Chirality across scales from tissues to turbulence

Michel Fruchart

ESPCI PARIS | PSL cnrs

MAX PLANCK INSTITUTE FOR DYNAMICS AND SELF-ORGANIZATION

Living Matter Physics

LMP Seminar

The seminar will be starting soon...

MAX PLANCK SCHOOL matter to life

LMP Seminars

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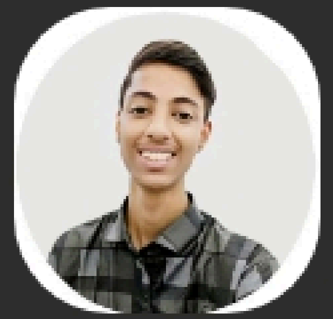
LMP Seminars

Participants (4)

 Naman Dixit (me)

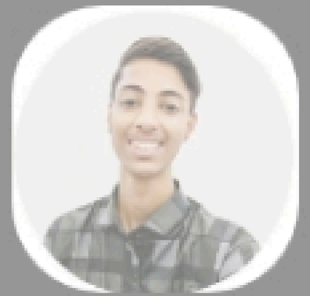
LMP Seminars (Host)

RB Robin Barta

 Yuto Hosaka (保阪 悠人)

Invite

Participants (4)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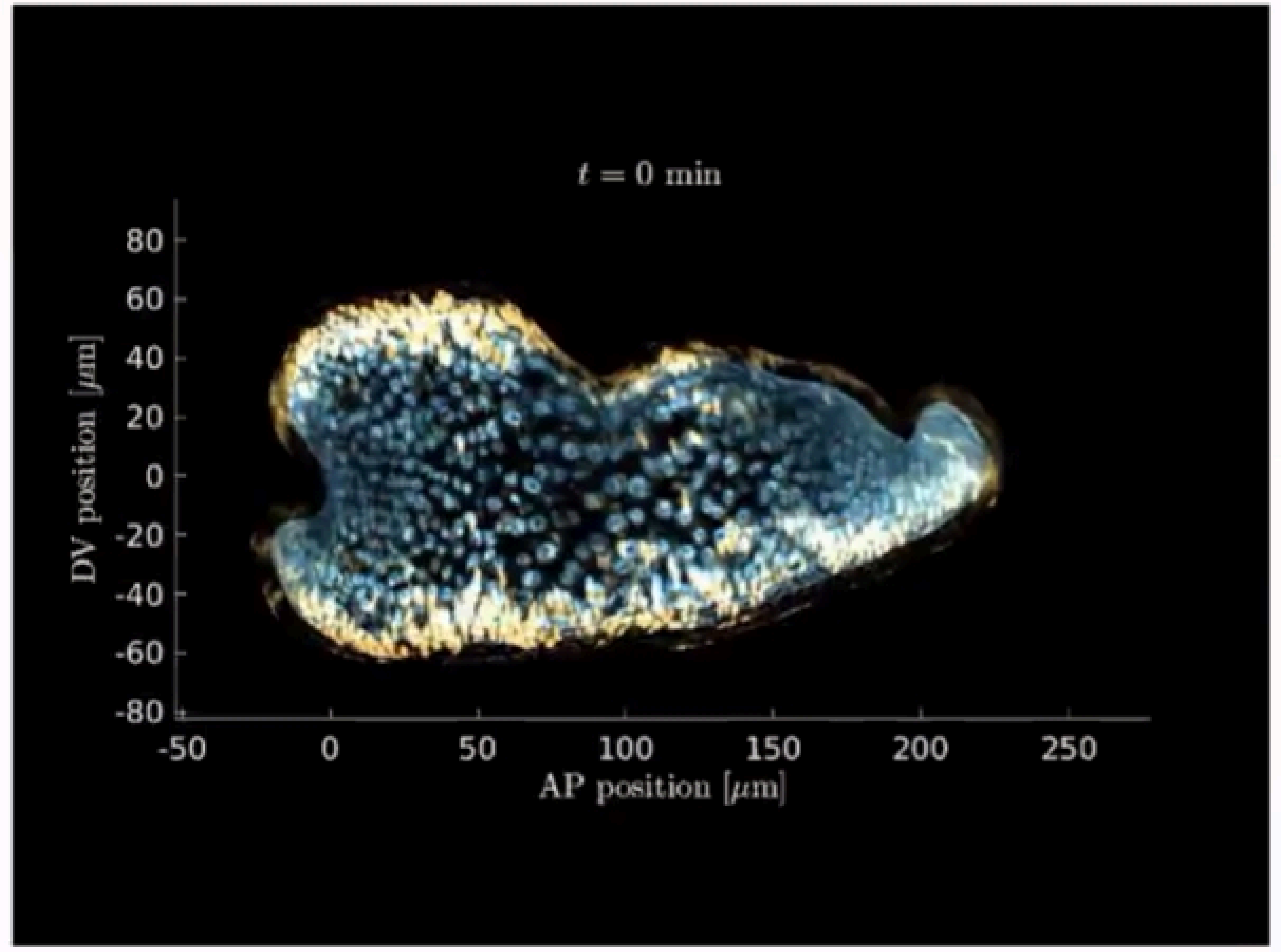
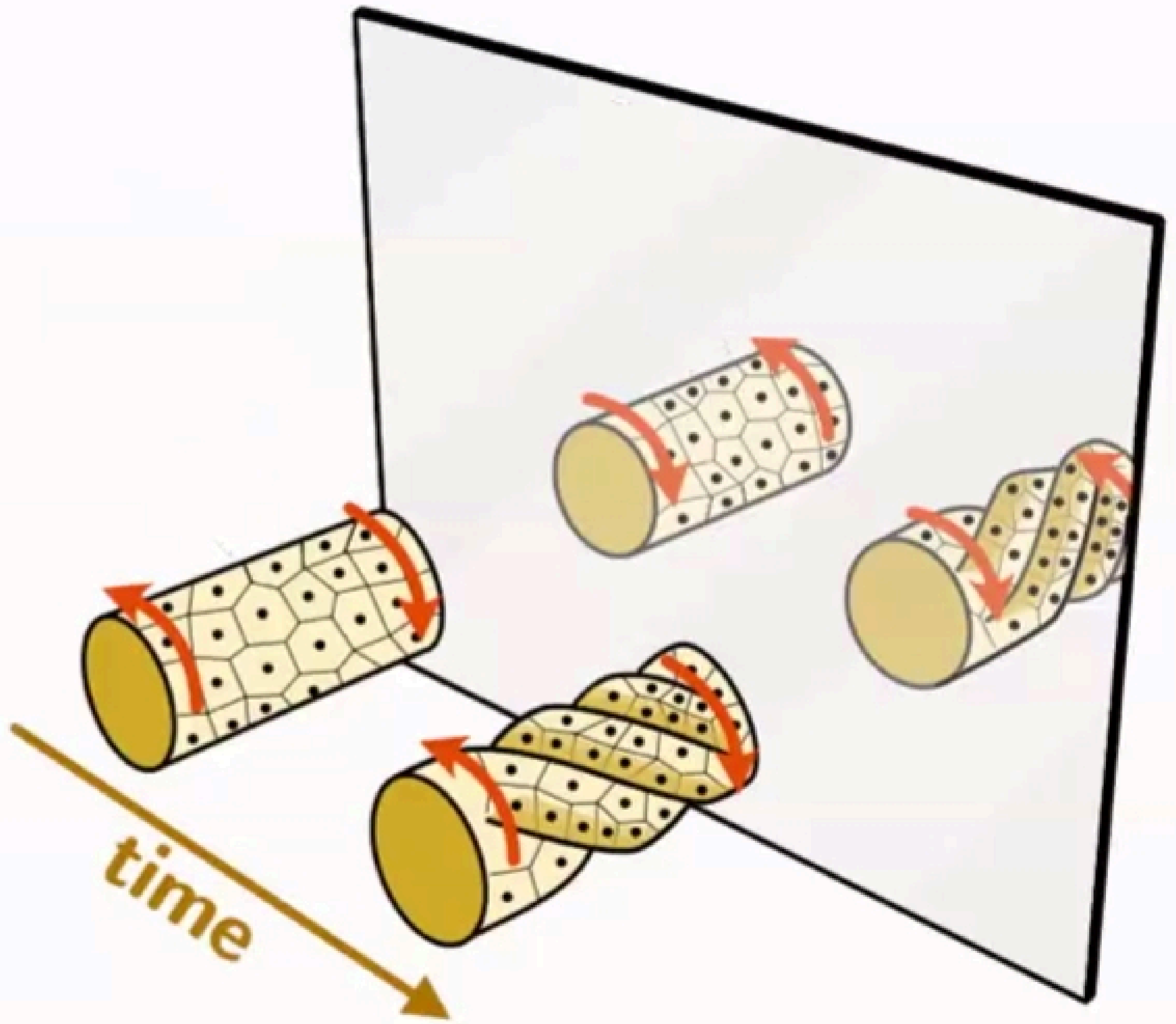
Chirality across scales in tissue dynamics

LMP Seminars



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

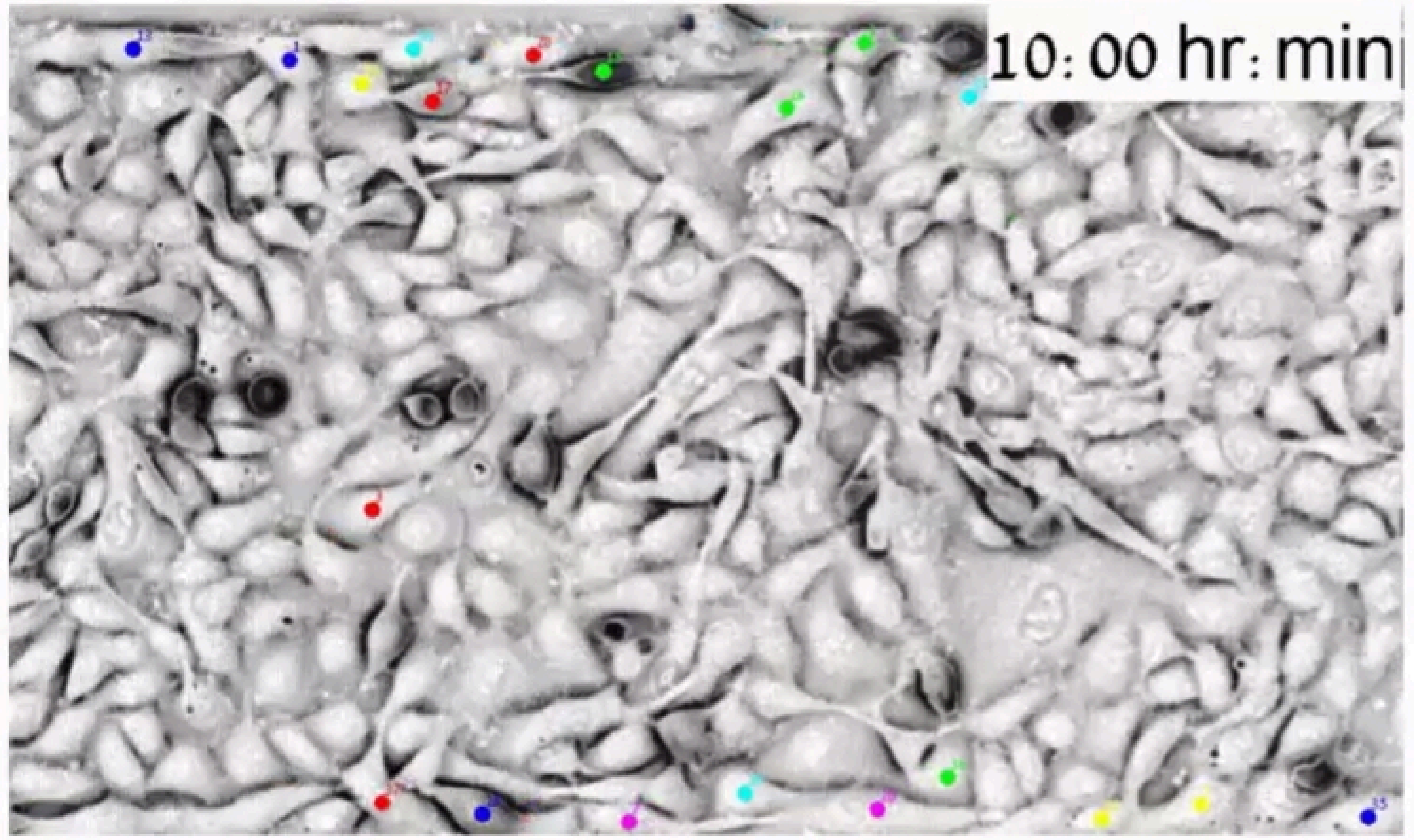


¿how does chirality propagate across scales in biological tissues?

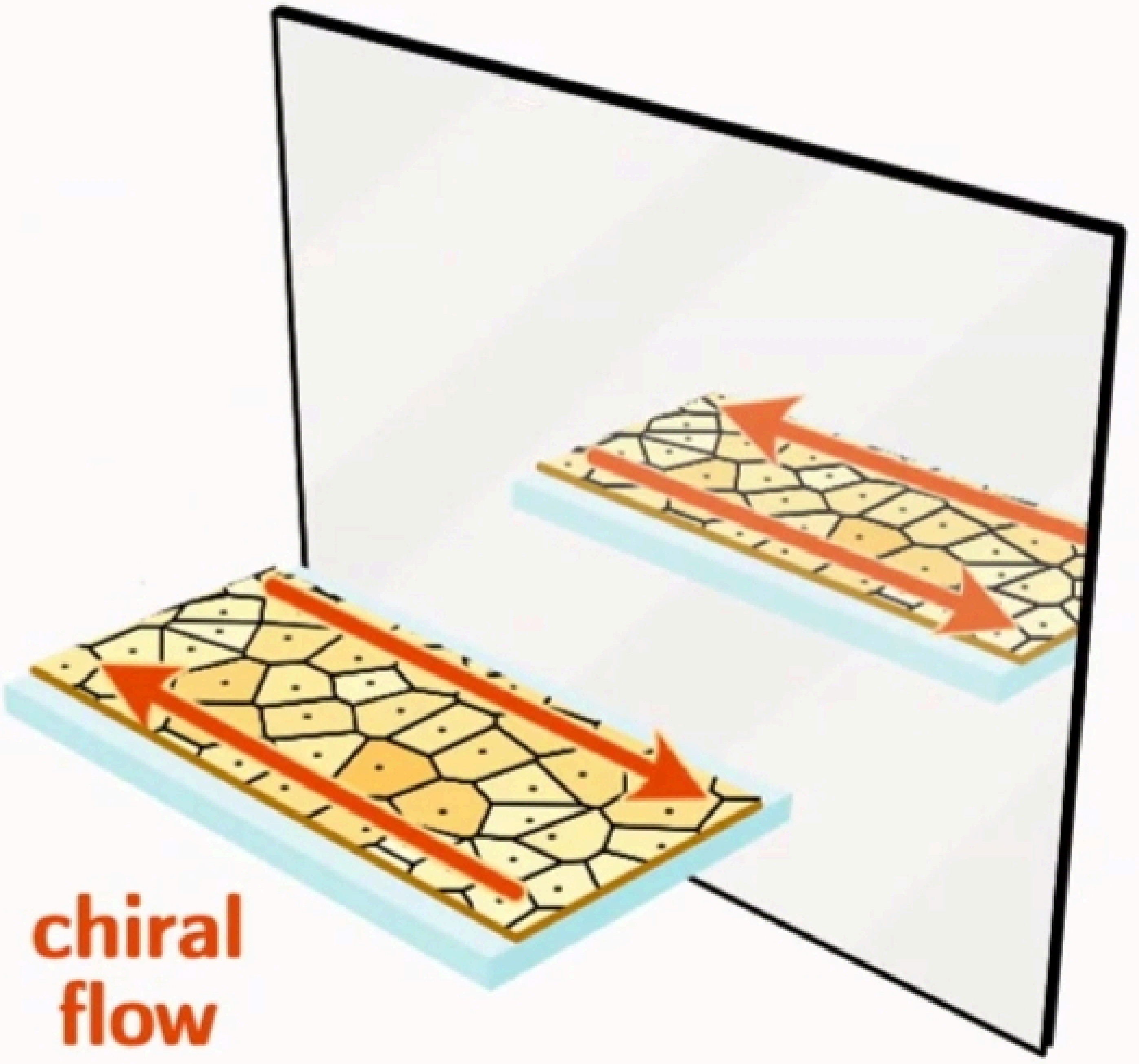
Chirality across scales in tissue dynamics

Pascal Silberzan

Victor Yashunsky



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

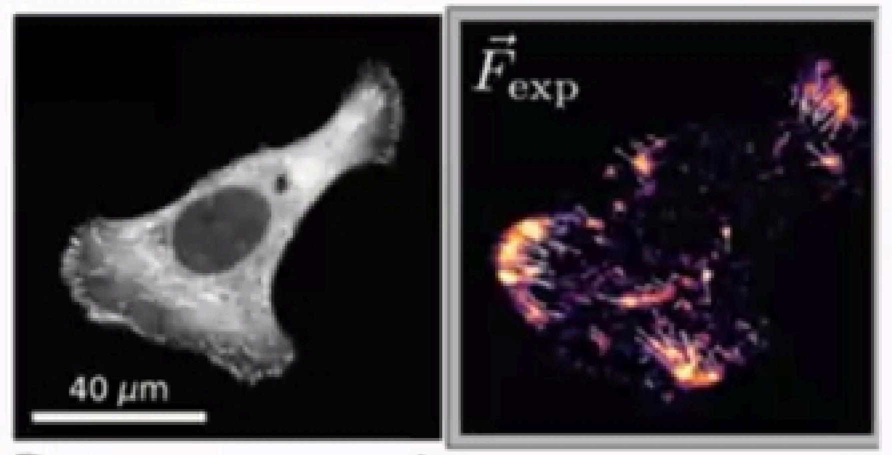


chiral flow

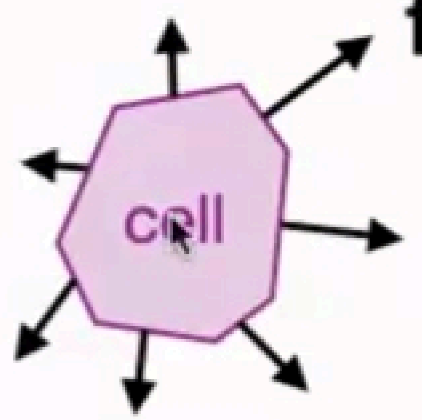
how to model chiral tissues?

How to model tissues?

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



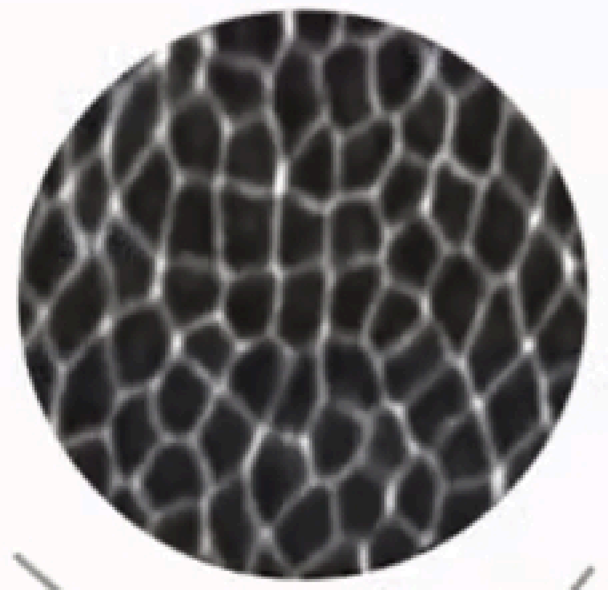
cell-level

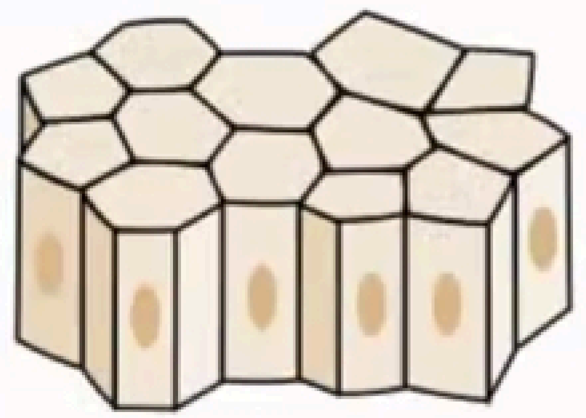


forces

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

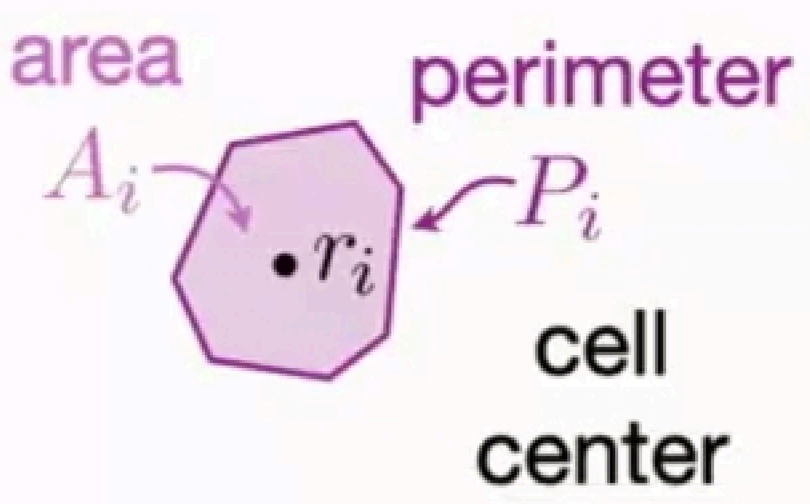
$\mathbf{u}(\mathbf{r}, t)$ $\sigma(\mathbf{r}, t)$

complex viscoelastic fluids/gels

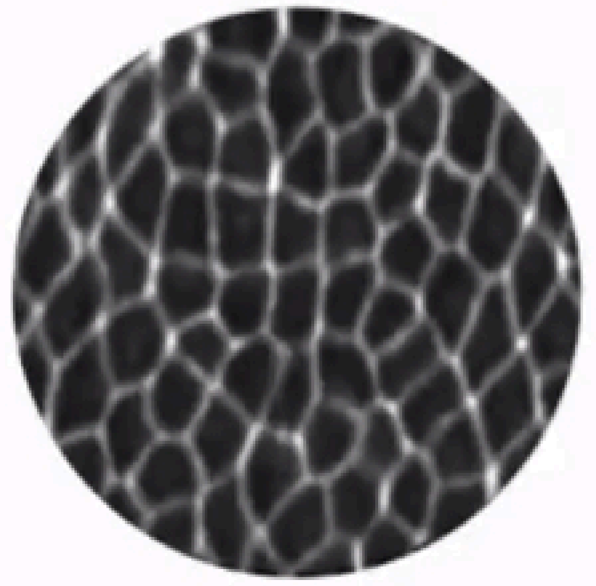
see e.g.
MC Marchetti et al., RMP (2013)
NI Petridou and CP Heisenberg, EMBO (2019)

vertex models are minimal descriptions of confluent biological tissues

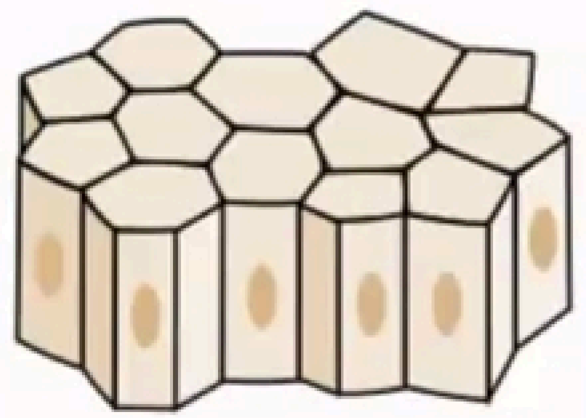
Vertex models



mesoscopic



Drosophila, courtesy S. Streichan



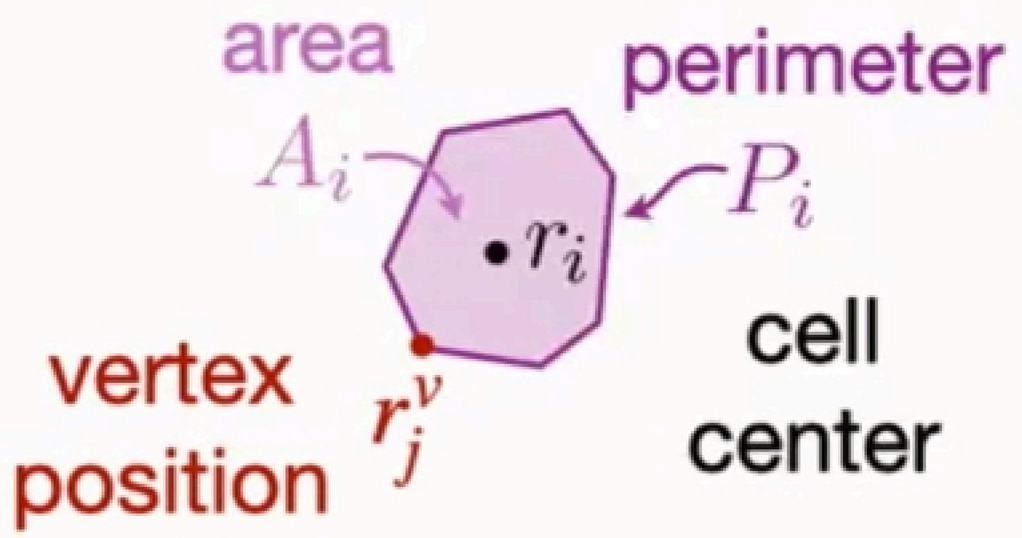
$$\gamma \partial_t \mathbf{r}_i = - \frac{\partial E}{\partial \mathbf{r}_i} \qquad E = \sum_i \left[\frac{K_P}{2}(P_i - P_0)^2 + \frac{K_A}{2}(A_i - A_0)^2 \right]$$

cells minimize an energy towards a preferred perimeter and area

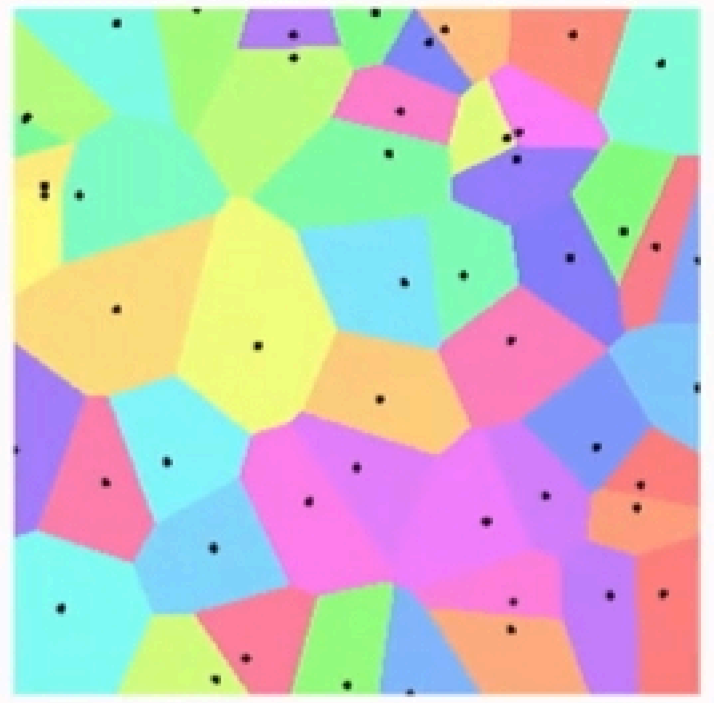
see Alt, Ganguly, Salbreux, RSTB (2017) ; Fletcher, Osterfield, Baker, Shvartsman, Biophysical Journal (2014)

