Exploring Quantum Light Driven Few-level Systems

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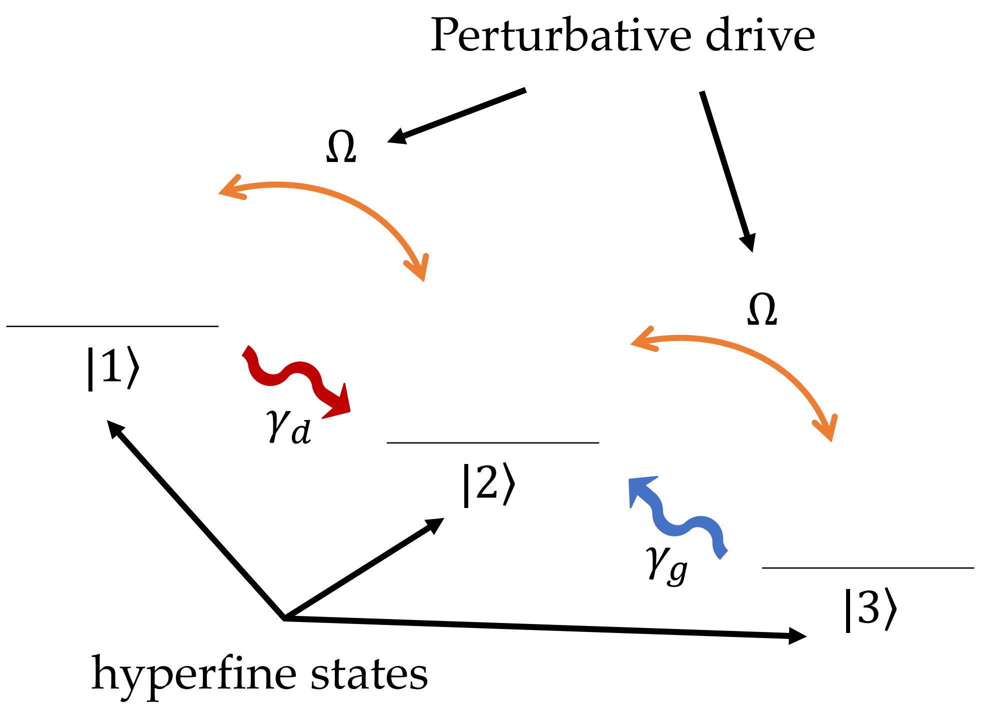
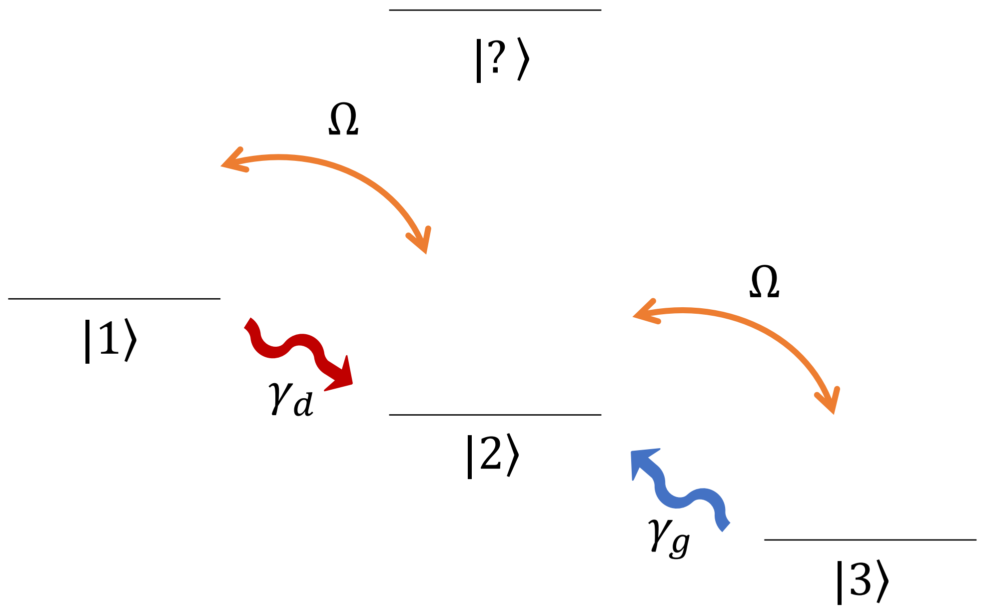
Spin-1 System (Classical Drive)

- The ideal spin-1 system is simple
- The three energy levels represent different spin orientations
- Without a coherent drive (Ω) incoherent dissipators (γ_d and γ_g), create a limit cycle (steady state) in $|2\rangle$

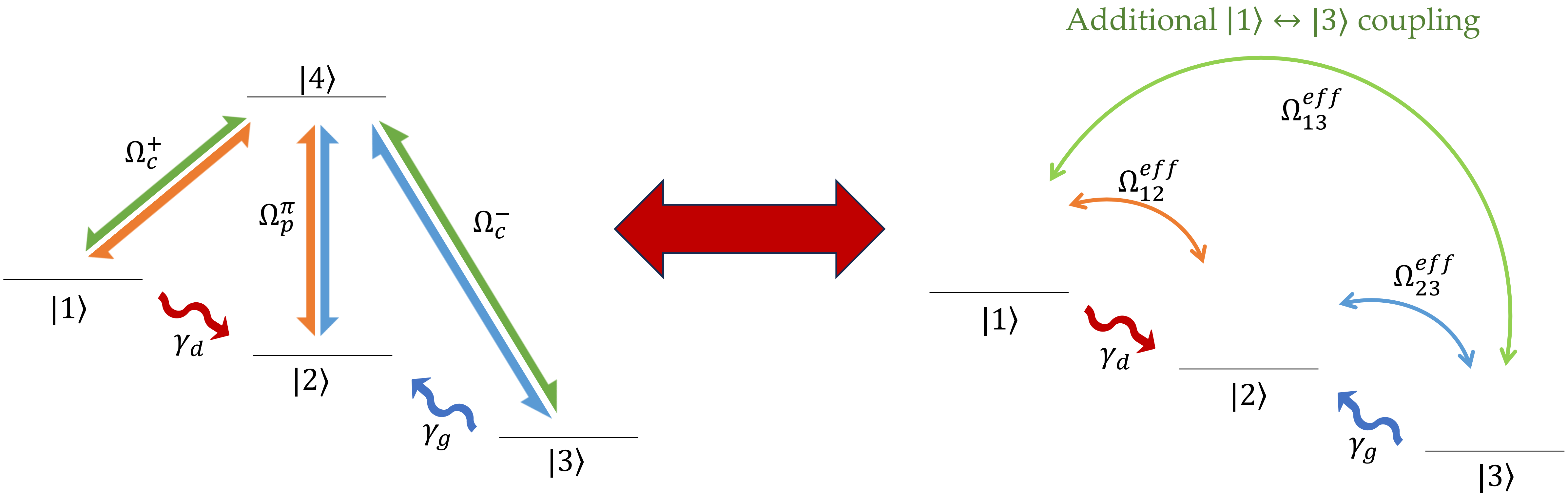


Spin-1 System (Classical Drive)

