2026-01-13 Eindhoven

Chirality across scales in tissue dynamics

Michel Fruchart

S. Chen, E. Gökmen, M. Fruchart, M. Krumbein, P. Silberzan, V. Yashunsky and V. Vitelli, arXiv:2506.12276 (2025)
https://arxiv.org/abs/2506.12276

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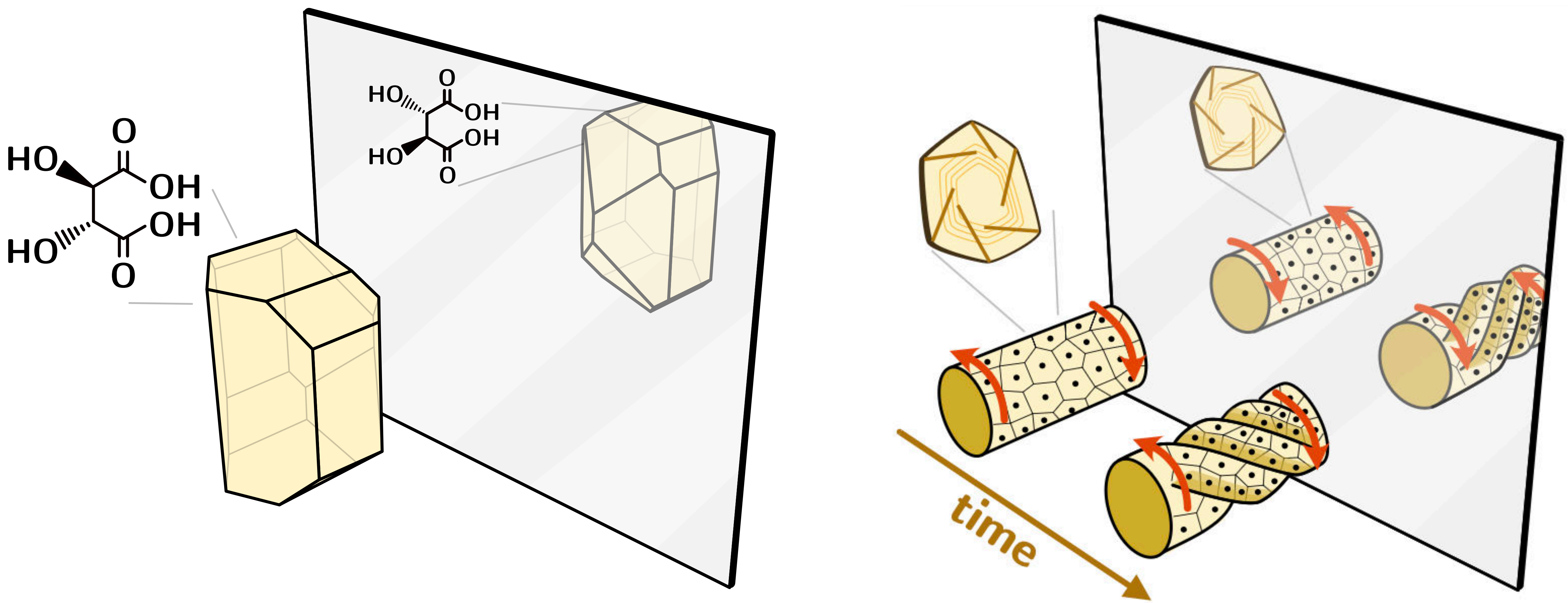
Chirality across scales in tissue dynamics




Sihan Chen


Efe Gökmen


Miriam Krumbein


Pascal Silberzan

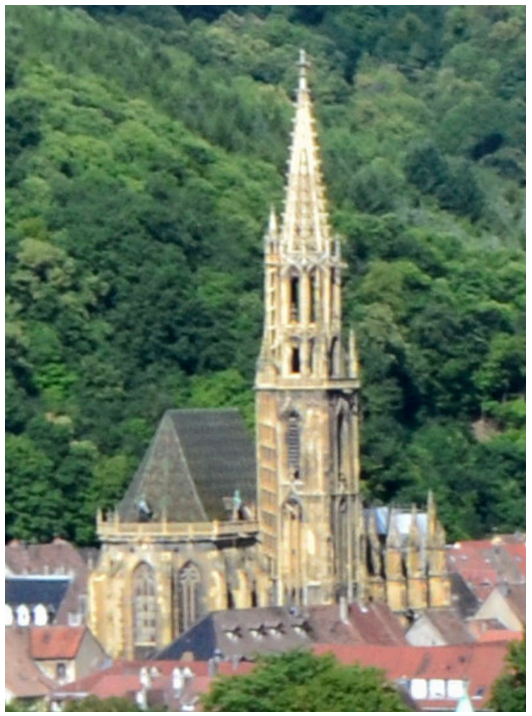

Victor Yashunsky


Vincenzo Vitelli

S. Chen, E. Gökmen, M. Fruchart, M. Krumbein, P. Silberzan, V. Yashunsky and V. Vitelli, arXiv 2506.12276 (2025)

Chirality across scales

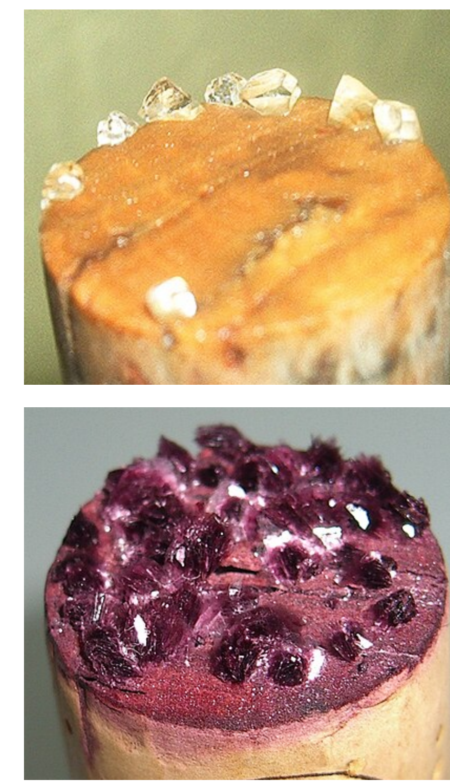
Eye of the Witch



Collegiate Church

Vineyard

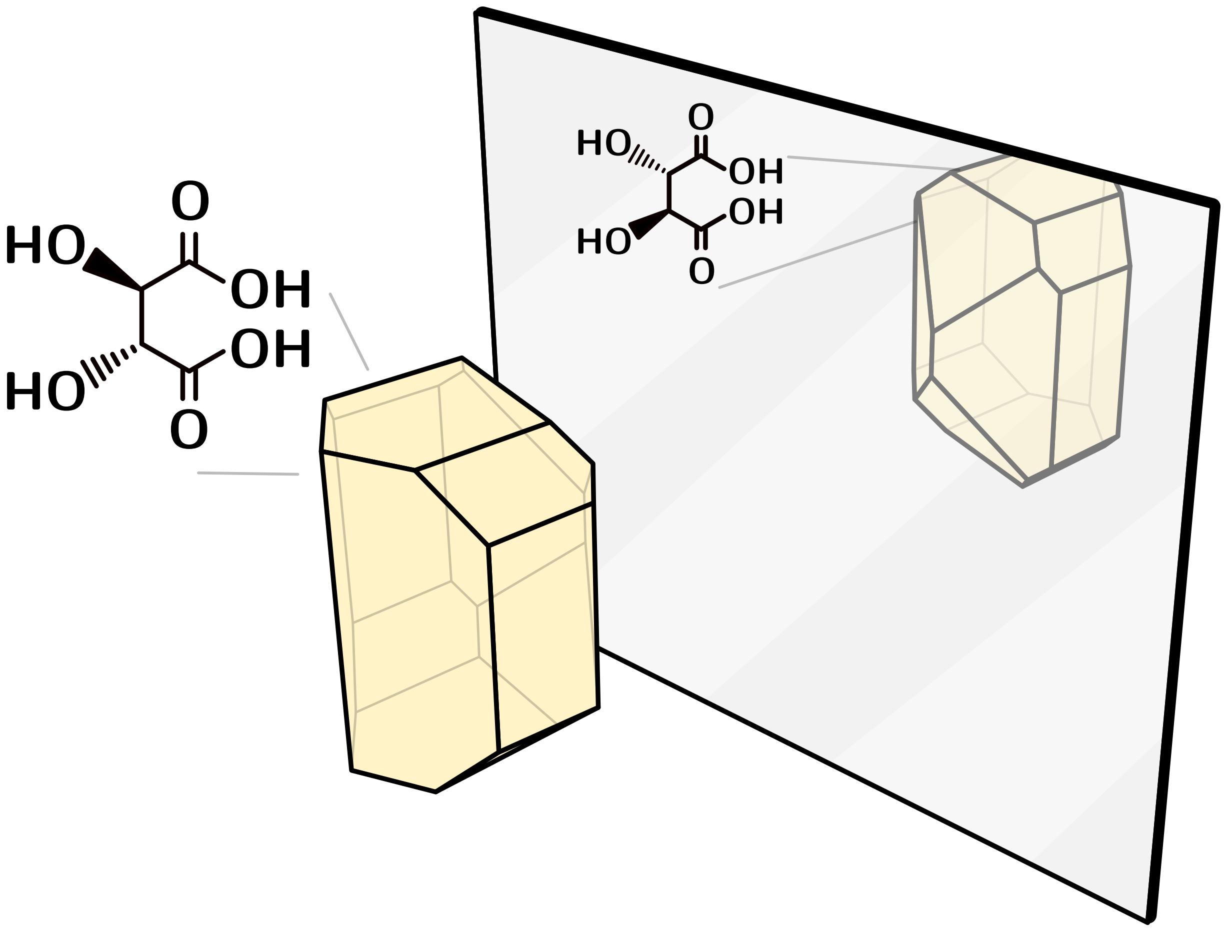
Thann, Alsace, France



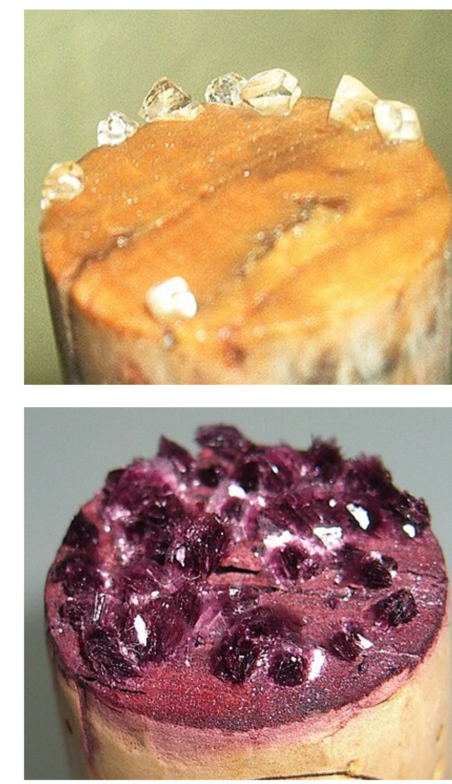
tartarum

photos: Florival_fr @ wikimedia ; Oliver Zimmer @ wikimedia ; Awakening @ wikimedia

