Title: The viscoelastic properties of the nematode C. elegans

Date: Dec 05, 2013 03:25 PM

URL: http://pirsa.org/13120019

Abstract: Undulatory motion is utilized by crawlers and swimmers such as snakes and sperm at length scales spanning more than seven orders of magnitude. The understanding of this highly efficient form of locomotion requires an experimental characterisation of the passive material properties of the organism as well as of its active force output on the surrounding medium. The millimeter-sized nematode Caenorhabditis elegans provides an excellent biophysical system for both static and dynamic biomechanical studies. Here we present a novel experimental technique where the deflection of a force-calibrated micropipette is used to directly probe the viscoelastic material properties of C. elegans. The worm was shown to have a self-similar elastic structure as well as a surprising shear-thinning viscous component (M. Backholm W. S. Ryu and K. Dalnoki- Veress PNAS 110 (2013)). The excellent force (pN) and time (ms) resolution provided by the micropipette deflection technique also enables measurements of the drag forces experienced by the microswimmer as it moves through a liquid. This direct experimental characterisation of C. elegans provides guidance for theoretical treatments of undulatory locomotion in general.

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The viscoelastic properties of the nematode *C. elegans*

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Waterloo Soft Matter Theory Conference, 5.12.2013

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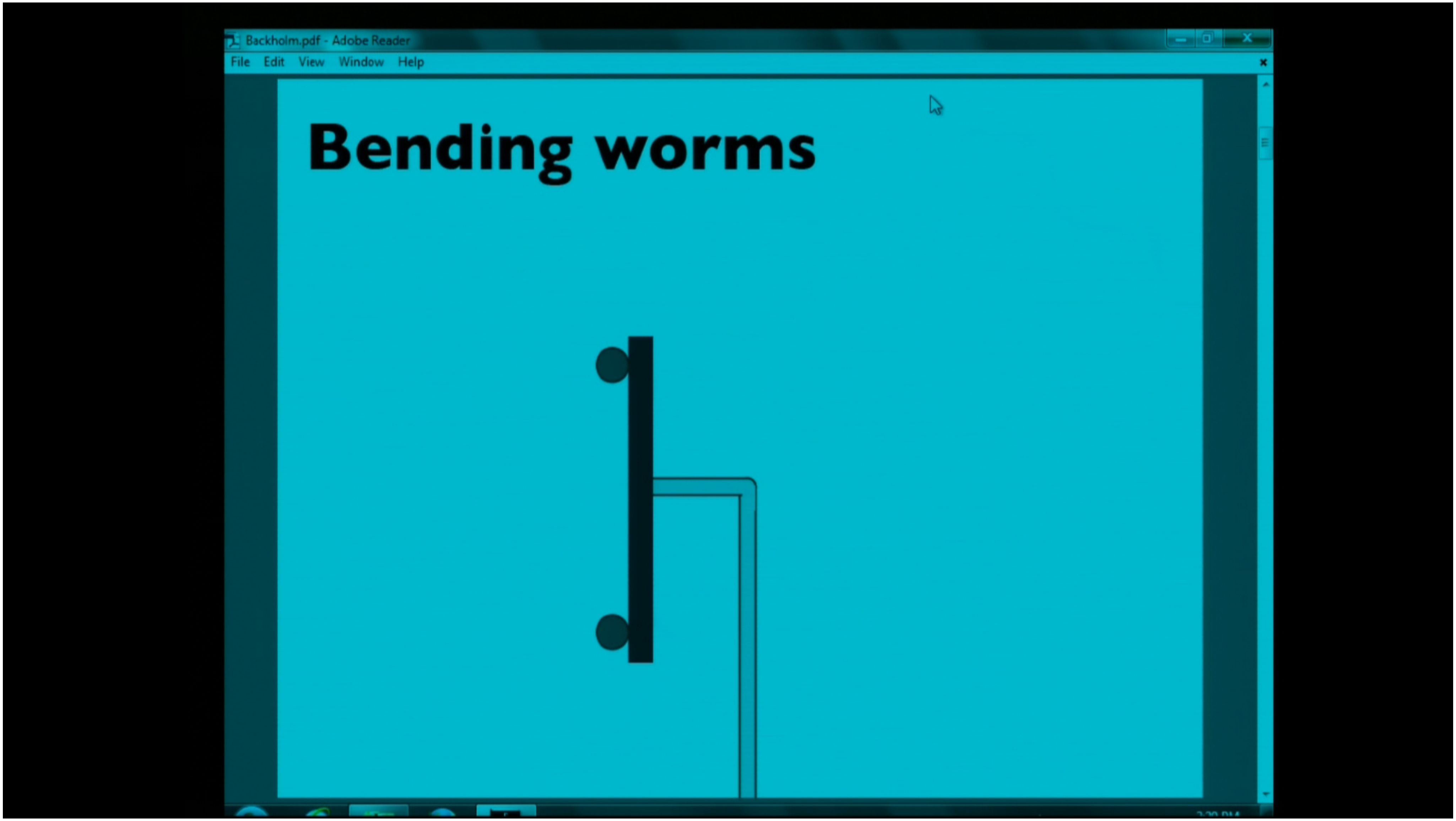
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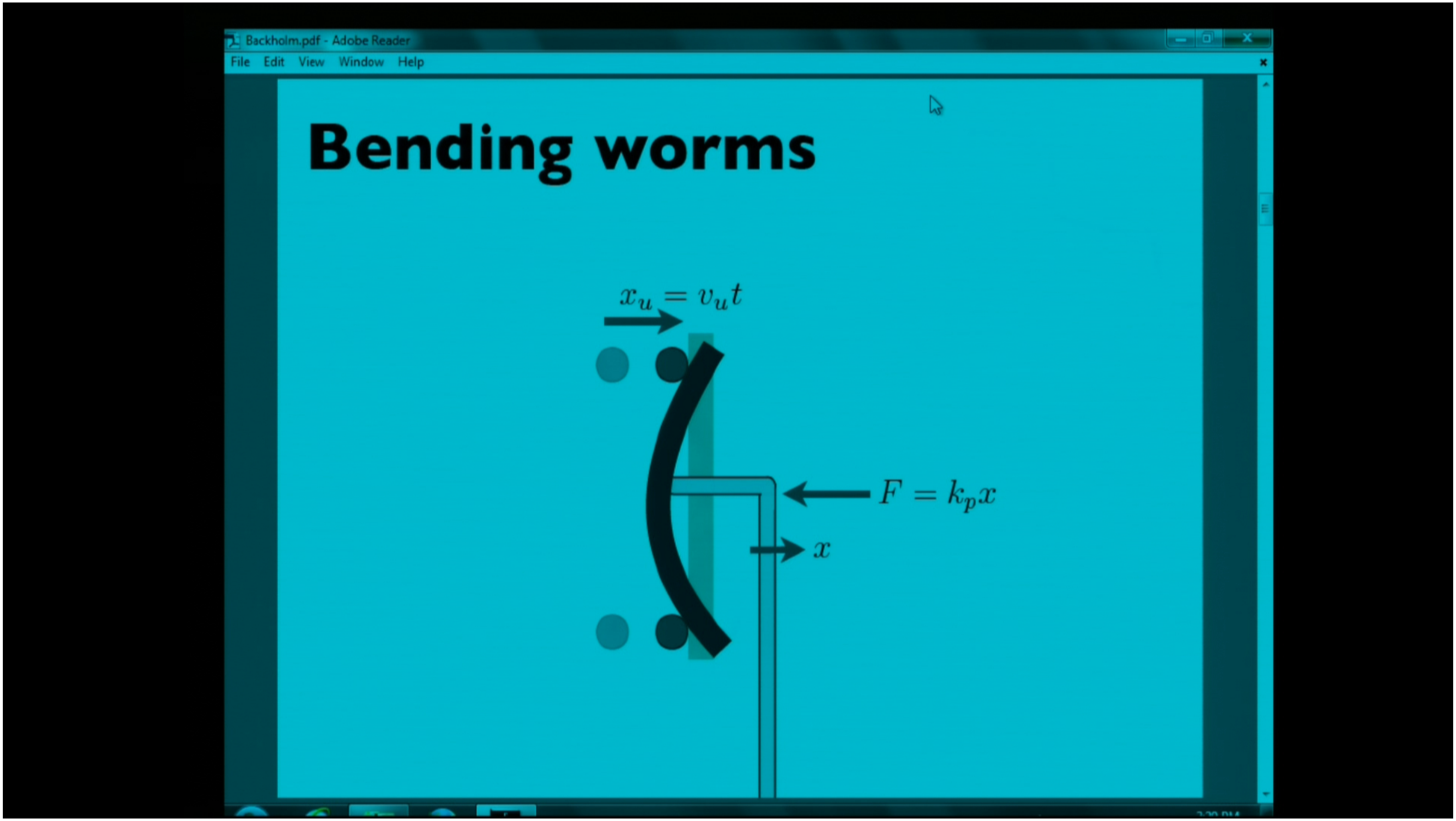
Bending worms



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Bending worms
$x_u = v_u t$
$F = k_p x$
x