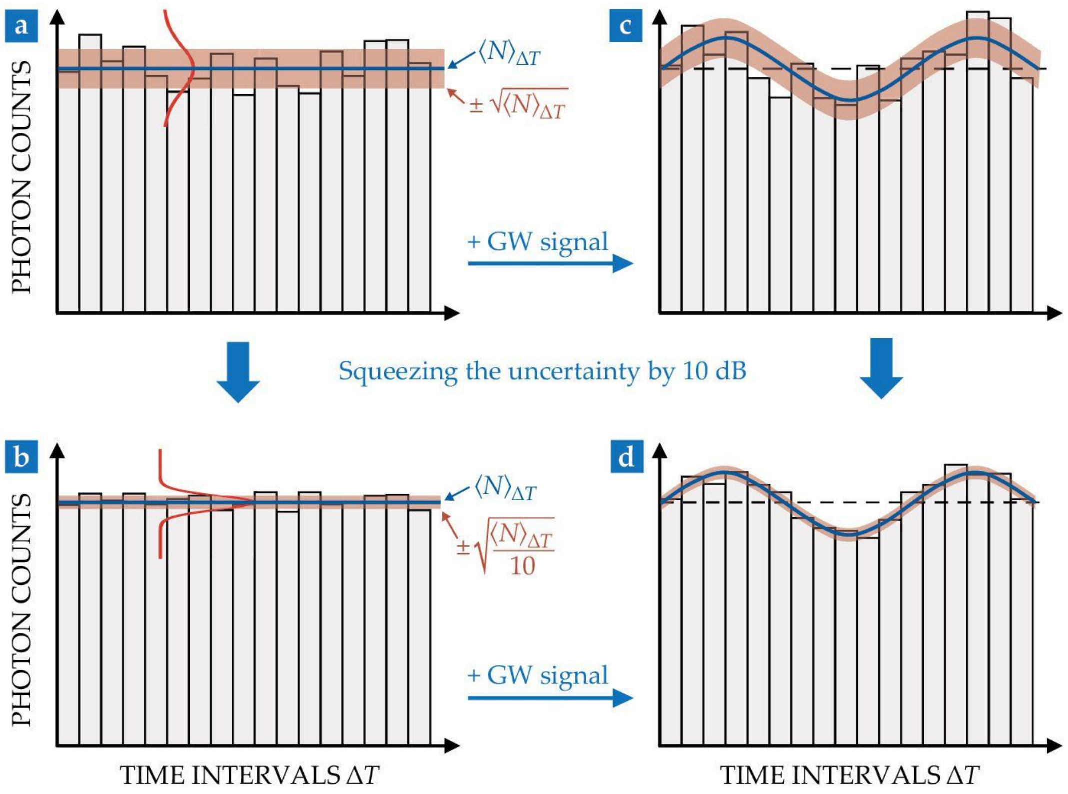
- We need rf fields to drive transitions in the 3-level system
- Lasers in the optical wavelengths are much more convenient
- We need to include an additional energy level



3-Level vs. 3+1 Level



Quantum Light



From Physics Today 75, 46 (2022).

- LIGO (Laser Interferometer Gravitational-Wave Observatory) first observed gravitational waves in 2015

- Today LIGO uses quantum light to reduce noise in their output field ⇒ <u>enhanced sensitivity</u>

Quantum Light

- Classical light does not ‘feel’ the effect of the atom emitting or absorbing a photon
- Quantum light ‘feels’ a significant change

$n \gg 0, \ \ \Delta n = 1 \rightarrow \sim 0\%$ change

$n = 5, \ \ \Delta \mathrm{n} = 1 \rightarrow 20\%$ change

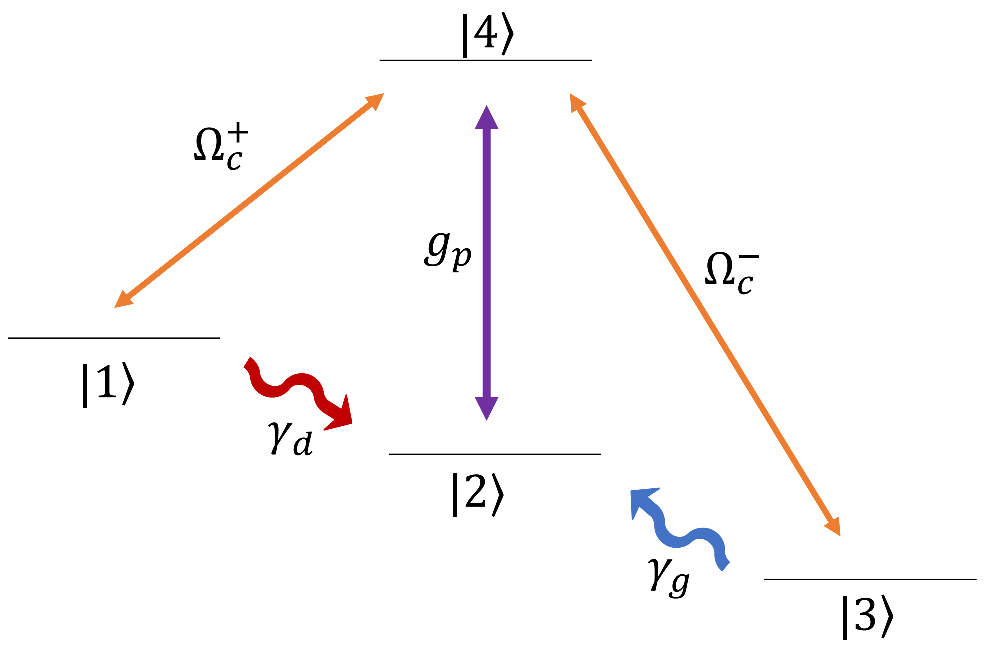
$n = 1, \ \Delta n = 1 \rightarrow 100\%$ change

photon number
(quantized)

3+1 Atomic System (Quantum Drive)

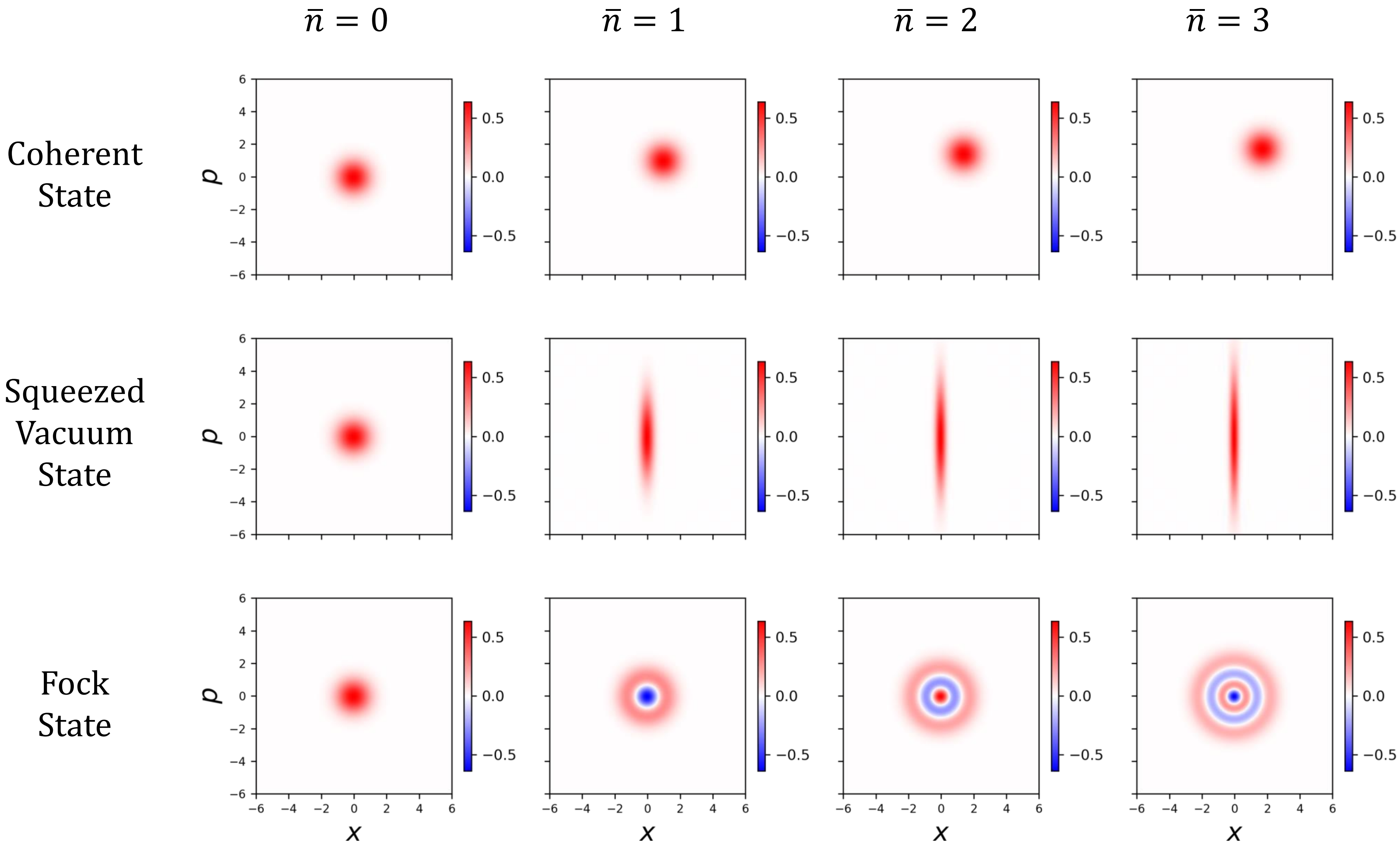
- Can synchronization be achieved with quantum light?

