Off-the-Grid Compressive Imaging: Recovery of Piecewise Constant Images from Few Fourier Samples

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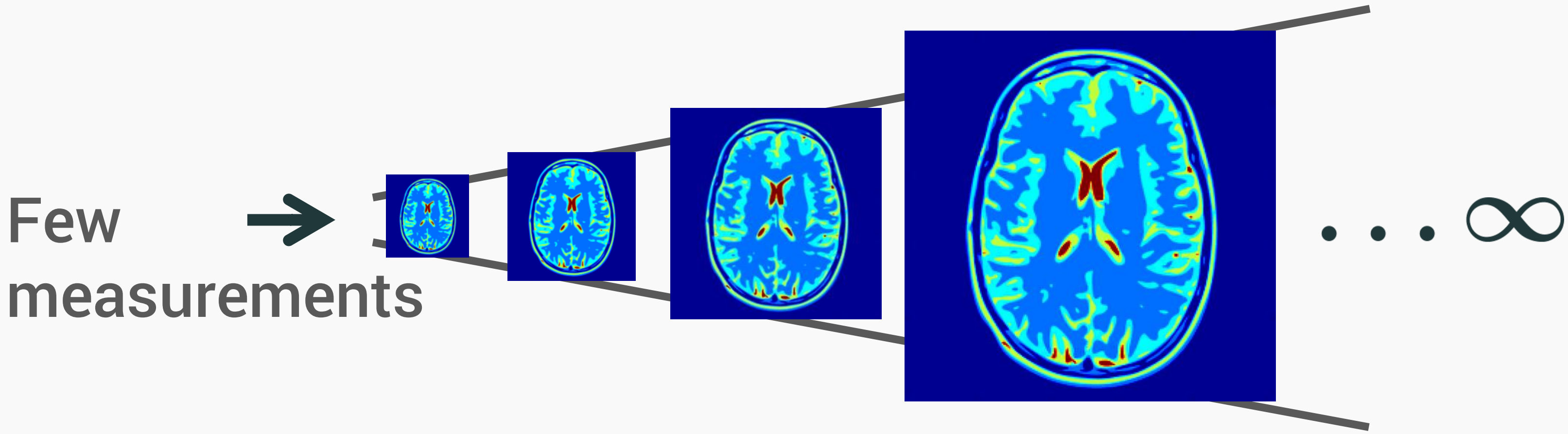
Our goal is to develop theory and algorithms for compressive off-the-grid imaging

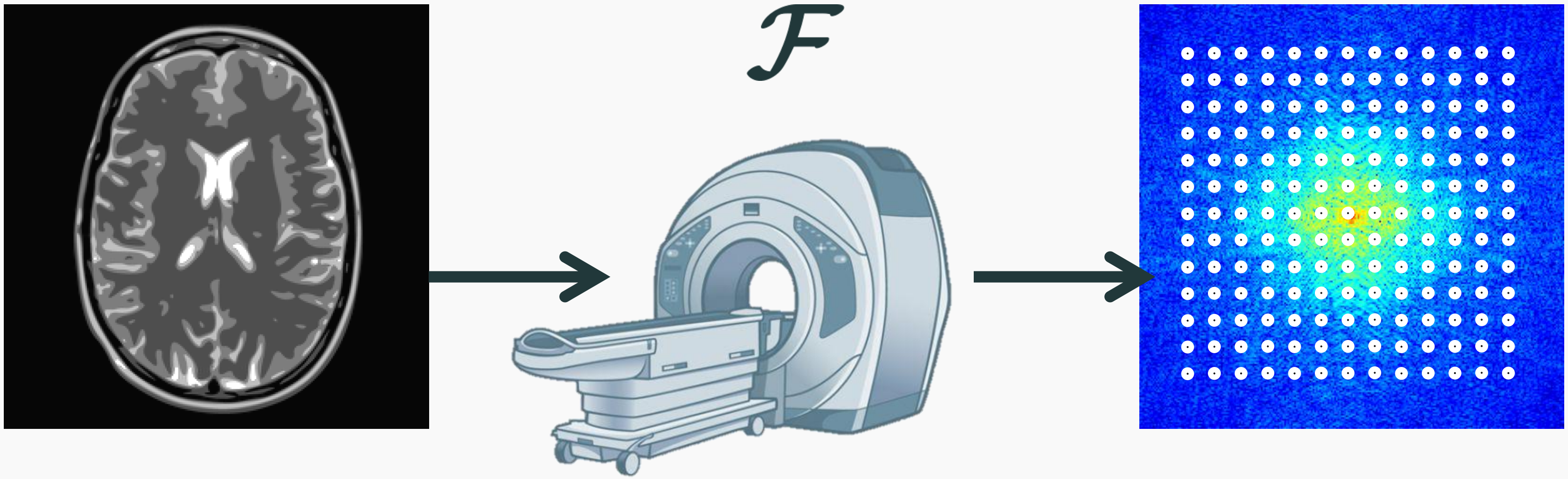


Off-the-grid = Continuous domain representation

Compressive off-the-grid *imaging*:

Exploit continuous domain modeling to improve image recovery from few measurements

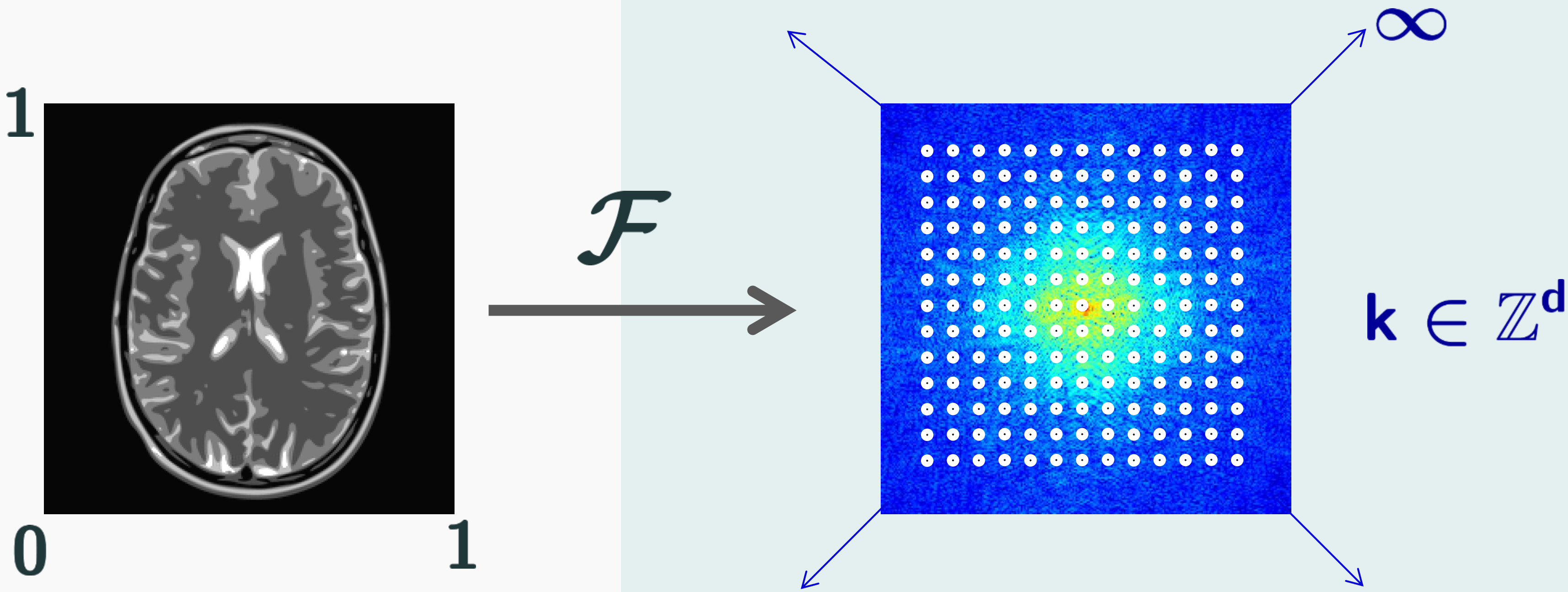
Motivation: MRI Reconstruction



Main Problem:

Reconstruct image from Fourier domain samples

Related: Computed Tomography, Florescence Microscopy



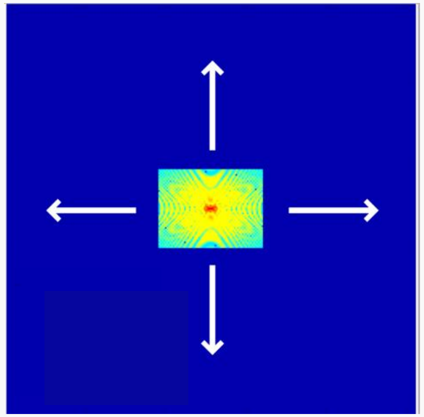
$$\mathbf{f}(\mathbf{x}), \quad \mathbf{x} \in [0,1]^d$$

$$\hat{\mathbf{f}}[\mathbf{k}] := \int_{[0,1]^d} \mathbf{f}(\mathbf{x}) e^{-j2\pi \mathbf{k}\cdot\mathbf{x}} d\mathbf{x}$$

Uniform Fourier Samples =
Fourier Series Coefficients

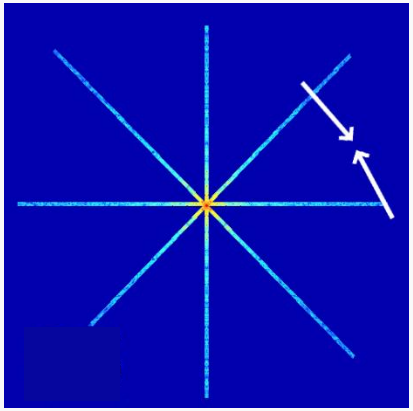
Types of “Compressive” Fourier Domain Sampling

low-pass

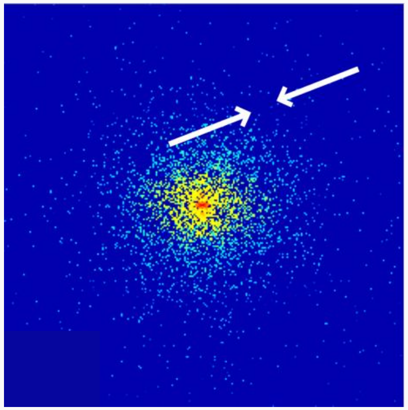


vs.

radial



random



Fourier Extrapolation

↓

Super-resolution recovery

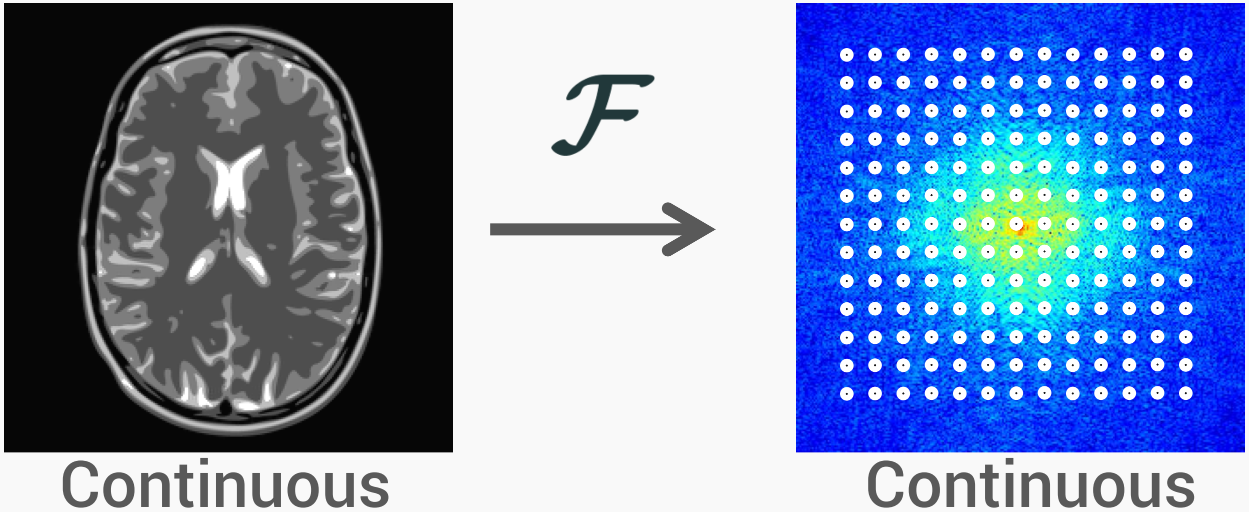
Fourier Interpolation

↓

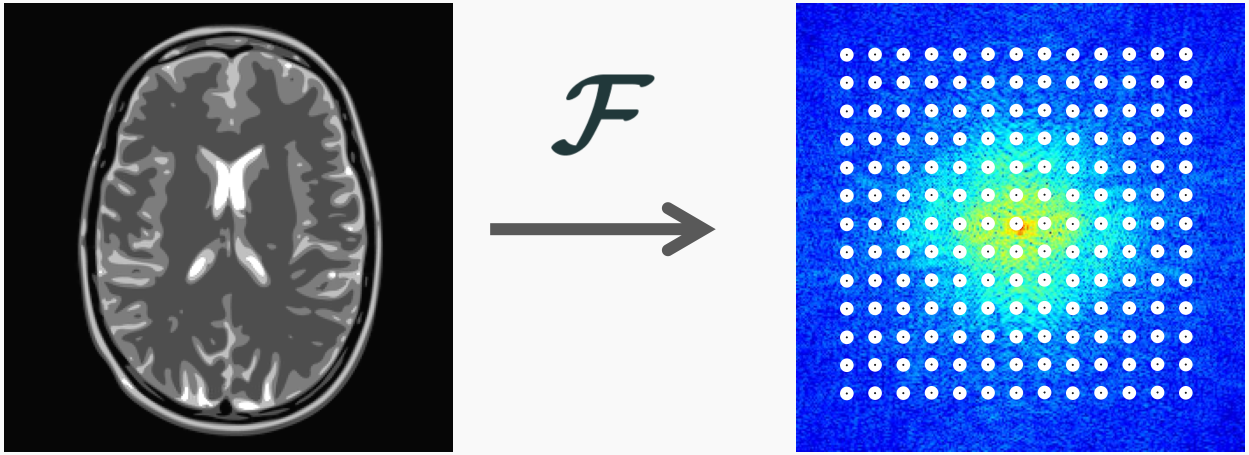
“Compressed Sensing” recovery

CURRENT DISCRETE PARADIGM

“True” measurement model:



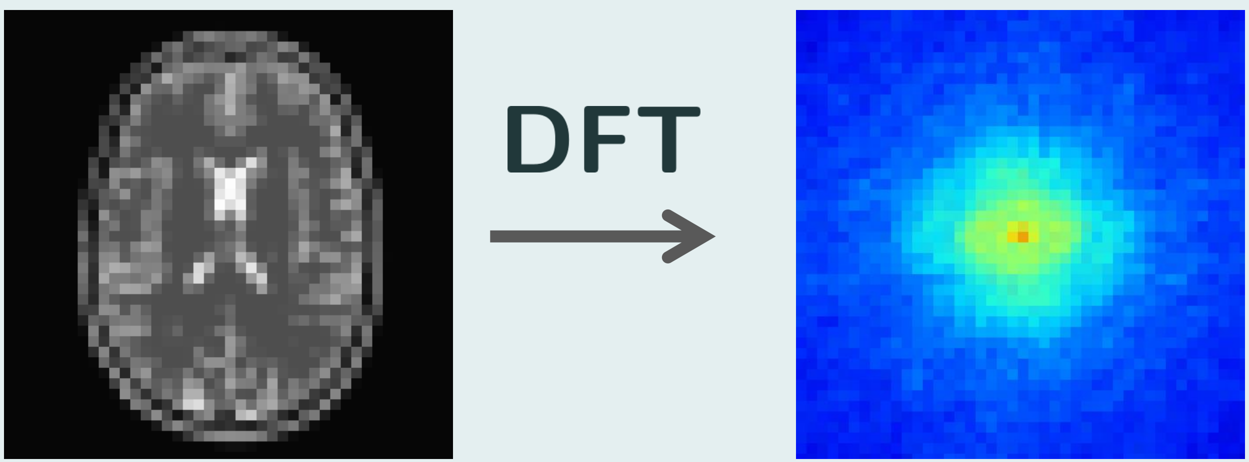
“True” measurement model:



Continuous | Continuous

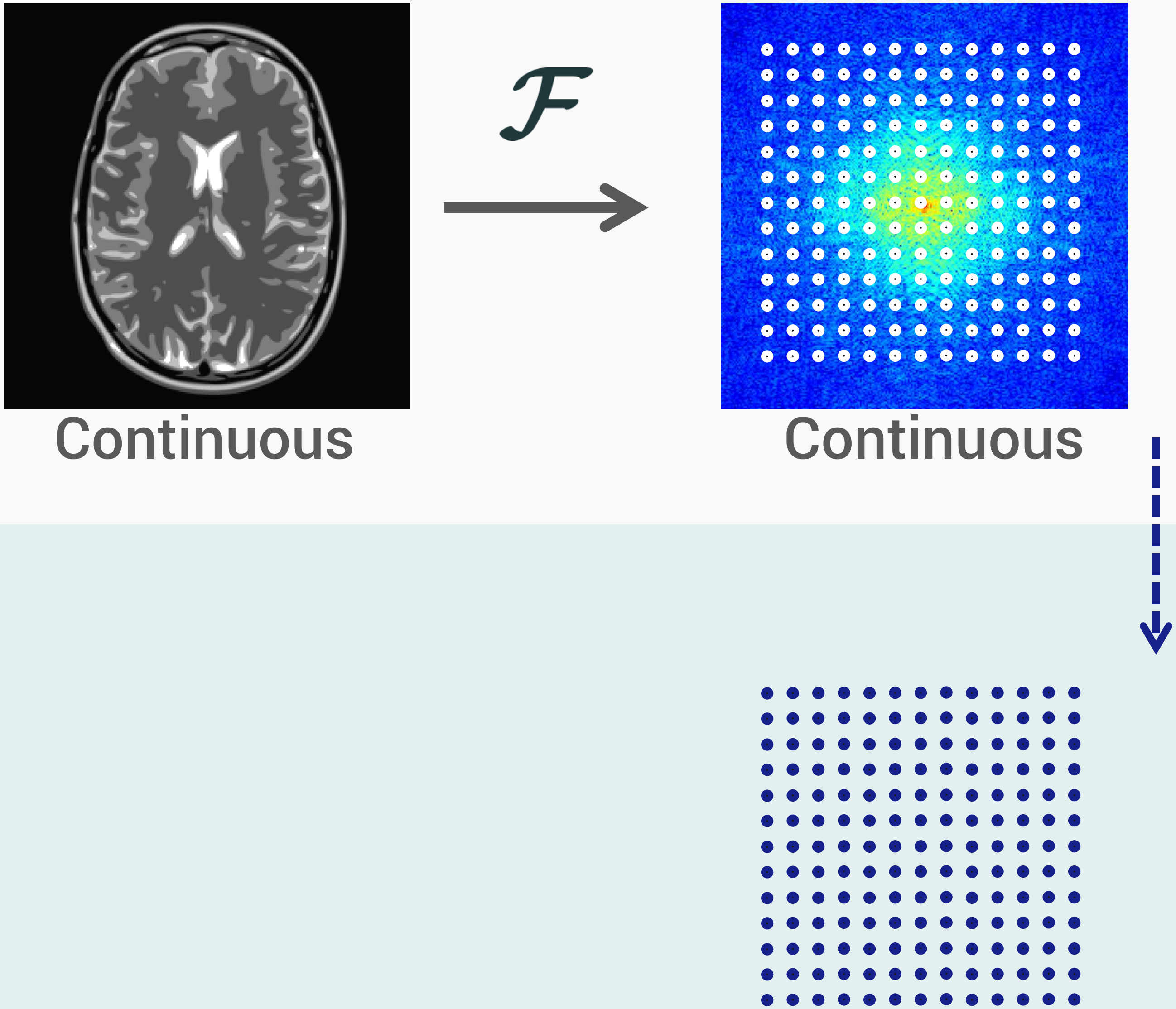
Approximated measurement model:

