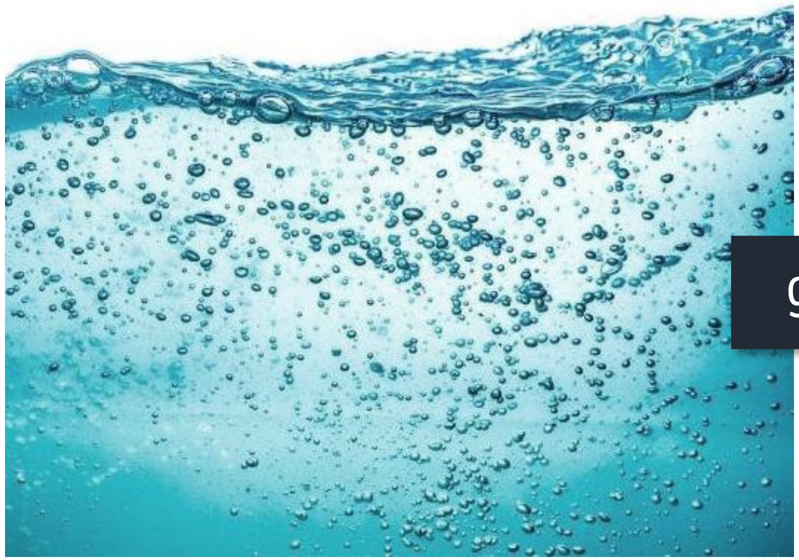
Glassy physics: from liquids to living cells

Liesbeth M.C. Janssen
Department of Applied Physics, Eindhoven University of Technology, NL

Edinburgh Statistical Physics and Complexity webinar, 18 Nov 2025

The glass transition: A ubiquitous, but highly complex phenomenon!

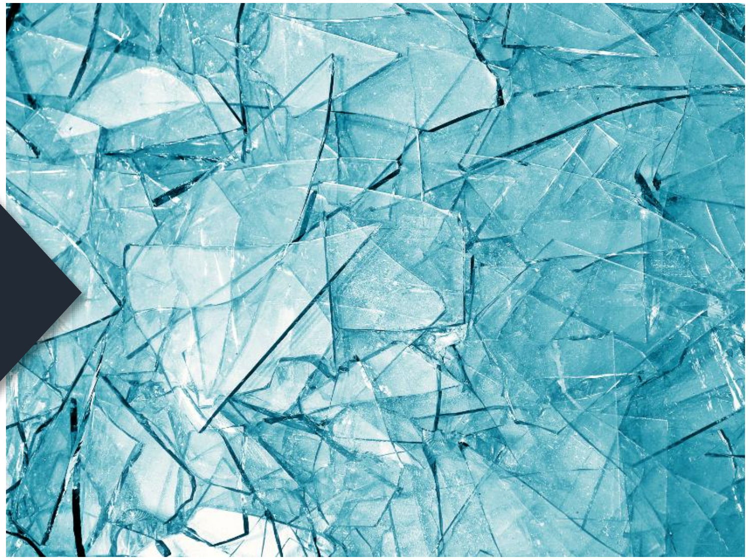
liquid



viscosity ~ 10^{-3} Pa.s

glass transition

glass

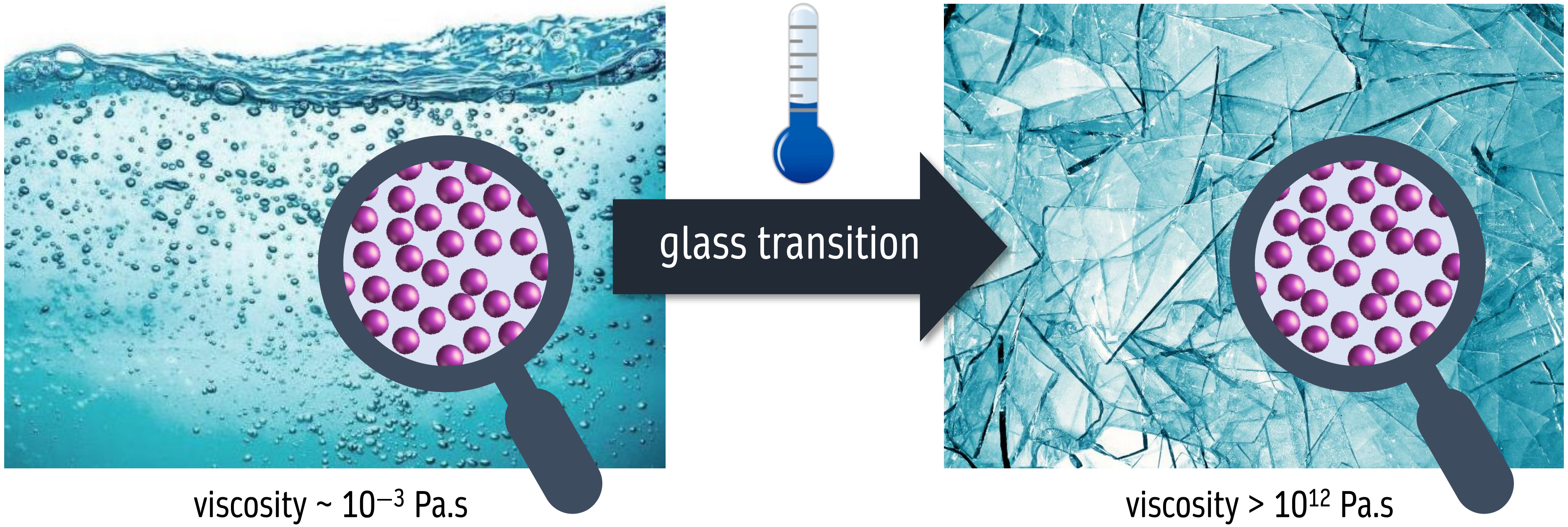


viscosity > 10^{12} Pa.s

The glass transition: A ubiquitous, but highly complex phenomenon!

liquid

glass



viscosity ~ 10^{-3} Pa.s

viscosity > 10^{12} Pa.s

The glass transition: A ubiquitous, but highly complex phenomenon!

The glass transition: A ubiquitous, but highly complex phenomenon!

liquid

glass

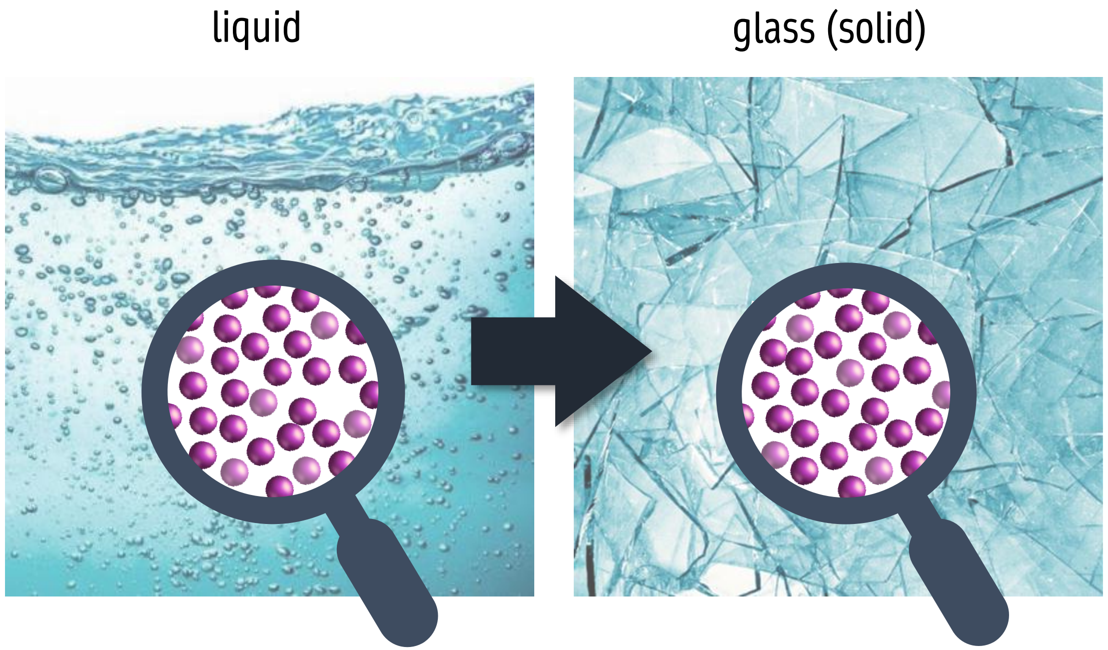
“the deepest and most interesting unsolved problem in solid state theory”

–Philip Anderson, Science 1995

Science, July 2005

A big problem for theoretical physics, but great for biology!

Physics

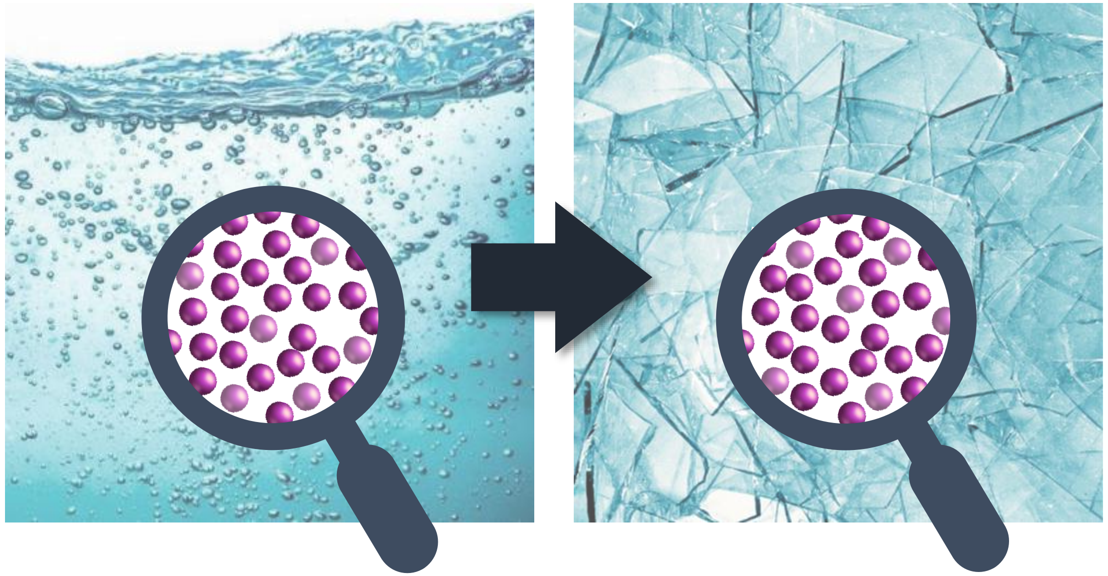


Lack of a clear structural order parameter …

A big problem for theoretical physics, but great for biology!

Physics

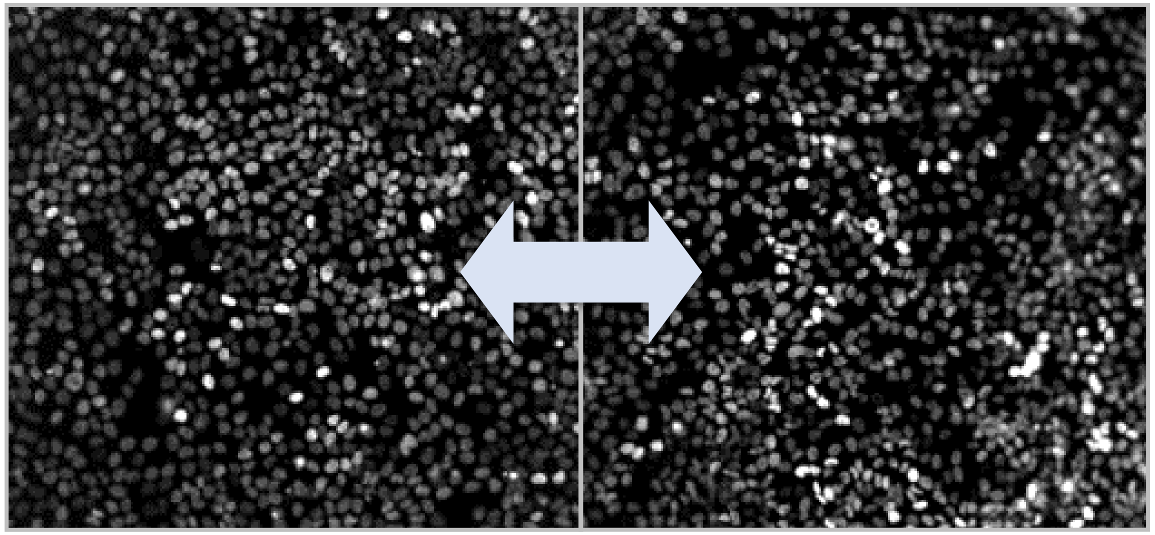
liquid　　glass (solid)



Lack of a clear structural order parameter …

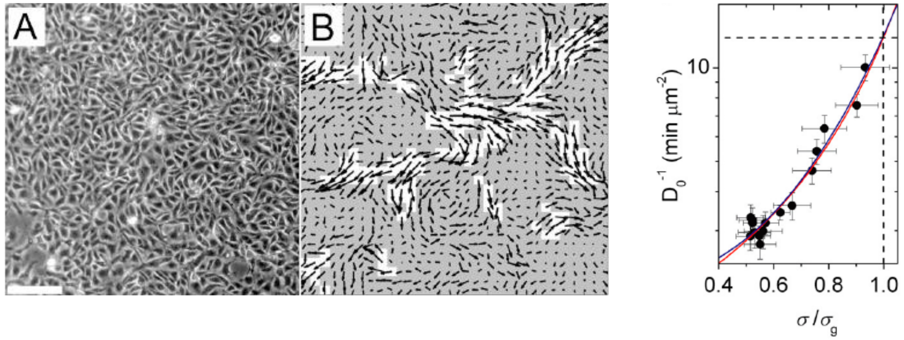
Biology

liquid-like (“unjammed”) cells　　solid-like (“jammed”) cells



Angelini *et al.*, PNAS (2011); Lång, … Janssen, … Nat. Comm. (2018)

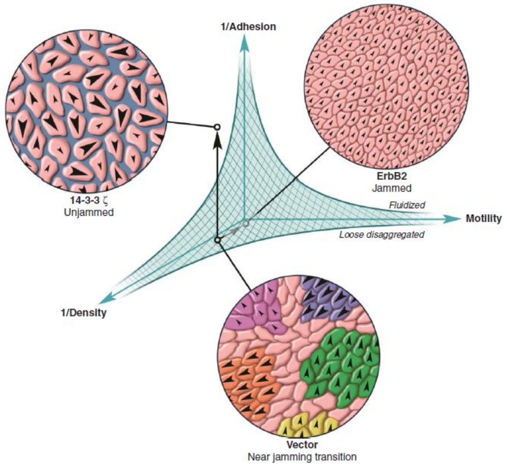
… admits ‘easy’ switching between liquid- and solid-like behavior!



