Driven generalized quantum Rayleigh-van der Pol oscillators

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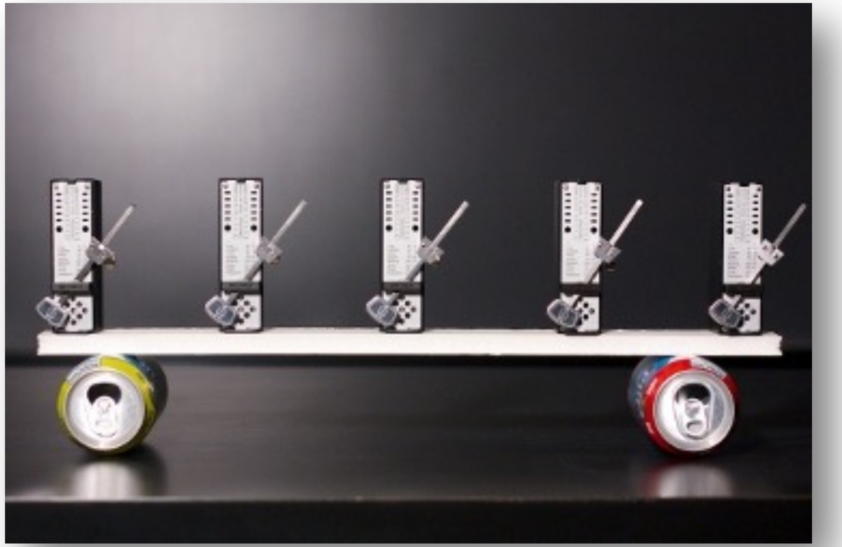
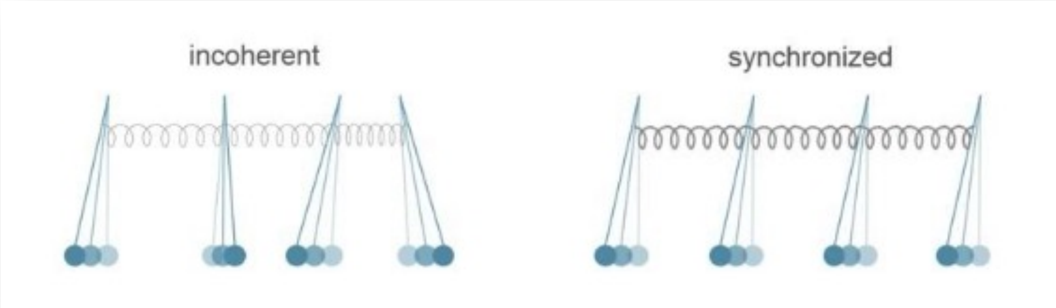
Synchronization

- **phase locking** and **entrainment** of self-sustained oscillator systems
  - i.e. pacemakers, blinking fireflies
- **self-sustained**: supporting asymptotic finite amplitude oscillations
- well understood classically



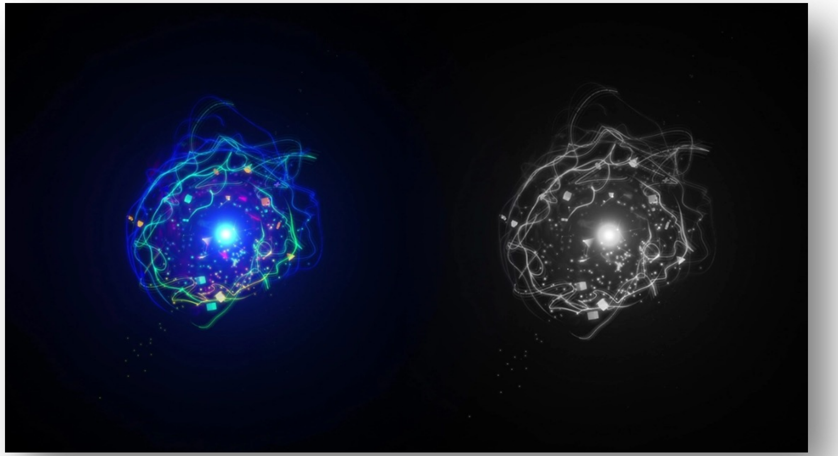
[1] Harvard Natural Sciences Lecture Demonstrations, https://sciencedemonstrations.fas.harvard.edu/presentations/synchronization-metronomes



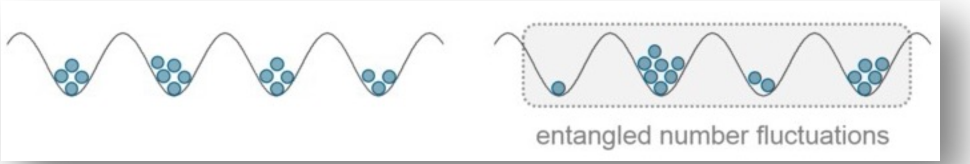
[2] Max Planck Society, "Classical synchronization indicates persistent entanglement in isolated quantum systems". https://phys.org/news/2017-05-classical-synchronization-persistent-entanglement-isolated.html

Quantum Synchronization Motivation

- less understood in the quantum regime
- exciting area for quantum technology
  - biology, telecommunications, etc.
- big questions:
  1. differences in single-oscillator systems?
  2. what is coupled with what?
  3. how does the response change?



