Implementation and Validation of Bubble Entropy for HRV Analysis

A comparative analysis against Sample Entropy

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Motivation: The Parameter Problem
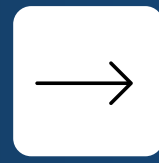
Sample Entropy relies on two parameters:

- m: Pattern Length
- r: Similarity Threshold

Problem: The r parameter makes results subjective and unstable.
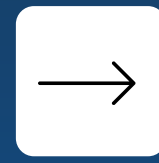
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Solution: Implement and Bubble Entropy to eliminate r and reduce the importance of m.
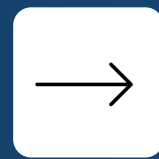
How Bubble Entropy Works

→ **Embedding**

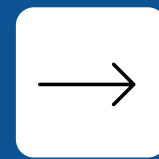The RR interval time series is broken into patterns.

→ **Distribution**
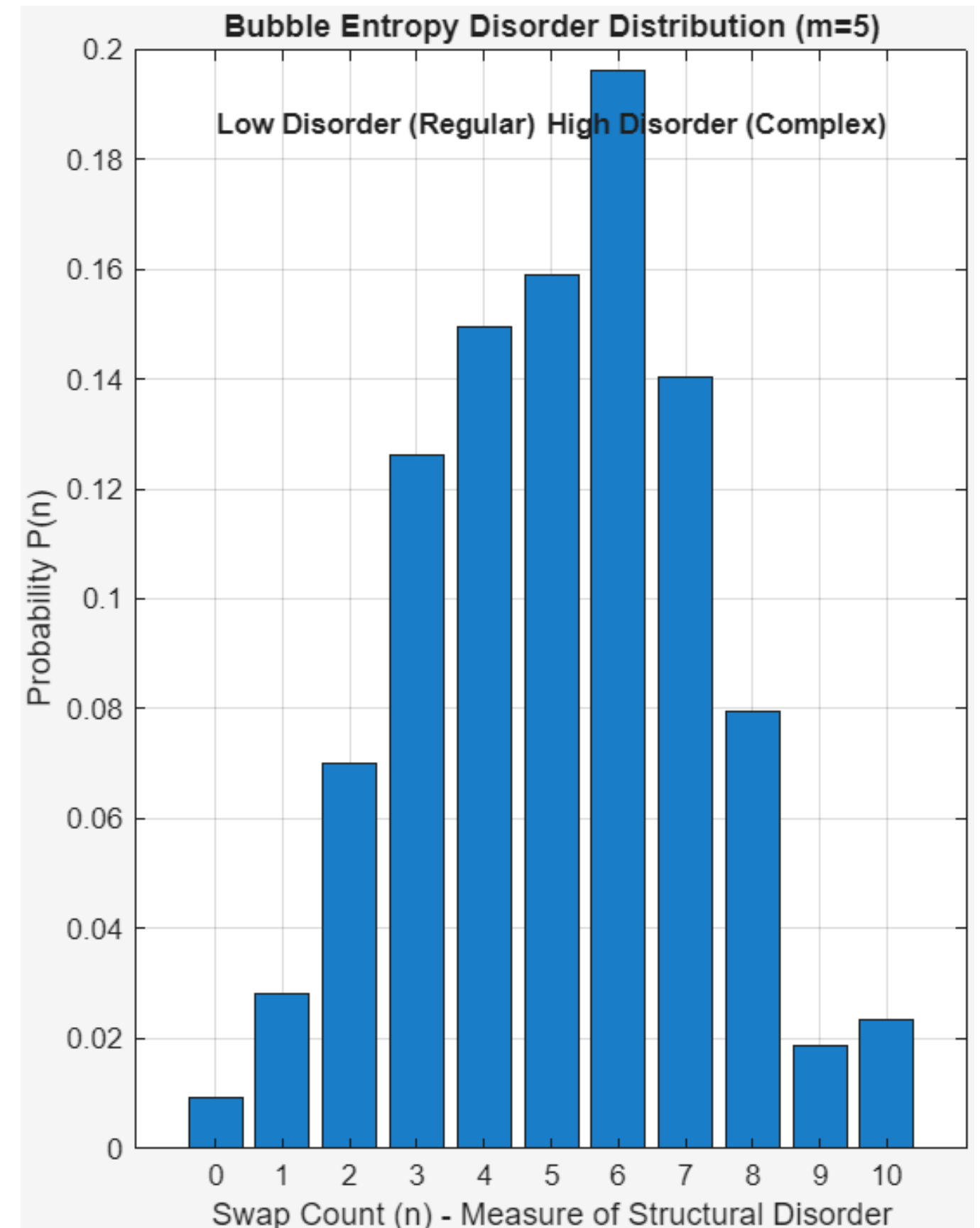
Scores are compiled into a probability distribution.

