RESERVOIR CHARACTERIZATION PROJECT

Compressive Sensing in Seismic Acquisition

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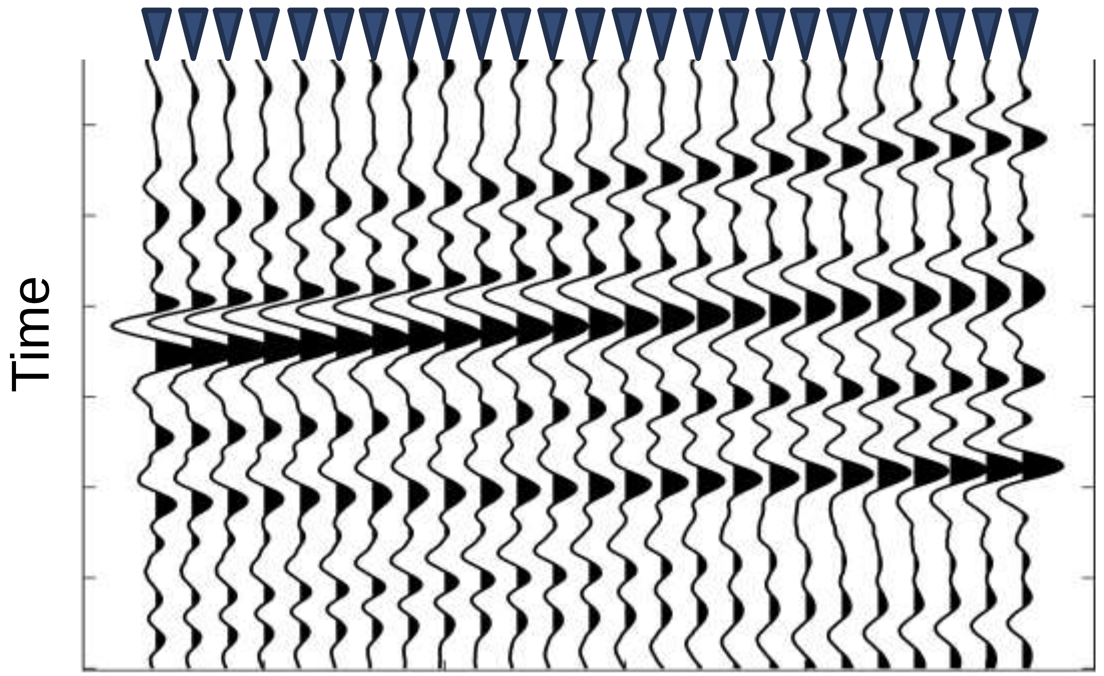
Outline

- Compressive sensing
- CS in seismic exploration
- CS sampling design
  - Mutual coherence
  - Measured energy
- SEG SEAM Barrett model data
- Conclusions
- Future work

Compressive Sensing

Traditionally acquired data



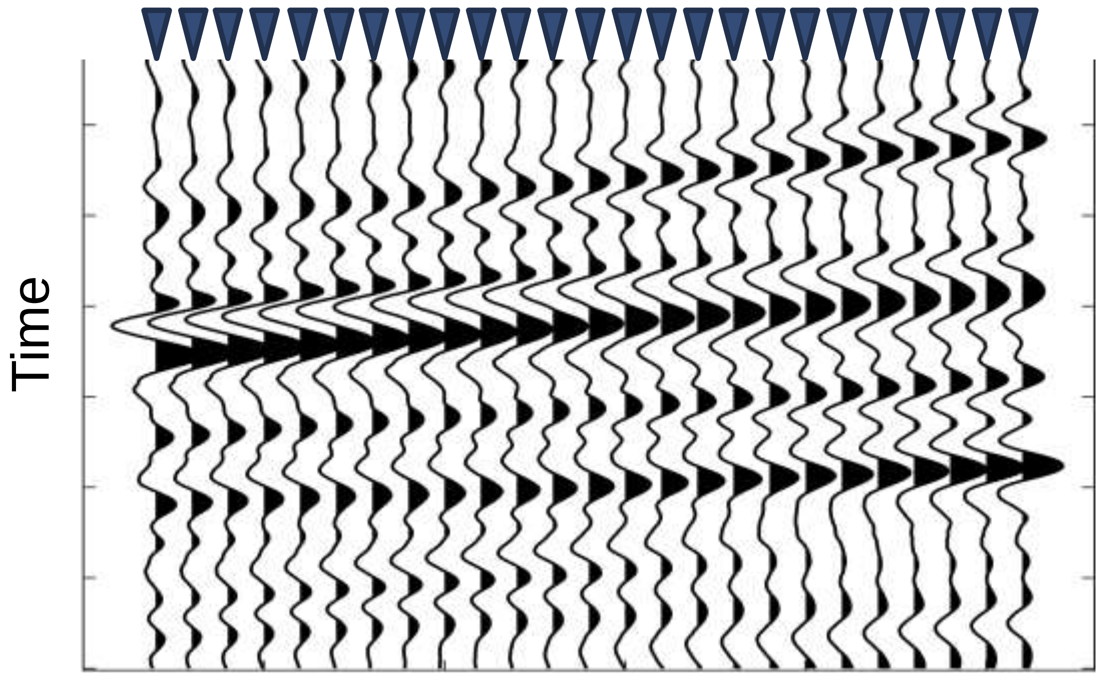
$$\Delta s = \Delta r \leq \frac{V_{min}}{2 \cdot f_{max}}$$

Marine: $\Delta s = \Delta r \leq \frac{1500}{2 \cdot 75} m = 10\ m \approx 33\ ft$

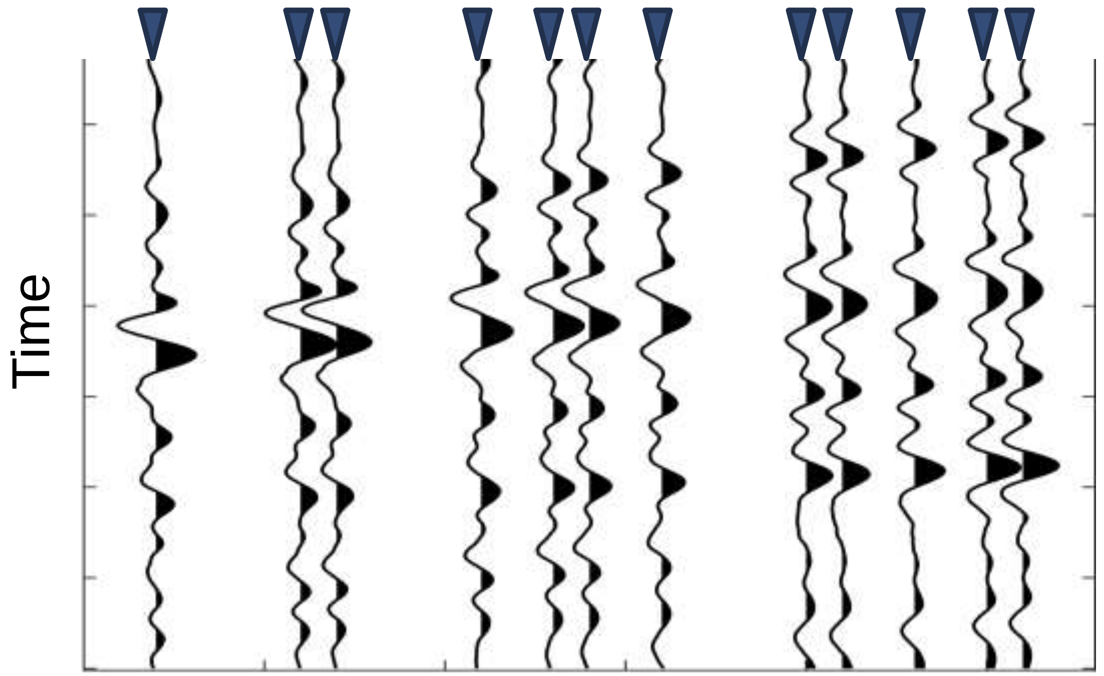
Land: $\Delta s = \Delta r \leq \frac{300}{2 \cdot 75} m = 2\ m \approx 7\ ft$

Compressive Sensing

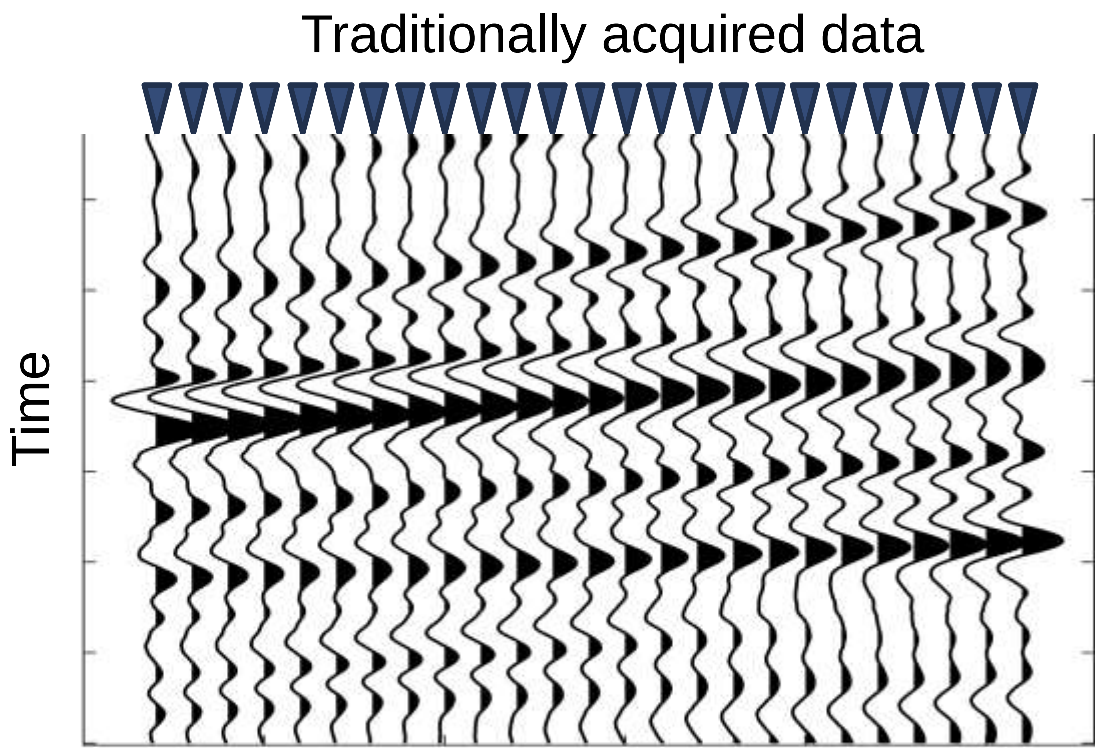
Traditionally acquired data

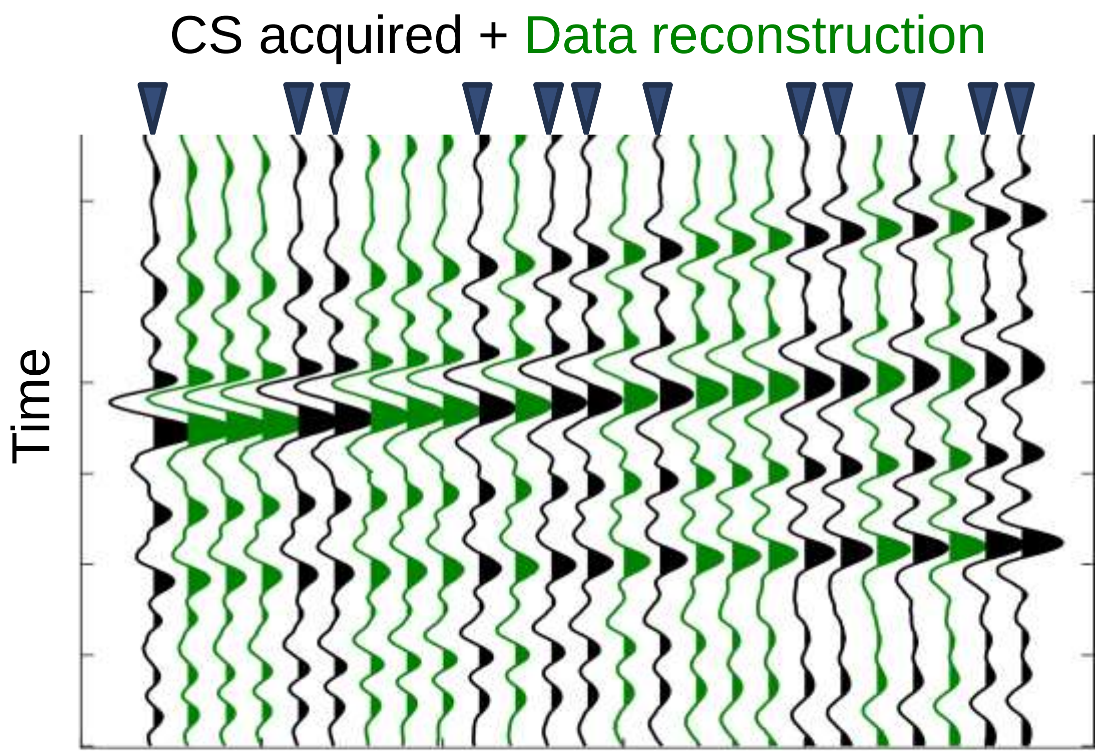


CS acquired data



Compressive Sensing

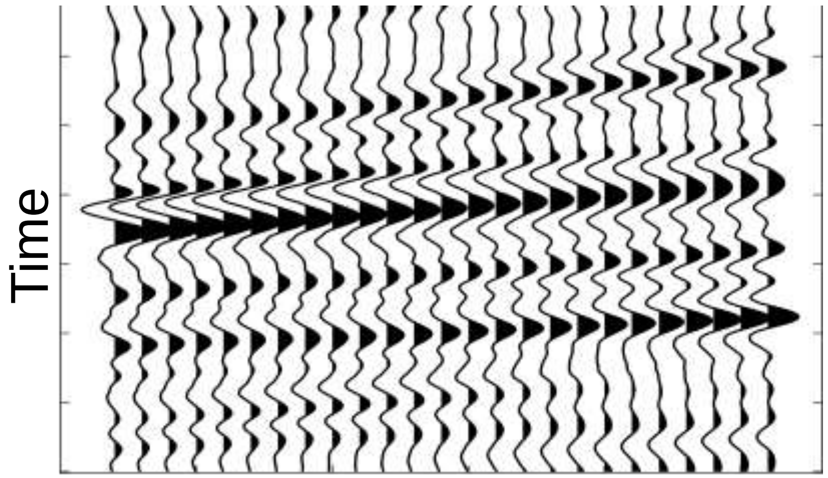




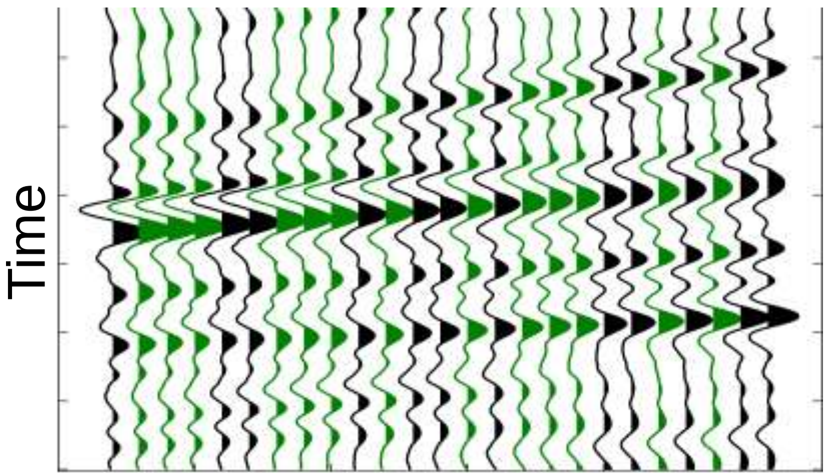
Black traces: acquired; green traces: reconstructed

Compressive Sensing

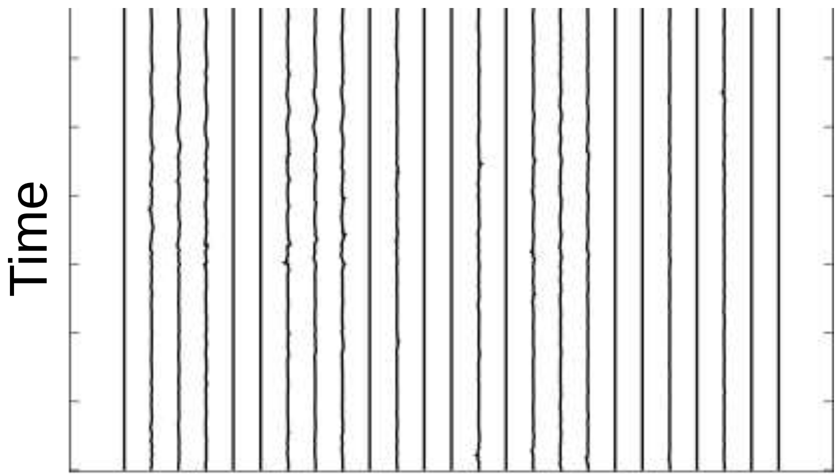
Traditionally acquired data



CS acquired + Data reconstruction



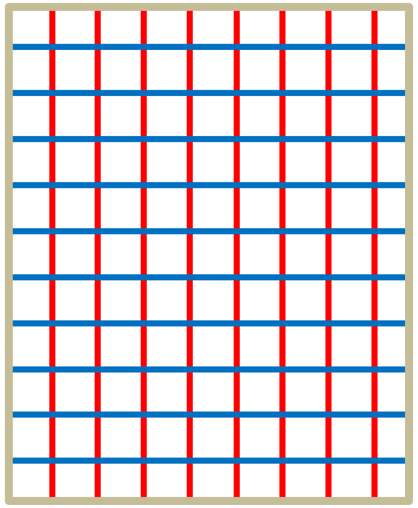
Difference



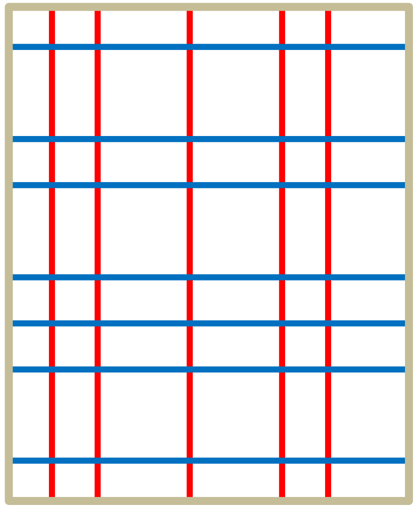
- Sparse transform
- Sampling scheme
- Reconstruction algorithm

