

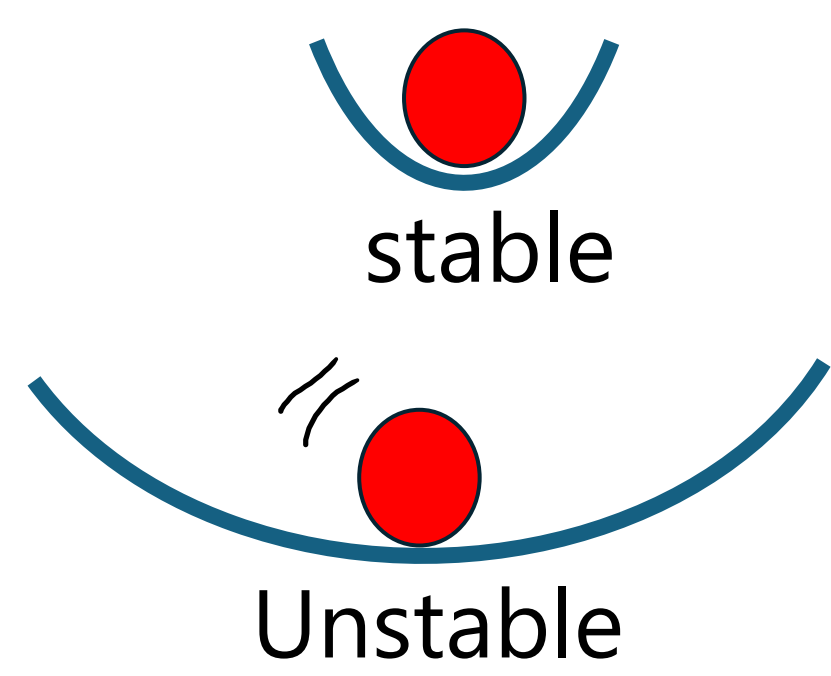
Data-driven Sequential Analysis of Tipping in High-dimensional Complex Systems

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Background and Challenges

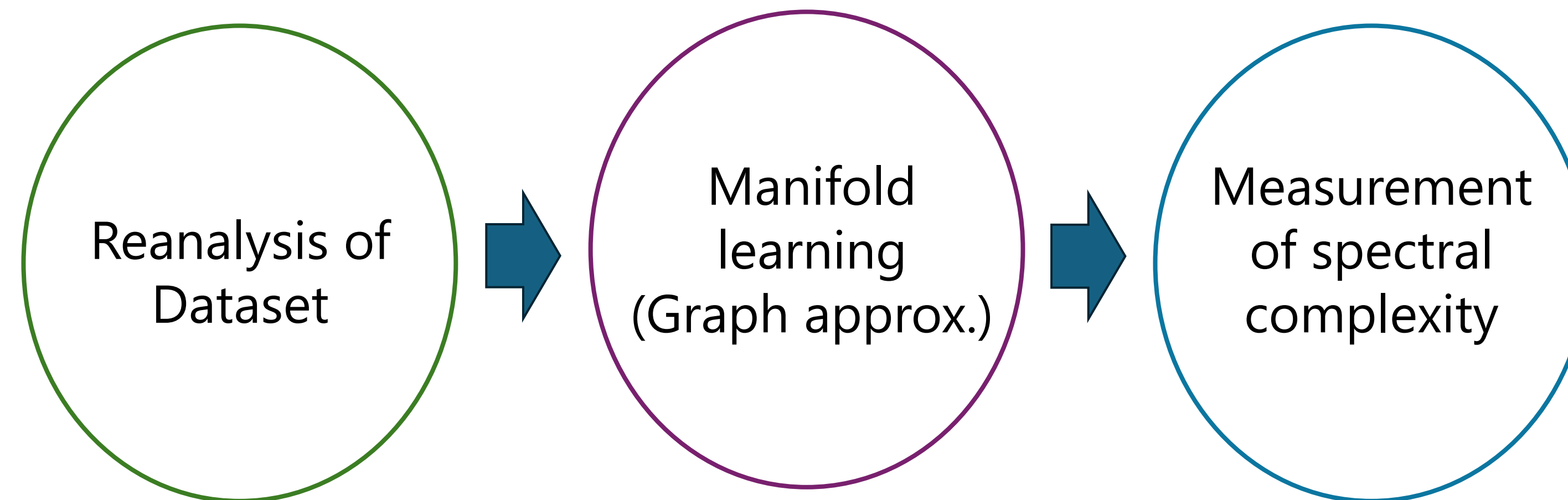
Early Warning Signal (EWS)/Tipping analysis
 Critical Slow Down (CSD) based EWS
 vs Different mechanisms of tipping
 vs High-dimensional systems
 Machine learning based analysis
 vs Noisy data
 vs Need of tipping "dataset"



