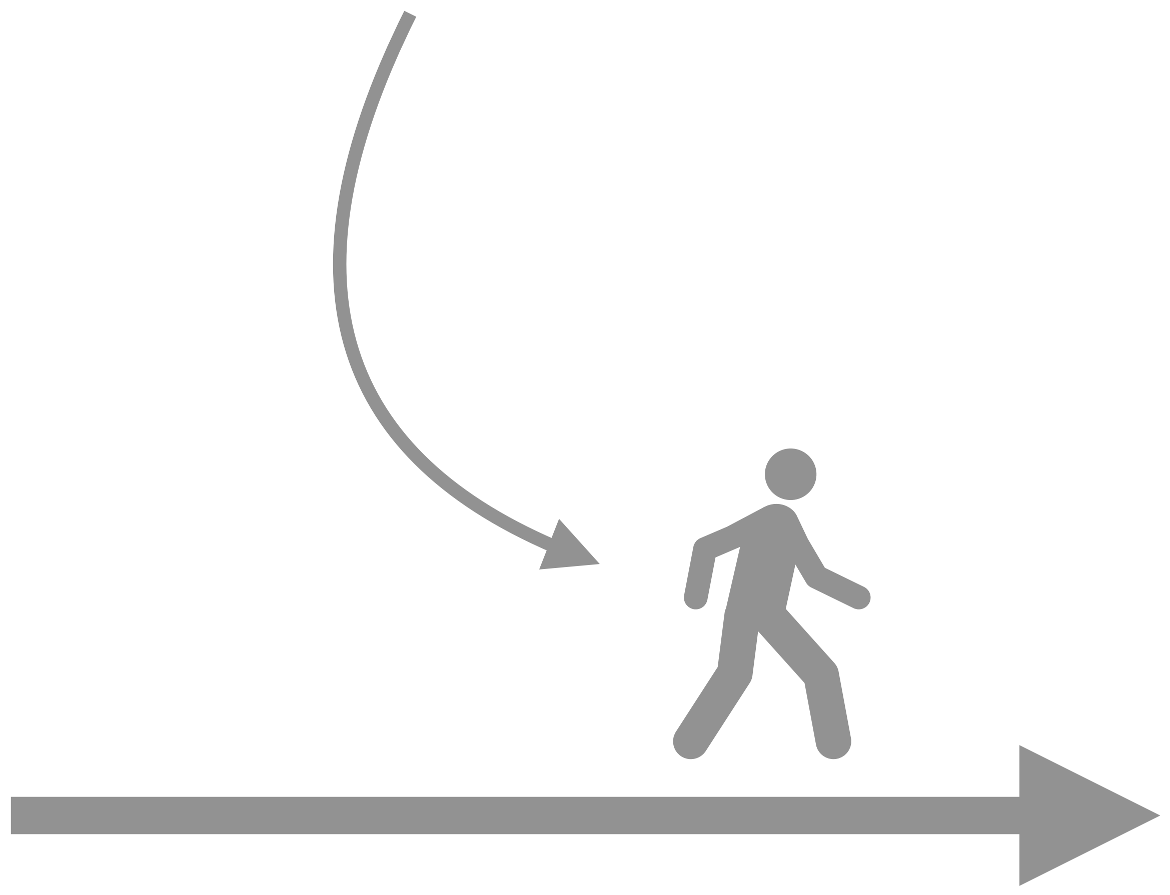
3 November 2025
Physical Colloquium, Universität Oldenburg

Nonreciprocal active matter

— Irreversibility, heat flows, and persistent currents

Sarah A. M. Loos



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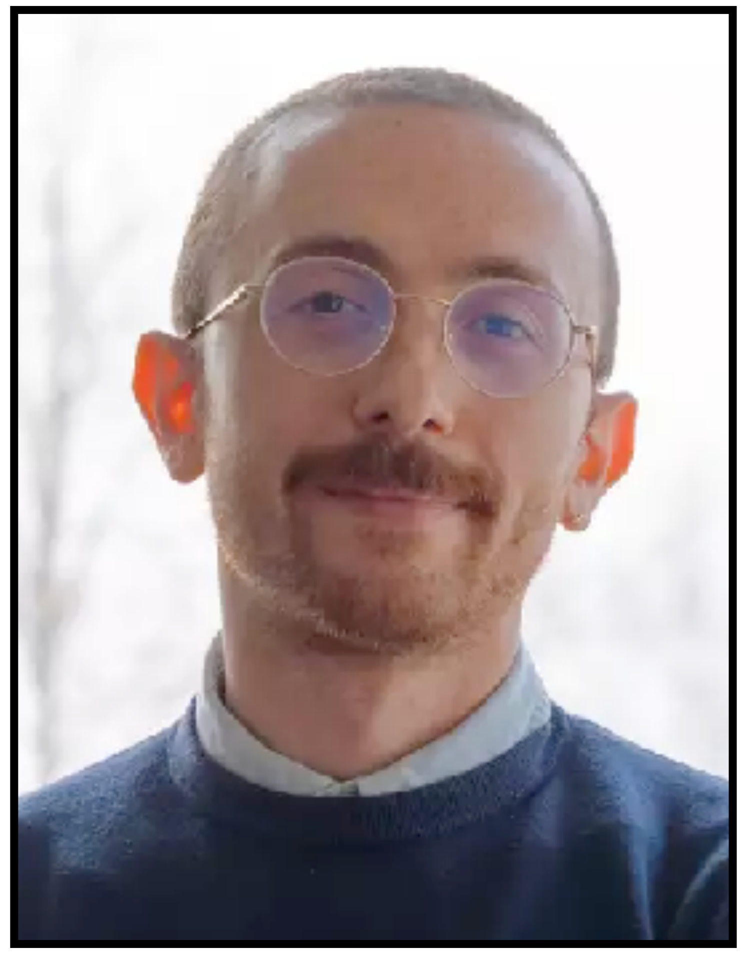
MAX PLANCK INSTITUTE FOR DYNAMICS AND SELF-ORGANIZATION

“Statistical Physics Beyond Equilibrium” - group

MAX PLANCK INSTITUTE
FOR DYNAMICS AND
SELF-ORGANIZATION

Sarah Loos



Gennaro Tucci
Postdoc

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Thomas Suchanek
PhD student

Joint supervision with Klaus Kroy

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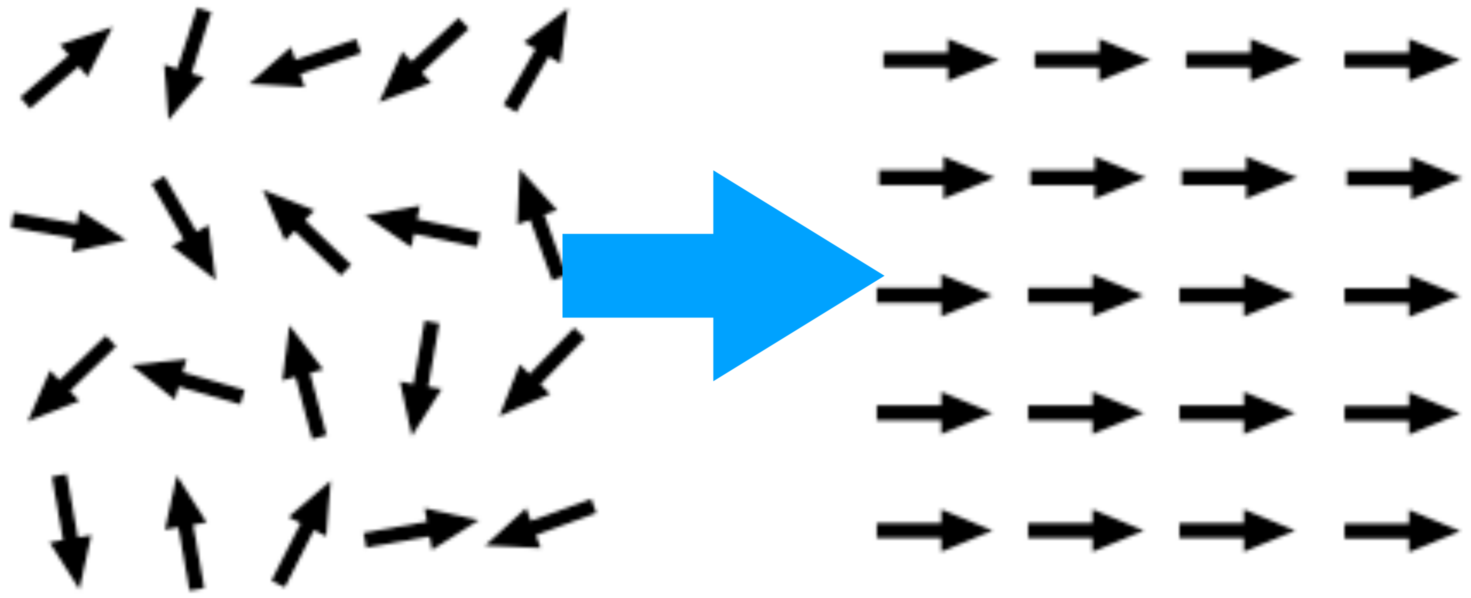
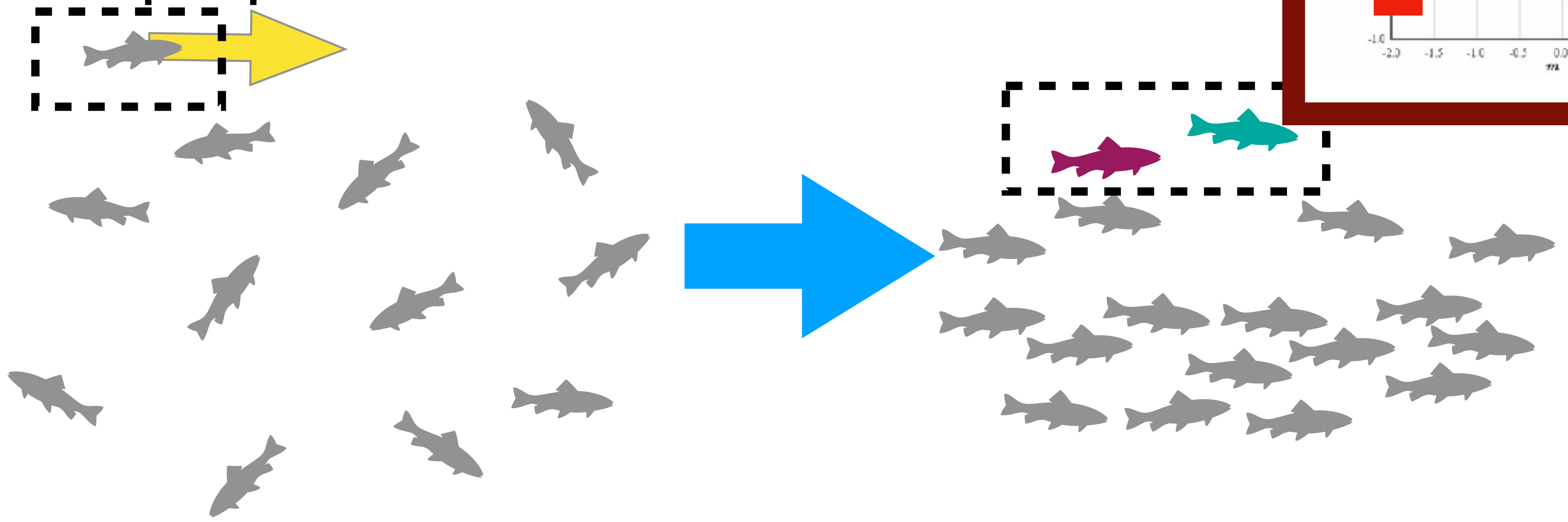
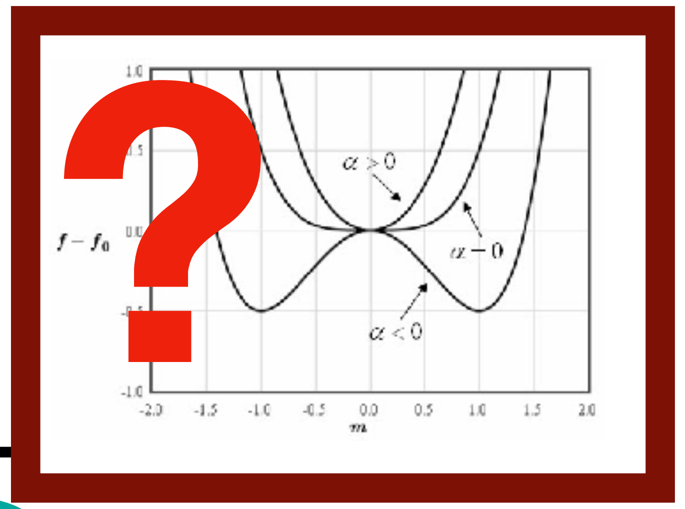
- **Goal:** Extend concepts from statical physics to far from equilibrium systems (including biological systems, synthetic systems under feedback control, micorobotic systems…)
- Focus: Noise, Memory, Nonreciprocity
- Incorporate ideas from **information theory** and **stochastic thermodynamics**

"Passive matter" vs. "Active matter"



Self-propulsion

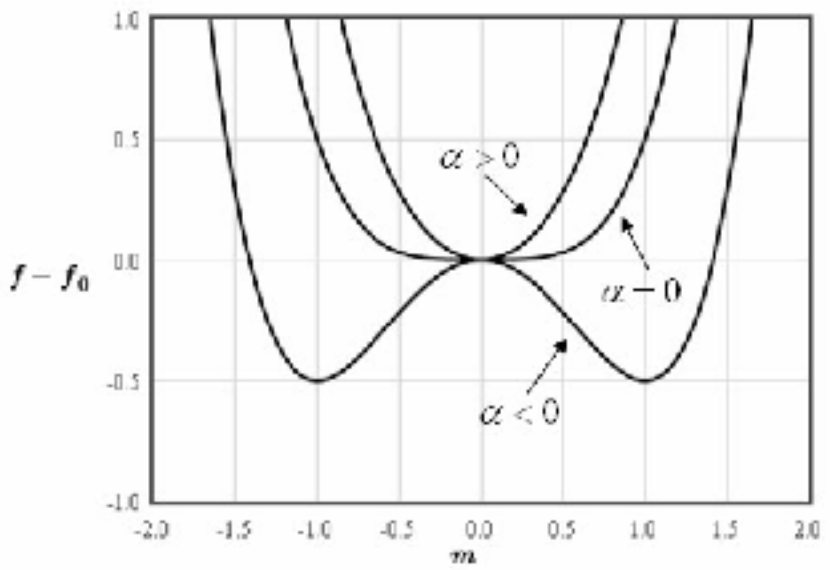




- **Energy input** on level of individual "particles" $\sim X(t)$
  (Not associated with explicit global symmetry breaking)

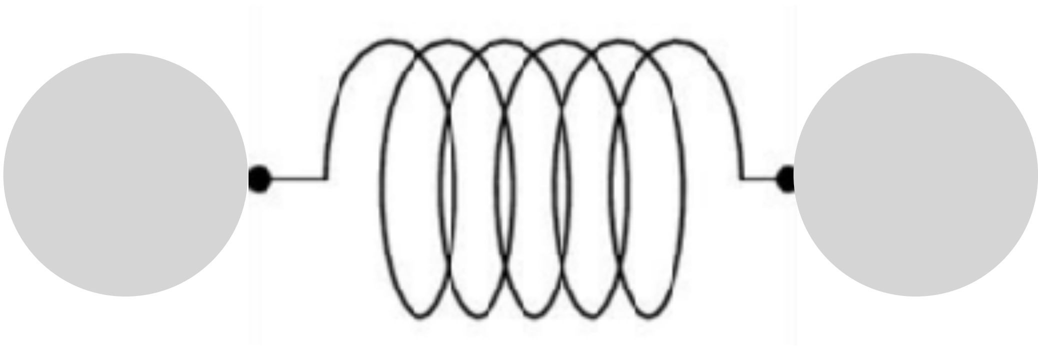
- Conservative Interactions:

Free energy
(Ginsburg-Landau)



$$f(T) = f_0(T) + \alpha m^2 + \frac{1}{2}\beta m^4$$

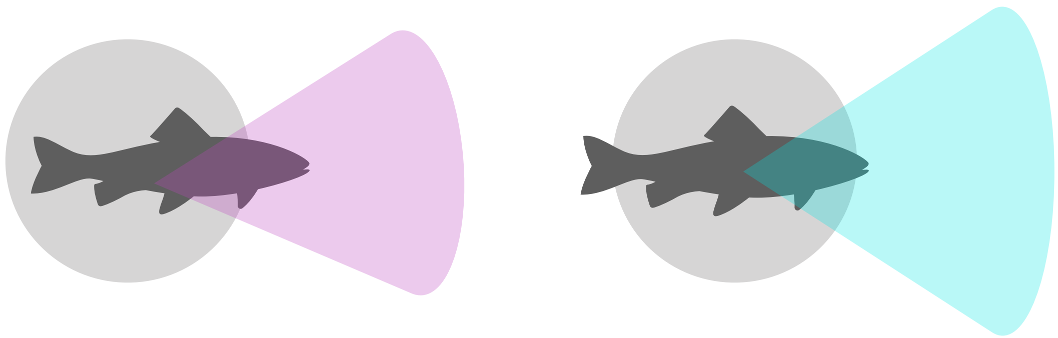
Reciprocity



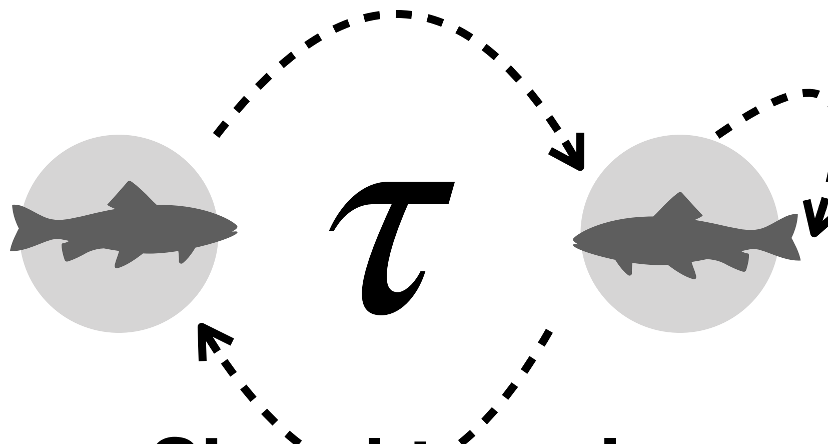
Action = Reaction

- Non-conservative* (effective) interactions:

Nonreciprocity (NR)



Action $\neq$ Reaction



Information processing time

Signal travel time

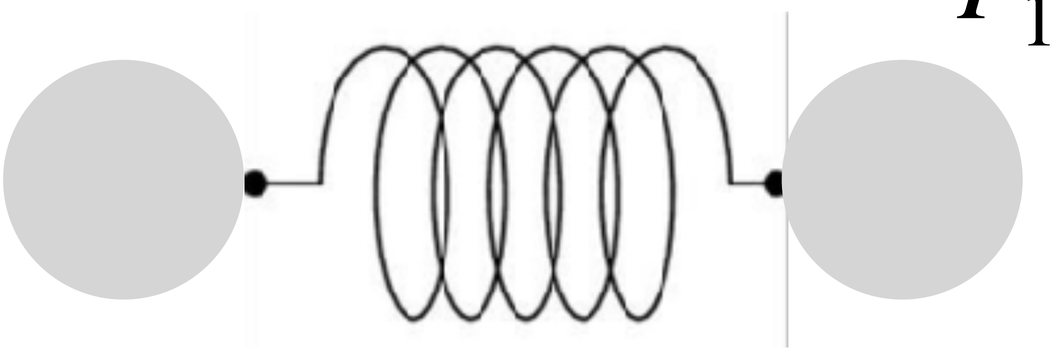
Delayed interactions

**Interaction forces not representable as ∇V*

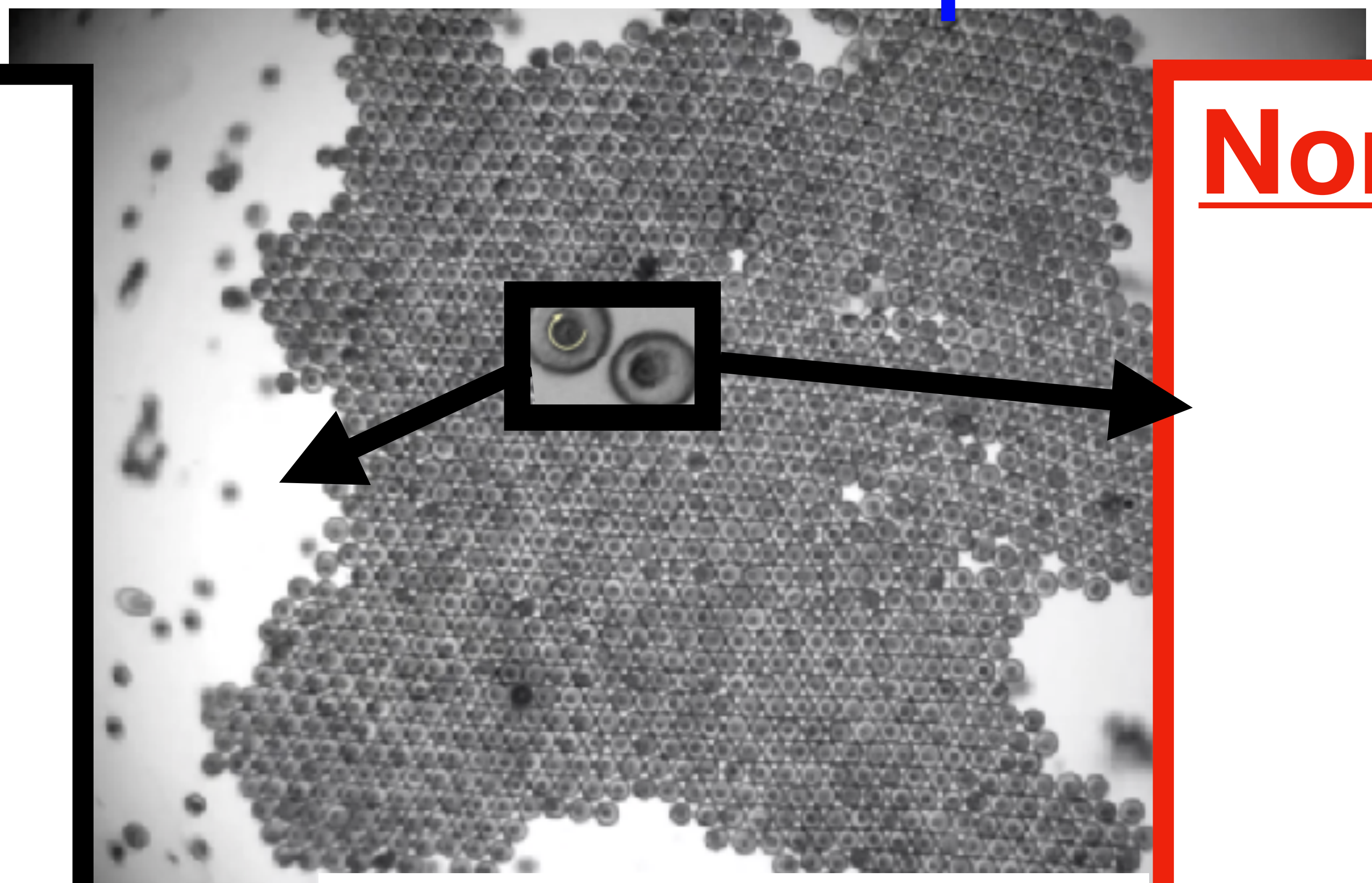
NR interactions in Nonequilibrium systems

Equilibrium:

Reciprocity $F_{12} = -F_{21}$



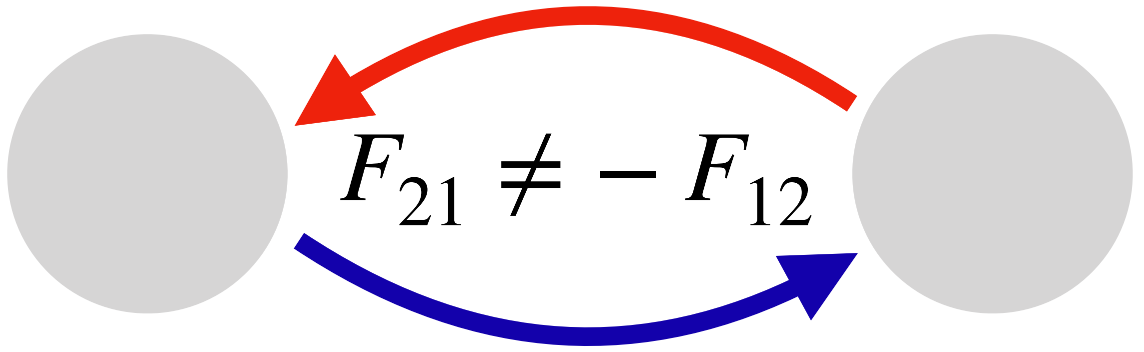
Action = Reaction



[Tan et al, Nature (2022)]

Non-Equilibrium:

Non-reciprocity



Action ≠ Reaction

Nonequilibrium complex systems with multiple scales
effective interactions often NR!

1. [Rieser et al, Science 2022] 2. [Agudo-Canalejo et al, PRL 2019] 3. [Dinelli et al., Nat Comm 2023] 4. [Hopfield, PNAS 1982] 5. [Loos et al., PRL 2023]

NR interactions in Nonequilibrium systems

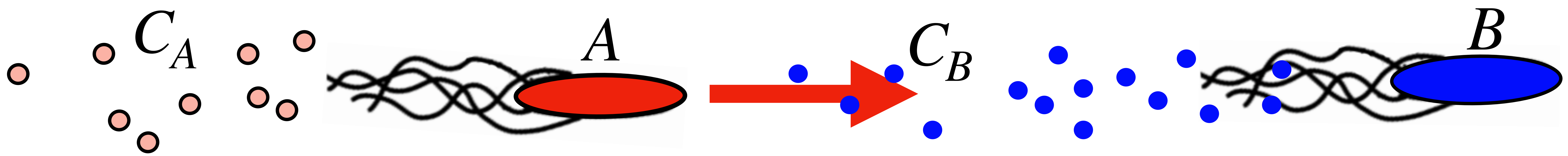
- **Mixtures of <u>Enzymes / Colloidal particles / Bacteria</u>:**

“Catalytic” activity
(consume/produce chemicals)

+

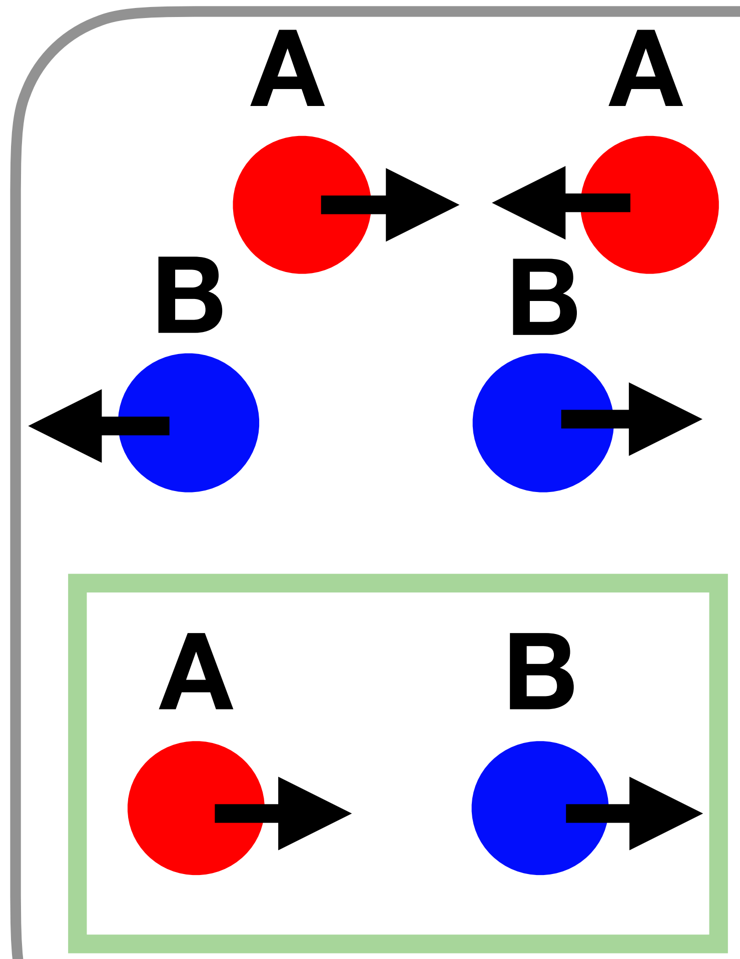
Chemophoresis / Chemotaxis
(move along chemical gradients)

Species A is chemotactically attracted to C_B (but not vice versa)

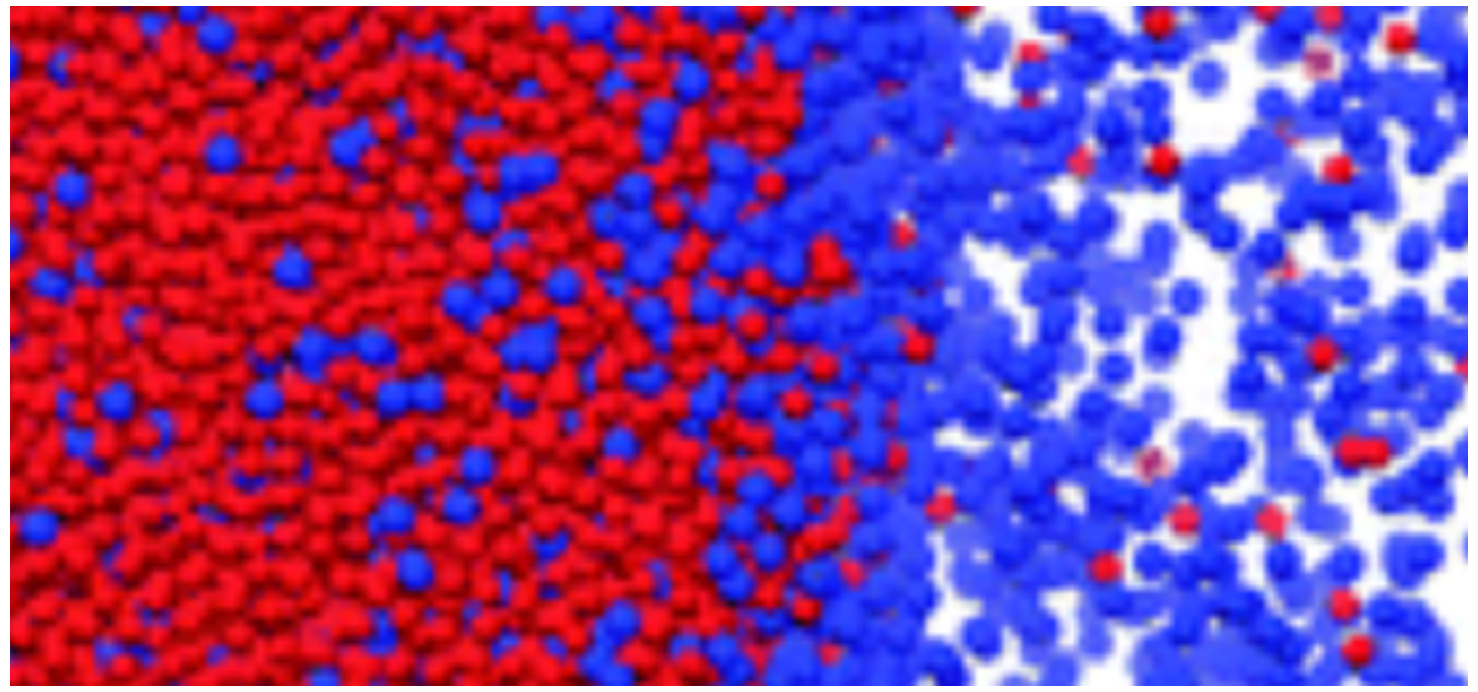


1. [Rieser et al, Science 2022] 2. [Agudo-Canalejo et al, PRL 2019] 3. [Dinelli et al., Nat Comm 2023] 4. [Hopfield, PNAS 1982] 5. [<u>Loos</u> et al., PRL 2023]

“Stat Phys of NR many-body systems”

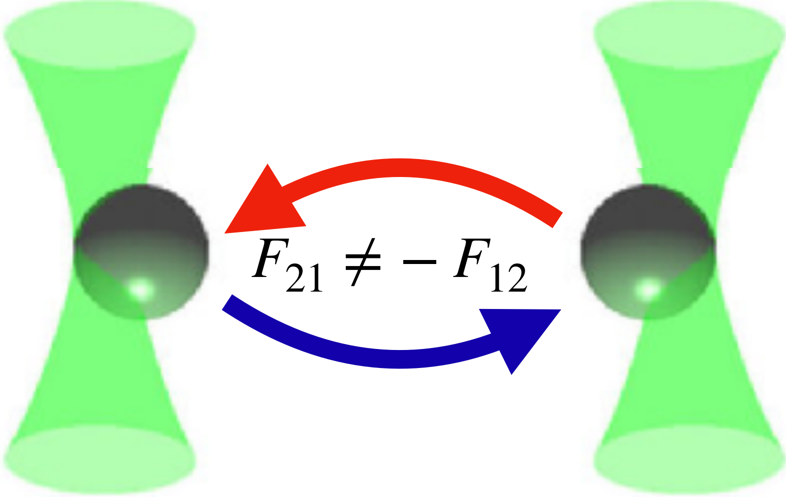


- **Binary NR fluids**



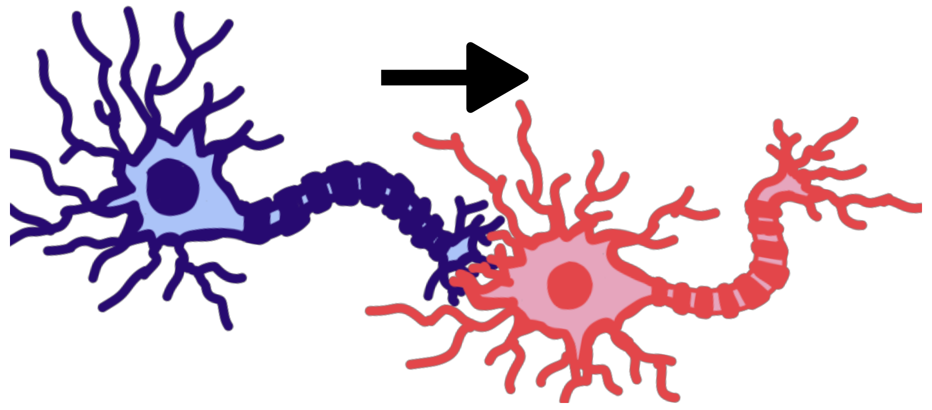
Suchanek, Kroy, **SL**, PRL (2024)

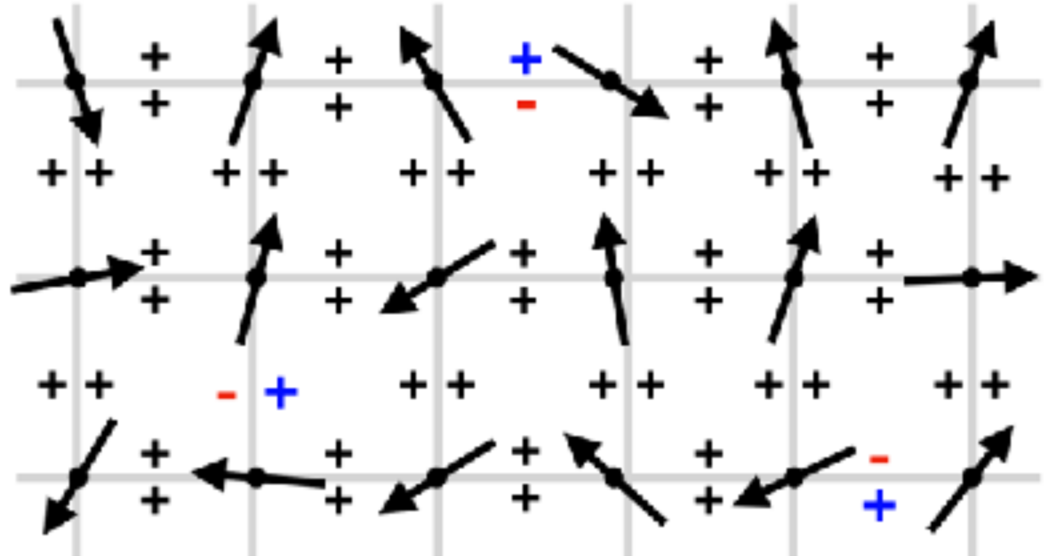
- **NR generated by optical feedback**

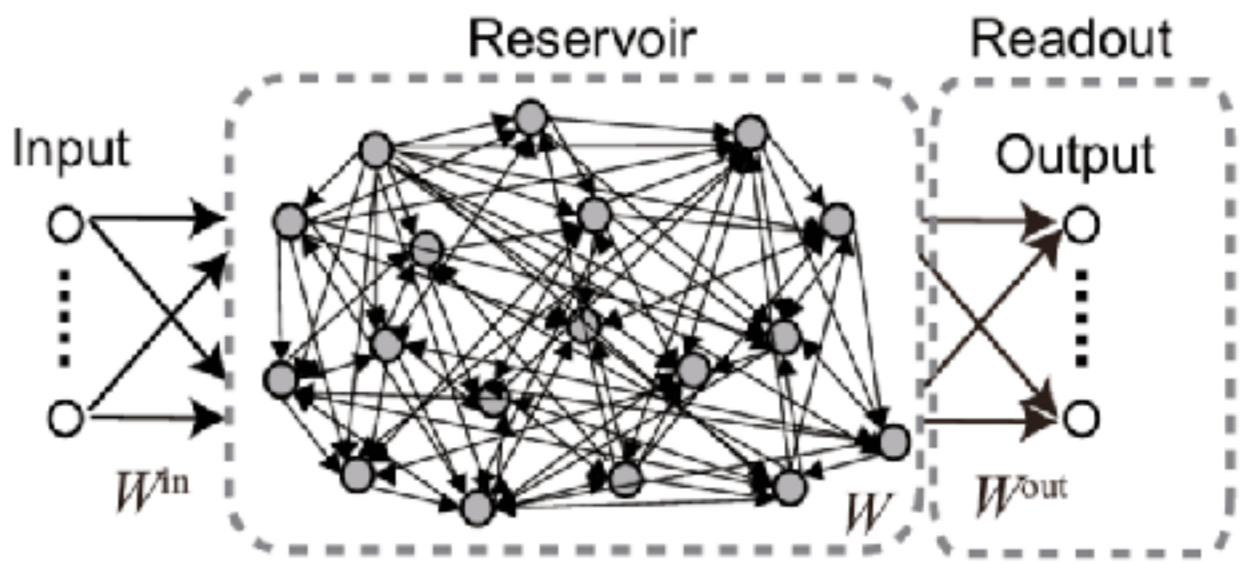


SL, Klapp, NJP (2020)

