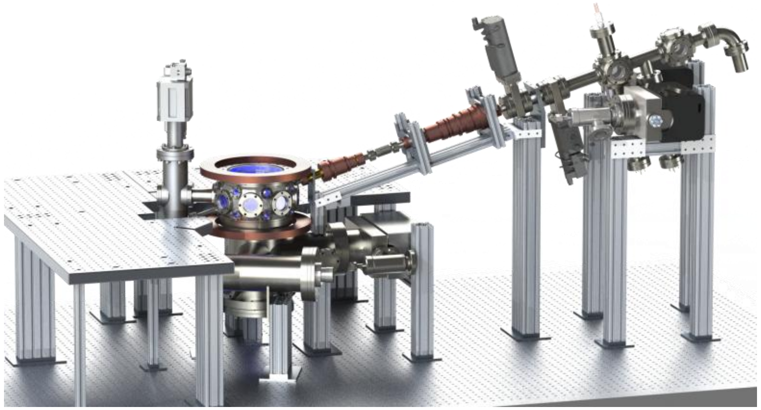
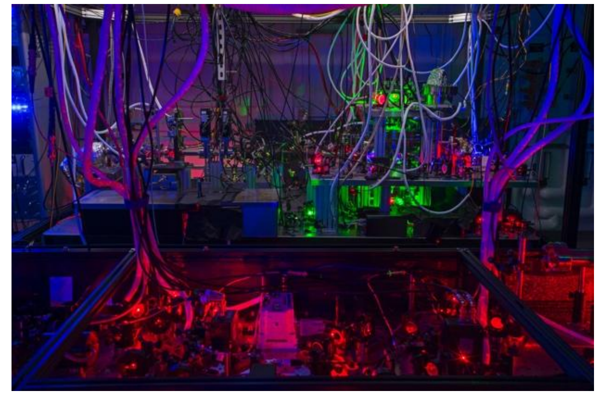
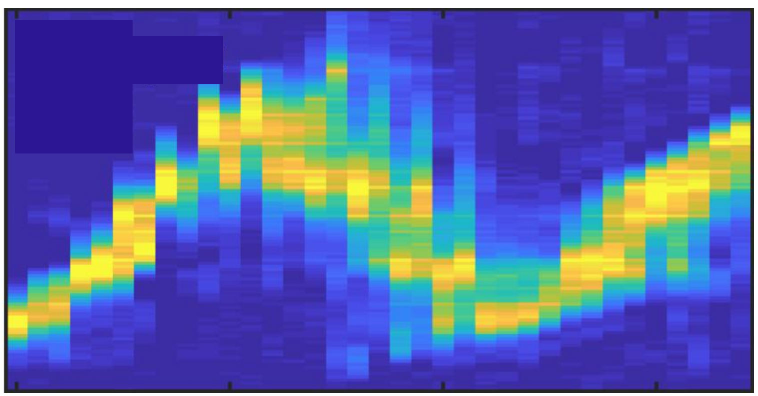
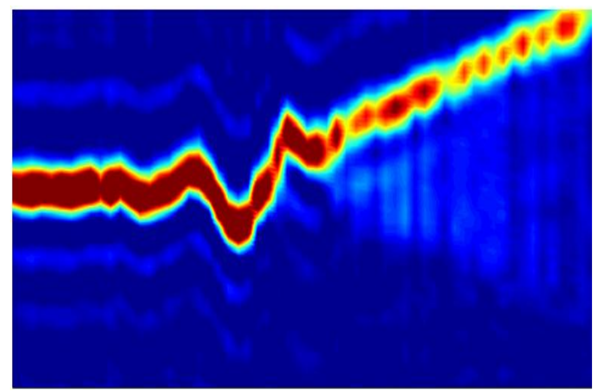
Cold atom experimental capabilities

prospects for low energy physics at the sensitivity frontier









David Weld
UC Santa Barbara, California Institute for Quantum Emulation

May 18, 2018
KITP

Outline

- Experimental Approaches
  - Short-distance gravity
  - Degenerate quantum gases

- Exploring driven quantum systems
  - Position-space Bloch oscillations
  - Relativistic harmonic motion
  - Transport in Floquet-Bloch bands

- Future possibilities
  - Enhanced metrology
  - Atoms near surfaces
  - Discussion…

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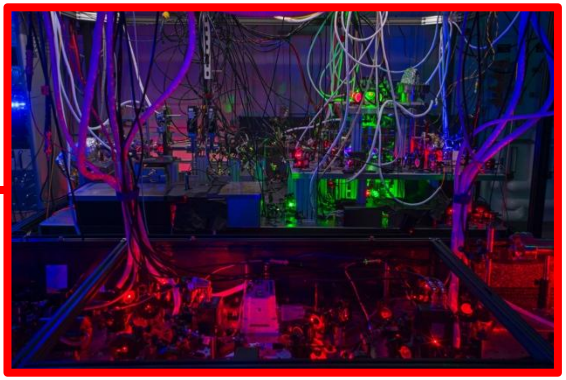

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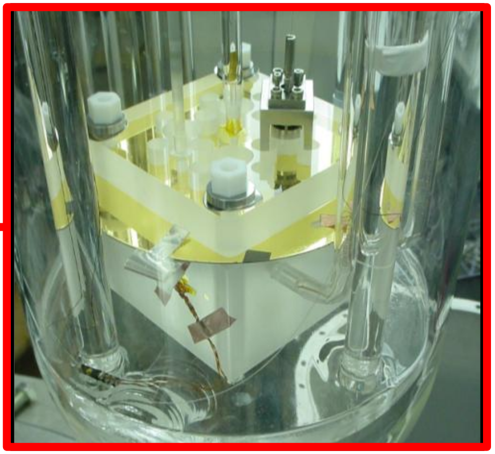

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The experimental challenge of Cavendish-type experiments

$$\frac{F_{Detectable}}{\sqrt{b}} = \left(\frac{4kk_BT}{Q\omega_0}\right)^{1/2}$$

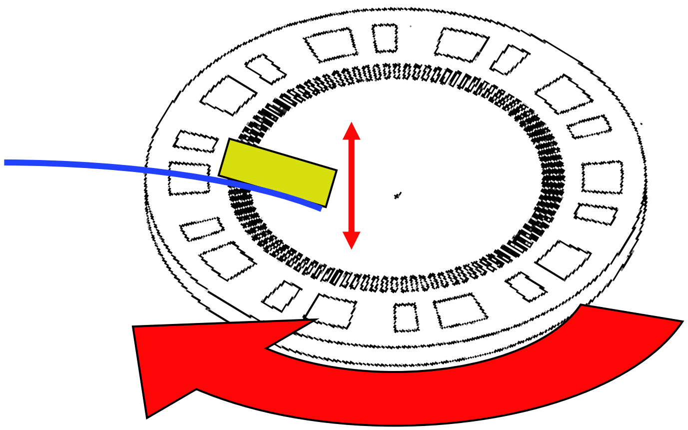
$$F_{Newton} = G\frac{m_1m_2}{r^2}$$

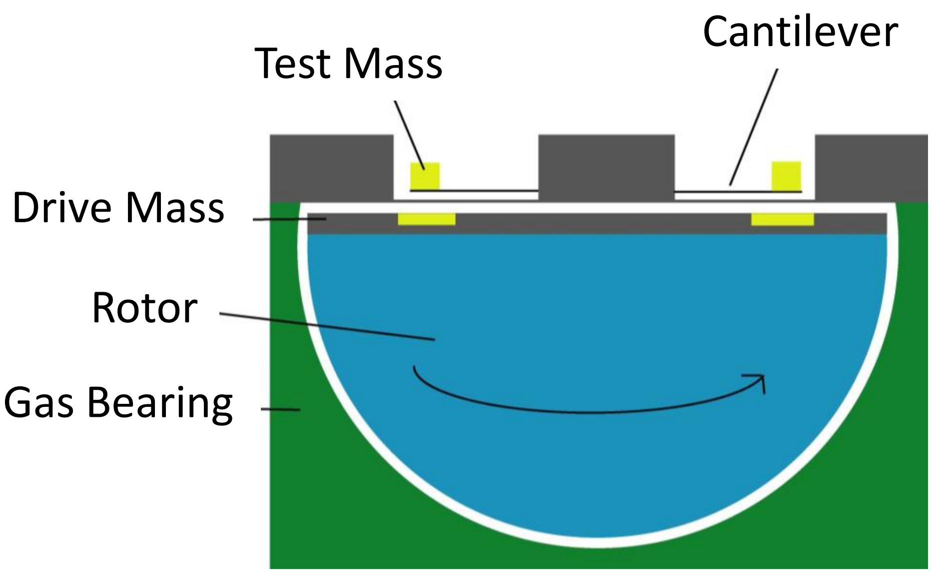
- **G<<1: Gravity is the weakest force in nature**
  - Force sensitivity must be very good
  - Weak forces (Casimir, van der Waals, Knudsen) all much larger than signal

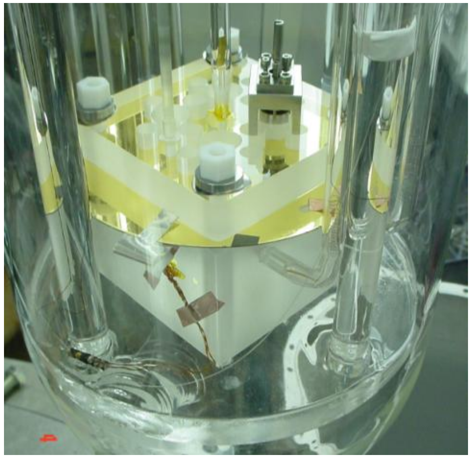
- **For largest force signal: High m, Low r**
  - Masses should be as large and dense and as close together as possible
  - Parallel-plate geometry best, but leads to fabrication and alignment challenges

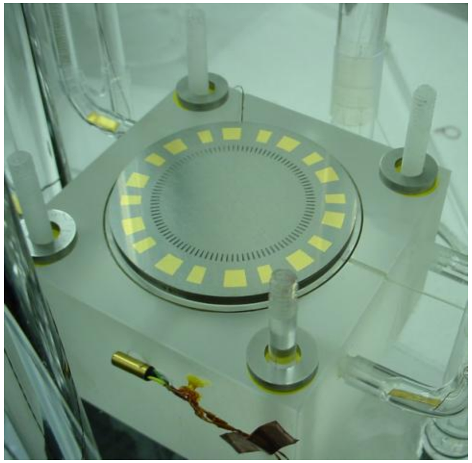
- **For best force sensitivity: High Q, Low k, Low T**
  - Precise alignment and actuation at low temperature required

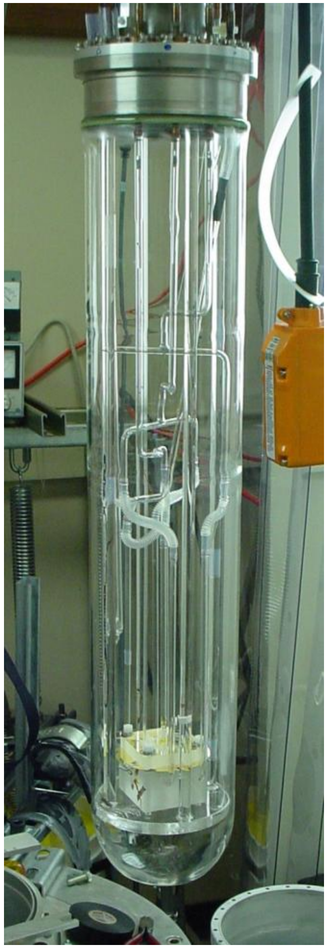
Cantilever Experiment



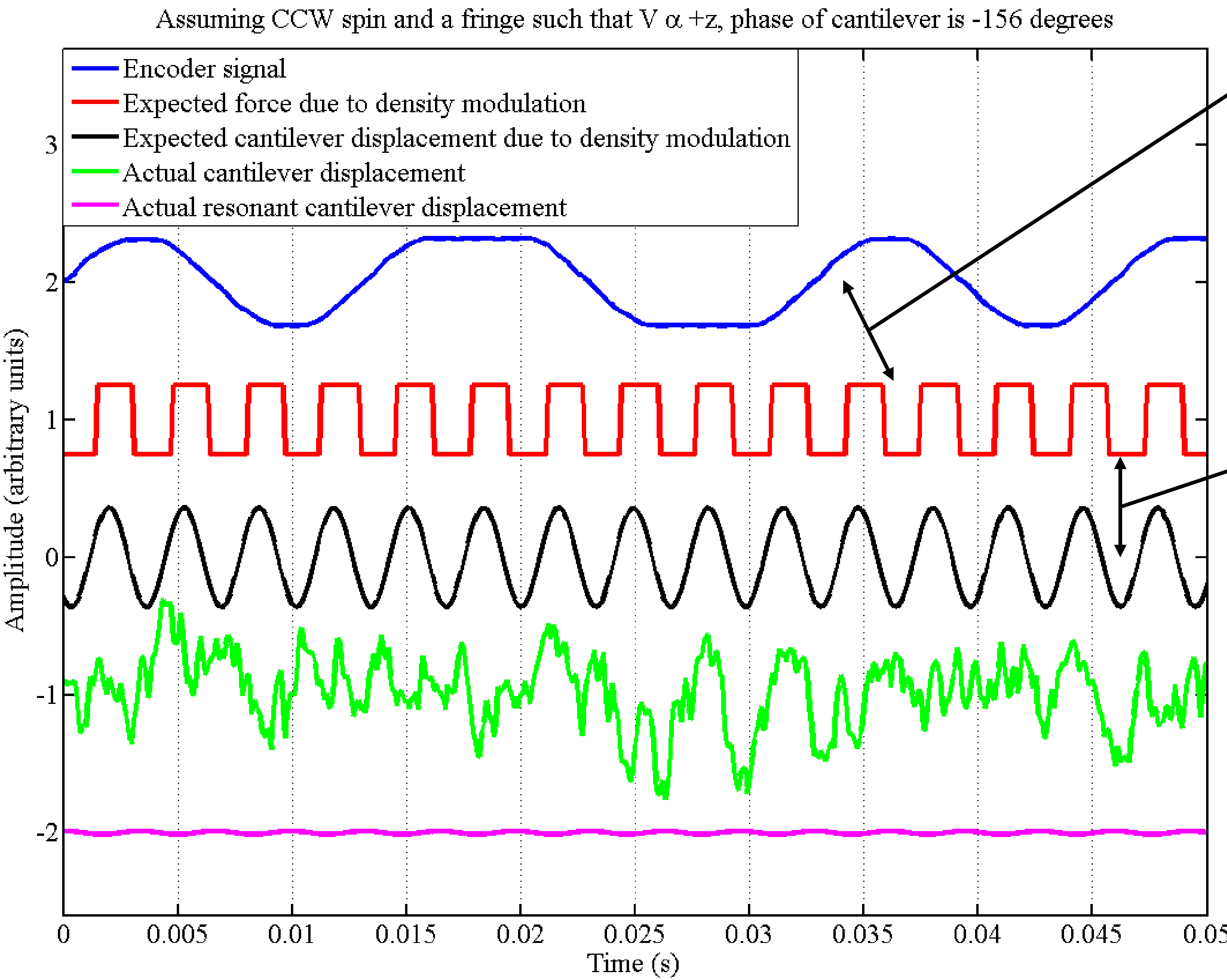


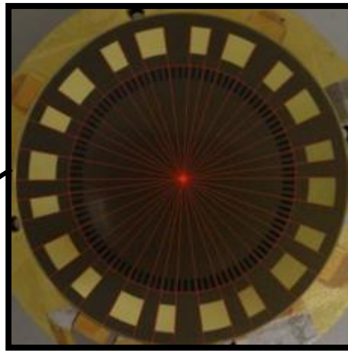


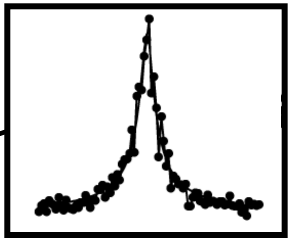




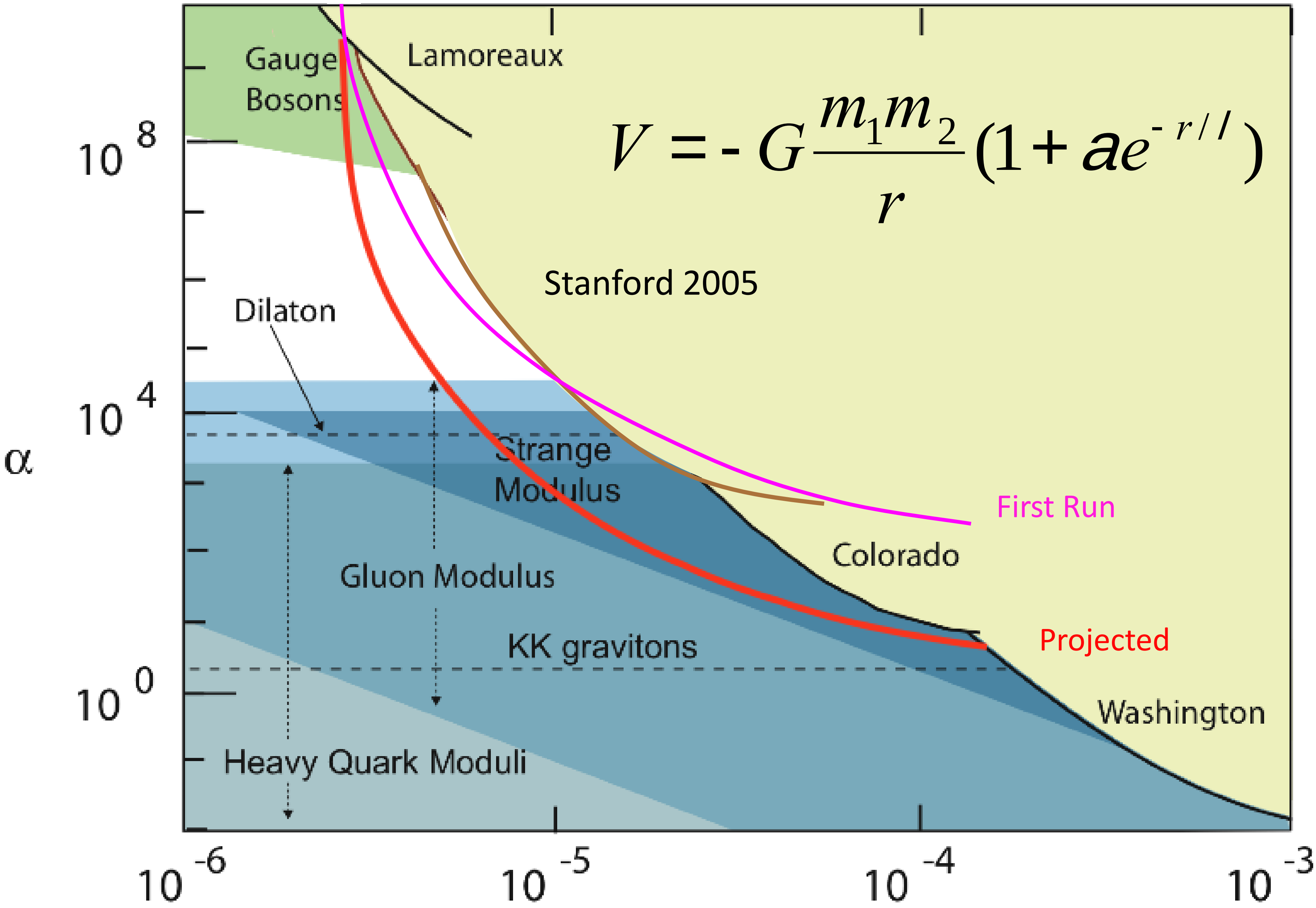
Phase determination







Yukawa Parameter Space (old plot!)