Glass-like dynamics of collective cell migration

Thomas E. Angelini[a], Edouard Hannezo[b], Xavier Trepat[c], Manuel Marquez[d], Jeffrey J. Fredberg[e], and David A. Weitz[f,1]

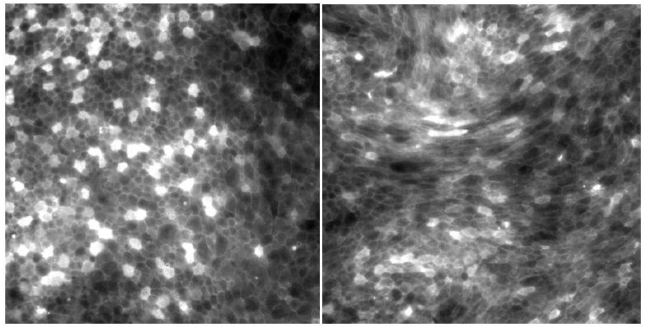
Proc. Natl. Acad. Sci. USA **108**, 4717 (2011)



Glass-like dynamics in the cell and in cellular collectives

Monirosadat Sadati,[1] Amir Nourhani,[2] Jeffrey J. Fredberg[1*] and Nader Taheri Qazvini[1,3]

WIREs Syst. Biol. Med. **6**, 137 (2014)



Collective migration and cell jamming in asthma, cancer and development

Jin-Ah Park[1,‡], Lior Atia[1], Jennifer A. Mitchel[1], Jeffrey J. Fredberg[1] and James P. Butler[1,2]

J. Cell Sci. **129**, 3375 (2016)

ARTICLES
PUBLISHED ONLINE: 3 AUGUST 2015 | DOI: 10.1038/NMAT4357
nature materials

Unjamming and cell shape in the asthmatic airway epithelium

Jin-Ah Park[1*†], Jae Hun Kim[1†], Dapeng Bi[2], Jennifer A. Mitchel[1], Nader Taheri Qazvini[1,3], Kelan Tantisira[4], Chan Young Park[1], Maureen McGill[1], Sae-Hoon Kim[1], Bomi Gweon[1], Jacob Notbohm[1], Robert Steward Jr[1], Stephanie Burger[1], Scott H. Randell[5], Alvin T. Kho[6], Dhananjay T. Tambe[1,7], Corey Hardin[1], Stephanie A. Shore[1], Elliot Israel[4], David A. Weitz[8], Daniel J. Tschumperlin[9], Elizabeth P. Henske[4], Scott T. Weiss[4], M. Lisa Manning[2], James P. Butler[1,4], Jeffrey M. Drazen[1] and Jeffrey J. Fredberg[1]

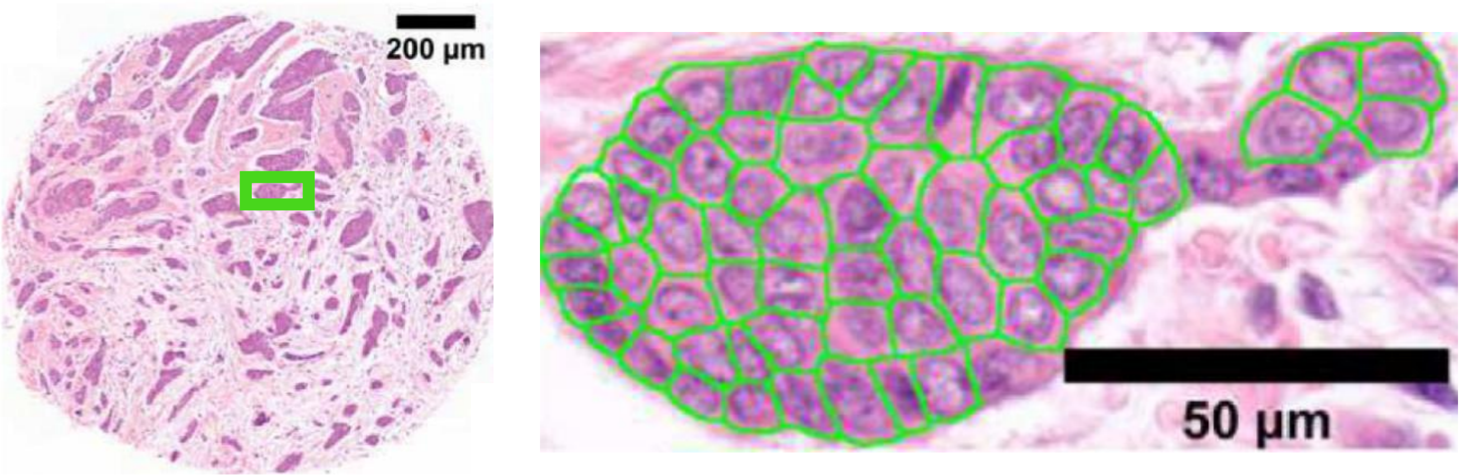
Review: L.M.C. Janssen, “Active glasses”, J. Phys. Condens. Matter (2019)

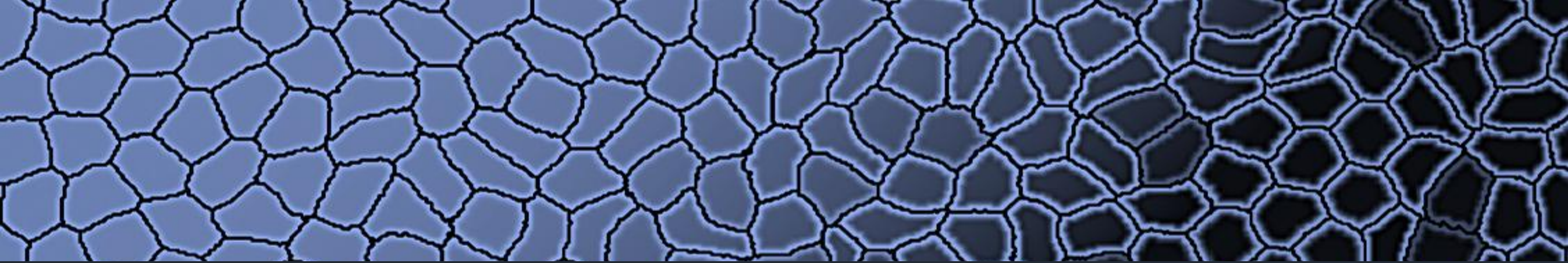
PHYSICAL REVIEW X **13**, 031003 (2023)

Featured in Physics

State of Cell Unjamming Correlates with Distant Metastasis in Cancer Patients

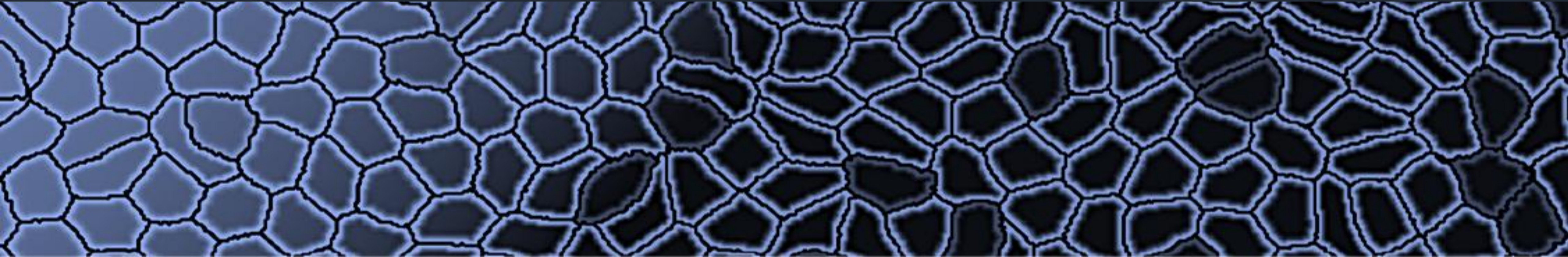
Pablo Gottheil,[1] Jürgen Lippoldt,[1] Steffen Grosser,[1] Frédéric Renner,[1] Mohamad Saibah,[1] Dimitrij Tschodu,[1] Anne-Kathrin Poßögel,[2] Anne-Sophie Wegscheider,[2] Bernhard Ulm,[3] Kay Friedrichs,[4] Christoph Lindner,[5] Christoph Engel,[6] Markus Löffler,[6] Benjamin Wolf,[7] Michael Höckel,[7] Bahriye Aktas,[7] Hans Kubitschke,[1] Axel Niendorf,[2] and Josef A. Käs[1,*]





Can we infer from solely structural information (i.e. a static image) whether:

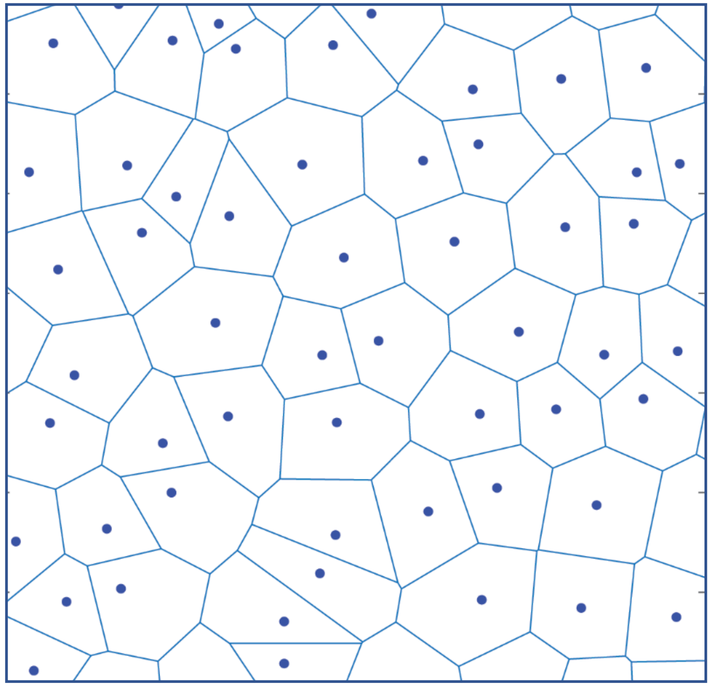
(a) the collective is jammed or unjammed (glassy or liquid)?
(b) a given cell is motile or nonmotile?



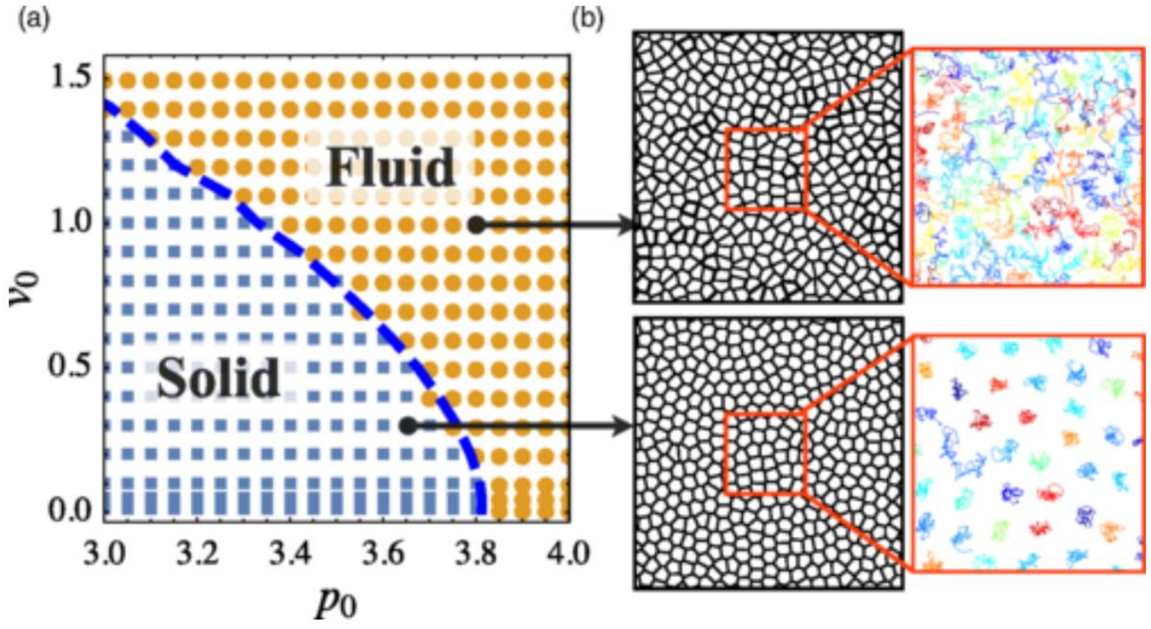
What is a good way to describe the structure?

What is a good way to describe the structure?

Self-propelled Voronoi (SPV) model



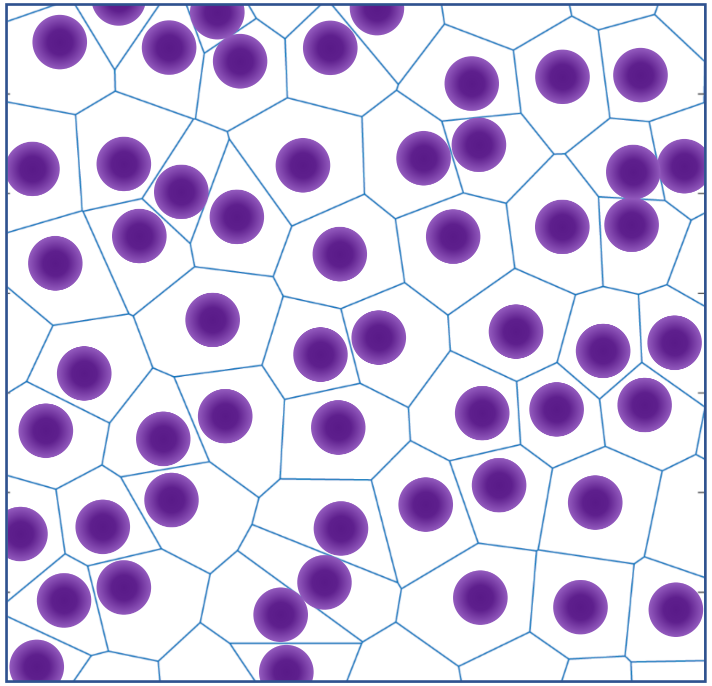
→ (dimensionless) shape index: $p = \langle P/\sqrt{A} \rangle$



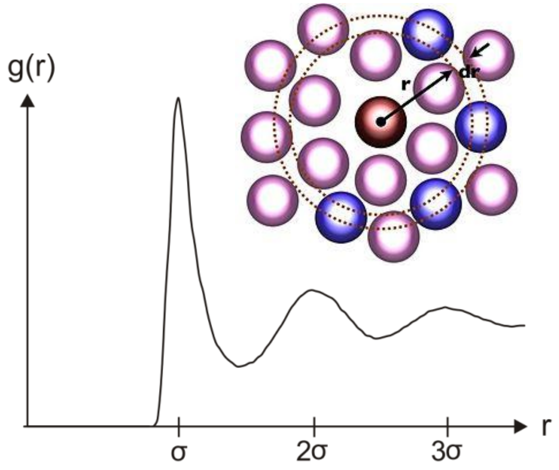
glass transition at $p^* = 3.81$

D. Bi, X. Yang, M.C. Marchetti, M.L. Manning, 'Motility-Driven Glass and Jamming Transitions in Biological Tissues', Phys. Rev. X (2016)

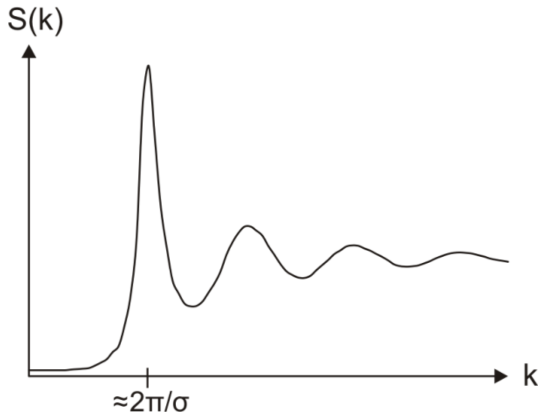
Can we also use concepts from condensed matter physics?



structure



Radial distribution function g(r)



Static structure factor S(k)

$$S(k) = 1 + \rho \int d\mathbf{r} e^{-i\mathbf{k}\mathbf{r}} g(r)$$

Relating structure to emergent dynamics using theoretical physics

Review: LMC Janssen, “Mode-Coupling Theory of the Glass Transition: A Primer”, Front. Phys. (2018)

Relating structure to emergent dynamics using theoretical physics

Disclaimer:

"There are more theories of the glass transition than there are theorists who propose them."