- **Quenched NR Disorder**

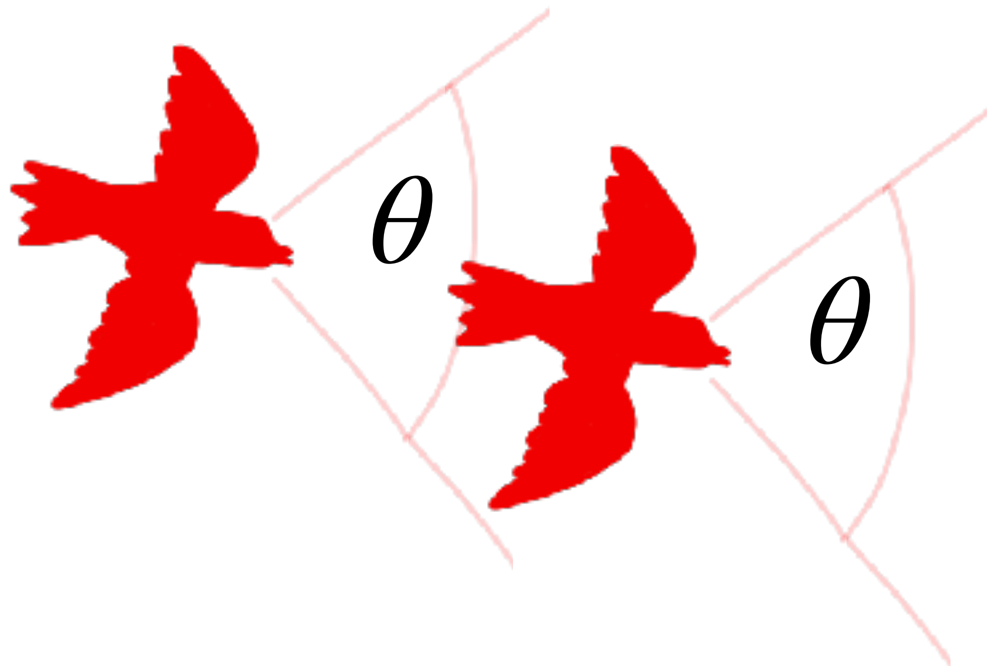


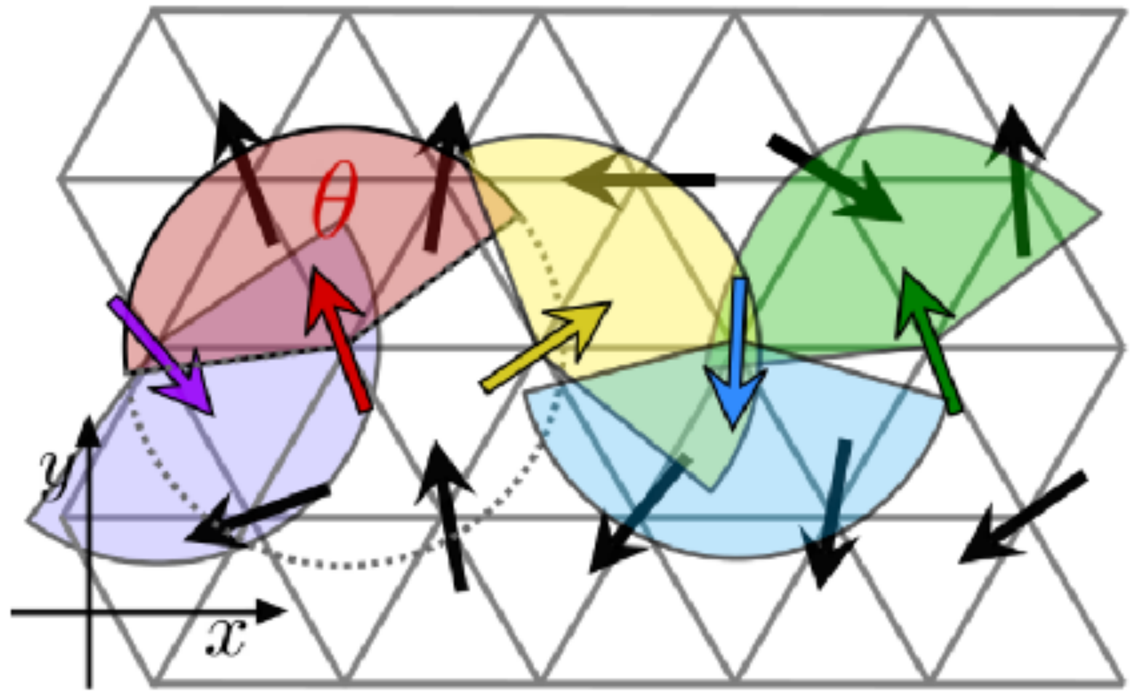




Suchanek, Cates, **SL**,
in preparation

- **Vision cone interactions**

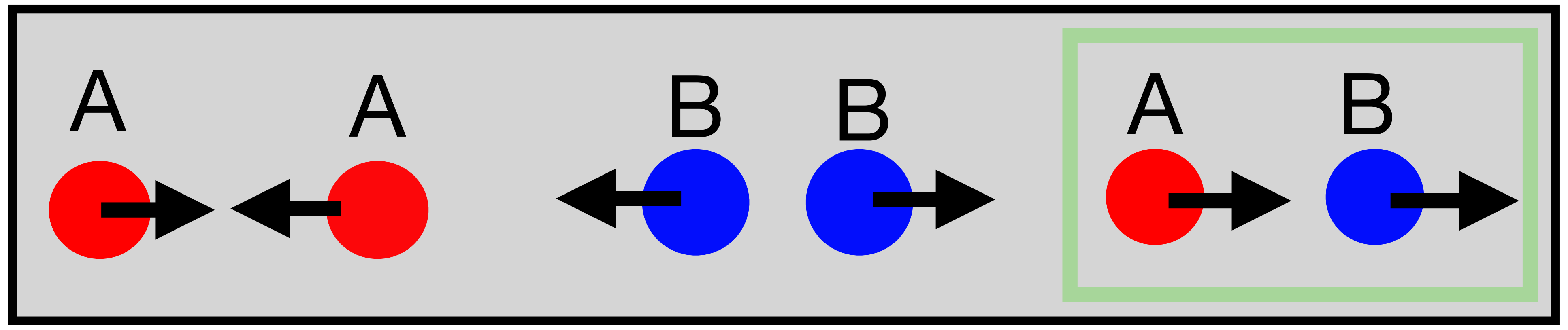




SL, Klapp & Martynec, PRL (2023)

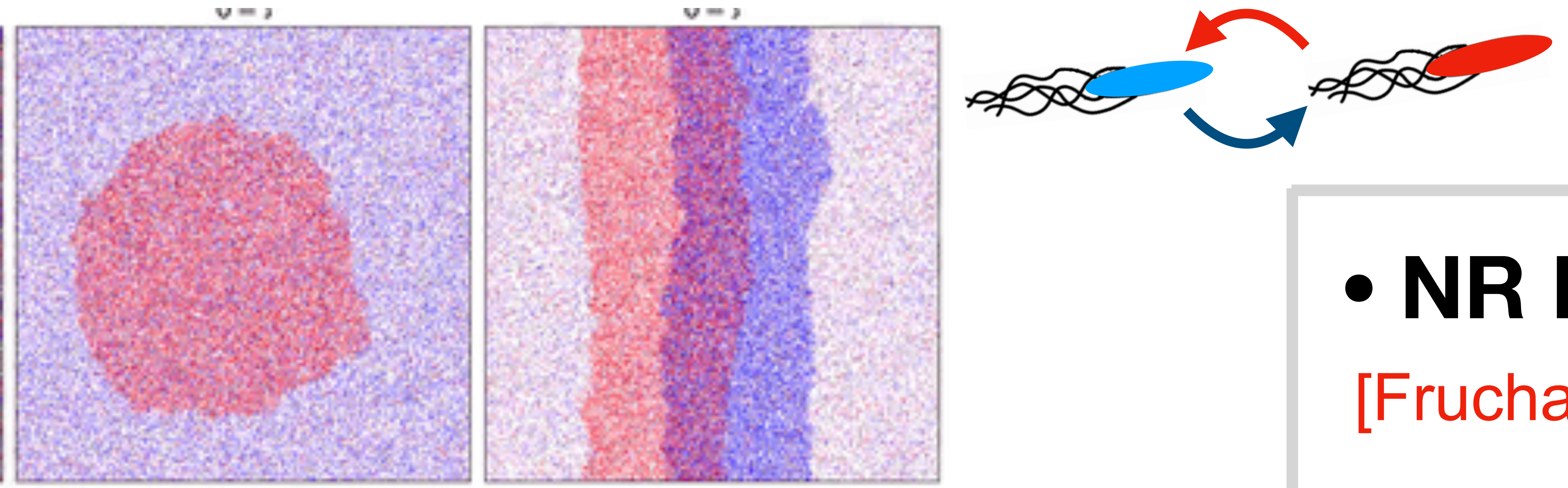
Bandini, Venturelli, **SL**, Jelic, Gambassi,
J. Stat. Mech. (2025)

Inter-species NR interactions



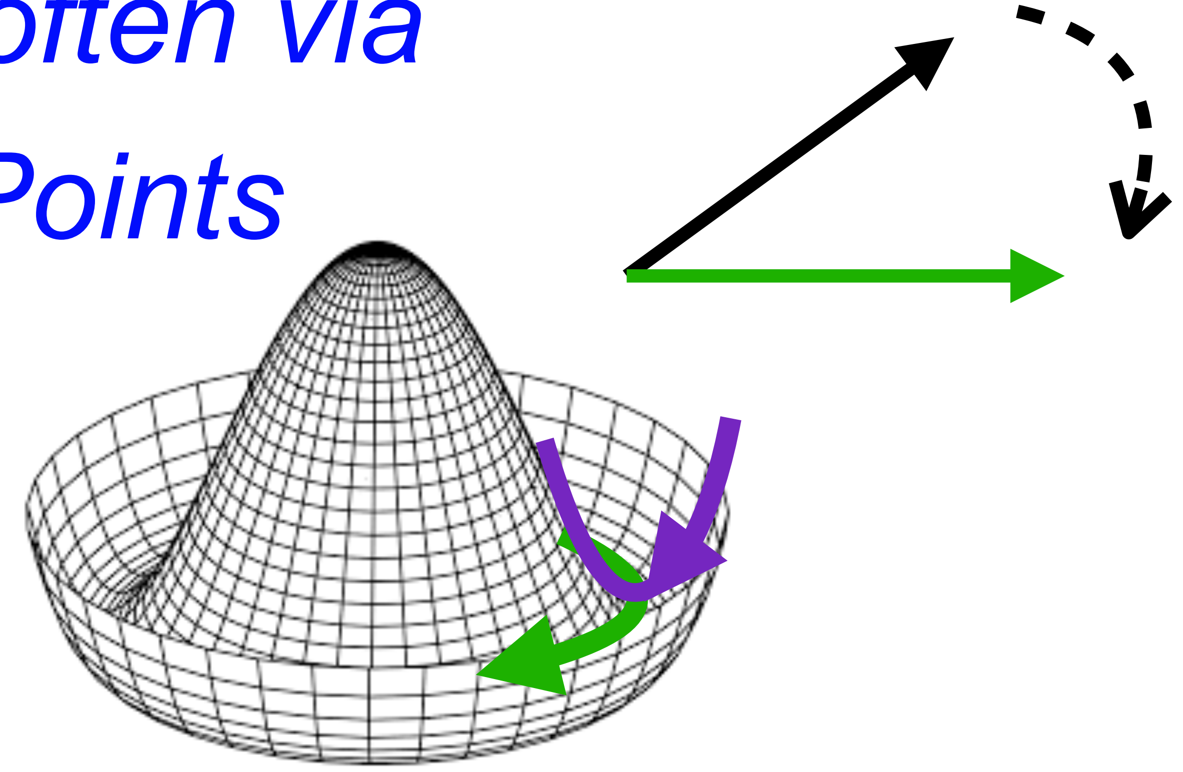
- **Quorum-sensing chemotactic bacteria**

[Dinelli et al., Nat Comm (2023), Duan et al., PRL (2023)]



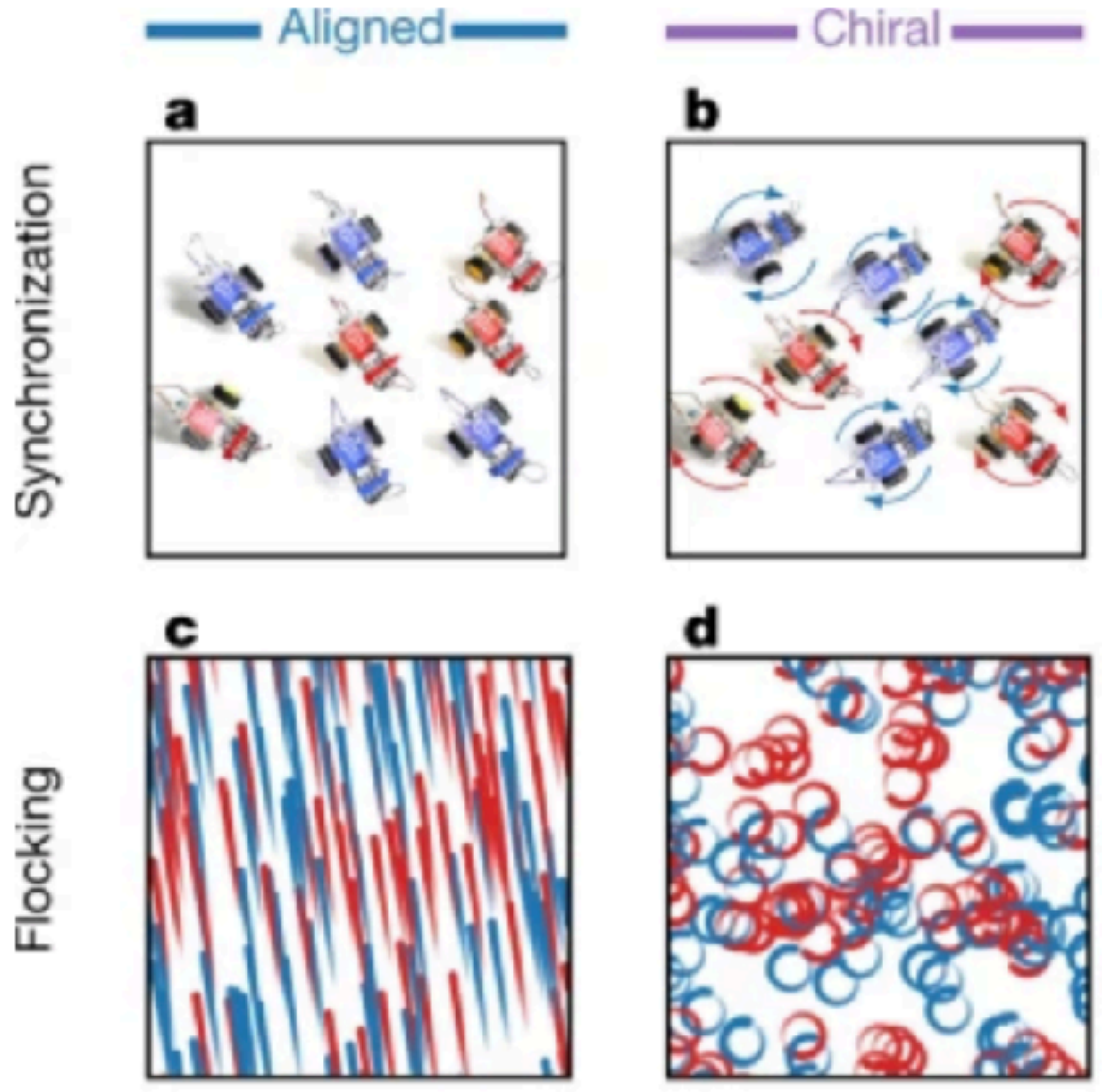
→ *Dynamical phases, often via*

Critical Exceptional Points

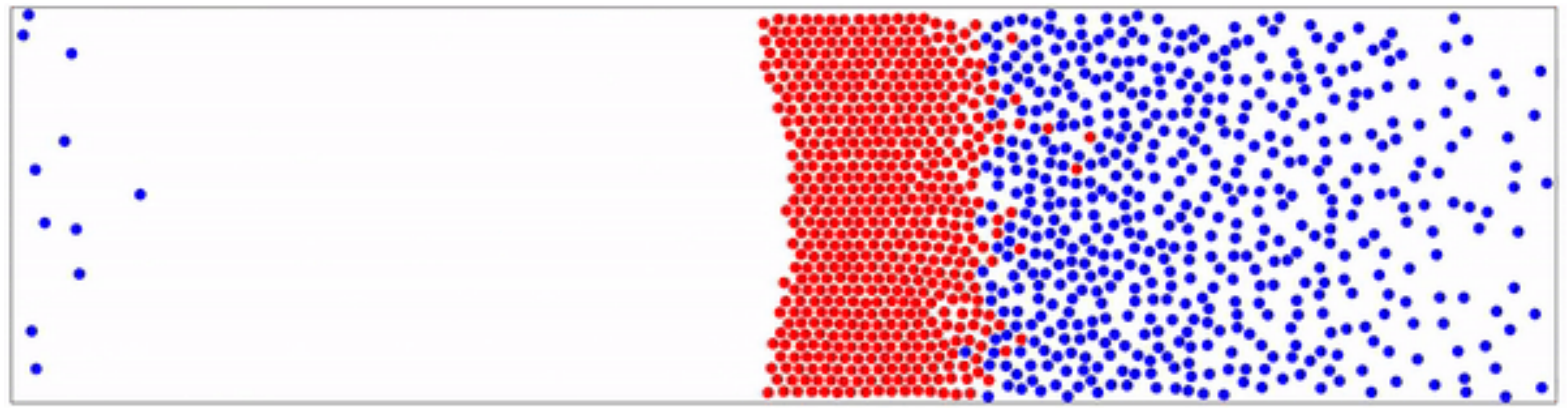


- **NR Flocking, …**

[Fruchart et al., Nature (2021)]



- **Binary mixtures (Active/Passive)**



[You et al., PNAS (2020)]

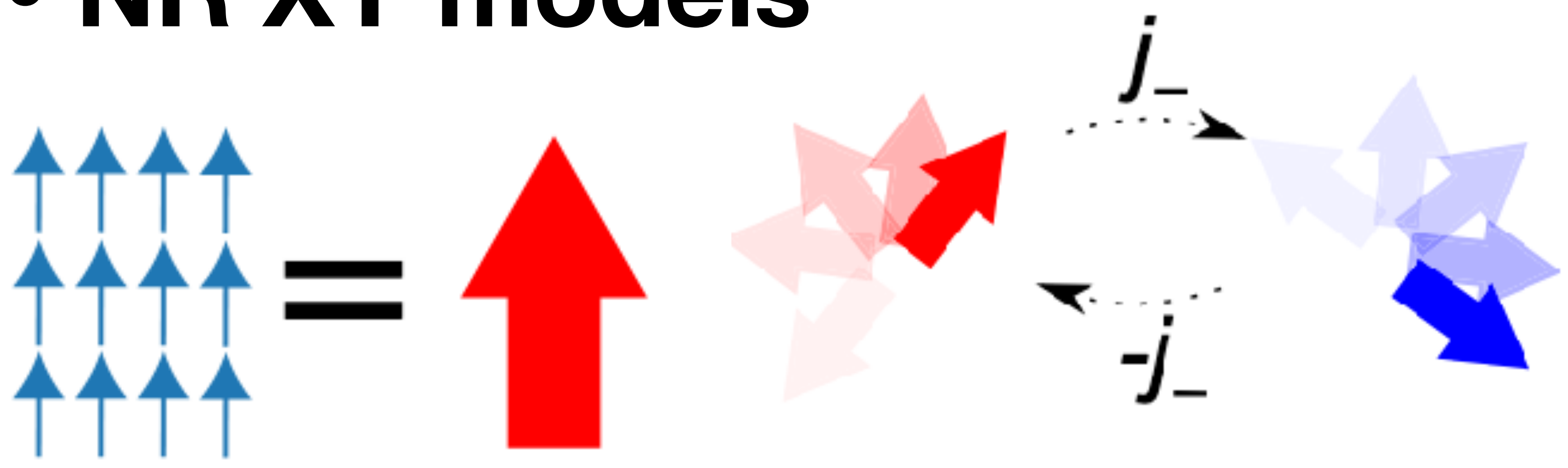
[Saha et al, PRX (2020)]]

[Mason et al., arXiv (2024)]

[Mandal et al., PRE (2024)]

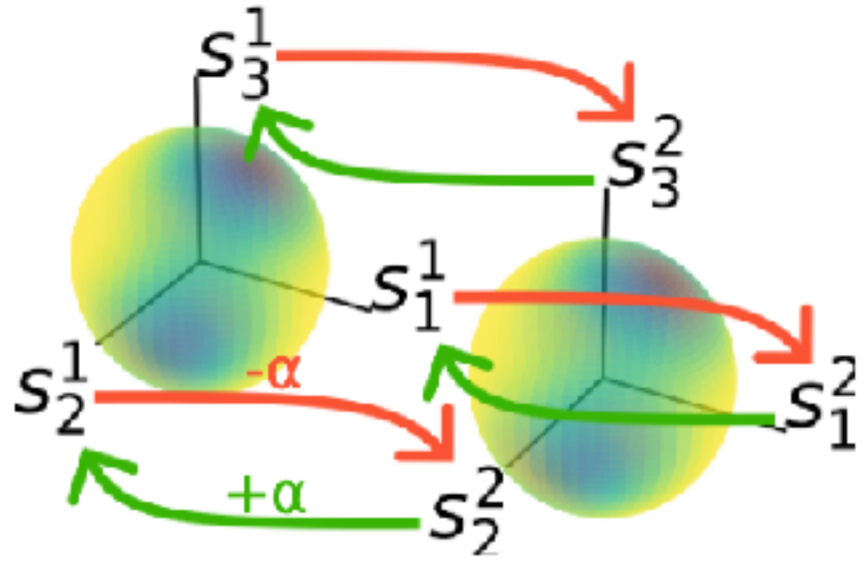
[Brauns et al., PRX (2025)] …

- **NR XY models**



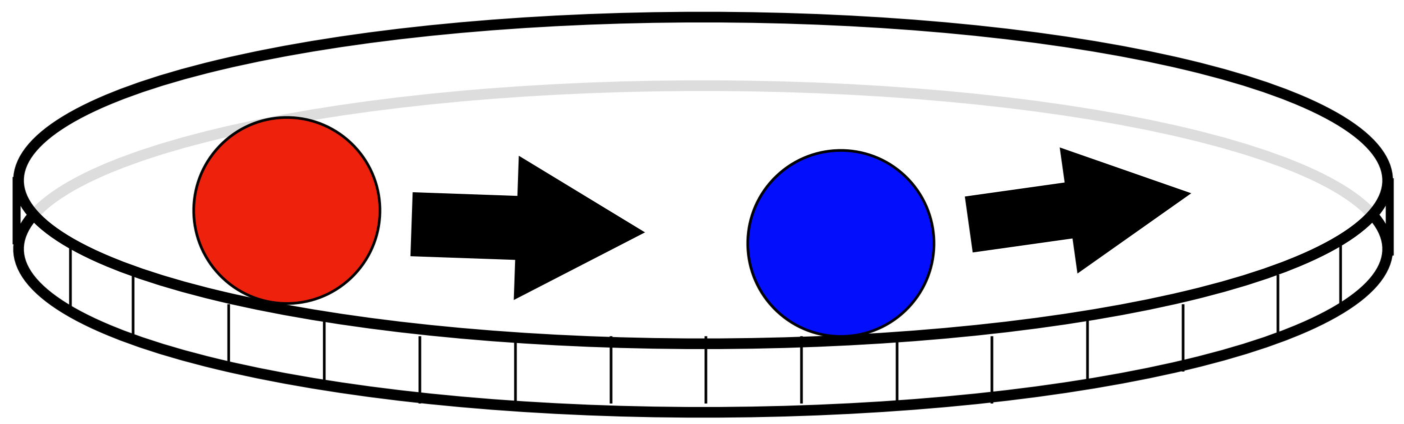
[Hanai, PRX (2024)]

[Garcia Lorenzana, ArXiv (2024)]

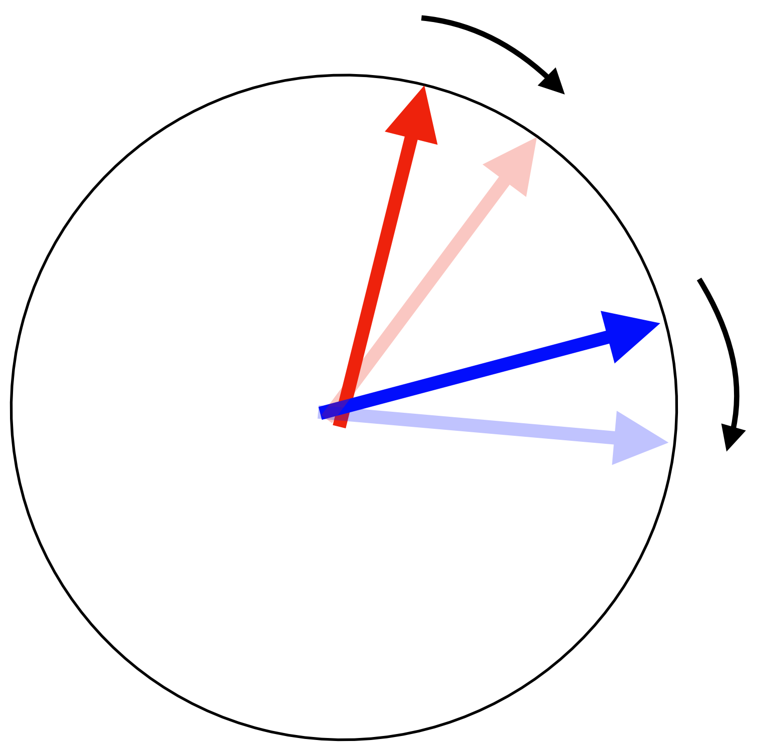


Nonreciprocal → Symmetry breaking

$$\dot{X}_j = F_{ij}$$



$$F_{ij} = -J_{ij}(X_i - X_j)$$



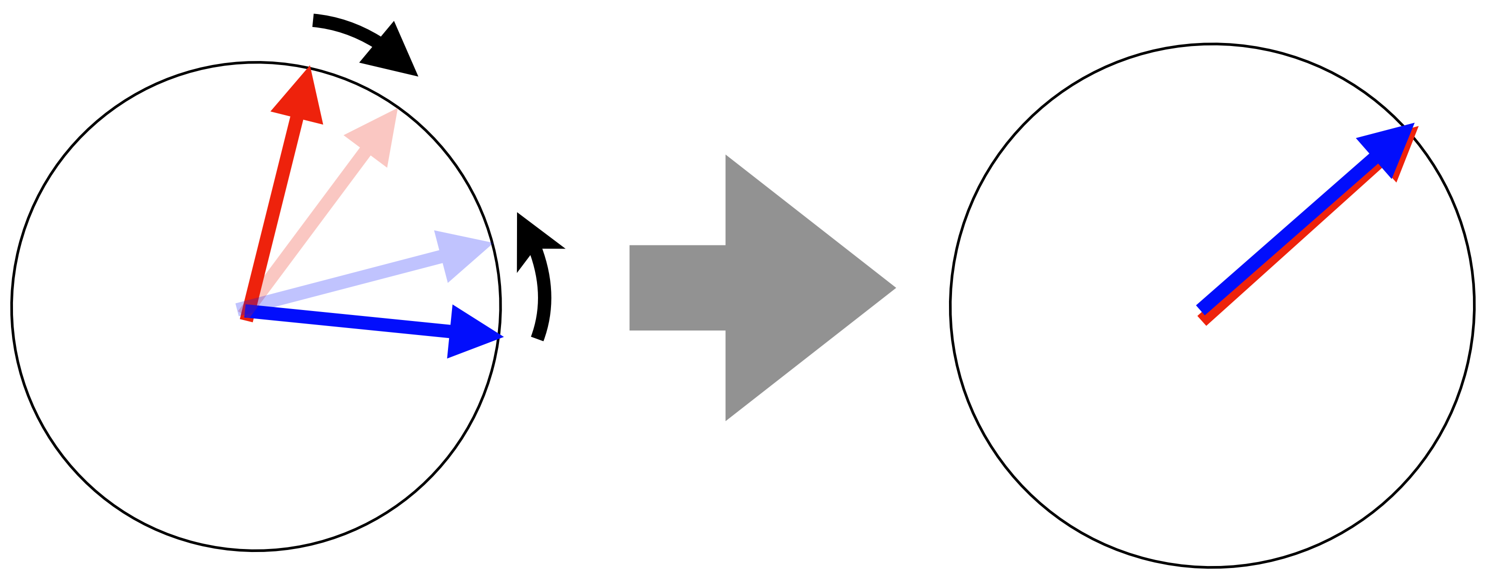
$$F_{ij} = -a_{ij}\sin(X_i - X_j)$$

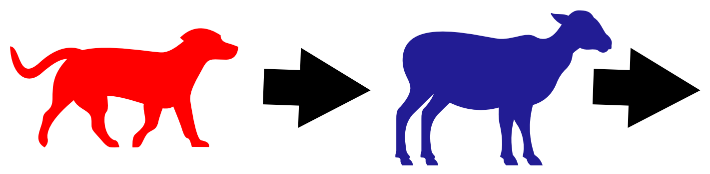
$J_{ij} \neq J_{ji}$ $\quad F_{ij} + F_{ji} \neq 0$

NR ⇒ **Linear momentum conservation broken**

Particle Current?

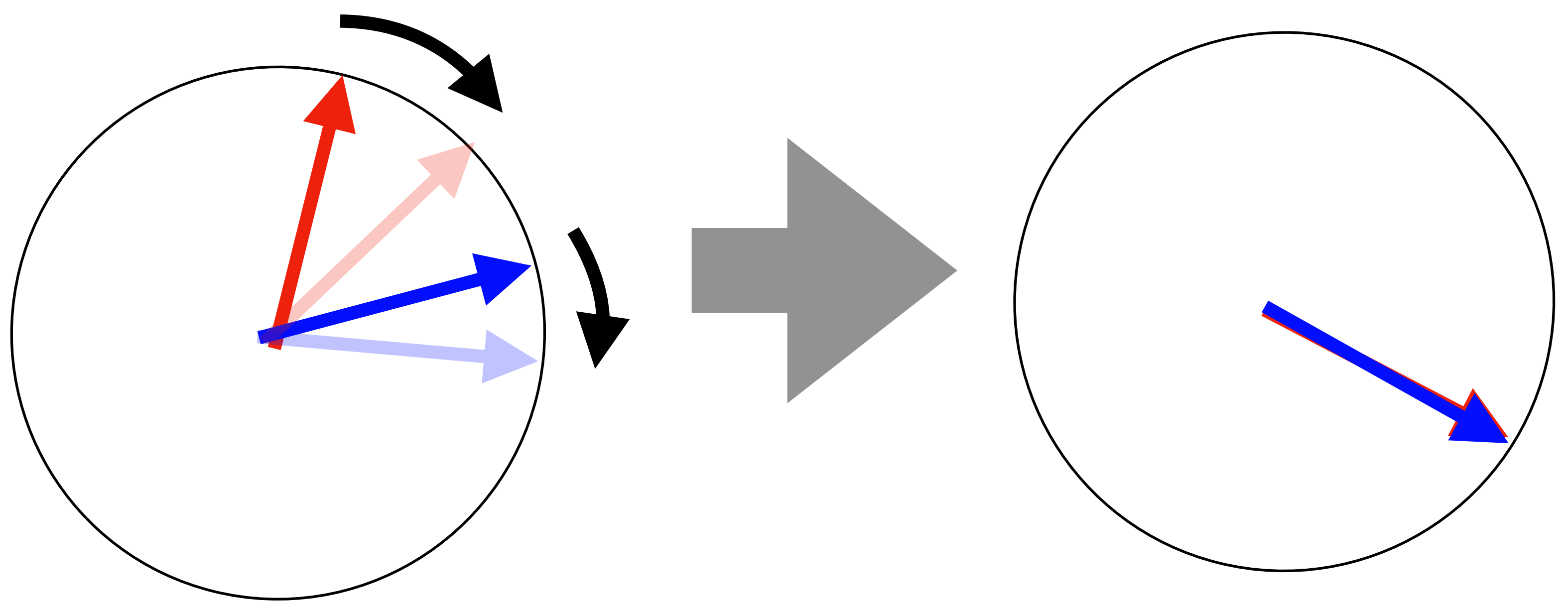
$J_{ij}J_{ji} > 0$



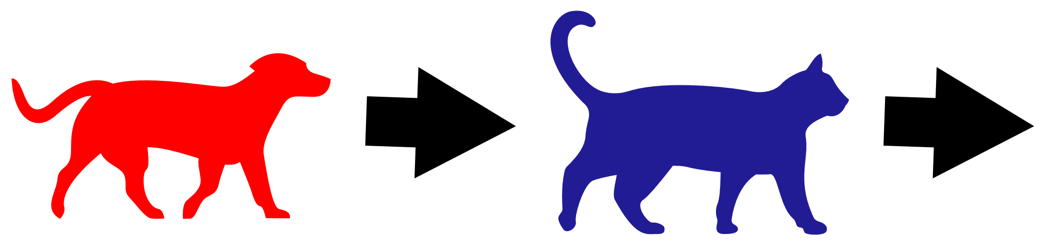


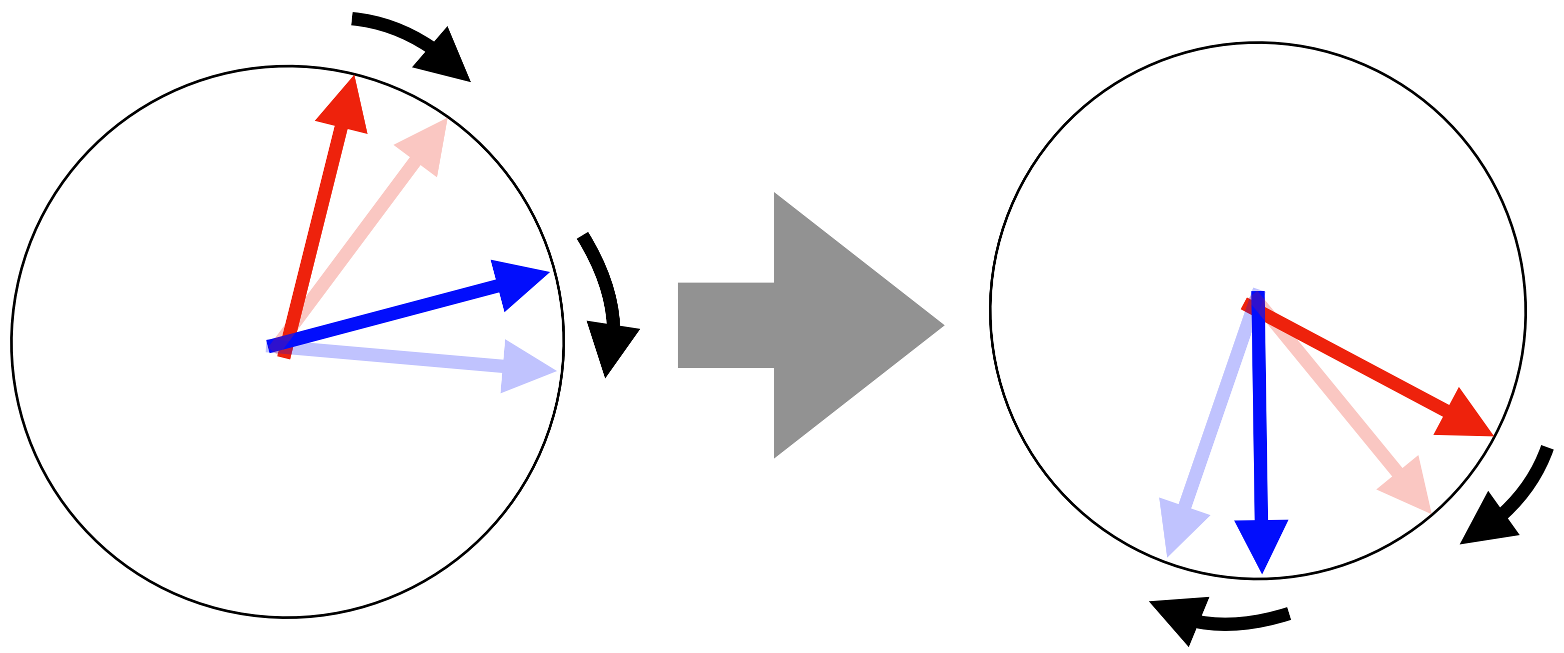
$J_{ij}J_{ji} < 0$

$|J_{ij}| > |J_{ji}|$



Anti-reciprocal $J_{ij} = -J_{ji}$





Nonreciprocal → Symmetry breaking

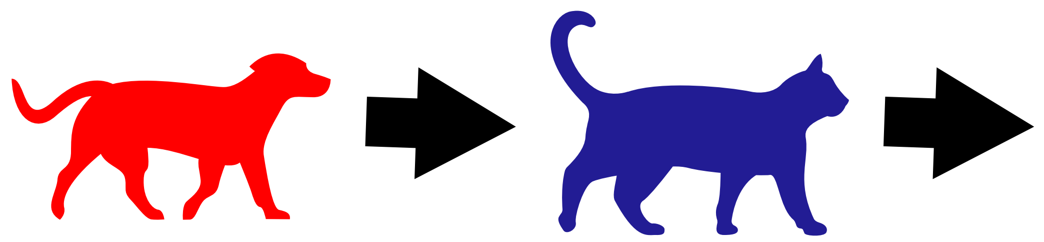
$\dot{X}_i = F_{ij}$

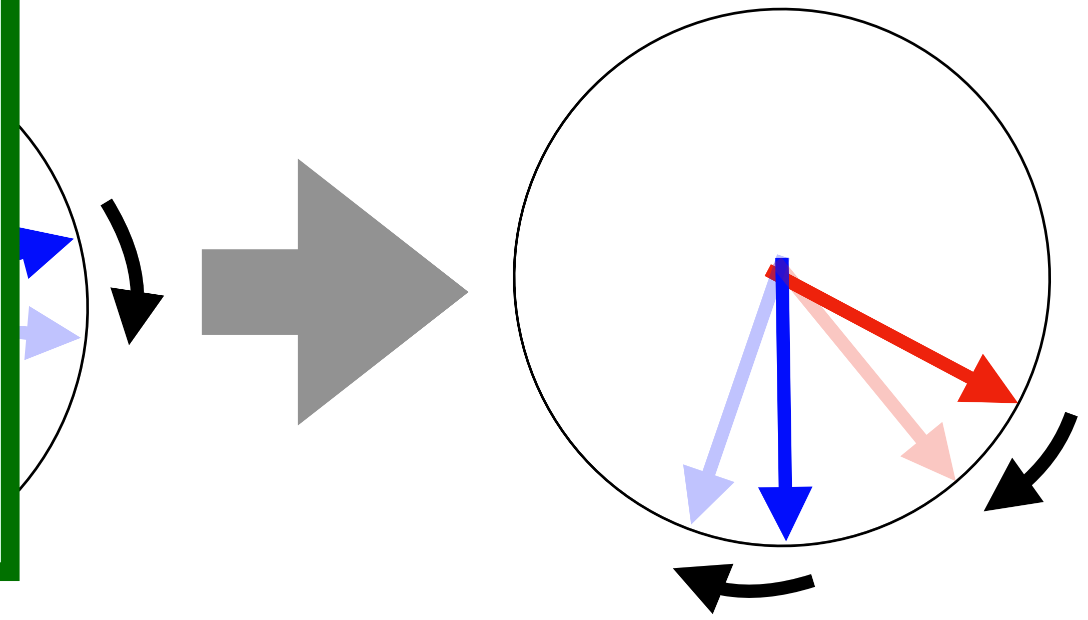
$_{ij} \neq J_{ji}$ $\quad F_{ij} + F_{ji} \neq 0$

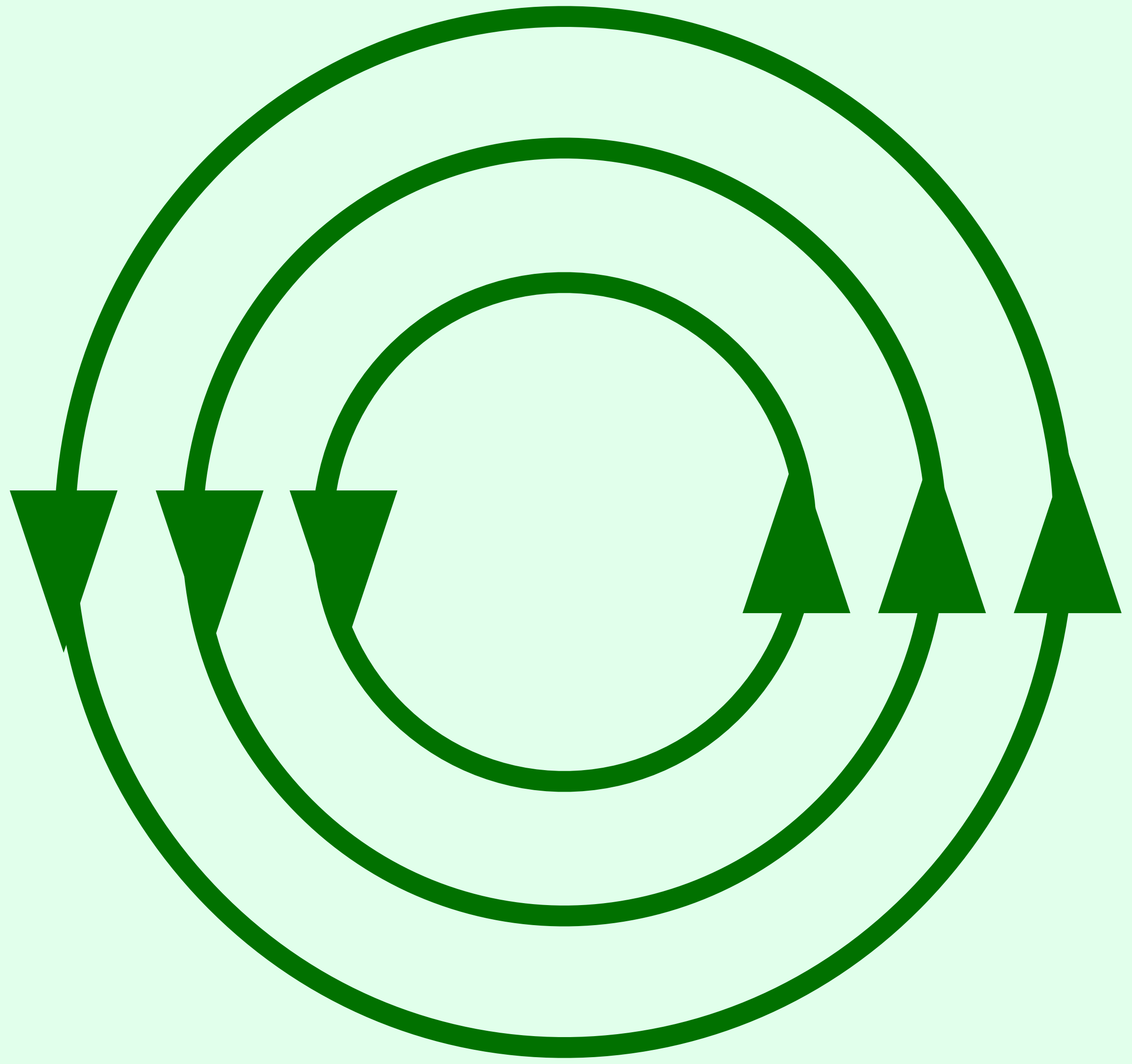
IR ⇒ Linear momentum onservation broken

Particle Current?