Chirality across scales



Louis Pasteur



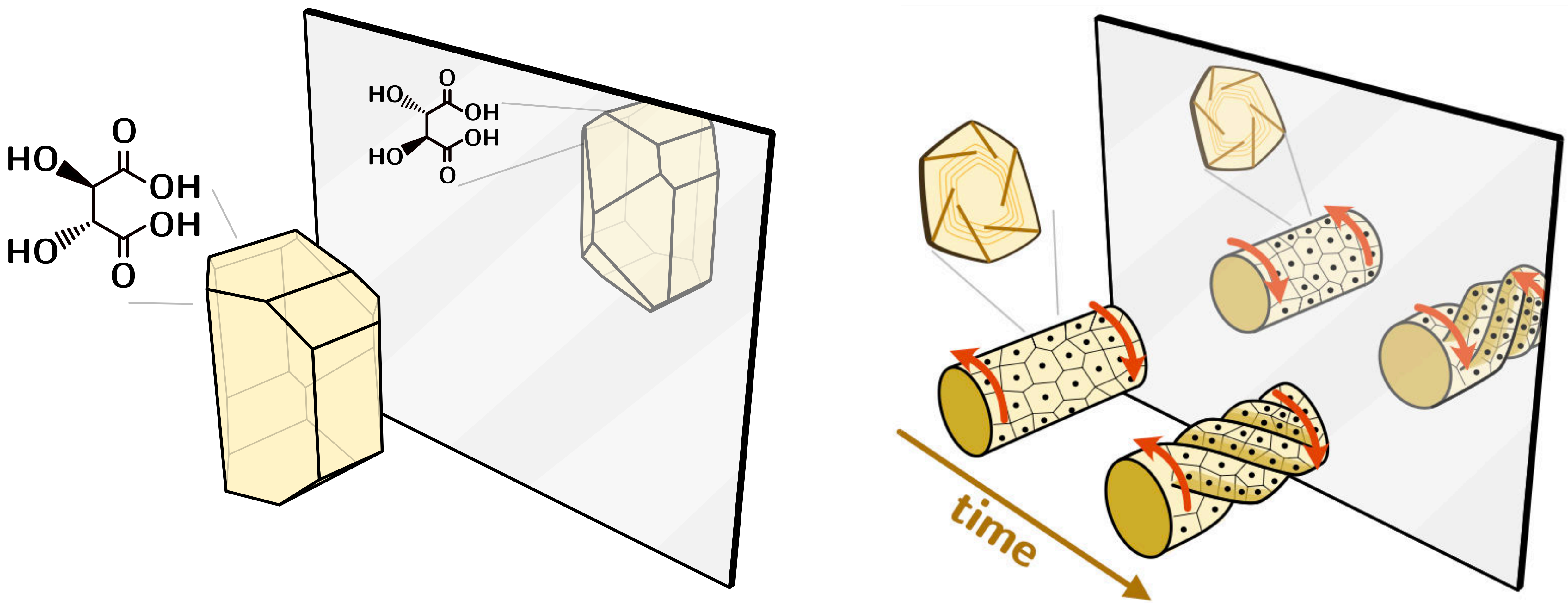
tartarum

chirality from microscopic (molecule) to macroscopic (crystal) scales

tartarum is a salf of tartaric acid, typically potassium bitartrate

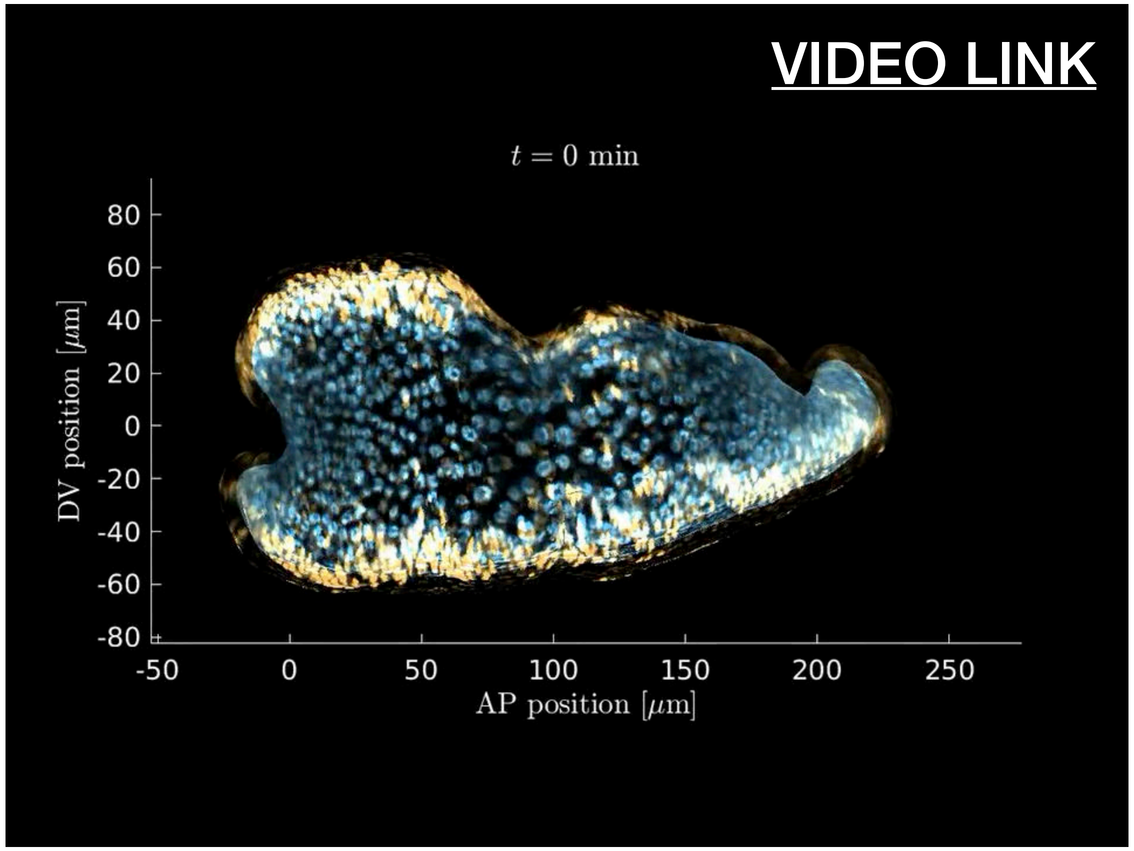
see Vantomme and Crassous (2021) ; Derewenda (2007)

Chirality across scales in tissue dynamics

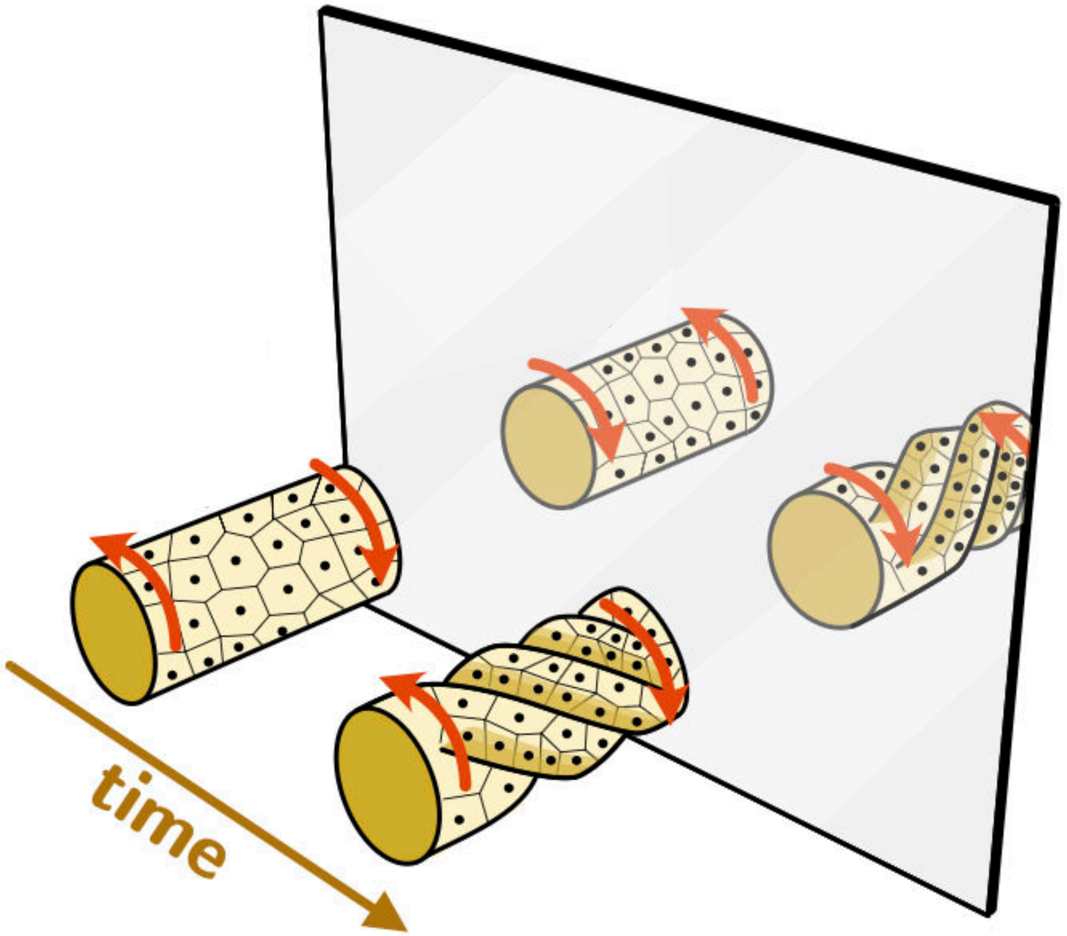


¿how does chirality propagate across scales in biological tissues?

Chirality across scales in tissue dynamics



***Drosophila* midgut morphogenesis**
Mitchell, Cislo, Shankar, Lin,
Shraiman, Streichan, eLife (2022)



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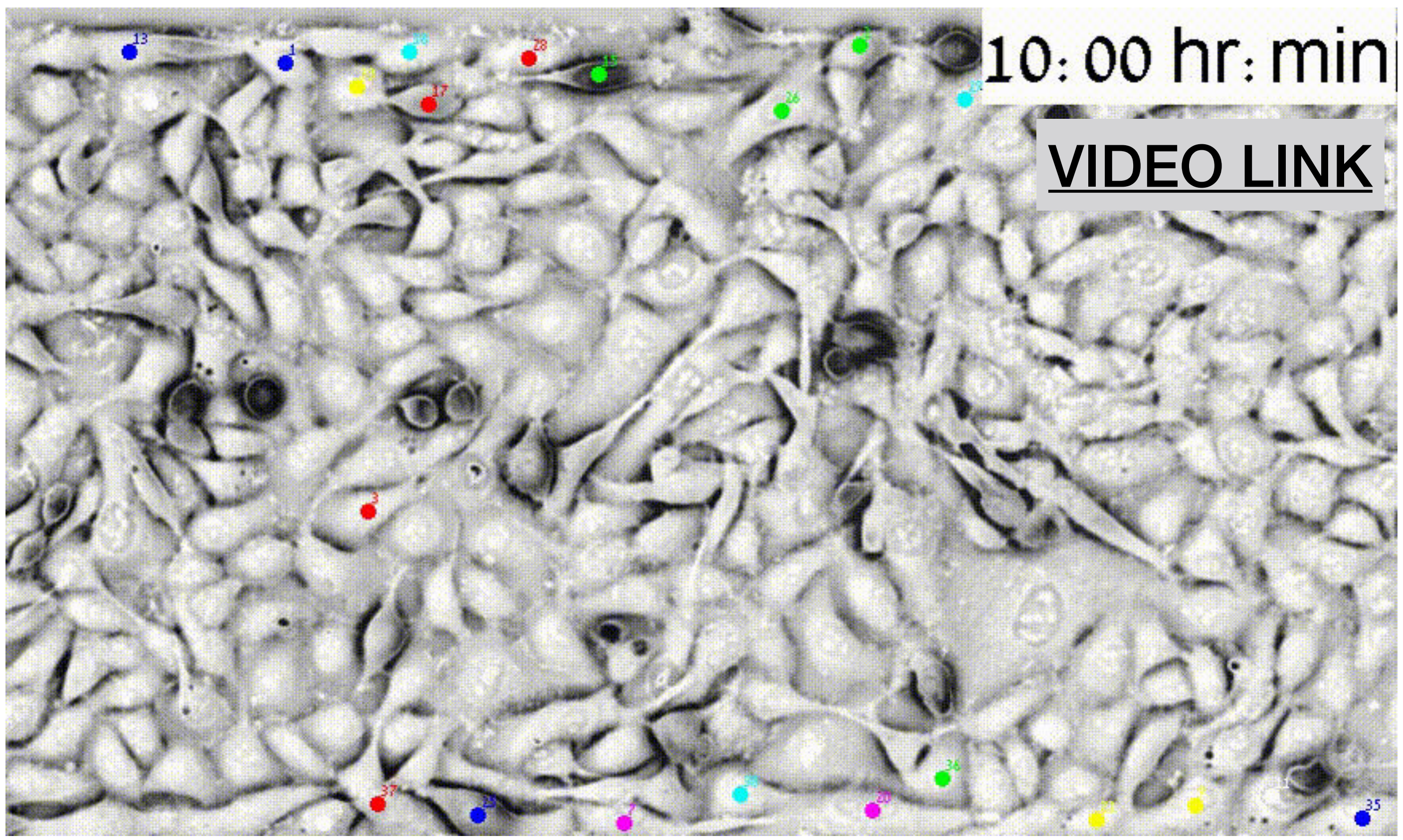
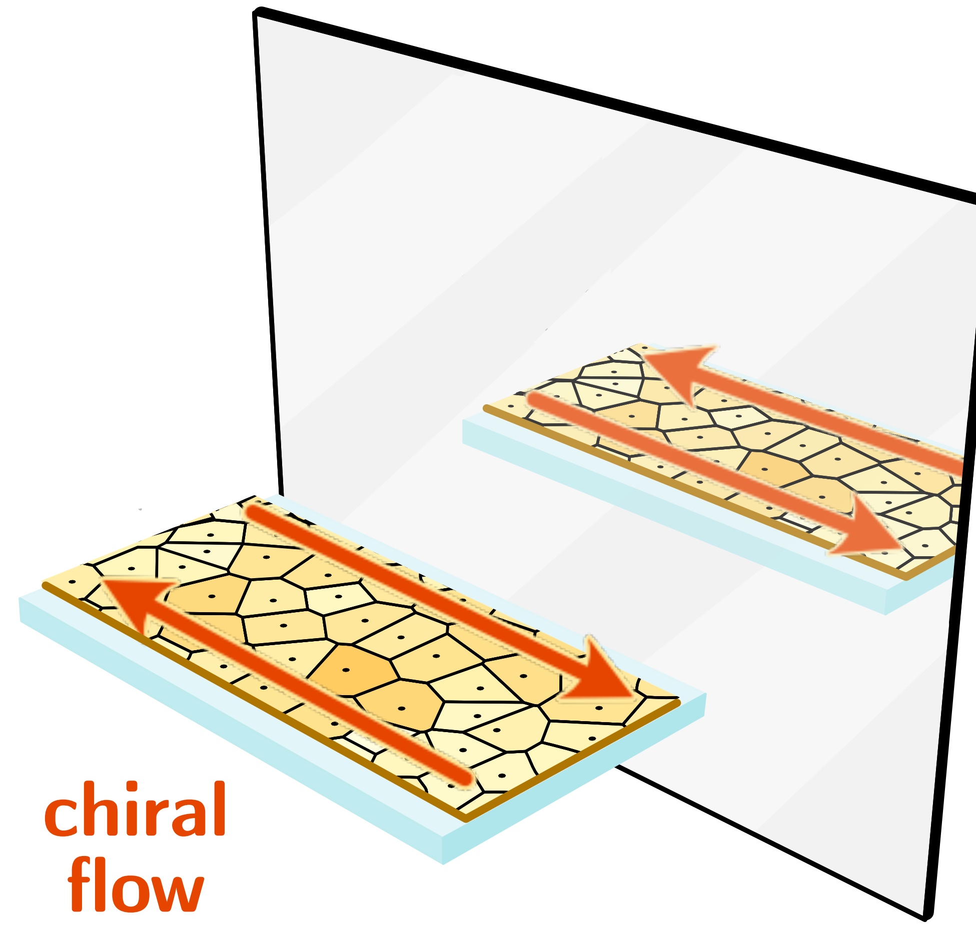
Chirality across scales in tissue dynamics

Pascal Silberzan Victor Yashunsky





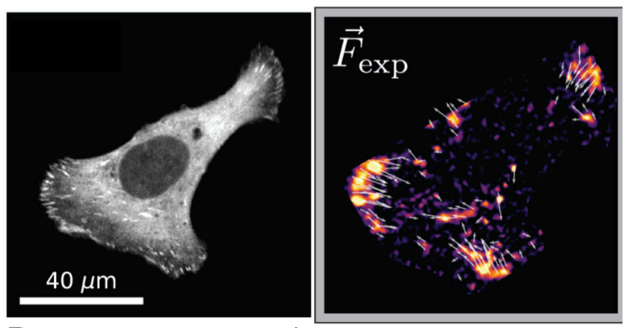
Human fibrosarcoma cells (HT1080)
Yashunsky, Pearce, Blanch-Mercader, Ascione, Silberzan, Giomi, PRX (2022)

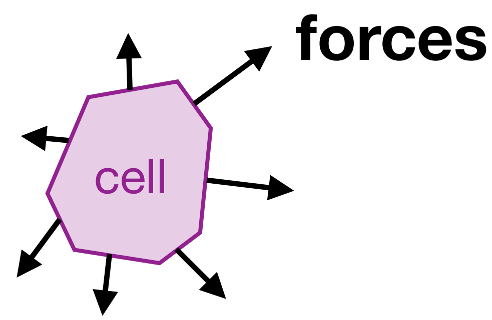
how to model chiral tissues?

