Dissipative time crystals in an atom-cavity system

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Jayson G. Cosme[3] , Hans Keßler[1] and Andreas Hemmerich[1,2]

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SPICE Young Research Leaders Group Workshop:
Recent advances in non-equilibrium and magnetic phenomena

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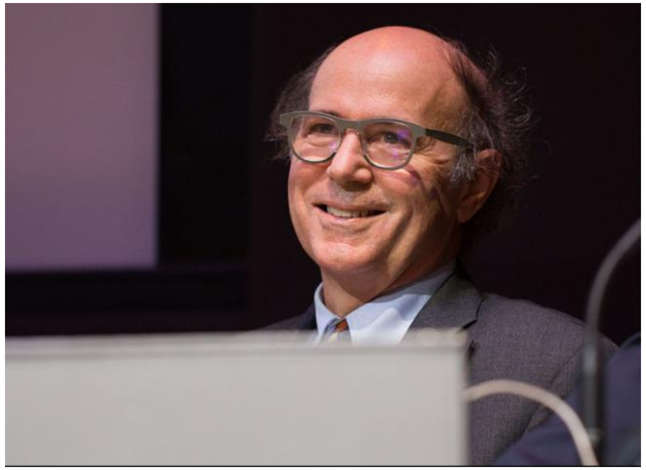
What is a time crystal?

Time crystal: the original idea



Frank Wilczek’s idea in 2012
Nobel prize: Physics 2004

2 Research
- 2.1 Asymptotic freedom
- 2.2 Axions
- 2.3 Anyons
- 2.4 Time crystals
- 2.5 Current research

“..Are there systems in nature that **spontaneously** break **time translational symmetry** in its ground state..”

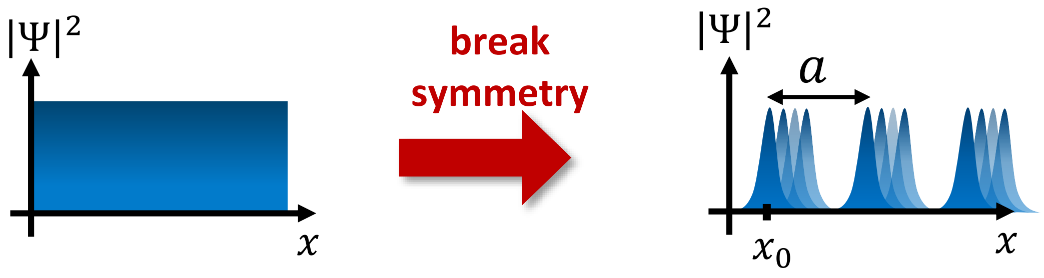
→ analogous to a solid-state crystal (space crystals)

F. Wilczek, *Quantum Time Crystals,* **PRL** 109, 160401 (2012)

A. Shapere and F. Wilczek, *Classical time crystals,* **PRL** 109, 160402 (2012)

"space" crystal

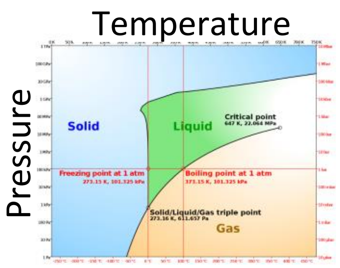
- **Intrinsic lattice constant →** spontaneously break **(spatial)** translational symmetry



liquid

solid

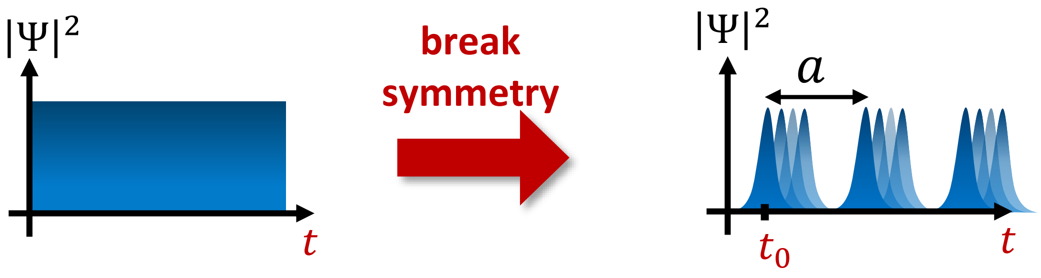
- **Phase diagram span by relevant parameters**



- **Robustness against parameter changes**

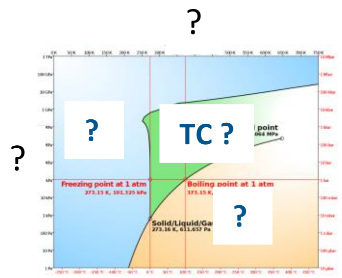
"time" crystal

- **Intrinsic lattice constant →** spontaneously break **(time)** translational symmetry



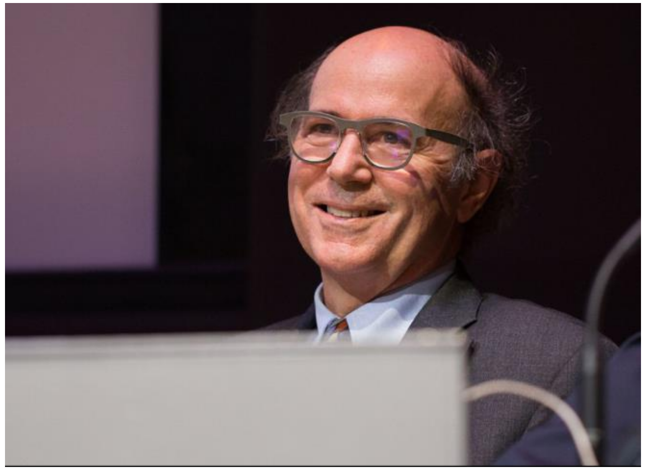
time crystal

- **Phase diagram span by relevant parameters**



- **Robustness against parameter changes**

Time crystal: the original idea



Frank Wilczek's idea in 2012
Nobel prize: Physics 2004

"..Are there systems in nature that **spontaneously** break **time translational symmetry** in its ground state.."

→ analogous to a solid-state crystal (space crystals)

01 (2012)

160402 (2012)

Impossibility of Spontaneously Rotating Time Crystals: A No-Go Theorem

Patrick Bruno*
European Synchrotron Radiation Facility, BP 220, F-38043 Grenoble Cedex 9, France

(Received 26 June 2013; published 14 August 2013)

Absence of Quantum Time Crystals

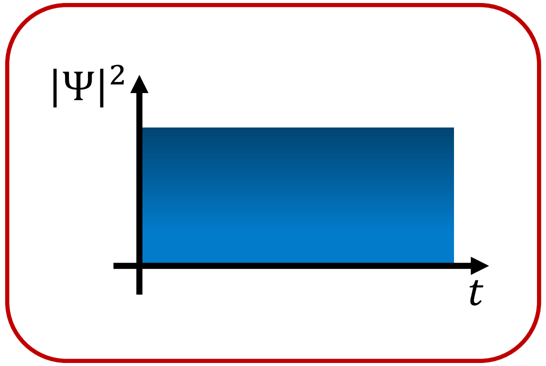
Haruki Watanabe[1,*] and Masaki Oshikawa[2,†]
[1]*Department of Physics, University of California, Berkeley, California 94720, USA*
[2]*Institute for Solid State Physics, University of Tokyo, Kashiwa 277-8581, Japan*

(Received 28 March 2015; published 24 June 2015)

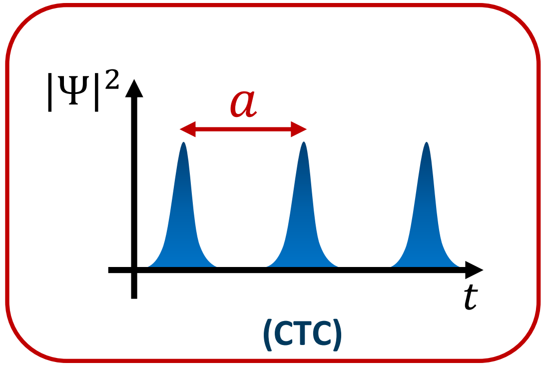
A quest to find time crystals

- **Original proposal**
  - Continuous time crystal (CTC)
  - in equilibrium & closed system

Theory: F. Wilczek 2012
→ **No go theorem**

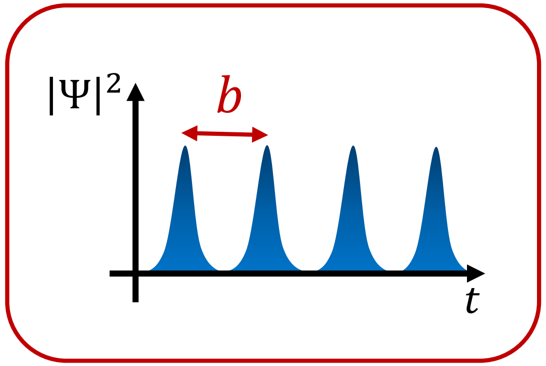


break cont. translational symmetry

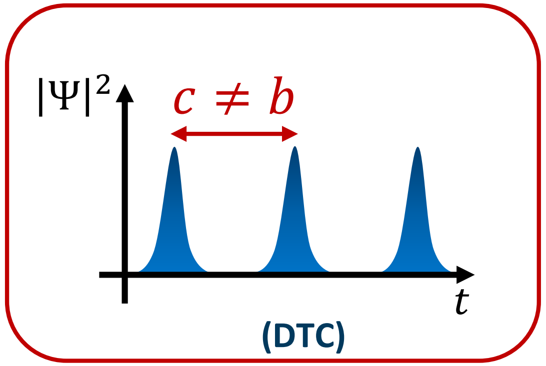


- **Discrete time crystal (DTC)**
  - *Driven* closed system
  - break *discrete* symmetry

