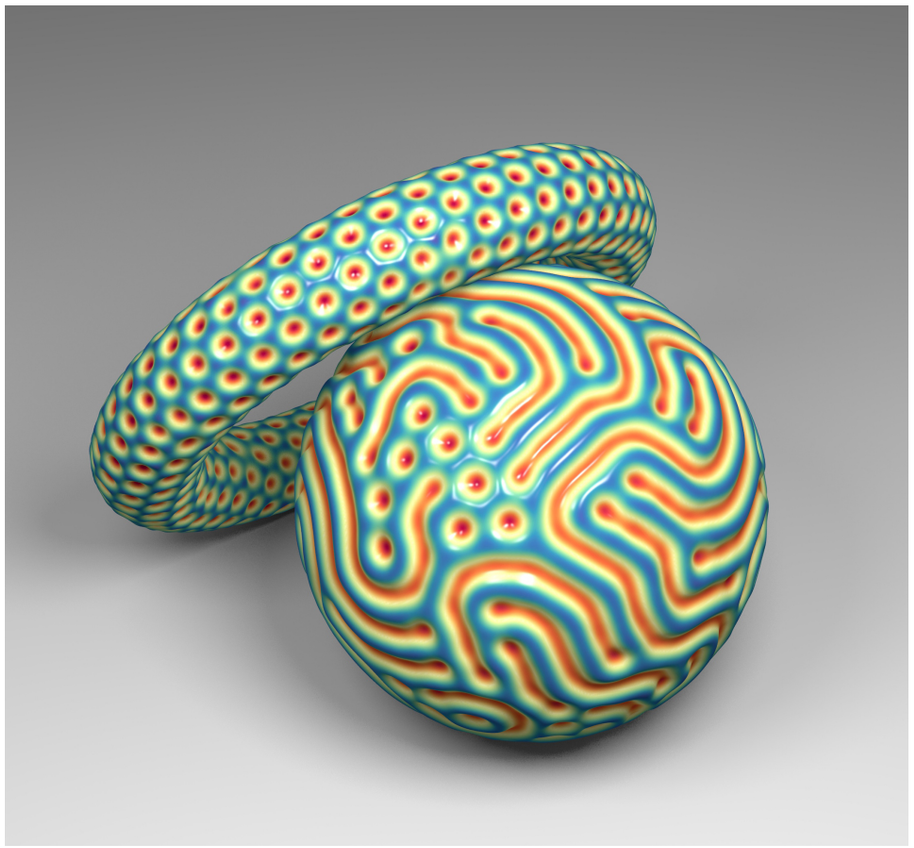
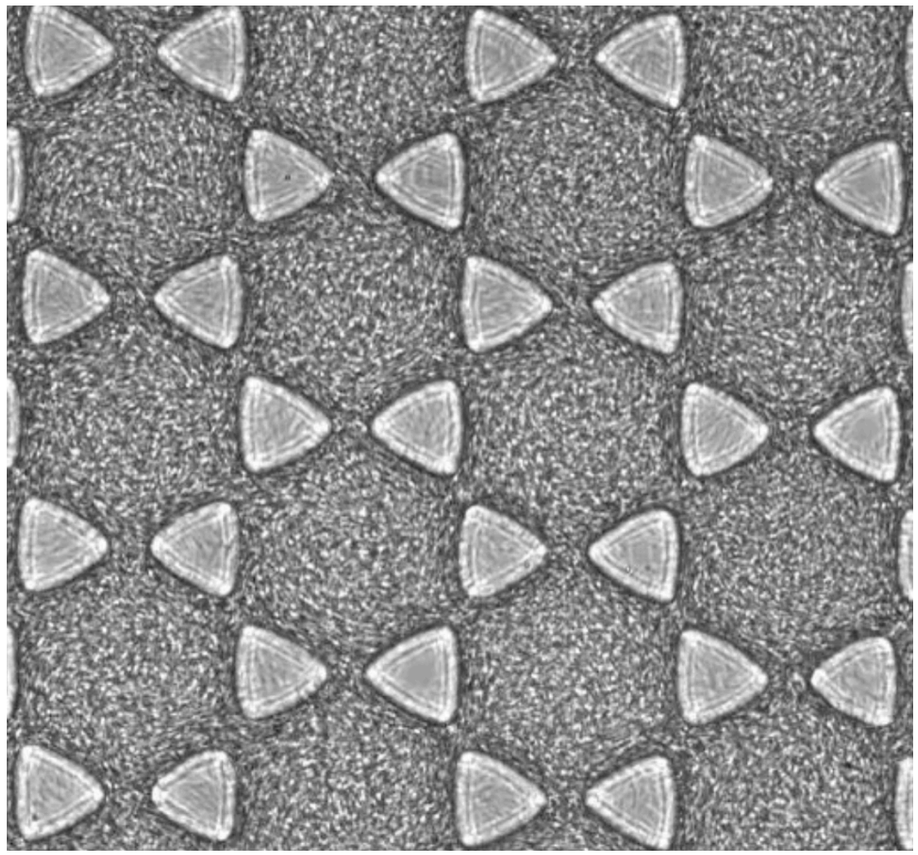
Mathematics of Soft and Living Matter





Jörn Dunkel

MIT
MATHEMATICS

Current group members



Jörn Dunkel
PI



Norbert Stoop
Postdoc



Philip Pearce
Postdoc/Instructor



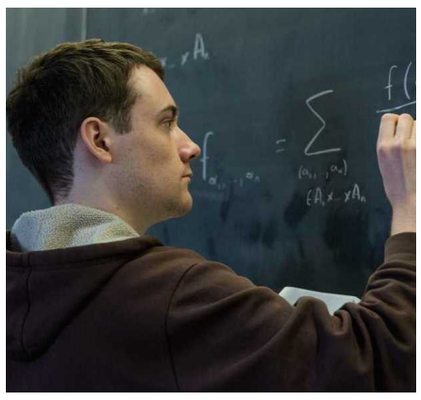
Vili Heinonen
Postdoc/Instructor



Henrik Ronellenfitsch
Postdoc/Instructor



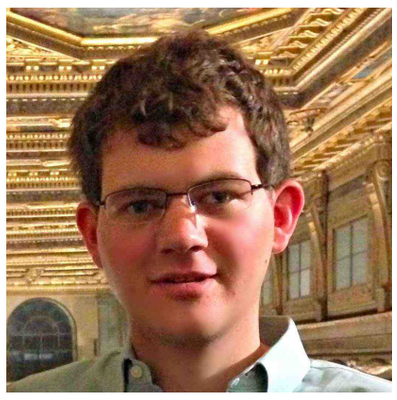
Jonasz Slomka
PhD Math 2018



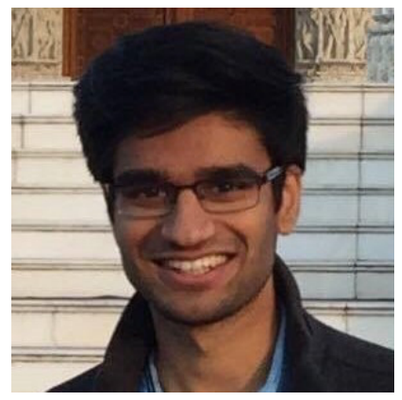
Aden Forrow
PhD Math 2018



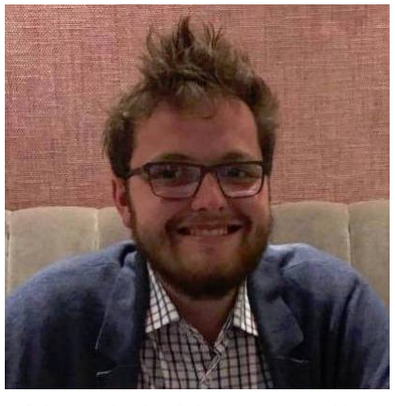
Rachel Mok
PhD MechE 2019



Pearson Miller
PhD Physics 2019



Vishal Patil
PhD Math 2021



Alasdair Hastewell
Senior Thesis 2018



Hannah Jeckel
Visting MSc Student

MIT
MATHEMATICS

Research goals

Develop new mathematical theory and computational methods to help

- understand symmetry breaking mechanisms in soft and biological matter and complex fluids

- identify principles of multicellular self-organization

- advance bio-inspired design of new classes of active materials

Test models against experimental data from collaborators whenever possible

MIT collaborations

Nature Material 2015

PRL 2016

Development 2017

Dunkel group

MIT MATHEMATICS

Matthias Kolle

MITMECHE



Elastic fibers

Nikta Fakhri

Physics of Living Systems



Active surface waves



Pedro Reis

MITMECHE

Surface wrinkling

Alex Shalek

Chemistry



scRNA-seq protocol optimization



Adam Martin

MIT DEPARTMENT OF BIOLOGY

Fly morphogenesis

In Song Kim

MIT POLITICAL SCIENCE



International trade data

Martin Zwierlein

rle RESEARCH LABORATORY OF ELECTRONICS AT MIT



Quantum hydrodynamics

Joint papers published

Joint papers in preparation

Joint grant applications pending

Started @ MIT daycare

Recent/current external collaborations

Nature Comm 2017

PRL 2017

PNAS 2016

Francis Woodhouse

UNIVERSITY OF CAMBRIDGE

Active networks

PNAS 2015

Kansler lab

THE UNIVERSITY OF WARWICK

Microbial fluids

Nature Physics 2016

eLife 2015

eLife 2014

Goldstein lab

UNIVERSITY OF CAMBRIDGE

Bacterial suspensions

Dunkel group

MIT MATHEMATICS

Guasto lab

Tufts UNIVERSITY

Porous media flows

National Science Foundation

NSF CBET 1510768

Shvartsman lab

PRINCETON UNIVERSITY

Oogenesis

Stone lab
Bassler lab

PRINCETON UNIVERSITY

Biofilms

PNAS 2016

Drescher lab

MAX PLANCK INSTITUTE FOR TERRESTRIAL MICROBIOLOGY

Bacterial biofilms

MISTI

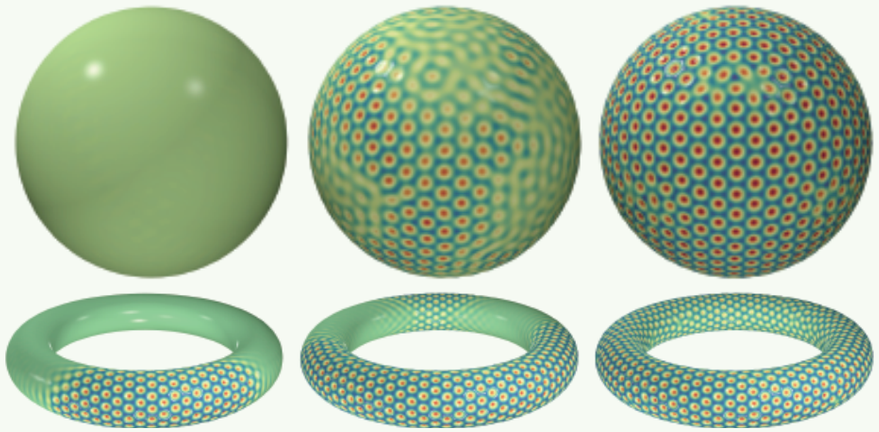
Joint papers published

Joint papers submitted

Joint papers in preparation

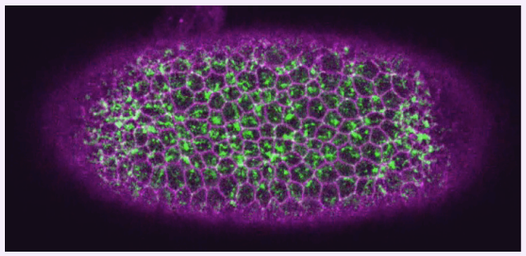
Examples from work completed since joining MIT

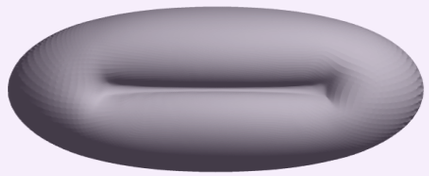
Surface pattern formation in soft materials



