

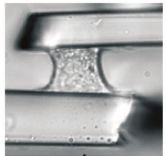
the actomyosin drive in morphogenesis

Jocelyn Étienne

LIPHY, CNRS–Univ. Grenoble Alpes

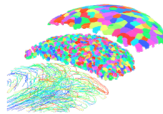


Dynamics of pulsatile apicomedial myosin in early embryo development



Jonathan Fouchard
Démosthène Mitrossilis
Nathalie Bui
Pauline Durand-Smet
Atef Asnacios

MSC, CNRS–Univ. Paris-Diderot



Guy Blanchard

PDN, Univ. Cambridge

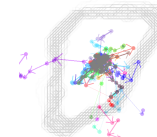
Pedro Machado
Alfonso Martinez Arias

Genetics, Univ. Cambridge

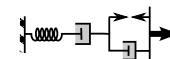
Julia Duque

Nicole Gorfinkiel

CIB, CSIC, Madrid



Nilankur Dutta

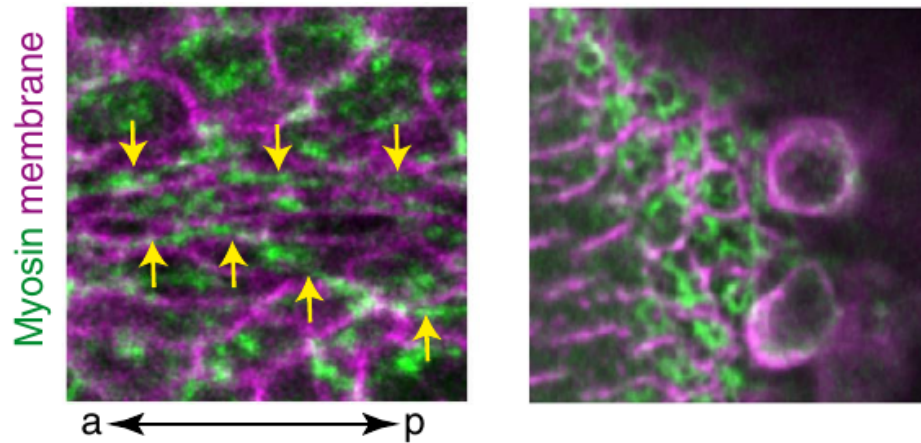


Jocelyn Étienne

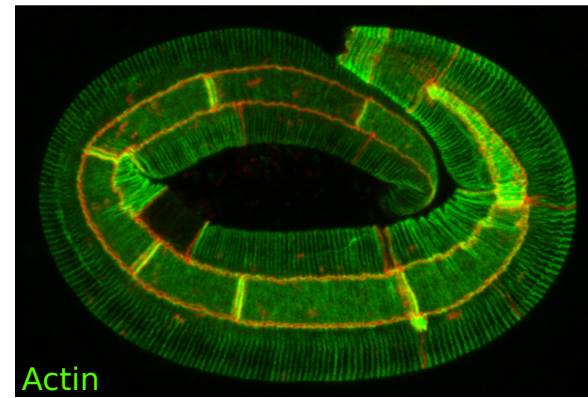
LIPHY, CNRS–Univ. Grenoble Alpes



Actomyosin in its diversity

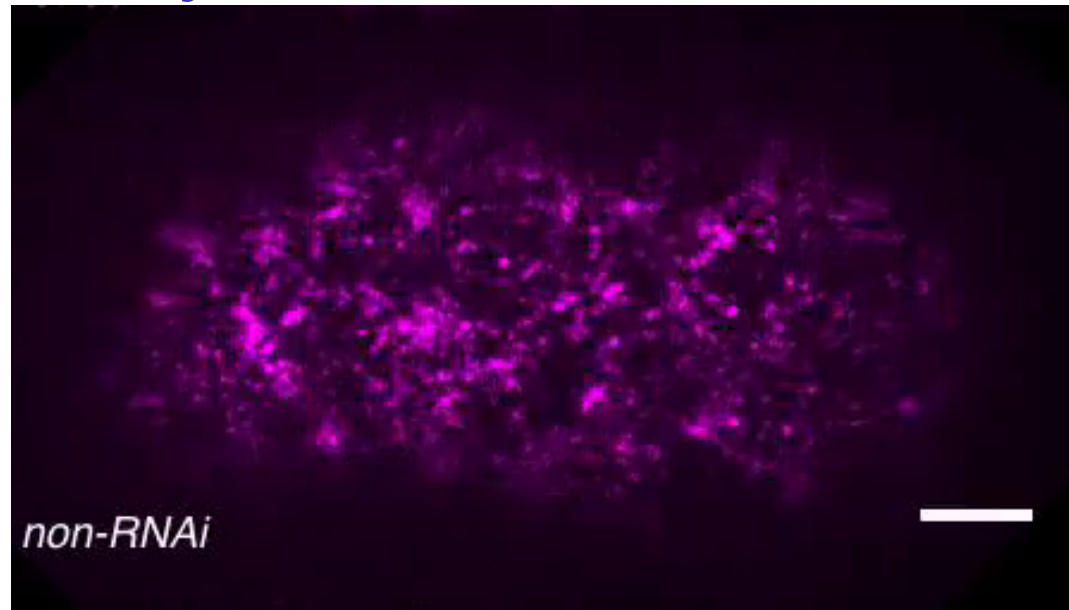


Drosophila mesoderm & PMG
[Chanet et al, 2017]

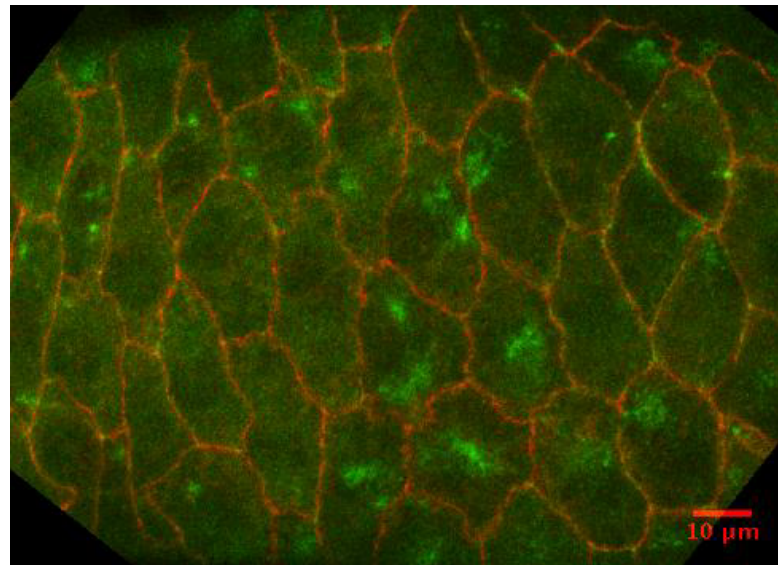


C. elegans
[G. Michaux, Rennes]

Pulsatility of actomyosin

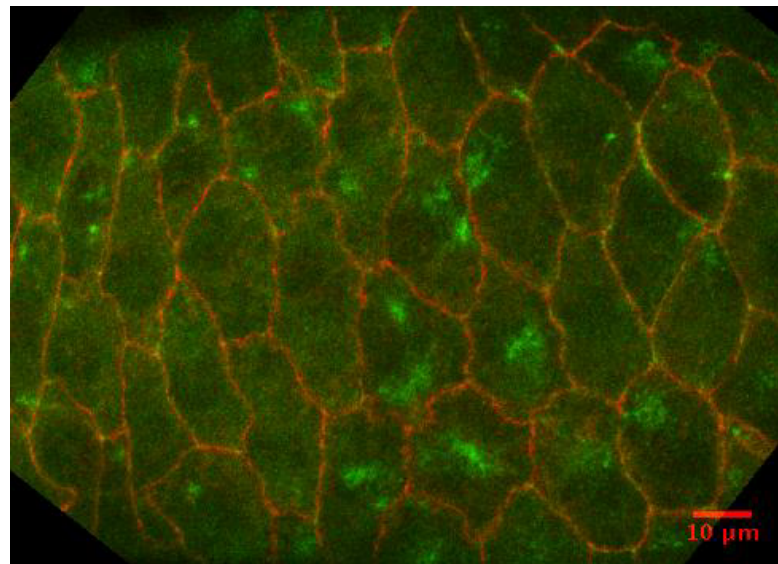
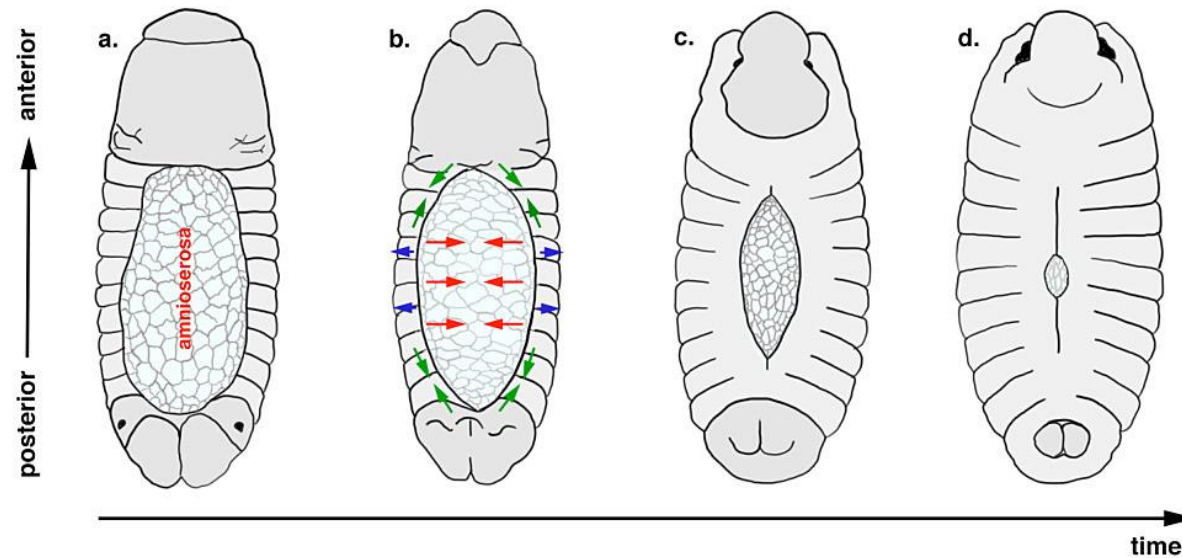


C. elegans zygote [Nishikawa et al, 2017]



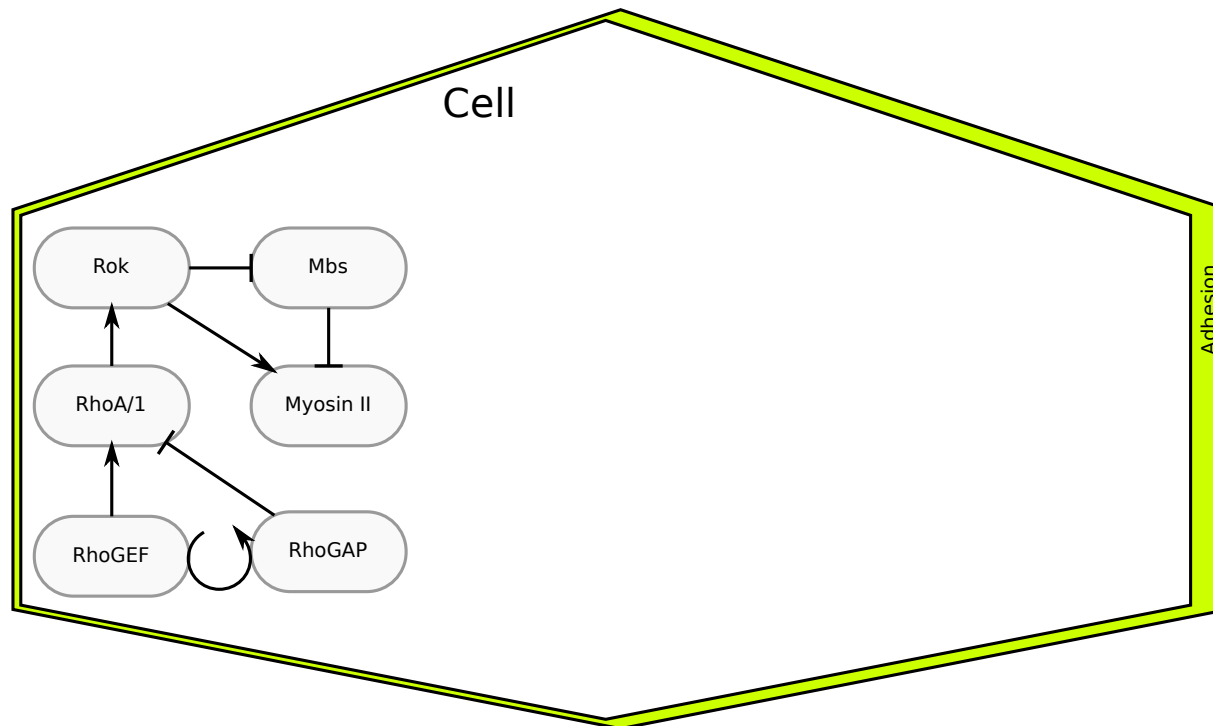
Drosophila amnioserosa during dorsal closure [Fischer et al, 2014]

Pulsatility of actomyosin and dorsal closure

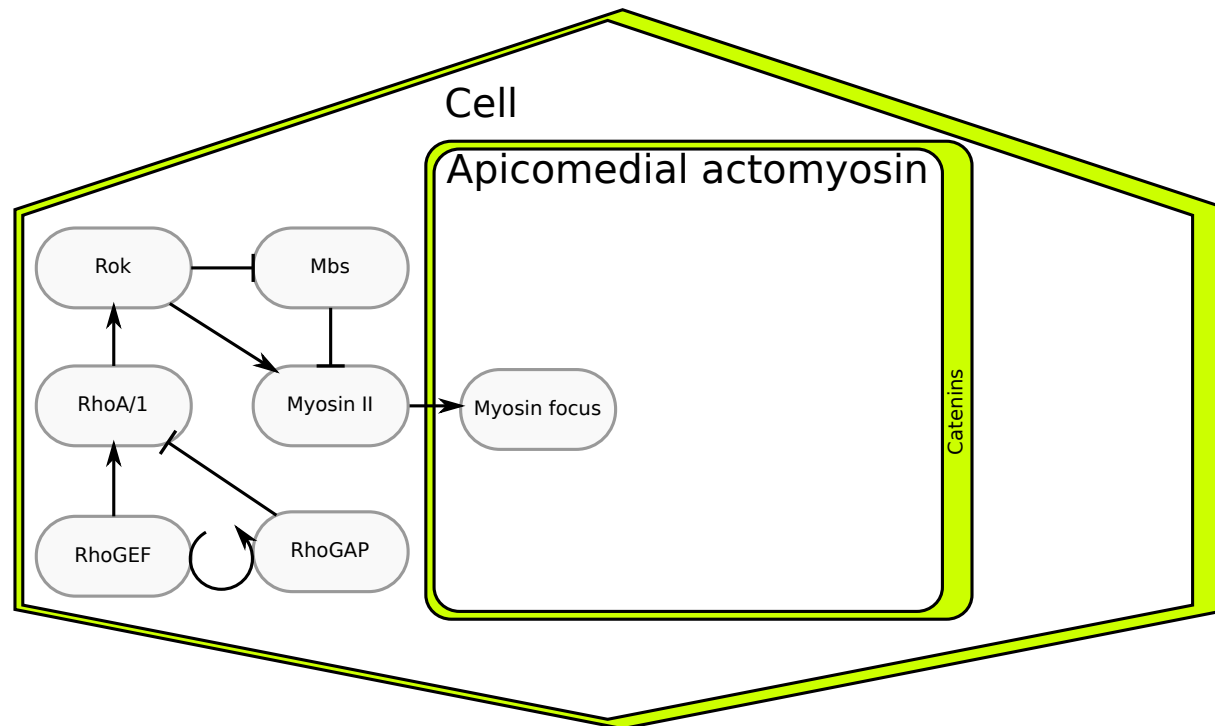


Drosophila amnioserosa during dorsal closure [Fischer et al, 2014]

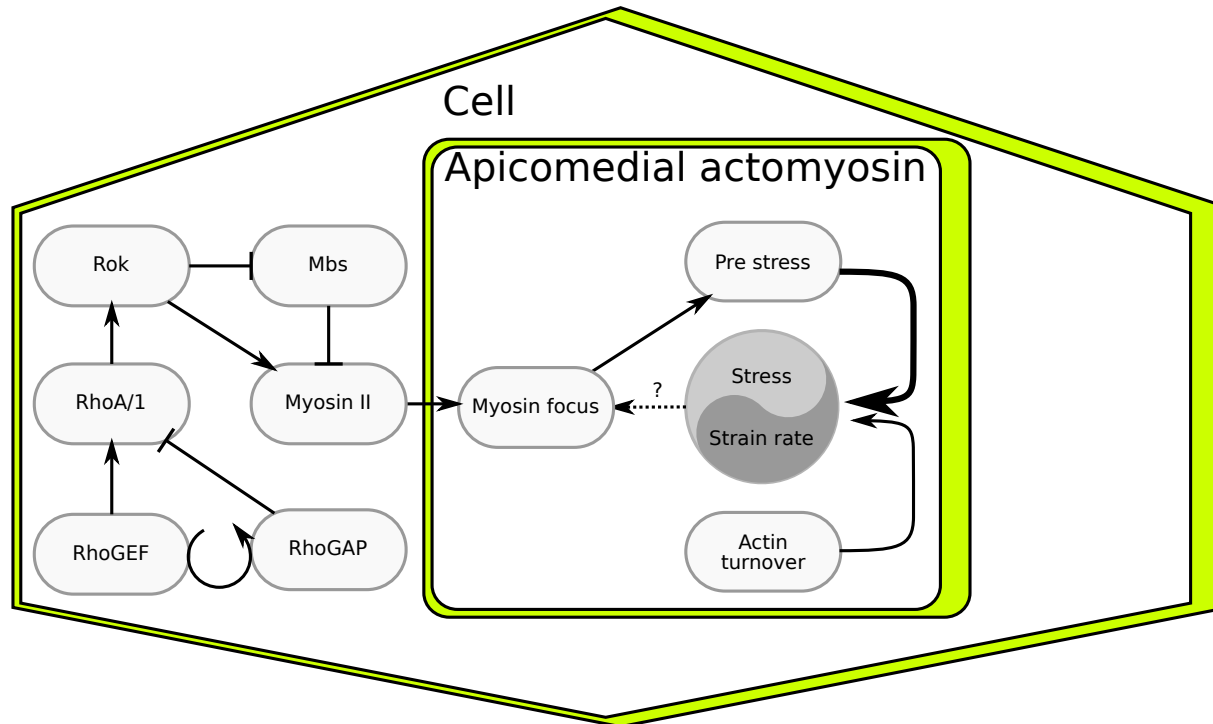
What I can't tell you about pulsatility



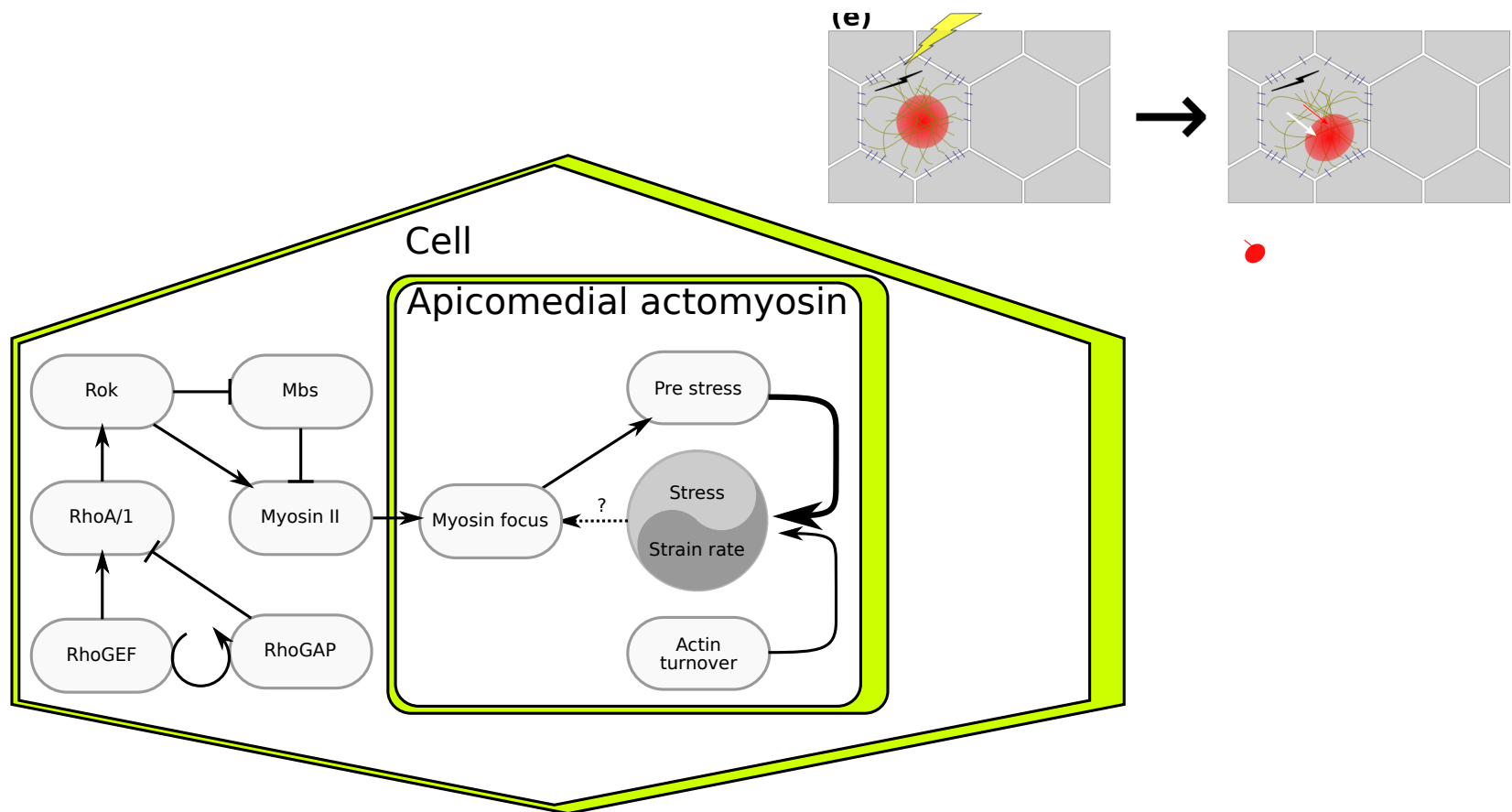
What I can't tell you about pulsatility



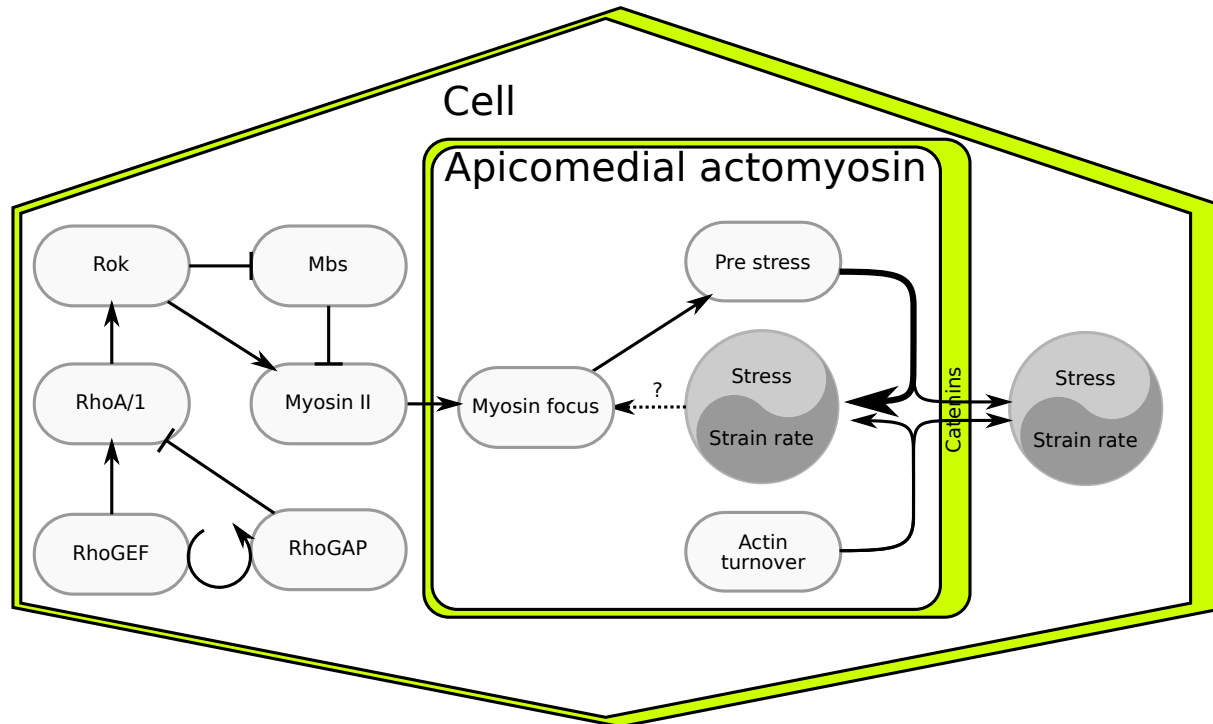
What I can tell you about pulsatility



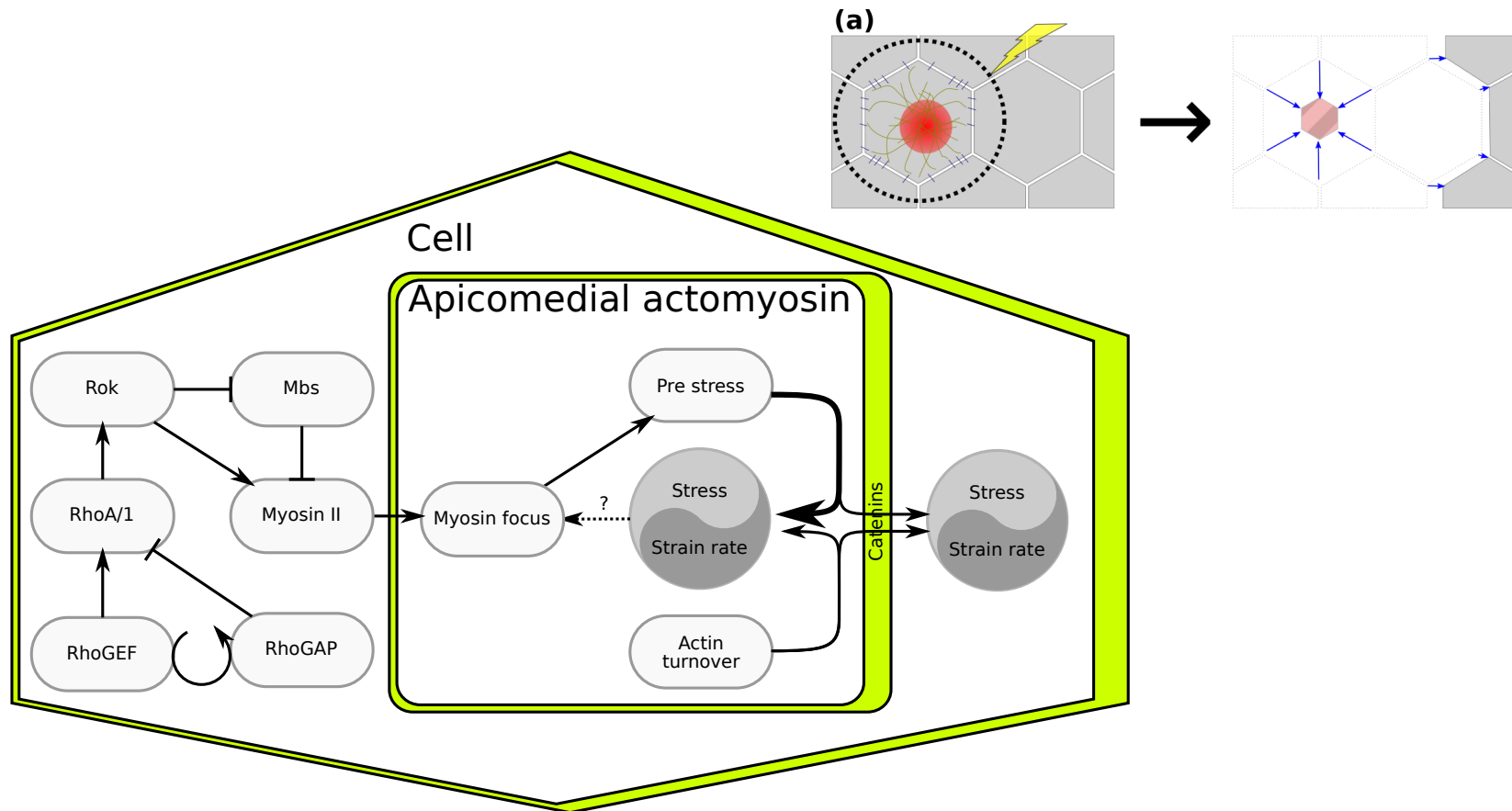
What I can tell you about pulsatility



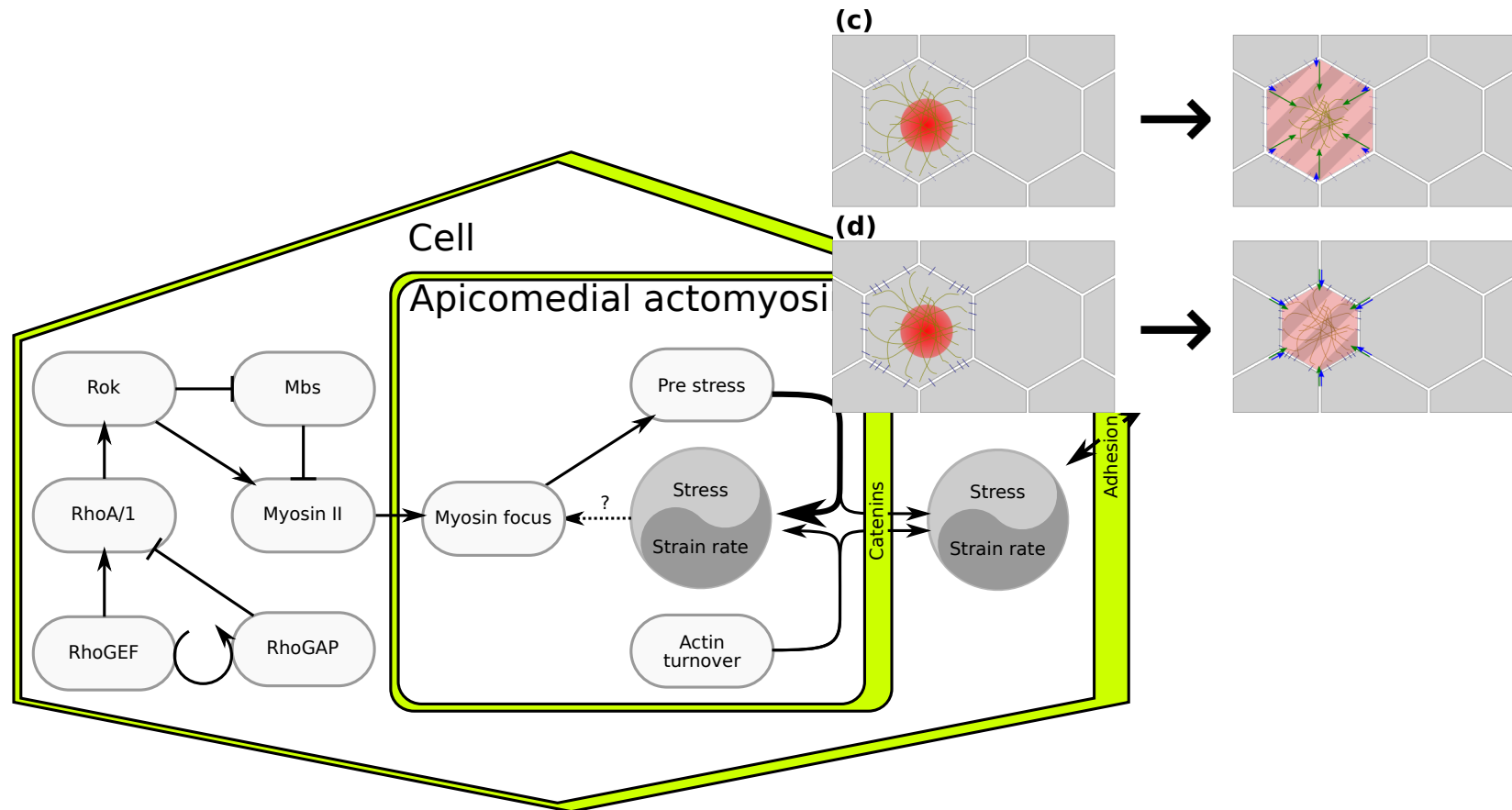
What I can tell you about pulsatility



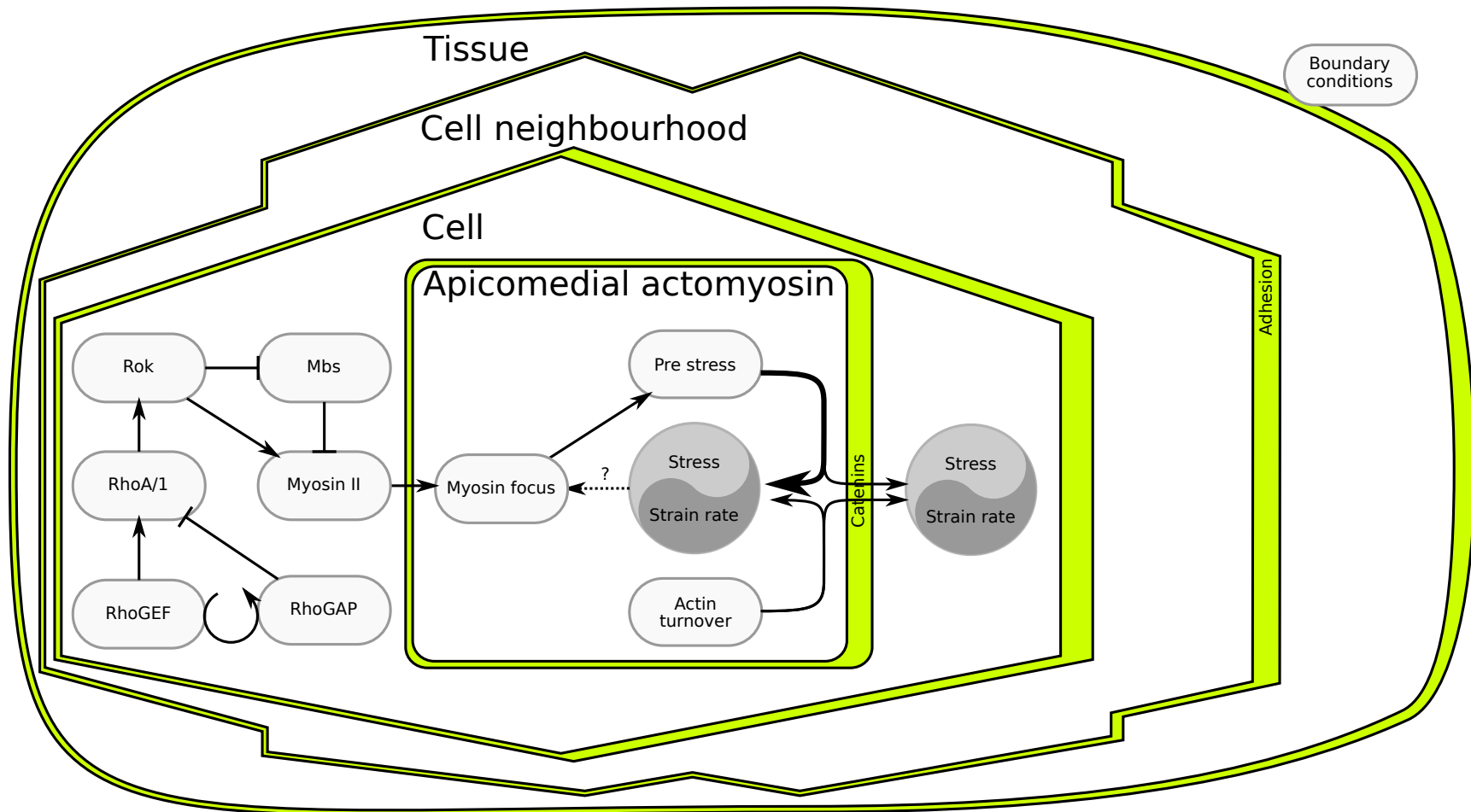
What I can tell you about pulsatility



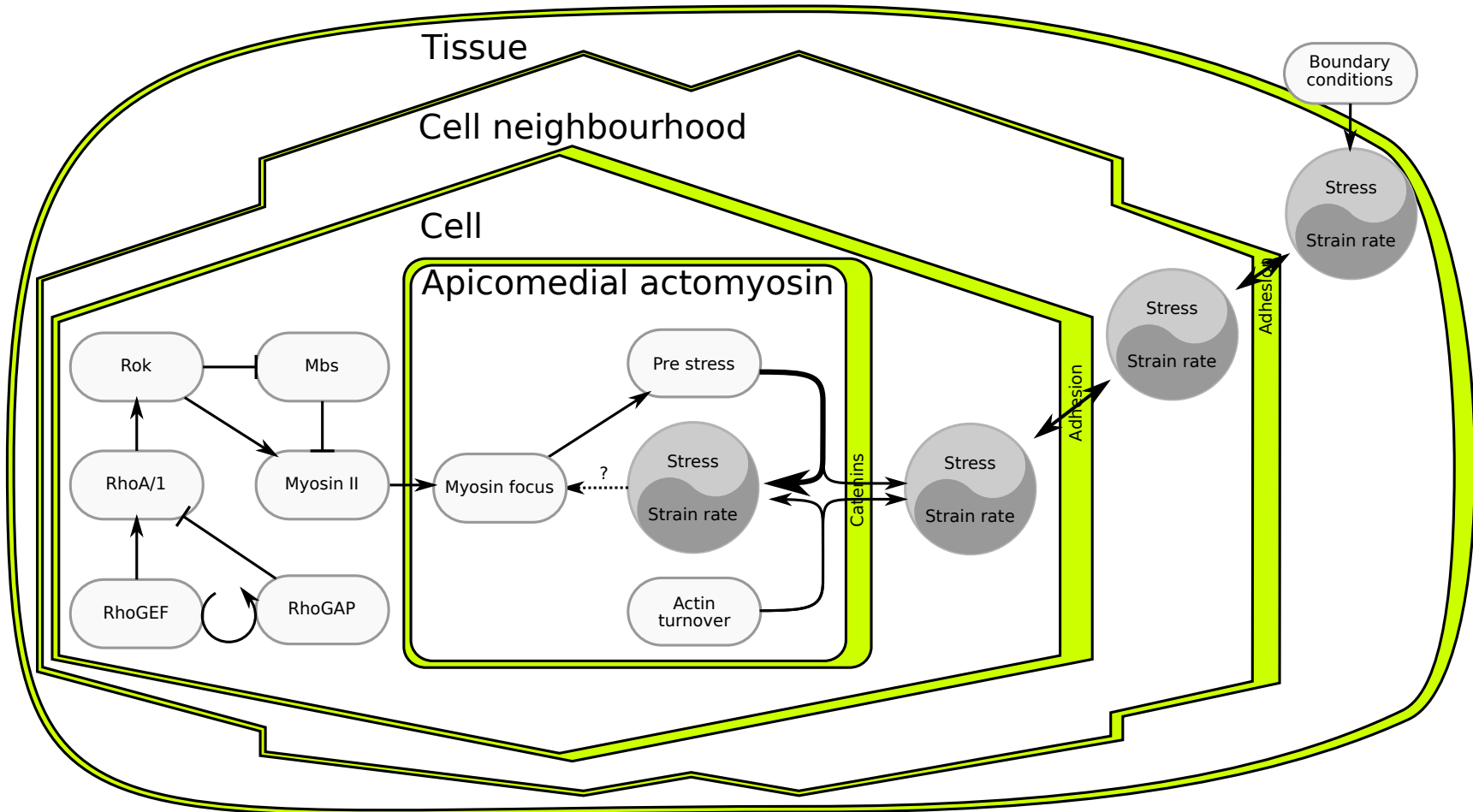
What I can tell you about pulsatility



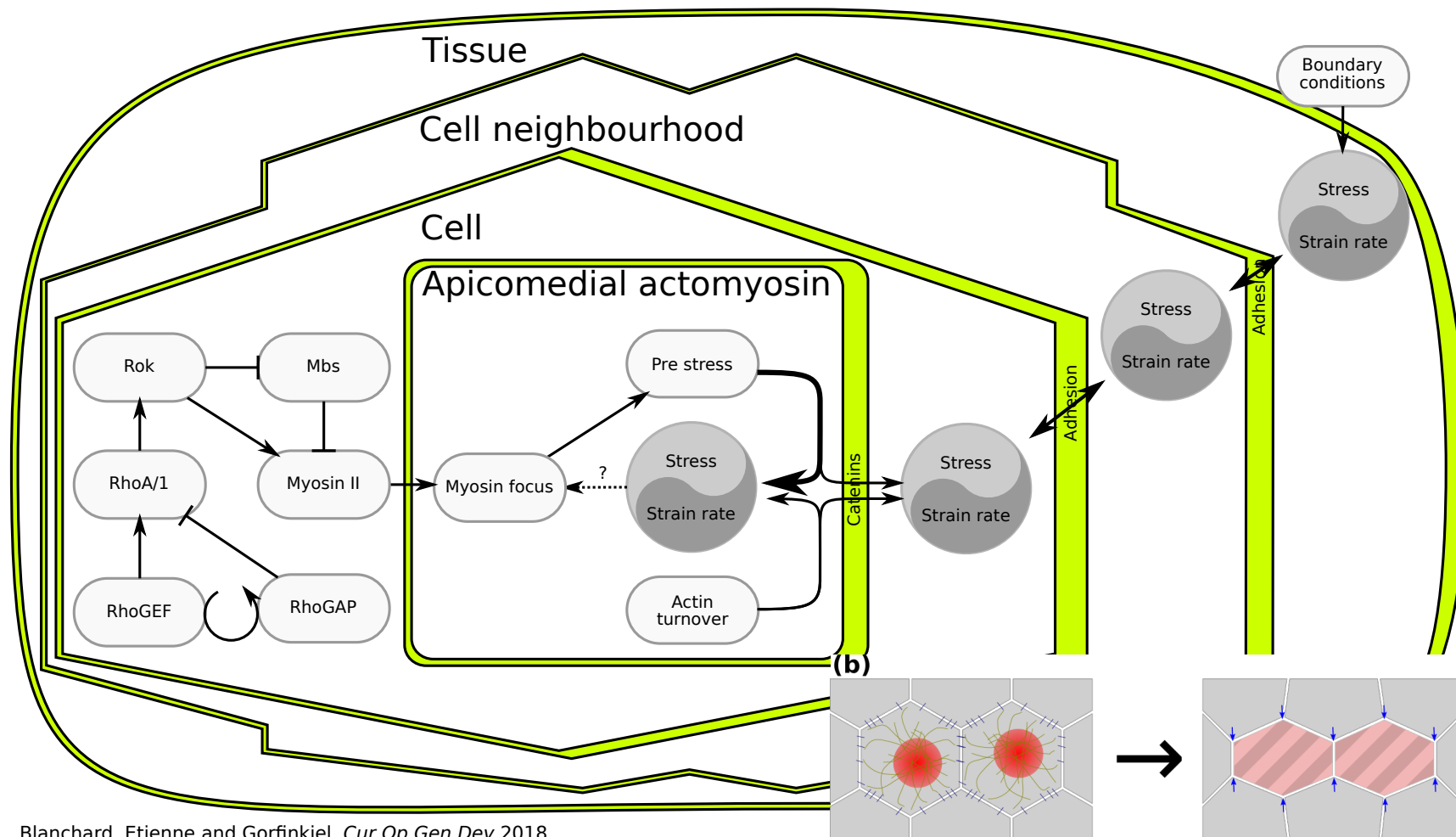
What I can tell you about pulsatility



What I can tell you about pulsatility

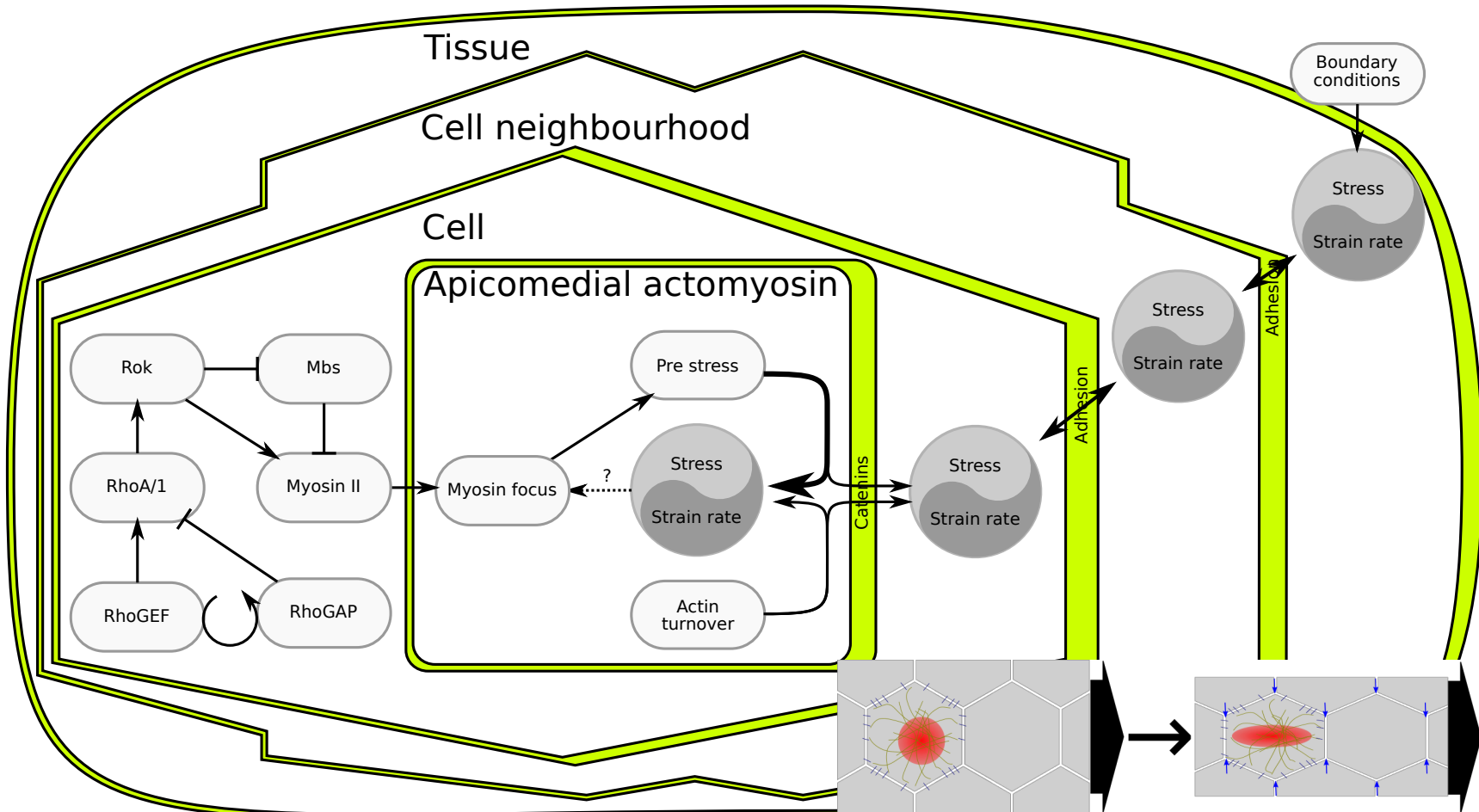


What I can tell you about pulsatility



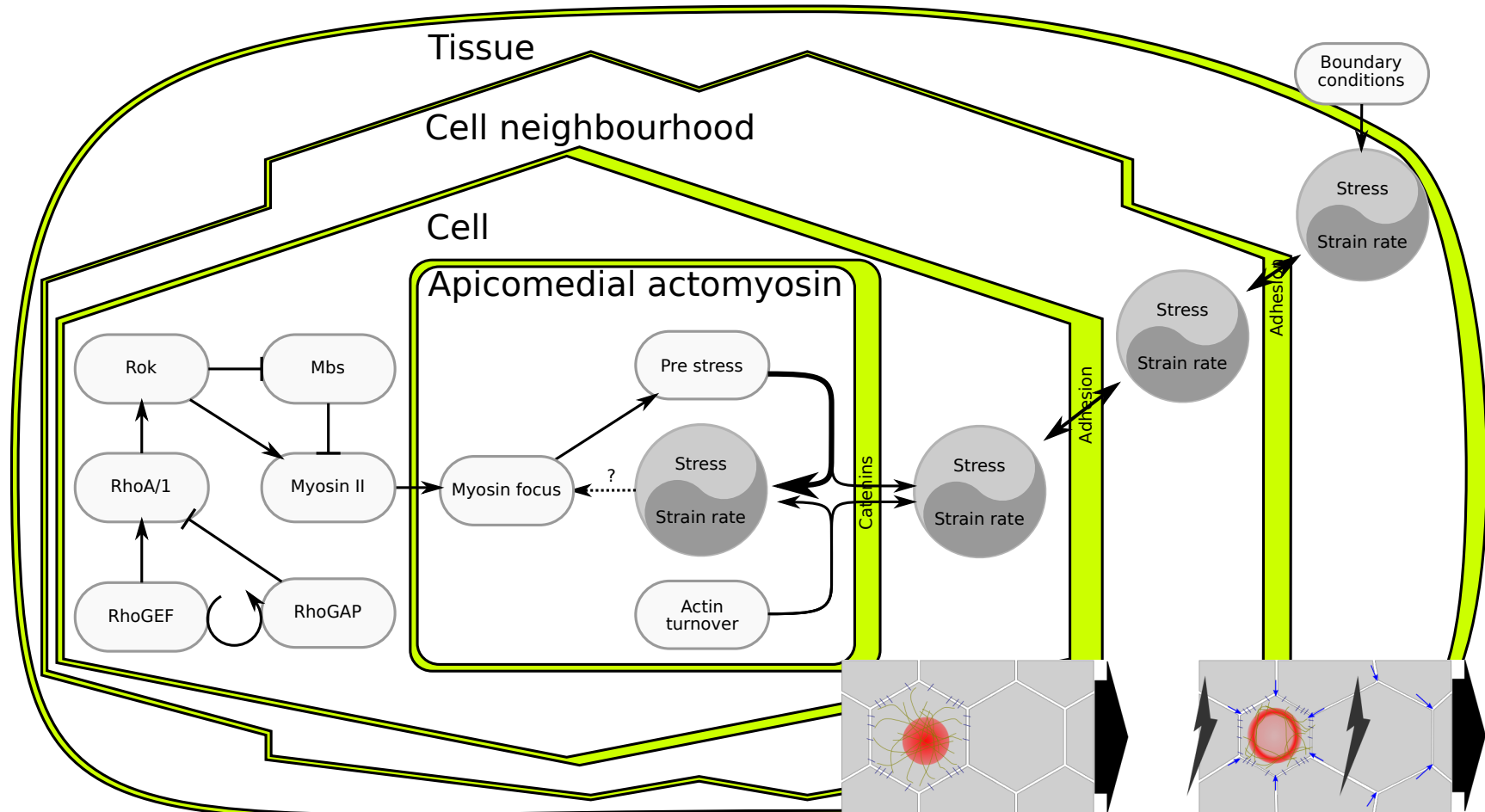
Blanchard, Etienne and Gorfinkiel, *Cur Op Gen Dev* 2018