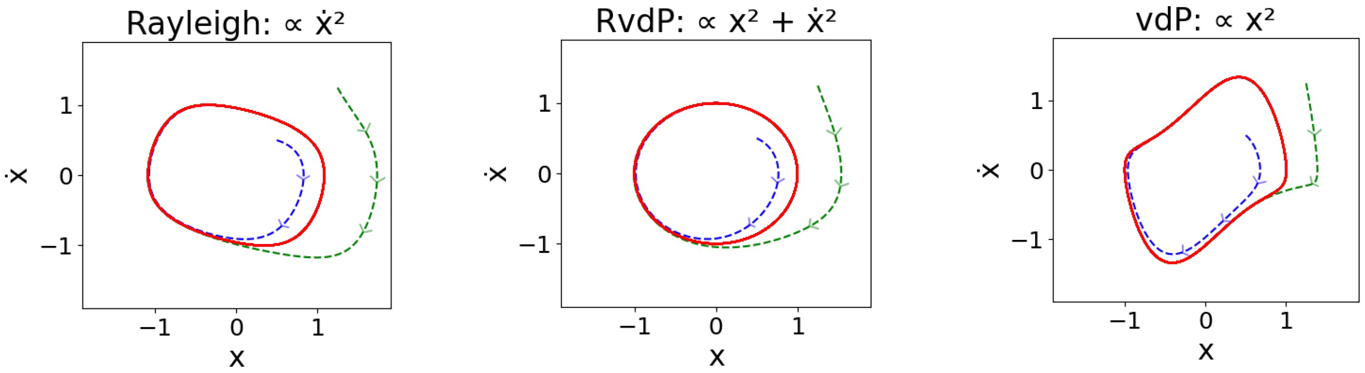
[3] Frank, Adam. “What is quantum mechanics trying to tell us?”, 2 June 2022. https://bigthink.com/13-8/quantum-mechanics-interpretation/

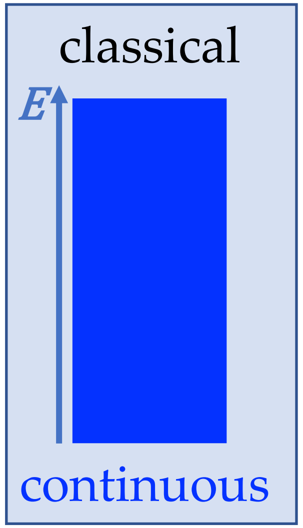


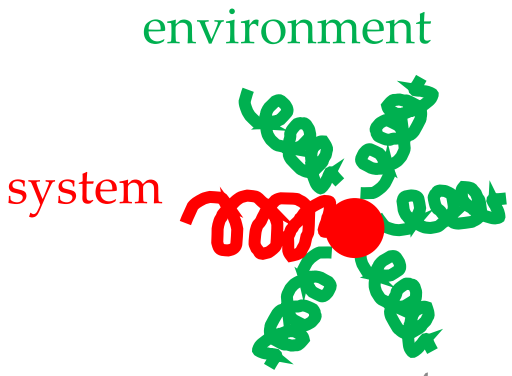
[2] Max Planck Society. “Classical synchronization indicates persistent entanglement in isolated quantum systems”. https://phys.org/news/2017-05-classical-synchronization-persistent-entanglement-isolated.html

Background: generalized Rayleigh-van der Pol (R-vdP) oscillators

- three gain/dissipative processes:
  1. linear energy gain, proportional to $\dot{x}$
  2. **van der Pol (vdP)** damping: non-linear energy loss proportional to x^2
  3. **Rayleigh (R)** damping: non-linear energy loss proportional to $\dot{x}^2$
- self-sustained
  - **limit cycles**

