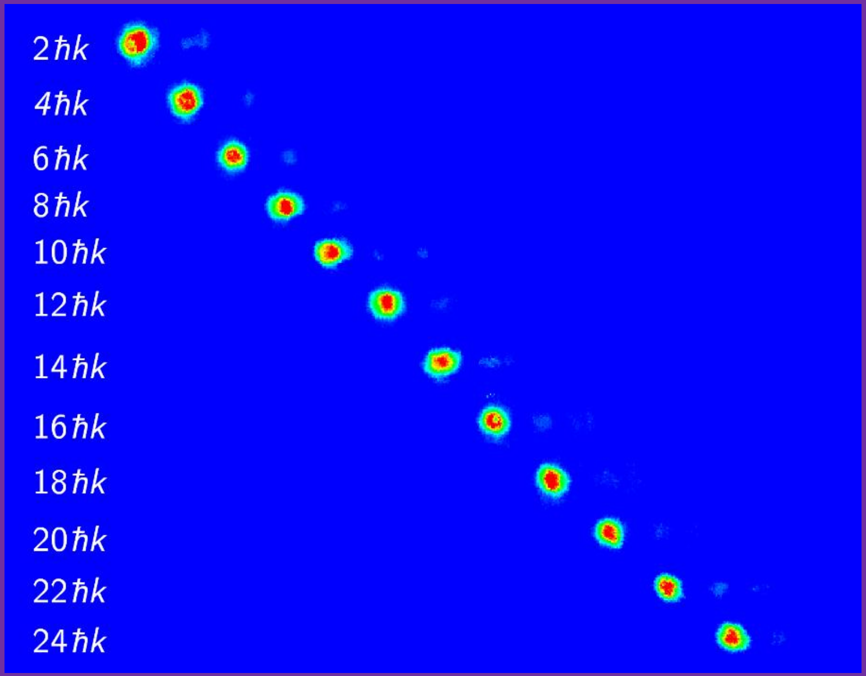
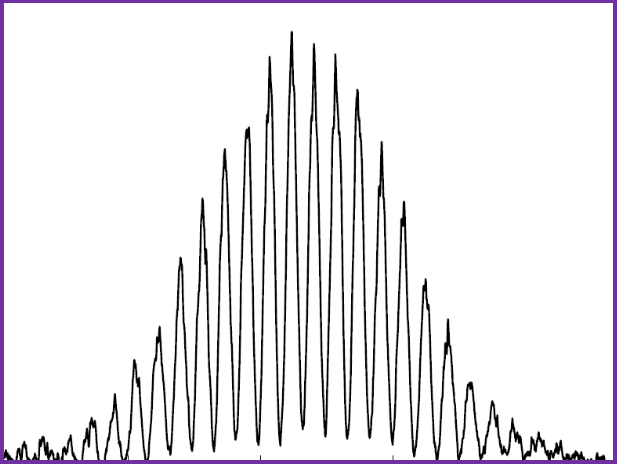
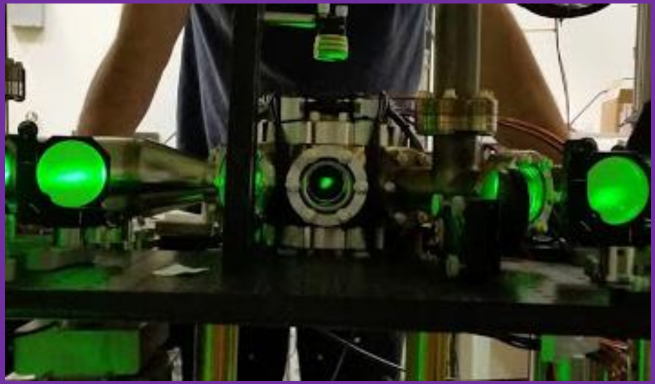
Managing Bloch Oscillation Phases for Large-Momentum-Transfer Atom Interferometry





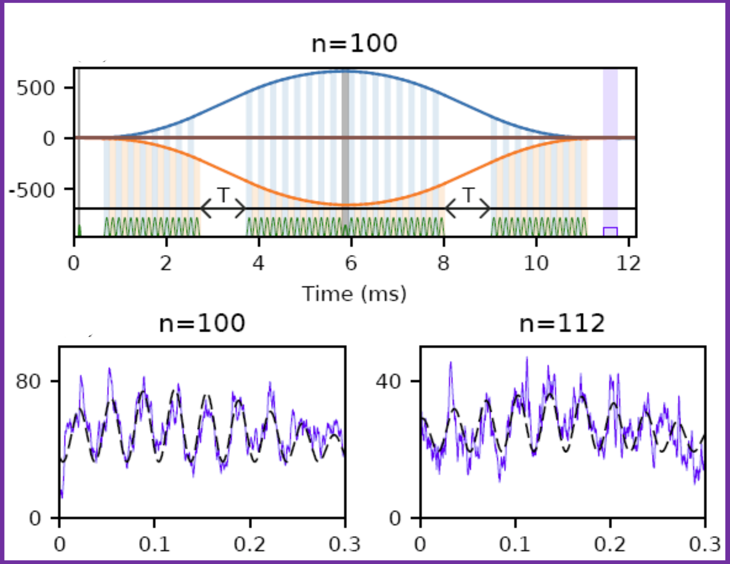


Subhadeep Gupta, University of Washington, Seattle

Terrestrial VLBAI Workshop, Imperial College, 3rd April 2024

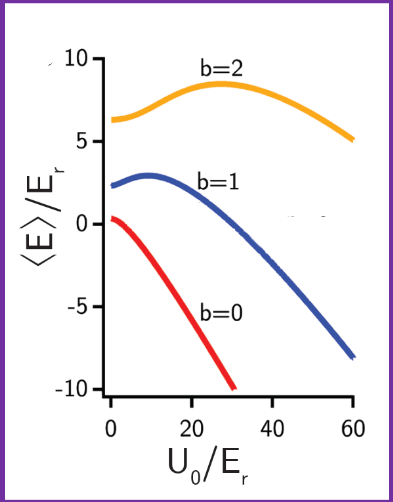
Atom Interferometry @UW with Yb

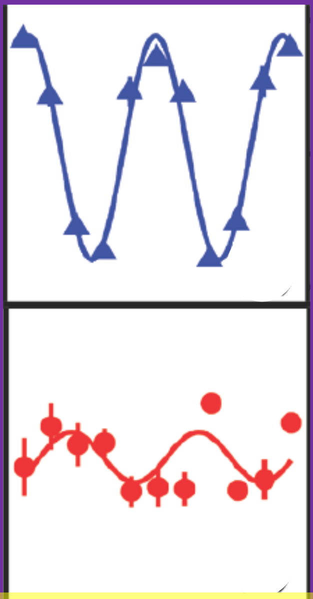
(alkaline earth-like
1 or 2-photon, isotopes)



Three-path LMT-AI for photon recoil

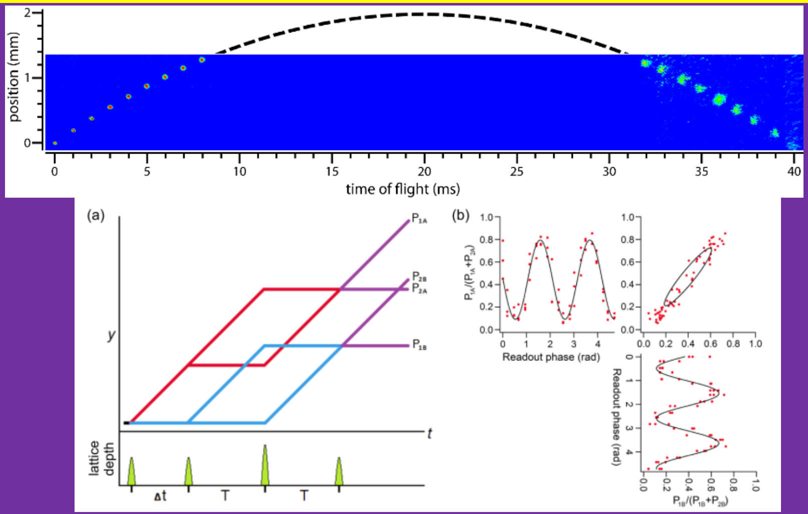
Ben Plotkin-Swing et al. PRL **121**, 133201 (2018)