Vertex models

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

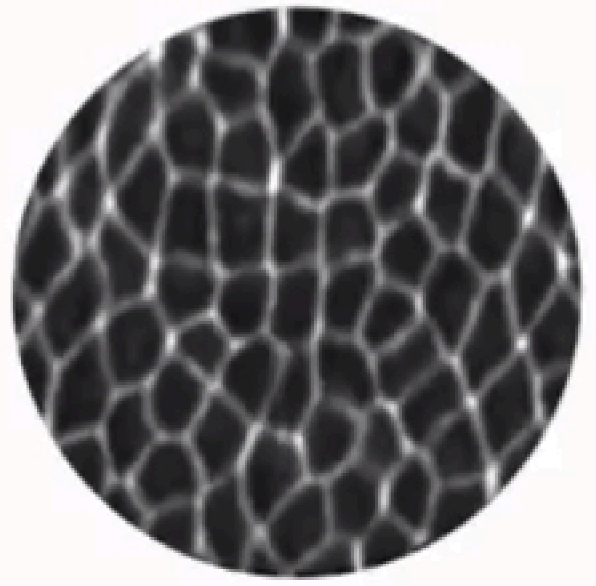


Voronoi tesselation

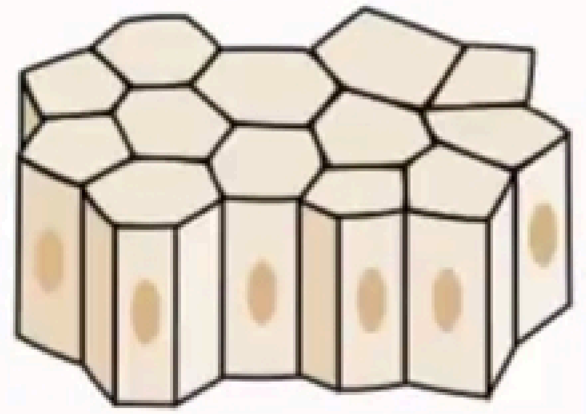


$\mathbf{r}_j^v(\{\mathbf{r}_i\}_i)$

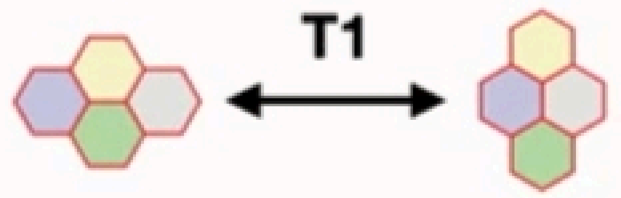
mesoscopic



Drosophila, courtesy S. Streichan



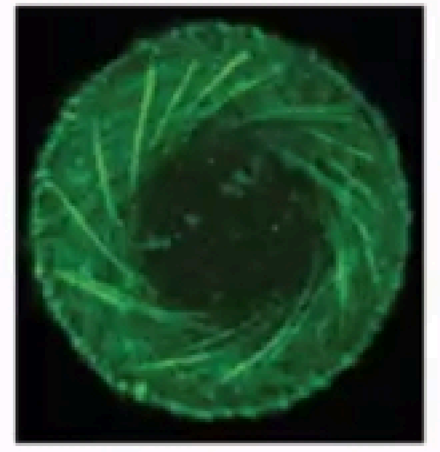
topological transitions



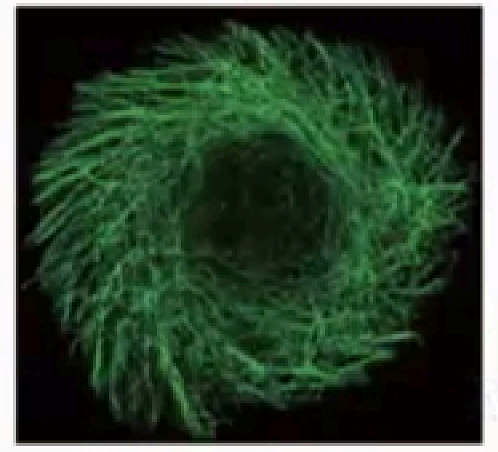
$$\gamma \partial_t \mathbf{r}_i = -\frac{\partial E}{\partial \mathbf{r}_j^v}\frac{\partial r_j^v}{\partial \mathbf{r}_i} = -\frac{\partial E}{\partial \mathbf{r}_i} \qquad E = \sum_i \left[\frac{K_P}{2}(P_i - P_0)^2 + \frac{K_A}{2}(A_i - A_0)^2\right]$$

vertex positions can be computed through Voronoi tesselation

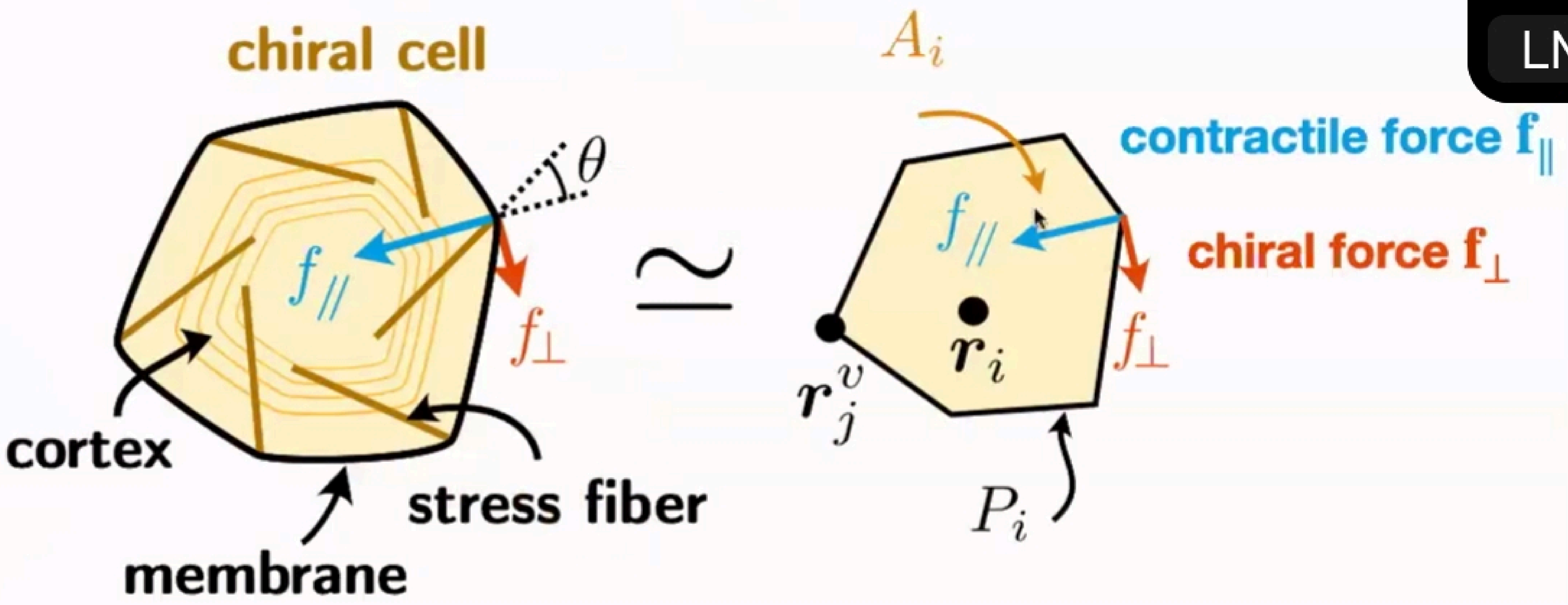
How to model chiral tissues?



Fibroblasts
Tee et al., 2015



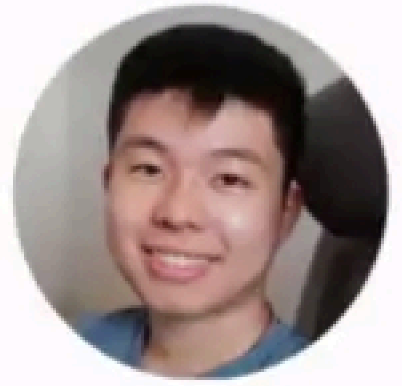
Carcinoma
Yamamoto et al., 2025



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

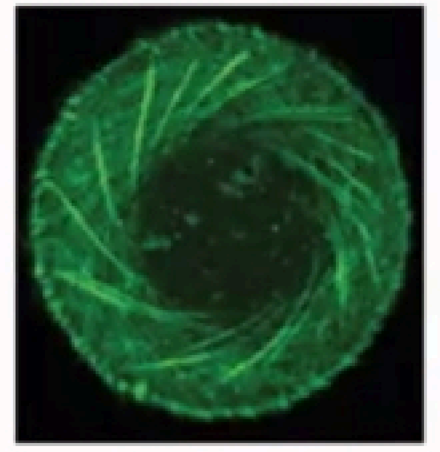


Sihan Chen

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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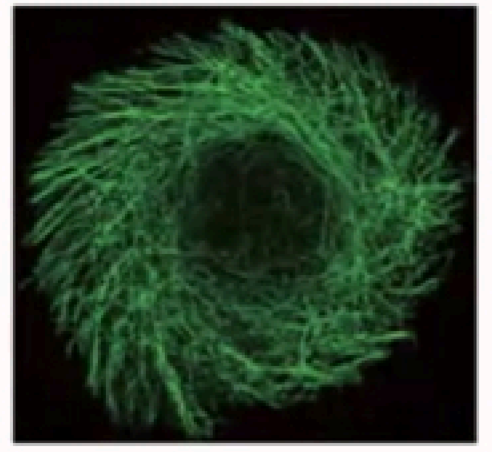
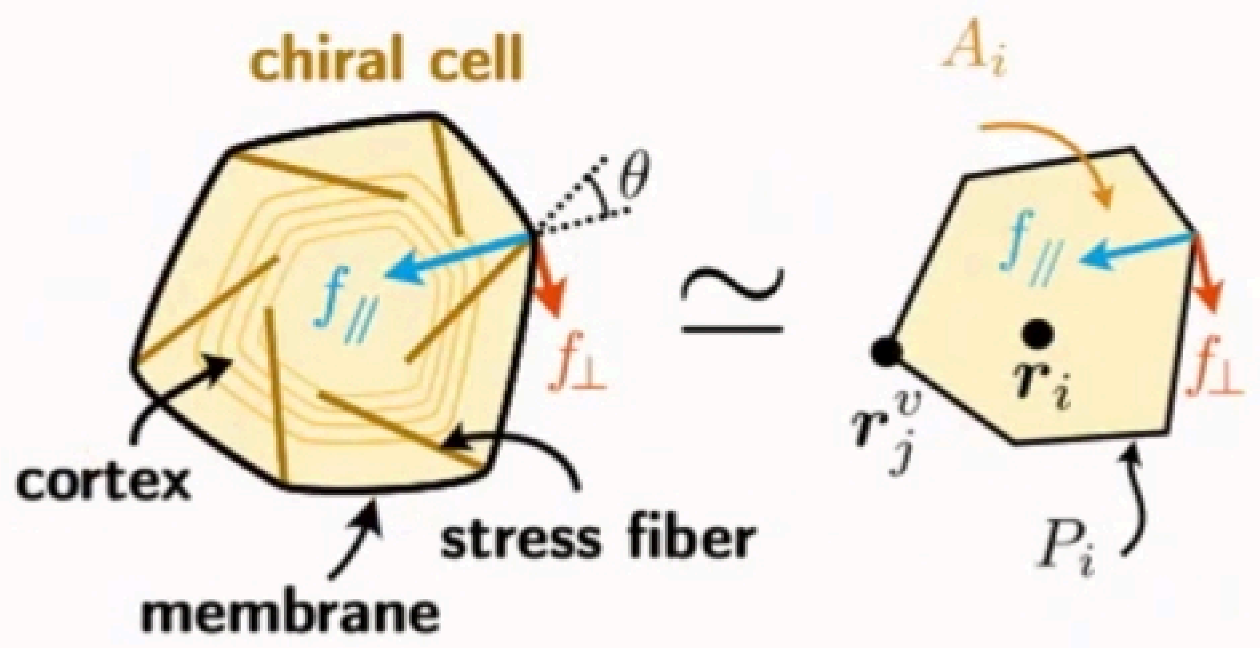
Tee et al., 2015



Carcinoma
Yamamoto et al., 2025



chiral force

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

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

mesoscopic

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

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?

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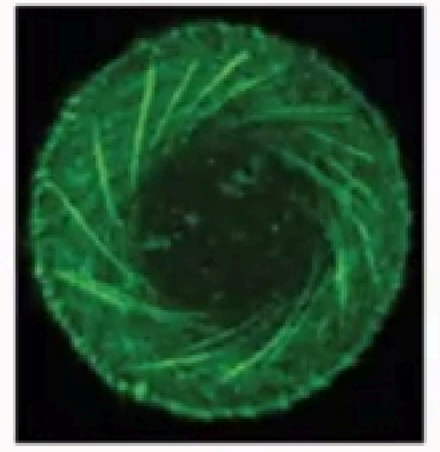

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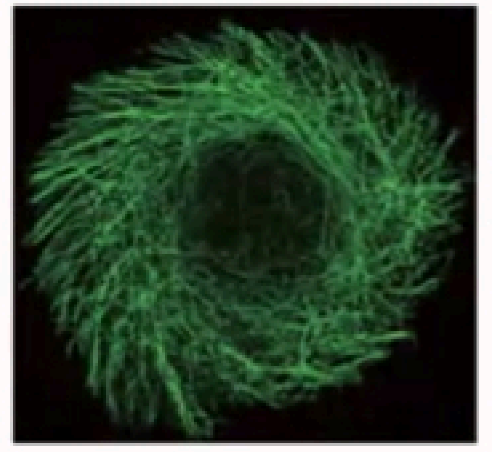
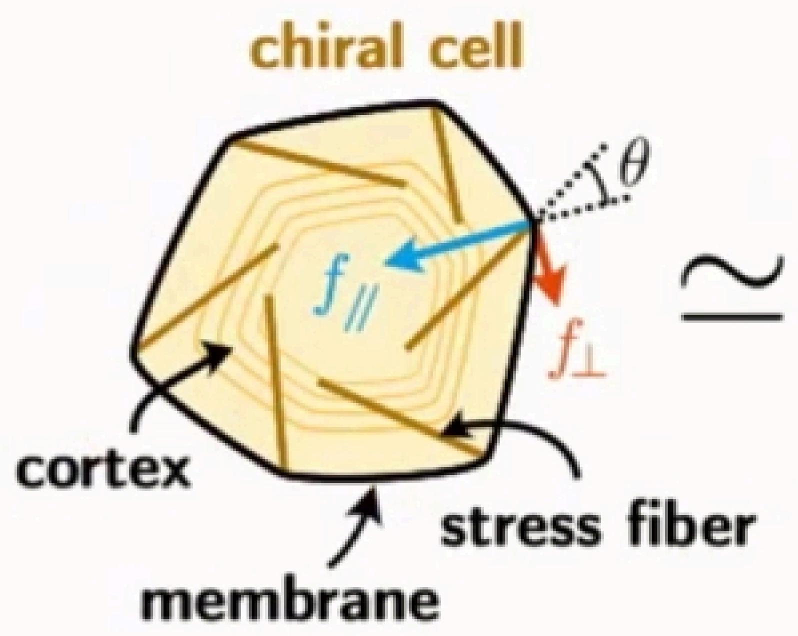
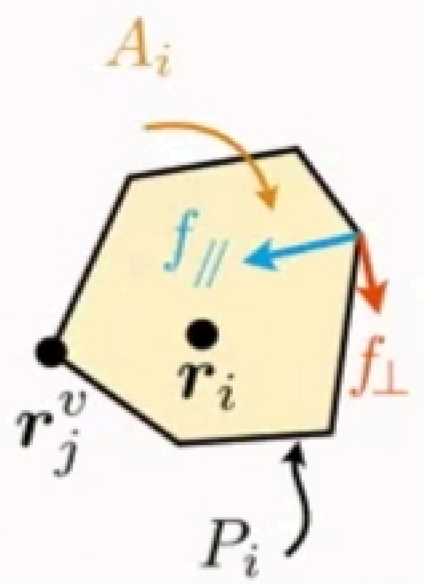
Tee et al., 2015



Carcinoma
Yamamoto et al., 2023



$\simeq$



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$\downarrow$ coarse-graining

continuum

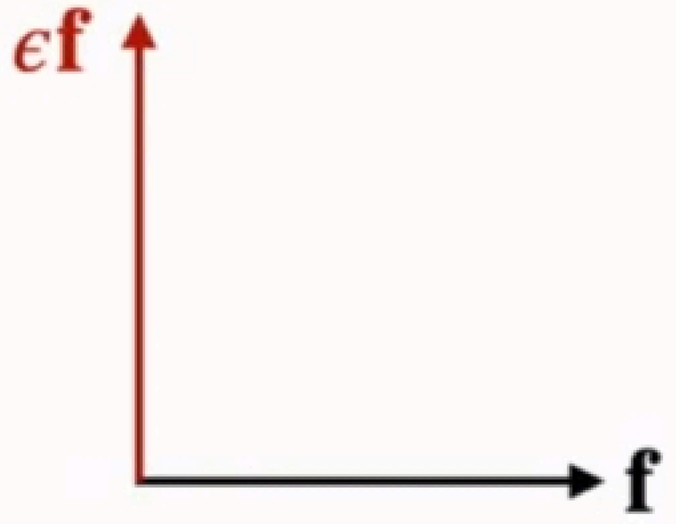
$\mathbf{u}(\mathbf{r}, t)$ $\sigma(\mathbf{r}, t)$

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

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)

Odd viscosity and elasticity



continuum

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2D overdamped viscoelasticity

review on odd vicosity/elasticity

Fruchart, Scheibner, Vitelli, Annual Reviews of Condensed Matter Physics 14 (2023)

minimal way of incorporating chirality in continuum mechanics

Odd viscosity and elasticity

$$\sigma_\alpha = \underbrace{\begin{pmatrix}-p\\-\tau\\0\\0\end{pmatrix}}_{\sigma^{\mathrm{h}}_\alpha} + \underbrace{\begin{pmatrix}\zeta & \eta^{\mathrm{B}} & 0 & 0\\ \eta^{\mathrm{A}} & \eta^{\mathrm{R}} & 0 & 0\\ 0 & 0 & \eta & \eta^{\mathrm{o}}\\ 0 & 0 & -\eta^{\mathrm{o}} & \eta\end{pmatrix}}_{\eta_{\alpha\beta}} \dot{e}_\beta \qquad \sigma_\alpha = \underbrace{\begin{pmatrix}-p^{(\mathrm{pre})}\\-\tau^{(\mathrm{pre})}\\0\\0\end{pmatrix}}_{\sigma^{(\mathrm{pre})}_\alpha} + \underbrace{\begin{pmatrix}B & \Lambda & 0 & 0\\ A & \Gamma & 0 & 0\\ 0 & 0 & \mu & K^{\mathrm{o}}\\ 0 & 0 & -K^{\mathrm{o}} & \mu\end{pmatrix}}_{C_{\alpha\beta}} e_\beta$$

viscosity

$$M_{ijk\ell}(\tau) = \eta_{ijk\ell}\,\delta(\tau)$$

elasticity

$$M_{ijk\ell}(\tau) = C_{ijk\ell}\,\Theta(\tau)$$

$$\sigma_{ij}(t) = \int_{-\infty}^{\infty} M_{ijk\ell}(\tau)\,\partial_\ell \dot{u}_k(t-\tau)\,\mathrm{d}\tau$$

viscoelasticity

continuum

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

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

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Fruchart, Scheibner, Vitelli, Annual Reviews of Condensed Matter Physics 14 (2023)

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[I'm not going to talk about convected derivatives because it does not matter here see the paper for references.]

Odd viscosity and elasticity

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\qquad
\underbrace{\sigma_\alpha}_{\sigma_\alpha} = \underbrace{\begin{pmatrix} -p^{(\mathrm{pre})} \\ -\tau^{(\mathrm{pre})} \\ 0 \\ 0 \end{pmatrix}}_{\sigma^{(\mathrm{pre})}_\alpha} + \underbrace{\begin{pmatrix} B & \Lambda & 0 & 0 \\ A & \Gamma & 0 & 0 \\ 0 & 0 & \mu & K^{o} \\ 0 & 0 & -K^{o} & \mu \end{pmatrix}}_{C_{\alpha\beta}} \underbrace{e_\beta}_{e_\beta}$$

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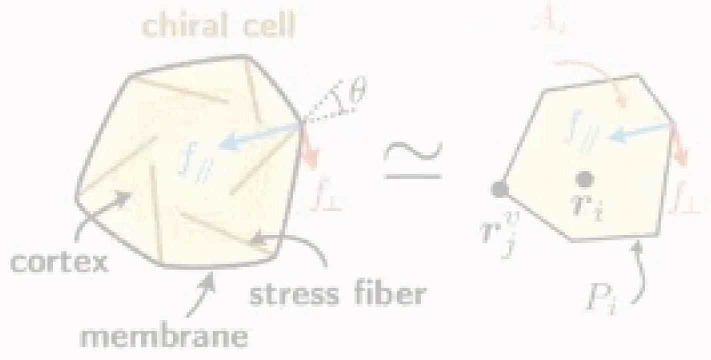
LMP Seminars

How to model chiral tissues?

cell-level

Fibroblasts
Tee et al., 2015

Carcinoma
Yamamoto et al., 2023



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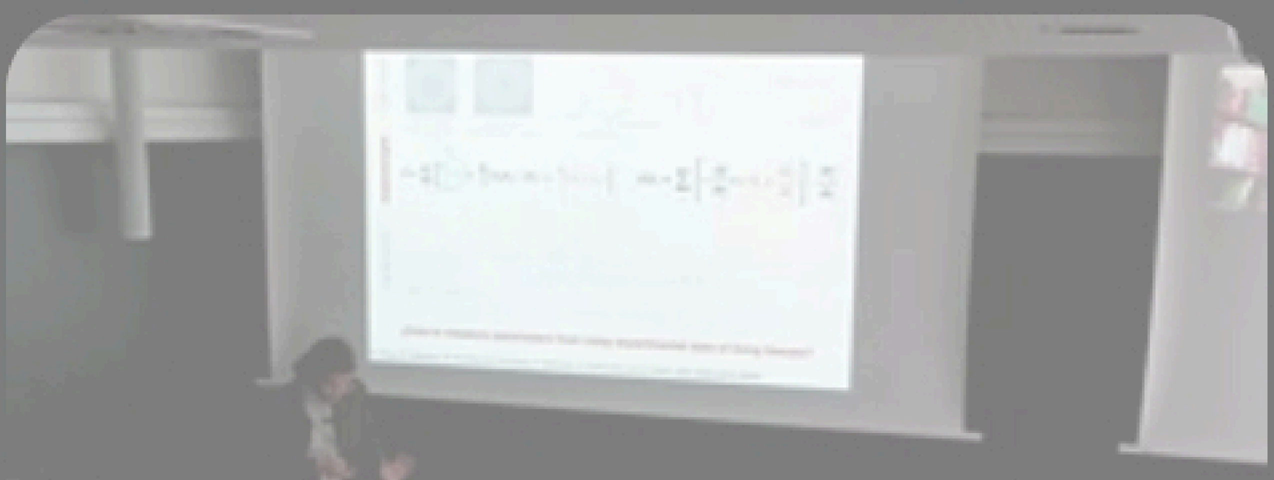
¿how to measure parameters from noisy experimental data of living tissues?

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

LMP Seminars's screen



LMP Seminars

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

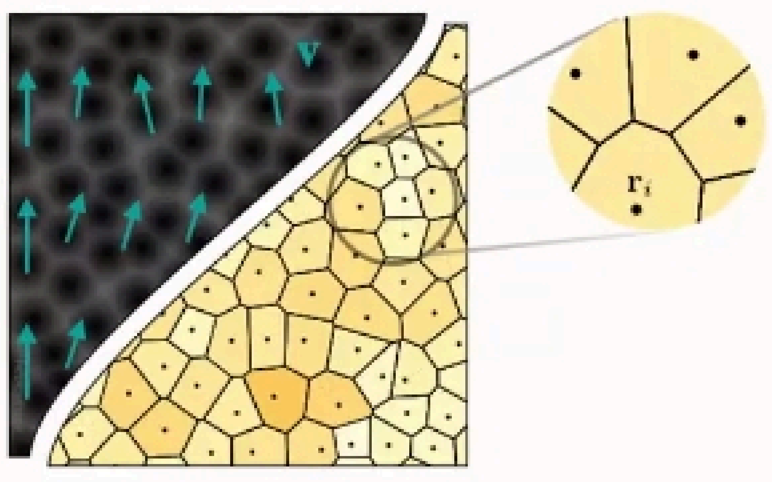
¿how to measure parameters from noisy experimental data of living tissues?

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

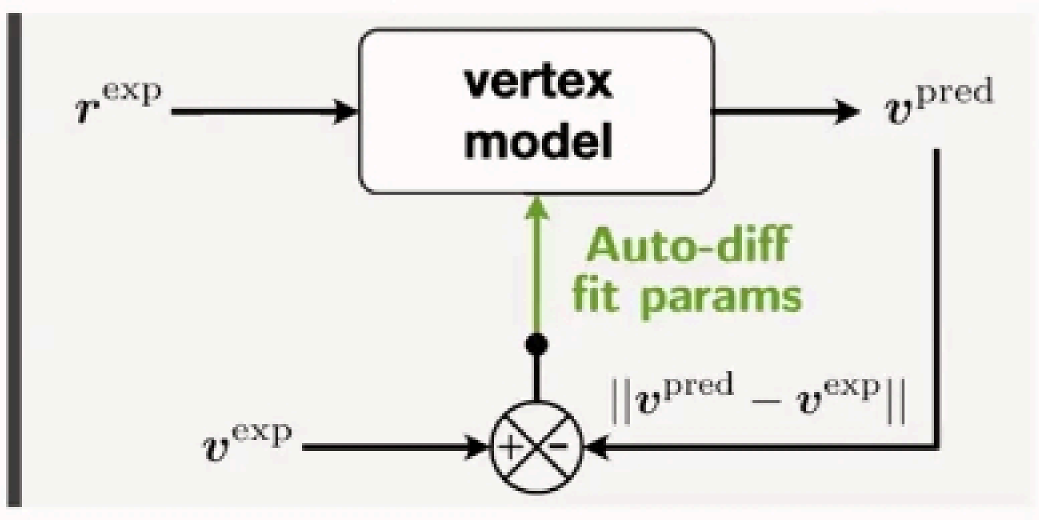
LMP Seminars's screen

6:46 41.6 KB/s 4G 9%

Let us fit the parameters!



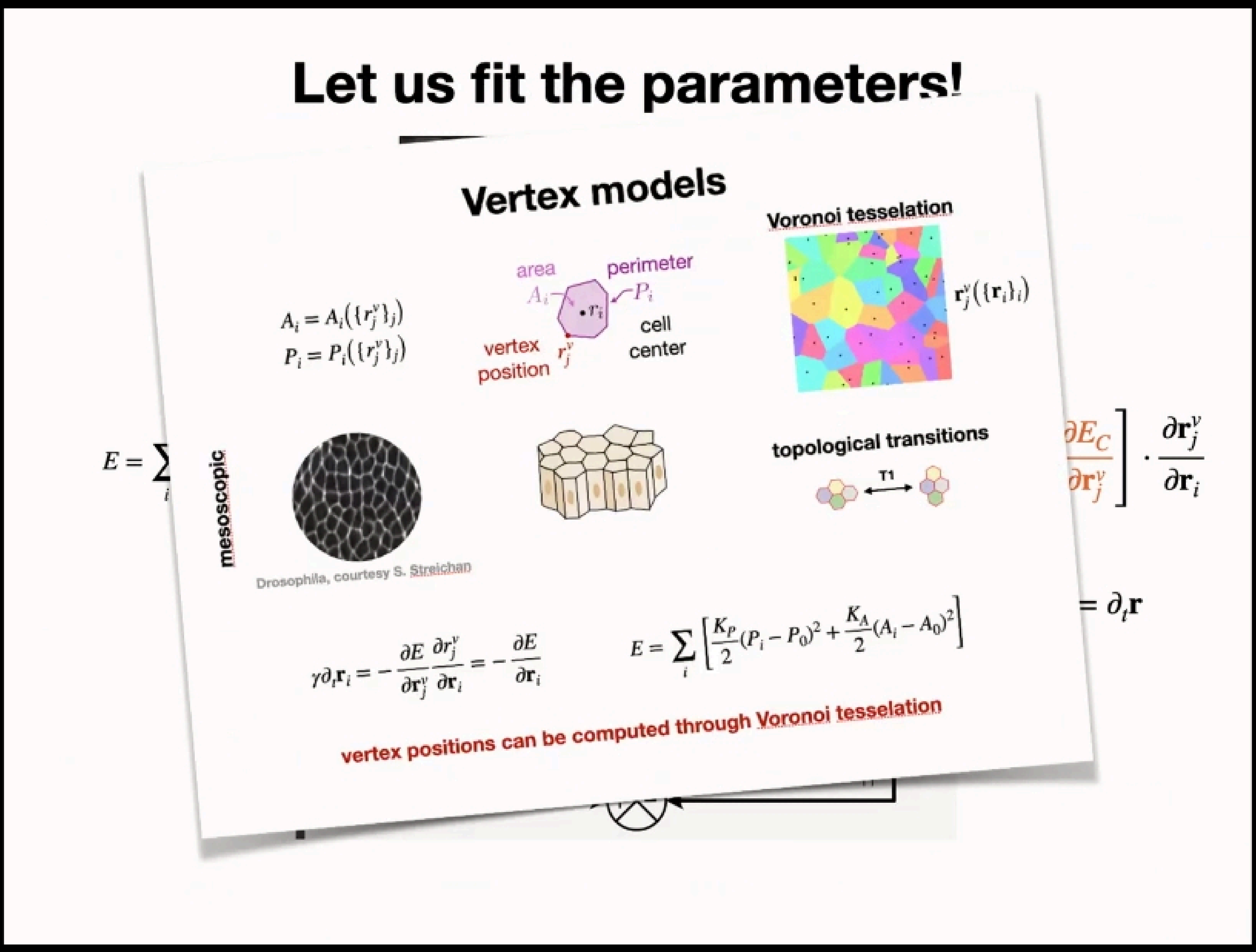
$$E = \sum_i \left[\overbrace{\frac{K_P}{2} P_i^2}^{E_C} + \frac{K_P}{2} P_0 (P_0 - 2P_i) + \frac{K_A}{2} (A_i - A_0)^2 \right] \qquad \gamma \partial_t \mathbf{r}_i = \sum_j \left[-\frac{\partial E}{\partial \mathbf{r}_j^v} + \alpha^o \hat{\mathbf{e}}_z \times \frac{\partial E_C}{\partial \mathbf{r}_j^v}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

