Impact of drops on a repellent surface and targets of various diameters

Carole-Ann Charles

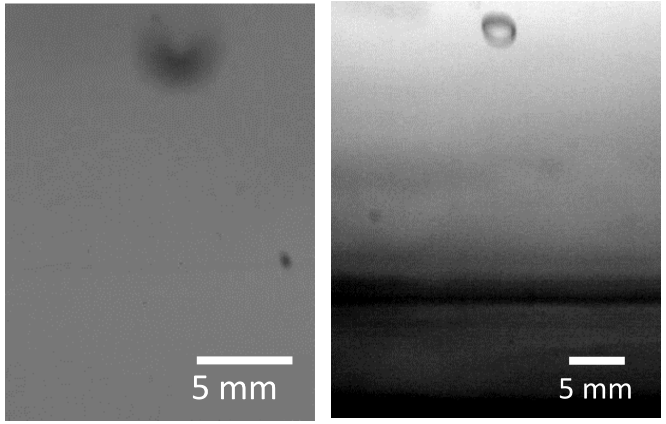
Supervisors:
Christian Ligoure
Laurence Ramos

Objectives

- Identify the **relevant dissipation** involved in the sheet expansion dynamics on a **repellent surface** and on **targets**.
- Rationalize the respective roles of **inertia**, **capillarity**, **elasticity** and **dissipation** on the impact process.
- Study the **elasto-capillary** effects on the mechanical deformation by impacting droplets of transient networks.

Context – Drop impact

Deceleration 300x



Upon impact :

Inertial forces → radial expansion of the sheet

Stored elastic energy → retraction after maximal expansion

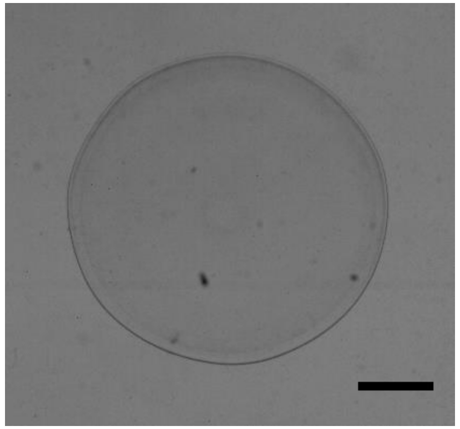
Goal:

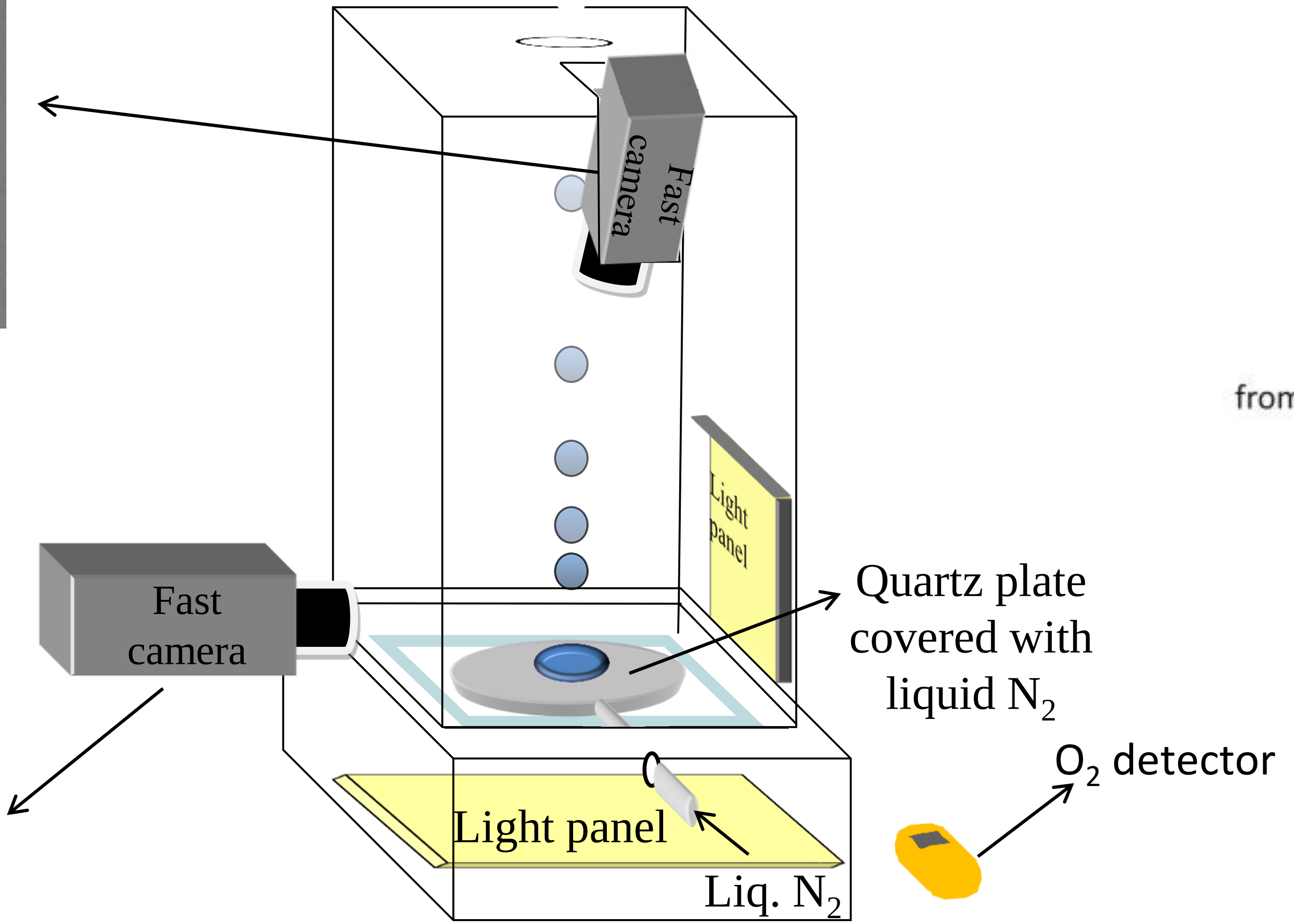
- Rationalize the respective role of

Inertia | Surface elasticity | Bulk elasticity | Dissipation

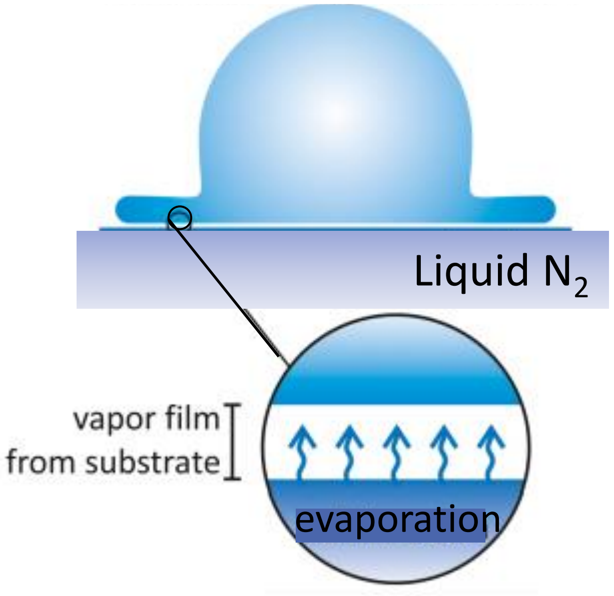
$$E_{\mathrm{K}} + E_{\gamma} + E_{\mathrm{Bulk}} + E_{\mathrm{Diss}} = \mathrm{cst}$$

Drop impact Part 1 – repellent surface



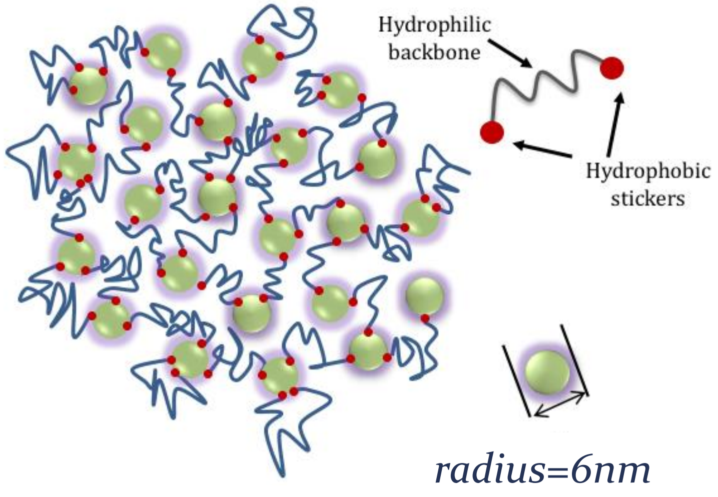


Inverse Leidenfrost effect

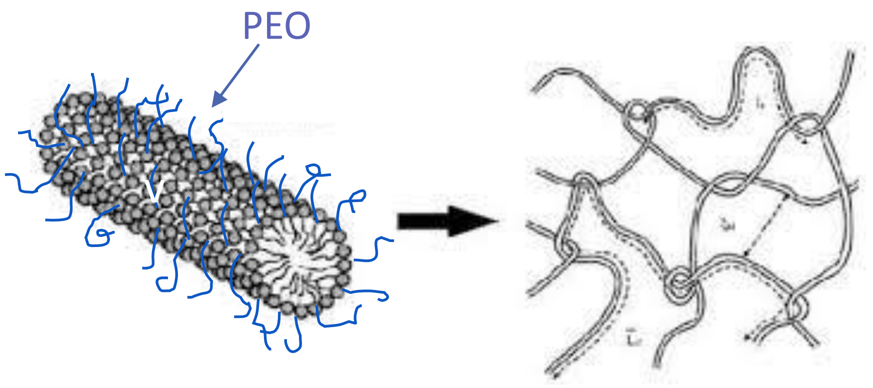


Drop impact Part 1 -Viscoelastic Samples

Microemulsions reversibly linked
by telechelic polymers,
C_n -(PEO)$_{35k}$- C_n (n = 12, 14, 18)



Decorated wormlike micelles



r = number of stickers per droplet
Φ = mass fraction of droplet

Φ = mass fraction of surfactant
α = mole fraction of amphiphilic polymer (PEO)

Impact of Beads and Drops on a Repellent Solid Surface: A Unified Description,
S. Arora, J.-M. Fromental, S. Mora, Ty Phou, L. Ramos, and C. Ligoure
Phys. Rev. Lett., 2018

Adapted from Schubert, B.A., The rheology and microstructure of charged, wormlike micelles. Ph.D. Thesis, 2003, University of Delaware, Newark.

