International Workshop Led by Young Researchers “Quantum thermalization, Hydrodynamics and Gravity"

Active Matter, KPZ, and (possibly) Gravity

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Department of Applied Physics, The University of Tokyo

Chat with Masataka (One of the Organizers)

I don’t really work on thermalization, hydrodynamics, or gravity.

What should I talk about ?

Our aim is to learn from different research fields.

Please share recent developments in nonequilibrium condensed matter physics.

How about active matter and KPZ ?

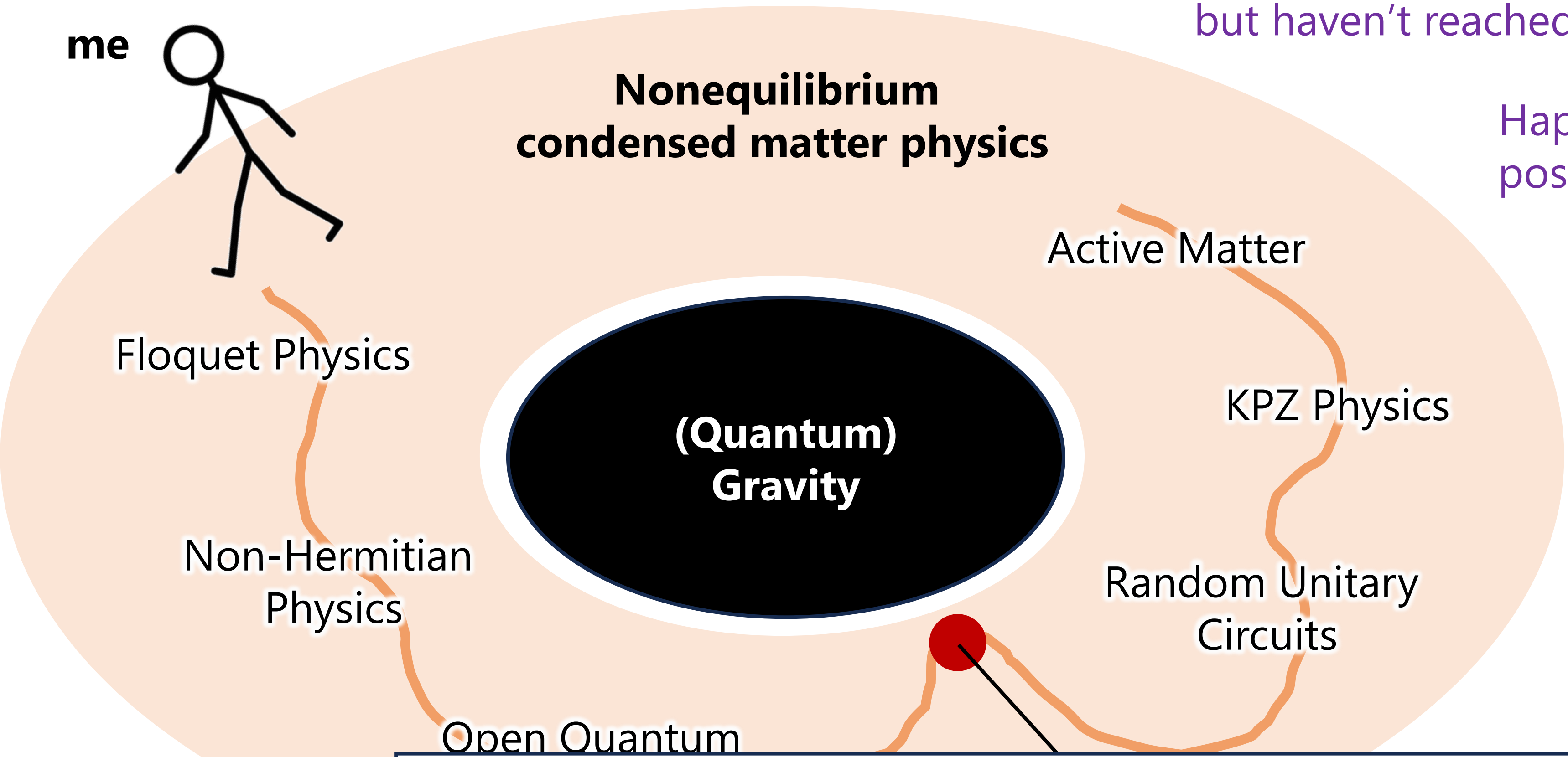
OK

Why I put “gravity” in the title of this talk

Because I’m interested in.

I feel attracted to it,
but haven’t reached the center yet

Happy to discuss
possible connections



me

**Nonequilibrium
condensed matter physics**

Active Matter

KPZ Physics

Random Unitary
Circuits

Floquet Physics

Non-Hermitian
Physics

Open Quantum

**(Quantum)
Gravity**

Holography,
Entanglement,
SYK, Random Matrix, etc.

Holography can be a tool for
nonequilibrium systems
(applied holography)

Patchwork Conditions for **Holographic Nonlinear Responses**: A Computational Method for Electric Conductivity and Friction Coefficient

S. Ishigaki, S. Nakamura, **KT**, arXiv: 2303.02633

Outline

Research Interests	Nonequilibrium Phases of Matter
Topic 1	Quantum Active Matter
Topic 2	KPZ in the Heisenberg Spin Chain

Collaborators

K. Adachi
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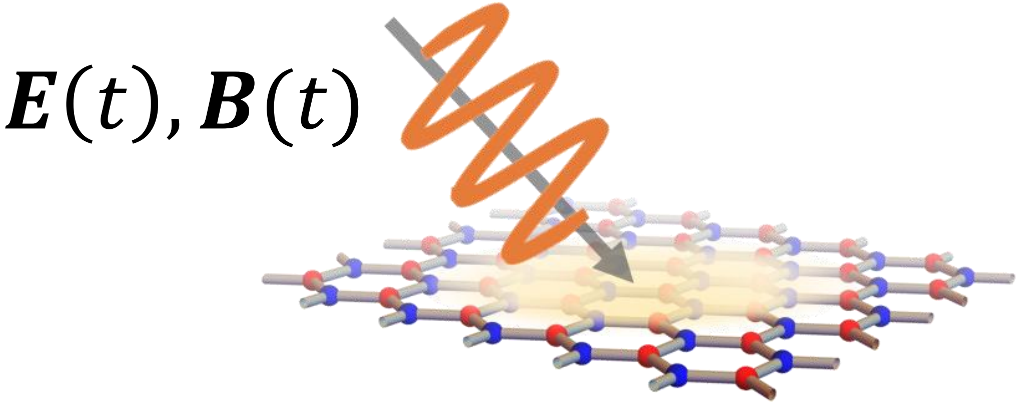
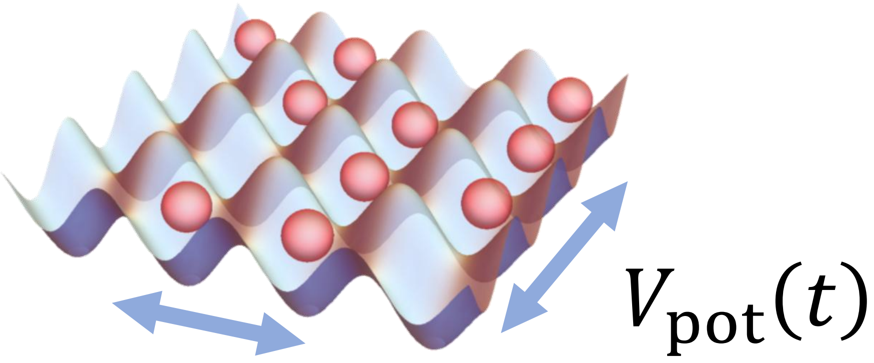
J. De Nardis
Cergy Paris Univ.

Nonequilibrium Phases of Matter

Stable (or metastable) quantum many-body states of matter realized far from equilibrium



Solid-state systems

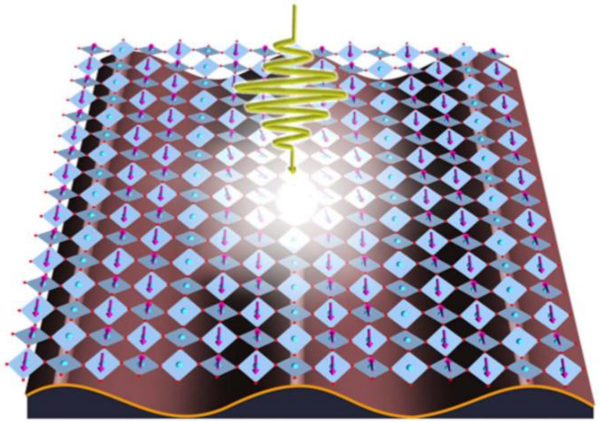


Ultracold atoms

Recent experimental developments allow us to investigate them

Nonequilibrium Phases of Matter

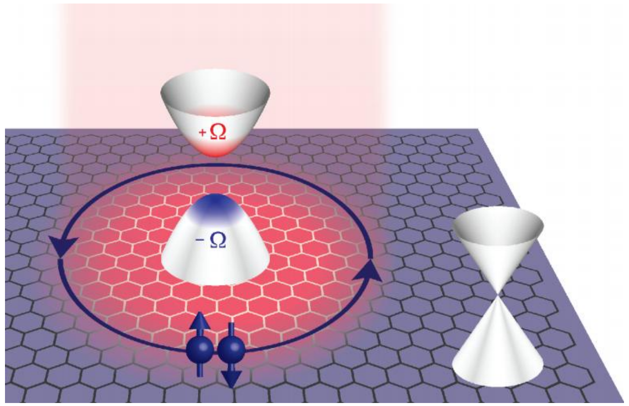
Light-induced superconductivity



Fausti *et al*. Science (2011), Kaiser *et al*. PRB (2014), Mitrano *et al*. Nature (2016), …

SC-like response even in room temperature

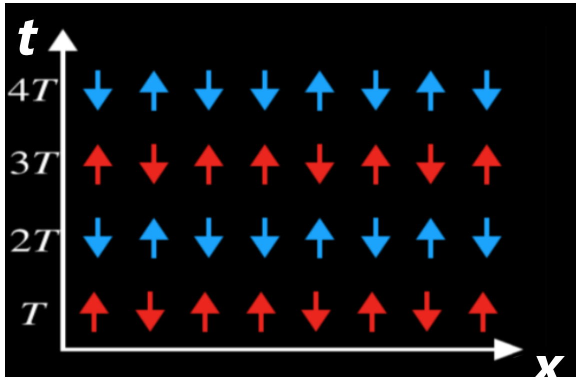
Floquet topological phases



Oka and Aoki PRB (2009), Jotzu *et al*. Nature (2014), McIver *et al*. Nat. Phys (2019)

Ultrafast (fs~ps) control of topological nature

Discrete time crystal



Else *et al*. PRL (2016), Khemani *et al*. PRL (2016), Zhang *et al*. Nature (2017), …

SSB in time direction, prohibited in equilibrium

Watanabe and Oshikawa PRL (2015)