$\approx$

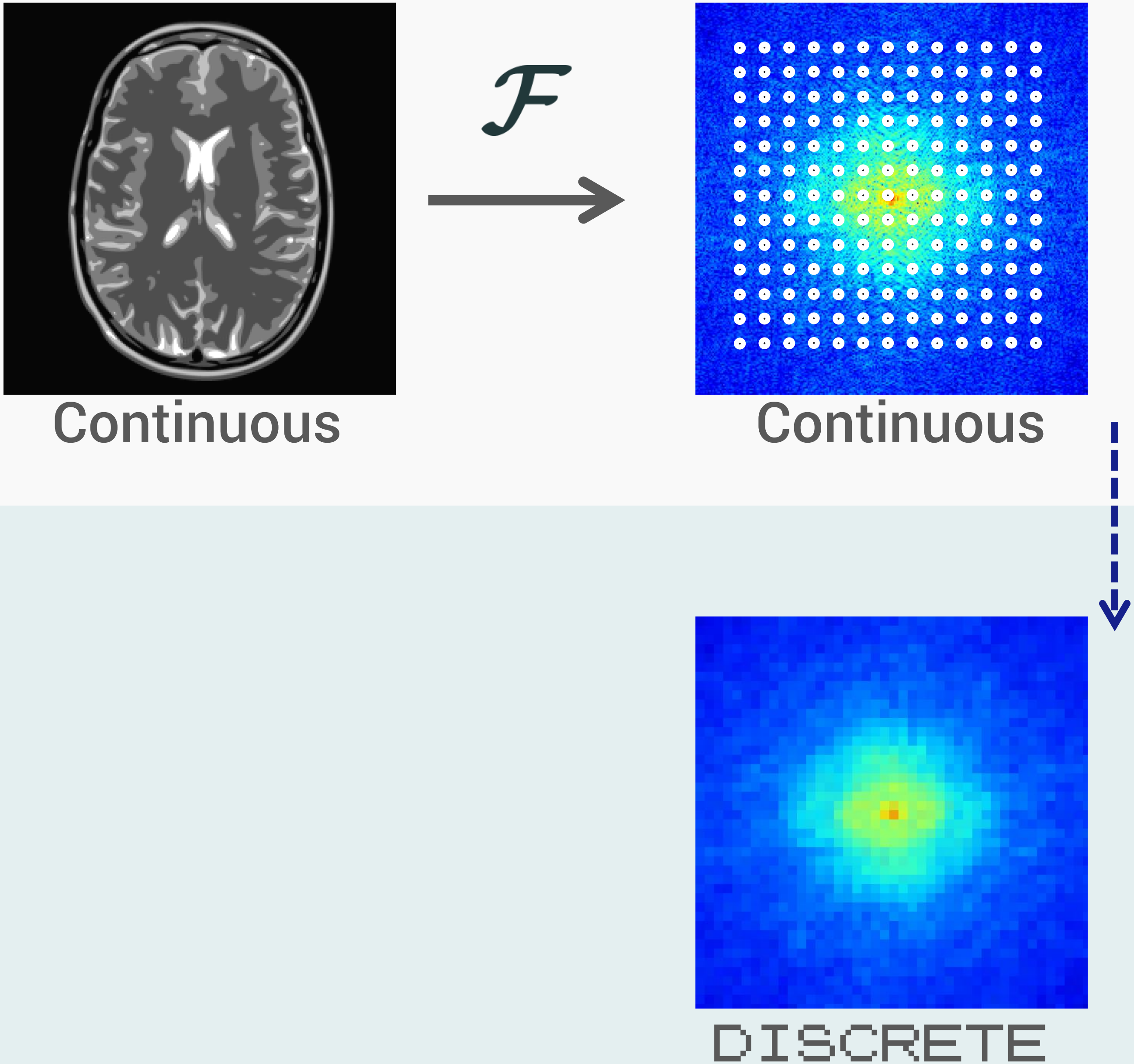


DISCRETE | DISCRETE

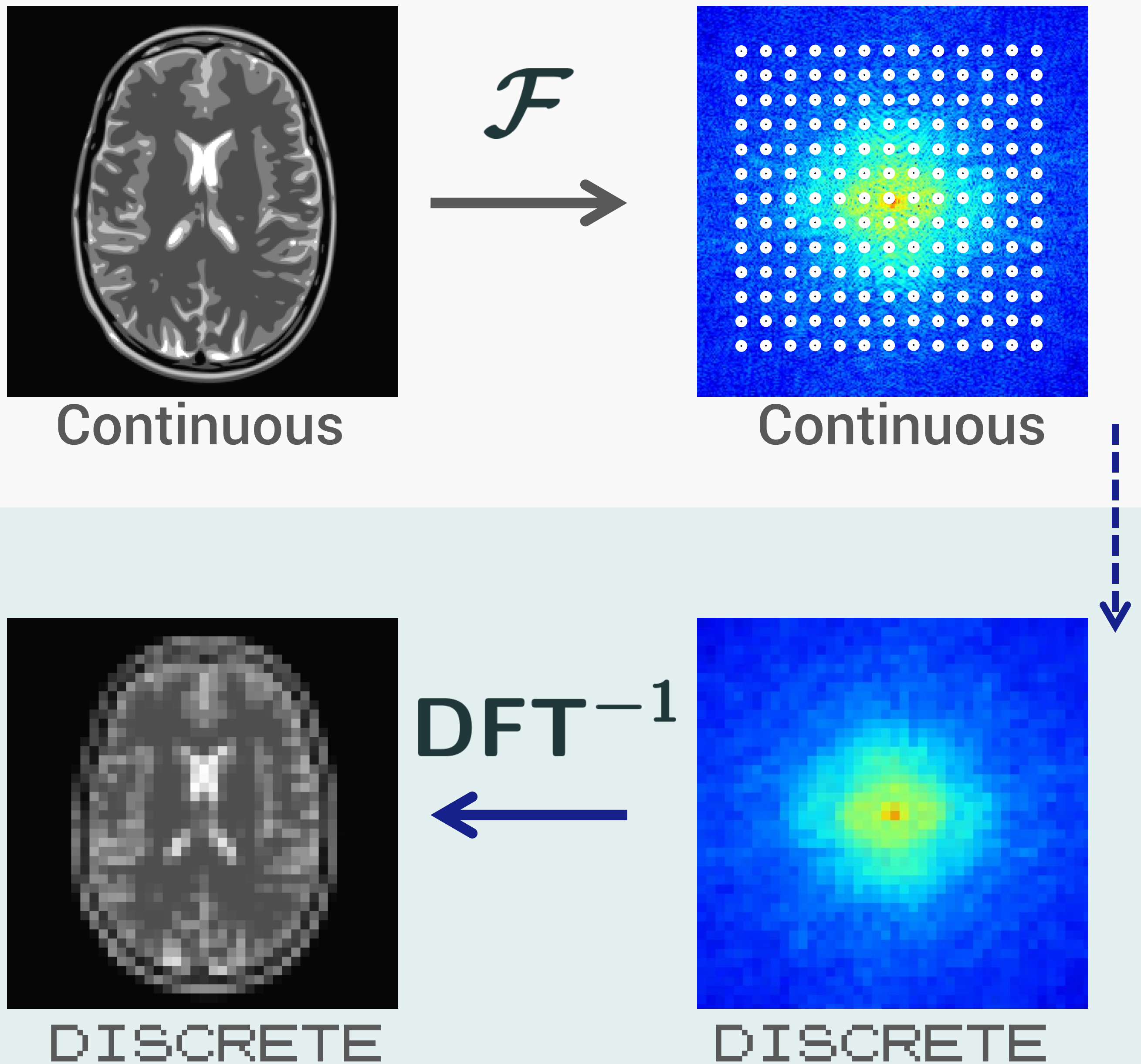
DFT Reconstruction



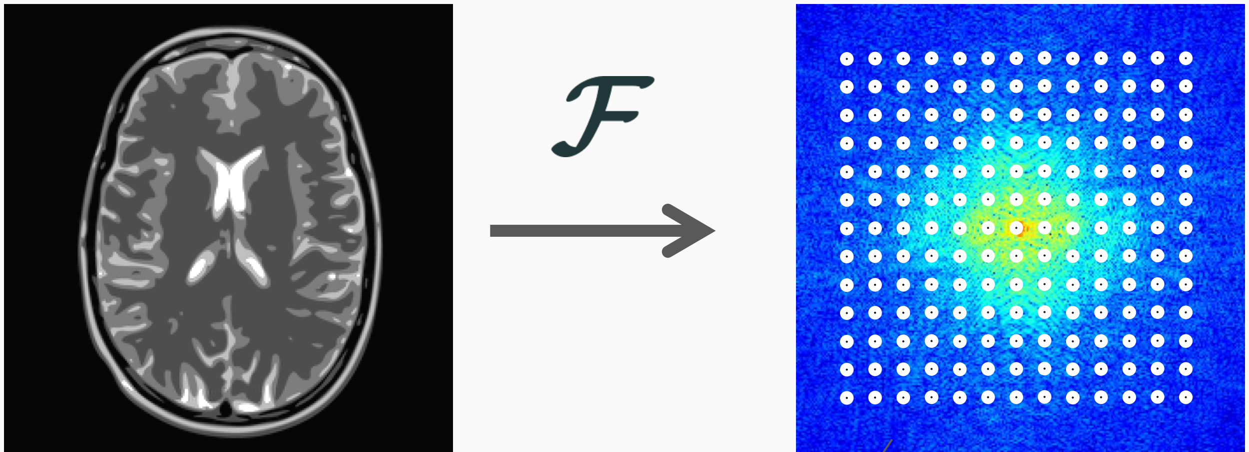
DFT Reconstruction



DFT Reconstruction

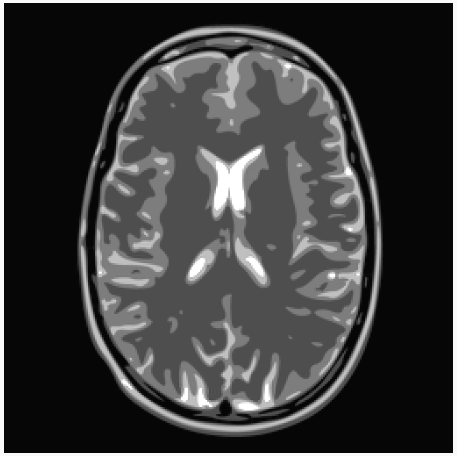


“Compressed Sensing” Recovery

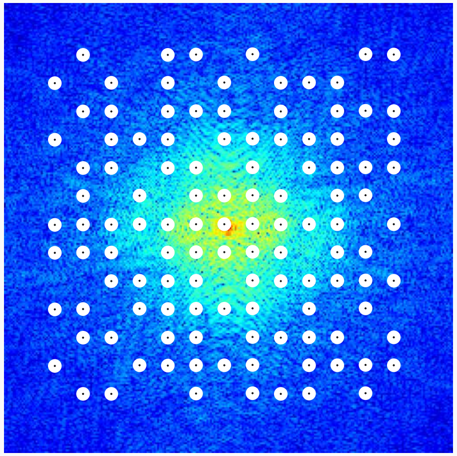


Full sampling is costly!
(or impossible—e.g. Dynamic MRI)

“Compressed Sensing” Recovery

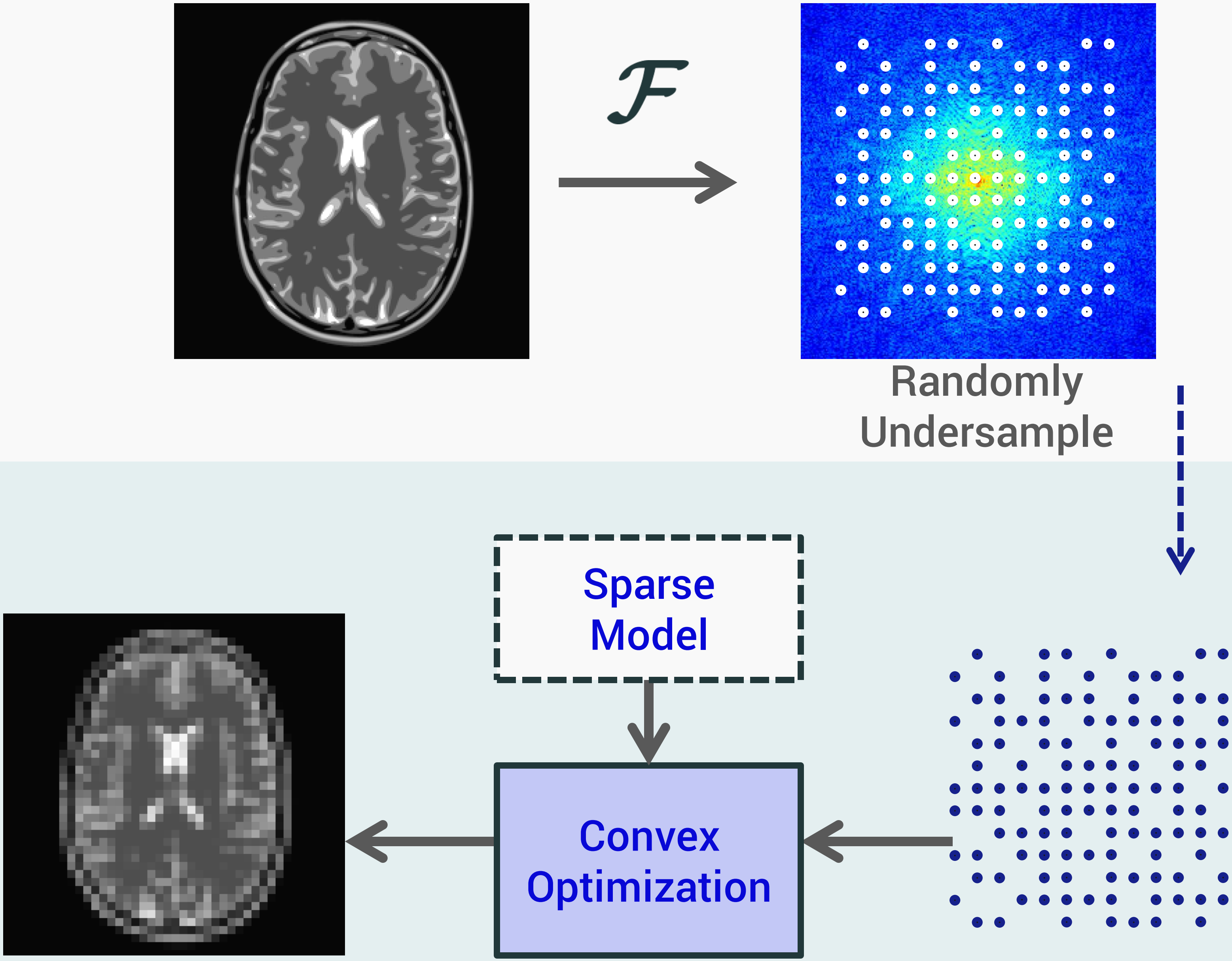


$\xrightarrow{\mathcal{F}}$



Randomly Undersample

“Compressed Sensing” Recovery

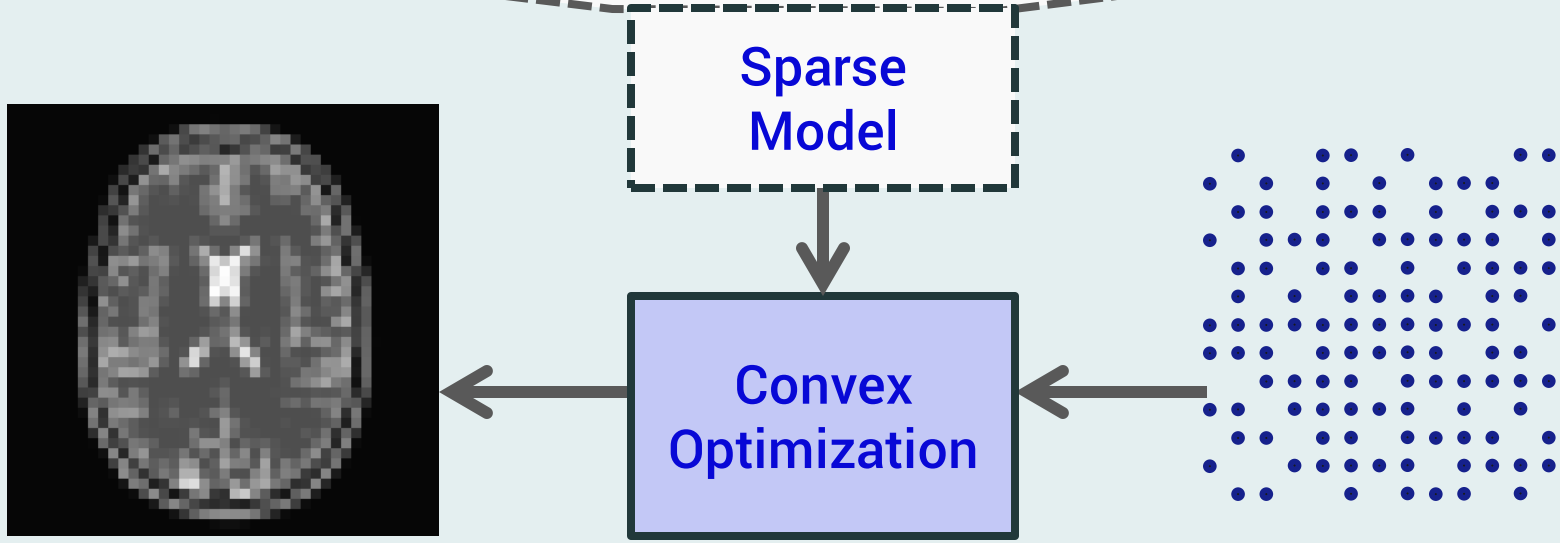


Example:

Assume discrete gradient of image is sparse

↕

Piecewise constant model



Recovery by Total Variation (TV) minimization

TV semi-norm: $\|\mathbf{g}\|_{TV} = \sum_{i,j} \sqrt{|\mathbf{g}_{i+1,j} - \mathbf{g}_{i,j}|^2 + |\mathbf{g}_{i,j+1} - \mathbf{g}_{i,j}|^2}$

i.e., L1-norm of discrete gradient magnitude

$\sum_{i,j}$

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$$\min_{\mathbf{g} \in \mathbb{C}^{N \times N}} \|\mathbf{g}\|_{\mathrm{TV}} \quad \text{subject to} \quad \mathbf{F}_\Omega \mathbf{g} = \mathbf{F}_\Omega \mathbf{f} \qquad (\mathbf{TV}\text{-min})$$

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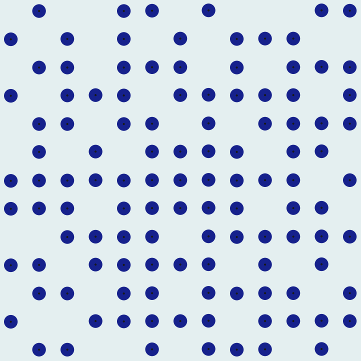
Restricted DFT

$\Omega =$ 

Sample locations

Recovery by Total Variation (TV) minimization

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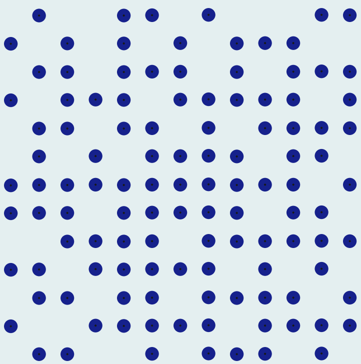
$\Omega =$ 

Sample locations

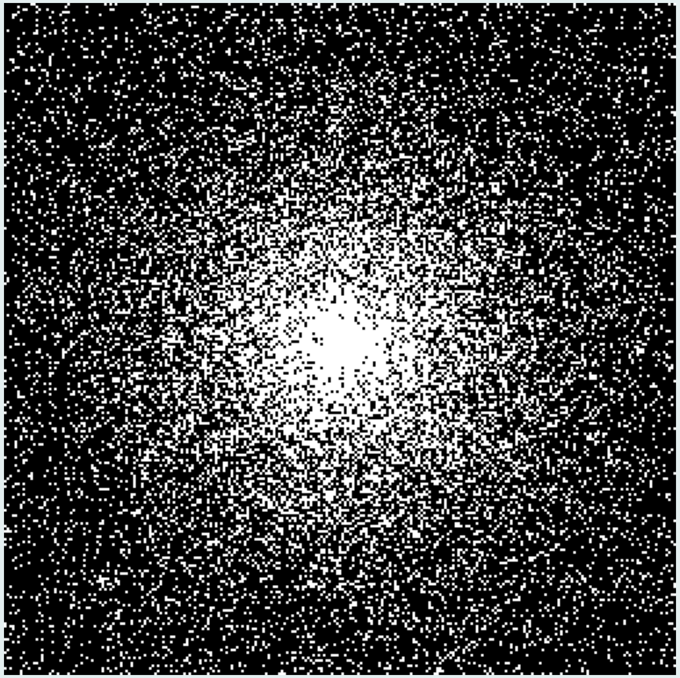
Convex optimization problem

Fast iterative algorithms:

ADMM/Split-Bregman,

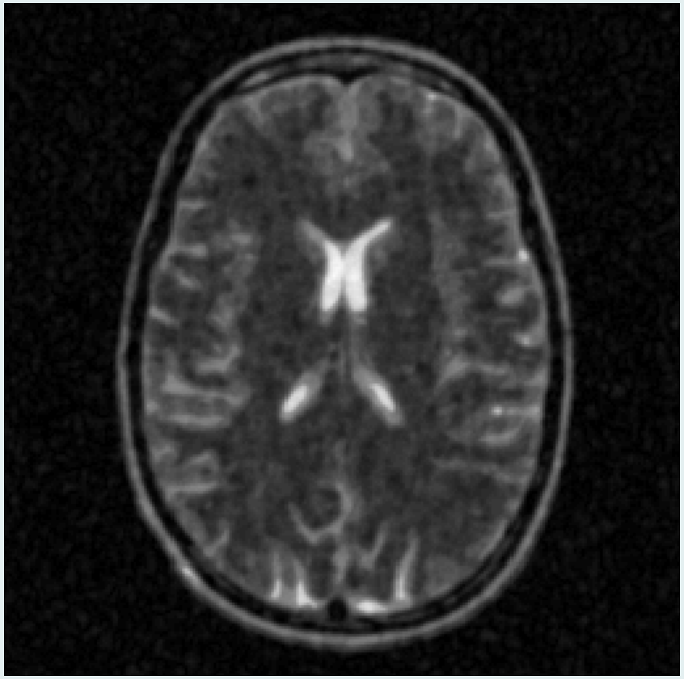
FISTA, Primal-Dual, etc.

Example:



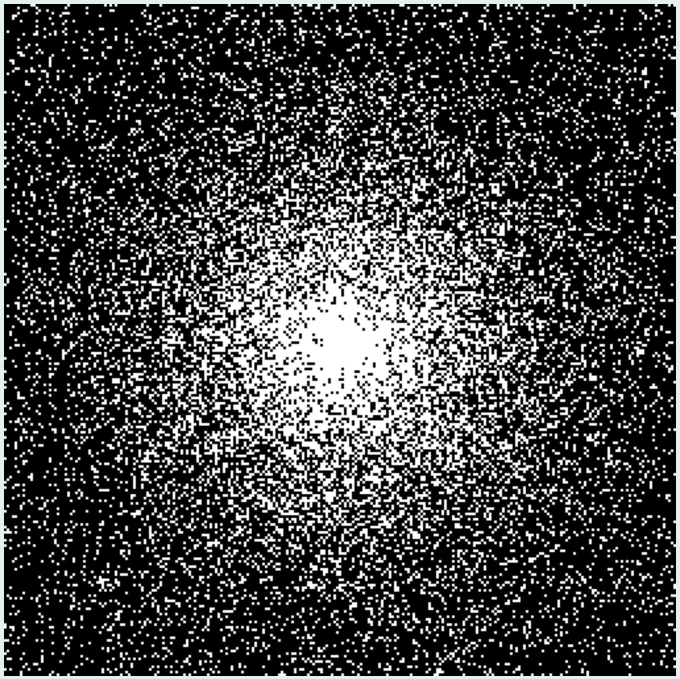
25% Random
Fourier samples
(variable density)

$\xrightarrow{\mathbf{DFT}^{-1}}$



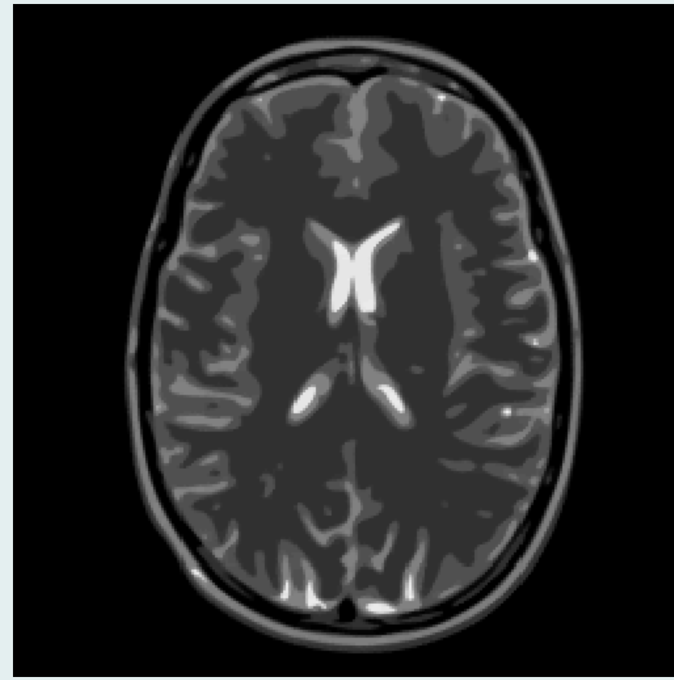
Rel. Error = 30%

Example:



25% Random
Fourier samples
(variable density)

TV-min



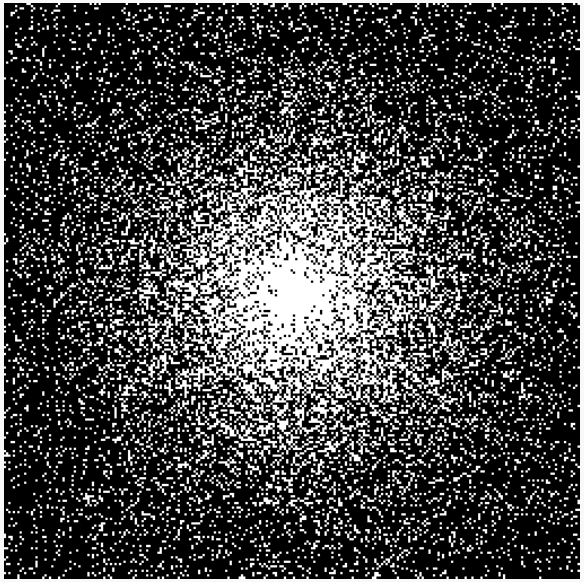
Rel. Error = 5%

Theorem [Krahmer & Ward, 2012]:

If $\mathbf{f} \in \mathbb{C}^{N \times N}$ has ***s*-sparse gradient**, then **f** is the unique solution to (**TV**-min) with high probability provided the number of random* Fourier samples **m** satisfies

$$\mathbf{m} \gtrsim \mathbf{s} \log^3(\mathbf{s}) \log^5(\mathbf{N})$$

* Variable density sampling



Summary of DISCRETE PARADIGM

- Approximate $\mathcal{F} \rightarrow \mathbf{DFT}$
- **Fully sampled:**
  Fast reconstruction by $\mathbf{DFT}^{-1}$
- **Under-sampled (*Compressed sensing*):**
  Exploit sparse models & convex optimization
  – E.g. TV-minimization
  – Recovery guarantees

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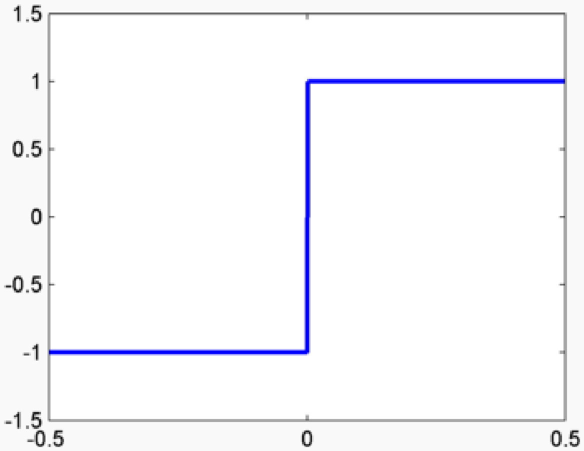
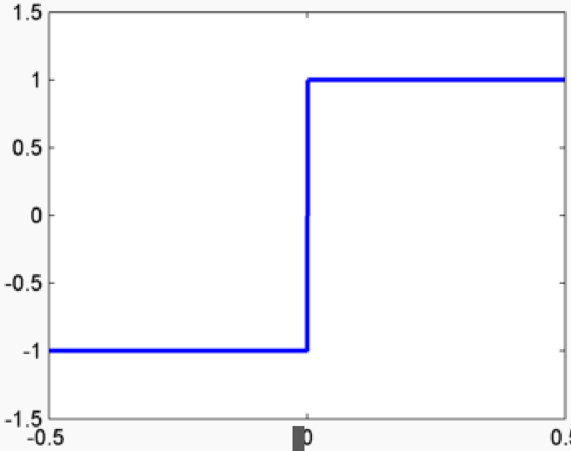
Problem: The DFT Destroys Sparsity!

