From Ceilidh dancing to mesoscale turbulence

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Outline

Introduction

Ceilidh dancing

Mesoscale turbulence

Conclusion

Outline & acknowledgements

EMBO Fellow

Introduction

Ceilidh dancing

Mesoscale turbulence

Conclusion

- Julia Yeomans (Oxford)
- Amin Doostmohammadi (Oxford)
- Kristian Thijssen (Eindhoven University)
- Sumesh Thampi (IIT Madras)
- Ramin Golestanian (Oxford)
- Yilin Wu (Chinese Uni. Hong Kong)
- Haoran Xu (CUHK)

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Dense suspensions of bacteria as active fluids

Figure: Swarm of self-motile, rod-like *S. marcescens*

Howard Berg & Rasika Harshey

Dense suspensions of bacteria as active fluids

Figure: A continuum of *B. subtilis*

Wensink, Dunkel, Heidenreich, Drescher, Goldstein, Löwen & Yeomans, Mesoscale turbulence in living fluids, PNAS, 2012

Spontaneous flows & mesoscale turbulence

Figure: Mesoscale turbulence of highly concentrated 3D suspensions of *Bacillus subtilis* (vorticity)

Dunkel, *et. al.*, Fluid Dynamics of Bacterial Turbulence, PRL (2013)

Spontaneous flows & mesoscale turbulence

Mesoscale turbulence is not true turbulence

- Possesses characteristic length scales
- Viscously overdamped; No inertia; Re $\to 0$

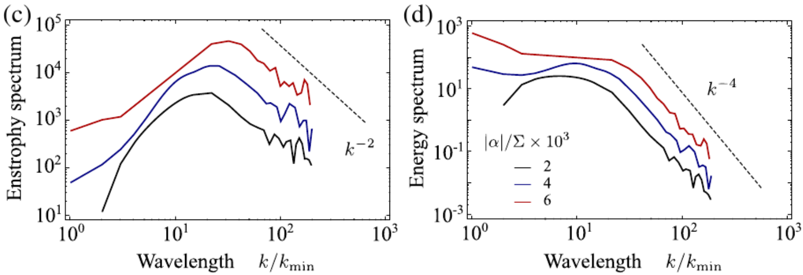

Figure: Inertial turbulence is scale-invariant; mesoscale turbulence is not.

Bratanov, *et. al.*, New class of turbulence in active fluids, PNAS (2015)
Giomi, Geometry & Topology of Turbulence in Active Nematics, PRX (2015)

Topology leads to characteristic length scale

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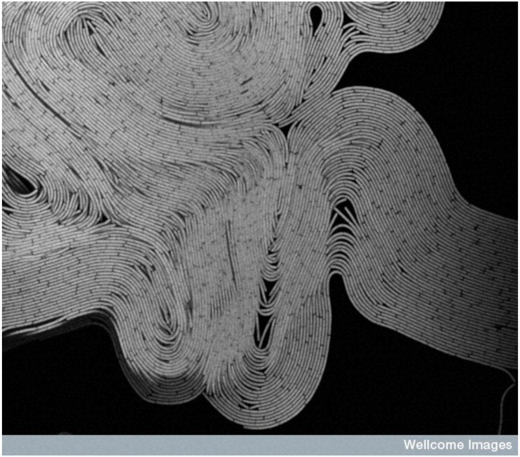


Figure: Rod-like (nematic) bacterial biofilm with clear disclinations

Federici & Haseloff, *Bacillus subtilis*, Wellcome Images (2011)

Topology leads to characteristic length scale

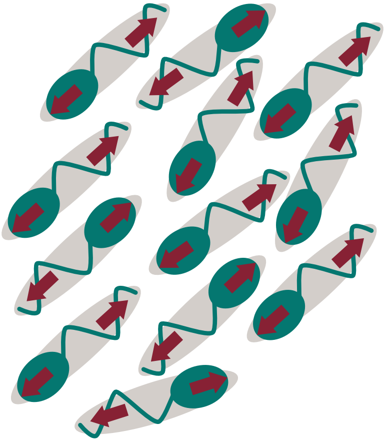


Figure: Force-free swimmers apply an active force dipole

Topology leads to characteristic length scale

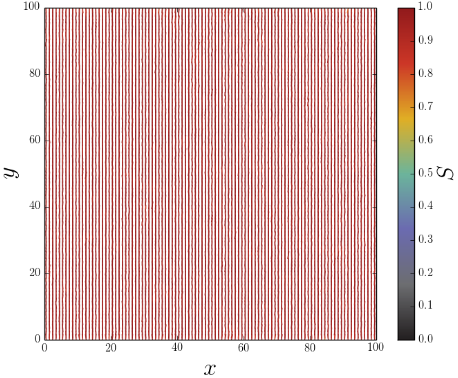
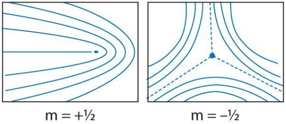
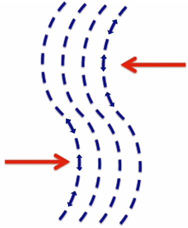


Figure: Generation of mesoscale turbulence in active nematics due to hydrodynamic instability





$$\ell_\zeta \sim \sqrt{\frac{K}{\zeta}}$$

Thampi, Golestanian & Yeomans, Instabilities and topological defects in active nematics, EPL (2013)

Topology leads to characteristic length scale

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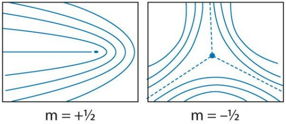

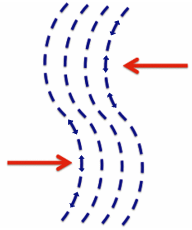

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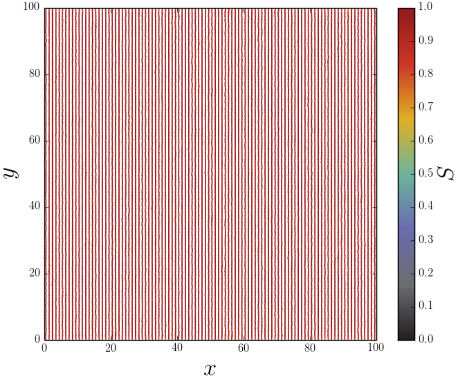

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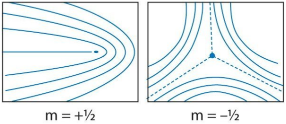

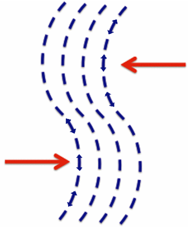

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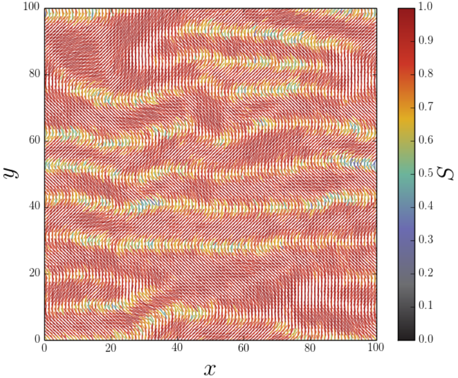

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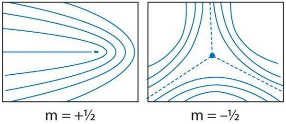

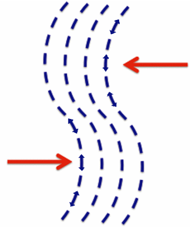

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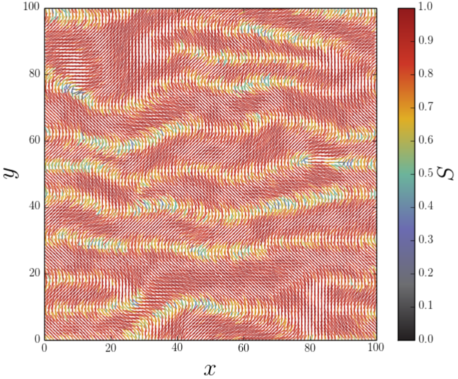

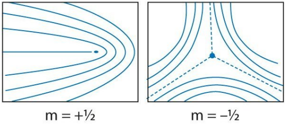

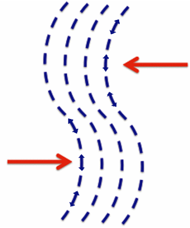

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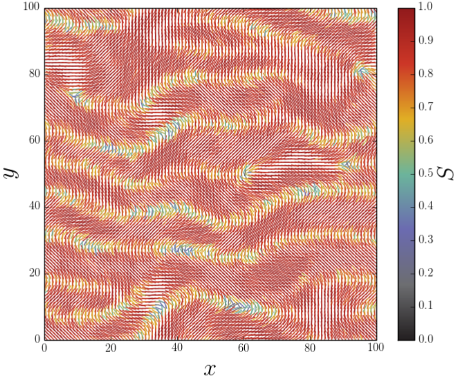

