Complex spatio-temporal dynamics in a shear-thickening cornstarch suspension

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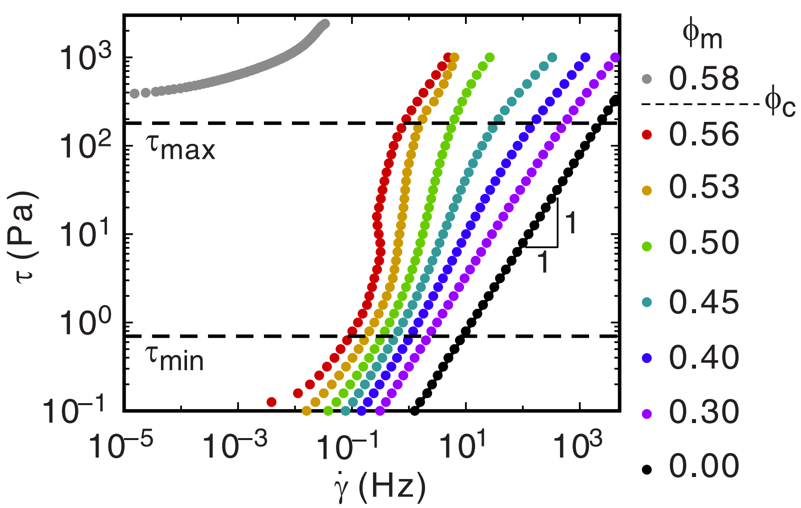
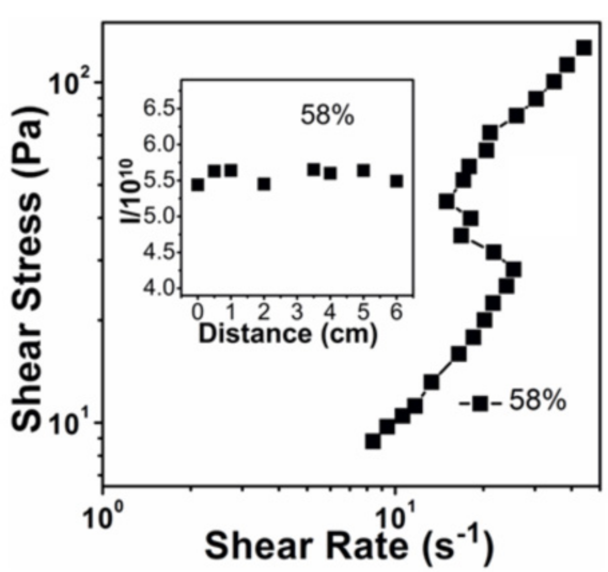
Discontinuous shear-thickening

S-shaped flow curves
<u>but</u> no vorticity bands in steady state?

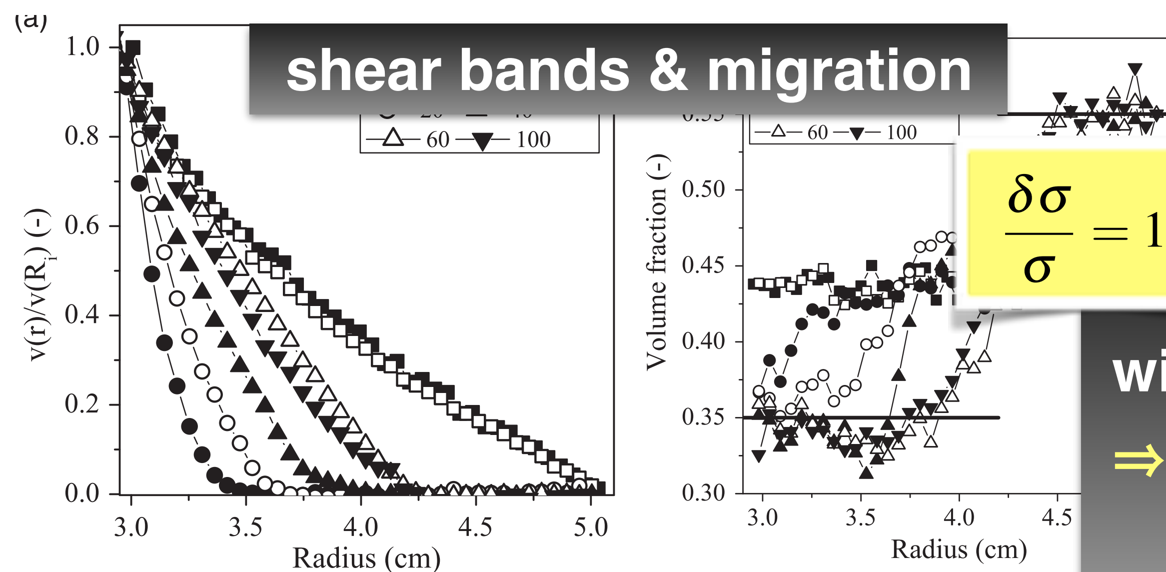


Brown & Jaeger, *PRL* **103**, 086001 (2009)



Pan *et al.*, *PRE* **92**, 032202 (2015)

shear bands & migration

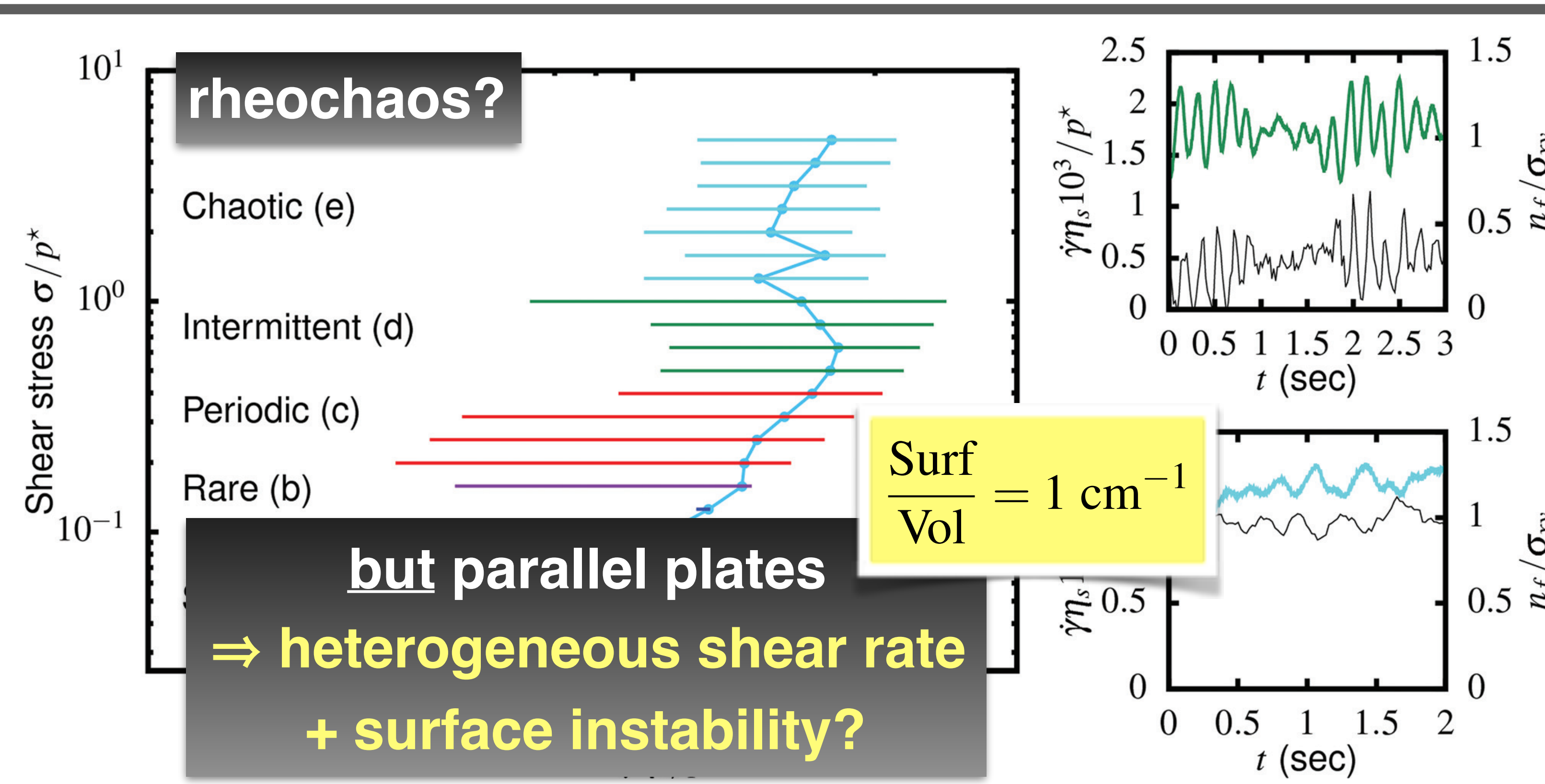


$$\frac{\delta\sigma}{\sigma} = 1.8$$

<u>but</u>
wide-gap Couette
⇒ heterogeneous shear rate

Fall *et al.*, *PRL* **114**, 098301 (2015)

rheochaos?



$$\frac{\text{Surf}}{\text{Vol}} = 1\ \text{cm}^{-1}$$

<u>but</u> parallel plates
⇒ heterogeneous shear rate
+ surface instability?

Hermes *et al.*, *J. Rheol.* **60**, 905-916 (2016)

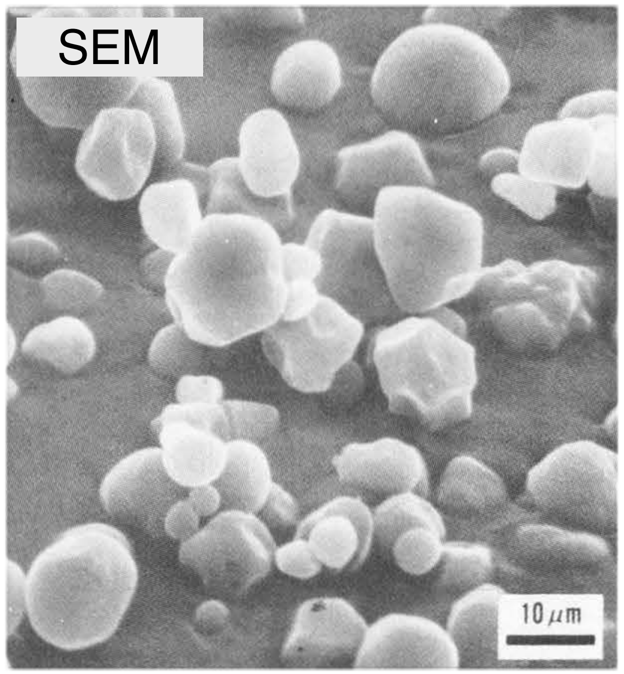
Goals & outline

- DST under <u>steady</u> shear stress
- perform <u>long</u> rheological experiments
- perform <u>local</u> measurements at “mesoscale”

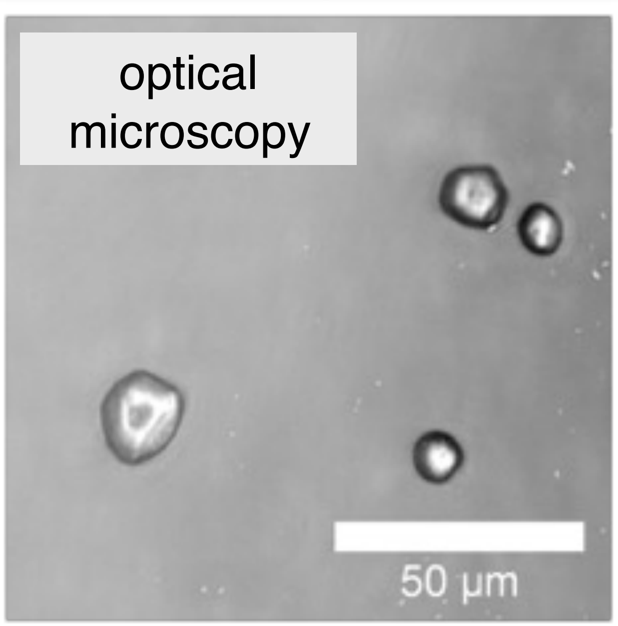
- ☆ check for gradient and/or vorticity banding
- ☆ understand the origin of unsteady dynamics

1. **Experimental system & setup**
2. **Dynamics of the global rheology**
3. **Spatiotemporal measurements**
4. **Comparison with model and simulations**

Dense cornstarch suspension



Christianson *et al.*,
Food Struct. **1**, 13-24 (1982)



polydisperse, anisotropic grains

- median diameter a = 13 µm
- standard deviation = 7 µm
- porous + absorbs moisture
- weakly adhesive

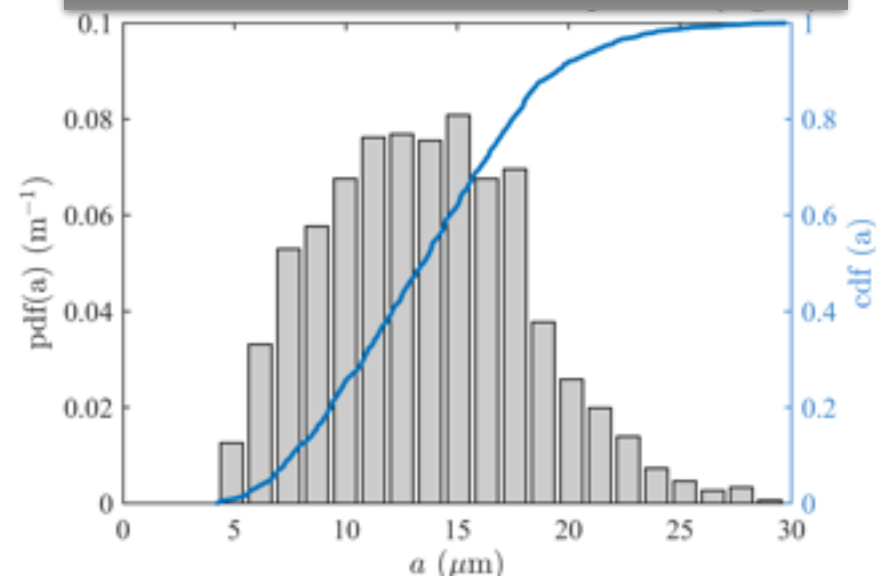
density-matched suspension

in water + CsCl at 46:54% wt.
(density = 1.63)