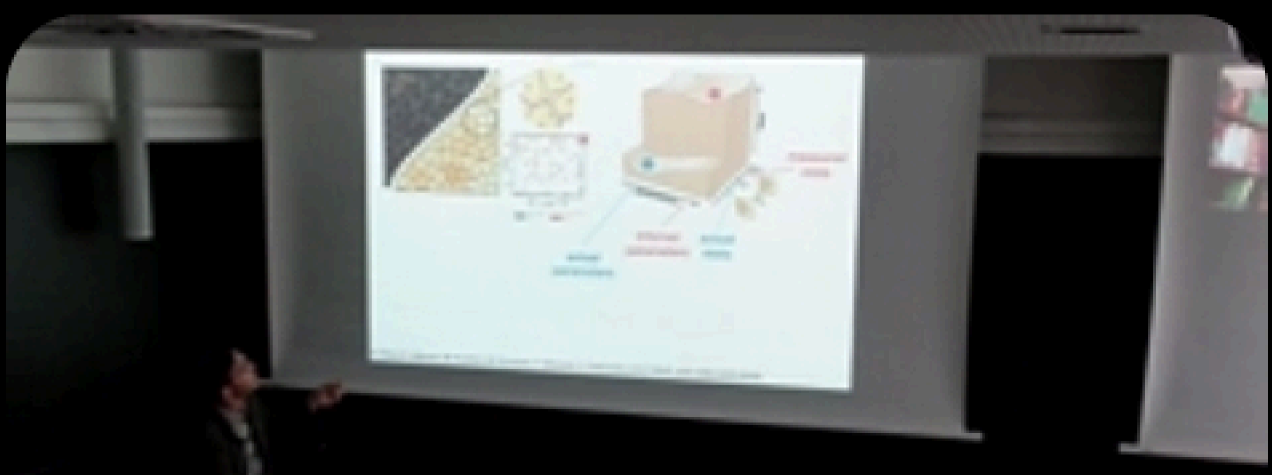


$$\mathbf{v} = \partial_t \mathbf{r}$$

6:47

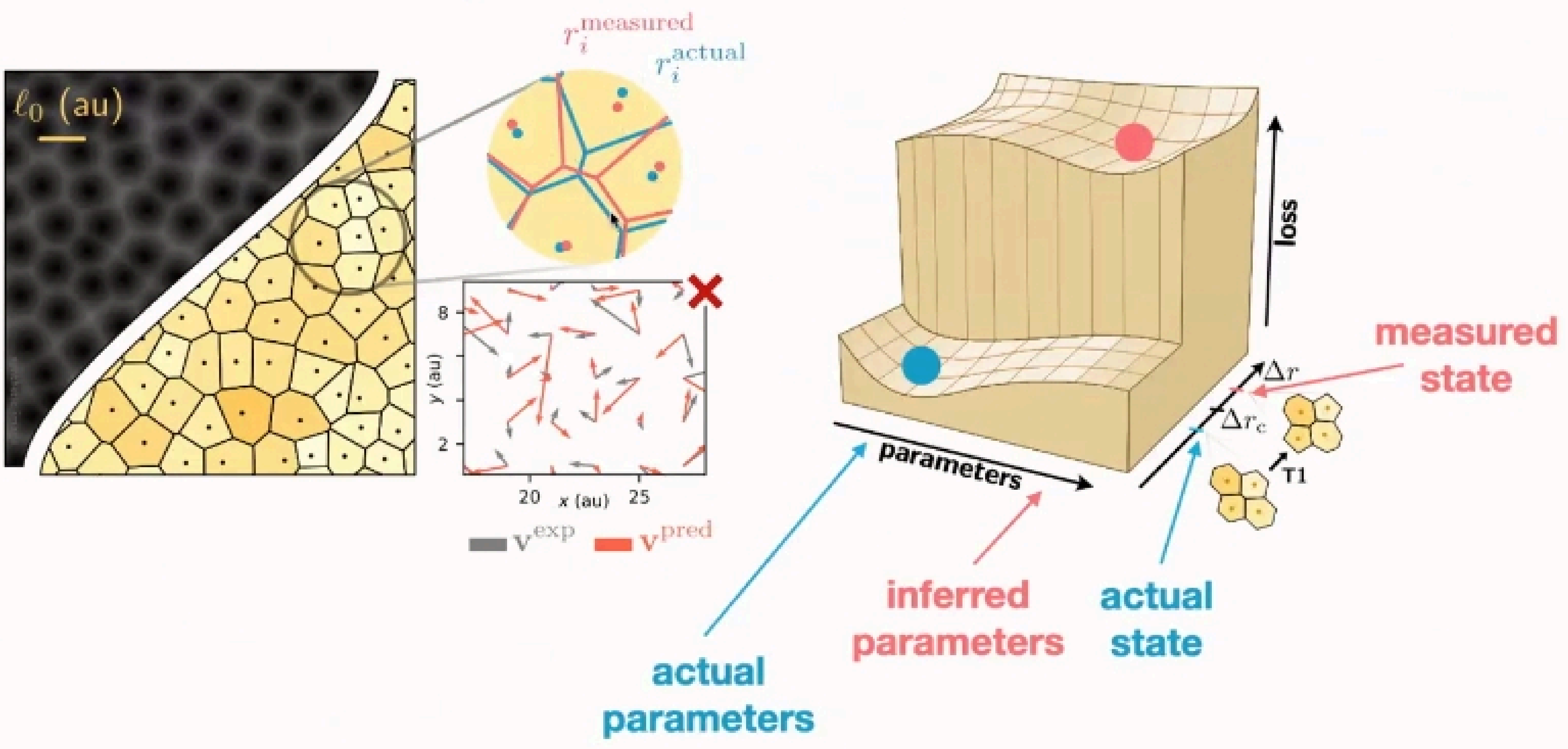

LMP Seminars


Let us fit the parameters!
Vertex models
Voronoi tesselation
area
perimeter
cell center
vertex position
$A_i = A_i(\{r_j^v\}_j)$
$P_i = P_i(\{r_j^v\}_j)$
$\mathbf{r}_j^v(\{\mathbf{r}_i\}_i)$
topological transitions
T1
mesoscopic
Drosophila, courtesy S. Streichan
$\gamma \partial_t \mathbf{r}_i = -\frac{\partial E}{\partial \mathbf{r}_j^v}\frac{\partial \mathbf{r}_j^v}{\partial \mathbf{r}_i} = -\frac{\partial E}{\partial \mathbf{r}_i}$
$E = \sum_i \left[\frac{K_P}{2}(P_i - P_0)^2 + \frac{K_A}{2}(A_i - A_0)^2\right]$
vertex positions can be computed through Voronoi tesselation
$E = \sum_i$
$\frac{\partial E_C}{\partial \mathbf{r}_j^v}$
$\frac{\partial \mathbf{r}_j^v}{\partial \mathbf{r}_i}$
$= \partial_t \mathbf{r}$



LMP Seminars

On the dark side of the topological transition



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

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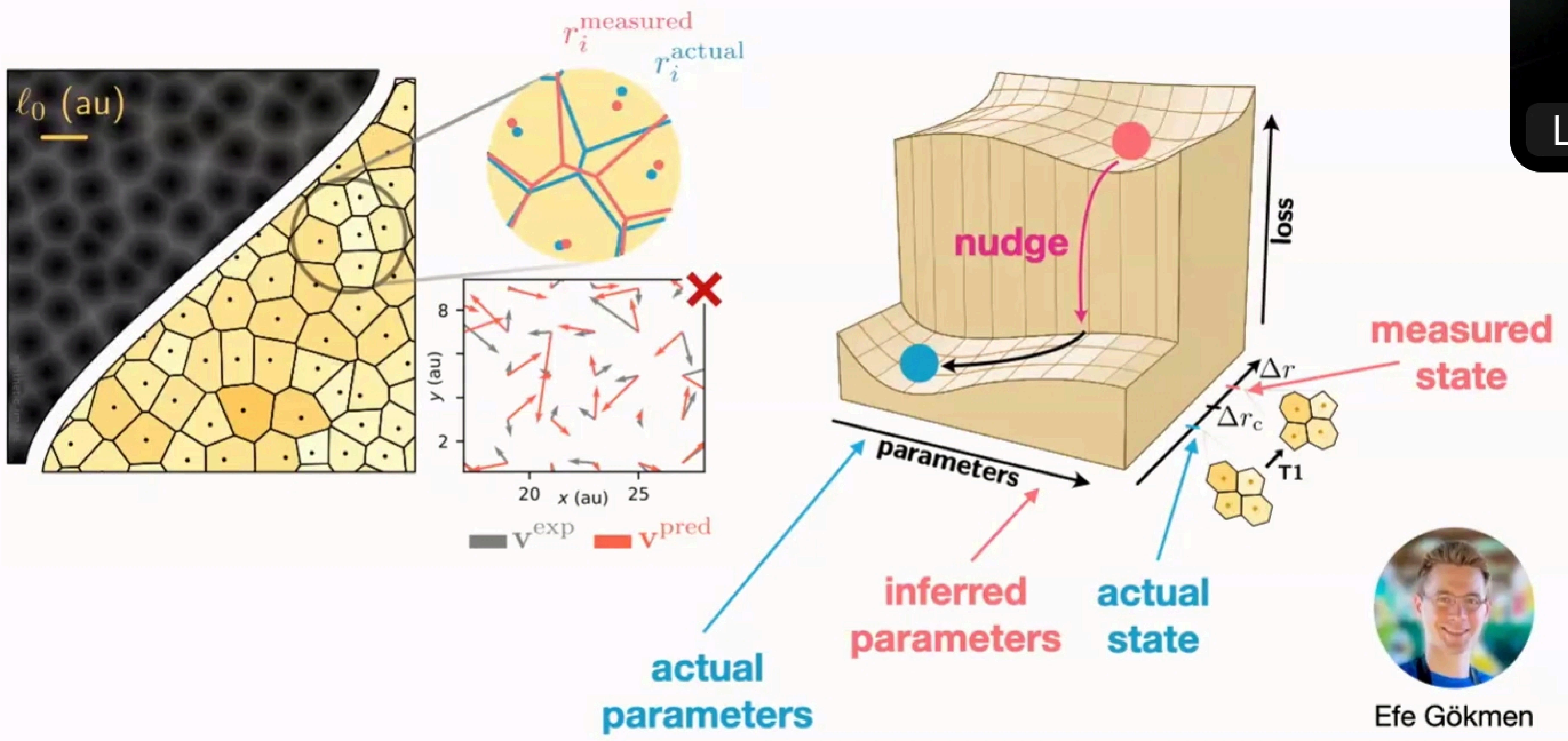
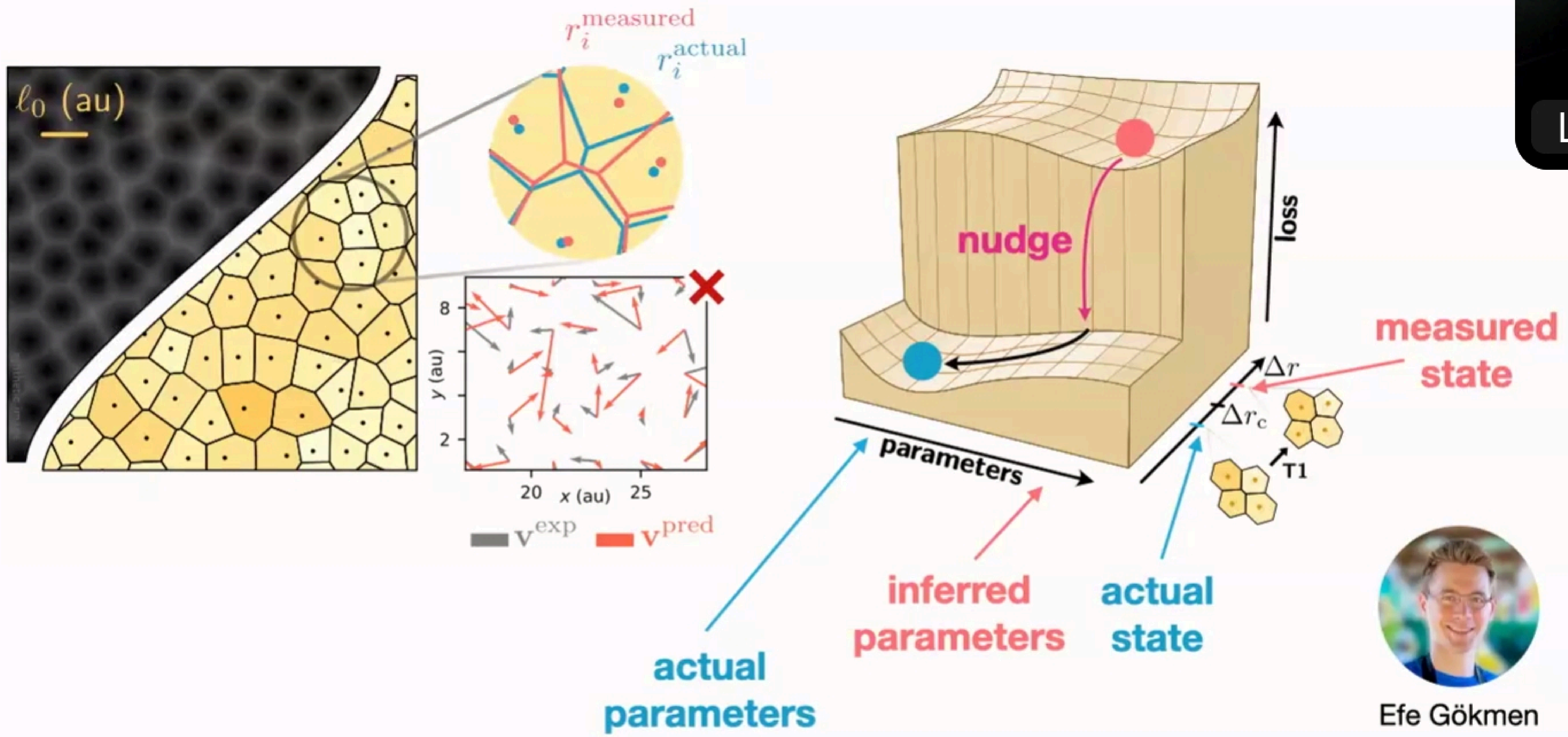


fit data to model to fit model to data

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

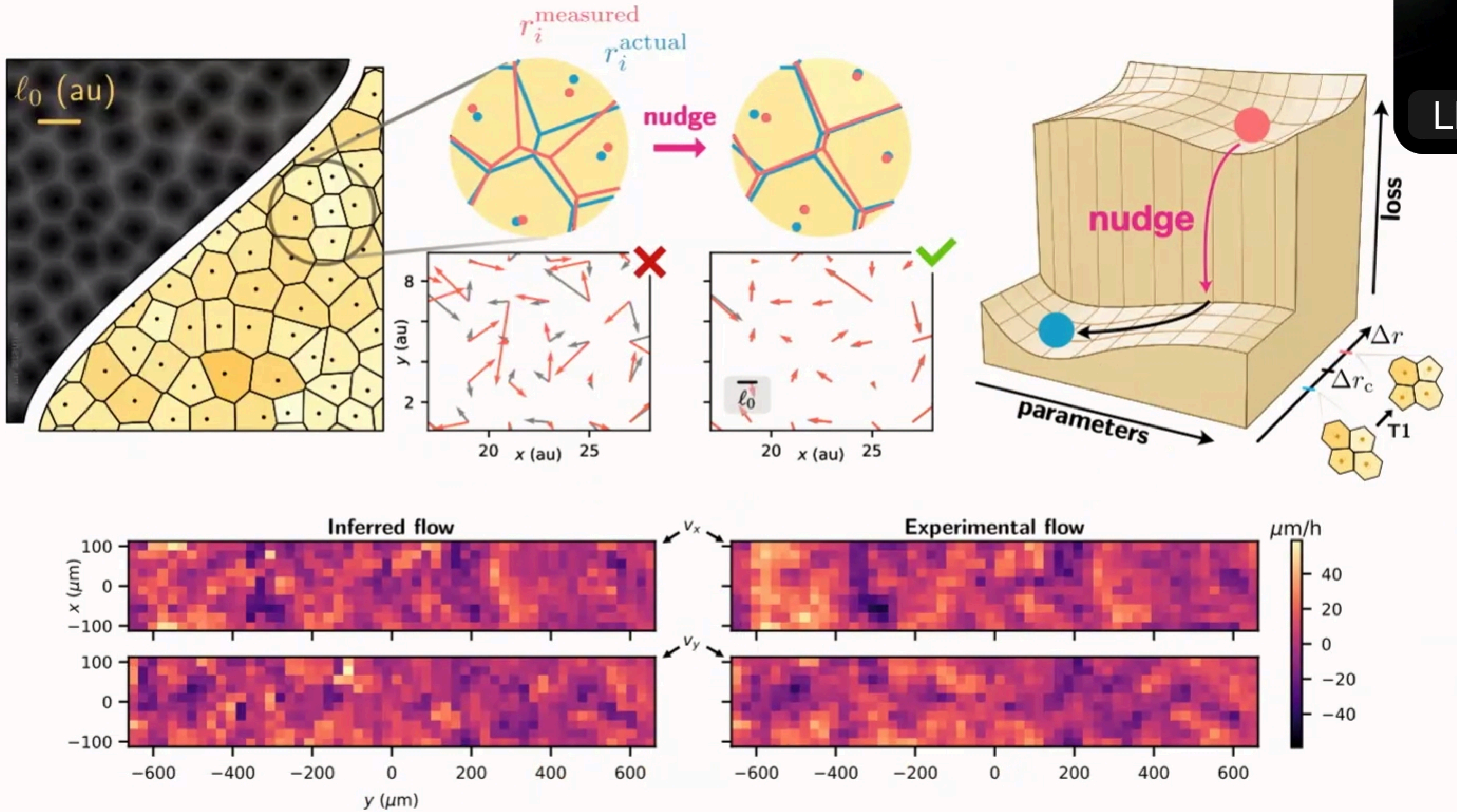
On the dark side of the topological transition

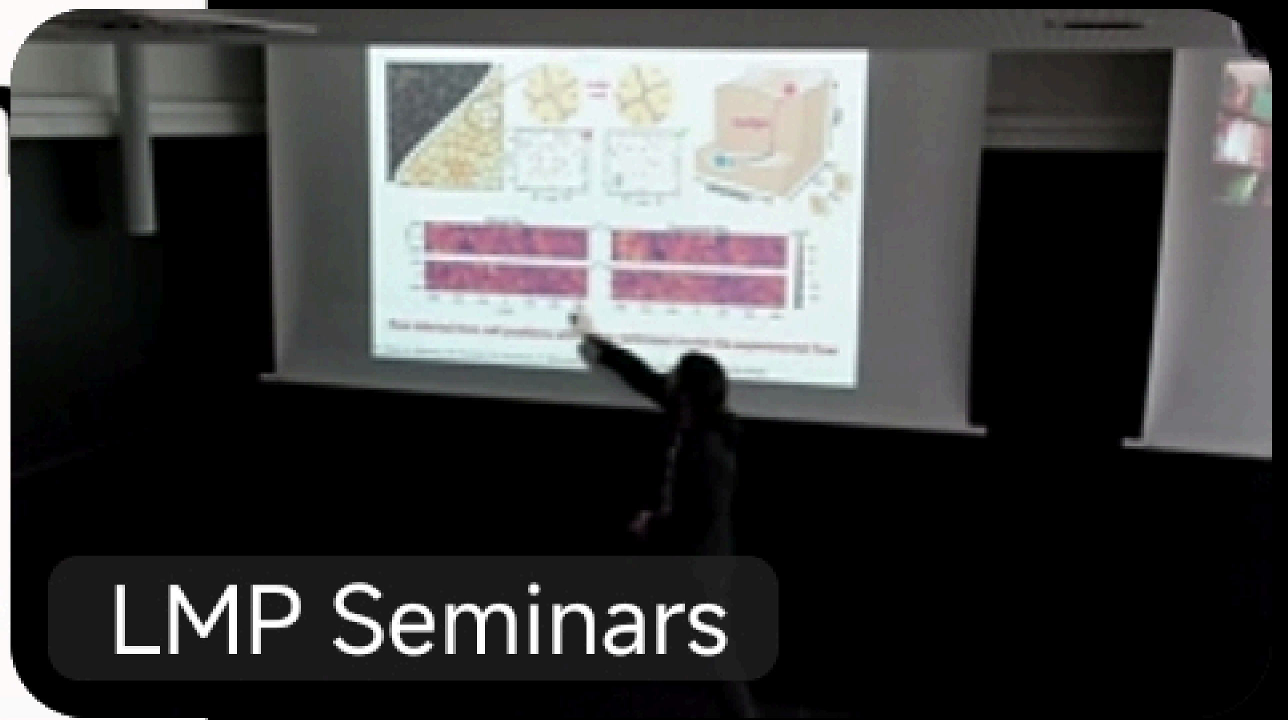


fit data to model **to fit model to data**

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

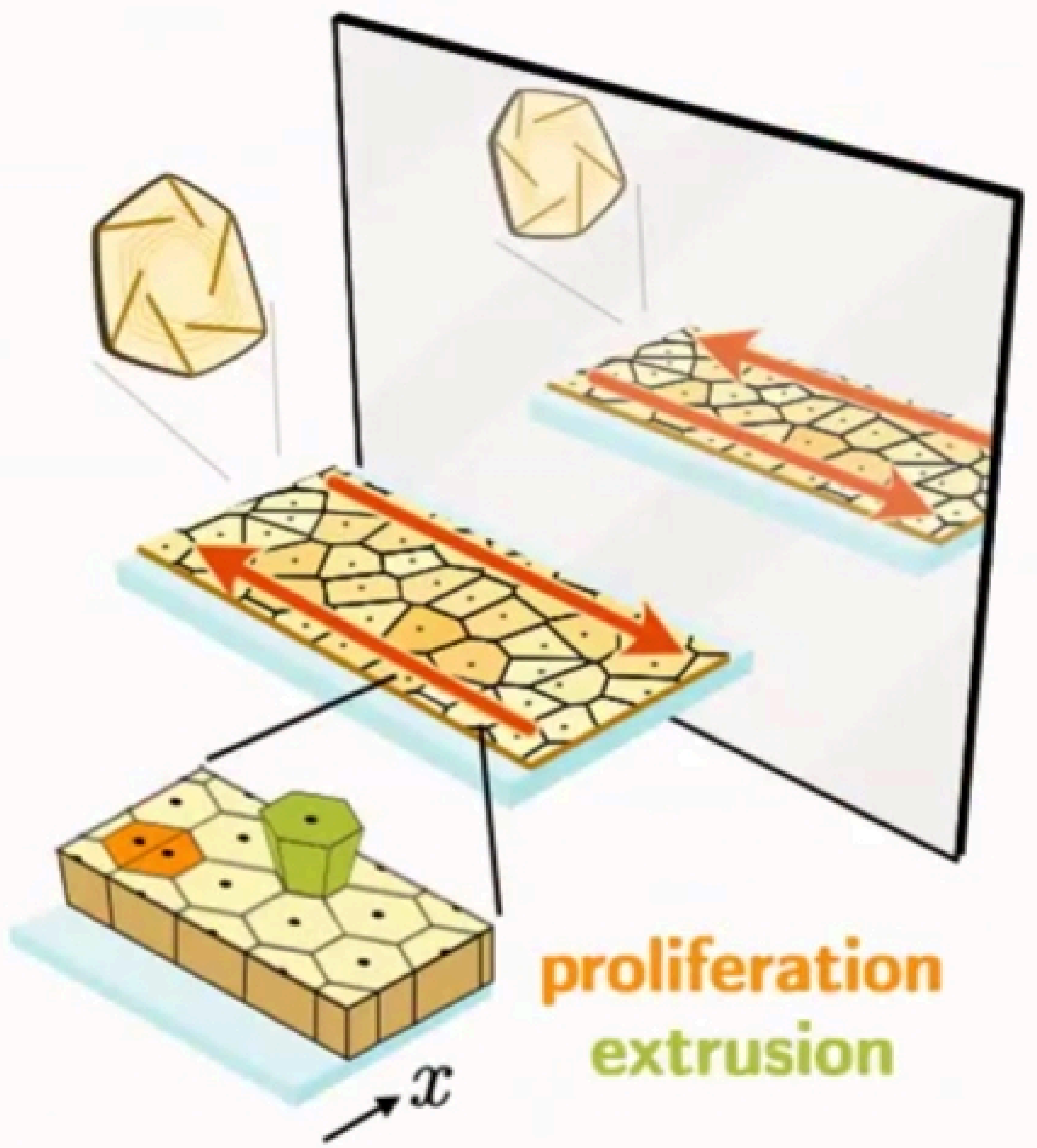


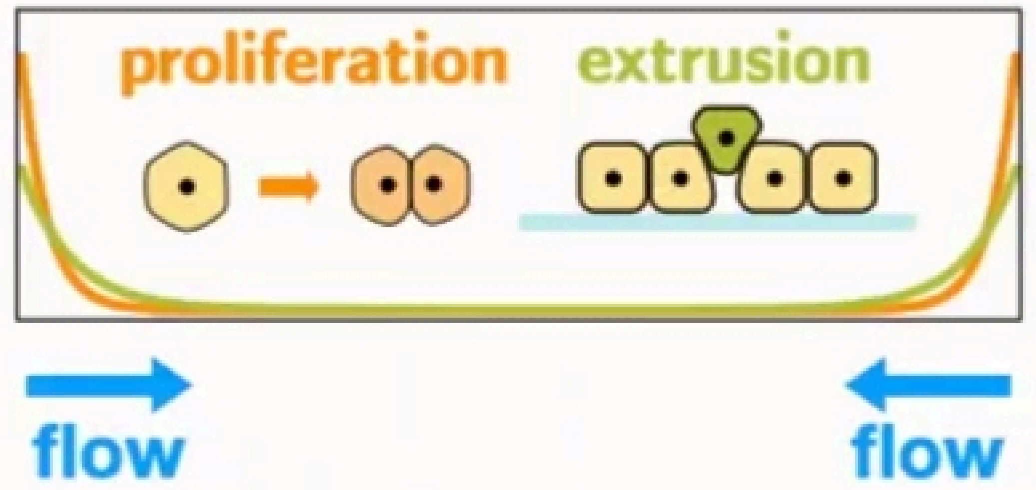


flow inferred from cell positions with nudge-optimized model fits experimental flow

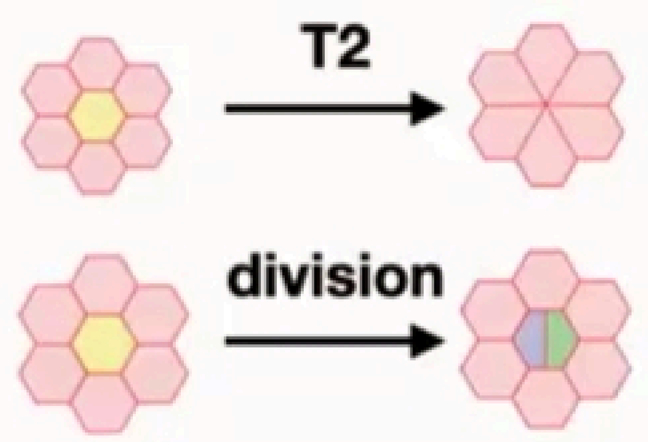
S. Chen, E. Gökmen, M. Fruchart, M. Krumbein, P. Silberzan, V. Yashunsky and V. Vitelli, arXiv 2506.12276 (2025)

Cells divide





mesoscopic



continuum

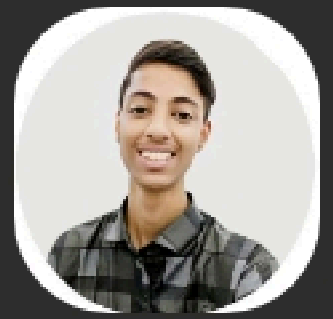
$$\partial_t \rho + \nabla \cdot [\rho \boldsymbol{v}] = [k_{\text{prolif}}(\boldsymbol{r}) - k_{\text{extr}}(\boldsymbol{r})]\rho$$

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)

Participants (5)



Naman Dixit (me)

LMP Seminars (Host)

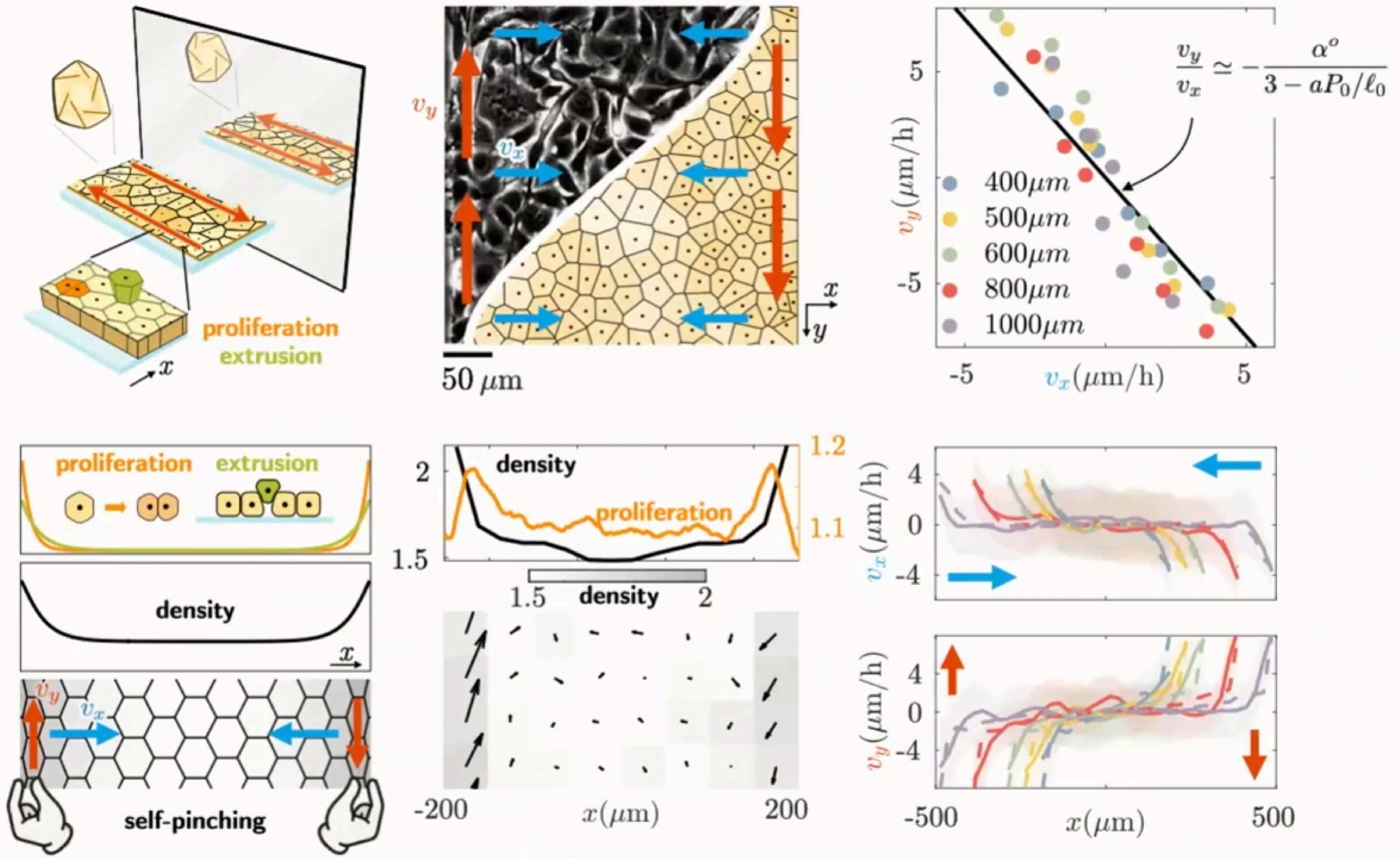
PB Philip Bittihn (Co-host)

