Discrete time crystal in a finite chain of Rydberg atoms without disorder

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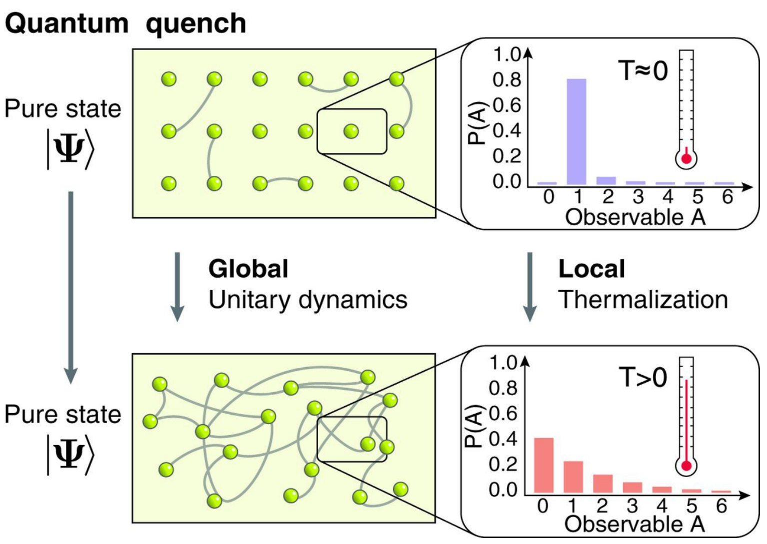
How does a quantum system thermalize?



Onset of thermalization:

→ *Eigenstate Thermalization Hypothesis*

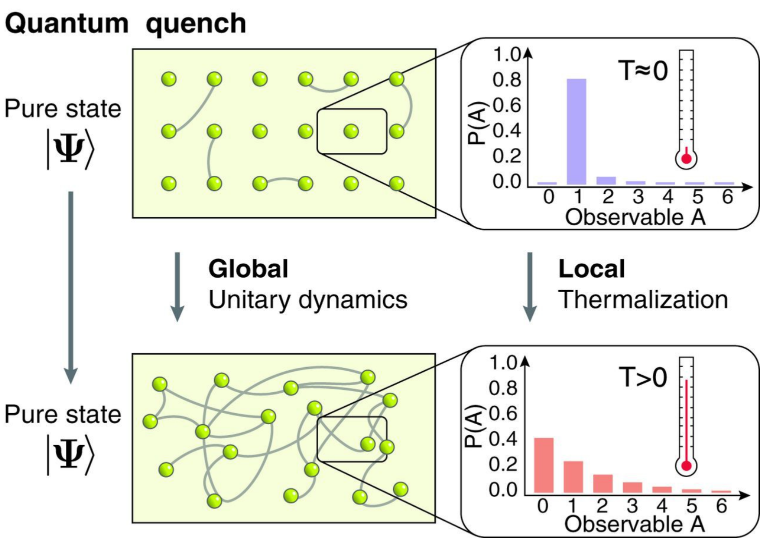
→ *equilibrium statistical mechanics* sets in

the system locally resembles a canonical state

diagonal ensemble = canonical ensemble

→ *entanglement growth* between subsystems

How does a quantum system thermalize?



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Nonthermal behavior in certain occasions:

→ *impurities and localization effects* (more complex behavior)

→ *exotic nonequilibrium* states of matter

Thermalization in static/driven systems

	emergence of thermalization $S_A \sim \lvert A \rvert$	absence of thermalization $S_A \sim \lvert \partial A \rvert$
Static systems	the system acts as its own bath $\rho_A \sim e^{-\beta_{\text{eff}} H_A}$	frozen-in impurities MBL
	ETH	
Periodically driven (Floquet) systems	heating up at $\beta \to 0$ $\rho_A \sim \mathbb{I}$	nonequilibrium states of matter $\to$ pre-thermal states $\to$ “crypto-equilibrium” DTC

Time crystals: three key manifestations

$$\langle O\rangle(t+nT)=\langle O\rangle(t)\quad (n\geq 2)$$

$\rightarrow$ Broken time-translation symmetry

After an initial transient, late-time oscillations appear
with a period longer than that of the drive (T)

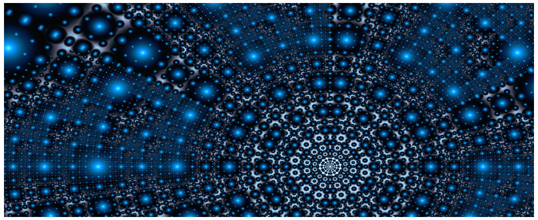
$\rightarrow$ Crypto-equilibrium

The system looks at equilibrium, in some time-dependent frame
No entropy generated by late-time oscillations

$\rightarrow$ Rigid long-range order

Oscillations remain in phase over long distances & times
(synchronization)

unfeasible at thermal equilibrium



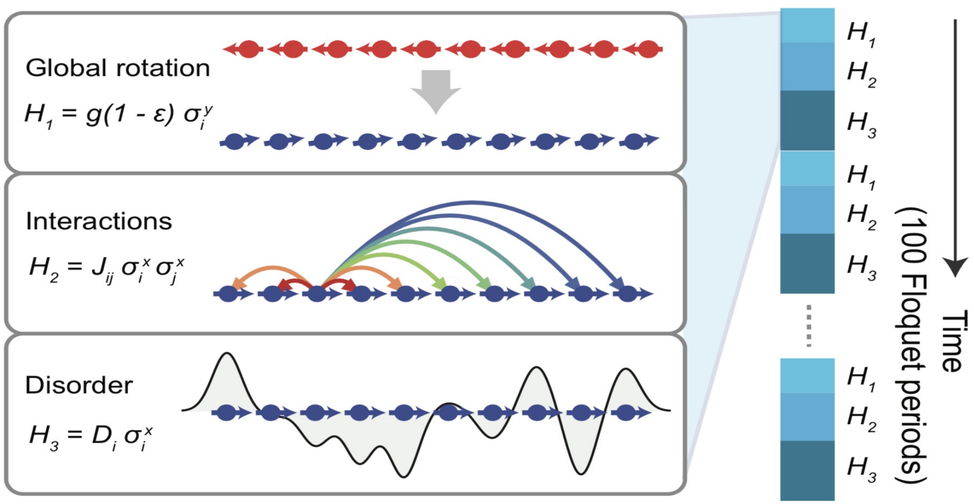
F. Wilczek, *PRL* ***109****, 160401 (2012)*