- Can we transfer entanglement from the quantum light to the atom?



$\bar{n}$ ≙ average photon number

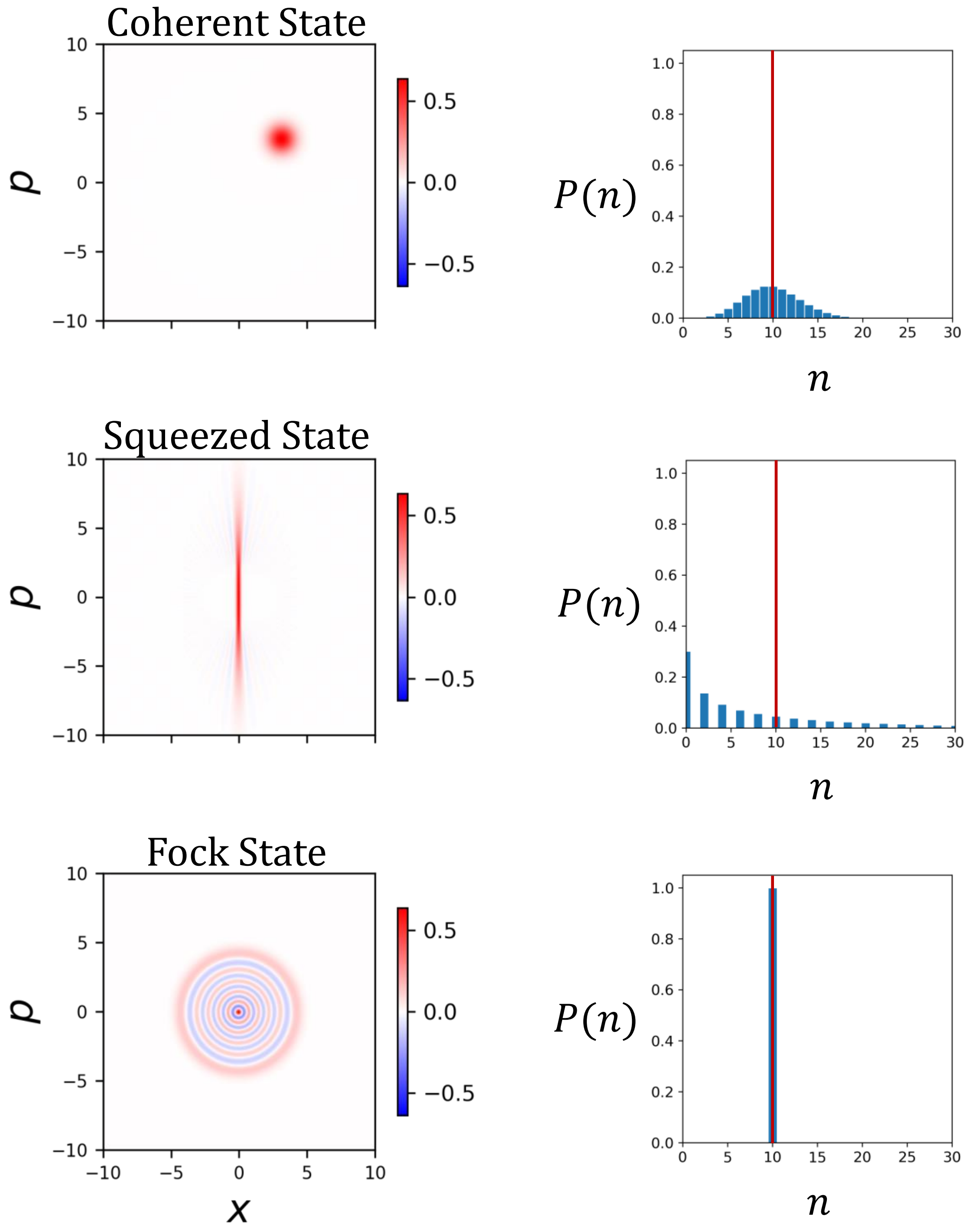
(x, p) ≙ amplitude and phase of electromagnetic field



Quantum Light

- Coherent states are considered the 'most classical' states of quantum light

- Fock states are considered the 'most quantum'