GL Giorgio Lovato

Yuto Hosaka (保阪 悠人)

Invite

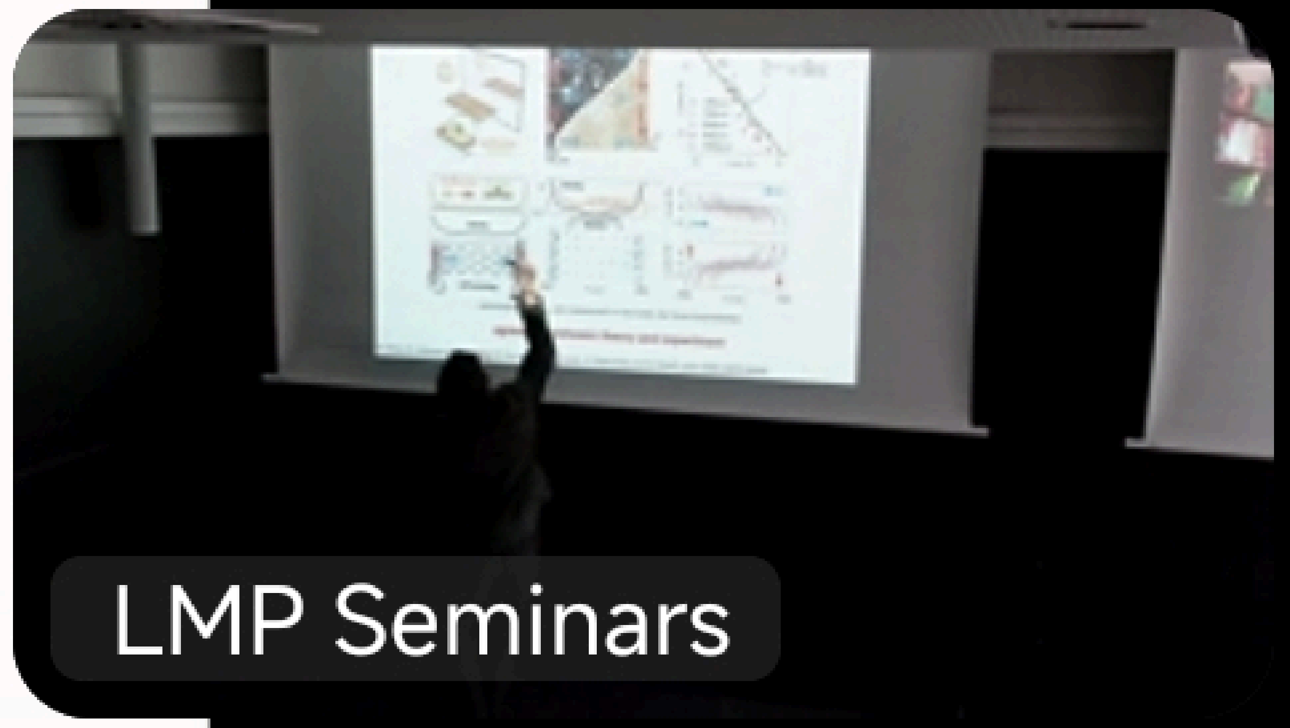
From self-pinching to chiral edge flow



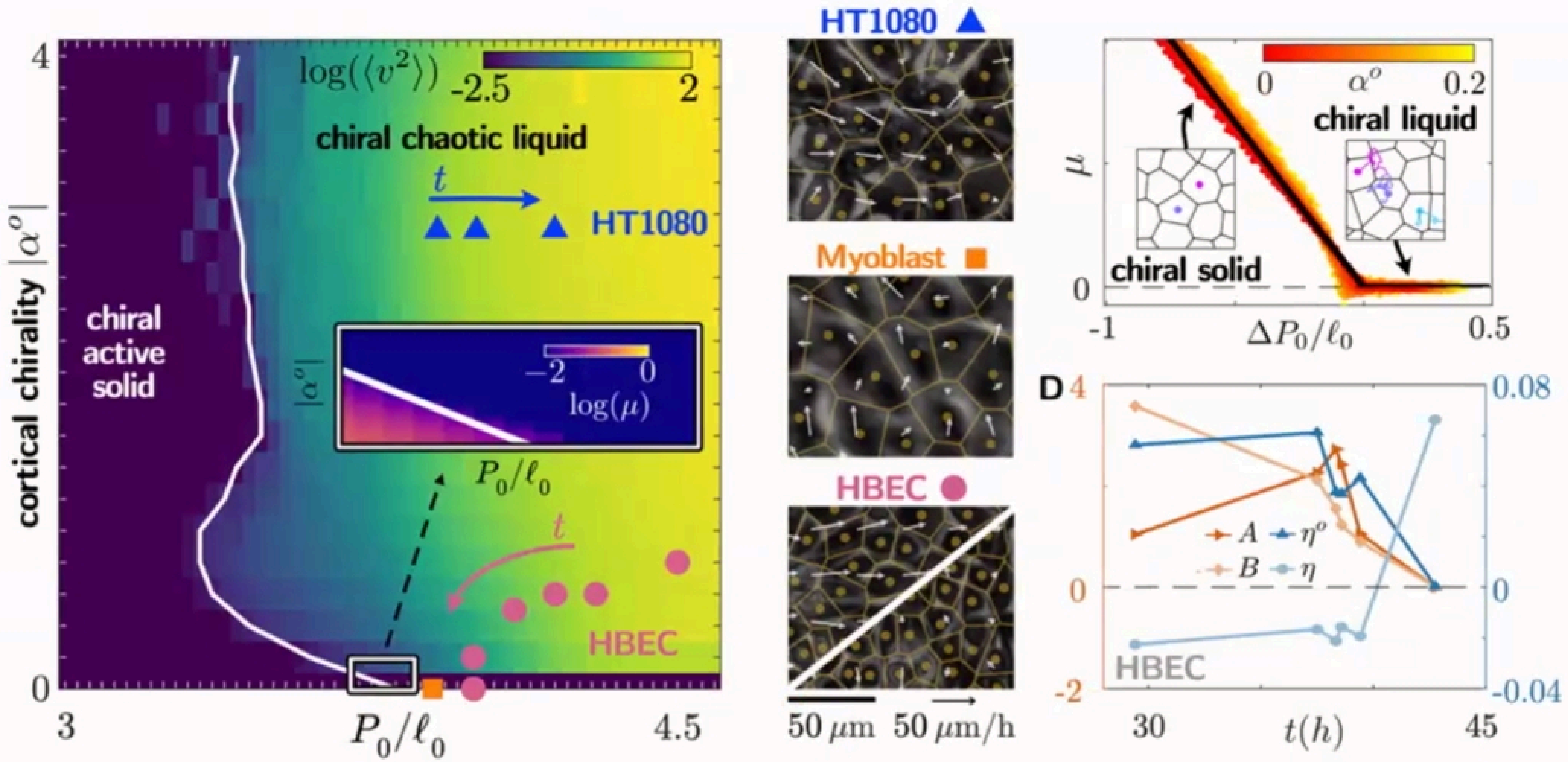
parameters like α_o are measured in the bulk, far from boundaries

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

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

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

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

odd viscoelasticity

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

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)

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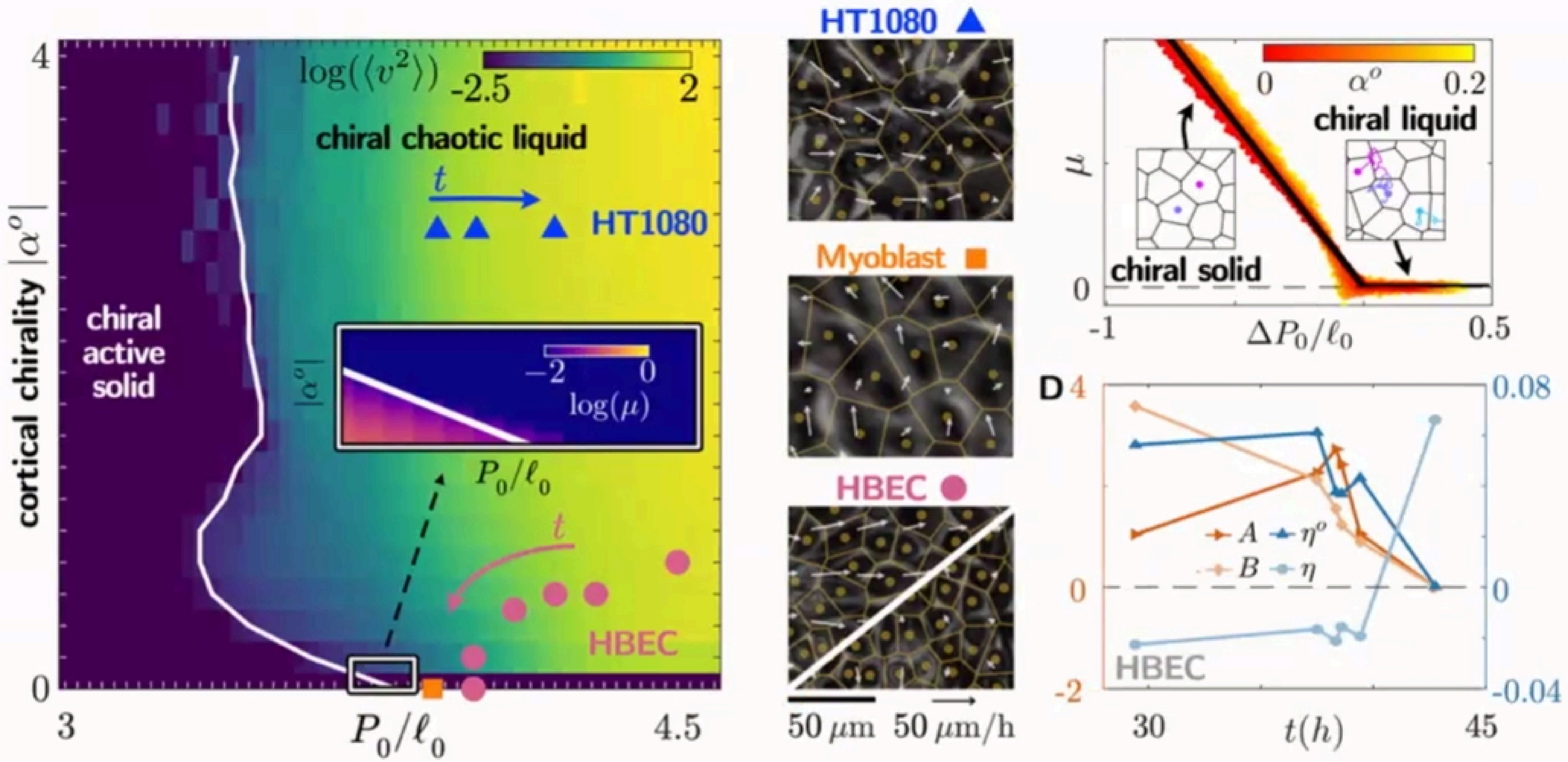
LMP Seminars's screen

Measuring viscoelastic moduli



continuum

$\mathbf{u}(\mathbf{r},t)$ $\sigma(\mathbf{r},t)$
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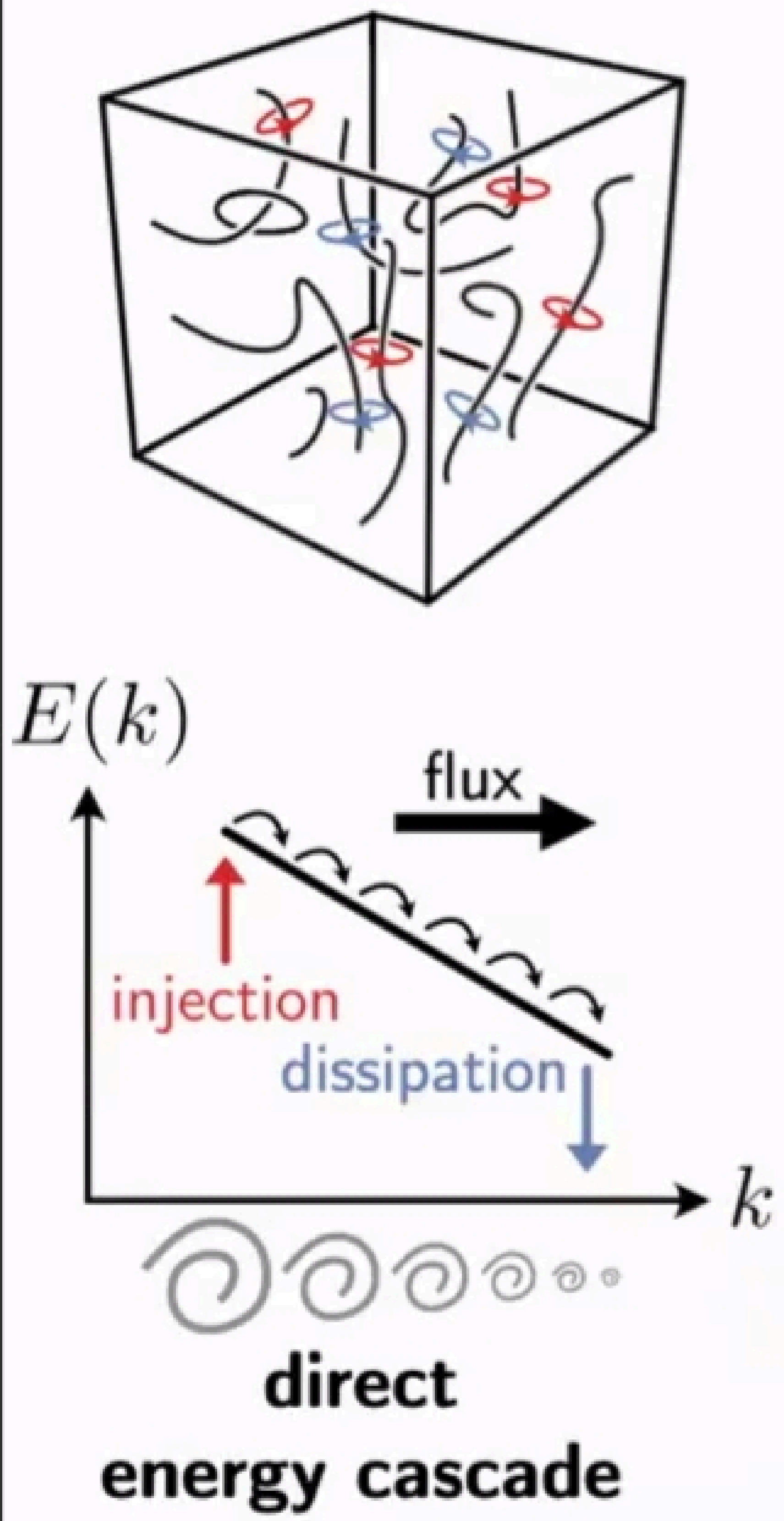
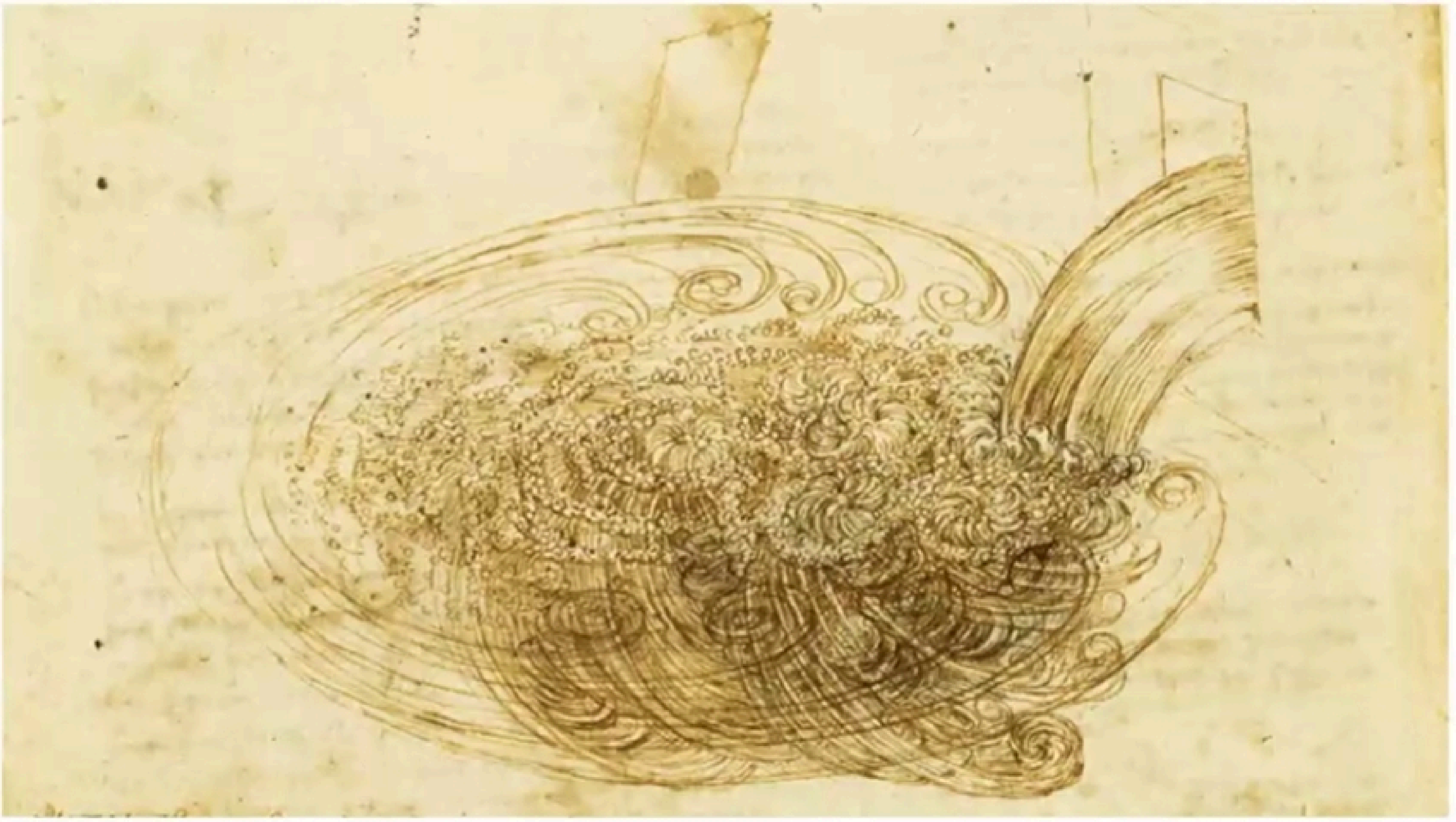
S. Chen, E. Gökmen, M. Fruchart, M. Krumbein, P. Silberzan, V. Yashunsky and V. Vitelli, arXiv 2506.12276 (2025)

LMP Seminars's screen

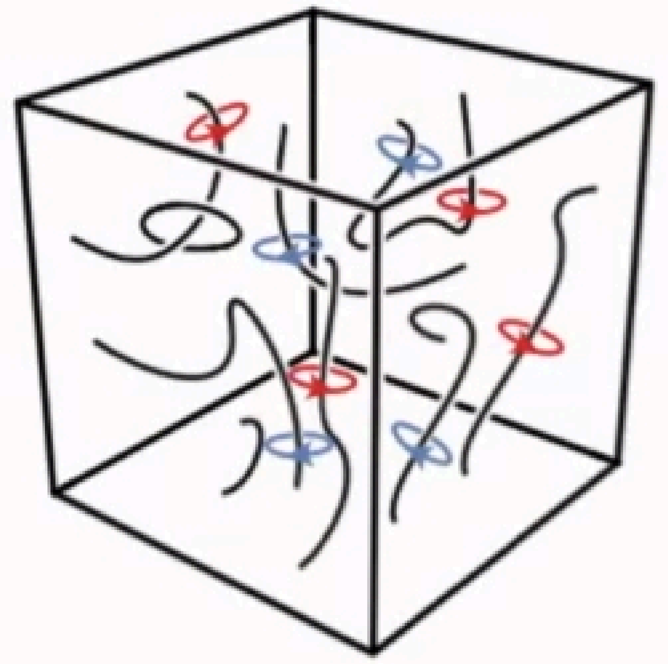
What is turbulence?



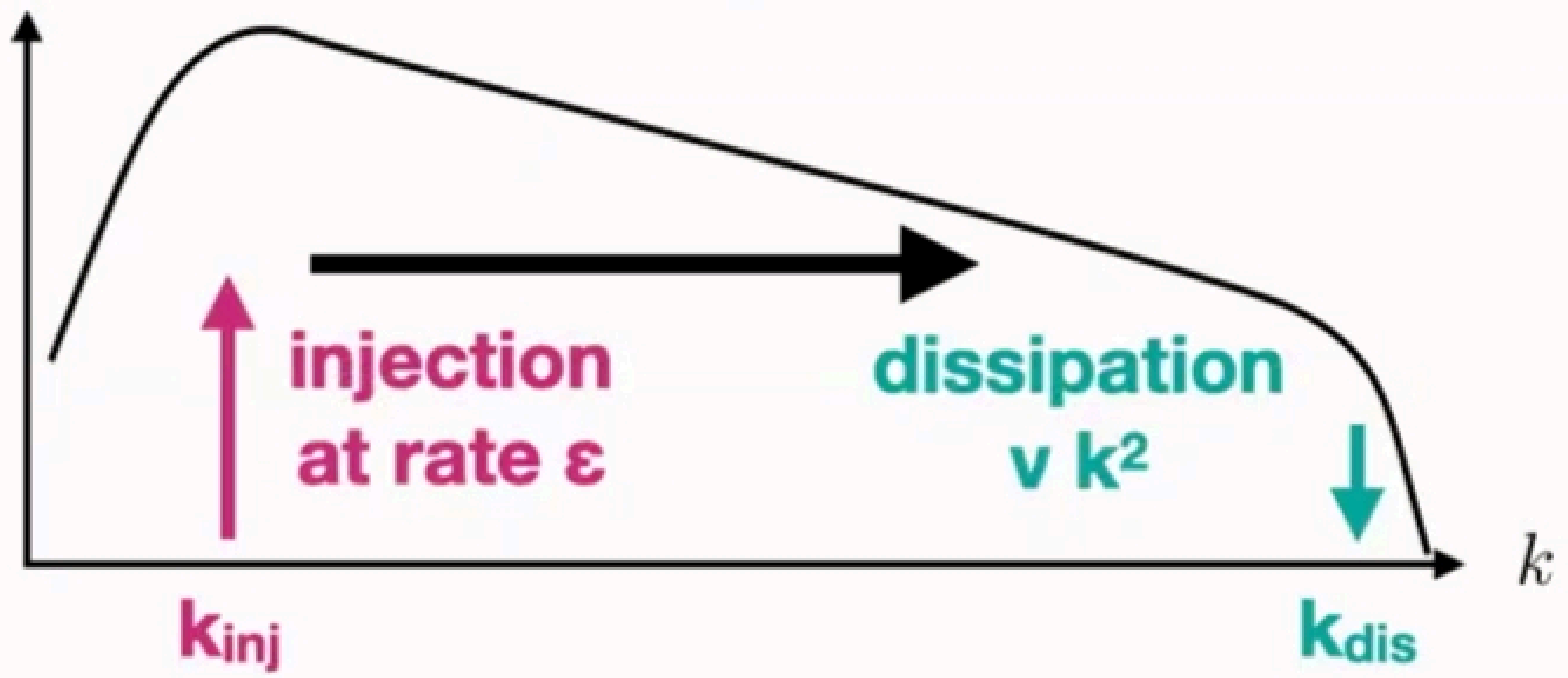


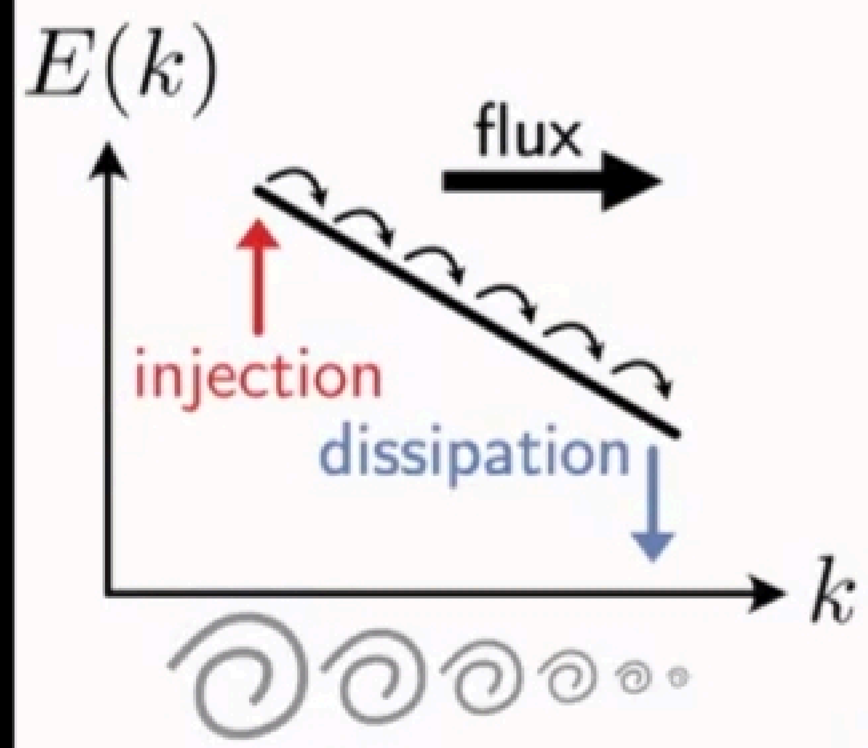
L. da Vinci (1508)

What is turbulence?