Nonequilibrium Phases of Matter

Not limited by the rule in equilibrium states

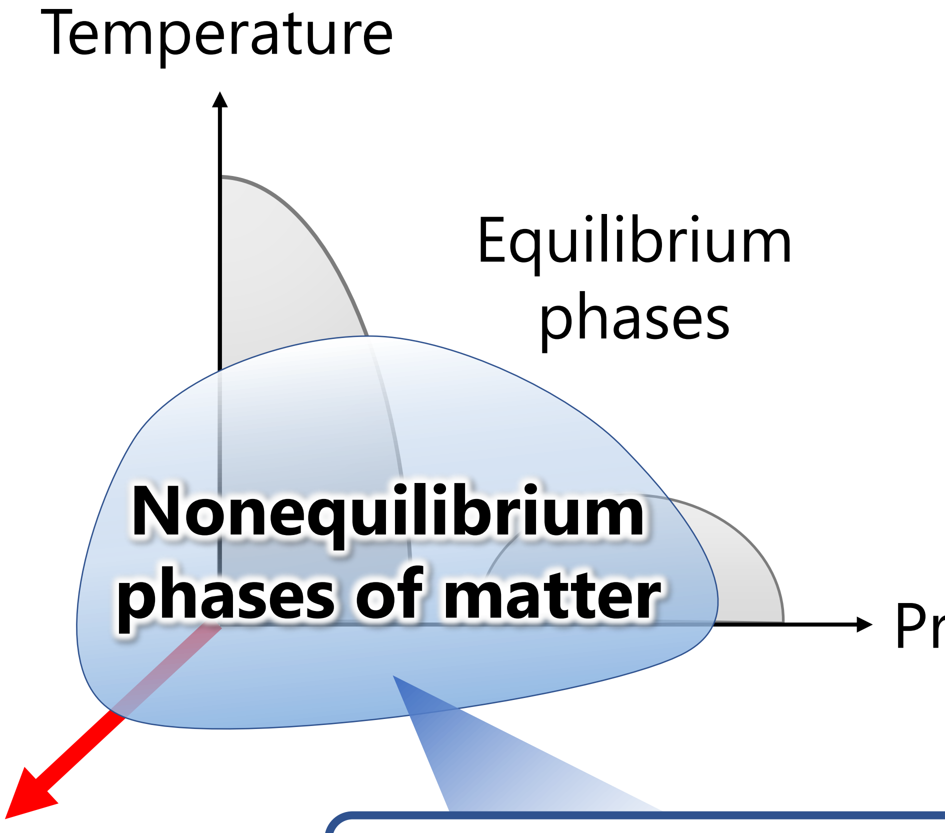
e.g., minimize free energy

Possibility to overcome "limitation" in current condensed matter physics

e.g., room-temp. SC

Deepen our understanding of phases of matter

Future novel technology



Temperature

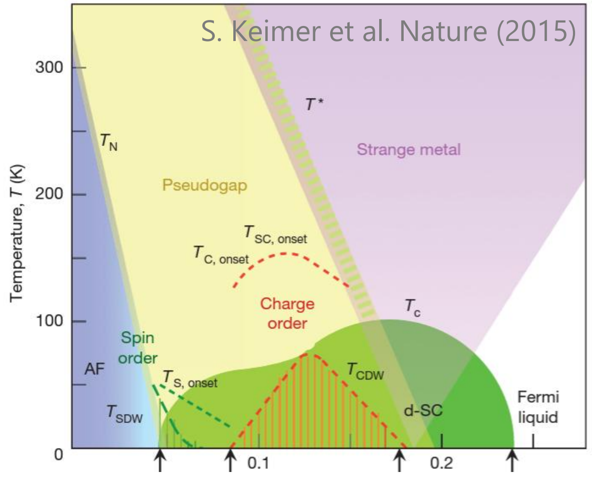
Equilibrium phases

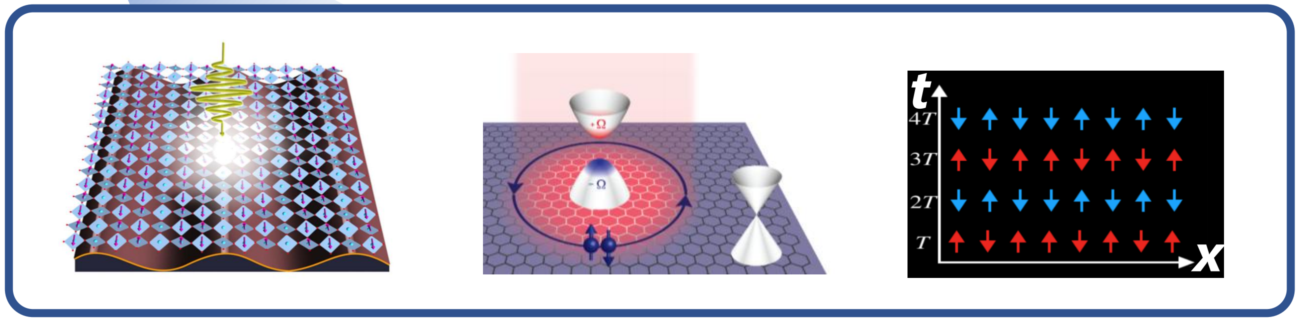
Nonequilibrium phases of matter

Pressure / Doping

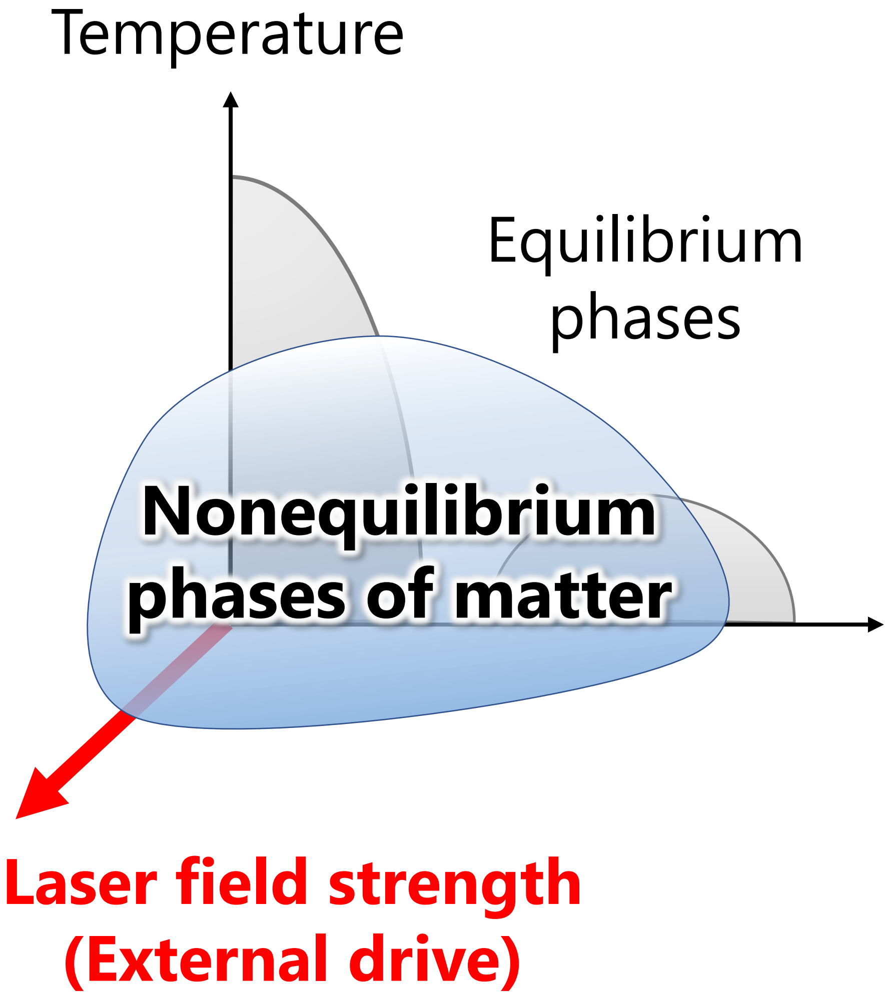
ength

ive)





Nonequilibrium Phases of Matter



Deepen our understanding of phases of matter

Future novel technology

There remain many challenges…

1. To explore new types of phases of matter

Quantum Active Matter (topic 1)

KT*, K. Adachi*, K. Kawaguchi, Phys. Rev. Research **6,** 023096 (2024)
K. Adachi, **KT**, K. Kawaguchi, Phys. Rev. Research **4**, 013194 (2022)

2. To understand their universal aspects

KPZ universality in spin chains (topic 2)

K. A. Takeuchi, **KT**, O. Busani, P. L. Ferrari, R. Vasseur, J. De Nardis, Phys. Rev. Lett. 134, 097104 (2025)

Outline

Research Interests	Nonequilibrium Phases of Matter
Topic 1	Quantum Active Matter
Topic 2	KPZ in the Heisenberg Spin Chain
Discussion	Possible Connections to Gravity

What is active matter ?

Self-propelled
particle

Collection of self-propelled particles = **Active matter**

Nonequilibrium phase transitions not happening in static matter

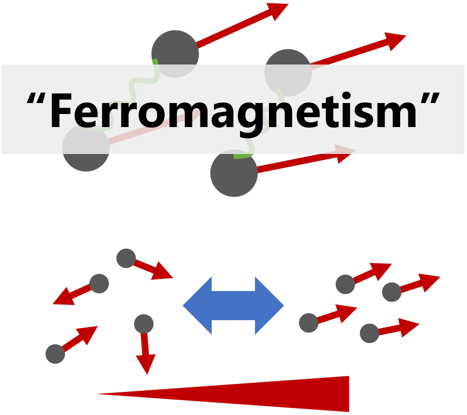
YouTube video "Flight of the Starlings: Watch This Eerie but Beautiful Phenomenon | Short Film Showcase" by National Geographic

Nonequilibrium phase transitions

Nonequilibrium phase transitions not happening in static matter

Flocking transition

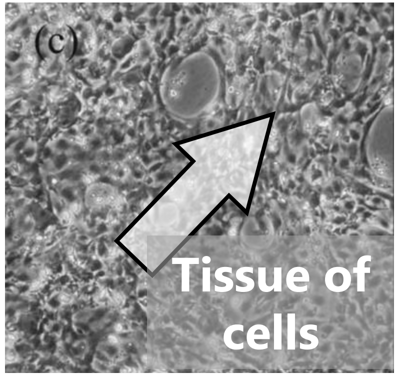
Flock = 群れ in Japanese



+ Aligning interaction

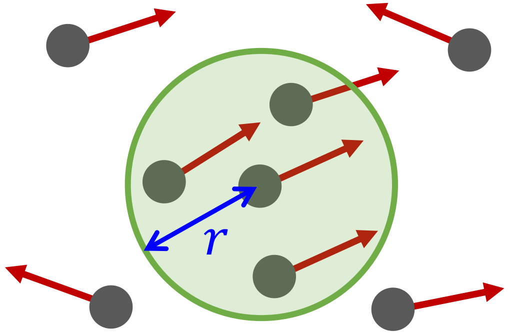
→ SSB of rotational symmetry

Can happen in 2D at finite-T, **PROHIBITED** by the Mermin-Wagner theorem



B. Szabó et al. Phys. Rev. E **74**, 061908 (2006)

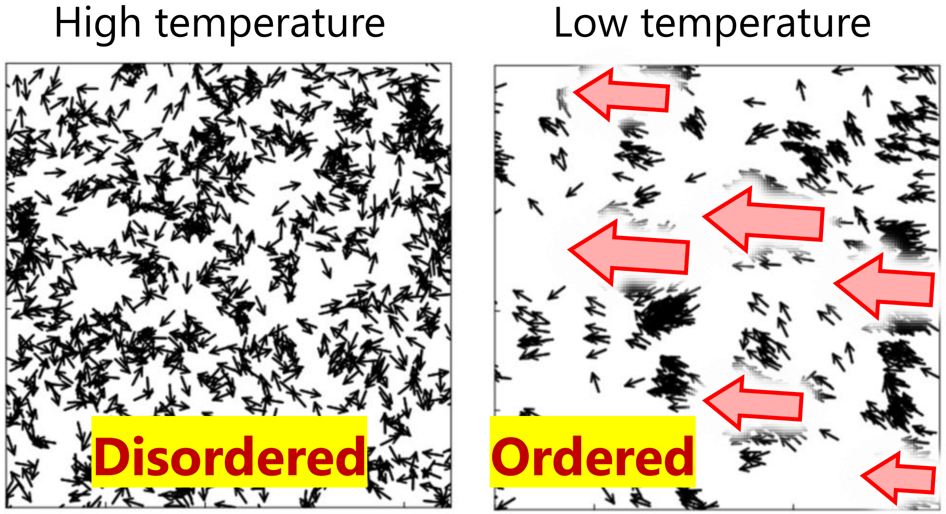
2D Vicsek model



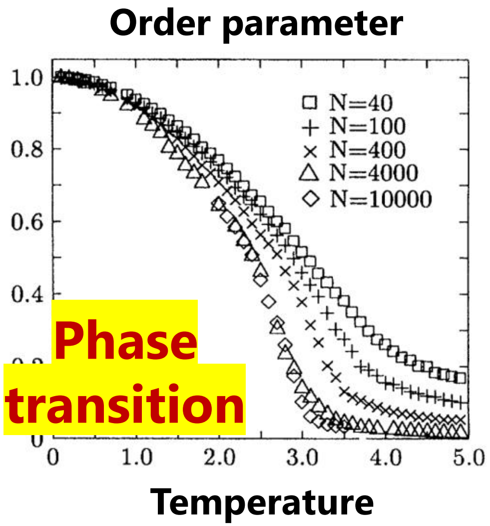
Fixed velocity

Directional noise

T. Vicsek *et al.* PRL (1995)



Video by K. Adachi

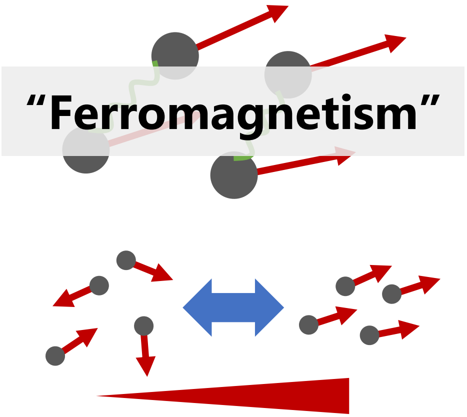


Nonequilibrium phase transitions

Nonequilibrium phase transitions not happening in static matter

Flocking transition

Flock = 群れ in Japanese



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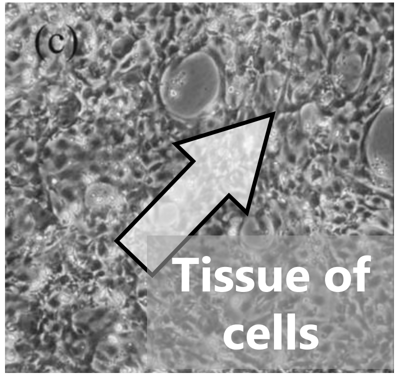
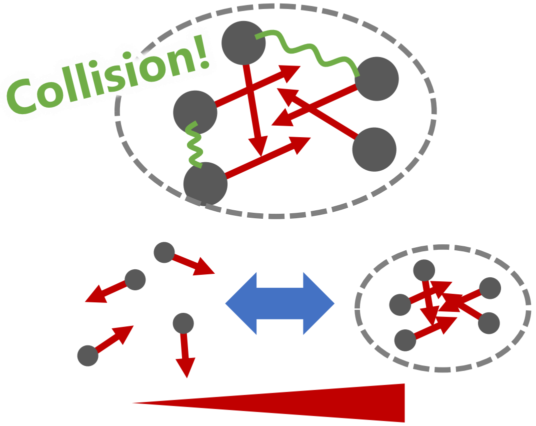