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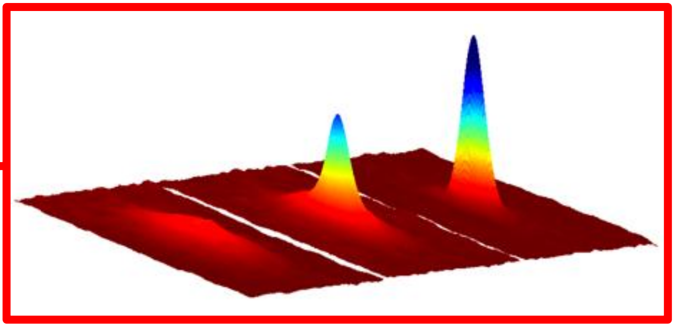

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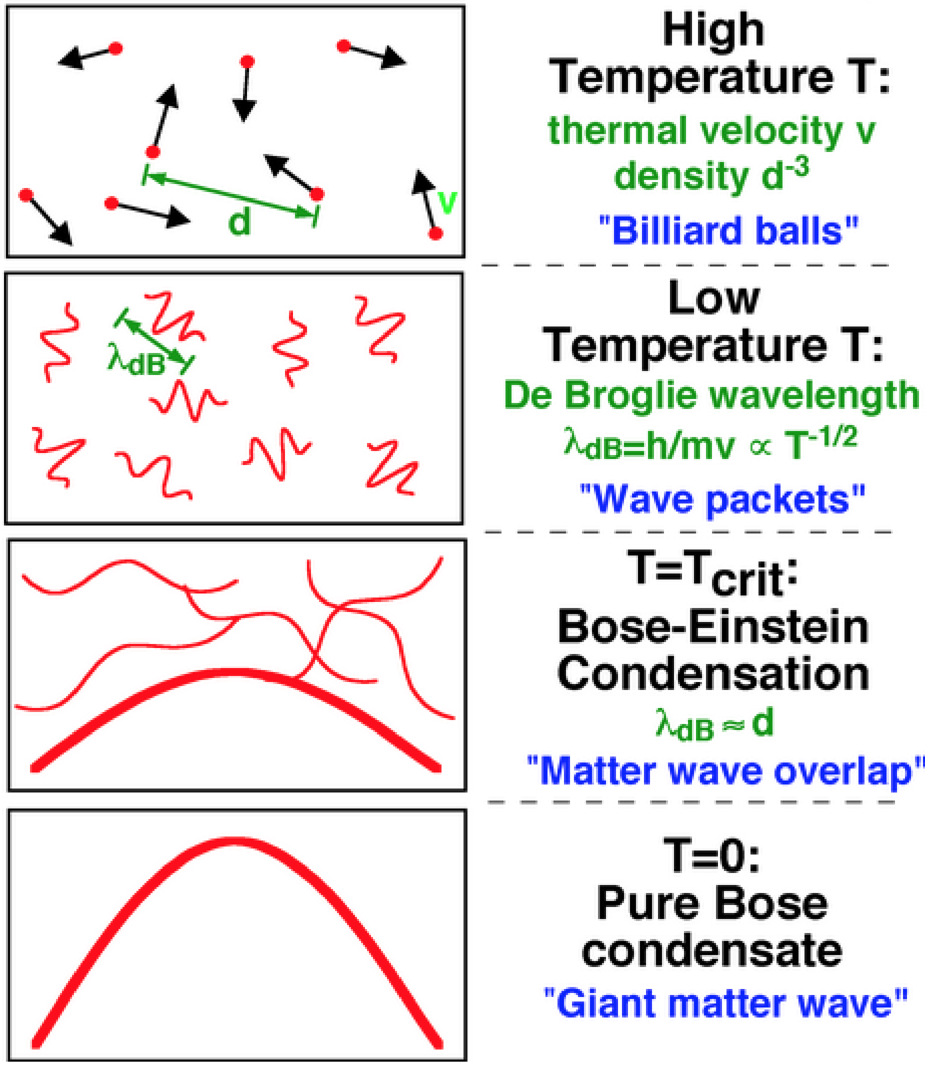
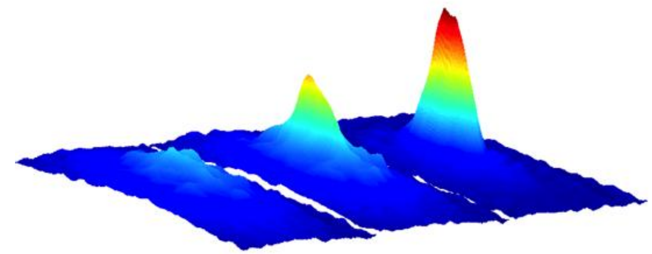
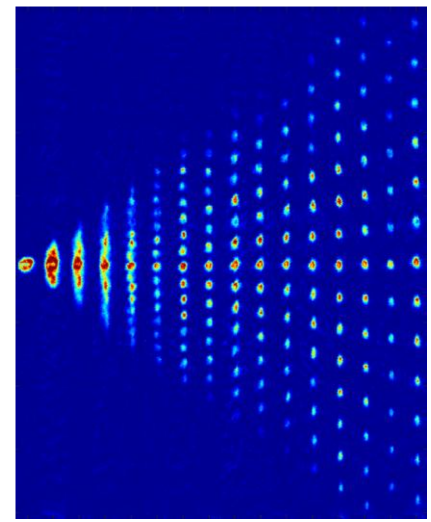
Bose-Einstein Condensates



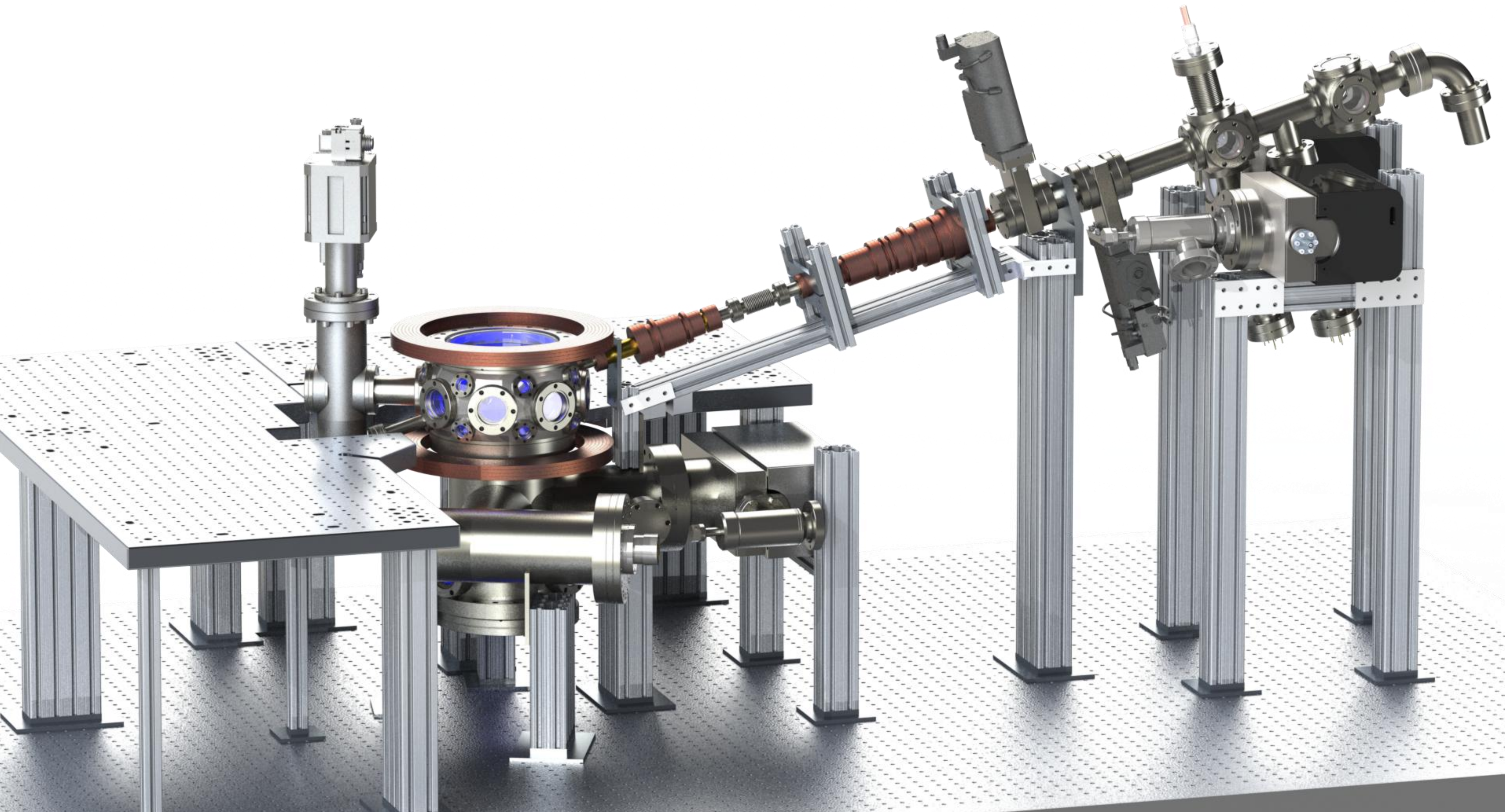


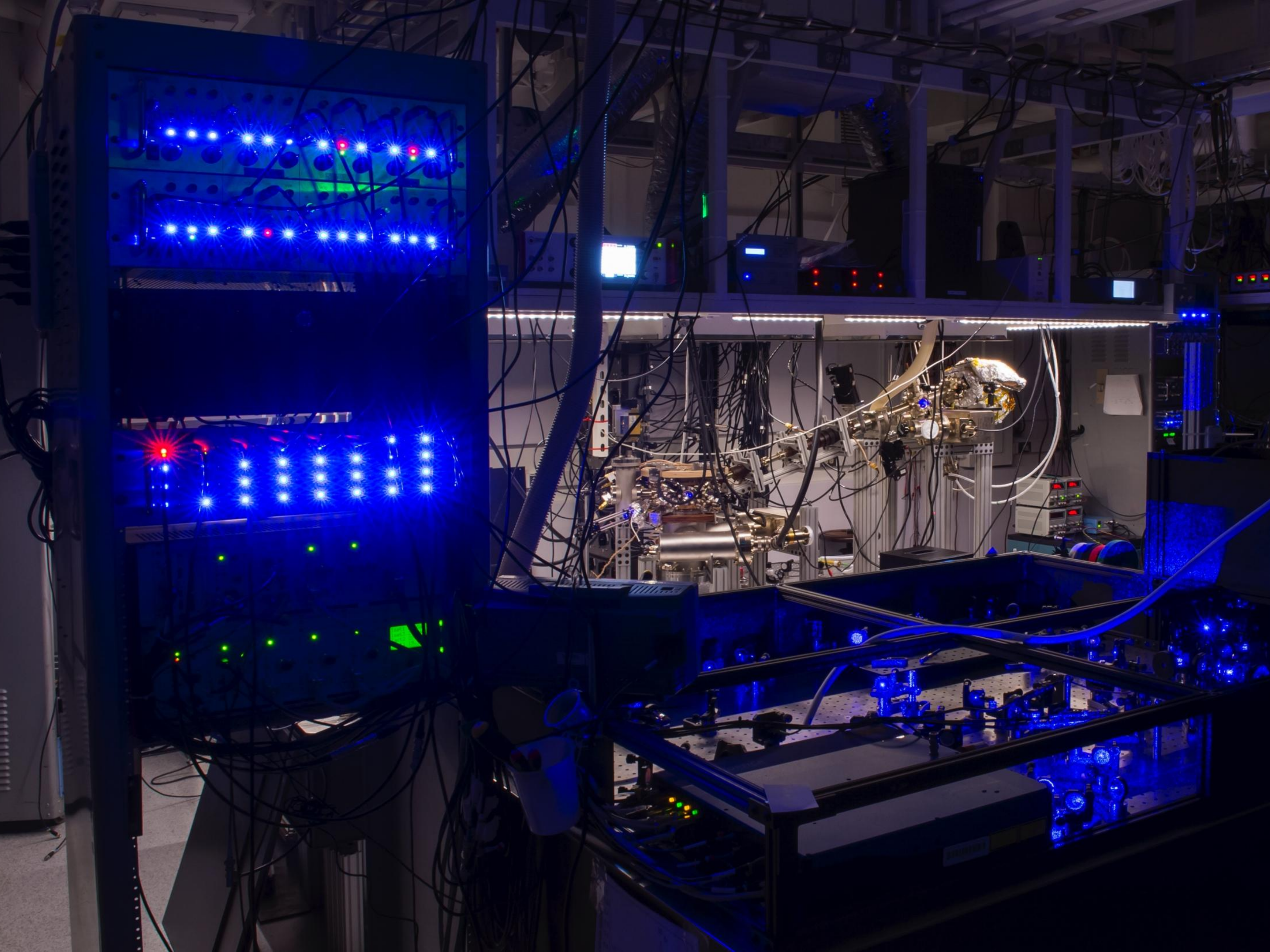


- Coldest* objects in the universe (pK-nK)
- Macroscopic quantum phenomena: superfluidity, matter-wave interference
- Tunable interactions
- Near-perfect quantum control

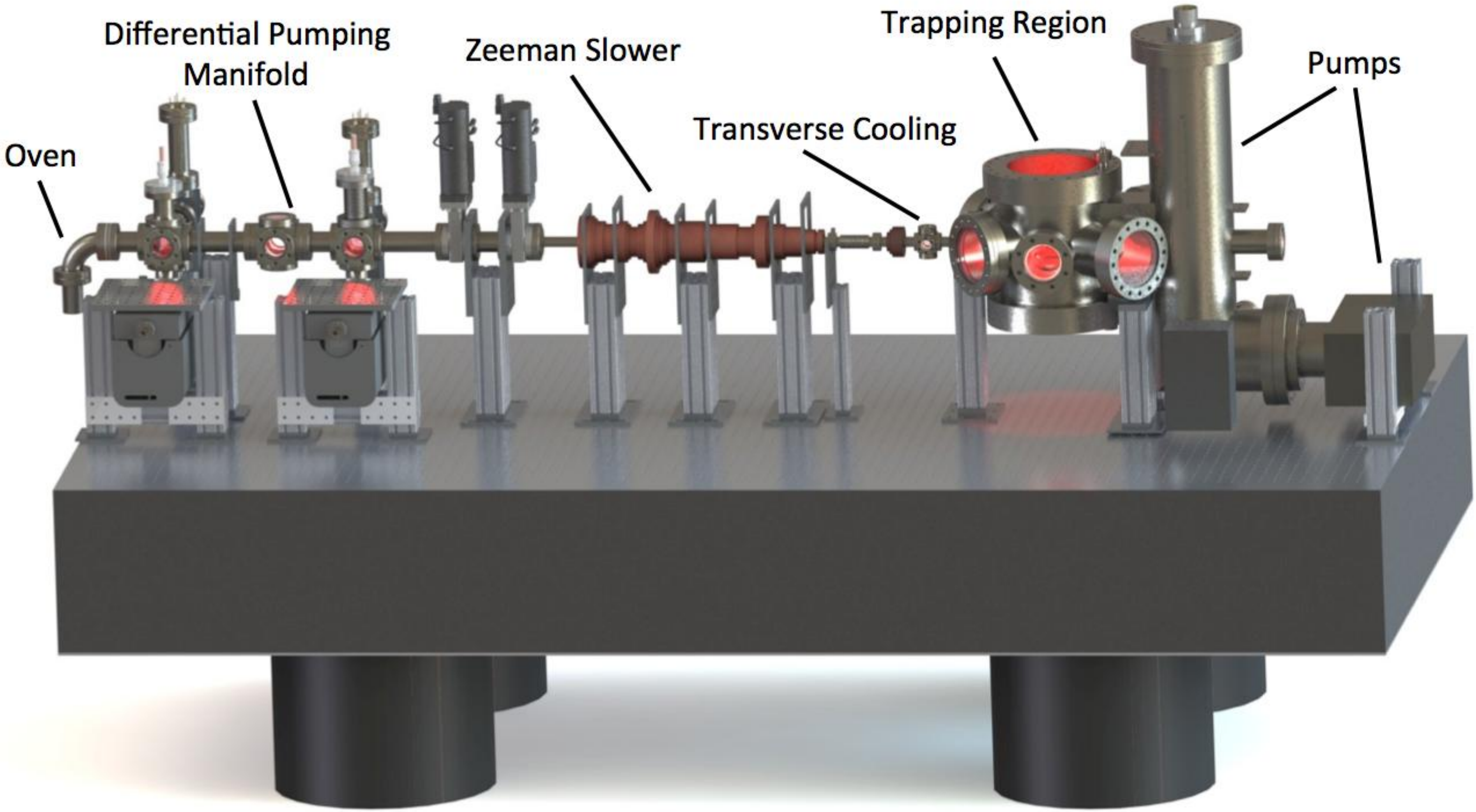
Strontium Machine

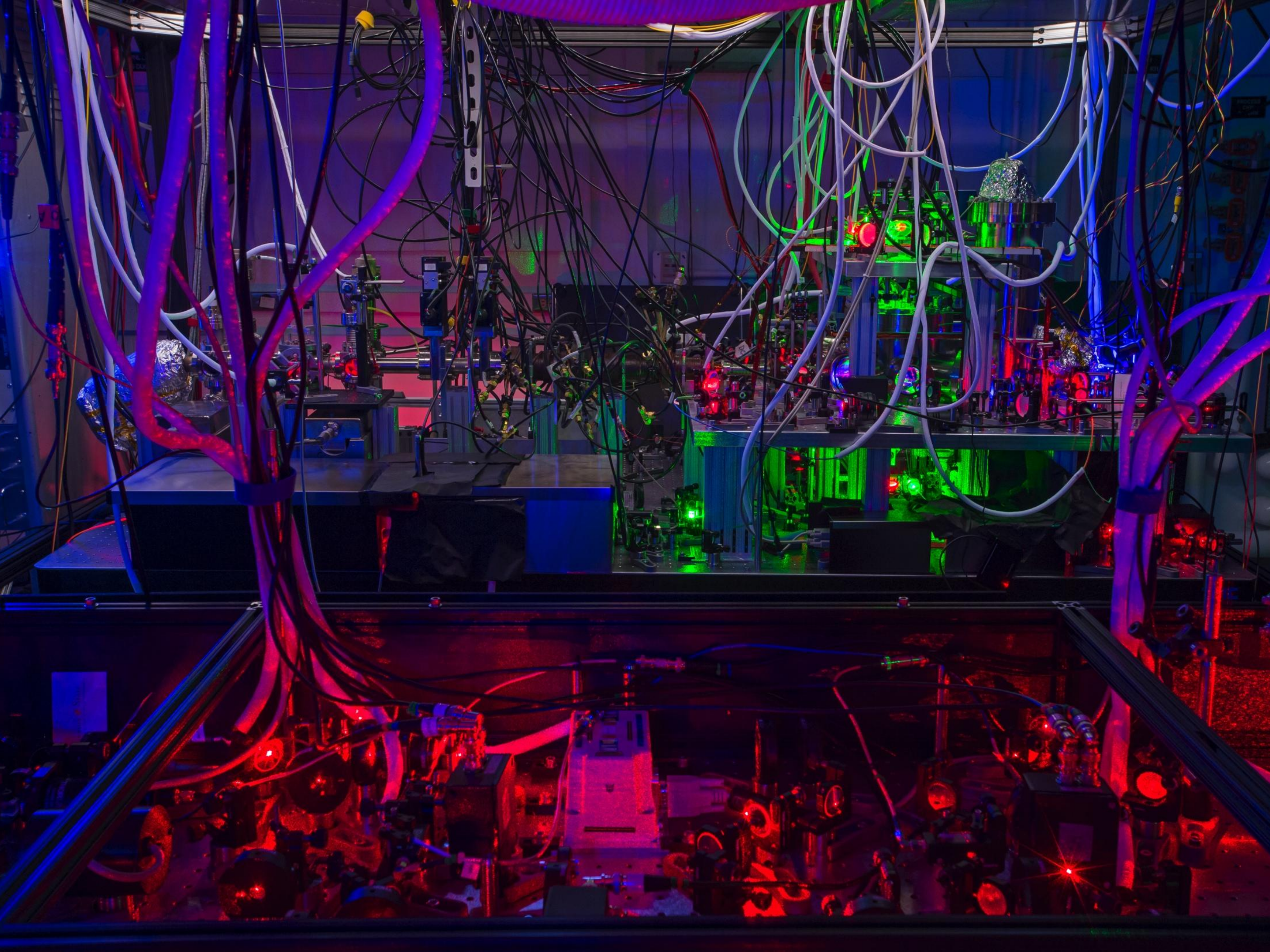
- Design favors optics over magnets
- Multiple isotopes (^{87}Sr, ^{84}Sr, ^{88}Sr, ^{86}Sr)
- Science chamber architecture (QGM, quantum sensing)



