C@fé-In

Une rencontre informelle autour d'un sujet scientifique.

The physics of spaghetti and other deformable objects

Dynamics and breaking

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Café-In

Sophia-Antipolis, Fébruary 5th 2019

informatics mathematics

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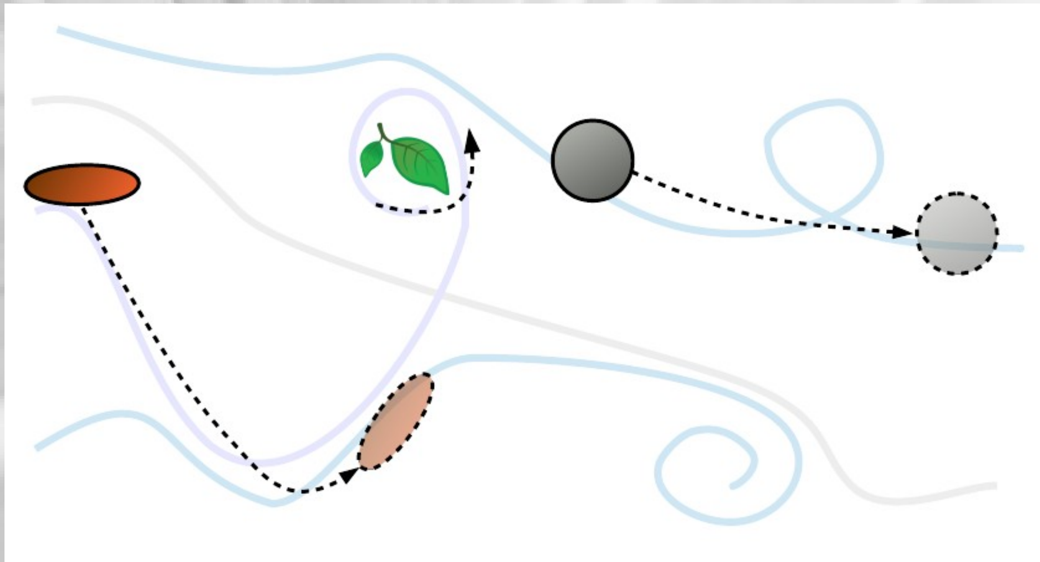
Context: particles in flows

- Main issue:
  - Dynamics of particles in flow
  - Dispersion



- Keywords
  - Transport
  - Dispersion
  - Deposition/resuspension
  - Clogging
  - Agglomeration

Context: elongated particles in flows

- Environmental issues
  - Branches/leaves in urban areas and marine systems

Leaves in rivers
(source: internet)

Leaves in a manhole
(source: internet)

Leaves in a rain gutter
(source: internet)

Context: elongated particles in flows

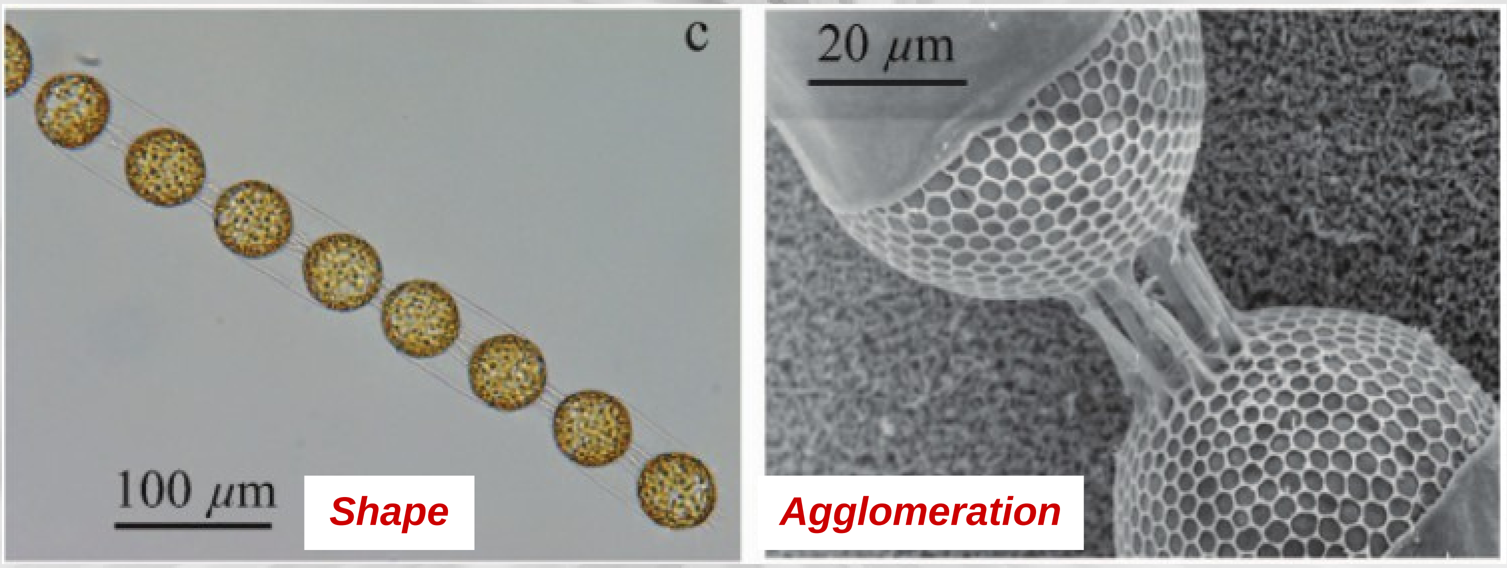
- Environmental issues
  - Branches/leaves in urban areas and marine systems
  - Dynamics of plastic in marine systems

Plastic debris in oceans
(source: internet)

Plastic debris on riverbanks or beaches
(source: internet)

Context: elongated particles in flows

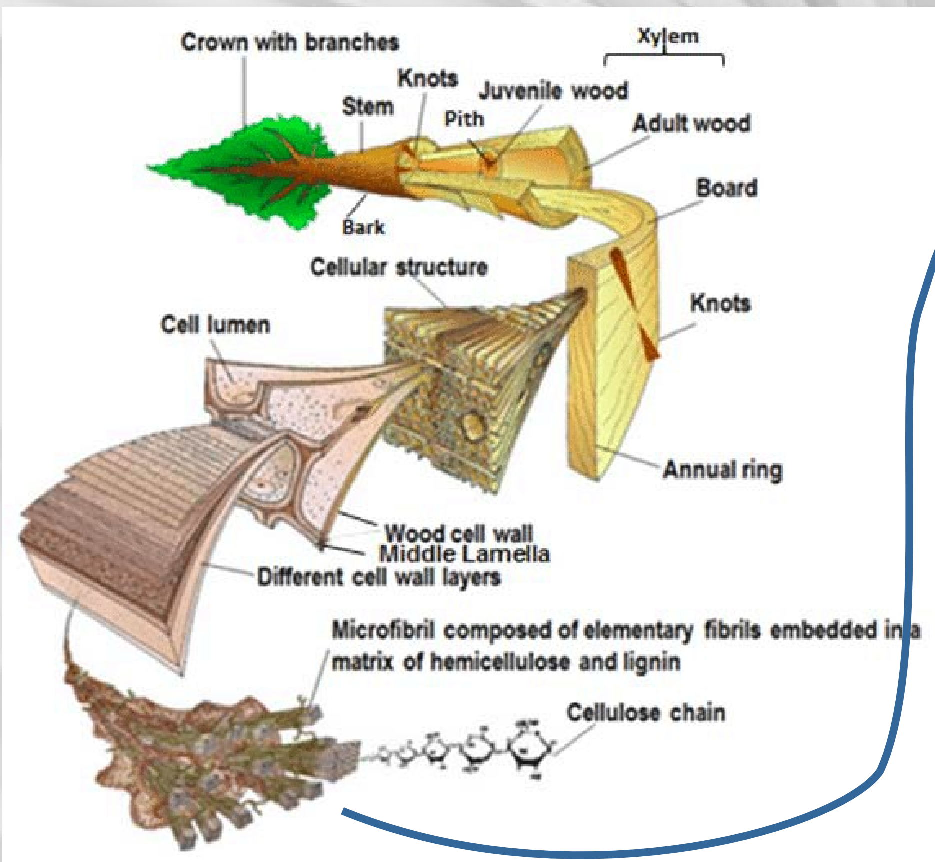
- Environmental issues
  - Branches/leaves in urban areas and marine systems
  - Dynamics of plastic in marine systems
  - Dynamics of plankton in oceans



