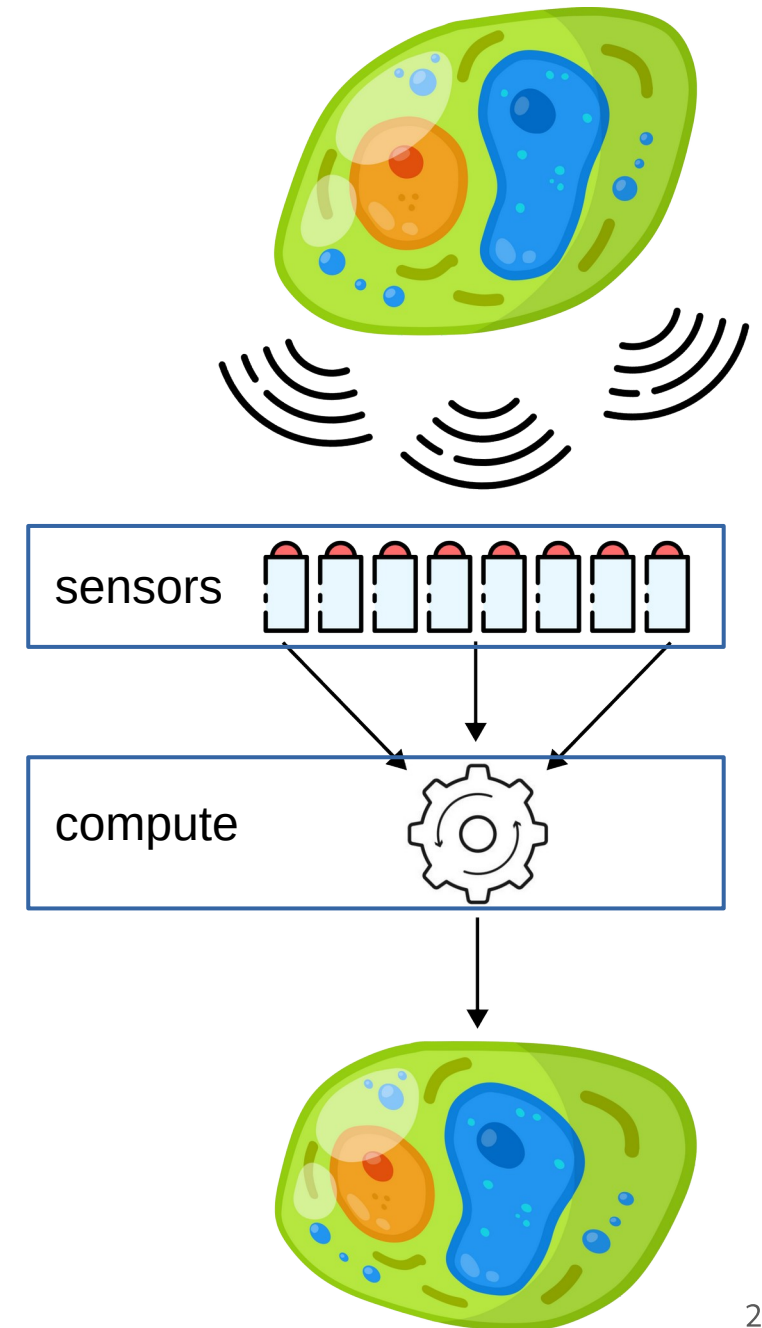
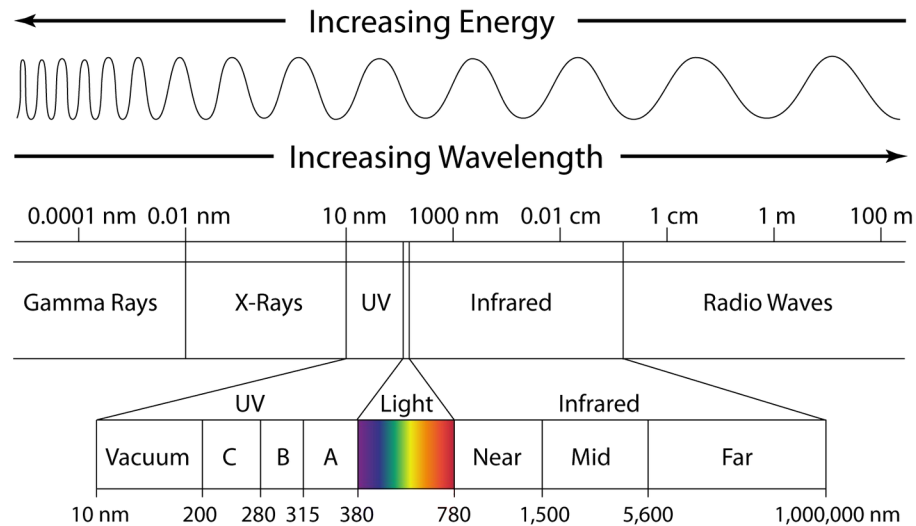


Signal Processing in the Wild

Sepand Kashani

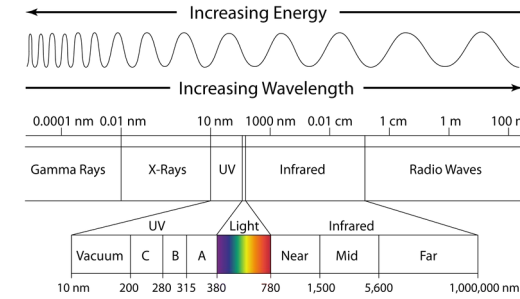
Signal Processing (SP)

- Capture signals from real world with sensors
- Infer something about quantity of interest via **computation**



Acoustic Imaging

- Determine acoustic intensity in different directions.
 - Microphone(s) record time series
 - Process signals to infer spherical intensity



Acoustic emitters



measurement

computation?

Microphone signals

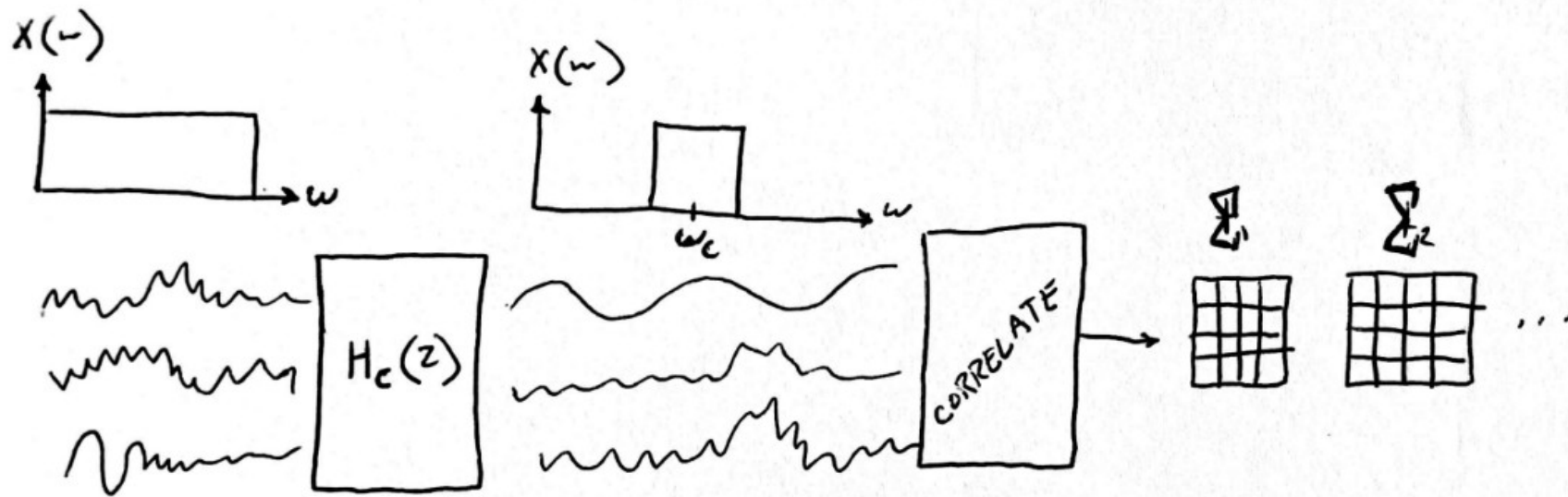
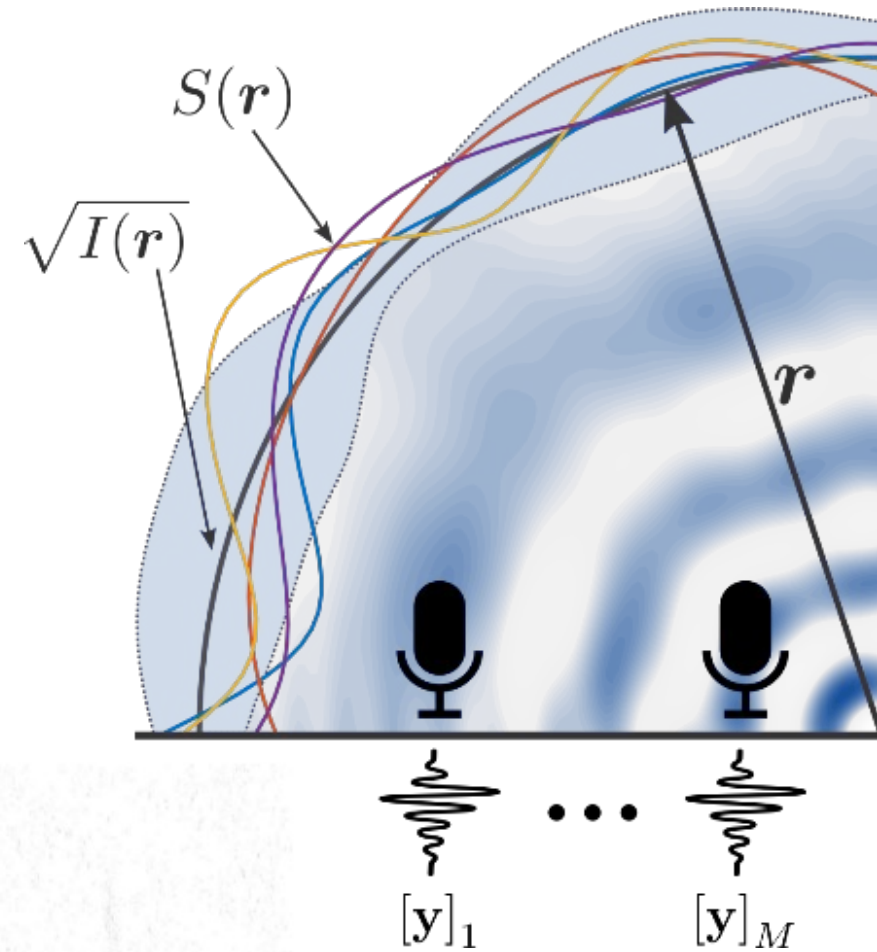


Acoustic Imaging 2

$$\mathbf{y}_m = \int_{\mathbb{S}^2} S(\mathbf{r}) \alpha_m^*(\mathbf{r}) e^{-j \frac{2\pi}{\lambda} \langle \mathbf{p}_m, \mathbf{r} \rangle} d\mathbf{r}$$

$$= \sum_{\mathbf{r} \in \theta} S(\mathbf{r}) \alpha_m^*(\mathbf{r}) e^{-j \frac{2\pi}{\lambda} \langle \mathbf{p}_m, \mathbf{r} \rangle}$$

$$\Sigma = \mathbb{E} [\mathbf{y} \mathbf{y}^H] = (\bar{\mathbf{A}} \circ \mathbf{A}) \mathbf{I} + \sigma^2$$



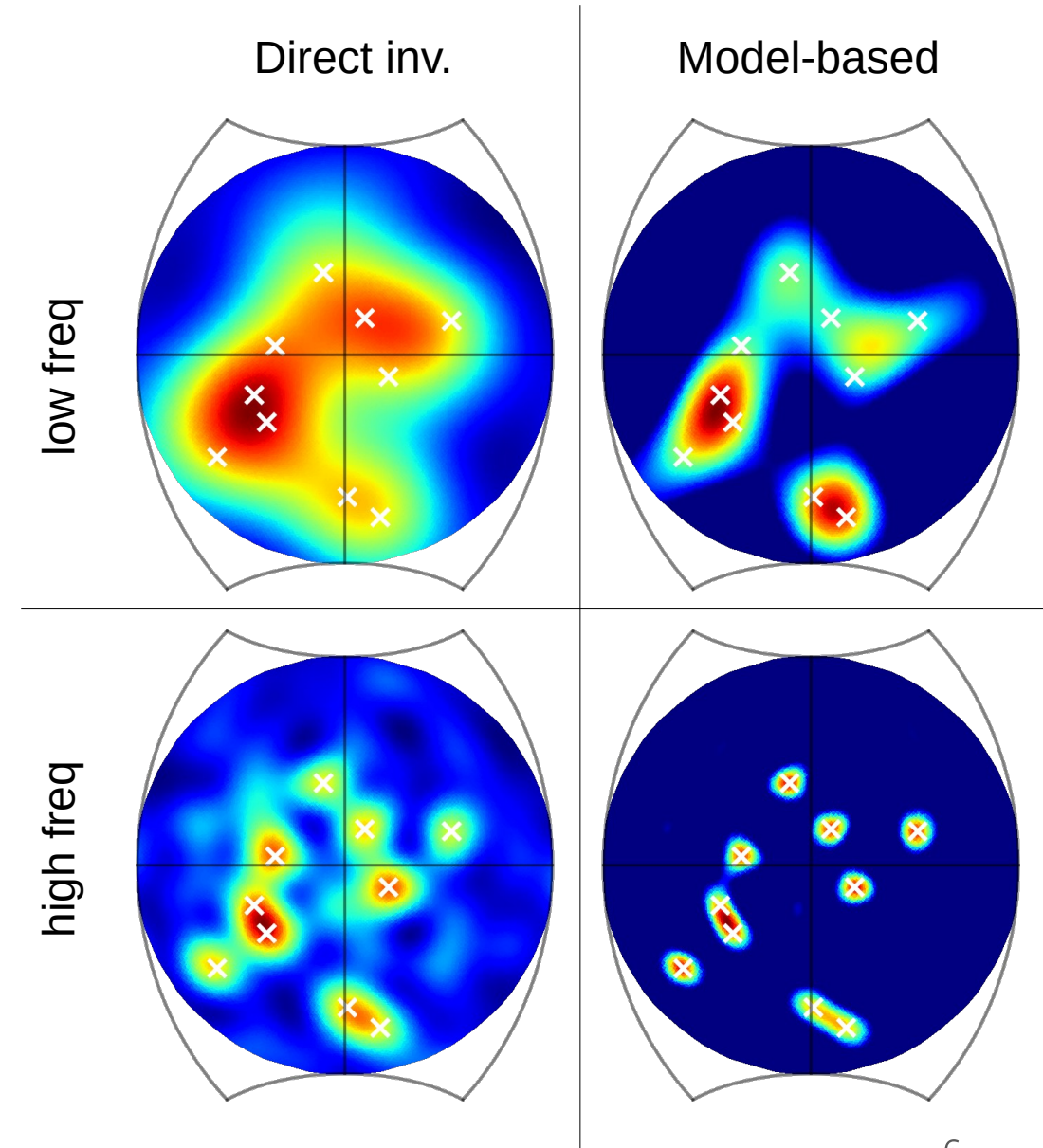
Acoustic Imaging: Real-Time Demo

Acoustic Camera Video

Acoustic Imaging 4

- Least-squares reconstruction to achieve real-time estimation.
 - Poor spatial resolution for compact arrays.
- Solution: inject prior knowledge.

