Precision characterization of the linear-zigzag transition in ultracold trapped ion crystals

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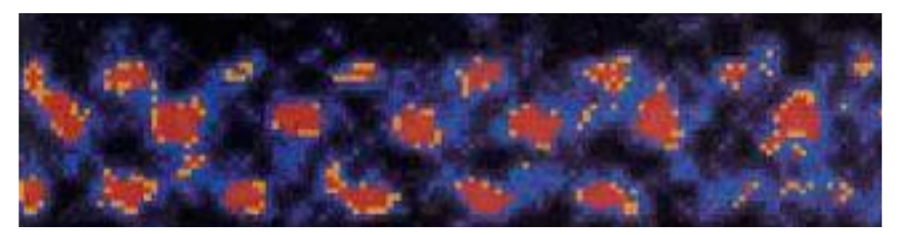
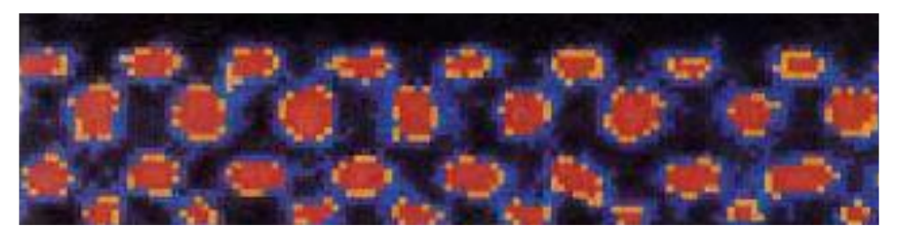
Summary

In a linear Paul ion-trap, the structural transition from a 1-D linear chain of ions to a 2-D zigzag structure, known as the linear-zigzag transition, is a well-known behavior for crystals of laser cooled, trapped ions. Here we present the first studies of the linear-zigzag transition at ultracold temperatures following cooling to near the ground-state of motion. We characterize the transition using Raman sideband spectroscopy, revealing the shape of the effective potential near the critical point and thereby the nature of the transition. In an ideal linear Paul trap, the linear-zigzag transition is associated with the onset of a symmetric double-well potential that is indicative of its continuous nature. Experimentally in our setup, we observe a bias in the double-well potential near the critical point; we attribute this to small asymmetries in the ion trap. We also observe a shift in the critical point of approximately 0.5% from the value predicted in the pseudopotential approximation for the ion trap, consistent with the effect of micromotion on the ions in the radio-frequency trap. At a technical level, our spectroscopic measurements of the linear-zigzag transition are enabled by a high level of long-term trap stability over the duration of data acquisition. This work sets the stage for measurements of coherent effects near the critical point.

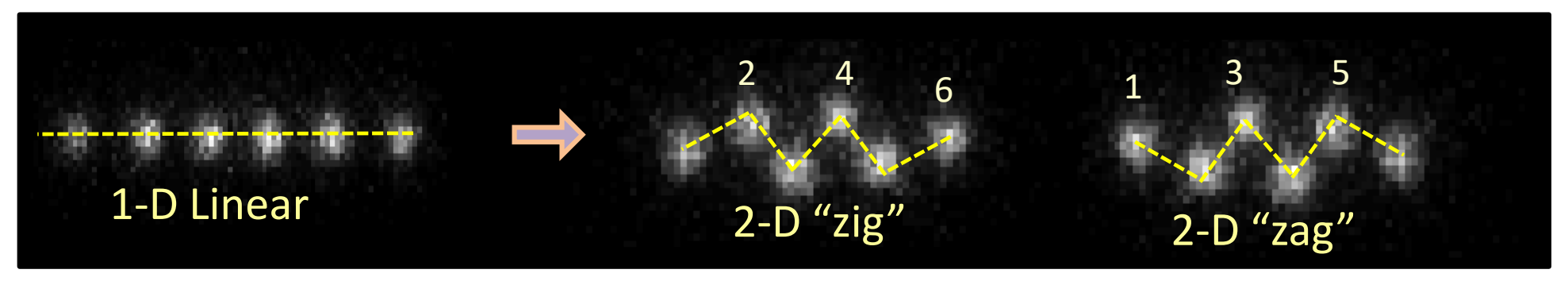
Introduction and Motivation

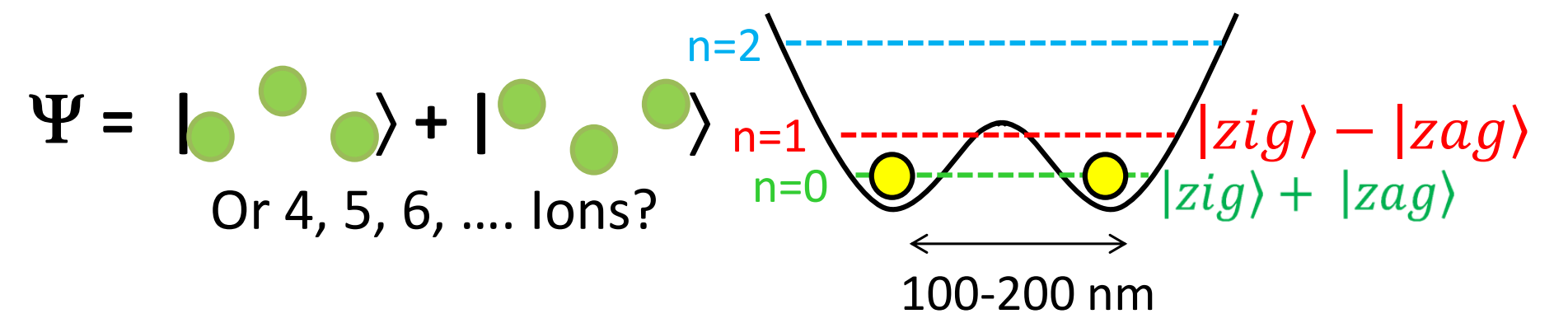
- **Structural Phase Transitions** in laser-cooled trapped ions occur where the ion crystal becomes unstable and distorts with increasing density or changing confinement into a new structure.
- The **Linear-Zigzag structural phase transition** is a second-order (continuous) phase transition with two possible symmetry broken states "zig" and "zag" (shown below).


Two interwoven helices


Three interwoven helices

Birkl et al. Nature 357,1992





Theory: Retzker et.al. PRL 101, 260504 (2008).
Related ion experiments: Spin-motion cat states (NIST 1996). Spin cat (GHZ) states states (N=6: NIST 2005, N=14: Innbruck 2011). Rotor tunneling (N=3 Osaka 2014)

We can explore **nonlinear dynamics** near the critical point of the Linear-Zigzag transition:

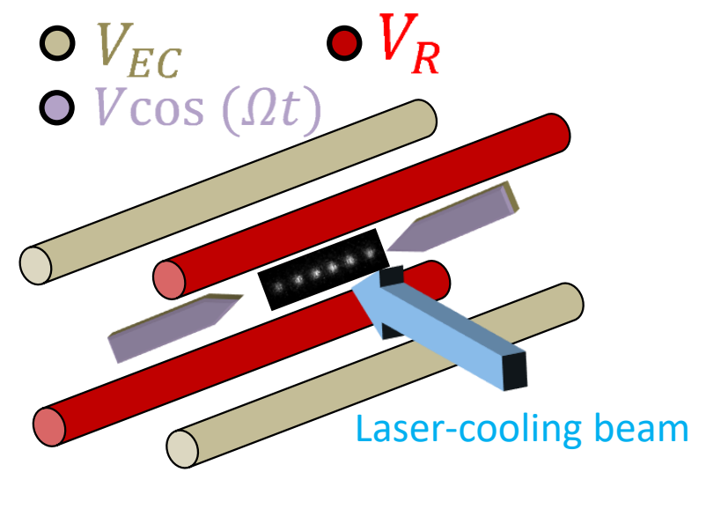
Classical Regime

- Nucleation and dynamics of topological kink defects (SFU, Freiburg, PTB ULM), Aubry physics (PTB)…

