Physical Oscillator Model for Supercomputing

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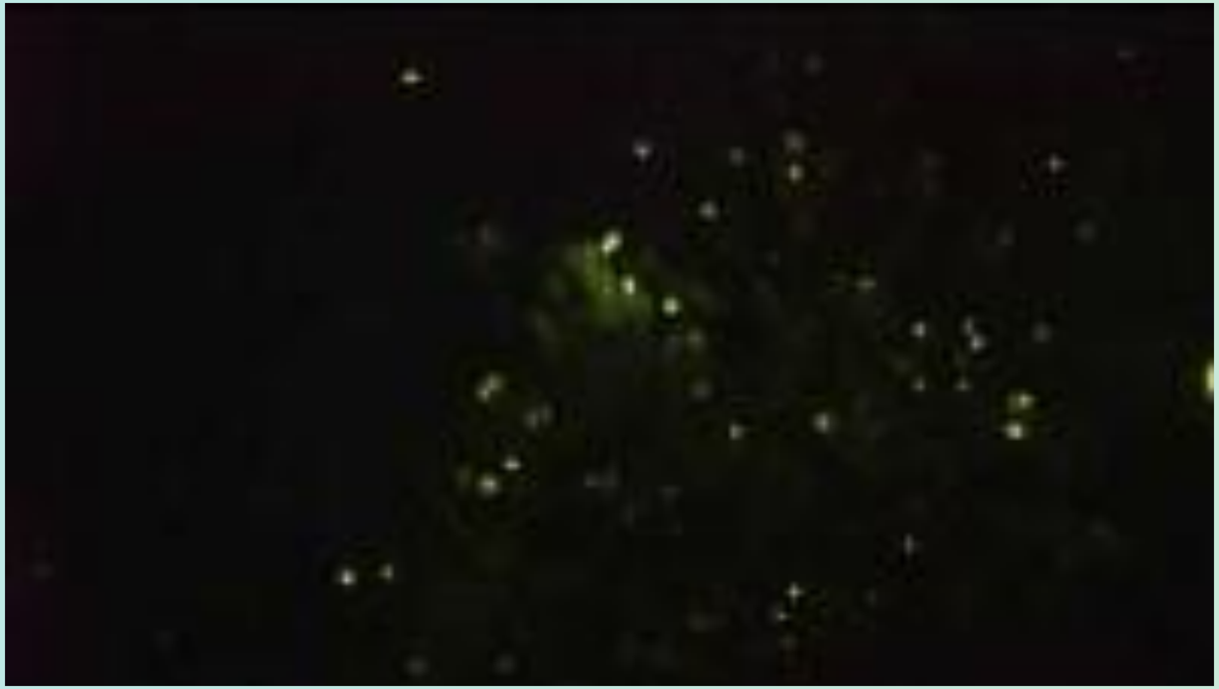
Coupled Oscillators: Fireflies and Metronomes!



