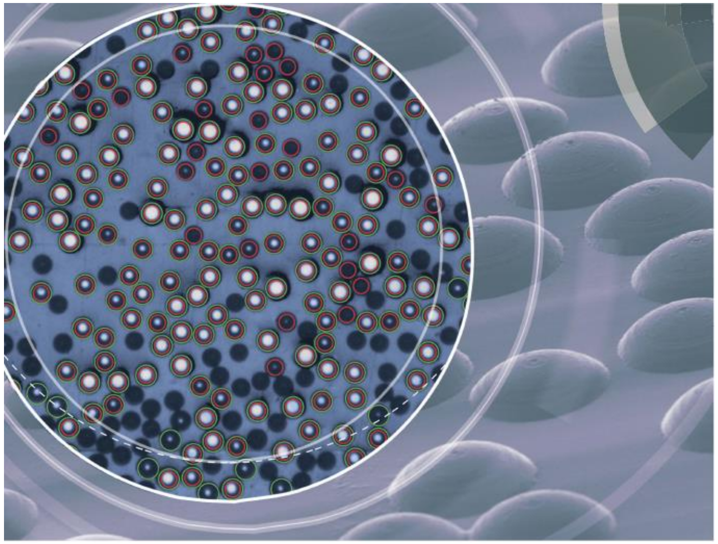
Normal contact and friction of rubber with model randomly rough surfaces



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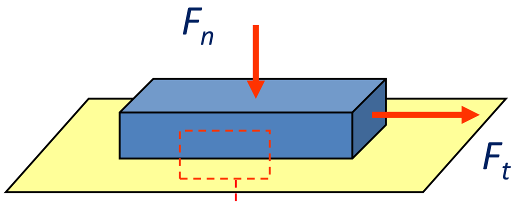
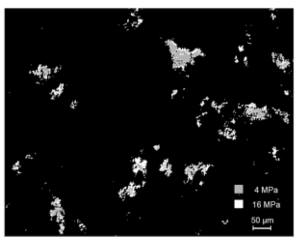
Friction between macroscopic bodies: a longstanding problem….



cm

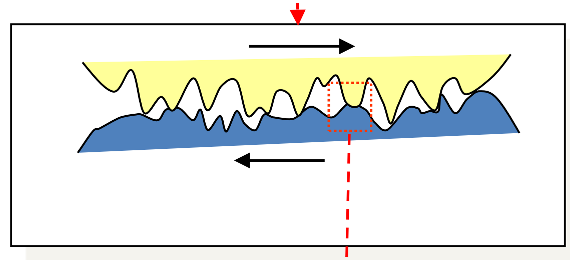
- **Surface geometry & contact mechanics**

Actual contact area << Apparent contact area



JH Dietrich & BD Kilgore, Technophys 1996

Surface roughness→ multi-contact interface



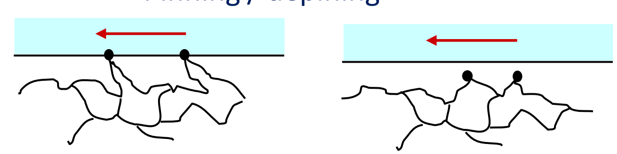
µm - cm

Bowden & Tabor , 1950's

- **Surface physical-chemistry**

Molecular scale dissipative processes

Pinning / depining



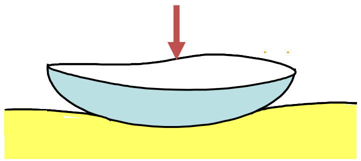
Rubbers

Schallamach, 1963

Rough contacts mechanics

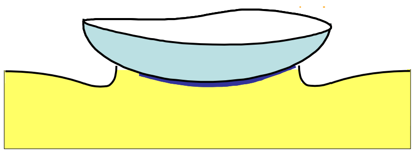
- Non adhesive single asperity elastic contacts

  Hertz (1881)



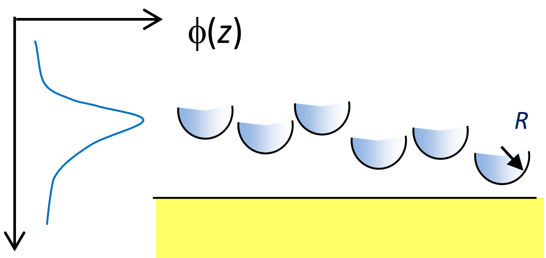
- Adhesive contact between smooth surfaces

  JKR & DMT (1971)



- Contact between nominally flat surfaces

  Greenwood & Williamson (1966)



Real contact area $A \propto P$

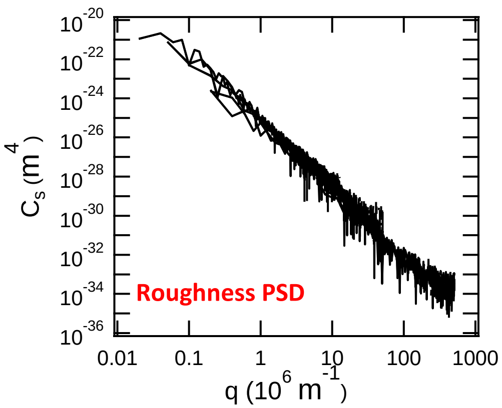
→ Justification of Amontons-Coulomb's friction law

