Chaos-Assisted Tunneling in Atom Optics

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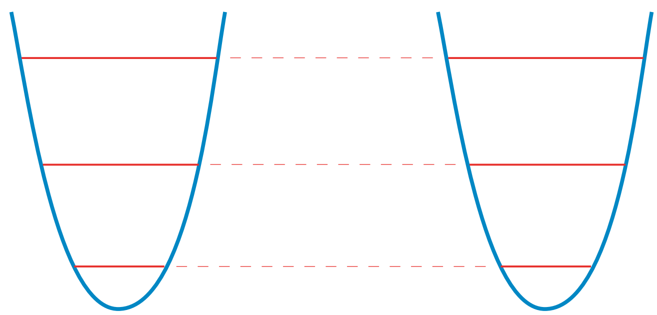
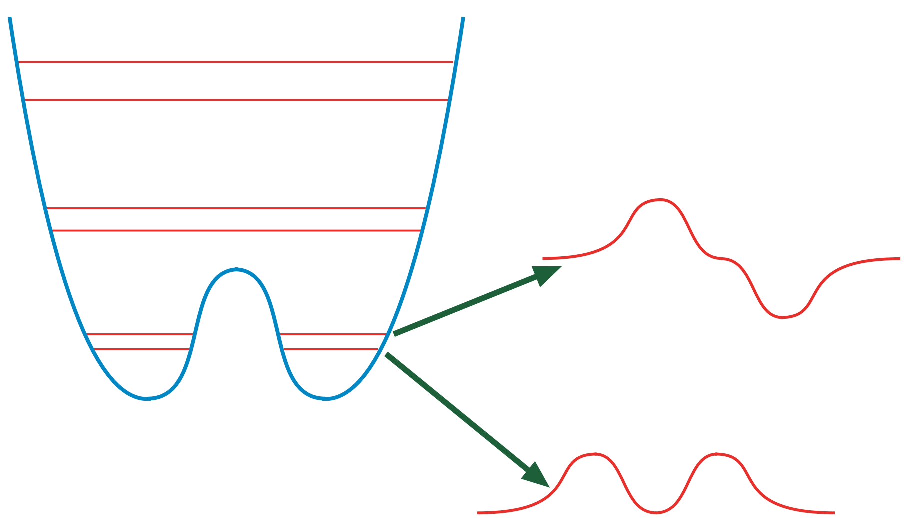
Barrier Tunneling

- Phase-space tunneling is related to tunneling in the double well potential

- Uncoupled limit: degenerate energy doublets



- Coupling (via the finite barrier) between the two wells leads to broken degeneracy and doublet structure



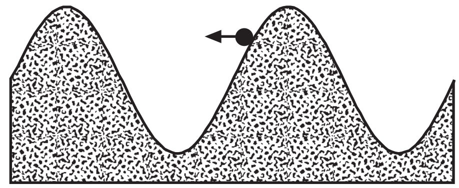
- Tunneling (Rabi oscillations) occur as the doublet states dephase

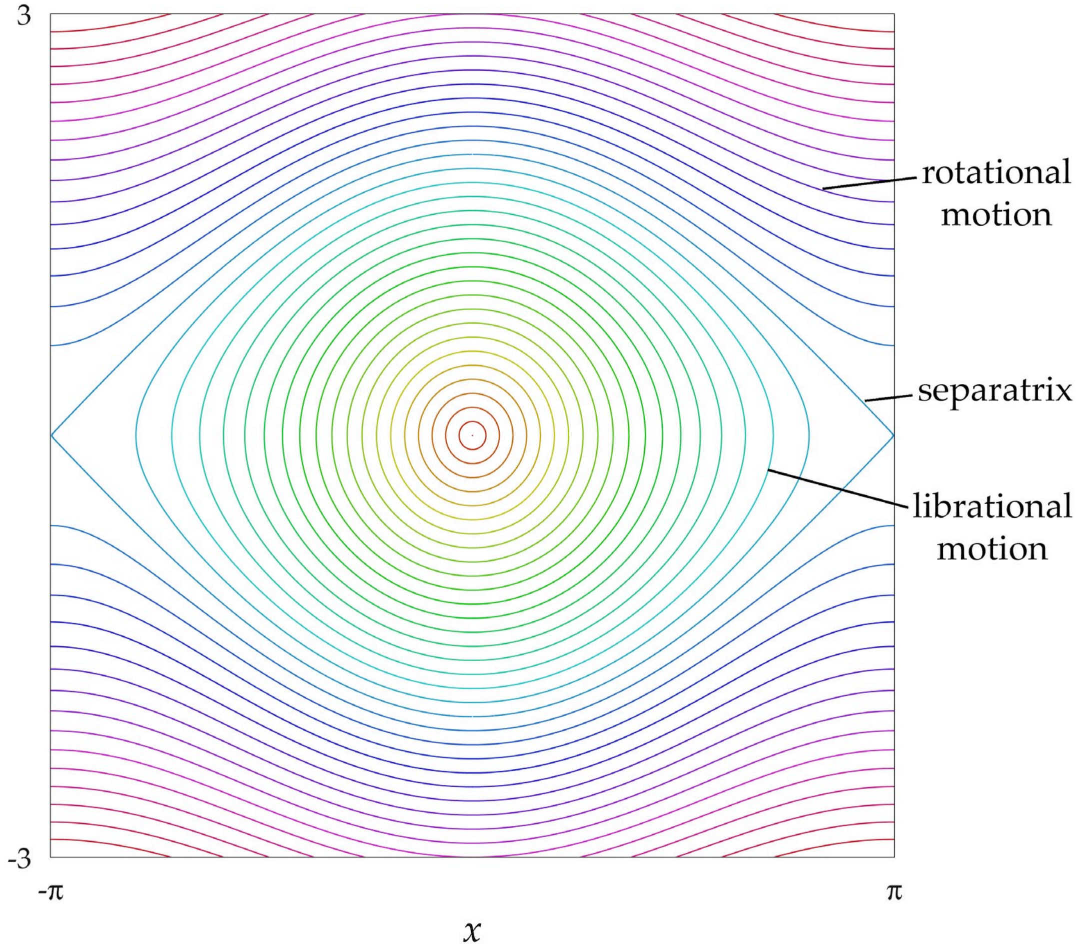
- Symmetry is important for tunneling, causes degeneracy in uncoupled limit (resonant Rabi oscillations)

Phase Space

- Graphical representation of the equations of motion

- Pendulum phase space:

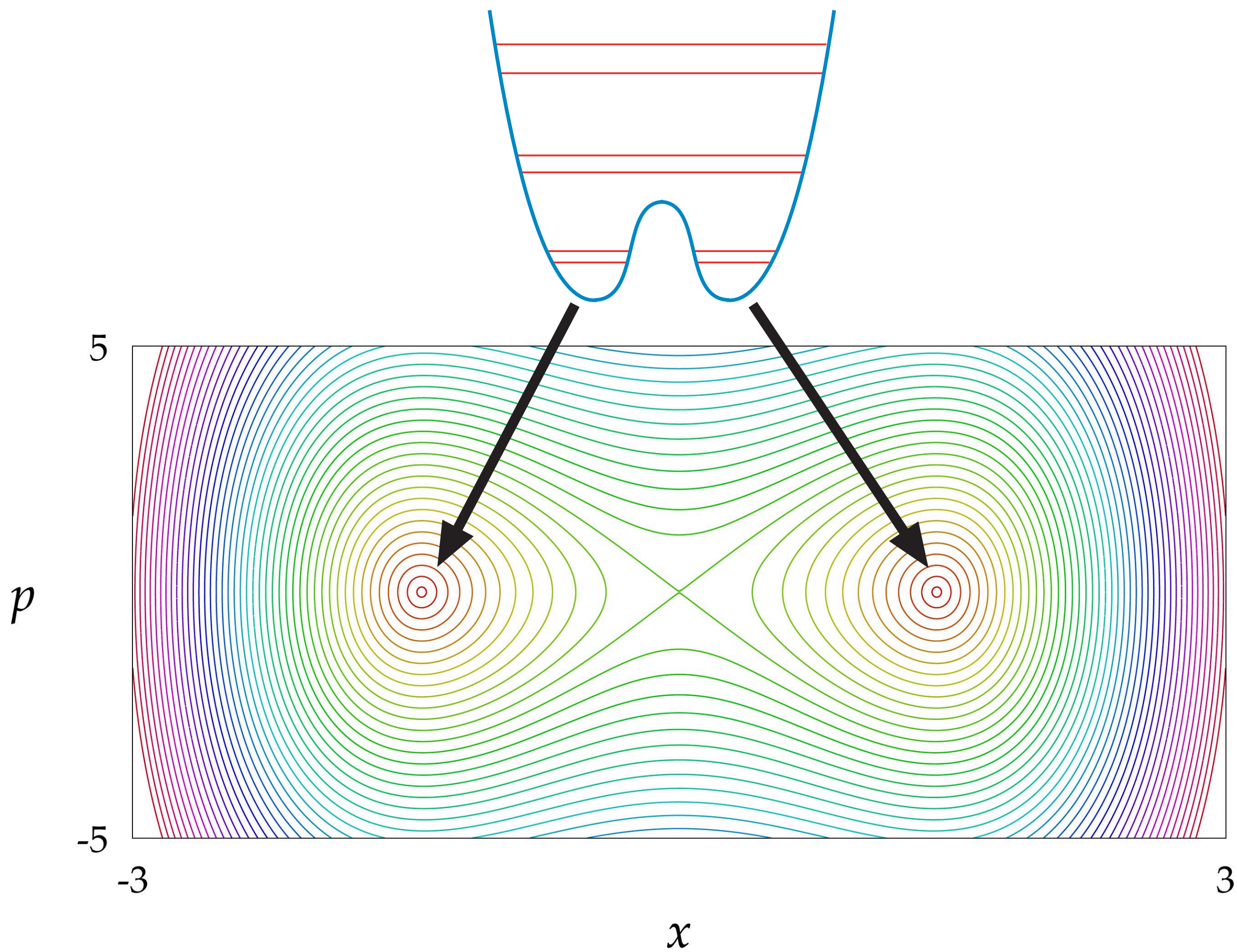




- Integrable systems: trajectories confined to surfaces of lower dimension in phase space

Double-Well Phase Space

- Can think of barrier tunneling in phase space



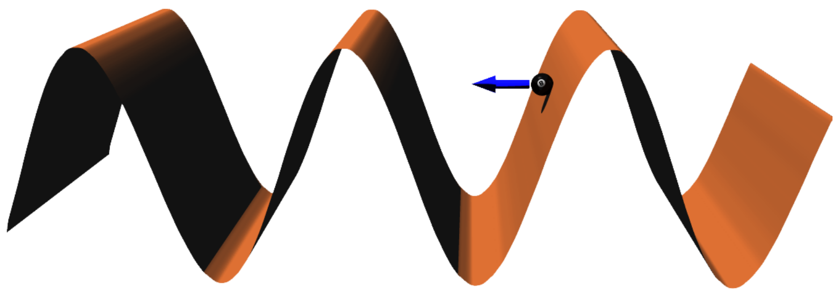
- Classical transport is forbidden: trajectories cannot cross invariant surfaces

- Quantum transport allowed: quantum paths can cross invariant surfaces, but are exponentially suppressed