Reis lab, MIT MechE

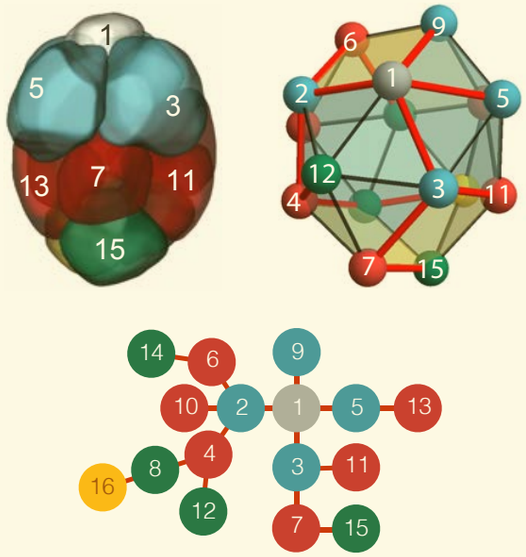
Morphogenesis





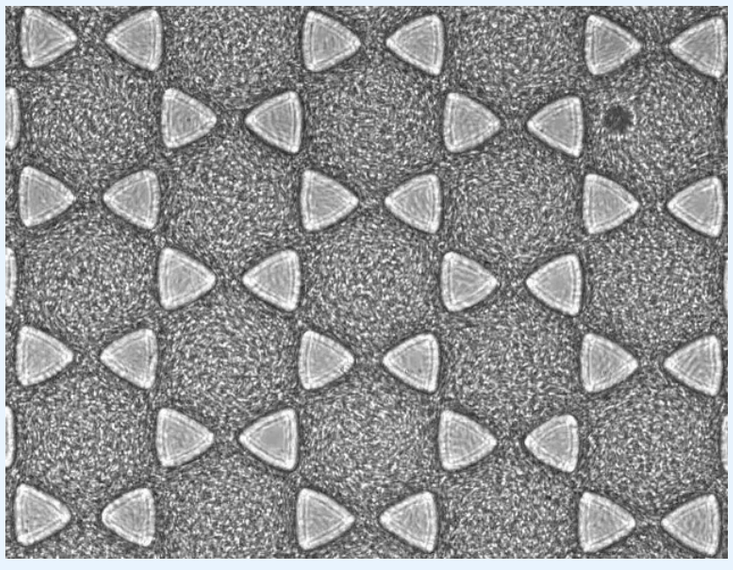
Martin lab, MIT Biology

Oogenesis



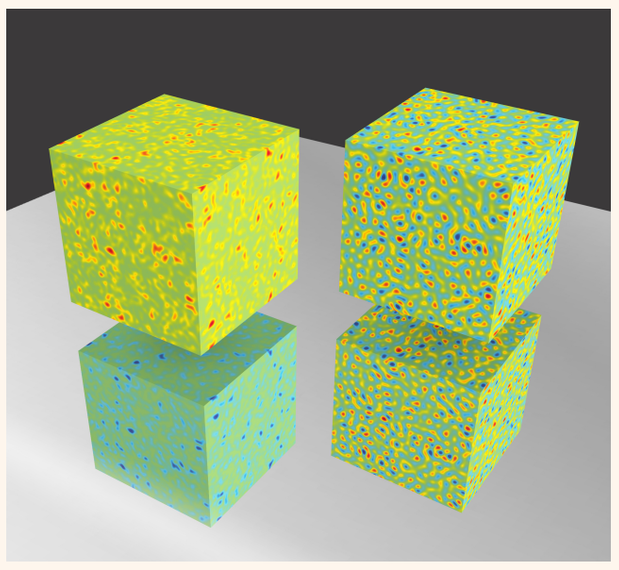
Shvartsman lab, Princeton

Geometric control of microbial suspensions

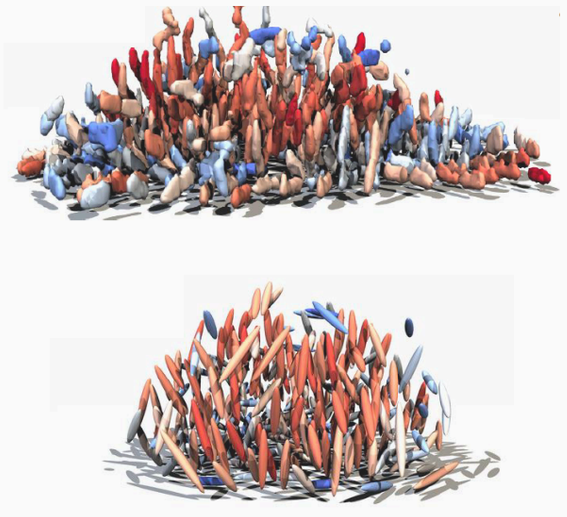


Goldstein lab, Cambridge

Chiral symmetry breaking in active turbulence



Bacterial biofilm architecture



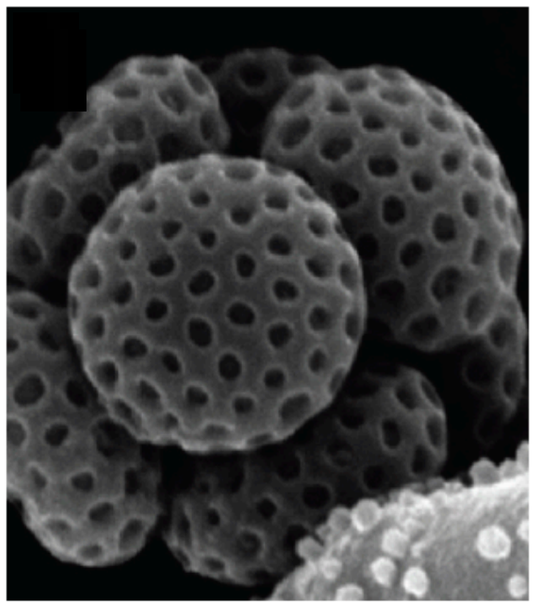
Drescher lab, MPI Marburg

Surface pattern formation in soft matter

Embryogenesis



Fungal spores

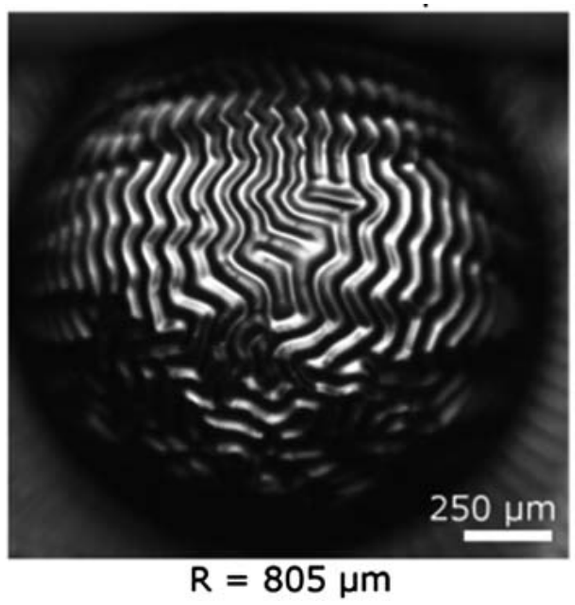




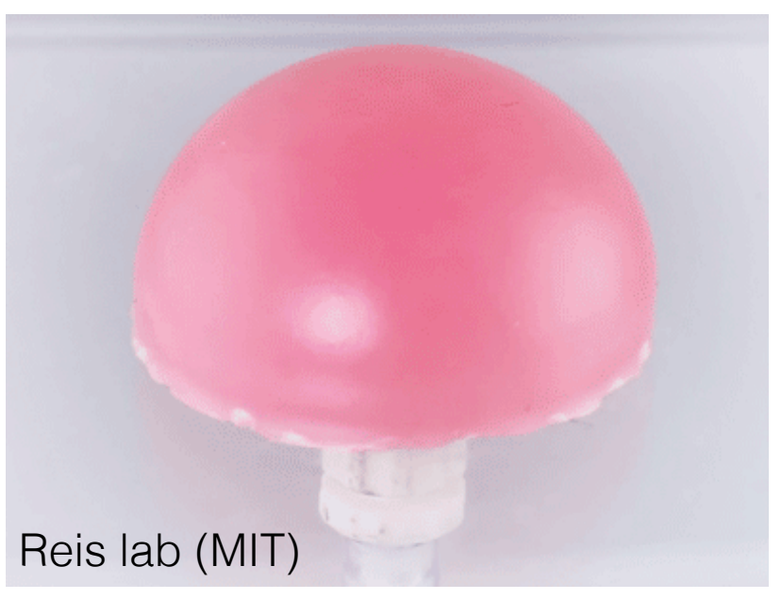
Fingerprints



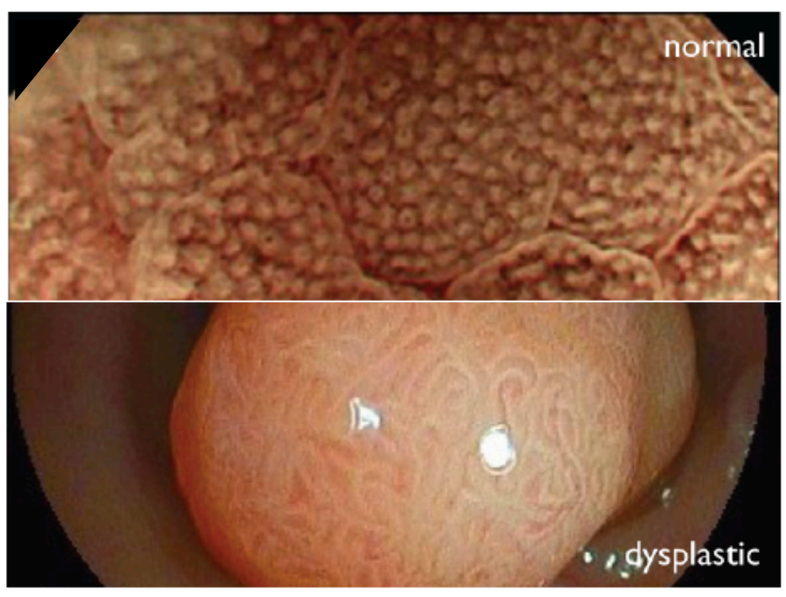
Breid lab (UMass)



Microstructure materials



Smart drag-reducing materials



Colon cancer

Planar case well understood - many open problems for curved geometry

nature materials

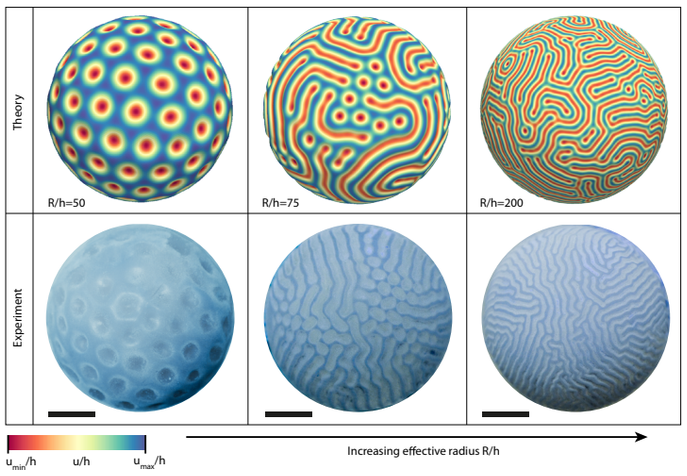
ARTICLES

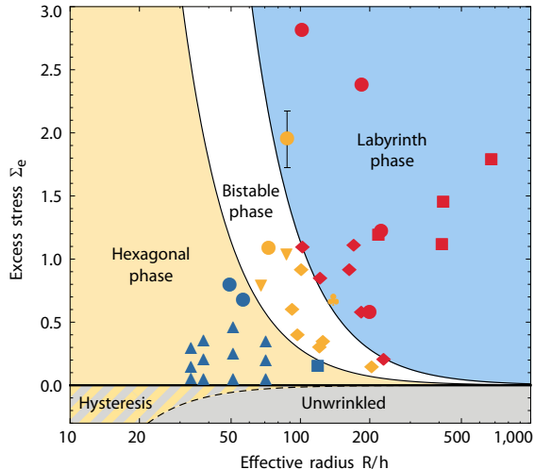
PUBLISHED ONLINE: 2 FEBRUARY 2015 | DOI: 10.1038/NMAT4202

Curvature-induced symmetry breaking determines elastic surface patterns

Norbert Stoop[1], Romain Lagrange[1], Denis Terwagne[2†], Pedro M. Reis[2,3] and Jörn Dunkel[1*]

$$\mu\partial_t u = \gamma_0\triangle u - \gamma_2\triangle^2 u - au - bu^2 - cu^3 + \frac{h}{2}\left\{(\nu-1)\left[b^{\alpha\beta}\nabla_\alpha u\nabla_\beta u + 2u\nabla_\beta\left(b^{\alpha\beta}\nabla_\alpha u\right)\right] + 2\nu\left[\mathcal{H}(\nabla u)^2 - 2\nabla\cdot(\mathcal{H}u\nabla u)\right]\right\} + \frac{h}{2}\left[(1-\nu)u\nabla_\beta\left(uc^{\alpha\beta}\nabla_\alpha u\right) - \nu\mathcal{R}u(\nabla u)^2 + \nu\nabla\cdot(\mathcal{R}u^2\nabla u)\right]$$





new covariant nonlinear fourth-order PDE theory

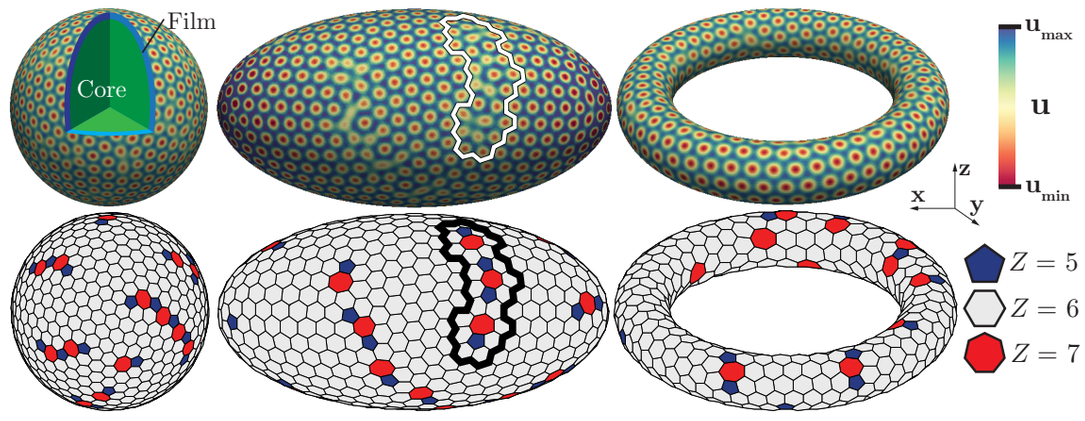
quantitative agreement with experiments

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PRL 116, 104301 (2016) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2016

Curvature-Controlled Defect Localization in Elastic Surface Crystals

Francisco López Jiménez,[1] Norbert Stoop,[2] Romain Lagrange,[2] Jörn Dunkel,[2,*] and Pedro M. Reis[1,3,†]



$$\gamma_0 = \frac{\kappa^2}{3} - \frac{1}{6}\sqrt{\eta^{4/3} + 24(1+\nu)\kappa^2 + 16\kappa^4}$$

$$a = \frac{\eta^{4/3}}{12} + \frac{6(1+\nu) - \eta^{2/3}}{3}\kappa^2 + \frac{\kappa^4}{3} + \tilde{a}_2\Sigma_e$$

$$b = 3(1+\nu)\kappa^3$$

$$c = \frac{2(1+\nu)\eta^{2/3}}{3}c_1 + (1+\nu)\kappa^4$$

$$\Gamma_1 = \frac{1+\nu}{2}\kappa$$

$$\Gamma_2 = \frac{1+\nu}{2}\kappa^2$$

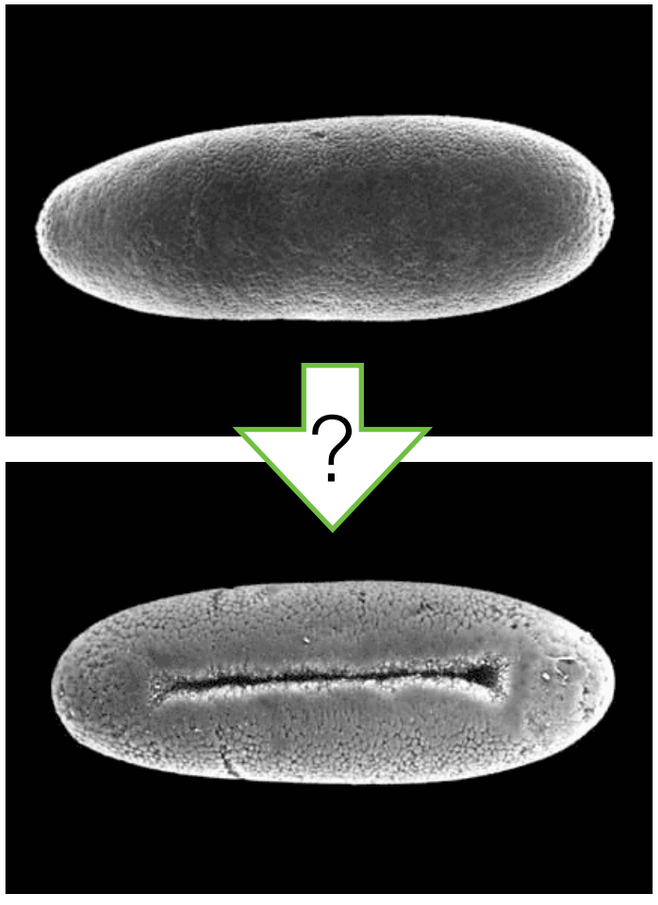
$$\tilde{a}_2 = -\frac{\eta^{4/3}(c+3|\gamma_0|\Gamma_2)}{48\gamma_0^2}$$