John Bernard Estrada, YouTube https://youtu.be/2IVBDDVPl68?si=vaEn-Ki4sAZHQsb-

UCLA Physics, YouTube https://youtu.be/T58lGKREubo?si=LGaB-xWwhiMl0uLg

Coupled Oscillators: The Kuramoto Model

Coupling strength

Actual frequency

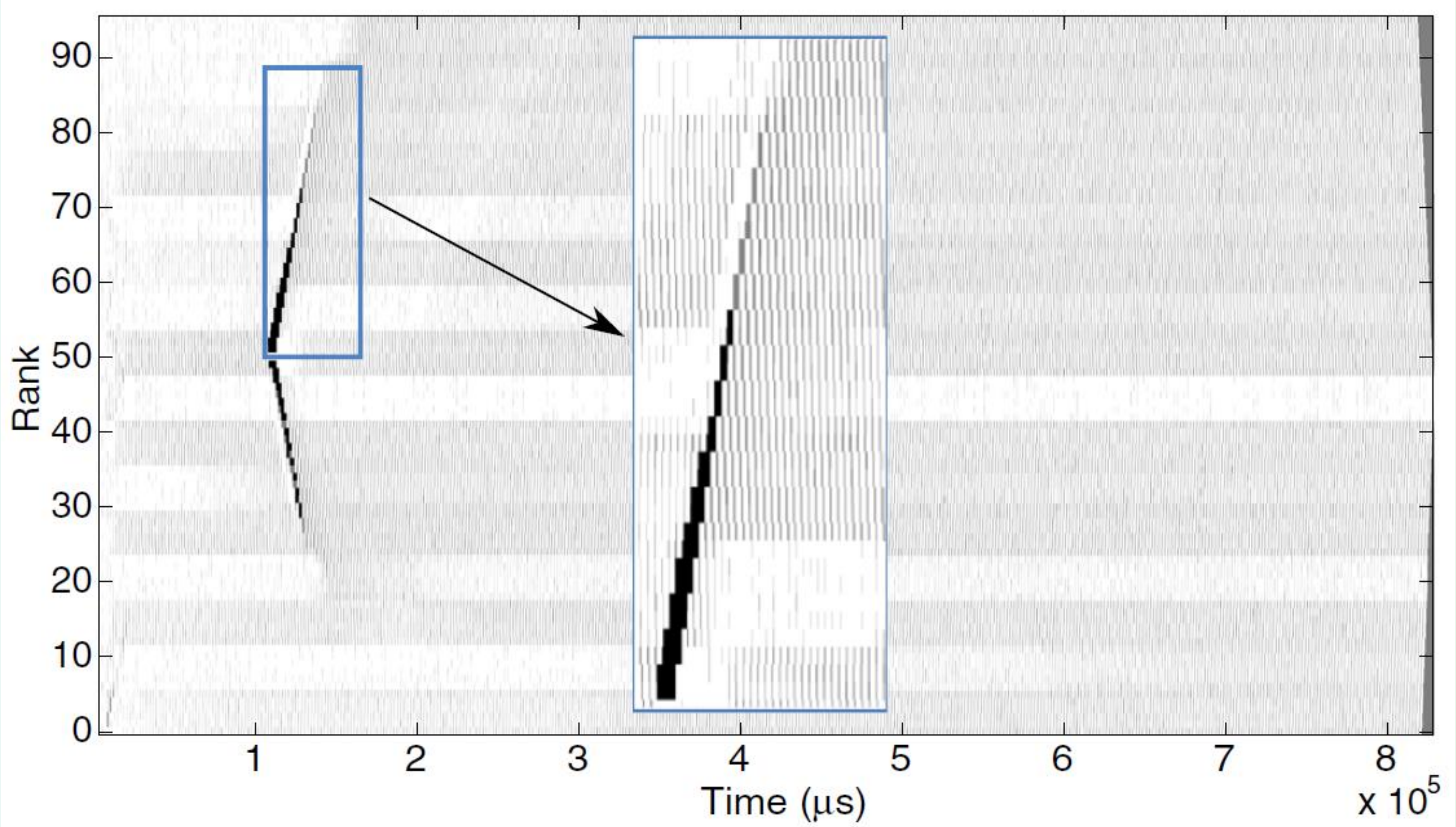
$$\dot{\theta}_i = \omega_i + \frac{K}{N}\sum_{j=1}^{N}\sin\left(\theta_j - \theta_i\right)$$