What I can tell you about pulsatility



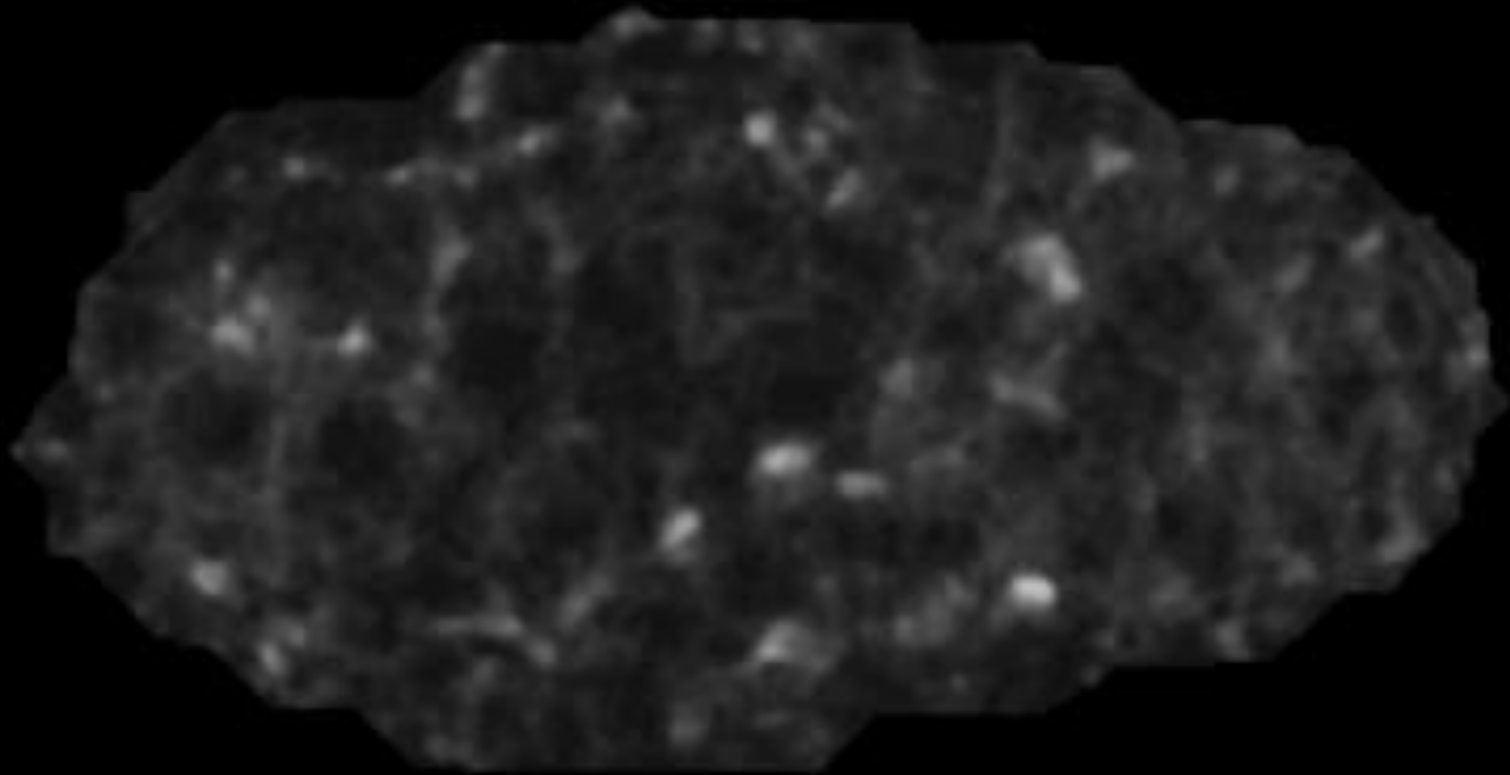
Blanchard, Etienne and Gorfinkiel, *Cur Op Gen Dev* 2018

What I can tell you about pulsatility



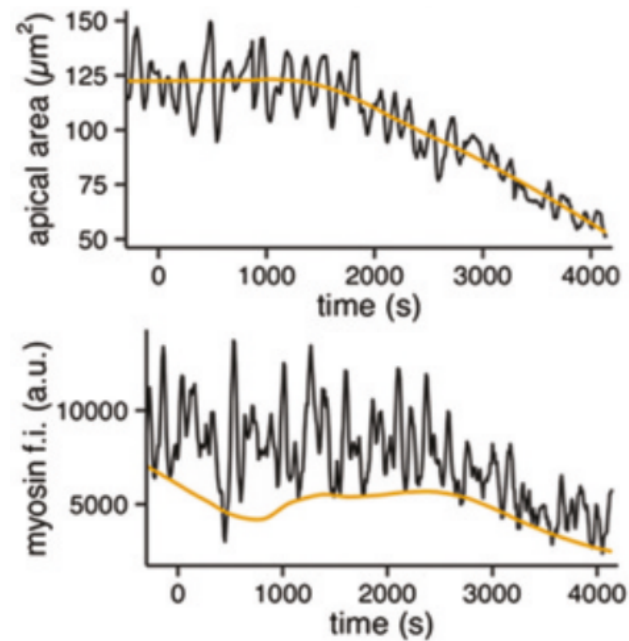
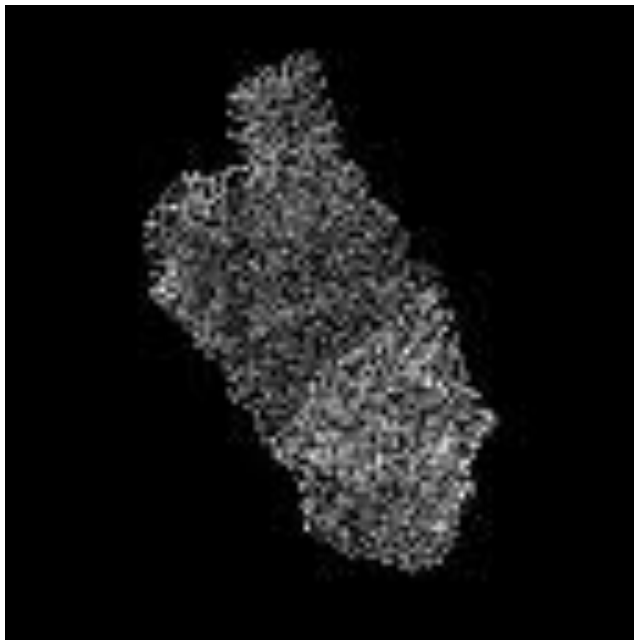
Blanchard, Etienne and Gorfinkiel, *Cur Op Gen Dev* 2018

Myosin pulsations in dorsal closure



Myosin pulsations in dorsal closure

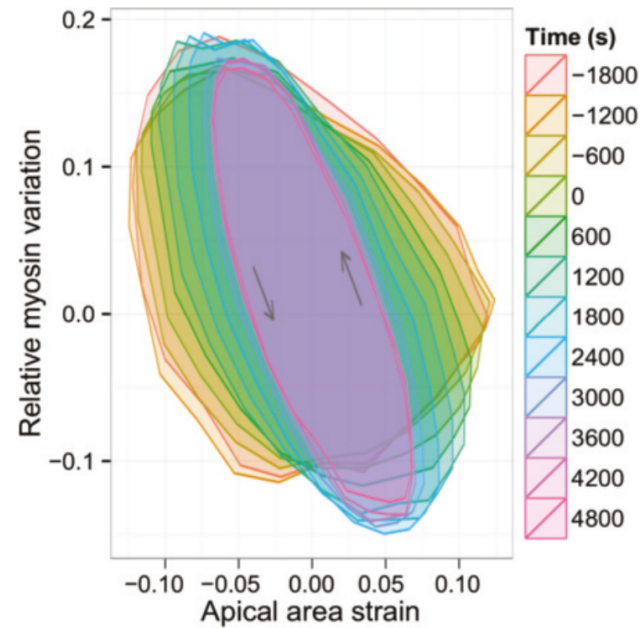
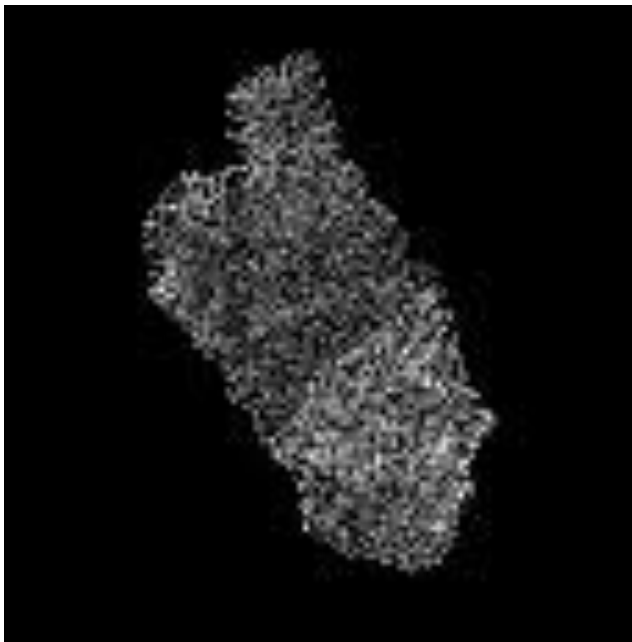
with Guy Blanchard, Alfonso Martinez-Arias (Cambridge) and Nicole Gorfinkiel (Madrid)



Machado et al, *BMC Biol* 2015

Myosin pulsations in dorsal closure

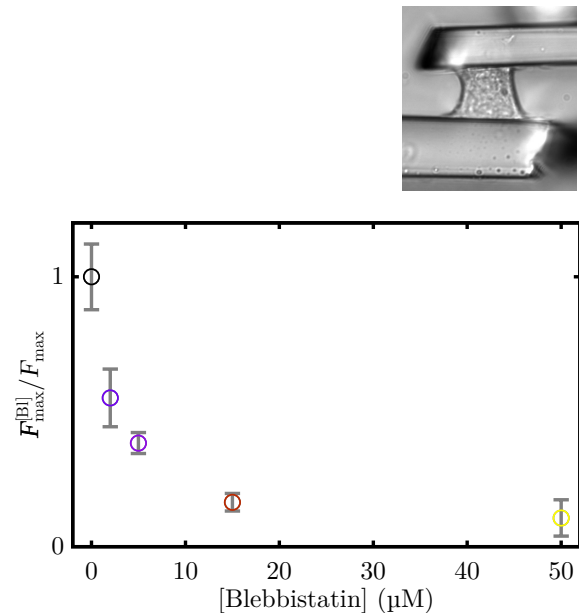
with Guy Blanchard, Alfonso Martinez-Arias (Cambridge) and Nicole Gorfinkiel (Madrid)



Machado et al, *BMC Biol* 2015

Can we use Myosin as a proxy for stress?

with Atef Asnacios, MSC Paris 7

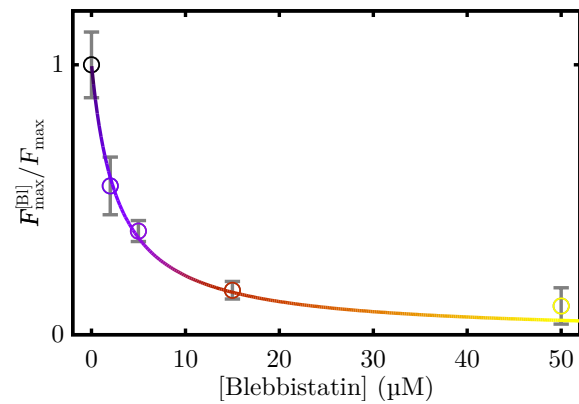
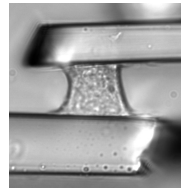


[Mitrossilis et al, *PNAS* 2009]



Can we use Myosin as a proxy for stress?

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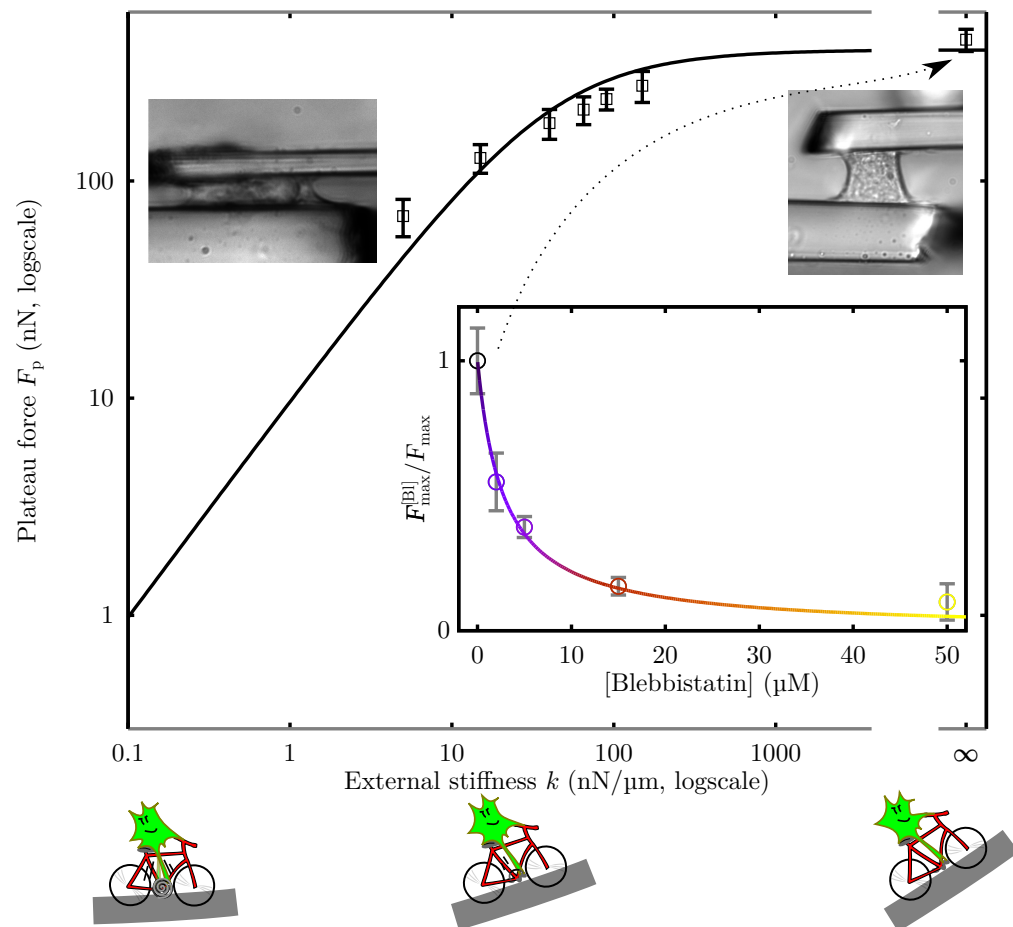


[Mitrossilis et al, *PNAS* 2009]



Can we use Myosin as a proxy for stress?

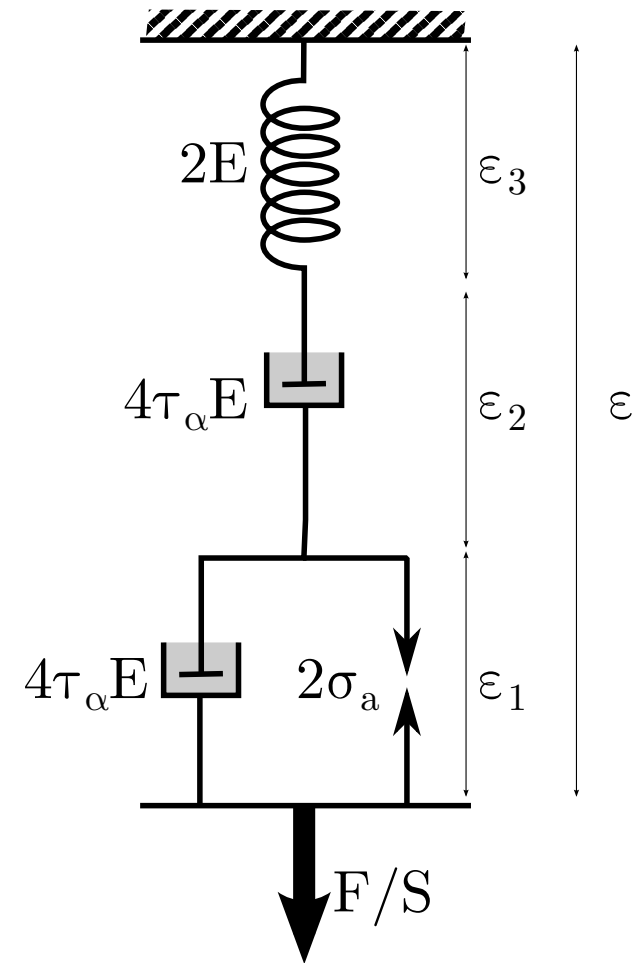
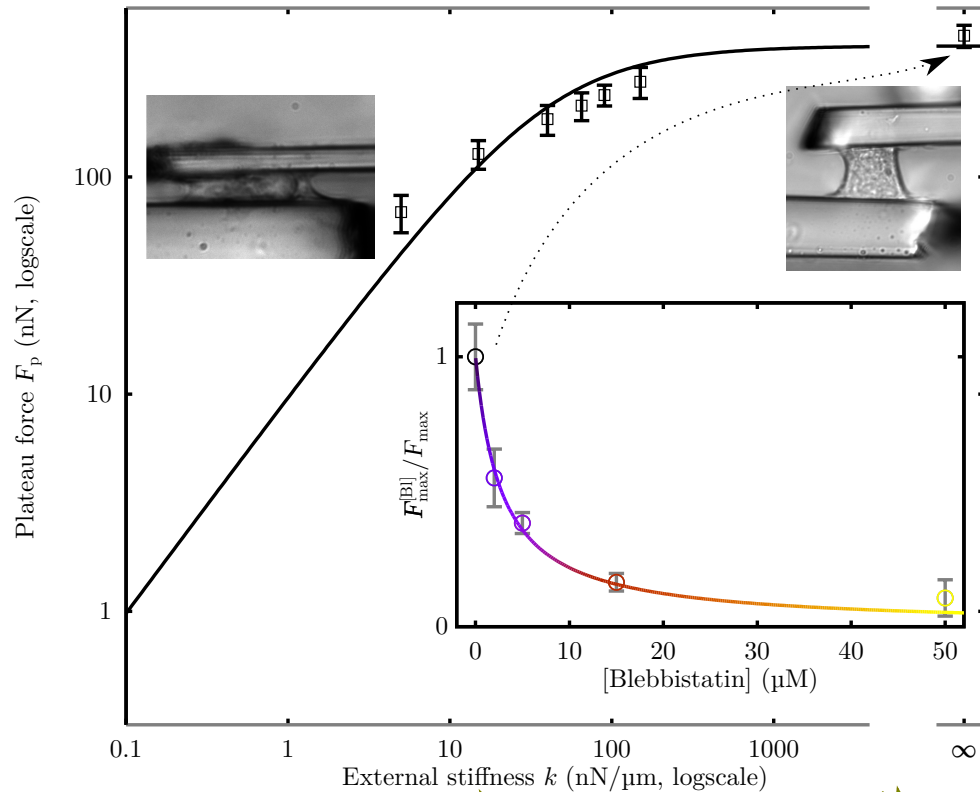
with Atef Asnacios, MSC Paris 7



[Mitrossilis et al, *PNAS* 2009]

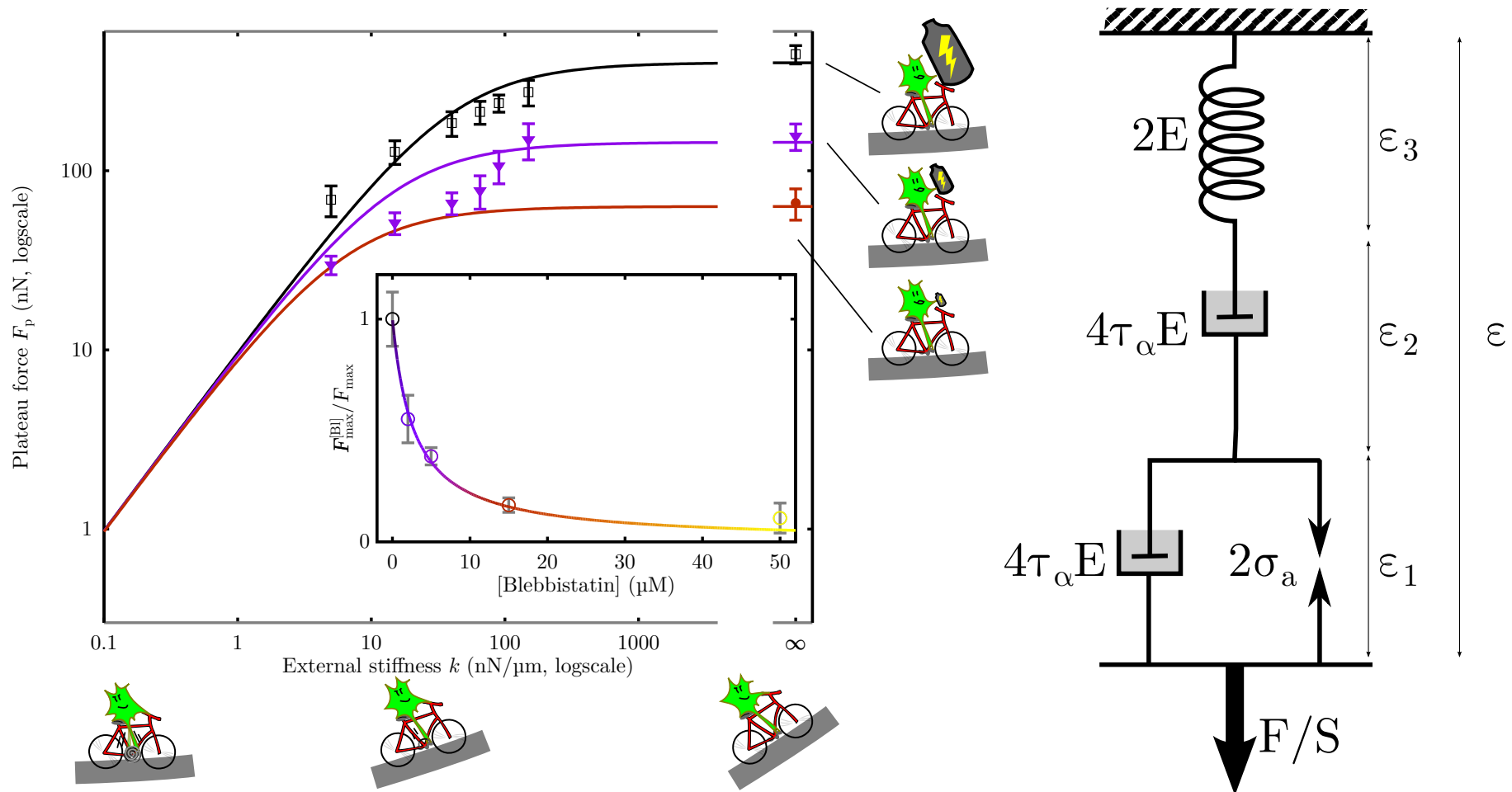


Can we use Myosin as a proxy for stress? not really



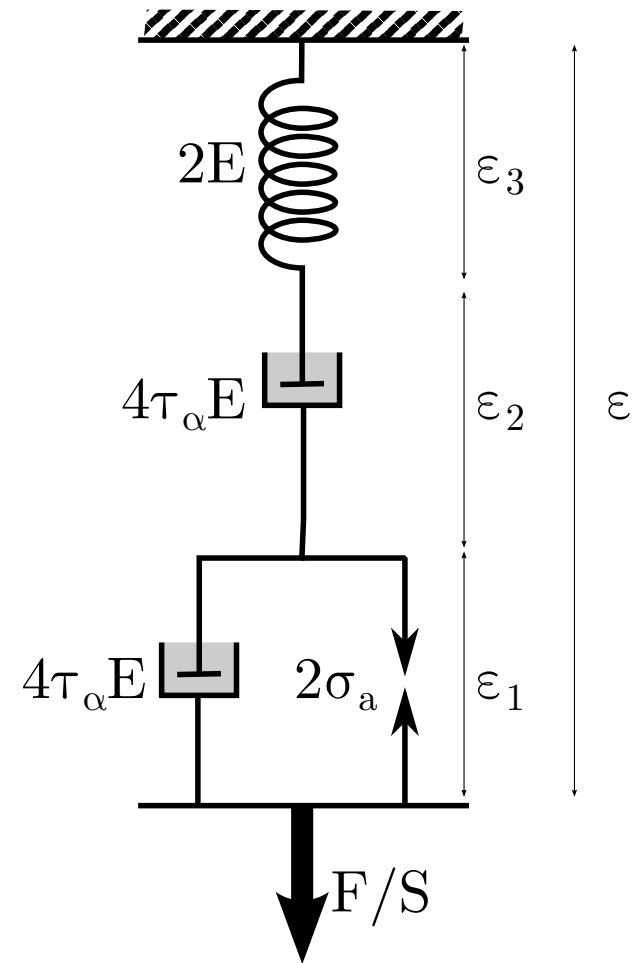
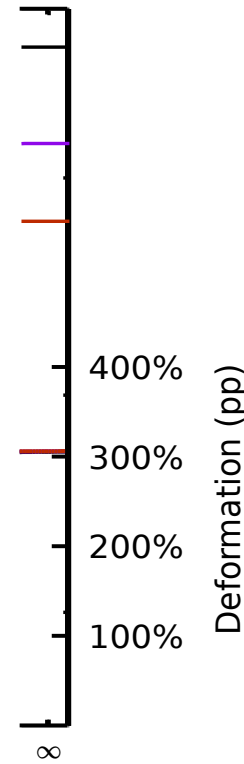
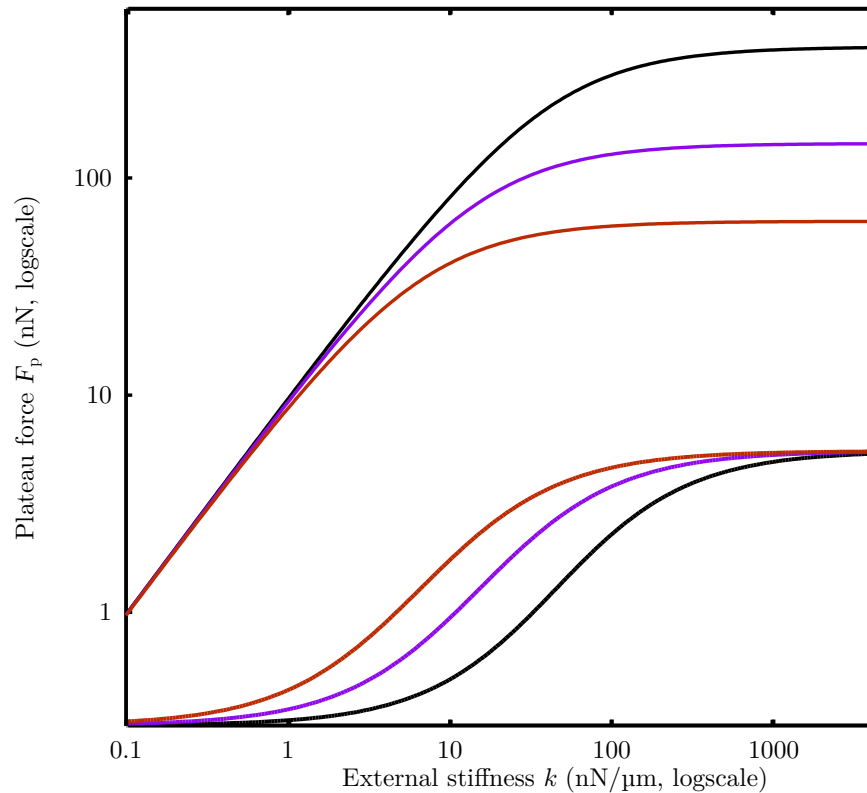
[Mitrossilis et al, *PNAS* 2009] , [Étienne et al, *PNAS* 2015]

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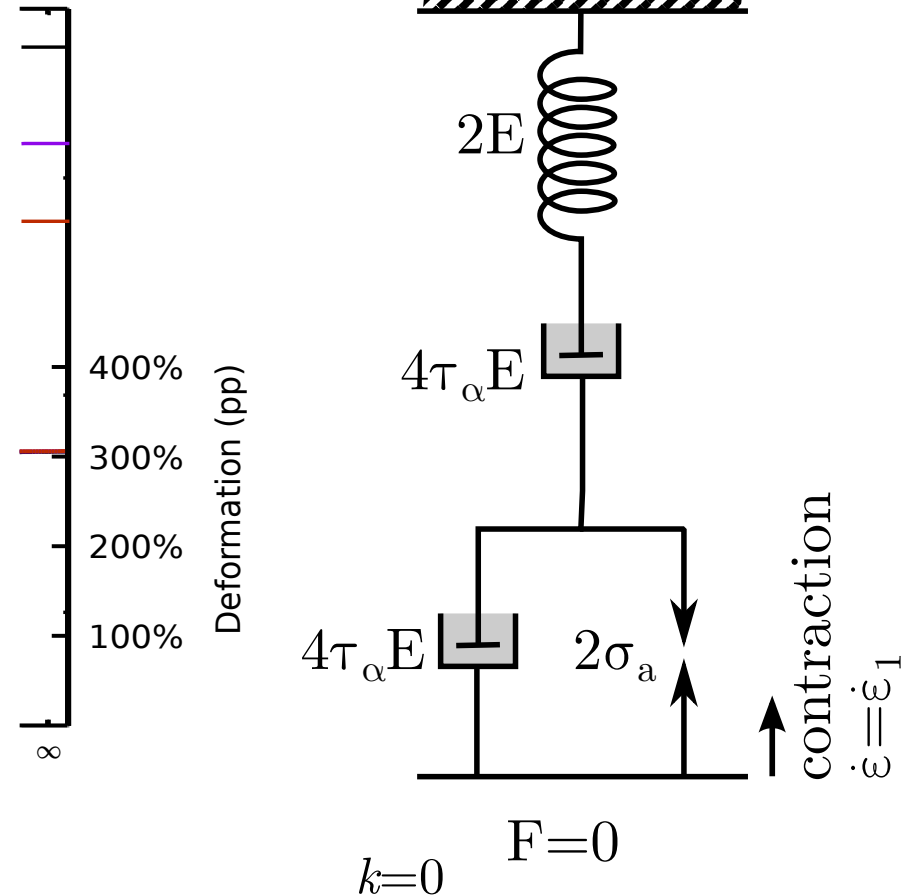
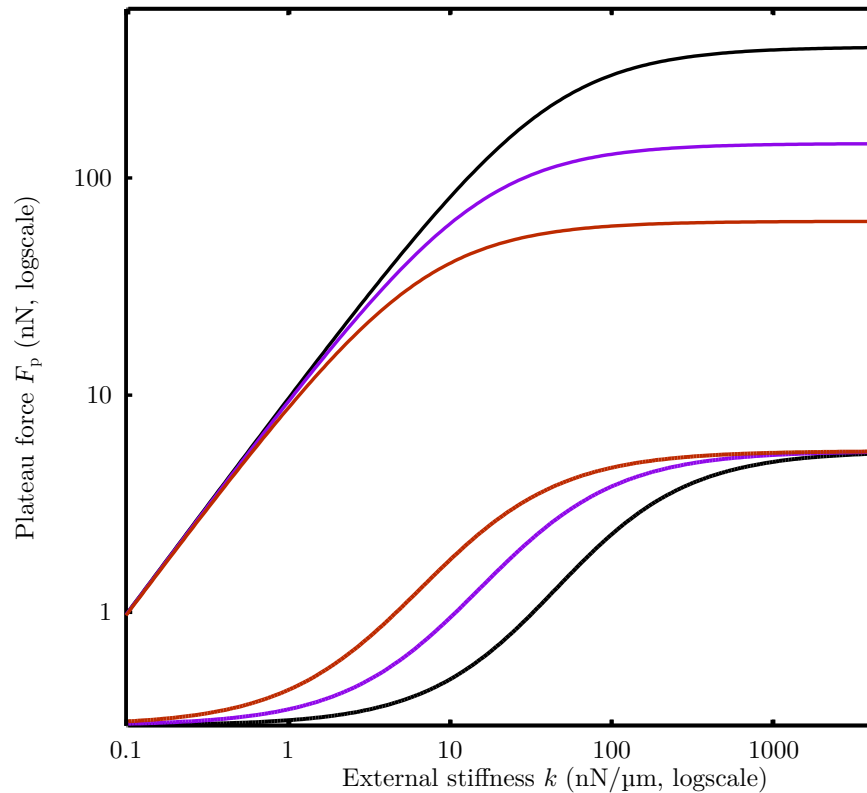
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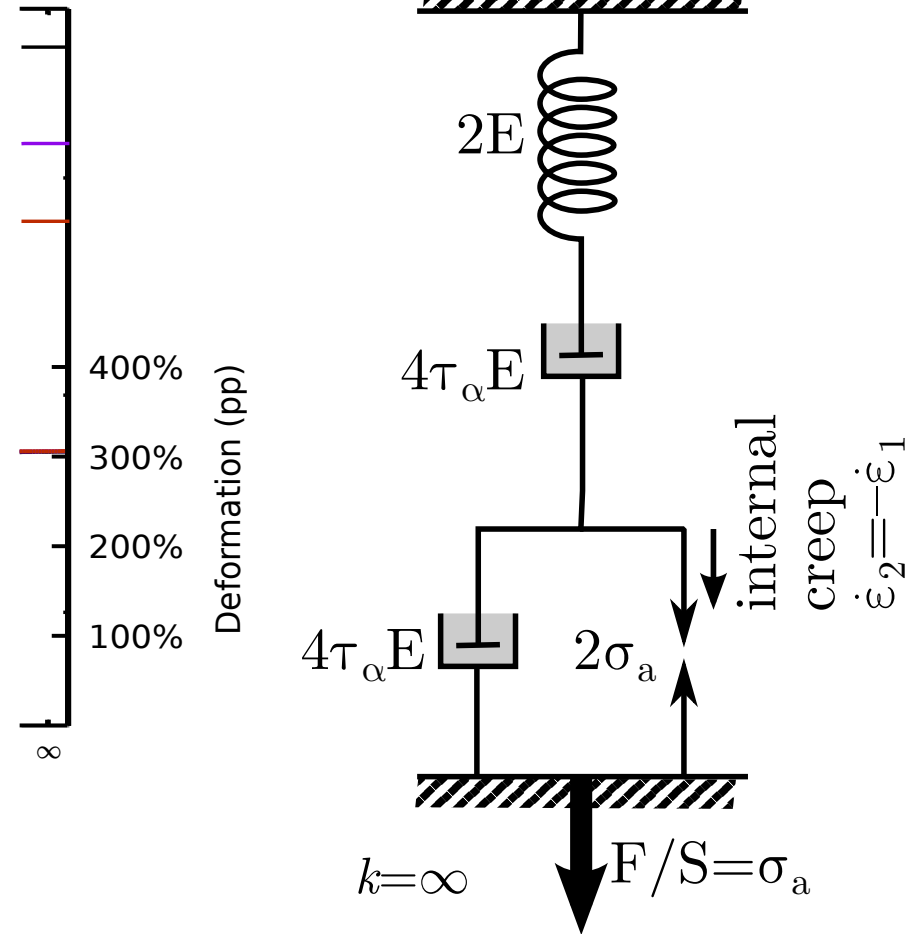
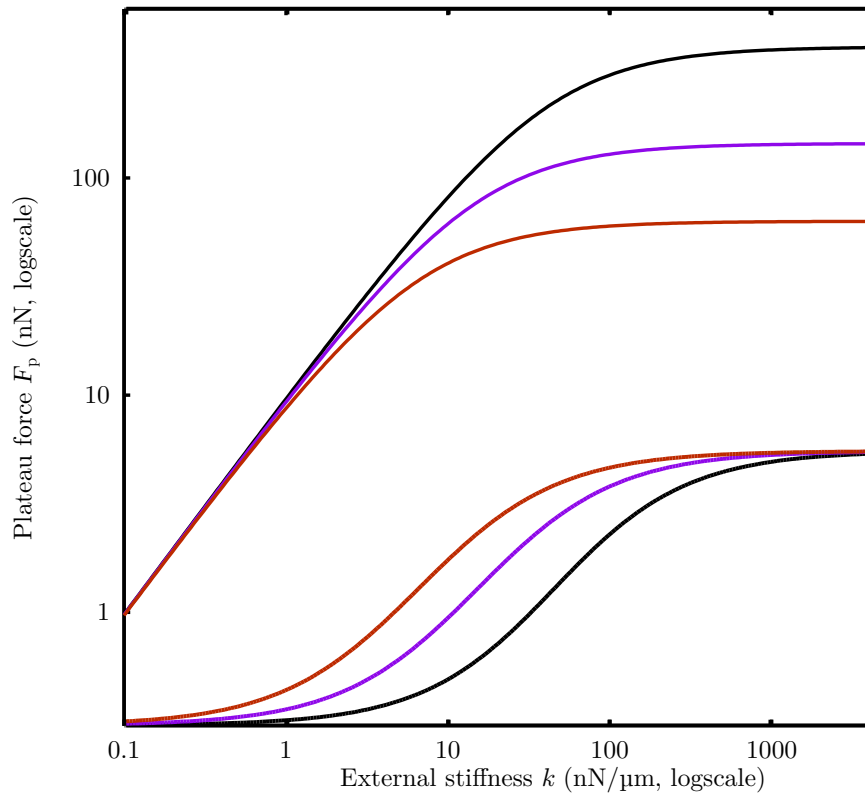
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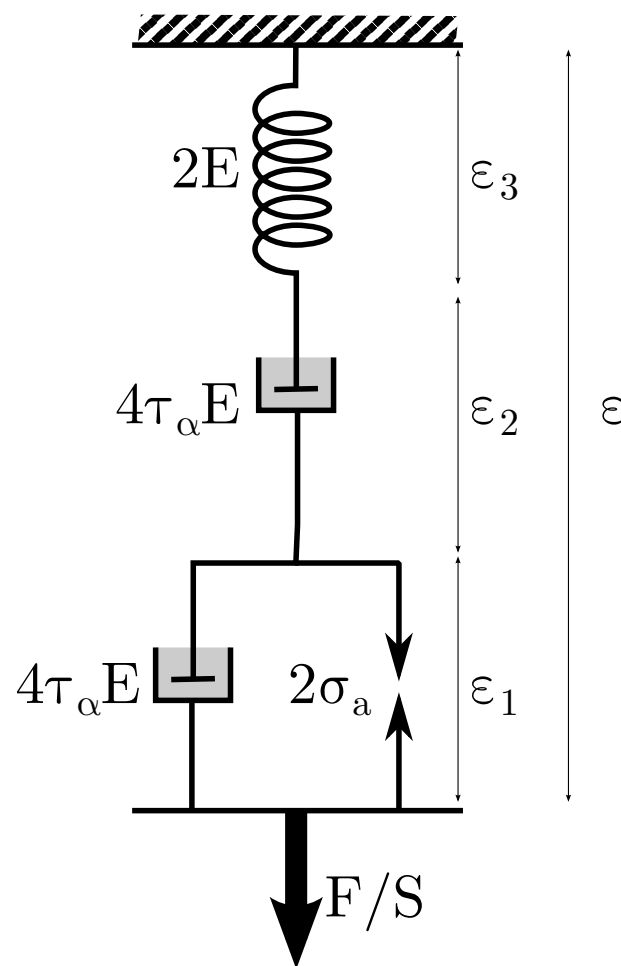
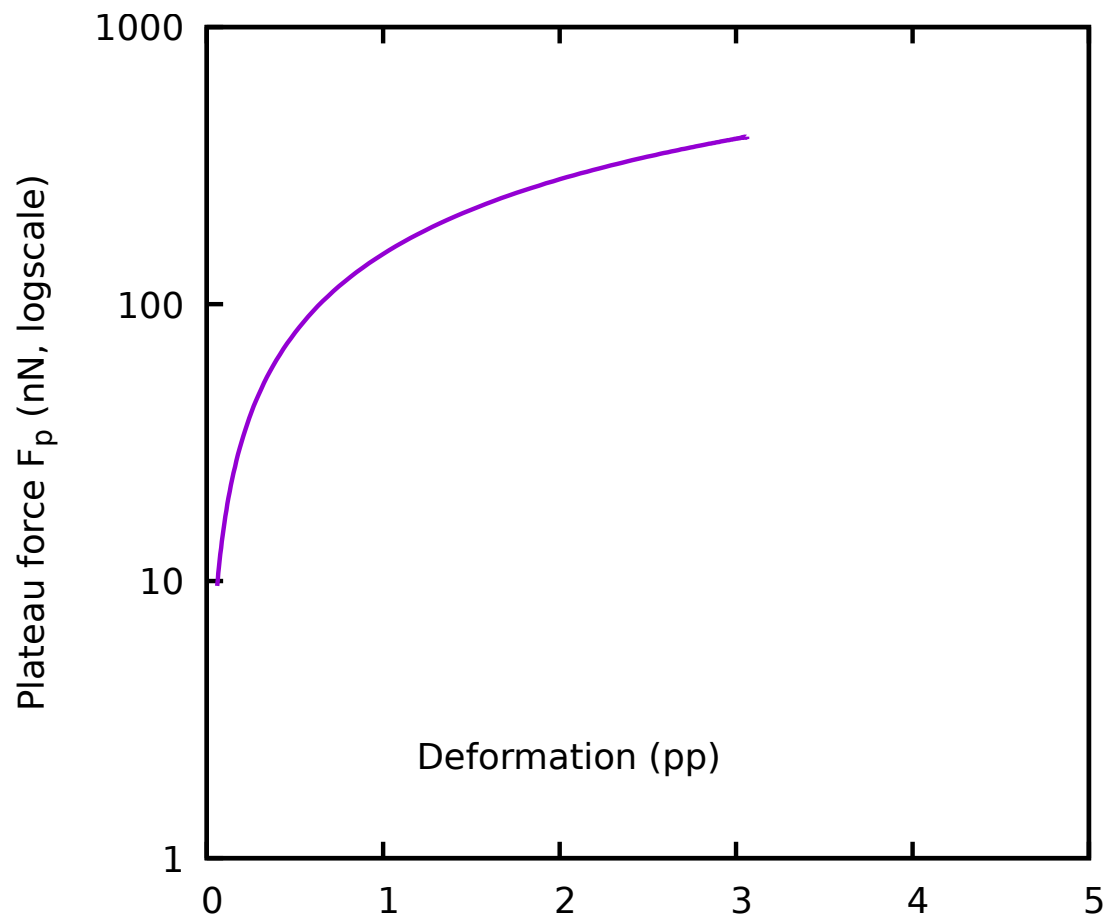
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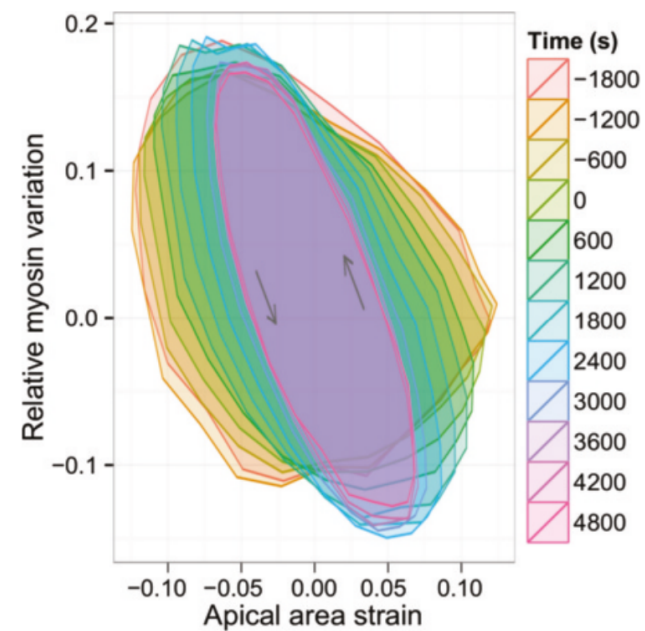
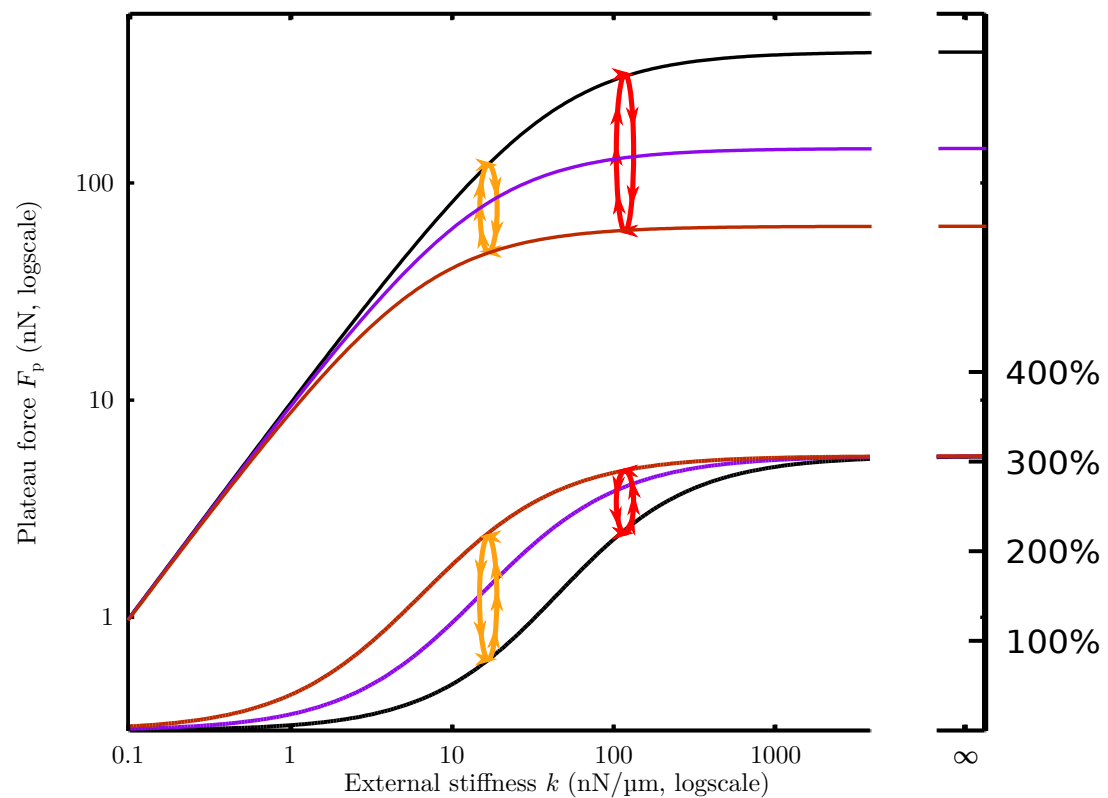


[Mitrossilis et al, *PNAS* 2009] , [Étienne et al, *PNAS* 2015]

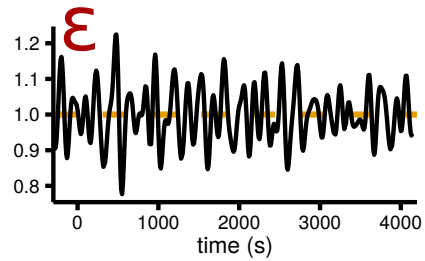
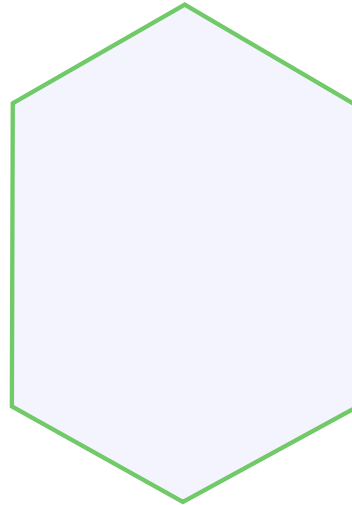
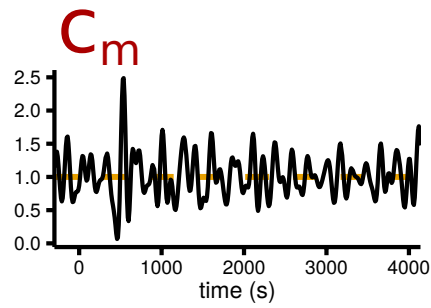
Can we use Myosin as a proxy for stress? not really