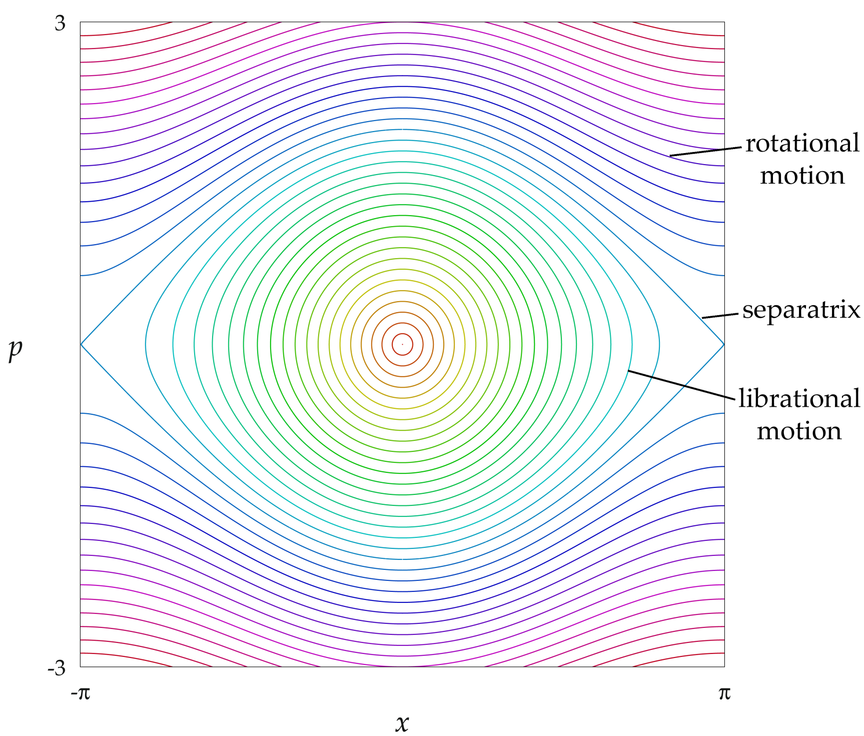
  - Leads to universal scaling: $\omega \sim \exp(-1/\hbar)$

Optical Lattices and Atom Optics

- Formed by retroreflecting a laser beam -- standing wave
  - stationary, 1-D sinusoidal intensity pattern:



- Far-detuned regime:
  - spontaneous (random) scattering negligible
  - intensity pattern creates spatial potential
- Atomic motion equivalent to pendulum:



Amplitude Modulation

- Full amplitude modulation of standing wave intensity:

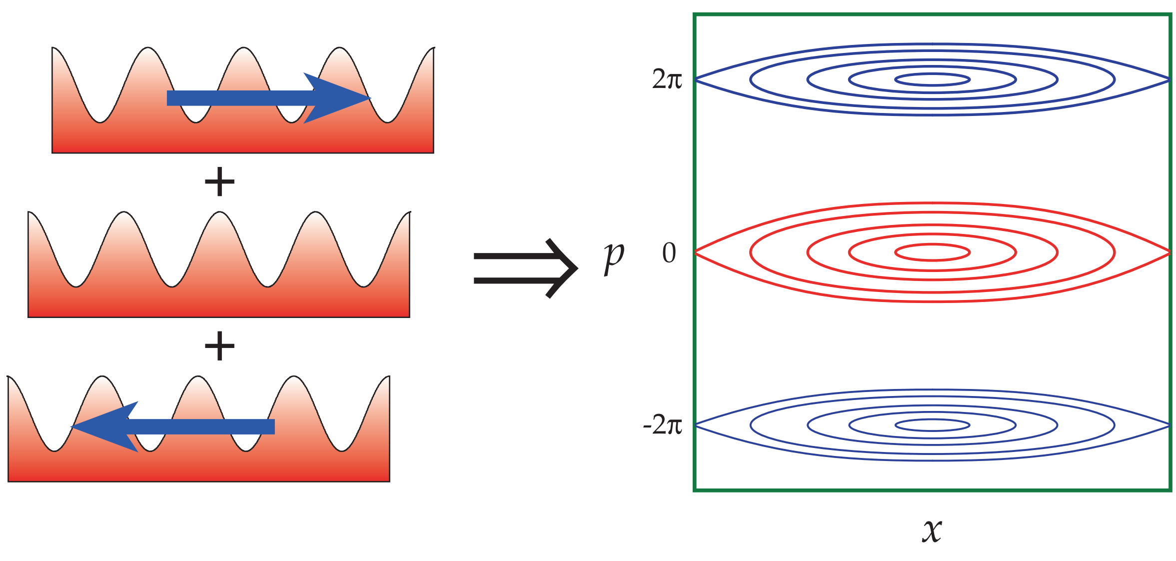
$$H = \frac{p^2}{2} - 2\alpha \cos^2(\pi t) \cos(x)$$

- Can rewrite potential as sum of 3 terms:

$$-\alpha \cos(x) - \frac{\alpha}{2} \cos(x + 2\pi t) - \frac{\alpha}{2} \cos(x - 2\pi t)$$

  - one stationary and two moving lattices (pendula)

- Phase space contains three pendulum-like features:

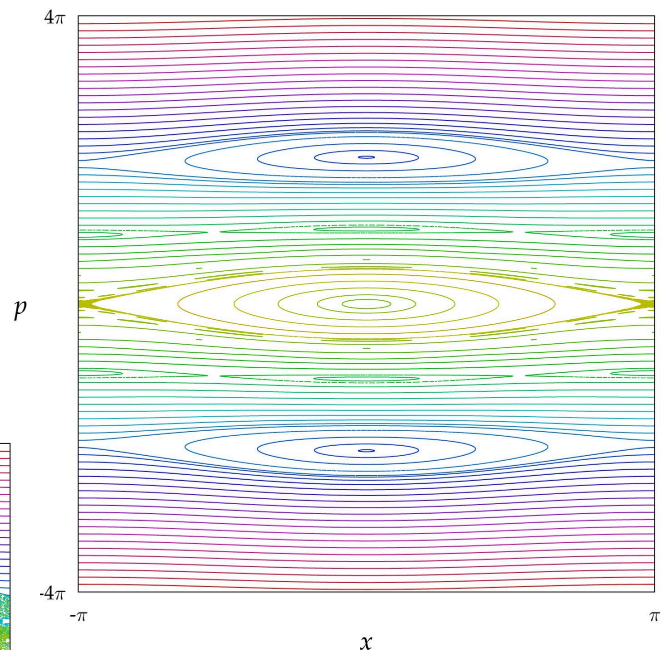


- Want to look for tunneling between two *symmetry-related* structures

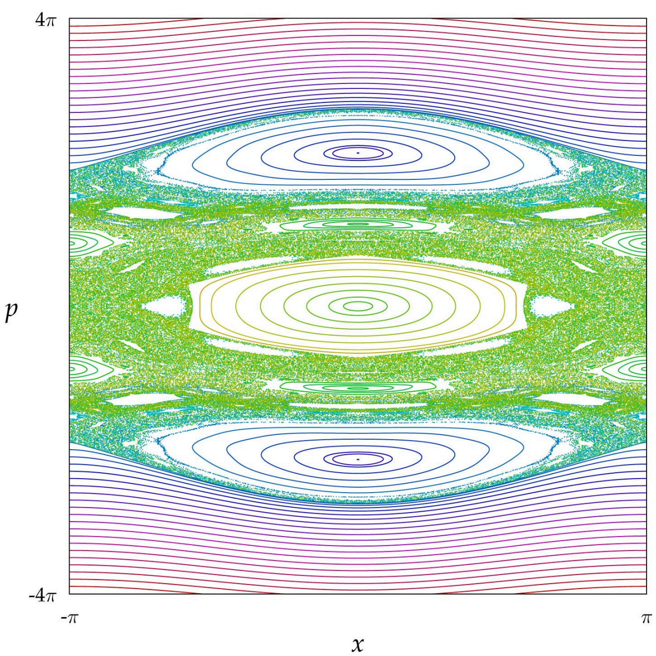
Chaos in Phase Space

- As α (well depth) increases, competition between the three modes of motion leads to chaos:

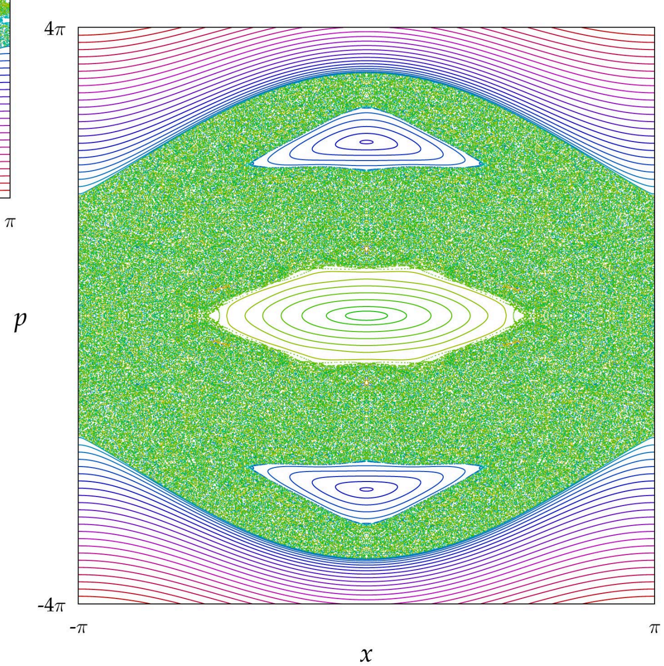
$\alpha = 0.6$



$\alpha = 2.0$

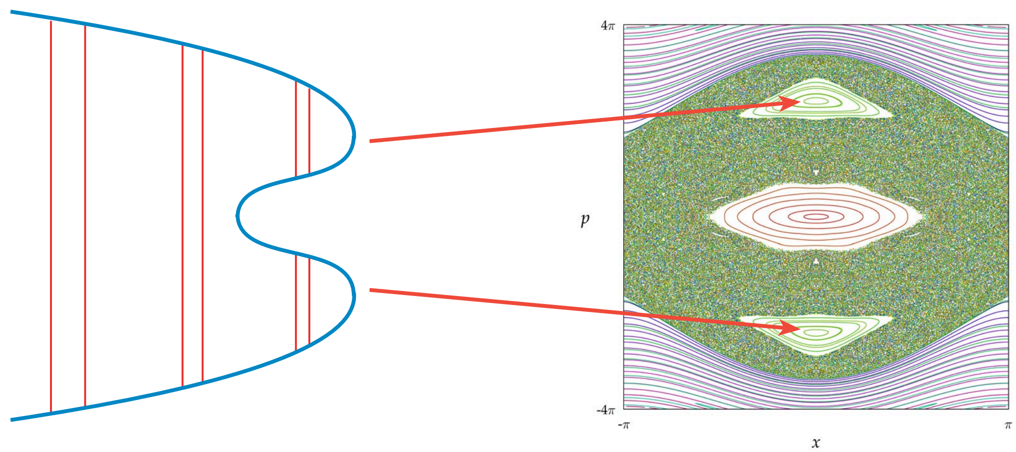


$\alpha = 6.0$



Dynamical Tunneling

- In our system, islands play the role of the two wells
  - Islands case localization of Floquet states
  - Transport out of islands is classically forbidden



- Simplest picture: tunneling between symmetric islands proceeds as symmetric/antisymmetric Floquet-state pair dephase

- This tunneling is *dynamical tunneling*: transport is forbidden by the dynamics, not a potential barrier