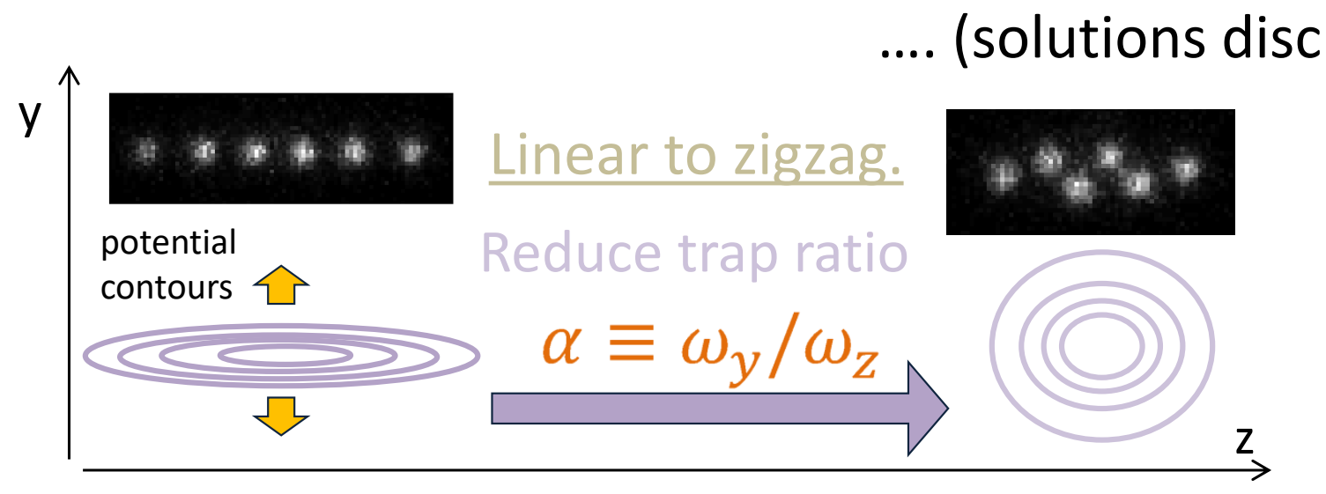
***Quantum* regime** (*ultra-cold temperature*) – this work

- **Aim:** Create quantum superpositions of "zig" and "zag" (Schrödinger cat state)? Measure their decoherence vs ion number.
- Initial step is to study the transition near the critical point and assess feasibility for quantum control.
- Here we make the first characterization of the linear-zigzag transition at ultracold temperatures.

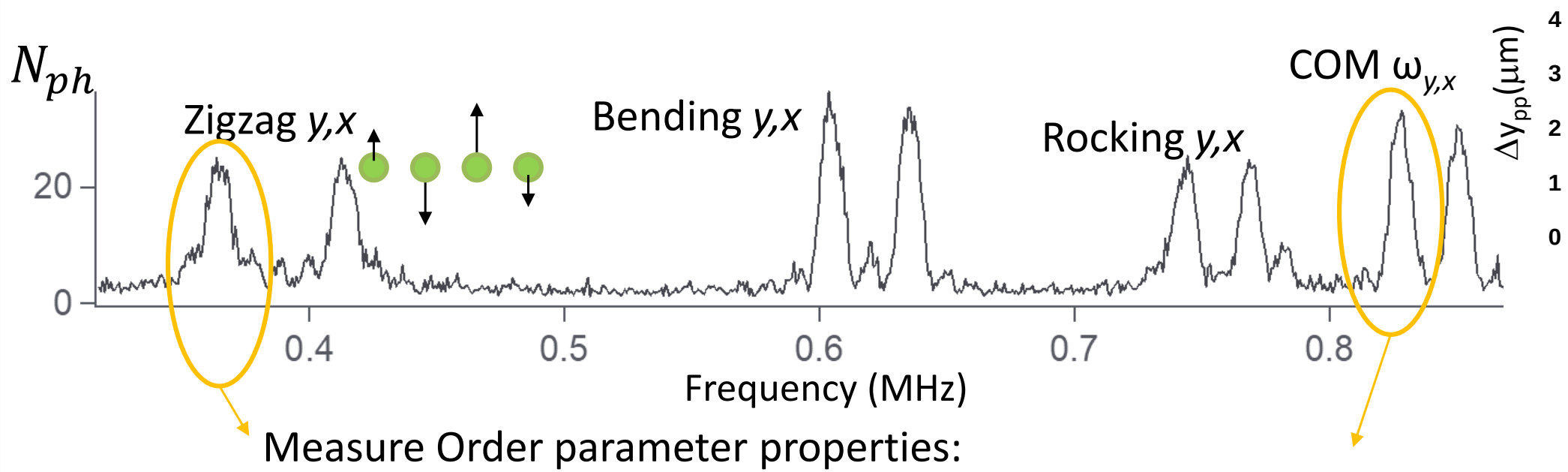
Linear-Zigzag Transition in a Linear Ion Trap



- Experiments involve Ytterbium ions laser-cooled to near ground-state in a linear-radio frequency Paul trap
- Technological challenges: Ground-state cooling of ion strings, high-stability trap potential, motional decoherence …. (solutions discussed later)



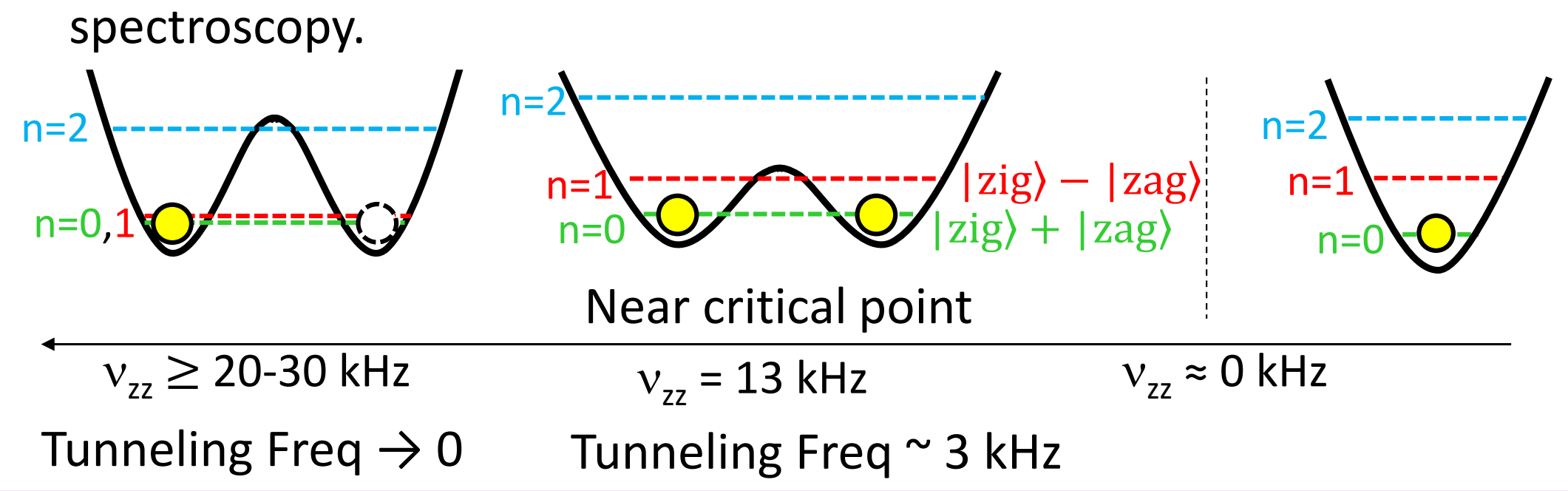
- $V_{rf} \approx 730$ V
- $V_{ec} \approx 97$ V
- $V_{dc,quad} \approx 0\text{-}3$ V (mV control)