Theory: V. Khemani et al., *PRL.*116, 250401 (2016).
D. V. Else et al., *PRL* 117, 090402 (2016).



break discrete translational symmetry



A quest to find time crystals

- **Discrete time crystal (DTC)**
  - *AC driven* closed system
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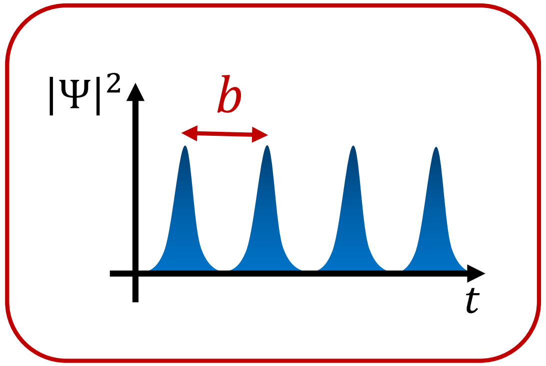
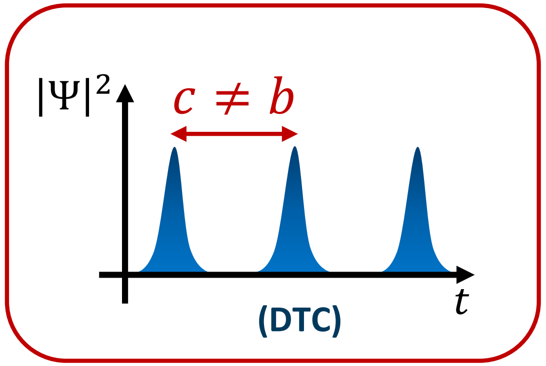
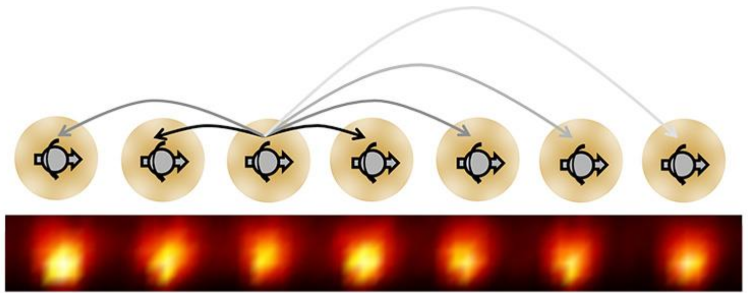


break discrete translational symmetry

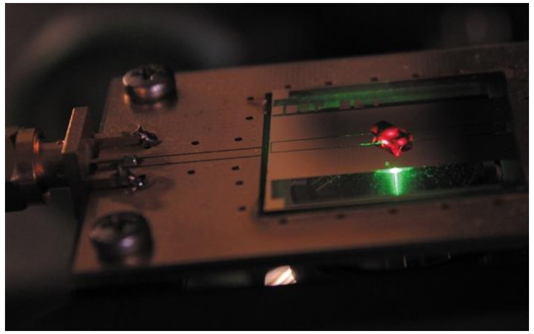


- First realization in 2017

Maryland: Zhang, Z. et al. Nature 543, 217–220 (2017).
Harvard: Choi, S. et al. Nature 543, 221–225 (2017).
Utrecht: J. Smits et al. PRL 121, 185301 (2018).
…



Monroe group, Maryland
Array of trapped ions



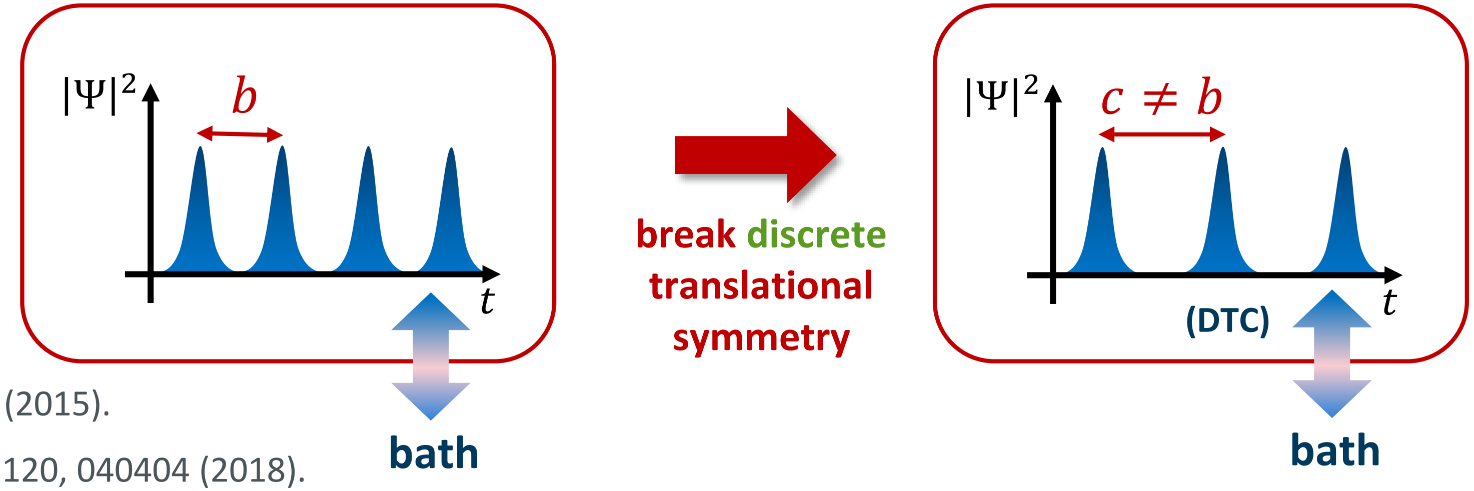
Lukin group, Harvard
NV centers in diamond

- It is challenging to prevent a *melting* of TC due to heating, …

A good dissipation channel can help!

A quest to find time crystals

- **Dissipative discrete time crystal (DTC)**
  - *AC driven opened* system
  - break discrete symmetry
  - well-controlled dissipation channel helps to stabilize DTC



Theory: R. Chitra and O. Zilberberg, Phys. Rev. A 92, 023815 (2015).

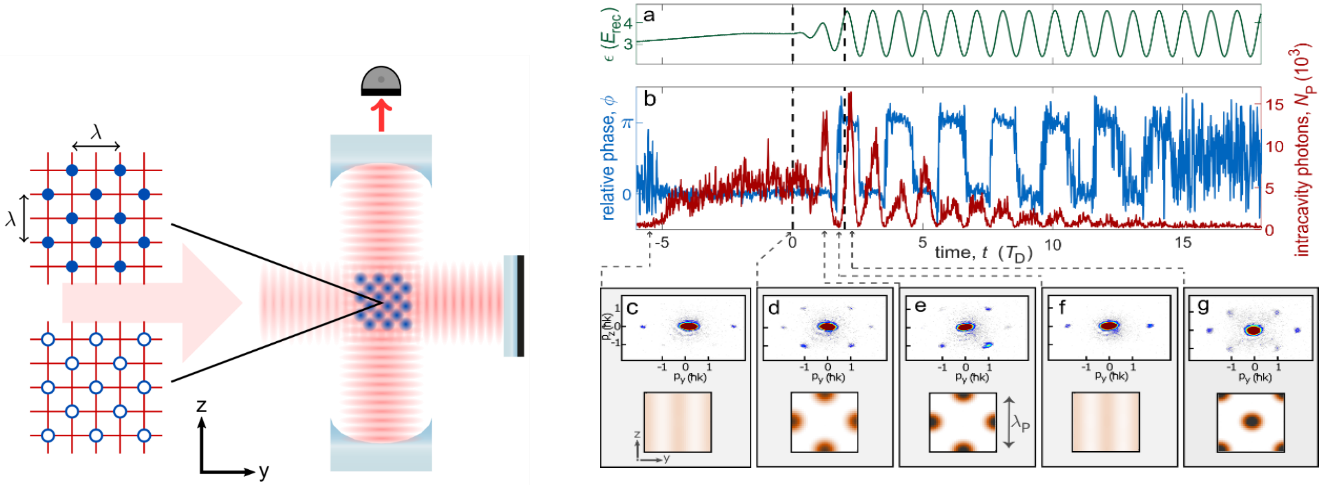
Z. Gong, R. Hamazaki, and M. Ueda, Phys. Rev. Lett. 120, 040404 (2018).

- First realization in 2021

Hamburg: H. Keßler et al., PRL 127, 043602 (2021)

P. Kongkhambut et al., PRL 127, 253601 (2021)

CA, USA: H. Taheri *et al.*, *Nat Commun* 13, 848 (2022).