$$\hat{\mathbf{I}} = \arg \min_{\mathbf{x} \in \mathbb{R}_+^N} \underbrace{\left\| \text{vec}(\hat{\mathbf{\Sigma}}) - (\bar{\mathbf{A}} \circ \mathbf{A}) \mathbf{x} \right\|_2^2}_{\text{Data Fidelity}} + \underbrace{\lambda \left[\gamma \|\mathbf{x}\|_1 + (1 - \gamma) \|\mathbf{x}\|_2^2 \right]}_{\text{Prior Model}}$$

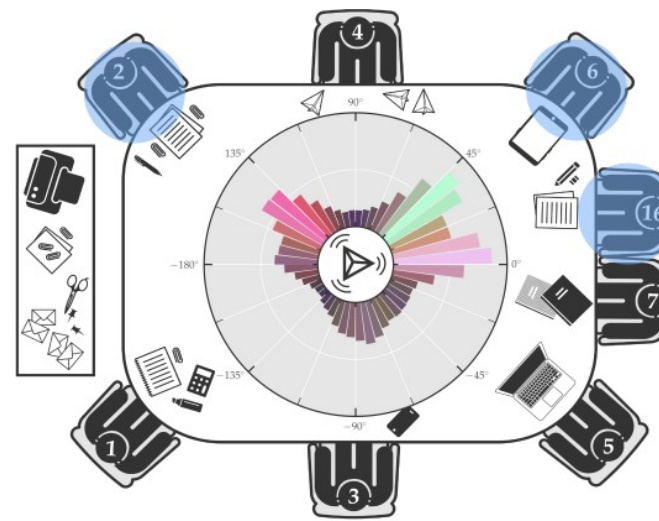
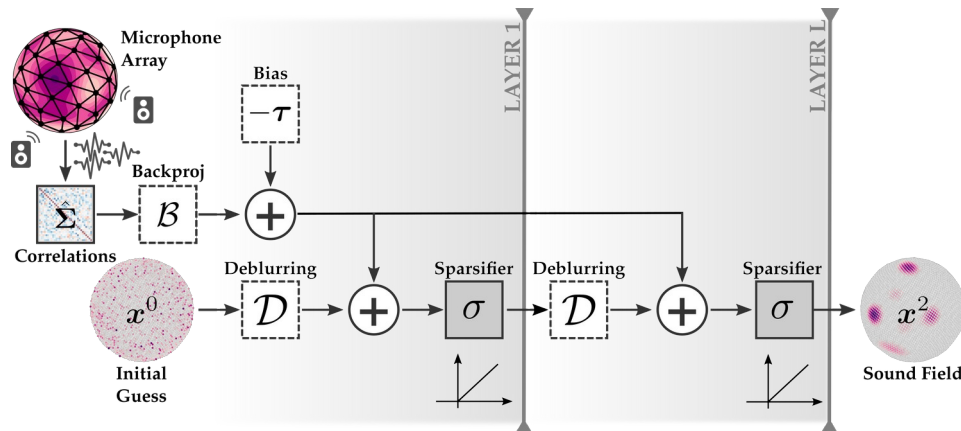


Acoustic Imaging 5

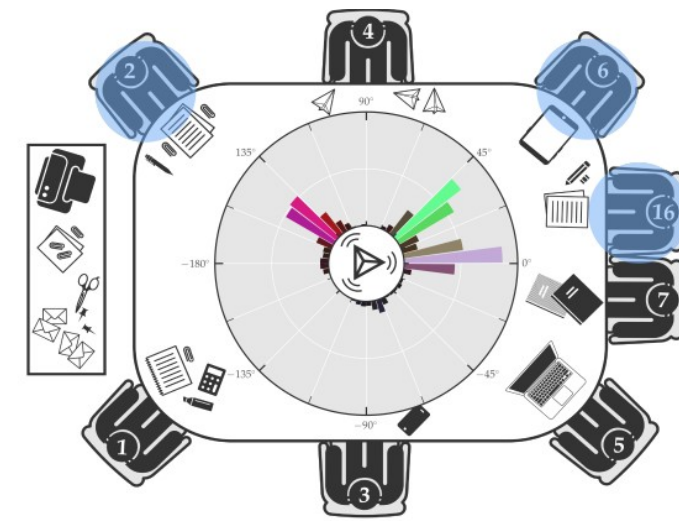
- Solve via iterative methods.

$$\begin{aligned}\mathbf{x}_{\text{PGD}}^k &= \text{prox}_g \left(\mathbf{x}^{k-1} - \alpha \nabla f(\mathbf{x}^{k-1}) \right) \\ &= \text{ReLU} \left[\mathcal{D} \mathbf{x}^{k-1} + \mathcal{B} \text{vec}(\hat{\Sigma}) - \tau \right]\end{aligned}$$

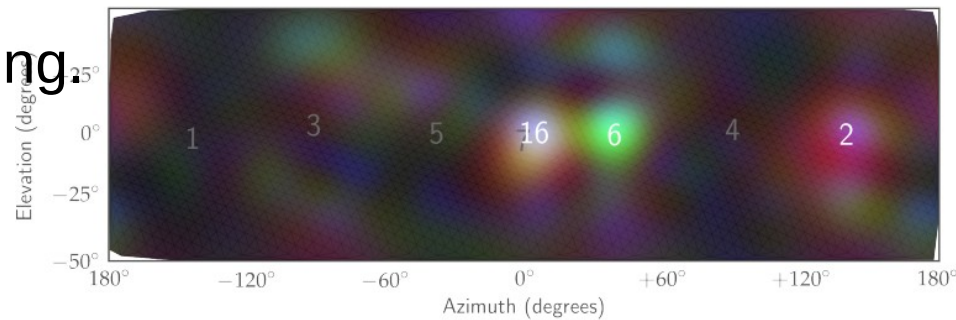
- Can be made real-time via loop-unrolling.



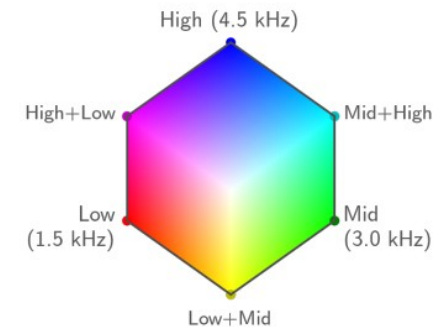
(a) DAS azimuthal sound field.



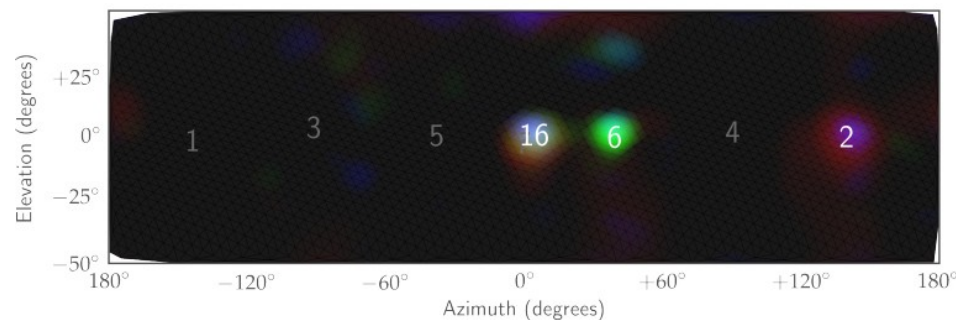
(b) DeepWave azimuthal sound field.



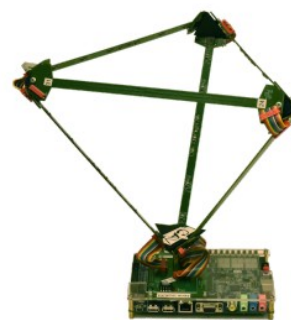
(c) DAS spherical sound field (resolution: 25.3°, RMS contrast: 0.78).



(d) Frequency-colour mapping.

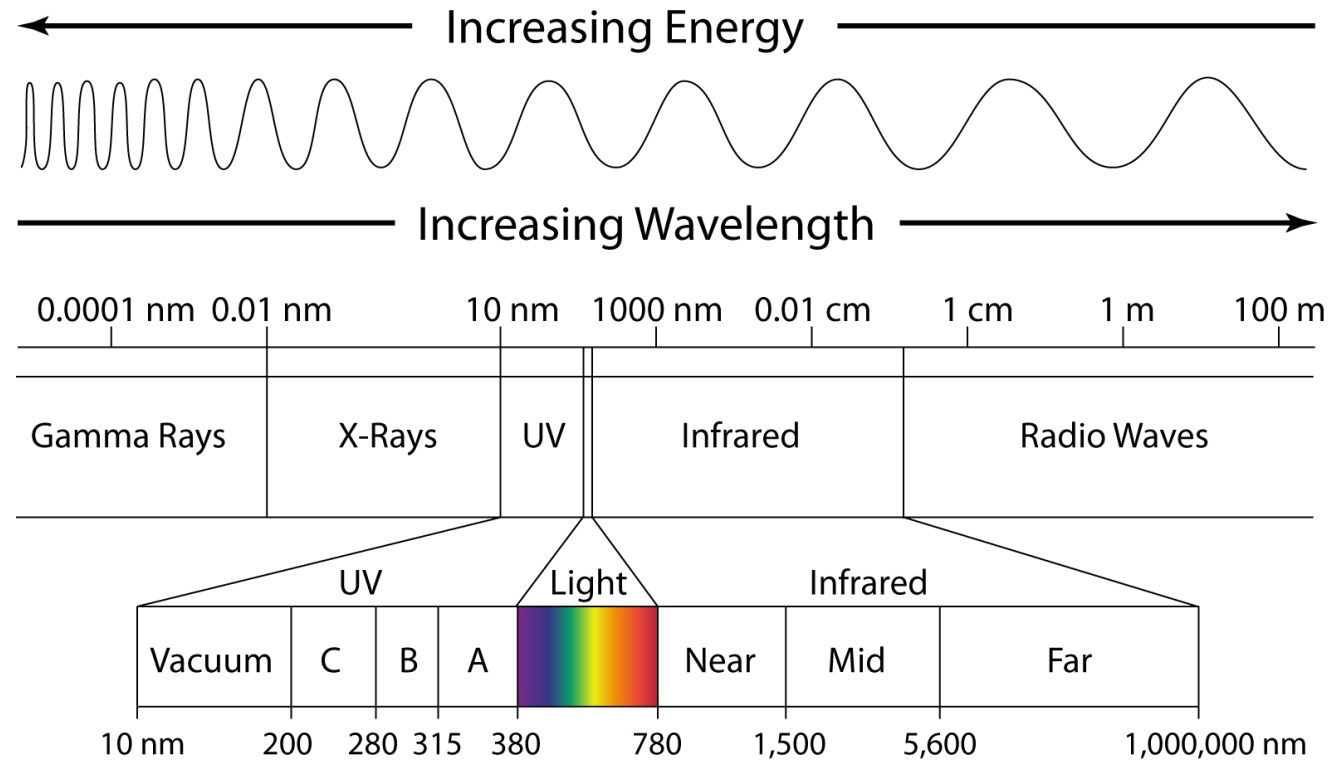


(e) DeepWave spherical sound field (resolution: 18.5°, contrast: 0.97).



(f) Pyramic array.