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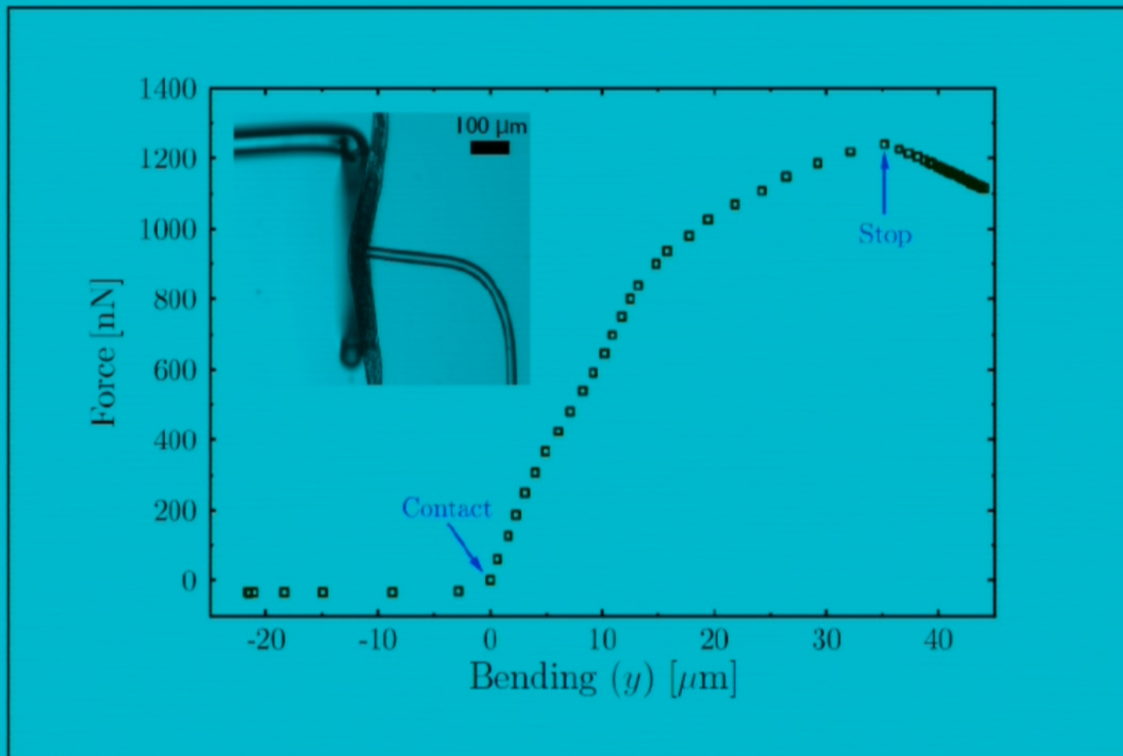
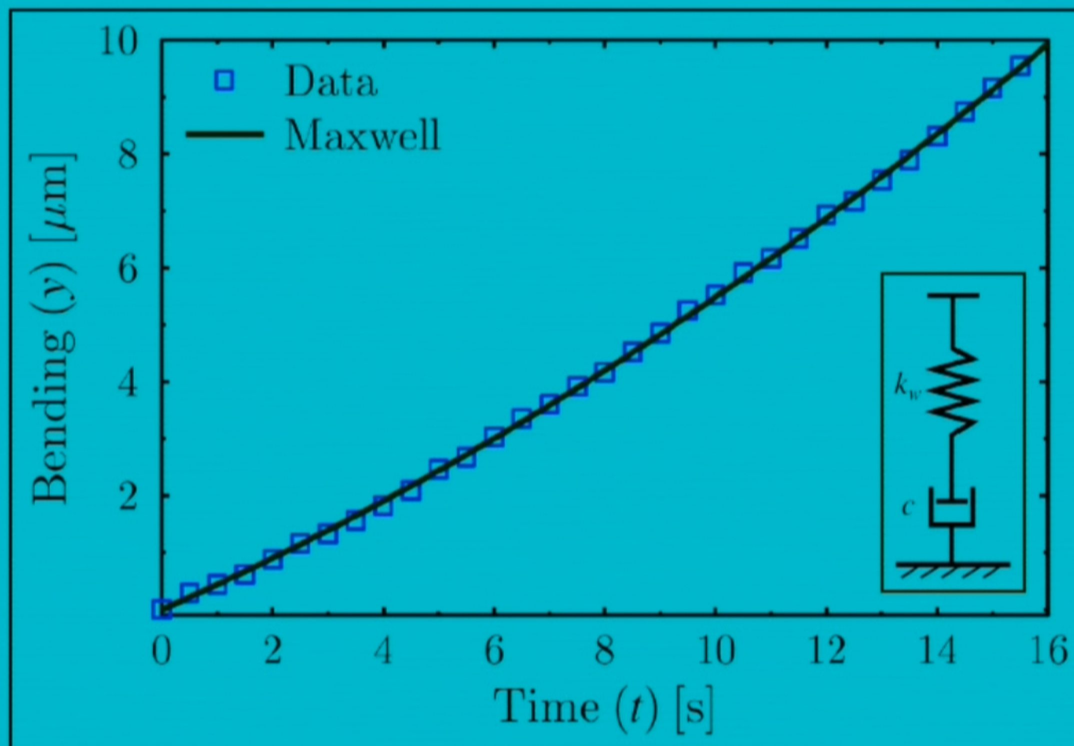
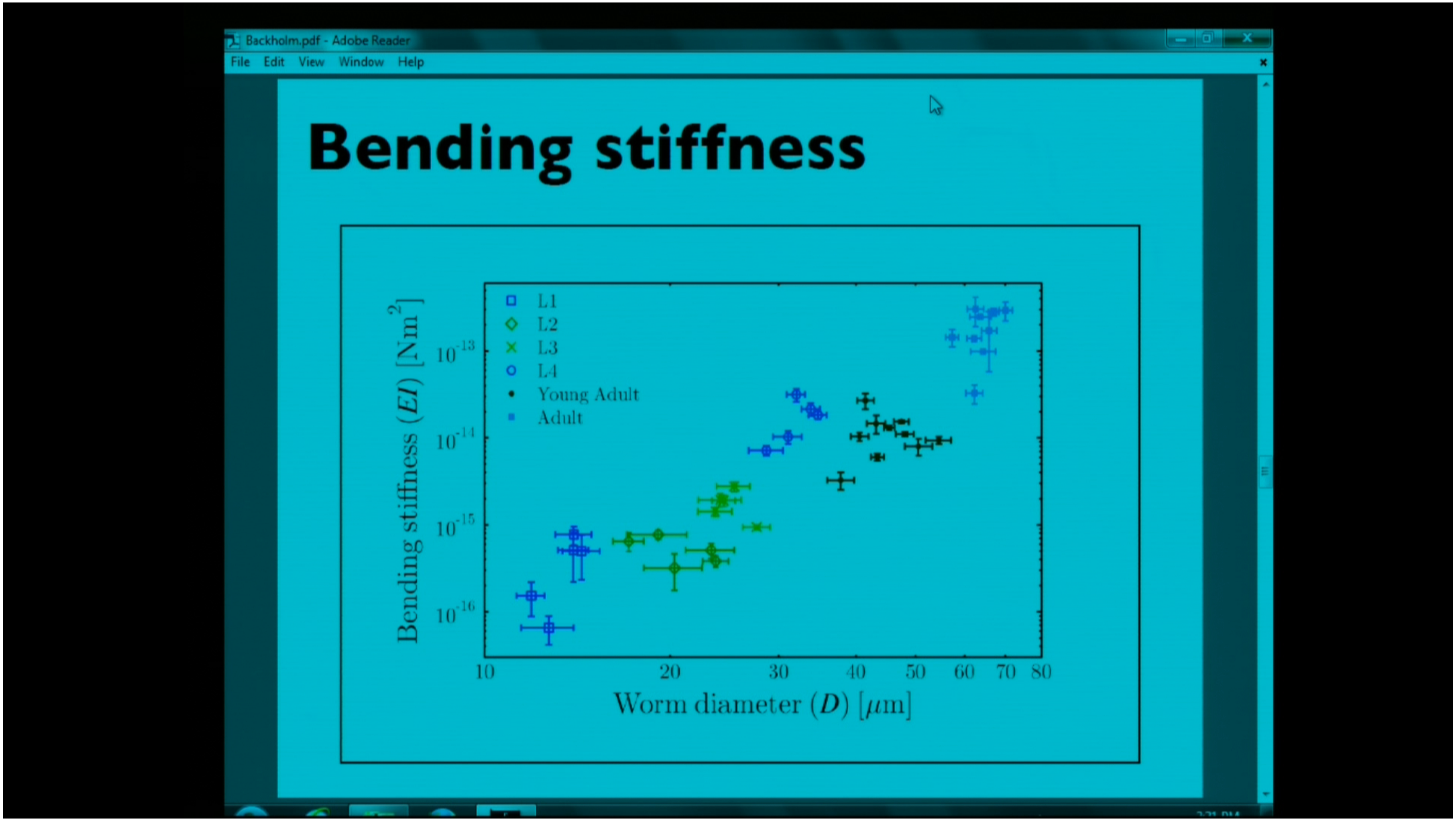
Force-deformation



Viscoelastic model

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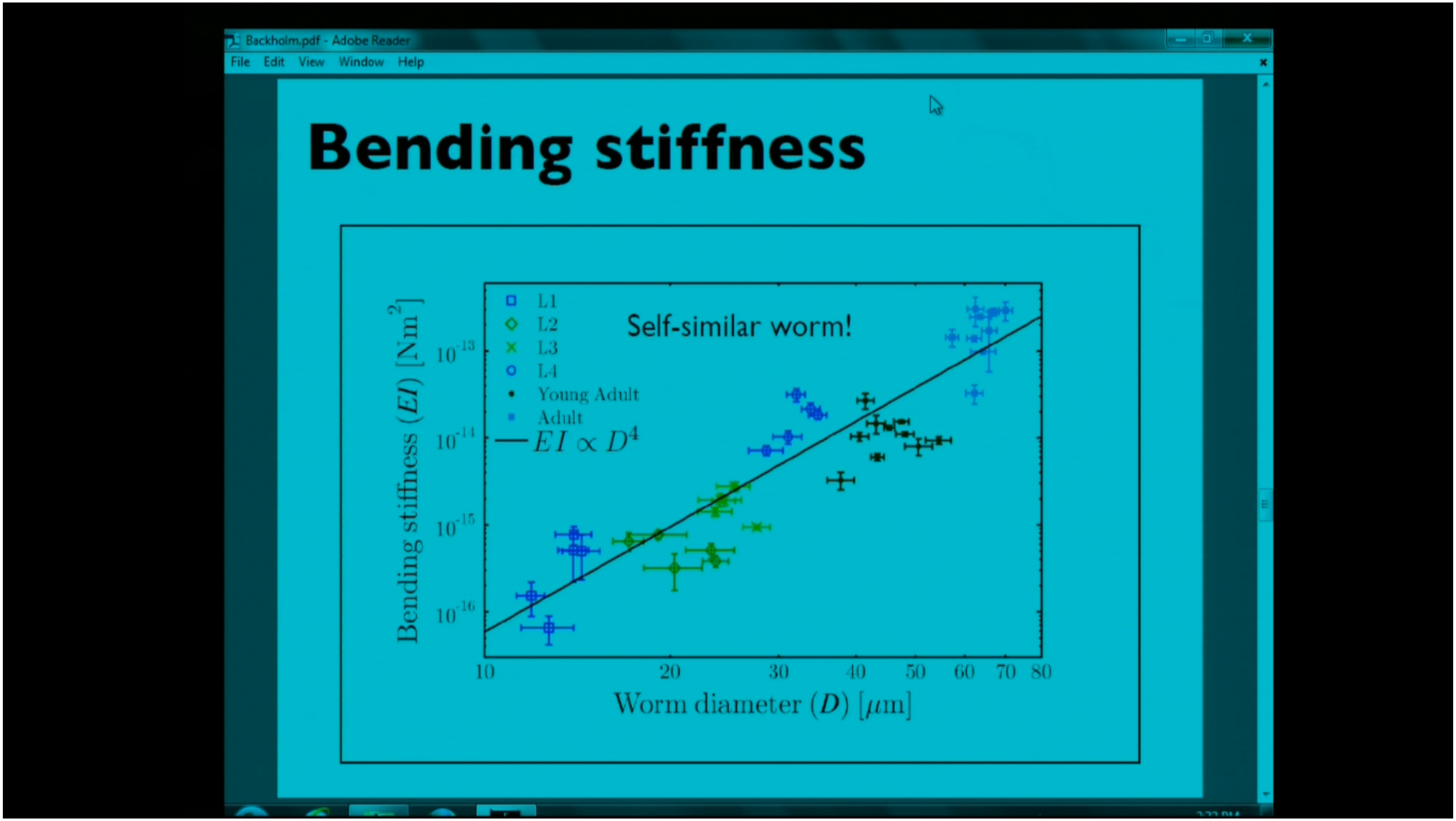
Bending stiffness
L1
L2
L3
L4
Young Adult
Adult
Bending stiffness (EI) $[\mathrm{Nm}^2]$
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10 20 30 40 50 60 70 80
Worm diameter (D) $[\mu\mathrm{m}]$