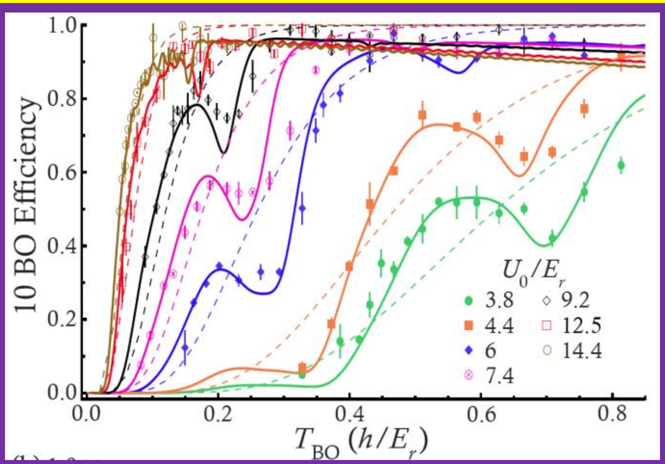
Magic Depth
Atom Interferometry

McAlpine et al, PRA **101**, 023614 (2020)



Vertical Yb AI, double Mach-Zehnder

Gochnauer et al, Atoms **9**, 58 (2021)



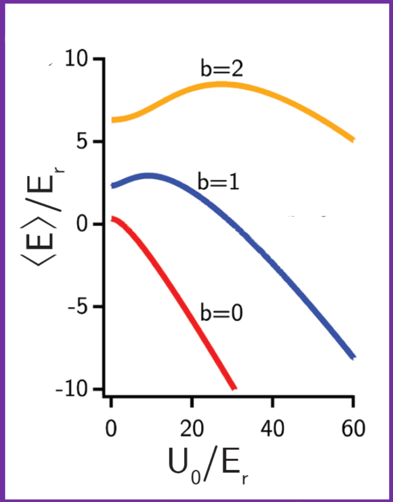
BO Phases with multi-path Stuckelberg AI

Rahman et al, arXiv:2308.04134 (2023)
To appear in Phys Rev Research

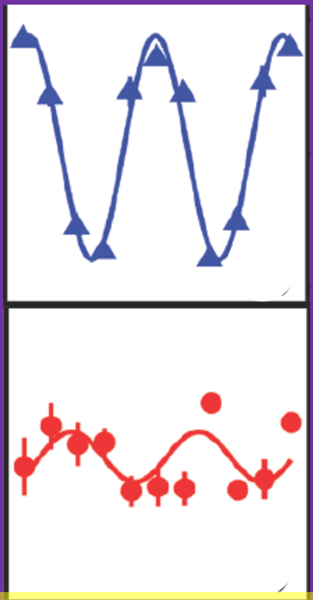
Managing Bloch Oscillation Phases for Large-Momentum-Transfer Atom Interferometry

Bloch Oscillations highly efficient LMT tool

Intensity noise turns into phase noise.
Challenge for scaling to 1000 recoil for next generation BO-enhanced AI.

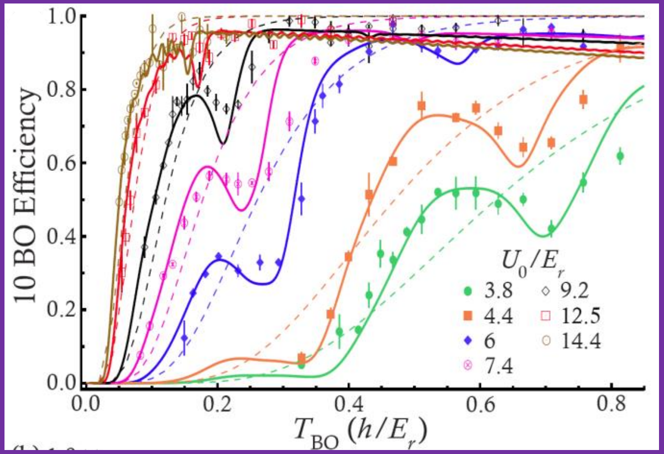


Magic Depth
Atom Interferometry



McAlpine et al, PRA **101**, 023614 (2020)

Excited-band BO as an alternate possibility for LMT.

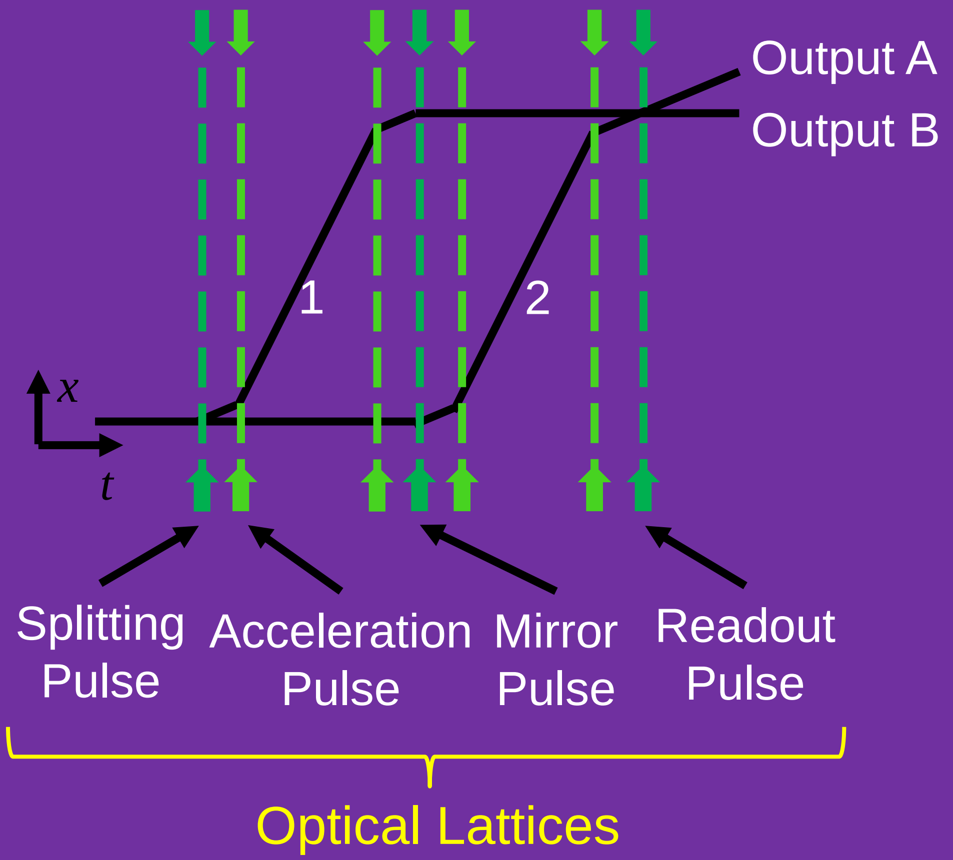


BO Phases with multi-path Stuckelberg AI

Observation of ground band BO phases upto 100 recoils, compare with theory.

Rahman et al, arXiv:2308.04134 (2023)
To appear in Phys Rev Research

Large Momentum Transfer for precision AI



Measurement Precision scales as
$\delta\Phi / \Phi \sim \delta\Phi$ / (space-time area)