Hemmerich group, Hamburg

^{87}Rb BEC-cavity system

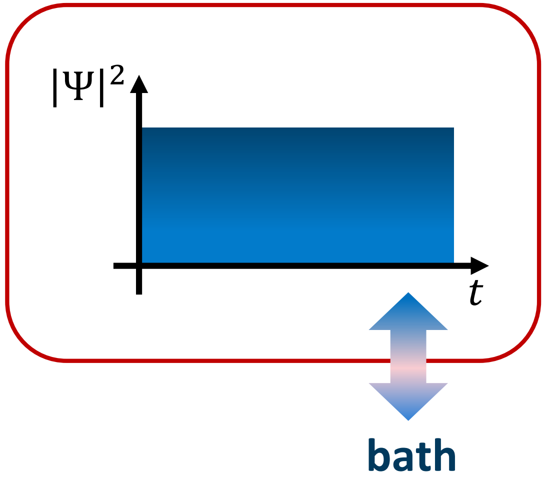
A quest to find time crystals

- **Dissipative continuous time crystal (CTC)**
  - *DC driven opened* system
  - break continuous symmetry

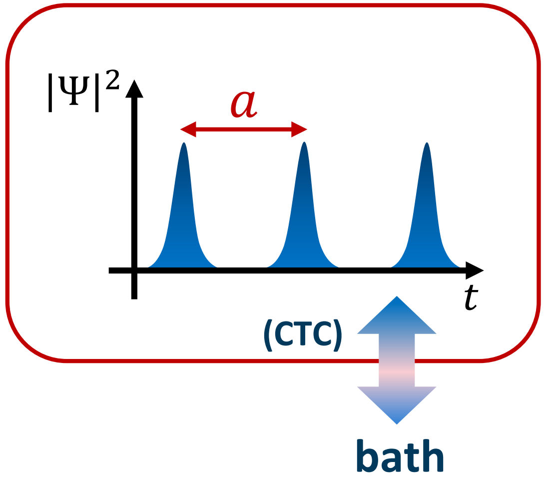
Theory: F. Piazza et al., PRL 115, 163601 (2015)
F. Iemini er al., PRL 121, 035301 (2018)
H. Keßler et al., PRA 99, 053605 (2019)
H. Keßler et al., NJP 22, 085002 (2020)

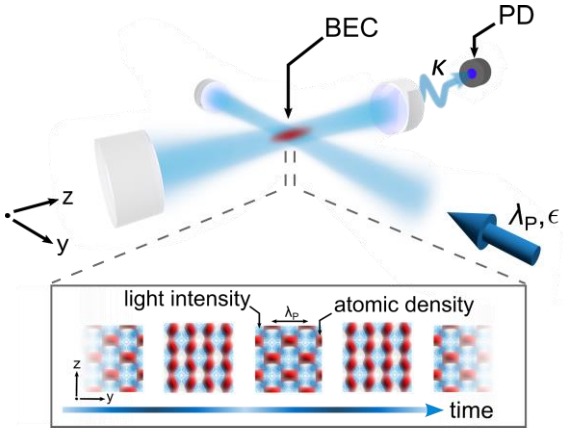
- First CTC observed!

Hamburg: P. Kongkhambut et al., Science 377, 670 (2022)



break cont. translational symmetry





Hemmerich group, Hamburg
^{87}Rb BEC-cavity system

This talk!

The experimental system

Our experiment: Atom-cavity system

Cavity:

Field decay rate: $\kappa \equiv \frac{1}{2\tau} \approx 2\pi \cdot 3.4\, kHz$

Finesse: $F \approx 425\,000$

Purcell factor: $\eta \equiv \frac{24}{\pi \omega_0^2 k^2} F \approx 44$

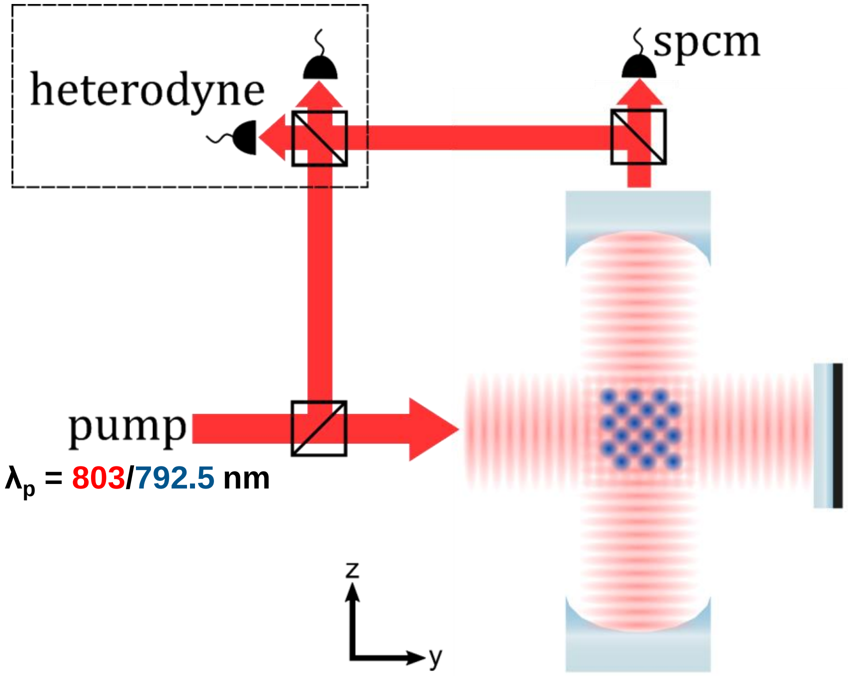
^{87}Rb BEC:

Recoil frequency: $\omega_{rec} \approx 2\pi \cdot 3.7\ \mathrm{kHz}$

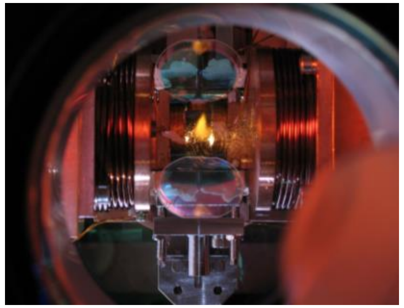
$N \approx 5 \cdot 10^4$

Cigared shape: $(120 \times 102 \times 25)\ \mathrm{Hz}$

Characteristics: Cavity field dynamics ~ atomic dynamics



Experimental Setup and detection schemes



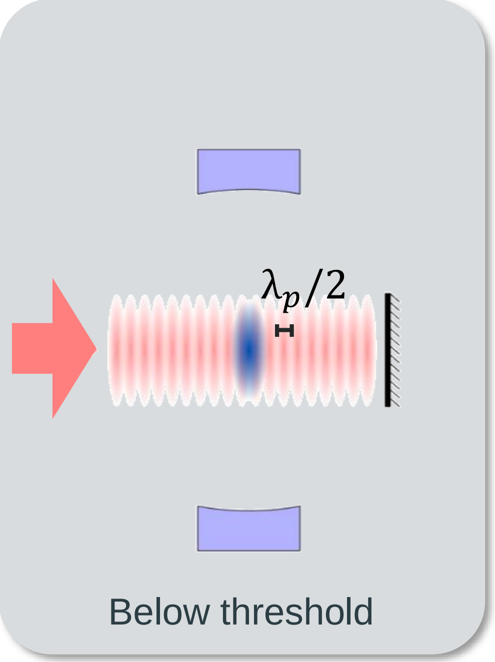
^{87}Rb transition:

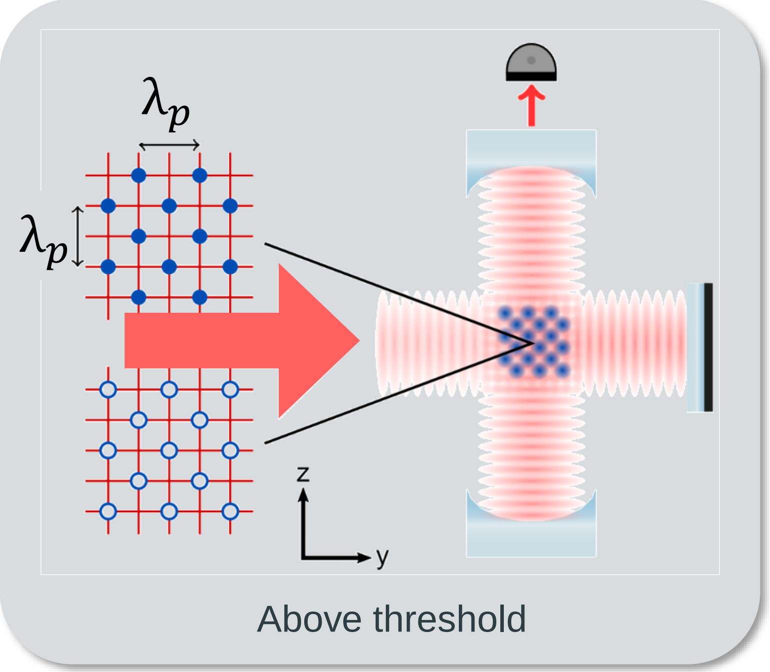
5S1/2 → 5P1/2 (794.97nm)

Red-detuned pump: 803nm

Blue-detuned pump: 792.5nm

Our experiment: Self-organization





J. Klinder, et. al., PNAS ***112****, 11 (2015)*

Normal phase (BEC) → **Self-organized/ Density wave phase (DW)**

Theory: Ritsch, Domokos, Chitra, Lode, ...
Exp: Vuletic, Esslinger
Observed for the first time: Vuletic (Thermal atoms), Esslinger (BEC)