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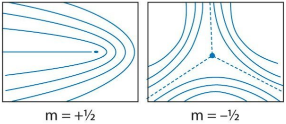

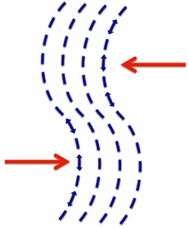

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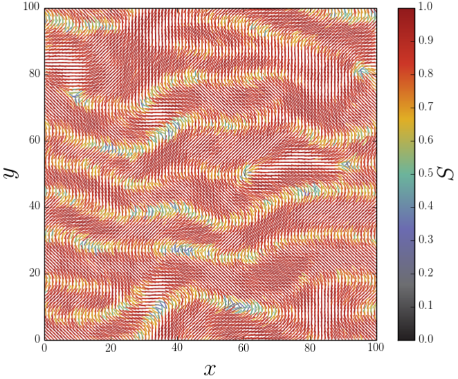

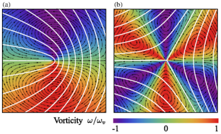

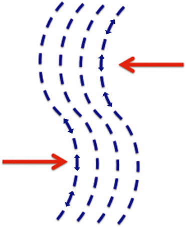

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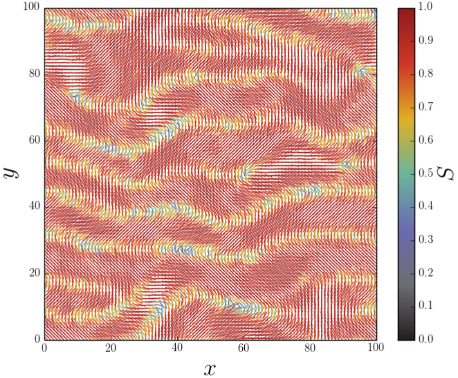

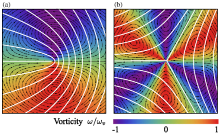

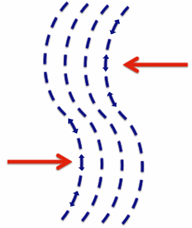

Figure: Deformations generate flow & +1/2 disclinations are self-motile since they are polar entities

$$\ell_\zeta \sim \sqrt{\frac{K}{\zeta}}$$

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What happens if we confine an active fluid?

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We expect

- **Mesoscale turbulence** for a large enough container/active enough fluid

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- **Stationary quiescence** for a small enough container/low enough activity

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What happens if we confine an active fluid?

We expect

- **Mesoscale turbulence** for a large enough container/active enough fluid
- **Stationary quiescence** for a small enough container/low enough activity
- Intermediate states?

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Confinement

Figure: Spontaneous unidirectional flow occurs when moderately active fluids are confined

FIFA WORLD CUP, Duck flood!, YouTube (2014)

Confinement

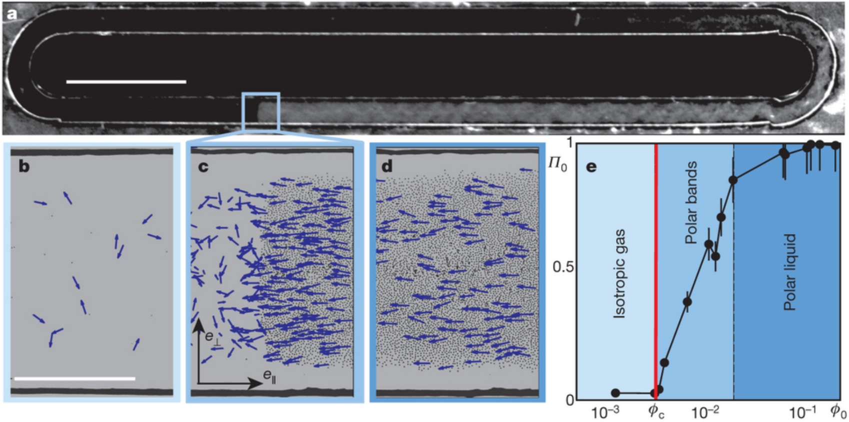


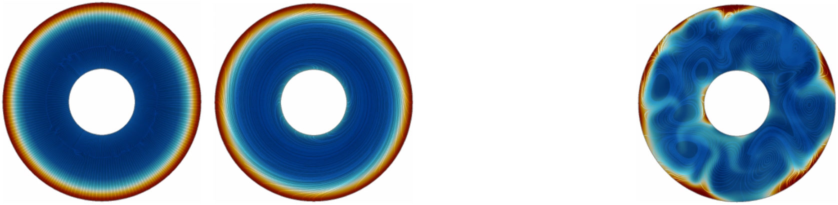
Figure: Spontaneous flow of motile colloids in a microfluidic racetrack

Bricard, *et. al.*, Emergence of macroscopic directed motion in populations of motile colloids, Nature (2013)

Figure: Rotational flows are stabilized by cylindrical confinement

Wioland, *et. al.*, Confinement Stabilizes a Bacterial Suspension into a Spiral Vortex, PRL (2013)

Confinement

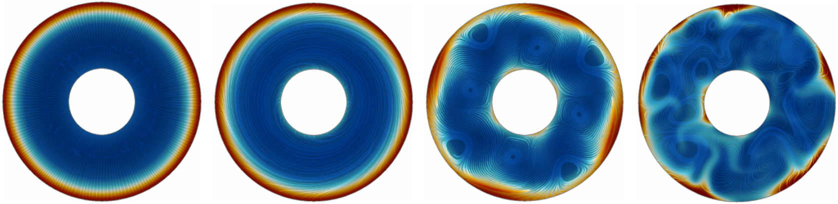


(a) $\alpha = -10$ (b) $\alpha = -40$ (c) $\alpha = -70$ (d) $\alpha = -100$

Figure: Various annular flows with increasing activity (quiescent, unidirectional, ordered vortices, mesoscale turbulence)

Theillard, Alonso-Matilla & Saintillan, Geometric control of active collective motion, ArXiv (2016)
Neef & Kruse, Generation of stationary and moving vortices in active polar fluids in the planar Taylor-Couette geometry, PRE (2014)

Confinement



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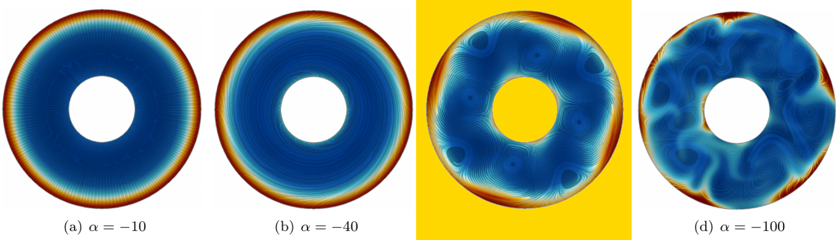
Confinement & vortex lattices



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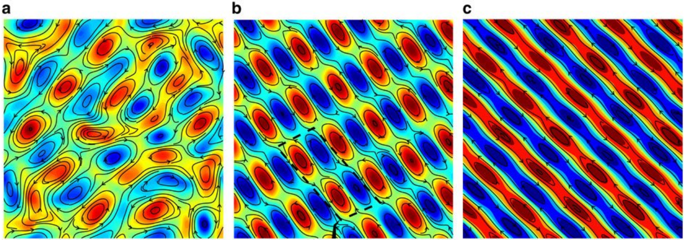

Figure: Vortex lattice is seen to exist in active nematics with dry friction term.

Doostmohammadi, Adamer, Thampi & Yeomans. Stabilization of active matter by flow-vortex lattices and defect ordering, Nat. Comm. (2015)

Confinement & vortex lattices

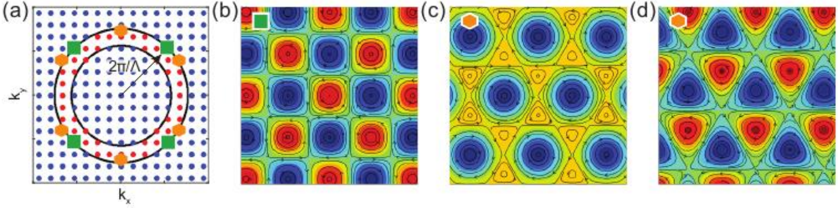

Figure: Using a generalized Navier-Stokes model, Jonasz Słomka has shown that these lattices arise as superimpositions of stress-free modes & are effectively frictionless flow states

Słomka & Dunkel, Geometry-dependent viscosity reduction in sheared active fluids, ArXiv (2016)

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Figure: Vortex lattice *Proteus mirabilis* swarm between air/water interface and sessile bio-film. Courtesy of Haoran Xu & Yilin Wu

Wioland, Lushi & Goldstein, Directed collective motion of bacteria under channel confinement, New J Phys (2016)

