A novel mixed species In^+/Yb^+ ion optical clock

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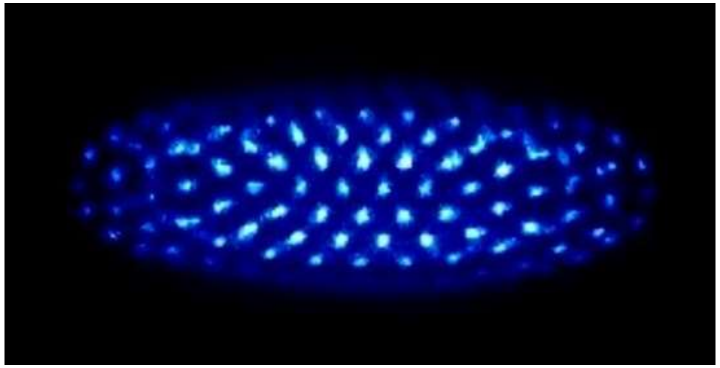

16. August 2022 – Mainz

Physikalisch-Technische Bundesanstalt
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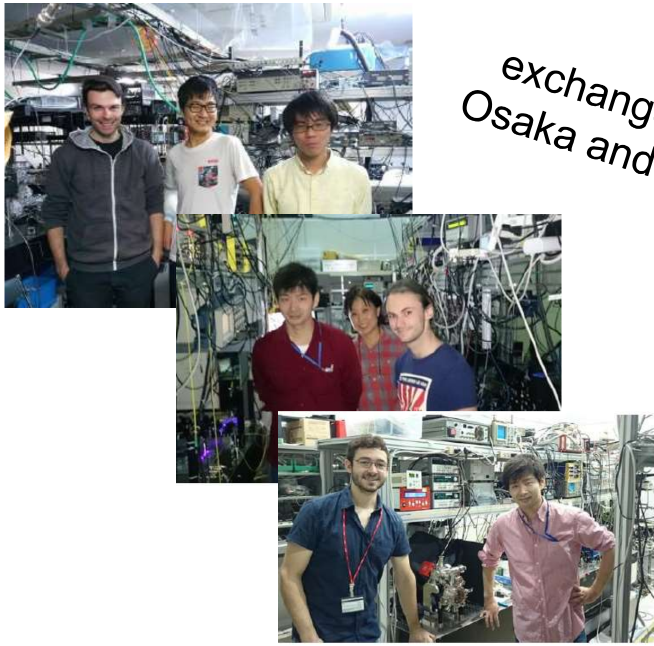
ca. 2200 employees

Founded 1887 by Werner von Siemens & Hermann von Helmholtz

The Team “Quantum Clocks and Complex Systems”



exchange with
Osaka and Tokyo

Int. Collaborations:
NICT Toyko (J)
University of Osaka (J)
CMI (Prag, Cz)
NPL (London, UK)
W. Zurek (Los Alamos NL)
R. Nigmatullin (Uni Sydney, Au)
Haggai Landa (IBM, IL)
…

Visiting scientists:
S. Ignatovich (ILP, Novosibirsk)
N. Ohtsubo (NICT, Tokyo)
M. Kitao (Osaka University)
M. Doležal (CMI, Prag)
L. Ye (JPL/CALTECH)
…

Industry Partners:
Grintech (Jena)
Naneo (Lindau)
D&G (Stuttgart)
Toptica (München)
Vacom (Jena)
Infineon (Munich)
…

TRiAC
International Joint Laboratory for
Trapped-Ion Integrated Atomic-Photonic Circuits

DFG
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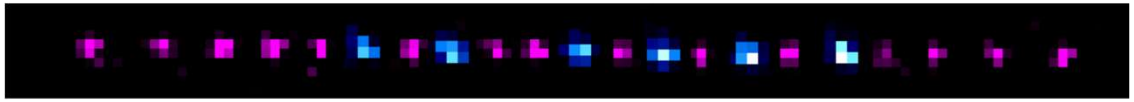
European Association of National Metrology Institutes
TC FS
Bundesministerium
für Bildung
und Forschung
mat
DLR

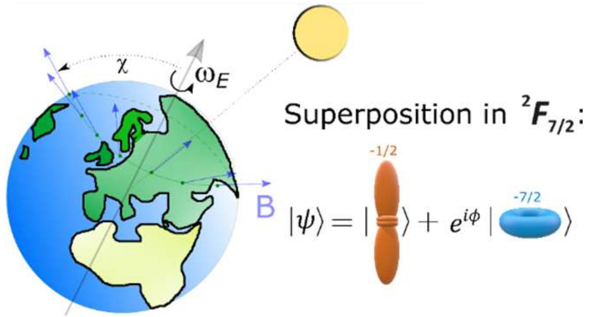
“Quantum Clocks and Complex Systems”

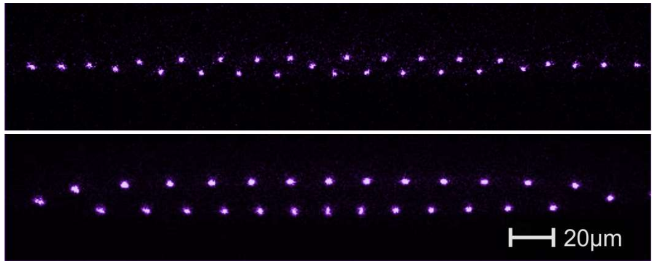
1. $^{115}In^{+}$ Multi-Ion Clock
2. Precision Spectroscopy in $^{172}Yb^{+}$ Ions
3. Dynamics of Coulomb-Crystals
4. Integrated Ion Traps
5. QTZ User Facility „Ion Traps“



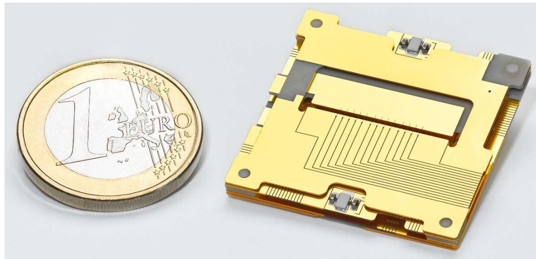
In^{+} / Yb^{+} crystals – optical clock

Test of Local Lorentz Invariance &
Isotope Shifts/search for new bosons





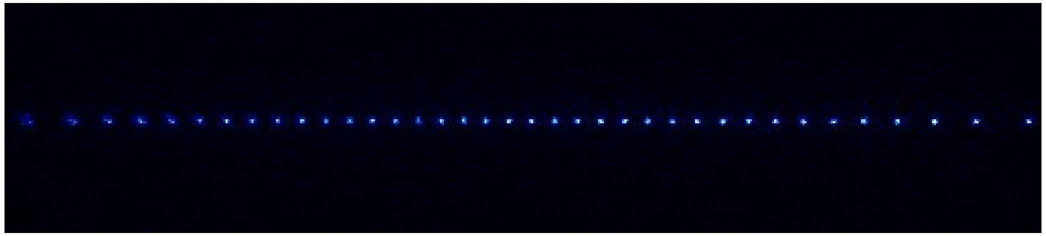
Topological Defects & Transport



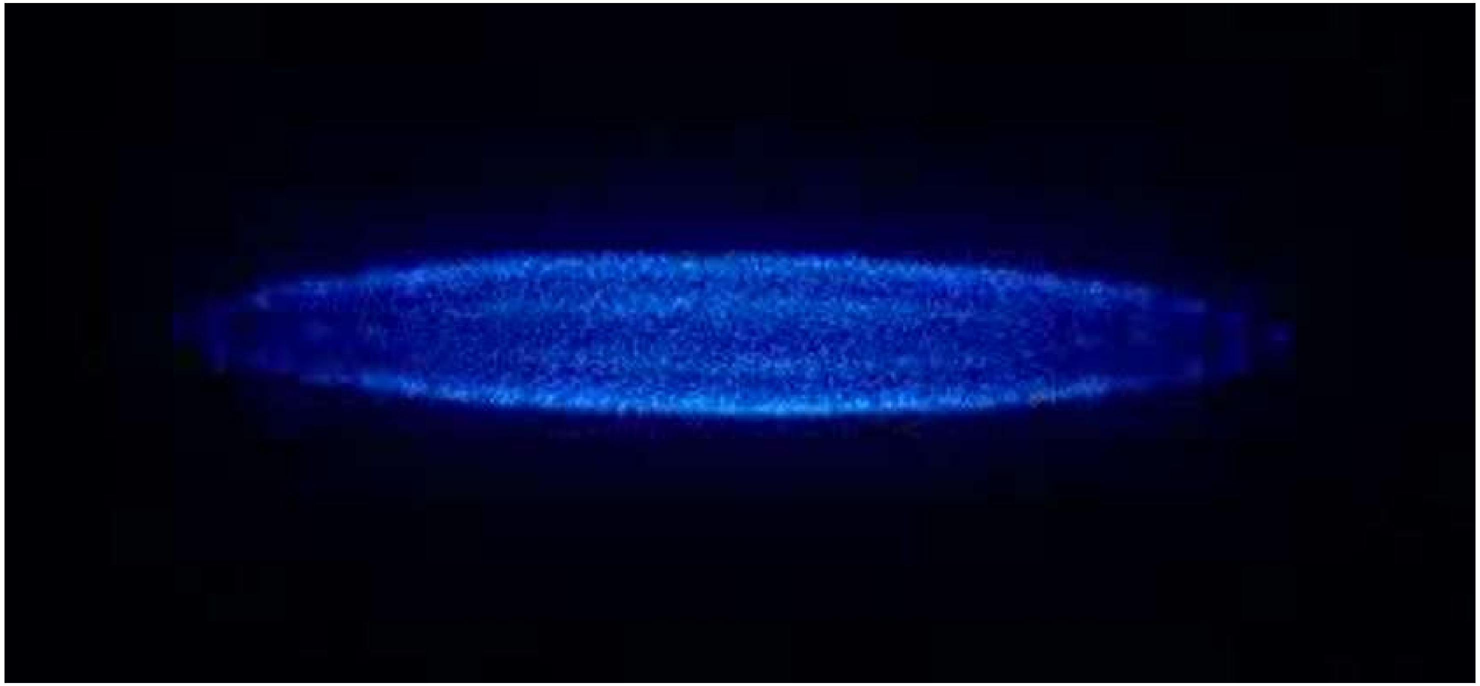
Integrated & Scalable Traps
→ Nanophotonics
→ Quantum Information

Ion Coulomb Crystals

if I may …



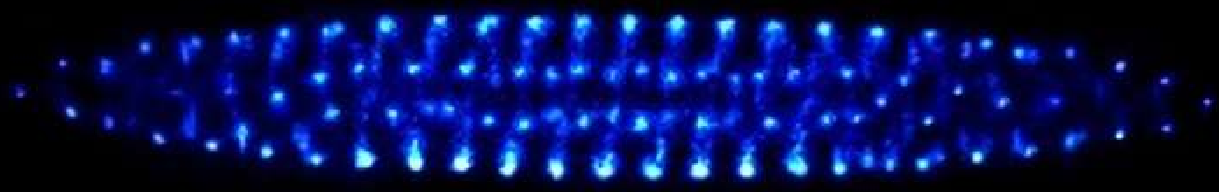
Hot Ion Plasma/Liquid $E_{kin} > E_{pot}$!



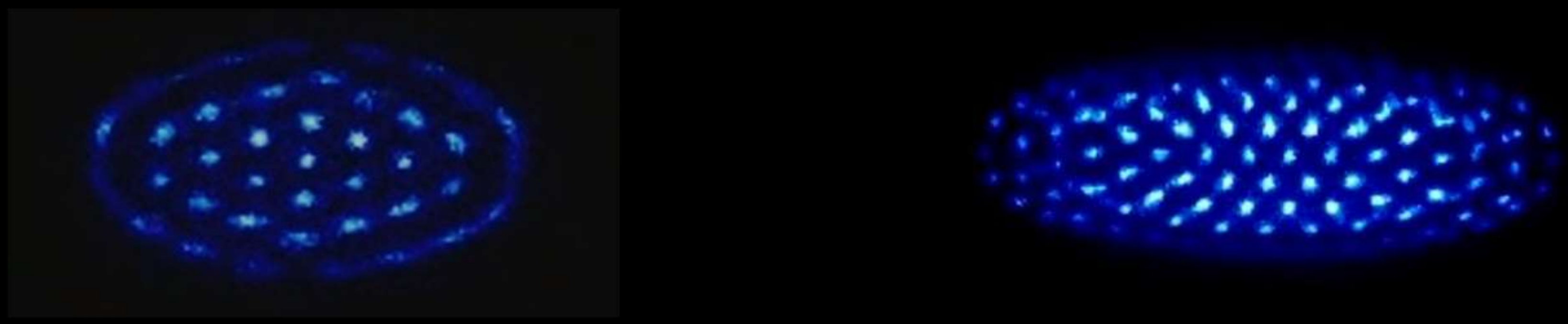
Self-organized system! Nonlinear chaotic dynamics

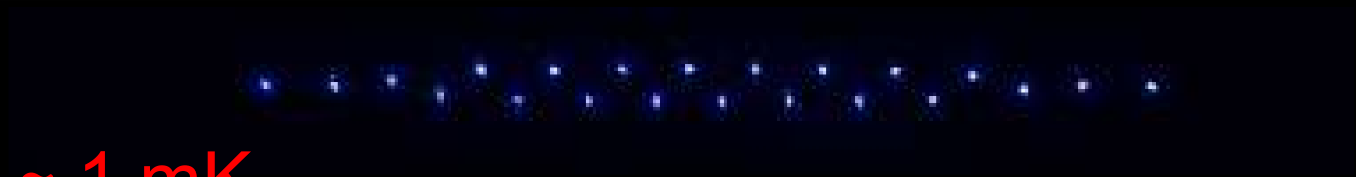
Ion Coulomb Crystals, $E_{pot} > E_{kin}$

T < 20 mK



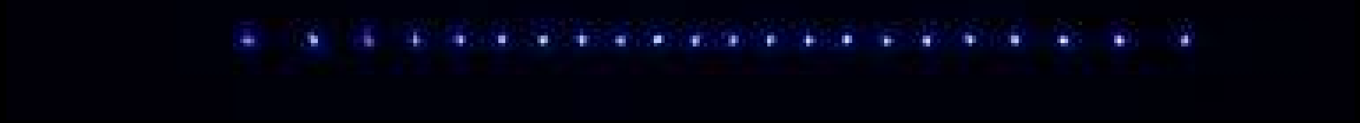
3D





2D

$T_{crystal} \approx 1$ mK



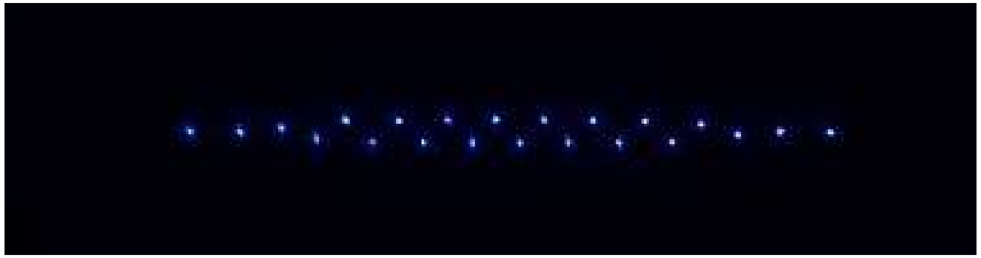
1D

Phases in Ion Coulomb Crystals

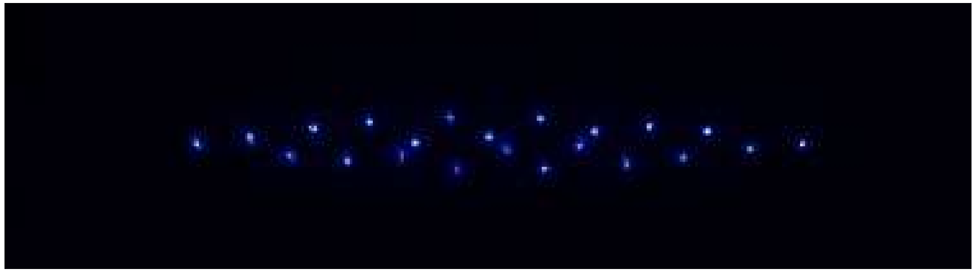
@ T = 1 mK

1 D

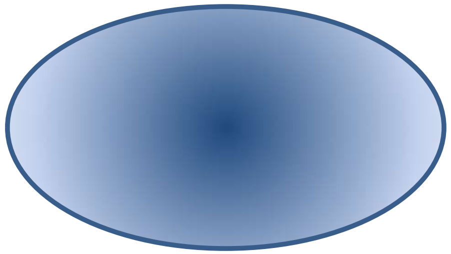
2 D



3 D



Control Parameter α:
Aspect Ratio of Trapping Potential



Lucretius "De rerum naturalium" / Proof according to Epicurus (300 B.C.)

The dilemma of argumentation in his physics lies in the fact that on one hand it wants to be based completely on the perception, but on the other hand it denies its world explanation directed against the superstition above all with the help of its doctrine of the invisible (more exactly: not perceptible) atoms.

This situation makes it necessary to develop reliable methods with the help of which conclusions can be drawn from the visible to the invisible.

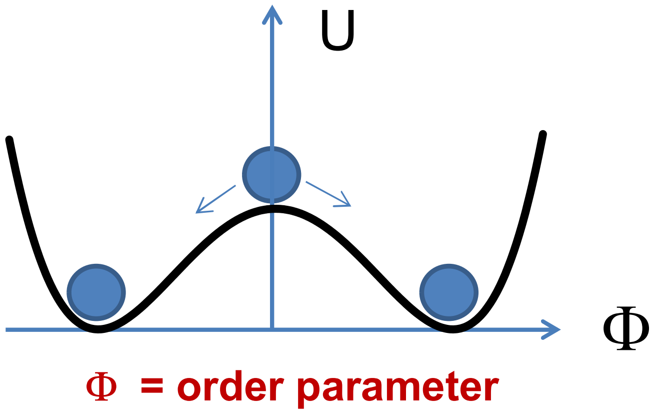
3 Forms of empirical cognition:

- Direct perception
- Based on certain (empirically gained) 'ideas' - (induction)
- Logical ways of inferring from phenomena (argumentatively) to the unknown
  → **Conclusion by analogy**

Symmetry breaking phase transitions

What happens when a system changes
from one equilibrium condition to another?

- Examples for 2nd-order phase transitions:
  - ferro-magnetism → para-magnetism
  - metal → superconductor
  - early universe



Symmetry breaking phase transitions

What happens when a system changes from one equilibrium condition to another?

