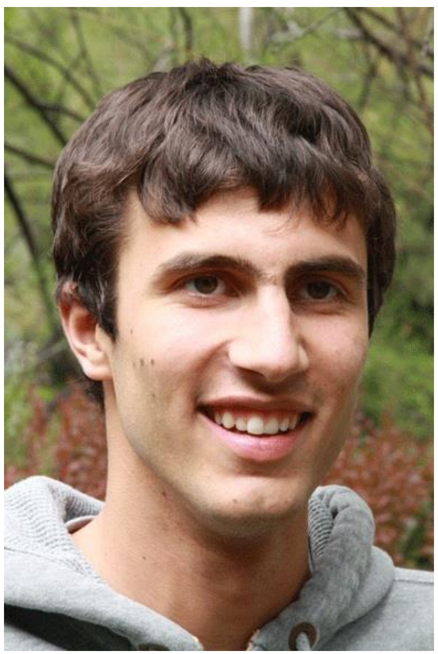
Microscopic dynamics and failure precursors during the creep of a colloidal gel



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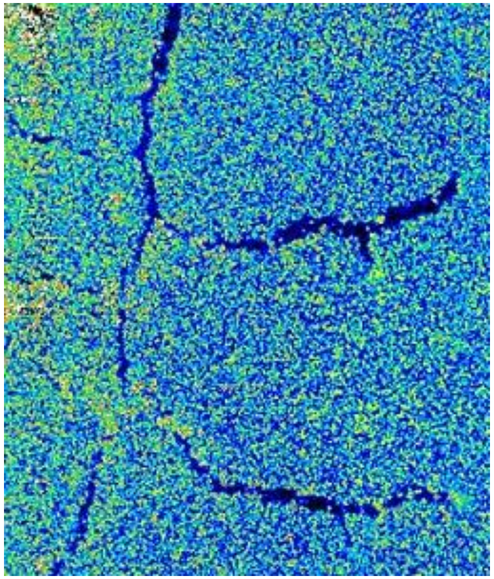
Laboratoire Charles Coulomb, CNRS UMR 5221, Université Montpellier, France