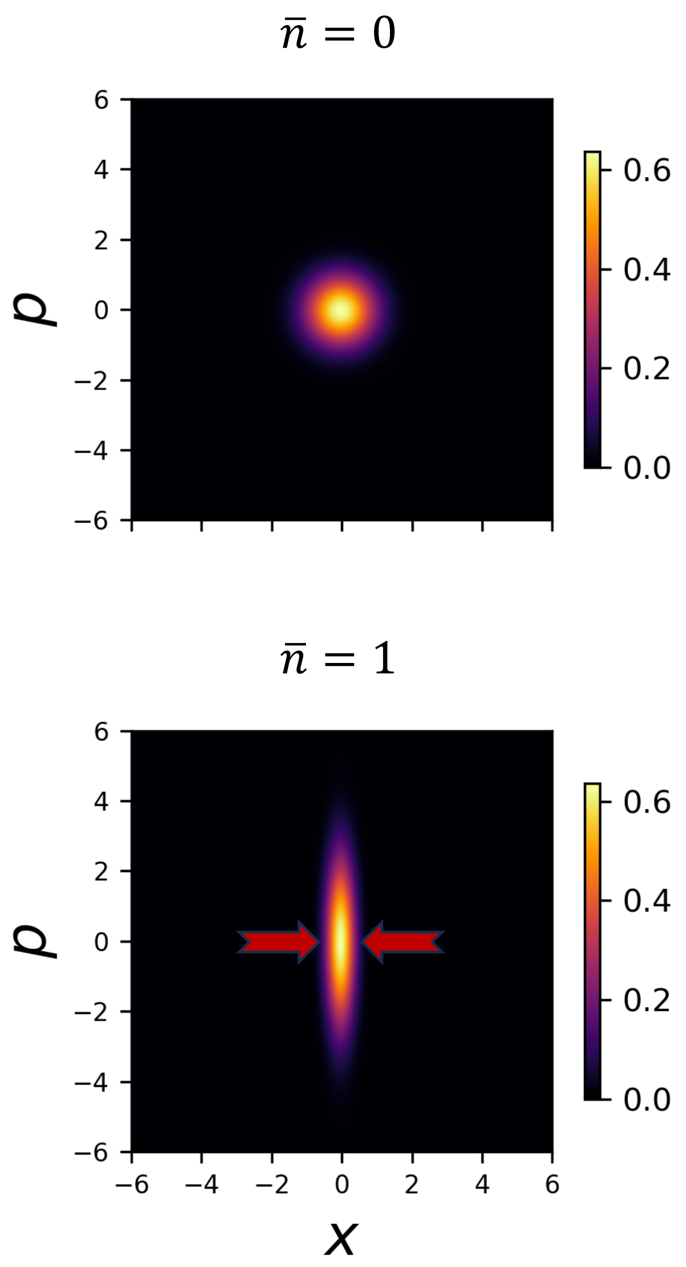


Squeezed State

- Heisenberg's uncertainty principle: $\Delta x \Delta p \geq \frac{\hbar}{2}$
- "Squeezing"→ squish along one quadrature and stretch along another
- The squeezing parameter ζ is complex