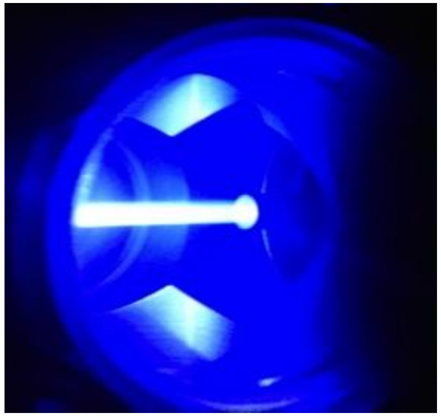


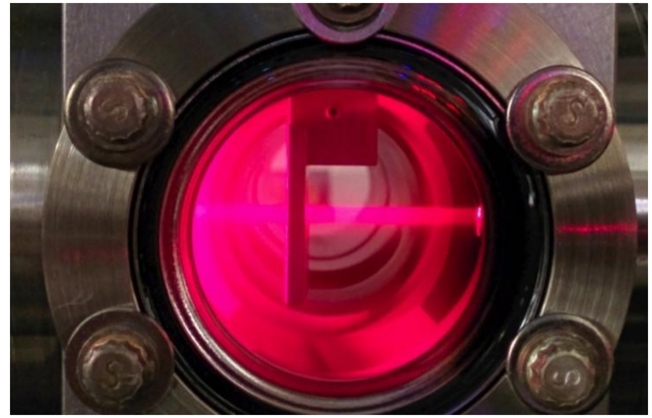
Lithium Machine

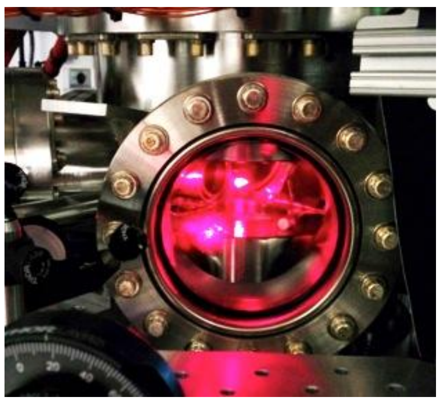


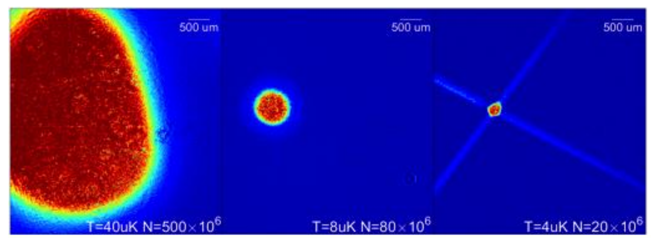


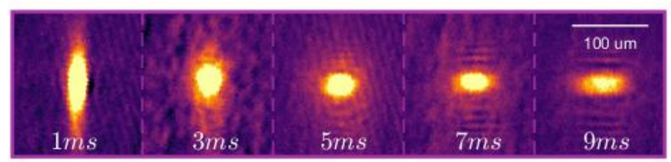
Hot and Cold Atoms

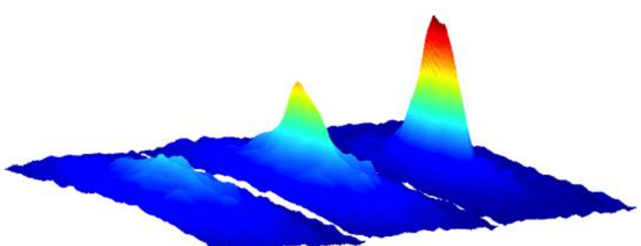


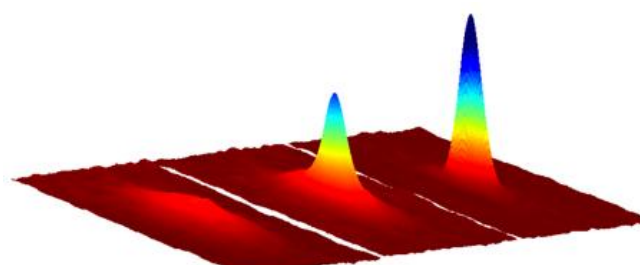












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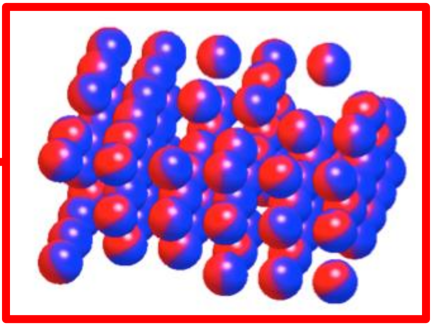

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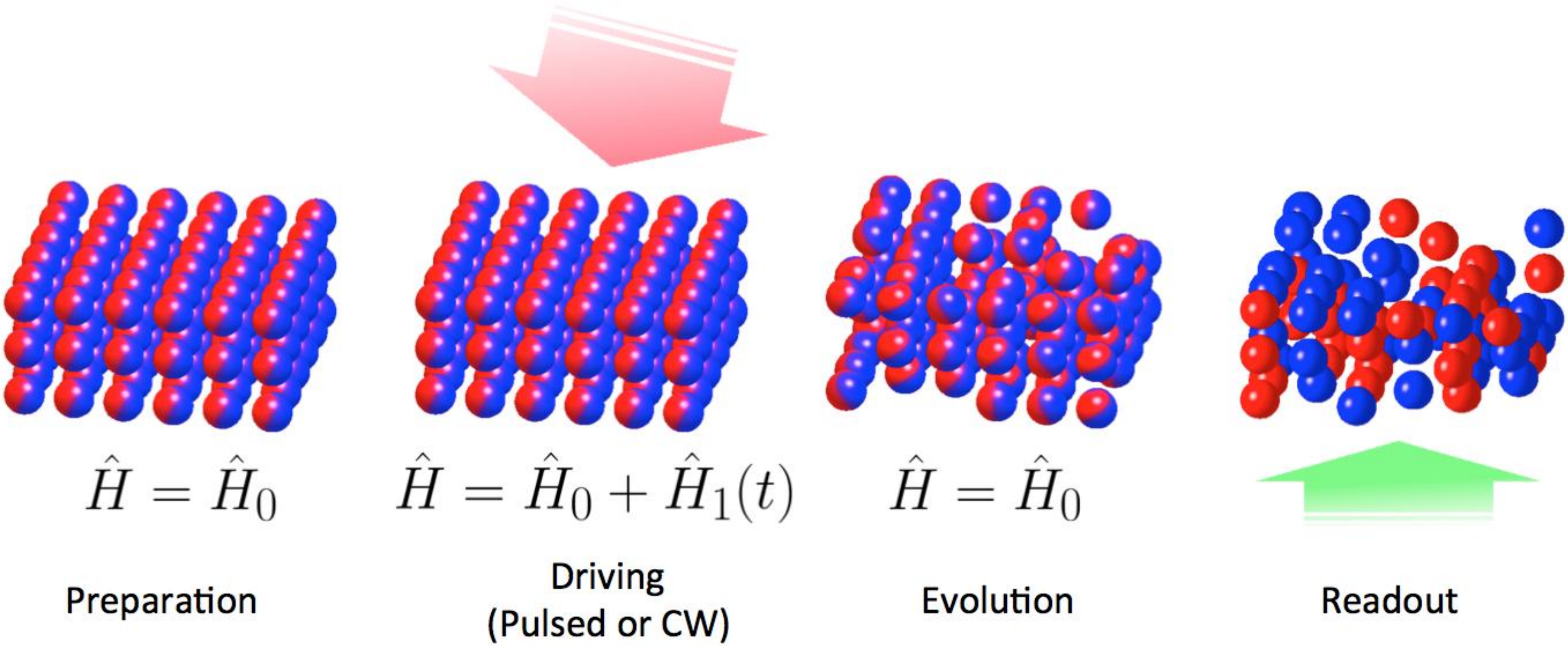
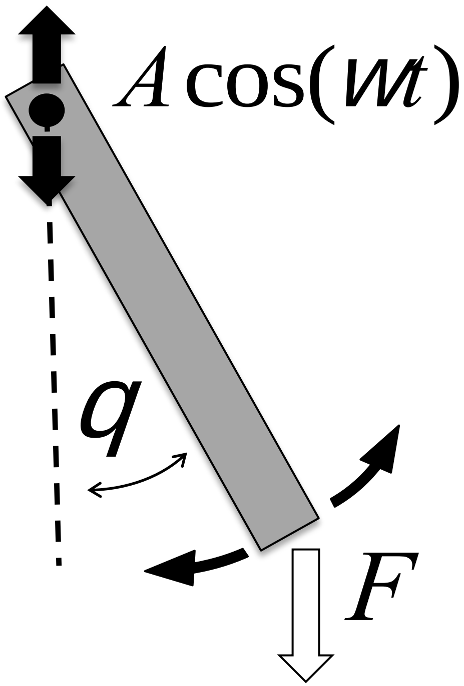
Driven Systems

The basic question: what happens when you shake things?



Driven Systems: Classical Example

Pendulum with vibrating pivot:

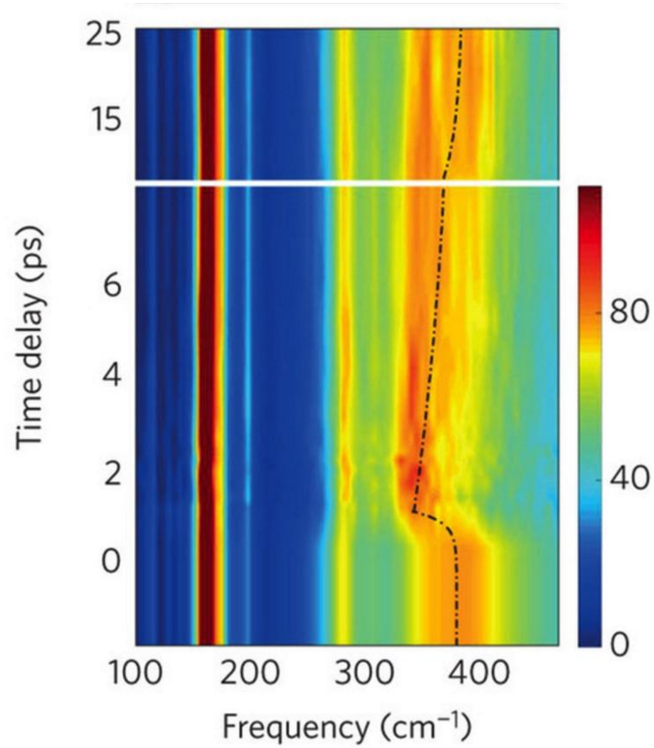


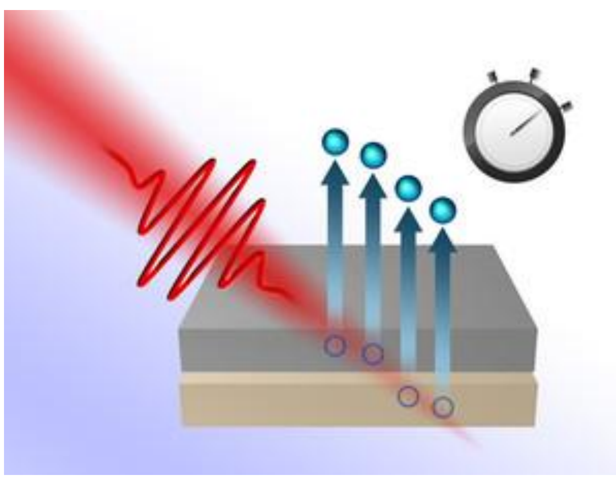
$$\ddot{\theta}+[\delta+\epsilon\cos(t)]\sin\theta=0$$

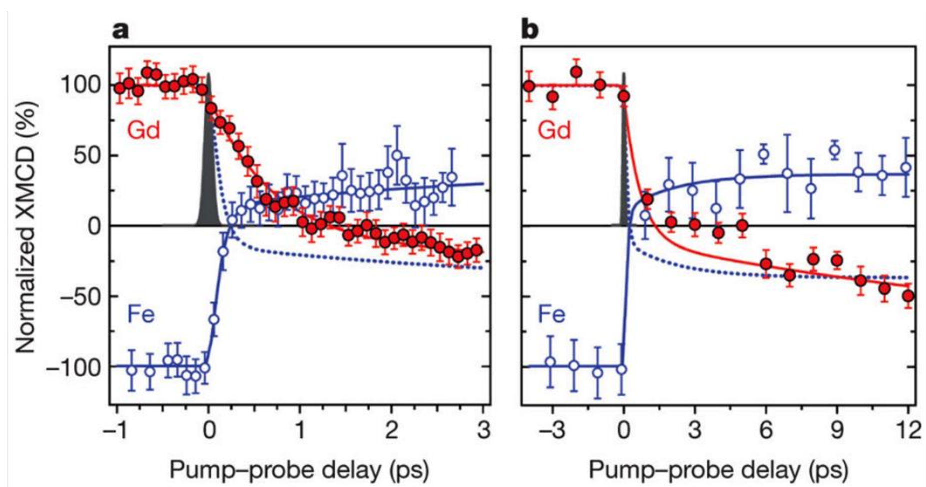
https://www.youtube.com/watch?v=rwGAzy0noU0

Driven Systems: Quantum Example

- Atoms and solids in pulsed-laser fields
- Nontrivial dynamical behavior (tunnel ionization, HHG)
- Emergent states of matter







Images: Nijmegen, Hamburg, Zurich

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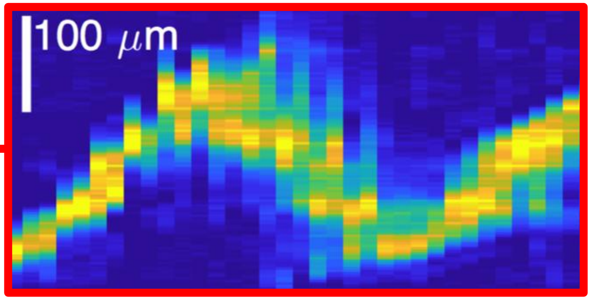

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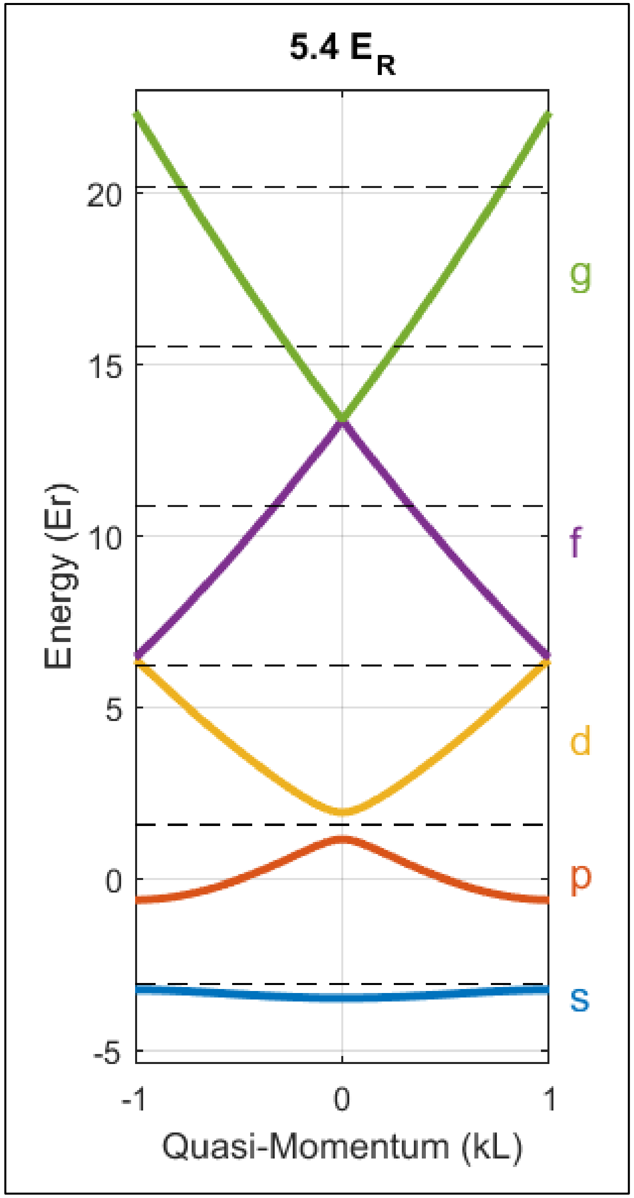
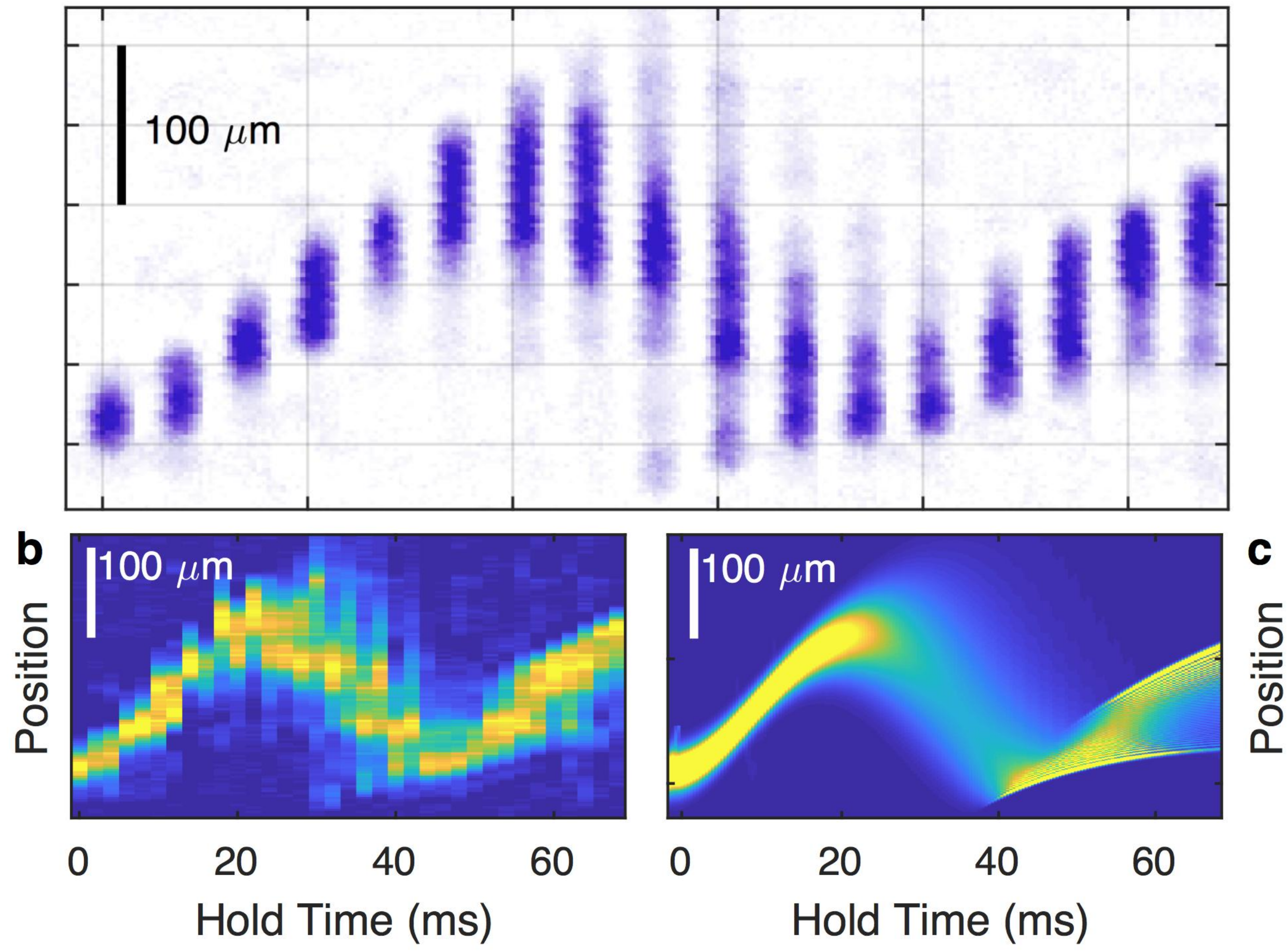
Position-Space Bloch Oscillations