Material failure

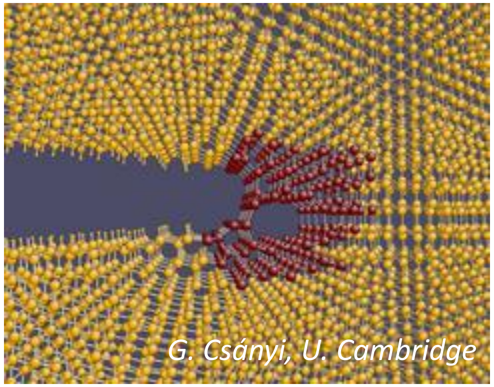
12th conference on sinkholes

I-35W Missisippi River Bridge



Cracks in cornstarch, *L2C*

Vasquez Canyon Road, CA

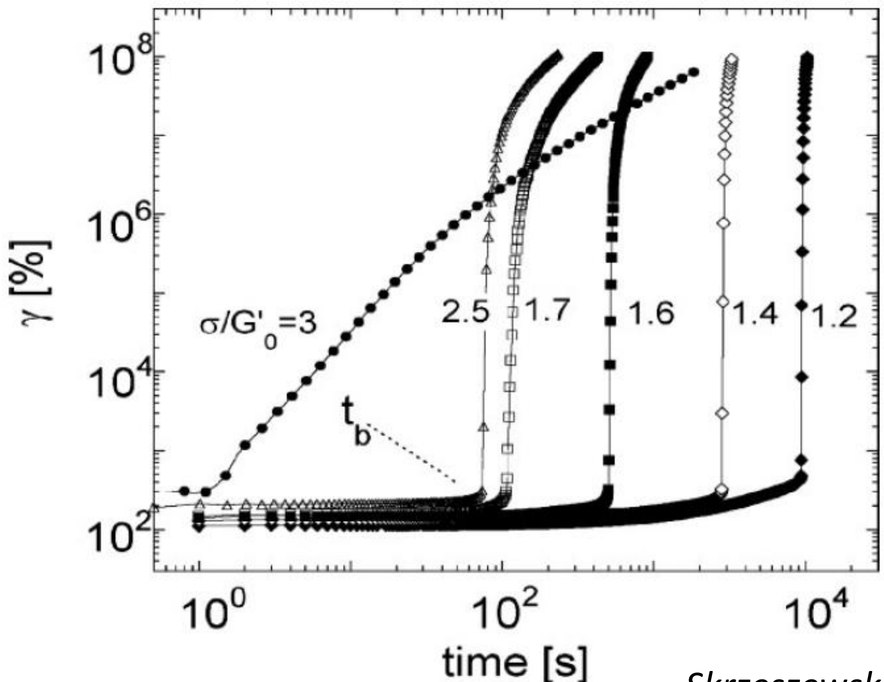


Crack at atomistic level

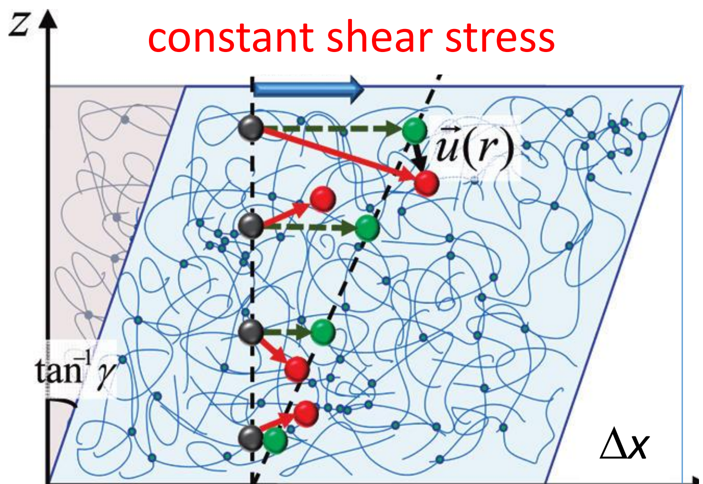
Material failure

- **Highly non-linear**
- **Abrupt**
- **Unpredictable**

Creep test on a polymer network



Skrzeszewska et al., 2010



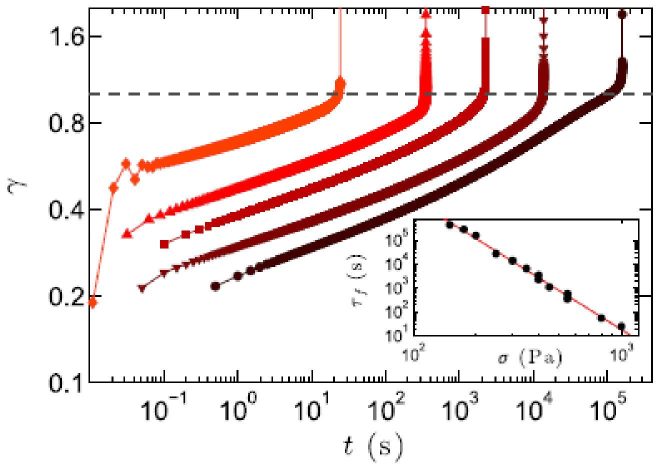
gap *e*

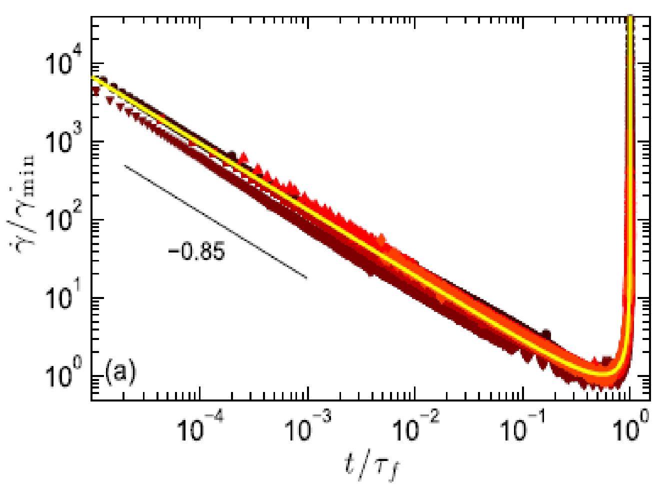
shear deformation $\gamma = \Delta x/e$

Adapted from Basu et al, 2011

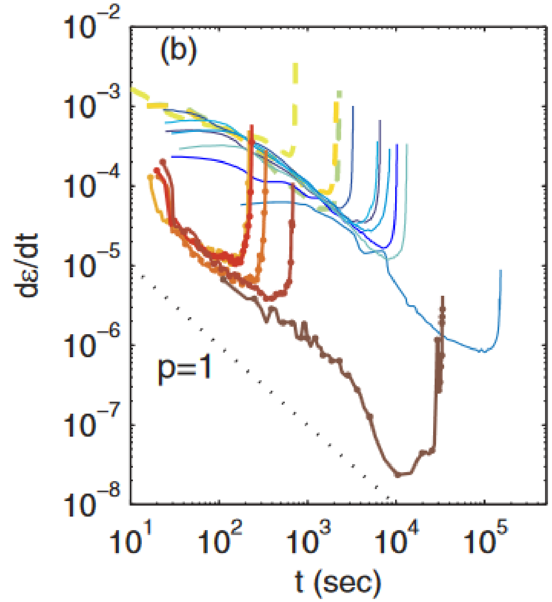
‘Delayed’ failure ubiquitous

Biopolymer gel under *shear* stress



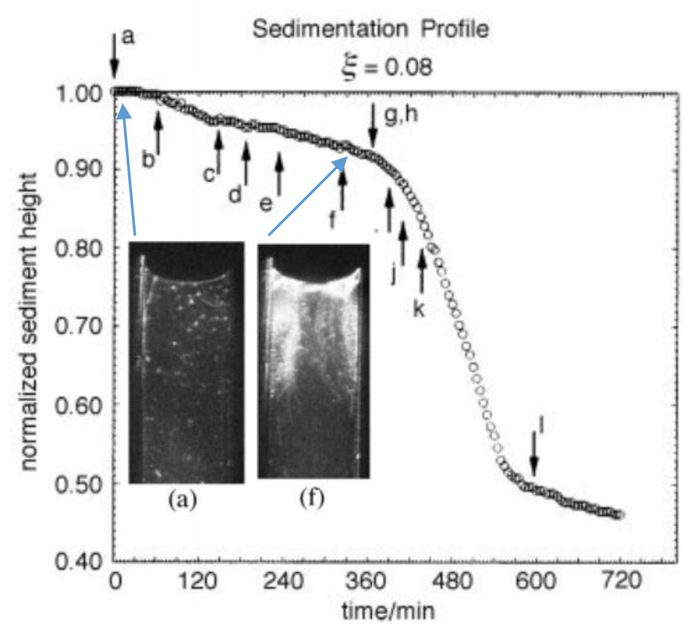


Leocmach et al, 2014



Composite fibers under *tensile* stress

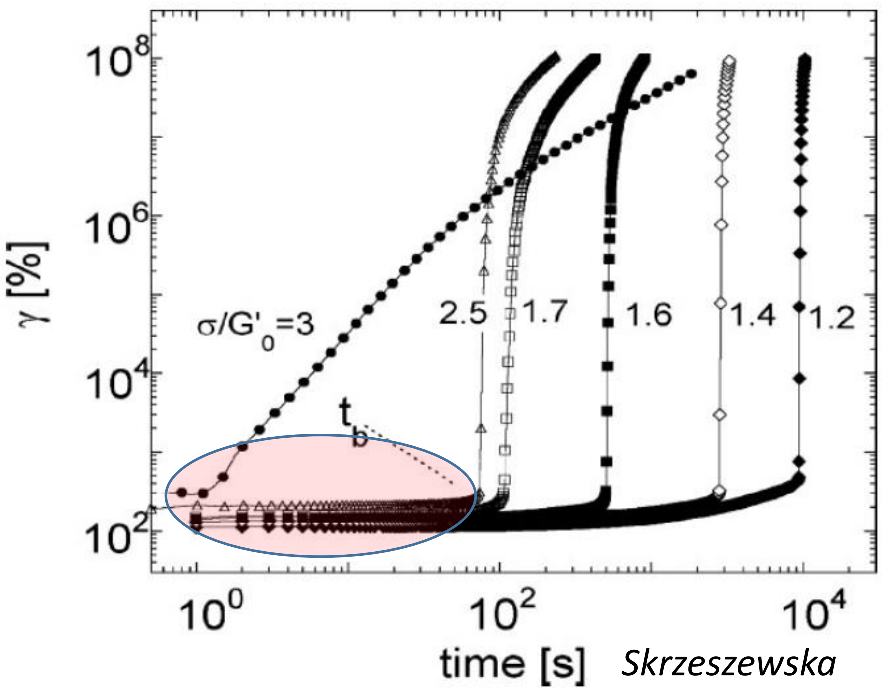
Nechad et al, 2005



Colloidal gel under *compressive* (gravitational) stress

Poon et al, 1999

Key questions



Skrzeszewska et al., 2010

1. Mechanisms at the **microscopic level** leading to catastrophic failure?

2. Relation between **microscopic** evolution and **macroscopic** (mechanical) properties?

Experiments

- Soft matter (tunable, length & time scale accessible)
- Couple rheology and microscopic measurements (structure, dynamics)