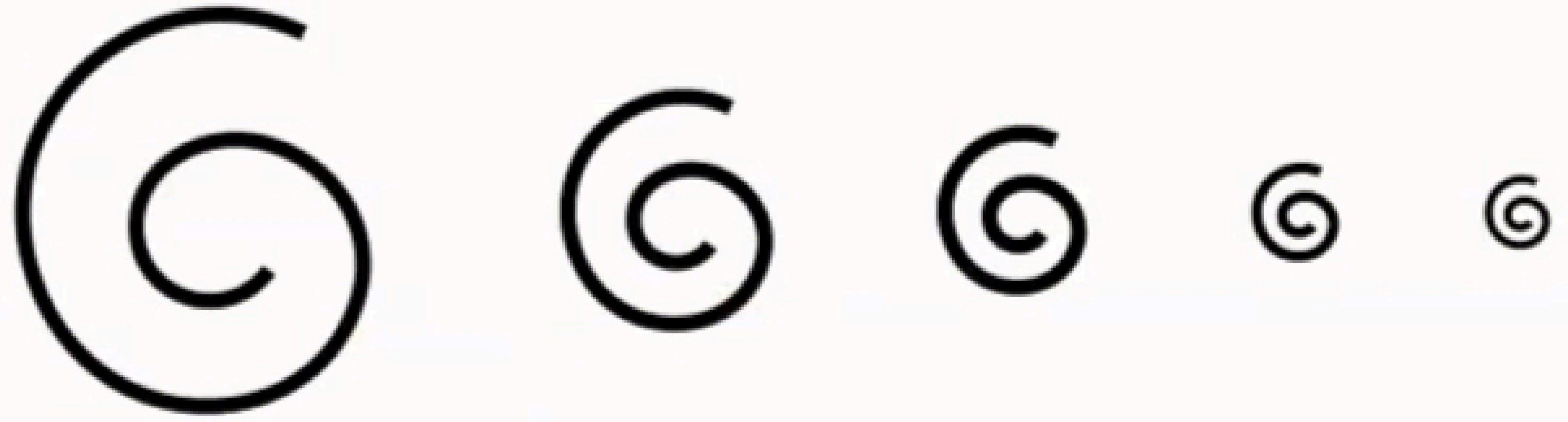


energy spectrum
$E(k) \sim \varepsilon^{2/3} k^{-5/3}$





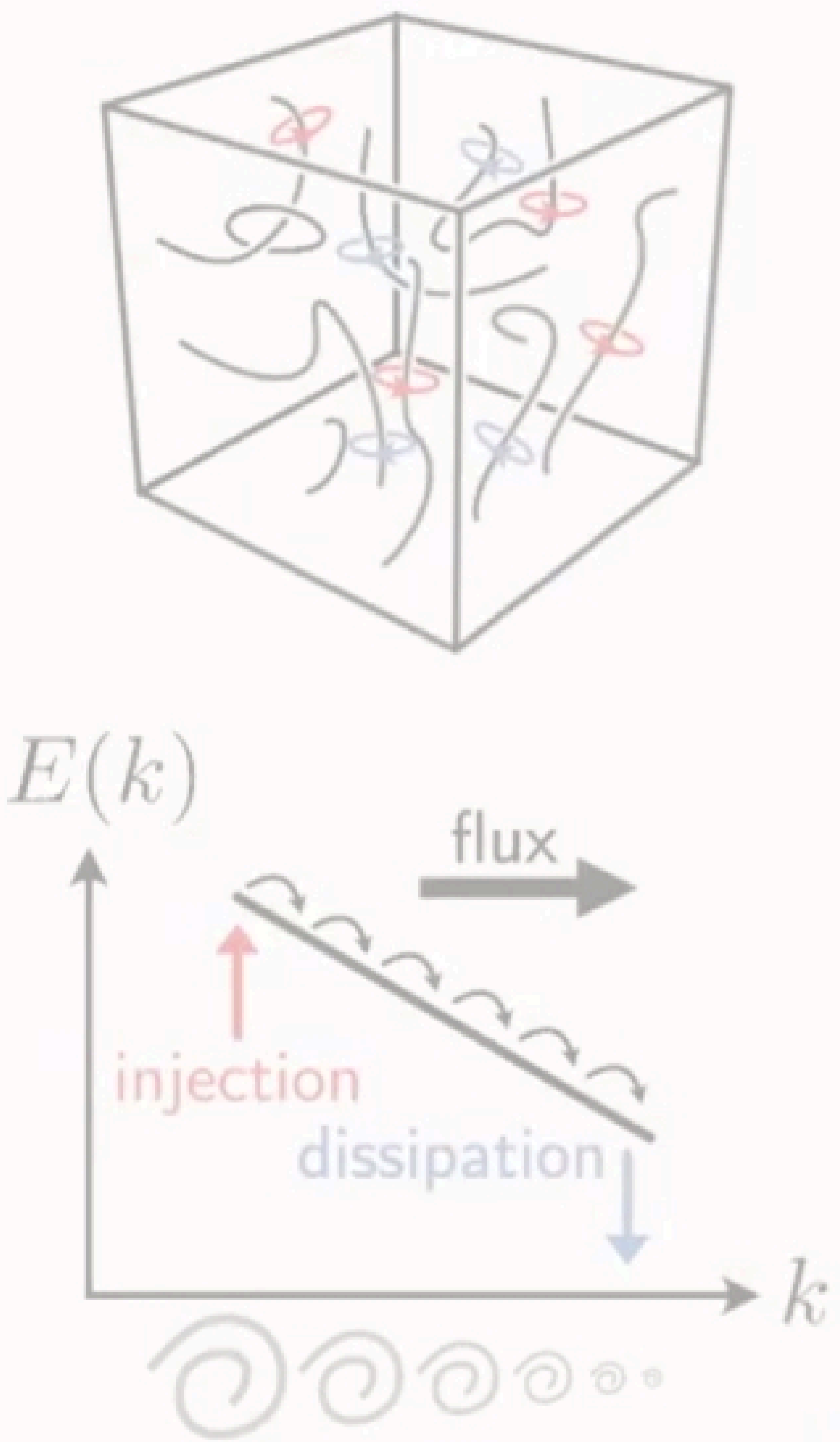
direct energy cascade



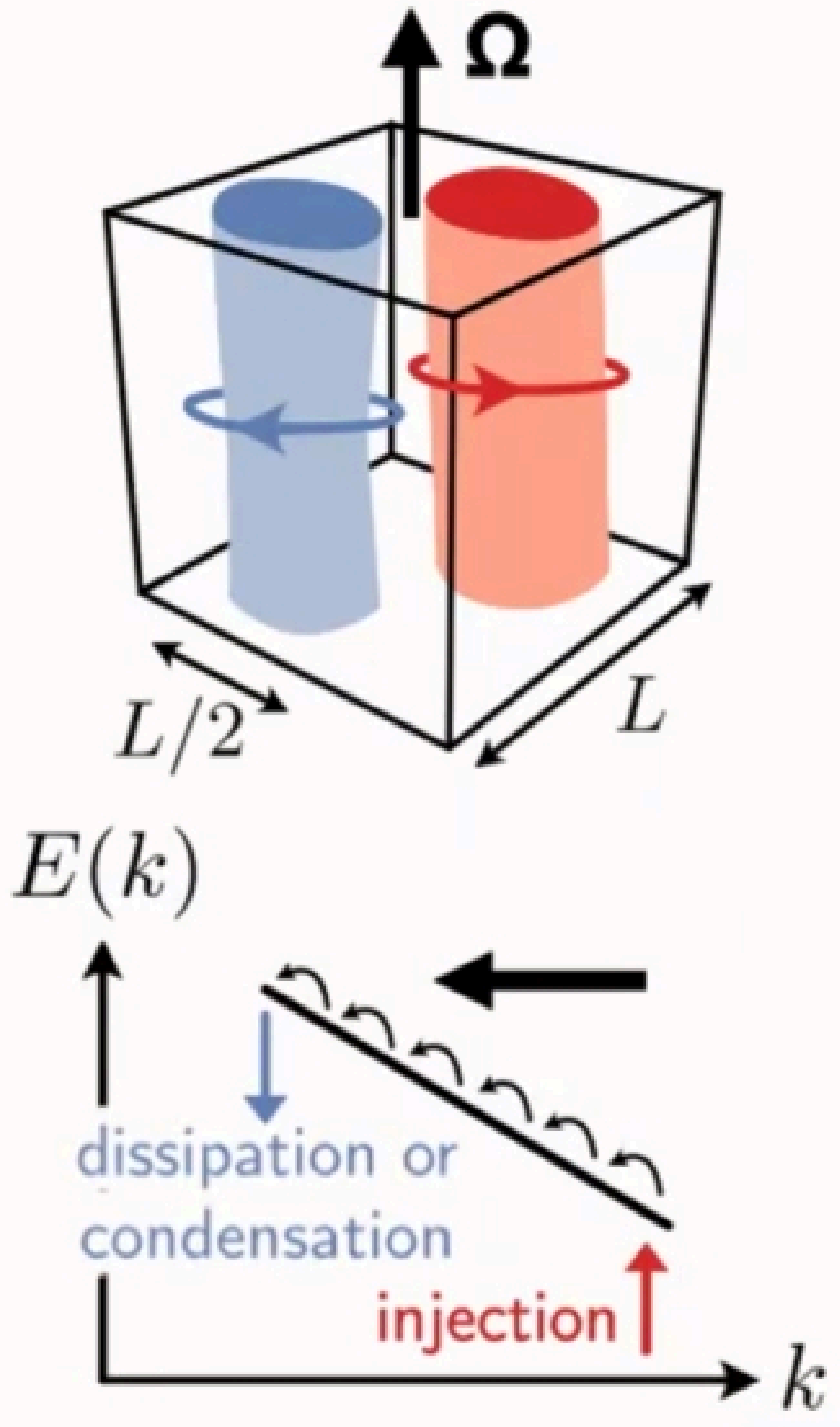
large vortices break down into smaller vortices

turbulent cascades are scale invariant, apparently featureless, chaotic states

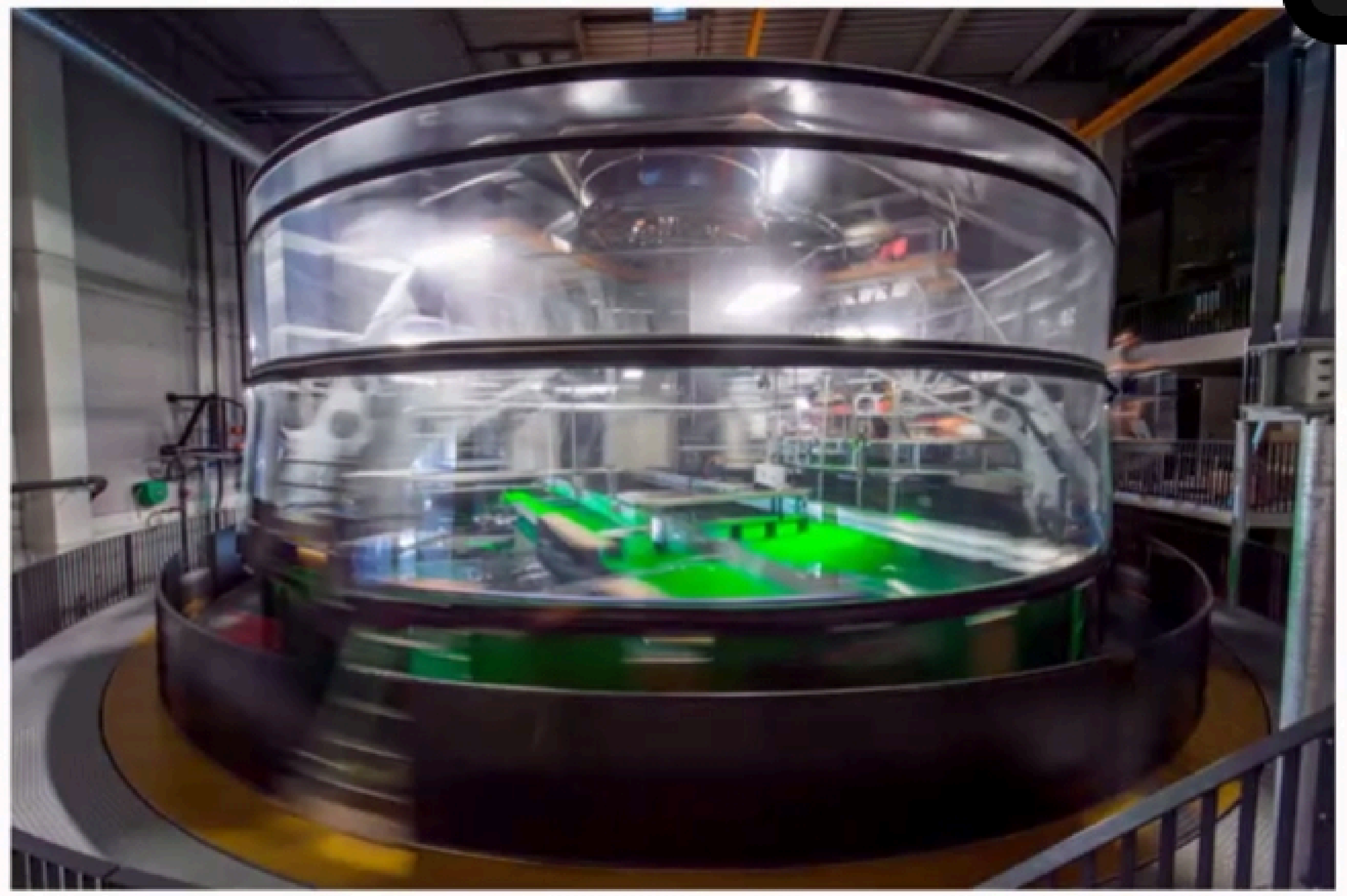
What is turbulence?



direct
energy cascade



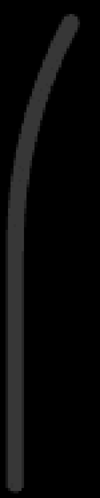
inverse
energy cascade



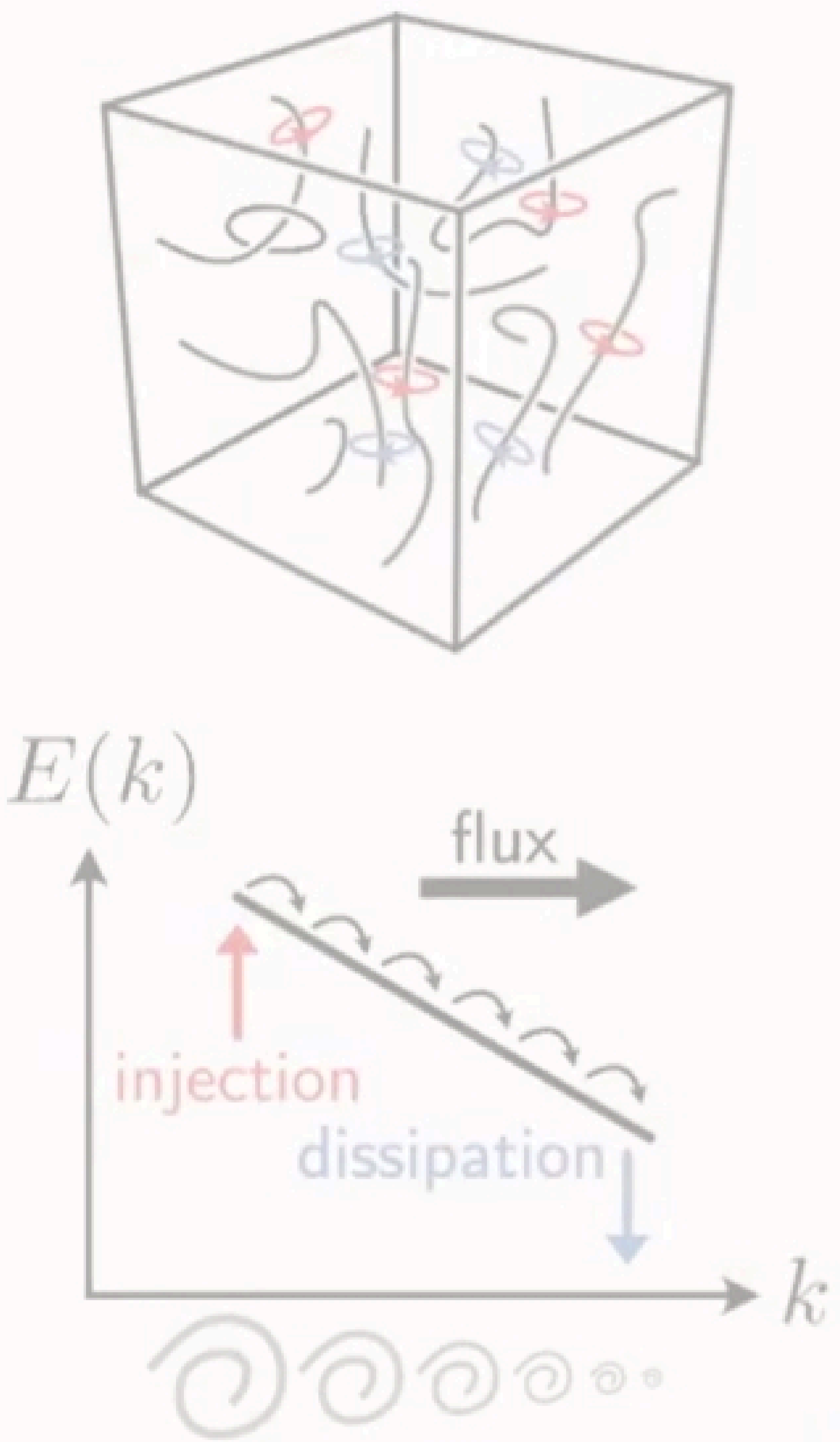
Coriolis @ LEGI

rotation leads to an inverse cascade

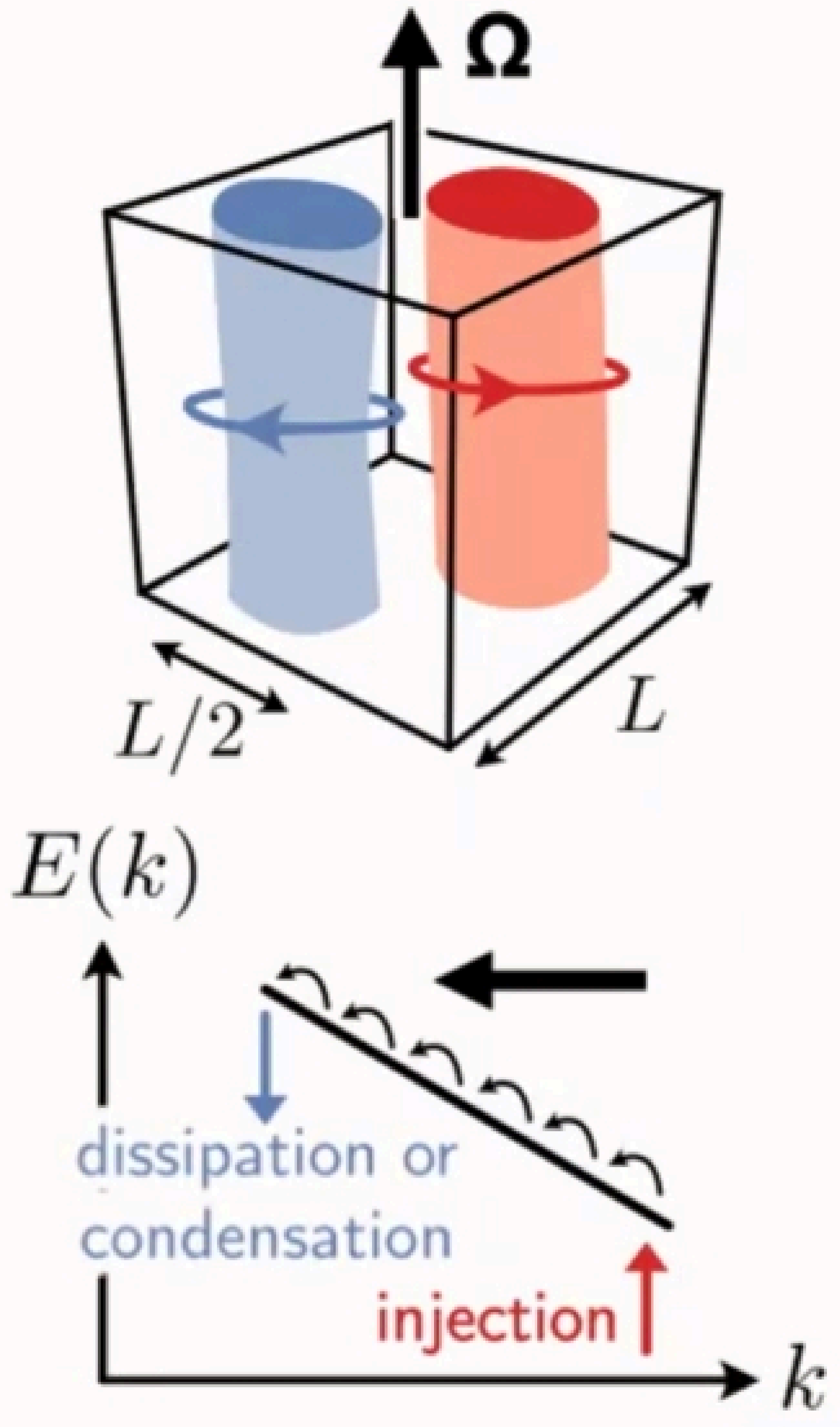
tank : 13 m diameter ; 130 tons of water



What is turbulence?



direct
energy cascade

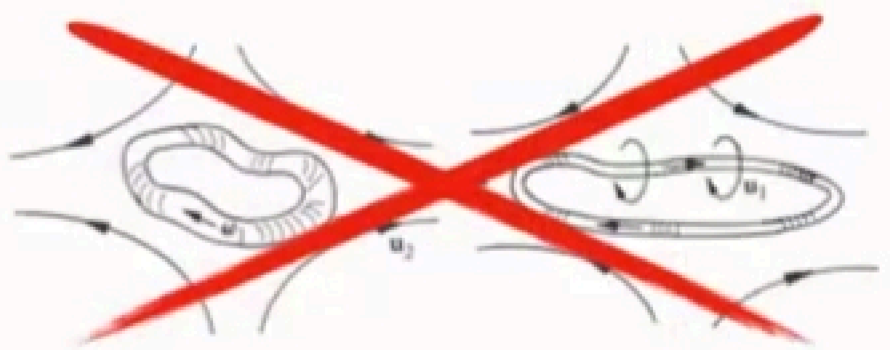


inverse
energy cascade

flow quasi-2D (Taylor-Proudman) $\partial_z v \simeq 0$

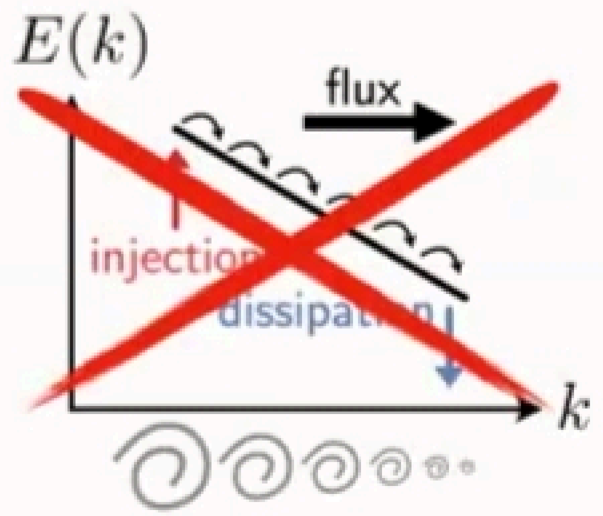
$\Downarrow$

vortices do not split



$\Downarrow$

no direct cascade



but vortices can still merge

rotation leads to an inverse cascade

Odd viscosity

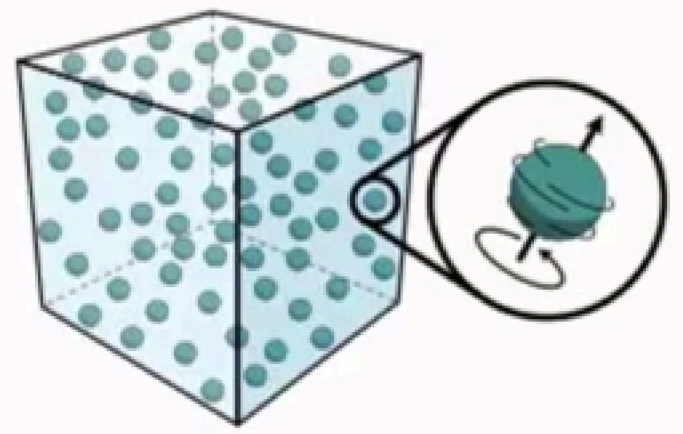
odd viscosity

$$D_t\vec{v} = -\frac{1}{\rho}\vec{\nabla}P + \nu\Delta\vec{v} + \boxed{\nu^{\mathrm{odd}}\vec{e}_z \times \Delta\vec{v}}$$

3D Navier-Stokes

small k	large k
like nothing	like Coriolis force
$\boxed{0}$	$\boxed{\Omega\vec{e}_z \times \vec{v}}$
3D direct cascade	2D inverse cascade

k



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

non-dissipative odd/Hall viscosity acts as scale-dependent Coriolis force

De Wit, Fruchart, Khain, Toschi, Vitelli, Nature 627, 515–521 (2024)

Odd viscosity

odd viscosity

$$D_t\vec{v} = -\frac{1}{\rho}\vec{\nabla}P + \nu\Delta\vec{v} + \boxed{\nu^{\mathrm{odd}}\vec{e}_z \times \mathbf{k}^2\,\vec{v}}$$

3D Navier-Stokes

small k	large k
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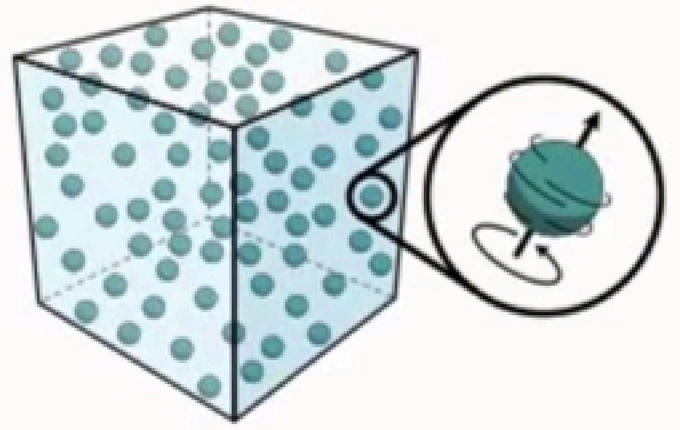
3D direct cascade	2D inverse cascade
→	←

k



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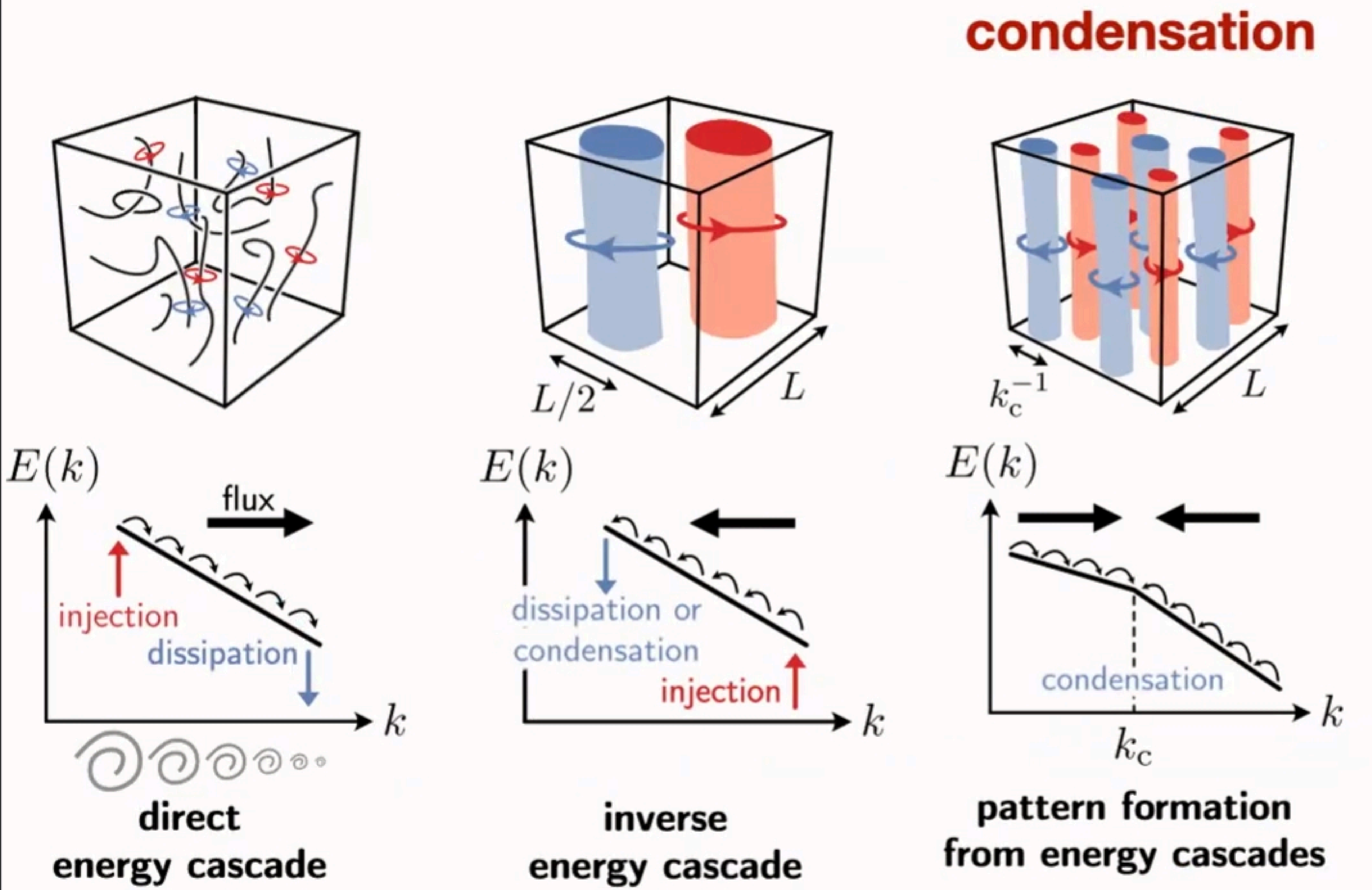
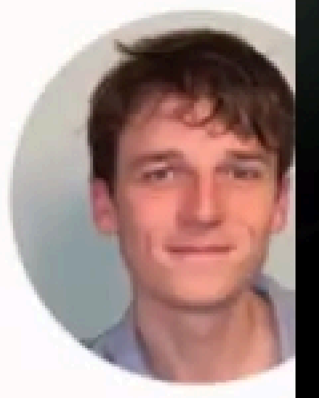
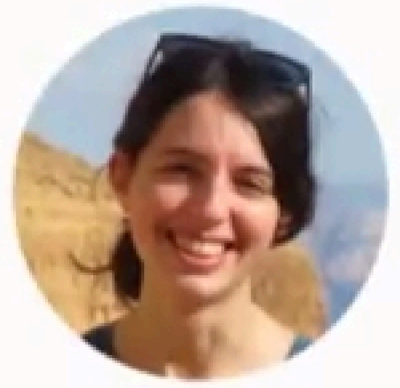
De Wit, Fruchart, Khain, Toschi, Vitelli, Nature 627, 515–521 (2024)

Pattern formation by turbulent cascades




Xander De


Tali Khain


Federico Toschi


Vincenzo Vitelli

large vortices split while small vortices merge ⇒ wavelength selection

De Wit, Fruchart, Khain, Toschi, Vitelli, Nature 627, 515–521 (2024)

Odd viscosity

fluid with odd viscosity

$$D_t\vec{v} = -\frac{1}{\rho}\vec{\nabla}P + \begin{pmatrix} \nu & \nu^{\mathrm{odd}} & 0 \\ -\nu^{\mathrm{odd}} & \nu & 0 \\ 0 & 0 & \nu \end{pmatrix} \Delta\vec{v}$$

odd waves

$$\omega(\boldsymbol{k}) = \pm\nu_{\mathrm{odd}} k_z |k|$$

odd viscosity induces waves in the fluid

Odd viscosity

fluid with odd viscosity

$$D_t\vec{v} = -\frac{1}{\rho}\vec{\nabla}P + \begin{pmatrix} \nu & \nu^{\mathrm{odd}} & 0 \\ -\nu^{\mathrm{odd}} & \nu & 0 \\ 0 & 0 & \nu \end{pmatrix} \Delta\vec{v}$$