Natural (base) frequency

All-to-all coupling

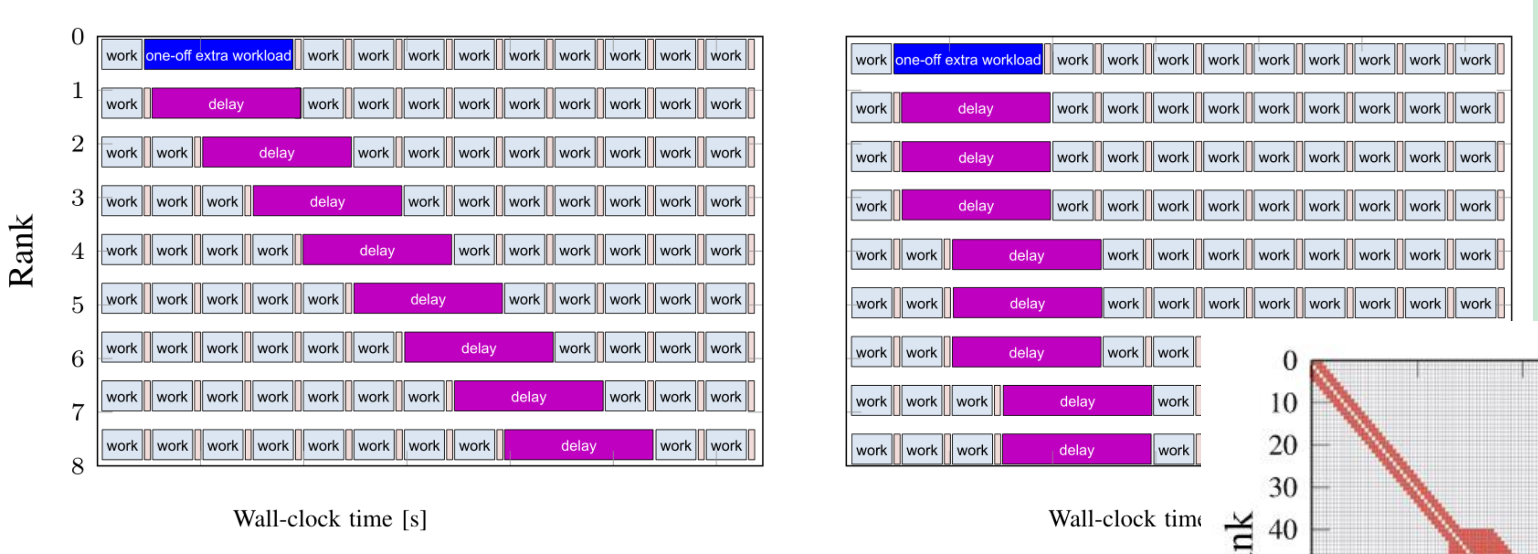
Interaction potential

Parallel Programs: Idle Wave Propagation and Decay

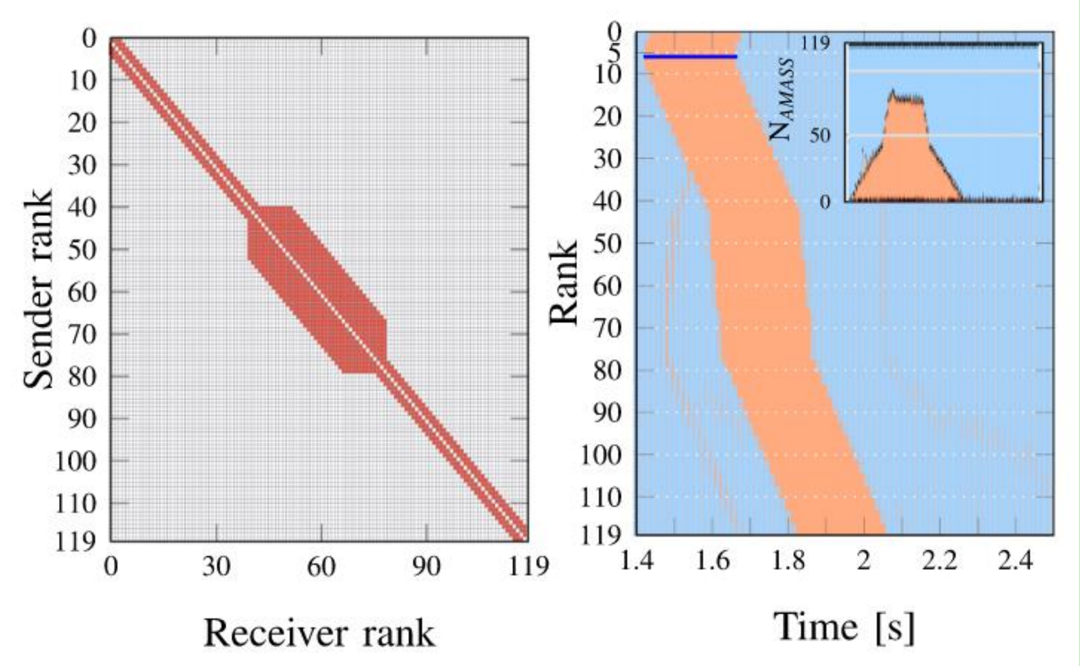


S. Markidis et al.: *Idle waves in high-performance computing*. Phys. Rev. E **91**(1), 013306 (2015). DOI: 10.1103/PhysRevE.91.013306

Idle Wave Speed and Communication Topology



(a) $d = \pm(1)$ (slow idle wave) (b) $d = \pm(1, 2)$ (three



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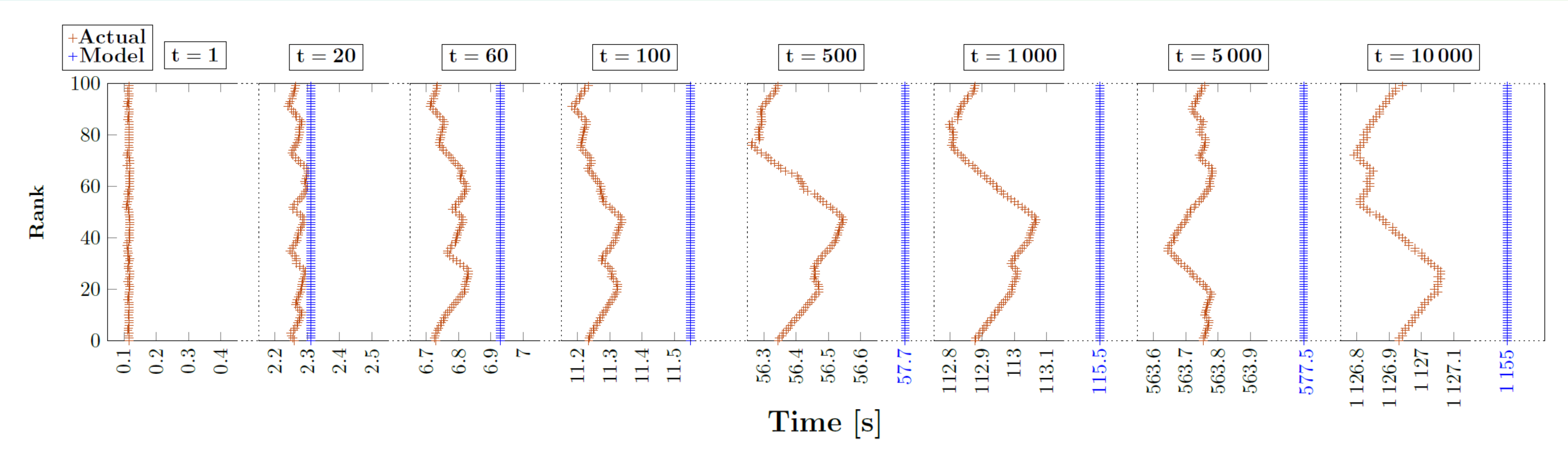
Bottlenecks, Computational Wavefronts, and Spontaneous Asynchronicity



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Core Analogies

MPI processes	Coupled oscillators
Process	Harmonic oscillator
Regular compute-communicate phases	Intrinsic oscillation
Load imbalance	Spread of natural frequencies
Noise	Variation of frequencies and/or phases
Delay propagation speed	Coupling strength
Communication topology	Coupling topology

An Oscillator Model for Communicating Processes

$$\dot{\theta}_i = \omega_i + \zeta_i(t) + \frac{K}{N}\sum_j T_{ij}\, V\big(\theta_j, \theta_i, \tau_{ij}(t)\big)$$

