

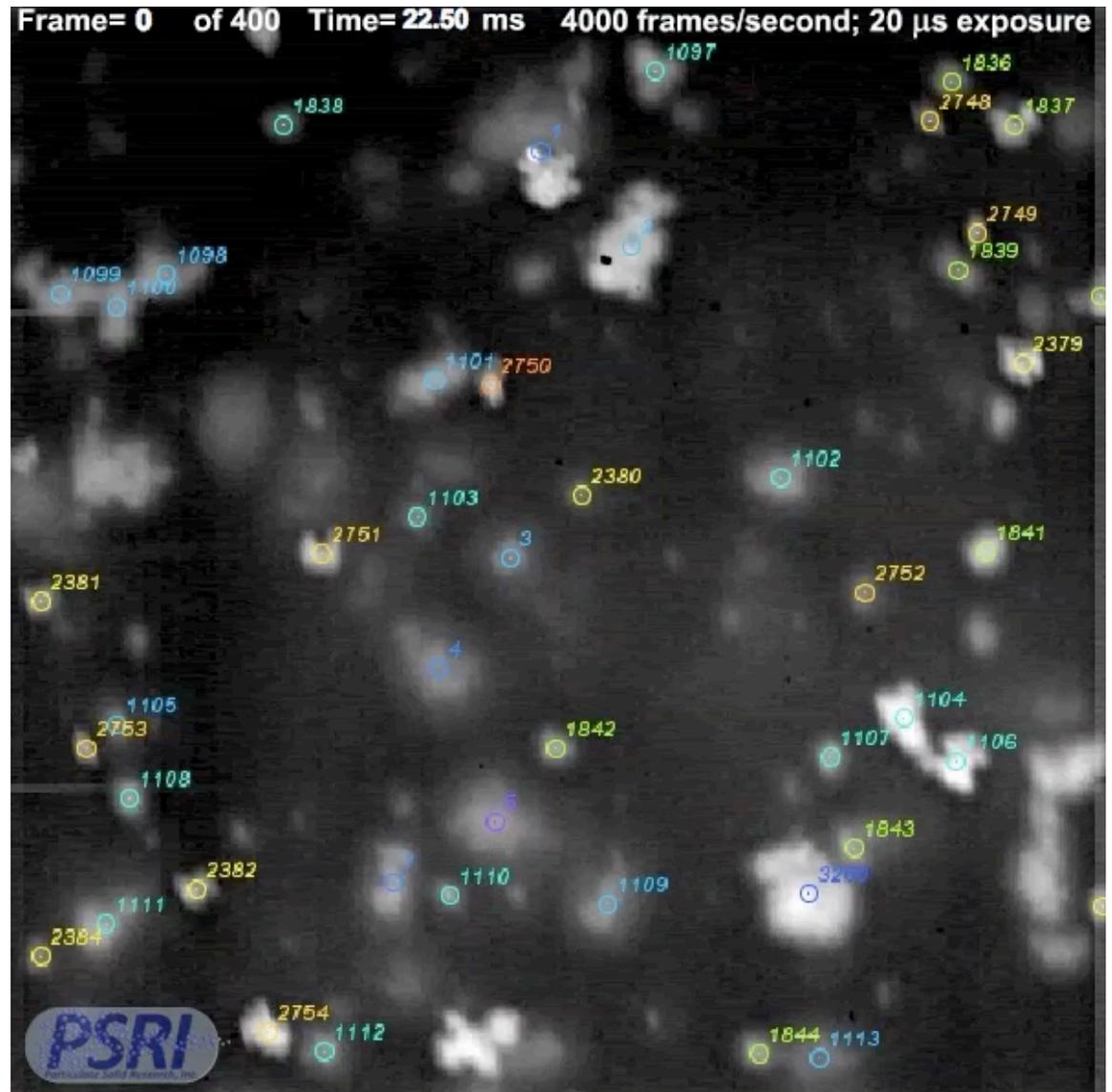
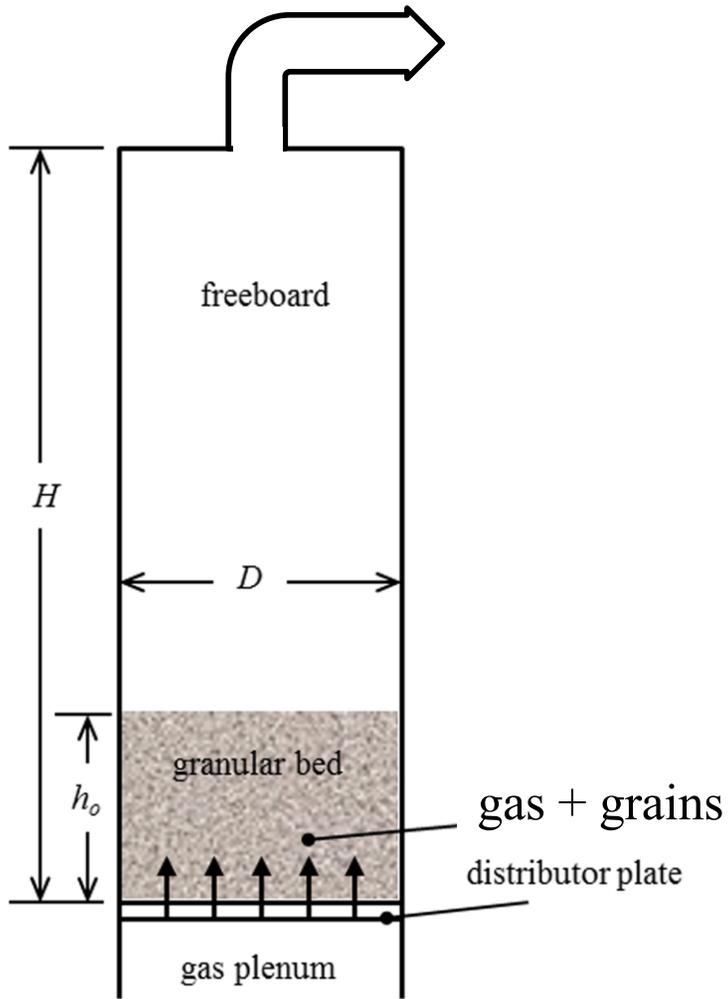
Electrostatics: Contact Charging in Granular Materials

Heinrich Jaeger

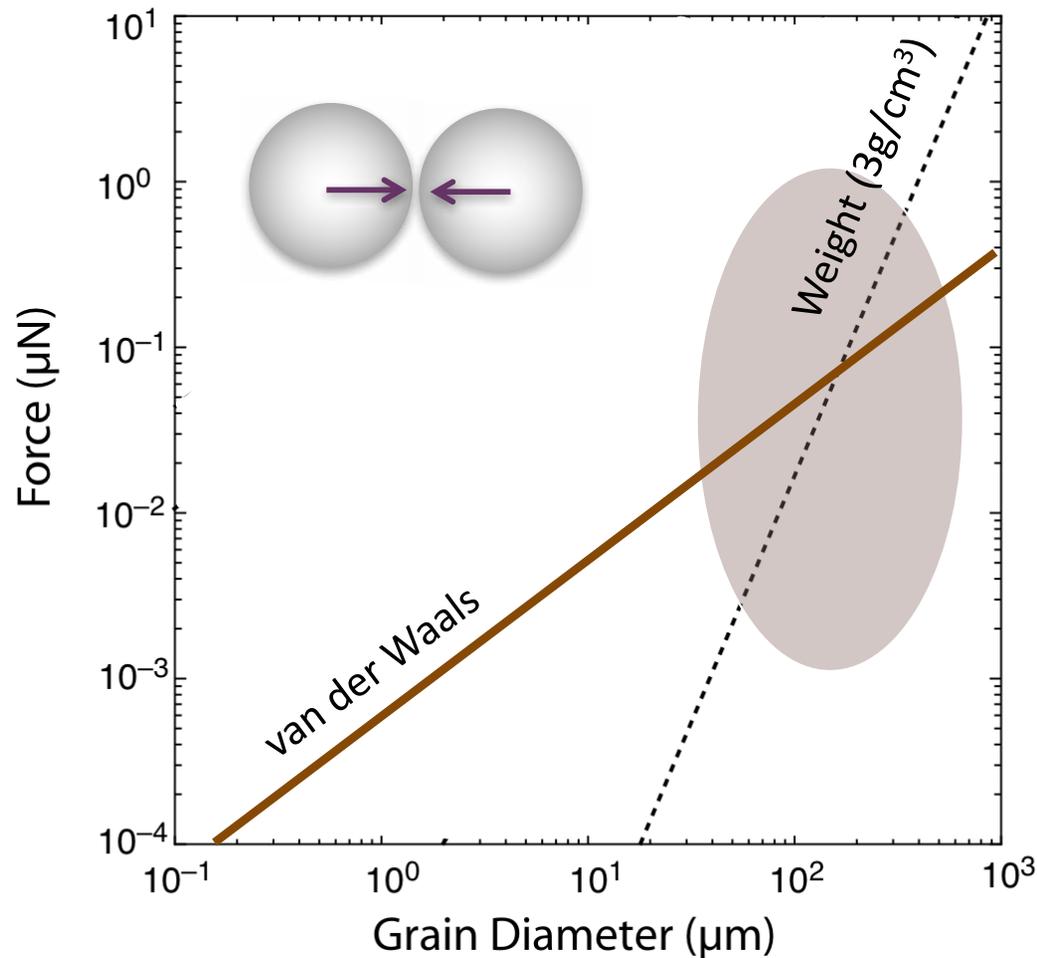
University of Chicago

<http://www.Jaegerlab.com>

Polyethylene clumps in freeboard region

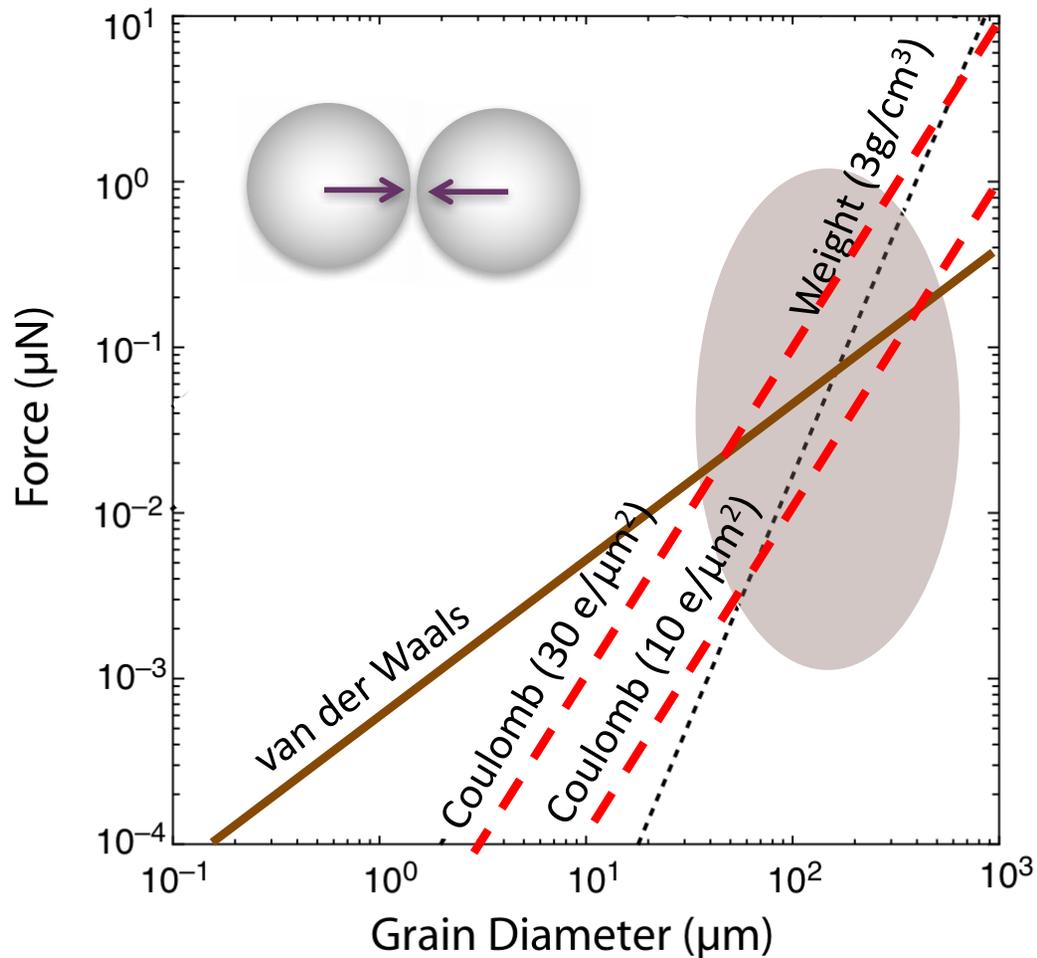


Attractive Interactions



- dry grains, freely flowing
- no liquid bridges
- vd Waals-type forces include all short-ranged (nm) adhesion

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- no liquid bridges
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Note: $30 \text{ e}/\mu\text{m}^2$ corresponds to one extra electronic charge per $\approx 30,000$ surface atoms

Triboelectric Series

Wilcke (1759).	Faraday (1840).	Jamin and Bouty's 'Physique' (1891).	Shaw (1917).
Glass Wool Quills Wood Paper Ground glass Pb Sulphur Metals	Cat's fur Wool Quills Flint glass Cotton Linen Silk Hand Wood Fe, Cu, Ag, Pb. Sulphur	Cat's fur Glass Wool Feathers Wood Paper Silk Resin Ground glass	Glass. Wool. Cat's fur. Pb. Silk. Paper. Cotton. Wood, Fe. Ground glass. Resin. Cu, Ag. Sulphur.

Shaw, Proc. Royal Society A - Math Phys (1917)

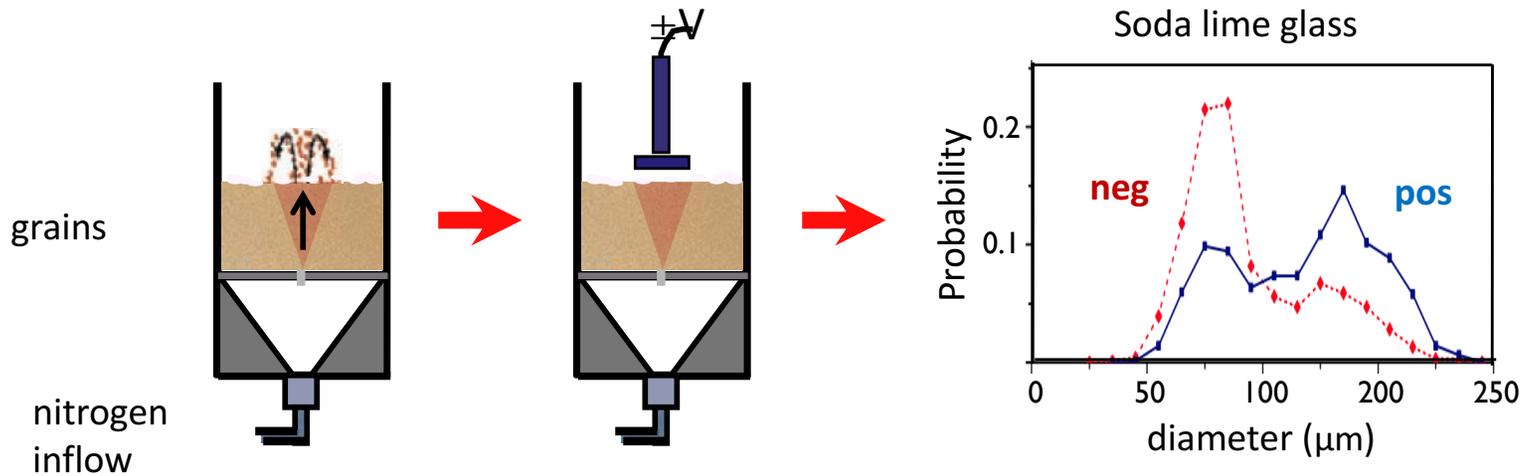
Triboelectric series



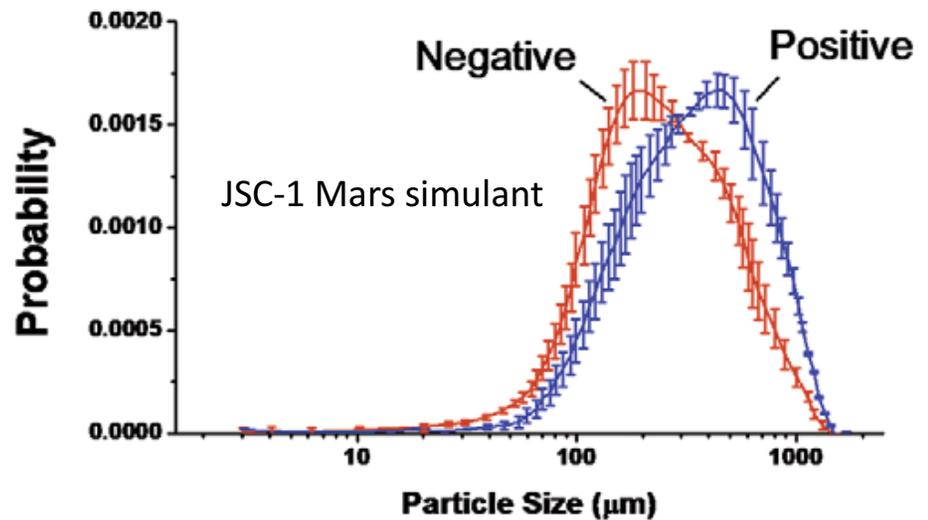
+	Asbestos
	Glass
	Mica
	Nylon
	Wool
	Aluminum
	Paper
	Steel
	Amber
	Hard rubber
	Nickel, Copper
	Brass, Silver
	Gold, Platinum
	Sulfur
	Polyester
	Orlon
	Saran
	Polyurethane
	Polyethylene
	Polypropylene
	Vinyl (PVC)
-	Teflon

C. K. Adams, *Nature's Electricity* (1987)

Net charge also develops with nominally identical particles



K. Forward, D. Lacks, R. Sankaran, Phys. Rev. Lett. 102 (2009)



K. Forward, D. Lacks, R. Sankaran,
Geophys. Res. Lett. 36 (2009)

➤ **What causes particles to develop positive or negative net charge?**

- How is charge generated and transferred?
- How can same material particles become charged?
- What is the charge carrier?
- What controls the shape of the charge distribution?

➤ **How do charged particles aggregate?**

- Do only positively and negatively particles aggregate?
- Do particles with same charge polarity always repel?