Can we use Myosin as a proxy for stress? not really



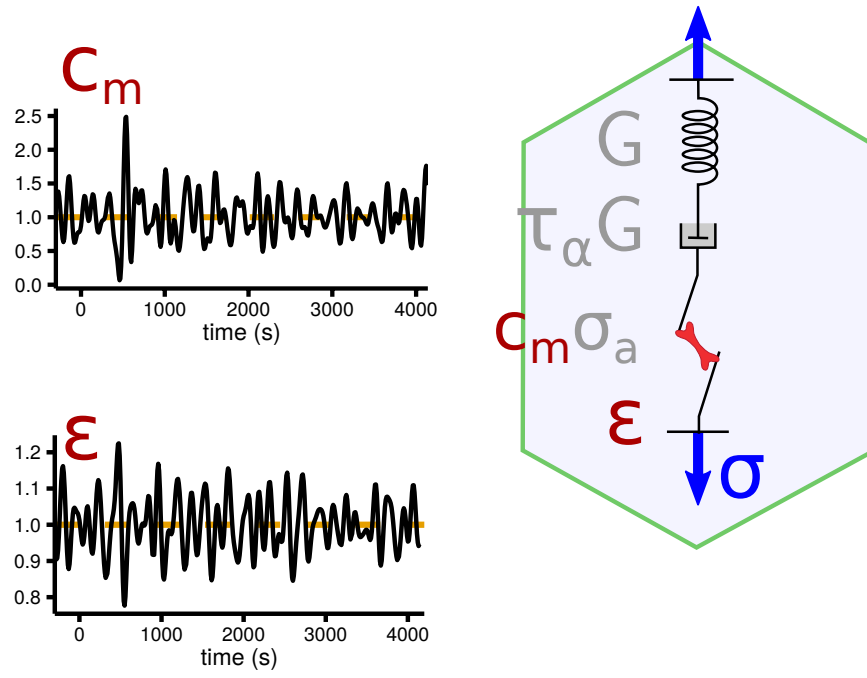
Stress inference combining myosin, strain and model



[Machado et al, *BMC Biol* 2015]

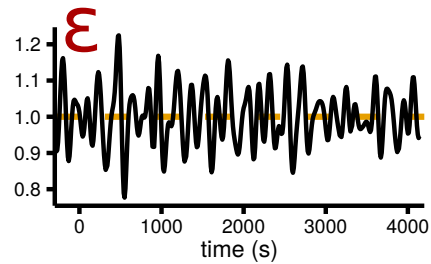
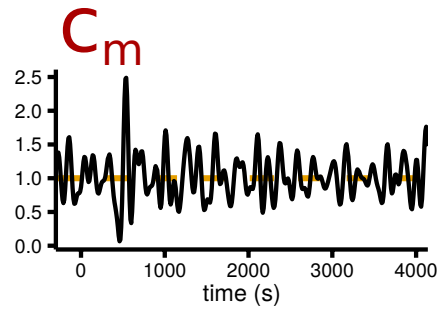


Stress inference combining myosin, strain and model



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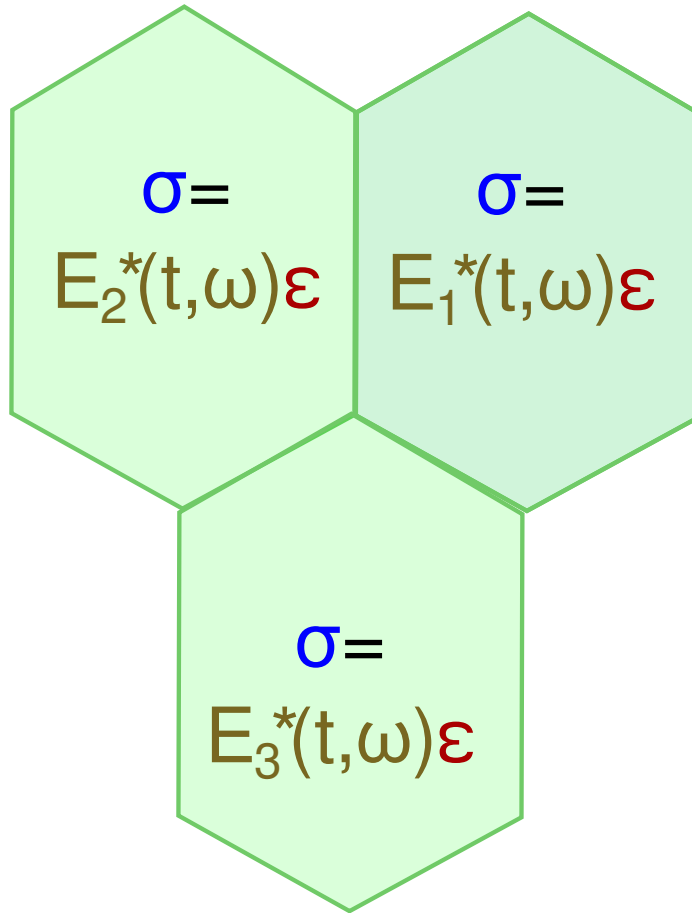
Stress inference combining myosin, strain and model



$$\sigma = E_1^*(t, \omega) \epsilon$$

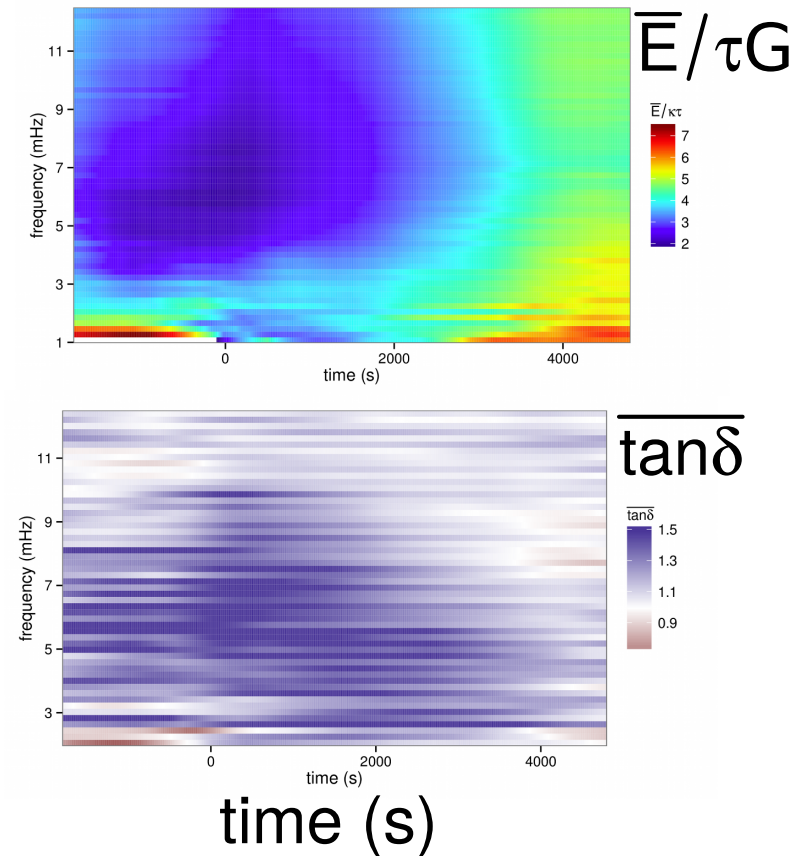
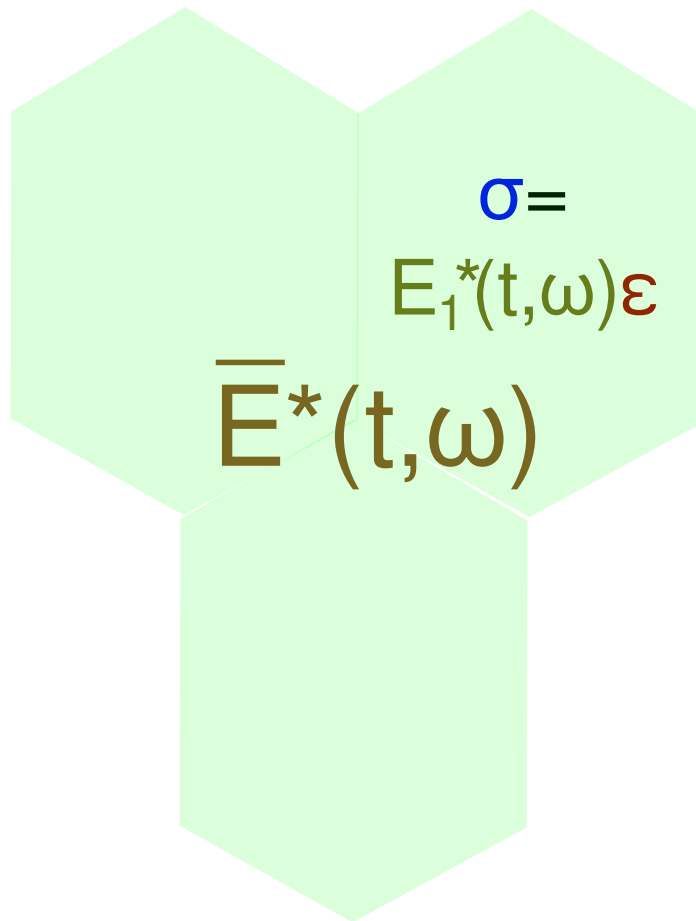
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Stress inference combining myosin, strain and model



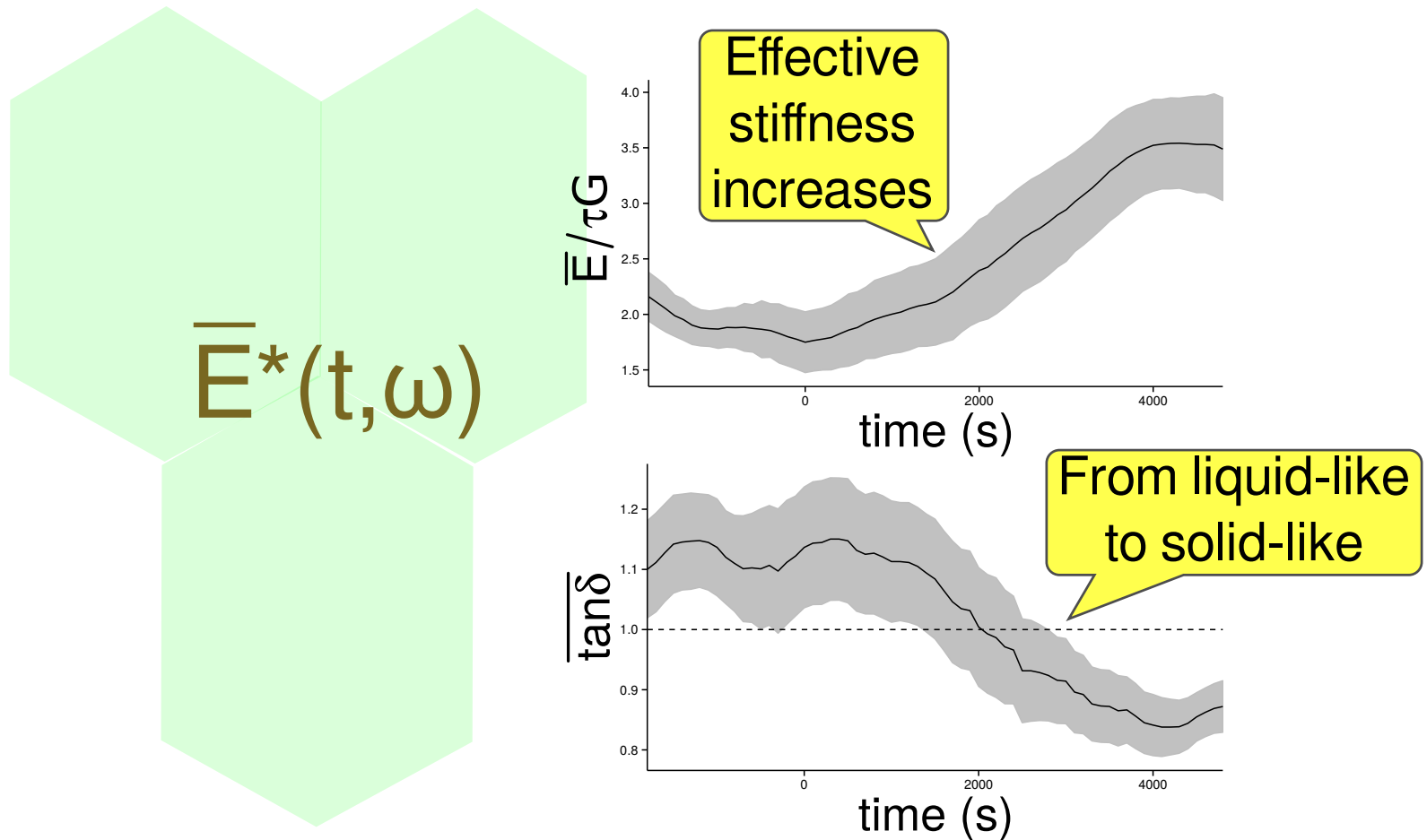
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Stress inference combining myosin, strain and model



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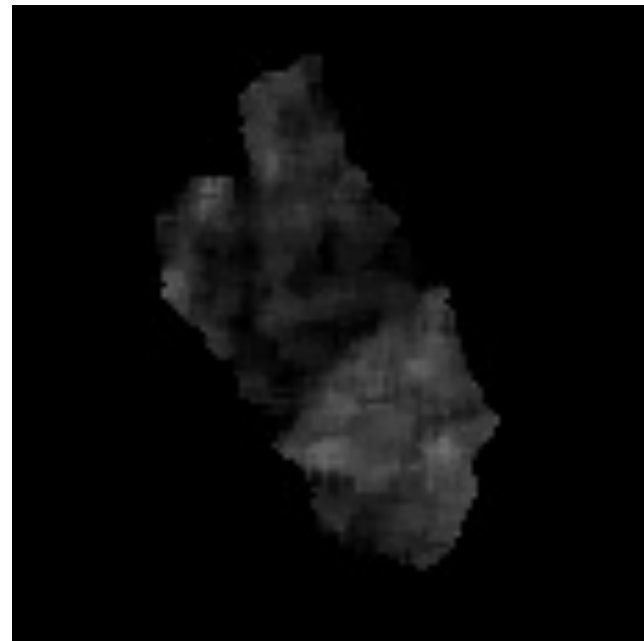
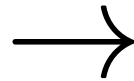
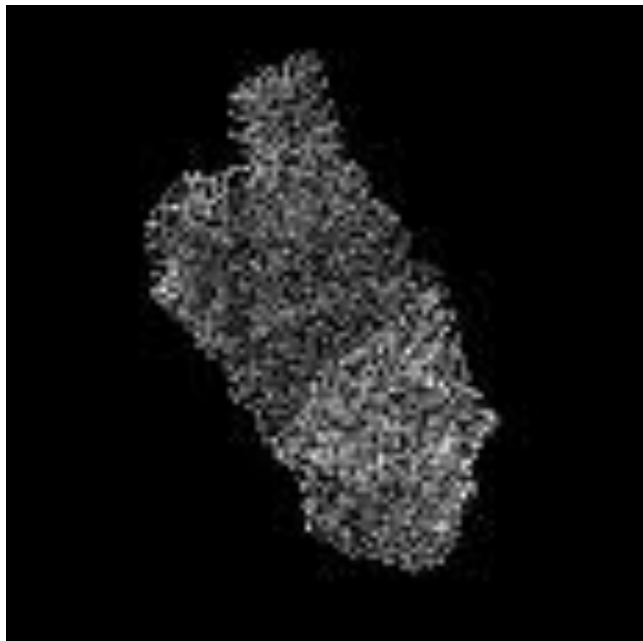
Stress inference combining myosin, strain and model



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Myosin pulsations in dorsal closure

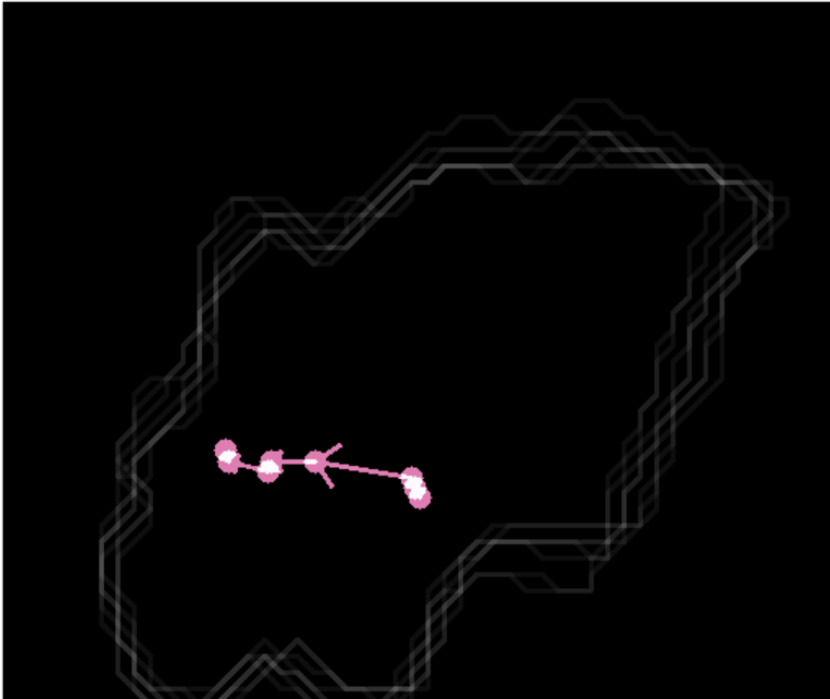
with Guy Blanchard (Cambridge) and Nicole Gorfinkiel (Madrid)
PhD of Nilankur Dutta



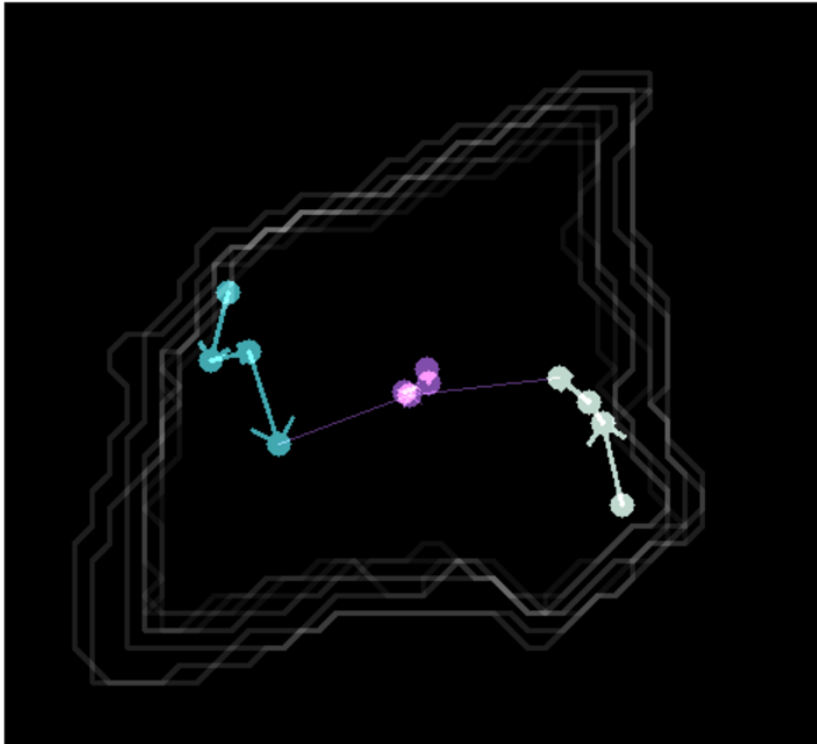
12 embryos, 400 cells, $\sim 10^5$ foci



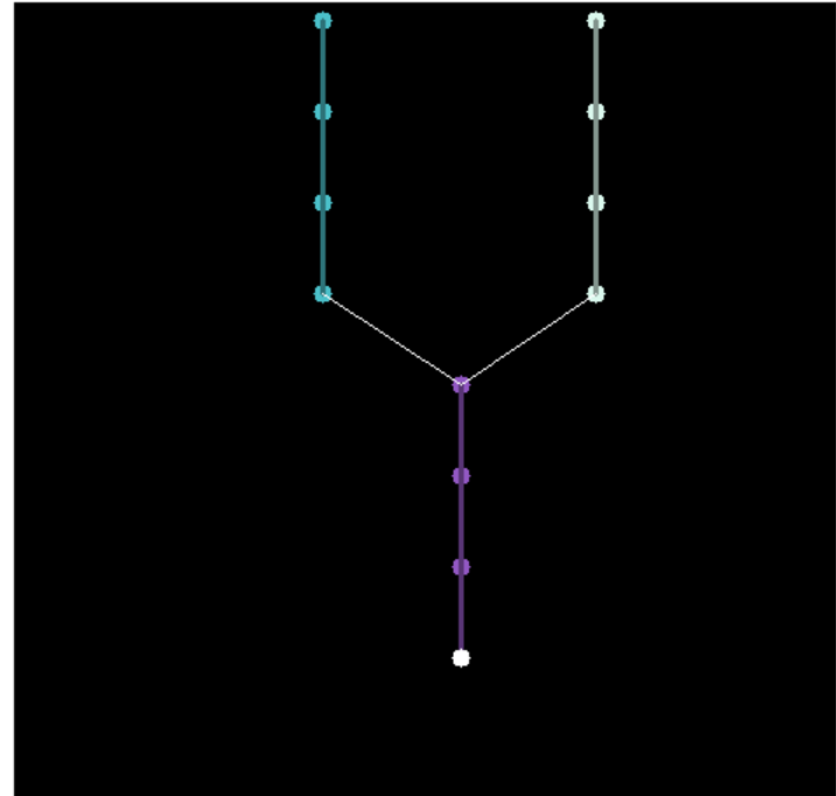
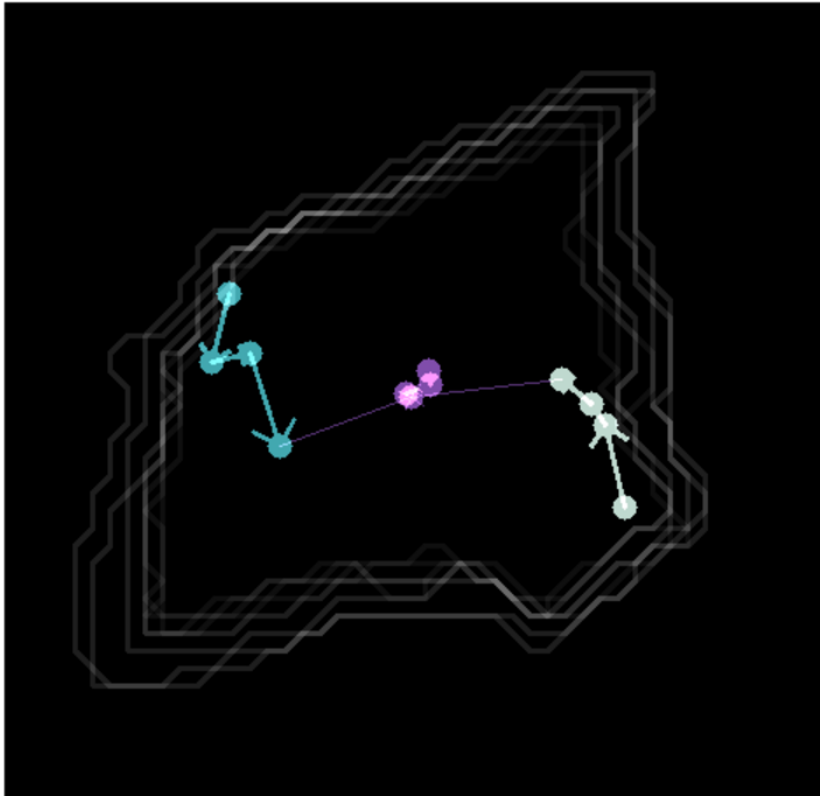
Travelling foci



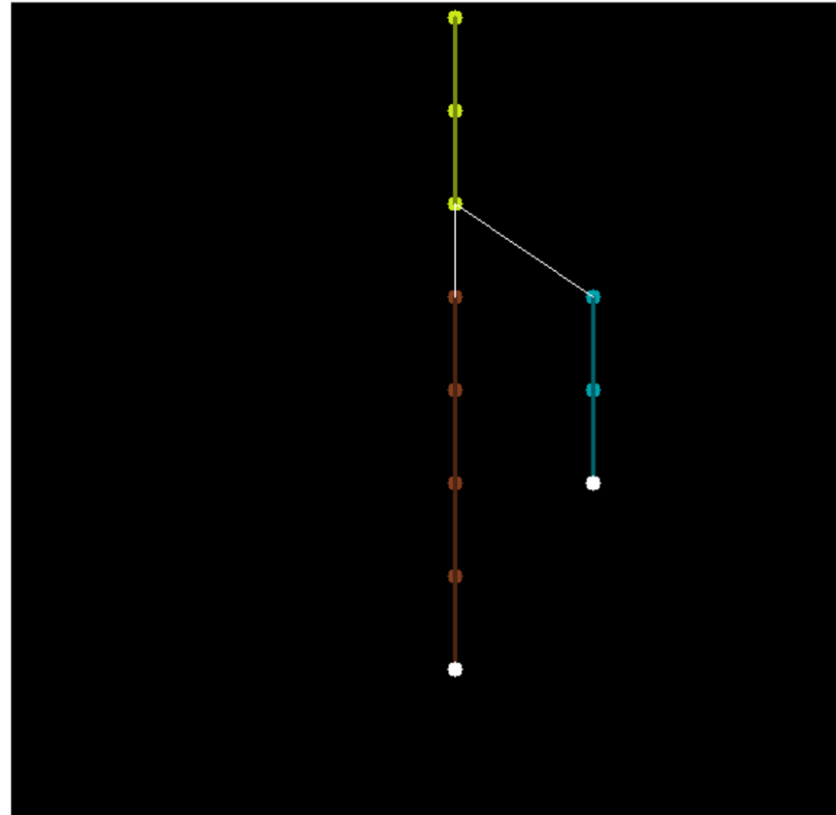
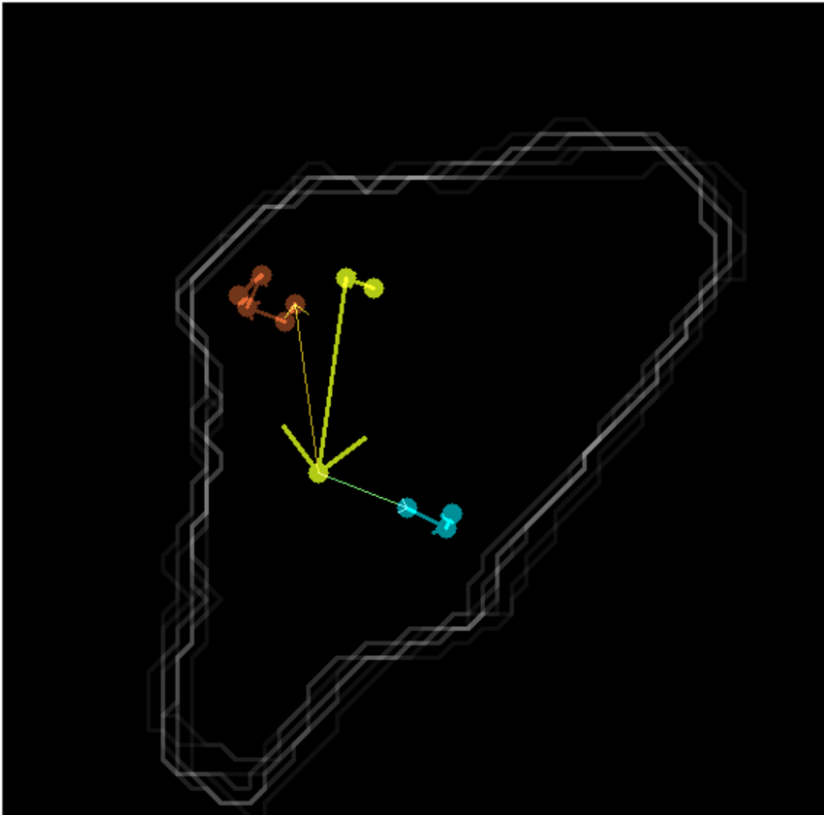
Travelling foci merging



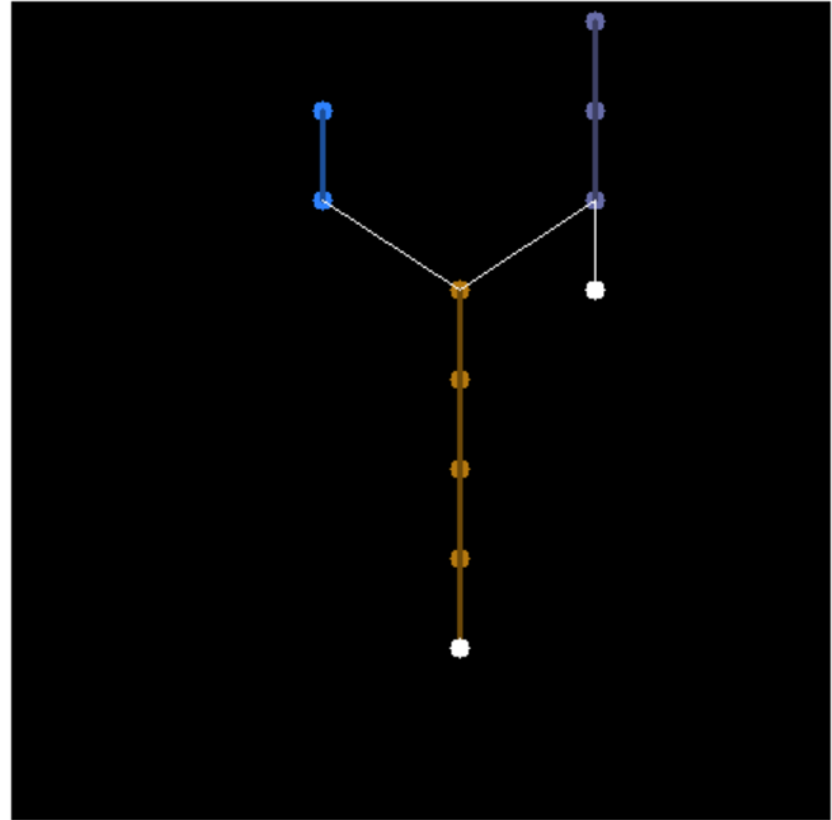
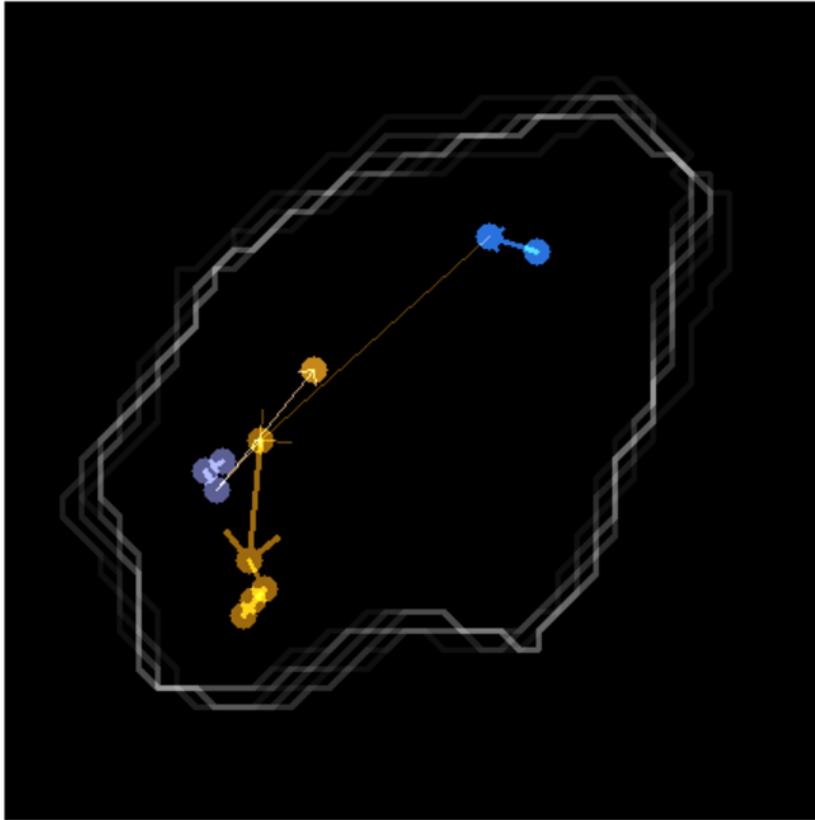
Travelling foci merging and splitting



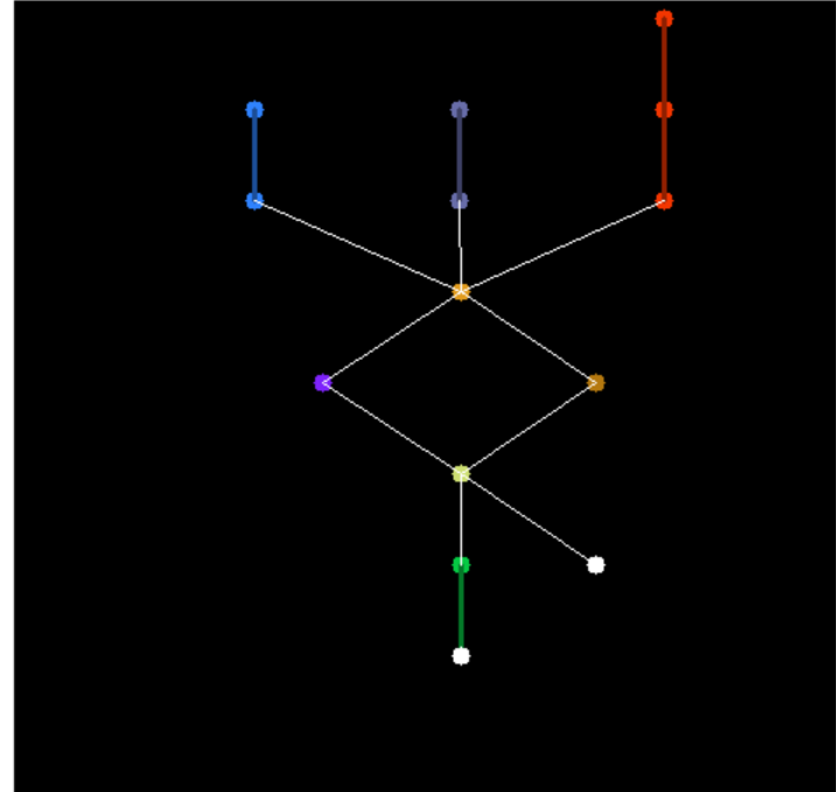
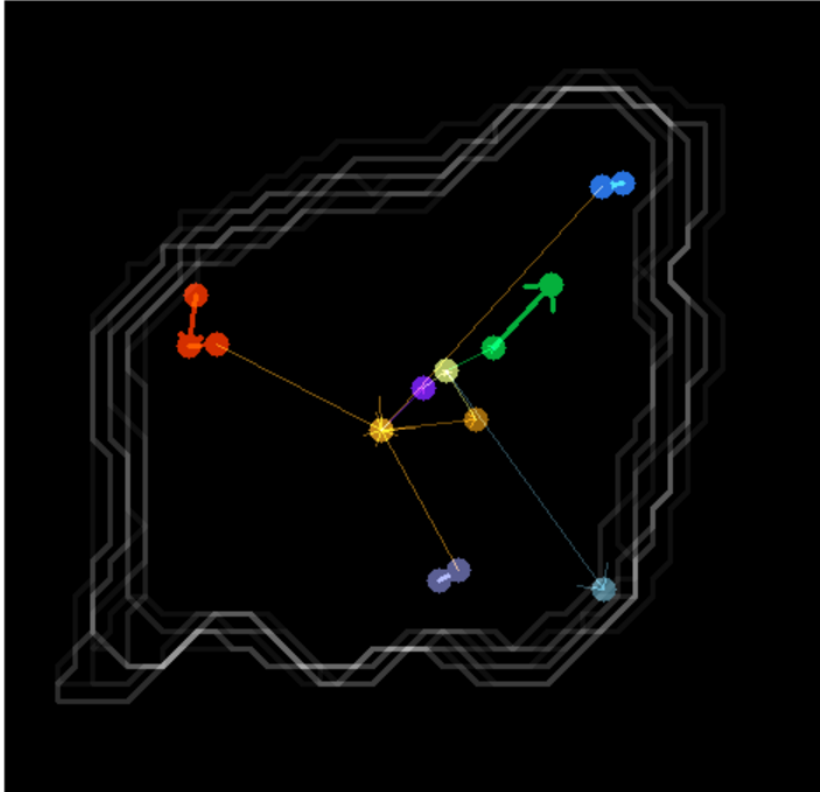
Travelling foci merging and splitting



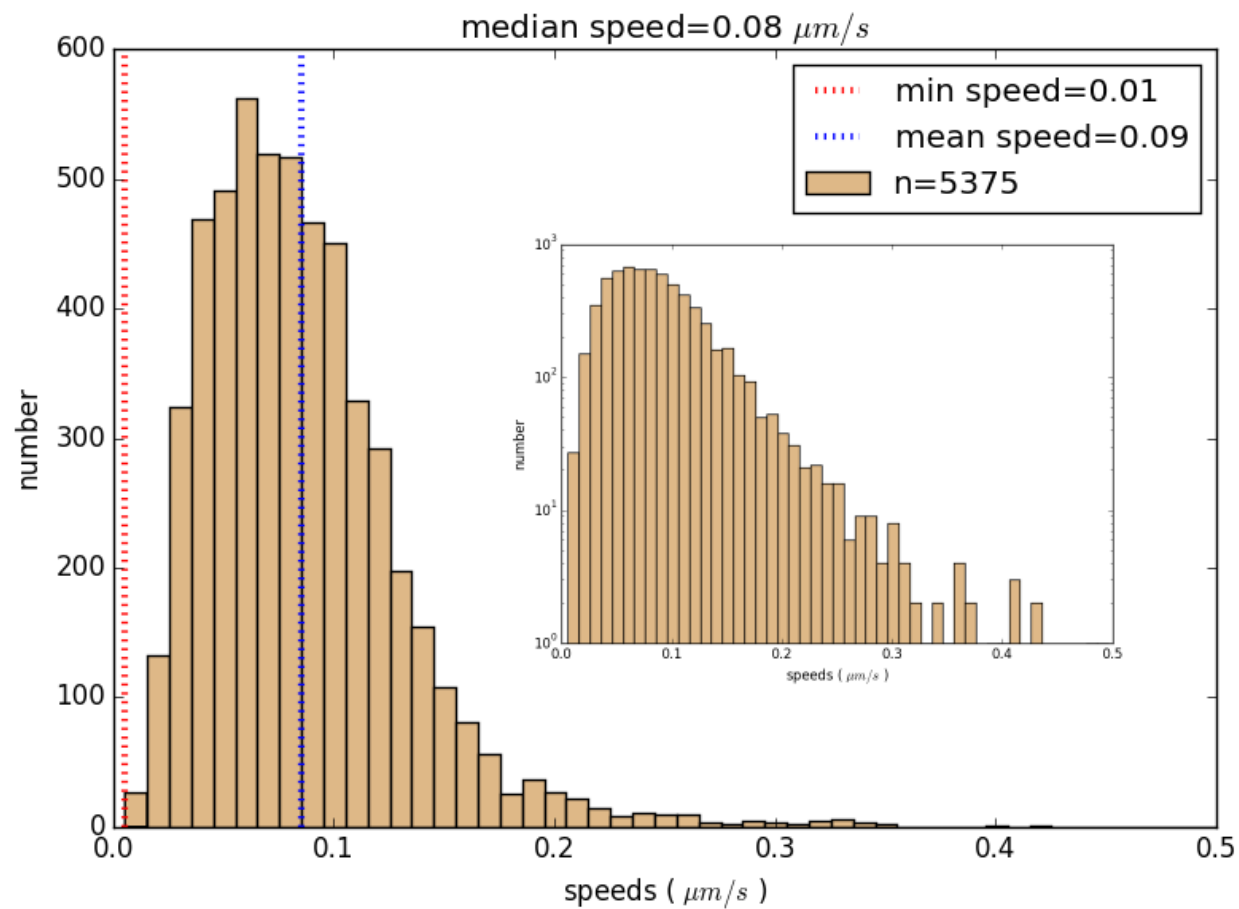
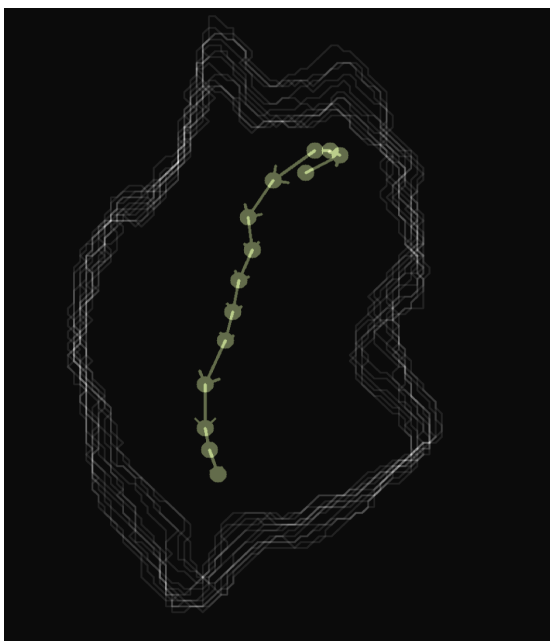
Travelling foci merging and splitting



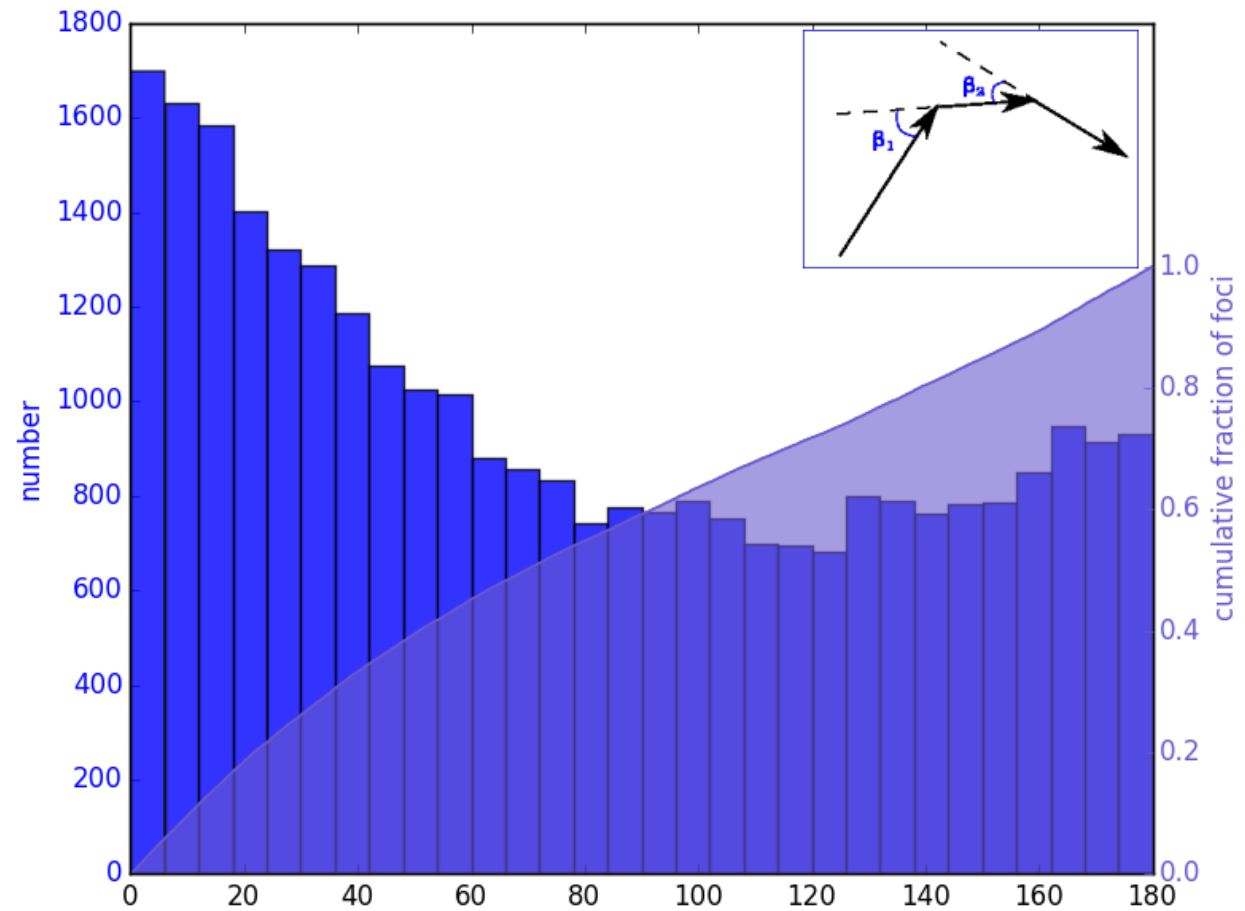
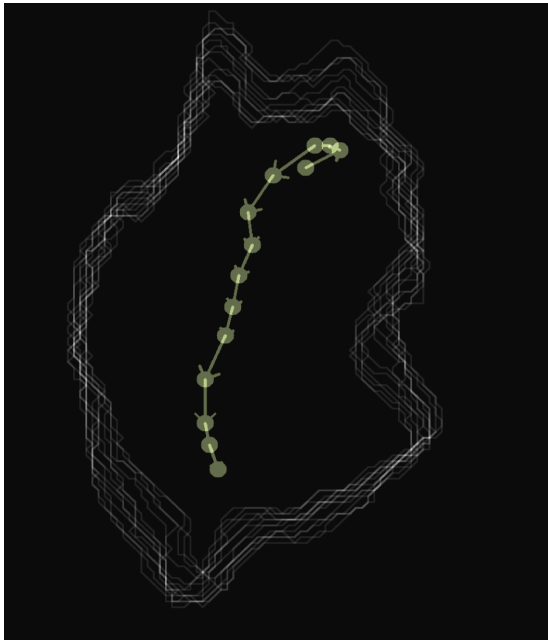
Travelling foci merging and splitting



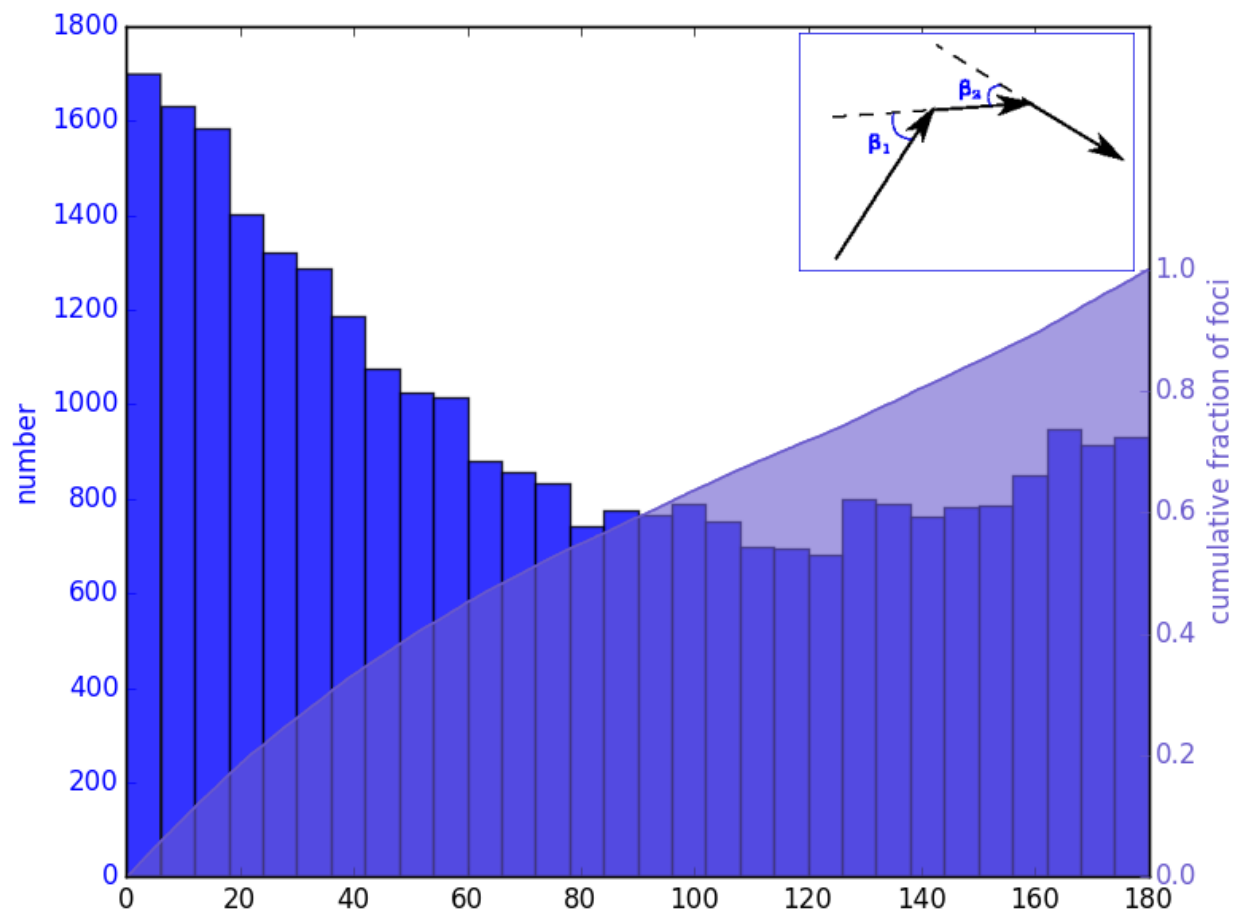
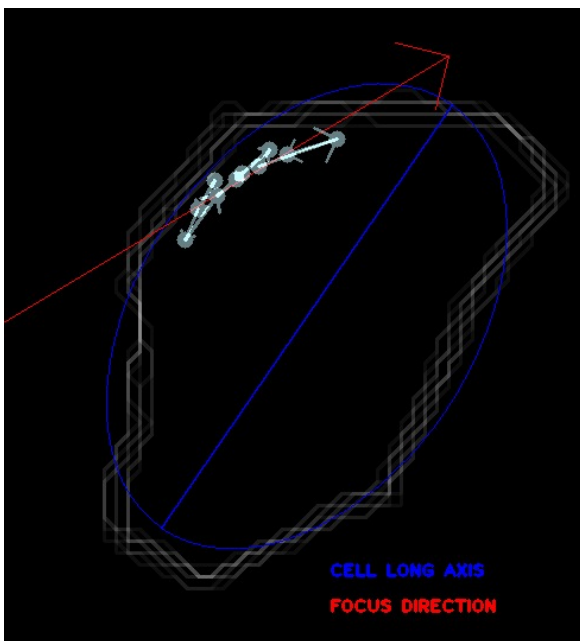
Kinematics of foci