Drop impact Part 1 - Viscoelastic Samples

Micro-emulsions				
Name	G_0 [Pa]	τ [ms]	η_0 [Pas]	De
M18ϕ10r4	10	178	1.78	45
M14ϕ8r9	189	8	1.5	5.3
M14ϕ8r8	128	6	0.77	2
M14ϕ10r6	48	5	0.23	1.2
M14ϕ8r6	31	4	0.12	0.9
M12ϕ10r8	194	2	0.39	0.73

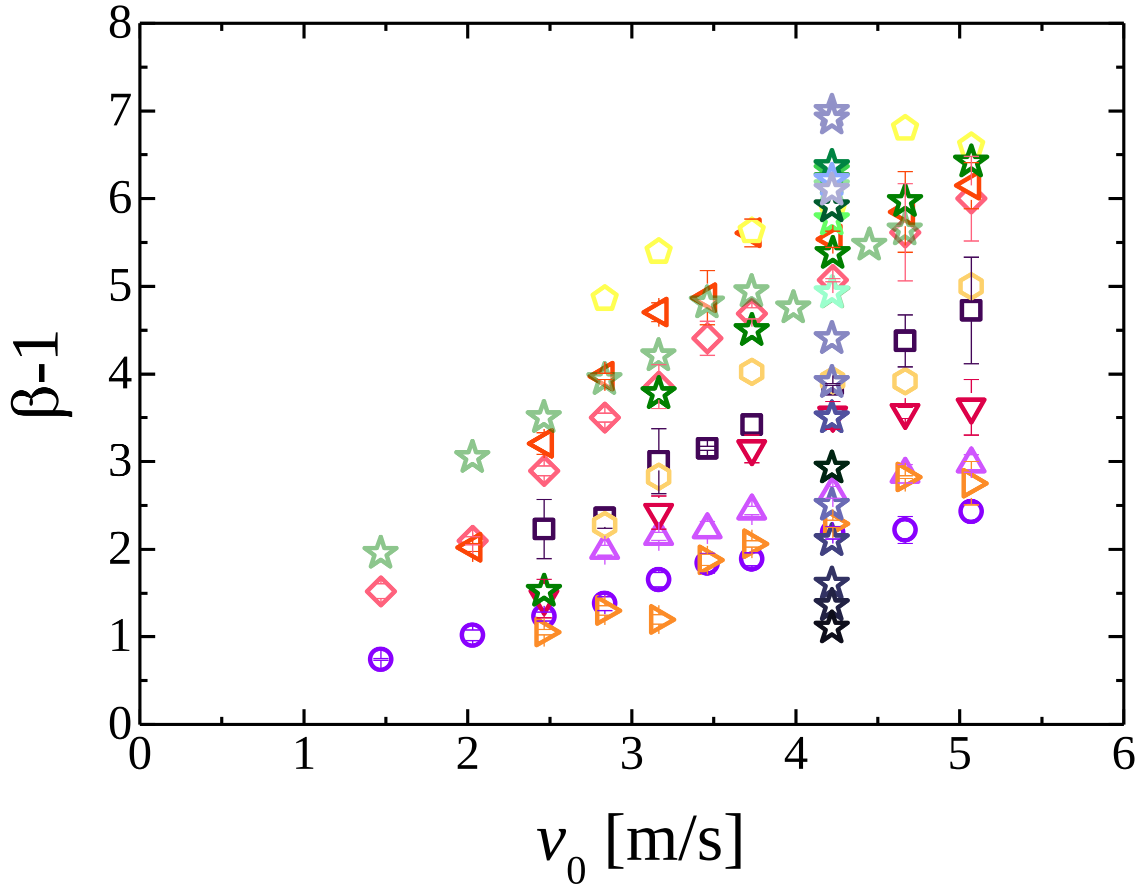
Wormlike micelles				
Name	G_0 [Pa]	τ [ms]	η_0 [Pas]	De
WMϕ5α0.24	50	8	0.4	3.34
WMϕ7α0.9	73	2	0.146	0.36
WMϕ9α2	64	1	0.031	0.16

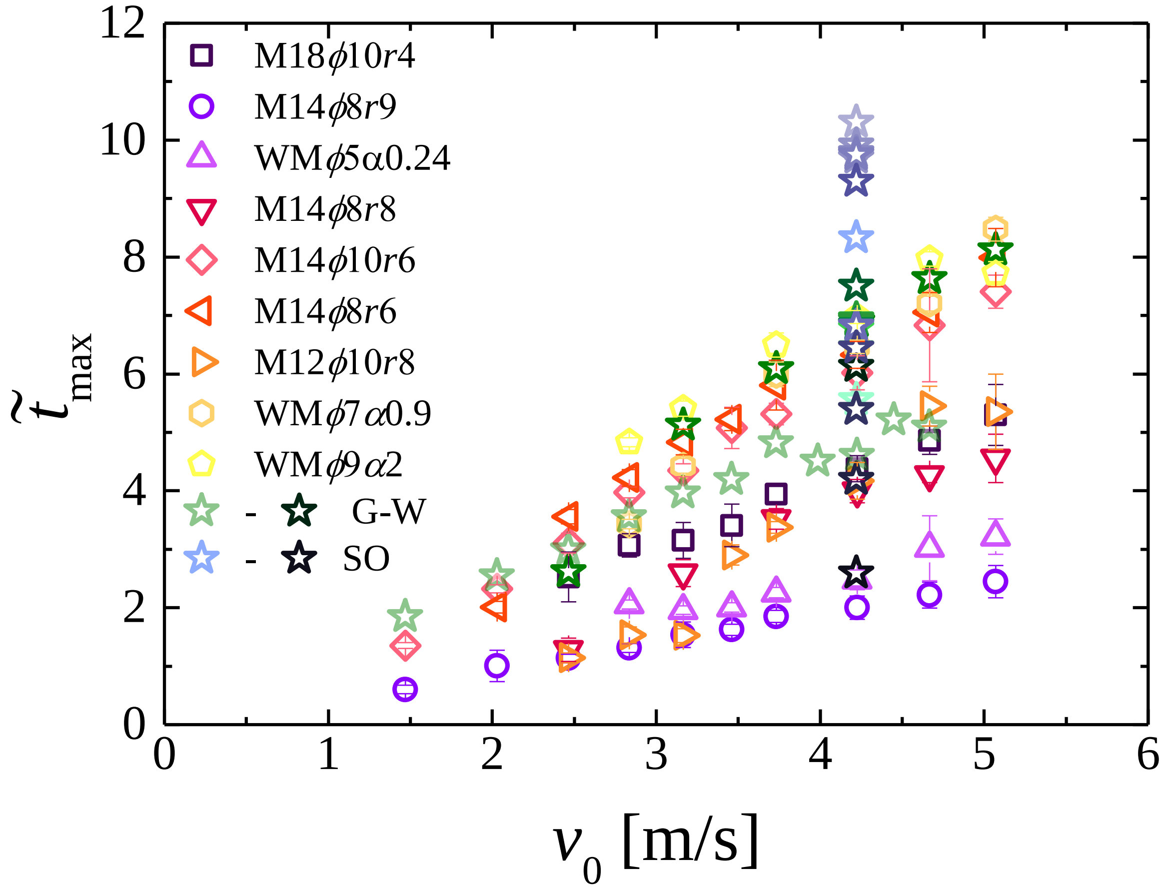
$$De = \frac{\tau}{t_{\max}}$$

Drop impact Part 1 – repellent surface

$$\beta = \frac{d_{\max}}{d_0}$$

$$\tilde{t}_{\max} = \frac{t_{\max}}{t_{\mathrm{col}}} \qquad t_{\mathrm{col}} = \frac{d_0}{v_0}$$





$$v_0 = \sqrt{2gh}$$

Glycerol-Water $\eta_0 = 1$ to 813 mPas

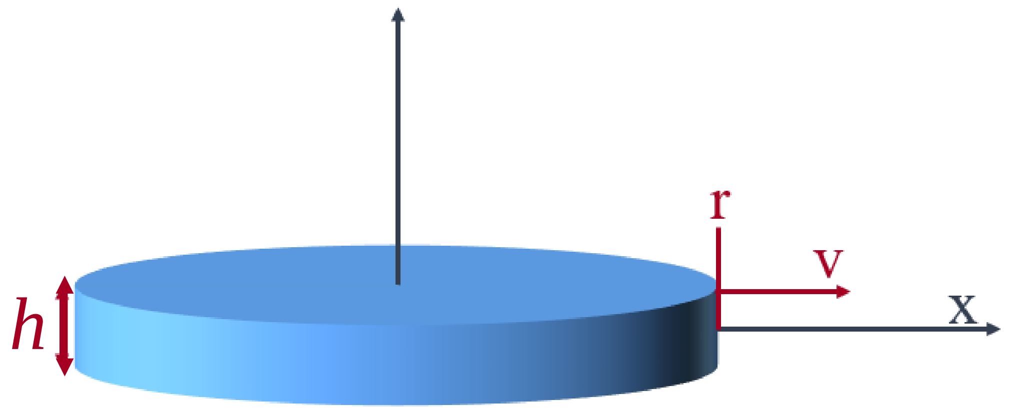
Silicone oil $\eta_0 = 5$ to 970 mPas

Drop impact Part 1 – Energy balance

Kinetic energy

$$E_{\mathrm{K}} + E_{\gamma} + E_{\mathrm{Bulk}} + E_{\mathrm{B}} = \mathrm{cst}$$