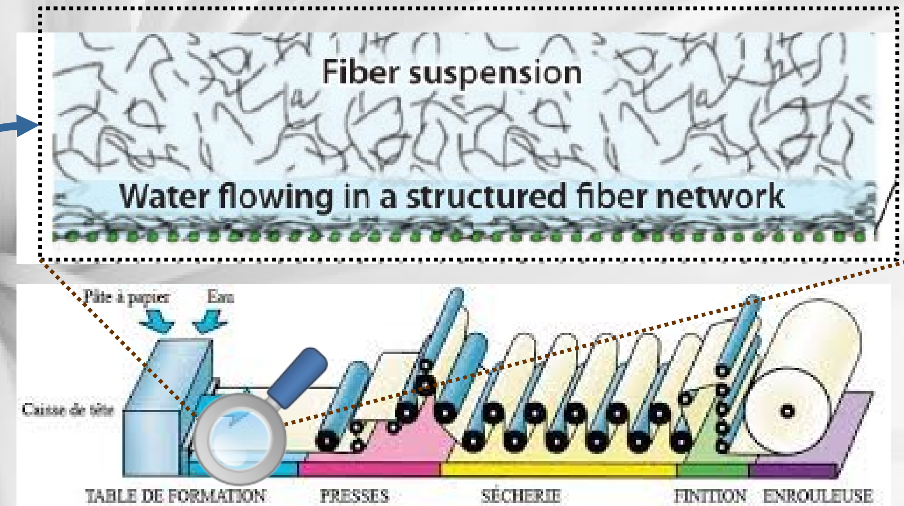
Chains of diatoms in the ocean
(source: internet)

Context: elongated particles in flows

- Industrial issues
  - Papermaking industry



Structure of wood fibers (source: internet)

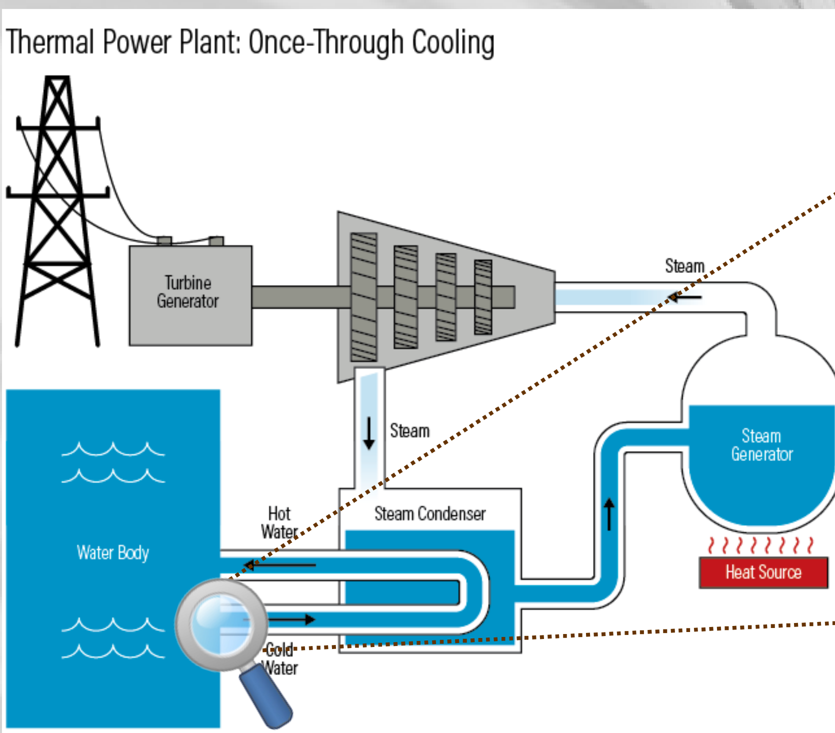


Entanglement

Fiber suspension used for paper (source: internet)

Context: elongated particles in flows

- Industrial issues
  - Papermaking industry
  - Branches/leaves/fishes in pump systems

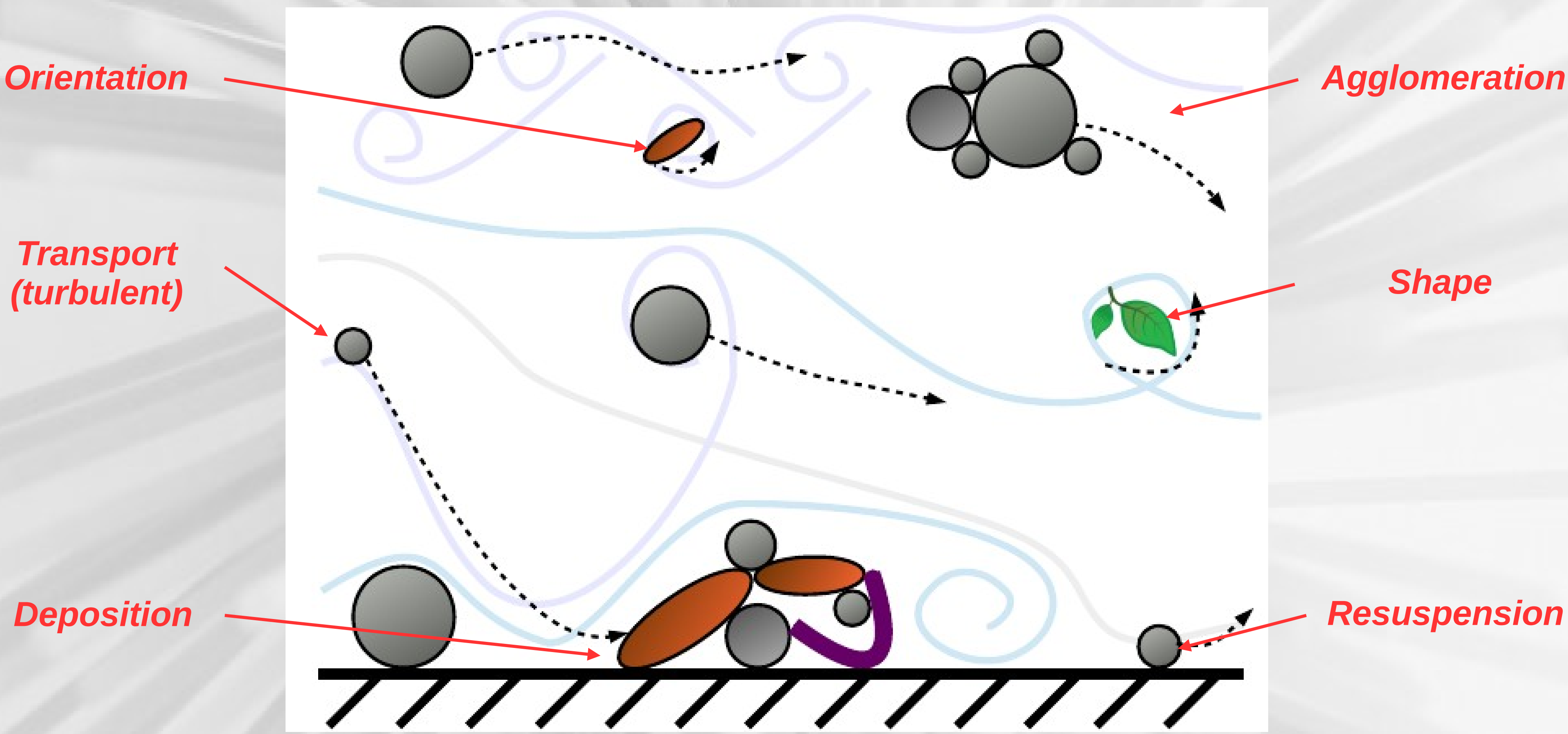


Sketch of a thermal power plant (source: internet)

Fouled filtration system in a pump (source: internet)