How to model tissues?

cell-level

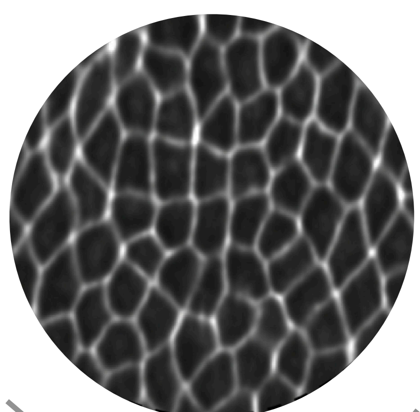
Human Osteosarcoma (U2OS) cells
Cell, 187(2), 481 (2024)

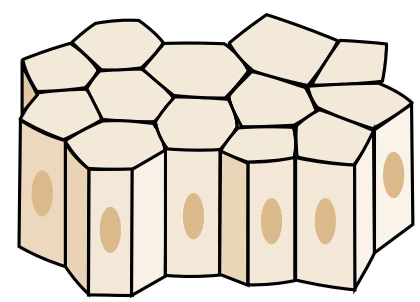




see e.g.
CP Broedersz and FC MacKintosh RMP (2014)
DA Fletcher and RD Mullins Nature (2010)

mesoscopic





vertex models

continuum

Drosophila, courtesy S. Streichan

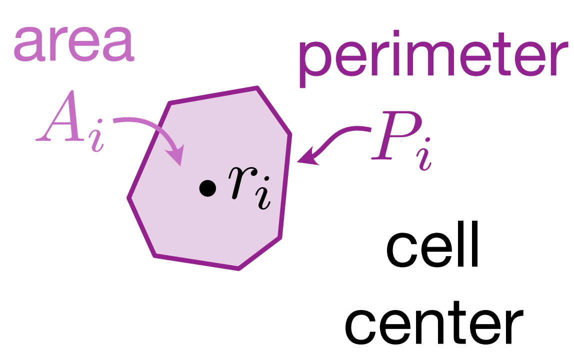
$\mathbf{u}(\mathbf{r}, t)$ $\sigma(\mathbf{r}, t)$

complex viscoelastic fluids/gels

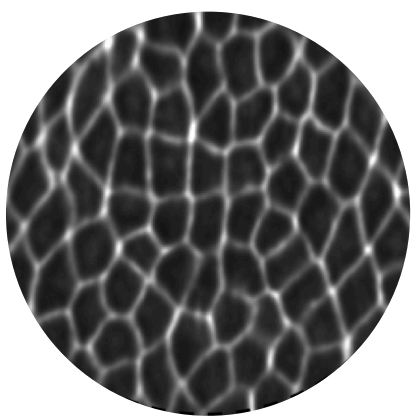
see e.g.
MC Marchetti et al., RMP (2013)
NI Petridou and CP Heisenberg, EMBO (2019)

vertex models are minimal descriptions of confluent biological tissues

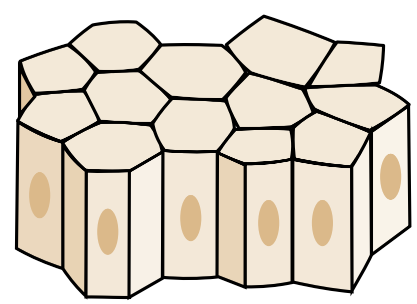
Vertex models



mesoscopic



Drosophila, courtesy S. Streichan



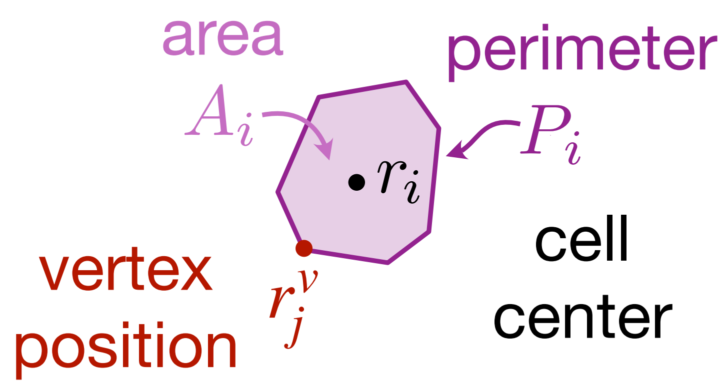
$$\gamma \partial_t \mathbf{r}_i = - \frac{\partial E}{\partial \mathbf{r}_i} \qquad E = \sum_i \left[\frac{K_P}{2}(P_i - P_0)^2 + \frac{K_A}{2}(A_i - A_0)^2 \right]$$

cells minimize an energy towards a preferred perimeter and area

see Alt, Ganguly, Salbreux, RSTB (2017) ; Fletcher, Osterfield, Baker, Shvartsman, Biophysical Journal (2014)

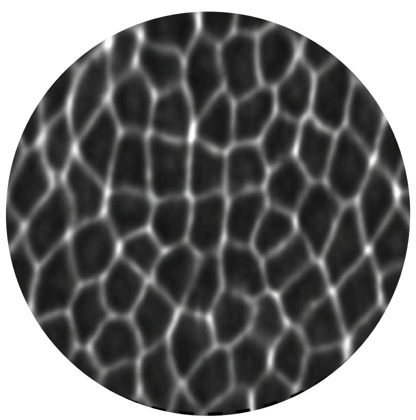
Vertex models

$$A_i = A_i\big(\{r_j^v\}_j\big)$$
$$P_i = P_i\big(\{r_j^v\}_j\big)$$

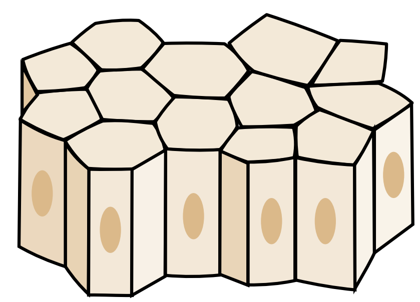


forces are applied on the edge
=> on vertices

mesoscopic



Drosophila, courtesy S. Streichan



chain rule

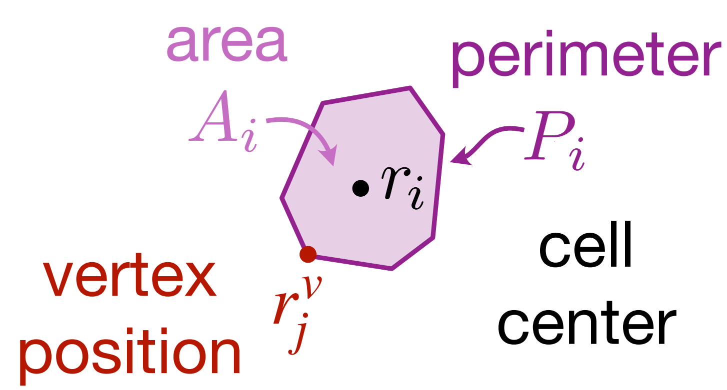
$$\gamma \partial_t \mathbf{r}_i = -\frac{\partial E}{\partial \mathbf{r}_j^v}\frac{\partial r_j^v}{\partial \mathbf{r}_i} = -\frac{\partial E}{\partial \mathbf{r}_i}$$

$$E = \sum_i \left[\frac{K_P}{2}(P_i - P_0)^2 + \frac{K_A}{2}(A_i - A_0)^2\right]$$

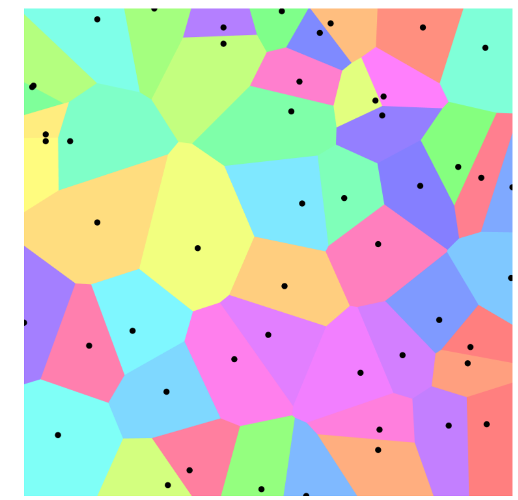
area and perimeter depend on the *vertex positions*

Vertex models

$$A_i = A_i\big(\{r_j^v\}_j\big)$$
$$P_i = P_i\big(\{r_j^v\}_j\big)$$

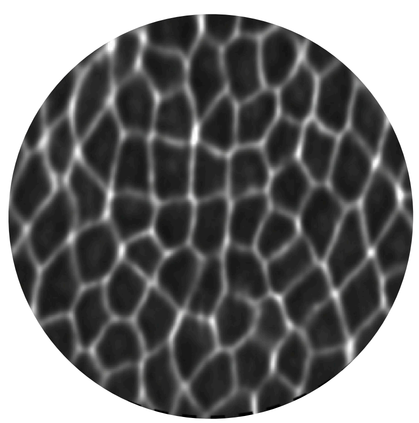


Voronoi tesselation

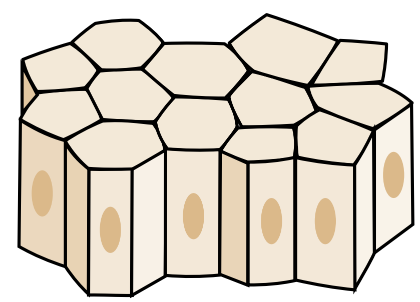


$$\mathbf{r}_j^v\big(\{\mathbf{r}_i\}_i\big)$$

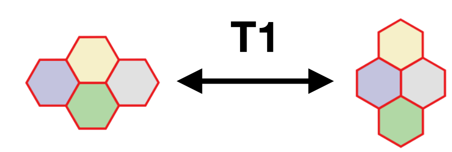
mesoscopic



Drosophila, courtesy S. Streichan



topological transitions

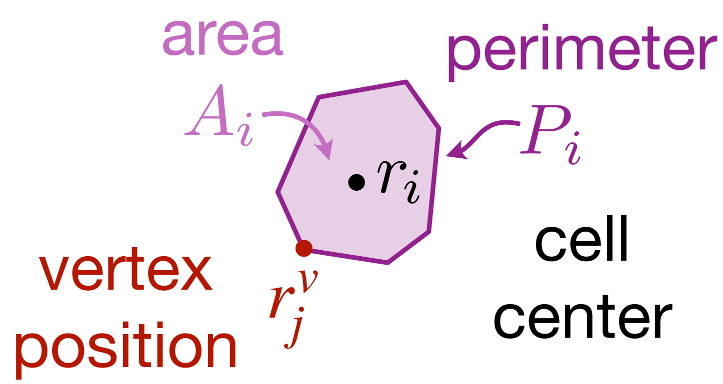


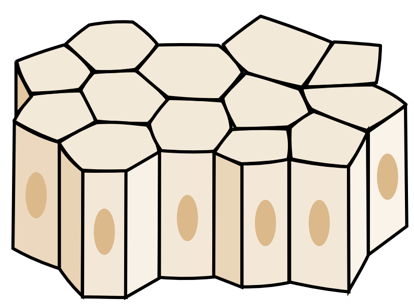
$$\gamma \partial_t \mathbf{r}_i = -\frac{\partial E}{\partial \mathbf{r}_j^v}\frac{\partial r_j^v}{\partial \mathbf{r}_i} = -\frac{\partial E}{\partial \mathbf{r}_i}$$

$$E = \sum_i \left[\frac{K_P}{2}(P_i - P_0)^2 + \frac{K_A}{2}(A_i - A_0)^2\right]$$

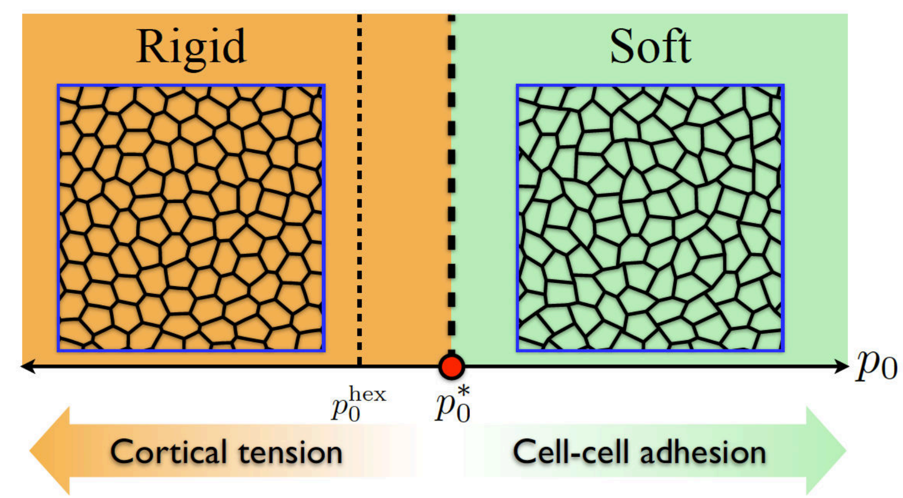
vertex positions can be computed through Voronoi tesselation