The Electro-Magnetic Spectrum



Digital Communications

UNITED STATES FREQUENCY ALLOCATIONS THE RADIO SPECTRUM

RADIO SERVICES COLOR LEGEND

AERONAUTICAL MOBILE	INTER-SATELLITE	RADIO ASTRONOMY
AERONAUTICAL MOBILE SATELLITE	LAND MOBILE	RADIO TERRESTRIAL SATELLITE
AERONAUTICAL RADIOCOMMUNICATION	LAND MOBILE SATELLITE	RADIOLOCATION
MARITIME	MARITIME MOBILE	RADIOLOCATION SATELLITE
MARITIME SATELLITE	MARITIME MOBILE SATELLITE	RADIOCOMMUNICATION
BROADCASTING	METEOROLOGICAL AIDS	SPACE RESEARCH
BROADCASTING SATELLITE	METEOROLOGICAL SATELLITE	STANDARD FREQUENCY AND TIME SIGNAL
FIXED	MOBILE	FIXED SATELLITE
FIXED SATELLITE	MOBILE SATELLITE	MOBILE SATELLITE

ACTIVITY CODE

GOVERNMENT EXCLUSIVE	GOVERNMENT/NON-GOVERNMENT SHARED
NON-GOVERNMENT EXCLUSIVE	

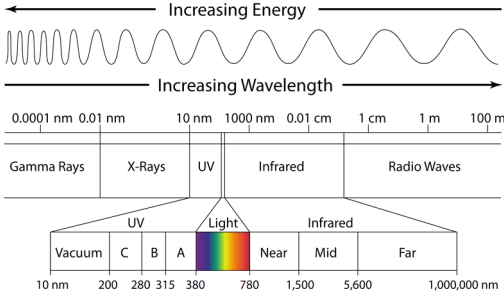
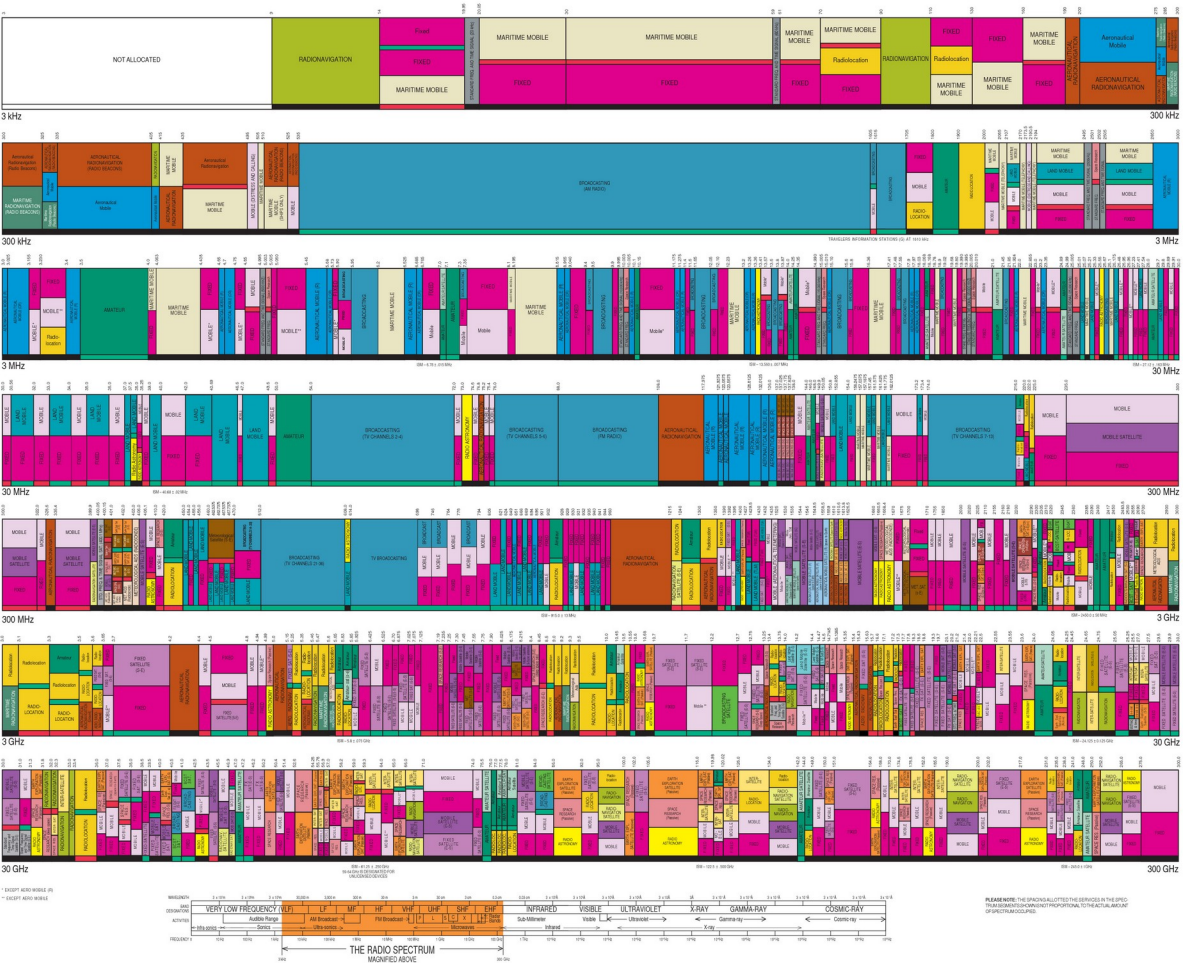
ALLOCATION USAGE DESIGNATION

SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	Mobile	1st Capital with lower case letters

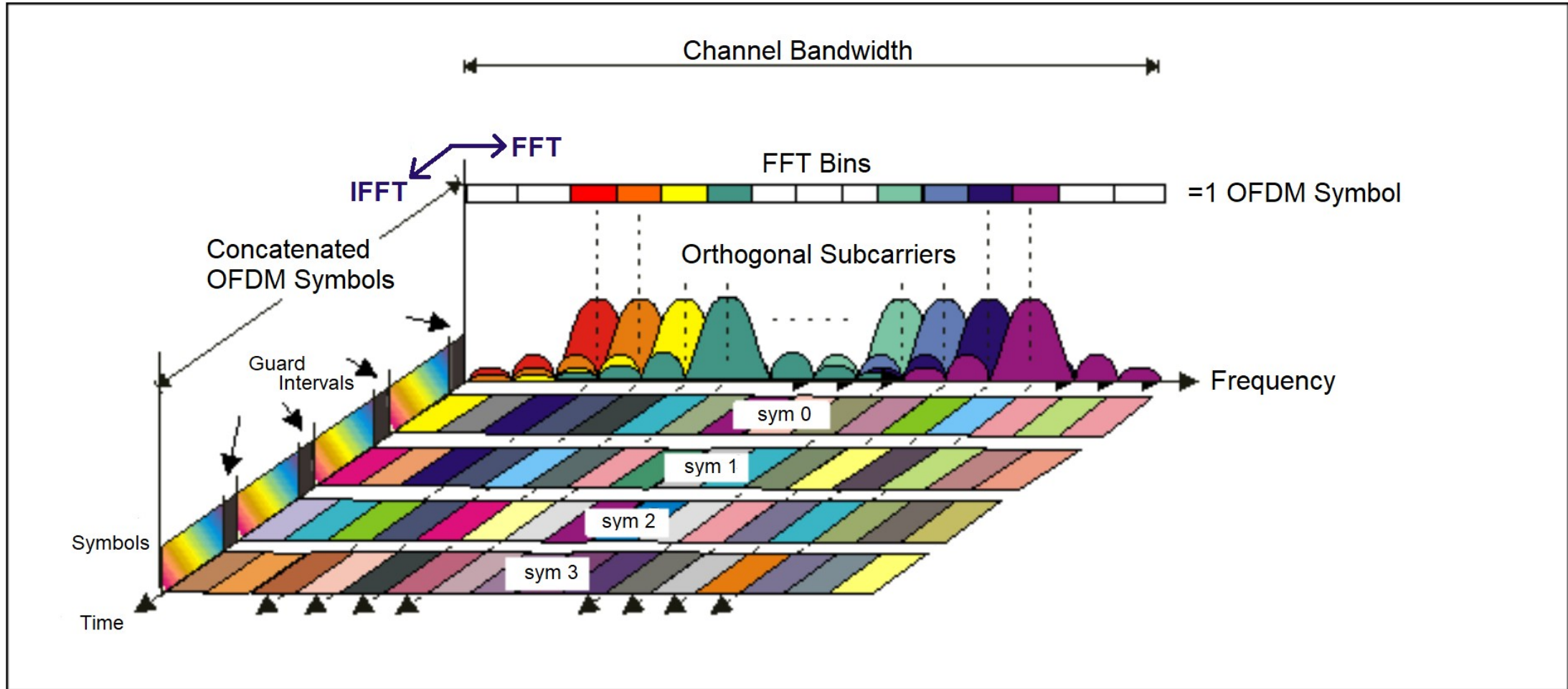
This chart is a graphic representation of the portions of the Table of Frequency Allocations used by the FCC and ICA. It is not a substitute for the actual Table of Frequency Allocations. For complete information, users should consult the Table to determine the current status of U.S. allocations.

U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management
October 2003

U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management
October 2003



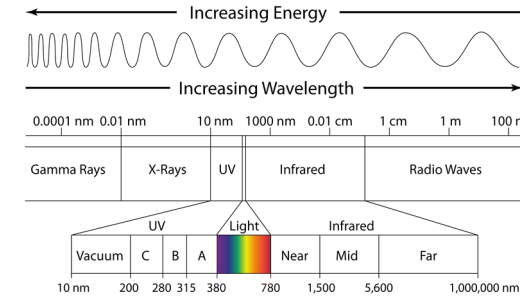
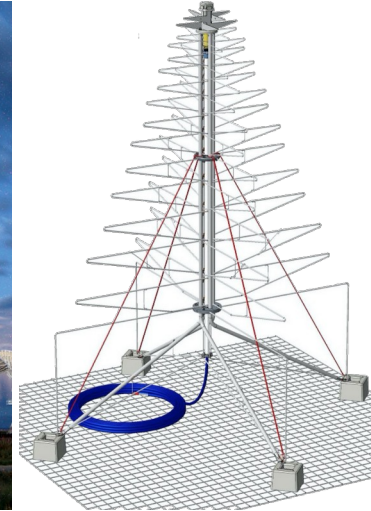
Digital Communications: 5G Coding



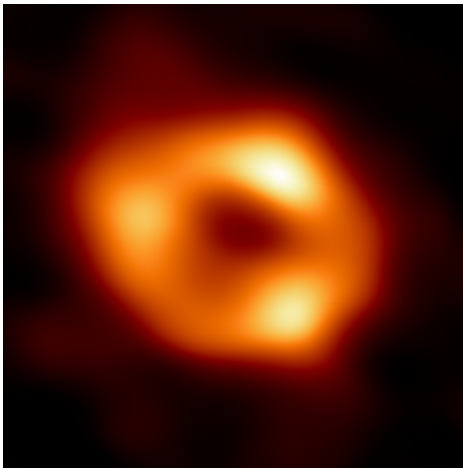
Frequency-Time Representative of an OFDM signal

Radio-Interferometry

- Determine sky brightness distribution
 - Stars emit radio emissions (among other things)
 - Recorded on Earth with antennas



Sgr A^*



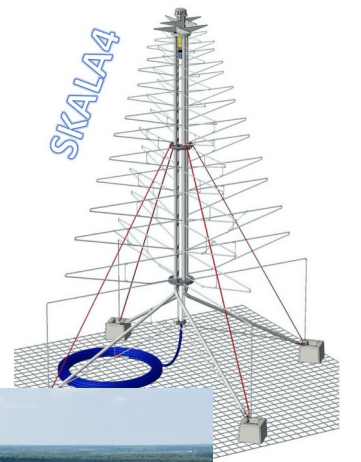
antenna time series



measurement

computation?