for $d >> d_0$



At all time $v(x) = \frac{vx}{r}$

$$\boxed{E_{\mathrm{K}} = \int_0^r \frac{1}{2}\left(\frac{vx}{r}\right)^2 2\rho\pi h x dx = \frac{1}{16} m\dot{d}^2}$$

$$v = \frac{1}{2}\frac{\partial d}{\partial t}$$

Drop impact Part 1 – Energy balance

Surface elastic energy

$$\frac{1}{16}m\dot{d}^2 + E_\gamma + E_{\mathrm{Bulk}} + E_{\mathrm{B}} = \mathrm{cst}$$

for $d >> d_0$

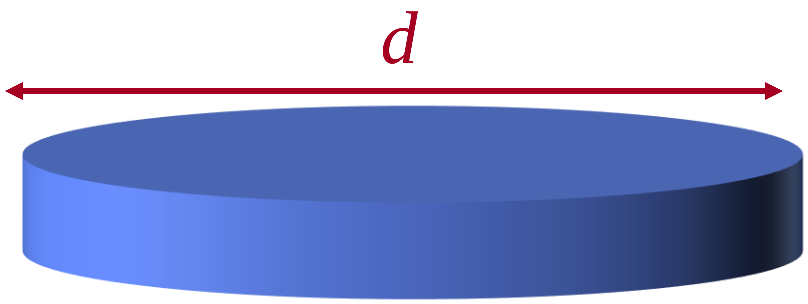
$$\boxed{E_\gamma = \frac{1}{2}\pi\gamma d^2}$$

Drop impact Part 1 – Energy balance

Bulk elastic energy

$$\frac{1}{16}m\dot{d}^2 + \frac{1}{2}\pi\gamma d^2 + E_{\text{Bulk}} + E_{\text{B}} = \text{cst}$$

for a **neo-Hookean solid** with a cylinder shape
of **homogenous thickness** and for ***d>>d$_o$***



$$\boxed{E_{\text{Bulk}} = \frac{VG'}{d_0^2}d^2}$$

Drop impact Part 1 – Energy balance

Biaxial dissipation

$$\frac{1}{16} m\dot{d}^2 + \frac{1}{2}\pi\gamma d^2 + \frac{VG'}{d_0^2} d^2 + E_\mathrm{B} = \mathrm{cst}$$

Dissipation function

$$E_\mathrm{B} = \int_0^{t_\mathrm{max}} \int_{V_\mathrm{drop}} \varphi \, dV \, dt$$

$$\varphi \approx \eta_\mathrm{B} \dot{\varepsilon}^2 \qquad \dot{\varepsilon} = \frac{1}{d}\frac{\partial d}{\partial t}$$

$$\boxed{E_\mathrm{B} \approx \eta_\mathrm{B} \pi \frac{d_0^3}{6} \int_0^{t_\mathrm{max}} \left(\frac{1}{d}\frac{\partial d}{\partial t} \right)^2 dt}$$

For Newtonian fluids :

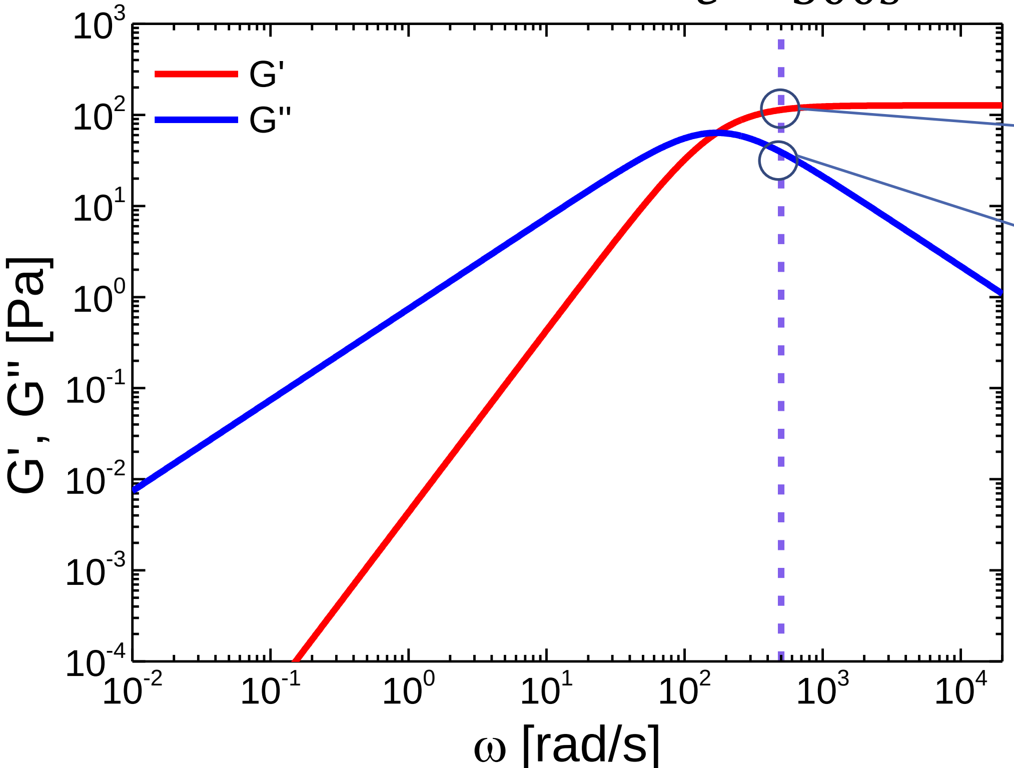
$$\eta_\mathrm{B} = 6\eta_0$$

"Biaxial extensional viscous dissipation in sheets expansion formed by impact of drops of Newtonian and non-Newtonian fluids"
A. Louhichi, C-A. Charles, T. Phou, D. Vlassopoulos, L. Ramos, and C. Ligoure, 2020, Physical Review Fluids (Vol. 5, No. 5)

Drop impact Part 1 – Energy balance

$$\frac{1}{16}m\dot{d}^2 + \frac{1}{2}\pi\gamma d^2 + \frac{VG'}{d_0^2}d^2 + \eta_B\pi\frac{d_0^3}{6}\int_0^{t_{\max}}\left(\frac{1}{d}\frac{\partial d}{\partial t}\right)^2 dt = \mathrm{cst}$$

$\bar{\dot{\varepsilon}} \approx 500 s^{-1}$



$$G' = G'(\bar{\dot{\varepsilon}})$$

$$\eta_B = \frac{6G''(\bar{\dot{\varepsilon}})}{\bar{\dot{\varepsilon}}}$$

Estimation of the strain rate:

$$\dot{\varepsilon} = \frac{1}{d}\frac{\partial d}{\partial t}$$

$$\bar{\dot{\varepsilon}} = \frac{\int_0^{t_{\max}} \dot{\varepsilon}\ dt}{t_{\max}}$$

Drop impact Part 1 – Equation of motion

$$\frac{1}{16}m\dot{d}^2 + \frac{1}{2}\pi\gamma d^2 + \frac{VG'}{d_0^2}d^2 + \eta_{\mathrm{B}}\pi\frac{d_0^3}{6}\int_0^{t_{\max}}\left(\frac{1}{d}\frac{\partial d}{\partial t}\right)^2 dt = \mathrm{cst}$$

$$\frac{1}{8}m\ddot{d} + \frac{\eta_{\mathrm{B}}\pi d_0^3}{6}\frac{1}{d^2}\dot{d} + \left(\pi\gamma + \frac{2VG'}{d_0^2}\right)d = 0$$