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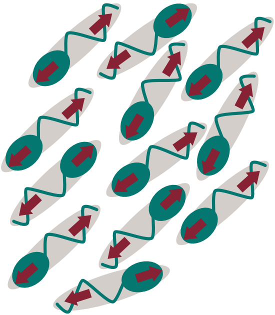
Modelling confined dense bacterial suspensions



Many swimmers with

- collective motion — velocity field
- shape-anisotropic — nematic (rod-like) orientation field
- dense suspension — continuity
- flagellated pushers — extensile activity

Modelling confined dense bacterial suspensions

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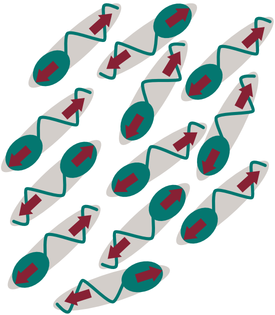

Many swimmers with

- collective motion — velocity field
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Dense bacteria suspension
↕
intrinsically-out-of-equilibrium
incompressible nematic liquid crystal

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Active nematohydrodynamics

Density

Assume mass conservation of the suspension:
$(\partial_t \rho + \underline{\nabla} \cdot [\rho \underline{u}]) = 0 \quad \rightarrow \quad \underline{\nabla} \cdot \underline{u} = 0$

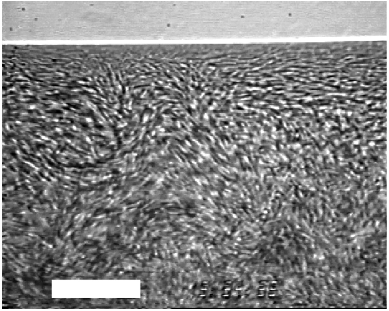

Figure: *B. subtilis* swarm

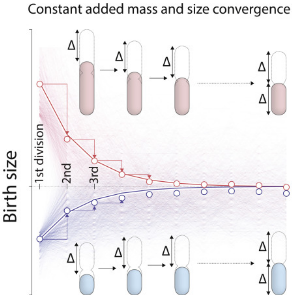

Figure: Cells sense & maintain mass

Ishikawa, Suspension biomechanics of swimming microbes, J R Soc Interface (2009)
Taheri-Araghi, *et. al.*, Cell-Size Control & Homeostasis in Bacteria, Current Biol. (2015)

Active nematohydrodynamics

Orientational Order

$$(\partial_t + \underline{u} \cdot \underline{\nabla}) \underline{\underline{Q}} - \underline{\underline{S}} = \Gamma \underline{\underline{H}}$$

$$\underline{\underline{Q}} = \frac{3q}{2} (\underline{n}\,\underline{n} - \underline{\underline{I}}/3)$$

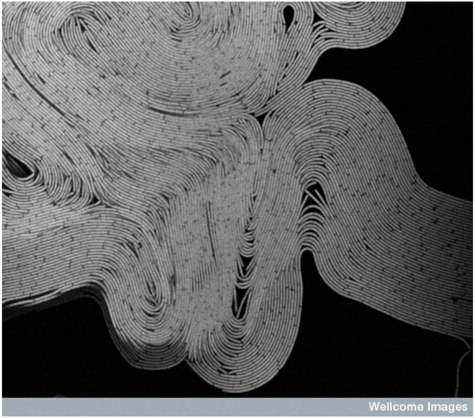

Figure: Bacterial biofilms with clear disclinations

Federici & Haseloff, *Bacillus subtilis*, Wellcome Images (2011)

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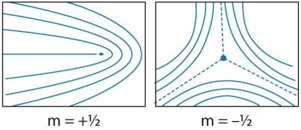
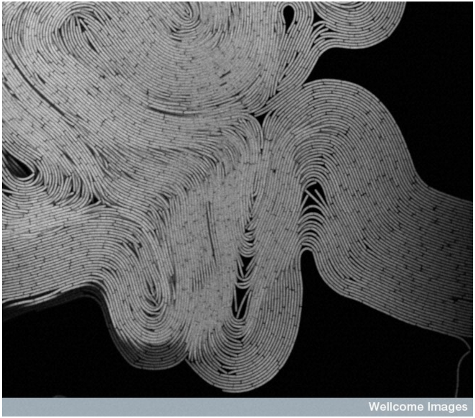


Figure: Topological charge must be conserved



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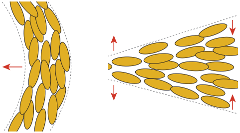
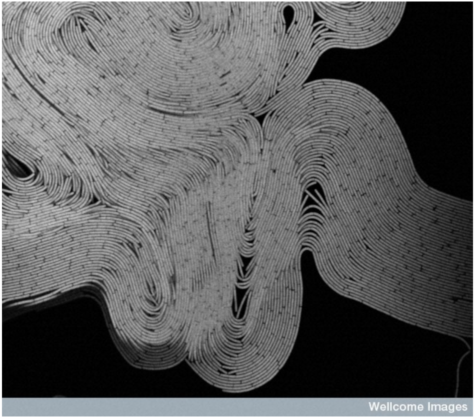


Figure: Nematic elasticity K



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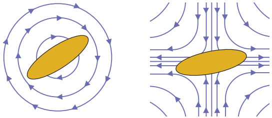

Figure: Co-rotational advection

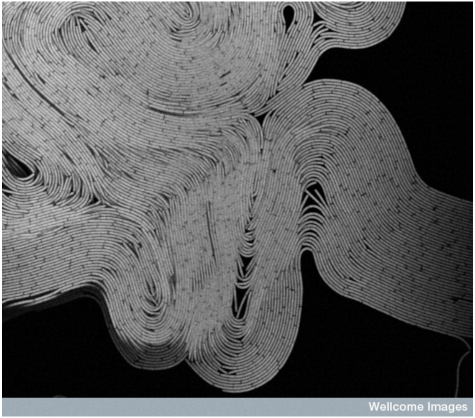

Figure: Bacterial biofilms with clear disclinations

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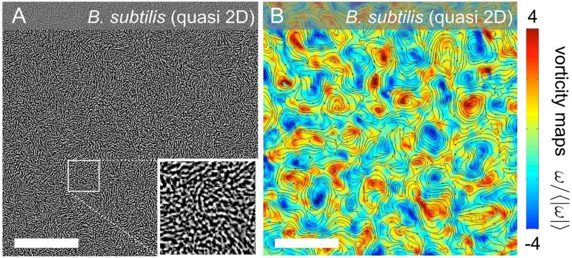
Momentum

Obeys Navier-Stokes $(\partial_t + \underline{u} \cdot \underline{\nabla})\, \underline{u} = \underline{\nabla} \cdot \underline{\underline{\Pi}}$
with a stress tensor $\underline{\underline{\Pi}}$ that includes



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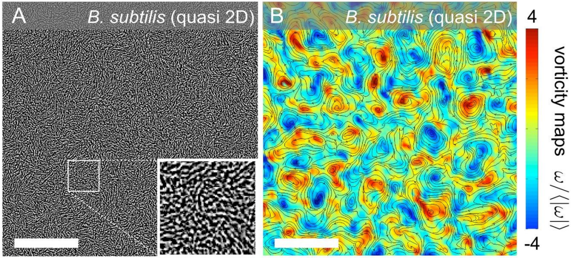
Viscosity $\underline{\underline{\Pi}}^{\text{visc}} = 2\eta \underline{\underline{E}}$



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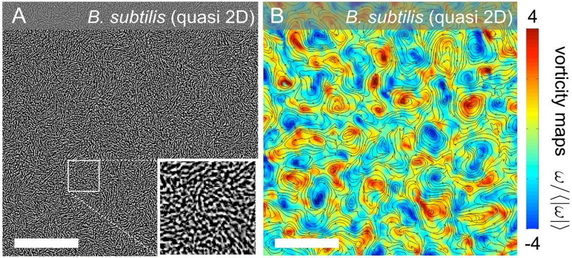
Nematic LC $\underline{\underline{\Pi}}^{\text{LC}}$



Wensink, *et. al.*, Mesoscale turbulence in living fluids, PNAS (2012)

Active nematohydrodynamics

EMBO Fellow

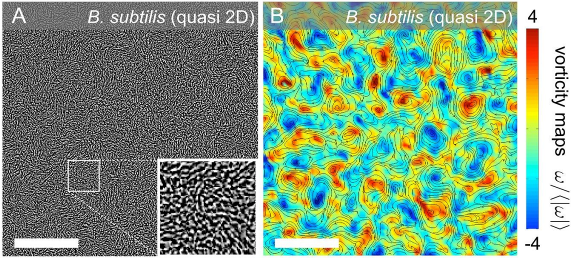
Momentum

Obeys Navier-Stokes $\left(\partial_t + \underline{u}\cdot\underline{\nabla}\right)\underline{u} = \underline{\nabla}\cdot\underline{\underline{\Pi}}$
with a stress tensor $\underline{\underline{\Pi}}$ that includes

Viscosity $\underline{\underline{\Pi}}^{\text{visc}} = 2\eta\underline{\underline{E}}$