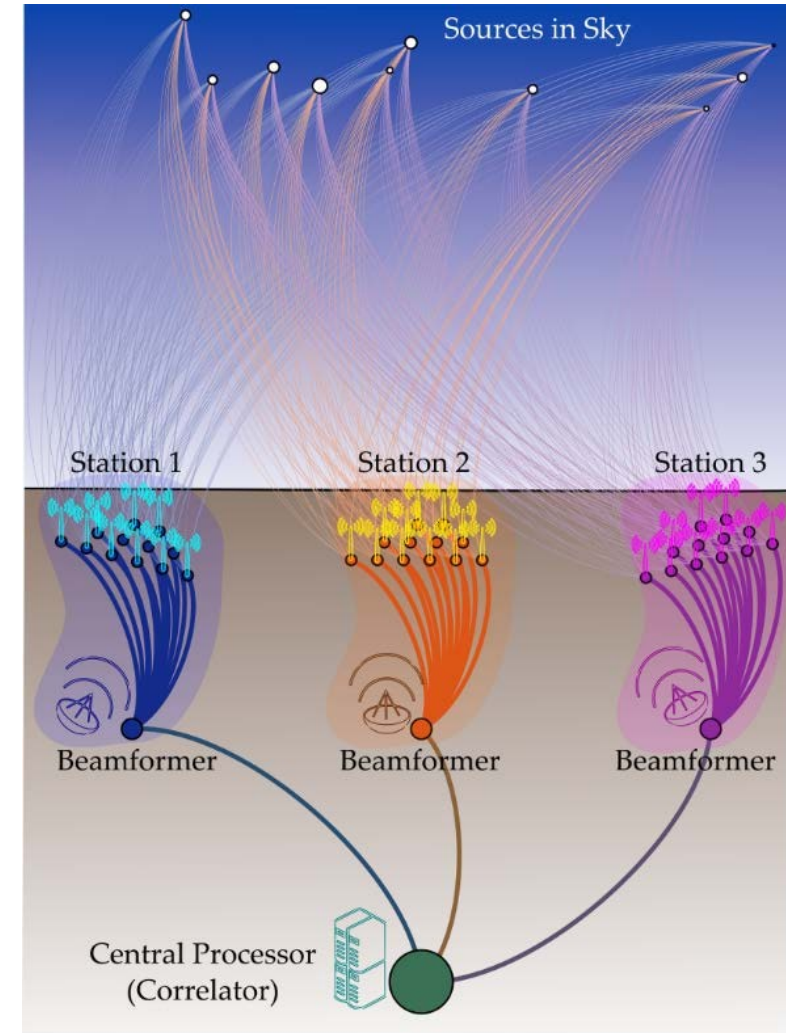
Radio-Interferometry



RI: Design of Modern Interferometers

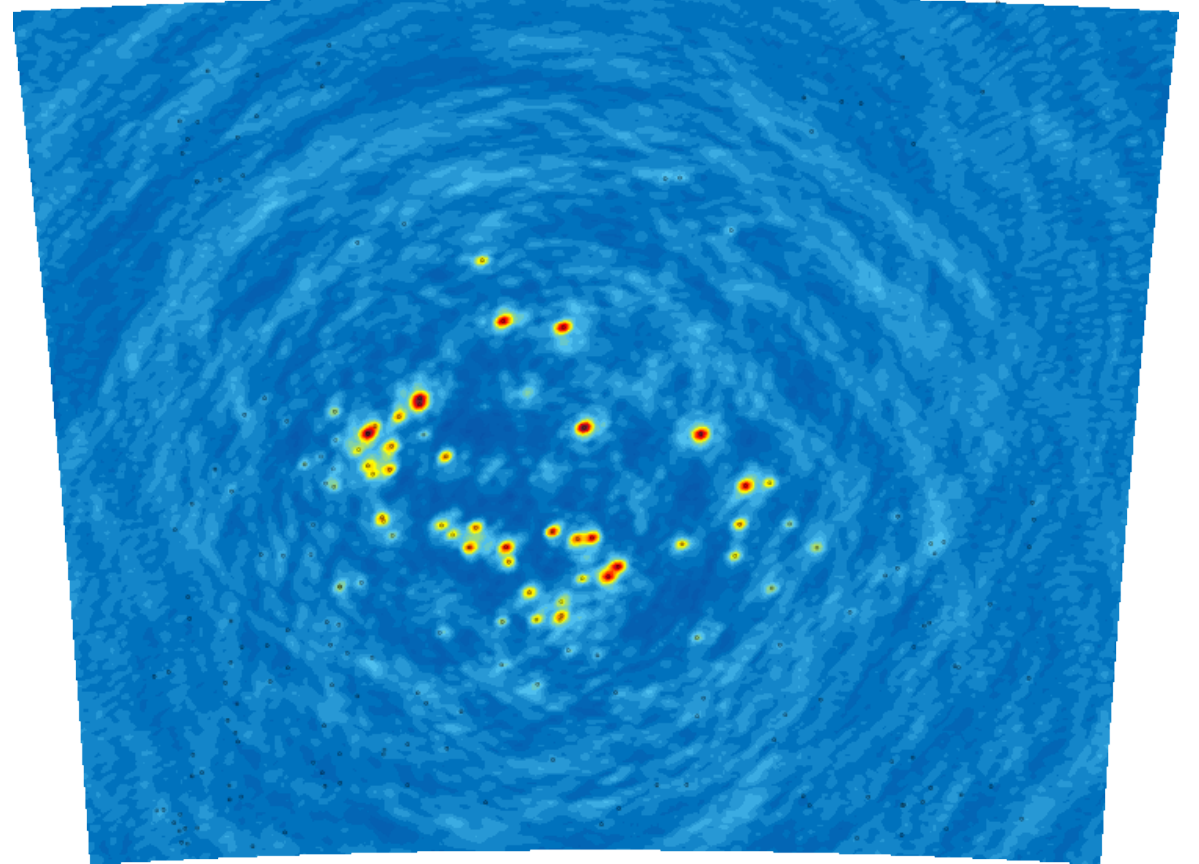
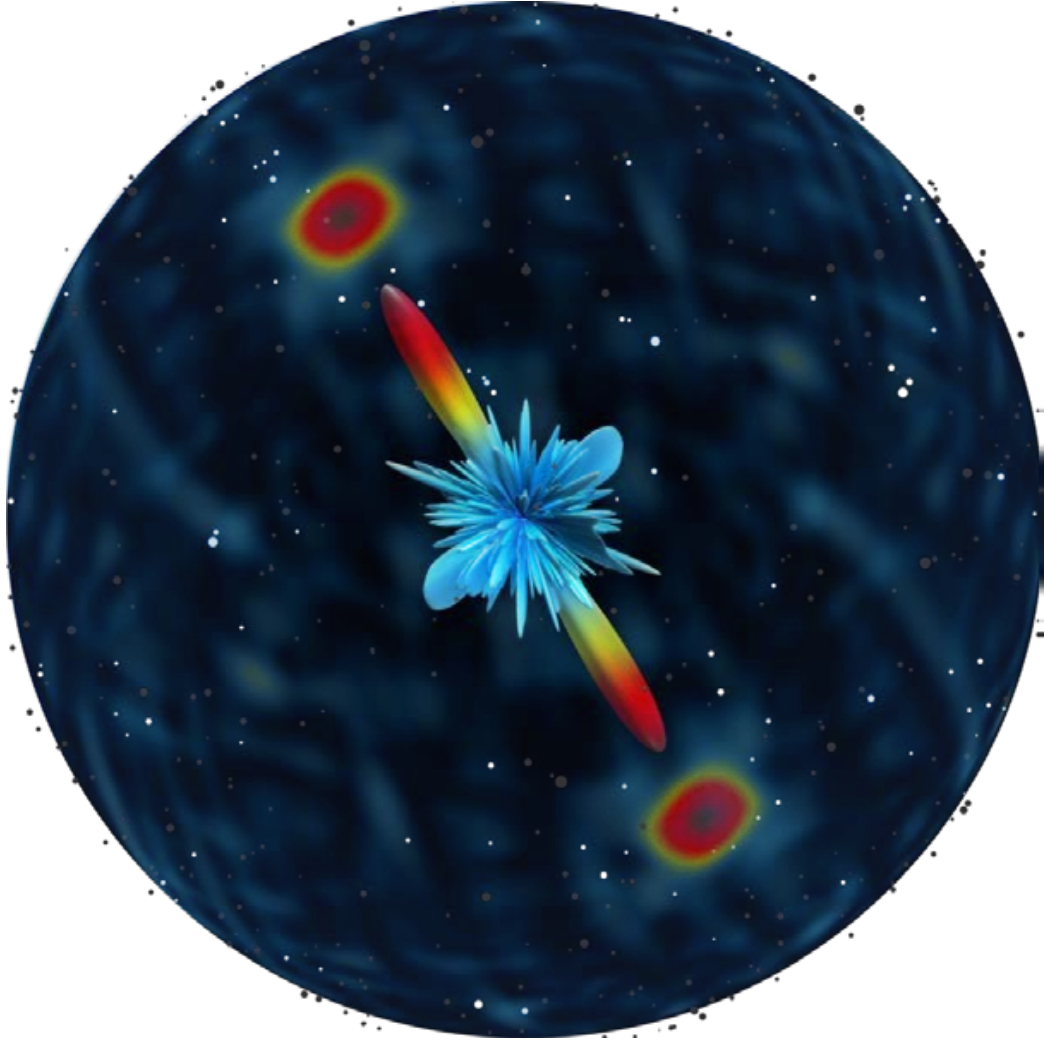
- Hierarchical phased-array architecture using beamforming.
 - Station-level spatial filtering.
 - Reduce data rate from antennas.

$$\begin{aligned}\mathbf{y}_m &= \int_{\mathbb{S}^2} S(\mathbf{r}) \alpha_m^*(\mathbf{r}) e^{-j \frac{2\pi}{\lambda} \langle \mathbf{p}_m, \mathbf{r} \rangle} d\mathbf{r} \\ &= \sum_{\mathbf{r} \in \theta} S(\mathbf{r}) \alpha_m^*(\mathbf{r}) e^{-j \frac{2\pi}{\lambda} \langle \mathbf{p}_m, \mathbf{r} \rangle} \\ \mathbf{x}_l &= \mathbf{w}^H \mathbf{y}\end{aligned}$$



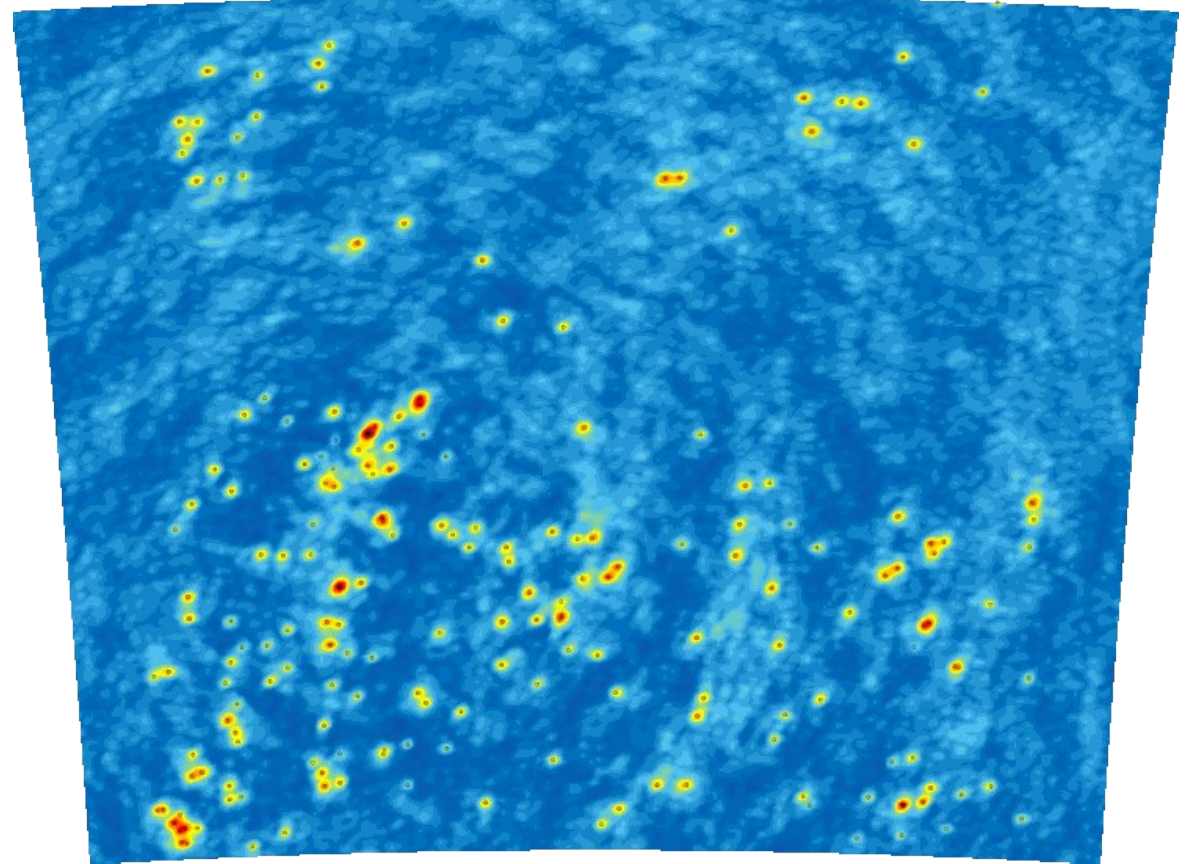
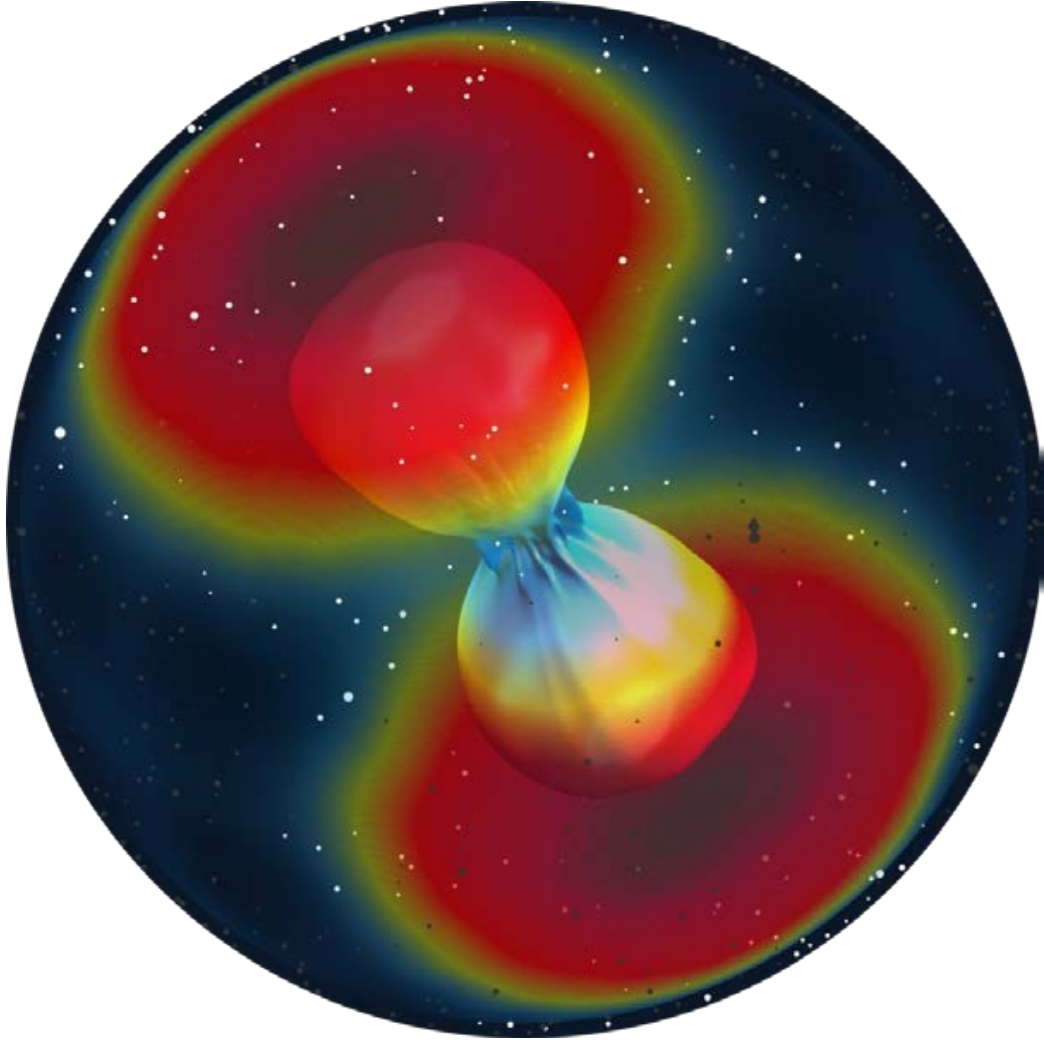
RI: Adaptive Beamforming