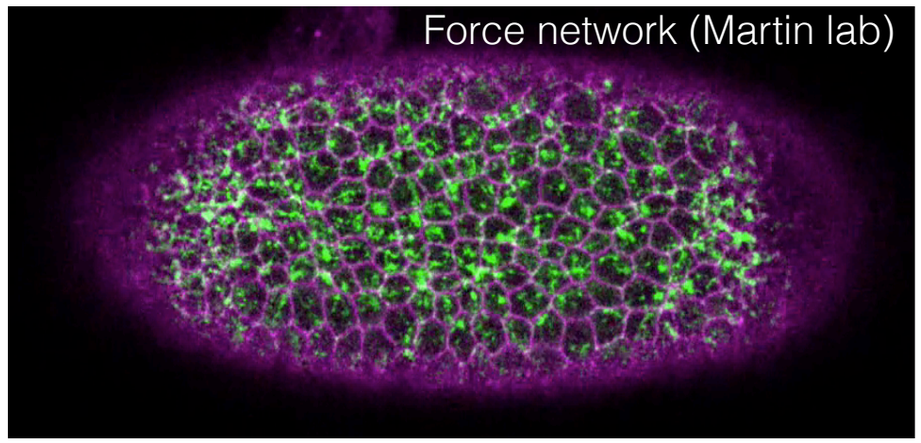
TABLE I: List of parameters for Eq. (1) in units $h = 1$, with $\eta = 3E_s/E_f$, $\gamma_2 = 1/12$, $\Sigma_e = (\sigma/\sigma_c) - 1$ and $\kappa = h/R$. The only remaining fitting parameter of the model is c_1.

In collaboration with Martin lab (MIT Biology):



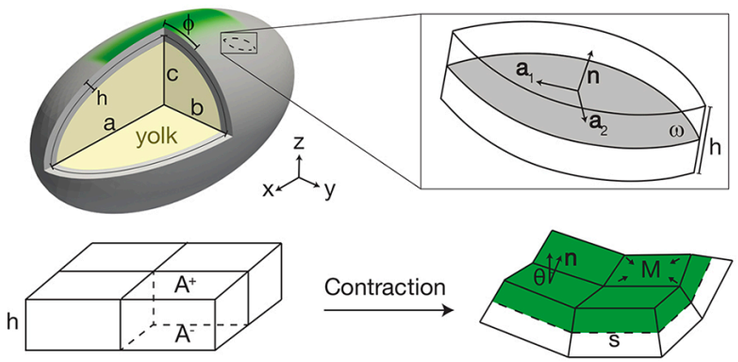
Developing 3D curved elasticity theory and force network models
to understand cell-cell interactions and symmetry breaking transitions
during embryogenesis





Simulation (Dunkel group)





$$\mathcal{E} = \frac{Yh}{8(1-\nu^2)} \int_{\bar{\omega}} S\Big\{(1-\nu)\mathrm{Tr}[(\mathbf{a}-\bar{\mathbf{a}})^2] + \nu\mathrm{Tr}(\mathbf{a}-\bar{\mathbf{a}})^2 + \frac{h^2}{3}[(1-\nu)\mathrm{Tr}[(\mathbf{b}-\bar{\mathbf{b}})^2] + \nu\mathrm{Tr}(\mathbf{b}-\bar{\mathbf{b}})^2]\Big\} d\bar{\omega}.$$

© 2017. Published by The Company of Biologists Ltd | Development (2017) 144, 1876-1886 doi:10.1242/dev.146761

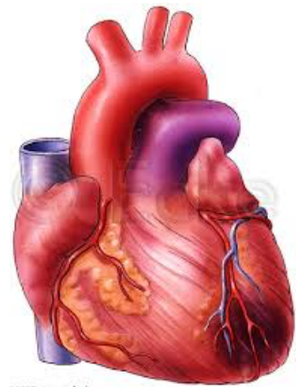
RESEARCH ARTICLE

Actomyosin-based tissue folding requires a multicellular myosin gradient

Natalie C. Heer[1], Pearson W. Miller[2,3], Soline Chanet[1], Norbert Stoop[3], Jörn Dunkel[3] and Adam C. Martin[1,*]

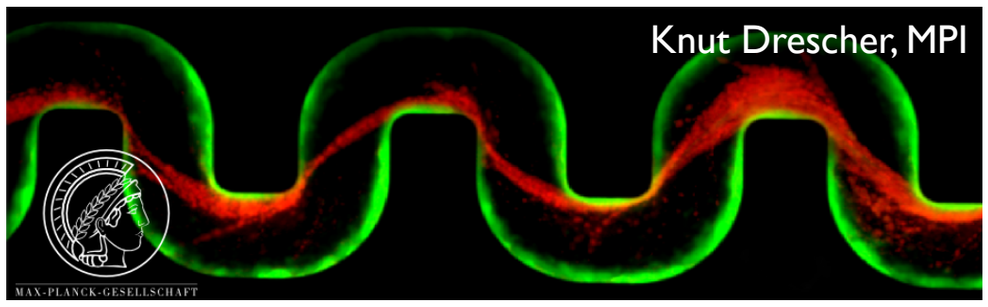
3D architecture of bacterial biofilms

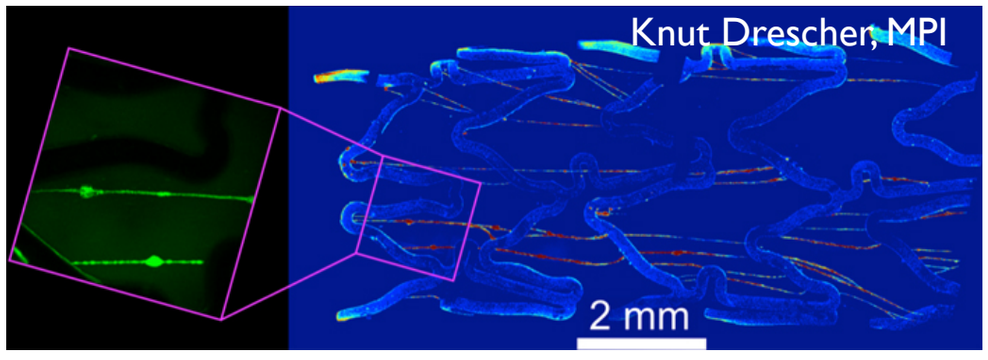
- bacterial films = most abundant life forms outside oceans
- ~10 times more bacterial cells than human cells in human body
- infections: ~100,000 amputations/yr, >90,000 deaths/yr in US
- antibiotic resistance
- pollution of water & clogging



www.julius-ecke.de

catastrophic stent clogging

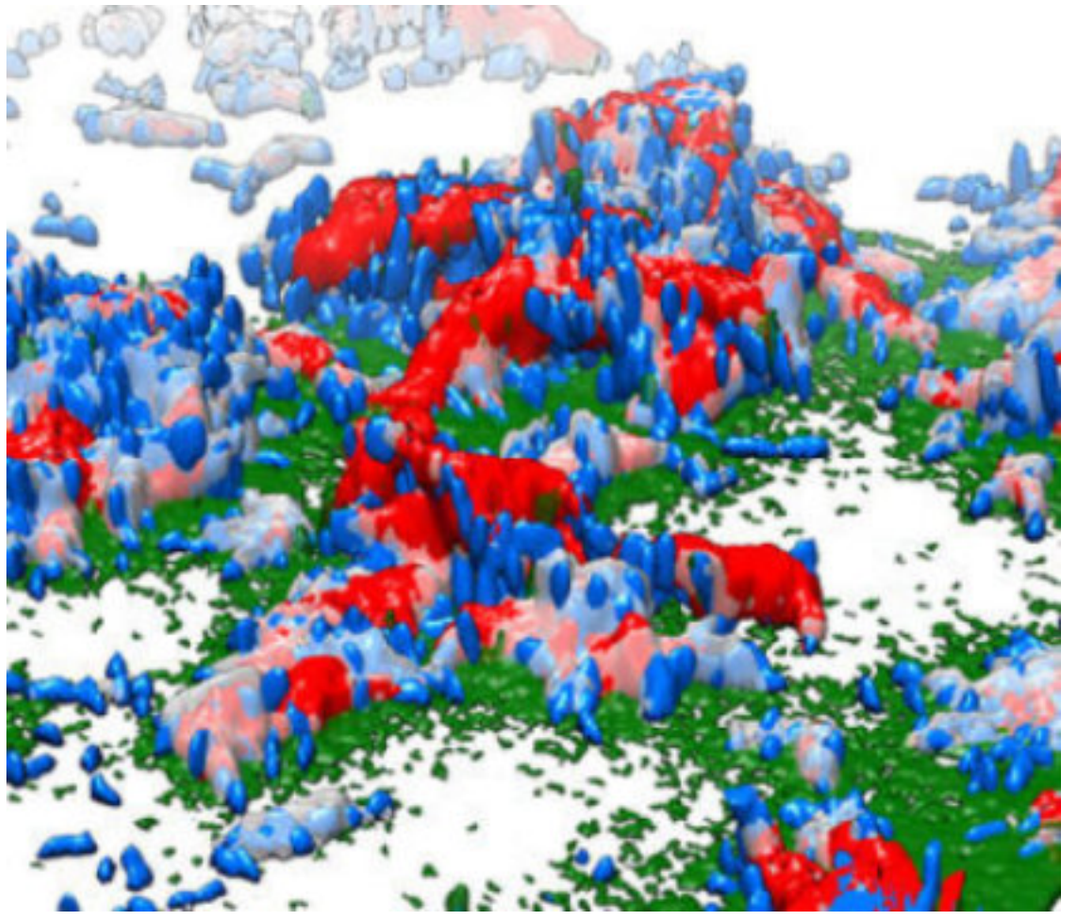








Previous state-of-the-art



Credit: Veysel Berk (Science, 2012)

Major breakthrough in 3D single-cell imaging

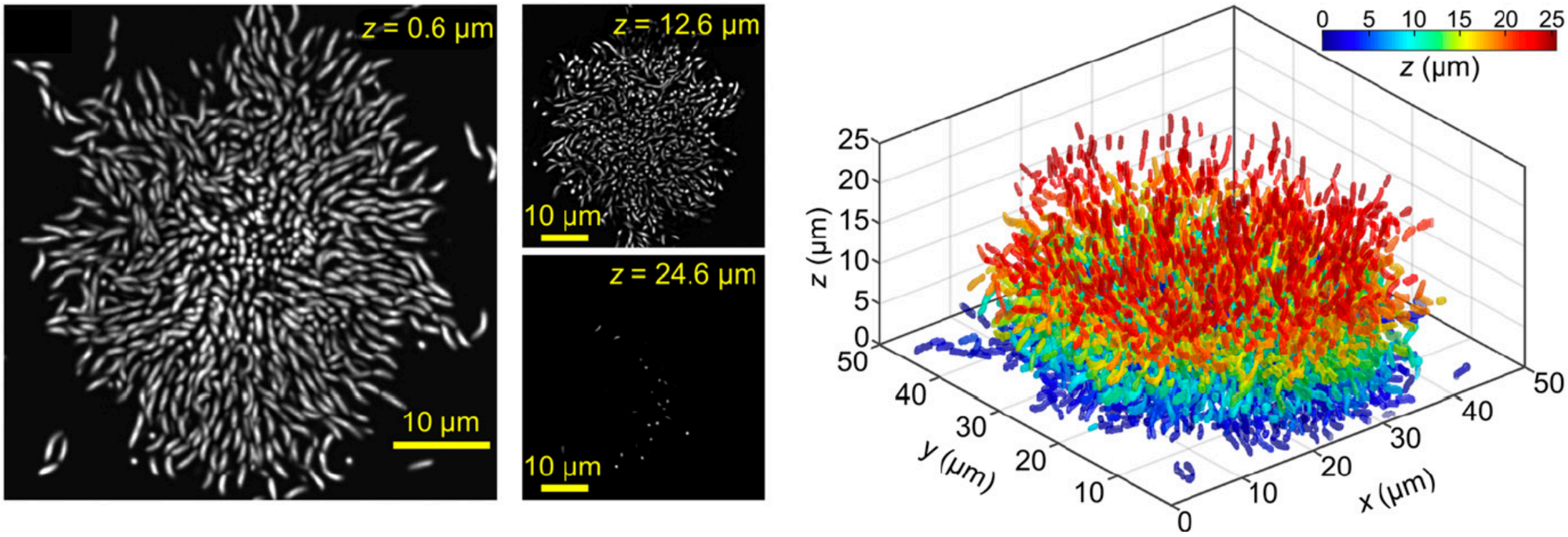
PNAS

Architectural transitions in *Vibrio cholerae* biofilms at single-cell resolution

Knut Drescher[a,b,c], Jörn Dunkel[d], Carey D. Nadell[a,b], Sven van Teeffelen[b,1], Ivan Grnja[a], Ned S. Wingreen[b], Howard A. Stone[c], and Bonnie L. Bassler[b,e,2]