David A. Weitz, New York Times (July 29, 2008)

Review: LMC Janssen, "Mode-Coupling Theory of the Glass Transition: A Primer", Front. Phys. (2018)

Relating structure to emergent dynamics using theoretical physics

Mode-Coupling Theory of the glass transition (MCT) [Götze et al., 1984]

Review: LMC Janssen, “Mode-Coupling Theory of the Glass Transition: A Primer”, Front. Phys. (2018)

Relating structure to emergent dynamics using theoretical physics

Mode-Coupling Theory of the glass transition (MCT) [Götze et al., 1984]

→ The only 'first principles' theory of glassy dynamics (starting from the exact microscopic picture):

Review: LMC Janssen, "Mode-Coupling Theory of the Glass Transition: A Primer", Front. Phys. (2018)

Relating structure to emergent dynamics using theoretical physics

Mode-Coupling Theory of the glass transition (MCT) [Götze et al., 1984]

→ The only 'first principles' theory of glassy dynamics (starting from the exact microscopic picture):

$$\ddot{F}(k,t) + \frac{k^2 k_B T}{m S(k)} F(k,t) + \int_0^t dt' M(k,t') \dot{F}(k,t-t') = 0$$

Review: LMC Janssen, "Mode-Coupling Theory of the Glass Transition: A Primer", Front. Phys. (2018)

Relating structure to emergent dynamics using theoretical physics

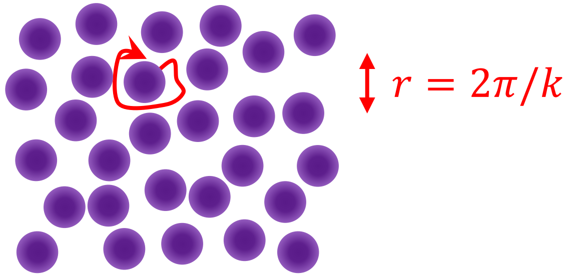
Mode-Coupling Theory of the glass transition (MCT) [Götze et al., 1984]

$\rightarrow$ The only ‘first principles’ theory of glassy dynamics (starting from the exact microscopic picture):

$$\ddot{F}(k,t) + \frac{k^2 k_B T}{mS(k)} F(k,t) + \int_0^t dt' M(k,t') \dot{F}(k,t-t') = 0$$

$$F(k,t) = \frac{1}{N} \langle \rho_{-\mathbf{k}}(0) \rho_{\mathbf{k}}(t) \rangle$$

dynamical observable of interest
[time-dependent analogue of S(k)]



Review: LMC Janssen, “Mode-Coupling Theory of the Glass Transition: A Primer”, Front. Phys. (2018)

Relating structure to emergent dynamics using theoretical physics

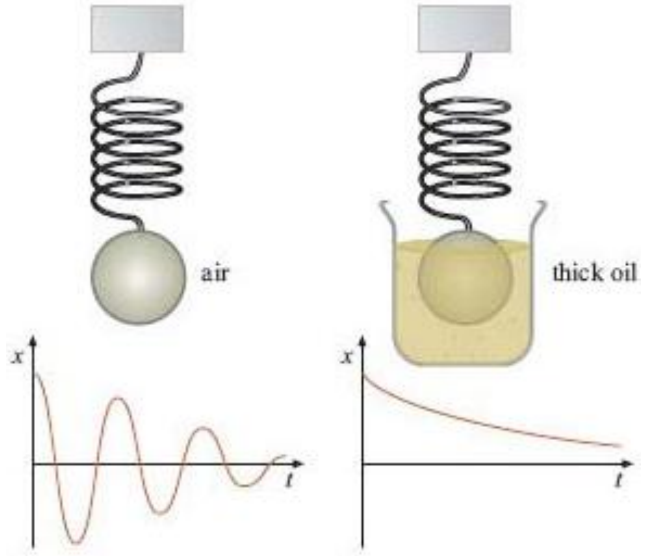
Mode-Coupling Theory of the glass transition (MCT) [Götze et al., 1984]

→ The only 'first principles' theory of glassy dynamics (starting from the exact microscopic picture):

$$\ddot{F}(k,t) + \frac{k^2 k_B T}{mS(k)} F(k,t) + \int_0^t dt' M(k,t') \dot{F}(k,t-t') = 0$$

→ Form of damped harmonic oscillator with time-dependent damping:

$$\ddot{x} + \omega^2 x + 2\zeta\omega\dot{x} = 0$$



Review: LMC Janssen, "Mode-Coupling Theory of the Glass Transition: A Primer", Front. Phys. (2018)

Relating structure to emergent dynamics using theoretical physics

Mode-Coupling Theory of the glass transition (MCT) [Götze et al., 1984]

→ The only 'first principles' theory of glassy dynamics (starting from the exact microscopic picture):

$$\ddot{F}(k,t) + \frac{k^2 k_B T}{mS(k)} F(k,t) + \int_0^t dt' M(k,t') \dot{F}(k,t-t') = 0$$

$$M_{MCT}(k,t) \sim \int dq \, \left|V_{q,k-q}\right|^2 F(q,t) F(k-q,t)$$

Review: LMC Janssen, "Mode-Coupling Theory of the Glass Transition: A Primer", Front. Phys. (2018)

Relating structure to emergent dynamics using theoretical physics

Mode-Coupling Theory of the glass transition (MCT) [Götze et al., 1984]

→ The only 'first principles' theory of glassy dynamics (starting from the exact microscopic picture):

$$\ddot{F}(k,t) + \frac{k^2 k_B T}{m S(k)} F(k,t) + \int_0^t dt' M(k,t') \dot{F}(k,t-t') = 0$$

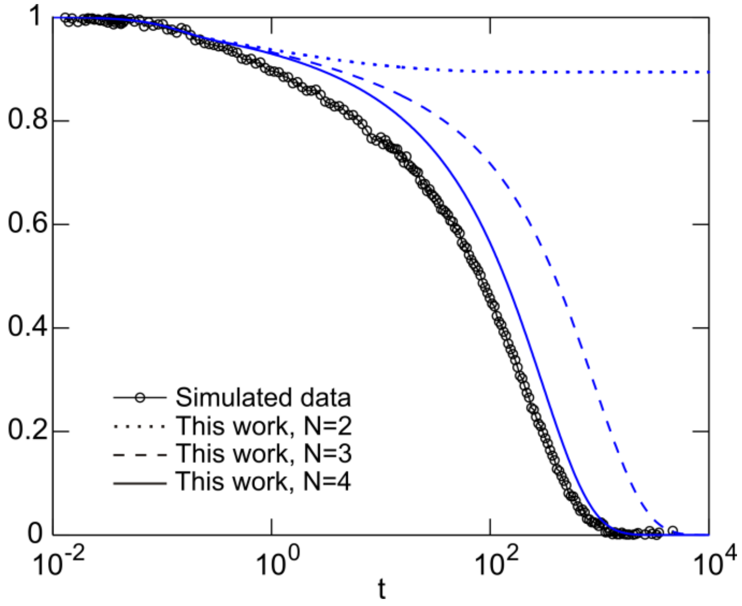
$$M_{MCT}(k,t) \sim \int dq \, \left|V_{q,k-q}\right|^2 F(q,t) F(k-q,t)$$

Overall, through several approximations, MCT arrives at a closed equation to predict the dynamics from the structure:

Review: LMC Janssen, "Mode-Coupling Theory of the Glass Transition: A Primer", Front. Phys. (2018)

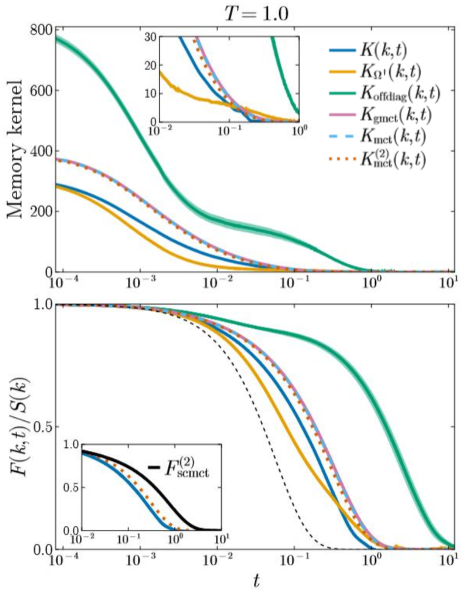
(... Work in progress: improving & extending mode-coupling theory)

Including higher-order correlations



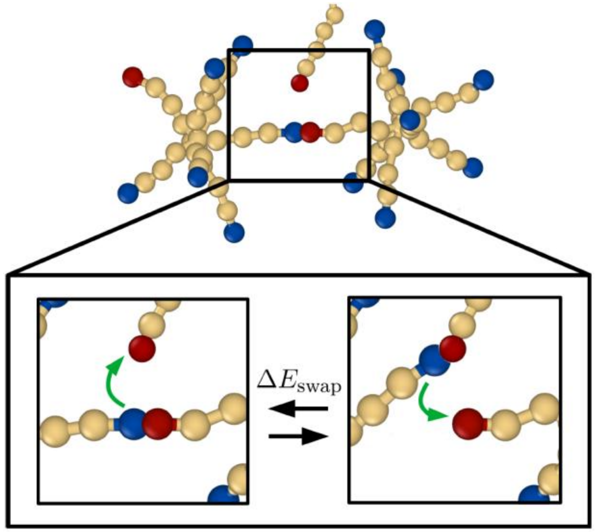
Szamel, PRL (2003), LMCJ et al. PRL (2015), Luo et al. PRL (2022), Pihlajamaa et al. PNAS Nexus (2023), Laudicina et al. (2025) ...

Testing each MCT approximation



Pihlajamaa, Debets, Laudicina, Janssen, SciPost (2023), Pihlajamaa & Janssen, Phys. Rev. Research (2024)

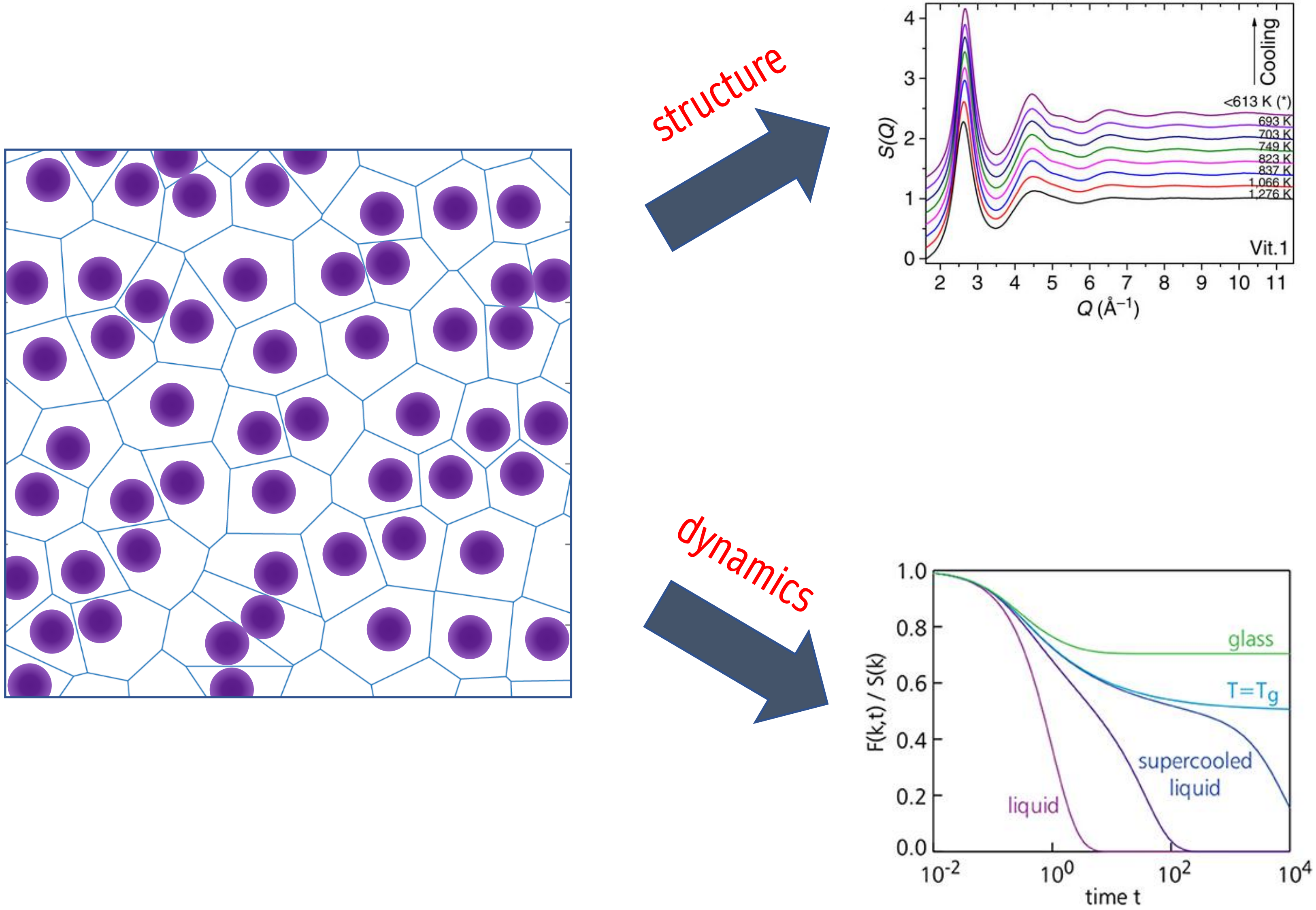
Extending MCT to polymers, active matter, ...



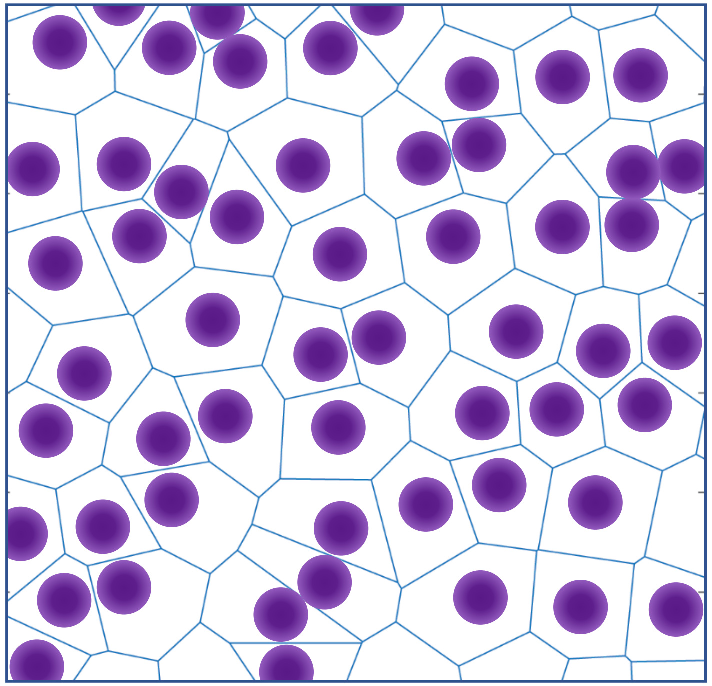
Ciarella, Biezemans, Janssen, PNAS (2019), Debets & Janssen, JCP (2022, 2023)

Open-source, generic solver for MCT-like equations (Julia code): Pihlajamaa et al. J. Open Source Software (2023)

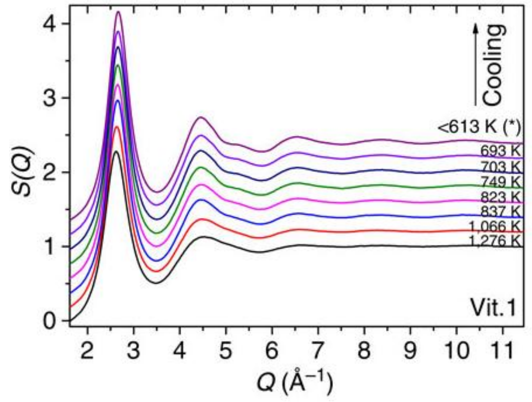
Applying mode-coupling theory to living cells