- In a periodic system, static force produces oscillatory response (Bloch, Zener 1929)
- Momentum evolves through edge of Brillouin zone
- Bloch oscillations in optical lattices are a nice force sensor (frequency depends on force).
- Used in a recent fine structure constant determination [*Science* **360**, 6385 (2018)]
- Typically probed in momentum space; position-space dynamics initially predicted by Zener too small to be observed



Position-Space Bloch Oscillations

- Li (light, non-interacting) in lattice enables PSBO observation



Z. Geiger, K. Fujiwara, DMW, arXiv 1803.02456 (accepted by PRL)

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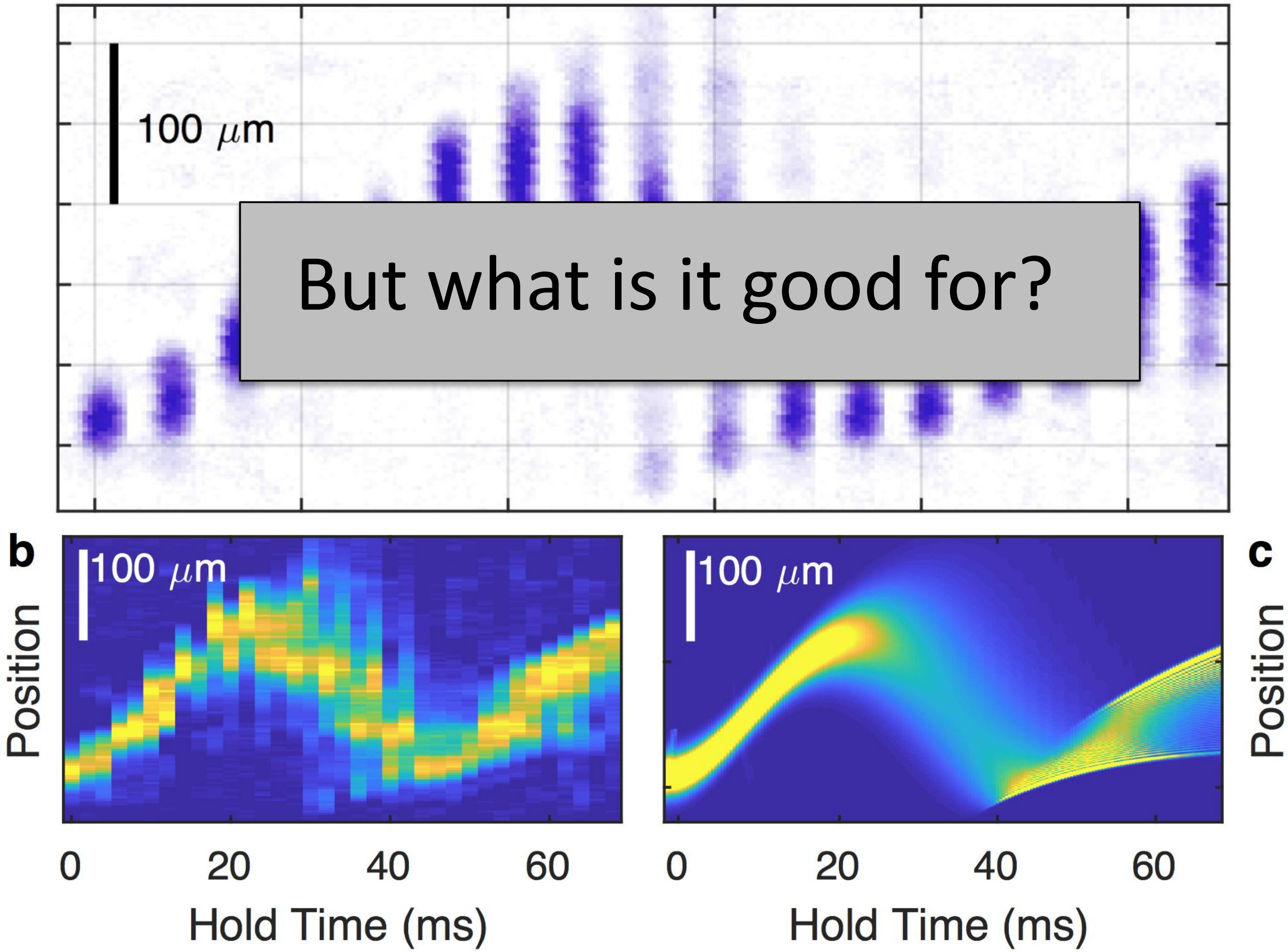
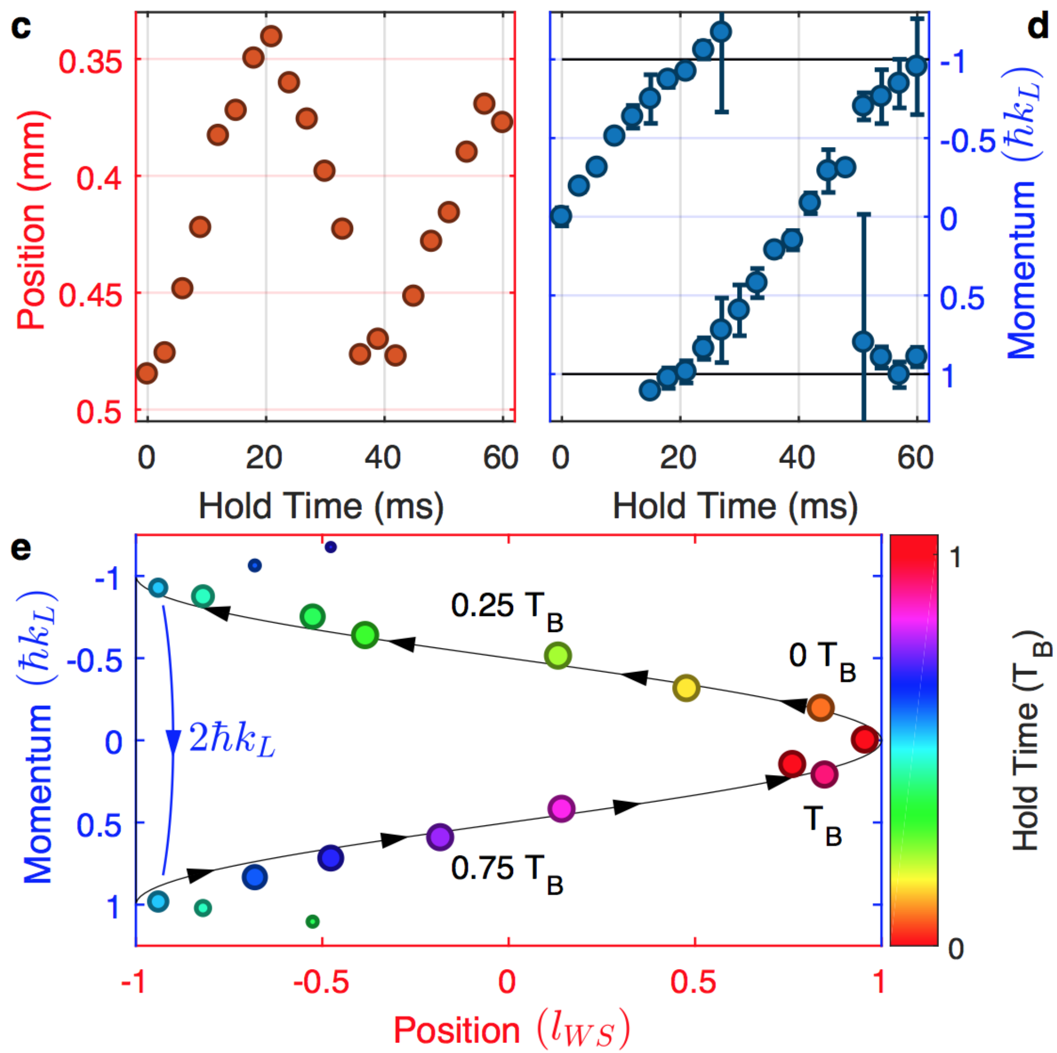


But what is it good for?

Z. Geiger, K. Fujiwara, DMW, arXiv 1803.02456 (accepted by PRL)

Position-Space Bloch Oscillations

- Use 1: directly map phase-space evolution during a Bloch oscillation



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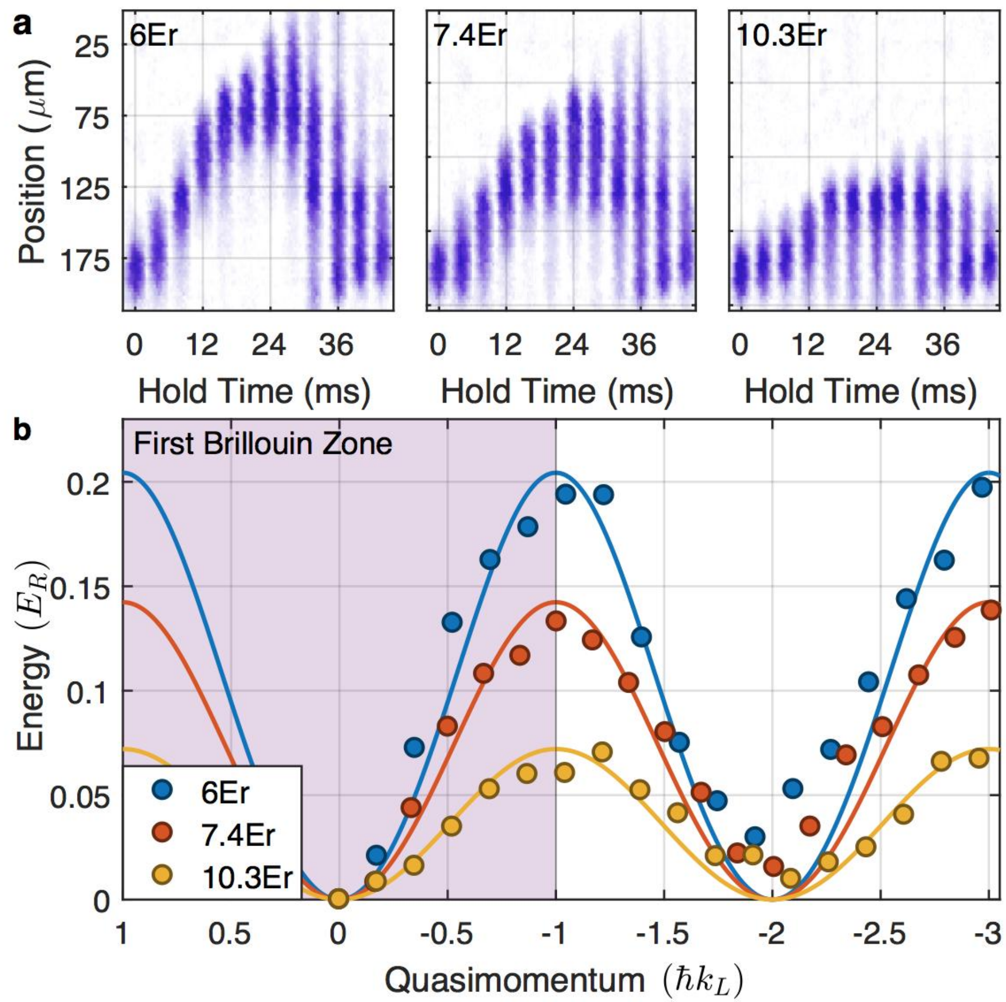
Position-Space Bloch Oscillations

- Use 2: direct imaging of band structure

- x(t) maps directly to E(k):

$$E = \frac{hf_B}{d}x, \qquad k = \frac{k_L}{2T_B}t$$

- ARPES-like measurement



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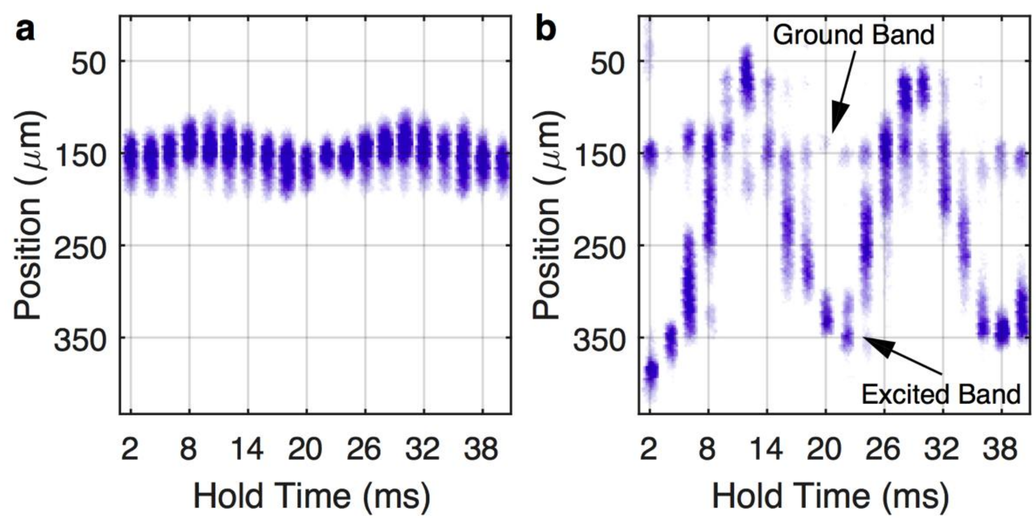
- Works in excited bands too…



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Position-Space Bloch Oscillations

- Use 2: direct imaging of band structure

- x(t) maps directly to E(k):

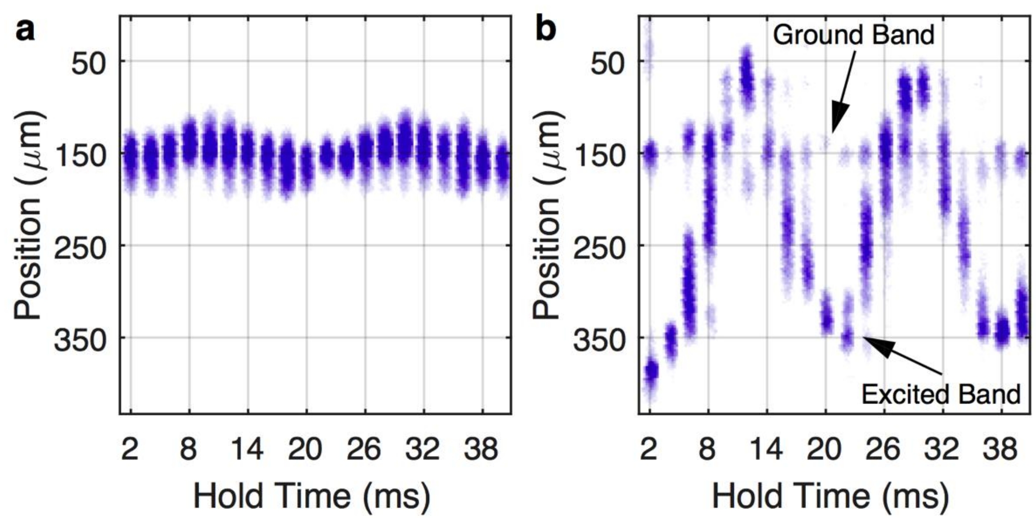
$E = \frac{hf_B}{\ }$ … k_L

→Position-space Bloch oscillations are visible and useful.

Next: How does physics change in higher bands?

- ARPES-

- Works in excited bands too…



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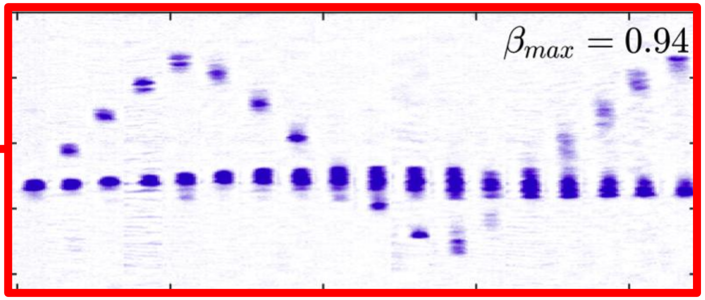