→ Extensions to more complex geometries

Archard (1957), Ciavarella (2008)…

- Rough contact models based on a spectral description of surface topography

  Persson (2001), Robbins (2007) , Müser (2008)…



→ Extensions to friction and adhesive contacts

Scope

Transparent randomly rough surfaces consisting in distributions of spherical asperities (~50 µm)

GW type surfaces

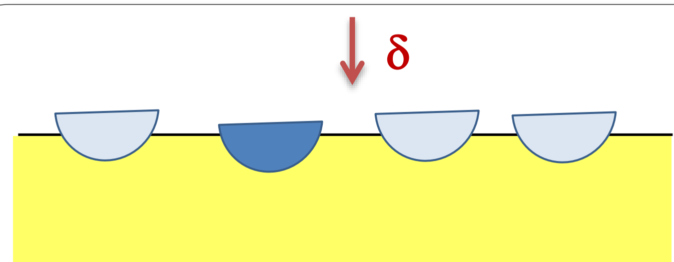
Imaging of micro-contacts distributions

Load dependence of the real contact area $A(P)$

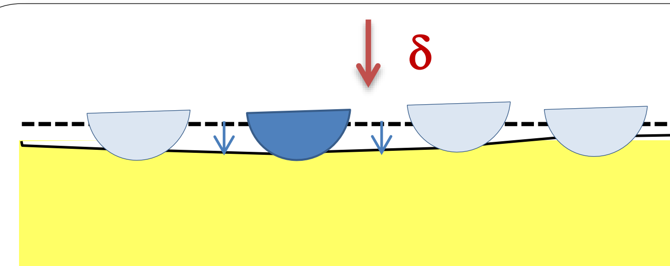
+

Statistical distributions of micro-contacts pressure and size

Role of elastic coupling between asperities ?



Without elastic coupling

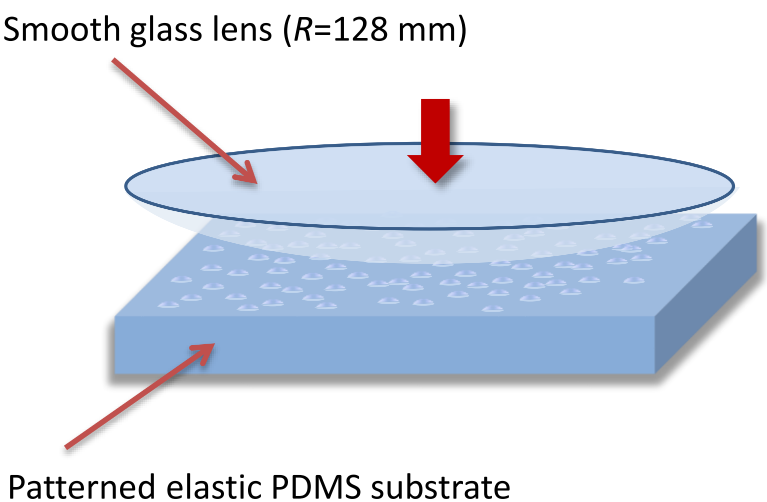


With elastic coupling

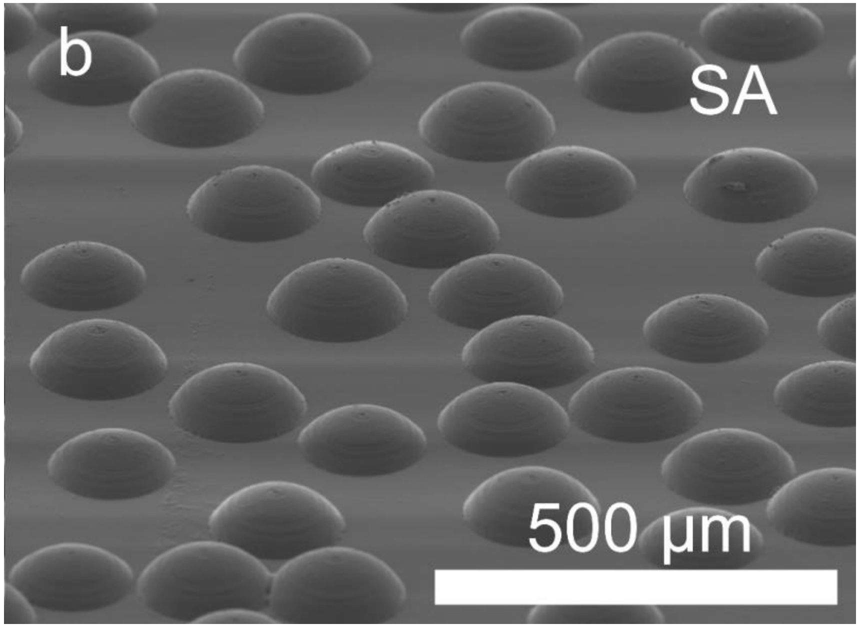
GW model

Patterned surfaces and associated sphere-on-plane contacts / I

- **Soft Asperities (SA) surfaces**



Surface density: ϕ = 0.1 and 0.4



Replication of a micro-machined PMMA template

- Lateral and height distributions of spherical asperities perfectly controlled by design