B. Szabó et al. Phys. Rev. E **74**, 061908 (2006)

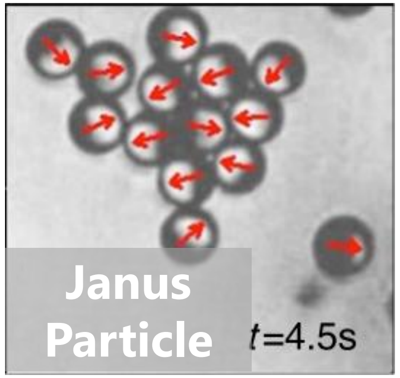
Motility-induced phase separation (MIPS)



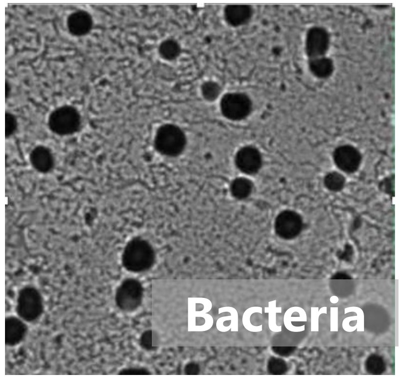
+ Repulsive interaction

→ “Droplet” is formed

Phase separation occurs **WITHOUT** attractive force



I. Buttinoni et al., Phys. Rev. Lett. **110**, 238301 (2013)

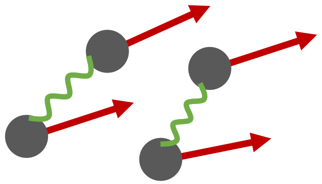


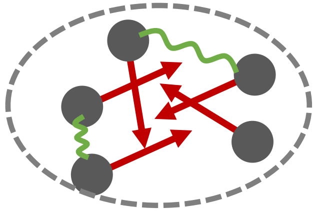
G. Liu et al. Phys. Rev. Lett. **122**, 248102 (2019)

Nonequilibrium phase transitions

Nonequilibrium phase transitions not happening in static matter

Flocking

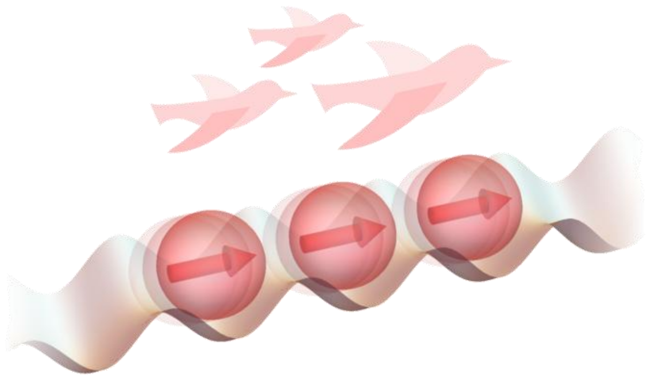




MIPS

Quantum analogue of these phase transitions ?

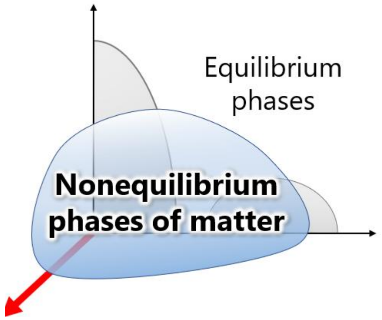
e.g., Increase activity (velocity) → Ferromagnetism



It has **not been considered** when we have started this project…

∵ The main target of active matter physics has been **living things** and it has been studied in the field of **biophysics**

I believe this is a natural question both for stat-phys and cond-mat



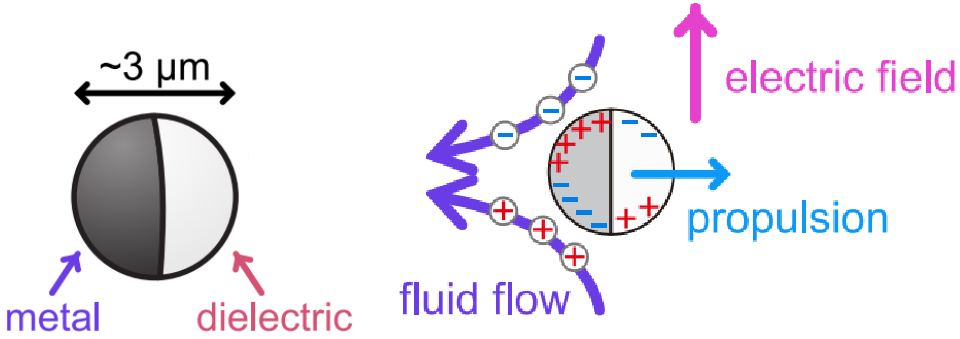
What is (can be) "quantum active matter" ?

We don't know "quantum living things" |

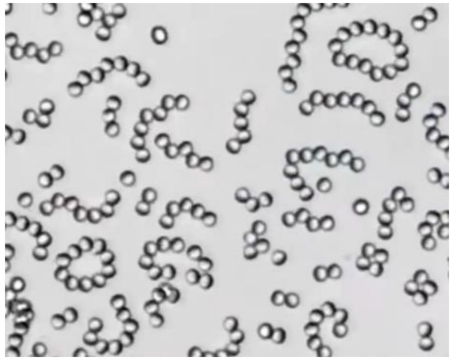
⟩

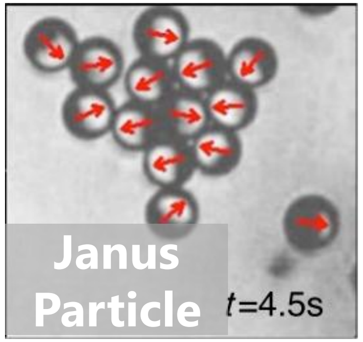
Our strategy: ***Design*** **quantum system that behaves like active matter**

Ex. Janus particle



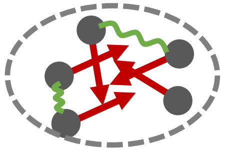
D. Nishiguchi, JPSJ, **92**, 121007 (2023)





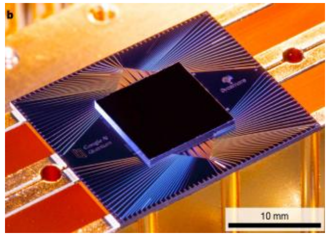
I. Buttinoni et al., Phys. Rev. Lett. **110**, 238301 (2013)

MIPS

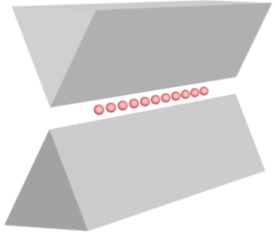


Now, we have various platforms for highly-tunable (programmable) quantum many-body systems

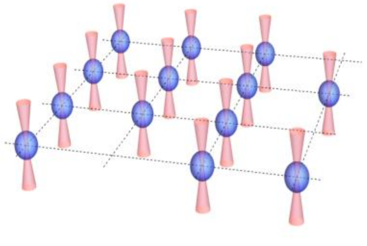
Let's use them to design quantum active matter!



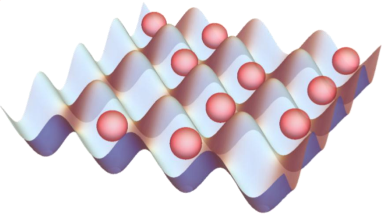
SC qubits



Trapped ions

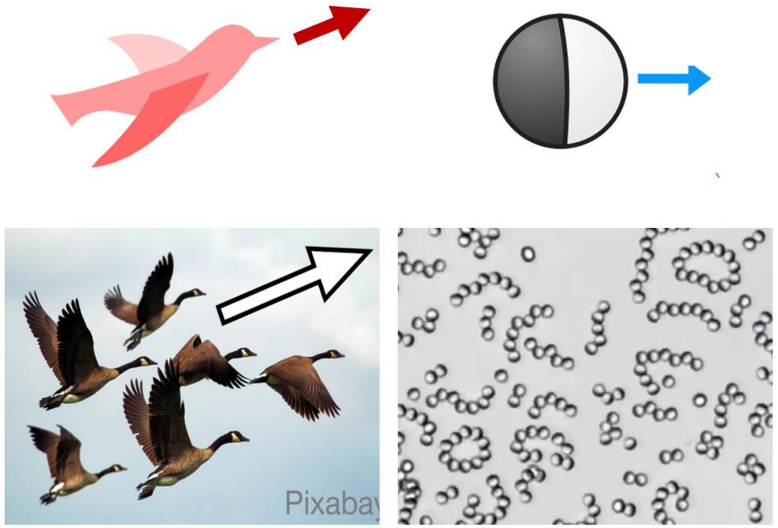


Optical tweezer



Optical lattice

Our guiding principles to construct quantum active matter



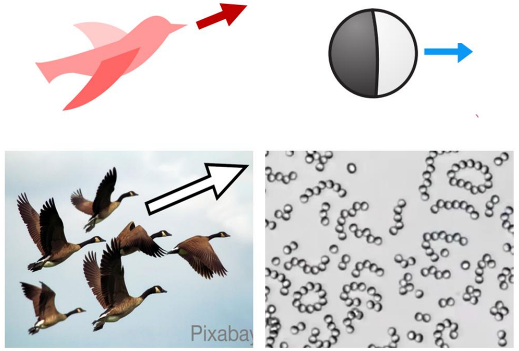
Our guiding principle to construct q. active matter

1. Governed by quantum mechanics
2. Nonequilibrium many-body system
3. Each element has own orientation
4. The orientation can change (no special direction)
5. **The orientation determines the kinetic motion**

Remark: We do not claim that this is the definition

K. Adachi, **KT**, K. Kawaguchi, Phys. Rev. Research **4**, 013194 (2022)
KT*, K. Adachi*, K. Kawaguchi, Phys. Rev. Research **6,** 023096 (2024)

Our quantum active matter model


Pixabay

1. Governed by quantum mechanics
2. Nonequilibrium many-body system
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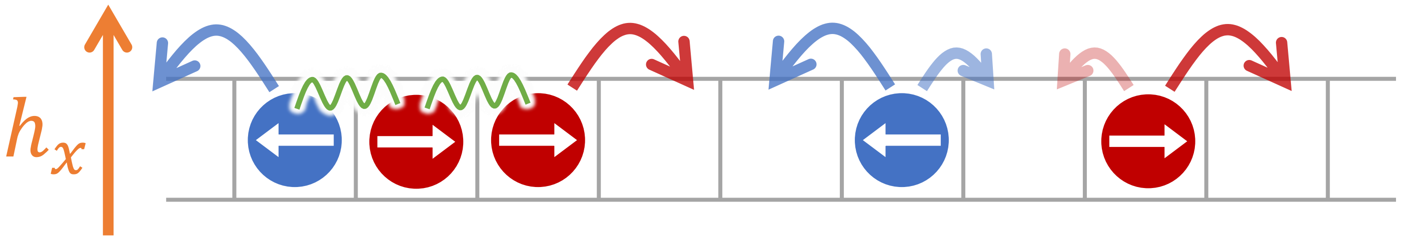
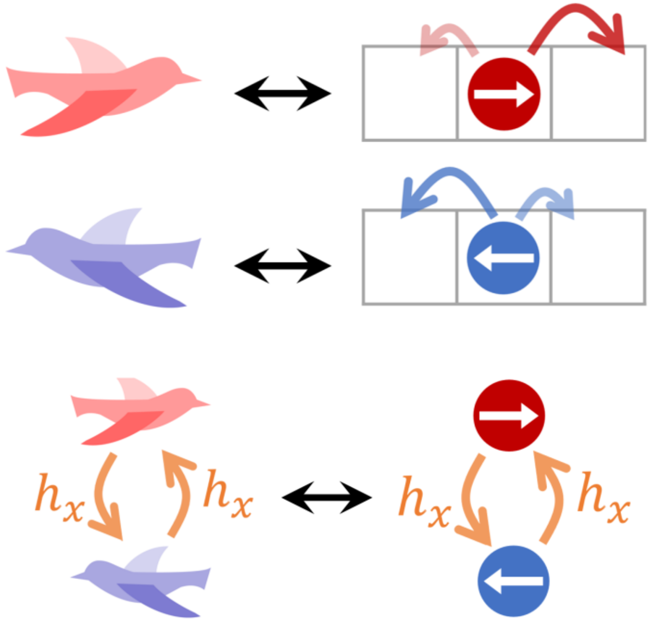
Two-component interacting bosons (fermions) in 1D



