# Abstracts – Contributed Talks

**M.Baity-Jesi**[1], C.P. Goodrich, S.R. Nagel, J.P. Sethna, A.J. Liu
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*"Shear jamming in frictionless soft sphere packings"*

Athermal frictionless spheres jam as their density is increased [1]. A few years ago, it was shown that at sufficiently high density, an initially unjammed system of frictional particles can jam under shear [2]. Very recently it has been shown that at least in finite-size systems shear jamming is possible also in the absence of friction [3].
Here, we study shear jamming in packings of frictionless particles, and we contextualize it within a general scaling theory for the jamming transition. We find that some of the critical exponents at the transition differ from regular jamming.
By rewriting basic observables as a function of stress correlation functions between contacts, we see that shear-jammed packings are structurally different from regular jammed packings, exhibiting long-range correlations along the direction of shear. Depending on the used protocol, these states should be achievable also in the thermodynamic limit.

[1] A. J. Liu and S. R. Nagel, Annu. Rev. Condens. Matter Phys. 2010. 1:347–69.
[2] D. Bi, J. Zhang, B. Chakraborty and R. P. Behringer, Nature 480, 355–358 (2011).
[3] Thibault Bertrand, Robert P. Behringer, Bulbul Chakraborty, Corey S. O'Hern, and Mark D. Shattuck, Phys. Rev. E 93, 012901(2016)

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**Stefan Boettcher**
Emory University, USA

*"Record Dynamics as the Origin of Aging"*

We provide a unified description of "aging", the increasingly sluggish dynamics widely observed in the jammed state of disordered materials, in terms of record dynamics. Structural evolution in aging materials requires ever larger, record-sized rearrangements in an uncorrelated sequence of intermittent events (avalanches or quakes). According to record statistics, these (irreversible!) rearrangements occur at a rate ~1/t. Hence, in this log-Poisson statistics, the number of events between a waiting time t_w and any later time t integrates to ~ln(t/t_w), such that any observable inherits the t/t_w-dependence that is the hallmark of pure aging. Based on this description, we can explain the relaxation dynamics observed in a broad range of materials, such as in simulations of low-temperature spin glasses and in experiments on high-density colloids and granular piles. We have proposed a phenomenological model of record dynamics (N Becker, et. al. Mesoscopic model of temporal and spatial heterogeneity in aging colloids 2014, *J. Phys.: Condens. Matt.*) that reproduces salient aspects of the experiments, for example, persistence, intermittency, and dynamic heterogeneity. Here, we compare the predictions of the model with the data available from experiments by Yunker, et. al. (P Yunker, et. al. Irreversible rearrangements, correlated domains, and local structure in aging glasses 2009 *Phys. Rev. Lett.*).

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**Patrick Charbonneau**
Duke University, USA

*"Universal criticality at and around the jamming transition"*

Recent theoretical advances offer an exact, first-principles theory of jamming for frictionless spheres in infinite dimension. I will discuss how this result informs our understanding of the Edwards entropy. The theory also predicts that non-trivial power-law exponent describe the packing structure near jamming and that an anomalous, non-Debye density of states persists well beyond packing. I will present our latest numerical advances assessing these predictions in finite-dimensional systems. Remarkably, many aspects are robustly preserved for spatial dimensions $d\geq2$. Constructing isostatic jammed packings with high accuracy further allows us to identify the small deviations from these predictions and their structural origin, such as localized buckling excitations.

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Shear-induced ordering and shear-thinning in dense soft particle suspensions

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We investigated shear-induced micro-structural changes in dense monodisperse soft particle emulsions and the effects on the fluid dynamic properties. Previous experiments on droplet emulsions have found that at very high volume fractions (0.6 and higher), small oscillatory shear induces the formation of hexagonal packed microstructures [1]. We employed a coarse-grained Langevin dynamics method to model the particle dynamics and deformation corresponding to oil-in-water emulsions with volume fractions ranging from 0.45 to 0.65. The fluid motion and full particle-fluid coupling are determined with a hybrid lattice Boltzmann - immersed boundary methods. We found that the collective particle structure factor is amorphous and isotropic at rest. With the application of low shear rate simple shear flow, the structure factor exhibits six secondary peaks corresponding to hexagonal closed packing for dense emulsions. At high shear rates, the microstructural is "melted" due to strong particle deformations. In addition, we also found the change in the emulsion viscosity corresponds to the changes in microstructure. Unlike hard colloidal suspensions, we found no dynamic arrest in the soft particle system. Instead, the viscosity increases by a factor of two to five as the volume fraction increases from 0.45 to 0.65, depending on the shear rate. This change is similar to that observed for red blood cells in blood [2] and has also been found in oil-in-water emulsions.