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➤ **How do charged particles aggregate?**

- Do only positively and negatively particles aggregate?
- Do particles with same charge polarity always repel?

- ❖ Rich & exceedingly complex set of problems
- ❖ Outcomes often depend on particle level properties (material, size & shape, surface roughness & preparation) as well as environmental/processing conditions (temperature, humidity, gas flow, ...)

Contact charging mechanisms still not well understood

Electron transfer	Lacks et al., Phys. Rev. Lett. 100, 188305 (2008) Liu & Bard, Nature Mat. 7, 505-509 (2008)
Ion transfer	McCarty & Whitesides, Angew. Chemie 47 (2008)
Material transfer	Baytekin et al, Science 333, 308-312 (2011)

Contact asymmetry	
	<ul style="list-style-type: none">• Strain or roughness induced temperature differences• Different number of available sites for charge carriers to transfer into

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Contact asymmetry

- Strain or roughness induced temperature differences
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For reviews see:

- Schein, Science 316, 1572-1573 (2007)
- Matsusaka, Maruyama, Matsuyama, Ghadiri, Chem. Eng. Sci. 65, 5781-5807 (2010)
- Mehrani, Murtomaa, Lacks, J. Electrostatics 87, 64-78 (2017)

Fluidized beds:

Kolehmainen, Ozel, Boyce, Sundaresan, AIChE J. 63, 1872-1891 (2017)

Volcanic eruptions:

Harper, Dufek. J. Geophys. Res.-Atmos. 121, 8209-8228 (2016)

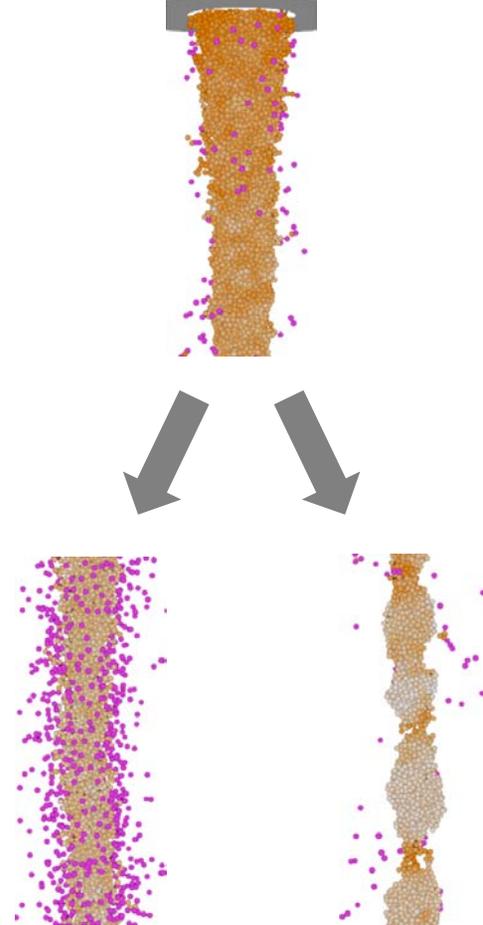
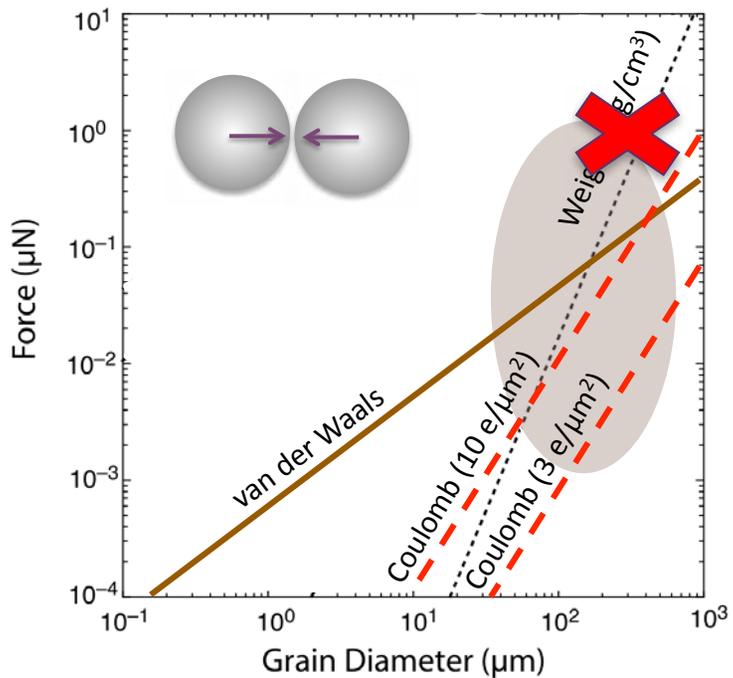
Cosmic grains:

Poppe & Schrapler, A&A 438, 1-9 (2005)

This talk:

1. Measuring particle charge & tracking clustering with granular streams
2. Collisional charging mechanisms
3. Experiments to ascertain the nature of the charge carriers & measure charge transferred/collision

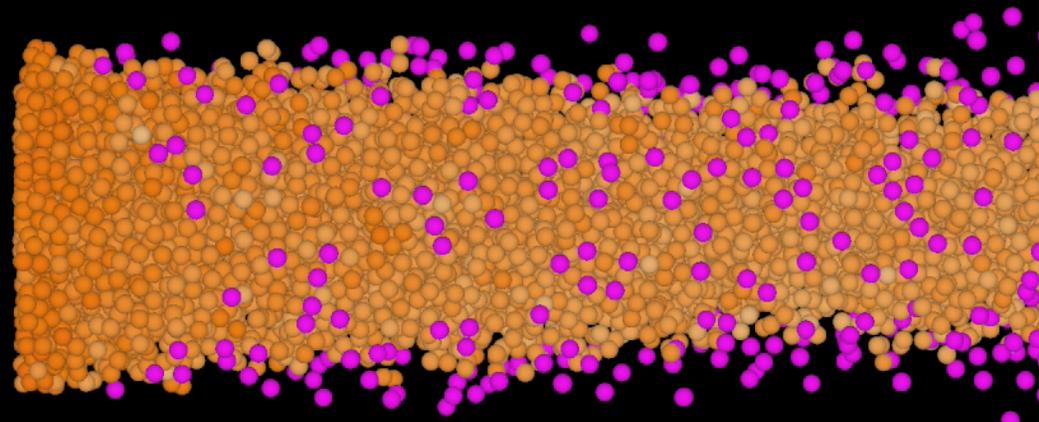
Granular Streams



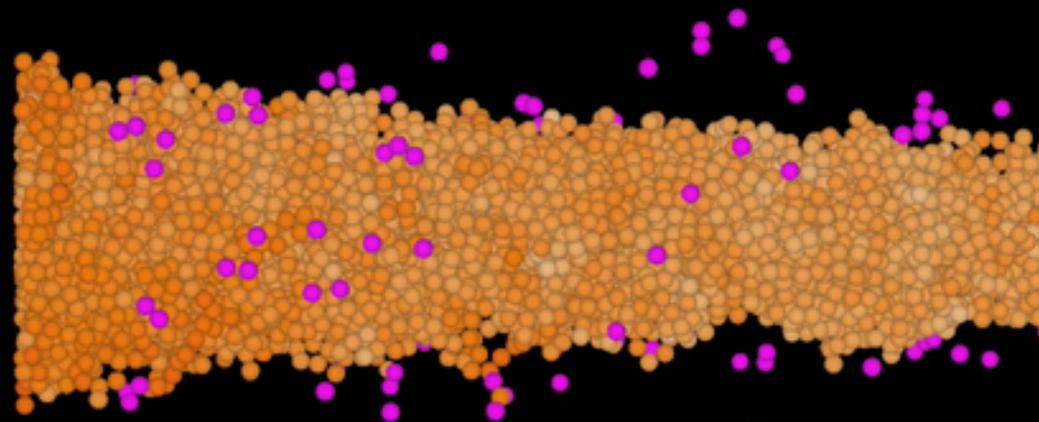
High density region at orifice:
Lots of interactions, “hot”

“cooling” due to inelastic collisions
+
gravitational stretching

Downstream:
Observe structure as direct result of interactions



$d = 200\mu\text{m}$ $D = 3.0\text{mm}$ $F_{coh} = 100 \text{ nN}$ $e = 0.80$



$d = 200\mu\text{m}$ $D = 3.0\text{mm}$ $F_{coh} = 1,000 \text{ nN}$ $e = 0.40$

Dilute streams: Can measure net charge of individual particles

Copper plates at potential difference V

Field E accelerates grains horizontally
obtain net grain charge from horizontal
acceleration $ma = qE$

Acceleration resolution $\sim 8 \times 10^{-3} \text{ m/s}^2$

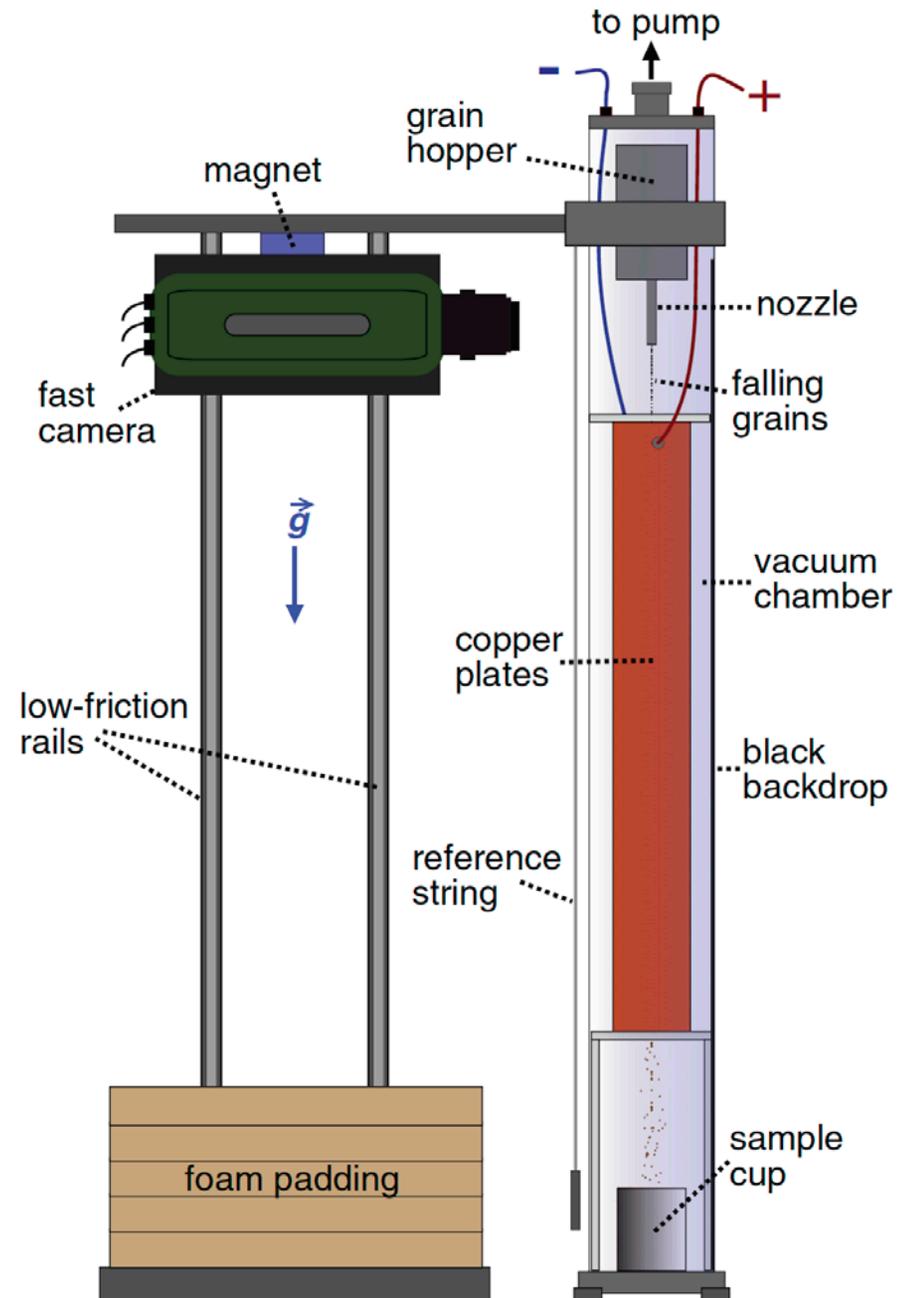
Charge resolution $\sim 6 \times 10^4 |e|$

- **q/m resolution:** $\sim 1|e| / \text{pg}$

- compare to Millikan's: $\sim 250|e| / \text{pg}$

Force resolution $\sim 500 \text{ pN}$

- **competes with AFM**



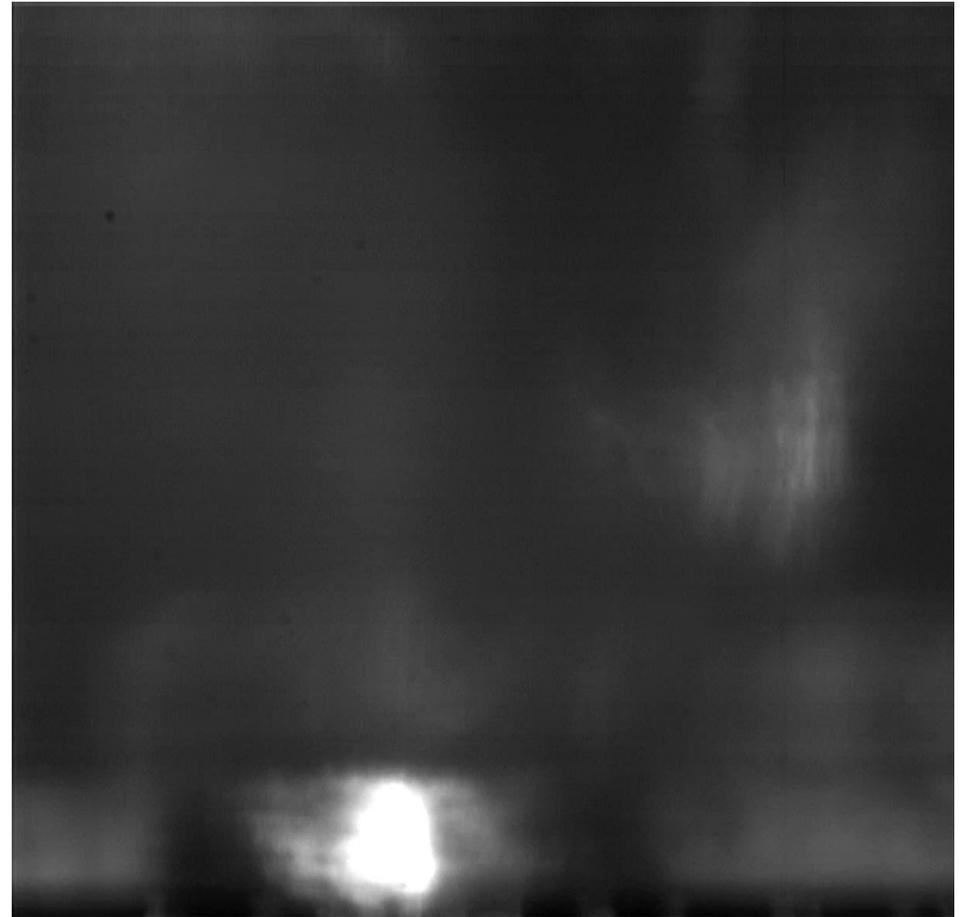
Dilute Streams → Track Individual Particles

- Small nozzle opening ($< 10d$)
- Stream expands after leaving nozzle (insufficient particle density & inelastic collisions to keep stream collimated)

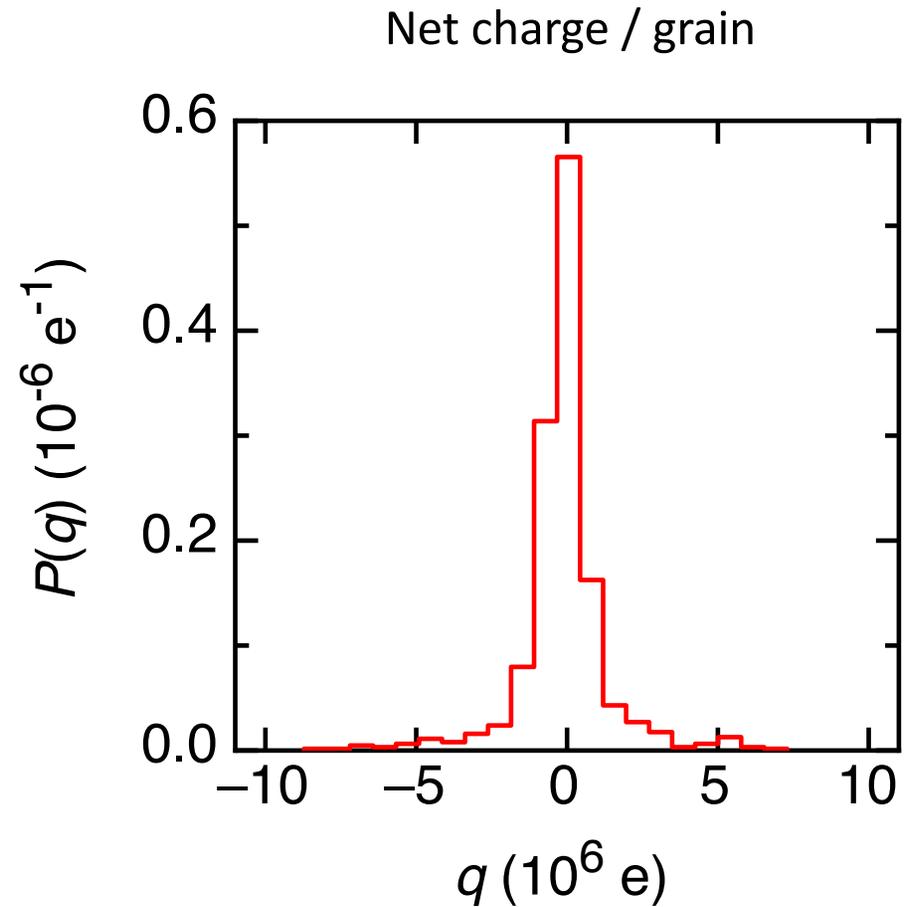
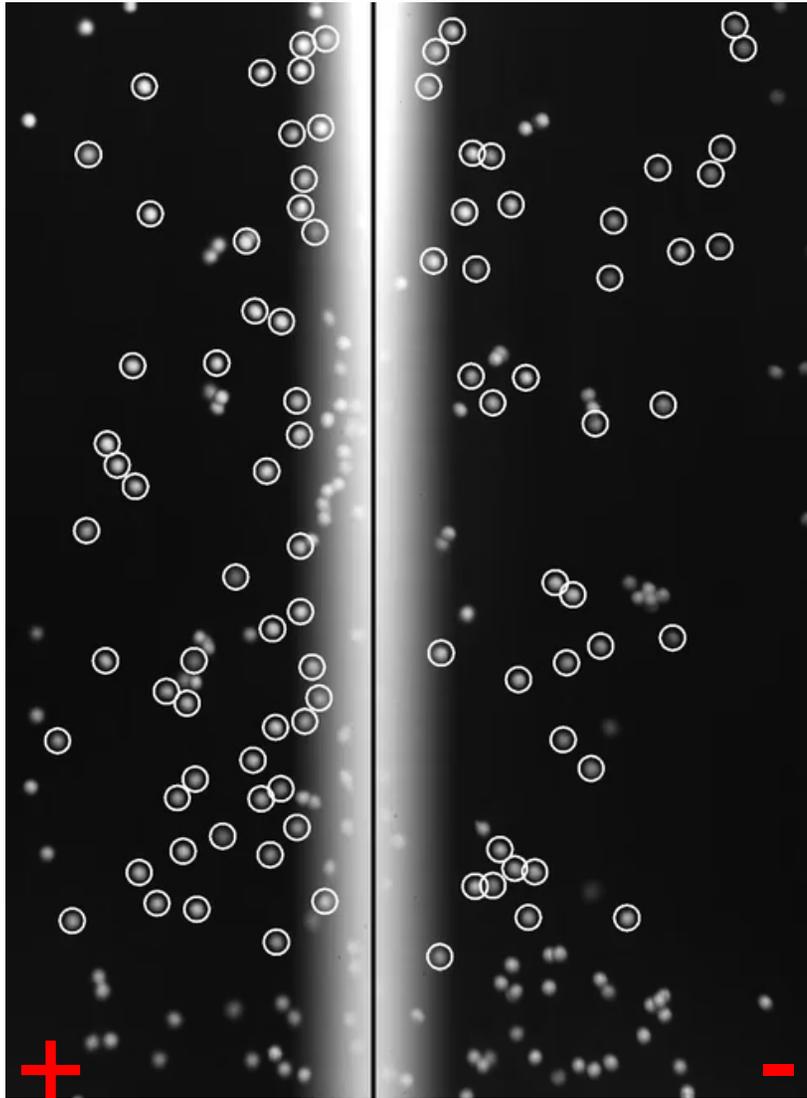
→ low-density granular gas