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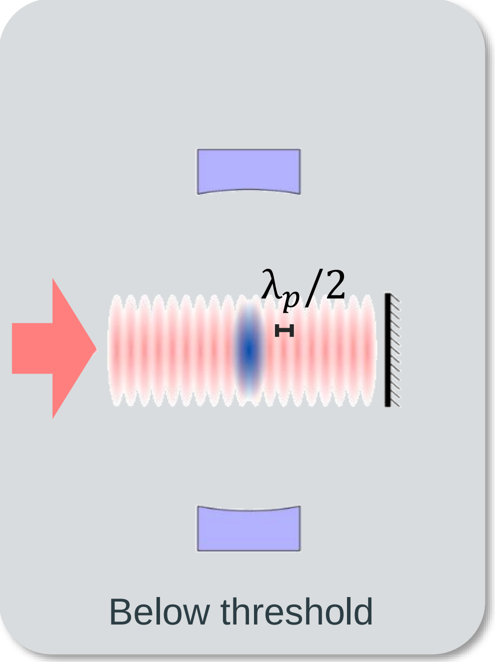
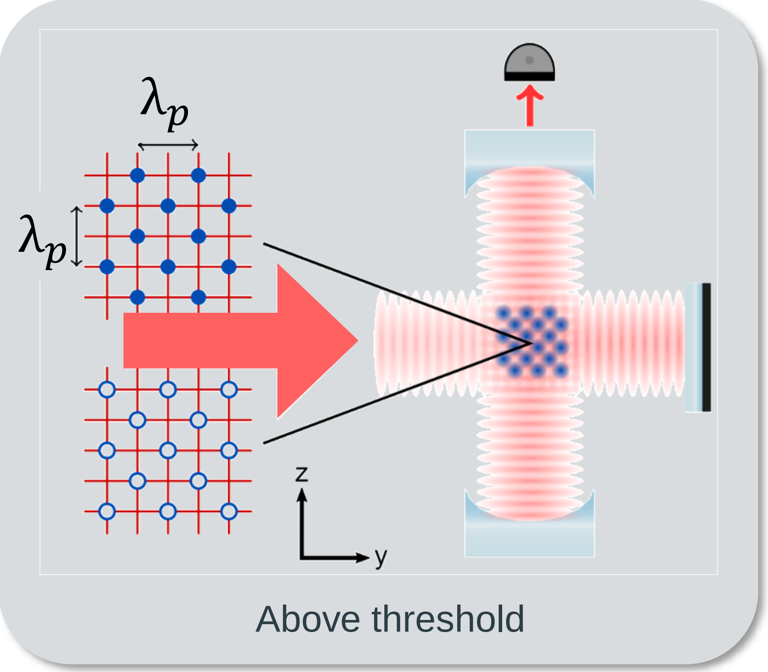
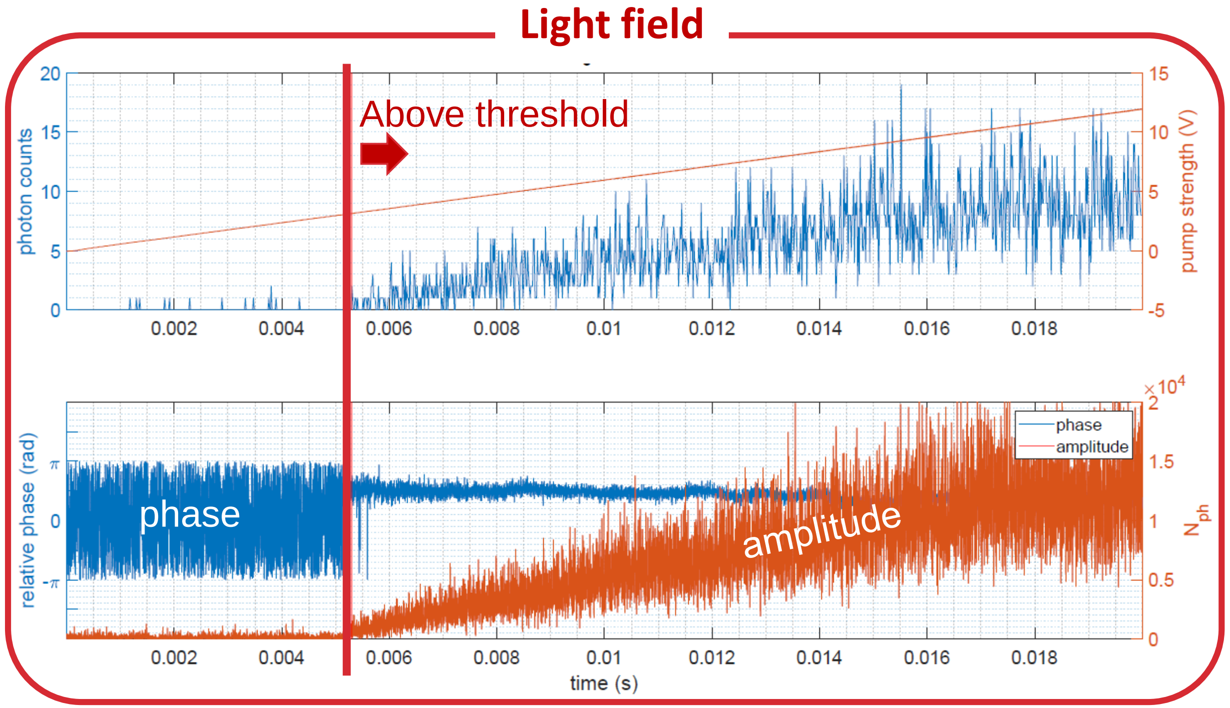




J. Klinder, et. al., PNAS ***112****, 11 (2015)*



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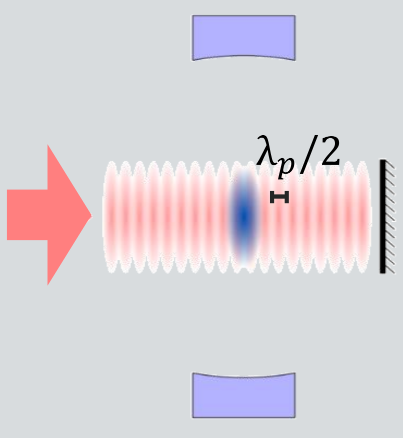
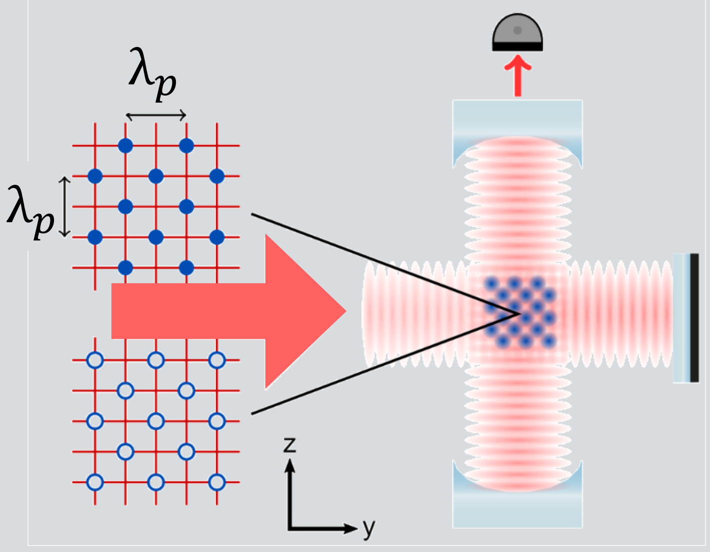
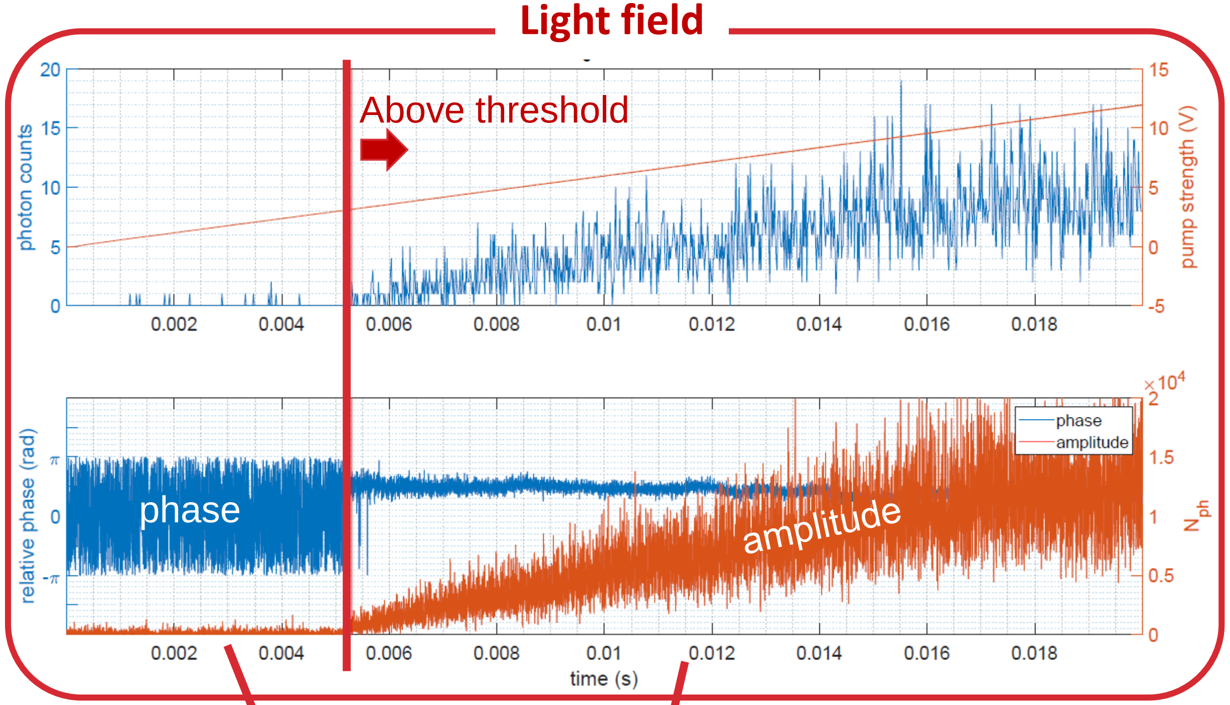


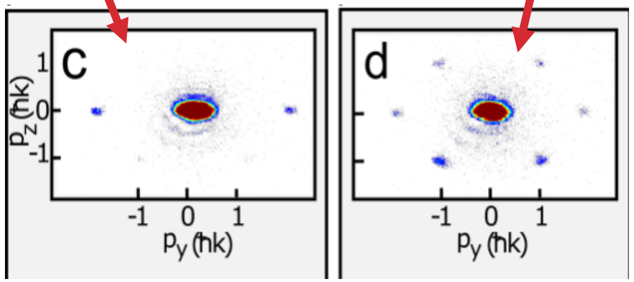
Below threshold



Above threshold

J. Klinder, et. al., PNAS ***112****, 11 (2015)*





after 25ms

TOF imaging

→ Momentum spectra

Normal phase (BEC) → **Self-organized/ Density wave phase (DW)**

Theory: Ritsch, Domokos, Chitra, Lode, ...