LMT photon recoils

eg.
$\Phi_1 - \Phi_2 \sim mgX*T \sim g(n)k*T^2$

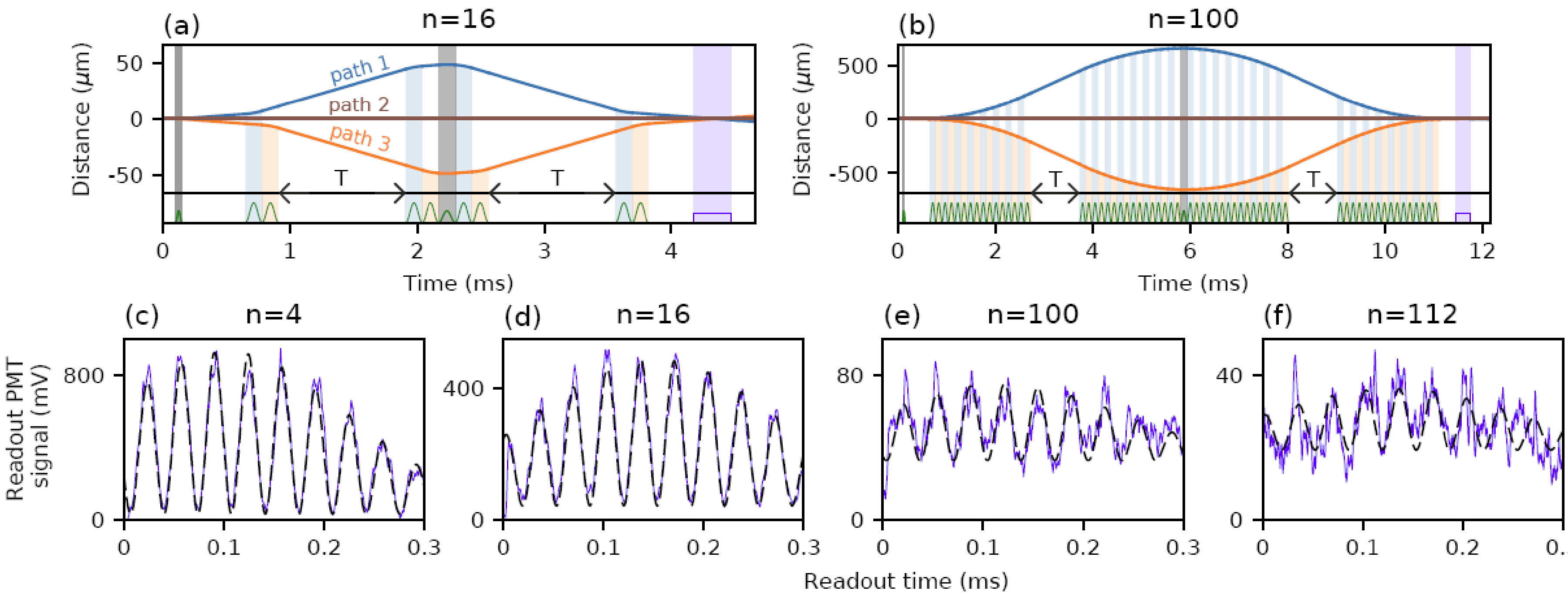
~ space-time area

Can increase T with fountain, drop tower, terrestrial VLBAI, rockets, in space

Can increase n with
Bragg Pulses
Bloch oscillations
Other techniques (eg Floquet)

Three-Path Atom Interferometry with Large Momentum Separation

Phase Stability, High Visibility for > 100 photon recoils



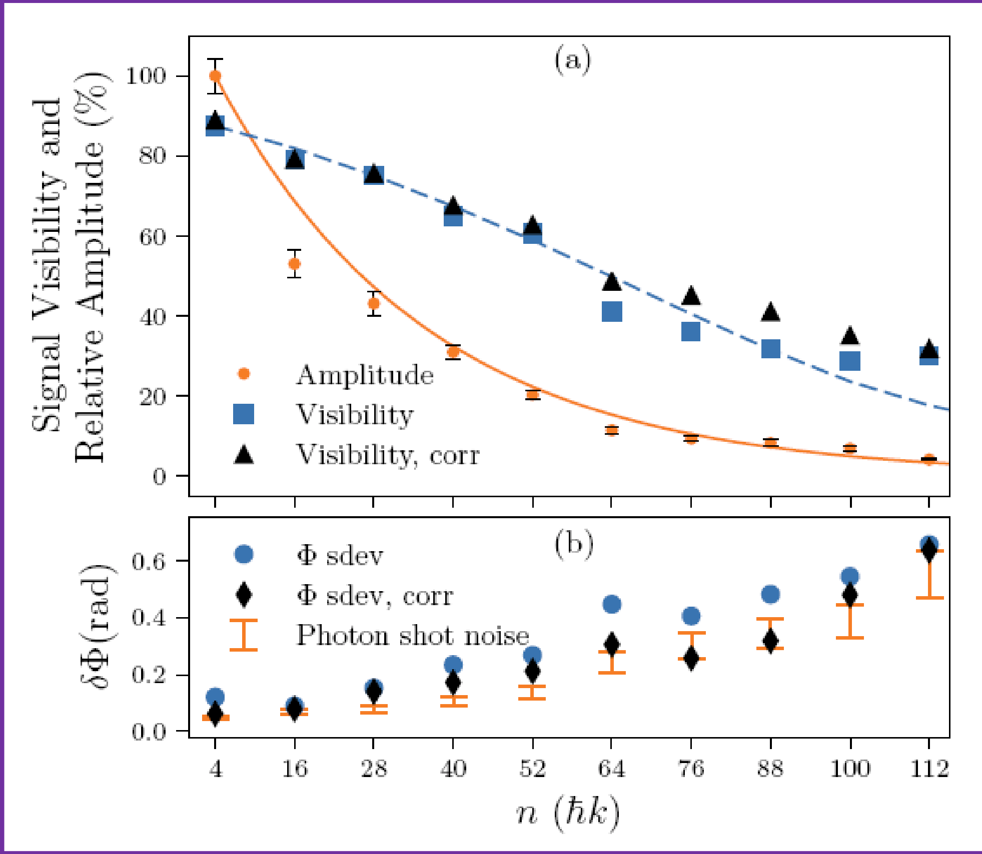
n = # recoils betw 1 and 3 increased by sequences of 3rd order Bragg pulses

Stability acquired from:
- Interferometer symmetry
- Atom-optics pulse control

Related large LMT works:
Hannover, Stanford, Berkeley, Toulouse, others

Ben Plotkin-Swing et al. PRL **121**, 133201 (2018)

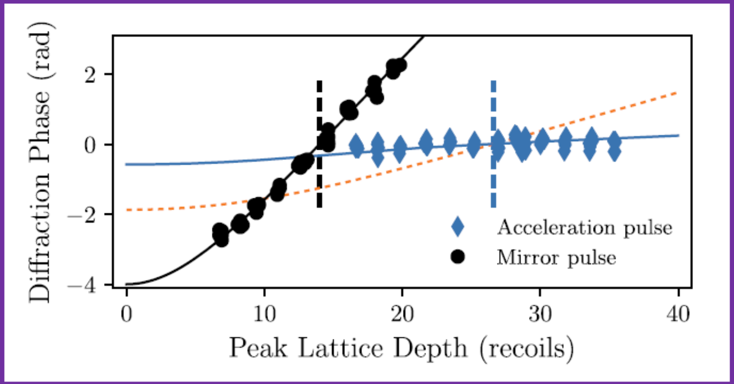
High n performance limited by efficiency and photon shot noise



Visibility = 100% x (Max-Min)/(Max+Min)

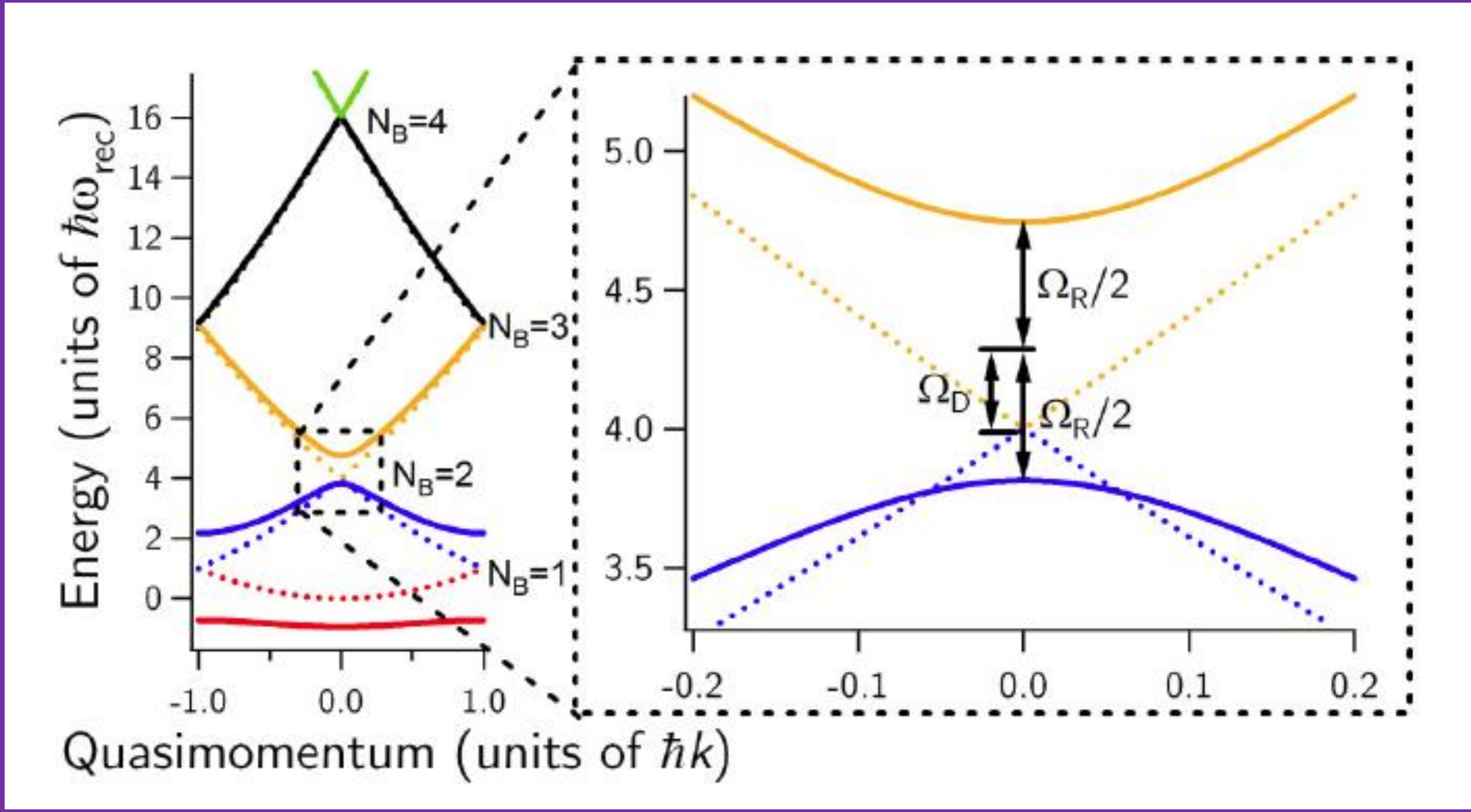
Amp ~ $(\text{Eff})^{\text{recoils}}$
Eff ~ 98.4%/recoil