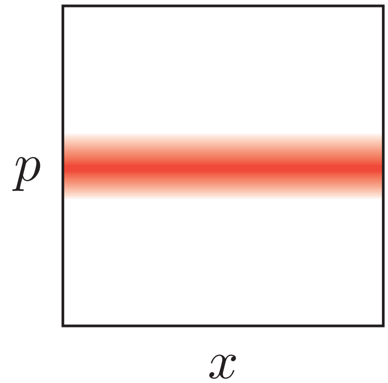
- Predicted by Davis and Heller, 1981

- Also under study by NIST/U. Queensland collaboration

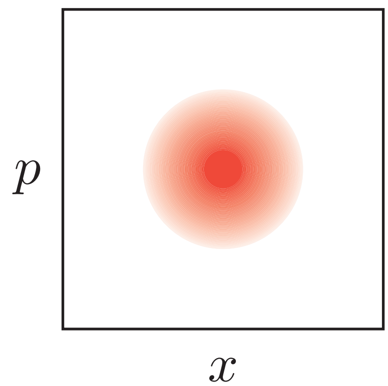
“Simple” Experiment

or “how not to observe tunneling”

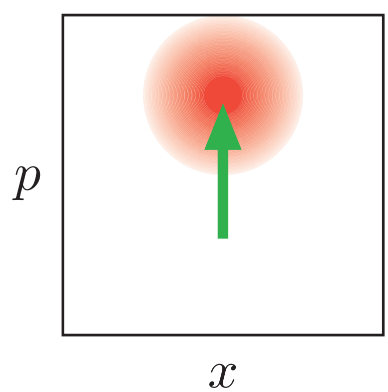
- Simplified approach: cool cesium atoms in a 3-D optical lattice to 400 nK ($\Delta p = 1.4\hbar k_{\mathrm{L}}$)



- Adiabatically turn on 1-D standing wave
  - size is three times that of a minimum-uncertainty packet



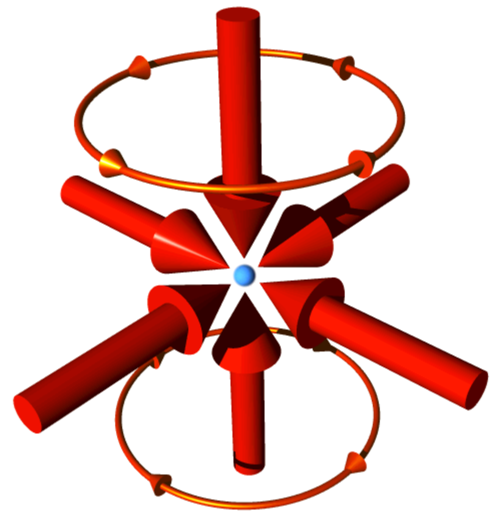
- Boost wave packet to match island velocity



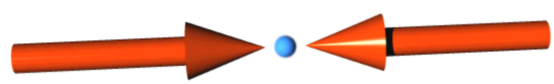
- Modulate lattice to realize amplitude modulated pendulum...

Measurement Sequence

1. Magneto-optic trap/
   preparation (5 s)

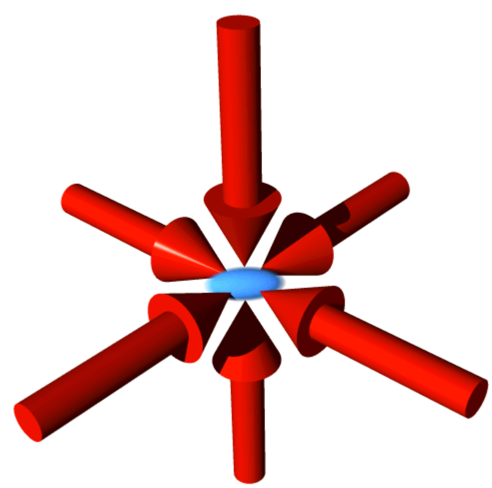


2. (State Preparation)
   (1 ms)
3. Time-Dependent
   Optical Lattice
   (1 ms)



4. Free expansion
   (15 ms)

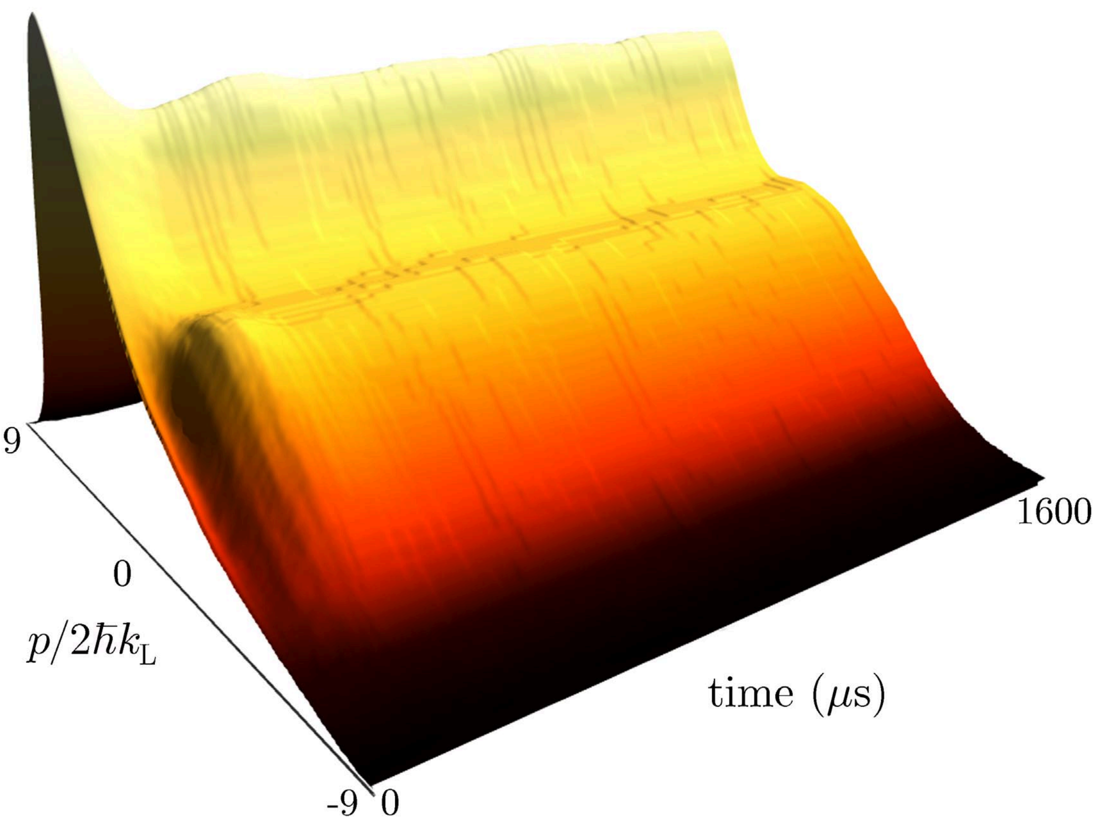
5. Freezing optical molasses/
   imaging (1 ms)



- Technique for measuring momentum distributions/energies

Tunneling in Phase Space?

- Experimental momentum distributions vs. time:

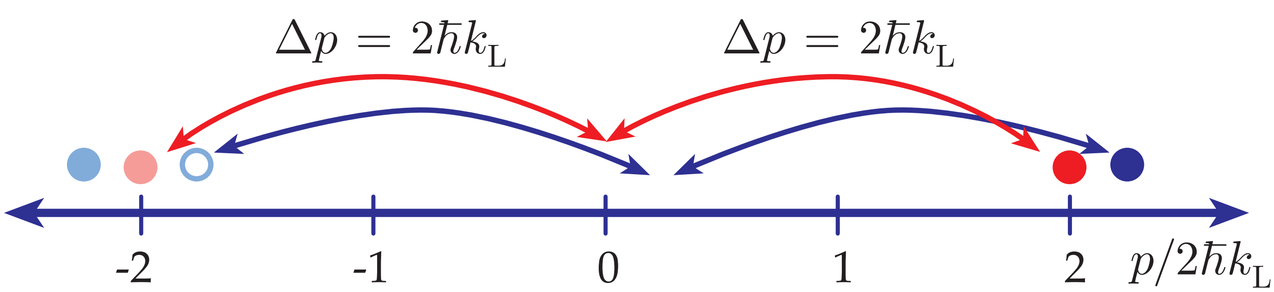


Symmetries

- *Classical symmetry*: satisfied due to island structure in phase-space
- *Quantum symmetry*: quantum mechanics imposes an additional symmetry

  - atoms change momentum in multiples of $2\hbar k_{\mathrm{L}}$

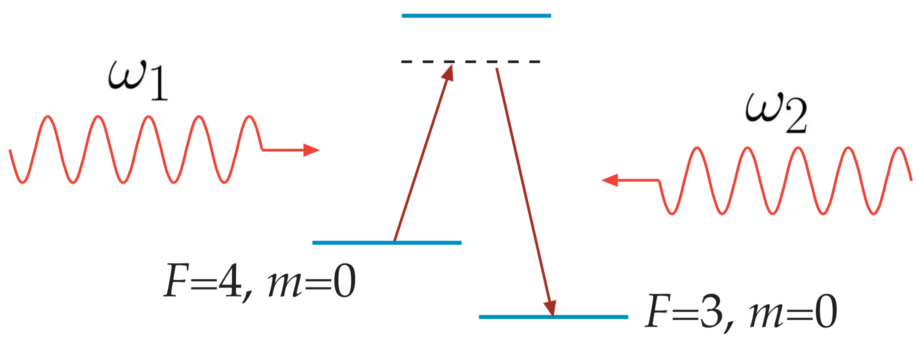
  - tunneling requires that states are coupled to their reflections about $p = 0$ via these discrete steps



- Consequence: only certain "integer states" can tunnel
- Analogous to asymmetric double well or broken time-reversal symmetry
- Requires subrecoil velocity selection

Raman Velocity Selection

- Use stimulated, two-photon transition between cesium ground states:



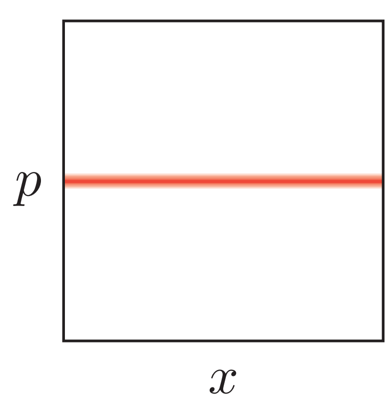
- If the two beams are counterpropagating, the atomic momentum enters into the resonance condition:

$$\omega_2 - \omega_2 = 2\pi \cdot 9.2\ \mathrm{GHz} + \frac{p}{\hbar k_{\mathrm{L}}} \cdot 4\omega_r$$

- Velocity selection procedure:

  1. Optically pump to $F = 4$, $m = 0$
  2. Tag atoms with proper velocity into $F = 3$
  3. Push away $F = 4$ atoms with resonant light

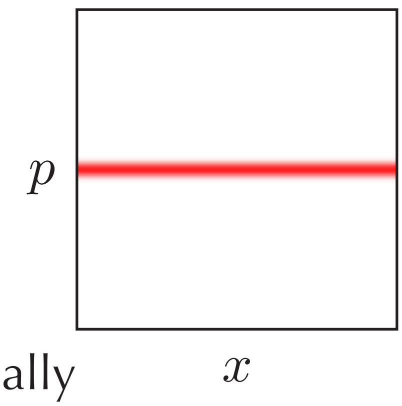
- Result: subrecoil atoms near $p = 0$



State Preparation

- Create localized state while preserving subrecoil structure

1. Begin with subrecoil sample from Raman tagging

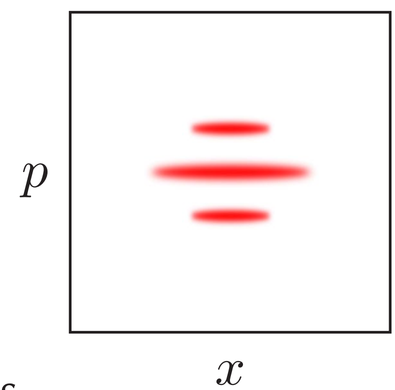


2. Turn on 1-D standing wave adiabatically

   - atoms become localized in the lattice wells, also heating

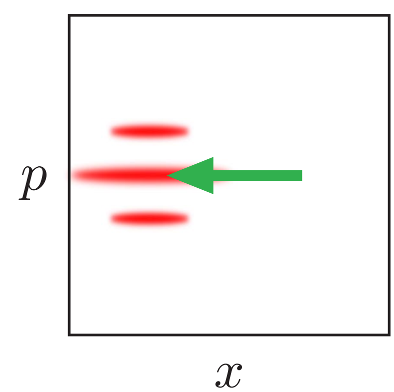
   - subrecoil slices within overall profile ⇒ coherence over several wells