Benefits of Utilizing CS for Seismic Acquisition

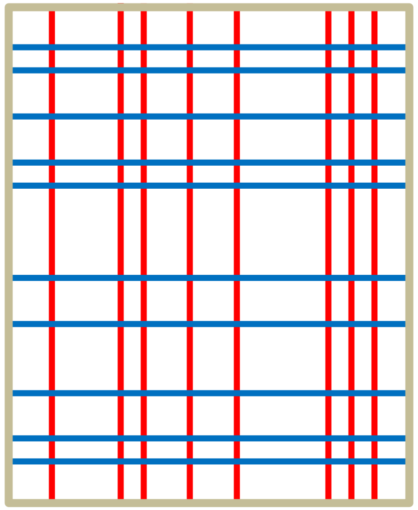
A:
uniform design



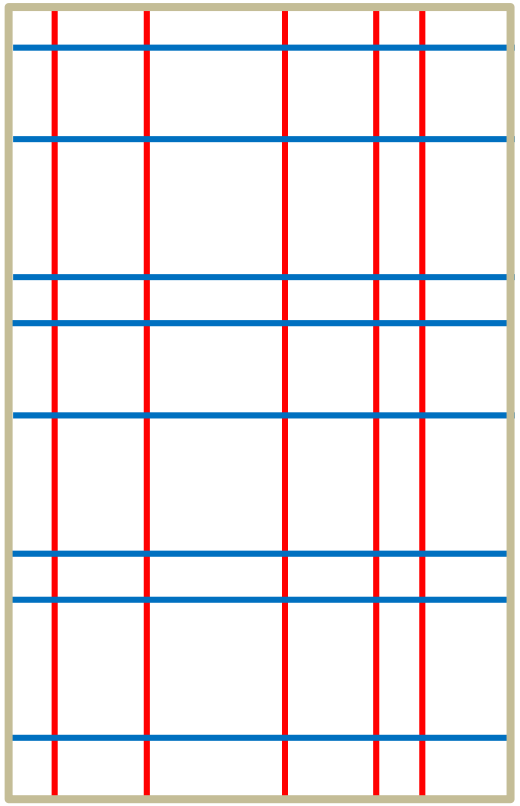
B:
- **less cost**
- same area
- same spatial bandwidth

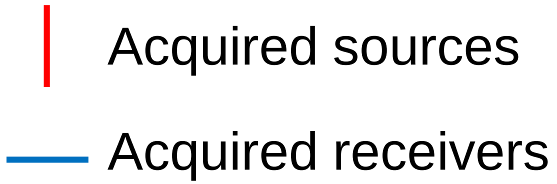


C:
- same cost
- same area
- **higher spatial bandwidth**



D:
- same cost
- **larger area**
- same spatial bandwidth



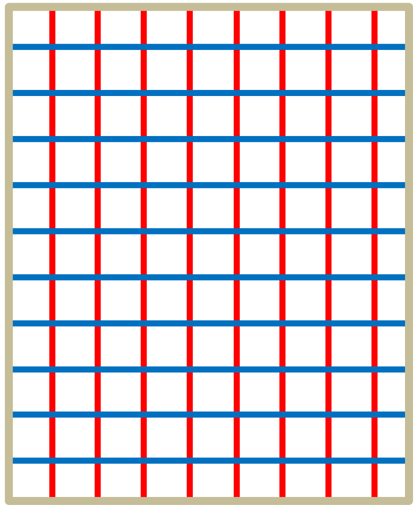


Mosher et al., 2012

Benefits of Utilizing CS for Seismic Acquisition

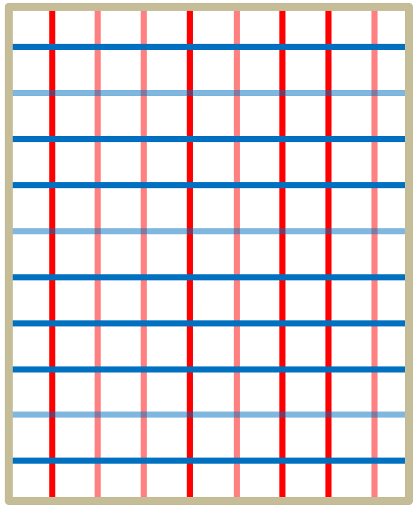
A:

uniform design



B:

- **less cost**
- same area
- same spatial bandwidth



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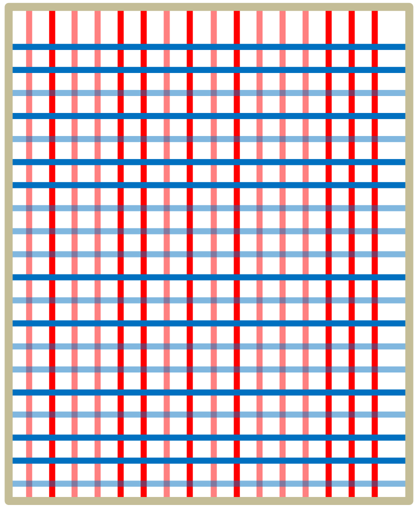
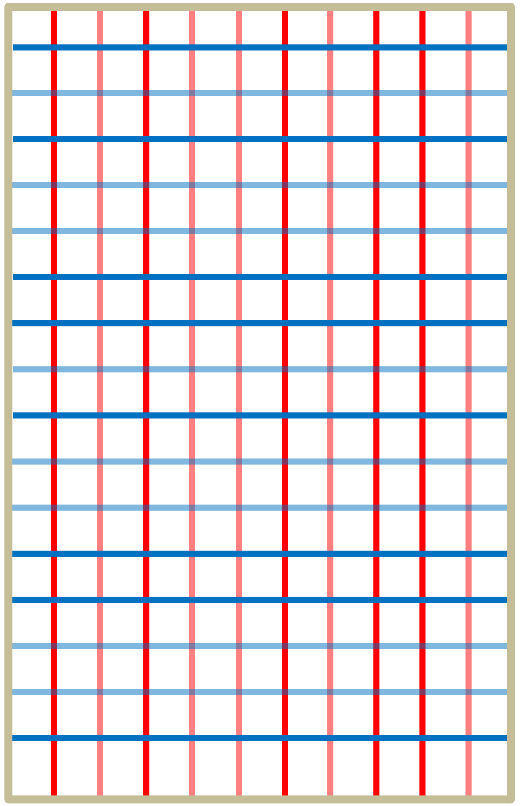


D:

- same cost
- **larger area**
- same spatial bandwidth



Acquired sources

Recovered sources

Acquired receivers

Recovered receivers

Mosher et al., 2012

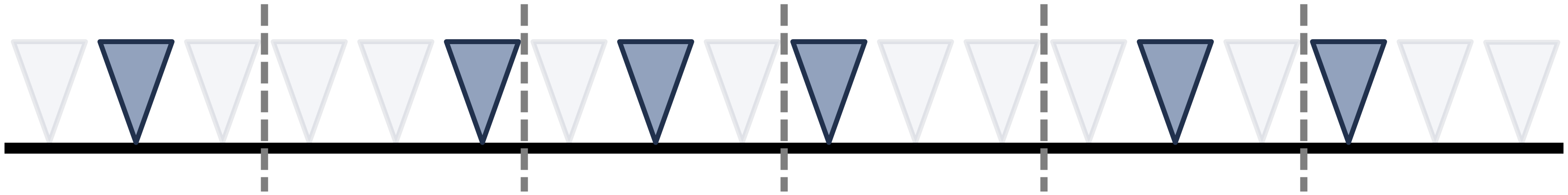
CS in Seismic Exploration

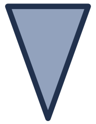
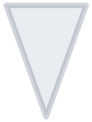
- ConocoPhillips (Mosher et al., 2012; Li et al., 2019)
- TGS (Jiang et al., 2018)
- In-Depth Compressive (Jiang et al., 2017; Jiang et al., 2019)
- Dawson Geophysical (Thomas et al., 2019)
- Occidental Petroleum Corporation (Jiang et al., 2019)
- BGP-CNPC (Li et al., 2019; Zhe et al., 2019)
- University of British Columbia (Herrmann et al., 2008; Kumar et al., 2017)
- University of Alberta (Naghizadeh and Sacchi, 2010; Bhuiyan and Sacchi, 2015)
- Colorado School of Mines (Pawelec et al., 2019; Titova et al., 2019)
- University of Texas at Dallas (Zhang and Lumley, 2019)

Jittered Undersampling

- Random

- Jittered



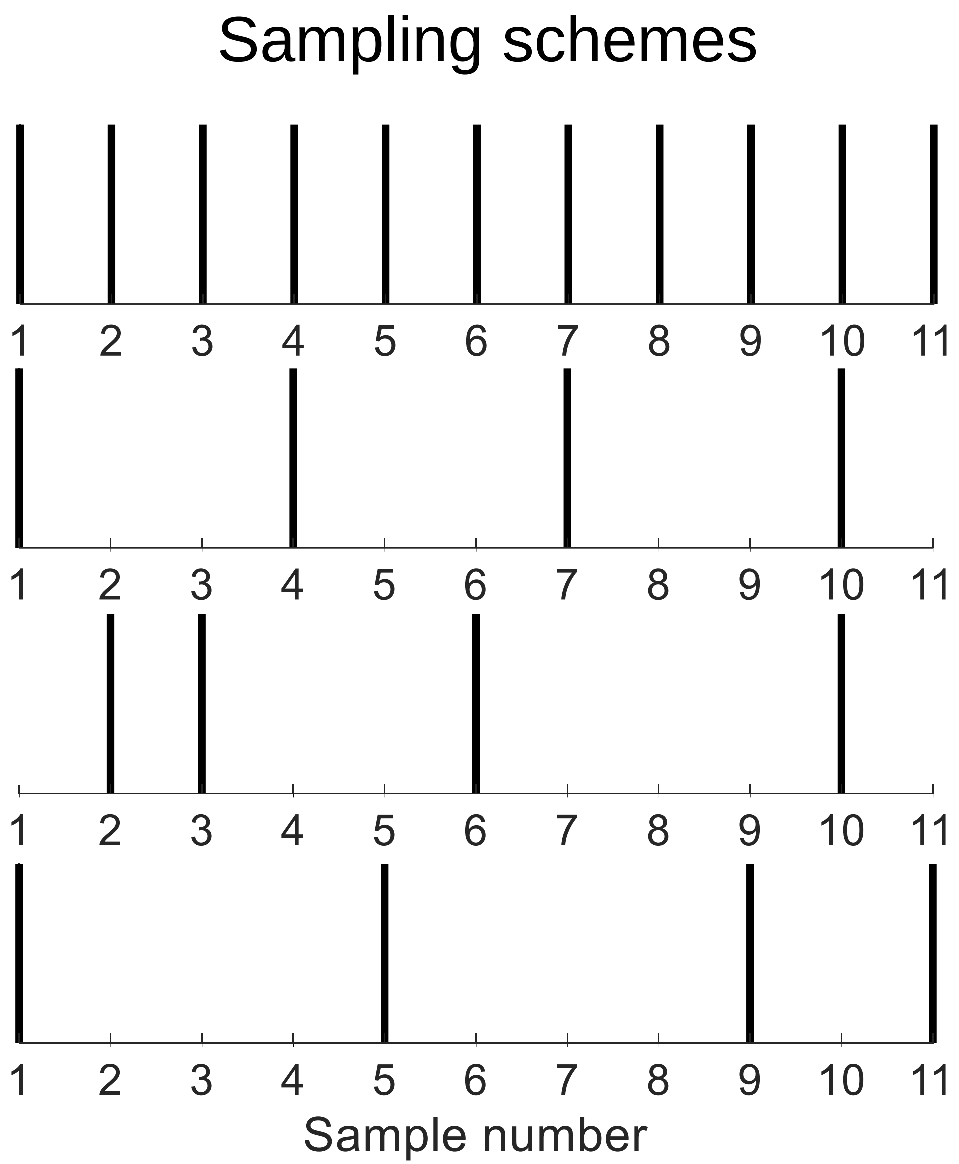
 active receiver  omitted receiver

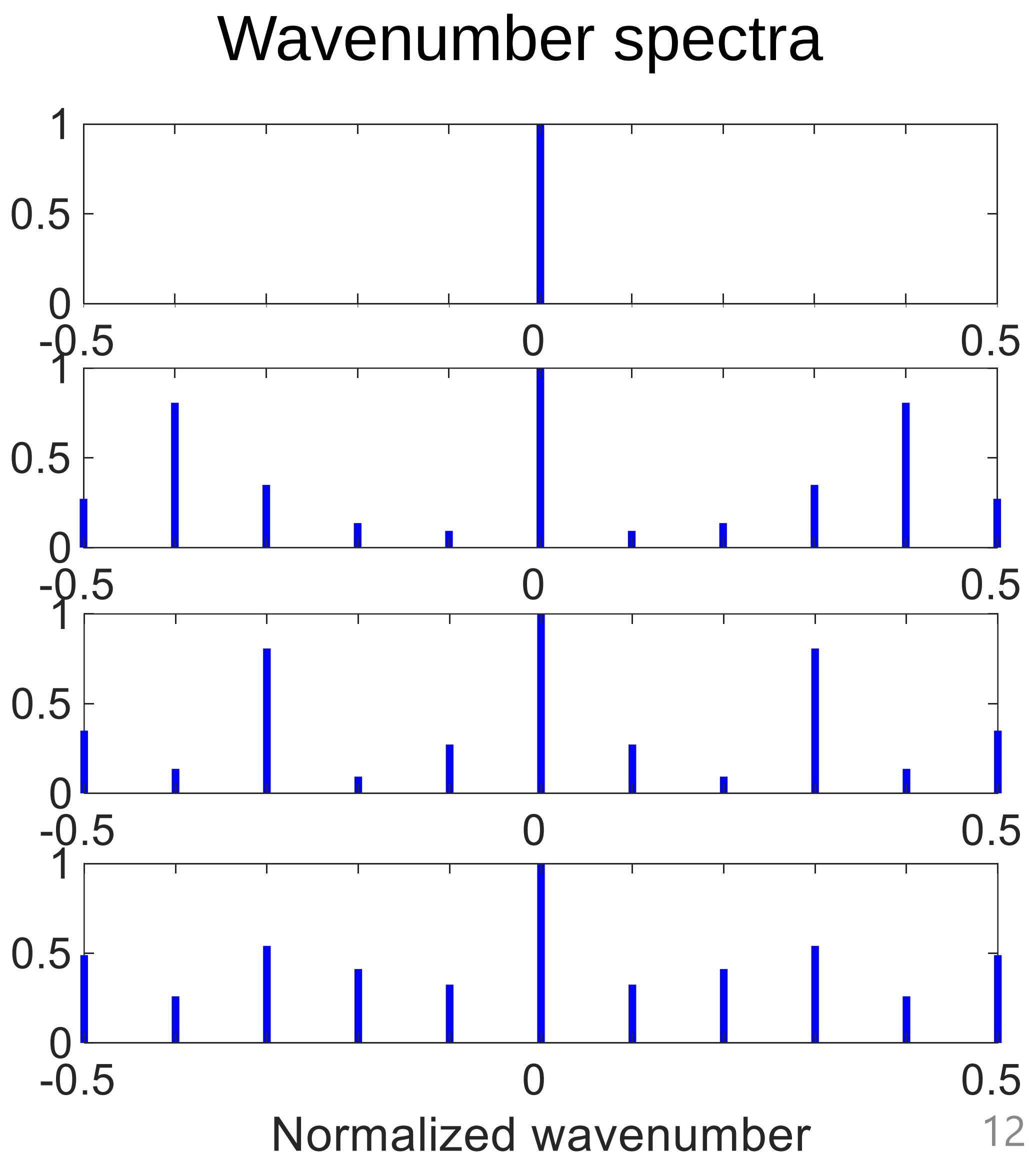
Optimized Undersampling

RCP
In pursuit of new ideas

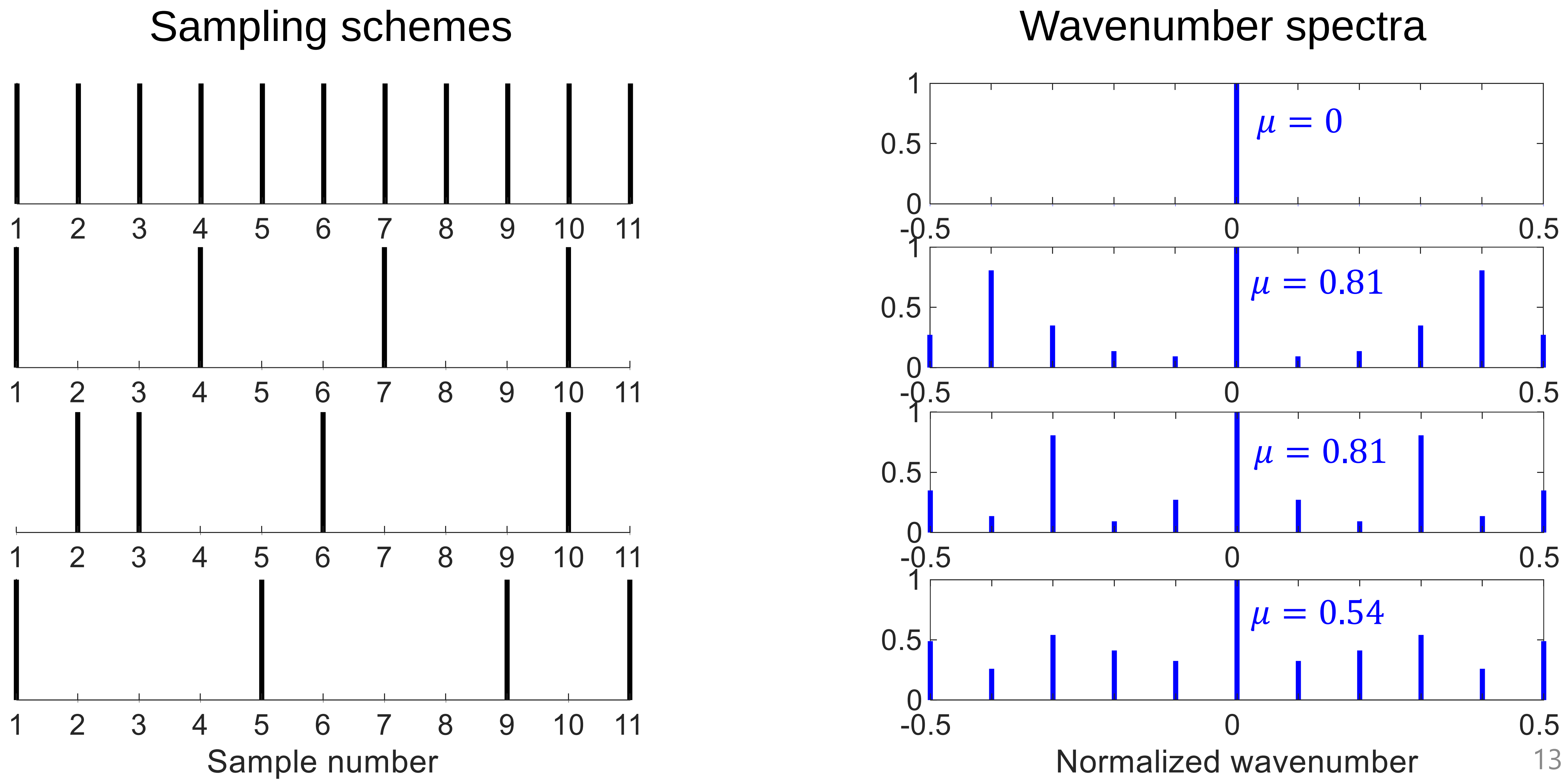
	Parameter	Domain	Year	Authors
1	Mutual coherence, Reconstruction error	Sources/receivers and shooting time	2012	Mosher et al.
2	Mutual coherence	Sources/receivers	2015	Bhuiyan and Sacchi
3	Mutual coherence	Sources/receivers	2016	Jamali-Rad et al.
4	Mutual coherence, Spark, a Golomb ruler	Sources/receivers and shooting time	2017	Campman et al.
5	Mutual coherence	Sources/receivers	2018	Jiang et al.
6	Mutual coherence	Shooting time	2018	Florez et al.
7	Reconstruction error	Sources/receivers and shooting time	2019	Nakayama et al.
8	Mutual coherence	Sources/receivers	2019	Zhang and Lumley

