LPTMC, Sorbonne University & CNRS
15 February 2024

A new universality class describes Vicsek's flocking phase in physical dimensions

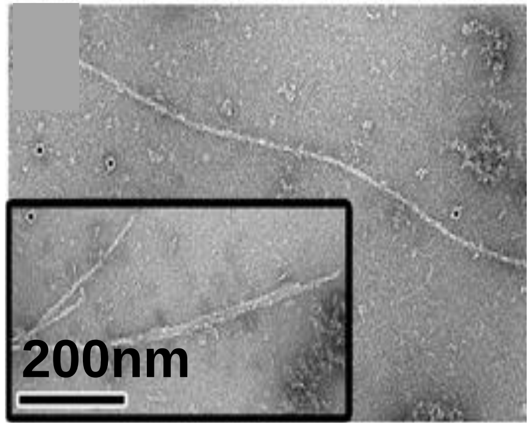
Patrick Jentsch & Chiu Fan Lee

Department of Bioengineering, Imperial College London, UK

Imperial College London

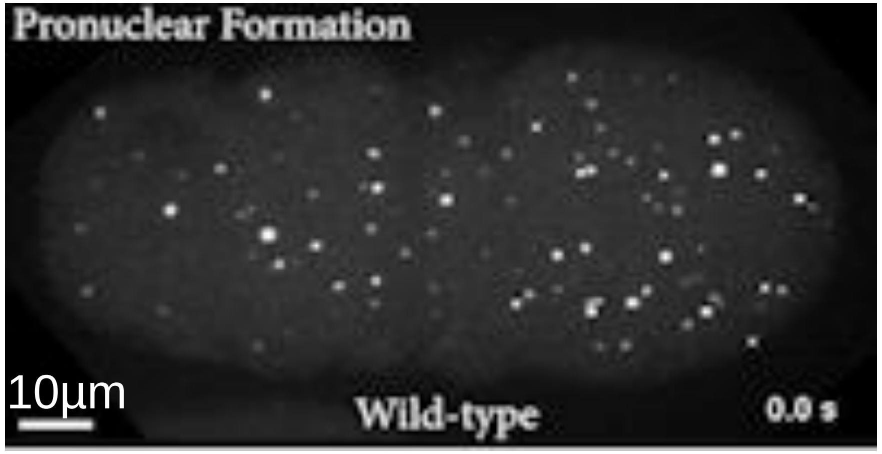
Universality in Biology

Amyloid formation



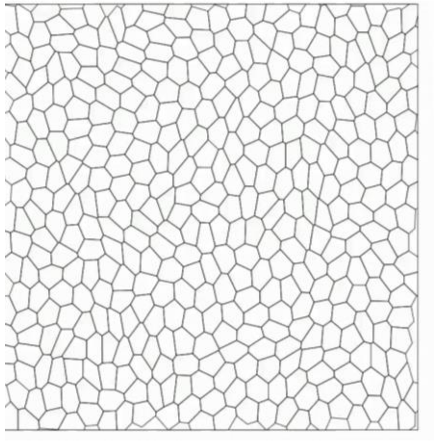
Pytowski, Lee, Foley, Vaux, Jean (2020)
Liquid–liquid phase separation of type II diabetes associated IAPP initiates hydrogelation and aggregation
PNAS

Biomolecular condensation



Folkmann, Putnam, Lee, Seydoux (2021)
Regulation of biomolecular condensates by interfacial protein clusters
Science

Active matter



Killeen, Bertrand, Lee (2022)
Polar Fluctuations Lead to Extensile Nematic Behavior in Confluent Tissues
Phys Rev Lett

Acknowledgement

John Toner (Oregon)

Leiming Chen (China U Mining & Technology)

Ananyo Maitra (CNRS, CY Cergy Paris Université)

Imperial College London

EPSRC Engineering and Physical Sciences Research Council

BBSRC bioscience for the future

The Leverhulme Trust

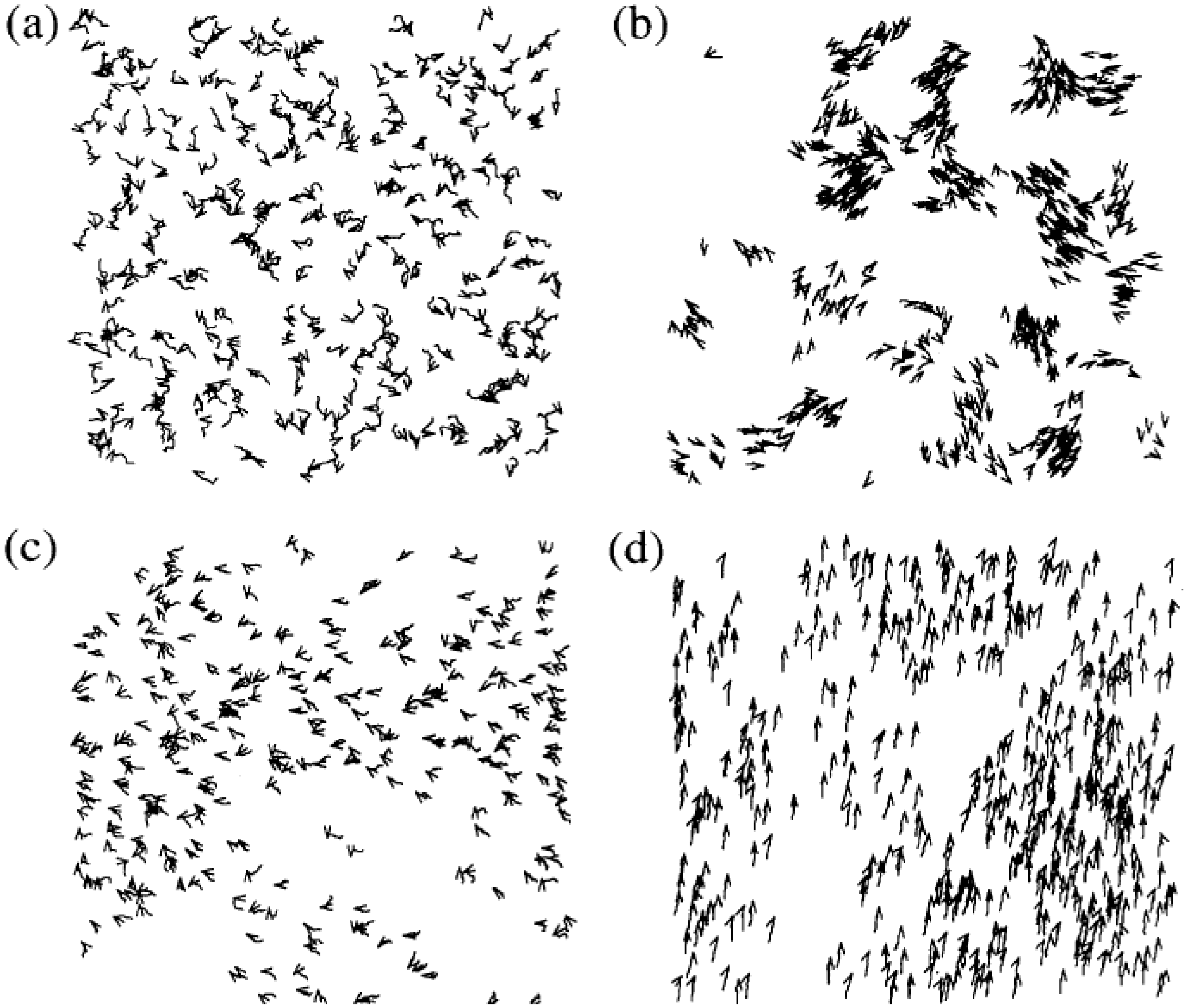
CANCER RESEARCH UK | IMPERIAL CENTRE

NIHR | Imperial Biomedical Research Centre

Plan of talk

1. A brief & biased history of active matter physics
2. Simplified Toner-Tu model
3. Linear theory
4. Nonlinear theory using FRG
5. FRG fixed points
6. Analytical treatment
7. Summary & Outlook

1. A brief & biased history of active matter physics



Tamás Vicsek, András Czirók, Eshel Ben-Jacob, Inon Cohen, and Ofer Shochet (1995) PRL

A simulation model for flocking in 1995

VOLUME 75, NUMBER 6 PHYSICAL REVIEW LETTERS 7 AUGUST 1995

Novel Type of Phase Transition in a System of Self-Driven Particles

Tamás Vicsek,[1,2] András Czirók,[1] Eshel Ben-Jacob,[3] Inon Cohen,[3] and Ofer Shochet[3]
[1]*Department of Atomic Physics, Eötvös University, Budapest, Puskin u 5-7, 1088 Hungary*
[2]*Institute for Technical Physics, Budapest, P.O.B. 76, 1325 Hungary*
[3]*School of Physics, Tel-Aviv University, 69978 Tel-Aviv, Israel*
(Received 25 April 1994)