   - minimum uncertainty for deep wells



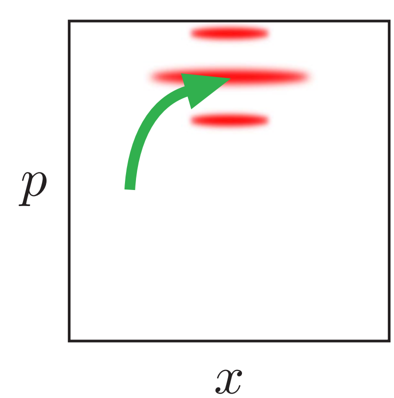
3. Sudden shift of standing-wave phase

   - using phase modulator before standing-wave retroreflector



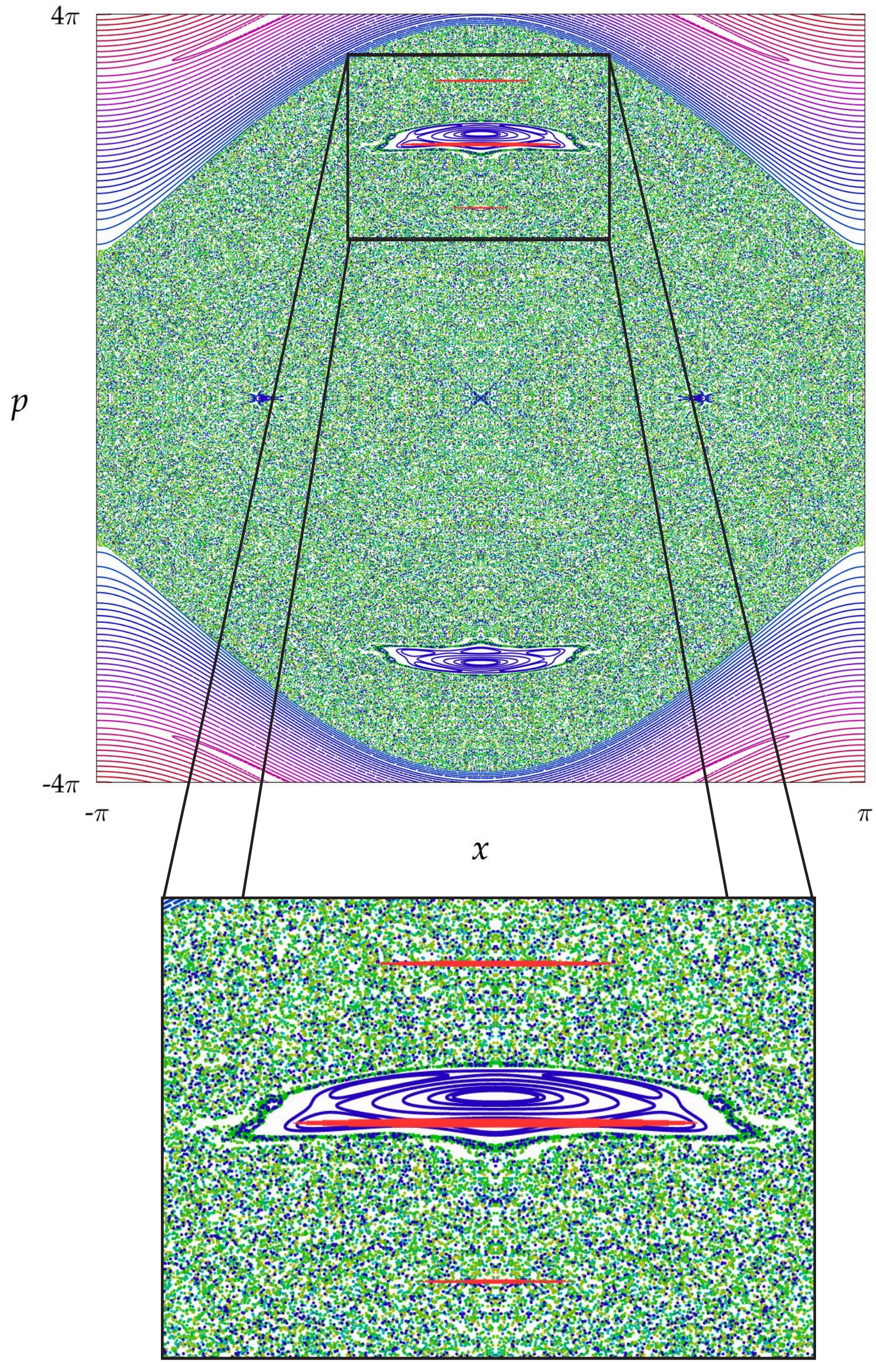
4. Free evolution of atoms in optical lattice

   - nearly harmonic evolution until p is maximized



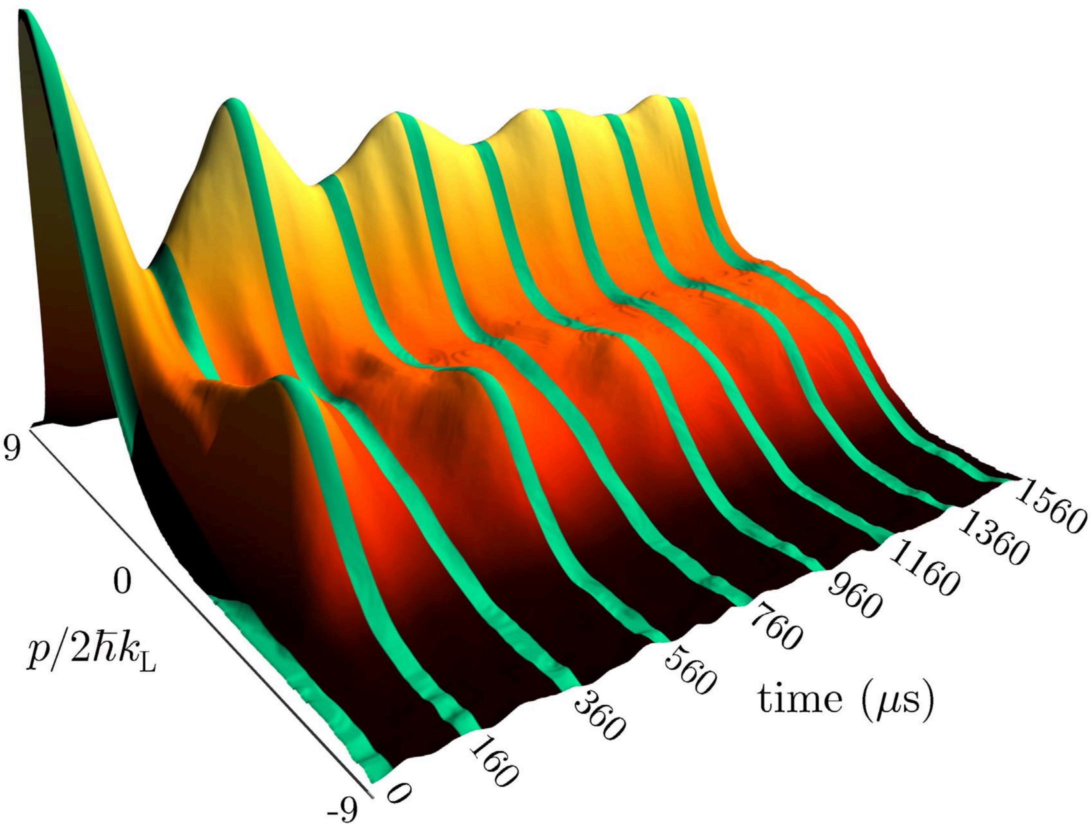
Initial Condition in Phase Space

- Initial conditions with Raman $\Delta p = 0.03{\times}2\hbar k_\mathrm{L}$
- Other parameters: $\alpha = 10.5$, $\bar{k} = 2.08$

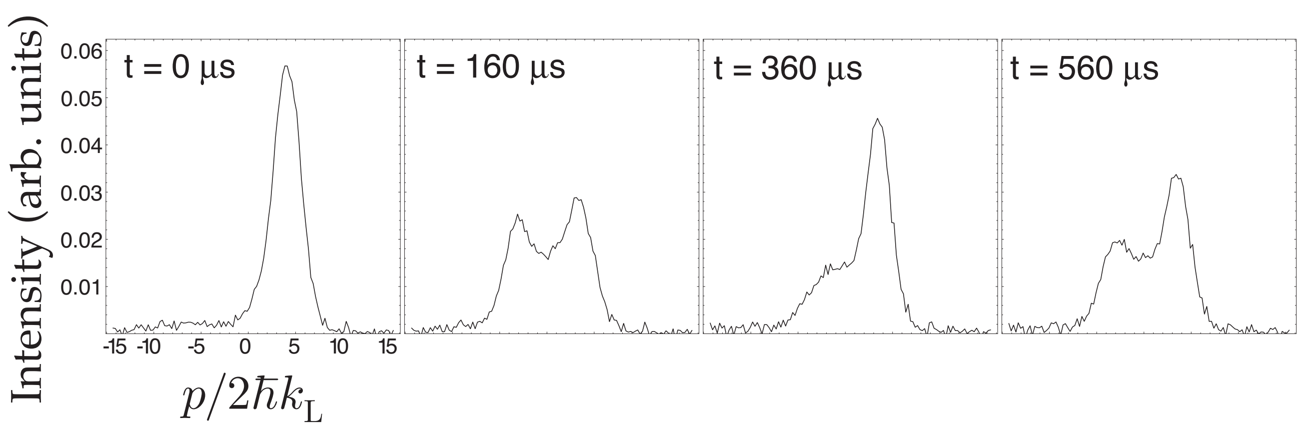


Tunneling in Phase Space

- Experimental momentum distributions vs. time, this time with Raman $\Delta p = 0.03 \times 2\hbar k_{\mathrm{L}}$ (800 μs tag):