[1] J.-R. Huang and T.G. Mason, Soft Matter, 5, 2208 (2009)

[2] K. M. Jan, S. Chien and J. T. Bigger, Circulation, 51, 1079 (1975)

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**Gary W. Delaney**
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*"Understanding the Role of Particle Shape and Friction in Determining the Internal Structure and Stability of Jammed Granular Matter"*

Particle shape and friction are critical factors controlling the behaviour of granular systems, playing a key role in determining both their internal static structure and their mechanical stability. We explore this role via an extensive set of three-dimensional Discrete Element Method simulations and analyses of jammed granular packings. We consider a broad range of particle shapes from perfectly spherically to highly elliptical and cuboidal particles, and the full range of particle friction coefficient values from perfectly smooth to infinite inter-particle friction. We demonstrate how the bulk structural properties in a jammed granular system can be manipulated by varying the shapes [1,2], surface properties and mixture ratios of different species of grains, making it possible to generate systems with desired and tunable properties. This can include packing density, flowability, energy dissipation, stability and resistance to shear. We employ a number of local and global geometric measures to quantify the internal granular structure including analysis of the contact network [1,3], Voronoi diagram [2,4], and geometrical order measures (both spatial and orientational) at the local and bulk scales.

1 Delaney G W, and Cleary P W. The packing properties of superellipsoids. *Europhysics Letters*, 2010, 89, 34002.
2 Schaller F M, Neudecker M, Saadatfar M, Delaney G W, Schroder-Turk G E, and Schroter M. Local origin of global contact numbers in frictional ellipsoid packings. *Physical Review Letters*, 2015, 114, 158001.
3 Stenzel O, Salzer M, Schmidt V, Cleary P W, Delaney G W. Quantitative structural analysis of simulated granular packings of non-spherical particles. *Granular Matter, 2014,* 16, 457-468.
4 Schaller F M, Kapfer S C, Hilton J E, Cleary P W, Mecke K, Michele C M, Schilling T, Saadatfar M, Schröter M, Delaney G W and Schröder-Turk G E. Non-universal Voronoi cell shapes in amorphous ellipsoid packs. *Europhysics Letters*, 2015, 111, 24002.

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**Giacomo Gradenigo**
UJF Grenoble

*"Effective thermodynamics for a driven athermal system with dry friction"*

Which are the situations where an effective thermodynamic theory works even in the lack of thermal equilibrium? Which is the meaning of "temperature" for an out-of-equilibrium system?
I present here the study of a driven athermal system, which is a one-dimensional chain of masses connected by harmonic springs and subject to Coulomb dry friction, where answers to the above questions can be provided. The main result of this investigation is the evidence that, even in presence of a driven dissipative dynamics, the probability to visit the mechanically stable configurations of this system fulfills the Edwards conjecture[1]: an effective equilibrium description for frictional systems is possible. Such an evidence is obtained by comparing the exact calculation of the partition function of our system, done by means of transfer matrix approach, to the numerical simulations of the driven dissipative dynamics. Interestingly enough, the existence of a critical point at infinite effective temperature is pointed out[1]. Finally, I will show how the prescription of the Edwards thermodynamics can

be generalized to the situation where the viscous friction is added on the top of dry friction[2].

[1] G. Gradenigo, E. E. Ferrero, E. Bertin, J.-L. Barrat, Phys. Rev. Lett. 115, 140601 (2015).
[2] G. Gradenigo, E. Bertin, J.-L. Barrat, in preparation.

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**Yoav Kallus**
Santa Fe Institute, USA

*"Do non-spheres always pack more densely than spheres?"*

Stanislaw Ulam reportedly conjectured that spheres are the worst case for the optimal packing density among convex solids. The conjecture is curious because the same doesn't happen in 2D. However, I proved spheres to be a local minimum of optimal packing density in the space of convex shapes. Similar techniques also show that higher dimensional spheres are not local minima, that regular heptagons are a local minimum in 2D, and, most relevant to the present meeting, that spheres are a local minimum of the random packing density in any dimension.