Vertex models





rigidity transitions



Bi et al. Nature Phys 11 (2015)

$$\gamma \partial_t \mathbf{r}_i = -\frac{\partial E}{\partial \mathbf{r}_j^v} \frac{\partial r_j^v}{\partial \mathbf{r}_i} = -\frac{\partial E}{\partial \mathbf{r}_i}$$

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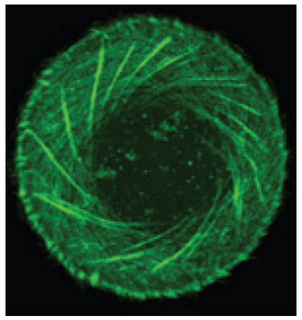
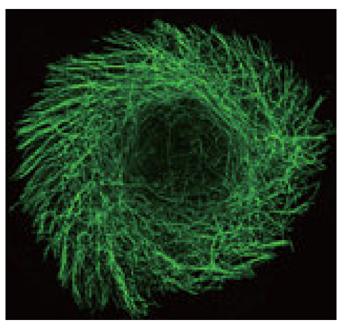
vertex models are minimal models for tissues

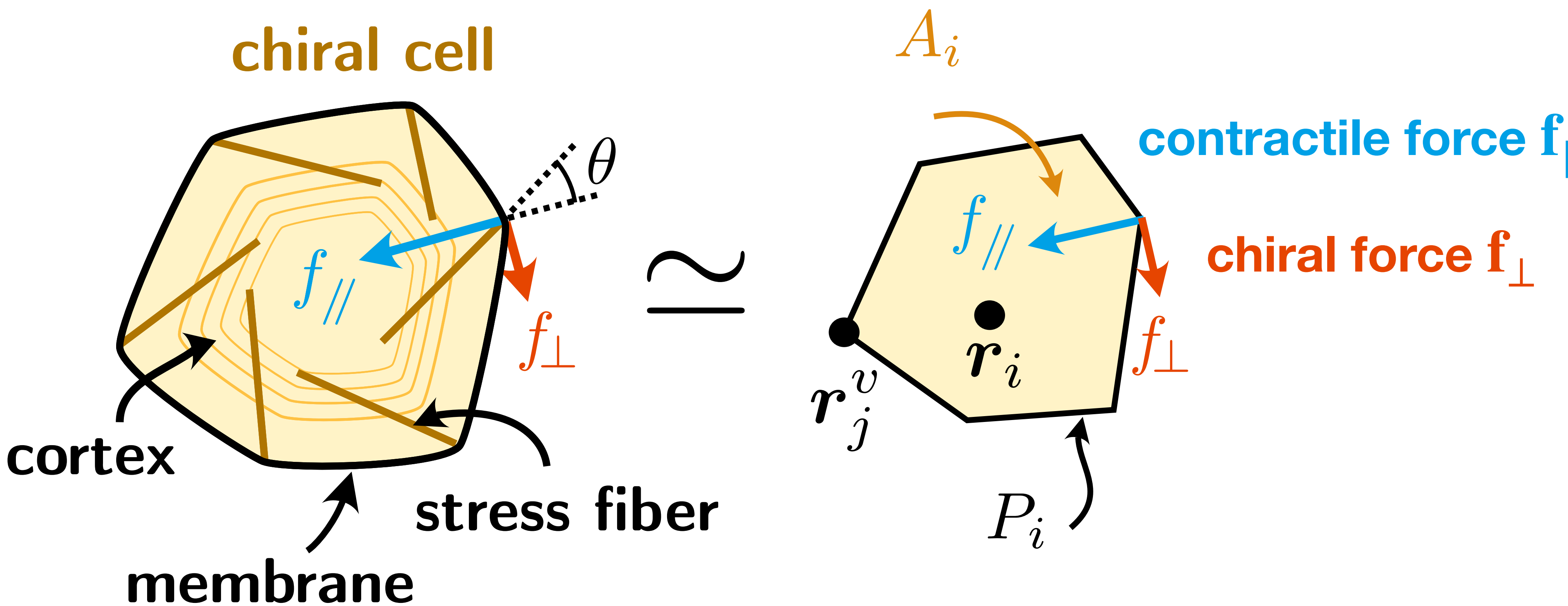
How to model chiral tissues?



Fibroblasts
Tee et al., 2015



Carcinoma
Yamamoto et al., 2025



Sihan Chen

cortical chirality
$\alpha^o = -\tan(\theta)$

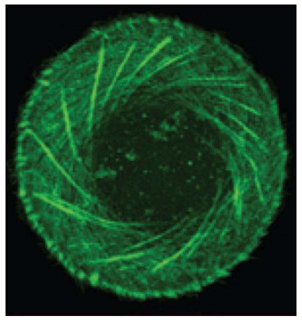
$$\mathbf{f}_\perp = -\,\alpha^o\,\hat{\mathbf{e}}_z \times \mathbf{f}_\parallel$$

non-conservative force from chiral active forces

S. Chen, E. Gökmen, M. Fruchart, M. Krumbein, P. Silberzan, V. Yashunsky and V. Vitelli, arXiv 2506.12276 (2025)

How to model chiral tissues?

cell-level



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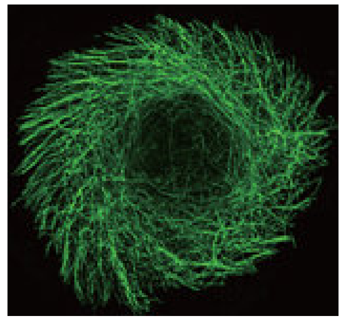

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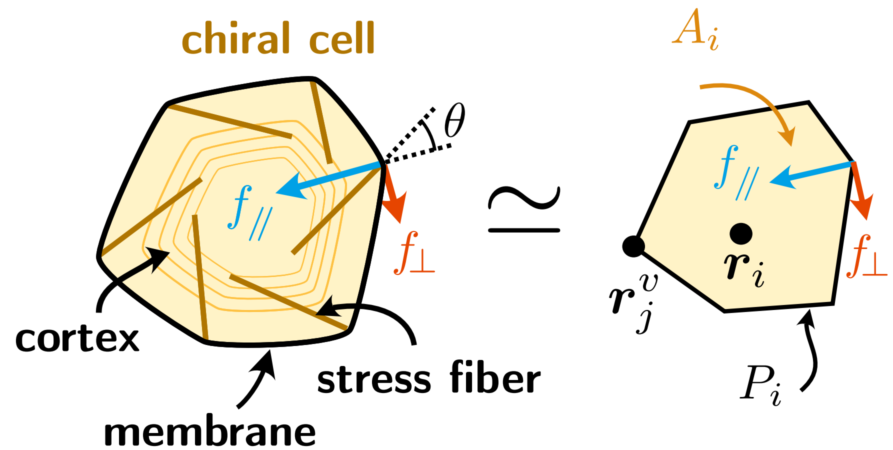
Yamamoto et al., 2025



chiral force

$$\mathbf{f}_{\perp} = -\alpha^o \, \hat{\mathbf{e}}_z \times \mathbf{f}_{\parallel}$$

$$\alpha^o = -\tan(\theta)$$

mesoscopic

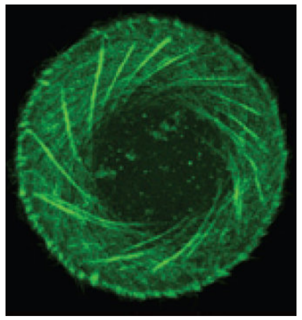
???

how to model non-variational chiral forces in a vertex model?

S. Chen, E. Gökmen, M. Fruchart, M. Krumbein, P. Silberzan, V. Yashunsky and V. Vitelli, arXiv 2506.12276 (2025)

How to model chiral tissues?

cell-level



Fibroblasts
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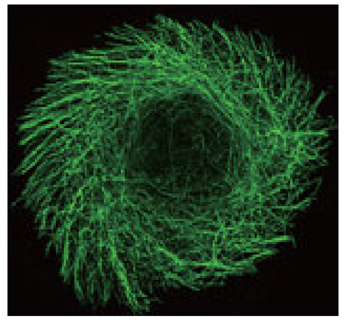

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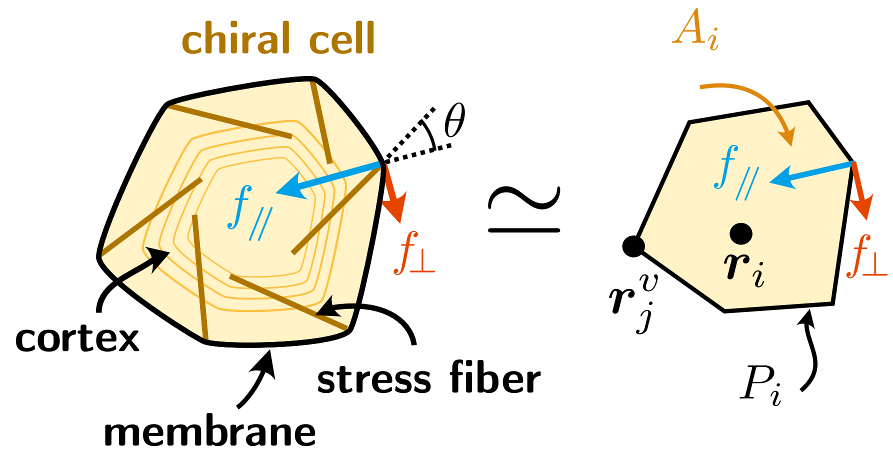

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mesoscopic

$$E = \sum_i \left[\frac{K_P}{2}(P_i - P_0)^2 + \frac{K_A}{2}(A_i - A_0)^2\right] = \sum_i \left[\underbrace{\frac{K_P}{2}P_i^2}_{E_C} + \frac{K_P}{2}P_0(P_0 - 2P_i) + \frac{K_A}{2}(A_i - A_0)^2\right]$$

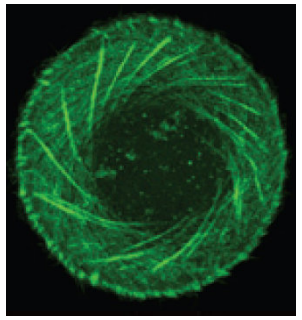
active contractility **cell-cell adhesion** **3D incompressibility**

contractile force $\mathbf{f}_\parallel = -\dfrac{\partial E_C}{\partial \mathbf{r}_j^v}$ **chiral force** $\mathbf{f}_\perp = \alpha^o \hat{\mathbf{e}}_z \times \dfrac{\partial E_C}{\partial \mathbf{r}_j^v}$

S. Chen, E. Gökmen, M. Fruchart, M. Krumbein, P. Silberzan, V. Yashunsky and V. Vitelli, arXiv 2506.12276 (2025)

How to model chiral tissues?

cell-level



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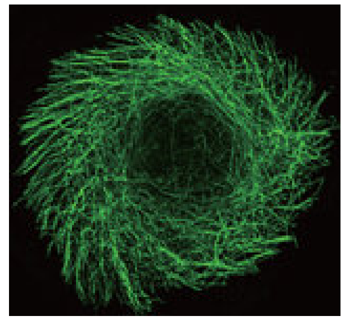
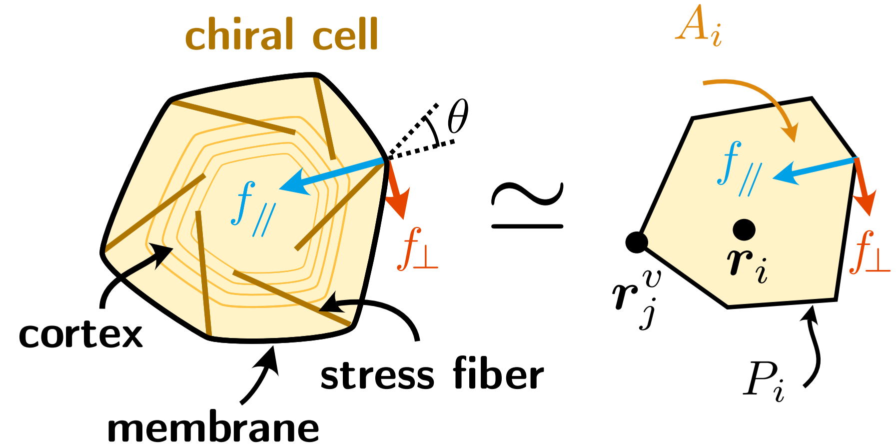


Carcinoma
Yamamoto et al., 2025



chiral force

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$$\alpha^o = -\tan(\theta)$$

mesoscopic

$$E = \sum_i \left[\frac{K_P}{2}(P_i - P_0)^2 + \frac{K_A}{2}(A_i - A_0)^2\right] = \sum_i \Bigg[\underbrace{\frac{K_P}{2}P_i^2}_{E_C} + \frac{K_P}{2}P_0(P_0 - 2P_i) + \frac{K_A}{2}(A_i - A_0)^2\Bigg]$$

contractile force $\mathbf{f}_\parallel = -\dfrac{\partial E_C}{\partial \mathbf{r}_j^v}$ chiral force $\mathbf{f}_\perp = \alpha^o \hat{\mathbf{e}}_z \times \dfrac{\partial E_C}{\partial \mathbf{r}_j^v}$

$$\gamma \partial_t \mathbf{r}_i = \sum_j \left[-\frac{\partial E}{\partial \mathbf{r}_j^v} + \alpha^o \hat{\mathbf{e}}_z \times \frac{\partial E_C}{\partial \mathbf{r}_j^v}\right] \cdot \frac{\partial \mathbf{r}_j^v}{\partial \mathbf{r}_i}$$

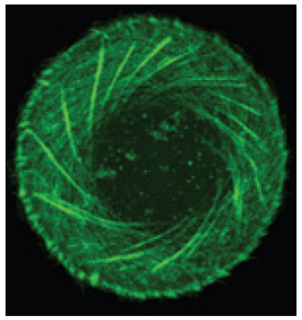
chain rule
does not save you here

chiral nonvariational extension of the vertex model

S. Chen, E. Gökmen, M. Fruchart, M. Krumbein, P. Silberzan, V. Yashunsky and V. Vitelli, arXiv 2506.12276 (2025)

How to model chiral tissues?