Signal-Blind Undersampling: Mutual Coherence

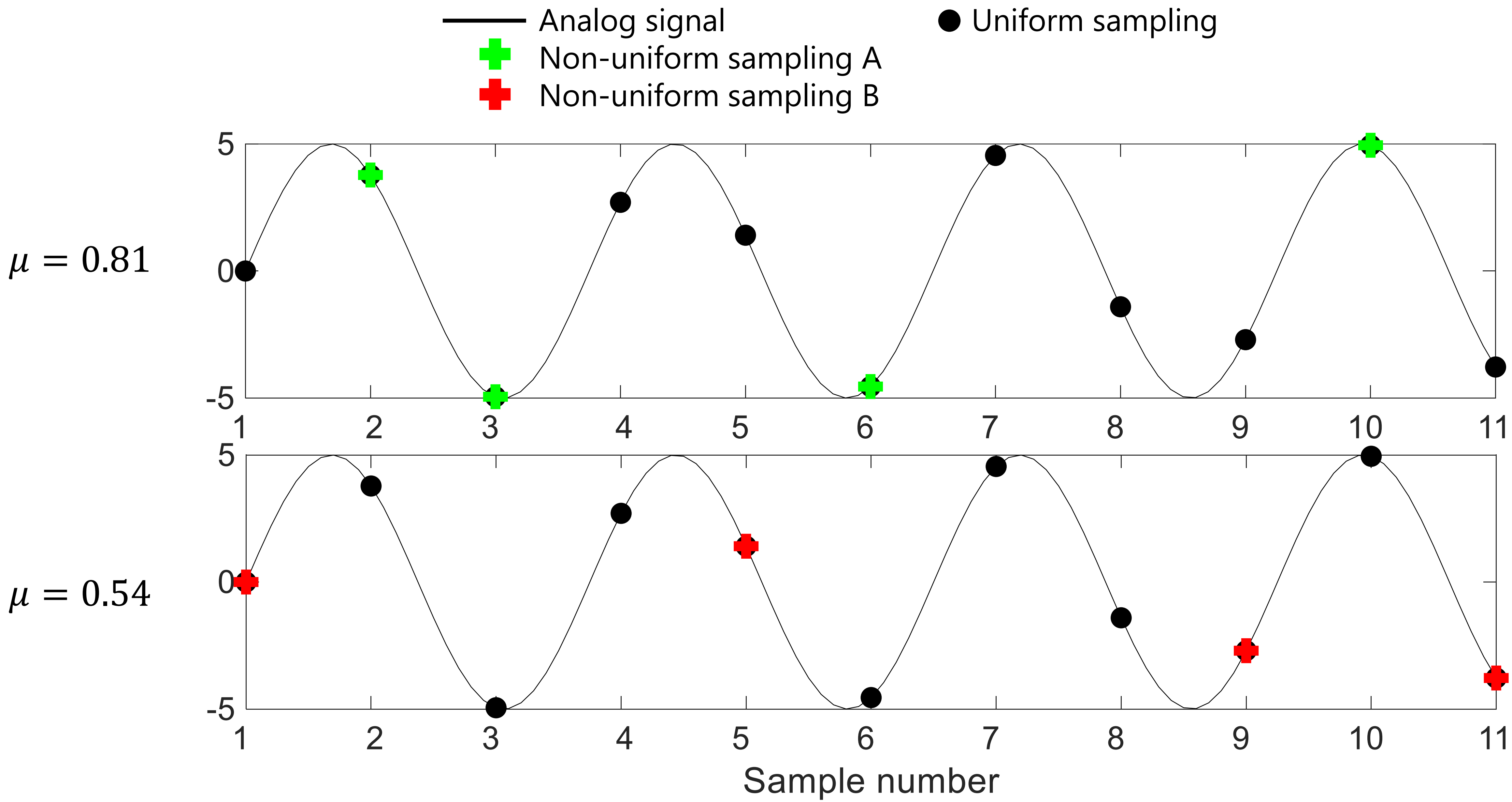




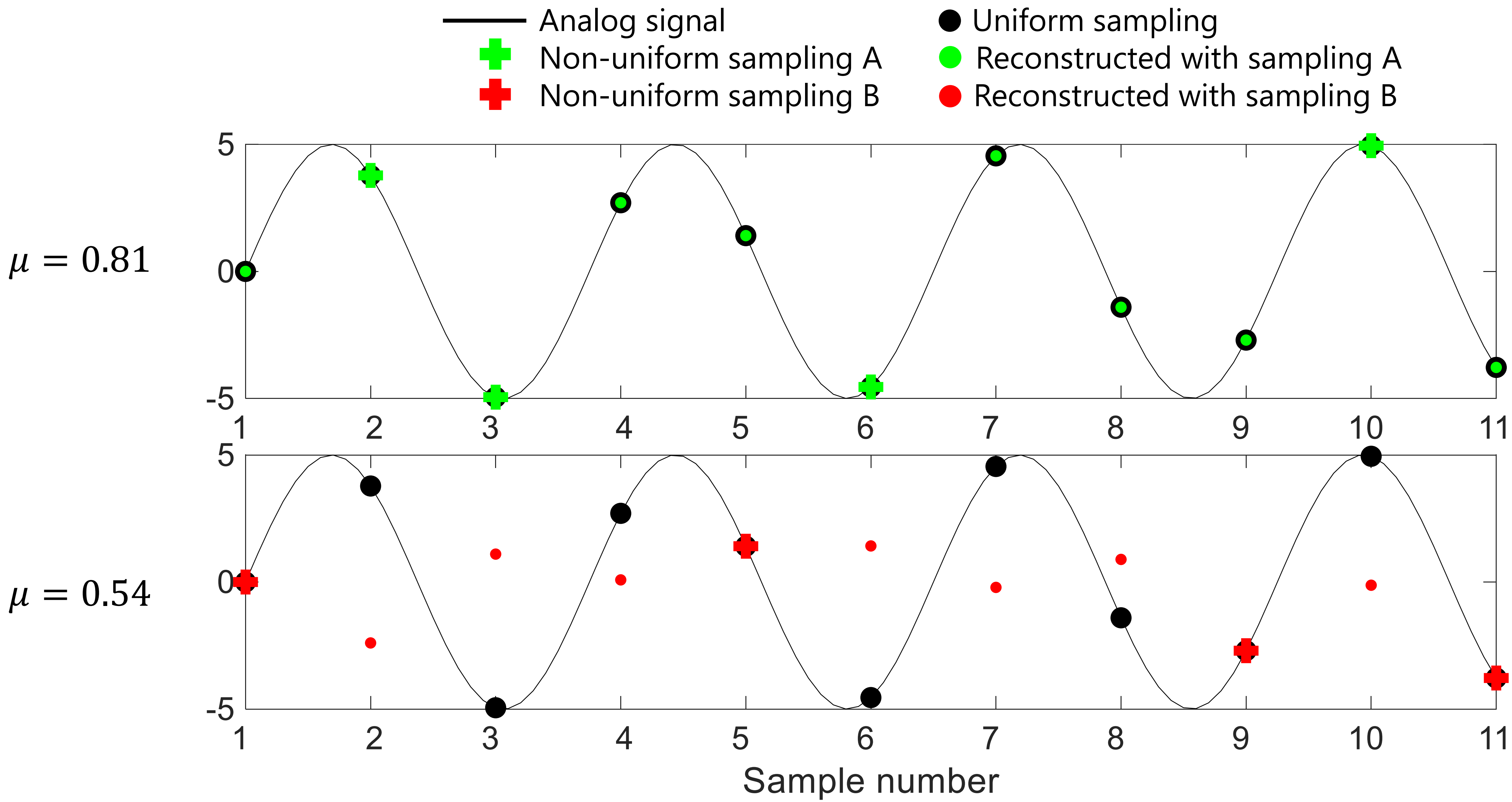
Signal-Blind Undersampling: Mutual Coherence



Sinusoidal Signal: Recording



Sinusoidal Signal: Reconstruction



Experiment #1

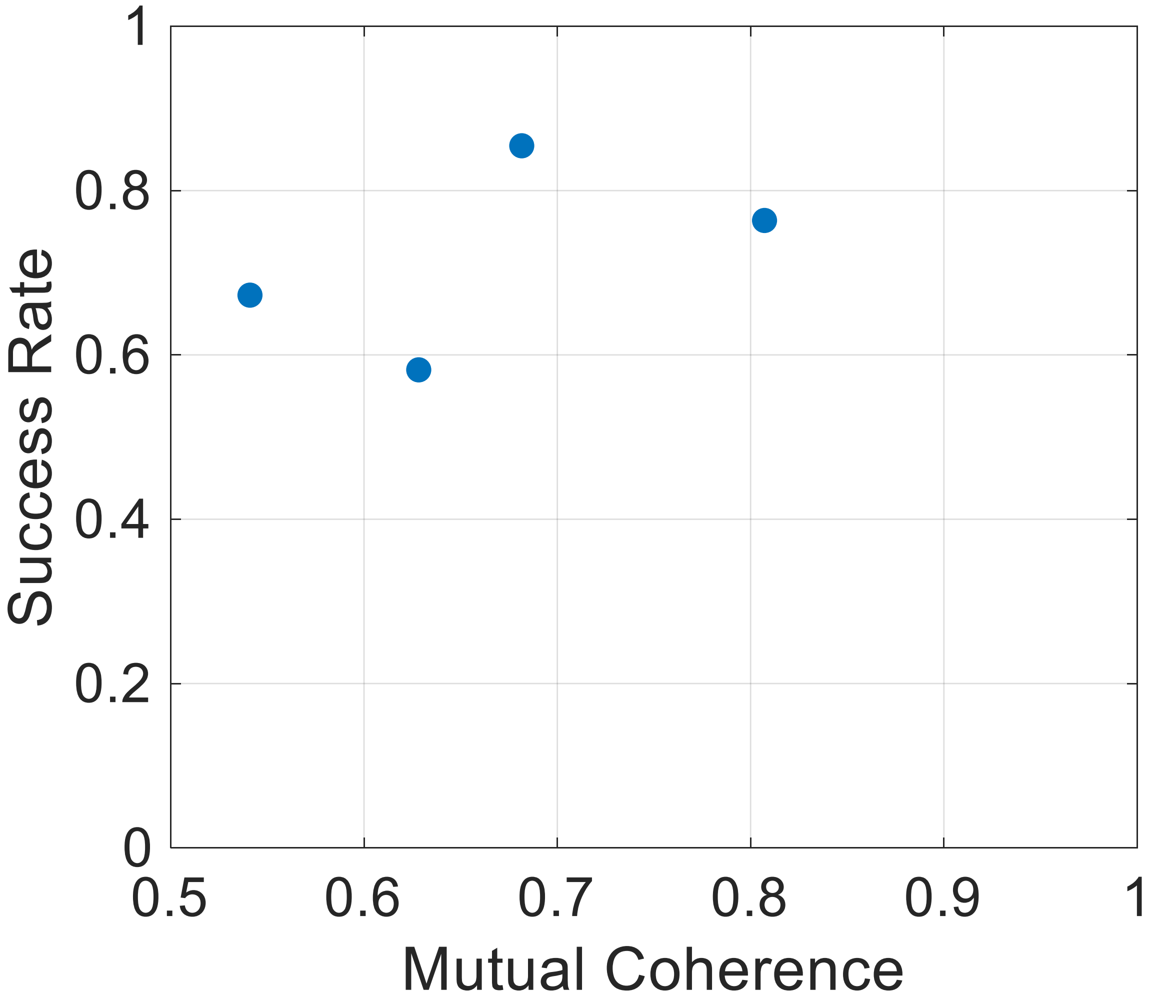
- Input:
  - Signal: sine wave
  - Transform: Fourier transform
  - Sampling: all combinations for M=4, N=11: $\binom{N}{M} = \binom{11}{4} = 330$
  - Reconstruction algorithm: l1-minimization
- Goal:
  - Find sampling schemes that provide successful reconstruction

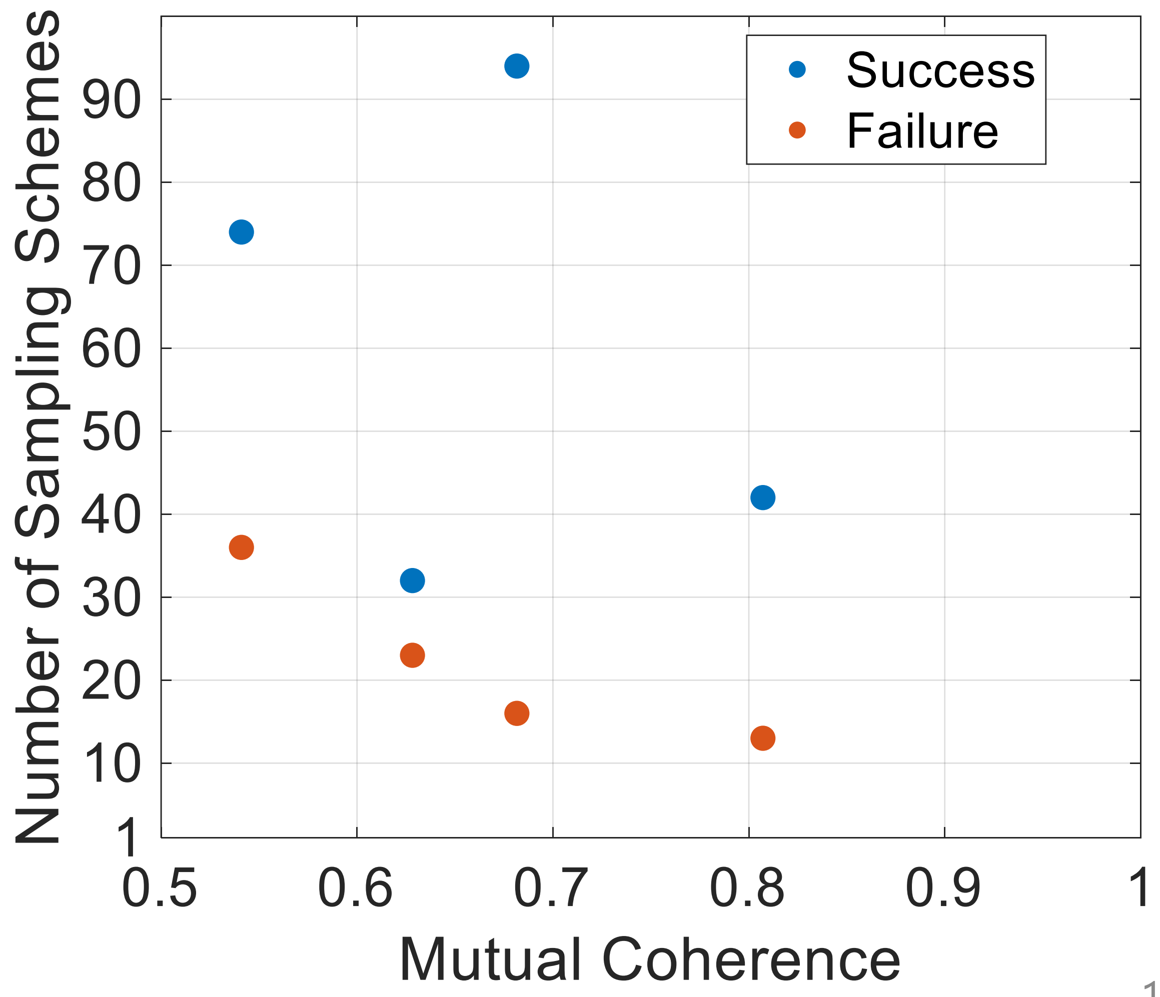
$$Success\ trial: \frac{\|Reconstructed\ Signal - Original\ Signal\|_2}{\|Original\ Signal\|_2} < 1e-6;$$

$$Success\ rate = \frac{Success\ trials}{Total\ number\ of\ trials}$$

#1: Mutual Coherence versus Success Rate

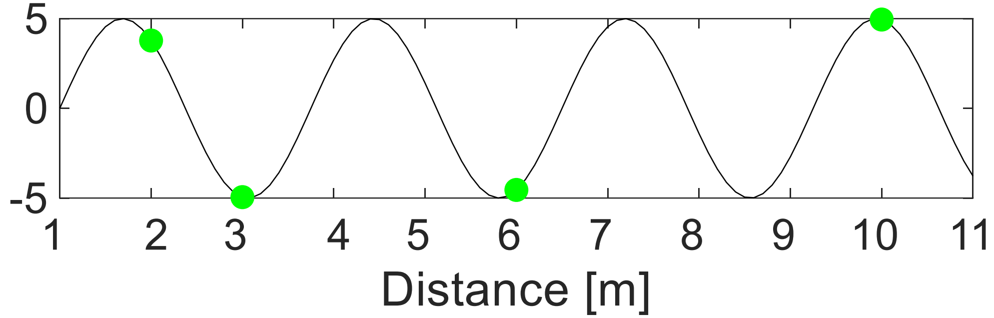
Total number of experiments is 330: 242 successes; 88 failures
73%; 27%

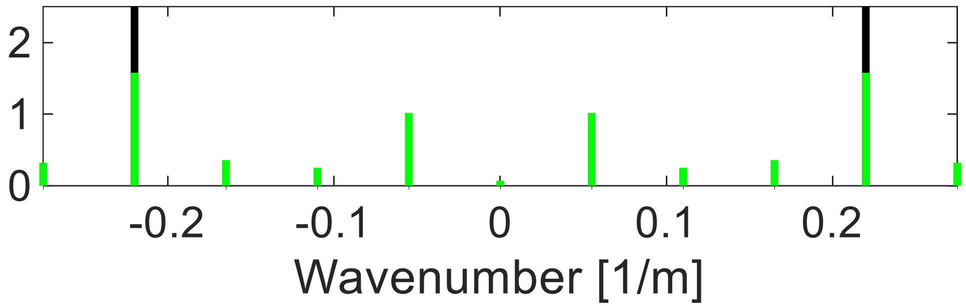




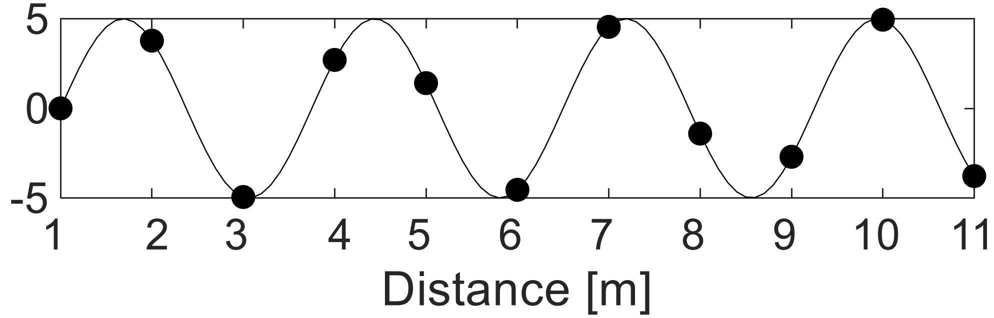
Signal-Based Undersampling: Measured Energy