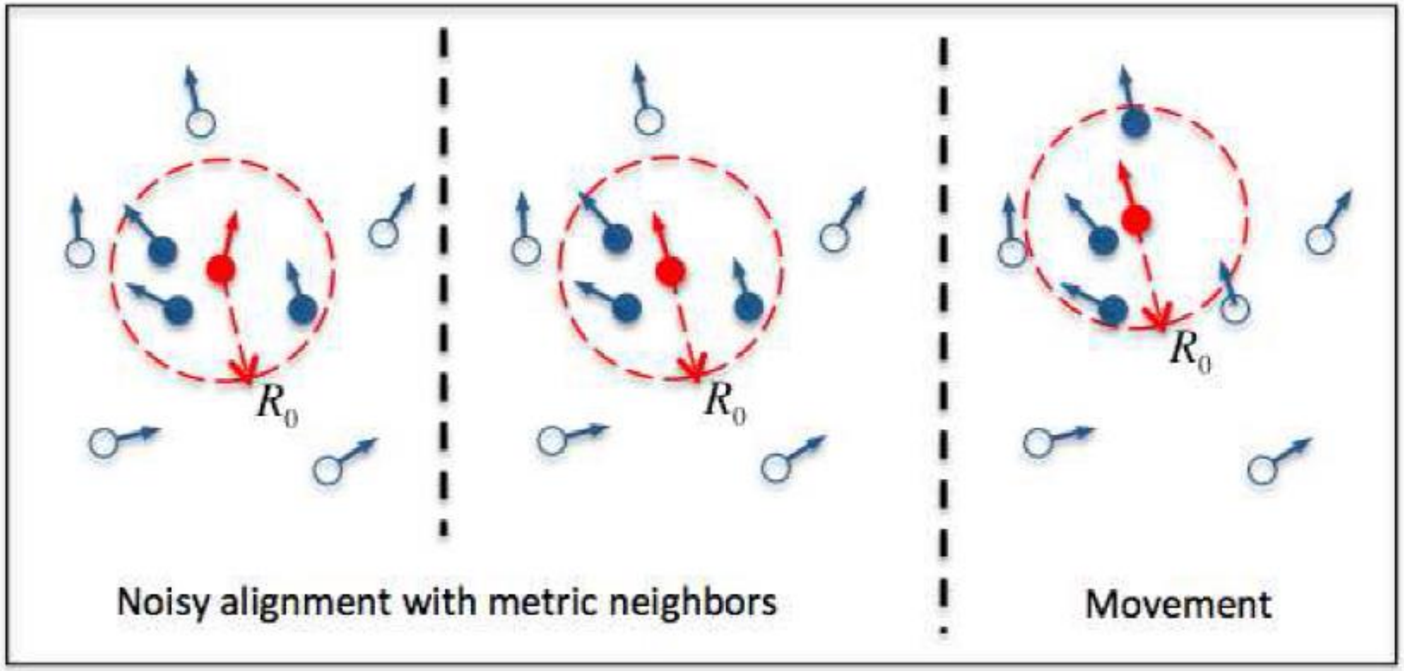


Figure from F. Ginelli, arXiv:1511.01451

Homogeneous disordered (D)

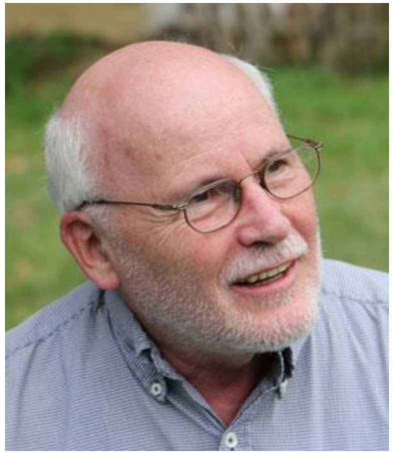
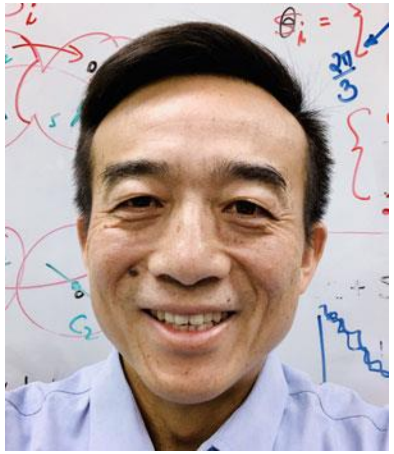
Homogeneous ordered (O)

Noise level

What’s the big deal?

- A continuous symmetry (rotational symmetry) seems to be broken in 2D!
  - A violation of the Mermin-Wagner-Hohenberg theorem at thermal equilibrium
  - Non-equilibrium dynamics is a crucial ingredient!
- “Order-disorder” may be a new type of transition [Vicsek et al (1995) PRL]
- Flocking phase may be a nonequilibrium phase [Toner & Tu (1995) PRL]

2020 APS Onsager Prize

Citation: "*For seminal work on the theory of flocking that marked the birth and contributed greatly to the development of the field of active matter.*"

See also Tu (2023) *The renormalization group for non-equilibrium systems,* Nat. Phys. **19**, 1536

Intriguingly, controversies soon emerged for both landmark studies !

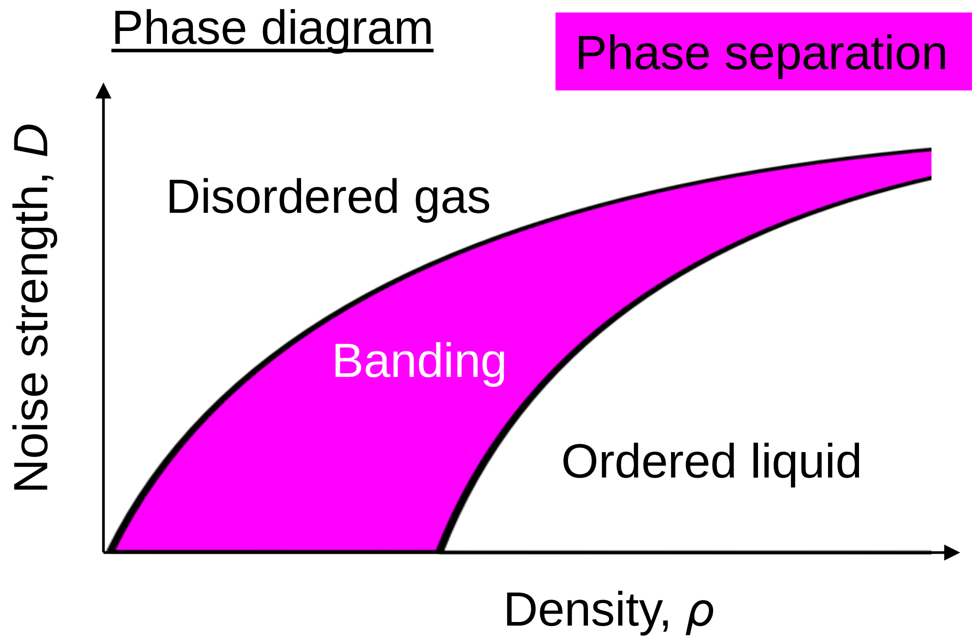
Controversy 1: Absence of critical transition in the Vicsek model