cell-level



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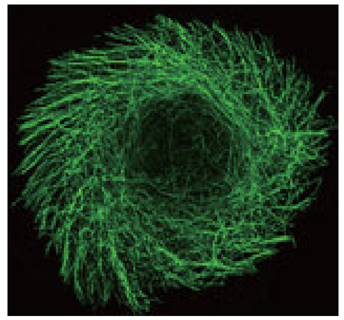
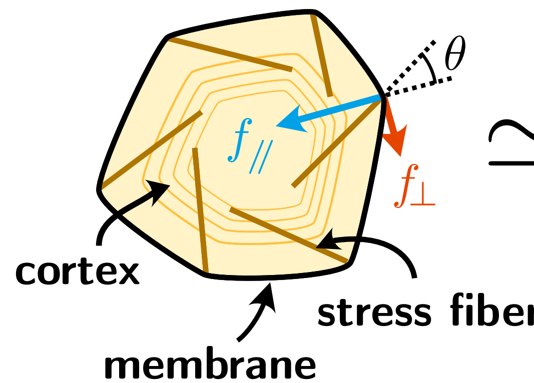
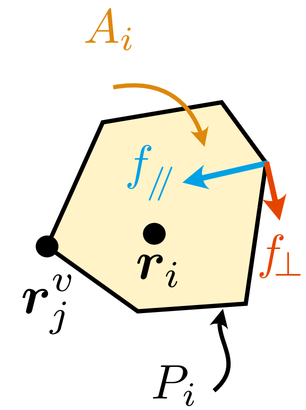


Carcinoma
Yamamoto et al., 2023



$\simeq$



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mesoscopic

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$$\gamma \partial_t \mathbf{r}_i = \sum_j \left[-\frac{\partial E}{\partial \mathbf{r}_j^v} + \alpha^o \hat{\mathbf{e}}_z \times \frac{\partial E_C}{\partial \mathbf{r}_j^v} \right] \cdot \frac{\partial \mathbf{r}_j^v}{\partial \mathbf{r}_i}$$

coarse-graining

continuum

$\mathbf{u}(\mathbf{r}, t)$ $\quad \sigma(\mathbf{r}, t)$

$$\zeta \partial_t \boldsymbol{u} = -\boldsymbol{\nabla} P + [(\mu + \eta \partial_t) + (K^{\mathrm{o}} + \eta^{\mathrm{o}} \partial_t)\boldsymbol{\epsilon}] \Delta \boldsymbol{u}$$
$$+ [(B + \eta^B \partial_t) - (A + \eta^A \partial_t)\boldsymbol{\epsilon}] \boldsymbol{\nabla}(\boldsymbol{\nabla} \cdot \boldsymbol{u}).$$

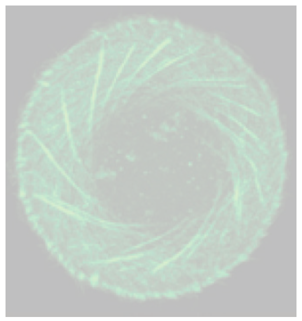
review on odd vicosity/elasticity
Fruchart, Scheibner, Vitelli, Annual Reviews of Condensed Matter Physics 14 (2023)

chiral tissues as odd viscoelastic media in the continuum

S. Chen, E. Gökmen, M. Fruchart, M. Krumbein, P. Silberzan, V. Yashunsky and V. Vitelli, arXiv 2506.12276 (2025)

How to model chiral tissues?

cell-level



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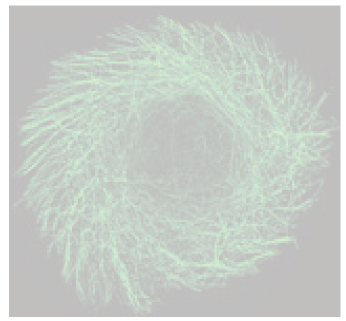
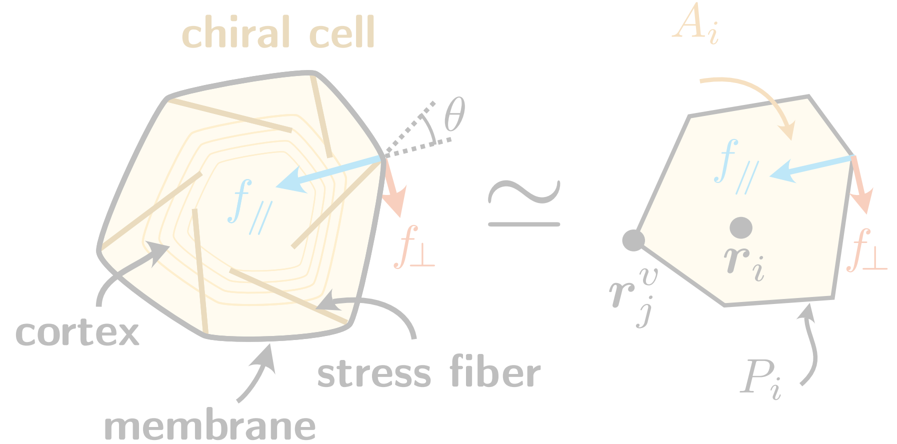
Tee et al., 2015



Carcinoma
Yamamoto et al., 2023



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mesoscopic

$$E = \sum_i \left[\overbrace{\frac{K_P}{2} P_i^2}^{E_C} + \frac{K_P}{2} P_0(P_0 - 2P_i) + \frac{K_A}{2}(A_i - A_0)^2 \right]$$

$$\gamma \partial_t \mathbf{r}_i = \sum_j \left[-\frac{\partial E}{\partial \mathbf{r}_j^v} + \alpha^o \hat{\mathbf{e}}_z \times \frac{\partial E_C}{\partial \mathbf{r}_j^v} \right] \cdot \frac{\partial \mathbf{r}_j^v}{\partial \mathbf{r}_i}$$

continuum

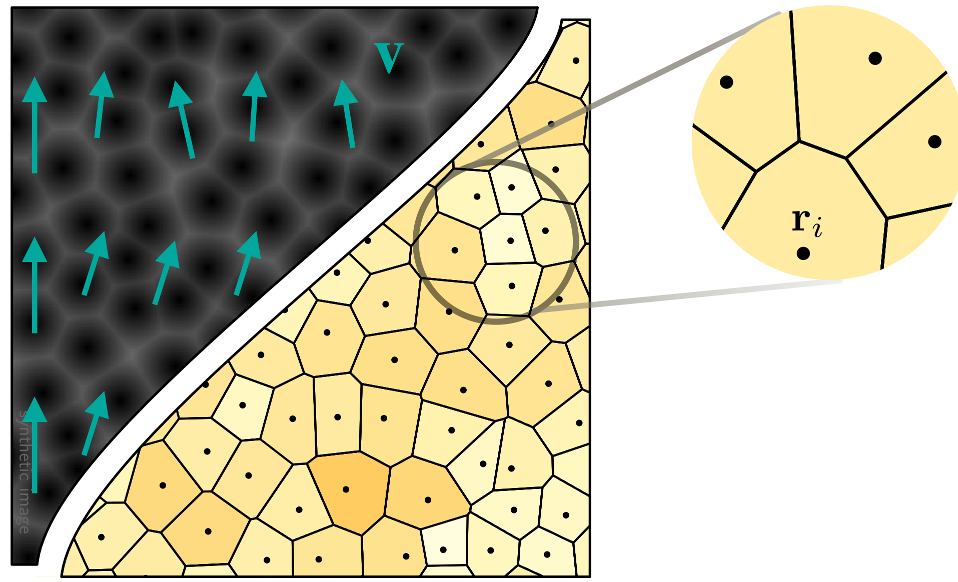
$\mathbf{u}(\mathbf{r}, t)$ $\sigma(\mathbf{r}, t)$

$$\zeta \partial_t \boldsymbol{u} = -\nabla P + [(\mu + \eta\partial_t) + (K^o + \eta^o \partial_t)\boldsymbol{\epsilon}]\Delta \boldsymbol{u} + [(B + \eta^B \partial_t) - (A + \eta^A \partial_t)\boldsymbol{\epsilon}]\nabla(\nabla \cdot \boldsymbol{u}).$$

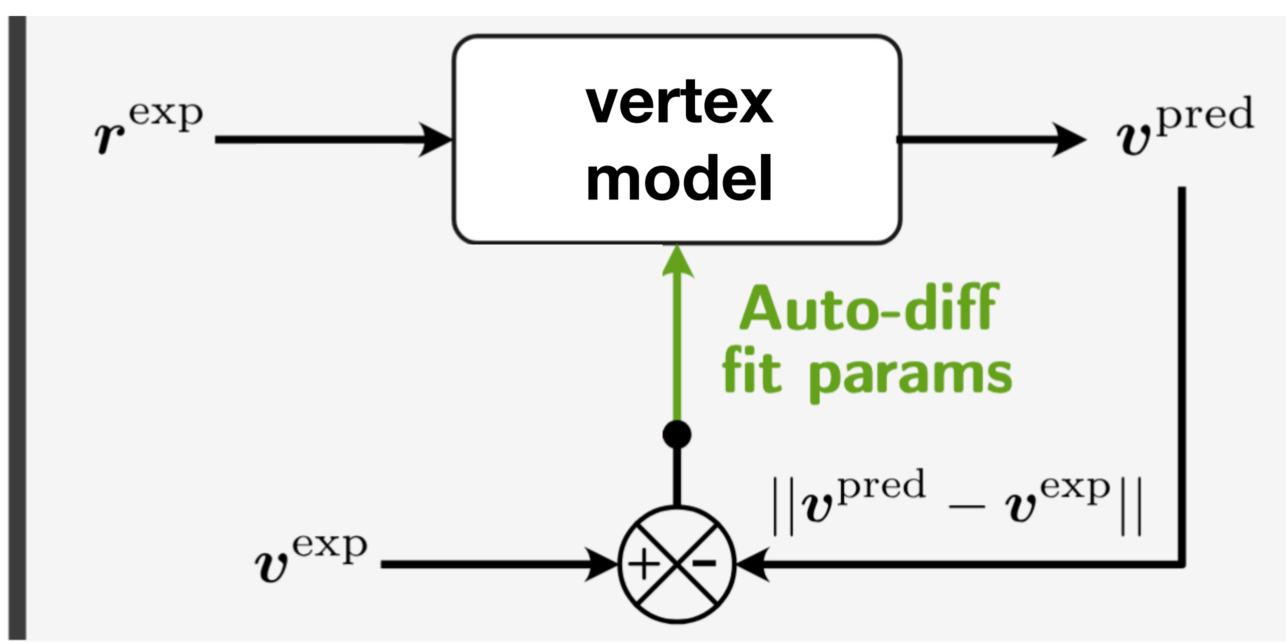
¿how to measure parameters from noisy experimental data of living tissues?

S. Chen, E. Gökmen, M. Fruchart, M. Krumbein, P. Silberzan, V. Yashunsky and V. Vitelli, arXiv 2506.12276 (2025)

Let us fit the parameters!



$$E = \sum_i \left[\overbrace{\frac{K_P}{2} P_i^2}^{E_C} + \frac{K_P}{2} P_0 (P_0 - 2P_i) + \frac{K_A}{2} (A_i - A_0)^2 \right] \qquad \gamma \partial_t \mathbf{r}_i = \sum_j \left[-\frac{\partial E}{\partial \mathbf{r}_j^v} + \alpha^o \hat{\mathbf{e}}_z \times \frac{\partial E_C}{\partial \mathbf{r}_j^v} \right] \cdot \frac{\partial \mathbf{r}_j^v}{\partial \mathbf{r}_i}$$

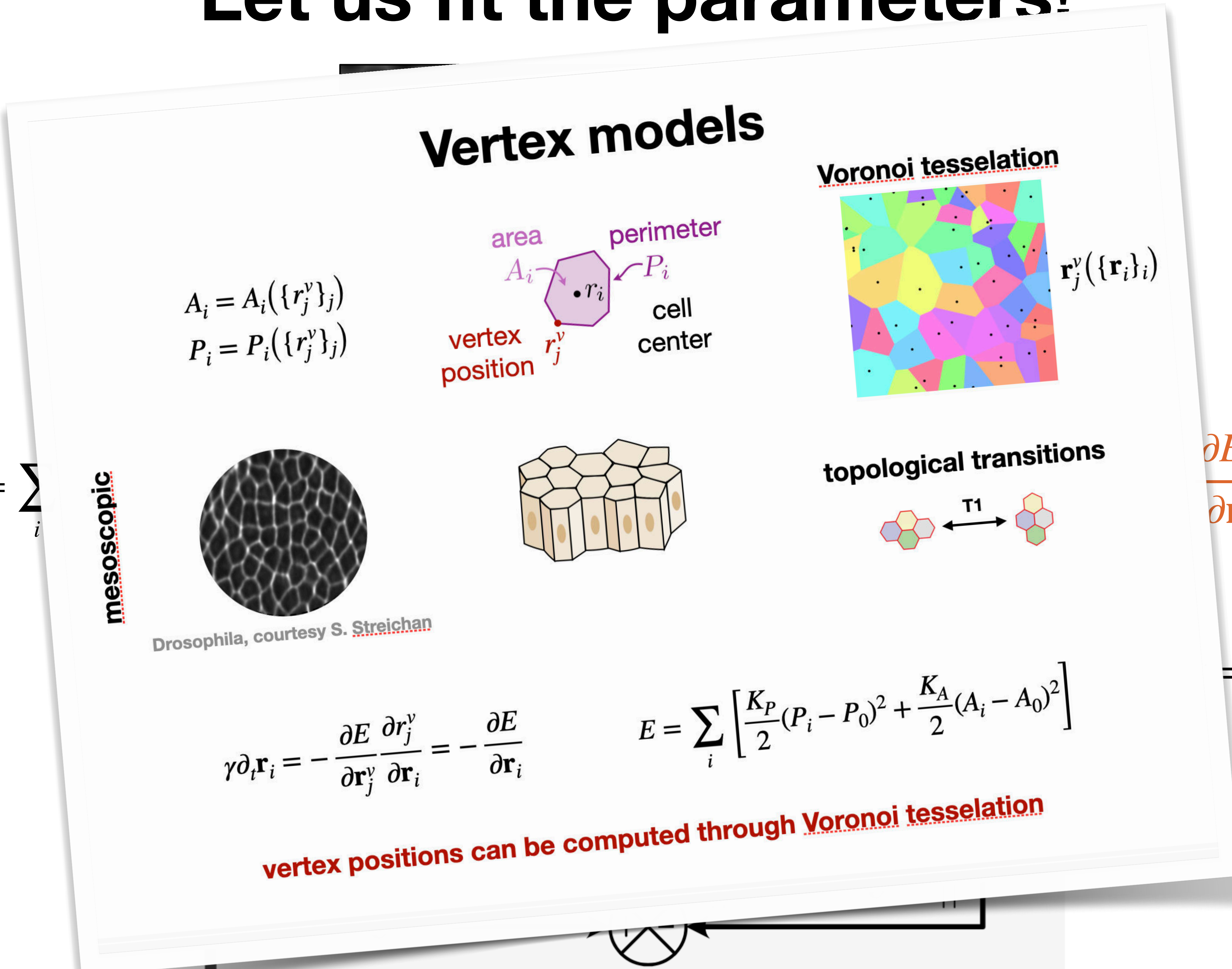


$$\mathbf{v} = \partial_t \mathbf{r}$$

there is just one problem...