Suppressing Diffraction (lattice-induced) Phases



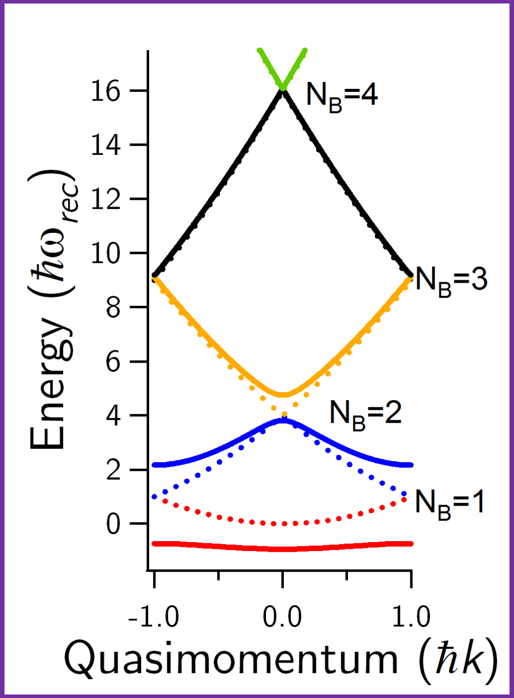
Ben Plotkin-Swing et al. PRL **121**, 133201 (2018)

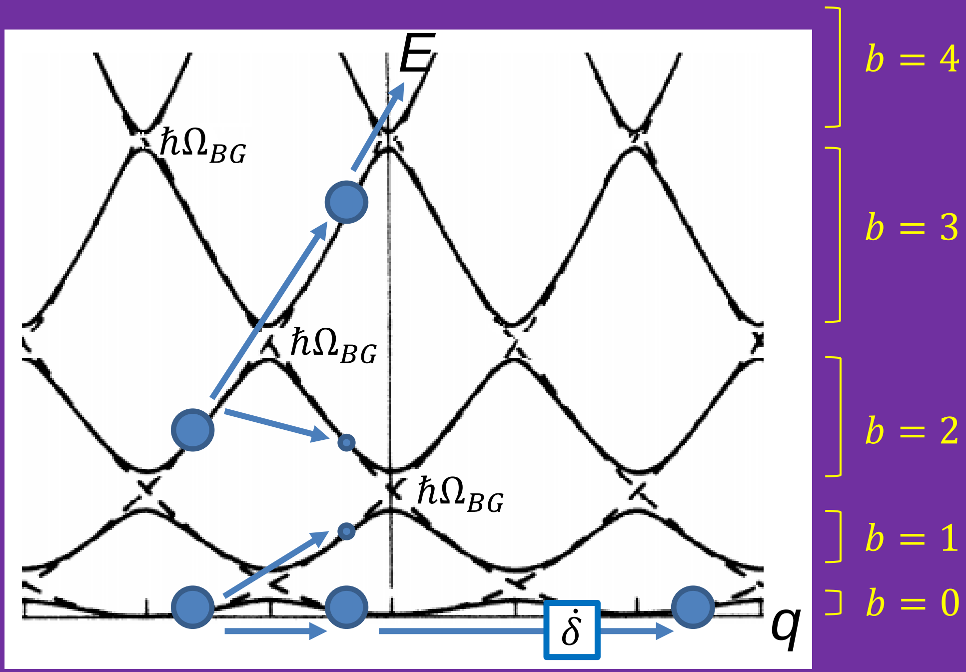
Bloch-band picture of Bragg Diffraction



Identify Ω_R as Rabi frequency and
Ω_D with an average energy shift during diffraction

Bragg Diffraction and Bloch Oscillations

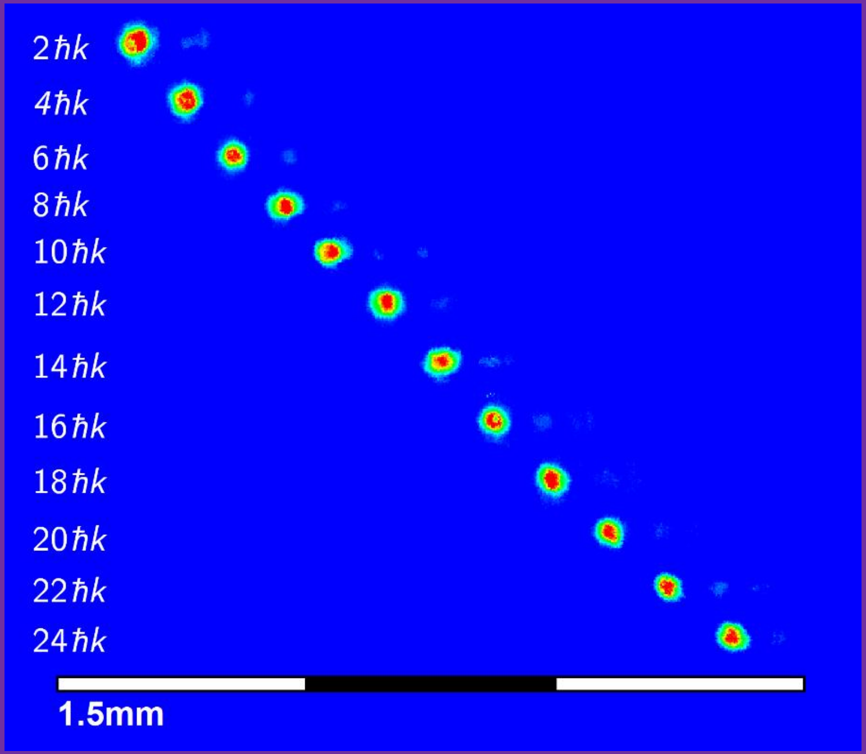




$$P_{LZ} = \exp\left(-\pi \frac{{\Omega_{BG}}^2}{4bka}\right) \quad \text{where} \quad a = \dot{\delta}/2k$$

Highly efficient large momentum transfer: ~99.9%/recoil in b = 0

Bloch Oscillation Atom Optics Tool



With Yb BECs:

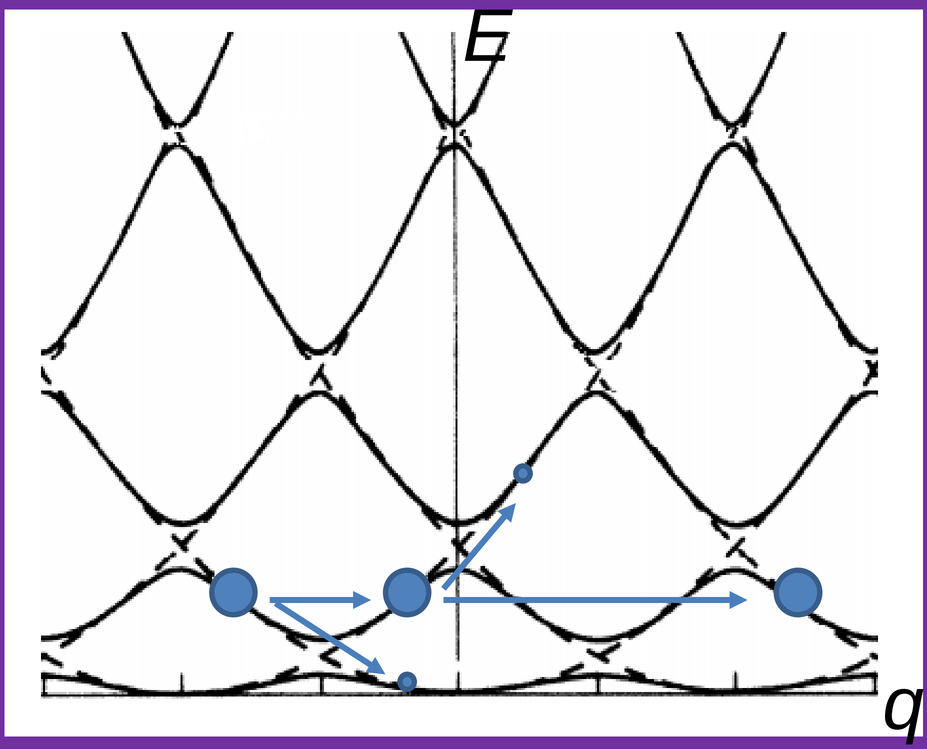
- Bragg (N_B=3) efficiency: 98.5% per $\hbar k$
- Band 0 BO efficiency: 99.9% per $\hbar k$
- Band 2 BO efficiency: >99.4% per $\hbar k$

L. Morel et al. (LKB), Determination of the fine-structure constant with an accuracy of 81 parts per trillion, Nature 588, (2020).

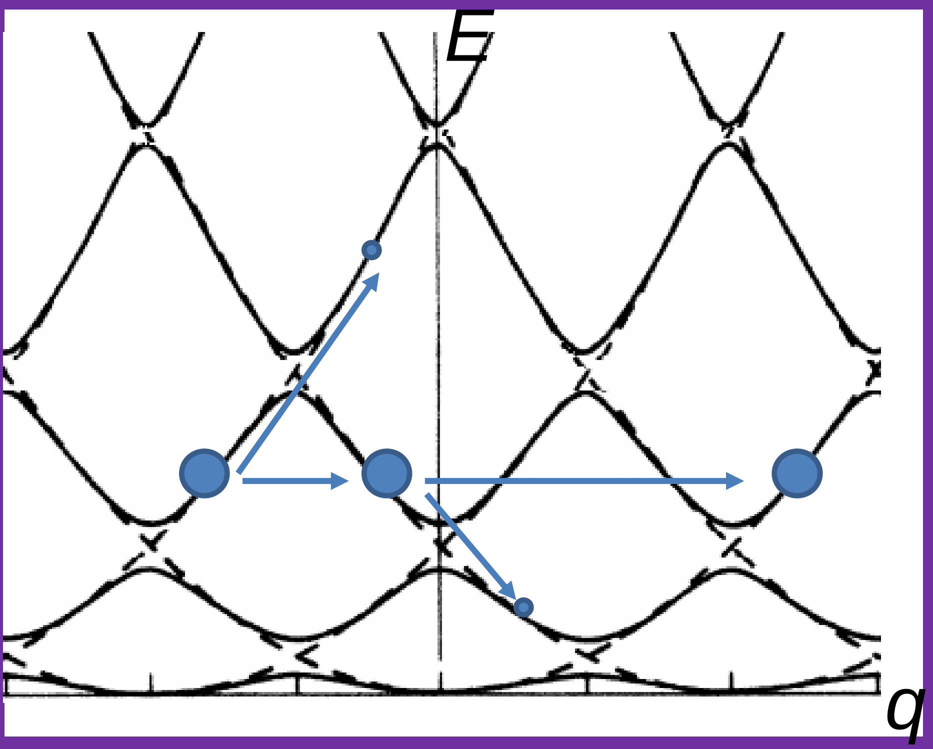
M. Gebbe et al. (Hannover), Twin-lattice atom interferometry, Nature Communications 12, 2544 (2021).