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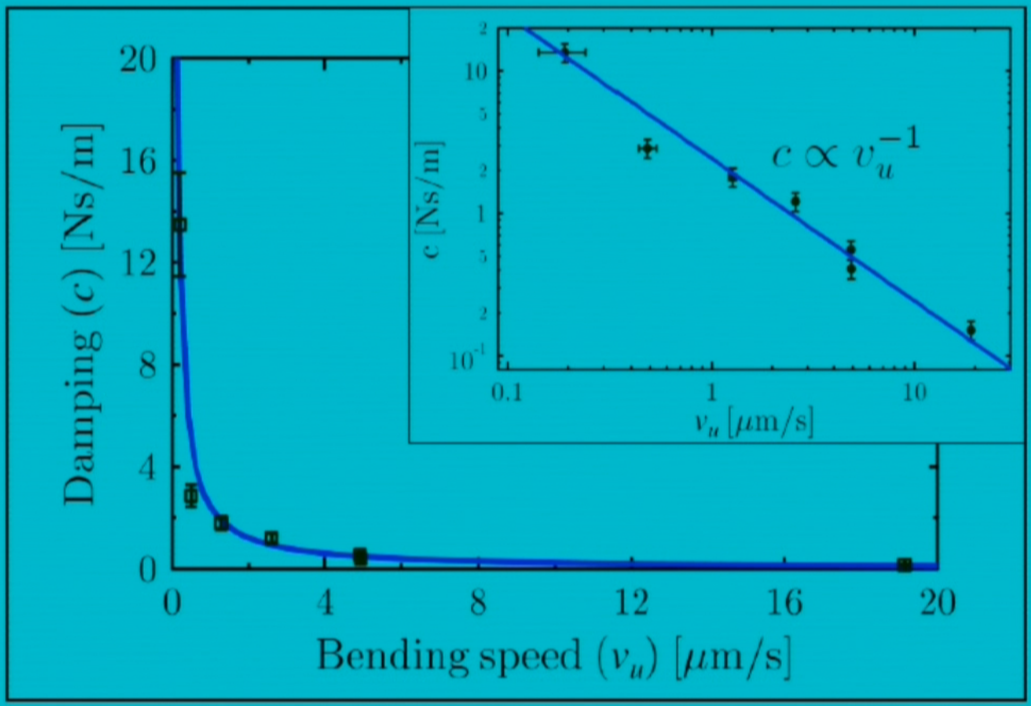
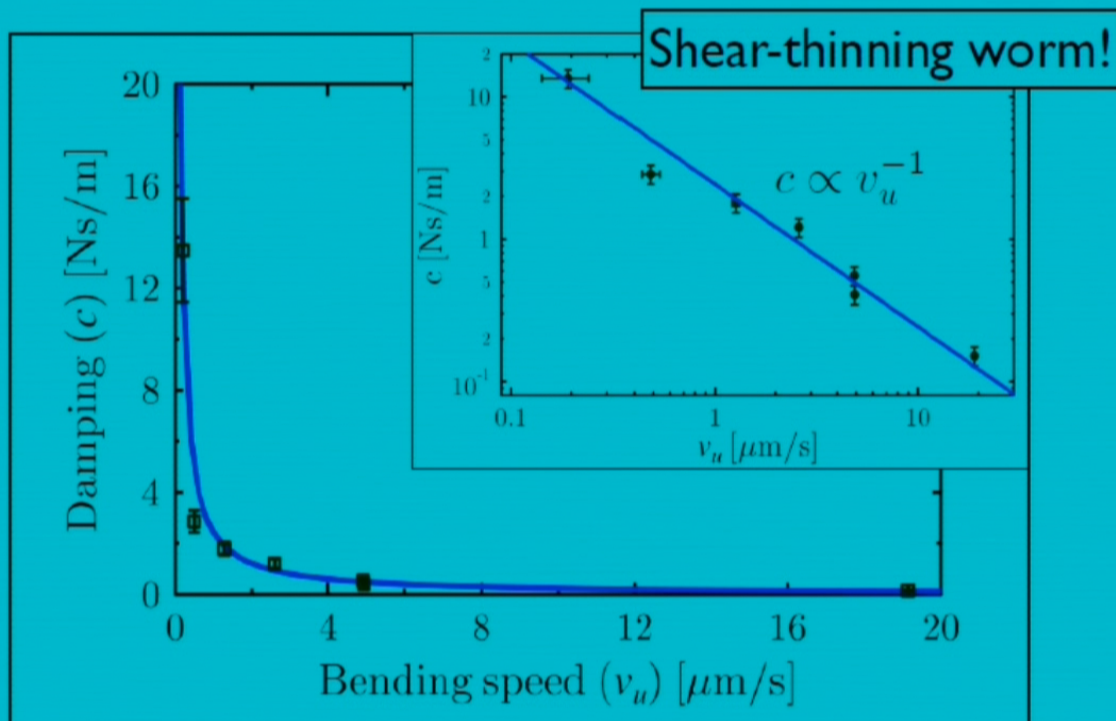
Bending stiffness
Self-similar worm!
L1
L2
L3
L4
Young Adult
Adult
$EI \propto D^4$
Bending stiffness (EI) [Nm^2]
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10
20
30
40
50
60
70
80
Worm diameter (D) [μm]

Speed dependence



Speed dependence



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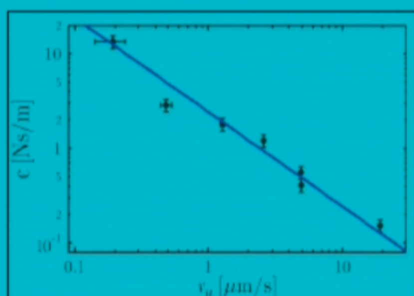
Conclusions

Dalnoki-Veress Group



- *C. elegans* directly probed with micropipette deflection
- Passive material properties
  (Backholm, Ryu, Dalnoki-Veress, PNAS **10** (2013))
  - Elastic: Self-similar, cylindrical
  - Viscous: Shear-thinning

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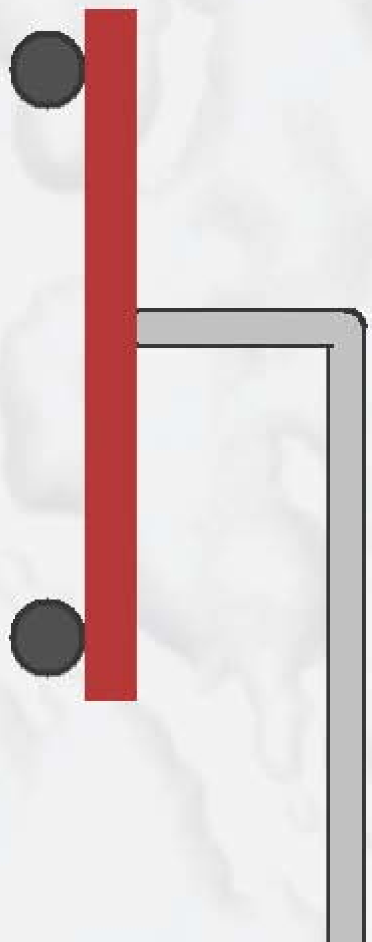

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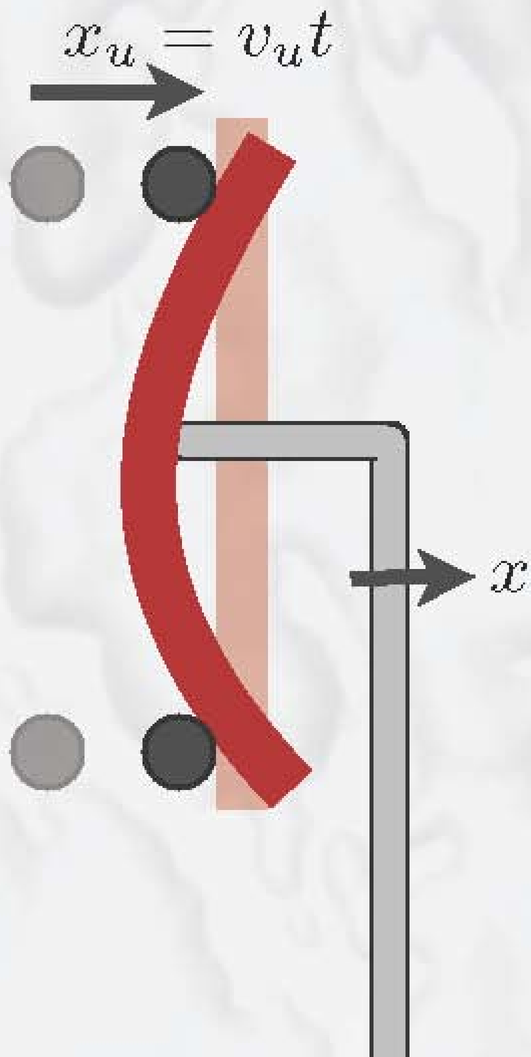