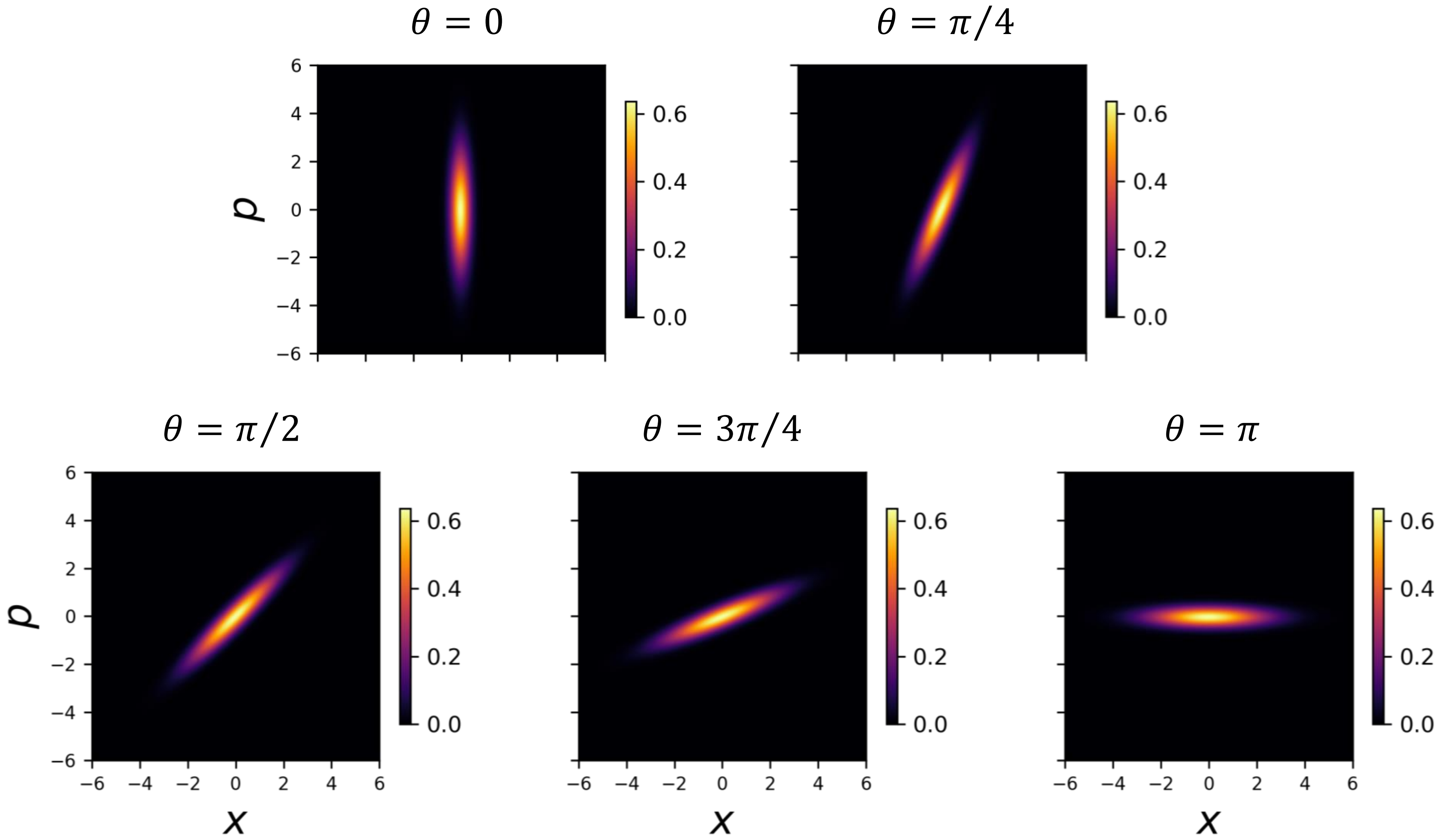
$\Delta x = \Delta p$

$\Delta x < \Delta p$



Squeezed State

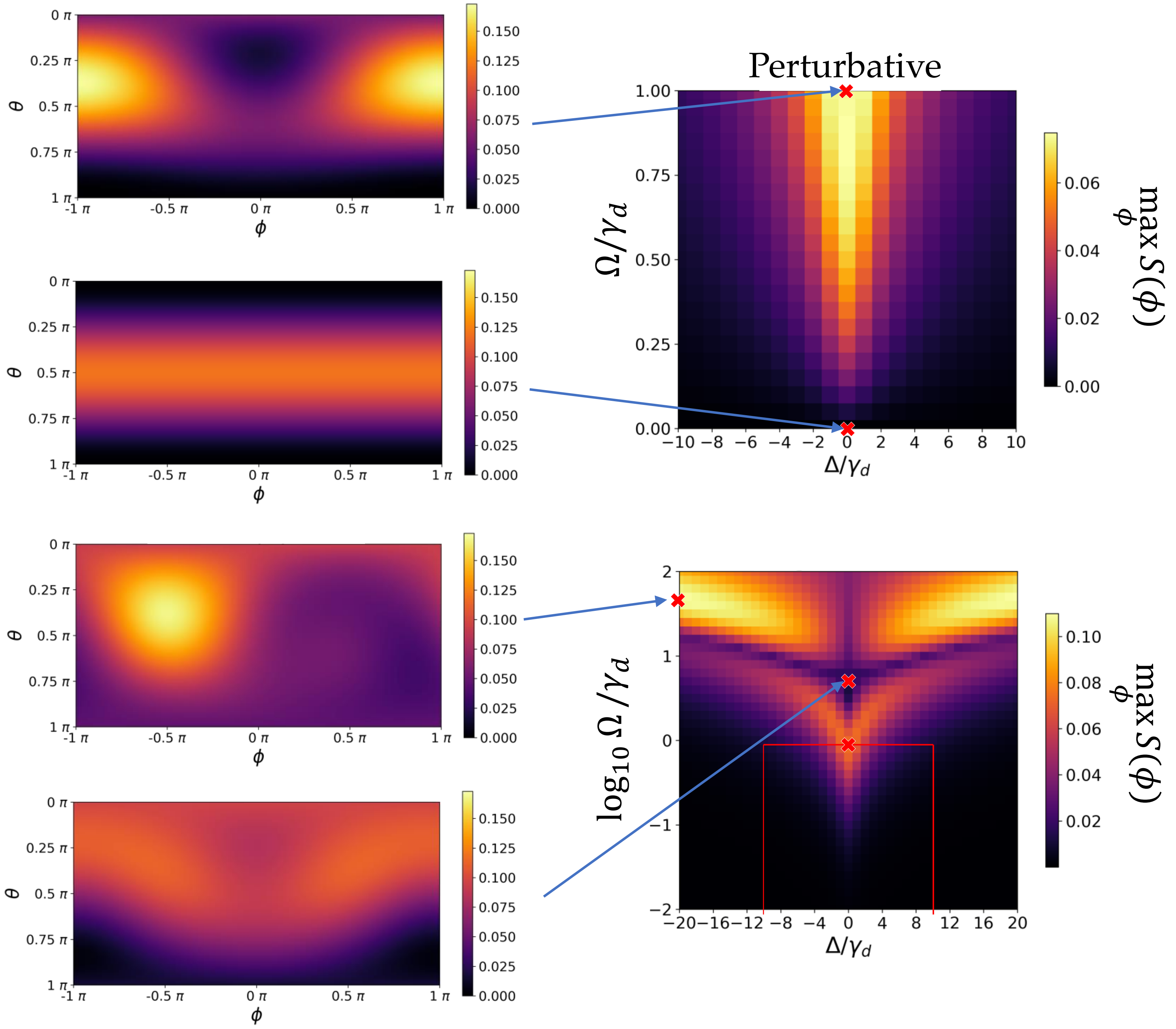
$\zeta = re^{i\theta}$ $\bar{n} = 1$



Synchronization

- We define synchronization as **phase localization in the steady state**

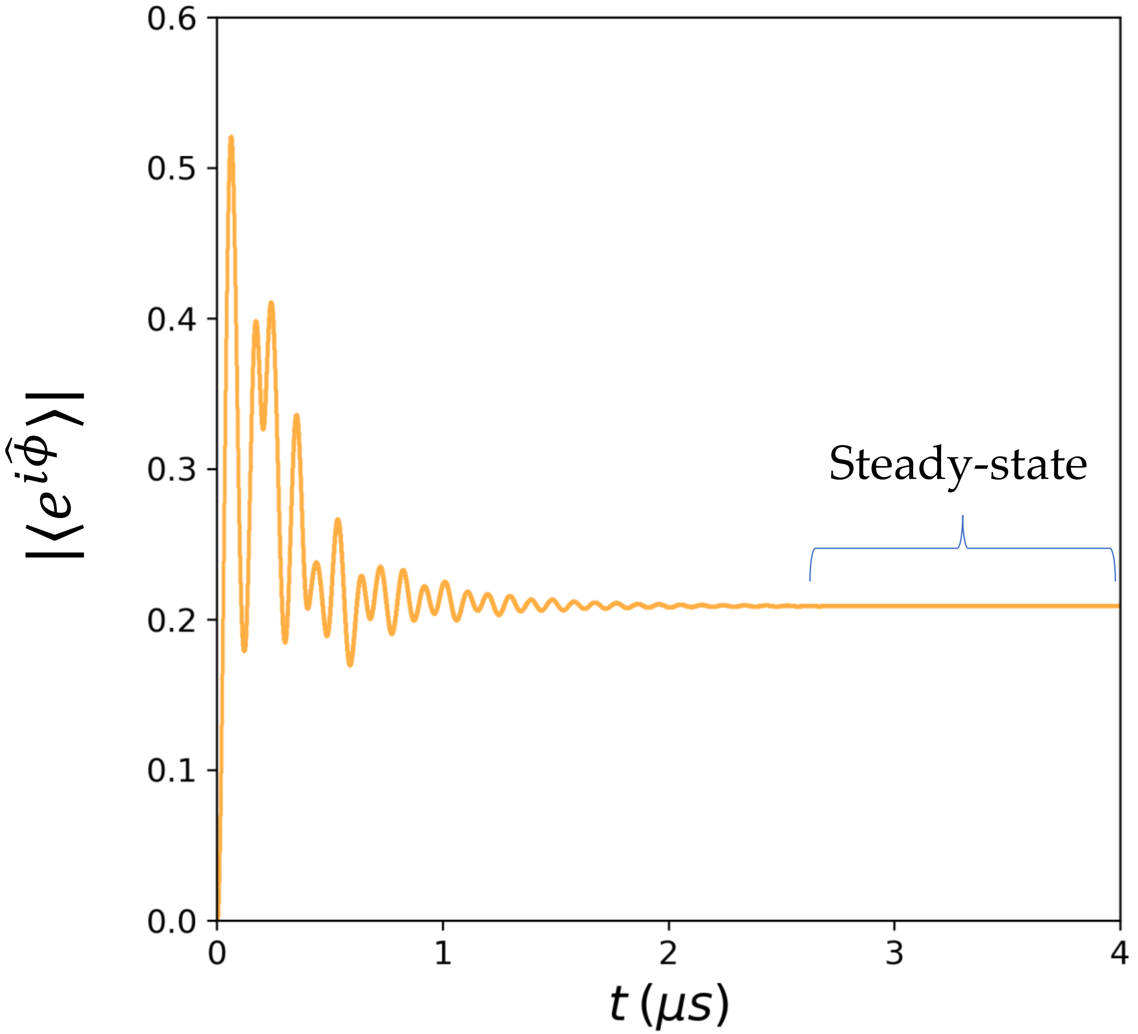
- A strong drive can destroy the limit cycle (= steady state without drive)