cal $J_{ij} = -J_{ji}$





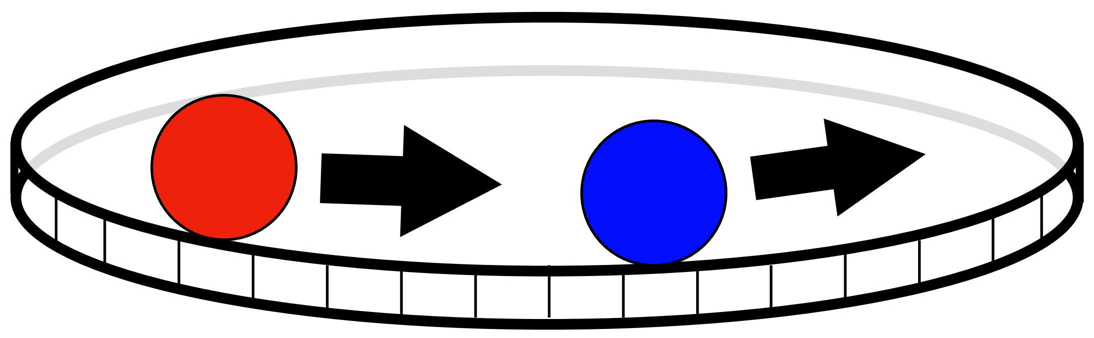


$$\dot{X} \propto \Delta\phi$$

<u>Marginal</u> orbits → **Not stable against noise** → No persistent current

Rotation due to period domain + "anti-reciprocity" $J_{ij} = -J_{ji}$

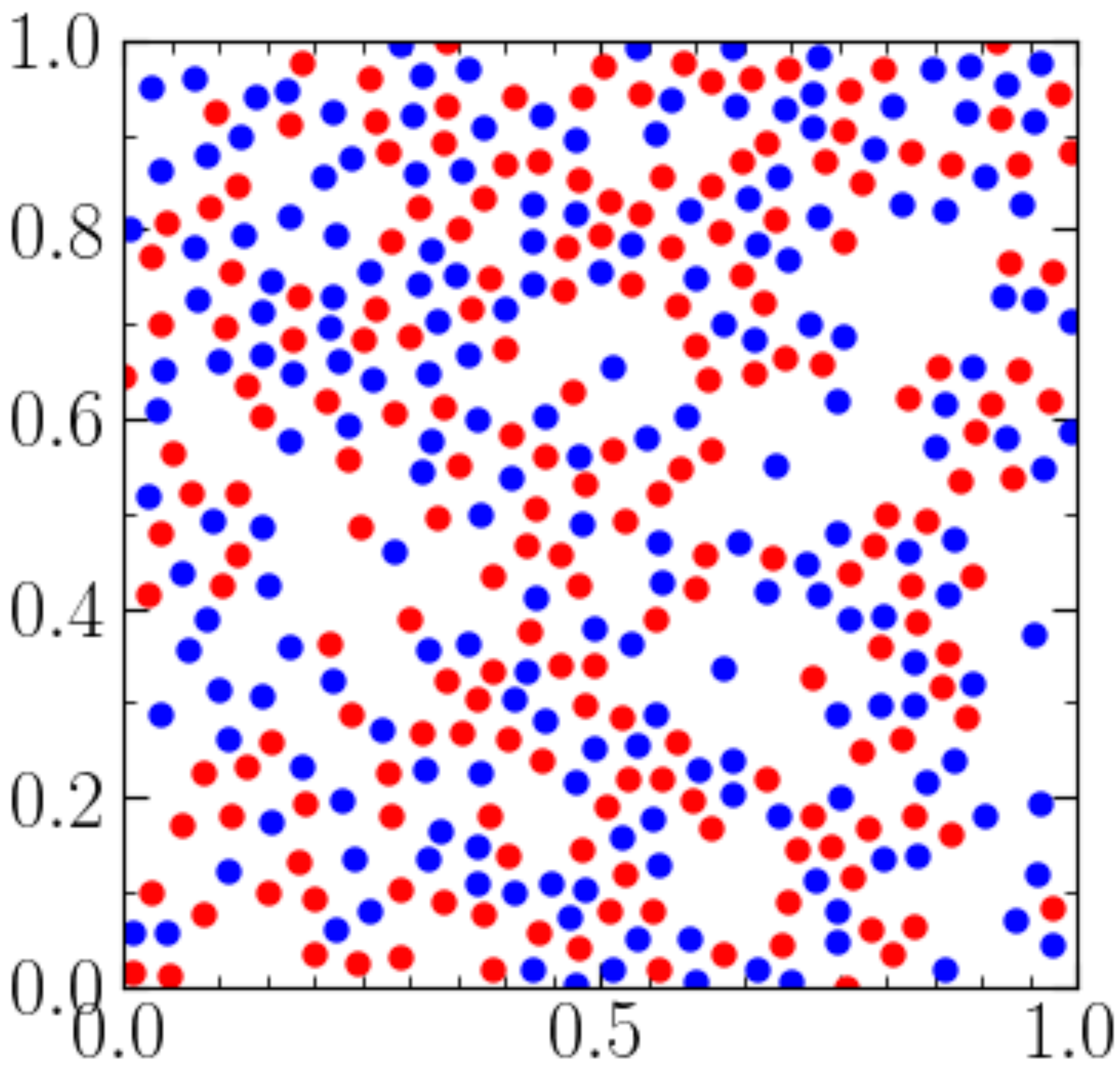
Nonreciprocal → Symmetry breaking



NR ⇒ **Linear momentum conservation broken**

⇒ **Time-reversal symmetry breaking (TRSB)**

SL, Klapp, NJP (2020)



Non-reciprocity (NR)

↑ ↓

Time-reversal symmetry breaking (TRSB)

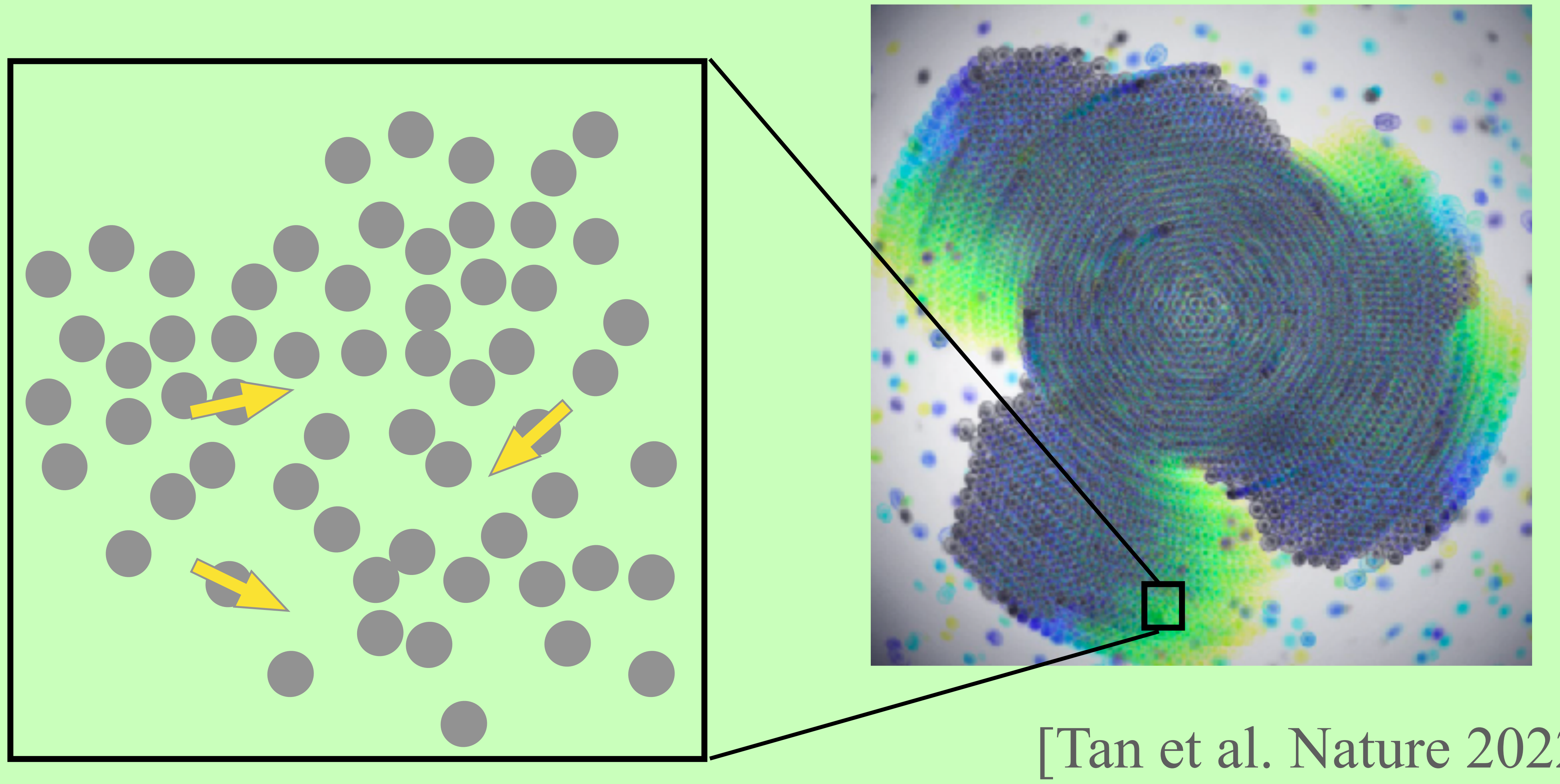
How much retrievable at different scales?

Nonreciprocal → Symmetry breaking

Emergence of macroscopic irreversible behaviour from microscale energy-input

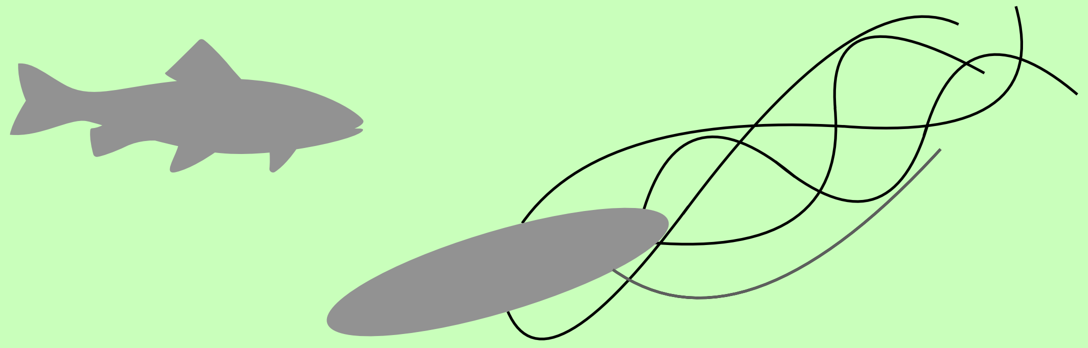
Energy input at particle scale
(Å – μm)

ATP → ADP + P



[Tan et al. Nature 2022]

Emergent irreversible behaviour at macro scale
(μm – mm – m **)**



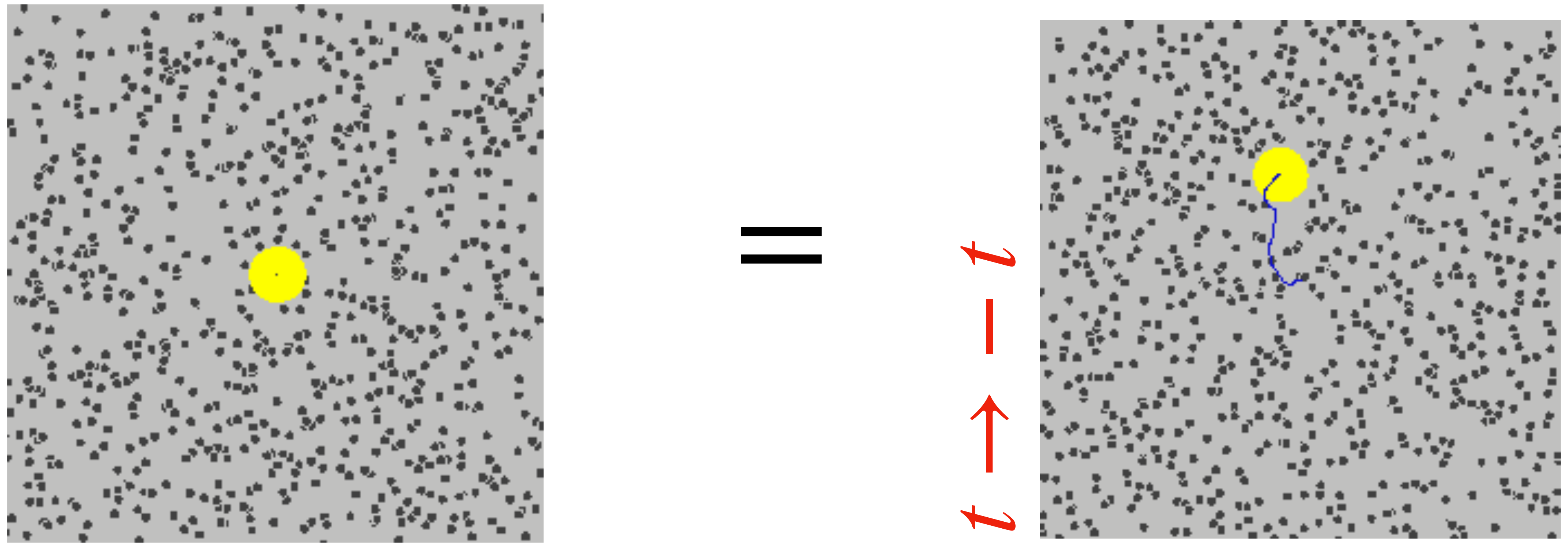
↑ ↓

Time-reversal symmetry breaking (TRSB)

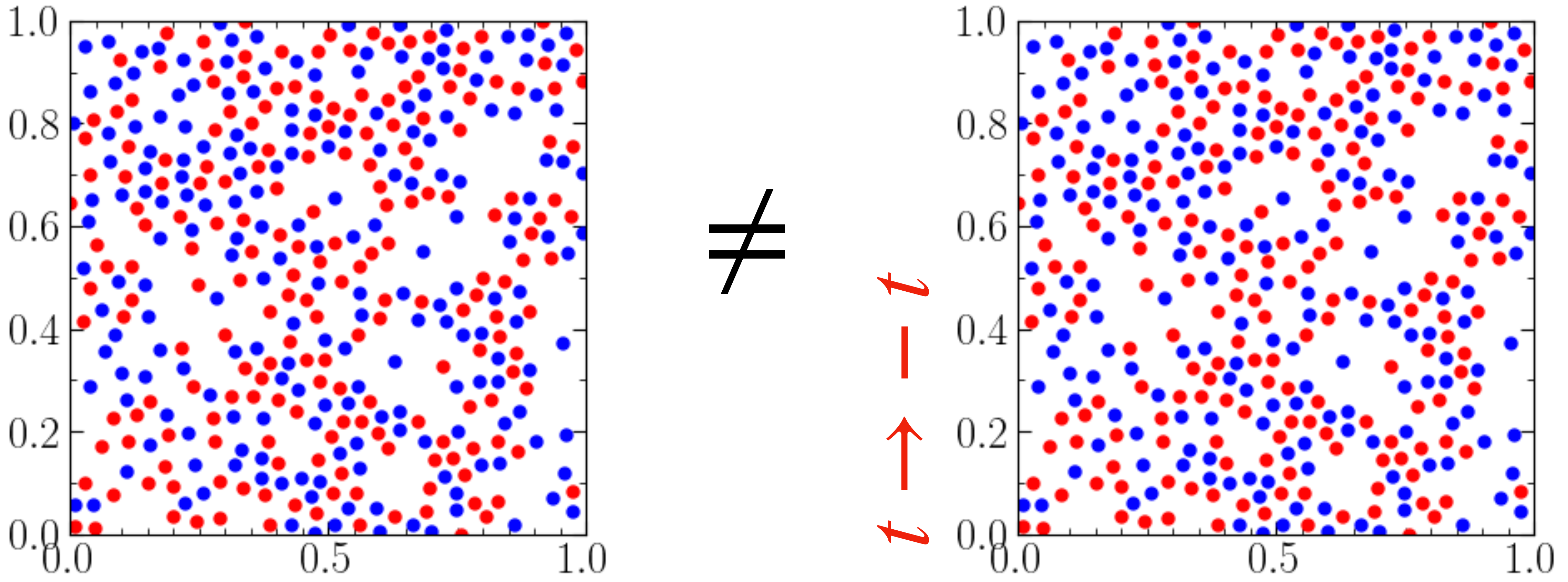
How much retrievable at different scales?

Quantifying non-equilibriumness via TRSB

EQUILIBRIUM: Time-reversal symmetry (TRS)



NON-EQUILIBRIUM: TRSB, *"Arrow of Time"*



- **(Informatic) entropy production rate[1]:**

$$\boxed{\dot{S} = \left\langle \ln\left(\frac{\mathbb{P}\left[X(t)\,|_0^T\right]}{\mathbb{P}_{\mathrm{R}}\left[X_{\mathrm{R}}(t)\,|_0^T\right]} \right) T^{-1} \right\rangle}$$

$$\Rightarrow \langle e^{-S} \rangle = 1 \quad \Rightarrow \langle S \rangle \geq 0$$

FTs, Generalisation of Second Law

$$\dot{S} = \int \frac{d\omega}{2\pi D}[\omega\tilde{C}(\omega) - 2D\tilde{R}'(\omega)]$$

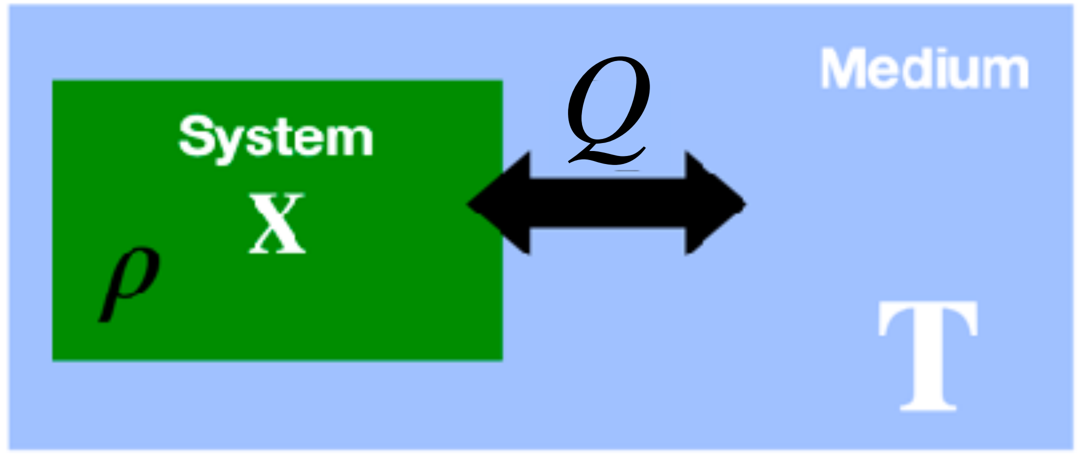
$X(t)\,|_0^T$: random trajectory $\mathrm{t} \in [0,\mathrm{T}], X \in \mathbb{R}^d$

$\mathbb{P}$: path probability, Onsager – Machlup

$\mathbb{P}_{\mathrm{R}}, X_{\mathrm{R}}$: time reversal, $\mathrm{t} \to -\mathrm{t}$

Heat dissipation

$$\boxed{\dot{S} = \dot{S}_{\mathrm{shannon}} - \frac{\dot{Q}}{T} \geq 0}$$



Quantifies TRSB = Distance from Equilibrium

[Seifert, PRL (2005)], [Sekimoto, Springer (2010)]
[Harada, Sasa, PRL (2005)]

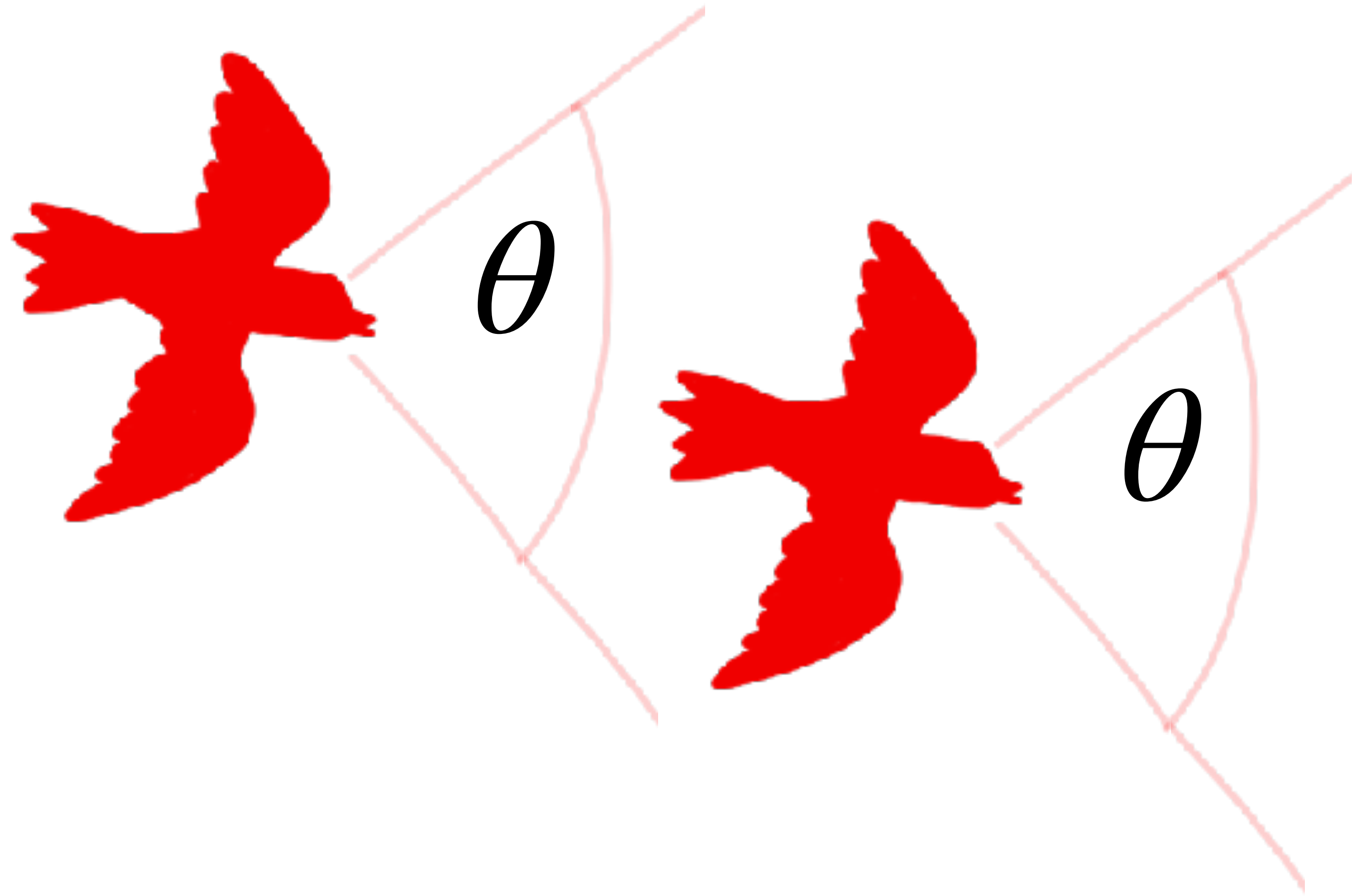
Outline

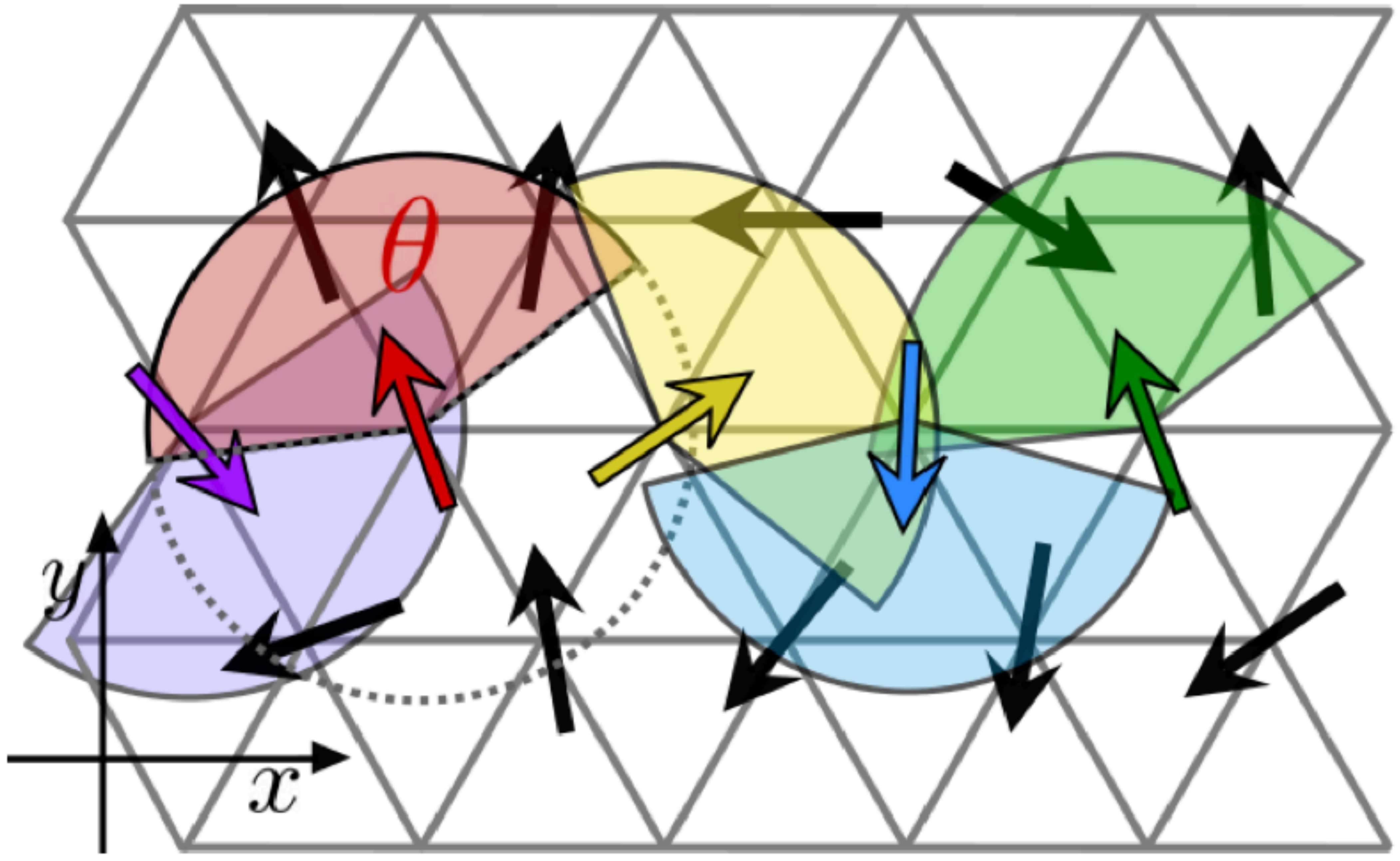
(I) NR spin systems with vision-cone interactions

(II) Two-Species system with inter-species nonreciprocity

(III) Spin systems with quenched, NR disorder

One-species NR system with vision cones



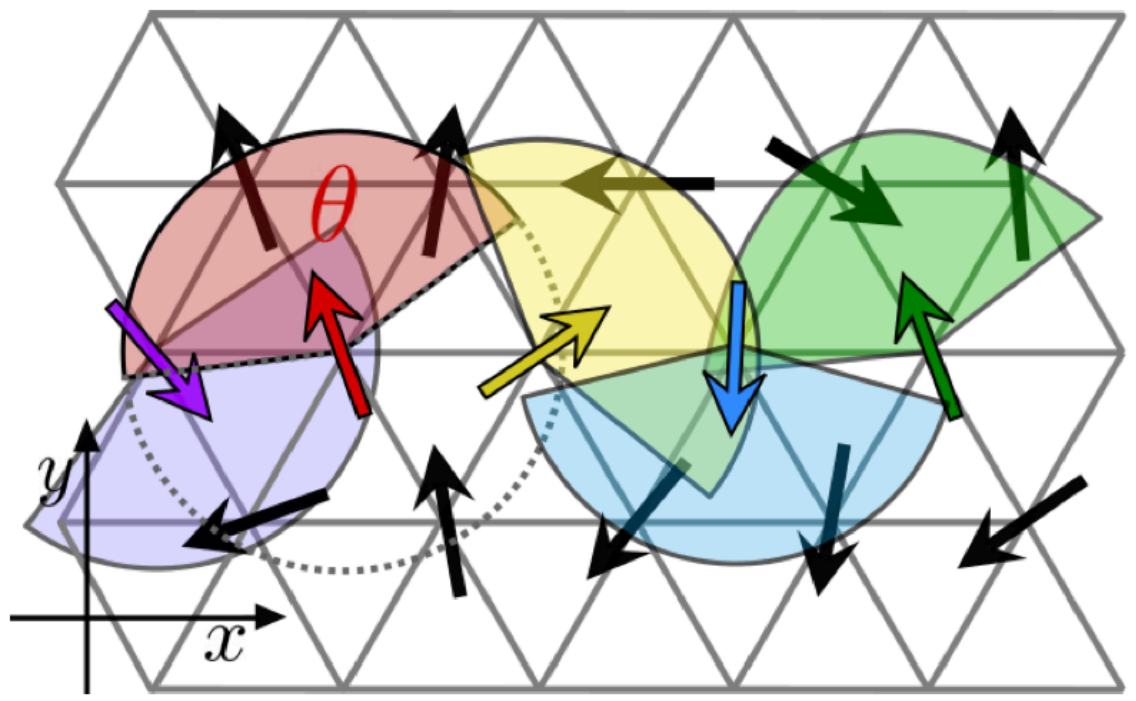


SL, Klapp & Martynec, Phys. Rev. Lett. (2023)

$$E_i = -\sum_{\langle i,j\rangle} J_{ij}(\phi_i)\cos(\phi_i - \phi_j),$$

$$J_{ij}(\phi_i) = \begin{cases} J, & \text{if } j \text{ is “within vision cone”} \\ 0, & \text{else} \end{cases}$$

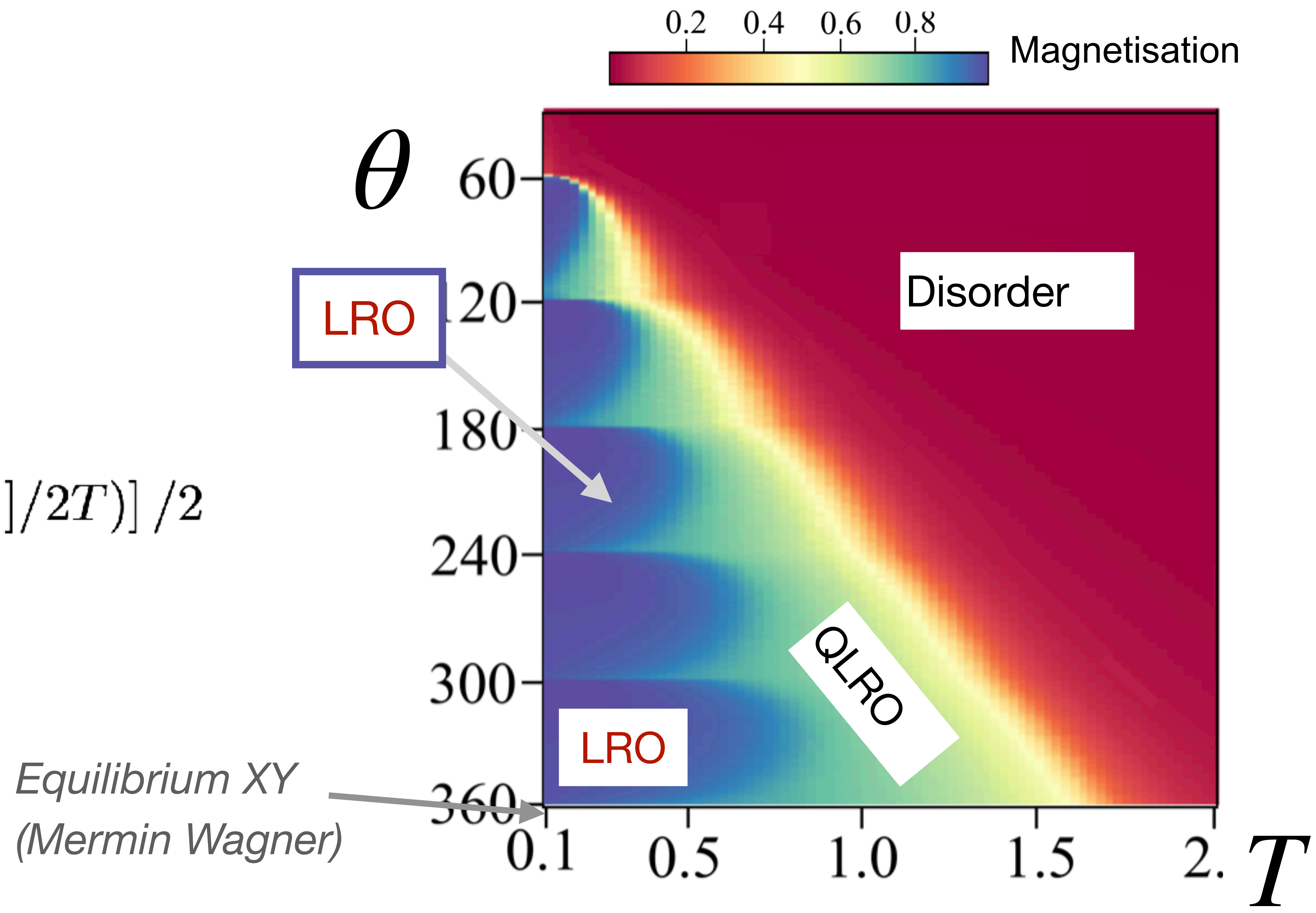
Vision-Cone XY model



- **Local Energy function:** a move that lowers E_i can increase E_j
- 2D, nearest-neighbour coupling
- Monte Carlo (Glauber)

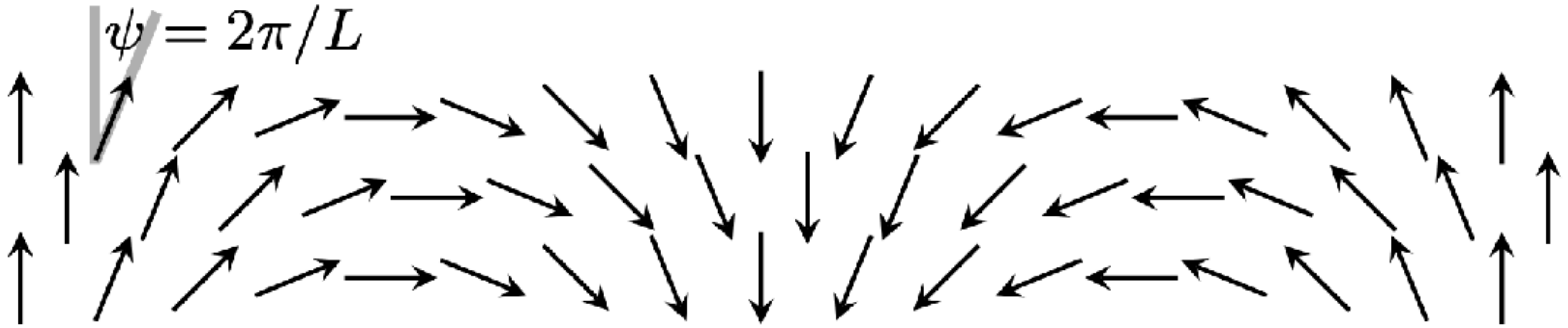
$$w(\phi_i \to \phi_i') = \left[1 - \tanh([E_i(\phi_i) - E_i(\phi_i')]/2T)\right]/2$$

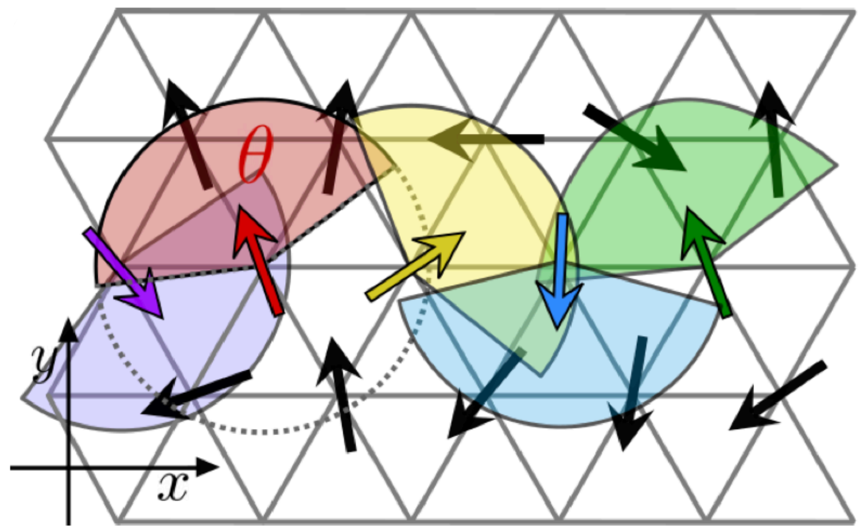
Emergence of true **Long-range order (LRO) !**