opaque, white grains (ZrO_2)
for better particle identification

Follow individual grains
and collisions *in-situ*



$E = 65 \text{ kV/m}$



Note: Hardly any collisions during free fall
→ we are detecting net charge due to particle interactions *prior* to leaving reservoir

$$10^6 \text{ e/grain} \sim 5 \text{ e}/\mu\text{m}^2$$

Given a charge distribution $P(q)$, what happens in those rare cases when two particles do interact?

Hunt for rare collision events



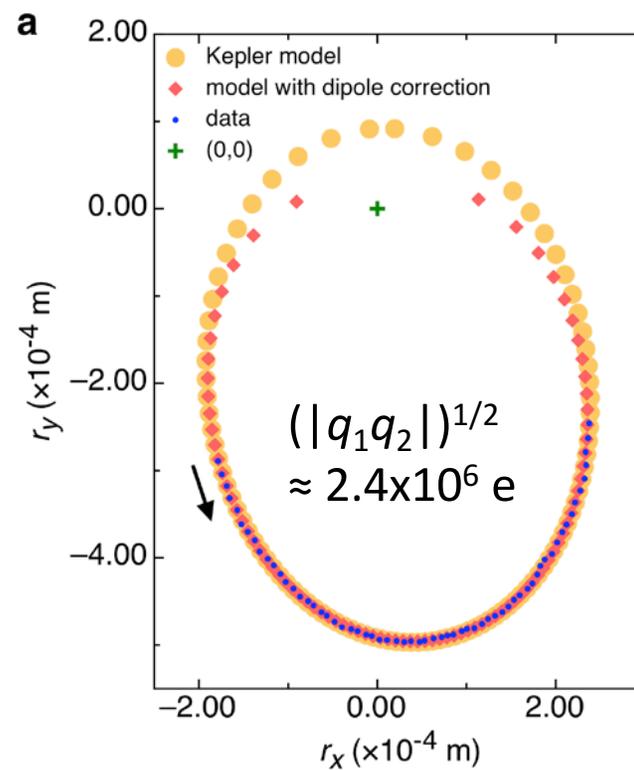
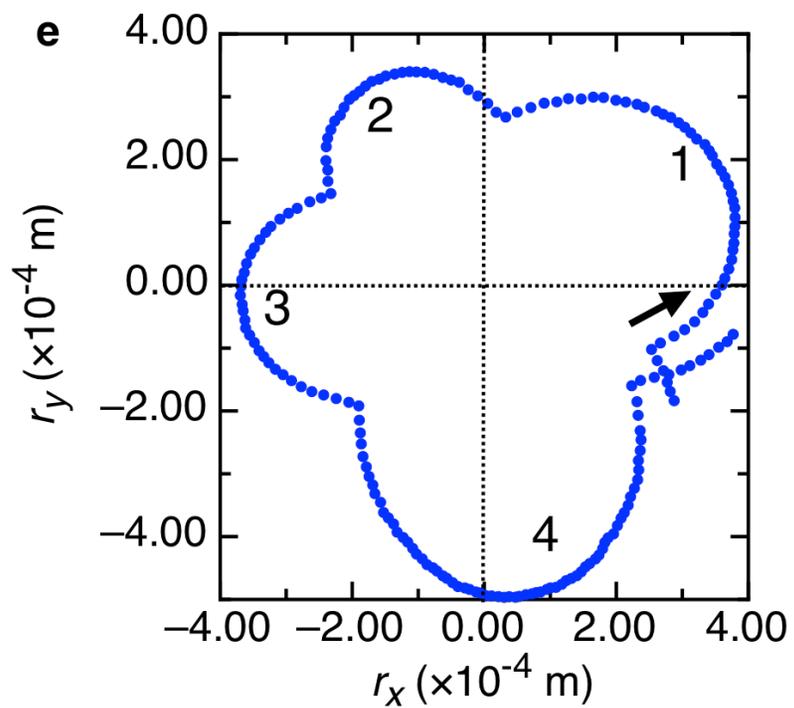
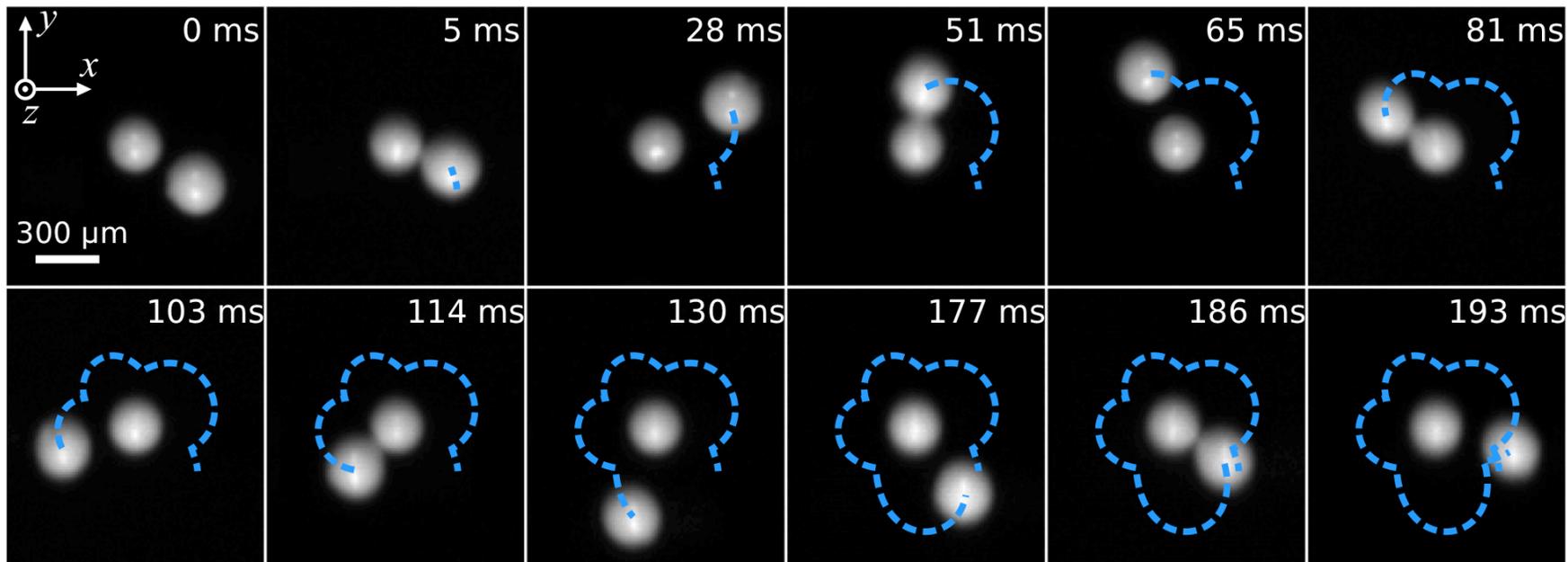
Victor Lee

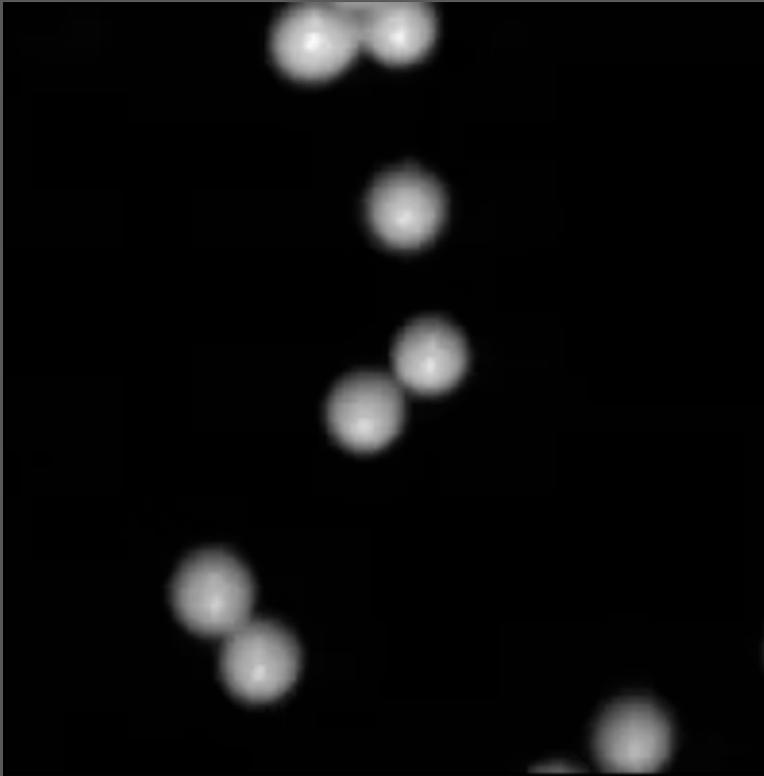
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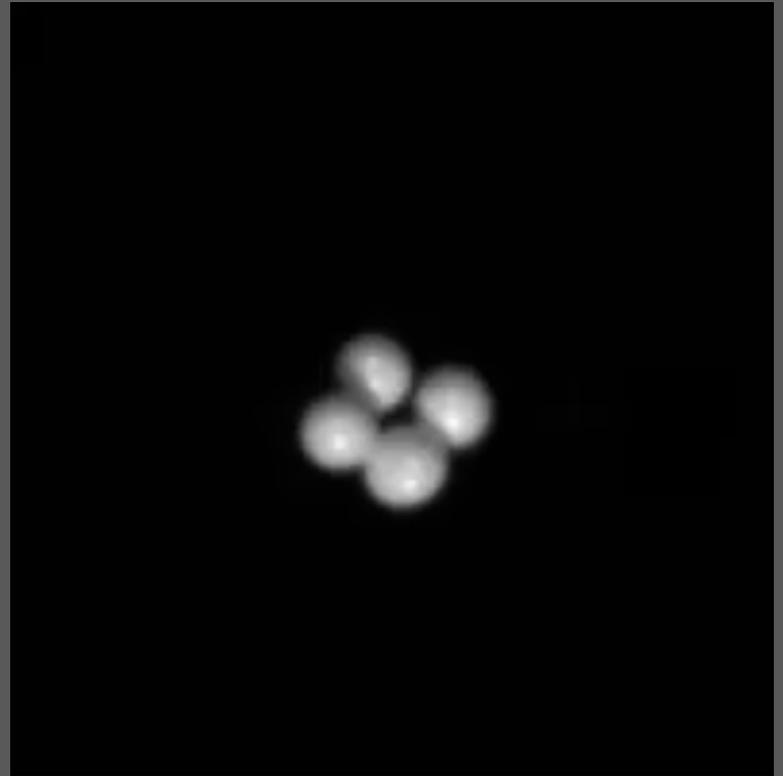
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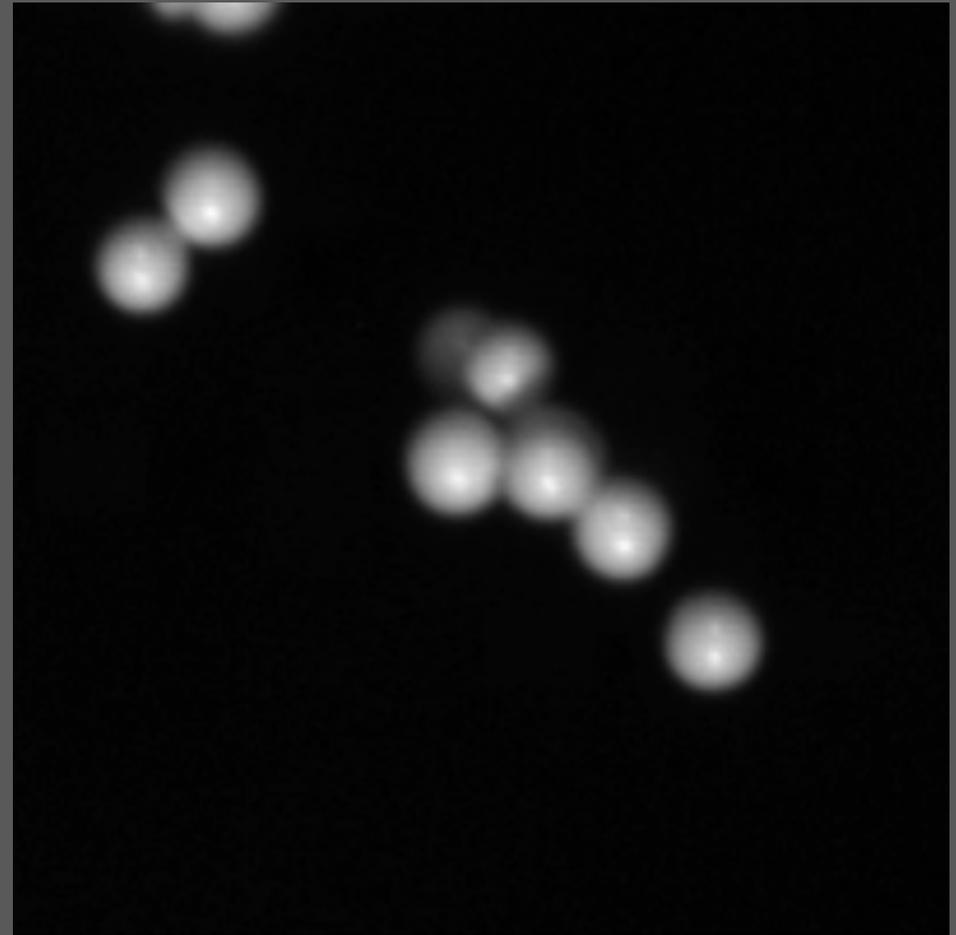


Spinning particles → conversion of rotation into translation



“granular molecules”: strong but flexible bonds due to direct Coulomb and polarization forces

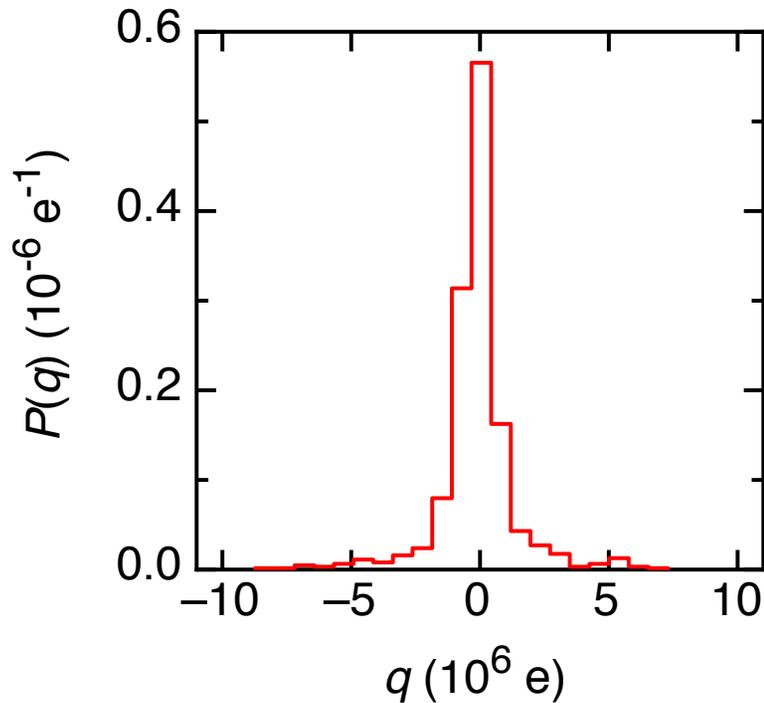
Direct observation of capture via Coulomb interactions