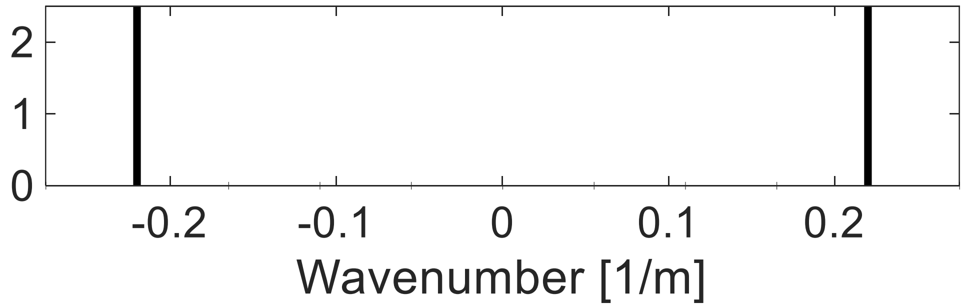
Recorded signal





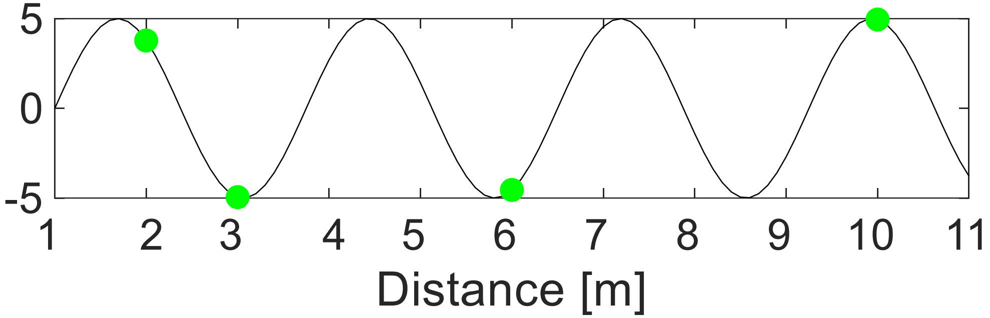
Full signal

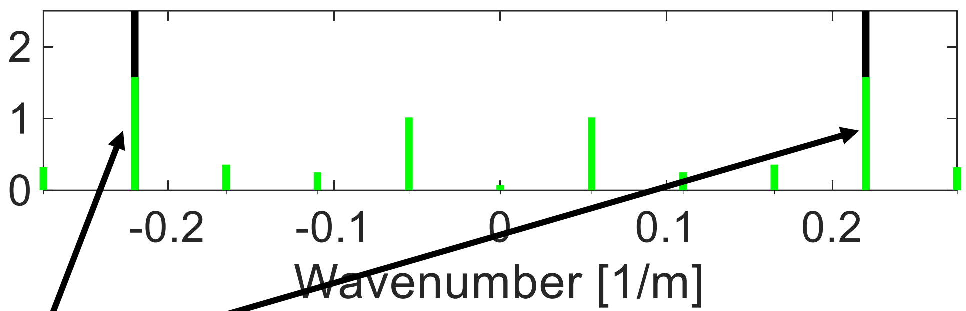




Signal-Based Undersampling: Measured Energy

Recorded signal

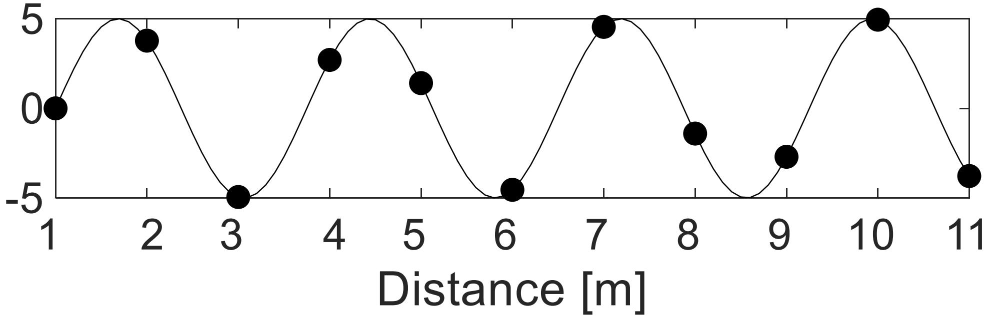


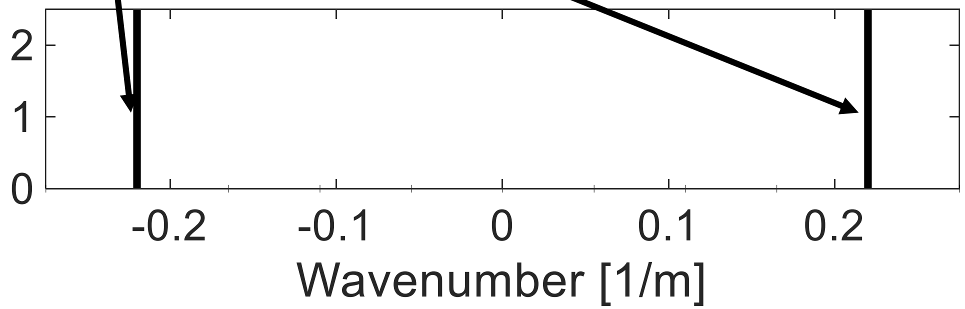


$Energy\ of\ the\ recorded\ signal$

$Energy\ of\ the\ full\ signal$

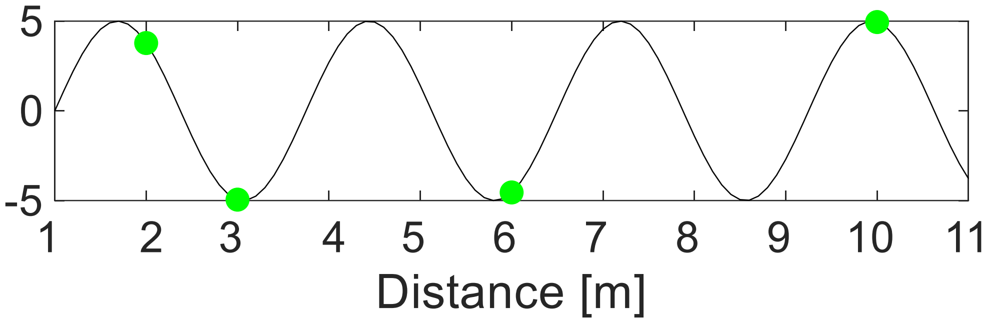
Full signal

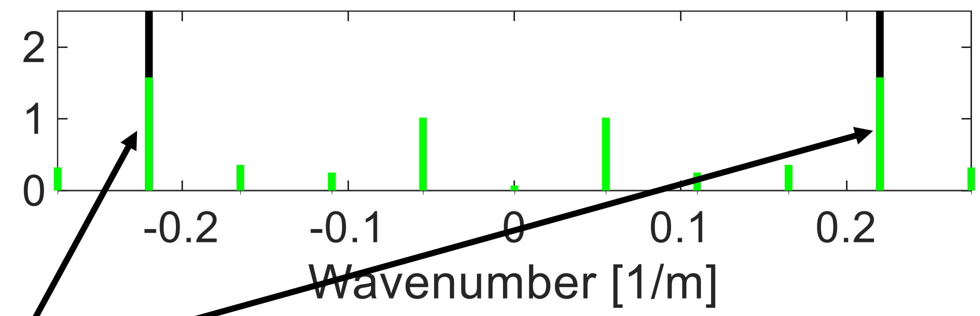




Signal-Based Undersampling: Measured Energy

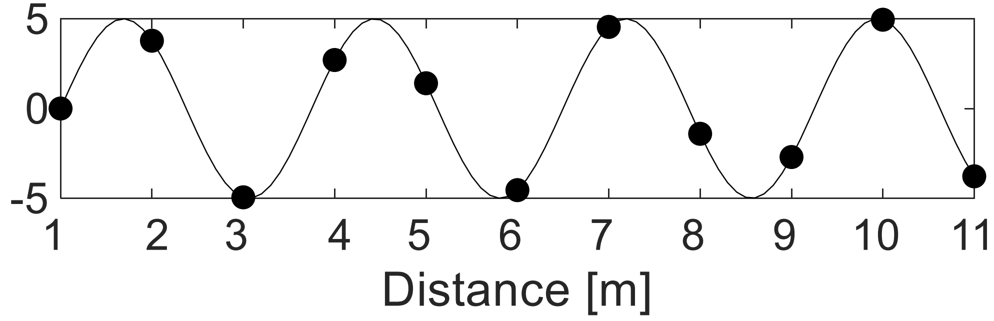
Recorded signal

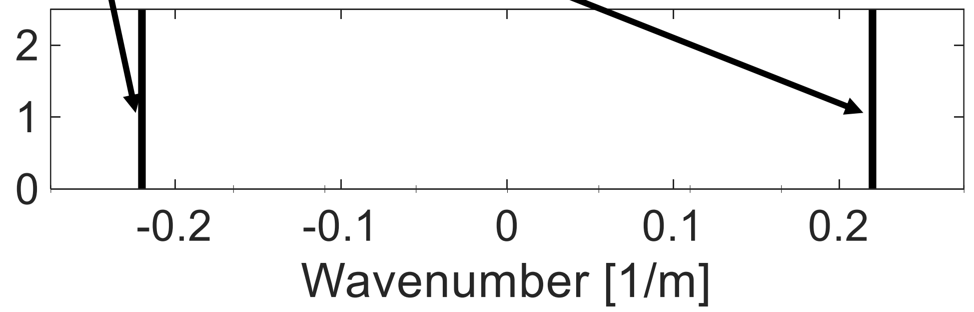




$$Measured\ Energy = \frac{Energy\ of\ the\ recorded\ signal}{Energy\ of\ the\ full\ signal}$$

Full signal

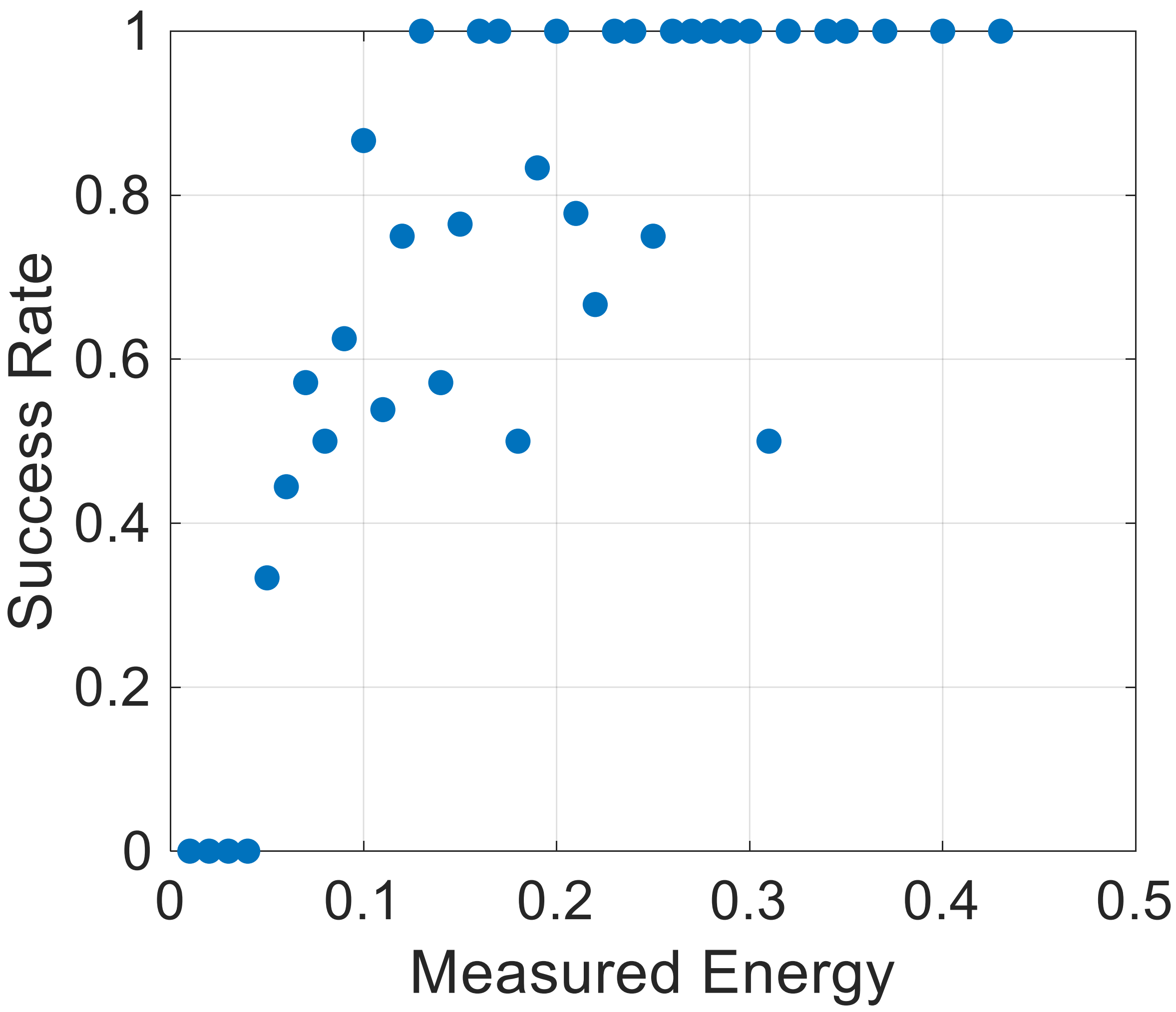


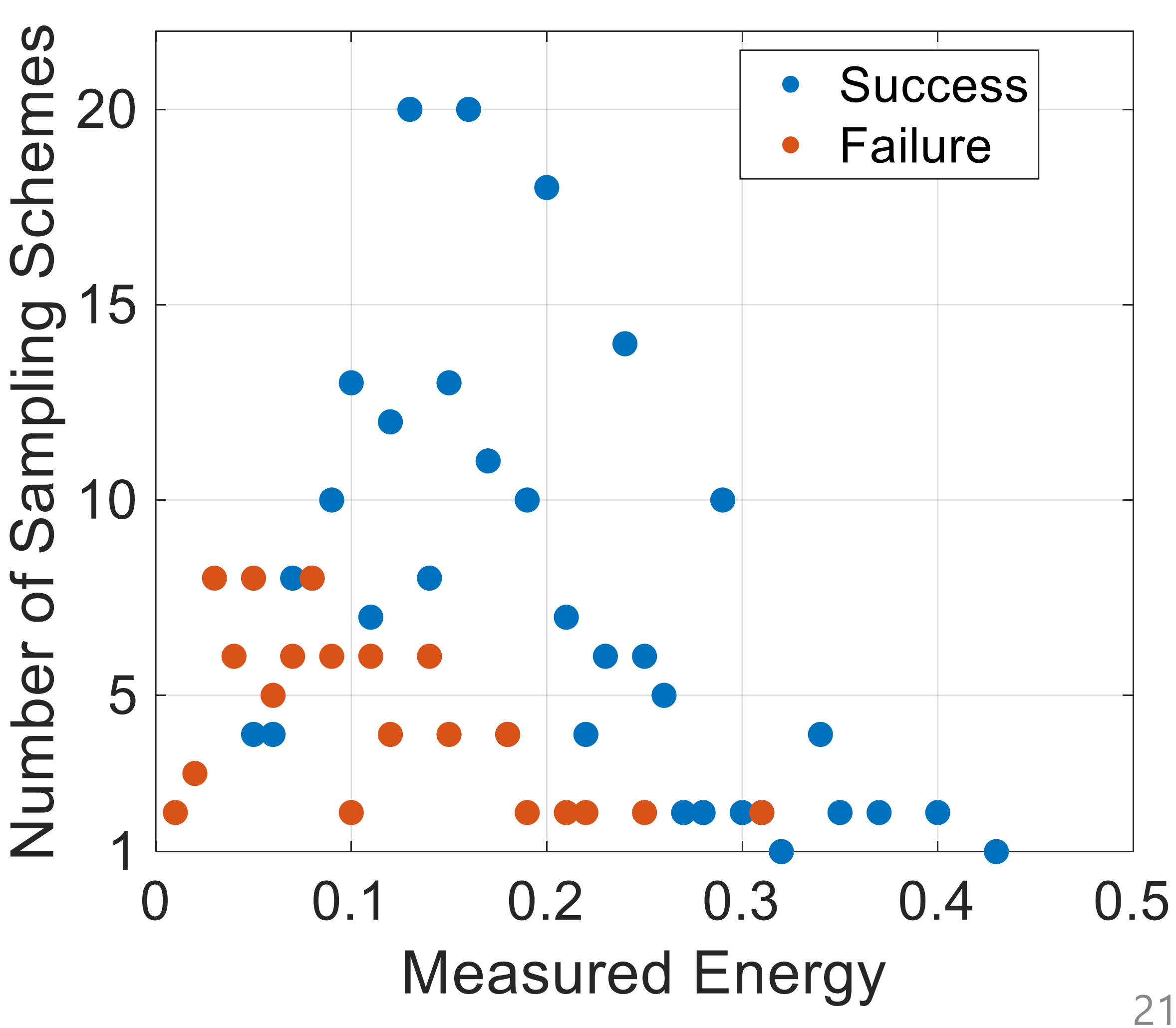


#1: Measured Energy versus Success Rate

Total number of experiments is 330: 242 successes; 88 failures

73%; 27%





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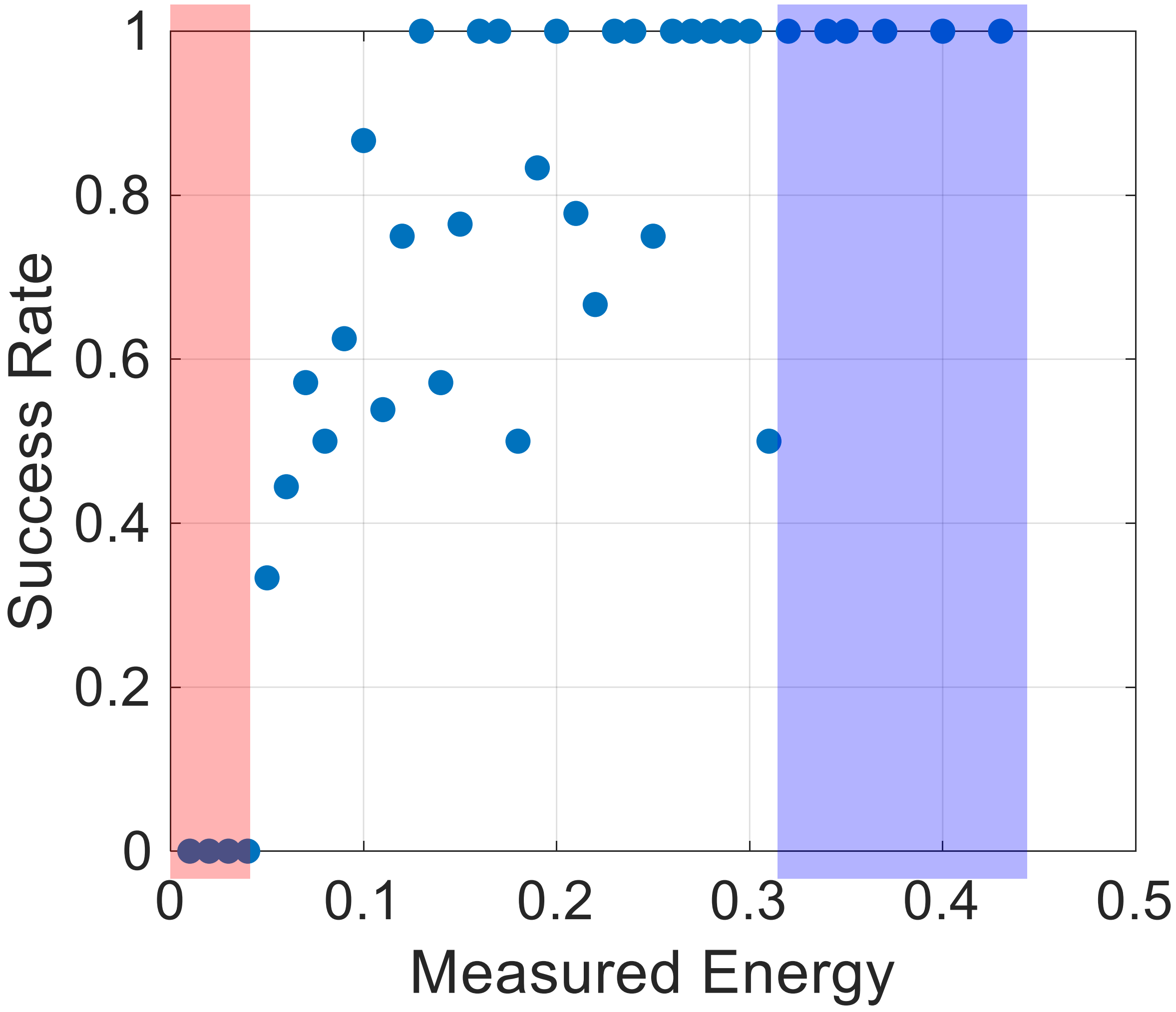
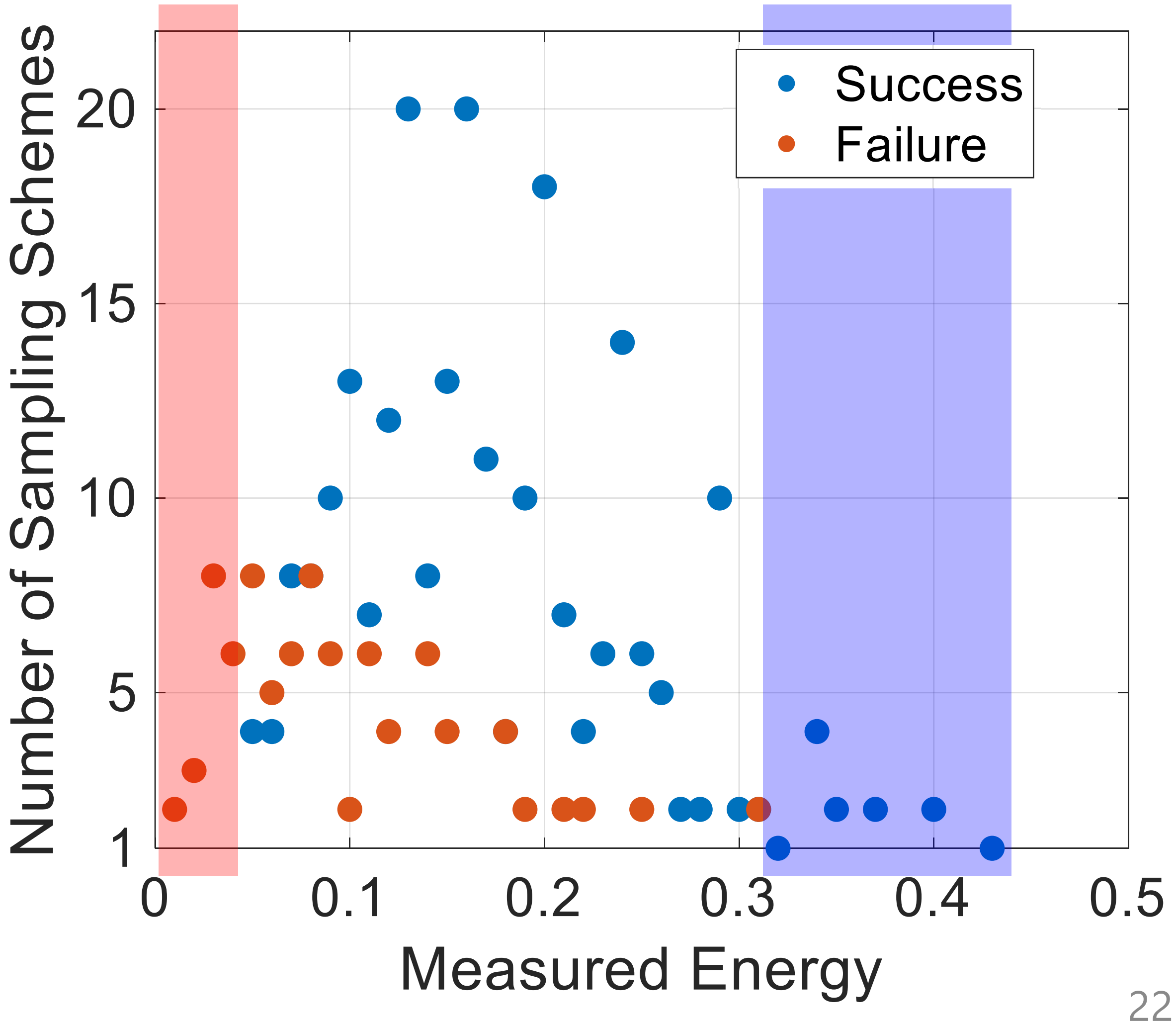