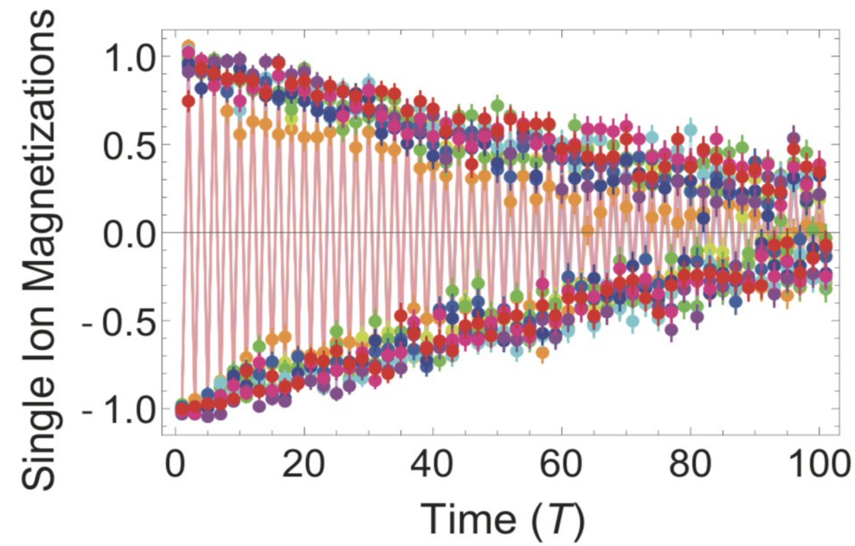
K. Sacha, J. Zakrzewski, *Rep. Prog. Phys.* ***81****, 016401 (2018)*
D. V. Else, C. Monroe, C. Nayak, N. Y. Yao, *arXiv:1905.13232*

Discrete time crystals with Rydberg atoms

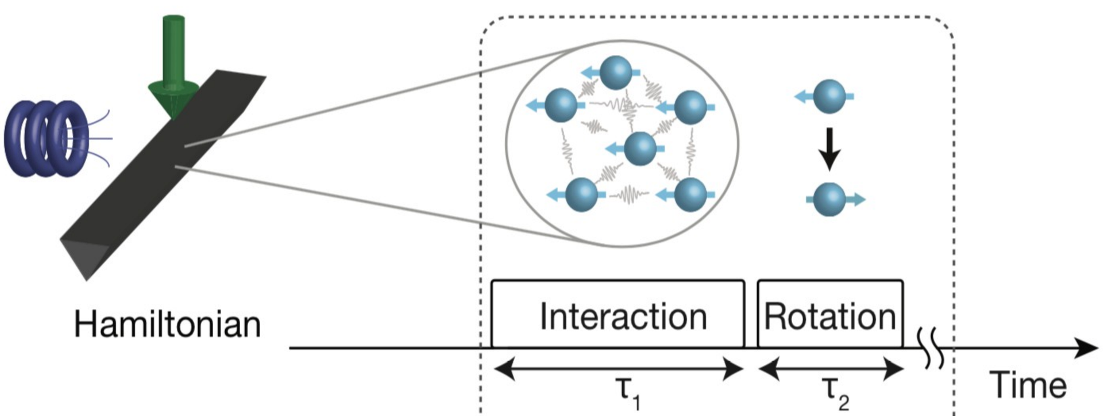
C.-H. Fan, DR, H.-X. Zhang, J.-H. Wu, M. Artoni, and G. C. La Rocca, *arXiv:1907.03446*

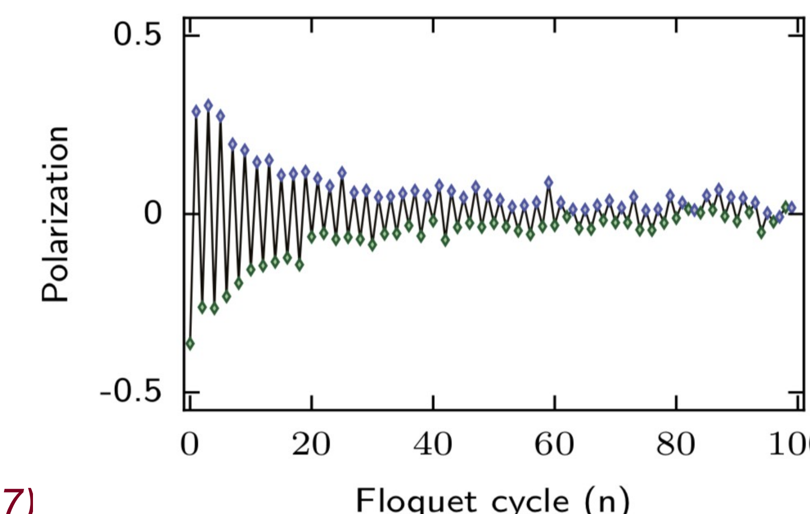
Experimental realizations of DTCs





Zhang et al. (trapped ions – Monroe), *Nature* ***543****, 217 (2017)*

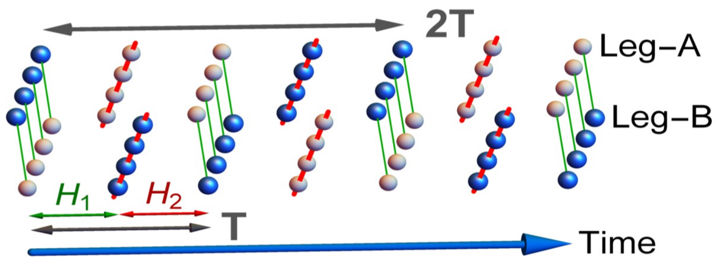




Choi et al. (NV centers – Lukin), *Nature* ***543****, 221 (2017)*

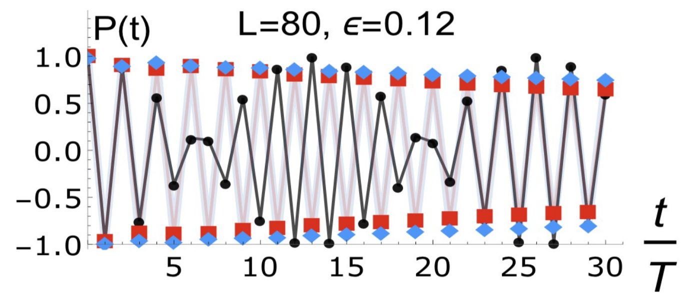
Clean DTCs

DTCs are not necessarily "protected" by MBL.
Proposals using non-disordered systems:



→ cold atoms in ladder configurations

B. Huang, Y. Wu, W. Liu, *PRL **120**, 110603 (2018)*



→ prethermal states with short-range interactions

D. Else, B. Bauer, C. Nayak, *PRX **7**, 011026 (2017)*

→ spin-chain models with variable-range interactions

A. Russomanno, F. Iemini, M. Dalmonte, R. Fazio, *PRB **95**, 214307 (2017)*
F. Surace, A. Russomanno, M. Dalmonte, A. Silva, R. Fazio, F. Iemini, *PRB **99**, 104303 (2019)*
W. Yu, J. Tangpanitanon, A. Glaetzle, D. Jaksch, D. Angelakis, *PRA **99**, 033618 (2019)*