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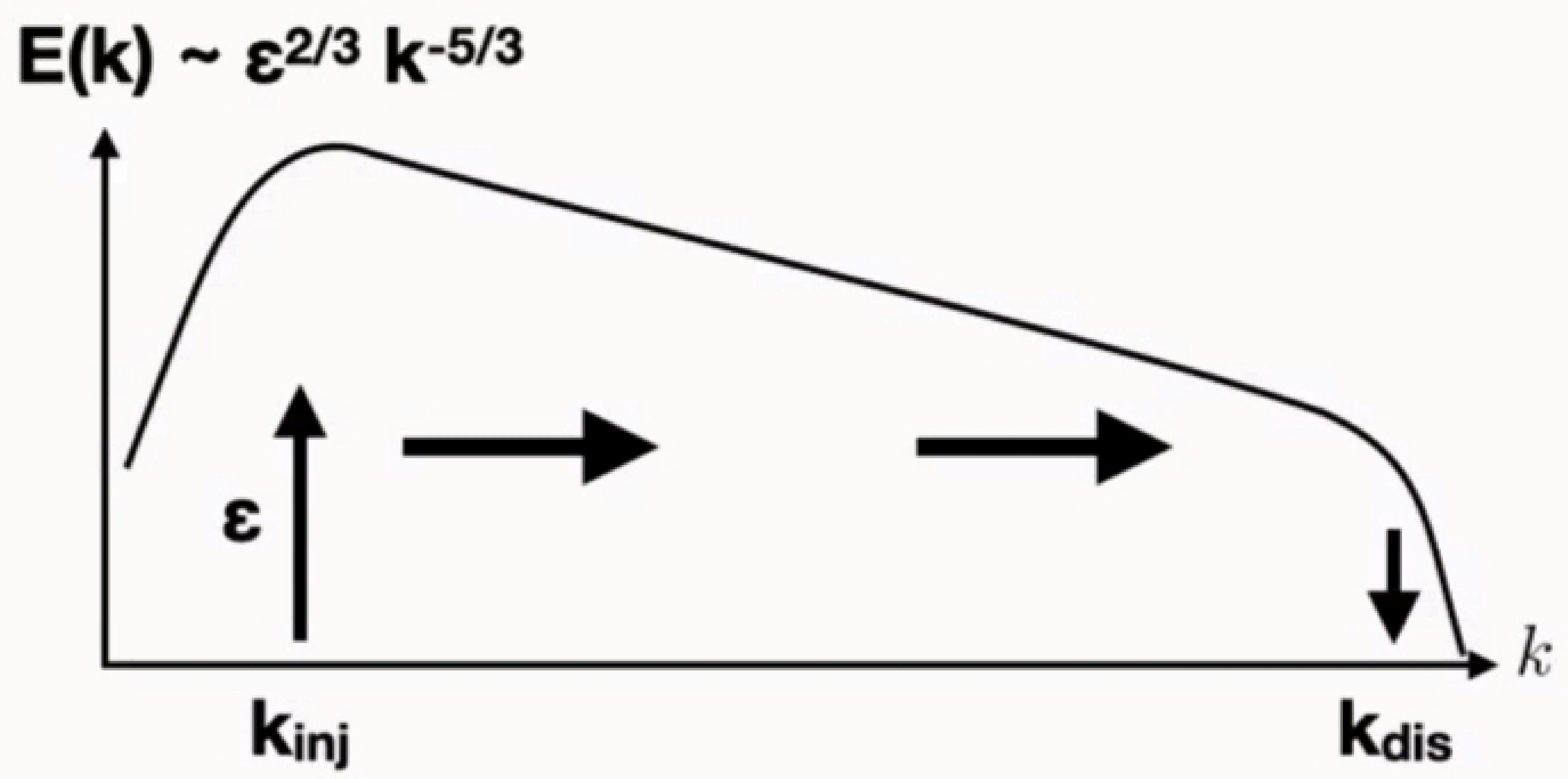
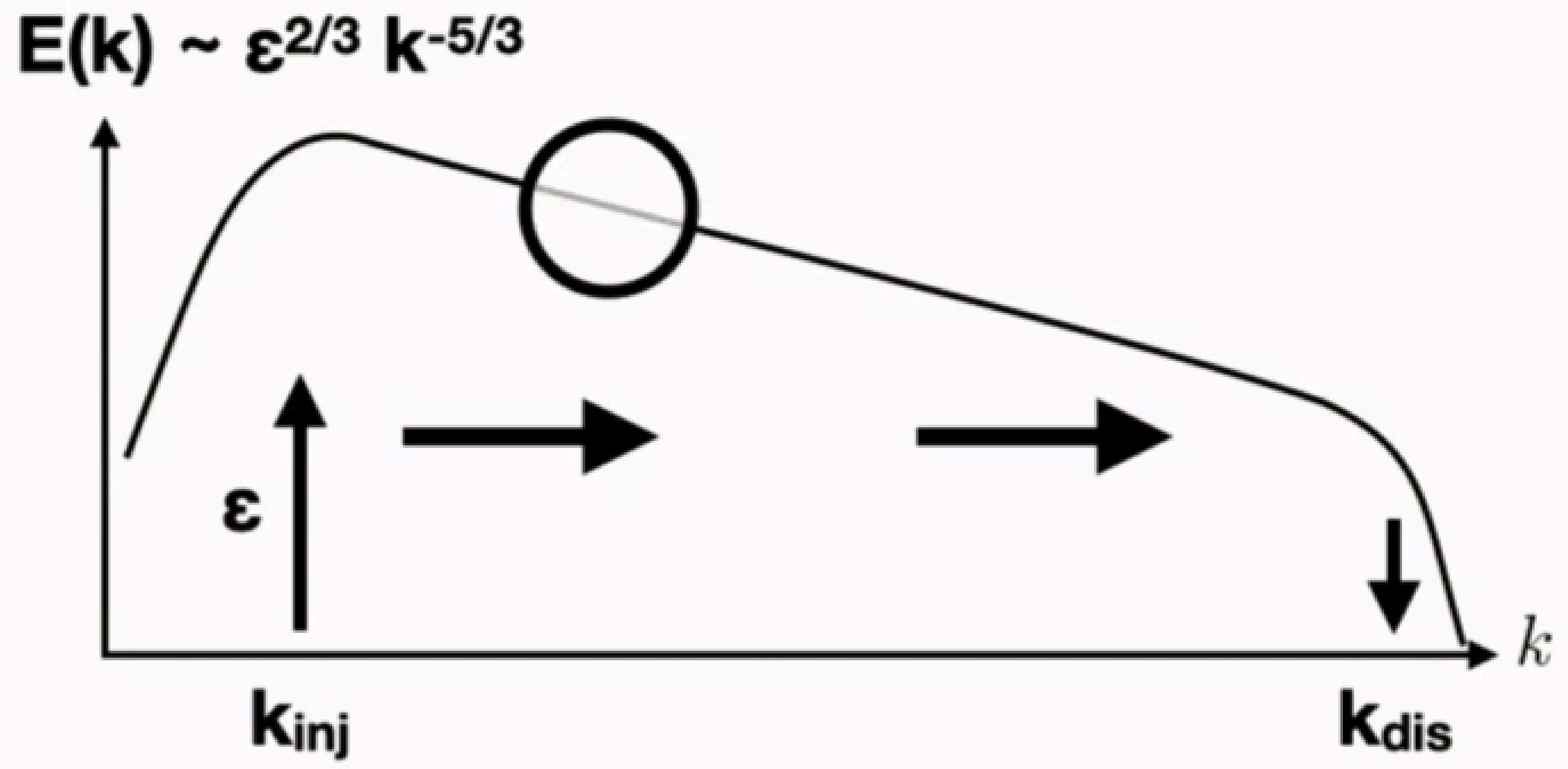
odd viscosity induces waves in the fluid

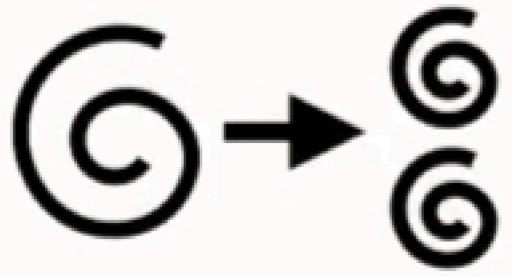
Waves vs Vortices



$k_{dis} \sim (\nu^3/\varepsilon)^{1/4}$

Waves vs Vortices





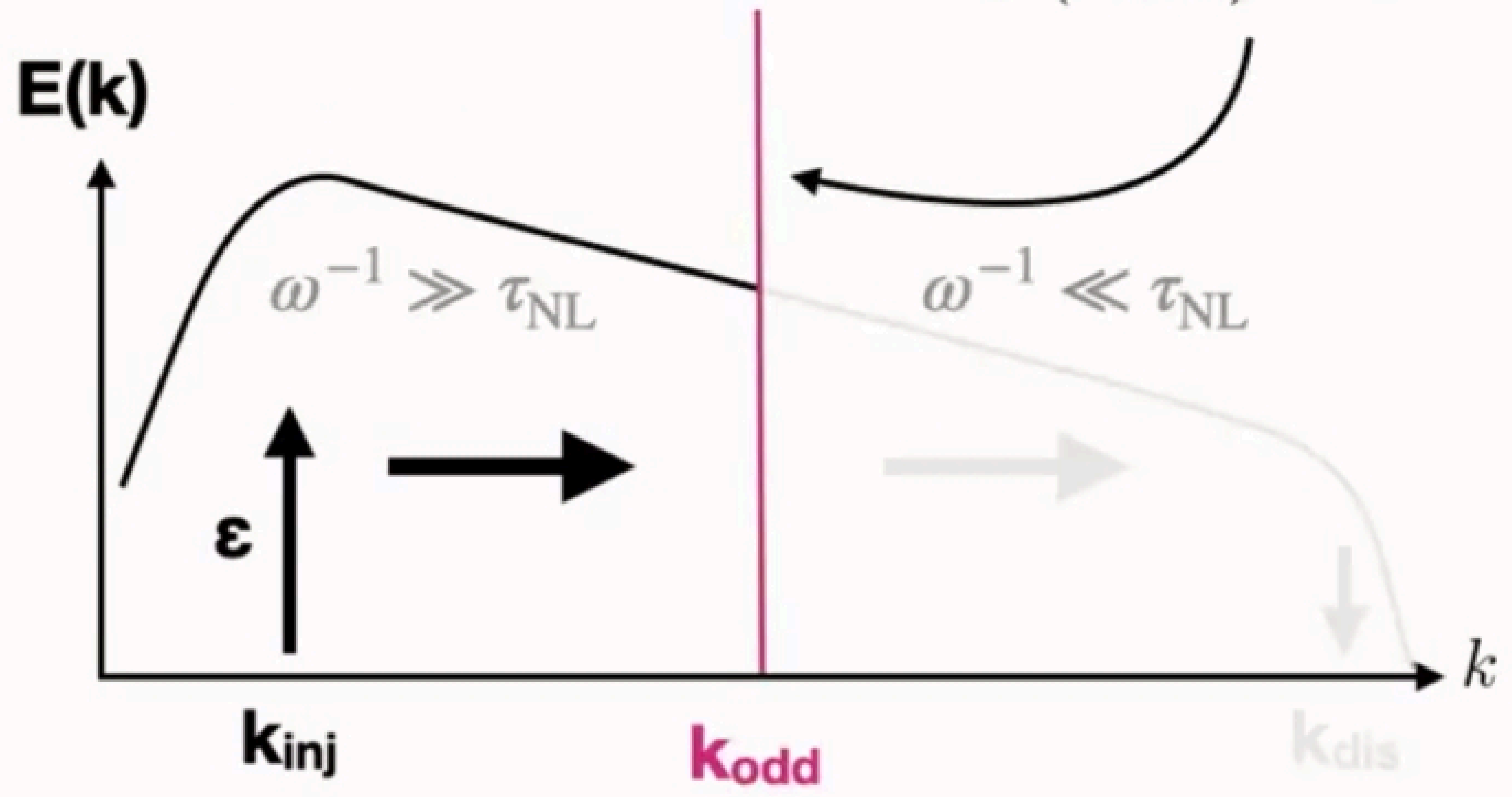
characteristic time
(eddy turnover time) $\tau_{\rm nl}(k)$

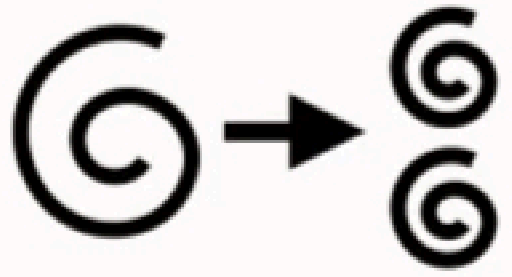
$k_{dis} \sim (\nu^3/\varepsilon)^{1/4}$

Waves vs Vortices

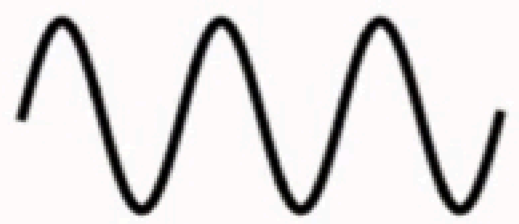
$$\tau_{\rm nl}(k_{\rm odd}) = \omega^{-1}(k_{\rm odd})$$

$$k_{\rm odd} \equiv \epsilon^{\frac{1}{4}} \nu_{\rm odd}^{-\frac{3}{4}}$$

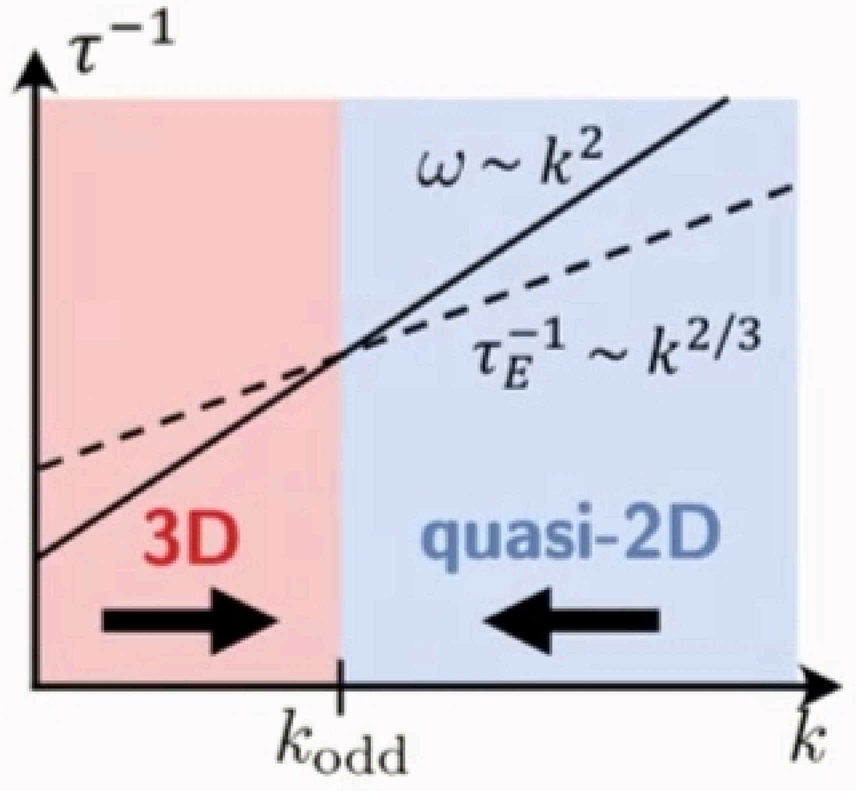




characteristic time (eddy turnover time) $\tau_{\rm nl}(k)$



dispersion of odd waves $\omega(k)$

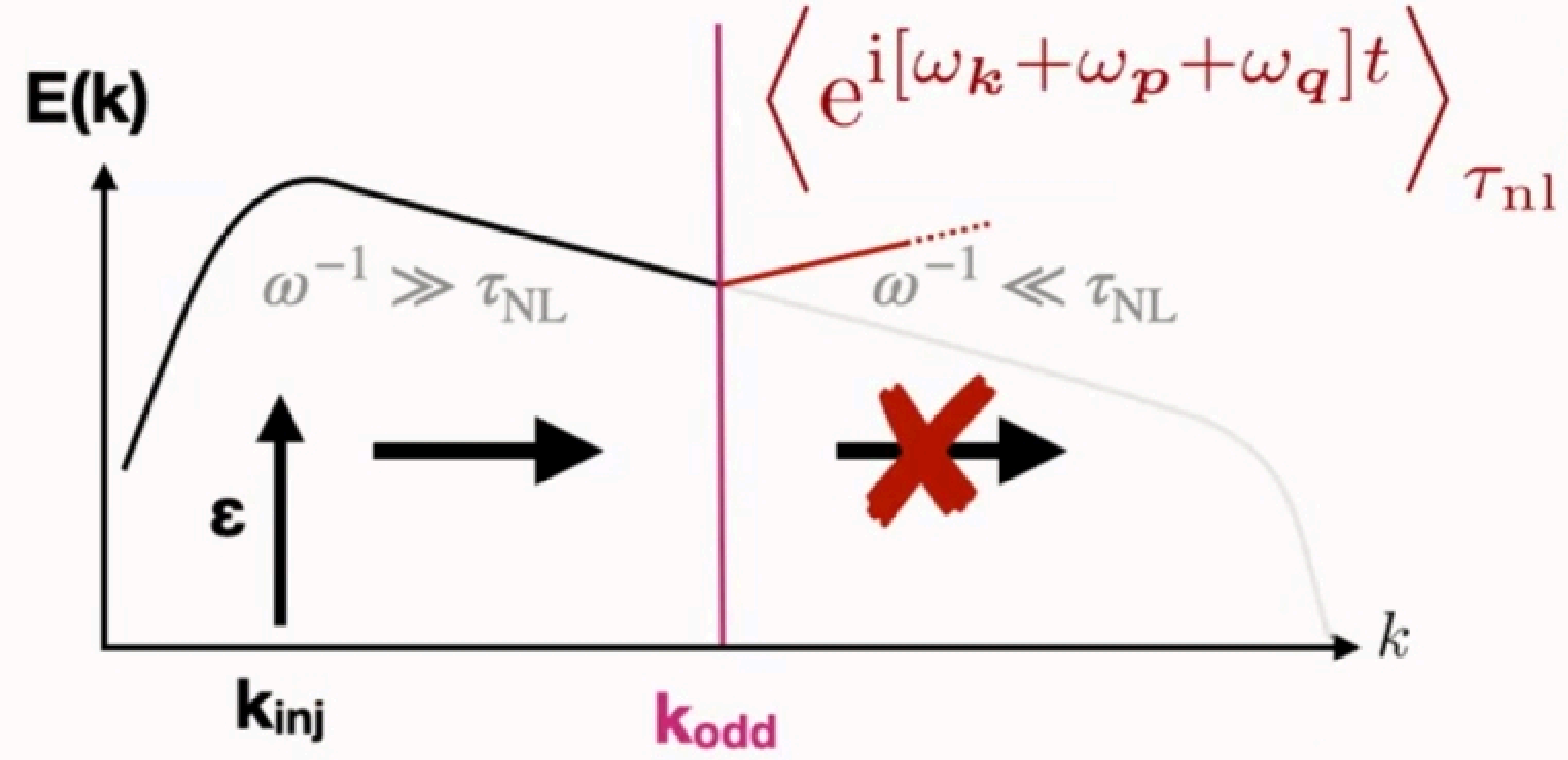


odd waves affect eddy turbulence

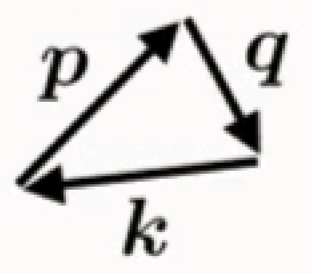
De Wit, Fruchart, Khain, Toschi, Vitelli, Nature 627, 515–521 (2024)

Waves vs Vortices

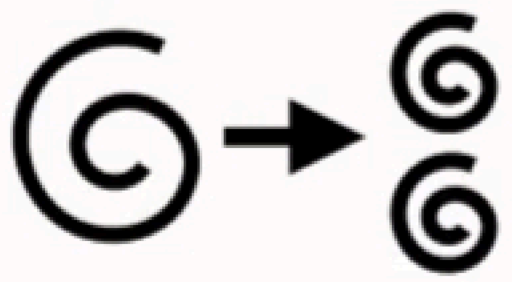
$$k_{\rm odd} \equiv \epsilon^{\frac{1}{4}} \nu_{\rm odd}^{-\frac{3}{4}}$$



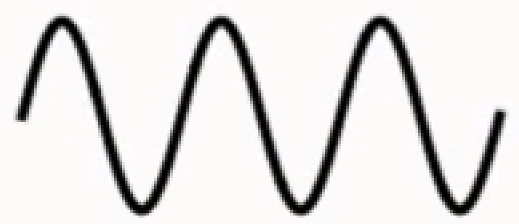
cascade is arres
so energy piles u



triads



characteristic time (eddy turnover time) $\tau_{\rm nl}(k)$



dispersion of odd waves $\omega(k)$

odd waves affect eddy turbulence

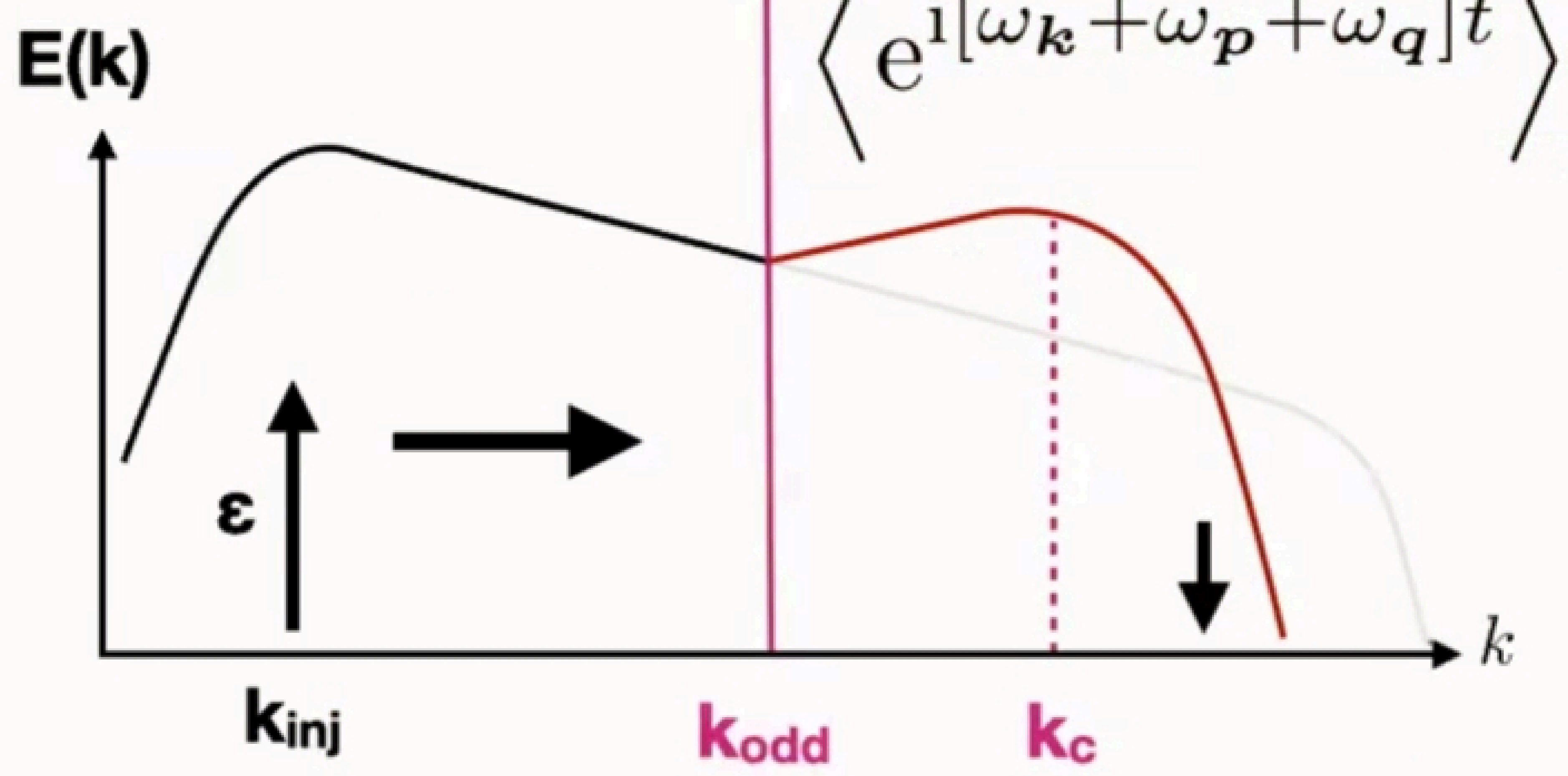
De Wit, Fruchart, Khain, Toschi, Vitelli, Nature 627, 515–521 (2024)

Waves vs Vortices

$$k_{\mathrm{odd}} \equiv \epsilon^{\frac{1}{4}} \nu_{\mathrm{odd}}^{-\frac{3}{4}}$$

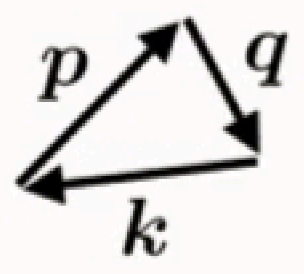
$$k_{\mathrm{c}} \propto \epsilon^{\frac{1}{4}} \nu^{-\frac{1}{2}} \nu_{\mathrm{odd}}^{-\frac{1}{4}}$$

$$\left\langle e^{i[\omega_{\boldsymbol{k}}+\omega_{\boldsymbol{p}}+\omega_{\boldsymbol{q}}]t} \right\rangle_{\tau_{\mathrm{nl}}}$$

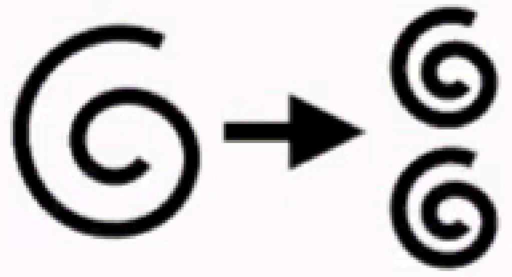


cascade is arres
so energy piles u

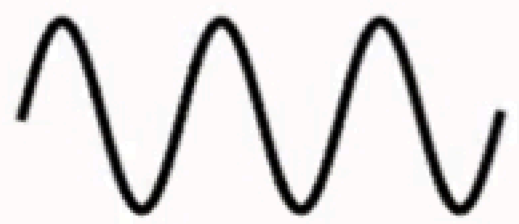
... until viscous dissipation ~ ν k² takes over



triads



characteristic time (eddy turnover time) $\tau_{\mathrm{nl}}(k)$



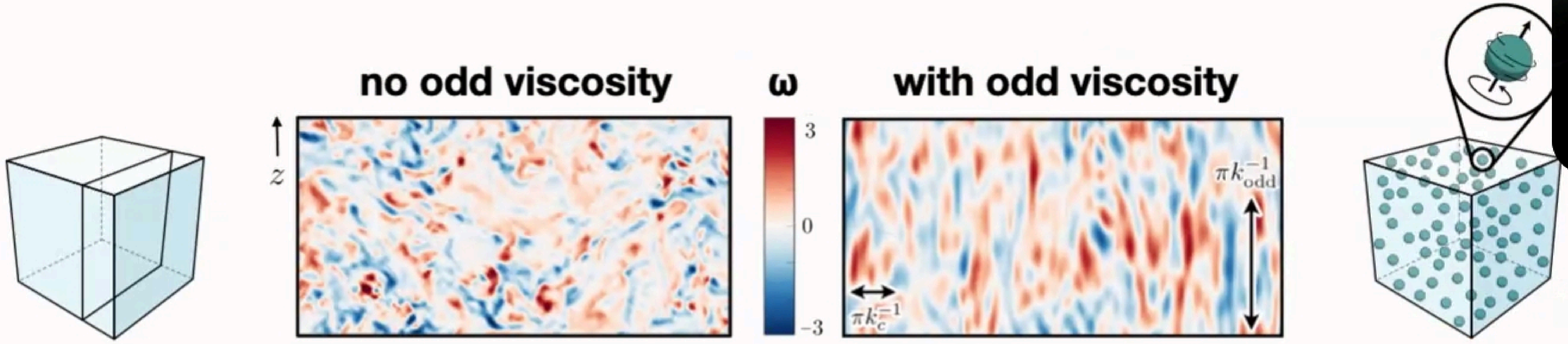
dispersion of odd waves $\omega(k)$

wavelength selection from arrest of turbulent cascade

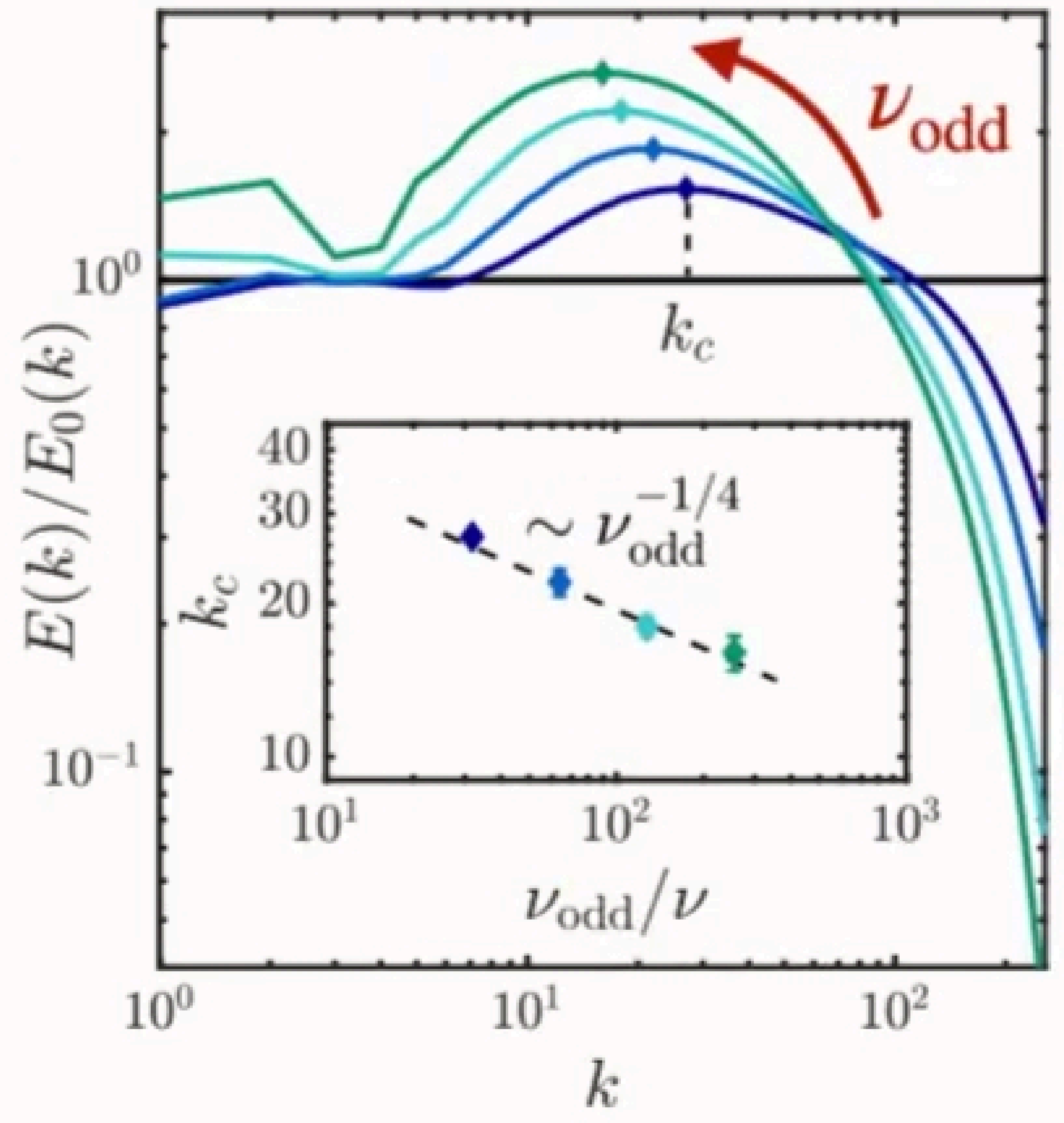
$$(\Delta E)_{\max} \sim \left(\frac{\nu_{\mathrm{odd}}}{\nu}\right)^{\frac{1}{3}}$$