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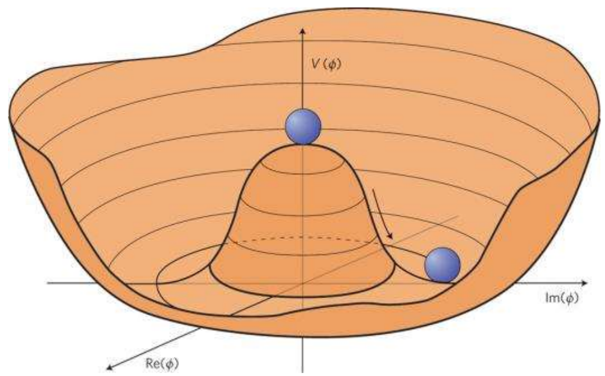
  - metal → superconductor
  - early universe

Spontaneous symmetry breaking of Higgs field →

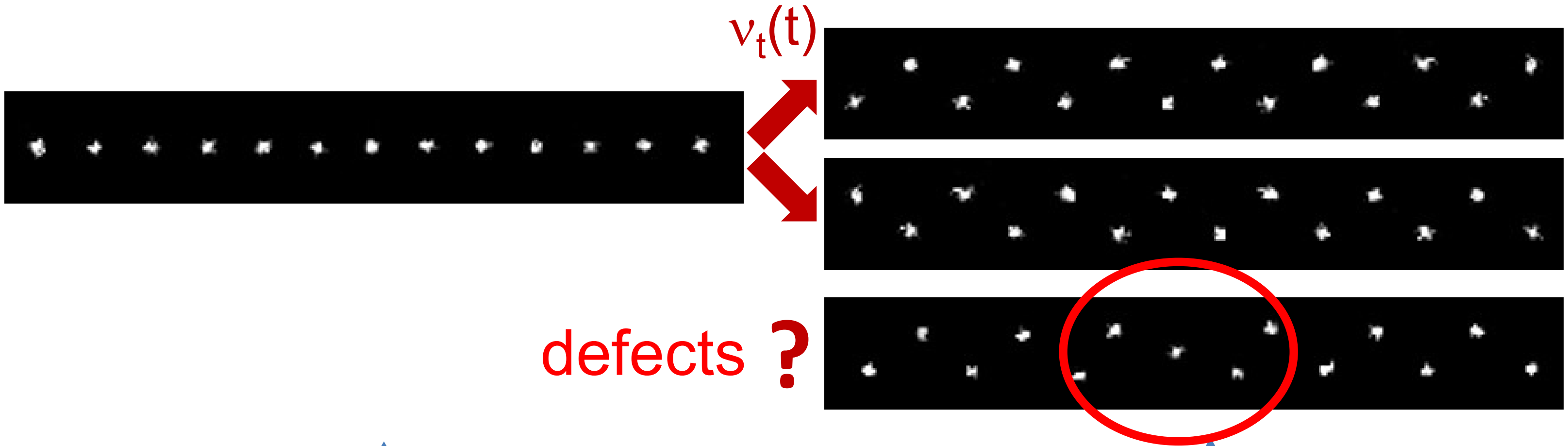


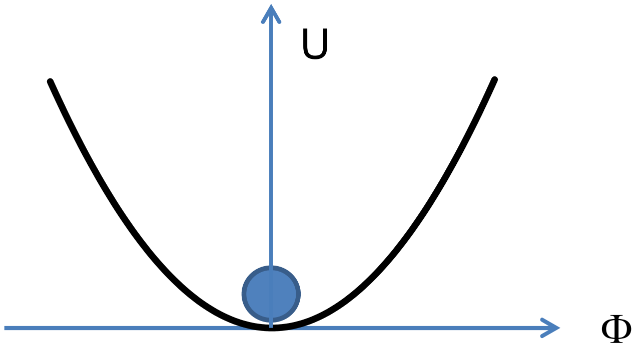
Nature Physics 7, 2 (2011)

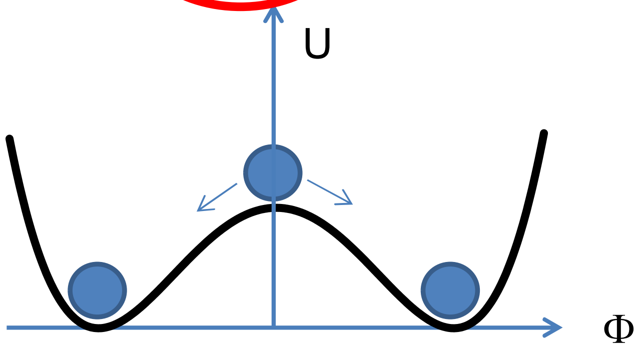
Symmetry breaking in ion Coulomb crystals

Rotational symmetry

Mirror symmetry







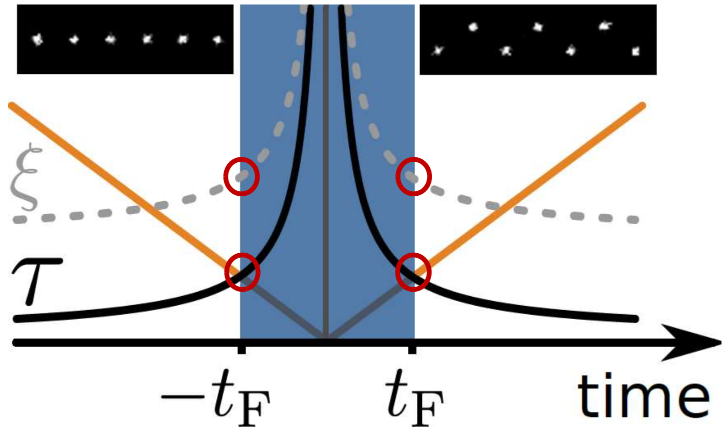
2nd order phase transition[1]

1: Fishman *et al.*, PRB 77, 064111 (2008)

The Kibble-Zurek Mechanism

- ξ: correlation length
- τ: relaxation time
- defect density: d = $\frac{\xi}{system\ size}$
- $\tau \sim \left|\frac{\tau_Q}{t}\right|^{\upsilon z}$
- $\xi \sim \left|\frac{\tau_Q}{t}\right|^{\upsilon}$
- KZM: d from ξ at freezeout
- friction (laser cooling) negligible $\Longrightarrow$ ν = ½, z = 1

Quenching the control field

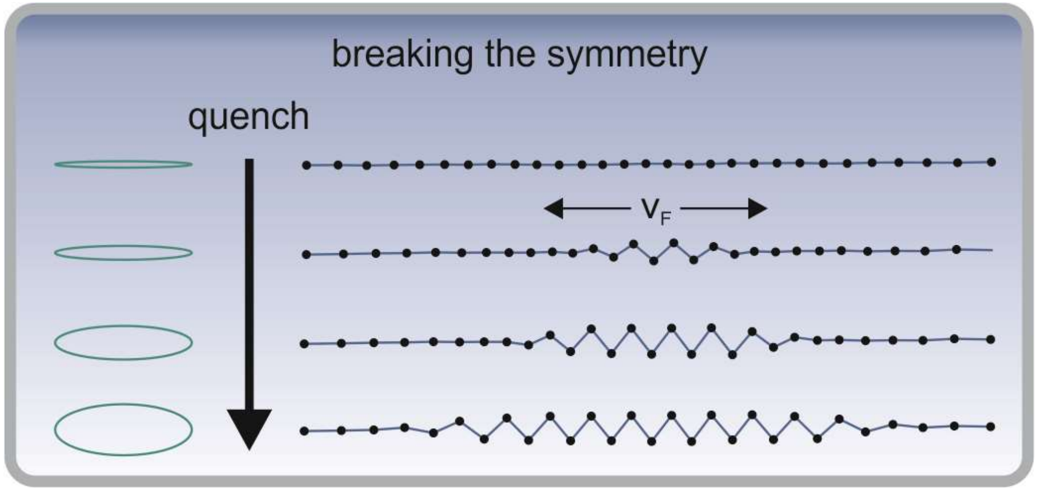


test of KZM with defined ν, z

del Campo *et al.,* PRL 105, 075701 (2010) Fishman *et al.,* PRB 77, 064111 (2008)

Harmonic Ion Traps – Inhomogeneous Case

- Ions in harmonic potential:
  phase transition spreads out from center!



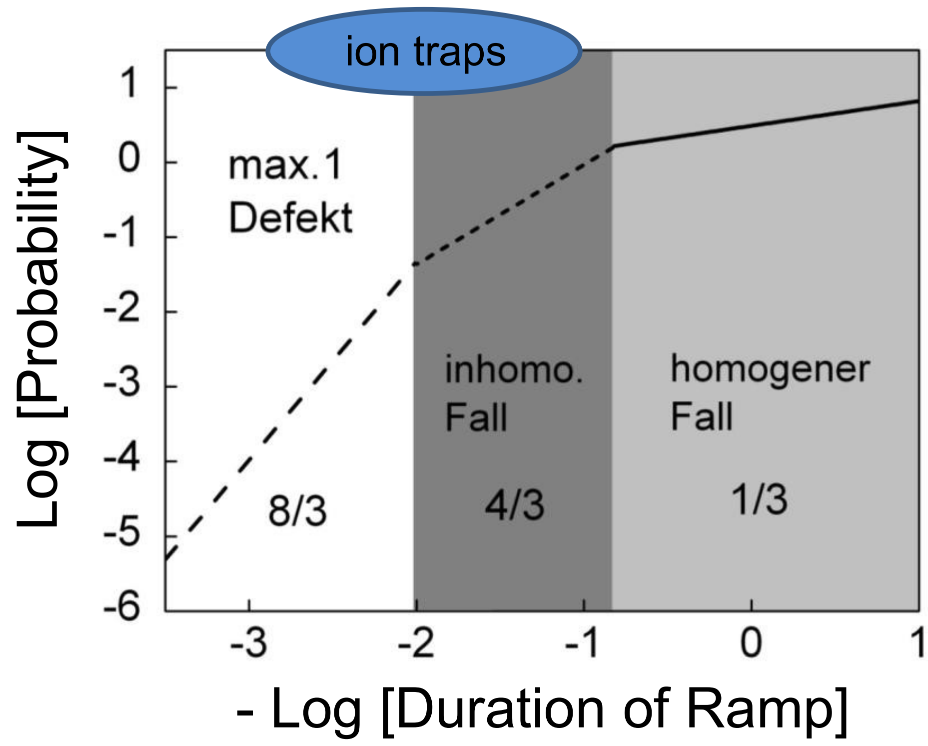
- Phase front faster than speed of sound!

A. Del Campo et al., Phys. Rev. Lett. 105, 075701 (2010)

Prediction of KZM

Power law scaling of defect density:

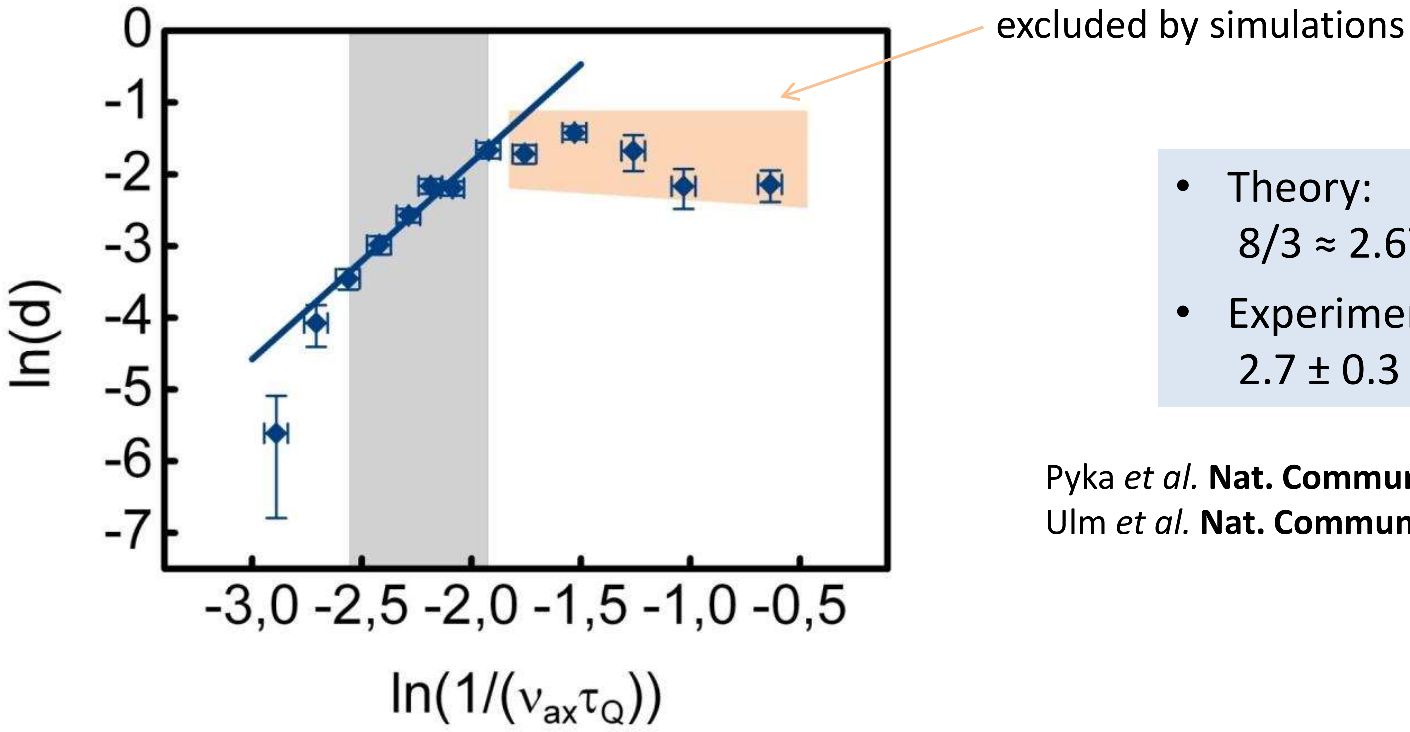
$$d \sim \left|\frac{1}{\tau_Q}\right|^{\upsilon/(1+\upsilon z)}$$



test of KZM with defined ν, z

Scaling of Defect Creation

Defect Probability as Function of Ramp Velocity:



- Theory: 8/3 ≈ 2.67
- Experiment: 2.7 ± 0.3

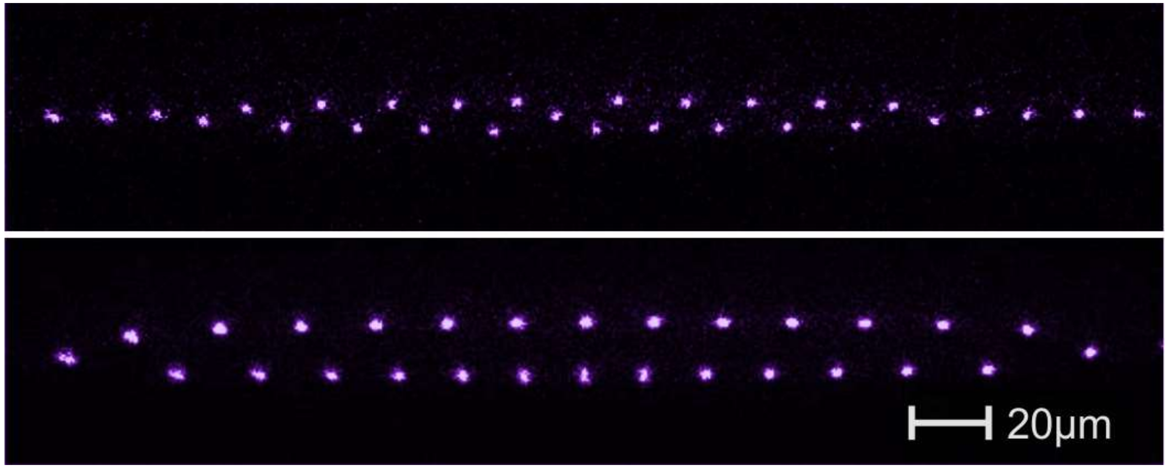
Pyka *et al.* **Nat. Commun**. 4, 2291 (**2013**)
Ulm *et al.* **Nat. Commun**. 4, 2290 (**2013**)

Nikoghosyan *et al.,* Universality in the dynamics of second-order phase transitions, **PRL** 116, 080601 (**2016**)

Puebla *et al.,* Fokker-Planck formalism approach to Kibble-Zurek scaling laws and nonequilibrium dynamics, **PRB** 95, 134104 (**2017**)

Topological defects in ion Coulomb crystals

Localized Defect $\nu_{rad}/\nu_z \approx 8$

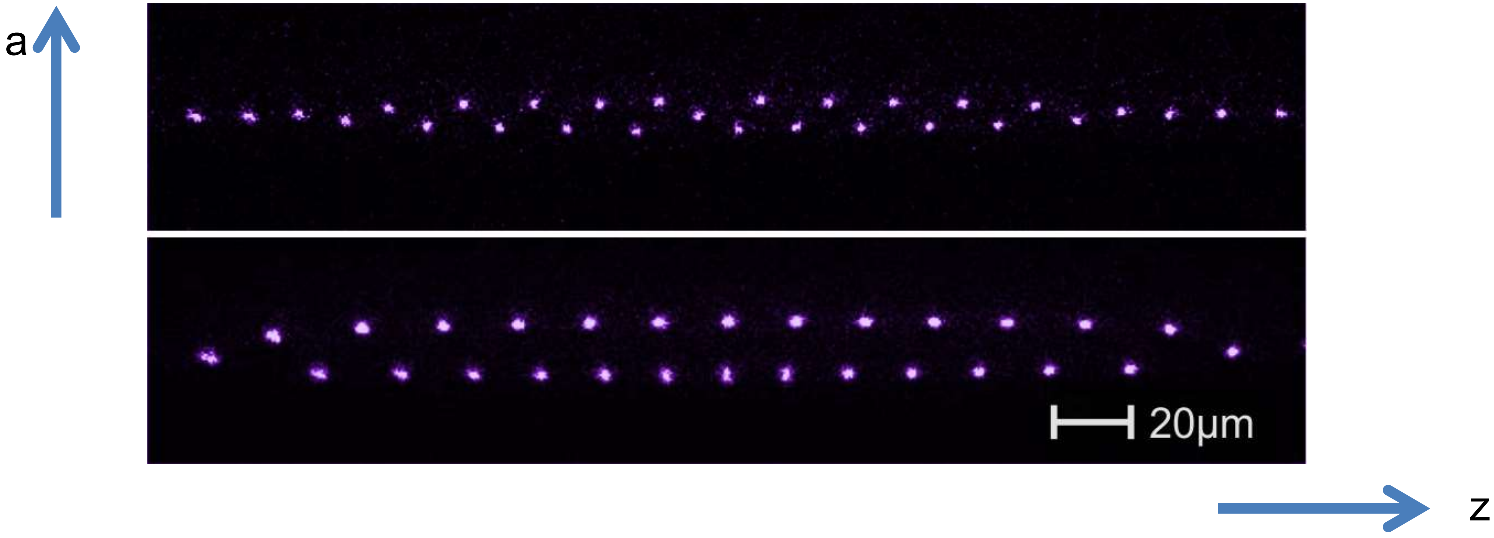


Extended Defect $\nu_{rad}/\nu_z \approx 5.5$

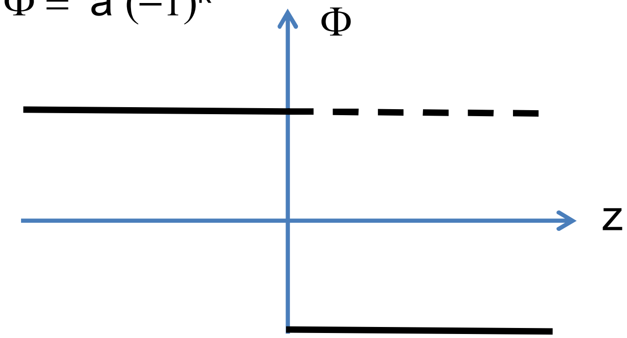
Pyka et al., Nat. Commun. 4, 2291 (**2013**)