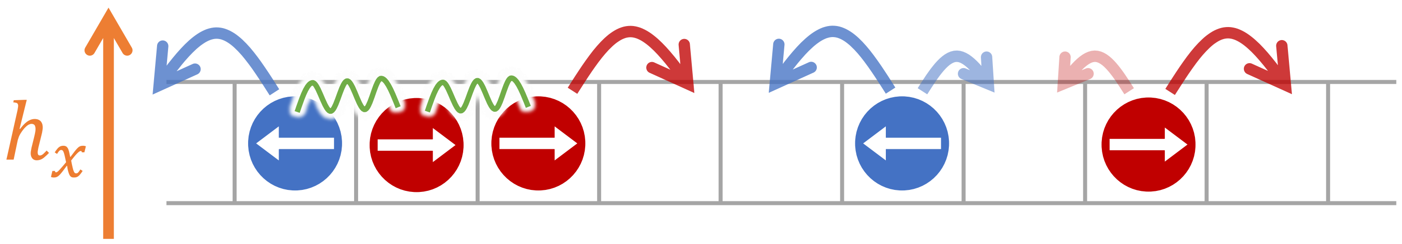


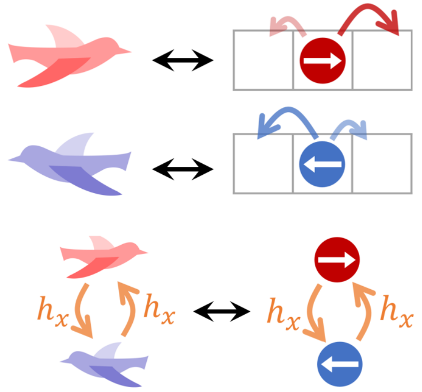
$$\hat{H} = -t\sum_{i=1}^{L}\sum_{s=\pm}\{(1+s\varepsilon)\hat{a}^\dagger_{i+1,s}\hat{a}_{i,s} + (1-s\varepsilon)\hat{a}^\dagger_{i,s}\hat{a}_{i+1,s} - h_x\hat{a}^\dagger_{i,s}\hat{a}_{i,-s}\} + \hat{H}_{\text{int}}$$

One of the simplest models of “quantum active matter”

*not a unique option

Our quantum active matter model





$$\hat{H} = -t \sum_{i=1}^{L} \sum_{s=\pm} \{(1+s\varepsilon)\hat{a}^\dagger_{i+1,s}\hat{a}_{i,s} + (1-s\varepsilon)\hat{a}^\dagger_{i,s}\hat{a}_{i+1,s} - h_x \hat{a}^\dagger_{i,s}\hat{a}_{i,-s}\} + \hat{H}_{\mathrm{int}}$$

1. Relation to classical active matter

$$\boxed{\frac{dp}{dt} = Hp}$$

Master equation of Markov process for active lattice gas model

Asymmetric hopping ⇔ Asymmetric transition rate

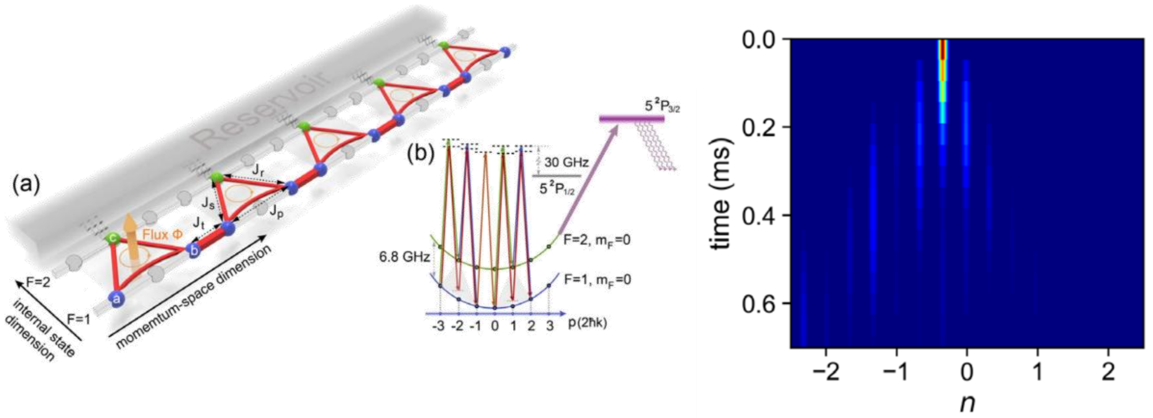
= activity in the classical cases

Our construction is not just an analogy!
Formal reason to call this model "active matter"

K. Adachi, **KT**, K. Kawaguchi, PRR **4**, 013194 (2022)

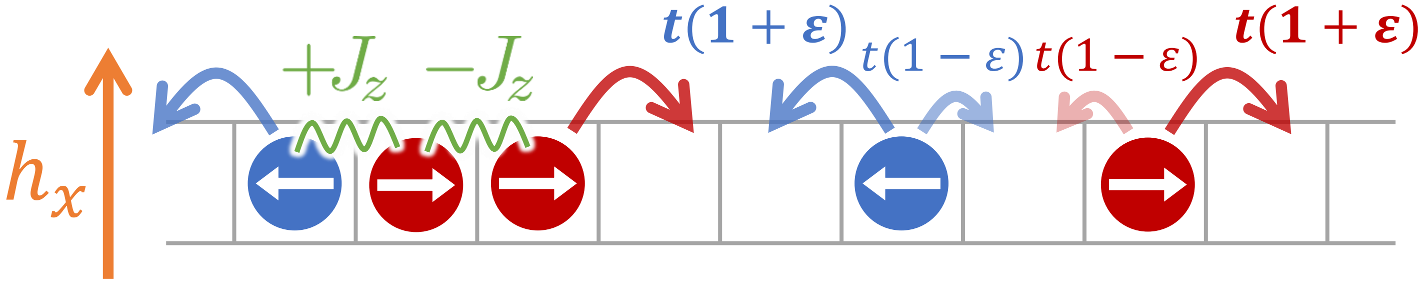
2. Experimental realization

Spin-**independent** one has been realized by ultracold atoms in a dissipative optical lattice



Q. Liang, …, B. Yan, Phys. Rev. Lett. **129**, 070401 (2022)

Model: Non-Hermitian 2-component interacting bosons



$$\hat{m}^z_i = \hat{n}_{i,+} - \hat{n}_{i,-}$$

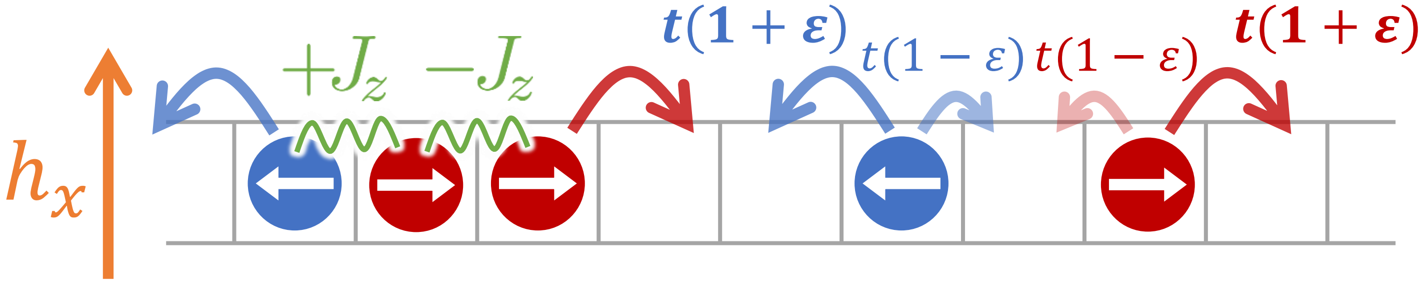
$$\hat{H} = -t\sum_{i,s}\{(1+s\varepsilon)\hat{a}^\dagger_{i+1,s}\hat{a}_{i,s}+(1-s\varepsilon)\hat{a}^\dagger_{i,s}\hat{a}_{i+1,s}\} - h_x\sum_{i,s}\hat{a}^\dagger_{i,s}\hat{a}_{i,-s} - J_z\sum_{i}\hat{m}^z_i\hat{m}^z_{i+1}$$

$$+U\sum_{i}\hat{n}_{i,+}\hat{n}_{i,-}$$

On-site repulsive interaction

KT*, K. Adachi*, K. Kawaguchi, Phys. Rev. Research **6,** 023096 (2024)

Model: Non-Hermitian 2-component interacting bosons



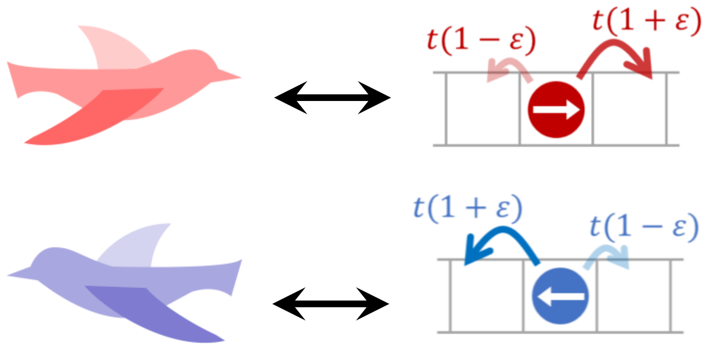
$\hat m_i^z = \hat n_{i,+} - \hat n_{i,-}$

Projection
(hard-core)

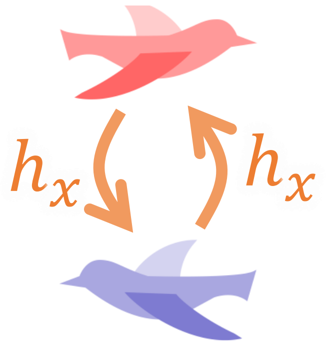
$$\hat H = \hat P_{n\le1}\left[-t\sum_{i,s}\{(1+s\varepsilon)\hat a^\dagger_{i+1,s}\hat a_{i,s}+(1-s\varepsilon)\hat a^\dagger_{i,s}\hat a_{i+1,s}\} - h_x\sum_{i,s}\hat a^\dagger_{i,s}\hat a_{i,-s} - J_z\sum_{i}\hat m_i^z\hat m_{i+1}^z\right]\hat P_{n\le1},$$

Relation to active matter

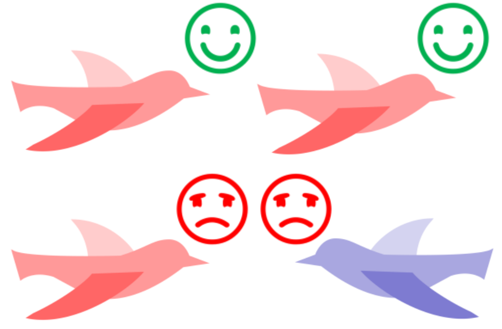
Spin-dep. asymmetric hopping (non-Hermitian)



Transverse mag. field



Ferromagnetic Ising int.

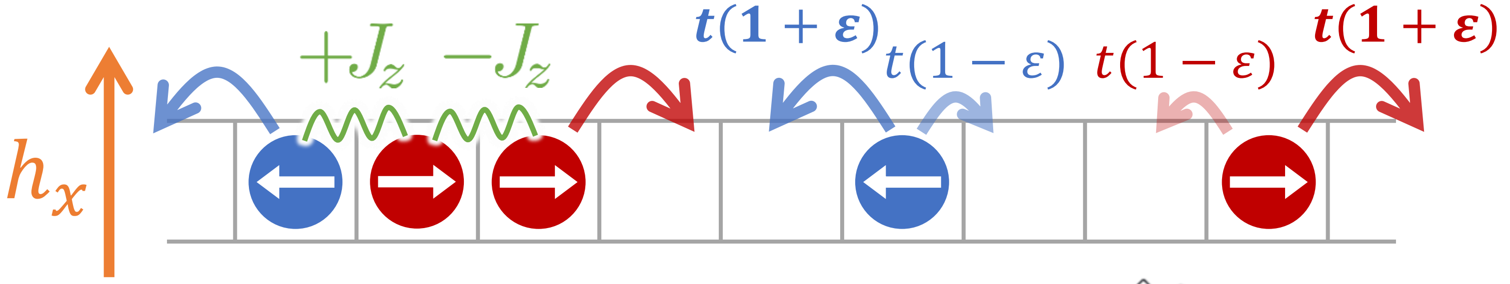


We study the ground state (= the eigenstate with the **smallest Re[E]**) of this model in the following