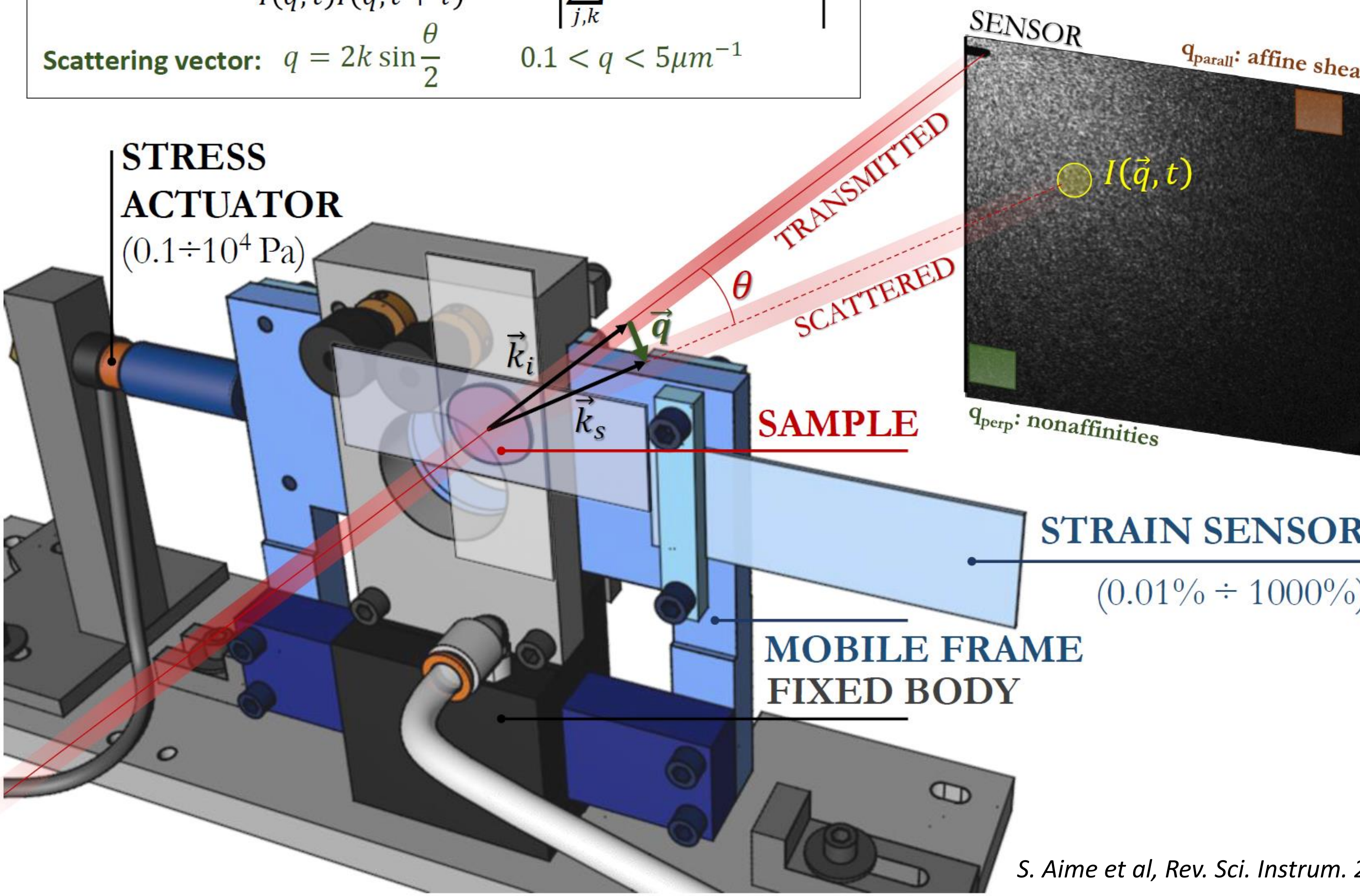
Custom setup: σ controlled shear cell + Small Angle Light Scattering

single scattering

Dynamic light scattering: probing particle displacements

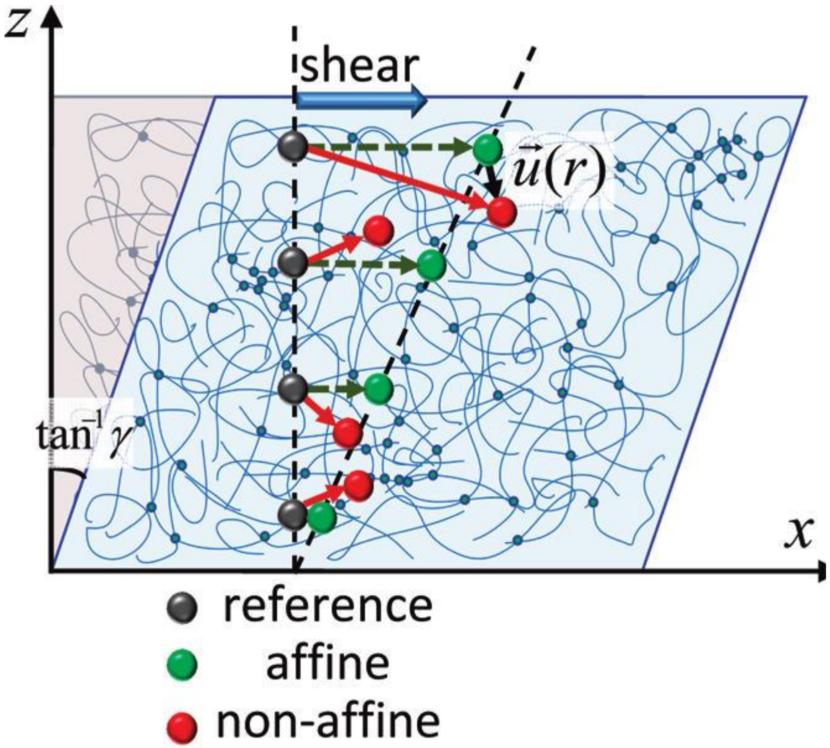
$$g_2(\vec{q},t,\tau) - 1 = \frac{I(\vec{q},t+\tau)I(\vec{q},t)}{I(\vec{q},t)I(\vec{q},t+\tau)} - 1 \propto \left| \sum_{j,k} e^{i\vec{q}\cdot[\vec{r}_j(t)-\vec{r}_k(t+\tau)]} \right|^2$$

Scattering vector: $q = 2k \sin\frac{\theta}{2}$ $\quad 0.1 < q < 5\mu m^{-1}$



S. Aime et al, Rev. Sci. Instrum. 2016

Affine vs non-affine particle displacements



Basu et al, 2011

Ideal solid: affine displacements only

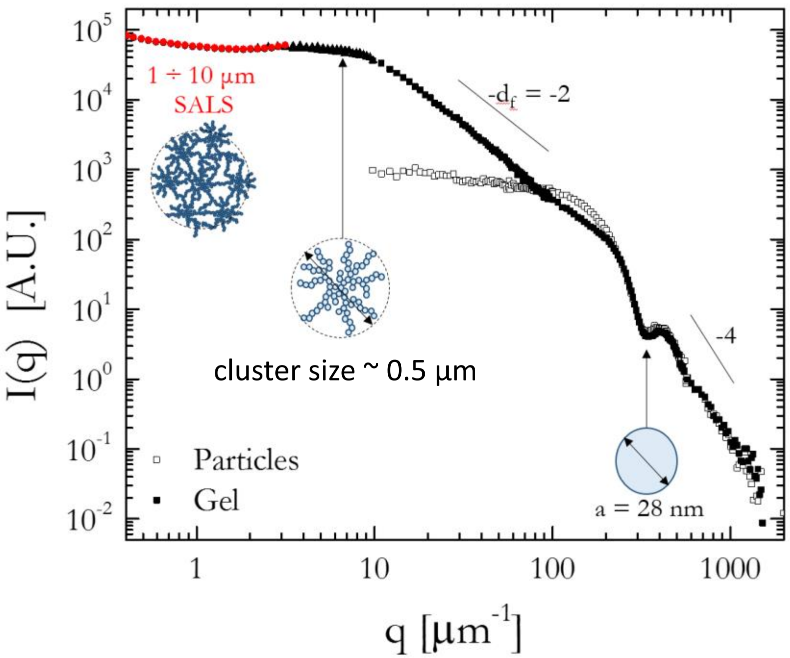
Non-affine displacements: *G'* heterogeneity, rearrangements...