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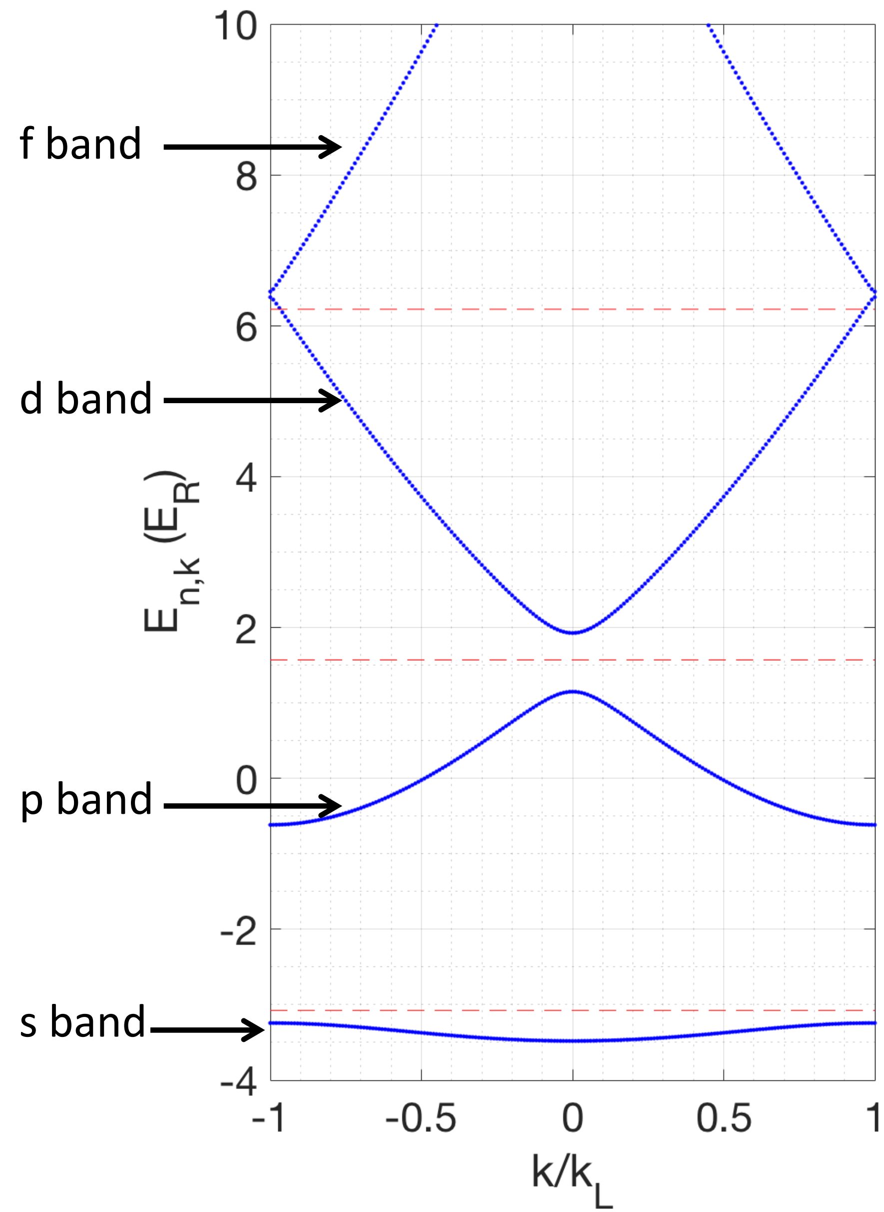
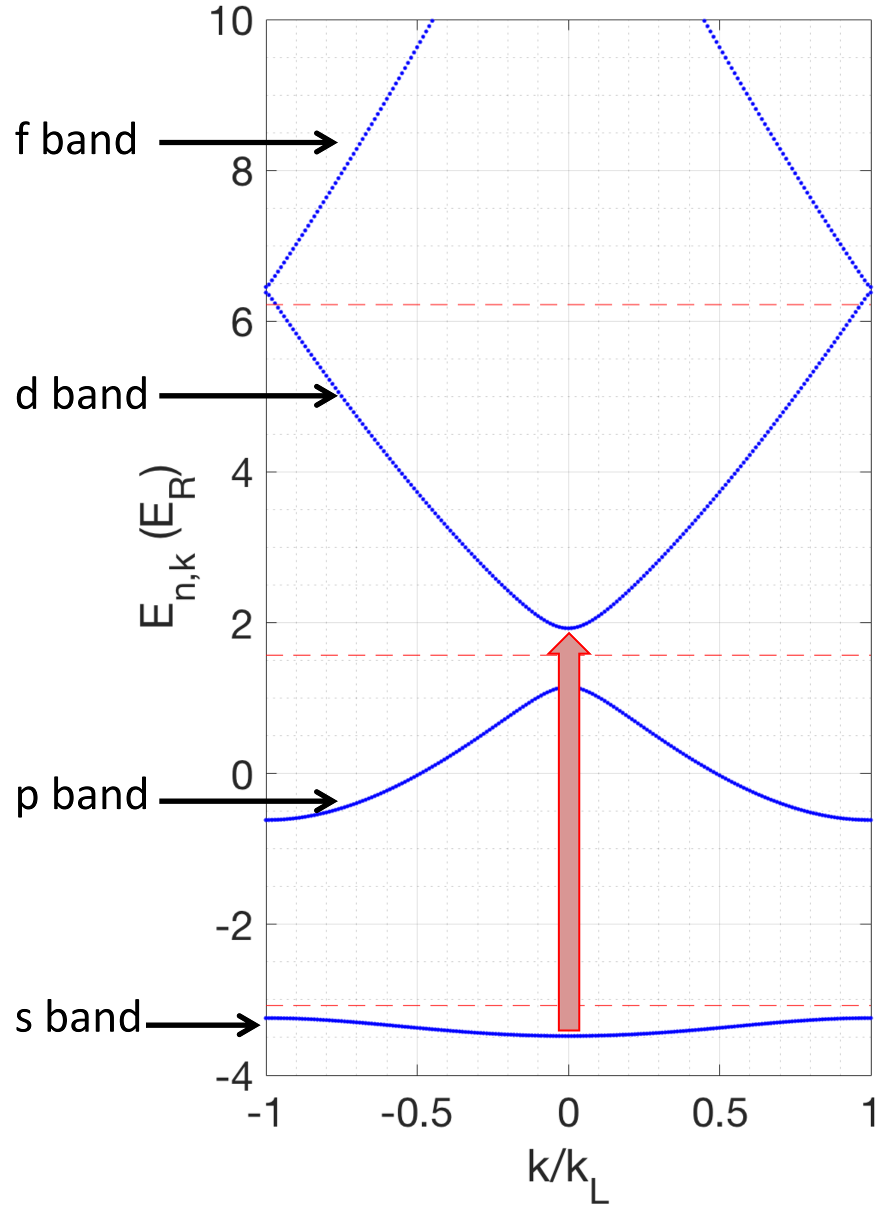
Relativistic Harmonic Motion in the d Band



Relativistic Harmonic Motion in the d Band

- Amplitude modulation can excite to the d band

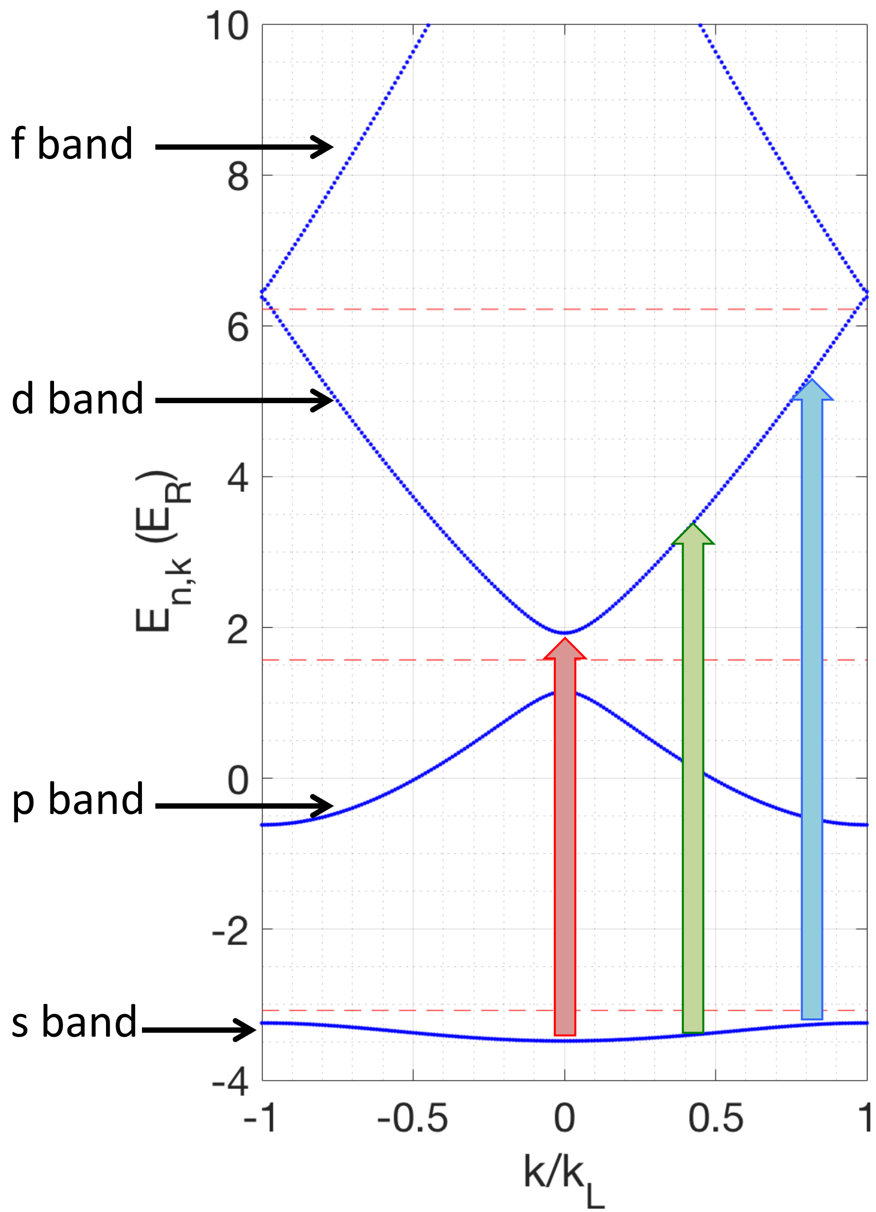


Relativistic Harmonic Motion in the d Band

- Amplitude modulation can excite to the d band

- AM frequency gives momentum selectivity

- What do we see if we drive such a transition?



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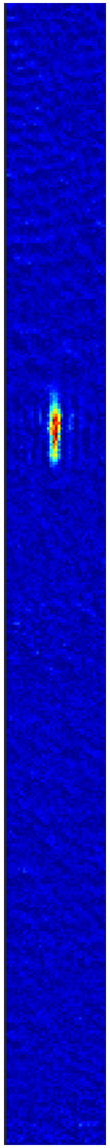


Relativistic Harmonic Motion in the d Band

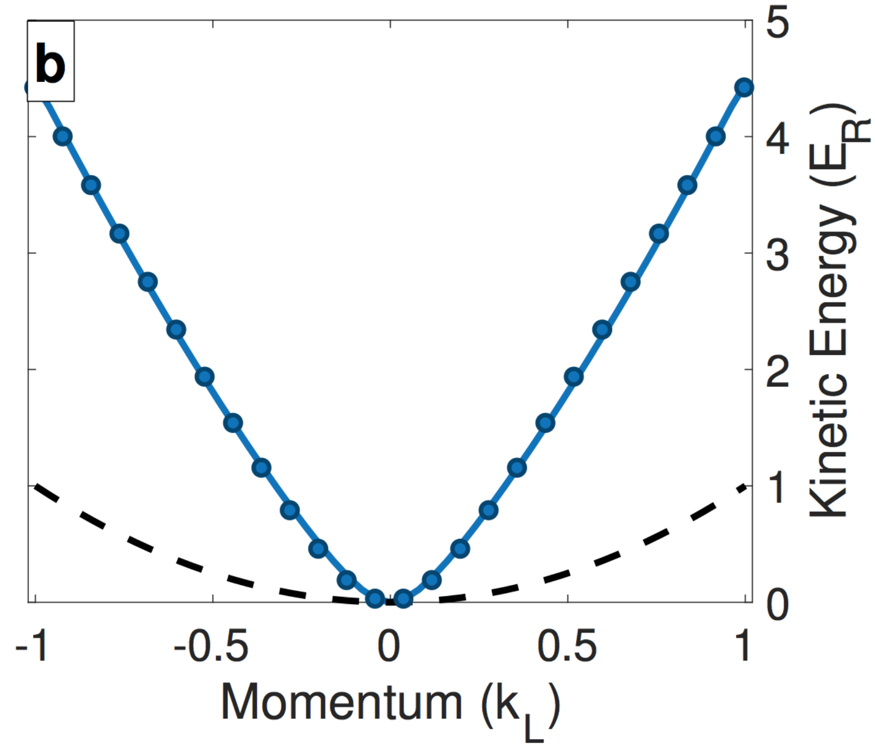
- Connects to a classic physics problem:
  What if a harmonic oscillator approaches the speed of light?

$$E = \frac{p^2}{2m} \quad \Longrightarrow \quad E = \sqrt{p^2c^2 + m^2c^4}$$

- Longstanding theory predictions:
  - Velocity saturation (obviously)
  - Relativistic anharmonicity
  - Increasingly photon-like worldlines

- Surprisingly hard to realize experimentally (requires trap depth of order mc²)

- d-band dispersion has exact relativistic form→ allows us to realize & study relativistic harmonic motion at extremely low energy



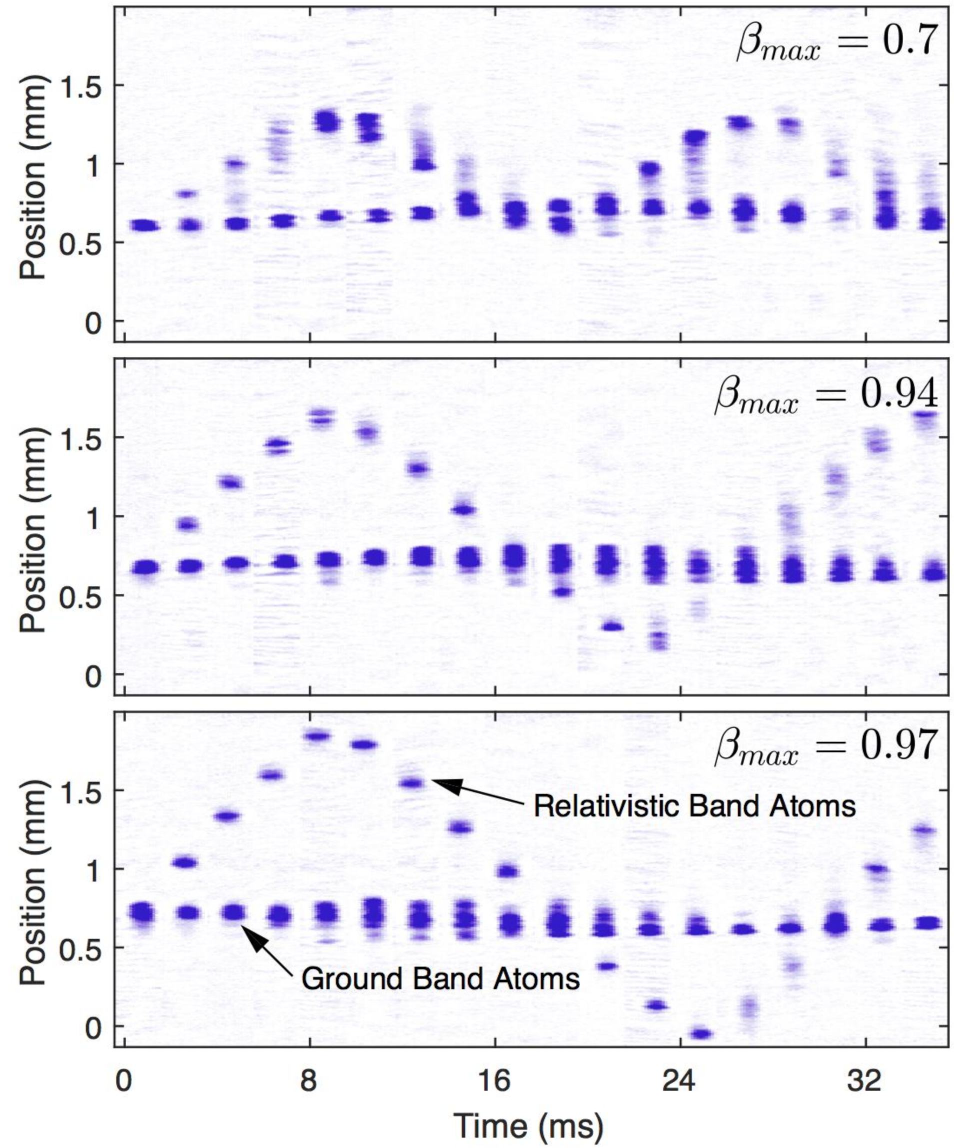
K. Fujiwara, Z. Geiger, DMW, arXiv 1712.09501 (2017)

Relativistic Harmonic Motion in the d Band

- We observe dynamics in good quantitative agreement with relativistic predictions

- Low-energy worldlines look harmonic

- Higher-energy: photon-like dynamics



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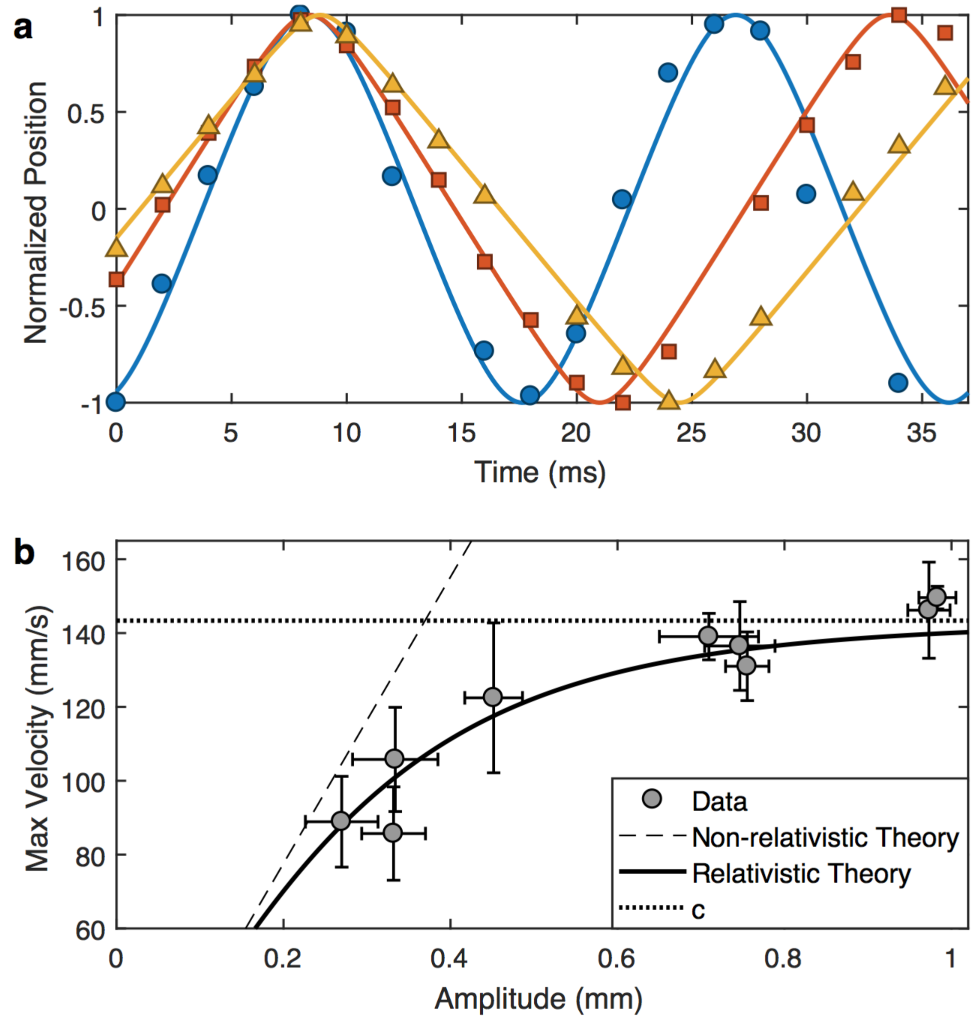
- Velocity saturates near c = 143 mm/s



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Relativistic Harmonic Motion in the d Band