Z. Pagel, et al. (Berkeley), Symmetric Bloch oscillations of matter waves, Physical Review A 102, 053312 (2020).

Ground- and Excited-Band BO

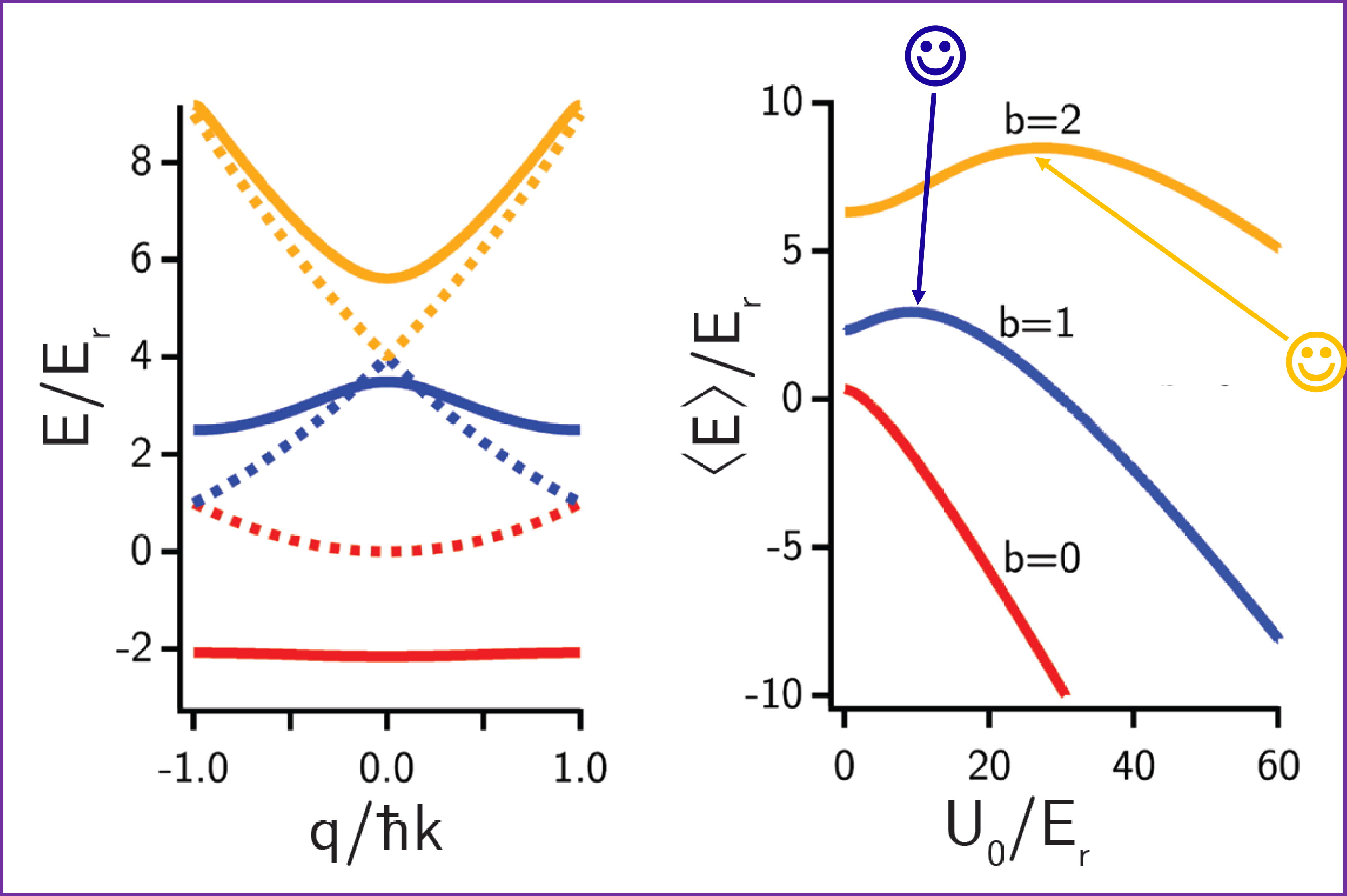


Ground-band BO



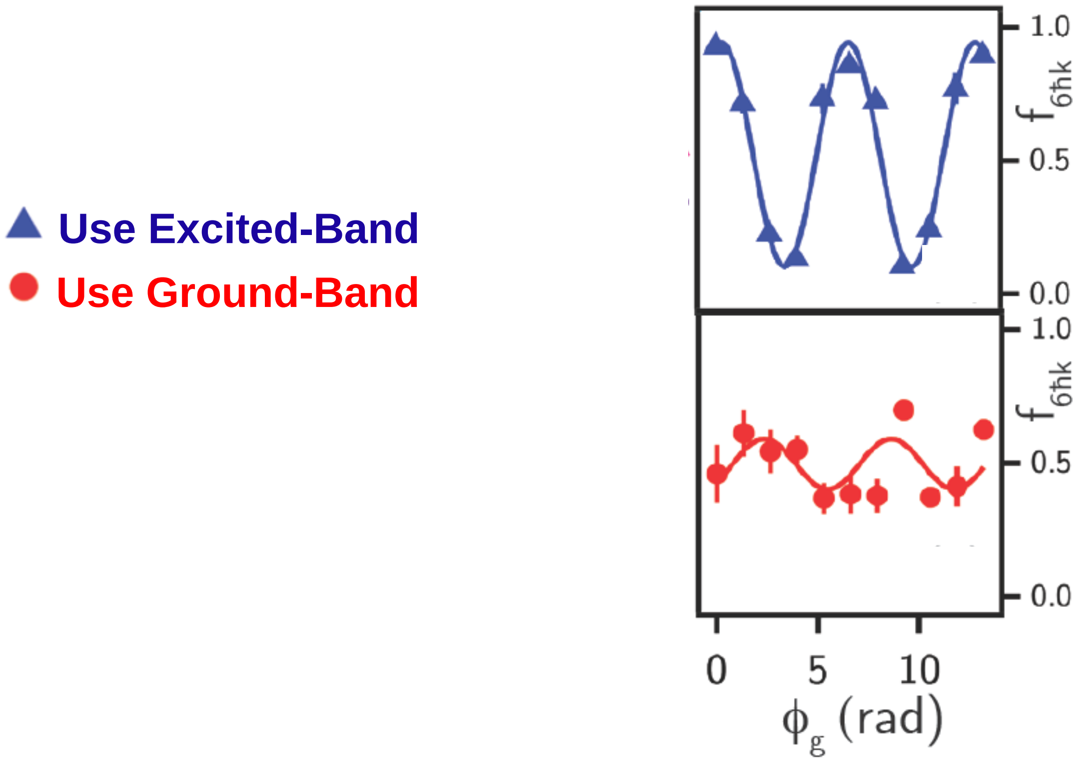
Band 2 BO

"Magic" Depths in Excited-Band BOs



Phase and phase noise during transport process as intensity (U_0) inevitably fluctuates

Excited-Band Atom Optics in a Mach-Zender AI

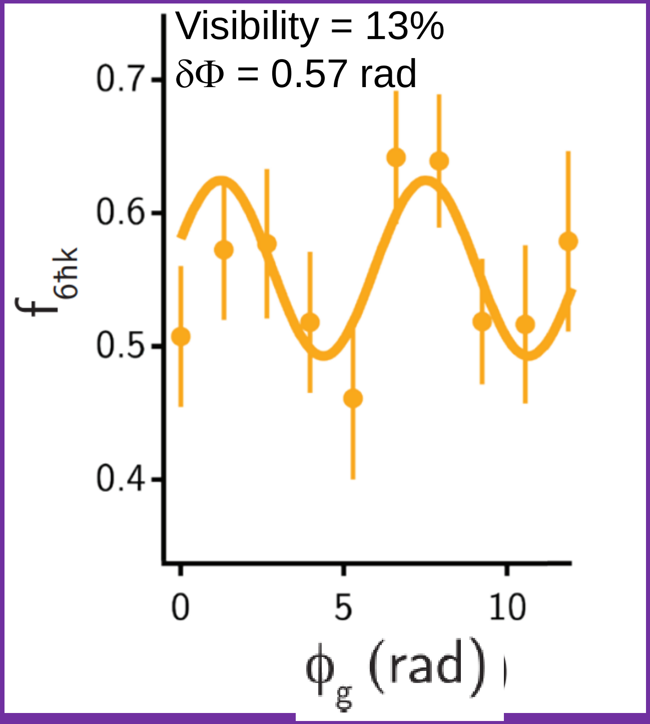


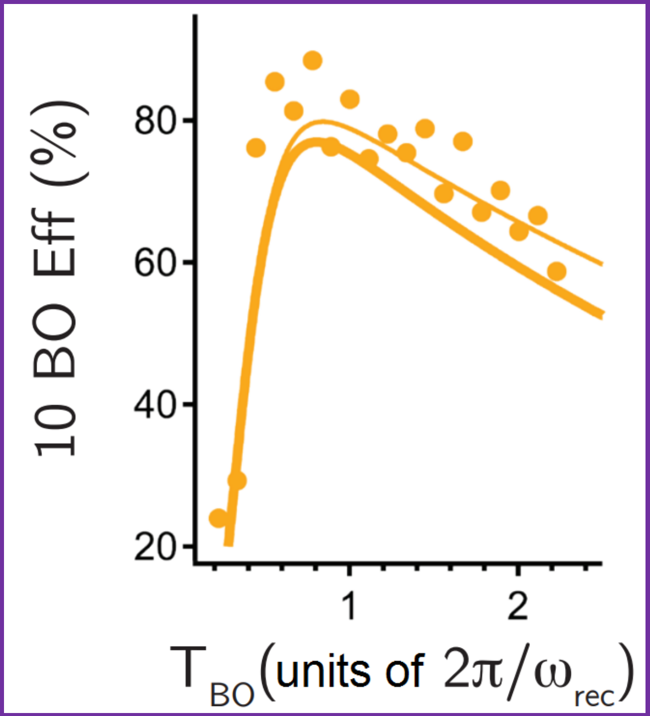
Katie McAlpine et al, PRA **101**, 023614 (2020)