De Wit, Fruchart, Khain, Toschi, Vitelli, Nature 627, 515–521 (2024)

Direct numerical simulations

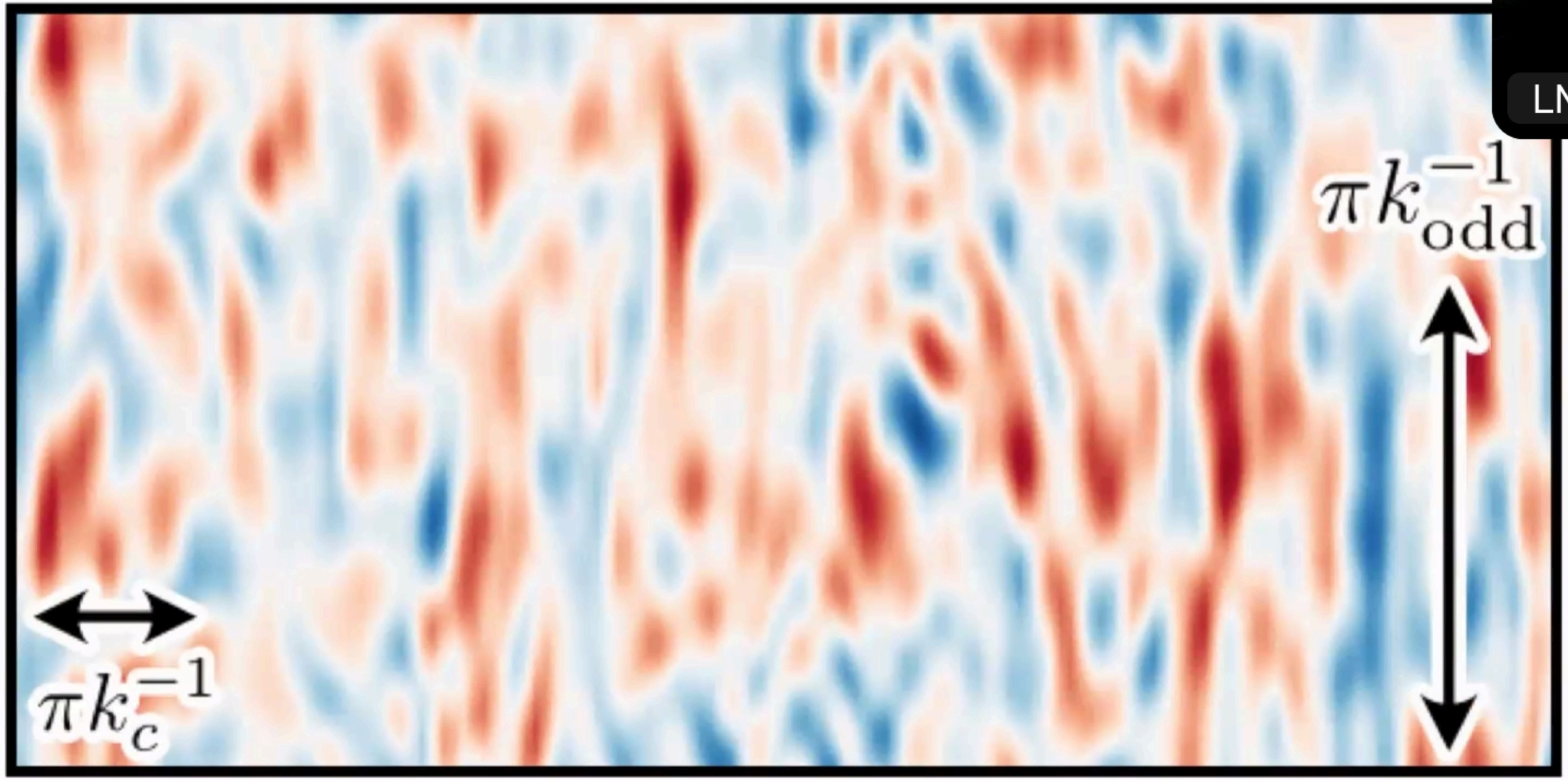


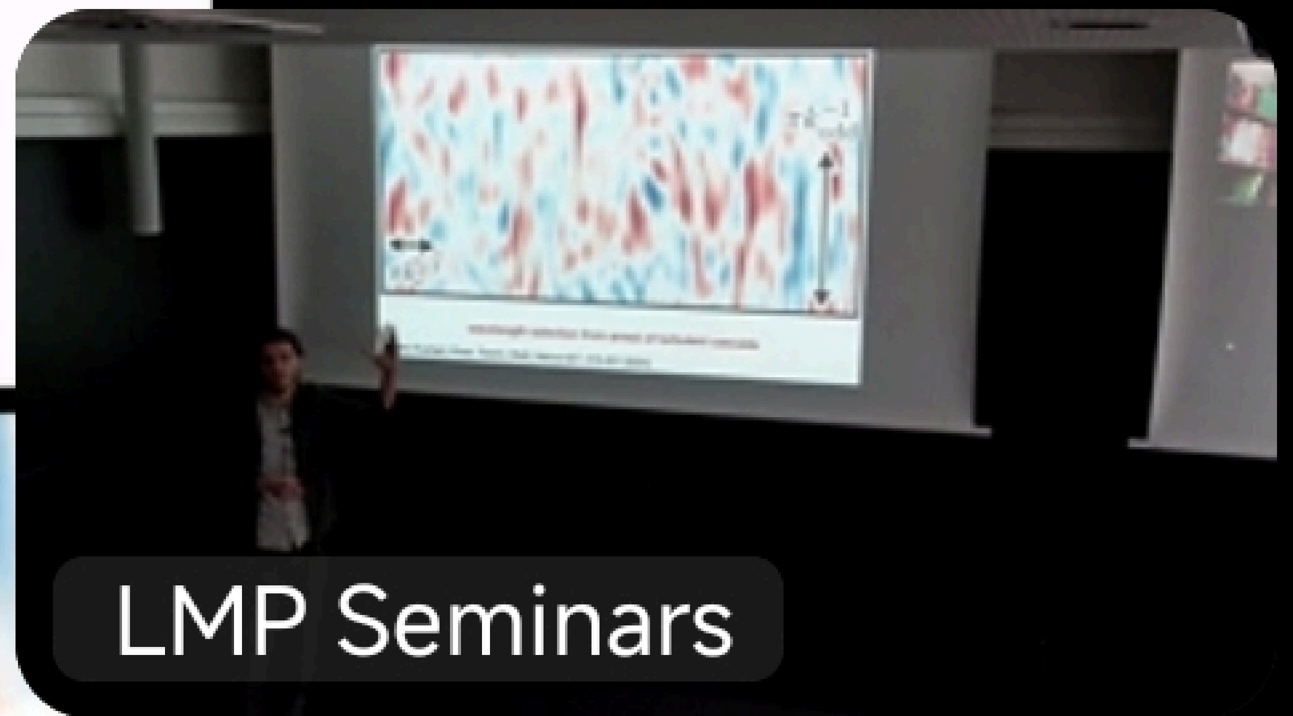
compensated spectrum E(k) / k$^{-5/3}$



wavelength selection from arrest of turbulent cascade

De Wit, Fruchart, Khain, Toschi, Vitelli, Nature 627, 515–521 (2024)





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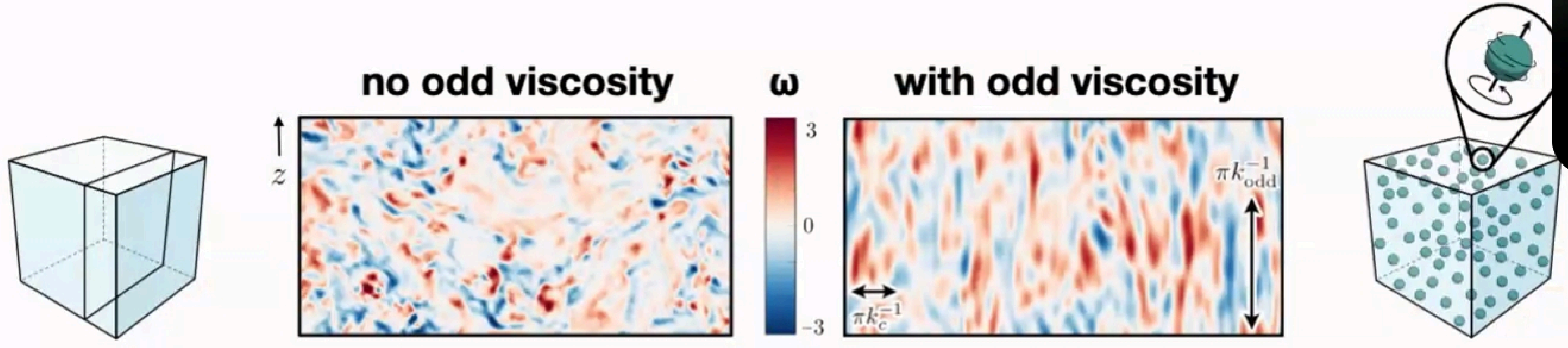

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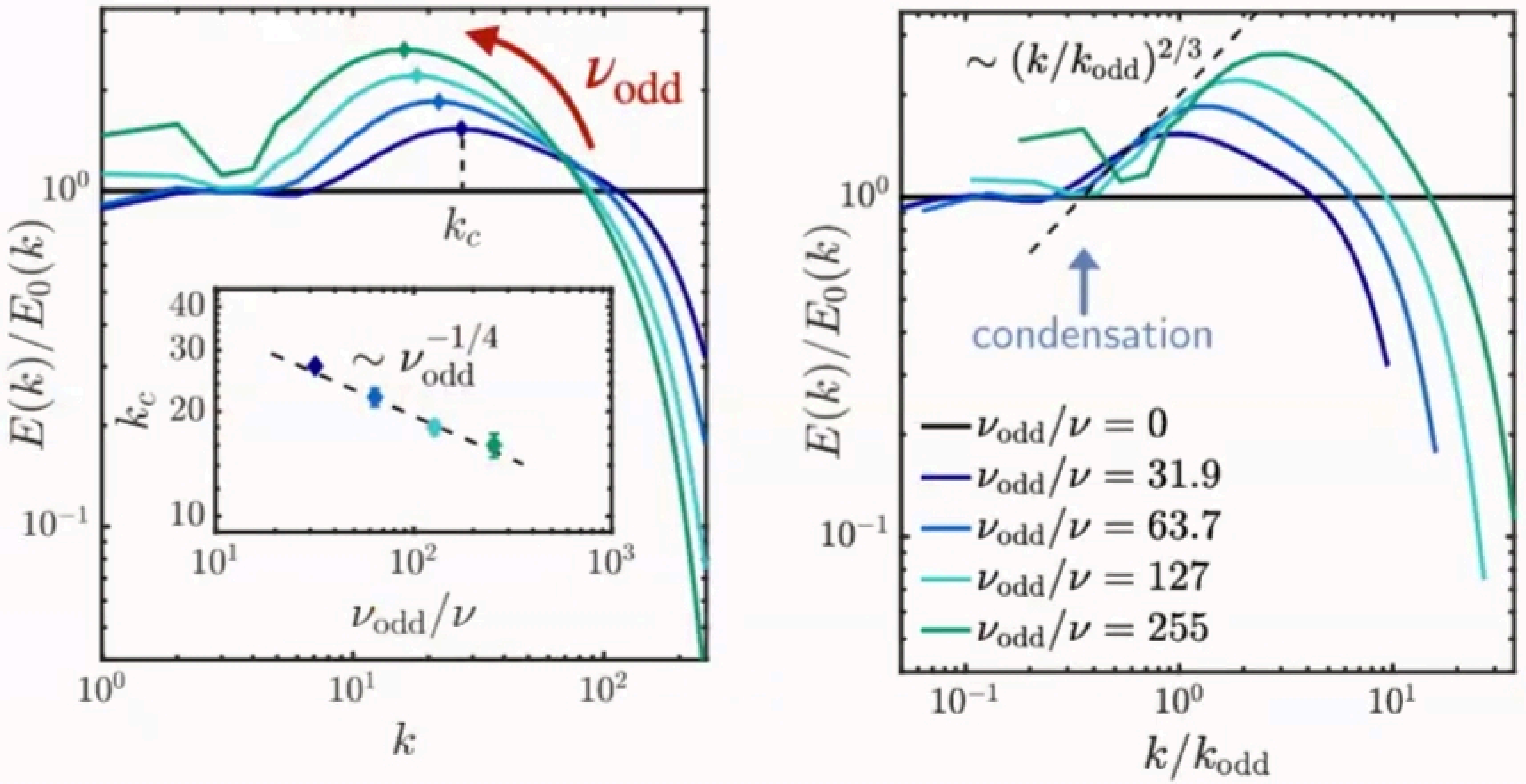
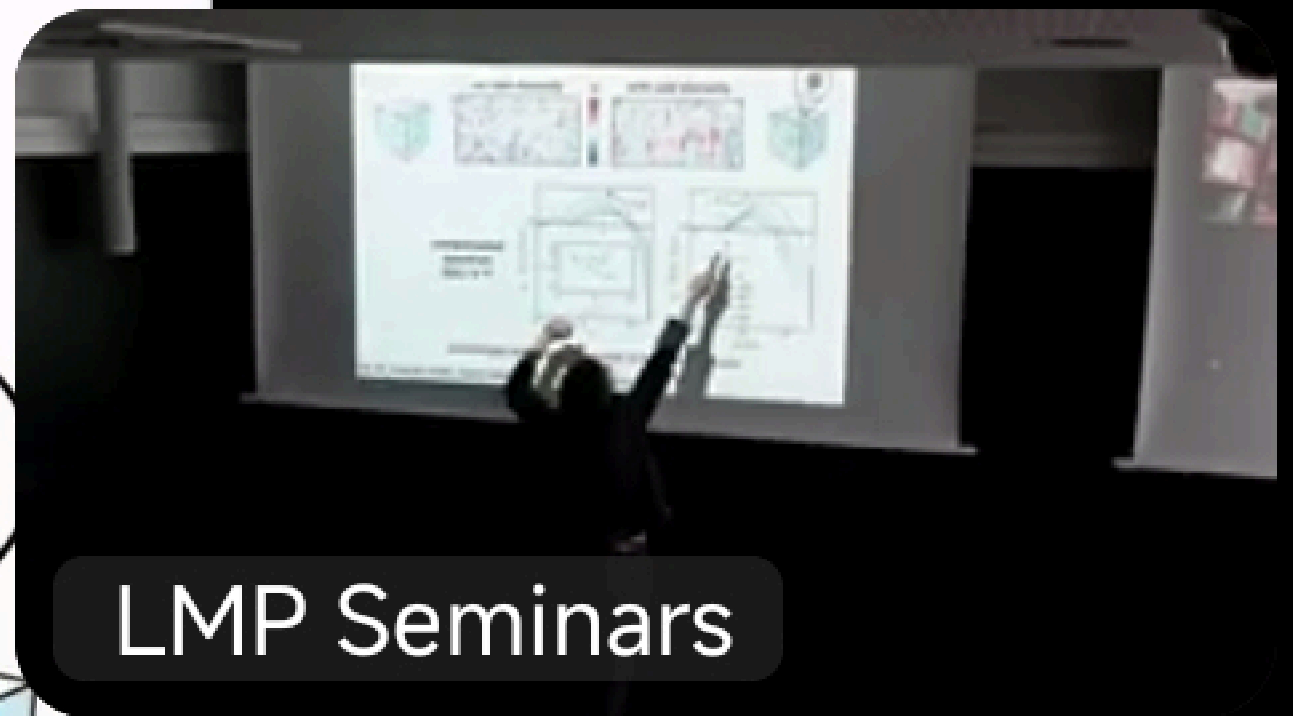


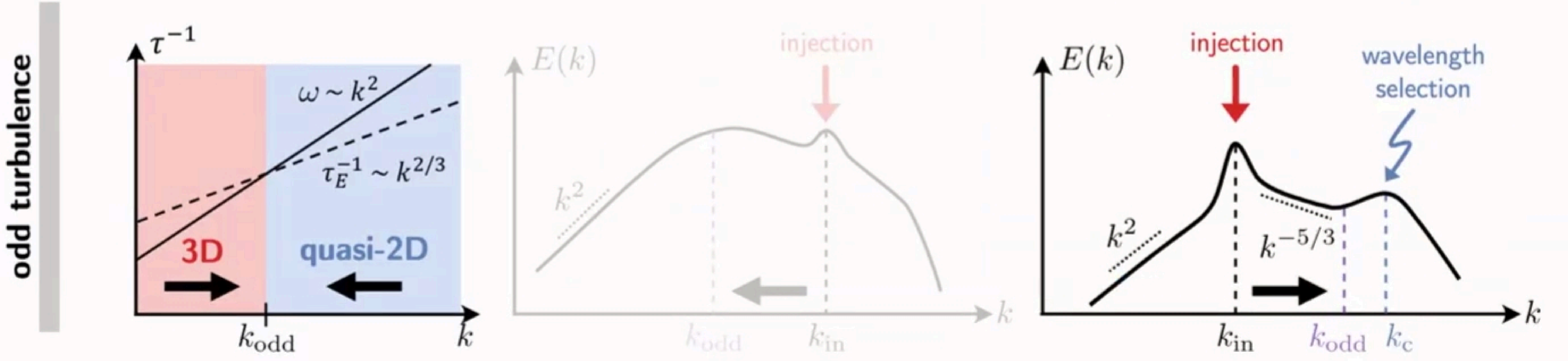
wavelength selection from arrest of turbulent cascade

De Wit, Fruchart, Khain, Toschi, Vitelli, Nature 627, 515–521 (2024)



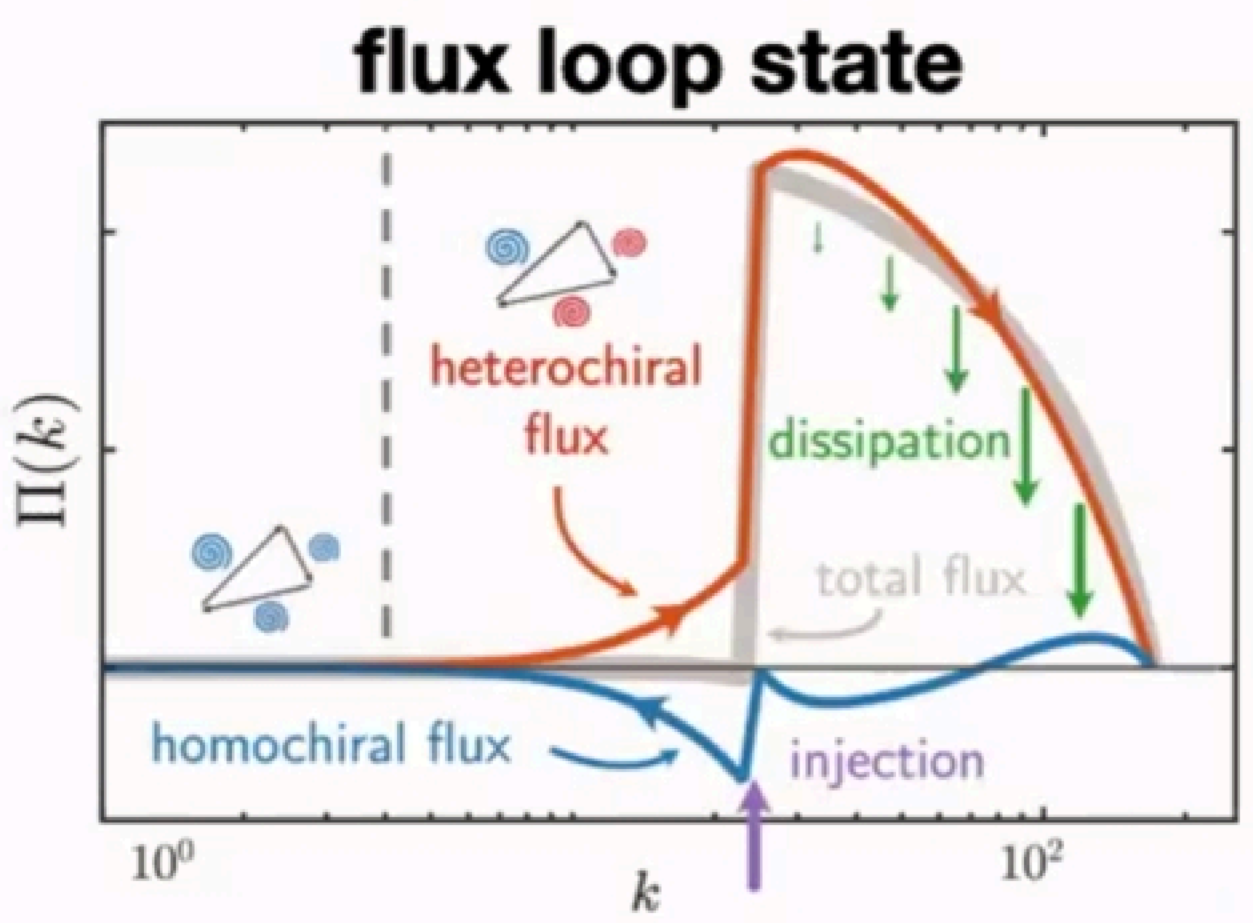
Odd turbulence

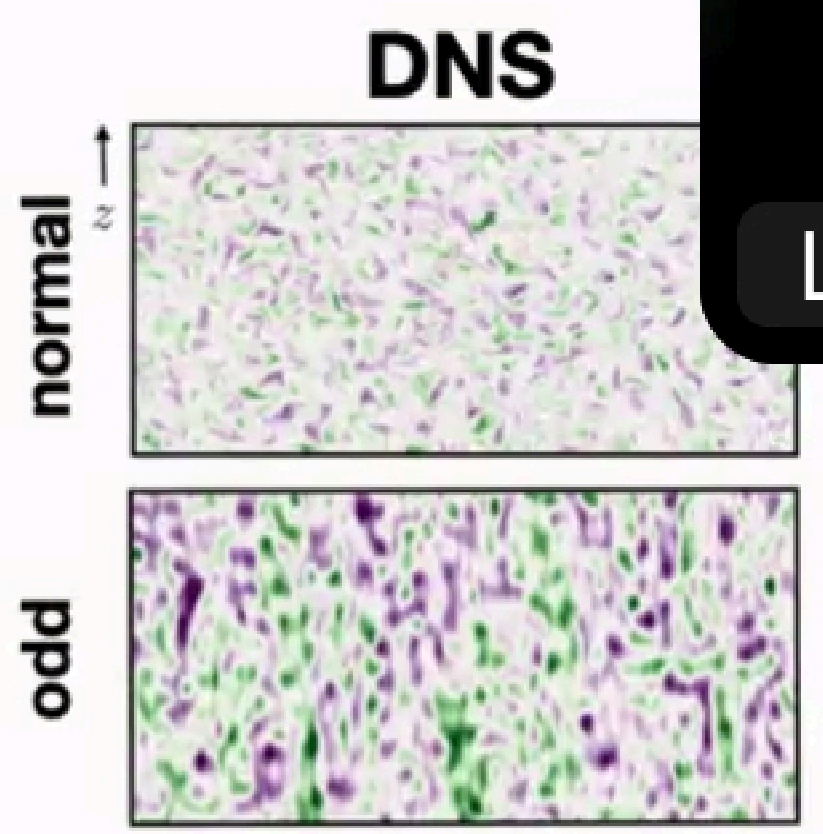
what we have seen up to now

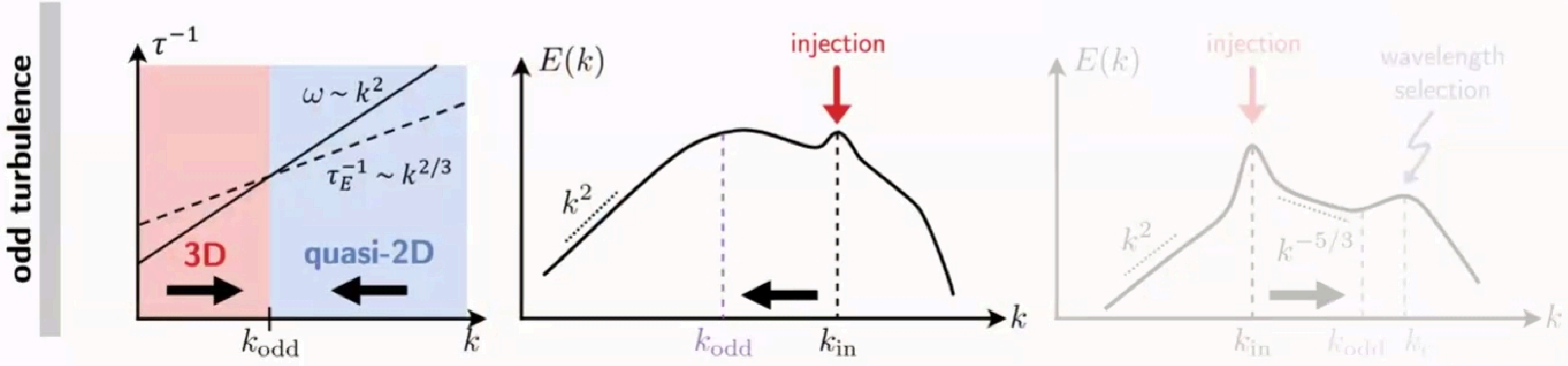


De Wit, Fruchart, Khain, Toschi, Vitelli, Nature 627, 515–521 (2024)