VOLUME 92, NUMBER 2 PHYSICAL REVIEW LETTERS week ending 16 JANUARY 2004

Onset of Collective and Cohesive Motion

Guillaume Grégoire and Hugues Chaté

- Critical order-disorder transition is pre-empted by phase separation



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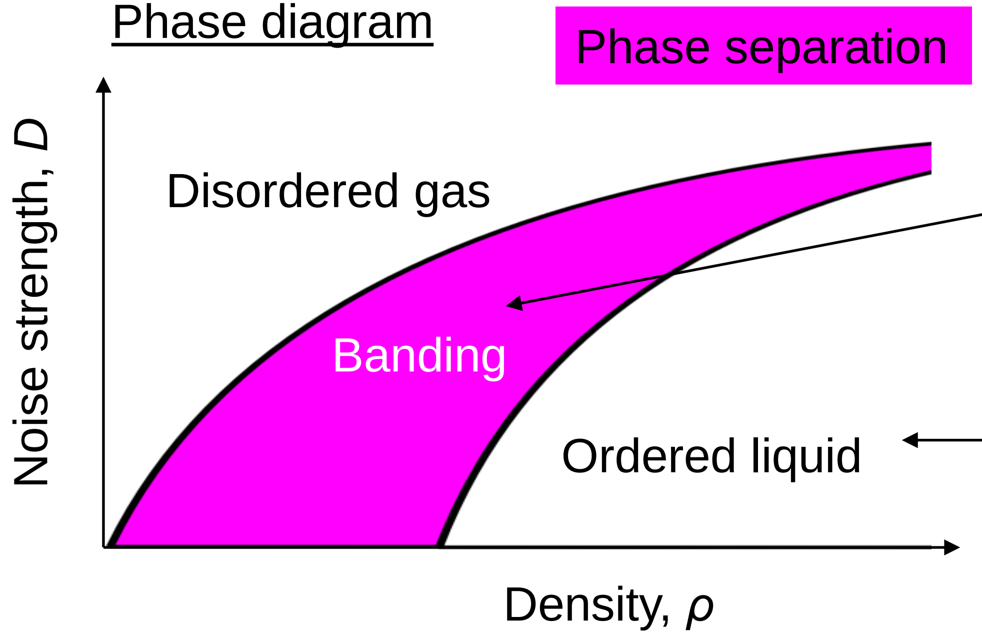
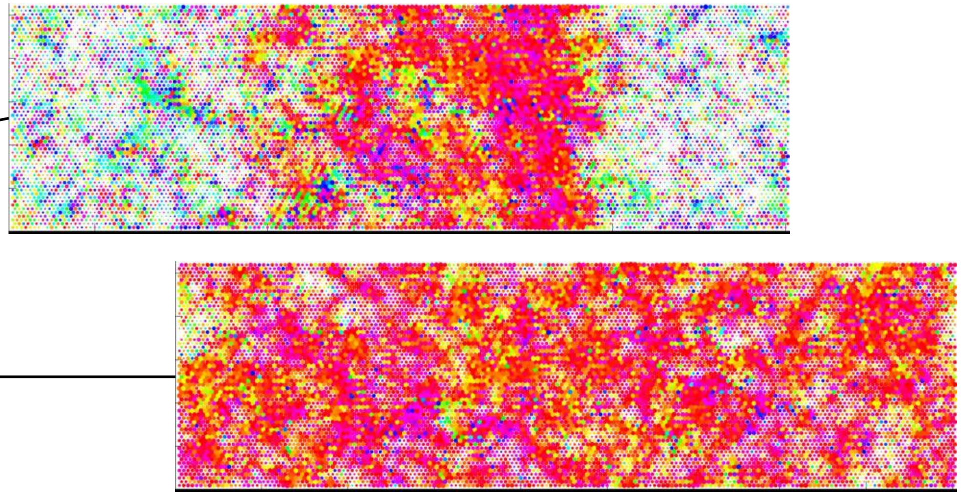
- Critical order-disorder transition is pre-empted by phase separation

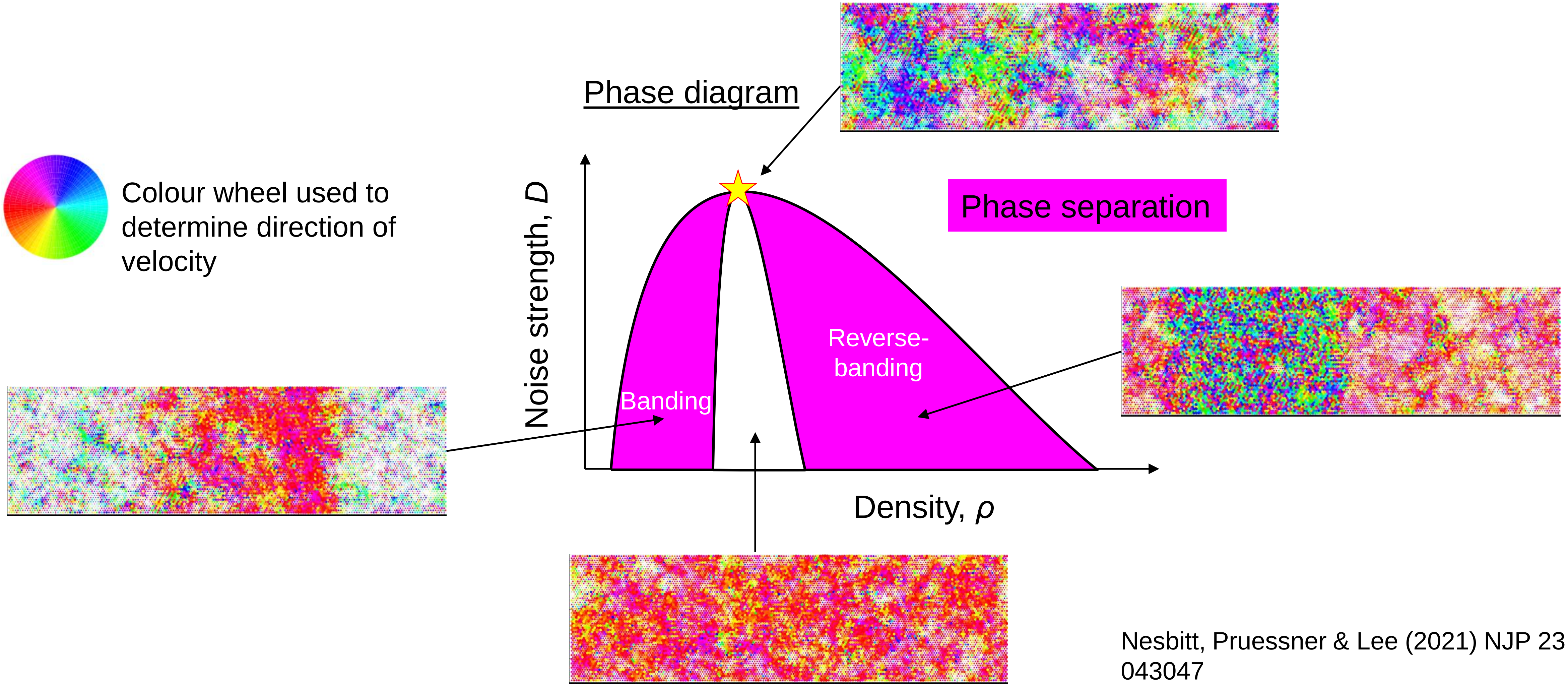
Colour wheel used to determine direction of velocity

<u>Phase diagram</u>





Aside: Critical order-disorder can exist when volume exclusion occurs



Nesbitt, Pruessner & Lee (2021) NJP 23, 043047

Controversy 2: Toner-Tu 95 RG analysis not as general as originally thought

- Missing terms leading to potentially invalid scaling exponents

PHYSICAL REVIEW E **86**, 031918 (2012)

Reanalysis of the hydrodynamic theory of fluid, polar-ordered flocks

John Toner

PHYSICAL REVIEW LETTERS **123,** 218001 (2019)

Editors' Suggestion

Quantitative Assessment of the Toner and Tu Theory of Polar Flocks

Benoît Mahault,[1,2] Francesco Ginelli,[3,4] and Hugues Chaté[1,5,6]

Spatial dimension (d)	χ	z	ζ
$d = 2:$			
TT 95	-0.20	1.20	0.6
simulation	$-0.31(2)$	1.33(2)	0.95(2)
$d = 3:$			
TT 95	-0.60	1.60	0.8
simulation	-0.62	1.77	1

$$(t, \mathbf{r}_\perp, x, \delta\mathbf{g}, \delta\rho) \to (te^{zl}, \mathbf{r}_\perp e^{l}, xe^{\zeta l}, \delta\mathbf{g}e^{\chi l}, \delta\rho e^{\chi l})$$

Where do we stand?

- No critical behaviour in the Vicsek model
- Universality class (UC) for Vicsek's flocking phase remains elusive

Here, we use nonperturbative, functional RG to study a *simplified* TT model

- TT UC applies for $\frac{11}{3} (\approx 3.67) < d < 4$

- Below $d = 11/3$, a new UC emerges, whose scaling exponents agree remarkably well with simulation in 2D & 3D

Spatial dimension (d)	χ	z	ζ
$d = 2$:			
TT 95	-0.20	1.20	0.6
simulation	$-0.31(2)$	$1.33(2)$	$0.95(2)$
new UC	-0.325	1.325	0.975
$d = 3$:			
TT 95	-0.60	1.60	0.8
simulation	-0.62	1.77	1
new UC	-0.65	1.65	0.95

2. Simplified Toner-Tu model

Simplified Toner-Tu model

- Toner-Tu model Toner, Tu, *Phys. Rev. Lett* (1995)
  - Ginzburg-Landau theory for flocking
- *Simplification 1*
  - Constrained fluctuations in flocking direction

  → Reduced linear complexity
- *Simplification 2*
  - No density dependent nonlinearities

  →Simplified nonlinear complexity
- Density fluctuations contribute linearly!