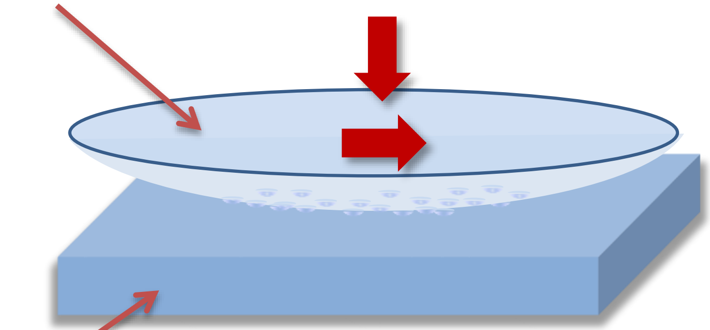
  → Uniform random height distribution (R=100 µm, 30 µm < height <60 µm)

- Small scale roughness on the micro-asperities → normal contact experiments only

Patterned surfaces and associated sphere-on-plane contacts /II

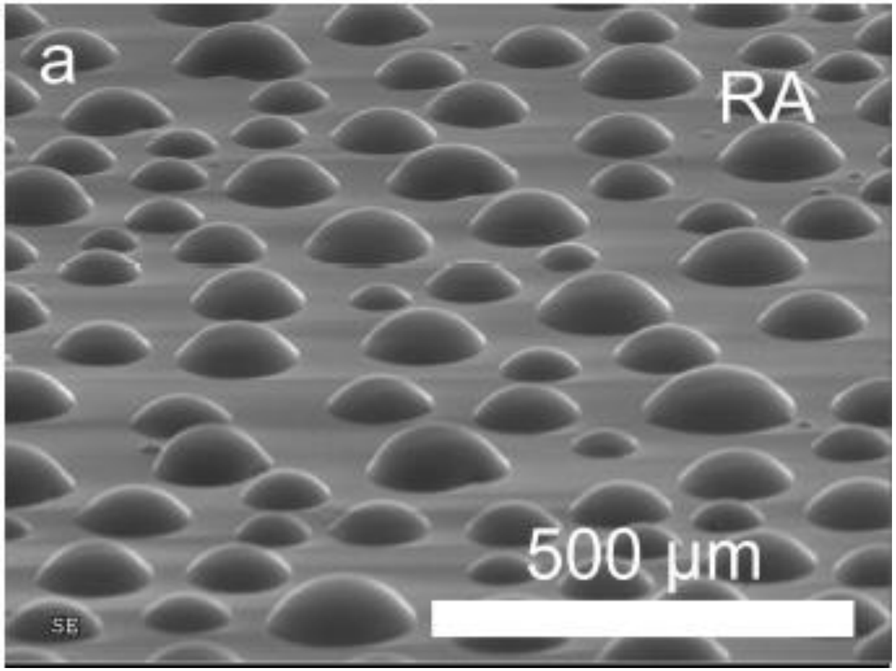
- **Rigid Asperities (RA) surfaces**

Patterned glass lens (*R*=13 mm)



smooth PDMS substrate

Surface density: ϕ=0.41

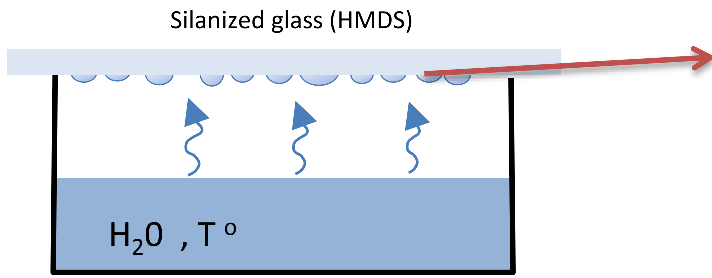


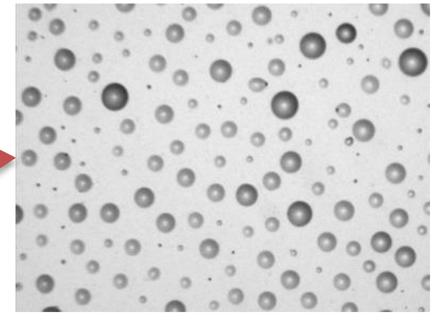
- Gaussian distribution of asperity sizes and heights (a posteriori characterization)
- Smooth micro-asperities → normal contact and friction experiments

Water droplet condensation method….