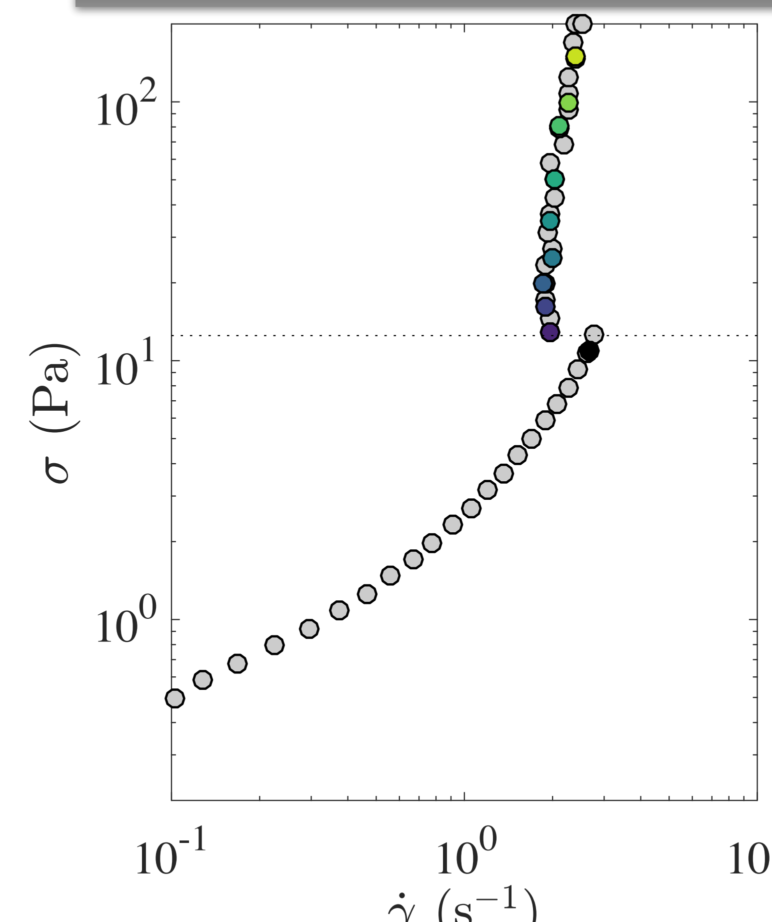
$\phi_w = 41\% \Leftrightarrow \phi \approx 47\%$

sharp DST transition
at $\sigma_c \approx 12$ Pa

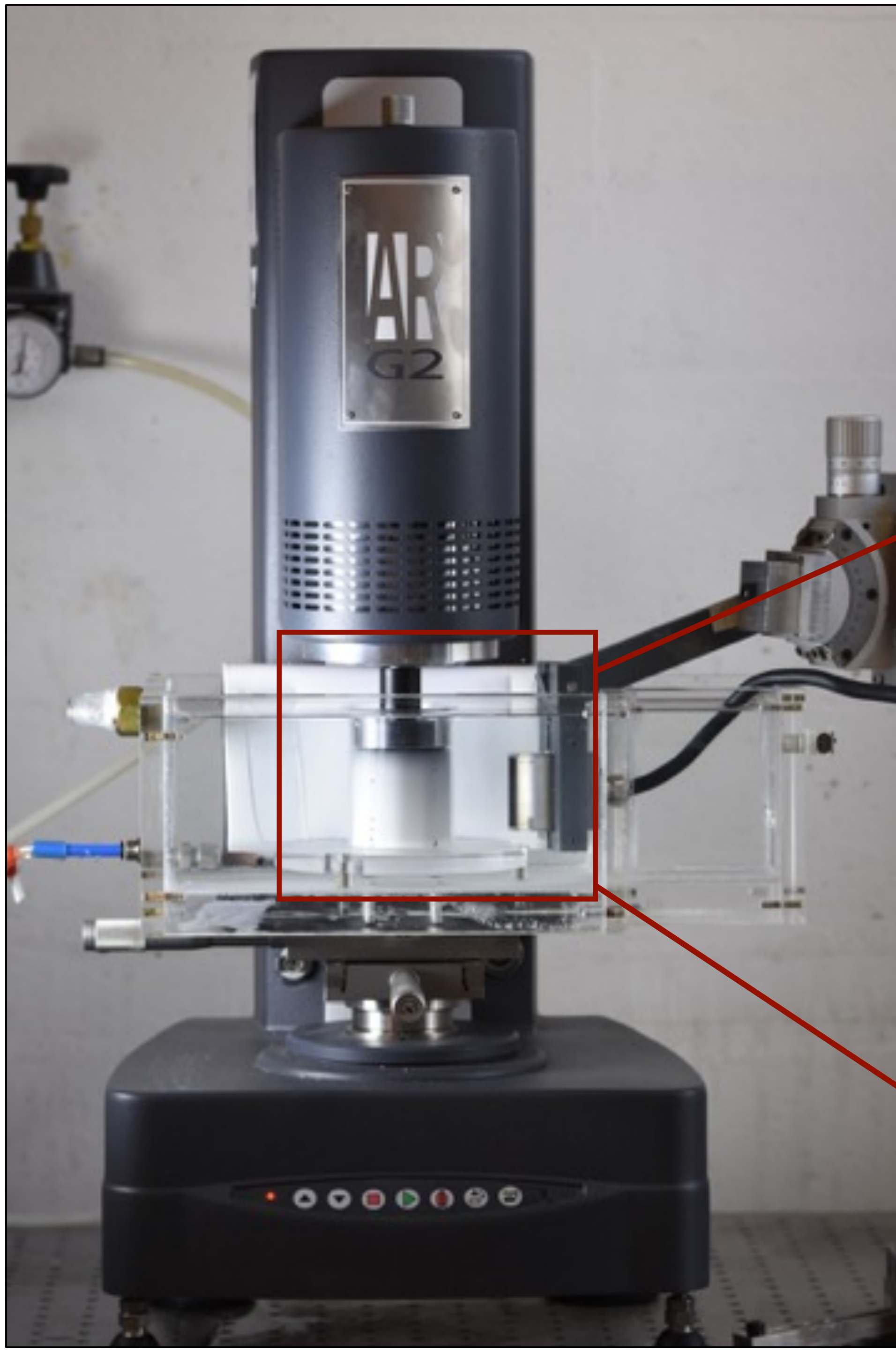
cornstarch size distribution (Sigma)



flow curve under increasing stress



Experimental setup

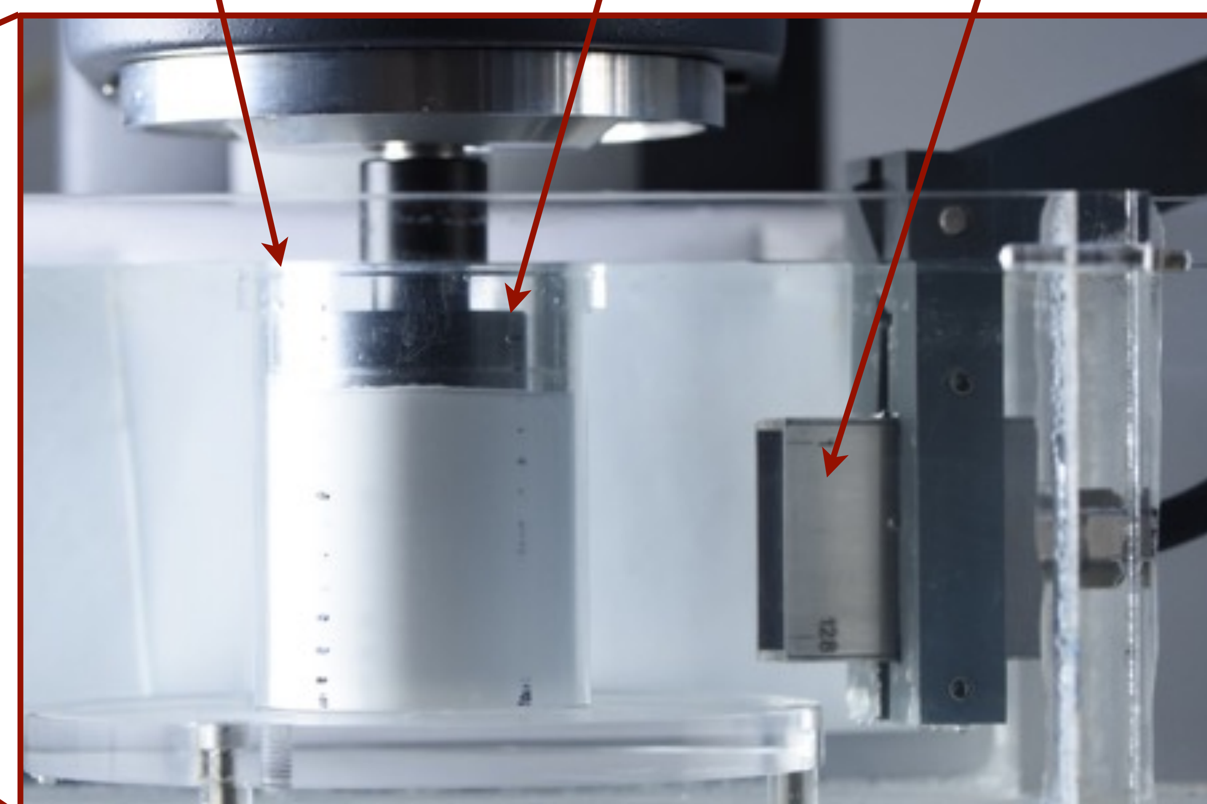


<u>small-gap</u> Couette geometry

- “smooth” Delrin
- rotor ∅ 46 mm, stator ∅ 50 mm
- gap $e = 2$ mm ≈ 150 a
- height $H = 63$ mm ≈ 5,000 a

$$\frac{\delta\sigma}{\sigma} = 0.18$$

$$\frac{\mathrm{Surf}}{\mathrm{Vol}} = 0.03\ \mathrm{cm}^{-1}$$



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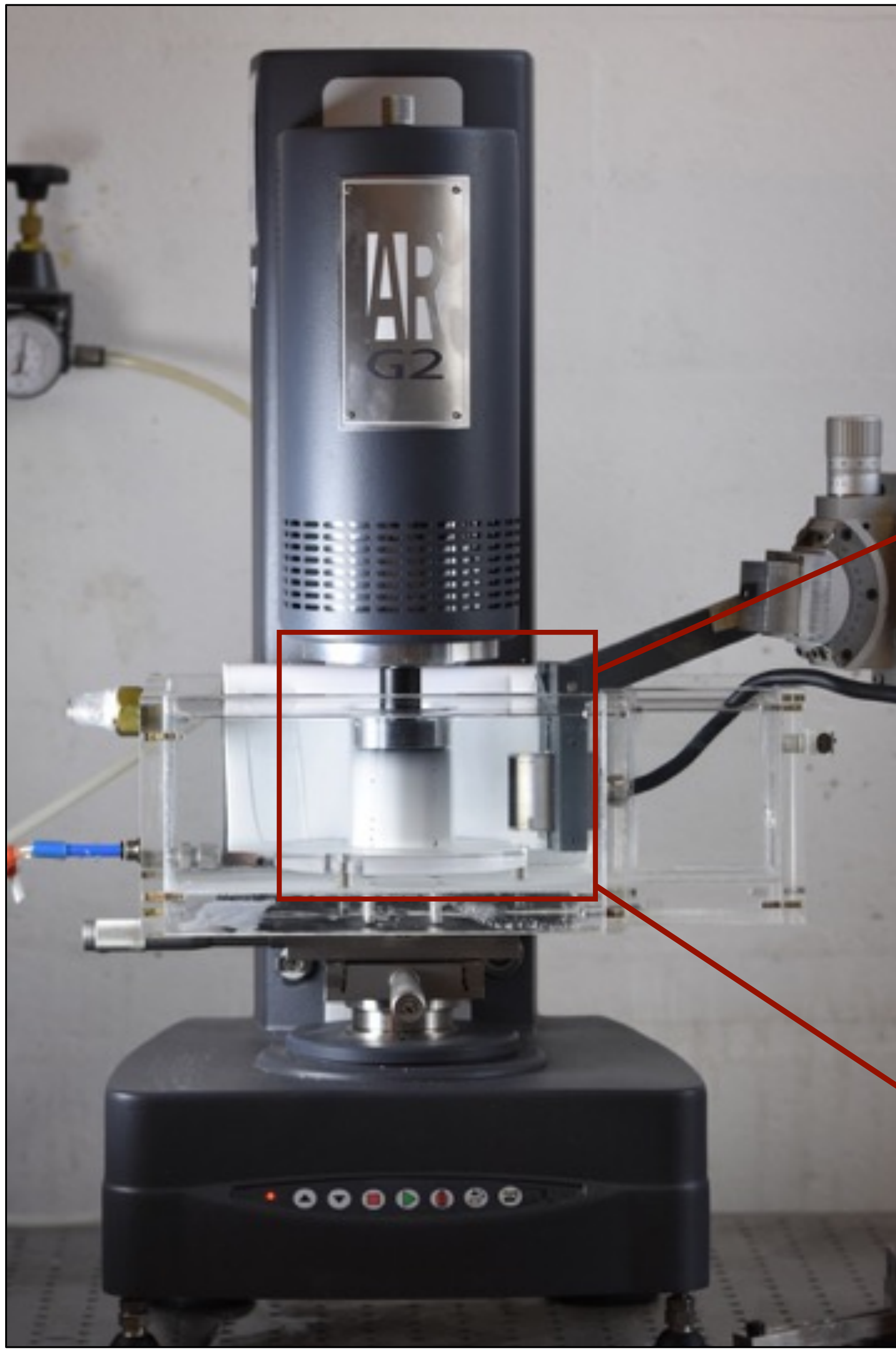