⇒ Data-driven robust white-box tipping analysis method applicable to high-dimensional noisy dataset?

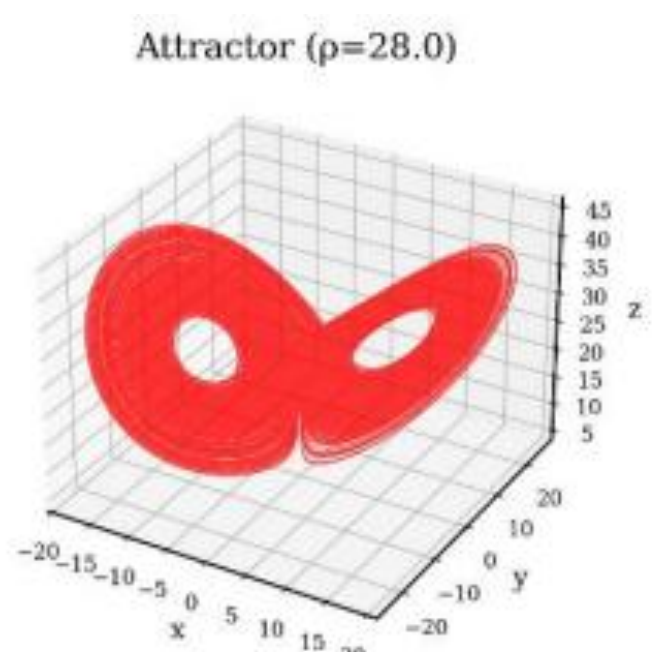
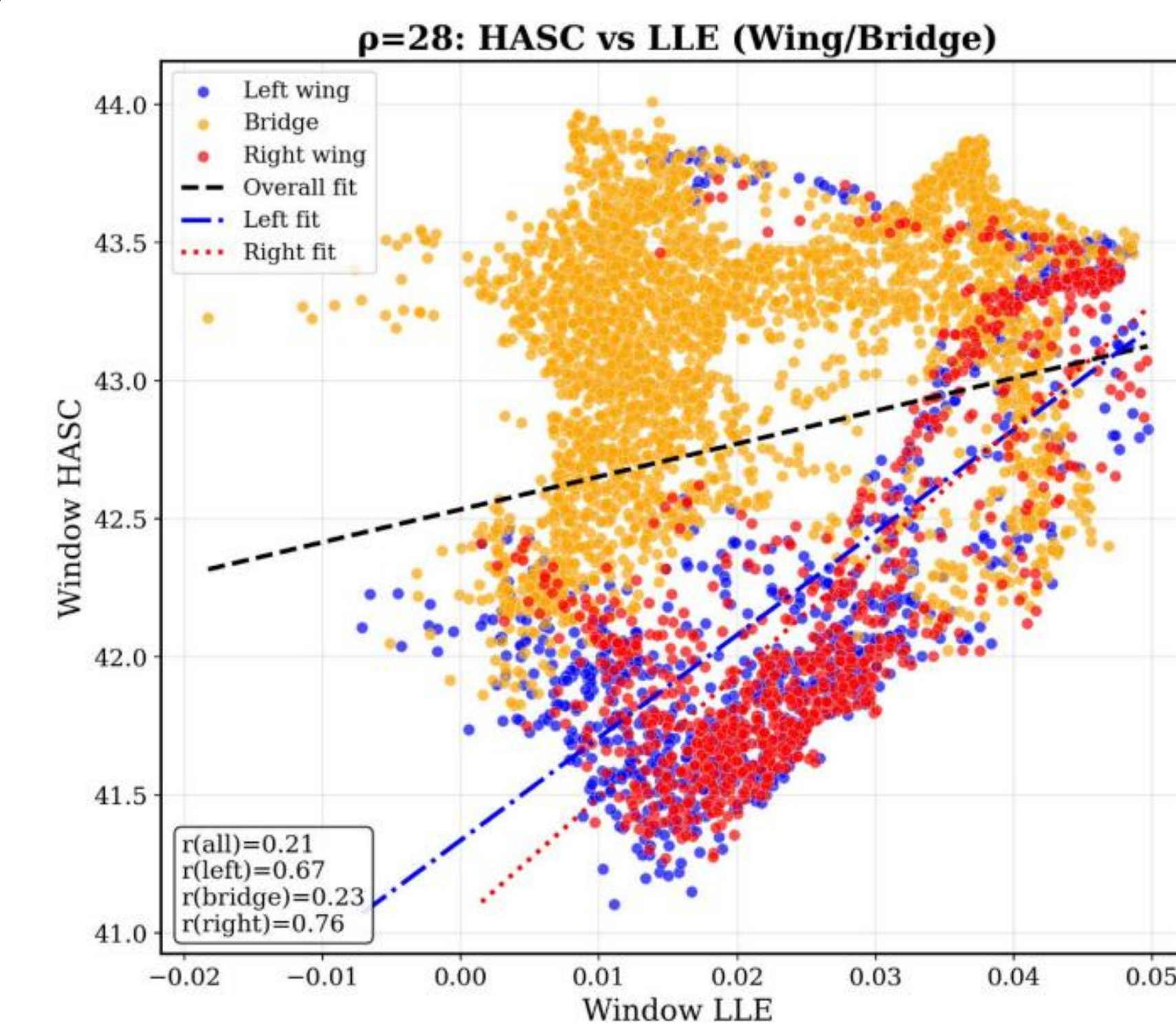
Proposed framework