Experiment #2

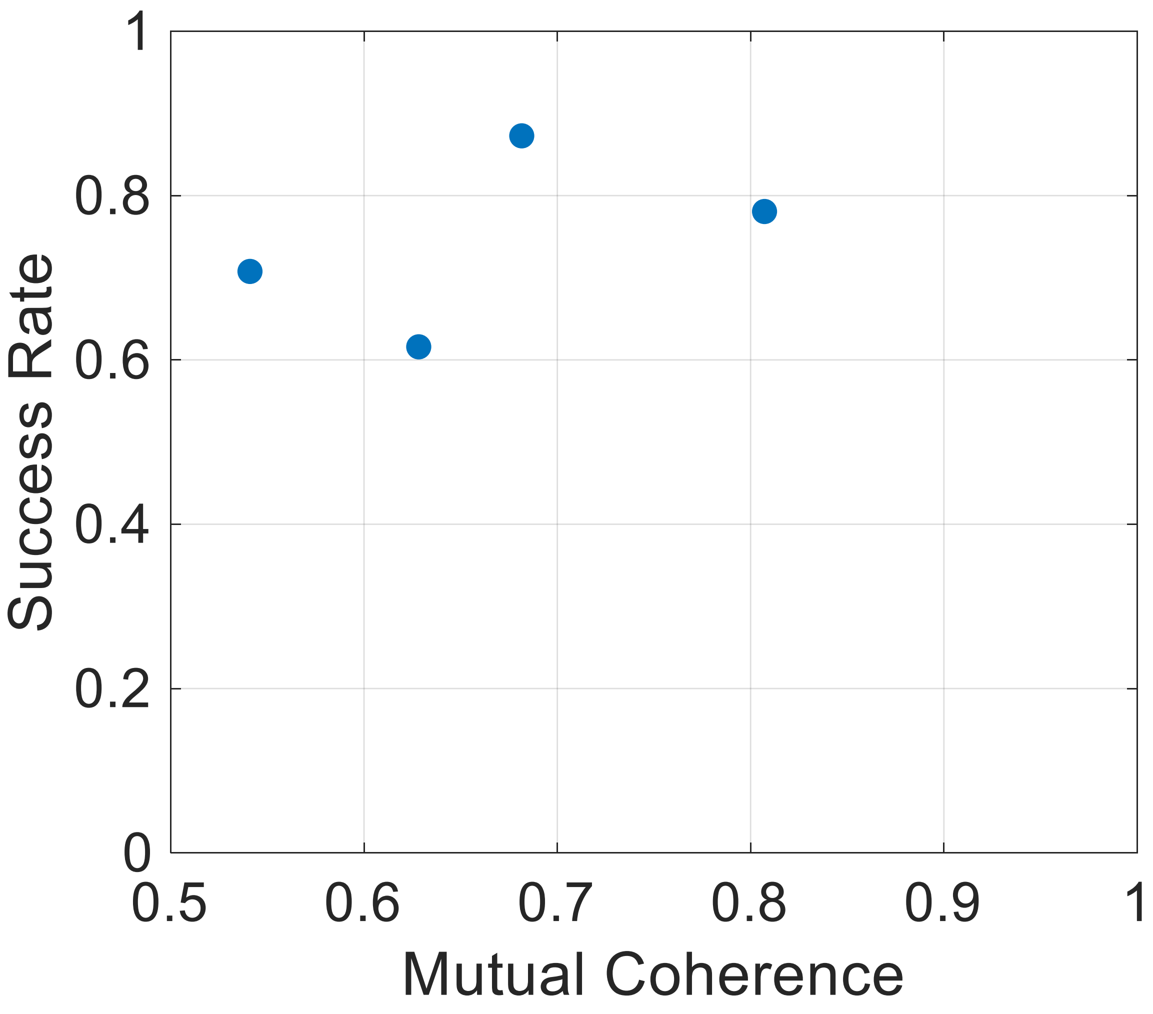
- Input:
  - Signal: 400 random signals, sparsity level=2
  - Transform: Fourier transform
  - Sampling: all combinations for M=4, N=11: $\binom{N}{M} = \binom{11}{4} = 330$
  - Reconstruction algorithm: l1-minimization

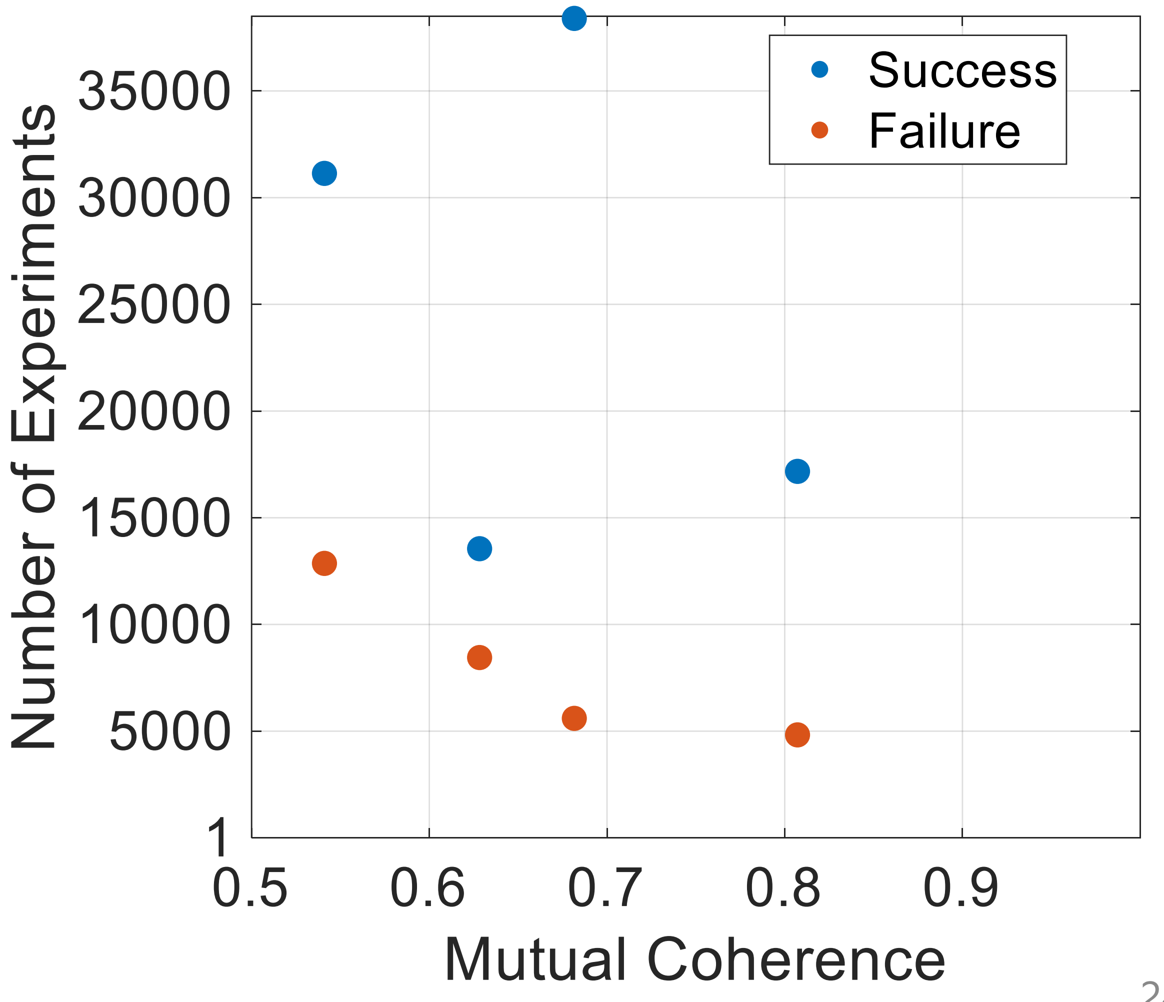
- Goal:
  - Find sampling schemes that provide successful reconstruction

#2: Mutual Coherence versus Success Rate

RCP
In pursuit of new ideas

Total number of experiments is $400 * 330 = 132000$: 100262 successes; 31738 failures
76%; 24%





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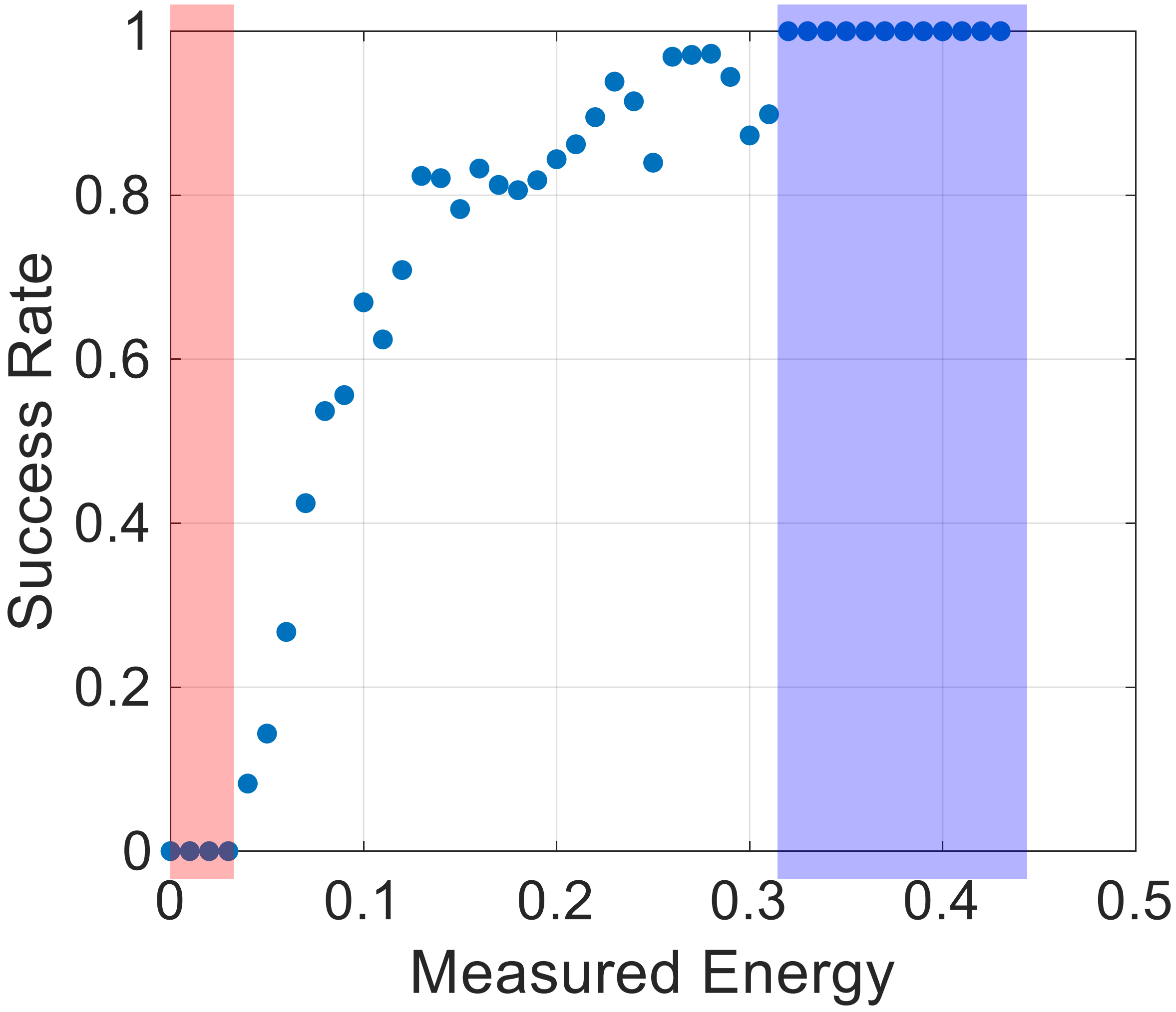