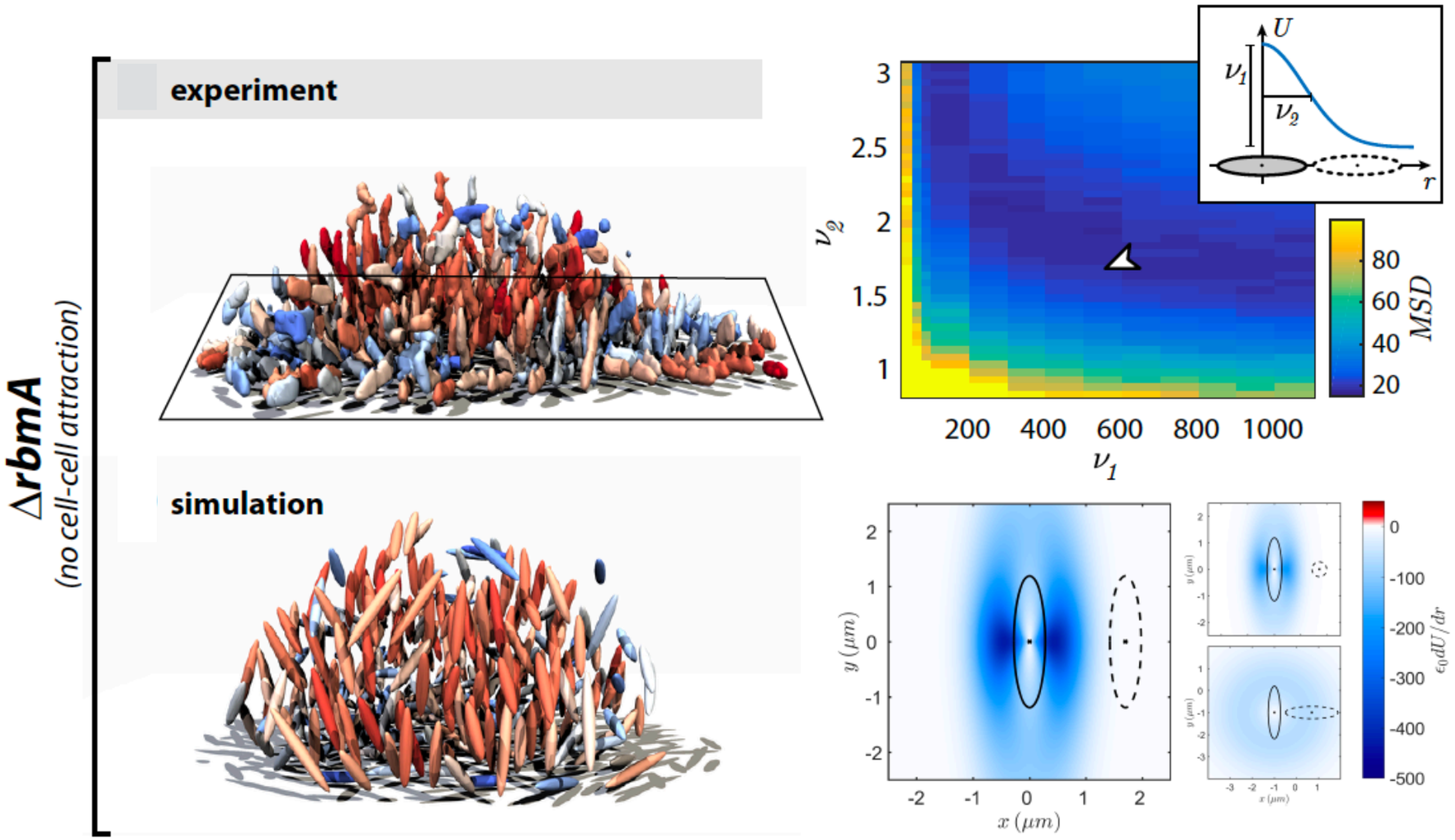
[a]Max Planck Institute for Terrestrial Microbiology, 35043 Marburg, Germany; [b]Department of Molecular Biology, Princeton University, Princeton, NJ 08544; [c]Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ 08544; [d]Department of Mathematics, Massachusetts Institute of Technology, Cambridge, MA 02139; and [e]Howard Hughes Medical Institute, Chevy Chase, MD 20815

Contributed by Bonnie L. Bassler, February 5, 2016 (sent for review December 2, 2015; reviewed by Gürol M. Süel and Gerard C. L. Wong)



Basis for ongoing collaboration with Drescher lab to establish the first quantitative cell-based model of 3D biofilm formation

In collaboration with Drescher lab (Max-Planck-Institute Marburg)



- GPU simulations of cell growth and interaction dynamics
- automated estimation of effective cell-cell interaction potentials for wild type and mutant strains using Markov Chain Monte Carlo methods
- effects of fluid flow and nutrient availability on biofilm architecture

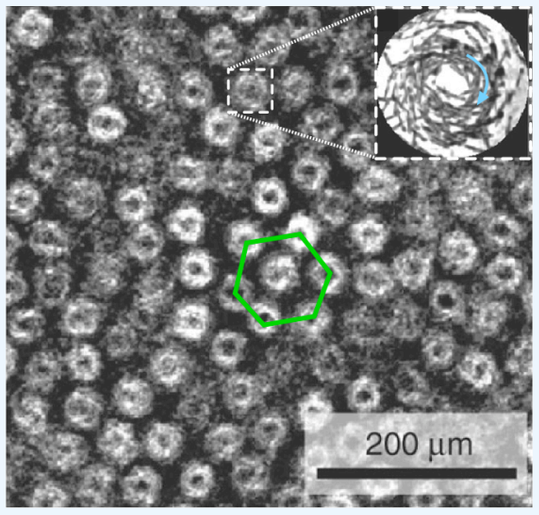
(two joint papers currently being finalized)

MISTI

Symmetry breaking in active fluids

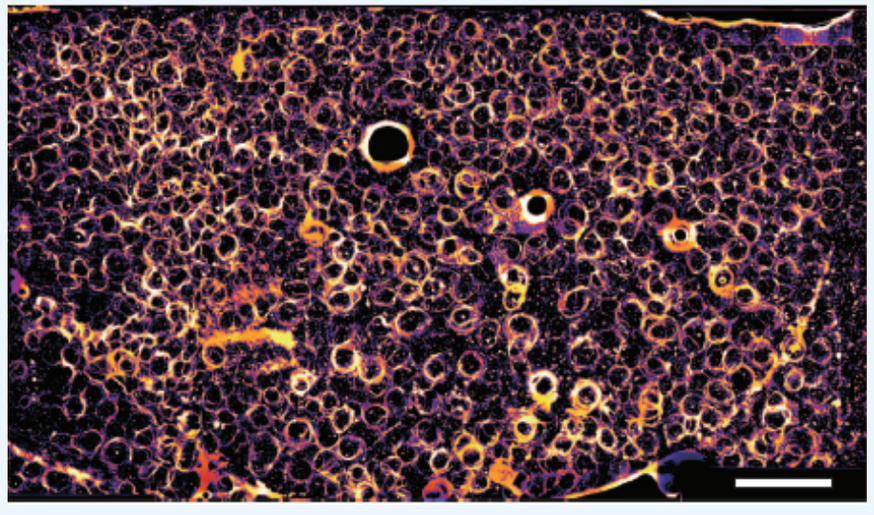
Active suspensions exhibit spontaneous flow pattern formation

Sea urchin sperm



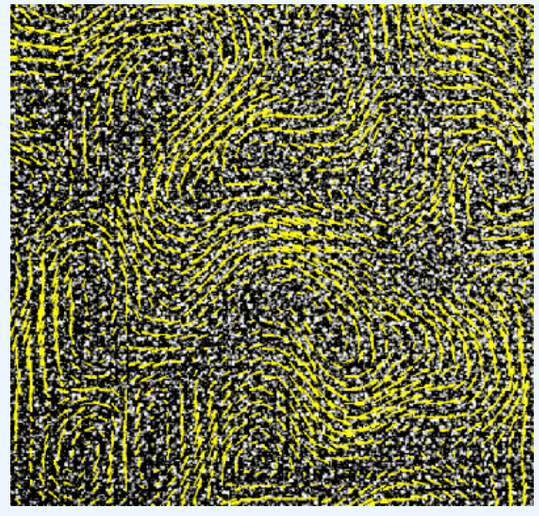
Riedel et al, Science 2005

ATP-driven microtubules



Sumino et al, Nature 2007

Bacterial suspensions



Dunkel et al, PRL 2013

Strong recent interest as basis for new class of active materials

Previous standard models

- involve several nonlinear coupled PDEs with >6 parameters unknown parameters
- important qualitative insights but no quantitative comparisons with experiments
- analytical progress difficult if not impossible

Goals

- experimentally testable broadly applicable Landau-type field theory
- analytical and numerical tractability

Chiral symmetry breaking in active turbulence

PNAS

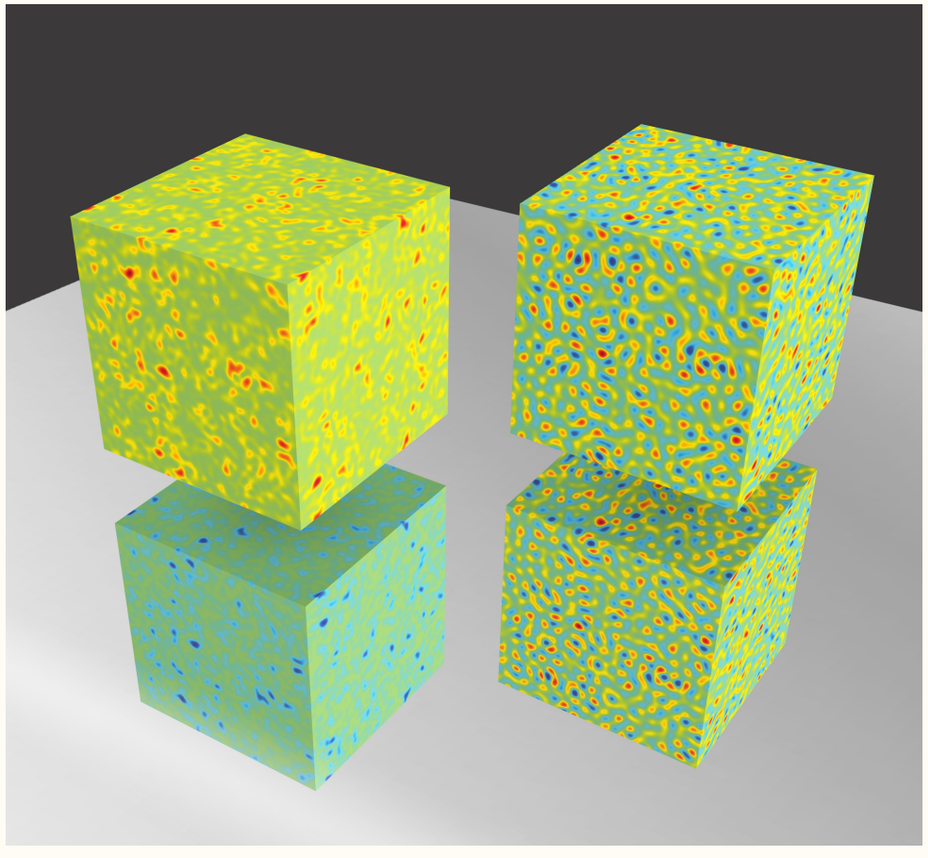
Spontaneous mirror-symmetry breaking induces inverse energy cascade in 3D active fluids

Jonasz Słomka[a] and Jörn Dunkel[a,1]

[a]Department of Mathematics, Massachusetts Institute of Technology, Cambridge, MA 02139-4307

Edited by David A. Weitz, Harvard University, Cambridge, MA, and approved January 4, 2017 (received for review September 2, 2016)

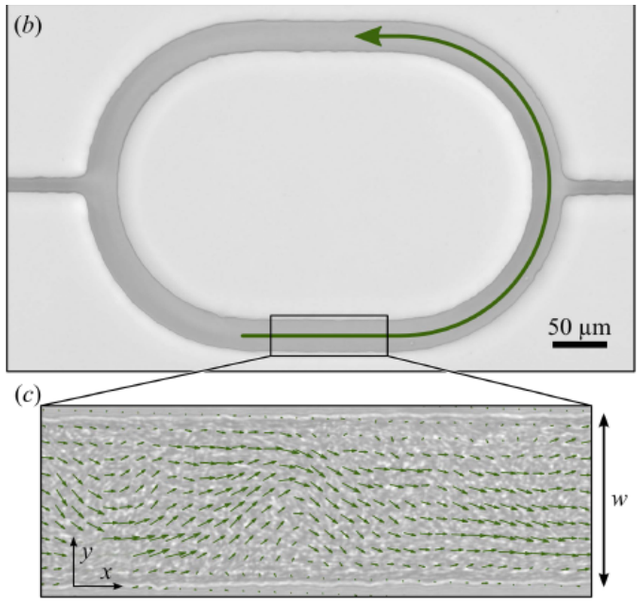
$$
\begin{aligned}
0 &= \nabla \cdot \boldsymbol{v} \\
\partial_t \boldsymbol{v} + (\boldsymbol{v} \cdot \nabla)\boldsymbol{v} &= -\nabla p + \Gamma_0 \nabla^2 \boldsymbol{v} - \Gamma_2 \nabla^4 \boldsymbol{v} + \Gamma_4 \nabla^6 \boldsymbol{v}
\end{aligned}
$$



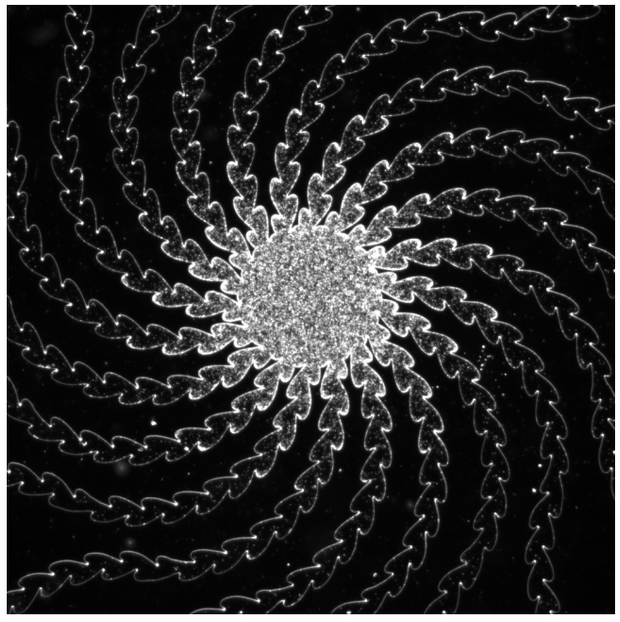
Main results

- fast spectral methods for generalized Navier-Stokes (GNS) equations in periodic and shear geometries
- new class of exact analytic Beltrami field solutions for GNS equations
- clarifying conditions for ‘inverse’ energy transport from small to large scales in 3D
- confirmation of 25 year-old hypothesis by Waleffe about triads supporting 3D inverse cascade
- discovery of a previously unknown cubic invariant for the triad dynamics of classical 3D turbulence, enabling the comprehensive geometric characterization of the phase space (arXiv:1708.01394)