Frequency noise

Communication topology

Phase noise

$$\omega_i = \frac{2\pi}{t^{comp} + t^{comm}}$$

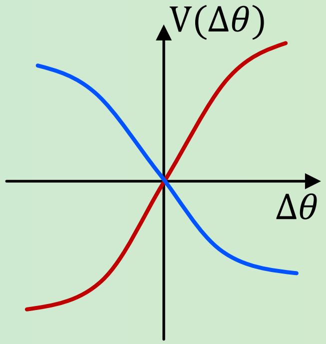
$$K = \frac{\beta\kappa}{t^{comp} + t^{comm}}$$

Requirements

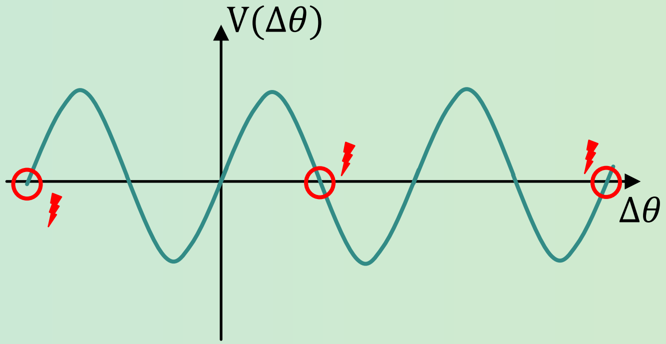
- T_{ij} must reflect the actual communication topology of the program

$$\begin{bmatrix} 1 & 0 & \cdots & 1 \\ 1 & 1 & & 0 \\ 1 & 1 & \ddots & \vdots \\ \vdots & & \ddots & 1 \\ 1 & \cdots & 1 & 1 \end{bmatrix}$$

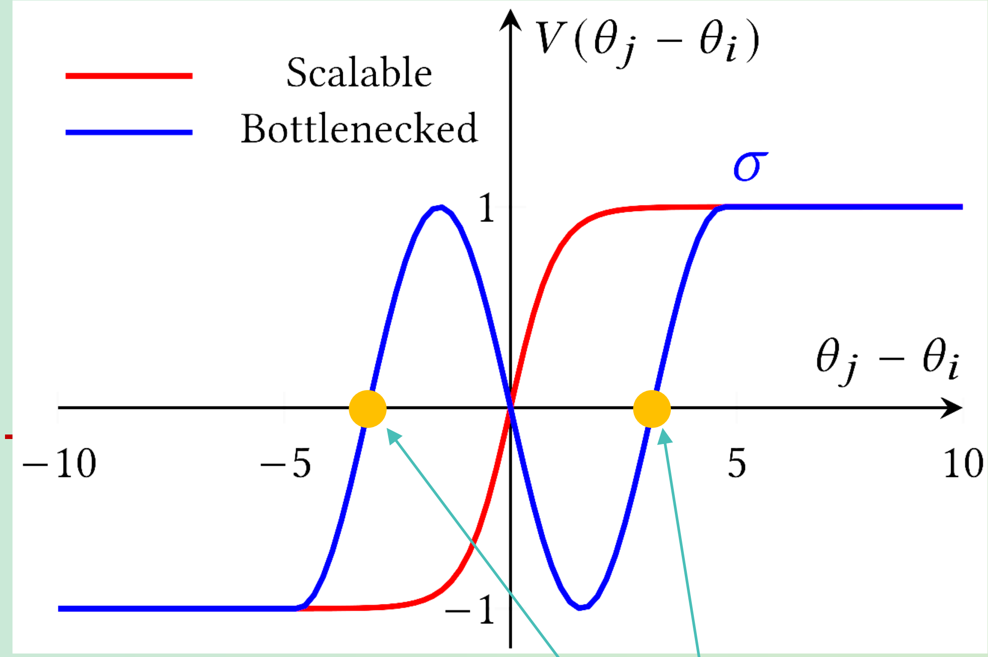
- $V(\cdot)$ must allow for re- or desynchronization: $V'(0) \gtreqless 0$



- $V(\cdot)$ must not be periodic (no phase slips)



Possible Choices for $V(\cdot)$



- Resynchronizing (scalable code)