→ **Swap Count**

For each pattern, we measure its disorder using Bubble Sort.

→ **Calculate Entropy**

$$bEn = (H_2^{m+1} - H_2^m)/log(\frac{m+1}{m-1})$$

Bubble Entropy Disorder Distribution (m=5)

Low Disorder (Regular)   High Disorder (Complex)

Probability P(n)

Swap Count (n) - Measure of Structural Disorder

Experimental Setup

→ **Data Source**: PhysioNet
  - **Normal Sinus Rhythm** (NSR) - Records: 31
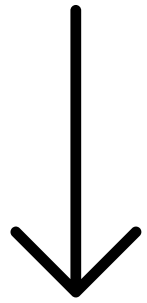 - **Congestive Heart Failure** (CHF) - Records: 27

→ **Analysis**:
  - **BEn** tested across m = 3 to 15.
  - **SampEn** tested at standard m=2, r=0.2.
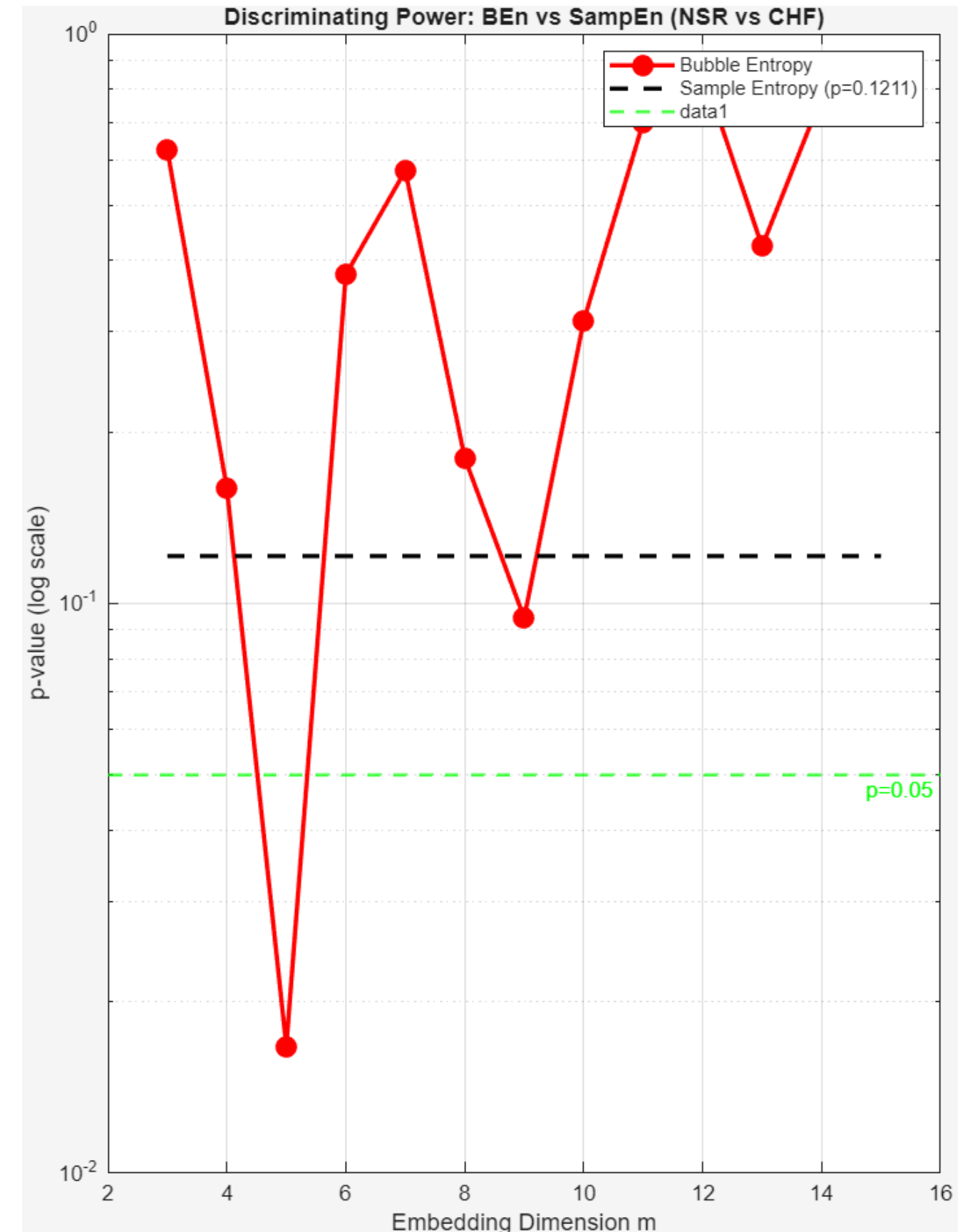 - **Performance Metric**: t-test (p-value).