Toner Tu Model

Toner, Tu, *Phys. Rev. Lett* (1995)

Continuity equation for **density**

$$\partial_t \rho = -\boldsymbol{\nabla} \cdot \boldsymbol{g}$$

EOM for **momentum** density

$$\gamma \partial_t \boldsymbol{g} + \lambda_1 \boldsymbol{g} \cdot \boldsymbol{\nabla} \boldsymbol{g} + \lambda_2 \boldsymbol{g} \boldsymbol{\nabla} \cdot \boldsymbol{g} + \lambda_3 \boldsymbol{\nabla}(|\boldsymbol{g}|^2)$$
$$= -U(\rho, g^2)\boldsymbol{g} - P_1(\rho, g^2)\boldsymbol{\nabla}\rho + \mu_1 \nabla^2 \boldsymbol{g} + \mu_2 \boldsymbol{\nabla}(\boldsymbol{\nabla} \cdot \boldsymbol{g})$$
$$+\mu_3 (\boldsymbol{g} \cdot \boldsymbol{\nabla})^2 \boldsymbol{g} + P_2 \boldsymbol{g}(\boldsymbol{g} \cdot \boldsymbol{\nabla}\rho) + \cdots + \boldsymbol{f}$$

Under assumptions of:

- Mass conservation
- Translation sym.
- Rotation sym.
- Chiral sym.

Toner Tu Model

Toner, Tu, *Phys. Rev. Lett* (1995)

Simplification 1:

No fluctuations in flocking direction

$$\delta \boldsymbol{g}_x = 0$$

Simplification 2:

No nonlinear density terms

Continuity equation for **density**

$$\partial_t \rho = -\boldsymbol{\nabla} \cdot \boldsymbol{g}$$

EOM for **momentum** density

$$\gamma \partial_t \boldsymbol{g} + \lambda_1 \boldsymbol{g} \cdot \boldsymbol{\nabla} \boldsymbol{g} + \lambda_2 \boldsymbol{g} \boldsymbol{\nabla} \cdot \boldsymbol{g} + \lambda_3 \boldsymbol{\nabla}(|\boldsymbol{g}|^2)$$

$$= -U(\cancel{\rho}, g^2)\boldsymbol{g} - P_1(\cancel{\rho}, g^2)\boldsymbol{\nabla}\rho + \mu_1 \nabla^2 \boldsymbol{g} + \mu_2 \boldsymbol{\nabla}(\boldsymbol{\nabla} \cdot \boldsymbol{g})$$

$$+\mu_3(\boldsymbol{g} \cdot \boldsymbol{\nabla})^2 \boldsymbol{g} + \cancel{P_2 \boldsymbol{g}(\boldsymbol{g} \cdot \boldsymbol{\nabla}\rho)} + \cdots + \boldsymbol{f}$$

Simplified Model

Toner, Tu, *Phys. Rev. Lett* (1995)

Simplification 1:

No fluctuations in flocking direction

$$\delta \boldsymbol{g}_x = 0$$

Simplification 2:

No nonlinear density terms

Continuity equation for **density**

$$\partial_t \rho = -\boldsymbol{\nabla} \cdot \boldsymbol{g}$$

EOM for **momentum** density ($\boldsymbol{g} = g_0 \widehat{\boldsymbol{x}} + \boldsymbol{g}_\perp, \quad \boldsymbol{g}_\perp = \delta \boldsymbol{g}_L + \delta \boldsymbol{g}_T$)

$$\gamma \partial_t \boldsymbol{g}_\perp + \lambda_1 g_0 \partial_x \boldsymbol{g}_\perp + \underline{\lambda_1 \boldsymbol{g}_\perp \cdot \boldsymbol{\nabla}_\perp \boldsymbol{g}_\perp + \lambda_2 \boldsymbol{g}_\perp \boldsymbol{\nabla}_\perp \cdot \boldsymbol{g}_\perp + \lambda_3 \boldsymbol{\nabla}_\perp (|\boldsymbol{g}_\perp|^2)}$$

$$= \underline{-\beta |\boldsymbol{g}_\perp|^2 \boldsymbol{g}_\perp} - \kappa_1 \boldsymbol{\nabla} \rho + \mu_1 ({\boldsymbol{\nabla}_\perp}^2 + {\partial_x}^2) \boldsymbol{g}_\perp + \mu_2 \boldsymbol{\nabla}_\perp (\boldsymbol{\nabla}_\perp \cdot \boldsymbol{g}_\perp)$$

$$+ \mu_3 {g_0}^2 {\partial_x}^2 \boldsymbol{g} + \boldsymbol{f}$$

3. Linear Theory

Linear Theory

- Expand EOM into $\boldsymbol{g} = g_0\hat{\boldsymbol{x}} + \boldsymbol{g}_\perp, \quad \boldsymbol{g}_\perp = \delta\boldsymbol{g}_L + \delta\boldsymbol{g}_T, \;\; \rho = \rho_0 + \delta\rho$
- Obtain propagators (response functions) $\boldsymbol{g}_\perp = \boldsymbol{G}\cdot\boldsymbol{\delta}, \;\; \delta\rho = H\delta$

$$\boldsymbol{G}_T = \frac{\boldsymbol{\mathcal{P}}_T(\boldsymbol{q})}{-i\gamma\omega + i\lambda_1 g_0 q_x + \mu_x {q_x}^2 + \mu_\perp {q_\perp}^2}$$

$$\boldsymbol{G}_L = \frac{-i\omega\boldsymbol{\mathcal{P}}_L(\boldsymbol{q})}{-i\omega(-i\gamma\omega + i\lambda_1 g_0 q_x + \mu_x {q_x}^2 + \mu_\perp^L {q_\perp}^2) + \kappa_1 {q_\perp}^2}$$

$$H = \frac{-i\gamma\omega + i\lambda_1 g_0 q_x + \mu_x {q_x}^2 + \mu_\perp^L {q_\perp}^2}{-i\omega(-i\gamma\omega + i\lambda_1 g_0 q_x + \mu_x {q_x}^2 + \mu_\perp^L {q_\perp}^2) + \kappa_1 {q_\perp}^2}$$

Linear Theory

- Scaling from equal-time correlation functions

$$\langle \delta \boldsymbol{g}_L(t,\boldsymbol{r})\delta \boldsymbol{g}_L(t,\boldsymbol{r}')\rangle = D\int_{\boldsymbol{q}} e^{-i\boldsymbol{q}\cdot\boldsymbol{r}}\frac{\boldsymbol{\mathcal{P}}_L(\boldsymbol{q})}{\mu_\perp^L {q_\perp}^2 + \mu_x {q_x}^2}$$

$$\langle \delta \boldsymbol{g}_T(t,\boldsymbol{r})\delta \boldsymbol{g}_T(t,\boldsymbol{r}')\rangle = D\int_{\boldsymbol{q}} e^{-i\boldsymbol{q}\cdot\boldsymbol{r}}\frac{\boldsymbol{\mathcal{P}}_T(\boldsymbol{q})}{\mu_\perp {q_\perp}^2 + \mu_x {q_x}^2}$$

$$\langle \delta \rho(t,\boldsymbol{r})\delta \rho(t,\boldsymbol{r}')\rangle = \frac{D}{\kappa_1}\int_{\boldsymbol{q}} e^{-i\boldsymbol{q}\cdot\boldsymbol{r}}\frac{1}{\mu_\perp^L {q_\perp}^2 + \mu_x {q_x}^2}$$

- Typical linear scaling $\chi^{\mathrm{lin}} = \chi_\rho^{\mathrm{lin}} = \frac{2-d}{2}$

4. Nonlinear theory using FRG

Nonlinear theory using FRG

- Martin-Siggia-Rose-de Dominicis-Janssen → Ansatz for effective action
- Same couplings as in microscopic action
- Keep only relevant nonlinearities: $d_c = 4$

$$\Gamma[\overline{\boldsymbol{g}}_\perp, \boldsymbol{g}_\perp, \overline{\rho}, \rho] = \int \{\overline{\rho}[\partial_t \rho + \boldsymbol{\nabla}_\perp \cdot \boldsymbol{g}_\perp] - D|\overline{\boldsymbol{g}}_\perp|^2 + \overline{\boldsymbol{g}}_\perp \cdot [\gamma \partial_t \boldsymbol{g}_\perp + \lambda_1 g_0 \partial_x \boldsymbol{g}_\perp$$

$$+\lambda_1 \boldsymbol{g}_\perp \cdot \boldsymbol{\nabla}_\perp \boldsymbol{g}_\perp + \lambda_2 \boldsymbol{g}_\perp \boldsymbol{\nabla}_\perp \cdot \boldsymbol{g}_\perp + \lambda_3 \boldsymbol{\nabla}_\perp (|\boldsymbol{g}_\perp|^2) + \beta |\boldsymbol{g}_\perp|^{\mathbf{2}} \boldsymbol{g}_\perp + \kappa_1 \boldsymbol{\nabla} \rho$$

$$- \mu_1 ({\boldsymbol{\nabla}_\perp}^2 + {\partial_x}^2) \boldsymbol{g}_\perp - \mu_2 \boldsymbol{\nabla}_\perp (\boldsymbol{\nabla}_\perp \cdot \boldsymbol{g}_\perp) - \mu_3 {g_0}^2 {\partial_x}^2 \boldsymbol{g}]\}$$