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## Low-frequency vibrational modes in disordered solids

**Edan Lerner**[1], Gustavo Düring[2], and Eran Bouchbinder[3]

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[2]Facultad de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
[3]Chemical Physics Department, Weizmann Institute of Science, Rehovot, Israel

Low-frequency vibrational modes play a central role in determining various basic properties of glasses, yet their statistical and mechanical properties are not fully understood. In my talk I will present results from extensive numerical simulations of several model glasses in three dimensions, showing that in systems of linear size $L$ sufficiently smaller than a crossover size $L_D$, the low-frequency tail of the density of states follows $D(\omega) \sim \omega^4$ up to the vicinity of the lowest Goldstone mode frequency. I will further show that the sample-to-sample statistics of the minimal vibrational frequency in systems of size $L < L_D$ is Weibullian, with scaling exponents in excellent agreement with the $\omega^4$ law. We find that the lowest frequency modes are spatially quasi-localized, and that their localization and associated quartic anharmonicity are largely frequency-independent. Finally, I will discuss the effect of preparation protocols and dimensionality on the low-frequency modes, and relate their statistics to a number of glassy lengthscales.

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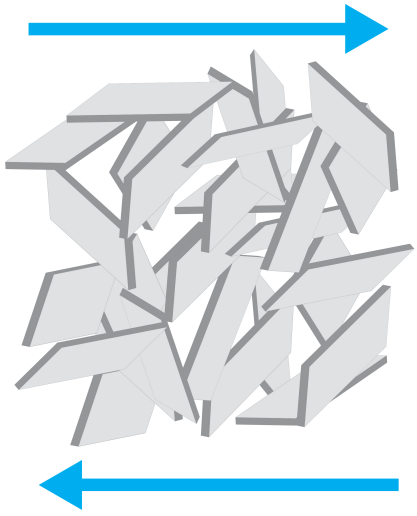
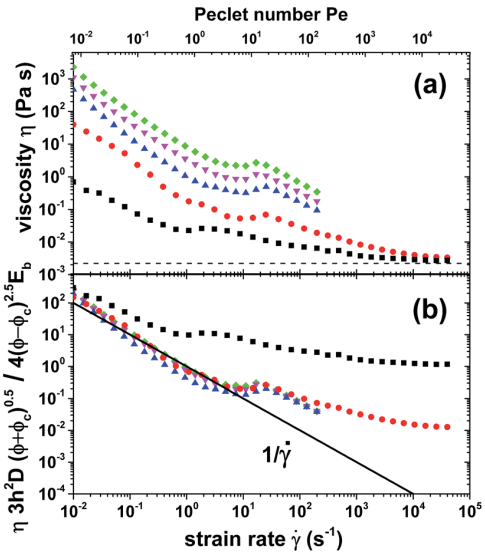
S. Barwich, J. N. Coleman, **M. E. Möbius**
School of Physics, CRANN, Trinity College Dublin, Dublin 2, Ireland

*"Yielding and flow of jammed, high aspect ratio graphene platelets"*

Micron-sized graphene platelets suspended in surfactant-free NMP solvent are an excellent experimental model system to probe jamming of particles with extremely high aspect ratios of around ~1000. We probe the microstructure of these dense suspensions of weakly-interacting, graphene platelets by measuring their viscoelastic properties at various concentrations beyond the jamming transition [1]. We developed a model that relates the yield strain to the mesh size of the microstructure as a function of volume fraction $\phi$. From the yield stress measurements we infer the typical bond energy ($\approx 20 k_b T$) and $\phi$ dependence of the coordination number. These results allow us to express the steady shear viscosity for Peclet number Pe < 10 in terms of the platelet dimensions, bond energy and $\phi$ using a relaxation ansatz which is in excellent agreement with our experimental results.






[1] S. Barwich, J.N. Coleman and M.E. Möbius, *Soft Matter*, 11 (16), 3159-3164

# Structural Properties of High Density Jamming Transition Points

Misaki Ozawa, Ludovic Berthier, and Daniele Coslovich

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It has been widely reported that the jamming transition point $\varphi_J$ is not uniquely determined but shows protocol dependence. Whereas $\varphi_J$ is obtained around 65% in three dimensions by compressing a dilute hard sphere fluid, higher value of $\varphi_J$ is attained when a dense thermally equilibrated fluid is compressed [1, 2].