Continuous

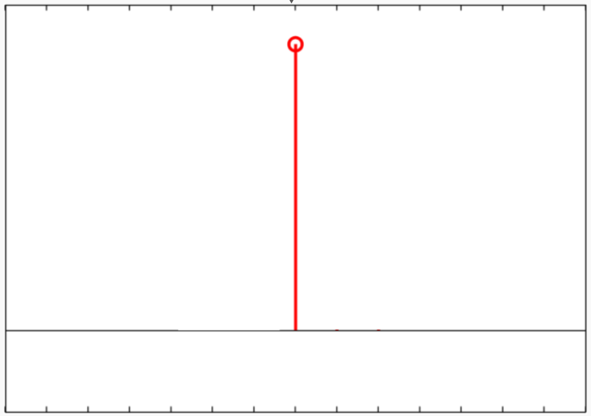


Problem: The DFT Destroys Sparsity!

Continuous

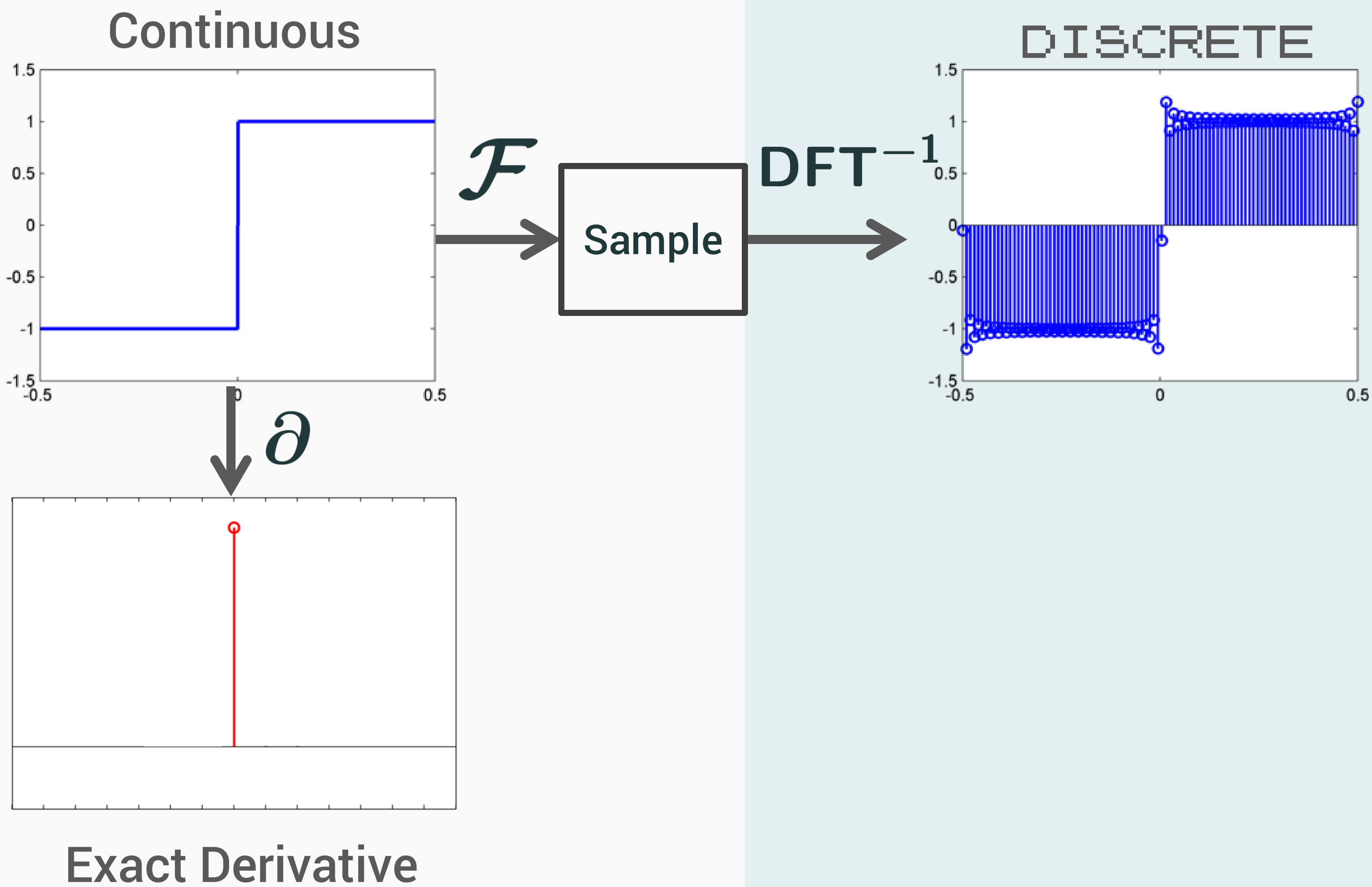


∂



Exact Derivative

Problem: The DFT Destroys Sparsity!



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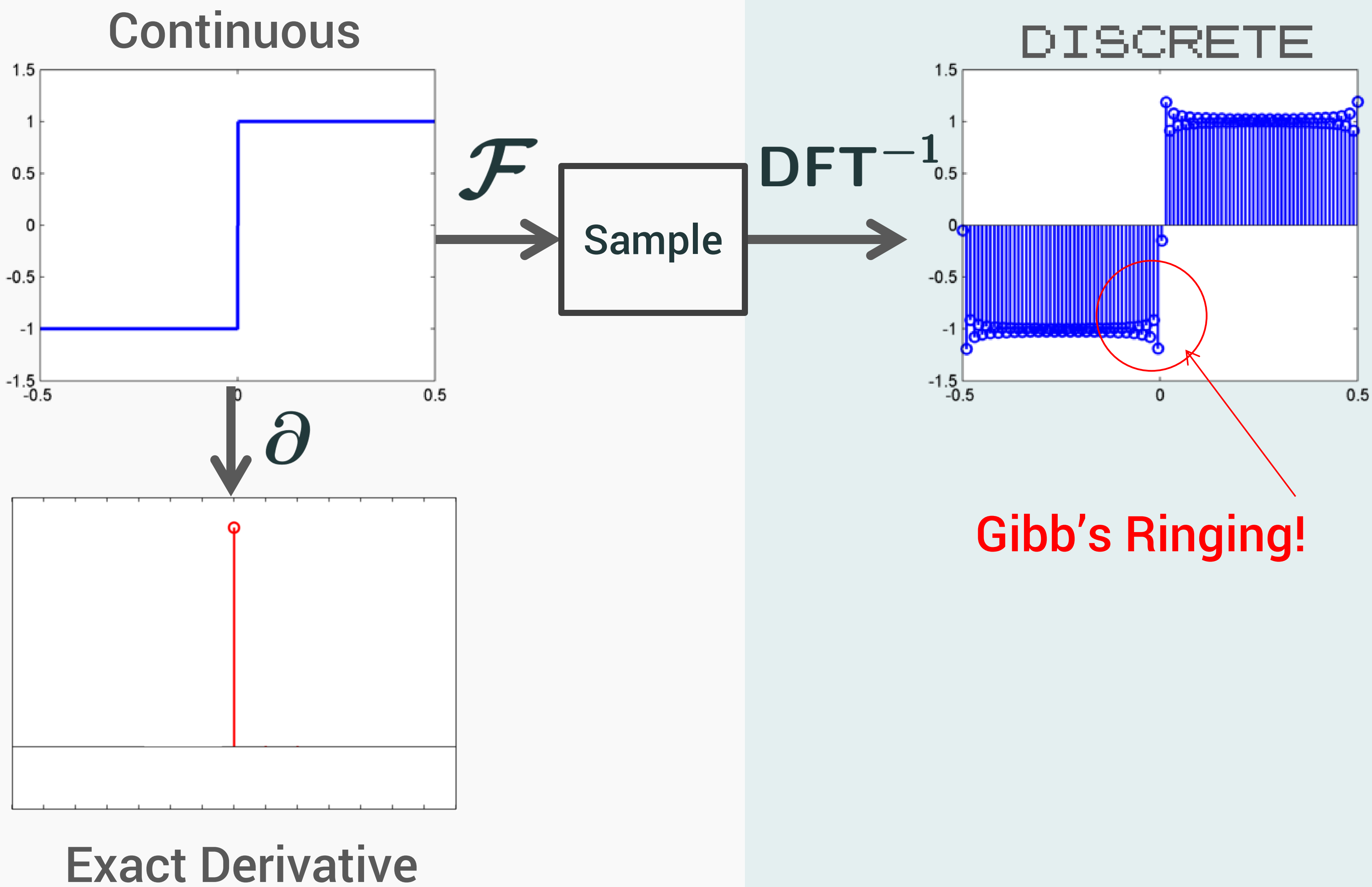

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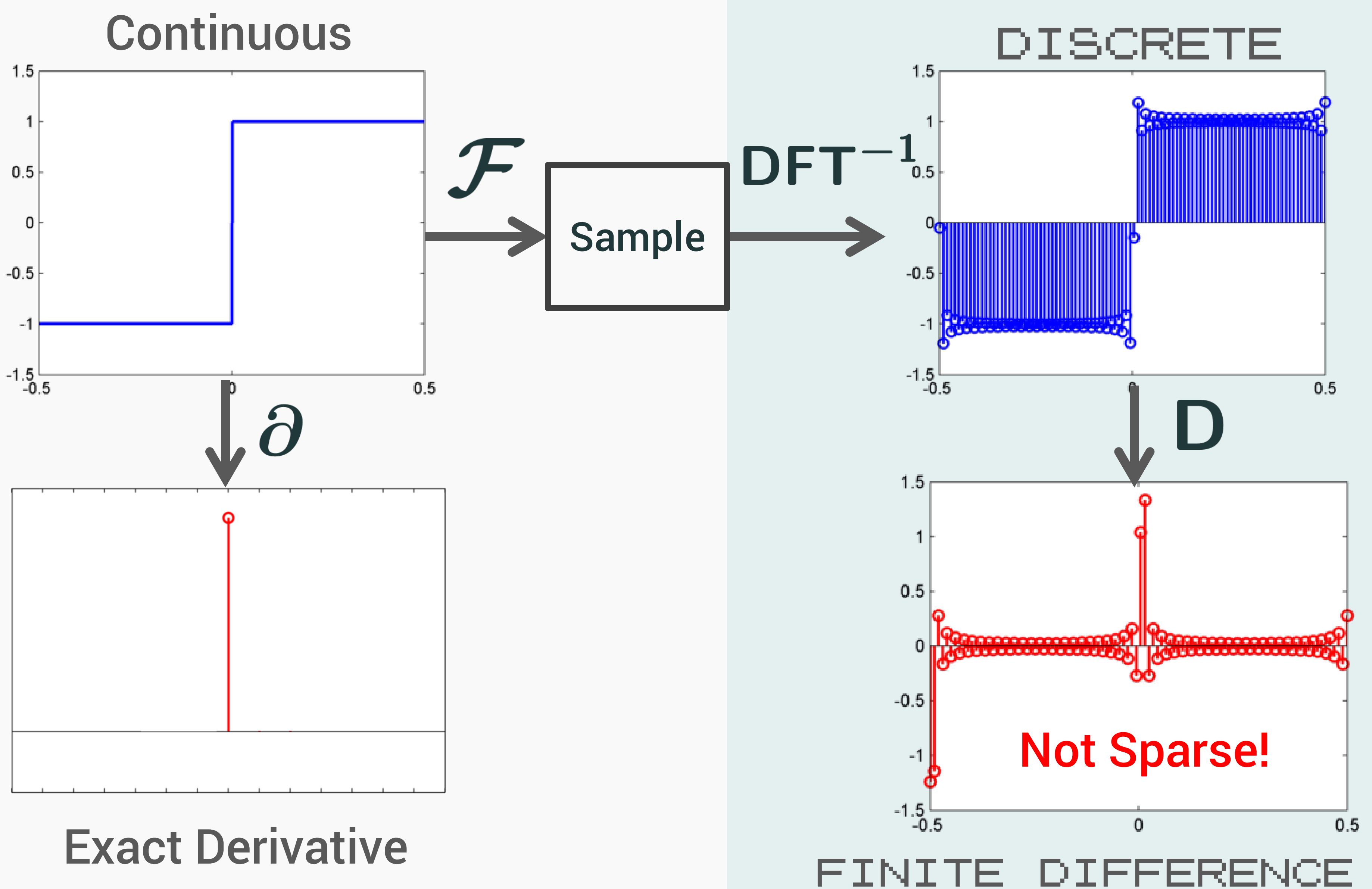
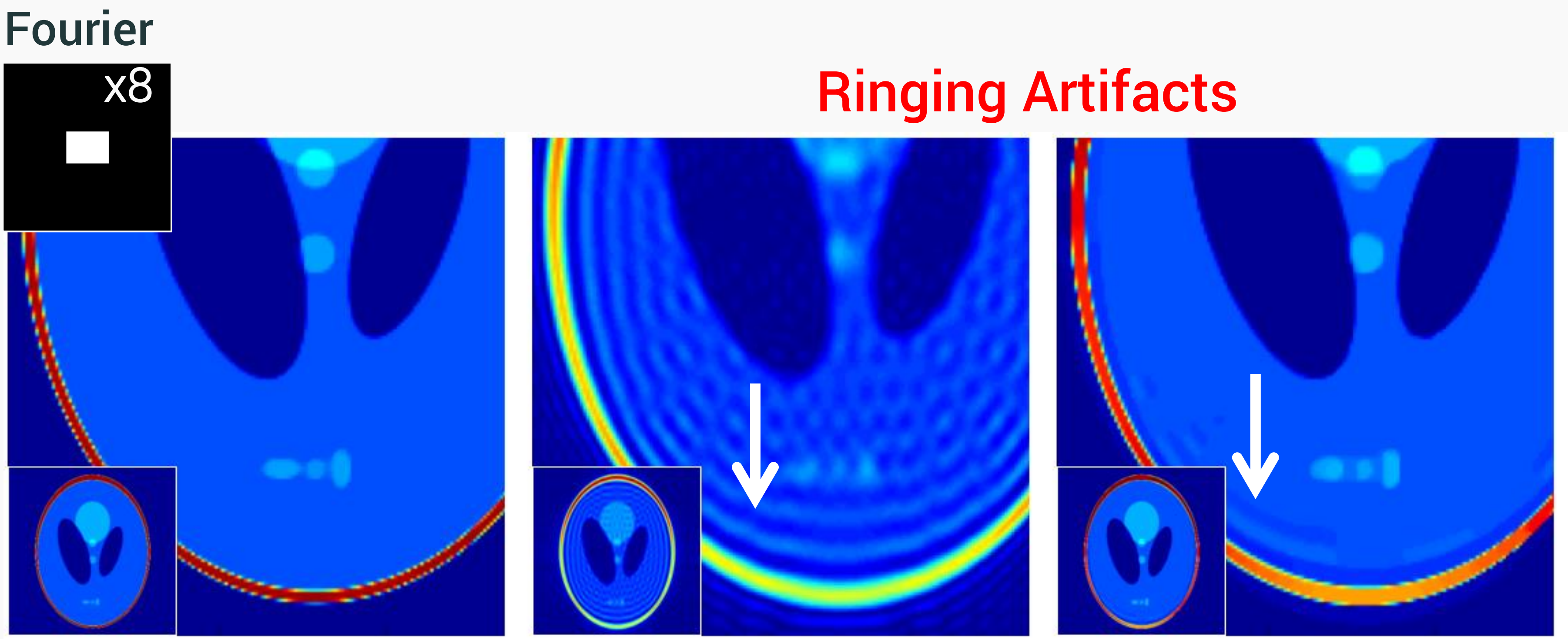


Consequence: TV fails in super-resolution setting

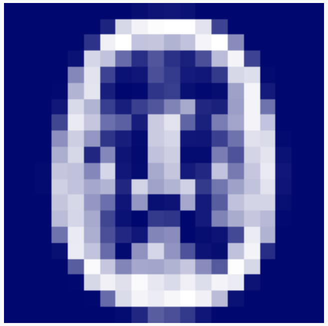


(a) Fully sampled (b) IFFT, SNR=10.8dB (c) TV, SNR=16.6dB

Can we move beyond the DISCRETE PARADIGM in Compressive Imaging?

Challenges:

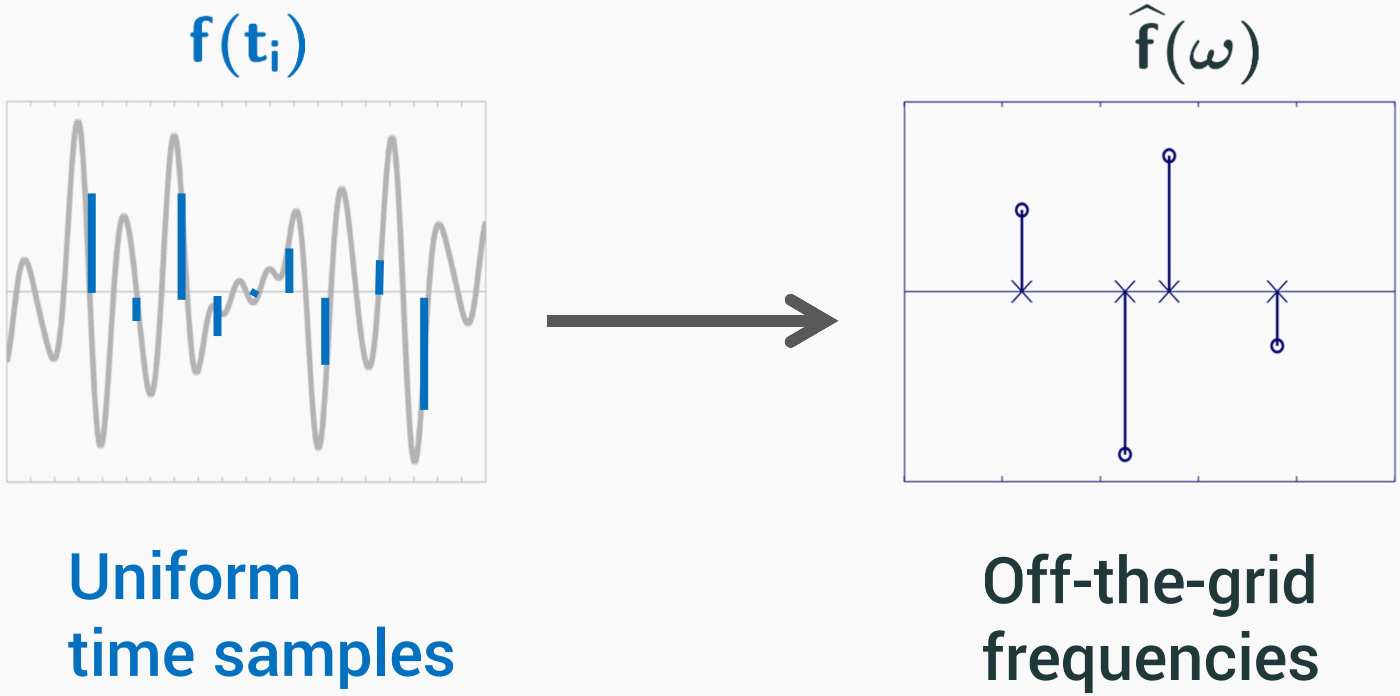
- Continuous domain sparsity $\neq$ Discrete domain sparsity



- What are the **continuous domain** analogs of **sparsity**?
- Can we pose recovery as a **convex optimization** problem?
- Can we give **recovery guarantees**, *a la* TV-minimization?