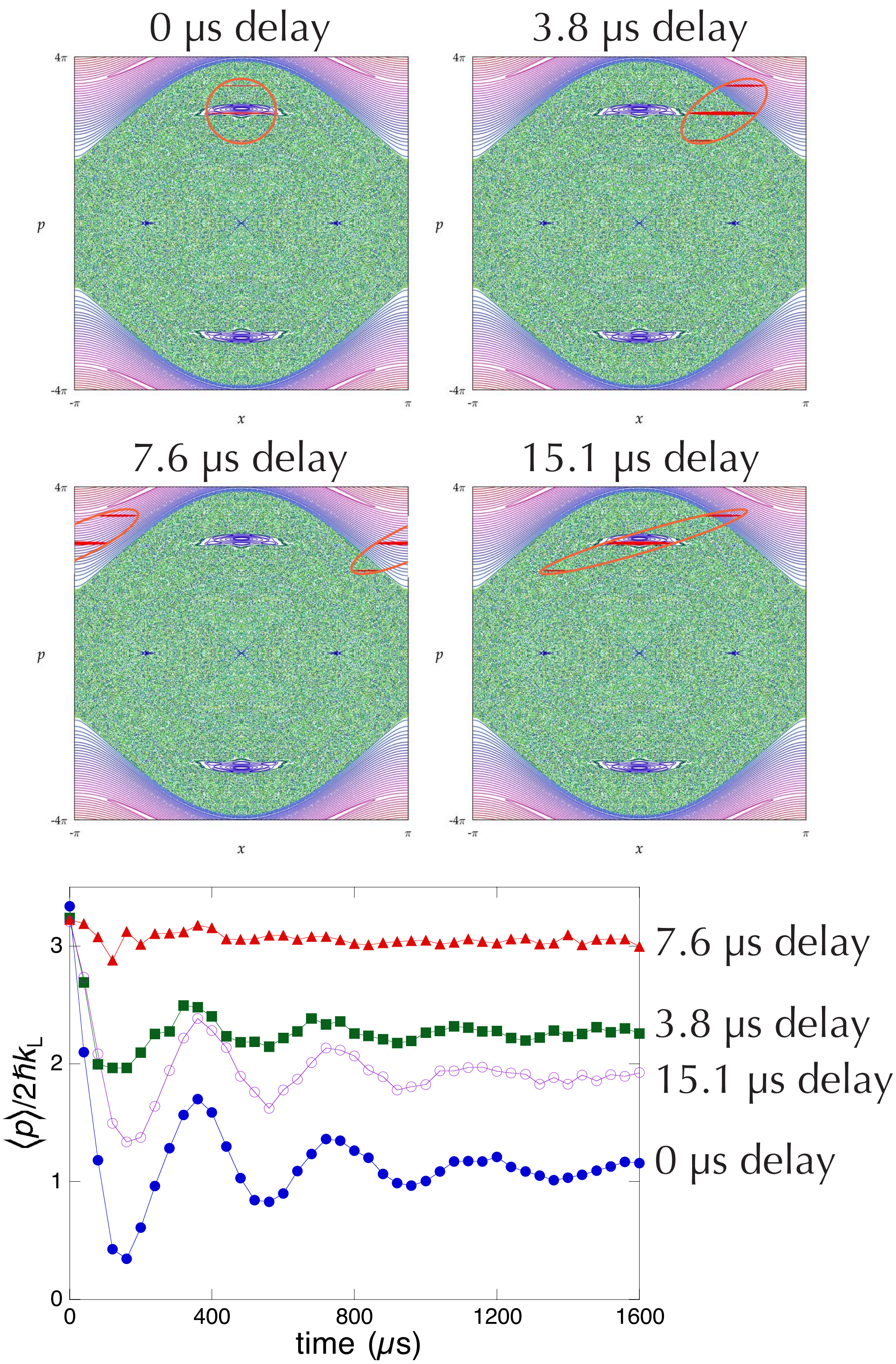


- Four oscillations before damping away
- Coherent, 16-photon transition
- Parameters: $\alpha = 10.5$, $\bar{k} = 2.08$



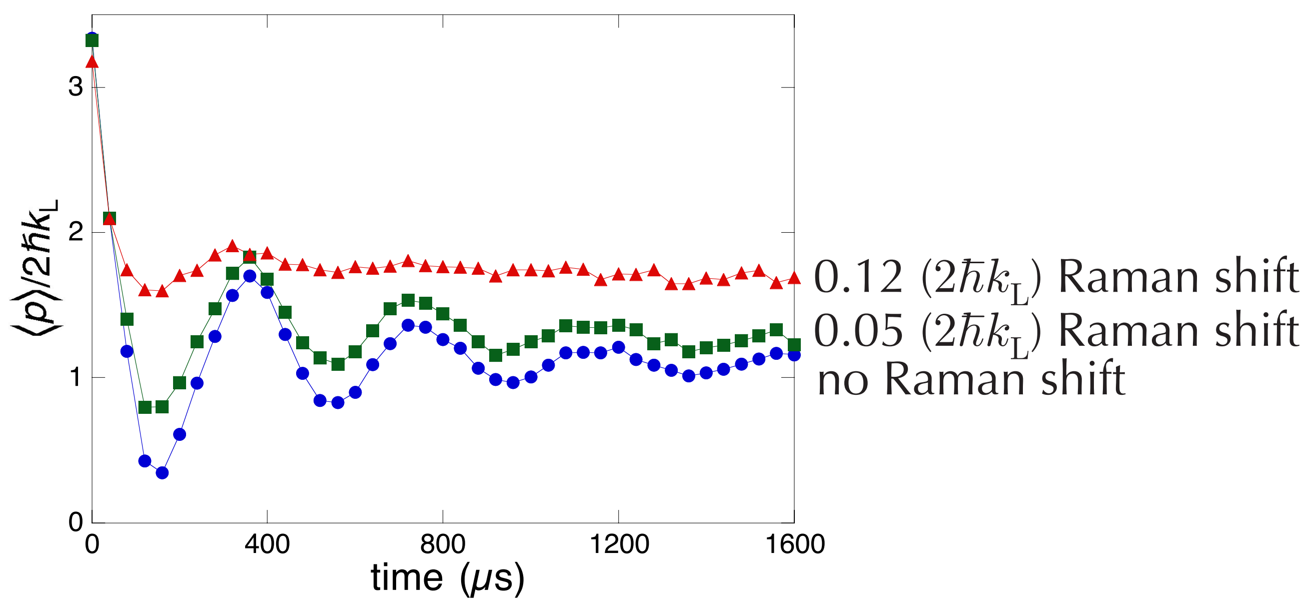
Island Dependence

- Verify that tunneling is indeed related to classical island structure, by inserting delay time after state preparation:

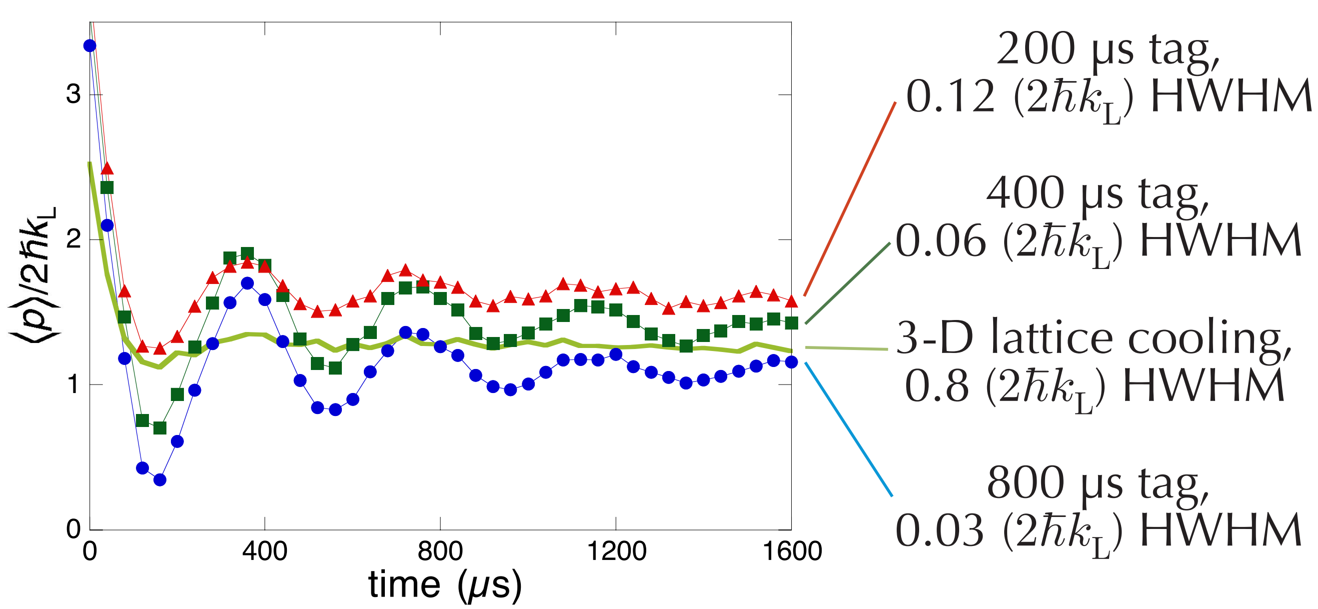


Raman Tagging Effects

- Shift locations of velocity slices within overall shape by changing Raman detuning:



- Vary width of Raman velocity selection:



- Incomplete tunneling due mostly to Raman tag width

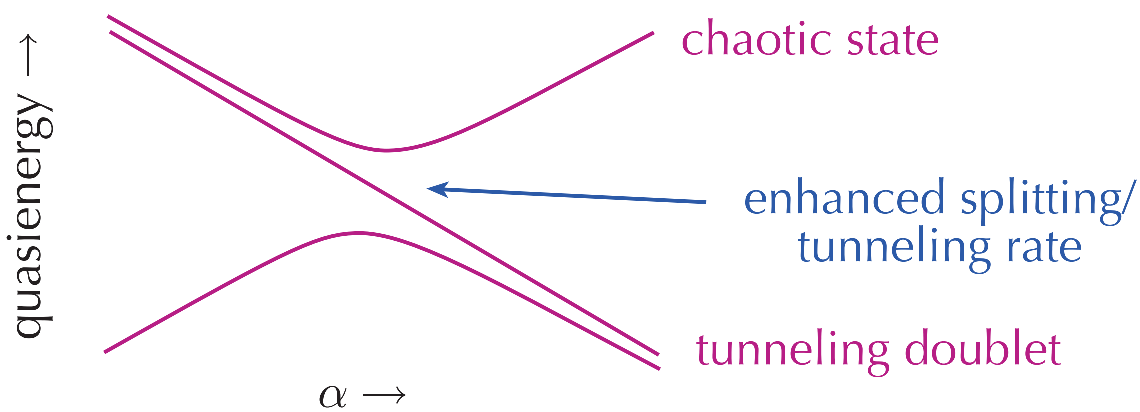
Chaos-Assisted Tunneling

- Tunneling is "assisted" by the chaos in the sense that tunneling can be greatly enhanced by the presence of chaos

- Enhancement can be understood in two ways:

  - Quantum paths: paths through chaotic region are not attenuated as strongly as those that cross KAM tori

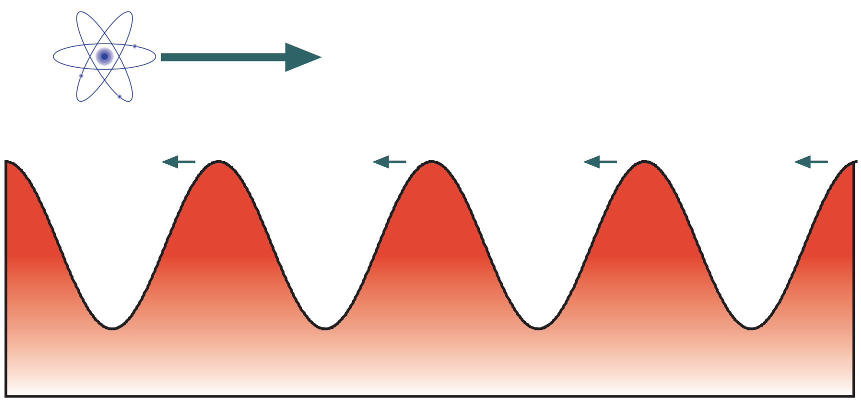
  - Avoided crossings: tunneling doublet can interact with a third chaotic state, prying apart the doublet