Let us fit the parameters!

$E = \sum_i$

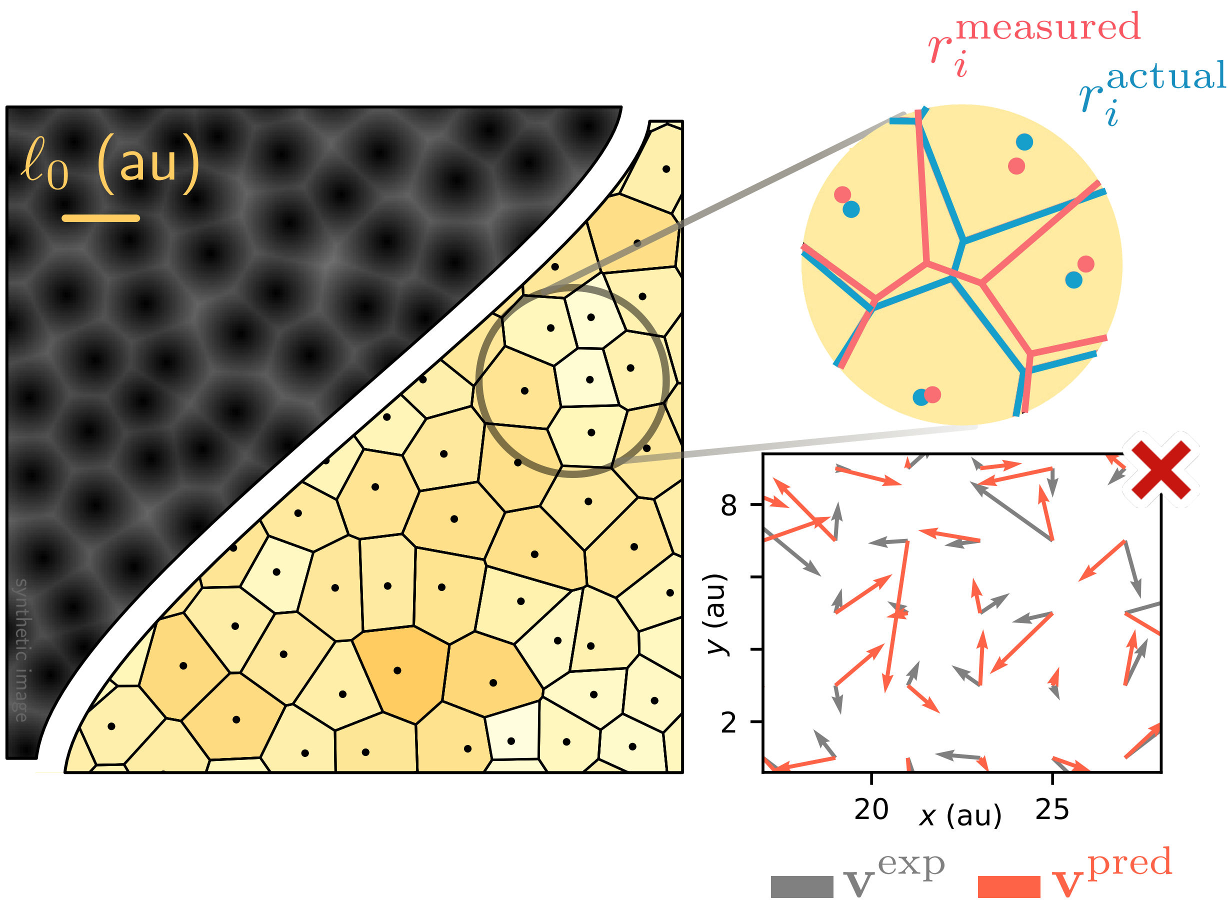


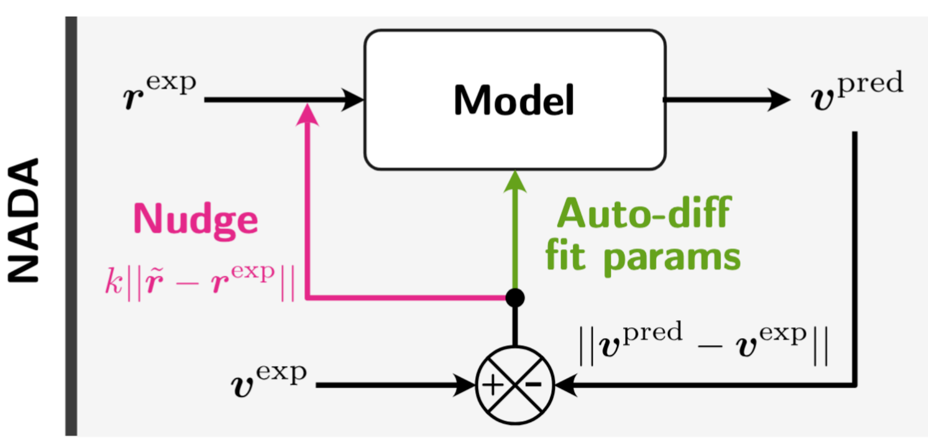
$\left.\frac{\partial E_C}{\partial \mathbf{r}_j^v}\right] \cdot \frac{\partial \mathbf{r}_j^v}{\partial \mathbf{r}_i}$

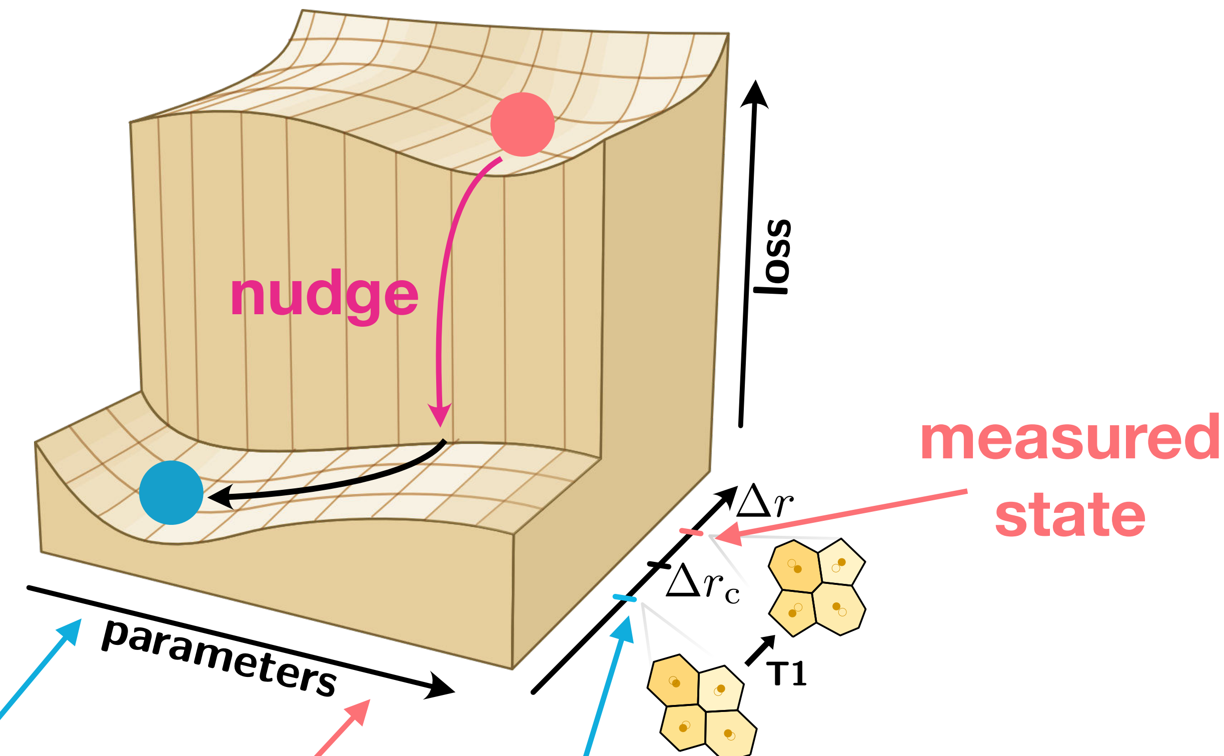
$= \partial_t \mathbf{r}$

...spurious topological transitions screw up the optimization :(

On the dark side of the topological transition







actual parameters

inferred parameters

actual state

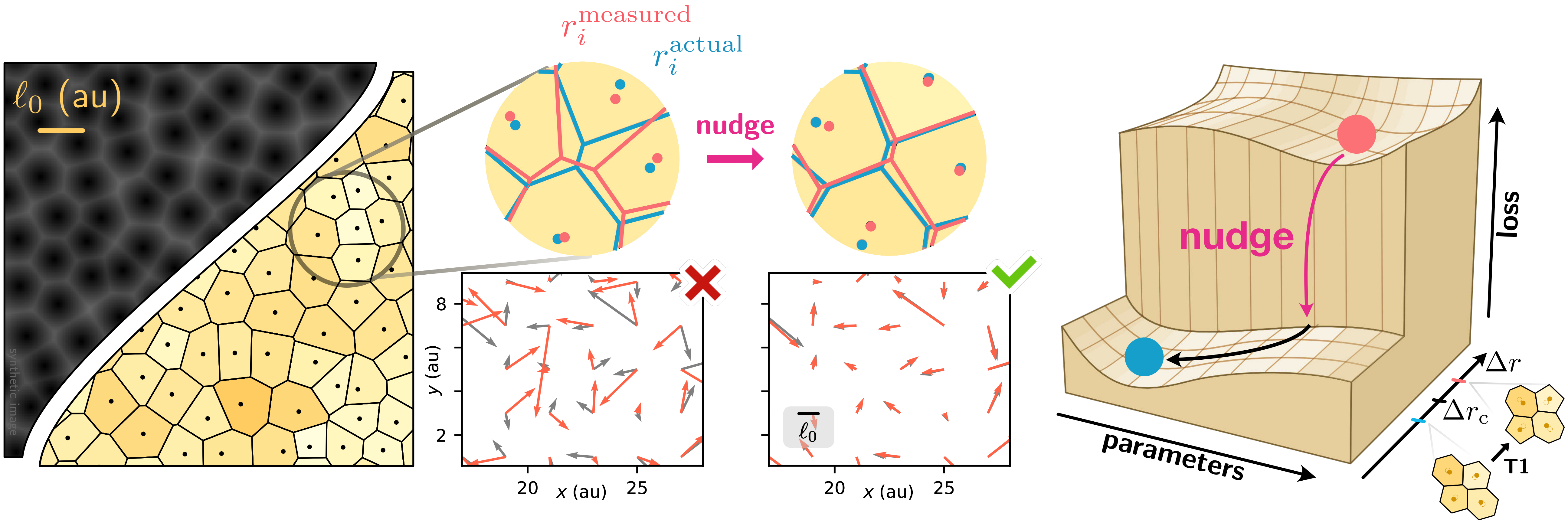
Efe Gökmen

(we make sure to only nudge within uncertainty!)