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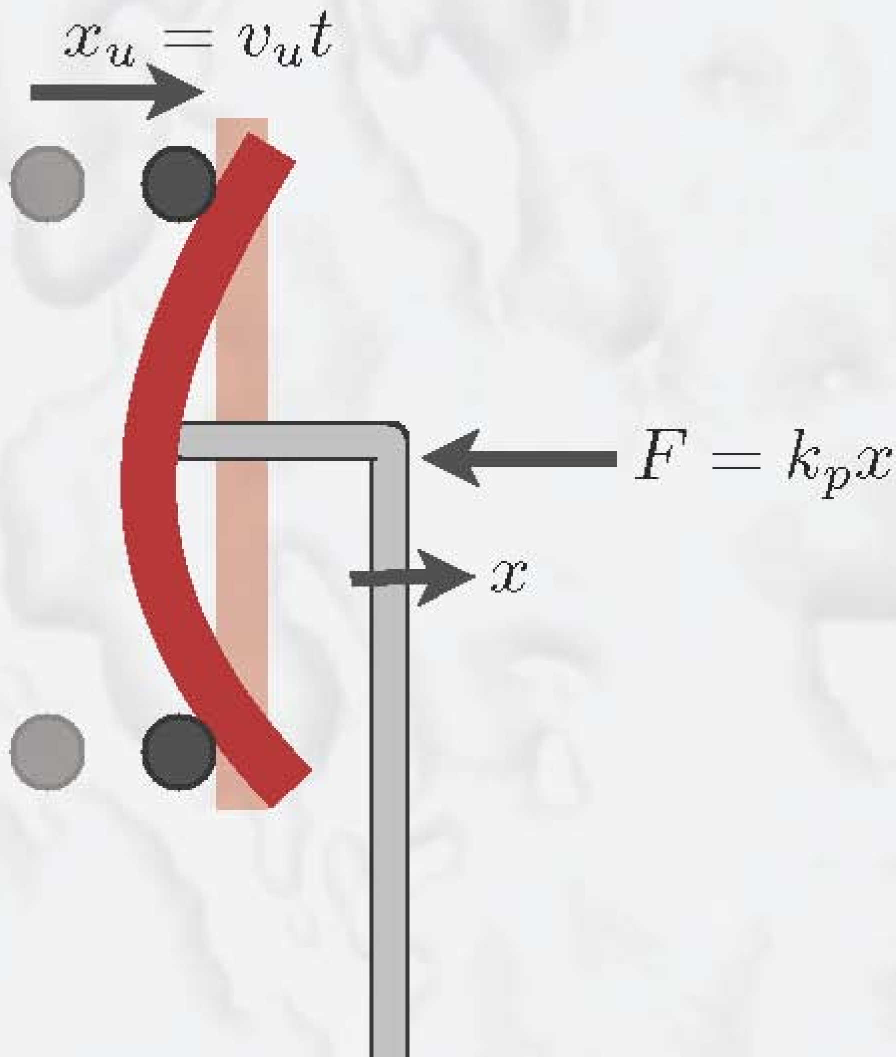
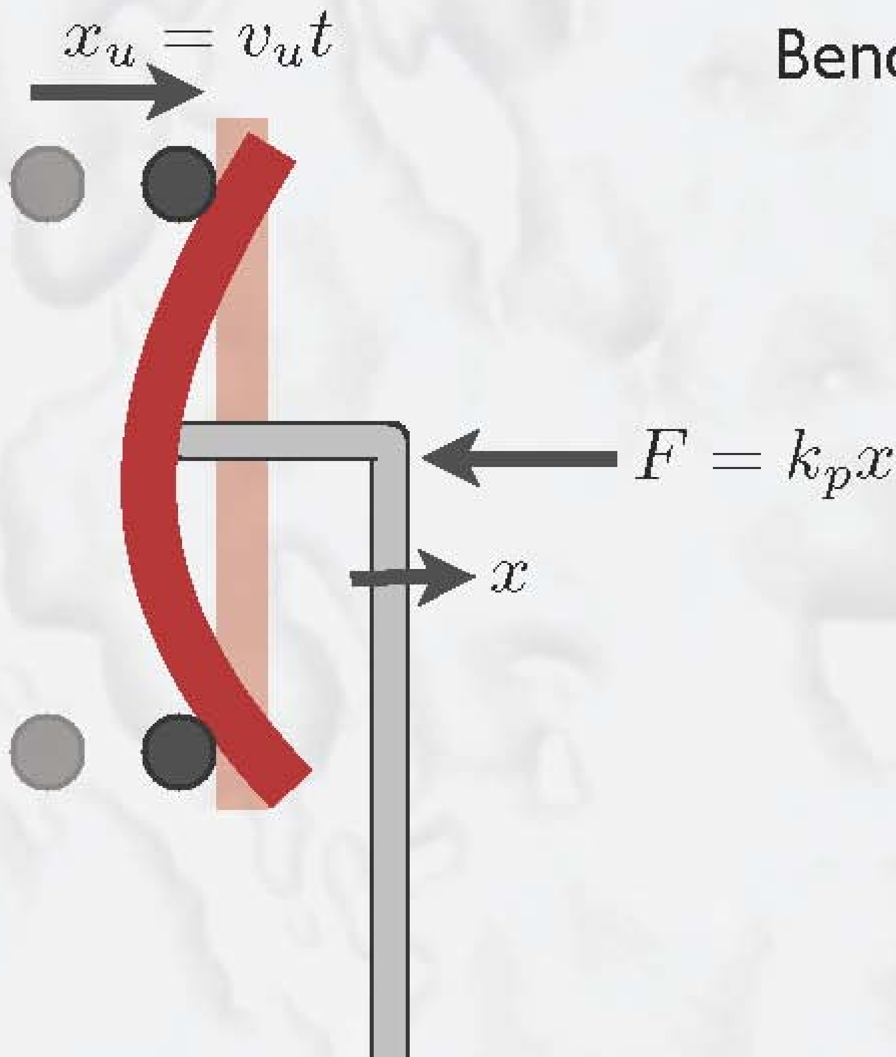