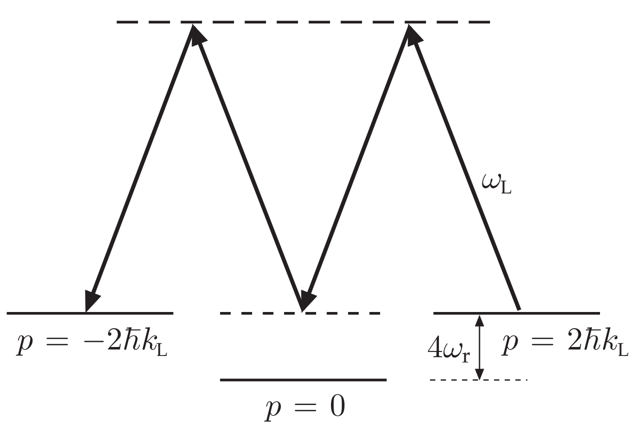
- Should be strong fluctuations in the tunneling rate as parameters vary; no universal dependence

Bragg Scattering

- This tunneling is reminiscent of another form of tunneling in optical lattices: Bragg scattering
- Dynamical tunneling in a stationary (integrable) lattice: atom can reverse direction quantum mechanically but not classically

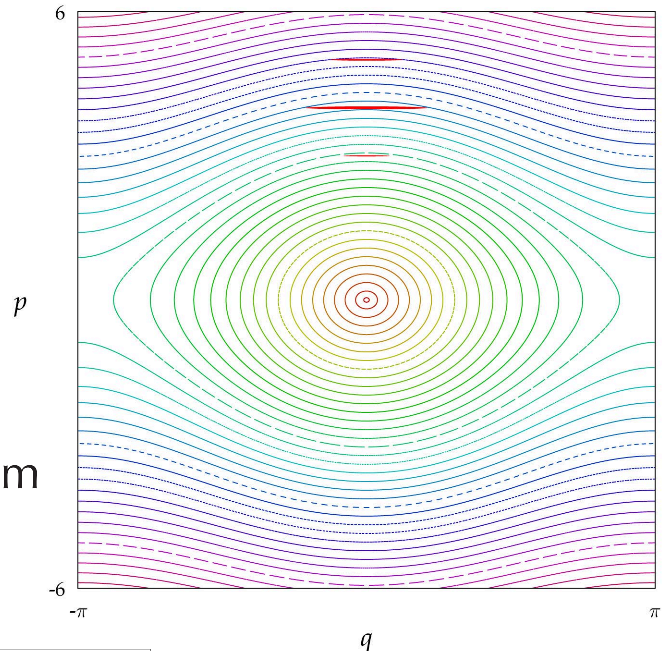


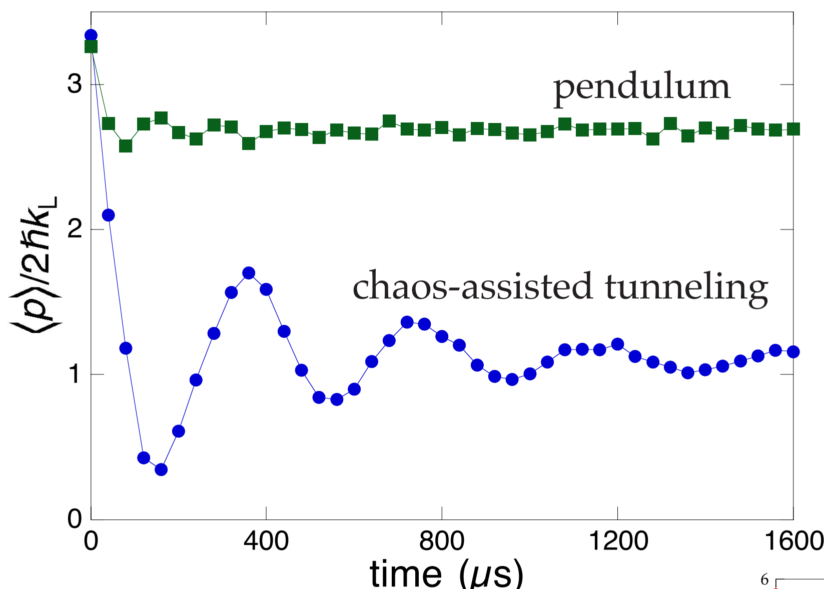
- Two-state process: transition between two symmetric plane-wave states
- Intermediate states are negligibly populated:



Comparison with Integrable Tunneling

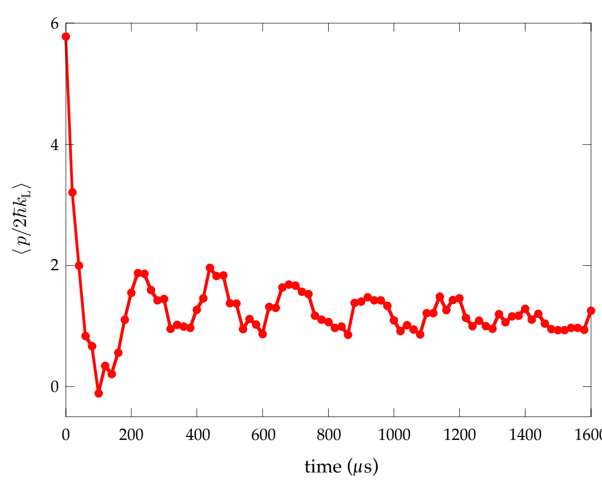
- Natural integrable counterpart of tunneling: Bragg scattering
- Consider time-averaged potential dynamics: pendulum
- Classical transport in pendulum forbidden by separatrix
- Bragg scattering provides similar transport mechanism in momentum





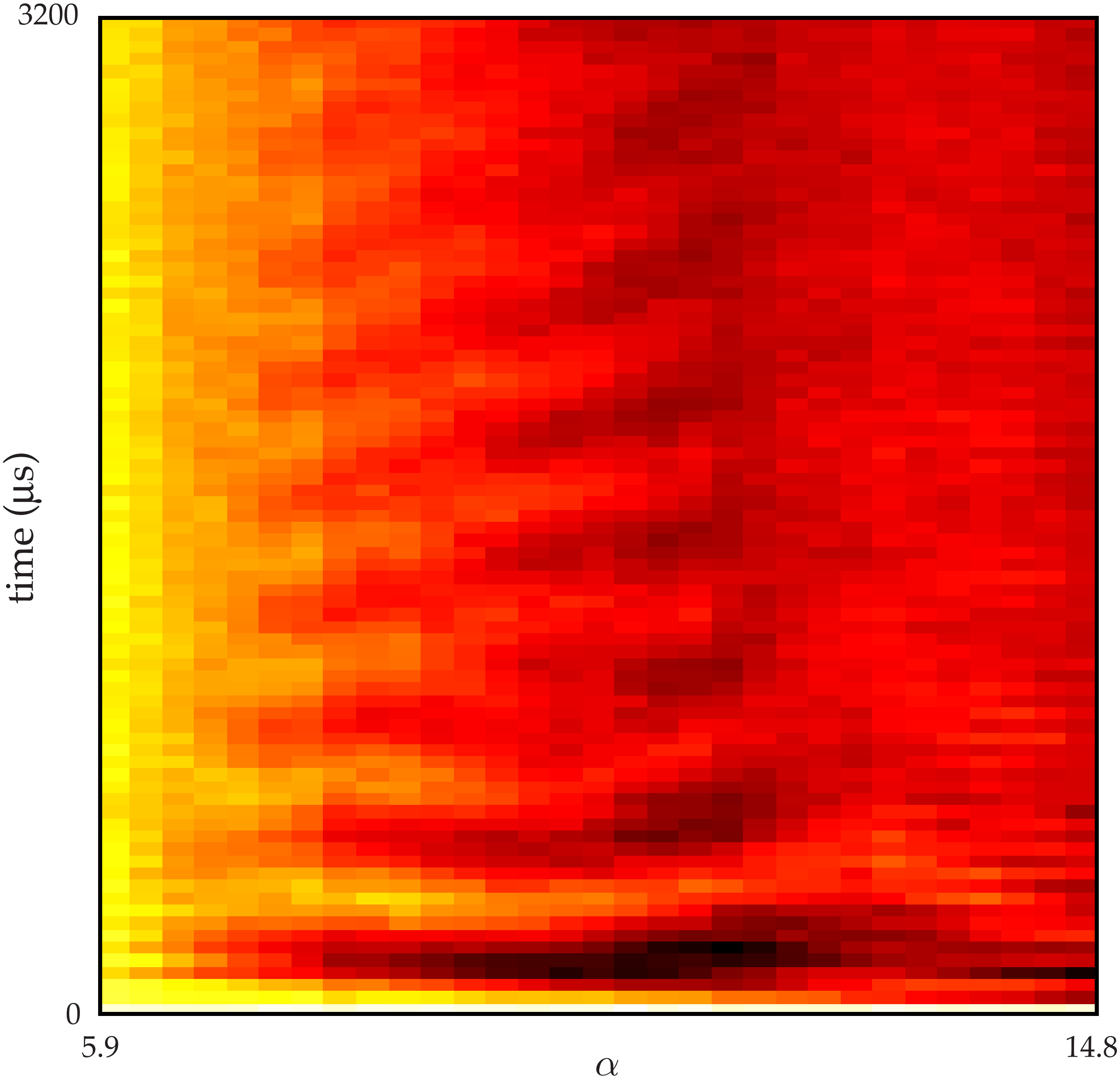
- No Bragg oscillations over time of experiment
- 8th order Bragg period for $\alpha = 10.5$, $\bar{k} = 2.1$ is 1 s

- Also 32-photon tunneling
- 16th order Bragg period for $\alpha = 11.2$, $\bar{k} = 1.0$ is 20 yr



Tunneling Variation

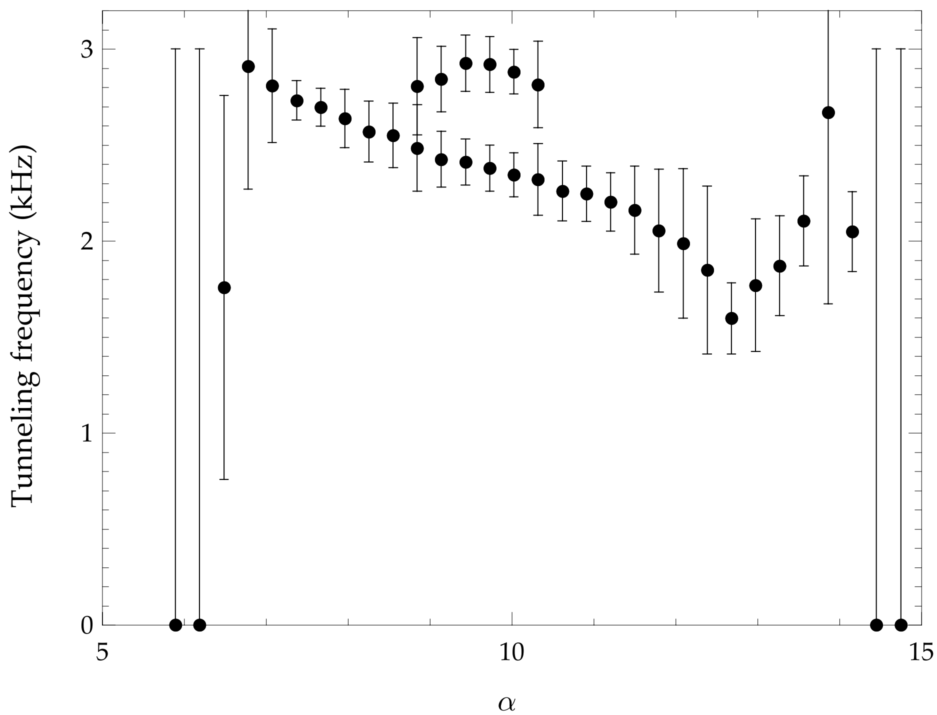
- Study dependence of tunneling on α ($\bar{k} = 2.08$)