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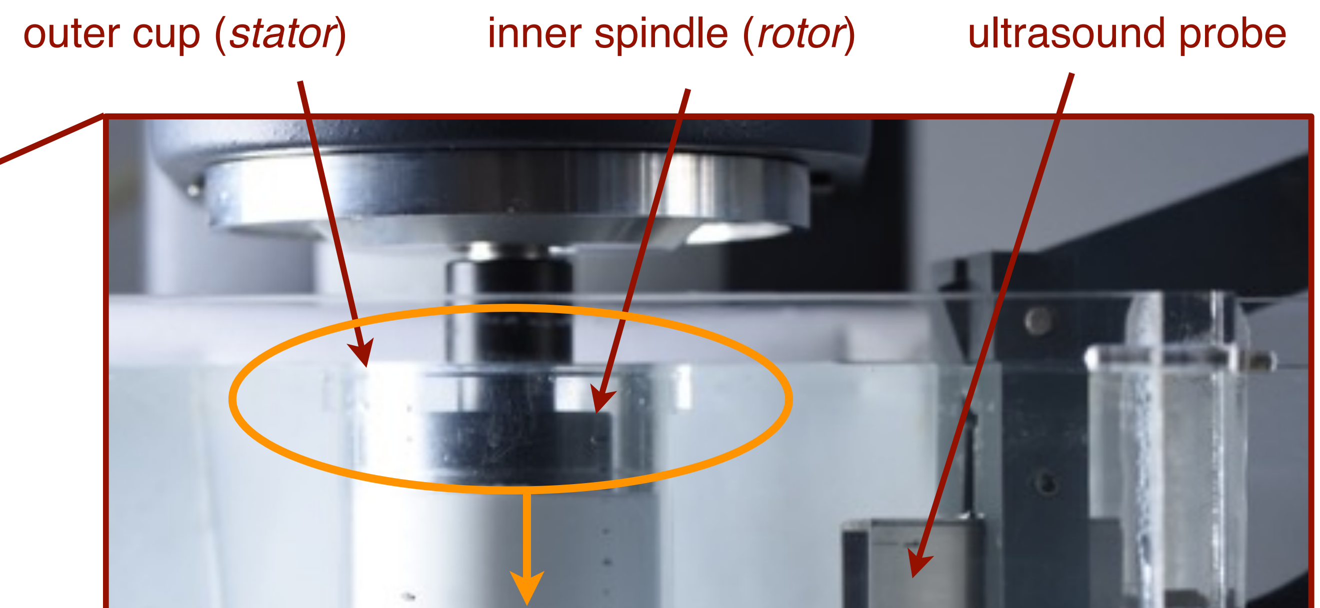
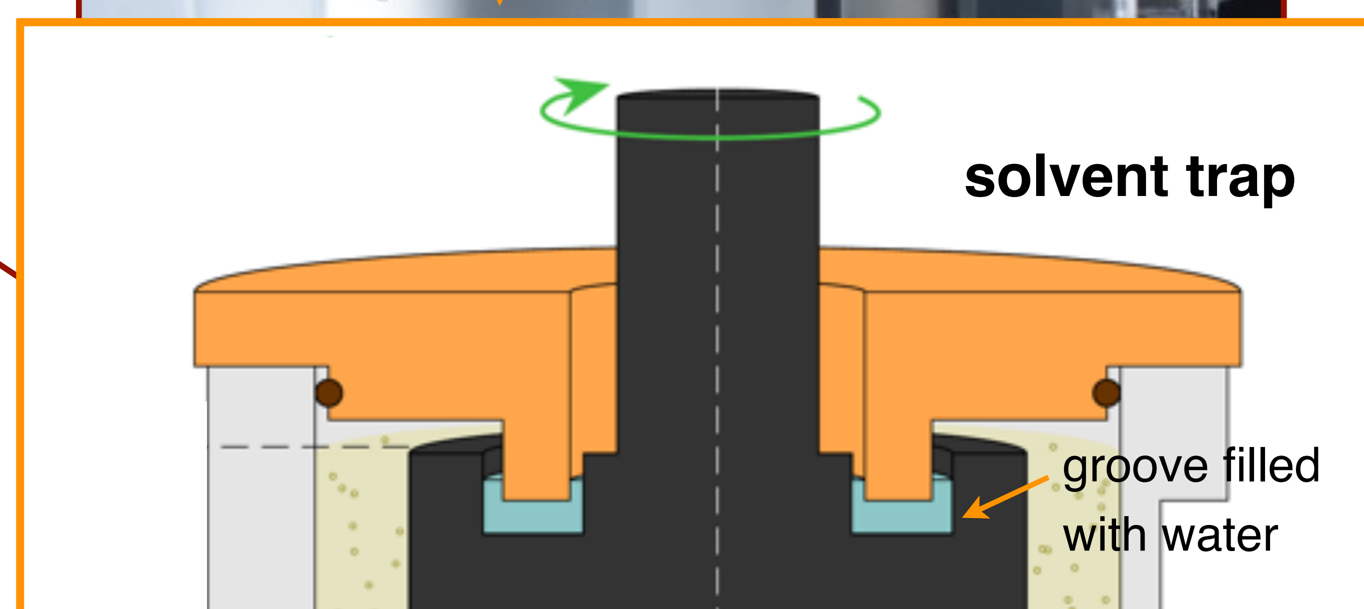
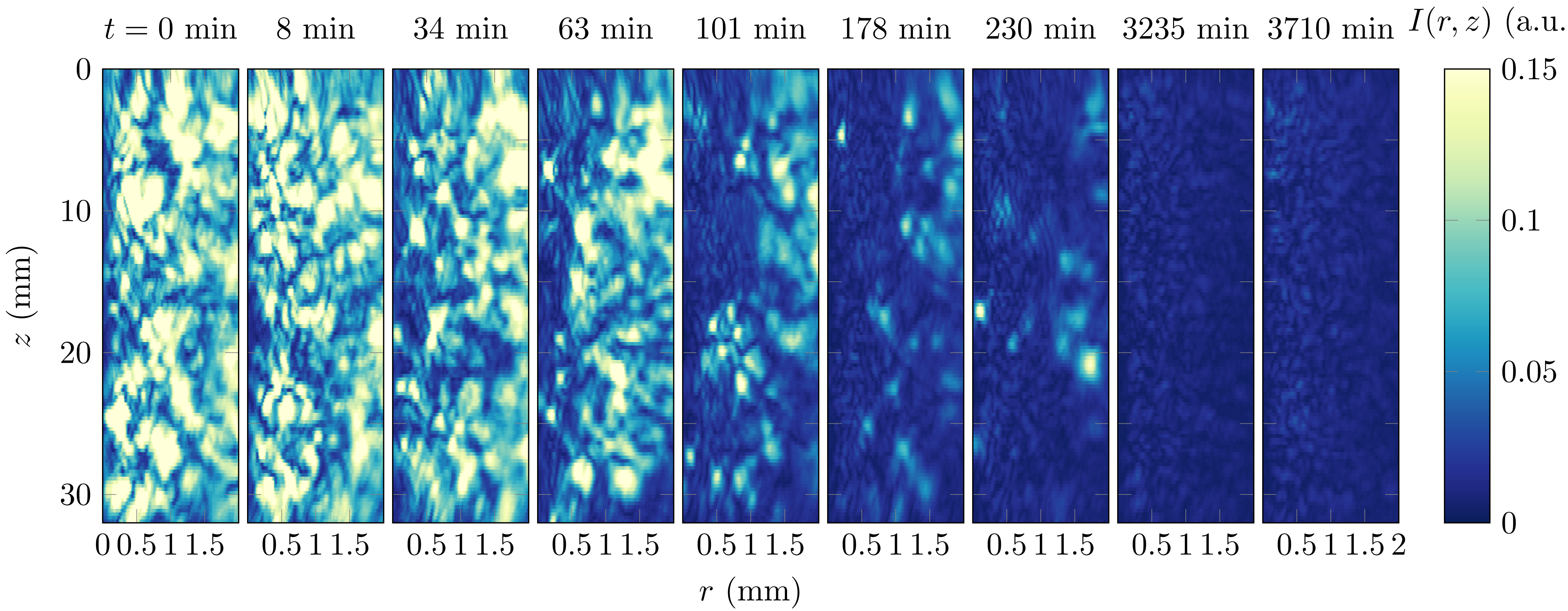




Controlling the sample

- ✓ Minimize sedimentation and migration… by density-matching and small gap
- ✓ Minimize evaporation… by using a solvent trap filled with water
- ✓ Avoid surface instability… by using small free surface to volume ratio (and a lid)
- ✓ Remove bubbles… by shearing for > 5 hours at low stress

ultrasonic imaging for several hours at σ =5 Pa



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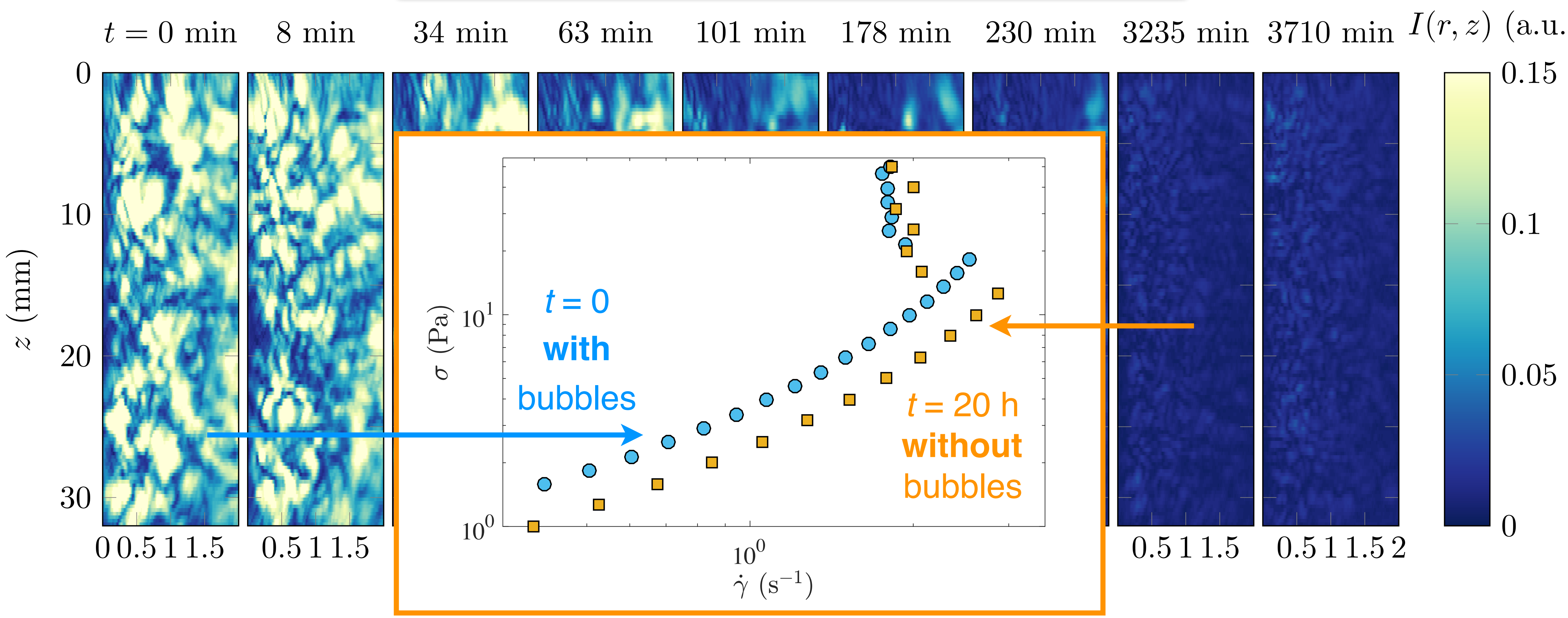
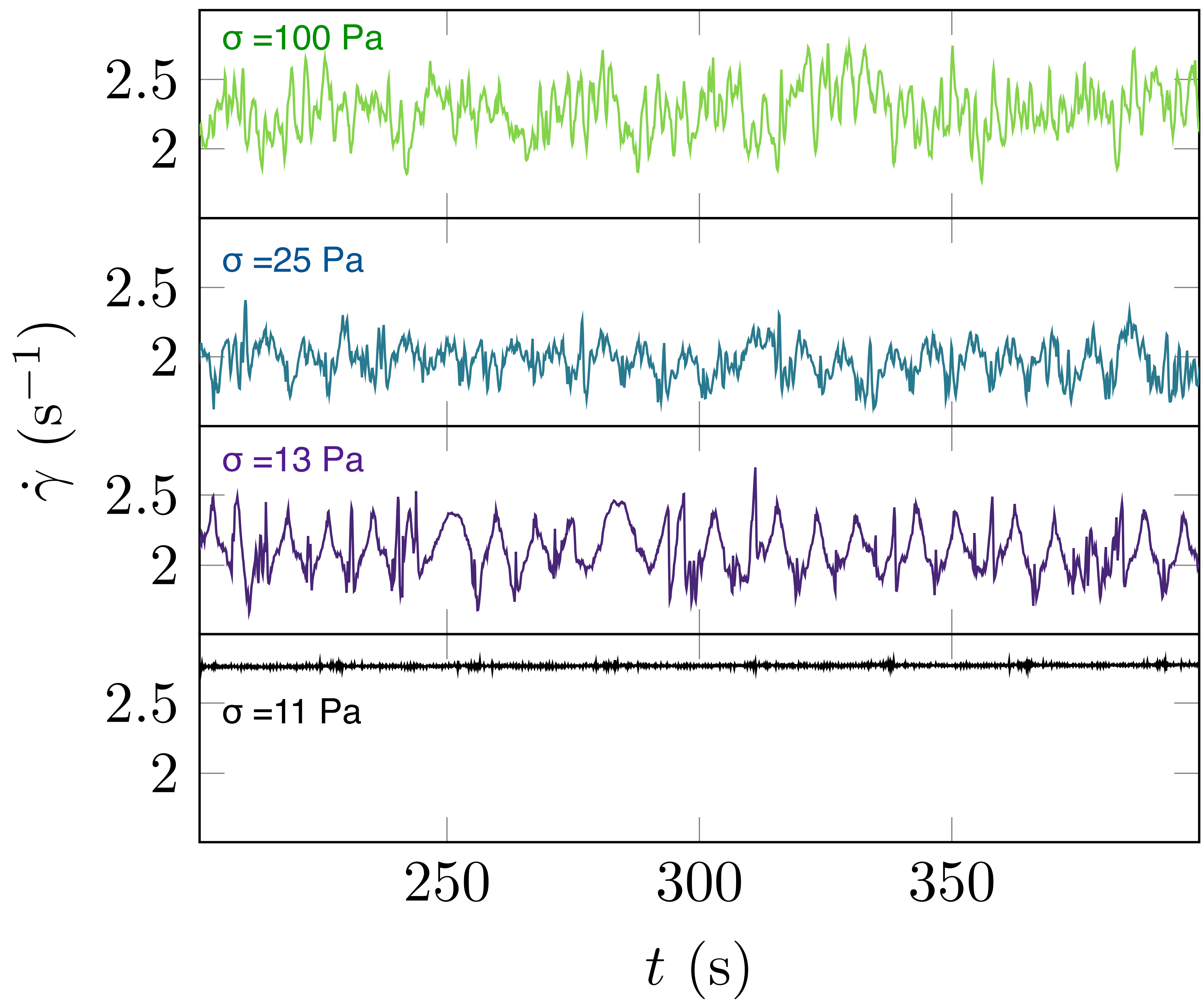


Dynamics of the global shear rate

long steps at constant stress (up to 3,000 s per stress value)



