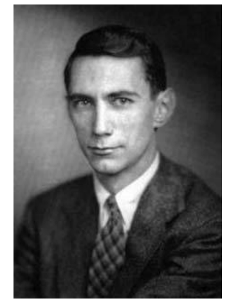


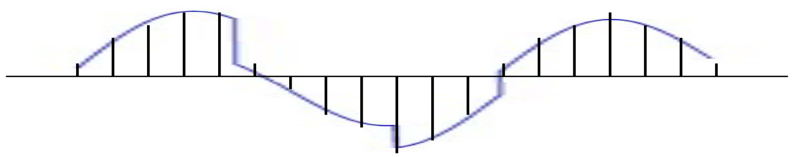


# Pressure is on Digital Signal Processing

- Shannon/Nyquist sampling theorem
  - no information loss if we sample at 2x signal bandwidth



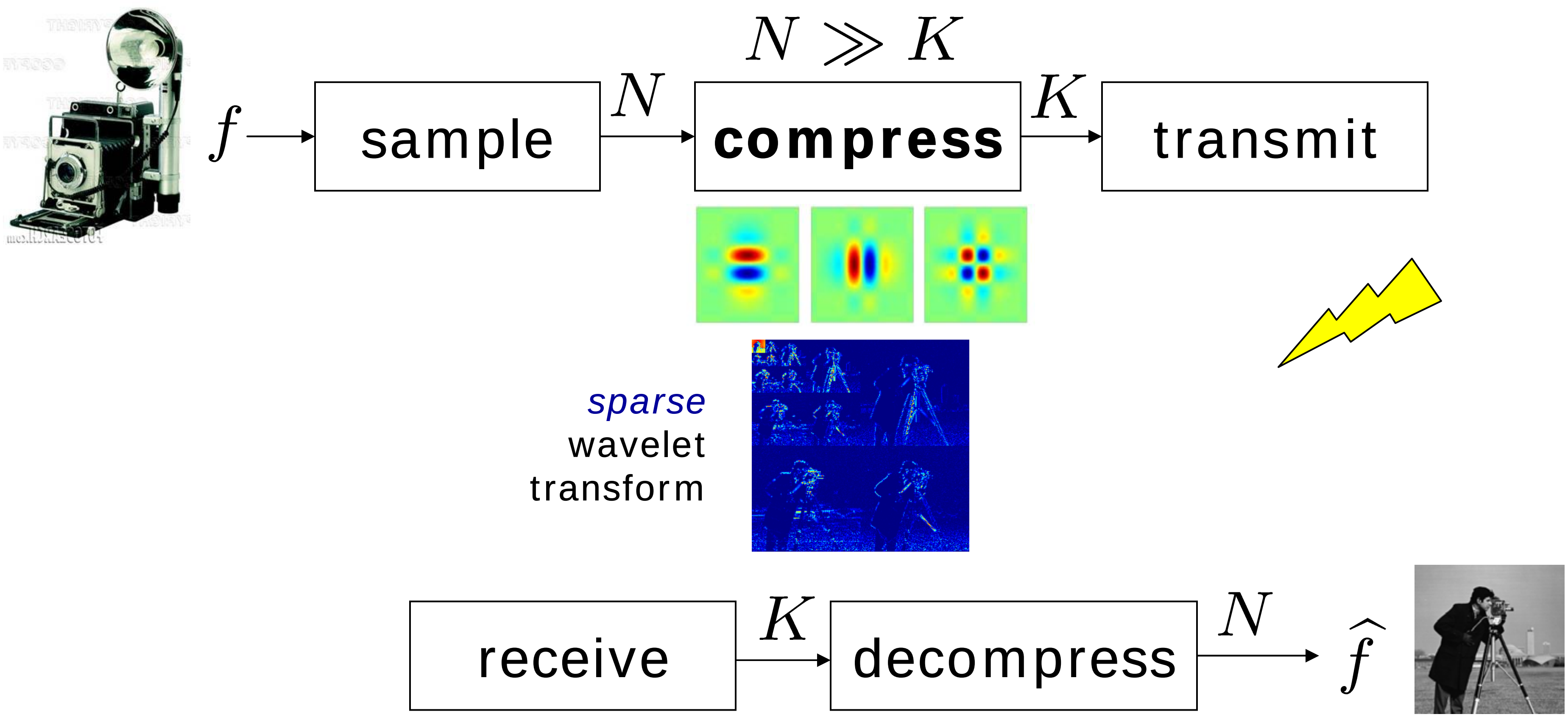
- DSP revolution:
  *sample first and ask questions later*



- Increasing *pressure* on DSP hardware, algorithms
  - ever faster sampling and processing rates
  - ever larger dynamic range
  - ever larger, higher-dimensional data
  - ever lower energy consumption
  - ever smaller form factors
  - multi-node, distributed, networked operation
  - radically new sensing modalities
  - communication over ever more difficult channels

# Sensing by *Sampling*

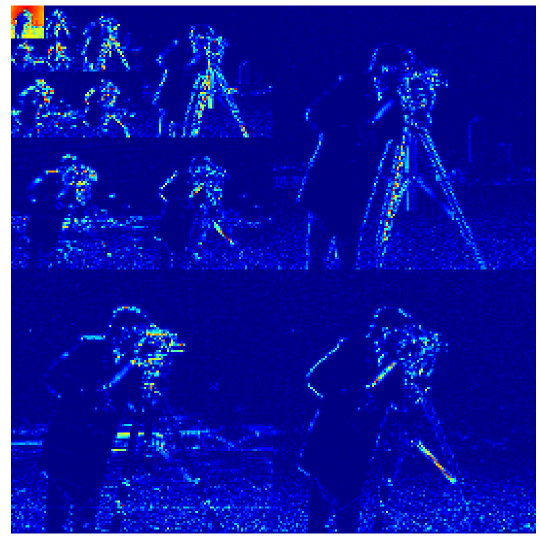
- Long-established paradigm for digital data acquisition
  - ***sample*** data (A-to-D converter, digital camera, …)
  - ***compress*** data (signal-dependent, nonlinear)
  - brick wall to performance of modern acquisition systems



# Sparsity

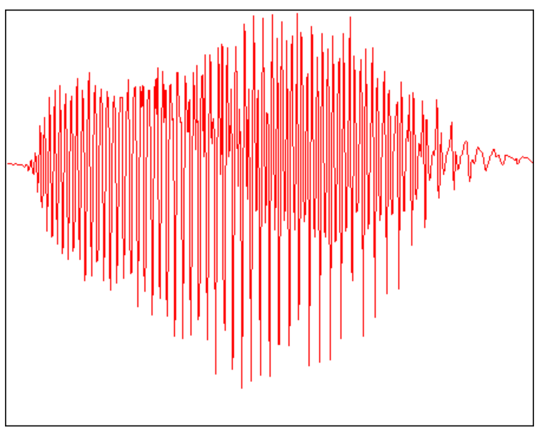
- Many signals can be *sparsely represented* in some representation/basis (Fourier, wavelets, ...)

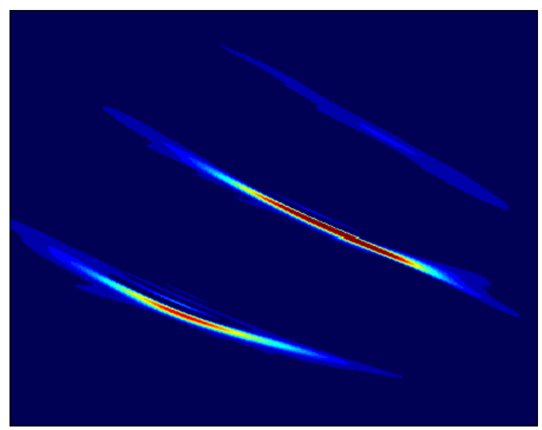
$N$
pixels



$K \ll N$
large
wavelet
coefficients

$N$
wideband
signal
samples

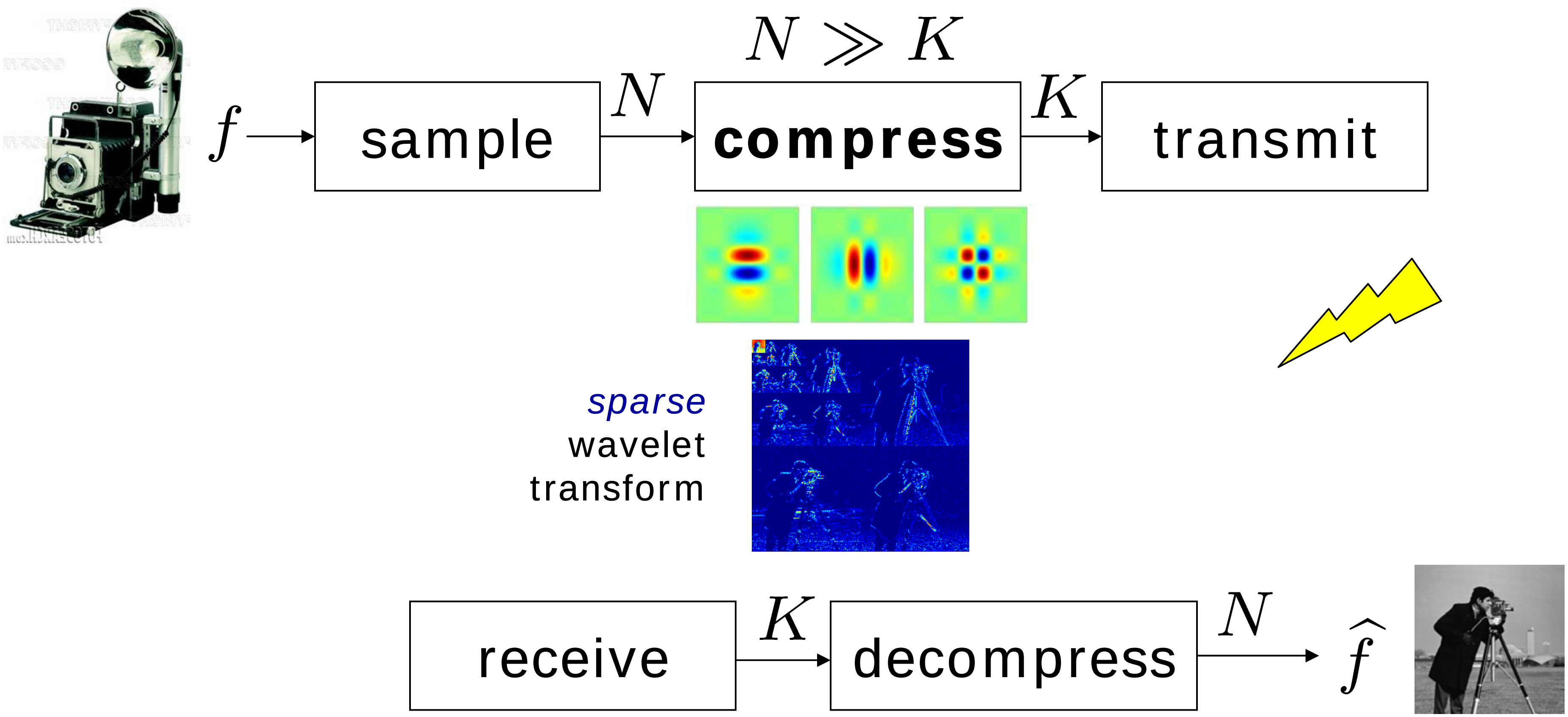




$K \ll N$
large
Gabor
coefficients

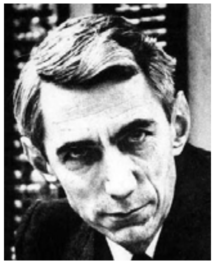
# Sensing by *Sampling*

- Long-established paradigm for digital data acquisition
  - ***sample*** data (A-to-D converter, digital camera, ...)
  - ***compress*** data (signal-dependent, nonlinear)
  - ***brick wall*** to performance of modern acquisition systems



# From Samples to *Measurements*

- Shannon/Nyquist sampling theorem
  - must sample at 2x signal bandwidth
  - *too pessimistic for many signal classes*
  - worst case bound for *any* bandlimited data



- *Compressive sensing* (CS) principle
  [Donoho; Candes, Romberg, Tao; Rice, …]