Synchronization, Classical Light

- $|\langle e^{i\hat{\phi}} \rangle|$ measures synchronization

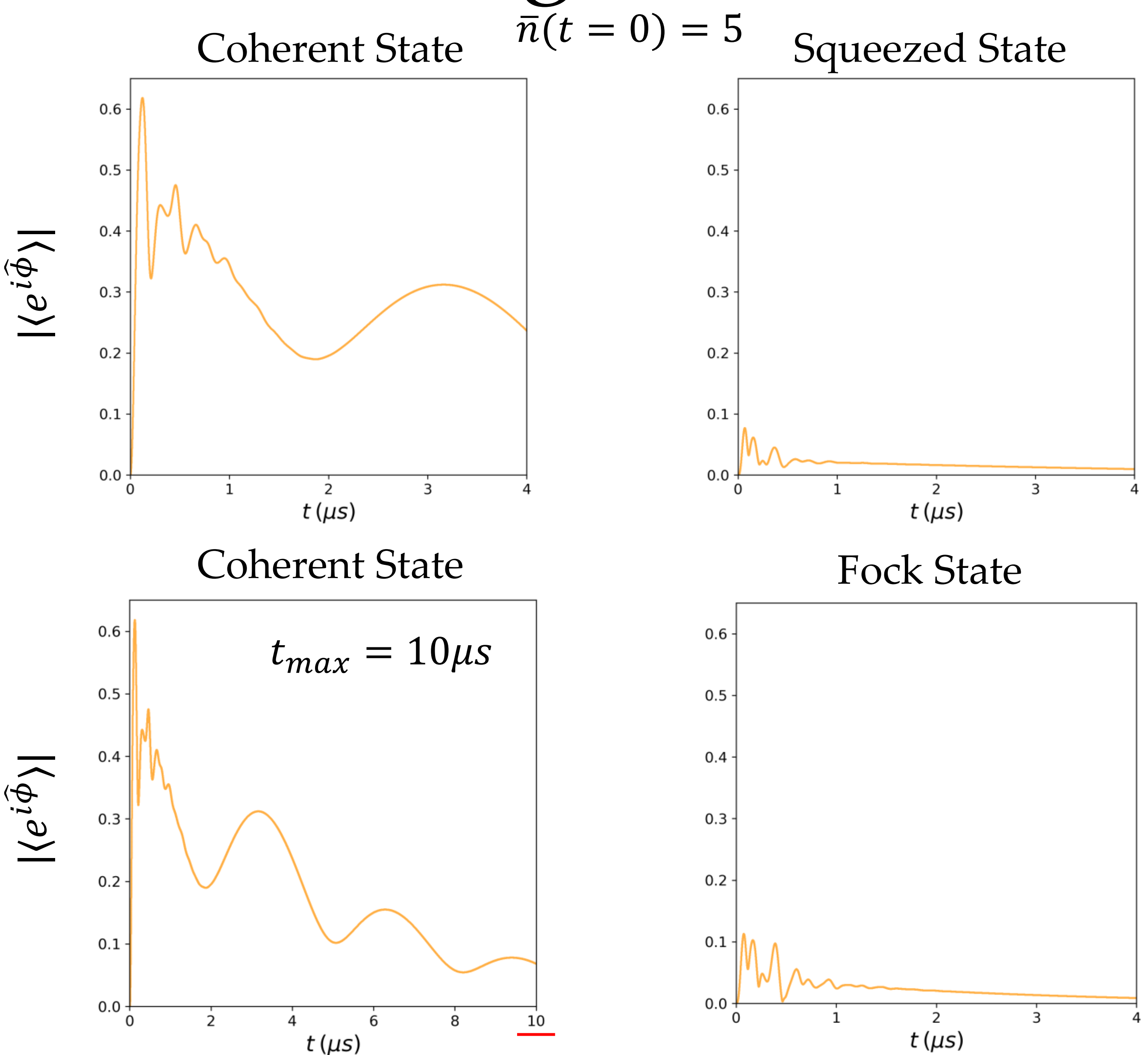
- Synchronization oscillates with time, approaching a steady-state limit



Synchronization, Quantum Light

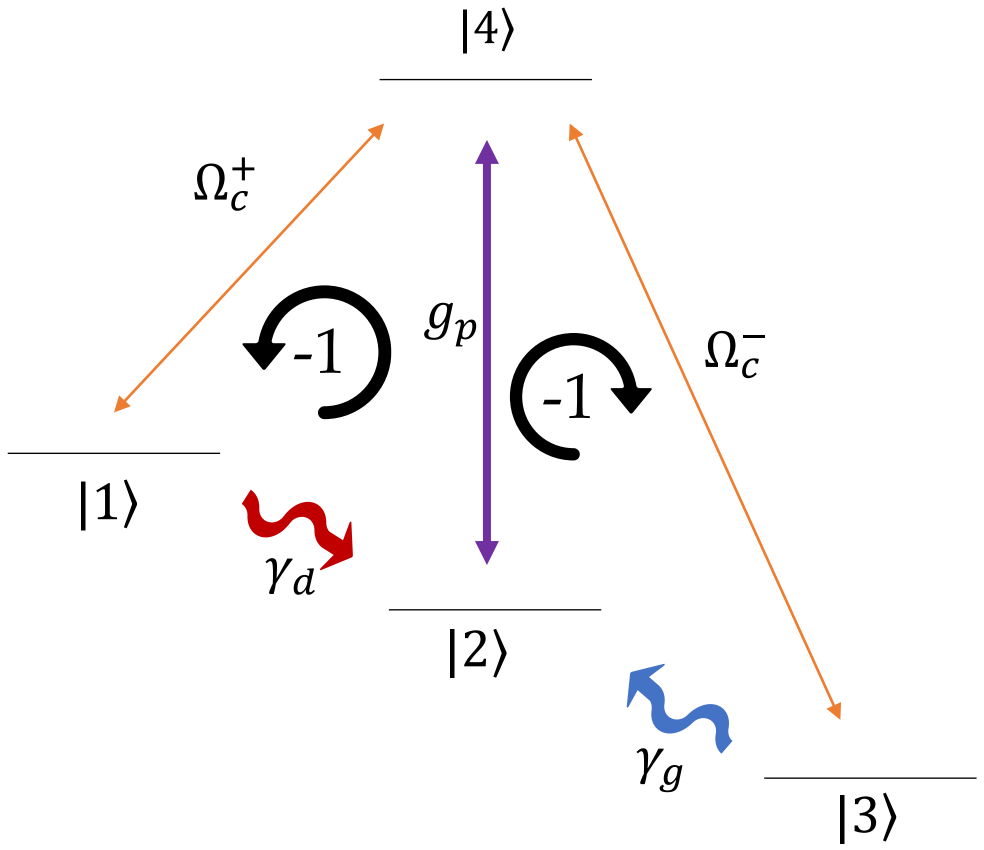
- Is $|\langle e^{i\hat{\phi}} \rangle|$ a valid measure of synchronization for a quantum drive?

- Synchronization oscillates with time, before decaying to zero



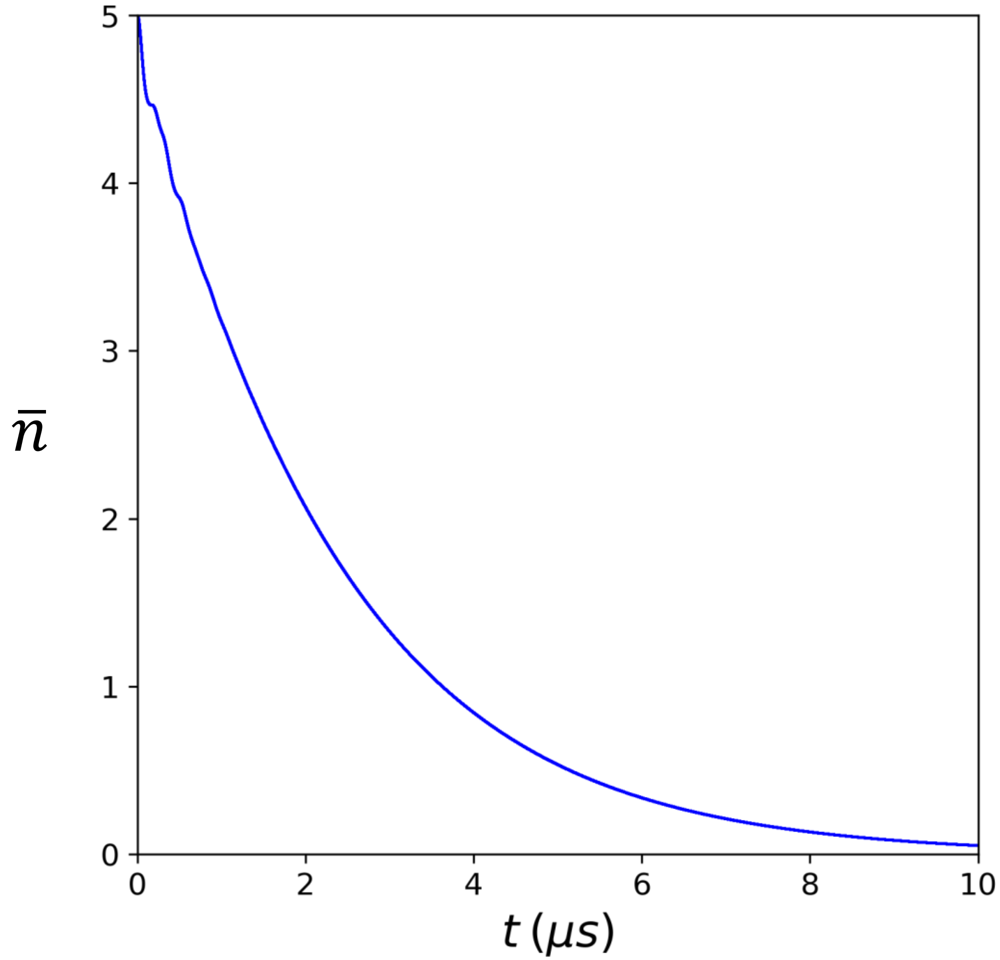
Synchronization, Quantum Light

- The nature of the system is such that photons can be repeatedly absorbed
- There is no analogous path for photon emission
- The reservoir loses photons with time