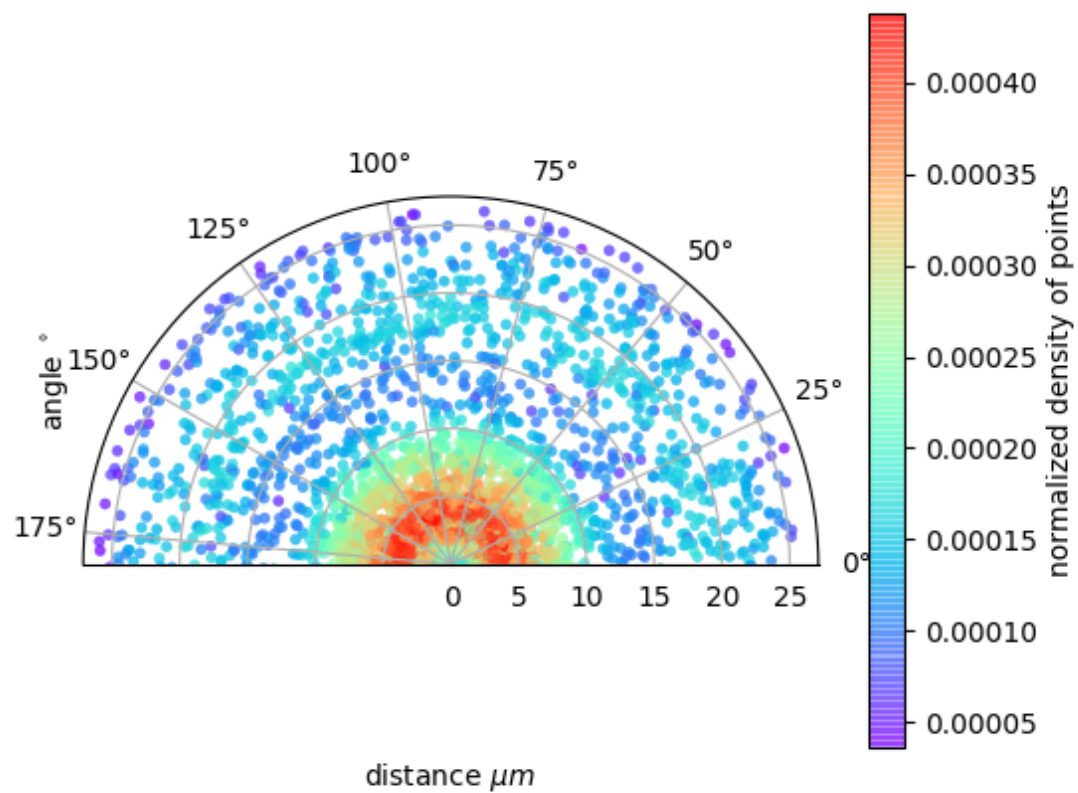
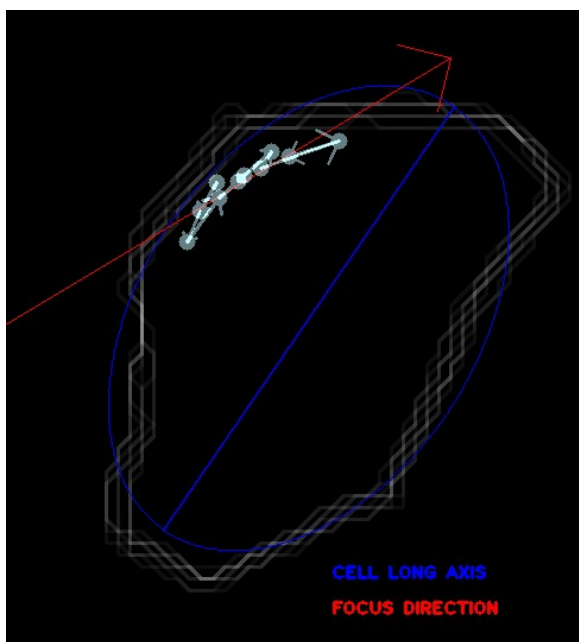
Kinematics of foci



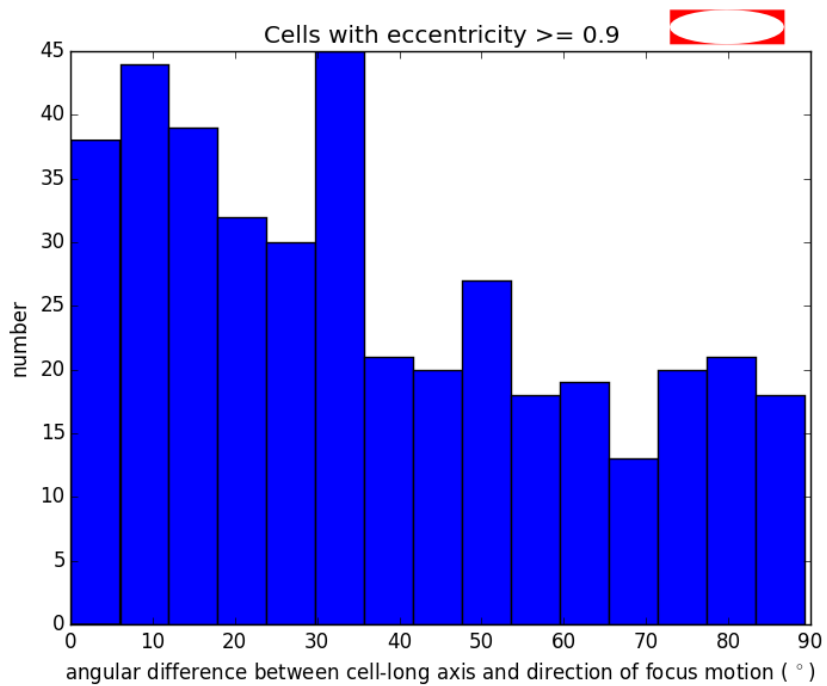
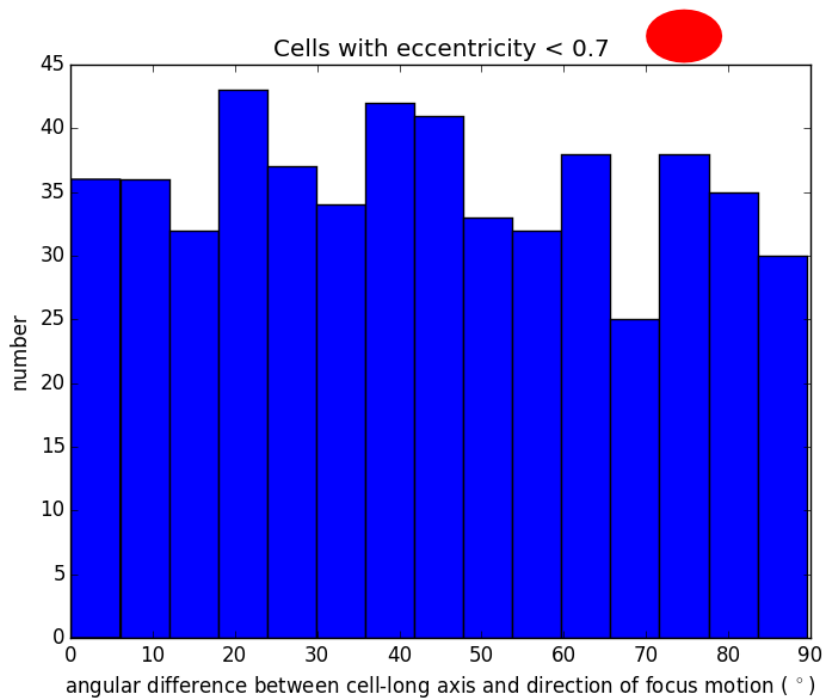
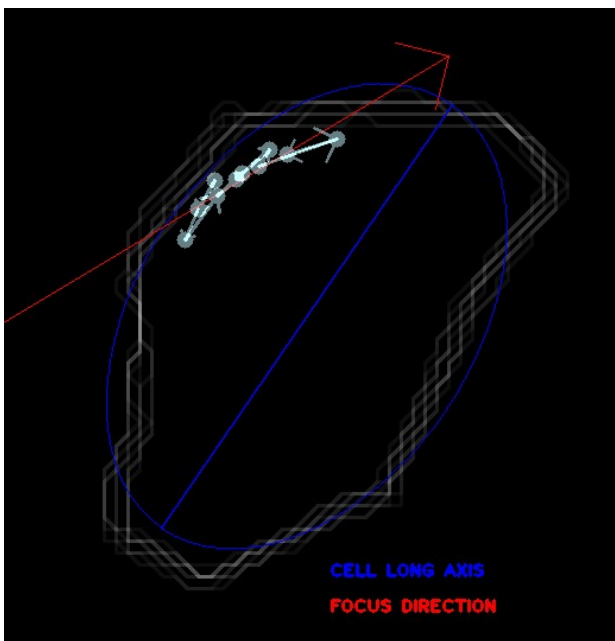
Kinematics of foci



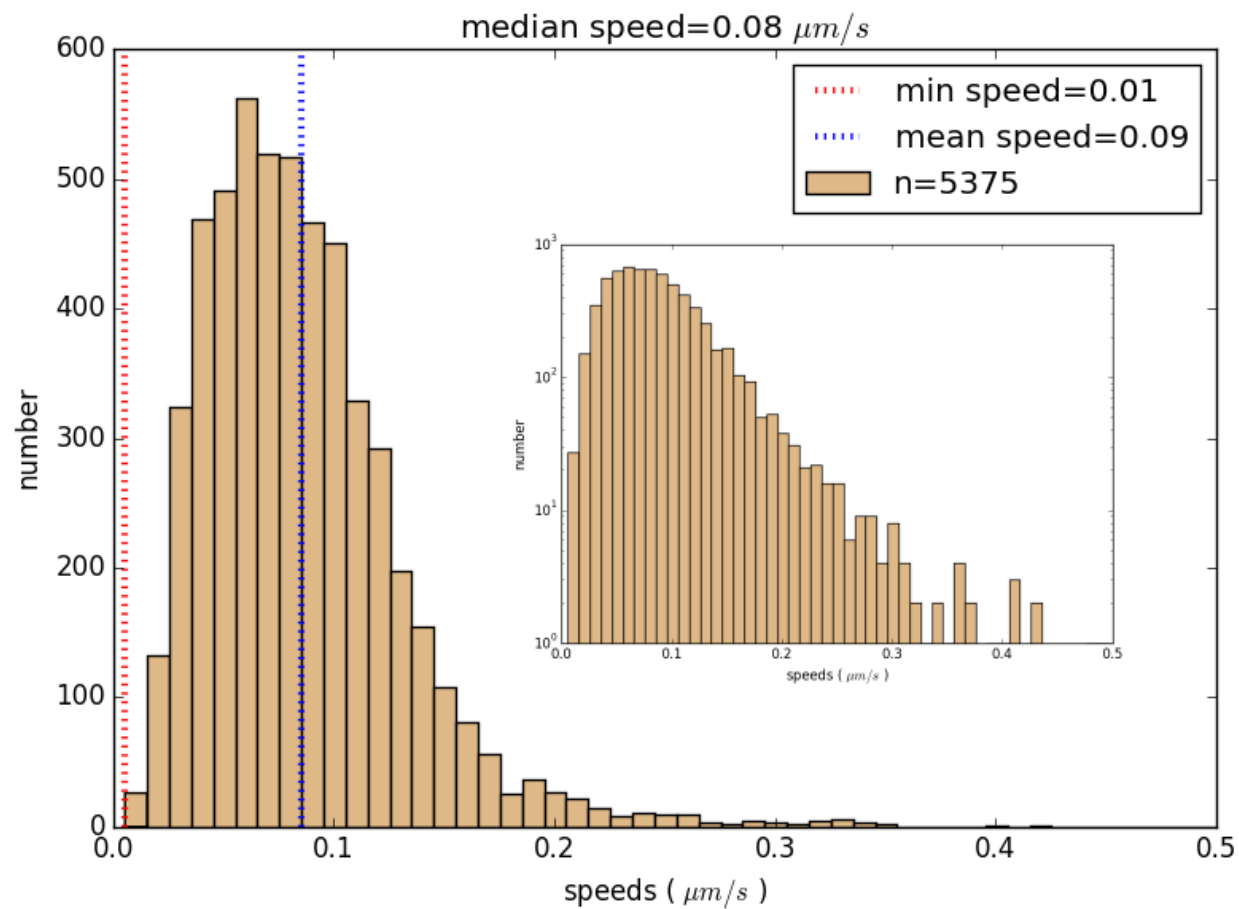
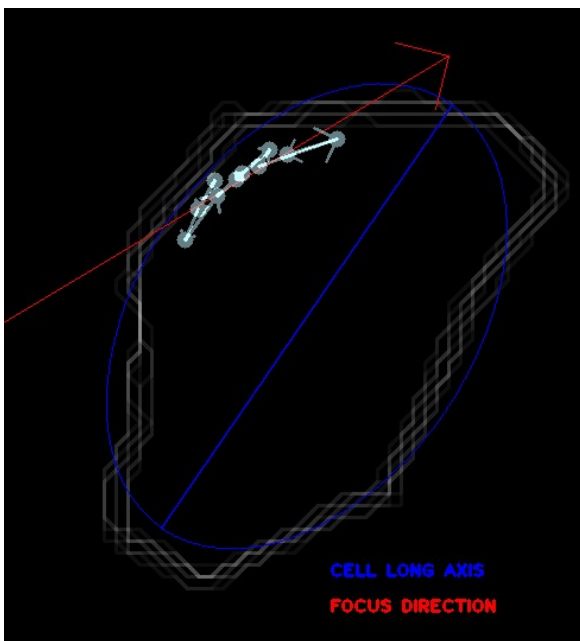
Kinematics of foci



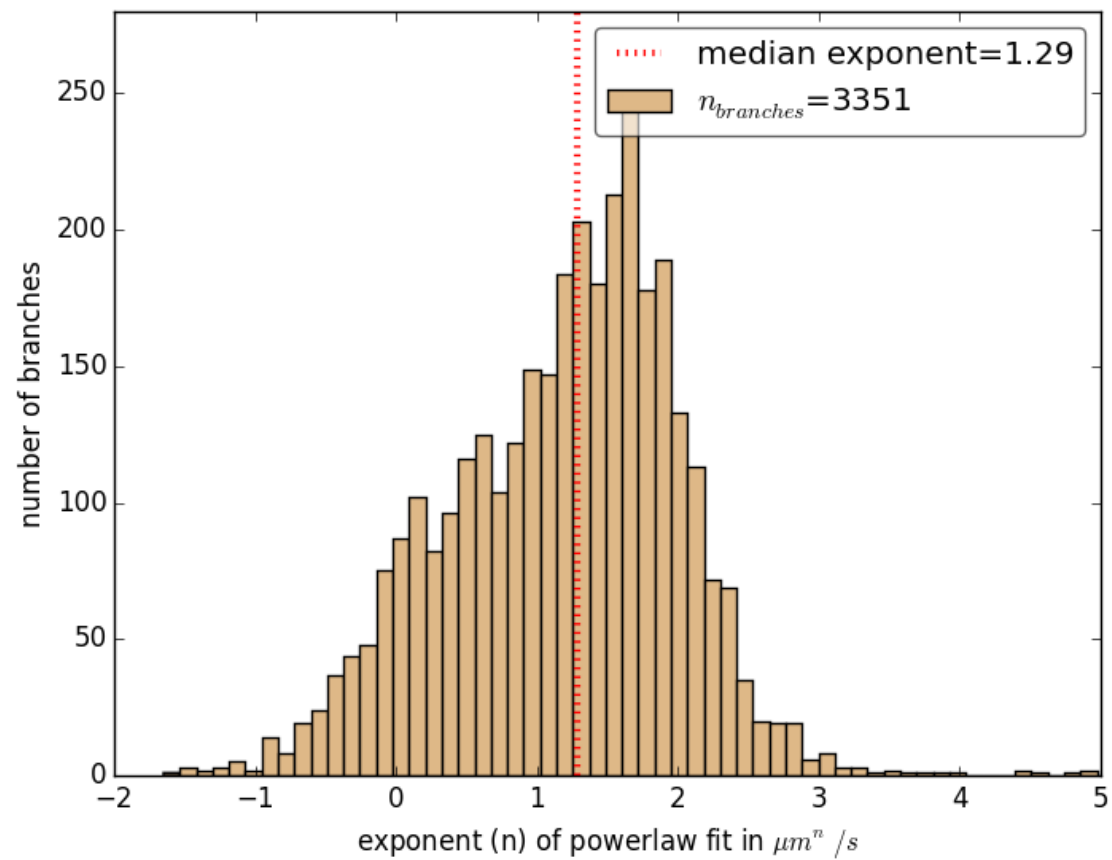
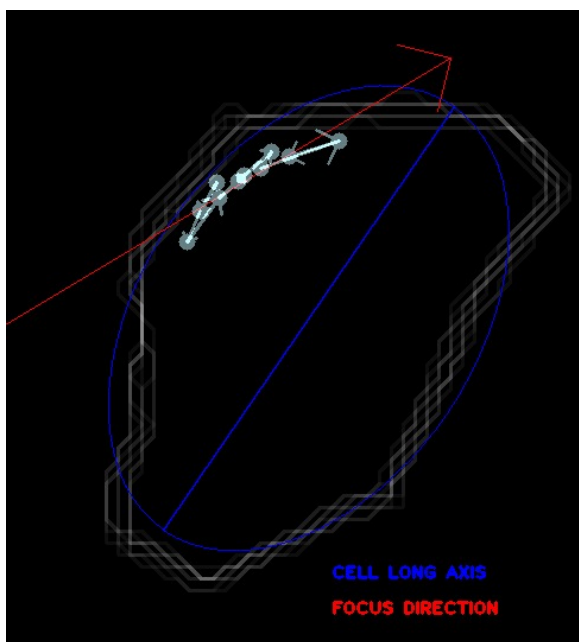
Kinematics of foci



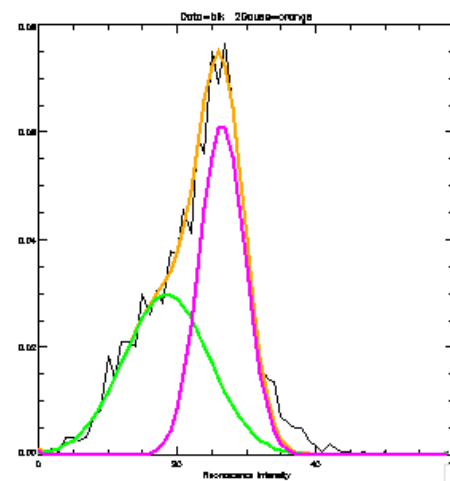
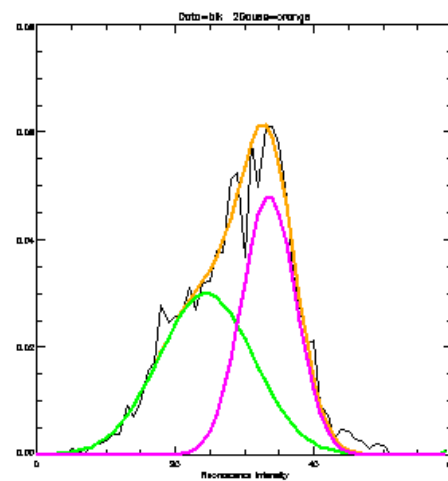
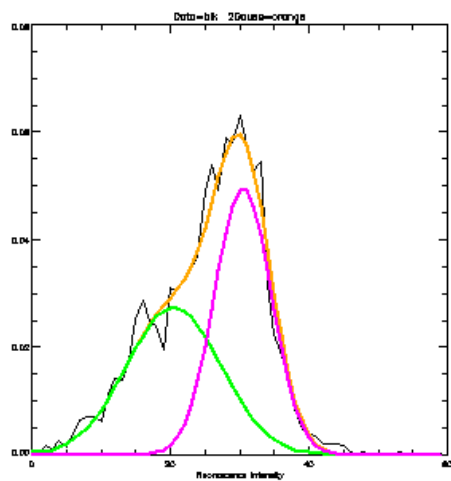
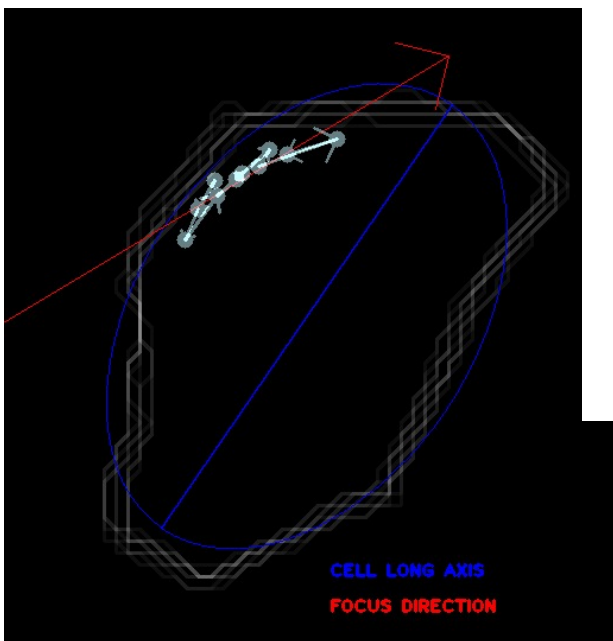
Kinematics of foci



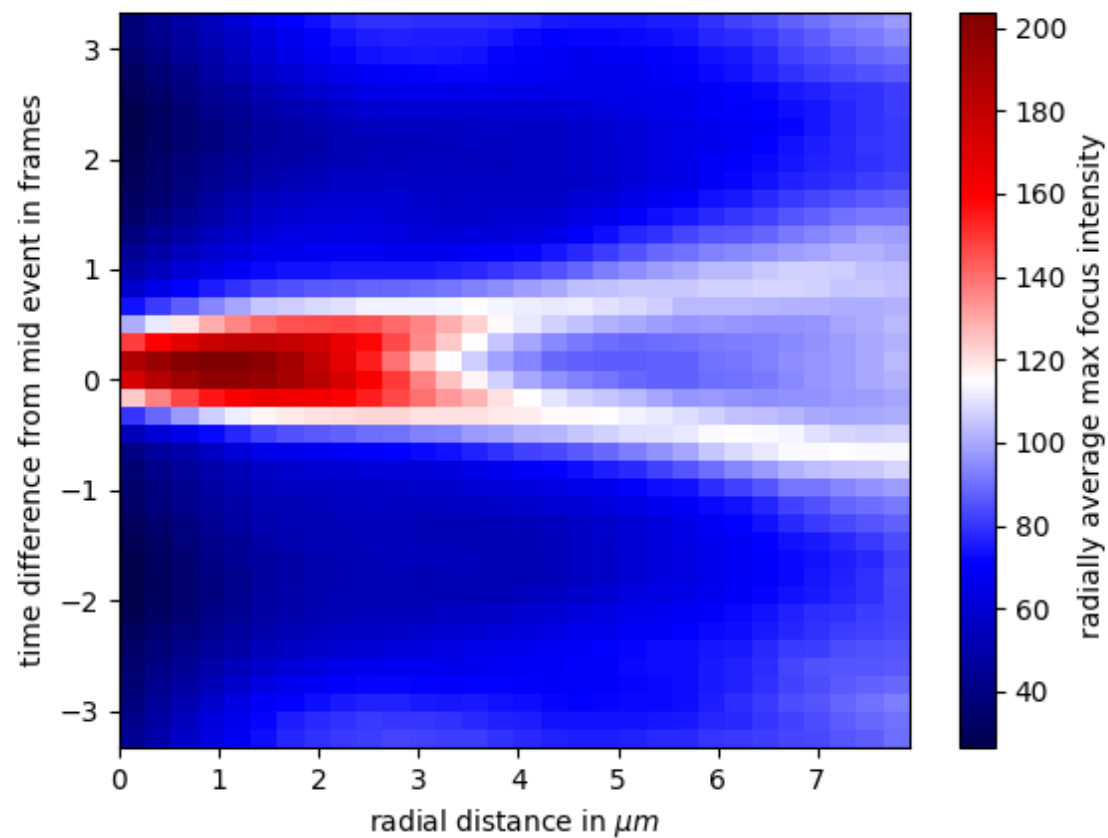
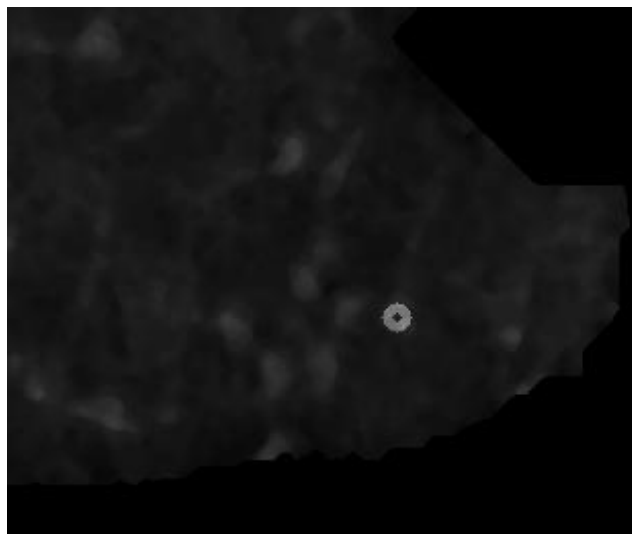
Kinematics of foci



Kinematics of foci

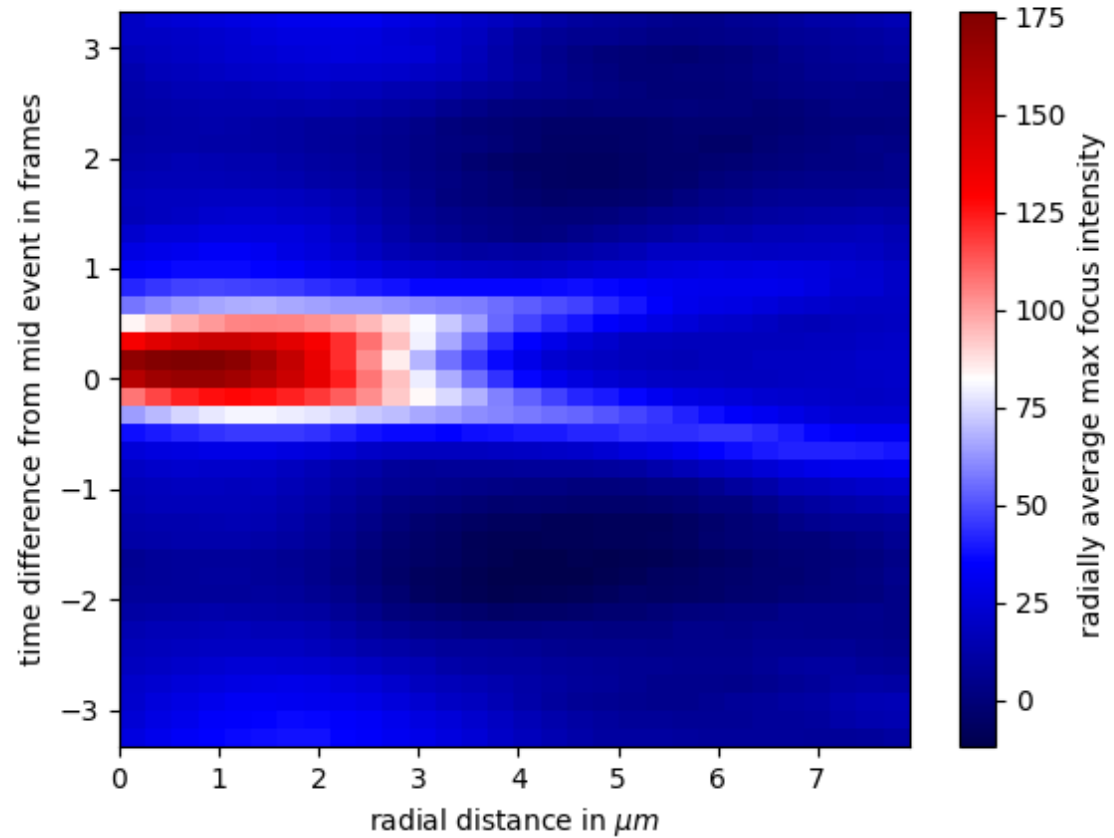
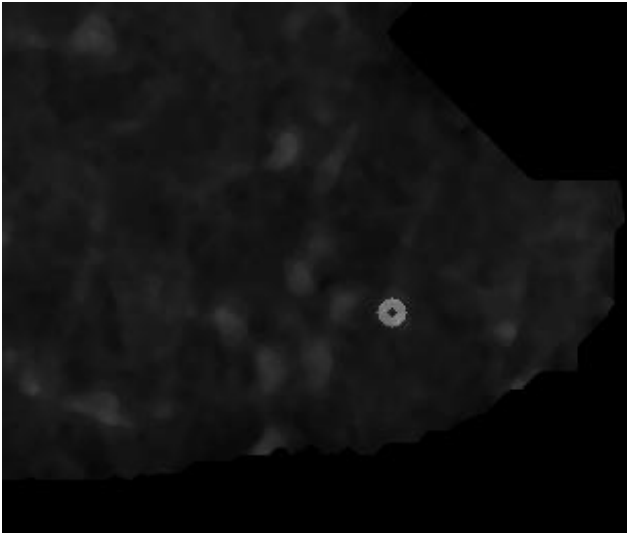


Myosin around foci



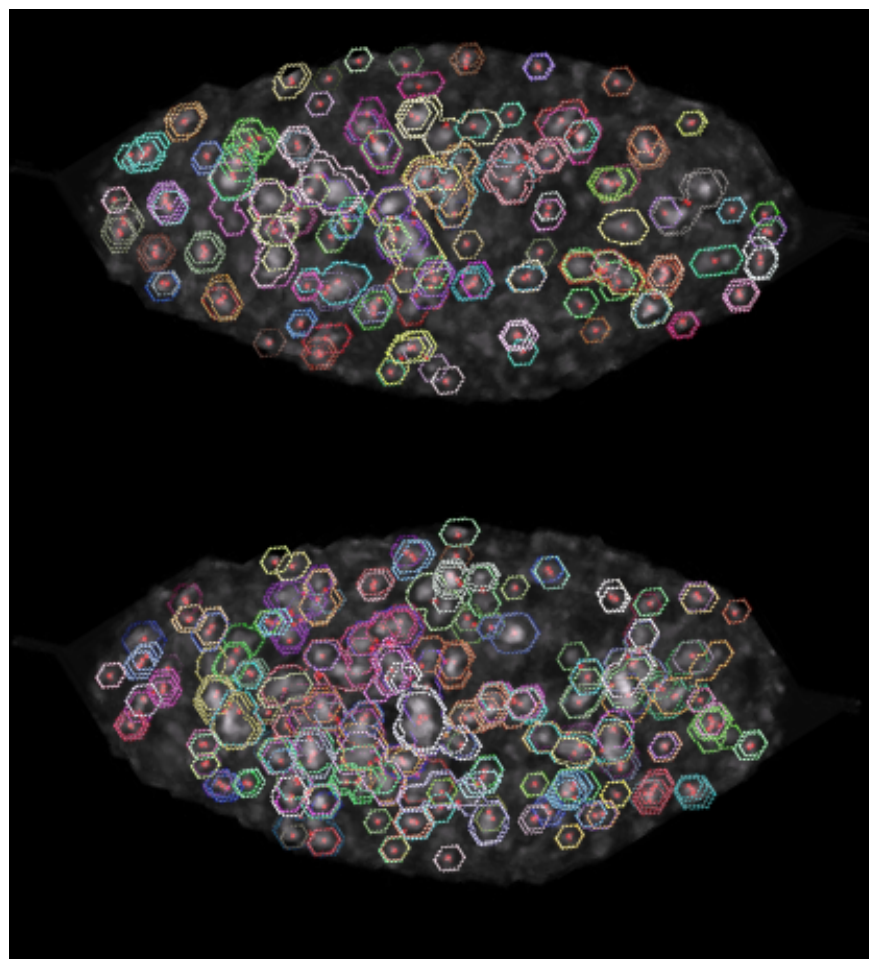
$$I_F(r, \tau) = \left\langle \max_{d(\mathbf{x}, \mathbf{x}_F)=r} I(\mathbf{x}, t_F + \tau) \right\rangle_{F_i \in F}$$

Myosin around foci

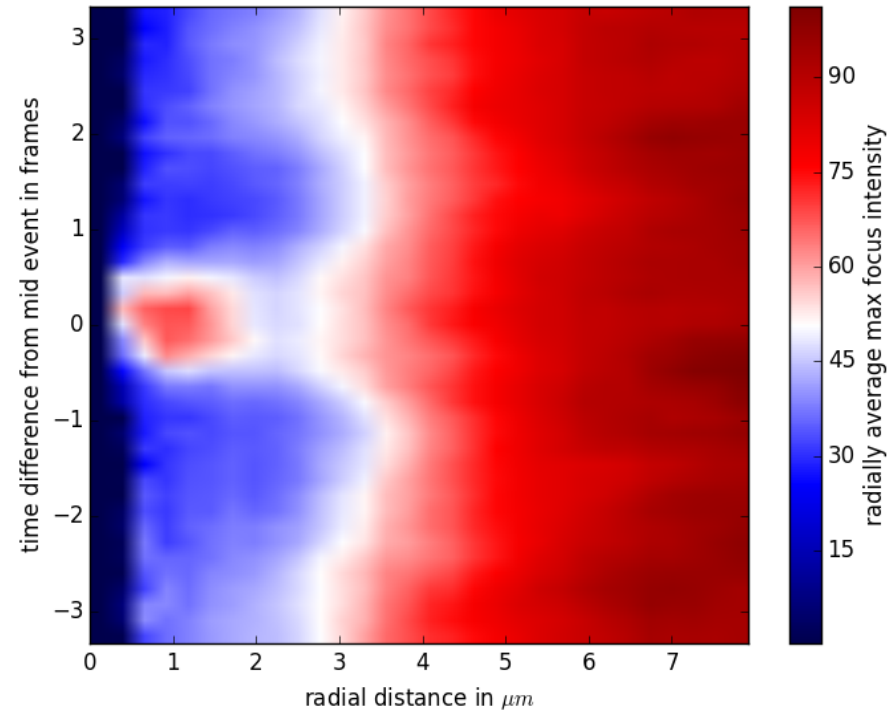


$$I_F(r, \tau) = \left\langle \max_{d(\mathbf{x}, \mathbf{x}_F)=r} I(\mathbf{x}, t_F + \tau) \right\rangle_{F_i \in F} - \left\langle \max_{d(\mathbf{x}, \mathbf{x}_b)=r} I(\mathbf{x}, t_F + \tau) \right\rangle_{\mathbf{x}_b}$$

Foci coverage of the tissue

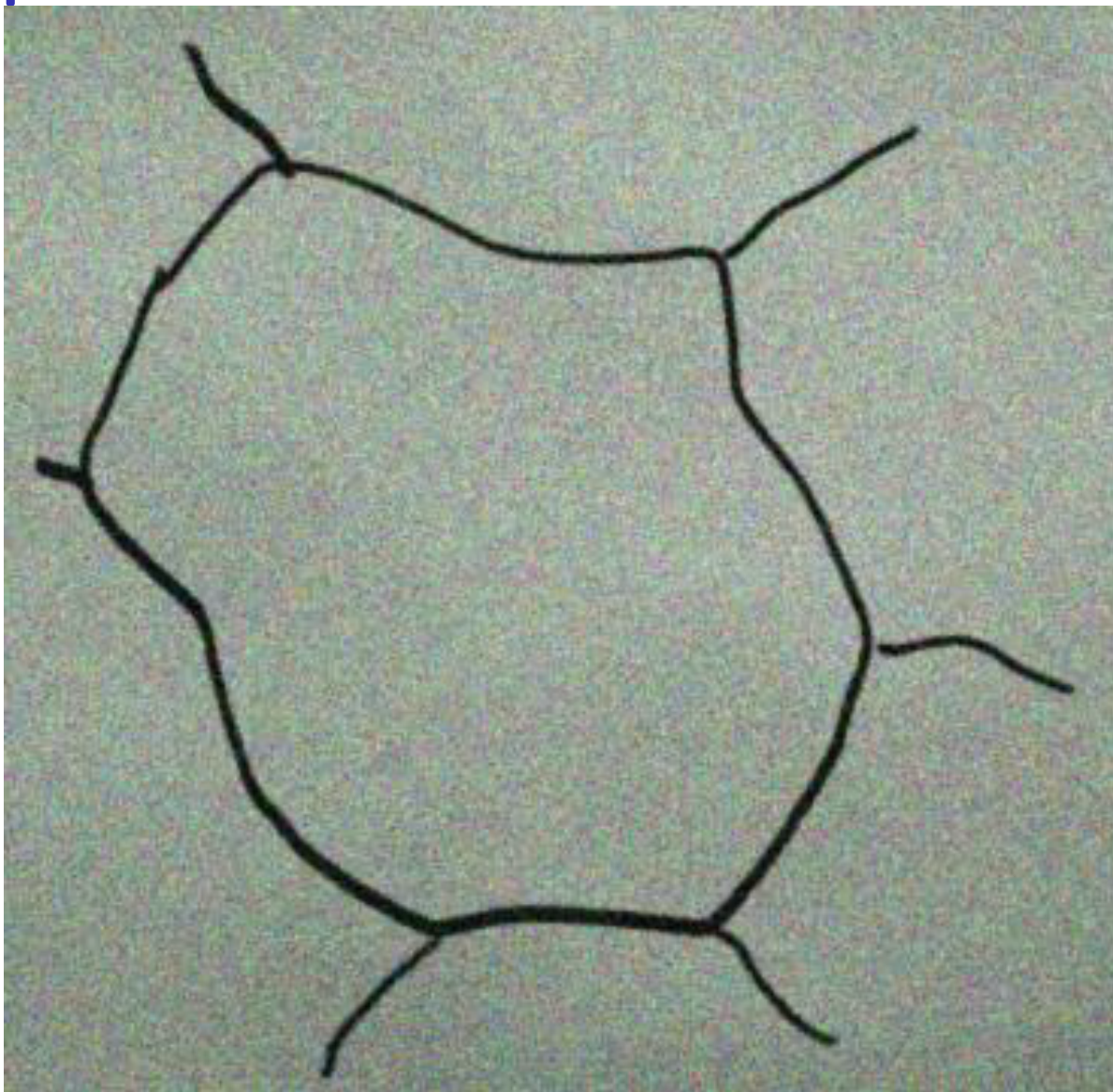


Myosin in other cells

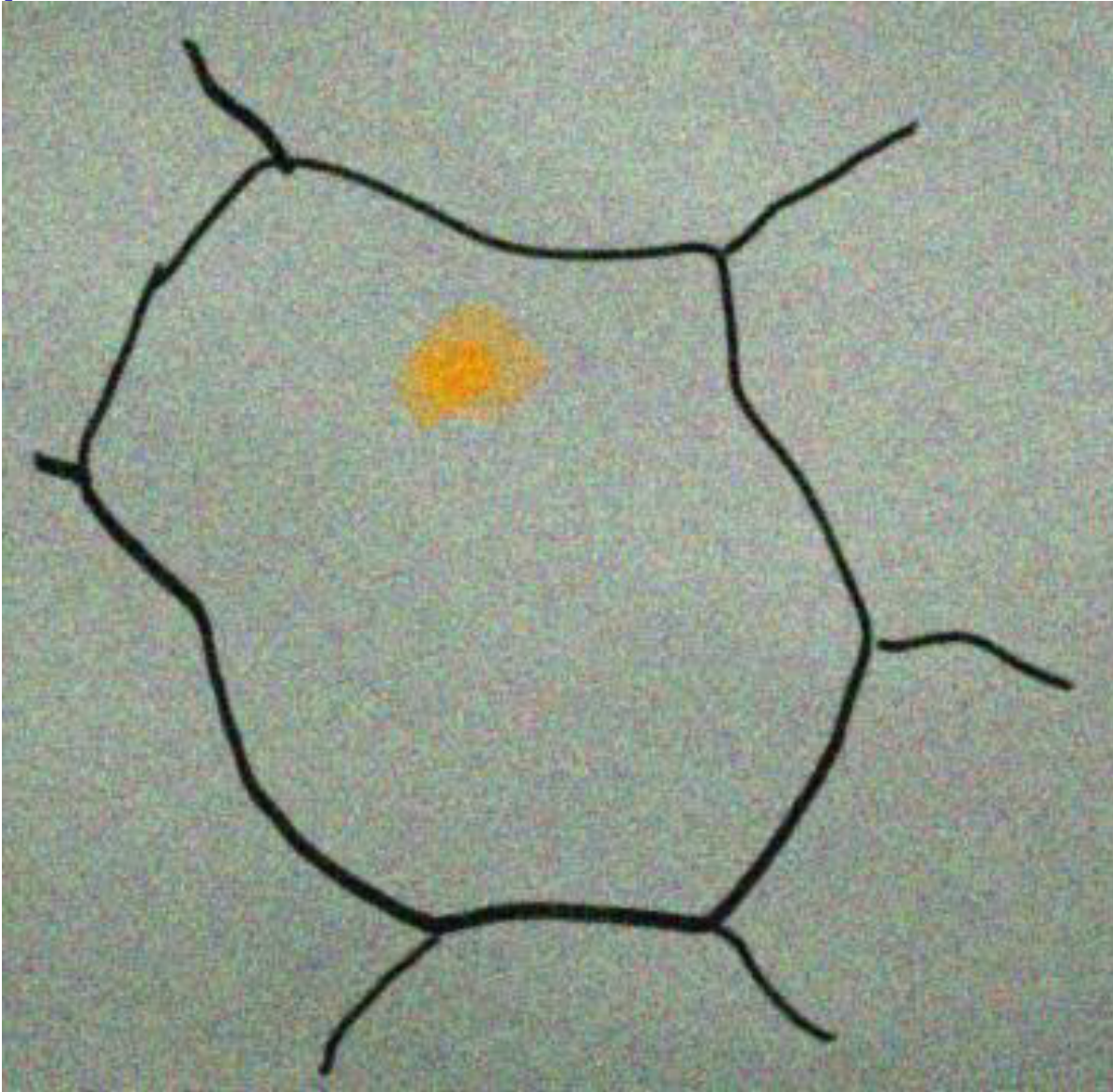


$$I_{\bar{F}}(r, \tau) = \left\langle \max_{\substack{d(\mathbf{x}, \mathbf{x}_F) = r \\ \mathbf{x} \notin \text{Cell}(F)}} I(\mathbf{x}, t_F + \tau) \right\rangle_{F_i \in F}$$

Proposed mechanism

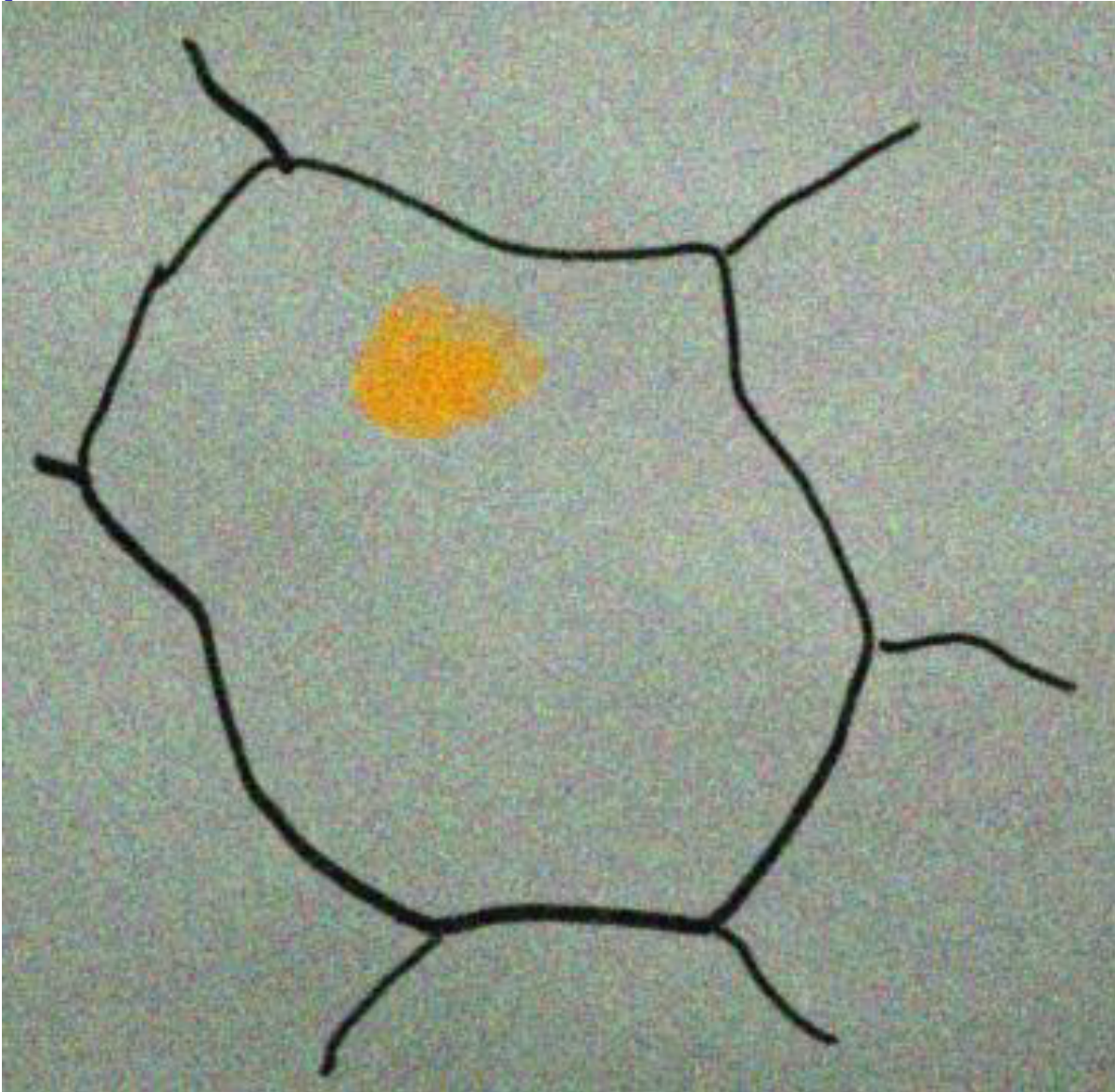


Proposed mechanism



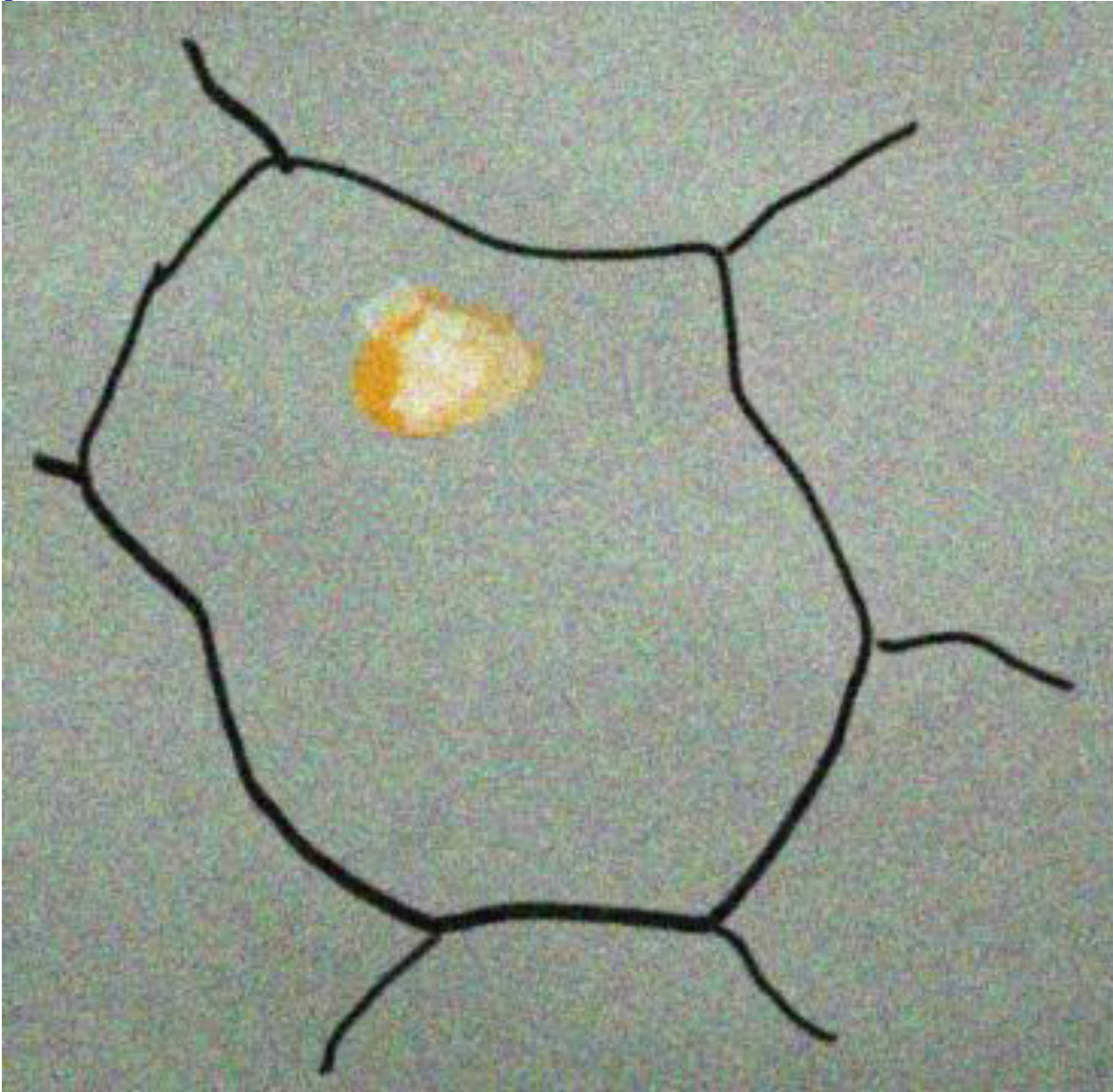
Assembly

Proposed mechanism



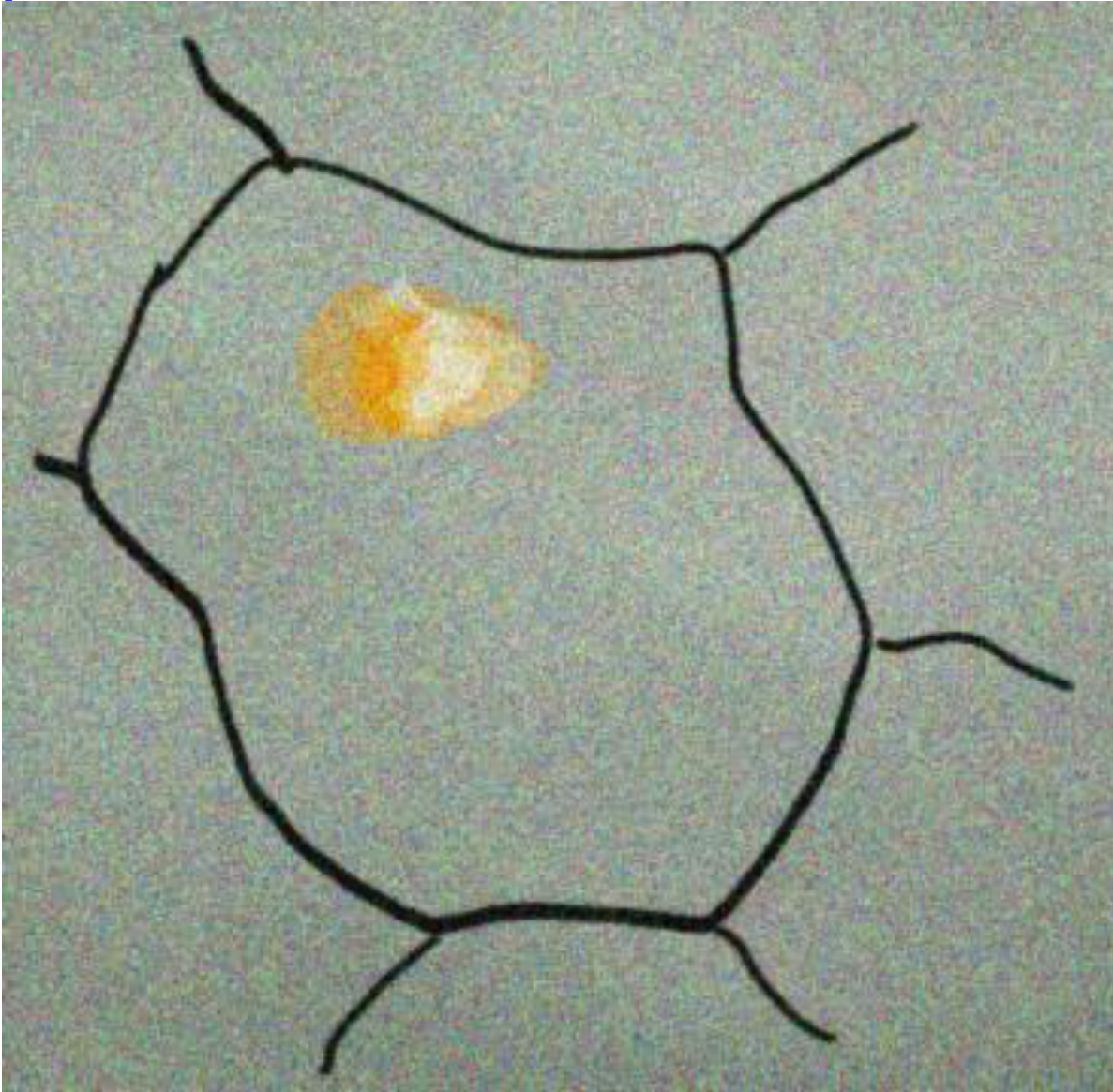
Assembly

Proposed mechanism



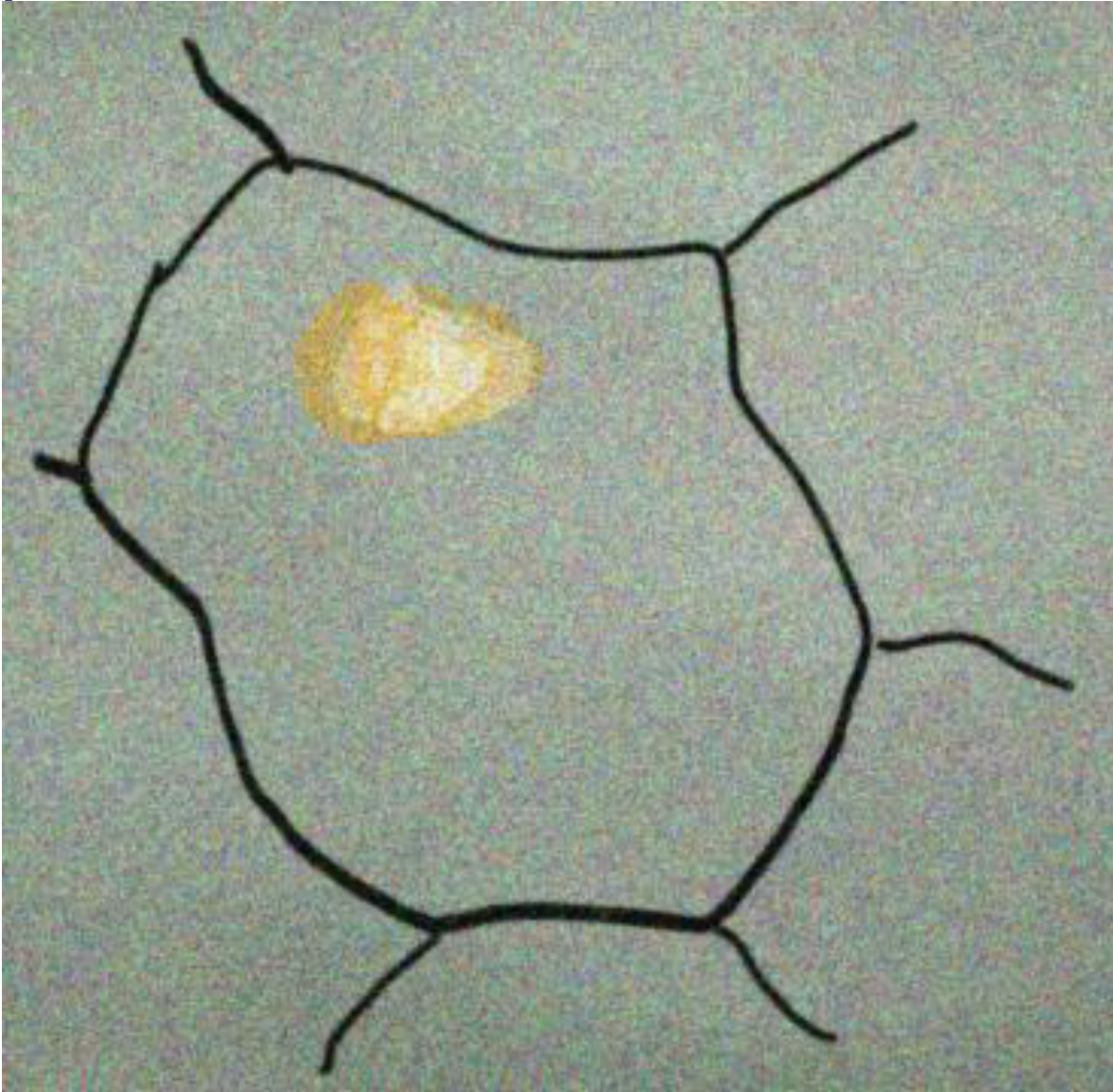
Assembly and appearance of Myosin-refractory regions