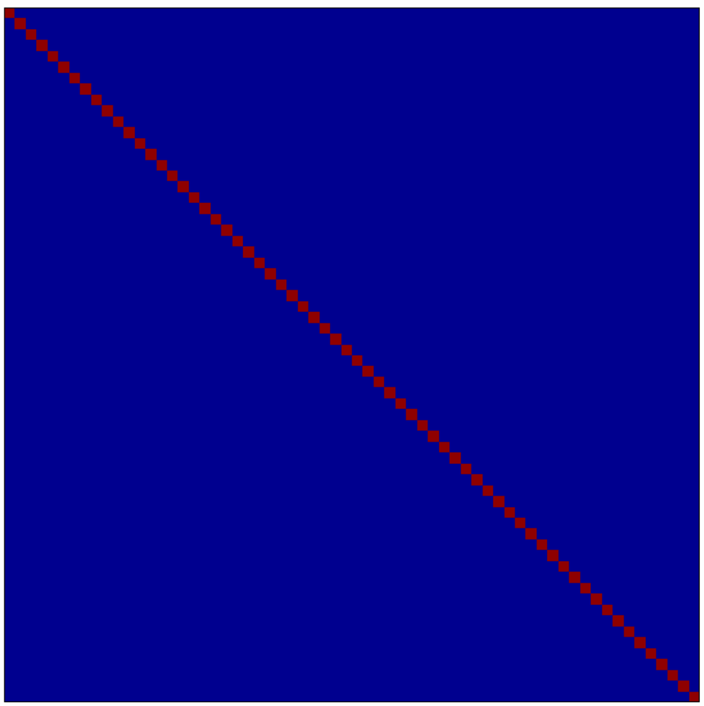
  “sparse signal statistics can be recovered from
  a small number of *non-adaptive linear measurements*

  - ***integrates sensing, compression, processing***
  - enables sub-Nyquist “measuring”
  - leverages new *sparse* data representations
  - based on new *uncertainty principles* that extend Heisenberg’s
  - features *random* projections/measurements
  - signal recovery via *optimization* (linear programming)

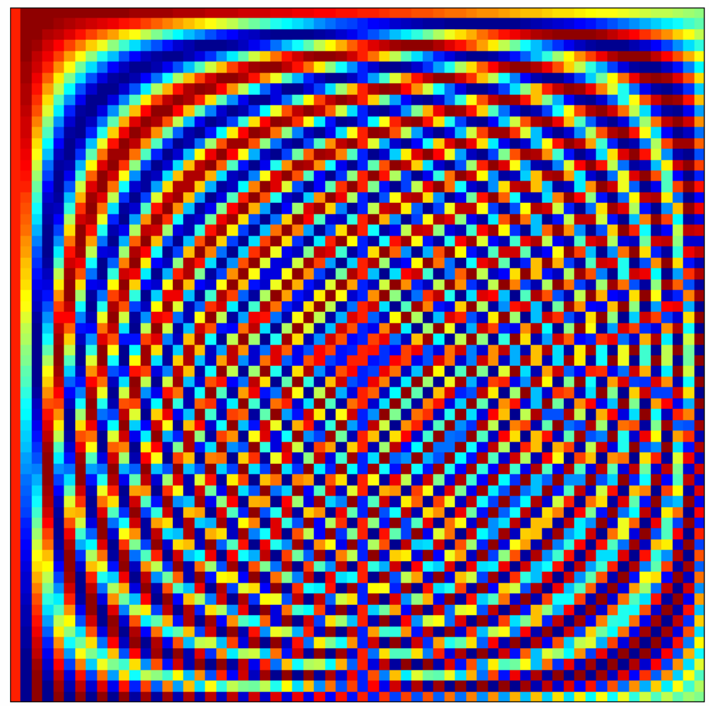
# Incoherent Bases

- Spikes and sines (Fourier) (Heisenberg)

$$\Psi = I$$



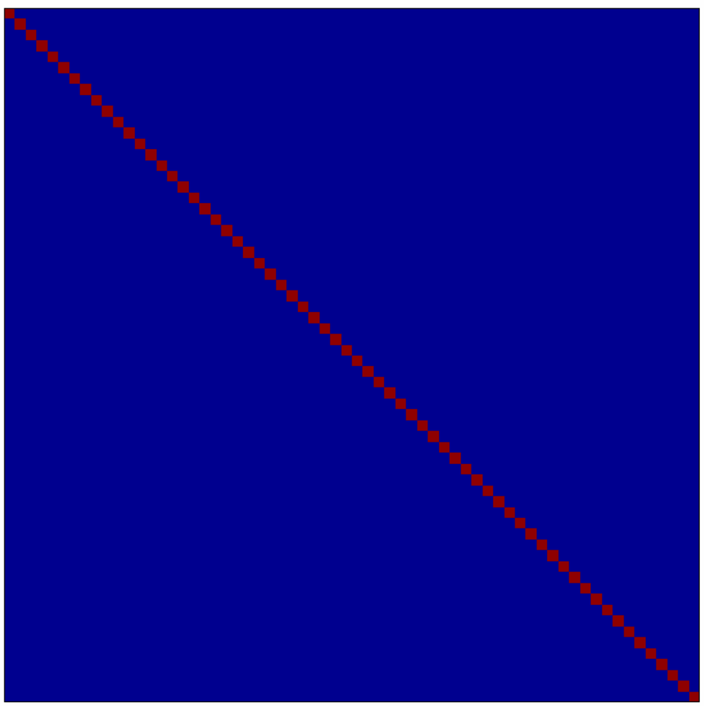
$$\Phi = \mathrm{idct}(I)$$



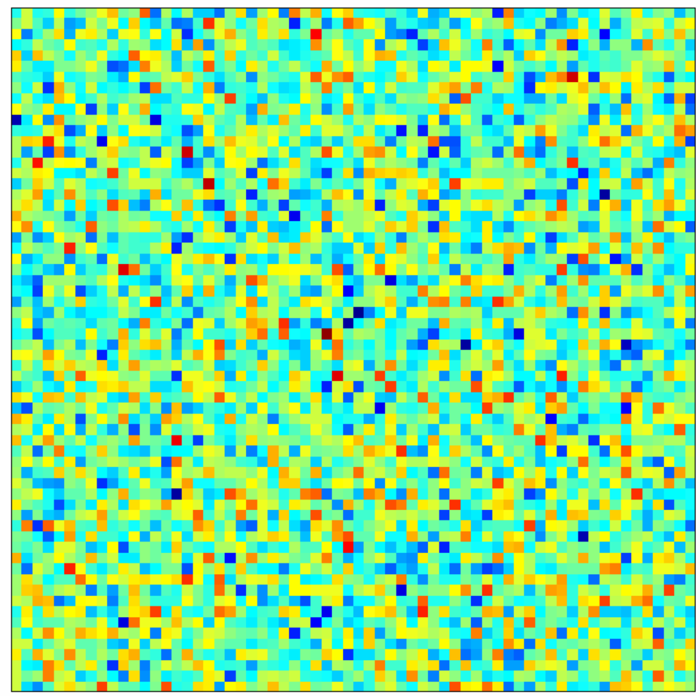
# Incoherent Bases

- Spikes and "random basis"