DA-HASC
 (High-dimensional Attractor's Structural Complexity)



- Combination of data scientific, geometric, spectral approach
- No arbitrary dimension reduction
- Spectral complexity \approx Graph complexity \approx Structural complexity

What complexity does it measure?

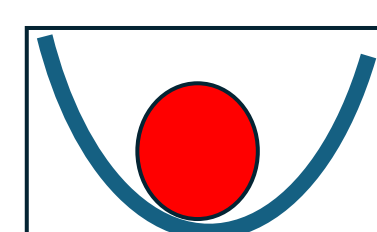


Quasi-stable regime
 HASC \approx Instantaneous LLE
 Unstable regime
 HASC is consistently high

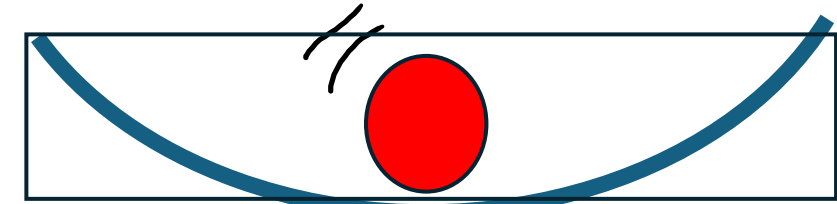
Complexity is "how mixed the dynamics is"

Applying HASC to Tipping analysis

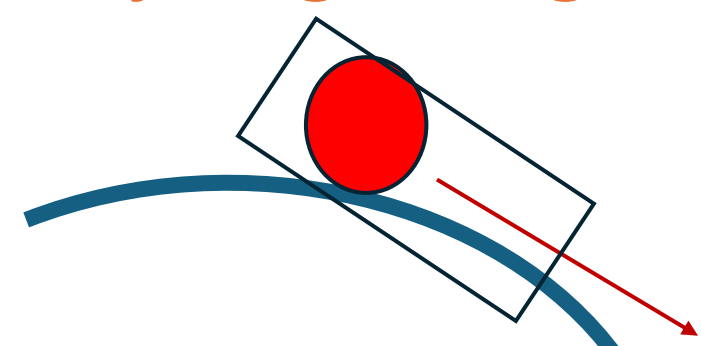
Calculating HASC on Running time-series windows