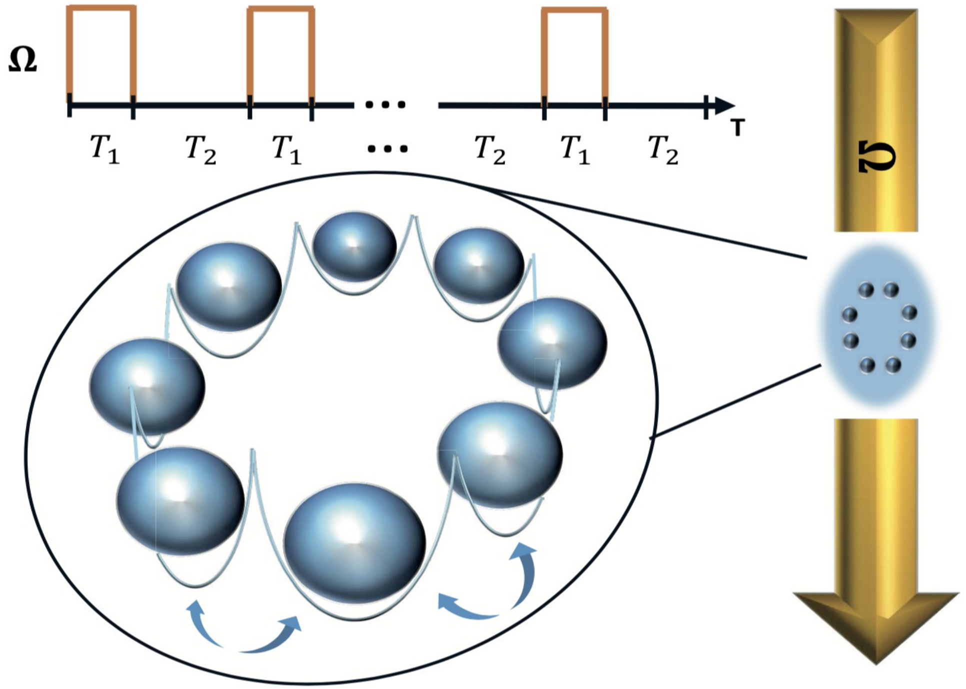
→ open quantum systems

F. Gambetta, F. Carollo, M. Marcuzzi, J. Garrahan, I. Lesanovsky, *PRL **122**, 015701 (2019)*

First experiments (NMR):

J. Rovny, R. Blum, S. Barrett, *PRL **120**, 180603 (2018)*
S. Pal, N. Nishad, T. Mahesh, G. Sreejith, *PRL **120**, 180602 (2018)*

DTC in a chain with Rydberg atoms



Initial state:

$$|\Psi(0)\rangle = \otimes_j |g\rangle_j$$

Floquet time evolution:

$$U_F(n) = \left[e^{-iH_2T_2/\hbar}e^{-iH_1T_1/\hbar}\right]^n$$

Step I

$$H_1 = \hbar\sum_j \left[\Omega(\sigma_j^+ + \sigma_j^-) + \Delta N_j^r + V N_j^r N_{j+1}^r\right] \qquad (n-1)T \le t < nT - T_2$$

Step II

$$H_2 = \hbar\sum_j \left[\Delta N_j^r + V N_j^r N_{j+1}^r\right] \qquad nT - T_2 \le t < nT$$

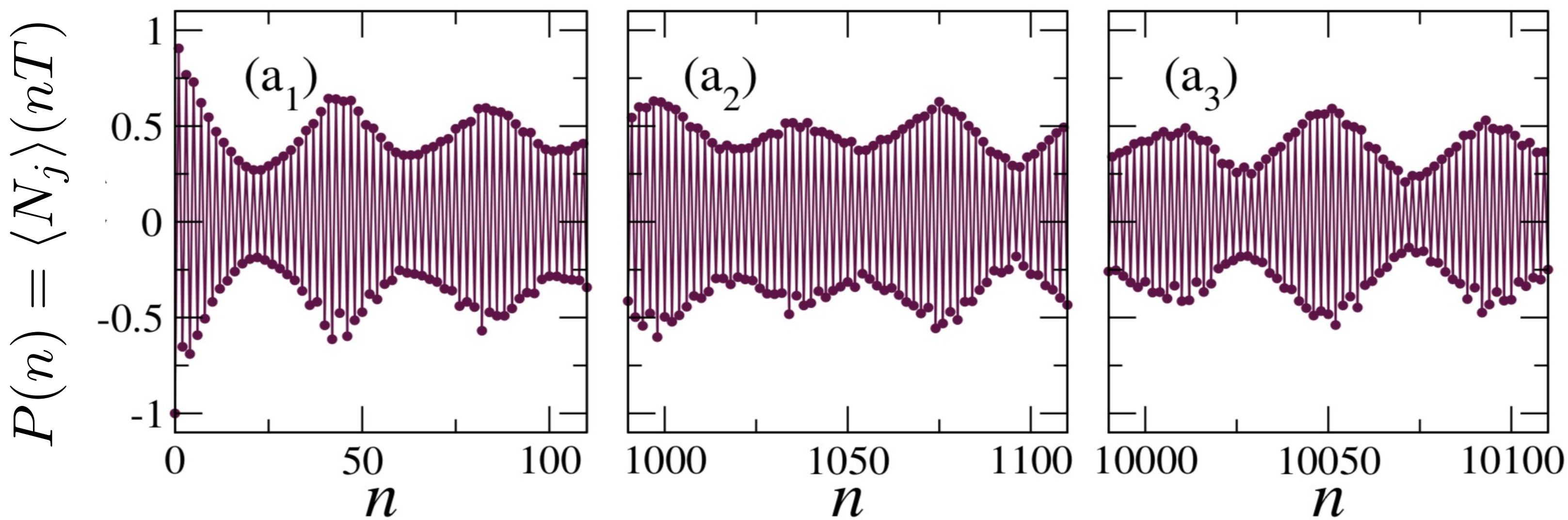
The DTC phase

The following conditions must be satisfied:

(i) ***time-translation symmetry breaking***

(ii) ***rigidity*** against variations of parameters

(iii) *persistence* in time with increasing size

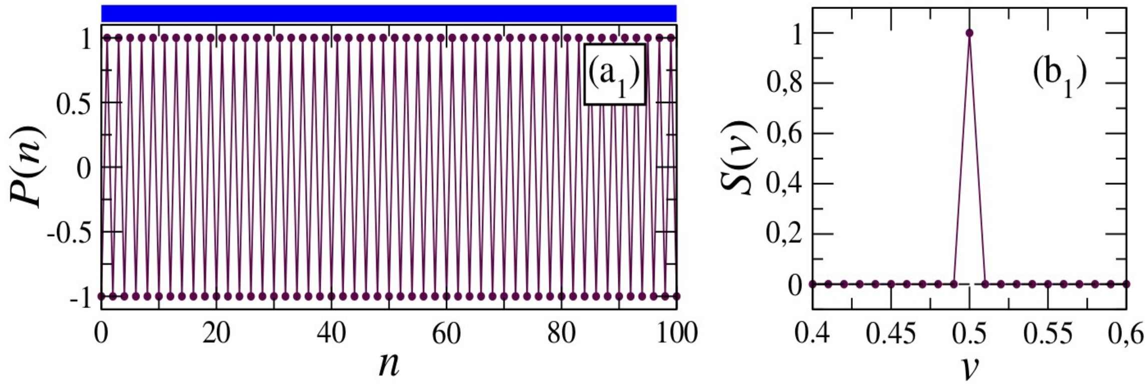


Emergence of $2T$ periodicity

$$\Omega T_1 = \frac{\pi}{2} + \epsilon T_1$$

$$\epsilon = 0; \quad V = 0$$

strict $2T$ periodicity



units of $T_1 = 1\,\mu s$

Emergence of 2*T* periodicity

$$\Omega T_1 = \frac{\pi}{2} + \epsilon T_1$$

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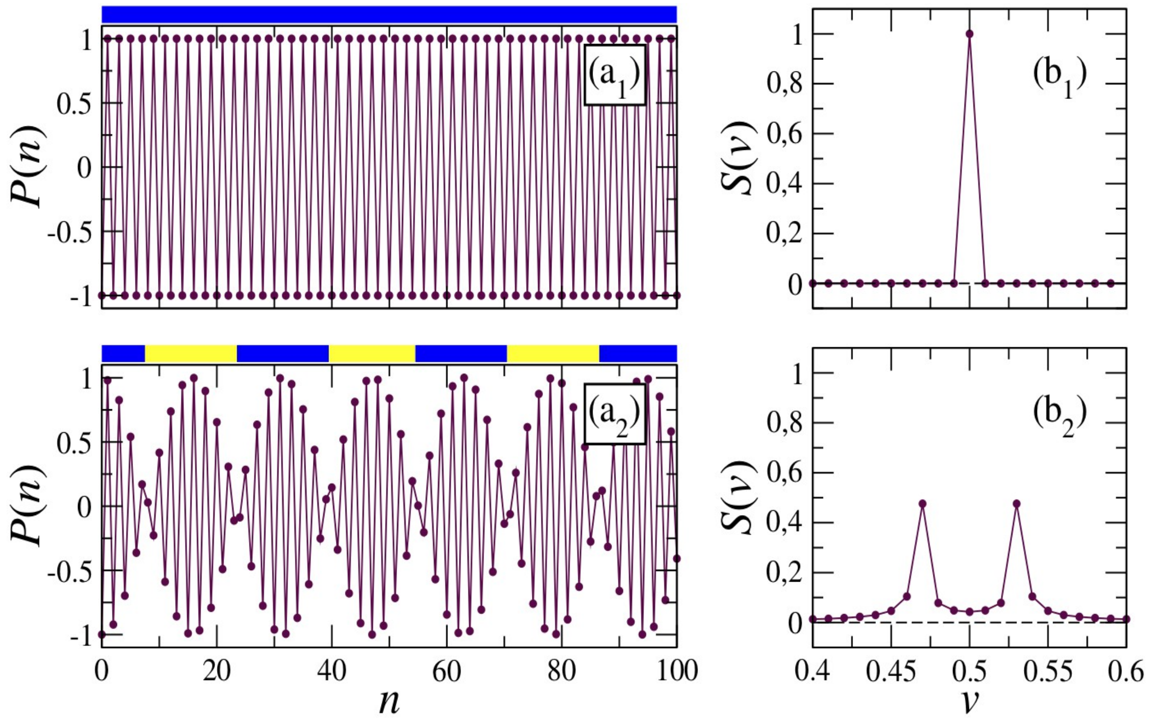
strict 2*T* periodicity

BUT

unstable against perturbations

$$\epsilon = 0.1; \quad V = 0$$



units of $T_1 = 1\,\mu s$

Emergence of 2T periodicity

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$$\epsilon = 0; \quad V = 0$$