Applying mode-coupling theory to living cells

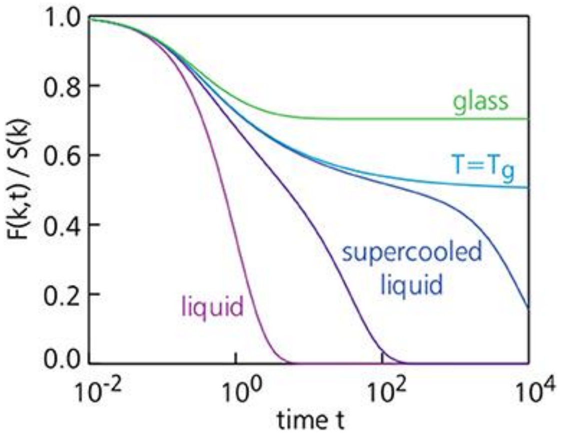


structure



MCT

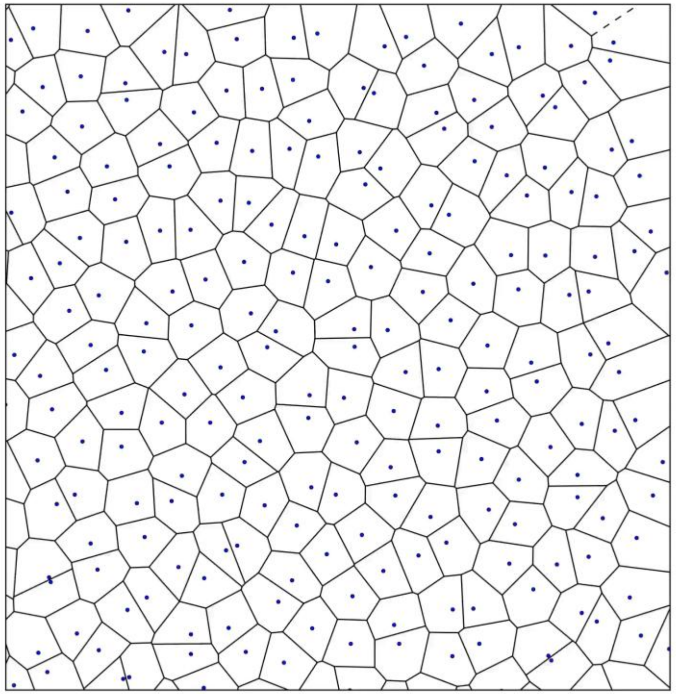
dynamics



‘Numerical experiments’: SPV simulations

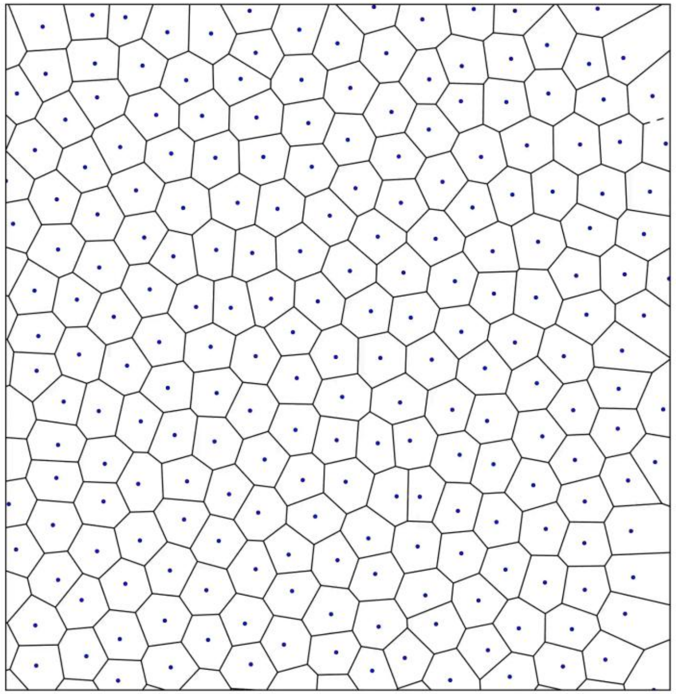
Marijke Valk

more liquid-like



cell perimeter $P_0 = 3.9$

more solid-like

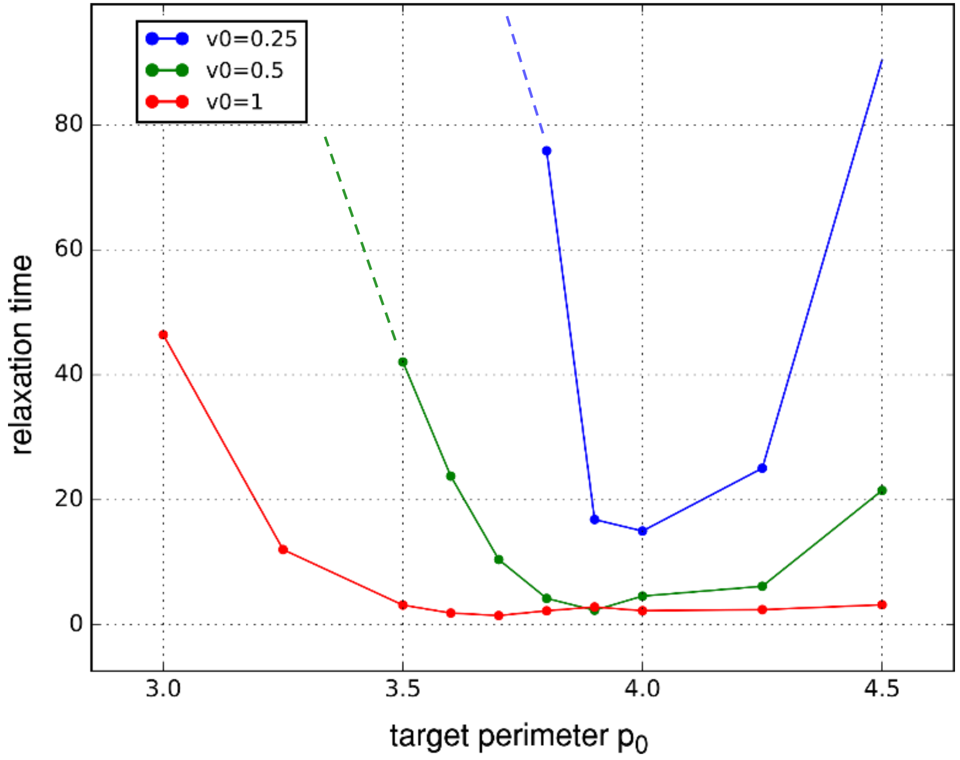


cell perimeter $P_0 = 3.4$

SPV model: D. Bi, X. Yang, M.C. Marchetti, M.L. Manning, Phys. Rev. X (2016)
cellGPU code: D. Sussman, Comput. Phys. Commun. (2017)

Mode-coupling theory for SPV simulation model

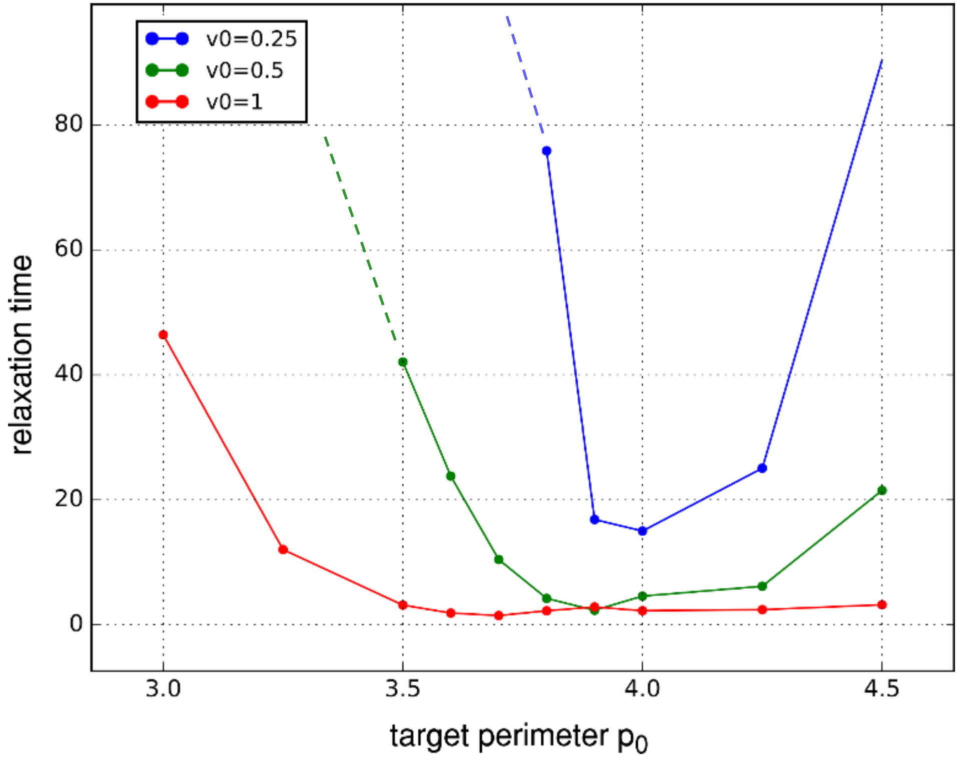
Using standard MCT (ignoring activity) to predict the cell dynamics [F(k,t)] from structure [S(k)]:



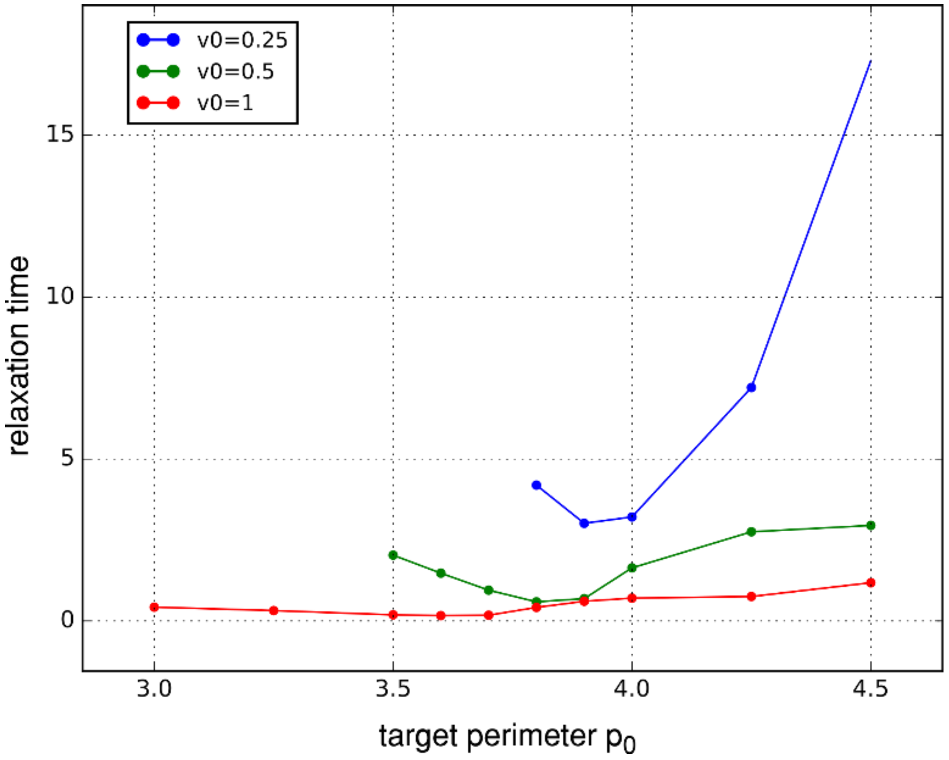
relaxation times from simulation

Mode-coupling theory for SPV simulation model

Using standard MCT (ignoring activity) to predict the cell dynamics [F(k,t)] from structure [S(k)]:



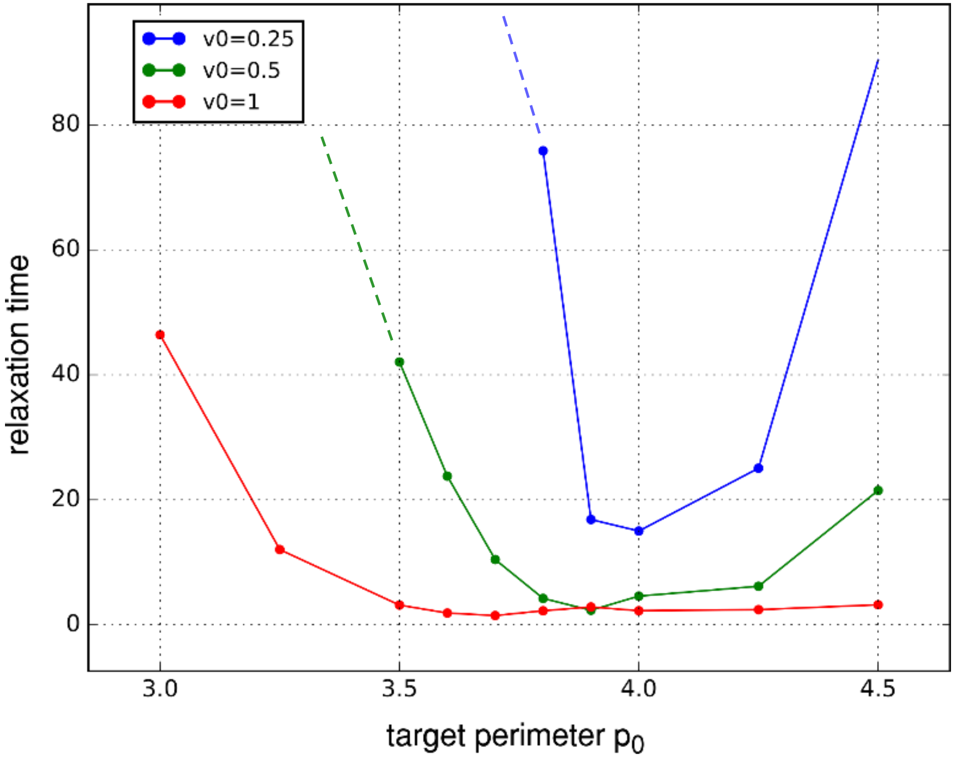
relaxation times from simulation



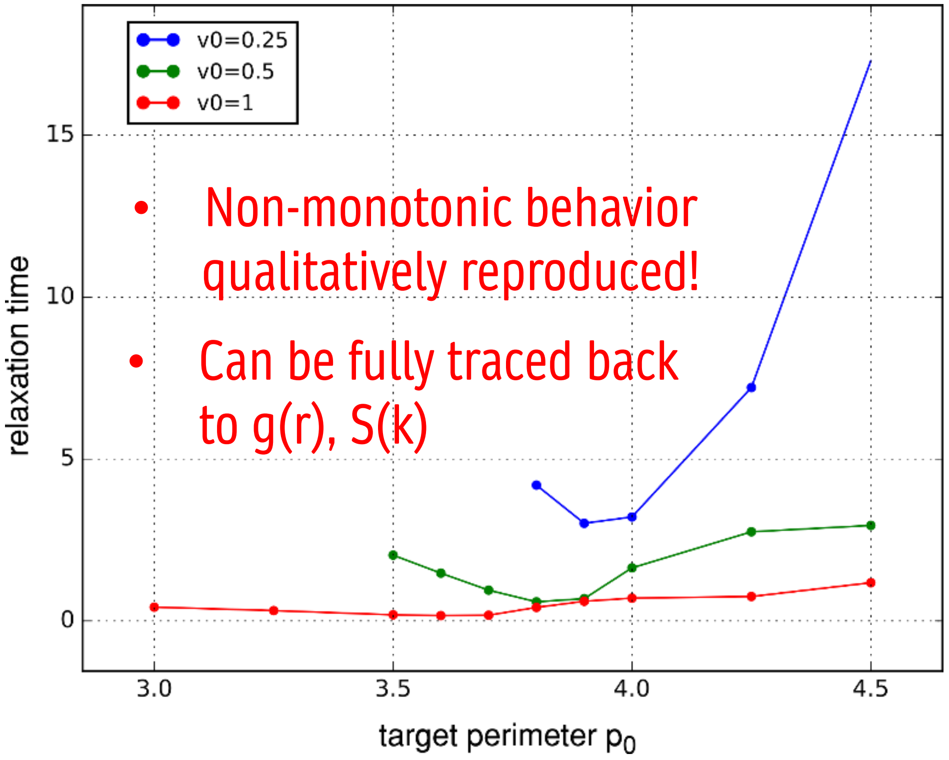
relaxation times from MCT

Mode-coupling theory for SPV simulation model

Using standard MCT (ignoring activity) to predict the cell dynamics [F(k,t)] from structure [S(k)]:



relaxation times from simulation

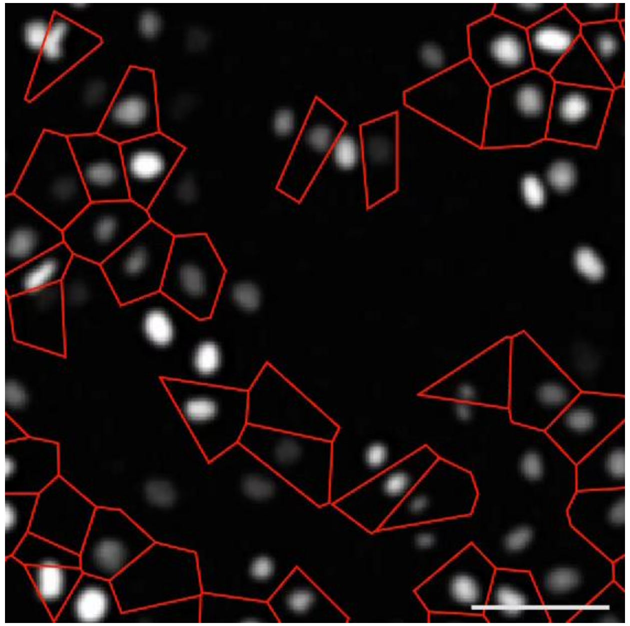


relaxation times from MCT

Preliminary results on experimental cell data


Marijke Valk

In collaboration with Profs. Jim Butler and Jeffrey Fredberg (Harvard)