Ligth scattering: sensitive to $\vec{q}\cdot\overrightarrow{\Delta r}$ → discriminate affine/ non-affine

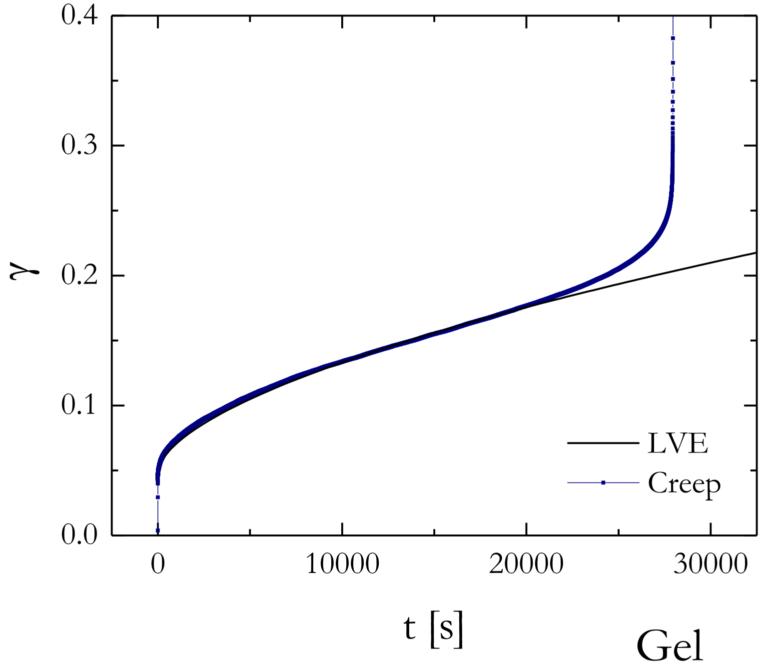
Colloidal gel: structure & rheology

Attractive colloidal particles, diam ~30 nm
Diluted gel: $\varphi = 5\%$, $G' \sim 5$ kPa