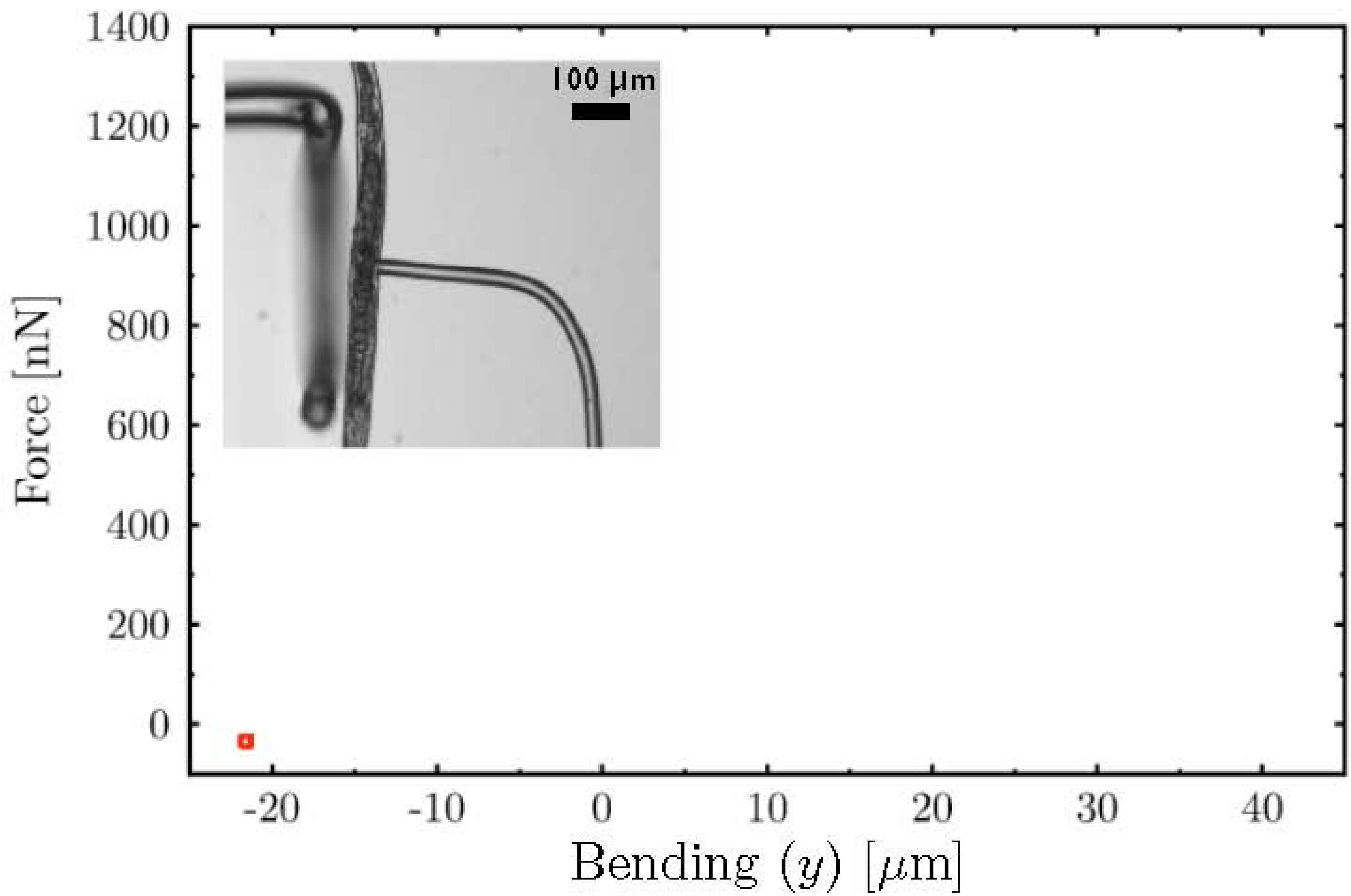
Bending worms



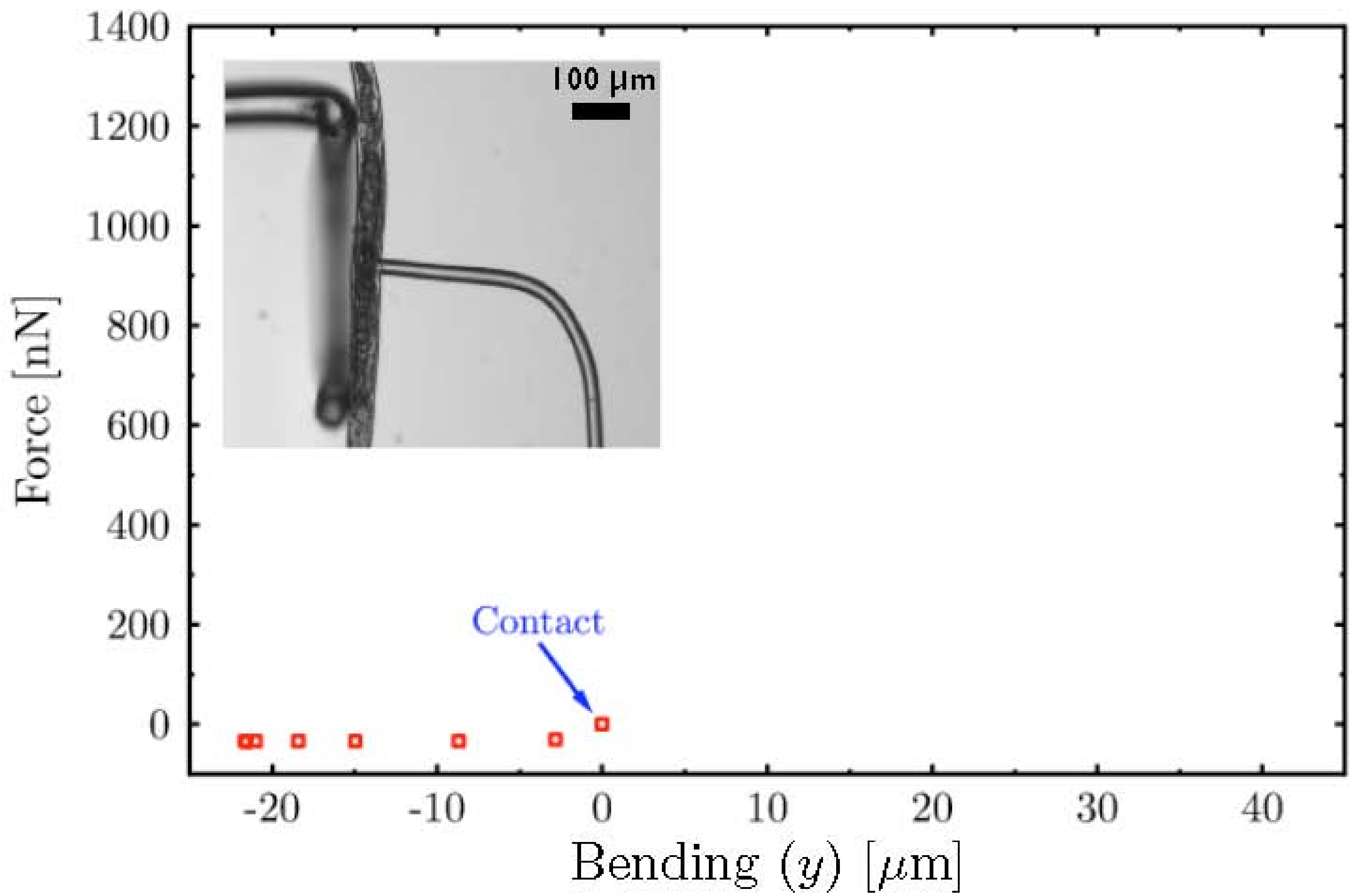
Bending of worm

$$y = x_u - x$$

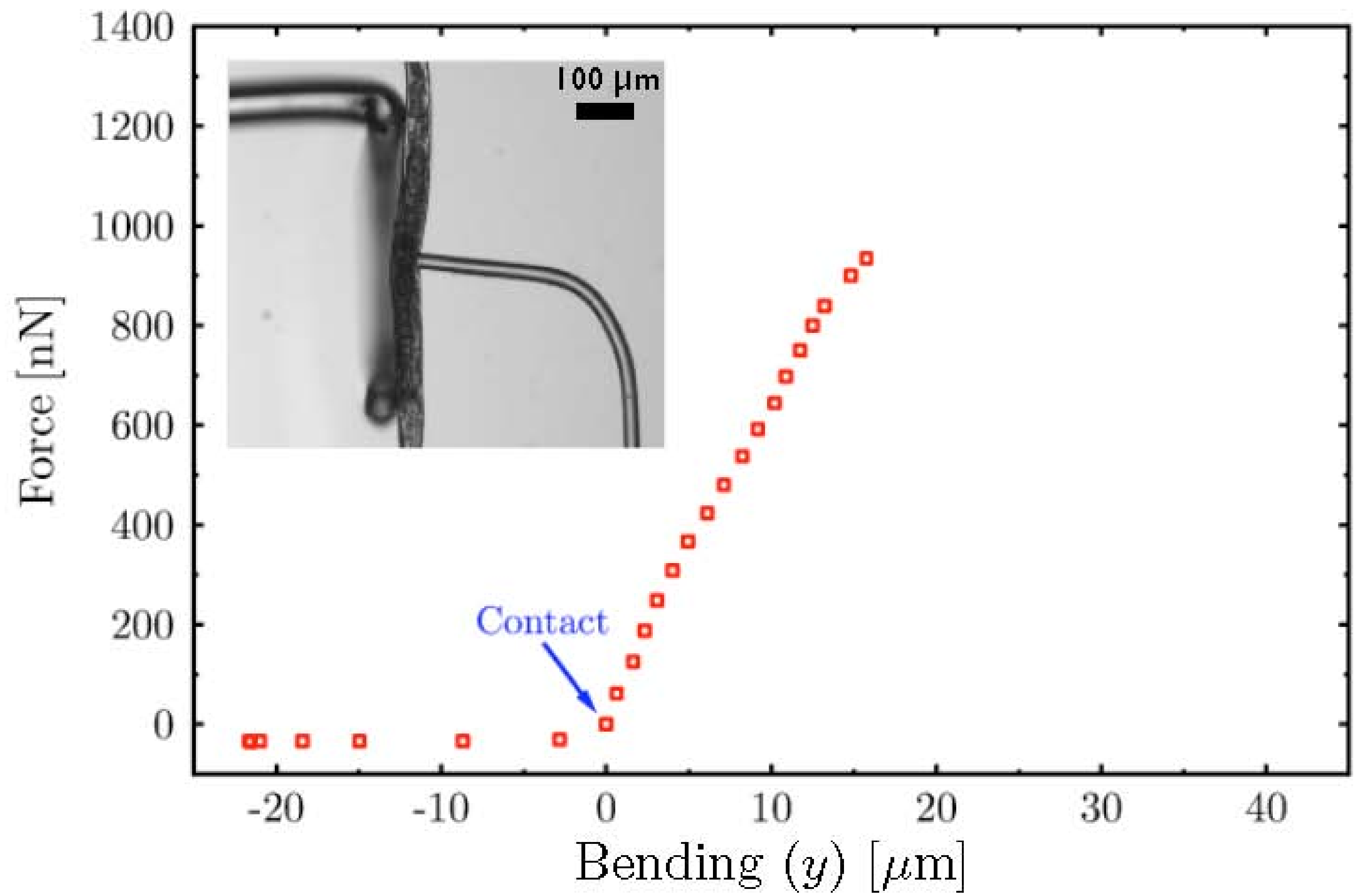
Force-deformation



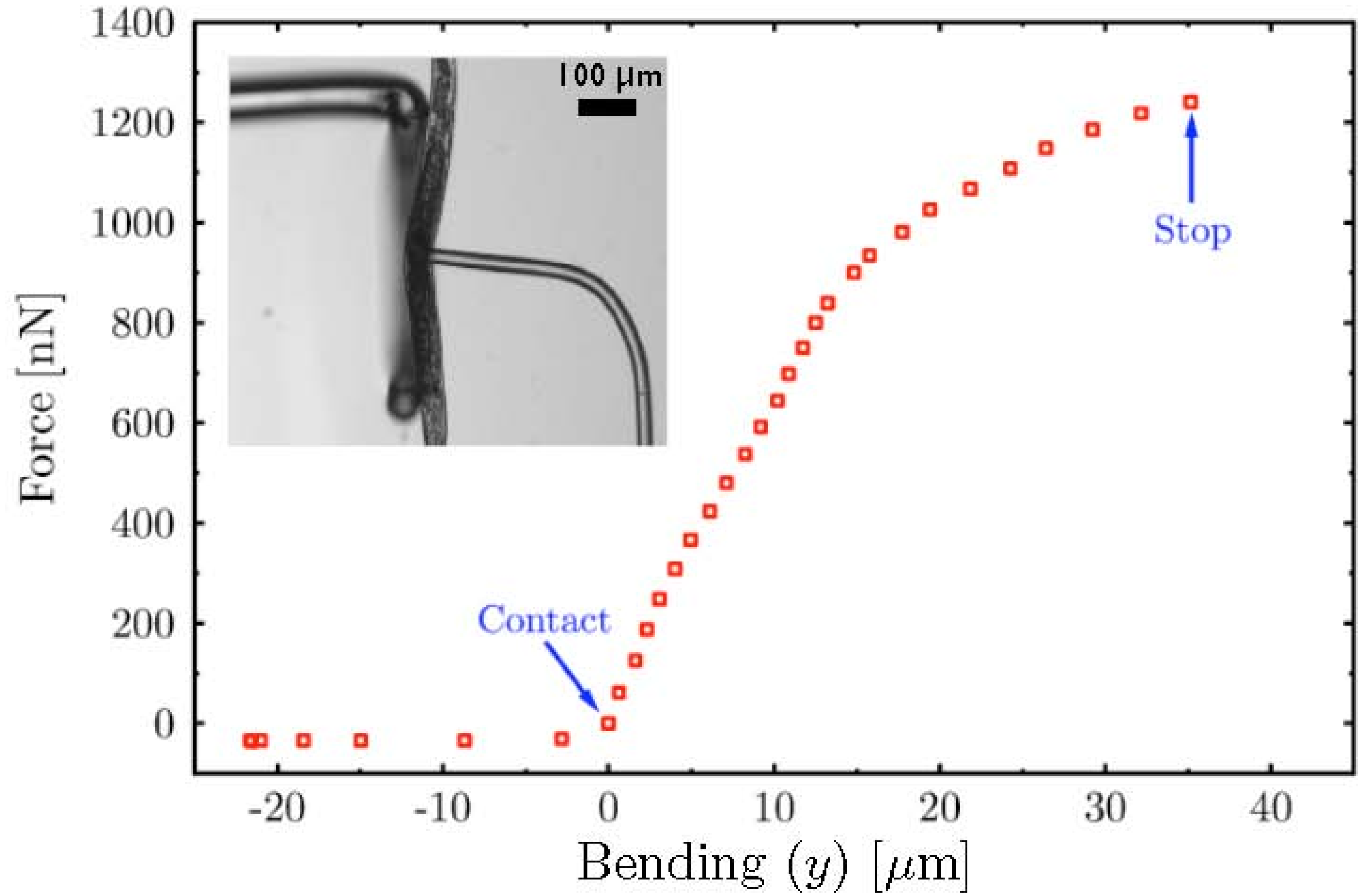
Force-deformation



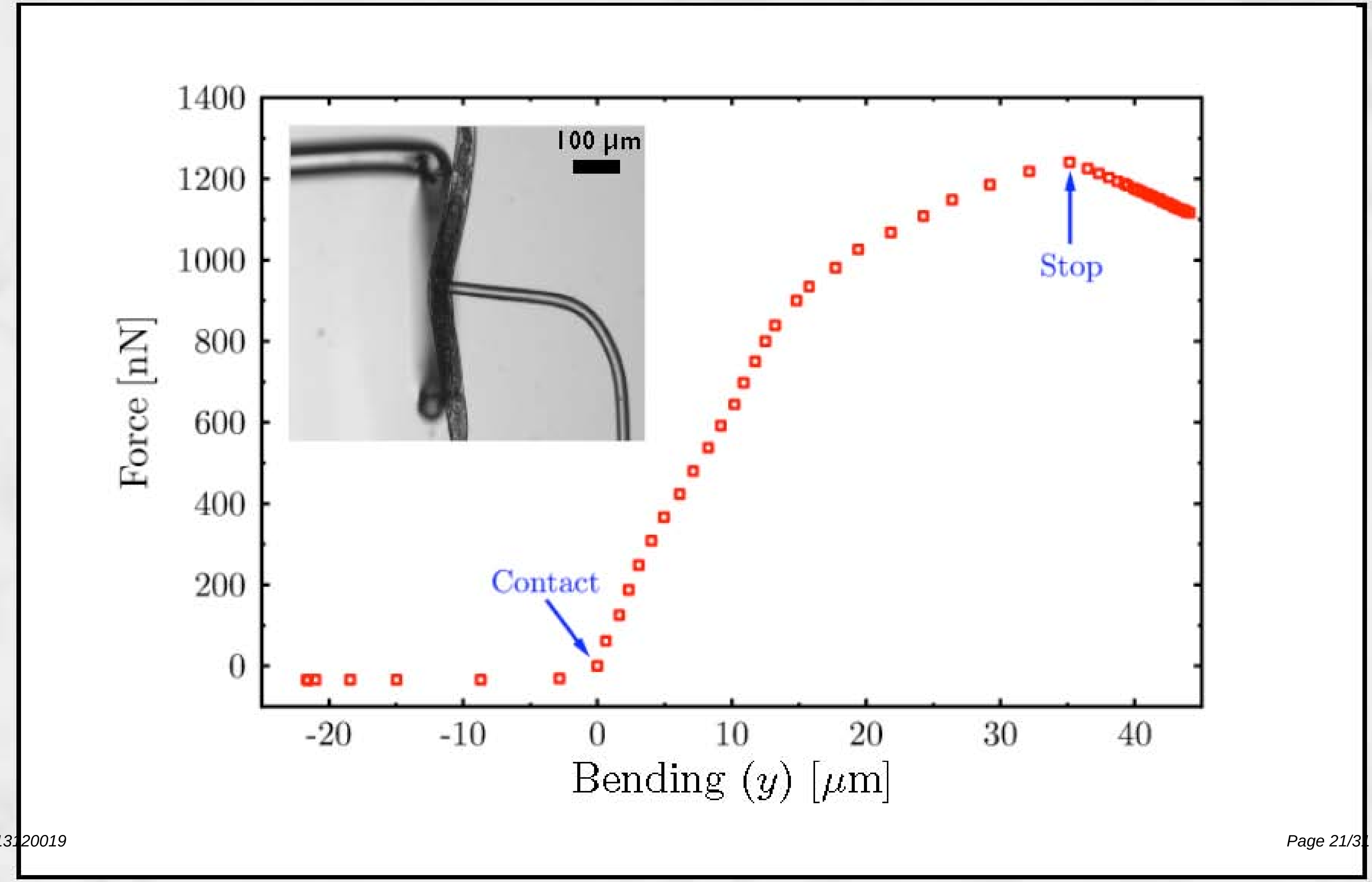