Exp: Vuletic, Esslinger

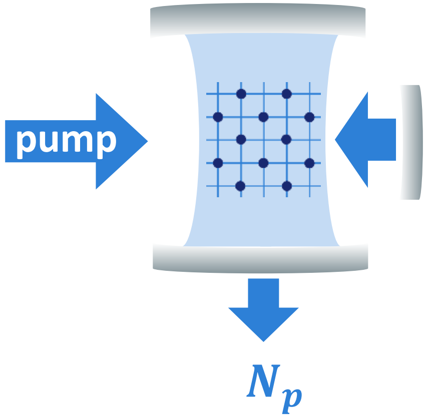
Observed for the first time: Vuletic (Thermal atoms), Esslinger (BEC)

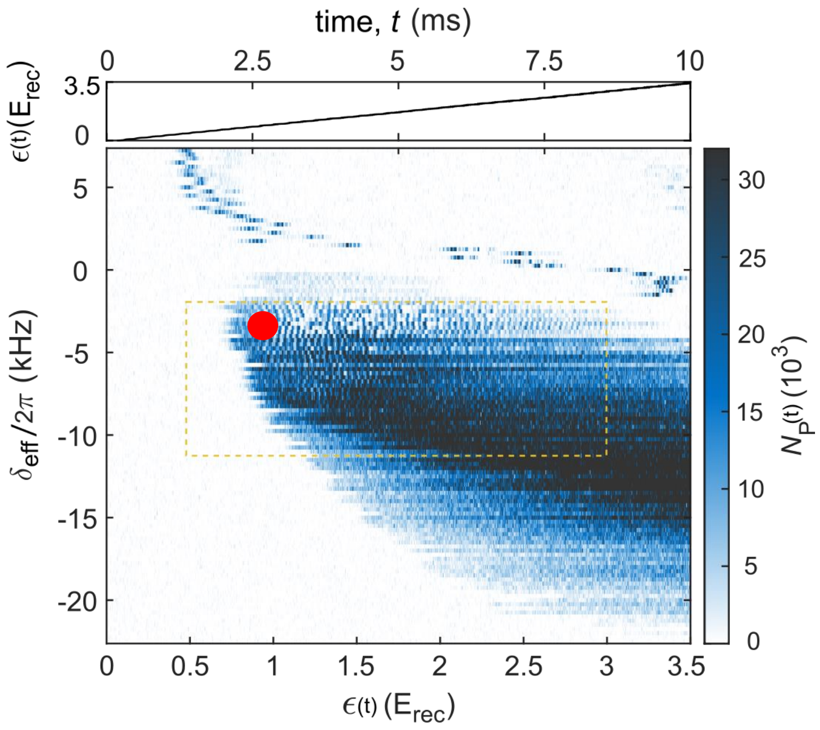
How can we realize a TC?

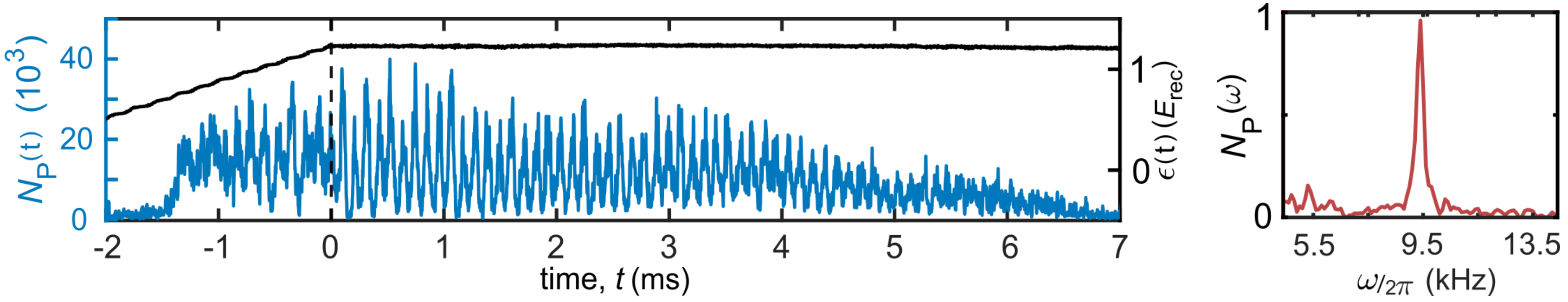
Observation of a CTC

P. Kongkhambut et al., Science 377, 670 (2022)

- Pump with 792.5nm light: blue pump-atom detuning
- Single frequency response of N_p



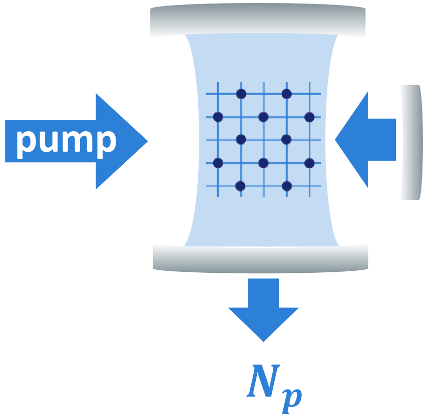


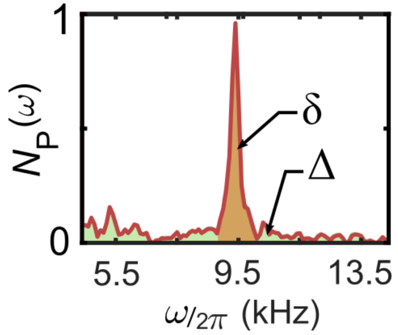


Observation of a CTC

P. Kongkhambut et al., Science 377, 670 (2022)

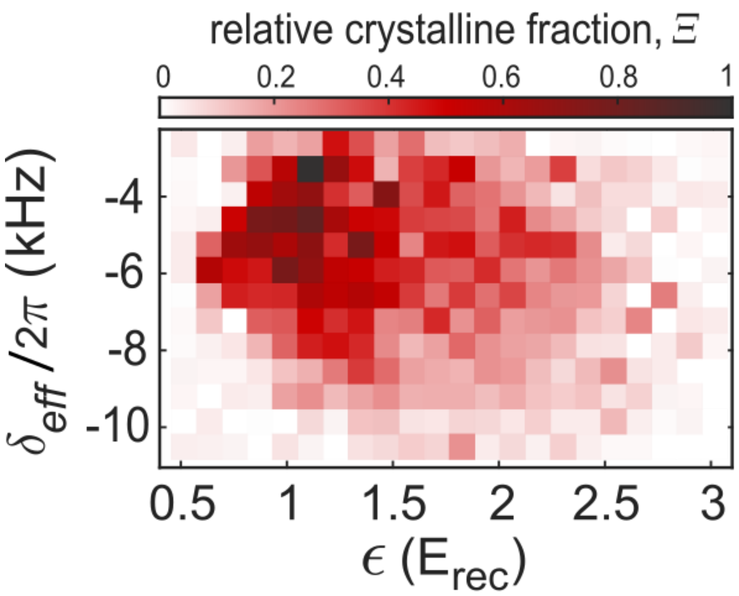
- Pump with 792.5nm light: blue pump-atom detuning
- Single frequency response of N_p
- Quantify with *relative crystalline fraction* Ξ

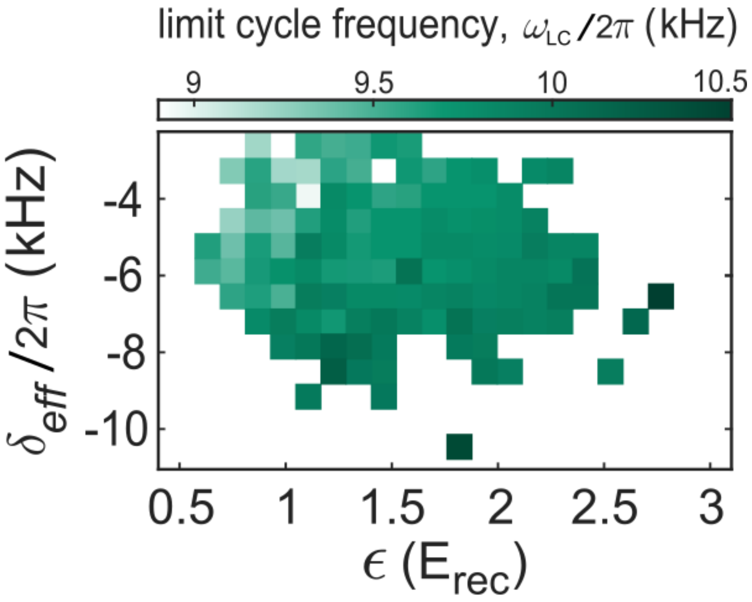


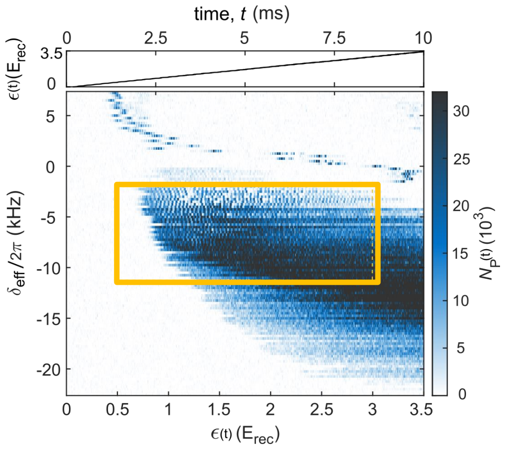


$$\Xi = \Xi'(\omega_{LC})/\Xi'_{max} \quad \text{where}$$

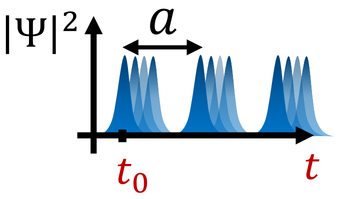
$$\Xi' = \sum_{\delta} N_p(\omega)/\sum_{\Delta} N_p(\omega)$$