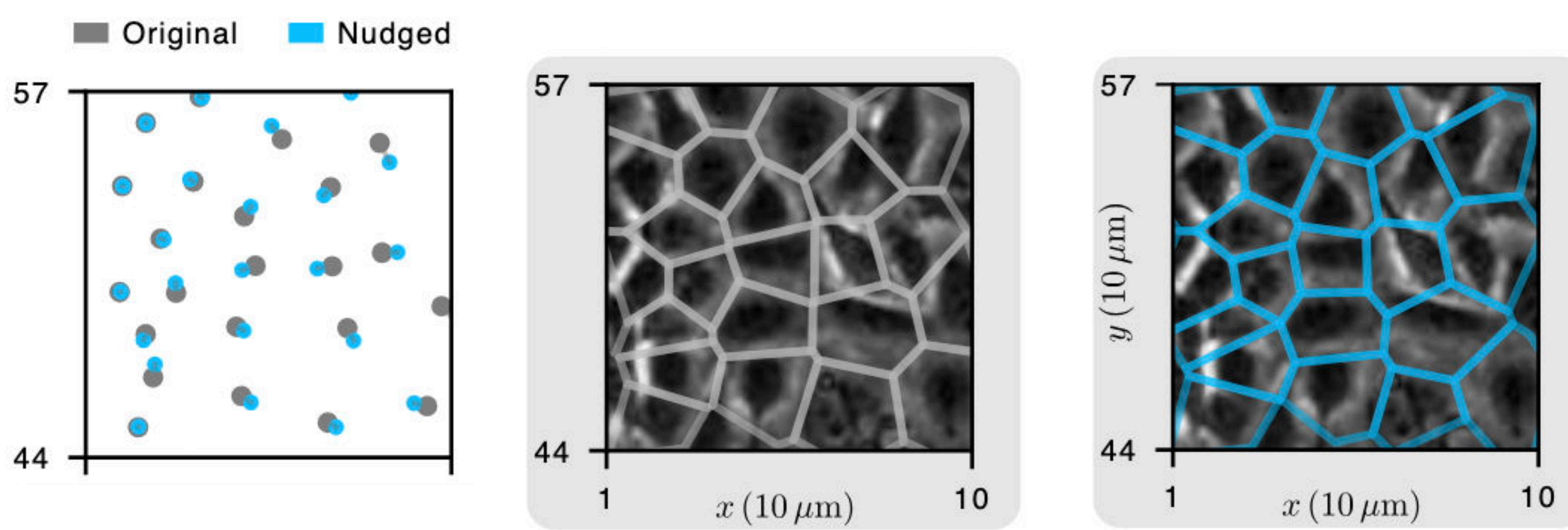
fit data to model **to fit model to data**

S. Chen, E. Gökmen, M. Fruchart, M. Krumbein, P. Silberzan, V. Yashunsky and V. Vitelli, arXiv 2506.12276 (2025)

On the dark side of the topological transition



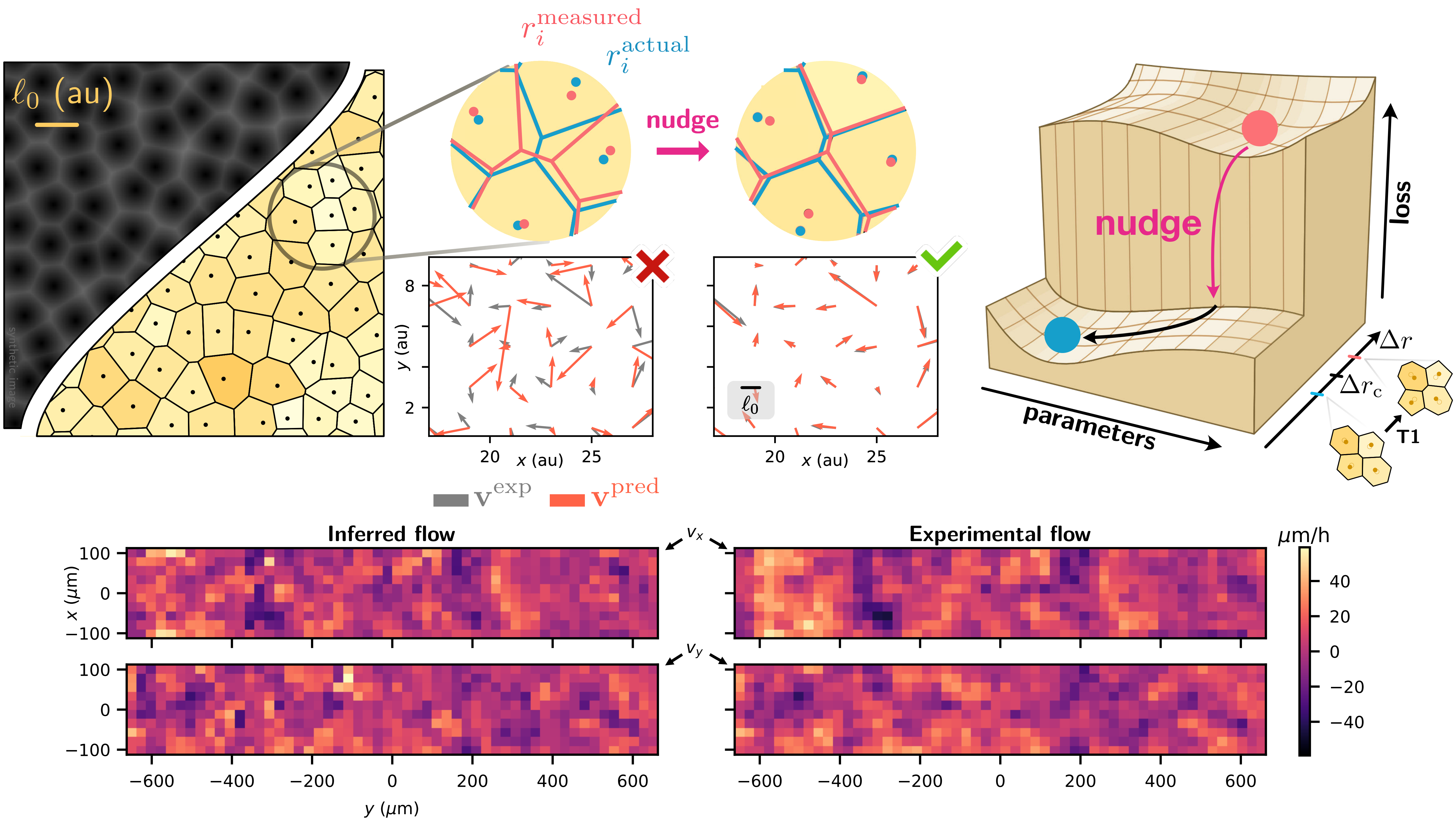
how it looks
on actual data



fix spurious topological transitions due to measurement errors by nudging data

S. Chen, E. Gökmen, M. Fruchart, M. Krumbein, P. Silberzan, V. Yashunsky and V. Vitelli, arXiv 2506.12276 (2025)

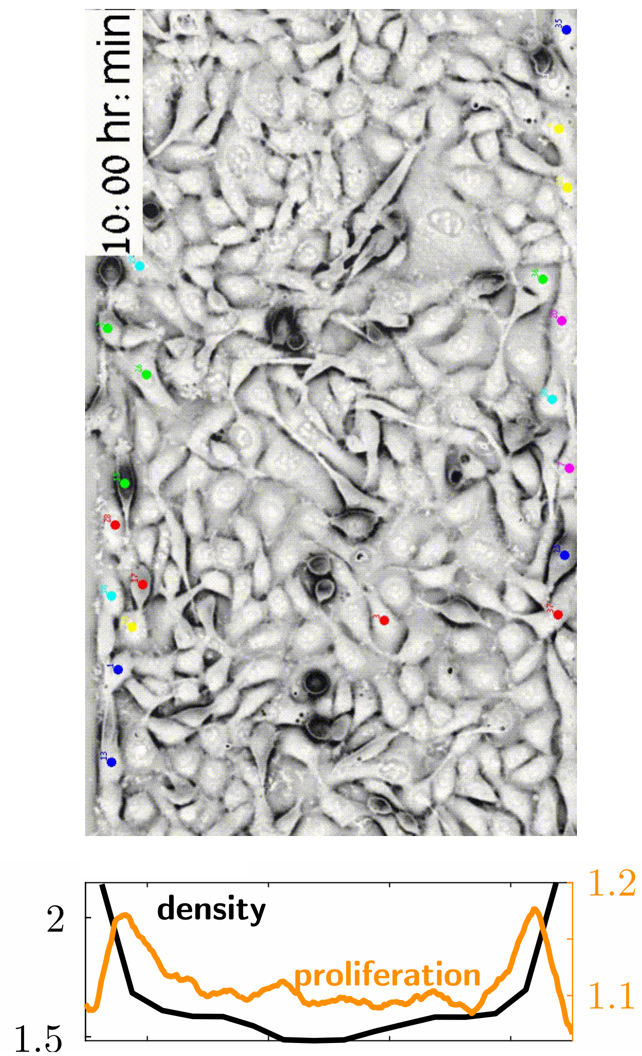
On the dark side of the topological transition

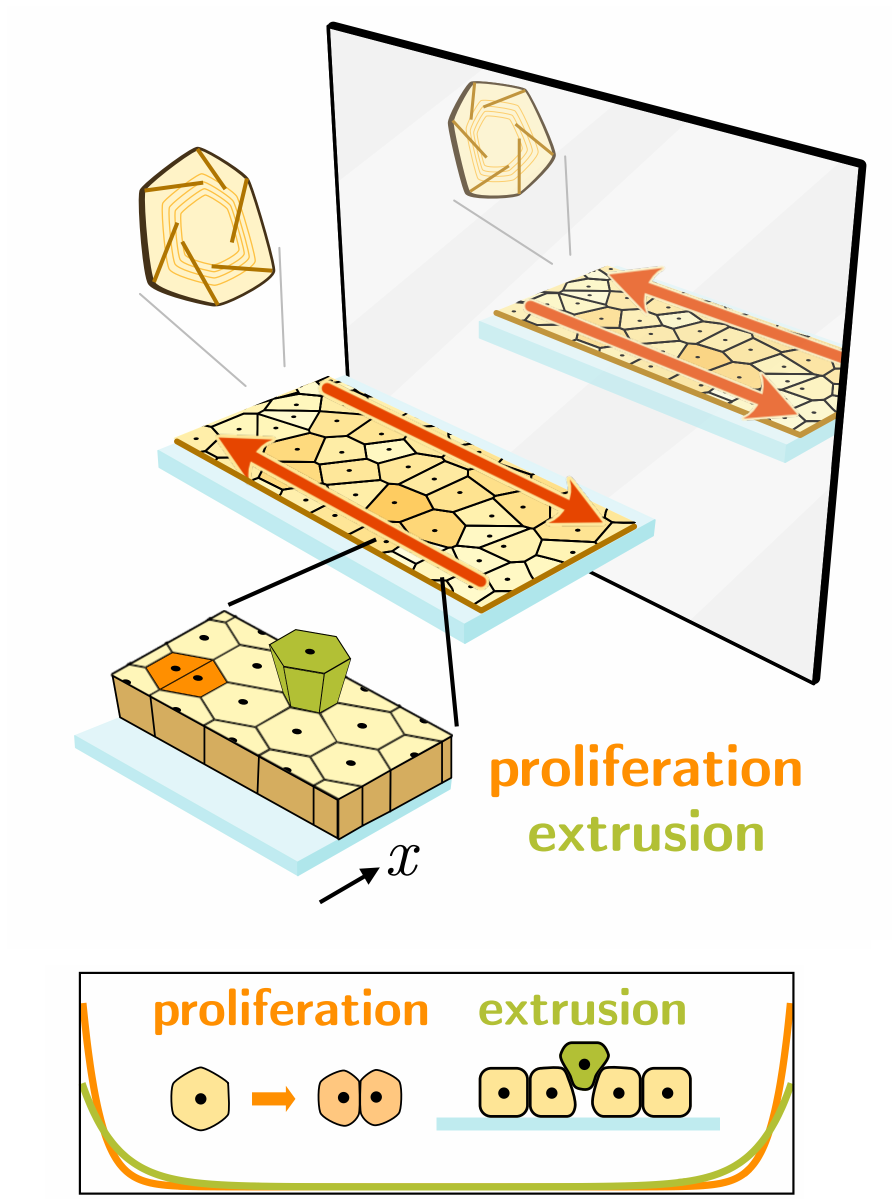


flow inferred from cell positions with nudge-optimized model fits experimental flow

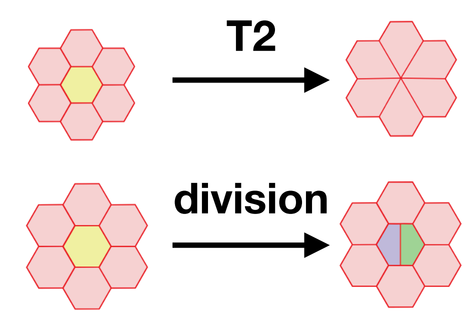
S. Chen, E. Gökmen, M. Fruchart, M. Krumbein, P. Silberzan, V. Yashunsky and V. Vitelli, arXiv 2506.12276 (2025)

Cells divide





mesoscopic



continuum

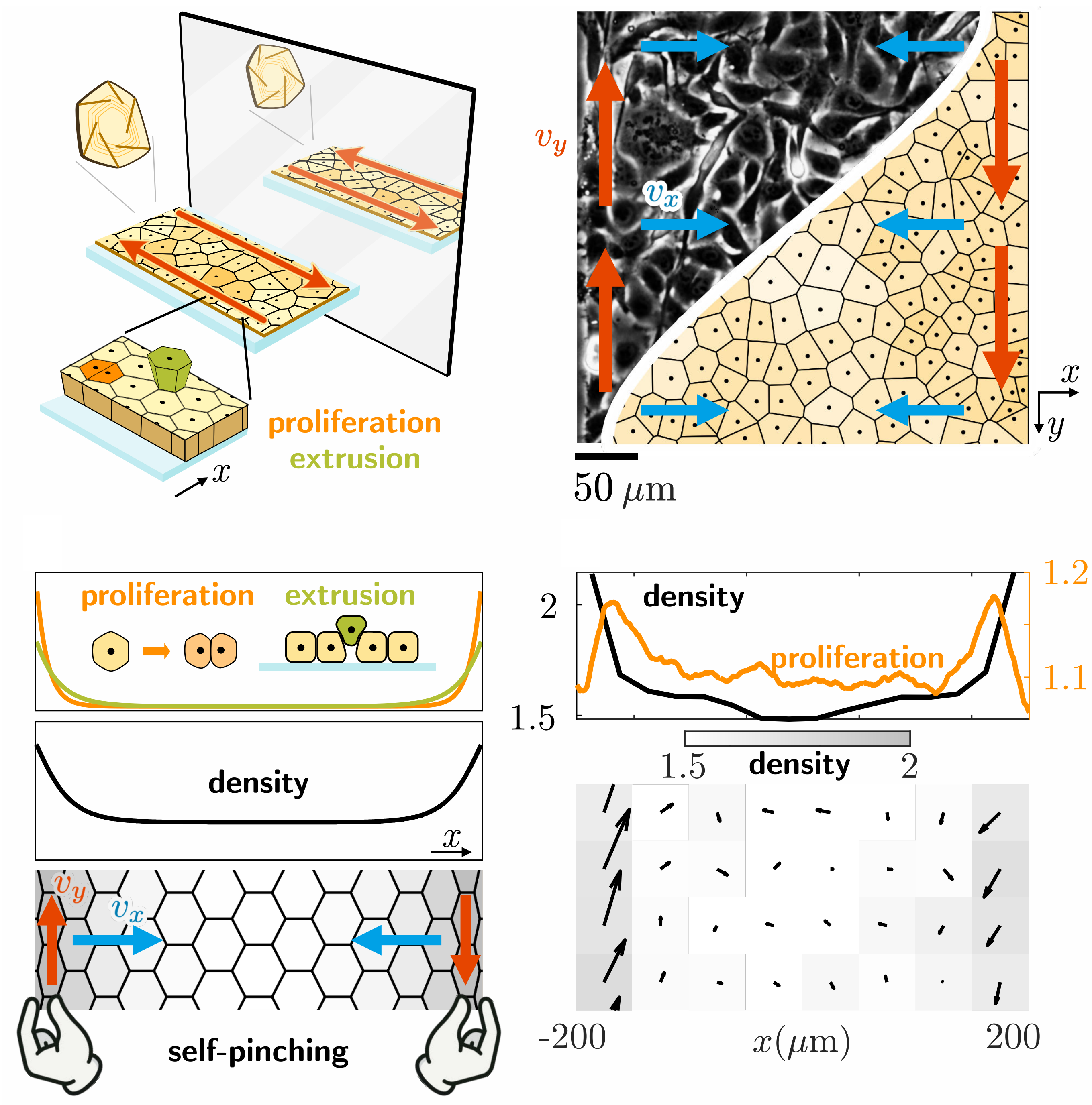
$$\partial_t \rho + \nabla \cdot [\rho \boldsymbol{v}] = [k_{\text{prolif}}(\boldsymbol{r}) - k_{\text{extr}}(\boldsymbol{r})]\rho$$