Context: elongated particles in flows

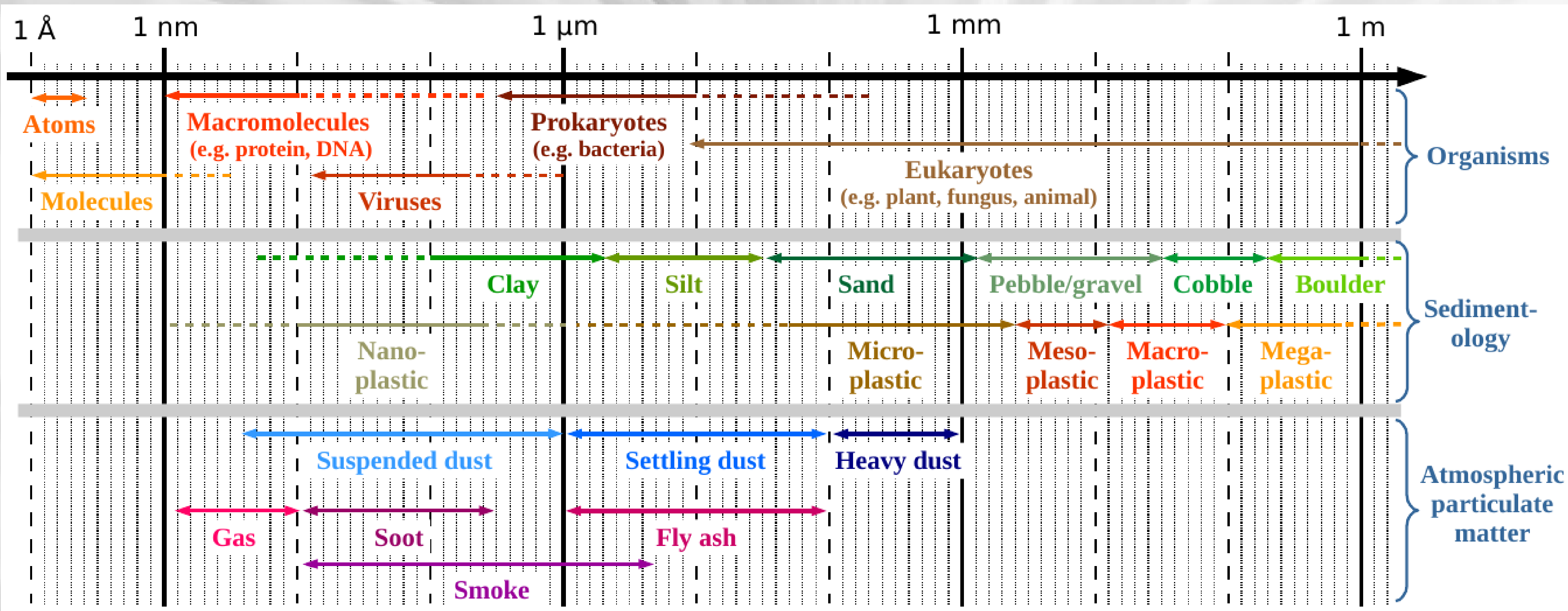
- Summary of the main processes:



→ **A large range of processes/mechanisms**

Context: elongated particles in flows

- Various type of particles involved



→ A large range of spatial and temporal scales

→ A large range of applications

Context: elongated particles in flows

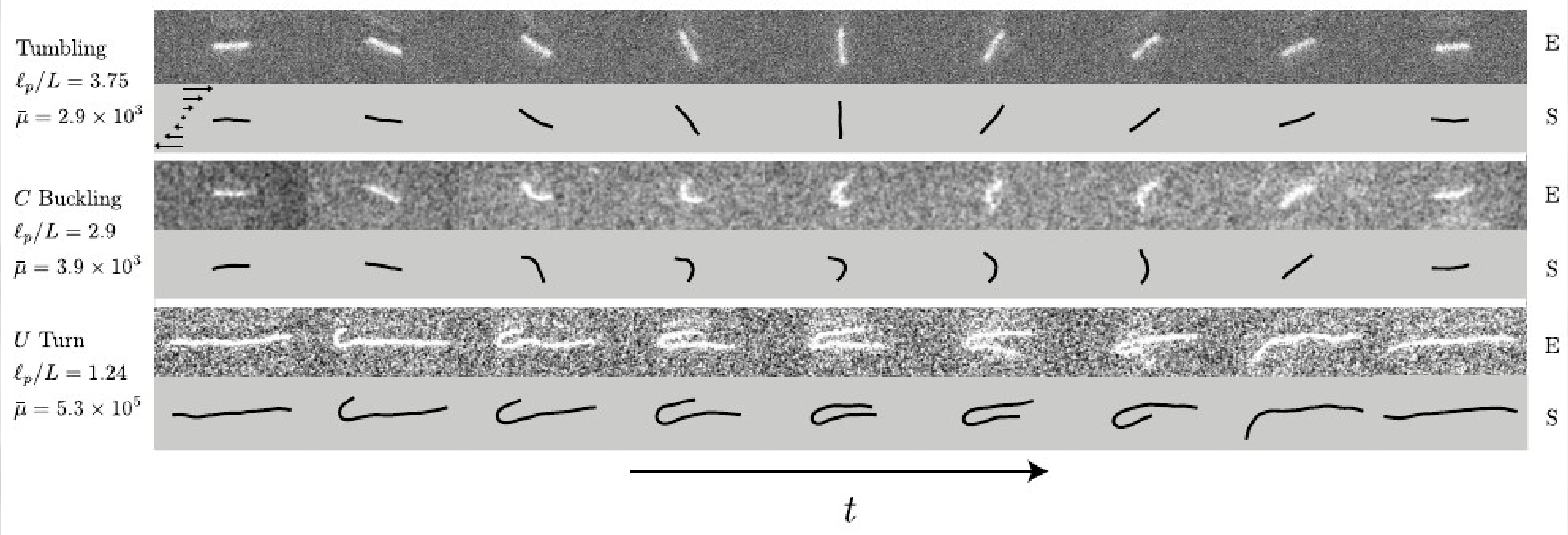
- Scientific domains involved

Field	
– Fluid dynamics	(drag and lift forces)
– Physico-chemistry of interfaces	(adhesion forces)
– Material physics	(resistance, heterogeneities)
– Solid mechanics	(plastic/elastic deformations)
– Biology	(organisms)
– Granular matter	(complex network of granular media)
– Surface hydrology	(plastic in riverbeds)
– Etc...	

→ **Highly multidisciplinary topic**

Main issue encountered

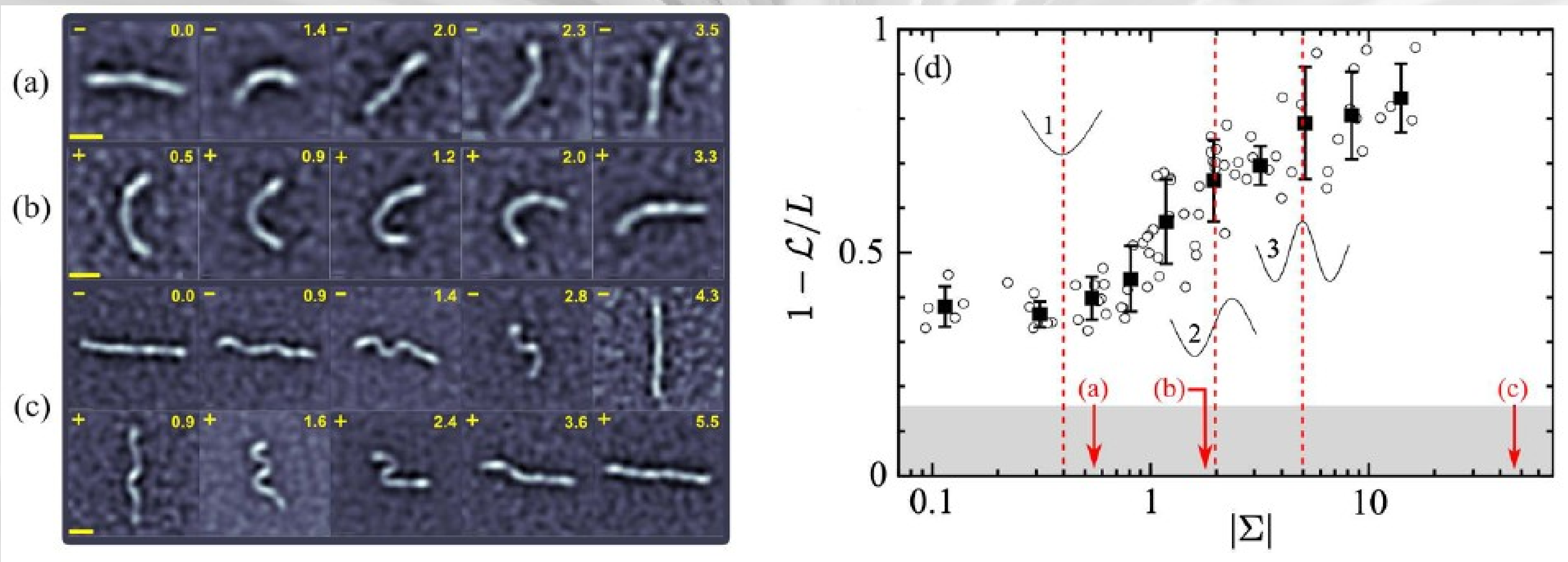
- Dynamics of deformable elongated particles
  - Tumbling & buckling instabilities