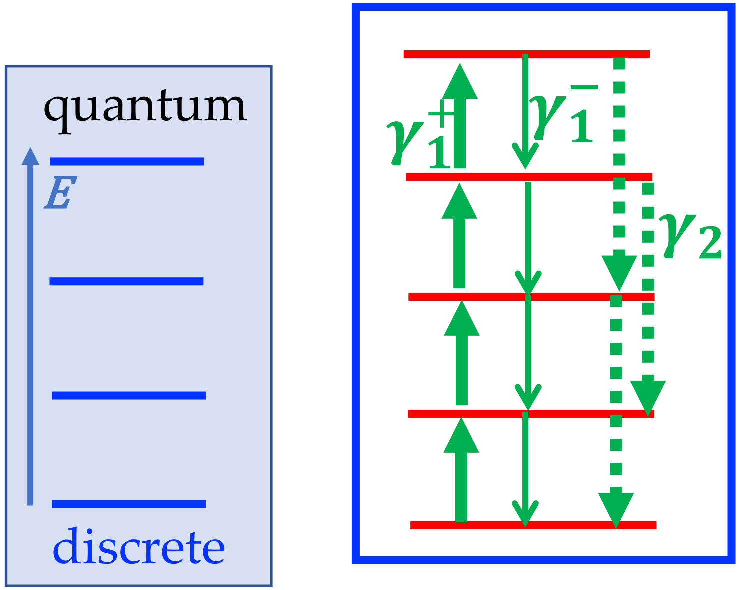


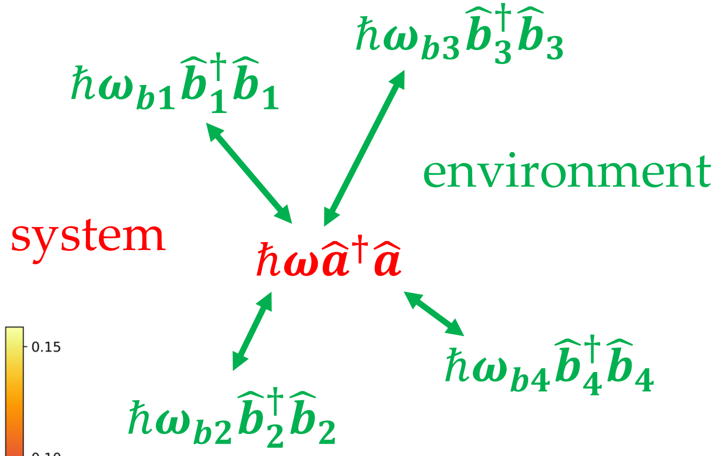


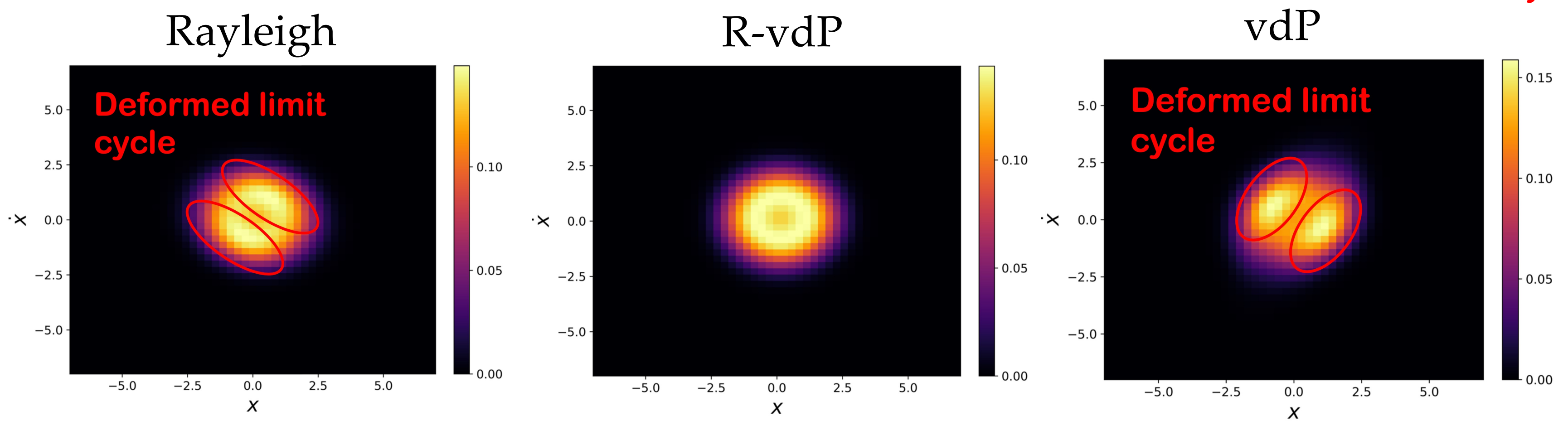


Quantum Description

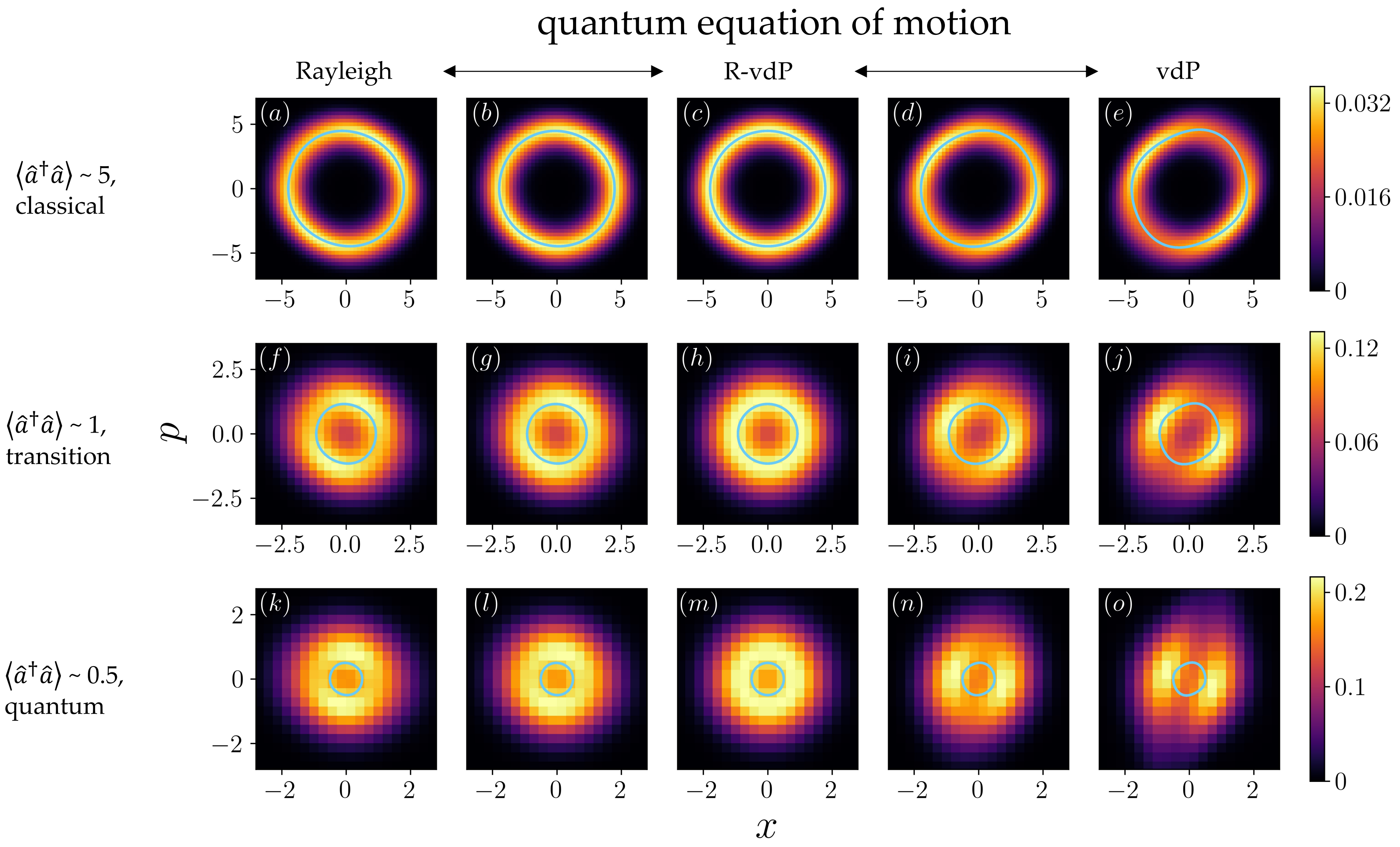
- quantum gain/dissipative processes:
  1. one-excitation gain (γ_1^+)
  2. one-excitation loss (γ_1^-)
  3. two-excitation loss (γ_2)
- $\langle \hat{a}^\dagger \hat{a} \rangle$ describes "quantumness"
- Wigner functions as a phase-space analog