$$\Psi = I$$



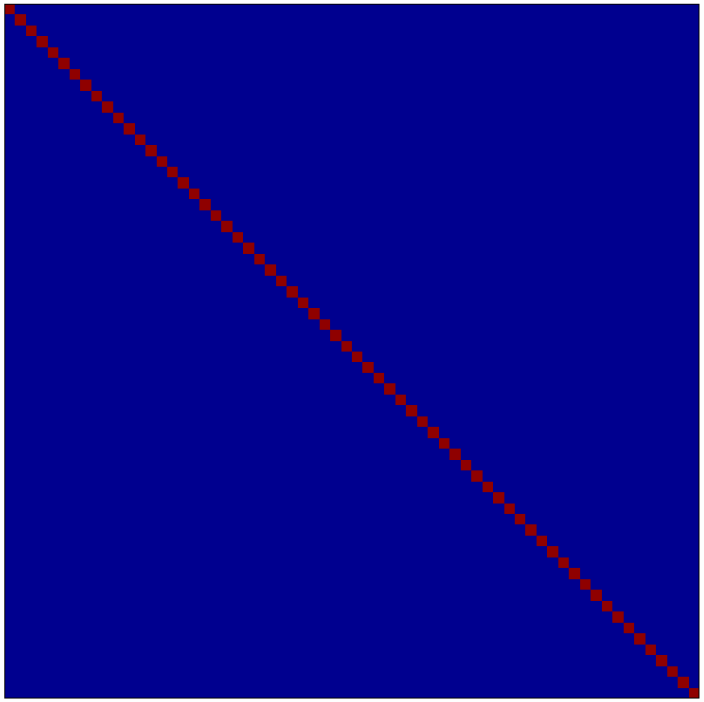
$$\Phi = \mathrm{randn}(N, N)$$

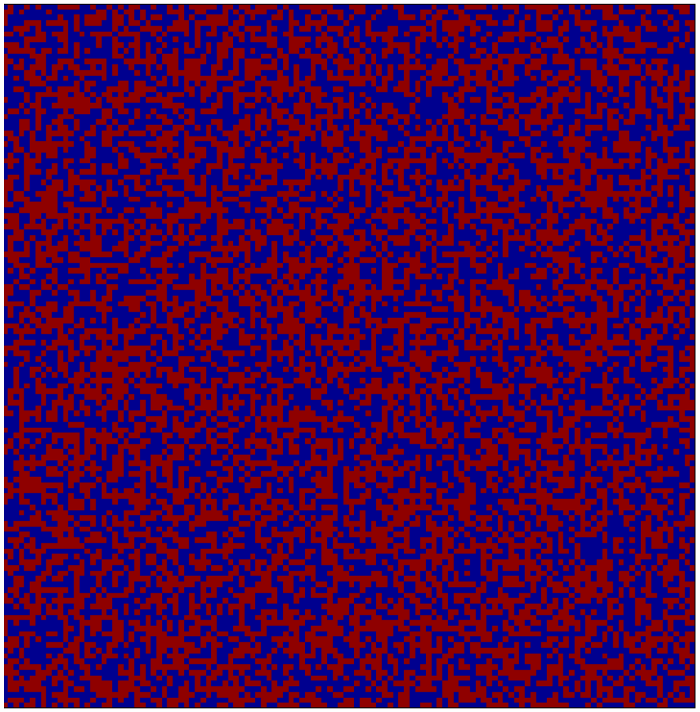


# Incoherent Bases

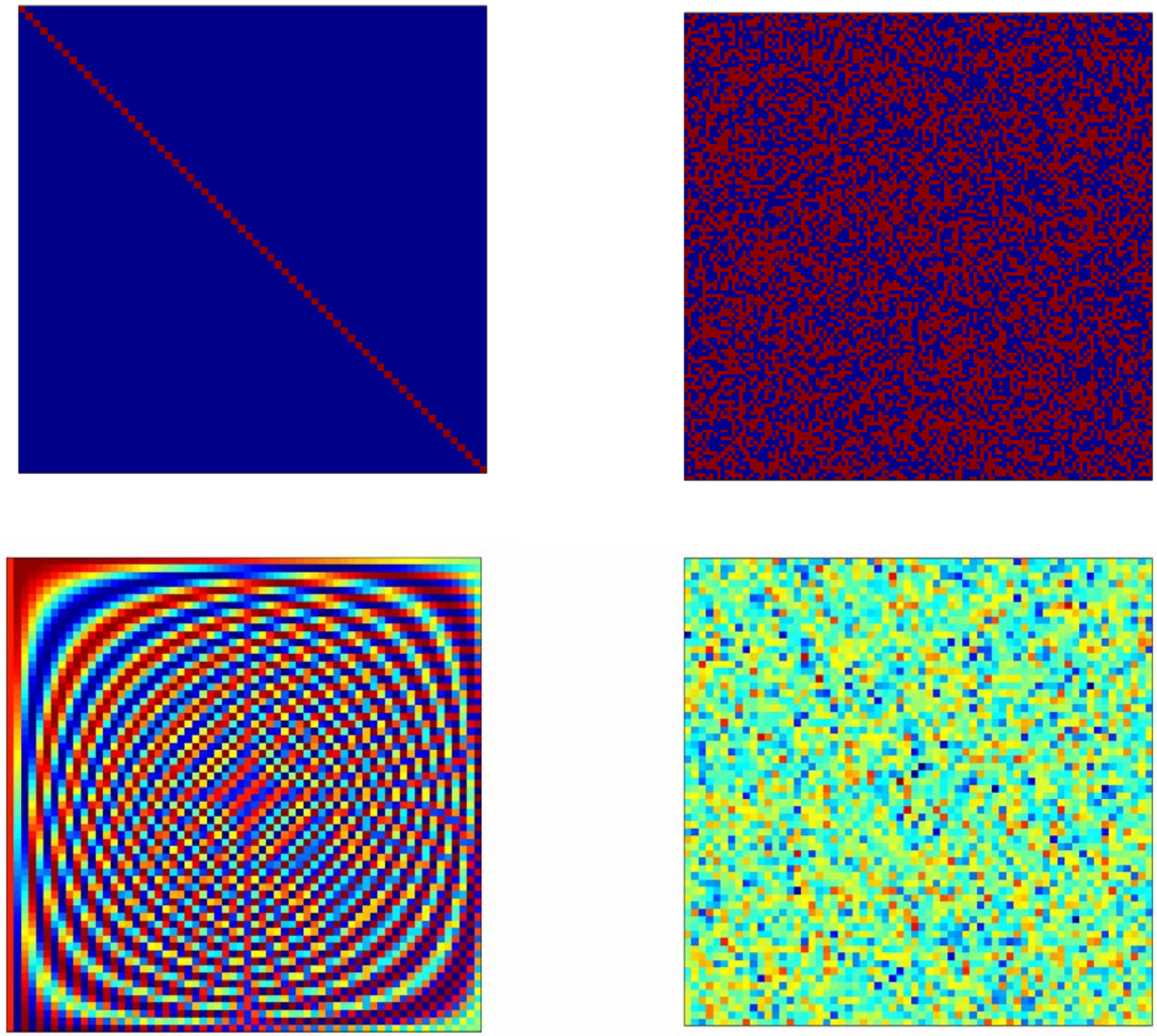
- Spikes and “random sequences” (codes)

$$\Psi = I \qquad \Phi$$



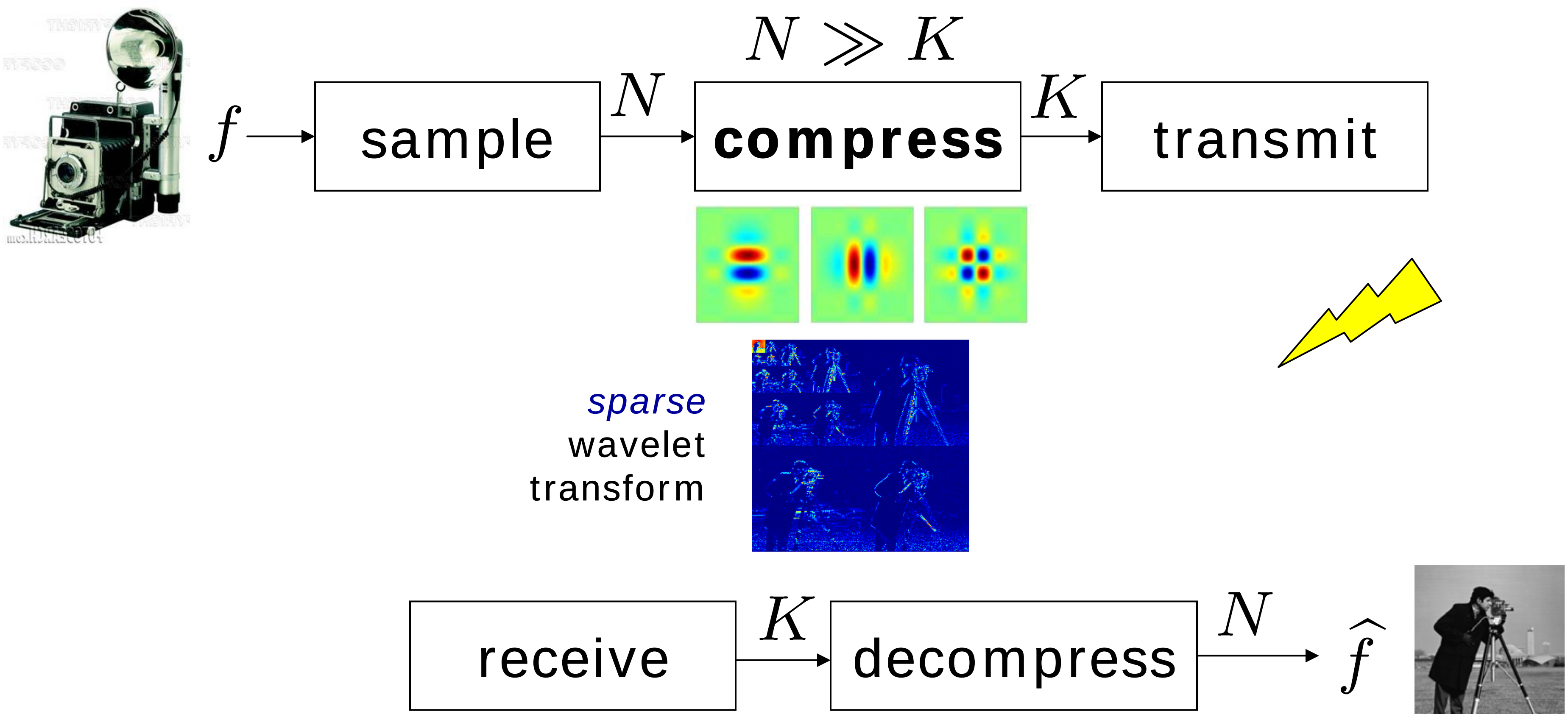


# Incoherent Bases



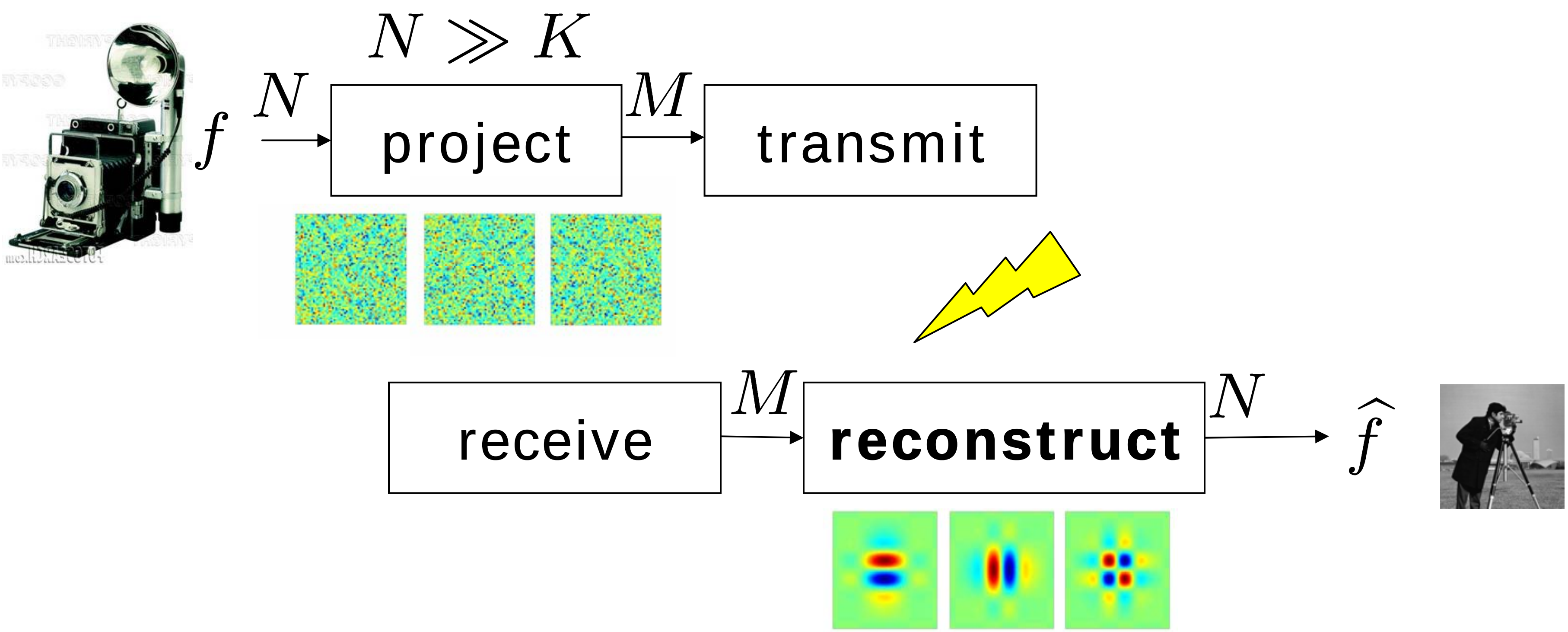
# Sensing by *Sampling*

- Long-established paradigm for digital data acquisition
  - ***sample*** data (A-to-D converter, digital camera, ...)
  - ***compress*** data (signal-dependent, nonlinear)
  - ***brick wall*** to performance of modern acquisition systems



# Compressive Sensing

- Measure linear projections onto *incoherent* basis where data is *not sparse*
  - random "white noise" is *universally incoherent*
  - mild "over-sampling" $M \approx O(K \log(N/K)) \ll N$

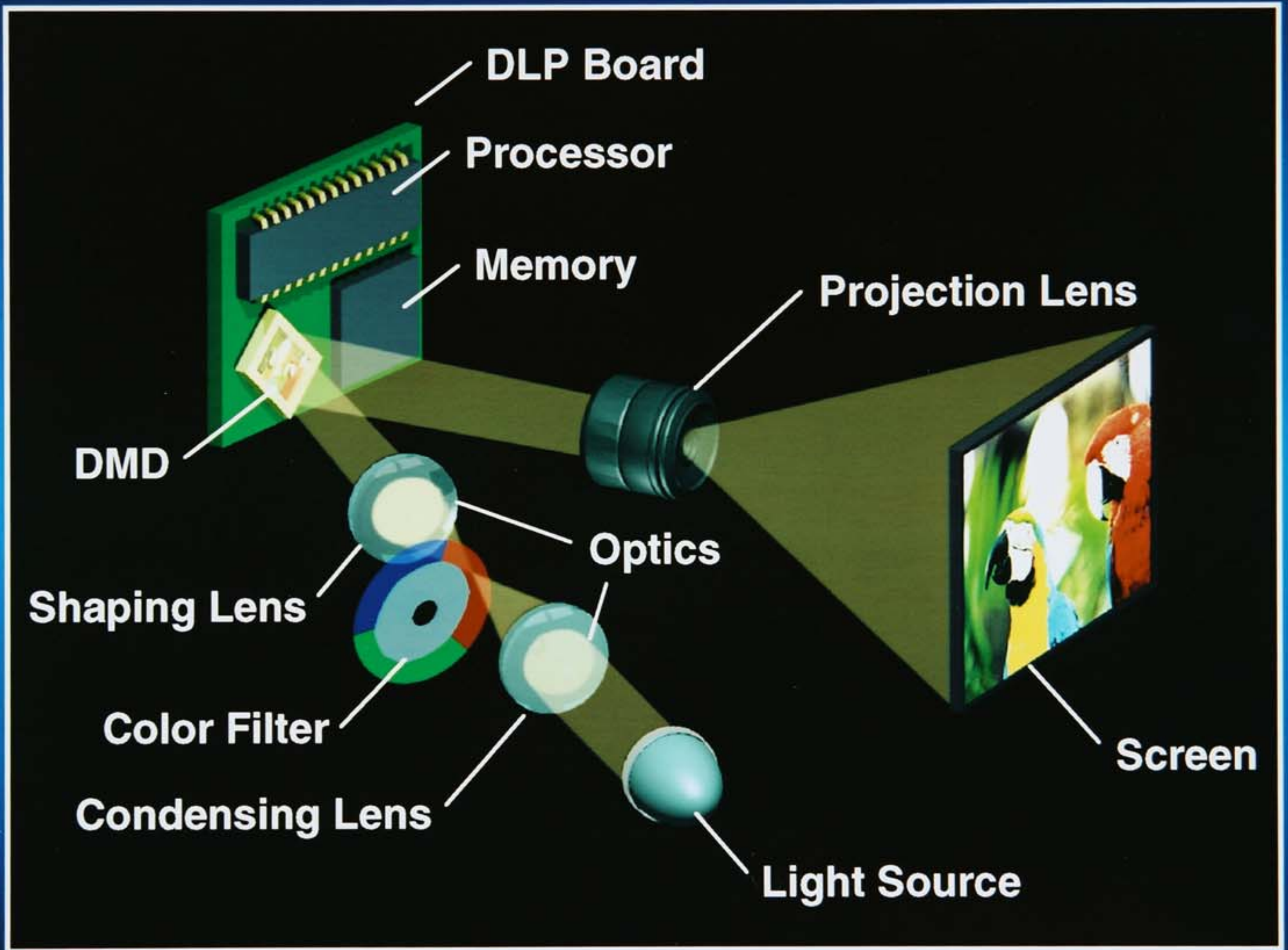



- Reconstruct via nonlinear optimization (linear programming)