Trading Resolution for Sensitivity

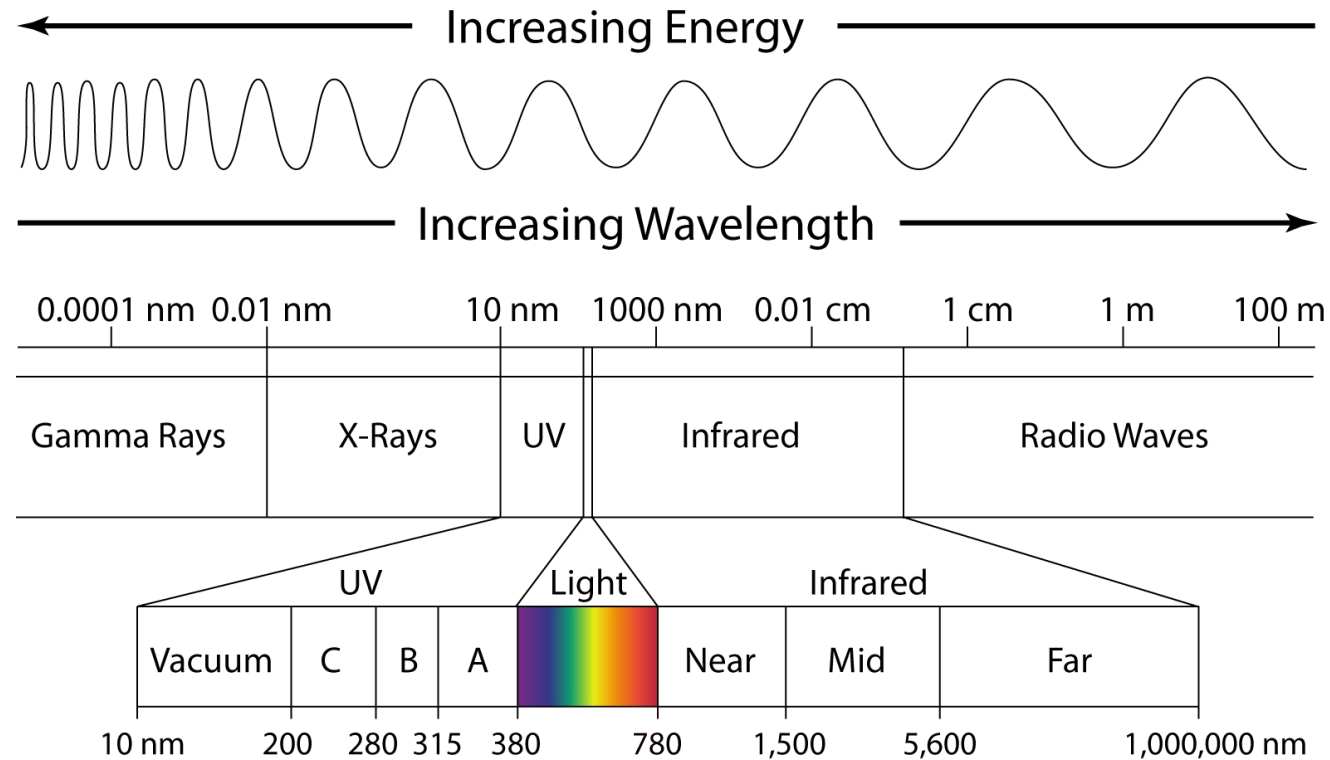


RI: Adaptive Beamforming

Trading Resolution for Sensitivity

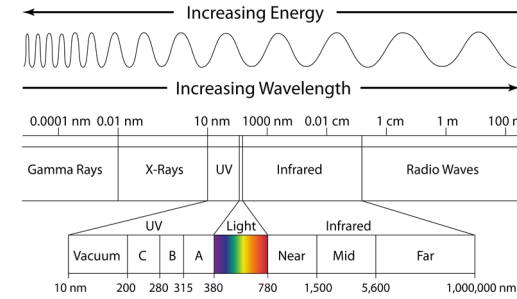


The Electro-Magnetic Spectrum



Optical Imaging

- Capture scene radiance
 - Visible light enters camera
 - Recorded on pixel detector



scene



camera picture (shown to user)

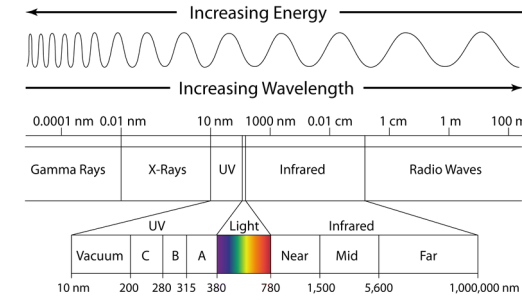
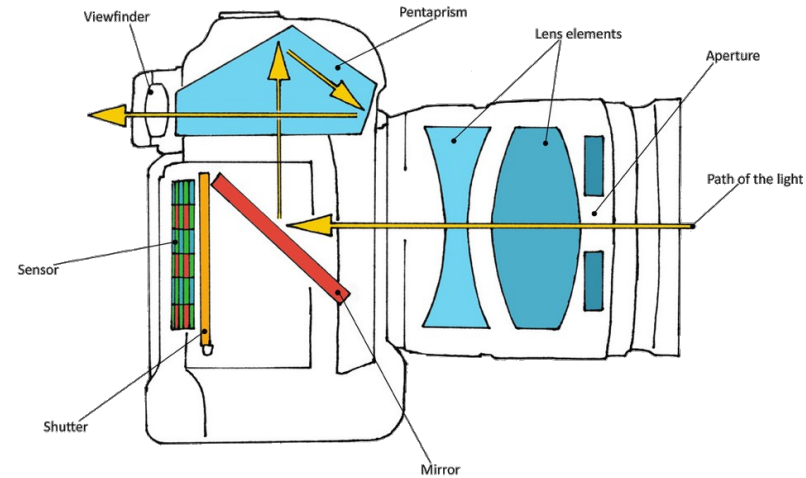


measurement

computation?

Optical Imaging 2

- Camera does not capture true scene
 - Use computation to recover it



scene



sensor recording



measurement

computation?

$$\mathbf{y}(\mathbf{r}) = (\mathbf{h} * \mathbf{x})(\mathbf{r})$$

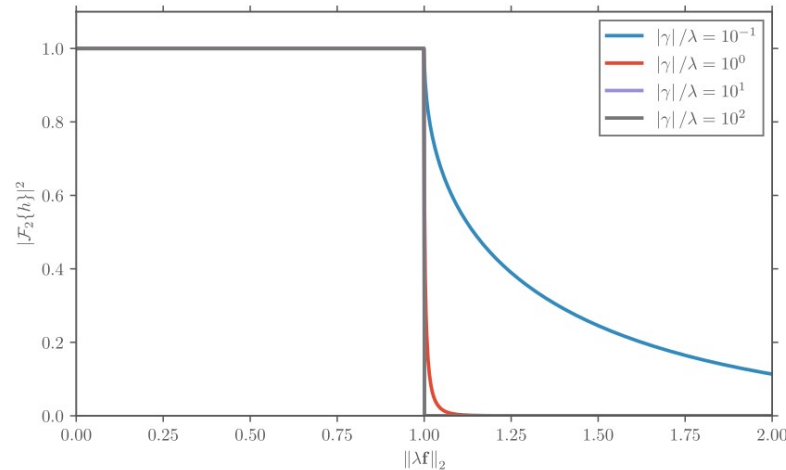
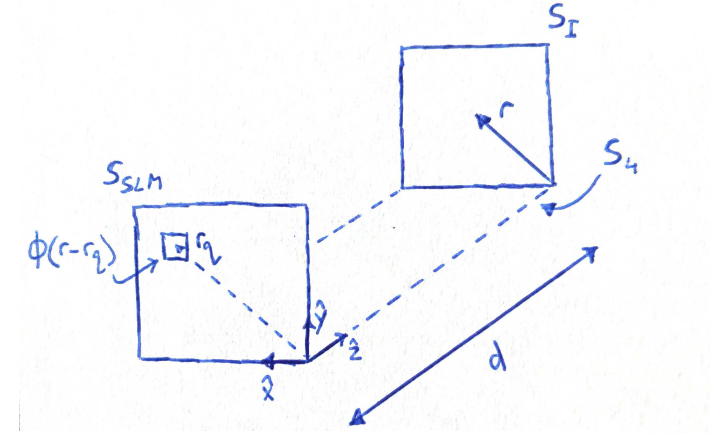
+ color channels...

Optical SP: A 2D LTI System

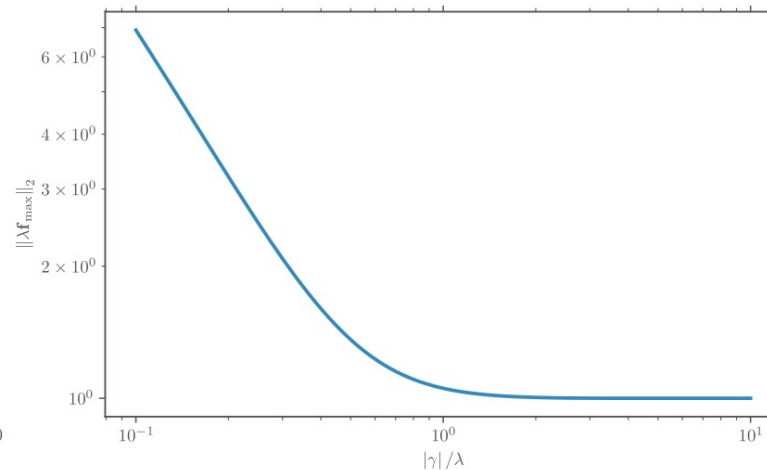
$$U(\mathbf{r}) = \sum_q \alpha_q (\chi \phi \star \tilde{h})(\mathbf{r} - \mathbf{r}_q), \quad \mathbf{r} \in \mathbb{R}^2$$

$$\tilde{h}(\mathbf{r}; d) = \frac{-d}{4\pi\beta^2(\mathbf{r}; d)} \left[\frac{2\pi}{j\lambda} + \frac{1}{\beta(\mathbf{r}; d)} \right] \exp \left(j \frac{2\pi}{\lambda} \beta(\mathbf{r}; d) \right),$$

$$\beta(\mathbf{r}; d) = \sqrt{\|\mathbf{r}\|_2^2 + d^2}.$$



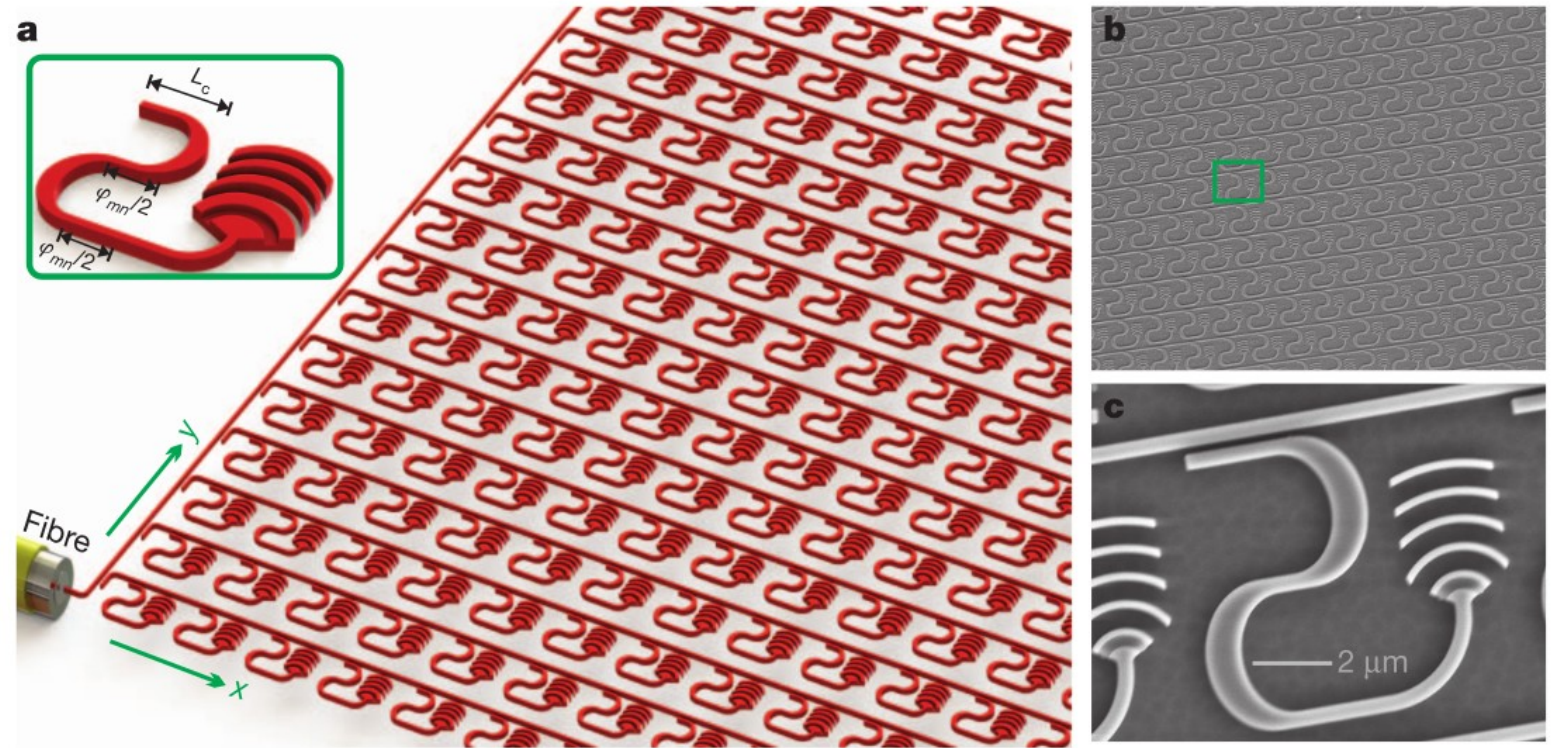
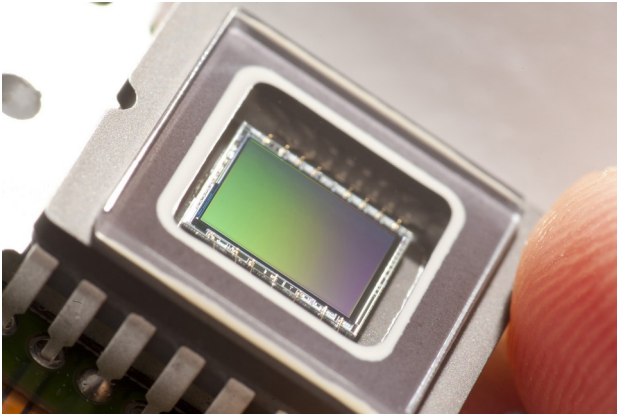
(a) Magnitude response