→ **Biological Rationale**: Healthy hearts exhibit high entropy (adaptability), while pathological states lead to rigid, predictable patterns (low entropy).

Result 1: Superior Discrimination

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BEn (Red Line): Achieves statistical significance at m=5.

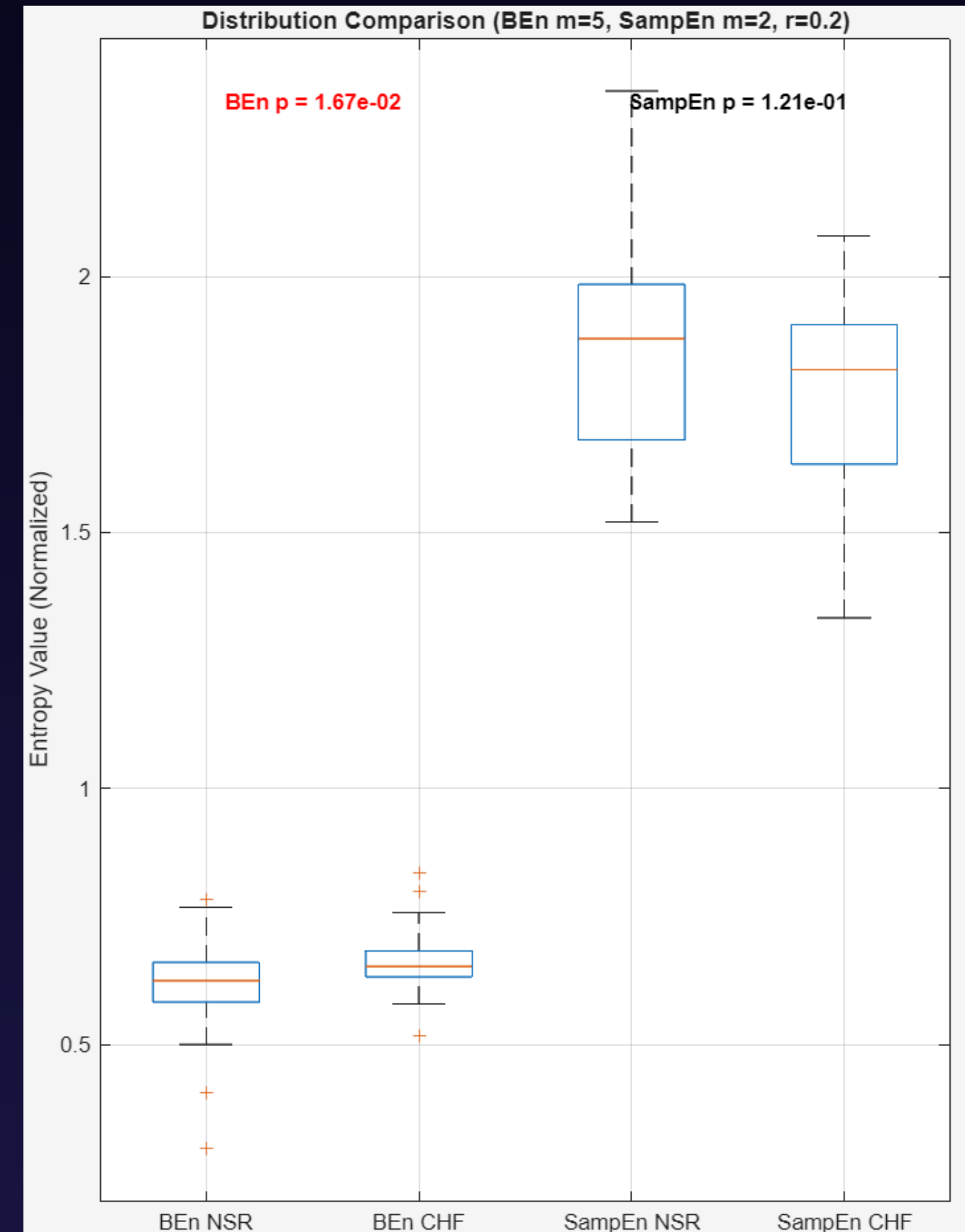**SampEn** (Black Line): Fails to achieve significance.
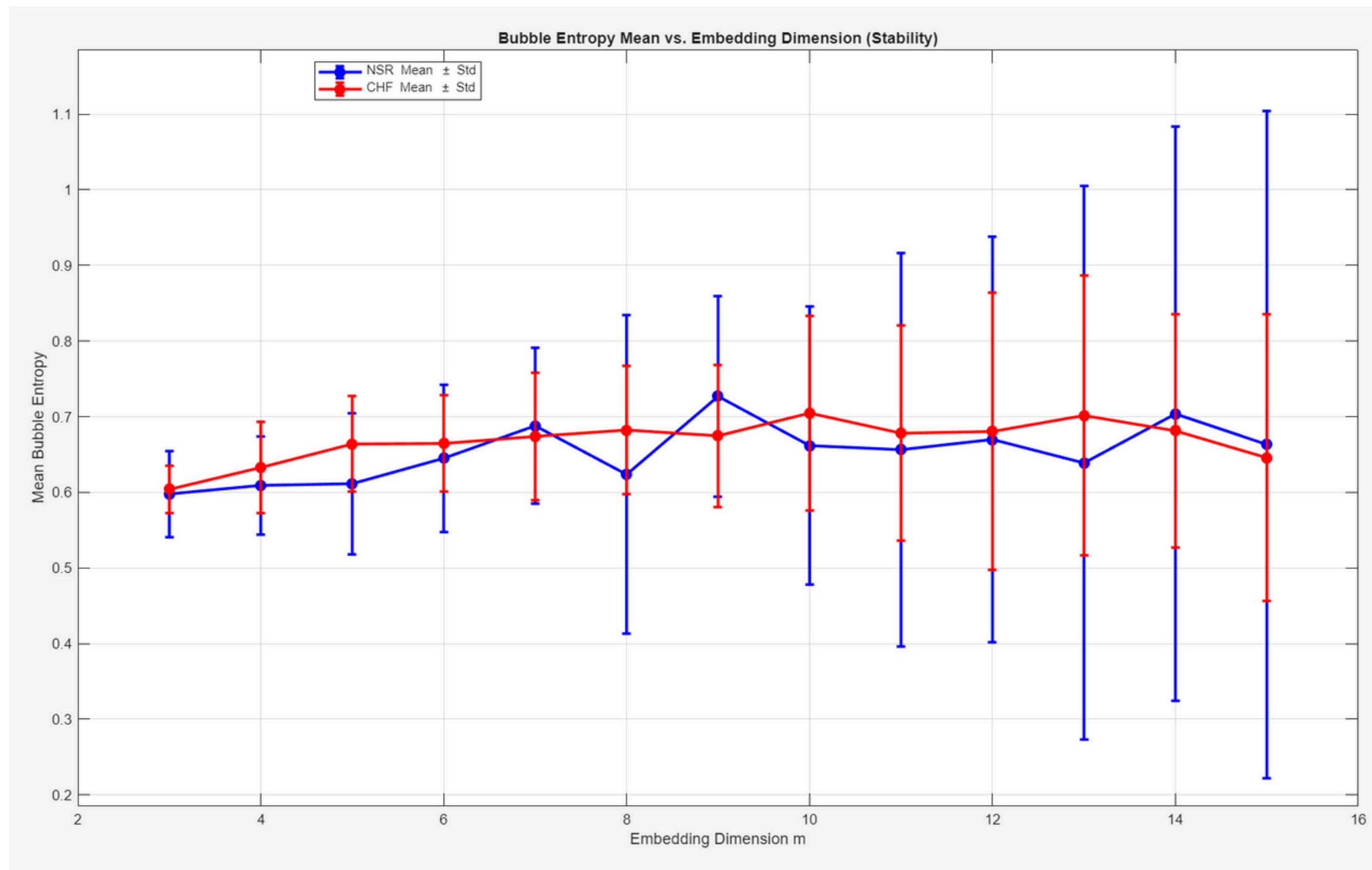
Result 1: Superior Discrimination

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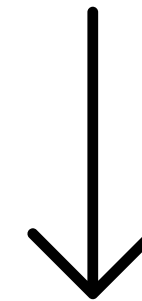**BEn**: The boxplots show visual separation.

SampEn: The boxplots show high overlap.