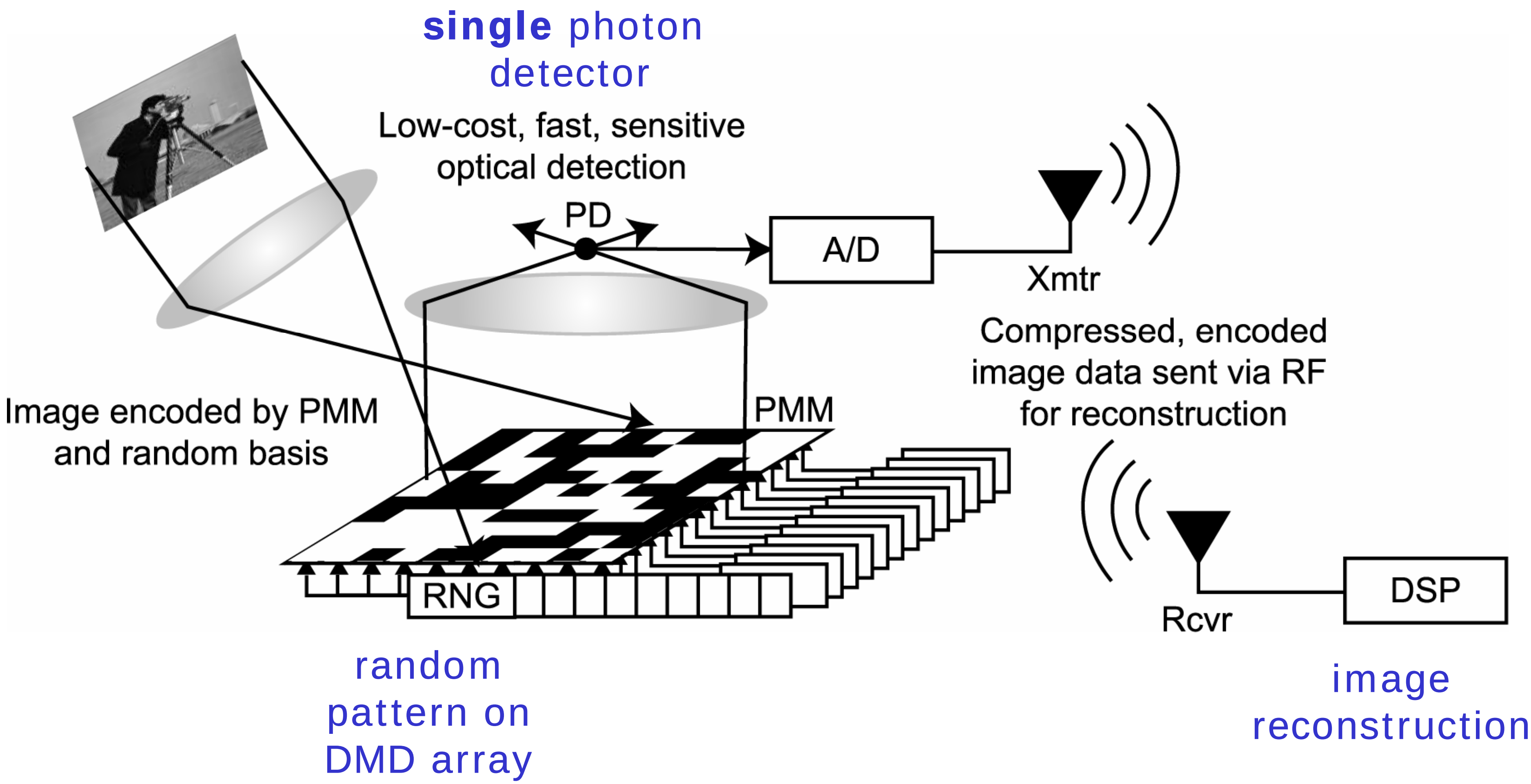
# CS Hallmarks

- CS changes the rules of the data acquisition game
  - beats the Nyquist limit
  - exploits a priori signal *sparsity* information
  - slogans: “sample less, compute more”
- Universal
  - same random projections / hardware can be used for *any* compressible signal class (*generic*)
- Democratic
  - each measurement carries the same amount of information
  - simple encoding
  - robust to measurement loss and quantization
  - natural “dimensionality reduction” for posing *vision* tasks
- Asymmetrical (most processing at decoder)
- Random projections weakly encrypted

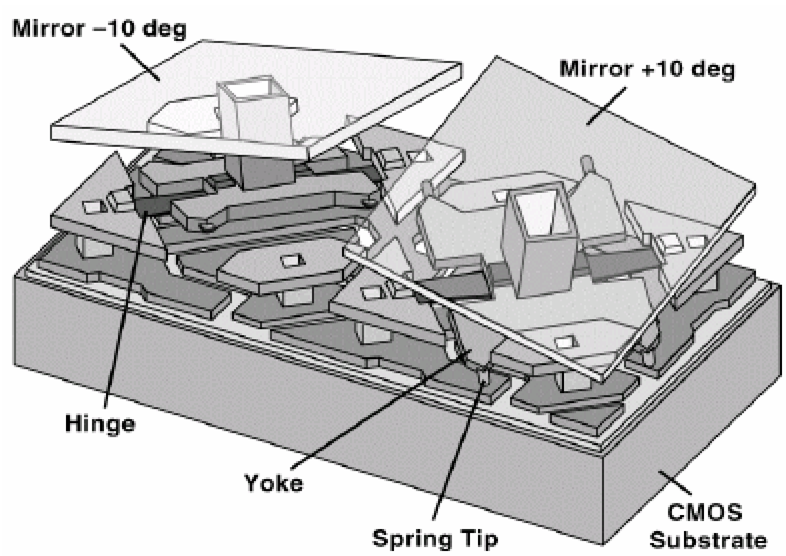
# 1 Chip DLP™ Projection

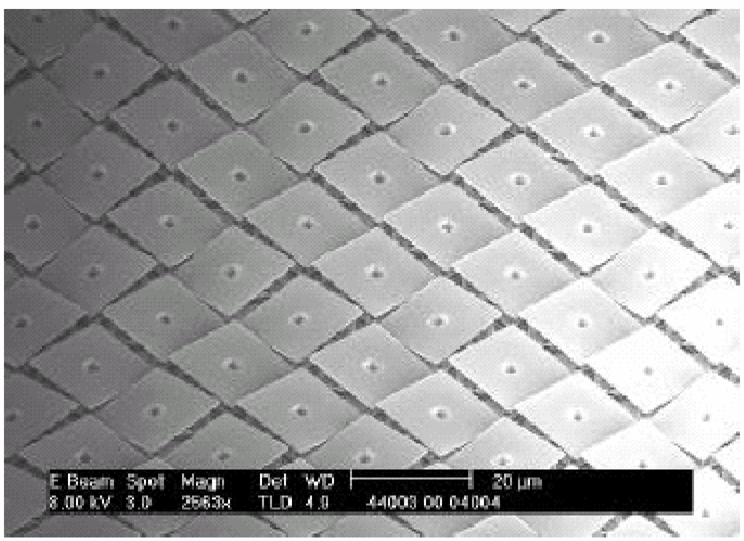


# DLP/DSP CS Camera



# TI Digital Micromirror Device (DMD)



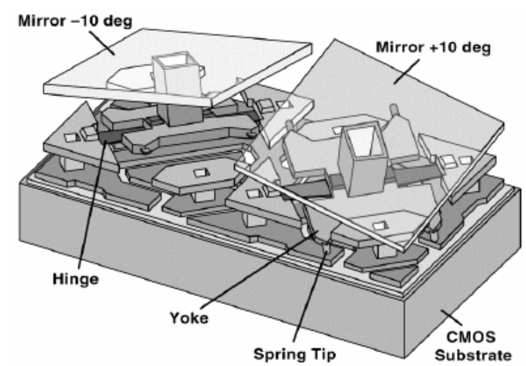





DLP 1080p --> 1920 x 1080 resolution

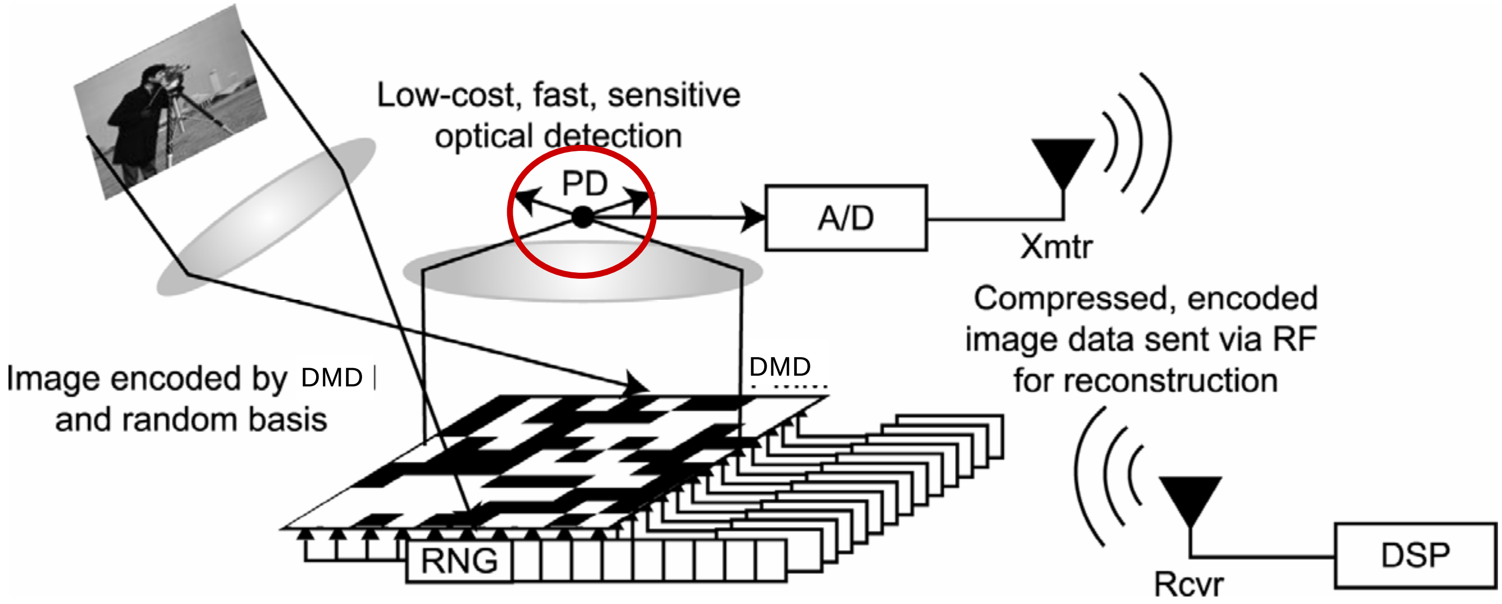
# (Pseudo) Random Optical Projections

- Binary patterns are loaded into mirror array:
  - light reflected towards the lens/photodiode (1)
  - light reflected elsewhere (0)
  - pixel-wise products summed by lens




- Pseudorandom number generator outputs measurement basis vectors
- Mersenne Twister [Matsumoto/Nishimura, 1997]
  - Binary sequence (0/1)
  - Period $2^{19937}$-1