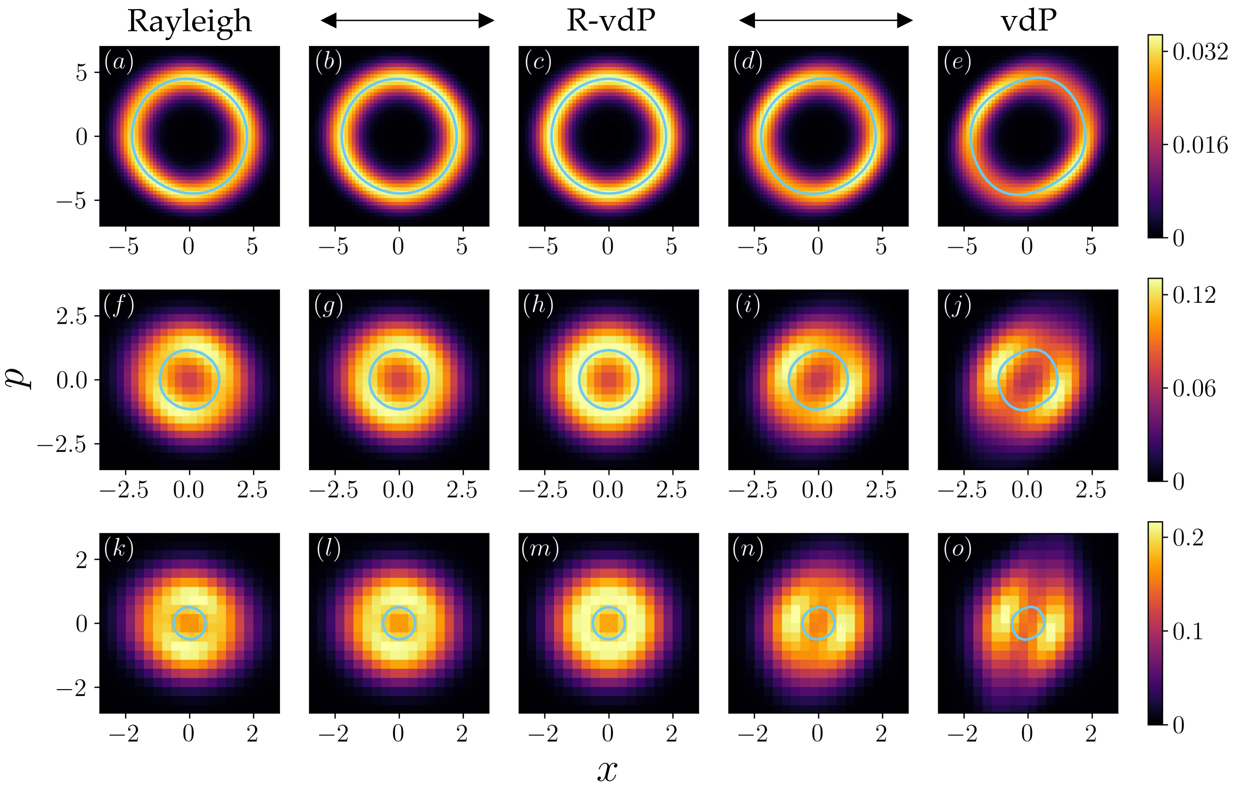


Quantum Limit Cycles

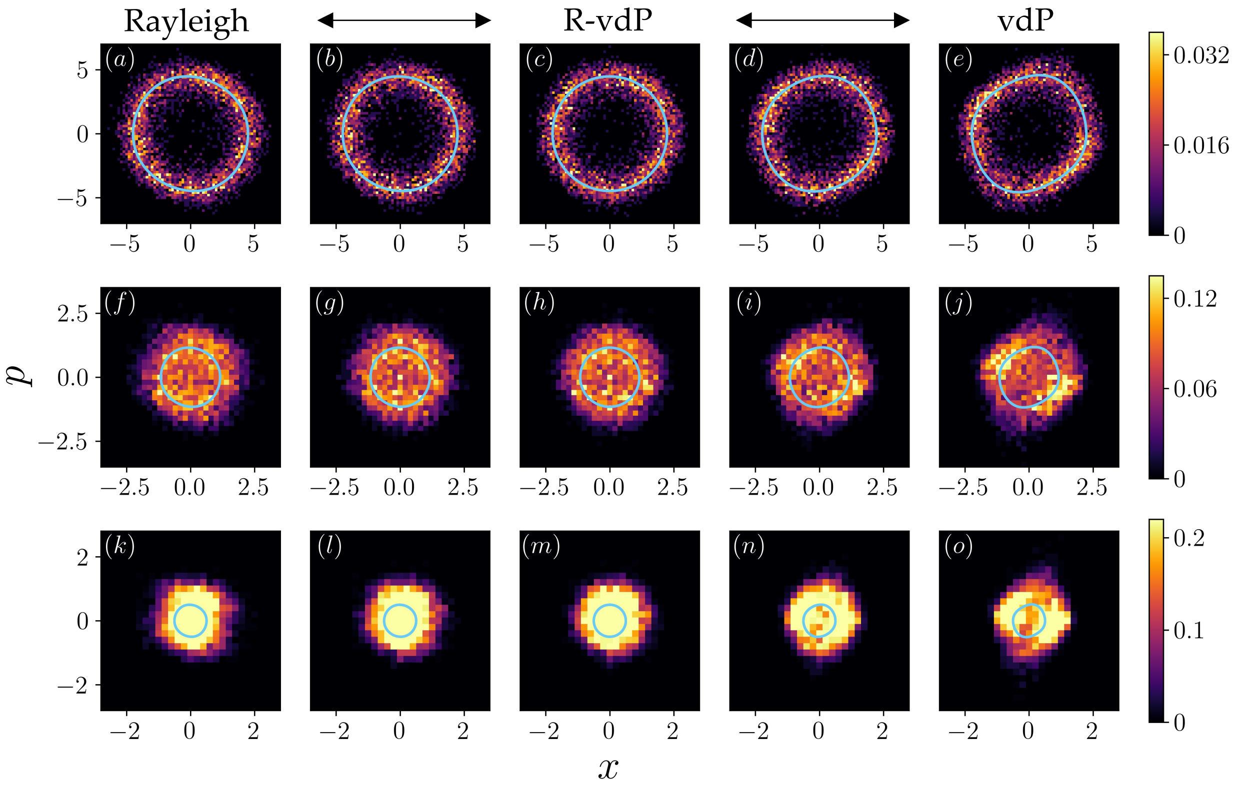


Quantum vs. Classical Comparison

quantum equation of motion

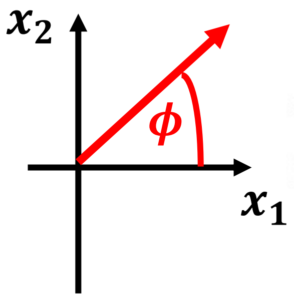


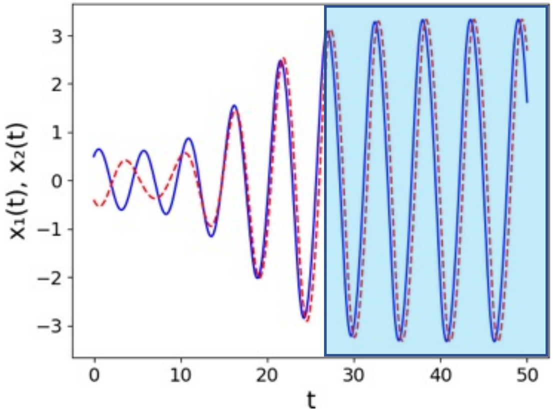