Sample structure



Rheology: creep test

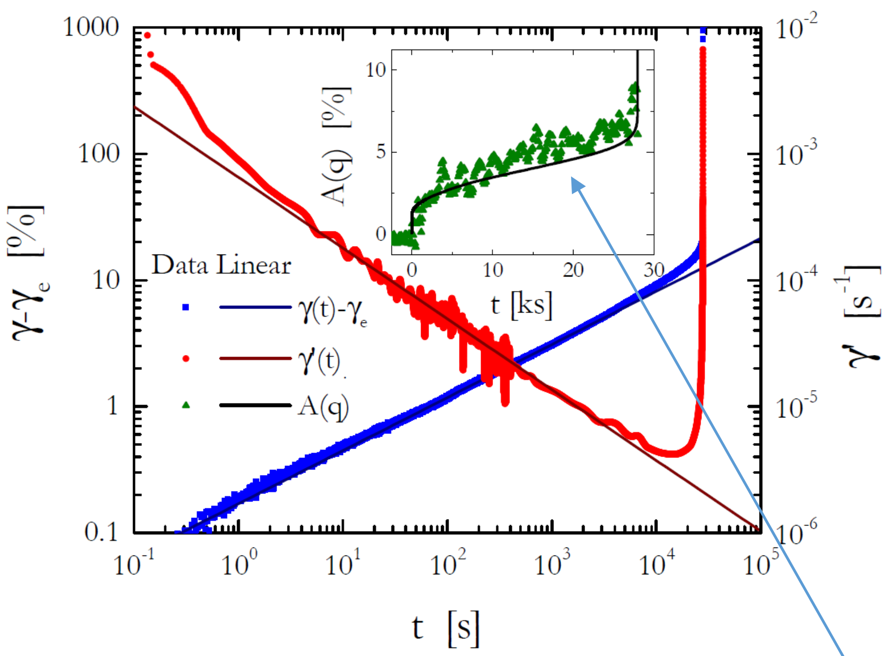


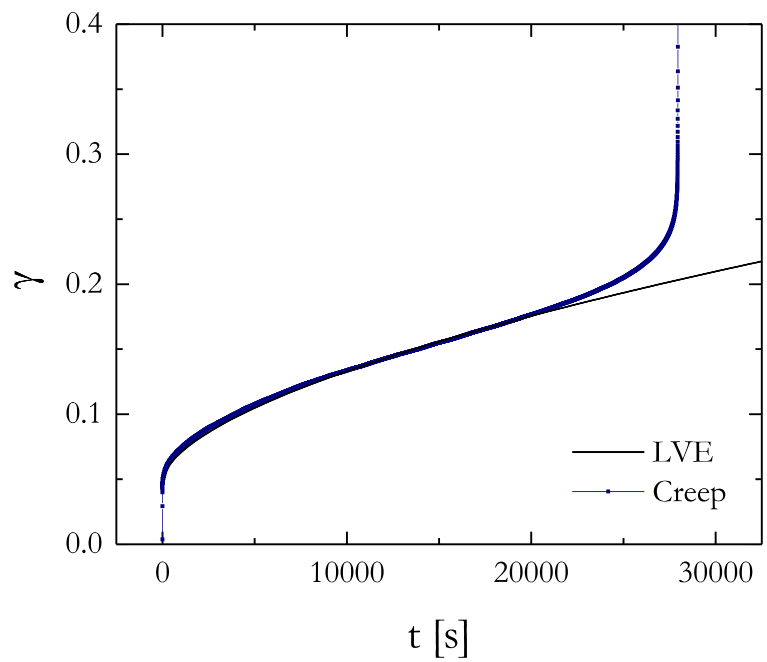
Colloidal gel: structure & rheology

Attractive colloidal particles, diam ~30 nm
Diluted gel: φ = 5%, G' ~ 5 kPa

Creep

Rheology: creep test



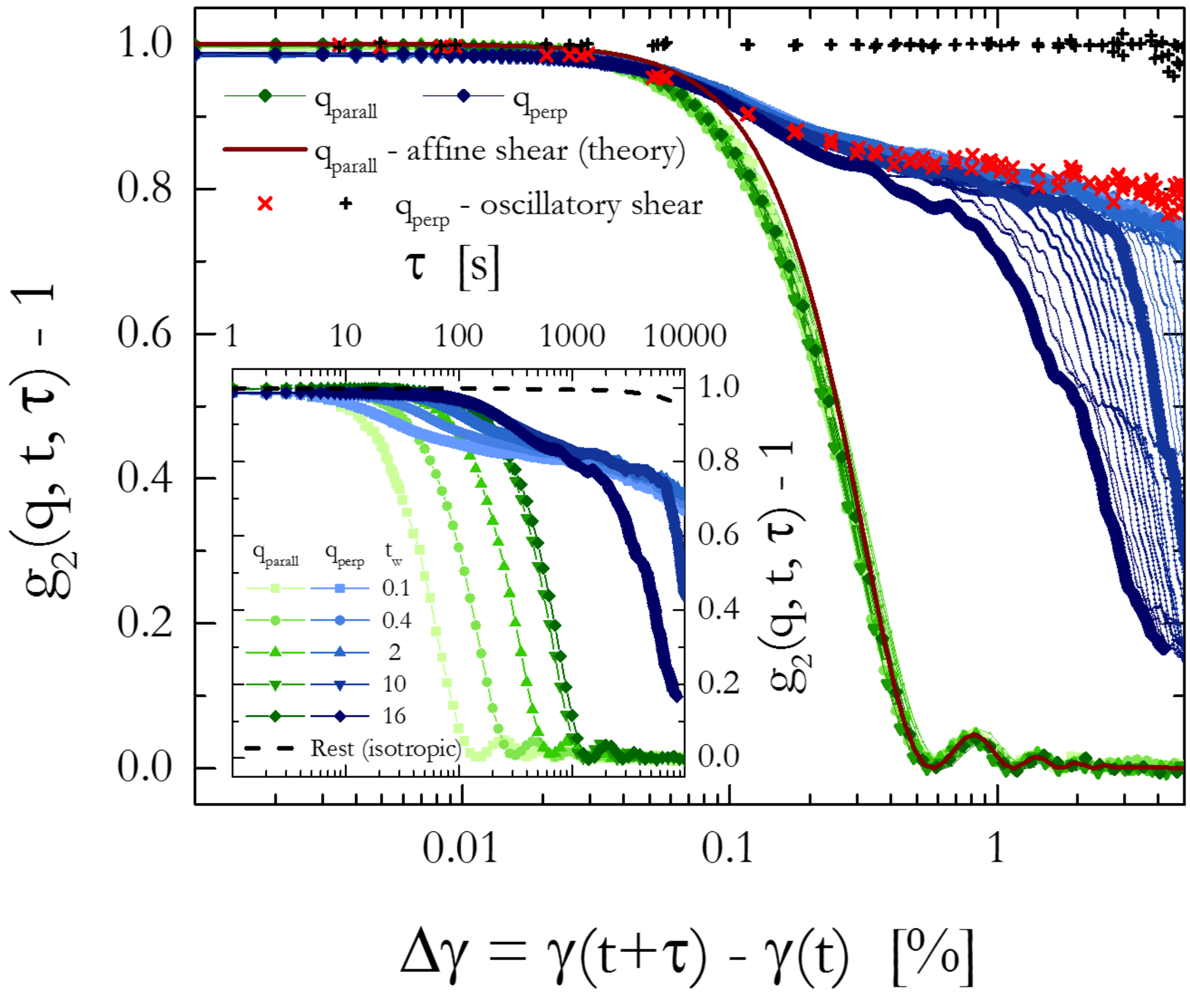


$$\dot{\gamma} \sim t^{-0.57}$$

Anisotropy of scattered intensity

Microscopic dynamics under creep

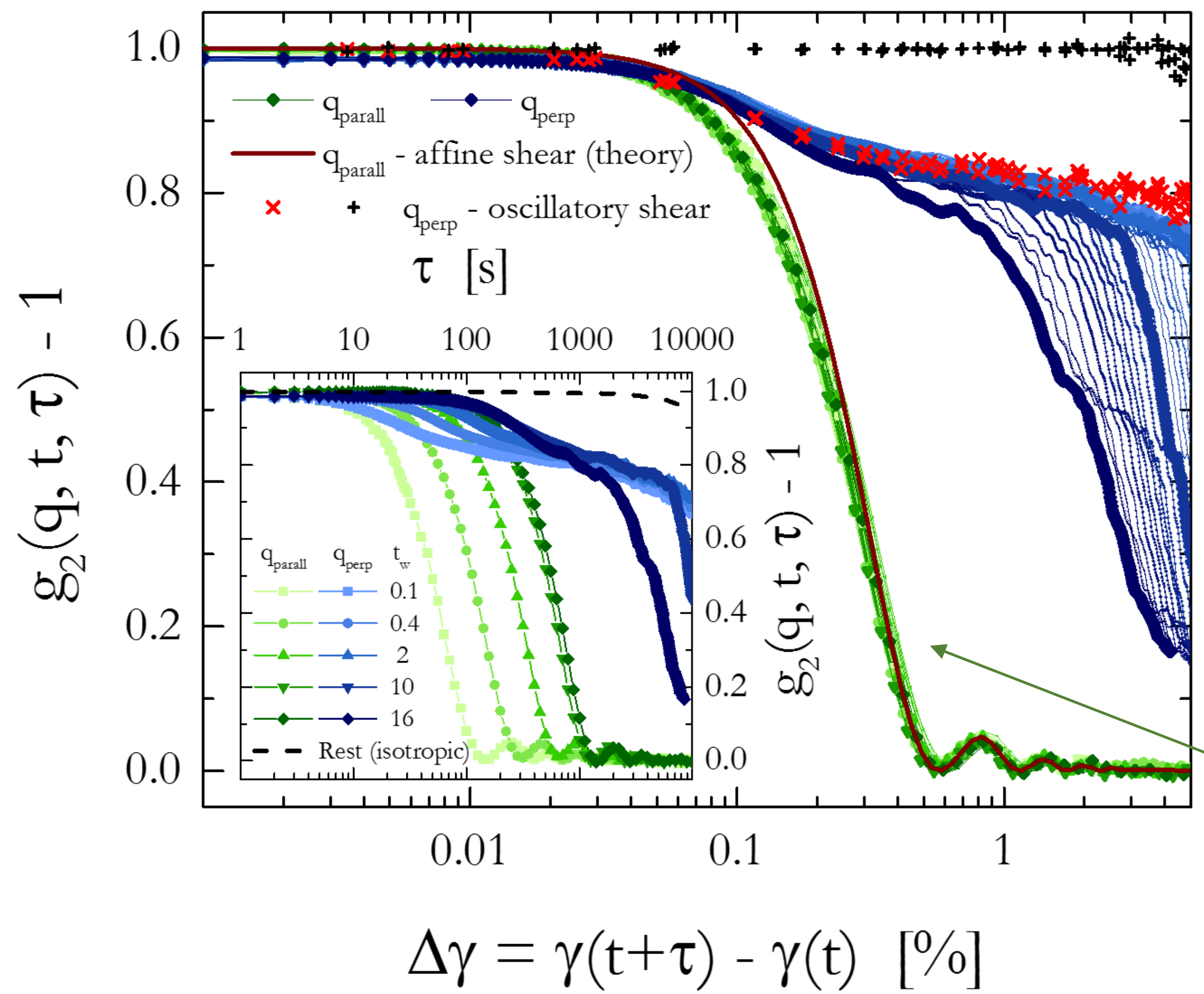
Intensity correlation function $\propto \left| \sum_{j,k} e^{i\vec{q}\cdot[\vec{r}_j(t)-\vec{r}_k(t+\tau)]} \right|^2$