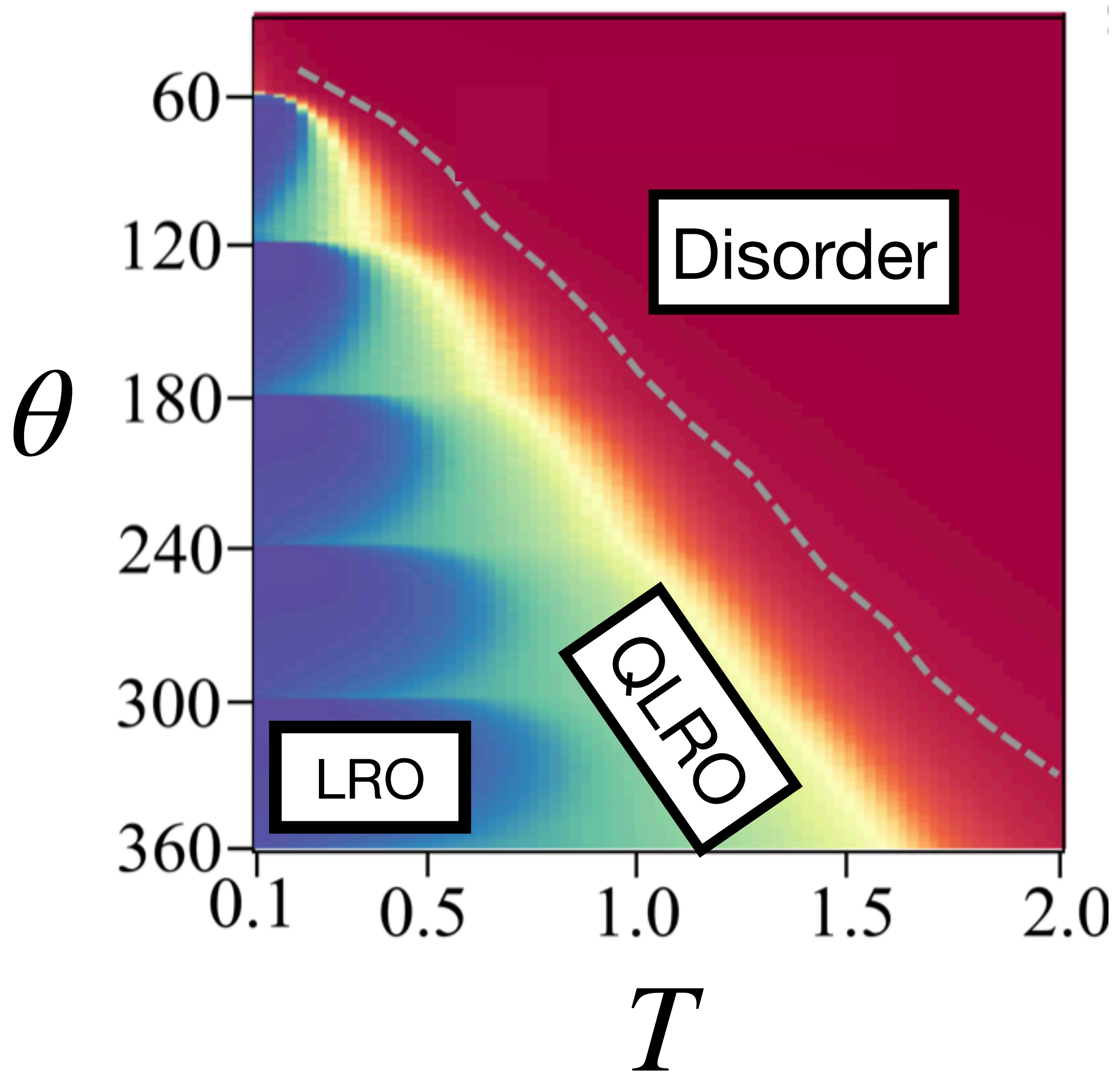


SL, Klapp & Martynec, Phys. Rev. Lett. (2023)

Suppression of spin waves







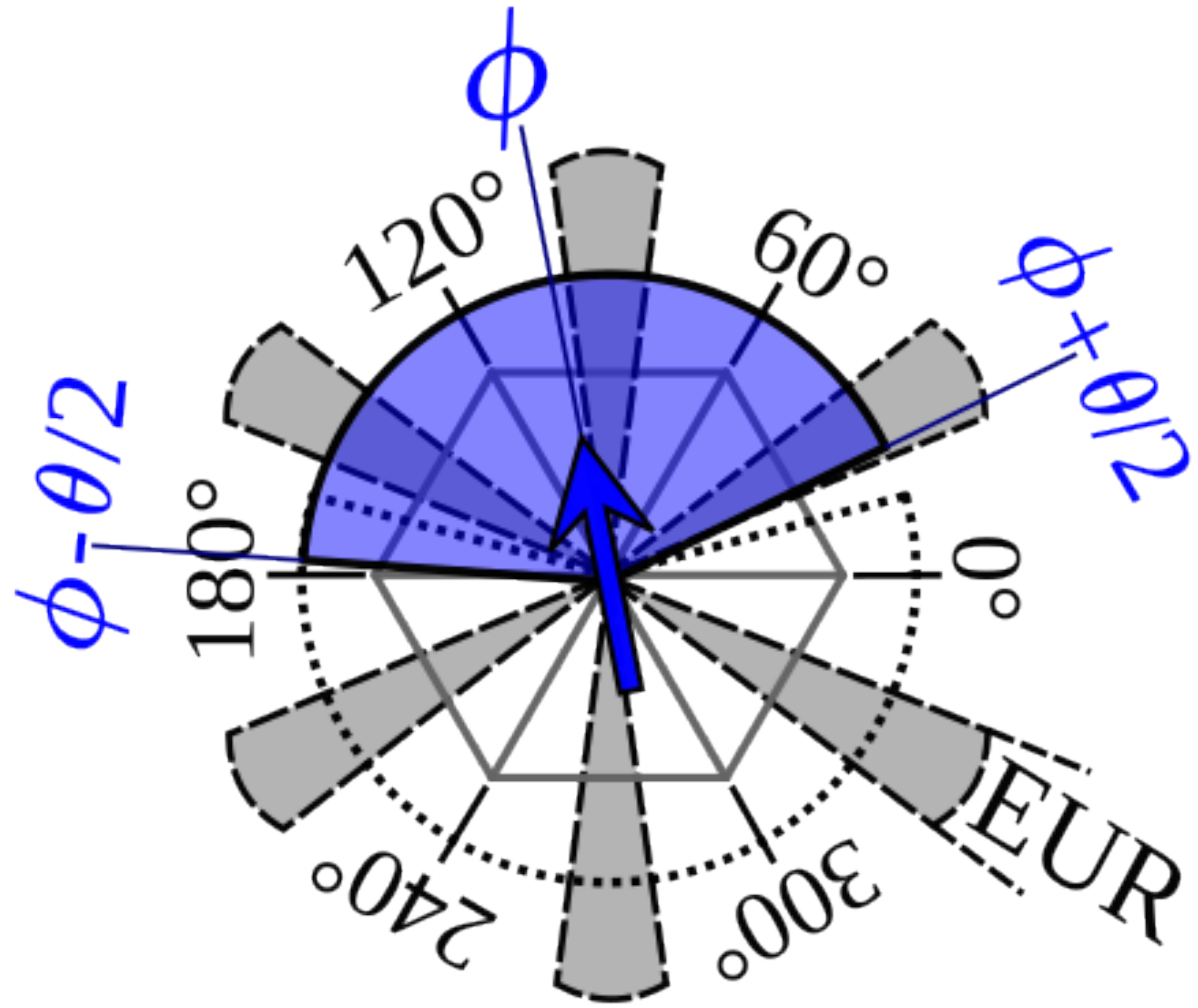
Cost to rotate spin i:

$$E_i \sim \psi^2 = 4\pi^2/L^2 \;+ J$$

Total cost to excite spin wave:

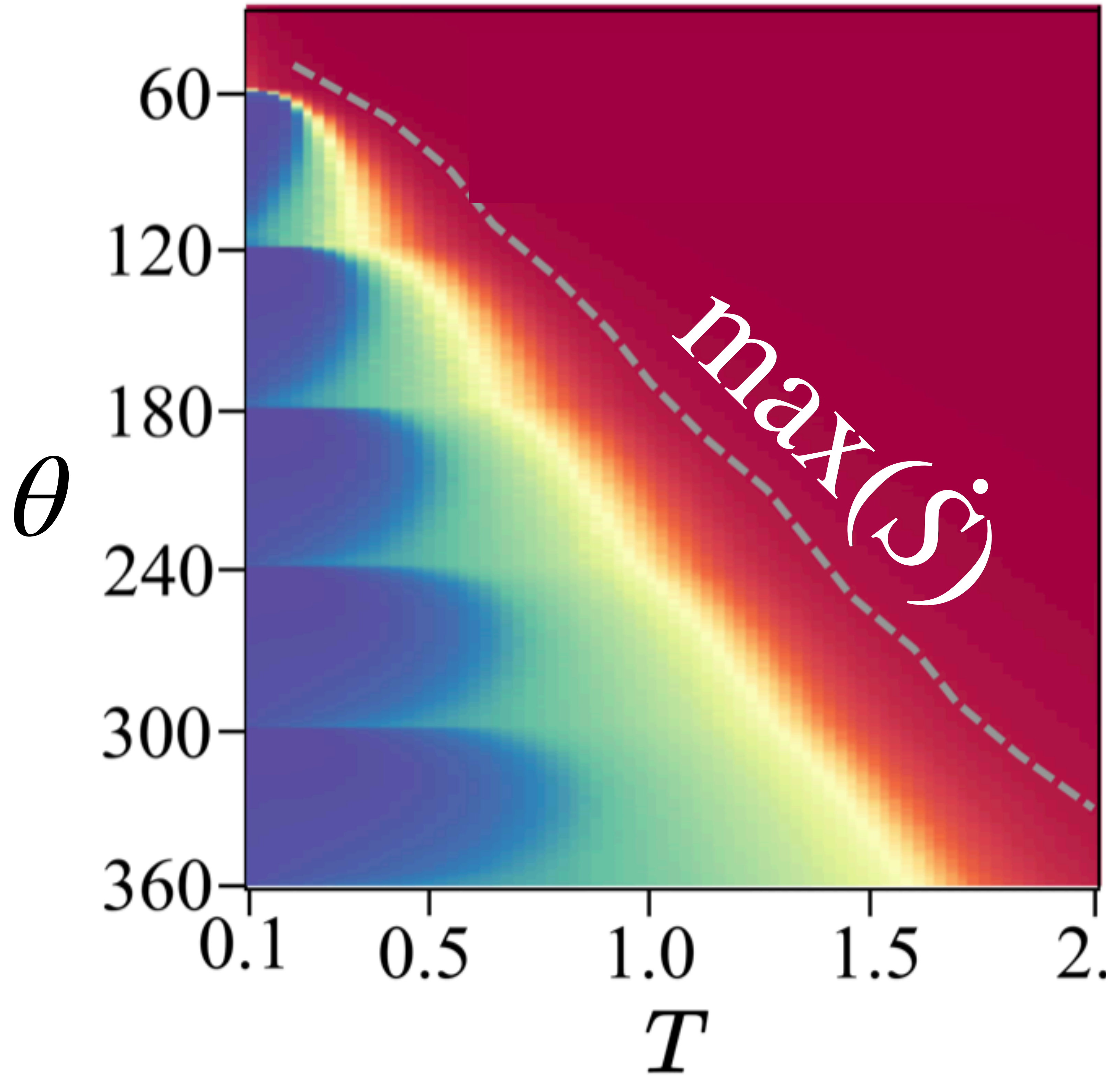
$$E_{\text{total}} = 4\pi^2 + L^2\eta J,$$

$$\eta \to 1 - \frac{[\theta \bmod (360^\circ/n)]}{(360^\circ/n)}$$



- “Energetically unfavourable regions” (EUR)
- Suppression of spin waves due to EUR → LRO
- No LRO at $\theta = n \cdot 60^\circ$

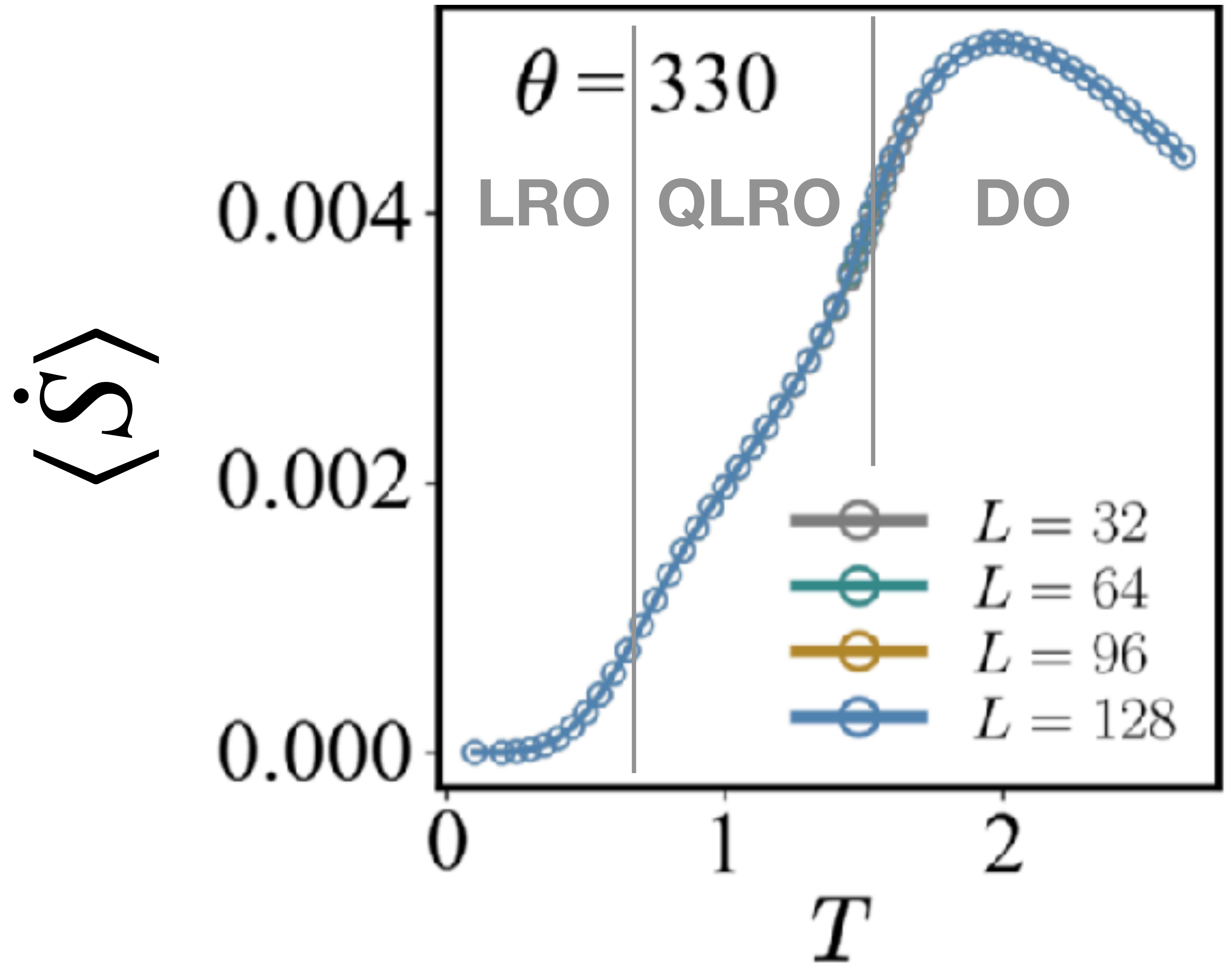
A nonreciprocal XY model — Arrow of time?



Unidirectional propagation of defect lines

Net entropy production:

$$\langle \dot{S} \rangle = \left\langle \ln \frac{w[\phi_i(t) \to \phi_i(t+\mathrm{d}t)]}{w[\phi_i(t+\mathrm{d}t) \to \phi_i(t)]} \right\rangle / \mathrm{d}t$$



<u>Unidirectional</u> propagation of defects

→ Manifestion of nonequilibrium-ness in **collective fluctuations**

<u>SL</u>, Klapp & Martynec, Phys. Rev. Lett. (2023), Y. Rouzaire, et al. PRL (2025).

A nonreciprocal XY model — devil in the details

PHYSICAL REVIEW LETTERS **135,** 088303 (2025)

Ordering and Defect Cloaking in Nonreciprocal Lattice XY Models

Pankaj Popli,[1,*] Ananyo Maitra,[2,3,†] and Sriram Ramaswamy[4,5,‡]
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PHYSICAL REVIEW LETTERS **135,** 088302 (2025)

Inescapable Anisotropy of Nonreciprocal XY Models

Dawid Dopierala,[1,2,*] Hugues Chaté,[3,4,2,†] Xia-qing Shi,[5,‡] and Alexandre Solon[2,§]
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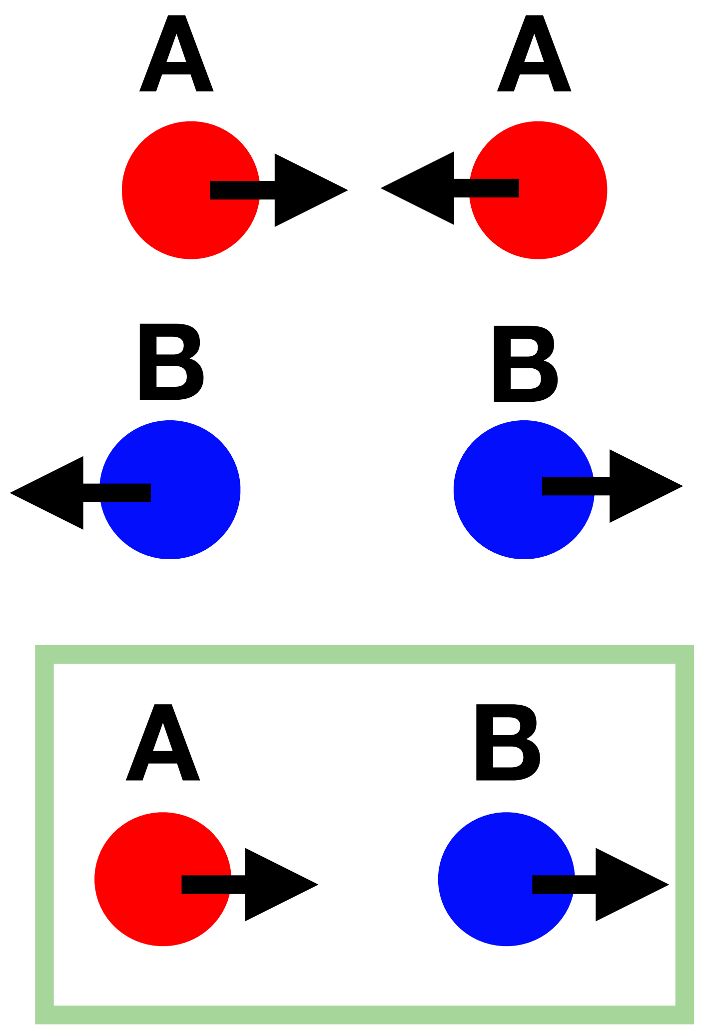
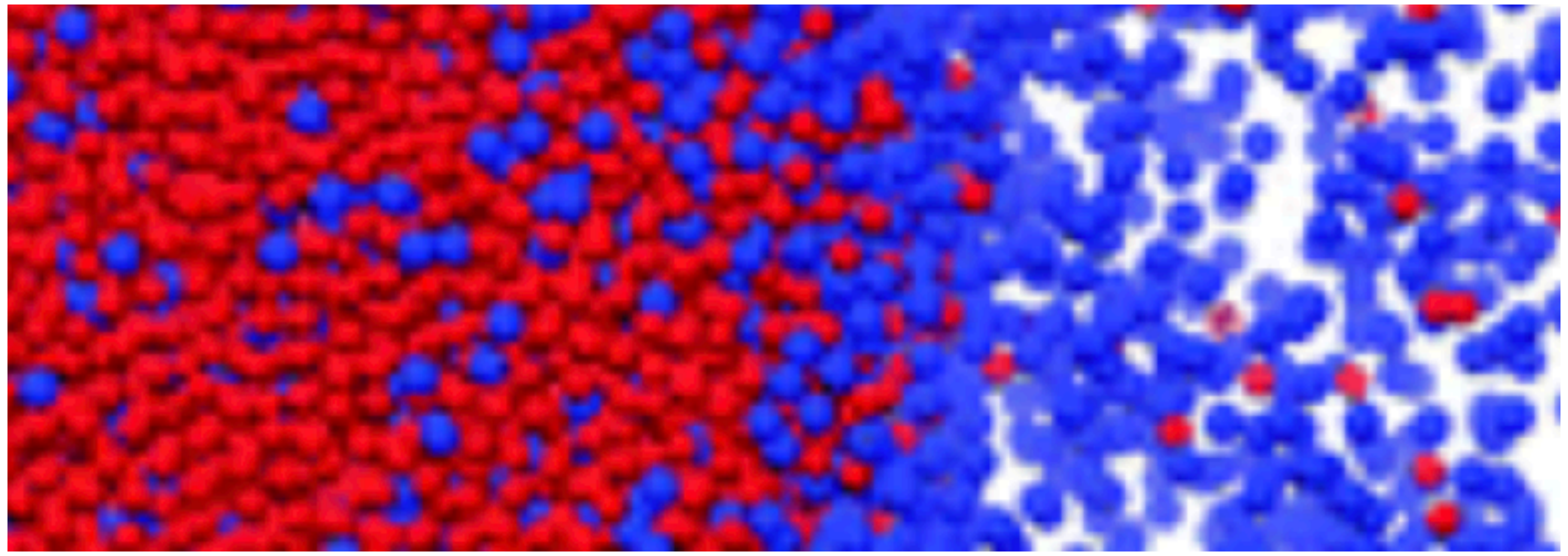
[4]*Computational Science Research Center, Beijing 100094, China*
[5]*Center for Soft Condensed Matter Physics and Interdisciplinary Research & School of Physical Science and Technology, Soochow University, Suzhou 215006, China*

- Z. Liu, et al. "Dynamic approach to the two-dimensional nonreciprocal XY model with vision cone interactions." PRE (2025).
- Y. Du, et al. "Collective behavior of the non-reciprocal vision cone XY lattice-gas model." Newton (2025).
- L. Dadhichi, et al. "Nonmutual torques and the unimportance of motility for long-range order in two-dimensional flocks." PRE (2020).
- Y-B. Sh, et al. "General Hamiltonian description of nonreciprocal interactions." arXiv preprint arXiv:2505.05246 (2025).
- …

Two-Species system with inter-species nonreciprocity



Binary fluids with NR interactions



Example: Nonreciprocal Cahn Hilliard model

$t \in \mathbb{R}, r \in \mathbb{R}^d, \quad \phi_{i=1,2,..}(r,t) \in \mathbb{R}$ scalar fields (densities)

$$\boxed{\dot{\phi}_i = -\nabla \cdot \left(-\nabla \frac{\delta F}{\delta \phi_i} + \kappa_{ij} \nabla \phi_j + \sqrt{2\epsilon}\Lambda_i \right)}$$

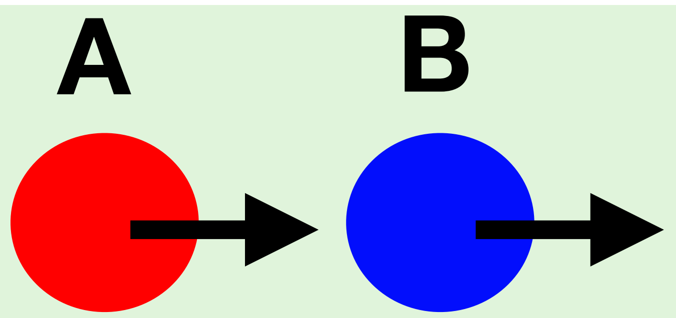
Gaussian space-time white noise

$$\langle \Lambda_i(x,t)\Lambda_j(x',t')\rangle = \delta_{ij}\delta(x-x')\delta(t'-t)$$

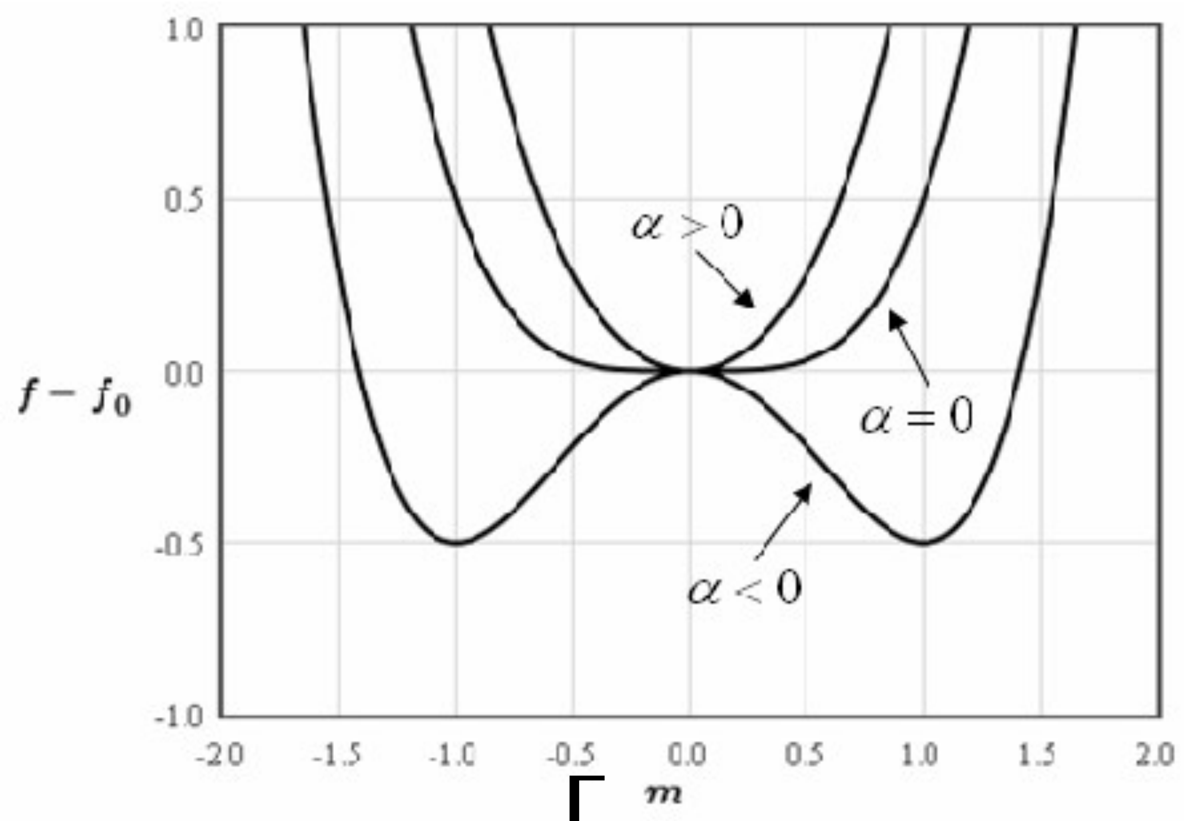
NR:

$$\kappa_{ij} \neq \kappa_{ji}$$

"Non-equilibrium term" (NR) : $\kappa_{AB} = \delta, \quad \kappa_{BA} = -\delta$



"Equilibrium term"

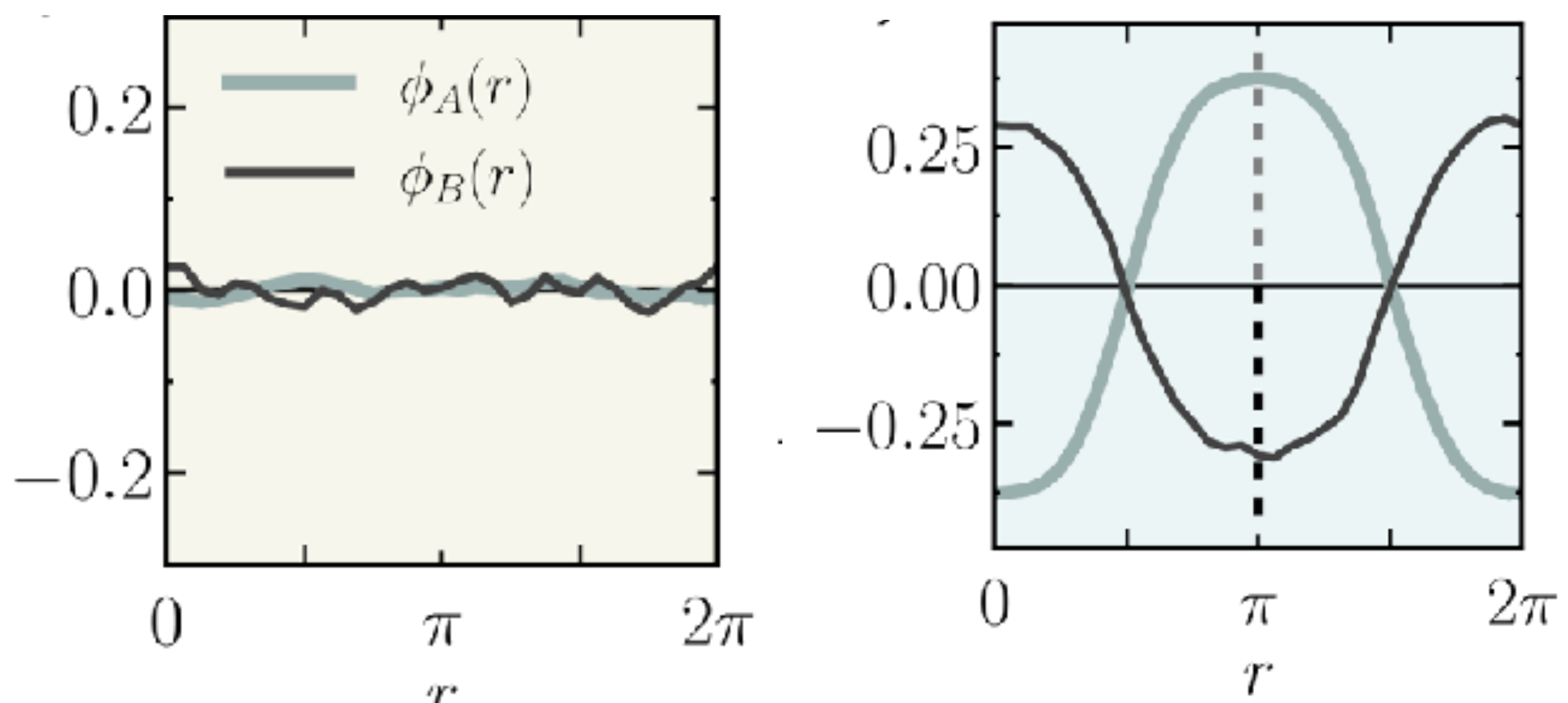


Example:

- Cahn-Hilliard (ϕ^4 theory)
- $\phi_{A,B}$ = concentrations

$$F = \frac{1}{2}\int_V dx \left[\sum_{i=A,B} \frac{1}{6}\phi_i^4 + \alpha_i \phi_i^2 + \gamma_i (\nabla \phi_i)^2 - \kappa \phi_A \phi_B \right]$$

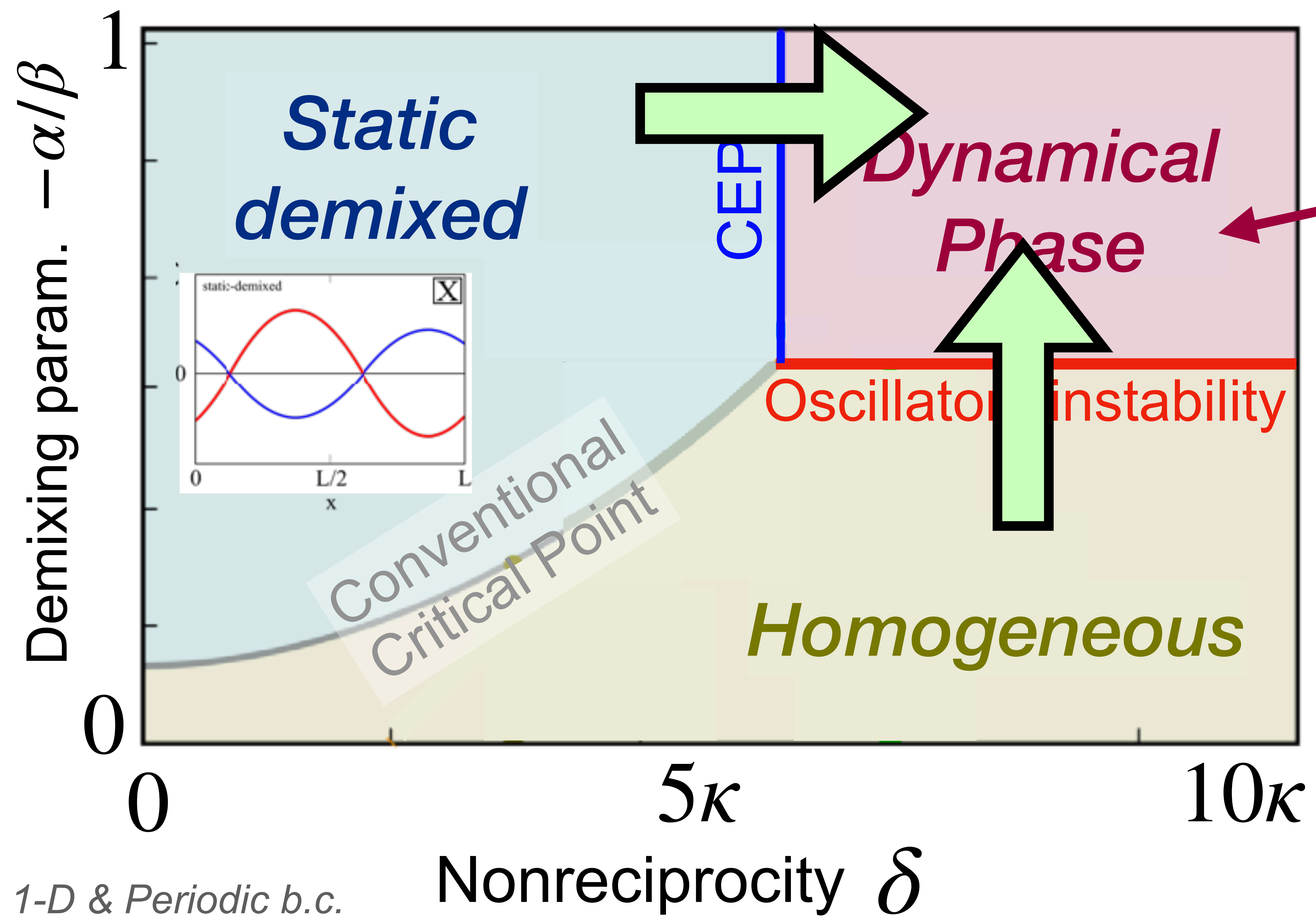
Demixing transition



[You et al., PNAS (2020)]
[Saha et al, PRX (2020)]]
[Mason et al., ArXiiv (2024)]
[Mandal et al., PRE (2024)]
[Brauns et al., PRX (2025)]

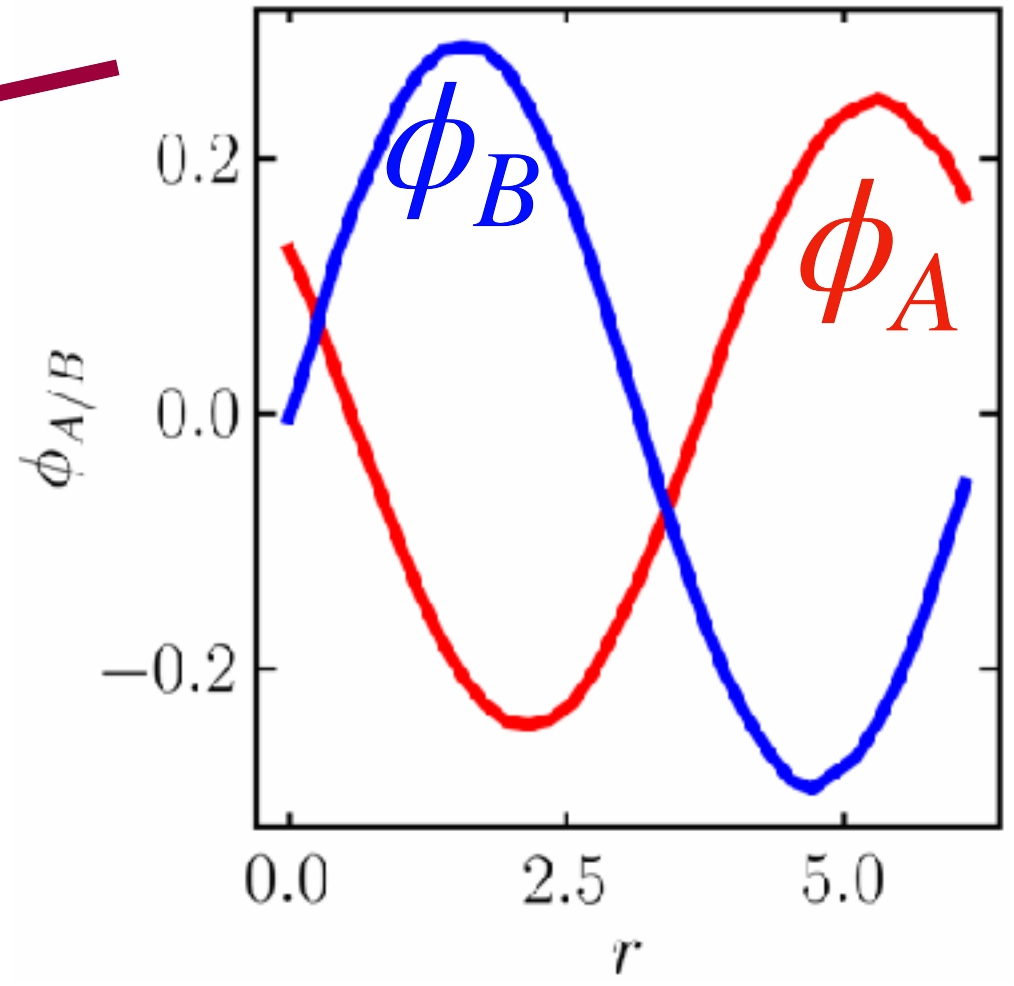
$$\dot{\phi}_A = \nabla[(\alpha + \phi_A^2 - \gamma\nabla^2)\nabla\phi_A + (1-\delta)\nabla\phi_B] + \sqrt{2\epsilon}\Lambda_A$$
$$\dot{\phi}_B = \nabla[(\beta + \cancel{\phi_B^2} - \cancel{\gamma\nabla^2})\nabla\phi_B + (1+\delta)\nabla\phi_A] + \sqrt{2\epsilon}\Lambda_B$$

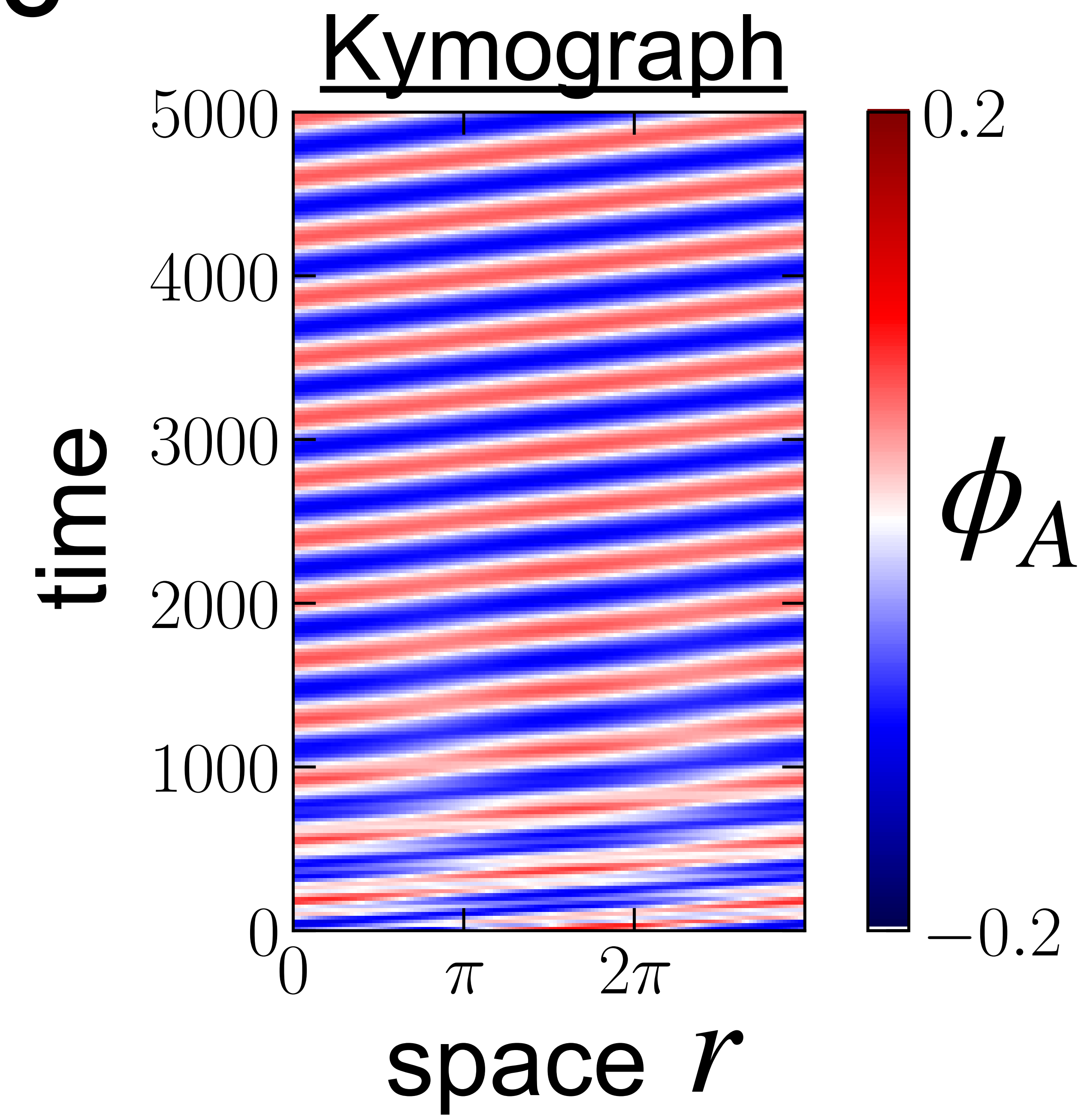
NR Cahn-Hilliard model



1-D & Periodic b.c.