Proposed mechanism



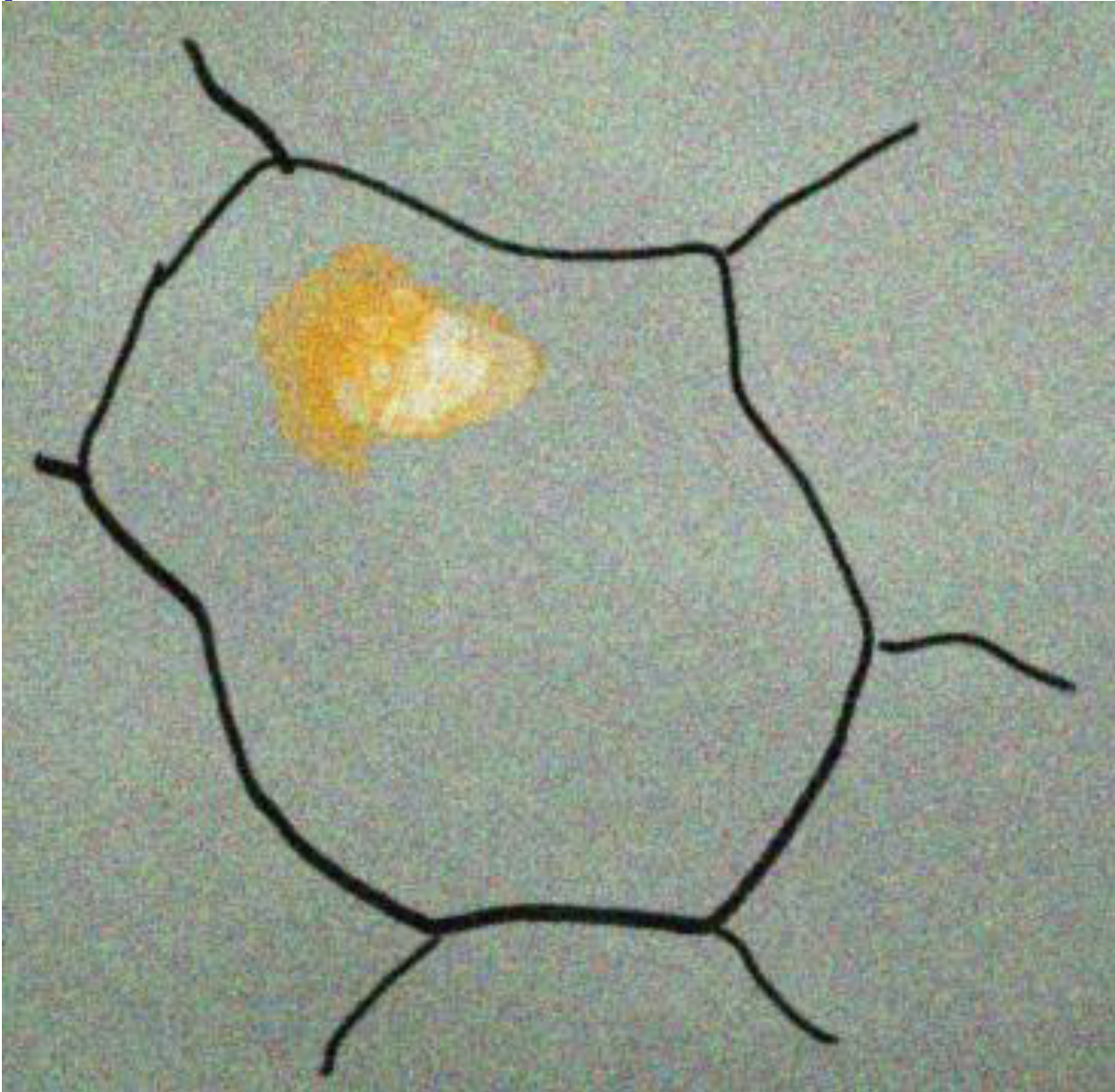
Assembly and appearance of Myosin-refractory regions

Proposed mechanism



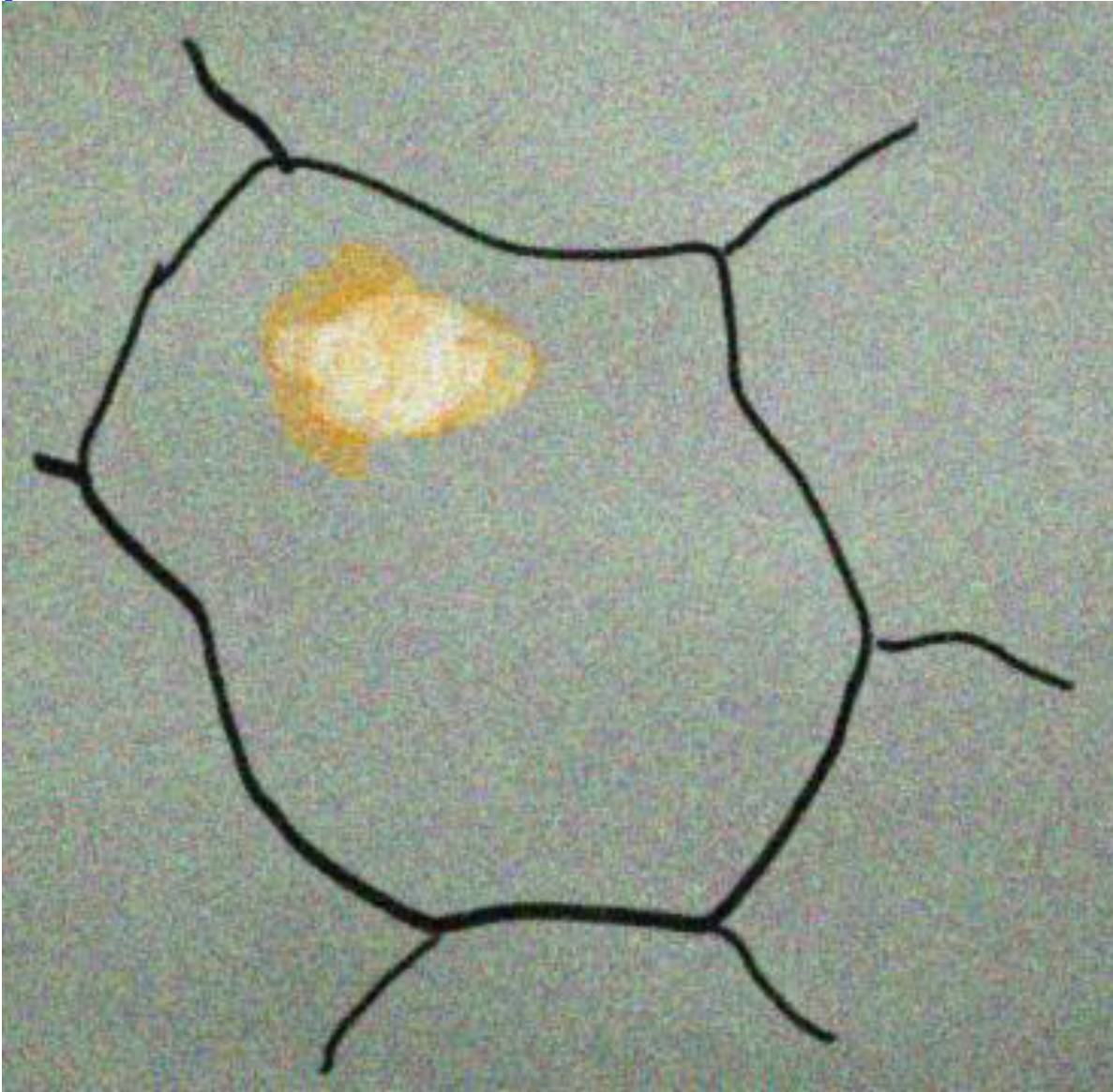
Assembly and appearance of Myosin-refractory regions

Proposed mechanism



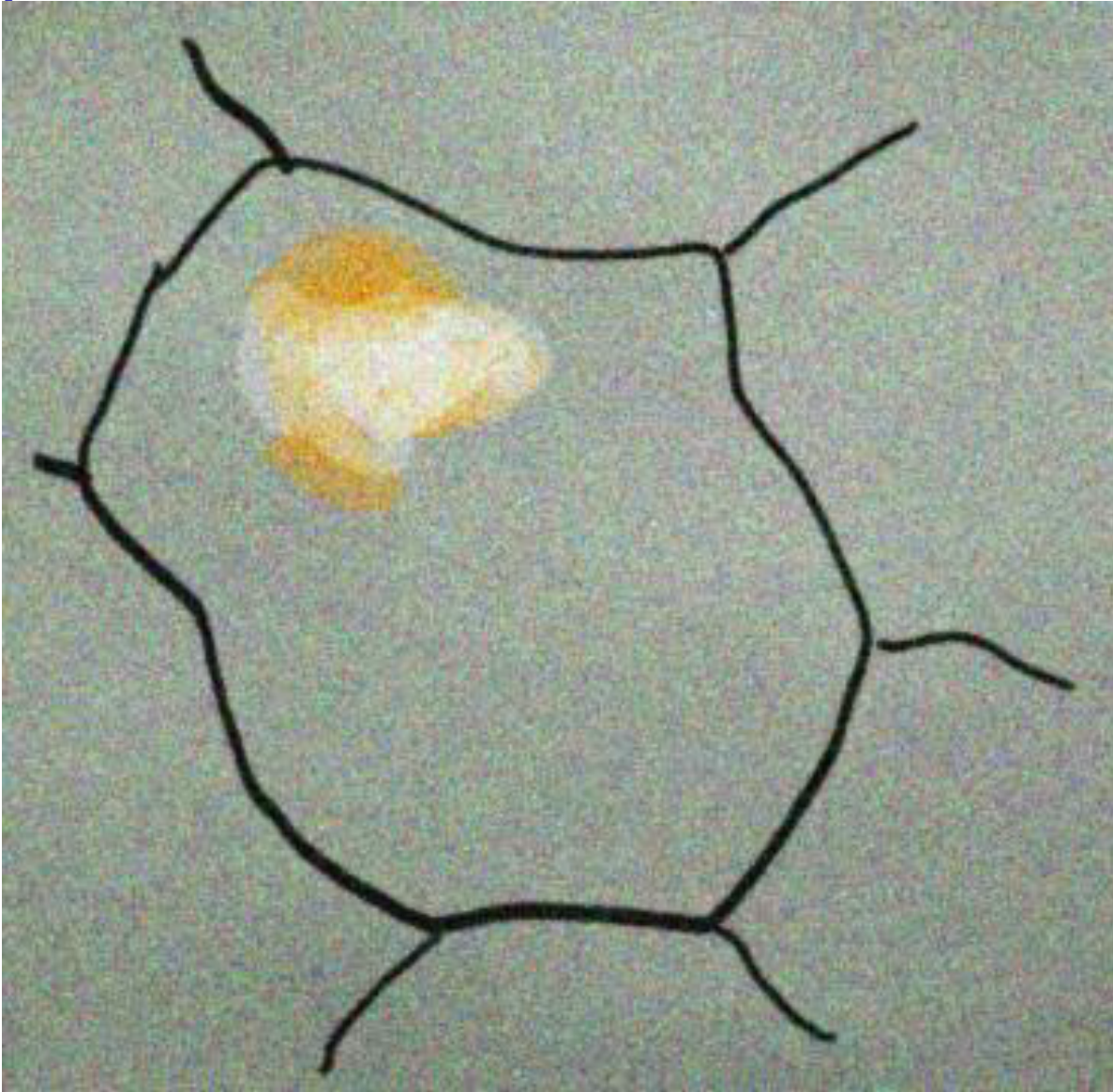
Assembly and appearance of Myosin-refractory regions leading to self-avoiding walk

Proposed mechanism



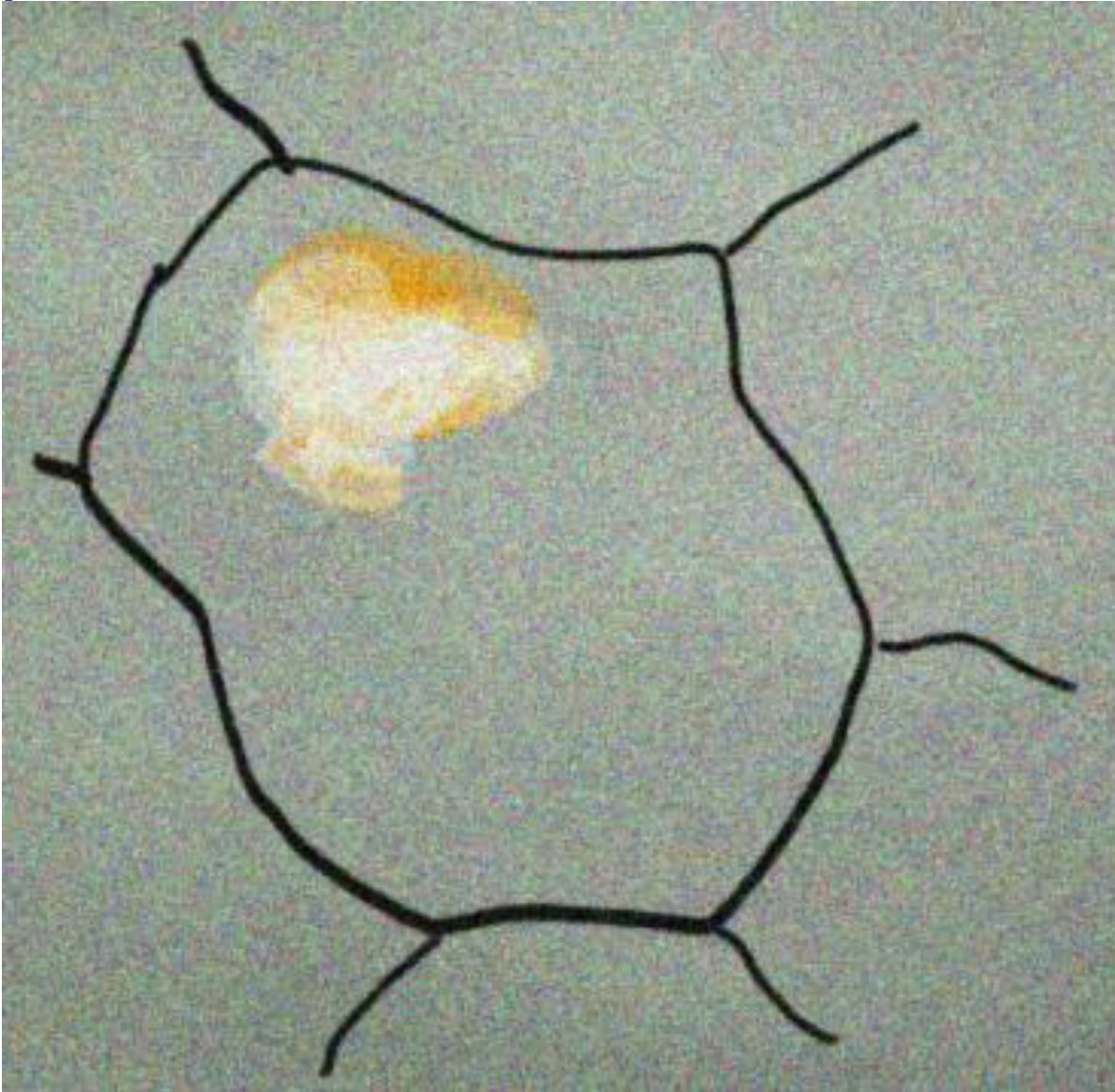
Assembly and appearance of Myosin-refractory regions leading to self-avoiding walk

Proposed mechanism



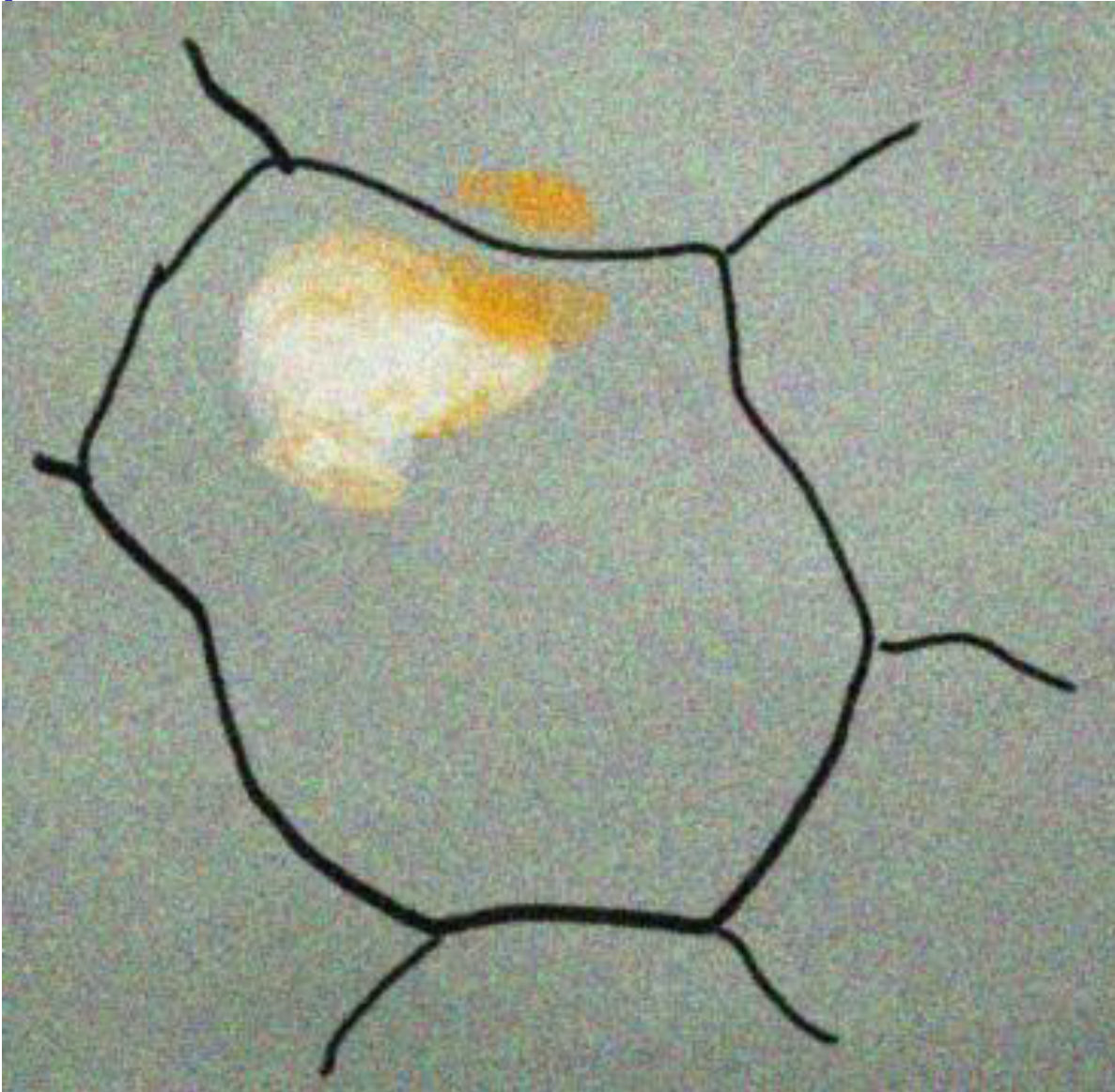
Assembly and appearance of Myosin-refractory regions leading to self-avoiding walk with occasional splitting.

Proposed mechanism



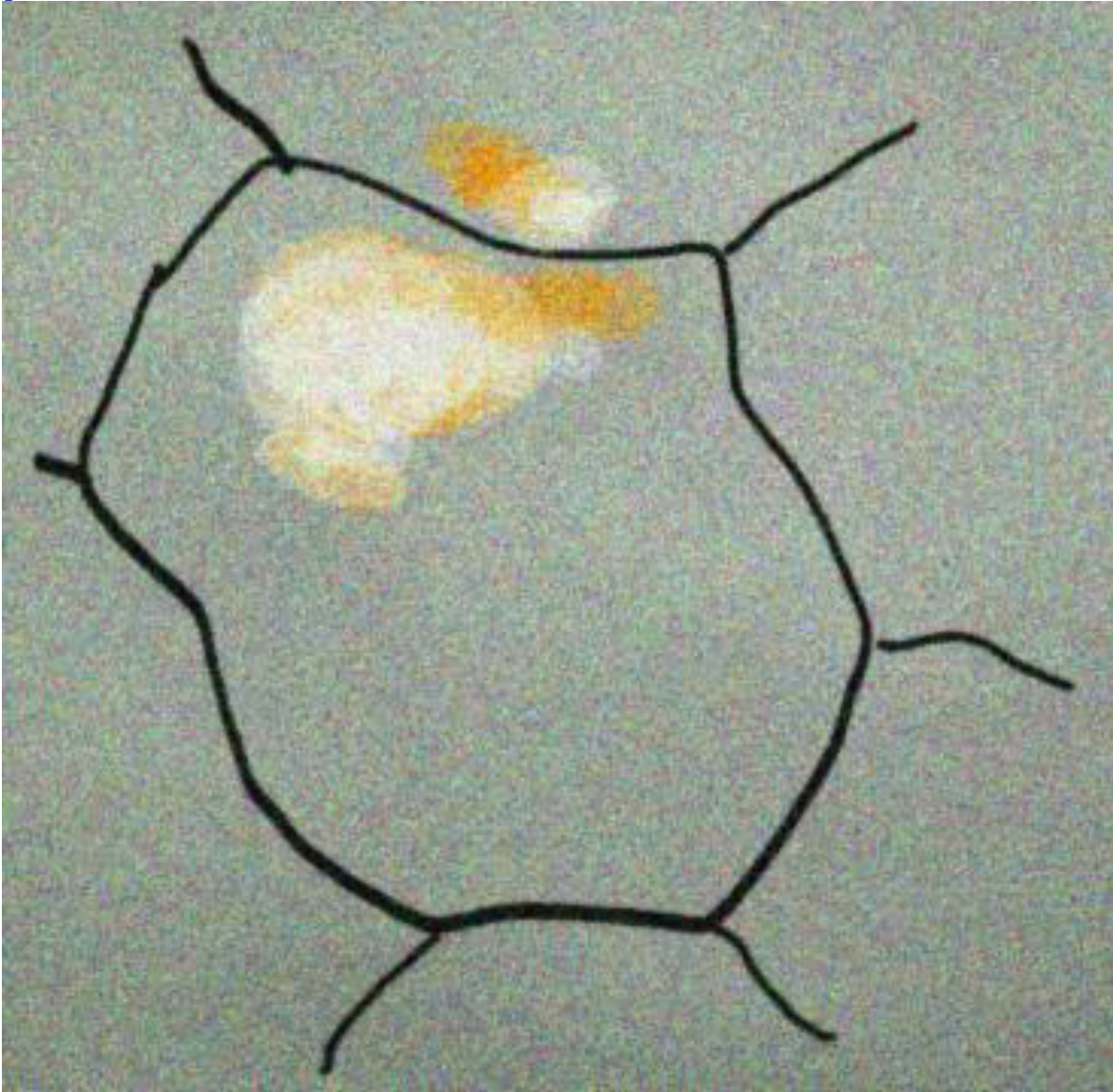
Assembly and appearance of Myosin-refractory regions leading to self-avoiding walk with occasional splitting.

Proposed mechanism



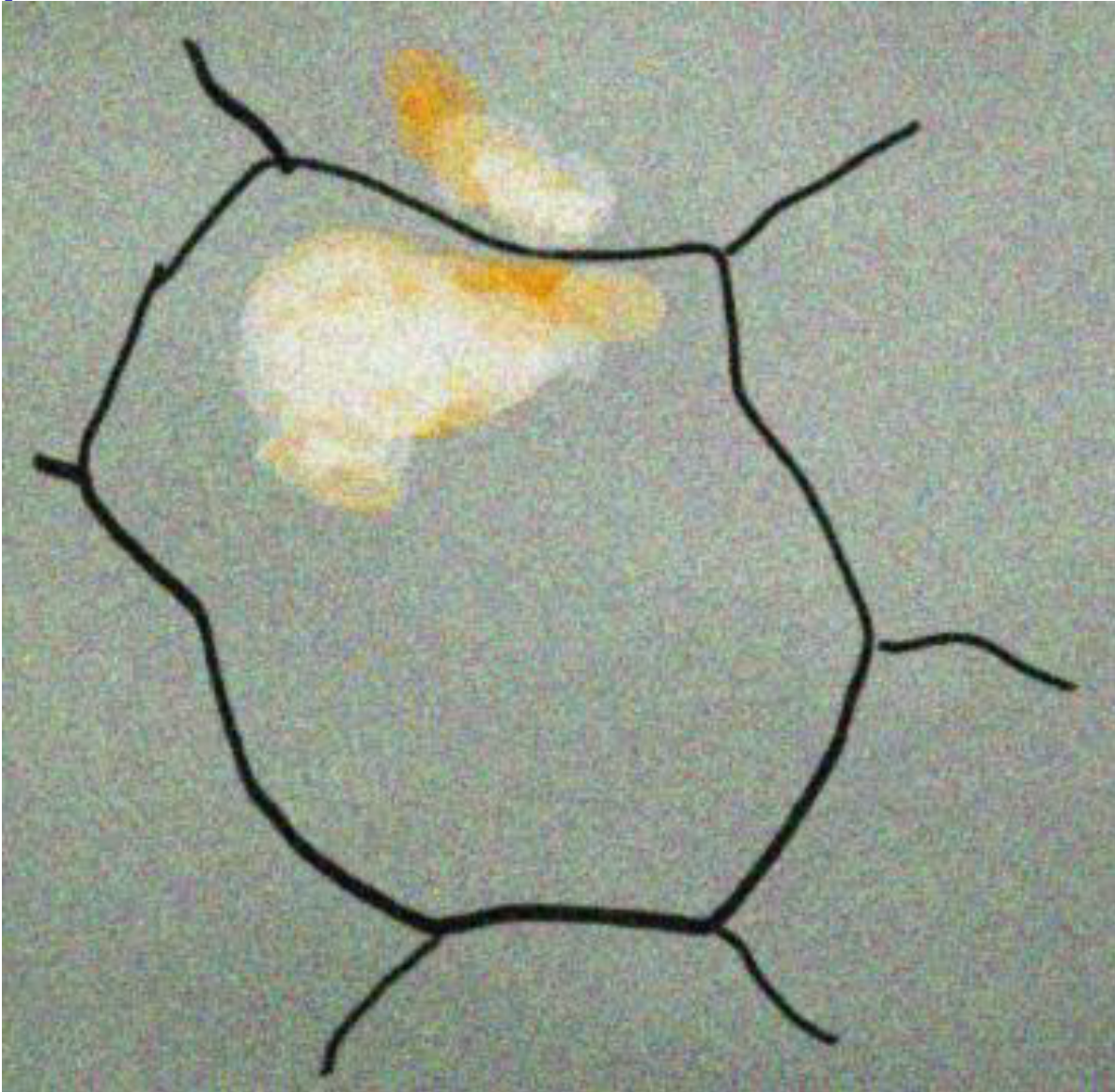
Assembly and appearance of Myosin-refractory regions leading to self-avoiding walk with occasional splitting.
'Infection' of nearby cells.

Proposed mechanism



Assembly and appearance of Myosin-refractory regions leading to self-avoiding walk with occasional splitting.
'Infection' of nearby cells.

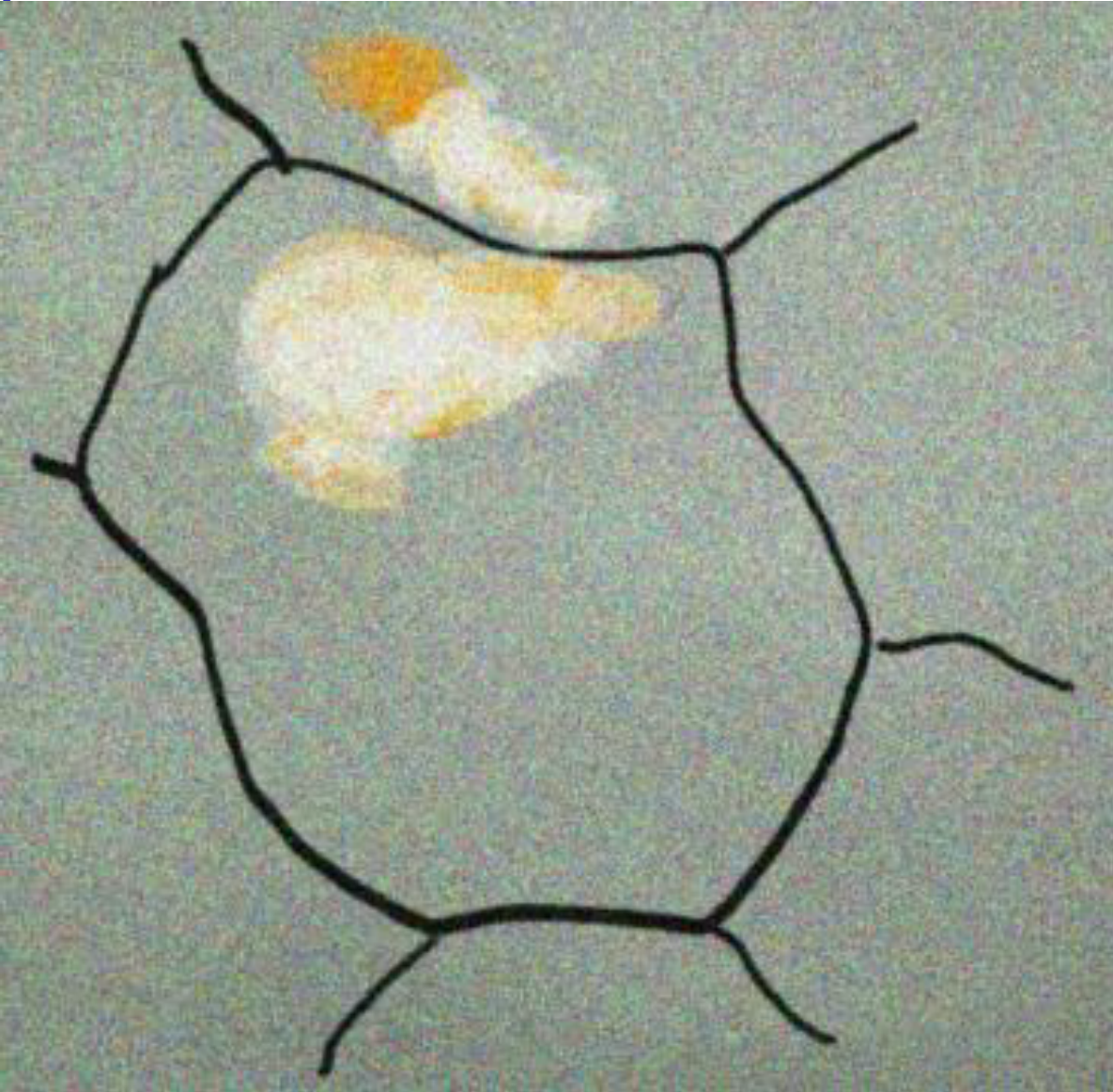
Proposed mechanism



Assembly and appearance of Myosin-refractory regions leading to self-avoiding walk with occasional splitting.

'Infection' of nearby cells. Disassembly when 'trapped'

Proposed mechanism

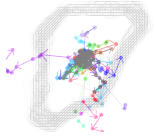


Assembly and appearance of Myosin-refractory regions leading to self-avoiding walk with occasional splitting.

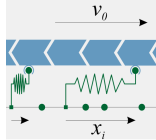
'Infection' of nearby cells. Disassembly when 'trapped'

Co-workers

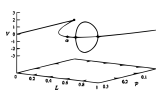
LIPHY:Physics@Grenoble



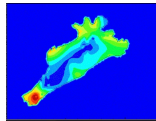
Nilankur Dutta



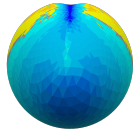
Haythem Chelly



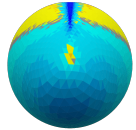
Pierre Recho



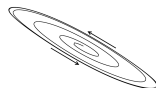
Claude Verdier



Catherine Quilliet



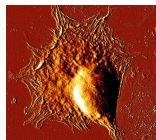
Philippe Marmottant



Alexandr Farutin

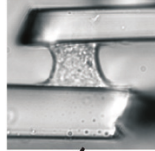


Chaouqi Misbah



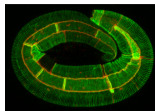
Valérie Laurent

MSC:Physics@Paris



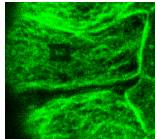
Atef Asnacios

IGDR:DevBiol@Rennes

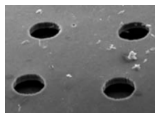


Grégoire Michaux

LTM:Nanomat@Grenoble

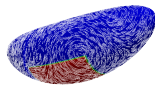


Sara Bouizakarne

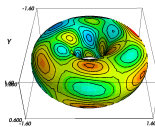


Alice Nicolas

LJK:Maths@Grenoble

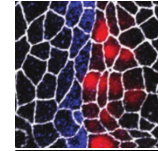


Mahamar Dicko

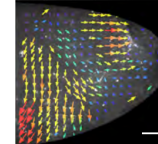


Pierre Saramito

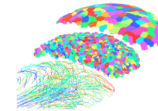
PDN:DevBiol@Cambridge



Bénédicte Sanson

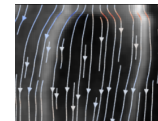


Claire Lye



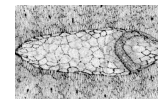
Guy Blanchard

DAMTP:Maths@Cambridge



Lukas Lang

CSIC:DevBiol@Madrid



Nicole Gorfinkiel

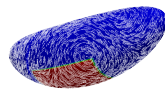


The apical drive of Myosin for
convergence-extension (and folding)



Guy Blanchard
Claire Lye
Bénédicte Sanson

PDN, Univ. Cambridge

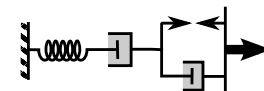


Mahamar Dicko
Pierre Saramito

LJK, CNRS-Univ. Grenoble Alpes



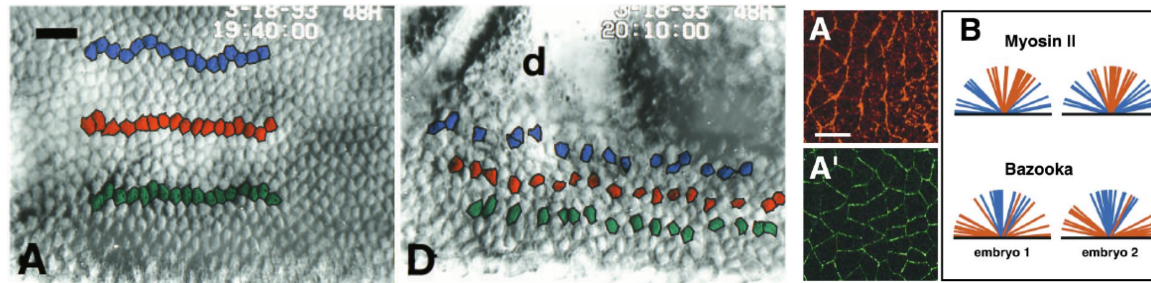
Julien Fierling
Alexandre Torzynski
Catherine Quilliet
Philippe Marmottant



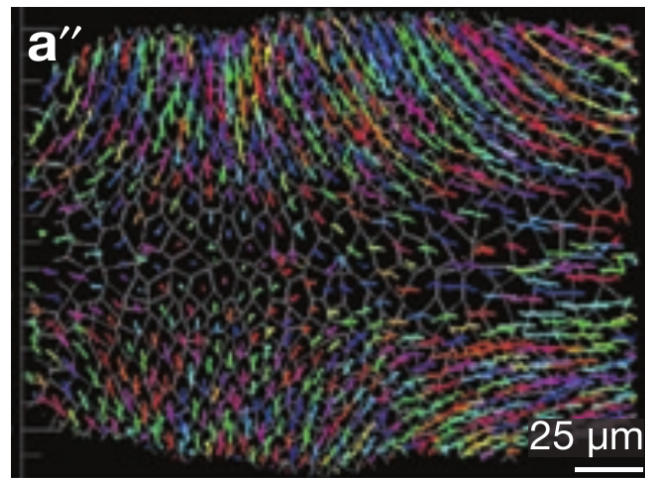
Jocelyn Étienne

LIPHY, CNRS-Univ. Grenoble Alpes

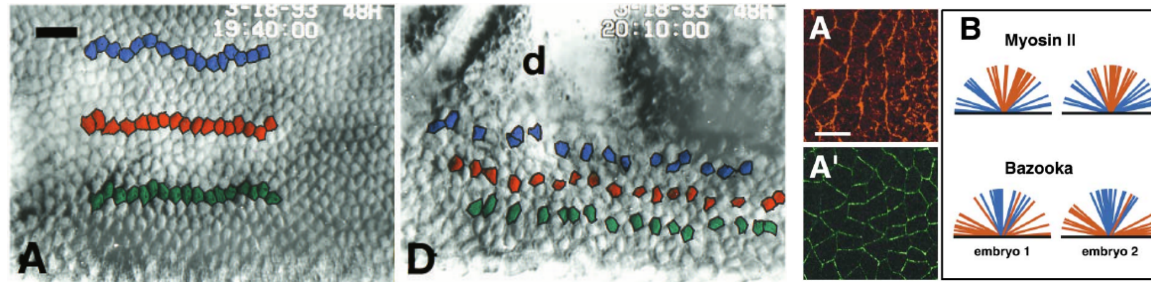
Convergence–extension during germband axis extension



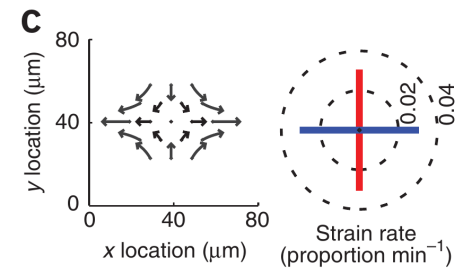
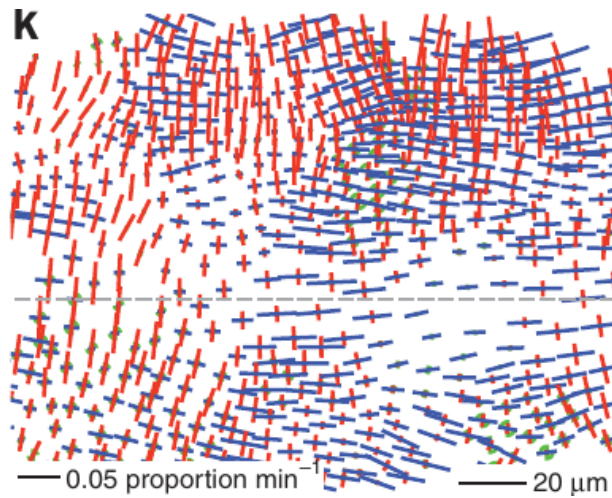
Irvine and Wieschaus, *Devel.* 1994, Zallen et al., *Dev. Cell* 2004



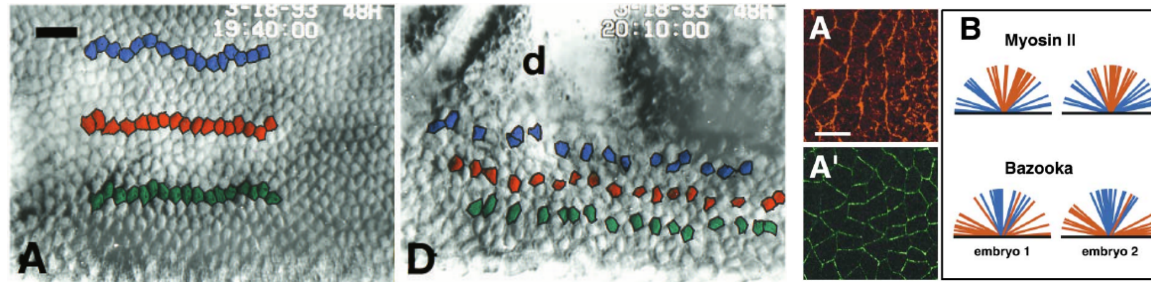
Convergence–extension during germband axis extension



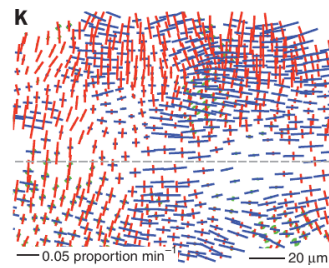
Irvine and Wieschaus, *Devel.* 1994, Zallen et al., *Dev. Cell* 2004



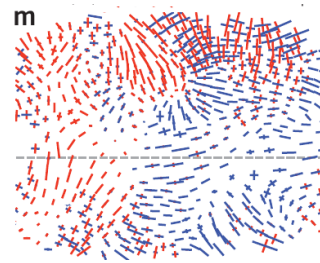
Convergence–extension during germband axis extension