New *Off-the-Grid* Imaging Framework: *Theory*

Classical Off-the-Grid Method: Prony (1795)



- Robust variants:

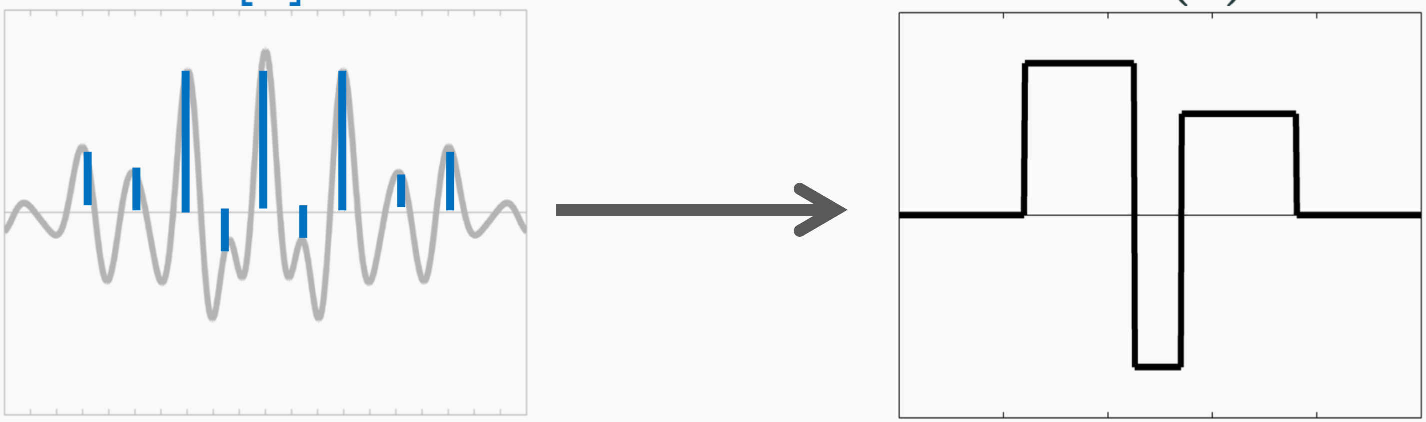
  Pisarenko (1973), MUSIC (1986), ESPRIT (1989),

  Matrix pencil (1990) . . . Atomic norm (2011)

Main inspiration: Finite-Rate-of-Innovation (FRI)
[Vetterli et al., 2002]

$\hat{f}[k]$

$f(x)$

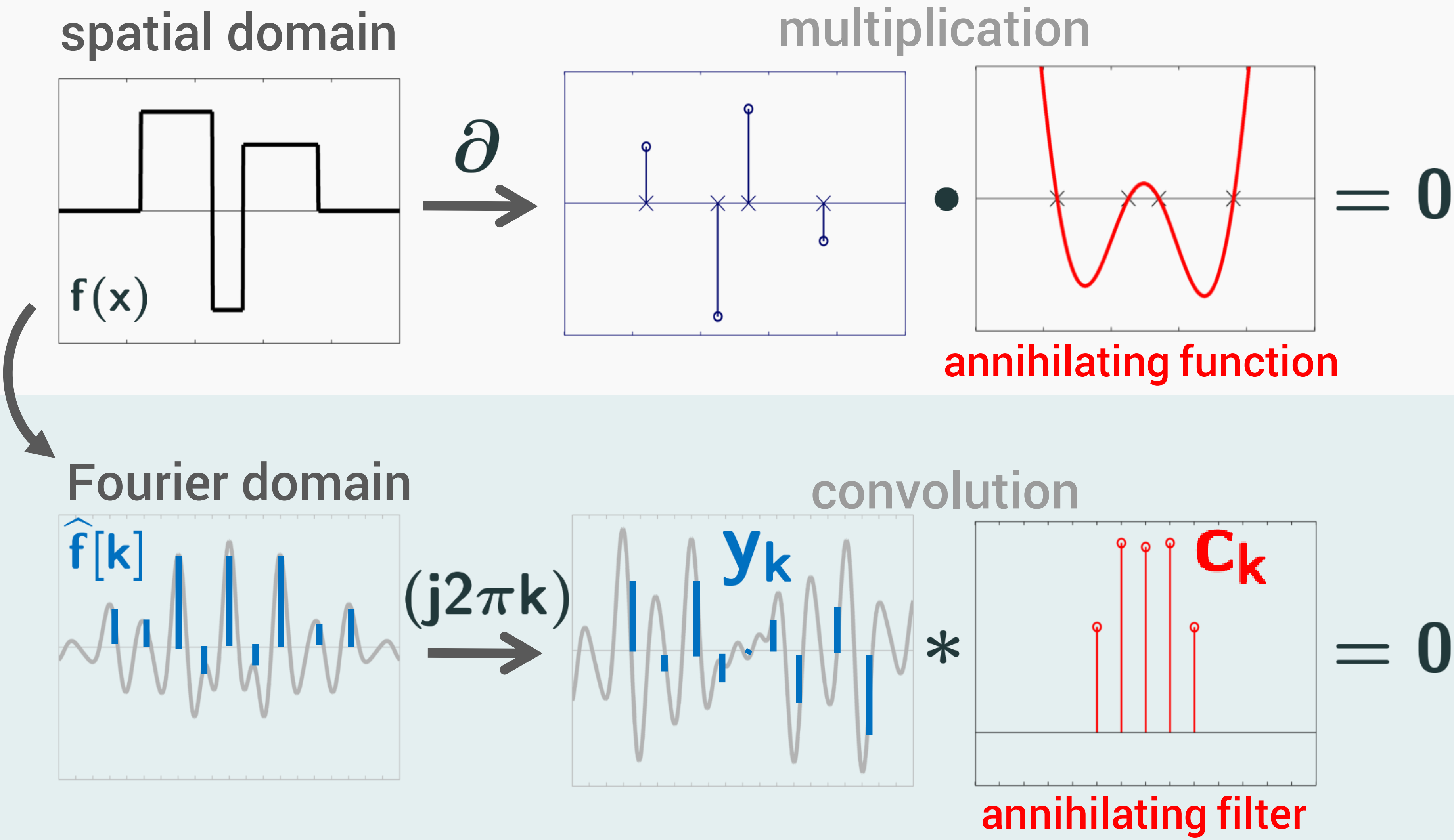


Uniform
Fourier samples

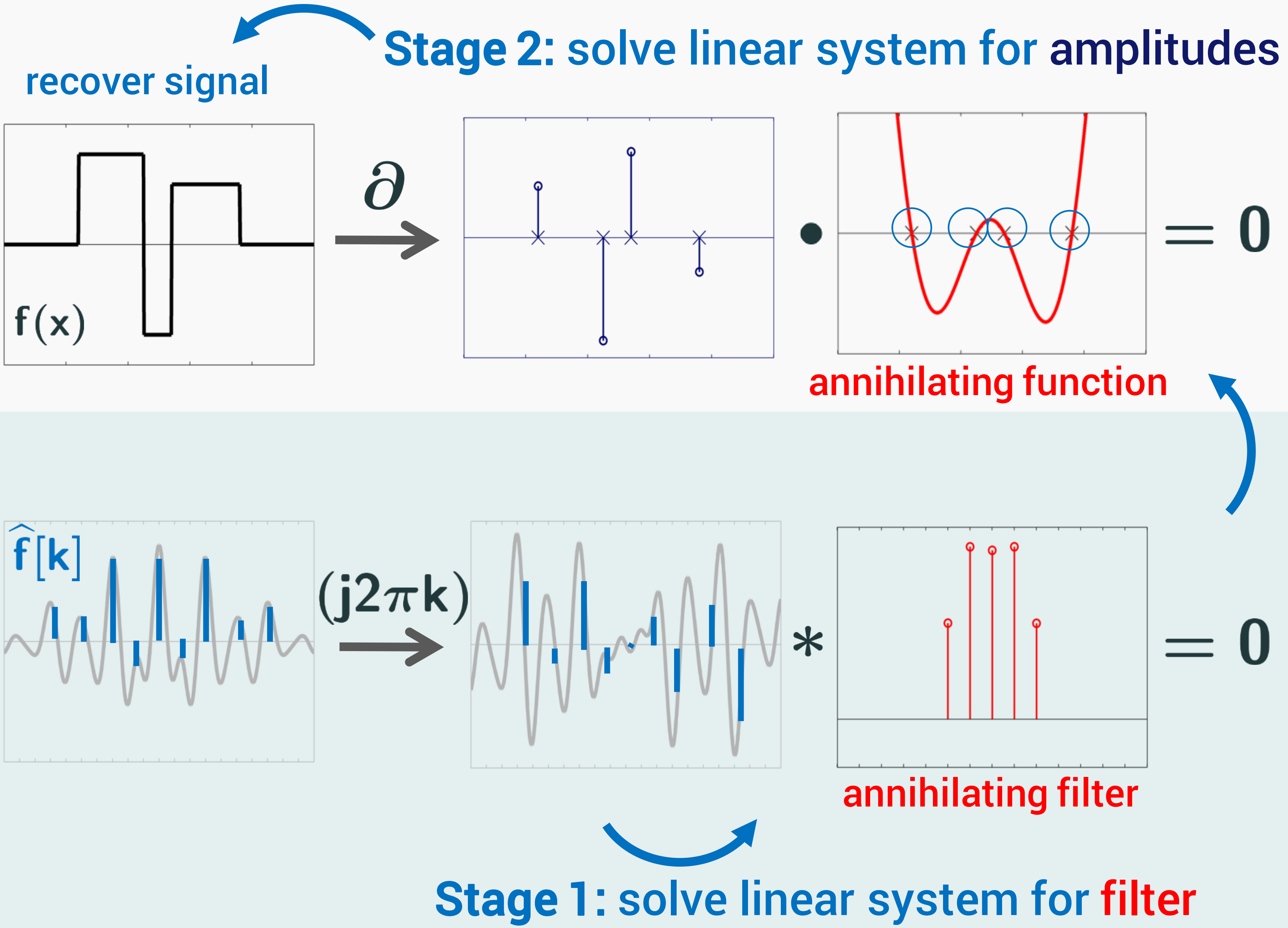
Off-the-grid
PWC signal

- Recent extension to 2-D images:

  Pan, Blu, & Dragotti (2014), "Sampling Curves with FRI".

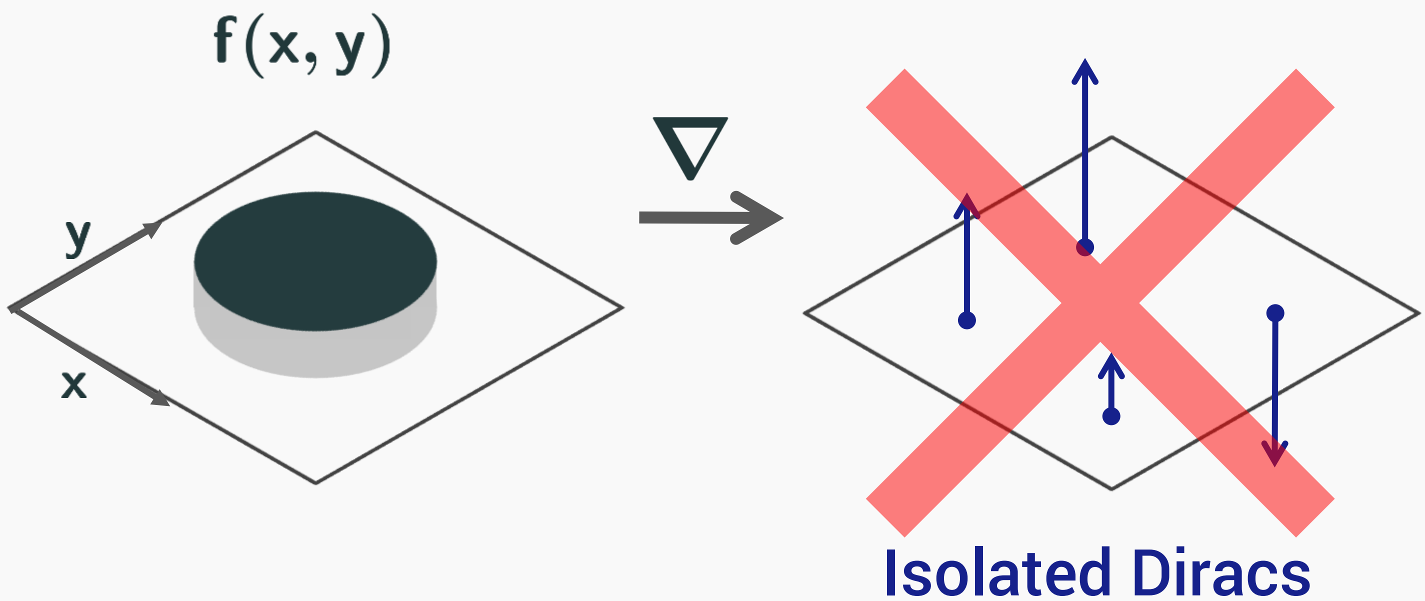


Annihilation Relation: $\sum_k y_{\ell-k} c_k = 0$


Stage 2: solve linear system for amplitudes
recover signal
f(x)
∂
•
= 0
annihilating function
f̂[k]
(j2πk)
*
= 0
annihilating filter
Stage 1: solve linear system for filter

Challenges extending FRI to higher dimensions:
Singularities not isolated

2-D PWC function



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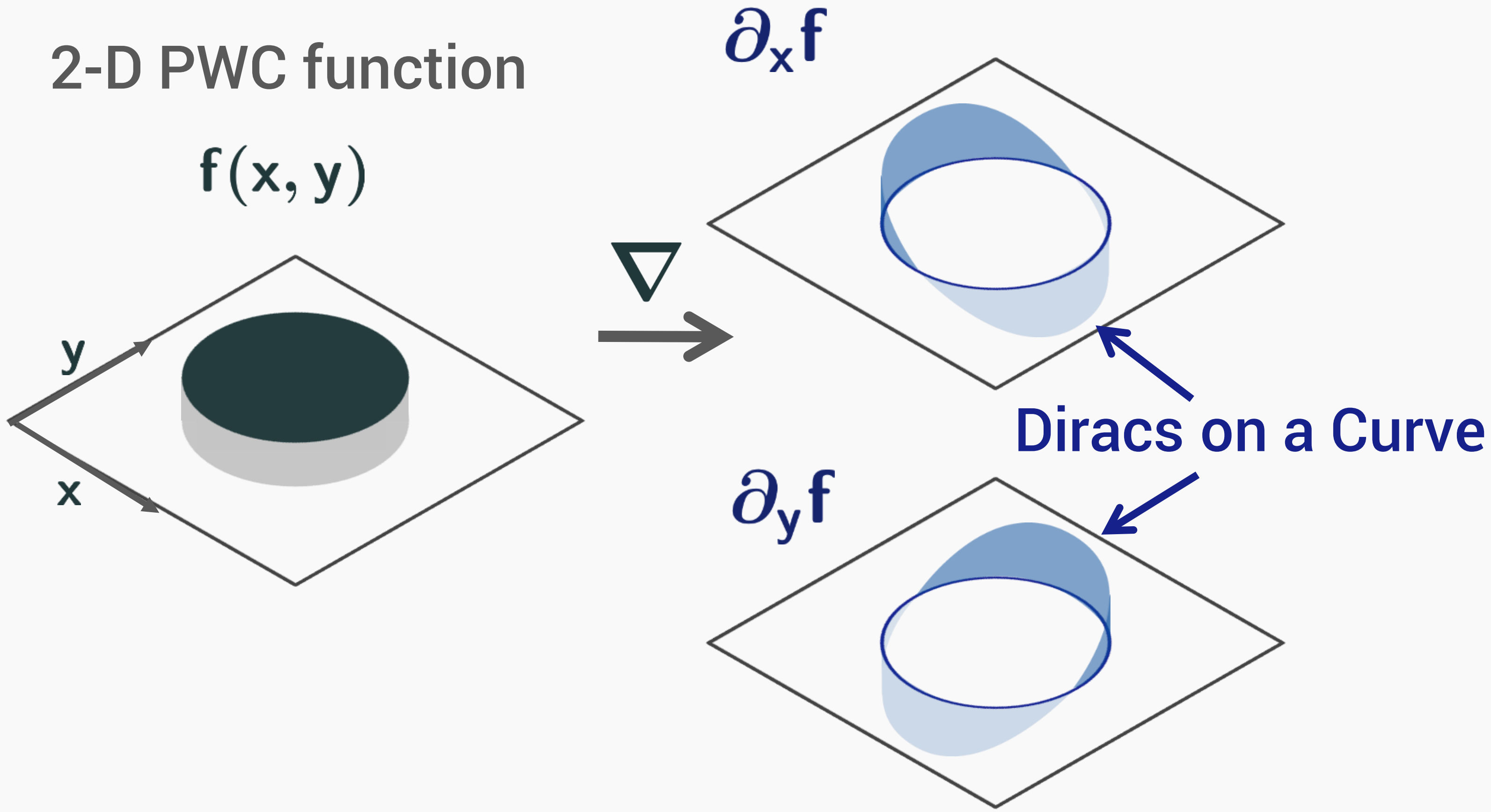
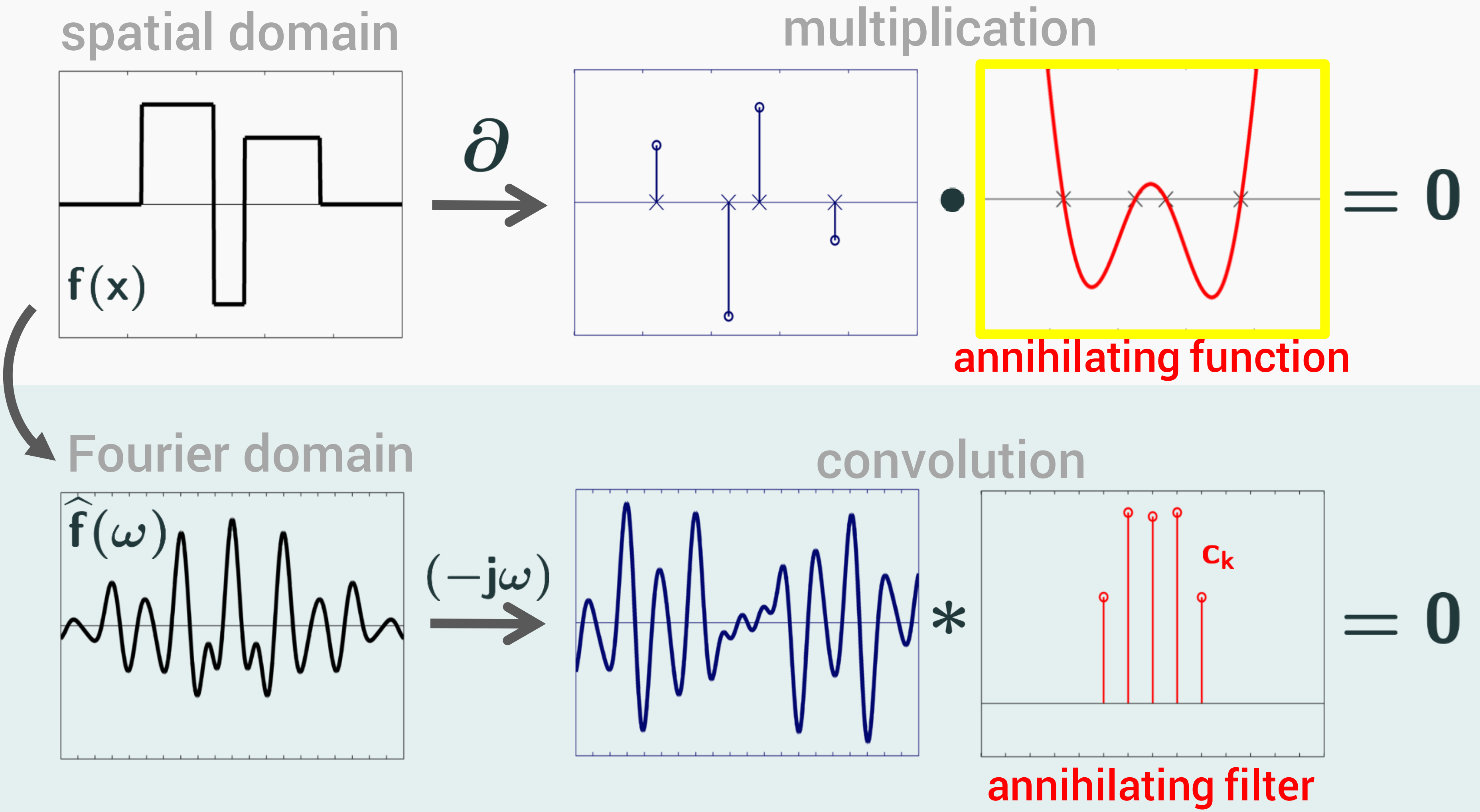
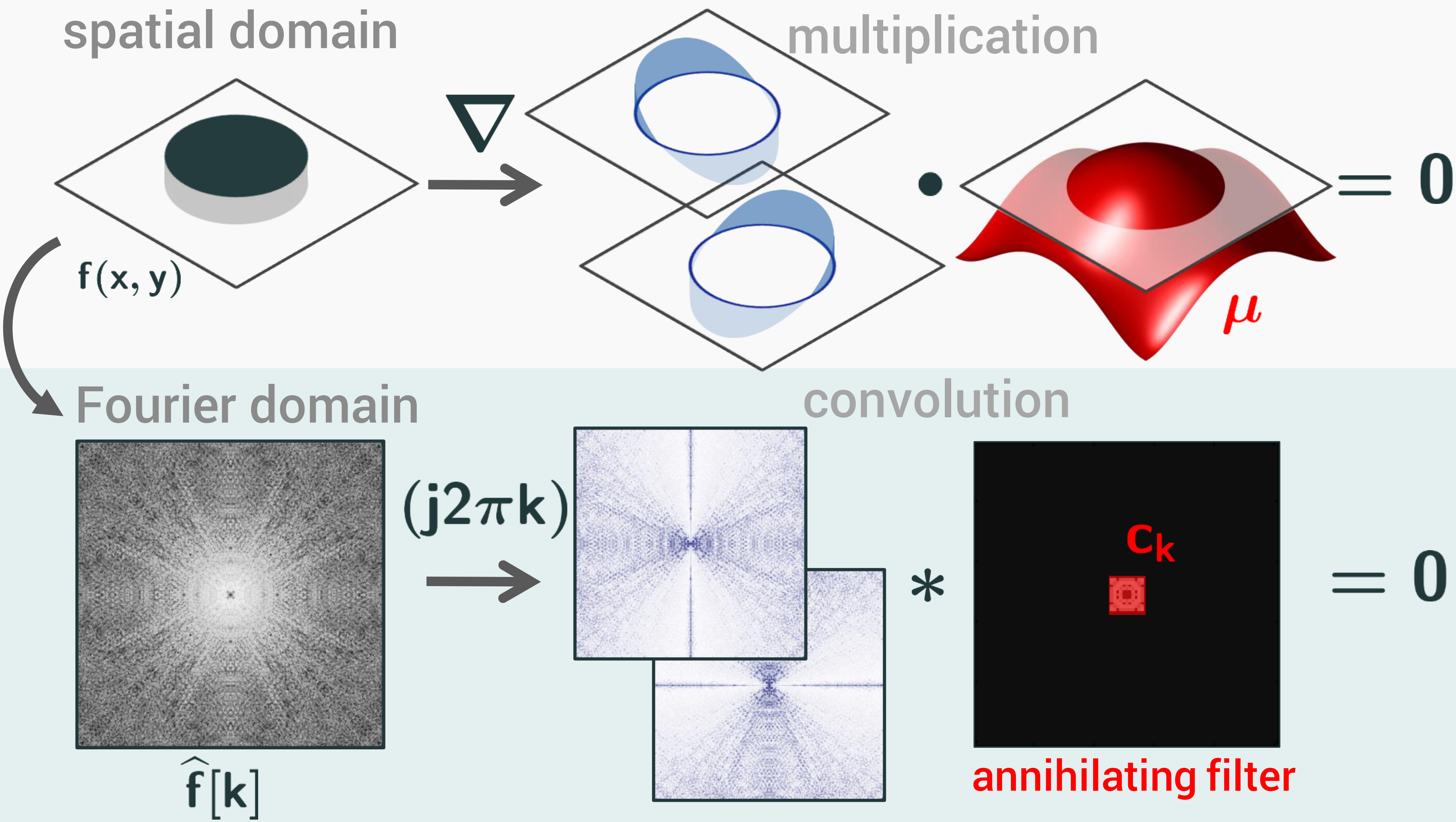


Recall 1-D Case...