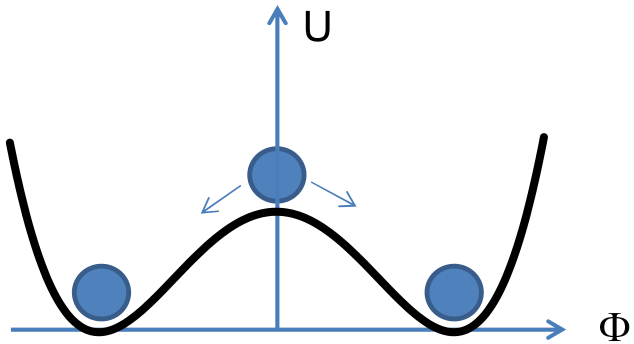
Order Parameter Φ

radial ion separation a:



Discrete field: $\Phi = a\,(-1)^k$





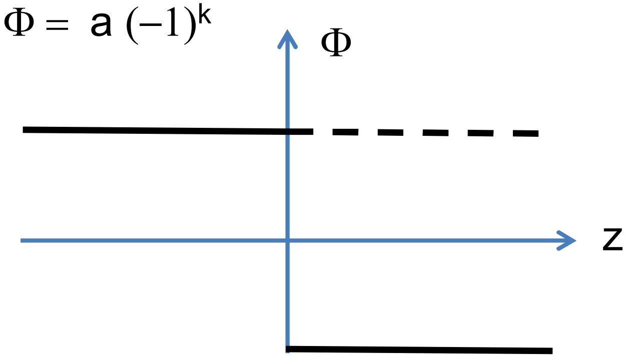
Topological Soliton:

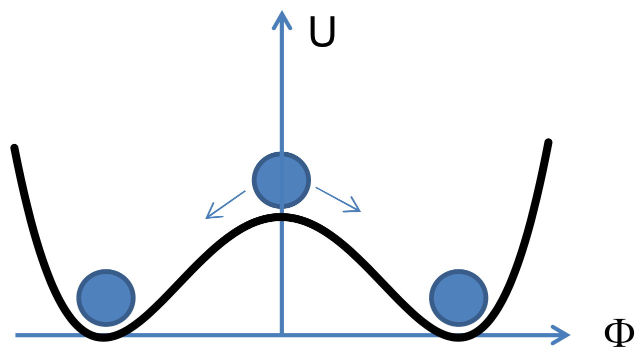
Langragian of Scalar Field:

$$L = \frac{1}{2}\left(\frac{\partial \Phi}{\partial t}\right)^2 - \frac{1}{2}\left(\frac{\partial \Phi}{\partial z}\right)^2 + \lambda \Phi^2 + A\Phi^4$$

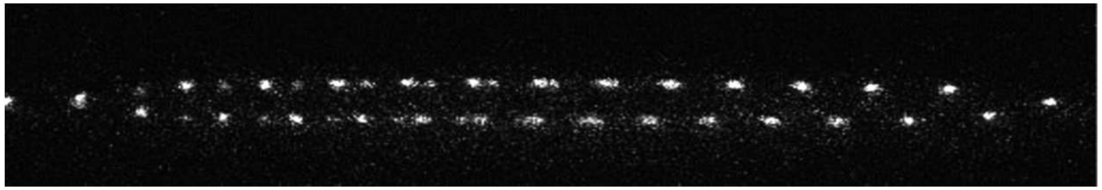
- field configurations, such that their presence can be detected by looking at the values of the field far away from the defect
- cannot be removed by local deformations of the field

$\Phi = a\,(-1)^k$





The Aubry Phase Transition
-
Friction at the Atomic Scale

 ?

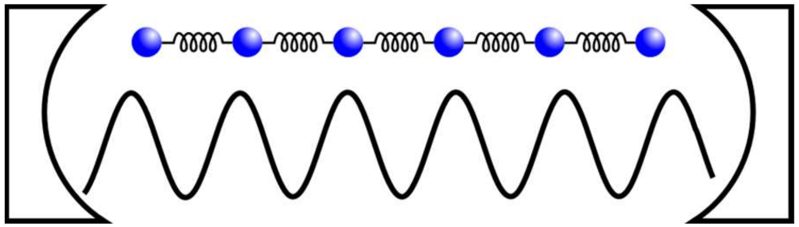
Complex, Self-Organized System with Back-Action

How can we experimentally realize nanofriction?

Vanossi *et al.,* Modeling friction: From nanoscale to mesoscale, Rev. Mod. Phys. 85 (2013)

Proposal: use linear ion chain in optical corrugation potential

Theory: Benassi et al., *Nature Commun* 2, 236 (2011)
Puttivarasin et al., *New J. Phys*. 13, 075012 (2011)
Fogarty et al., *Phys. Rev. Lett.* 115, 233602 (2015) ...



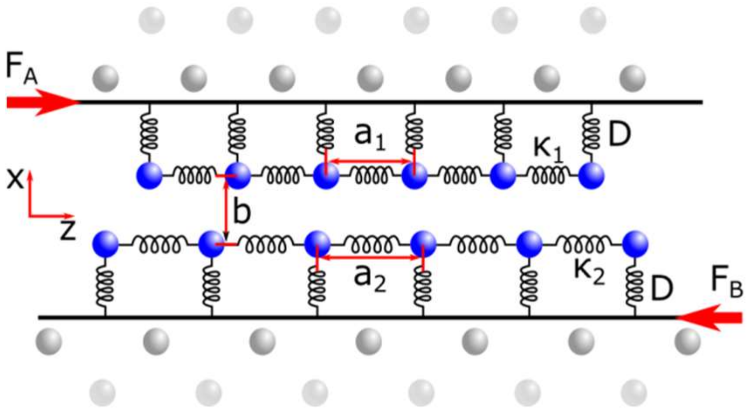
Standing optical wave in cavity

here: Frenkel-Kontorova model → gives sine-Gordon equation

$$\mathcal{L} = \frac{1}{2}\left(\frac{\partial\phi}{\partial t}\right)^2 - \frac{1}{2}\left(\frac{\partial\phi}{\partial z}\right)^2 + A\sin\phi$$

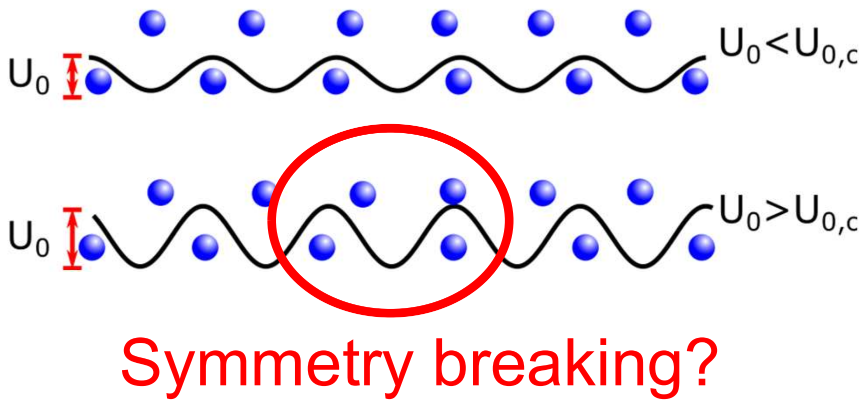
Self-organized crystal with back-action

Locally the kink disturbes the quasi-periodicity of the two atomic layers



$D = m\,\omega_{ax}^2$: ion trap

$\kappa \sim \frac{e^2}{\pi\epsilon_0}\frac{1}{ma^3}$: ion interaction



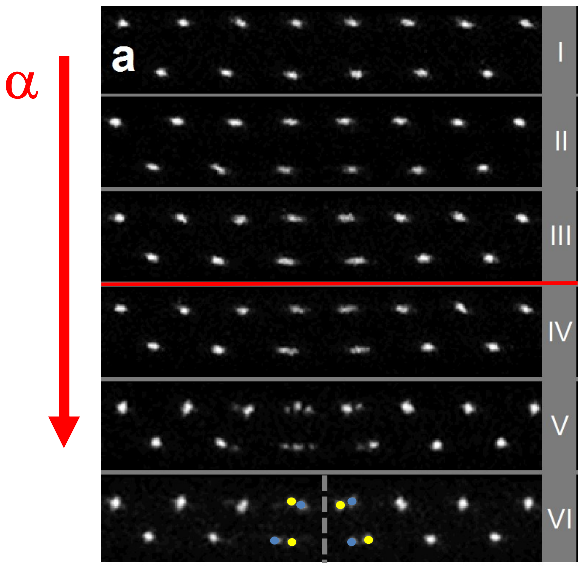
Interaction between the ion layers gives corrugation potential!

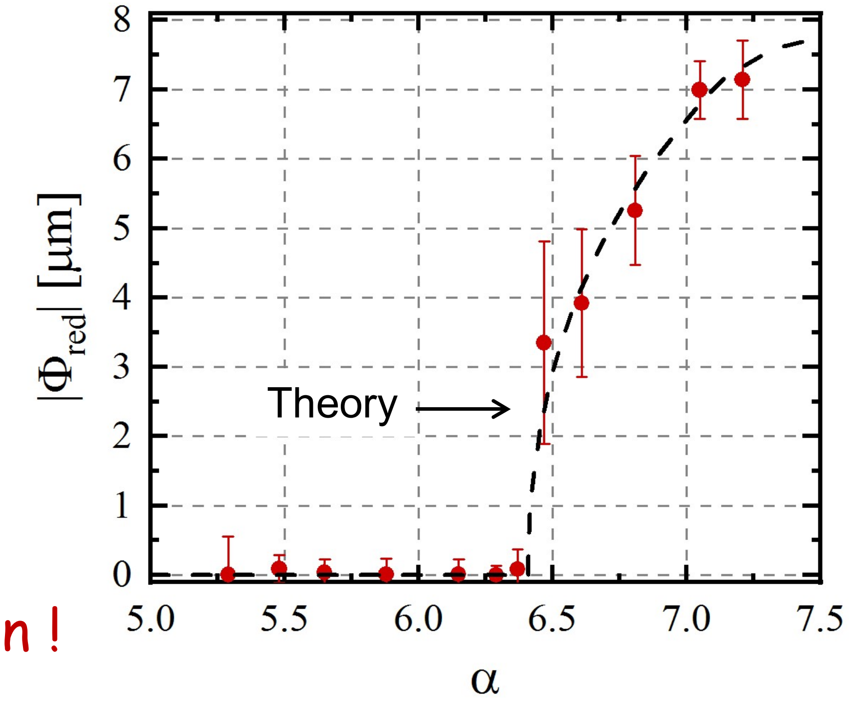
Order parameter → parametrizes symmetry breaking

Order parameter Φ := relative distance to closest ion in other layer

$$\Phi = \sum_{i \in Chain\,A} \mathrm{sgn}(z_i) \cdot \min_{j \in Chain\,B} |z_i - z_j|$$

Experimental observation:

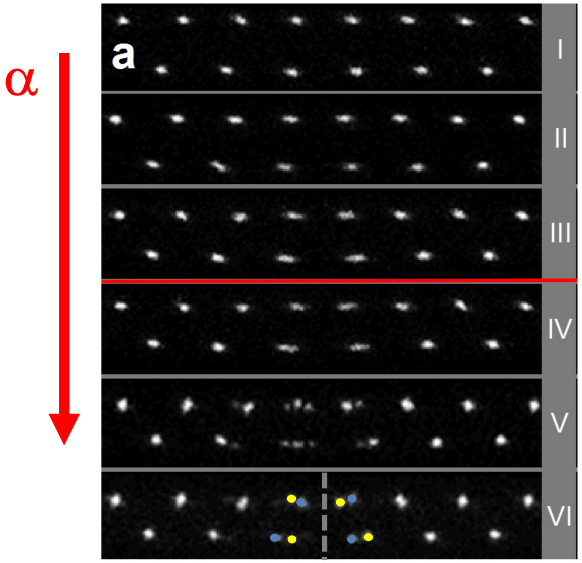




2nd-order phase transition !

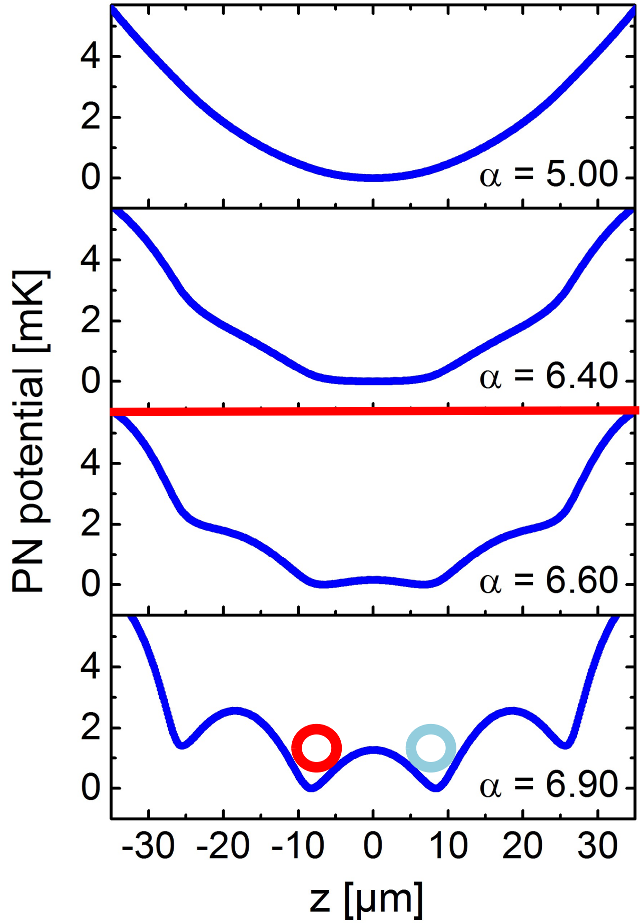
Order parameter → parametrizes symmetry breaking

Experimental observation:

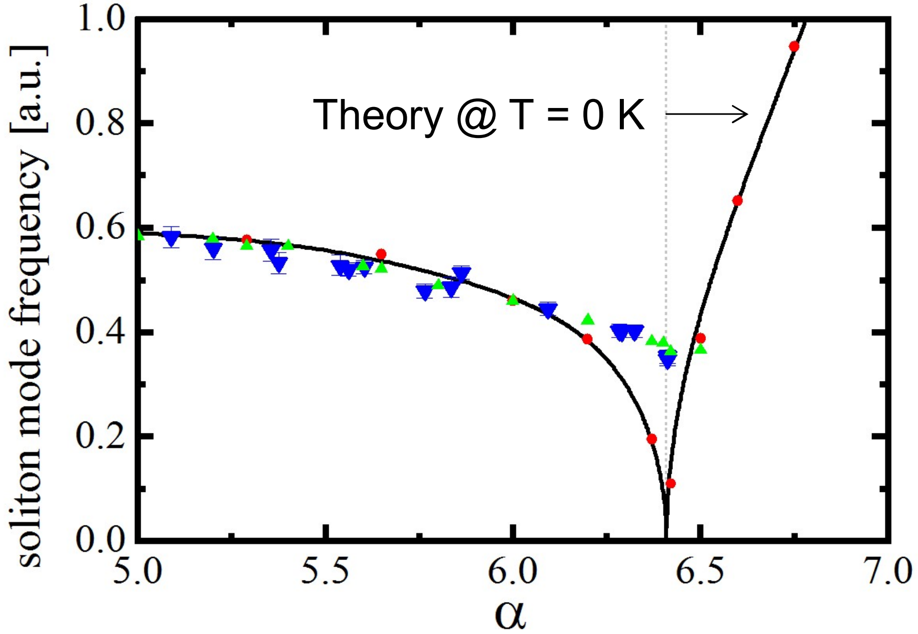


Peierls-Nabarro Barriers

= potential energy of kink soliton

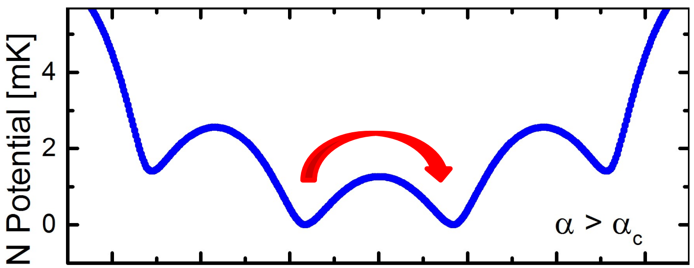


First Experimental Observation of the Soft Mode



legend:
— Hessian matrix $T = 0\mathrm{K}$
● simulations $T = 5\mu\mathrm{K}$
▲ simulations $T = 1\mathrm{mK}$
▼ **exp. data**

PN-energy barriers of kink soliton:
→ thermal energy allows for switching



Yes, but strong non-linearities due to finite temperature!

How does a soft mode couple to thermal phonon environment?