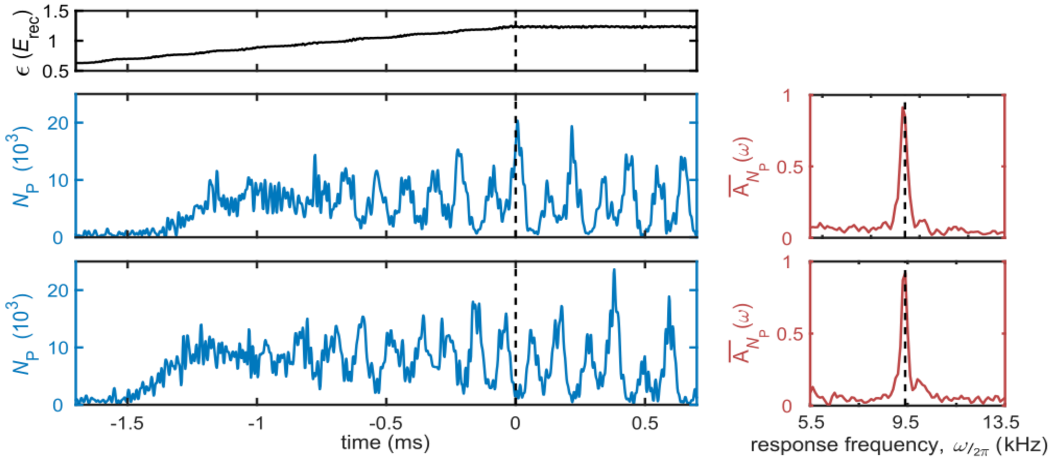


Spontaneous symmetry breaking



P. Kongkhambut et al., Science 377, 670 (2022)

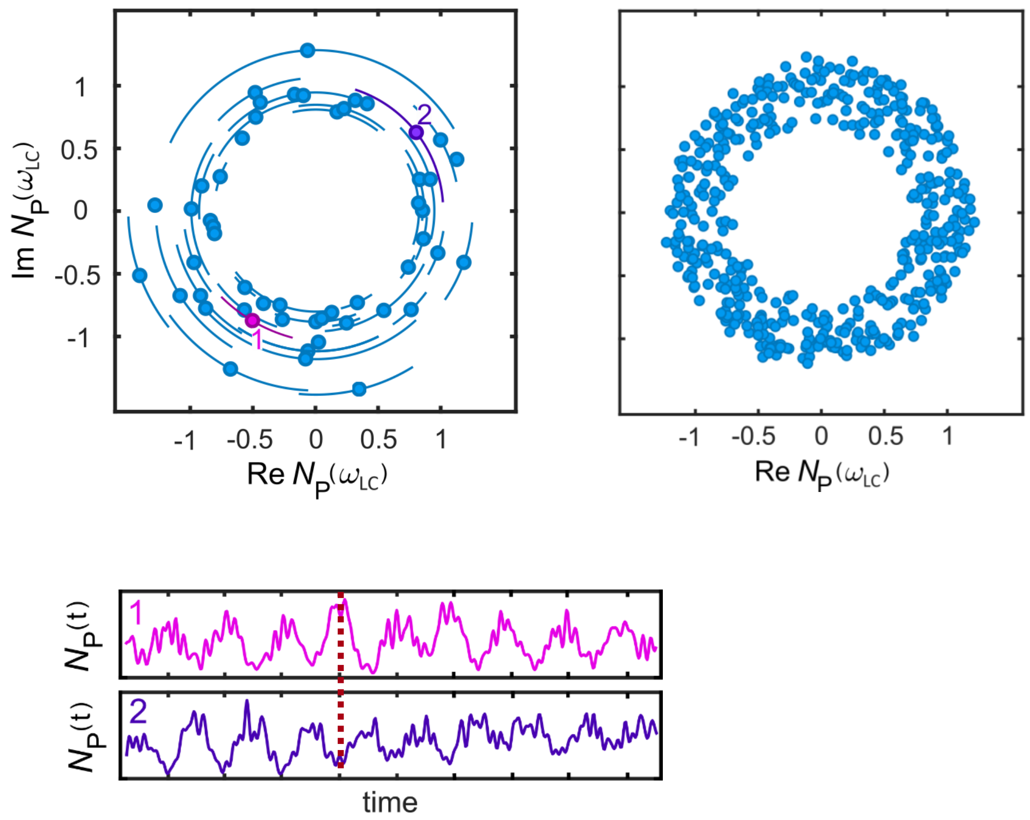
- Repeat experiment more than 1500 times, post select data with the same frequency within ±50Hz
- Observe a random time phase between 0 and 2π
- Confirm with TWA simulations



Repeat over 1500 times

Experiments

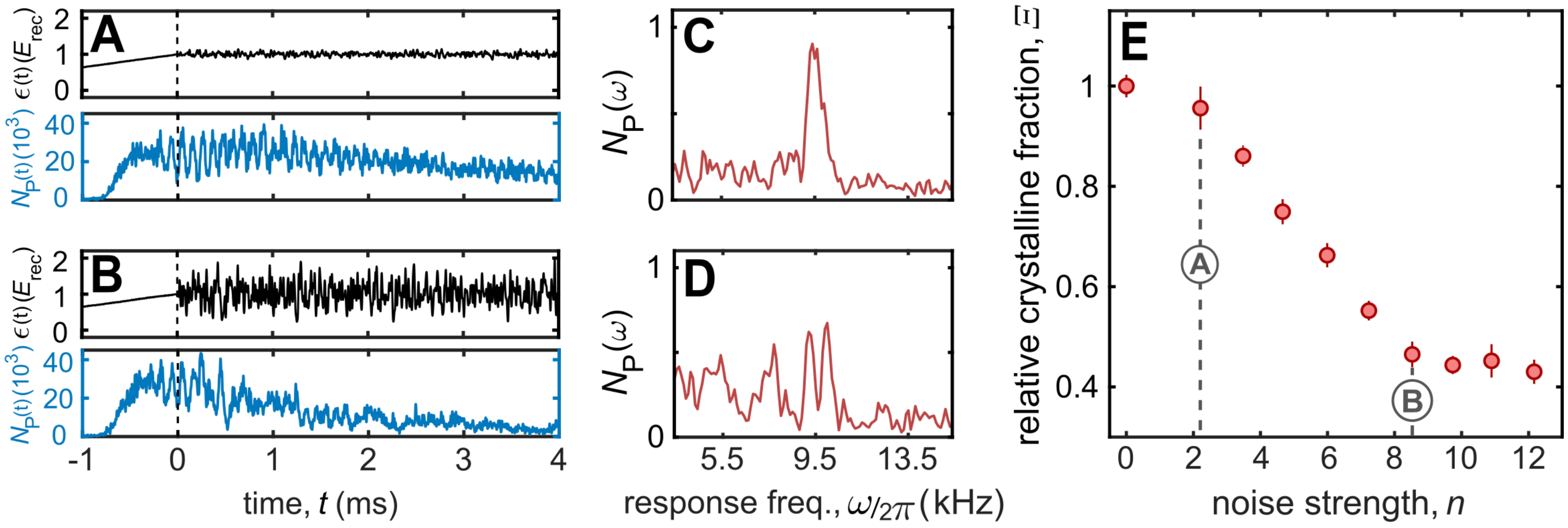
TWA simulations



Robustness against temporal perturbations

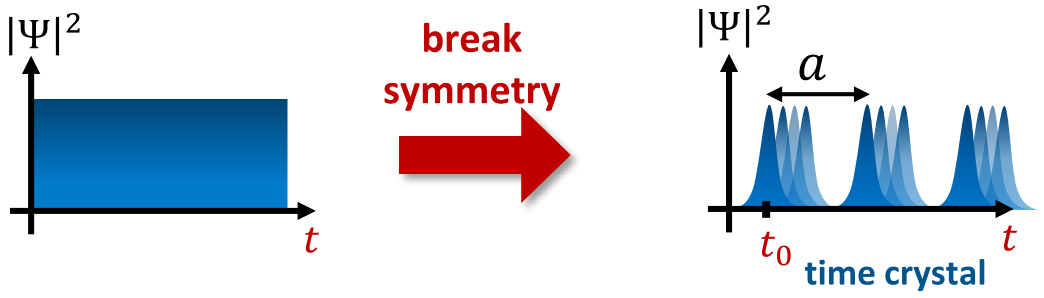
P. Kongkhambut et al., Science 377, 670 (2022)

- Add white noise on pump strength ϵ
- Analogous to that of changing T and P can slowly melt the ice
- Here the crystalline fraction slowly decreases with noise ➔ CTC is slowly *"melting"*

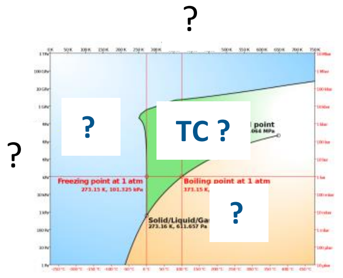


time crystal

- **Intrinsic lattice constant →** spontaneously break **(time)** translation symmetry