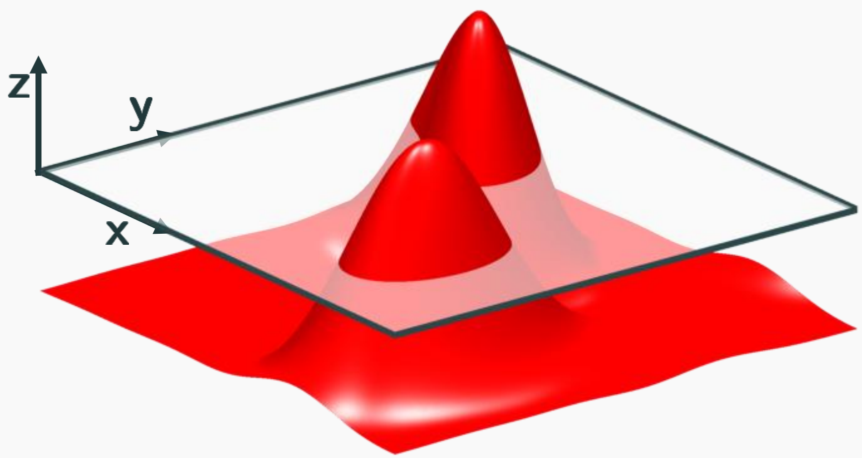


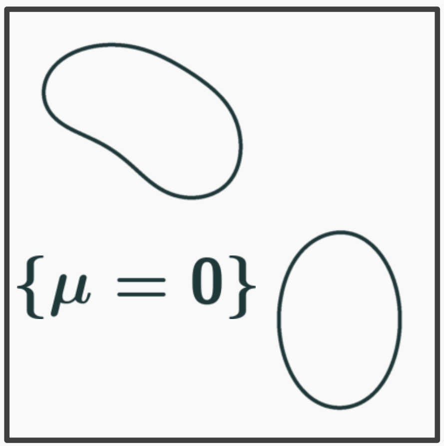
2-D PWC functions satisfy an annihilation relation



Annihilation relation: $\sum_k \widehat{\nabla f}[\ell - k] c_k = 0$

Can recover edge set when it is the **zero-set of a 2-D trigonometric polynomial** *[Pan et al., 2014]*

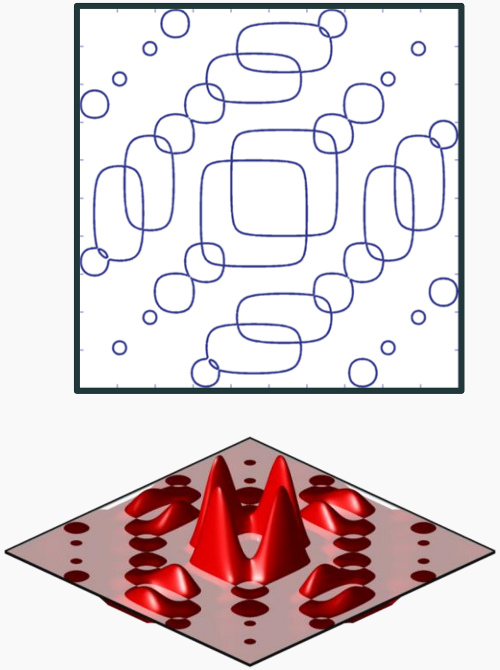
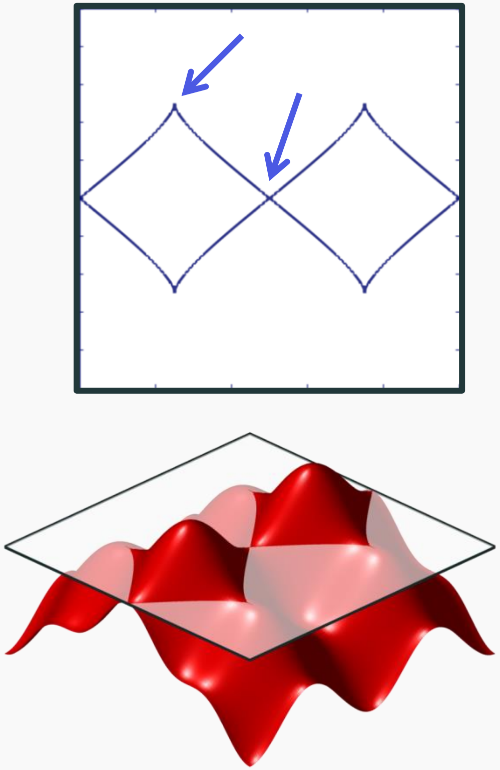
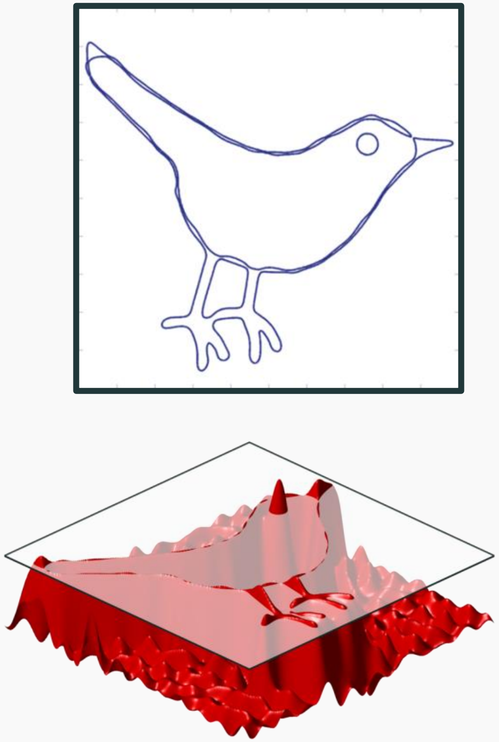




$$\mu(x, y) = \sum_{(k,l)\in\Lambda} c_{k,l}\, e^{j2\pi(kx+ly)}$$

“FRI Curve”

FRI curves can represent complicated edge geometries with few coefficients

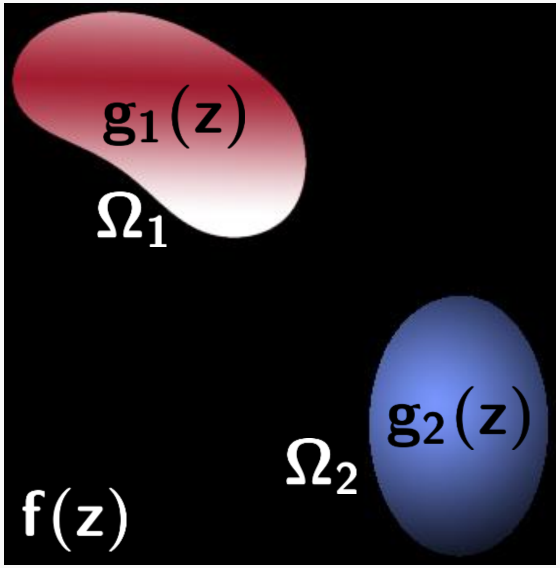
Multiple curves & intersections	Non-smooth points	Approximate arbitrary curves
		
13x13 coefficients	7x9 coefficients	25x25 coefficients

We give an improved theoretical framework for higher dimensional FRI recovery

- *[Pan et al., 2014]* derived annihilation relation for **piecewise complex analytic signal model**

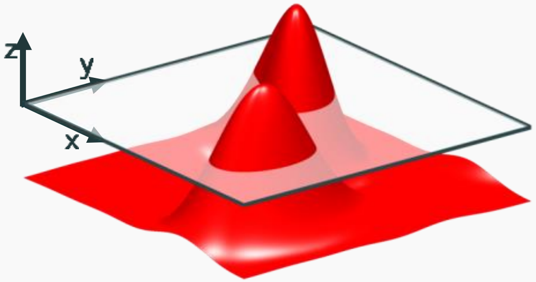
$$f(z) = \sum_{i=1}^{N} g_i(z) \cdot 1_{\Omega_i}(z)$$

$$\text{s.t.} \quad g_i \text{ analytic in } \Omega_i$$



- Not suitable for natural images
- 2-D only
- Recovery is ill-posed:

  Infinite DoF



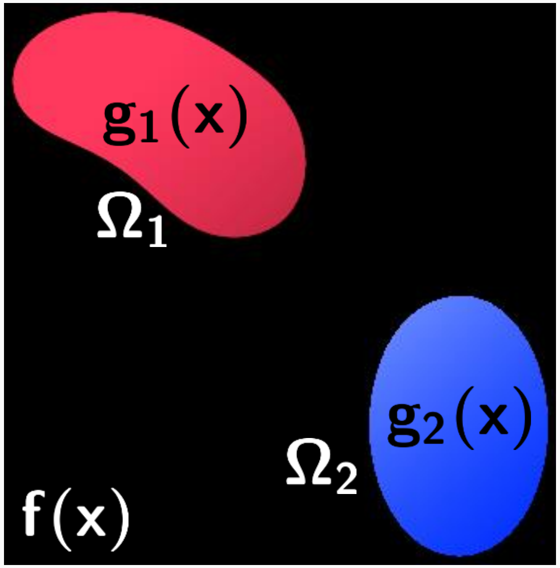
We give an improved theoretical framework for higher dimensional FRI recovery *[O. & Jacob, SampTA 2015]*

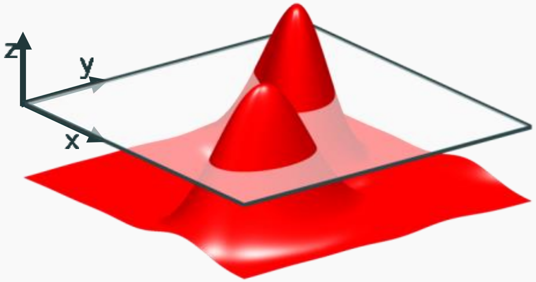
- Proposed model:
  piecewise smooth signals

$$f(x) = \sum_{i=1}^{N} g_i(x) \cdot 1_{\Omega_i}(x)$$

$$\text{s.t. } \; g_i \text{ smooth in } \Omega_i$$

- Extends easily to n-D
- Provable sampling guarantees
- Fewer samples necessary for recovery



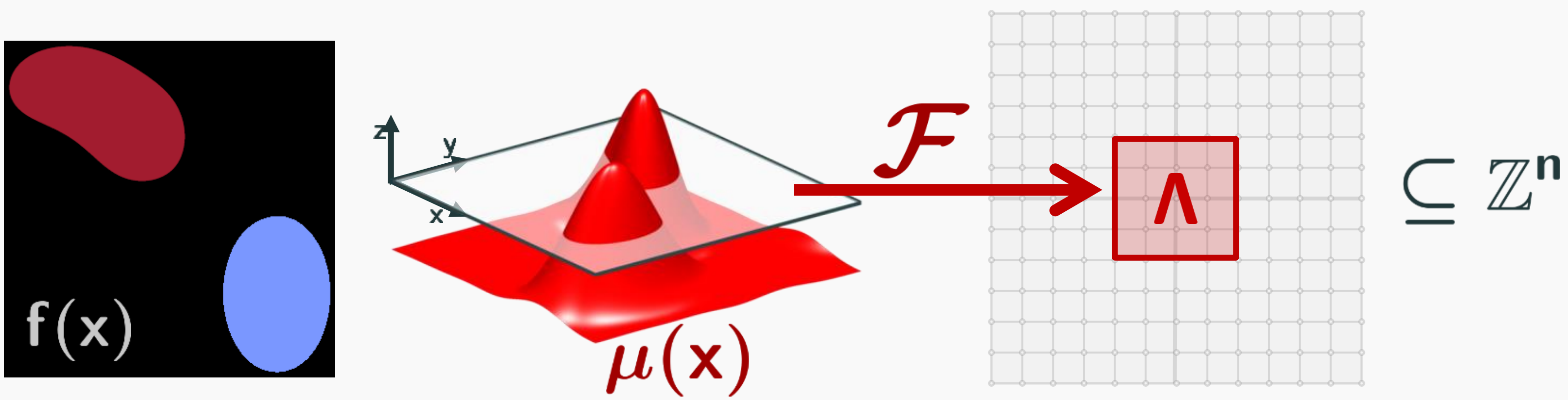


Annhilation relation for PWC signals

Prop: If *f* is PWC with edge set $\mathbf{E} \subseteq \{\mu = \mathbf{0}\}$ for μ bandlimited to Λ then

$$\sum_{\mathbf{k}\in\Lambda} \widehat{\mu}[\mathbf{k}]\widehat{\partial \mathbf{f}}[\ell - \mathbf{k}] = \mathbf{0}, \quad \forall \ell \in \mathbb{Z}^{\mathbf{n}}$$

any 1st order partial derivative



Annhilation relation for PWC signals

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any 1st order partial derivative

Proof idea:

Show $\mu \cdot \partial \mathbf{f} = \mathbf{0}$ as tempered distributions

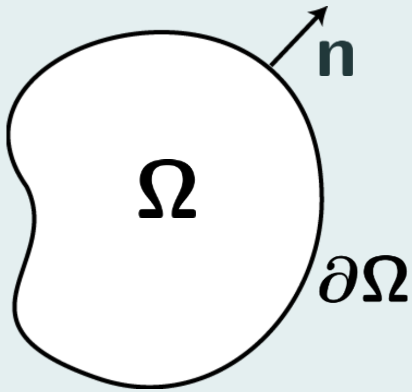
Use convolution theorem

Distributional derivative of indicator function:

smooth test function

divergence theorem

$$
\begin{aligned}
\langle \partial_j \mathbf{1}_\Omega, \varphi \rangle &= -\langle \mathbf{1}_\Omega, \partial_j \varphi \rangle \\
&= -\int_\Omega \partial_j \varphi \, \mathrm{d}x \\
&= -\oint_{\partial\Omega} \varphi \, n_j \, \mathrm{d}\sigma
\end{aligned}
$$



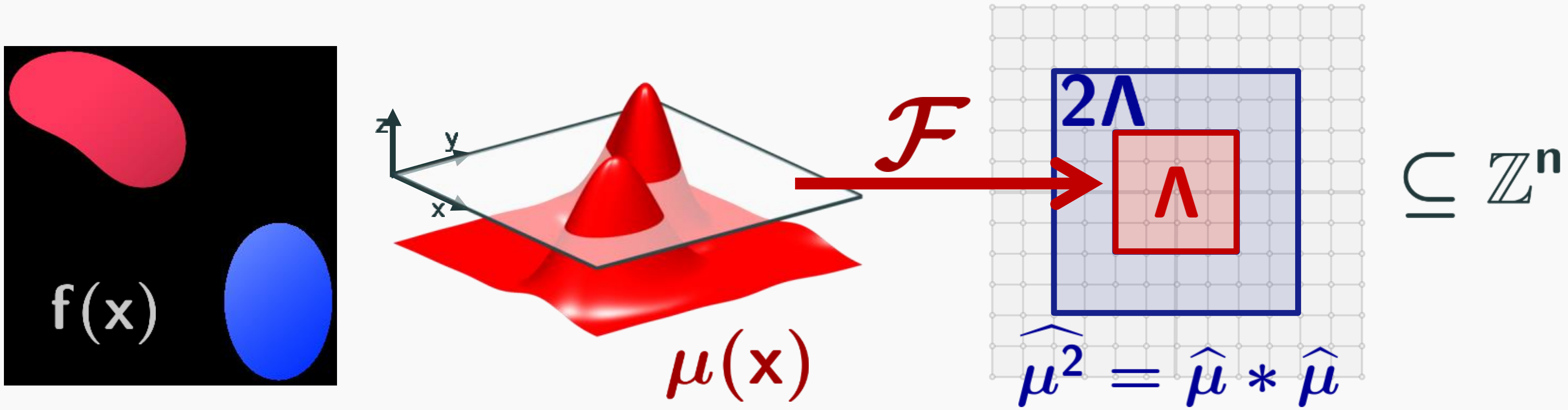
Weighted curve integral

Annhilation relation for PW linear signals

Prop: If **f** is PW linear, with edge set $\mathbf{E} \subseteq \{\mu = 0\}$ and μ bandlimited to $\boldsymbol{\Lambda}$ then

$$\sum_{\mathbf{k} \in 2\boldsymbol{\Lambda}} \widehat{\mu^2}[\mathbf{k}]\,\widehat{\partial^2 \mathbf{f}}[\ell - \mathbf{k}] = \mathbf{0}, \quad \forall \ell \in \mathbb{Z}^{\mathbf{n}}$$

any 2^{nd} order partial derivative



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any 2nd order partial derivative

Proof idea: $\mathbf{f} = \mathbf{g} \cdot 1_\Omega, \quad \mathbf{g}$ linear

product rule x2 $\partial^2 \mathbf{f} = \cancel{\partial^2 \mathbf{g} \cdot 1_\Omega} + 2\partial \mathbf{g} \cdot \partial 1_\Omega + \mathbf{g} \cdot \partial^2 1_\Omega$

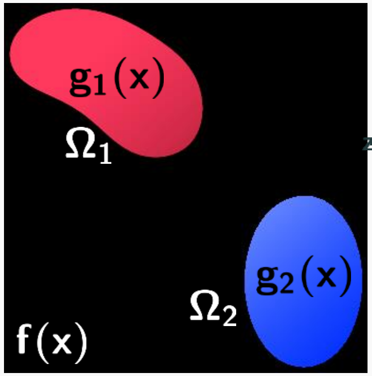
annihilated by μ^2

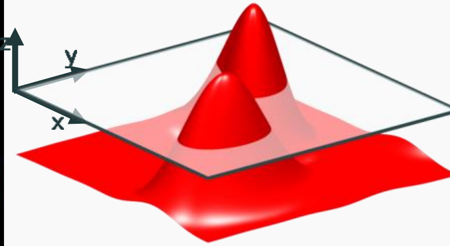
Can extend annihilation relation to a wide class of **piecewise smooth** images.

$$f(x) = \sum_{i=1}^{N} g_i(x) \cdot 1_{\Omega_i}(x)$$

$$\text{s.t.} \quad Dg_i = 0 \text{ in } \Omega_i$$

Any constant coeff. differential operator





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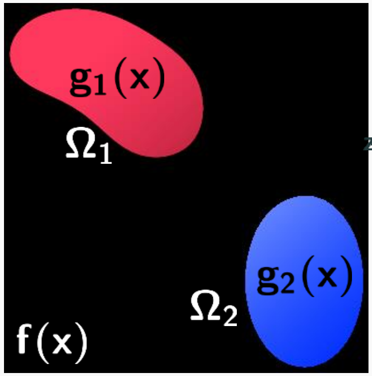

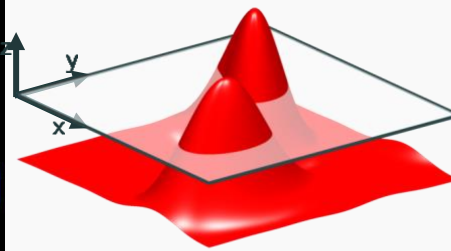

Signal Model:	Choice of Diff. Op.:
PW Constant	$D = \nabla$
PW Analytic*	$D = \partial_x + j\partial_y$

1^{st} order

Can extend annihilation relation to a wide class of **piecewise smooth** images.

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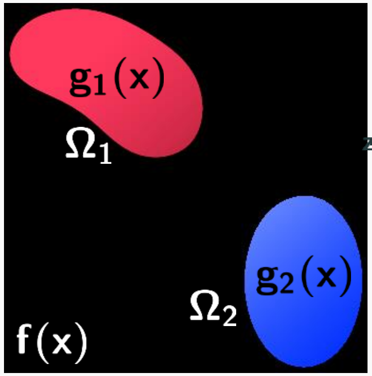

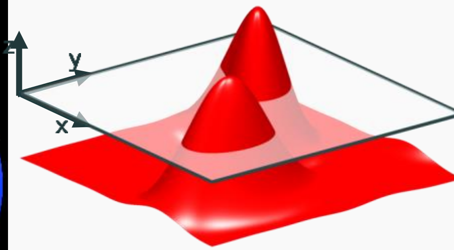

Signal Model:	Choice of Diff. Op.:	
PW Constant	$D = \nabla$	1st order
PW Analytic*	$D = \partial_x + j\partial_y$	
PW Harmonic	$D = \Delta$	2nd order
PW Linear	$D = \{\partial_{xx}, \partial_{xy}, \partial_{yy}\}$	

Can extend annihilation relation to a wide class of **piecewise smooth** images.

$$f(x) = \sum_{i=1}^{N} g_i(x) \cdot 1_{\Omega_i}(x)$$

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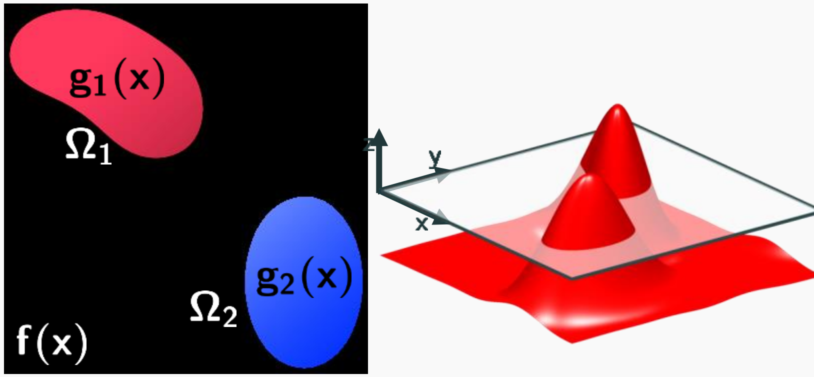


Signal Model:	Choice of Diff. Op.:	
PW Constant	$D = \nabla$	1st order
PW Analytic*	$D = \partial_x + j\partial_y$	1st order
PW Harmonic	$D = \Delta$	2nd order
PW Linear	$D = \{\partial_{xx}, \partial_{xy}, \partial_{yy}\}$	2nd order
PW Polynomial	$D = \{\partial^\alpha\}_{\|\alpha\|=n}$	nth order

Sampling theorems:

Necessary and sufficient number of Fourier samples for

1. Unique recovery of edge set/annihilating polynomial
2. Unique recovery of full signal given edge set
   - Not possible for PW analytic, PW harmonic, etc.
   - Prefer PW polynomial models

➔ Focus on 2-D PW constant signals

Challenges to proving uniqueness

1-D FRI Sampling Theorem [Vetterli et al., 2002]:

A continuous-time PWC signal with K jumps can be uniquely recovered from 2K+1 uniform Fourier samples.

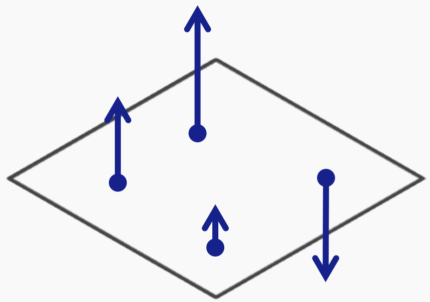
Proof (a la Prony's Method):

Form Toeplitz matrix $\mathbf{T}$ from samples, use uniqueness of Vandermonde decomposition: $\mathbf{T} = \mathbf{V}\mathbf{D}\mathbf{V}^H$

"Caratheodory Parametrization"

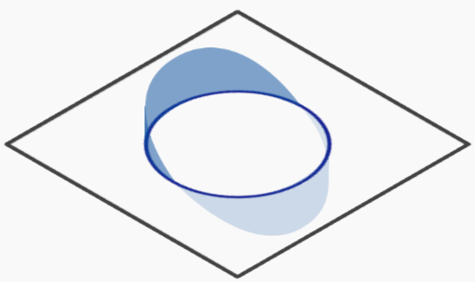
Challenges proving uniqueness, cont.