Finite temperature spectrum at the symmetry-breaking linear-zigzag transition

J. Kiethe,[1] L. Timm,[2] Haggai Landa,[3,4] D. Kalincev,[1] Giovanna Morigi,[5] and T. E. Mehlstäubler[1,6,*]

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[2] *Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstr. 2, 30167 Hannover, Germany*
[3] *Institut de Physique Théorique, Université Paris-Saclay, CEA, CNRS, 91191 Gif-sur-Yvette, France*
[4] *IBM Quantum, IBM Research Haifa, Haifa University Campus, Mount Carmel, Haifa 31905, Israel*
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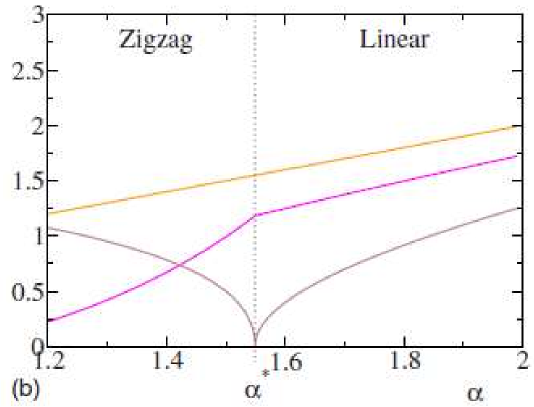
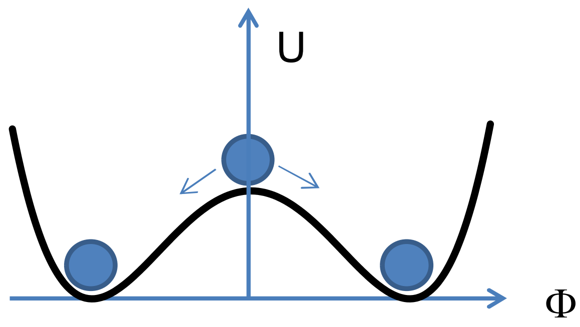
(Dated: December 22, 2020)



Also at linear-to-zigzag transition:
System changes between potential minima
→
similar at Aubry-type transition

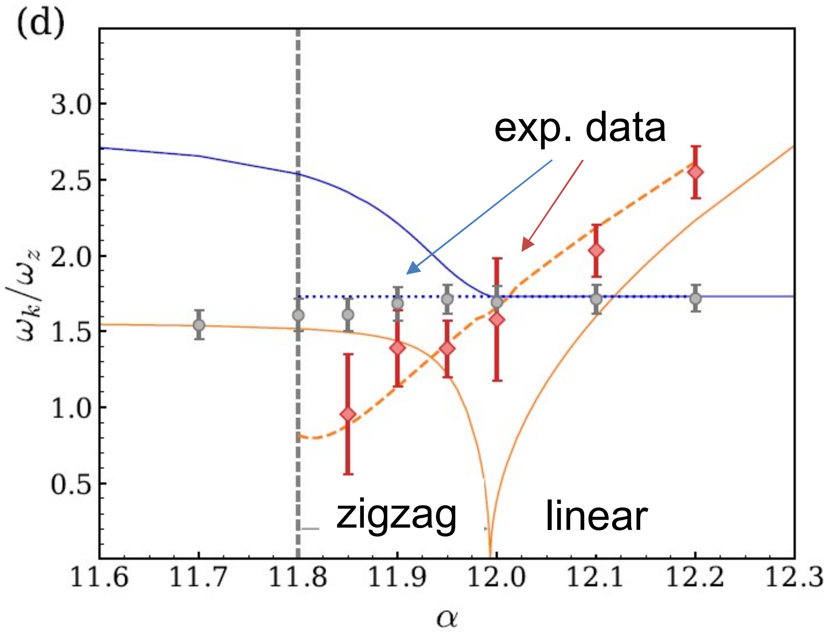
effective potential



Fishman *et al.,* PRB 77, 064111 (2008)

Coupling of soft mode to thermal phonon environment

Theory for two lowest frequency modes:



dashed lines = new theory

Equation of motion of phonon *i* under non-linear interaction:

$$V_4 = \frac{1}{2!}\sum_{i=1}^{3N} m\omega_i^2\Theta_i^2 + \frac{1}{3!}\sum_{ijk=1}^{3N} L_{ijk}\Theta_i\Theta_j\Theta_k + \frac{1}{4!}\sum_{ijkl=1}^{3N} M_{ijkl}\Theta_i\Theta_j\Theta_k\Theta_l$$

$$\ddot{\Theta}_i = -\frac{1}{m}\frac{\partial V_4}{\partial \Theta_i} - \gamma_i\Theta_i + \Xi_i(t)$$

Time average over higher frequency phonons:

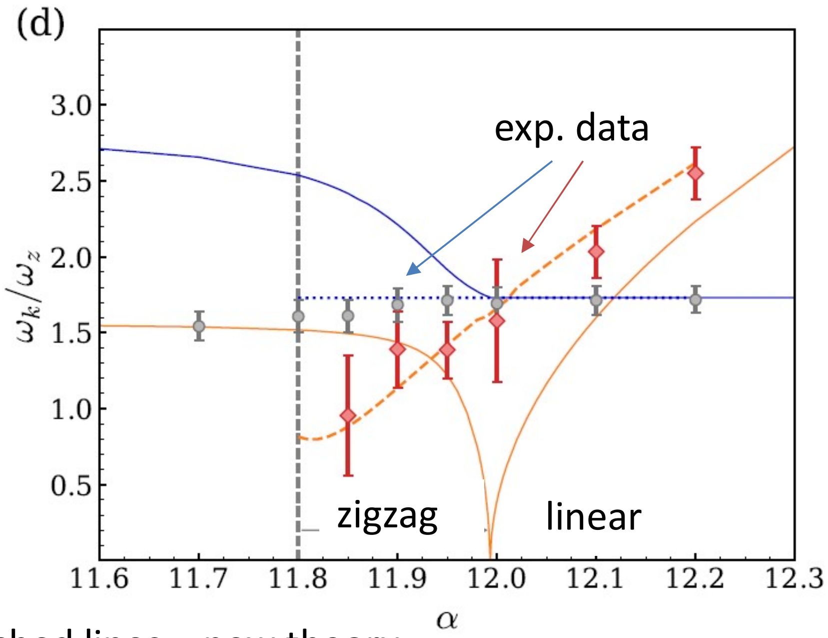
$$\ddot{\Theta}_1 = -\tilde{\omega}_1^2\Theta_1 - \frac{1}{2}\nu_{12}^2\Theta_2 + \eta_1 - \gamma_1\Theta_1 + \Xi_1$$

$$\ddot{\Theta}_2 = -\tilde{\omega}_2^2\Theta_2 - \frac{1}{2}\nu_{12}^2\Theta_1 + \eta_2 - \gamma_2\Theta_2 + \Xi_2$$

with $\tilde{\omega}_i(T)^2 = \omega_i^2 + \nu_{\text{eff},i}^2 T$ $\quad \nu_{\text{eff},i}^2 = \frac{1}{2m}\sum_{k\neq 1,2} M_{iikk}\frac{k_B}{m\omega_k^2}$

Coupling of soft mode to thermal phonon environment

Theory for two lowest frequency modes:



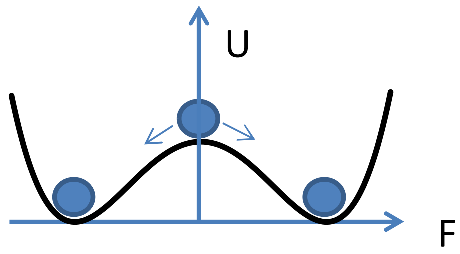
dashed lines = new theory

Conclusion:
also at Linear-to-Zigzag Transition…

→ soft mode is modified due to non-linear coupling to thermal phonon environment

→ soft-mode sees **modified Coulomb environment due to oscillating phonon environment**

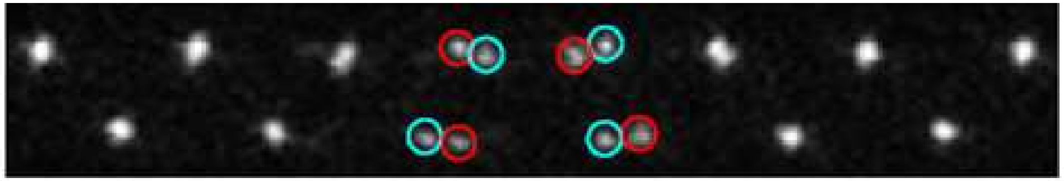
→ Floquet physics



J. Kiethe, L. Timm, H. Landa, D. Kalincev, G. Morigi, T. E. Mehlstäubler
Finite-temperature spectrum at the symmetry-breaking linear to zigzag transition
Phys. Rev. B, **103**, 104106 (2021)

Is there quantum nanofriction ?

Tunneling over 10s of micrometer? → collective excitation!
→ ions move by only a few nm while top. defect moves by 10s µm



Define effective mass of the quasi particle:

$$M_{\mathrm{eff}}(X) = m \sum_i \left(\frac{d\vec{r}_{i,C}(X)}{dX} \right)^2$$

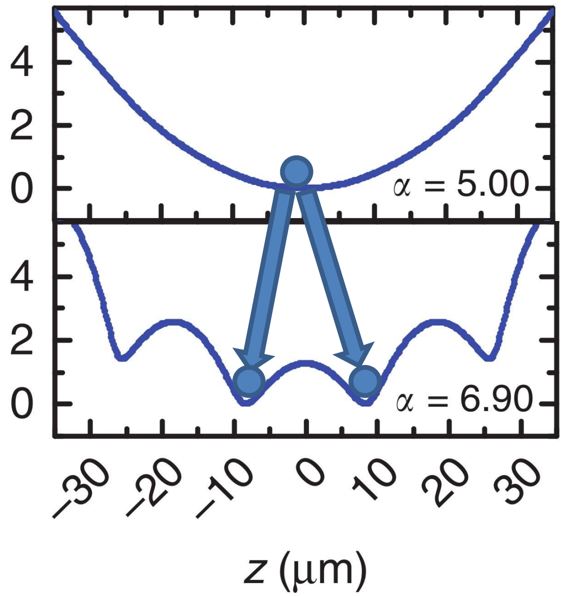
Solve Hamiltonian for quasi particle:

$$\hat{H}_s = \hat{P} \frac{1}{2M_{\mathrm{eff}}(\hat{X})} \hat{P} + U(\hat{X})$$

L. Timm, L. A. Rüffert, H. Weimer, L. Santos, T. E. Mehlstäubler
Quantum nanofriction in trapped ion chains with a topological defect, Phys. Rev. Research, 3, 043141 (2021)

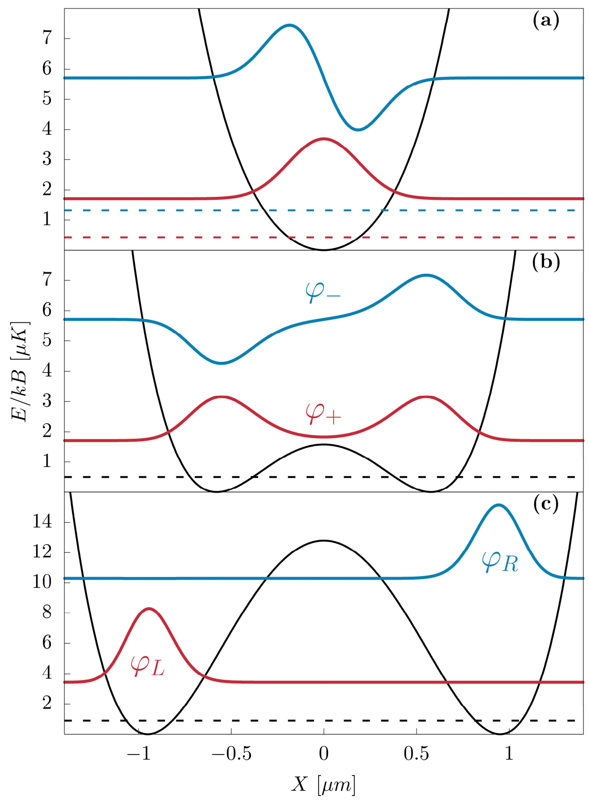
Quantum nanofriction

Critical α



QUANTUM WORLD

Assumption: Kink = quantum particle in classical PN potential



Sliding phase:

- Harmonic eigenstates
- Equidistant spectrum

Tunneling regime:

- Barrier splits ground state wavefunction
- Sym. and antisym. pairs

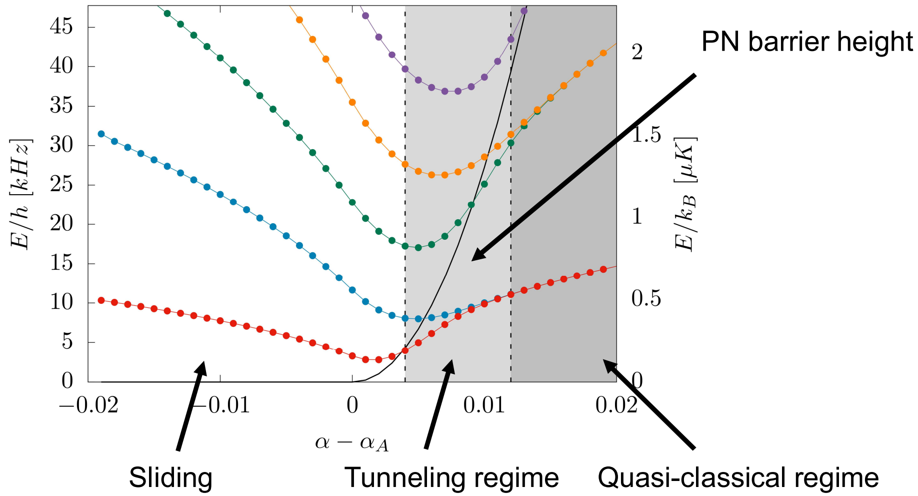
Quasi-classical regime:

- Large barrier →tunneling negligible
- Localized states

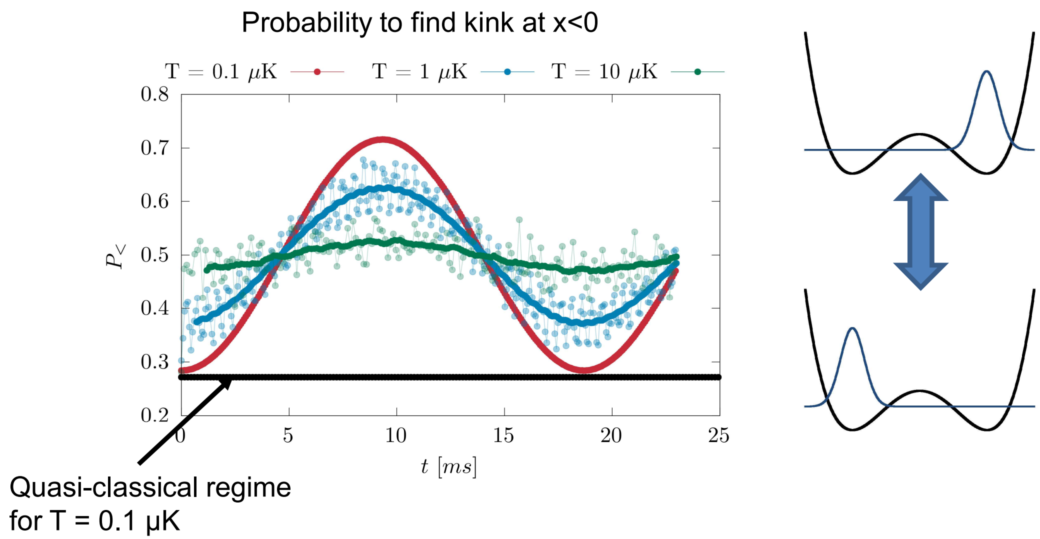
Consequences for observables in experiments?

Quantum nanofriction

ENERGY SPECTRUM



TUNNELING DYNAMICS



- Quantum fluctuations: No "softmode"
- Tunneling regime: Eigenstate energy below barrier height but tunneling causes energy gap
- Quasi-classical regime: Degenerate sets of eigenstates, localized left/right

→ Spectroscopic measurement of the energy spectrum after ground-state cooling

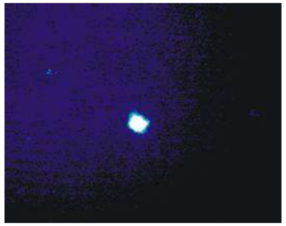
- Initialize a localized state in one potential minimum and monitor evolution
- Oscillation between left and right minimum due to tunneling
- Not observable in quasi-classical regime

→ At low μK temperatures tunneling dynamics is observed

Optical Clocks and Trapped Ions

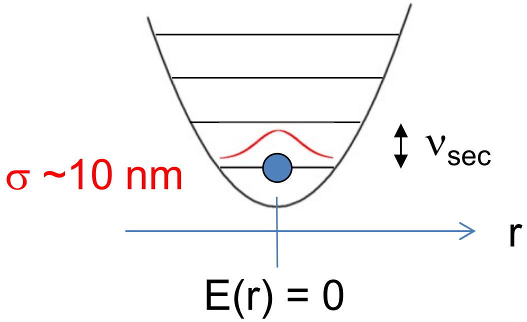
Accuracy of Single Ion Clocks

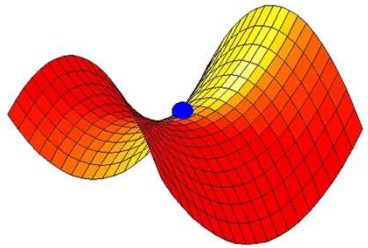
3D-Paul trap



single Yb^+-ion

Trap Depth ~ 10^4 K





ponderomotive potential

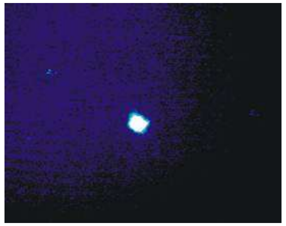
$$\Psi = \frac{e^2|E|^2}{4m\Omega^2}$$

- 10^4 K deep traps → **long trapping times** for single ion (**up to months**)
- ions are trapped at **E = 0** → no systematic shifts to 1^{st} order
- strong trap potential → strong localization **(σ ≈ nm**)
- high level control of internal (**pseudo-spin**) & external degrees of freedom (**bosonic degree of motion**)
- Laser-cooling to mK → resolved sideband-cooling to quantum mechanical ground-state of motion!

Current world record in clock accuracy: *Brewer et al., PRL 2019:* *accuracy* $\Delta\nu/\nu$ = 9.4 x 10^{-19}

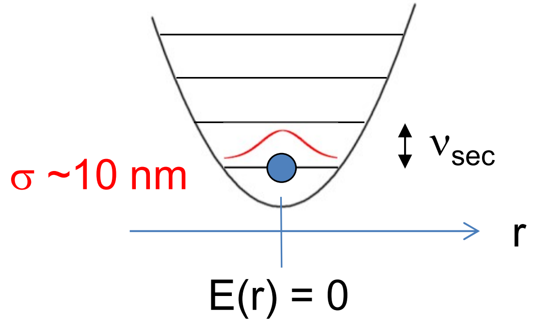
Accuracy of Single Ion Clocks

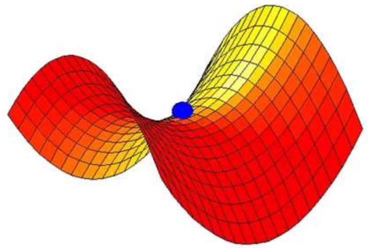
3D-Paul trap



single Yb^+-ion

Trap Depth ~ 10^4 K

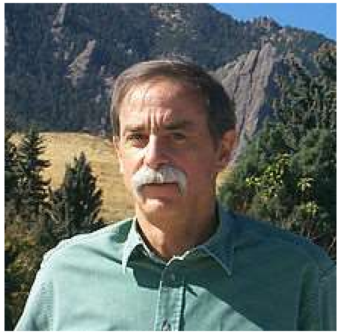


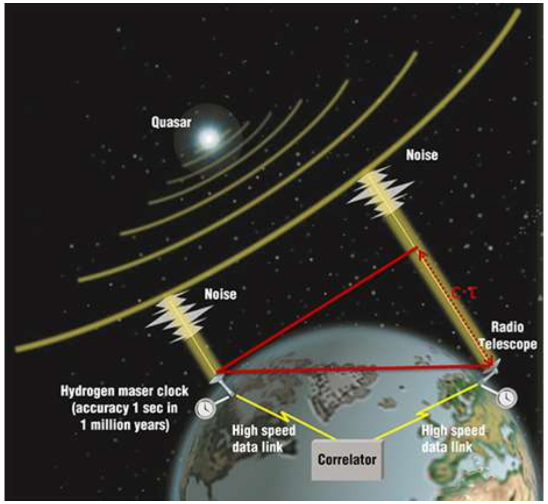


ponderomotive potential

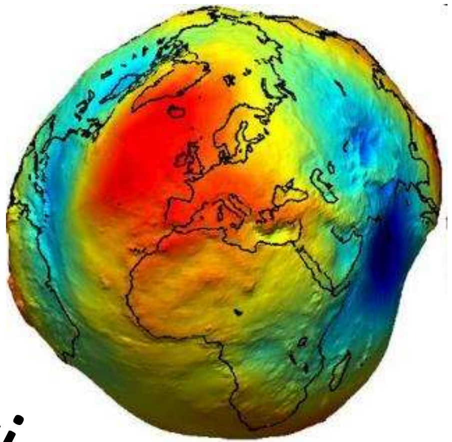
$$\Psi = \frac{e^2|E|^2}{4m\Omega^2}$$

<u>Nobel Prize 2012:</u>
"for groundbreaking experimental methods, that allow to manipulate and measure single quantum systems."