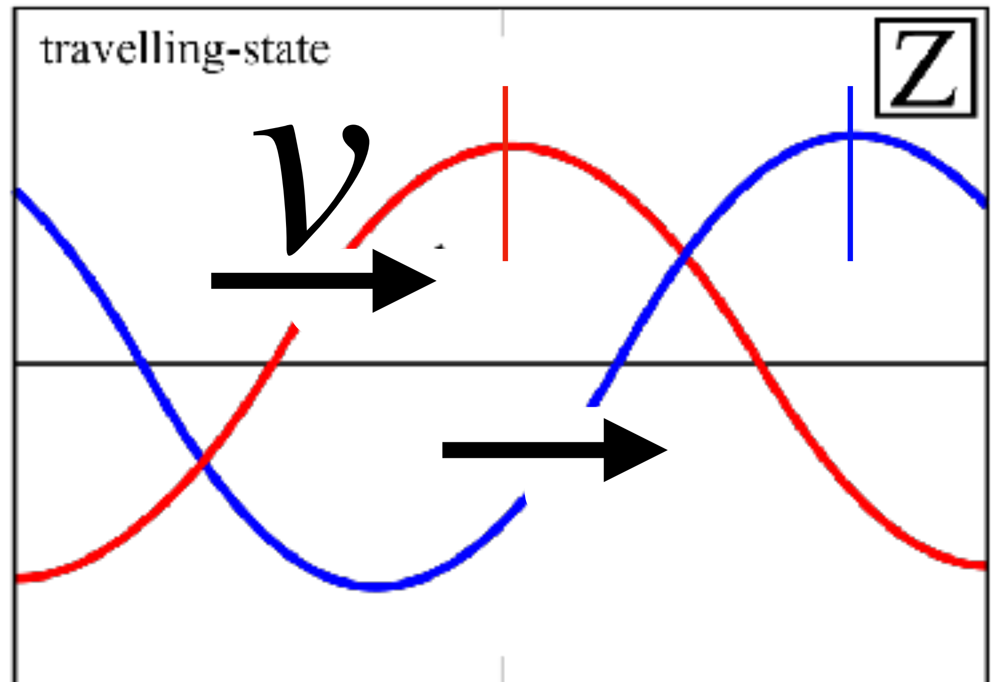
Travelling wave

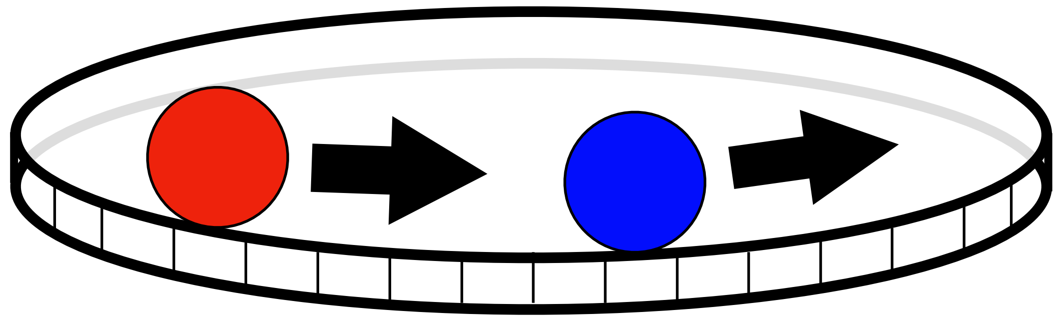




Dynamical phase:
<u>sustained mass flows</u>

$$\Delta\theta^{\pi} = \left[\theta_A^1 - (\theta_B^1 + \pi)\right]$$
$$|v| \approx \sqrt{|\delta - \delta_c|}$$



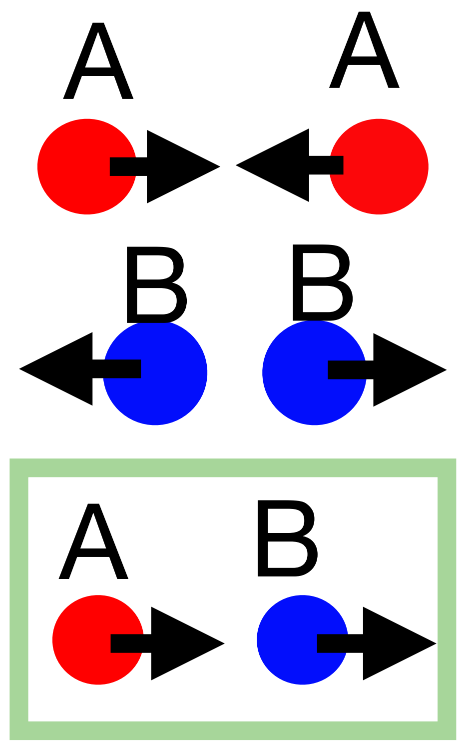


Combination of NR +
many-body effects → net flow

[You et al, PNAS (2020)]
[Saha et al, PRX (2020)]
[Brauns et al, PRX (2024)]

Emergence of TRSB at macroscopic scale

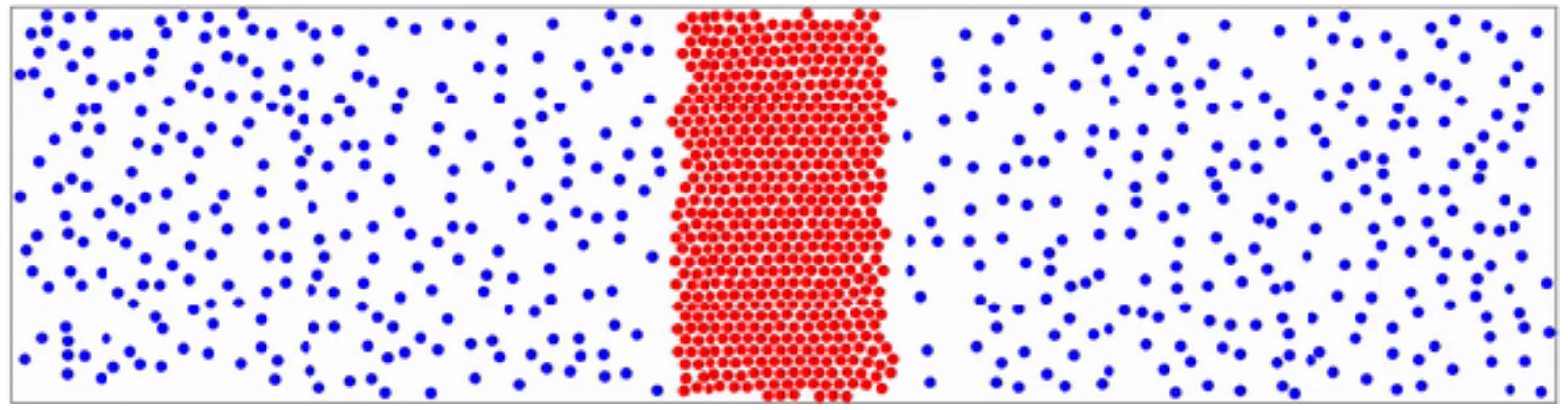
[You, PNAS (2020)]

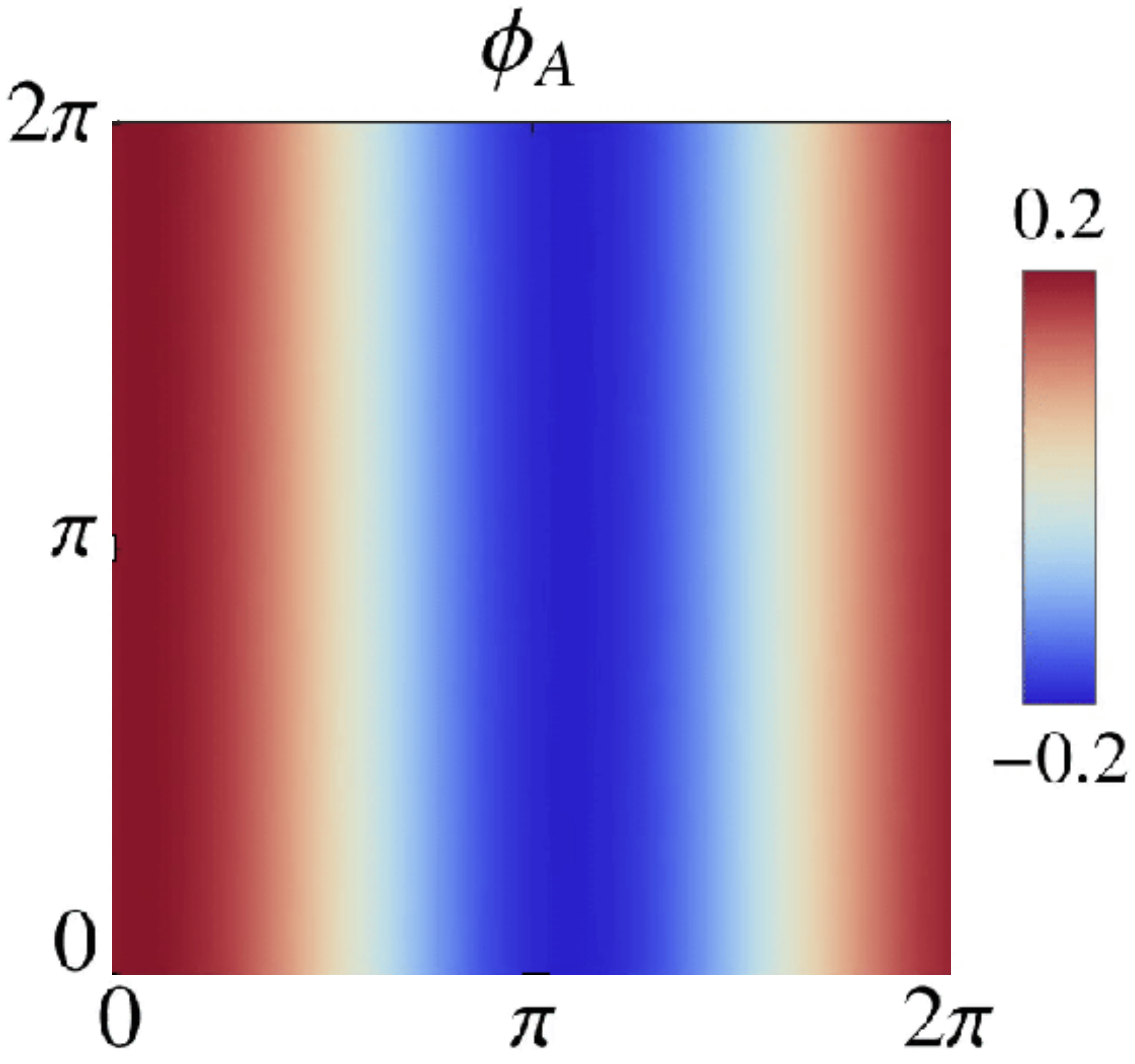


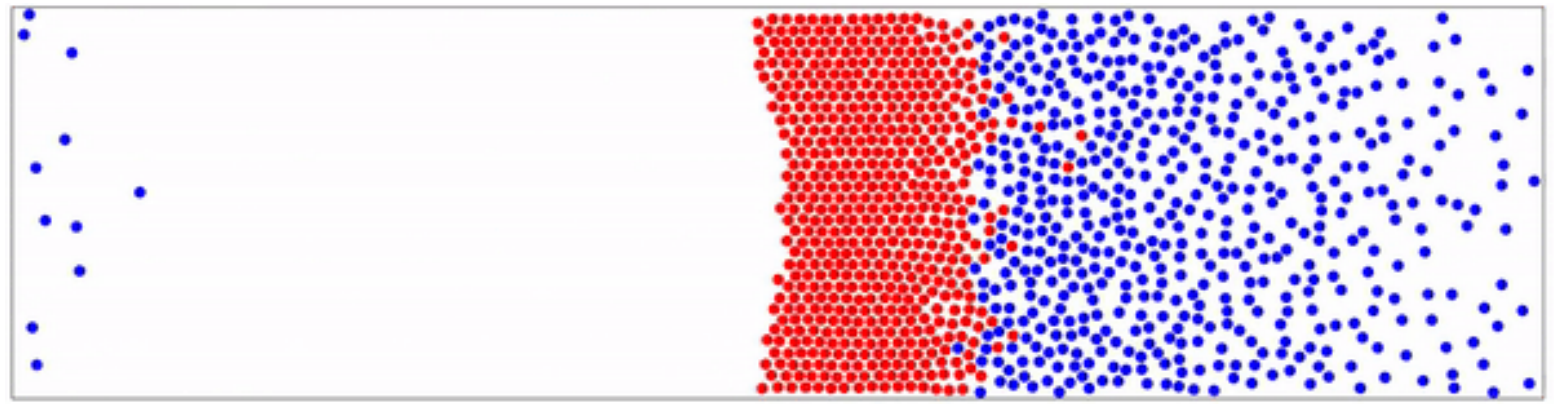
Static phase

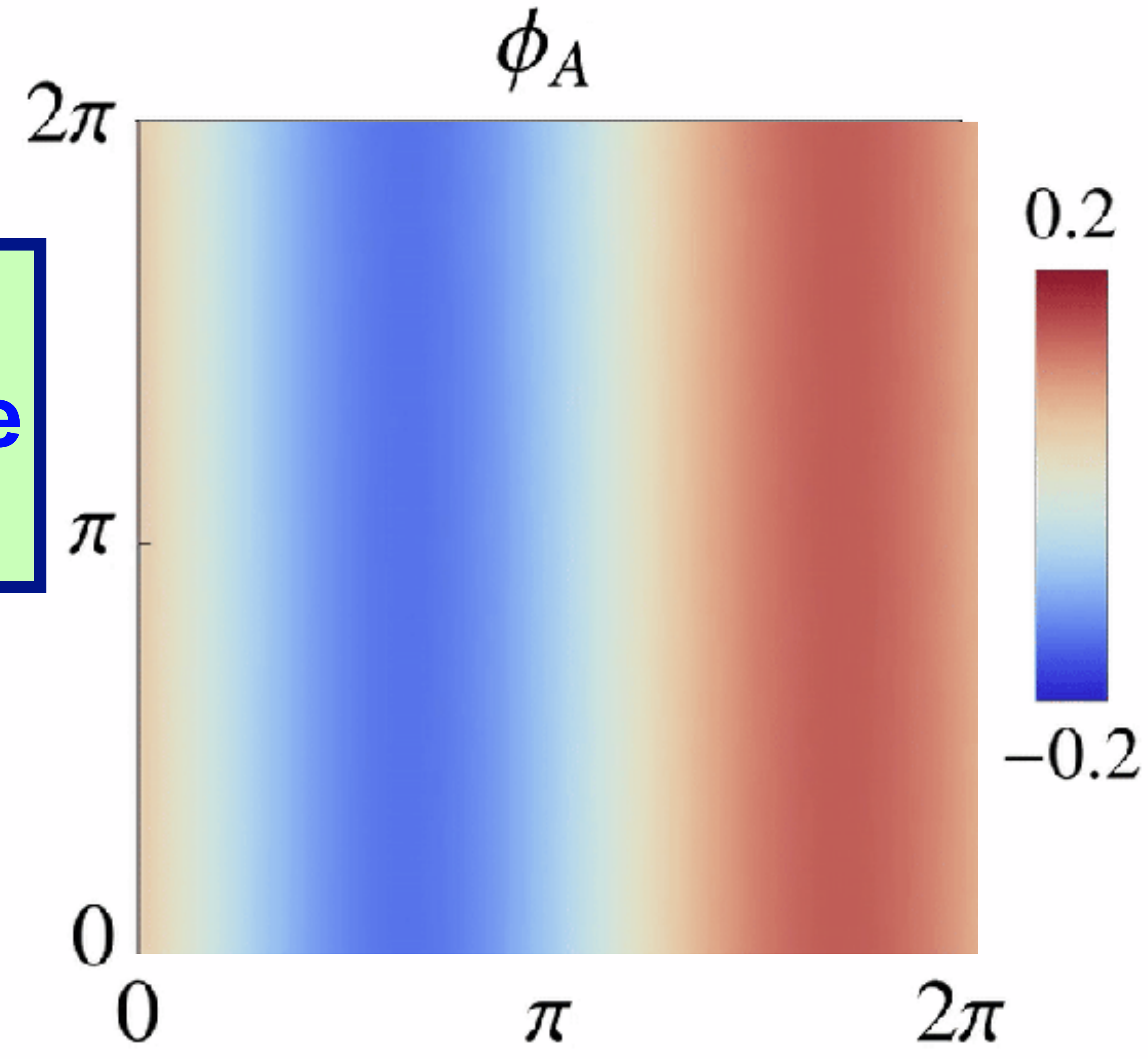
Increase Nonreciprocity

Dynamic phase









Emergence of TRSB at collective level?

“Equilibrium-like” phase

Clearly nonequilibrium

Entropy production in travelling wave phase

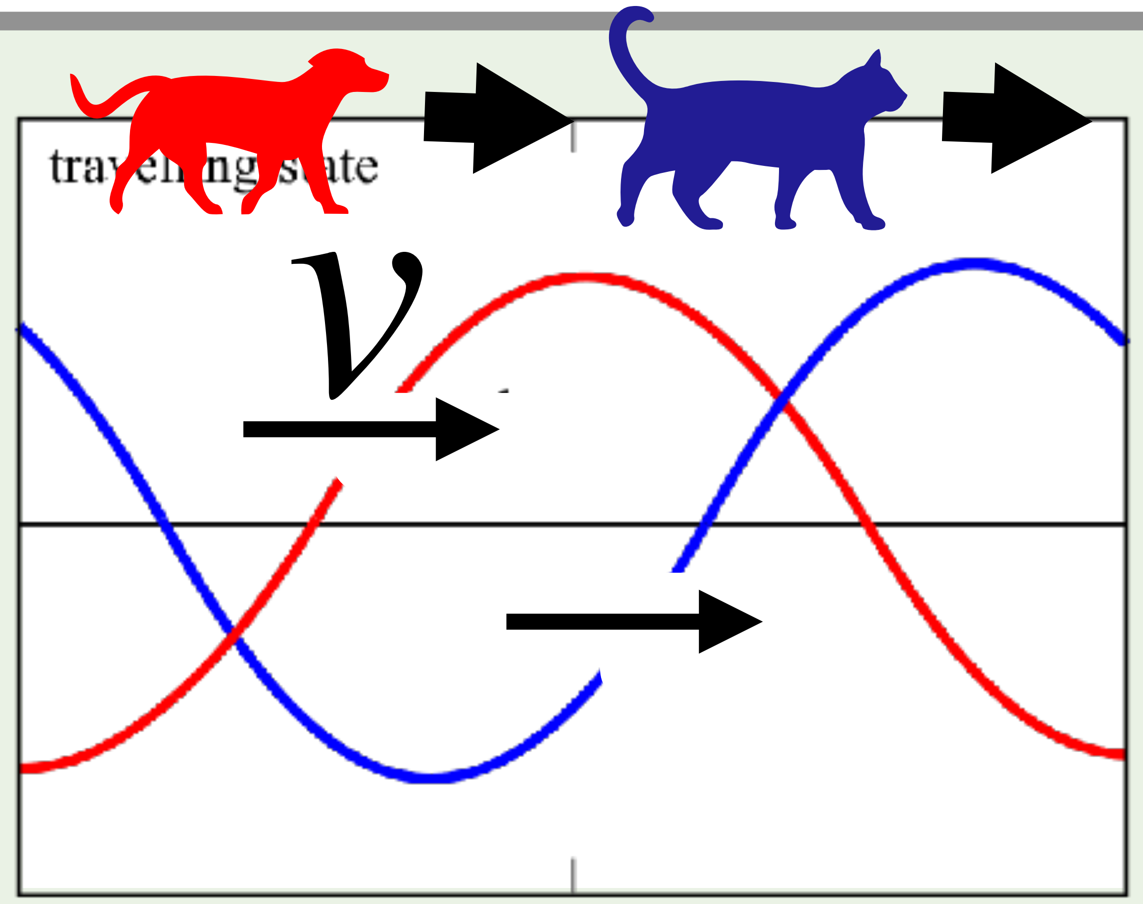
NRCH

In Dynamical Phase

$$\dot{S} = \left\langle \ln \frac{P\left[\{\phi_{A,B}(t')\}_0^t\right]}{\hat{P}\left[\{\hat{\phi}_{A,B}(t')\}_0^t\right]} / t \right\rangle \sim \frac{1}{\epsilon}$$

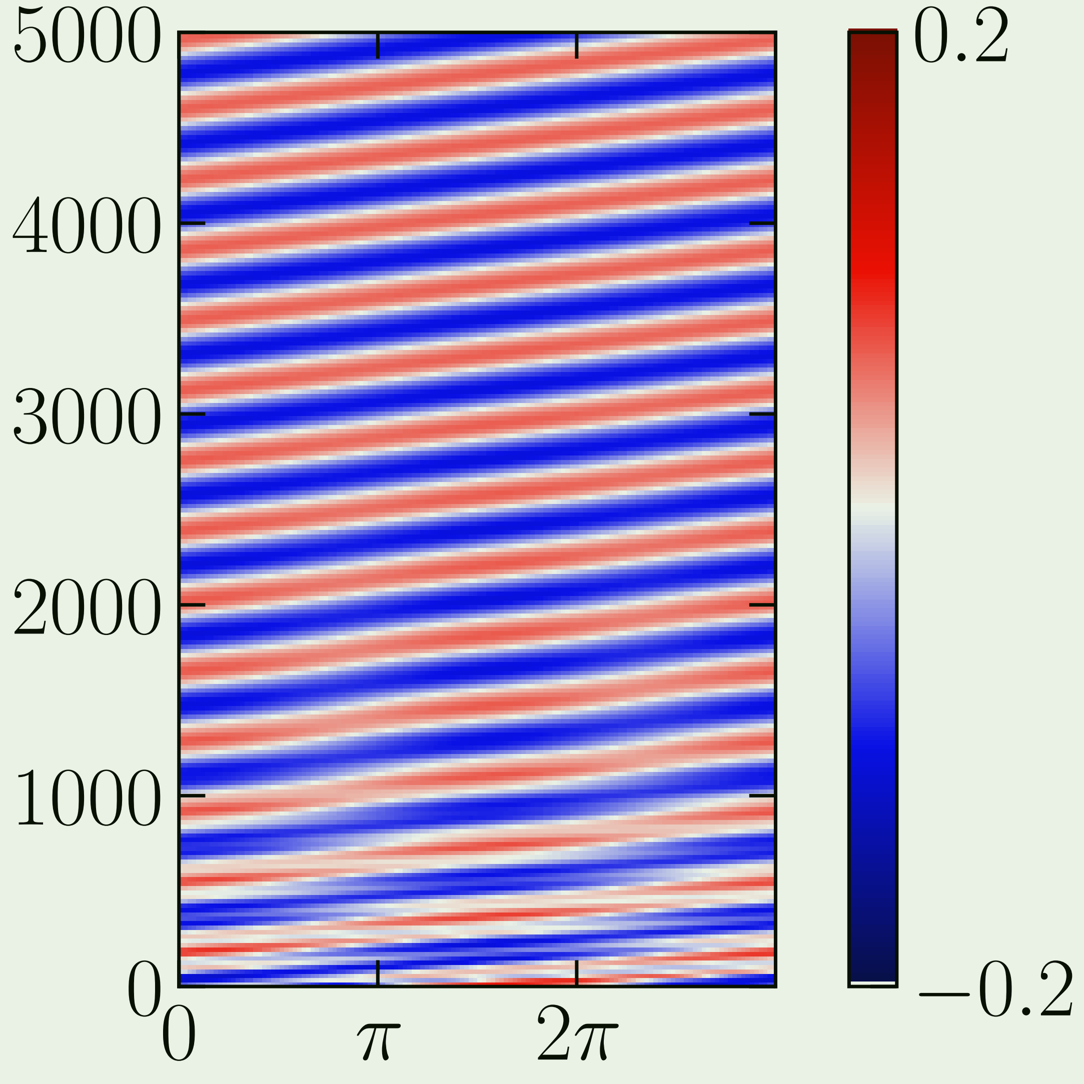
Diverges in thermodynamic limit!

"Macroscopic arrow of time"

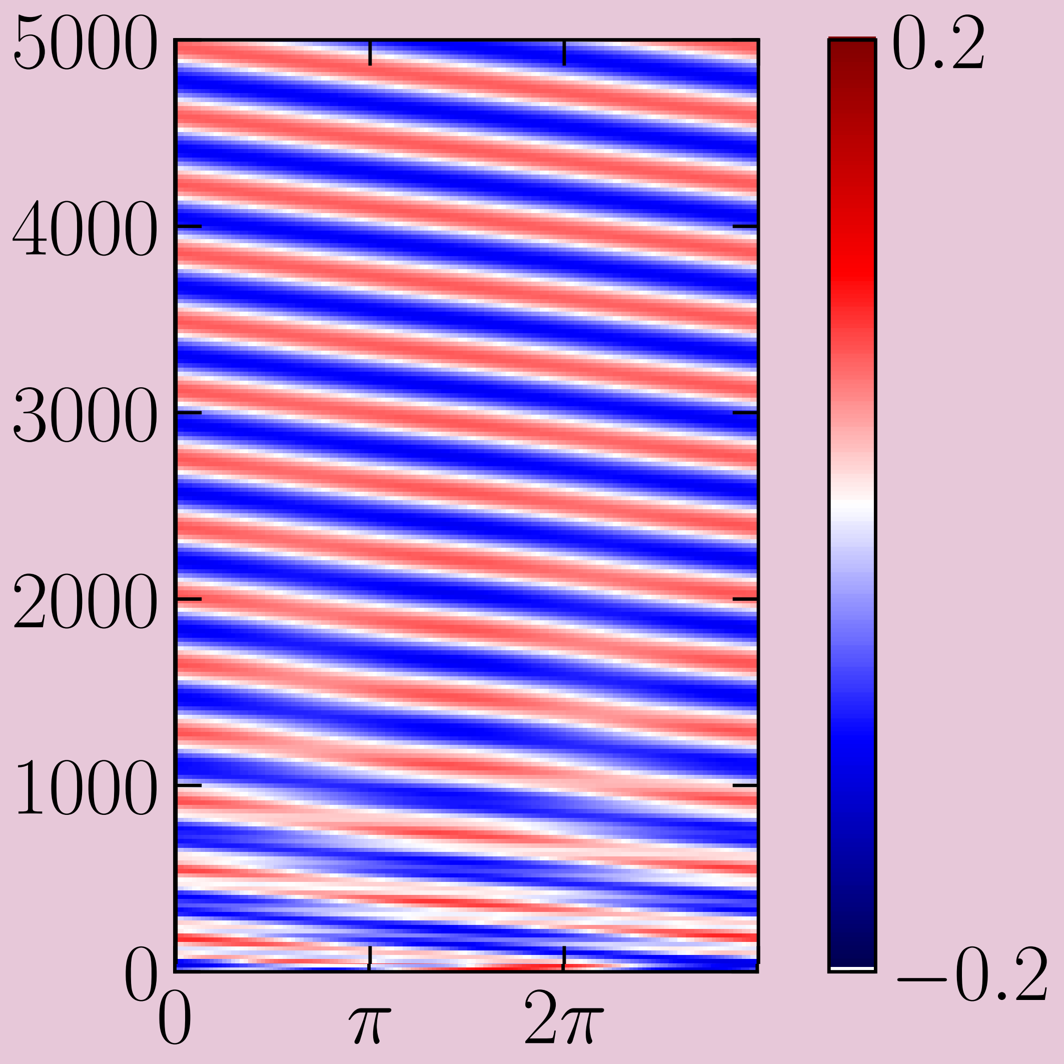


$t \rightarrow -t$

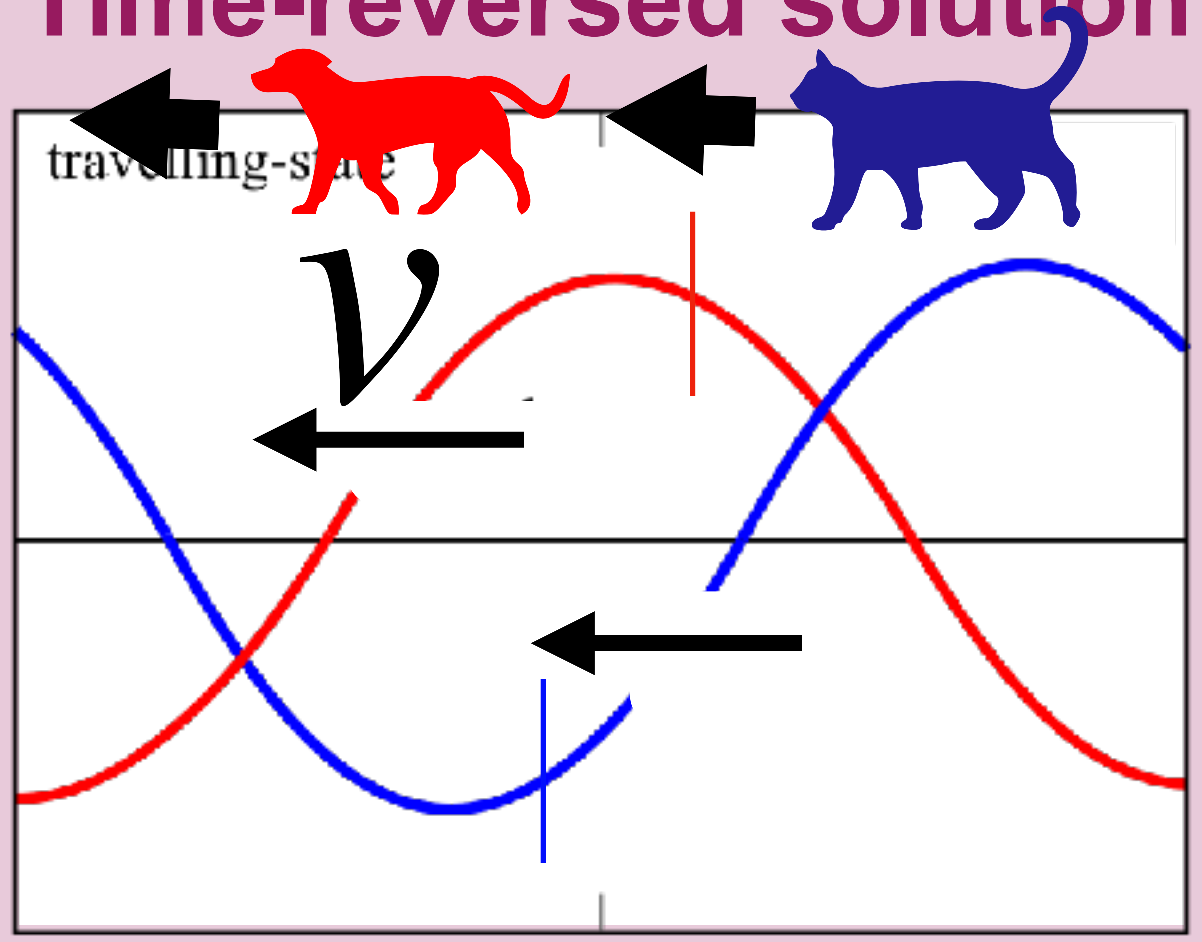
But sign(v) spontaneously broken symmetry!