- **Phase diagram span by relevant parameters**

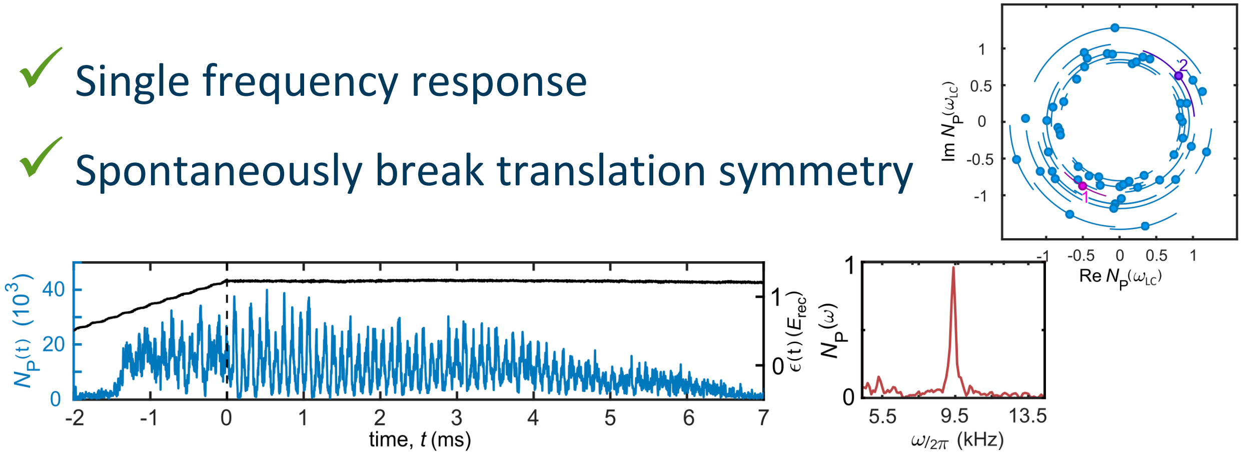


- **Robustness against perturbations**

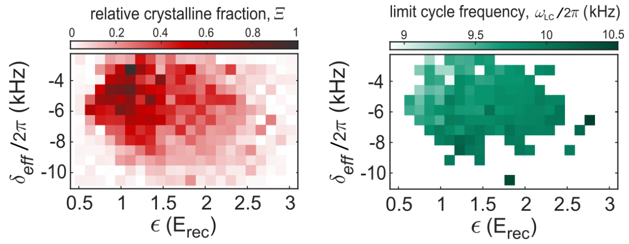
our observations

✓ Single frequency response

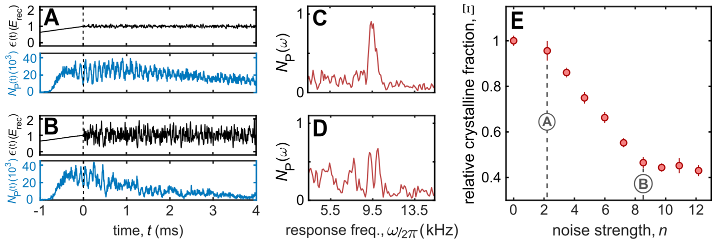
✓ Spontaneously break translation symmetry



✓ Phase diagram

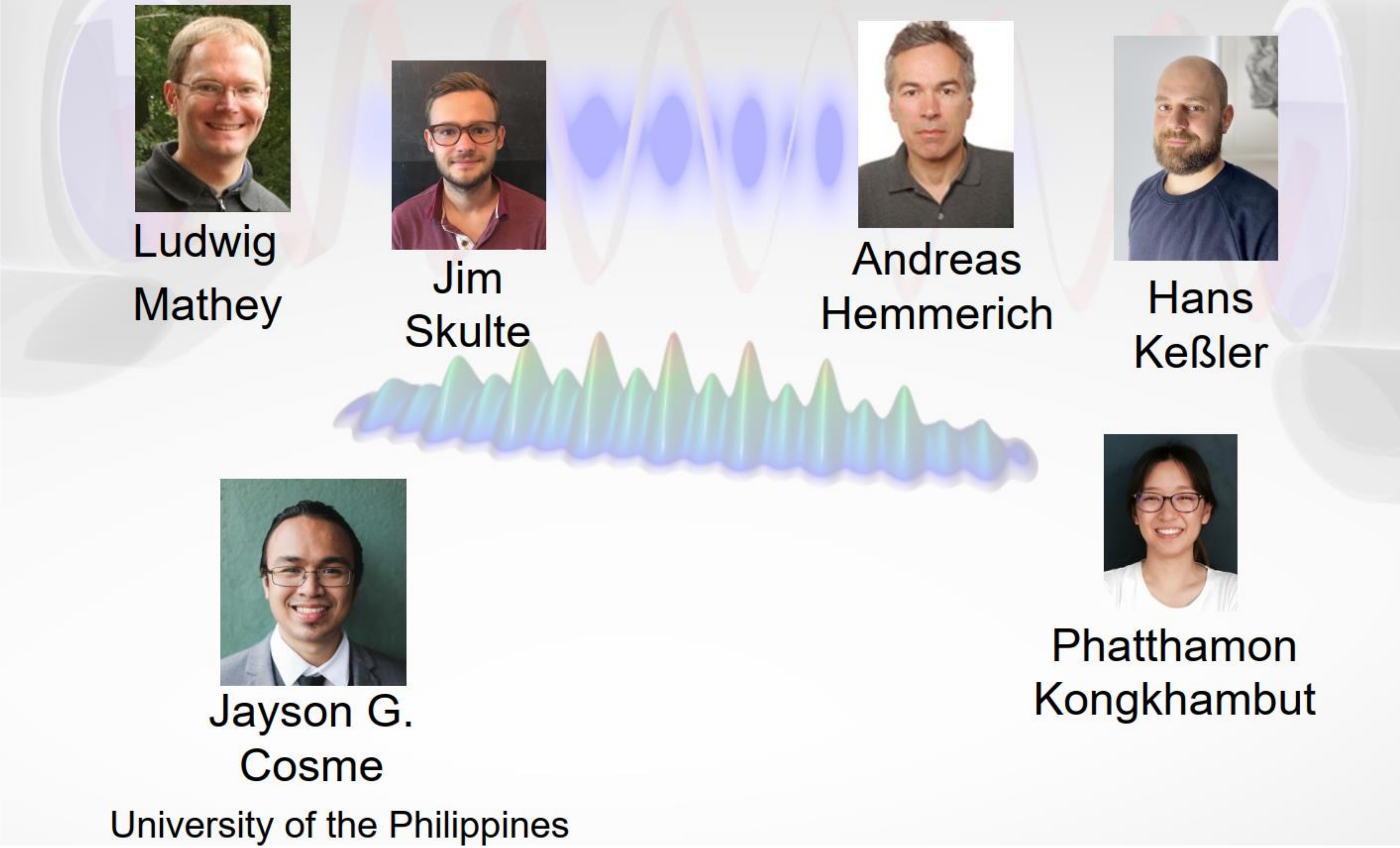


✓ Robustness against perturbations



Hamburg atom-cavity team

Theory **Experiment**



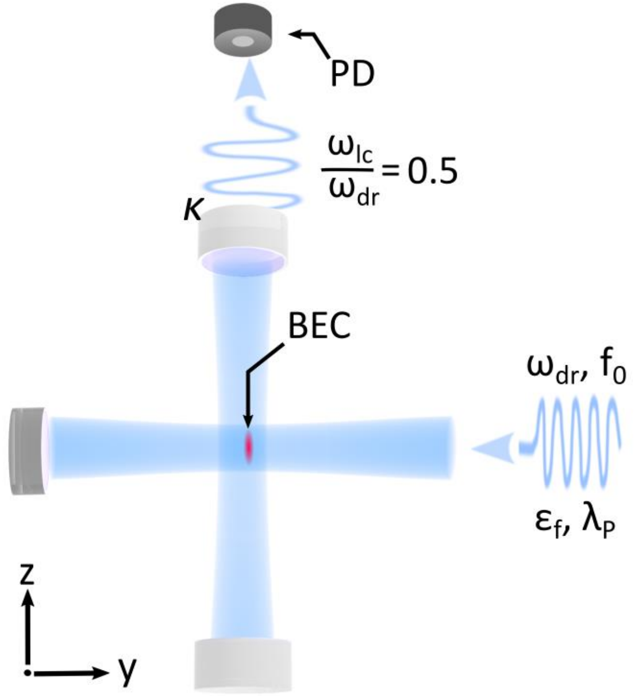
Outlook: From continuous to discrete TC

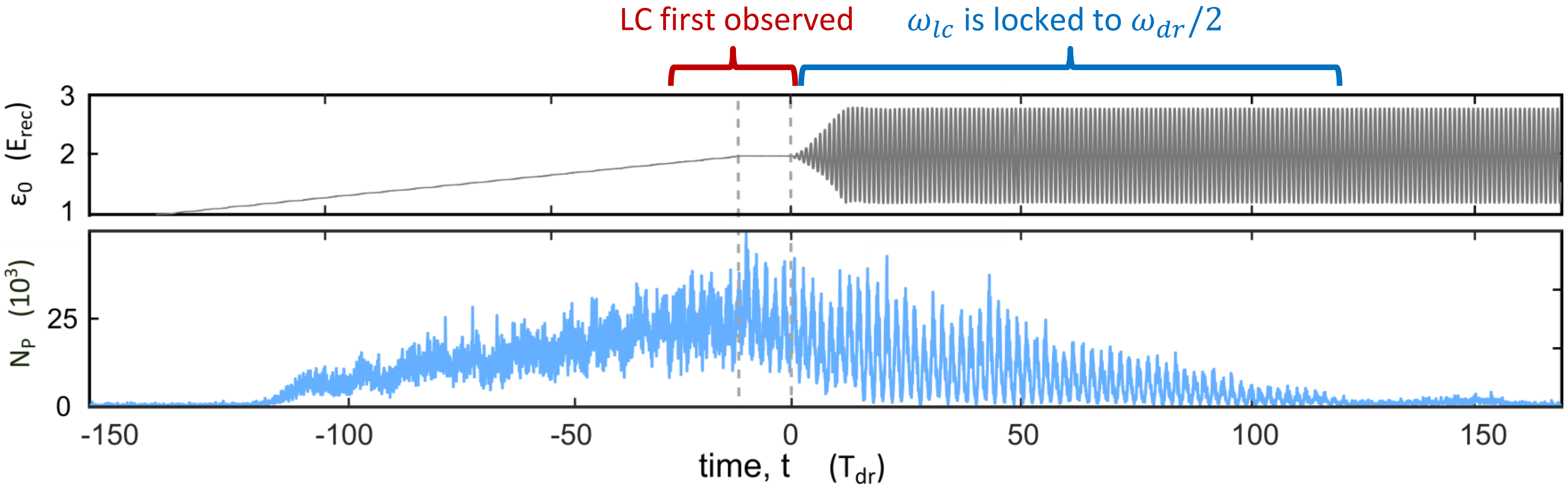
Proposal: H. Keßler et. al., NJP **22**, 085002 (2020)