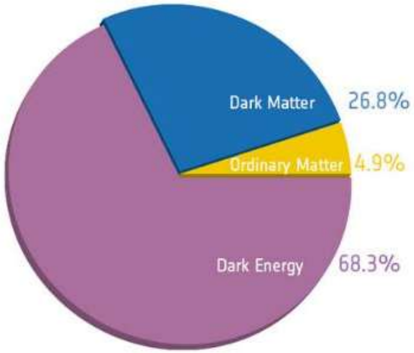
https://space-geodesy.nasa.gov/techniques/VLBI.html



Timing & Navigation,

autonomous driving...

Relativistic Geodesy



Test of Fundamental Physics

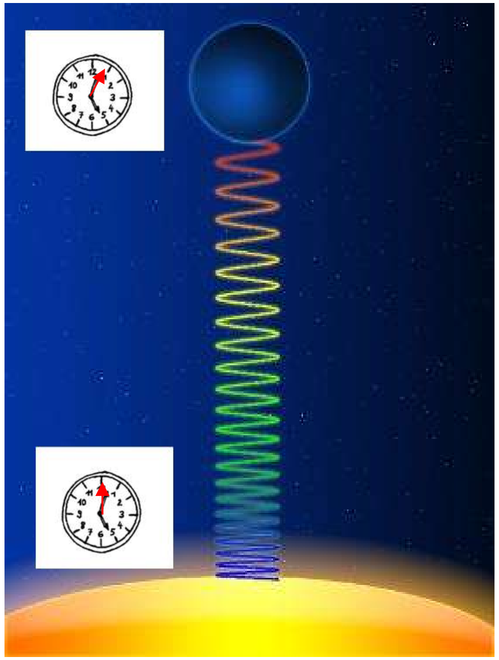
Clocks as Quantum Sensors for Geodesy

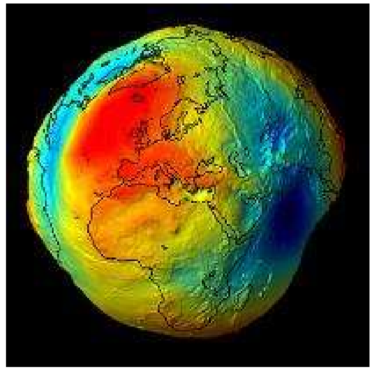
Gravity red-shift

$$Z \equiv \frac{\Delta \upsilon}{\upsilon} = (1+\alpha)\frac{\Delta U}{c^2} \quad = \mathbf{10^{-18}}$$

$\Delta\nu/\nu = \mathbf{10^{-18}}$ → **1 cm** height resolution

gravimeter
→ **measures acceleration g**
= local gradient of potential





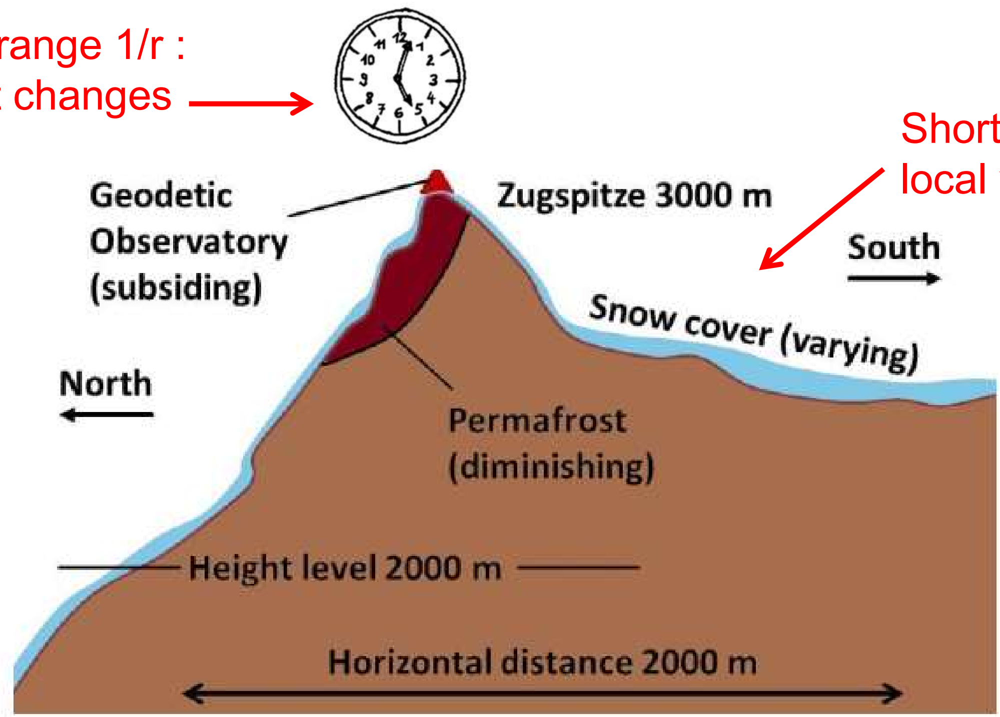
Earth's geoid/ESA

clocks
→ **measure difference in potential**

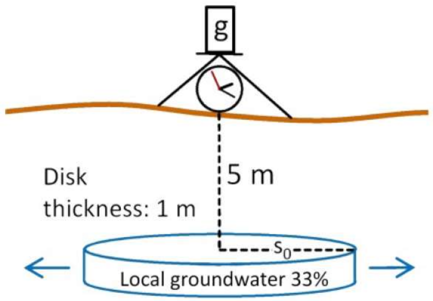
Examples for Geodetic Observations

Long-range 1/r :
height changes

Short-range 1/r²
local variations



Example: impact of groundwater body on gravity acceleration δg and gravitational potential δN



S_0 [m]	δg [nm/s²]	δN [mm]
10	77.1	0.0001
100	131.5	0.0014
1 000	137.7	0.0141
10 000	138.3	0.1400
100 000	138.3	1.3650
1 000 000	138.3	10.7170

Resolution of FG5 gravimeter: **10 nm/s² ≈ 10^{-9} g**

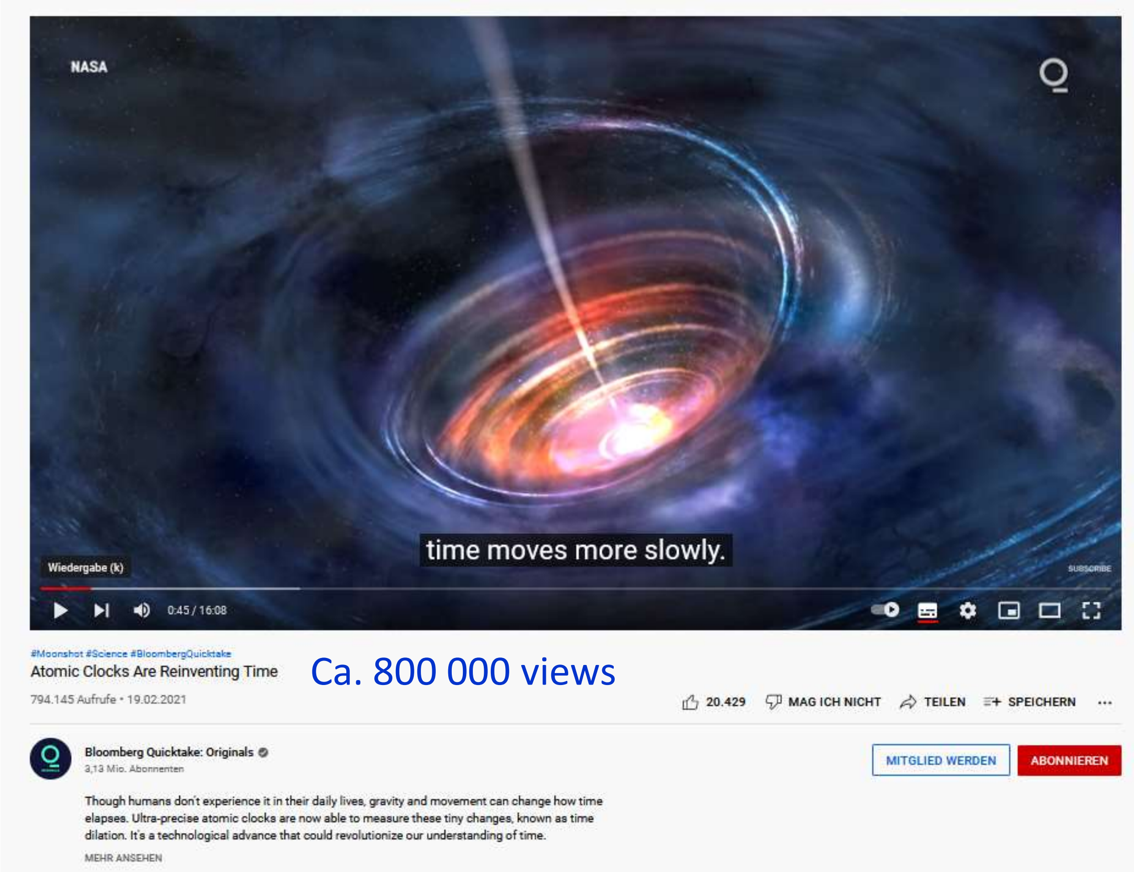
Review article: **Mehlstäubler *et al.*, „Atomic Clocks for Geodesy“, Rep. Prog. Phys. 81, 6 (2018)**

More about Time Dilation…

Bloomberg TV "Atomic Clocks are Reinventing Time"

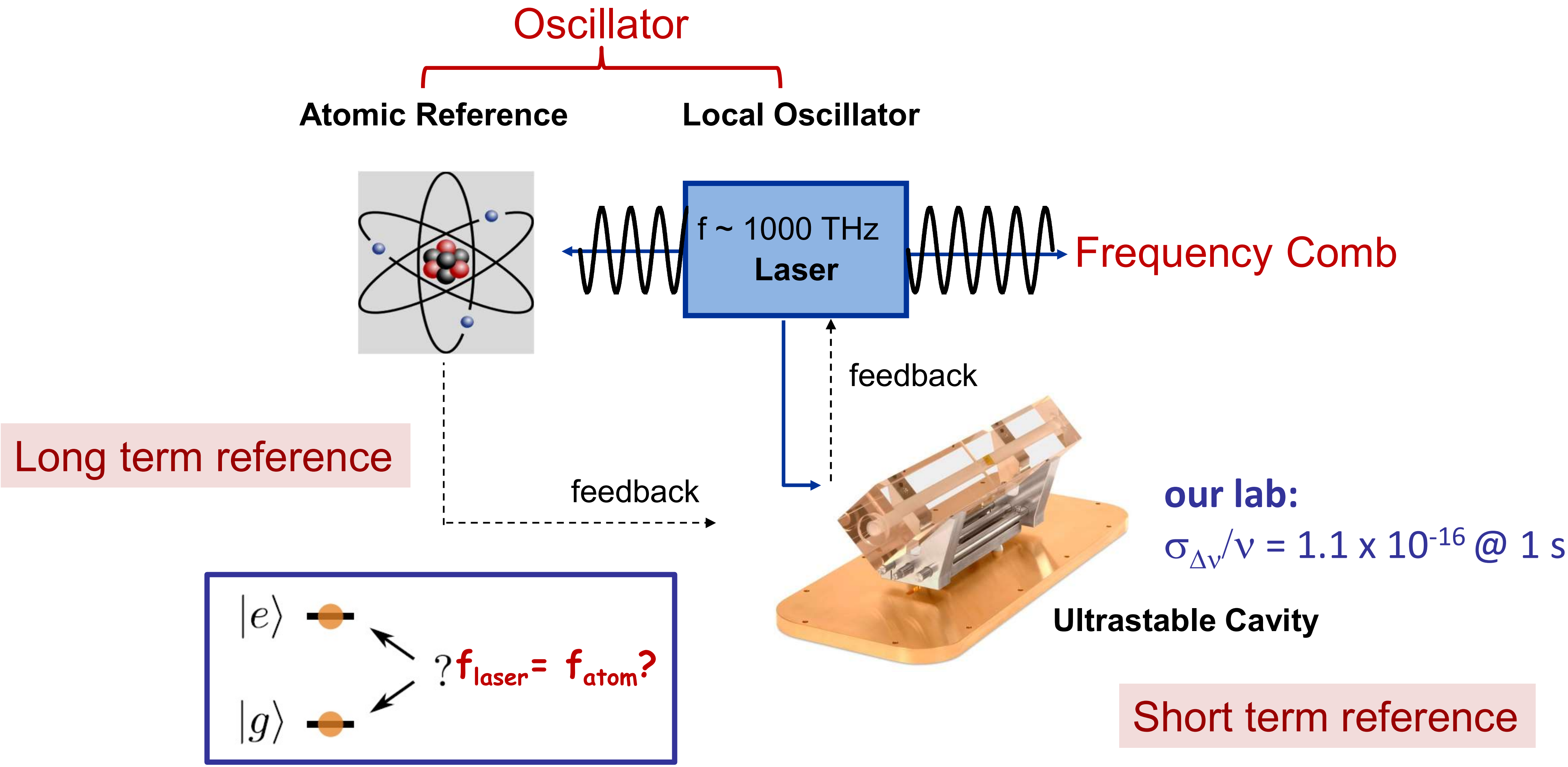
Featuring Don Lincoln (**Fermi Lab**),
David Hume (**NIST**) and
Tanja Mehlstäubler (**PTB/LUH**).

On Bloomberg TV and YouTube:
https://www.youtube.com/watch?v=hzLTgtFaPLY



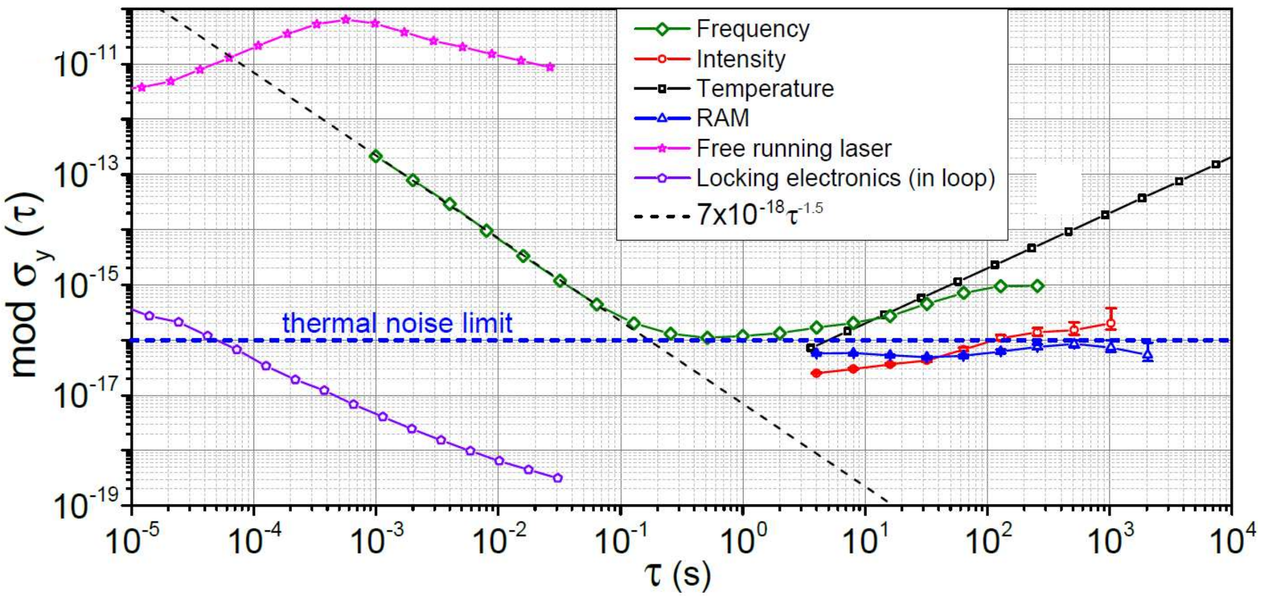
Ca. 800 000 views

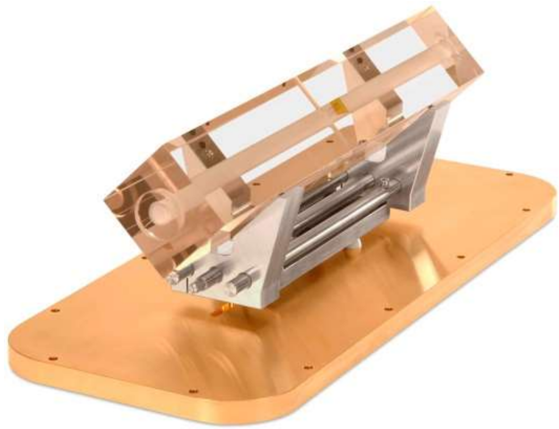
Ingredients for an optical clock



State-of-the-art with dedicated $^{115}In^+$ set-up

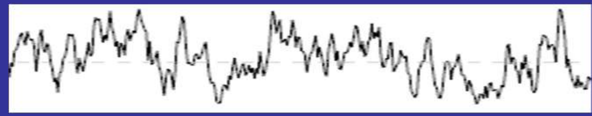
- Self-built lasers at **230 nm and 946 nm (→236 nm)** operational for direct In^+ detection and clock spectroscopy
- In^+ **clock laser (30 cm ULE)** operational at **1.1×10^{-16} in 1s** *
- drift compensation: low BW transfer-lock to cryogenic Si cavity (PTB)





*Didier et al., Optics Letters 44,1781 (**2019**)

Instability: statistical error



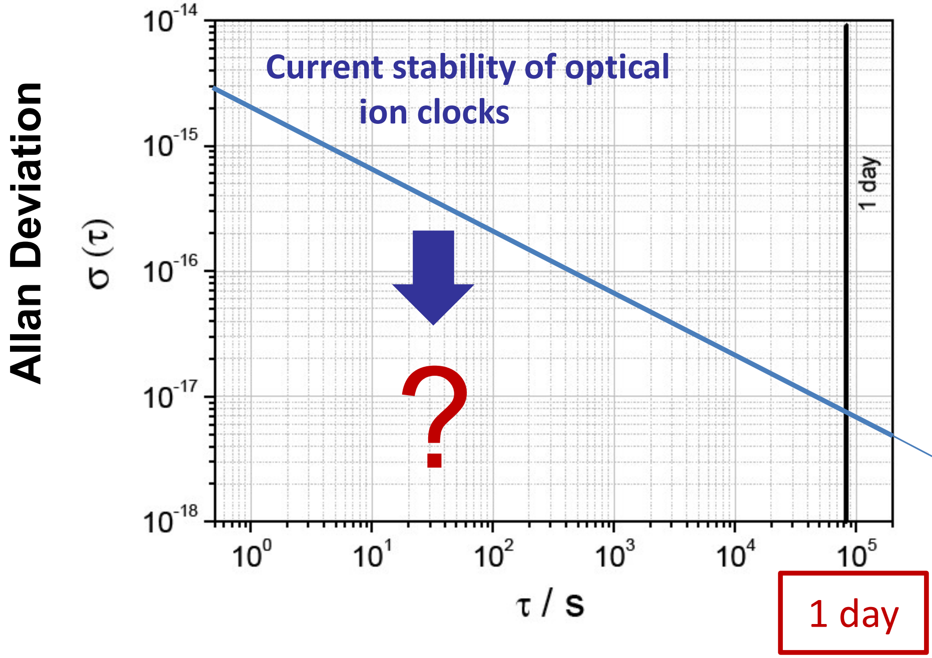
How well can we resolve the atomic frequency?

$$\sigma_y \approx \frac{1}{Q} \cdot \frac{1}{\sqrt{N_A}} \cdot \sqrt{\frac{T_c}{\tau}}, \qquad \text{mit} \qquad Q = \frac{f}{\Delta f}$$

Number of atoms

Frequency

Resolved linewidth (laser, atom)



Ion clocks: stability limited by quantum projection noise; high duty cycle

10s - 100 days !