Irvine and Wieschaus, *Devel.* 1994, Zallen et al., *Dev. Cell* 2004

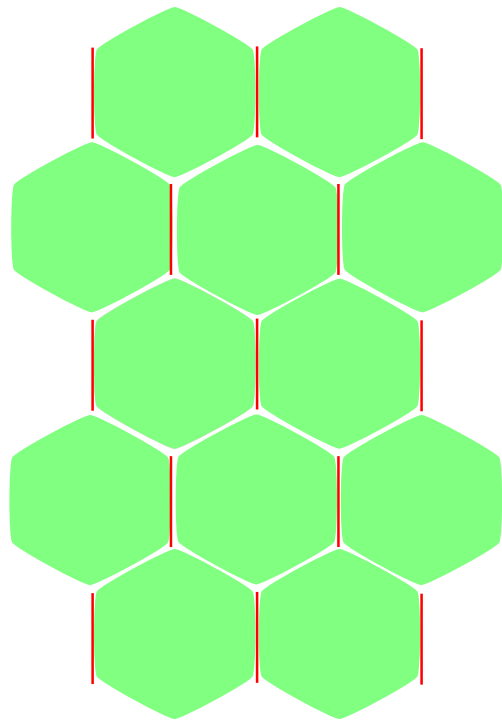


tissue strain rate

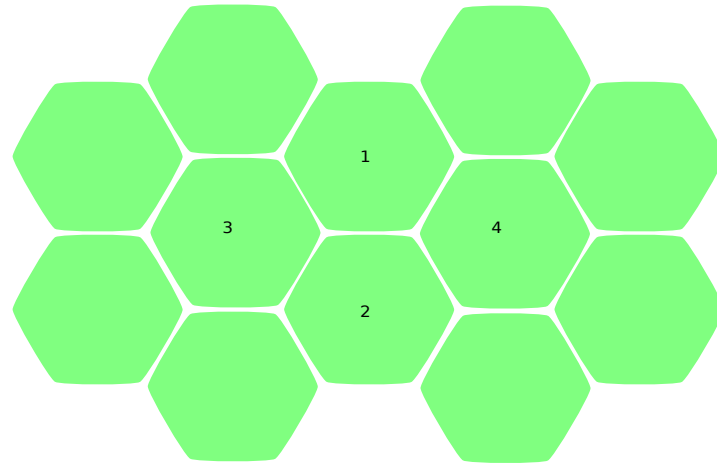
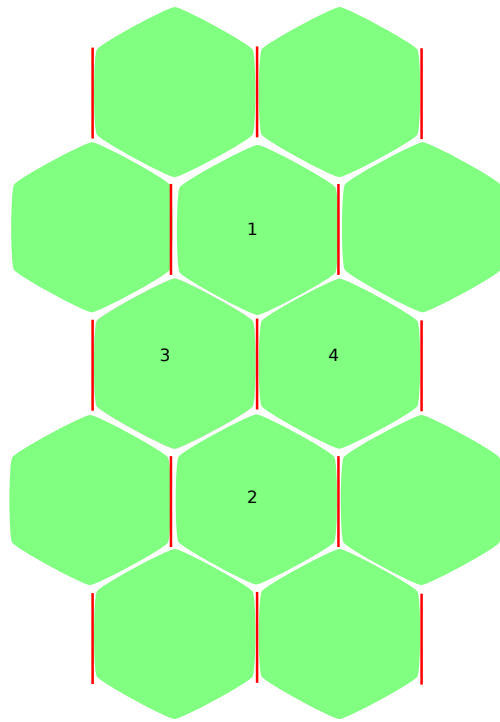


cell strain rate

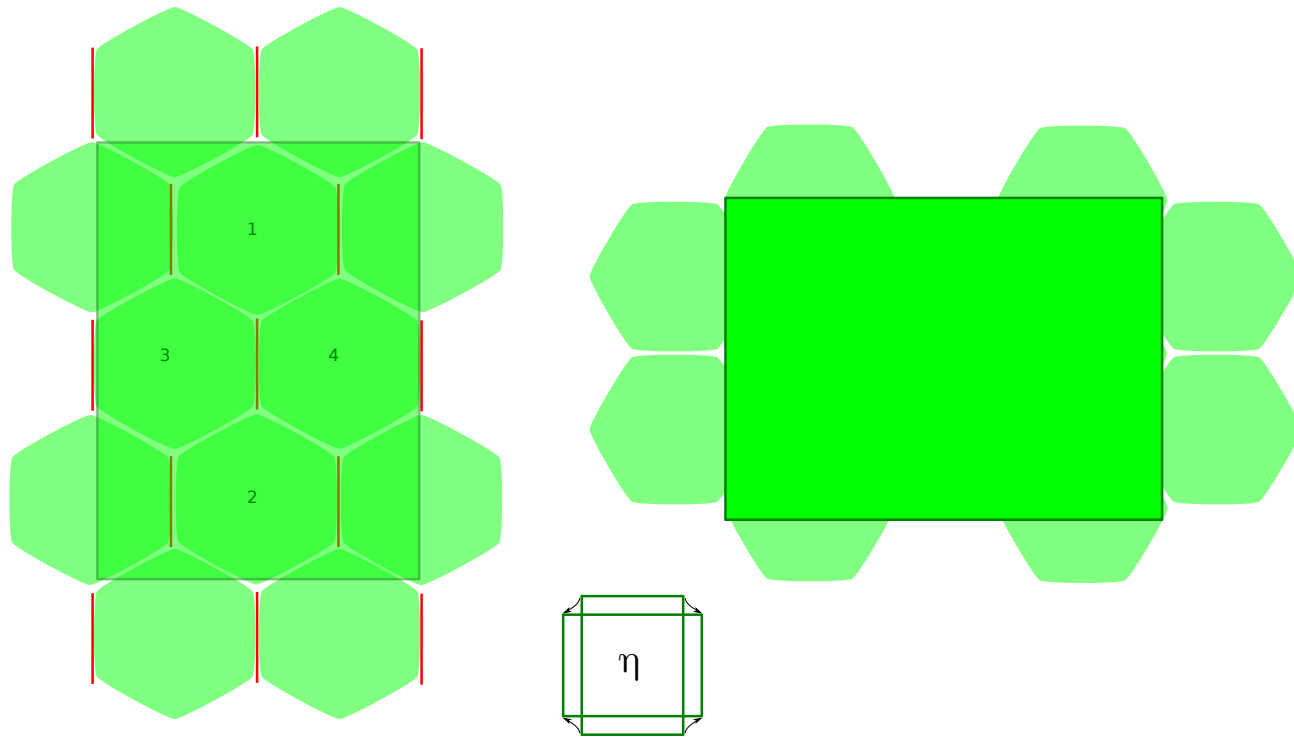
Planar-polarised myosin and convergence–extension



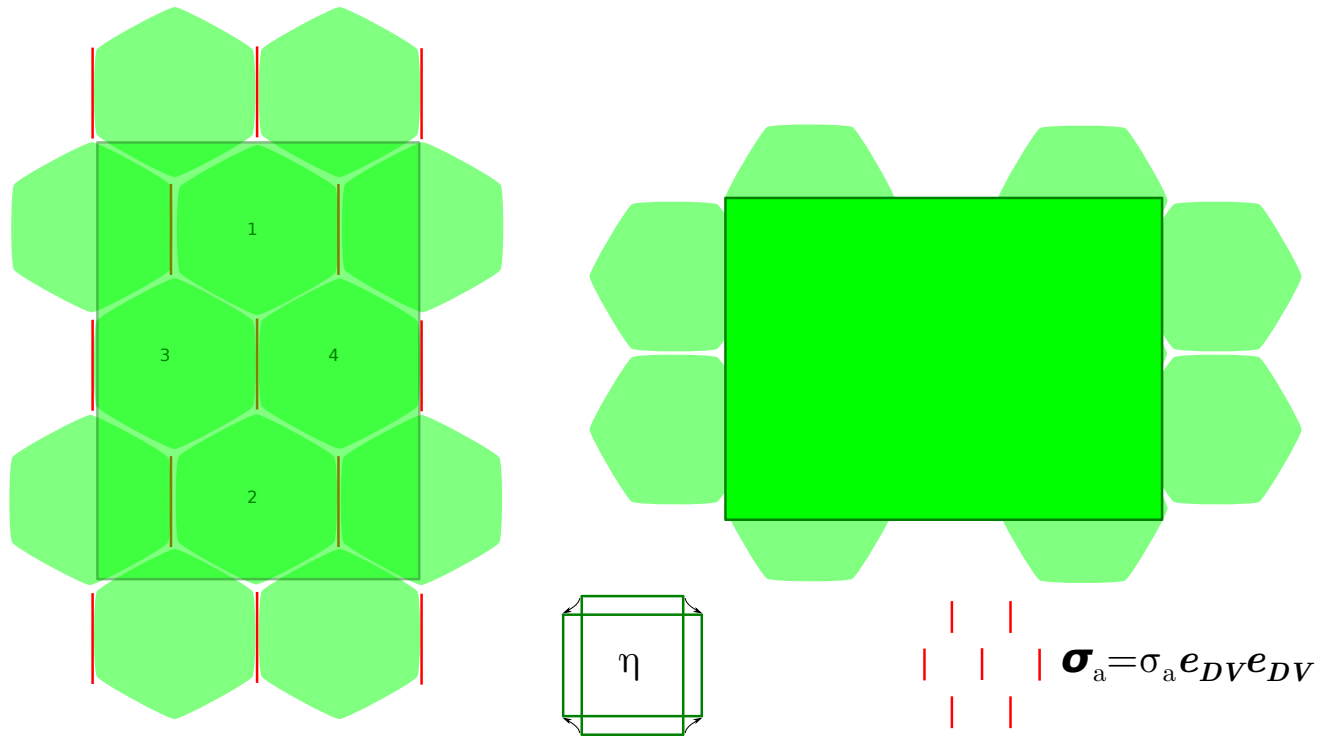
Planar-polarised myosin and convergence–extension



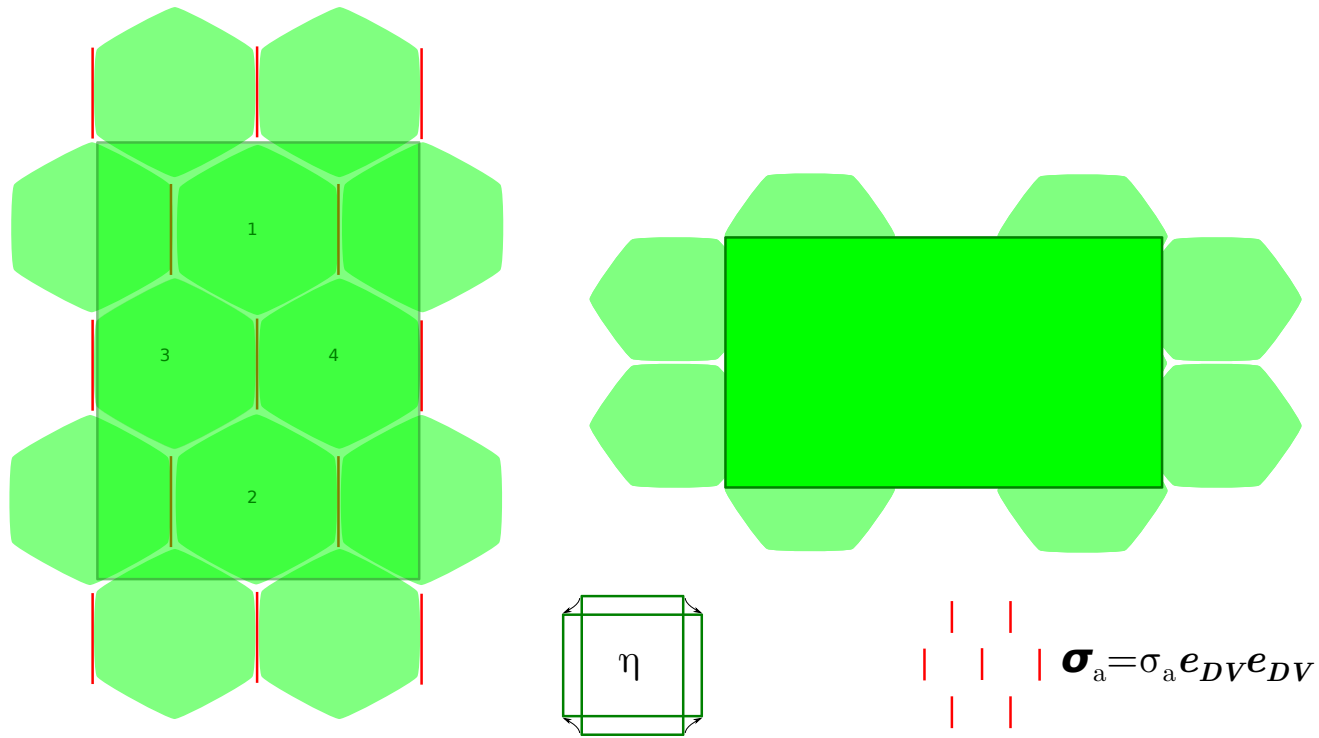
Planar-polarised myosin and convergence-extension



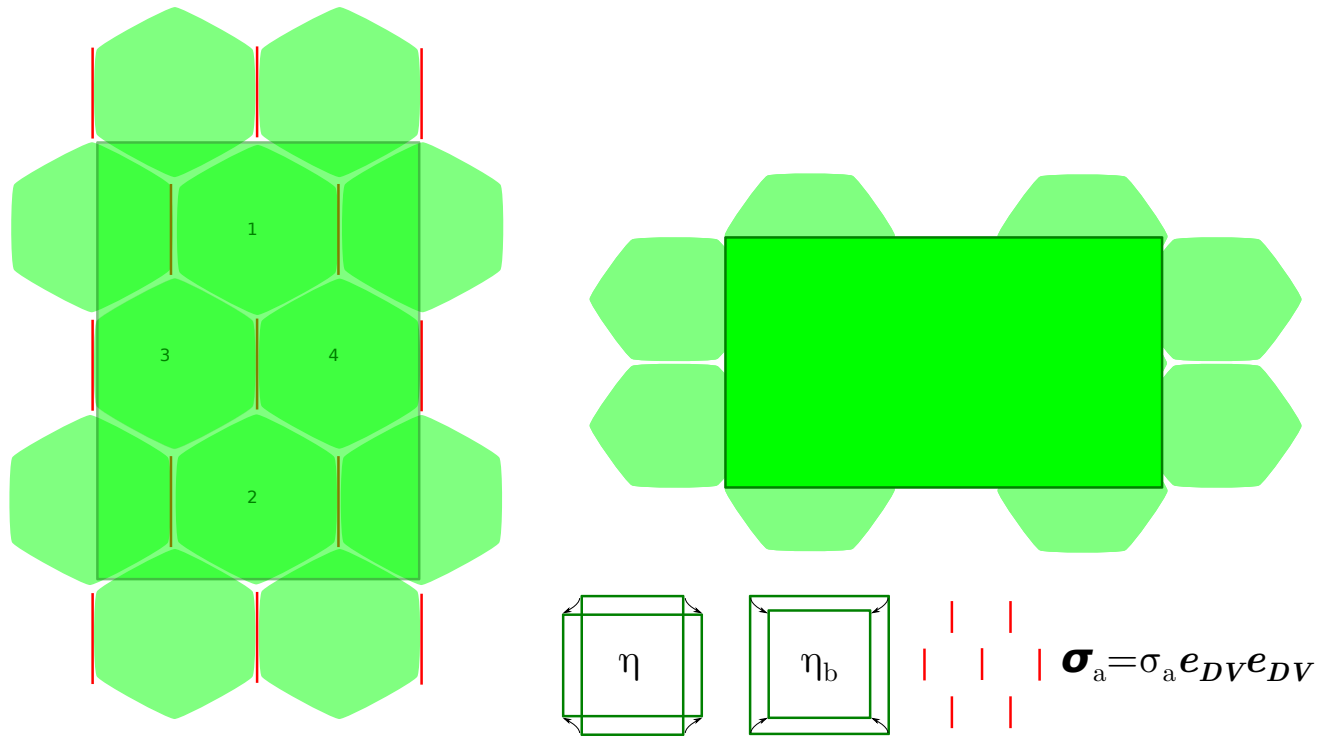
Planar-polarised myosin and convergence-extension



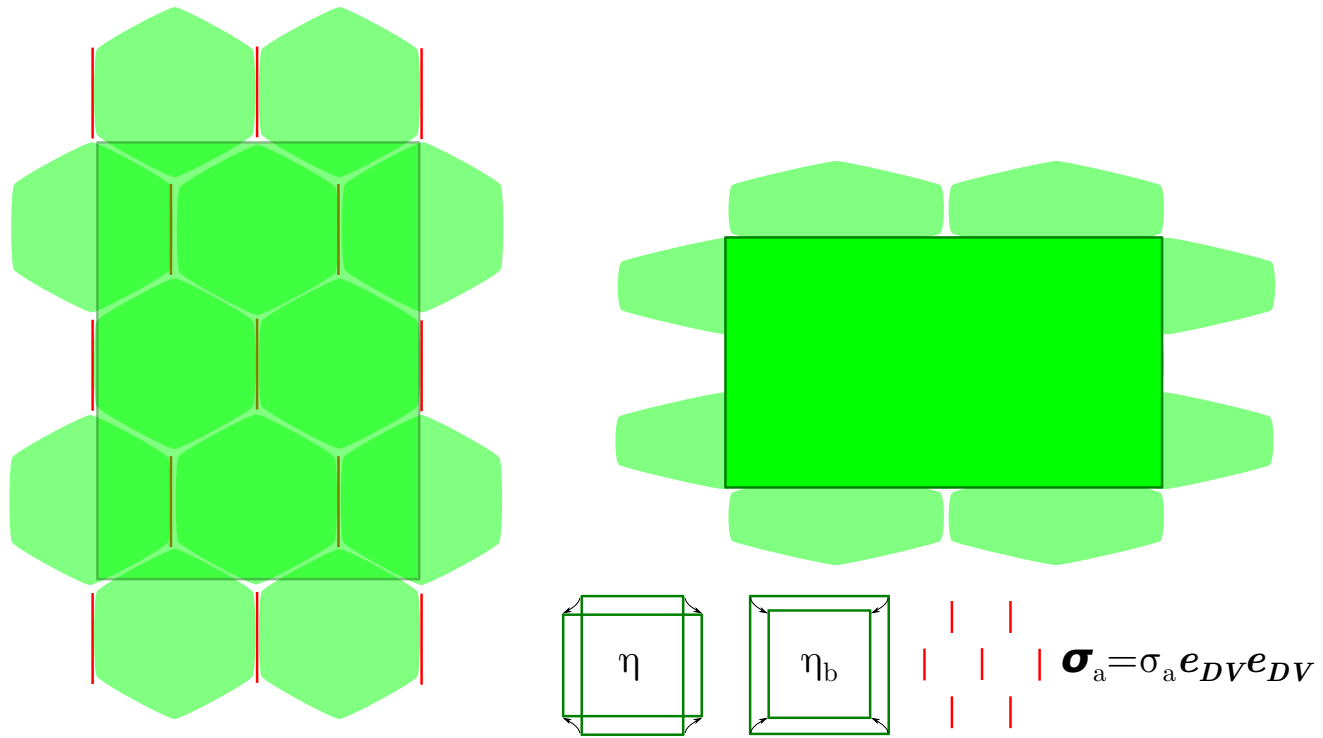
Planar-polarised myosin and convergence-extension



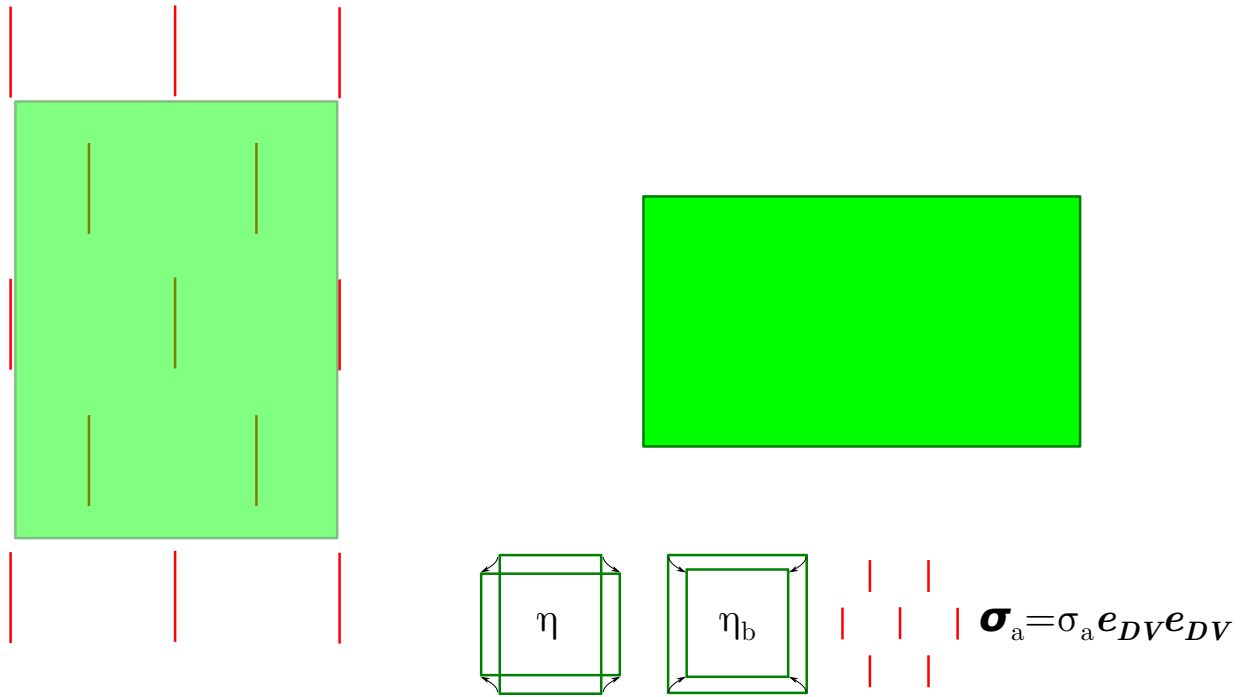
Planar-polarised myosin and convergence-extension



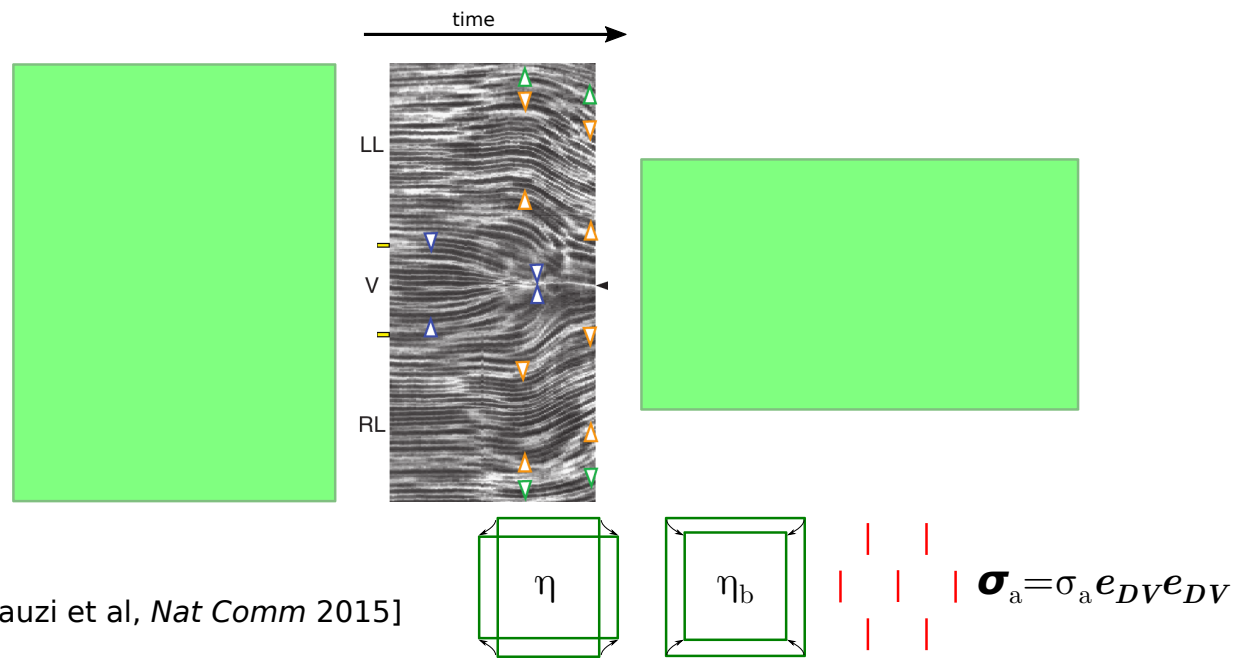
Planar-polarised myosin and convergence-extension



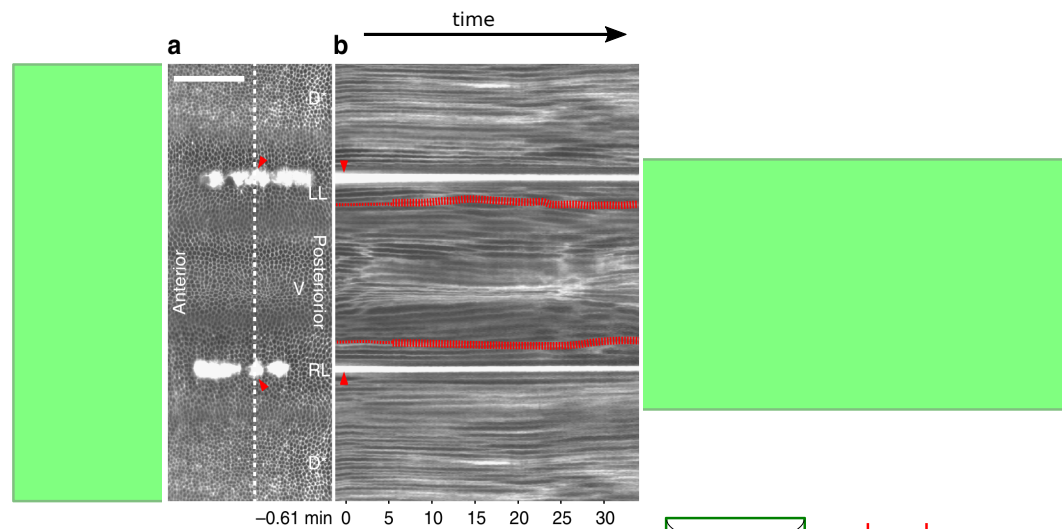
Tissue stress-strain relation



Tissue stress-strain relation...is not enough!



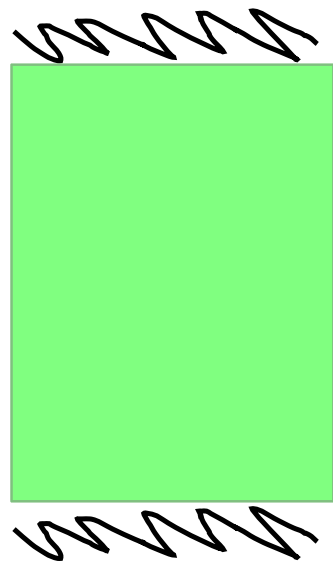
Tissue stress-strain relation...is not enough!



[Rauzi et al, *Nat Comm* 2015]

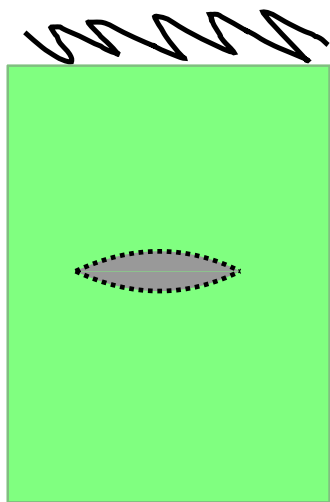
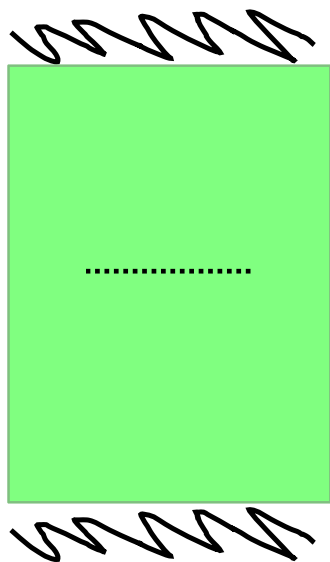
$$\eta \quad \eta_b \quad \sigma_a = \sigma_a e_{DV} e_{DV}$$

Mechanical balance



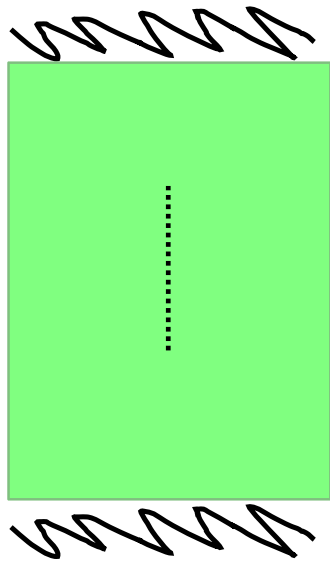
$$\boldsymbol{\sigma} + \boxed{\eta} + \boxed{\eta_b} = \boldsymbol{\sigma}_a = \sigma_a e_{DV} e_{DV}$$

The equation represents the mechanical balance of the fluid element. On the left side, the total stress tensor is the sum of three terms: $\boldsymbol{\sigma}$ (the Cauchy stress tensor), $\boxed{\eta}$ (the shear stress tensor, shown in a green box), and $\boxed{\eta_b}$ (the bulk stress tensor, also shown in a green box). On the right side, the total stress tensor is equated to $\boldsymbol{\sigma}_a = \sigma_a e_{DV} e_{DV}$, where σ_a is the scalar pressure and e_{DV} are the basis vectors of the volume element.



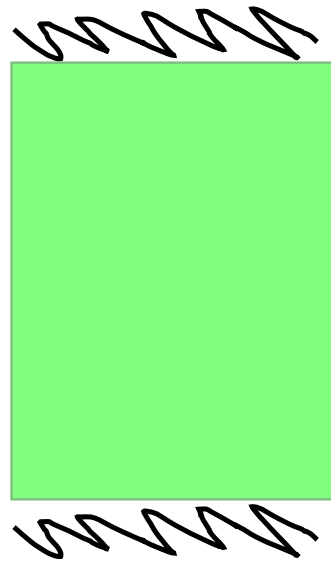
$$\sigma + \boxed{\eta} + \boxed{\eta_b} = \text{---} \text{---} \text{---}$$

$$\sigma_a = \sigma_a e_{DV} e_{DV}$$



$$\boldsymbol{\sigma} + \boxed{\eta} + \boxed{\eta_b} = \boldsymbol{\sigma}_a = \sigma_a e_{DV} e_{DV}$$

Mechanical balance



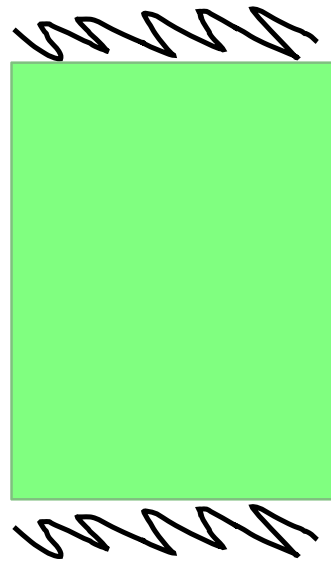
Mechanical balance

$$\nabla \cdot \boldsymbol{\sigma} = \mathbf{0}$$

$$\boldsymbol{\sigma} + \boxed{\eta} + \boxed{\eta_b} = \boldsymbol{\sigma}_a = \sigma_a e_{DV} e_{DV}$$

The equation shows the decomposition of the stress tensor $\boldsymbol{\sigma}$ into its symmetric part $\boldsymbol{\sigma}_a$ and antisymmetric part $\boldsymbol{\sigma}_a^*$. The symmetric part is further decomposed into a shear stress η and a bulk stress η_b . The antisymmetric part is represented by a red dashed box.

Mechanical balance



Mechanical balance

$$\nabla \cdot \boldsymbol{\sigma} = F_{\text{friction}}$$

$$\boldsymbol{\sigma} + \boxed{\eta} + \boxed{\eta_b} = \text{---} \quad \boldsymbol{\sigma}_a = \sigma_a e_{DV} e_{DV}$$

The diagram shows the decomposition of the stress tensor $\boldsymbol{\sigma}$ into its antisymmetric part η (represented by a green box with a diagonal line), its symmetric part η_b (represented by a green box with a double-line border), and a set of red vertical lines representing the friction force. The final part of the equation shows the friction force as a diagonal stress tensor $\boldsymbol{\sigma}_a = \sigma_a e_{DV} e_{DV}$.

Model of epithelium

Mechanical balance

$$\nabla \cdot \boldsymbol{\sigma} = F_{\text{friction}}$$

Constitutive relation (material property):

$$\boldsymbol{\sigma} - 2\eta\dot{\boldsymbol{\epsilon}}(\boldsymbol{v}) - \eta_b(\nabla \cdot \boldsymbol{v})\boldsymbol{I} = \boldsymbol{\sigma}_a$$

stress
tensor

dissipation due
to pure shear

dissipation due
to area changes

myosin
pre-stress

$$\boldsymbol{\sigma} + \boxed{\eta} + \boxed{\eta_b} = \boldsymbol{\sigma}_a = \sigma_a e_{DV} e_{DV}$$

Model of epithelium

Mechanical balance

$$\nabla \cdot \boldsymbol{\sigma} = F_{\text{friction}}$$

Constitutive relation (material property):

$$\tau_{\alpha} \overset{\nabla}{\boldsymbol{\sigma}} + \boldsymbol{\sigma} - 2\eta \dot{\boldsymbol{\epsilon}}(\boldsymbol{v}) - \eta_b (\nabla \cdot \boldsymbol{v}) \boldsymbol{I} = \boldsymbol{\sigma}_a$$

viscoelastic
behaviour

stress
tensor

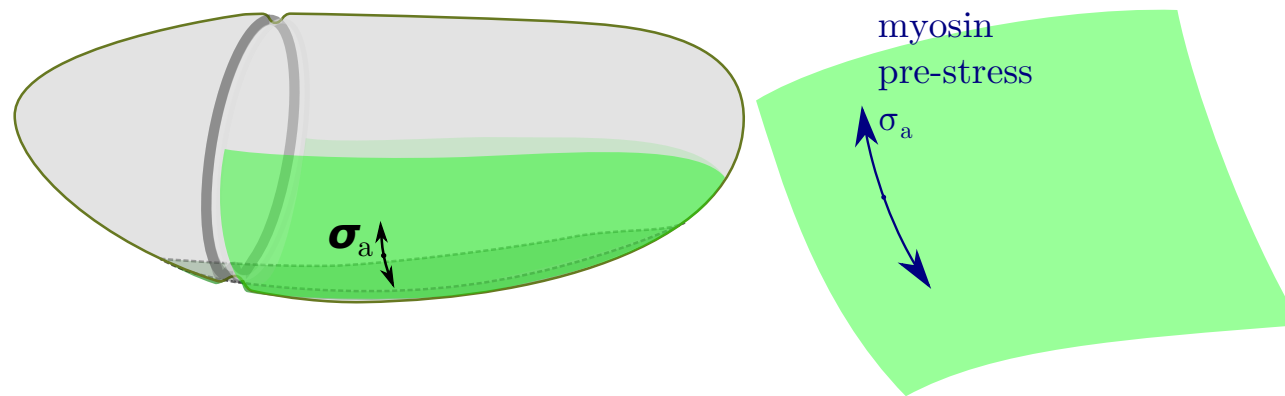
dissipation due
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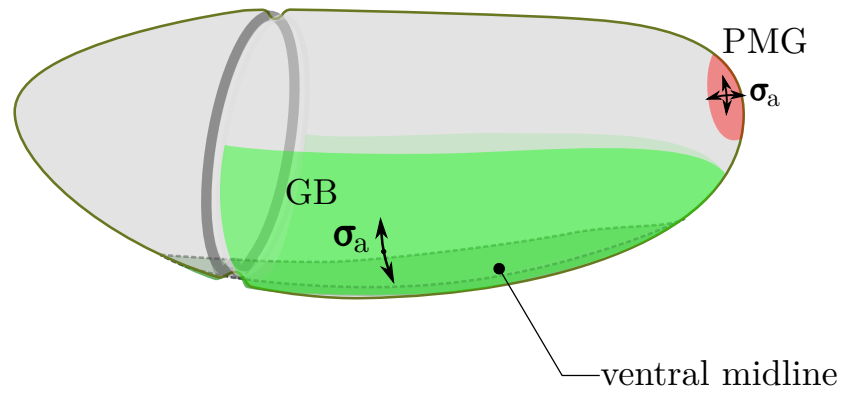
$$\boldsymbol{\sigma} + \boxed{\eta} + \boxed{\eta_b} = \boldsymbol{\sigma}_a = \sigma_a e_{DV} e_{DV}$$

Germband extension modelling



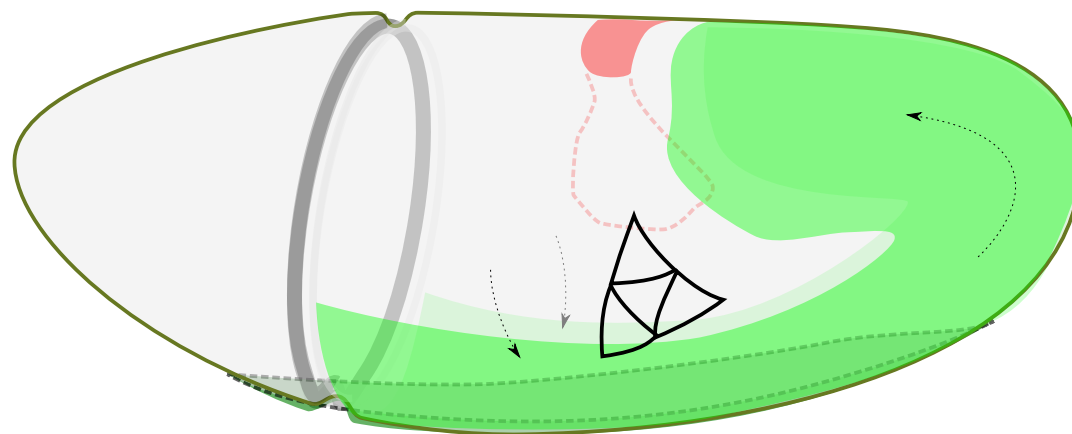
[Dicke et al. PLoS CR 2017]

Mimicking PMG invagination

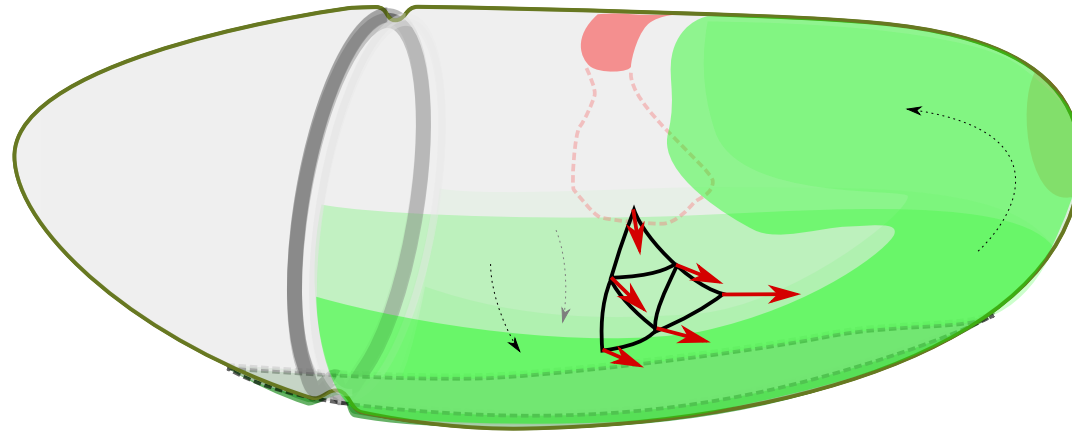


[Butler et al. 2000; Collinet et al. Iye et al. 2015]

Numerical method

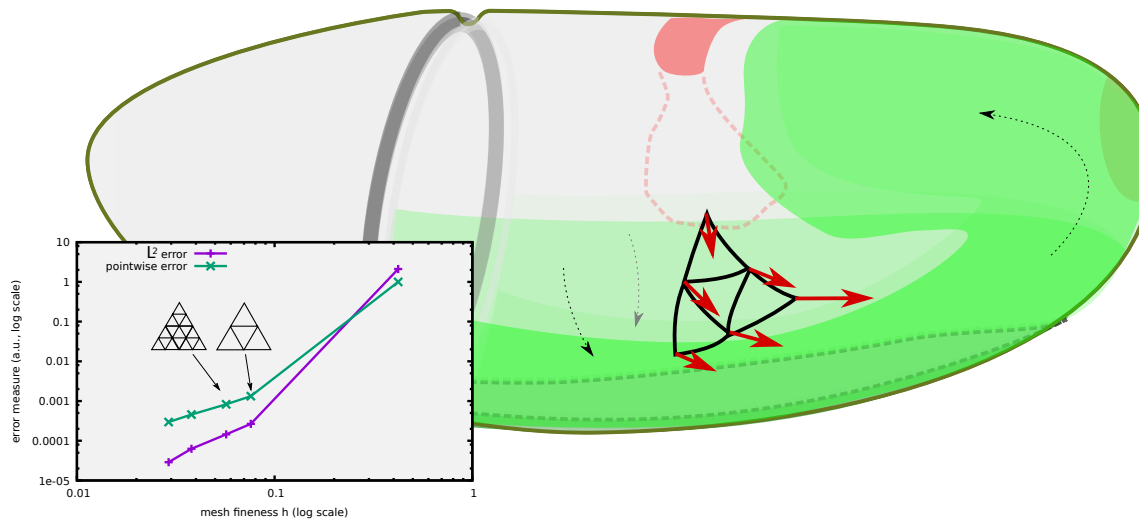


Numerical method



Solve as a constrained minimisation problem, $\min_{\{\mathbf{v} \cdot \mathbf{n} = 0\}} E(\mathbf{v})$

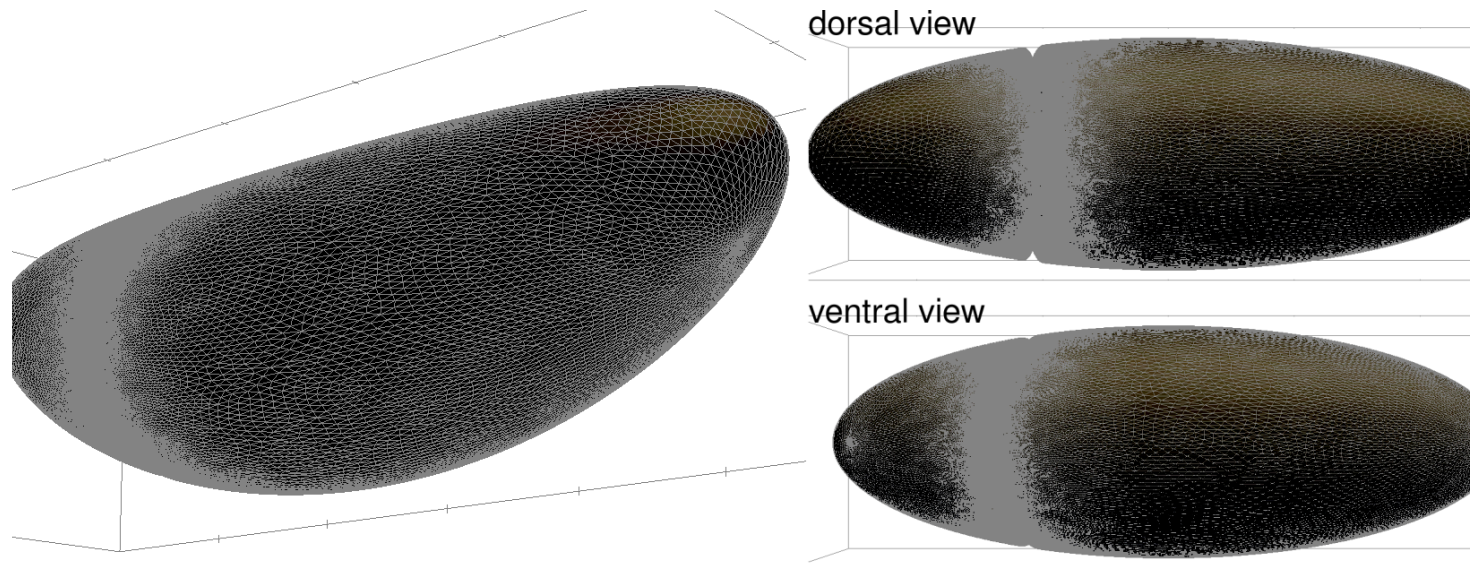
Numerical method : accuracy



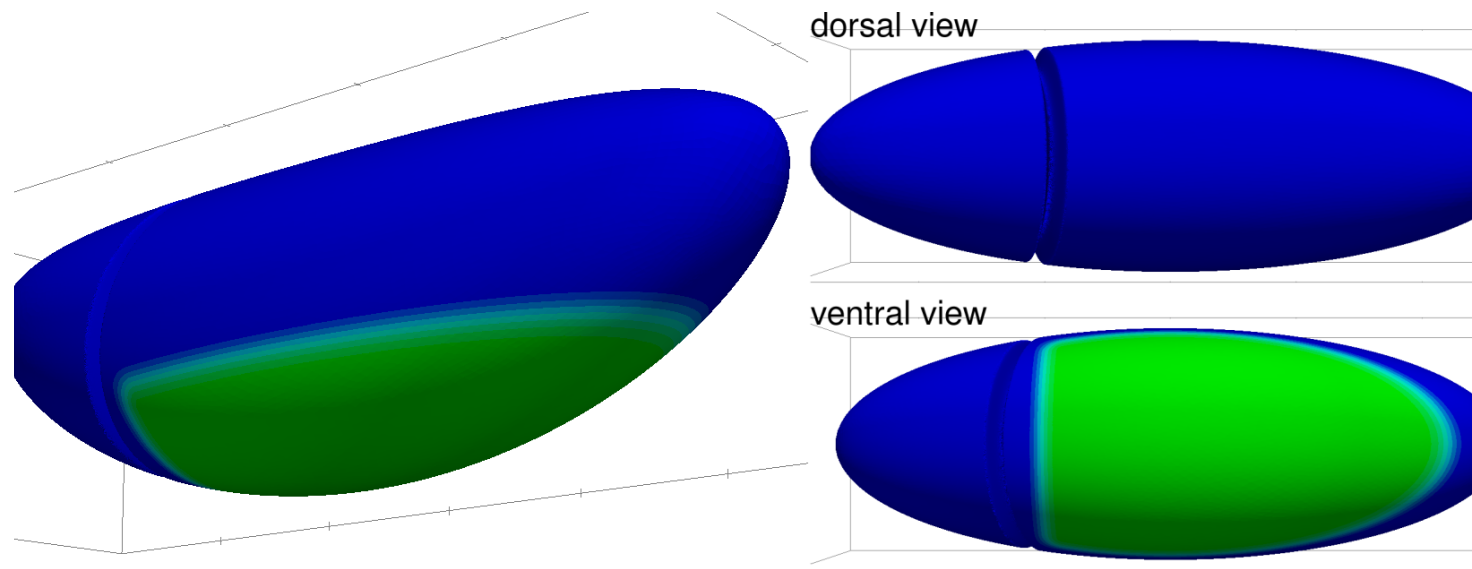
Solve as a constrained minimisation problem, $\min_{\{\mathbf{v} \cdot \mathbf{n} = 0\}} E(\mathbf{v})$

FEM code available on GitHub [Dijkstra et al. DICS-CP 2017]

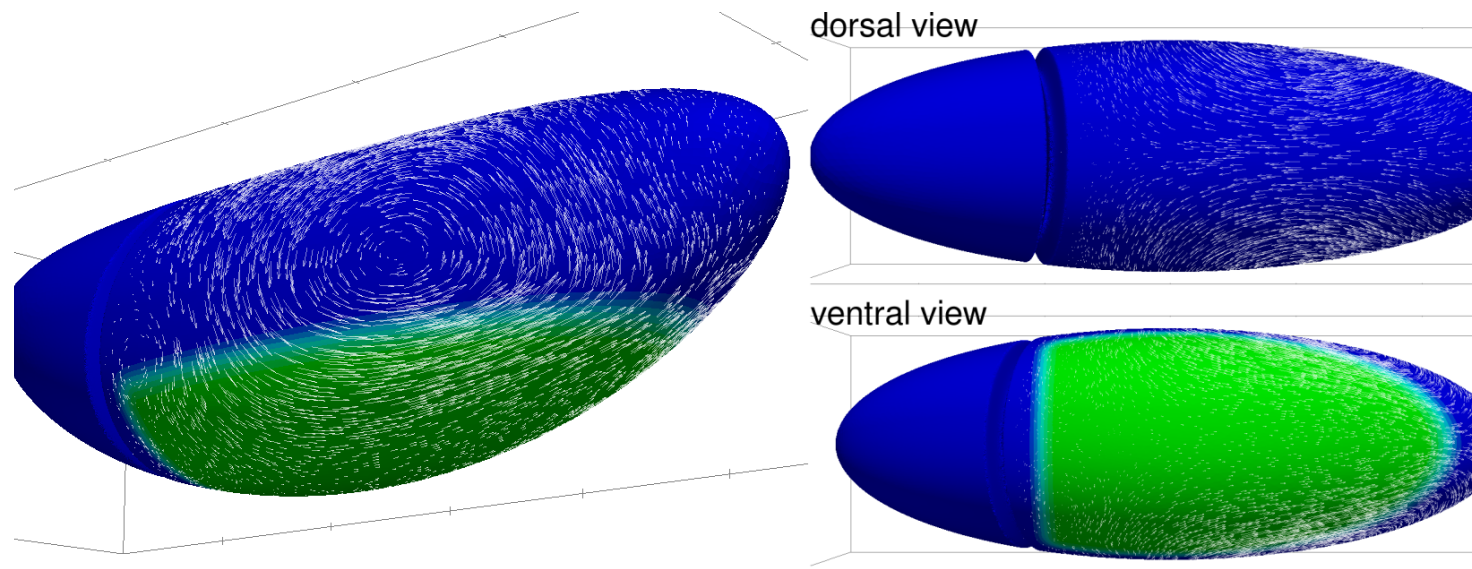
Simulation: Mesh



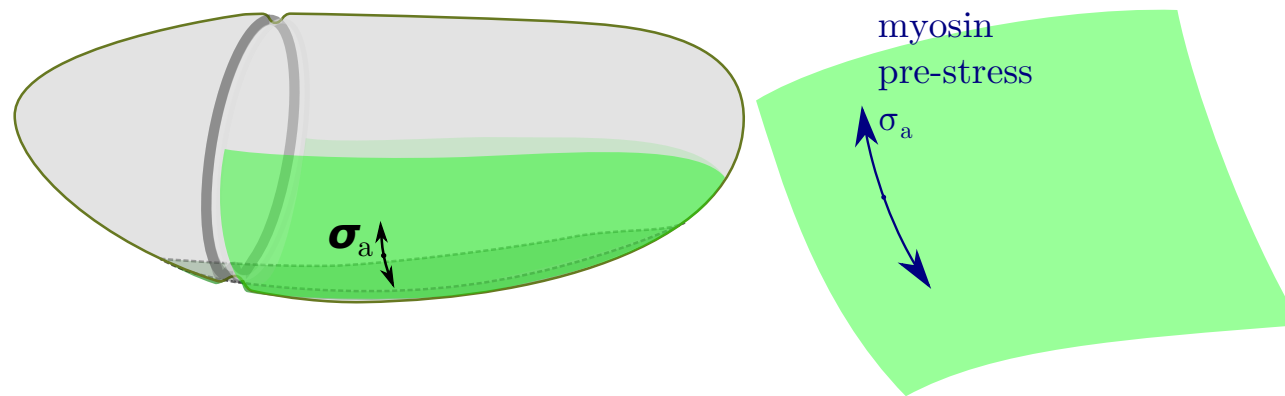
**Simulation:
Planar-polarised myosin**



Simulation:
Planar-polarised myosin can explain germband extension

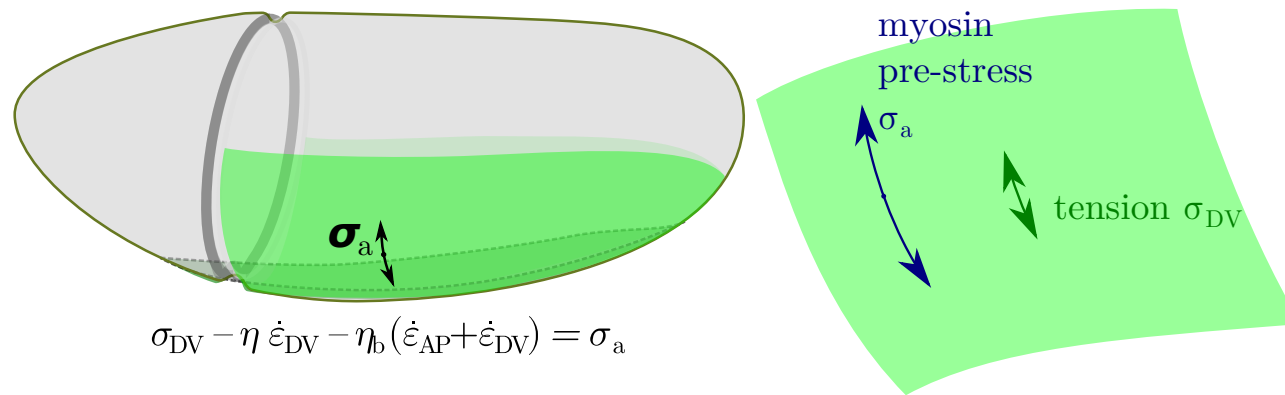


Germband extension modelling



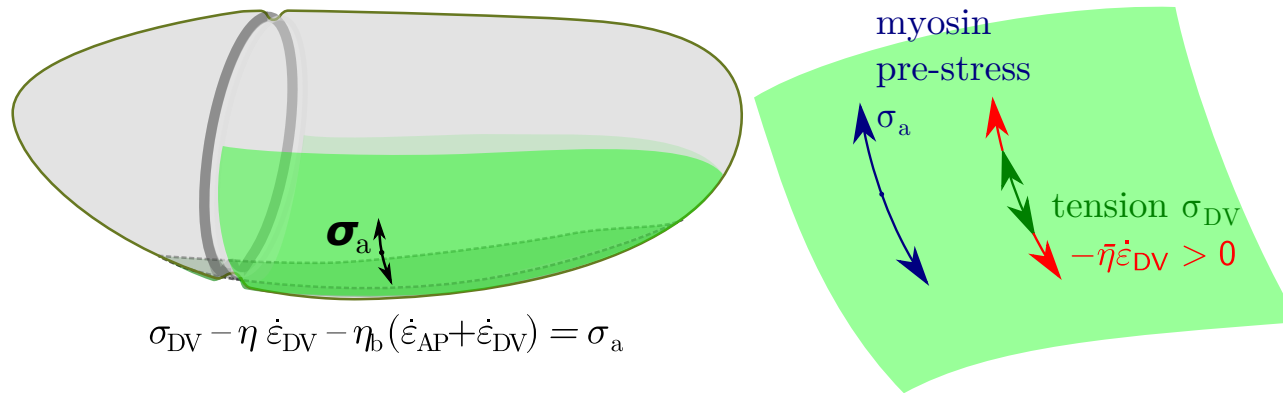
[Dicke et al. PLoS CR 2017]