Evolution of a filament 20 µm filament in a shear flow
(source: Liu et al., ArXiv, 2018)

Main issue encountered

- Dynamics of deformable elongated particles
  - Tumbling & buckling instabilities



Buckling of 10 µm filaments in a shear flow *End-to-end length L as a function of the shear/stress rate*

(source: Kanstler & Goldstein, PRL, 2012, 108, 038103)

→ How do rods deform and break?

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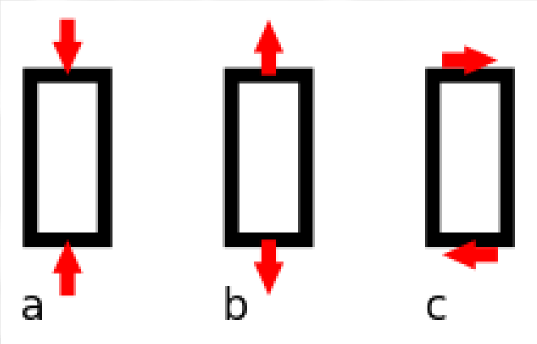
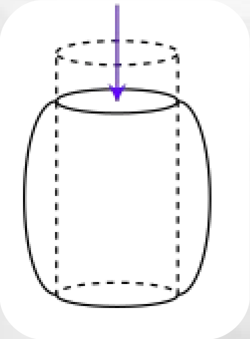
What is deformation or breakup?

- Mechanics of materials
  - Stress = force per unit area (N/m^2)
    - a) Compression
    - b) Tension
    - c) Shear



Material being loaded (source: internet)

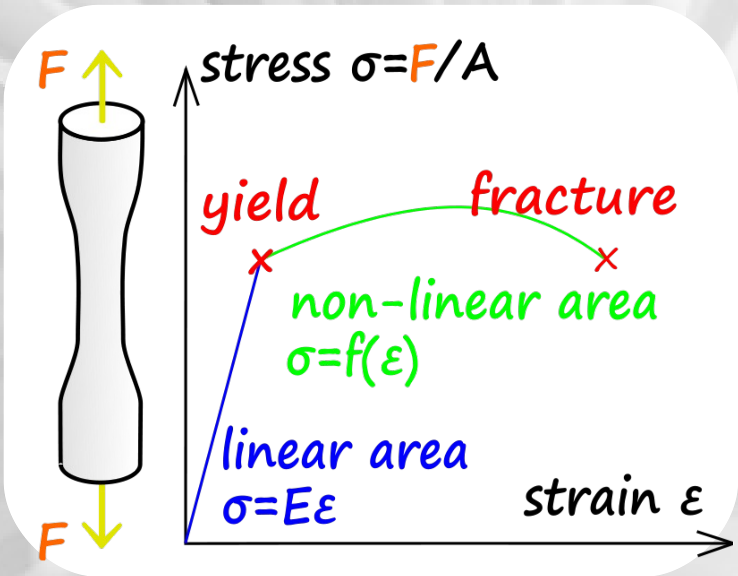
  - Strain / deformation = change of geometry



Deformation under loading (source: internet)

What is deformation or breakup?

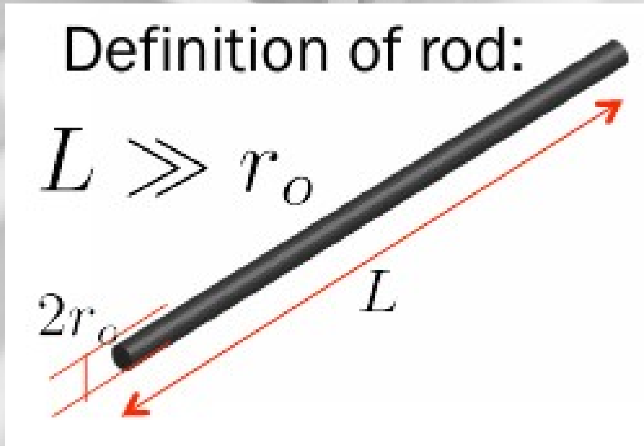
- Mechanics of materials = Relation between stresses and strain



  - **Elasticity** = ability to deform
    - Young modulus E = measure of the stiffness
    - Yield stress = threshold before permanent deformation
  - **Plasticity** = unrecoverable strain
    - Compressive stress = threshold before compressive failure/fracture
    - Tensile stress = threshold before tensile failure/fracture

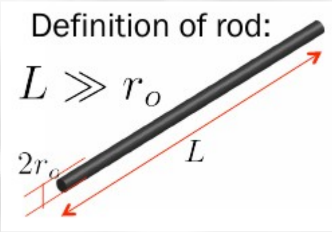
Case of elongated particles

- Case considered:
  - Rod of length L
  - Radius r_0 (circular cross-section)

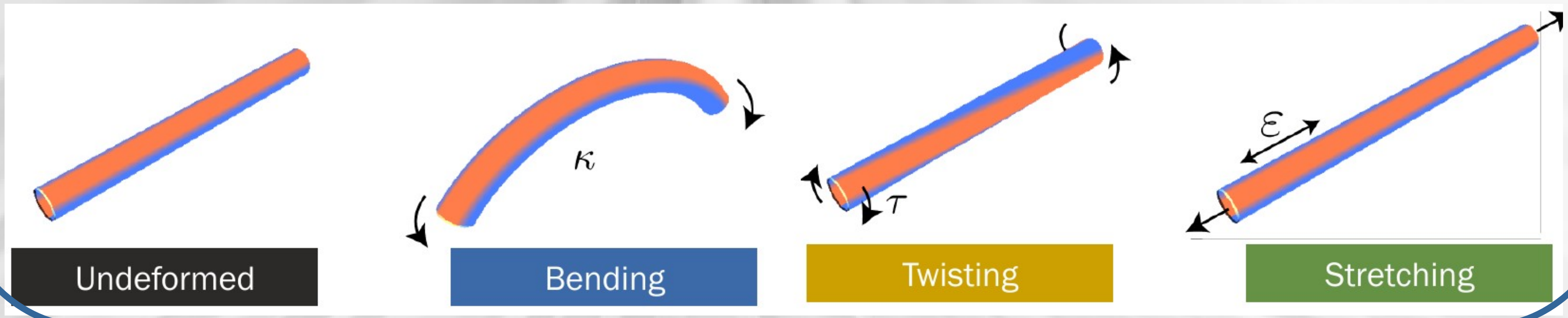


Case of elongated particles

- Case considered:
  - Rod of size L and radius r_0



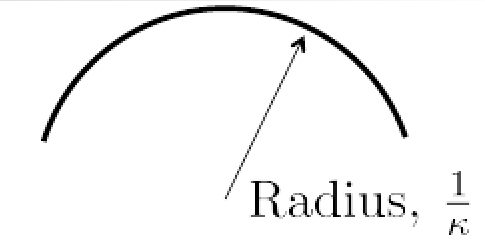
- Kirchhoff equations
  - Energies due to:
    - Bending
    - Twisting
    - Stretching