Recently, we develop a very efficient thermalization setting of a hard sphere system which is composed of continuous polydispersity of the particle diameters $\sigma$ and a non-local swap Monte-Carlo algorithm [3]. This method enabled us to thermalize the hard sphere fluid up to nearly 66%, which is beyond $\varphi_J$ of the system obtained by the compression of dilute states. By compressing these high density equilibrium fluids, we obtain an unprecedentedly wide range of $\varphi_J$, so-called J-line, from around 65% to almost 70%. These denser $\varphi_J$ states also have on average 6 contact number per particle (isostaticity) as shown in Figure 1. Also, the power law singularity near contact in the radial distribution function, $g(r) \sim (r-\sigma)^{-\gamma}$, is observed over the entire J-line with a fixed exponent $\gamma$ whose value is consistent with the prediction of the mean-field theory [4].

Furthermore, we examine local and global structural properties of high density jammed states. Even though the isostaticity and critical behavior are preserved over the entire J-line, the high density jammed states show qualitatively distinct structural properties compared to the lowest jamming transition point, $\varphi_J \simeq 65\%$, which has been widely studied in the past. Especially, we demonstrate the following local and global structural properties.

**Growing local order**

Even though our jammed configurations are all isostatic, they do differ at the local structure level. We reveal this by a combination of bond-orientational order analysis and Voronoi tessellation [5]. This analysis detects growing icosahedral order with increasing $\varphi_J$ and shows no signs of crystallization in our configurations.

**Disturbing the hyperuniformity**

Hyperuniformity, which corresponds to vanishing of the density (or volume fraction) fluctuations at long wavelengths is believed to be one of the characteristic properties of the jamming transition point [6]. We analyze the two body correlation function of the volume fraction to examine the hyperuniformity in our system. We observe excitations at small wavenumbers which disturb the hyperunifromity at the high density jammed states. Also, these excitations increase with increasing $\varphi_J$.

**Suppression of the finite size effect**

It has been argued that the jamming transition is a phase transition which occurs at the thermodynamic limit $N \to \infty$. Also, several length scales diverging at $\varphi_J$ are well characterized as a consequences of the isostaticity of the system [7]. However, the length scale which causes finite size effects at the jamming transition is not yet understood. We study finite size effects for two protocols, compression of dilute and of dense fluids. Interestingly, we find that finite size effects are significantly suppressed by the protocol using compression of the dense fluid. This observation implies that the length scale causing finite size effects is not related to the isostaticity of the system. Instead we discuss the mechanism of the finite size effect of the jamming transition using an analogy with the potential energy landscape thermal systems.

## References

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[4] Patrick Charbonneau, Jorge Kurchan, Giorgio Parisi, Pierfrancesco Urbani, and Francesco Zamponi. Fractal free energy landscapes in structural glasses. *Nature communications*, 5, 2014.

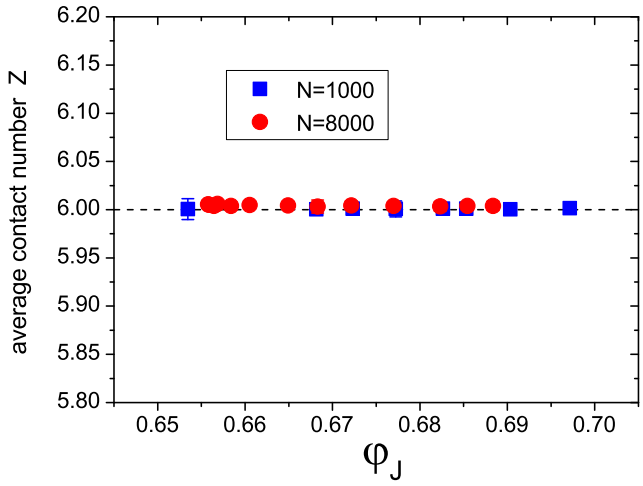


Figure 1: The averaged contact number $Z$ as a function of the jamming transition density $\varphi_J$. The horizontal dashed line corresponds to the isostatic consition, $Z = 2d$, where $d = 3$ is the spatial dimensions.

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[7] Carl P Goodrich, Wouter G Ellenbroek, and Andrea J Liu. Stability of jammed packings i: the rigidity length scale. *Soft Matter*, 9(46):10993–10999, 2013.

