Figure 1. **Setup of cyclic shear experiment.** (a) Particles are placed into the shear cell, formed by a bottom plate attached to a stepper motor, two side plates in shear direction articulated to the bottom, and another two perpendicular side plates (not shown here). These two side plates are connected to the perpendicular plates by four pivots (two of them are shown) to maintain the shear geometry. The system is slowly sheared by driving the bottom plate by the motor. We define $L = 24d$ and the deformation γL. X-ray tomography scans are performed at $\gamma = 0$ when the motion is stopped. (b) Visualization of a 3D-printed particle with a bumpy surface (BUMP).

Figure 2. **Dynamics of cyclic shear demonstrates absence of caging but pronounced memory effect.** (a) and (b): Mean squared displacement in horizontal directions vs. shear cycle number Δn for the ABS and BUMP systems, respectively. Errors are smaller the the size of the symbols. A universal crossover from sub-diffusion (dashed lines) to normal diffusion is observed, and occurs at the Γ-dependent yielding strain $\Delta\gamma_c$. Panel (b) includes also two trajectories, $\Gamma = 0.05$ and 0.1, using a higher sampling rate (factor of 5 and 10/3 respectively), to validate our measurements with lower sampling rate. (c): Γ-dependent diffusion coefficient D for the two systems. A crossover at $\Gamma \approx 0.1$ is found for the ABS system, but not for the BUMP system. (d) and (e): Memory effect (M is defined in Eq. (1)) as a function of $\Delta\gamma$ for both systems from which we define the strain $\Delta\gamma_M$ (triangles) corresponding to the vanishing of M. Color codes are the same as in panels (a) and (b) and errors are estimated to be 0.02. In certain cases $\Delta\gamma_M$ is estimated from a linear extrapolation of $M(\Delta\gamma)$. (f): For both systems $\Delta\gamma_c(\Gamma)$ tracks $\Delta\gamma_M(\Gamma)$ and one observes for the ABS system again a crossover at $\Gamma \approx 0.1$. The data of $\Gamma = 0.03$ for the BUMP systems are not shown due to the poor statistics. Error bars represent the standard deviations from different realizations for ABS, and fitting uncertainty for BUMP.

Figure 3. **Self-part of Van Hove function is a superposition of Gumbel law and excess exponential tail.** Panels (a)-(c) and (d)-(f) refer to ABS and BUMP systems, respectively, with the same color codes as in Figs. 2(a) and (b), respectively. The particle displacement is expressed in terms of the normalized distance $d_x = |\delta x|/\sqrt{\langle \delta x^2 \rangle}$. For each system the data is presented for $\Delta\gamma = 0.25\Delta\gamma_c(\Gamma)$, $\Delta\gamma_c(\Gamma)$, and $3\Delta\gamma_c(\Gamma)$. Solid and dotted curves are, respectively, the Gumbel [G^g, Eq. (2)] and Gaussian distributions, showing that G_s is non-Gaussian even at small $\Delta\gamma$. For both systems the shape parameter λ of the Gumbel distribution is independent of $\Delta\gamma$ and Γ, and it depends only weakly on the system (see main text). Insets show the ratio G_s/G^g and one concludes that the excess exponential tail with respect to the Gumbel law becomes notable if $d_x 2$ for ABS and $d_x 3$ for BUMP.

Figure 4. **Dynamical heterogeneity shows a peak/crossover with increasing strain for the ABS/BUMP system.** (a) and (b): Magnitude of the excess tail as a function of $\Delta\gamma/\Delta\gamma_c$ obtained by averaging G_s/G^g in the interval $d_x \in [3.5, 4.5]$ for the ABS and BUMP systems, respectively. For the ABS system the average is larger than for the BUMP system at $\Delta\gamma \approx \Delta\gamma_c$, showing that G_s has a more pronounced tail at $\Delta\gamma \approx \Delta\gamma_c$. (c) and (d): Fraction of particles involved in the largest connected cluster (two particles are defined as connected if the center distance is smaller than 1.2 times

their average diameter), among the top 10% mobile particles as a function of $\Delta\gamma/\Delta\gamma_c$. Note that for the BUMP system we have set $\Delta\gamma_c(\Gamma = 0.03) = 1500$. The color codes in (a)/(c) and (b)/(d) are the same as in Figs. 2(a) and (b), respectively.

Figure 5. **Non-Gaussian parameter displays qualitatively different $\Gamma-$dependence for the two systems.** (a) and (b): Non-Gaussian parameter α_2 as a function of $\Delta\gamma$ for the ABS and BUMP systems, respectively (with the same color codes as in Figs. 2(a) and (b)). Solid curves show a fit $\alpha_2(\Delta\gamma) = B\cdot\exp[-(\Delta\gamma/\Delta\gamma_g)^\theta]$, with $\theta = 1$ (exponential) and 0.5 (stretched exponential) for ABS and BUMP, respectively. (c) and (d): Associated fit parameters as a function of Γ, demonstrating that $\Delta\gamma_c(\Gamma)$ and $\Delta\gamma_g(\Gamma)$ are proportional to each other. Insets: Γ-dependence of $B(\Gamma)$. Error bars represent the standard deviations from different realizations for ABS, and fitting uncertainty for BUMP.

Figure 6. **Overlap function for the ABS system reveals the change in microscopic dynamics at yielding.** (a)-(c): Overlap function distribution $P(Q)$ as a function of $\Delta\gamma/\Delta\gamma_c$ for $\Gamma = 0.05$, 0.1, and 0.2. $P(Q)$ shifts to smaller values as $\Delta\gamma/\Delta\gamma_c$ grows (see legends). (d): $P(Q)$ at the yielding point $\Delta\gamma = \Delta\gamma_c$ shows the presence of two master curves. Inset: The standard deviation of $P(Q)$ versus Γ has a sharp transition at $\Gamma \approx 0.1$. (e): $\langle Q\rangle$ as a function of $\Delta\gamma - \Delta\gamma_c$. The decay is slowest for $\Gamma \approx 0.1$ indicating the presence of a critical slowing down close to a critical point. Inset: Also $\langle Q\rangle$ versus $\Delta\gamma$ shows a slowing down at $\Gamma \approx 0.1$. In (d) and (e) the color codes are the same as in Fig. 2(a).

Figure 7. **Dynamic phase diagram of granular systems with roughness.** (a) and (b) correspond to the ABS and BUMP systems, respectively. For all Γ, the system evolves with increasing $\Delta\gamma$ from a sub-diffusive dynamics (yellow area) to a diffusive dynamics (blue area), with the yielding point at $\Delta\gamma = \Delta\gamma_c$ (symbols). For small particle roughness (ABS) (panel (a)) this yielding resembles a dynamic phase transition for $\Gamma 0.1$ (green solid line), while for larger Γ as well as large particle roughness (BUMP) (panel (b)) one has only a continuous crossover.

Figure 8. **Schematics of how a granular system explores its potential energy landscape.** Due to the particle surface roughness, the PEL has not only a structure on the particle scale d (green line), but also a micro-corrugation with a characteristic size ξ. Starting in the left metabasin (MB) of the PEL, the double arrows indicate the back and forth motion of the system during a shear cycle. (a) The dynamics for small roughness ($\xi \ll d$) shows two regimes depending on whether the system leaves the MB during a cycle (blue arrow) or not (red arrow). (b) The dynamics for large roughness evolves smoothly with Γ since ξ becomes comparable to d.