Time-reversed solution



Time-reversed solution



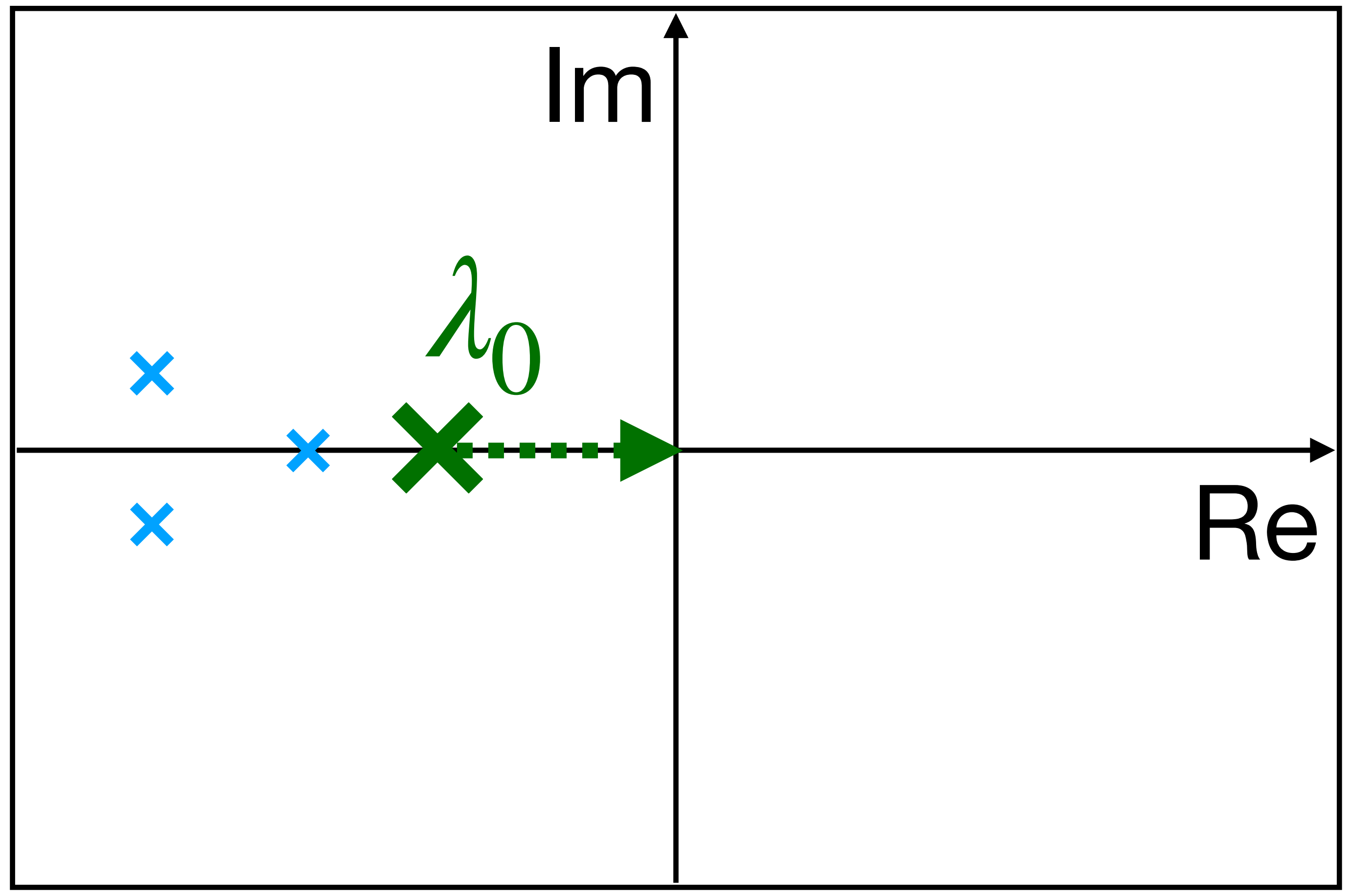
Characteristic Phase Shift

TRSB $\leftrightarrow$ PT-symmetry breaking

3 different transition scenarios

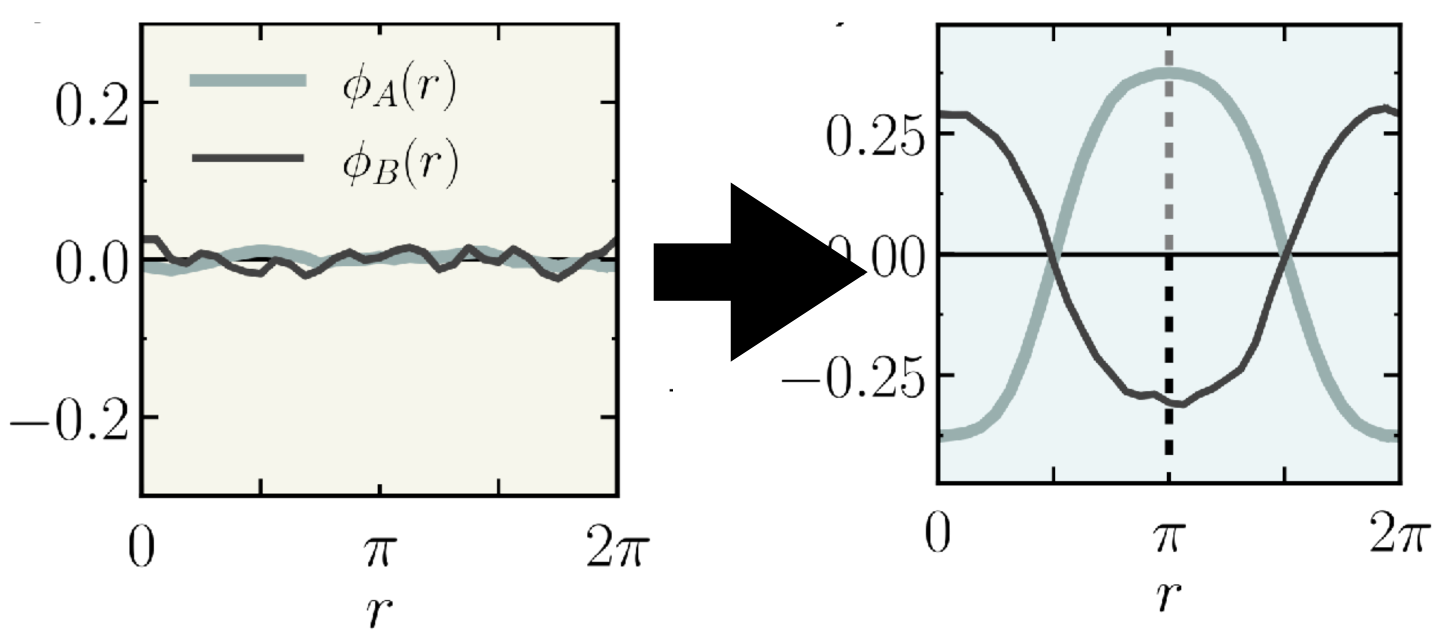
Static—Static transition

Conventional Critical Point



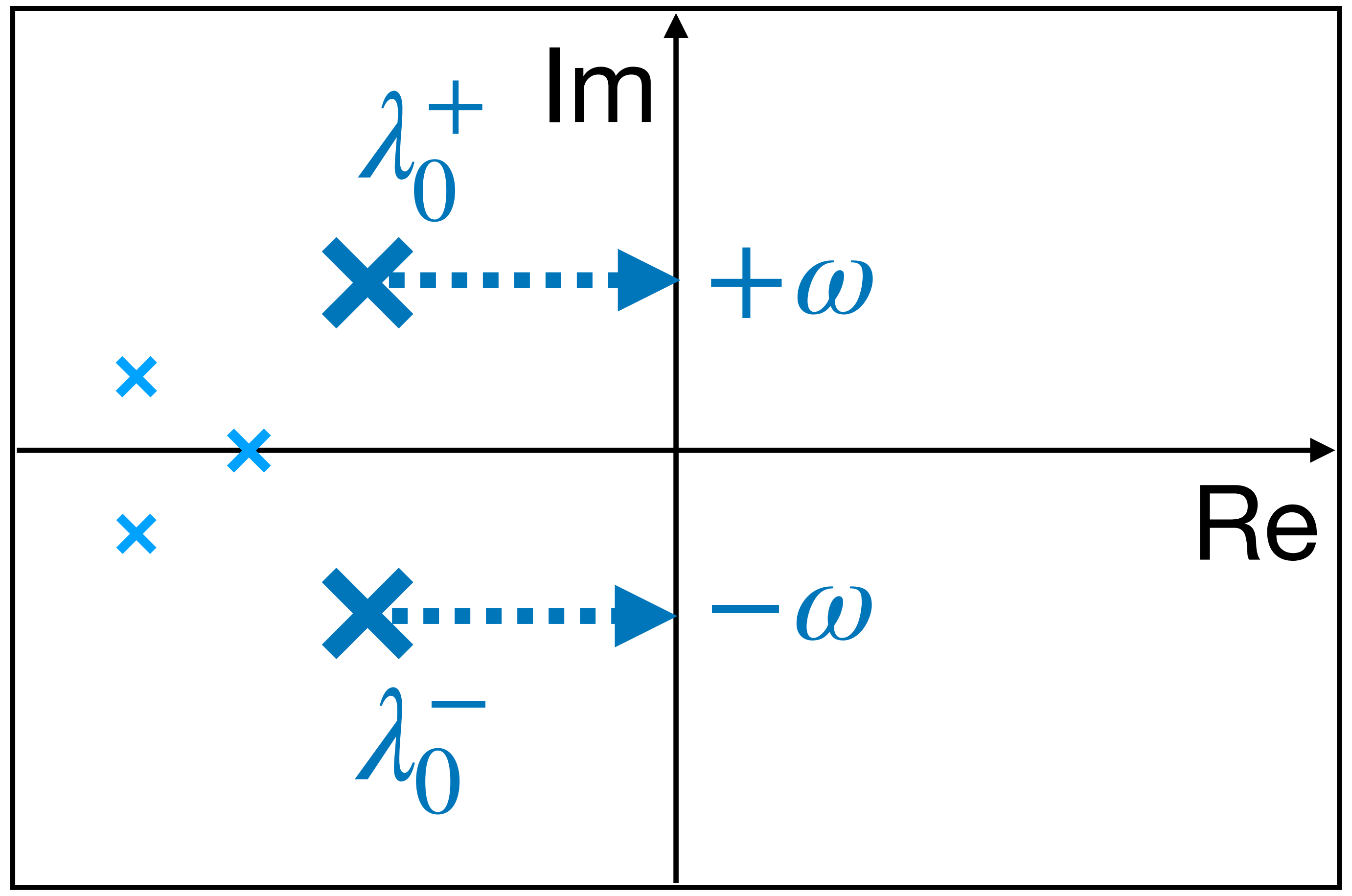
Primary Bifurcation

Hom. → Static demixed



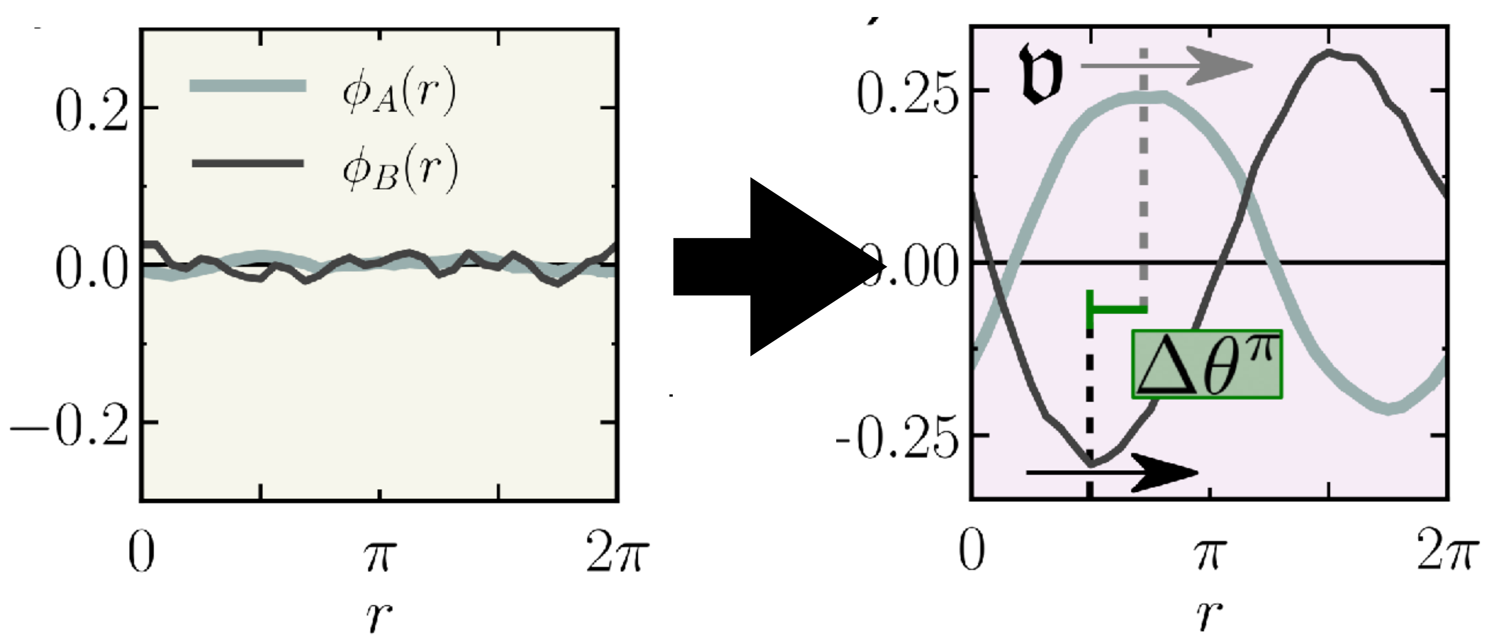
Static—Dynamic transitions

Oscillatory Instability

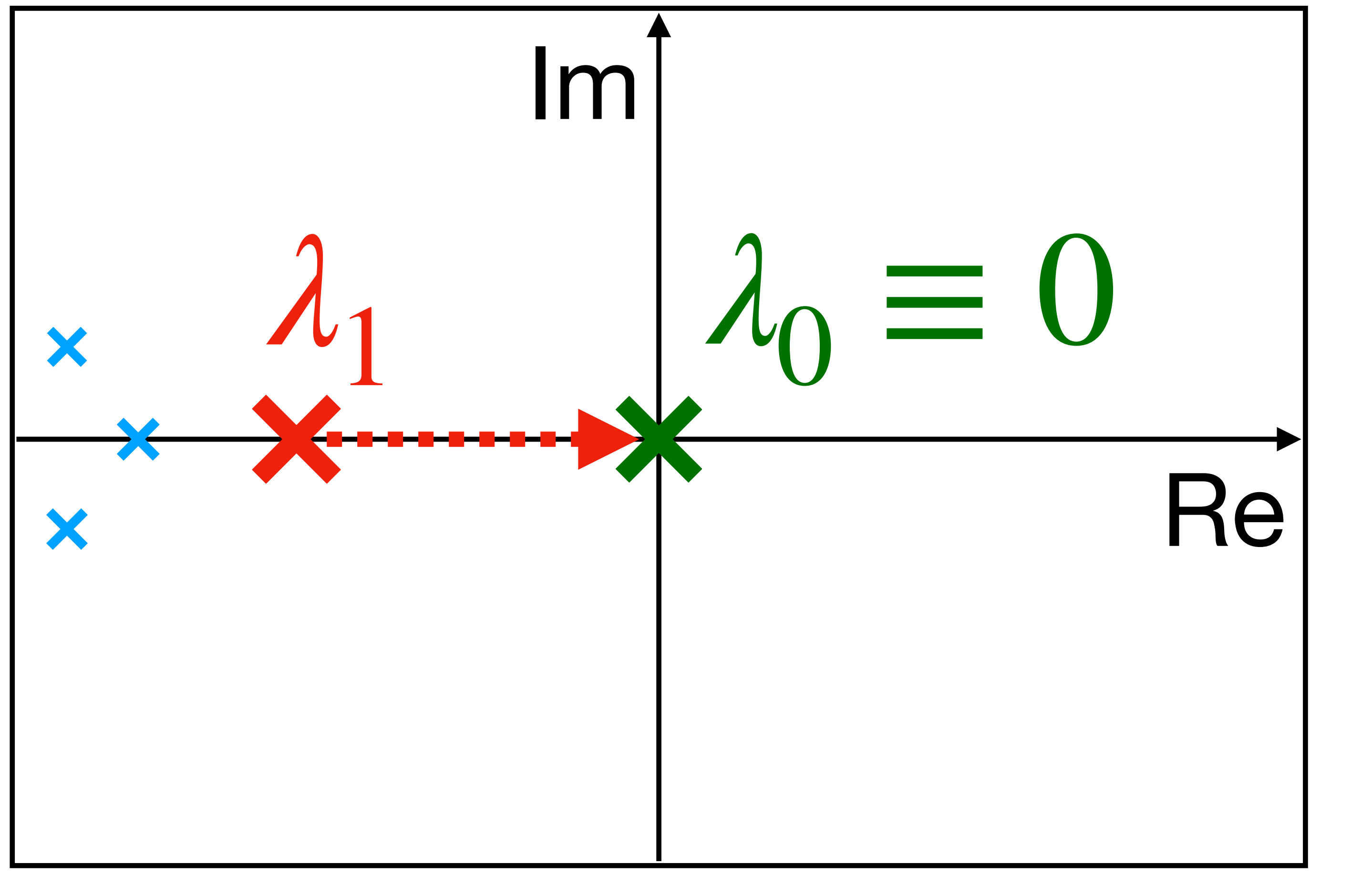


Primary Bifurcation

Hom. → Travelling wave

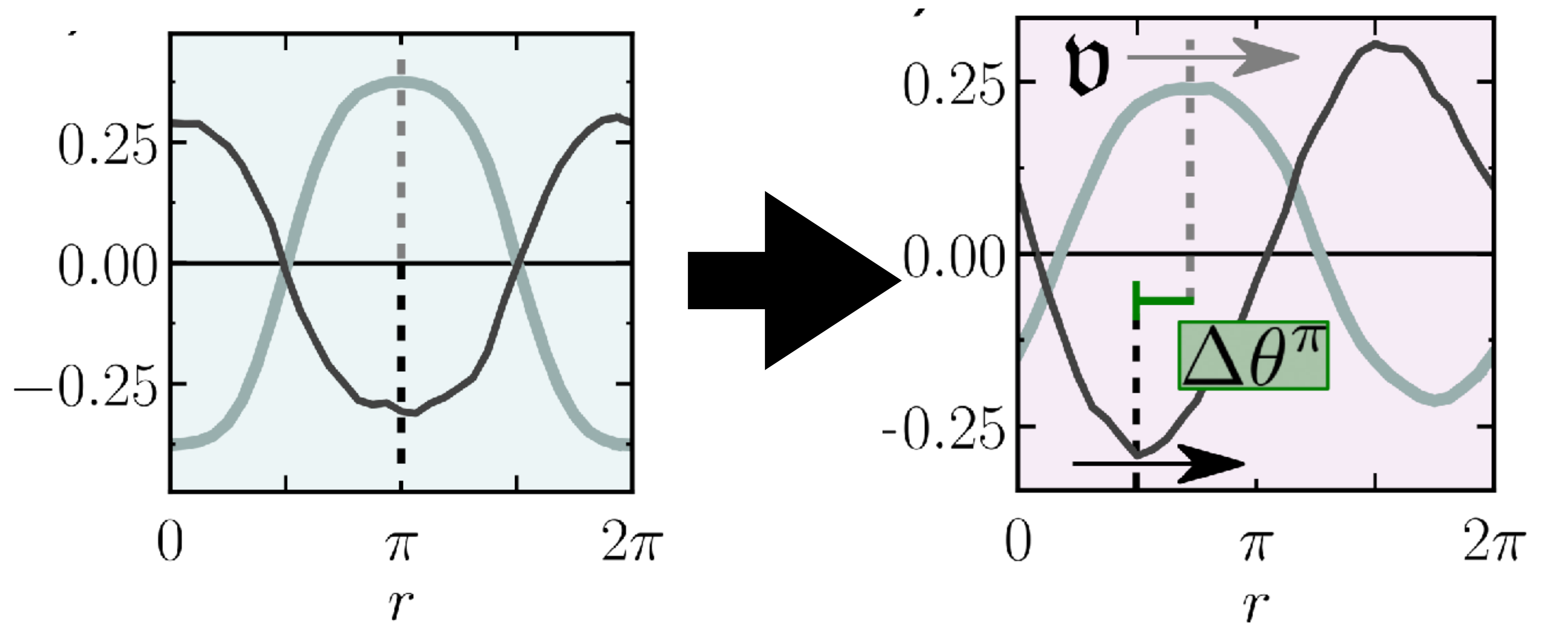


Critical Exceptional Point (CEP)



Secondary Bifurcation

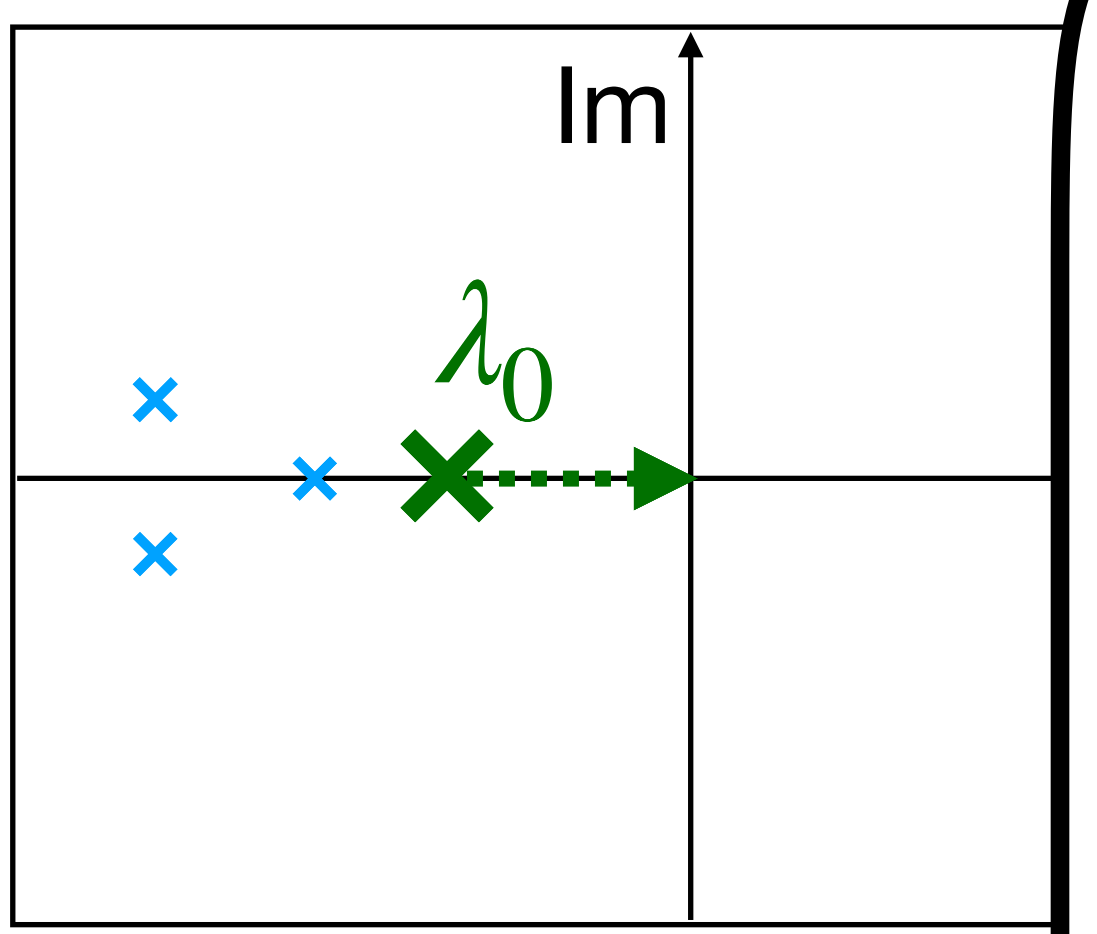
Static dem. → Travelling wave



3 different transition scenarios

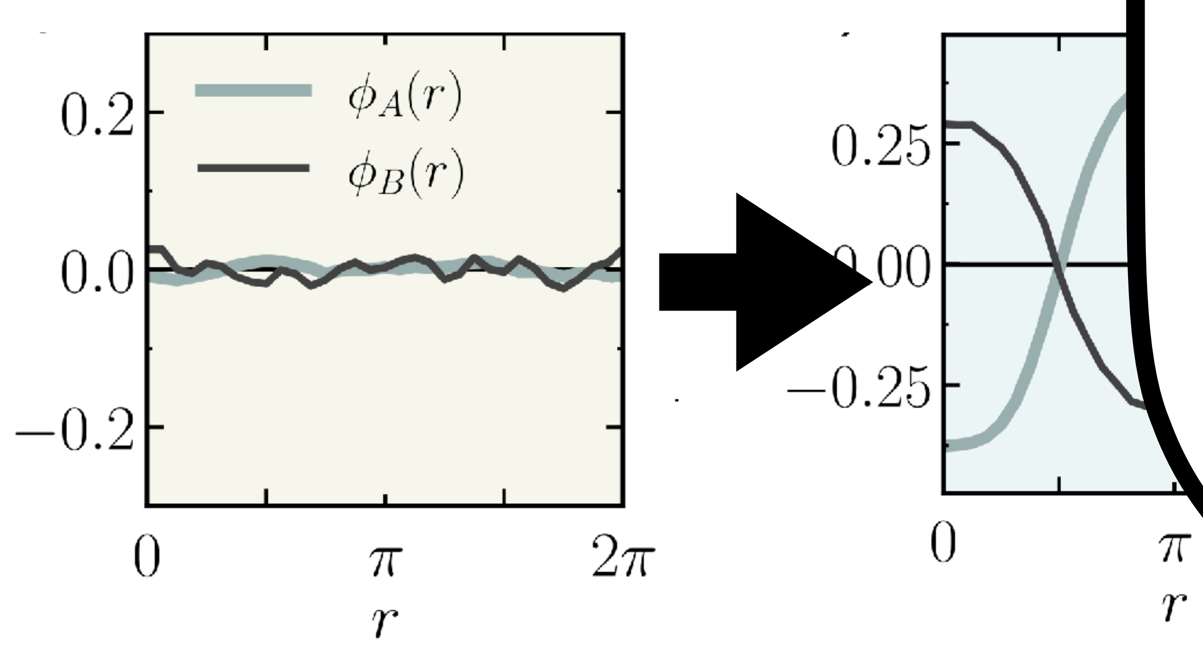
Static—Static transition

Conventional Critical P

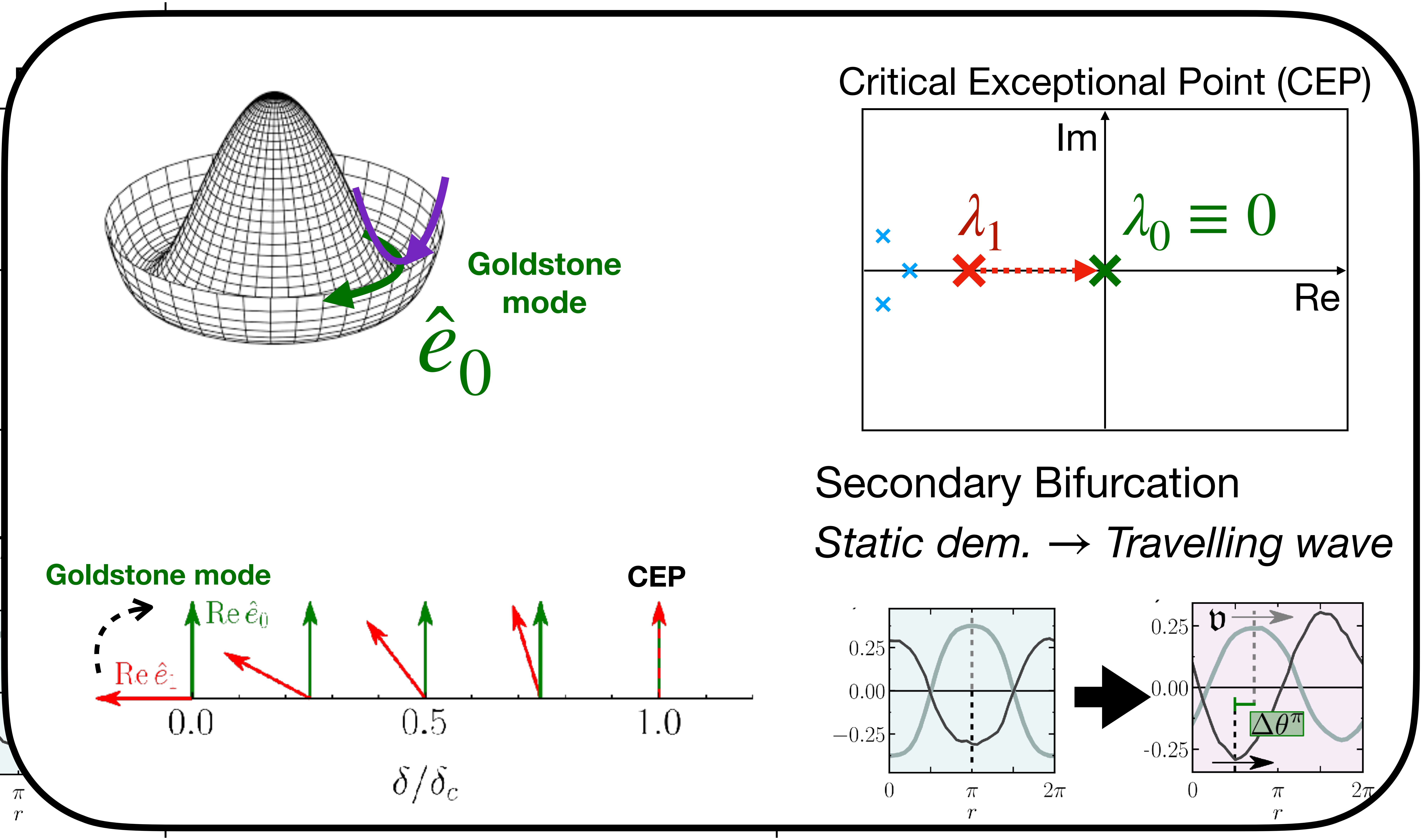


Primary Bifurcation

Hom. → Static dem



Static—Dynamic transitions



Characteristics of fluctuations close to transitions

$$\dot\phi_i = -\nabla\cdot\left(J_i^d + \sqrt{2\epsilon}\Lambda_i\right)$$

- Typical size $\chi = \lim_{\epsilon\to 0}\sum_i \int_V \mathrm{d}r \left\langle (\phi_i - \phi_i^*)^2 \right\rangle/\epsilon$
- TRSB ("Nonequilibrium-ness") $\dot S = \left\langle \ln \frac{\mathbb{P}\left[\phi(t)\,|_0^T\right]}{\mathbb{P}_\mathrm{R}\left[\phi_\mathrm{R}(t)\,|_0^T\right]}/T \right\rangle$

  [Nardini et al., PRX (2017)]

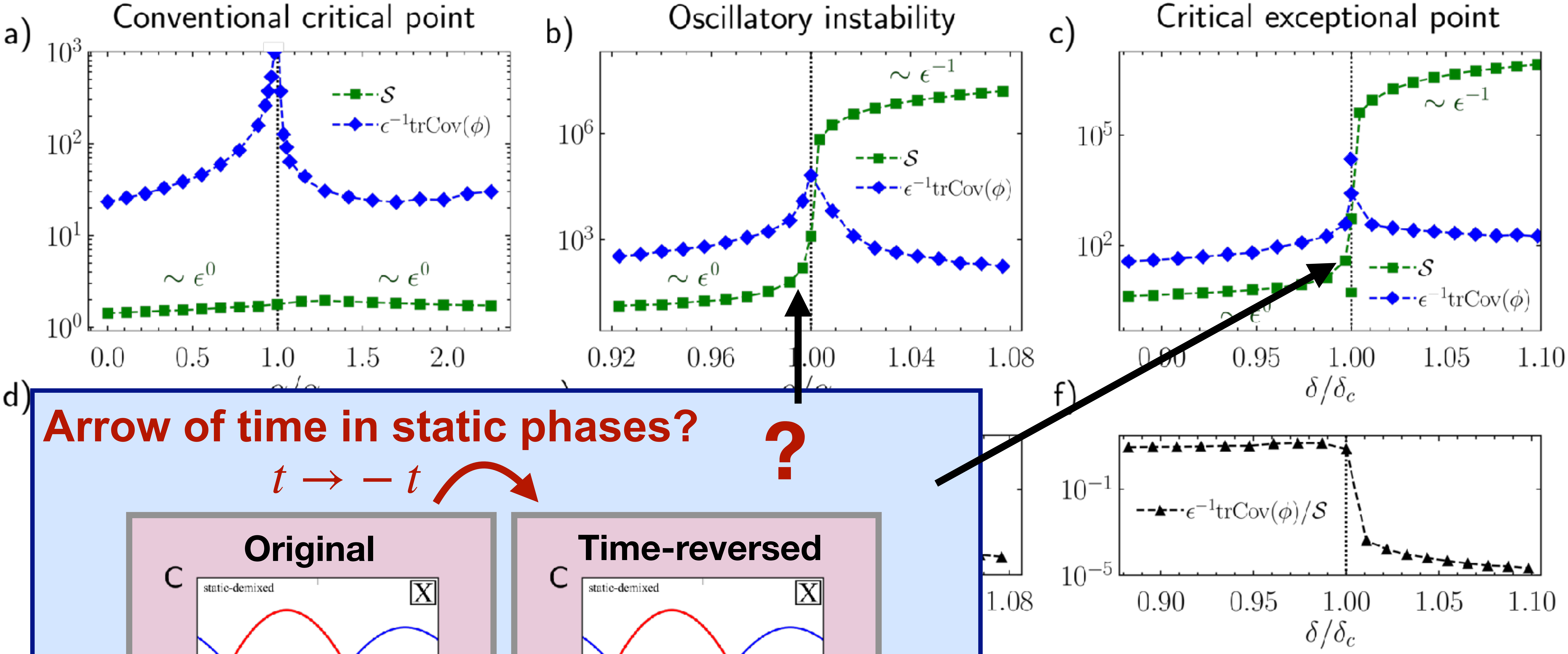
Static-to-Static	• Conventional Critical Points:	$\chi \sim \mathrm{Re}[\lambda_0^k] \to \infty$	$\dot S$ finite
Static-to-Dynamic	• Oscillatory Instabilities:		$\dot S \sim \frac{\omega^2}{\lvert q^l\rvert^2}\chi \to \infty$
	• Critical Exceptional Point:		$\dot S \sim \frac{1}{\lvert q^l\rvert^2}\chi \to \infty$

***<u>Prediction:</u>* $\dot S$ heralds approach to dynamical phase transition**

- In dynamical phase: $\dot S = \sim \epsilon^{-1}(1/\tau)^2$

Suchanek, Kroy, & <u>Loos</u>, PRL (2023)

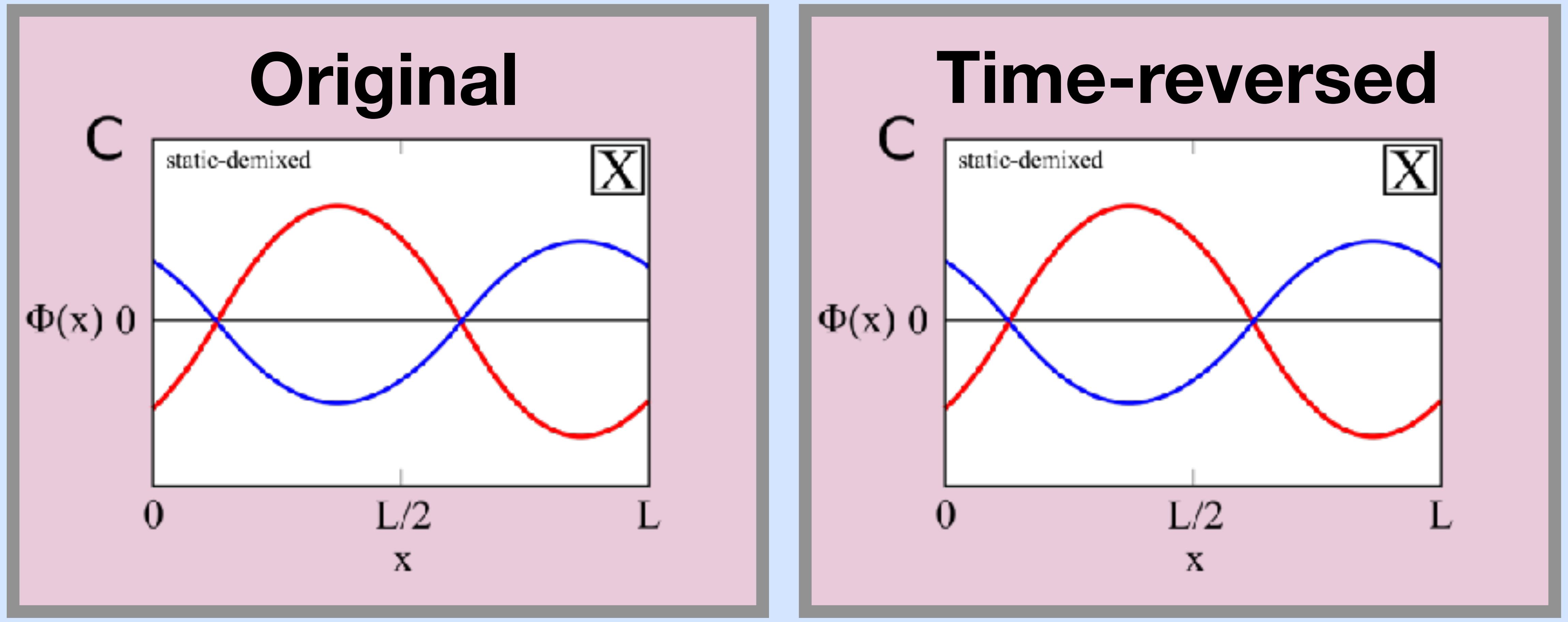
NRCH



Arrow of time in static phases?

$t \to -t$

?

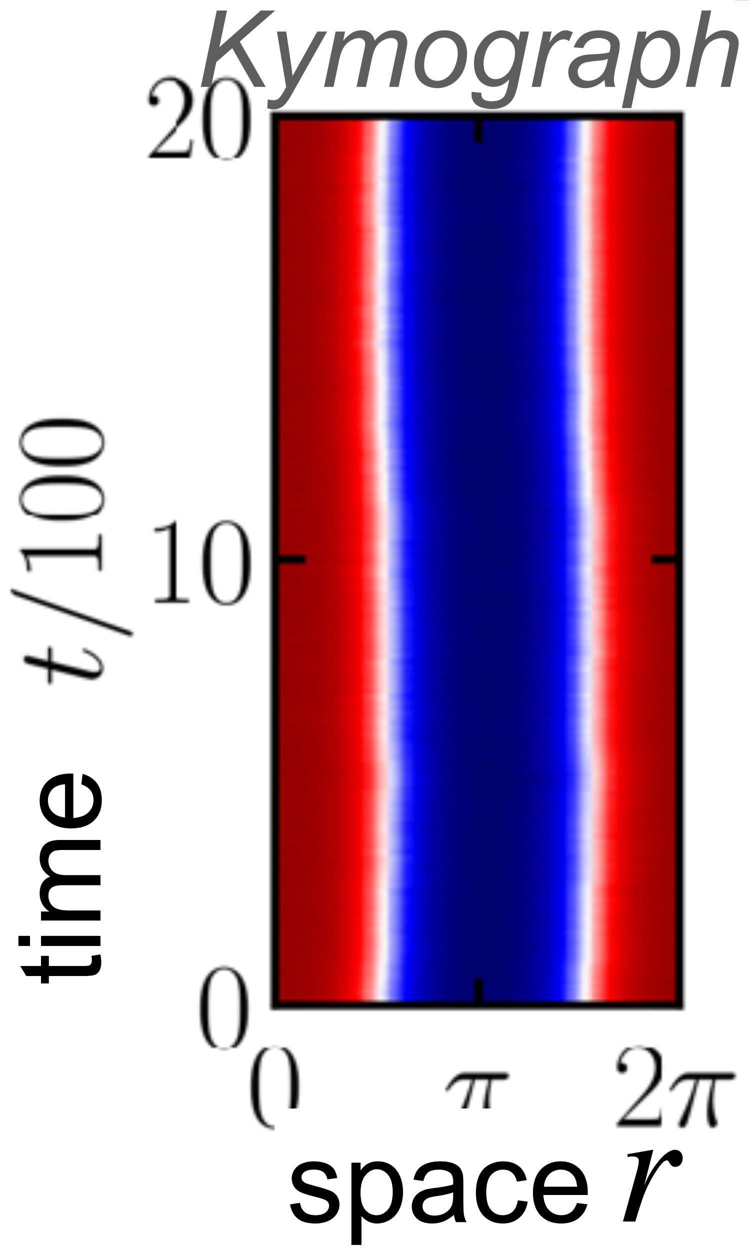


- D
- N

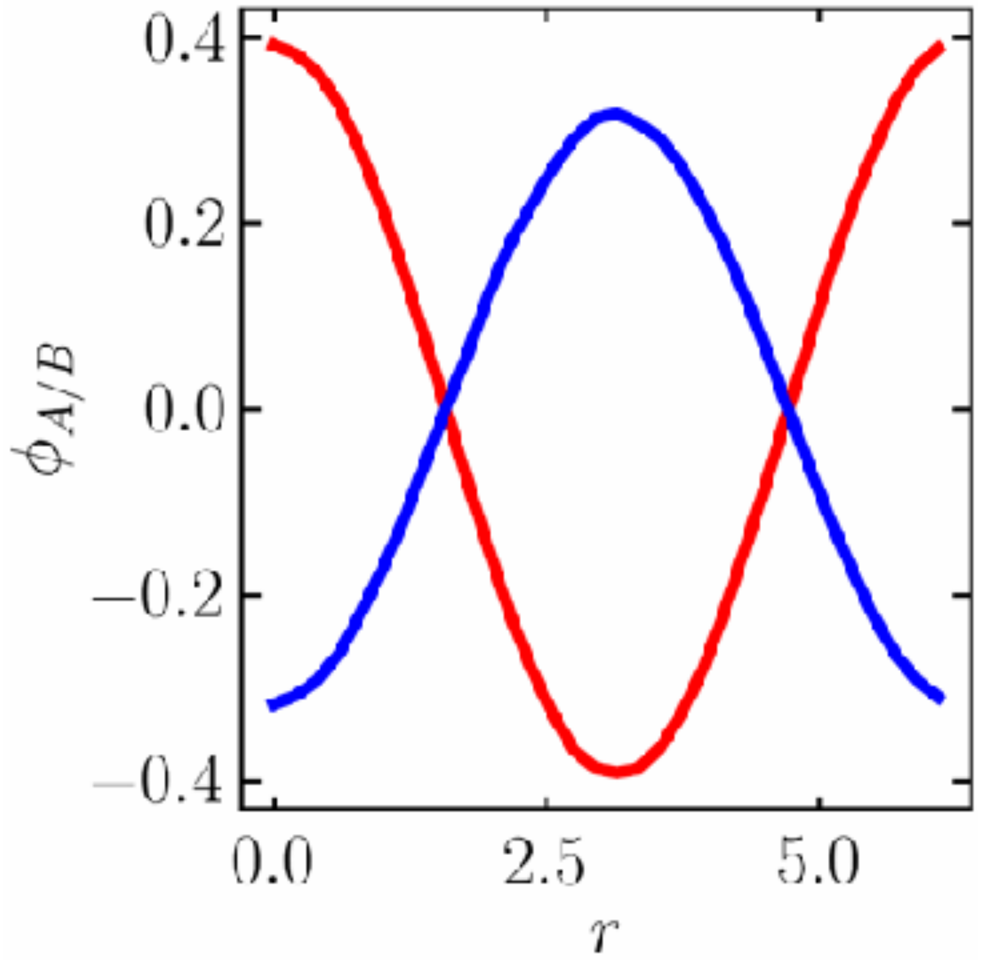
production ($\mathcal{S} \propto \epsilon^0$)

both diverge $\dot{S} \sim \chi \sim \mathrm{Re}[\lambda_0^k]^{-1}$

Spectral singularity: Critical Exceptional Point (CEP)