- Tunneling only visible in a relatively narrow range of α

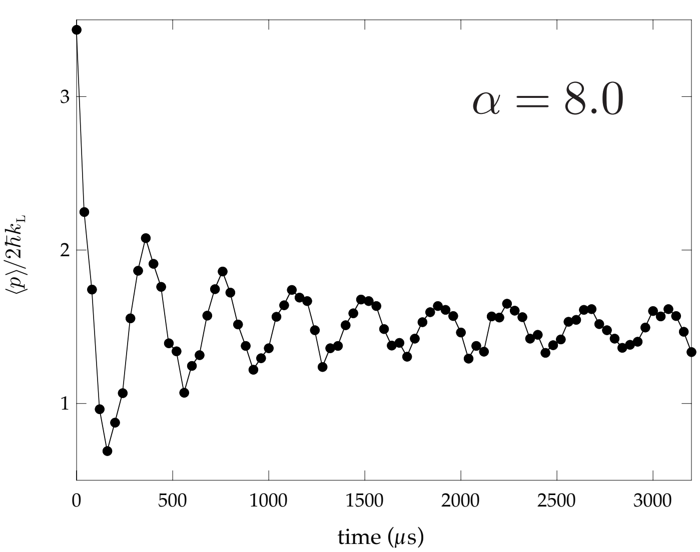
Tunneling Rate Variation

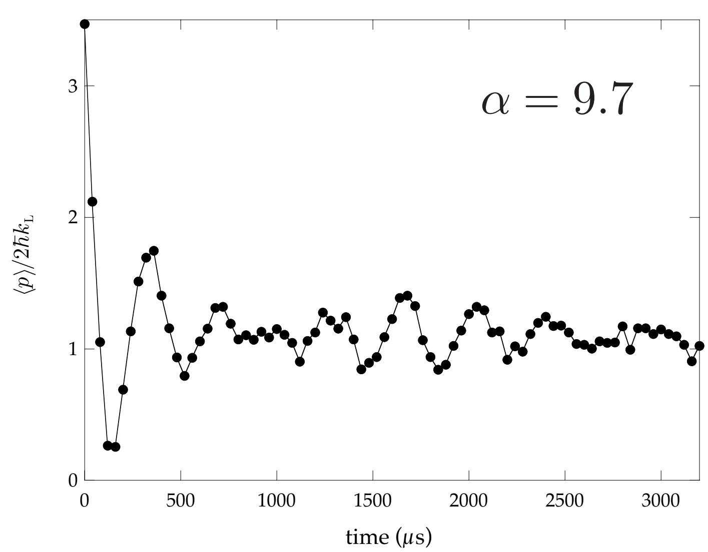
- Study dependence on tunneling rate vs. α ($\bar{k} = 2.08$)



- Rate shows overall *decrease* with α

- Also observe both one- and two-frequency behavior

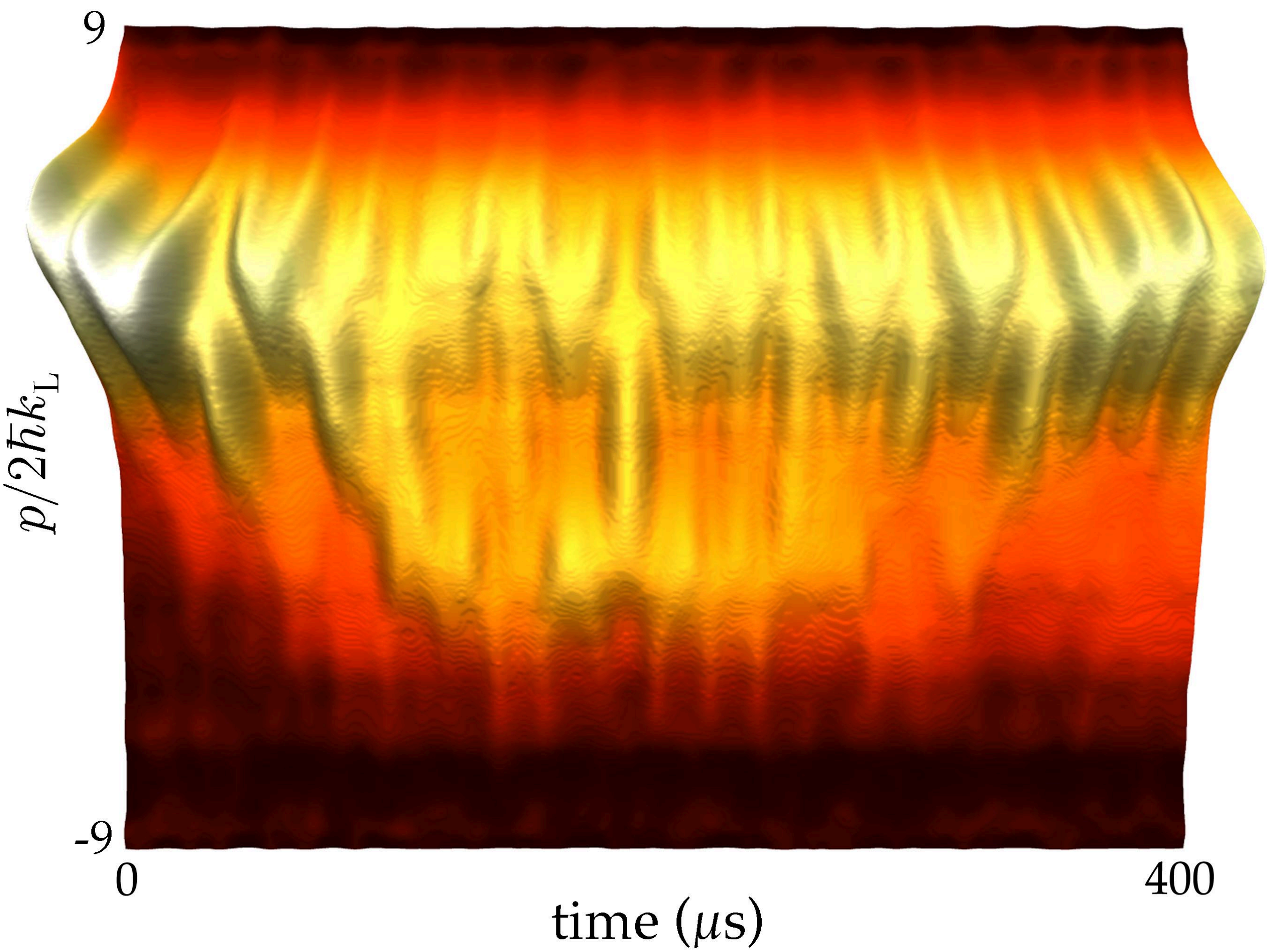




- Two-frequency behavior consistent with center of avoided crossing

High Time Resolution

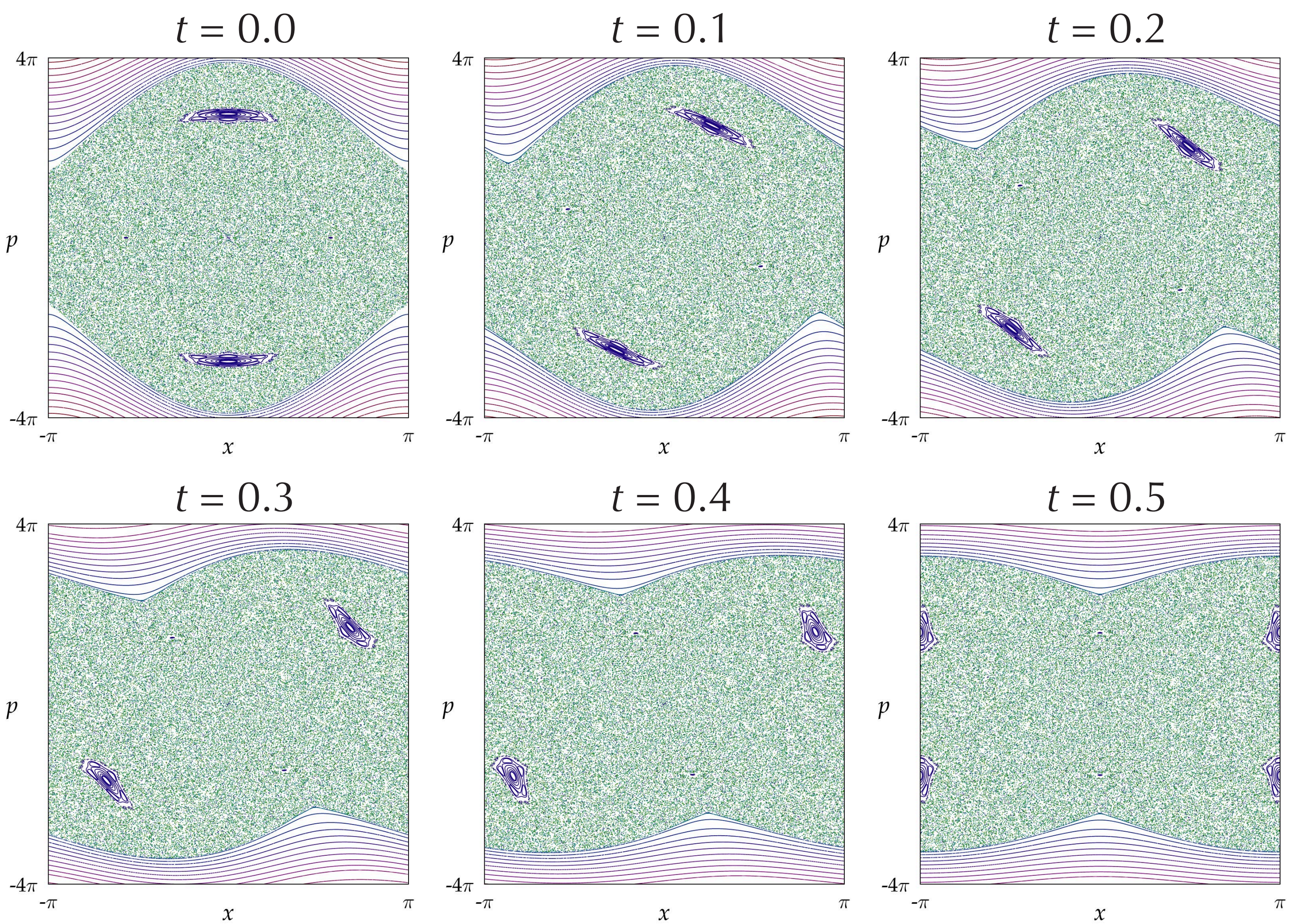
- Sample momentum distribution 10 times/modulation period
- Measurement spans 1 tunneling period, $\alpha = 7.7$, $\bar{k} = 2.08$



- Oscillations on 3 time scales:
  1. longest is tunneling
  2. shortest is classical island motion
  3. intermediate is influence of third level