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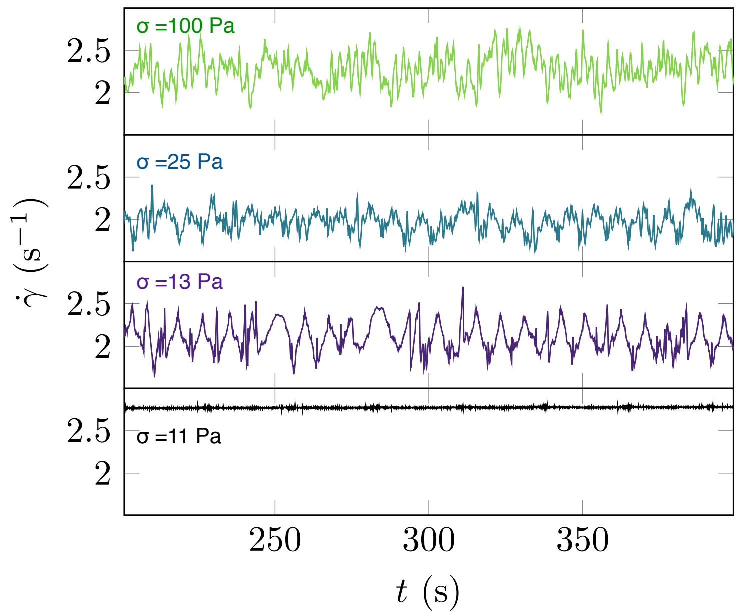
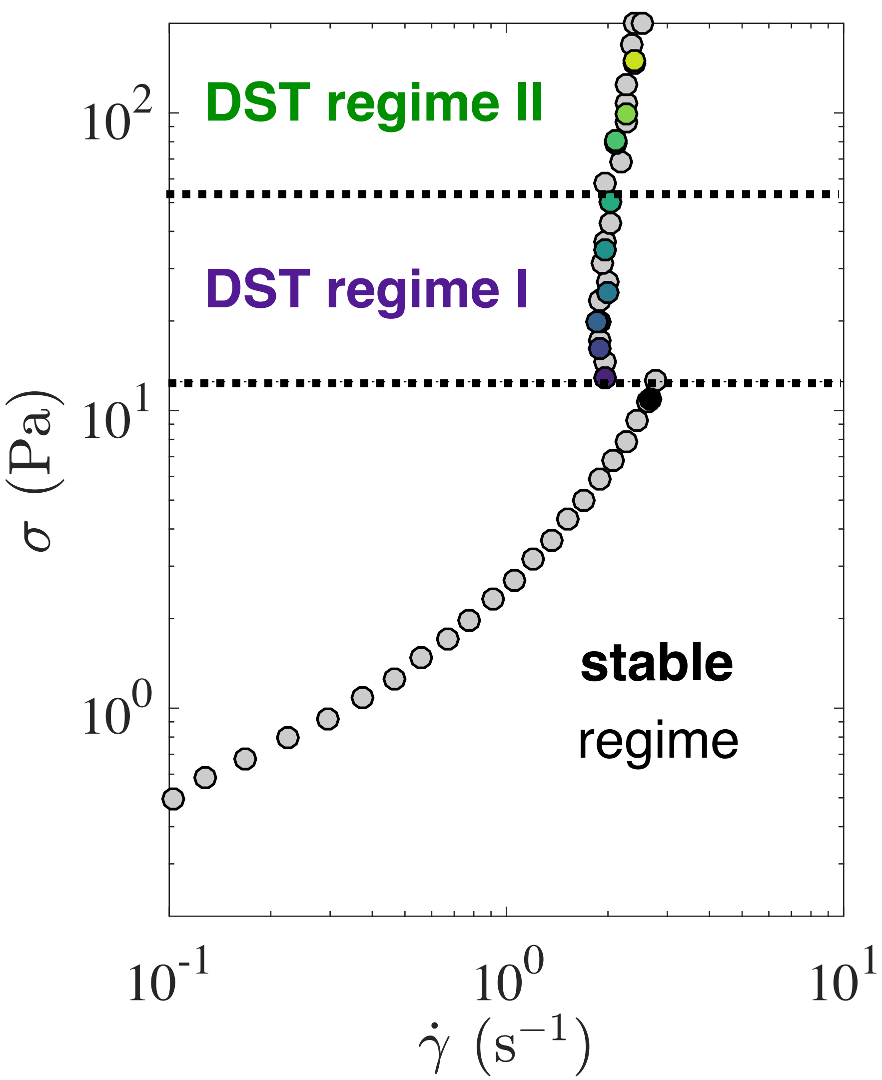
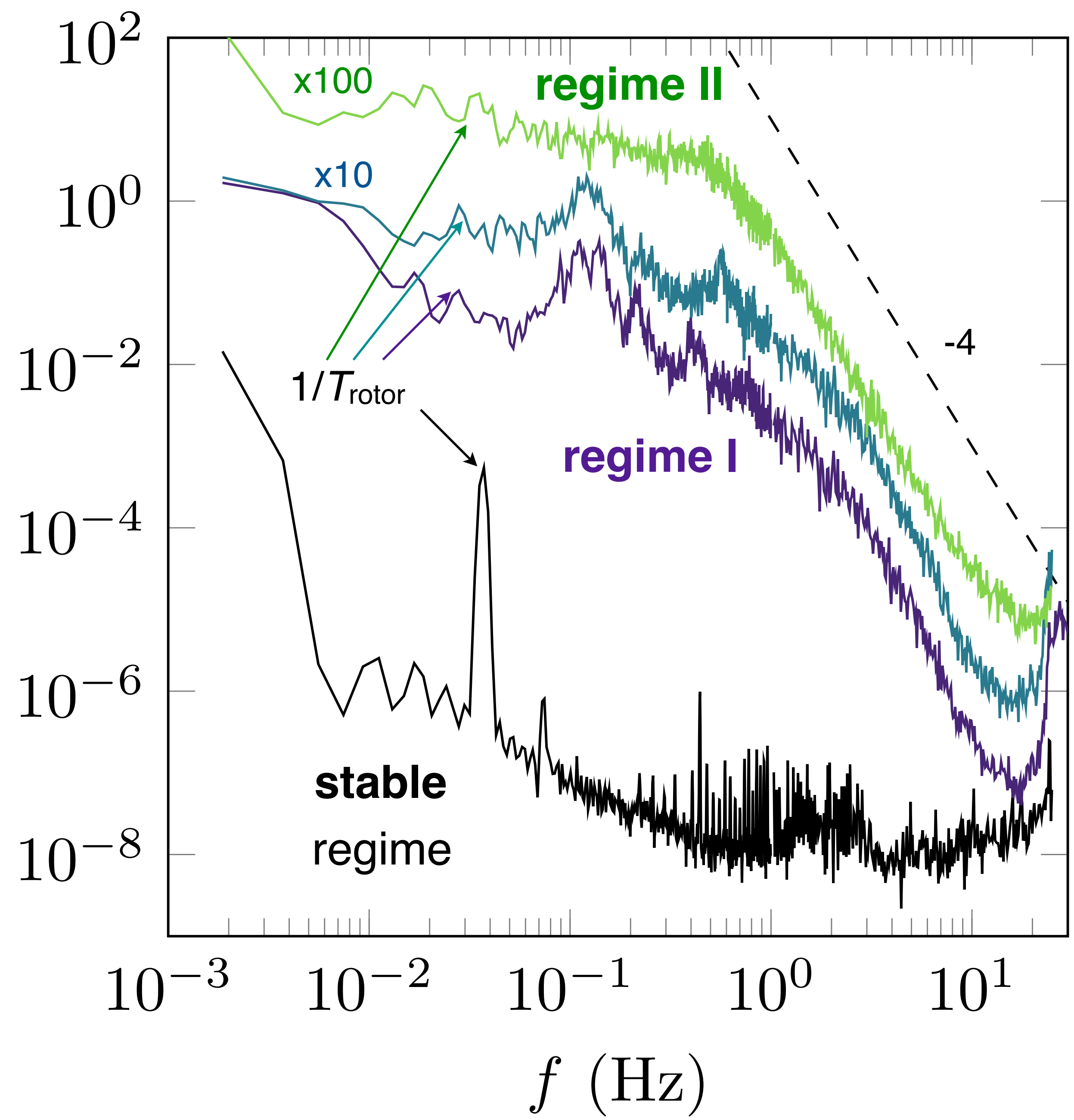






dynamical regime I: complex

dynamical regime II: simpler?

Statistics of the shear rate increments

coll. Laurent Chevillard (ENS Lyon)

$$\delta\dot{\gamma}(t,\Delta t) = \dot{\gamma}(t+\Delta t) - \dot{\gamma}(t)$$

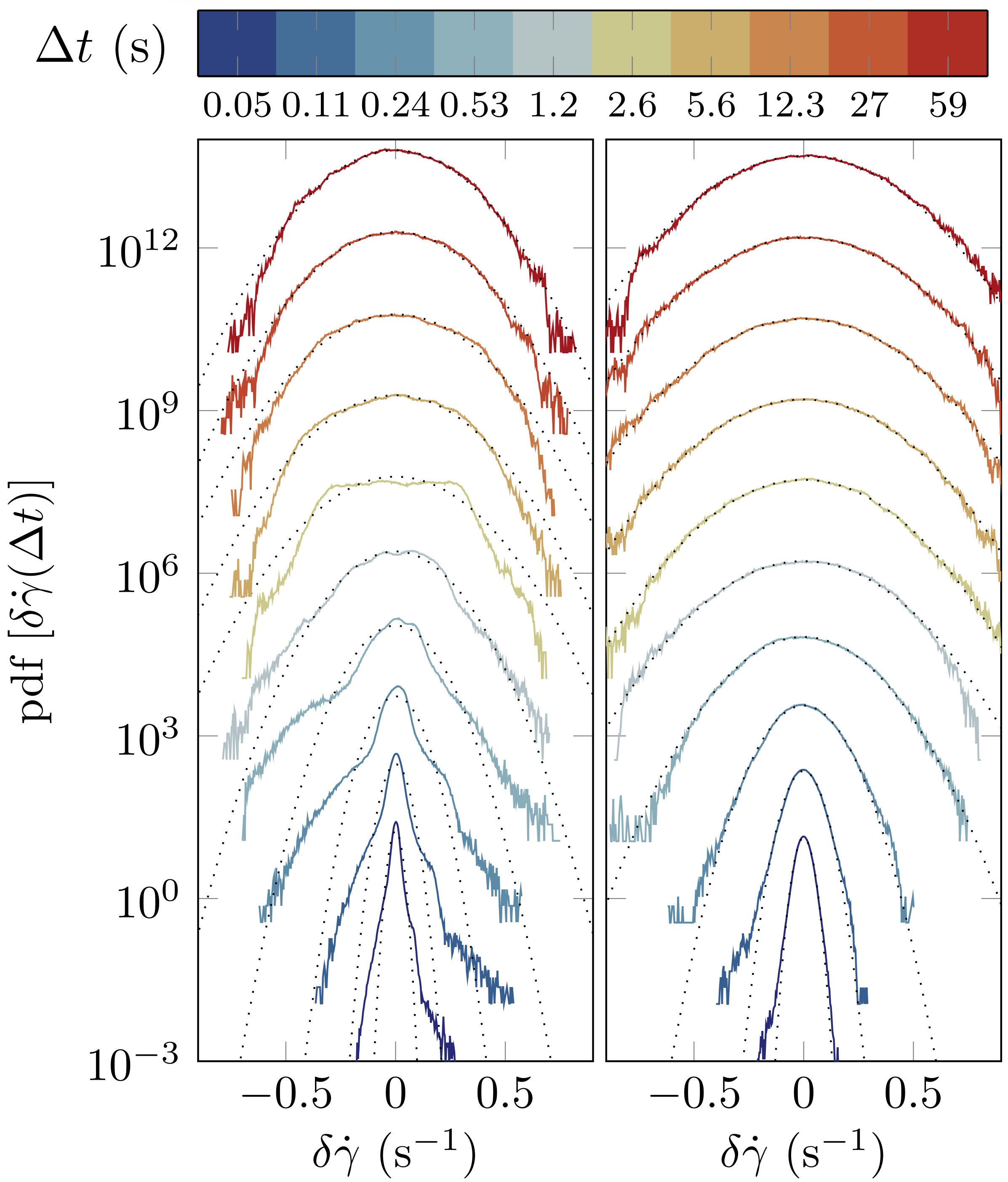
regime I

σ =16 Pa

Gaussian

↑

strong asymmetry + exponential tails ⇓ intermittency



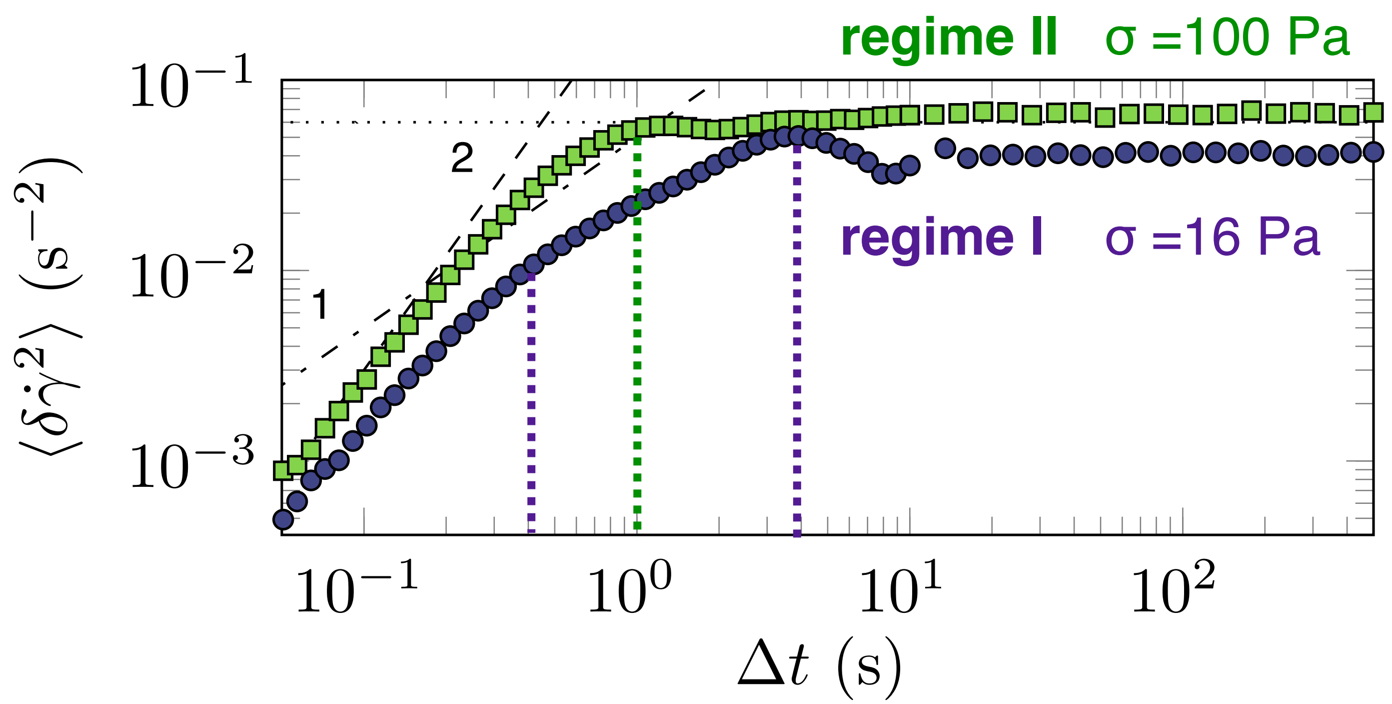
regime II

σ =100 Pa

always Gaussian

Statistics of the shear rate increments

Variance: $\langle \delta\dot{\gamma}^2 \rangle(\Delta t) = \langle \delta\dot{\gamma}(t,\Delta t)^2 \rangle_t$



regime II

- $\Delta t \lesssim 1$ s: Gaussian, ballistic-like
- $\Delta t \gtrsim 1$ s: Gaussian, uncorrelated