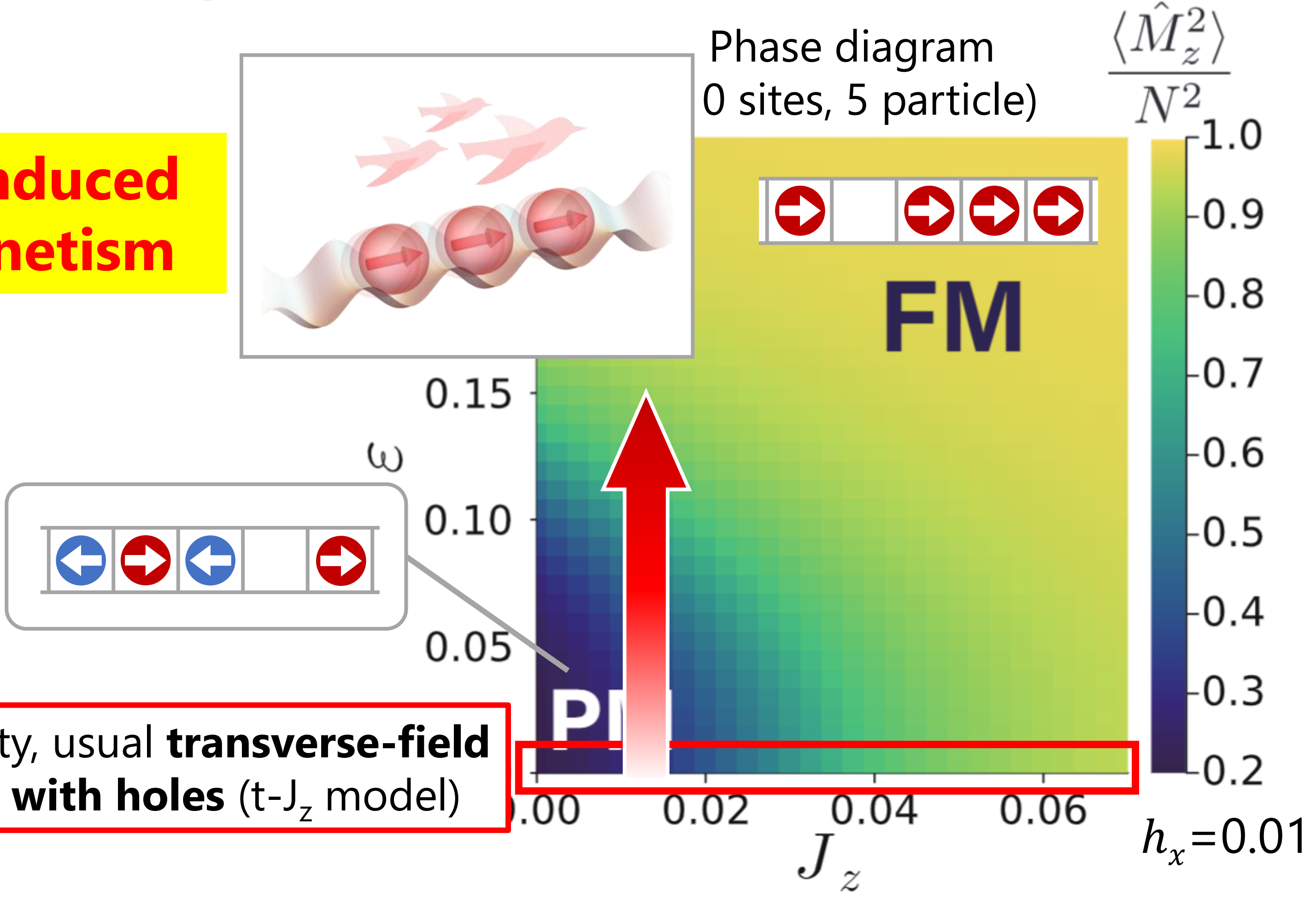
Reasons: 1. Experimentally relevant, 2. Corresponds to the steady state in Markov process

KT*, K. Adachi*, K. Kawaguchi, Phys. Rev. Research **6,** 023096 (2024)

Numerical results: Exact diagonalization

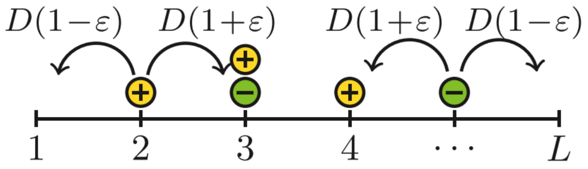


Activity-induced ferromagnetism



Without activity, usual **transverse-field Ising model with holes** (t-J_z model)

cf. Active Ising model (classical)

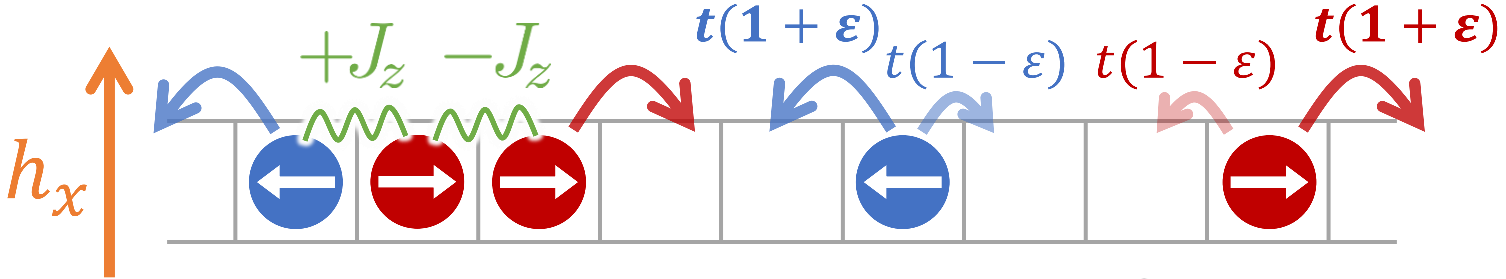


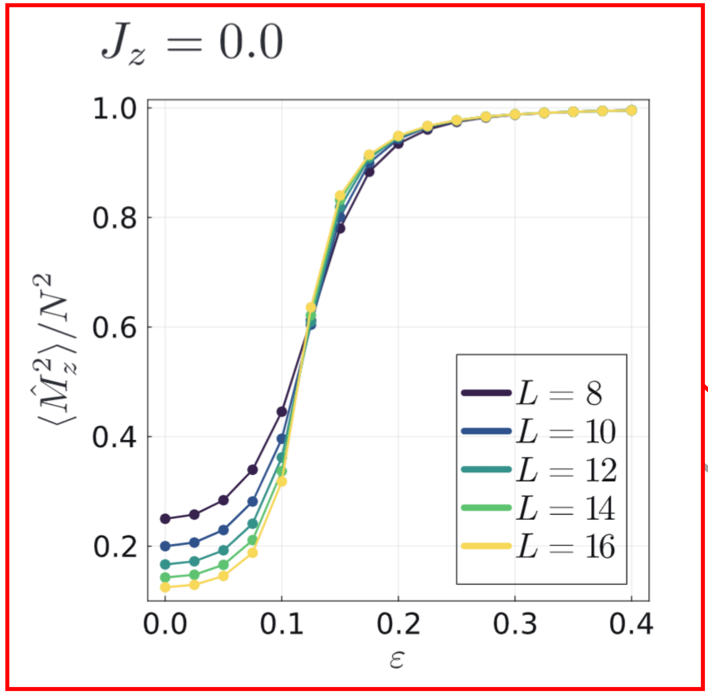
No FM order in 1D

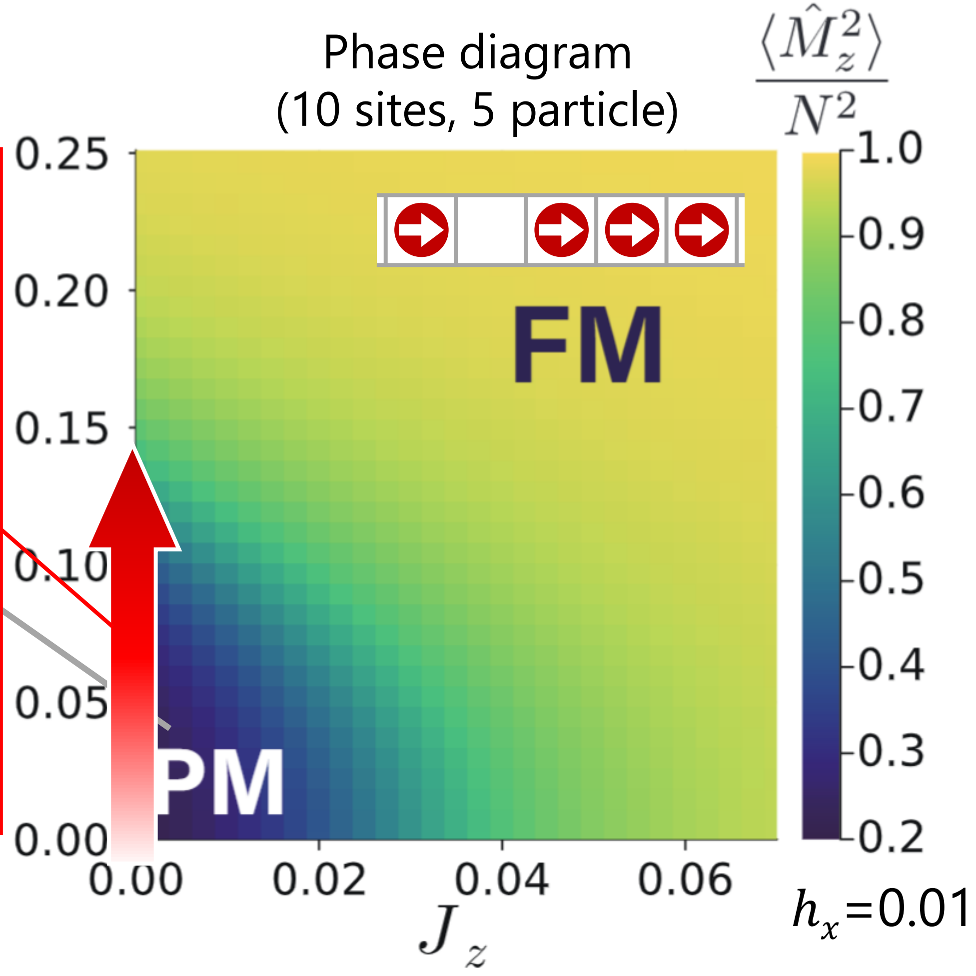
A. P. Solon, J. Tailleur,
Phys. Rev. Lett. (2013);
Phys. Rev. E (2015)

KT*, K. Adachi*, K. Kawaguchi, Phys. Rev. Research **6,** 023096 (2024)

Numerical results: Exact diagonalization



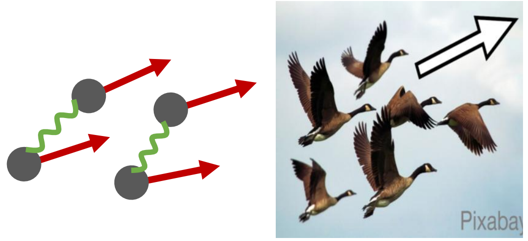



Phase diagram
(10 sites, 5 particle)

h_x=0.01

Ferromagnetic order emerges without the Ising interaction

cf.



Flocking without aligning interaction is a **unique feature of quantum**?

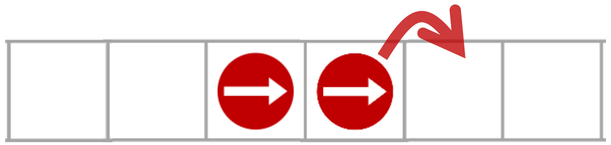
KT*, K. Adachi*, K. Kawaguchi, Phys. Rev. Research **6,** 023096 (2024)

$J_z = 0, h_x = +0$

Two-particle problem

Hamiltonian for the relative motion

Ferromagnetic state $(M = \pm 2)$



$$H = -2t \begin{pmatrix} 0 & 1 & & & & & \\ 1 & 0 & 1 & & & & \\ & 1 & 0 & & & & \\ & & & \ddots & & & \\ & & & & 0 & 1 & \\ & & & & 1 & 0 & 1 \\ & & & & & 1 & 1 \end{pmatrix}$$

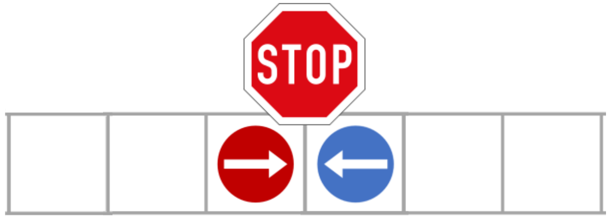
Ground state energy

Ground state

$$\boxed{-4t\cos(\pi/L)}$$

$$\wedge$$

Paramagnetic state $(M = 0)$



“Collision” makes the energy higher!

$$H = -2t \begin{pmatrix} 0 & 1+\varepsilon & & & & \\ 1-\varepsilon & 0 & 1+\varepsilon & & & \\ & 1-\varepsilon & 0 & & & \\ & & & \ddots & & \\ & & & & 0 & 1+\varepsilon \end{pmatrix}$$

$$\boxed{-4t\sqrt{1-\varepsilon^2}\cos(\pi/L)}$$

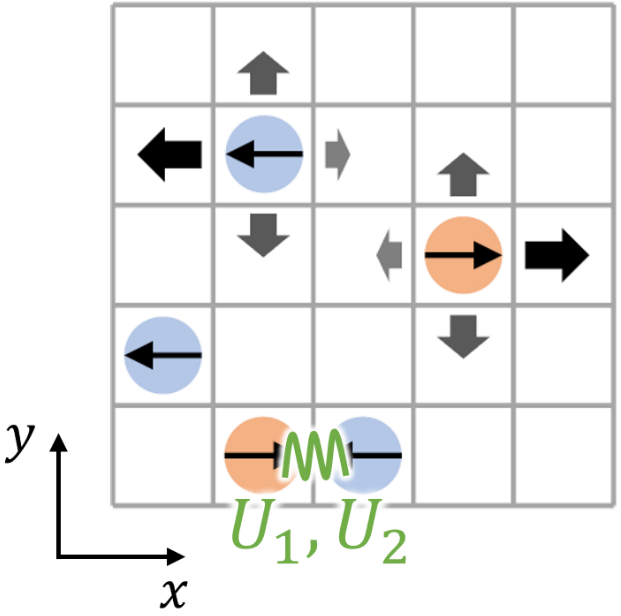
Hatano-Nelson model with OBC

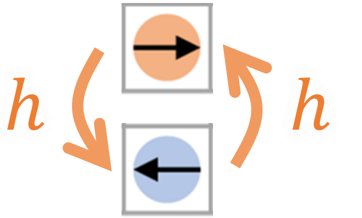
Non-Hermitian skin effect
S. Yao *et al.* PRL (2018)