Force-deformation



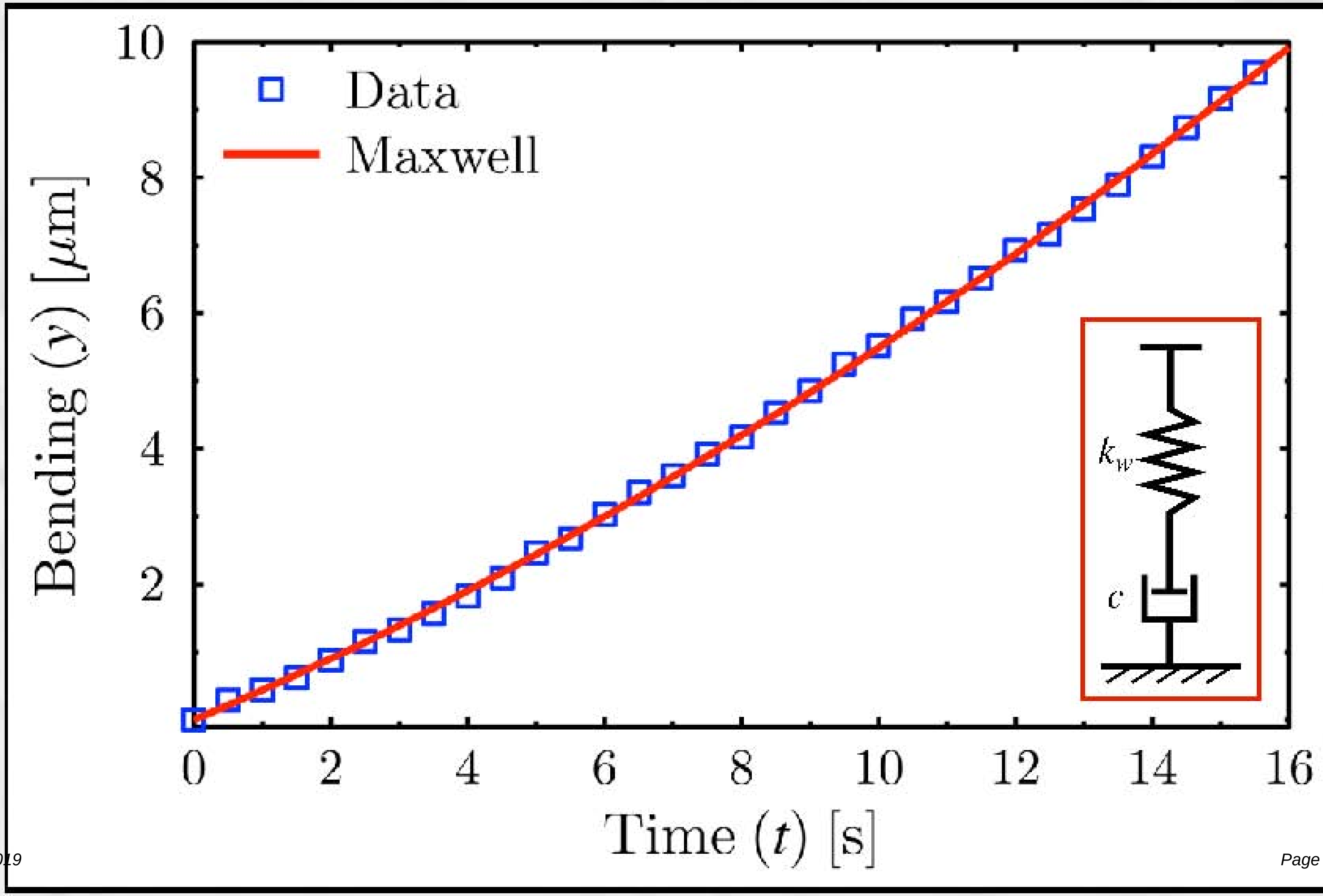
Force-deformation



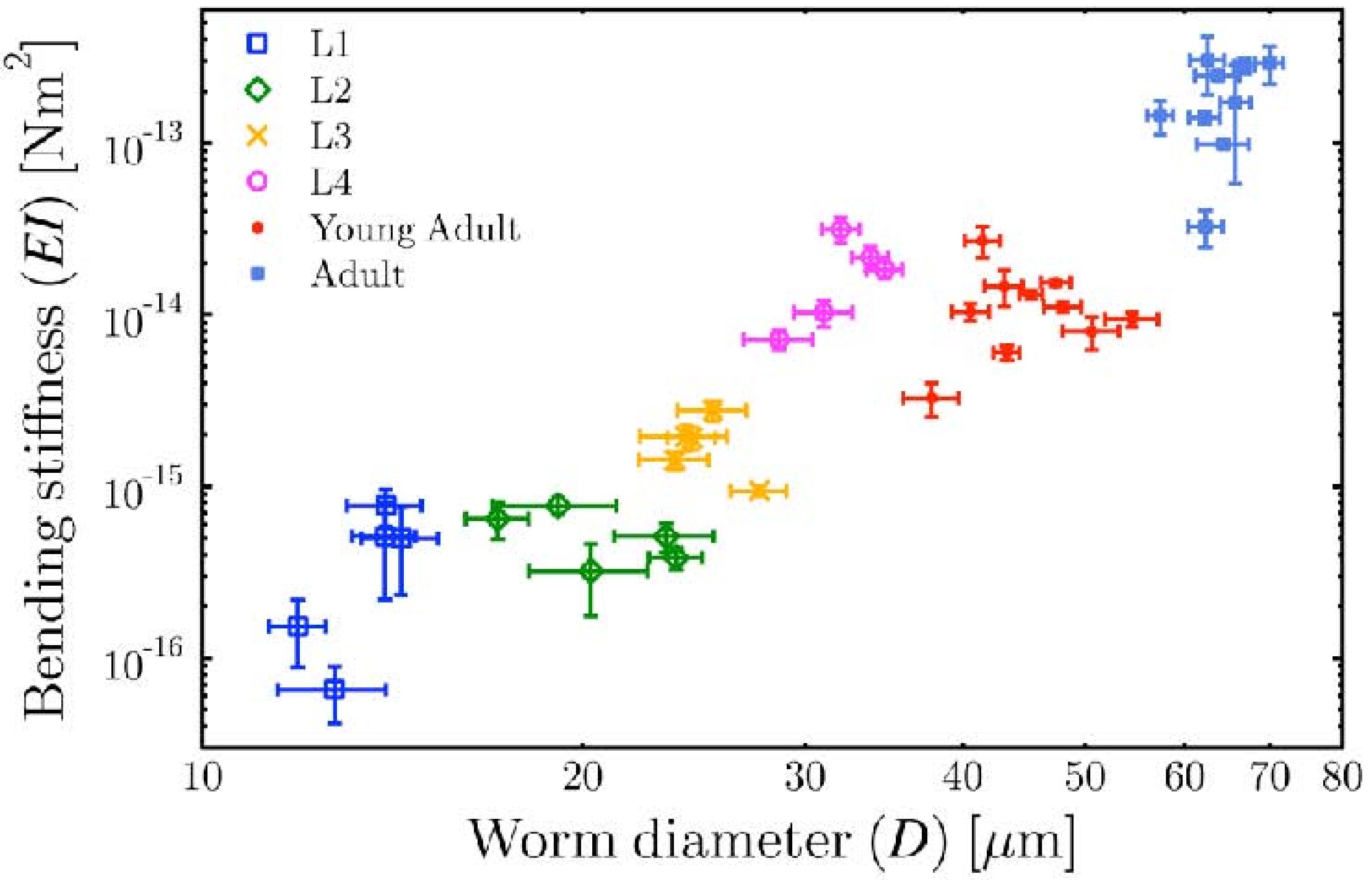
Force-deformation



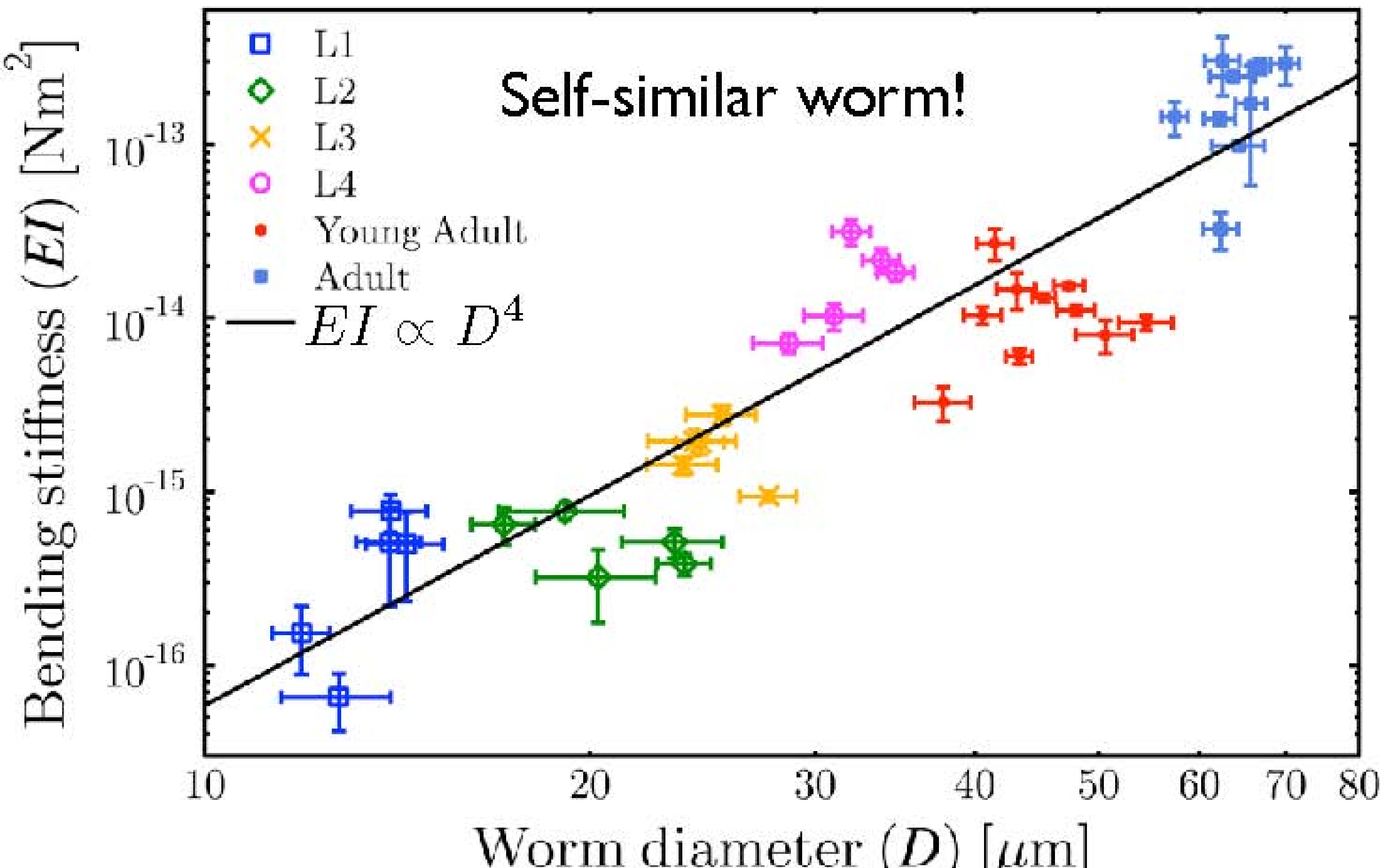
Viscoelastic model



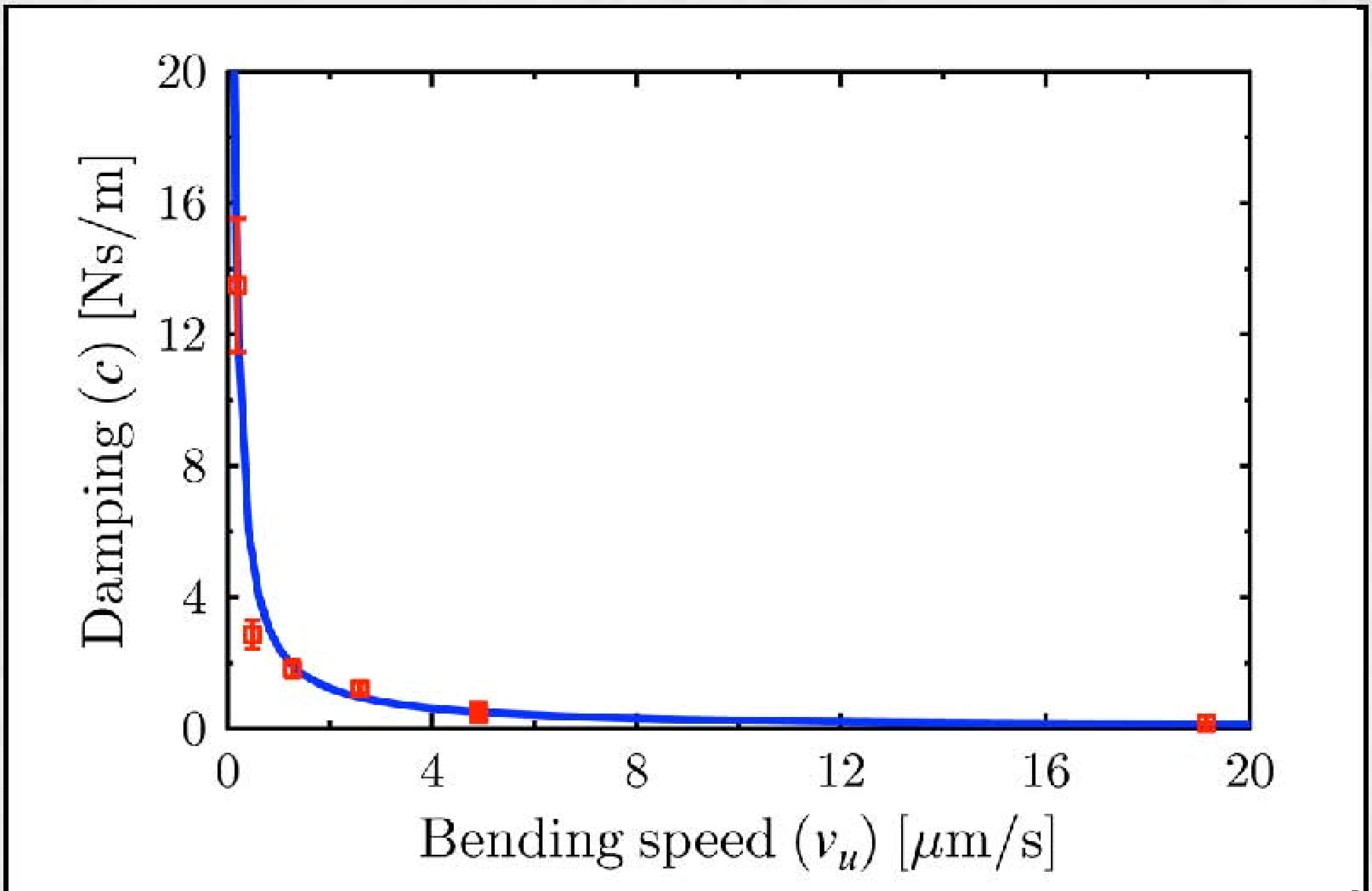
Bending stiffness