Fabrication of rigid asperities patterns by droplet condensation method

- 1. Water droplet condensation





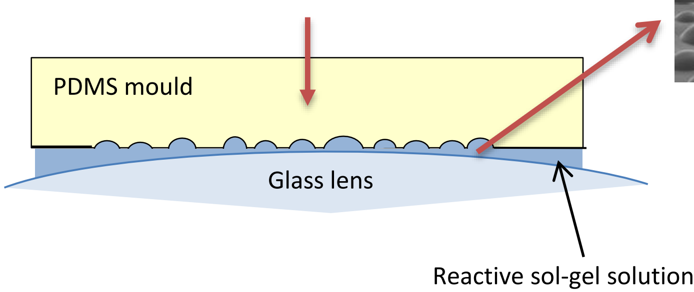
Time of exposure to water vapor

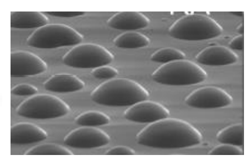
↓

Size of the droplets

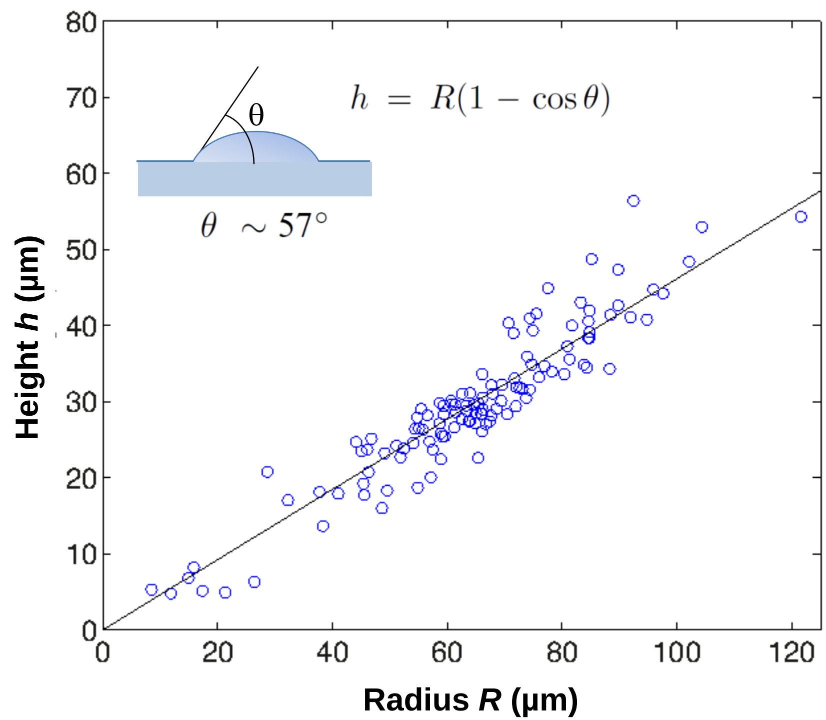
- 2. PDMS replica

- 3. Sol gel replica on a glass lens





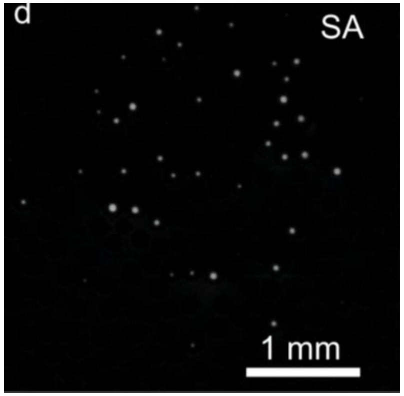
Shape of the asperities controlled by the contact angle



Contact devices

Contact imaging of micro-asperities contacts

✓ Contact radii & spatial distributions of micro-contacts (RA & SA surfaces)

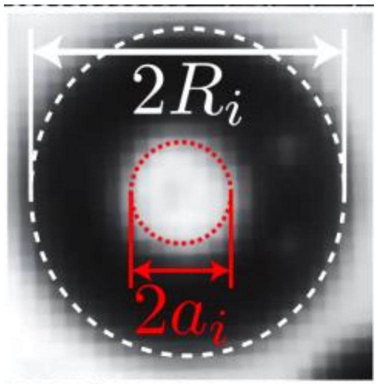


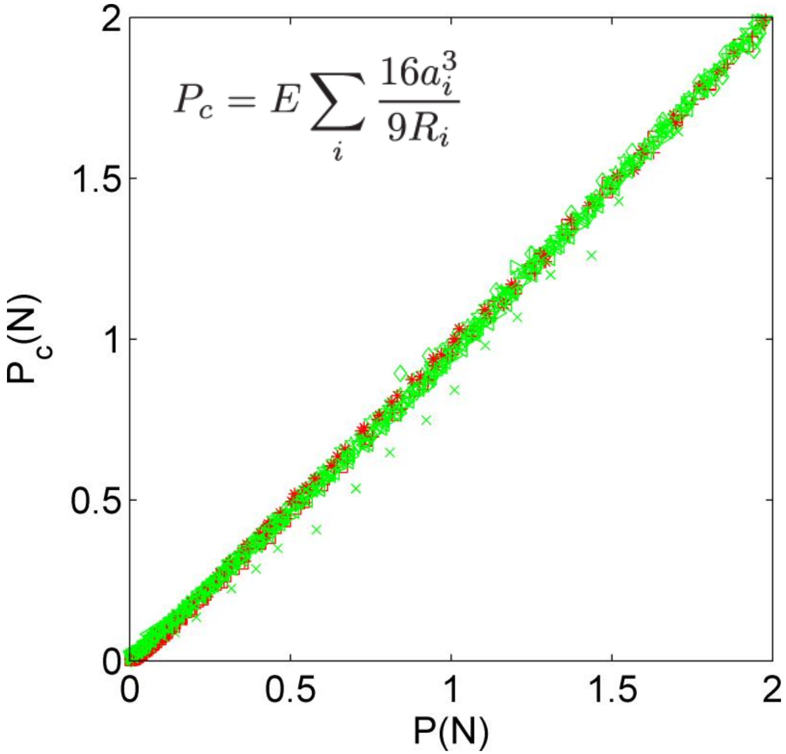
P=20 mN

✓ Contact pressure distribution (RA surfaces only)