Nematic LC $\underline{\underline{\Pi}}^{\text{LC}}$

Activity $\underline{\underline{\Pi}}^{\text{act}} = -\zeta\underline{\underline{Q}}$



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Active nematohydrodynamics

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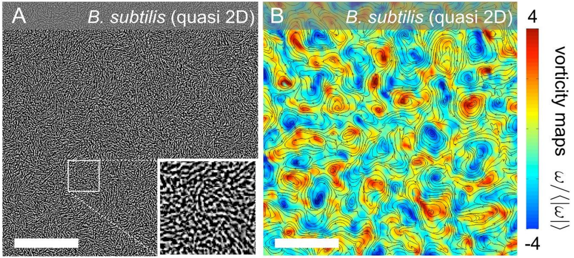

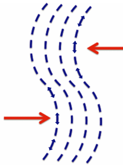

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Active nematohydrodynamics

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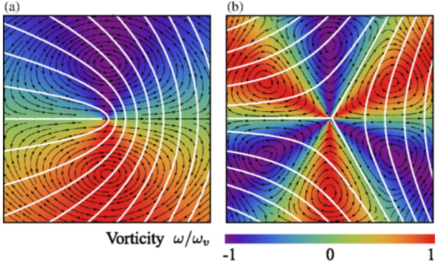

Giomi, Geometry & Topology of Turbulence in Active Nematics, PRX (2015)

2D active nematic in a microchannel

EMBO Fellow

Figure: At very low activity, unidirectional flow (in 2D channel of height h)

Figure: At moderate activity, an ordered vortex-lattice forms

Figure: At high activity, active turbulence arises

TNS, Doostmohammadi, Thijssen & Yeomans, Dancing disclinations in confined active nematics (submitted)

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2D active nematic in a microchannel

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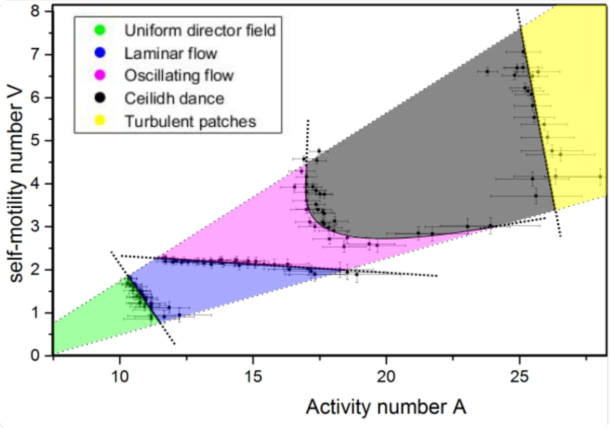

Figure: Dynamical steady state diagram of flow structures ("phase diagram").
$A = \sqrt{\zeta h^2/K}$ & $V \sim v_{+1/2} \sim h\zeta/\eta$

TNS, Doostmohammadi, Thijssen & Yeomans, Dancing disclinations in confined active nematics (submitted)

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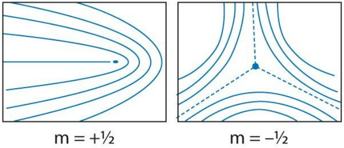
Confined vortex lattice

Consider the intermediate vortex lattice

- Intermediate behaviour:
  - Ordered flow state → vortex lattice
  - Dynamically ordered topological state → disclination dynamics

Figure: Intermediate behaviour; ● = +1/2 disclinations; ▲ = −1/2 disclinations



TNS, Doostmohammadi, Thijssen & Yeomans, Dancing disclinations in confined active nematics (submitted)

Confined ~~vortex lattice~~Ceilidh dynamics

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Consider the intermediate vortex lattice

- Intermediate behaviour:
  - Ordered flow state → vortex lattice
  - Dynamically ordered topological state → disclination dynamics

Figure: Ceilidh dancing (Strip the willow)

BBC Scotland, Strip The Willow, YouTube (2015)

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Quantifying Ceilidh dynamics

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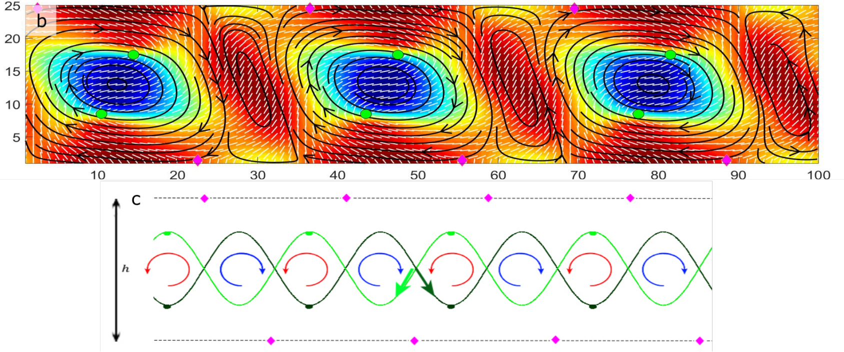

Figure: One pair of disclinations per vortex

TNS, Doostmohammadi, Thijssen & Yeomans, Dancing disclinations in confined active nematics (submitted)

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Quantifying Ceilidh dynamics

EMBO Fellow

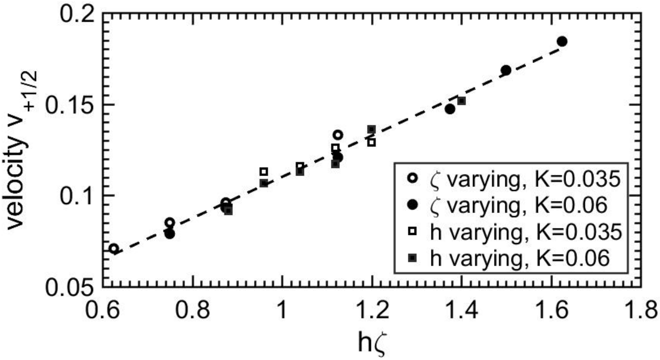

Figure: +1/2 disclination velocity $v_{+1/2} \sim h\zeta/\eta$ (as predicted by Giomi for a solitary disclination with $L \to h$)

Giomi, Bowick, Mishra, Sknepnek & Marchetti, Defect dynamics in active nematics, Phil. Trans. R. Soc. A (2014)
TNS, Doostmohammadi, Thijssen & Yeomans, Dancing disclinations in confined active nematics (submitted)

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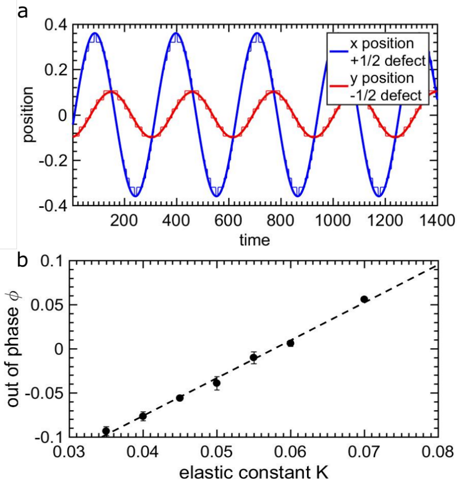

Figure: $-1/2$ disclinations oscillate weakly

TNS, Doostmohammadi, Thijssen & Yeomans, Dancing disclinations in confined active nematics (submitted)

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Quantifying Ceilidh dynamics

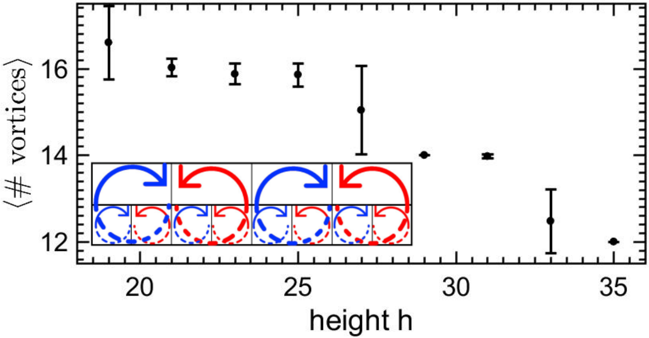

Figure: Only pairs of counter-rotating vortices & disclinations are allowed

TNS, Doostmohammadi, Thijssen & Yeomans, Dancing disclinations in confined active nematics (submitted)

Lattice defects

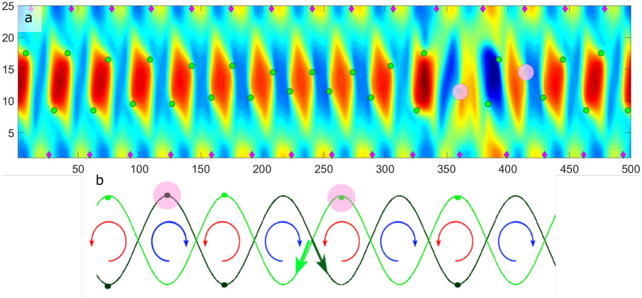

Figure: Spatialy structured Ceilidh dance can have impurities

TNS, Doostmohammadi, Thijssen & Yeomans, Dancing disclinations in confined active nematics (submitted)