Large Momentum Transfer with excited-band BOs

Peak eff.
99.4% /recoil

$40\ \hbar k$ with BOs in $b = 2$



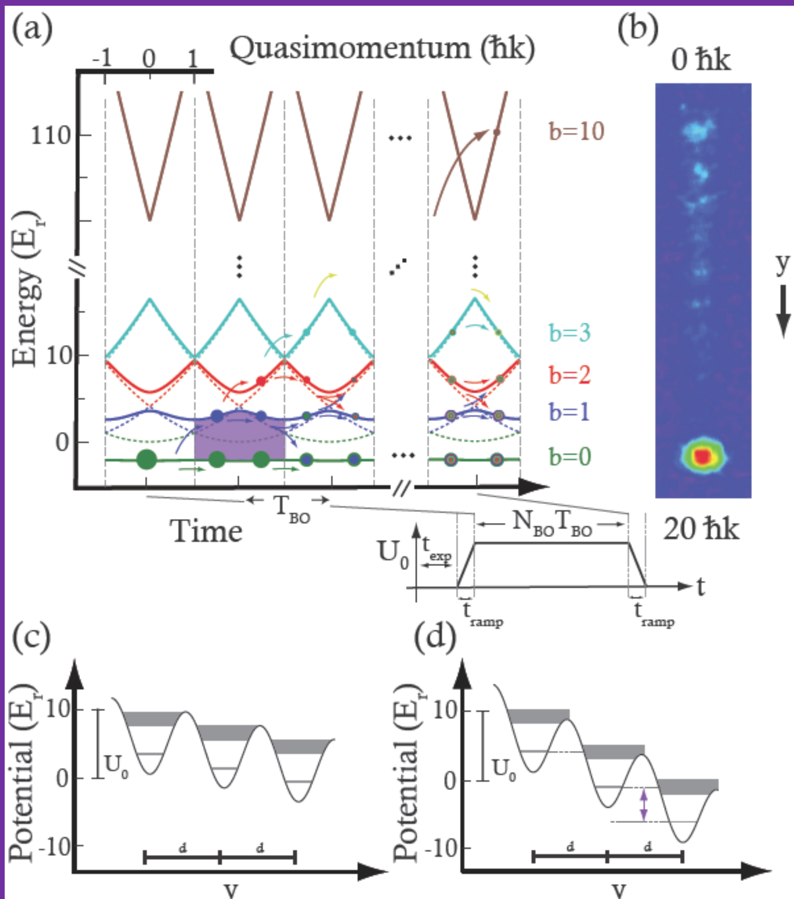


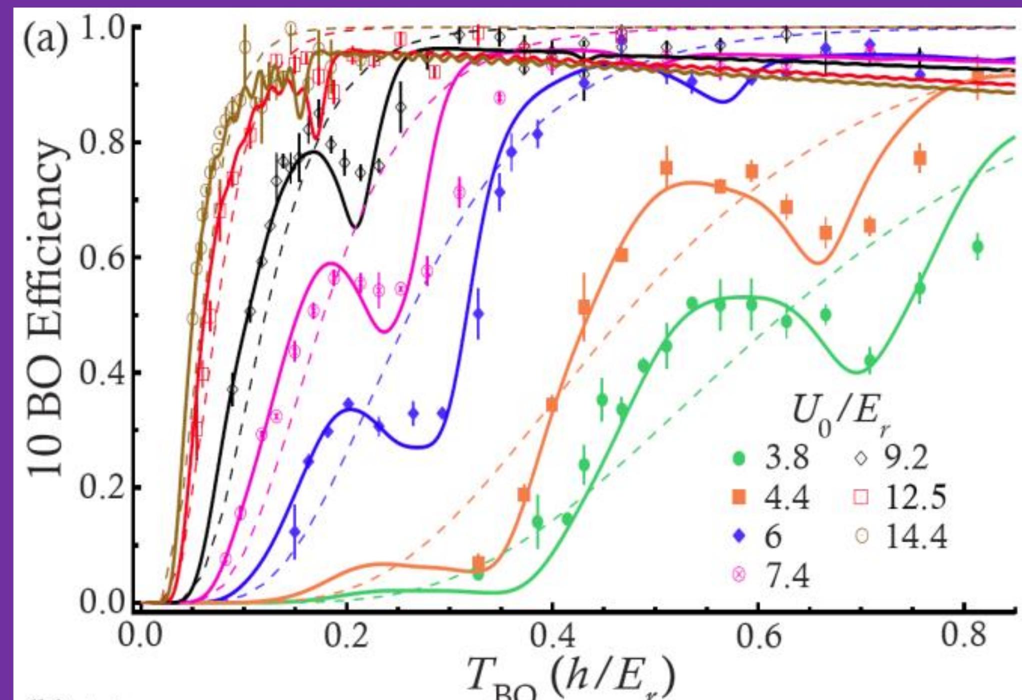
$$Eff = (1 - P_{\mathrm{int}})^2 \times [(1 - P_{\mathrm{LZ}}) \times \exp(-R_s T_{\mathrm{BO}})]^N$$

where $\mathrm{R_s} \simeq \frac{U_0}{8\hbar}\frac{\Gamma}{\Delta}$

Katie McAlpine et al, PRA **101**, 023614 (2020)

Bloch Oscillation Phases investigated by Multi-path Stuckelberg Interferometry (MPSI)



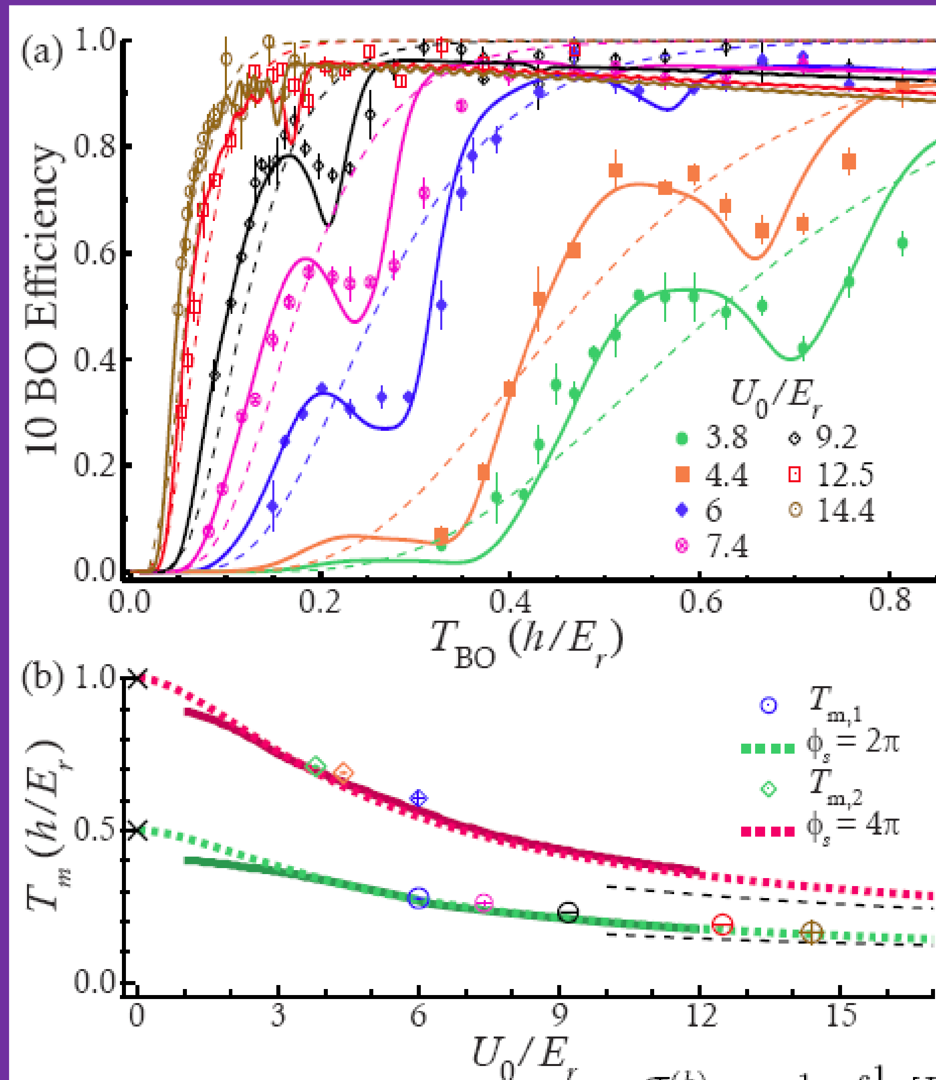


Interference Pattern from phase accumulation during BOs

$$\hat{H} = \frac{\hat{p}^2}{2m} + U_0 \cos^2\left(\pi \frac{\hat{y}}{d}\right) - \frac{h}{T_{BO}} \frac{\hat{y}}{d}$$

Tahiyat Rahman et al, arXiv:2308.04134 (2023)

Bloch Oscillation Phases investigated by Multi-path Stuckelberg Interferometry (MPSI)