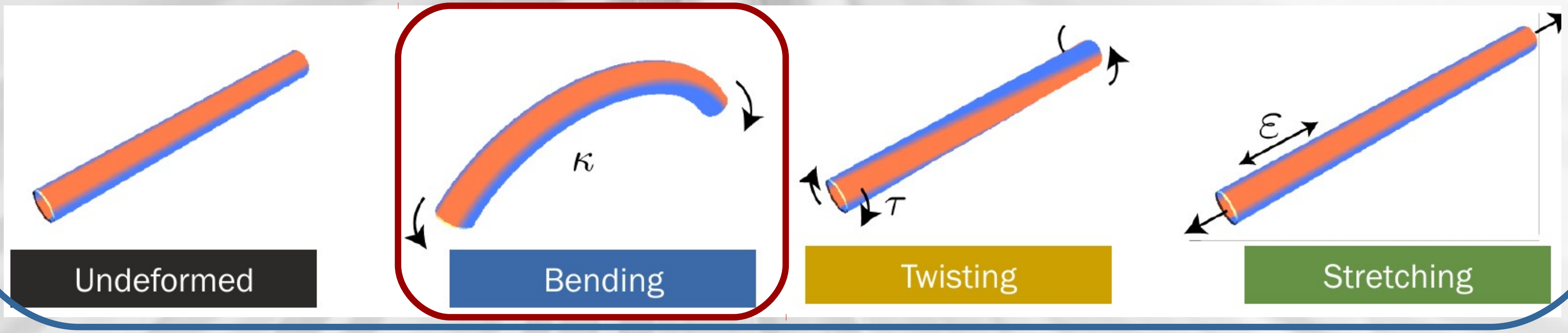


Case of elongated particles

- Case considered:
  - Rod of size L and radius r_0
- Kirchhoff equations
  - Energies due to:
    - Bending (energy per length)
    - Twisting
    - Stretching

$$E_b = \frac{1}{2} EI\,\kappa^2$$

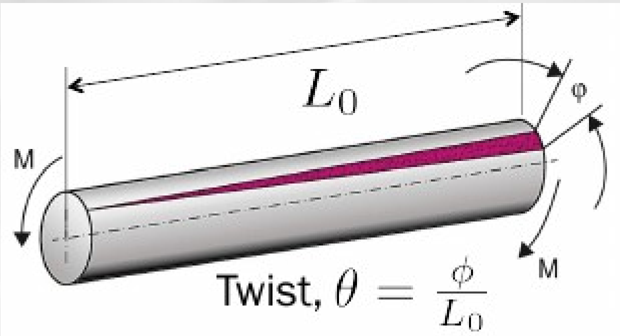


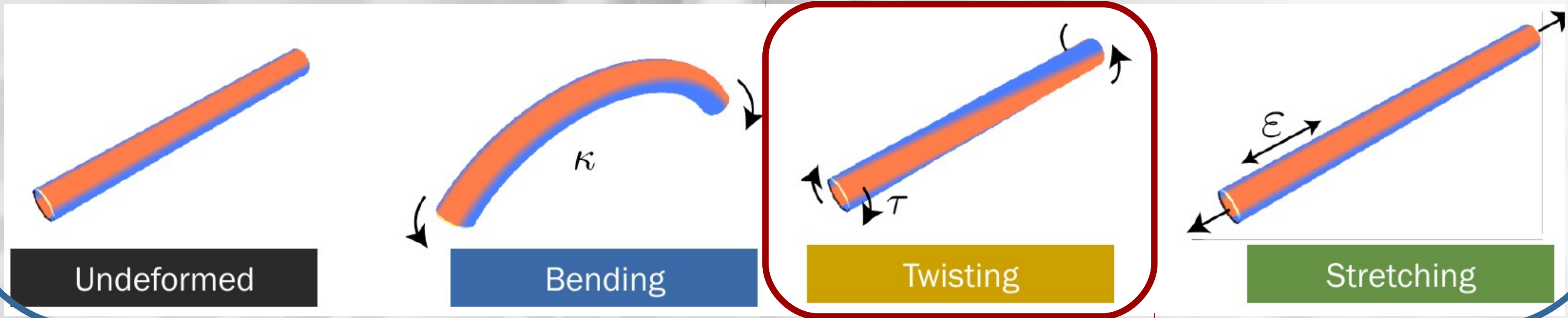


Case of elongated particles

- Case considered:
  - Rod of size L and radius r_0
- Kirchhoff equations
  - Energies due to:
    - Bending
    - Twisting (energy per length)
    - Stretching

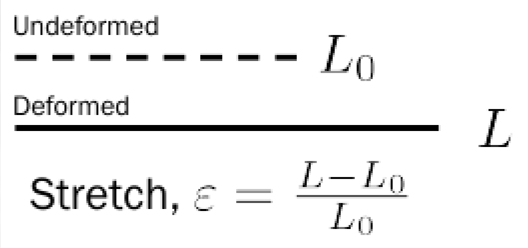
$$E_t = \frac{1}{2} G J \theta^2$$

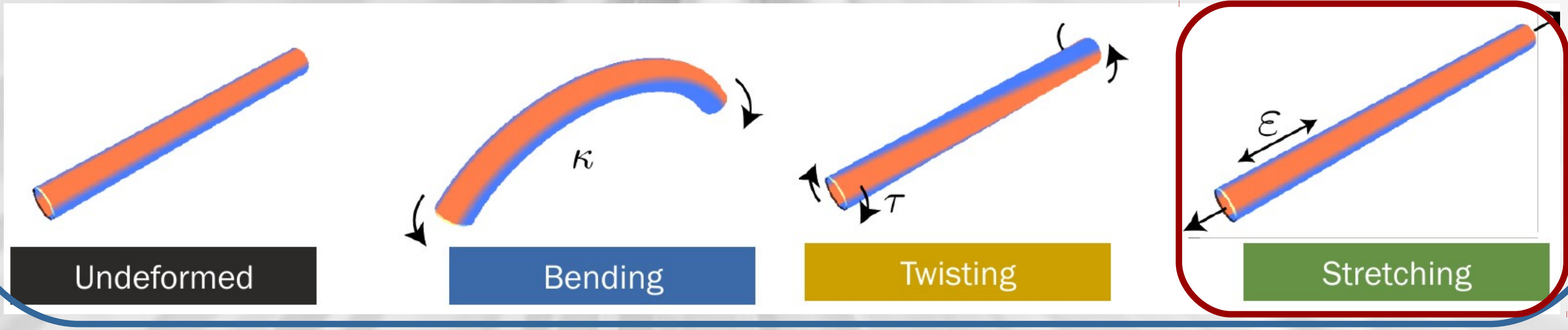




Case of elongated particles

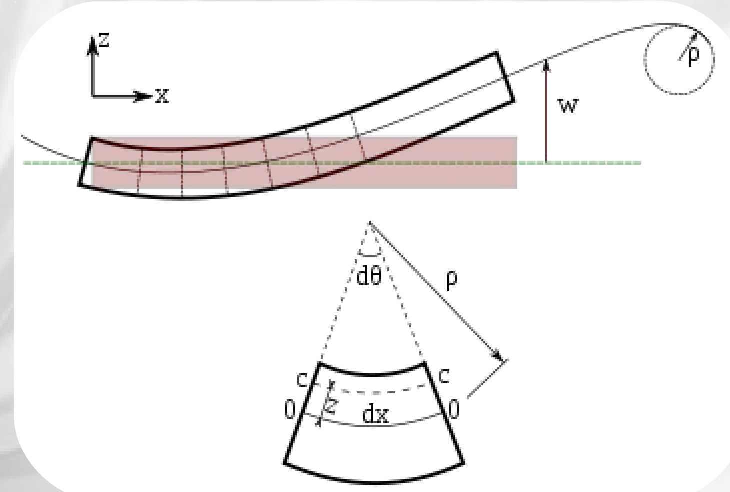
- Case considered:
  - Rod of size L and radius r_0
- Kirchhoff equations
  - Energies due to:
    - Bending
    - Twisting
    - Stretching (energy per length) $E_s = \frac{1}{2} E A \varepsilon^2$