Lattice defects

EMBO Fellow

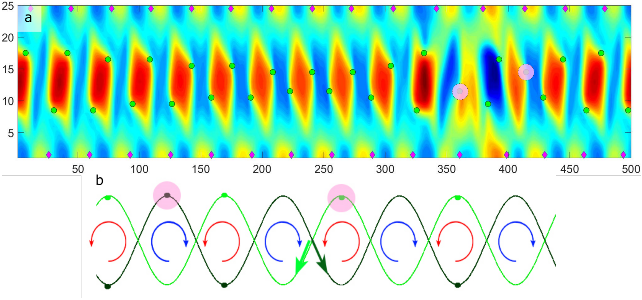

Figure: Spatialy structured Ceilidh dance can have impurities

Nomenclature

- Topologically disclinations (±1/2)
- ● = +1/2 disclinations; ▲ = −1/2

- Lattice defects
  - Broken-pairs lattice defects
  - Drift lattice defects

TNS, Doostmohammadi, Thijssen & Yeomans, Dancing disclinations in confined active nematics (submitted)

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Broken-pair lattice defects

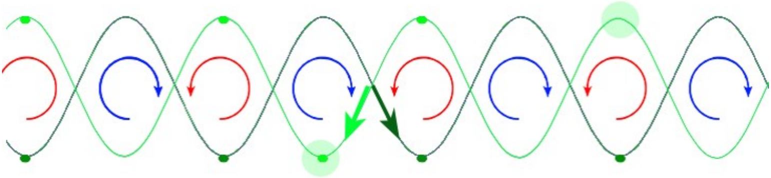

Figure: A pair of • = +1/2 topological disclinations are separated & reside on distant vortices

TNS, Doostmohammadi, Thijssen & Yeomans, Dancing disclinations in confined active nematics (submitted)

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Drift lattice defects

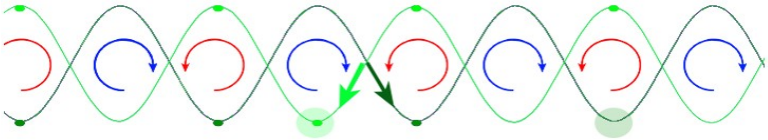


Figure: Like a broken-pair lattice defect but • = +1/2 topological disclinations on unexpected trajectory. Results in drift

TNS, Doostmohammadi, Thijssen & Yeomans, Dancing disclinations in confined active nematics (submitted)

Drift lattice defects

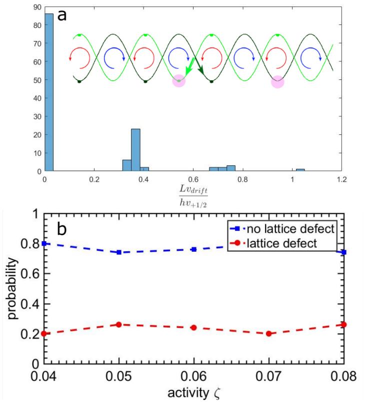
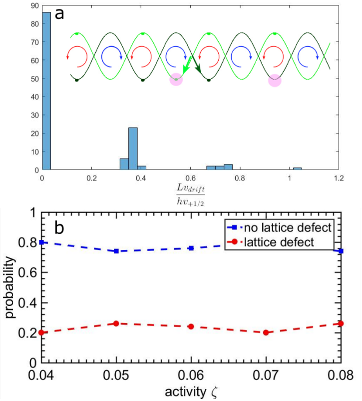


Figure: Drift velocity quantized since only integer number of lattice defects allowed.

Drift velocity

TNS, Doostmohammadi, Thijssen & Yeomans, Dancing disclinations in confined active nematics (submitted)

Drift lattice defects



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Drift velocity

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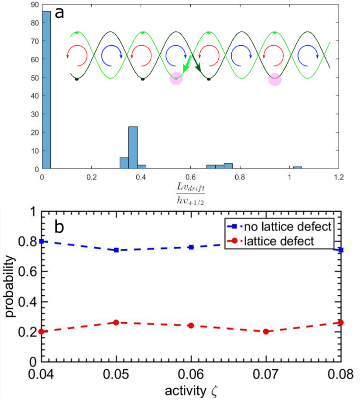
TNS, Doostmohammadi, Thijssen & Yeomans, Dancing disclinations in confined active nematics (submitted)

Drift lattice defects



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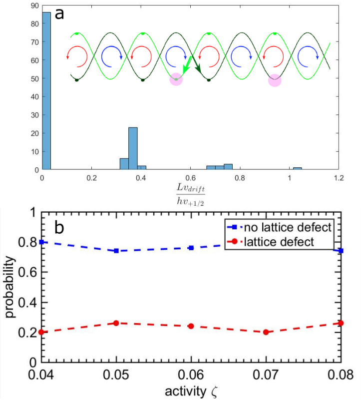
Drift velocity

- Active force density $\underline{f}_{\text{act}} = -\zeta \underline{\nabla} \cdot \underline{\underline{Q}}$
- Dominated by disclinations $\underline{n}_{\pm 1/2} \approx [\cos(\pm\phi/2), \sin(\pm\phi/2)]$
- $F^{(1)}_{\text{act}} \approx \int_{h^2} f_{\text{act}} dA \sim \eta v_{+1/2}$.

TNS, Doostmohammadi, Thijssen & Yeomans, Dancing disclinations in confined active nematics (submitted)

Drift lattice defects



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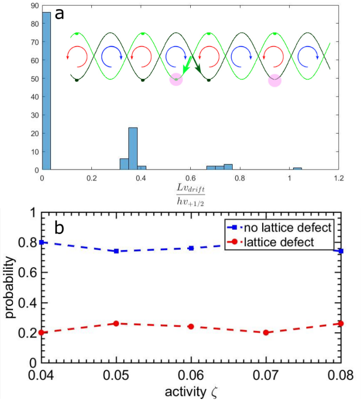
TNS, Doostmohammadi, Thijssen & Yeomans, Dancing disclinations in confined active nematics (submitted)

Drift lattice defects



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Drift velocity

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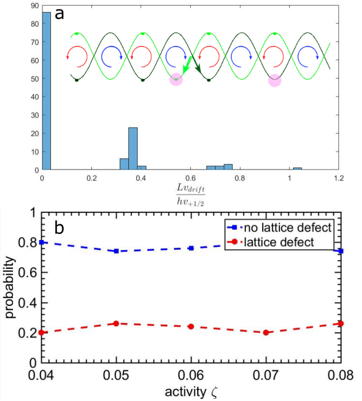
- $F_{act}^{(1)} \approx \int_{h^2} f_{act} dA \sim \eta v_{+1/2}$.
- n drift lattice defects produce $F_{act}^{(n)} = n\, F_{act}^{(1)}$

- Mid-channel region moves *en masse*; viscous dissipation only in near-wall region
- $F_{drag} \sim -(L/h)\, \eta v_{drift}^{(n)}$.

TNS, Doostmohammadi, Thijssen & Yeomans, Dancing disclinations in confined active nematics (submitted)

Drift lattice defects



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- $F_{\text{drag}} \sim -(L/h)\, \eta v_{\text{drift}}^{(n)}$.

$$v_{\text{drift}}^{(n)} \sim n \left(\frac{h}{L}\right) v_{+1/2}$$

TNS, Doostmohammadi, Thijssen & Yeomans, Dancing disclinations in confined active nematics (submitted)

Onset of active turbulence in a channel

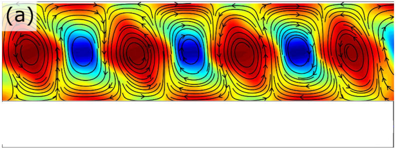

Figure: Ceilidh dynamics & vortex lattice

Doostmohammadi, TNS, Thijssen & Yeomans, Onset of mesoscale turbulence in living fluids, (submitted)

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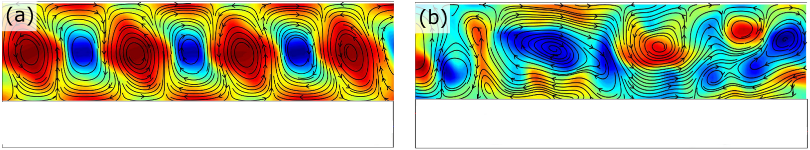

Figure: Fully formed mesoscale turbulence in a channel

Doostmohammadi, TNS, Thijssen & Yeomans, Onset of mesoscale turbulence in living fluids, (submitted)