# Single Sensor Camera

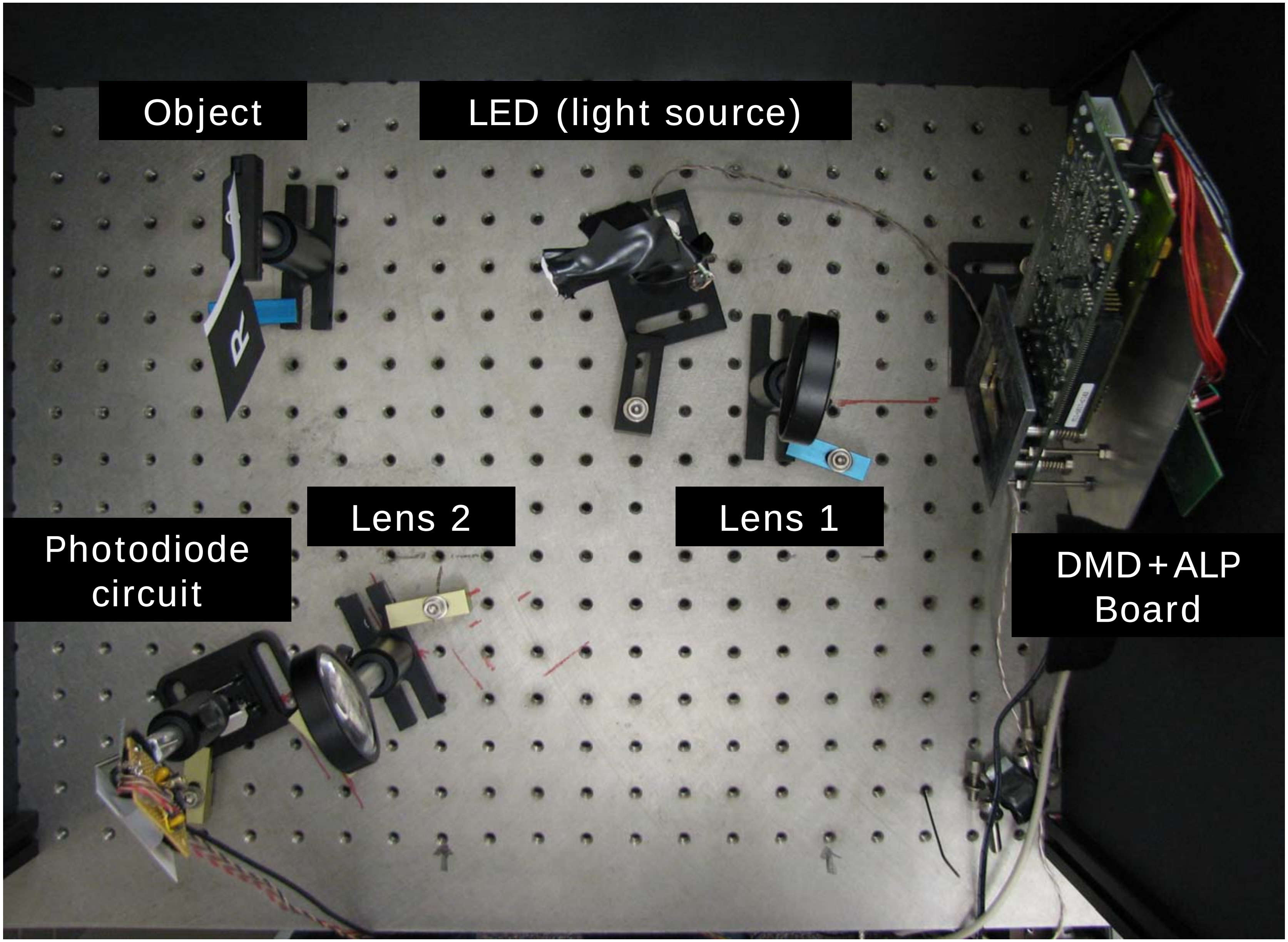



**Potential for:**

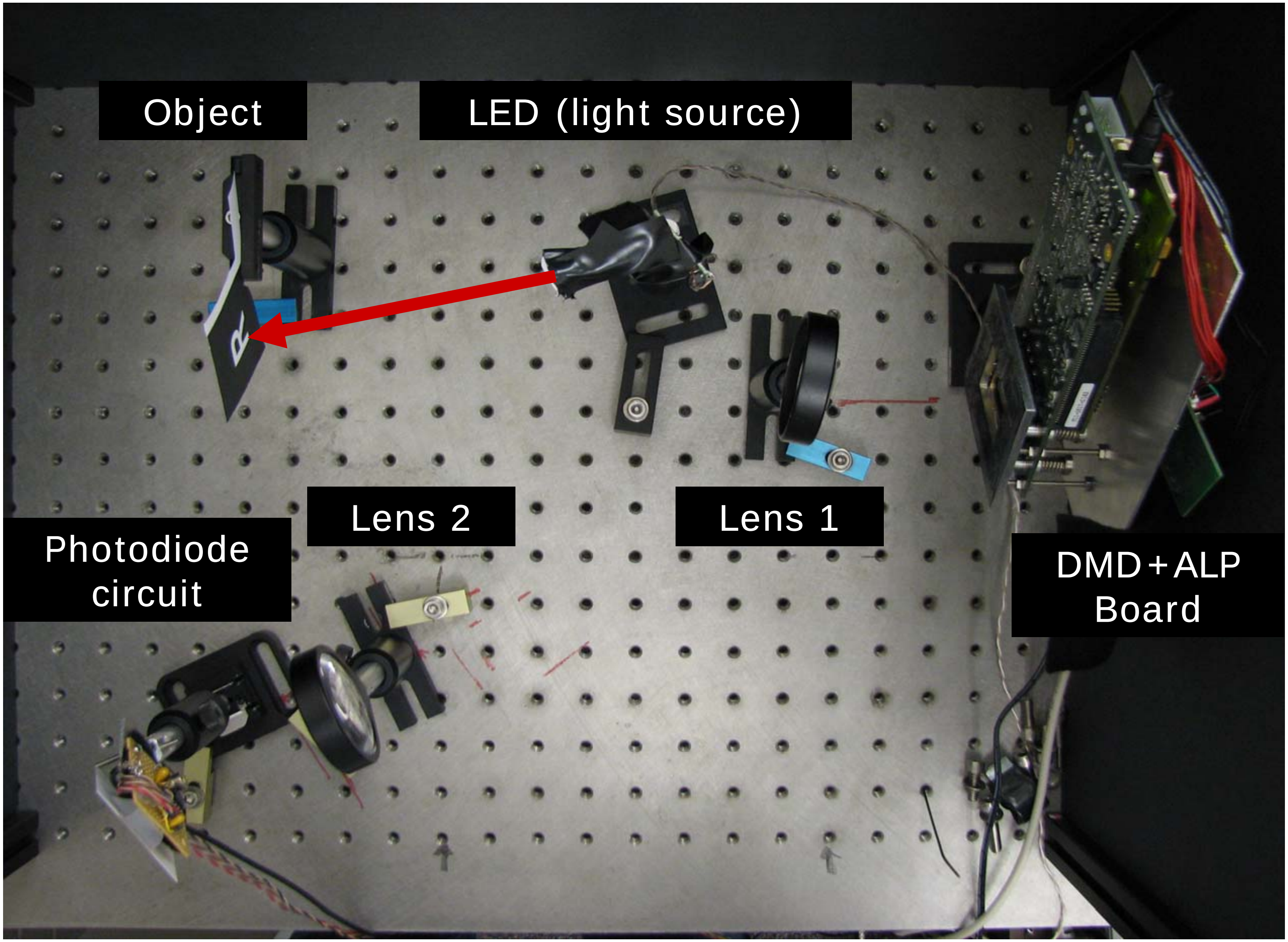
- new modalities

  beyond what can be sensed by CCD or CMOS imagers
- low cost
- low power

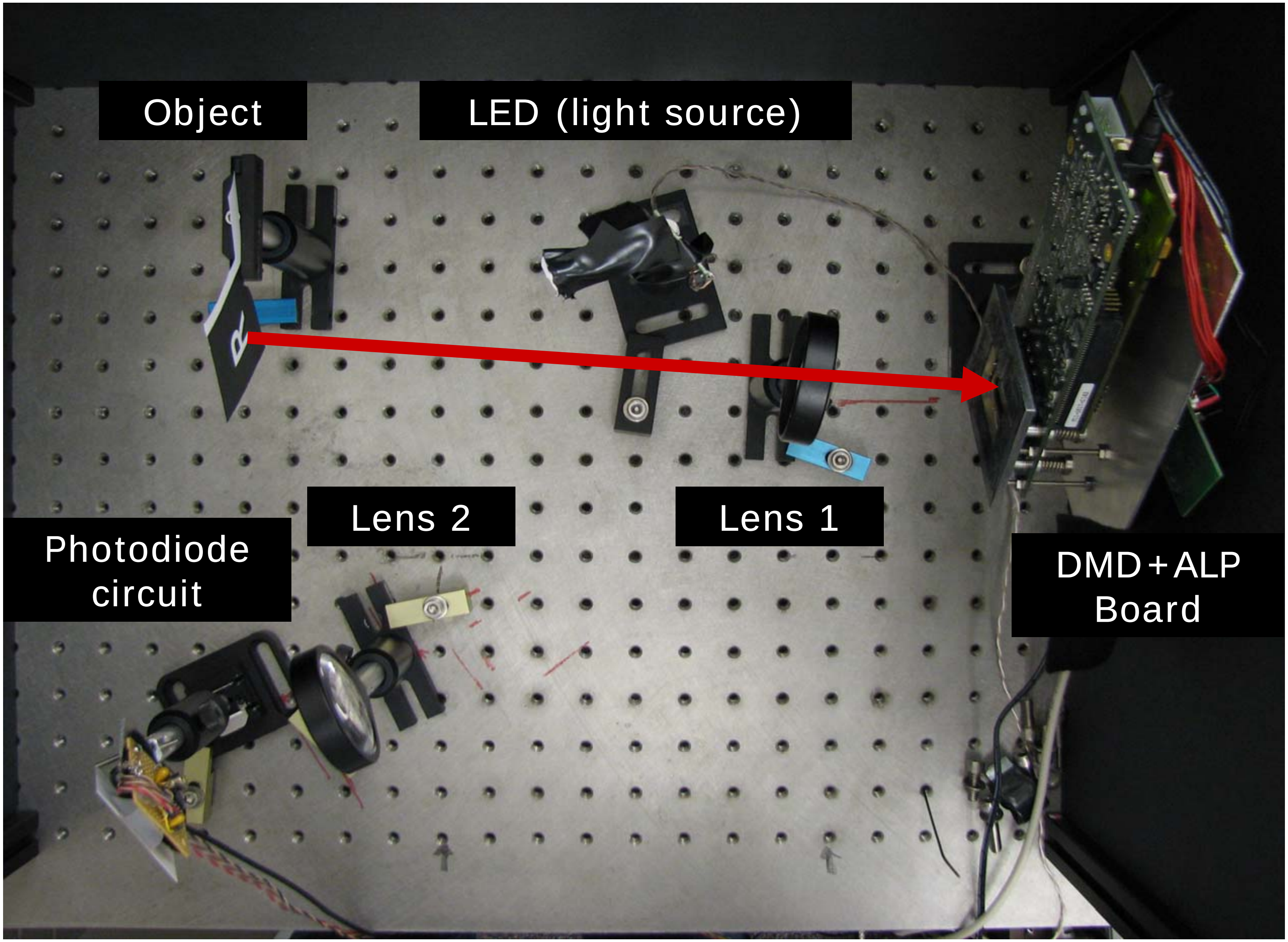
# DLP/DSP CS Camera



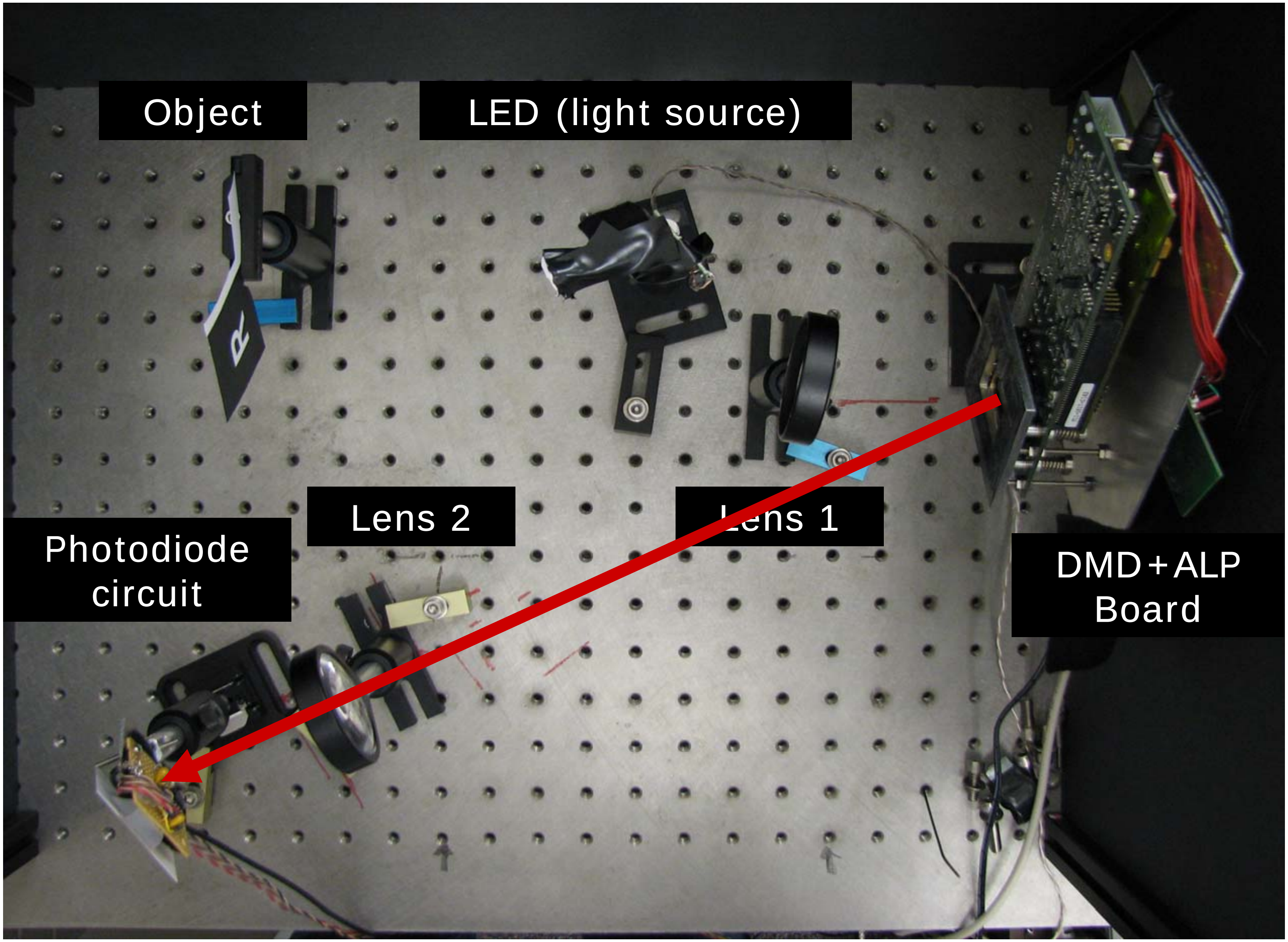
# DLP/DSP CS Camera



# DLP/DSP CS Camera



# DLP/DSP CS Camera



# First Image Acquisition

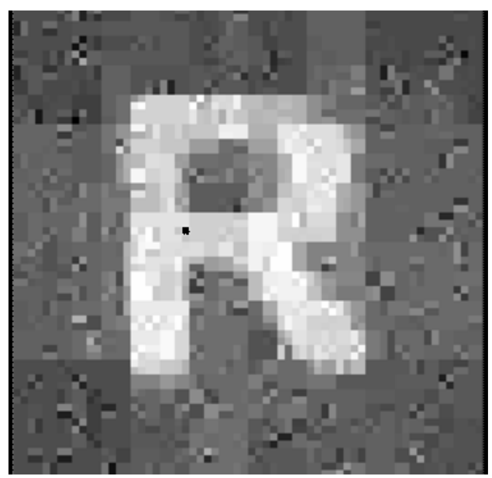
ideal 4096 pixels

205 wavelets

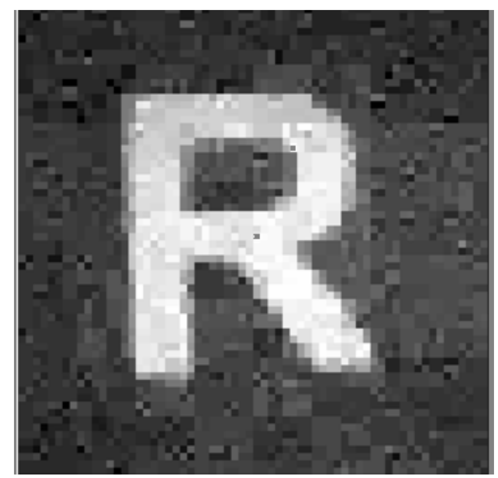
409 wavelets

image at
DMD array

820