Multi-Ion Approach

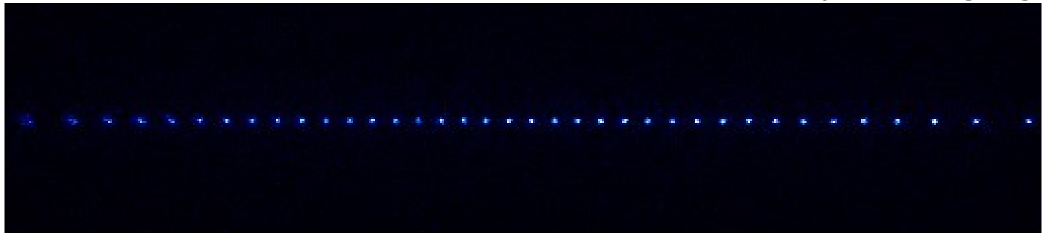
New Quantum Clocks ?

<u>Now needed</u>: „experimental methods, that allow to manipulate and measure many-body quantum systems."

37 days averaging

single Yb^+ ion

1 day averaging



Coulomb crystal of 37 Yb^+ ions

Quantum Metrology ↔ Quantum Simulation & Information

Herschbach et al., *Appl. Phys. B* 107, 891 (**2012**)

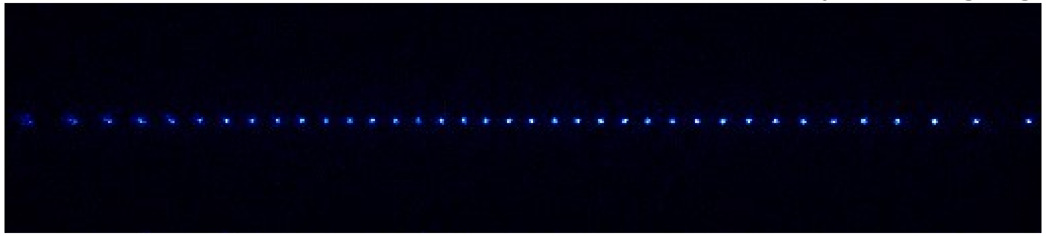
New Quantum Clocks ?

- Multi-Ion Clocks
- Entangled Clocks → 1/N scaling !
- Quantum-Logic Clocks

37 days averaging

single Yb^+ ion

1 day averaging



Coulomb crystal of 37 Yb^+ ions

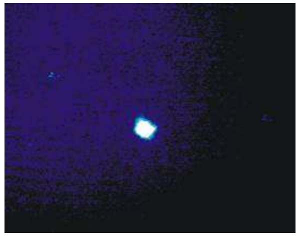
Quantum Metrology ↔ Quantum Simulation & Information

Herschbach et al., *Appl. Phys. B* 107, 891 (**2012**)

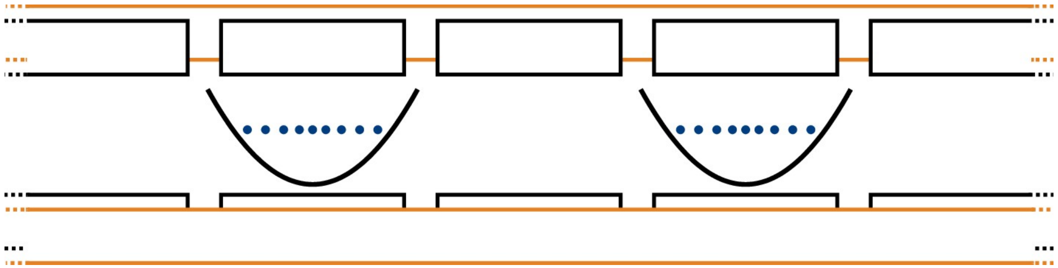
Scaling up the number of ions for metrology

- Basis for **multi-ensemble clocks** and new **interrogation protocols**[1] - in one system

our approach: bottom up, scalable ion traps



single Yb^+-ion



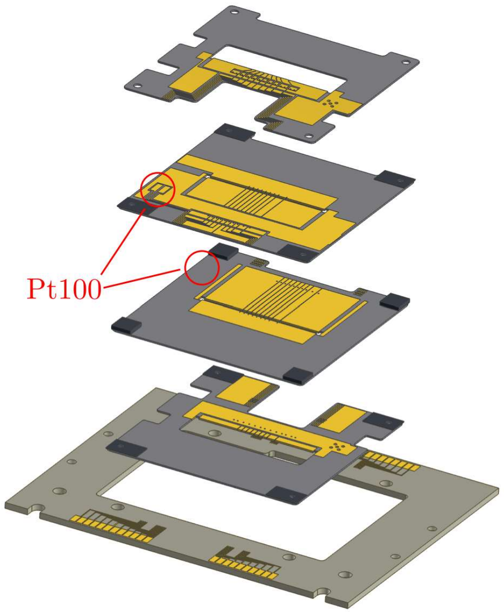
Linear array of Coulomb crystals

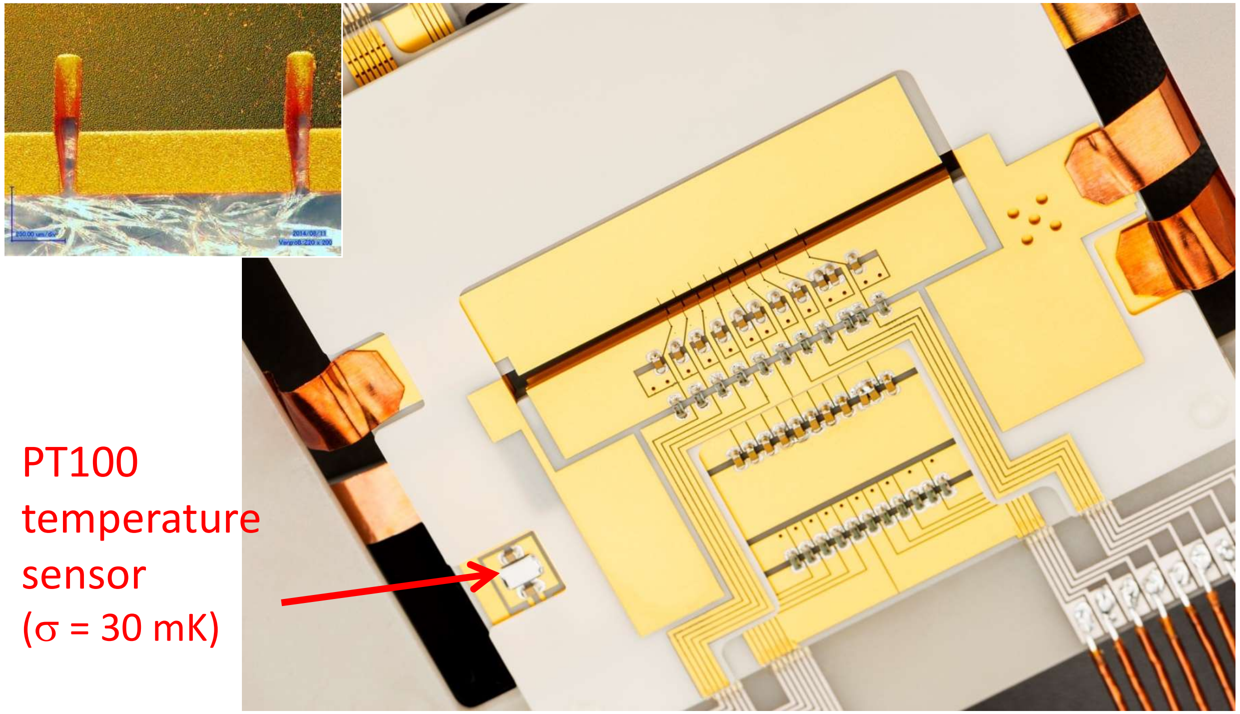
- Cascaded clock operation

1) Rosenband and Leibrandt, *arXiv:1303.6357* (**2013**), Borregaard and Sorensen, *PRL 111*, 090802 (**2013**), Kessler et al., *PRL* 112 (**2014**), Lebedev et al., *PRA* 89 (**2014**)

High-Precision Scalable Chip Ion Traps – AlN

- **Laser cut and structured: high-precision, µm-tolerances**
- **P = 10^{-11} mbar, non-magnetic materials, excellent heat management**
- **Controlled micromotion, low heating rates, 3D high optical access**

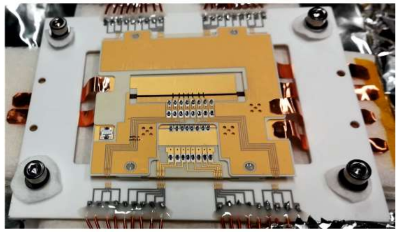




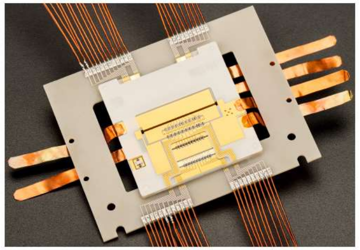
Dolezal *et al.,* Metrologia **(2015),** Keller *et al.,* PRA 99, 1 (**2019**), …

Ion traps built for other labs

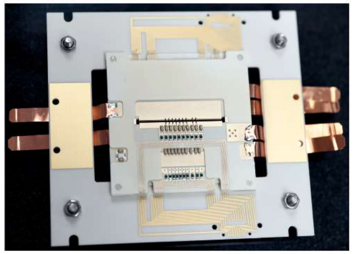
AlN and Rogers chip traps produced by PTB



Trap for the group of **Prof. Kjeld Eikema (FU Amsterdam)**. The trap will be used for He$^+$ 1S-2S spectroscopy to test bound-state quantum electrodynamics and to search for new physics beyond the standard model.



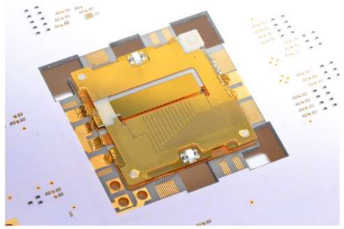
Traps for the group of **Prof. Tanja Mehlstäubler (PTB/LUH)**.
1. A multi-ion clock where In$^+$ sympathetically cooled with Yb$^+$ ions.
2. A multi-ion system with Yb$^+$ ions to study topological defects and many-body physics.



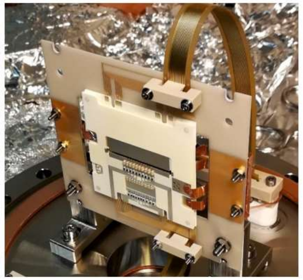
Trap for the group of **Prof. Andreas Schell (LUH)**. The trap will be used for levitation of nanoparticles to investigate if they behave in a classical way or in a quantum mechanical one.

Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

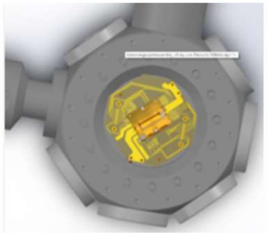
Trap for **Prof. Piet Schmidt (PTB/LUH)**.
It is a Rogers chip trap based on the PTB design for a Al$^+$/Ca$^+$ clock. [4]



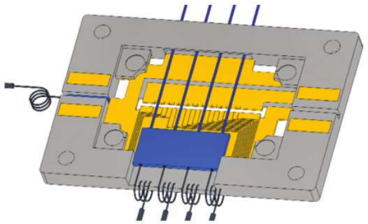
Trap for the Opticlock project, the trap is in the group of **Prof. Christof Wunderlich (Universität Siegen)**. The trap is for a portable multi-ion clock.



Trap for **Dr. Nils Huntemann (PTB)**. The trap is used for a Yb$^+$ ion clock where the ions are sympathetically cooled with Sr$^+$ ions.

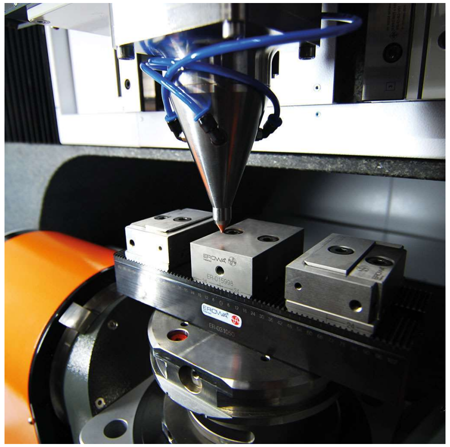


Trap for **Dr. Stephan Hannig (DLR)**. The trap will be used as a portable Al$^+$ clock.

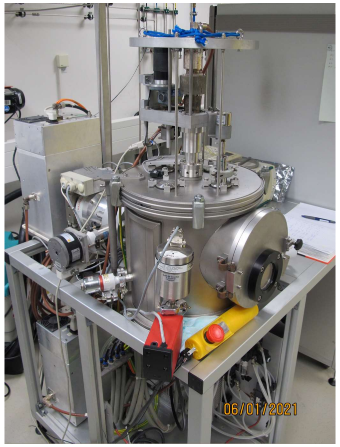


Trap for the IDEAL project, **ongoing development** of a chip trap with integrated micro-optics.

Ion Trap Production at PTB Clean Room

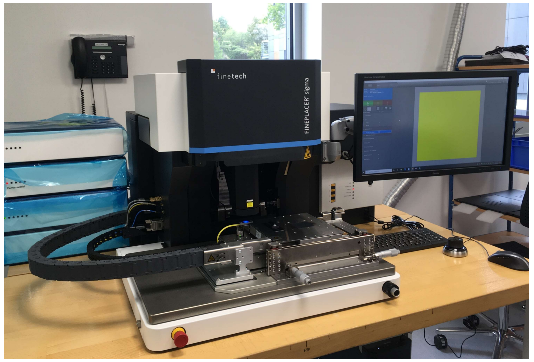


Industrial grade fs-laser
µm precision machining



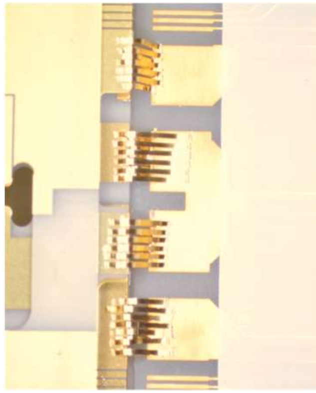
Ti and Au sputtering

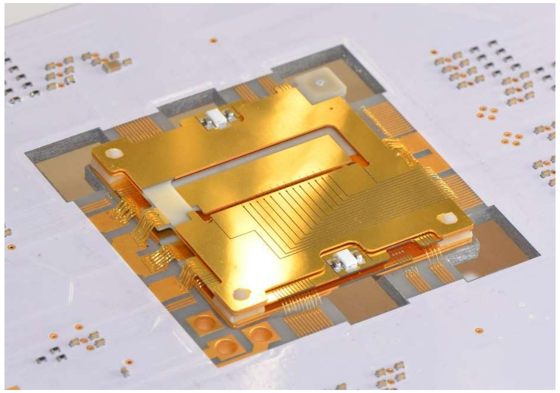
Precision measurement microscope



Fineplacer®, precision < 1 µm

- Flip-Chip-Bonding
- Thermo-Compression
- Ribbon Bonding
- Wire Bonding



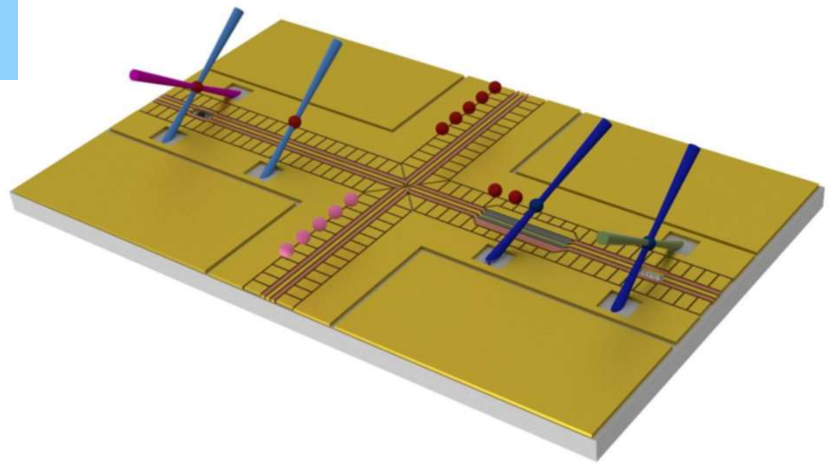


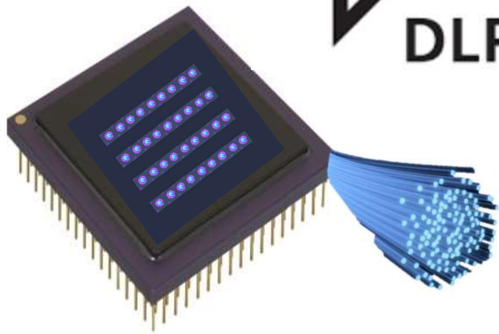
Future → CGPA Size Optically Integrated Ion Traps (incl. detection)

For Quantum Computers and Clocks → for scalability > 50 qubits

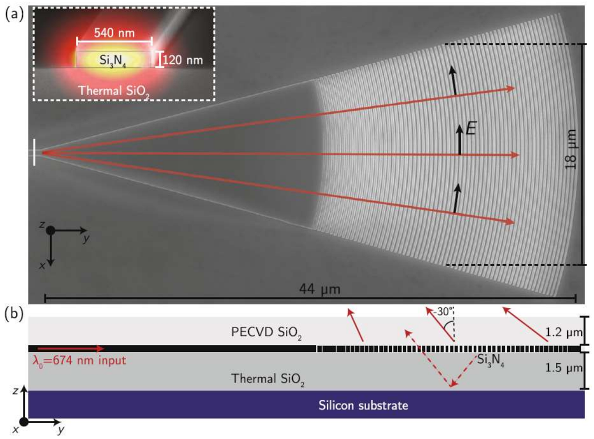
Quantum Valley Lower Saxony

DLR





Integrated Waveguides



K. Mehta et al., **Integrated optical addressing of an ion qubit**, *Nature Nanotechnology* **11** (2016)

K. Mehta et al., **Precise and diffraction-limited waveguide-to-free-space focusing Gratings**, *Scientific Reports* **7** (2017)

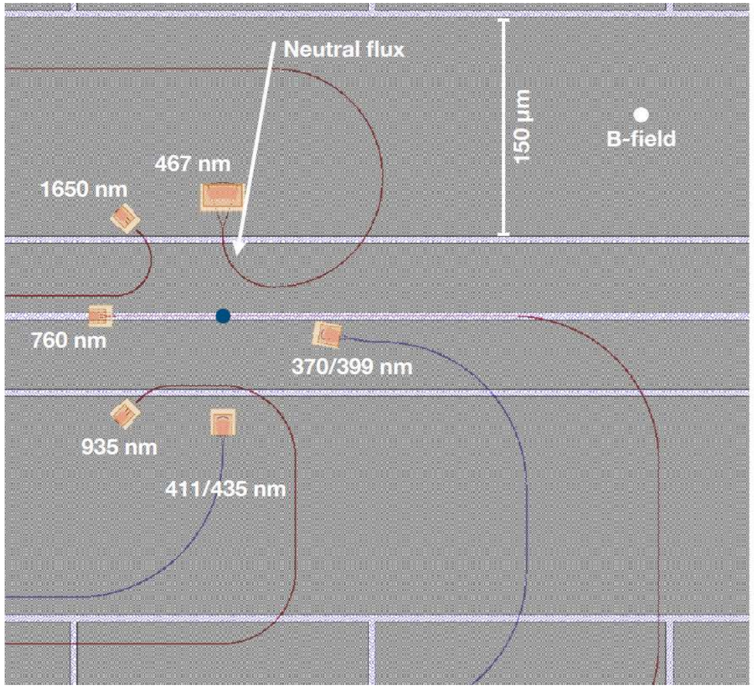
Excellence Cluster „Quantum Frontiers"