Extends to *n*-D if singularities isolated [Sidiropoulos, 2001]



$$\xrightarrow{\mathcal{F}} \quad \hat{f}[\mathbf{k}] = \sum_i a_i e^{-j2\pi \mathbf{k}\cdot \mathbf{x}_i}$$

Not true in our case--singularities supported on curves:



$$\xrightarrow{\mathcal{F}} \quad \widehat{\nabla f}[\mathbf{k}] = \oint_{\partial\Omega} e^{-j2\pi \mathbf{k}\cdot \mathbf{x}} \mathbf{n}\, ds$$

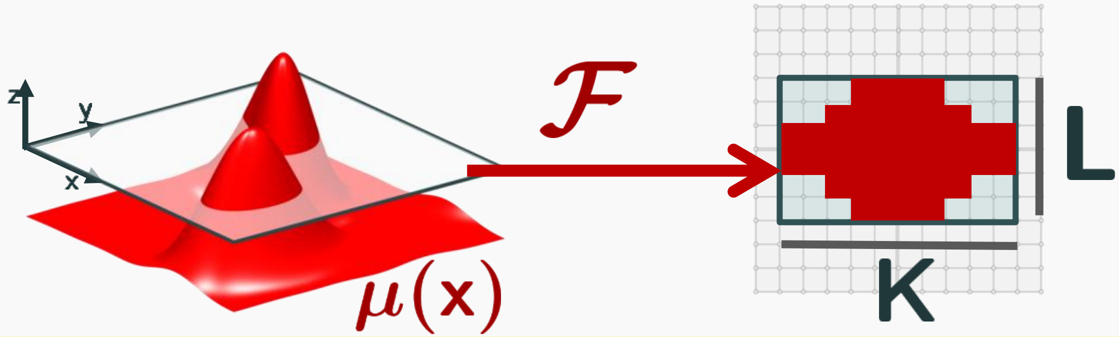
Requires new techniques:

– Spatial domain interpretation of annihilation relation

– Algebraic geometry of trigonometric polynomials

Minimal (Trigonometric) Polynomials

Define $\mathbf{deg}(\mu) = (\mathsf{K}, \mathsf{L})$ to be the dimensions of the smallest rectangle containing the Fourier support of μ



Prop: Every zero-set of a trig. polynomial **C** with no isolated points has a *unique* real-valued trig. polynomial μ_0 of minimal degree such that if $\mathsf{C} = \{\mu = 0\}$ then $\mathbf{deg}(\mu_0) \leq \mathbf{deg}(\mu)$ and $\mu = \gamma \cdot \mu_0$

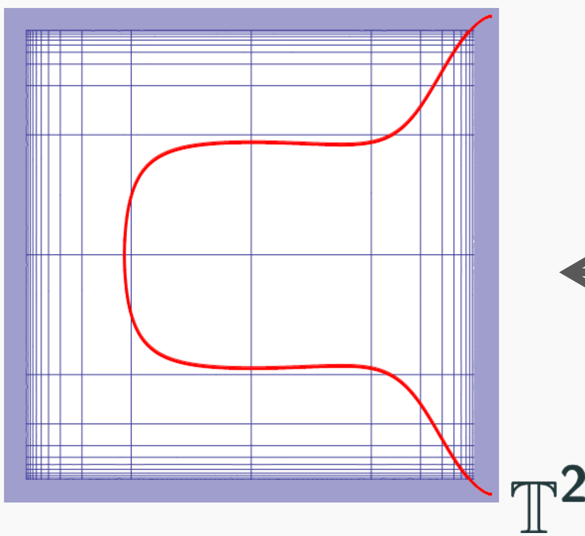
Degree of min. poly. = analog of sparsity/complexity of edge set

Proof idea: Pass to Real Algebraic Plane Curves

Zero-sets of trig polynomials of degree (K,L)

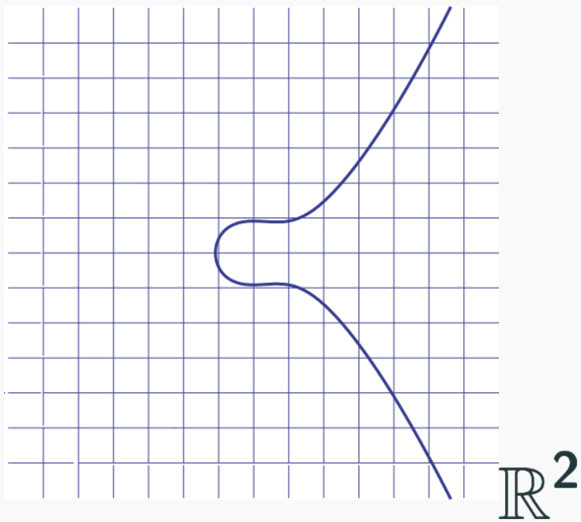
are in 1-to-1 correspondence with

Real algebraic plane curves of degree (K,L)



Conformal change of variables

$\longleftrightarrow$



$$\mu(z, w) = 0;$$
$$|z| = |w| = 1$$

$$p(t, s) = 0;$$
$$t, s \in \mathbb{R}^2$$

Uniqueness of edge set recovery

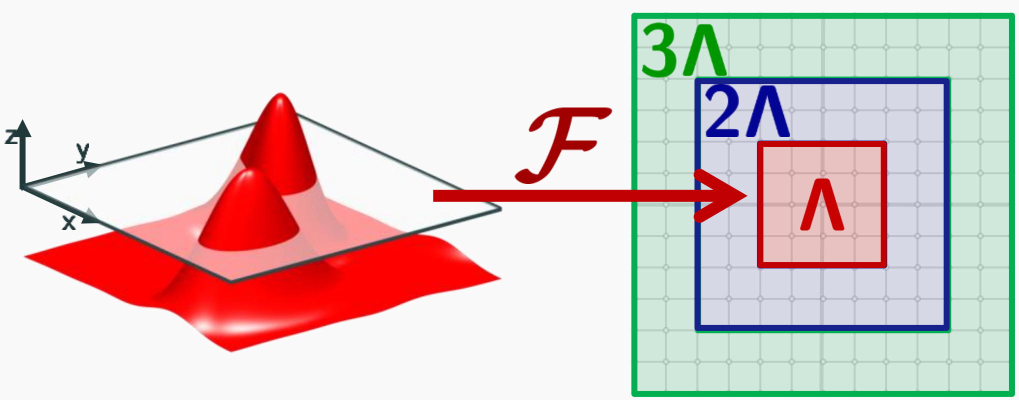
Theorem: If **f** is PWC* with edge set $\mathbf{E} = \{\mu = 0\}$

with μ minimal and bandlimited to Λ then

$\mathbf{c} = \widehat{\mu}$ is the unique solution to

$$\sum_{\mathbf{k}\in\Lambda} \mathbf{c}[\mathbf{k}]\widehat{\nabla \mathbf{f}}[\ell - \mathbf{k}] = 0 \text{ for all } \ell \in 2\Lambda$$

*Some geometric restrictions apply

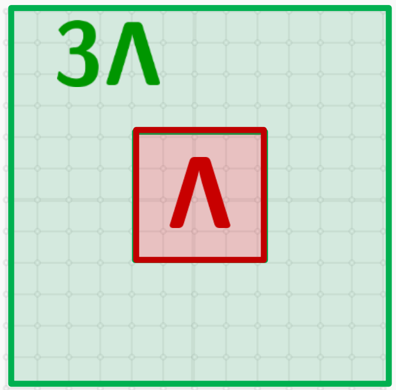


$\subseteq \mathbb{Z}^2$

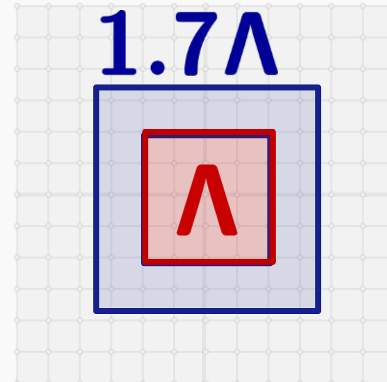
Requires samples of $\widehat{\mathbf{f}}$ in 3Λ to build equations

Current Limitations to Uniqueness Theorem

- Gap between necessary and sufficient # of samples:

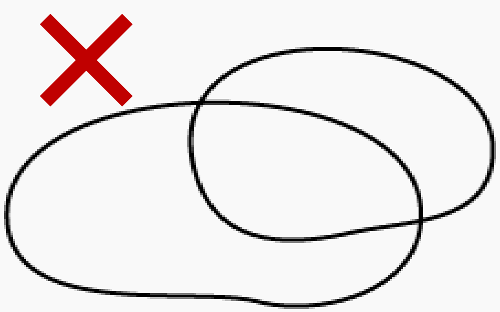


Sufficient

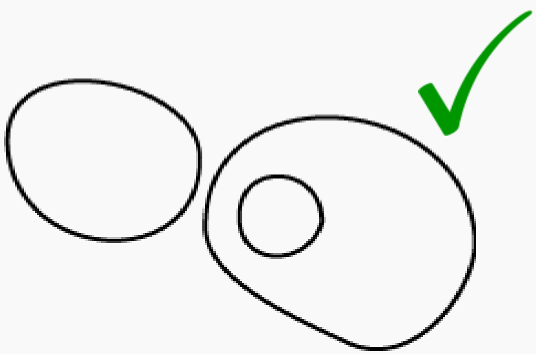


Necessary

- Restrictions on geometry of edge sets: *non-intersecting*



$\{\mu = 0\}$



$\{\mu = 0\}$

Uniqueness of signal (given edge set)

Theorem: If $\mathbf{f}$ is PWC* with edge set $\mathbf{E} = \{\mu = \mathbf{0}\}$

with μ minimal and bandlimited to $\mathbf{\Lambda}$ then

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$$\mu \cdot \nabla \mathbf{g} = \mathbf{0} \quad \text{s.t.} \quad \widehat{\mathbf{f}}[\mathbf{k}] = \widehat{\mathbf{g}}[\mathbf{k}], \mathbf{k} \in \mathbf{\Gamma}$$

when the sampling set $\mathbf{\Gamma} \supseteq 3\mathbf{\Lambda}$

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*Some geometric restrictions apply

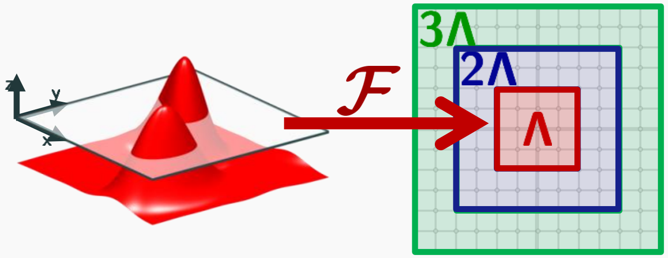
Equivalently,

$$\mathbf{f} = \arg\min_{\mathbf{g}} \|\mu \cdot \nabla \mathbf{g}\| \quad \text{s.t.} \quad \widehat{\mathbf{f}}[\mathbf{k}] = \widehat{\mathbf{g}}[\mathbf{k}], \mathbf{k} \in \Gamma$$

Summary of Proposed *Off-the-Grid Framework*

- Extend Prony/FRI methods to recover multidimensional singularities (curves, surfaces)

- Unique recovery from *uniform* Fourier samples: # of samples proportional to degree of edge set polynomial



- Two-stage recovery
  1. Recover edge set by solving linear system
  2. Recover amplitudes

Summary of Proposed *Off-the-Grid Framework*

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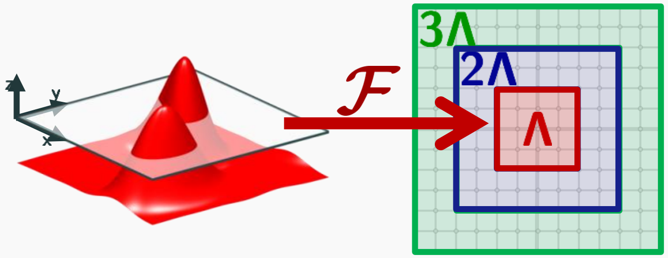
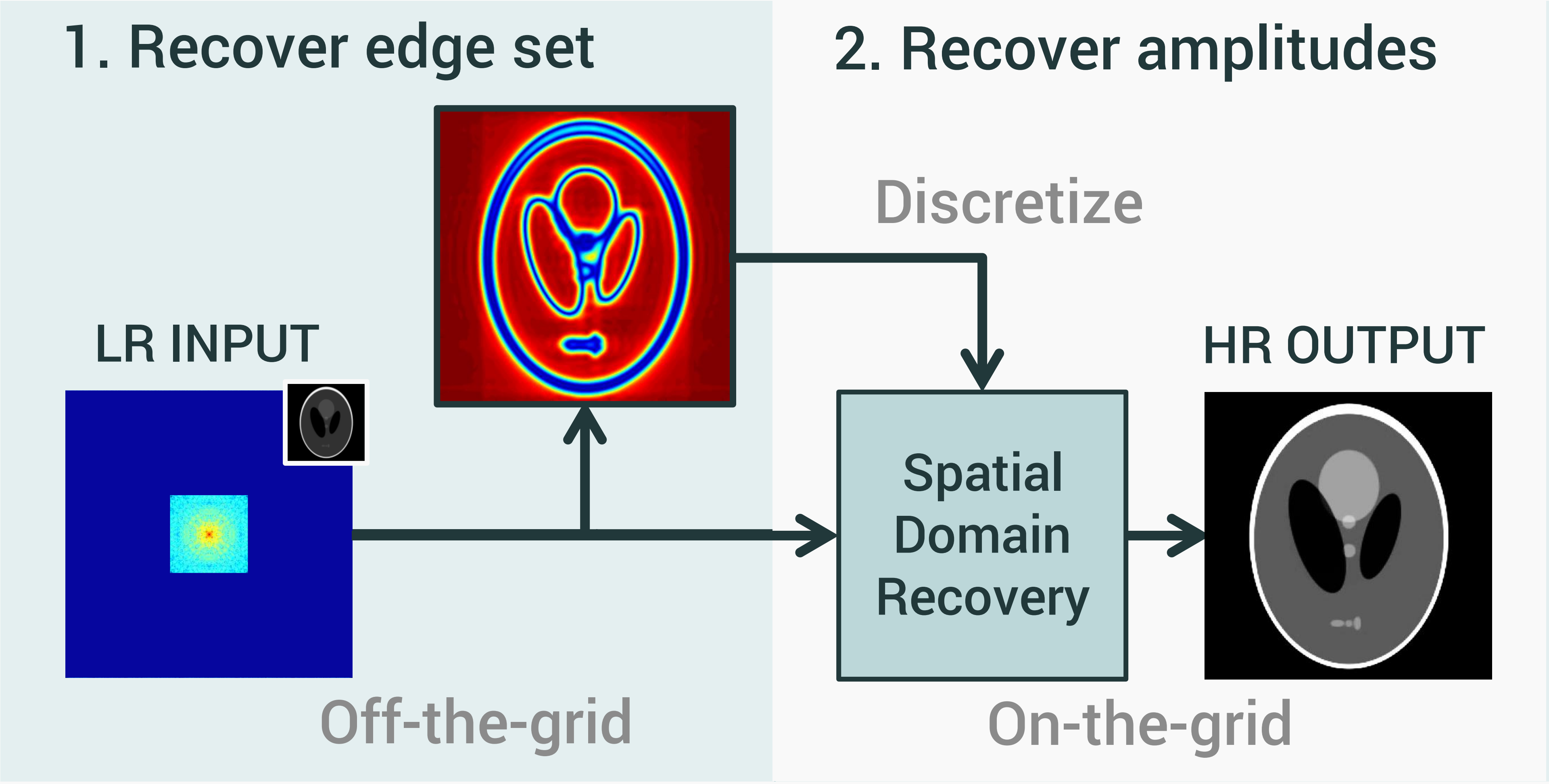


- Two-stage recovery
  1. Recover edge set by solving linear system (Robust?)
  2. Recover amplitudes (How?)

New *Off-the-Grid* Imaging Framework: *Algorithms*

Two-stage Super-resolution MRI Using Off-the-Grid Piecewise Constant Signal Model [O. & Jacob, ISBI 2015]

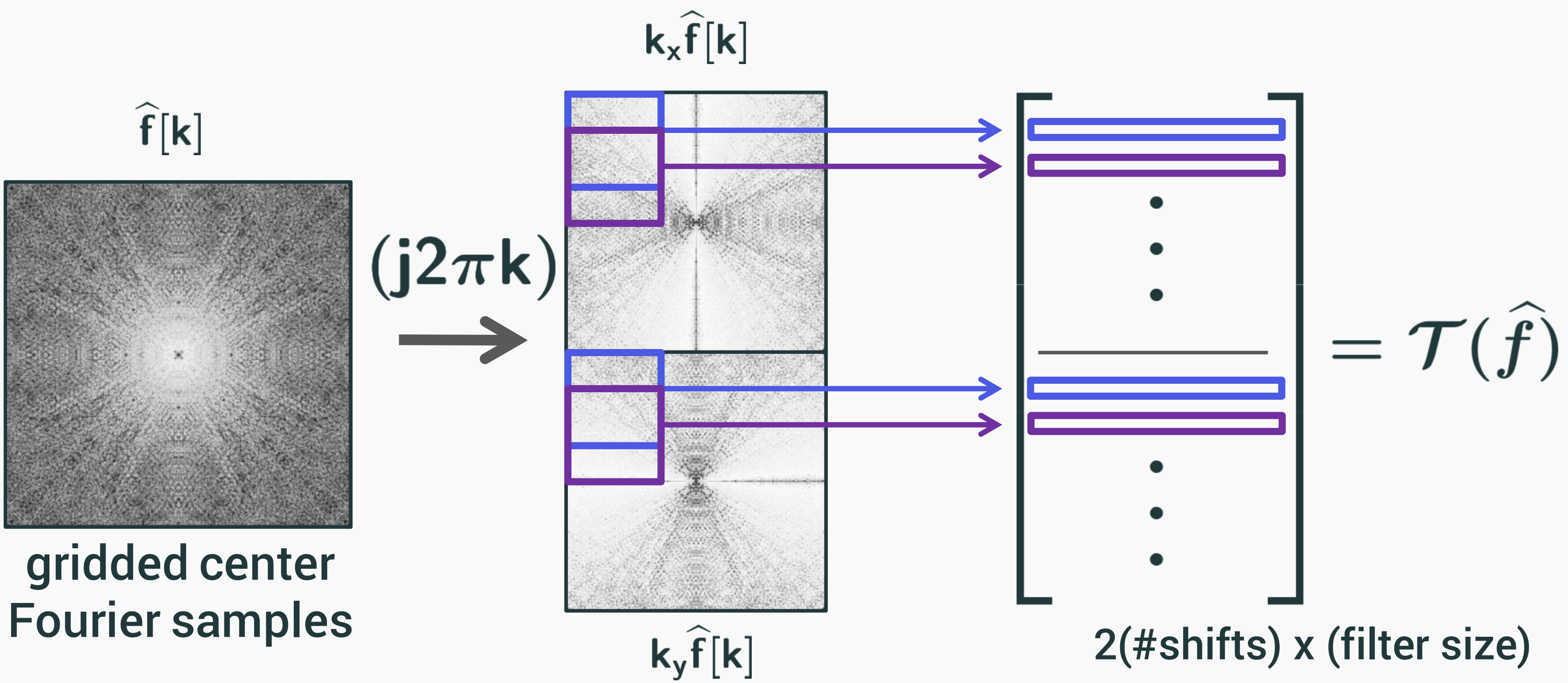


Matrix representation of annihilation

$$\mathcal{T}(\widehat{f})\color{red}{c} = 0$$

2-D convolution matrix (block Toeplitz)

vector of filter coefficients

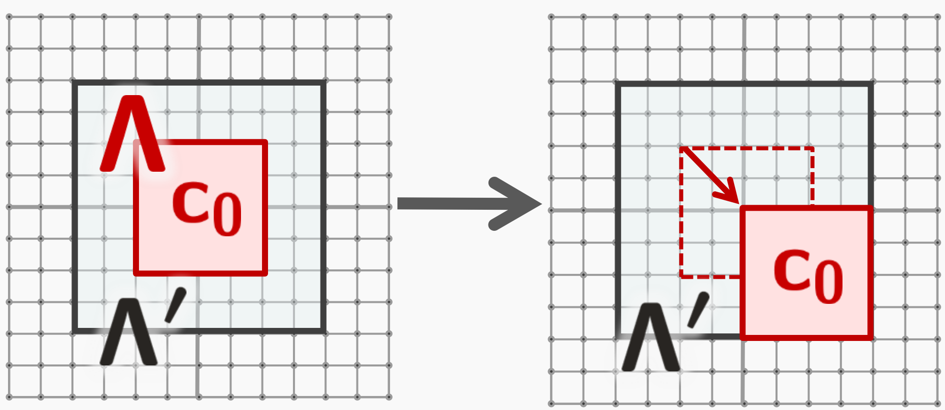


Basis of algorithms:
Annihilation matrix is low-rank

Prop: If the level-set function is bandlimited to Λ and the assumed filter support $\Lambda' \supset \Lambda$ then

$$\mathrm{rank}[\mathcal{T}(\widehat{\mathbf{f}})] \leq |\Lambda'| - (\#\text{shifts } \Lambda \text{ in } \Lambda')$$

Fourier domain



Spatial domain $\mu(x, y) \longrightarrow e^{j2\pi(kx+ly)}\mu(x, y)$

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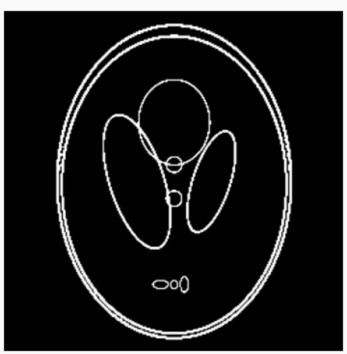
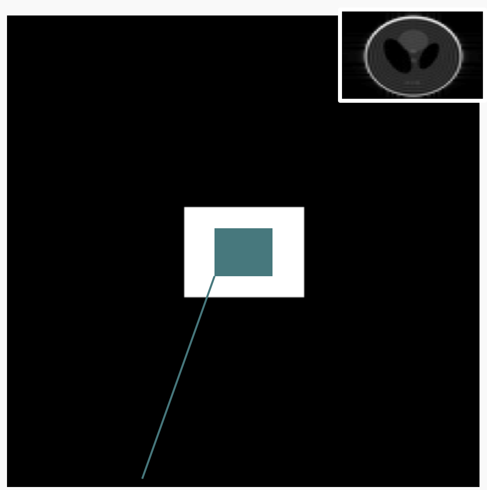
Example:
Shepp-Logan



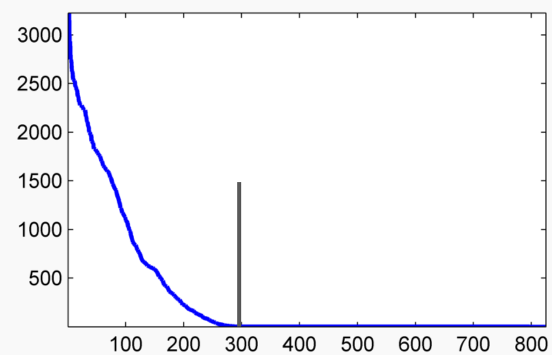
Fourier domain



Assumed filter: 33x25

Samples: 65x49

$\sigma(\mathcal{T}(\widehat{f}))$



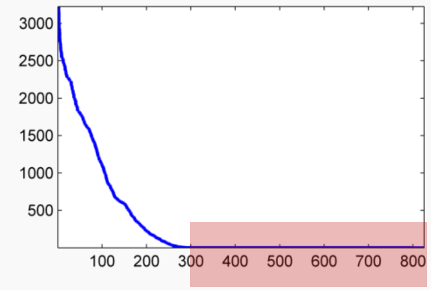
Rank $\approx$ 300

Stage 1: Robust annihilting filter estimation

1. Compute SVD

$$\mathcal{T}(\widehat{\mathbf{f}}) = \mathbf{U}\boldsymbol{\Sigma}\mathbf{V}^H$$

$$\sigma(\mathcal{T}(\widehat{\mathbf{f}}))$$

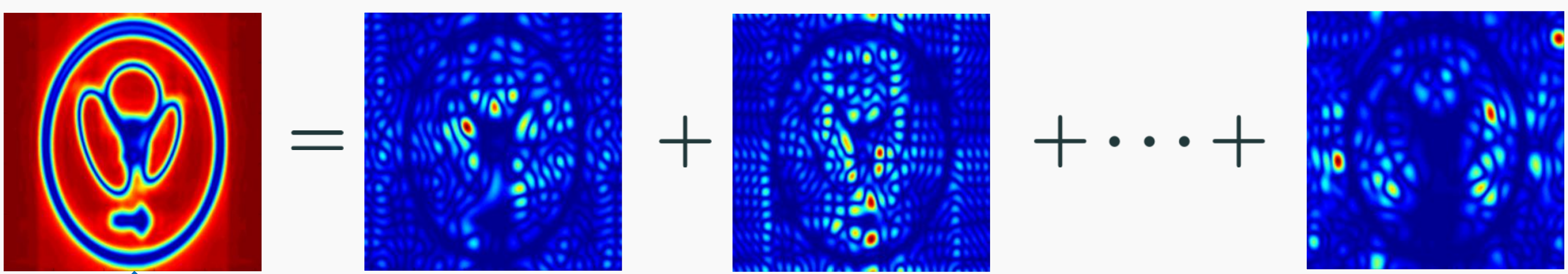


2. Identify **null space**

$$\mathbf{V} = [\mathbf{V_S}\ \mathbf{V_N}], \qquad \mathbf{V_N} = [\mathbf{c_1}, \ldots, \mathbf{c_n}]$$