Odd turbulence



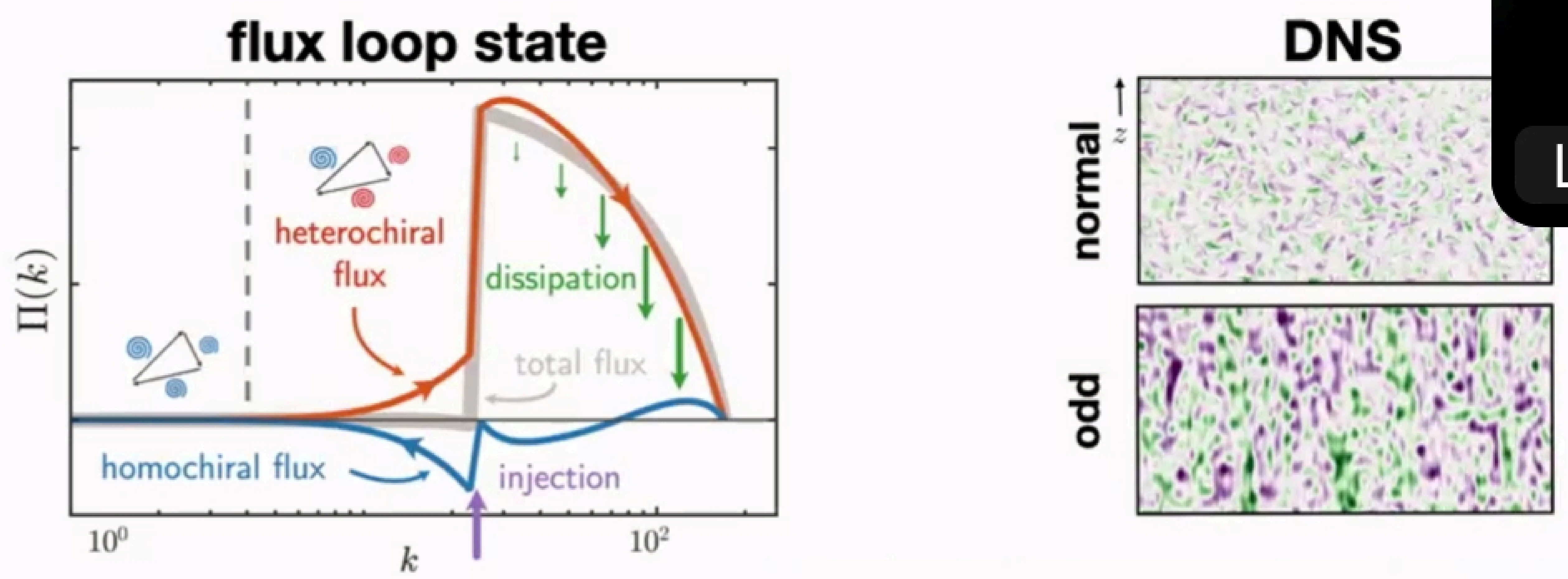


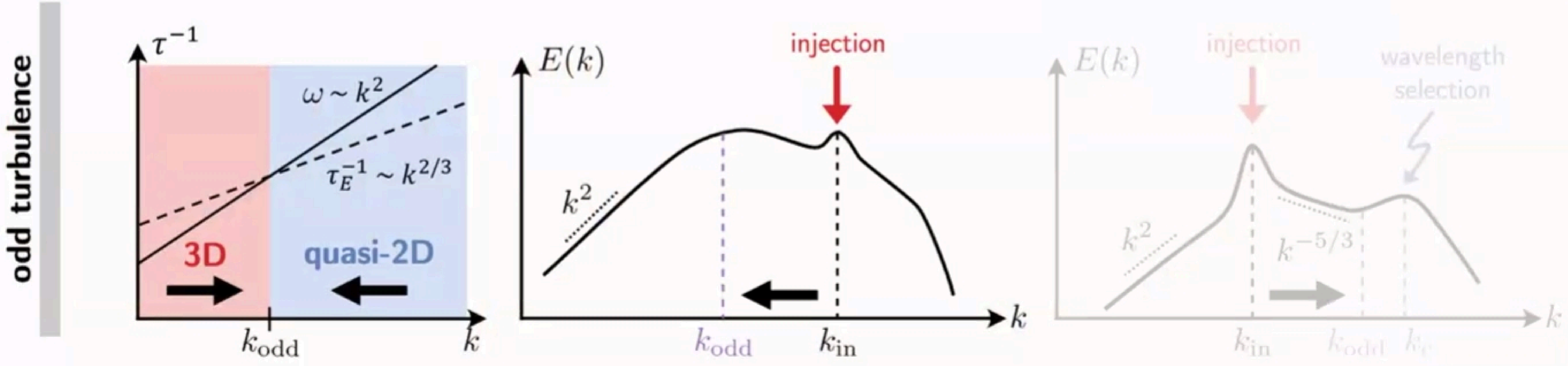


the inverse cascade can also be arrested

De Wit, Fruchart, Khain, Toschi, Vitelli, Nature 627, 515–521 (2024)

Odd turbulence





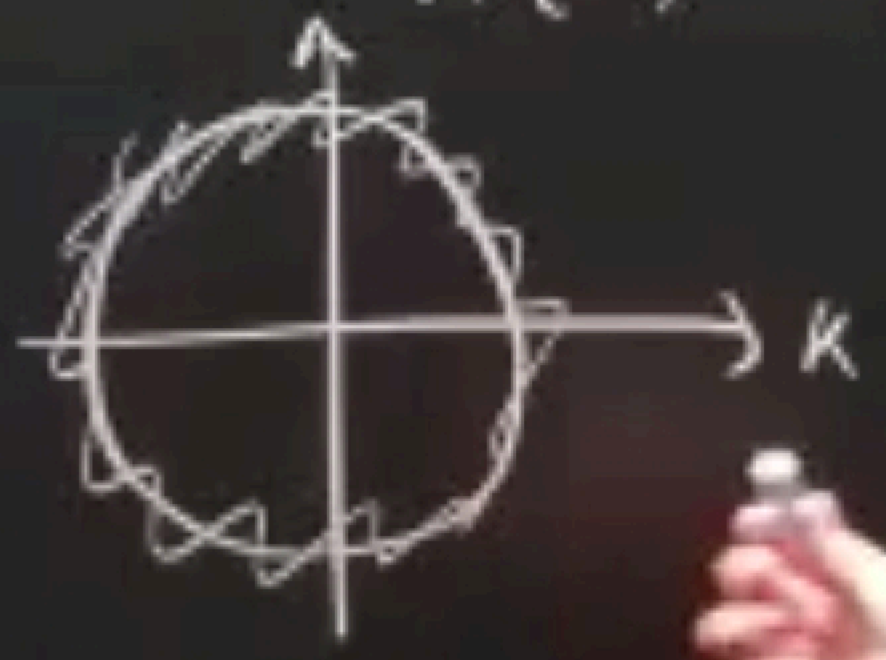
the inverse cascade can also be arrested

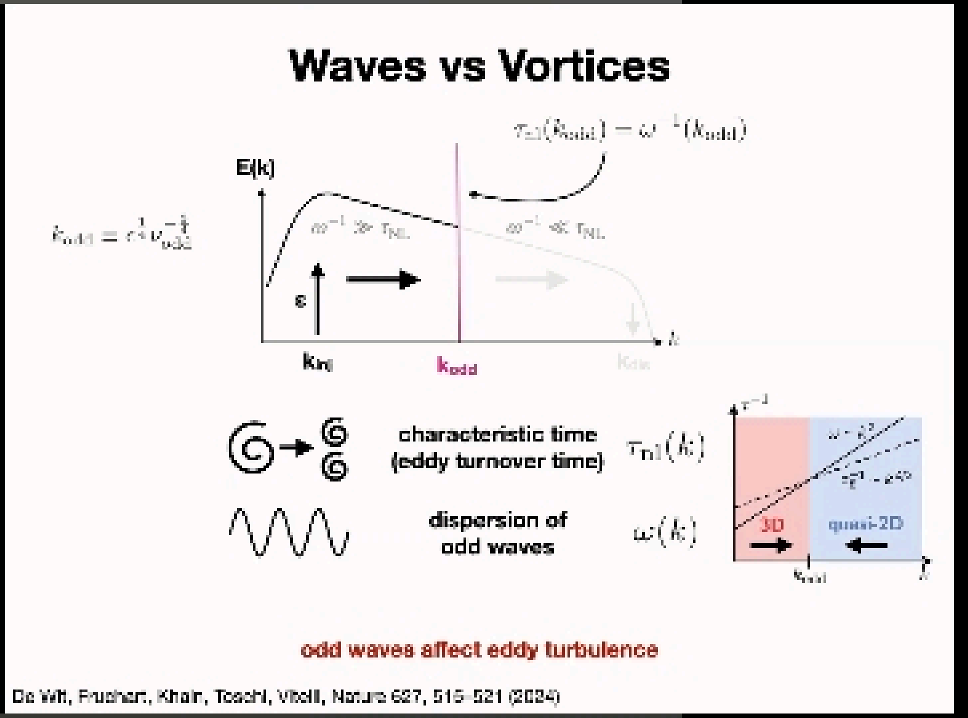
De Wit, Fruchart, Khain, Toschi, Vitelli, Nature 627, 515–521 (2024)

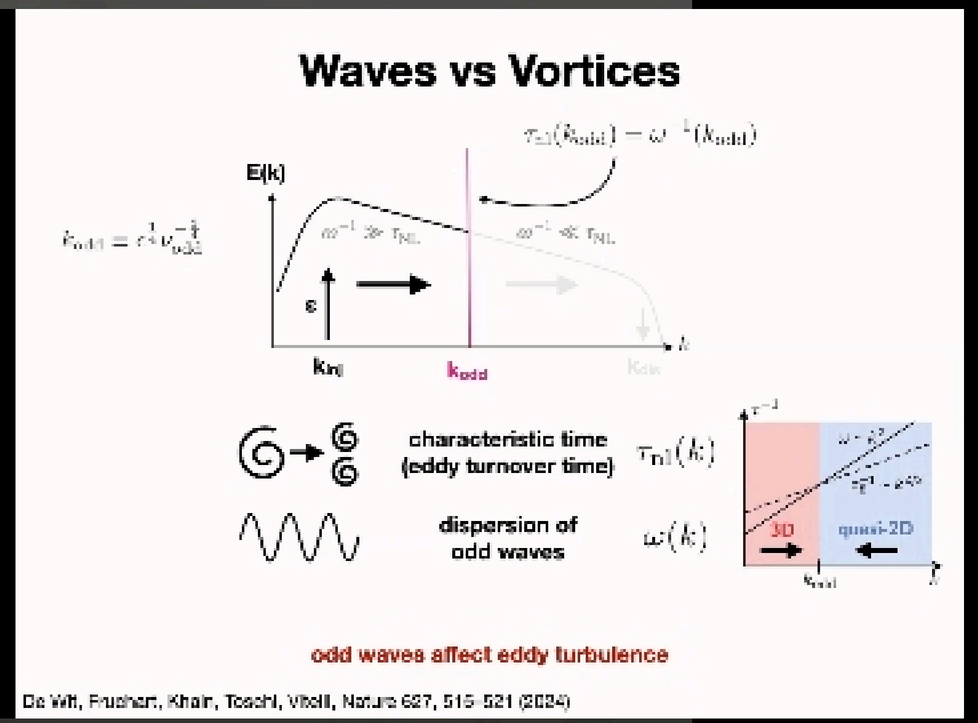
$$\rho D_t v = -\nabla P + \eta \Delta v + \eta\, \xi_{z\cdot\cdot} \Delta v + \xi(t,x)$$

$$D_t v \;\downarrow\; \partial_t v + v\cdot\nabla v$$

$$\langle \hat{\xi}(t,k)\, \hat{\xi}(t,-k) \rangle$$



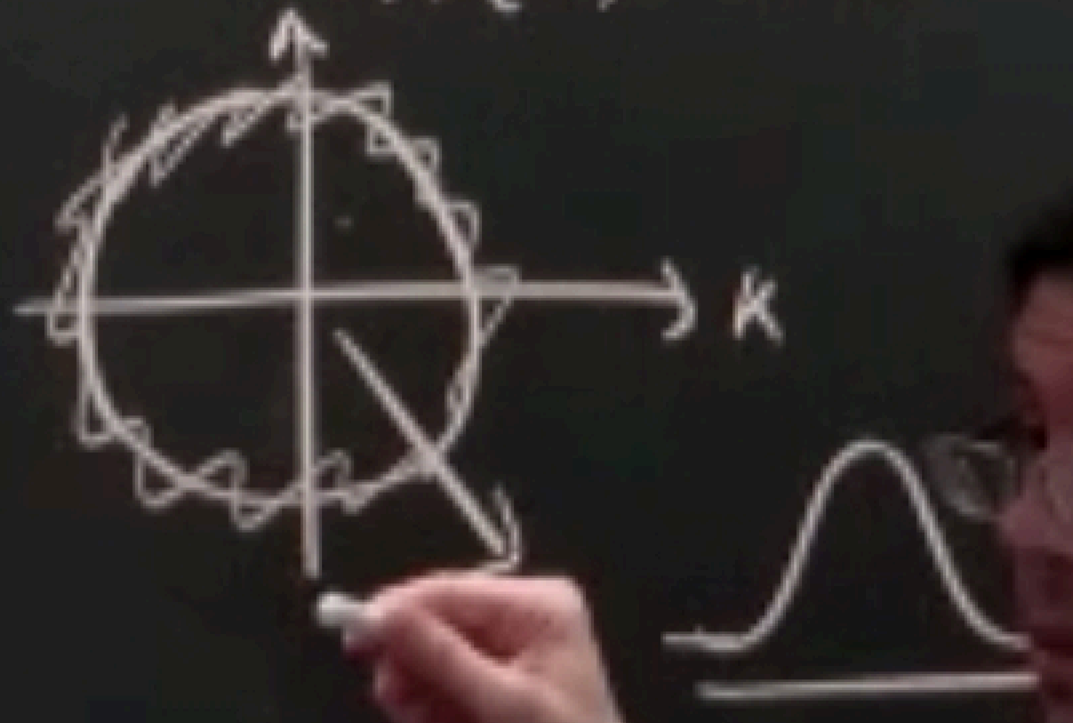




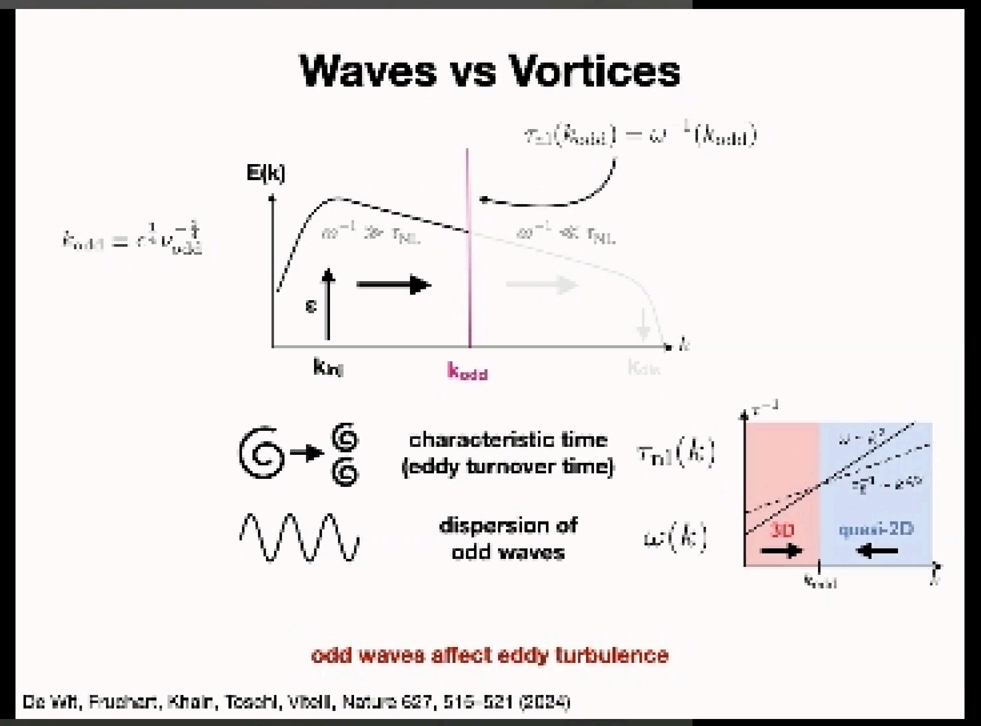
$$\rho D_t v = -\nabla P + \eta \Delta v + \cancel{\eta_o \epsilon \Delta v} + \xi(t,x)$$

$$\langle \hat{\xi}(t,k)\, \hat{\xi}(t,-k) \rangle$$

$$D_t v \downarrow \partial_t v + v \cdot \nabla v$$




Waves vs Vortices
characteristic time (eddy turnover time)
dispersion of odd waves
odd waves affect eddy turbulence
LMP Seminars



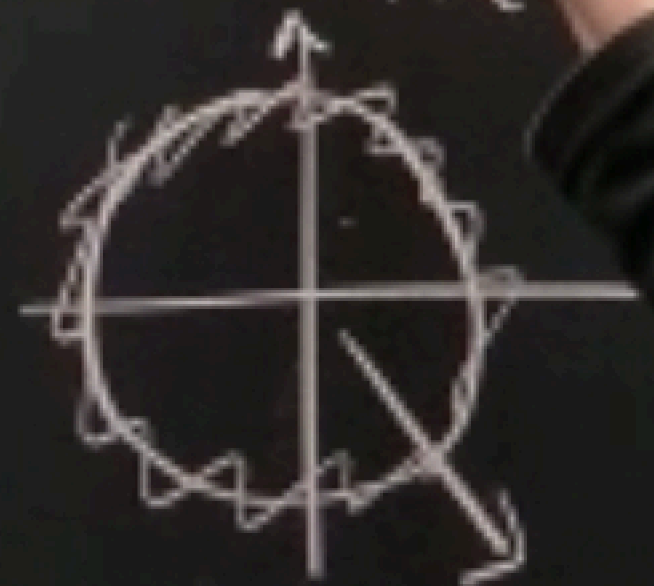
$$\nabla\cdot(\xi_2 \xi) \to 0$$

$$\rho D_t v = -\nabla P + \eta \Delta v + \cancel{\eta_o \xi_2 \Delta v} + \cancel{\xi(t,x)}$$

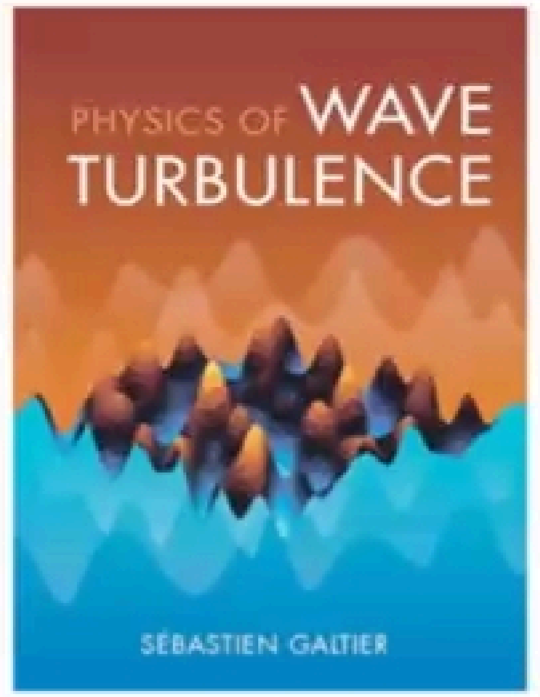
$$\langle \hat\xi(t,k)\, \hat\xi(t,-k) \rangle$$

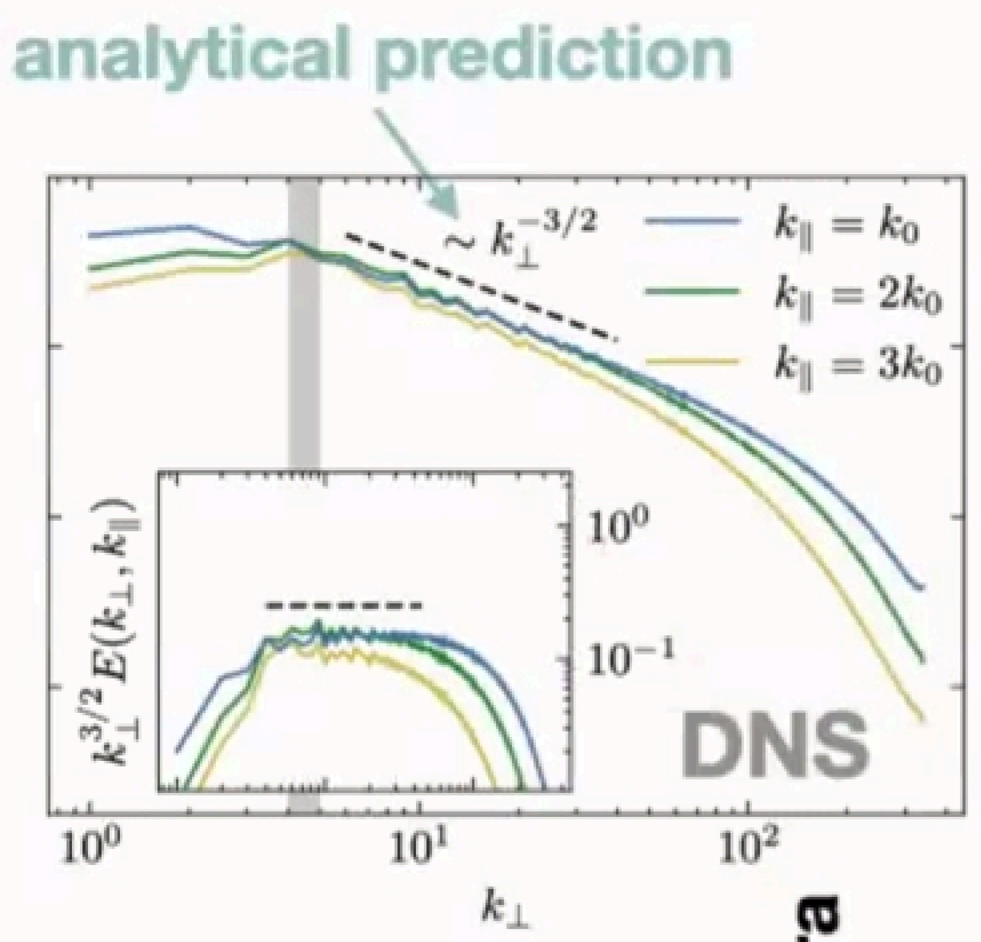
$$D_t v \to \partial_t v + v\cdot\nabla v$$

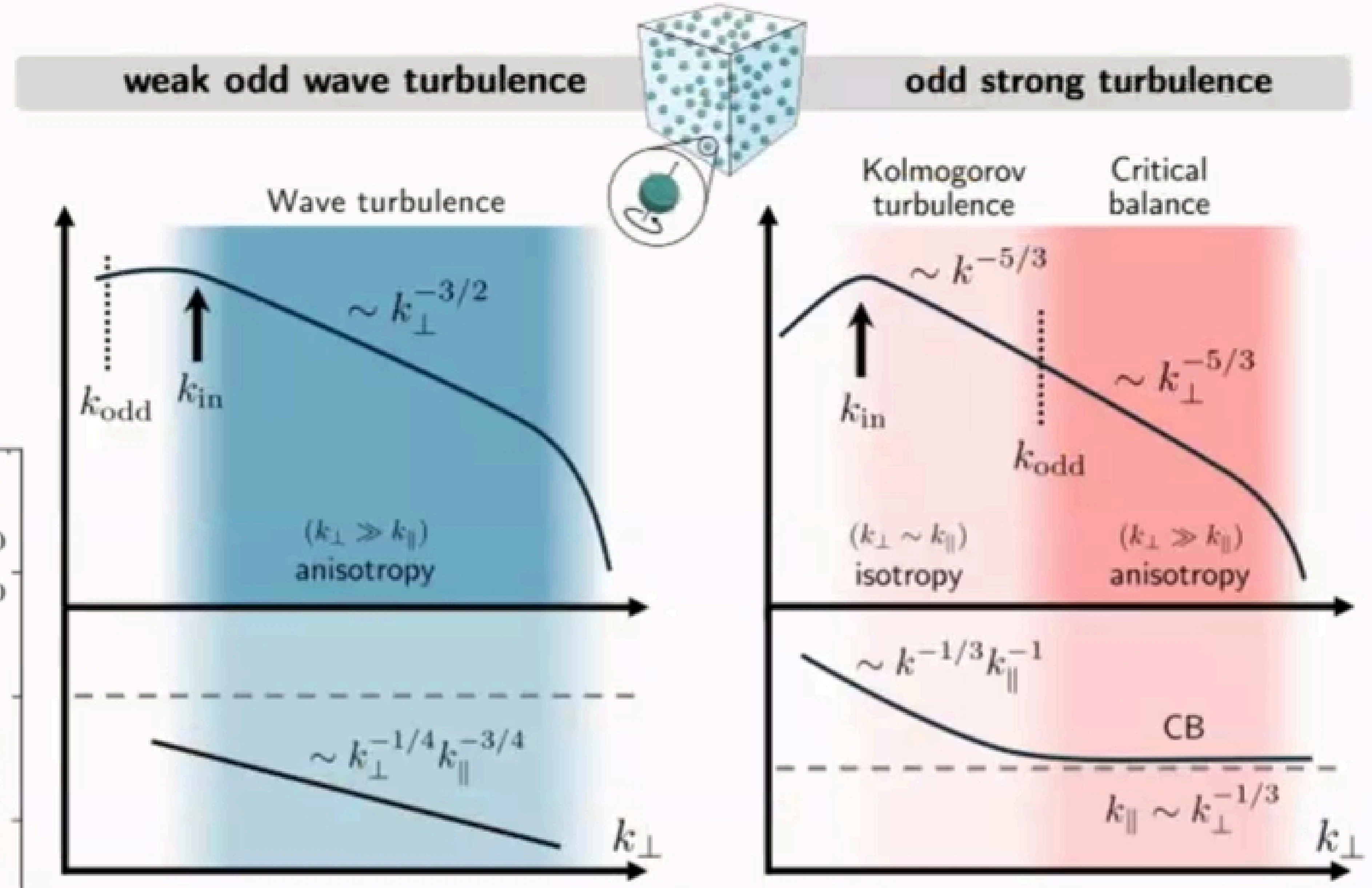
$$\eta \to 0$$

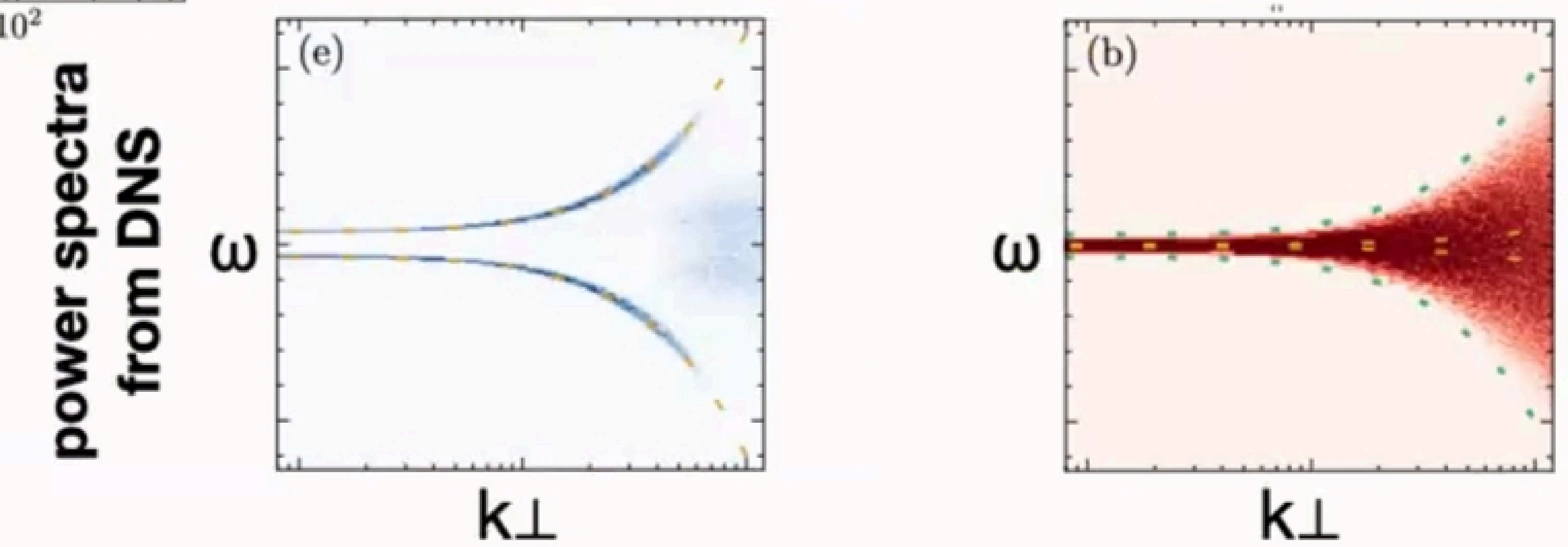


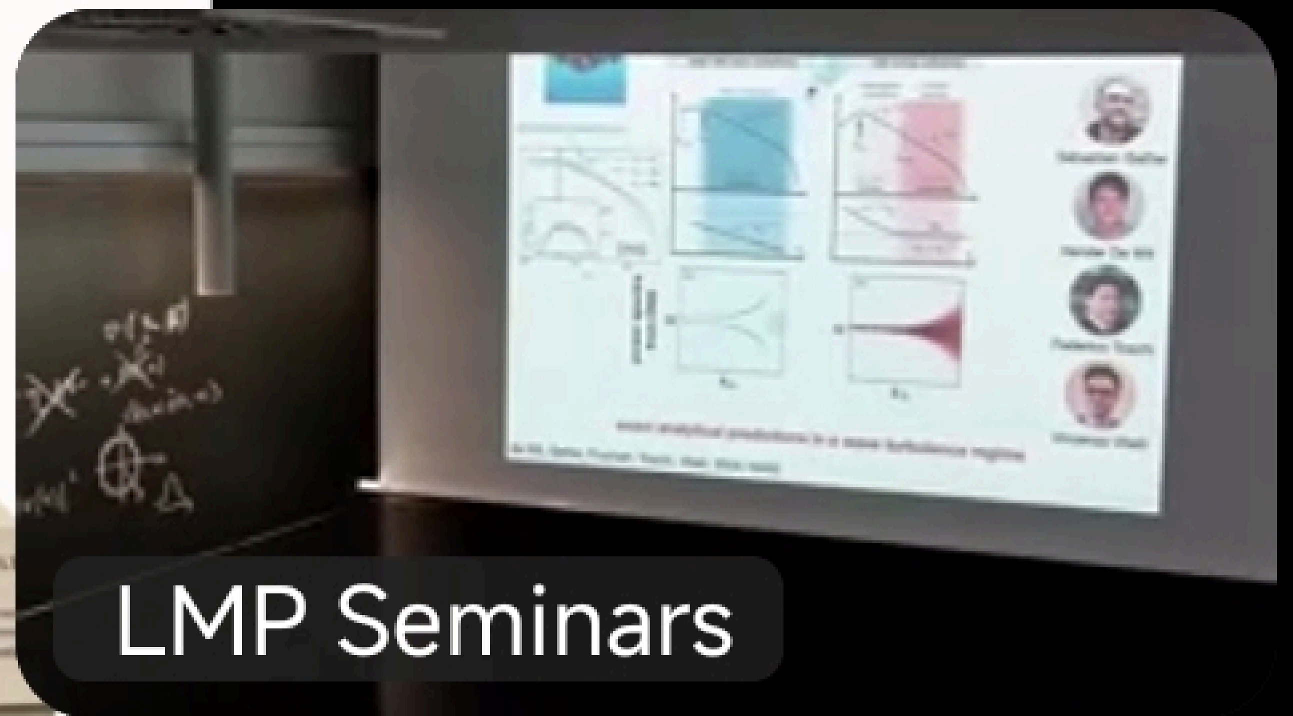
Odd wave turbulence











exact analytical predictions in a wave turbulence regime

de Wit, Galtier, Fruchart, Toschi, Vitelli, 2504.15403