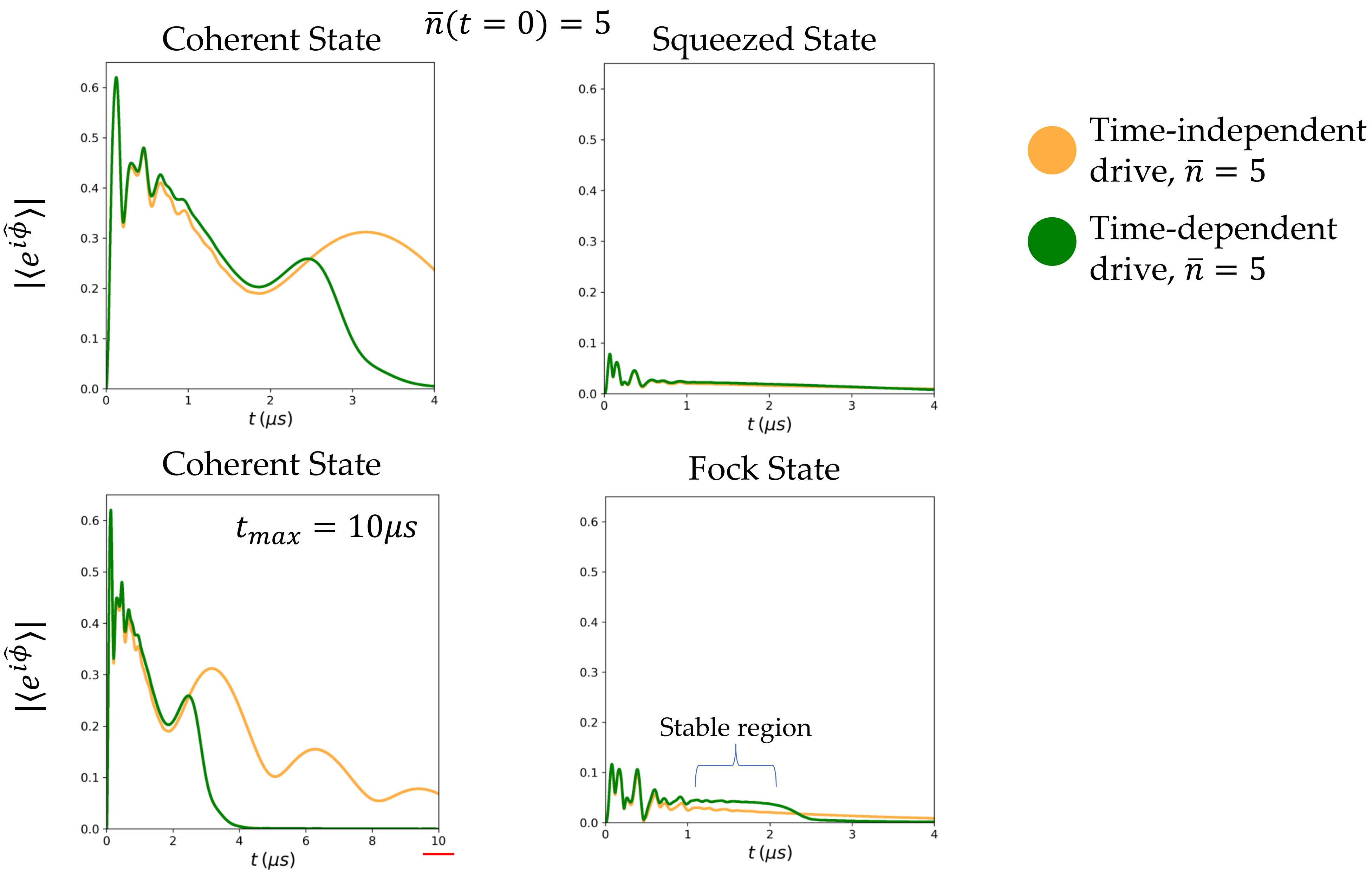


Quantum Light

- The effective drive strength (g_{eff}) evolves with time:
- $g_{eff} = g\sqrt{\bar{n}}$
- We can account for the absorbed photons by increasing the drive strength (g) with time