3. Compute sum-of-squares average

$$\mu = |\mathcal{F}^{-1}\mathbf{c_1}|^2 + |\mathcal{F}^{-1}\mathbf{c_2}|^2 + \cdots + |\mathcal{F}^{-1}\mathbf{c_n}|^2$$



Recover common zeros

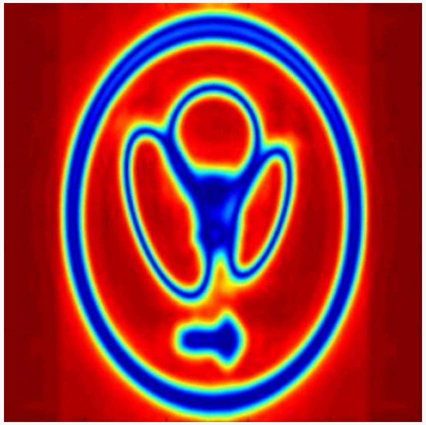
Stage 2: Weighted TV Recovery

$$\mathbf{f} = \arg\min_{\mathbf{g}} \|\mu \cdot \nabla \mathbf{g}\|_1 \quad \text{s.t.} \quad \hat{\mathbf{f}}[\mathbf{k}] = \hat{\mathbf{g}}[\mathbf{k}], \mathbf{k} \in \boldsymbol{\Gamma}$$

discretize

relax

$$\min_{\mathbf{x}} \sum_{\mathbf{i}} \mathbf{w_i} \cdot |(\mathbf{Dx})_{\mathbf{i}}| + \lambda \|\mathbf{Ax} - \mathbf{b}\|^2$$



Edge weights

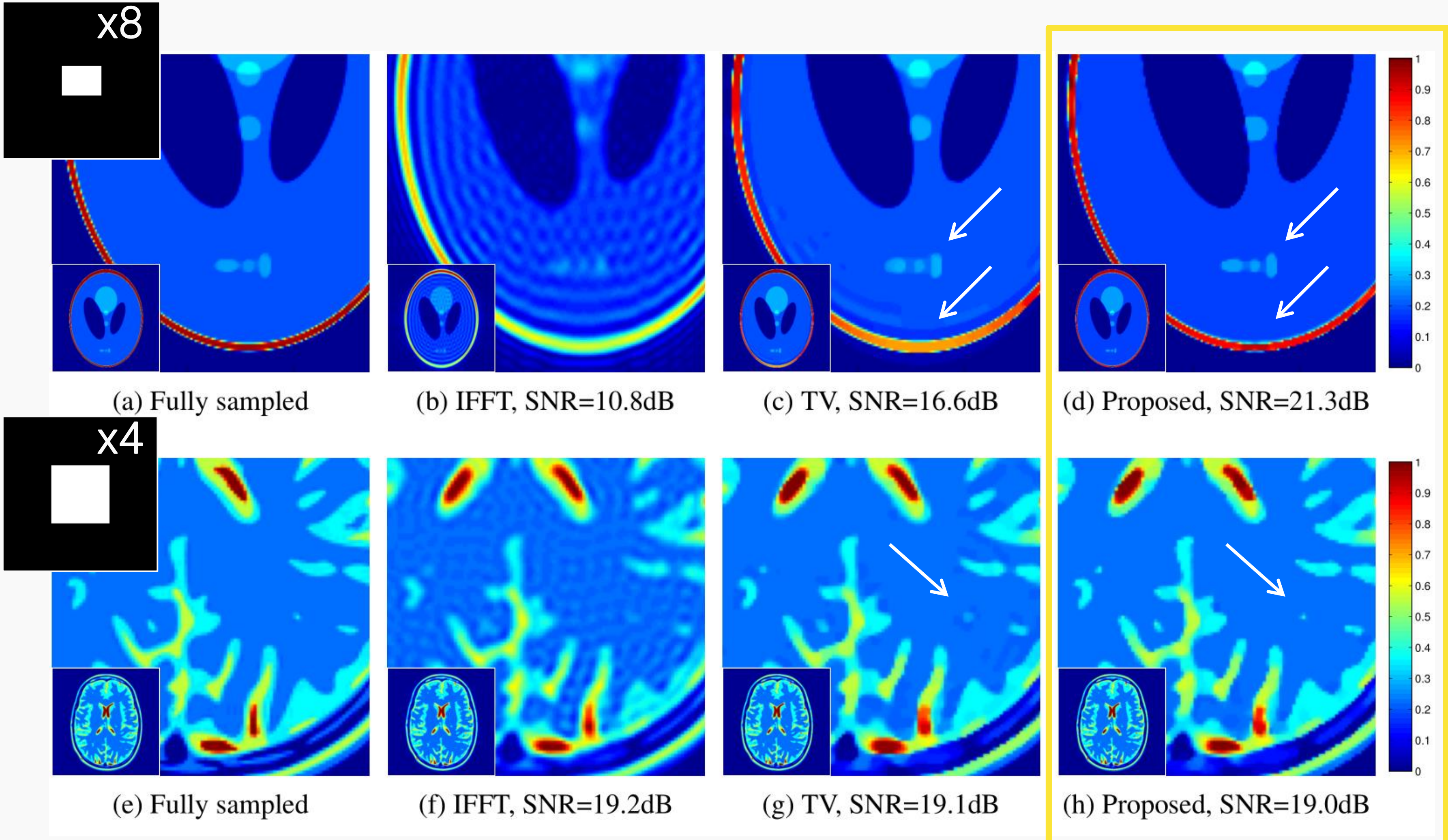
x = discrete spatial domain image

D = discrete gradient

A = Fourier undersampling operator

b = k-space samples

Super-resolution of MRI Medical Phantoms

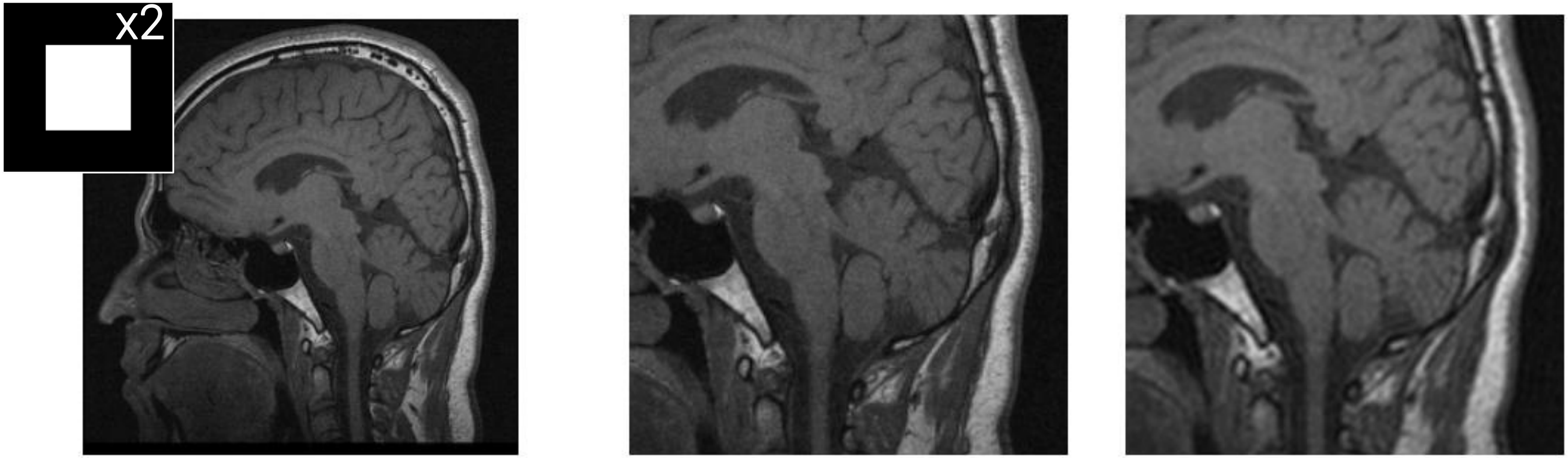


(a) Fully sampled (b) IFFT, SNR=10.8dB (c) TV, SNR=16.6dB (d) Proposed, SNR=21.3dB

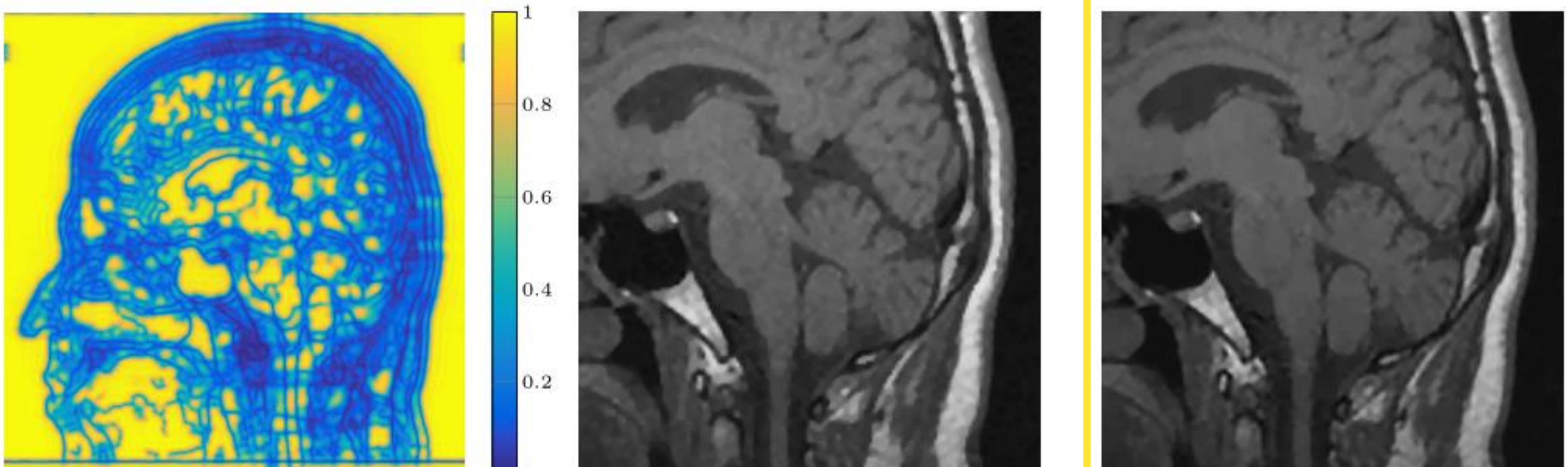
(e) Fully sampled (f) IFFT, SNR=19.2dB (g) TV, SNR=19.1dB (h) Proposed, SNR=19.0dB

Analytical phantoms from *[Guerquin-Kern, 2012]*

Super-resolution of Real MRI Data



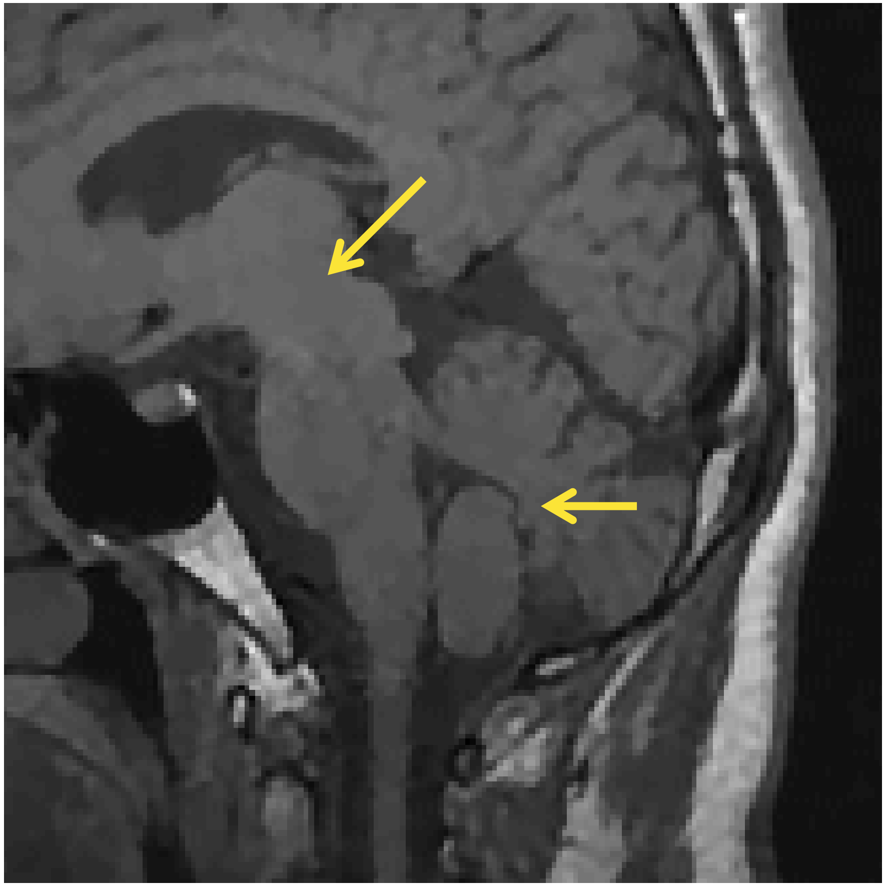
(a) Fully-sampled (b) Fully-sampled (zoom) (c) Zero-padded SNR=18.3dB



(d) Edge set estimate (65×65 coefficients) (e) TV reg. SNR=18.5dB (f) Proposed, LSLP SNR=18.9dB

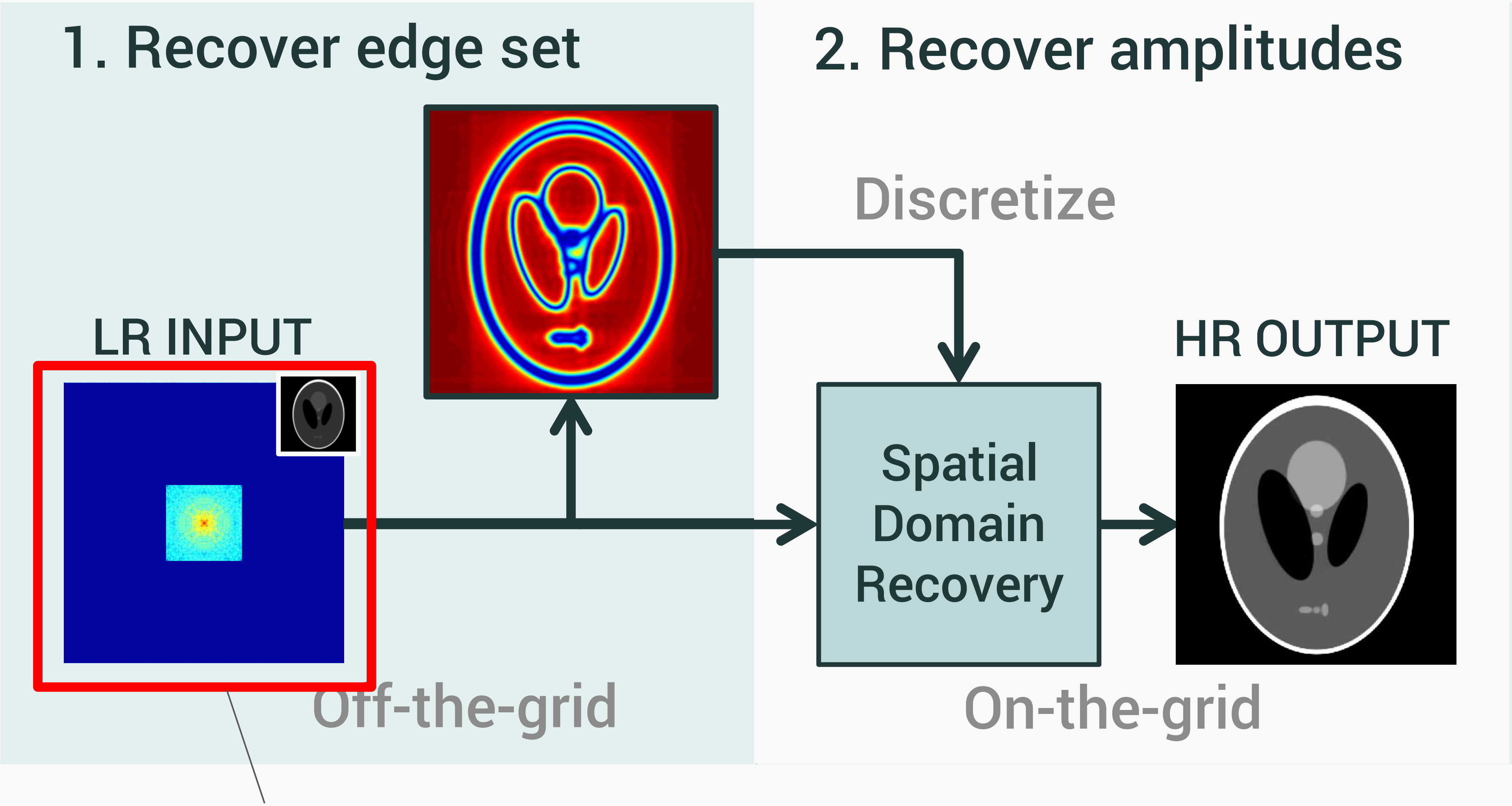
Super-resolution of Real MRI Data (Zoom)

(e) TV reg.
SNR=18.5dB



(f) Proposed, LSLP
SNR=18.9dB

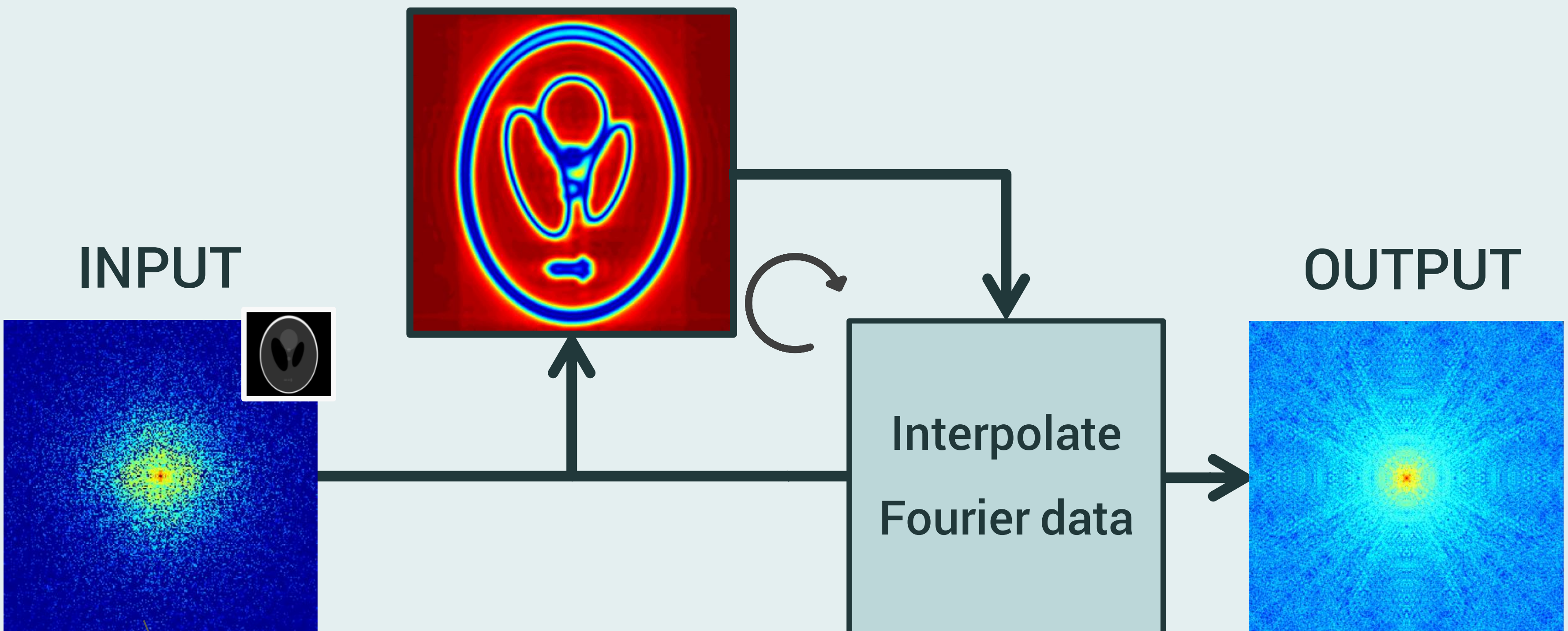
Two Stage Algorithm



Need uniformly sampled region!