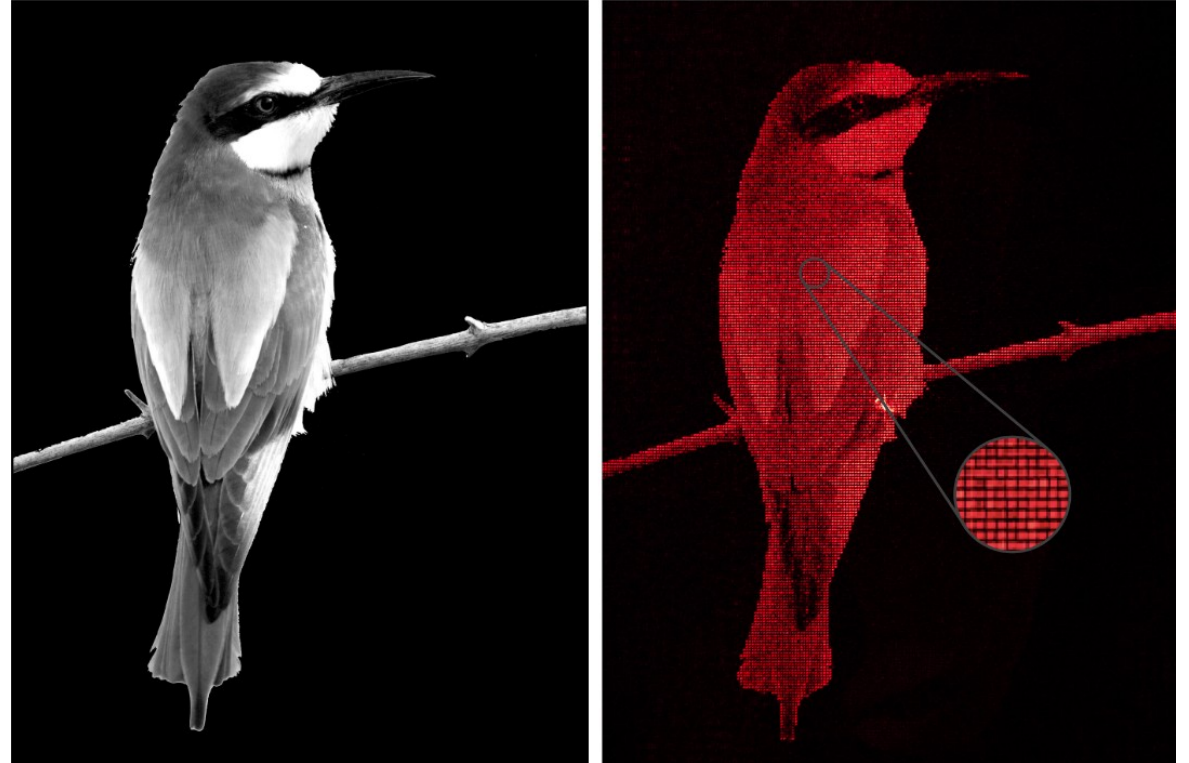
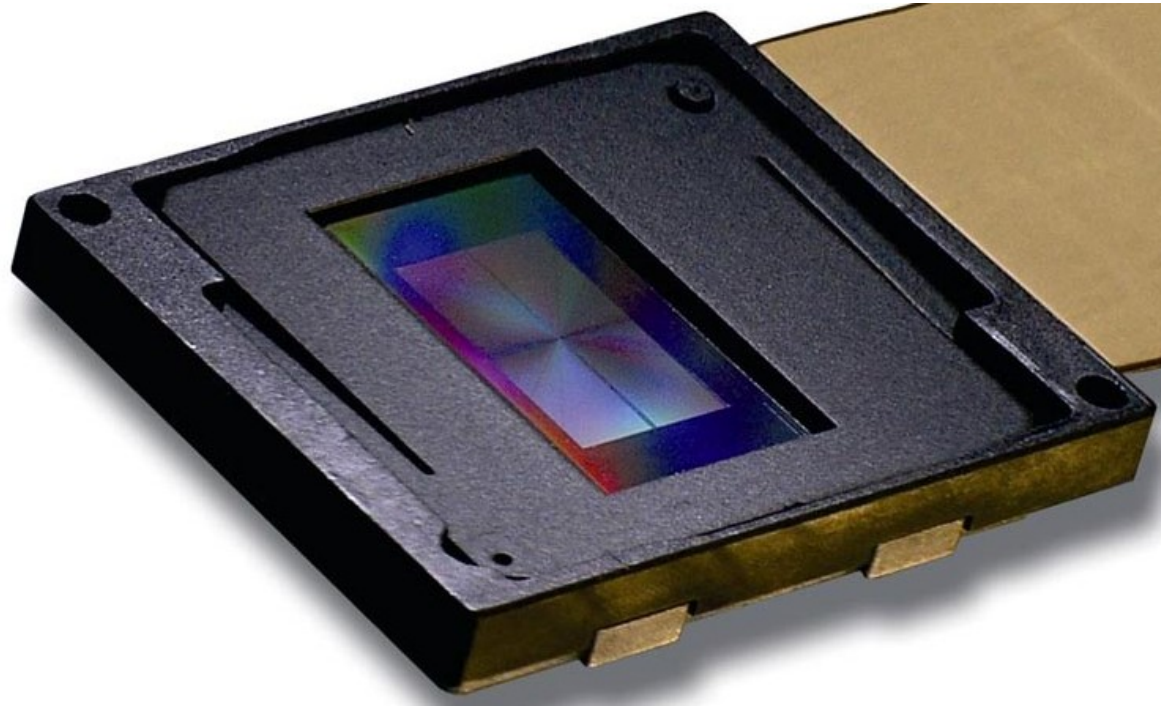
(b) 99.9% normalized bandwidth

Figure 5. Spectral properties of coherent propagation in homogeneous media. When not in the sub-wavelength regime, the channel is effectively $\frac{1}{\lambda}$ -bandlimited.

Optical SP 2

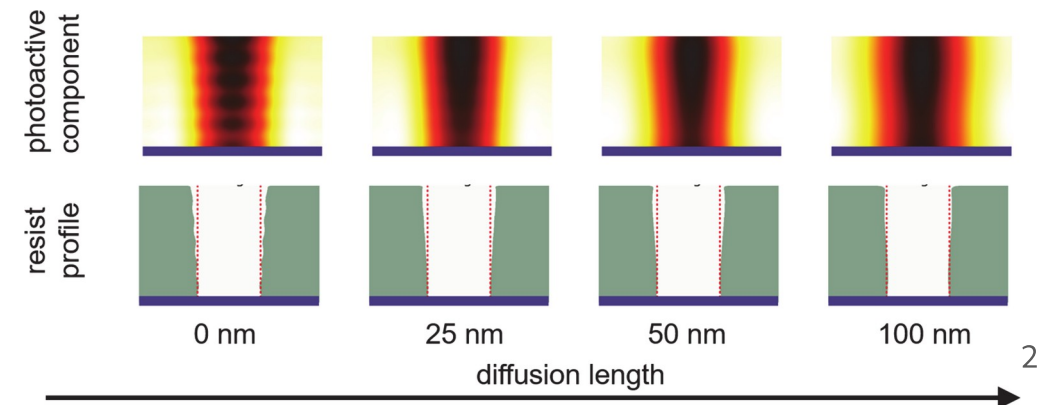
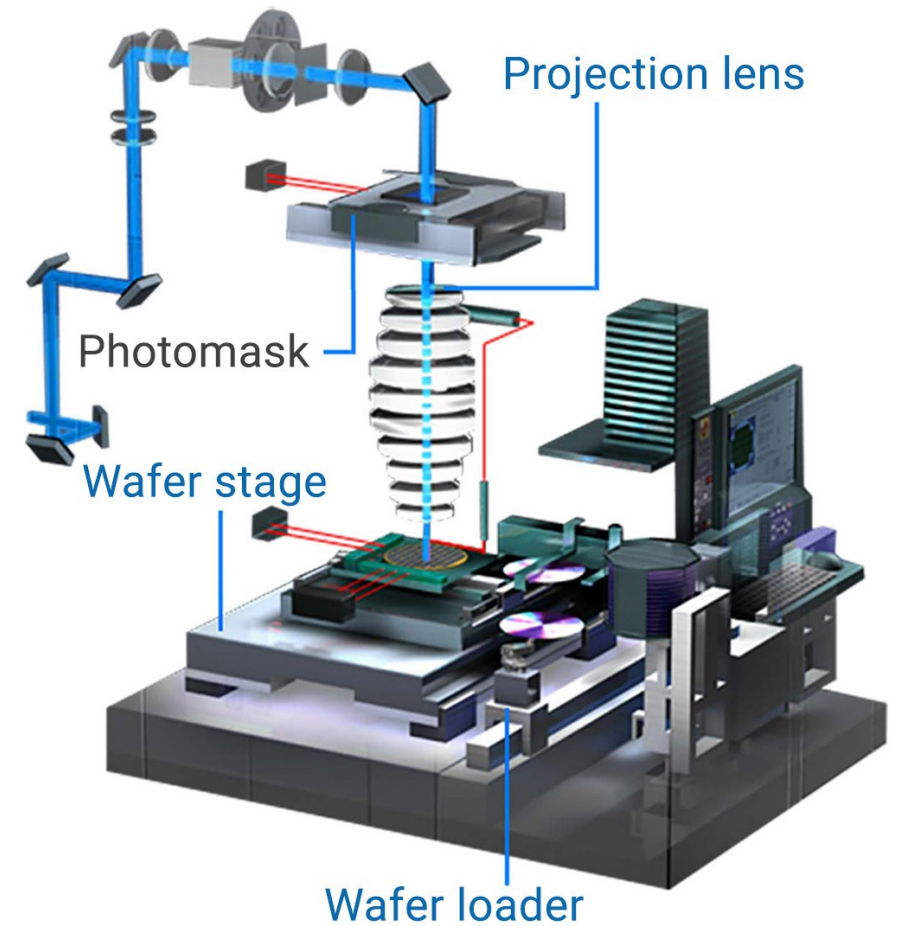
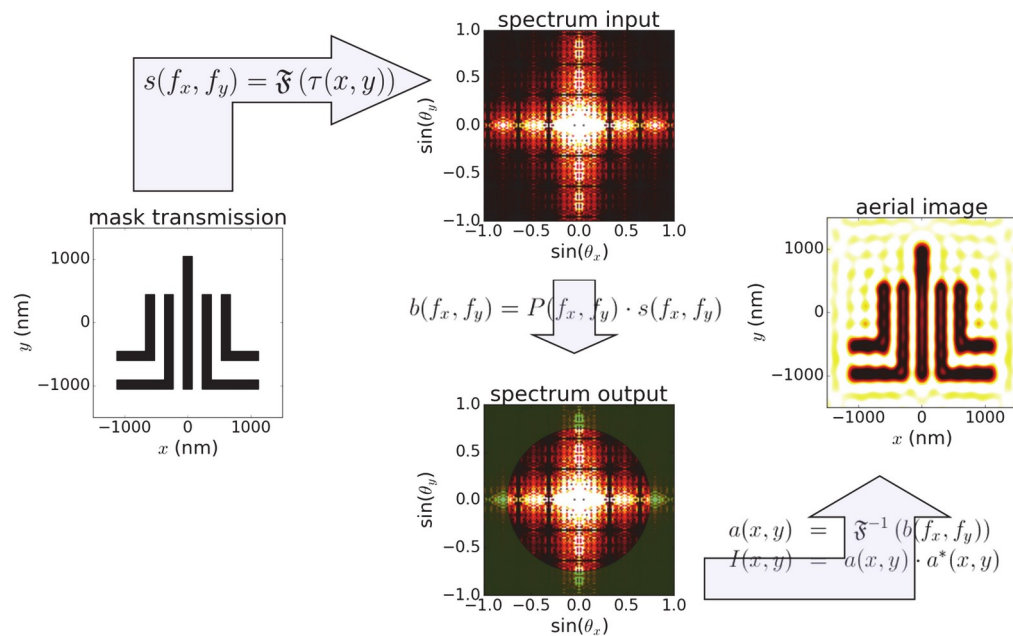