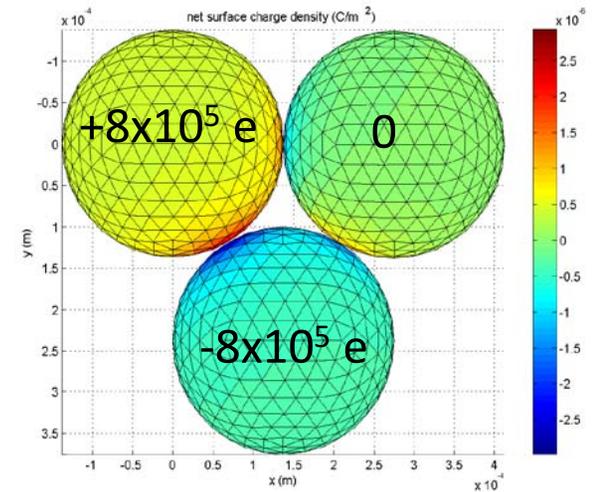
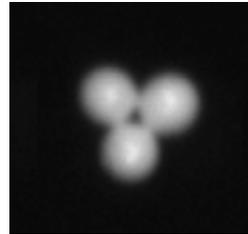
Compared to immediate sticking, Coulomb interactions enhance capture probability

- through larger impact parameter, and
- by trapping particles with velocities $v_{capture} > v_{coh} = (2W_{coh}/m)^{1/2}/\epsilon_{eff}$

Lots of close-packed configurations, incl. trimers

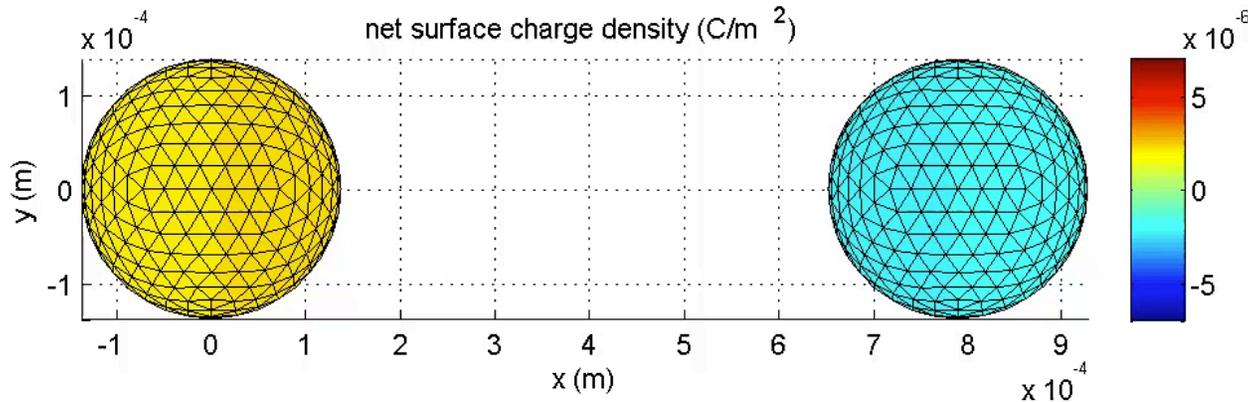


trimer



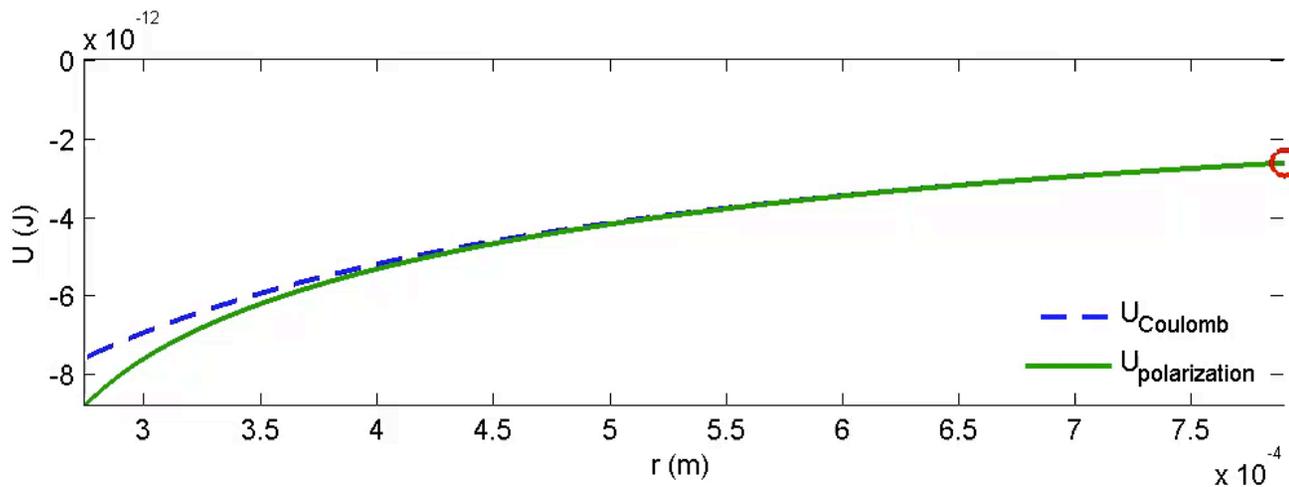
$P(q)$ peaked at zero,
polarization terms always attractive
→ Closely packed configurations likely

Polarization contributions important at close approach



Molecules
Colloids
Plasmas

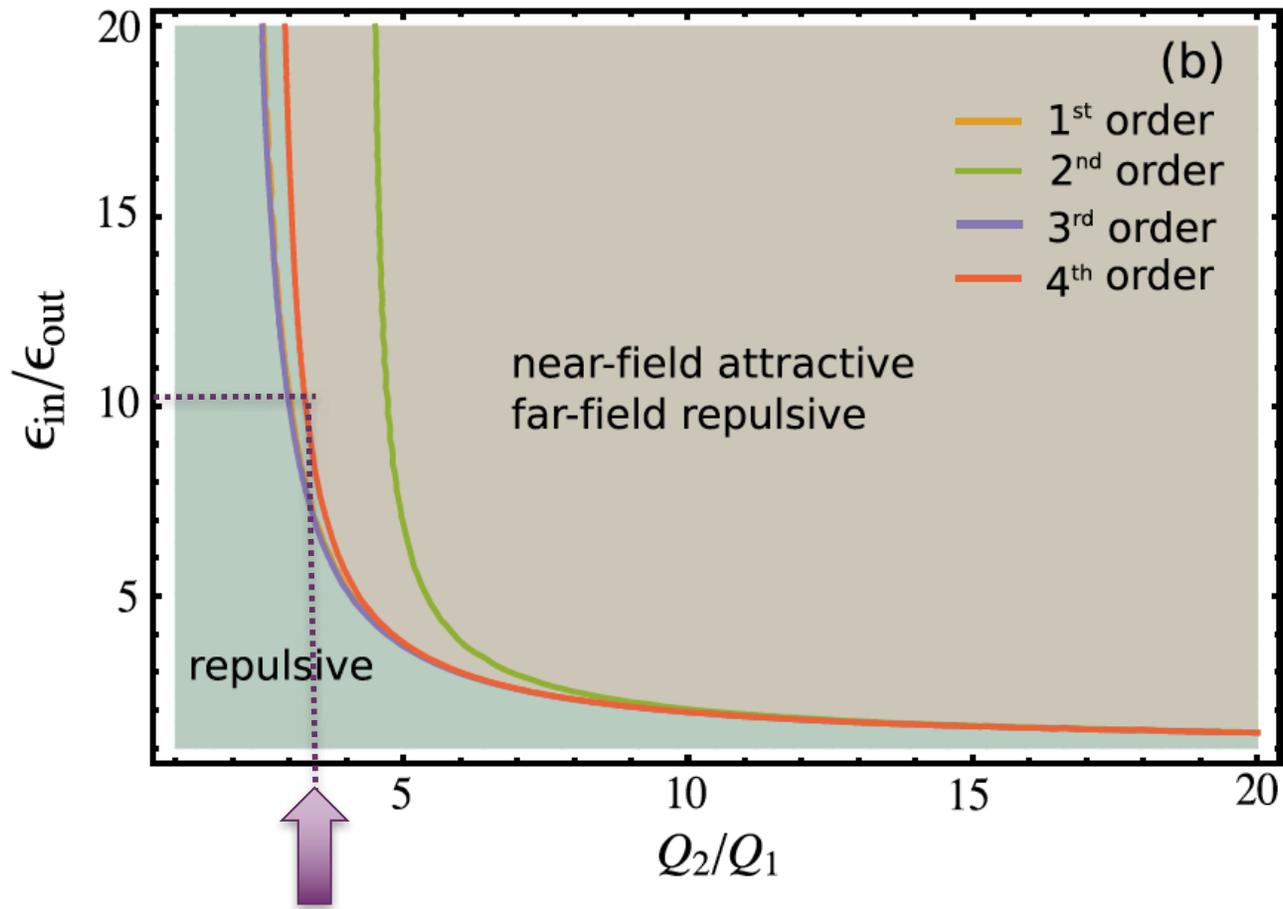
...



Y. Nakayima, J E-Stat. 45 ('99)
Z. Xu, PRE 87 ('13)
T. Murovec, APL 105 ('14)
K. Barros, PRL 113 ('14)
K. Freed, JCP 141 ('14)

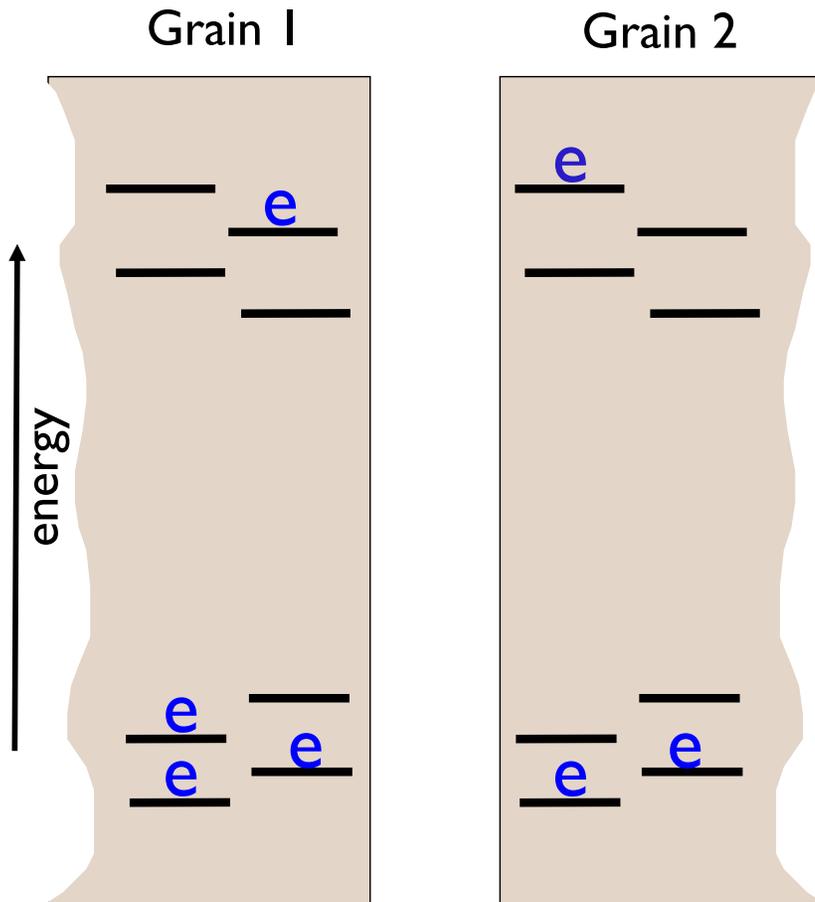
Nearfield polarization:

Same-polarity particles ***attract on close approach*** if charge magnitude ratio is sufficiently large



1. Measuring particle charge & tracking clustering with granular streams
2. **Collisional charging mechanisms**
3. Experiments to ascertain the nature of the charge carriers & measure charge transferred/collision

Transfer of electrons trapped in high-energy surface states



- Some electrons are trapped in high-energy states at the surface of insulating particles.
- These electrons cannot relax, unless....
- on contact with another grain they can tunnel into low energy states on the second grain

Lowell & Truscott., J Phys D 19 (1986)

Lacks & Levandovsky, J. Electrostatics 65 (2007)

Lacks, Duff, Kumar, Phys. Rev. Lett. 100 (2008)

Forward, Lacks, Sankaran, Phys. Rev. Lett. 102 (2009)

Direct charge measurements:

$> 100,000 |e|/\text{grain}$ or $> 0.4 |e|/\mu\text{m}^2$

Thermo-luminescence exp'ts:

$< 10^{-4} |e|/\mu\text{m}^2$

→ Not enough trapped electrons
to account for the grain
charges we measured

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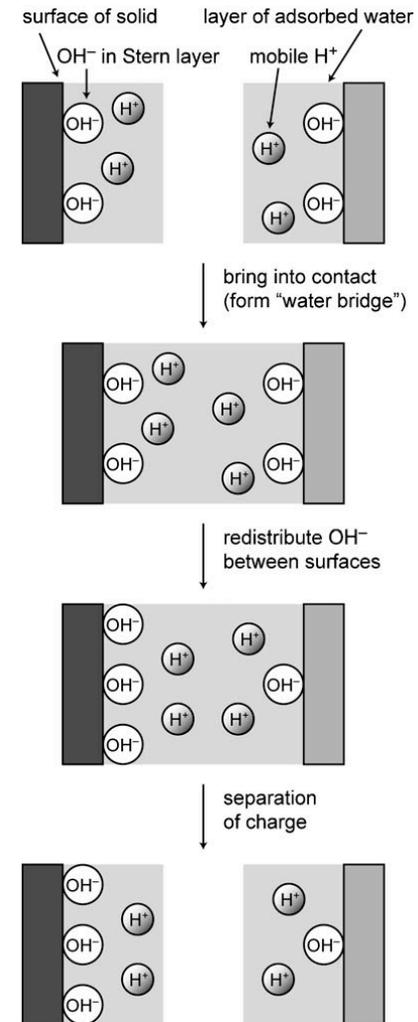
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Waitukaitis et al, Phys. Rev. Lett. 112 (2014)

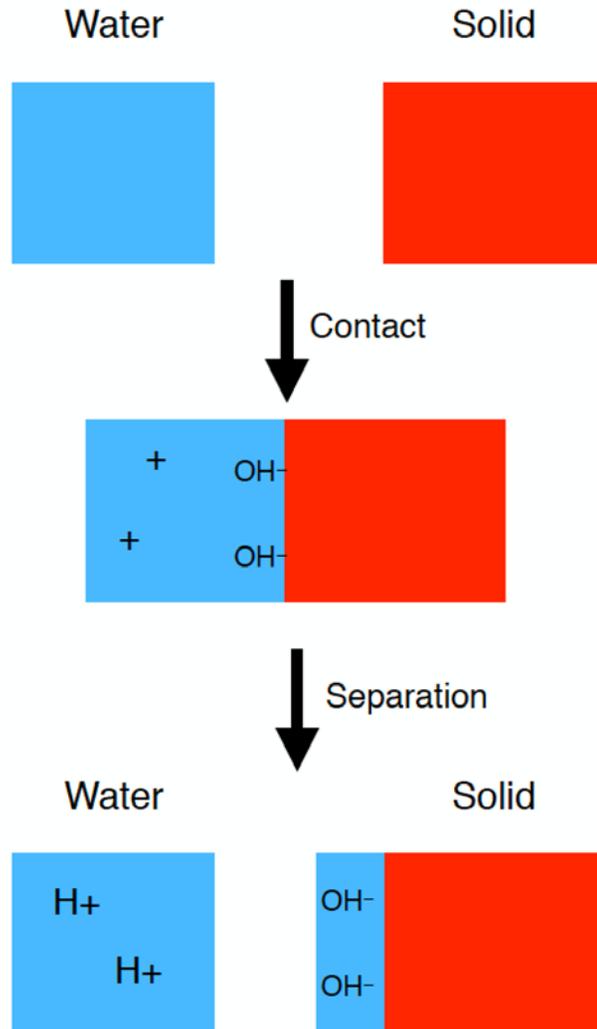
Possible Way Out:

Charges transferred are ions!

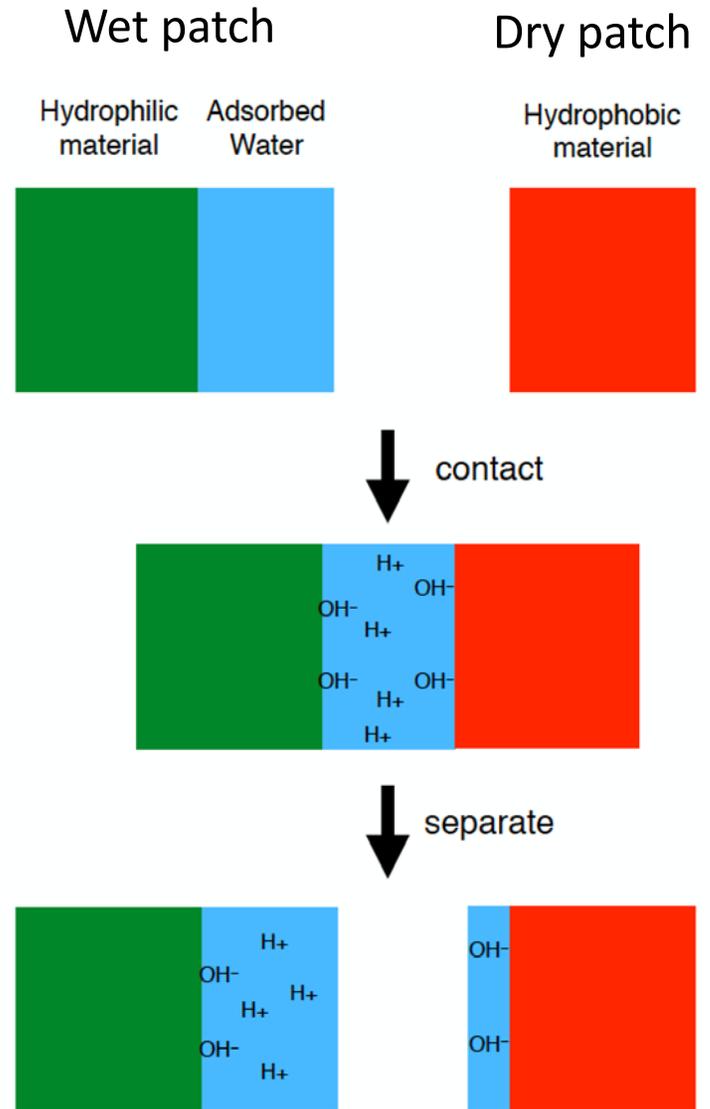
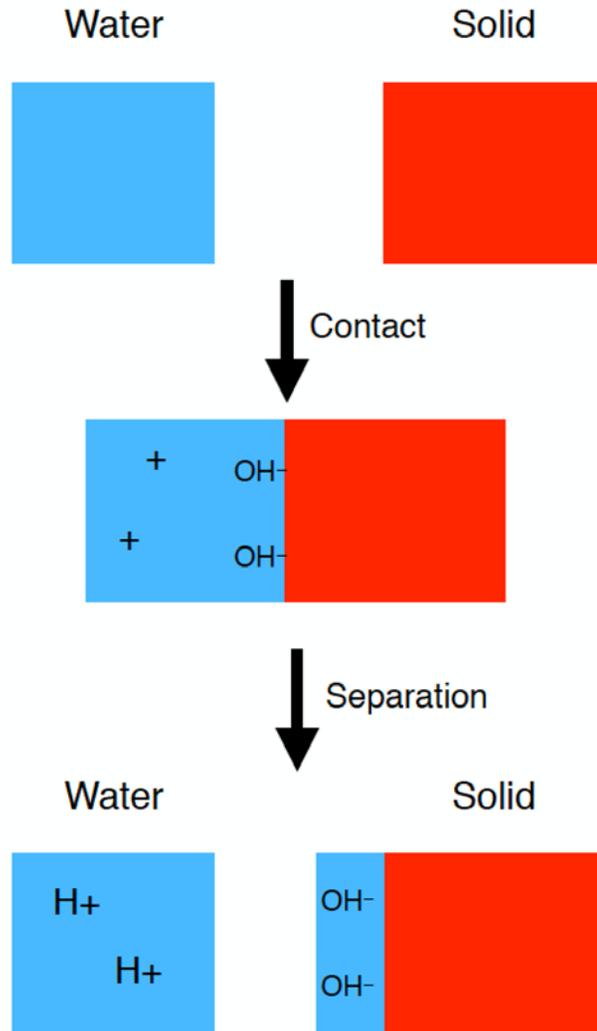


McCarty & Whitesides,
Angewandte Chemie 47, 2188 (2008).