fixed q = 3.1 μm^{-1}

Microscopic dynamics under creep

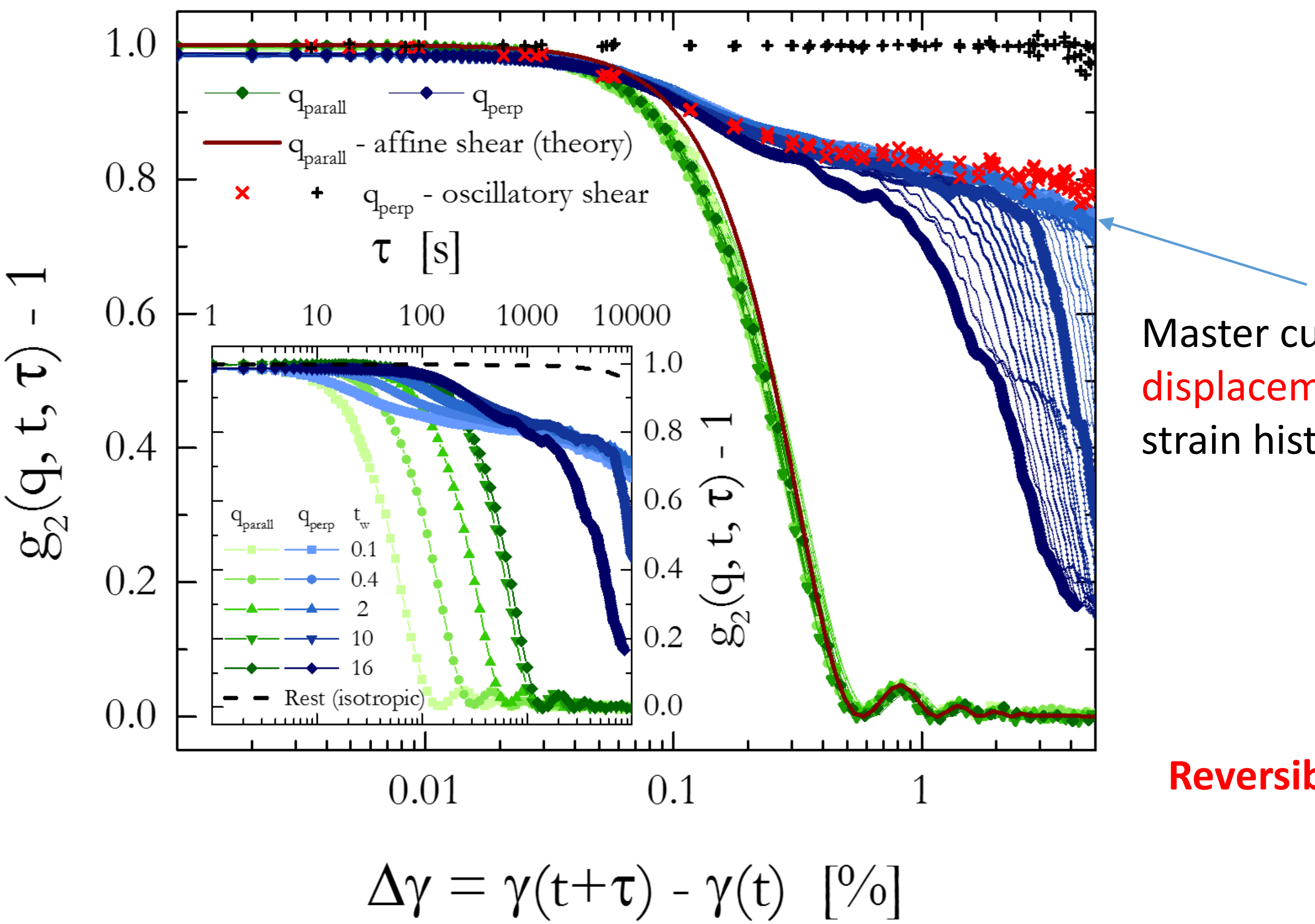
Intensity correlation function $\propto \left| \sum_{j,k} e^{i\vec{q}\cdot[\vec{r}_j(t)-\vec{r}_k(t+\tau)]} \right|^2$



perpendicular to shear direction:
non-affine deformation, plasticity

parallel to shear direction:
affine deformation

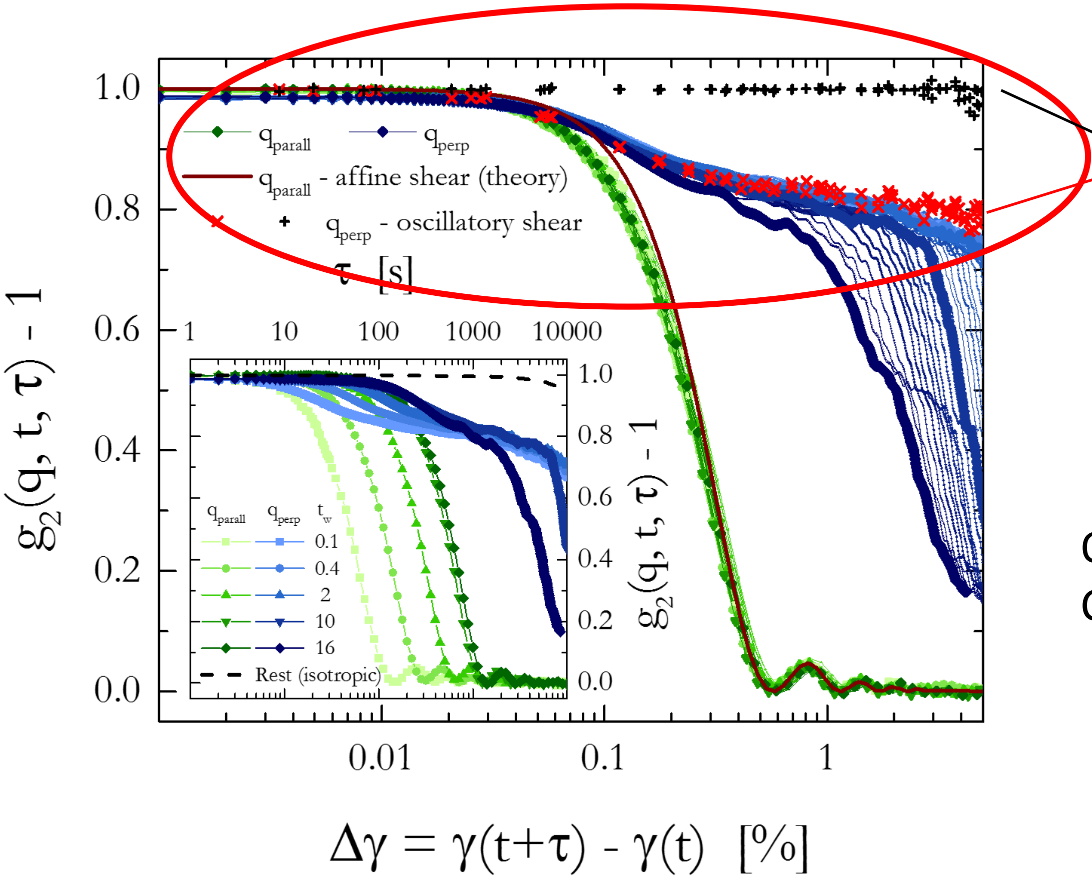
Initial regime ($\gamma \leq 5\%$): reversible?