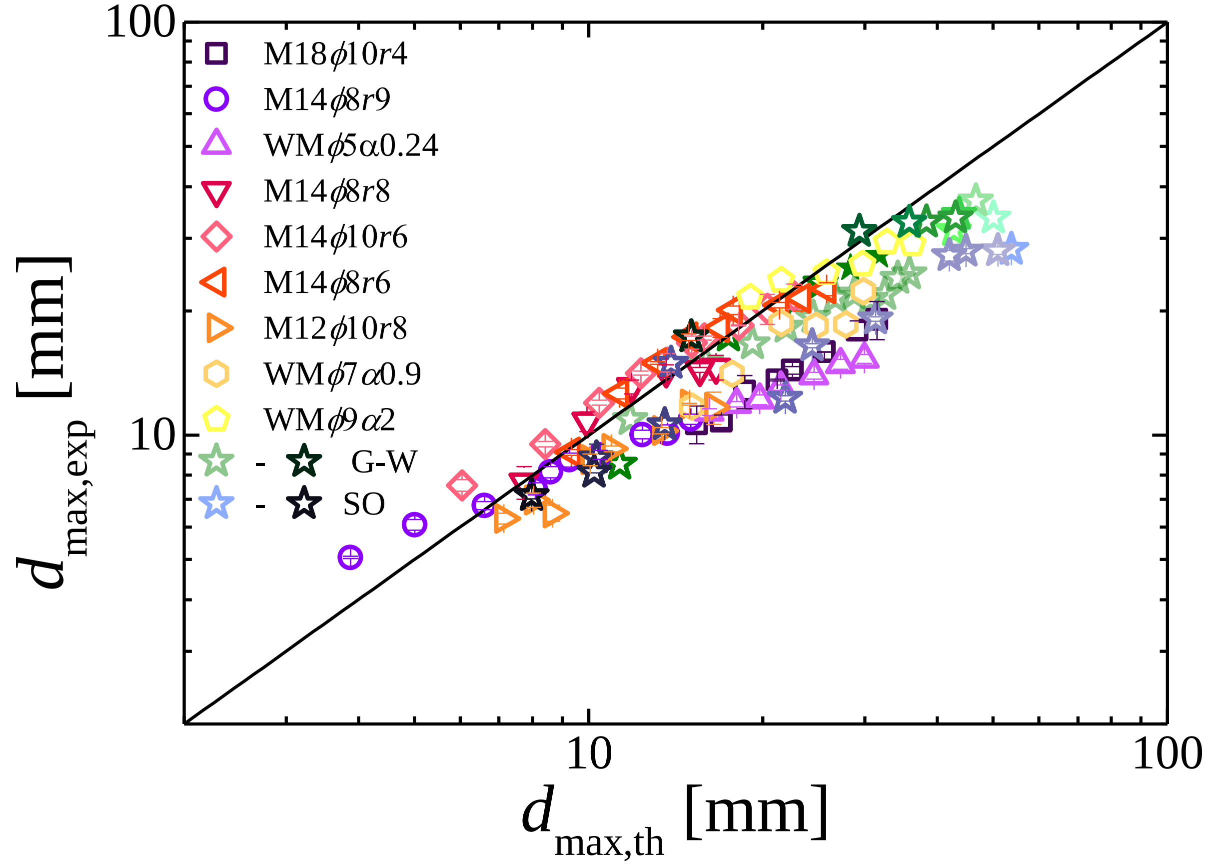
$$G' = G'(\dot{\bar{\varepsilon}})$$

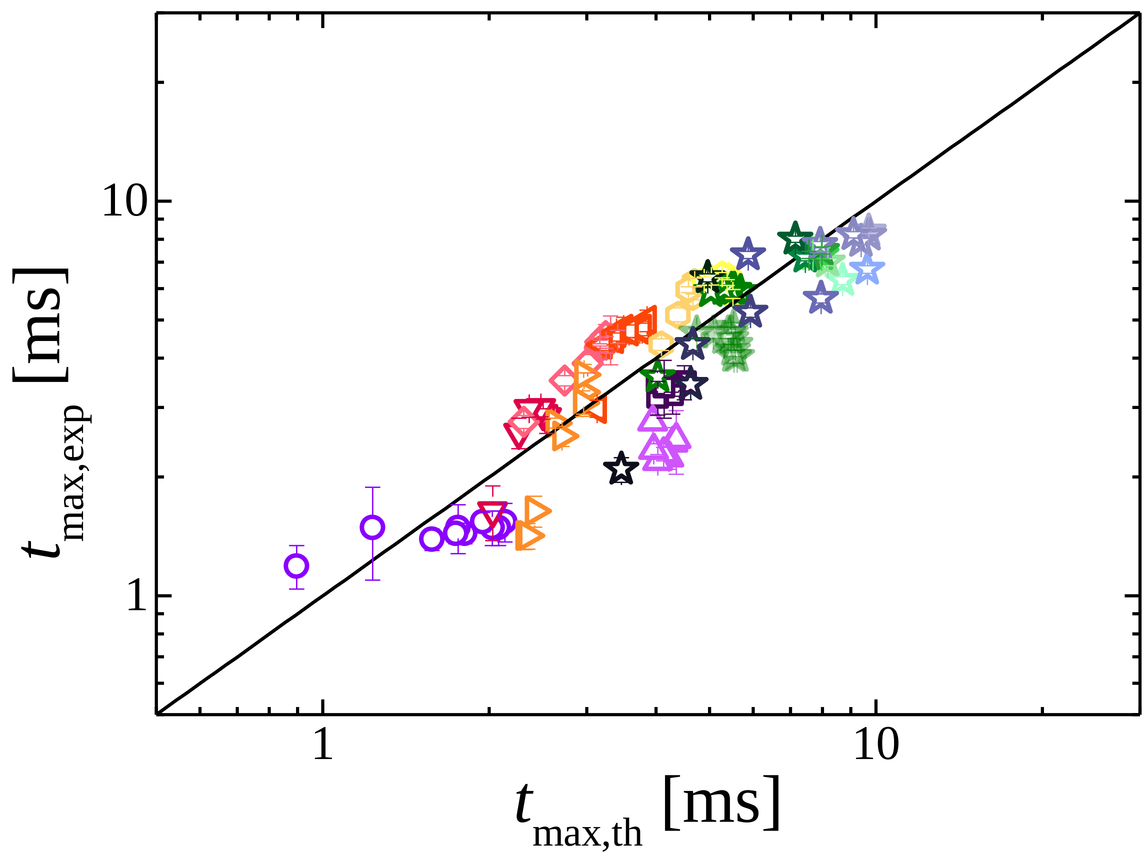
$$\eta_{\mathrm{B}} = \frac{6G''(\dot{\bar{\varepsilon}})}{\dot{\bar{\varepsilon}}}$$

Second order nonlinear ordinary differential equation → Numerical resolution

Drop impact Part 1 – Underdamped Harmonic Oscillator

Numerical resolution

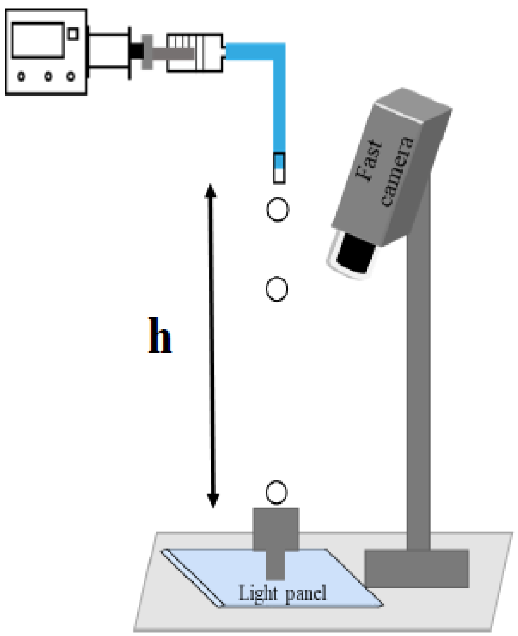




Conclusions Part 1

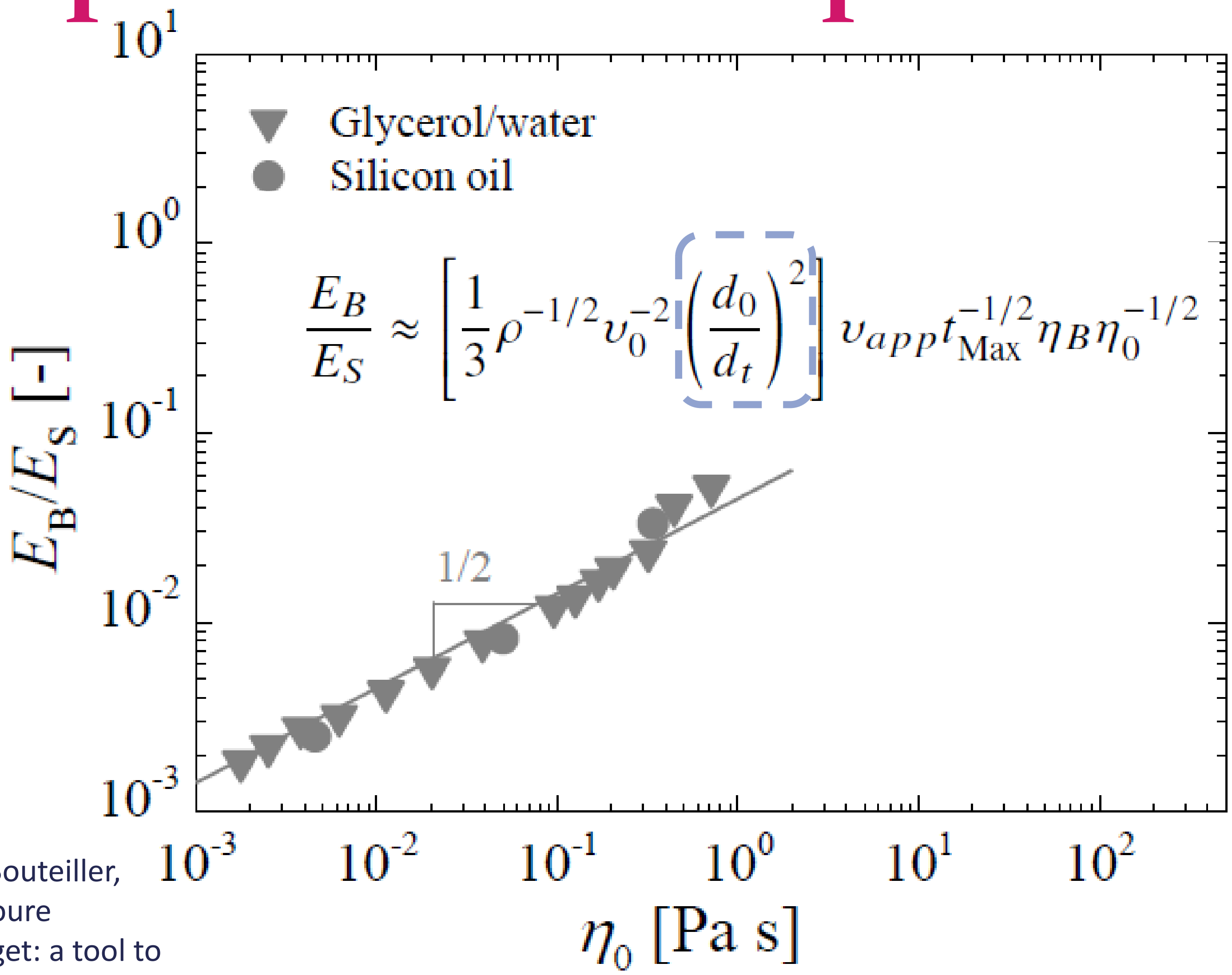
- ✓ Successful building of a set-up allowing one to eliminate the viscous shear dissipation.
- ✓ Impact of samples with viscoelastic properties and evidence of a nontrivial combination of viscosity, bulk and surface elasticity.
- ✓ Interpretation of the experimental results by modeling the drop impact dynamic by a free harmonic oscillator subjected to biaxial dissipations that depends on the expansion.