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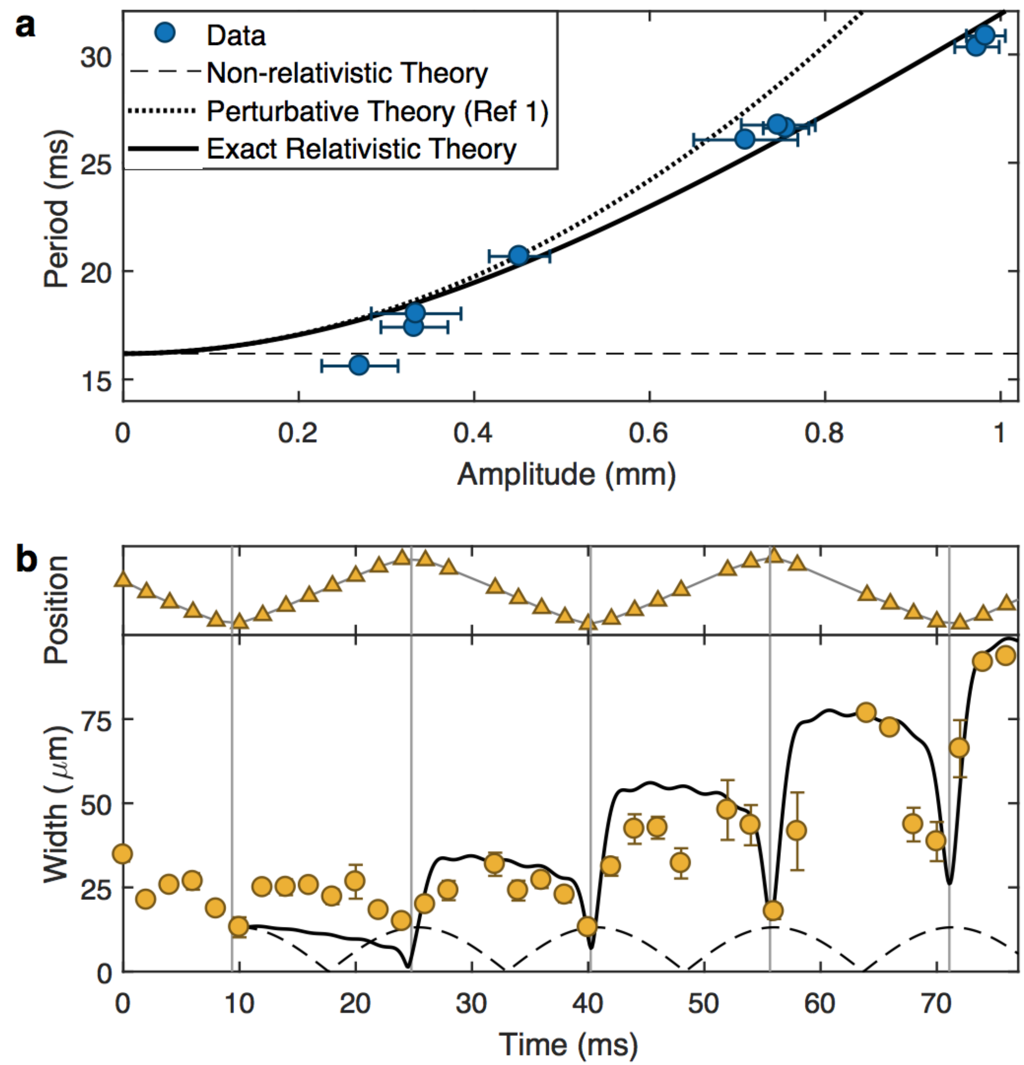
- Low-energy worldlines look harmonic
- Higher-energy: photon-like dynamics
- Velocity saturates near c = 143 mm/s
- Anharmonicity beyond leading order
- Relativistic dephasing of ensembles
- Phase-shifted relativistic breathing mode



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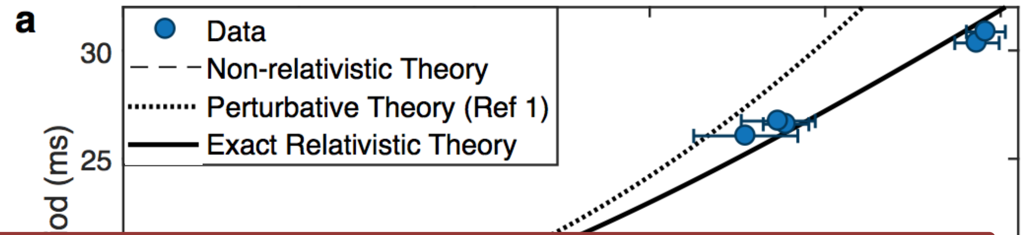
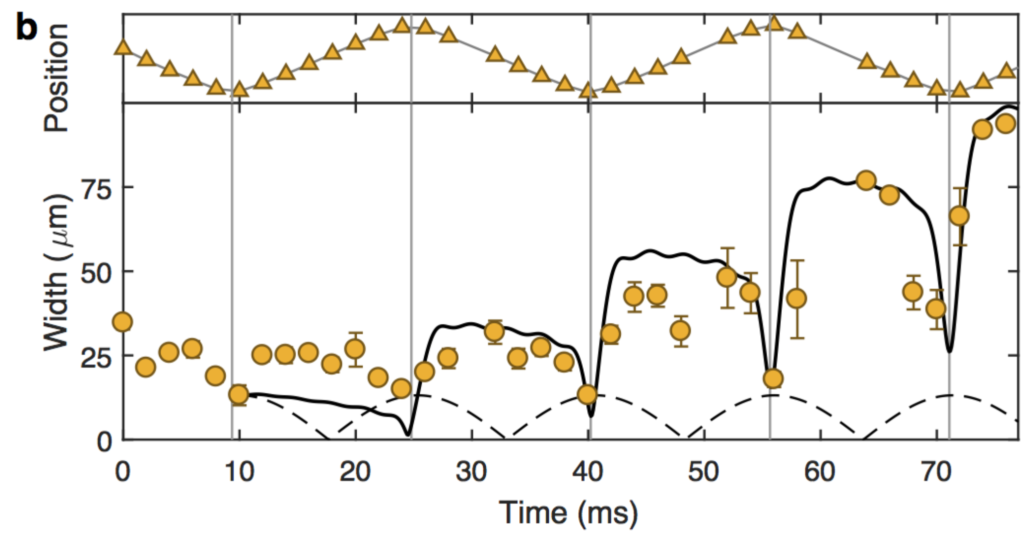


→Realized relativistic harmonic motion by driving to higher band.

Next: What if we leave the driving on?

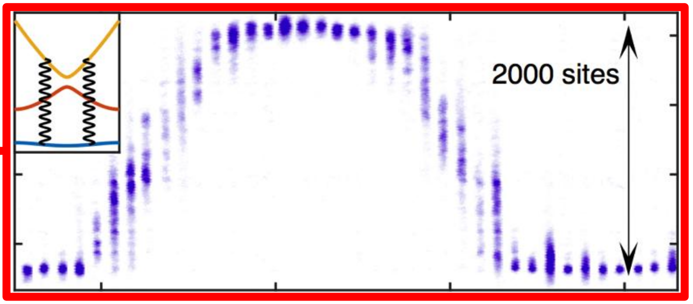


K. Fujiwara, Z. Geiger, DMW, arXiv 1712.09501 (2017)

Outline

- Experimental Approaches
  - Short-distance gravity
  - Degenerate quantum gases

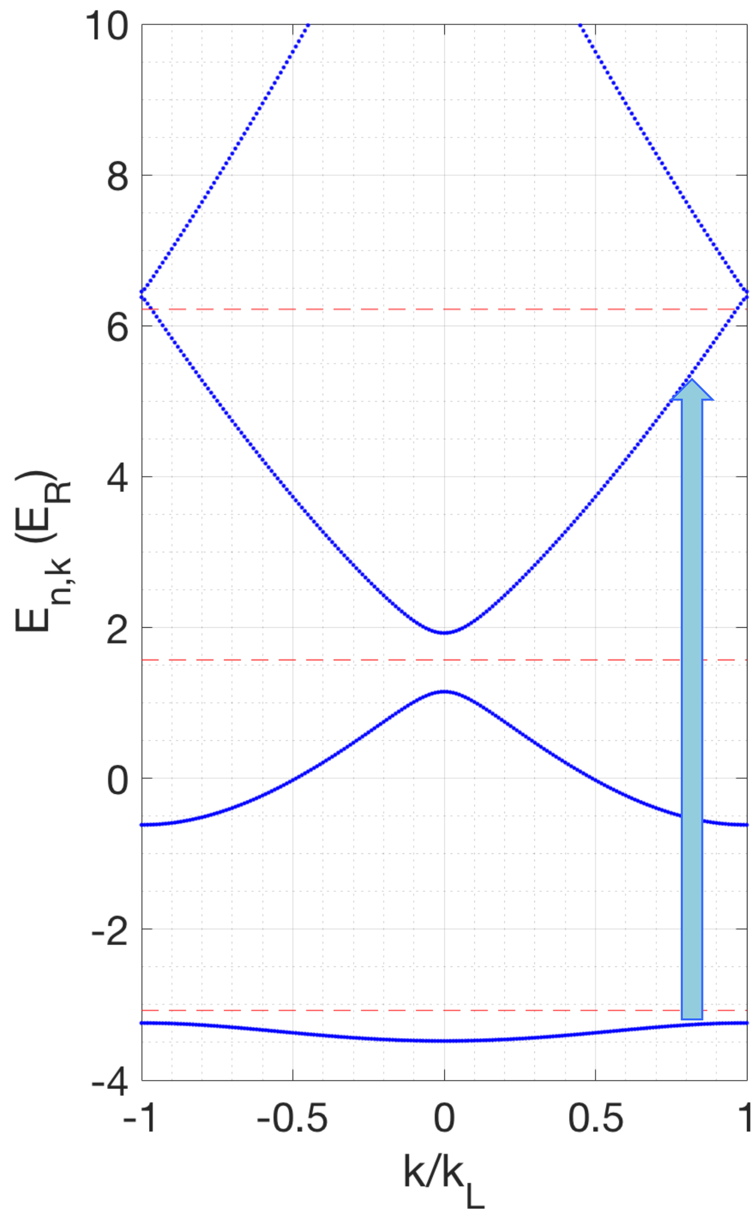
- Exploring driven quantum systems
  - Position-space Bloch oscillations
  - Relativistic harmonic motion
  - **Transport in Floquet-Bloch bands**



- Future possibilities
  - Enhanced metrology
  - Atoms near surfaces
  - Discussion…

Floquet-Bloch Oscillations

- Putting these techniques together:
  - Apply constant AM drive resonant with s-d transition at finite k
  - Allow atoms to Bloch oscillate
  - What happens?



Floquet-Bloch Oscillations

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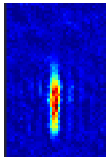
Drive Off



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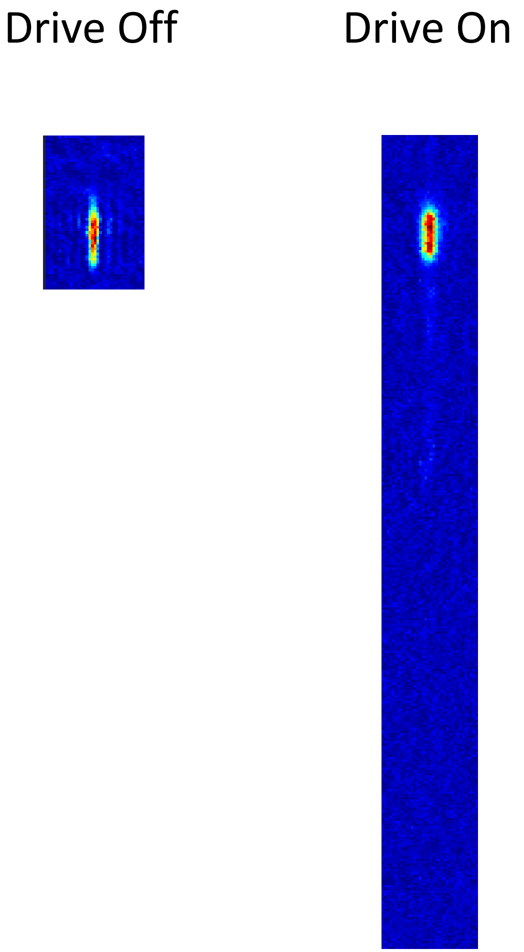

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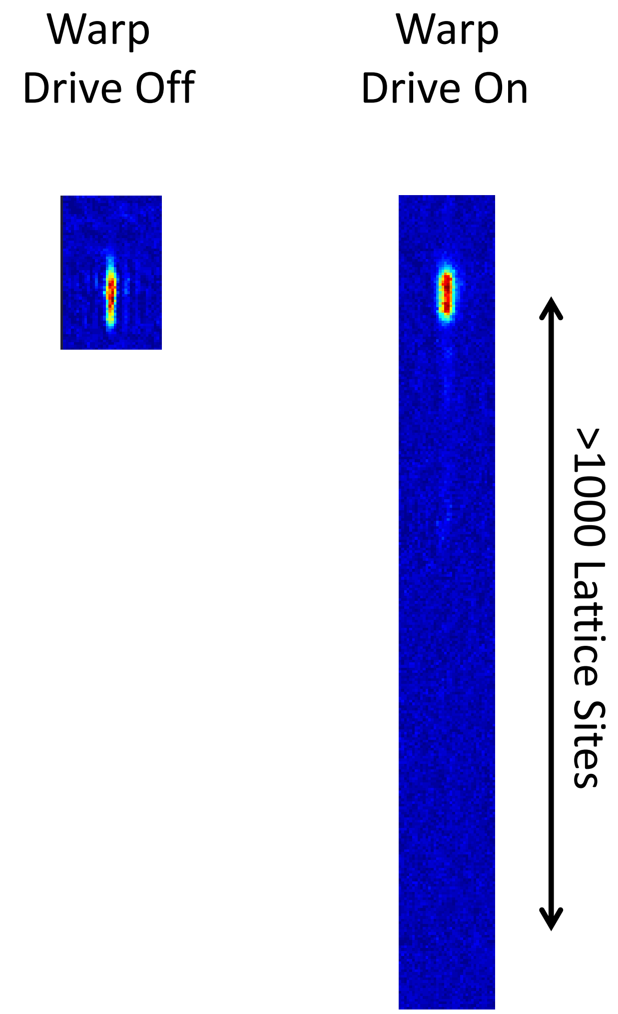
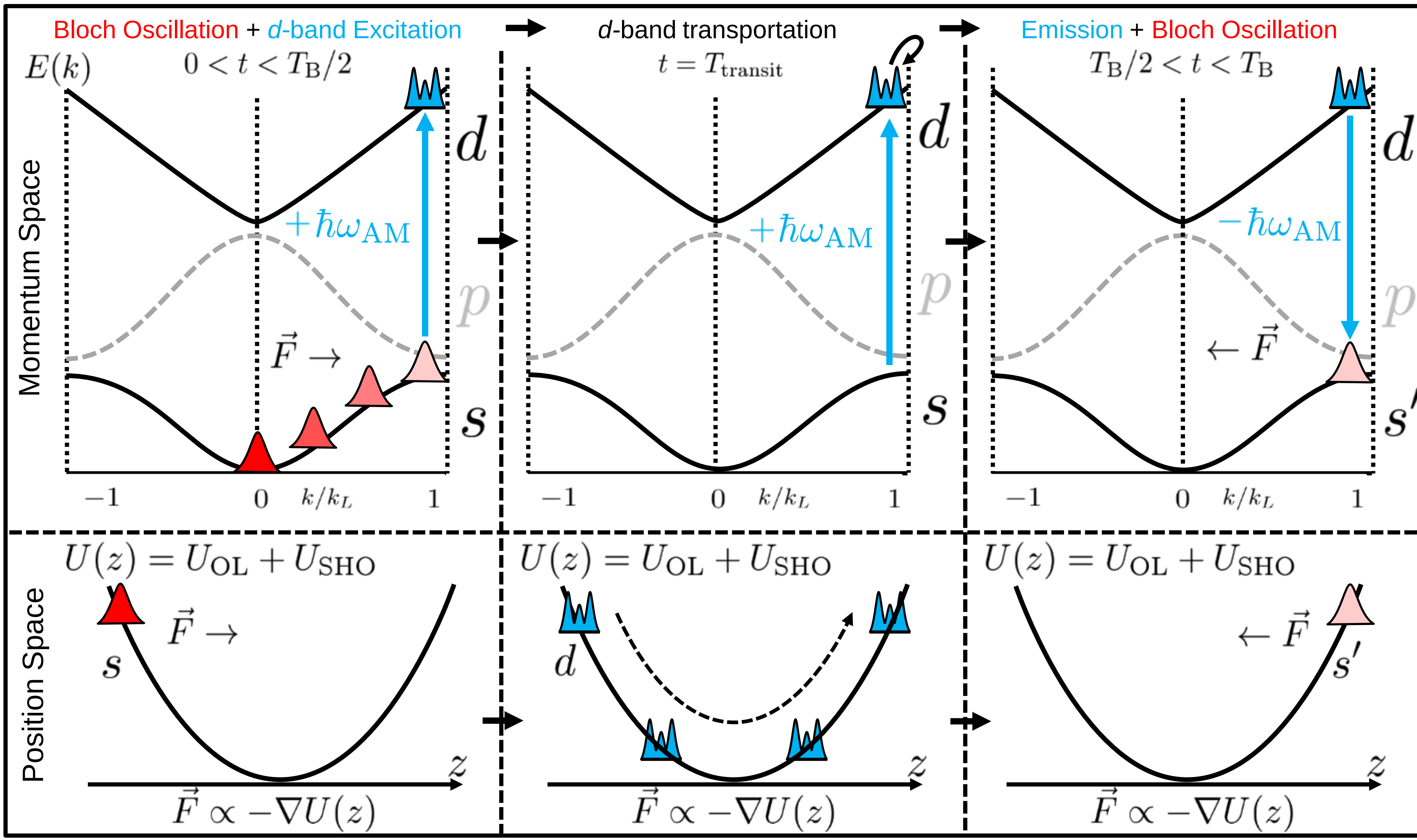