classical equation of motion + white-noise temperature



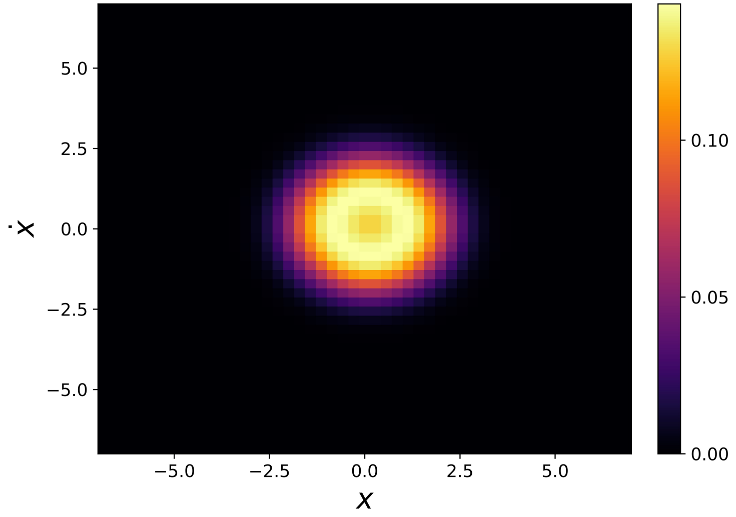
Synchronizing Quantum Systems

- systems synchronized by **external drive** (ω_D, Ω)
- angular preference apparent in phase space