Frequency locking at sub-harmonic

Preliminary! Manuscript in preparation

- Drive the pump with 2xω_{lc} → response frequency locked to ω_{LC}

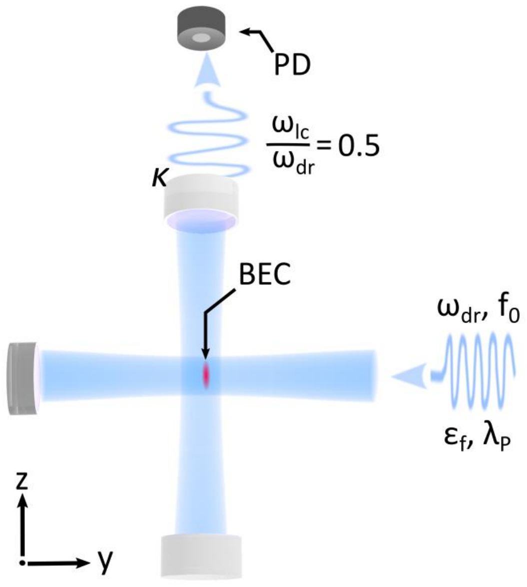




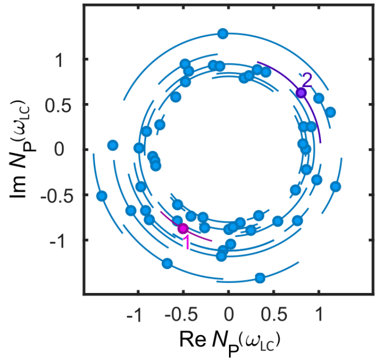
Frequency locking at sub-harmonic

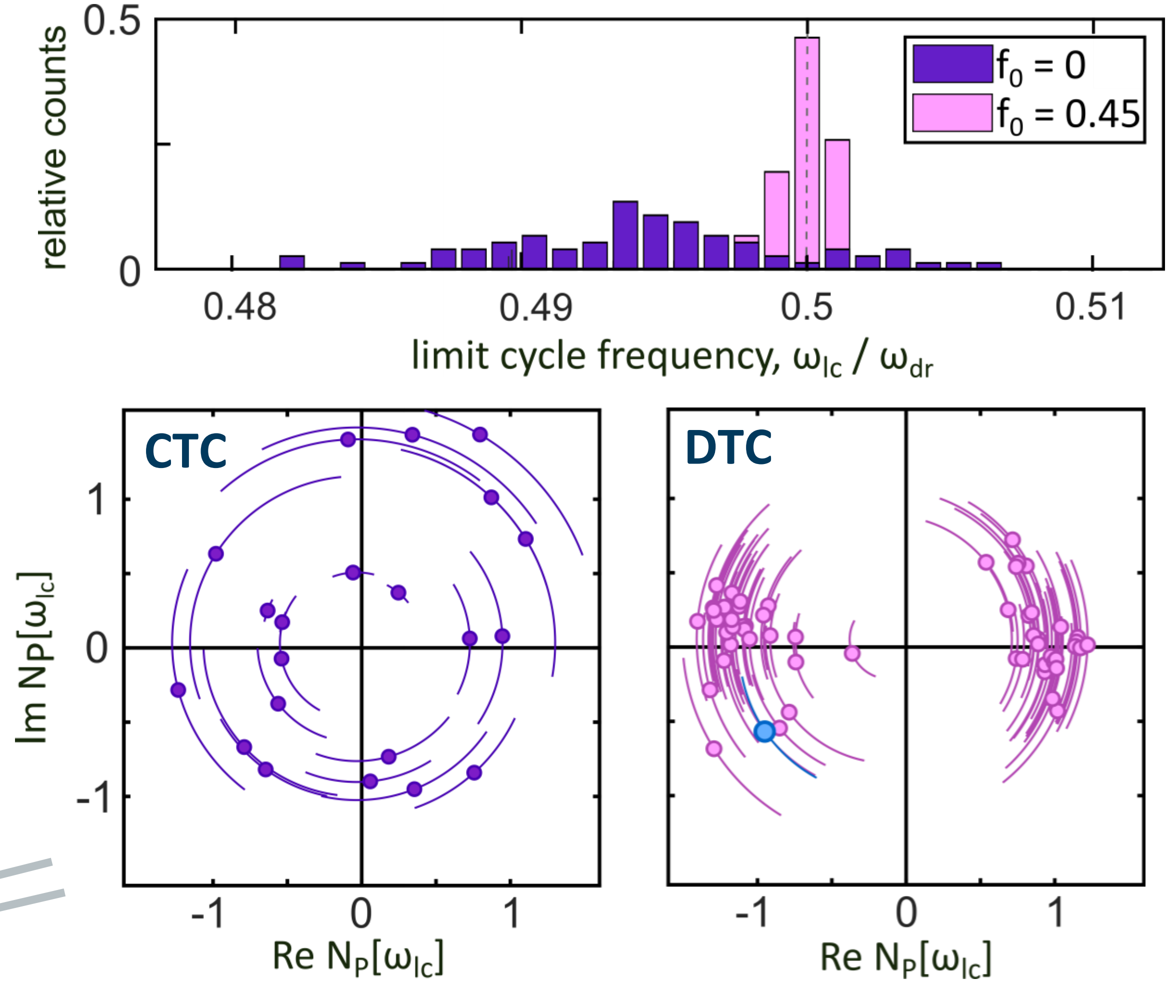
Preliminary! Manuscript in preparation

- Histogram comparing ω_{lc} **with** and **without** driving shows a frequency-locking effect
- Extract ω_{lc} and its time phase
- Synchronization of oscillators



Recall:



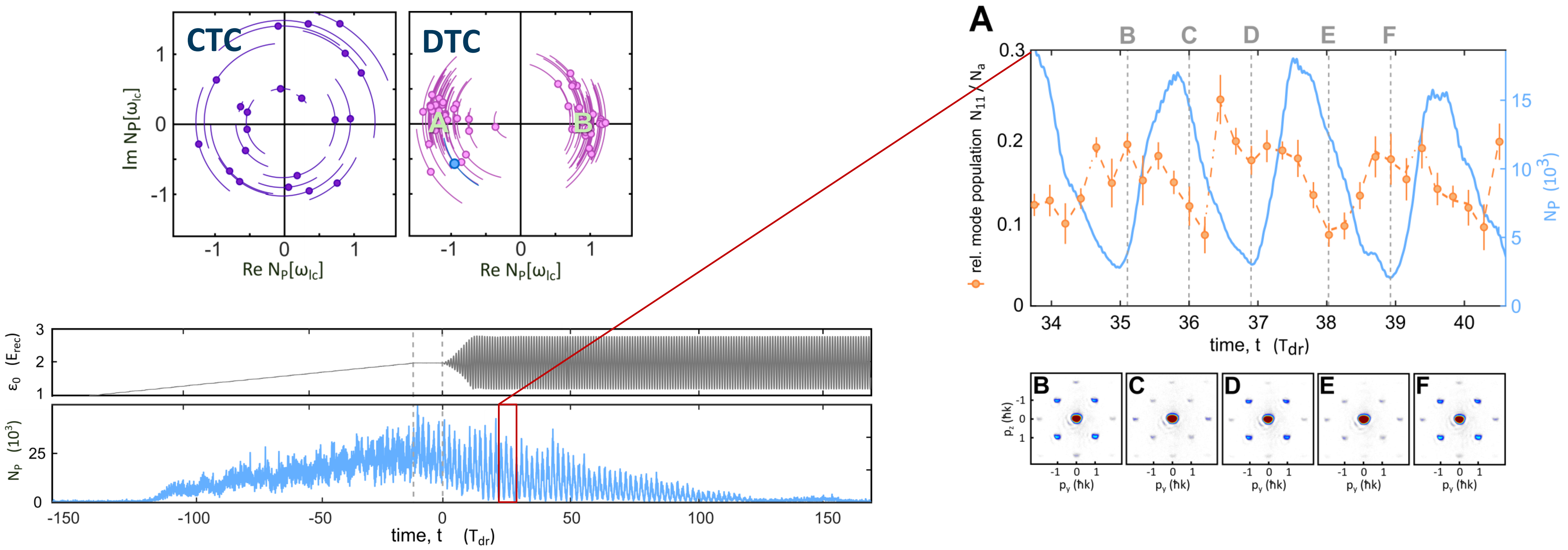


What's going on macroscopically?

Preliminary! Manuscript in preparation

Looking into the momentum distribution of TOF image → reveal real space populations

- CTC paper cannot map out atomic dynamics.
- Now with DTC , the oscillation phase is either A or B, we post-select one of them and see this



Thank you for your attention!

Q&A