Drop impact Part 2 – Impact on target



Target diameter=6.5mm

$$v_0 = \sqrt{2gh} = 4.2\,\mathrm{ms}^{-1}$$



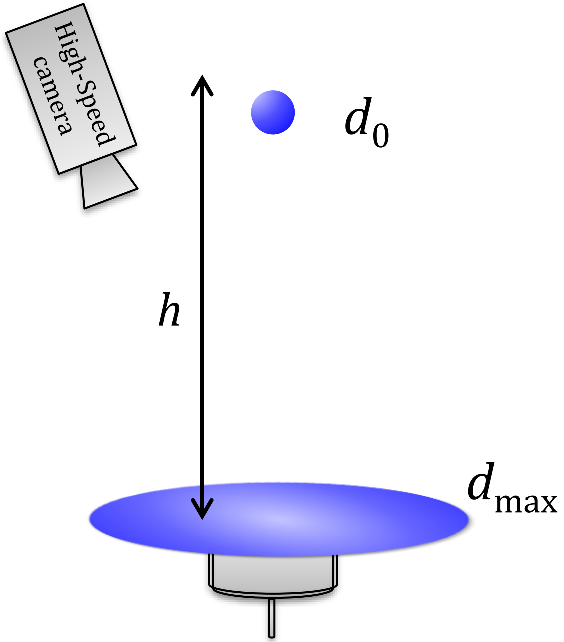
$$v_{app} = \frac{(d_{\mathrm{Max}} - d_0)^2}{d_{\mathrm{Max}} t_{\mathrm{Max}}}$$

What happens when we change the size of the target?

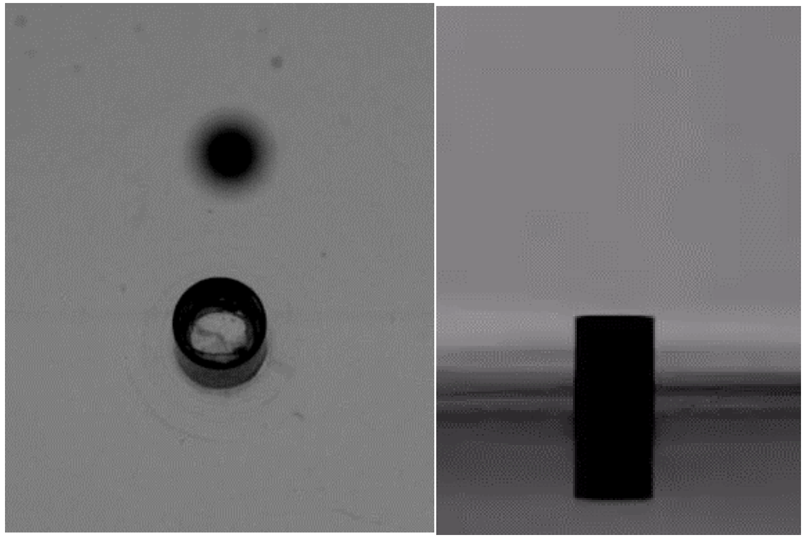
A. Louhichi, S. Arora, C. A. Charles, L. Bouteiller, D. Vlassopoulos, L. Ramos, C. Ligoure
"Drop impact experiments on a small target: a tool to quantify the competition between shear and biaxial extensional viscous dissipation in the expansion dynamics of Newtonian and non-Newtonian liquid sheets" submitted to J. Fluid mech.

For Newtonian fluids, shear dissipation dominates with a dependence with the target size, d_t.

Drop impact Part 2 – Targets of different sizes

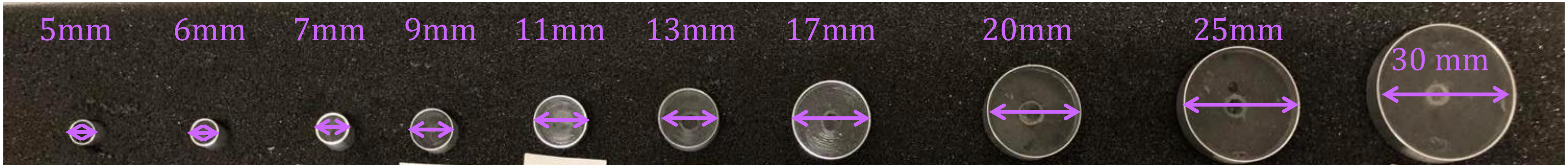


$v_0 = \sqrt{2gh} = 3.7 \text{ m/s}$



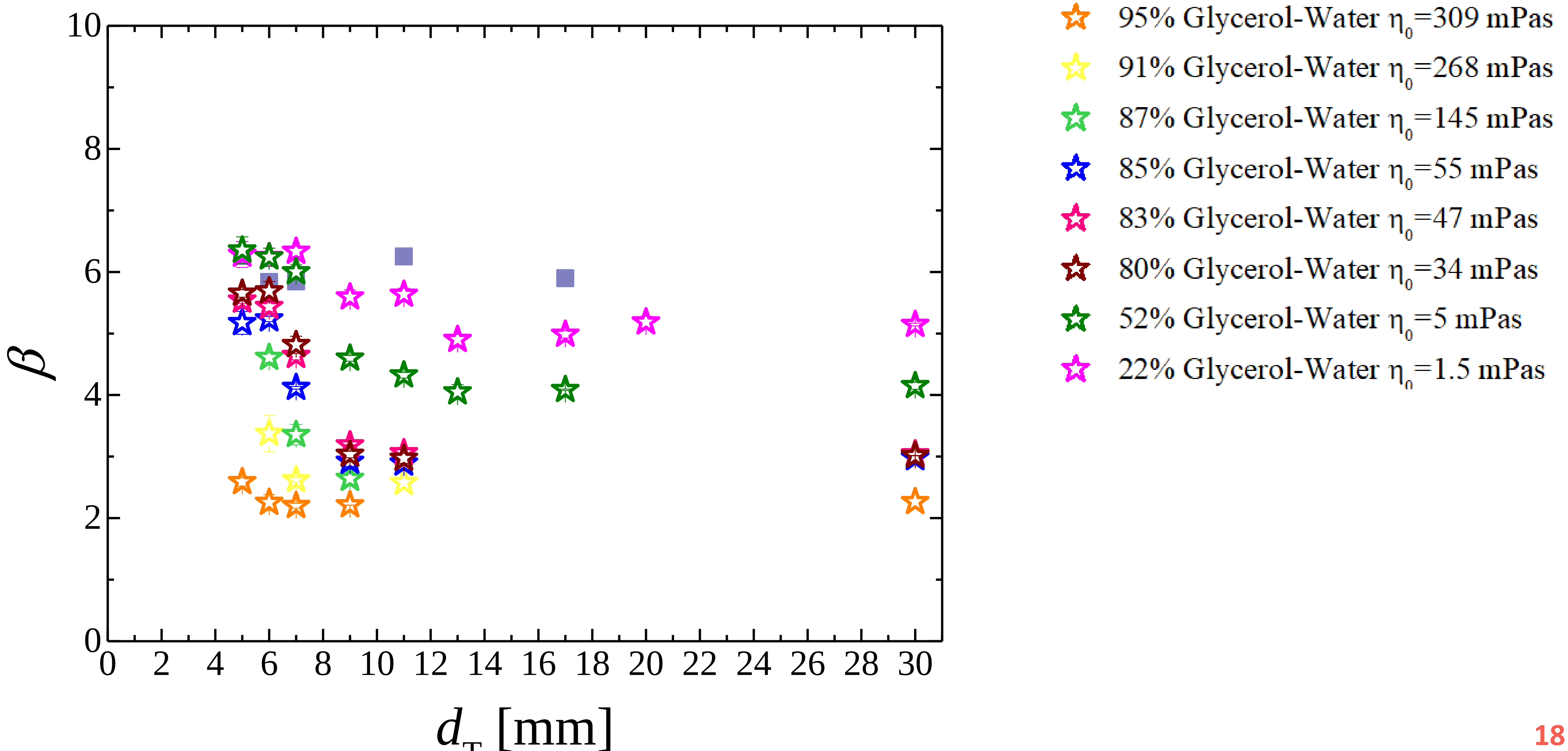
Slowed down 200x $d_T = 5$ mm

Effect of the target diameter on **shear** dissipation?