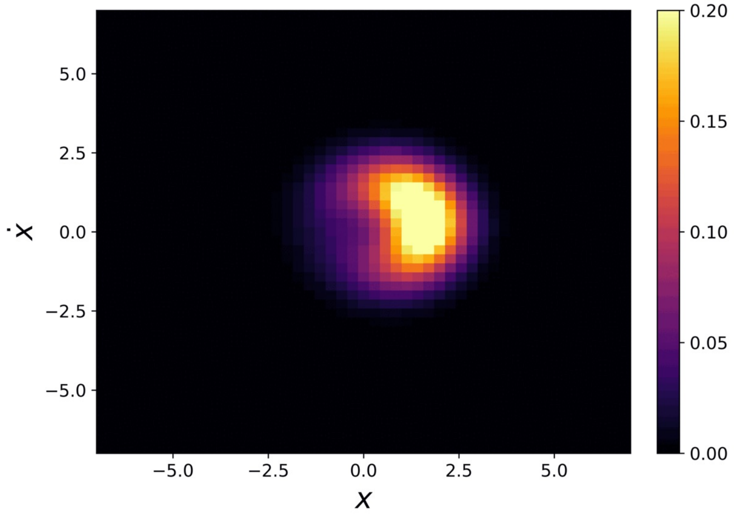




no drive → sync. = 0



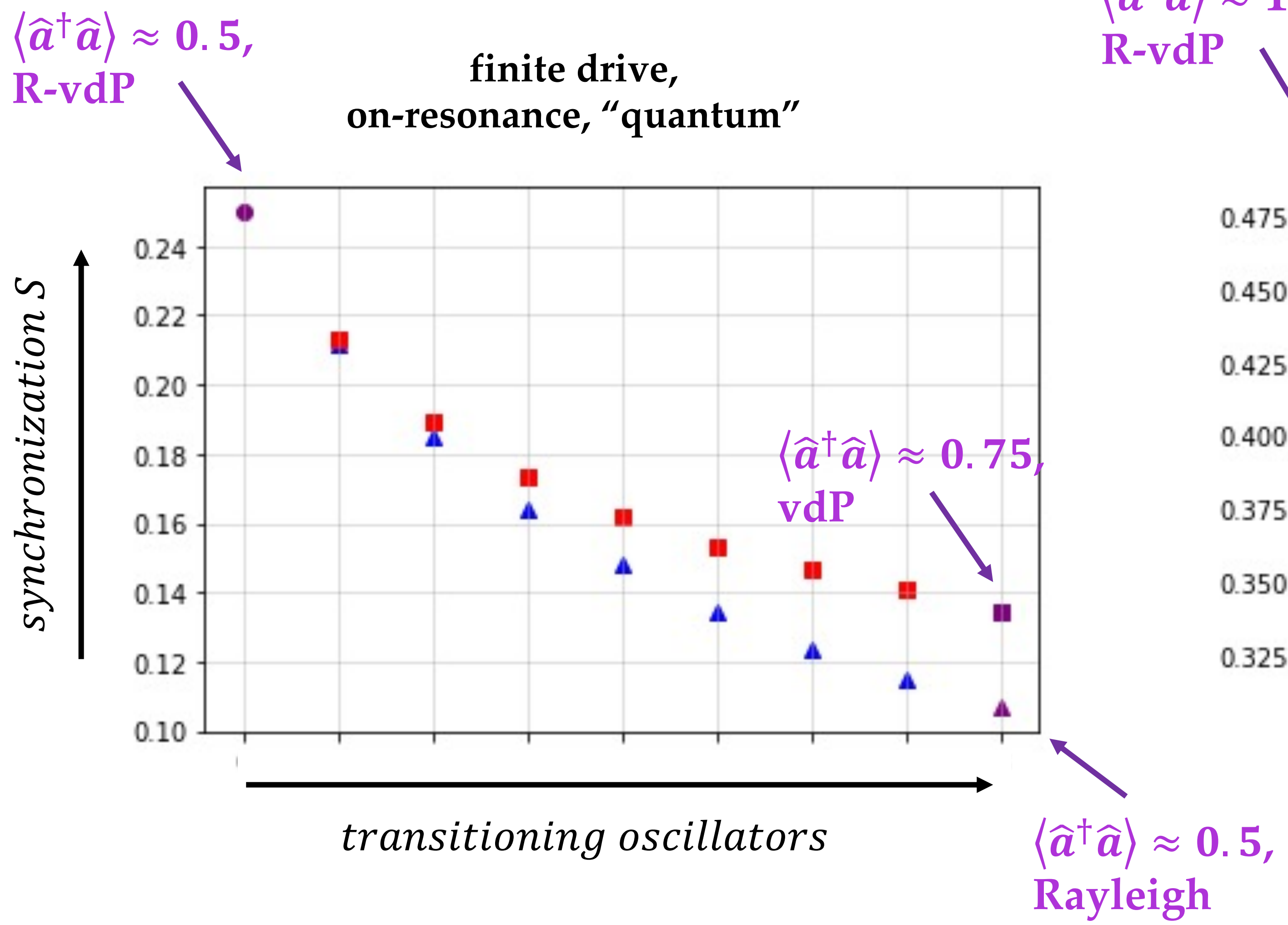