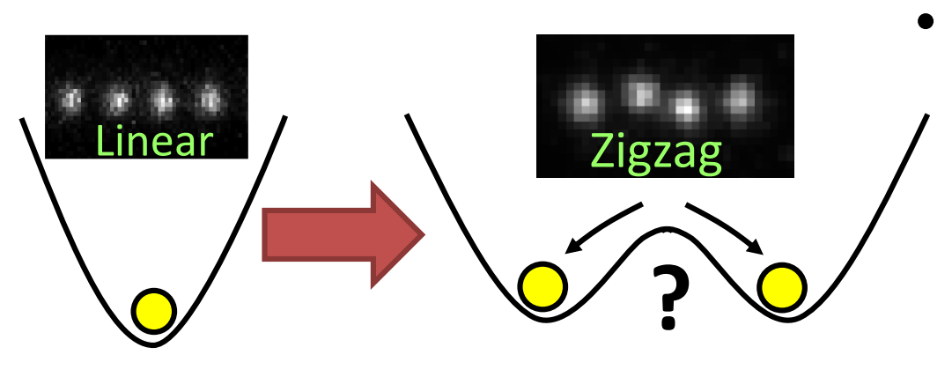
Measure Order parameter properties: Energy level structure, $\bar{n}$ thermometry (Rabi), Coherences (Ramsey), …

Measure control parameter

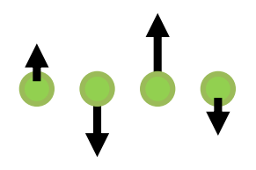
- **Quantum transition** occurs at close to ground-state temperature.
- Mesoscopic quantum simulation with "self-assembled" setup.
- Quantum energy level structure can be probed with optical sideband spectroscopy.



Soft Modes and Effective Field Theory



- Near-transition dynamics dominated by soft zigzag mode.

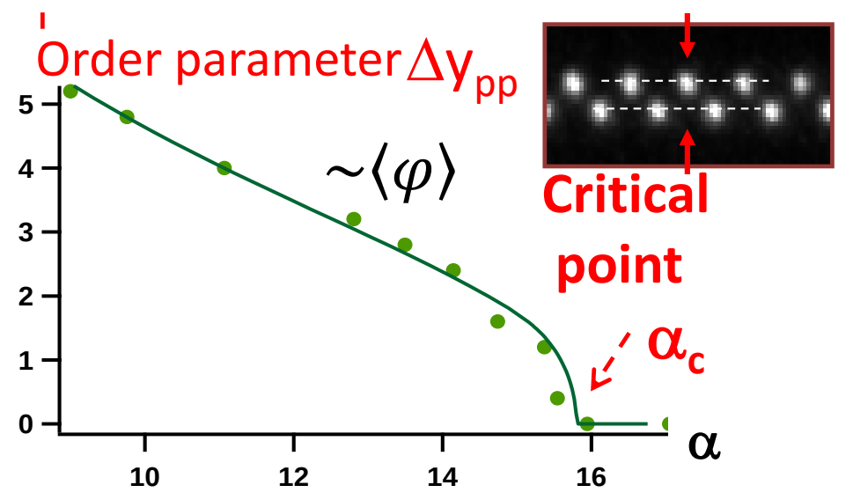


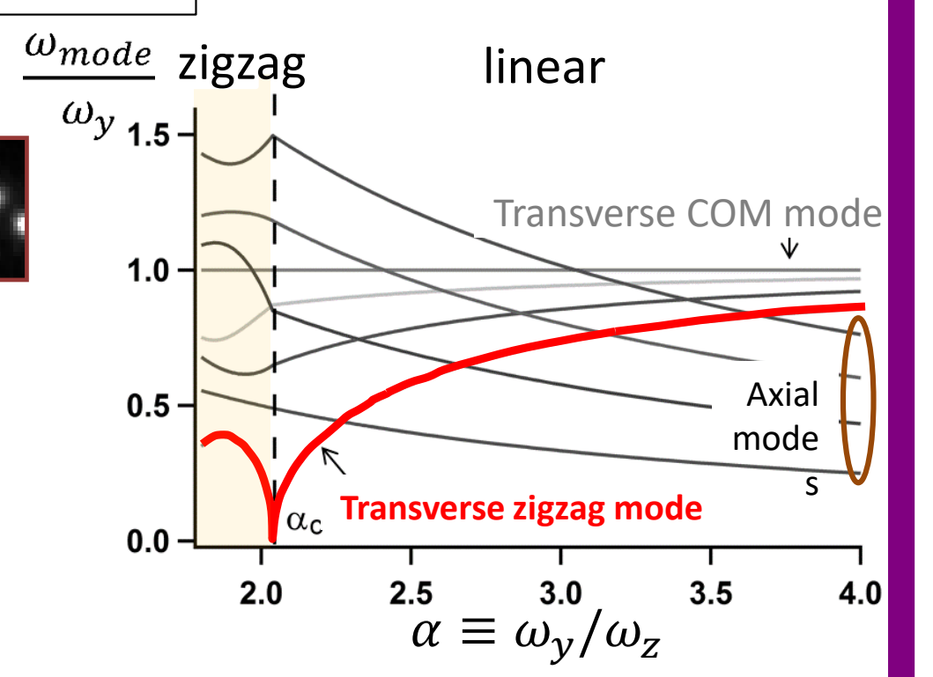
- Expand potential energy near critical point in terms of zigzag mode amplitude:

$$V(\varphi) = \frac{1}{2}(\alpha^2 - \alpha_c^2)\varphi^2 + \frac{1}{4}c_4\varphi^4$$