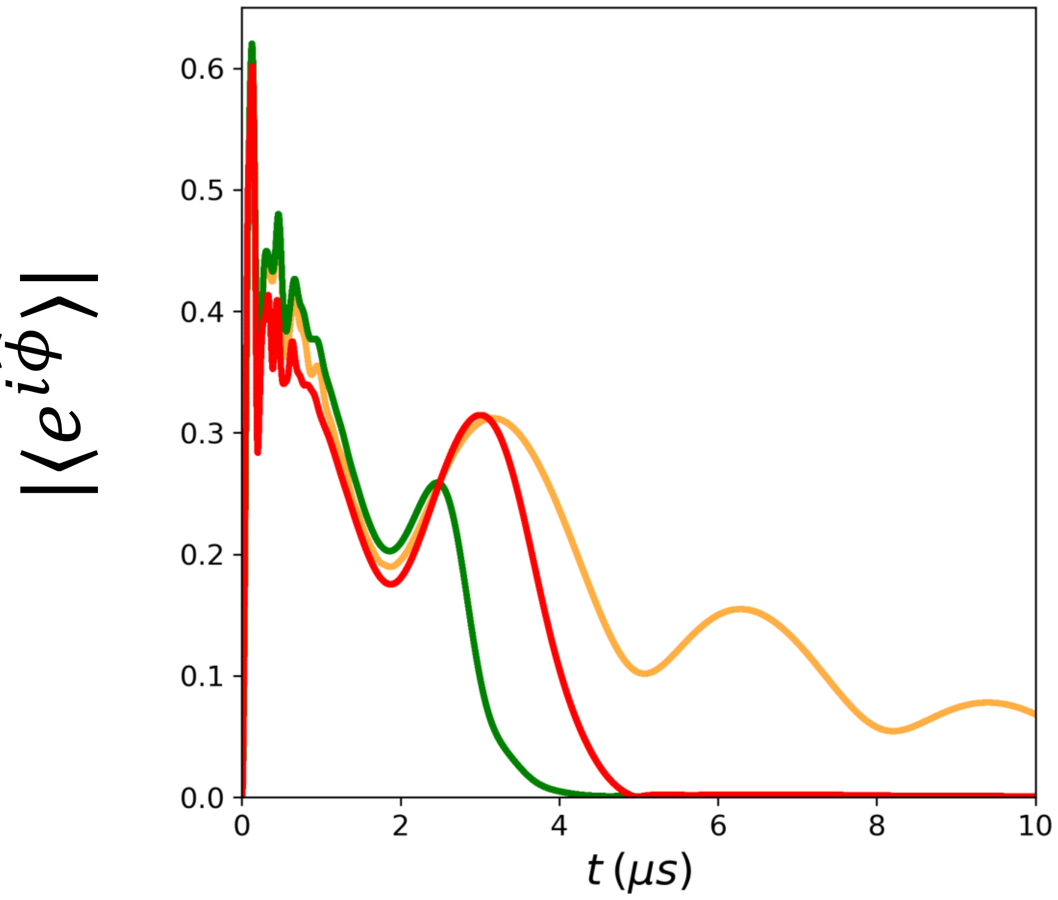
Synchronization, Time-dependent Drive



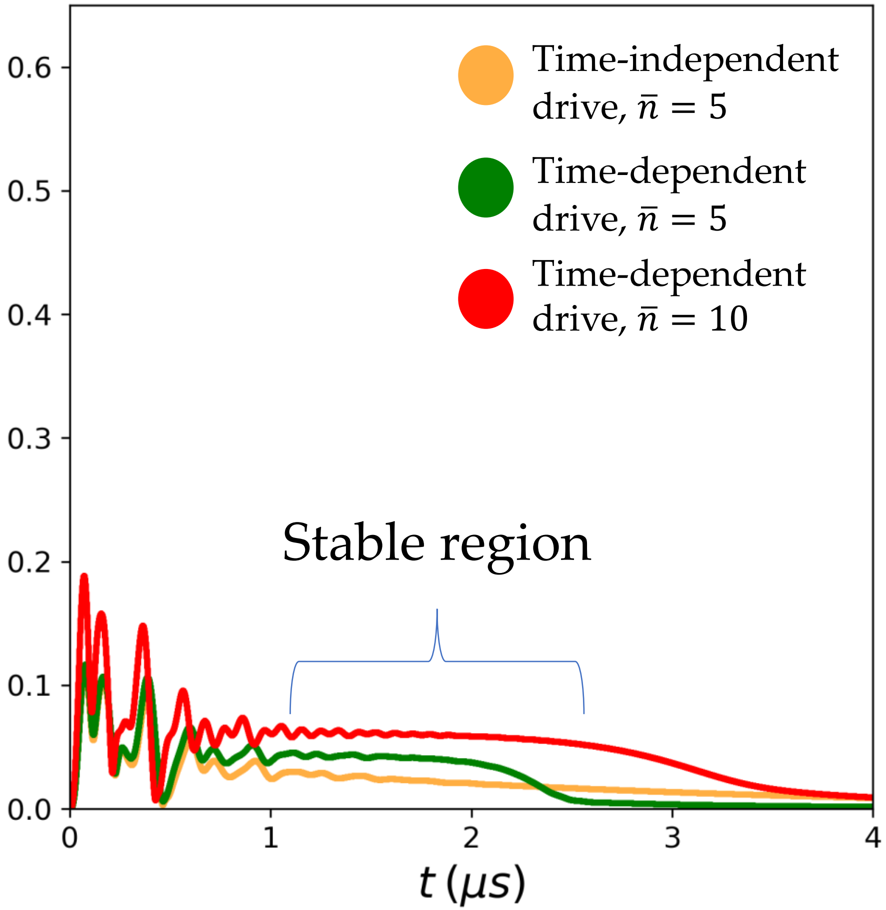
Synchronization, time-dependent drive

$\bar{n}(t=0) = 10$

Coherent State

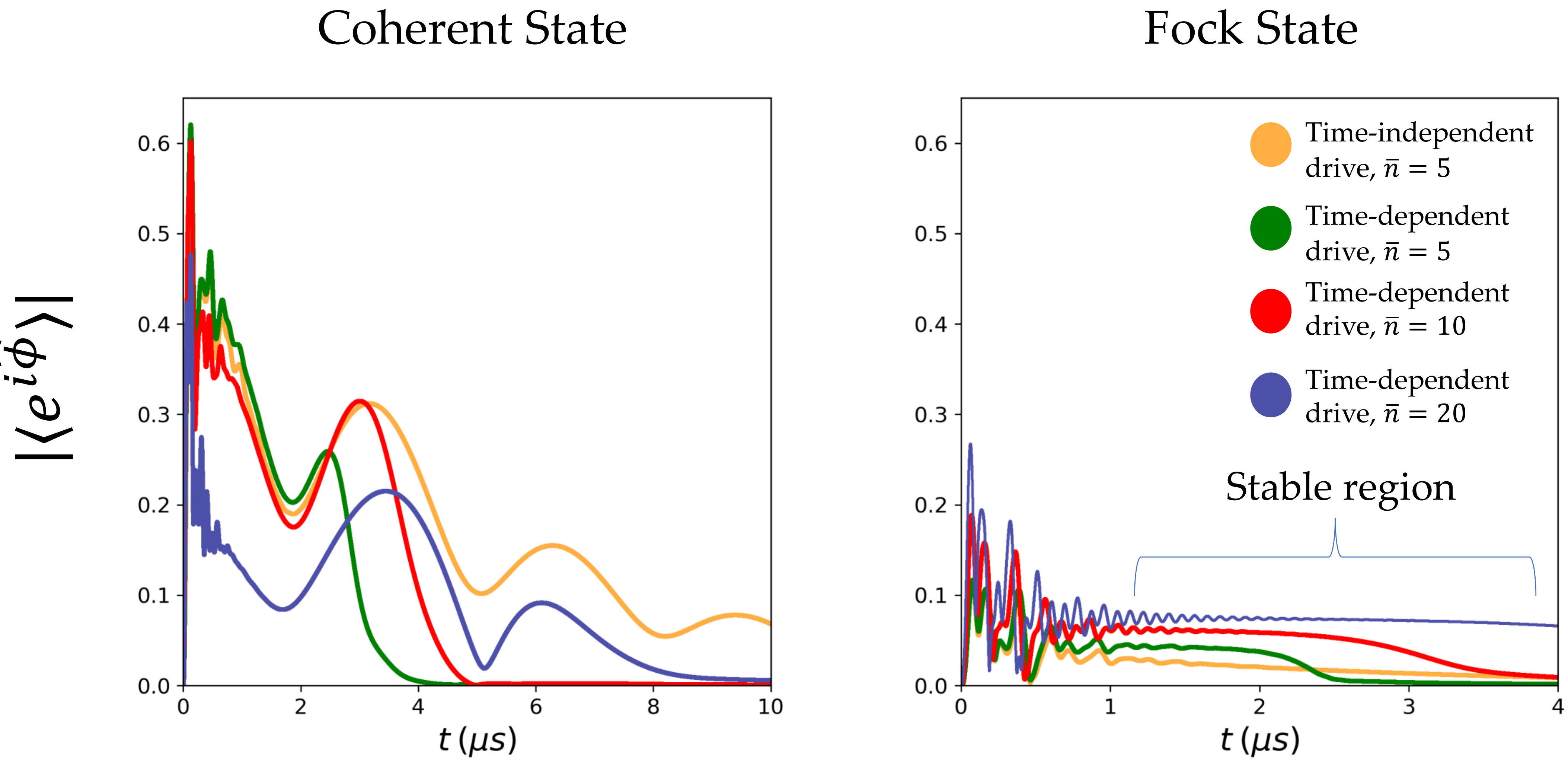


Fock State



Synchronization, time-dependent drive

$\bar{n}(t = 0) = 20$



Conclusion

- Quantum light uniquely interacts with the spin-1 system
- It is possible to tune quantum light such that the synchronization resembles that of classical light
- We open a dialogue on whether quantum synchronization can be achieved and measured with improved accuracy using quantum light