Germband extension modelling



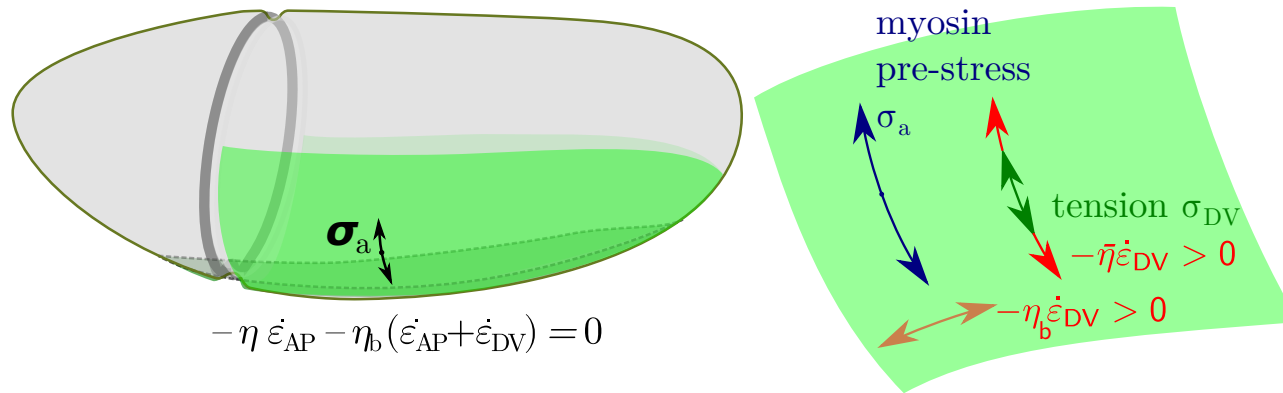
[Dicke et al. PLoS CR 2017]

Germband extension modelling



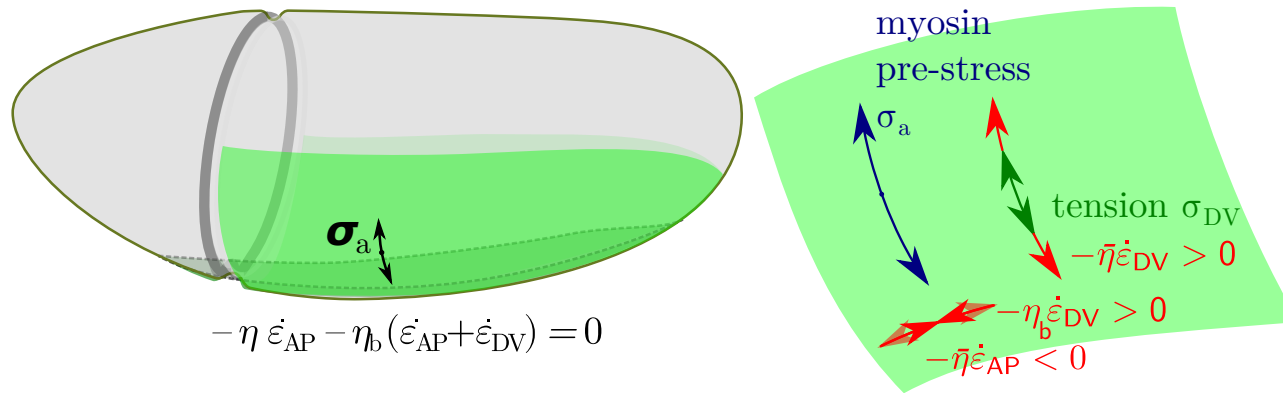
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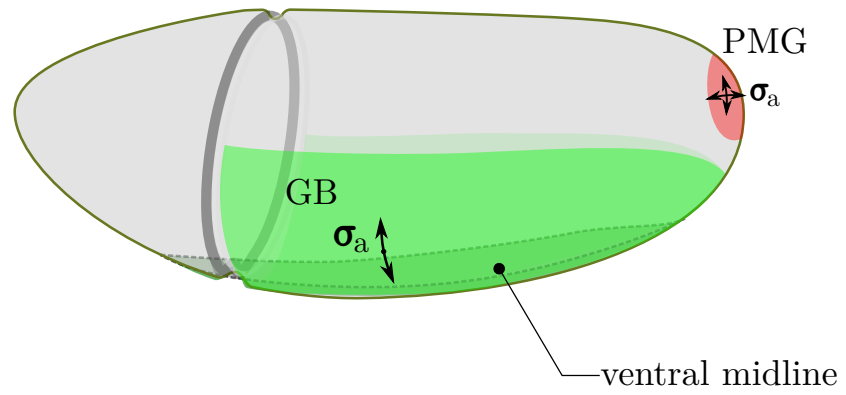
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Germband extension modelling



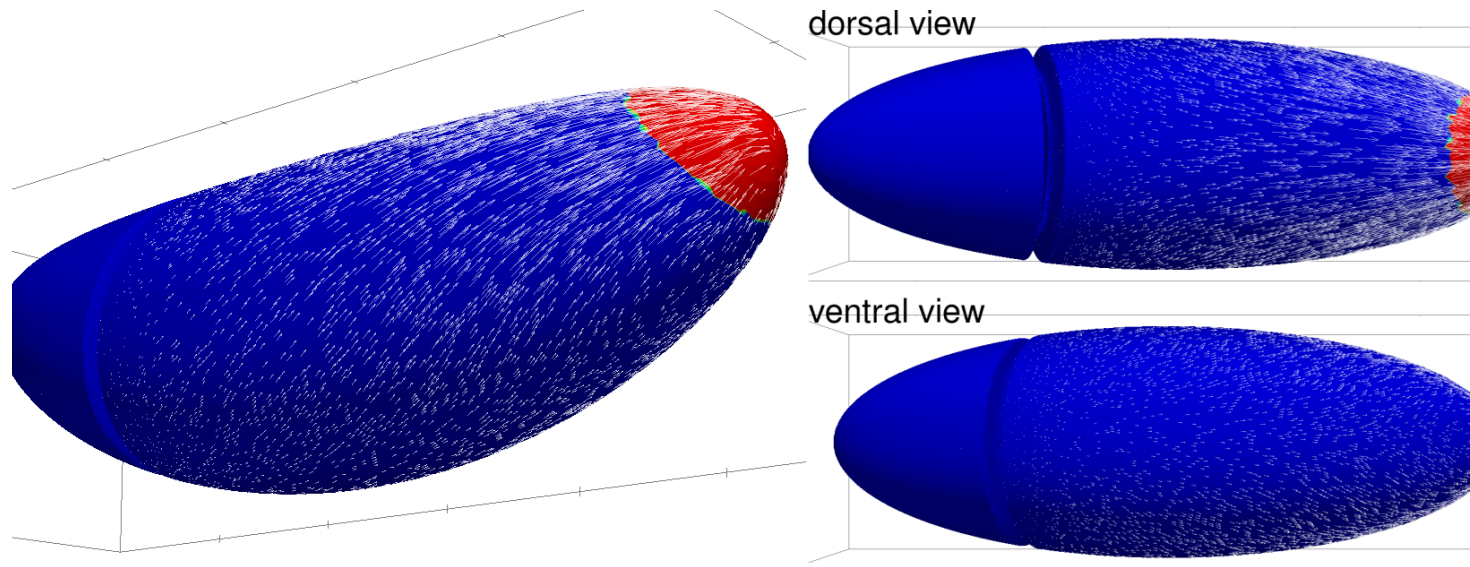
[Dicke et al. PLoS CR 2017]

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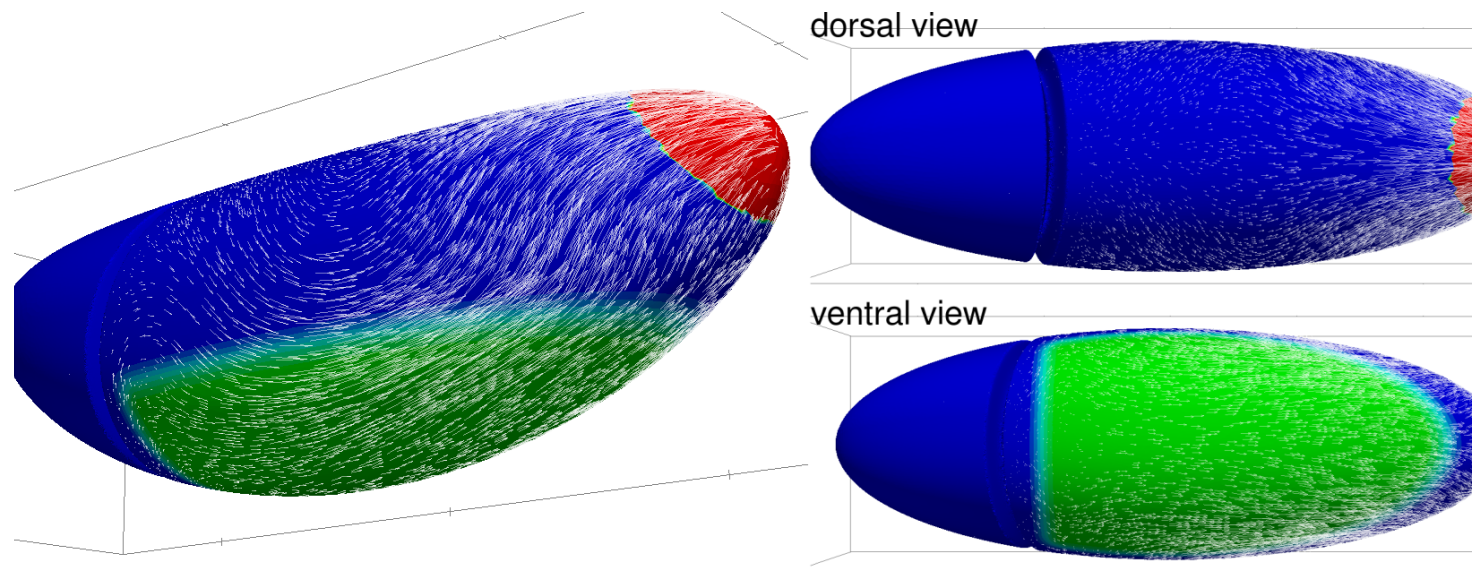


[Butler et al. 2000; Collinet et al. Iye et al. 2015]

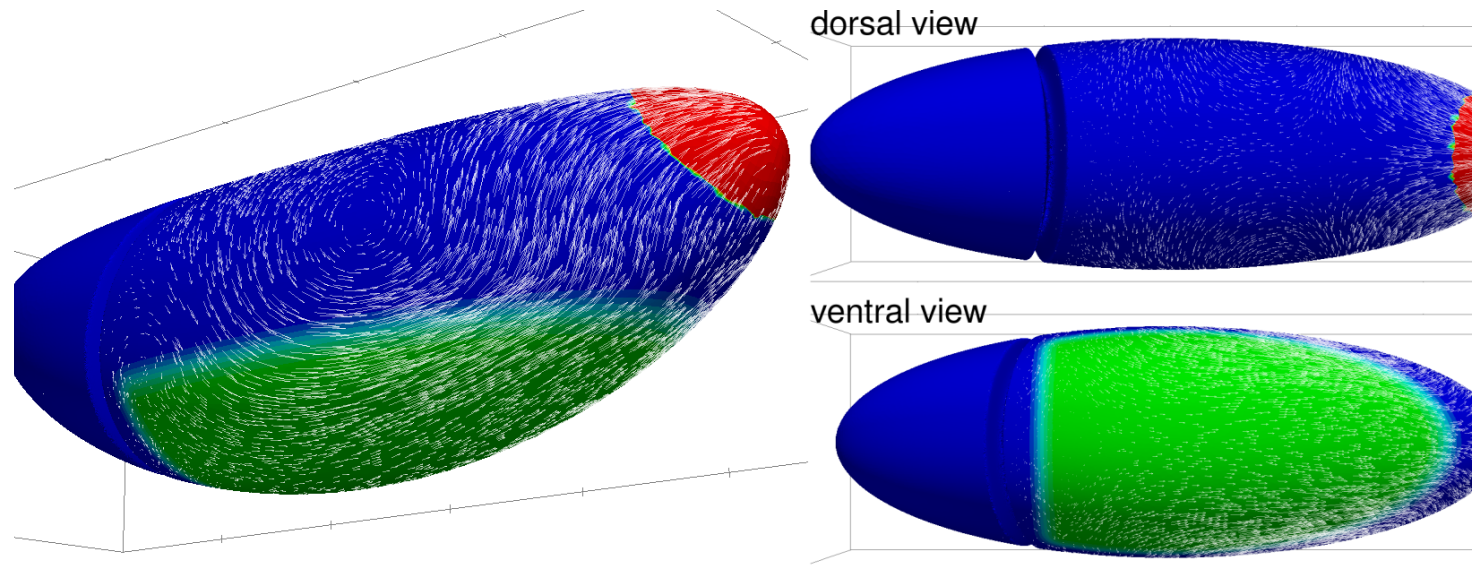
Germband extends under the action of PMG pull



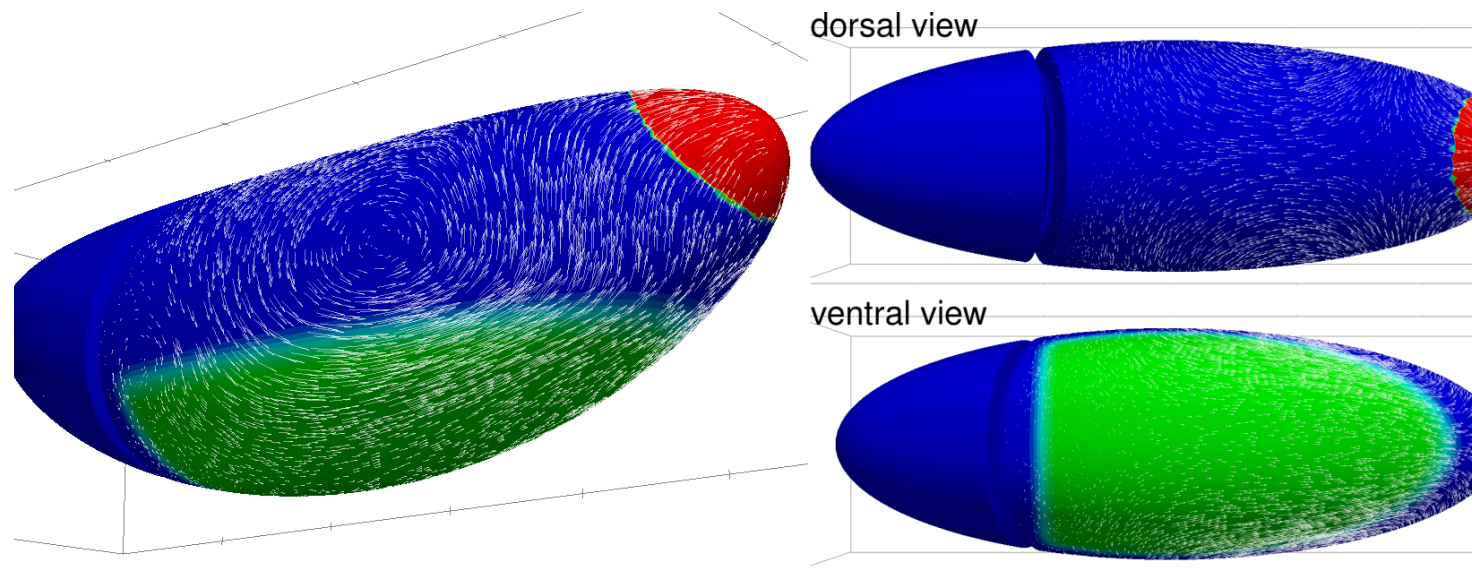
**Germband extends under the action of PMG pull
and/or planar-polarised myosin**



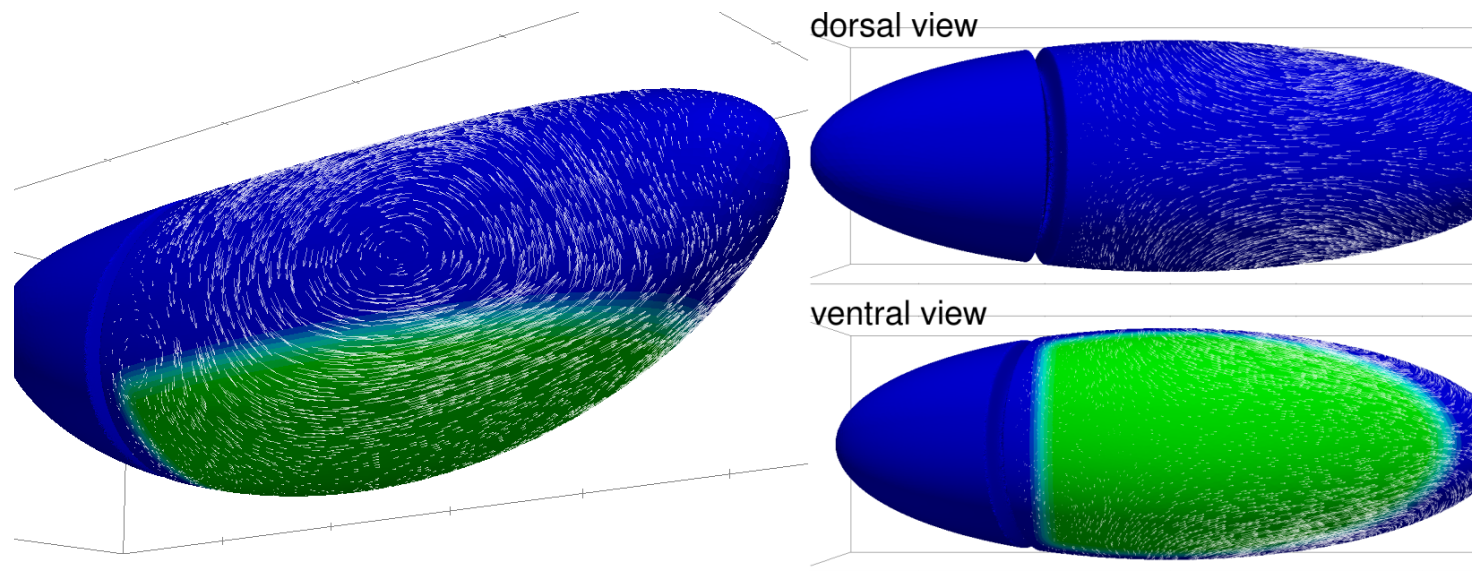
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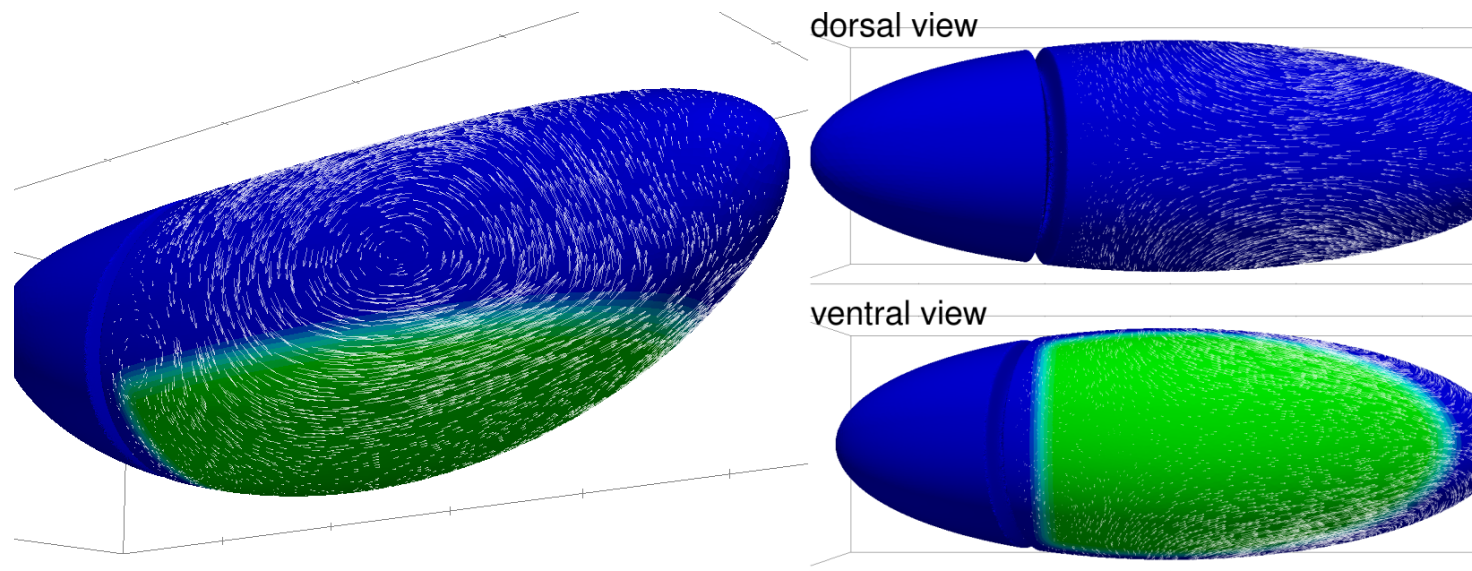
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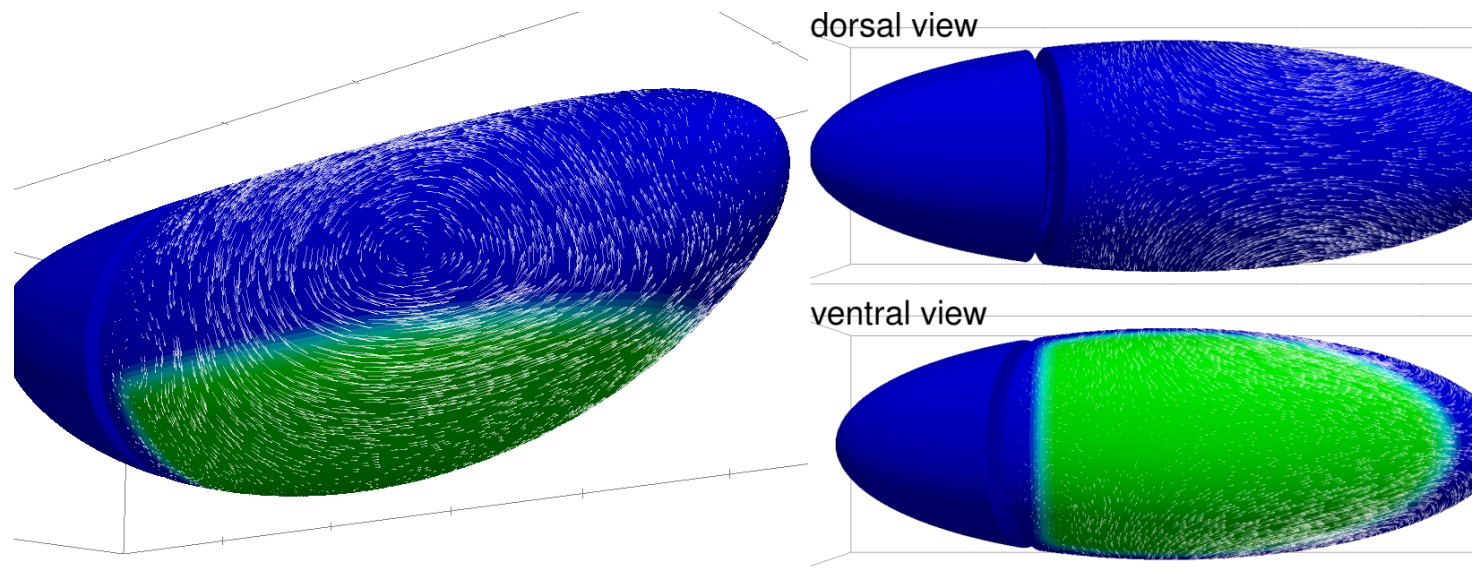
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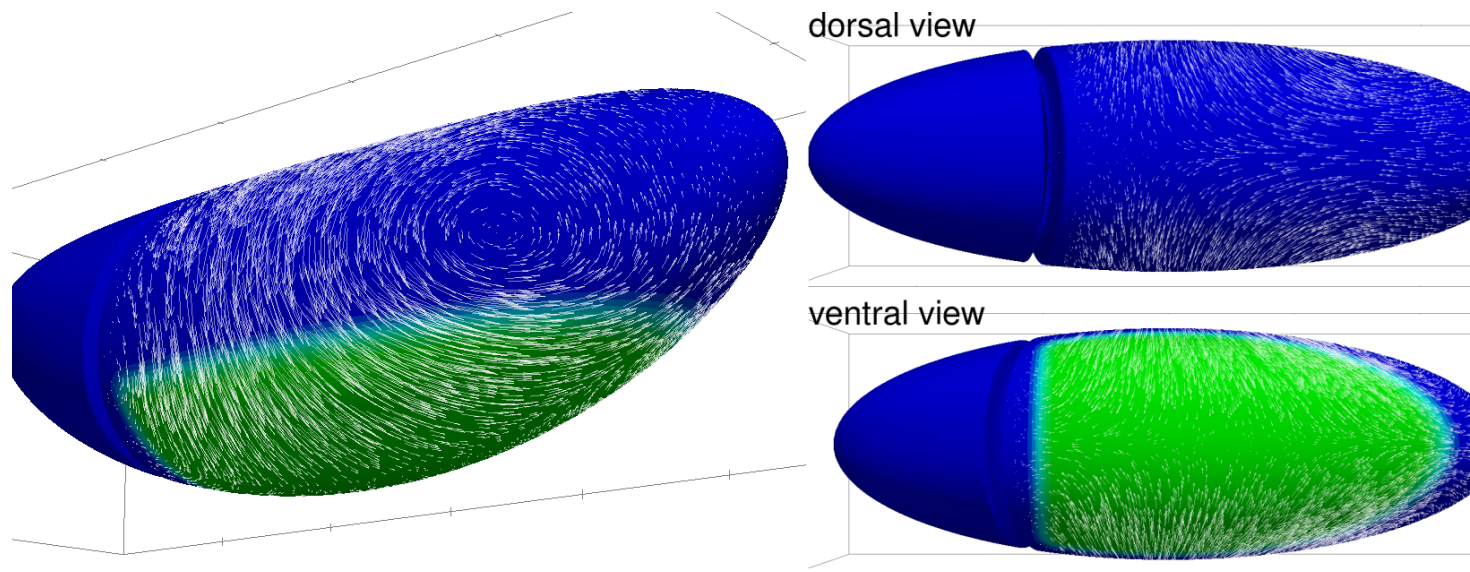
Resistance to changes of apical area and morphogenetic flow



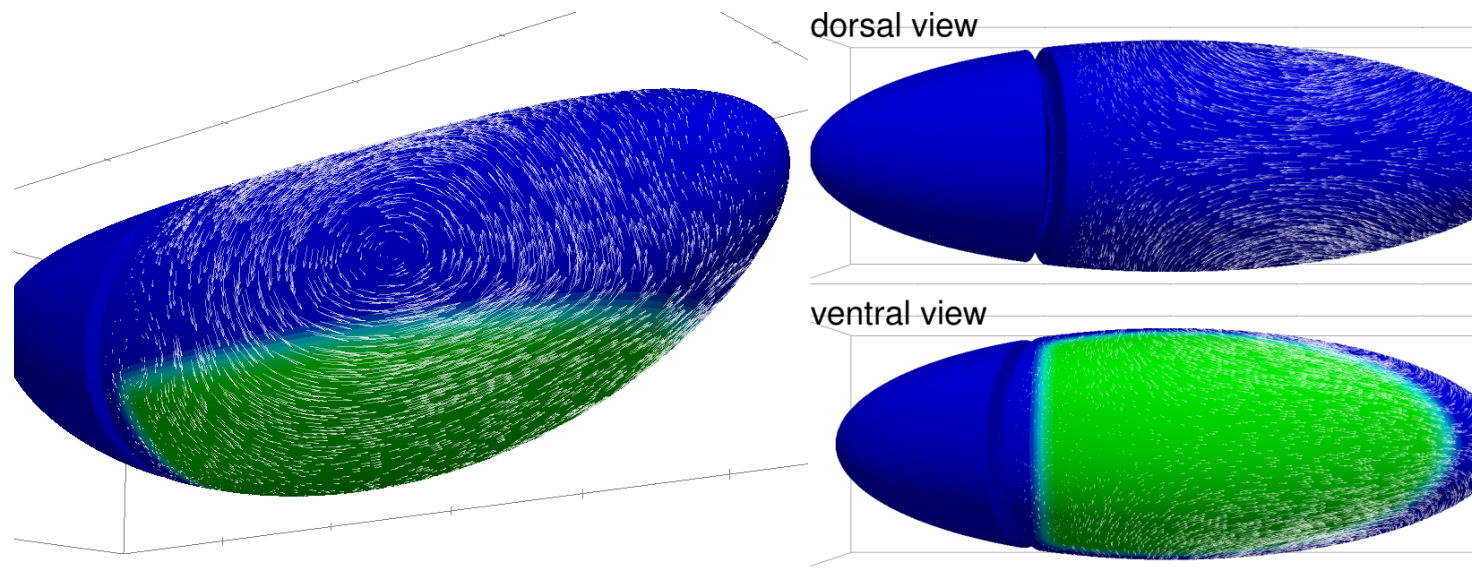
Resistance to changes of apical area and morphogenetic flow



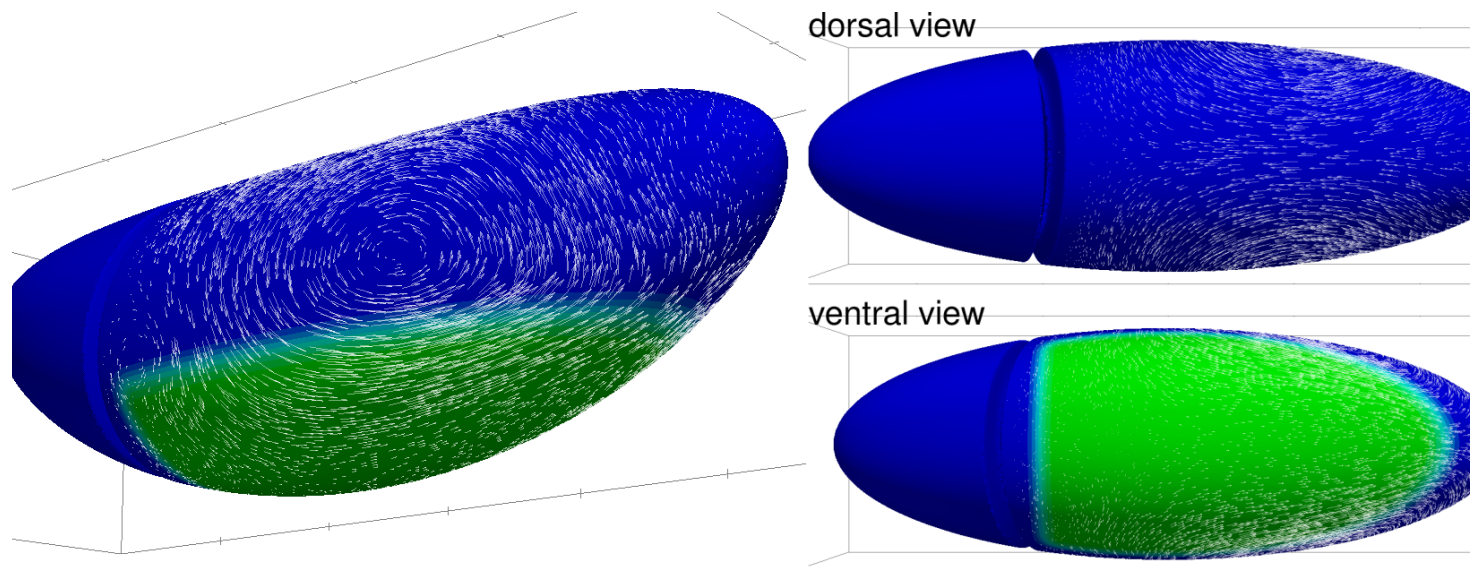
Resistance to changes of apical area and morphogenetic flow



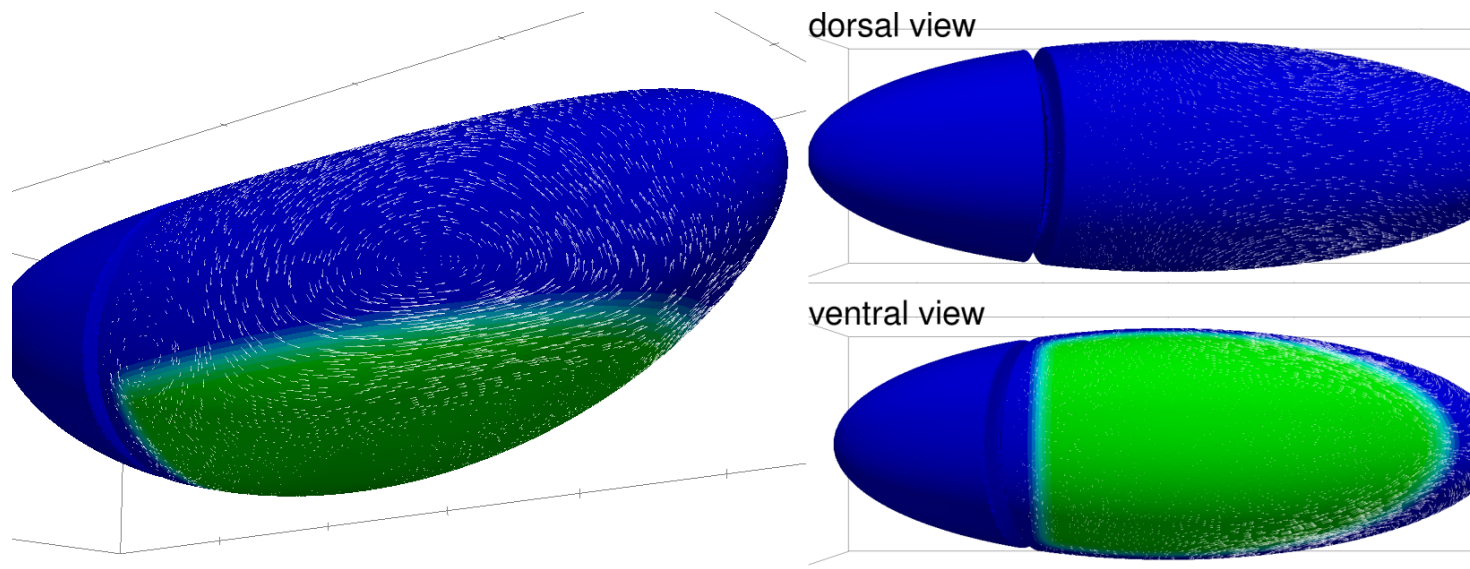
Hydrodynamic length and morphogenetic flow



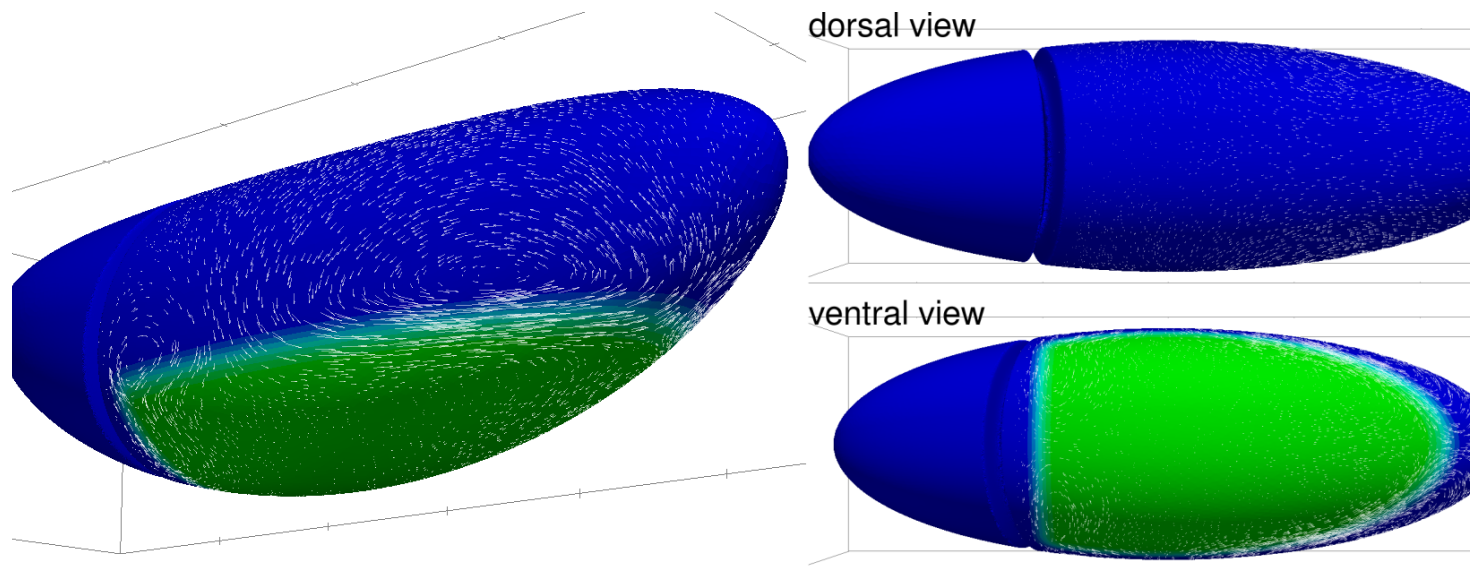
Hydrodynamic length and morphogenetic flow



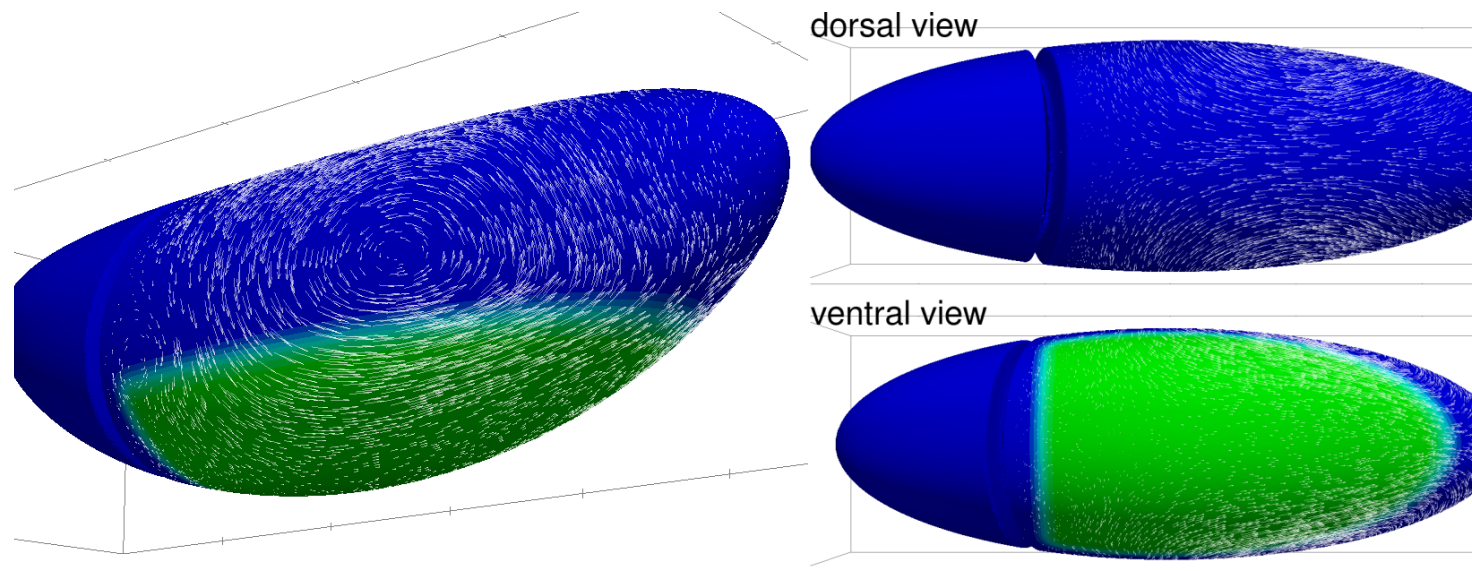
Hydrodynamic length and morphogenetic flow



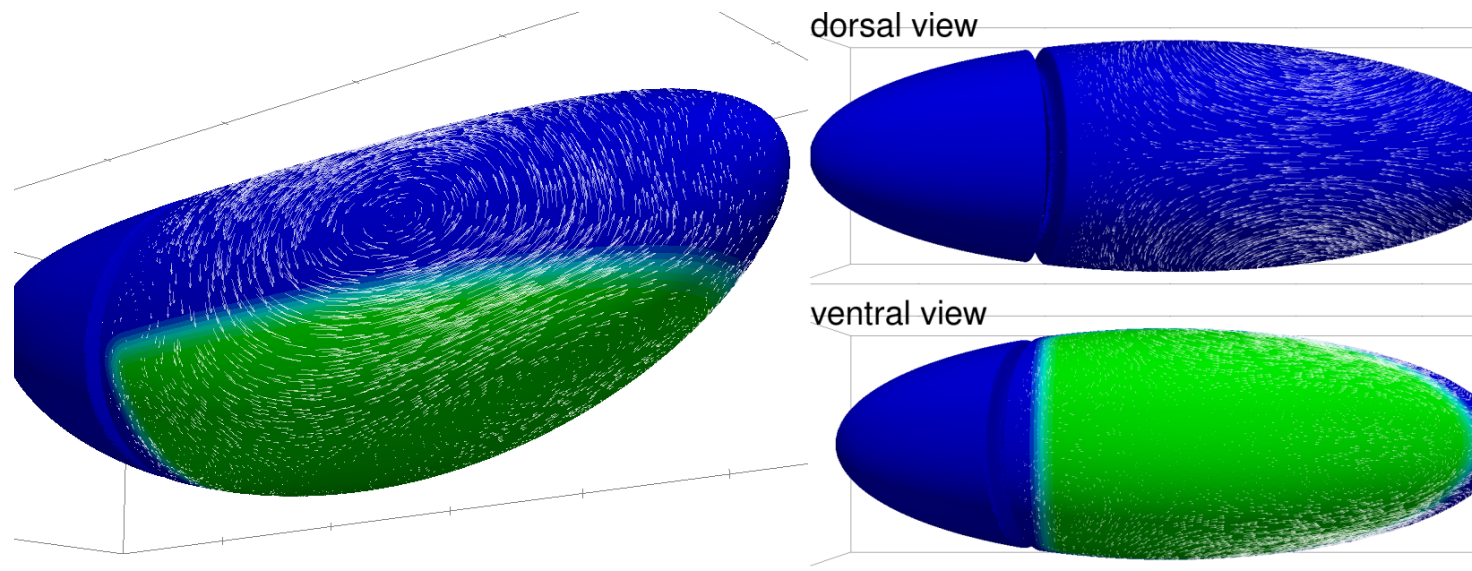
Hydrodynamic length and morphogenetic flow



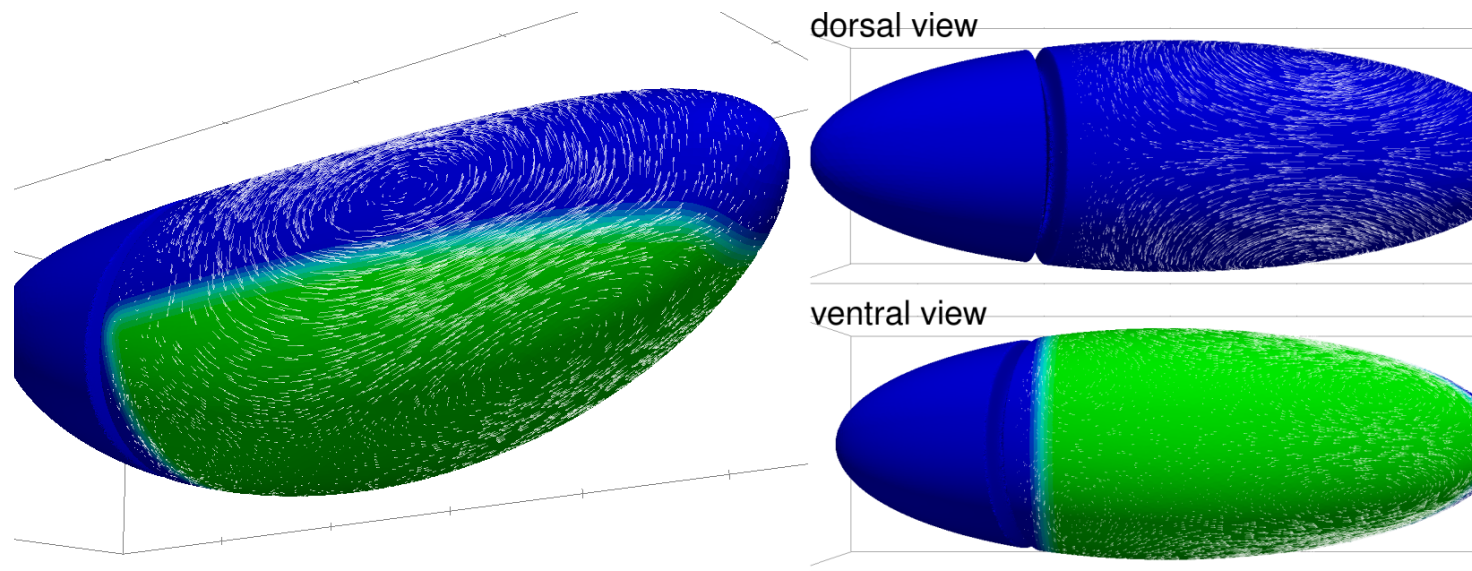
Geometry of myosin patterning and morphogenetic flow



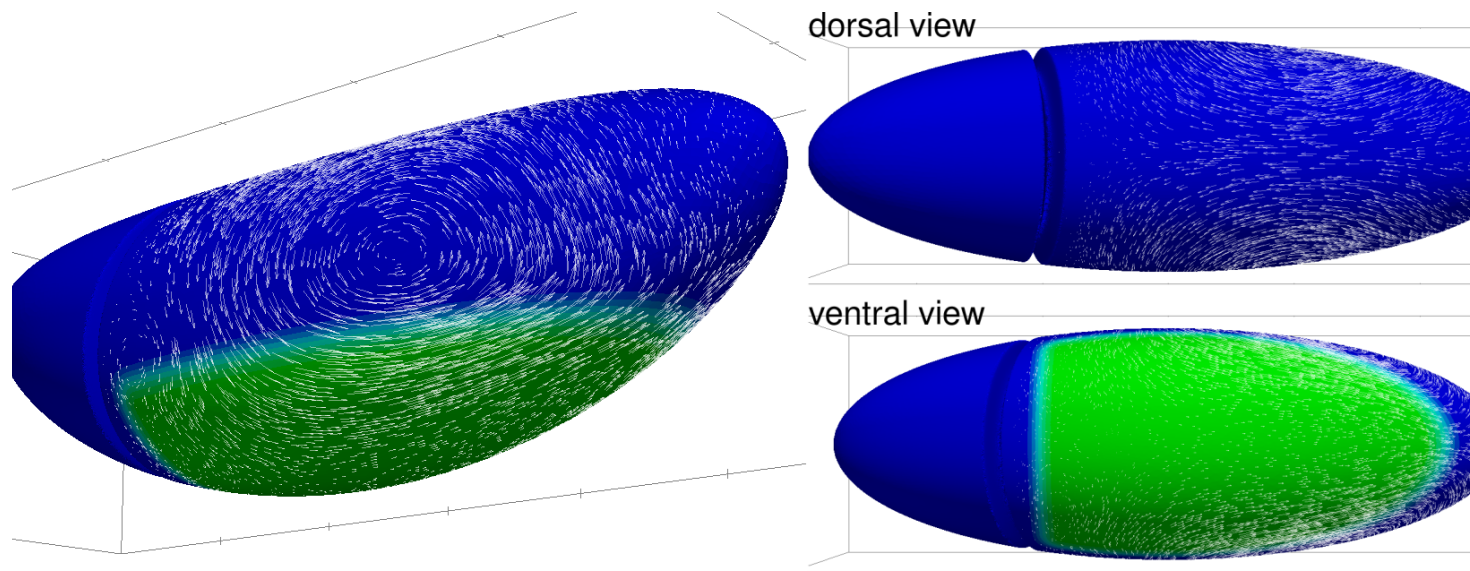
Geometry of myosin patterning and morphogenetic flow