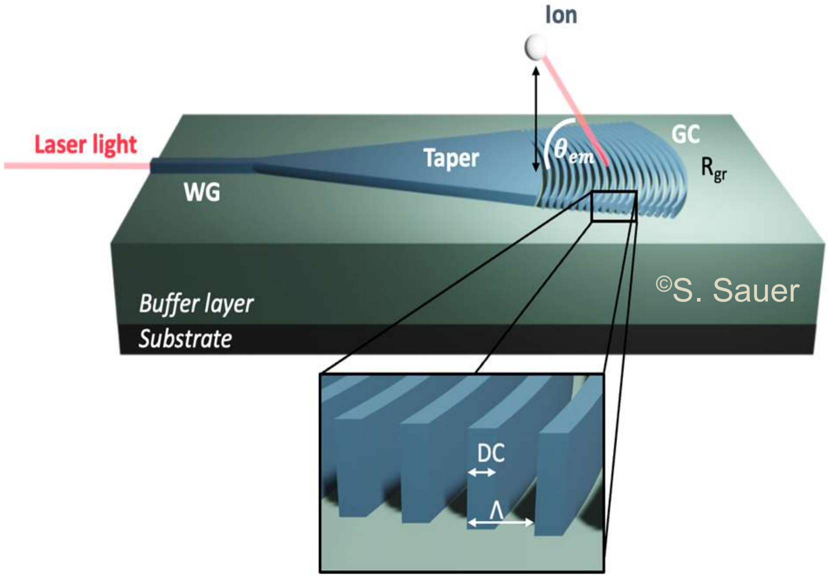
TrapFab

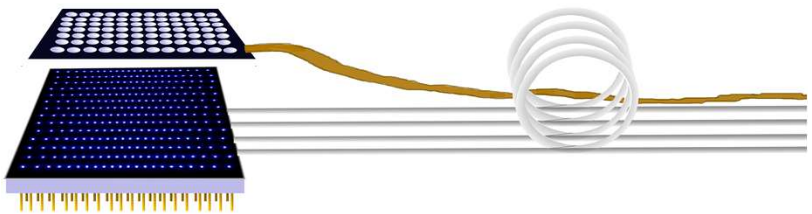
Atomic „Clock on a Chip“

- Collaboration: **Karan Mehta (ETH, now Cornell);** production at **LioniX (NL)**

Design of a waveguide trap for an Yb^+ ion clock

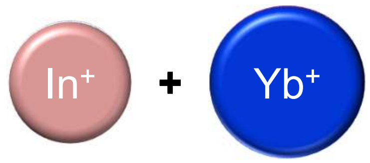






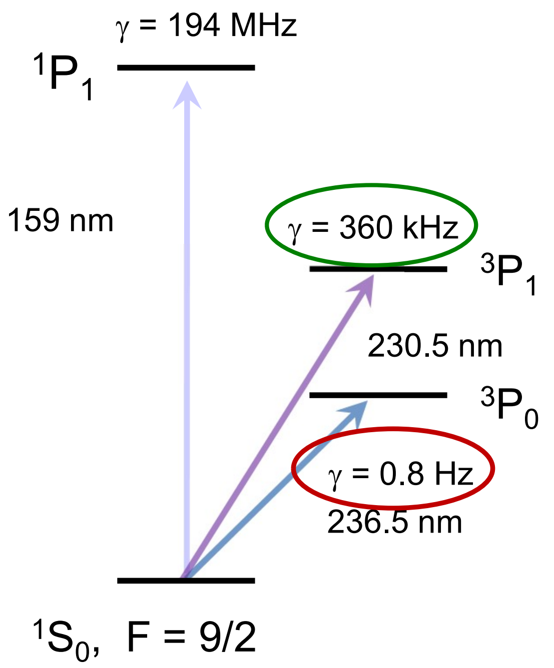
Precision Spectroscopy in Trapped Ions

Our atomic candidates:



$^{115}In^+$ …a first „*simple*“ approach:

- **Large mass**, m=115:
  Time dilation: $\Delta\nu/\nu = -E_{kin}/mc^2 = -\overline{v}^2/2c^2$
- **Low blackbody shift[1]:**
  $\Delta\nu/\nu = (1.36 \pm 0.1)\times10^{-17}$ @ T = 300 K
- **2nd order Zeeman shift:** 4.1 Hz/mT²
  ($^{27}Al^+$: 72 Hz/mT², $^{171}Yb^+$: 52 kHz/mT²)
- **Directly detectable** transition to $^3P_1$!
  direct cooling: T < 100 µK

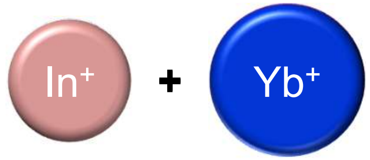


[1] *Safronova et al., Phys. Rev. Lett. 107, 143006 (**2011**)*

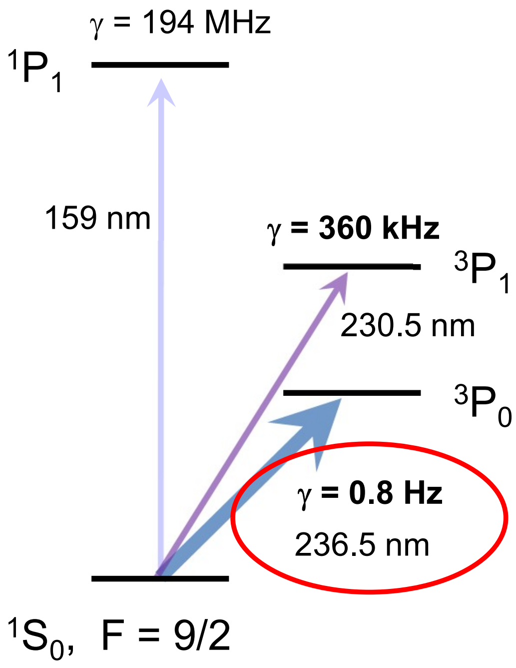
*N. Herschbach et al., Appl. Phys. B 107, 891 (**2012**)*

Our atomic candidates:

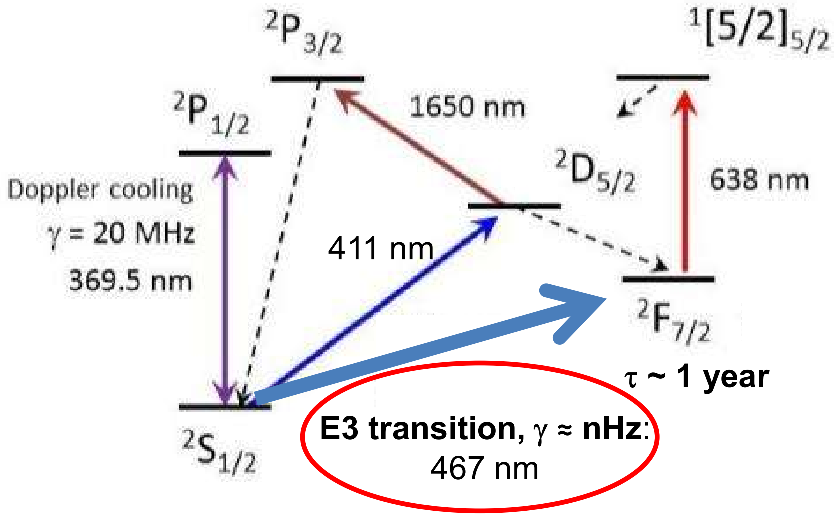
- **Sympathetic cooling of In⁺ via Yb⁺ ions**
- **Spatially resolved detection with ROIs on CCD**



$^{115}In^{+}$ …1st order free of quadrupole shift



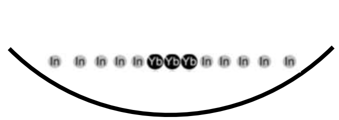
$^{172}Yb^{+}$ …low quadrupole shift



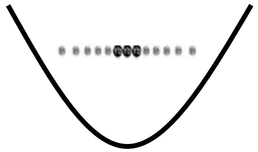
2019: Measurement based multi-ion uncertainty budget

A) Direct cooling

Confinement A



Confinement B



B) Sympathetic cooling

Effect	Max shift $\Delta\nu/\nu_0$	$\mathrm{u}(\Delta\nu/\nu_0)$	Max shift $\Delta\nu/\nu_0$	$\mathrm{u}(\Delta\nu/\nu_0)$
Time dilation (thermal)	-2	0.4	-19	4
Heating (per second)	-3.1	0.2	-0.6	0.02
Time dilation (EMM)	-1.8	0.8	-1.3	0.6
AC Stark (thermal MM)	-0.003		-0.03	
AC Stark (EMM)	-0.2	0.1	-0.2	0.1
El. quadrupole shift	-0.02	<0.01	-1.1	0.02
BBR at 300 K temperature uncertainty	-137	0.15	-137	0.54
Total	-141.3	0.9	-158.7	4.1

Units: 10^{-19}

Keller et al., "**Controlling systematic frequency uncertainties at the 10^{-19} level in linear Coulomb crystals**", PRA 99, 1 **(2019)**

First Step: Development of Scalable Chip Ion Traps

…since dominant uncertainties of optical ion clocks are trap related

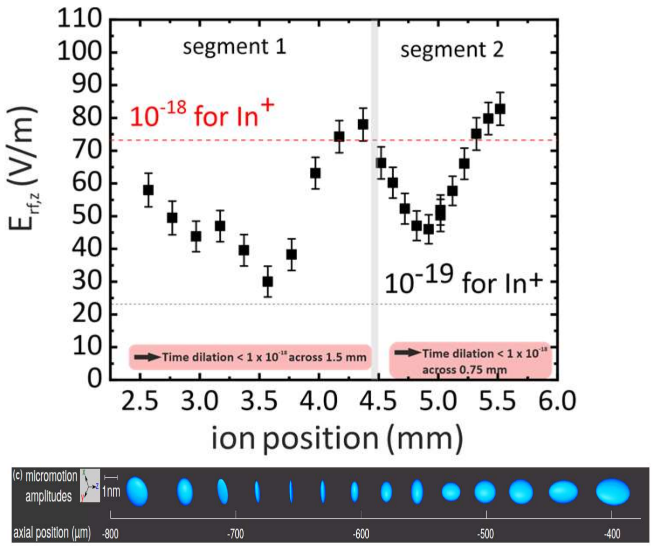
1) **Very low trap warming**

→ trap-related BBR shift uncertainty $<10^{-18}$

Nordmann et al., *Rev. Sci. Instrum.* **99**, 11301 (2020)
Dolezal et al., *Metrologia*, **52**, 842-856 (2014);

2) **Low axial excess micromotion** across all trapping regions

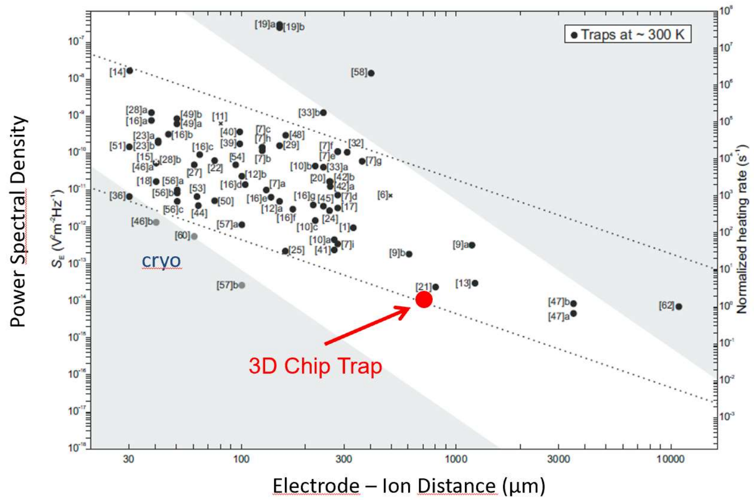
→ time dilation shifts $<10^{-18}$



"Probing Time Dilation in Coulomb Crystals in a high-precision Ion Trap",
Keller et al., *Phys. Rev. Appl.* 11, 011002 (2019)

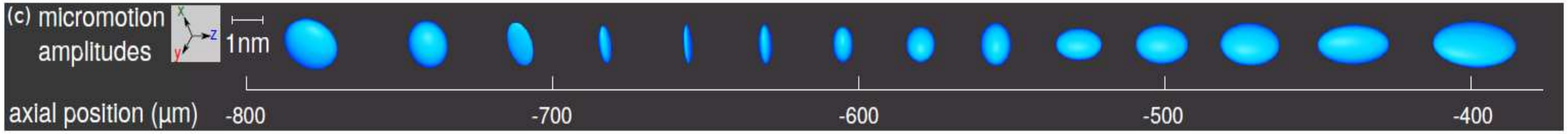
3) **Low heating rate** of <0.5 phonons/s at 1MHz

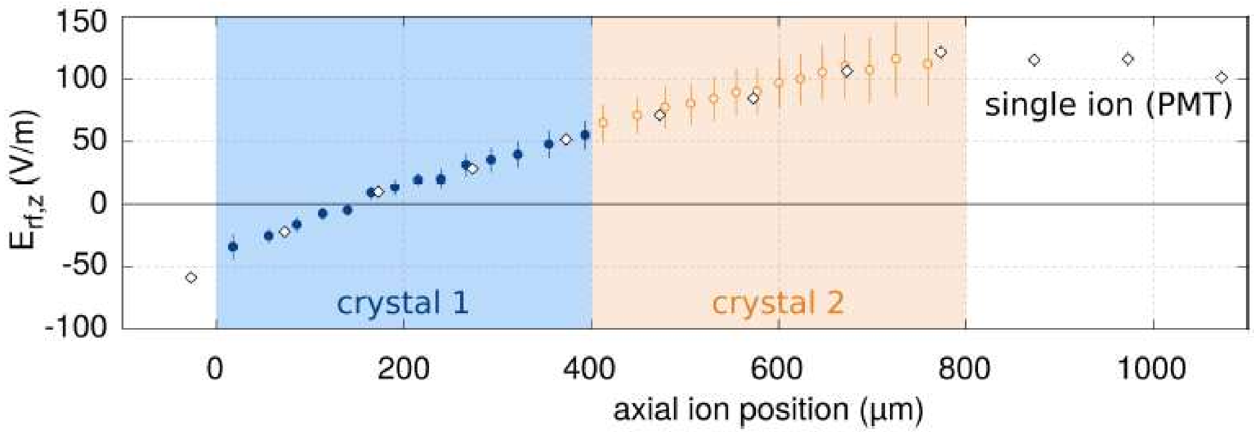
Comparison to international ensemble of ion traps:



Kalincev et al., *Quantum Sci. Technol.* 6, 034003 (2021)
Brownnutt et al., *Rev. Mod. Phys.* 87, 1419 (2015)

Atomically resolved micromotion of individual ions

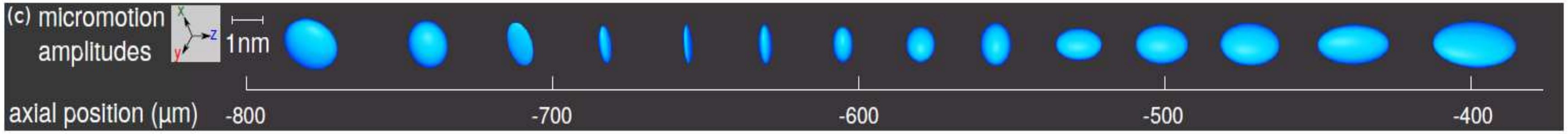


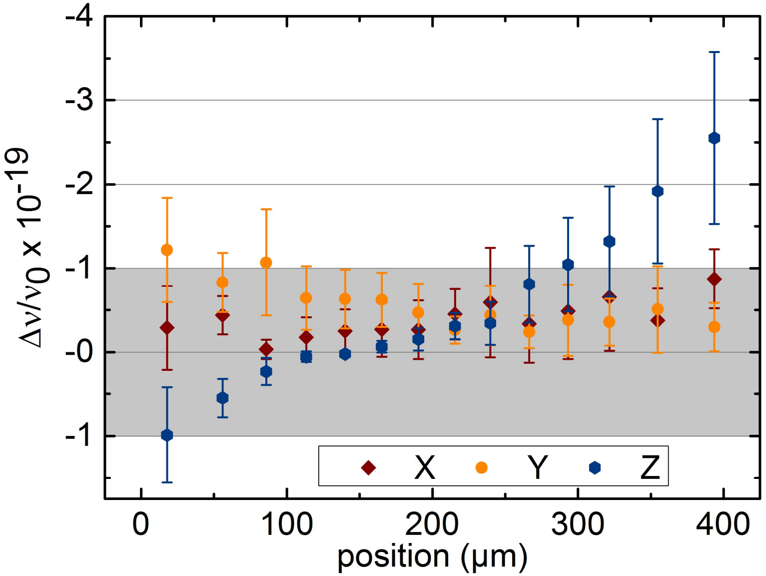


Crystal aligns at RF nodal axis; agrees with single ion probe

“Probing Time Dilation in Coulomb Crystals in a high-precision Ion Trap”, *Keller et al., Phys. Rev. Appl.* 11, 011002 (**2019**)