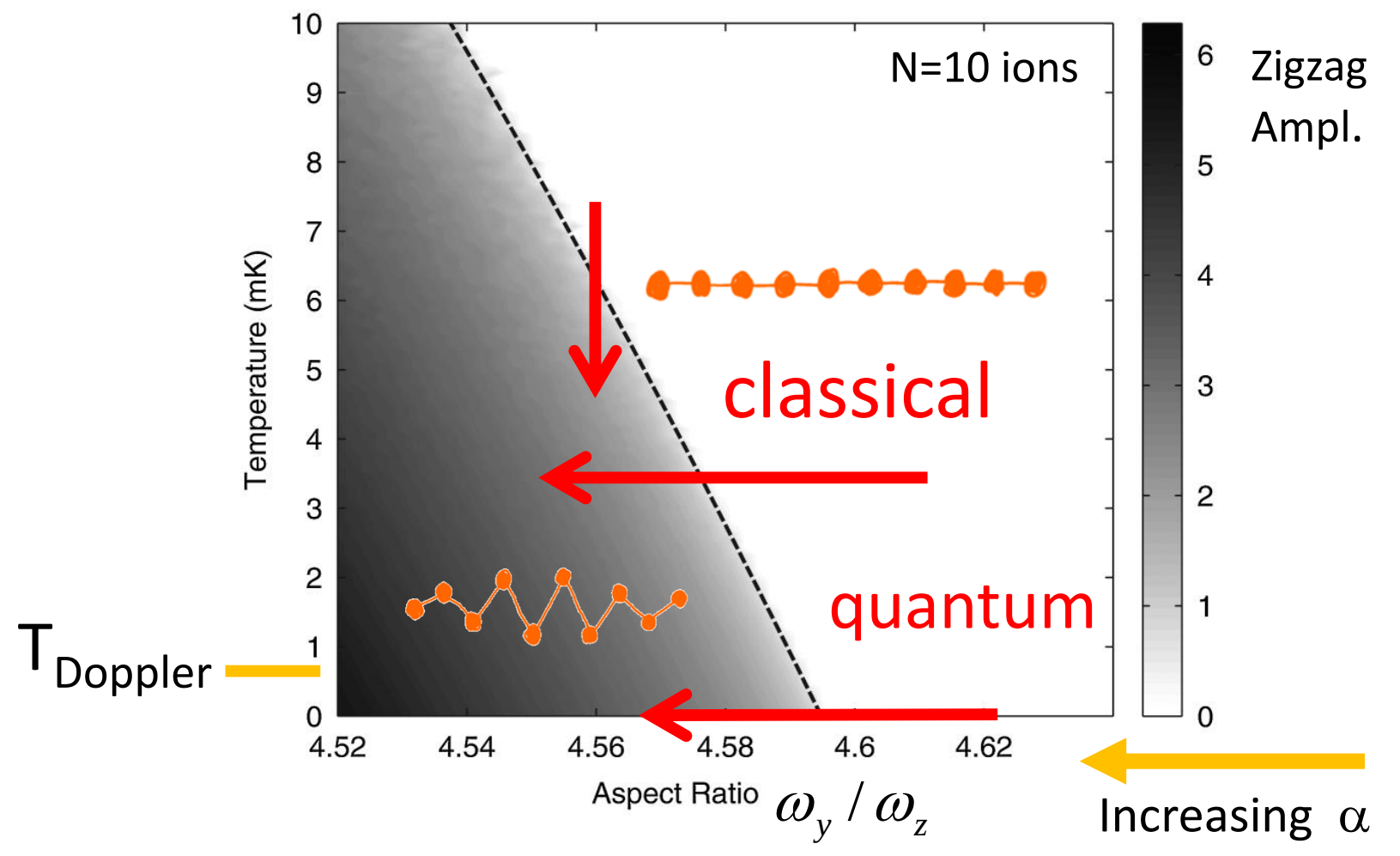
Tunable intrinsic double well

Retzker et.al. PRL 101, 260504 (2008)





- Zigzag mode frequency goes to zero at the onset of the zigzag structure in the classical limit.

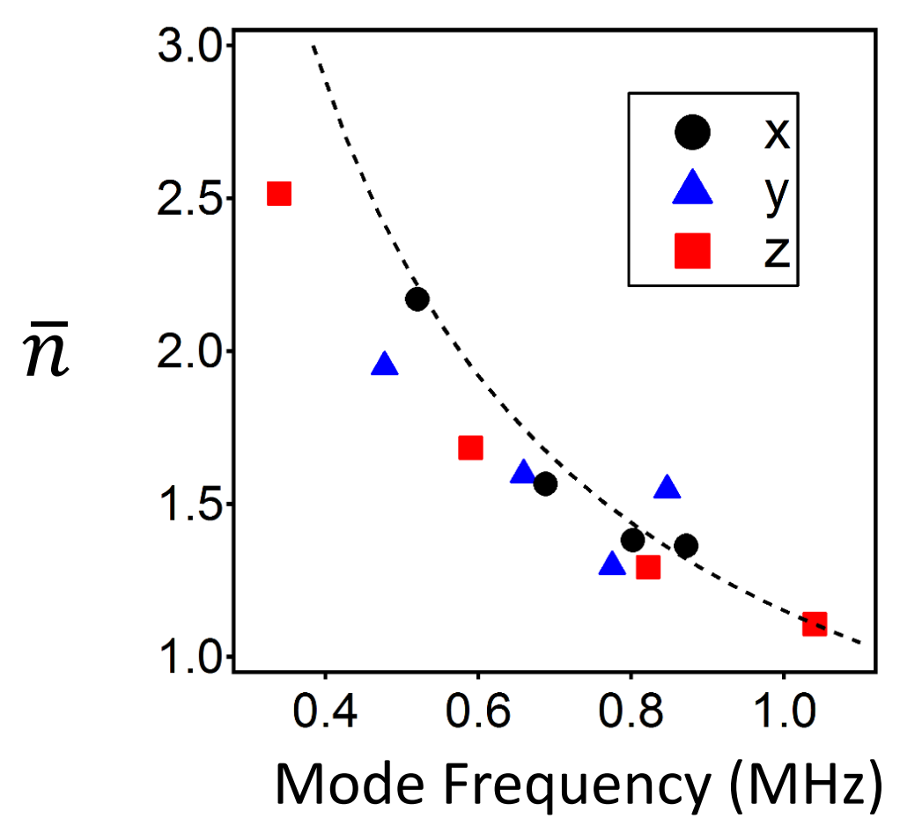


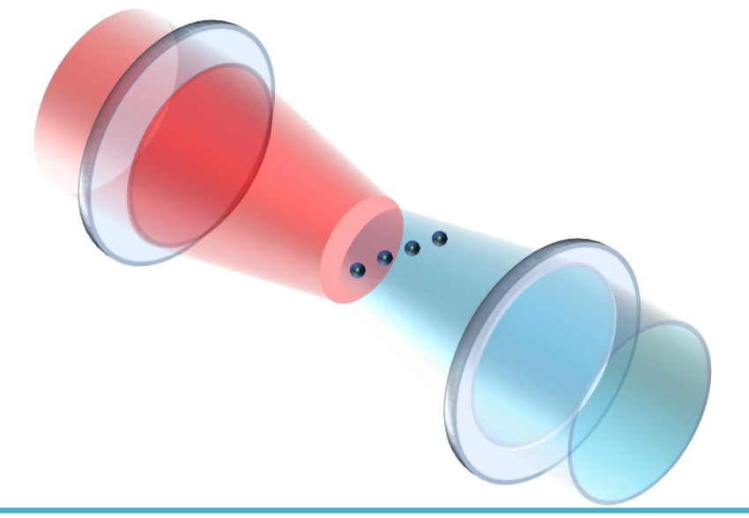
Theory of temperature dependence: Z-H Gong, G-D Lin, L-M Duan PRL(2010).

Technological Improvements:

3-D Sisyphus cooling of ion strings

3-D Polarization Gradient Cooling of 4-Ion String





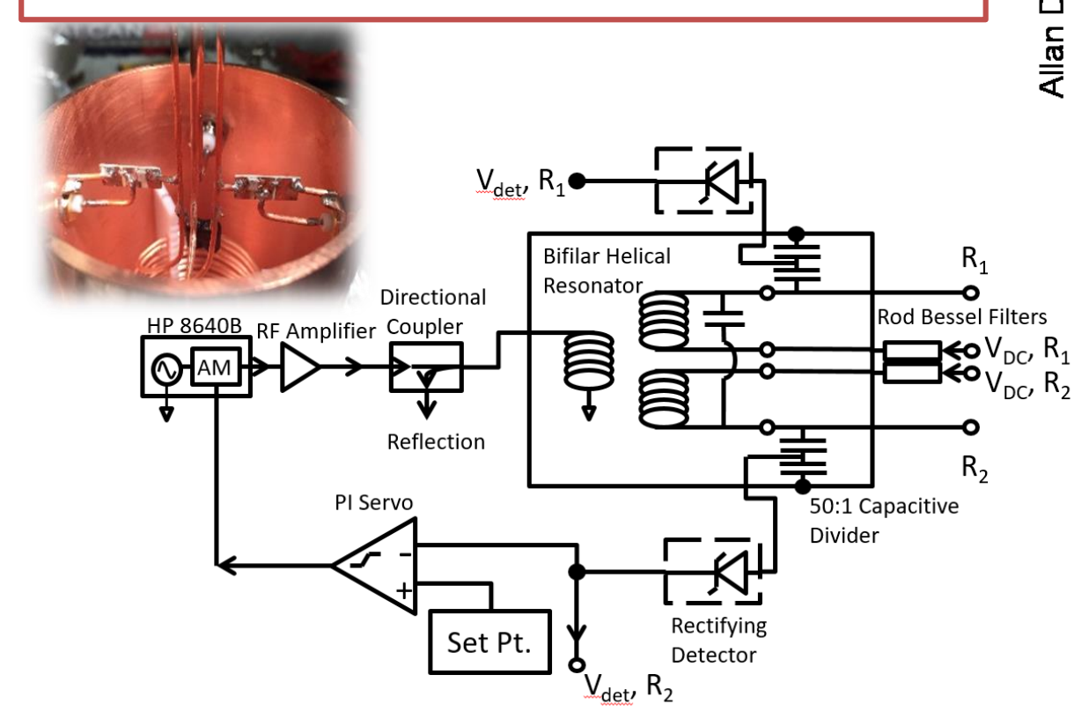
- **Simple, robust precooling**
- All modes cooled in 3D simultaneously to a few phonons with an cooling time of 6 ms.
- Subsequent ground-state cooling of various modes (sideband cooling).
- Wider utility for weaker traps and larger ion crystals.