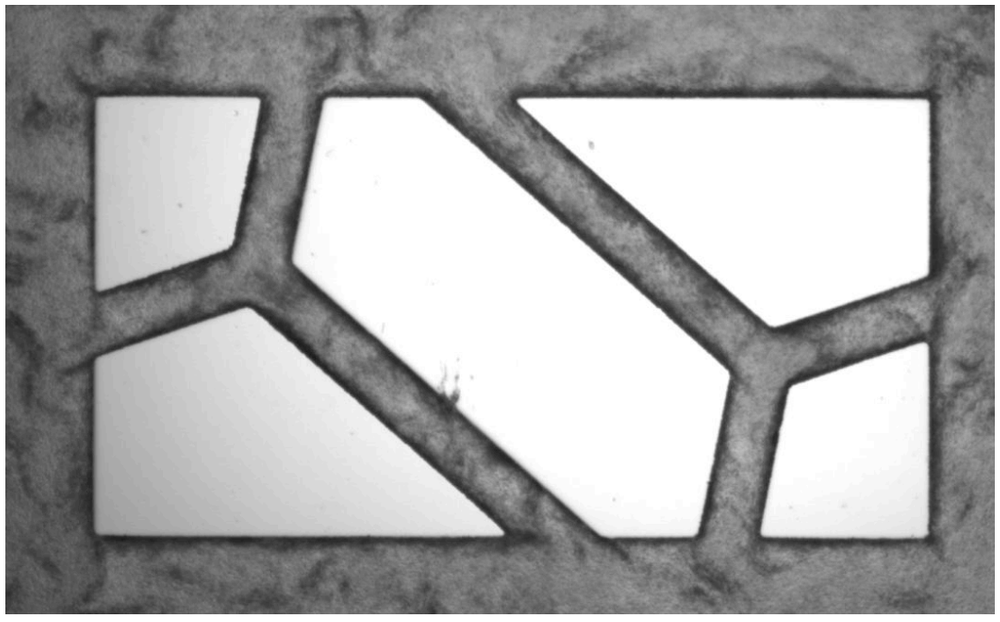
Active flows in complex geometries



Goldstein lab



Kantsler lab



Kantsler lab

State of the field

- standard PDE models numerically unfeasible in nontrivial network geometries
- recent breakthroughs in microfluidic experiments but no tractable theory

Goals

- effective network theory generalizing classical transport theories
- conceptual basis for autonomous microfluidics & active fluid-based metamaterials
- use framework to study active analogous of topologically protected transport

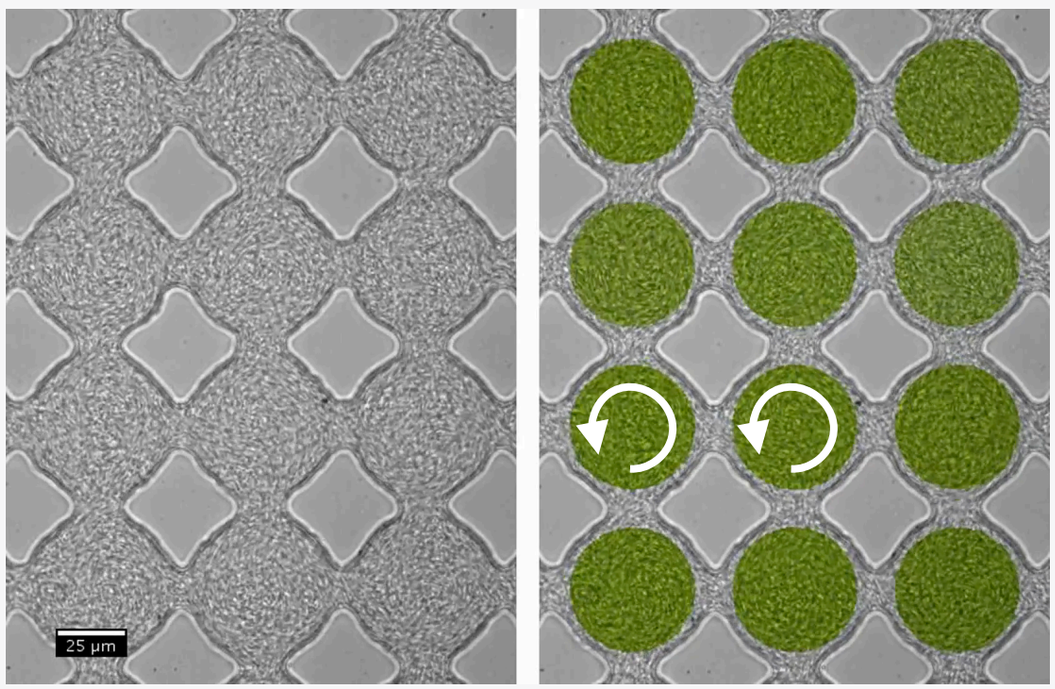
Geometric control of microbial suspensions

Strategy: exploit emergent scale selection and spontaneous symmetry breaking

nature physics
LETTERS
PUBLISHED ONLINE: 4 JANUARY 2016 | DOI: 10.1038/NPHYS3607

Ferromagnetic and antiferromagnetic order in bacterial vortex lattices

Hugo Wioland[1,2†], Francis G. Woodhouse[1,3†], Jörn Dunkel[4] and Raymond E. Goldstein[1*]



$$H(\mathbf{V},\mathbf{P}) = -J_v \sum_{V_i \sim V_j} V_i V_j - J_p \sum_{V_i \sim P_j} V_i P_j + \sum_{V_i} \left(\tfrac{1}{2} a_v V_i^2 + \tfrac{1}{4} b_v V_i^4\right) + \sum_{P_j} \tfrac{1}{2} a_p P_j^2$$

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National Science Foundation

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arts | athletics | social media

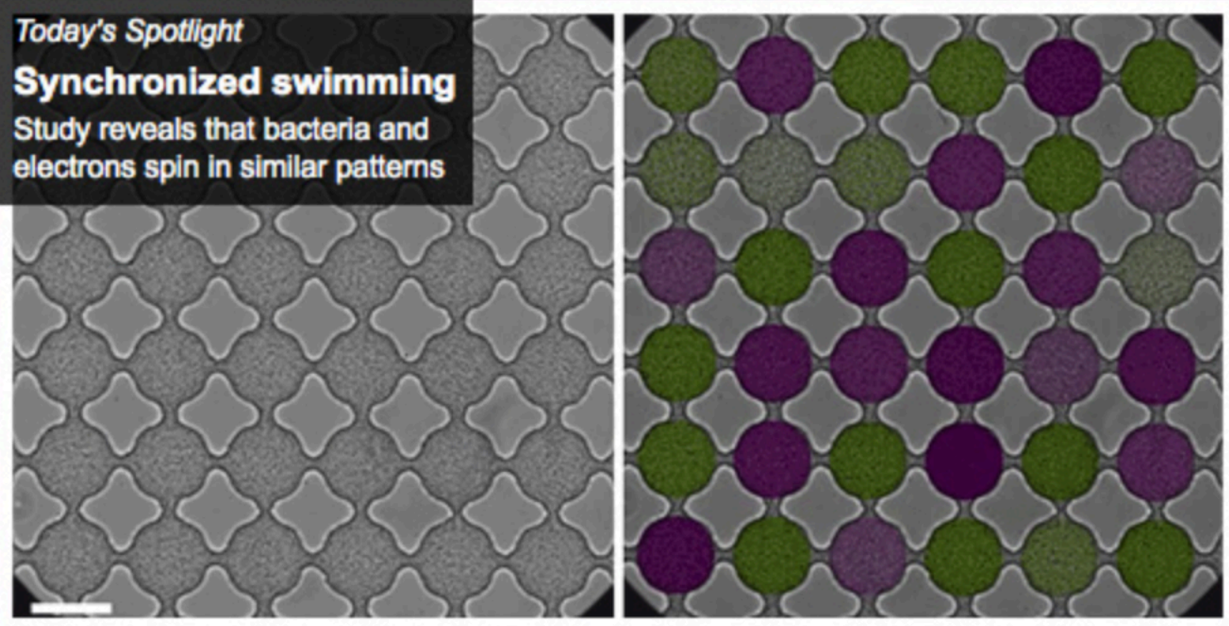
initiatives
energy | cancer | diversity | global

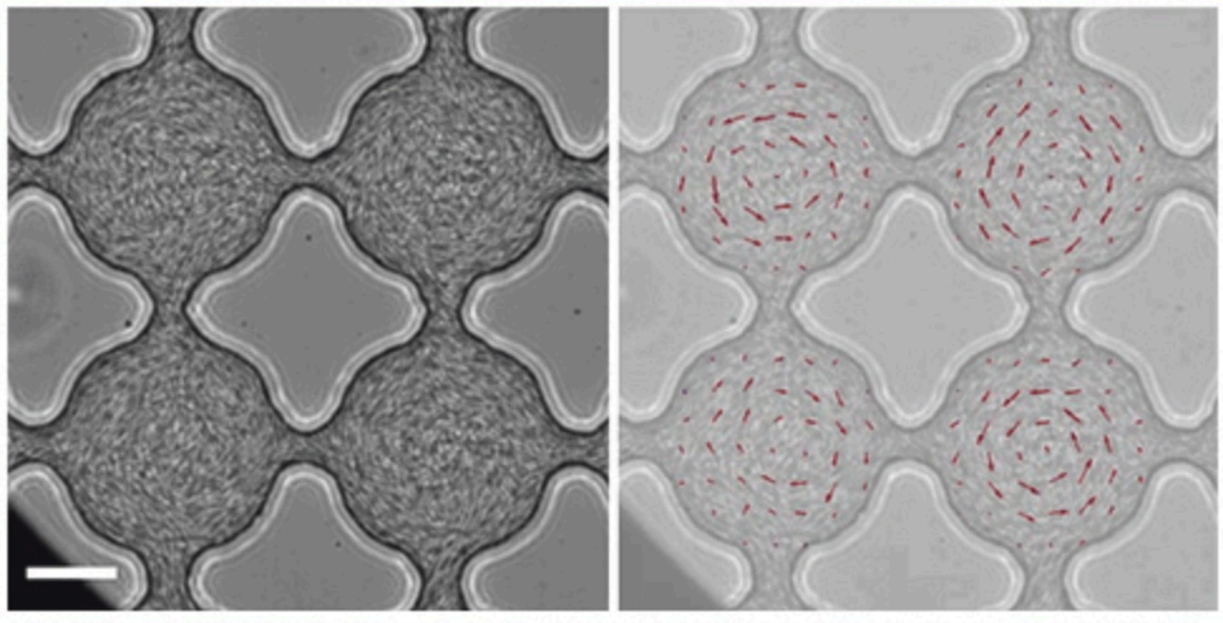
impact
industry | public service

Today's Spotlight

Synchronized swimming

Study reveals that bacteria and electrons spin in similar patterns





news

3Q: Neil Gershenfeld and the spread of Fab Labs

Study: Global mercury regulations to have major economic benefits for US

Researchers discover how some organisms process oxalate

Michael Artin, Shirley Jackson win National Medal of Science

research | campus | press

events

Alumni Class Funds request for proposals

Register: Get Fit @ MIT

Abstract & Experimental Film: 2001: A Space Odyssey (today)

Today's image

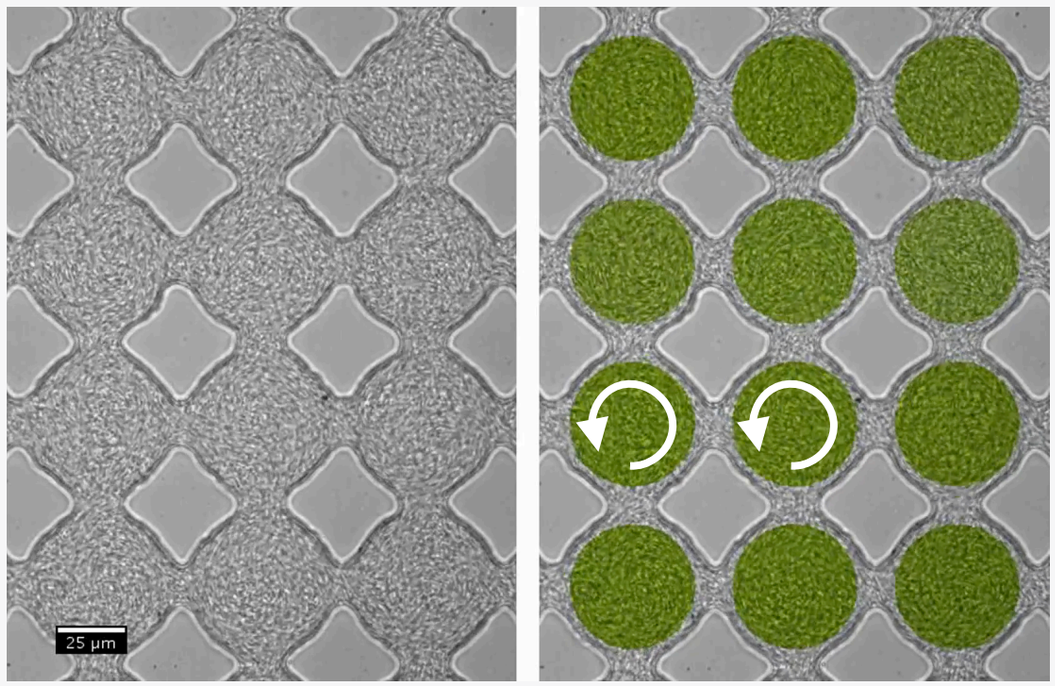
Geometric control of microbial suspensions