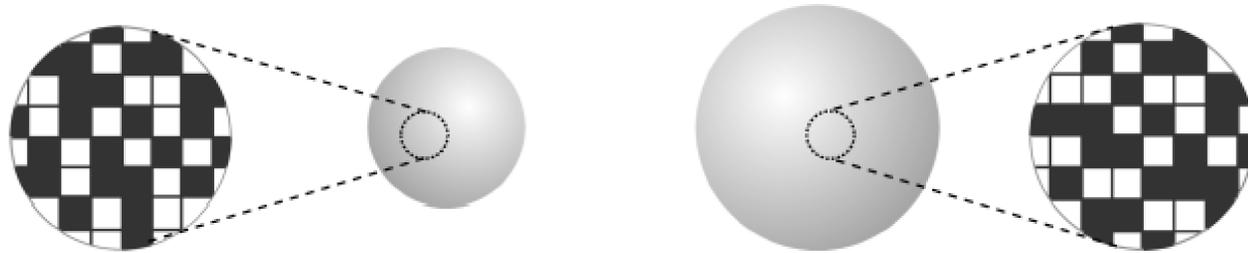
OH^- ions like to stick to surfaces



OH⁻ ions like to stick to surfaces

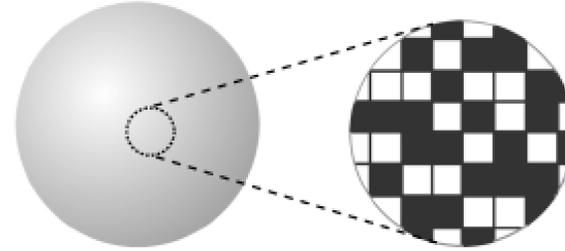
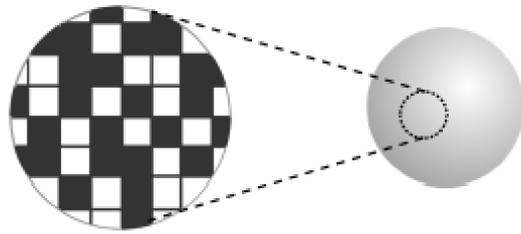


Assume constant areal density of patches that can transfer charge
Differences in particle surface area → same material tribo-charging



Same geometry-based model as for electrons (see Lacks et al.),
but now for OH^- ions instead of electrons:

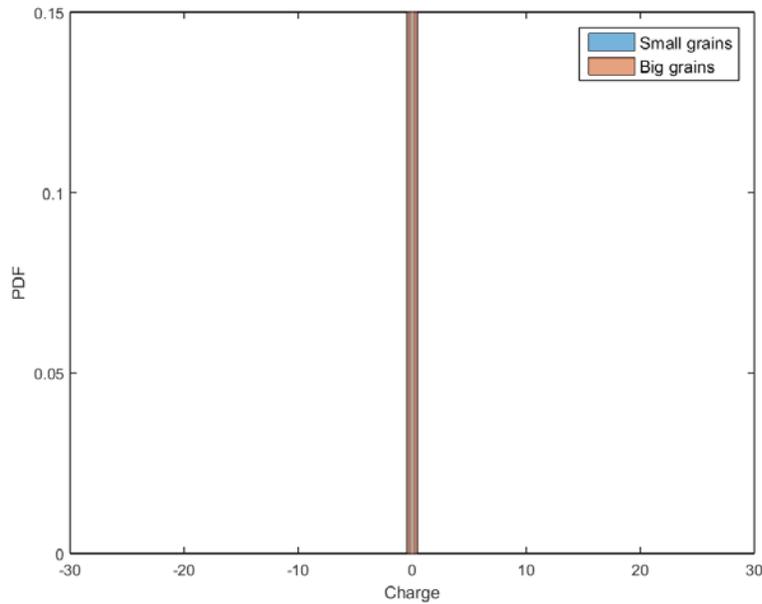
- Small particles run out of charge carriers to transfer before large particles
- Large particles still can transfer charge.... and thus turn positive



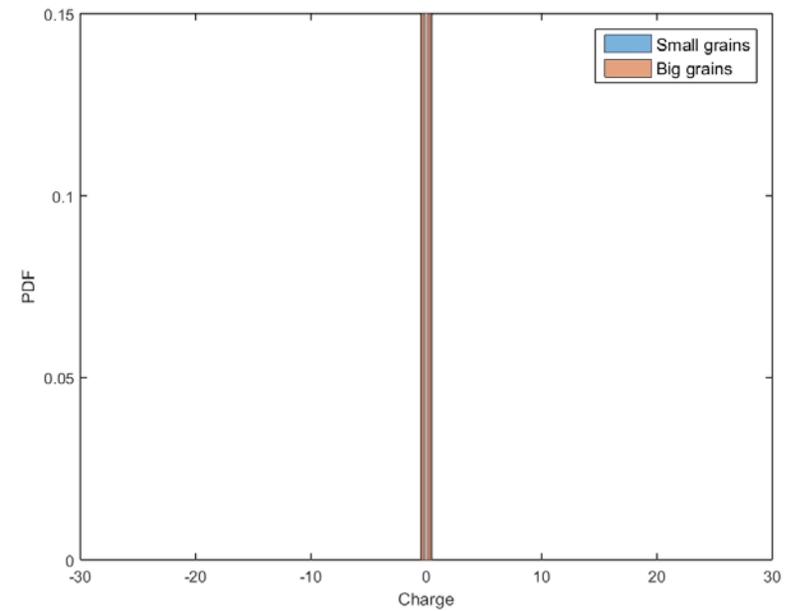
1000 large grains, 1000 small grains

30% wet patches 70% dry patches per grain

Initial state neutral; negative charge transferred only if wet patch hits dry patch

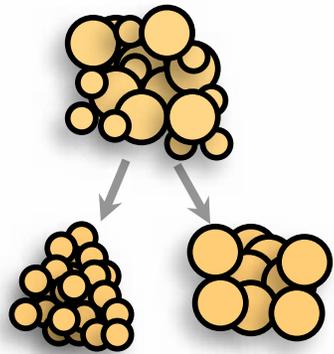


300µm – 100µm



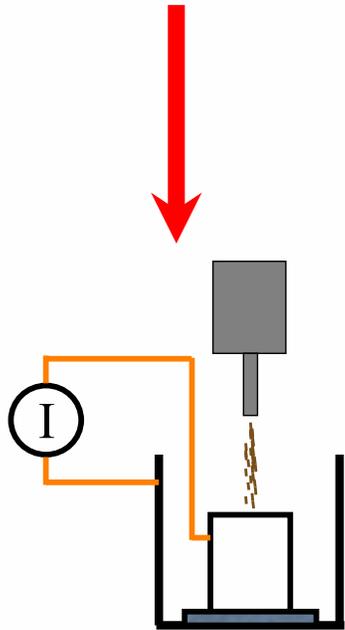
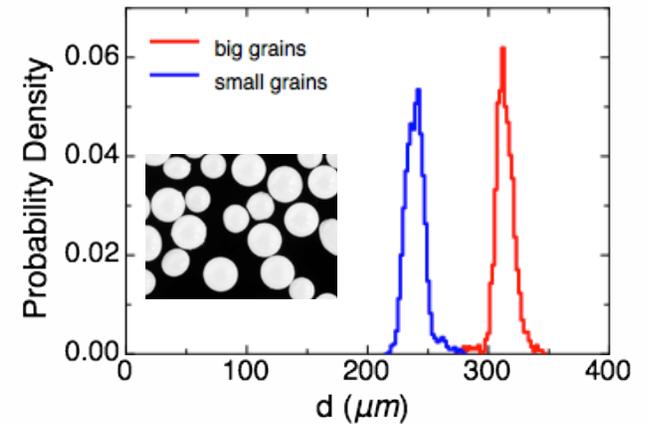
300µm - 200 µm

Charge measurements with binary PSD



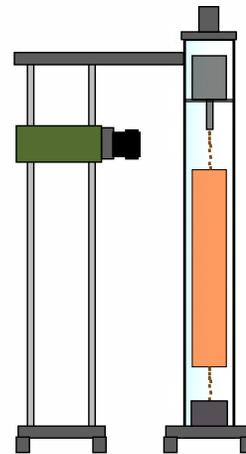
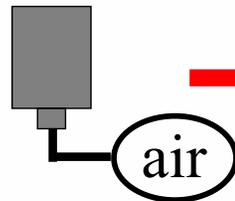
1. sieve grains from *same batch* to several tight PSDs

measure PSD with optical microscope

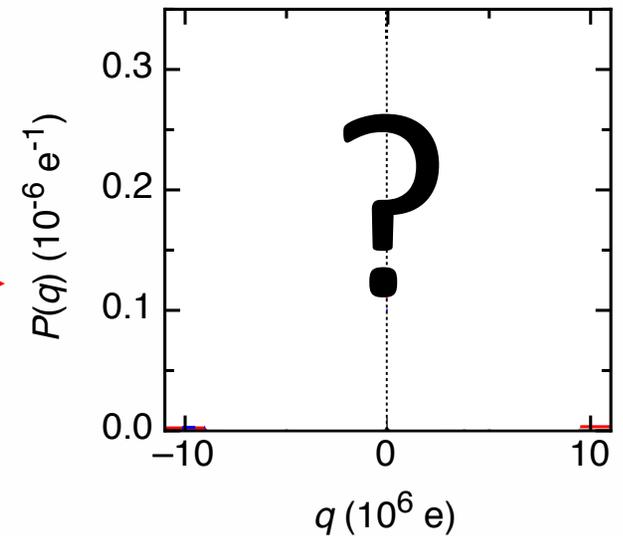


2. measure average charge for small/large grains with Faraday cup

3. mix grains via fluidization

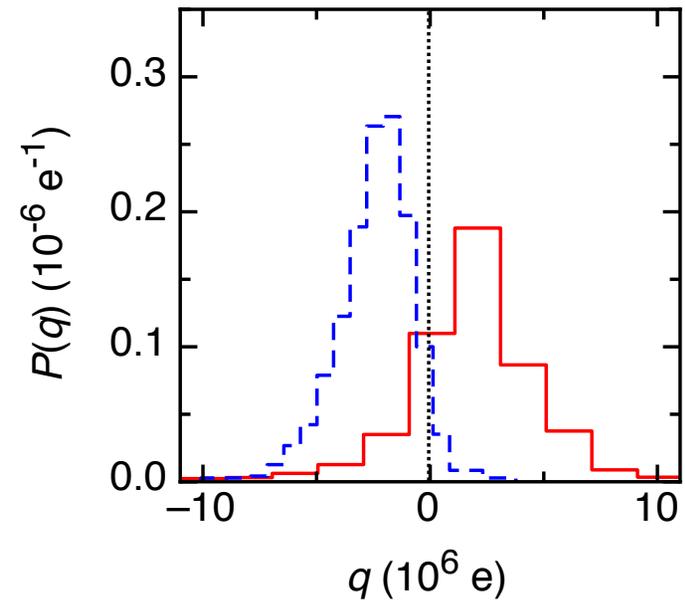
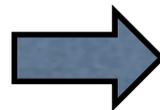
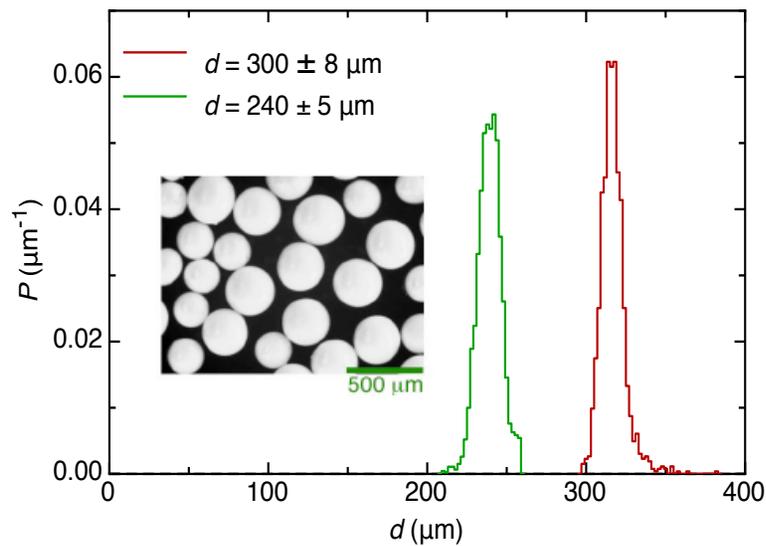
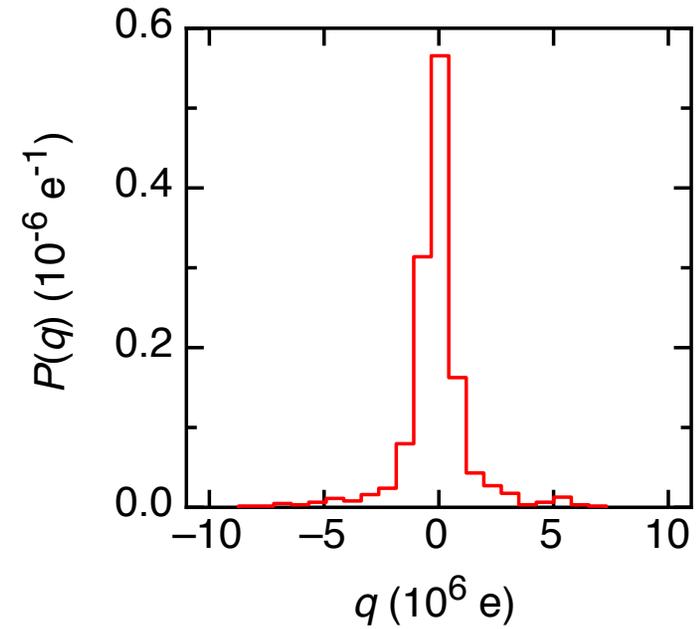
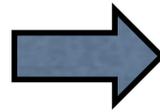
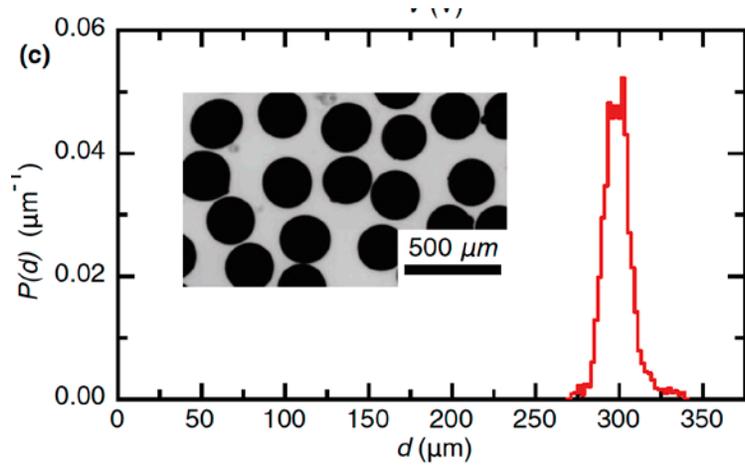


4. measure charge in free fall apparatus

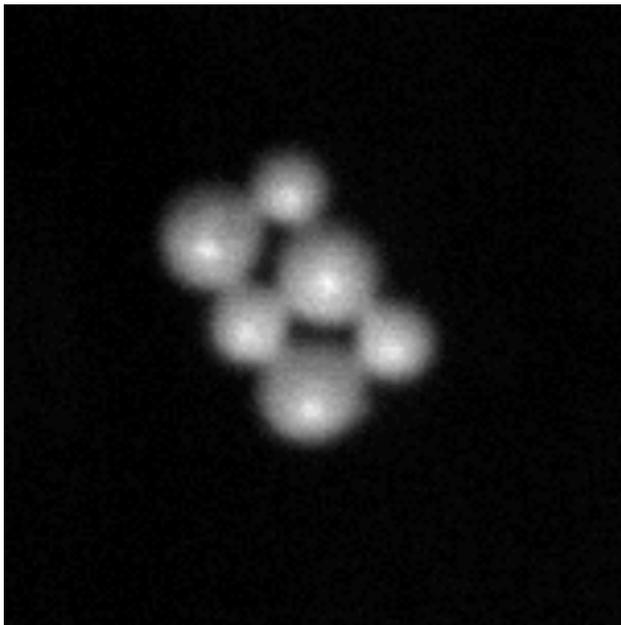


5. extract charge distribution

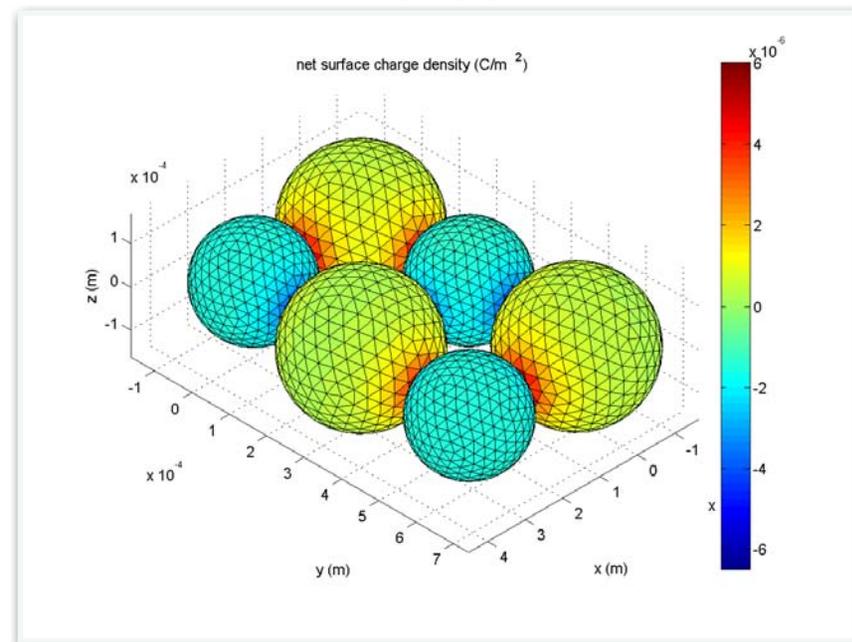
Shape of charge distribution $P(q)$ reflects size distribution



Shape of $P(q)$ \longleftrightarrow Shape of granular aggregates!