regime I

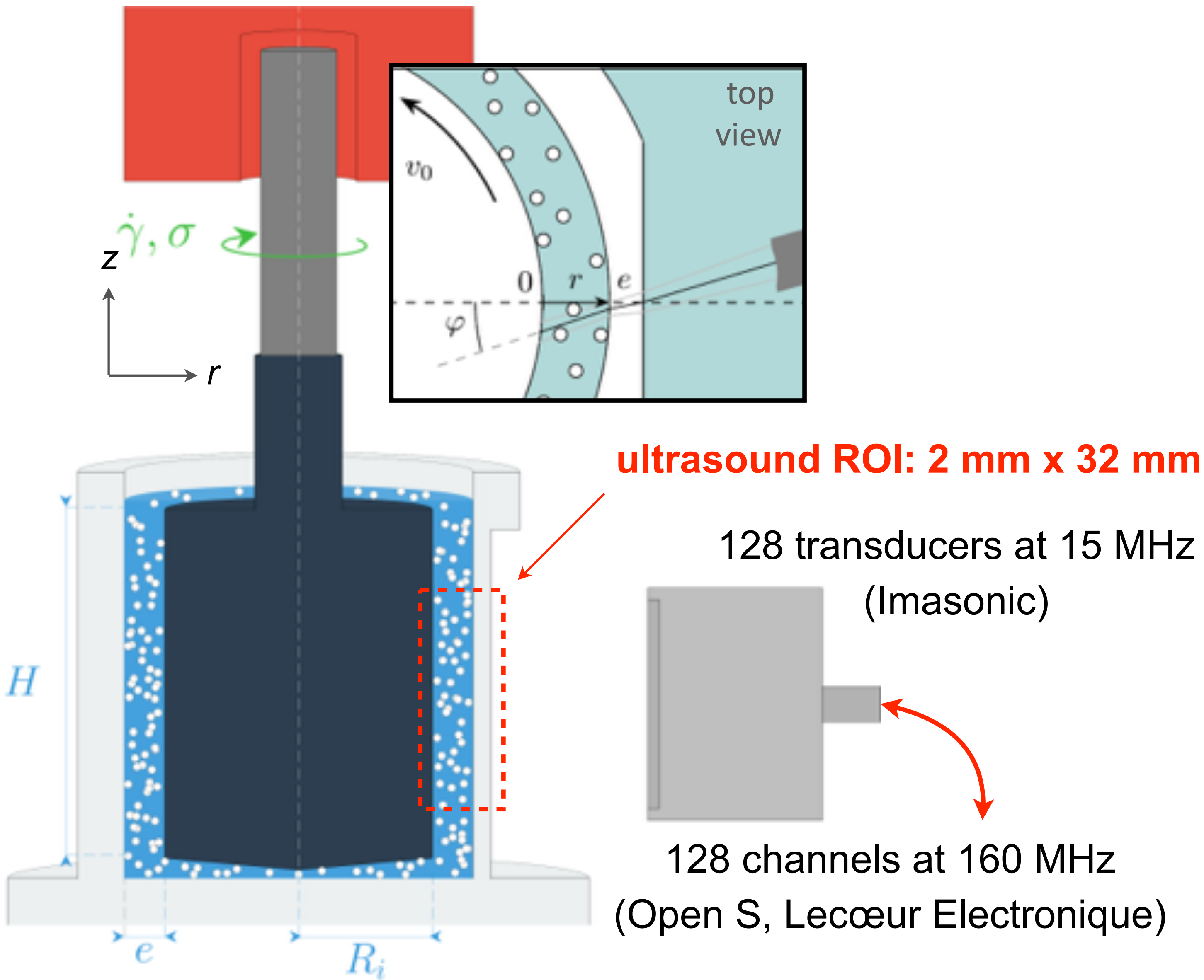
- $\Delta t \lesssim 0.4$ s: intermittent, ballistic-like
- $0.4 \lesssim \Delta t \lesssim 4$ s: non-Gaussian, diffusive-like
- $\Delta t \gtrsim 4$ s: Gaussian, uncorrelated dynamics

“turbulent” rather than “chaotic” dynamics

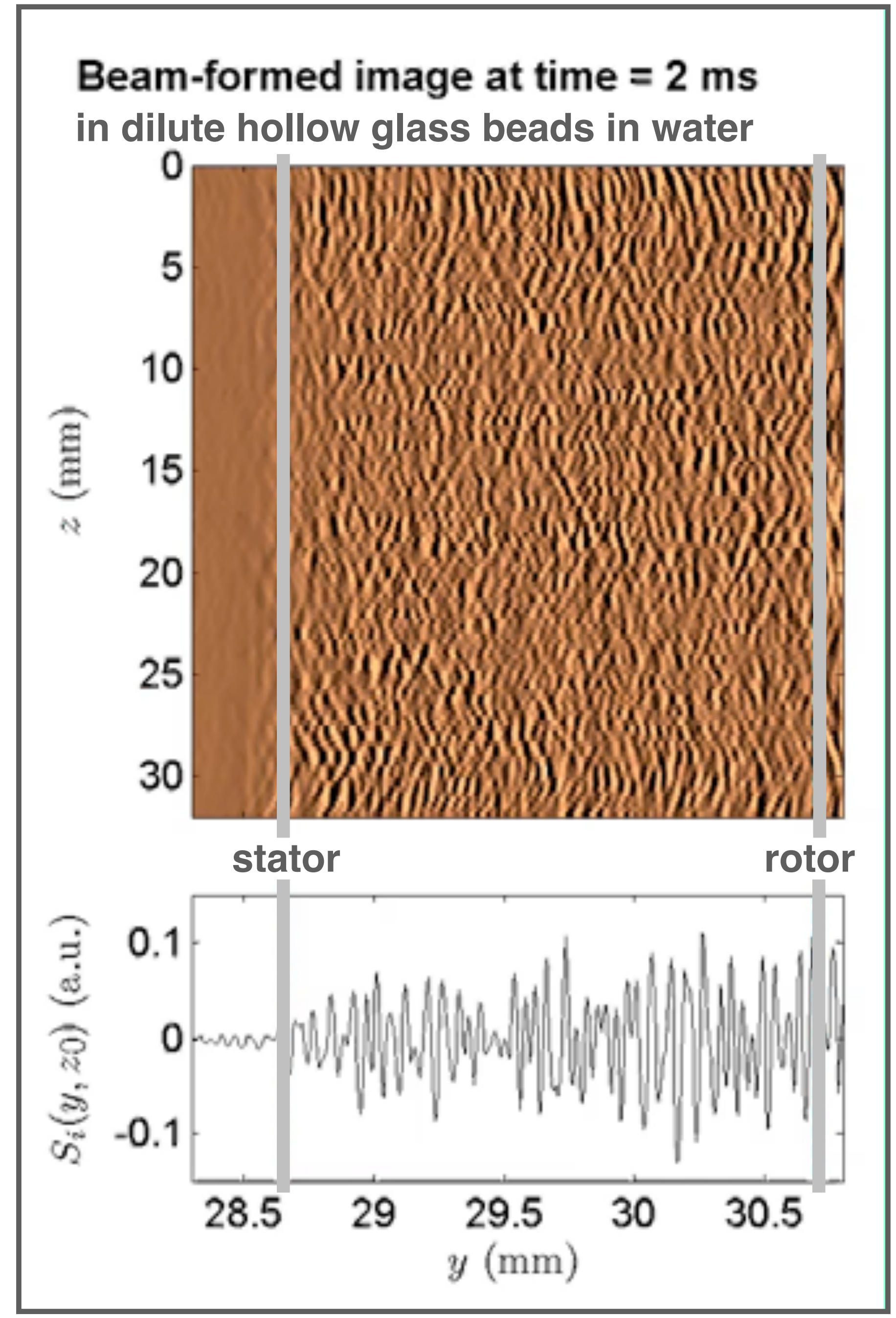
but what does short-time intermittency correspond to?

what do the various timescales correspond to?

Ultrasonic imaging under shear



Gallot *et al.*, *Rev. Sci. Instr.* **84**, 045107 (2013)

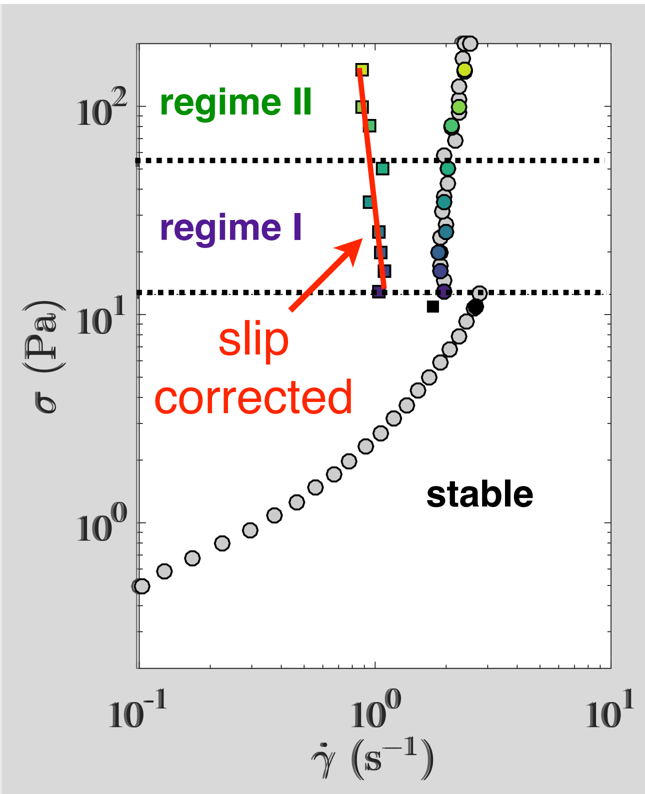


- plane wave emissions up to 20,000 fps
- 128 back-scattered speckle signals
- standard parallel beam-forming
- resolution: δr=100 µm, δz=250 µm

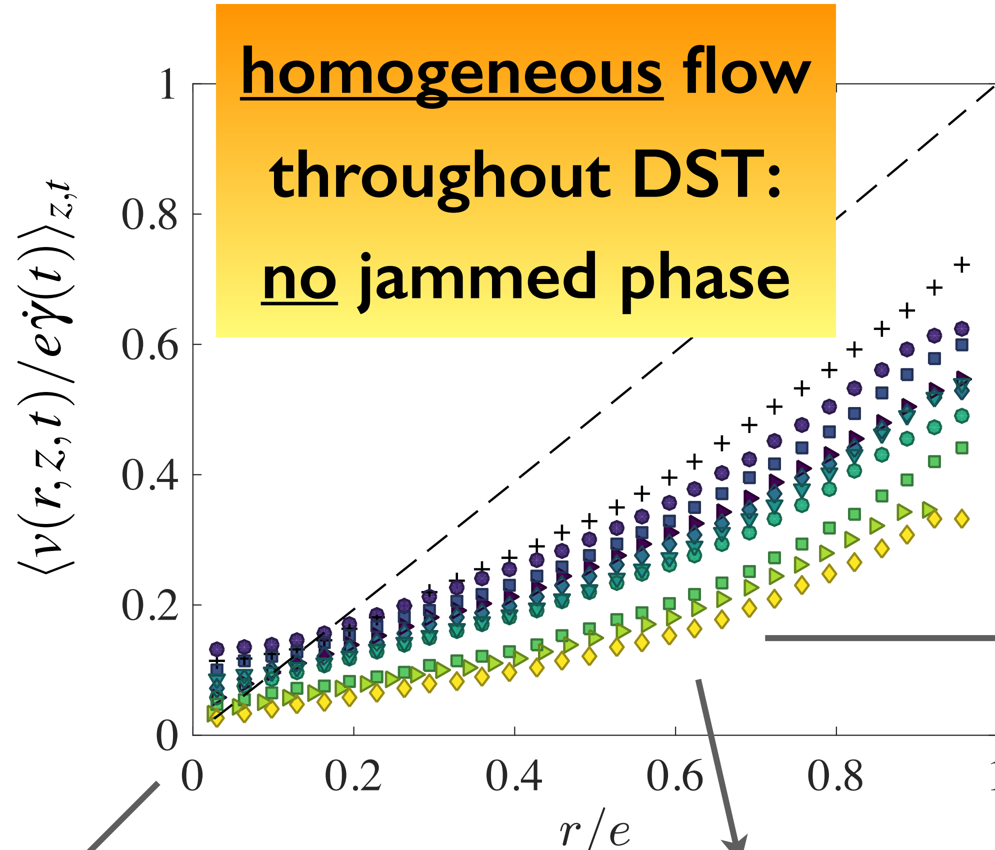
$\Rightarrow$

- 1D cross-correlation along r
- calibration in a Newtonian fluid
- 2D velocity maps $v_\theta(r,z,t)$

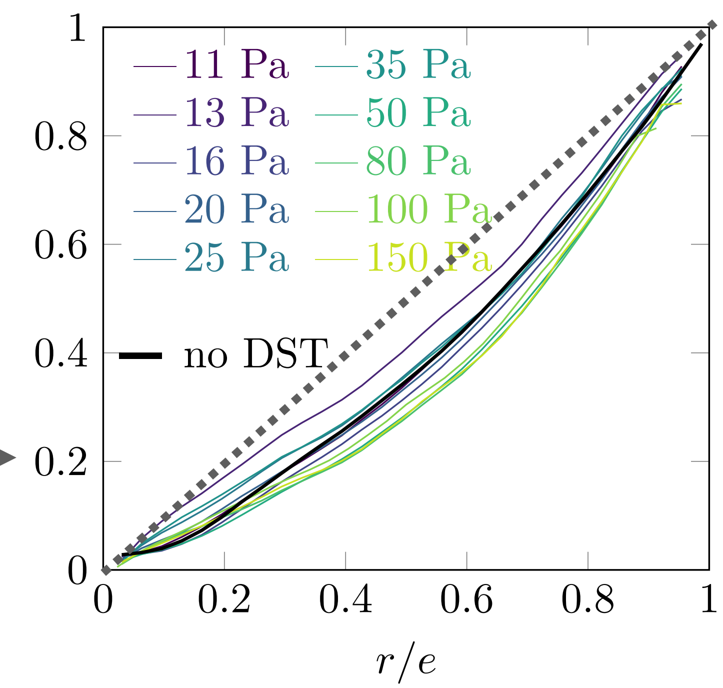
Time-averaged velocity profiles



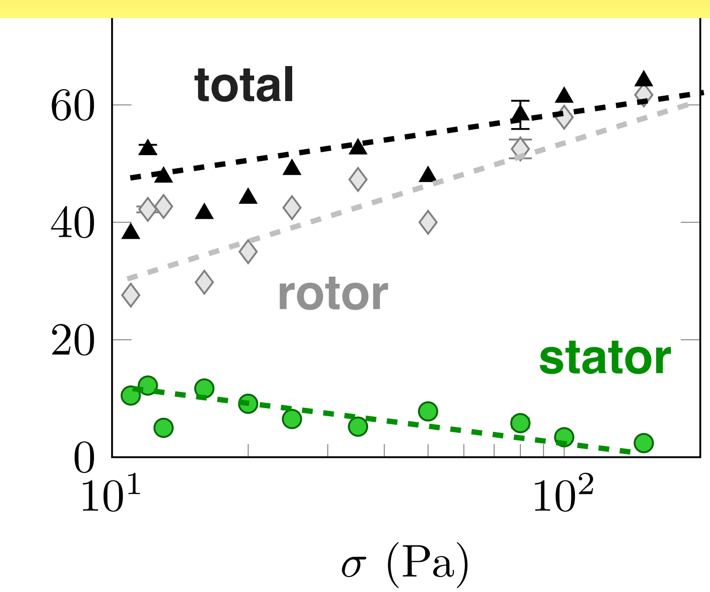
homogeneous flow throughout DST: no jammed phase