Strategy: exploit emergent scale selection and spontaneous symmetry breaking

nature physics
LETTERS
PUBLISHED ONLINE: 4 JANUARY 2016 | DOI: 10.1038/NPHYS3607

Ferromagnetic and antiferromagnetic order in bacterial vortex lattices

Hugo Wioland[1,2†], Francis G. Woodhouse[1,3†], Jörn Dunkel[4] and Raymond E. Goldstein[1*]



$$H(\mathbf{V},\mathbf{P}) = -J_v \sum_{V_i \sim V_j} V_i V_j - J_p \sum_{V_i \sim P_j} V_i P_j + \sum_{V_i} \left(\tfrac{1}{2} a_v V_i^2 + \tfrac{1}{4} b_v V_i^4\right) + \sum_{P_j} \tfrac{1}{2} a_p P_j^2$$

PNAS

Stochastic cycle selection in active flow networks

Francis G. Woodhouse[a,1], Aden Forrow[b], Joanna B. Fawcett[c], and Jörn Dunkel[b]

[a]Department of Applied Mathematics and Theoretical Physics, Centre for Mathematical Sciences, University of Cambridge, Cambridge CB3 0WA, United Kingdom; [b]Department of Mathematics, Massachusetts Institute of Technology, Cambridge MA 02139-4307; and [c]Centre for the Mathematics of Symmetry and Computation, School of Mathematics and Statistics, The University of Western Australia, Crawley, WA 6009, Australia

Edited by David A. Weitz, Harvard University, Cambridge, MA, and approved June 1, 2016 (received for review March 1, 2016)

- develops and analyzes first network theory for incompressible active flows based on effective Hamiltonians
- establishes analogy with spin-ice models

MIT News
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National Science Foundation

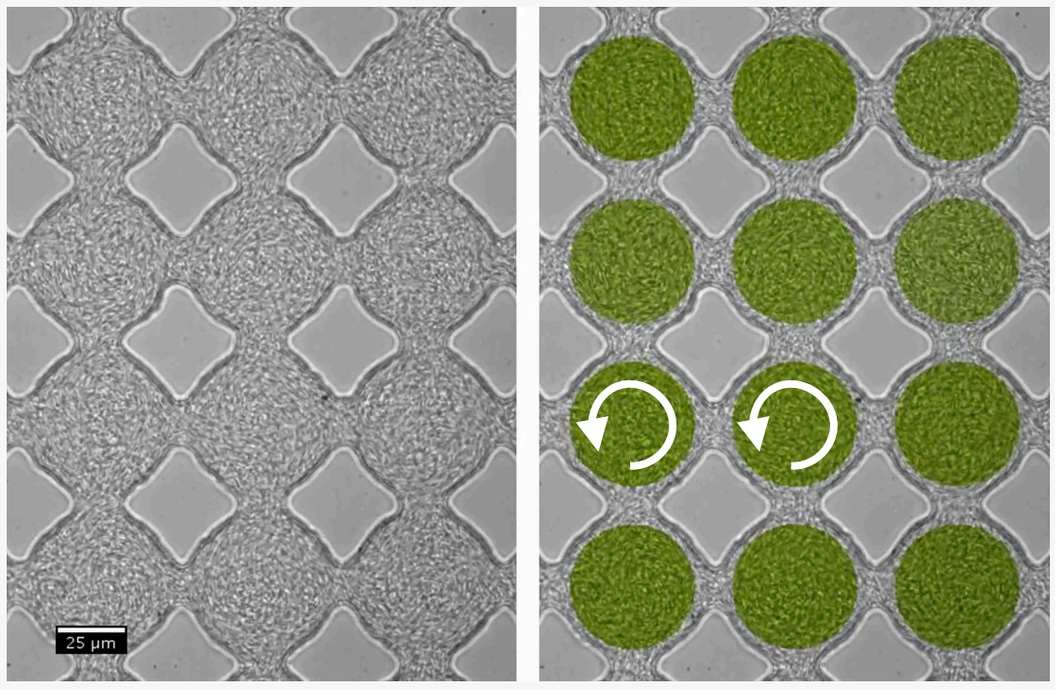
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PRL 119, 028102 (2017) PHYSICAL REVIEW LETTERS week ending 14 JULY 2017

Mode Selection in Compressible Active Flow Networks

Aden Forrow,[1] Francis G. Woodhouse,[2] and Jörn Dunkel[1,*]

- extends network theory to compressible active flows
- demonstrates active mode selection principles and band gap effects as a step towards active metamaterials

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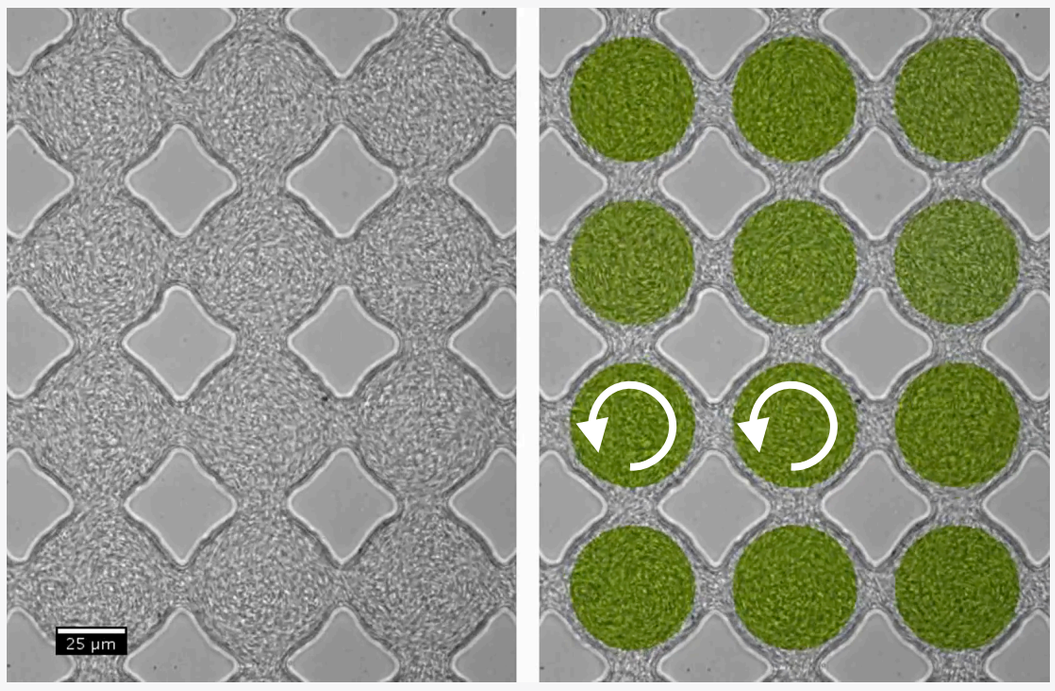
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nature COMMUNICATIONS

ARTICLE

Received 2 Nov 2016 | Accepted 6 Mar 2017 | Published 25 Apr 2017 DOI: 10.1038/ncomms15169 OPEN

Active matter logic for autonomous microfluidics

Francis G. Woodhouse[1] & Jörn Dunkel[2]

- design principles for basic logic gates in active fluid circuits (experimental test under way in Kantsler lab)

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Thermodynamics of small systems

Modern experiments can probe thermodynamic properties of small isolated systems realizing a microcanonical ensemble with strictly conserved energy (ultra-cold atoms in optical traps, etc.)

For such **small** systems, **ensembles** are generally **inequivalent** and thermodynamic limit simplifications do not apply.

Recent high-profile papers use microcanonical entropy definitions that are ok for majority of infinite systems but **provably** give **incorrect predictions for pressure** and other observables in small systems, leading to paradoxical claims (e.g., Carnot efficiencies > 1).

Consistent finite-size thermodynamics developed by Boltzmann, Gibbs, Planck, Einstein and Hertz at around 1900 but their mathematically exact results ‘lost’ in many modern textbooks.

nature physics

ARTICLES

PUBLISHED ONLINE: 8 DECEMBER 2013 | DOI: 10.1038/NPHYS2815

Consistent thermostatistics forbids negative absolute temperatures

Jörn Dunkel[1]* and Stefan Hilbert[2]

Effective negative spin ‘temperatures’ in marginal quasi-canonical PDFs ok/useful, but should not be used to claim Carnot efficiencies > 1 or dark energy candidates.

Invited review for Rep Prog Phys forthcoming

$$dE = \delta W + \delta Q = -p_i dA_i + T dS$$

Assume non-degenerate ordered spectrum

$$E(A_i, n) \qquad n = 1, 2, 3, \ldots$$

Then

$$\begin{aligned} dE = \frac{\partial E}{\partial A_i} dA_i + \frac{\partial E}{\partial n} dn &= \frac{\partial E}{\partial A_i} dA_i + \frac{\partial E}{\partial n} \frac{n}{n} dn \\ &= \frac{\partial E}{\partial A_i} dA_i + \frac{\partial E}{\partial (\ln n)} d(\ln n) \\ &= \frac{\partial E}{\partial A_i} dA_i + \frac{\partial E}{\partial S} dS \end{aligned}$$

$$\overset{k_B = 1}{\Rightarrow} \quad S = \ln n \ \text{ non-decreasing and } \ T > 0$$

Differs from 'popular' $S' = \ln\left(\epsilon \dfrac{\partial n}{\partial E}\right)$ which can be decreasing, so that $T' \gtrless 0$

$$dE = \frac{\partial E}{\partial A_i} dA_i + \frac{\partial E}{\partial (\ln n)}\, d(\ln n) = \frac{\partial E}{\partial A_i} dA_i + \frac{\partial E}{\partial S}\, dS$$

- heat exchange $\Leftrightarrow$ change of quantum state n
- adiabatic process $\Leftrightarrow$ quantum state n remains fixed

Straightforward extension to classical Hamiltonians $H(A, \xi)$

Number of classical states up to energy E is $\Omega = \int_{H(A,\xi) \leq E} d\xi$

$h = 1$
$k_B = 1$

$$S = \ln \Omega \quad \Rightarrow \quad T = \left(\frac{\partial S}{\partial E} \right)^{-1} \geq 0$$ (Gibbs 1902)

This entropy can be derived analogously to above and associated temperature satisfies exact microcanonical equipartition theorem (e.g. Khinchin 1949).

Invalidates erroneous counter-'arguments' claiming that Gibbs' entropy does not describe equilibration.

Incomplete timeline

- 1902 Gibbs compares different entropy definitions for isolated systems and shows explicitly which of them is consistent with micro-canonical probability distribution for systems of arbitrary size
- 1910 Hertz shows that Gibbs' entropy is an adiabatic invariant; paper edited by Planck, praised by Einstein in subsequent comment
- 1949 Khinchin's textbook presents rigorous derivations of micro-canonical equipartition theorems supporting the results of Gibbs & Hertz
- 1956 Ramsay publishes paper on statistical mechanics and negative temperatures of spin systems using a micro-canonical entropy definition that differs from that identified by Gibbs
- 2013 Braun *et al* publish paper Science reporting population-inverted momentum distribution in ultra-cold quantum gas; adopting Ramsay's formalism, they propose negative temperature interpretation and speculate about possibility of Carnot efficiencies >1 and relevance for dark matter candidates
- 2014 Dunkel & Hilbert publish paper in Nature Physics pointing out that entropy/temperature definitions leading to negative temperatures for isolated micro-canonical systems contradict those of Gibbs, Hertz, Khinchin
- 2014 Frenkel & Warren [arXiv:1403.4299v1] claim that Gibbs' entropy does not describe thermalization; Dunkel & Hilbert [arXiv: 1403.6058] point out that this claim contradicts exact mathematical results including the micro-canonical equipartition theorem
- 2014 Hilbert, Hanggi & Dunkel publish detailed comparison of various suggested entropies in Phys Rev E 90: 062116
- 2015 Comment by Braun *et al* [arXiv:1407.4127v1] on Nature Physics paper rejected by referees due to several incorrect claims and misrepresentations which are addressed by Dunkel & Hilbert in [arXiv:1408.5392]
- 2016 Sasa & Yokokura (PRL 116, 140601) characterize Gibbs' entropy as Noether invariant
- 2005-2016 several papers by Campisi support and extend results by Gibbs to quantum systems
- 2015-2017 Swendsen & collaborators publish several manuscripts on the arXiv critical of Gibbs' entropy but use/introduce non-standard definitions of the microcanonical ensemble which differ from those of Gibbs
- 2016 Hilbert, Hanggi & Dunkel publish invited contribution in Royal Society Conference Proceedings "Towards implementing the new kelvin"
- 2017 Dunkel accepts invitation to write review for Reports on Progress in Physics (to appear in 2018)

ELEMENTARY PRINCIPLES

IN

STATISTICAL MECHANICS

DEVELOPED WITH ESPECIAL REFERENCE TO

THE RATIONAL FOUNDATION OF THERMODYNAMICS

BY

J. WILLARD GIBBS

Professor of Mathematical Physics in Yale University

In this case, the choice between the variables of (485) or of (489) will be determined partly by the relative importance which is attached to average and probable values. It would seem that in general average values are the most important, and that they lend themselves better to analytical transformations. This consideration would give the preference to the system of variables in which $\log V$ is the analogue of entropy. Moreover, if we make ϕ the analogue of entropy, we are embarrassed by the necessity of making numerous exceptions for systems of one or two degrees of freedom.