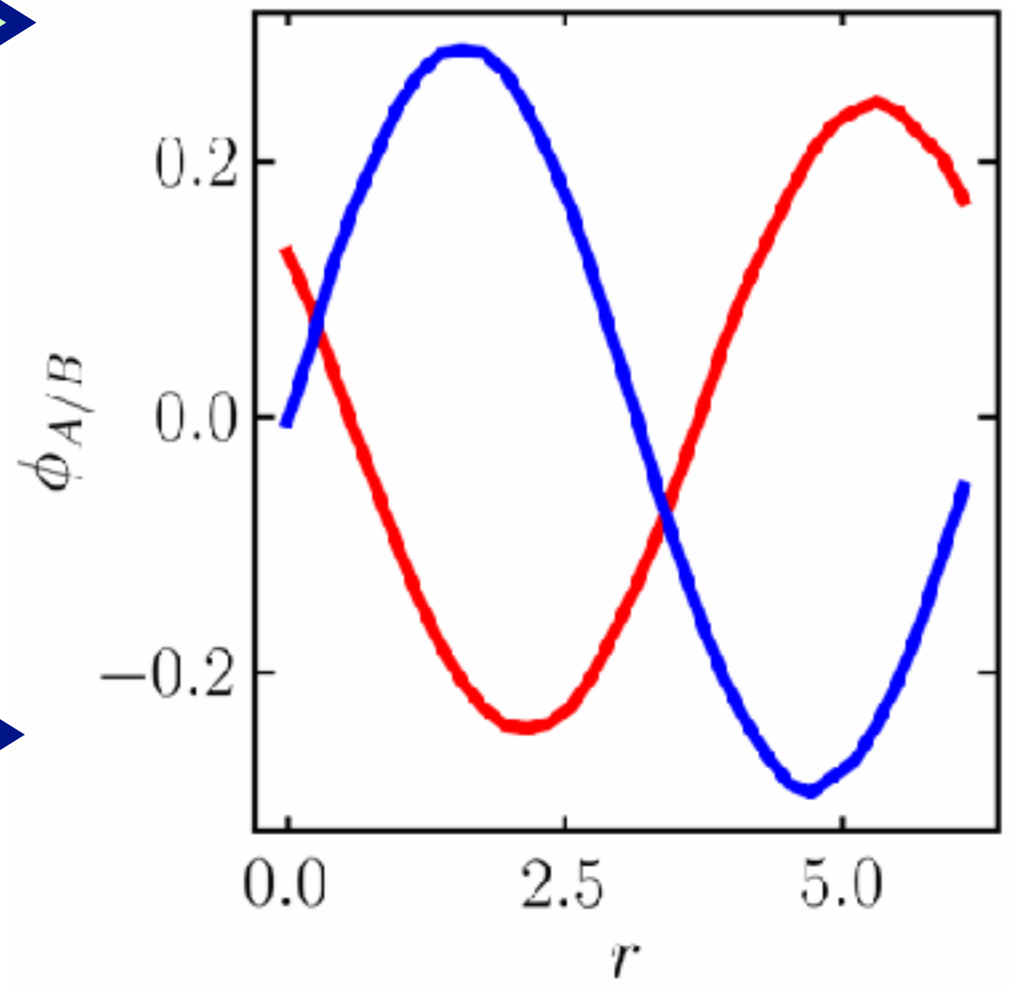


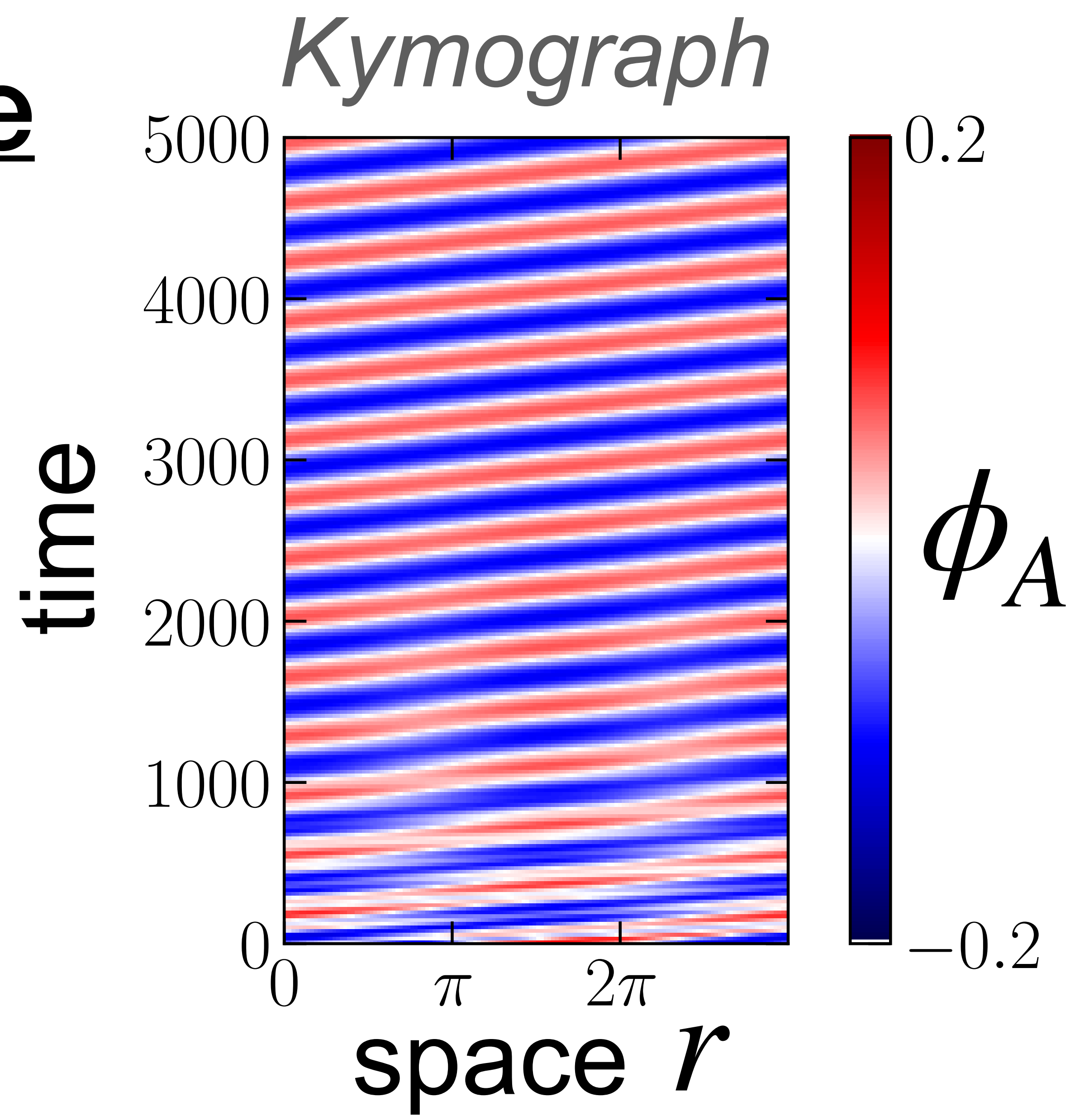
Static demixed



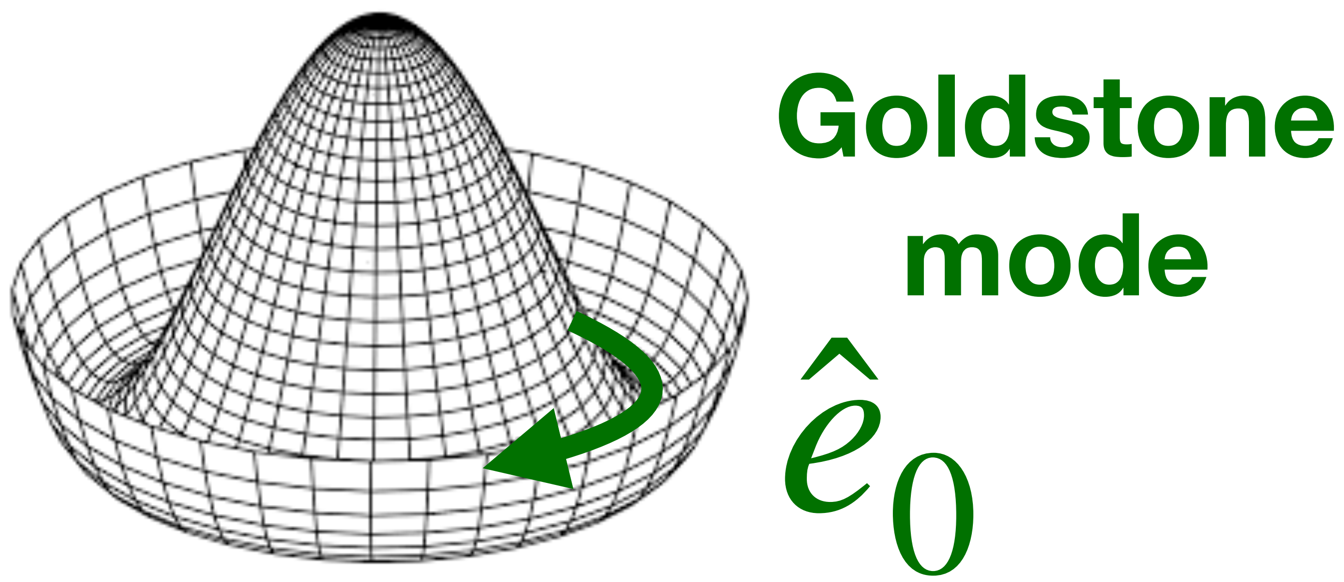
CEP

Travelling wave

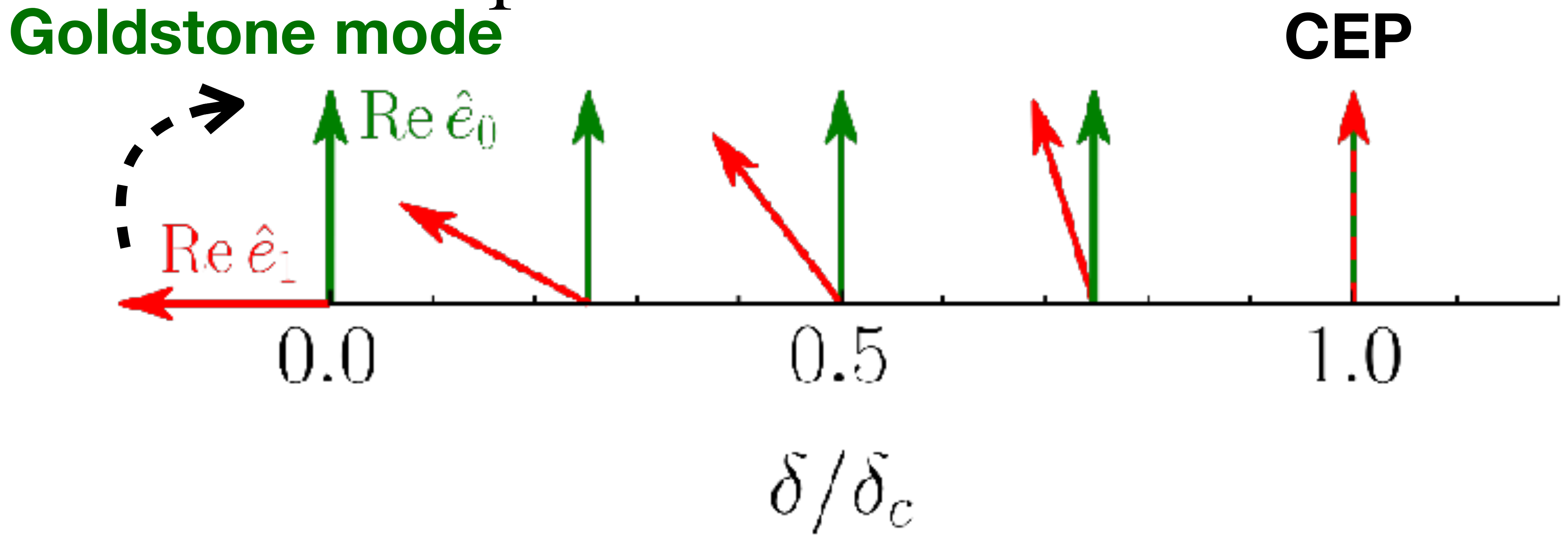




- Before CEP: Broken translational symmetry
  → Goldstone mode ($\hat{e}_0$, $\lambda_0 = 0$)



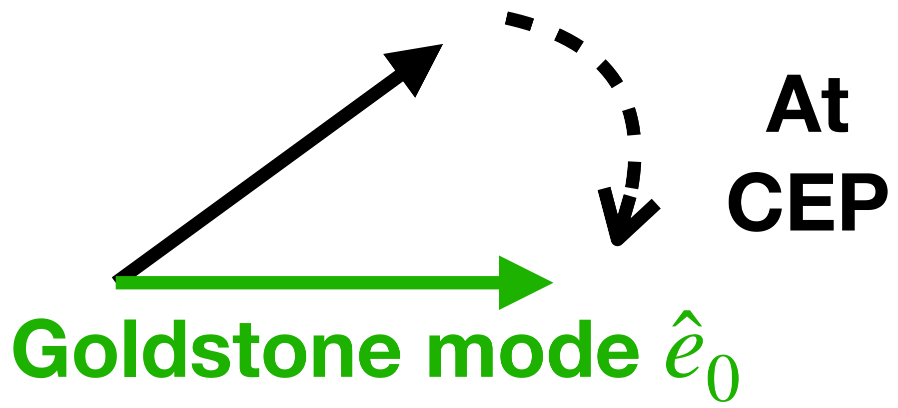
- At CEP: another eigenmode of $\mathscr{L}$ becomes unstable: $\lambda_1 \to 0$, while coalescing with $\hat{e}_0$

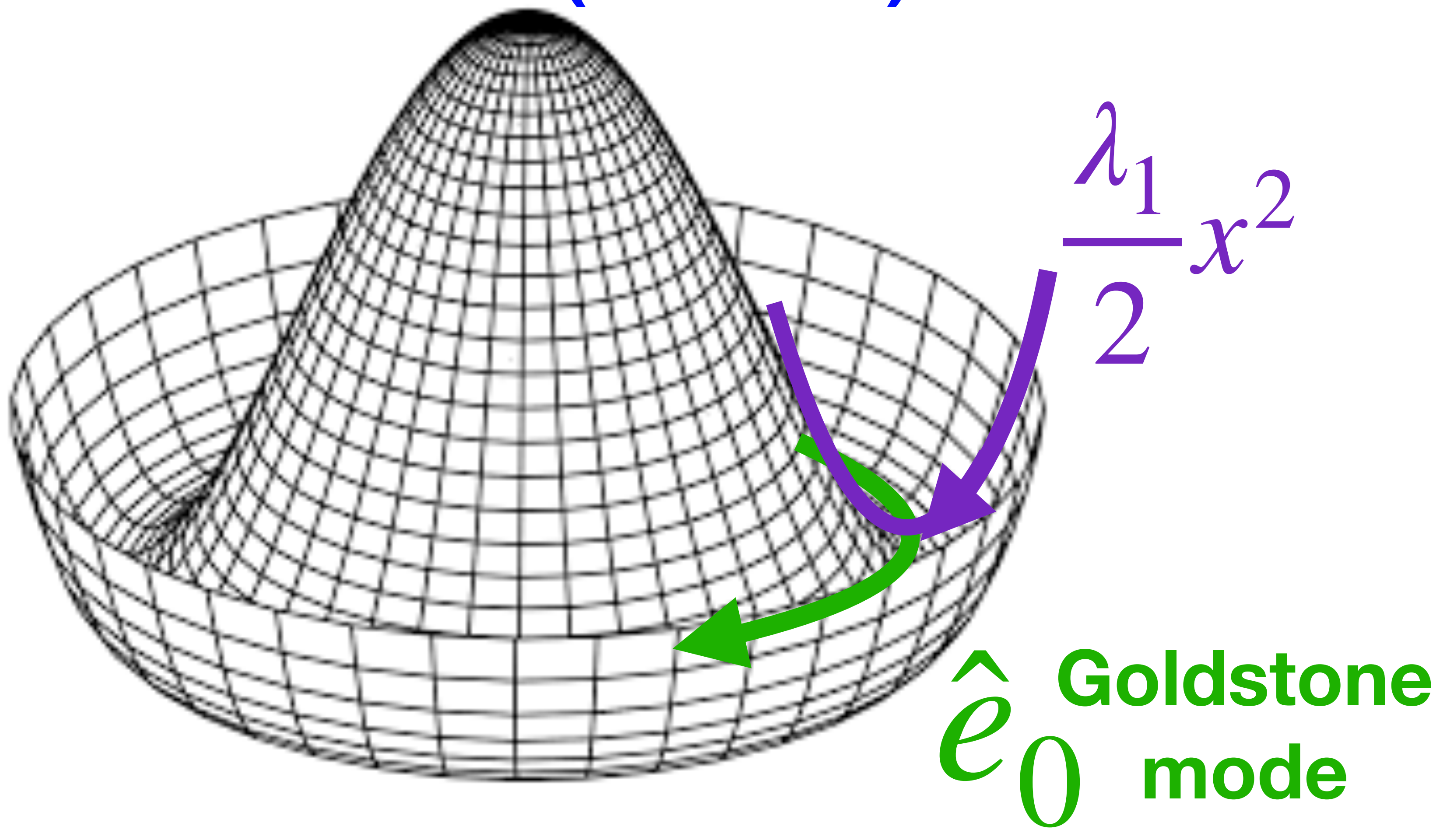


Entropy production at "Critical Exceptional Point" (CEP)

- Dynamics of relevant modes in eigenbasis of $\mathscr{L}$ $\{\hat{e}_0, \hat{e}_1\}$:

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\psi_0\\ \psi_1\end{pmatrix} = \begin{pmatrix}0 & 0\\ 0 & \lambda_1\end{pmatrix}\begin{pmatrix}\psi_0\\ \psi_1\end{pmatrix} + \underline{\xi}$$

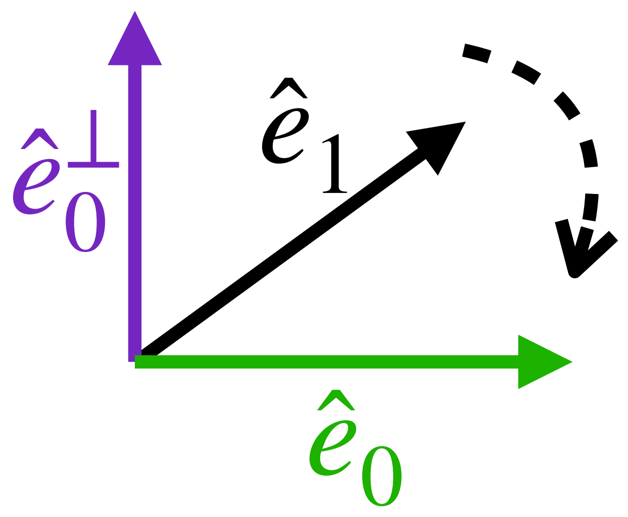


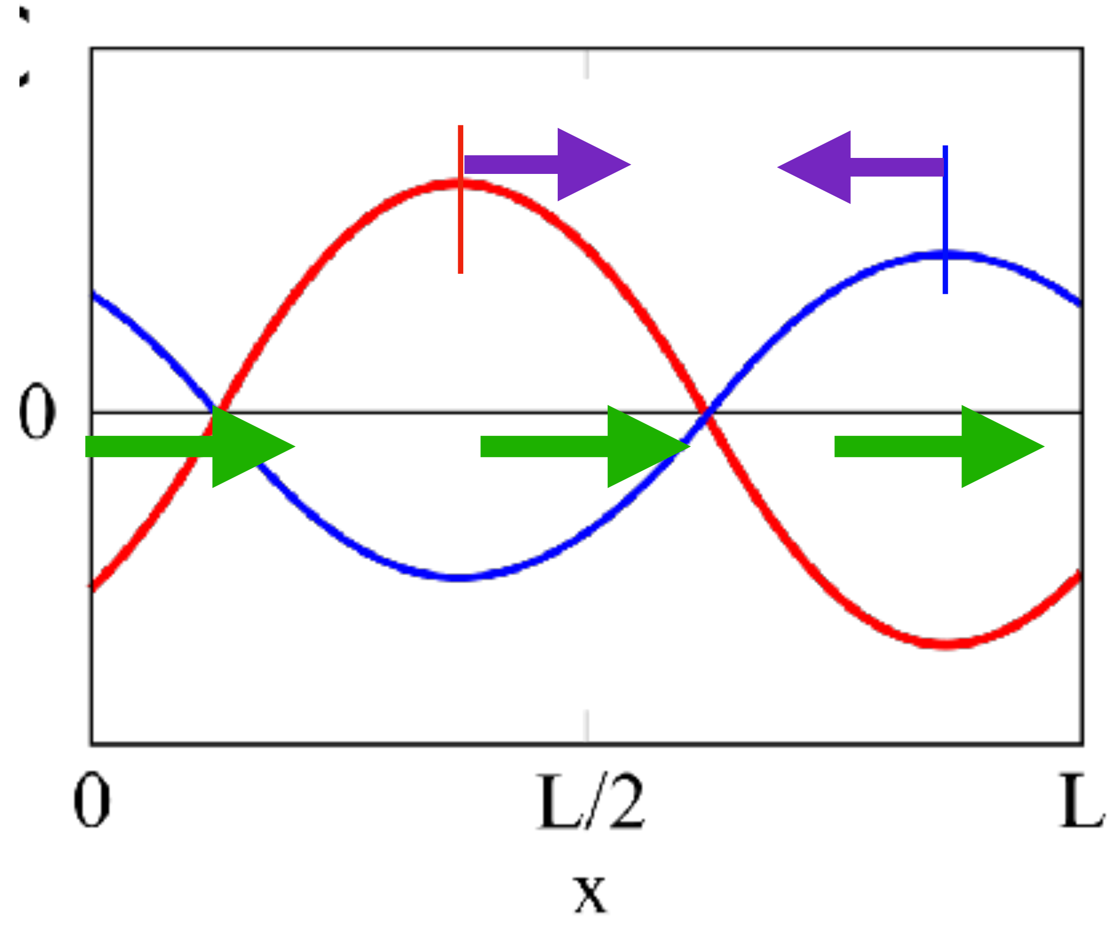


- Dimension reduction of $\mathscr{L}$ at CEP: Change basis to $\{\hat{e}_0, \hat{e}_0^{\perp}\}$:

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\theta_c\\ \Delta\theta^{\pi}\end{pmatrix} = \begin{pmatrix}0 & 2\delta\\ 0 & \lambda_1\end{pmatrix}\begin{pmatrix}\theta_c\\ \Delta\theta^{\pi}\end{pmatrix} + \underline{\xi}$$

$\Delta\theta^{\pi} \propto \left[\theta_A^1 - (\theta_B^1 + \pi)\right]$





- Small perturbation ϵ in direction $\hat{e}_0^{\perp}$ yields:

$$\theta_c(t) = \frac{\epsilon\, 2\delta}{\lambda_1}(e^{\lambda_1 t} - 1)$$

$$\Delta\theta^{\pi}(t) = \epsilon\, e^{\lambda_1 t}$$

- At CEP: $\lambda_1 \to 0$: Giant noise amplification

$\Rightarrow$ *Squeezing patterns $\to$ Shifting patterns along Goldstone*

$\Rightarrow$ *TRSB fluctuations* $\to$ **Real space interpretation?**

[R Hanai, P Littlewood, PRR (2020)] Suchanek, Kroy, SL, PRL (2023)

Entropy production at “Critical Exceptional Point” (CEP)

- *Towards CEP: Patterns move ballistically*

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\theta_c \\ \Delta\theta^\pi\end{pmatrix} = \begin{pmatrix}0 & 2\delta \\ 0 & \lambda_1\end{pmatrix}\begin{pmatrix}\theta_c \\ \Delta\theta^\pi\end{pmatrix} + \underline{\xi}$$

$$\Delta\theta^\pi \propto \left[\theta_A^1 - (\theta_B^1 + \pi)\right]$$

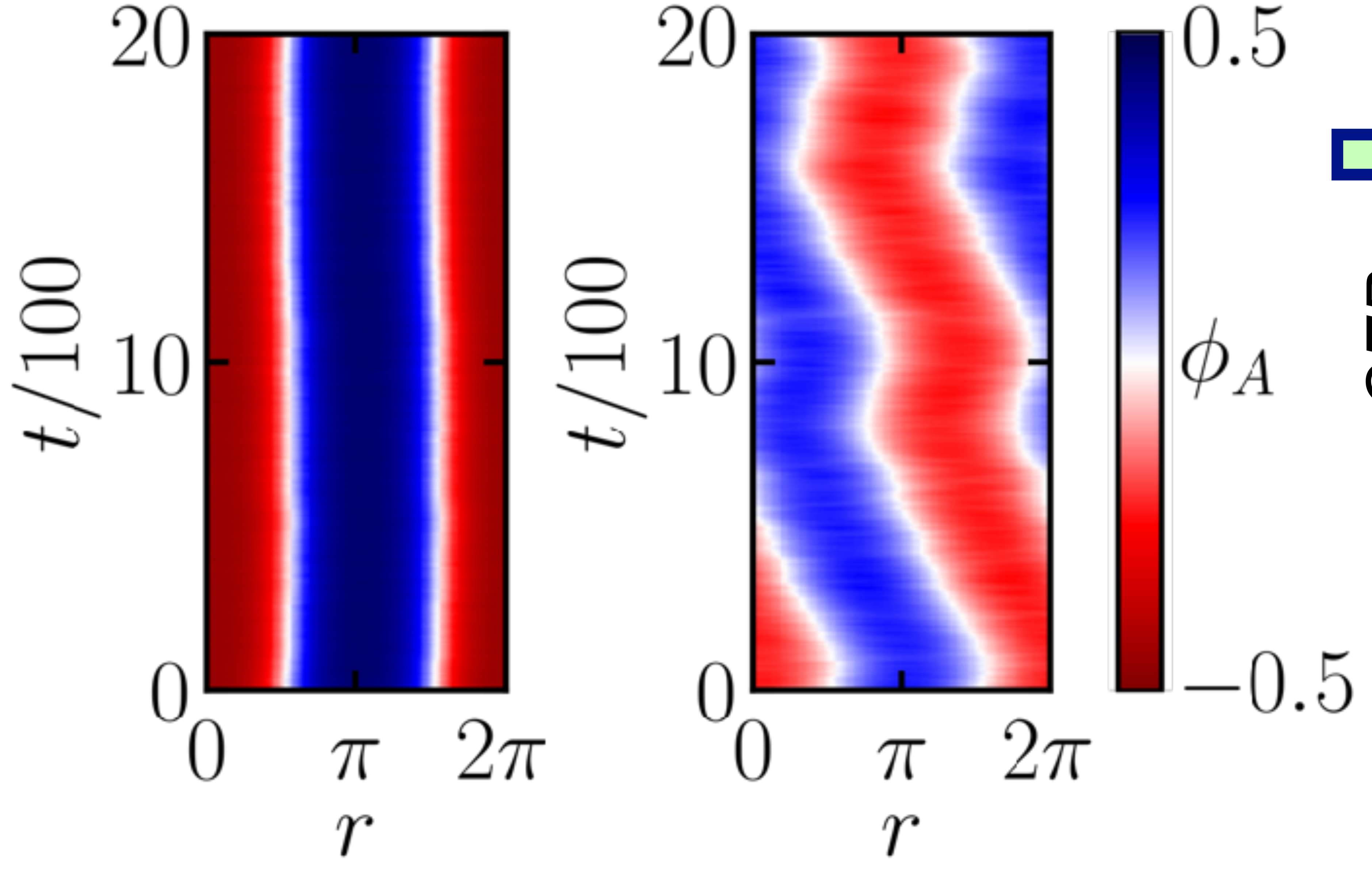
→ Can be mapped onto AOUP model

→ “self-propelled patterns”

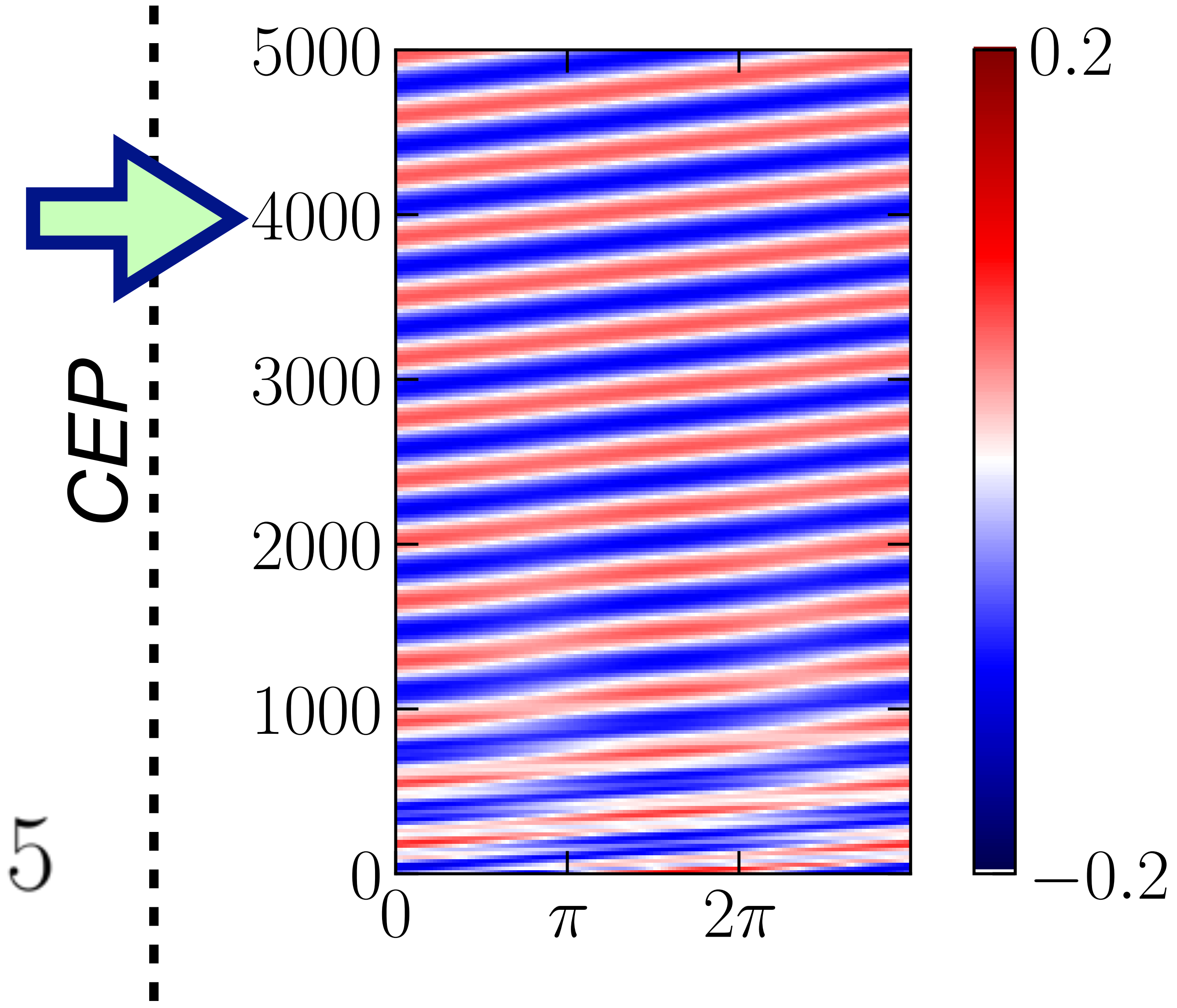
$$\Delta\theta^\pi \longrightarrow \theta_c$$

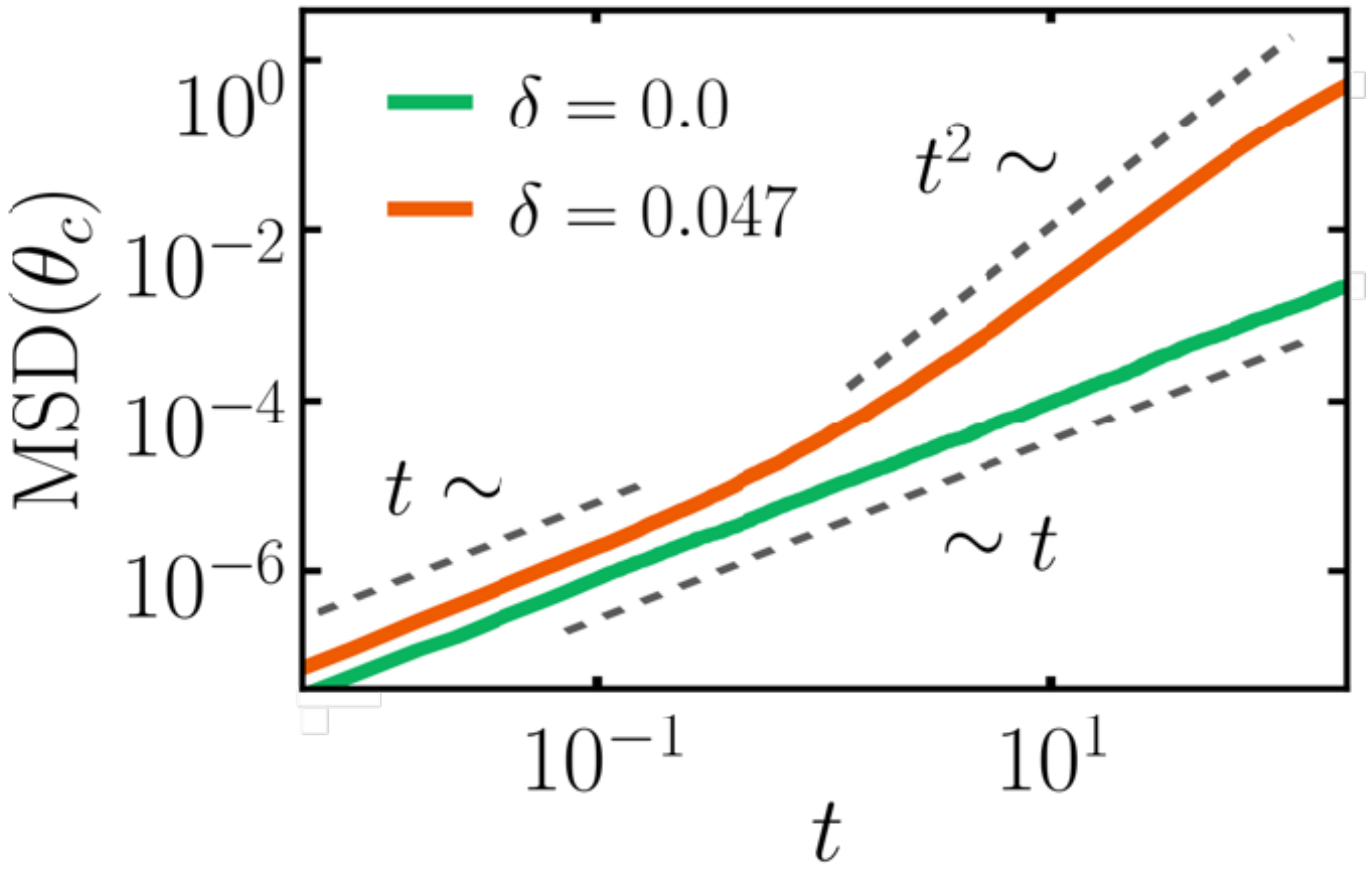
Static demixed

Equilibrium **Towards transition**



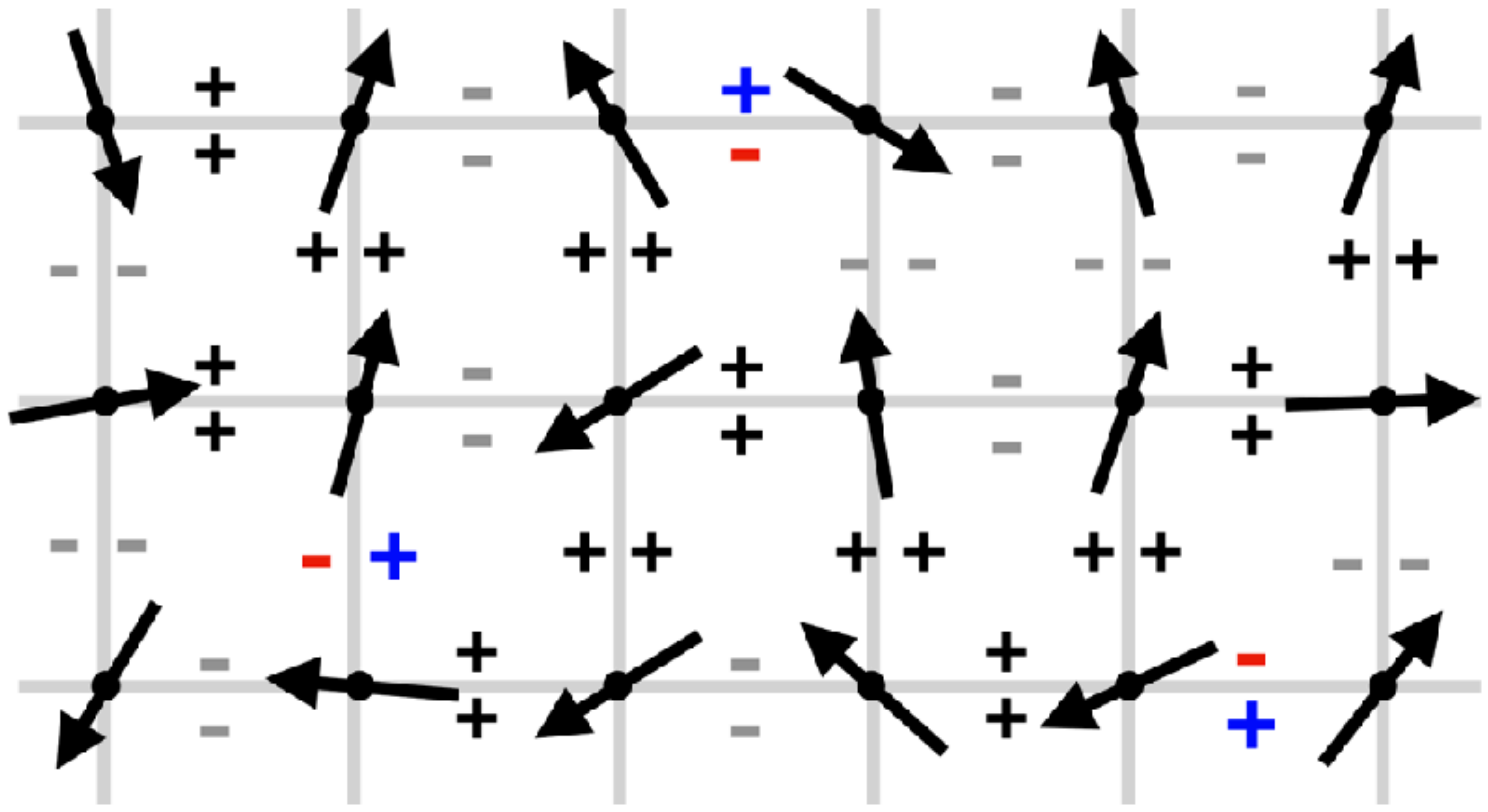
Travelling wave



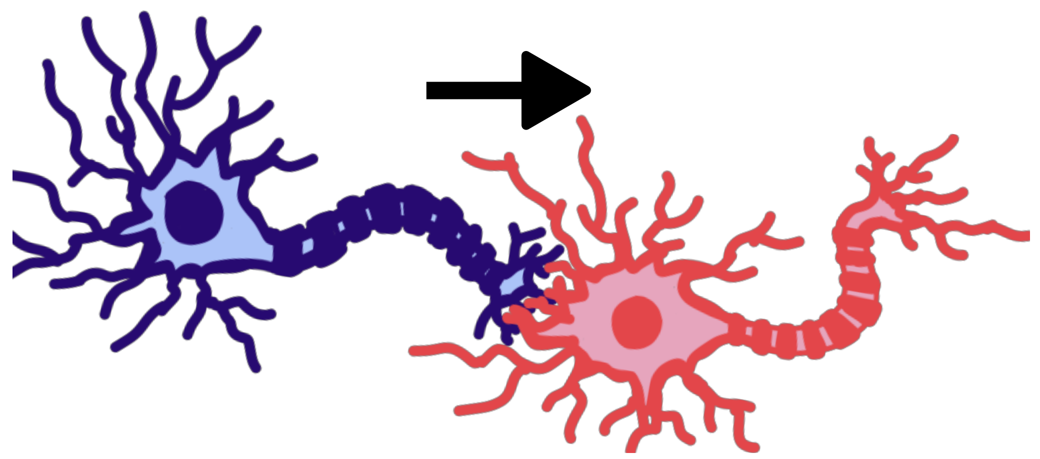


Suchanek, Kroy, & SL, PRL (2023)

One-species NR system with disorder

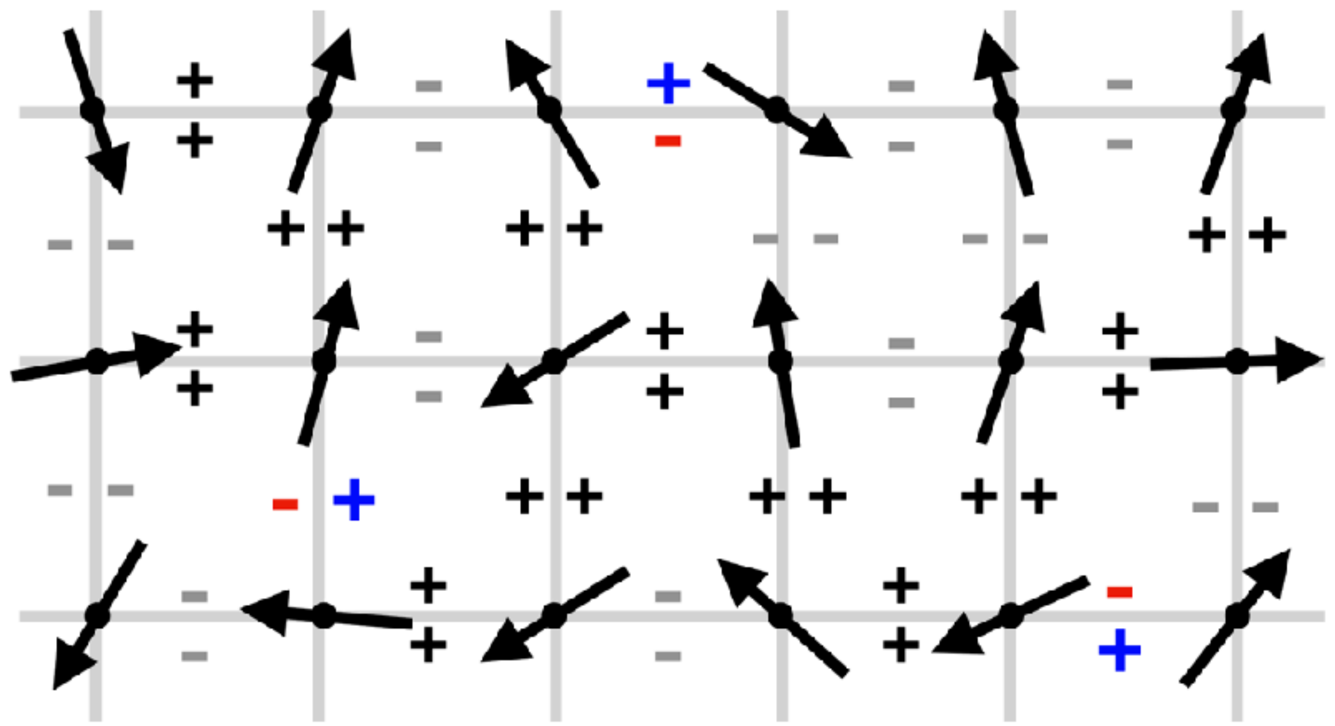


Single species NR XY model with quenched disorder



$$\boxed{\dot{\phi}_i = -\sum_j J_{ij}\sin(\phi_i - \phi_j) + \sqrt{2D}\xi_i}$$

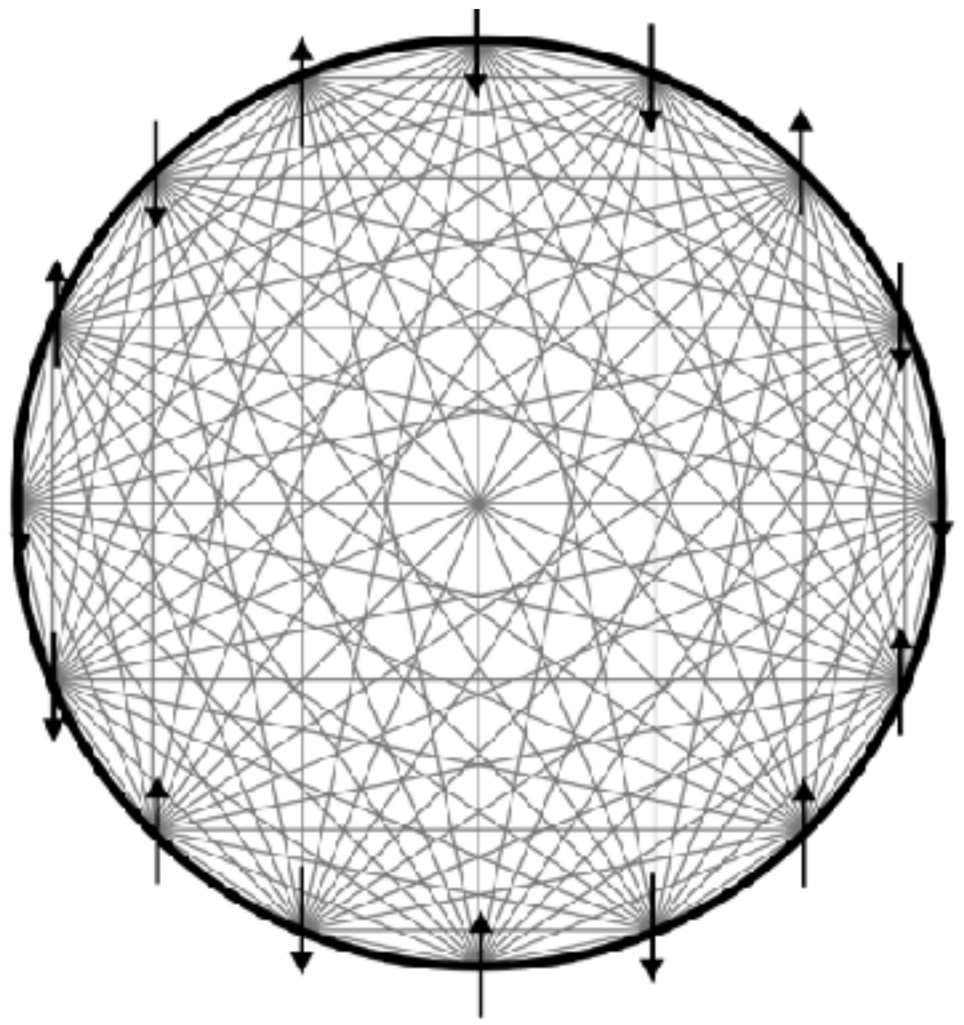
$\{J_{ij}\} \sim$ some distribution (quenched disorder) and can be asymmetric