Stable regime = Strong confinement to dynamics
 ⇒ Structural complexity is relatively simple



Unstable regime = Confinement gets weaker
 ⇒ Structural complexity is getting complex

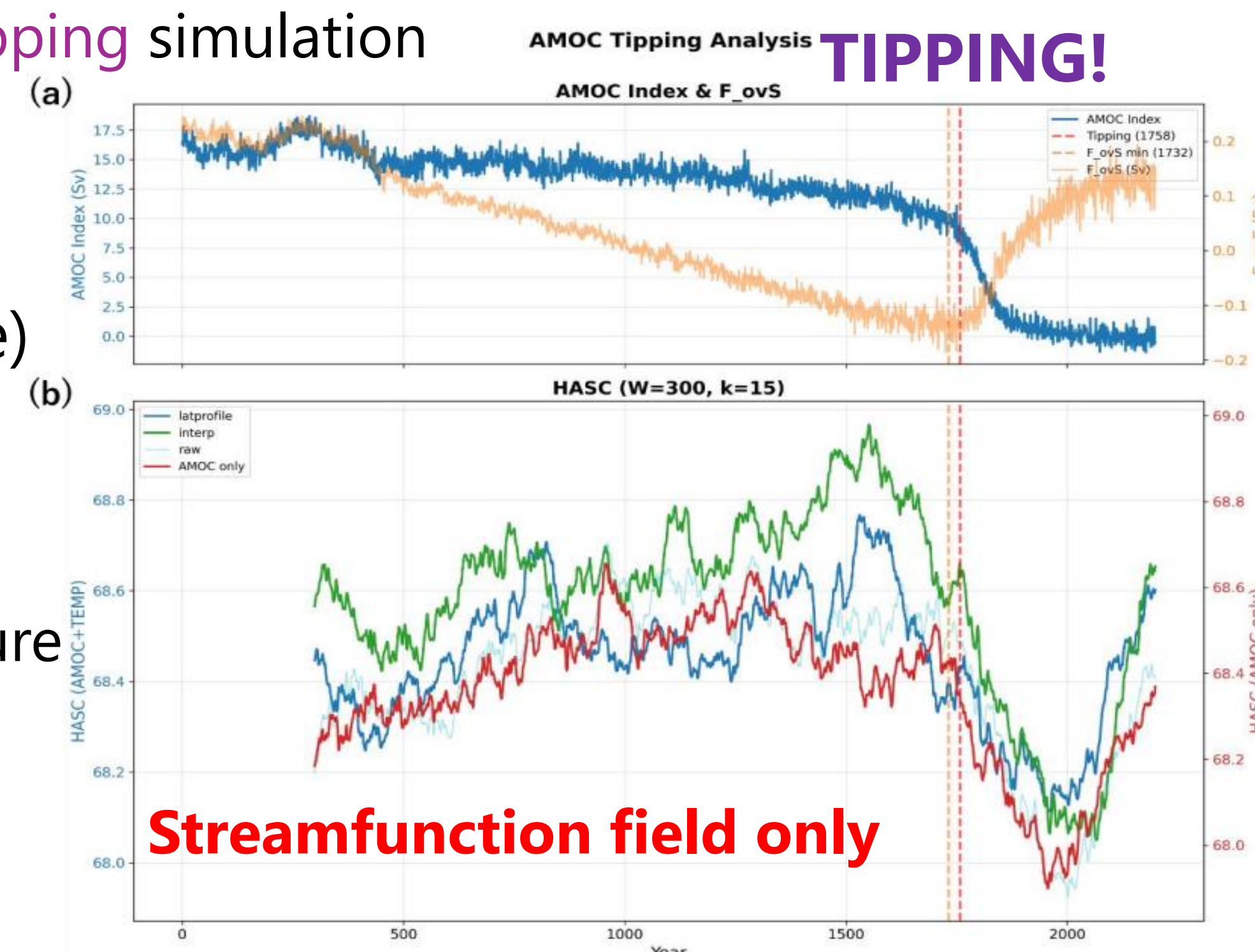


Transition regime = Very strong confinement to transition
 ⇒ Structural complexity is the simplest

Application to high-dimensional system

• Analysis of data from van Westen et al. (2024)