KT*, K. Adachi*, K. Kawaguchi, Phys. Rev. Research **6,** 023096 (2024)

Two-dimensional quantum active matter

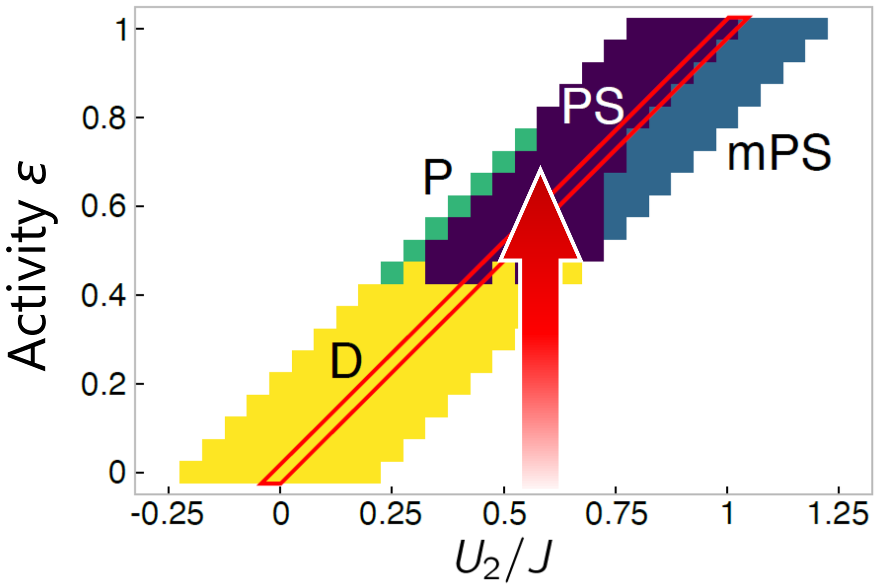
two-component hardcore
bosons on the square lattice



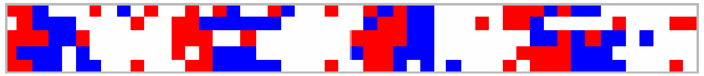


Quantum Monte Carlo simulation
(Diffusion Monte Carlo)

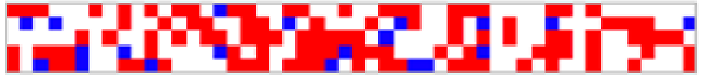
$U_1 = 2J$

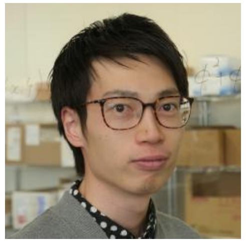


micro PS (mPS)

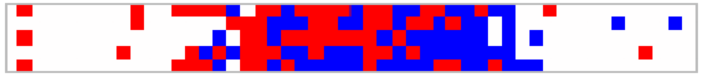


Polar order (ferromag.)

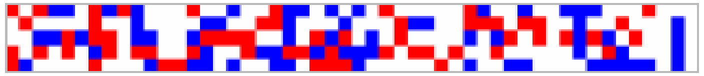




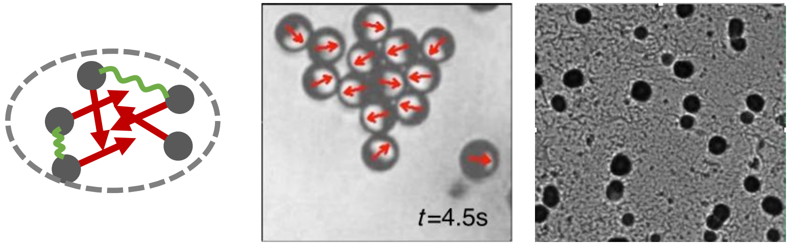
Phase separation



Disorder



MIPS in quantum active matter

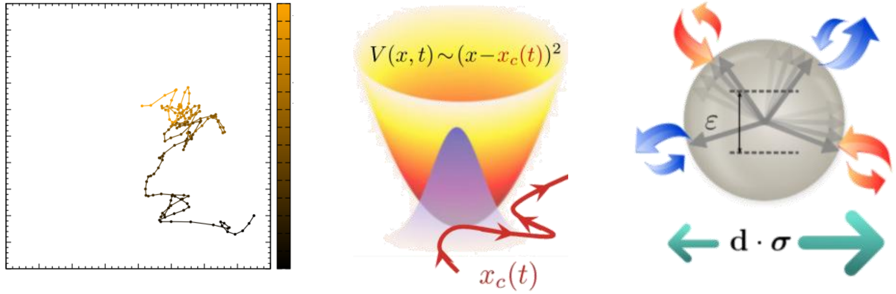


stabilized by quantum effect

K. Adachi, **KT**, K. Kawaguchi, Phys. Rev. Research **4**, 013194 (2022)

Recent Developments

Active quantum particle



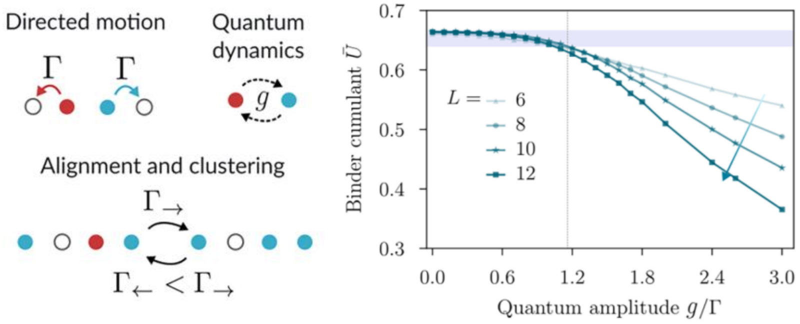
Yamagishi, Hatano, Obuse, Sci. Rep. (2024)

Antonov, Zheng, Liebchen, Löwen, PRR (2025)

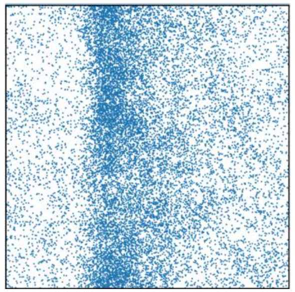
Penner, Viotti, Fazio, Arrachea, von Oppen, PRB (2025)

J. Gipouloux, M. Brunelli, L. Cugliandolo, R. Fazio, M. Schirò, arXiv (2026)

Flocks in different quantum models



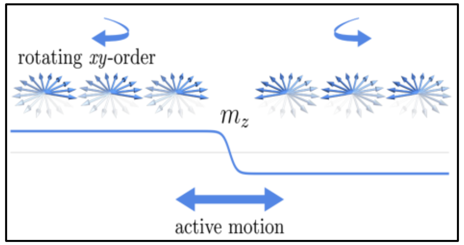
Khasseh, Wald, Moessner, Weber, Heyl, PRL (2025)



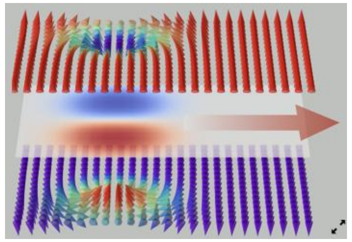
Yuan, Cui, Chen, Sun, arXiv (2024)

Steiner, von Oppen, Egger arXiv (2026)

Topological spin texture behaving like active matter

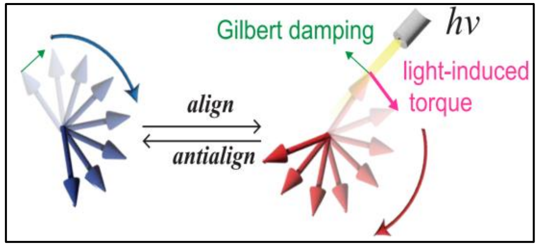


Hardt, Doostani, Diehl, del Ser, Rosch, Nat. Comm. (2025)



de Souza Silva, Correia, Pina Velasquez PRL (2025)

Nonreciprocal phase transitions



Hanai, Ootsuki, Tazai, Nat. Comm. (2025)

Challenges: 1. Properties unique to "quantum" active matter? , 2. Universal description, 3. Experiments.

Outline

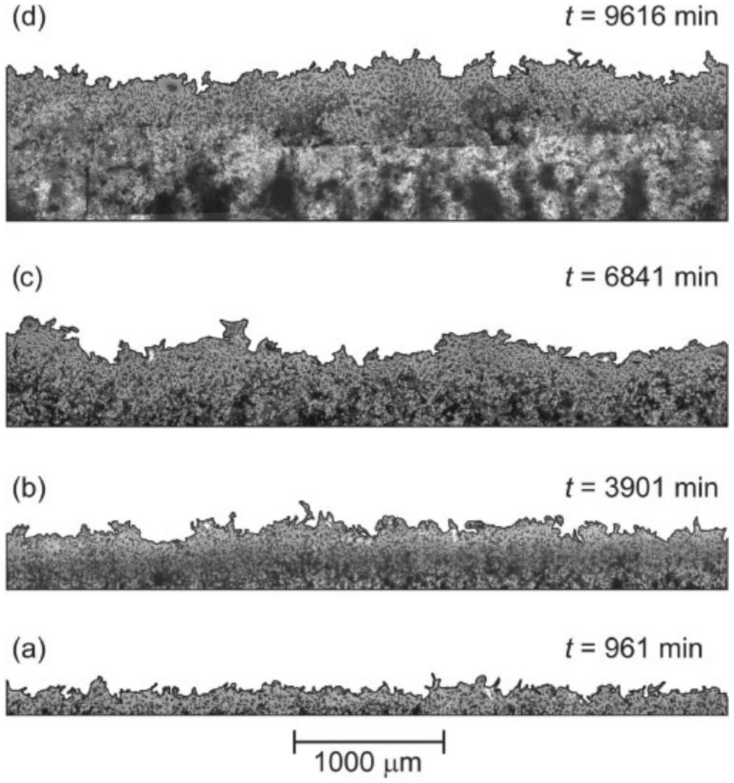
Research Interests	Nonequilibrium Phases of Matter
Topic 1	Quantum Active Matter
Topic 2	KPZ in the Heisenberg Spin Chain
Discussion	Possible Connections to Gravity

Kardar-Parisi-Zhang (KPZ) Universality

= One of the universality classes for nonequilibrium fluctuations

Interface Growth

Cancer cells

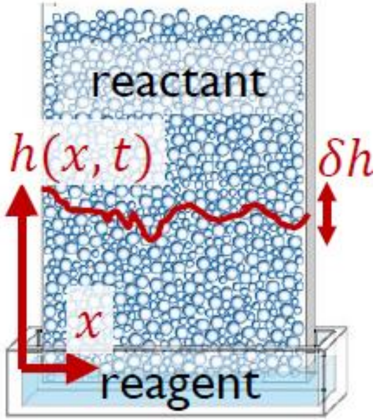


M. A. C. Huergo et al. PRE (2015)

Fire front

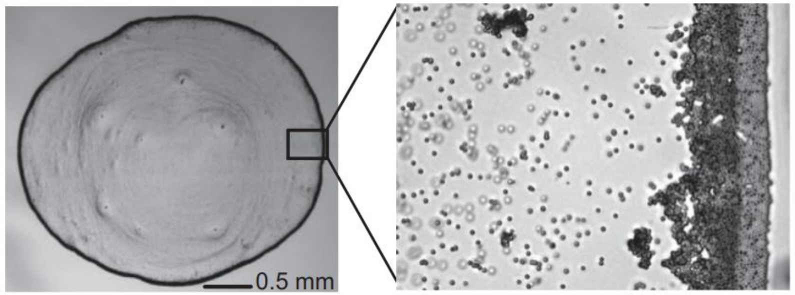
J. Maunuksela et al PRL (1997)

Chemical reaction



S. Atis et al PRL (2013)

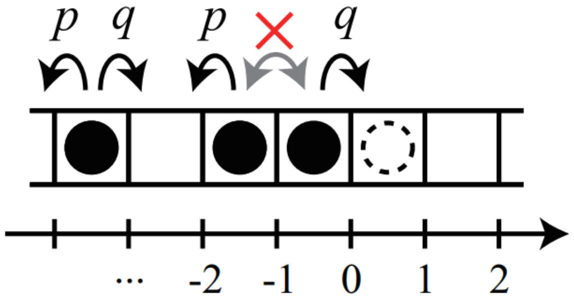
Particle deposition



P.J. Yunker et al. Nature (2011)

Particle Transport

ASEP



Nonlinear Fluctuating Hydrodynamics

Anharmonic chain

$$H = \sum_{j=1}^{N} \left(\tfrac{1}{2} p_j^2 + V(q_{j+1} - q_j) \right)$$

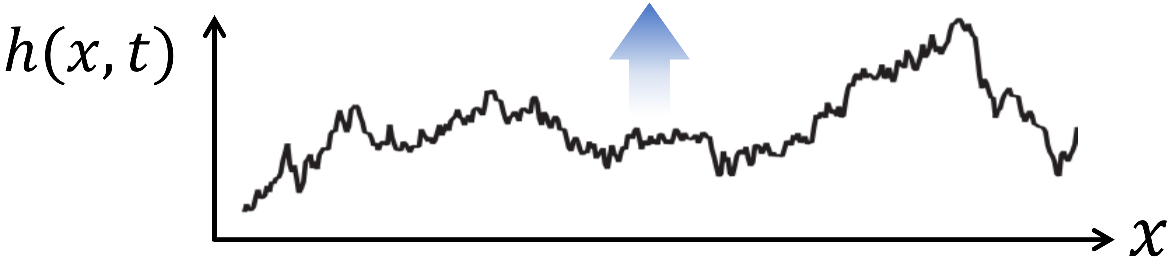
Caveat: Not all interface growth are KPZ