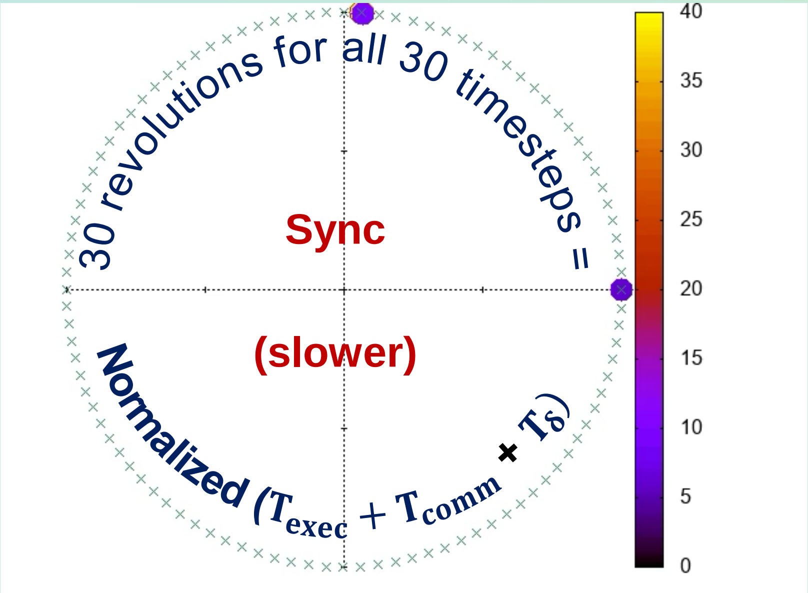
$$V(\theta_j - \theta_i) = \tanh(\theta_j -$$

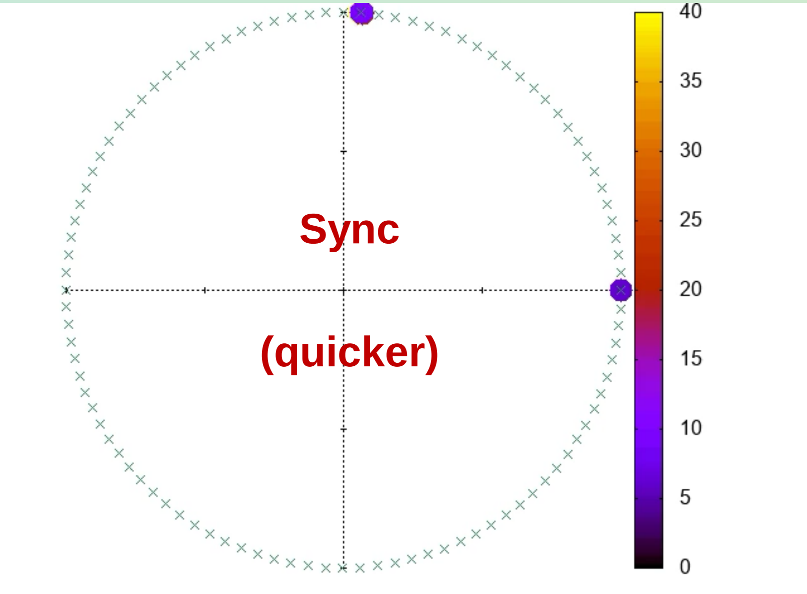
- Desynchronizing (bottlenecked code)

$$V(\theta_j - \theta_i) = \begin{cases} -\sin\left(\frac{3\pi}{2\sigma} \cdot (\theta_j - \theta_i)\right) & \text{if } |\theta_j - \theta_i| < \sigma \\ \operatorname{sgn}(\theta_j - \theta_i) & \text{else} \end{cases}$$

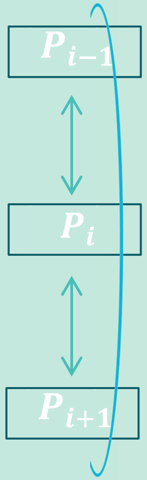
Interaction horizon
“Attractor” at $2\sigma/3$