Regulator

- Sharp regulator for $\boldsymbol{q}_\perp$ only

$$R_k(\boldsymbol{q}_\perp, q_x, \omega) = \Gamma_k^{(2)}(\boldsymbol{q}_\perp, q_x, \omega)\left(\frac{1}{\Theta_\epsilon(|\boldsymbol{q}_\perp| - k)} - 1\right)$$

- q_x and ω remain unregulated

→ ω and $\boldsymbol{q}_\perp$ Integrals can be performed analytically

Flow Equations

- Projection from Wetterich equation straightforward

$$\partial_k \Gamma_k = \frac{1}{2} \partial_{k'} \operatorname{Tr} \log \left(\Gamma_k^{(2)} + R_{k'} \right) \Big|_{k'=k}$$

- Main challenge: Interaction between longitudinal and transverse modes

$$G_T = \frac{\boldsymbol{\mathcal{P}}_T(\boldsymbol{q})}{-i\gamma\omega + i\lambda_1 g_0 q_x + \mu_\perp {q_\perp}^2 + \mu_x {q_x}^2}$$

$$G_L = \frac{-i\omega \boldsymbol{\mathcal{P}}_L(\boldsymbol{q})}{-i\omega(-i\gamma\omega + i\lambda_1 g_0 q_x + \mu_\perp {q_\perp}^2 + \mu_x^L {q_x}^2) + \kappa_1 {q_\perp}^2}$$

→ Requires Computer algebra

Flow equations

Anomalous Dimensions → Anomalous Scaling

$$\partial_l D_k = \eta_{D,k} D_k$$

$$\partial_l \gamma_k = \eta_{\gamma,k} \gamma_k$$

$$\partial_l \mu_{\perp,k} = \eta_{\perp,k} \mu_{\perp,k}$$

$$\partial_l \mu_{x,k} = \eta_{x,k} \mu_{x,k}$$

Nonlinear Couplings

$$\partial_l \bar{\beta}_k = \left(4 - d - \frac{3}{2}\eta_{\perp,k} - \frac{1}{2}\eta_{x,k}\right)\bar{\beta}_k + \cdots$$

$$\partial_l \bar{\lambda}_{i,k} = \frac{1}{4}\left(2(4 - d + \eta_{D,k} - \eta_{\gamma,k}) - 5\eta_{\perp,k} - \eta_{x,k}\right)\bar{\lambda}_{i,k} + \cdots$$

2 Relevant Couplings

$$\partial_l \bar{\kappa}_{1,k} = \left(2 + \eta_{\gamma,k} - 2\eta_{\perp,k}\right)\bar{\kappa}_{1,k} + \cdots$$

$$\partial_l \bar{\lambda}_{g,k} = \left(1 - \frac{1}{2}\eta_{\perp,k} - \frac{1}{2}\eta_{x,k}\right)\bar{\lambda}_{g,k} + \cdots$$

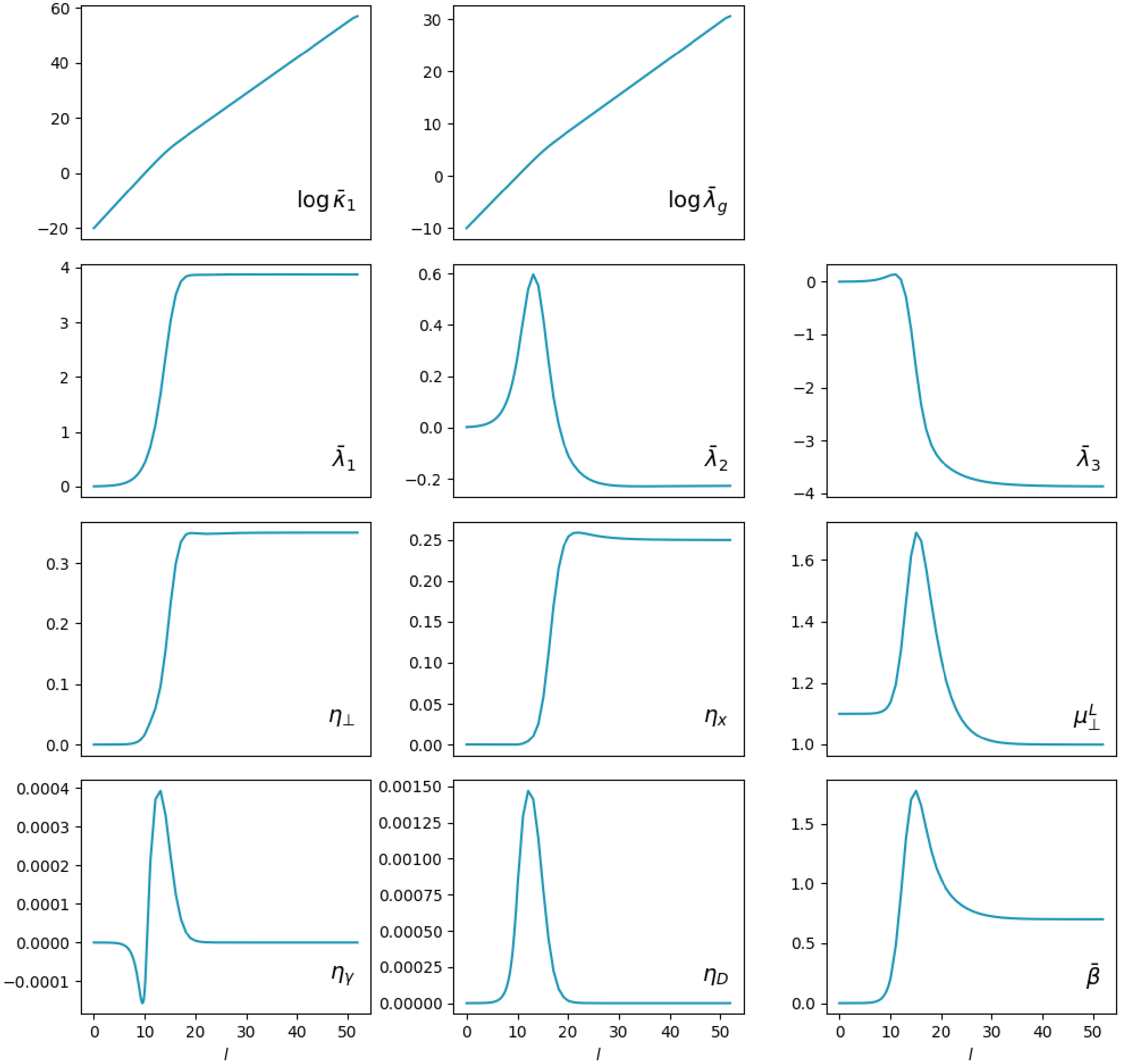
Marginal Linear Coupling

$$\partial_l \bar{\mu}^L_{\perp,k} = -\eta_{\perp,k}\bar{\mu}^L_{\perp,k} + \cdots$$