drive → finite sync. < 1

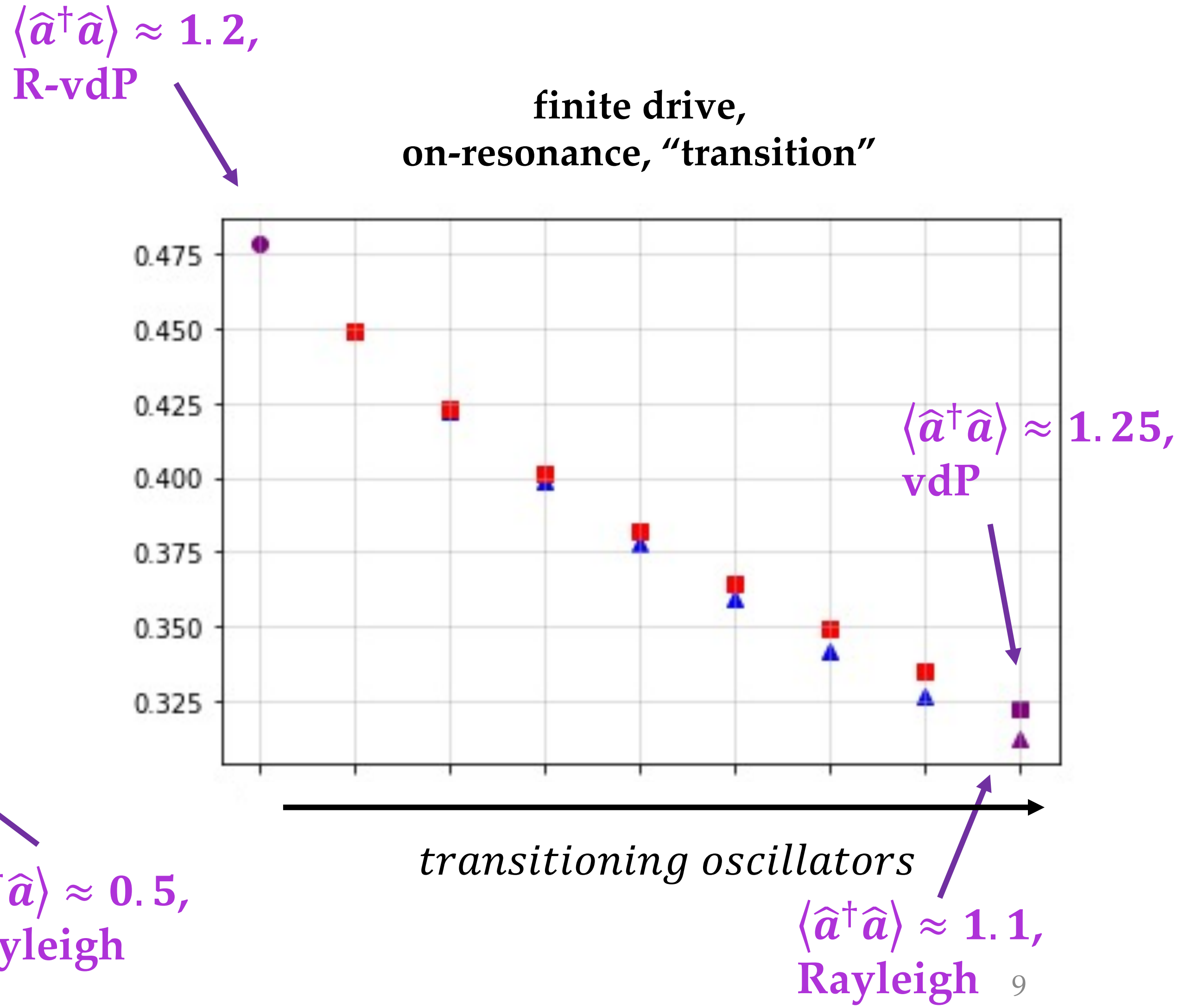


quantified by **synchronization** (S)