Review: K. A. Takeuchi, Physica A 504, 77-105 (2018)

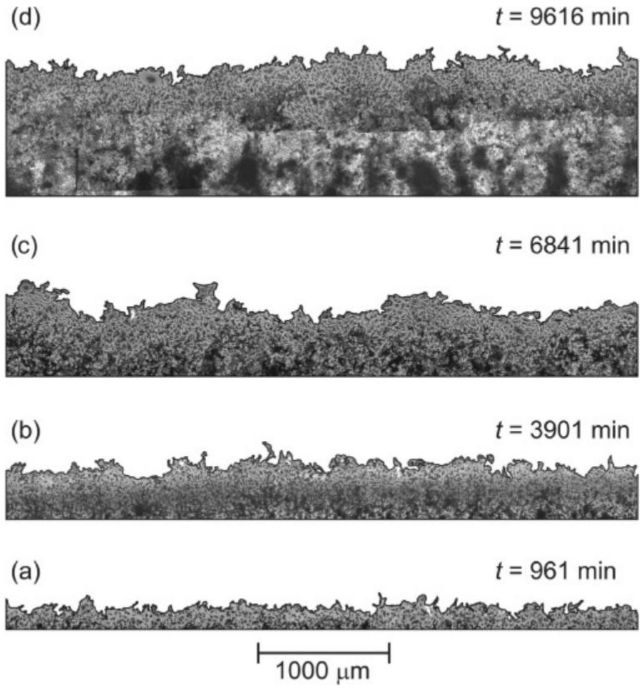
Kardar-Parisi-Zhang (KPZ) Universality

= One of the universality classes for nonequilibrium fluctuations

Interface Growth



Cancer cells



M. A. C. Huergo et al. PRE (2015)

KPZ equation

K.-P.-Z. PRL (1986)

$$\partial_t h = v_0 + \nu \partial_x^2 h + \frac{\lambda}{2}(\partial_x h)^2 + \sqrt{D}\eta$$

Universal Exponent

$$h(x_0,t) \sim v_\infty t + (\Gamma t)^{1/3} \chi_{\mathrm{St}}$$

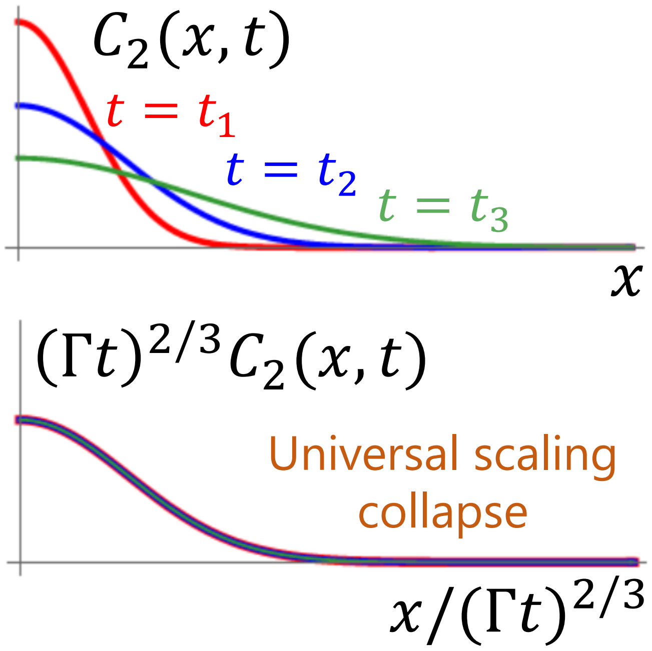
Universal Distribution

Correlation function

$$C_2(x,t) = \langle \partial_x h(x,t) \partial_x h(0,0) \rangle$$

$$\simeq \frac{A}{(\Gamma t)^{2/3}} f_{\mathrm{KPZ}}\left(\frac{x}{(\Gamma t)^{2/3}}\right)$$

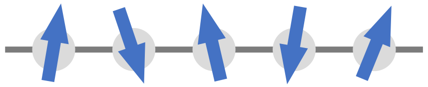
f_{KPZ} : Prähofer–Spohn scaling function



*This talk only treats
the stationary subclass

Emergence of the KPZ universality in a spin chain

Heisenberg spin chain



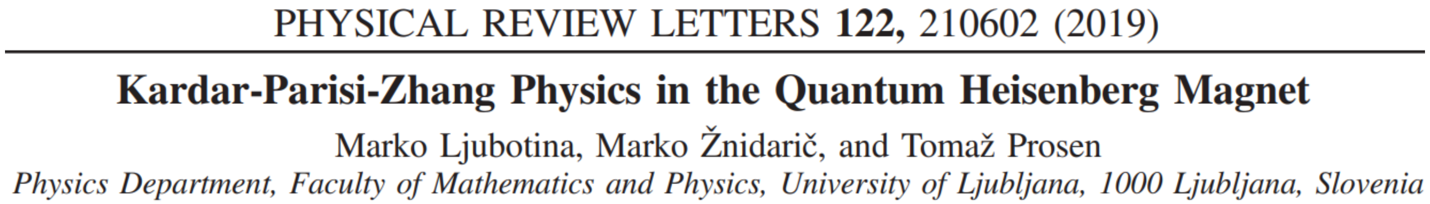
$$\hat{H} = J\sum_{i=1}^{L-1}\hat{\boldsymbol{S}}_i\cdot\hat{\boldsymbol{S}}_{i+1}$$

Two-point function at $T=\infty$

$$\left(\hat{S}^z_x(t) = e^{i\hat{H}t}\hat{S}^z_x e^{-i\hat{H}t}\right)$$

$$C_2(x,t) = \frac{1}{2^L}\mathrm{Tr}[\hat{S}^z_x(t)\hat{S}^z_0(0)]$$

The KPZ scaling function f_{KPZ} emerges in the infinite temperature two-point function !

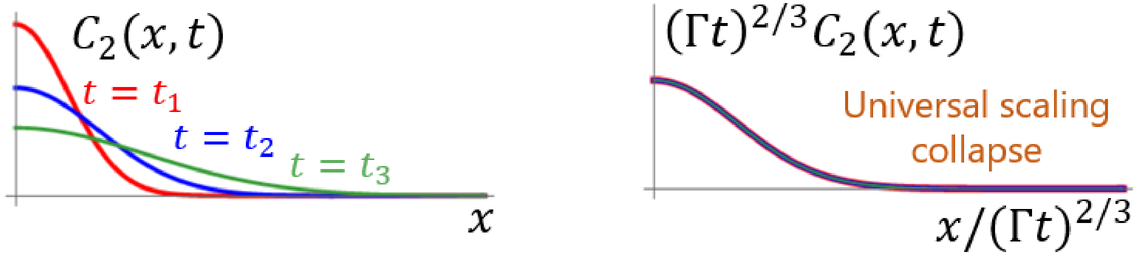


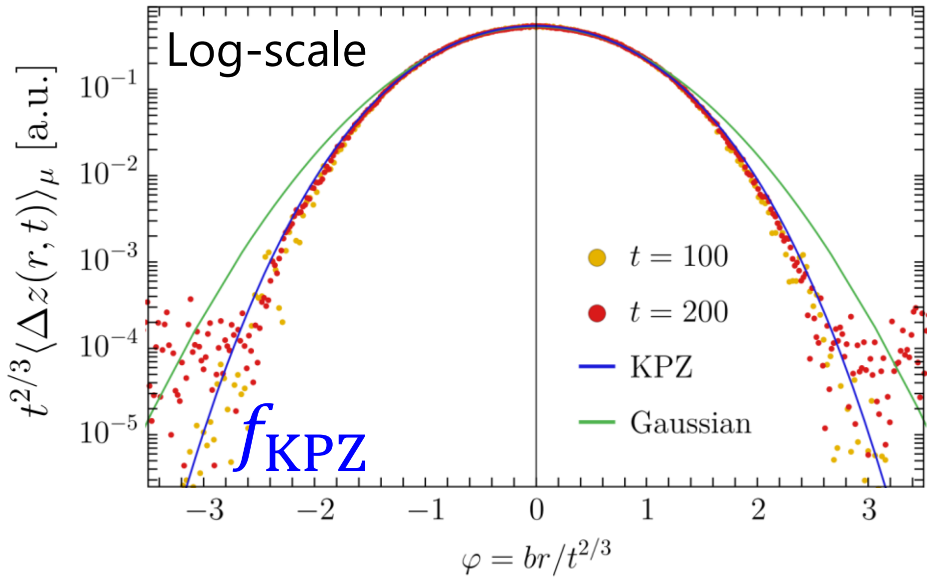
PHYSICAL REVIEW LETTERS **122,** 210602 (2019)

Kardar-Parisi-Zhang Physics in the Quantum Heisenberg Magnet

Marko Ljubotina, Marko Žnidarič, and Tomaž Prosen

Physics Department, Faculty of Mathematics and Physics, University of Ljubljana, 1000 Ljubljana, Slovenia





Surprise

KPZ behavior emerges in deterministic quantum dynamics,
whereas it is conventionally associated with classical stochastic systems.

Remark: The KPZ behavior can also appear in the classical Heisenberg-type spin chain.

Discrepancy with the KPZ predictions

Dictionary

$$C_2(x,t) = \langle \partial_x h(x,t) \partial_x h(0,0) \rangle \simeq \langle S_x^z(t) S_0^z(0) \rangle_{T=\infty}$$

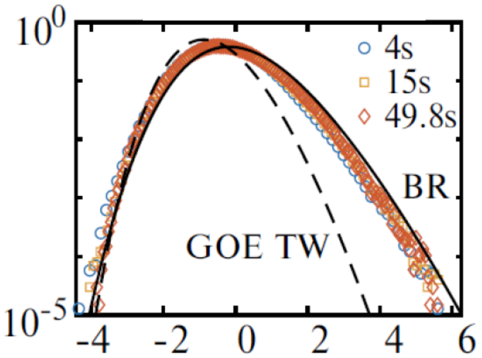
Slope $\partial_x h(x,t) \leftrightarrow -\hat{S}_x^z(t)$

Height $h(x,t) \leftrightarrow \int_0^t \hat{j}_{x+1/2}^z(t)dt =: \hat{Q}(t)$ Integrated spin current

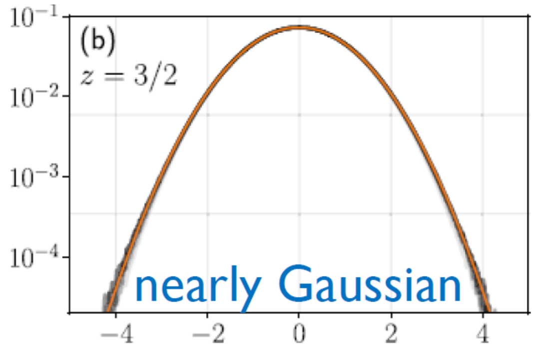
(Spin current op. $\hat{j}_{x+1/2} = \frac{iJ}{2}(S_x^+ S_{x+1}^- - S_x^- S_{x+1}^+)$)

Other quantities not matching with the KPZ predictions

One-point distribution of $h(x,t)$ vs $\hat{Q}_x(t)$



[Iwatsuka et al. PRL (2020)]



[Krajnik et al. PRL (2024)]

Clear discrepancy with the KPZ predictions

$h(x,t)$: Baik-Rains Distribution

Finite Skewness & Kurtosis

$\hat{Q}_x(t)$: Nearly Gaussian

Skewness = 0 & **Kurtosis ≒ 0**

Confirmed via

numerical simulation

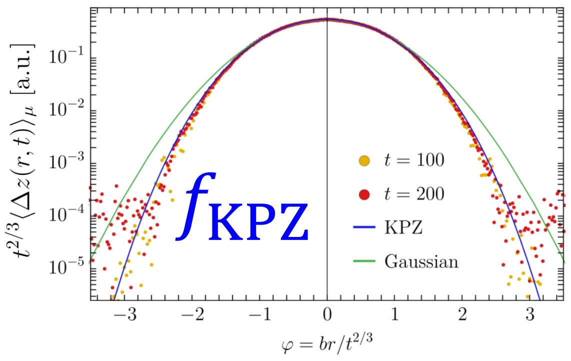
Krajnik et al. Phys. Rev. Lett. 132, 017101 (2024)

and **q. comp. simulation**

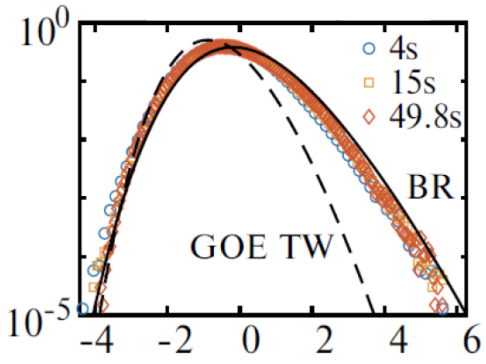
Rosenberg et al. (Google) Science 384, 48 (2024)

Then, is it really KPZ ?