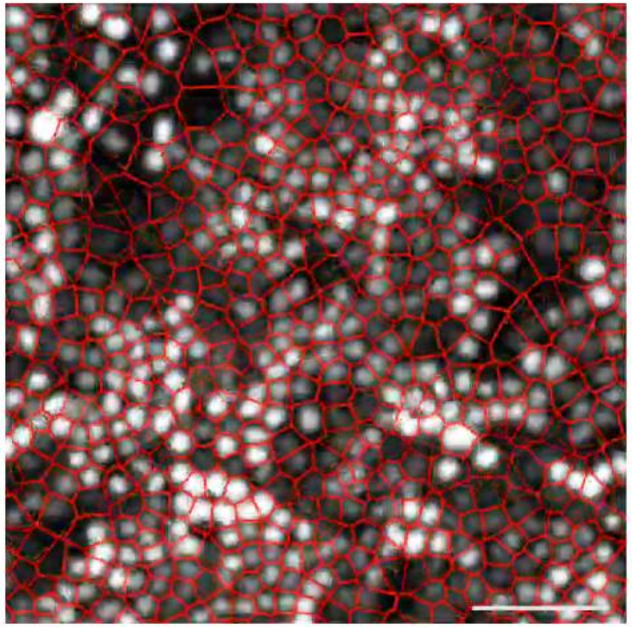
MDCK cells
Atia *et al.*, Nat. Phys. (2018)

Unpublished

Preliminary results on experimental cell data

Marijke Valk

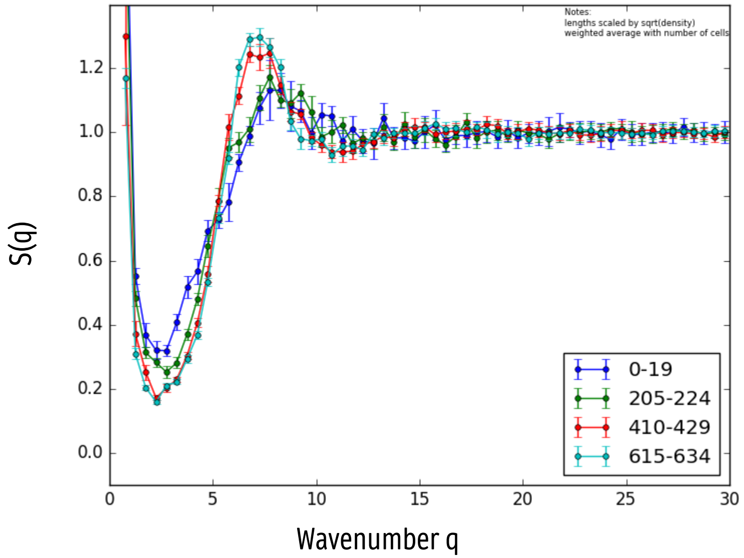
In collaboration with Profs. Jim Butler and Jeffrey Fredberg (Harvard)



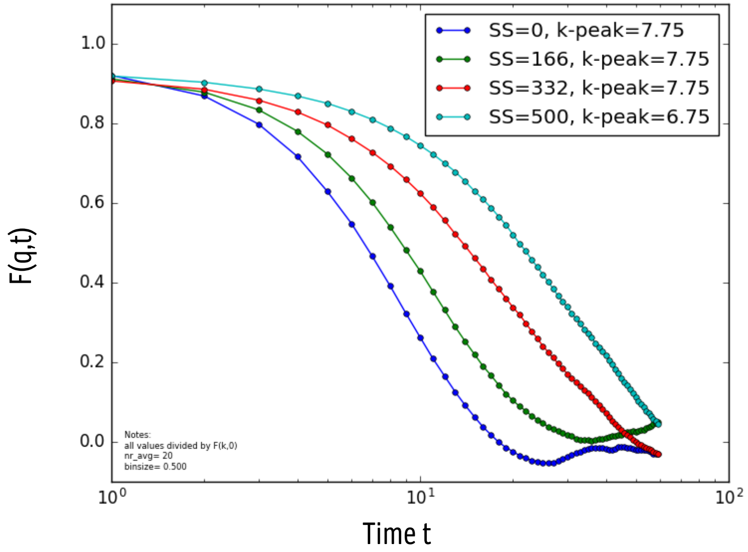
MDCK cells

Atia *et al.*, Nat. Phys. (2018)

structure



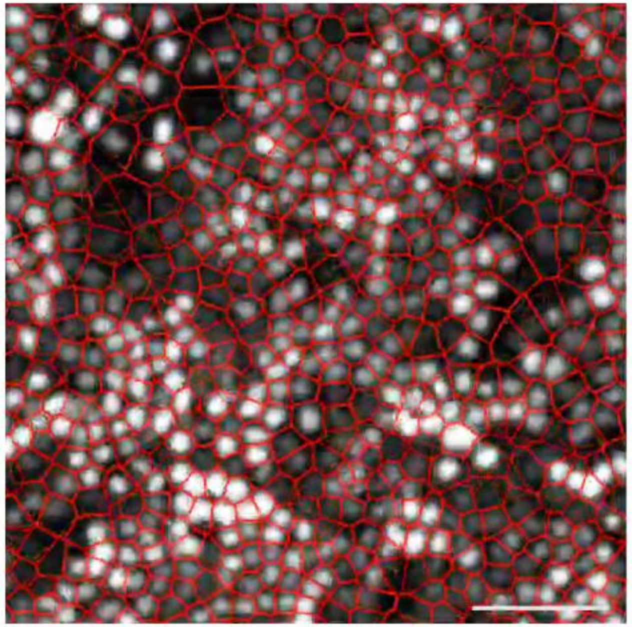
dynamics



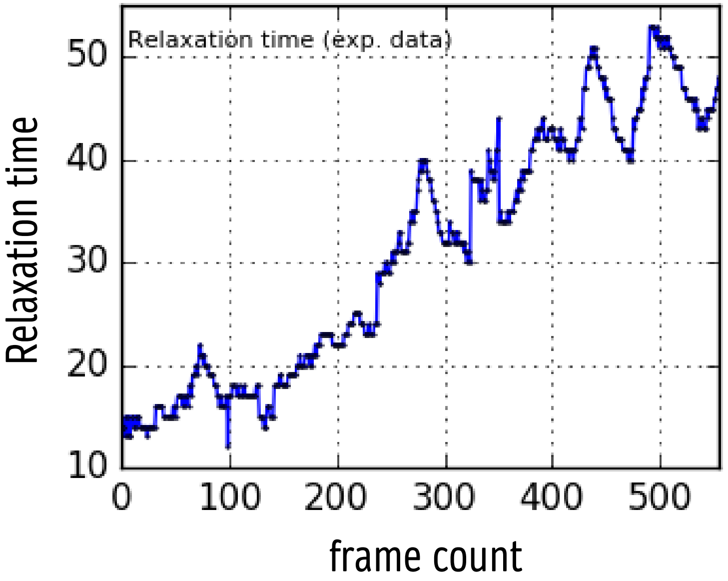
Unpublished

Preliminary results on experimental cell data

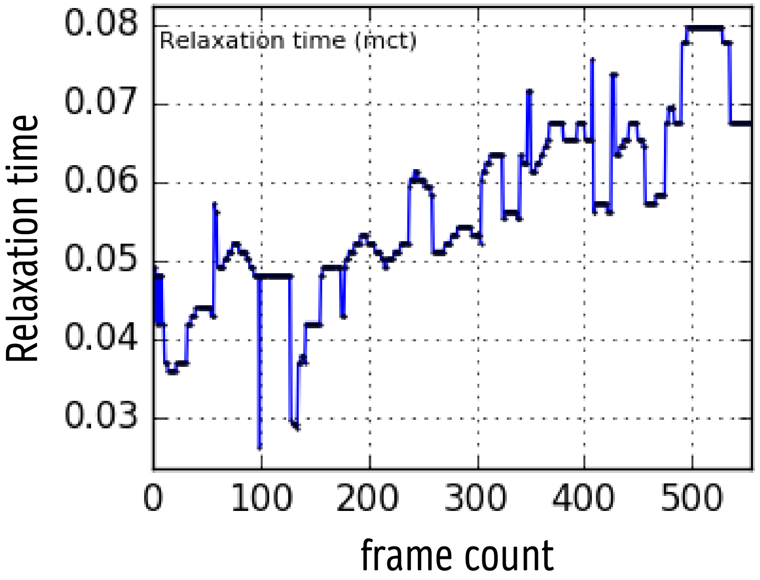
In collaboration with Profs. Jim Butler and Jeffrey Fredberg (Harvard)



MDCK cells
Atia *et al.*, Nat. Phys. (2018)



relaxation times from experiment

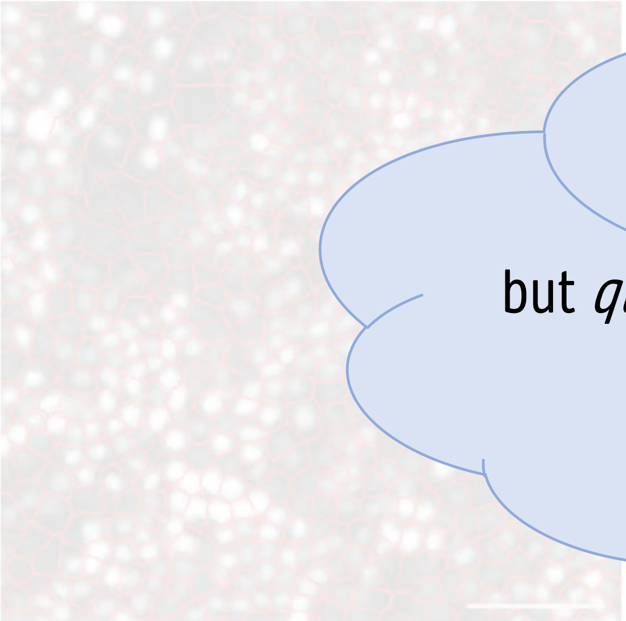


relaxation times from MCT

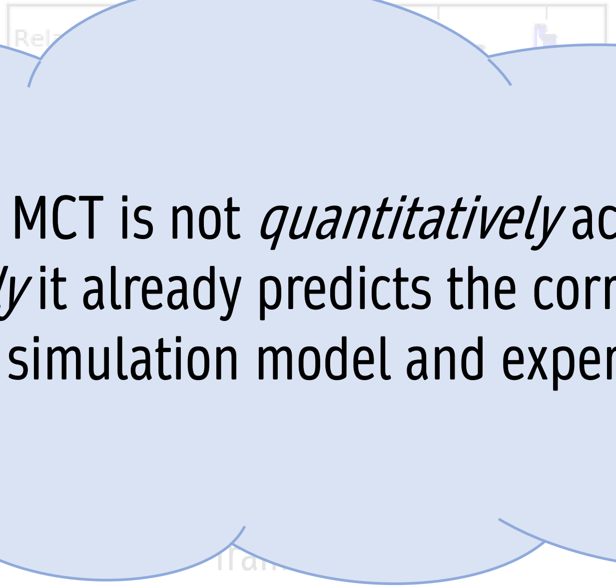
Unpublished

Preliminary results on experimental cell data

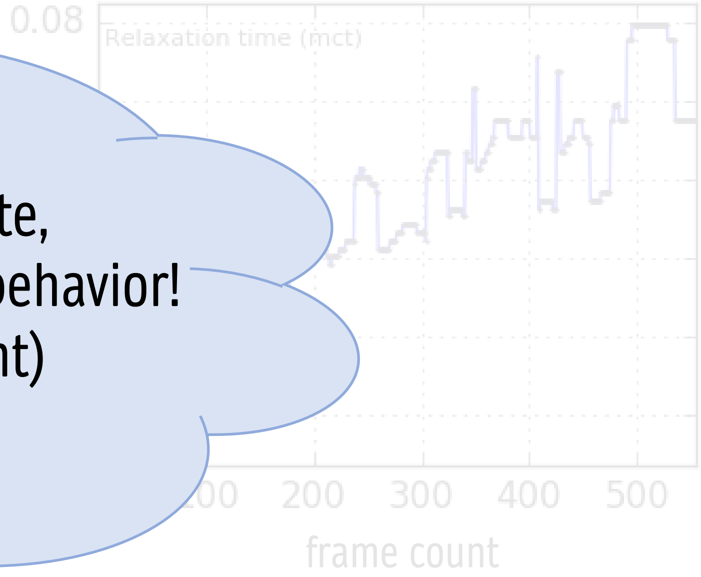
In collaboration with Profs. Jim Butler and Jeffrey Fredberg (Harvard)



MDCK cells
Atia *et al.*, Nat. Phys. (2018)



relaxation times from experiment

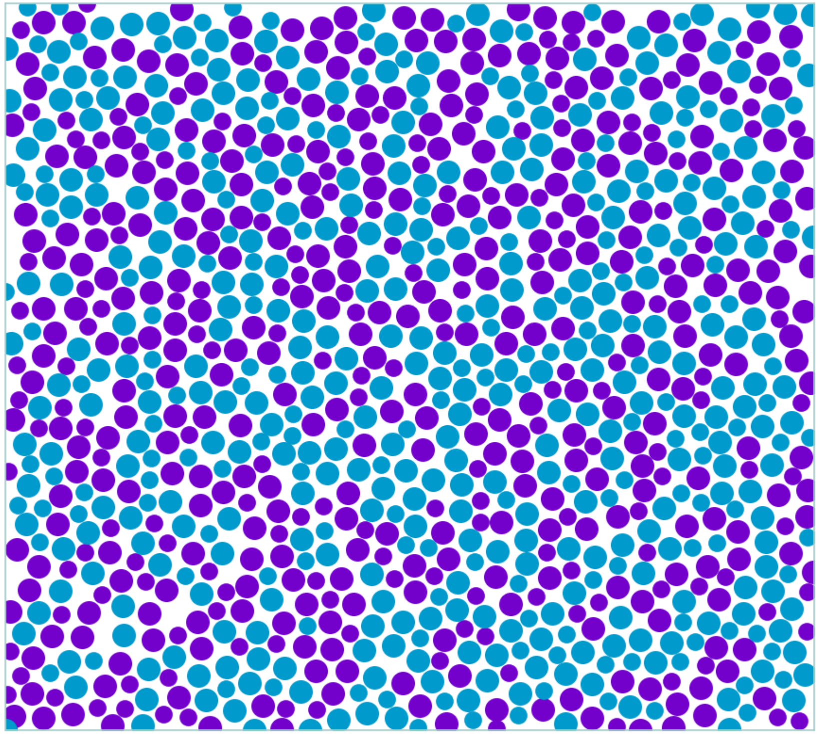


relaxation times from MCT

Standard MCT is not *quantitatively* accurate,
but *qualitatively* it already predicts the correct behavior!
(both for simulation model and experiment)

Thus far, we considered emergent collective dynamics. Now let's zoom in further ...