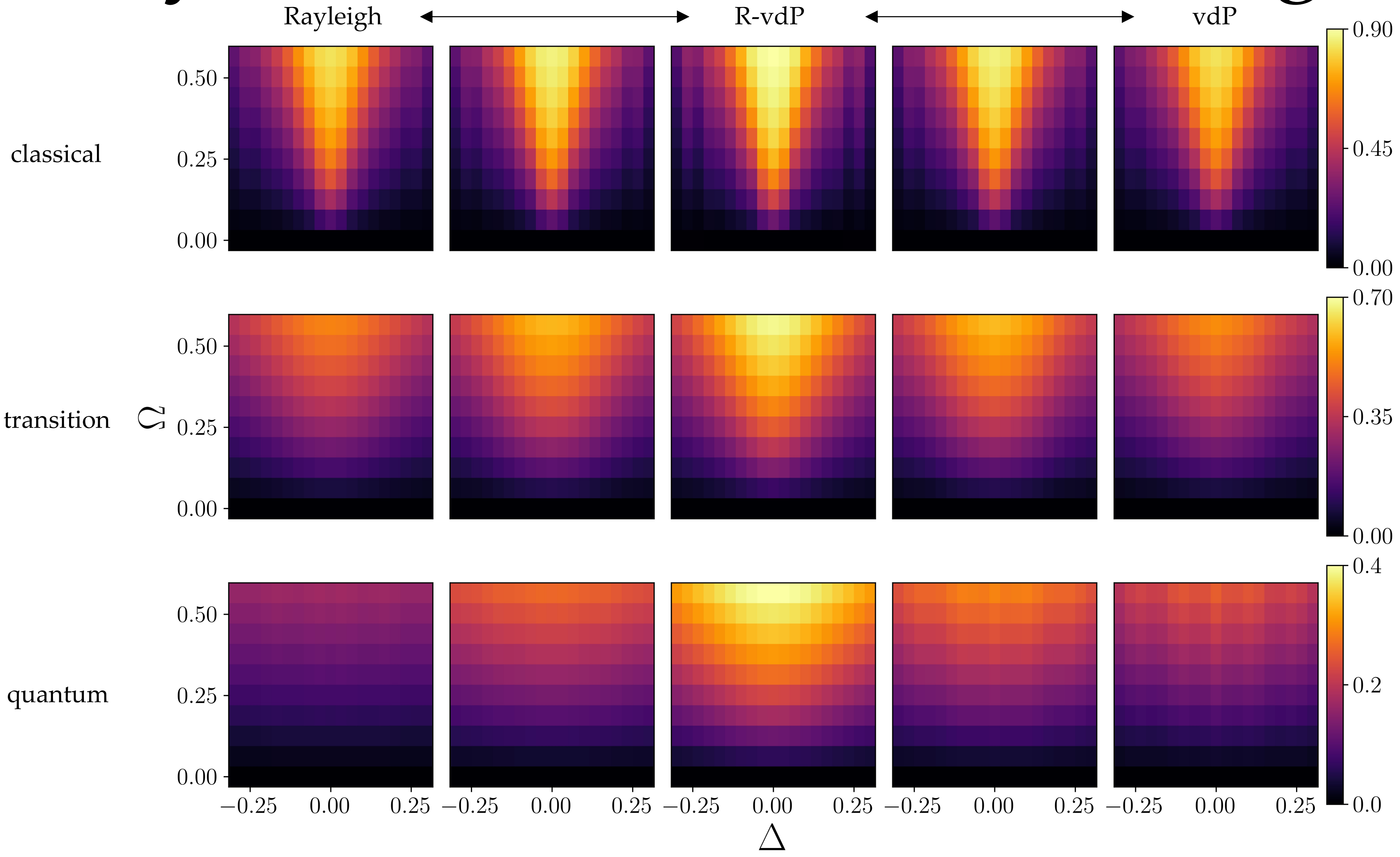
- defined by the mean resultant length calculated from $\hat{\phi}$
- $0 < S < 1$

Synchronization and Drive Strength





Synchronization Arnold Tongues



Ω = drive strength

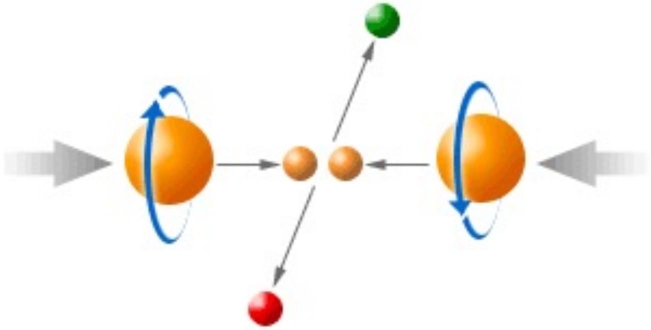
$\Delta = \omega_D - \omega_0$ = detuning

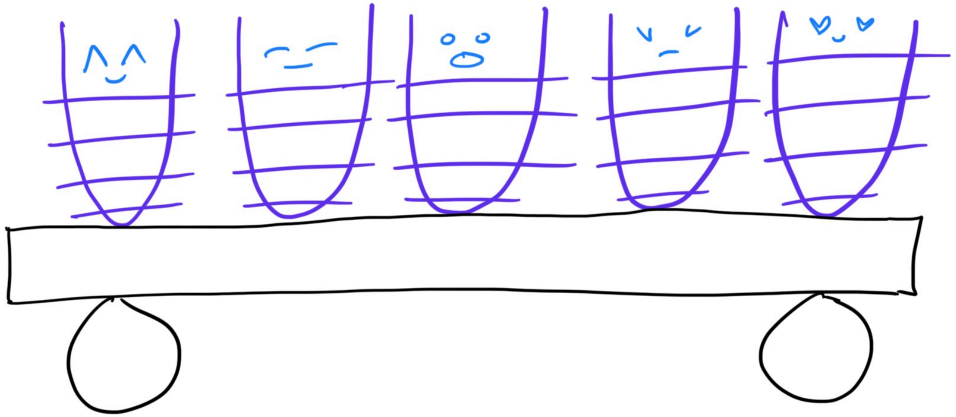
For a larger detuning, we need a higher drive strength to achieve the same synchronization.

The classical regime experiences the highest synchronization for no detuning.

Future Direction with Synchronization

- Continue to monitor results as the higher-energy regimes approach convergence
  - Rotations and reference frames
- Couple several quantum oscillators to one another to explore synchronization effects
- Spin vs. Spatial degrees of freedom





[4] Brookhaven National Laboratory. "Spin Physics". https://www.bnl.gov/rhic/spin.php

Acknowledgements and References

- Thank you to Dr. Blume!!!
- Thanks to all the graduate students in the group who have helped me—Jugal, Dave, and Kevin.

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Questions?