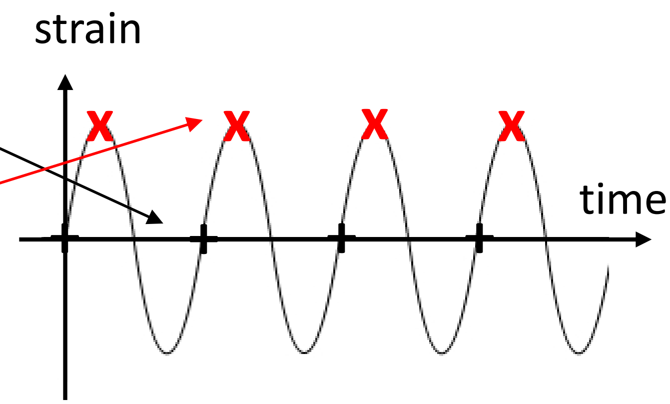


Master curve: non-affine displacements *independent* of strain history

Reversible non-affinities?

Initial regime: reversible non-affine elasticity





Oscillatory experiments:
Confirm reversibility for $\gamma \leq 5\%$

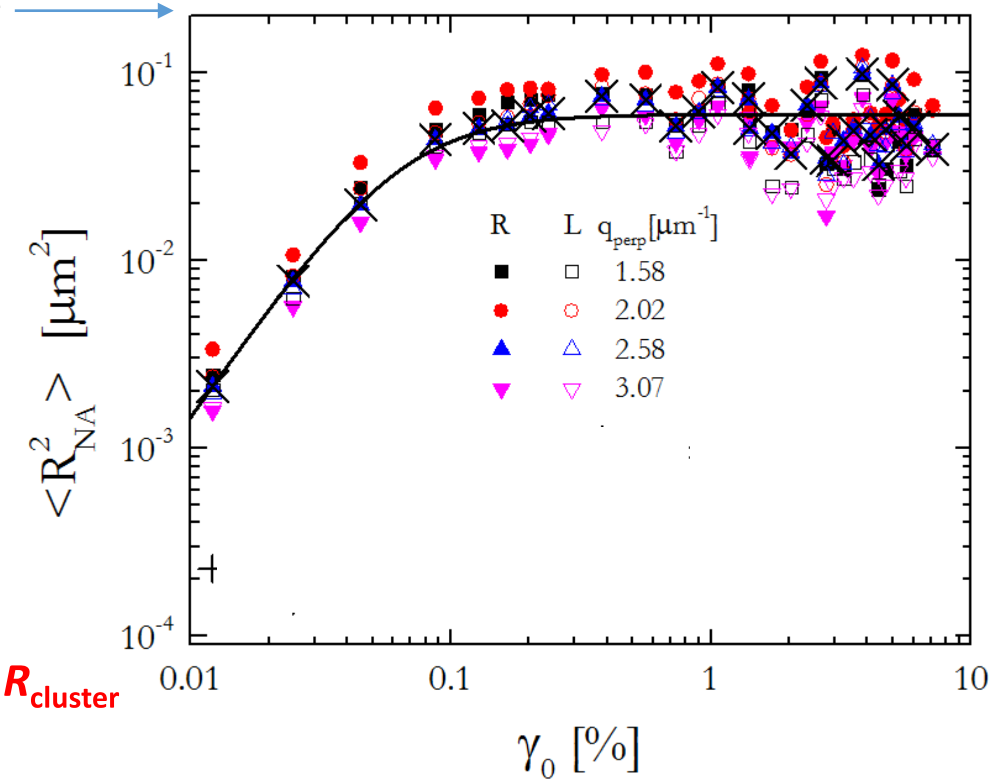
Non-affinity stems from ***G' heterogeneity***

Reversible regime: length scale of *G'* heterogeneity

$$g_2(\gamma) - 1 \approx \exp\left(\frac{-R_{NA}^2(\gamma)}{3} q^2\right)$$

Non-affine msd

cluster size

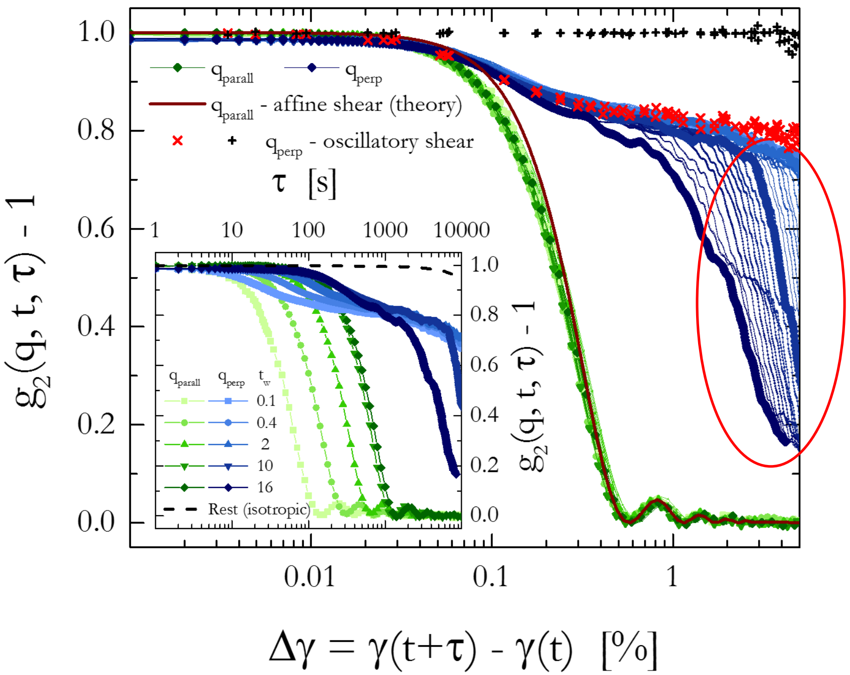


low γ : $R_{NA}^2(\gamma) \sim \gamma^2$ Hook's law
(see also Basu et al. 2011)

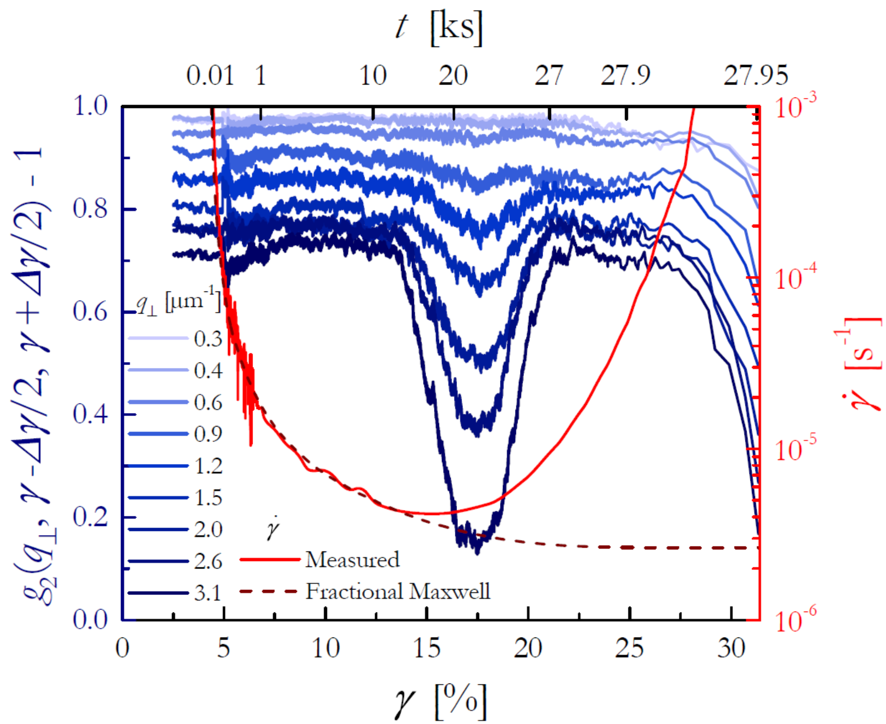
R_{NA}^2 **saturates** close to **cluster size**