Evaluation: Scalable Code

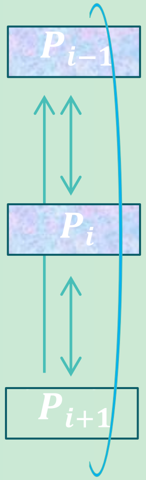




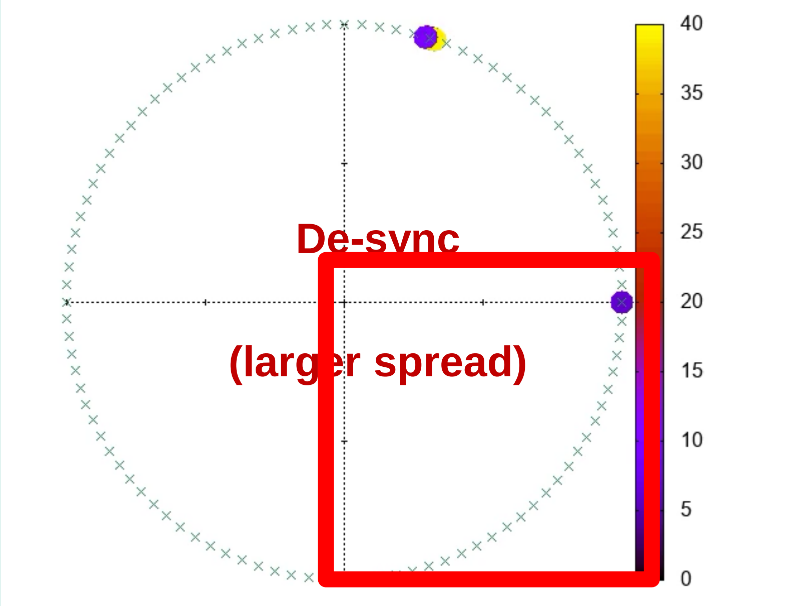
d = $\pm$1



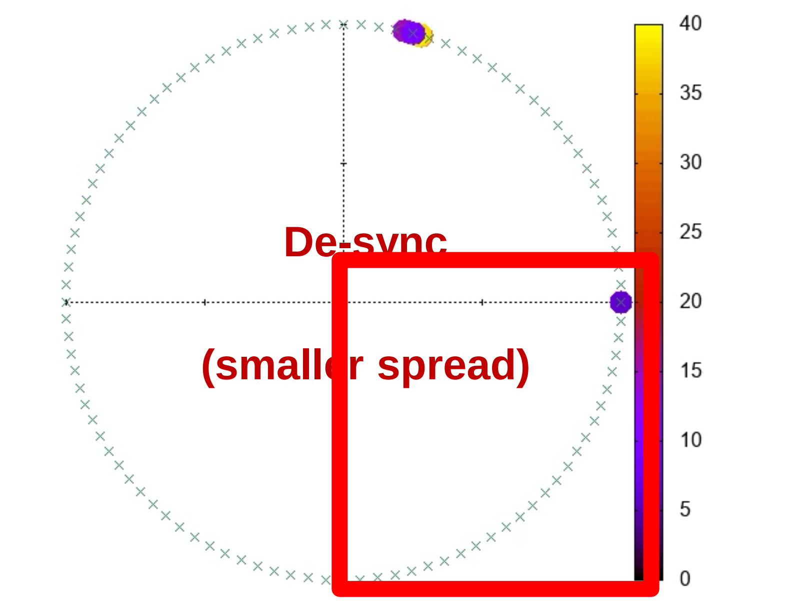
d = $\pm$1, -2



Evaluation: Bottlenecked Code



d = $\pm$1



d = $\pm$1, -2

Outlook and future work

- This is a wild concept; we have no idea if it has merit
- The model provides a good qualitative representation of some of the features of parallel programs
- The model can be used to characterize systems with “interesting” collective behavior
- Co-design?
- A continuum limit is as yet unknown
- Future work
    - Quantitative exploration of the role of the noise functions
    - Connecting the symmetry-breaking transition to the Goldstone mode

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