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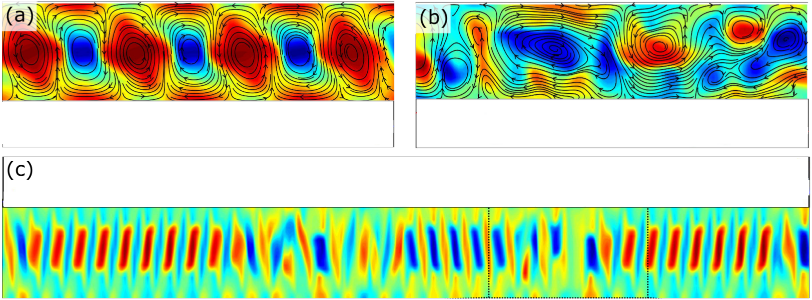

Figure: Active turbulence begins as localized "puffs"

Doostmohammadi, TNS, Thijssen & Yeomans, Onset of mesoscale turbulence in living fluids, (submitted)

Onset of active turbulence in a channel

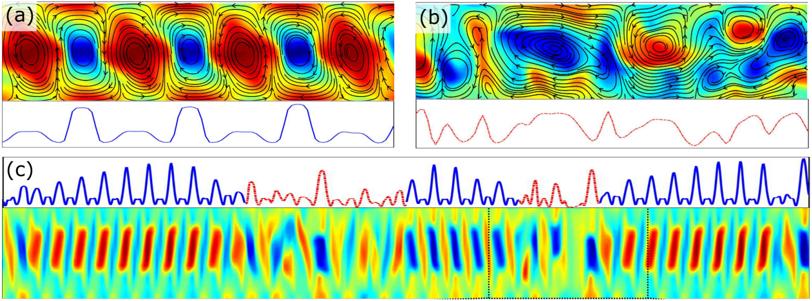

Figure: Active turbulence begins as localized "puffs", observable in the magnitude of the vorticity signal

Doostmohammadi, TNS, Thijssen & Yeomans, Onset of mesoscale turbulence in living fluids, (submitted)

EMBO Fellow

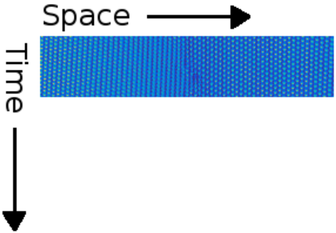

Figure: Raw enstrophy kymograph of spontaneous active puff creation

Doostmohammadi, TNS, Thijssen & Yeomans, Onset of mesoscale turbulence in living fluids, (submitted)

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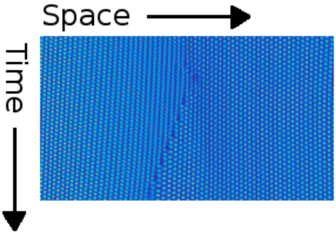
Onset of active turbulence in a channel



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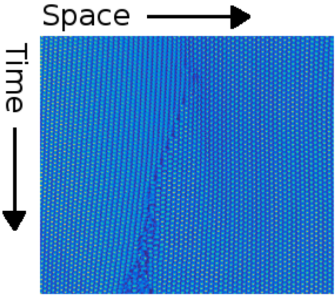

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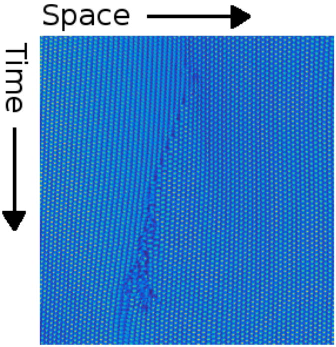
Onset of active turbulence in a channel



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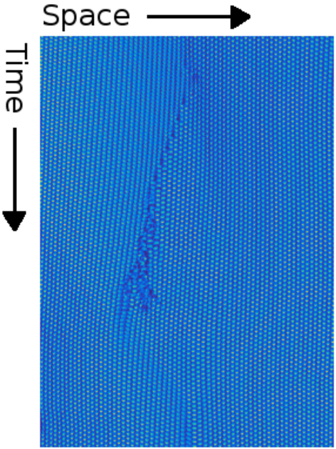

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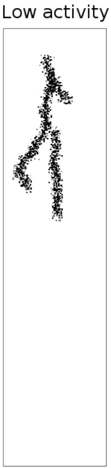

Figure: Turbulent puffs decay or split

Doostmohammadi, TNS, Thijssen & Yeomans, Onset of mesoscale turbulence in living fluids, (submitted)

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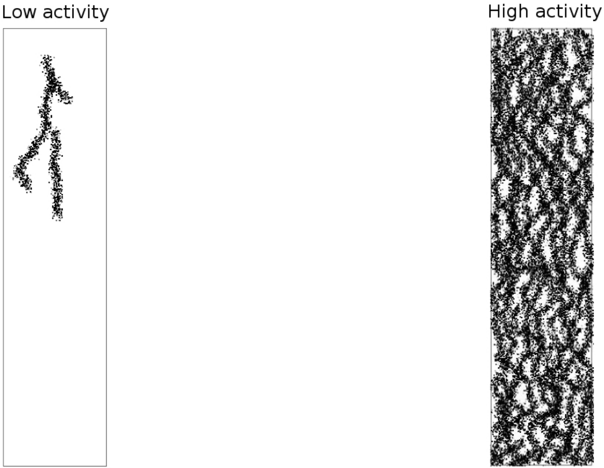

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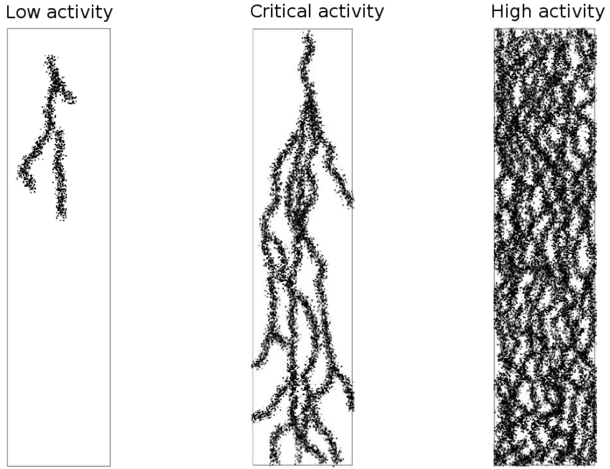

Figure: Turbulent puffs decay or split

Doostmohammadi, TNS, Thijssen & Yeomans, Onset of mesoscale turbulence in living fluids, (submitted)

Puffs fill the channel above critical activity

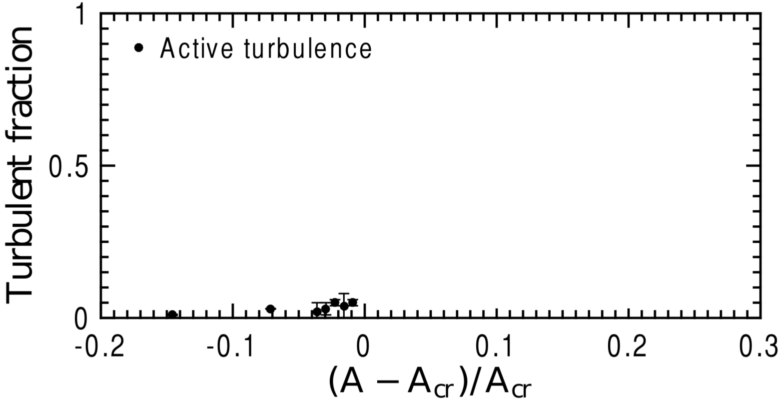

Figure: Looks like phase transition & grows like $\propto (A - A_{\mathrm{cr}})^{\beta}$, where $A = \sqrt{\zeta h^2 / K}$

Doostmohammadi, TNS, Thijssen & Yeomans, Onset of mesoscale turbulence in living fluids, (submitted)

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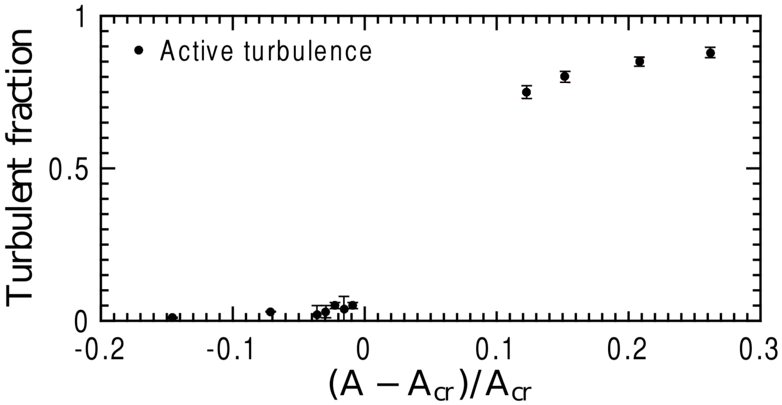