strict 2T periodicity

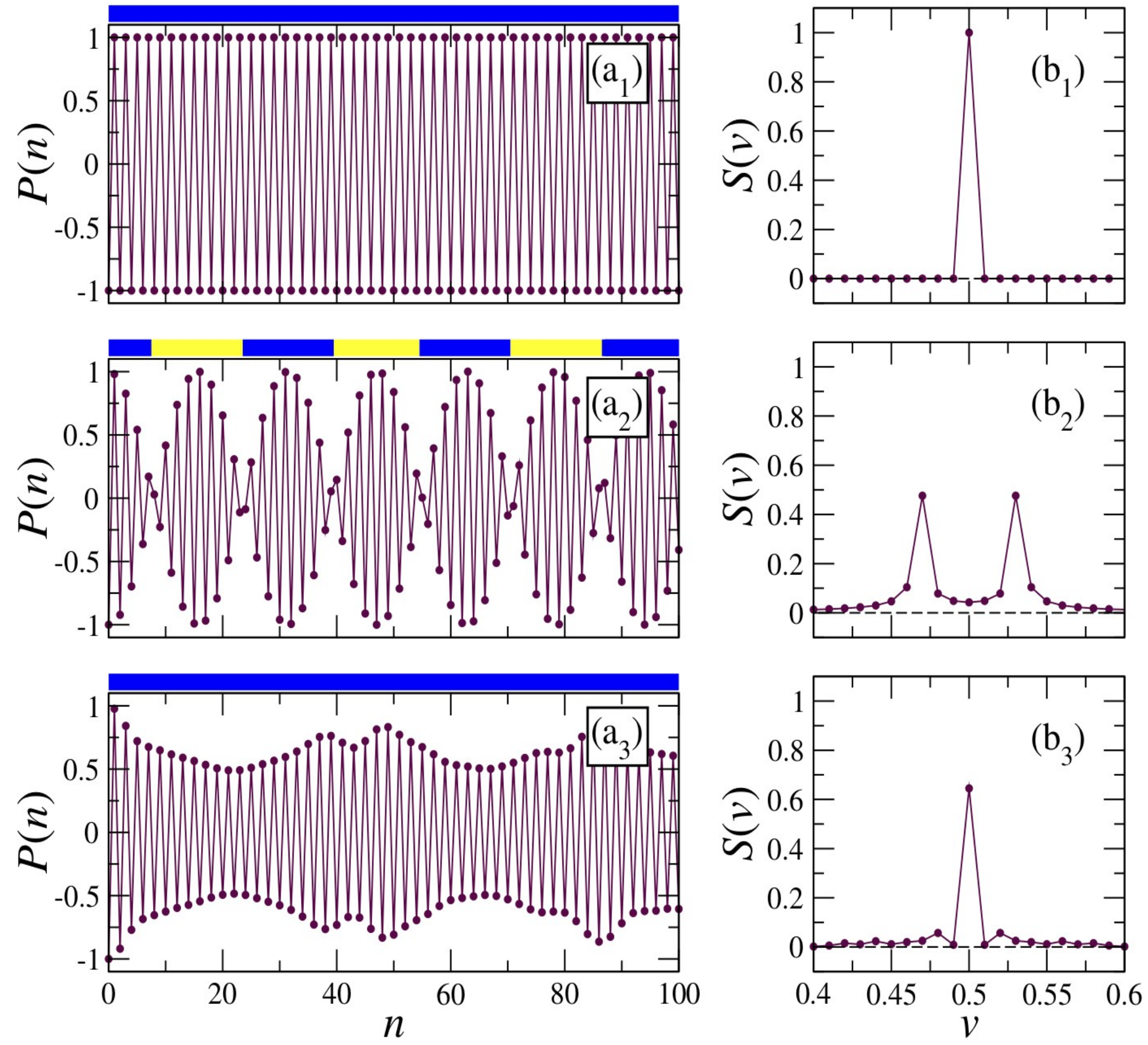
BUT

unstable against perturbations

$$\epsilon = 0.1; \quad V = 0$$

interactions restore periodicity

$$\epsilon = 0.1; \quad V = 0.1; \; T_2 = 10$$



Other proposals turn off the interactions during H_1

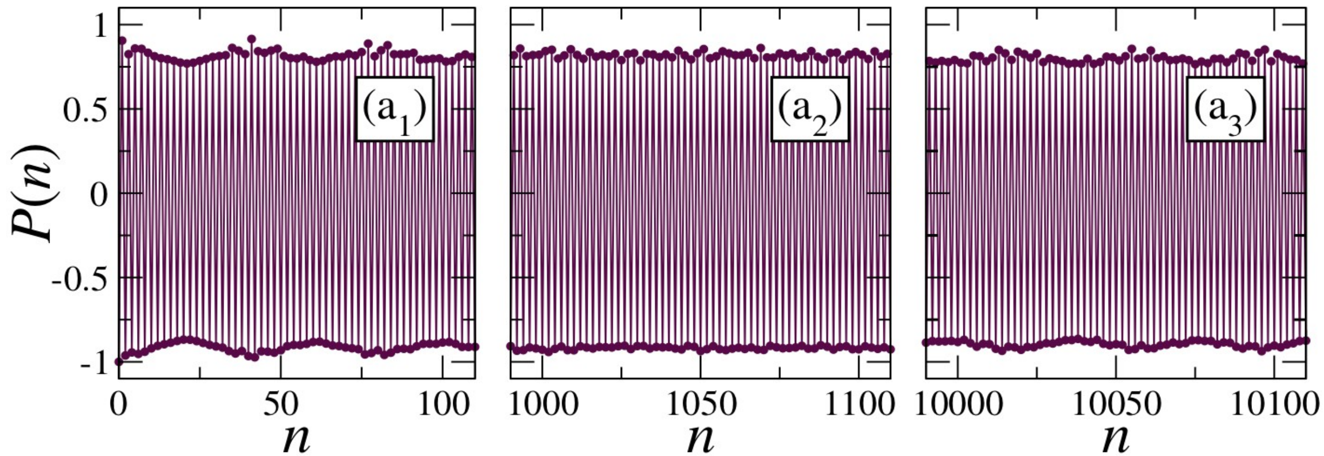
here we set $\Omega \gg V, \; T_1 \ll T_2 \;\Rightarrow\; \omega T_1 \approx V T_2$

units of $T_1 = 1\,\mu s$

Persistence of the DTC

Persistence in time:

stability of oscillations over tens of thousands of Floquet cycles



$V = 0.09,\ L = 14$

$\Delta = 0.6,\ \epsilon = 0,\ T_2 = 15$

Persistence of the DTC

Persistence in time:

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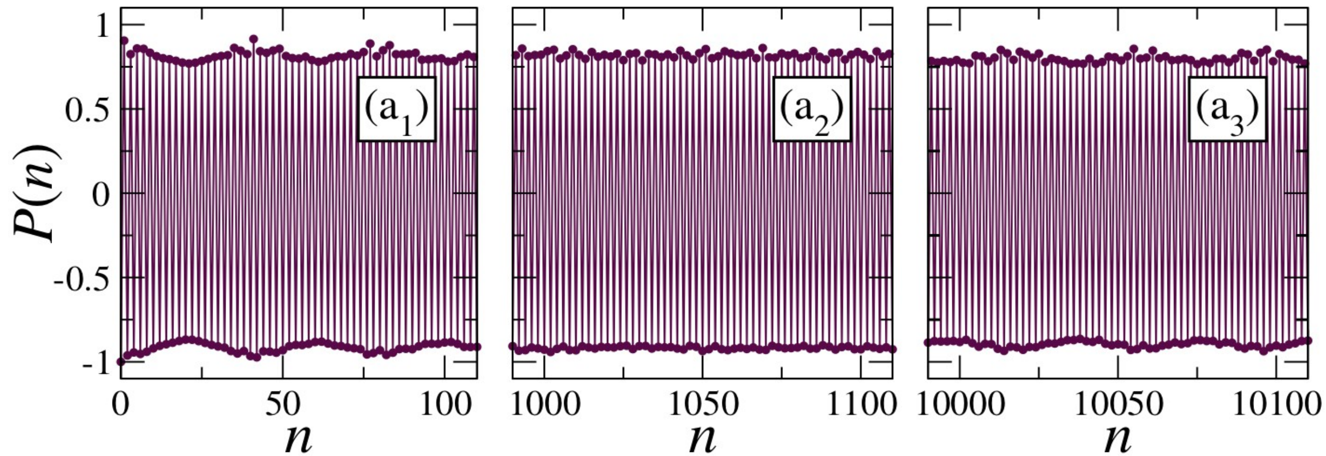
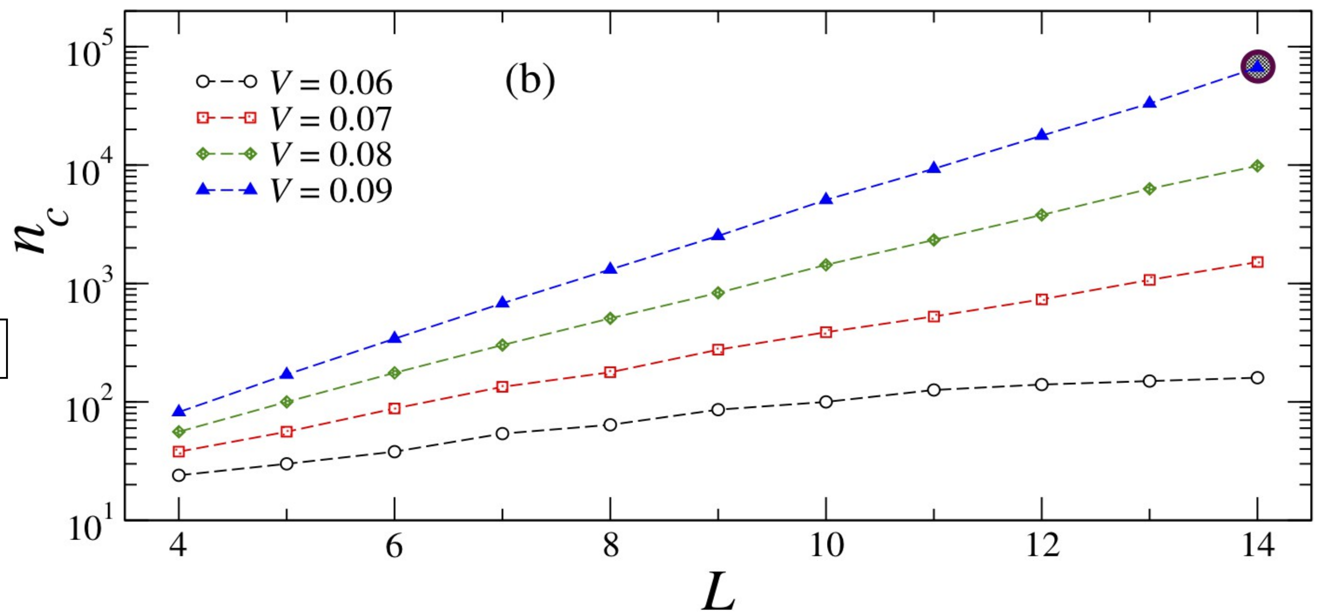