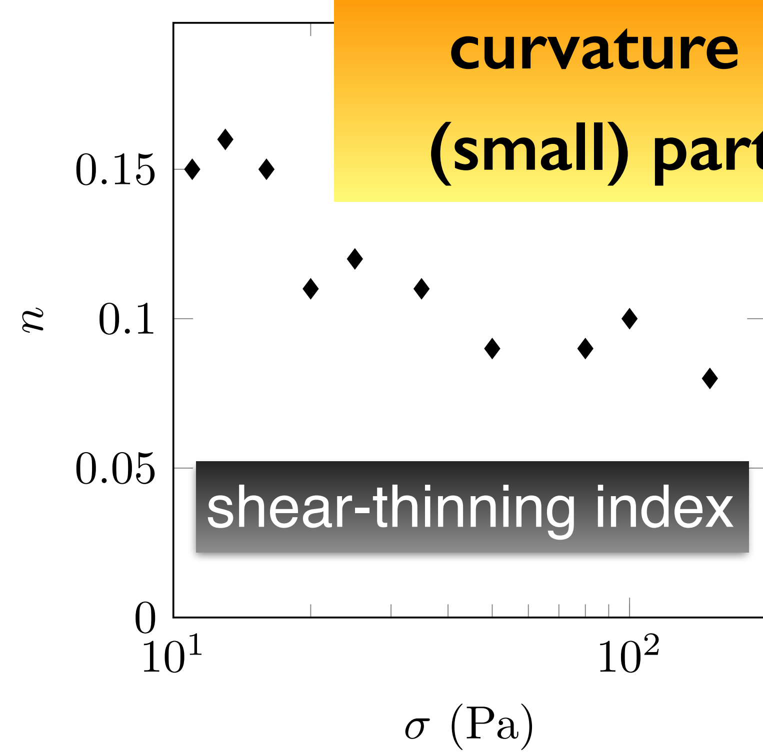
normalized bulk velocities

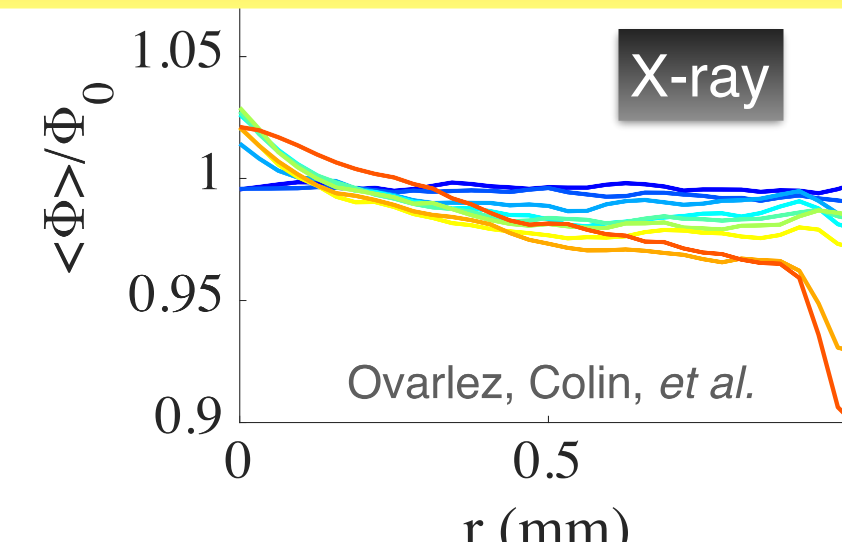


dissymmetric wall slip + weak global increase

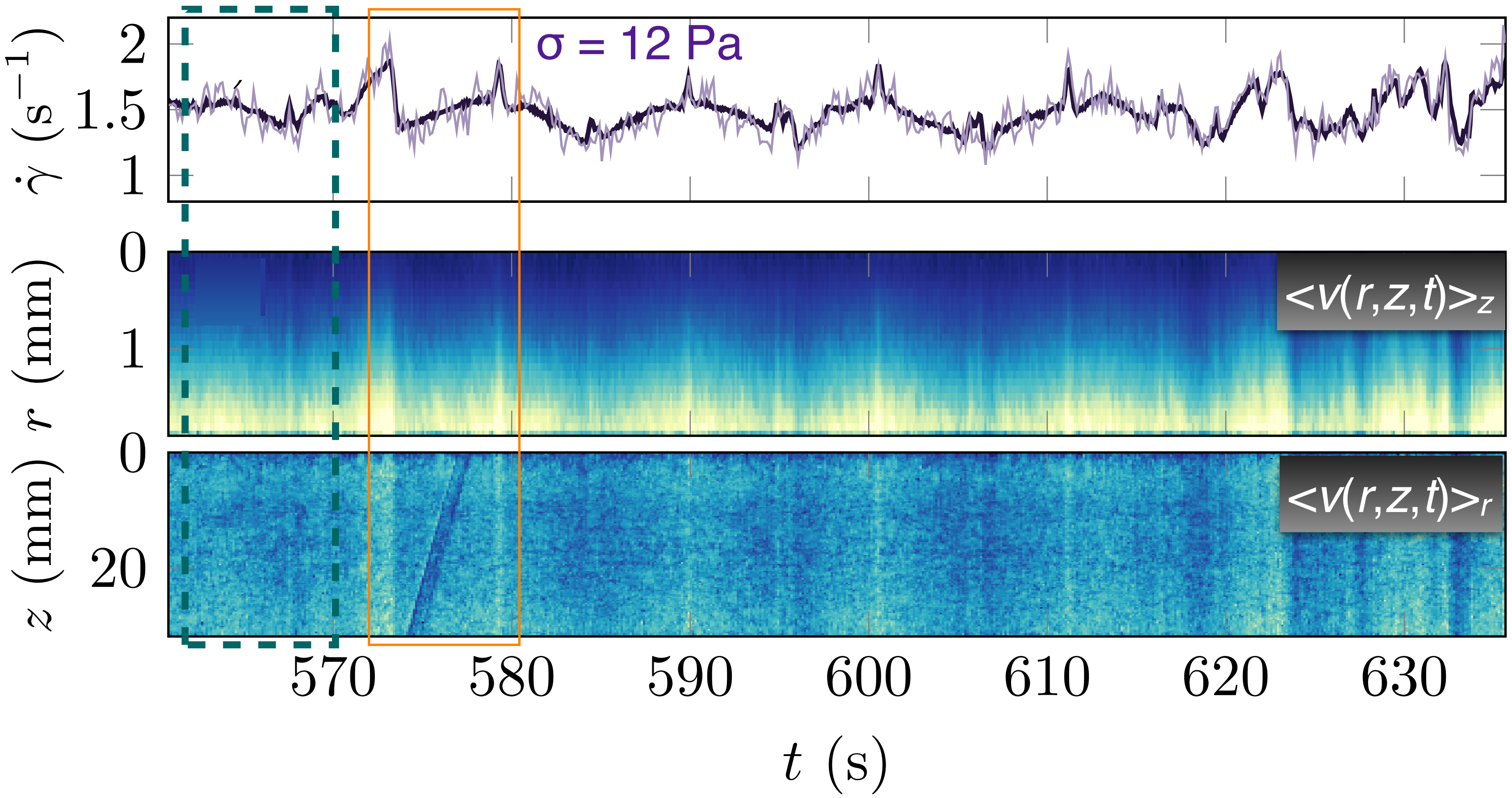


curvature ⇔ apparent shear-thinning
(small) particle migration to the stator

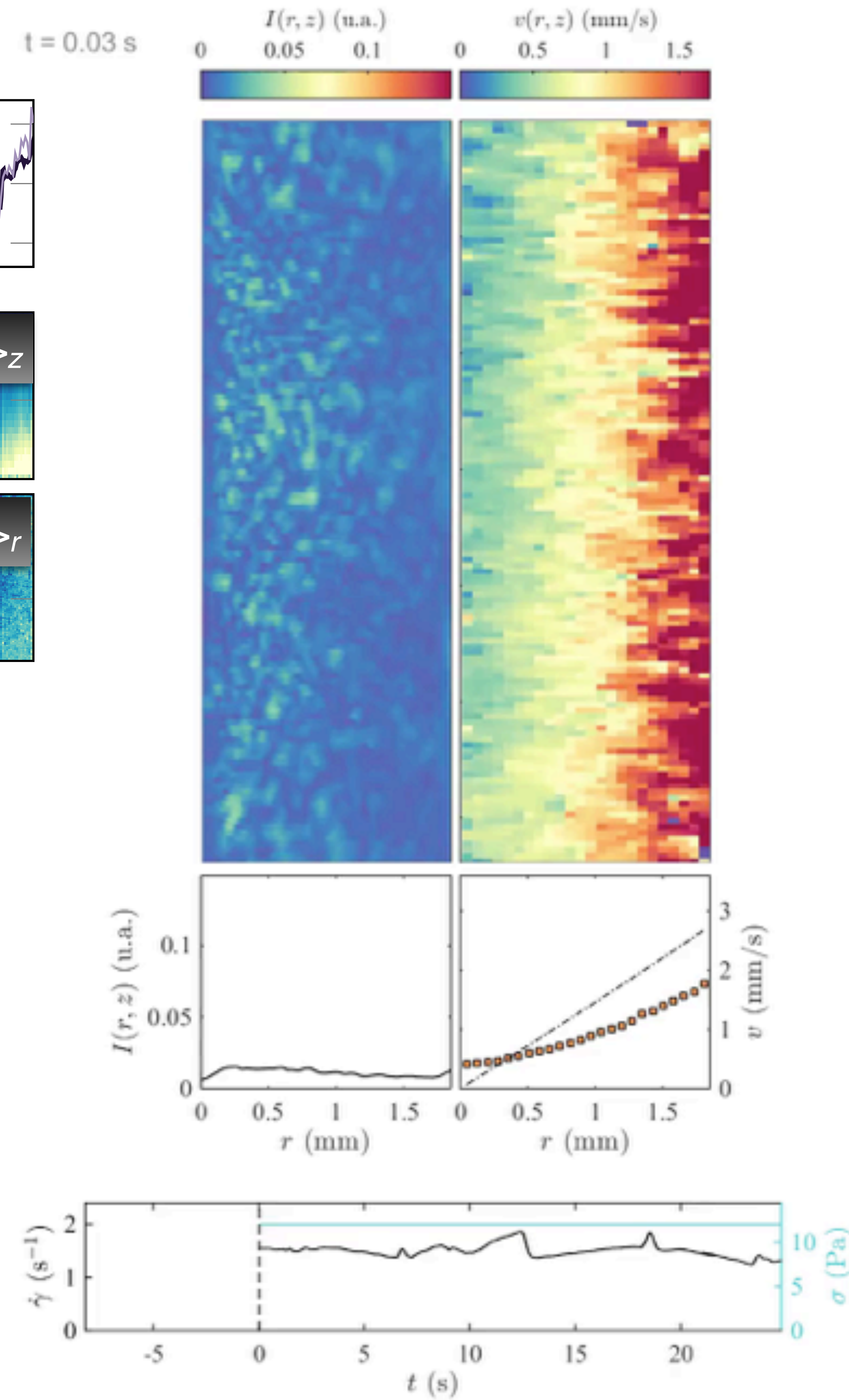




Spatiotemporal patterns in regime I

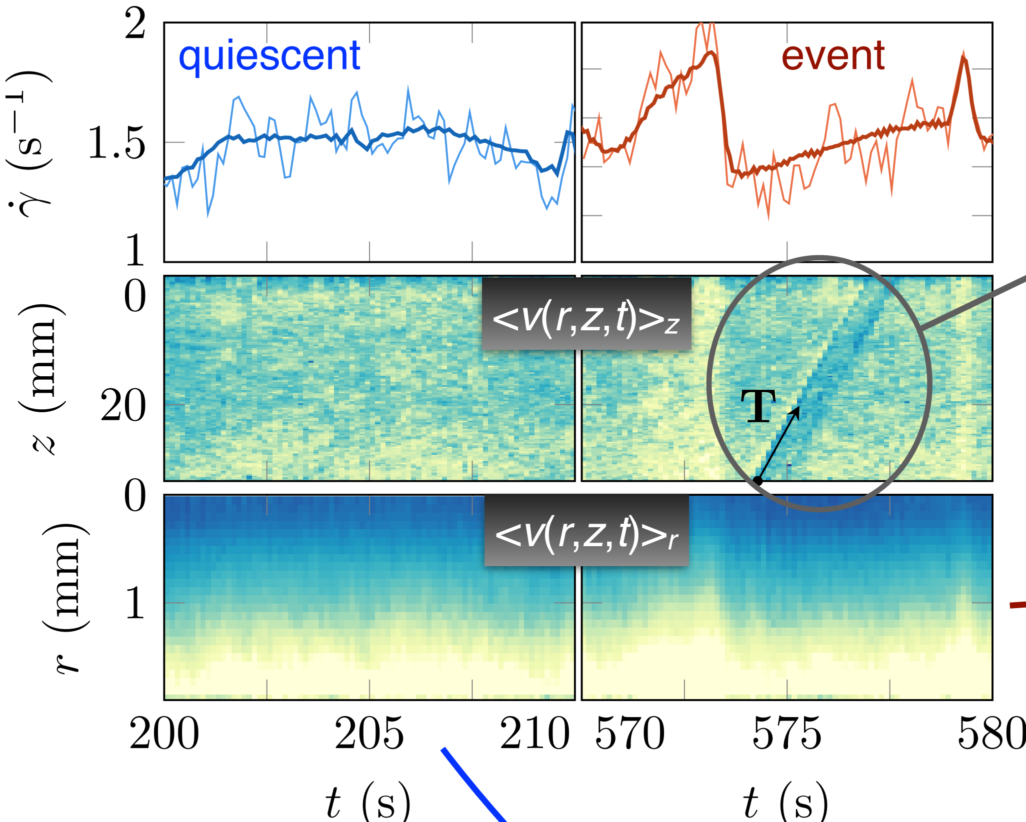


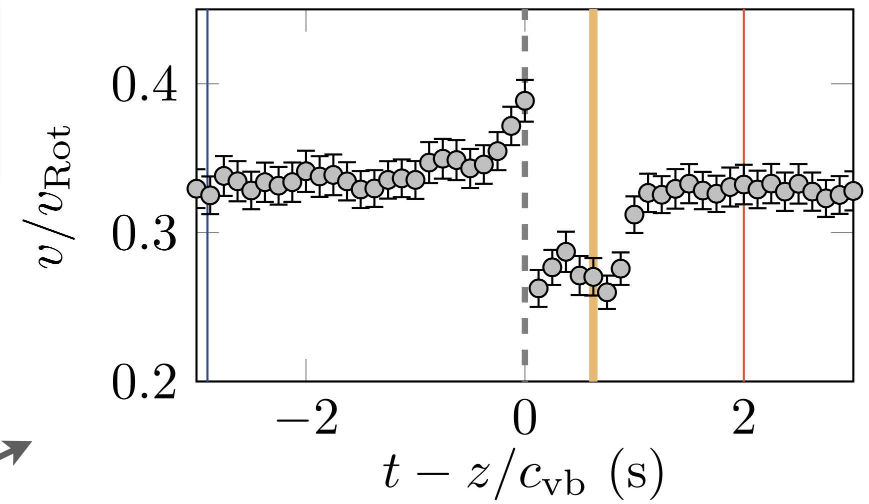
- <u>homogeneous</u> flow, <u>no</u> jammed phase, <u>slip</u>
- strong correlation between global and local measurements
- intermittent propagating events

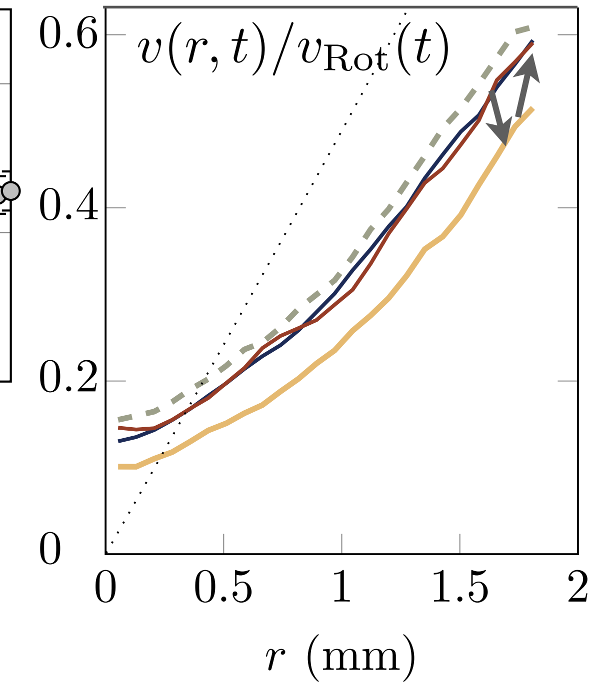


Intermittent events in regime I

splitting the spatiotemporal dynamics into "quiescent" phases *vs* propagating "events"