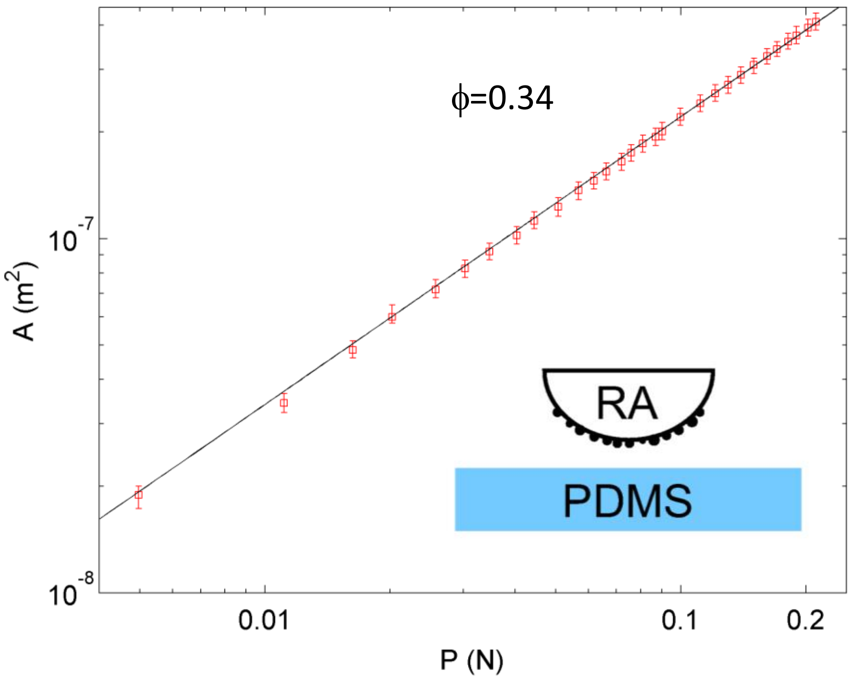
Hertz law assumed to be obeyed locally

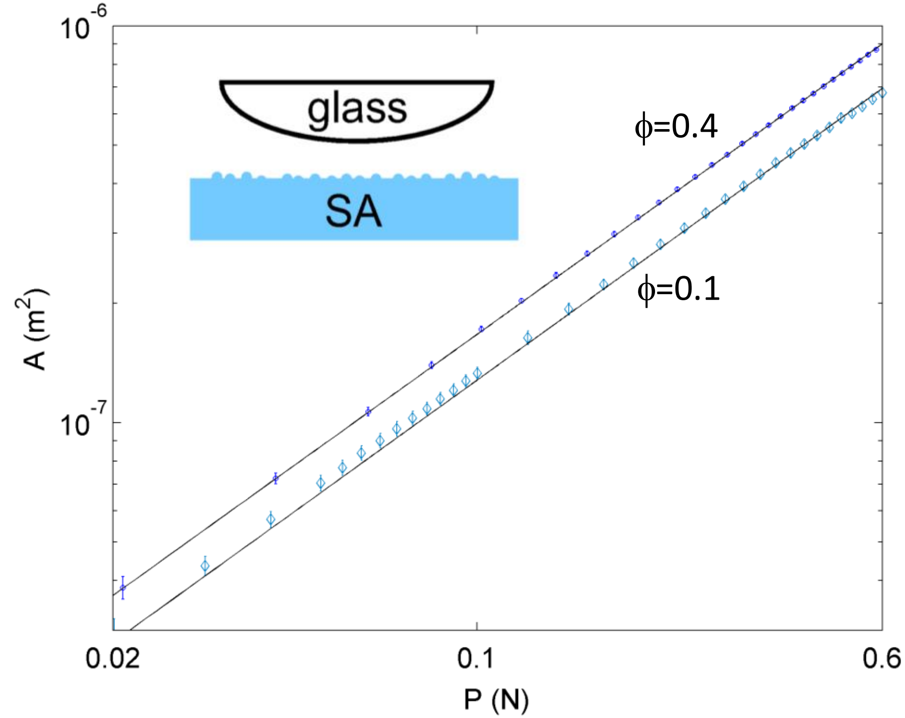
$$P_i = \frac{16a_i^3}{9R_i}$$





Load dependence of the real contact area *A*(*P*)





Power law dependence $A \propto P^n$

RA surface n=0.81 ± 0.01

SA surface n=0.94 ± 0.01 independent of surface density of micro-asperities

A(P) relationship: role of elastic interactions ?