Critical Floquet oscillation number:

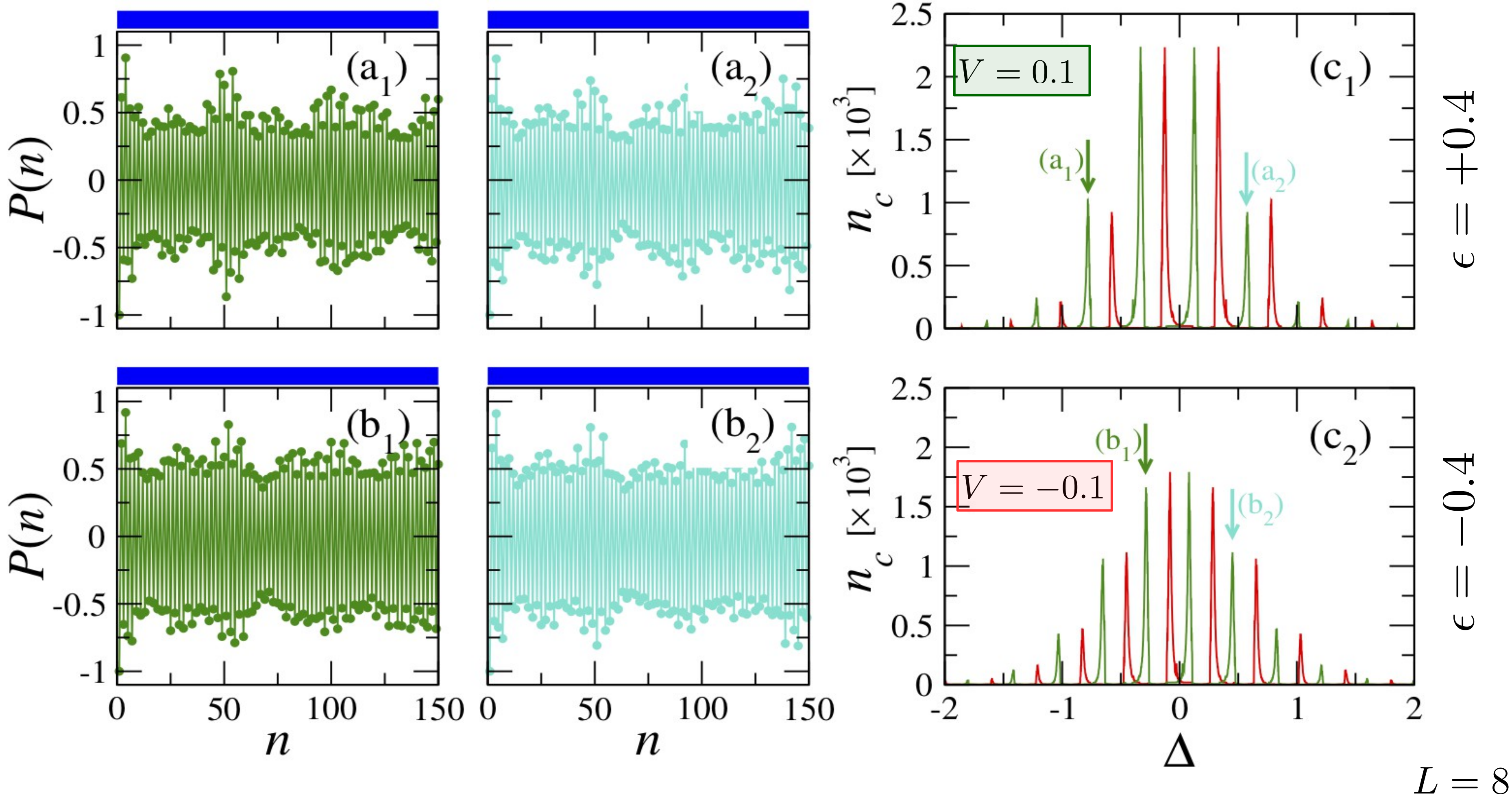
$$Q(n) = \mathrm{sgn}\big[(-1)^n P(n)\big]$$