3L3S

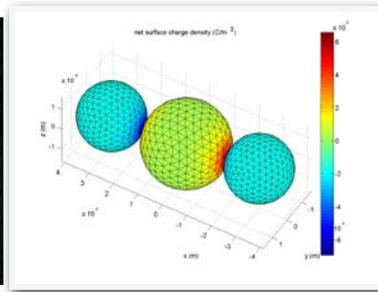
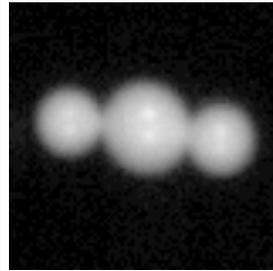
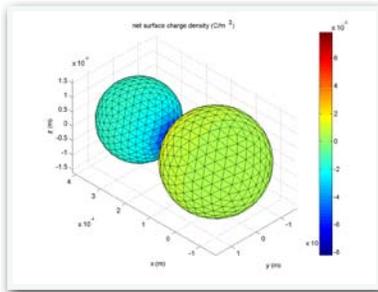


$$Q_{\text{large}} = +1.8 \times 10^6 e$$
$$Q_{\text{small}} = -2.3 \times 10^6 e$$

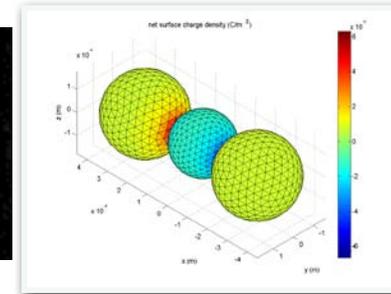
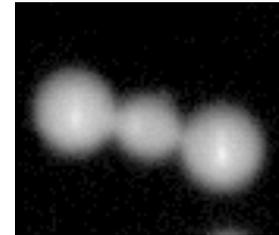
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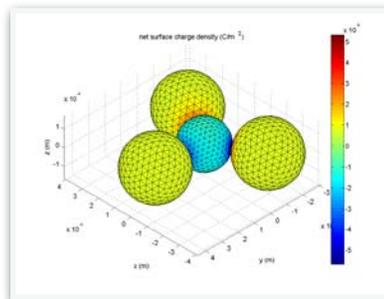
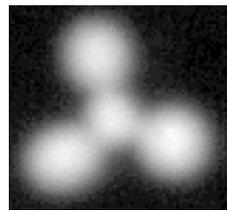
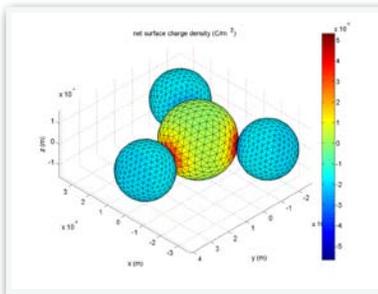
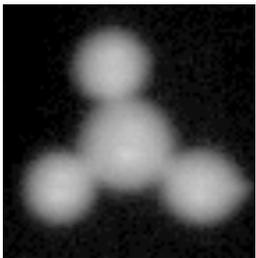
1L1S



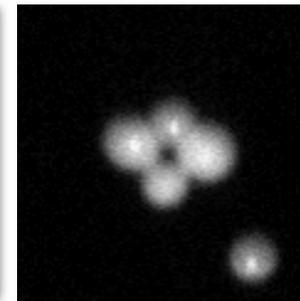
2L1S



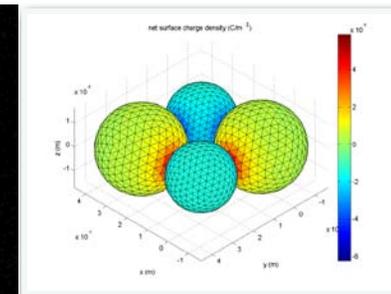
1L3S



3L1S

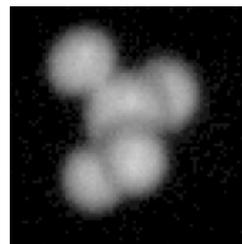
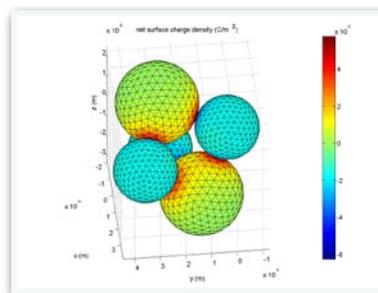
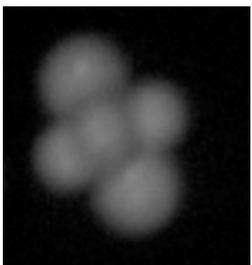


2L2S

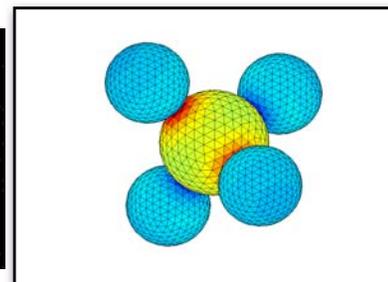


$$U = 4.67 \text{ pJ}$$

2L3S

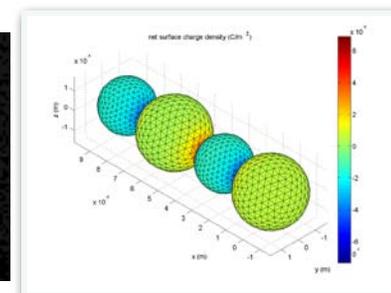
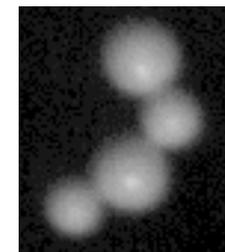


1L4S



$$Q_{\text{large}} = +1.8 \times 10^6 e$$

$$Q_{\text{small}} = -1.8 \times 10^6 e$$



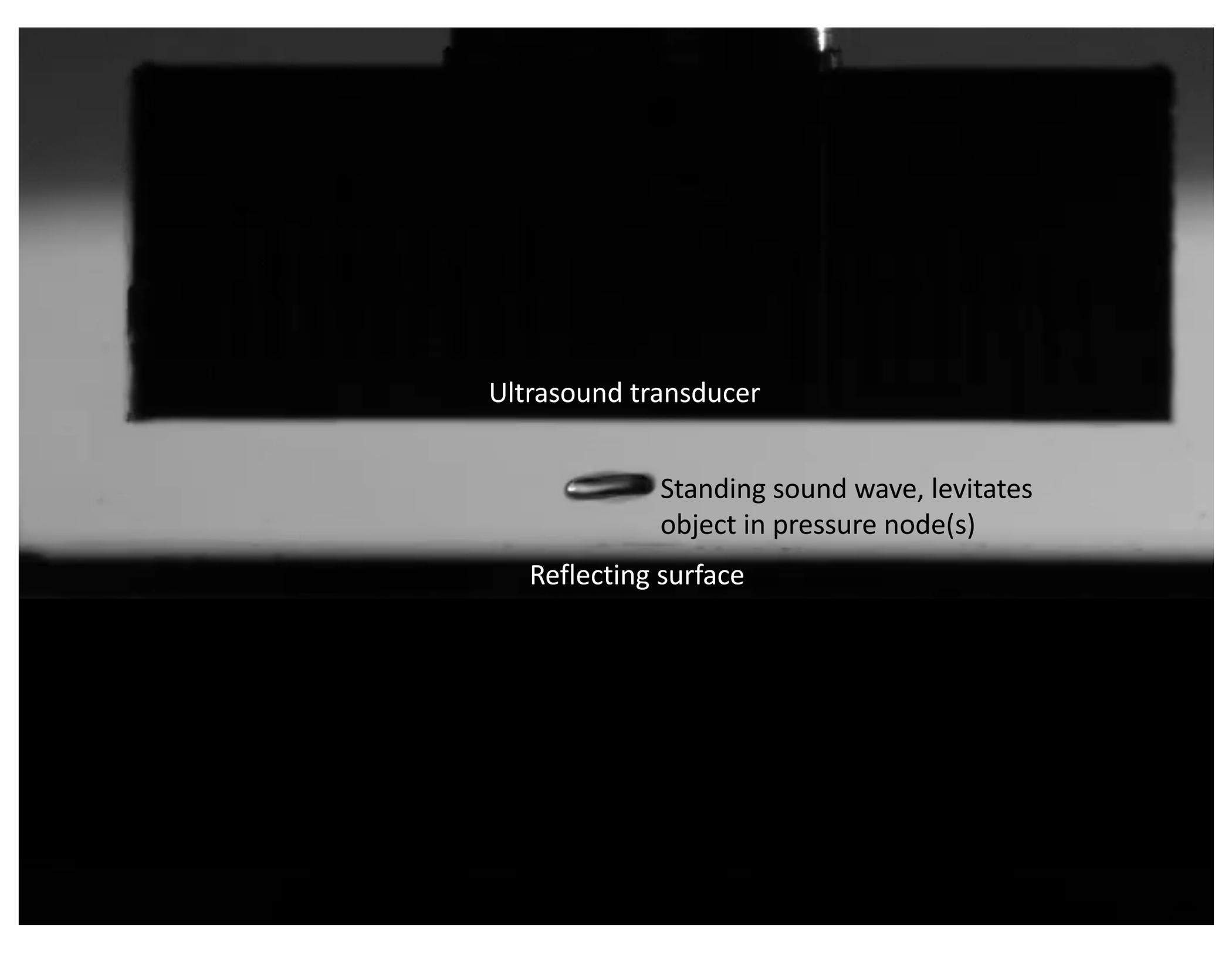
$$U = 5.65 \text{ pJ}$$

1. Measuring particle charge & tracking clustering with granular streams
2. Collisional charging mechanisms
3. Experiments to ascertain the nature of the charge carriers & measure charge transferred/collision

1. Measuring particle charge & tracking clustering with granular streams
2. Collisional charging mechanisms
3. Experiments to ascertain the nature of the charge carriers & measure charge transferred/collision

Experimental Problem:

Need extreme resolution to extract the amount of charge transferred in a single collision!



Ultrasound transducer



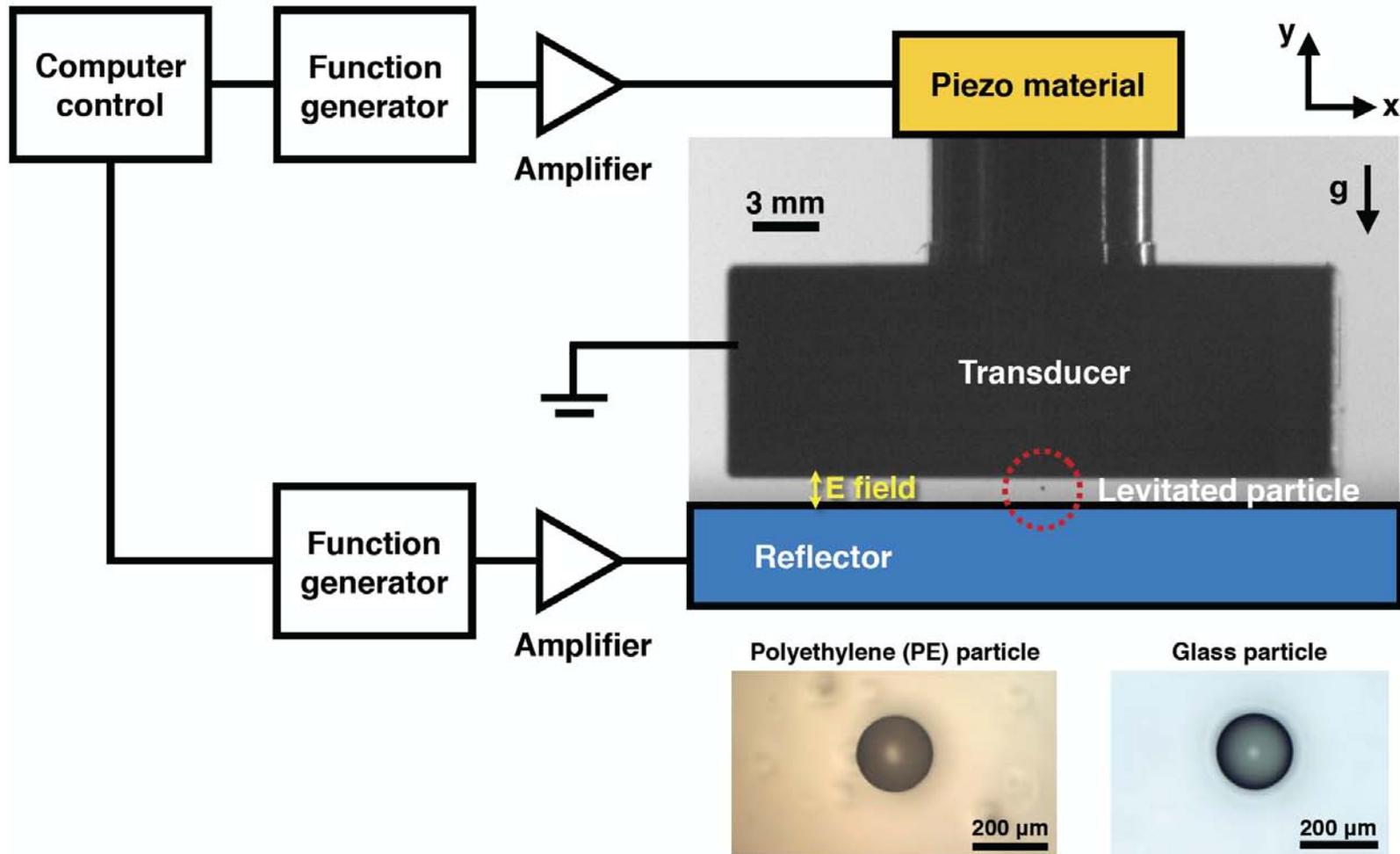
Standing sound wave, levitates
object in pressure node(s)