active/passive binary mixture

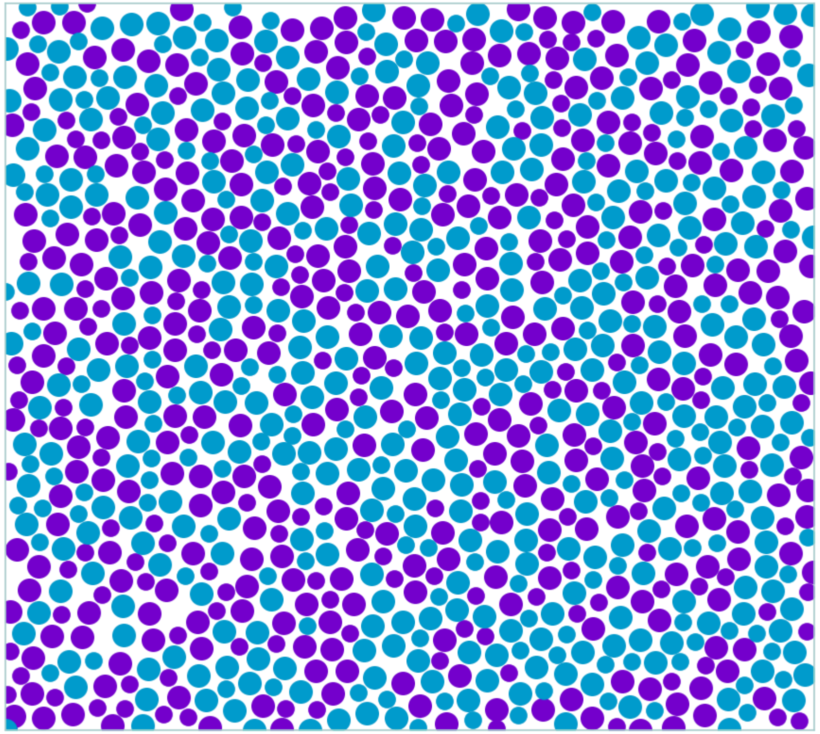


passive ("epithelial")

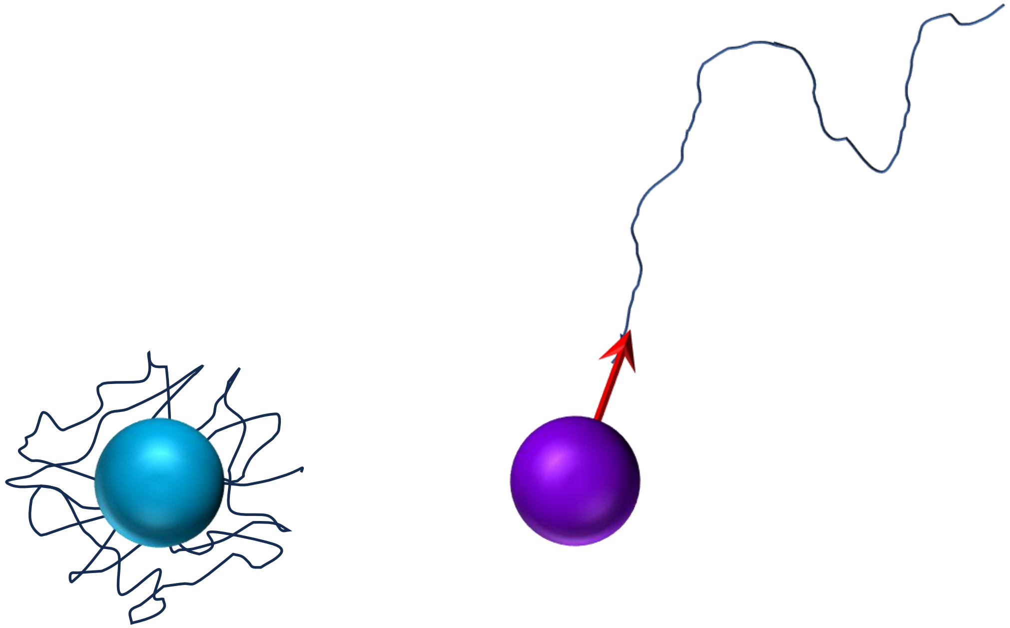
active (self-motile, "mesenchymal")

Thus far, we considered emergent <u>collective</u> dynamics. Now let's zoom in further ...

active/passive binary mixture



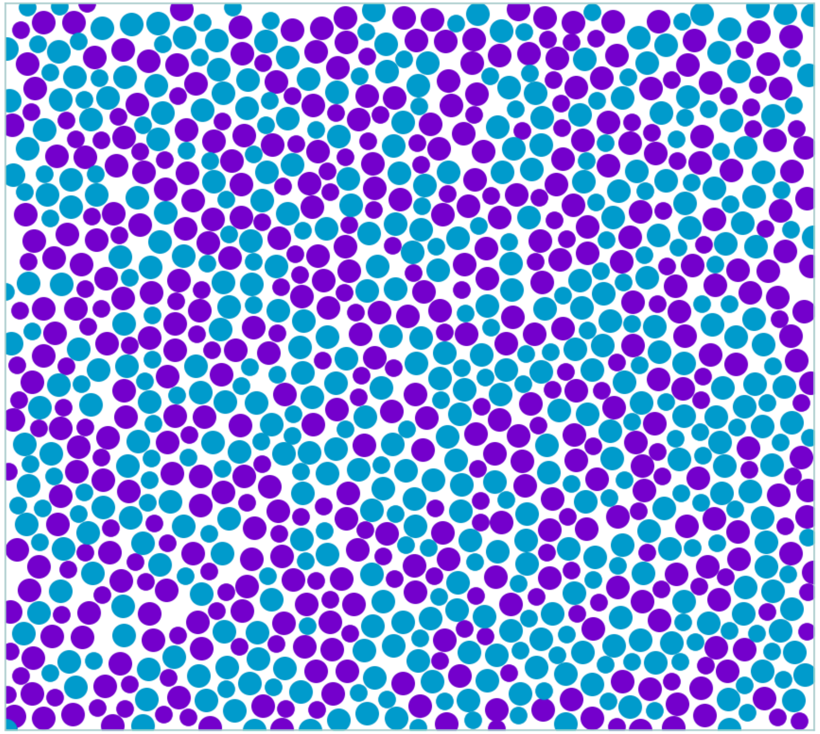
passive ("epithelial")
active (self-motile, "mesenchymal")

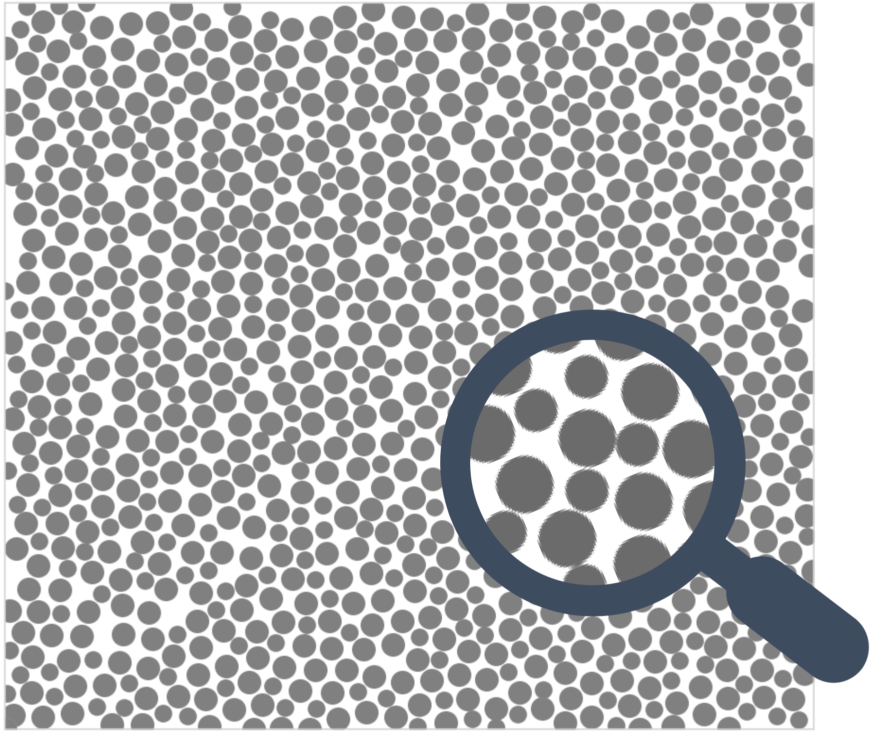


minimal model for epithelial-to-mesenchymal transition in cells; associated with metastasis

Thus far, we considered emergent collective dynamics. Now let's zoom in further ...

active/passive binary mixture





passive ("epithelial")

active (self-motile, "mesenchymal")

Can we infer from the instantaneous local structure whether a particle is active (i.e. self-motile) or not?

An ideal task for machine learning

Giulia Janzen

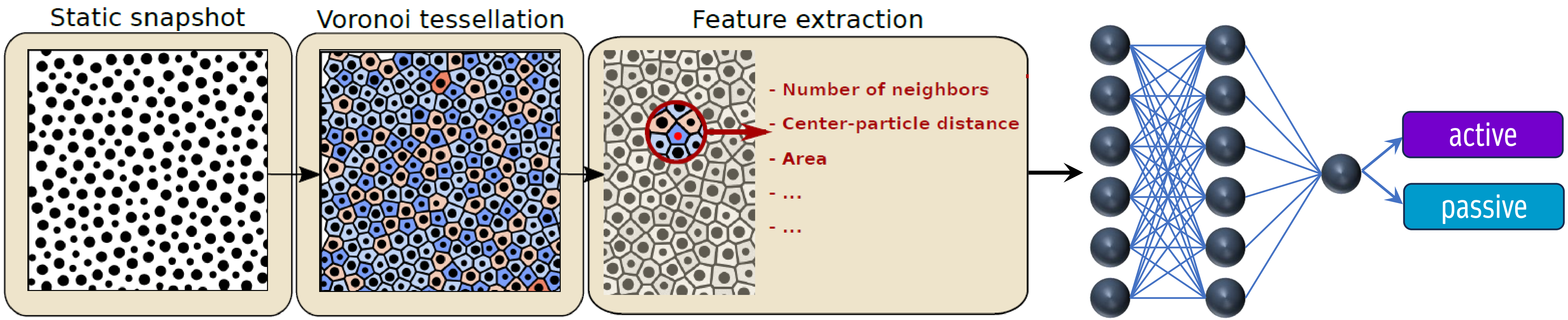
Janzen et al., ‘Dead or alive: Distinguishing active from passive particles using supervised learning’, EPL (2023)

An ideal task for machine learning

Giulia Janzen

- For passive glassformers, ML has been successfully used to predict the dynamic propensity of particles, based on (many, hundreds) local structural descriptors [e.g. Boattini et al., PRL 2021]

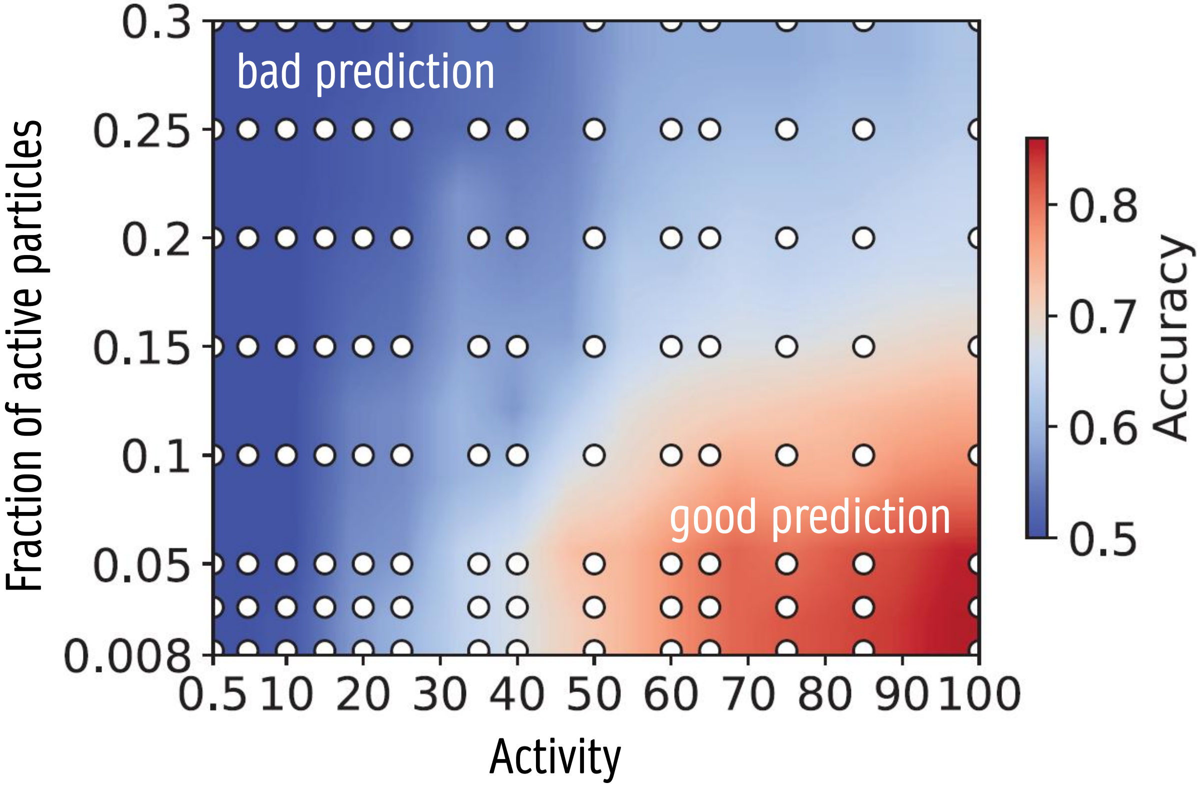
- For our active particles, we find that a simple Voronoi tessellation (only 11 features) is just as good!



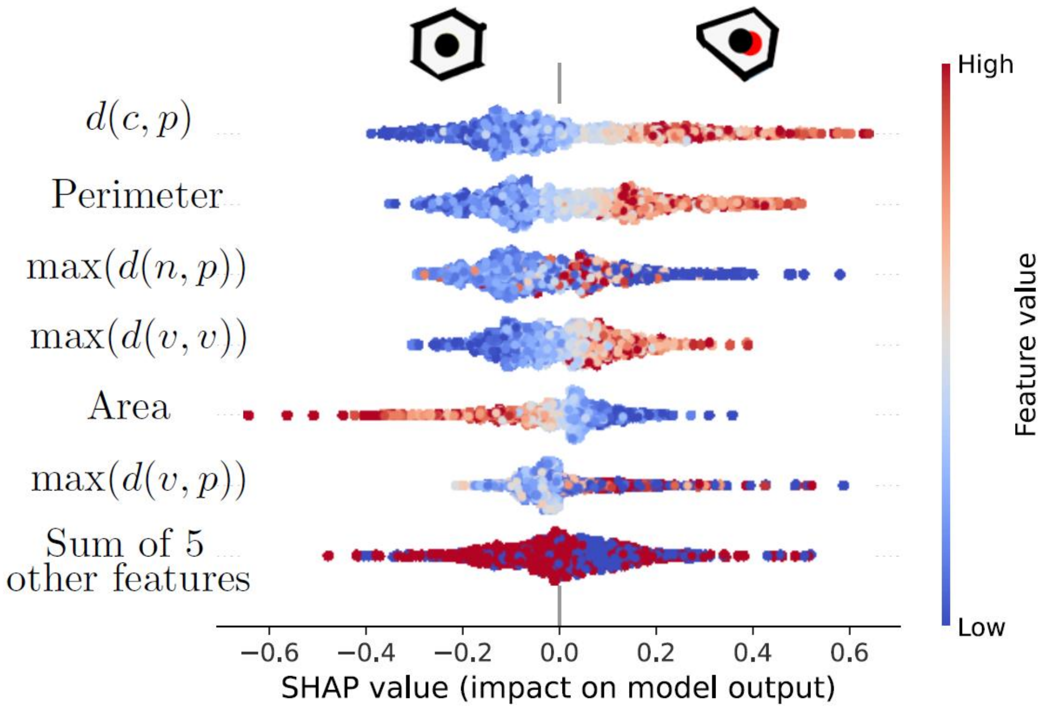
Janzen et al., 'Dead or alive: Distinguishing active from passive particles using supervised learning', EPL (2023)