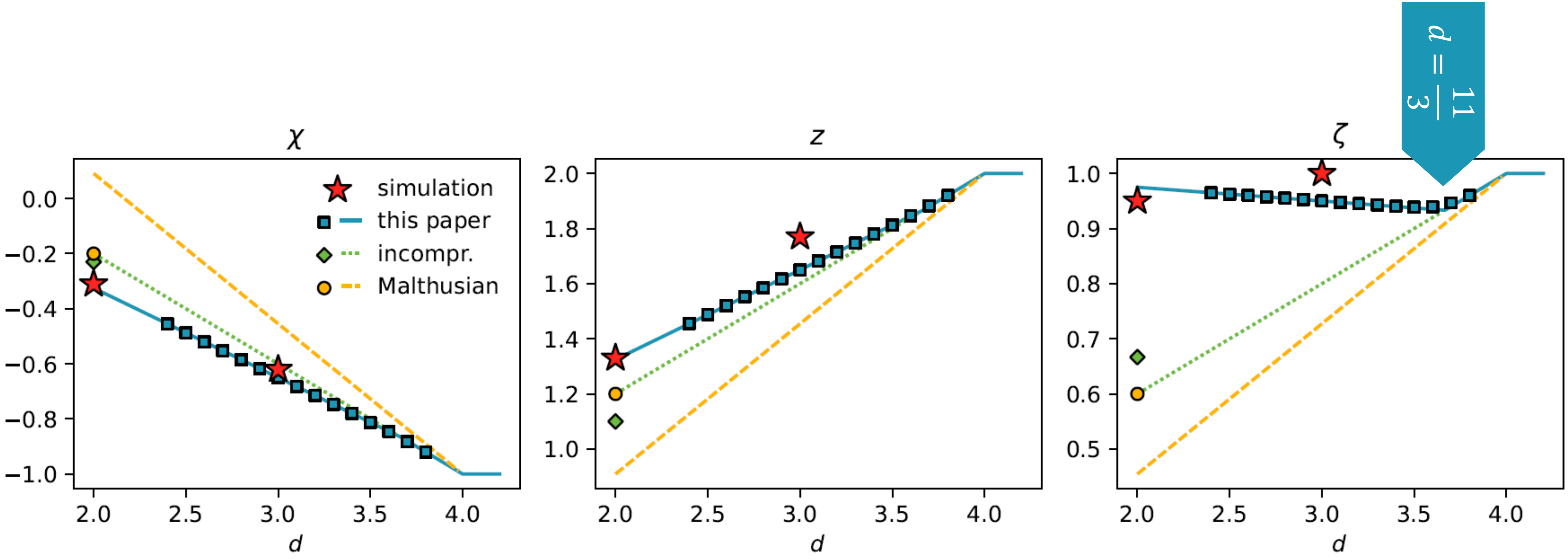
5. FRG fixed points

Numerical Integration of Flow Equations

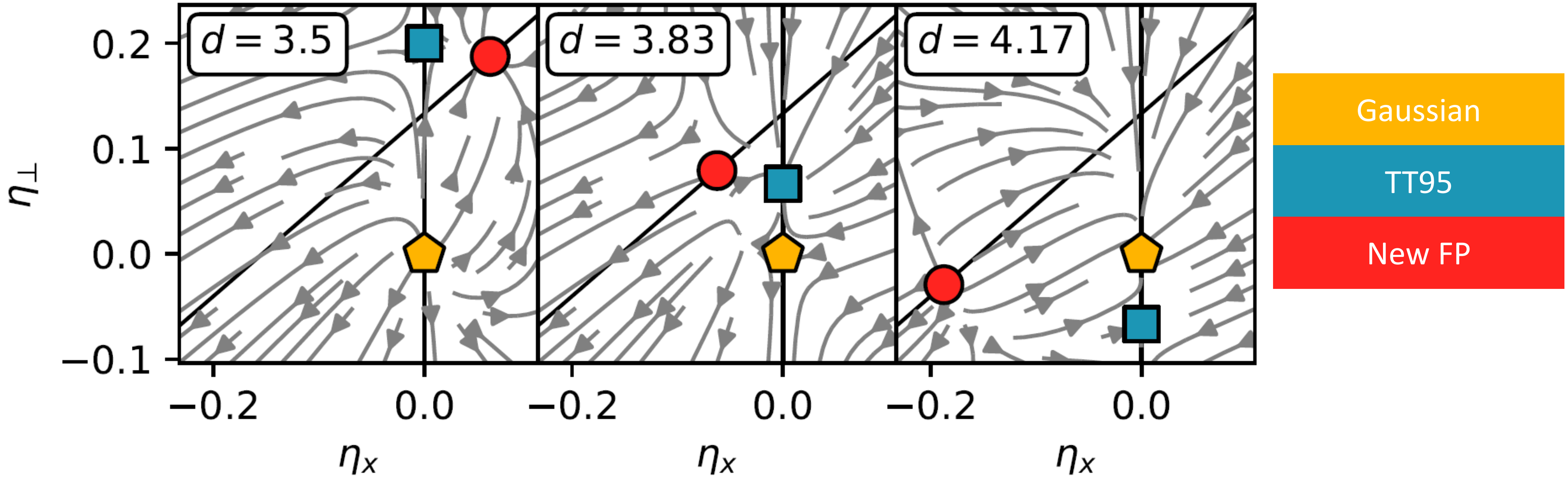
→ Fixed point



Scaling Exponents



Fixed points



6. Analytical treatment

Analytical Approach

- Full flow equations are intractable analytically
- Take limit of large relevant couplings
- Advantages are:

1. Obtain analytical expressions for scaling exponents
2. Why are exponents so accurate?
3. Understand stability exchange

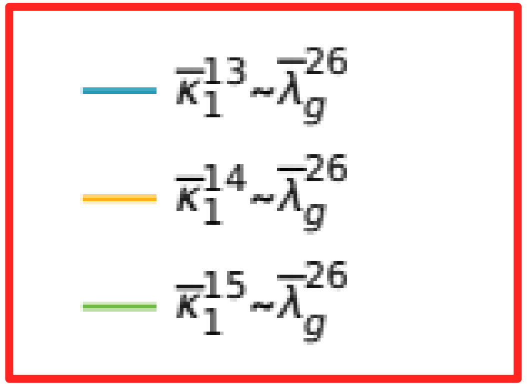
Limit of large relevant couplings

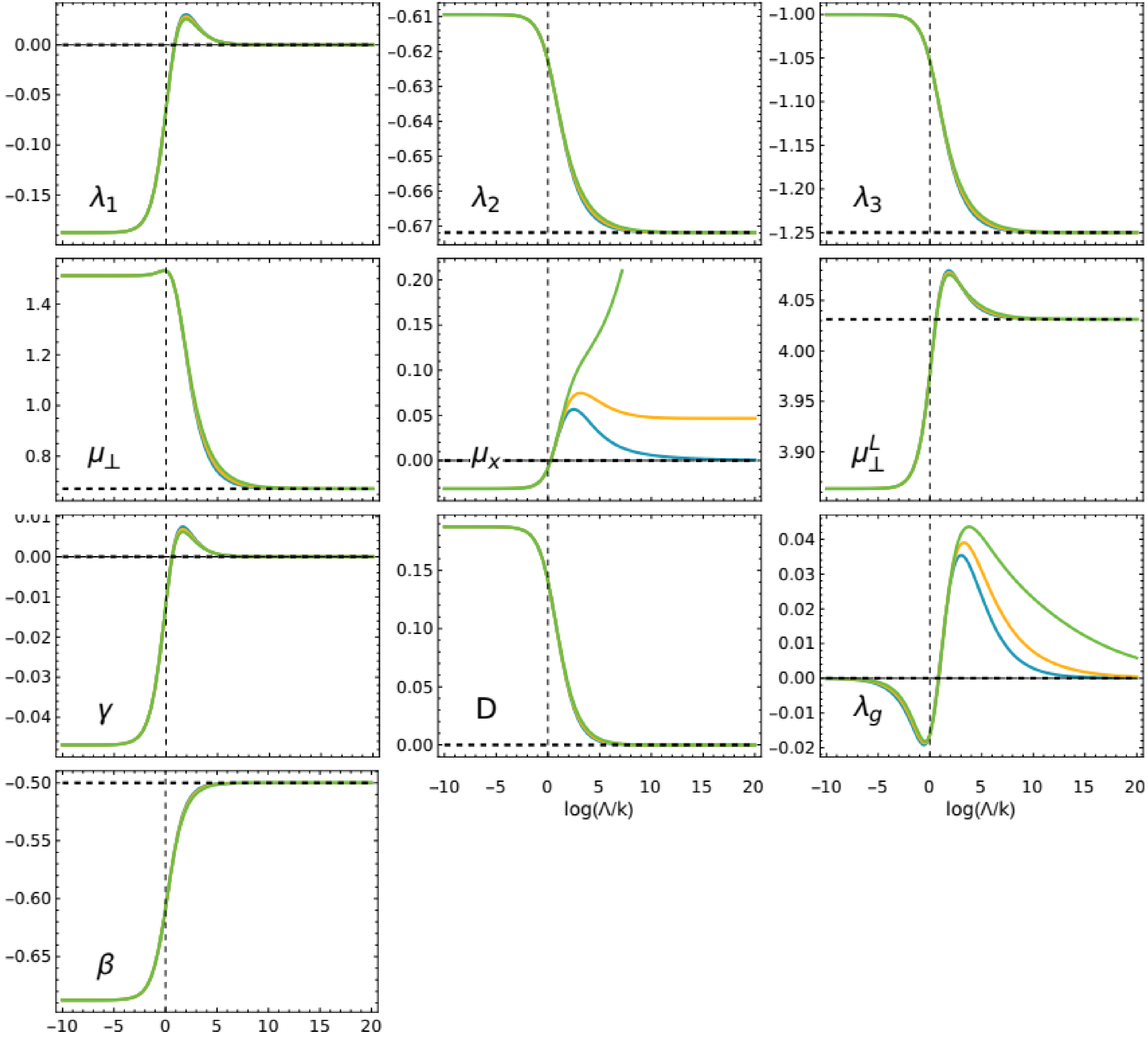
- $\bar{\kappa}_{1,k}$ and $\bar{\lambda}_{g,k}$ have positive scaling dimension → ∞
- Assume $\bar{\kappa}_{1,k} \sim k^{-a}, \bar{\lambda}_{g,k} \sim k^{-b}$
- Evaluate Graphical corrections in this limit
- Set other couplings constant

$$\boxed{\begin{aligned} \partial_l \bar{\kappa}_{1,k} &= (2 + \eta_{\gamma,k} - 2\eta_{\perp,k})\bar{\kappa}_{1,k} + \cdots \\ \partial_l \bar{\lambda}_{g,k} &= \left(1 - \frac{1}{2}\eta_{\perp,k} - \frac{1}{2}\eta_{x,k}\right)\bar{\lambda}_{g,k} + \cdots \end{aligned}}$$