Optical SP 3

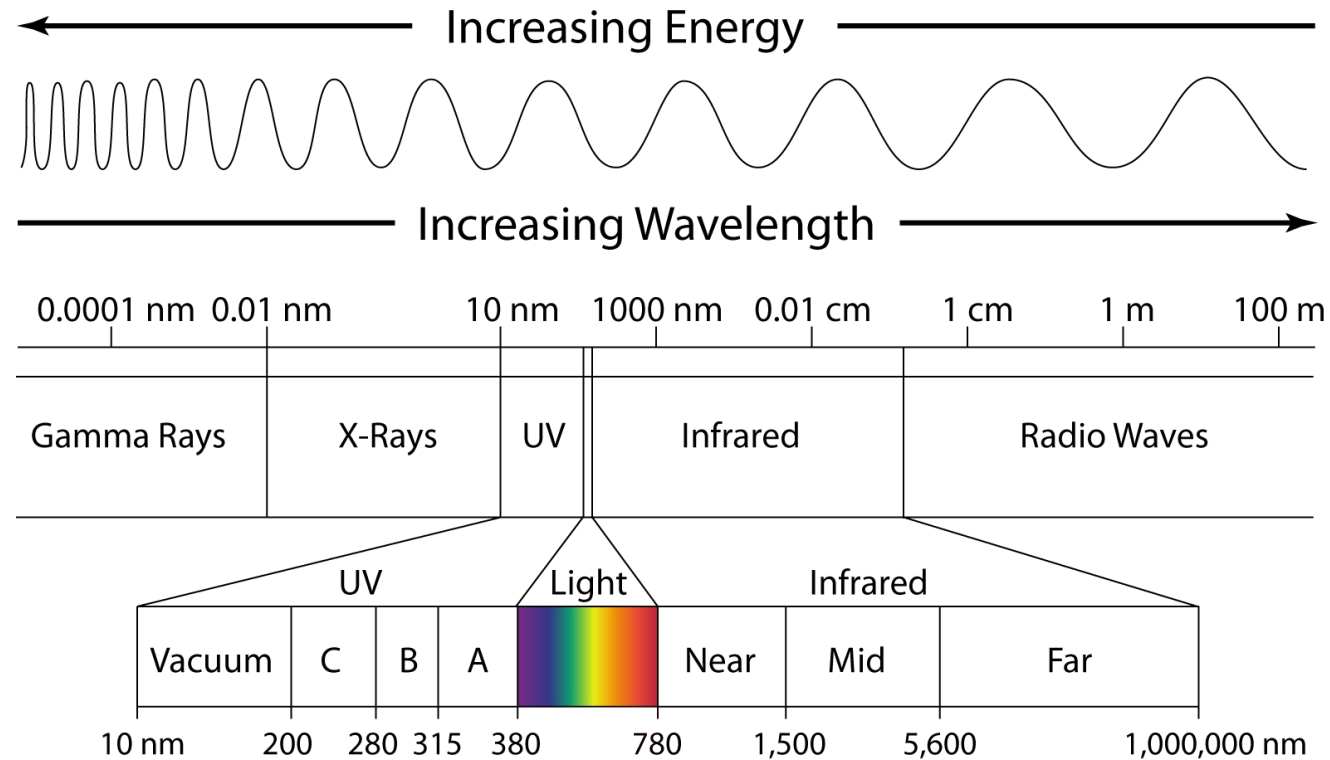


OSP: Photo-Lithography

- DUV/EUV light shines onto mask/SLM
 - Free-space propagation + lens effects
 - Intensity pattern at wafer surface
 - Non-linear chemical etching.

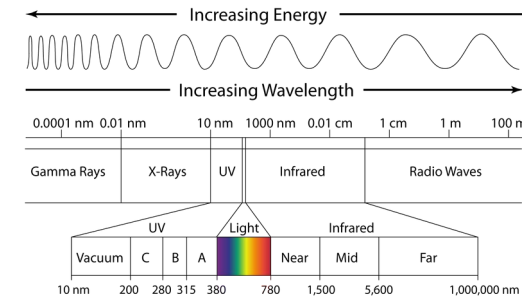
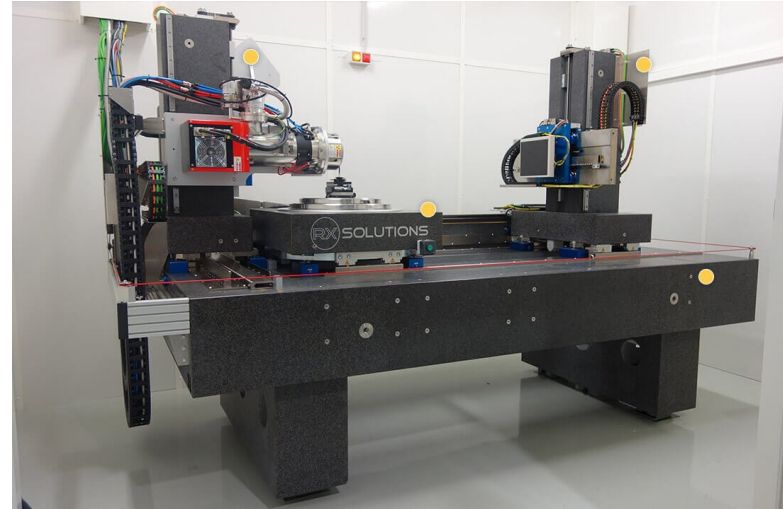


The Electro-Magnetic Spectrum

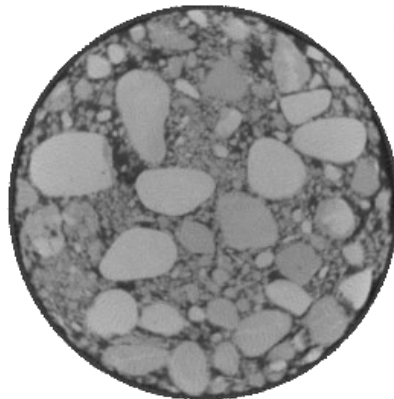


Tomography

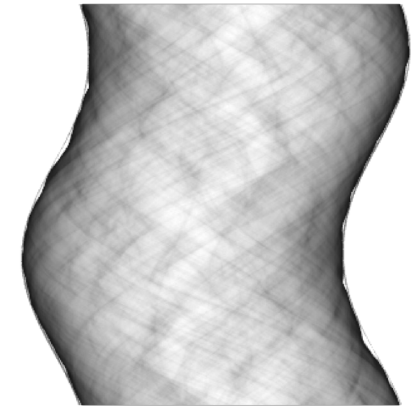
- Determine volume absorption profile
 - Project X-rays through object
 - Record shadows from different directions



3D volume



2D projections



measurement

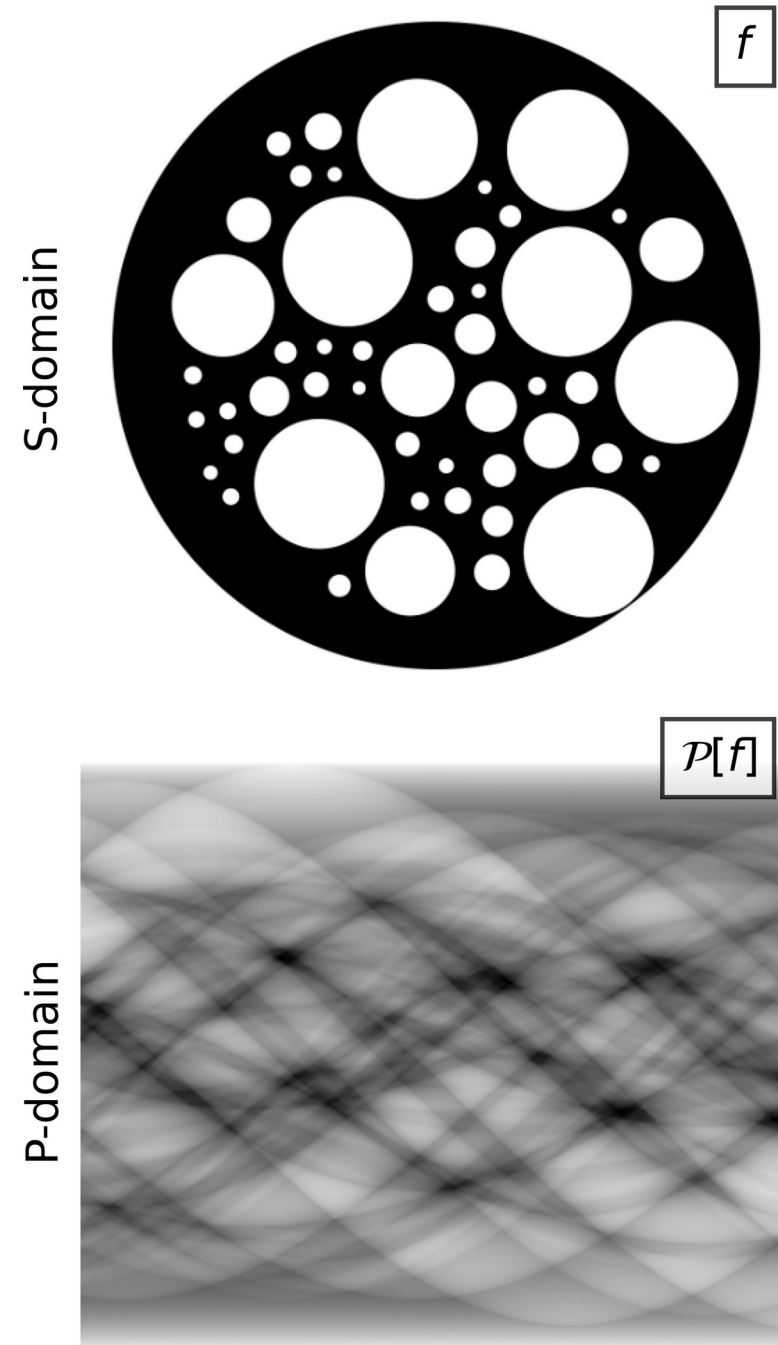
computation?

X-Ray Tomography

- Applications
 - Non-Destructive Testing (NDT)
 - Medical Imaging: X-CT
 - Material Science Research
 - Absorption CT
 - Multi-Modal Imaging: PXCT, PyXL

$$P[f](\mathbf{n}, \mathbf{s}) = \int_{\mathbb{R}} f(\mathbf{n}\alpha + U_{\mathbf{n}^\perp} \mathbf{s}) d\alpha$$

- Goal: recover f from samples of $g = \mathcal{P}[f]$



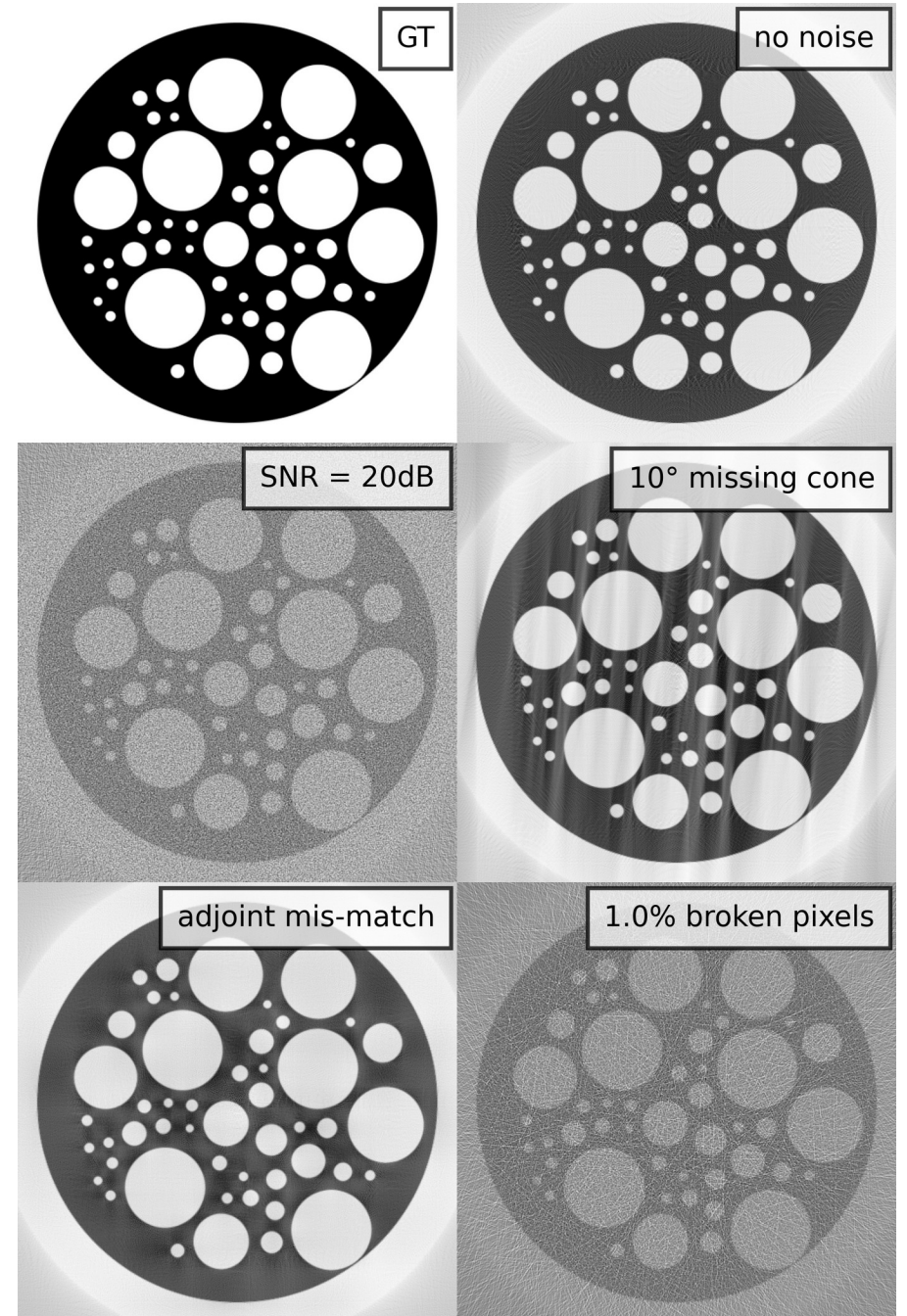
Filtered Back-Projection

- Analytic **direct** inverse

$$\begin{aligned}\hat{f} &= (P^* P)^{-1} P^*[g](\mathbf{x}) \\ &= P^*[h * g](\mathbf{x})\end{aligned}$$