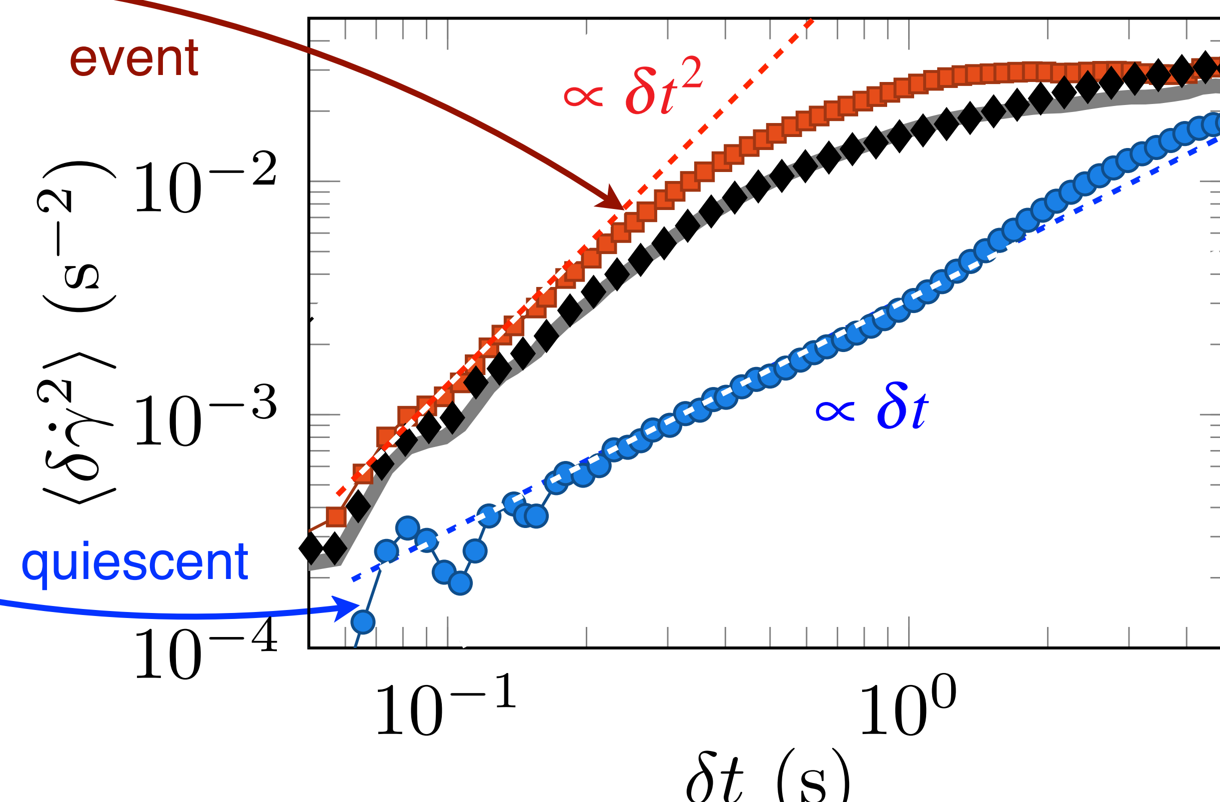




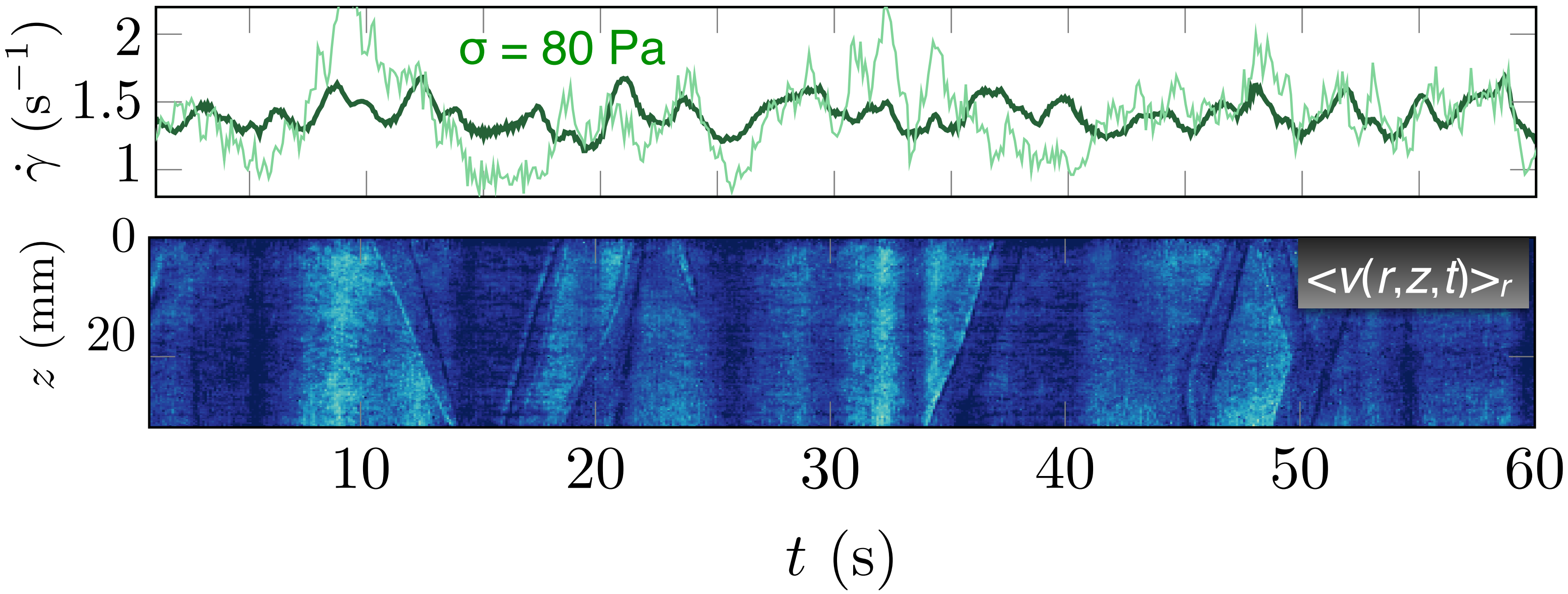
transient slip variation

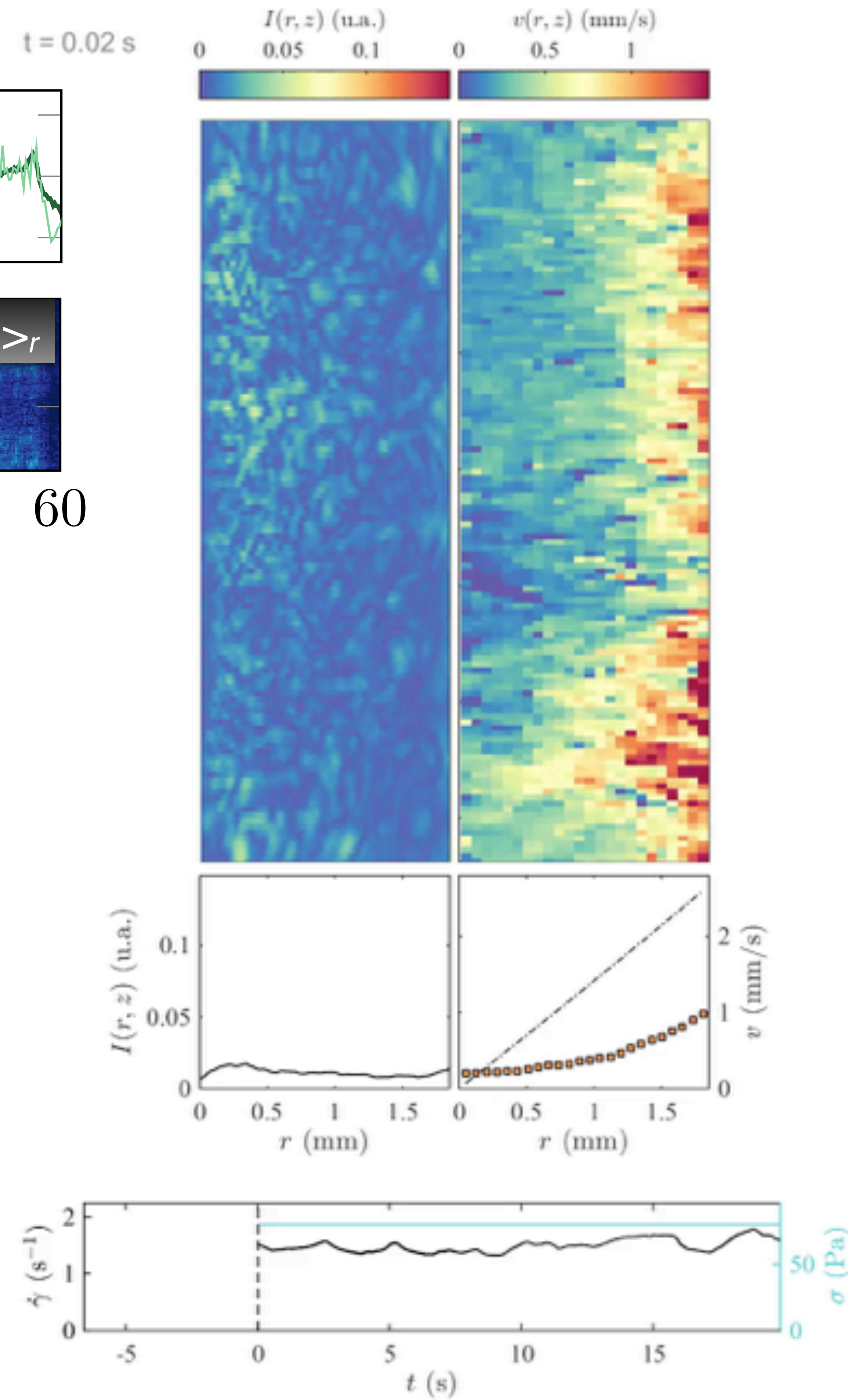
(not stick-slip)

- **quiescent phases = diffusive**
- **propagating events = ballistic**
- **global dynamics = superposition of the two local dynamics**



Spatiotemporal patterns in regime II





- homogeneous flow, no jammed phase, slip
- loss of correlation between global and local measurements
- proliferation of propagating bands

- no quiescent, diffusive-like periods
- only propagating events ⇒ global dynamics is ballistic at short times

Dynamics summary

broad peak in the PSD

around ~0.1 Hz

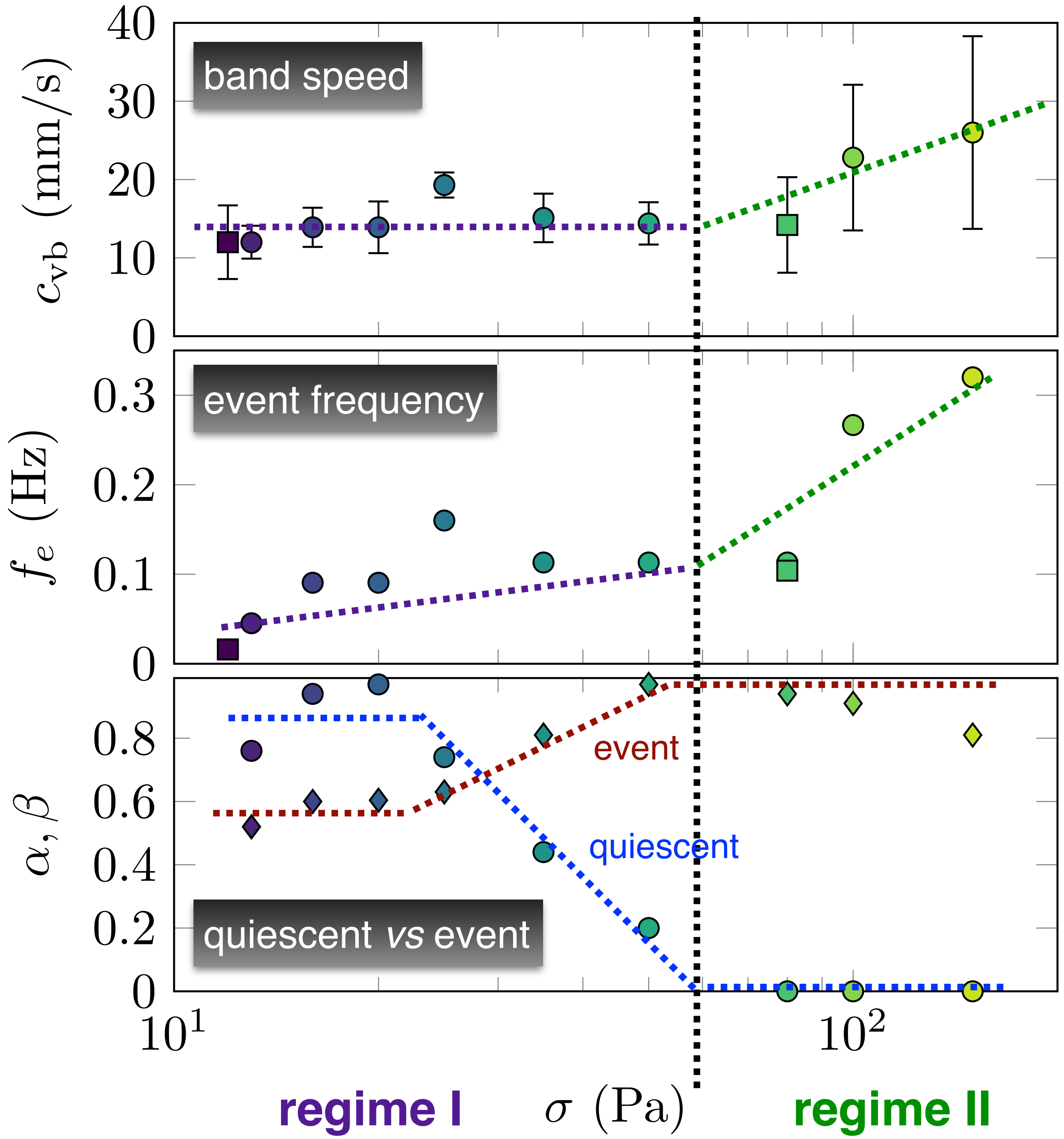
cell height ~60 mm

band width ~10 mm

speed ~15 mm.s^{-1}

<u>slow</u> timescale ~4 s

<u>fast</u> timescale ~0.5 s



cut-off in the PSD

at ~0.3 Hz

cell height ~ band width

speed ~30 mm.s^{-1}

<u>one</u> timescale ~1-2s

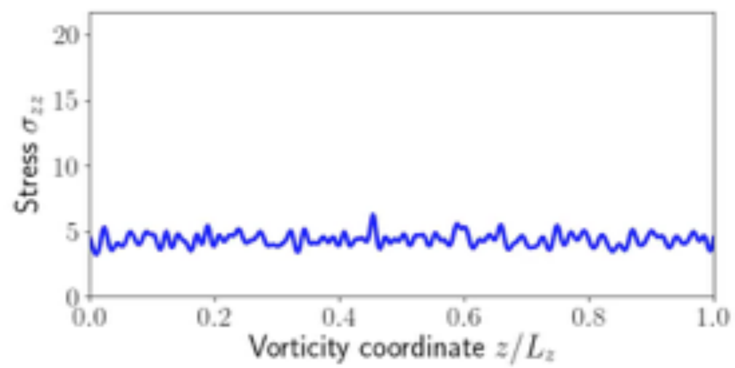
- **short-time intermittency is due to isolated propagating bands**
- **long-time Gaussian dynamics suggests non-interacting bands**

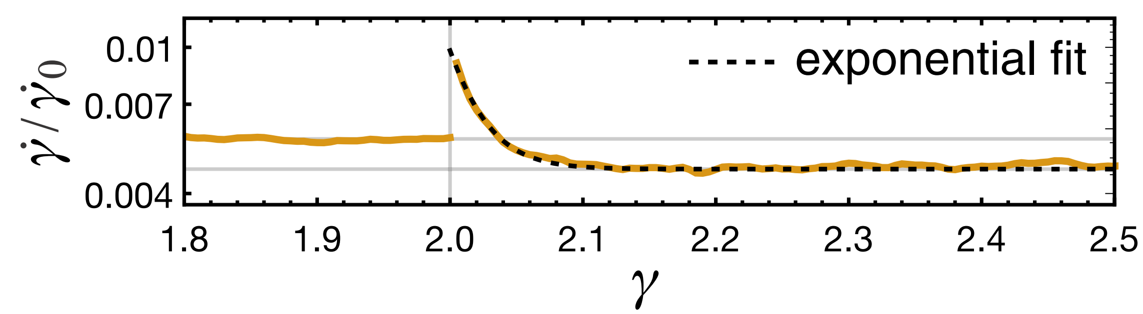
Discussion

propagating vorticity bands predicted by model & simulations

Chacko, Fielding, Mari & Cates, *in preparation* (2018)

⇒ slip events as an indirect signature of such vorticity bands?