Atomically resolved micromotion of individual ions

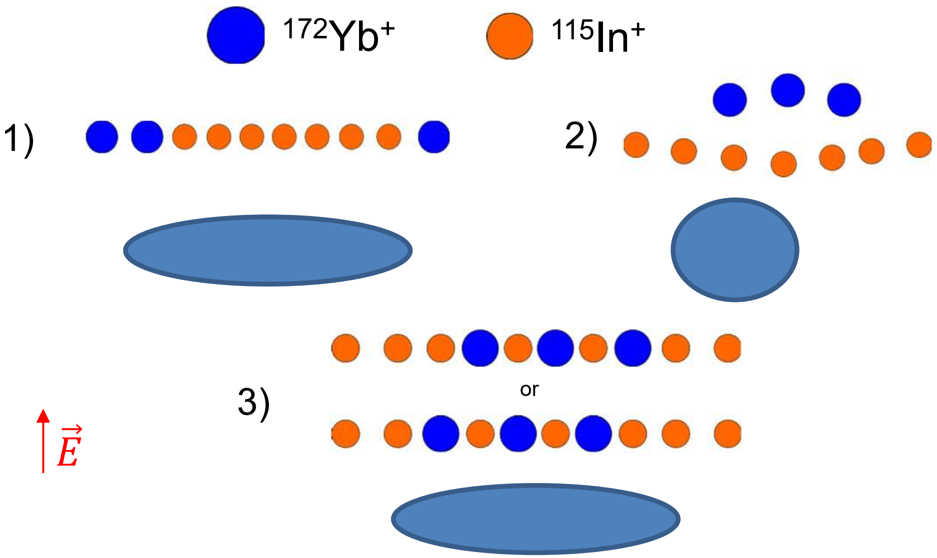


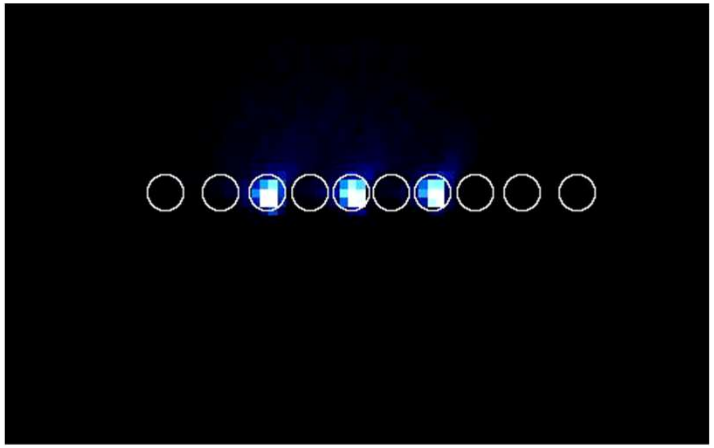


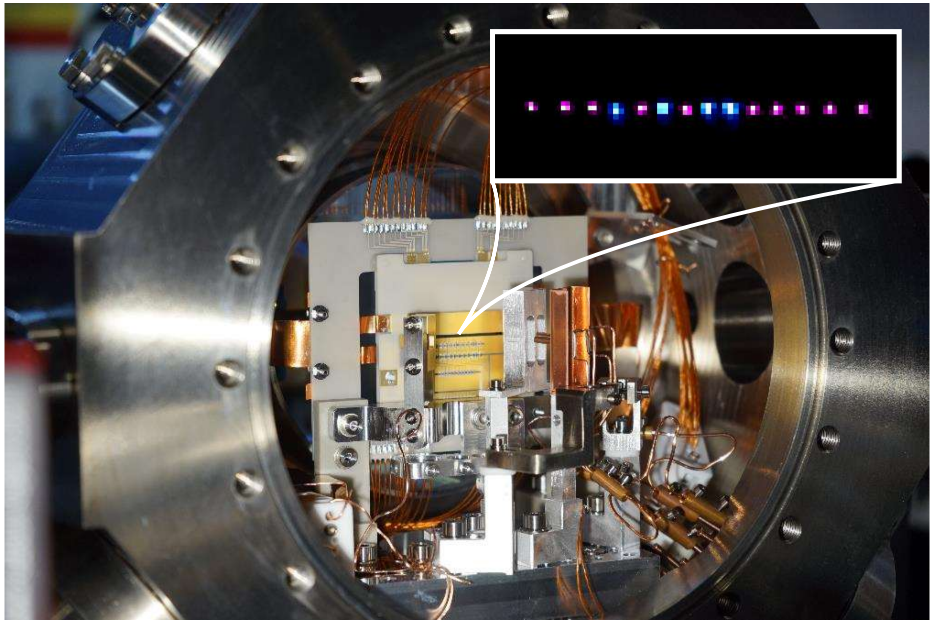
Time dilation shift due to rf motion : $|\Delta\nu/\nu|_{D2}$ **< 1 × 10^{-19} over 300 µm**

"Probing Time Dilation in Coulomb Crystals in a high-precision Ion Trap", *Keller et al., Phys. Rev. Appl.* 11, 011002 (**2019**)

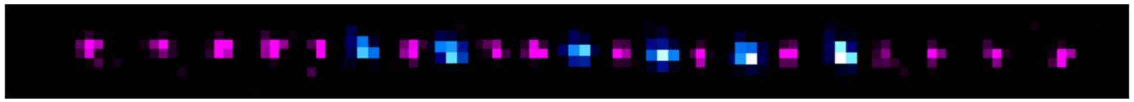
For optimal cooling: Automatized sorting of In^+/Yb^+ crystals



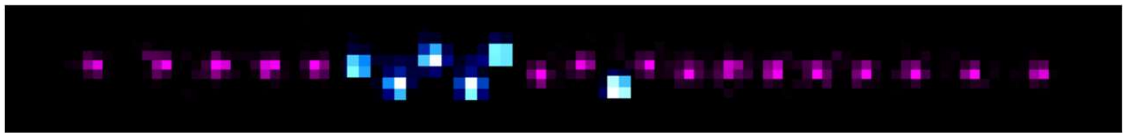




6 Yb^+ and 15 In^+



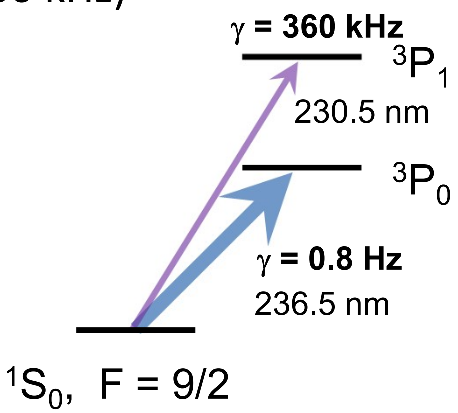
6 Yb^+ and 16 In^+



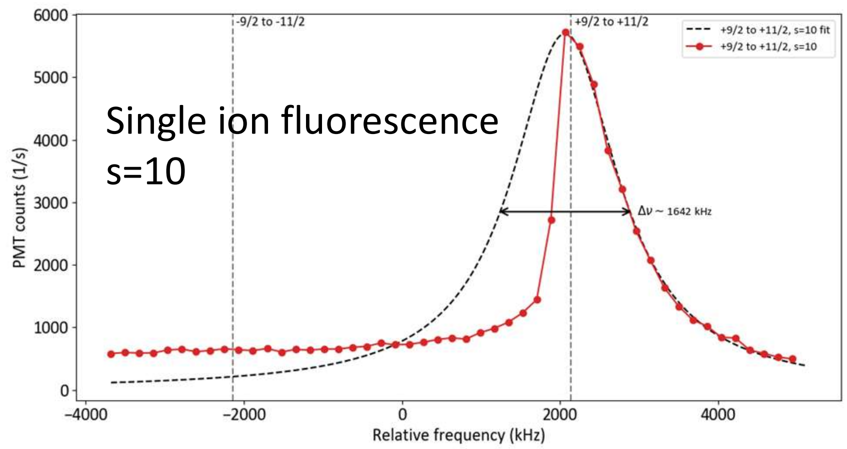
Clock scheme of $^{115}In^{+}$ / $^{172}Yb^{+}$ clock

Direct fluorescence of In^{+} (γ = 360 kHz)

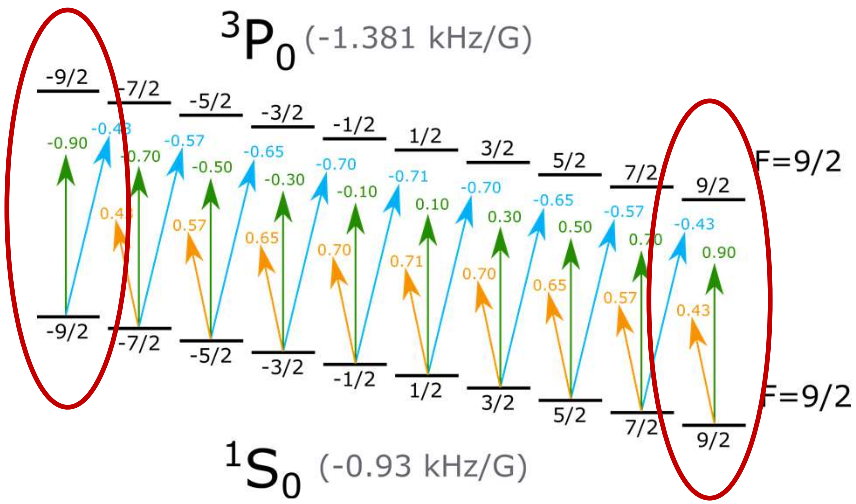
→ detection + cooling



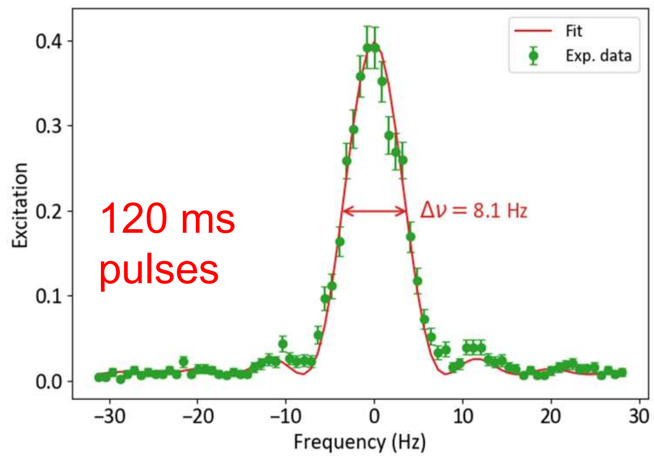
In⁺ detection at 230 nm while sympathetically cooling on Yb⁺



2021:
First scans of clock transition



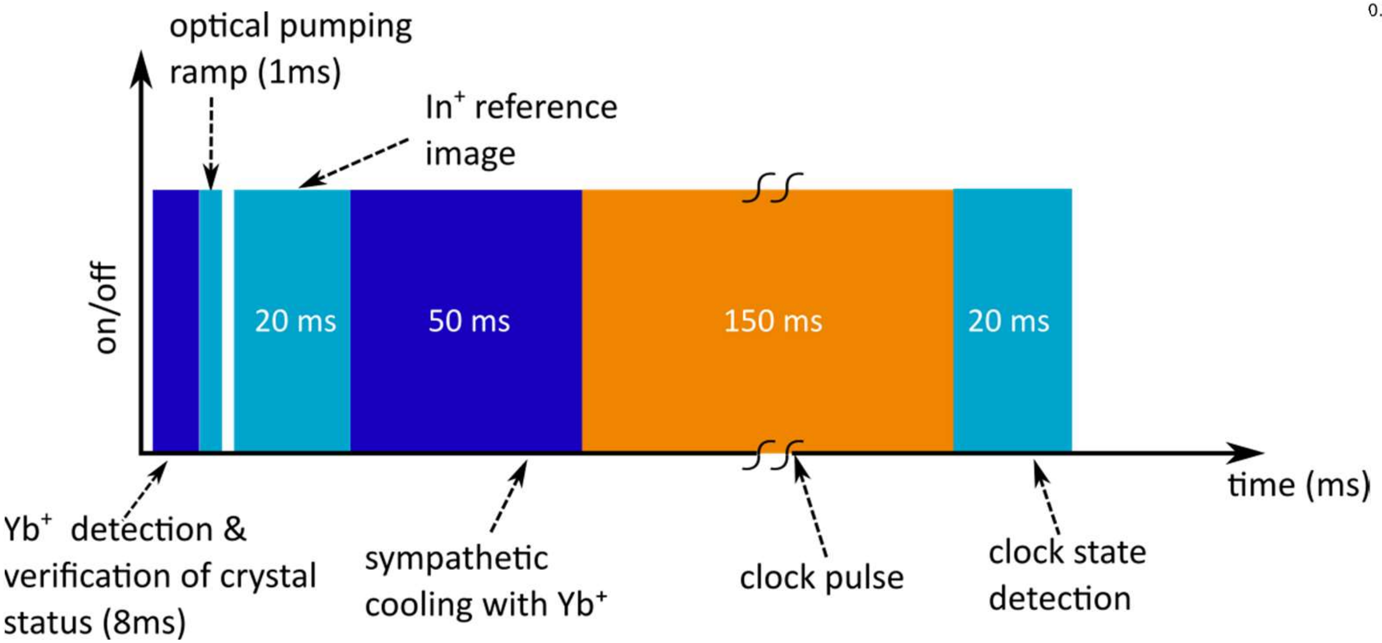
Signal of In⁺ clock transition at 236 nm

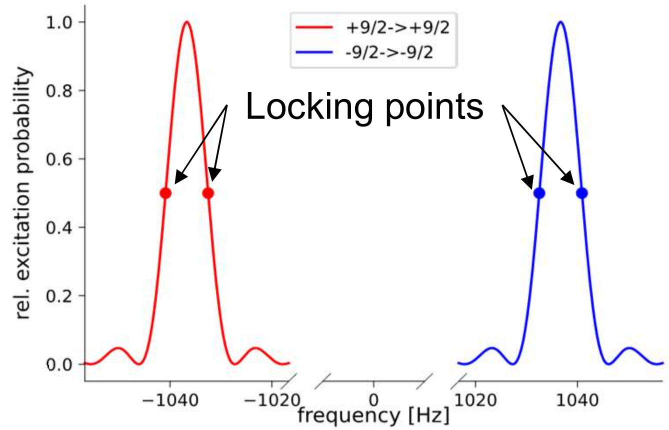


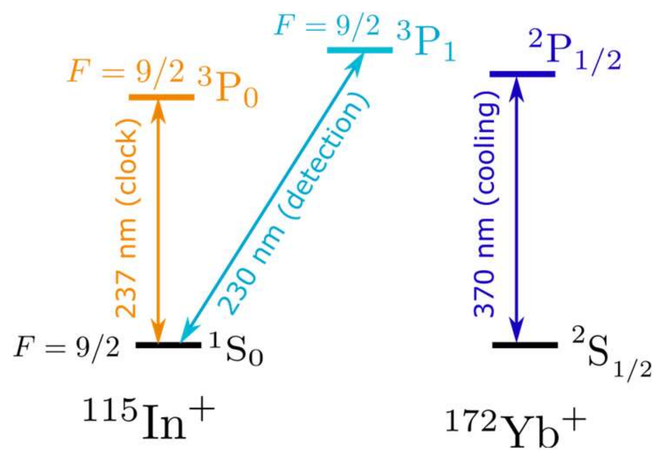
Clock scheme of $^{115}In^{+}$ / $^{172}Yb^{+}$ clock

Probing on -9/2 → -9/2 and +9/2 → +9/2 during one clock cycle to cancel 1st order Zeeman shift

10 x per locking point:

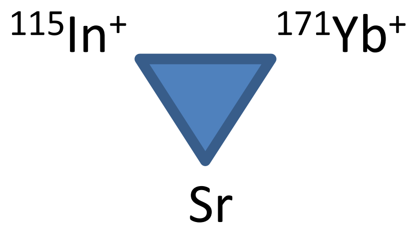






Frequency Ratio Measurement $^{115}In^{+}$ - Sr - $^{171}Yb^{+}$

→ EMPIR project „ROCIT“



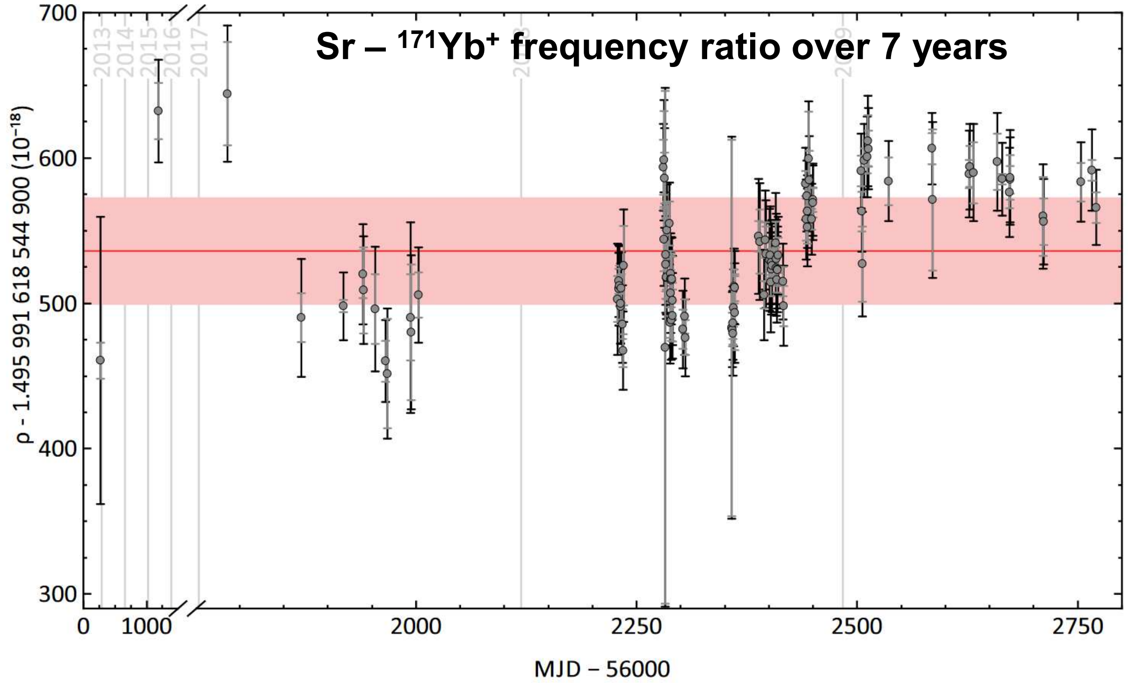
Three corner hat comparison: **Frequency ratio In^{+} -Sr- $^{171}Yb^{+}$**

→ Sr - $^{171}Yb^{+}$ mit u = 2.5 x 10^{-17}

Long-term variation f(Sr)/f(Yb^{+}) is larger than expected from individual uncertainties

Dörscher *et al., Metrologia* **58** 015005 (**2021**)

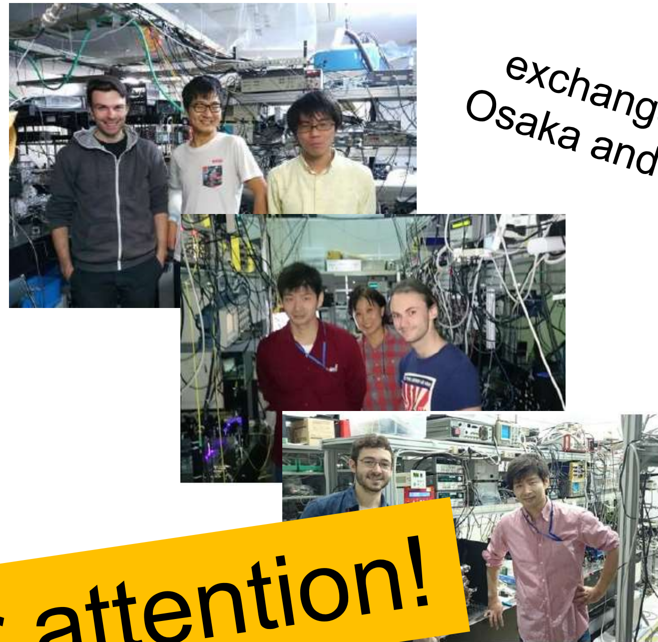
The importance of frequency ratio measurements!



Following results are preliminary!

…not published yet

The Team "Quantum Clocks and Complex Systems"



exchange with Osaka and Tokyo

Thank you for your attention!

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Naneo (Lindau)
D&G (Stuttgart)
Toptica (München)
Vacom (Jena)
Infineon (Munich)
…

TRIAC
International Joint Laboratory for
Trapped-Ion Integrated Atomic-Photonic Circuits

DFG
EURAMET European Association of National Metrology Institutes
TC FS
Bundesministerium für Bildung und Forschung
mat
DLR