One Stage Algorithm [O. & Jacob, SampTA 2015]

Jointly estimate edge set and amplitudes



Off-the-grid

Accommodate random samples

Pose recovery as a one-stage structured low-rank matrix completion problem

Recall: $\mathcal{T}(\widehat{\mathbf{f}})$ low rank $\leftrightarrow$ $\mathbf{f}$ piecewise constant

Toeplitz-like matrix built from Fourier data

Pose recovery as a one-stage
structured low-rank matrix completion problem

$$\min_{\widehat{\mathbf{f}}} \quad \mathrm{rank}[\mathcal{T}(\widehat{\mathbf{f}})] \quad \textbf{s.t.} \quad \widehat{\mathbf{f}}[\mathbf{k}] = \widehat{\mathbf{b}}[\mathbf{k}], \mathbf{k} \in \boldsymbol{\Gamma}$$

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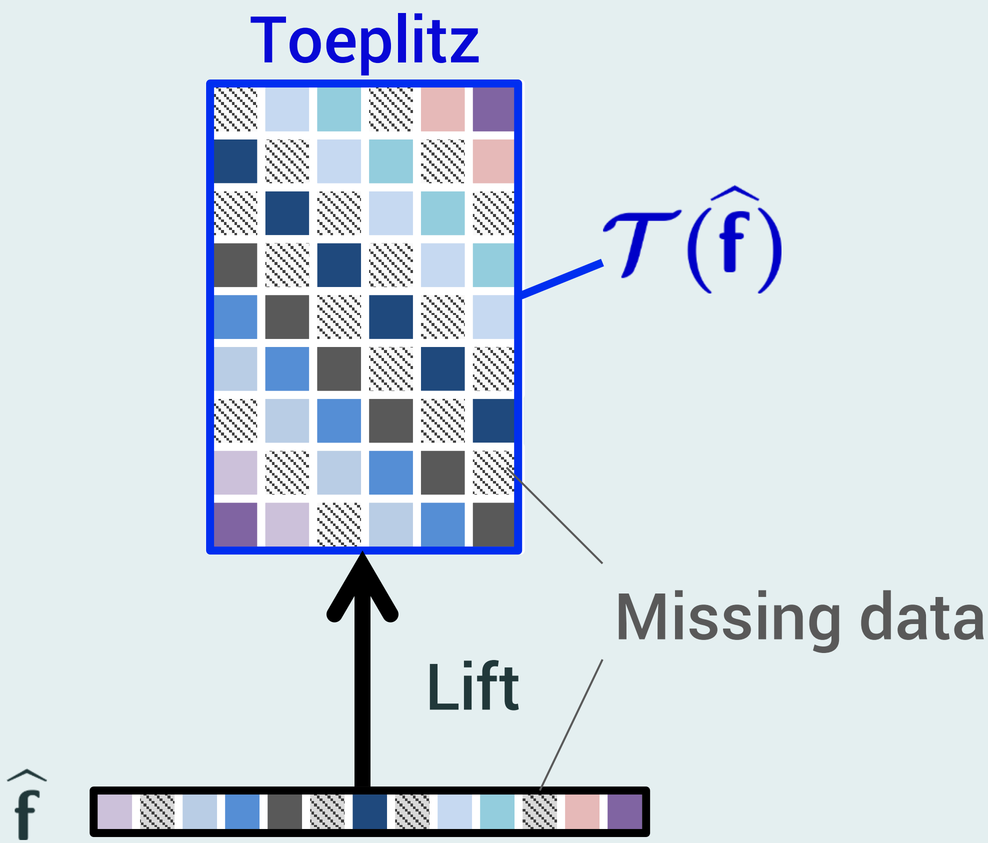
1-D Example:

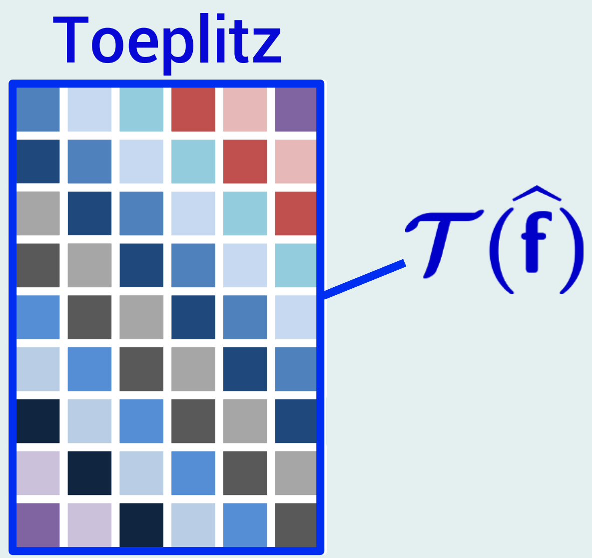


Pose recovery as a one-stage **structured low-rank matrix completion** problem

$$\min_{\widehat{\mathbf{f}}} \quad \mathrm{rank}[\mathcal{T}(\widehat{\mathbf{f}})] \quad \textbf{s.t.} \quad \widehat{\mathbf{f}}[\mathbf{k}] = \widehat{\mathbf{b}}[\mathbf{k}], \mathbf{k} \in \mathbf{\Gamma}$$

1-D Example:

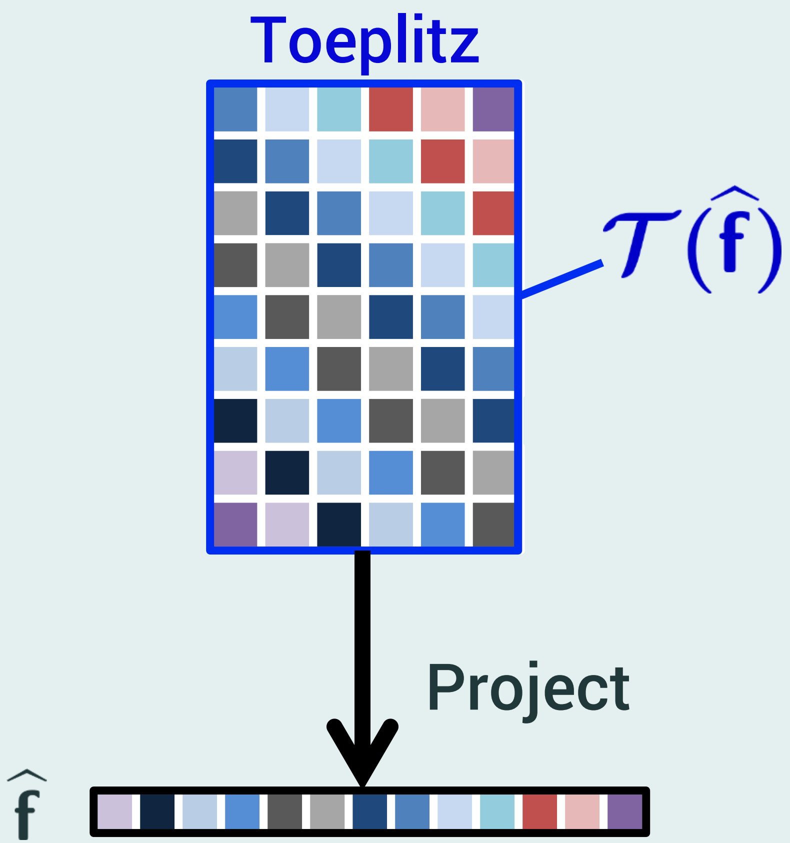
Complete matrix



Pose recovery as a one-stage structured low-rank matrix completion problem

$$\min_{\widehat{\mathbf{f}}} \quad \mathrm{rank}[\mathcal{T}(\widehat{\mathbf{f}})] \quad \textbf{s.t.} \quad \widehat{\mathbf{f}}[\mathbf{k}] = \widehat{\mathbf{b}}[\mathbf{k}], \mathbf{k} \in \mathbf{\Gamma}$$

1-D Example:



Pose recovery as a one-stage structured low-rank matrix completion problem

$$\min_{\widehat{\mathbf{f}}} \quad \mathrm{rank}[\mathcal{T}(\widehat{\mathbf{f}})] \quad \textbf{s.t.} \quad \widehat{\mathbf{f}}[\mathbf{k}] = \widehat{\mathbf{b}}[\mathbf{k}], \mathbf{k} \in \mathbf{\Gamma}$$

NP-Hard!

Pose recovery as a one-stage structured low-rank matrix completion problem

$$\min_{\widehat{\mathbf{f}}} \quad \mathrm{rank}[\mathcal{T}(\widehat{\mathbf{f}})] \quad \textbf{s.t.} \quad \widehat{\mathbf{f}}[\mathbf{k}] = \widehat{\mathbf{b}}[\mathbf{k}], \mathbf{k} \in \boldsymbol{\Gamma}$$

Convex Relaxation

$$\min_{\widehat{\mathbf{f}}} \quad \|\mathcal{T}(\widehat{\mathbf{f}})\|_* \quad \textbf{s.t.} \quad \widehat{\mathbf{f}}[\mathbf{k}] = \widehat{\mathbf{b}}[\mathbf{k}], \mathbf{k} \in \boldsymbol{\Gamma}$$

Nuclear norm – sum of singular values

Computational challenges

- **Standard algorithms are slow:**

  Apply ADMM = Singular value thresholding (SVT)

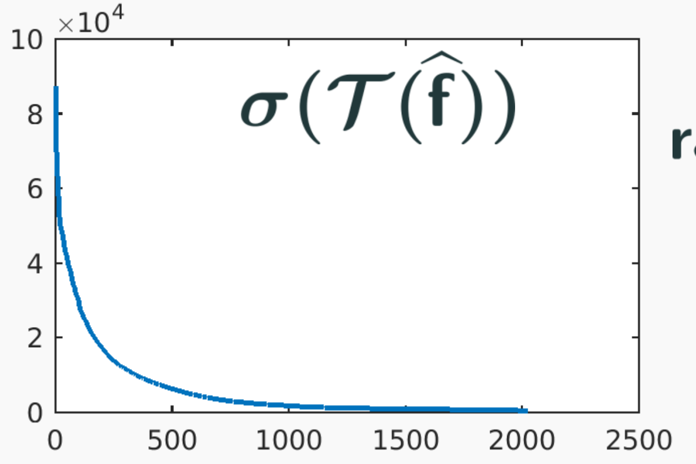
  Each iteration requires a large SVD:

  $$\dim(\mathcal{T}(\widehat{\mathbf{f}})) \approx \text{(\#pixels) x (filter size)}$$

  e.g. 10^6 x 2000

- **Real data can be "high-rank":**

e.g.
Singular values of
Real MR image



$$\mathrm{rank}(\mathcal{T}(\widehat{\mathbf{f}})) \approx 1000$$

Proposed Approach: Adapt IRLS algorithm

- IRLS: Iterative Reweighted Least Squares
- Proposed for low-rank matrix completion in [Fornasier, Rauhut, & Ward, 2011], [Mohan & Fazel, 2012]
- Adapt to structured matrix case:

$$\begin{cases} \mathbf{W} \leftarrow [\mathcal{T}(\widehat{\mathbf{f}})^*\mathcal{T}(\widehat{\mathbf{f}}) + \epsilon\mathbf{I}]^{-\frac{1}{2}} & \text{(weight matrix update)} \\ \widehat{\mathbf{f}} \leftarrow \arg\min_{\widehat{\mathbf{f}}} \|\mathcal{T}(\widehat{\mathbf{f}})\mathbf{W}^{\frac{1}{2}}\|_{\mathbf{F}}^2 \ \ \textbf{s.t.} \ \ \mathbf{P}\widehat{\mathbf{f}} = \mathbf{b} & \text{(LS problem)} \end{cases}$$

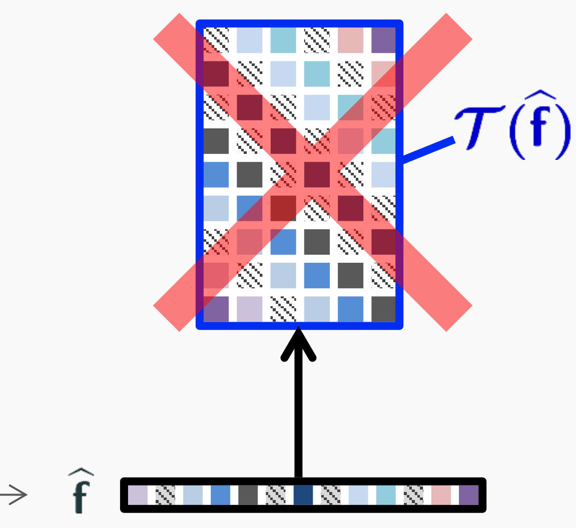
- Without modification, this approach is slow!

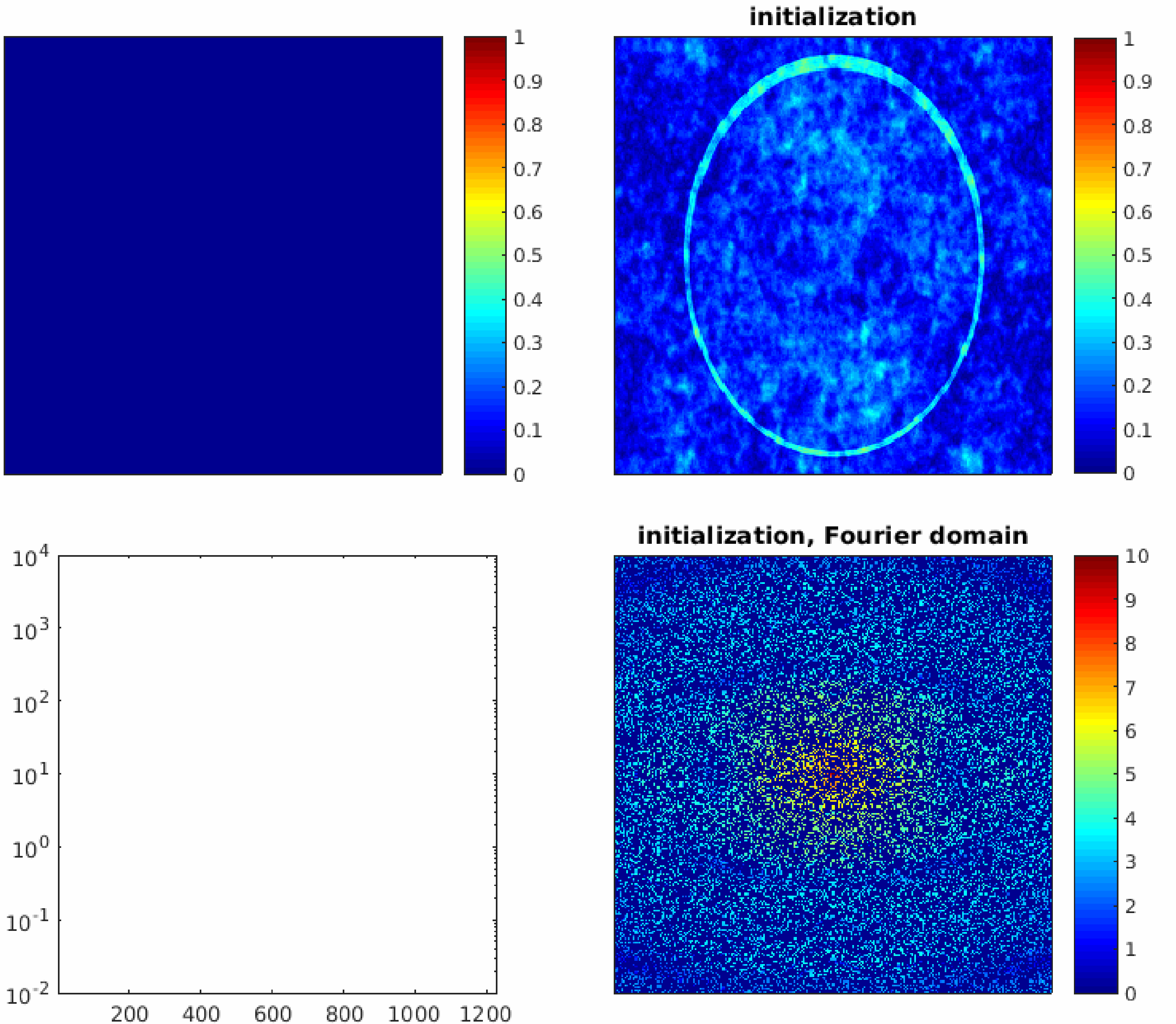
GIRAF algorithm [O. & Jacob, ISBI 2016]

- GIRAF = Generic Iterative Reweighted Annihilating Filter
- Exploit convolution structure to simplify IRLS algorithm:

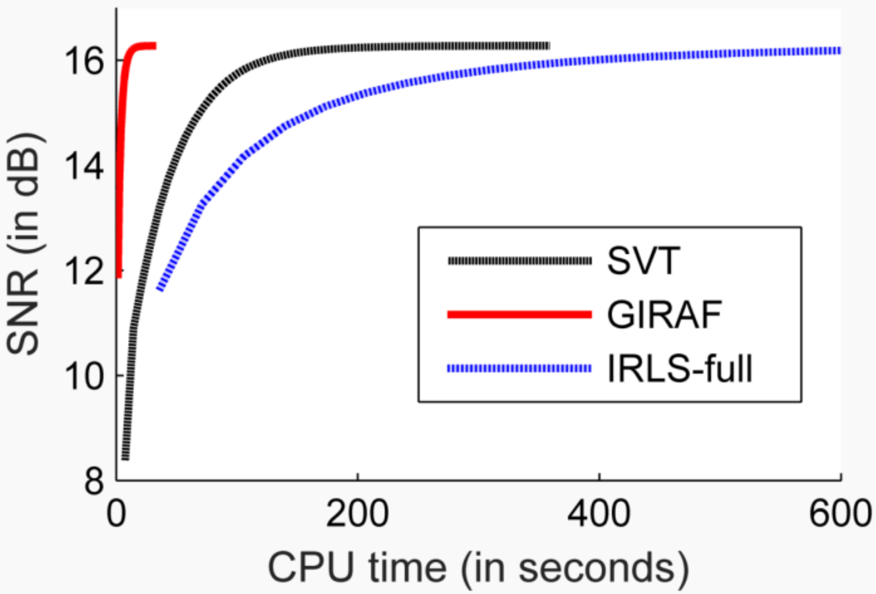
$$\begin{cases} \mu \leftarrow \sum \lambda_i^{-\frac{1}{2}} \mu_i & \text{(annihilating filter update)} \\ \widehat{\mathbf{f}} \leftarrow \arg\min_{\widehat{\mathbf{f}}} \|\widehat{\mathbf{f}} * \widehat{\mu}\|_2^2 \ \ \textbf{s.t.} \ \ \mathbf{P}\widehat{\mathbf{f}} = \mathbf{b} & \text{(LS problem)} \end{cases}$$

- Condenses weight matrix to *single* annihilating filter
- Solves problem in *original domain*



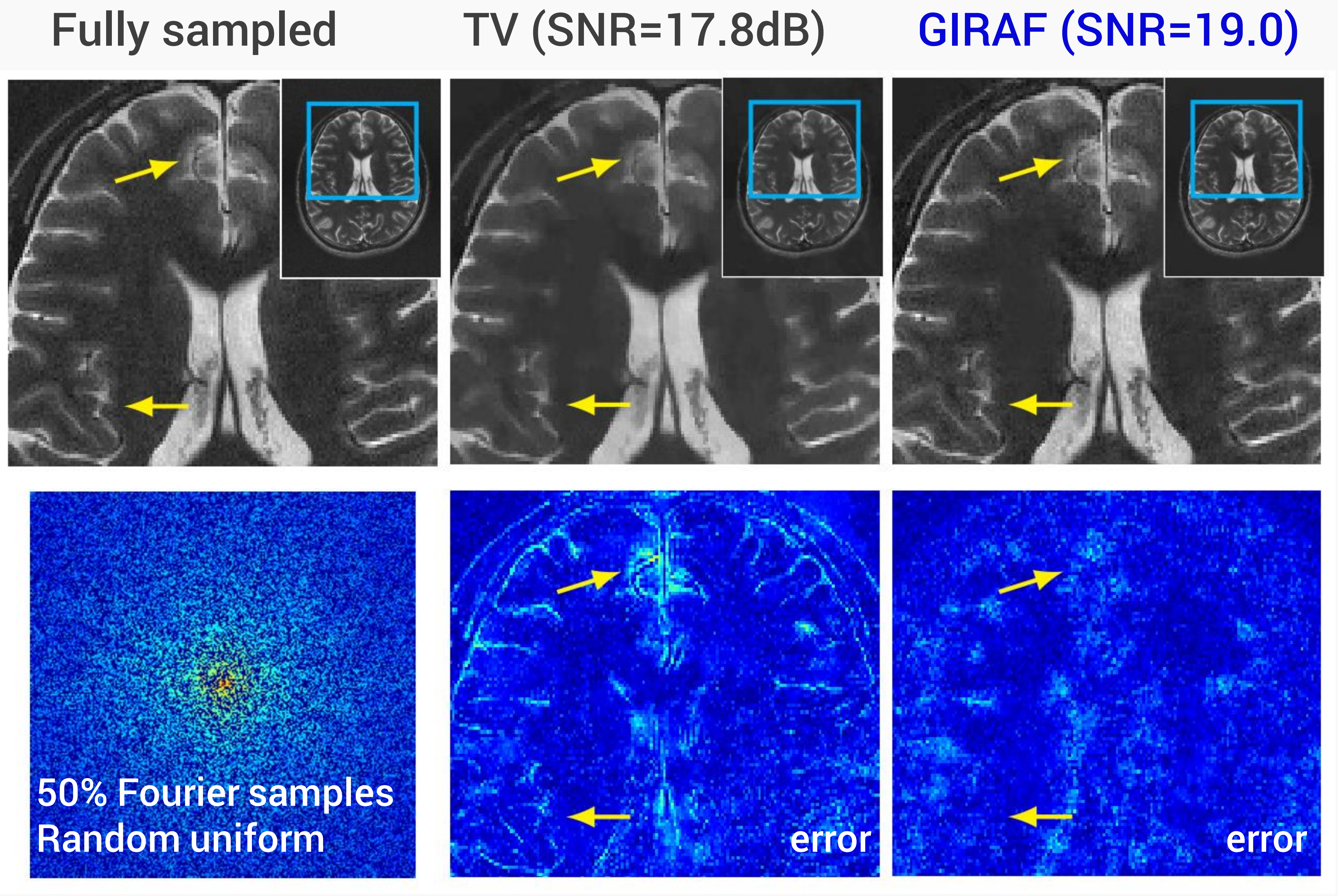

initialization
initialization, Fourier domain
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
0 1 2 3 4 5 6 7 8 9 10
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4}
200 400 600 800 1000 1200

Convergence speed of GIRAF



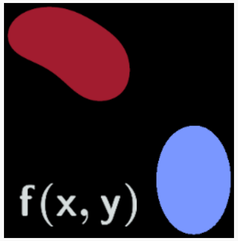
	15×15 filter		31×31 filter	
Algorithm	# iter	total	# iter	total
SVT	7	110s	11	790 s
GIRAF	6	20s	7	44 s

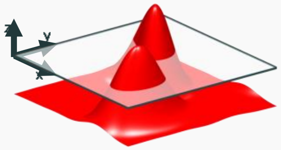
Table: iterations/CPU time to reach convergence tolerance of NMSE < 10^{-4}.


Fully sampled
TV (SNR=17.8dB)
GIRAF (SNR=19.0)
50% Fourier samples
Random uniform
error
error

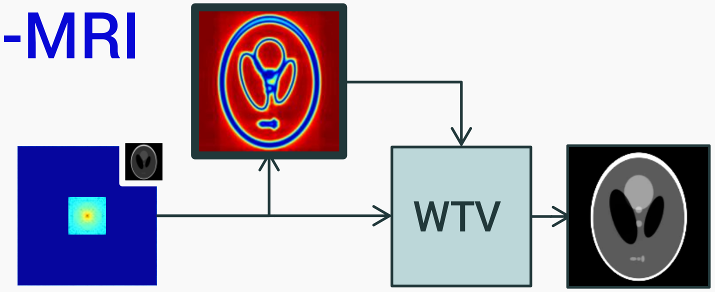
Summary

- New framework for off-the-grid image recovery
  - Extends FRI annihilating filter framework to piecewise polynomial images
  - Sampling guarantees





- Two stage recovery scheme for SR-MRI
  - Robust edge mask estimation
  - Fast weighted TV algorithm

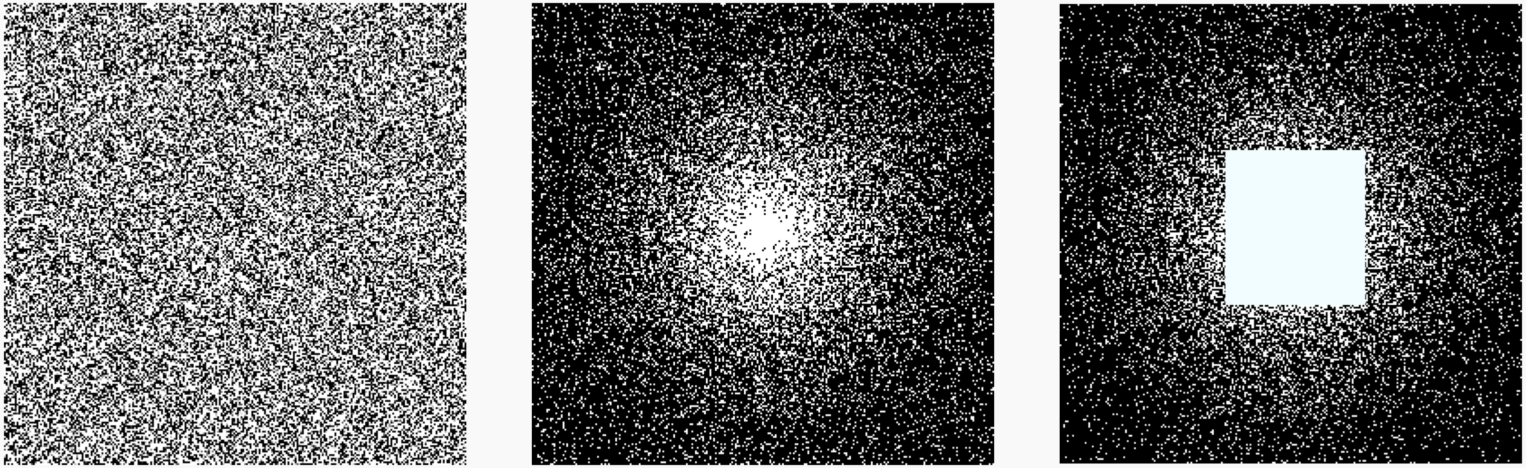


- One stage recovery scheme for CS-MRI
  - Structured low-rank matrix completion
  - Fast GIRAF algorithm

$$\min_{\hat{\mathbf{f}}} \|\mathcal{T}(\hat{\mathbf{f}})\|_*$$

Future Directions

- Focus: One stage recovery scheme for CS-MRI
  - Structured low-rank matrix completion $$\min_{\widehat{\mathbf{f}}} \|\mathcal{T}(\widehat{\mathbf{f}})\|_*$$
- Recovery guarantees for random sampling?
- What is the optimal random sampling scheme?



Thank You!

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