Mari *et al.*, *PRE* **91**, 052302 (2015)

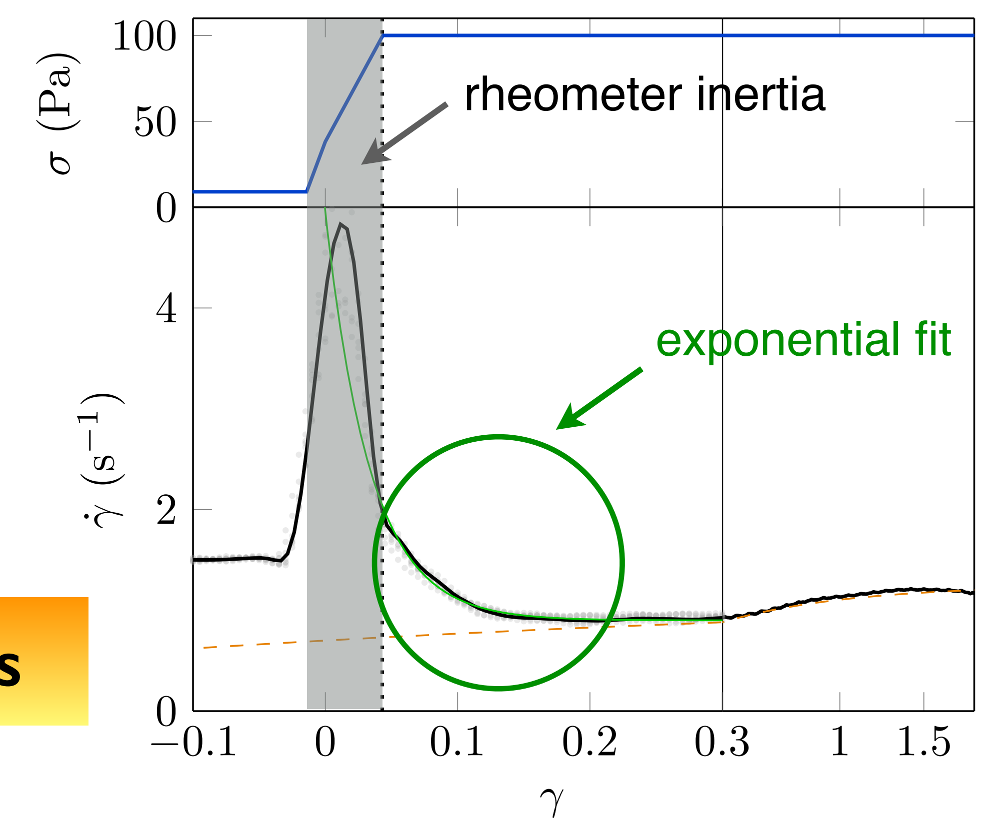
prediction #1: analytical upper bound for the propagation speed

$$c \lesssim \frac{\dot{\gamma}\delta}{\gamma_0}$$

interface width ~ 0.5 mm

microstructure relaxation strain scale

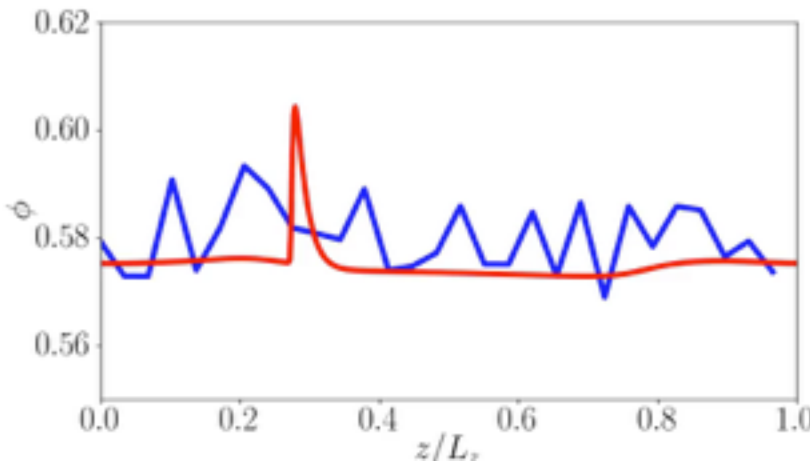
γ_0 ~ 0.034 from response to step-stress

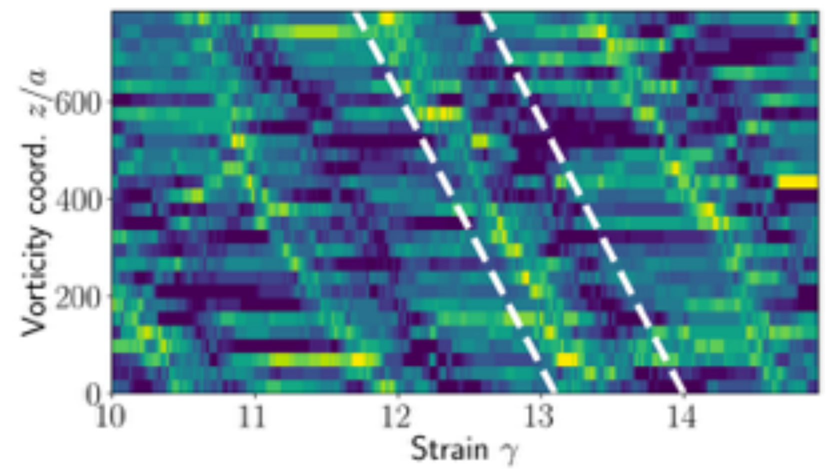


c ≲ 30 mm.s^{-1} ⇒ compatible with experiments

Discussion

<u>prediction #2</u>: vorticity bands ⇒ (tiny) local volume fraction variations



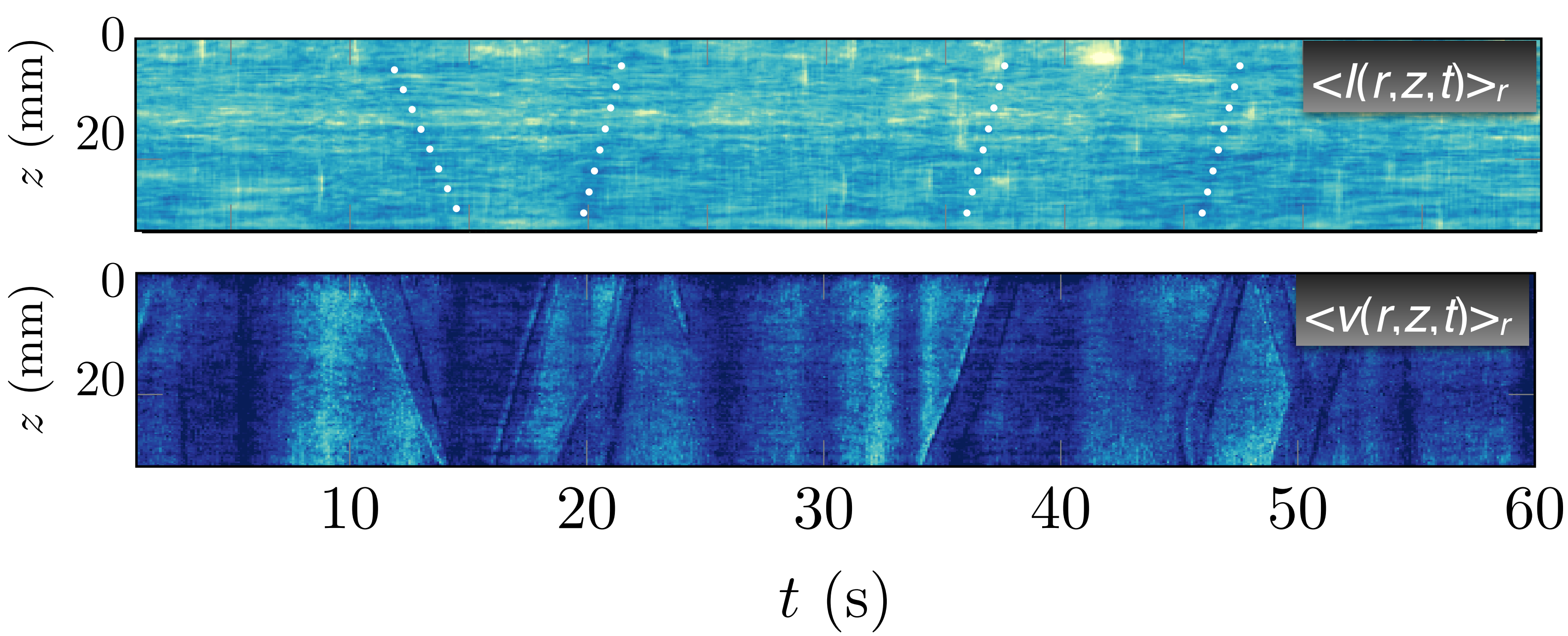


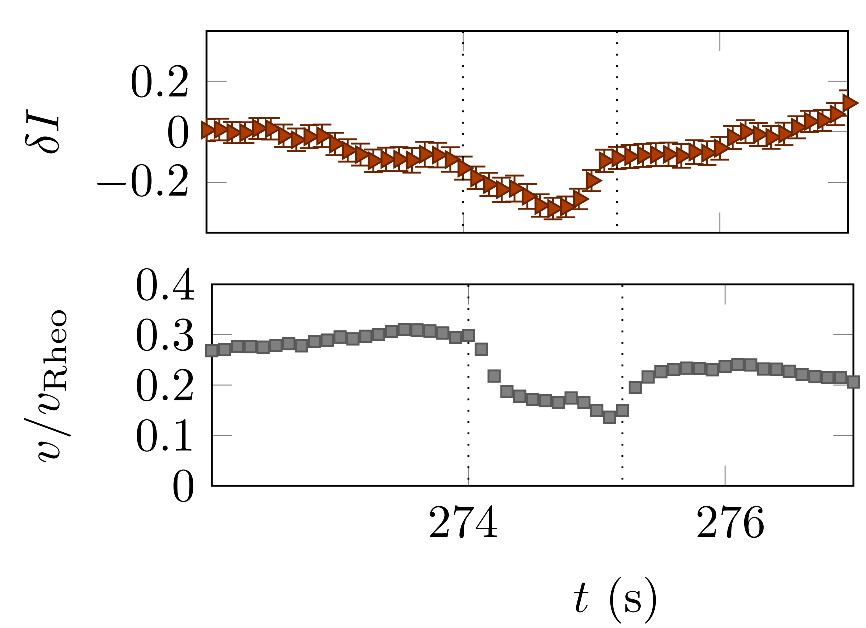
compatible with propagating local variations of Φ

local volume fraction from speckle intensity: *I* increases with ϕ

Saint Michel *et al.*, *Phys. Rev. Applied* **8**, 014023 (2017)

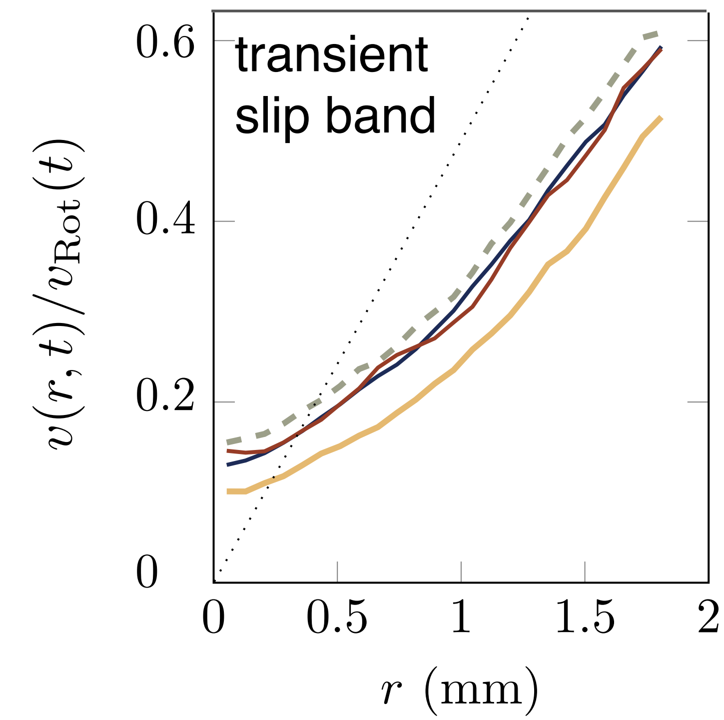
σ =80 Pa





Conclusions & open questions

- **DST in cornstarch under steady shear stress**
- **unsteady yet homogeneously sheared flow**
- **signal analysis ⇒ ballistic *vs* diffusive dynamics**
- **ultrasound ⇒ travelling slip bands (not stick-slip)**
- **compatible with recent model & simulations**
  if local slip is assumed to reflect local stress variations



- wall slip = lubrication or sliding friction?
- measurements of $\Phi(r,z,t)$ (X-ray) and $\sigma(r,z,t)$ (BSM)?
- size dependence ⇒ chaos only in "small" systems?
- evidence for vertical displacements?
- azimuthal extension of the bands?
- what happens to the bands at the cell boundaries?
- what about the bottom of the Couette cell?
- what about other concentrations? other systems?