random meas.

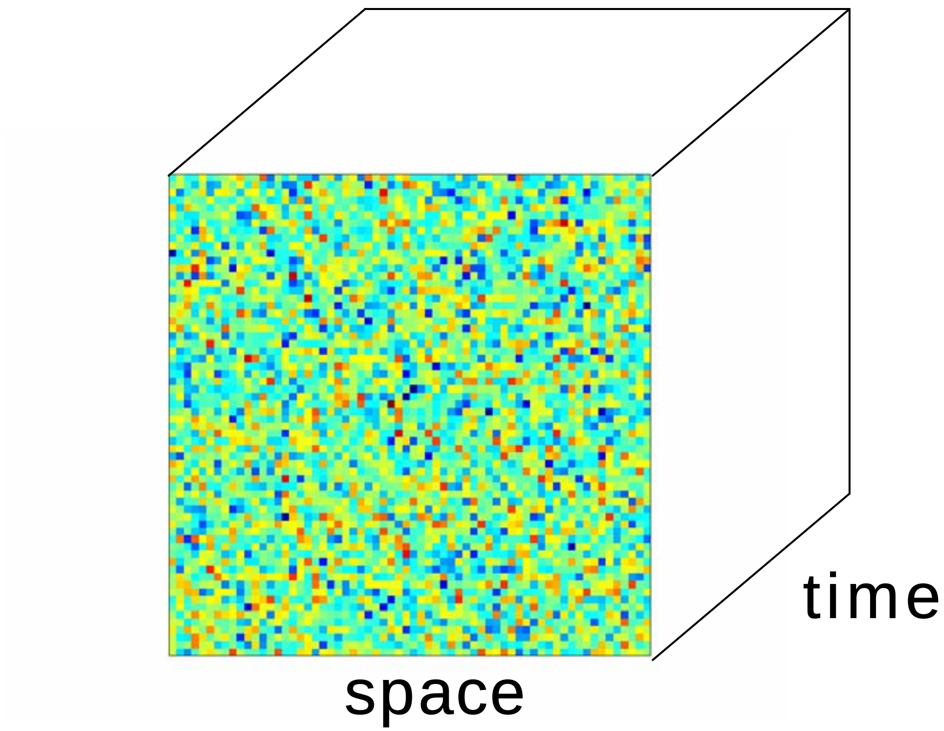


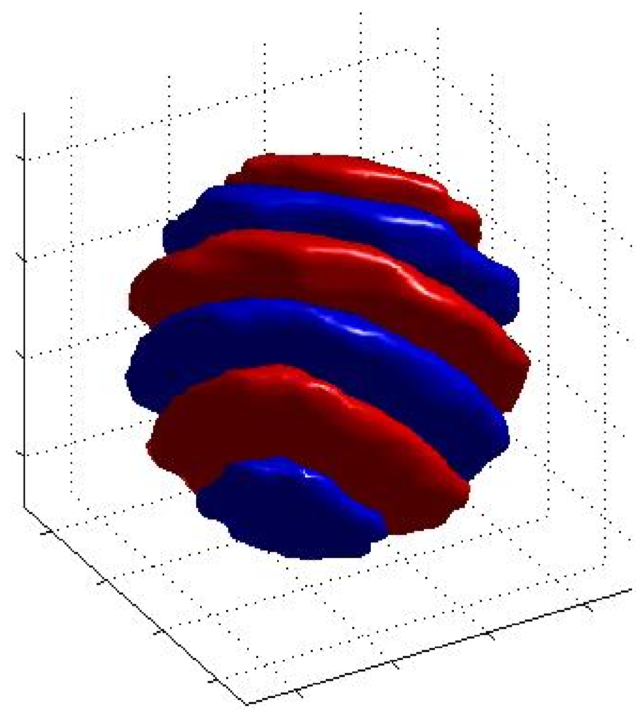
1638
random meas.



# CS Video Imaging

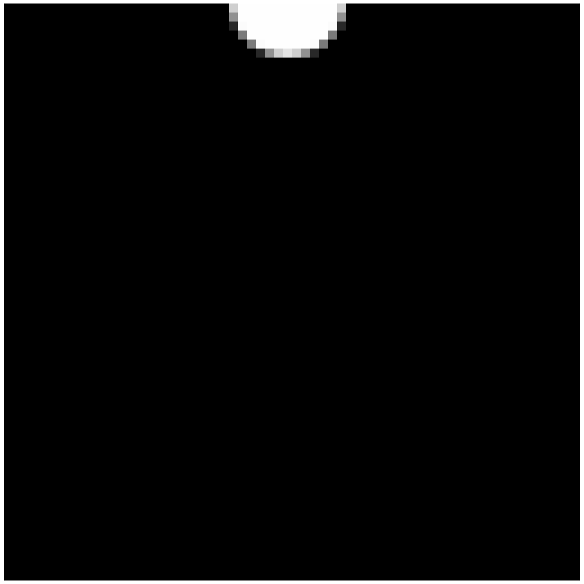
- Incoherent projections in space-time (random)
- Reconstruct using 3-D wavelets (localized in space-time)



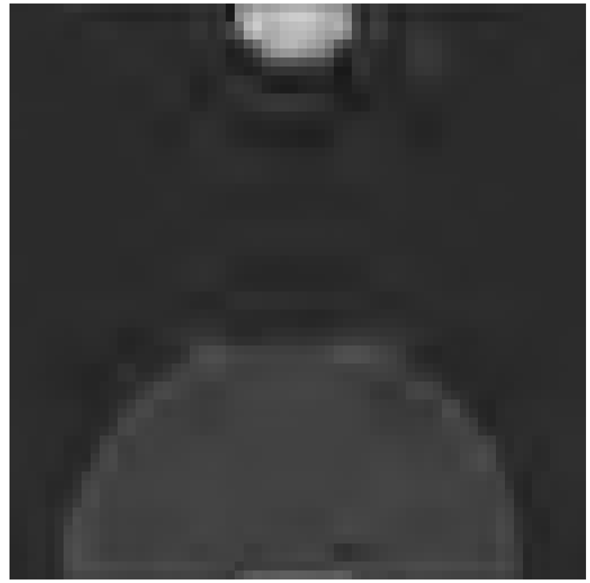



M. Wakin & R. Baraniuk

original 64x64x64

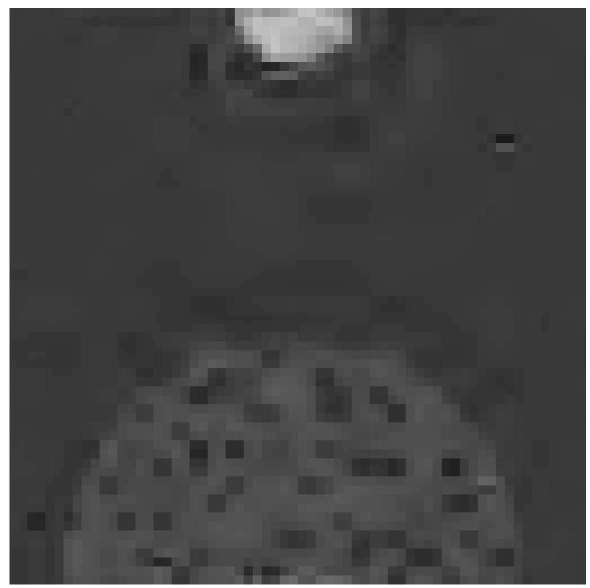


**3-D wavelet thresholding**
2000 coeffs, MSE = 3.5



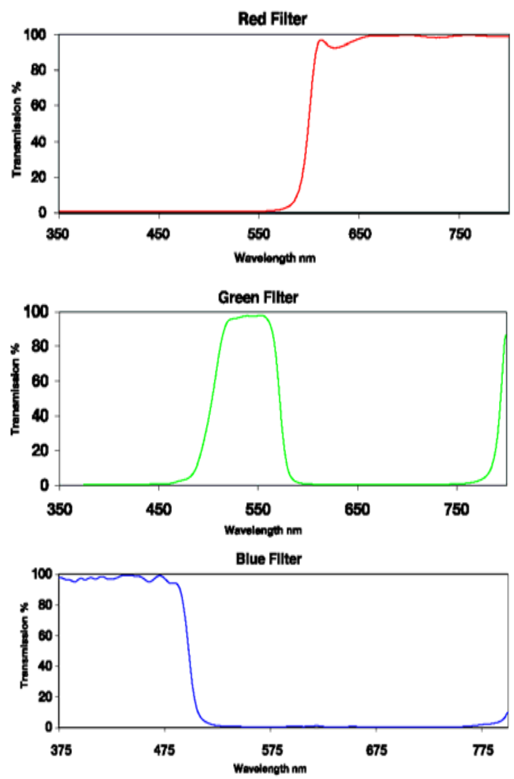
**frame-by-frame 2-D CS recon**
20000 coeffs, MSE = 18.4