- Modified form of the GW model : Ciavarella's model

Ciavarella, 2008

Indentation depth of the i^th micro-asperity contact:

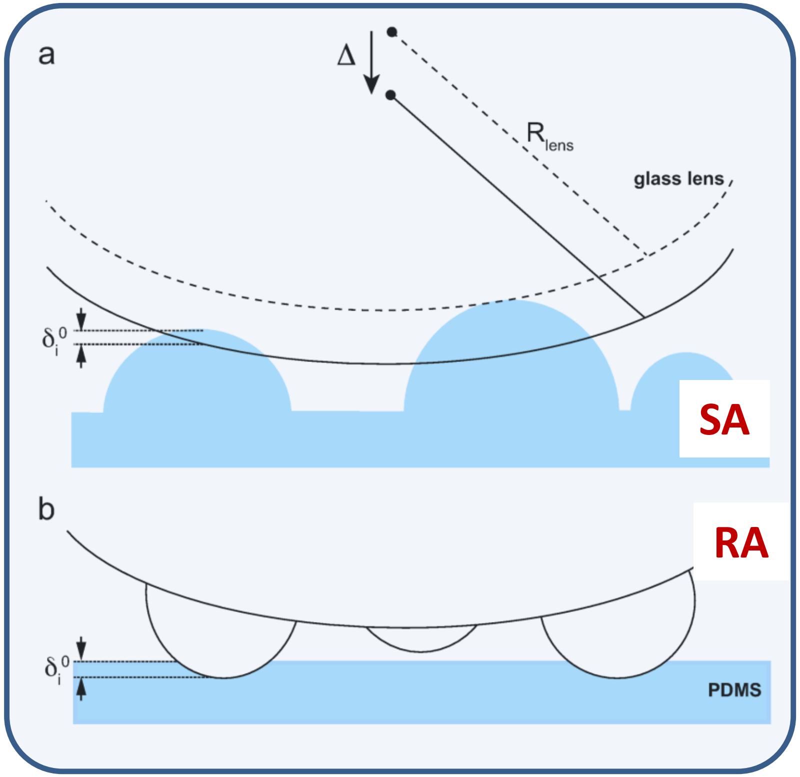
$$\delta_i = \underbrace{\delta_i^0}_{\text{Geometrical term}} + \underbrace{\sum_{j \neq i}^{N} \alpha_{ij} \delta_j^{3/2}}_{\text{Elastic interaction term}},$$

→ With elastic interactions

$$[\alpha_{ij}] = -\frac{4\sqrt{R_j}}{3\pi}\frac{1}{r_{ij}}, \quad i \neq j,$$

→ Without elastic interactions

$$[\alpha_{ij}] = 0$$



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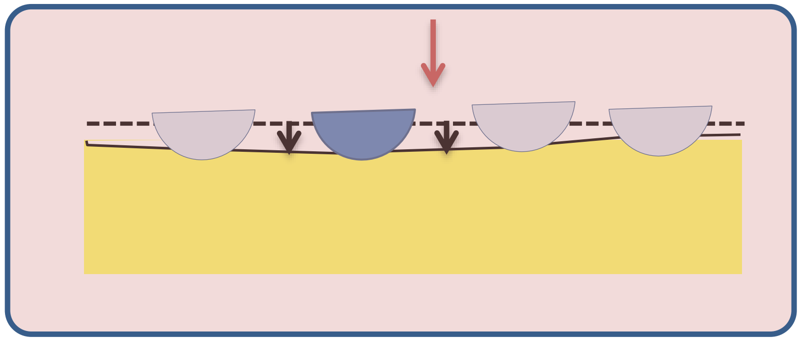
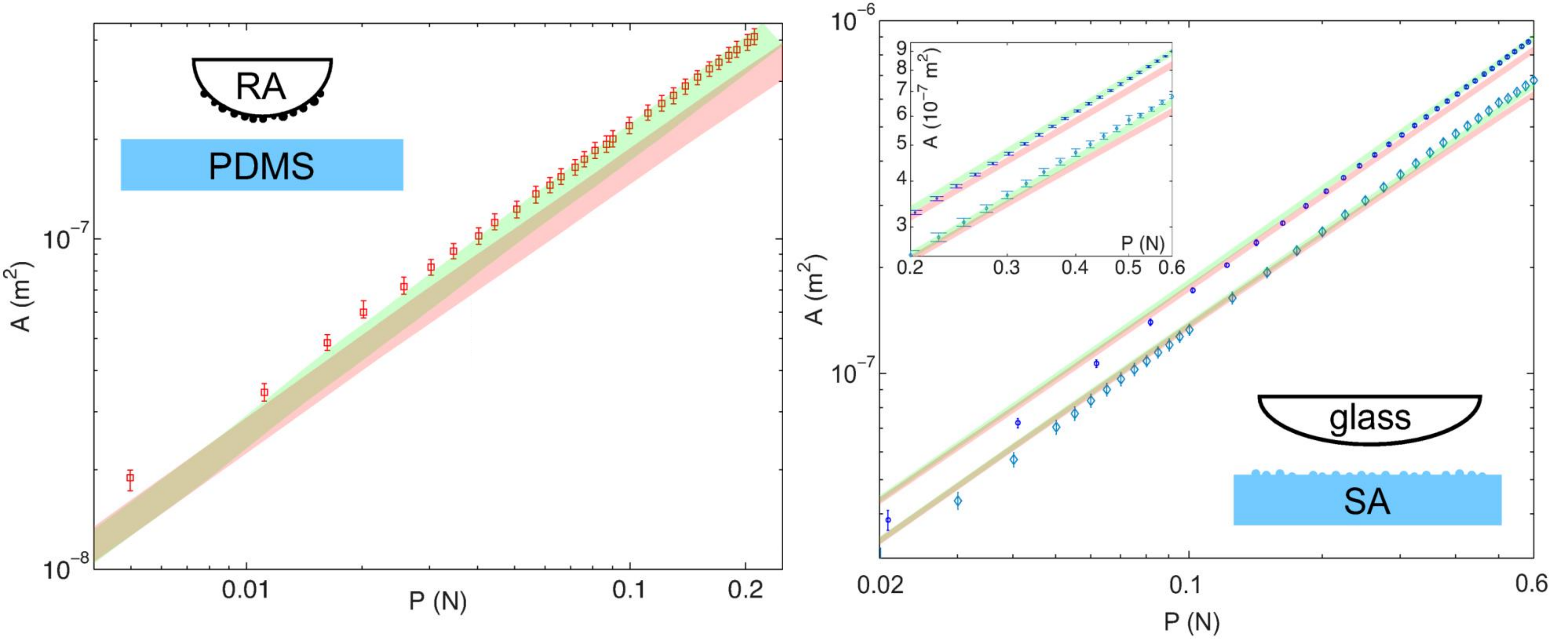