Earth-scale AMOC tipping simulation
 Hosing experiment

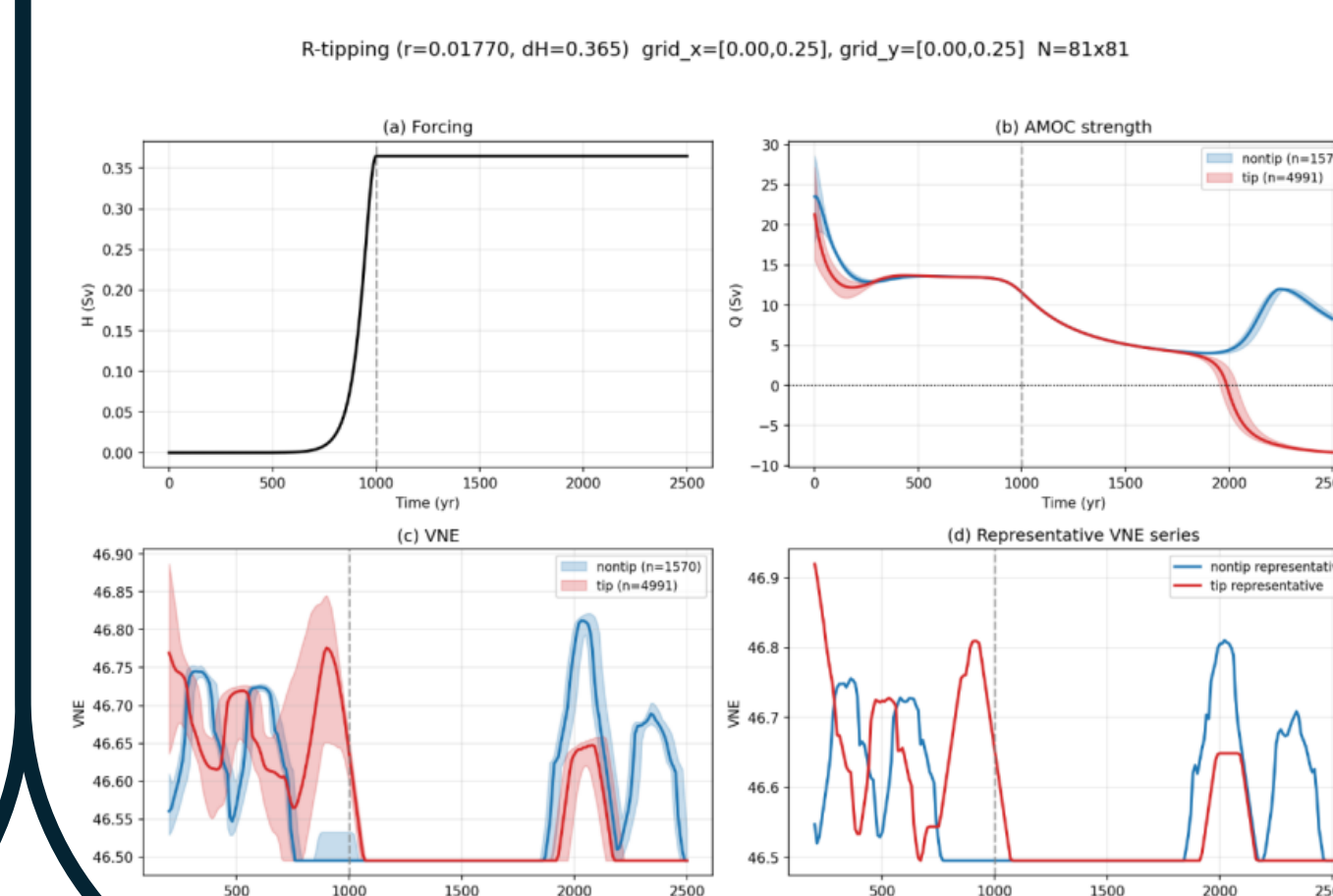
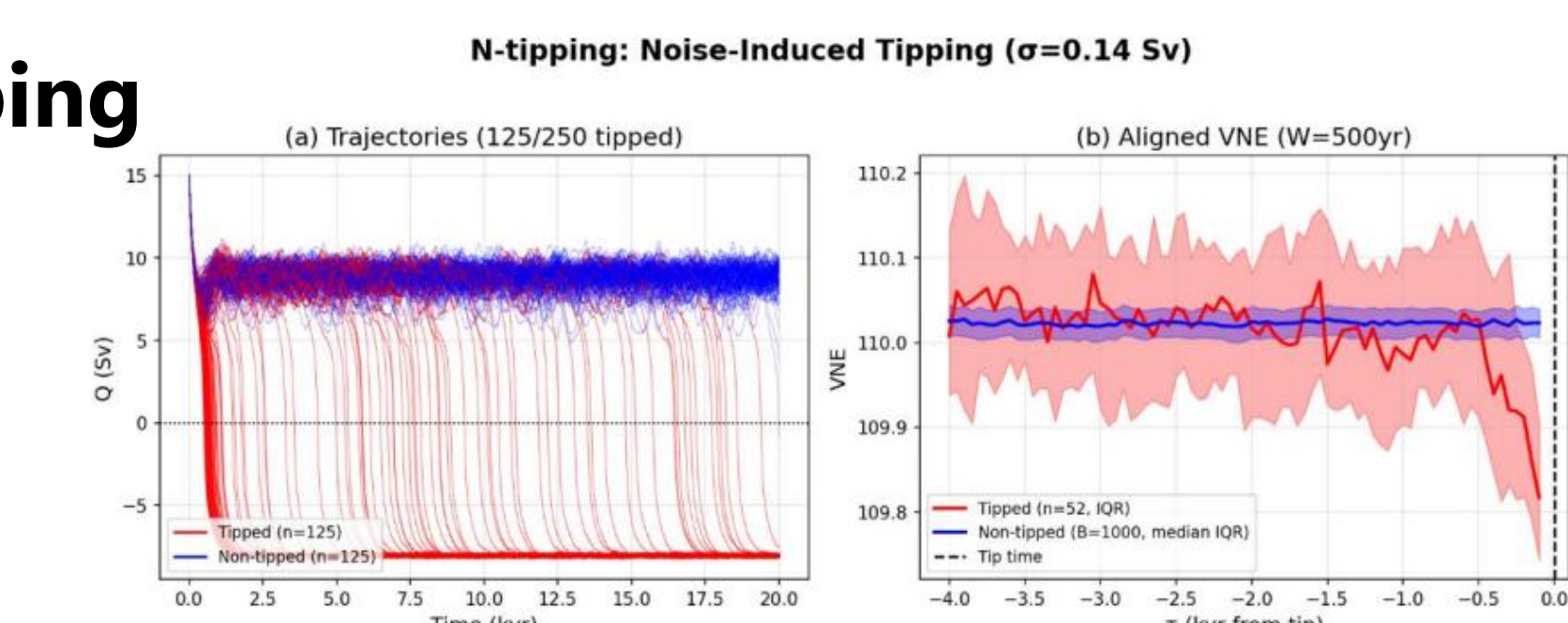


Streamfunction field only
 Streamfunction + SST field (interpolated) (resampled)

Potential as a universal indicator

For Noise-induced tipping

Reactive trajectories have the similar trend before tipping



For Rate-induced tipping

Tipping initial values have distinct HASC time-series compared to non-tip ones

Conclusion

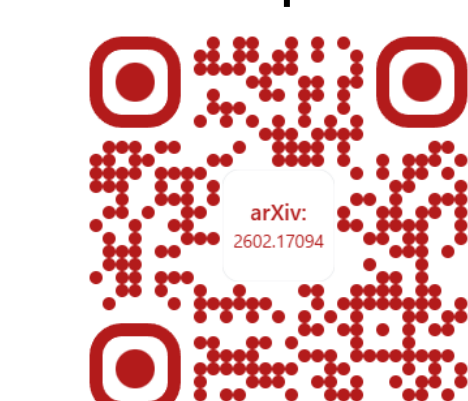
Data-driven tipping indicator with imperfect dynamical knowledge

Application to high-dimensional tipping dataset (36k+ dim)

Integrated geometrical interpretations on Noise-induced and Rate-induced tipping analysis

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▼ Preprint



▼ Abstract