exponential increase with L



$\Delta = 0.6,\ \epsilon = 0,\ T_2 = 15$

Role of the detuning Δ



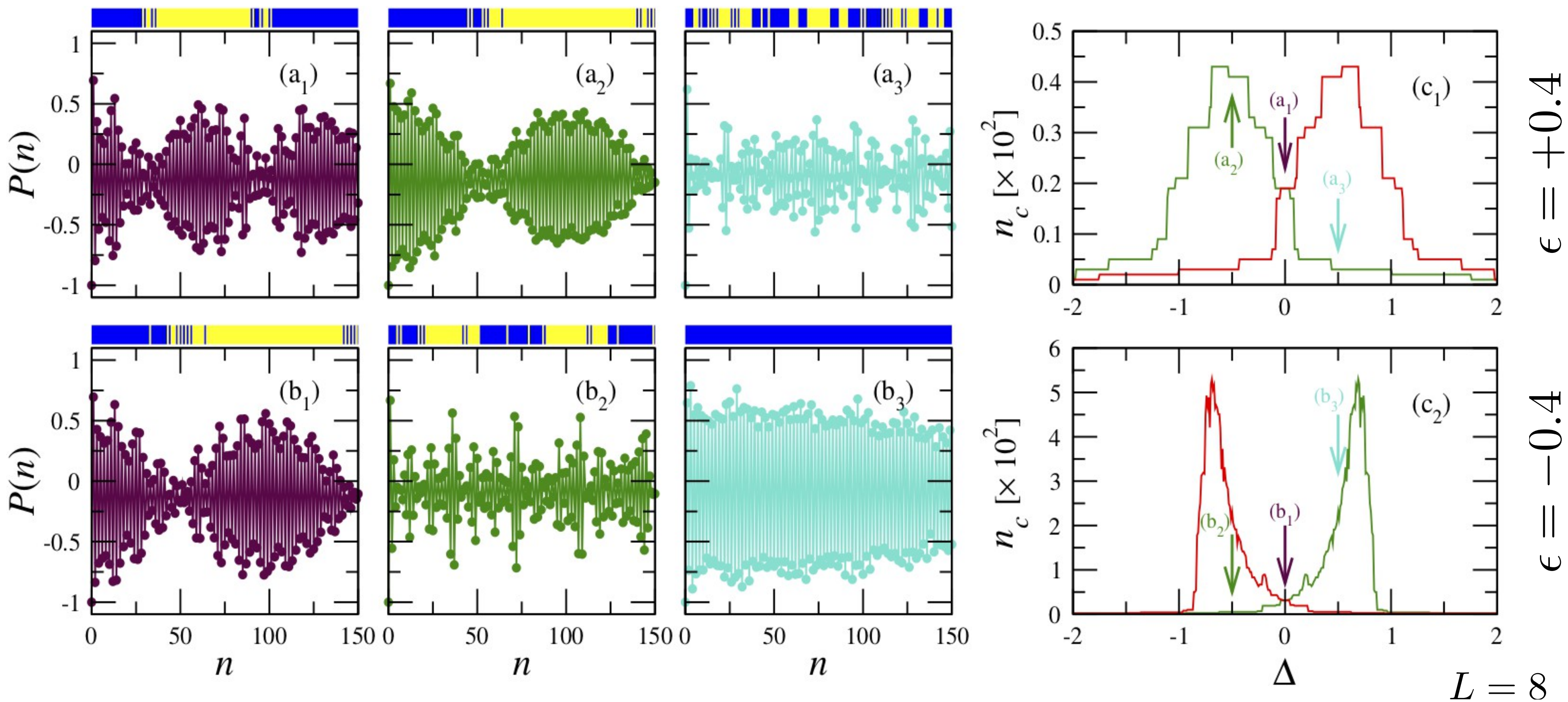
Emergence of *sharp peaks* of n_c vs. Δ

Symmetry: invariant results for simultaneous sign change of V and Δ

Model II: externally controlled detuning

$$H_1 = \hbar \sum_j \left[\Omega(\sigma_j^+ + \sigma_j^-) + \Delta N_j^r + V N_j^r N_{j+1}^r \right]$$

$$\boxed{\widetilde{H}_2 = \hbar \sum_j V N_j^r N_{j+1}^r}$$



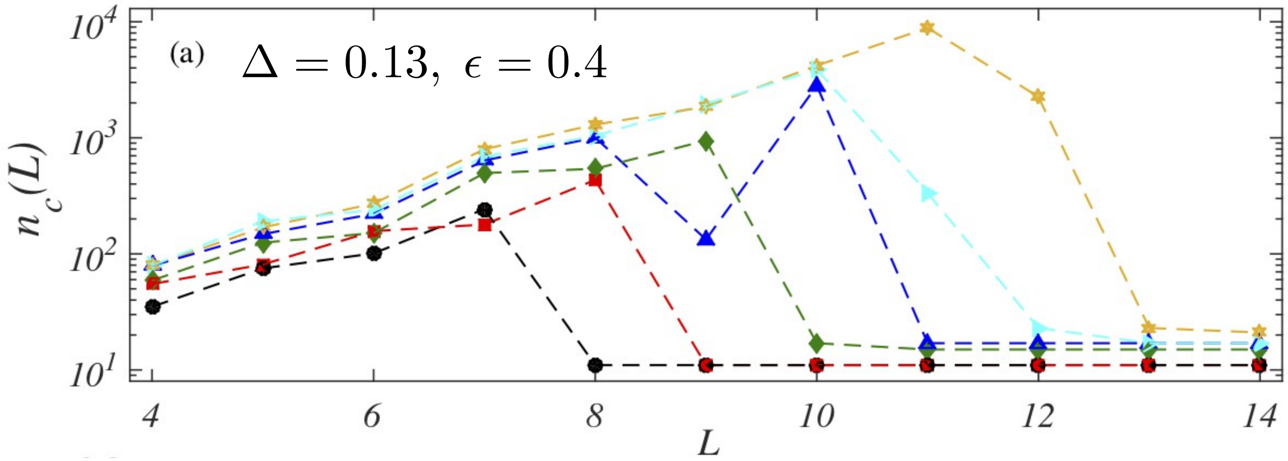
Sharp peaks of n_c vs. Δ are replaced by a *smooth envelope*

The effect of Δ can be reduced taking $\varepsilon < 0$ (DTC more stable): $\Omega_e = \sqrt{[\pi/(2T_1) + \epsilon]^2 + \Delta^2}$

Same symmetry: invariant results for simultaneous sign change of V and Δ

Pre-thermal time crystal?

A "*boundary effect*" for the persistence of a DTC in the parameter space



Pre-thermal time crystal?

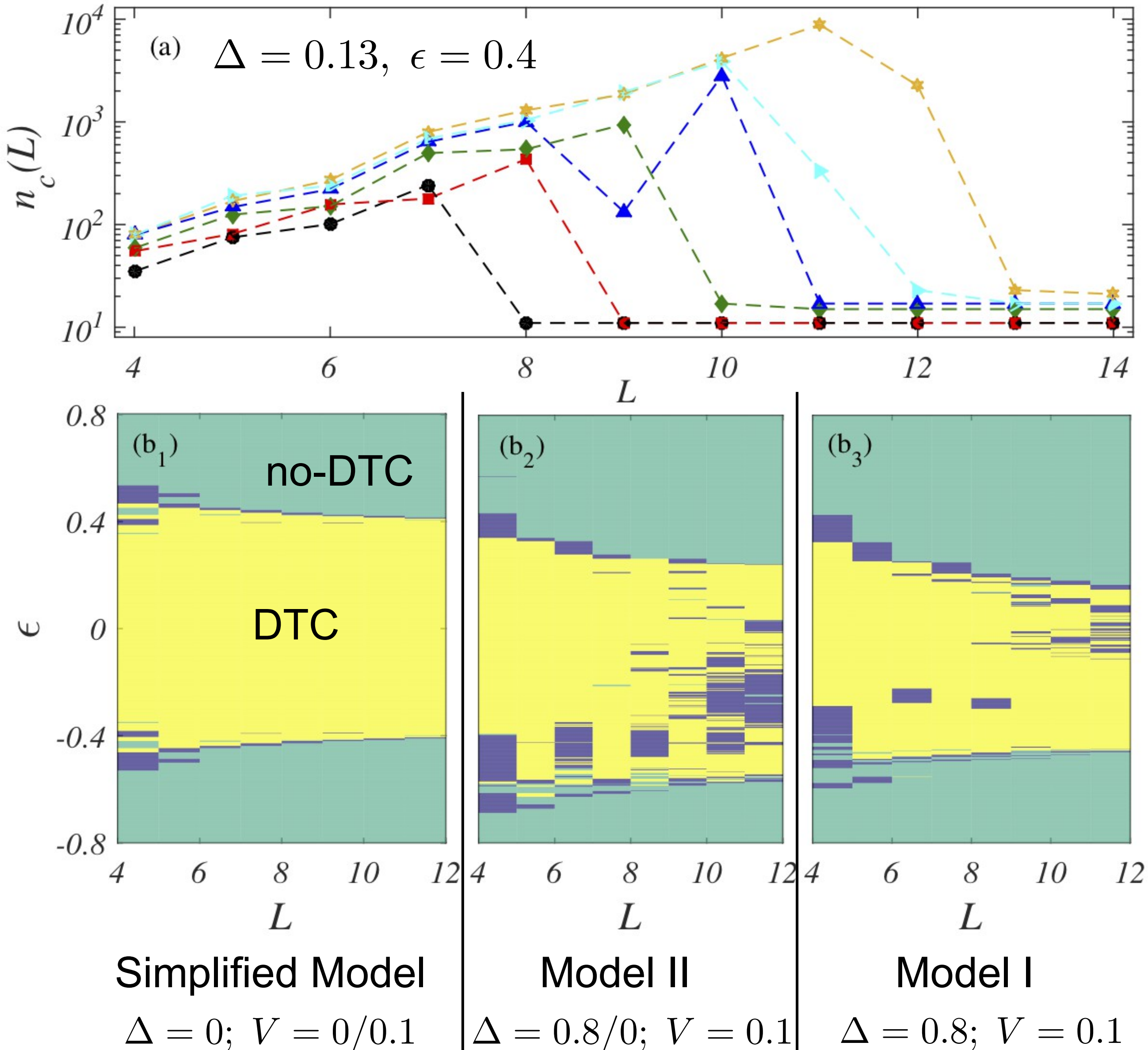
A “*boundary effect*” for the persistence of a DTC in the parameter space