Drop impact Part 2 – Viscous fluids

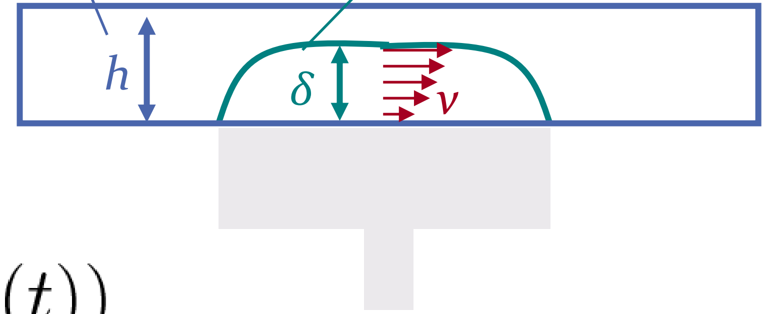
$$v_0 = \sqrt{2gh} = 3.7 \text{ m/s} \qquad \beta = \frac{d_{\max}}{d_0}$$



Drop impact Part 2 – Shear dissipation

$$E_S = \int_0^{t_{\max}} \int_{V_{\text{Shear}}} \eta_0 \dot{\gamma}^2 dV\, dt$$

$$h(t) = \frac{2d_0^3}{3v_0^2 t^2} \qquad \delta(t) \propto \sqrt{\frac{\eta t}{\rho}}$$

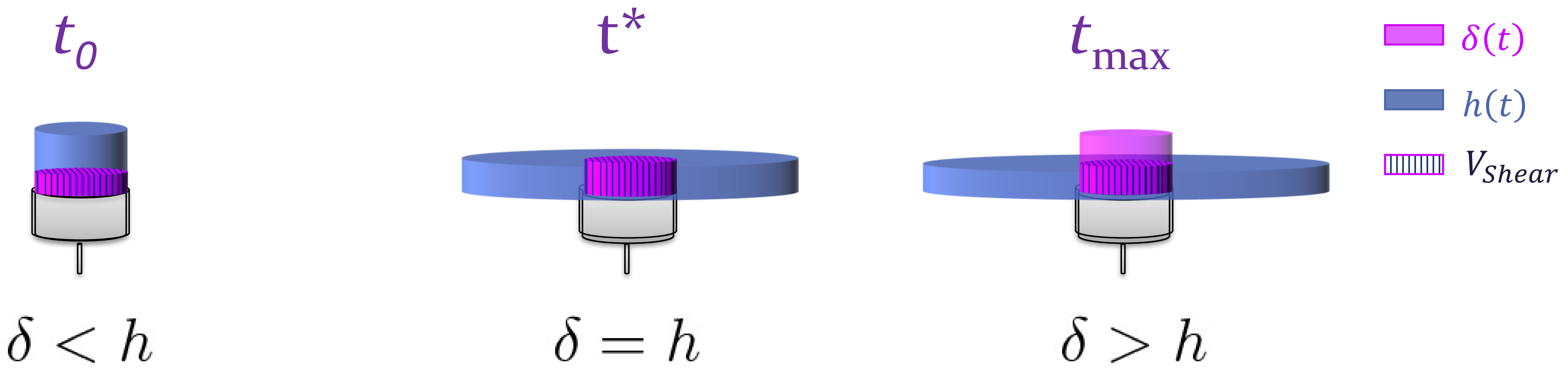


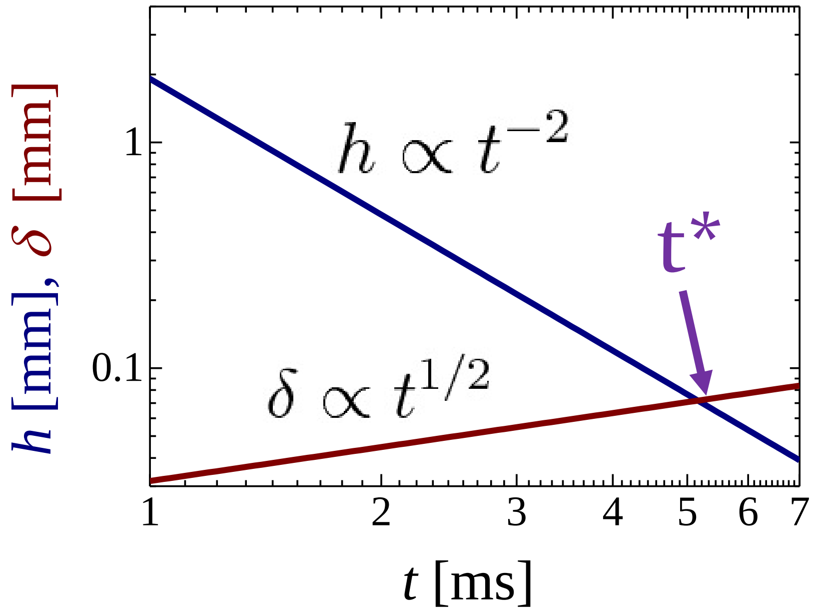
with $\dot{\gamma} = \dfrac{v_0}{\inf(h(t), \delta(t))}$ $\qquad V_{\text{shear}} = \dfrac{\pi d_T^2}{4} \inf(h(t), \delta(t))$

What part of the sheet is actually sheared ?

The whole thickness, h(t)
or the viscous boundary layer, δ(t) ?

Drop impact Part 2 – Shear dissipation





$t<t^*$ $\quad V_{Shear} = \frac{\pi d_T^2}{4}\delta(t) \qquad \dot{\gamma} = \frac{v_0}{\delta(t)}$

$t>t^*$ $\quad V_{Shear} = \frac{\pi d_T^2}{4}h(t) \qquad \dot{\gamma} = \frac{v_0}{h(t)}$

Drop impact Part 2 – Shear dissipation

Negligible

$$E_{\mathrm{S}} = \frac{\pi v_0^2 \eta d_{\mathrm{T}}^2}{4}\left[\int_0^{t^*} \frac{1}{\delta(t)}dt + \cancel{\int_{t^*}^{t_{max}} \frac{1}{h(t)}dt}\right]$$

$$E_{\mathrm{S}} \approx \pi d_{\mathrm{T}}^2 \left(\frac{v_0^8 \eta_0^2 \rho^3 d_0^3}{48}\right)^{1/5}$$

Drop impact Part 2 – Biaxial viscosity vs Shear

$$E_B \approx \eta_B \pi \frac{d_0^3}{6} \int_0^{t_{max}} \left(\frac{1}{d} \frac{d(d)}{dt} \right)^2 dt$$

$$E_{\mathrm{S}} = \int_0^{t_{\max}} \int_{V_{\mathrm{Shear}}} \eta_0 \dot{\gamma}^2 dV\, dt$$

For Newtonian fluids : $\eta_{\mathrm{B}} = 6\eta_0$

$$E_{\mathrm{B}} \approx \pi \eta_0 d_0^2 v_0$$

$$E_{\mathrm{S}} \approx \pi d_{\mathrm{T}}^2 \left(\frac{v_0^8 \eta_0^2 \rho^3 d_0^3}{48} \right)^{1/5}$$

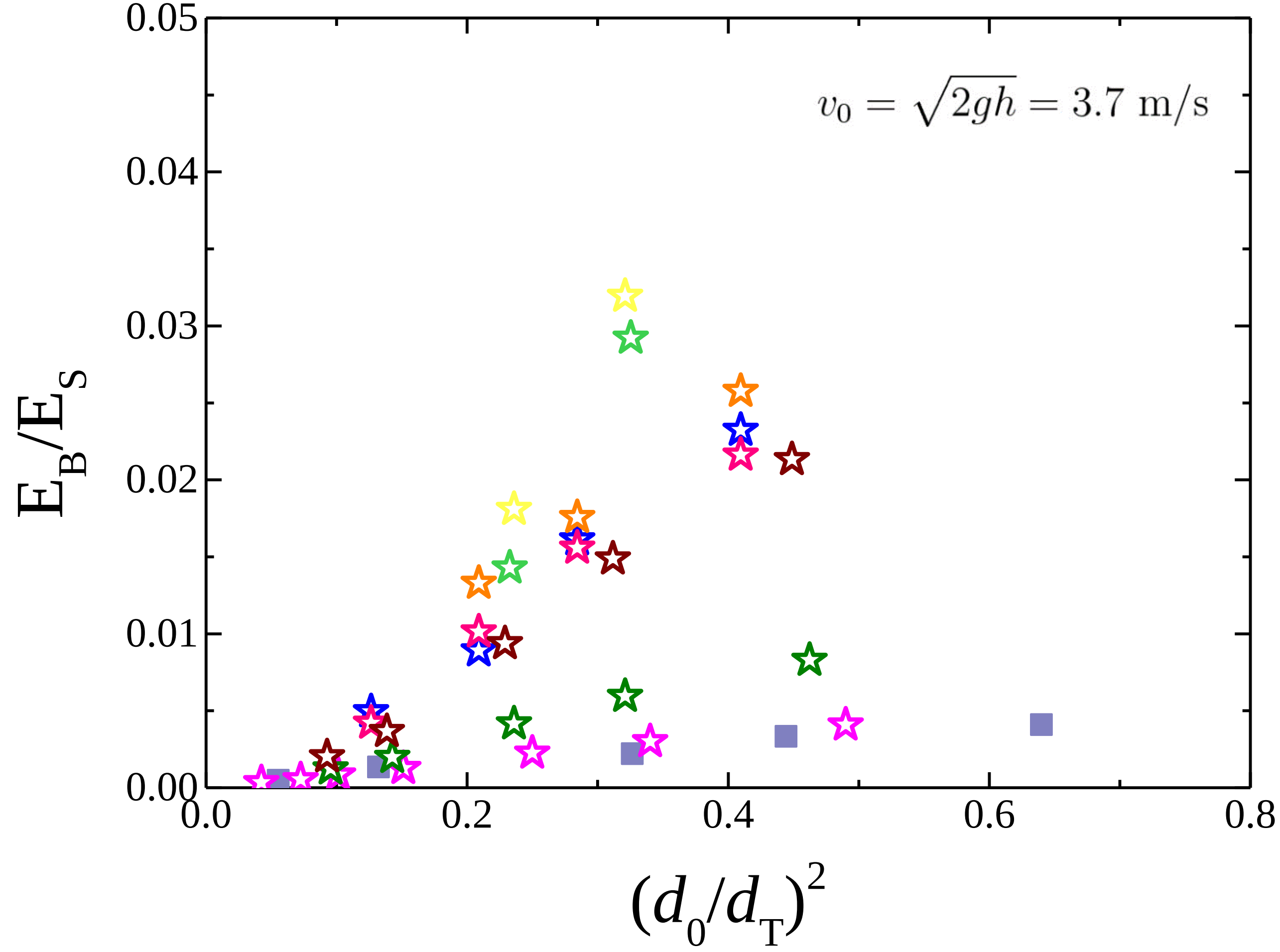
$$\boxed{\frac{E_{\mathrm{B}}}{E_{\mathrm{S}}} \approx 2 Re^{-3/5} \left(\frac{d_0}{d_{\mathrm{T}}} \right)^2}$$