Case of elongated particles

- Specific case: Euler-Bernoulli equation
  - Valid for slender rods ($L >> r_0$)
  - Isotropic and homogeneous material
  - Under Hooke's law (linearly elastic) $\sigma = E\varepsilon$
  - Pure bending
  - Relation between beam's deflection (w) and applied load (q)



$$EI\frac{d^4 w}{dx^4} = q(x).$$

with E the Young modulus and I the moment of area

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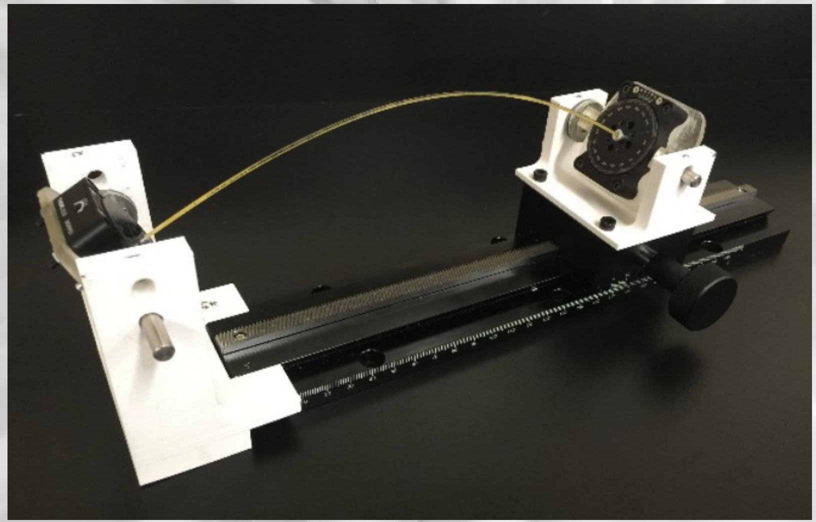
How dry spaghettis break under load?

Problem (known as Feynman conjecture)

- What happens when spaghettis are bent between the two ends?



Picture of the fracture device (Taken from Heissner et al., PNAS, 2018, 115, 8665)

How dry spaghettis break under load?

- Problem (known as Feynman conjecture)

(source: science&vie)

How dry spaghettis break under load?

- Problem (known as Feynman conjecture)
  - What happens when spaghettis are bent between the two ends?

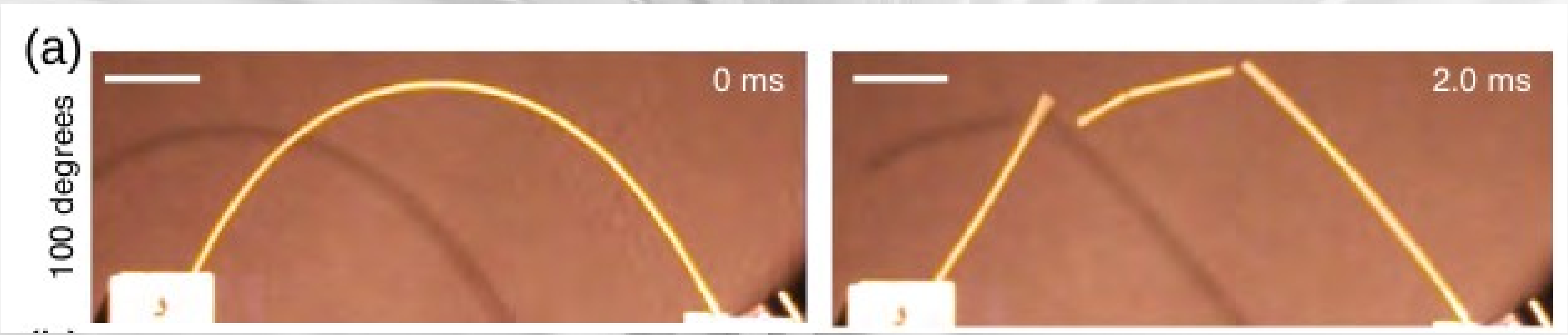
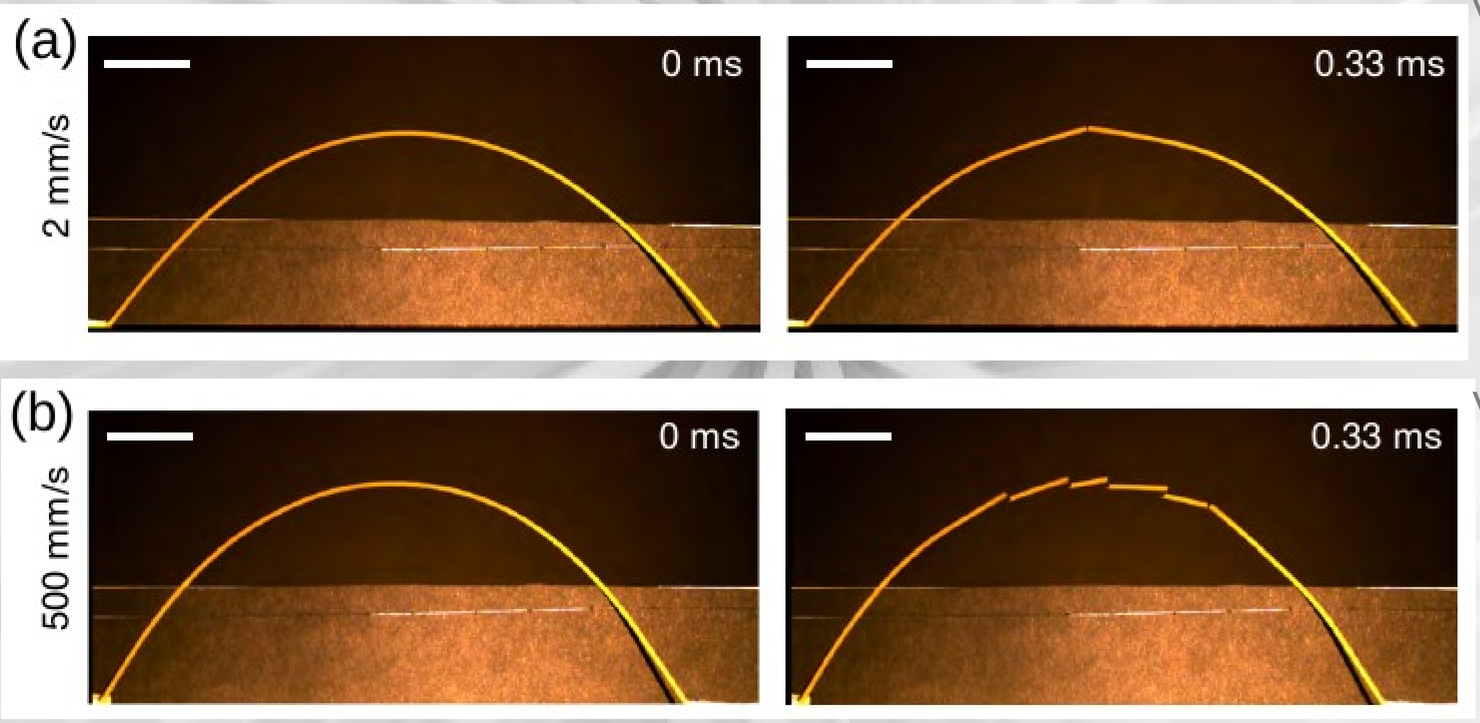


Image of a spaghetti breaking
(Taken from Heissner et al., PNAS, 2018, 115, 8665)

→ Does it always break in several pieces?

How dry spaghettis break under load?

- Problem (known as Feynman conjecture)
  - Does it always break in several pieces?