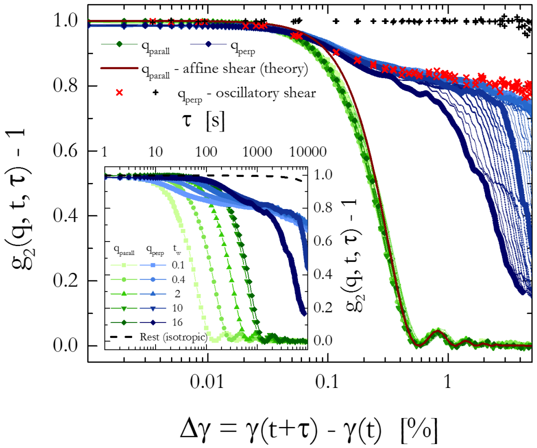
Gel elastically homogeneous beyond ~ $R_{cluster}$

$\gamma \geq 5\%$: plastic (irreversible) rearrangements



Dynamics over a fixed strain increment





Plastic activity

Non-affine dynamics: reversible plastic

$$g_2(q,\gamma,\Delta\gamma) - 1 = R(q,\Delta\gamma) \times P(q,\gamma,\Delta\gamma)$$

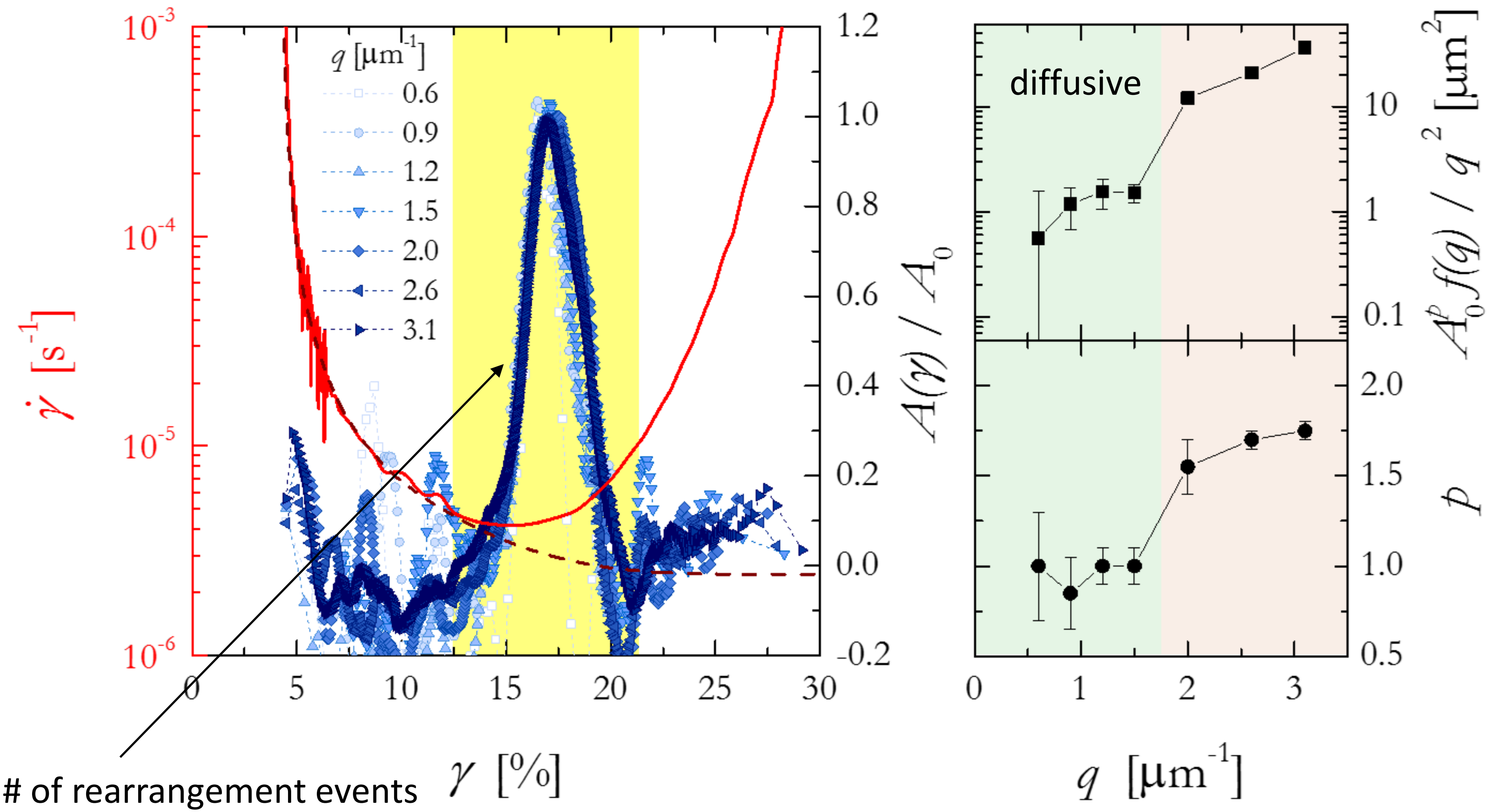
1. Brownian motion: $\exp[-2q^2 D\tau]$
2. Stationary shear-induced diffusion: $\exp[-q^2(\boldsymbol{A}\cdot\Delta\gamma)]$ (**Plastic activity**)
3. Generalize to non-diffusive dynamics: $\exp[-\boldsymbol{f}(\boldsymbol{q})(\boldsymbol{A}\cdot\Delta\gamma)^{\boldsymbol{p}}]$ (**exponent**; **scaling factor**)
4. Generalization to strain dependent plasticity: $A \mapsto A(\gamma)$

$$A\cdot\Delta\gamma \mapsto \int_{\gamma}^{\gamma+\Delta\gamma} A(\gamma')d\gamma'$$

MODEL: $$P(q,\gamma,\Delta\gamma) = \exp\left\{-\boldsymbol{f}(\boldsymbol{q})\left[\int_{\gamma}^{\gamma+\Delta\gamma} \boldsymbol{A}(\boldsymbol{\gamma}')d\gamma'\right]^{\boldsymbol{p}}\right\}$$

Failure precursors in the dynamics of a colloidal gel under creep

Burst of plastic activity precedes failure



# of rearrangement events per unit volume & unit γ increment

Microscopic dynamics of a colloidal gel under creep: Recap

- Initial regime: creep is (microscopically!) **reversible,** non-affinity due to heterogeneity of G'.
- **Dynamic precursor** of failure
- Plastic rearrangerments: **diffusive** at low *q*, additional dynamics at larger *q*

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cnes

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MARIE CURIE ACTIONS

supolen

… you all for your attention!