→ **Giant Floquet-Bloch oscillations**

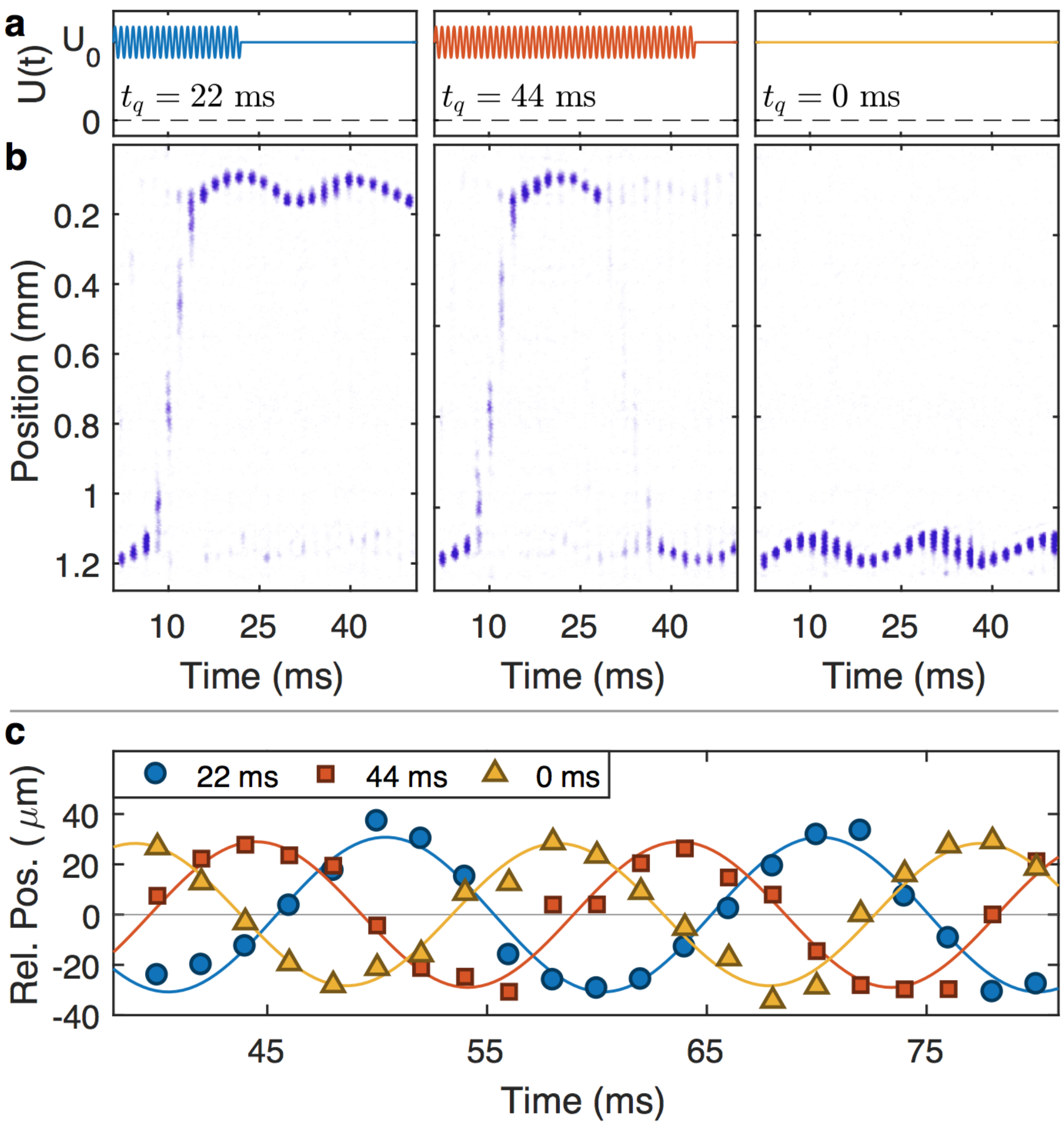
Floquet-Bloch Oscillations

- Can think of this as evolution in a single Floquet-hybridized s/d band



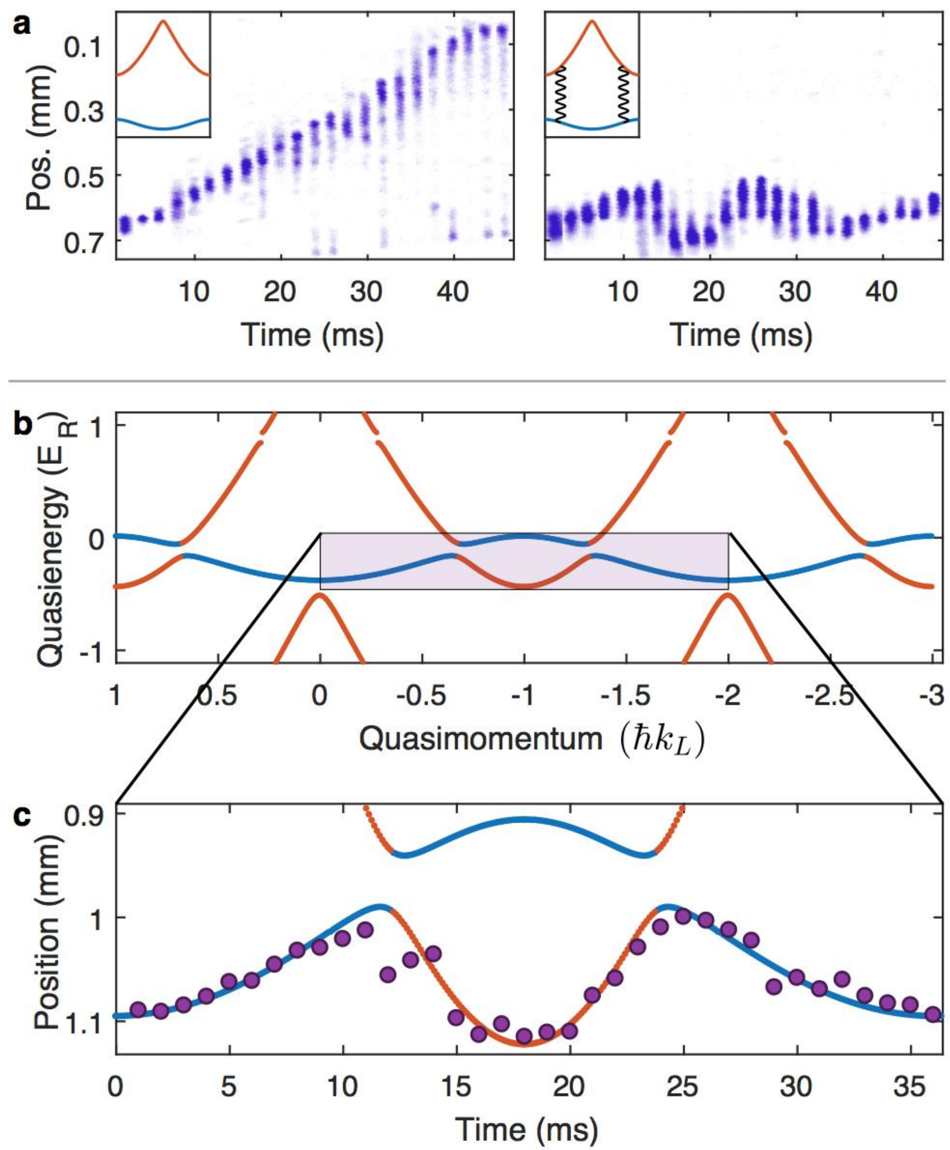
Floquet-Bloch Oscillations

- Allows precise coherent control of long-range transport



Floquet-Bloch Oscillations

- Can image dispersion of s-p hybridized Floquet-Bloch band via PSBOs
- Flexible tool for band engineering
- Some future possibilities:
  - Gradiometry
  - Atom interferometry
  - Multi-frequency driving
  - Topological bands



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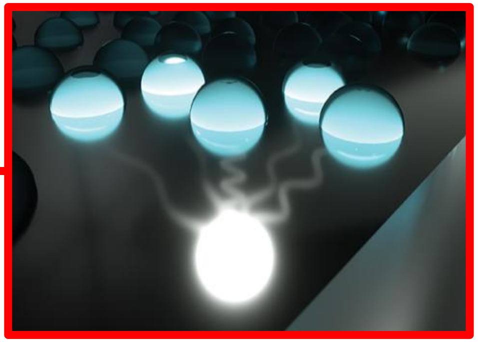


Some Metrological Possibilities

- Quantum control techniques can improve measurements at the precision frontier

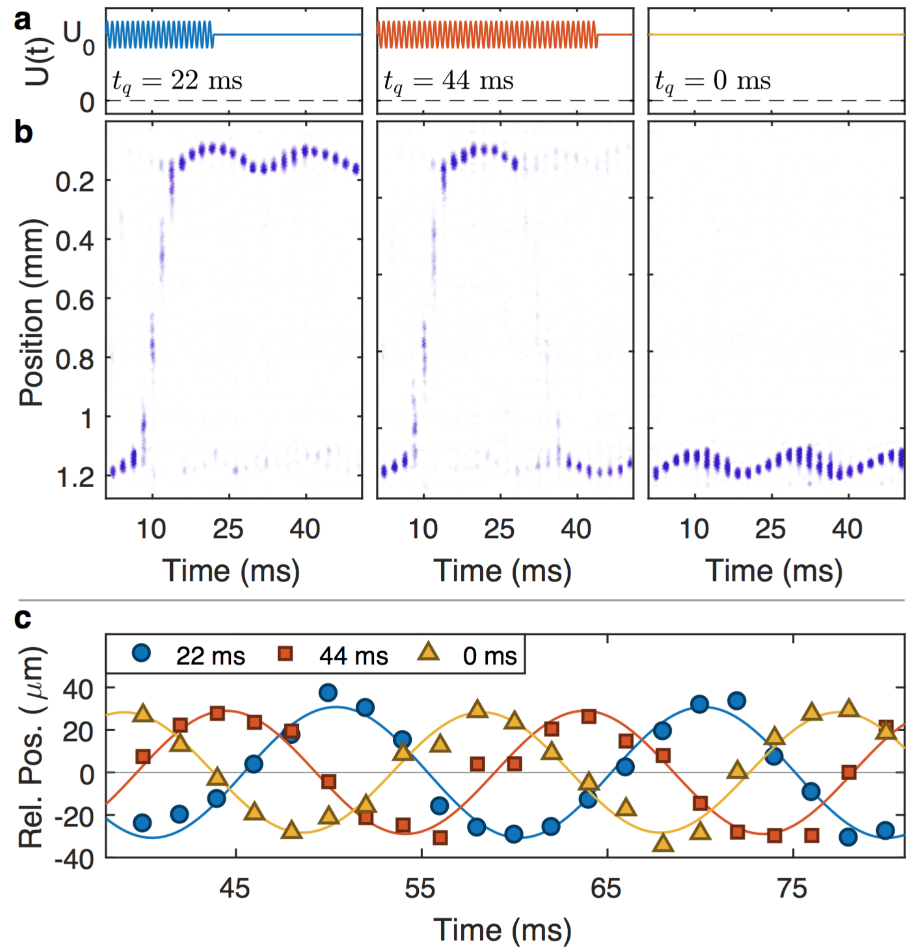
- Bloch oscillations for force sensing

- α^{-1}=137.035999046(27)*

- Floquet-Bloch atom interferometry?

- AC experiments to look for $\dot{\alpha}$ (e.g. near Feshbach resonances)

- What good are 1 million atoms in the same state? Superradiant effects? Bosonic stimulation? Tunable resonant interactions? Other ideas?

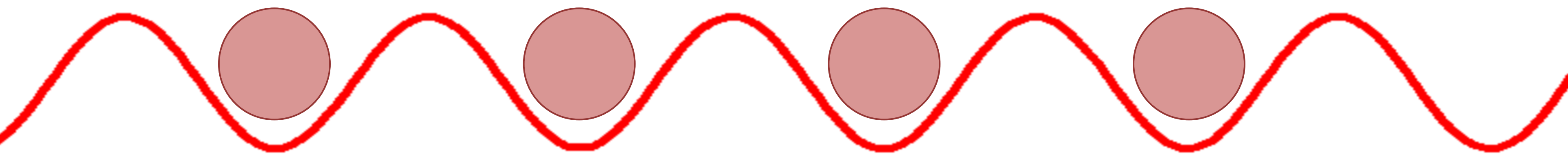


- Another possible tool: **hybrid quantum systems**

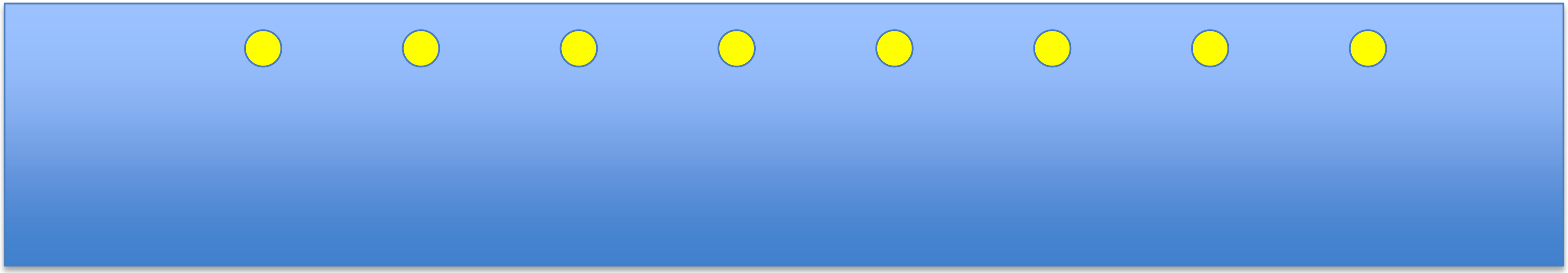
*Parker *et al*, *Science* **360**, 6385 (2018)

Atoms + Defects

- Atoms: Good emulators. Uniform. Controllable. Ephemeral.



- Defects: Good sensors. Small. Variable. Long-lived.



→ **Some expts could benefit from a combination of these virtues.**

Atoms + Defects

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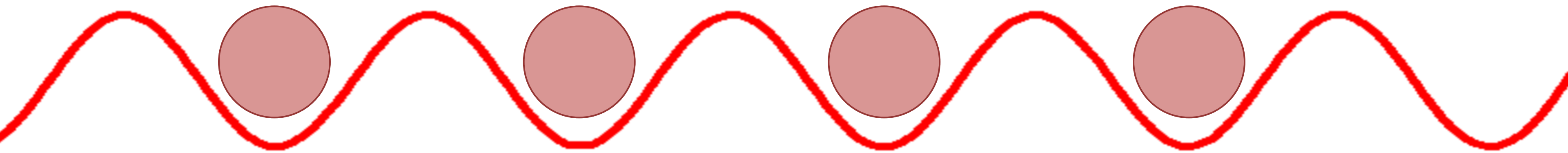

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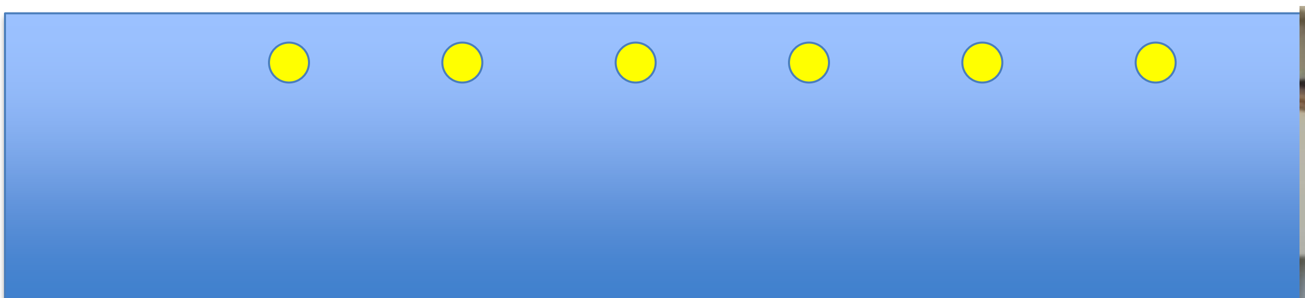
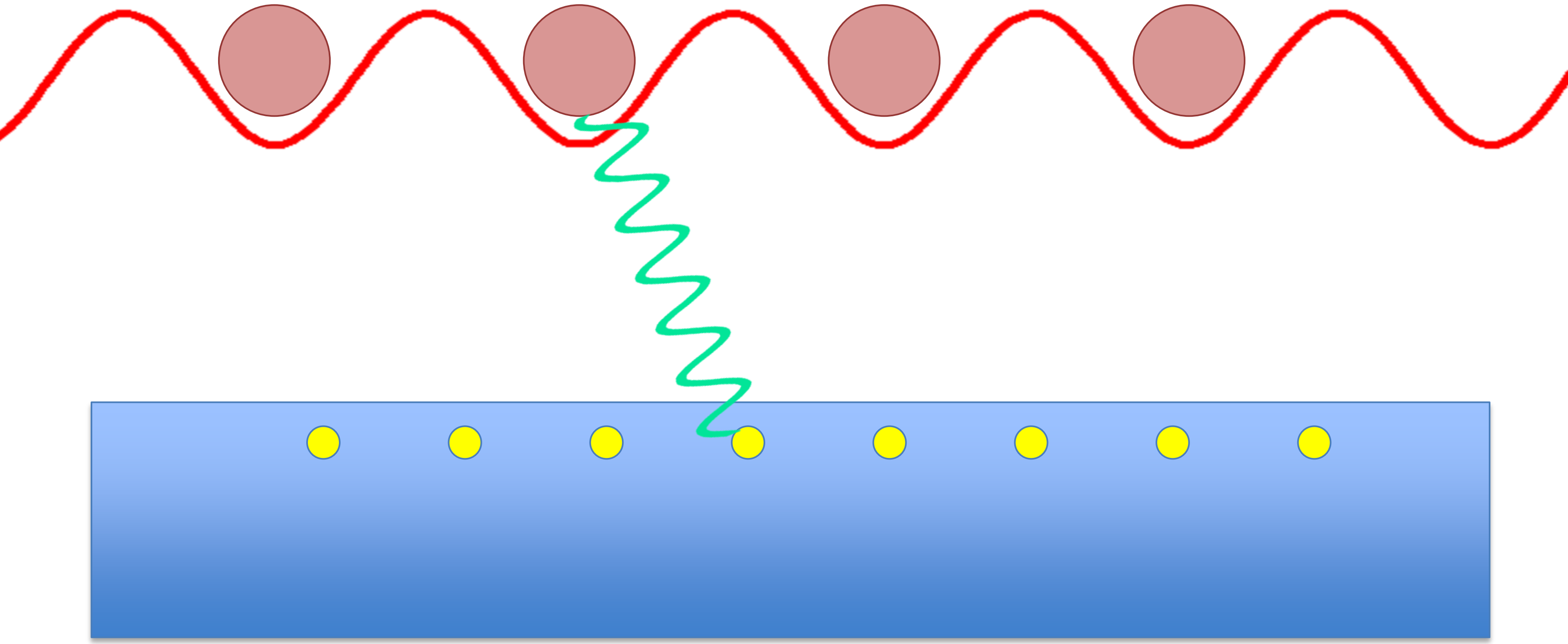


Collaboration w/ A.B. Jayich Group

→ **Some expts could benefit from a combination of t**

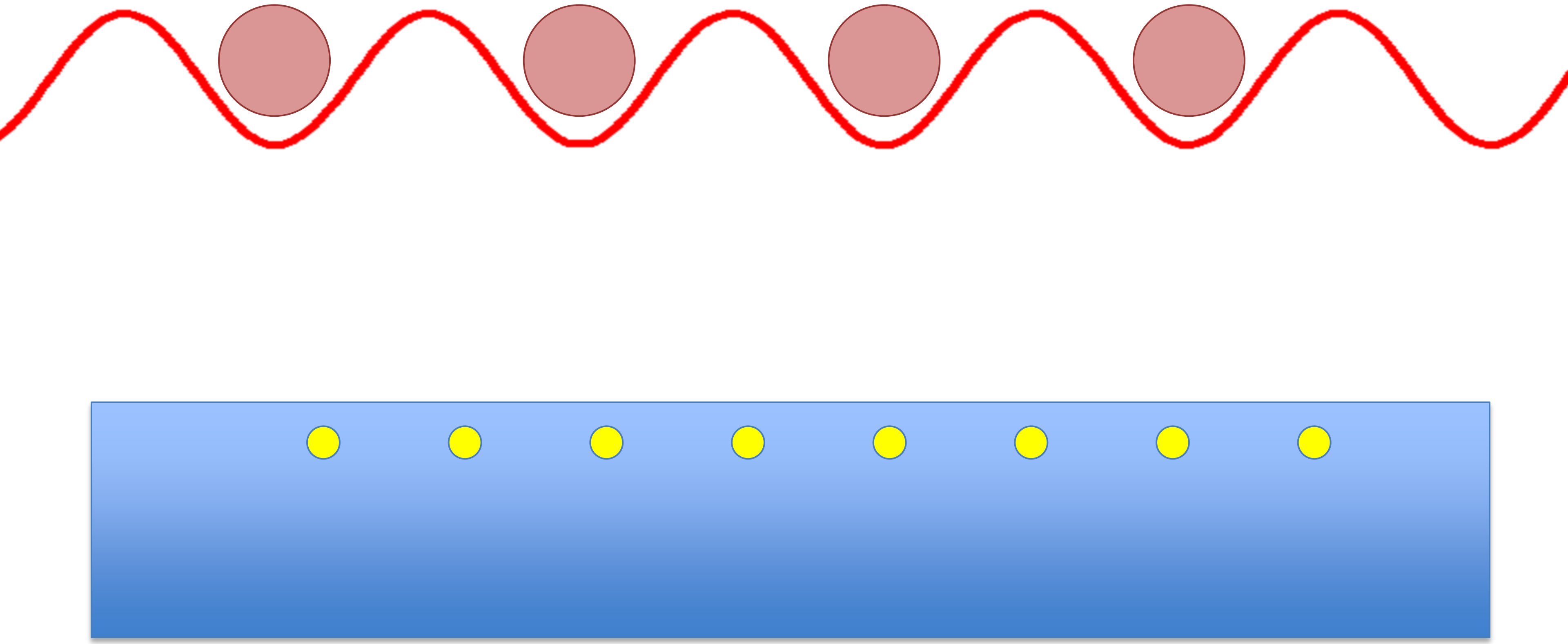
Atoms + Defects

- Direct optical coupling is challenging.



Atoms + Defects

- Is magnetic coupling possible?