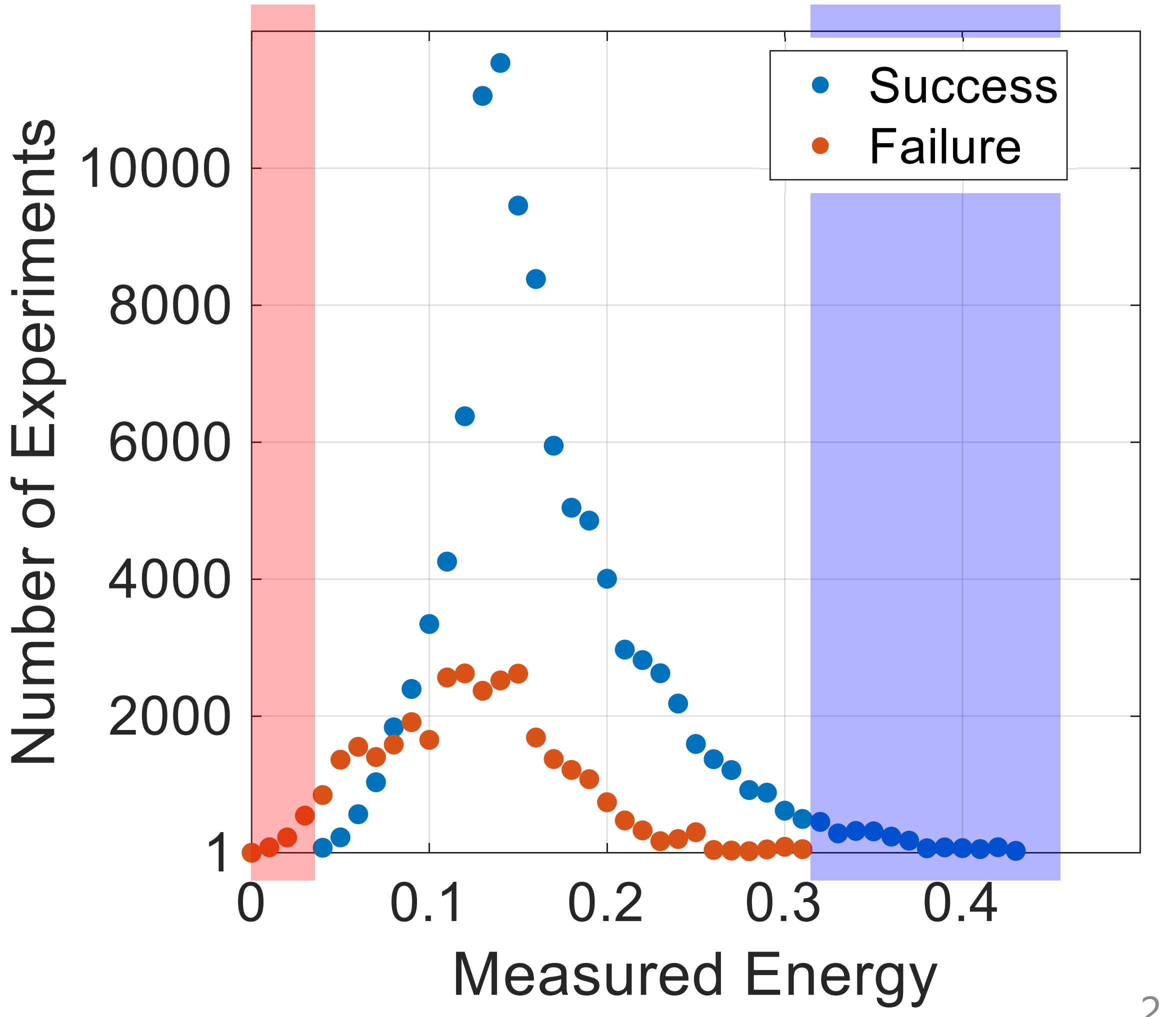

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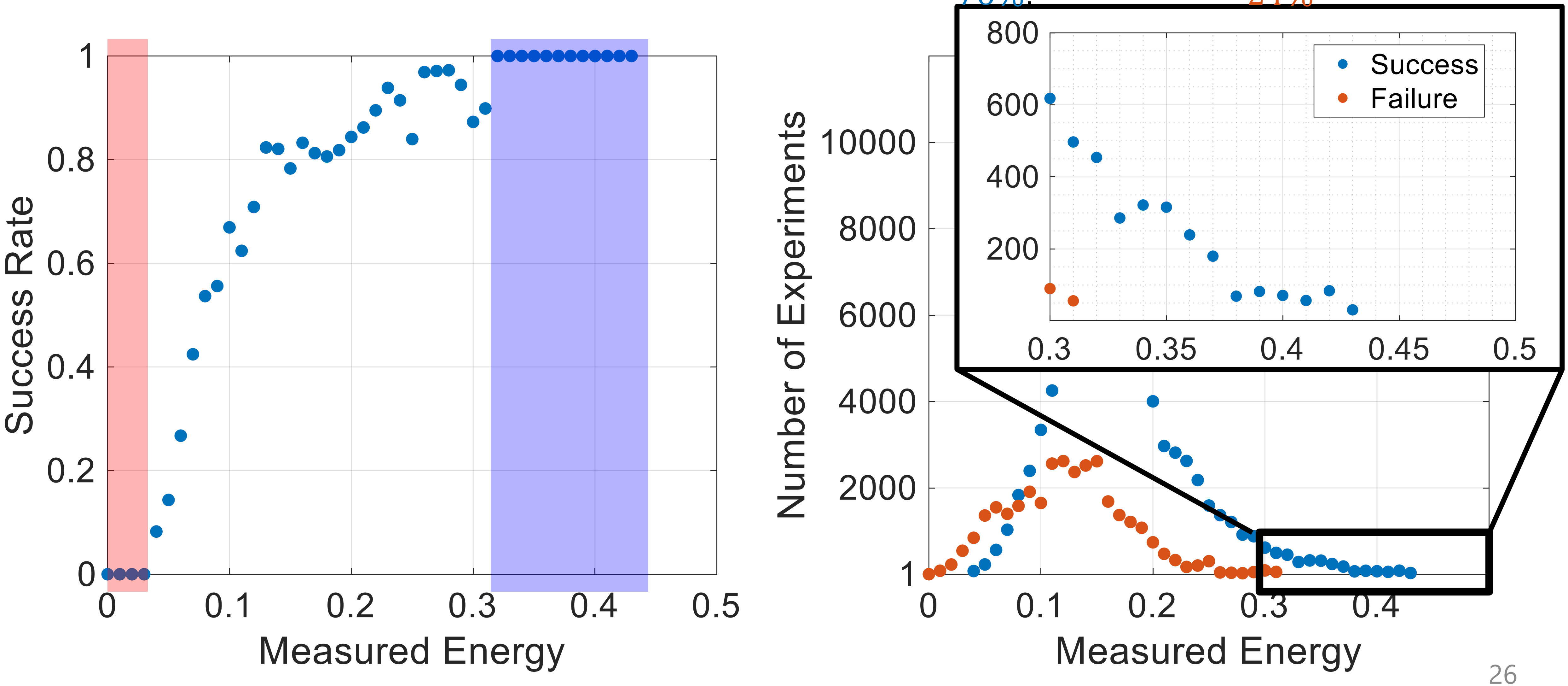
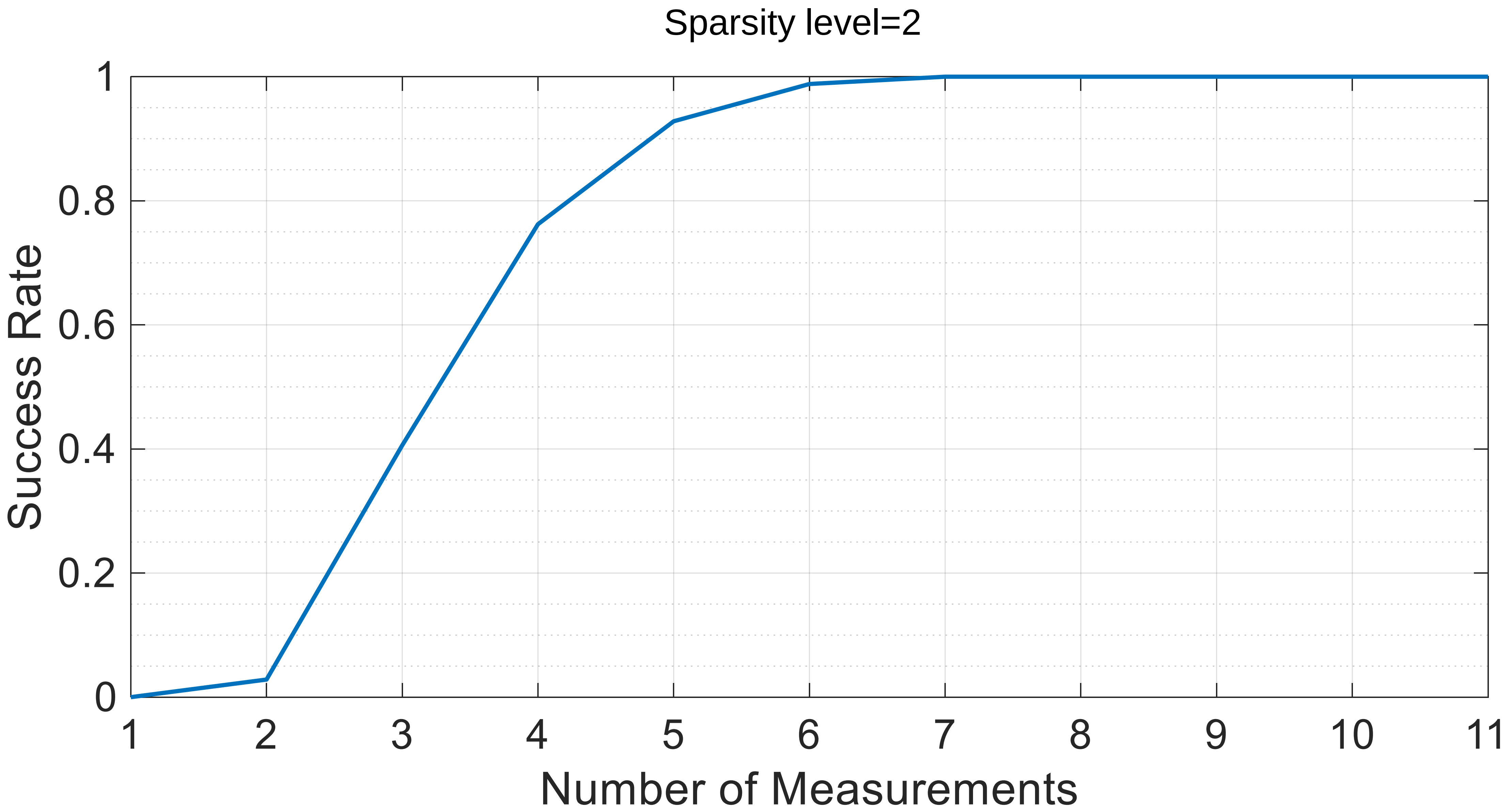


Experiment #3

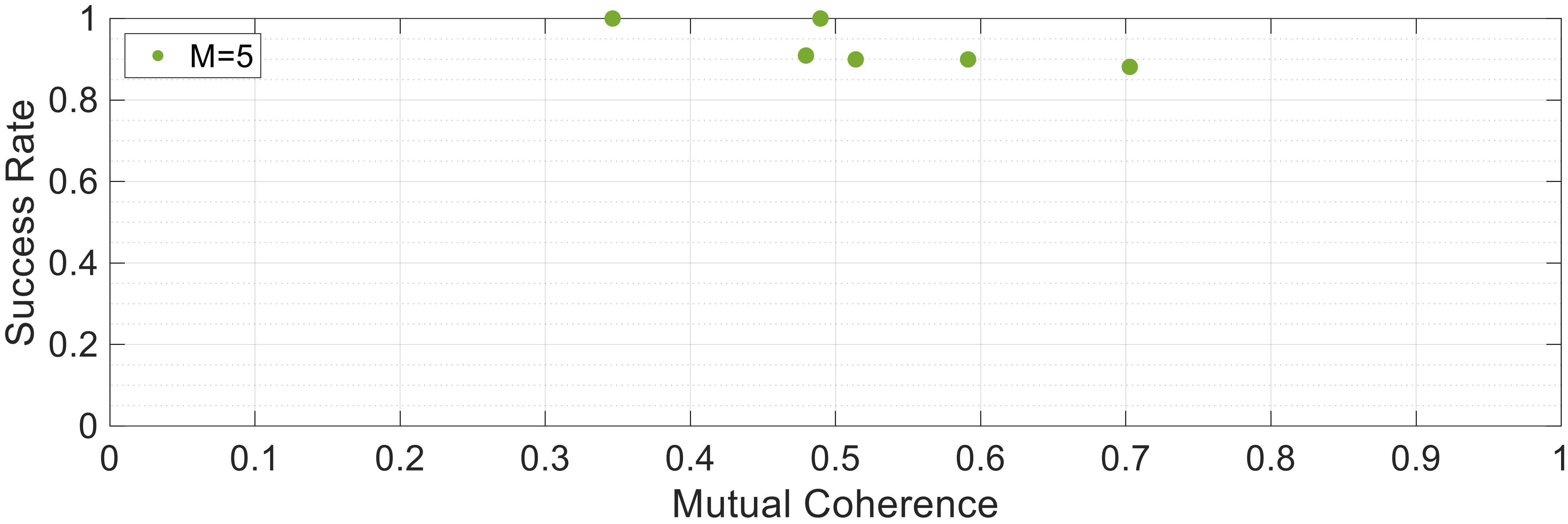
- Input:
  - Signal: 400 random signals, sparsity level=2
  - Transform: Fourier transform
  - Sampling M=1:10, N=11: $\binom{11}{1}, \binom{11}{2}, \binom{11}{3}, \binom{11}{4}, \binom{11}{5}, \binom{11}{6}, \binom{11}{7}, \binom{11}{8}, \binom{11}{9}, \binom{11}{10}$
  - Reconstruction algorithm: l1-minimization

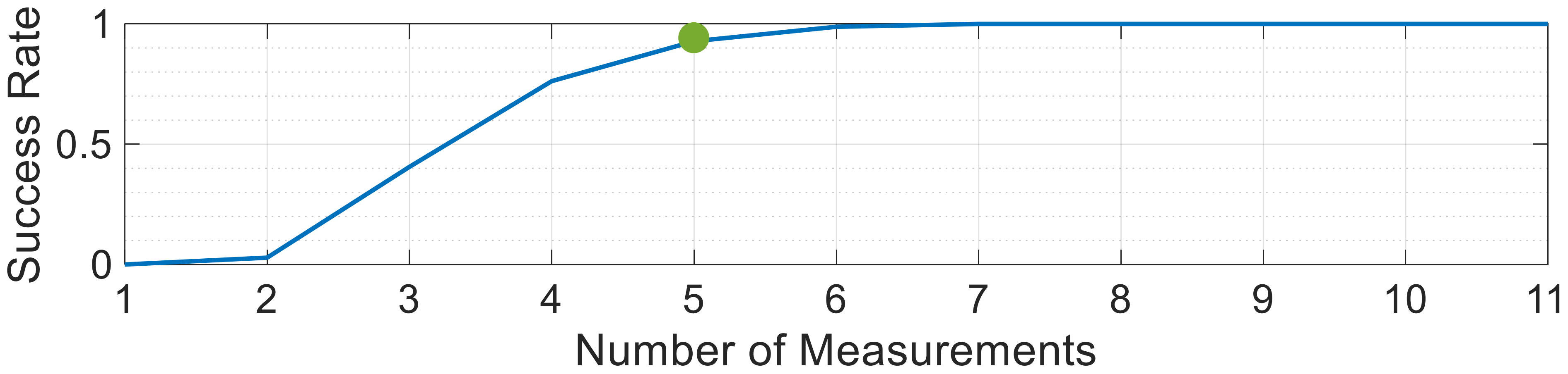
- Goal:
  - Find sampling schemes that provide successful reconstruction