S. Ejtemaee and PCH, PRL 119, 043001 (2017)

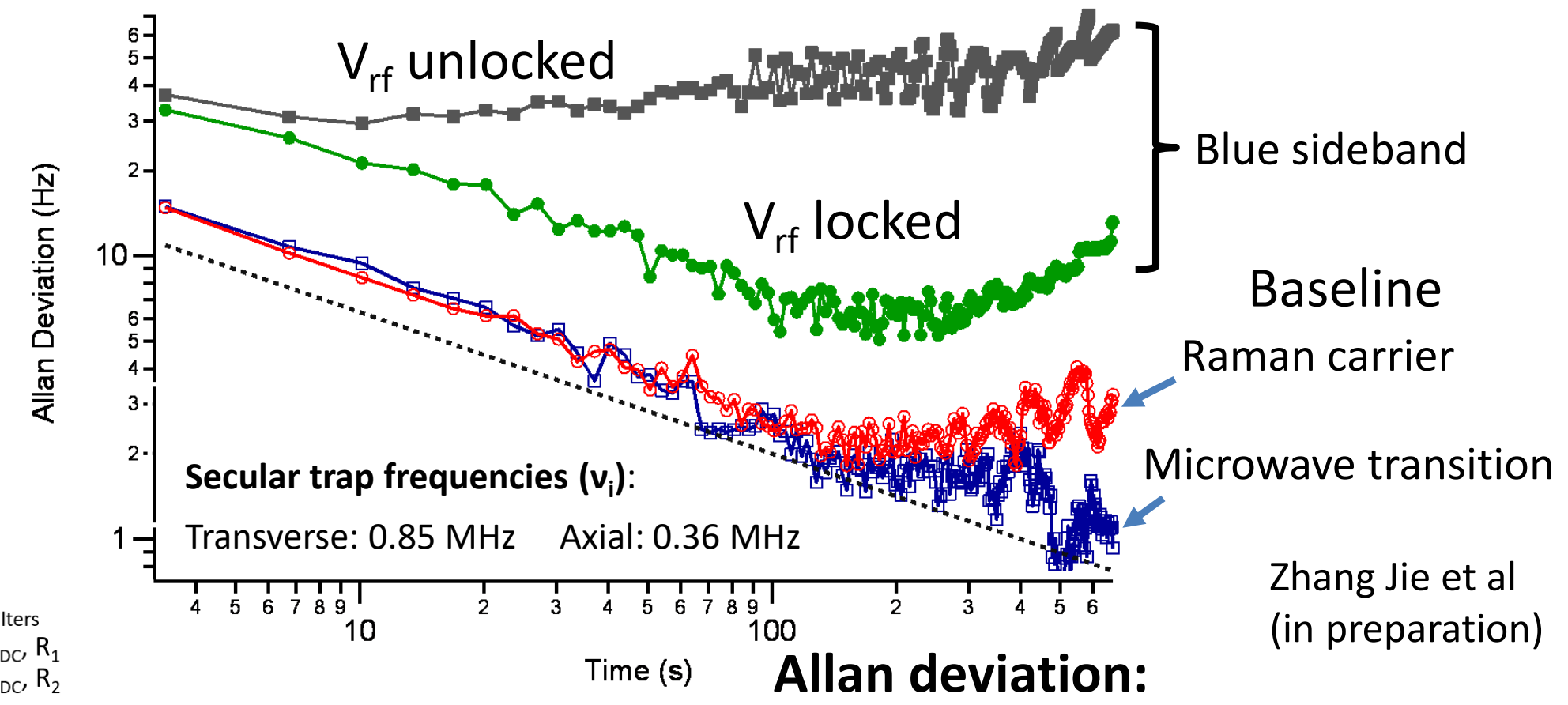
Related work: multimode EIT cooling of ion strings (Innsbruck, NIST)

Trap potential stabilization

- High stability (long and short term) needed for the critical point.
- Initial target for long term stability of ~10 ppm in both transverse and axial direction.



Transverse trap stability



Zhang Jie et al (in preparation)

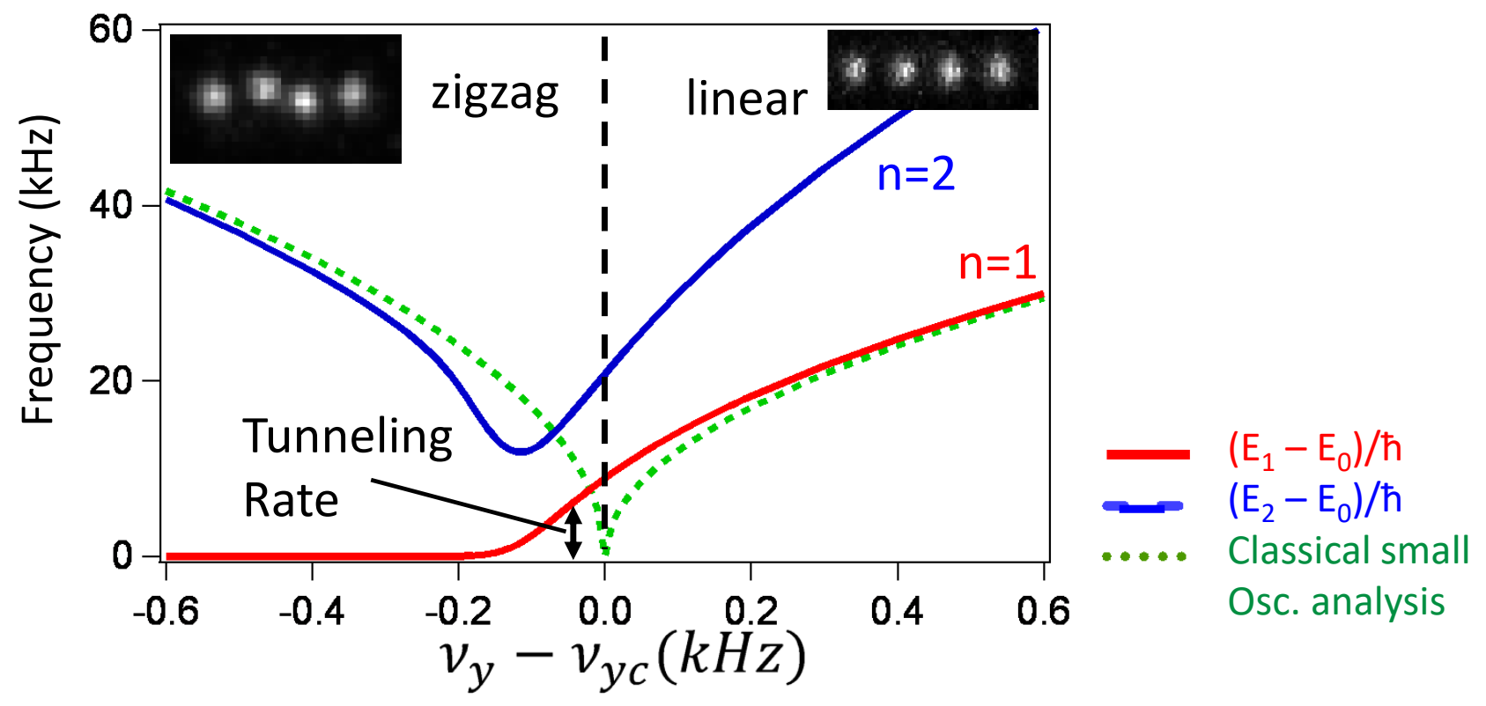
- Passive and active stabilization of RF and DC voltages.