Video

→ **Binary breaking**

Video

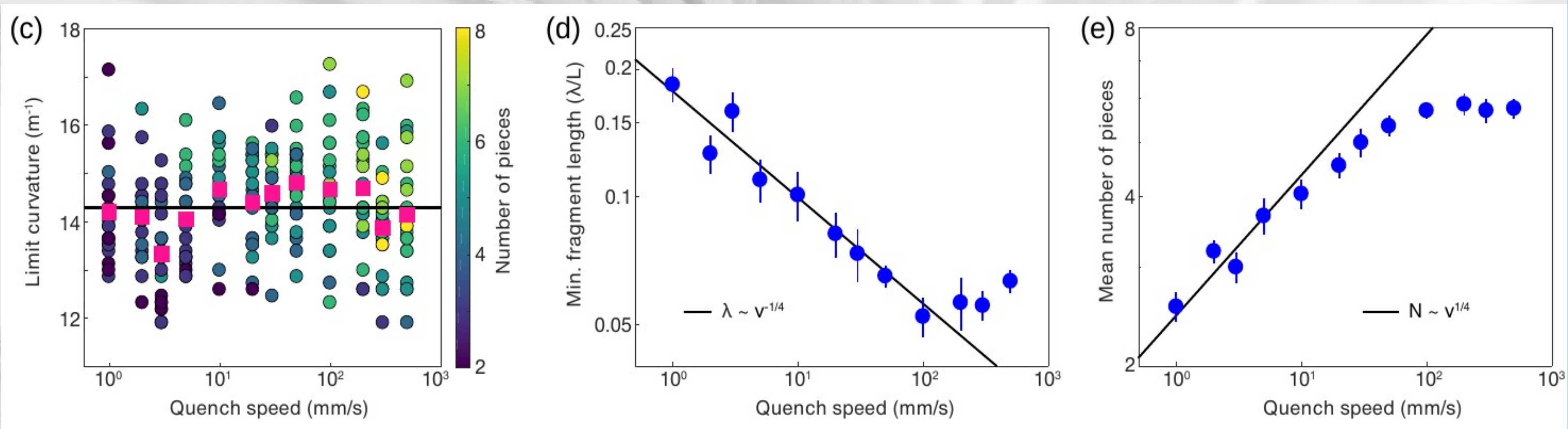
→ **Multiple fragments**

Image of a spaghetti breaking at two quenching speeds
(Taken from Heissner et al., PNAS, 2018, 115, 8665)

→ How does breaking depends on quenching?

How dry spaghettis break under load?

- Problem (known as Feynman conjecture)
  - How does breaking depends on quenching?



Bristle elastic rods fractured by quenching
(Taken from Heissner et al., PNAS, 2018, 115, 8665)

→ Curvature at breaking independent of quenching

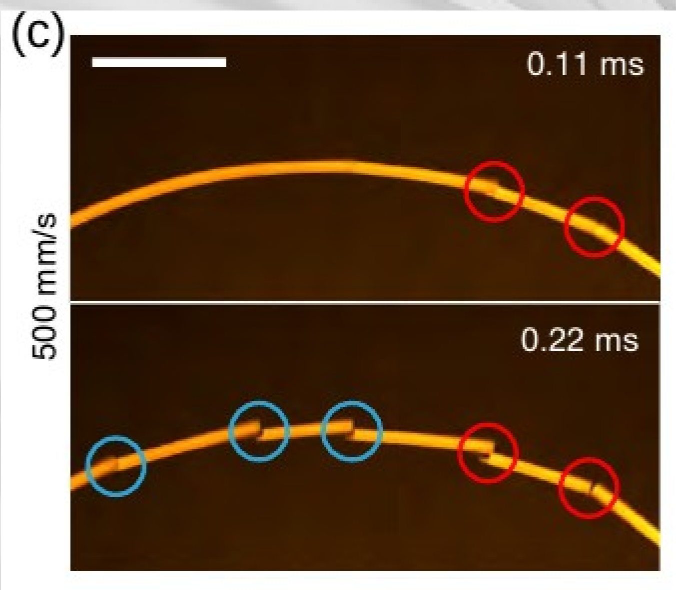
→ Power-law scaling of the minimum fragment length

→ Asymptotic power-law for the number of fragments

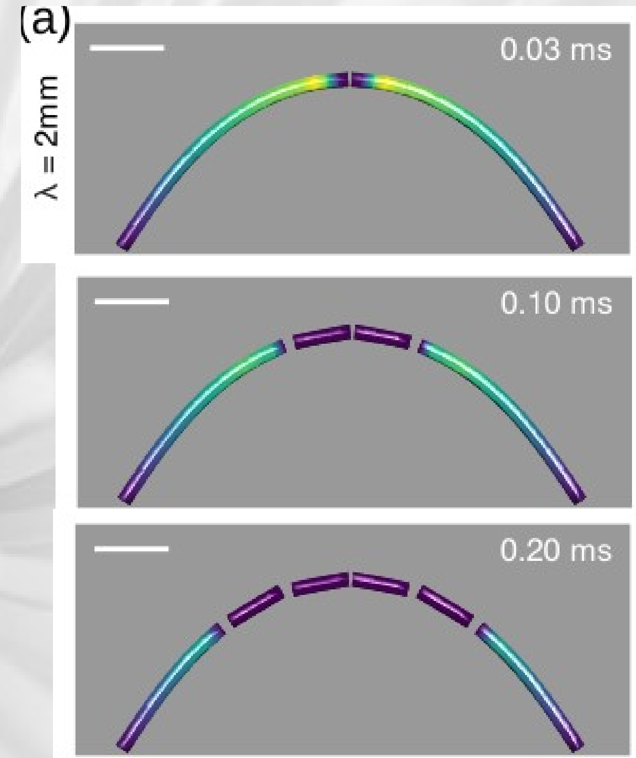
→ What leads to multiple fragmentation?

How dry spaghettis break under load?

- Problem (known as Feynman conjecture)
  - What leads to multiple fragmentation?



Fracture cascade observed in experiments
(Taken from Heissner et al., PNAS, 2018, 115, 8665)



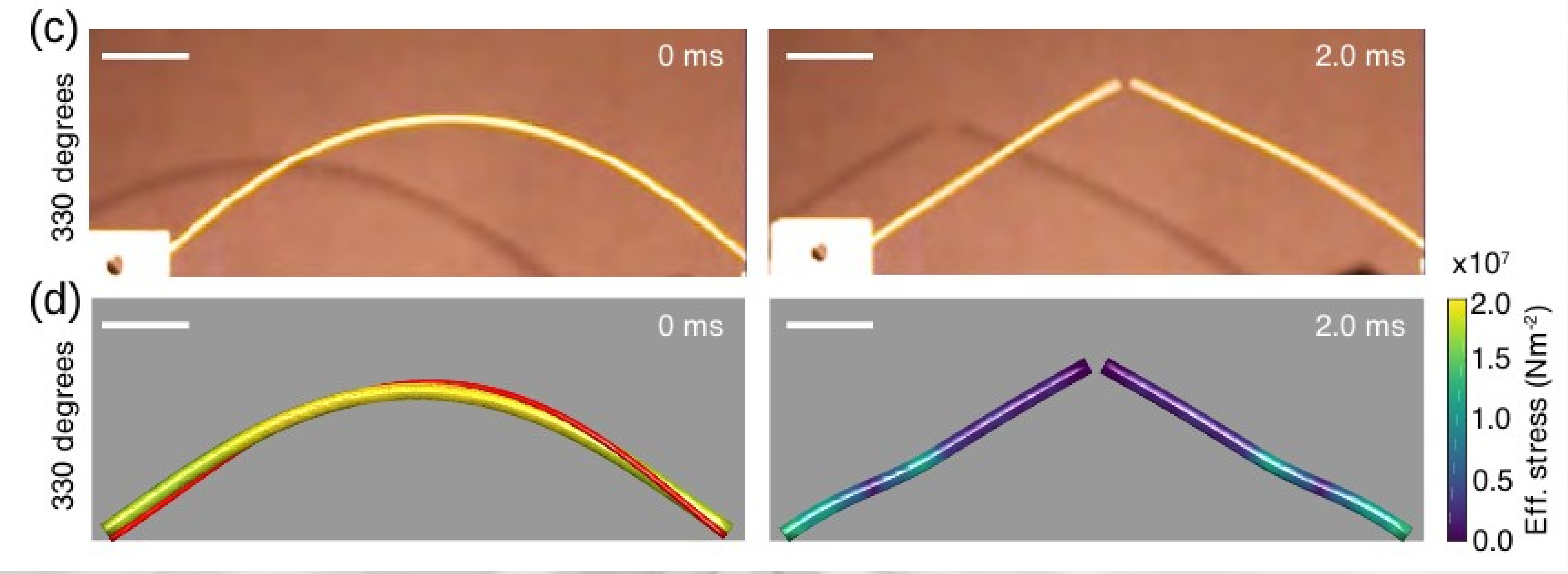
Simulations showing bending waves after breakage
(Taken from Heissner et al., PNAS, 2018, 115, 8665)

→ **Fracture cascade due to bending waves**

→ **Is there another way to avoid multiple braekage?**

How dry spaghettis break under load?