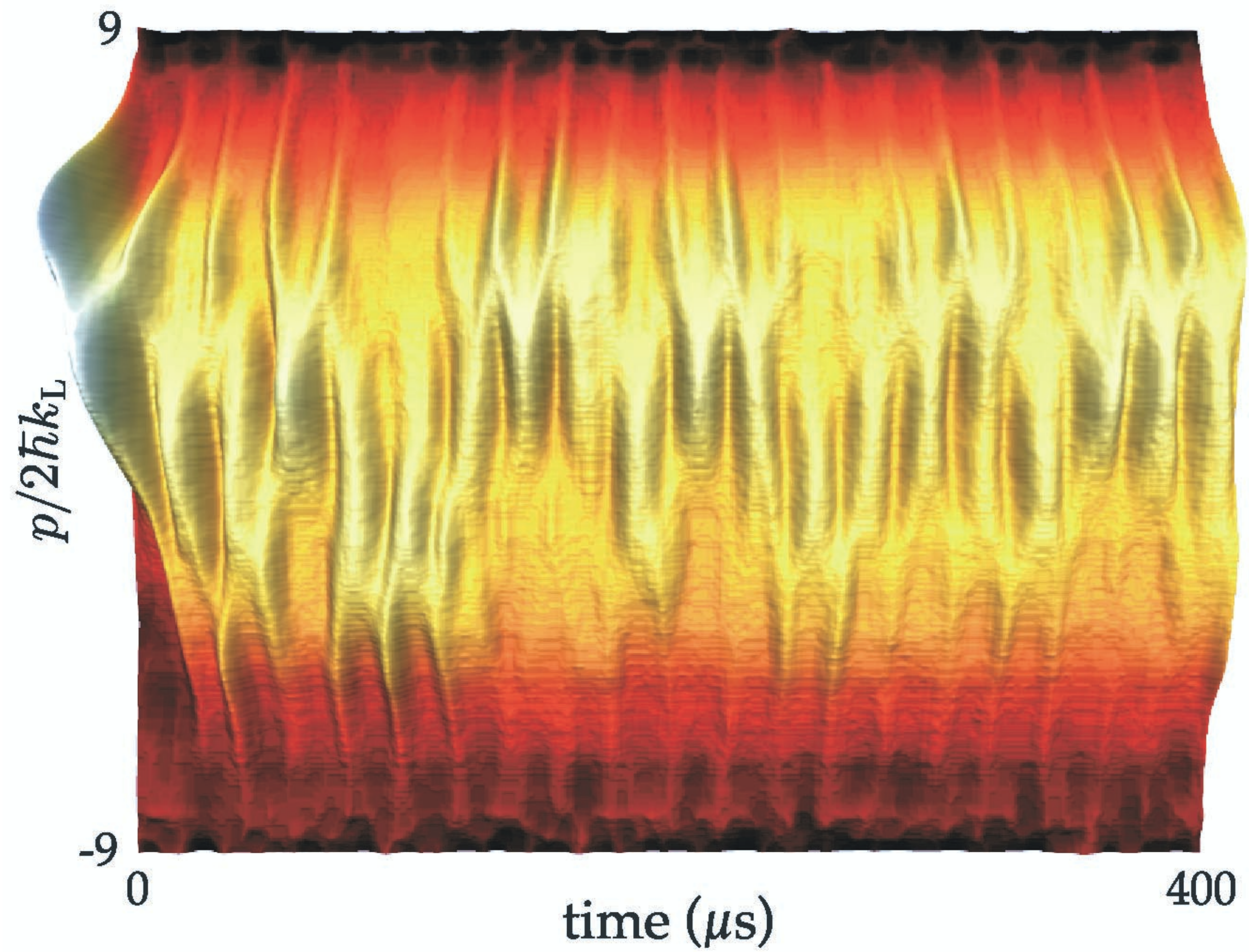
Continuous Phase Space Evolution

- Islands move continuously between stroboscopic samples
- Islands move together during first half of modulation cycle:

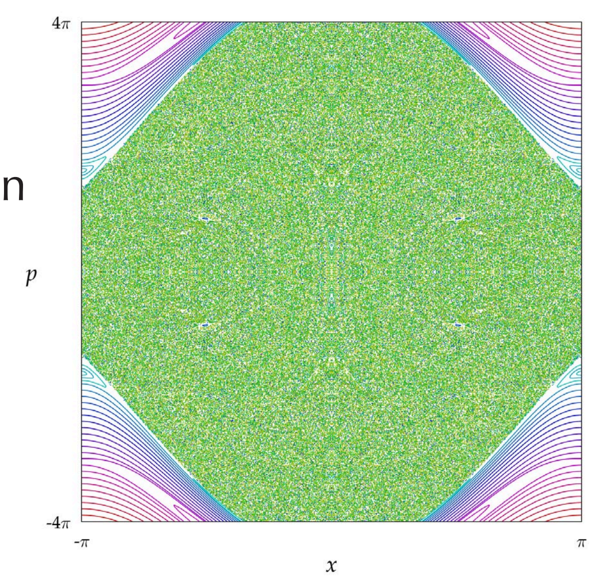


Strongly Coupled Regime

- Measurement for $\alpha = 17$, $\bar{k} = 2.08$:



- Fast, irregular oscillations
- Classical islands have broken down
- Quantum states can no longer be grouped into doublets



Noise and Decoherence

- Tunneling behavior poses problem for classical limit

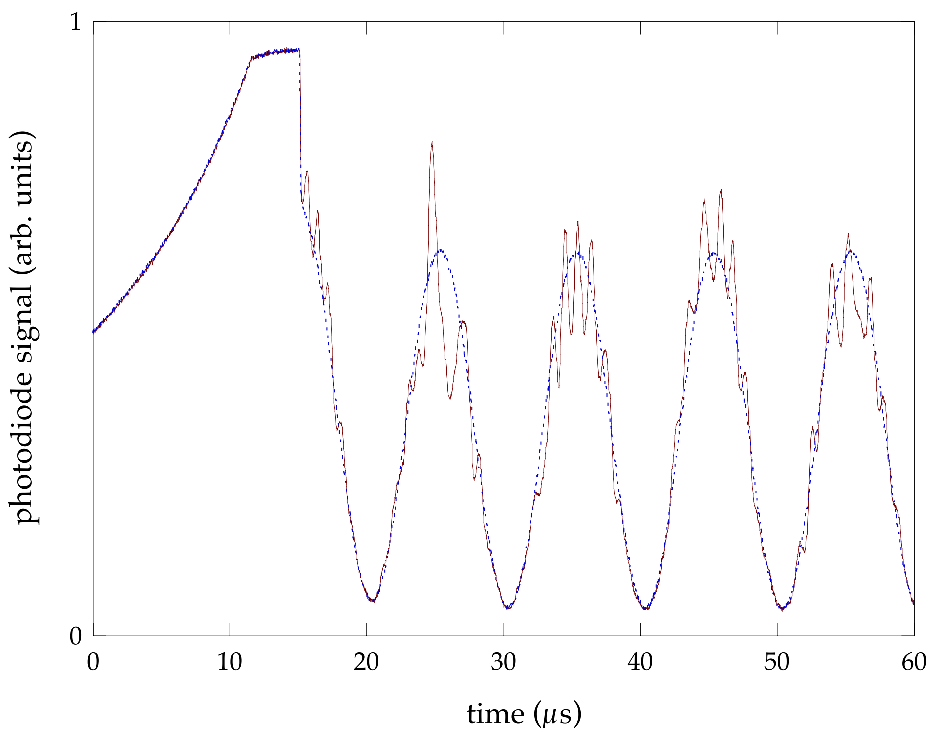
  - two-state tunneling: $\exp(-S/\hbar)$ scaling of tunneling rate ensures that macroscopic tunneling doesn't happen

  - three-state tunneling: no universal scaling of tunneling rate, so need alternate mechanism for classical behavior

- Tunneling is a coherent effect, so can be destroyed by noise or interaction with the environment (decoherence)

- Study experimentally by adding noise to the optical lattice intensity:

$$H = p^2/2 + 2\alpha[1 + \varepsilon(t)] \cos(x) \cos^2(\pi t)$$

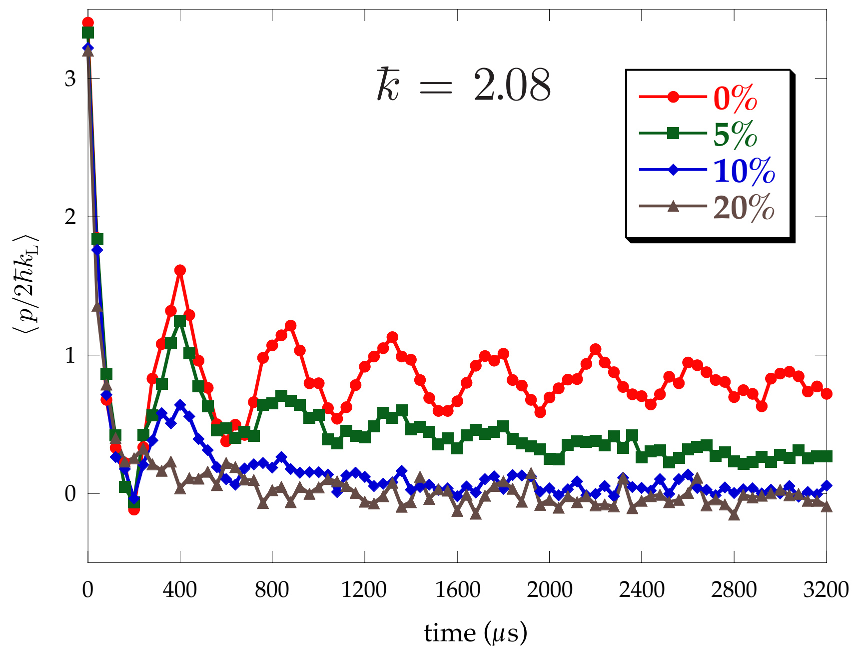


Amplitude Noise Effects

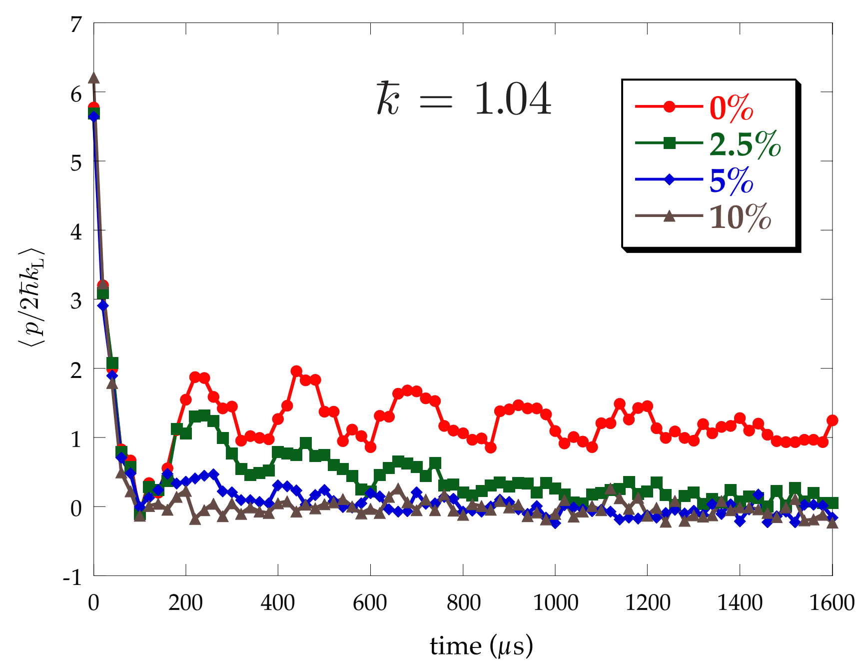
- Can compare effects for different effective Planck constant $\bar{k}$ $(\alpha = 11.2)$

- Noise level is the standard deviation compared to the average intensity

- Bandwidth-limited to the same scaled cutoff frequency for meaningful comparison



- Smaller $\bar{k}$ is more sensitive to the noise



Summary

- Studied chaos-assisted tunneling of cesium atoms in a modulated standing wave
- Studied several features of dynamical tunneling:
  - sensitivity to classical phase-space structure
  - sensitivity to momentum class
- Studied several features specific to CAT
  - enhancement relative to integrable tunneling
  - extra oscillation in tunneling process
  - avoided crossing behavior by varying well depth
- Noise effects
  - damping of oscillations, relaxation
  - different sensitivity for different scaled Planck constant