Accuracy is best for highly active particles, and few active particles (up to ~15%)

accuracy map



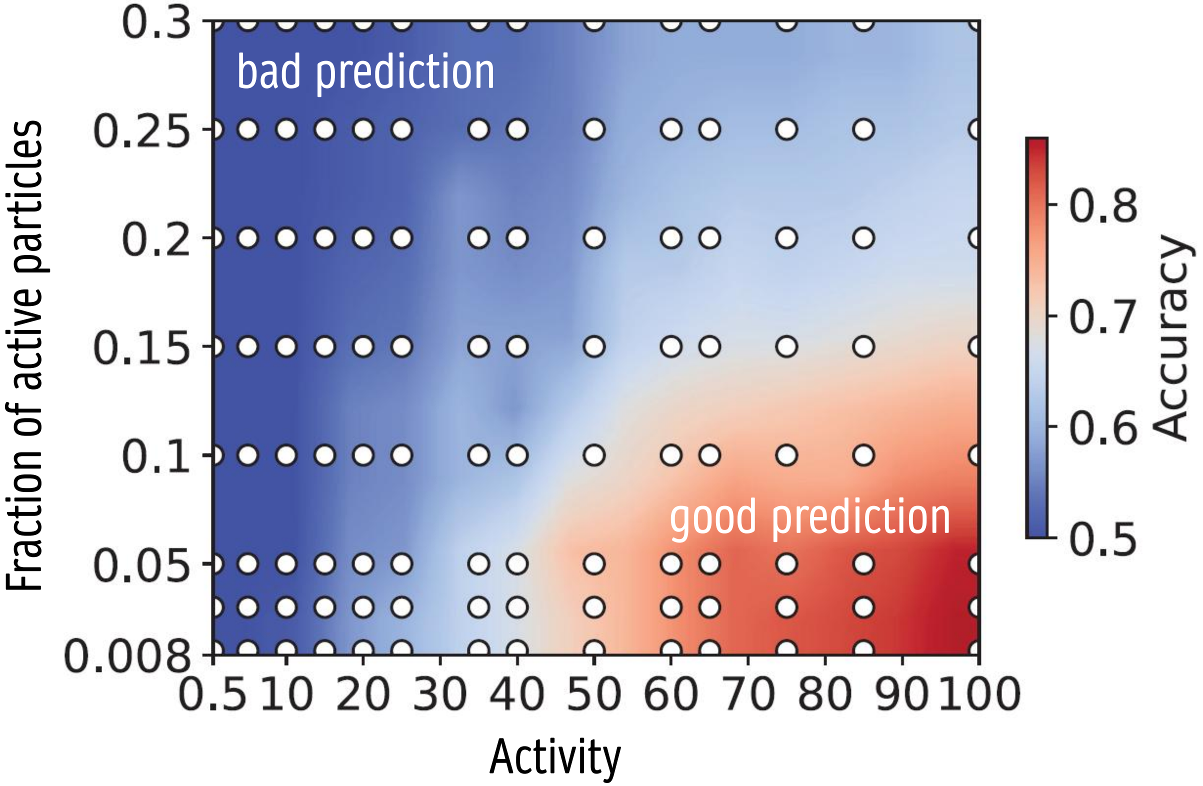
feature importance analysis (SHAP)



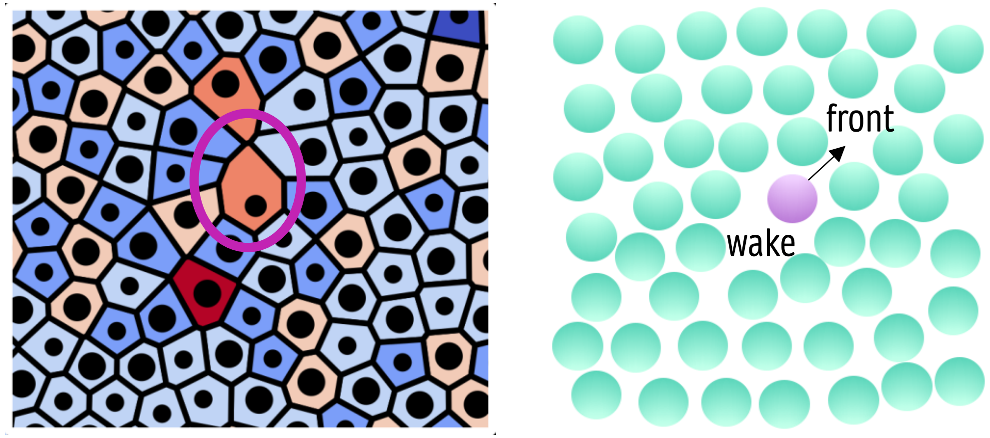
Janzen et al., 'Dead or alive: Distinguishing active from passive particles using supervised learning', EPL (2023)

Accuracy is best for highly active particles, and few active particles (up to ~15%)

accuracy map



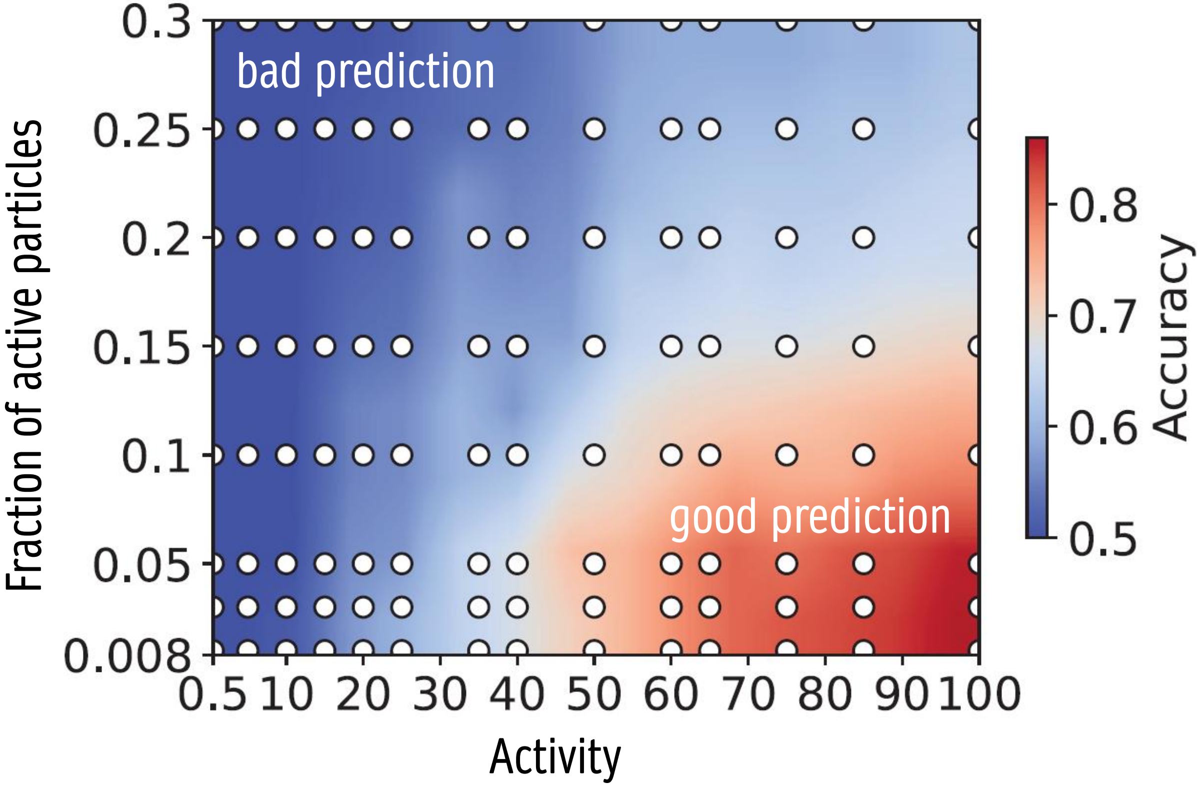
active particles leave a distinct wake:



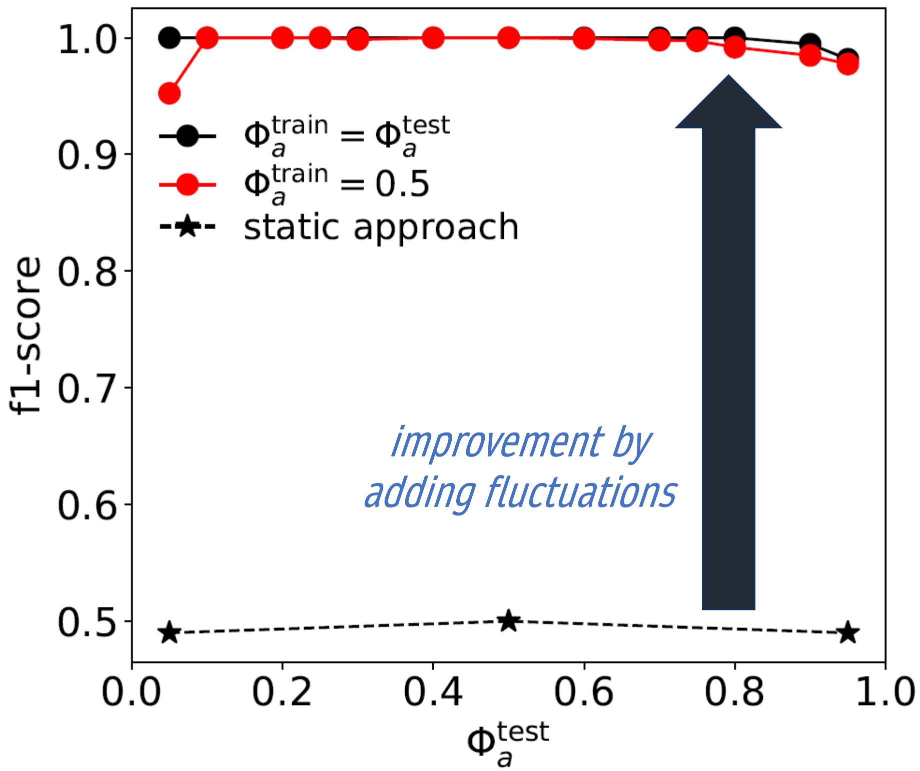
Janzen et al., 'Dead or alive: Distinguishing active from passive particles using supervised learning', EPL (2023)

Accuracy is best for highly active particles, and few active particles (up to ~15%)

accuracy map



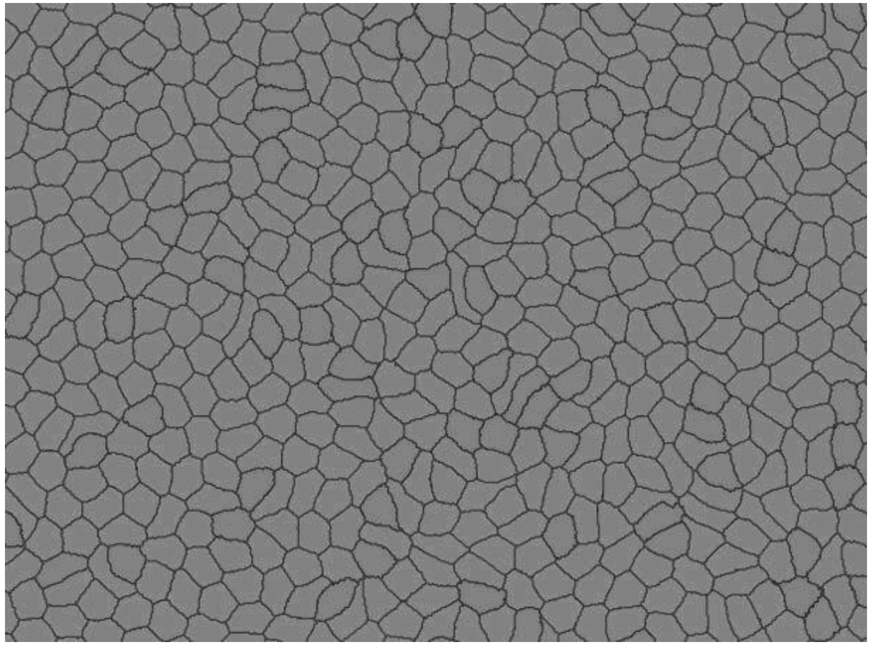
N.B. accuracy in the 'bad' regime can be greatly improved by including information on the structural *fluctuations*

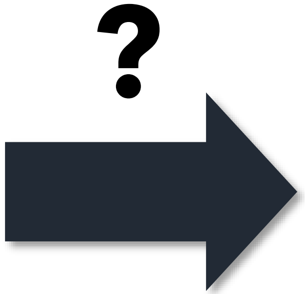


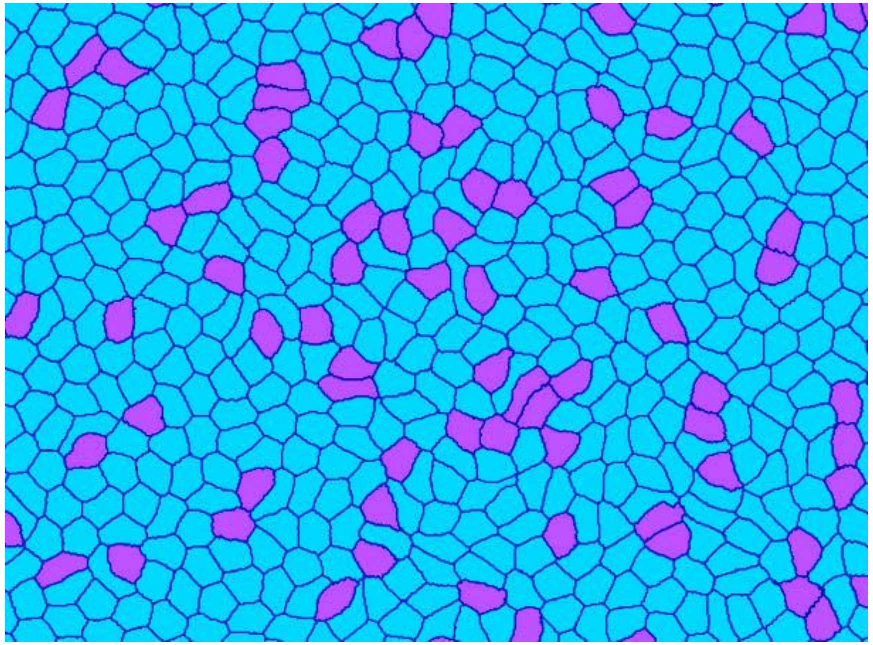
Janzen et al., 'Dead or alive: Distinguishing active from passive particles using supervised learning', EPL (2023)

Inferring individual cell motility in a confluent layer from a static image

Cellular Potts model, binary active/passive mixture

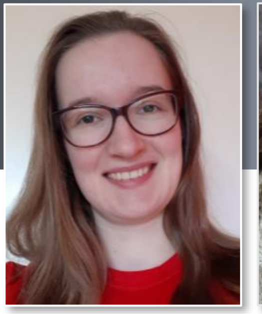






Braat, Janzen, Jansen, … Janssen, 'Shape matters: Inferring the motility of confluent cells from static images', Soft Matter (2025)

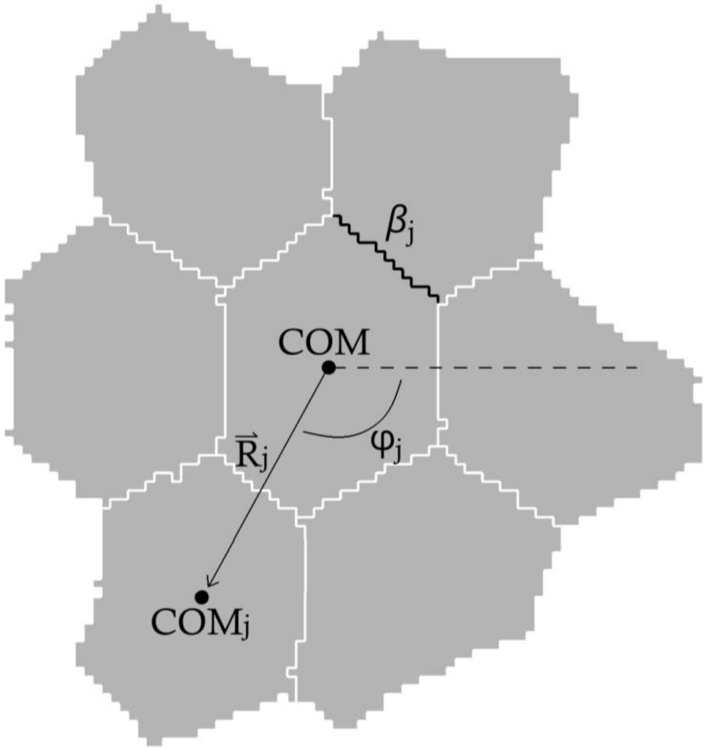
Inferring individual cell motility in a confluent layer from a static image