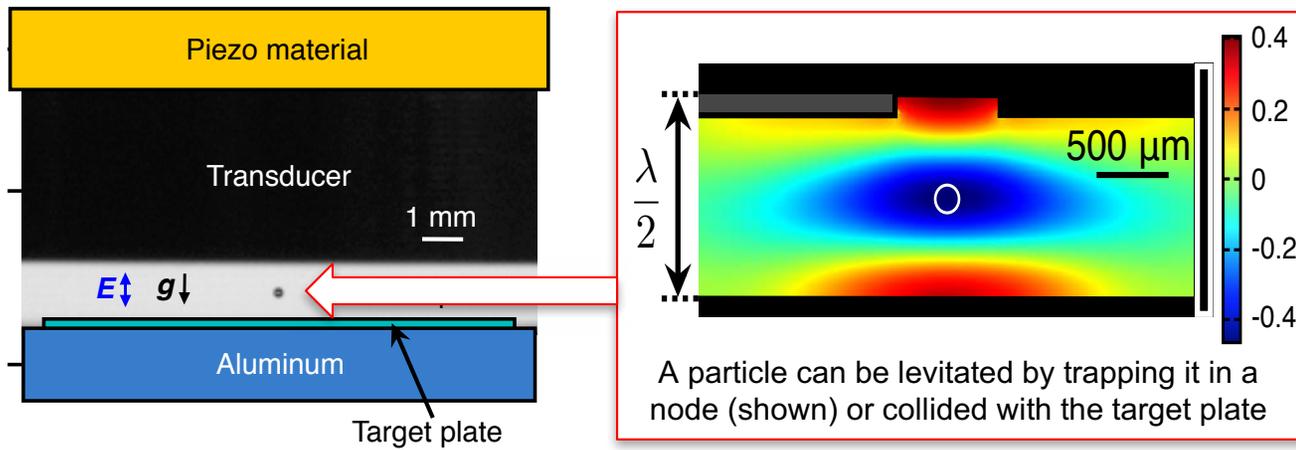
Reflecting surface

Precision tracking of particle tribo-charging



Victor Lee

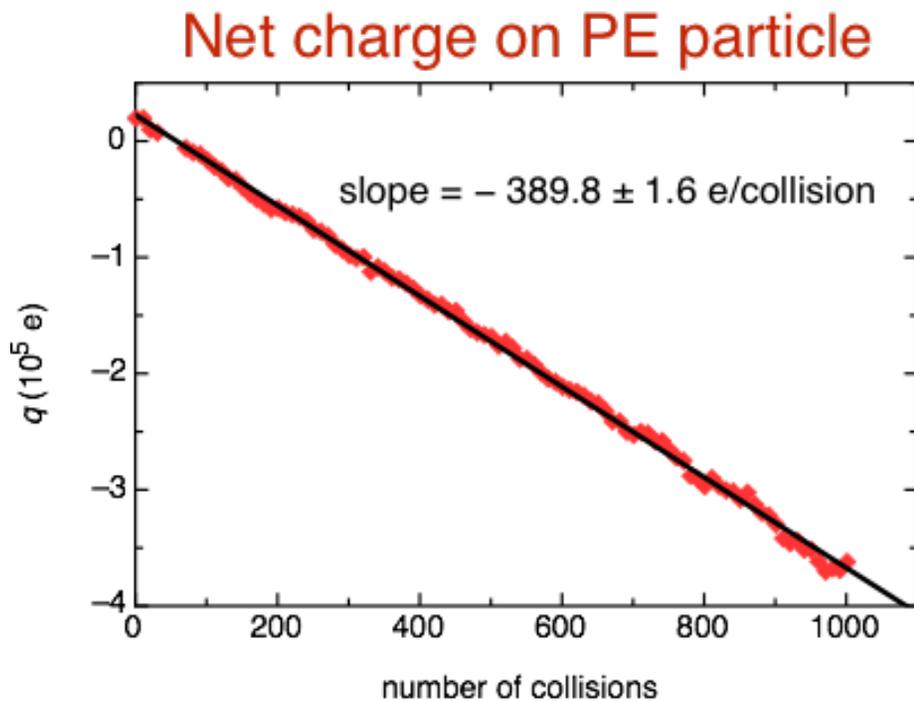




AC field \rightarrow $|q|/m$
 DC field \rightarrow polarity

Tracking particle charge one collision at a time

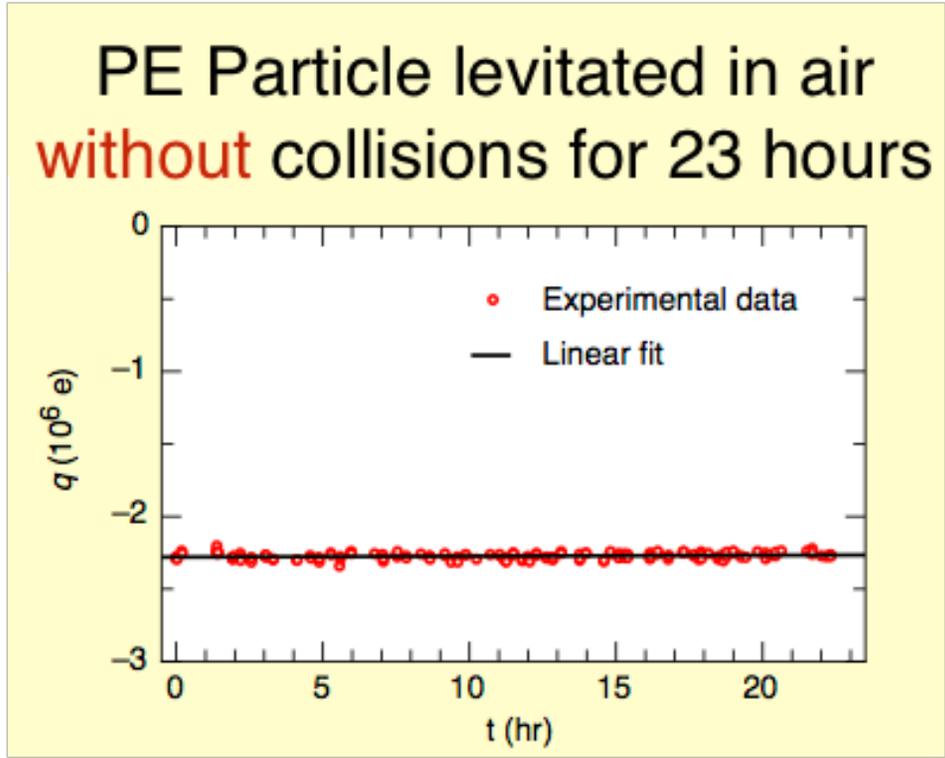
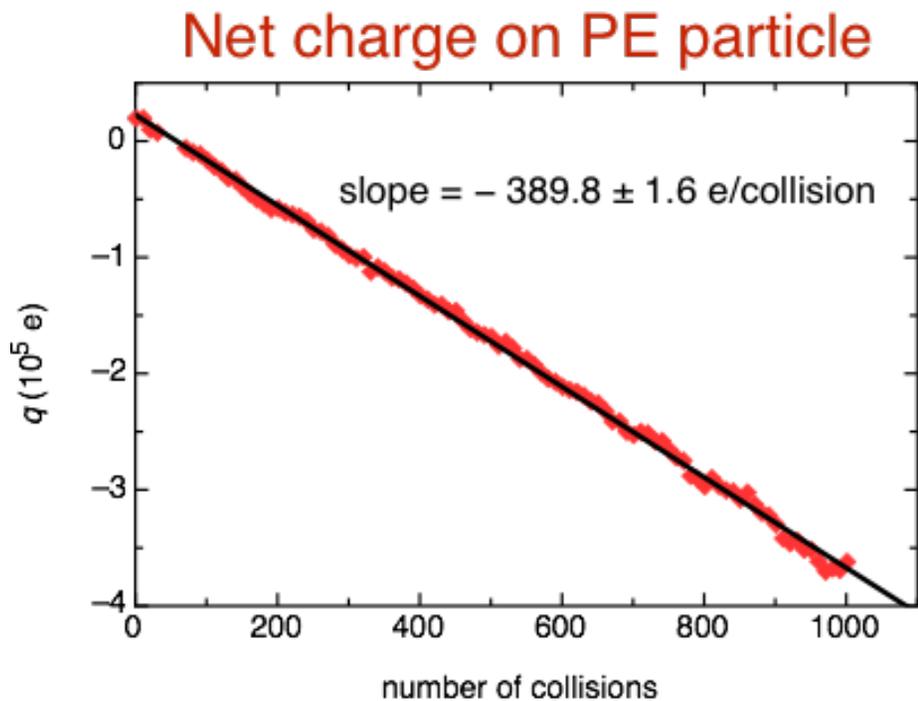
PE particle colliding with aluminum substrate @ impact velocity 0.18 m/s



Note: No saturation even for 1,000 collisions because particle rotates

Tracking particle charge one collision at a time

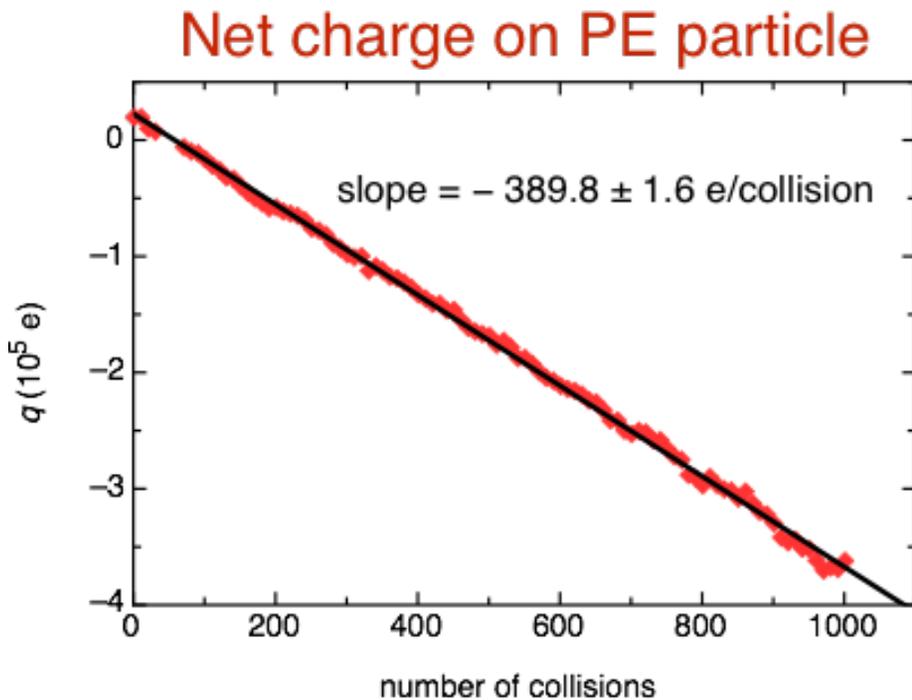
PE particle colliding with aluminum substrate @ impact velocity 0.18 m/s



Note: No saturation even for 1,000 collisions because particle rotates

Tracking particle charge one collision at a time

PE particle colliding with aluminum substrate @ impact velocity 0.18 m/s

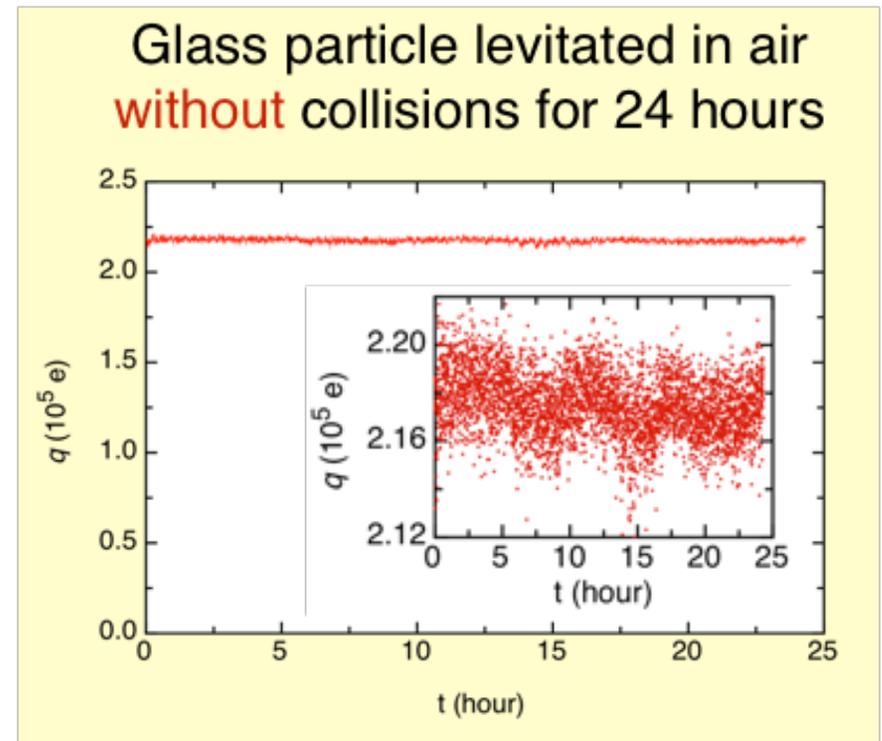
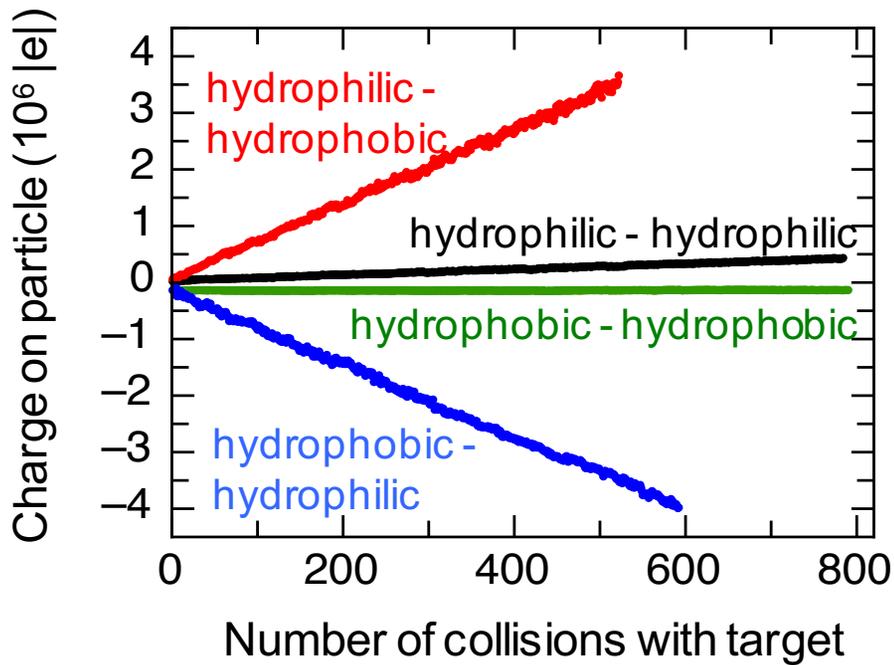
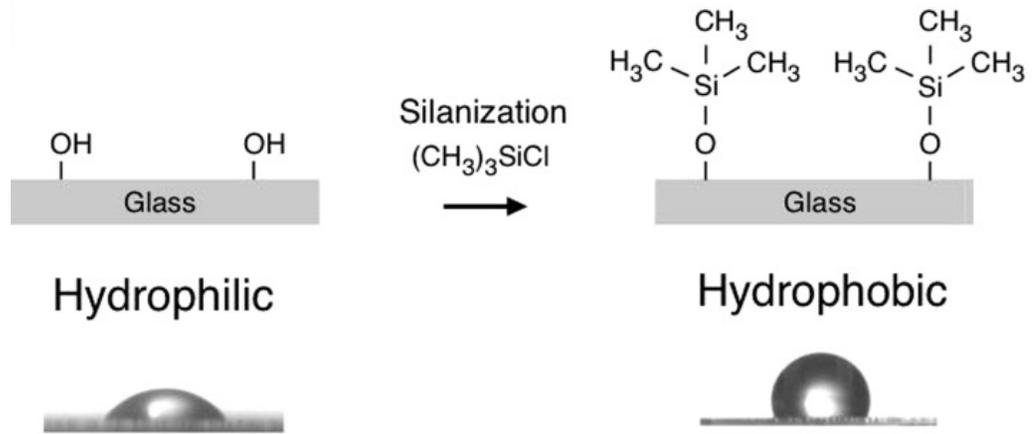


Triboelectric series

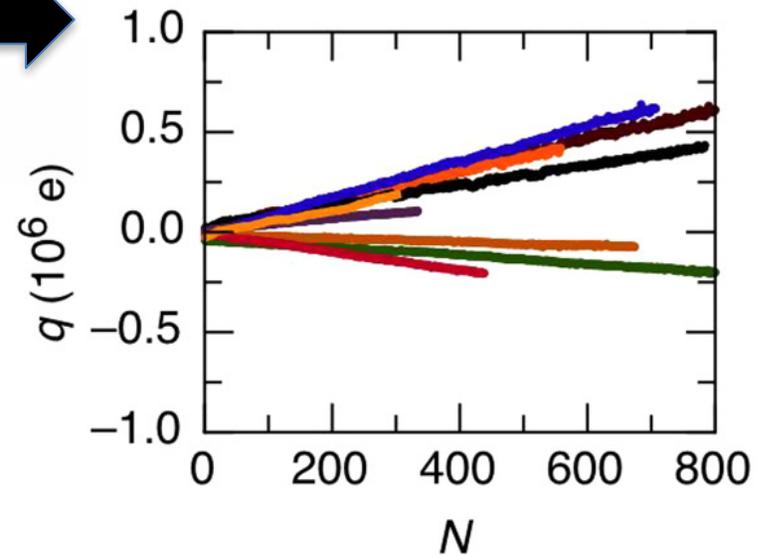
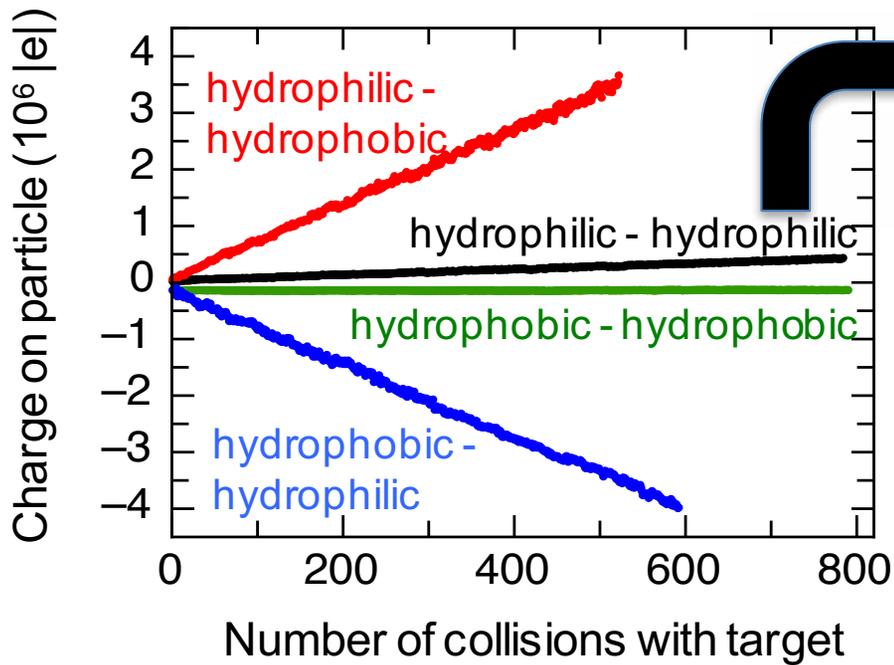
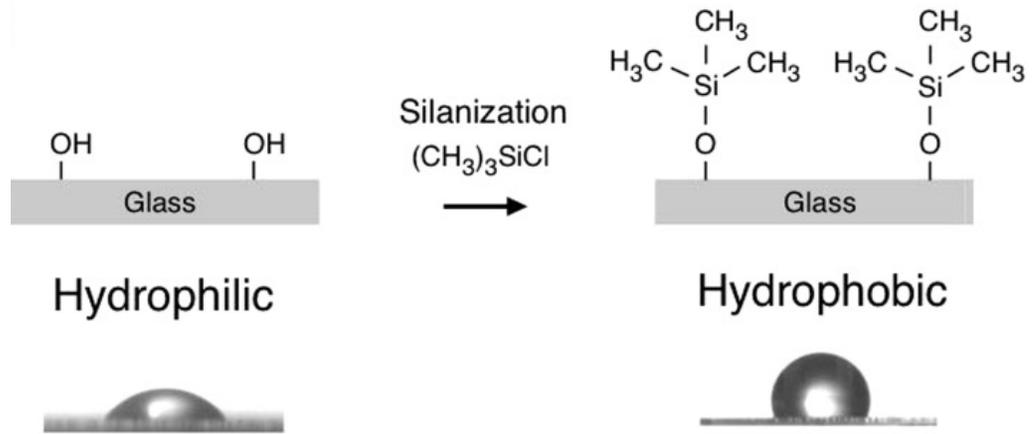
+	Asbestos
	Glass
	Mica
	Nylon
	Wool
	Aluminum
	Paper
	Steel
	Amber
	Hard rubber
	Nickel, Copper
	Brass, Silver
	Gold, Platinum
	Sulfur
	Polyester
	Orlon
	Saran
	Polyurethane
	Polyethylene
	Polypropylene
	Vinyl (PVC)
-	Teflon

C.K. Adams (1987)