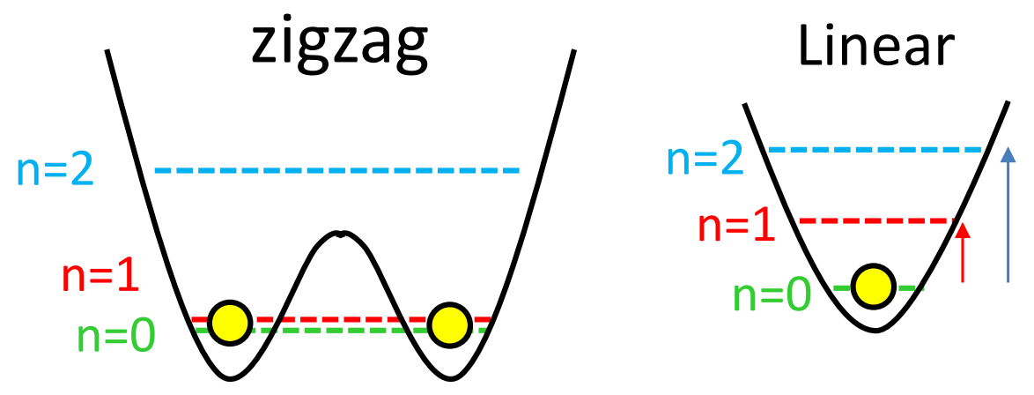
Allan deviation:
Axial/Transverse: ≤6 ppm in 200 s
Stability over 1 hour:
Axial/Transverse: ≤15 ppm

Transverse results ~2X improvement compared to K. G. Johnson et al. (2016).

Characterization of the Linear-Zigzag Transition

Ideal Transition:



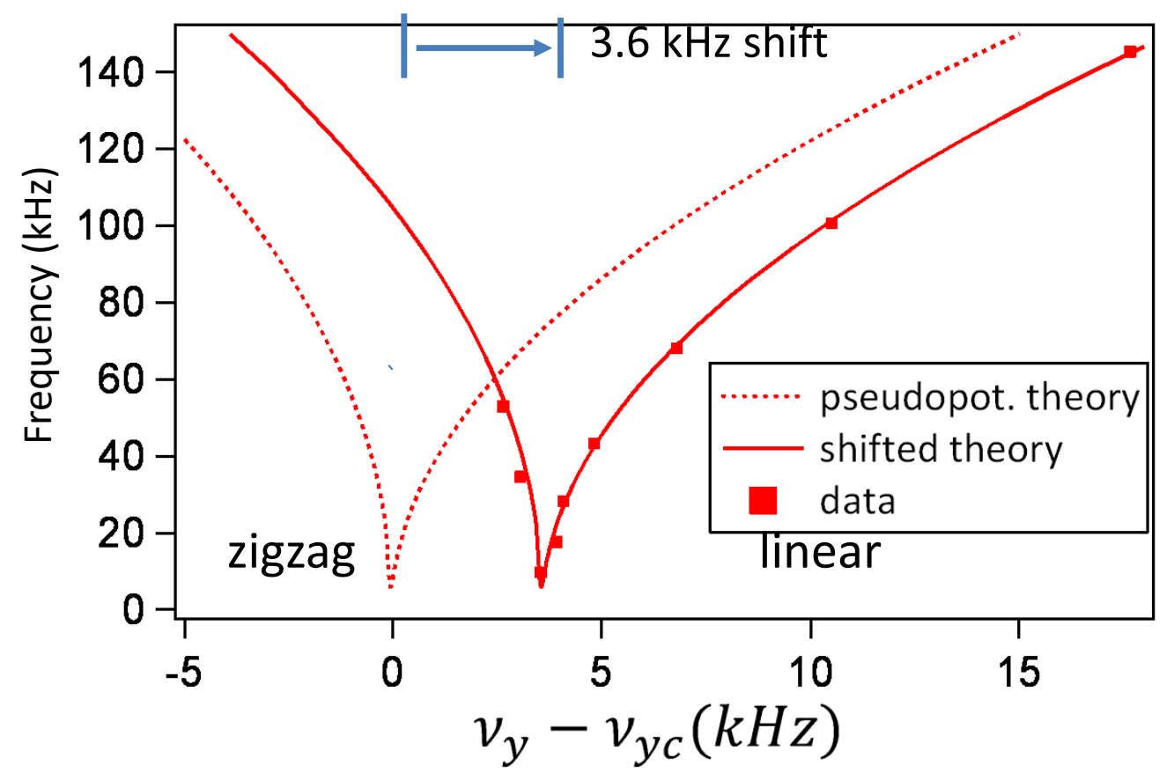


- In the ideal transition the two lowest energy levels approach degeneracy further into the zigzag regime (tunneling rate → 0).

Deviations from simple theory:

- Shifts in critical point
- Bias in the double-well potential.
- Noise, decoherence.

RF shift in the critical point for $\nu_{y,c} \approx 740$ kHz:

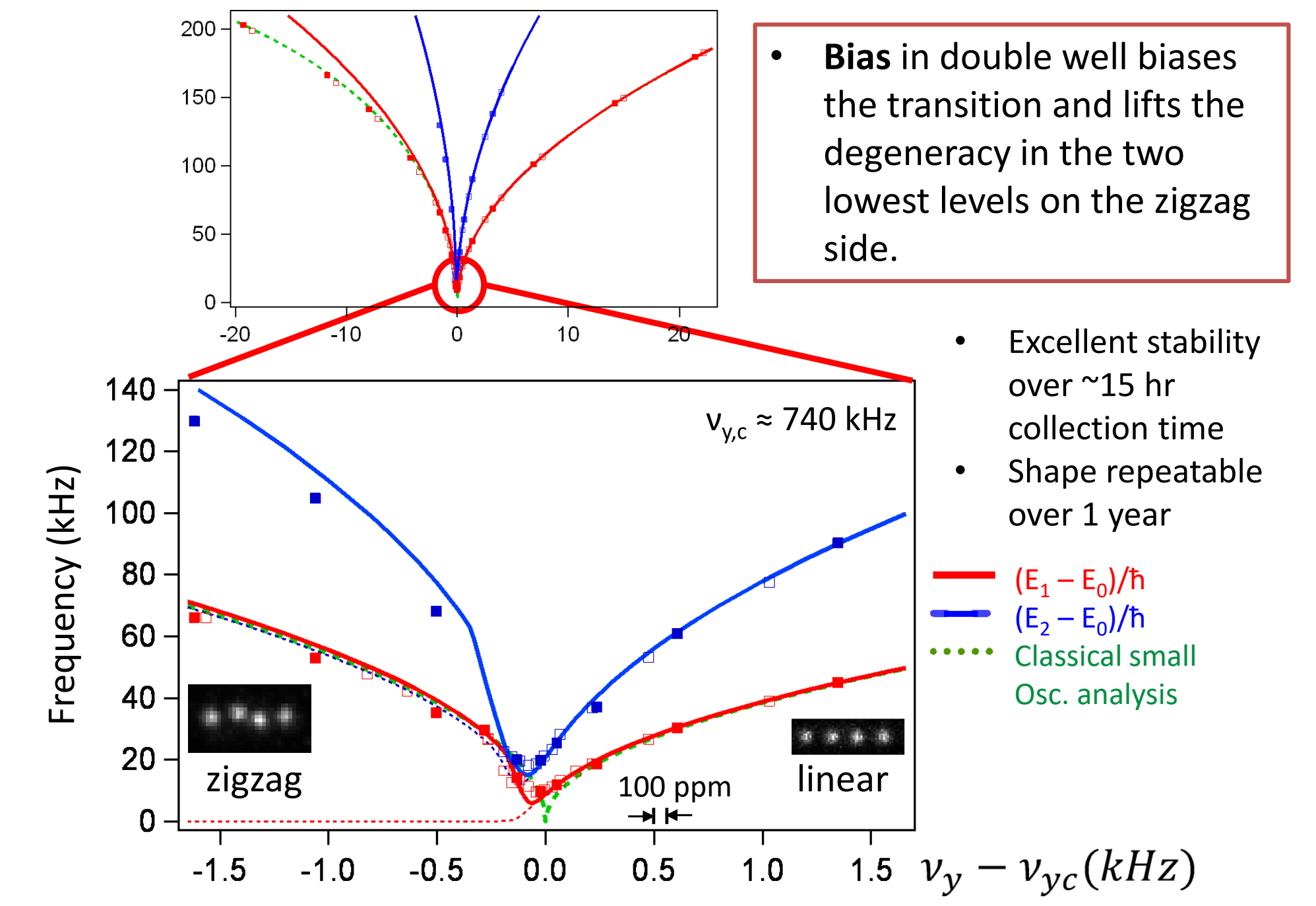


- 0.5% effect due to micromotion shift of zigzag mode (beyond pseudopotential approximation): Landa NJP 2012.
- First measurement of this shift enabled by trapping potential stability and near ground-state cooling.
- Related to prior work on micromotion induced shifts of modes (Kaufmann PRL 2012).

Match to theory for "real" trap (with H. Landa)

Nature of the Linear-Zigzag Transition (Biasing):

Zigzag Mode spectroscopy near the transition:



- **Bias** in double well biases the transition and lifts the degeneracy in the two lowest levels on the zigzag side.

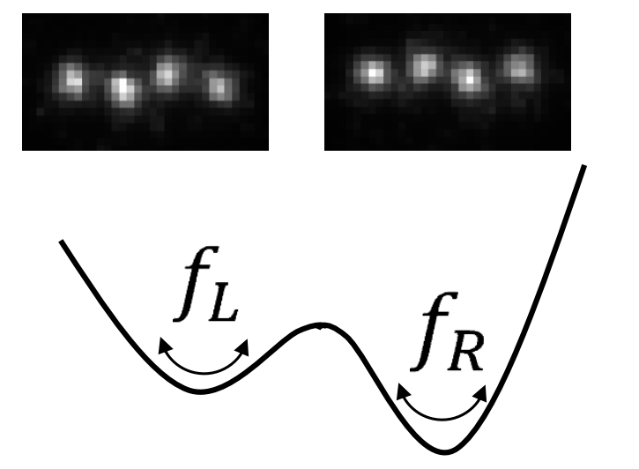
- Excellent stability over ~15 hr collection time
- Shape repeatable over 1 year

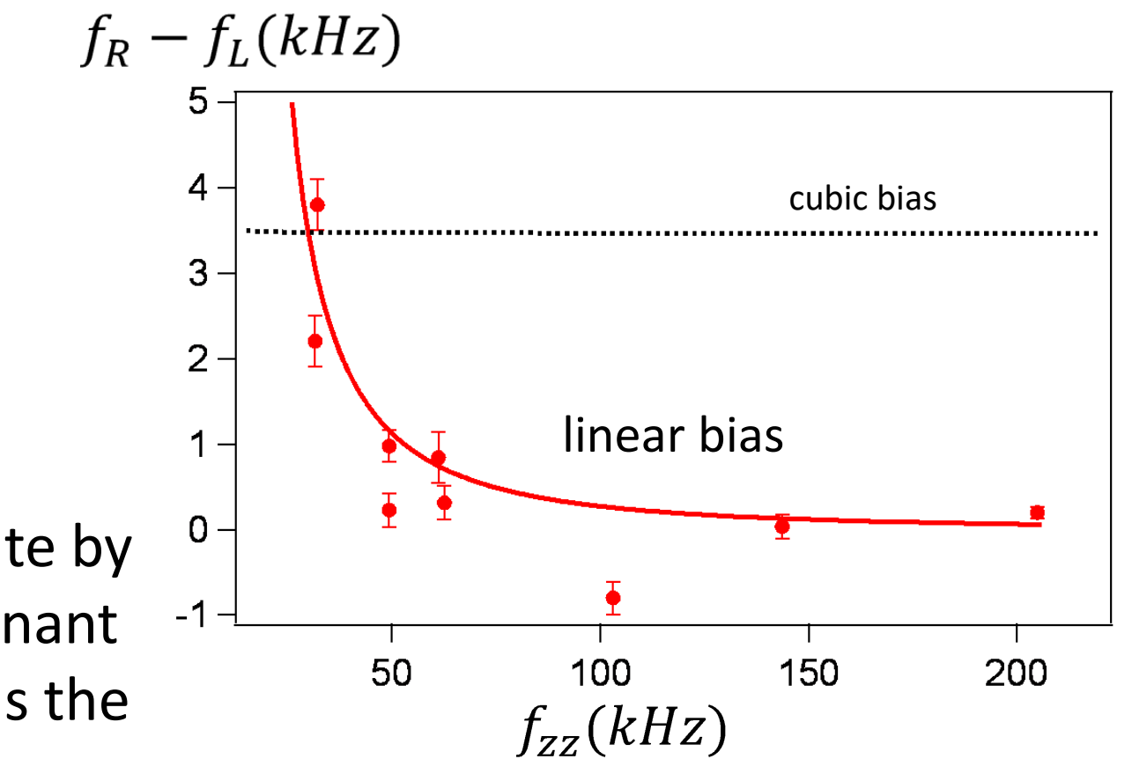
$$V(\varphi_{zz}) = \underbrace{C_1\varphi_{zz}} + \frac{1}{2}C_2\varphi_{zz}^2 + \underbrace{\frac{1}{3}C_3\varphi_{zz}^3} + \frac{1}{4}C_4\varphi_{zz}^4$$

Bias terms in effective field theory: affect **nature** of the transition.

Bias spectroscopy:

- Compare zigzag mode frequency for ion structure initialized into left or right side of double well (zig or zag)

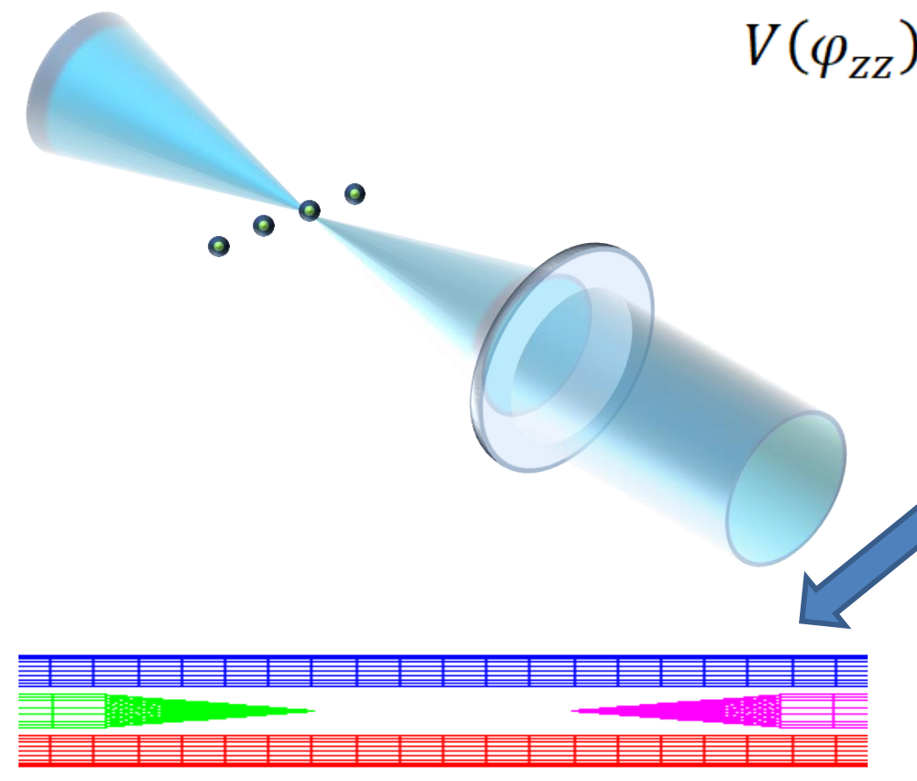




- Initialized into either state by a tightly focused off-resonant laser (dipole force) to bias the transition

$$V(\varphi_{zz}) = \boxed{C_1\varphi_{zz}} + \frac{1}{2}C_2\varphi_{zz}^2 + \frac{1}{3}C_3\varphi_{zz}^3 + \frac{1}{4}C_4\varphi_{zz}^4$$