#3: Minimum Number of Measurements

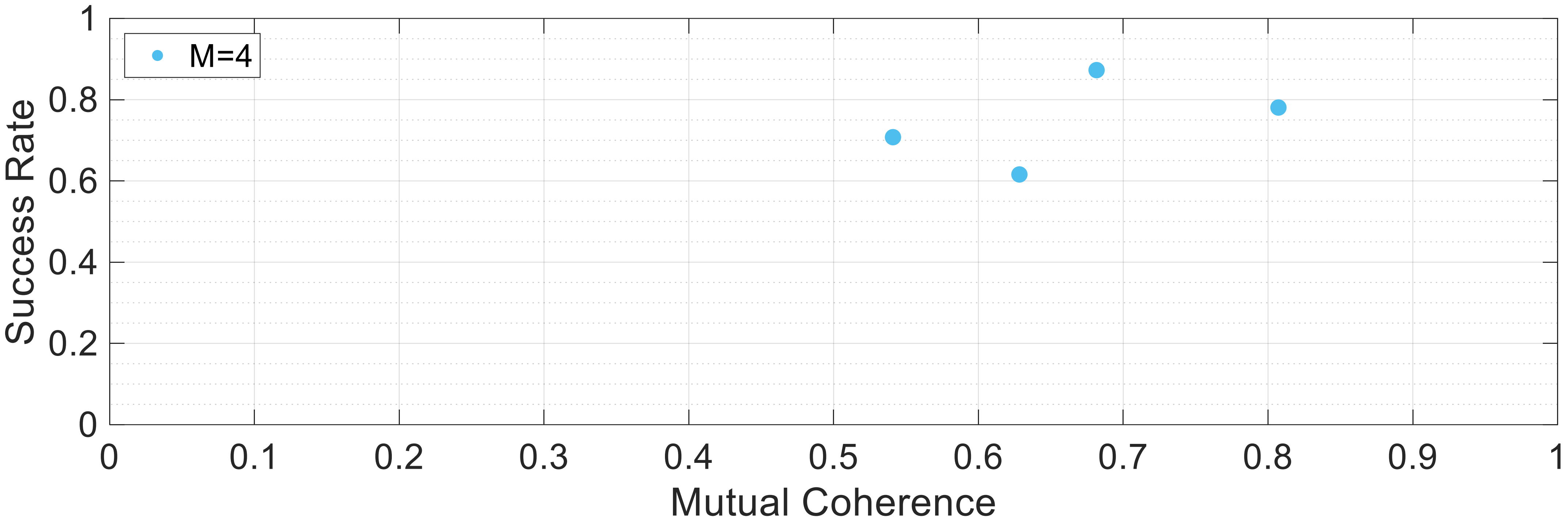


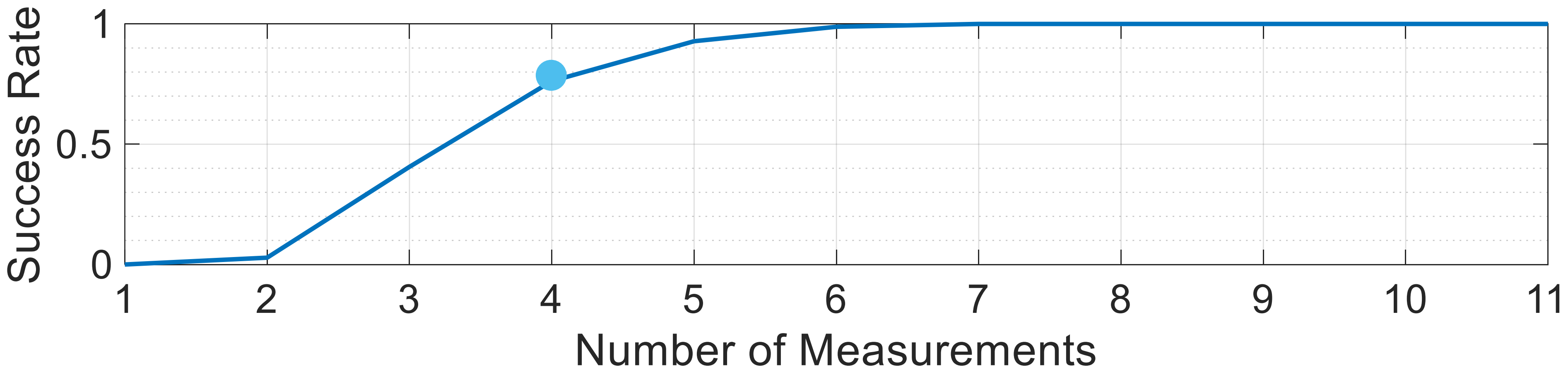
Success Rate versus Mutual Coherence



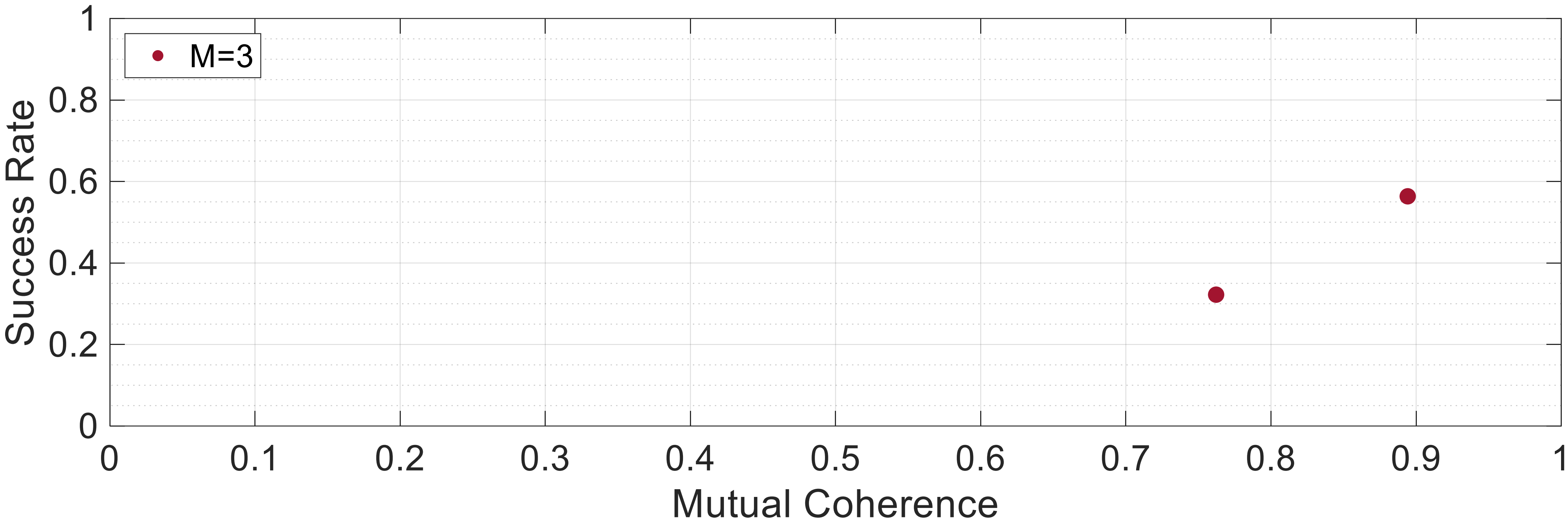


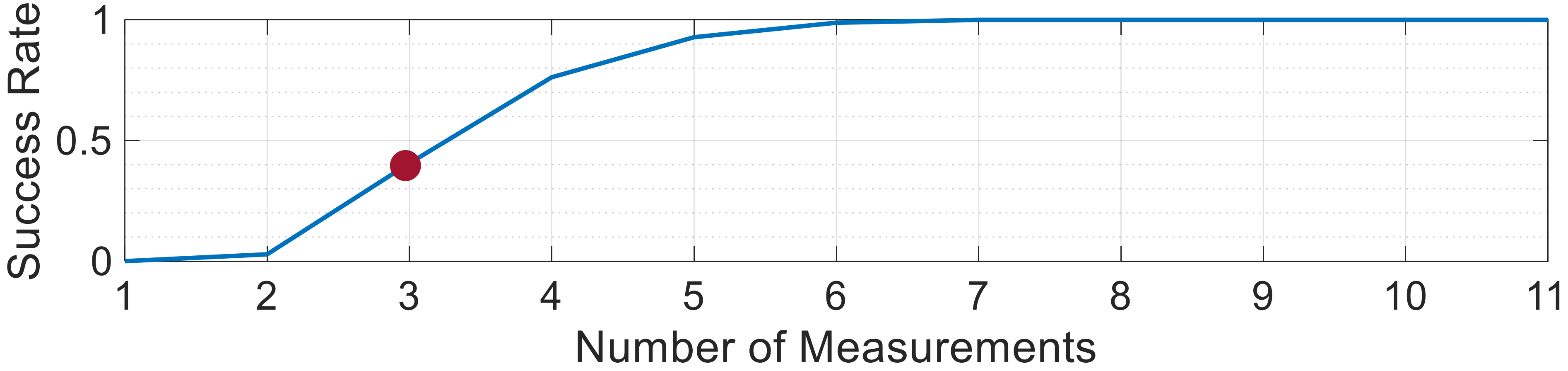
Success Rate versus Mutual Coherence



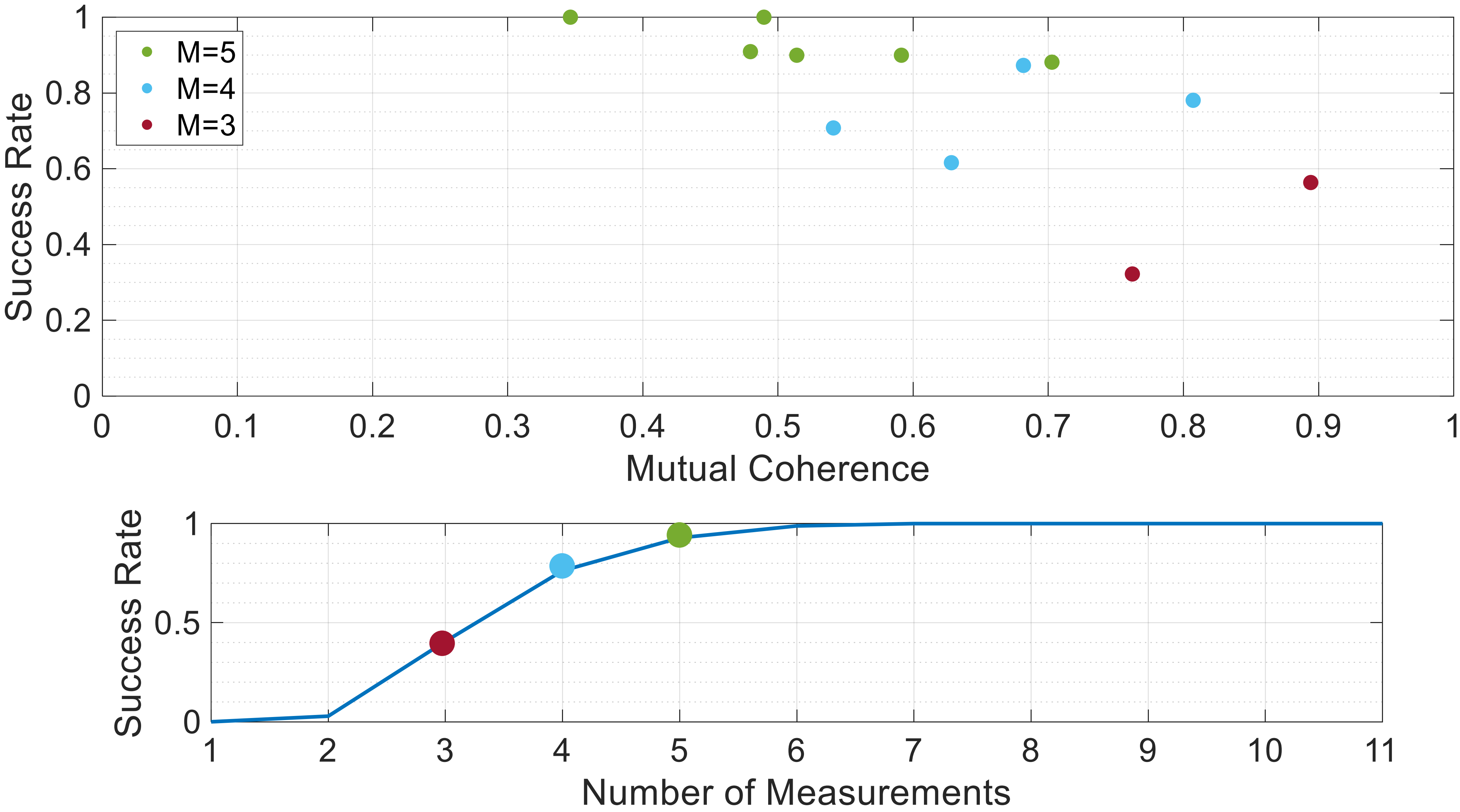


Success Rate versus Mutual Coherence

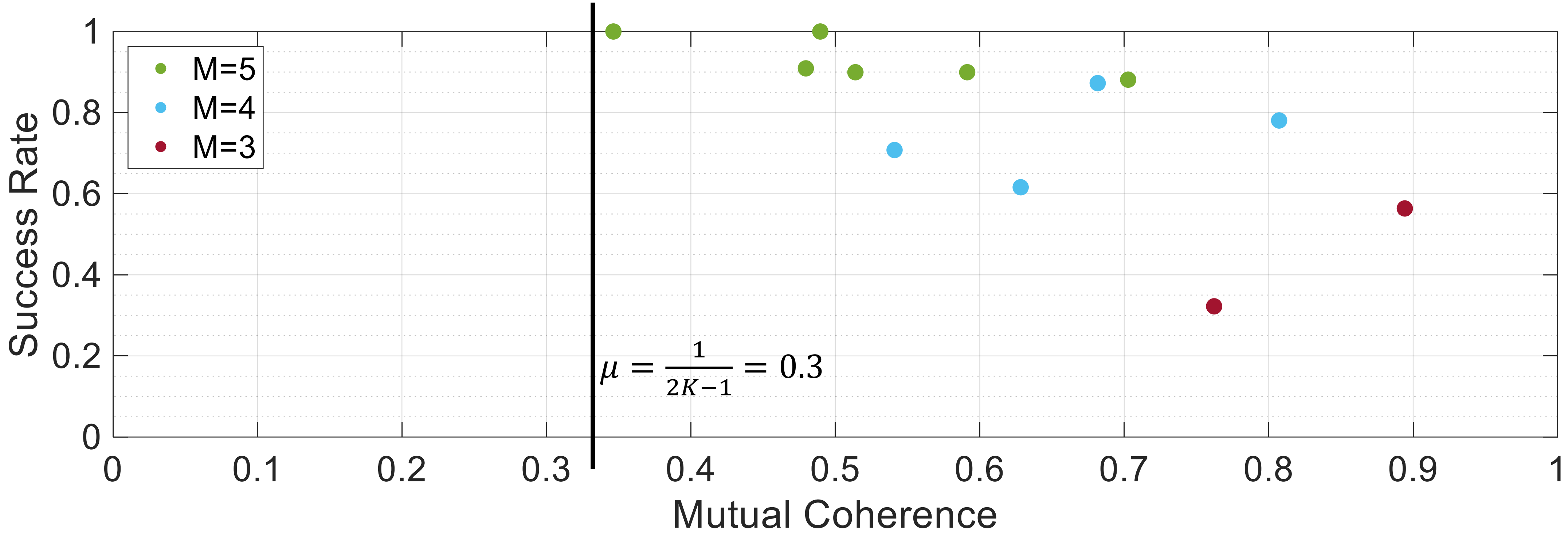


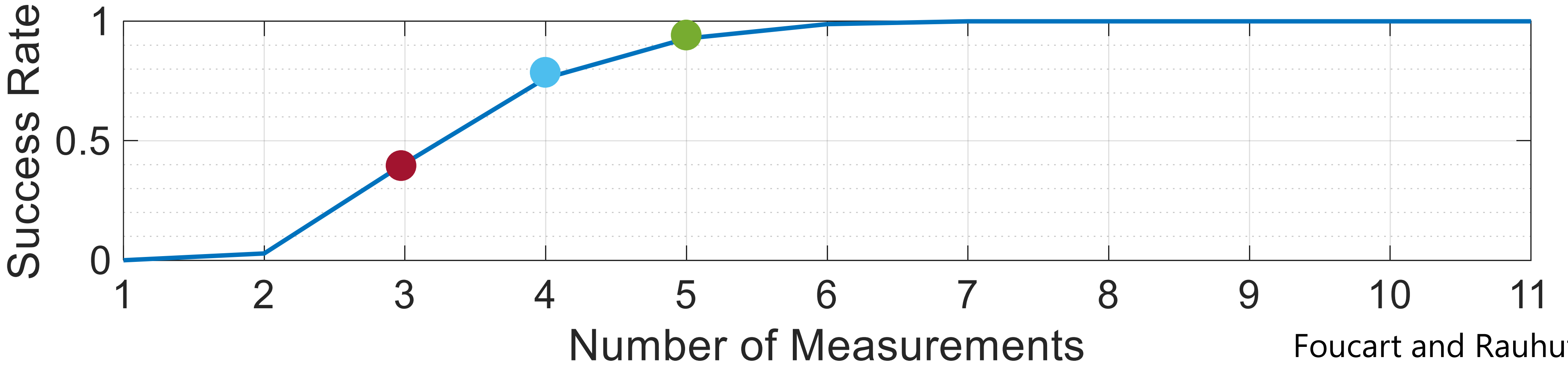


Success Rate versus Mutual Coherence



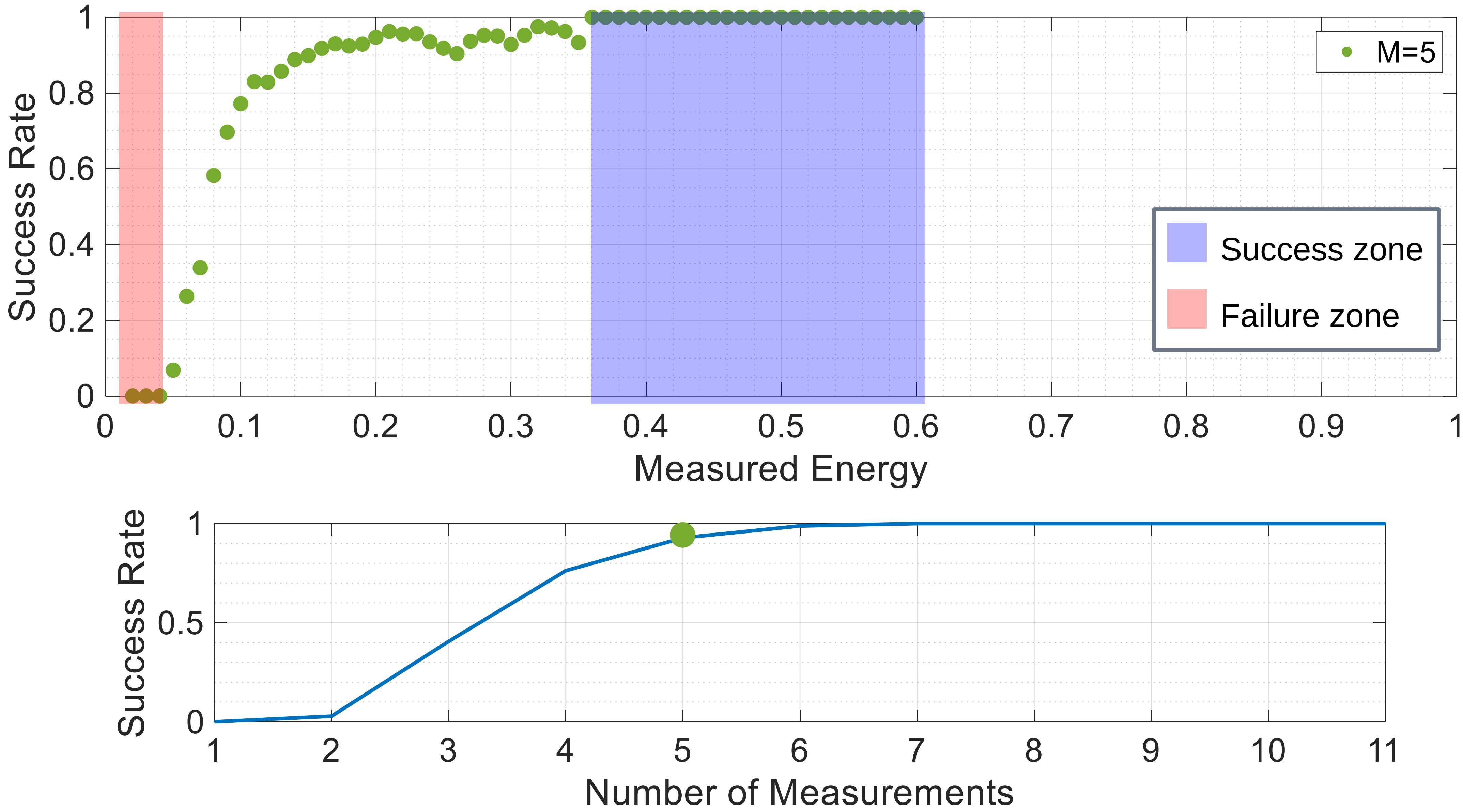
Success Rate versus Mutual Coherence



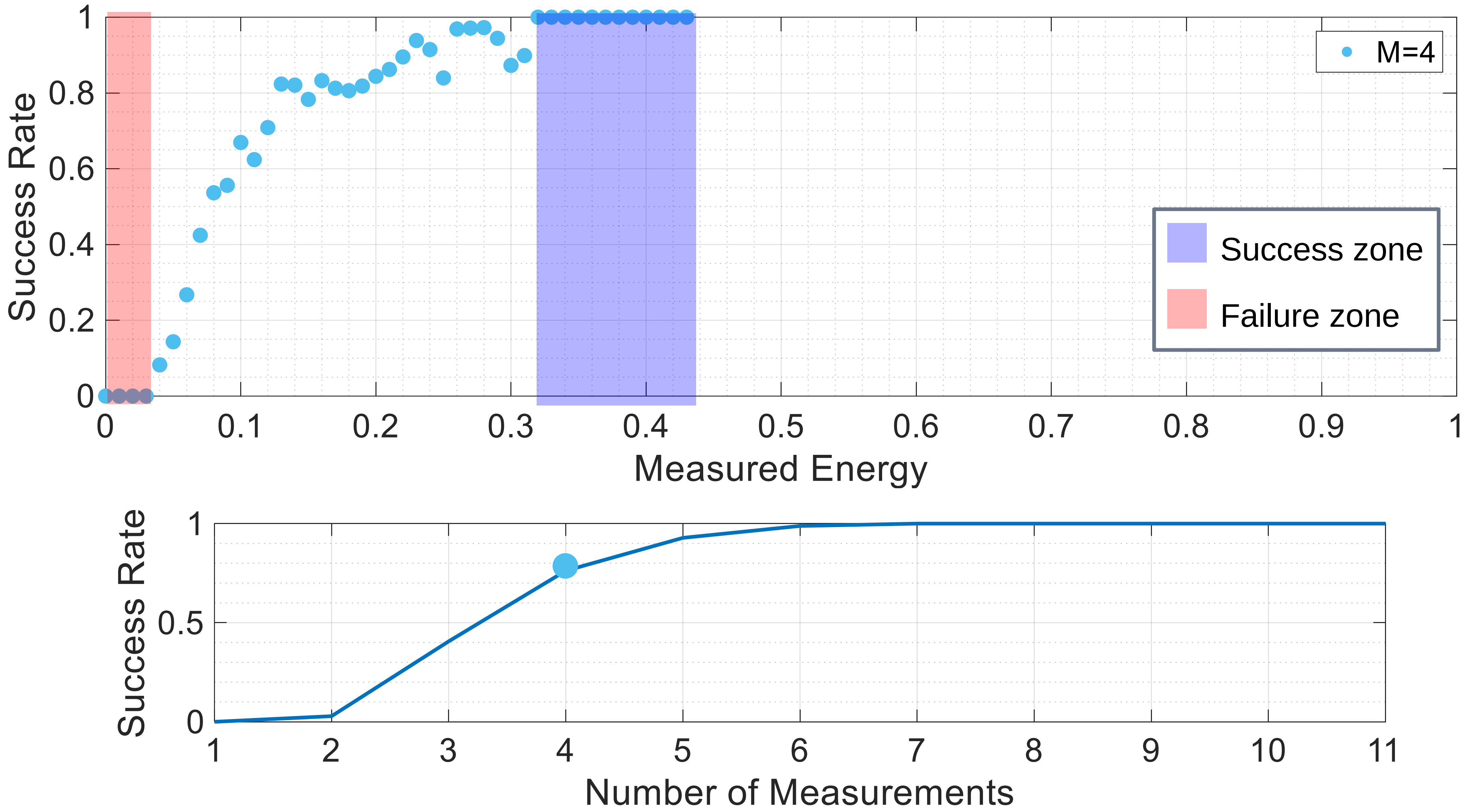


Foucart and Rauhut, 2013

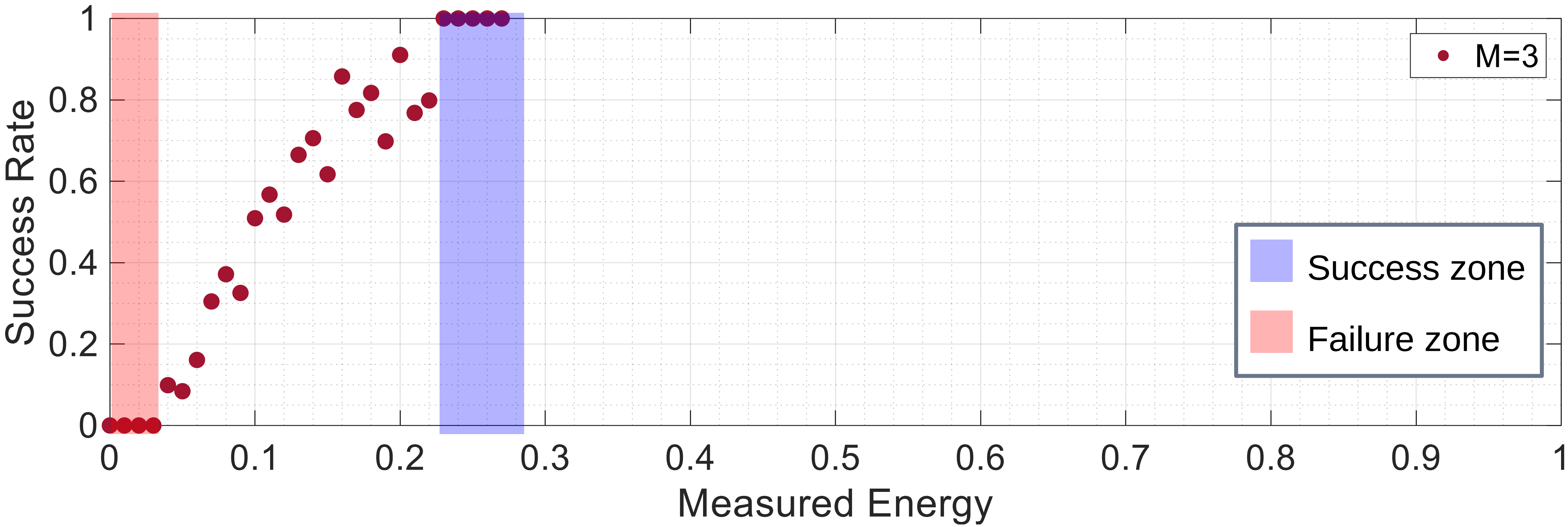
Success Rate versus Measured Energy

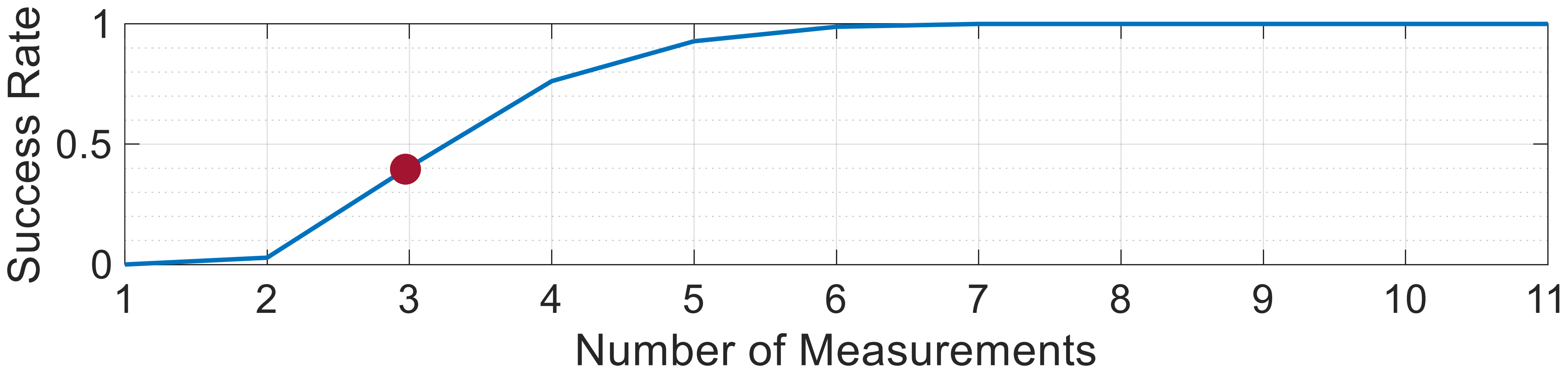


Success Rate versus Measured Energy

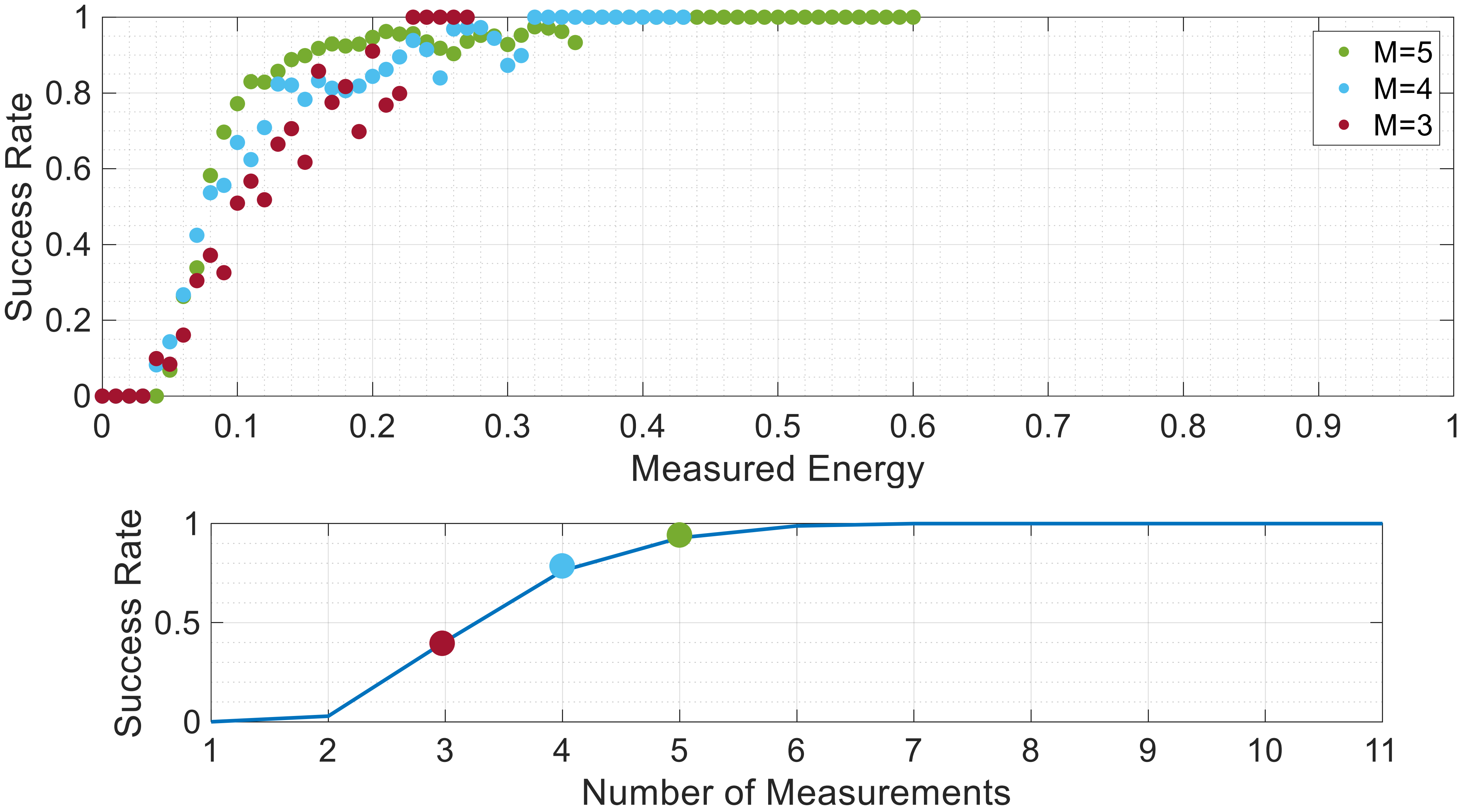


Success Rate versus Measured Energy





Success Rate versus Measured Energy



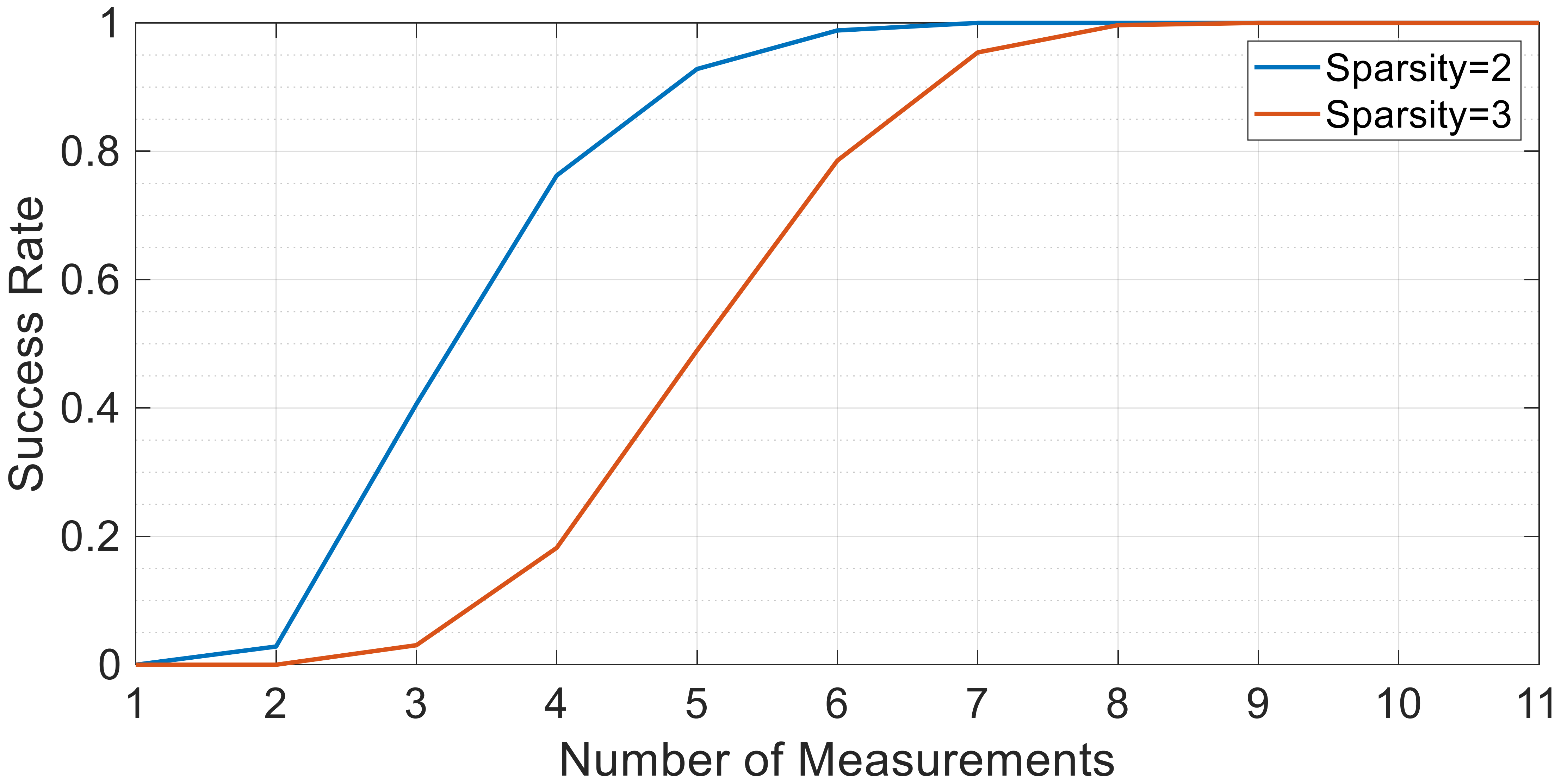
Experiment #4

RCP
In pursuit of new ideas

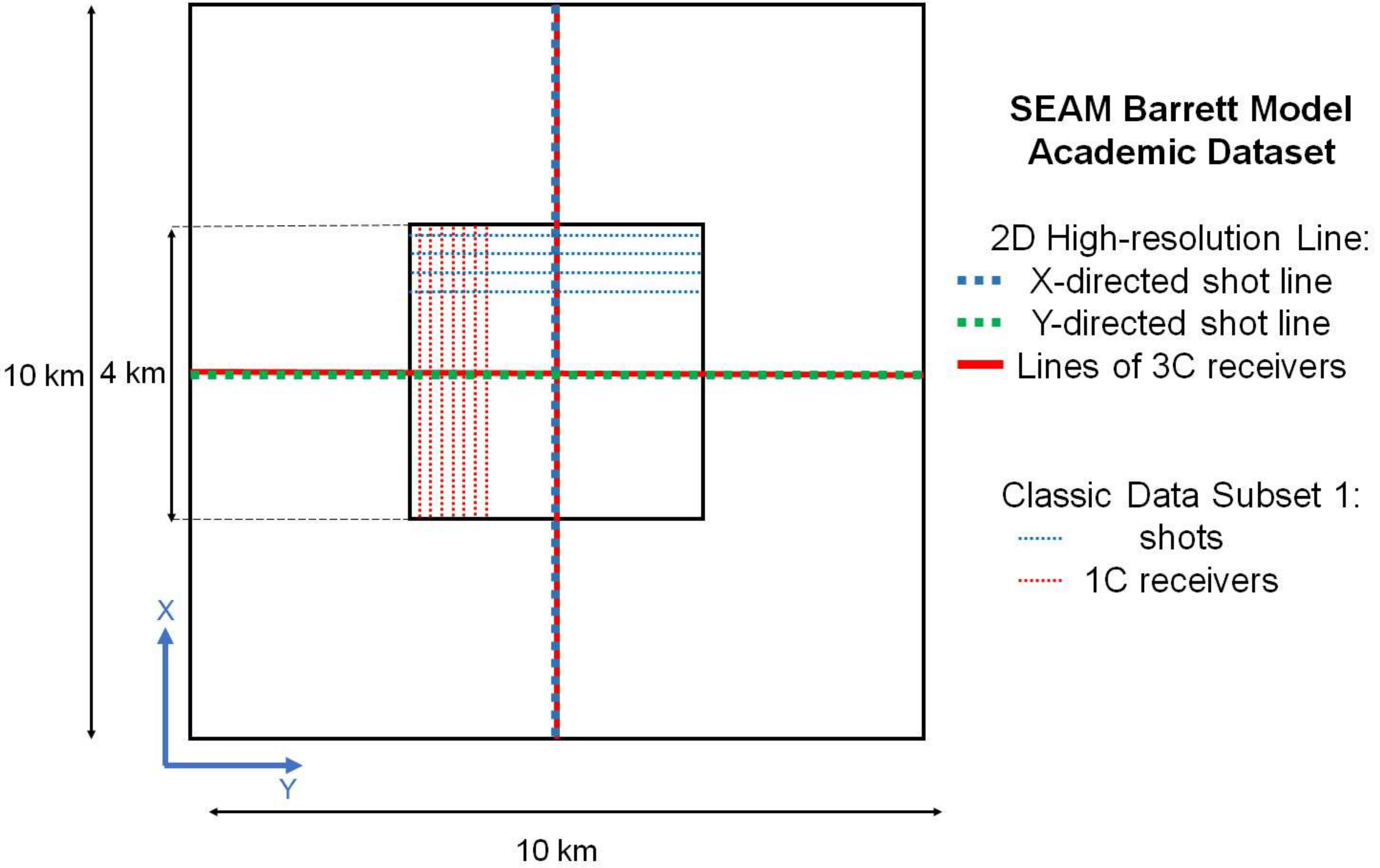
- Input:
  - Signal: 400 random signals, sparsity level=3
  - Transform: Fourier transform