- $|J_{ij}| = 1$
- $\mathbb{E}(J_{ij}) = 0$ $\rightarrow$ **Frustrated system**

- With probability $(1-p)$, $J_{ij} = J_{ji}$
- With probability p, $J_{ij} = -J_{ji}$ $\rightarrow$ **NR system**

- Fully connected graph

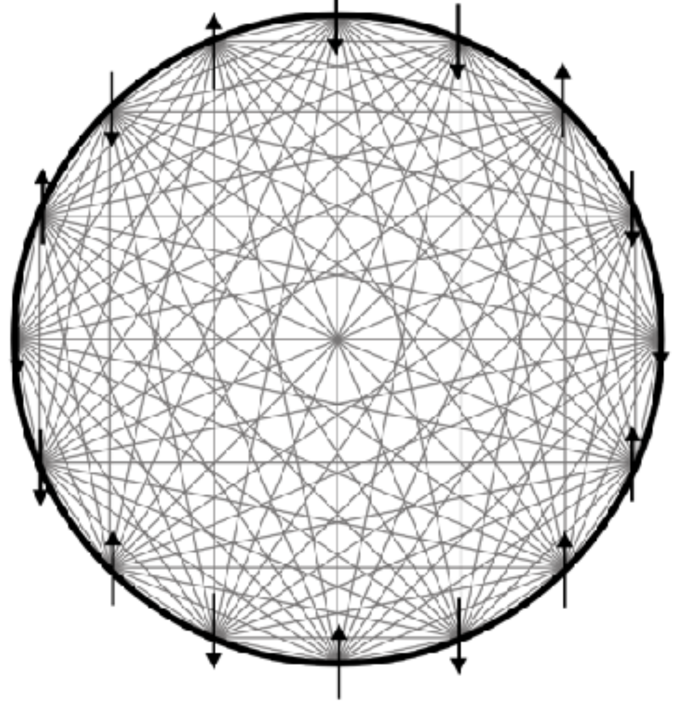


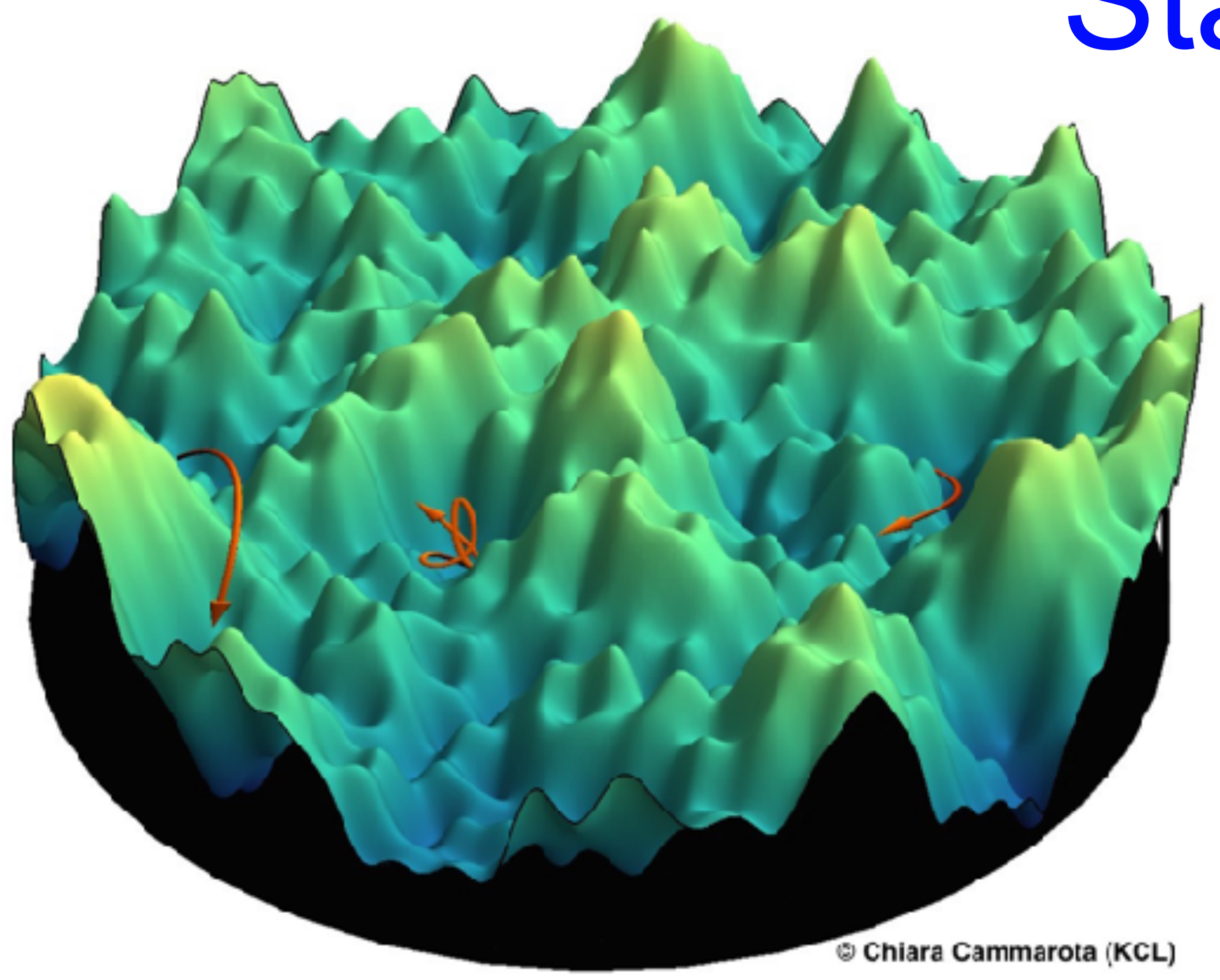
<u>Spin Glass/Hopffield models under asymmetry:</u>

H. Gutfreund, J D Reger[1] and A. P. Young J Phys A (1988),
J. Hopfield PNAS (1982), G. Parisi J Phys A (1986),
A. Crisanti and H. Sompolinsky PRA (1987), L. F. Cugliandolo, et al. PRL (1997) …

Starting point, XY spin glass (p=0)

- $|J_{ij}| = 1$
- $\mathbb{E}(J_{ij}) = 0$
- $J_{ij} = J_{ji}$





Spin Glass

Shallow and degenerate energy landscape with
<u>high number of</u> <u>marginally stable directions</u>

→ **highly susceptible to perturbations**

→ *Glass destroyed by asymmetry, leading to chaos*

Difference to SK, p-spin model… (usually Ising-based)
<u>U(1) symmetry</u> ($\lambda_0 = 0$)

<u>Spin Glass/Hopffield models under asymmetry:</u>

H. Gutfreund, J D Reger[1] and A. P. Young J Phys A (1988),
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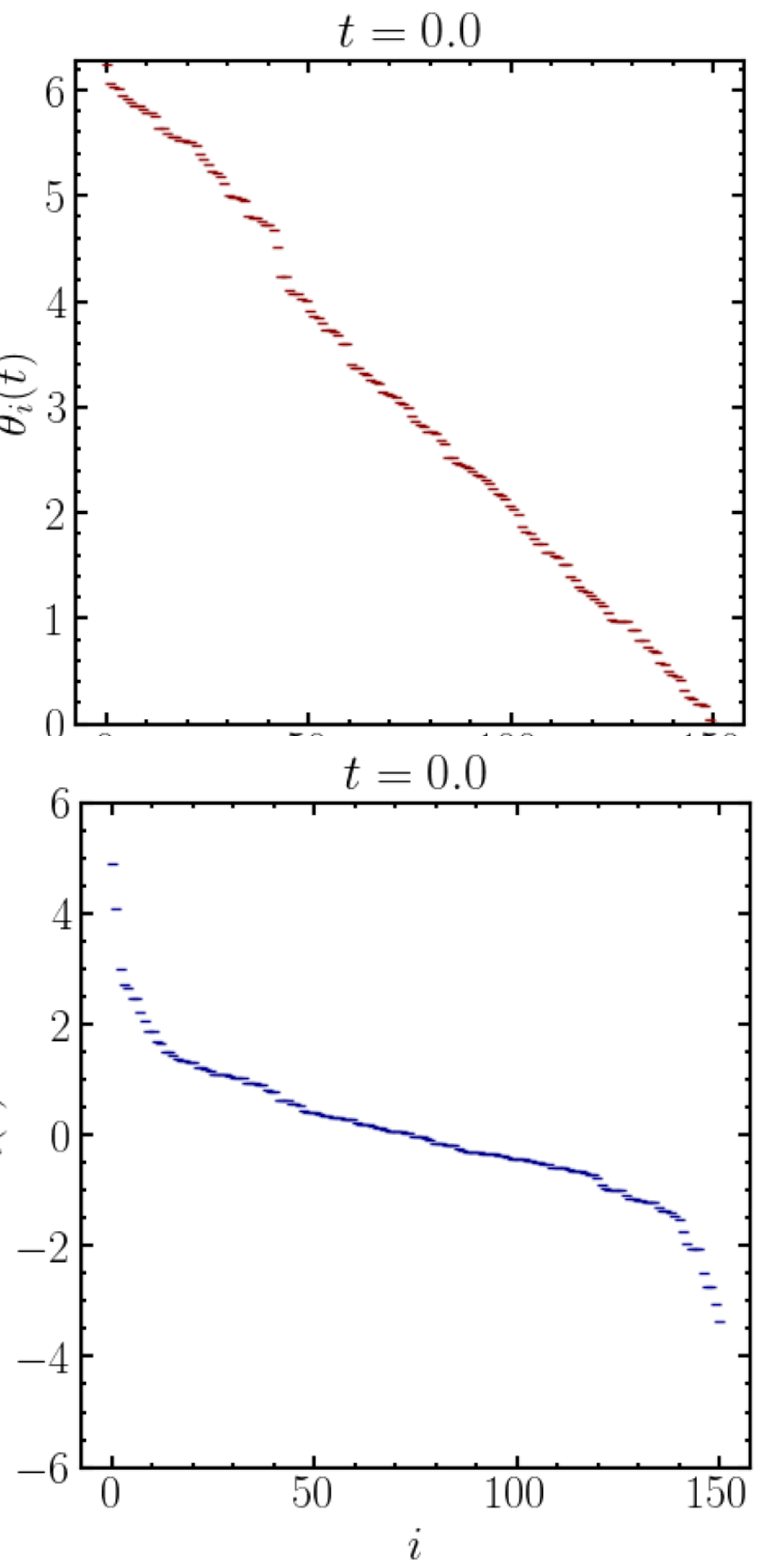
Chaotic State **p=0.3**

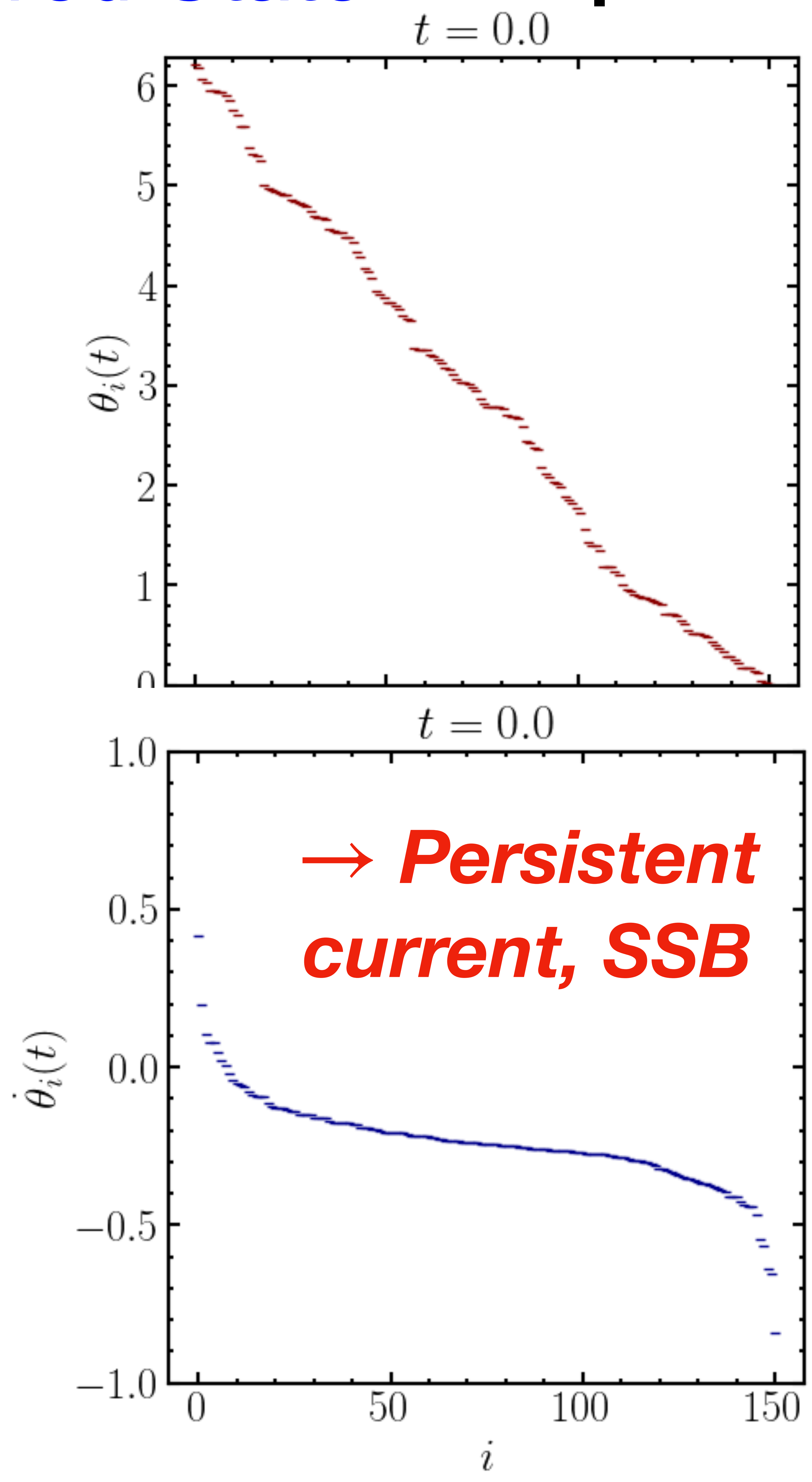
Rotating Disordered State

p=0.05 **Rotating Disordered State**

Phases θ_i

Angular velocities $\dot{\theta}_i$



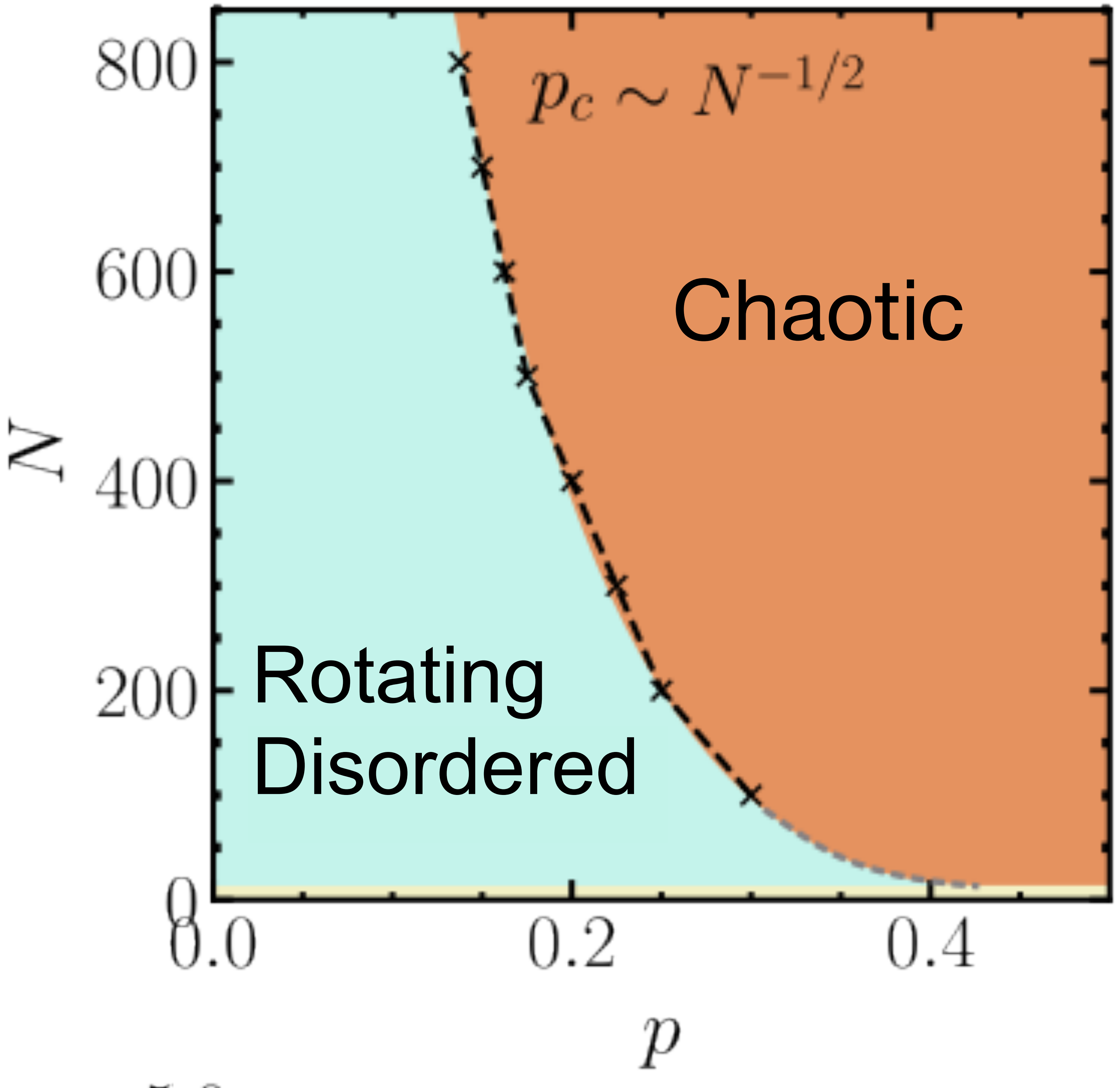


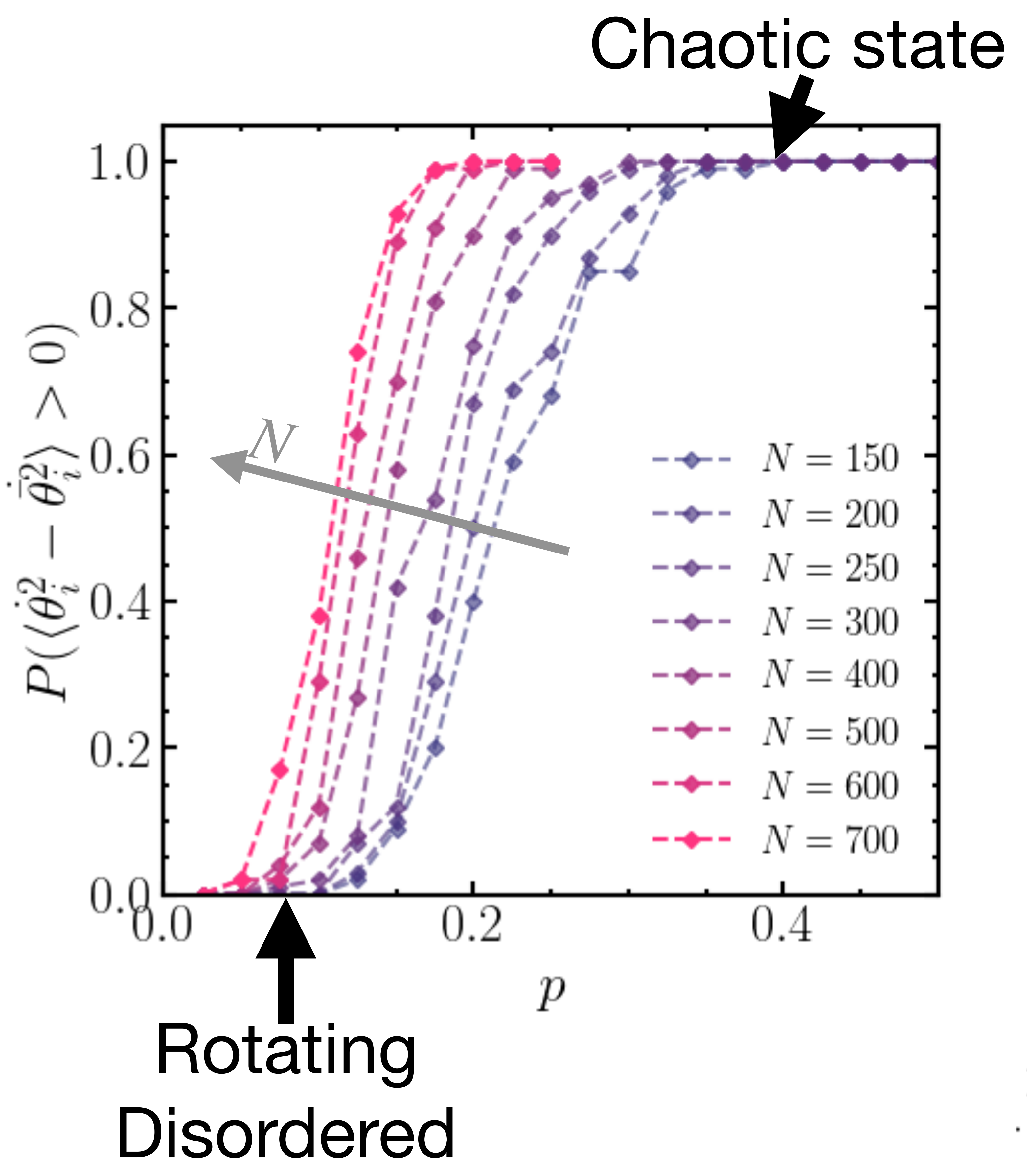
→ Persistent current, SSB

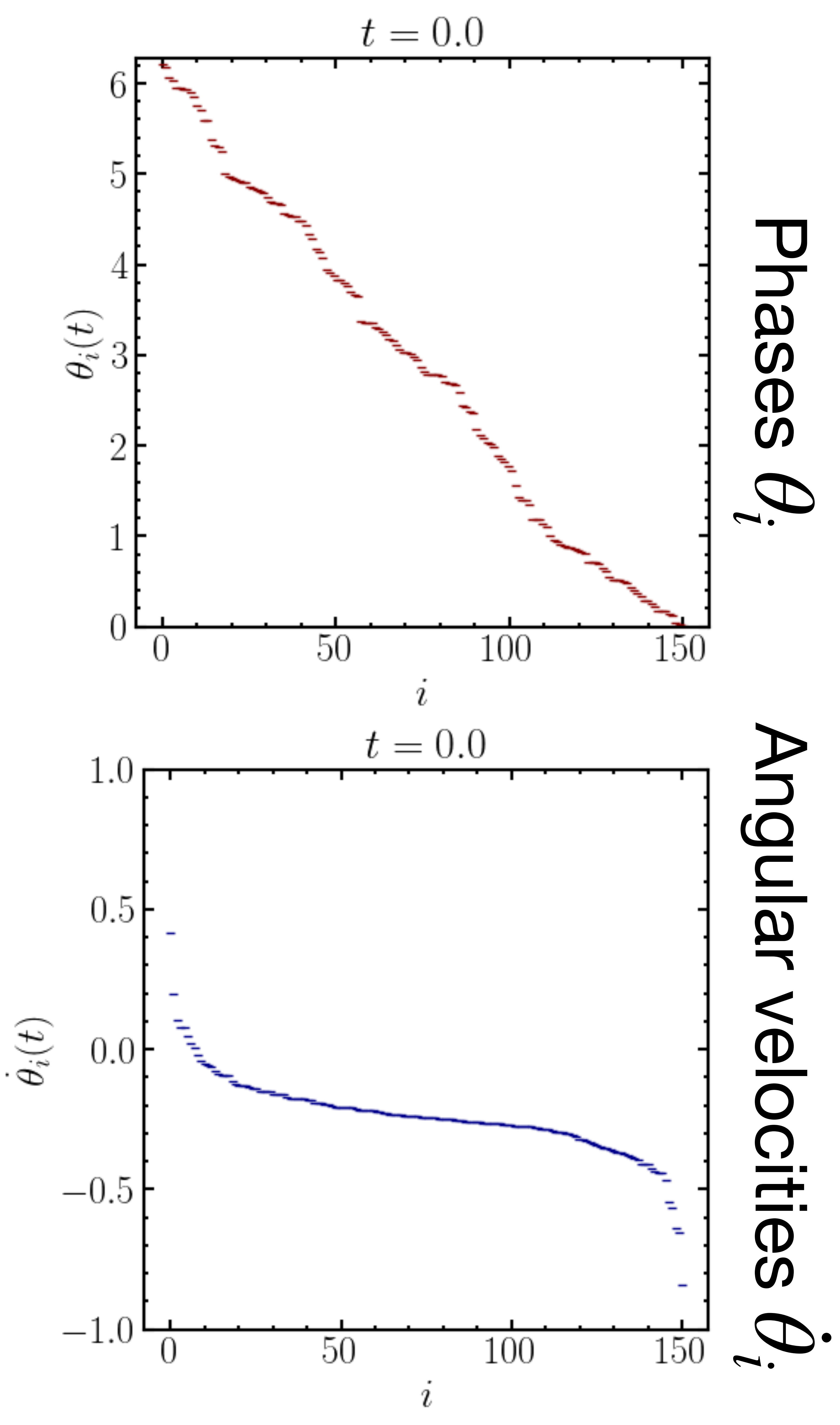
Phases θ_i

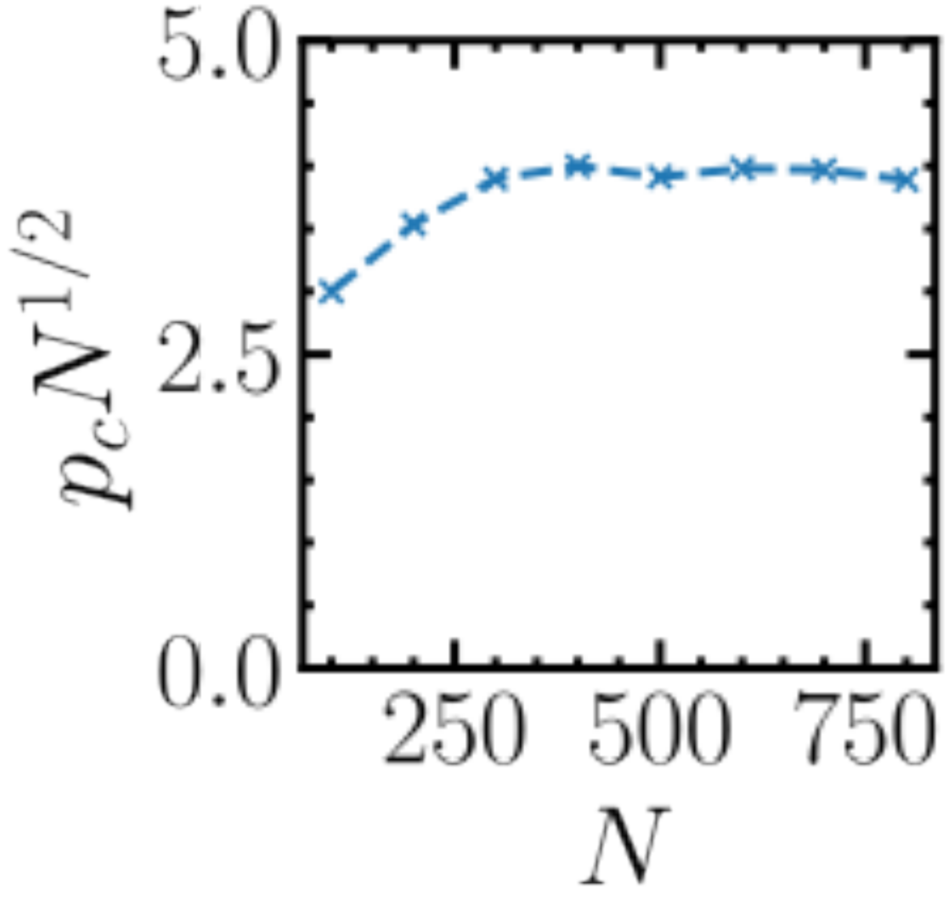
Angular velocities $\dot{\theta}_i$

Rotating Disordered State









Disappears for $N \to \infty$

But slowly $p_{\mathrm{c}} \sim N^{-1/2}$

Thank you to my collaborators!

- **<u>Fluctuating NR field theories:</u>**

  Thomas Suchanek (U Leipzig)
  Klaus Kroy (U Leipzig)

  Suchanek, Kroy, & <u>SL</u>, PRL (2023)
  Suchanek, Kroy, & <u>SL</u>, PRE 108, 064610 (2023)
  Suchanek, Kroy, & <u>SL</u>, PRE 108, 064123 (2023)

- **<u>Vision-cone NR XY Model:</u>**

  Thomas Martynec (then, TU Berlin)
  Sabine Klapp (TU Berlin)

  <u>SL</u>, Klapp & Martynec, PRL (2023)

- **<u>Disordered NR YX Model:</u>**

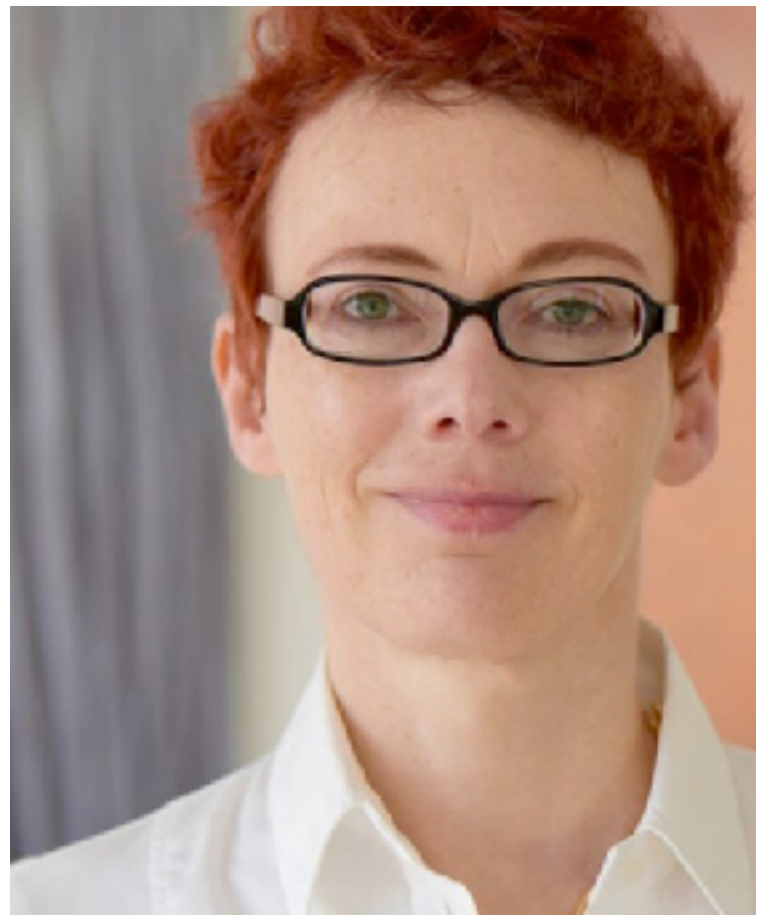
  Thomas Suchanek (U Leipzig)
  Mike Cates (U Cambridge)
  Peter Sollich (U Göttingen)

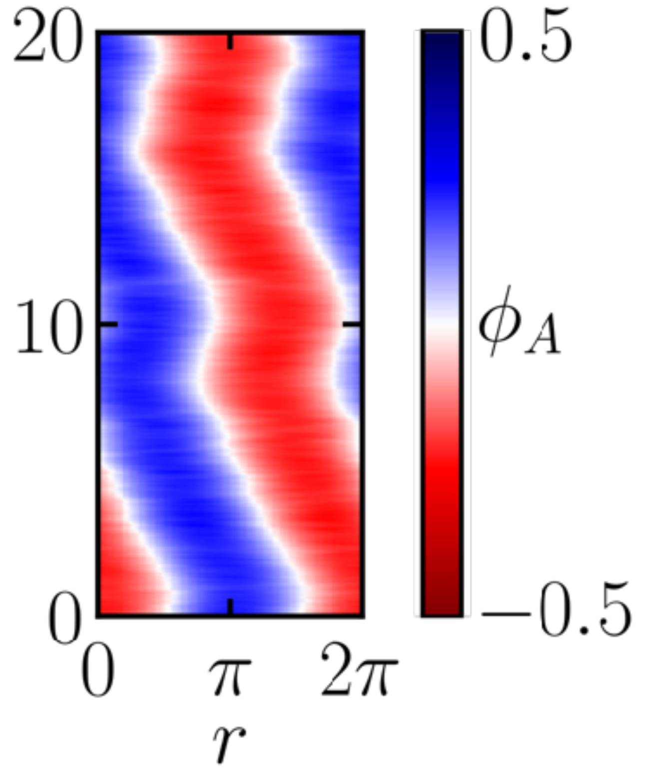
[in preparation]

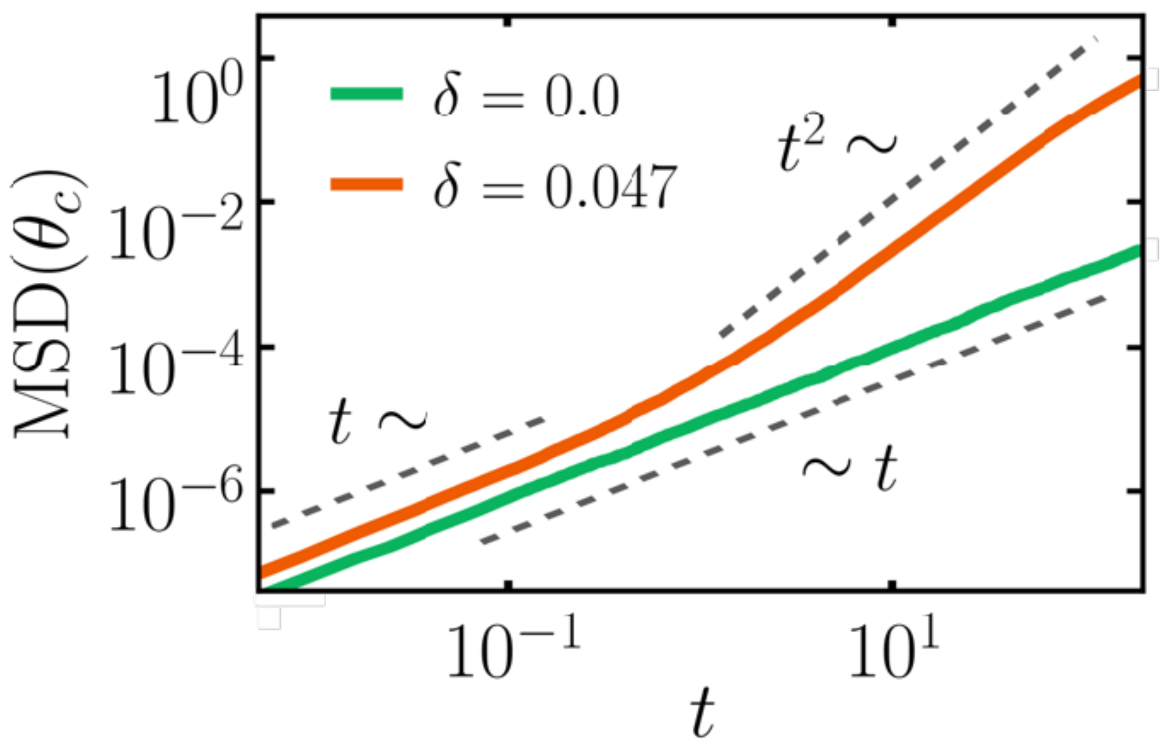
Thomas Suchanek

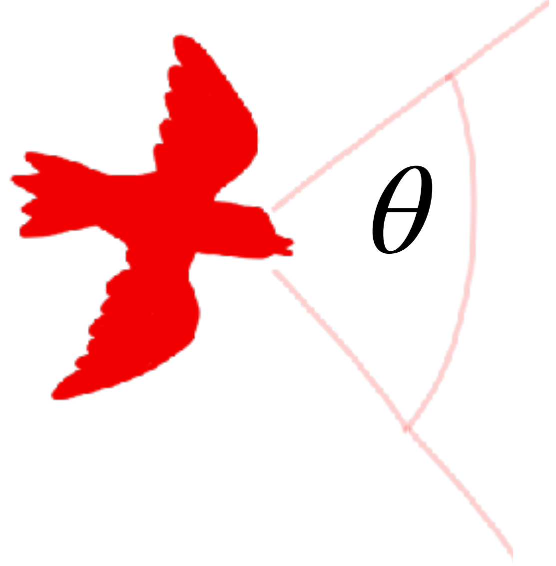
Klaus Kroy

Sabine Klapp

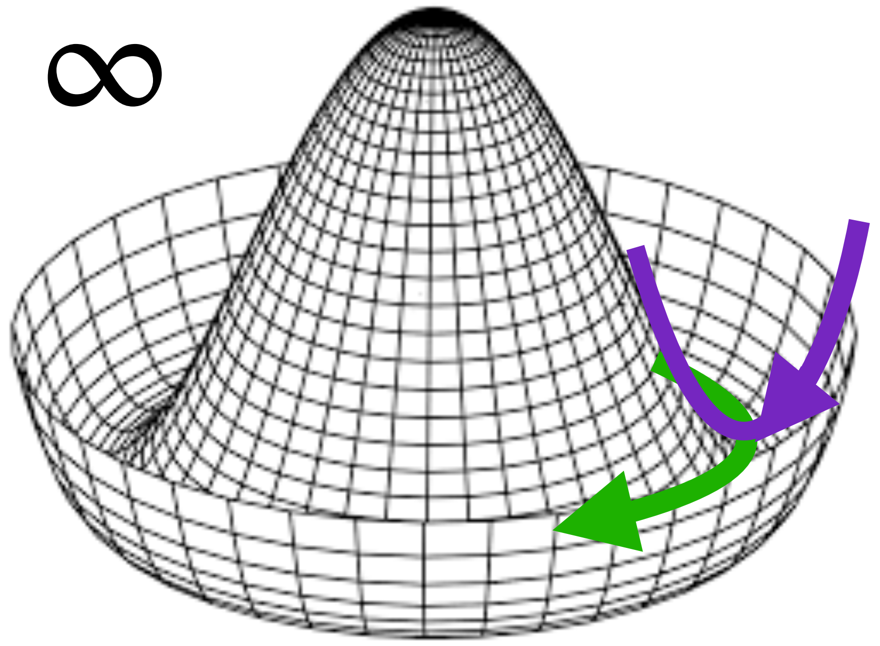








$\dot{S} \sim \chi \rightarrow \infty$



Thank you!

- NR Field theories: Fluctuations close to Critical Exceptional Point+Oscillatory instability
- NRCH: $\dot{S} \sim \chi \rightarrow \infty$ driven by ballistic dynamics of interfaces (coupling to Goldstone mode)
- Vision-cones lead long-range order due to effective pinning to lattice
- Disordered NR system with U(1): Chaos and Rotating disordered state