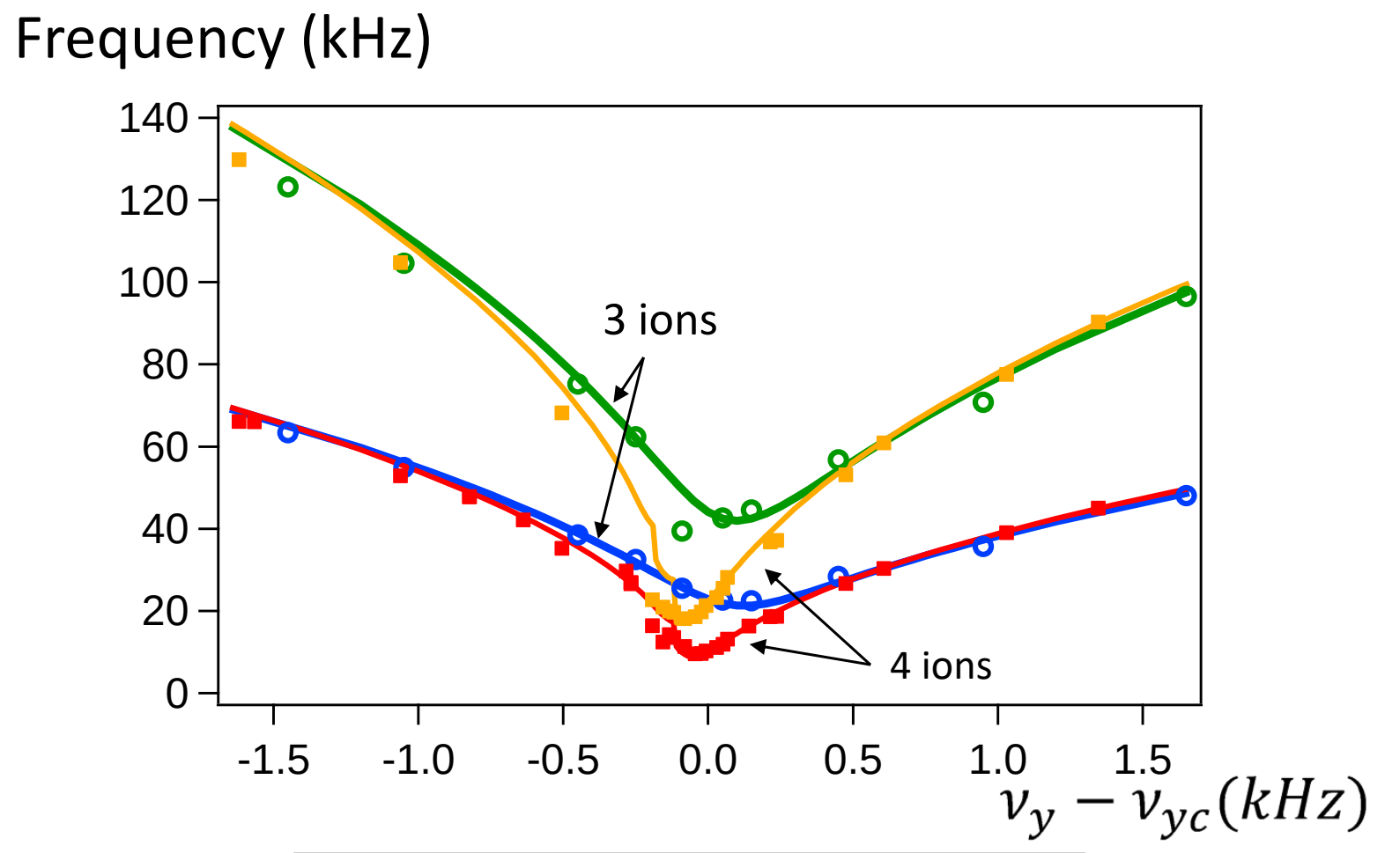
Linear Term Dominates



Connection to asymmetries in linear RF Paul trap potential being explored through numerical simulations.

Can they be controlled, manipulated for effect? (with H Landa)

Effects of ion number at the critical point:



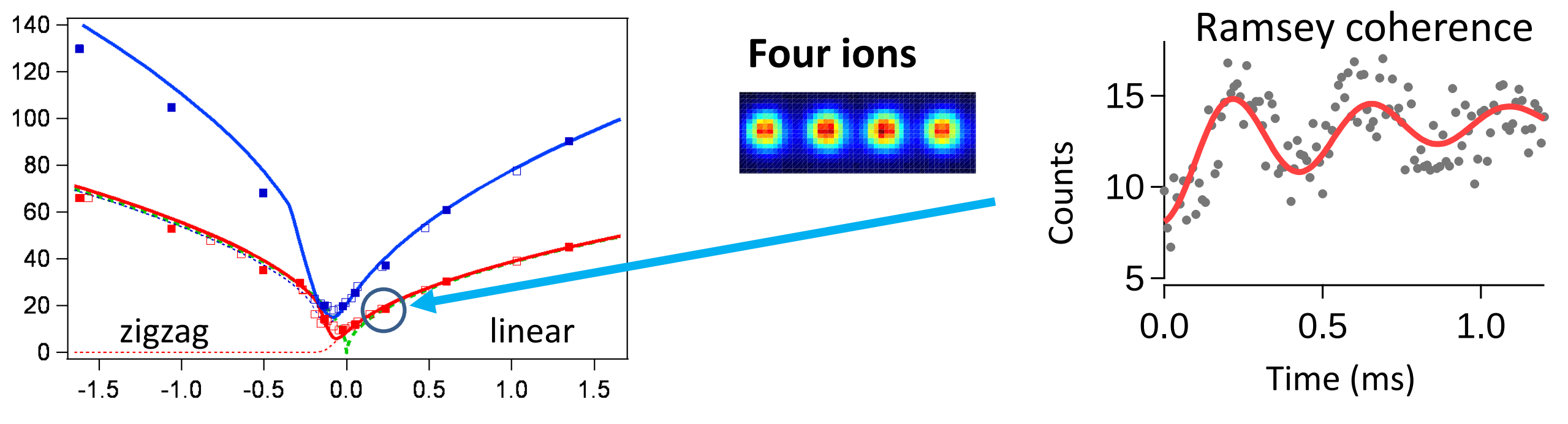
Four-ion transition is sharper

Not a number scaling effect …. Four ions are expected to be better symmetry-protected from trap imperfections.

Conclusions:

- Extension to larger crystals (5+ ions) in progress.
- Transition along other transverse axis shows less asymmetry.
- Further reductions/control of double well bias through trap design being considered for ultimate goal of quantum manipulation near critical point.

Quantum coherence of the zigzag mode close to the transition



Coherence at f_{zz} = 20 kHz on the linear side

- Motional heating of the zigzag mode and Ramsey coherence are being investigated near the transition to understand decoherence properties of the order parameter and short term trap noise.

Conclusion

- Linear-zigzag transition in a ion trap provides a prototype mesoscopic phase transition with good control and single atom resolution.
- Raman sideband techniques used to probe the nature of the transition and shifts in the critical point with high precision derived from the trap stability.
- Bias, coherences in the order parameter near the transition being explored.
- Spin-off technologies of wider utility in cold trapped ion experiments: Demonstration of 3D Sisyphus cooling technique for trapped ion strings.