Quirine Braat

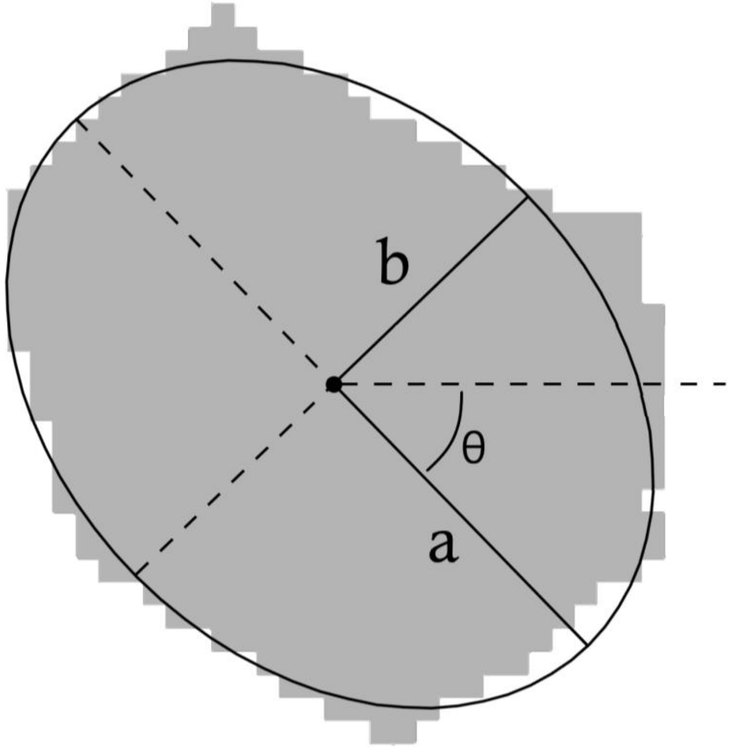
Giulia Janzen

‘structural’ features



(based on center-of-mass positions)

‘shape’ features

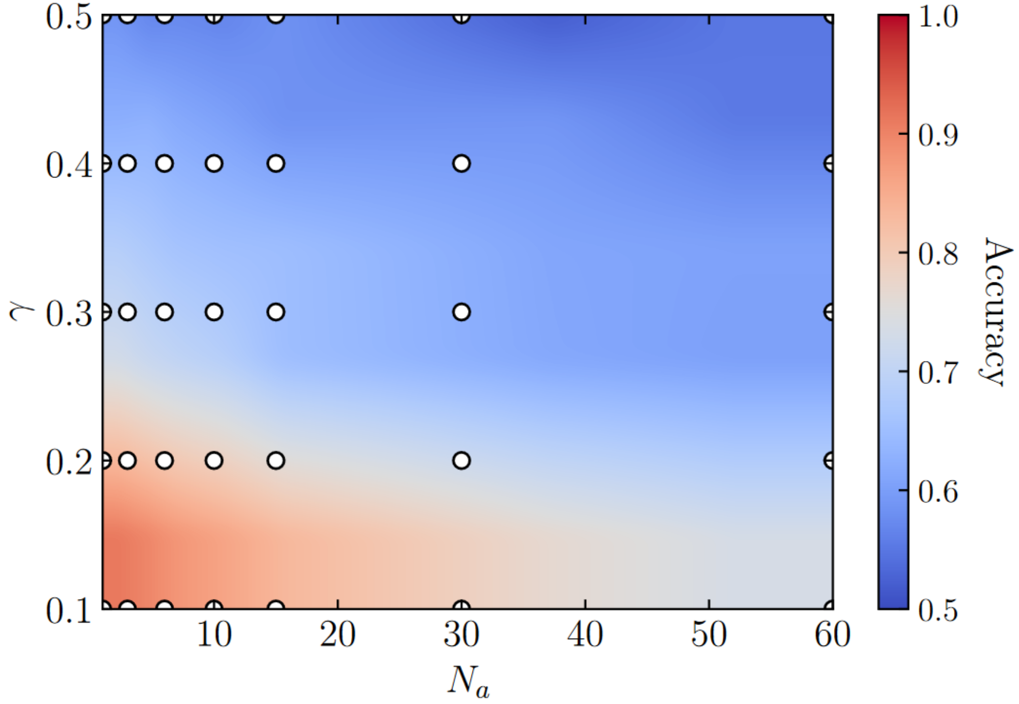


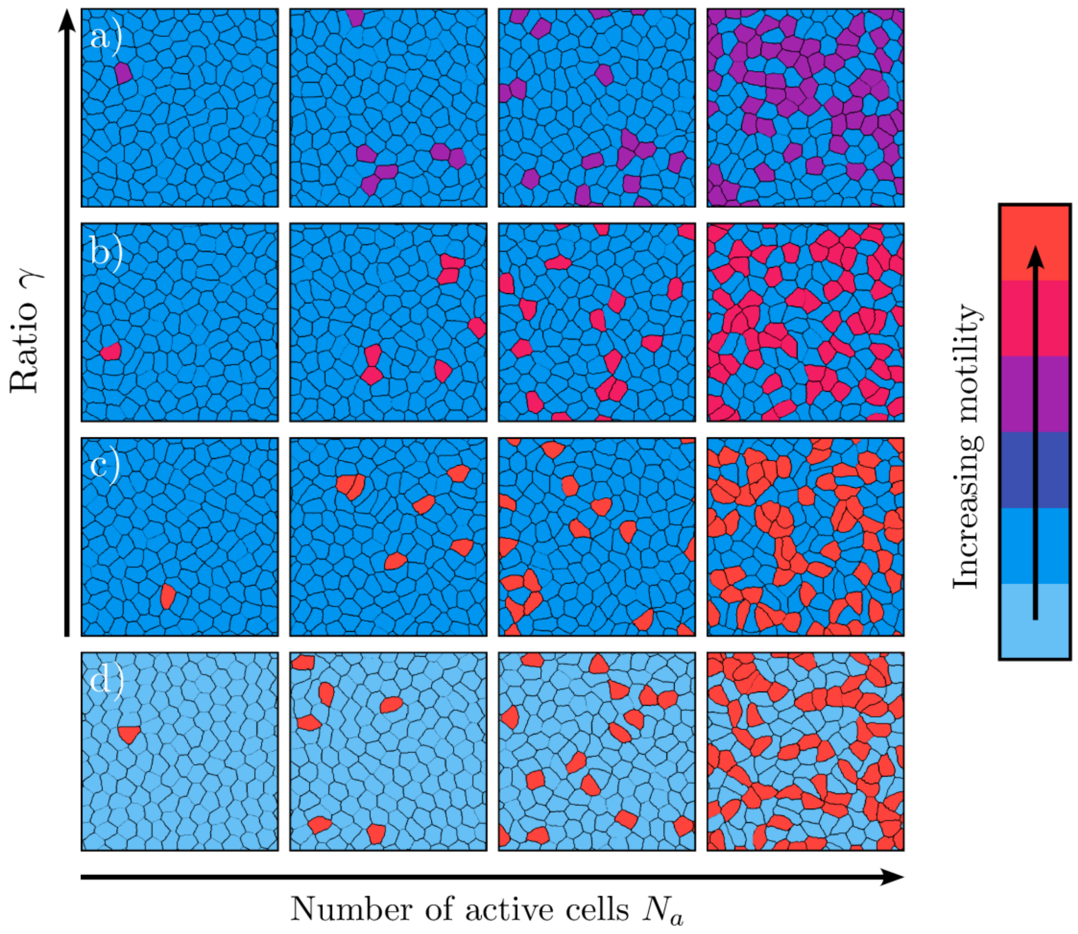
(based on single-cell geometry)

Braat, Janzen, Jansen, … Janssen, ‘Shape matters: Inferring the motility of confluent cells from static images’, Soft Matter (2025)

Inferring individual cell motility in a confluent layer from a static image

accuracy map (similar to previous case)

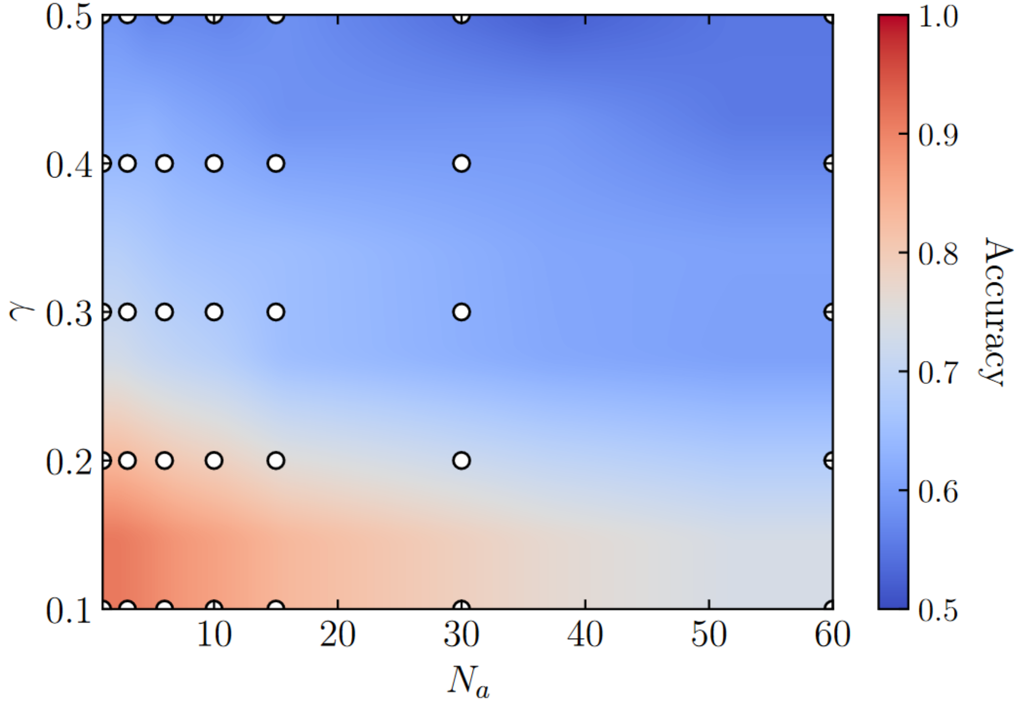




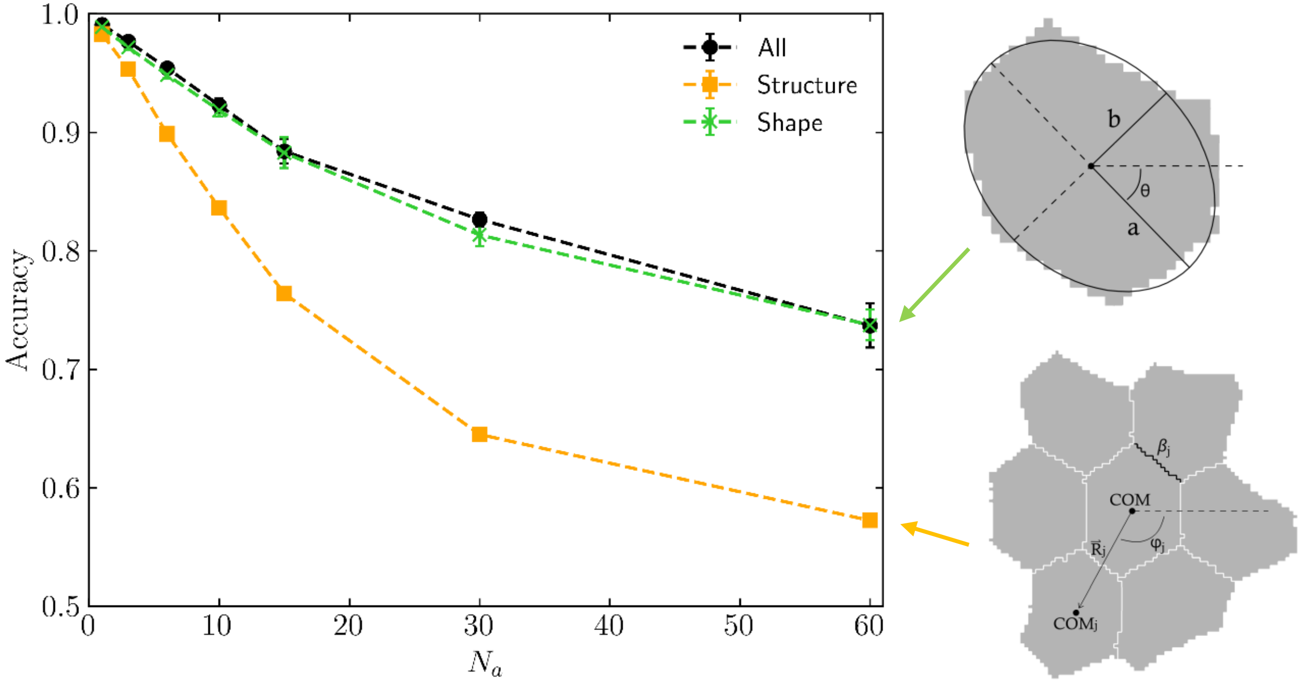
Braat, Janzen, Jansen, … Janssen, 'Shape matters: Inferring the motility of confluent cells from static images', Soft Matter (2025)

Inferring individual cell motility in a confluent layer from a static image

accuracy map (similar to previous case)



feature importance analysis



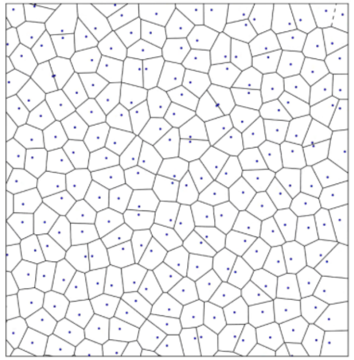
→ individual cell shape is a good* proxy for motility

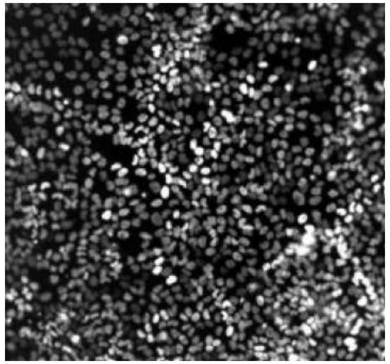
Braat, Janzen, Jansen, … Janssen, 'Shape matters: Inferring the motility of confluent cells from static images', Soft Matter (2025)

structure → ? → dynamics

Collective jamming/unjamming dynamics

MCT as a novel approach to predict & understand the emergent dynamics of cells from solely structural data

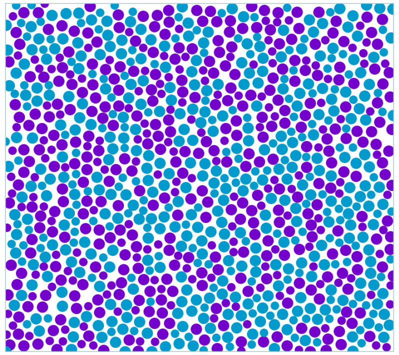


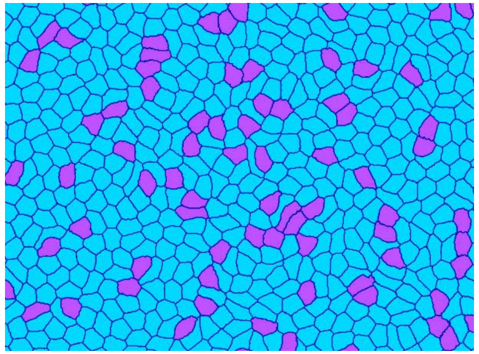


Debets, de Wit, Janssen, PRL (2021), Debets & Janssen, PRR (2022)
Debets & Janssen, JCP (2022), Debets & Janssen, JCP (2023)

Single-cell dynamics

(Voronoi) cell shape is a structural indicator of motility





Janzen et al., EPL (2023)
Braat, Janzen, et al., Soft Matter (2025)

Non-Equilibrium Soft Matter group @ TU Eindhoven

Max Kerr Winter

Simone Ciarella

Chengjie Luo

Vincent Debets

Giulia Janzen

Leon Hillmann

Kees Storm

Ilian Pihlajamaa

Corentin Laudicina

Quirine Braat

Francis Jose

Jannis Kolker

Marijke Valk

TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

NWO

netherlands eScience center

Collaborators: Jim Butler & Jeff Fredberg (Harvard Medical School)