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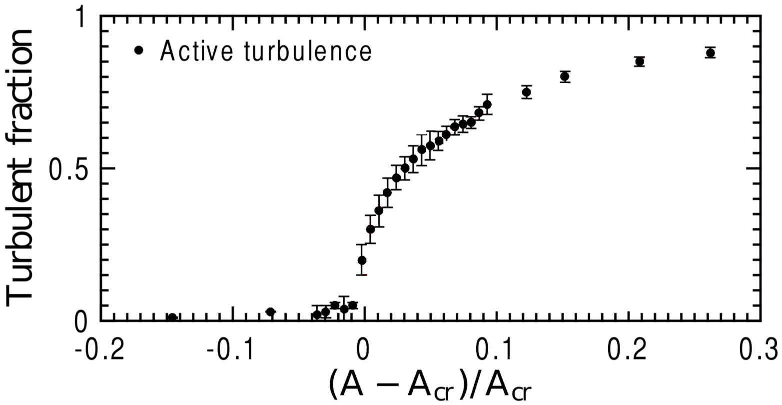

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Doostmohammadi, TNS, Thijssen & Yeomans, Onset of mesoscale turbulence in living fluids, (submitted)

Puffs fill the channel above critical activity

EMBO Fellow

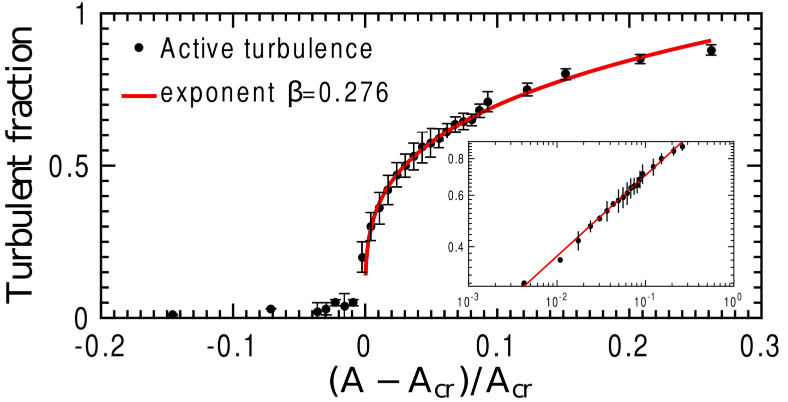

Figure: Looks like phase transition & grows like $\propto (A - A_{\rm cr})^\beta$, where $A = \sqrt{\zeta h^2/K}$

Doostmohammadi, TNS, Thijssen & Yeomans, Onset of mesoscale turbulence in living fluids, (submitted)

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Puffs fill the channel above critical activity

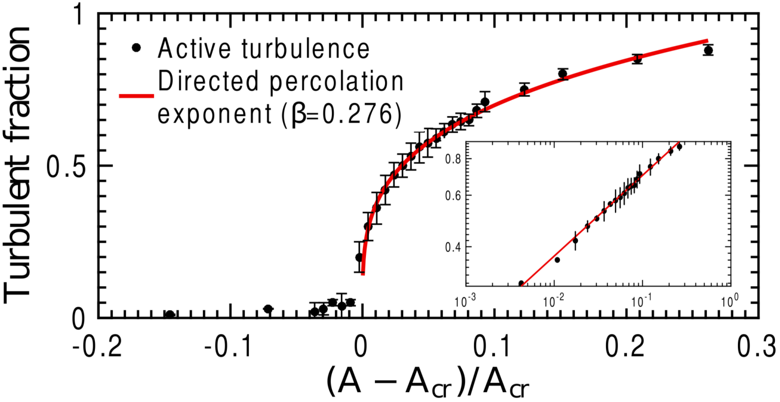

Figure: $\beta = 0.276$ corresponds to directed percolation universality class

Doostmohammadi, TNS, Thijssen & Yeomans, Onset of mesoscale turbulence in living fluids, (submitted)

Puffs fill the channel above critical activity

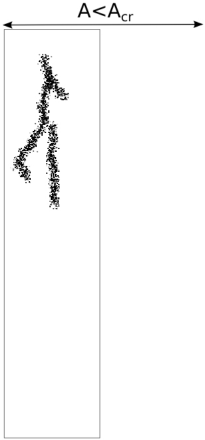

Figure: $\beta = 0.276$ corresponds to DP; puffs decay or split.

Doostmohammadi, TNS, Thijssen & Yeomans, Onset of mesoscale turbulence in living fluids, (submitted)

Puffs fill the channel above critical activity

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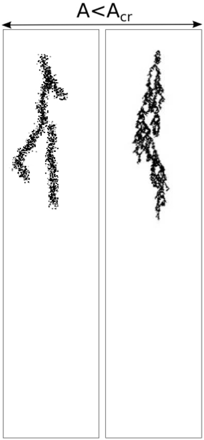

Figure: $\beta = 0.276$ corresponds to DP; puffs decay or split. p is probability that a site is activated at time t if one of its two backward sites is occupied. Critical probability p_c

Doostmohammadi, TNS, Thijssen & Yeomans, Onset of mesoscale turbulence in living fluids, (submitted)

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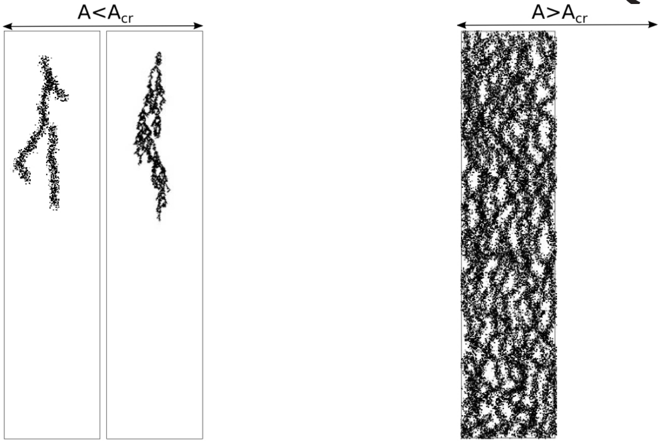
Puffs fill the channel above critical activity



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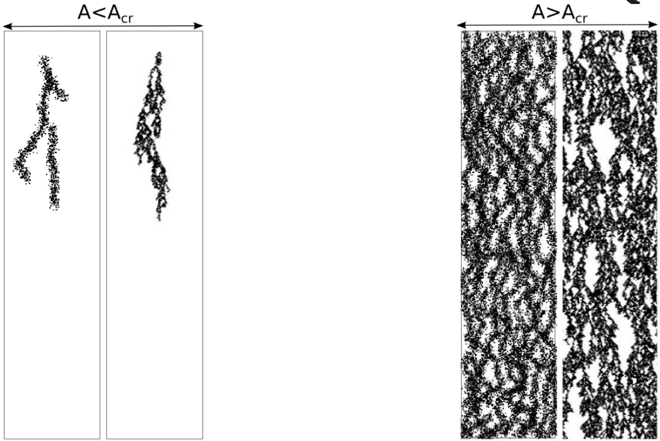

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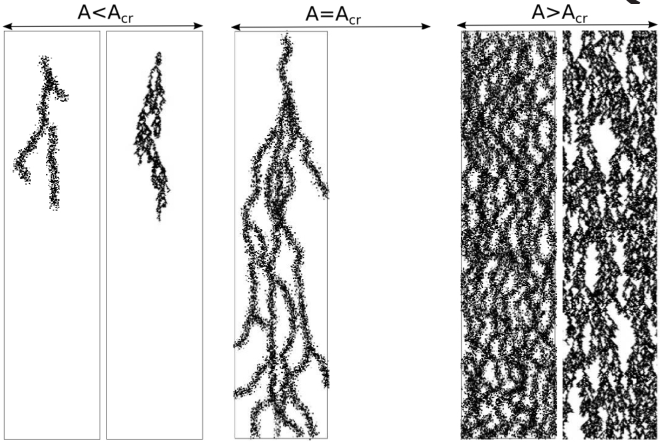

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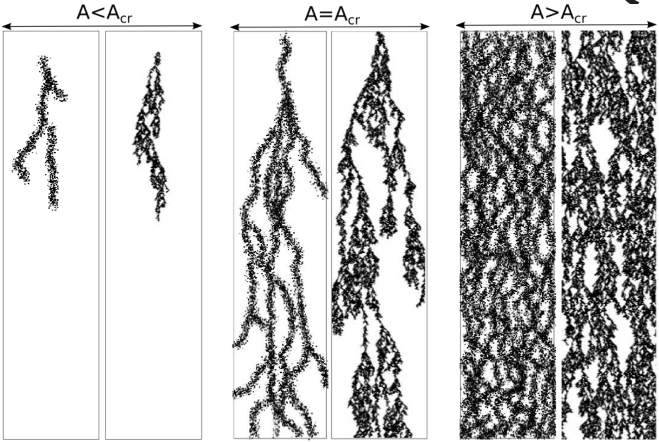