Reynolds number :

$$Re = \frac{v_0 d_0 \rho}{\eta_0}$$

Drop impact Part 2 – Biaxial viscosity vs Shear

$$\boxed{\frac{E_\mathrm{B}}{E_\mathrm{S}}} \approx 2Re^{-3/5} \boxed{\left(\frac{d_0}{d_\mathrm{T}}\right)^2}$$



- Water η_0=1 mPas
- 95% Glycerol-Water η_0=309 mPas
- 91% Glycerol-Water η_0=268 mPas
- 87% Glycerol-Water η_0=145 mPas
- 85% Glycerol-Water η_0=55 mPas
- 83% Glycerol-Water η_0=47 mPas
- 80% Glycerol-Water η_0=34 mPas
- 52% Glycerol-Water η_0=5 mPas
- 22% Glycerol-Water η_0=1.5 mPas

$$\boxed{\frac{E_\mathrm{B}}{E_\mathrm{S}} << 1}$$

→ **Dissipation dominated by shear for Newtonian fluids**

Drop impact Part 2 – Targets

Viscous fluid :

$$E_K = E_\gamma + E_S$$

$$\frac{\pi}{2}\frac{\rho d_0^3 v_0^2}{6} = \frac{\pi}{2}\gamma d_{\mathrm{max}}^2 + \pi d_{\mathrm{T}}^2 \left(\frac{v_0^8 \eta_0^2 \rho^3 d_0^3}{48}\right)^{1/5}$$

Inviscid fluid :

$$E_K = E_\gamma$$

$$\frac{\pi}{2}\frac{\rho d_0^3 v_0^2}{6} = \frac{\pi}{2}\gamma d_{\mathrm{max,inv}}^2$$

$$\tilde{d} = \frac{d_{\mathrm{max}}}{d_{\mathrm{max,\ inv}}}$$

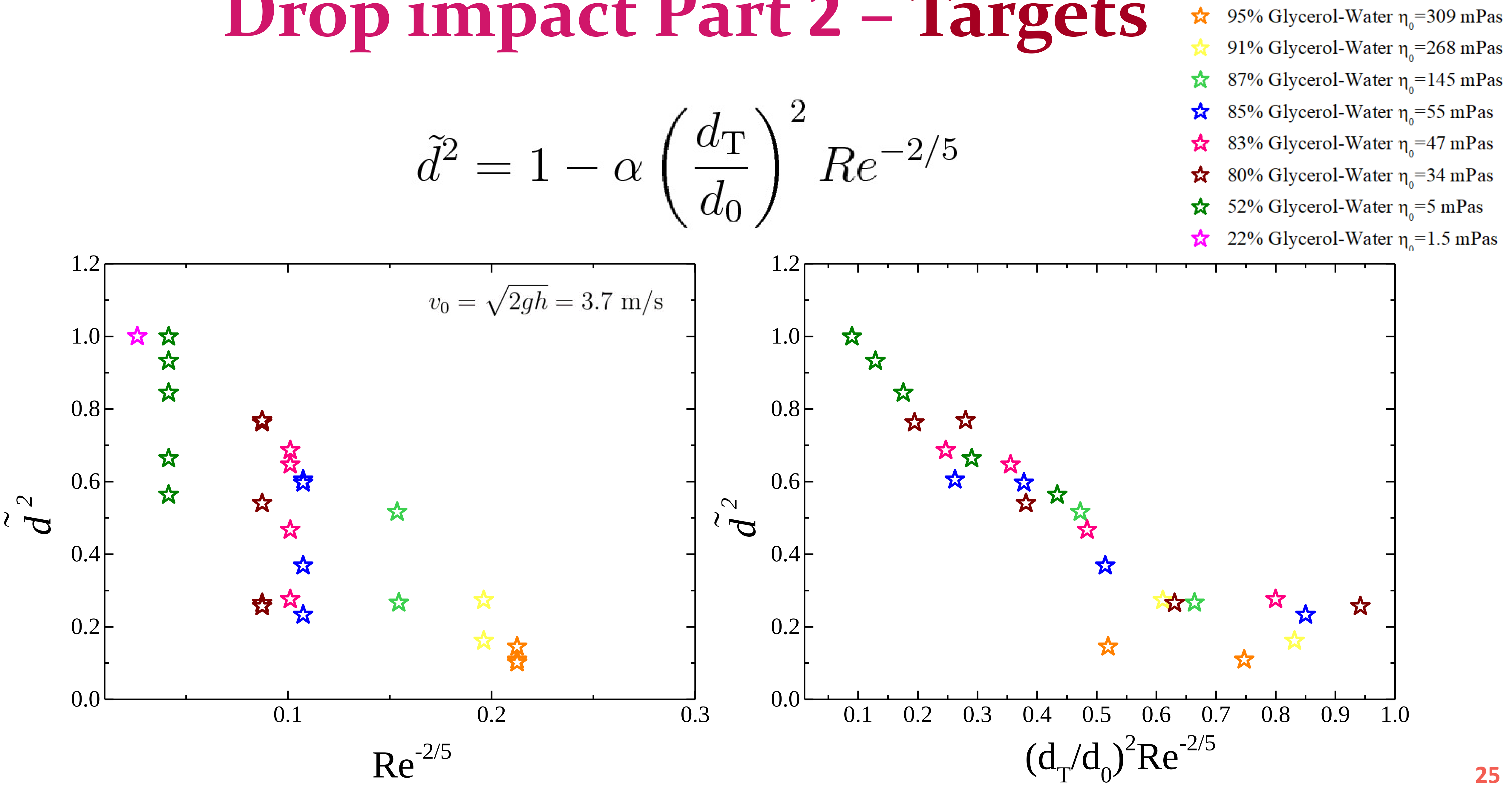
$$\boxed{\tilde{d}^2 = 1 - \alpha \left(\frac{d_{\mathrm{T}}}{d_0}\right)^2 Re^{-2/5}}$$

Reynolds number :