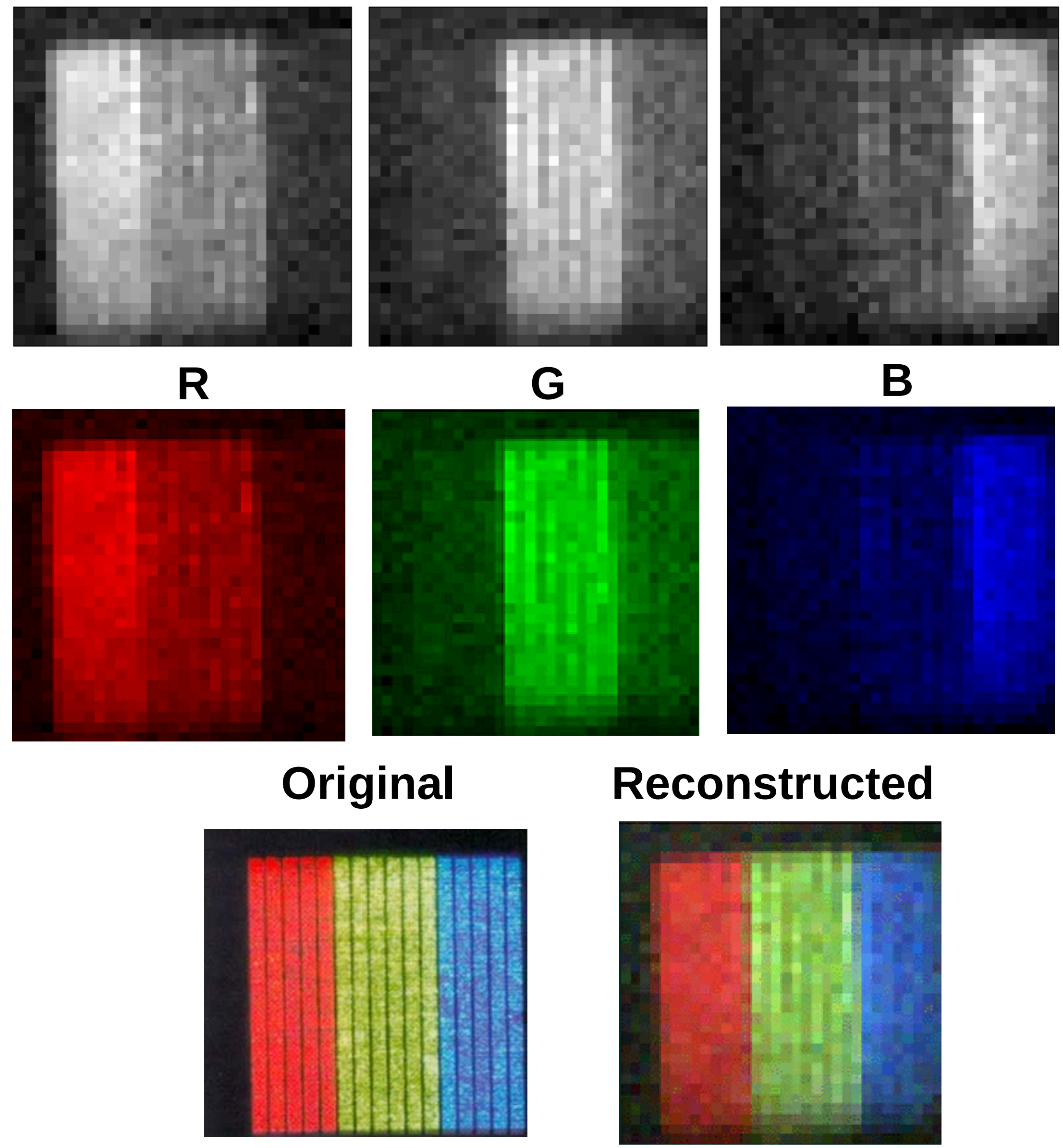
**joint 3-D CS recon**
20000 coeffs, MSE = 3.2



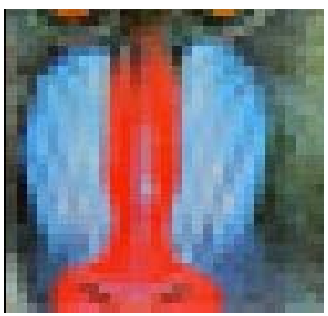
**M. Wakin & R. Baraniuk**

# Color CS Camera

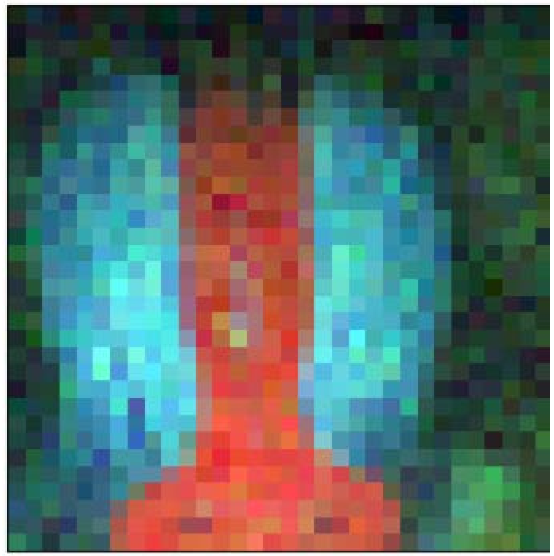



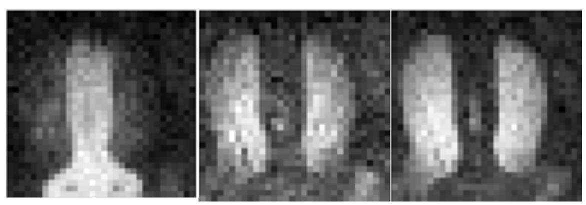



# Color Imaging with CS Camera

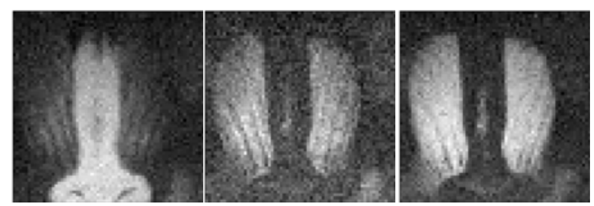


**Mandrill 32x32**



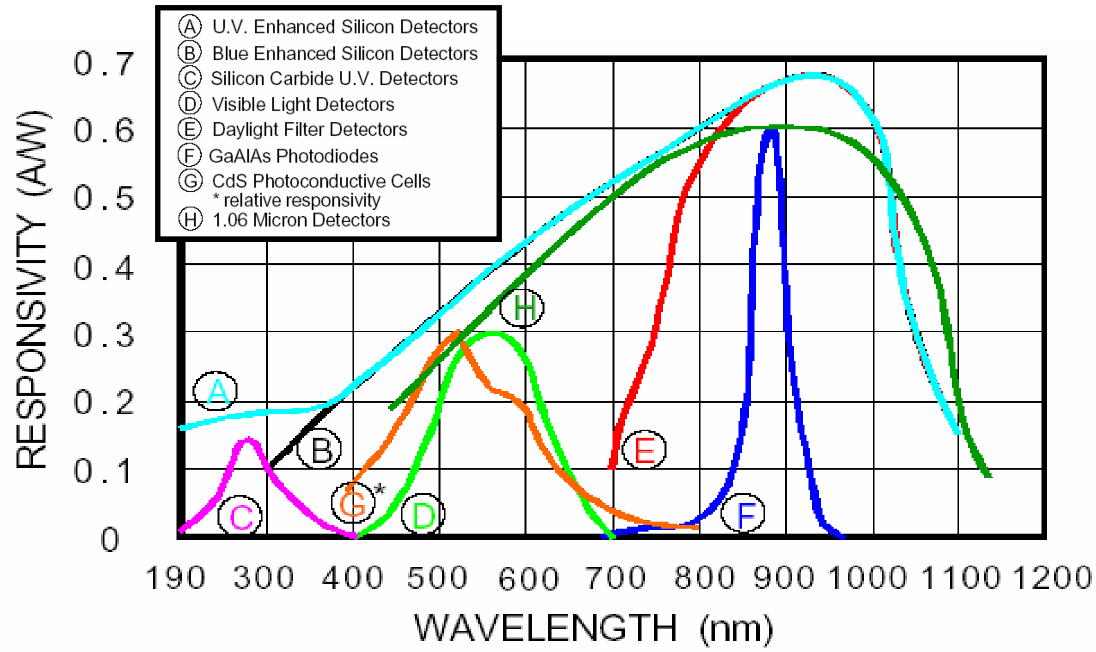


**Mandrill 64x64**



# Multispectral/Hyperspectral Imaging

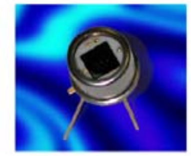
## Carousel of Differing Photodiodes

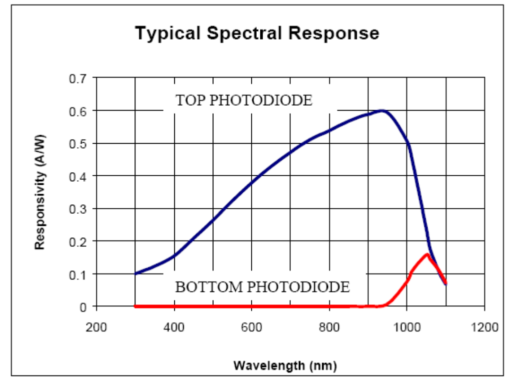



## Dual Photodiode Sandwich

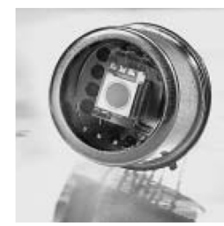
ADVANCED PHOTONIX, INC.®

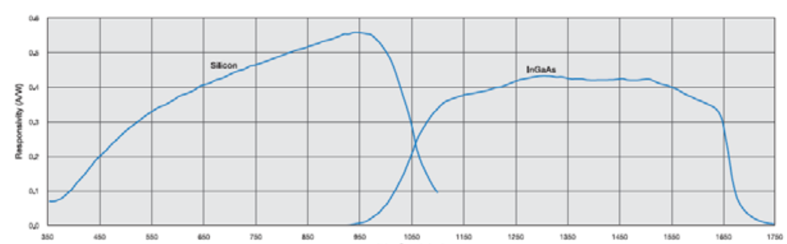
**SD138-11-31-211**
**Silicon PIN Photodiode Sandwich Detector**