- Problem (known as Feynman conjecture)
  - Is there another way to avoid multiple breakage?

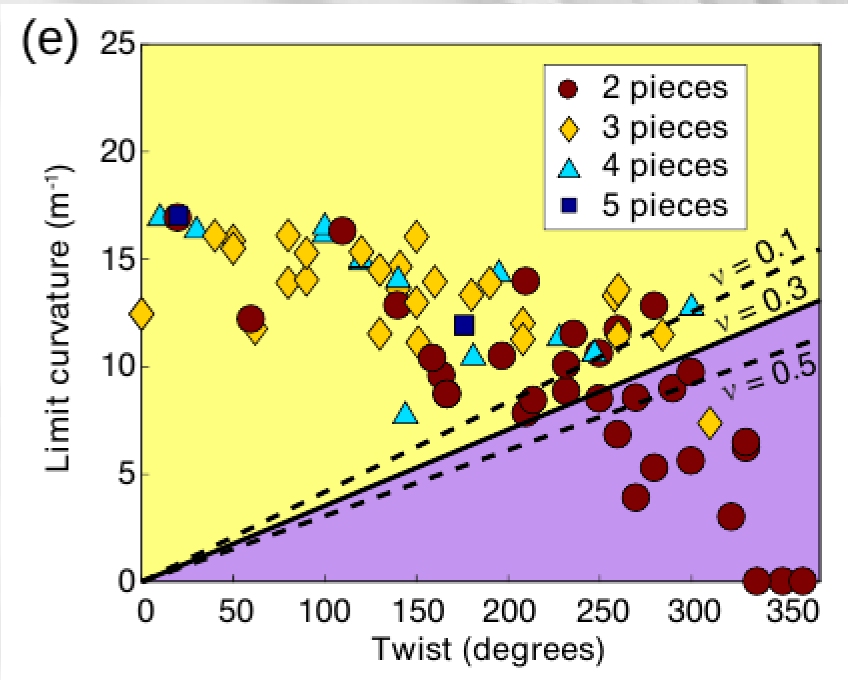


Observation and simulation of breakage using twisting and quenching
(Taken from Heissner et al., PNAS, 2018, 115, 8665)

→ Use of twist

How dry spaghettis break under load?

- Problem (known as Feynman conjecture)
  - Is there another way to avoid multiple breakage?



Video

Video

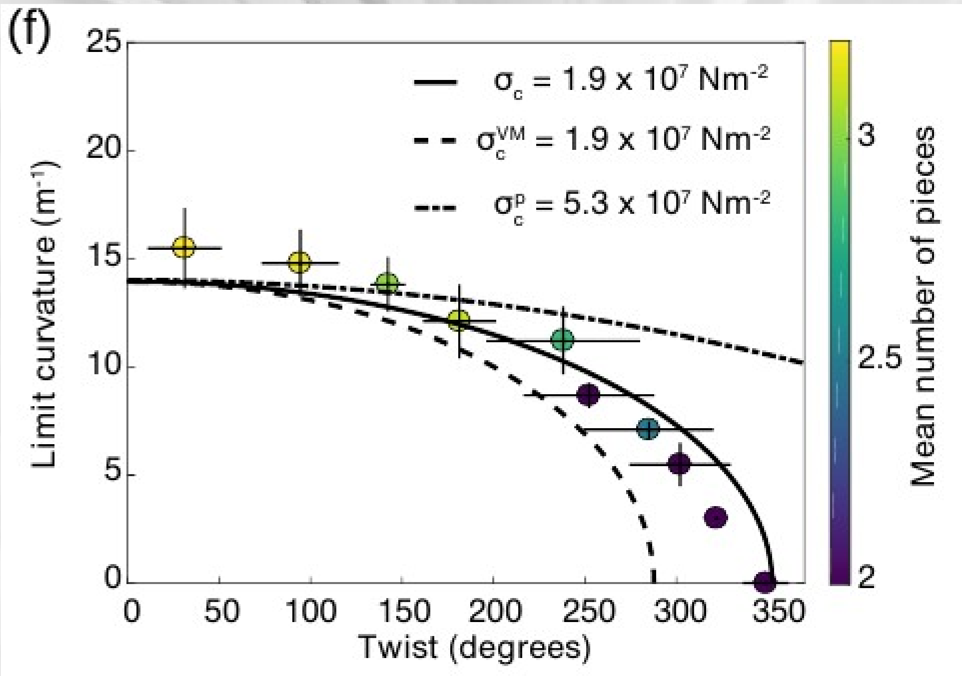
Phase diagram for breakage at different twist angles (Taken from Heissner et al., PNAS, 2018, 115, 8665)

→ Twisting favors binary breakage

→ What is the role of twisting?

How dry spaghettis break under load?

- Problem (known as Feynman conjecture)
  - What is the role of twisting?

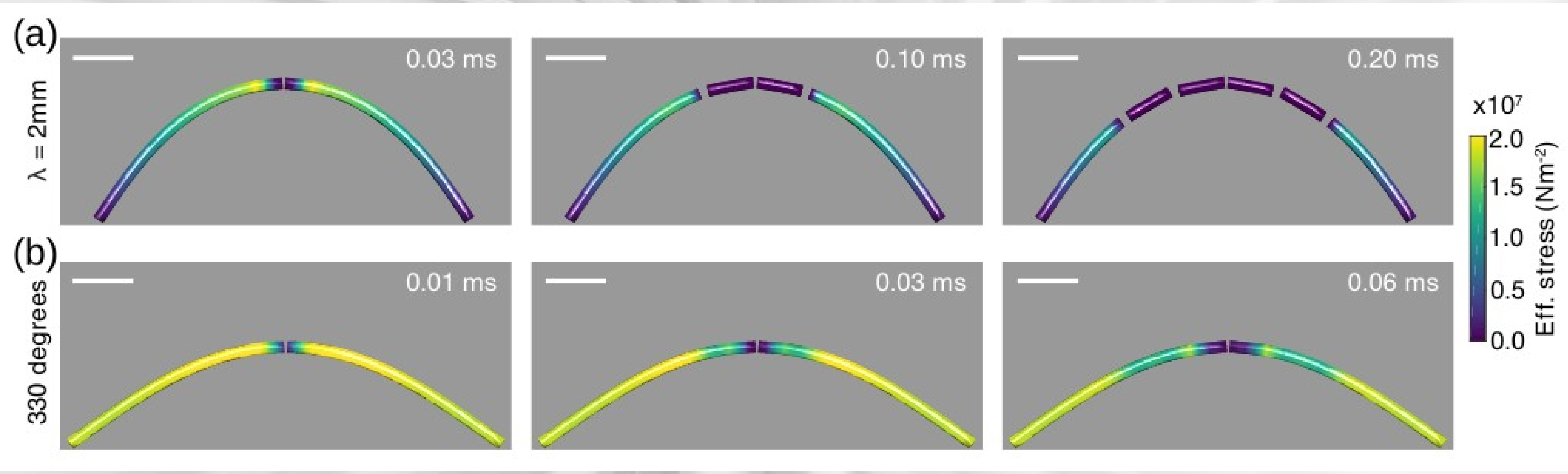


Evolution of the critical curvature for breakage with twisting angle (Taken from Heissner et al., PNAS, 2018, 115, 8665)

→ Twist waves lower the critical curvature for breakage

How dry spaghettis break under load?

- Problem (known as Feynman conjecture)
  - What is the role of twisting?



Simulations showing bending (a) and twisting (b) waves after breakage
(Taken from Heissner et al., PNAS, 2018, 115, 8665)

→ Twist waves lower the critical curvature for breakage
→ Twist waves propagate faster

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Conclusion and perspectives

- Take home message
  - Particles in flow:
    - Complex shapes
    - Complex dynamics (deformation, breakage)
  - Deformation and breakage:
    - Role of compression, tension and shear
    - Material dependent
  - Specific case of spaghettis
    - Multiple breakage due to bending wave propagation
    - Binary breakage favored by twisting

Thank you for your attention

And happy cooking!

Any question?