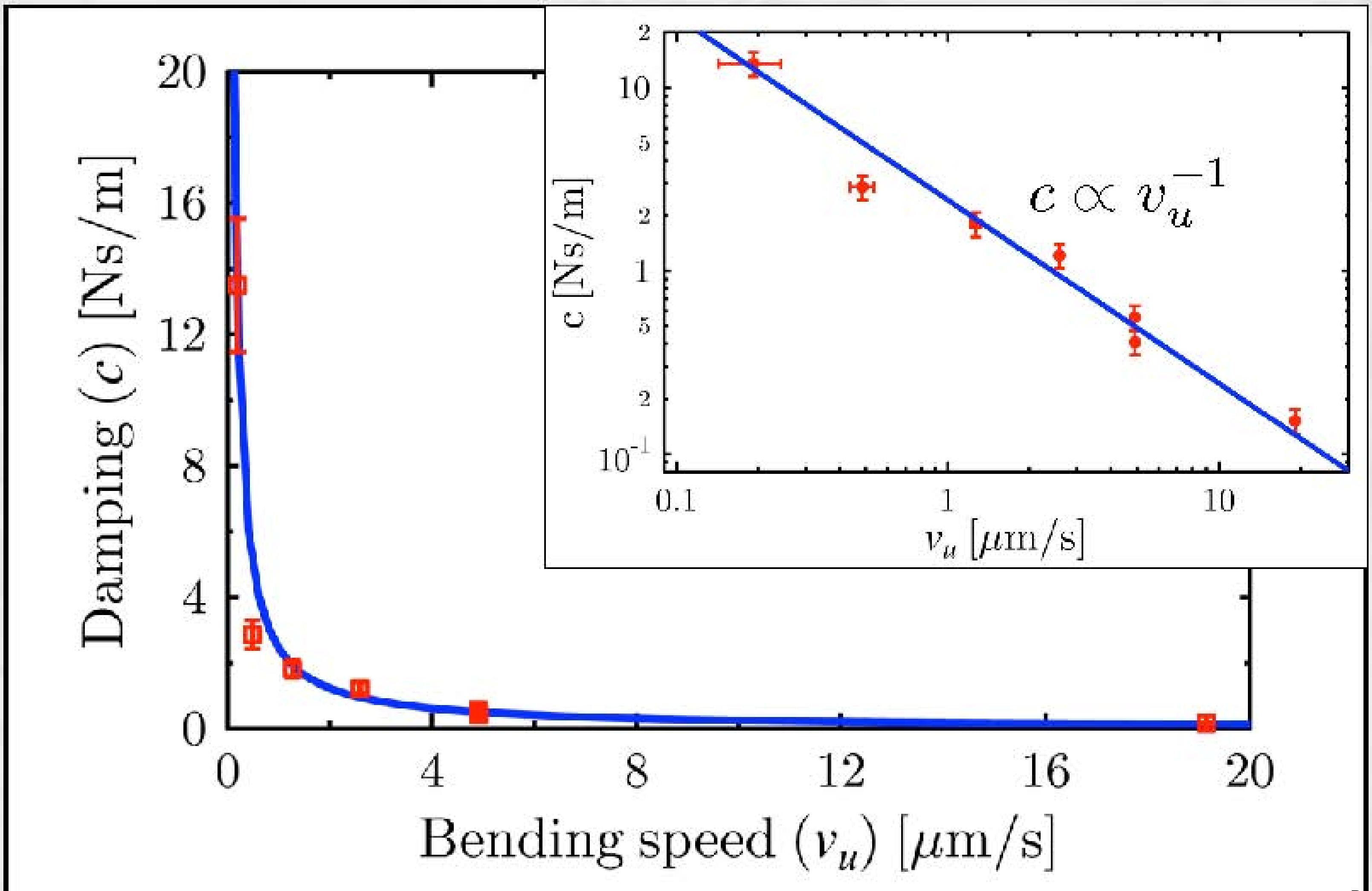
Bending stiffness



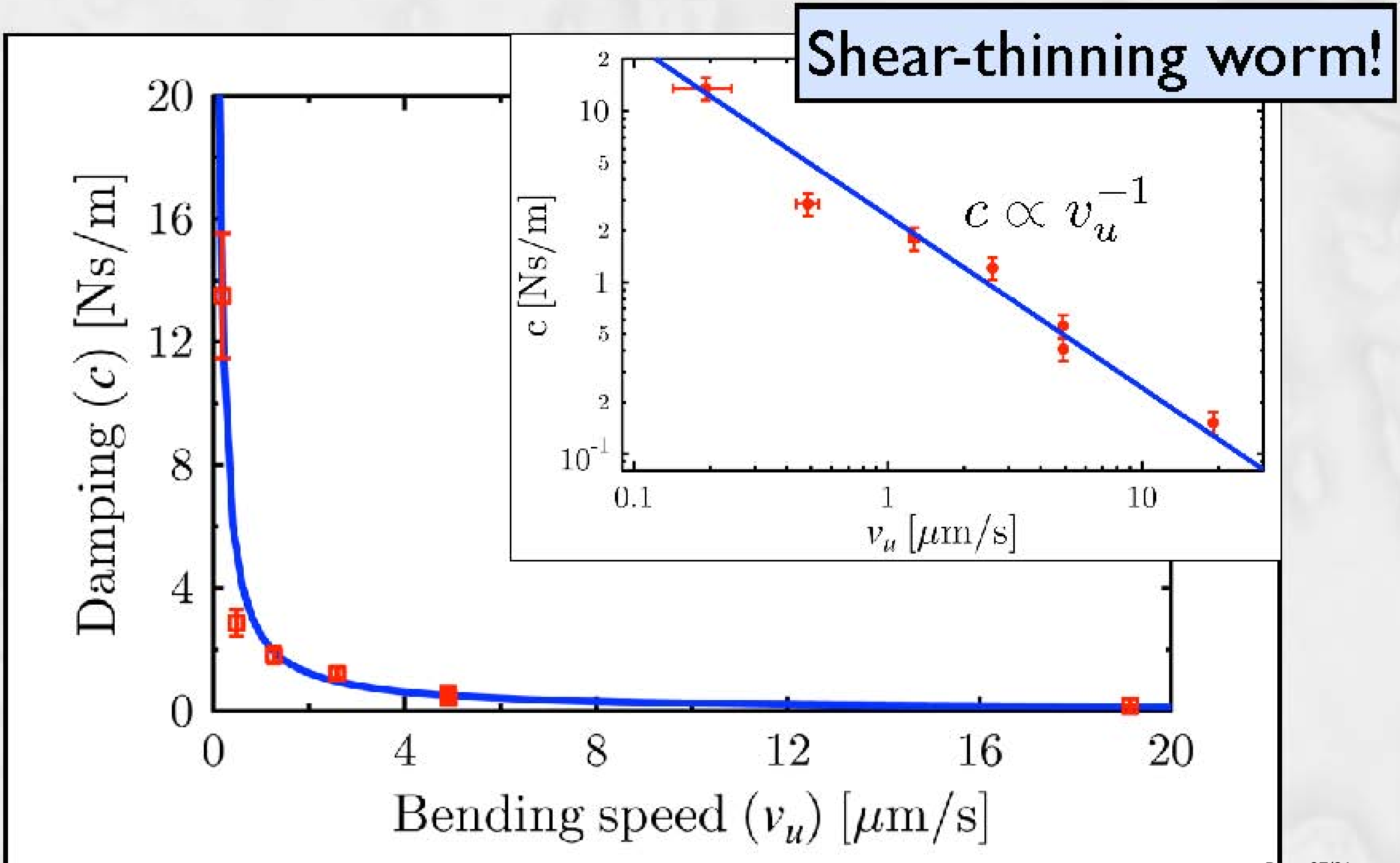
Speed dependence



Speed dependence



Speed dependence



Conclusions

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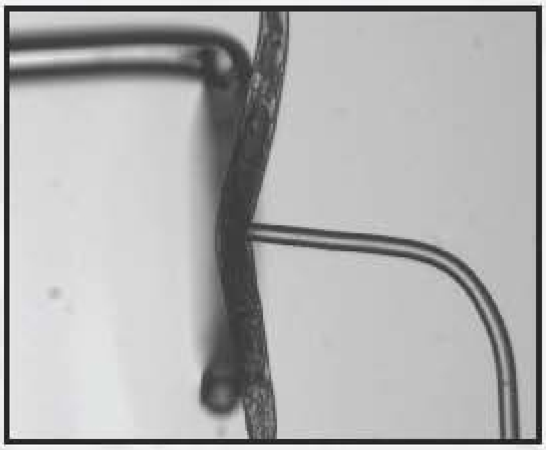