see e.g.
Hallatschek et al., Nat Rev Phys (2023)

inhomogeneous proliferation and extrusion near walls

S. Chen, E. Gökmen, M. Fruchart, M. Krumbein, P. Silberzan, V. Yashunsky and V. Vitelli, arXiv 2506.12276 (2025)

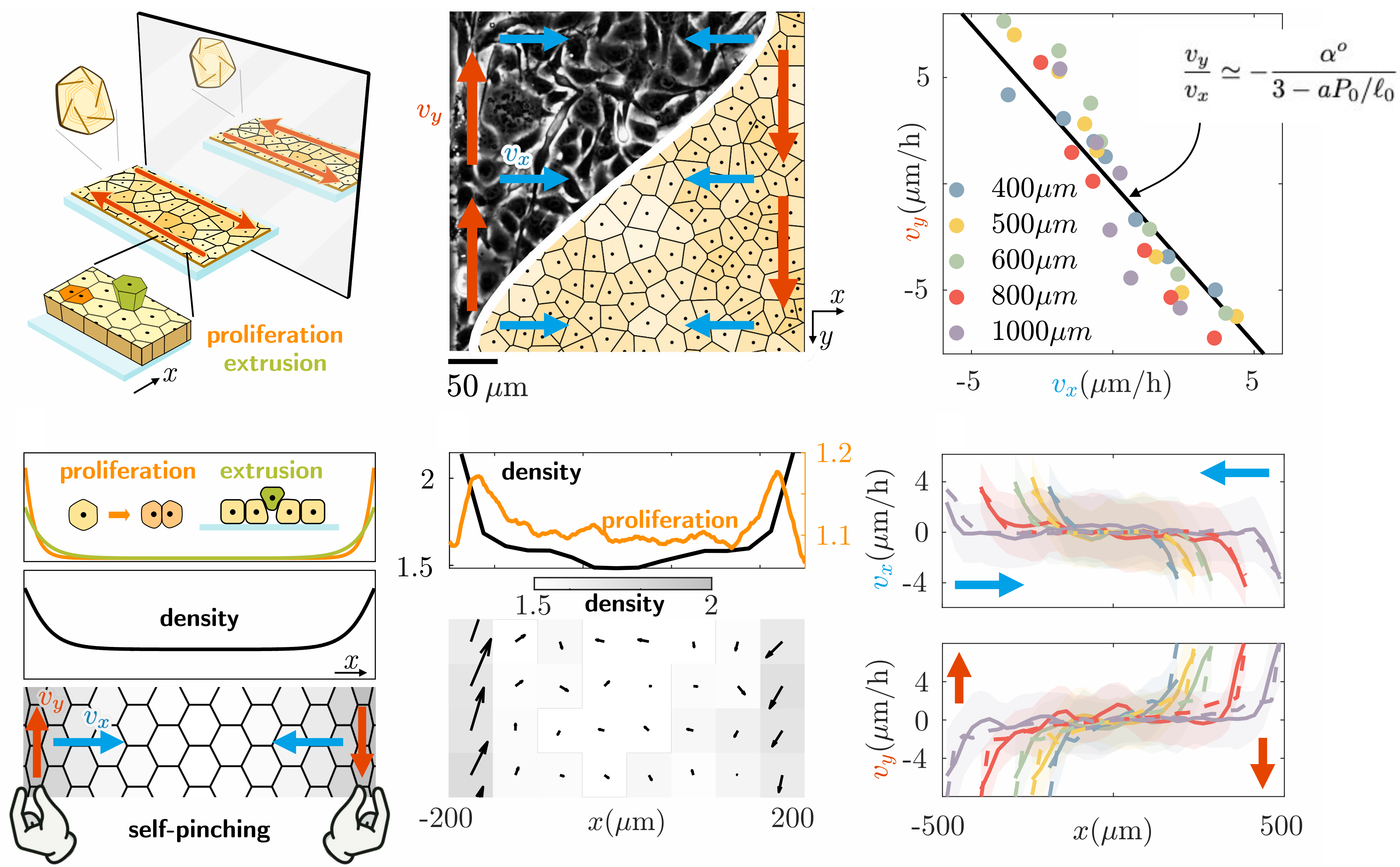
From self-pinching to chiral edge flow



self-pinching causes transverse flows via chiral response

S. Chen, E. Gökmen, M. Fruchart, M. Krumbein, P. Silberzan, V. Yashunsky and V. Vitelli, arXiv 2506.12276 (2025)

From self-pinching to chiral edge flow

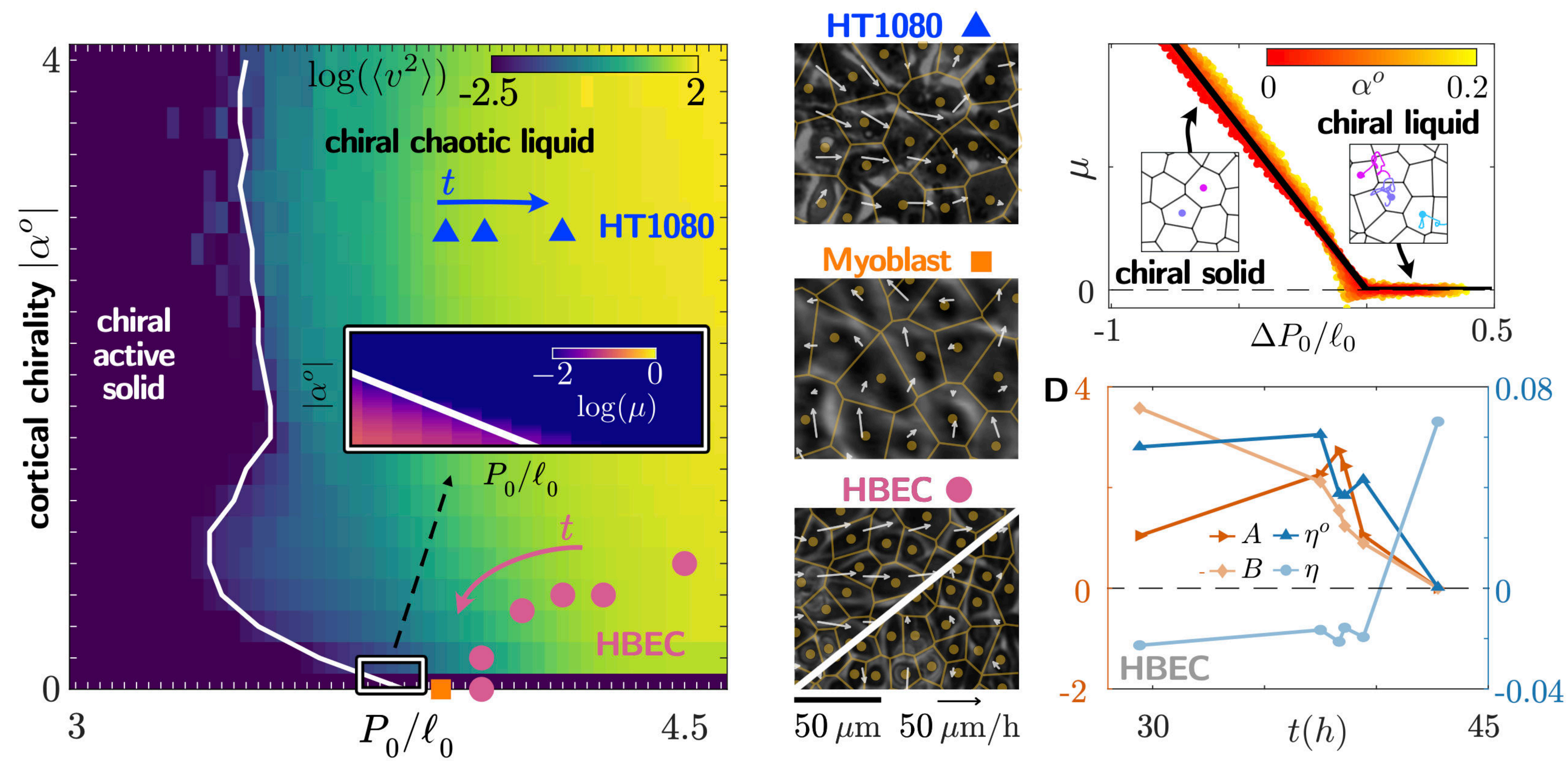


parameters like α_o are measured in the bulk, far from boundaries

agreement between theory and experiment

S. Chen, E. Gökmen, M. Fruchart, M. Krumbein, P. Silberzan, V. Yashunsky and V. Vitelli, arXiv 2506.12276 (2025)

Measuring viscoelastic moduli



continuum

$\mathbf{u}(\mathbf{r},t)$ $\sigma(\mathbf{r},t)$

$\rho(\mathbf{r},t)$

$$\zeta\partial_t \boldsymbol{u} = -\boldsymbol{\nabla} P + [(\mu+\eta\partial_t) + (K^o+\eta^o\partial_t)\boldsymbol{\epsilon}]\Delta\boldsymbol{u} + [(B+\eta^B\partial_t) - (A+\eta^A\partial_t)\boldsymbol{\epsilon}]\boldsymbol{\nabla}(\boldsymbol{\nabla}\cdot\boldsymbol{u}).$$

odd viscoelasticity

$$\partial_t\rho + \nabla\cdot[\rho\boldsymbol{v}] = [k_{\mathrm{prolif}}(\boldsymbol{r}) - k_{\mathrm{extr}}(\boldsymbol{r})]\rho$$

inhomogeneous proliferation

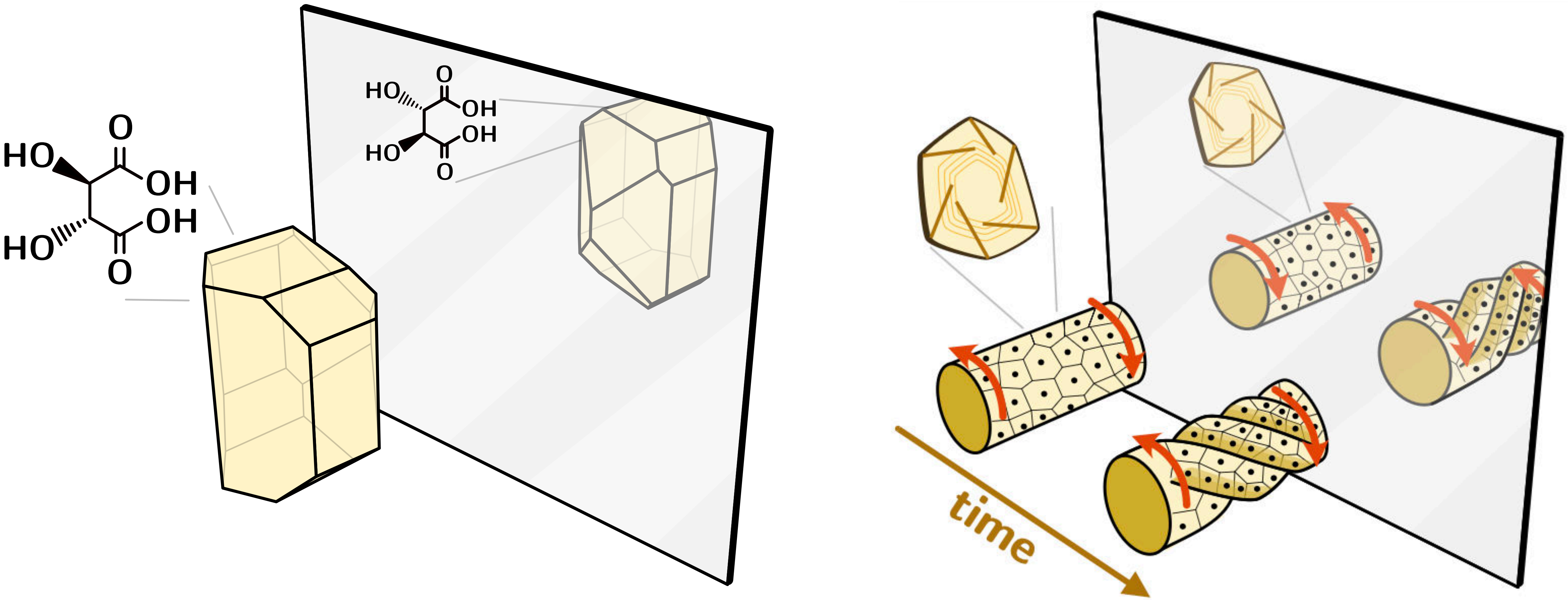
moduli can be time-dependent

S. Chen, E. Gökmen, M. Fruchart, M. Krumbein, P. Silberzan, V. Yashunsky and V. Vitelli, arXiv 2506.12276 (2025)

Chirality across scales in tissue dynamics

S. Chen, E. Gökmen, M. Fruchart, M. Krumbein, P. Silberzan, V. Yashunsky and V. Vitelli

https://arxiv.org/abs/2506.12276



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