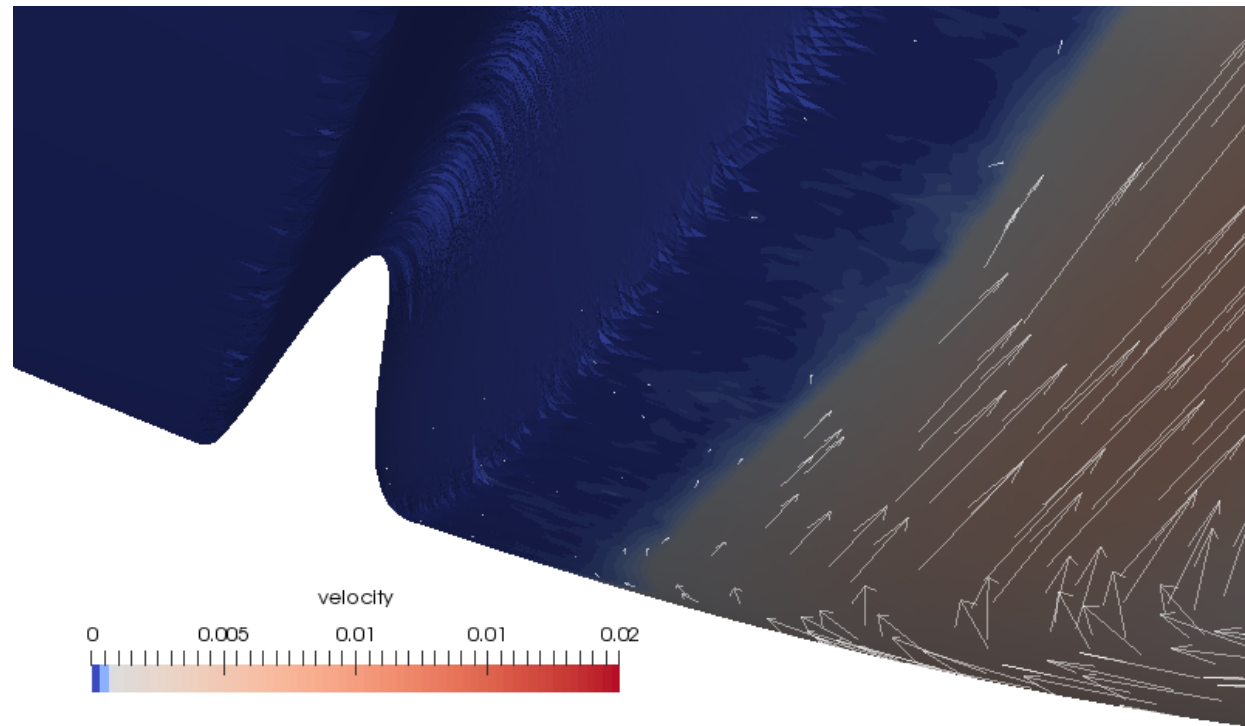
Geometry of myosin patterning and morphogenetic flow



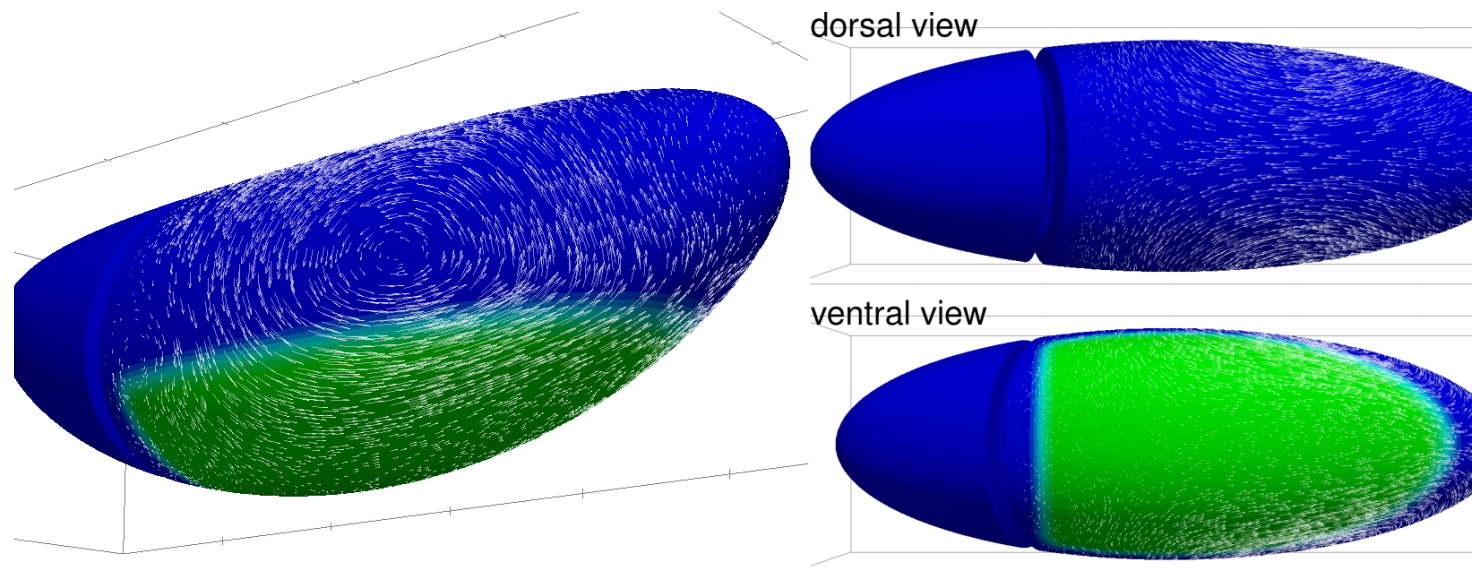
Cephalic furrow guides morphogenetic flow



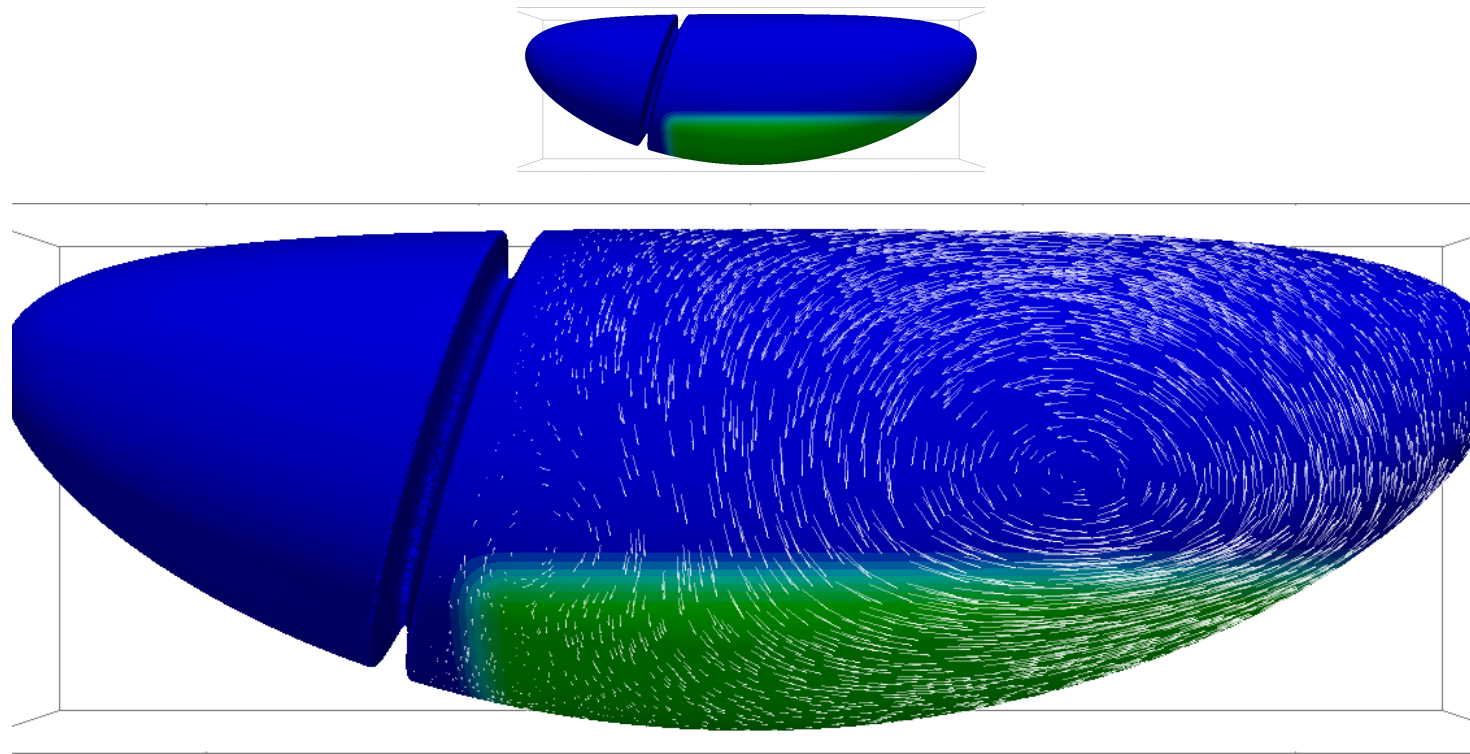
Cephalic furrow guides morphogenetic flow



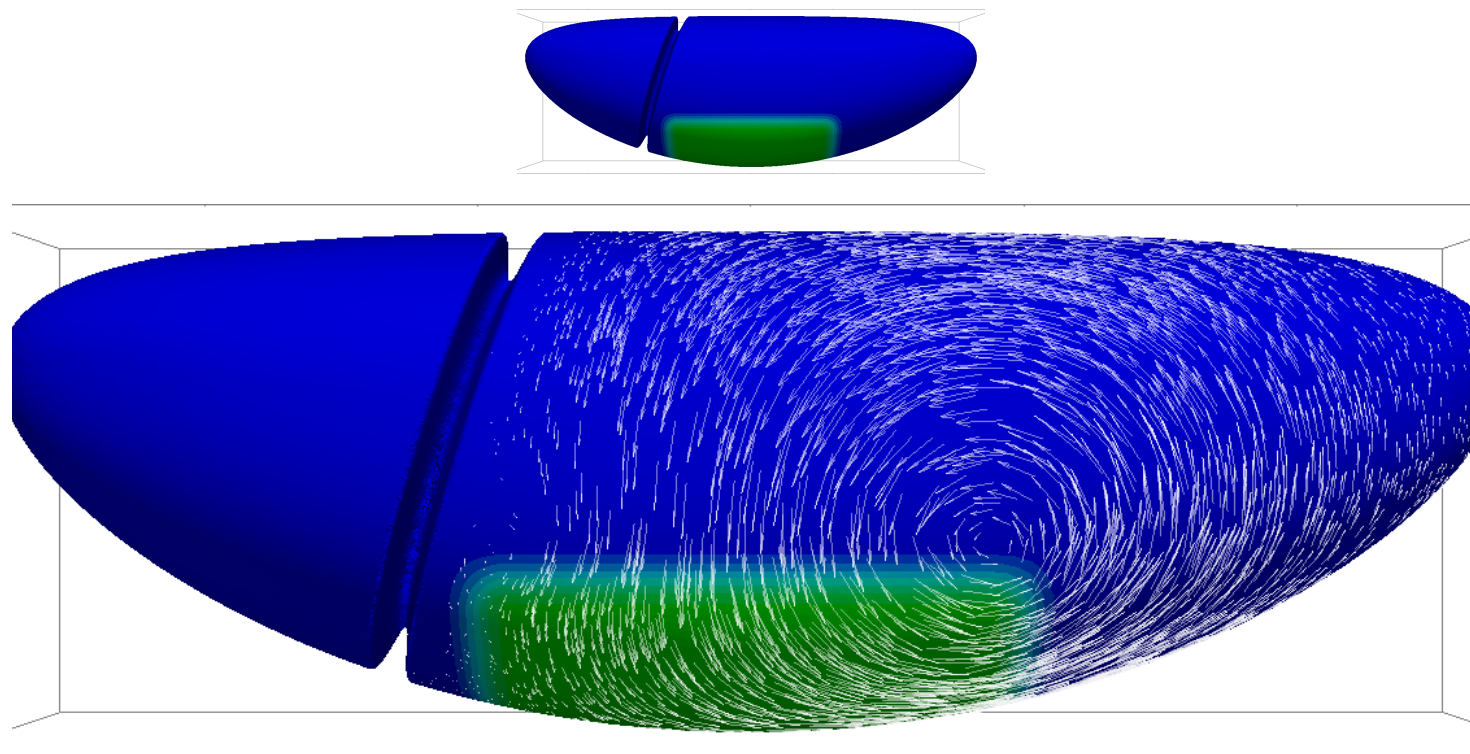
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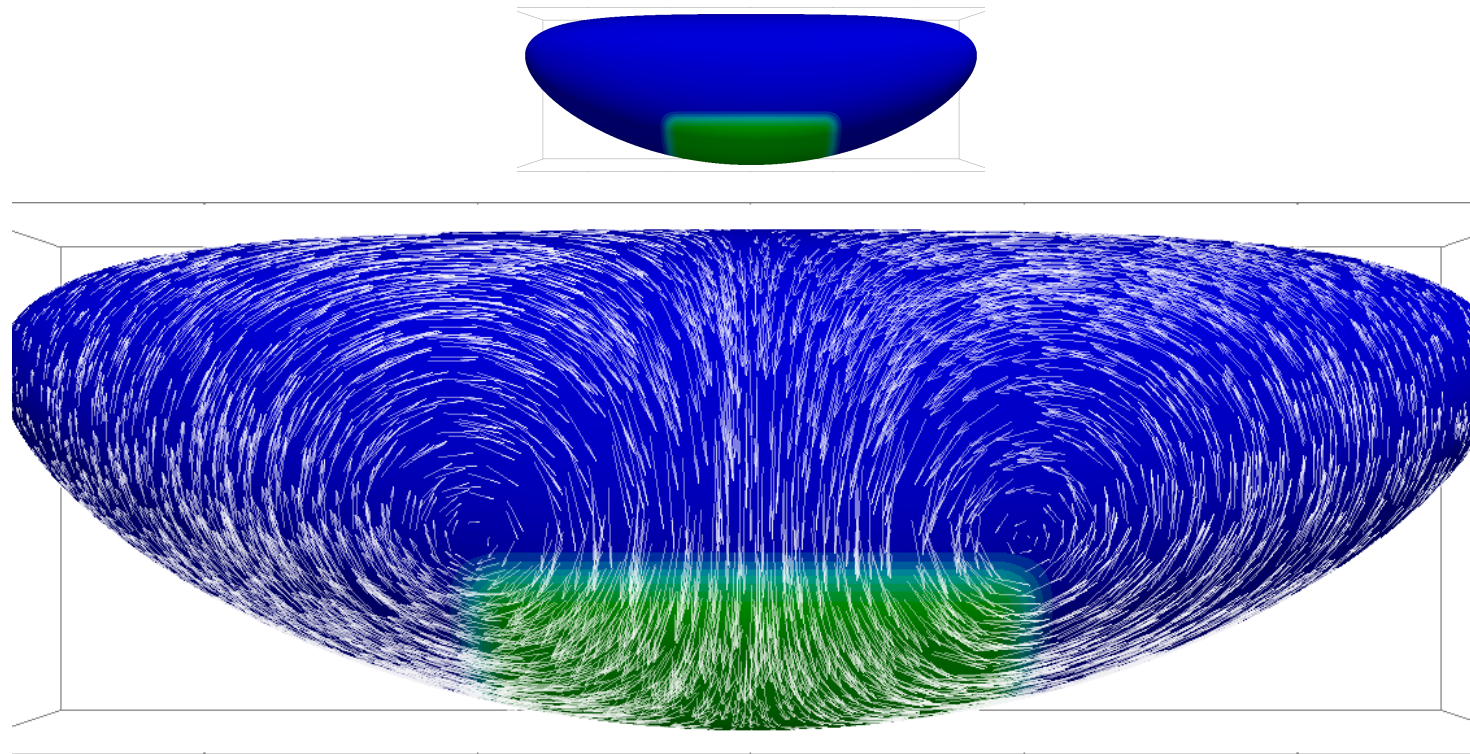
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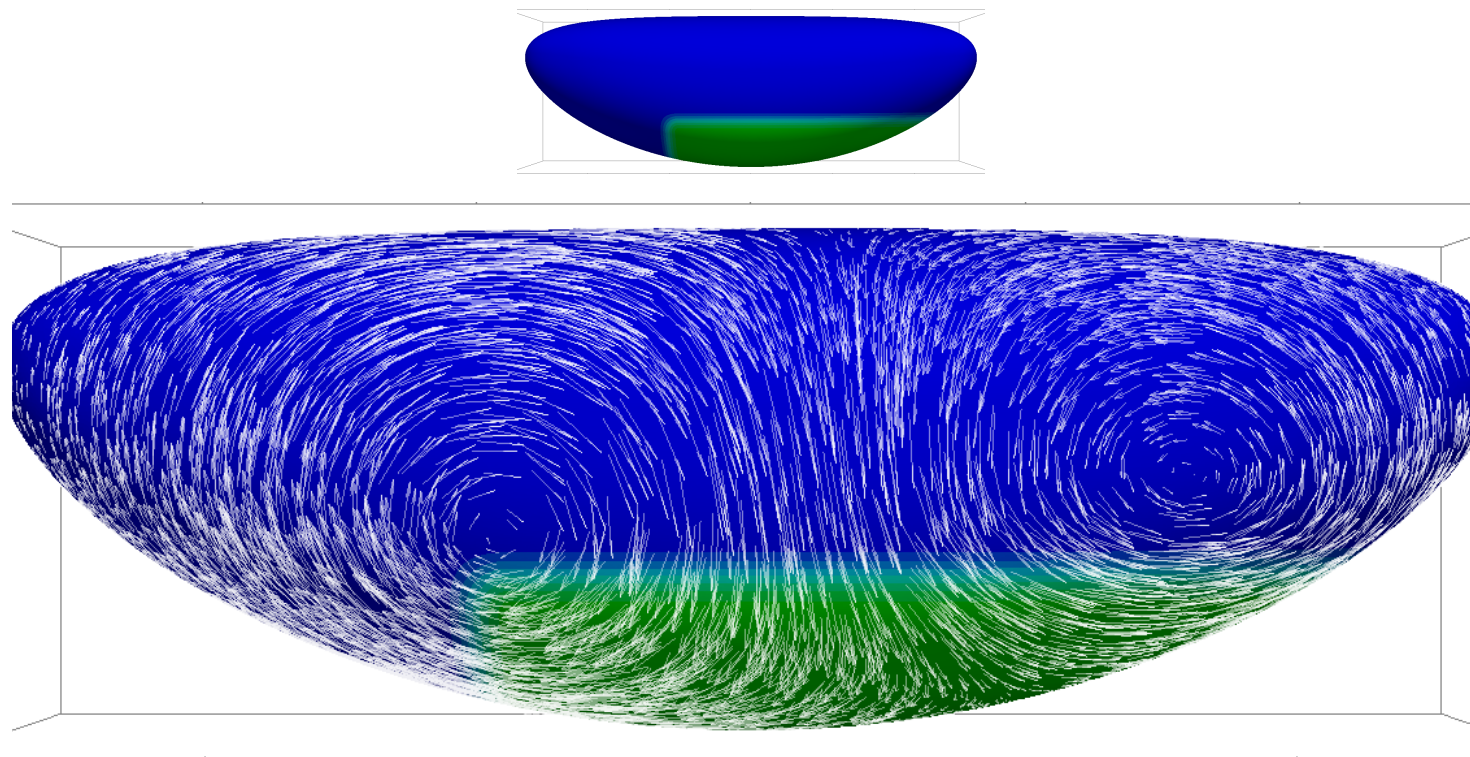
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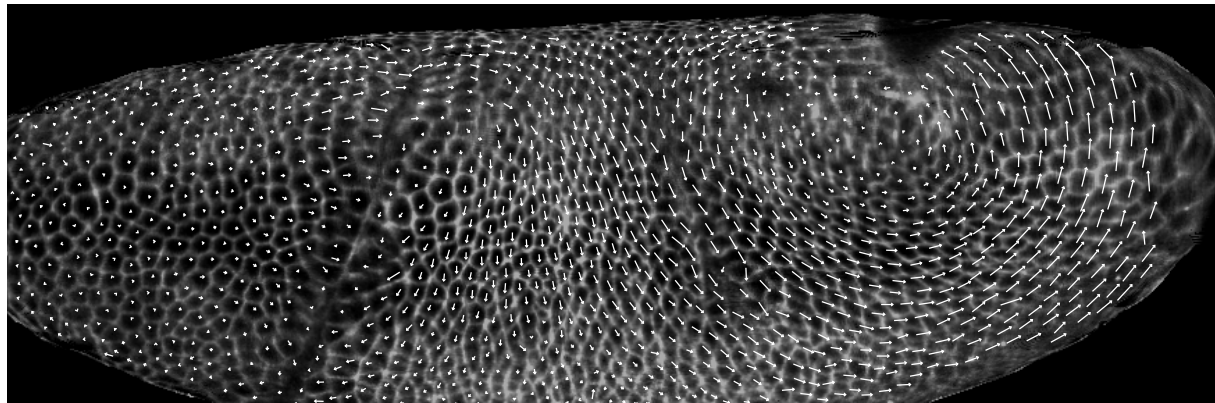
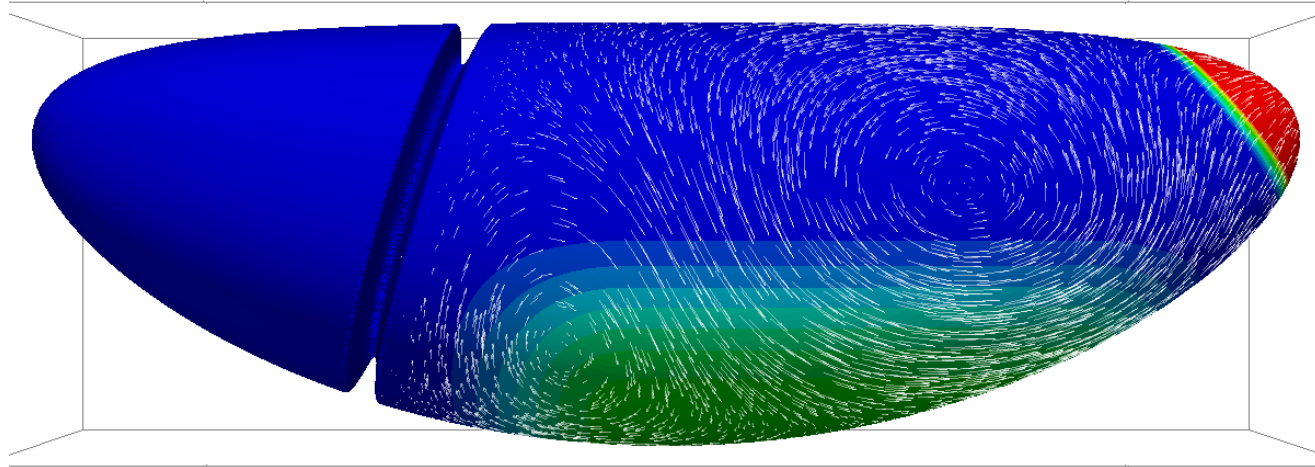
Cephalic furrow guides morphogenetic flow



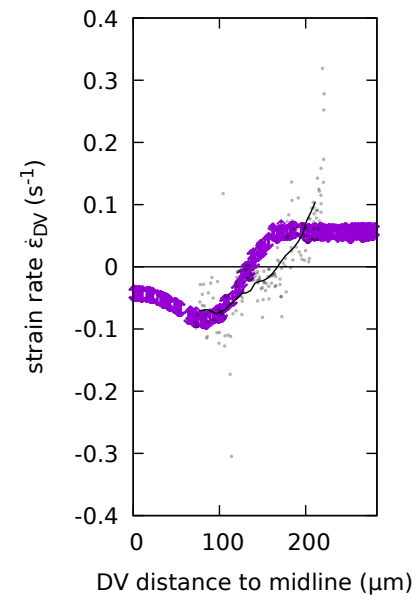
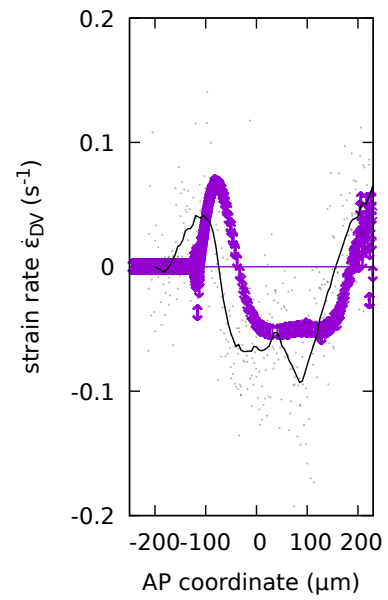
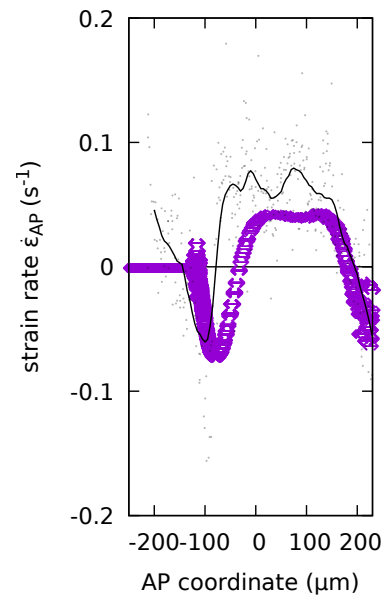
Cephalic furrow guides morphogenetic flow



Comparison with real data



Comparison with real data



Conclusions and perspectives

- ▶ Whole embryo mechanics can be crucial for our understanding

Conclusions and perspectives

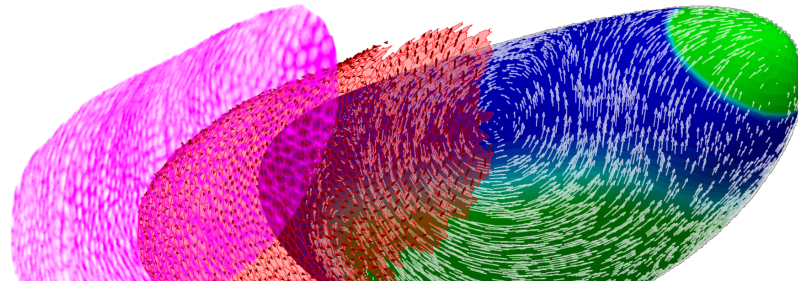
- ▶ Whole embryo mechanics can be crucial for our understanding
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Conclusions and perspectives

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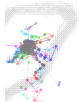
Conclusions and perspectives

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- ▶ Towards an integration with whole-embryo imaging: are geometry and myosin signal fully predictive of flows?

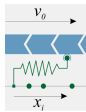


Co-workers

PHY:Physics@Grenoble



Nilankur Dutta



Haythem Chelly



Pierre Recho



Claude Verdier



Catherine Quilliet



Philippe Marmottant

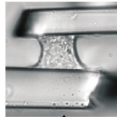


Alexandr Farutin



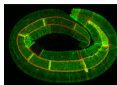
Chaouqi Misbah

MSC:Physics@Paris



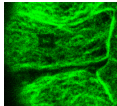
Atef Asnacios

IGDR:DevBiol@Rennes

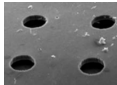


Grégoire Michaux

LTM:Nanomat@Grenoble

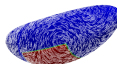


Sara Bouizakarne



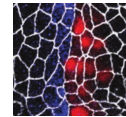
Alice Nicolas

LJK:Maths@Grenoble

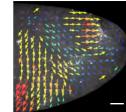


Mahamar Dicko

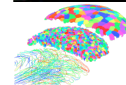
PDN:DevBiol@Cambridge



Bénédicte Sanson

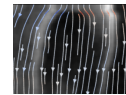


Claire Lye



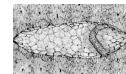
Guy Blanchard

DAMTP:Maths@Cambridge



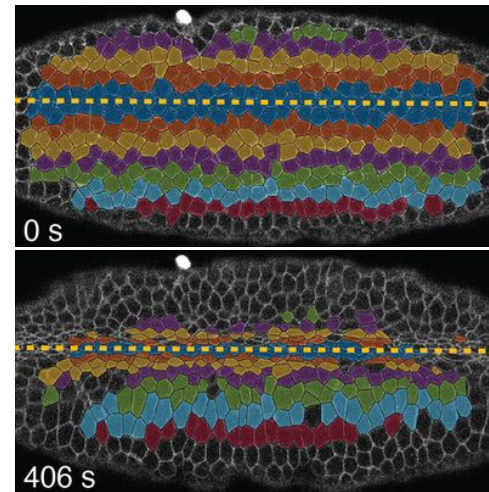
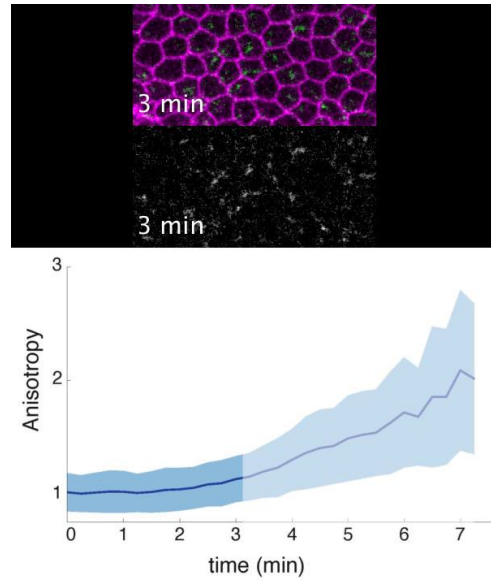
Lukas Lang

CSIC:DevBiol@Madrid



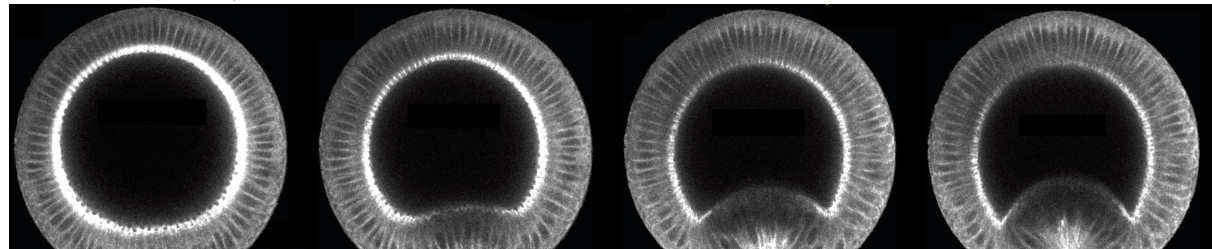
Nicole Gorfinkiel

Contraction and ventral furrow formation

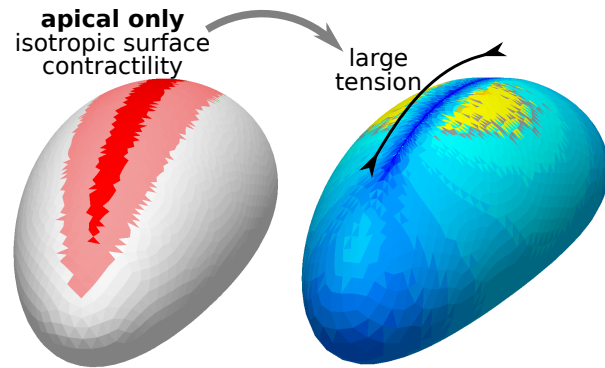


Heer et al., 2017

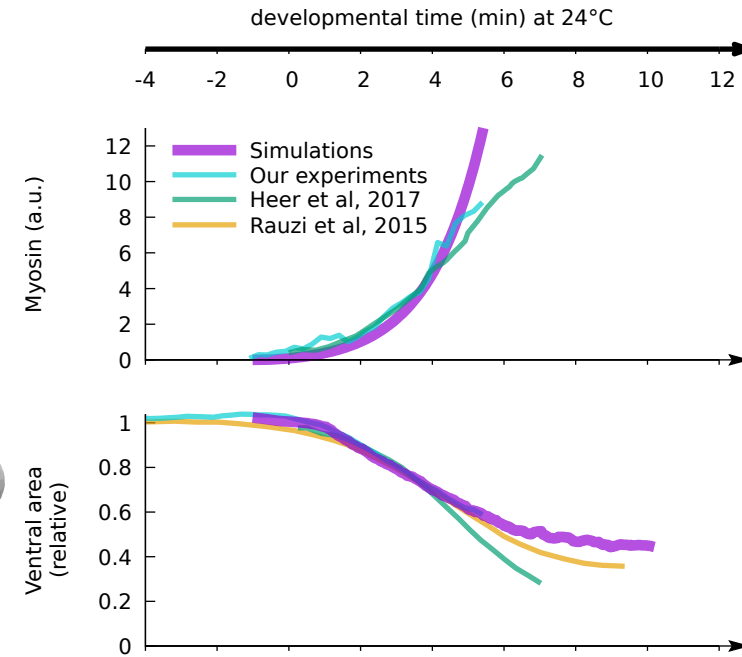
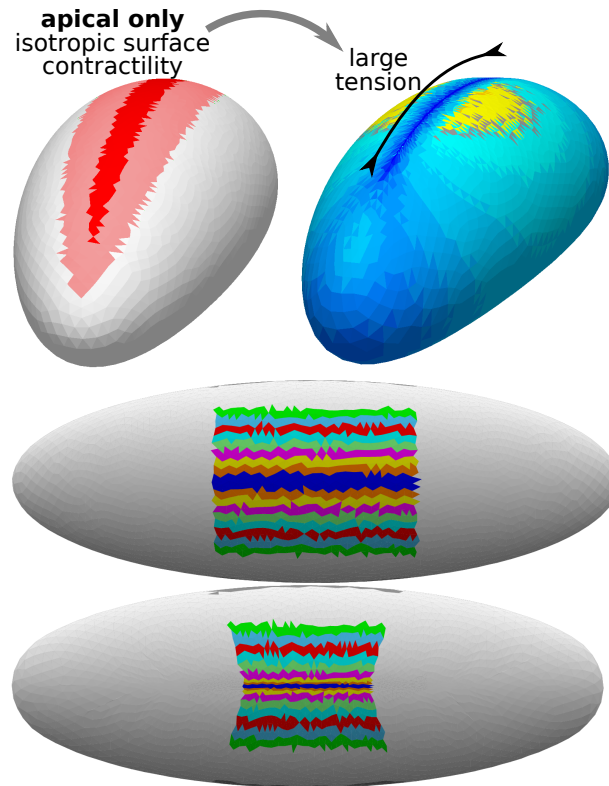
Chanet et al, 2017



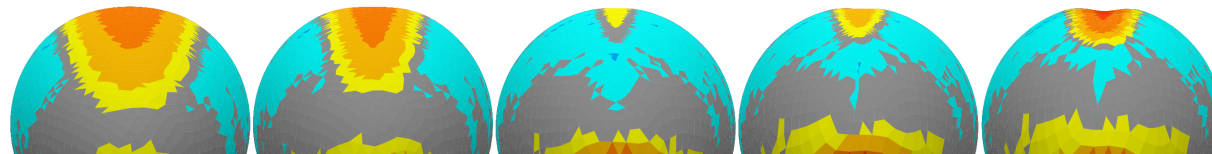
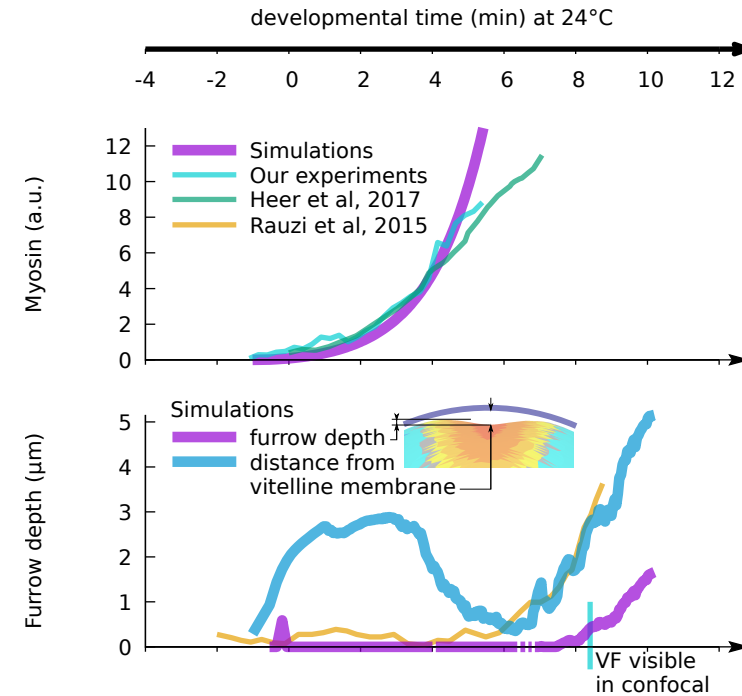
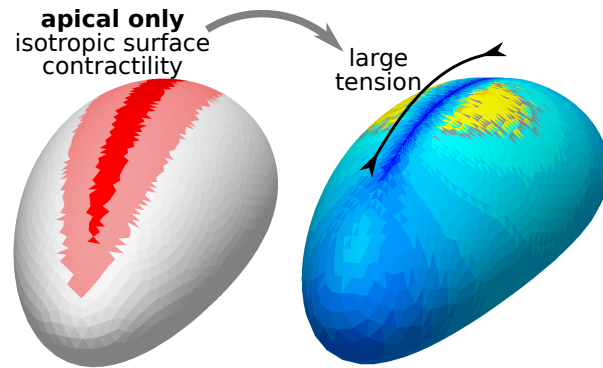
Apical drive of ventral furrow formation



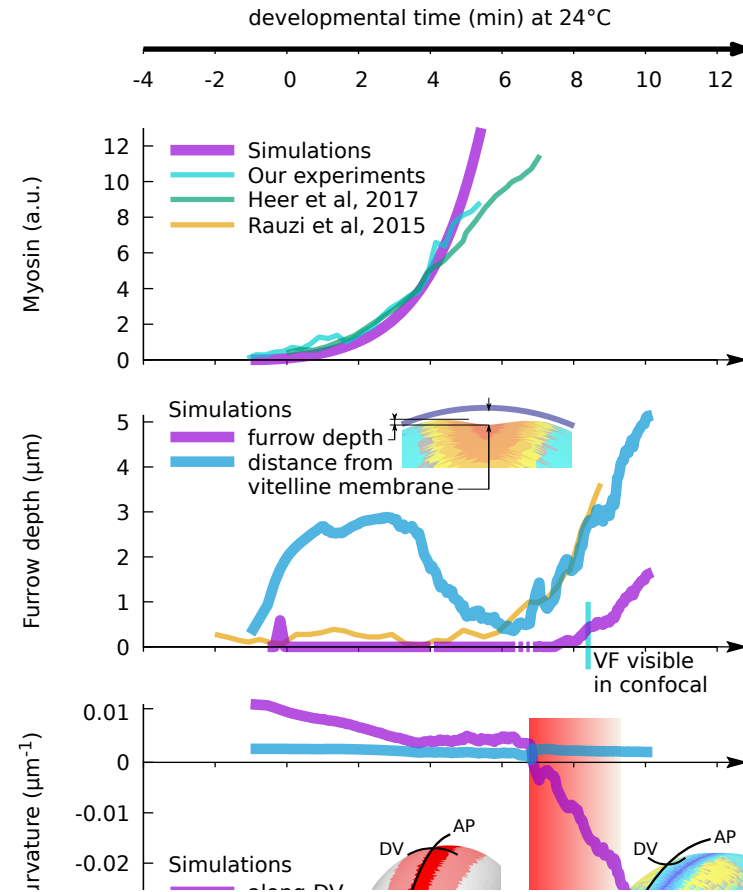
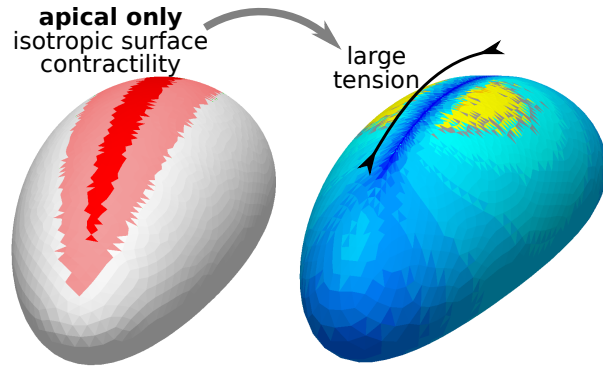
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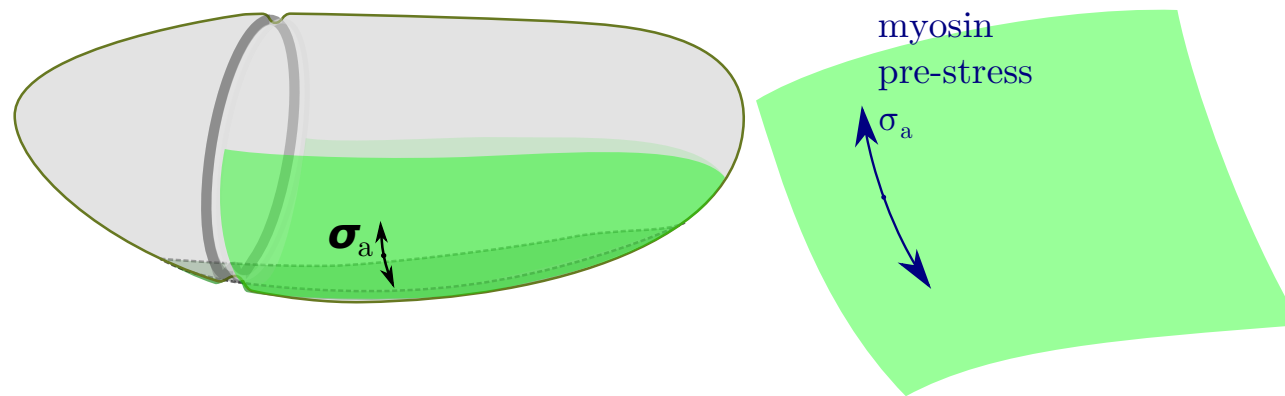
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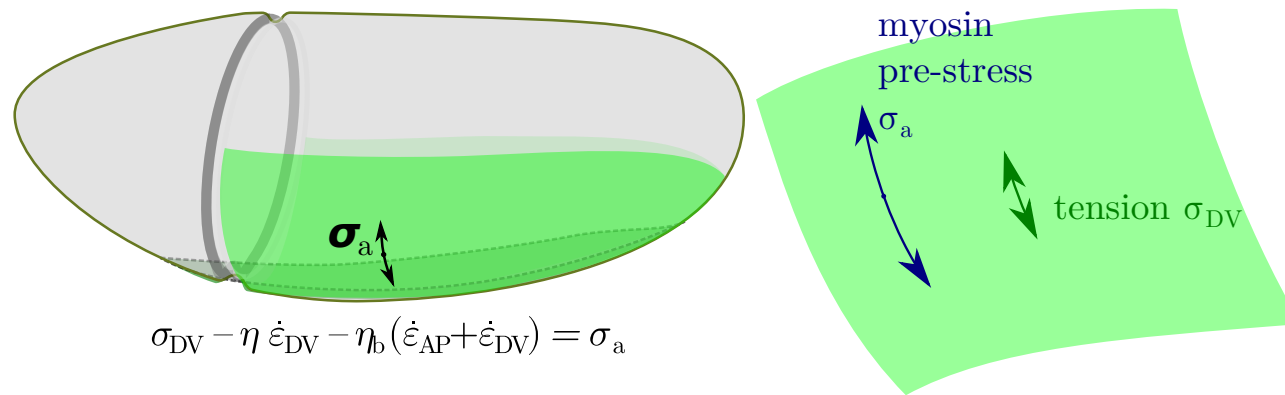


Germband extension modelling



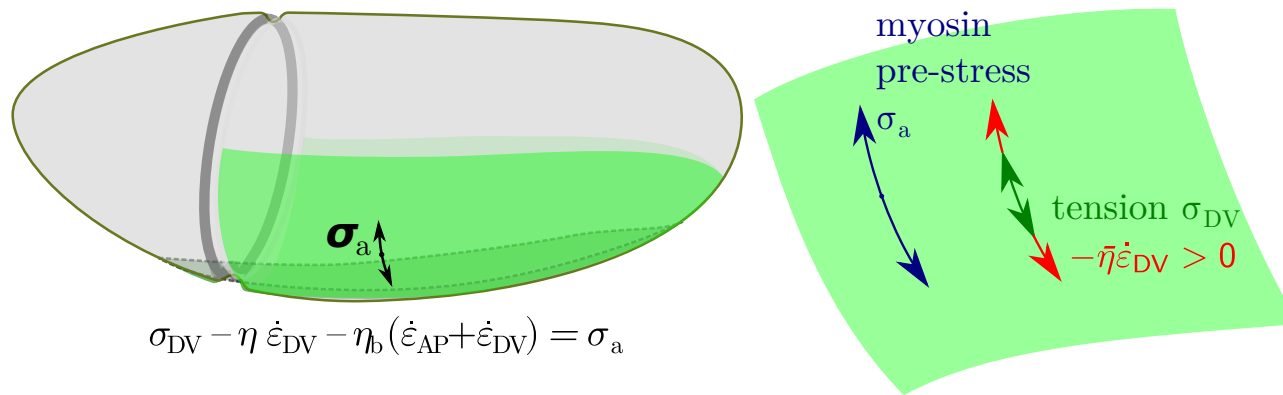
[Dicke et al. PLoS CR 2017]

Germband extension modelling



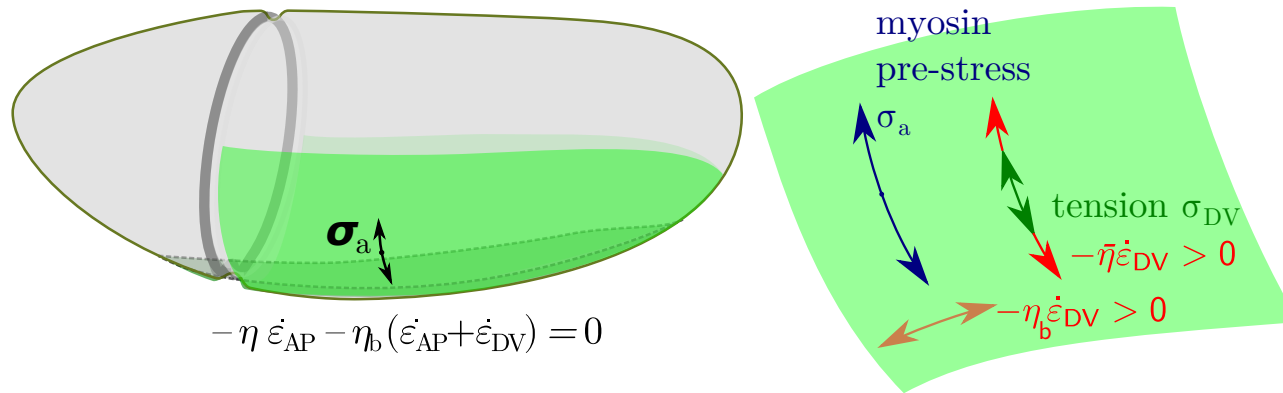
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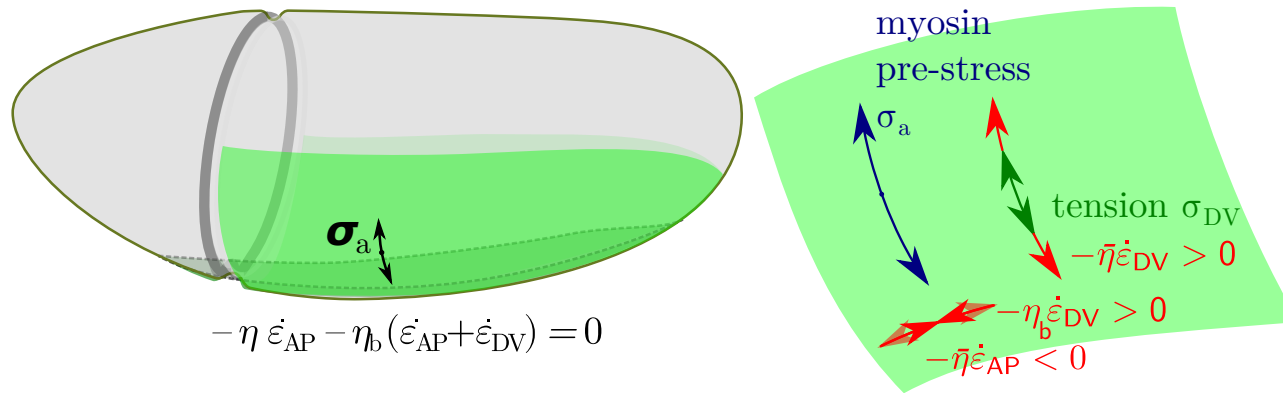
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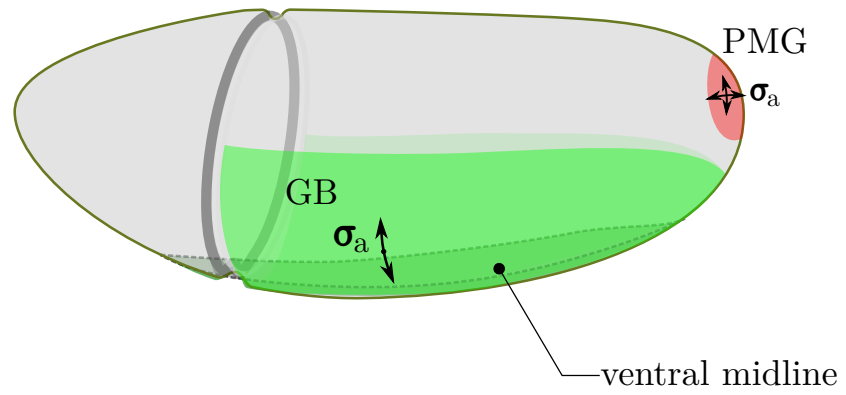
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