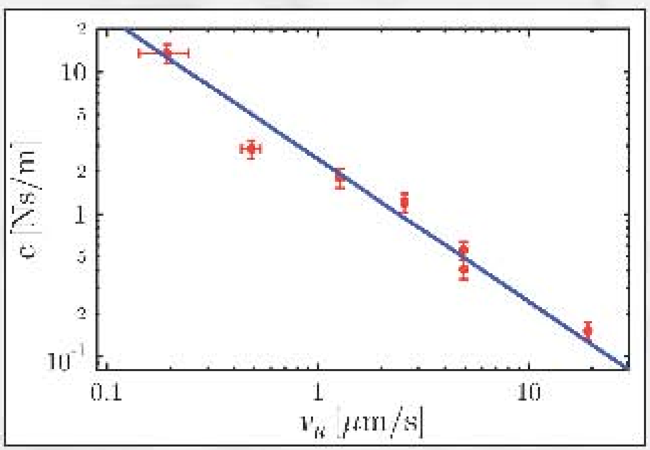

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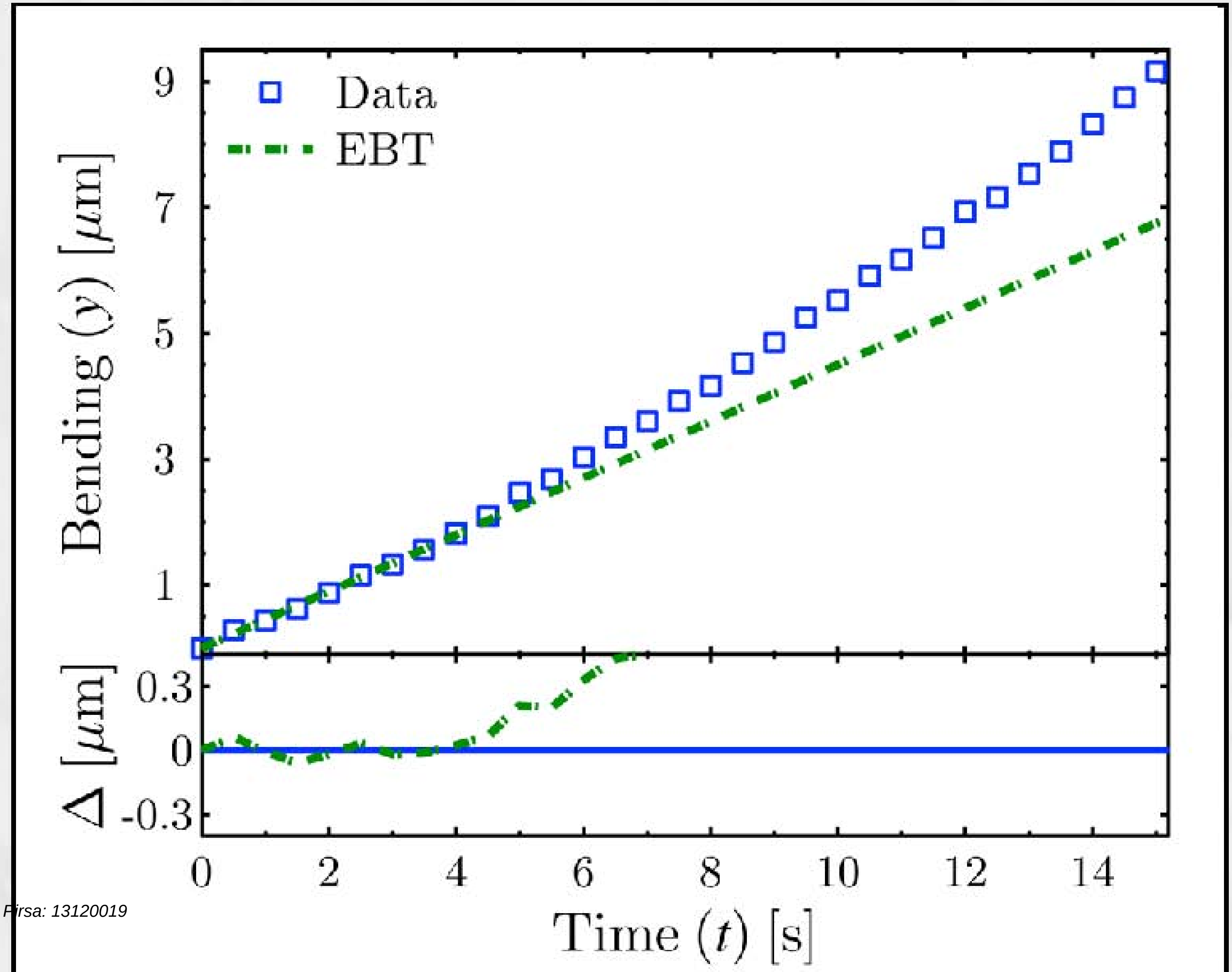
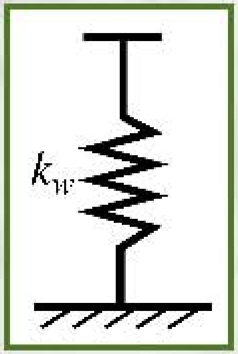
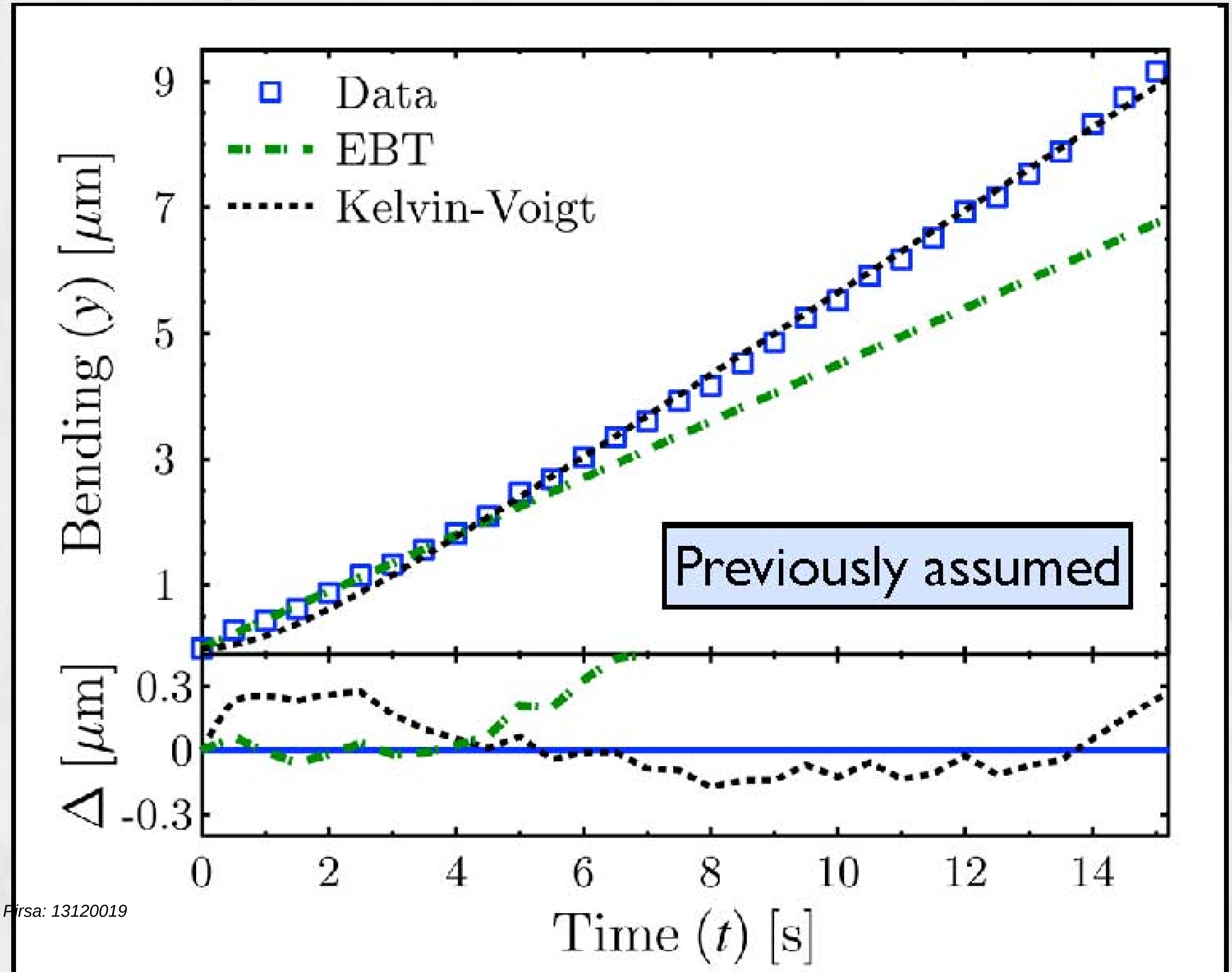
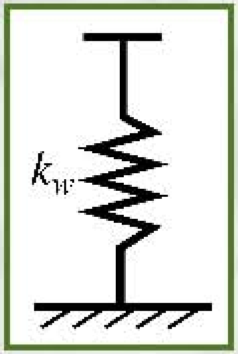
Viscoelastic models

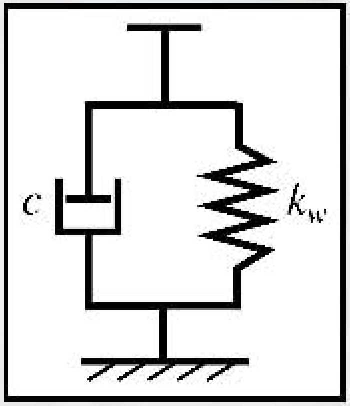




Viscoelastic models







Viscoelastic models