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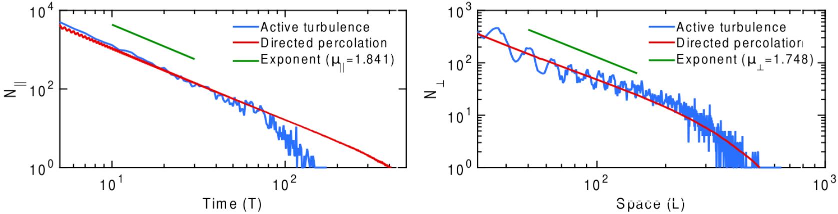

Figure: Distribution of gaps between puffs (in time & in space) also corresponds to the DP universality class

Doostmohammadi, TNS, Thijssen & Yeomans, Onset of mesoscale turbulence in living fluids, (submitted)

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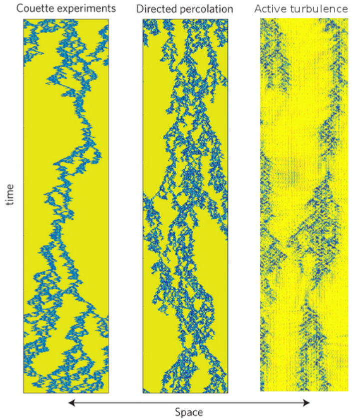

Figure: Both active turbulence & inertial turbulence belong to the DP universality class

Doostmohammadi, TNS, Thijssen & Yeomans, Onset of mesoscale turbulence in living fluids, (submitted)

Onset of inertial turbulence

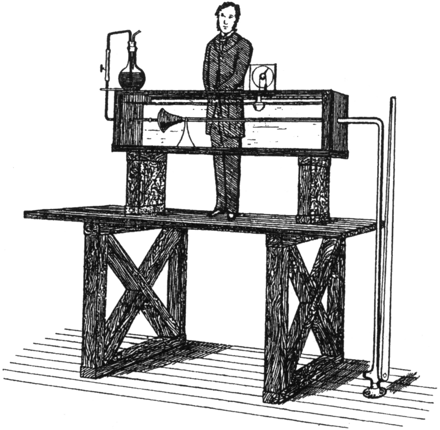

Figure: Osborne Reynolds studied the nature of turbulence in pipes in 1883

Reynolds, An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous, & of the law of resistance in parallel channels, Proceedings of the Royal Society of London (1883)

Onset of inertial turbulence

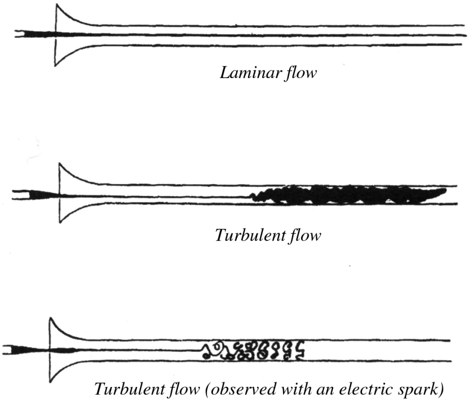

Figure: Laminar flow is linearly stable

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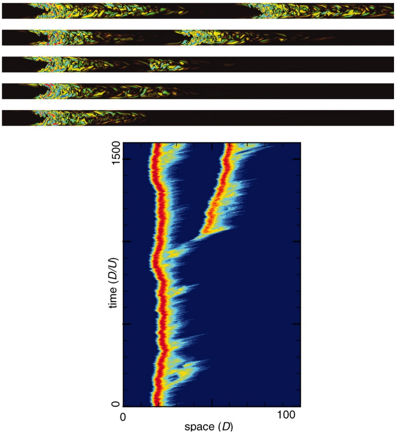

Figure: Using glass pipes (4mm×15000mm) and impulsive jets to form puffs, Björn Hof tied the onset of turbulence in pipes to DP in 2011

Avila, *et. al.*, The Onset of Turbulence in Pipe Flow, Science (2011)

Directed percolation & absorbing states

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Janssen/Grassberger conjecture

Short-range interacting systems, exhibiting a continuous phase transition into a unique absorbing state generically belong to the DP universality class (provided there are no additional symmetries)

Hinrichsen, Non-equilibrium critical phenomena and phase transitions into absorbing states, Adv Phys (2002)

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Spontaneous activation destroys the absorbing state and drives the system away from criticality

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- Equivalent to an external non-ordering field

Hinrichsen, Non-equilibrium critical phenomena and phase transitions into absorbing states, Adv Phys (2002)

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Directed percolation & absorbing states

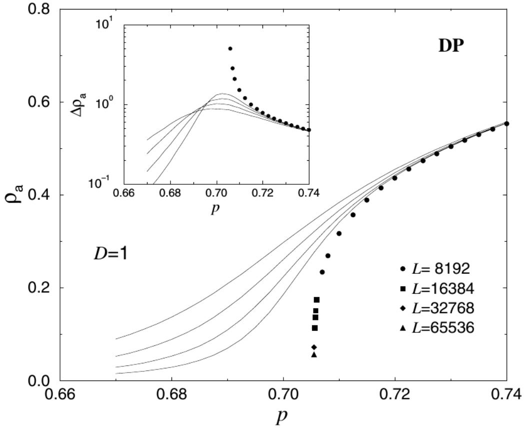

Figure: For sufficiently small rate of spontaneous creation, the critical point moves suddenly (but by a small amount) & the DP universal critical exponents hold, as well as the generalized homogeneous universal scaling functions

Lübeck & Willmann, Universal scaling behaviour of directed percolationa dn the pair contact process in an external field, J Phys A (2002)

Directed percolation & absorbing states

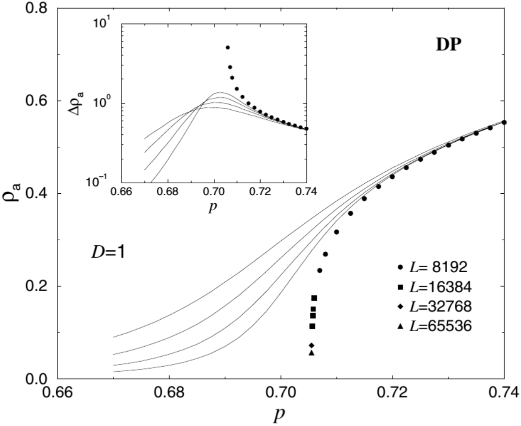

Figure: Pair Contact, diffusive pair contact & thereshold transfer processes each have a non-unique absorbing state, yet yield DP critical exponents

Lübeck & Willmann, Universal scaling behaviour of directed percolationa dn the pair contact process in an external field, J Phys A (2002)

Directed percolation & absorbing states

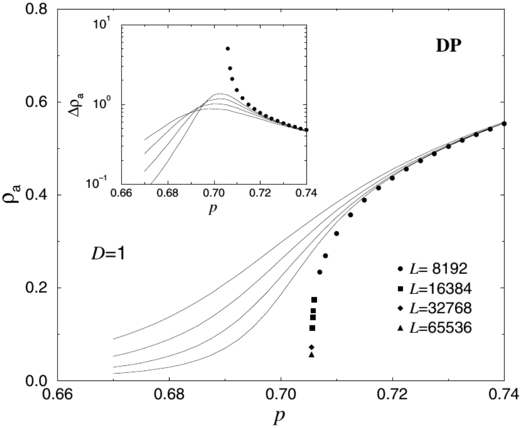

Figure: Lübeck *et. al.* consider this explicit evidence that the Janssen/Grassberger conjecture does not uniquely define the DP universality class

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Conclusion

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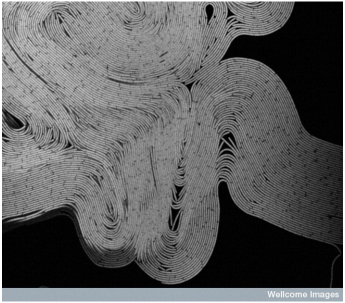
Dancing & Turbulence in Active Matter

- Model dense bacterial suspensions as active nematics
- Ceilidh Dance
  - Dynamic ordered state
  - Pairs of topological disclinations
  - Lattice defects
    - Broken-pairs
    - Quantized-drift
- Mesoscale Turbulence
  - Not true turbulence
    - Zero-Reynolds number
    - Characteristic length scale
  - In a channel
    - Onset determined by puff dynamics (just like inertial turbulence)
    - Critical exponents belong to the DP universality class
    - despite spontaneous puff activation



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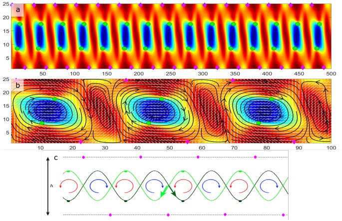

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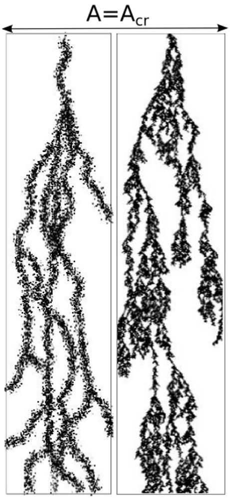

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