Calculated load dependence of the real contact area

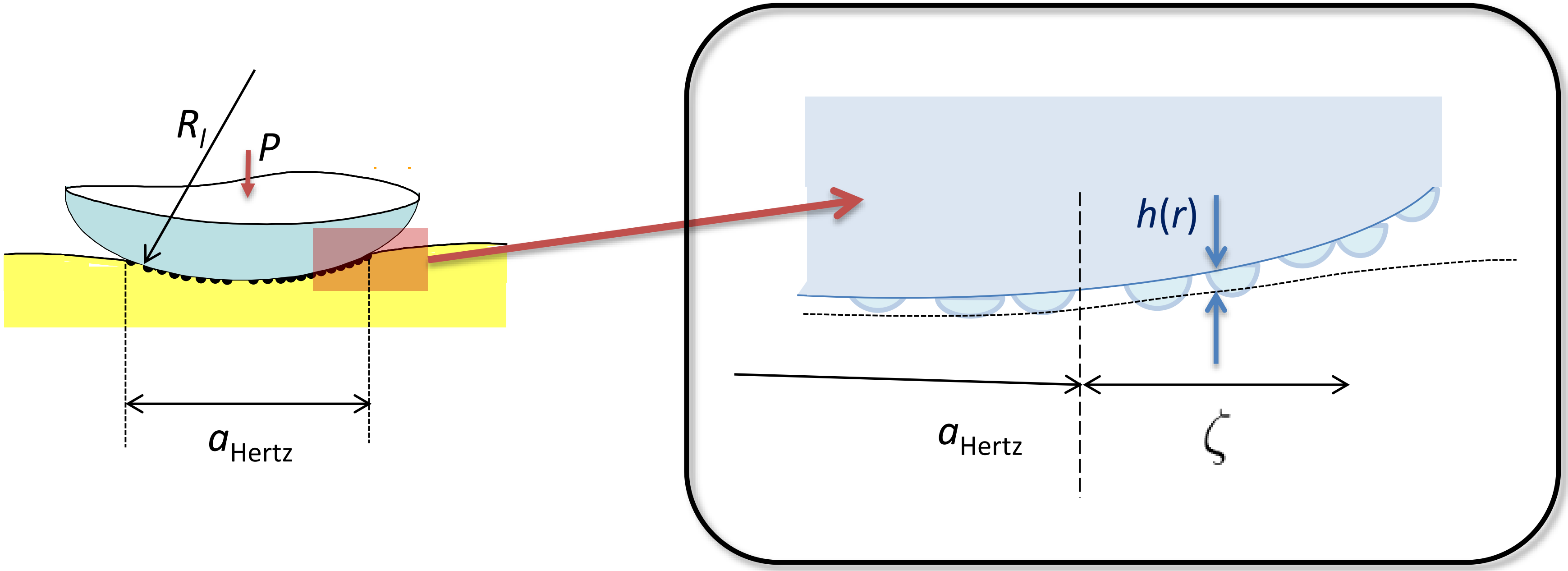


With elastic interactions $[\alpha_{ij}] \neq 0$

Without elastic interaction $[\alpha_{ij}] = 0$

Departure of the A(P) relationship from linearity

- Lens curvature effect



Gap between the nominal ~ micro-asperity size → $\zeta \propto P^{-1/9} R_l^{5/9}$