$$Re = \frac{v_0 d_0 \rho}{\eta_0}$$

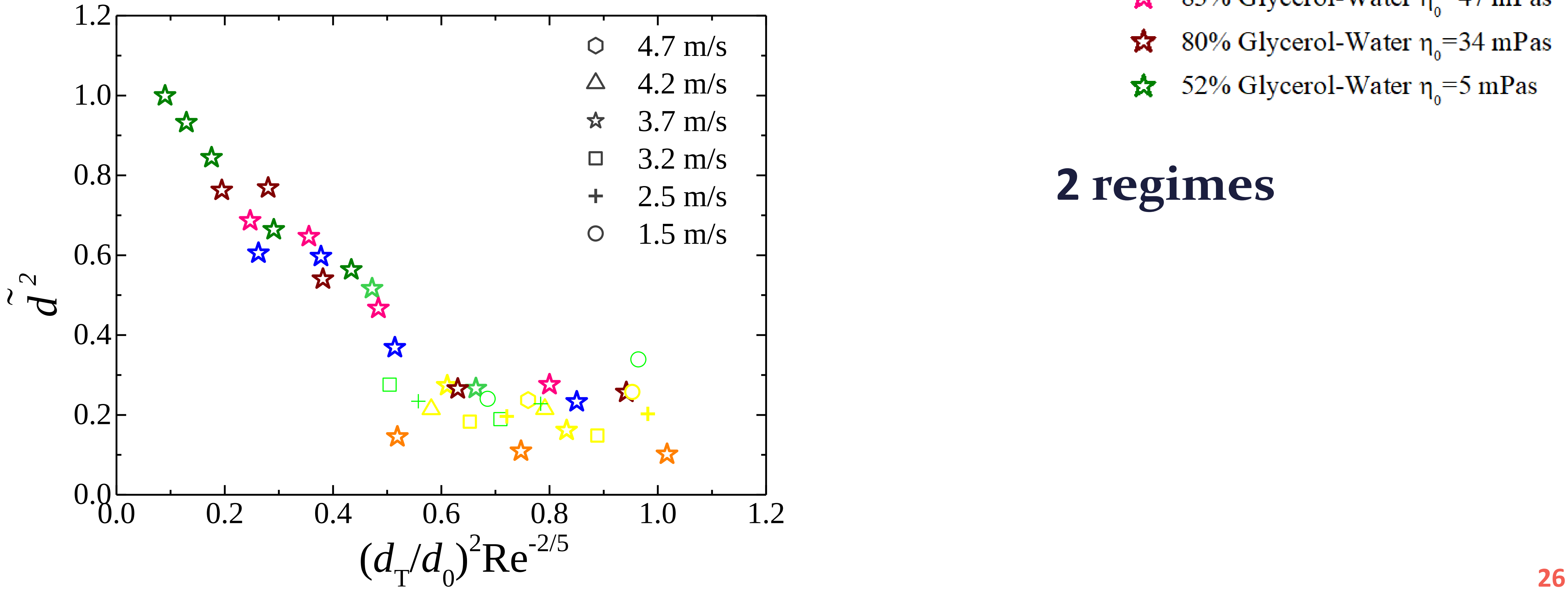
Drop impact Part 2 – Targets

$$\tilde{d}^2 = 1 - \alpha \left(\frac{d_T}{d_0} \right)^2 Re^{-2/5}$$



Drop impact Part 2 – Targets

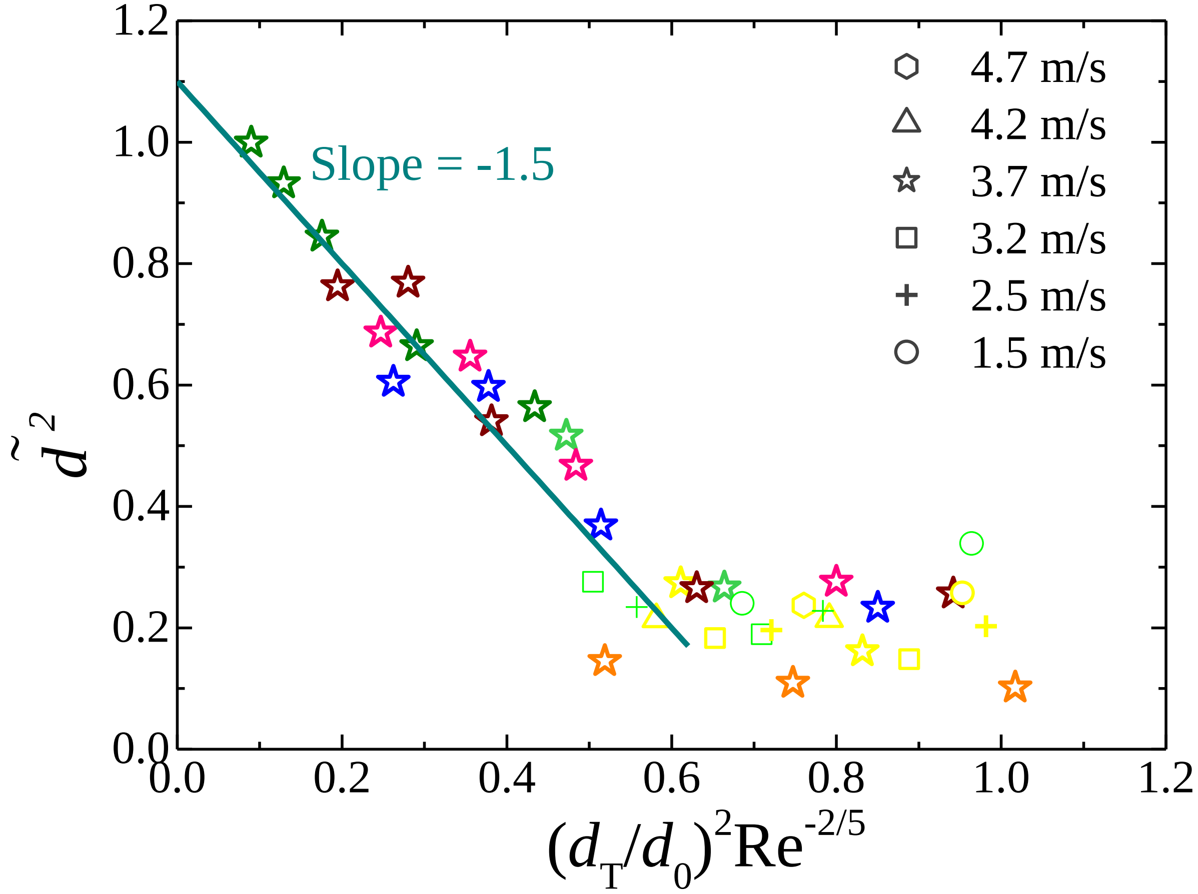
$$\tilde{d}^2 = 1 - \alpha \left(\frac{d_T}{d_0} \right)^2 Re^{-2/5}$$

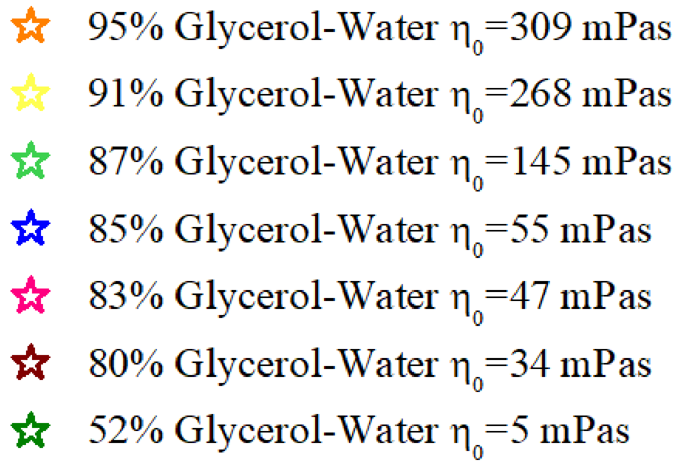


2 regimes

Drop impact Part 2 – Targets

$$\tilde{d}^2 = 1 - \alpha \left(\frac{d_T}{d_0} \right)^2 Re^{-2/5}$$



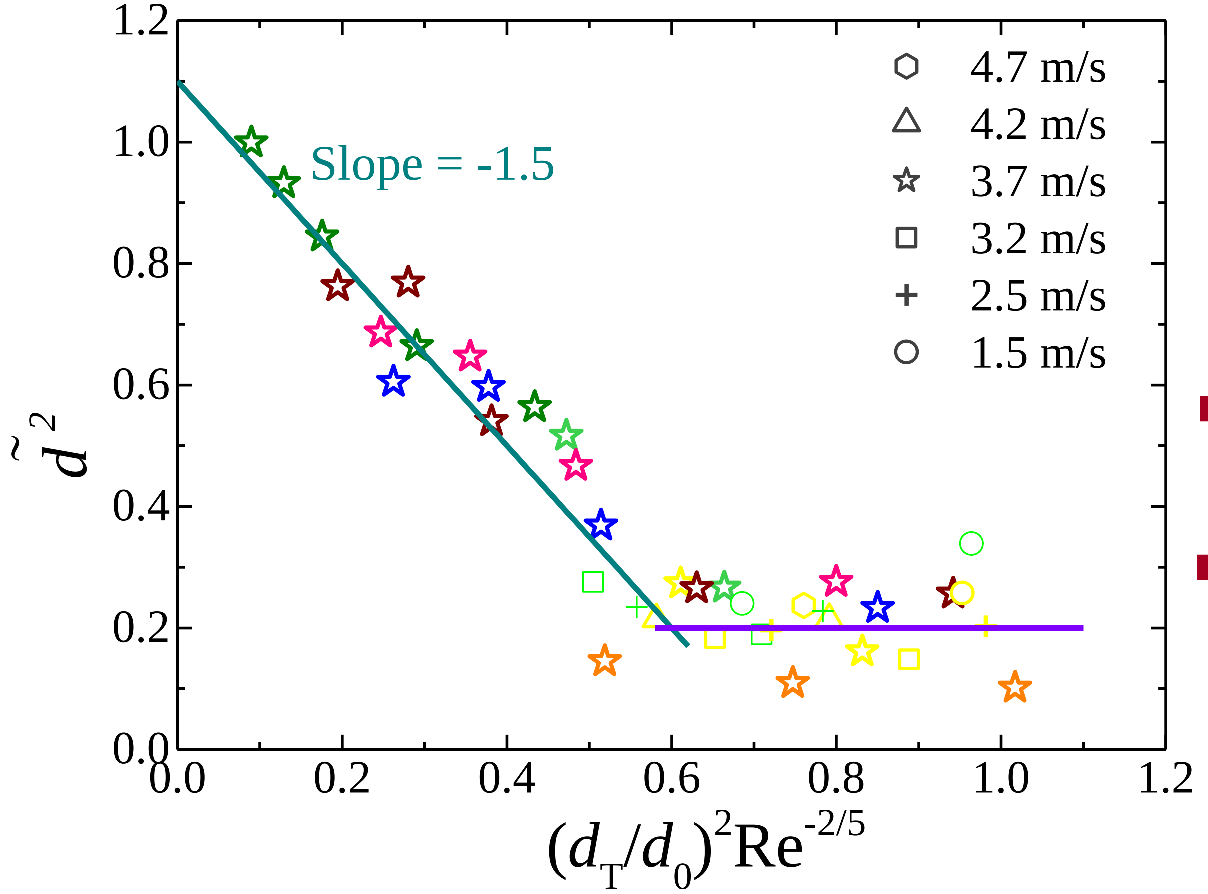


2 regimes

→ **Good predictions for lower viscosities**

Drop impact Part 2 – Targets

$$\tilde{d}^2 = 1 - \alpha \left(\frac{d_\mathrm{T}}{d_0} \right)^2 Re^{-2/5}$$



95% Glycerol-Water η_0=309 mPas
91% Glycerol-Water η_0=268 mPas
87% Glycerol-Water η_0=145 mPas
85% Glycerol-Water η_0=55 mPas
83% Glycerol-Water η_0=47 mPas
80% Glycerol-Water η_0=34 mPas
52% Glycerol-Water η_0=5 mPas

2 regimes

Good predictions for lower viscosities

For high viscosities, we have an unexpected plateau

Conclusions Part 2

- ✓ Progressive introduction of **shear dissipation** with targets of different diameters.
- ✓ Accounting of the effect of the **target diameter** on shear dissipation during Newtonian sheet expansion for low viscosity Newtonian fluids.
- ✓ Identification of two regimes for the expansion on targets.
- ✓ The expansion of shear thinning fluids (PEO solutions) does not change with the target size.

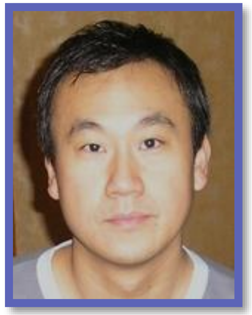
What is next ?

- ✓ Analyze of the **evolution of the rim** with time for different viscosities on liquid nitrogen and targets.
- ✓ Impact of saliva droplets on targets (preliminary experiments).
- ✓ Manuscript writing.

Aknowledgement

Christian
Ligoure

Laurence
Ramos



Ty
Phou

Jean-Marc
Fromental

Ameur
Louhichi

Thank you for your attention