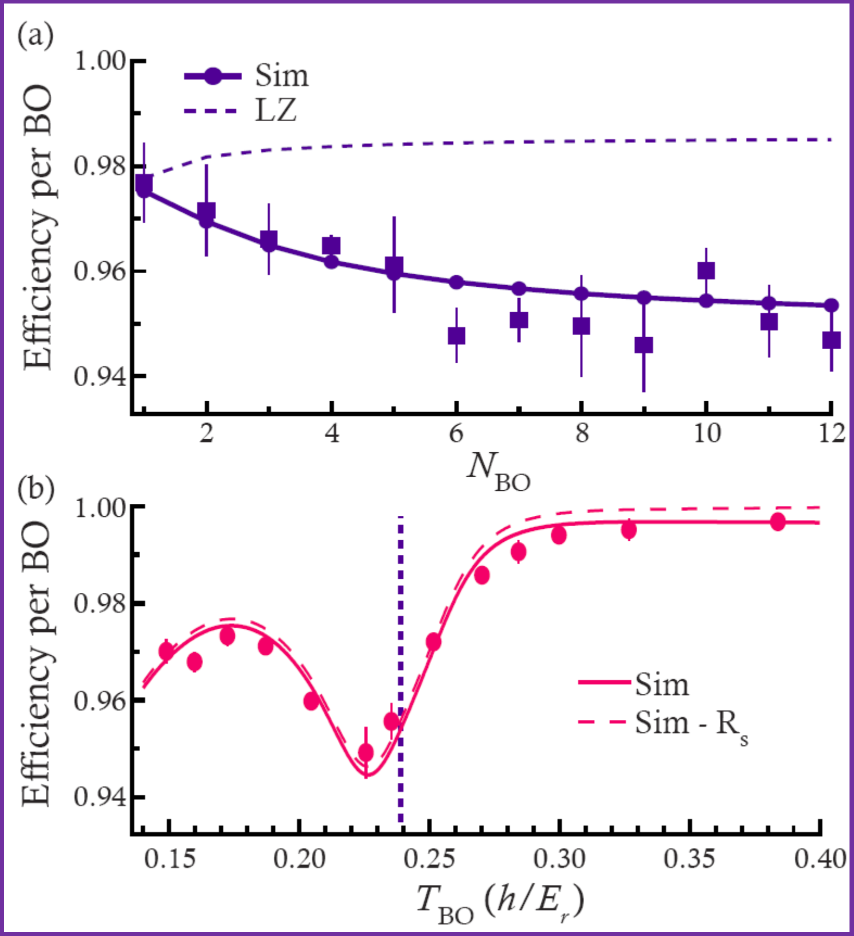


$$\phi_S^{(b)}(U_0) = \frac{E_r T_{\mathrm{BO}}}{\hbar} \mathcal{I}^{(b)}$$

$$\mathcal{I}^{(b)} = \frac{1}{2E_r} \int_{-1}^{1} [E^{(b+1)}(q, U_0) - E^{(b)}(q, U_0)] dq$$

Tahiyat Rahman et al, arXiv:2308.04134 (2023)

Bloch Oscillation Phases investigated by Multi-path Stuckelberg Interferometry (MPSI)

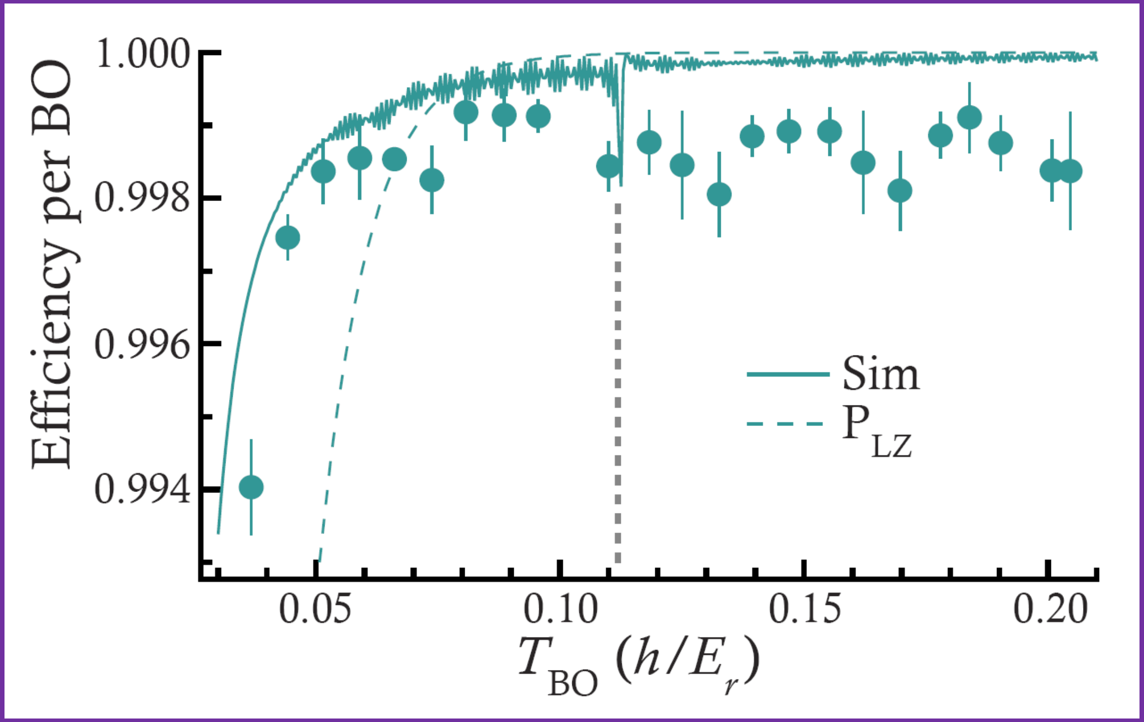


$U_0/E_r = 8$

LMT of 100 $\hbar k$

Tahiyat Rahman et al, arXiv:2308.04134 (2023)

Bloch Oscillation Phases investigated by Multi-path Stuckelberg Interferometry (MPSI)



U_0/E_r = 25.5

LMT of 200 $\hbar k$

For 1000 $\hbar k$, 100mrad requires intensity stability of < 3 x 10^{-5}

Also see:

F. Fitzek et al (Hannover), arXiv:2306.09399 (2023)

Tahiyat Rahman et al, arXiv:2308.04134 (2023)

Managing Bloch Oscillation Phases for Large-Momentum-Transfer Atom Interferometry

Bloch Oscillations highly efficient LMT tool

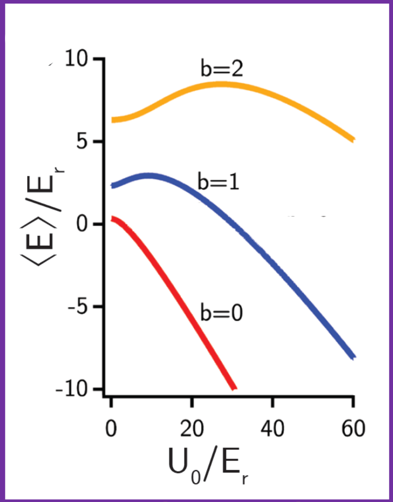
Intensity noise turns into phase noise.
Challenge for scaling to 1000 recoil for next generation BO-enhanced AI.

Excited-band BO as an alternate possibility for LMT.

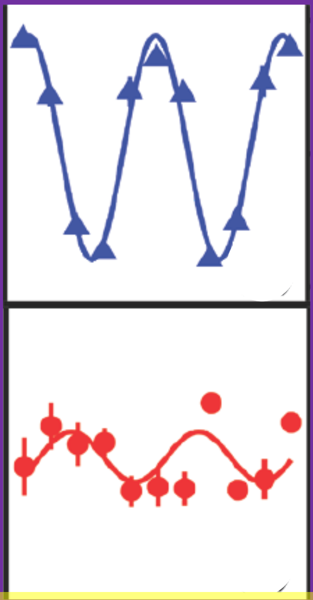
Observation of ground band BO phases upto 100 recoils, compare with theory.

Potential applications of ground and excited-band BOs in VLBAI

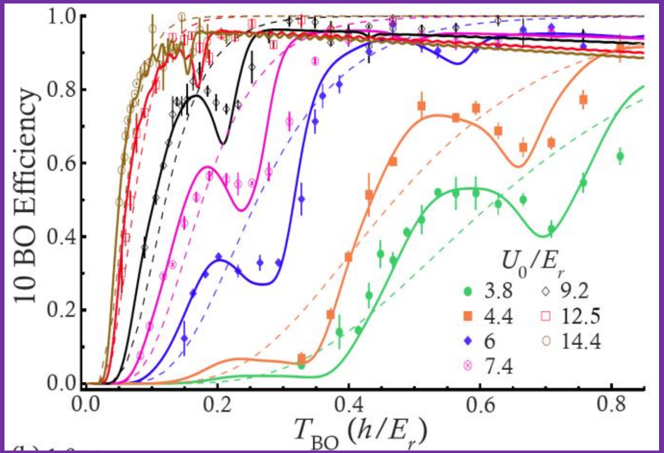
Magic Trapped AI: Gravimetry and equivalence principle test



Magic Depth
Atom Interferometry



McAlpine et al, PRA **101**, 023614 (2020)



BO Phases with multi-path Stuckelberg AI

Rahman et al, arXiv:2308.04134 (2023)
To appear in Phys Rev Research

UW Ultracold Atoms and Quantum Gases Group

Yb Atom Interferometry
Tahiyat Rahman
Emmett Hough
Harini Ravi
Dan Gochnauer (PhD 20)
Katie McAlpine (PhD 19)
Ben Plotkin-Swing (PhD 18)
DG

Quantum Dynamics and Simulation
Nicolas Williams
Lynnx
DG

Funding: NSF, AFOSR