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## Determining the Force-Law in "Static" Amorphous Solids from a Visual Image

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Given an athermal and amorphous packing of particles (for example athermal glasses, colloids and granular systems), the conditions of mechanical equilibrium are not sufficient for determining all the inter-particle forces: there are many more forces than equations and the the resulting linear system is under-determined, which poses a difficulty for studying phenomena such as jamming and force chains. We propose a solution of this long-standing problem for amorphous solids by expanding the inter-particle normal force-laws in a Laurent series of the inter-particle distances, so that the number of coefficients is much smaller that the number of constraints. A visual providing the particle positions in addition to a measurement of the pressure is then all that is required to solve the resulting linear problem [1]. As an example, the method is shown to accurately recover the force-law in an athermal packing of particles with Lennard-Jones interactions. Quite remarkably, this new method can also be employed to correct the unavoidable experimental errors in measured positions, which not only improves our own results, but is also expected to benefit many experiments in the field. Possible extensions of this procedure to thermal systems, with the aim of defining an effective potential for the study of stability and soft excitations in thermal glasses, both Lennard-Jones and Hard Sphere, are currently under development.

[1] O. Gendelman, Y. G. Pollack and I. Procaccia, Phys. Rev. E. **93**, 060601(R) (2016).

# A stochastic approach to mechanics of jammed granular materials

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The microscopic origin of *mechanical responses of jammed granular materials* is the complicated restructuring of force-chain networks. The restructuring of force-chains is caused by the irreversible rearrangements, i.e. *non-affine displacements*, of constituent particles. In addition, there are re-combinations of force-chain networks, where force-chains are either generated or broken, i.e. *closing or opening contacts*, during deformations, which makes it further difficult to model constitutive relations for jammed granular materials.

To understand mechanics of jammed granular materials, we have proposed a stochastic method from a point of view of non-equilibrium statistical mechanics. At microscopic scale, the mechanical properties are determined by force-chain networks (**figure**), where any macroscopic quantities (e.g. stress tensor) can be deduced from the *probability distribution functions* (PDFs) of inter-particle forces. During quasi-static deformations, the PDFs change (**figure**) as force-chains are randomly restructured with the closing and opening contacts. Thus, we first generalized force-chain networks by using the *Delaunay triangulations* to include not only the particles in contacts, but also the nearest neighbors without contacts. Then, we introduced a *master equation* for the PDFs, where *transition rates* in the master equation capture all kinds of restructuring and re-combinations of force-chain networks.

To clarify the statistical property of the restructuring of force-chains, we measured the transition rates, or *conditional probability distributions* (CPDs) of forces, by MD simulations. Applying isotropic (de)compressions to jammed granular materials, we found that the CPDs were *symmetric* around mean forces and were *self-similar* with respect to a dimensionless parameter, $\gamma = \delta\phi/(\phi - \phi_J)$, defined as the ratio of applied strain to the distance from the jamming point. We also found that the deviation from affine deformation and the width of the CPDs were linearly scaled by the dimensionless parameter, implying that the strength of *non-affine deformations* and *spatial correlations of forces* increase as the system approaches jamming transition. The evolution of the PDF was perfectly described by the solution of the master equation (**figure**) and the irreversible mechanical responses of jammed granular materials were also explained by the master equation (**figure**) [1].

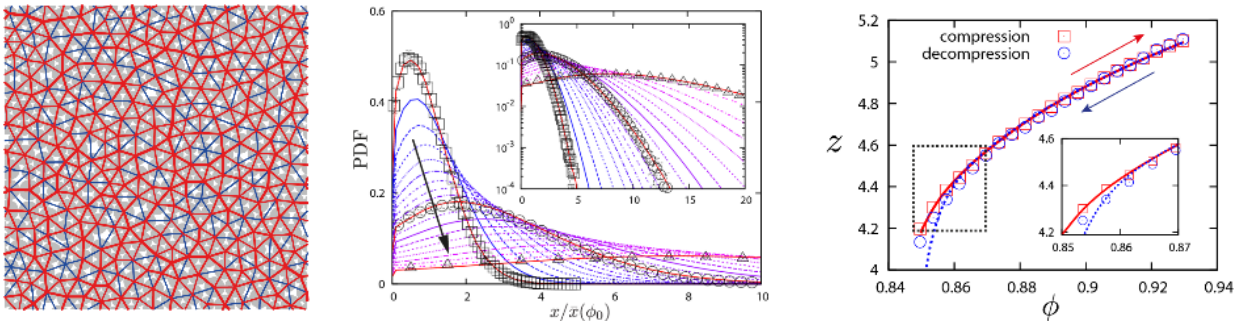


**FIG.**: (Left) *The Delaunay triangulations* of jammed granular materials, where the red solid lines correspond to *force-chains*. (Middle) The evolution of the PDF of forces obtained from MD simulations (open symbols) and the master equation (lines). (Right) The evolution of *coordination number* obtained from MD (open symbols) and the master equation (lines).