- Issues

- Dense P-space sampling
- Model mis-match
- Implementation details

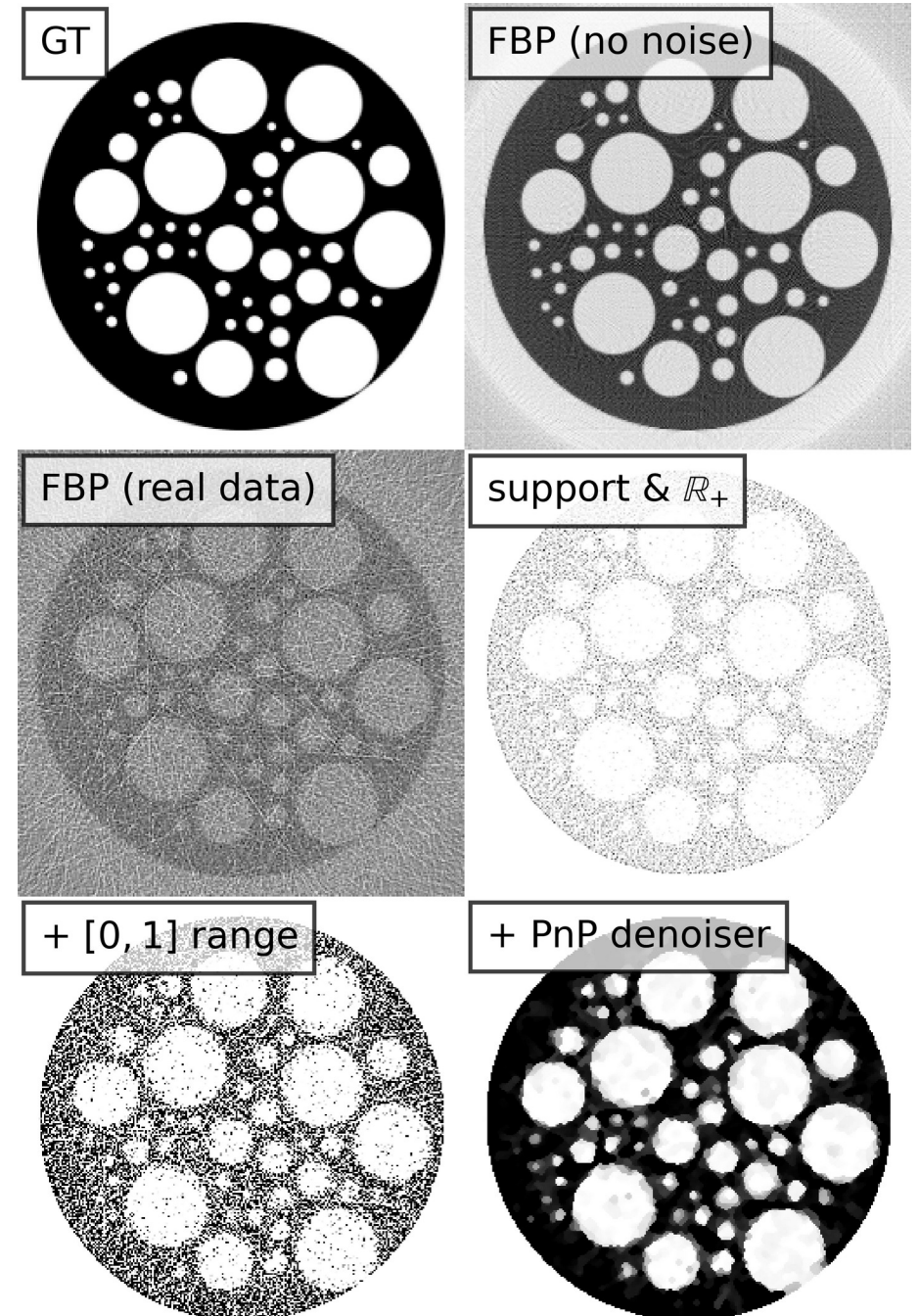


General Image Reconstruction

- Image reconstruction formulated as an inverse problem

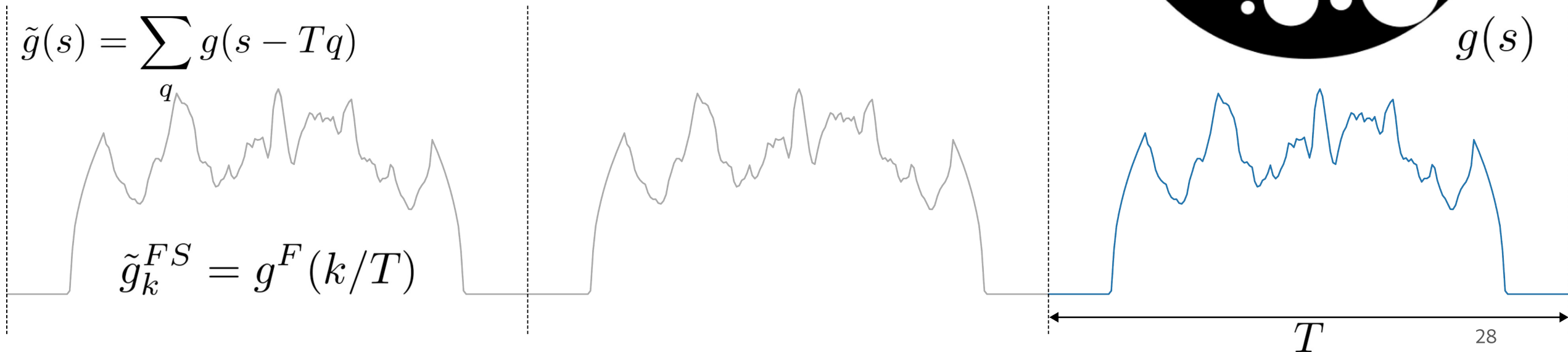
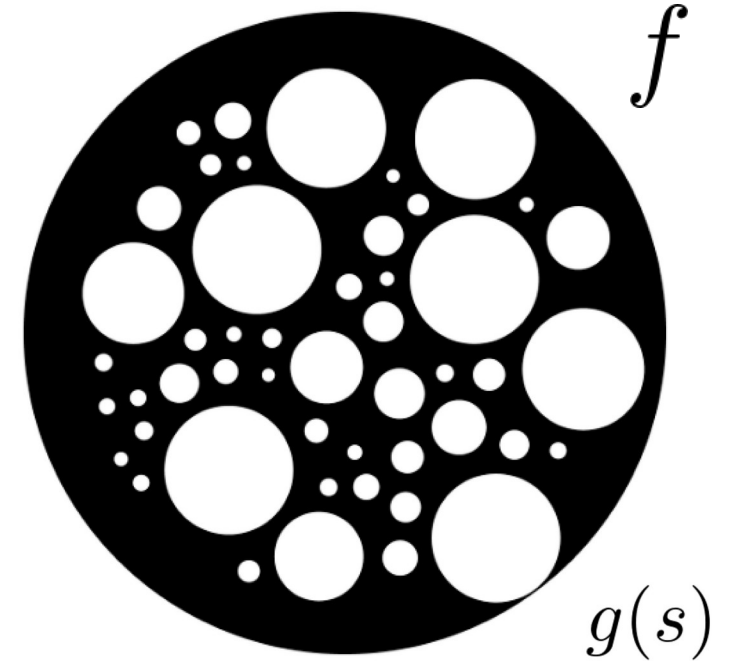
$$\hat{f} = \arg \min_{f \in \mathcal{L}^2(\mathbb{R}^D, \mathbb{R})} \mathcal{F}\{g - \underbrace{\Phi}_{\dots \circ \mathcal{P} \circ \dots} f\} + \lambda \mathcal{G}\{f\}$$

- Advantages
 - Inject prior knowledge
 - Less measurements
 - Account for instrument deviations
 - Leverage **AI** in imaging pipeline
 - Denoisers, generative priors, ...
- Solved via **iterative** 1st-order methods
 - PGD, CG, PDS, SGD, Adam, ...



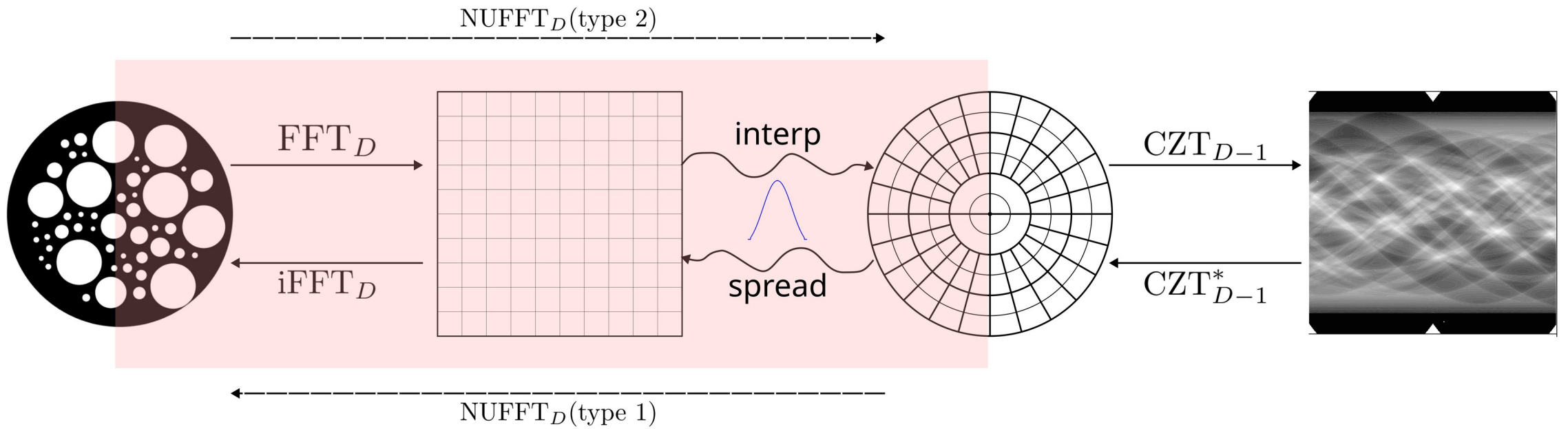
FourierXRT: Idea

- Projections $g(s)$ are **finite-support** and **band-limited**
 - FS coefficients \tilde{g}_k^{FS} can be computed exactly via the FFT
 - $g^F(v)$ obtained via FS \longleftrightarrow FT equivalence
 - *Fourier Slice Theorem* relates $g^F(v)$ with $f^F(v)$

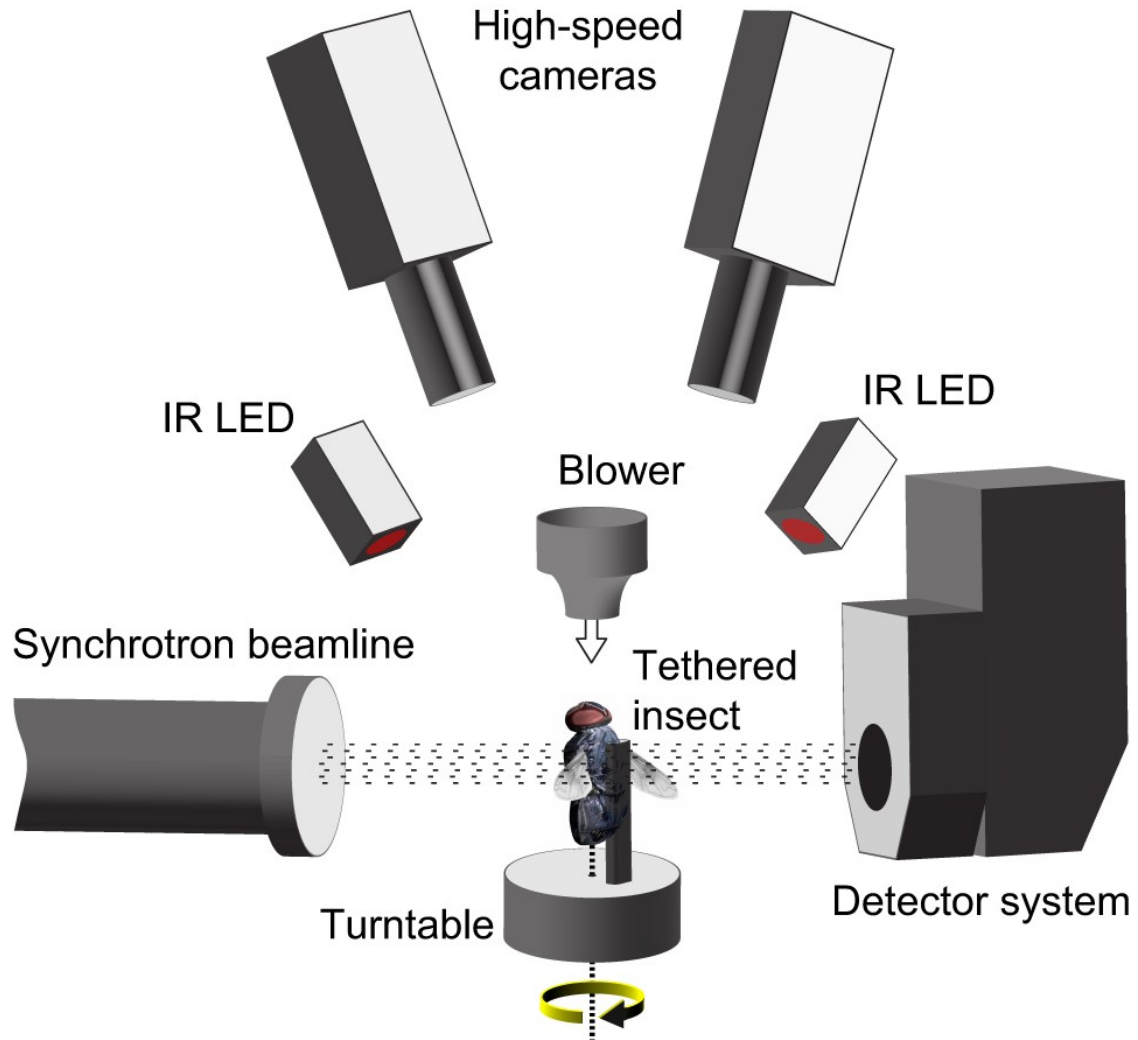


FourierXRT: Idea

$$\mathcal{P}[f](\mathbf{n}, \mathbf{s}) = \frac{1}{T^{D-1}} \sum_{\mathbf{m} \in [-N, N]^{D-1}} \boxed{\mathcal{F}_D[f] \left(\frac{1}{T} U_{\mathbf{n}^\perp} \mathbf{m} \right)} \exp \left[j \frac{2\pi}{T} \langle \mathbf{m}, \mathbf{s} \rangle \right]$$



XRT: In-Vivo Imaging



- Fly video (see link below)

XRT: Non-Destructive Processor Inspection

- Processor 3D structure video (see link below)