  - Sampling M=1:10, N=11: $\binom{11}{1}, \binom{11}{2}, \binom{11}{3}, \binom{11}{4}, \binom{11}{5}, \binom{11}{6}, \binom{11}{7}, \binom{11}{8}, \binom{11}{9}, \binom{11}{10}$
  - Reconstruction algorithm: l1-minimization

- Goal:
  - Find sampling schemes that provide successful reconstruction

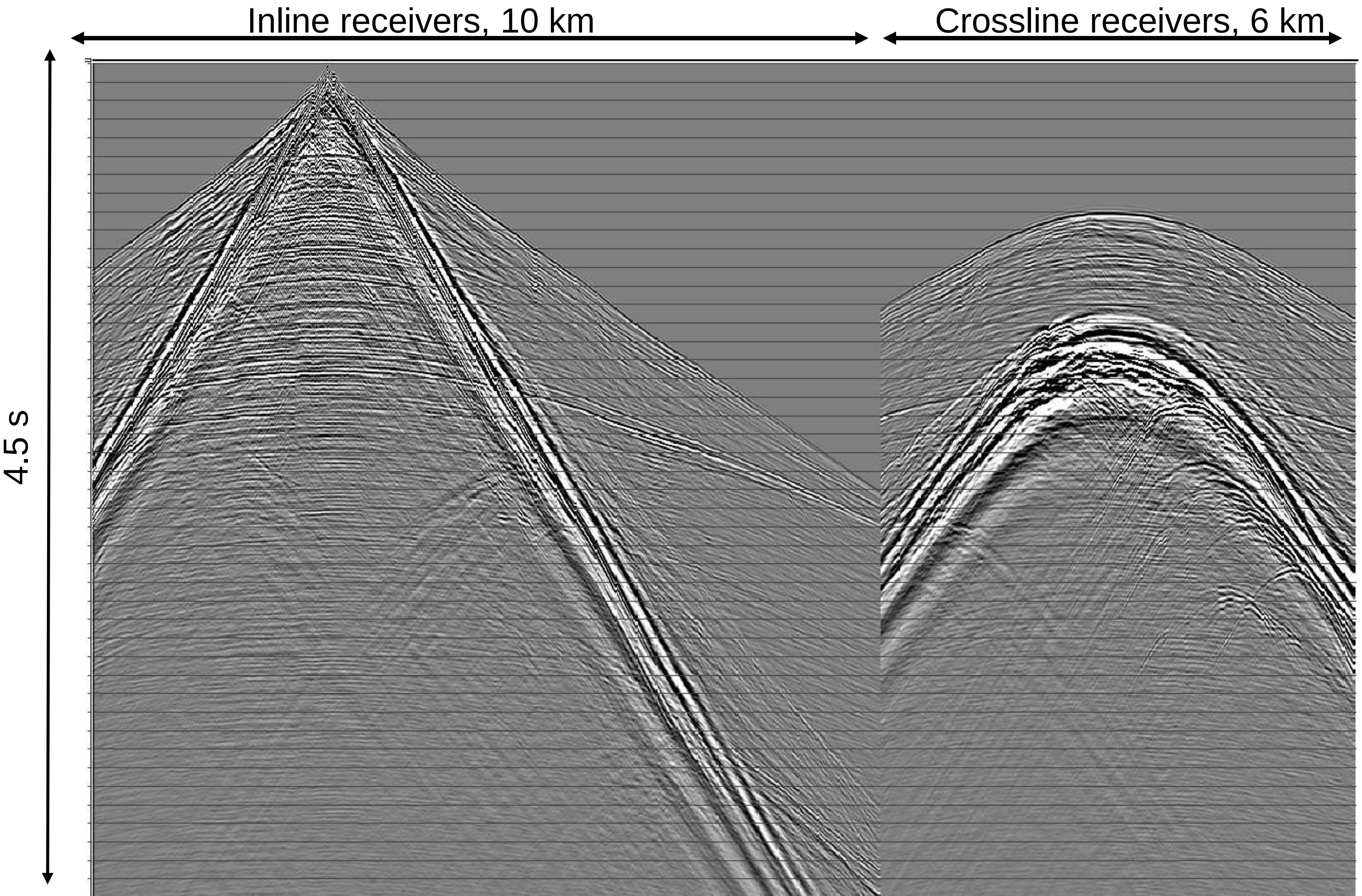
#4: Minimum Number of Measurements

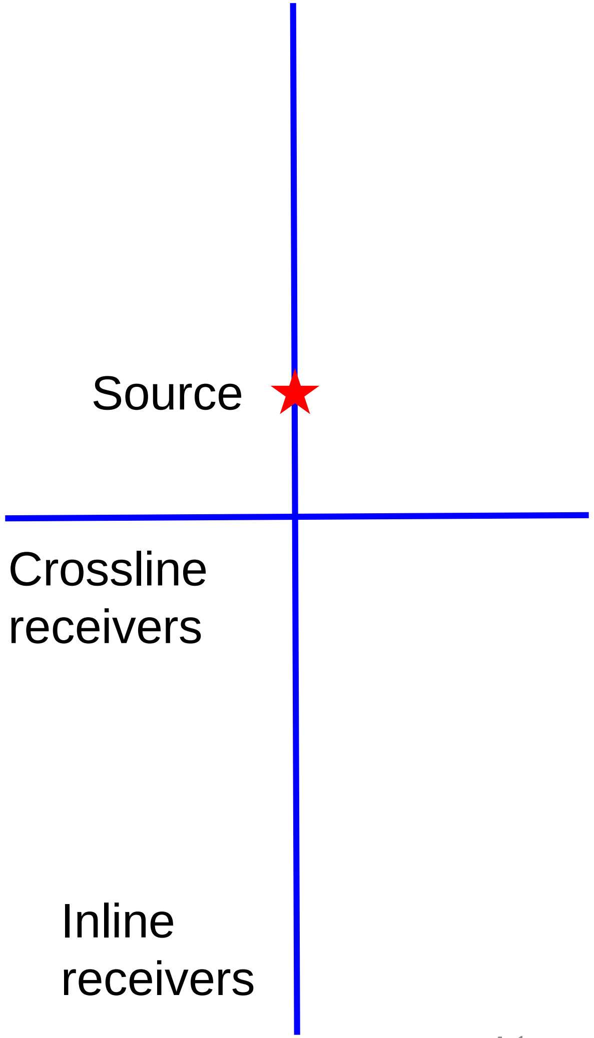


SEAM Barrett Model: Acquisition Geometry



SEAM Barrett Model: Shot Gather Example





Conclusions

- Mutual coherence is a crude way to predict the performance of sampling scheme

- Measured energy is able to differentiate between successful and failure sampling patterns

- Reconstruction results depend on the data and the sampling scheme

Future Work

- Test measured energy on approximately sparse signals
- Consider theoretical background for measured energy
- Adapt measured energy for seismic sampling design
- Explore other signal-blind sampling strategies
- Study noise influence on seismic data reconstruction

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Chevron
CIMAREX
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Minimum Number of Measurements

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