Graphical corrections

- For large mass-scales
- Evaluated analytically and numerically

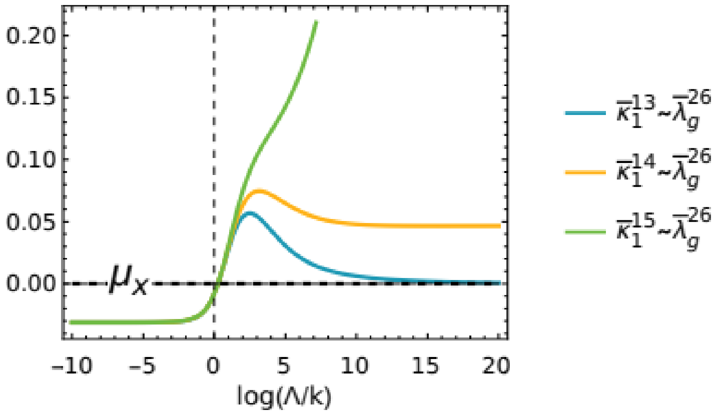




Unprecedented scaling relation

$$\eta_{x,k} = \frac{1}{\mu_{x,k}} \partial_l \mu_{x,k} = F(\bar{\lambda}_{1,k}, \bar{\lambda}_{2,k}, \bar{\lambda}_{3,k}, \bar{\lambda}_{g,k}, \bar{\kappa}_{1,k})$$

$$\rightarrow F\left(\bar{\lambda}^*_{1,k}, \bar{\lambda}^*_{2,k}, \bar{\lambda}^*_{3,k}, \frac{\bar{\lambda}^{13}_{g,k}}{\bar{\kappa}^{7}_{1,k}}\right)$$



$F\left(\bar{\lambda}^*_{1,k}, \bar{\lambda}^*_{2,k}, \bar{\lambda}^*_{3,k}, 0\right) = 0$ $\rightarrow \eta_x = 0$ → TT Univsersality Class

$F\left(\bar{\lambda}^*_{1,k}, \bar{\lambda}^*_{2,k}, \bar{\lambda}^*_{3,k}, \infty\right) = \infty$ → No FP

$F\left(\bar{\lambda}^*_{1,k}, \bar{\lambda}^*_{2,k}, \bar{\lambda}^*_{3,k}, const\right) = const$ $\rightarrow \bar{\lambda}_{\kappa,k} = \frac{\bar{\lambda}^{13}_{g,k}}{\bar{\kappa}^{7}_{1,k}} = const$

$$\rightarrow \partial_l \bar{\lambda}_{\kappa,k} = [13(z-\zeta) - 7(2z-2)]\bar{\lambda}_{\kappa,k} = 0$$

Analytical expression for exponents

$$\partial_l \bar{\lambda}_{\kappa,k} = 0 \;\longrightarrow \qquad 13(z-\zeta) - 7(2z-2) \;= 0$$

$$\partial_l \lambda_{1,k} = 0 \;\longrightarrow \qquad z - 1 + \chi \;= 0$$

$$\partial_l D_k = 0 \;\longrightarrow \qquad z - 2\chi - \zeta - (d-1) = 0$$

$$\longrightarrow \qquad \chi = \frac{13(1-d)}{40}, \qquad z = \frac{27+13d}{40}, \qquad \zeta = \frac{41-d}{40}$$

3 exponents are constrained by 3 scaling relations:

Conjecture: Robust exponents with no truncation dependence

Stability of Fixed point

Expanding around TT Fixed point:

$$\partial_l \bar{\lambda}_{\kappa,k} = [13(z-\zeta) - 7(2z-2)]\bar{\lambda}_{\kappa,k}$$

$$\chi = \frac{3-2d}{5}, \qquad z = \frac{2(d+1)}{5}, \qquad \zeta = \frac{d+1}{5}$$

TT Fixed point becomes unstable below $d = \frac{11}{3}$

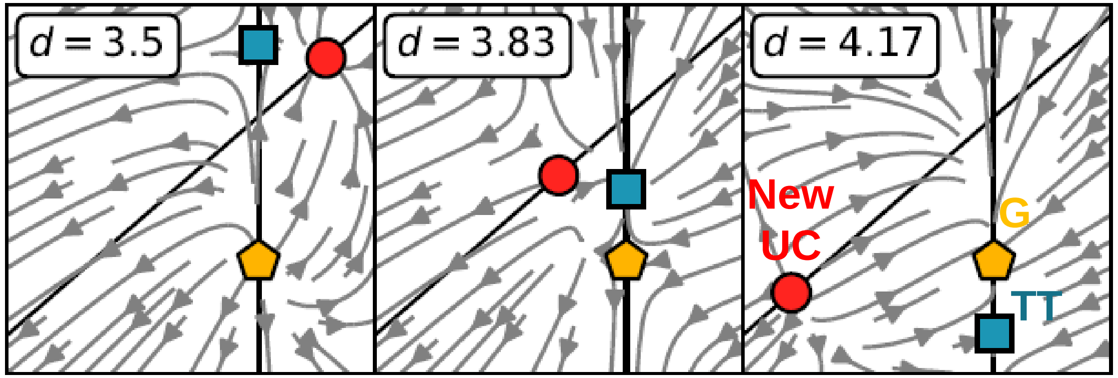
TT and our exponents agree in $d = \frac{11}{3}$

Supports conjecture of stability exchange

7. Summary and Outlook

Summary

- We used nonperturbative, functional RG to study a simplified TT model
- TT UC applies for
$$\frac{11}{3}(\approx 3.67) < d < 4$$
- Below $d = 11/3$, a new UC emerges, whose scaling exponents agree remarkably well with simulation in 2D & 3D



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Outlook: Active Matter - a treasure trove new UCs