Our regime:

energy scale of external driving ($2\pi/T$) comparable to intrinsic (V) energy scale

pre-thermal DTC is unlikely

BUT it cannot be ruled out: the reduction of “favourable” ε range may be due to faster thermalization @ large L



Dissipation effects

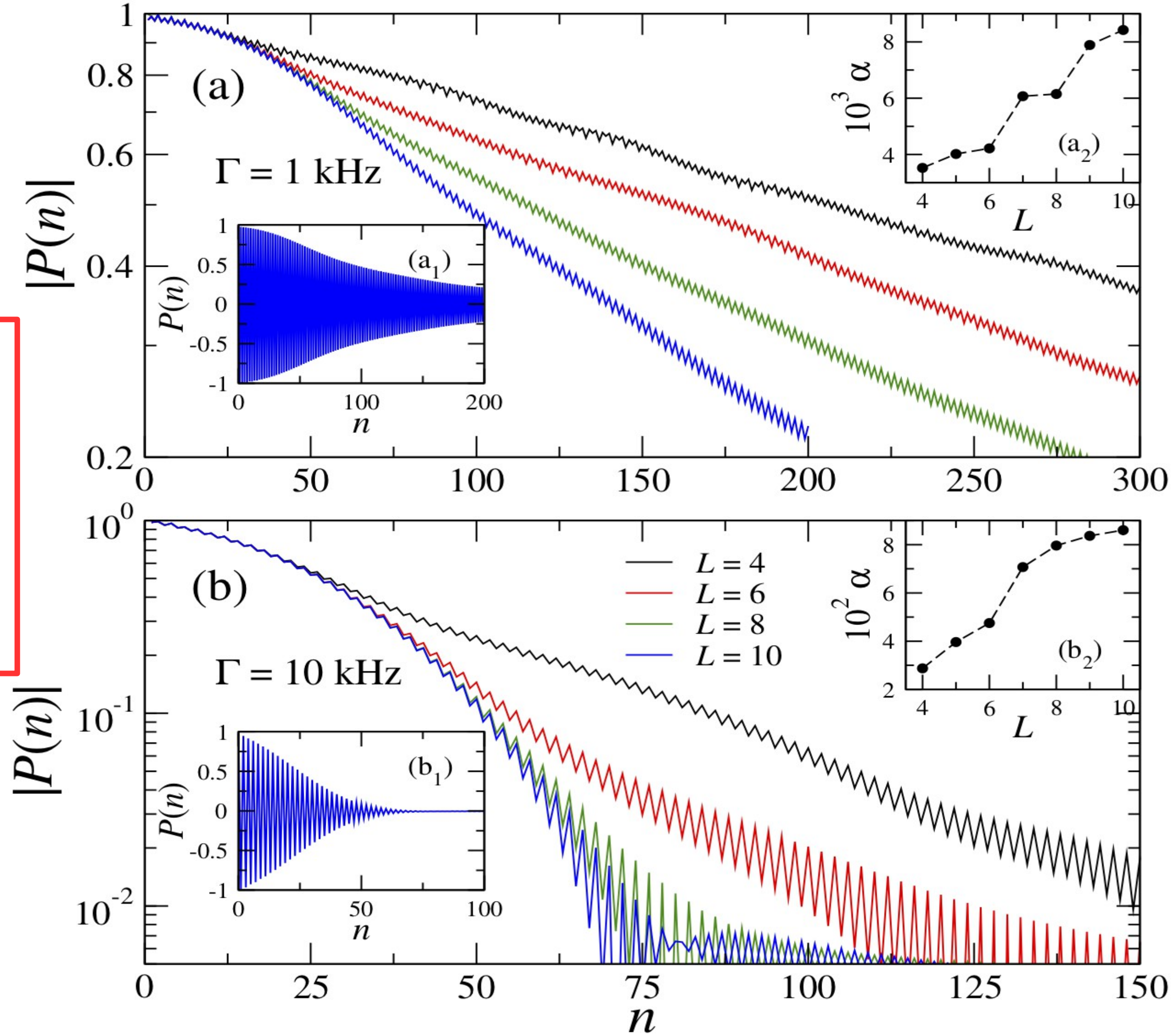
$$\partial_t \rho = -\tfrac{1}{\hbar}[H(t),\rho] + \Gamma \sum_j \sigma_j^- \rho \sigma_j^+ - \tfrac{1}{2}\{\rho, \sigma_j^+\sigma_j^-\}$$ decay of Rydberg states

Typical exponential decay:

$$|P(n)| \sim \exp(-\alpha n)$$

Controllability
→ Ω (Δ): intensity (frequency) of driving field
→ V: distance btw potential wells

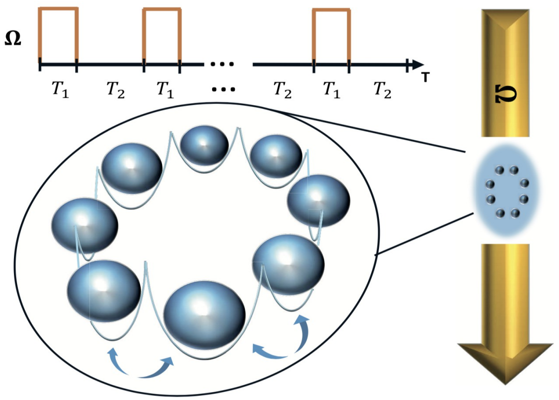
Reliability over larger values of Γ: *experimental viability*



Conclusions

- **Discrete time crystals in non-disordered Rydberg atoms chains**

→ time-translation symmetry breaking
→ robustness to system's parameters
→ persistence over long times already @ L~10



experimental viability (losses under control)

→ DTC in clean and short-range systems:

Which mechanism is preventing the system from heating up?

Quantum Many-body scars?