[1] Kuniyasu Saitoh, Vanessa Magnanimo, and Stefan Luding, "*A Master equation for the probability distribution functions of forces in soft particle packings*", Soft Matter **11** (2015) 1253. *Communication*.

# Theoretical analysis of a granular gas experiment: low gravity and granular convection

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April 28, 2016

Granular matter is abundant in the Universe, and with frequency forms systems with ample free spaces between grains, specially under high excitation and/or low-gravity conditions. In its lowest density limit, we have the so-called *granular gas*. For instance, in the Earth, atmospheric conditions create low density granular plumes that can last for months, this having an important impact on the biosphere. Moreover, granular gases are also present in a variety of applications in industry and technology and it is a fundamental area of research in aerospace science (granular dynamics under low-gravity conditions is an active area of interest for NASA's and ESA's projects). Unfortunately, experimental studies on granular gases are scarce in the granular matter literature. Most surprisingly, elaborate and careful theoretical analysis have been developed and not tested in real environments so far. Phenomena like segregation, diffusion, mixing, self-organization, and flow patterns have long been solved theoretically, awaiting for implementation in applications.

Motivated by this, we built a simple set-up (see Figure 0.1) consisting in a vibrated granular gas monolayer . For this experiment, we show the appearance of theory-predicted boundary-induced granular convection.

More specifically, we show that a horizontal temperature gradient, here induced by limiting dissipative lateral walls (DLW), leads always to a granular thermal convection (DLW-TC) that is essentially different from ordinary buoyancy-driven convection (BD-TC). In an experiment where BD-TC is inhibited, by reducing gravity with an inclined plane, we always observe a DLW-TC cell next to each lateral wall. Such a cell squeezes towards the nearest wall as the gravity and/or the number of grains increase. Molecular dynamics simulations reproduce the experimental results and indicate that at large gravity or number of grains the DLW-TC is barely detectable.

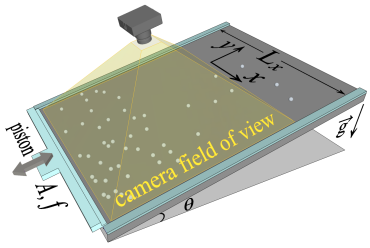


**Figure 0.1:** *Sketch of the experimental setup.*

## References

G. Pontuale, A. Gnoli, F. Vega Reyes, and A. Puglisi, *Thermal convection in granular gases with dissipative lateral walls*, submitted to *Phys. Rev. Lett.*, 2016.

**Alessio Zaccone**
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*"Emergence of power-law creep from the interplay of soft vibrational modes and nonaffine dynamics in athermal jammed solids"*

We studied jammed systems of athermal particles interacting harmonically [1], within the framework of the nonaffine response formalism [2]. Sum rules for the viscoelastic response can be derived and evaluated numerically using the vibrational density of states for the system. Assuming a microscopic (Markovian) friction coefficient, we evaluated the viscoelastic and relaxation moduli for this system, and we also can provide analytical scaling relationships. It is found that soft vibrational modes (around the boson peak frequency) are associated with strongly localized nonaffine rearrangements. This part of the vibrational spectrum is dominated by a random-matrix character which gives rise to characteristic power-laws in the viscoelastic moduli. The loss modulus features a broad alpha-relaxation peak with power-law scaling on both sides. The relaxation modulus, G(t), features power-law creep over a broad time range when the system is close to isostaticity. Interestingly, there is no pre-stress in our system, as all interparticle contacts are initally at equilibrium in the harmonic well. From the theory in its analytical limits, we can conclude that pre-stress is not crucial to power-law creep because pre-stress affects only the affine part of the modulus, whereas the relaxation is controlled by the nonaffine contribution. We can show that pre-stress does not affect the nonaffine (relaxational) part of the response to a significant extent. In conclusion, our approach is able to trace back the power-law creep in granular jammed matter to power-law features of the vibrational density of states at the boson peak frequency, where wave propagation is dominated by random-matrix behaviour (hence the power-law scaling [3]).

[1] Milkus and Zaccone, Phys. Rev. B (2016). [2] Lemaitre and Maloney J. Stat. Phys. (2006); Zaccone and Scossa-Romano, Phys. Rev. B (2011). [3] Franz, Parisi, Urbani, Zamponi, PNAS (2015).