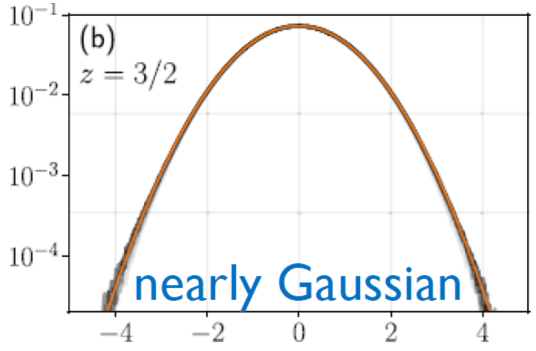
Two- point spin-spin correlation function



One-point distribution of height / Integrated spin current



[Iwatsuka et al. PRL (2020)]



[Krajnik et al. PRL (2024)]

It is not a conventional emergence of the KPZ universality.
But, what's going on here ? We need more information.

Our work K. A. Takeuchi, **KT**, O. Busani, P. L. Ferrari, R. Vasseur, J. De Nardis, PRL 134, 097104 (2025)

Based on the detailed numerical simulation, we have examined other correlators:

- **All the two-point correlators match with KPZ, including the numerical prefactor**
- **Higher-order / non-two-point quantities do not match with KPZ**

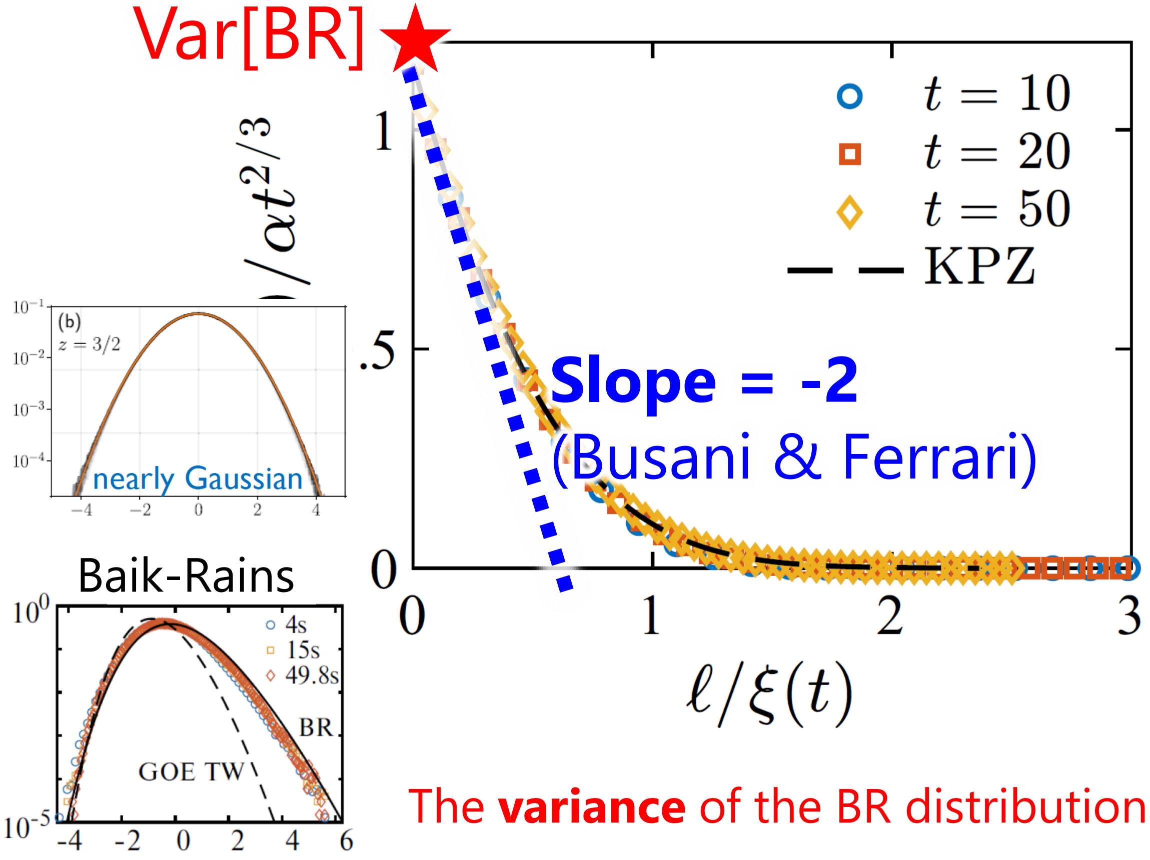
Then, we have concluded that this is a **partial** yet **definite** emergence of the KPZ universality

Our results: Partial yet definite emergence of KPZ

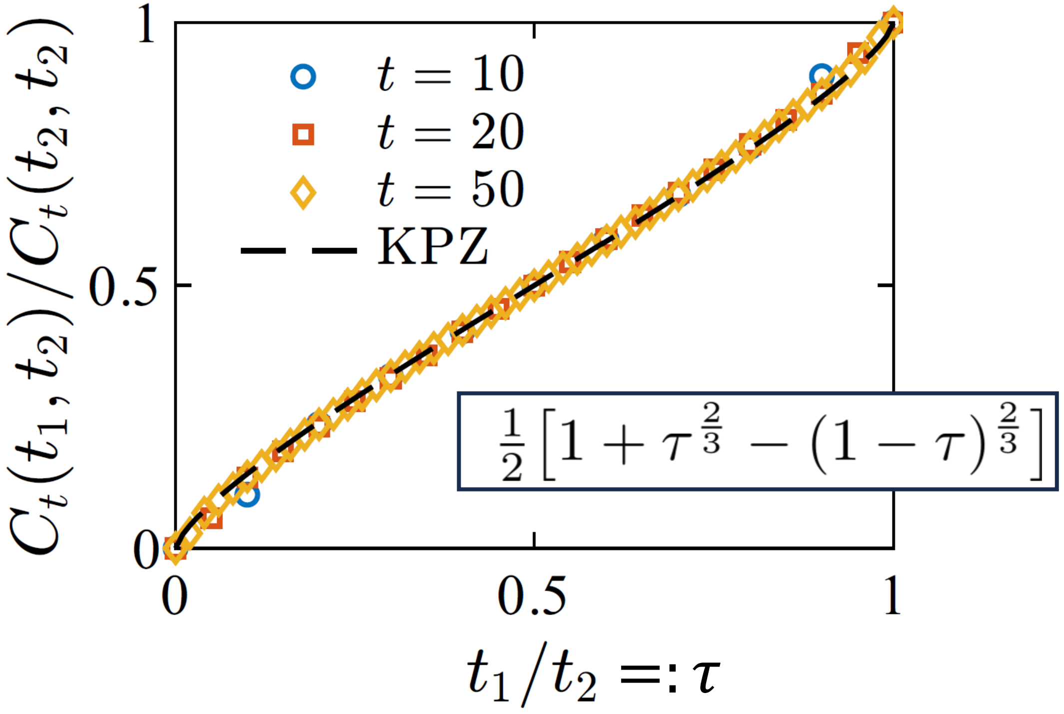
Spatial correlation of integrated spin current $C_s(\ell,t) = \langle h(x,t)h(x+\ell,t)\rangle - \langle h(x,t)\rangle^2$

Temporal correlation of integrated spin current $C_t(t_1,t_2) = \langle h(x,t_1)h(x,t_2)\rangle - \langle h(x,t_1)\rangle\langle h(x,t_2)\rangle$

[c.f. Previous works: two-point spin-spin correlation $C_2(x,t) = \langle \partial_x h(x,t)\partial_x h(0,0)\rangle$]



The **variance** of the BR distribution appears !



Recent situation

1. Extending the quantum lattice models showing the KPZ-like behavior

i. Integrability and **ii . Non-Abelian symmetry** play an important role

e.g., One-dimensional Hubbard model C. P. Moca et al. PRB 108, 235139 (2023)

Remark: The dynamical exponent $z = 3/2$ (superdiffusion) is not enough to claim KPZ.
The **scaling function** needs to be examined.

$\xi(t) \sim t^{1/z}$

Sharp conditions to obtain the KPZ behavior are not obtained yet.

2. Theoretical/Analytical understanding of the KPZ behavior is still an open problem

Two-component nonlinear fluctuating hydrodynamics

J. De Nardis, S. Gopalakrishnan, R. Vasseur, Phys. Rev. Lett. **131**, 197102 (2023)

Related review: S. Gopalakrishnan, R. Vasseur, Ann. Rev. Cond. Matt. Phys. 15, 159 (2024)

Their hydrodynamics does not reproduce the kurtosis correctly

Further theoretical investigation for why there is the partial emergence is necessary

Outline

Research Interests	Nonequilibrium Phases of Matter
Topic 1	Quantum Active Matter
Topic 2	KPZ in the Heisenberg Spin Chain
Discussion	Possible Connections to Gravity

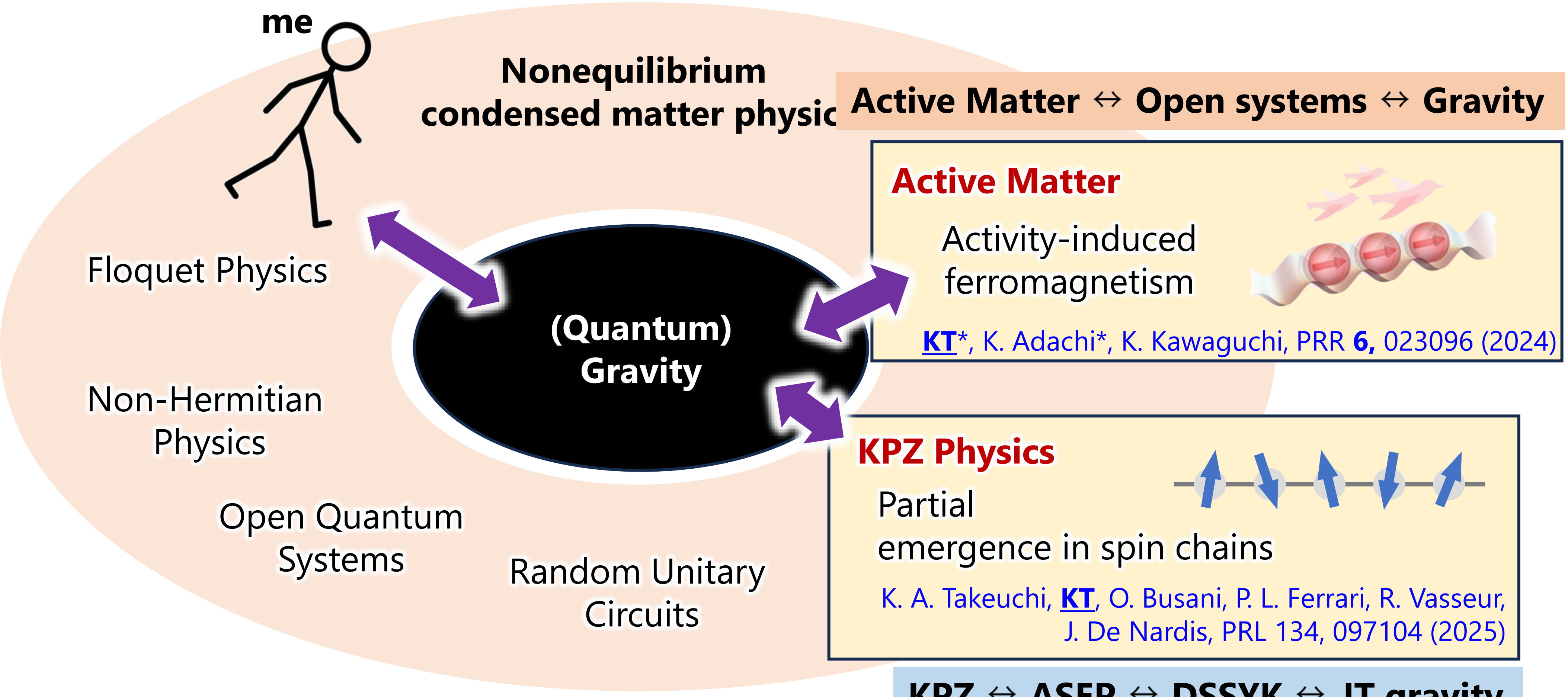
Discussions: Possible Connections to Gravity

Omitted in the shared version

Discussions: Possible Connections to Gravity

Omitted in the shared version

Summary: Active Matter, KPZ, and (possibly) Gravity



me

Nonequilibrium
condensed matter physic

Floquet Physics

Non-Hermitian
Physics

Open Quantum
Systems

Random Unitary
Circuits

**(Quantum)
Gravity**

Active Matter ↔ Open systems ↔ Gravity

Active Matter

Activity-induced
ferromagnetism

KT*, K. Adachi*, K. Kawaguchi, PRR **6,** 023096 (2024)

KPZ Physics

Partial
emergence in spin chains

K. A. Takeuchi, **KT**, O. Busani, P. L. Ferrari, R. Vasseur,
J. De Nardis, PRL 134, 097104 (2025)

KPZ ↔ ASEP ↔ DSSYK ↔ JT gravity

KPZ ↔ Heisenberg spin chain ↔ AdS holography ↔ Gravity etc.

I would be happy to discuss this with you,
hear your ideas, and hopefully explore a possible collaboration.

Kazuaki Takasan (Univ. of Tokyo)
E-mail: takasan@ap.t.u-tokyo.ac.jp