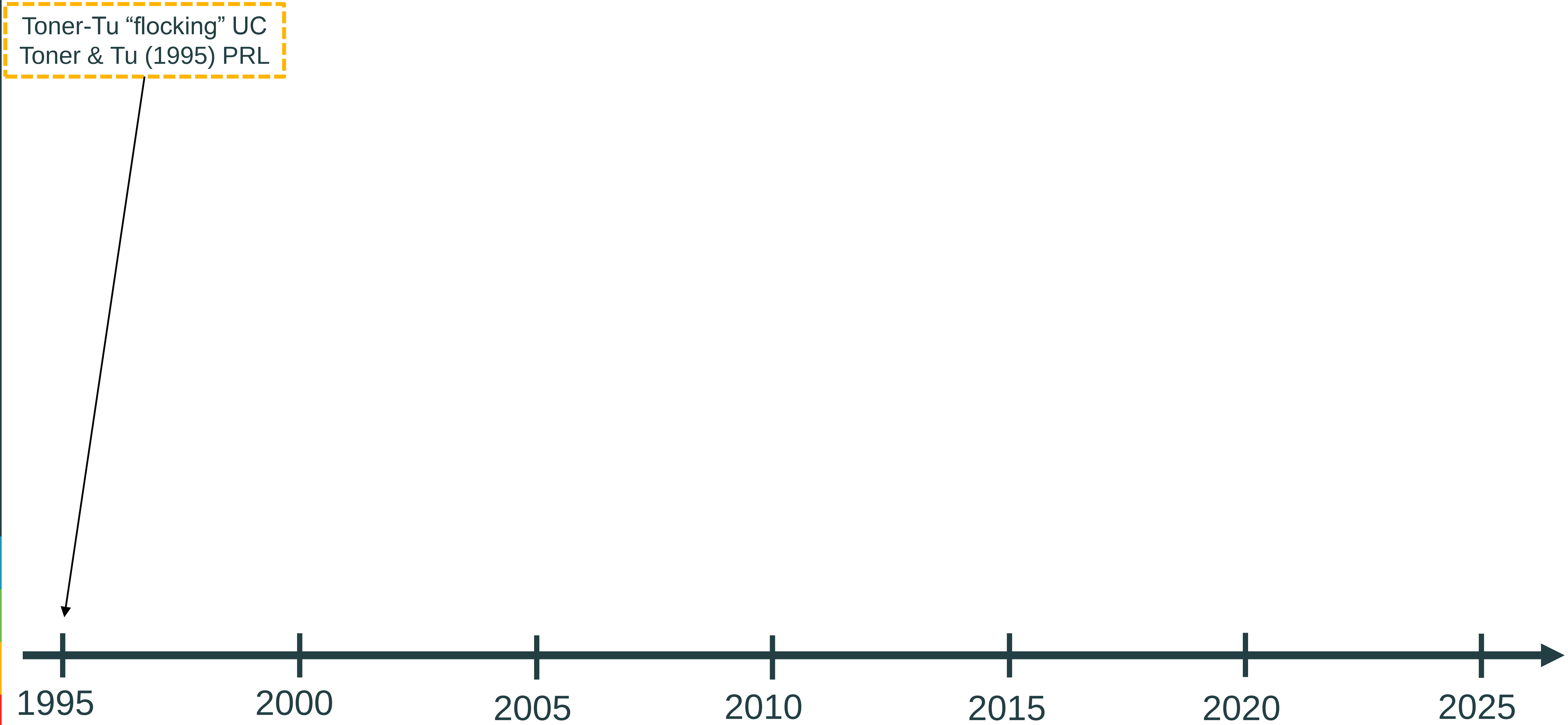
Marchetti, Joanny, Ramaswamy, Liverpool, Prost, Rao, & Aditi Simha
Hydrodynamics of soft active matter
Rev. Mod. Phys. 85, 1143 (2013)

“The hope is to be able to classify active matter in a small number of universality classes, based on considerations of symmetry and conservation laws, each with a well-defined macroscopic behavior. We consider here four classes of active matter according to the nature of the broken symmetry of the ordered phase and the type of momentum damping.”

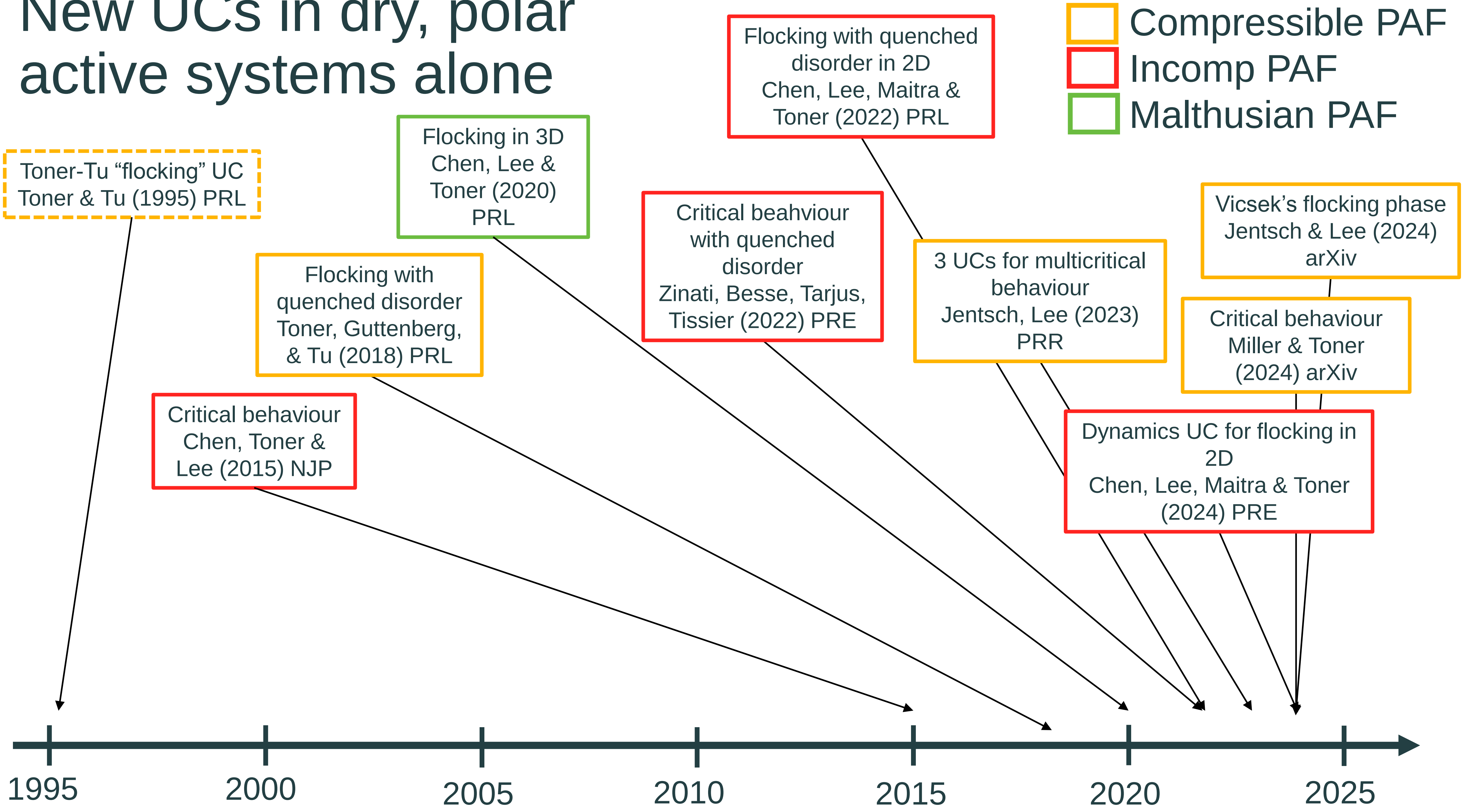
TABLE I. Examples of active systems classified according to symmetry and to the relevance of momentum conservation (wet or dry).

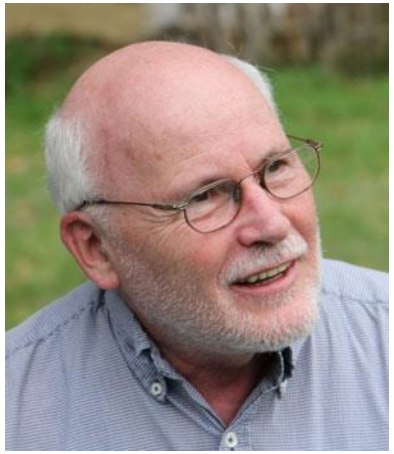
	Nematic	Polar
Dry		Migrating animal herds (Parrish and Hamner, 1997)
	Melanocytes (Kemkemer *et al.*, 2000)	Migrating cell layers (Serra-Picamal *et al.*, 2012)
	Vibrated granular rods (Narayan, Ramaswamy, and Menon, 2007)	Vibrated asymmetric granular particles (Kudrolli *et al.*, 2008)
		Films of cytoskeletal extracts (Surrey *et al.*, 2001)
Wet		Cell cytoskeleton and cytoskeletal extracts in bulk suspensions (Bendix *et al.*, 2008)
	Suspensions of catalytic colloidal rods (Paxton *et al.*, 2004)	Swimming bacteria in bulk (Dombrowski *et al.*, 2004)
		Pt catalytic colloids (Palacci *et al.*, 2010)

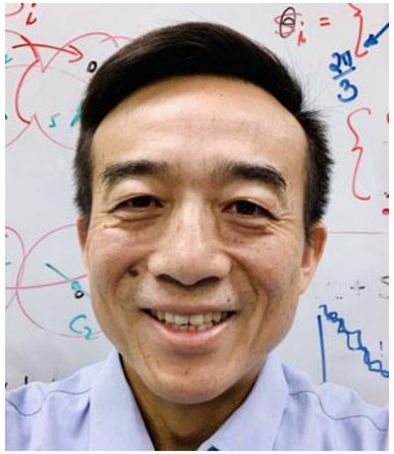
New UCs in dry, polar active systems alone



New UCs in dry, polar active systems alone







No one will drive us from the paradise which Toner, Vicsek, & Tu created for us.

Outlook 2

5 decades ago, technological relevance, experimental advances, and abundance of novel physics propelled condensed matter physics to become the ‘King of Physics’ [Martin (2019) Physics Today]

With its relevance to health and life, experimental advances, and abundance of novel physics, I believe living matter physics will be the next ‘condensed matter physics’