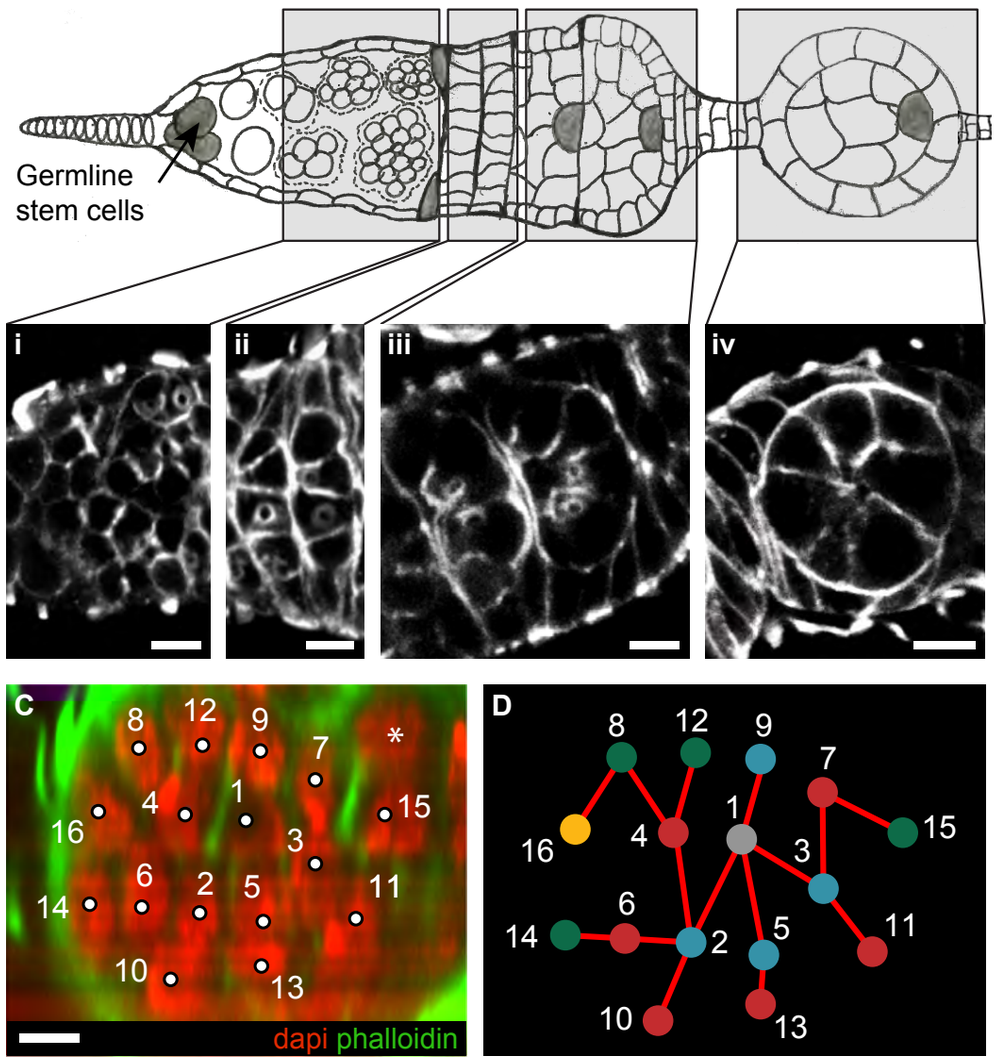
Examples of projects in progress

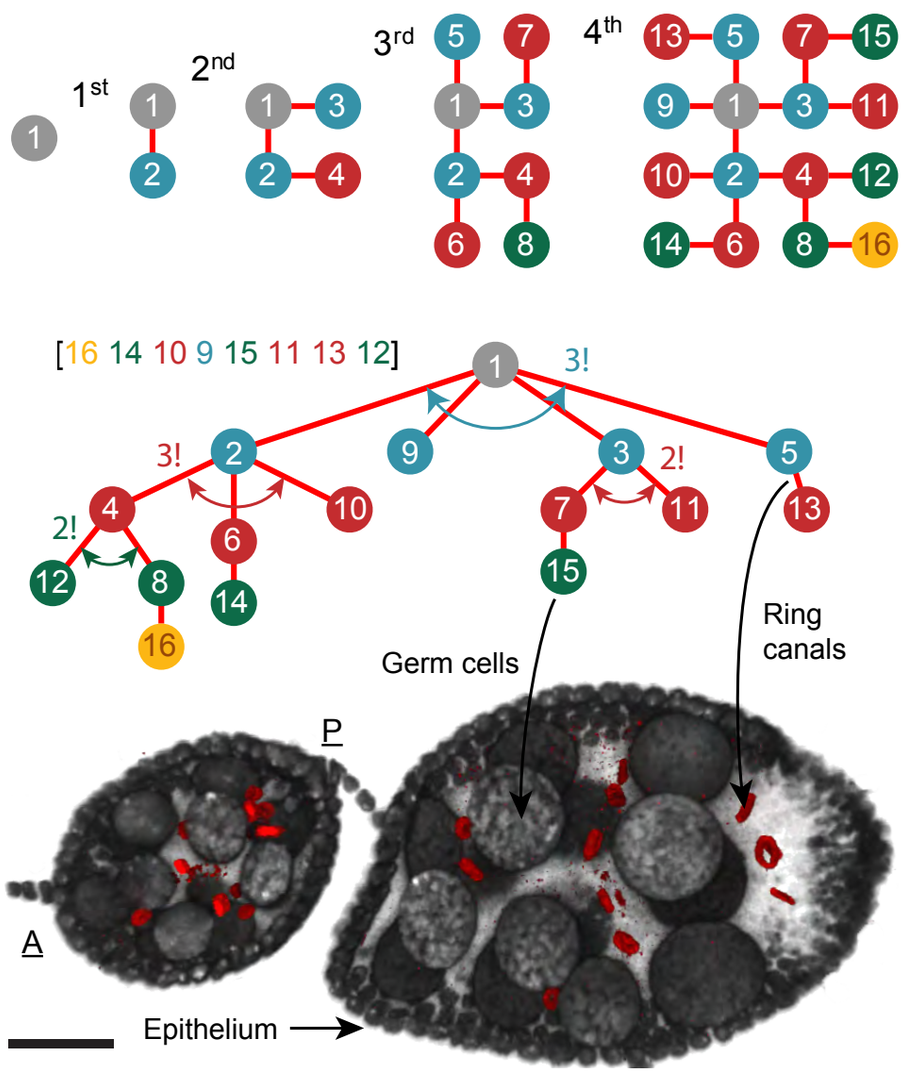
Cell-lineage tree packings

(with Shvartsman lab, Princeton)

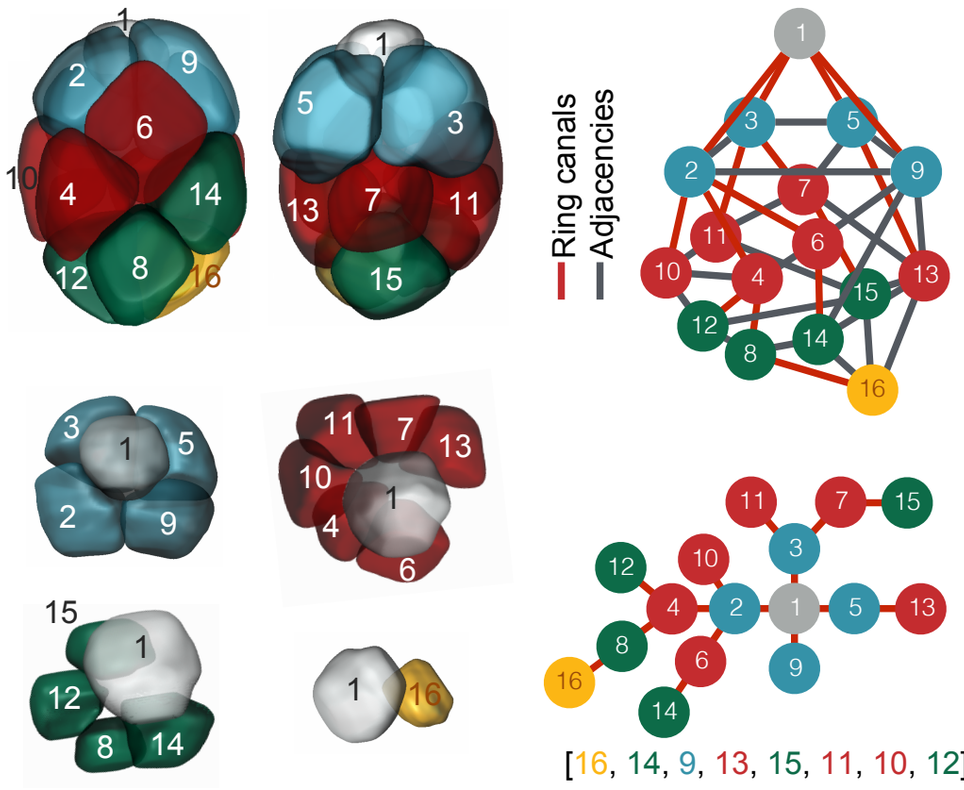


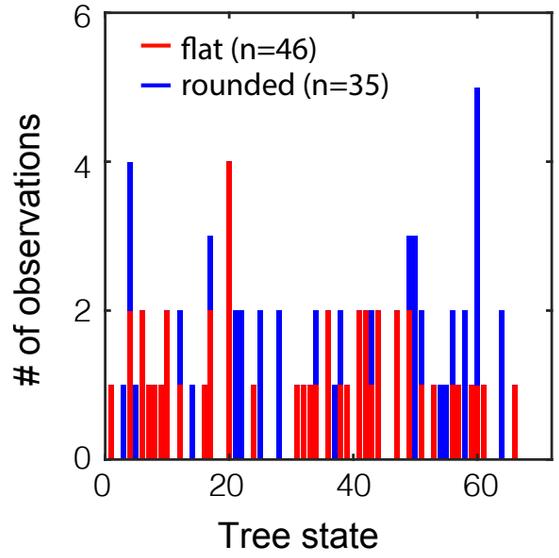
Incomplete cytokinesis in early oogenesis/embryogenesis of many organisms leads to generic constrained tree-packing problem

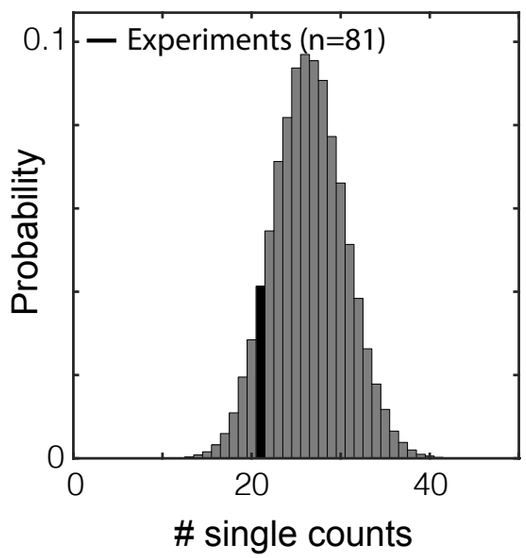




Alsous et al, under review at Nature Physics (2017)

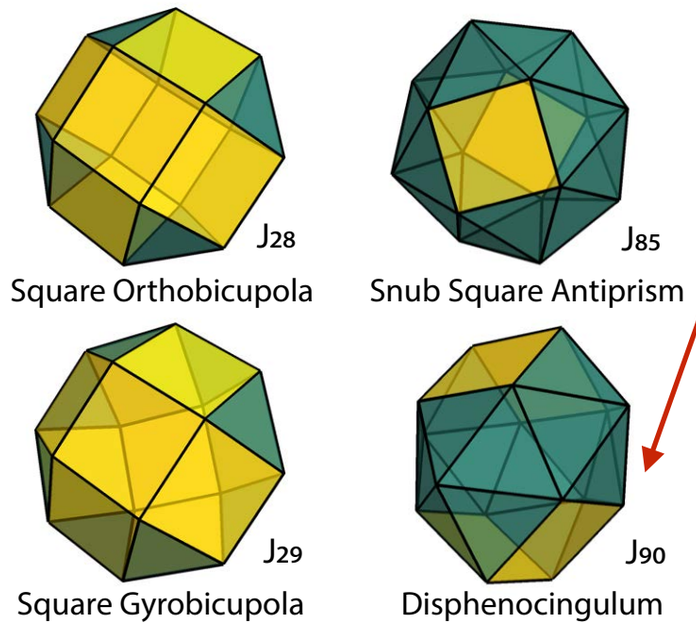




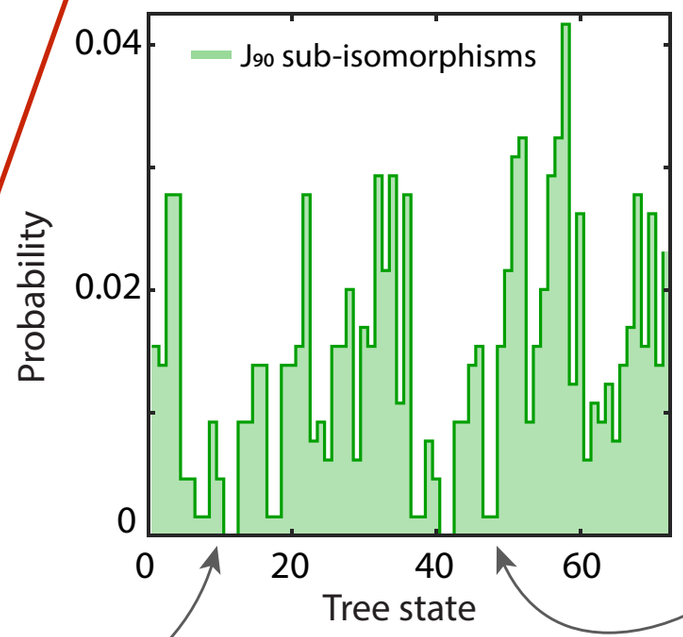


data suggest non-uniform distribution over tree topologies …

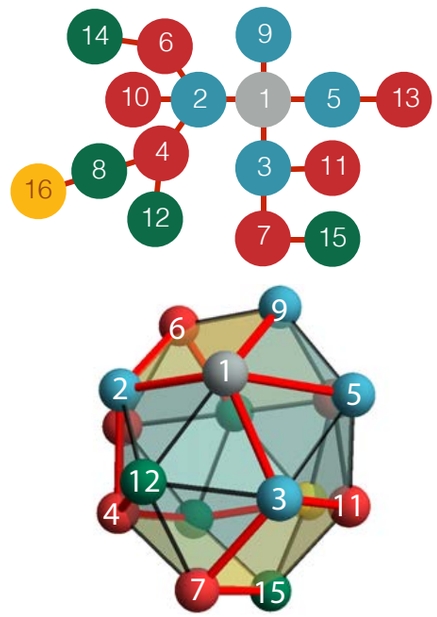
4 Johnson solids with 16 vertices



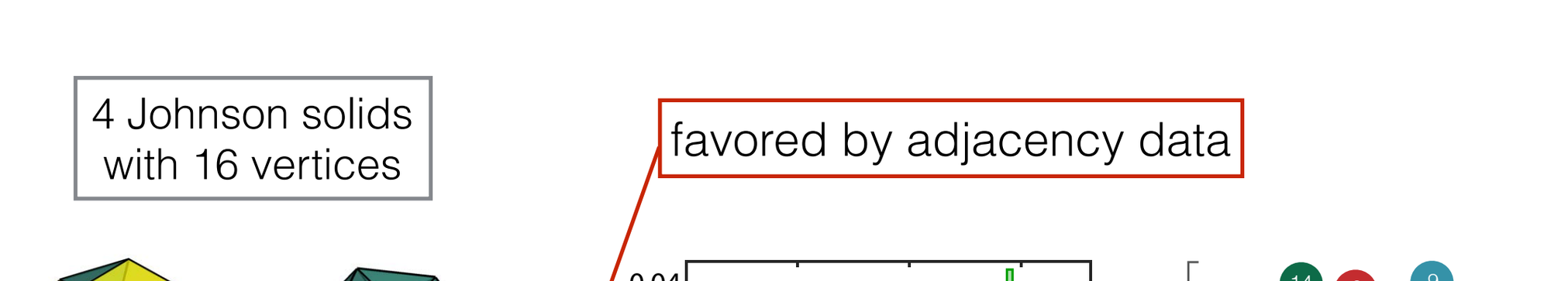
favored by adjacency data



State 48 (1 isomorphism)
[16, 12, 15, 11, 13, 9, 14, 10]