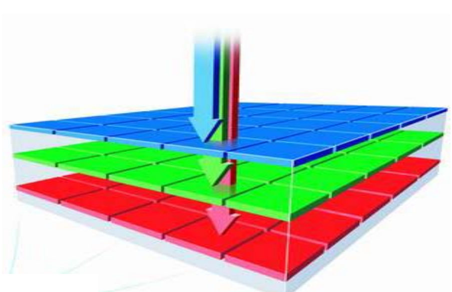



**UDT Sensors, Inc.**



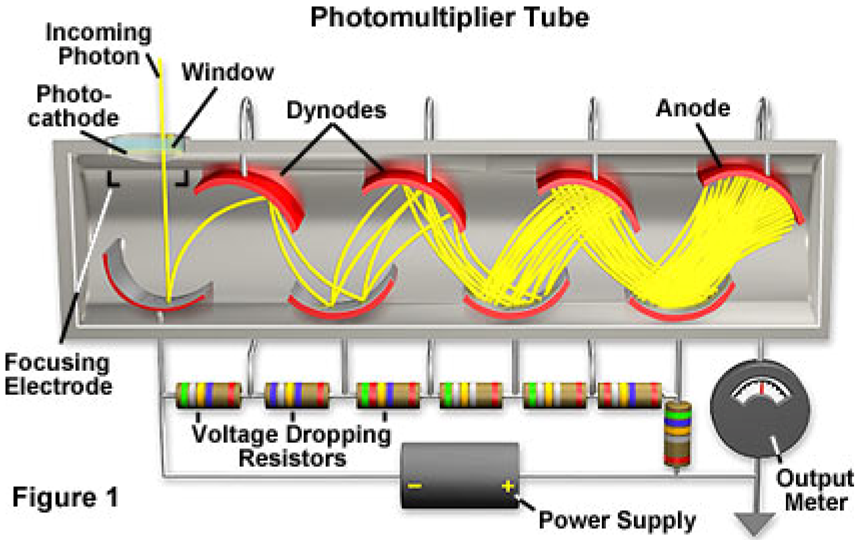



## Broadband vs.
## Narrow-Region (*Near-IR*/*UV*)

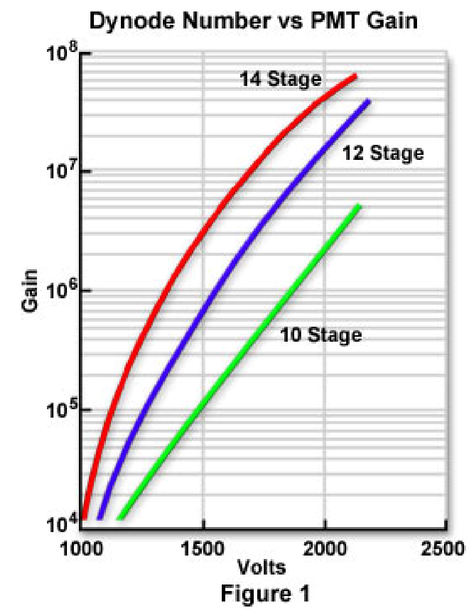


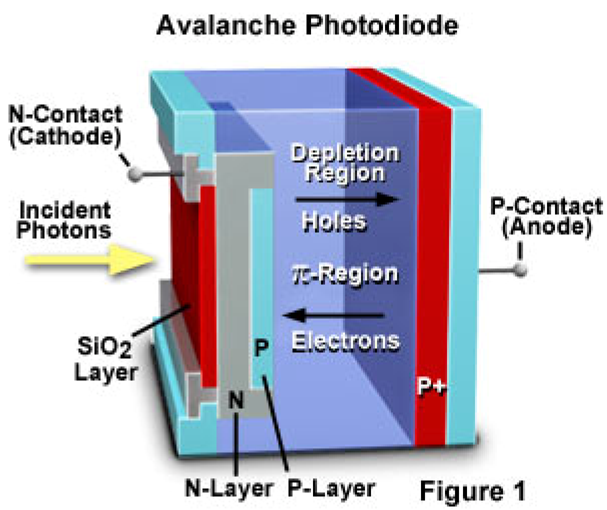
**ala the Foveon Image Array**

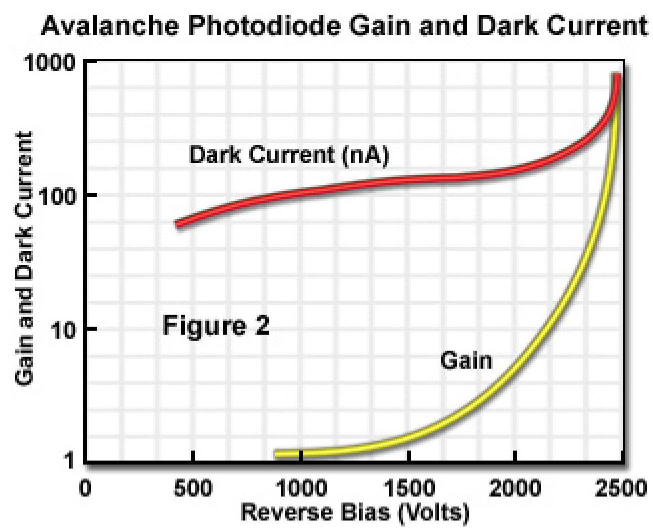
# More Complex Photodetectors

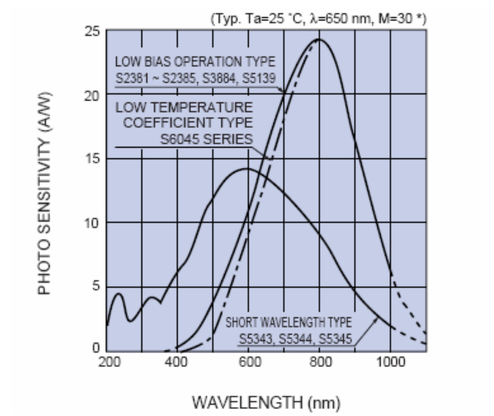






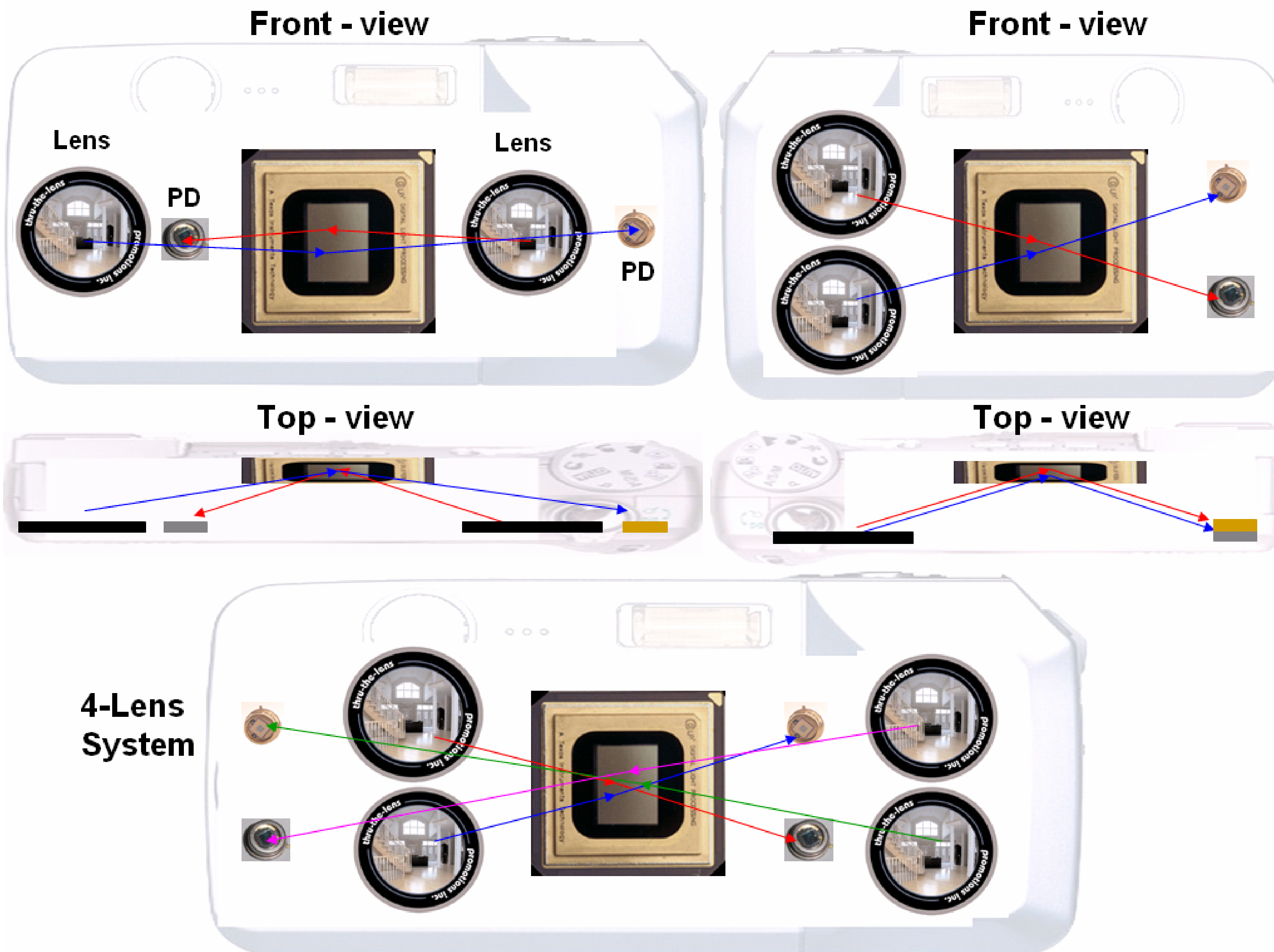




**http://micro.magnet.fsu.edu/primer/digitalimaging/concepts/photomultipliers.html**

# Multisensor DMD Camera



# Conclusions

- **Compressive sensing**
  - exploit image sparsity information; beat Nyquist
  - based on new uncertainty principles
  - “sample smarter”, “universal hardware”
  - integrates sensing, compression, processing
- **Ongoing research**
  - new kinds of *imagers*: image and video
  - *information scalability* for vision applications
    reconstruction > approximation > estimation > classification > detection
  - multi-camera *light field* acquisition and processing (3-D)
  - *fast algorithms* (DSP)
  - *R/D* analysis of CS (quantization)
  - new *“analog-to-information”* converters (analog CS)

**dsp.rice.edu/cs**

## IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, modifications, enhancements, improvements, and other changes to its products and services at any time and to discontinue any product or service without notice. Customers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All products are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its hardware products to the specifications applicable at the time of sale in accordance with TI's standard warranty. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by government requirements, testing of all parameters of each product is not necessarily performed.

TI assumes no liability for applications assistance or customer product design. Customers are responsible for their products and applications using TI components. To minimize the risks associated with customer products and applications, customers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any TI patent right, copyright, mask work right, or other TI intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information published by TI regarding third-party products or services does not constitute a license from TI to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. Reproduction of this information with alteration is an unfair and deceptive business practice. TI is not responsible or liable for such altered documentation.

Resale of TI products or services with statements different from or beyond the parameters stated by TI for that product or service voids all express and any implied warranties for the associated TI product or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

| **Products** | | **Applications** | |
|---|---|---|---|
| Amplifiers | amplifier.ti.com | Audio | www.ti.com/audio |
| Data Converters | dataconverter.ti.com | Automotive | www.ti.com/automotive |
| DSP | dsp.ti.com | Broadband | www.ti.com/broadband |
| Interface | interface.ti.com | Digital Control | www.ti.com/digitalcontrol |
| Logic | logic.ti.com | Military | www.ti.com/military |
| Power Mgmt | power.ti.com | Optical Networking | www.ti.com/opticalnetwork |
| Microcontrollers | microcontroller.ti.com | Security | www.ti.com/security |
| Low Power Wireless | www.ti.com/lpw | Telephony | www.ti.com/telephony |
| | | Video & Imaging | www.ti.com/video |
| | | Wireless | www.ti.com/wireless |

Mailing Address: Texas Instruments
Post Office Box 655303 Dallas, Texas 75265