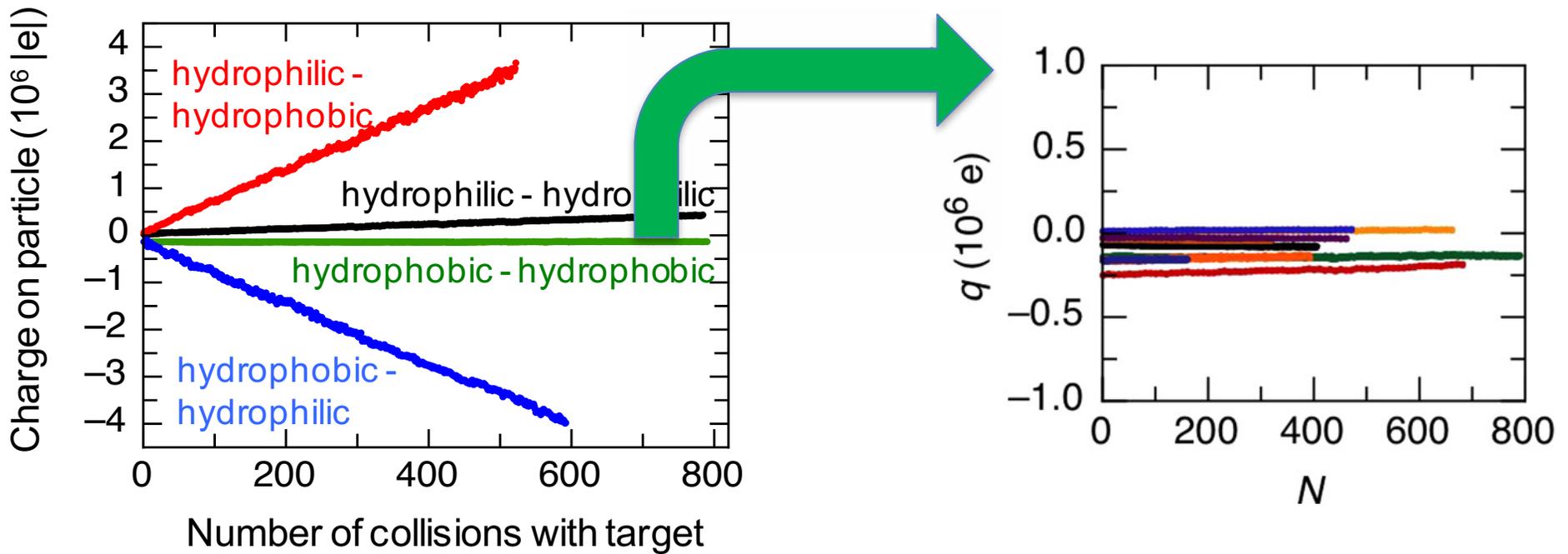
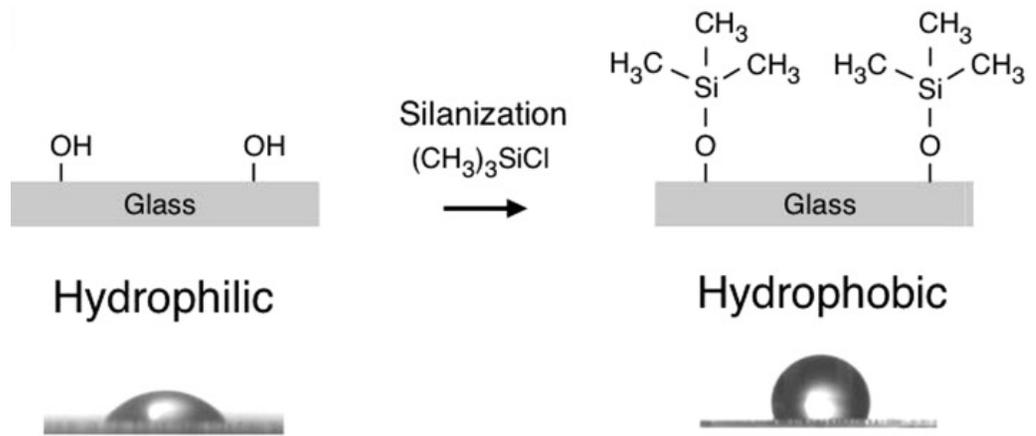
Glass particle colliding with glass plate



Glass particle colliding with glass plate

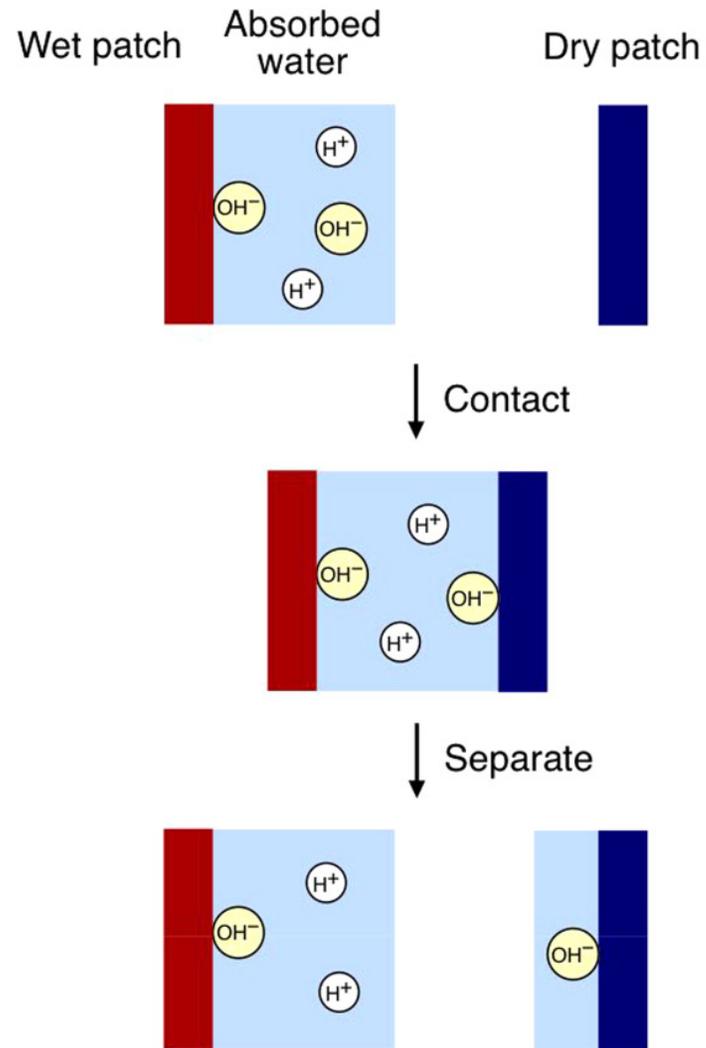


Glass particle colliding with glass plate



Most direct evidence so far for tribocharging of dielectrics due to molecular water patches and transfer of OH⁻ ions

OH⁻ ion transfer scenario

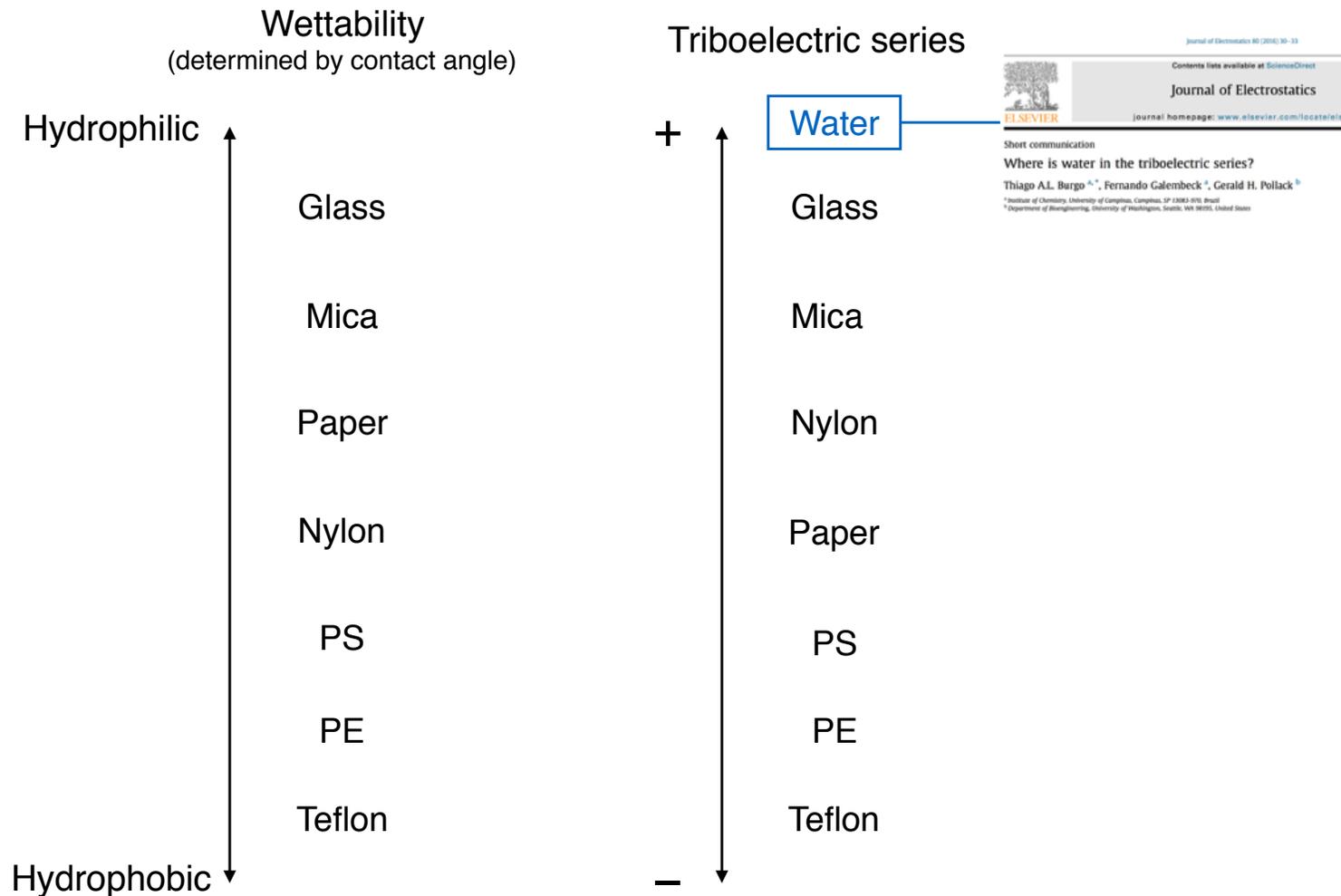


See also:

- McCarty & Whitesides, *Angew. Chemie* 47 (2008)
- Matsusaka, Maruyama, Matsuyama, Ghadiri, *Chem. Eng. Sci.* 65 (2010)

All surfaces are covered with molecularly thin patches of water (unless in UHV)

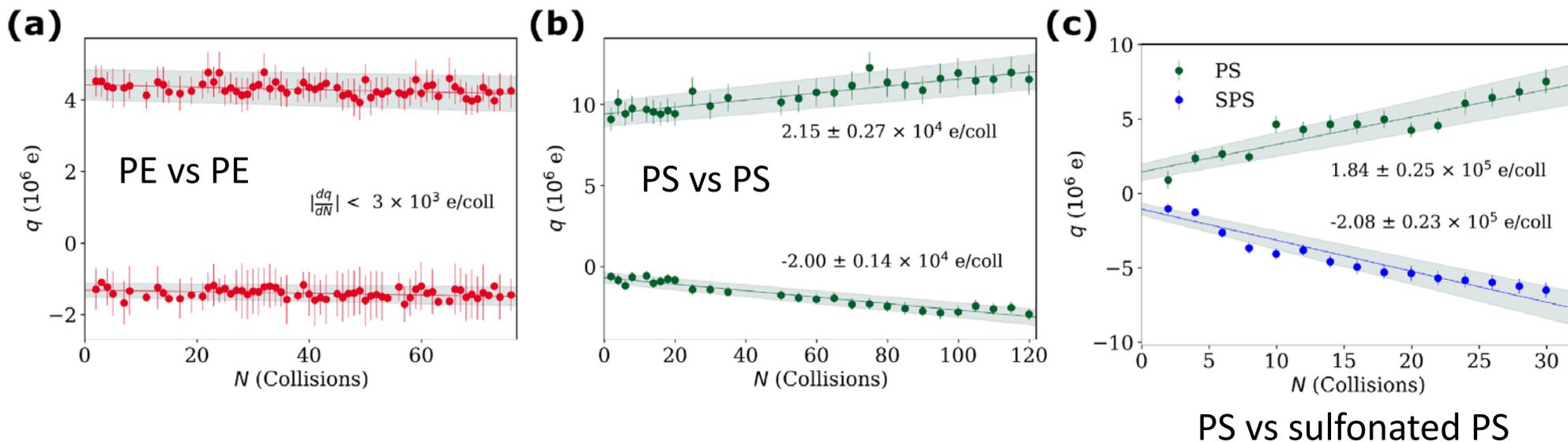
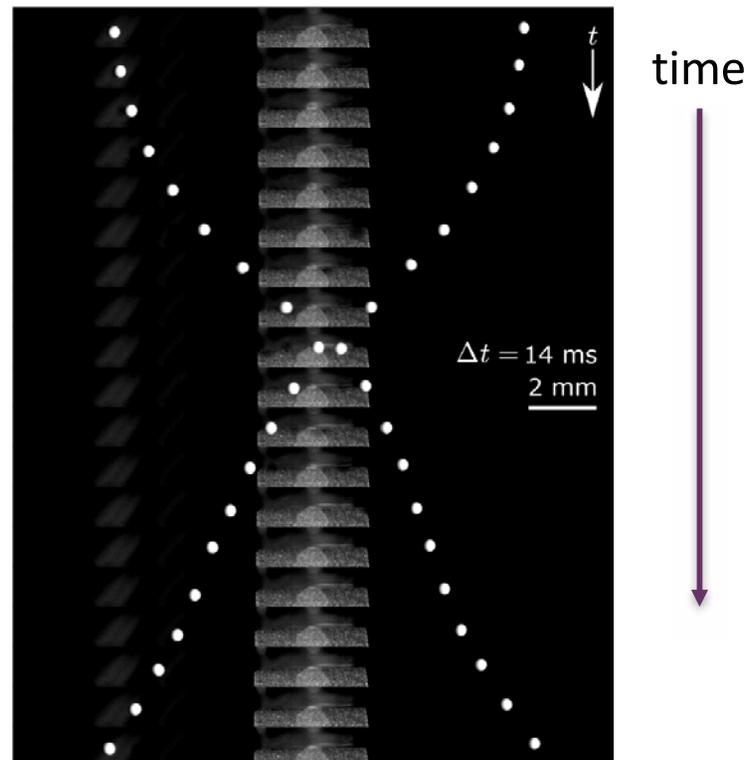
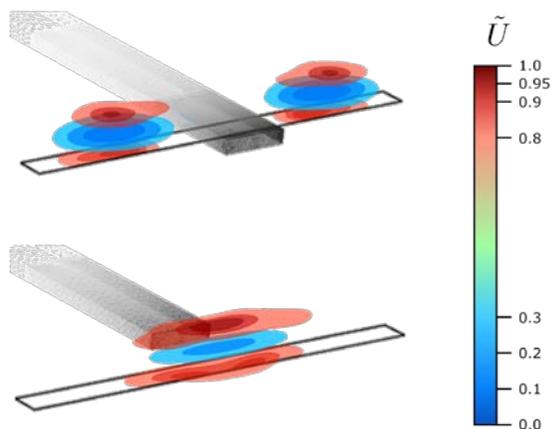
Is the tribo-electric series actually a series ordered by hydrophilicity?



The latest experiments:

Acoustic trap enables repeated head-on collisions of 2 particles

Mechanical arm, moves under computer control to transform double well into single well acoustic potential

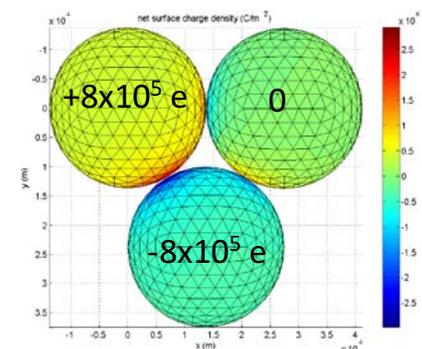
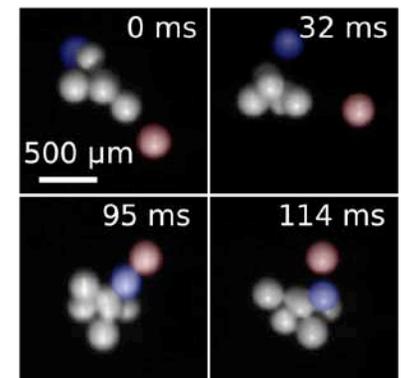
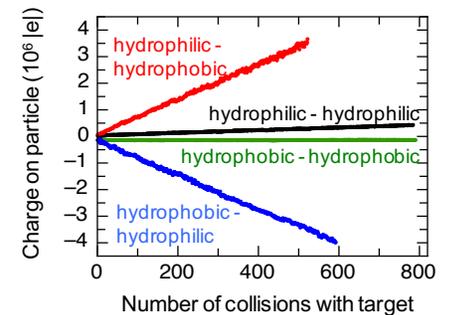
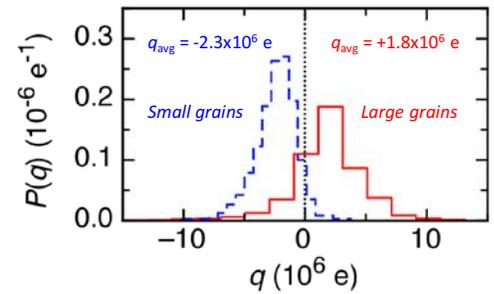


A. Kline et al., Rev. Sci. Instr., in press

TO SUM UP

- Particle size distribution controls particle charge distribution for collisional interactions among same-material particles
- For glass, ceramics, polyethylene: smaller particles tend to be negatively charged; larger ones positively
- Charge carriers in these materials are negative, but thermoluminescence results rule out trapped electrons
- Ultrasonic levitation experiments can track net charge evolution one collision at a time
- Strong evidence for charging by transfer of OH^- ions
- Granular stream experiments provide direct access to collide-and-capture events of individual charged particles
- Nearfield polarization effects are key to understanding particle clustering and aggregation

<http://www.Jaegerlab.com>



TO SUM UP

- Collisional particle charging is a rich & difficult problem with a long history
- Much recent progress has been made, but many fundamental aspects are still unresolved
- A particular challenge: include charging mechanisms in the modeling of fluidized beds