State 13 (6 isomorphisms)
[16, 12, 11, 15, 9, 13, 10, 14]



data suggest non-uniform distribution over tree topologies …

consistent with entropic counting arguments based on possible tree embeddings on equilateral convex polyhedrons with 16 vertices

Torsion controlled fracture

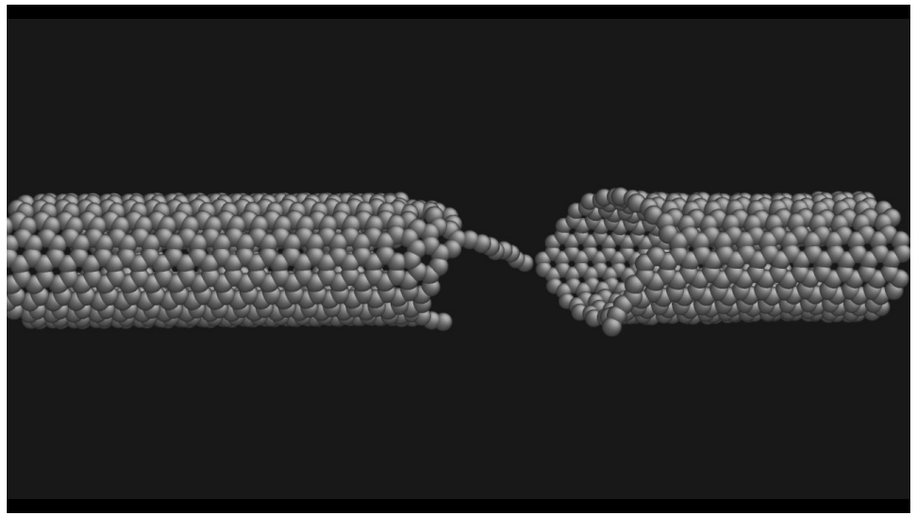
joint work with MechE undergraduate Ronald Heisser (experiments, 18.354 course project)
and first year Math PhD student Vishal Patil (theory)

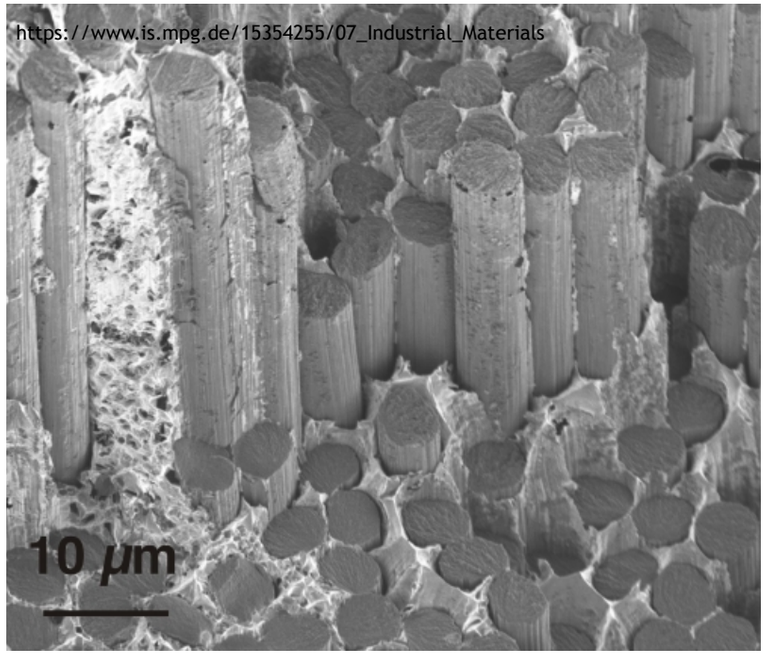
Why study 1D fracture?









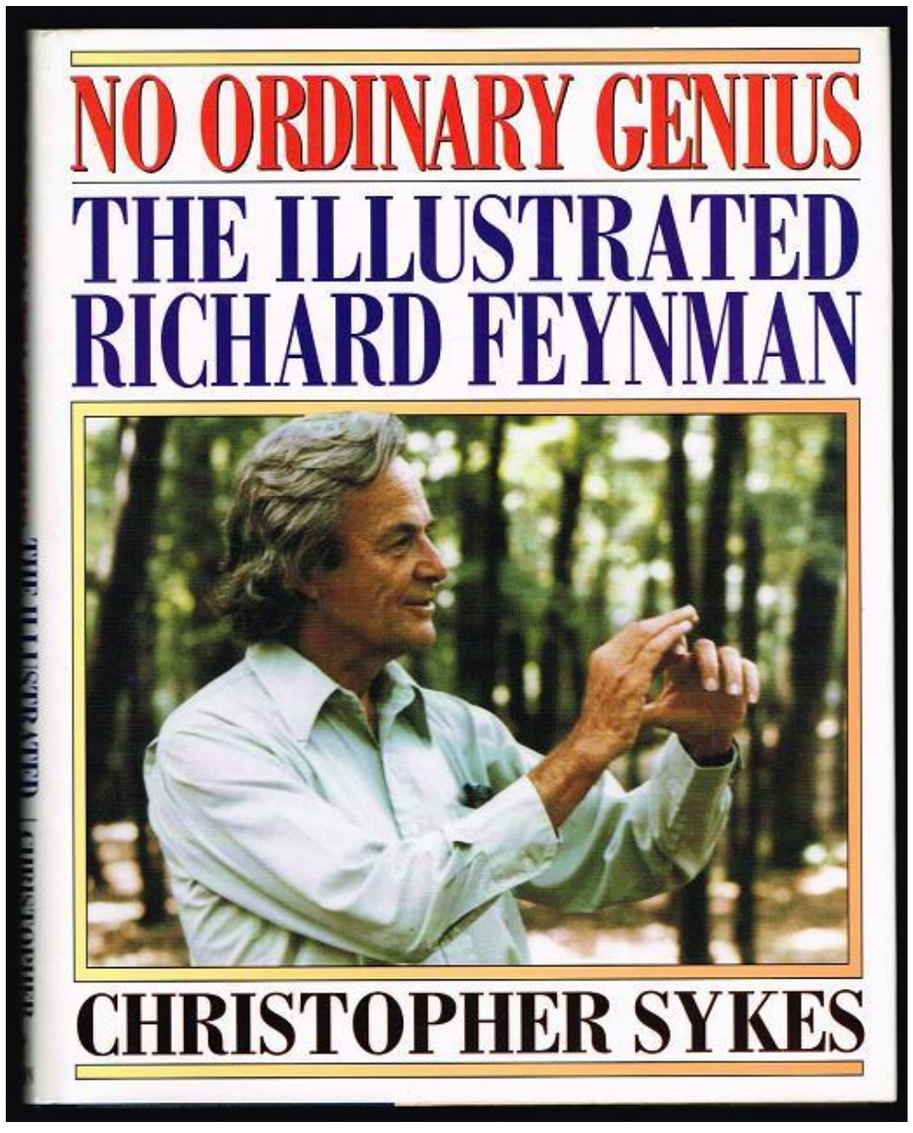


Fracture theory has long history but role of torsion & twist not clear

Why do dry spaghetti almost always break into more than two pieces ?

“Why does it break into three pieces? We spent the next two hours coming up with crazy theories…well, we ended up at the end of a couple of hours with broken spaghetti all over the kitchen and no real good theory about why spaghetti breaks in three."



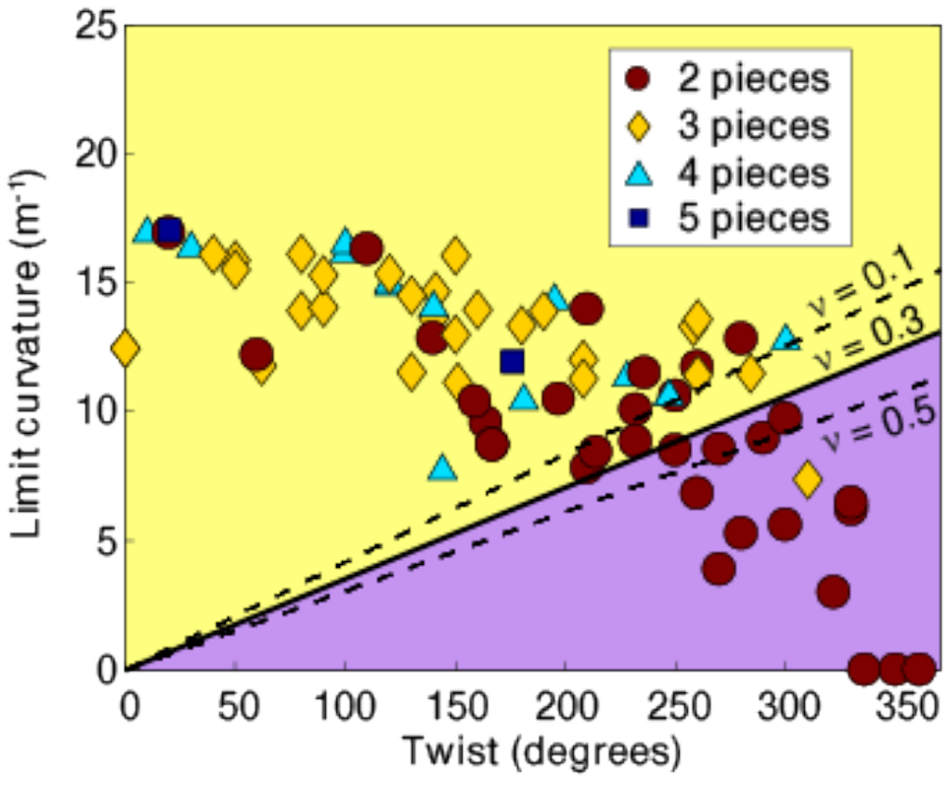


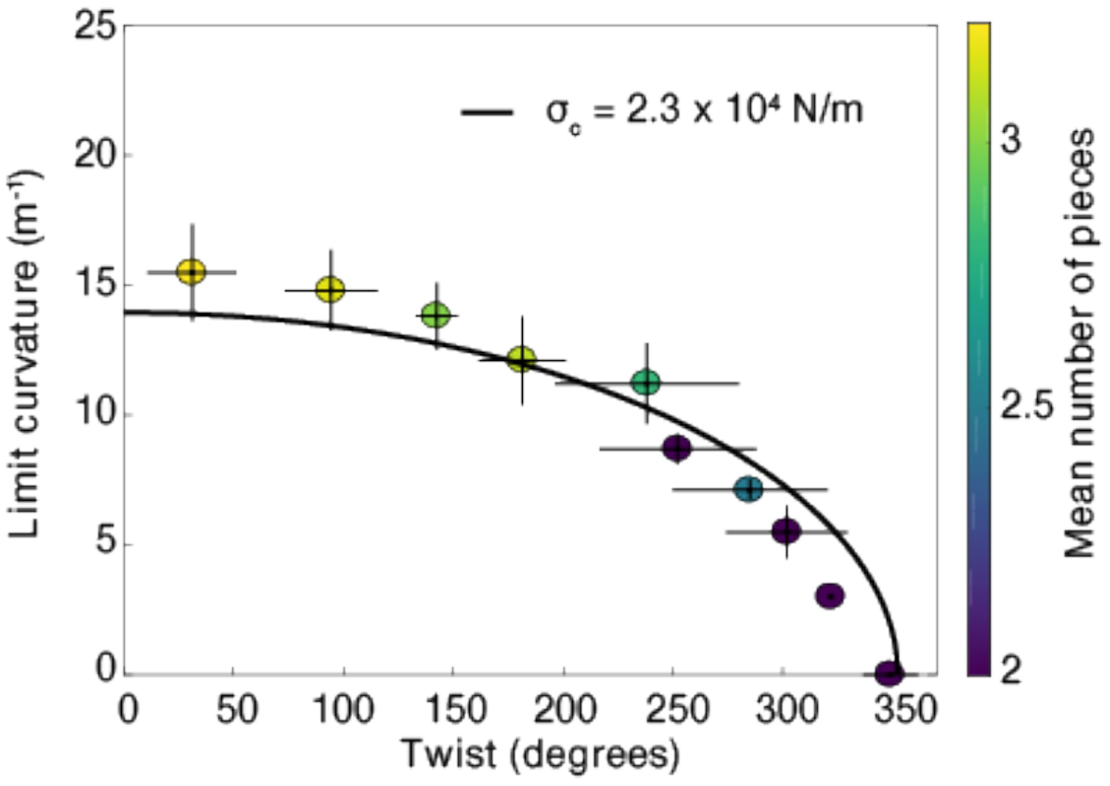
low twist

high twist









Twist criterion for binary fracture

$$\kappa_c < \frac{Tw}{\sqrt{2}L(1+\nu)\sqrt{C^2-1}}$$

Modified von-Mises ellipse

$$\sigma_c^2 = E^2 I \kappa_c^2 + \mu^2 J \left(\frac{Tw}{L}\right)^2$$

Heisser et al, under review at Nature Materials (2017)

Recent & current grants

- Alfred P. Sloan Research Fellowship (50K)
- NSF CBET 1510768 (281K)
- James S. McDonnell Complex Systems Scholar Award (450K)
- Royal Society Exchange Grant (10K)
- MISTI MIT-Germany (26K)
- MIT Solomon Buchsbaum Fund Award (75K)

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Pending grant applications

- NSF Career (497K)
- NSF-Simons Research Centers for Mathematics of Complex Biological Systems (1.2M/10M)
- Volkswagen Foundation ‘Life’ Initiative (400K/1.5M)
- Chan Zuckerberg Initiative (113K/220K)