Distribution Comparison (BEn m=5, SampEn m=2, r=0.2)

BEn p = 1.67e-02   SampEn p = 1.21e-01

Result 2: Parameter Stability

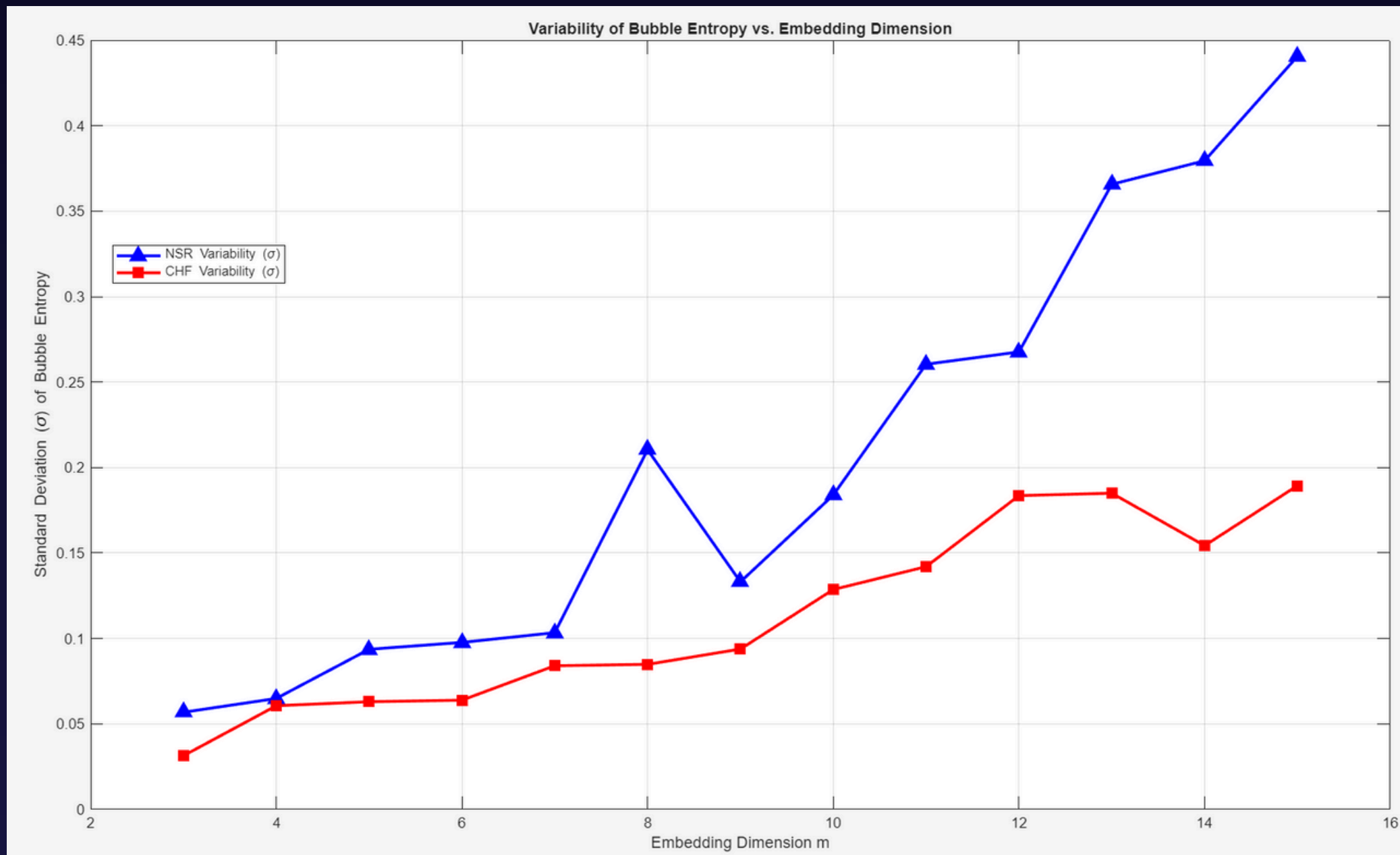Bubble Entropy Mean vs. Embedding Dimension (Stability)

The mean entropy values are stable across the m range.

The choice of m is not critical.

Note: increased variance due to short time-series length.

Result 2: Parameter Stability

The standard deviation increases as *m* grows.

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Despite this, variability of the CHF group is lower than the NSR group.

Clinical Advantage: BEn eliminates the need for the threshold parameter (r), making it ideal for Real-time Remote Patient Monitoring where signal noise and baseline shifts are common.

Future Work: Scaling the analysis to longer time-series recordings to mitigate the observed variance at higher embedding dimensions (m).

Conclusions

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