Atoms + Defects

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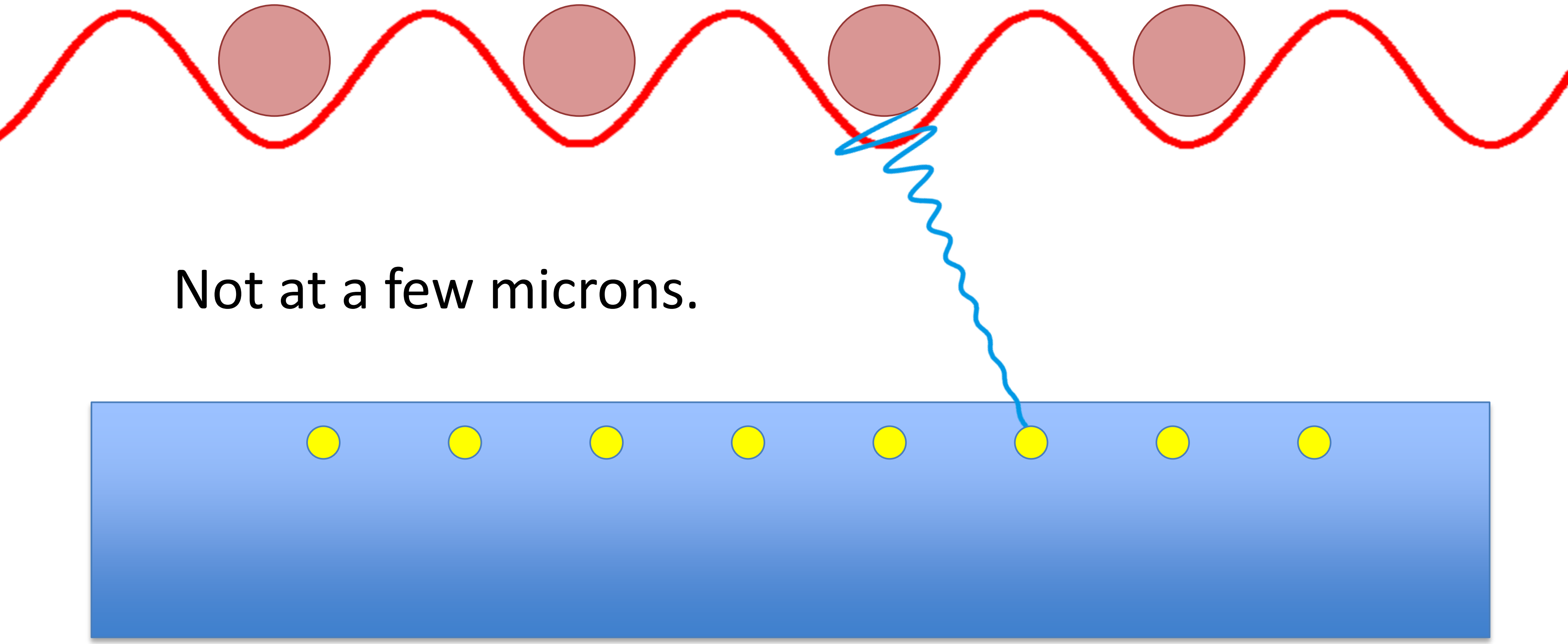
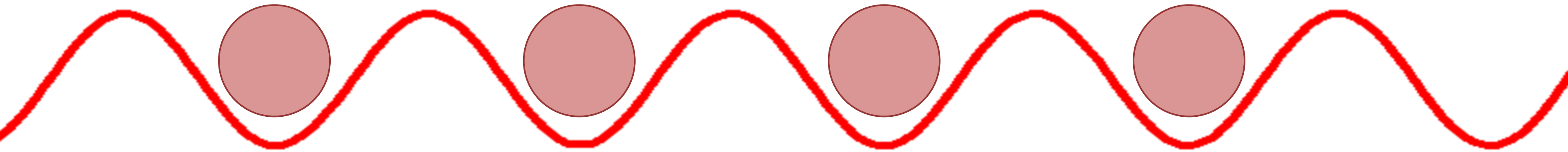
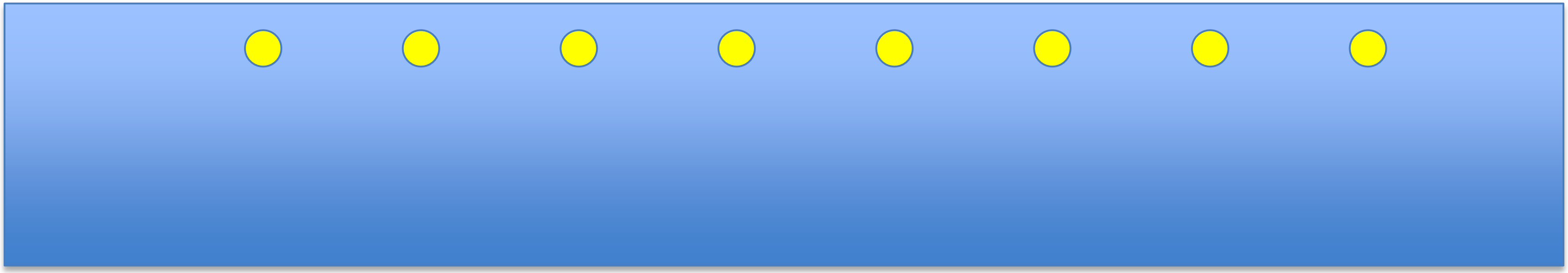


Not at a few microns.

Atoms + Defects

- Another possibility:

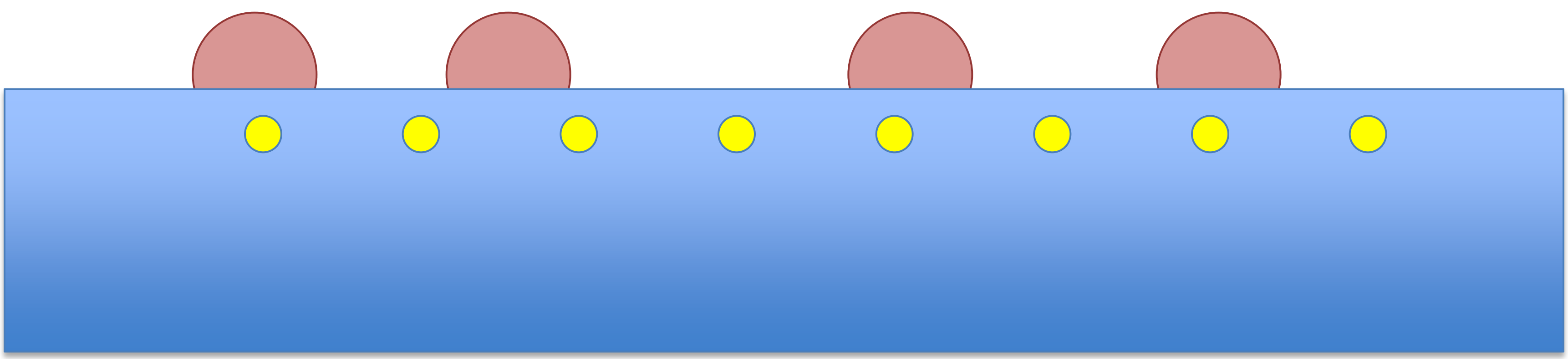




Atoms + Defects

- Another possibility:
  - NVs 20nm deep can sense single e^- spins on surface
  - Nuclear spins harder, but within plausible reach
  - Atoms can be removed from surface to reinitialize

  → Non-reversible transport of info about atoms to NVs.

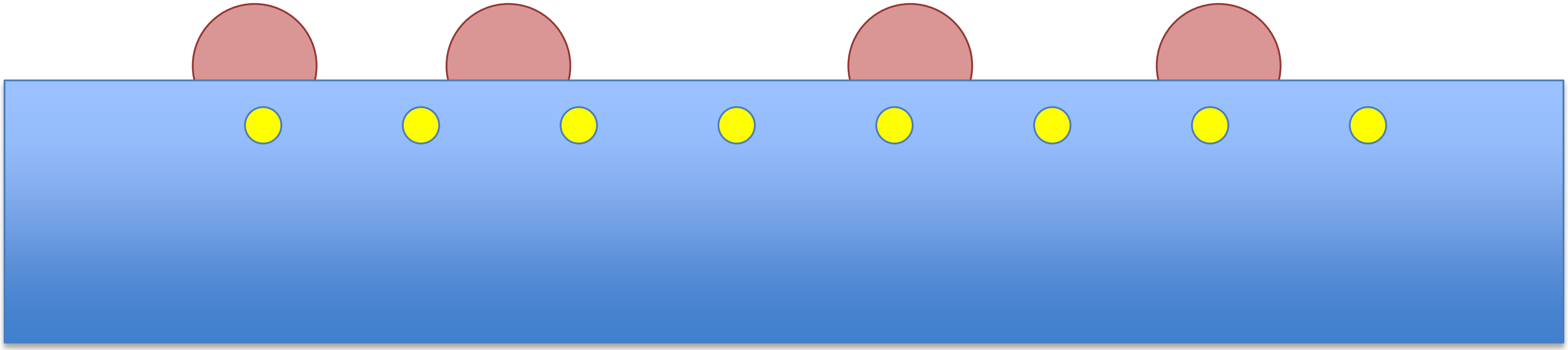


Is this useful?

Atoms + Defects

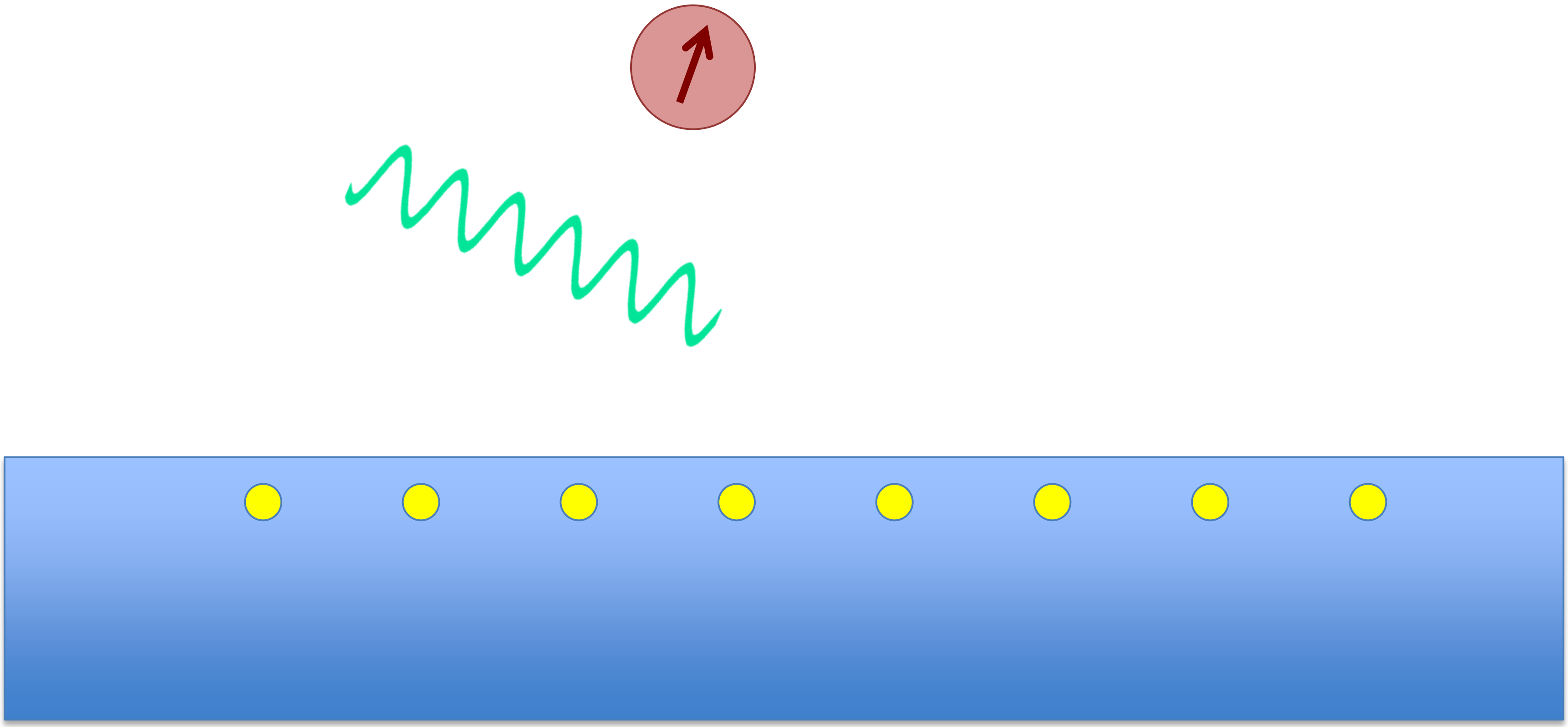
Possible uses:

- Ultra-high-resolution quantum gas microscopy
- Controllable test of surface decoherence mechanisms
- **Sensitive probe of atom-surface interactions**
  - **Reservoir spectroscopy of clock shifts near surfaces**
  - **Short-distance spin-spin forces**
  - **Many other interactions**



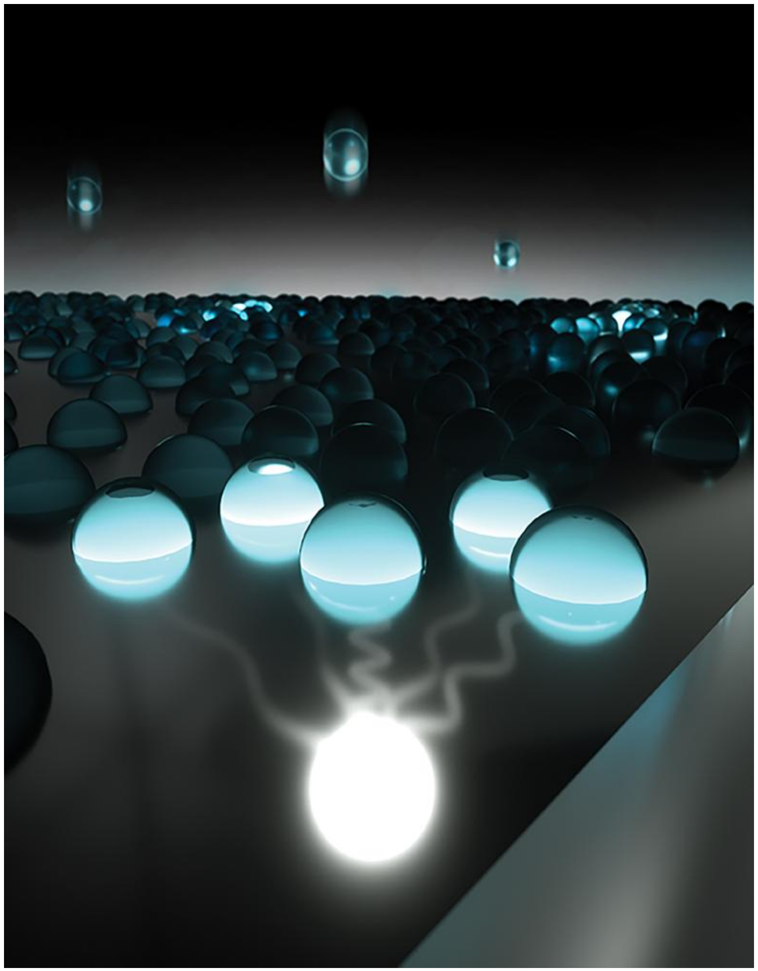
Adsorbate Reservoir Spectroscopy

- Start with spin-polarized atomic sample (e.g. ^{87}Sr)
- Spin-changing clock transitions allowed near surface
- Apply probe laser at varying time
- NV reads out spin state after adsorption
- Sensitive to interactions that affect (shift/broaden/allow) intercombination transitions

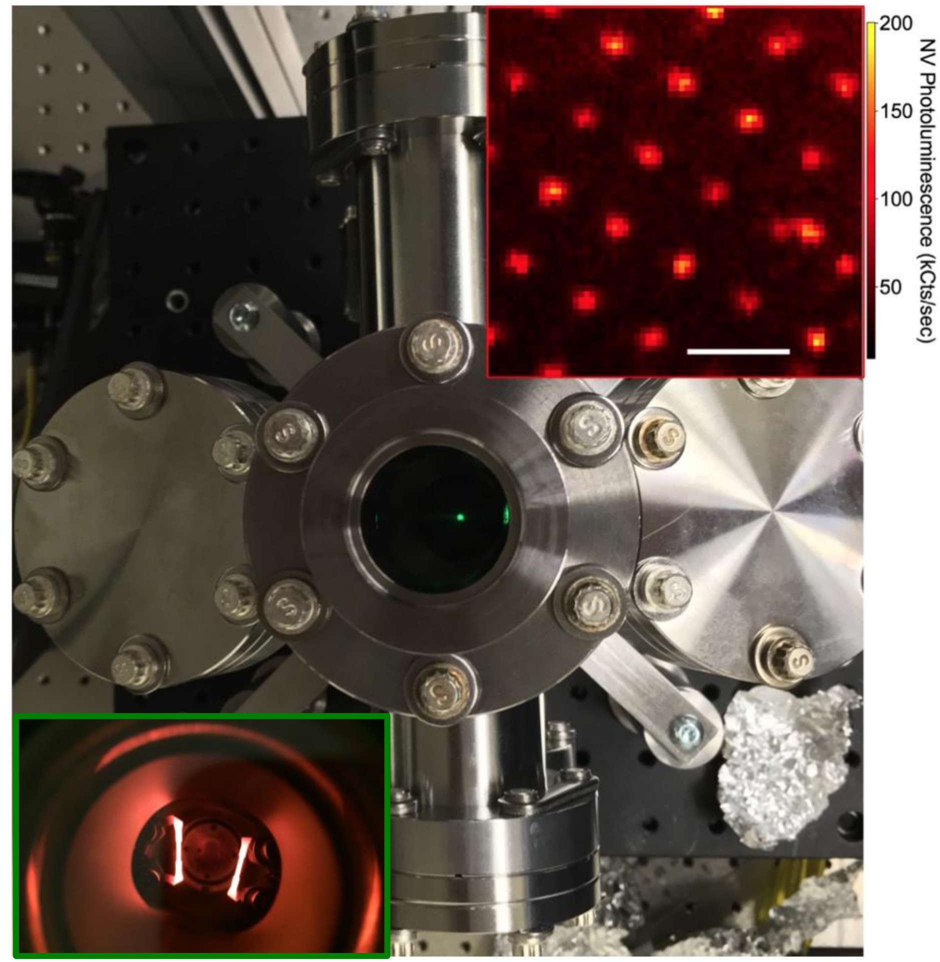


Quantum Interfaces

Artist's Conception



Prototype Experiment



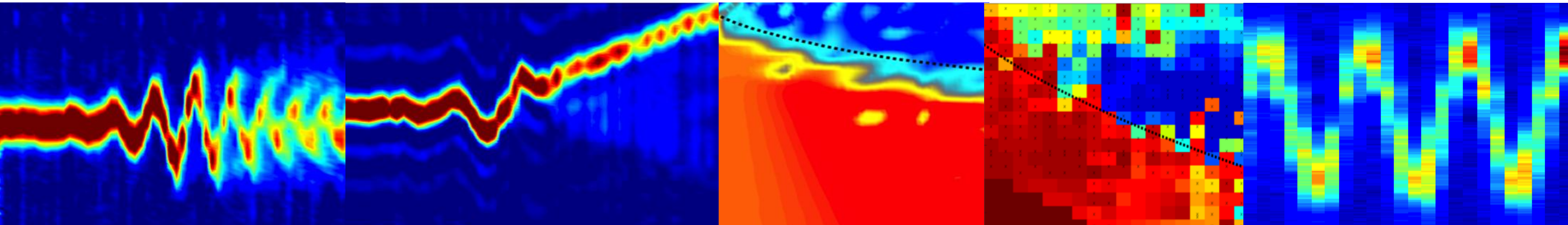
→ Work is ongoing. First goal: demonstrate atom-defect interactions.

Conclusions

- Cold atoms are a natural tool for probing nonequilibrium systems
  - Position-space Bloch oscillations
  - Relativistic harmonic motion
  - Floquet band engineering

- New quantum control techniques may give rise to new measurement capabilities
  - Force sensing
  - Atom interferometry
  - Calibration & enhancement of existing techniques

- Atoms near surfaces may enable new probes of short-distance interactions
  - One possibility: adsorbate reservoir spectroscopy



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Ania Jayich
CAIQuE Team
MURI Team