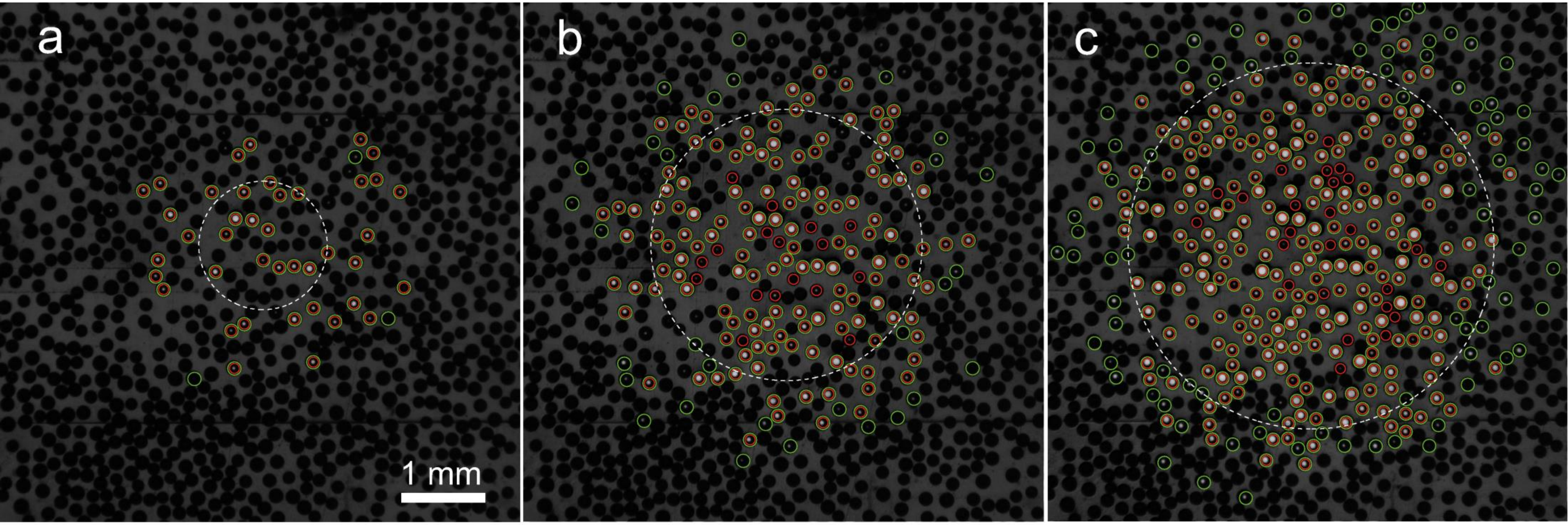
$A \propto P^n$

RA surface	R_l = 13 mm	n = 0.81
SA surface	R_l = 128 mm	n = 0.94

Micro-contacts spatial distributions

- **SA Surface**

P=0.02 N P=0.2 N P=0.5 N



Predictions from Ciavarella's model

$[\alpha_{ij}] \neq 0$

$[\alpha_{ij}] = 0$

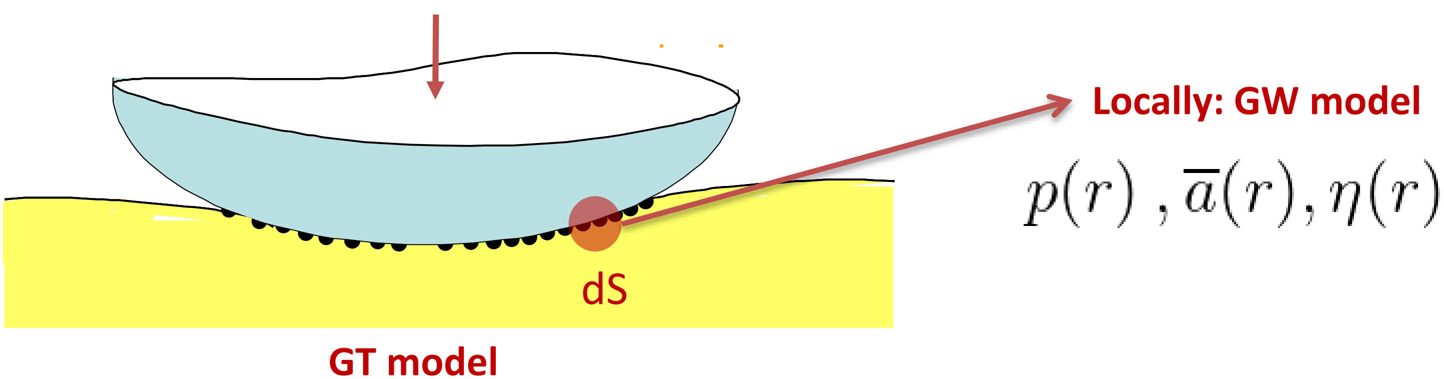
Contact pressure distribution $p(r)$

- **Experimentally** : summation of the local micro-contacts forces p_i within r and $r+dr$
  (averaging over more than 20 realizations of the SA contacts)

- **Theoretically**:

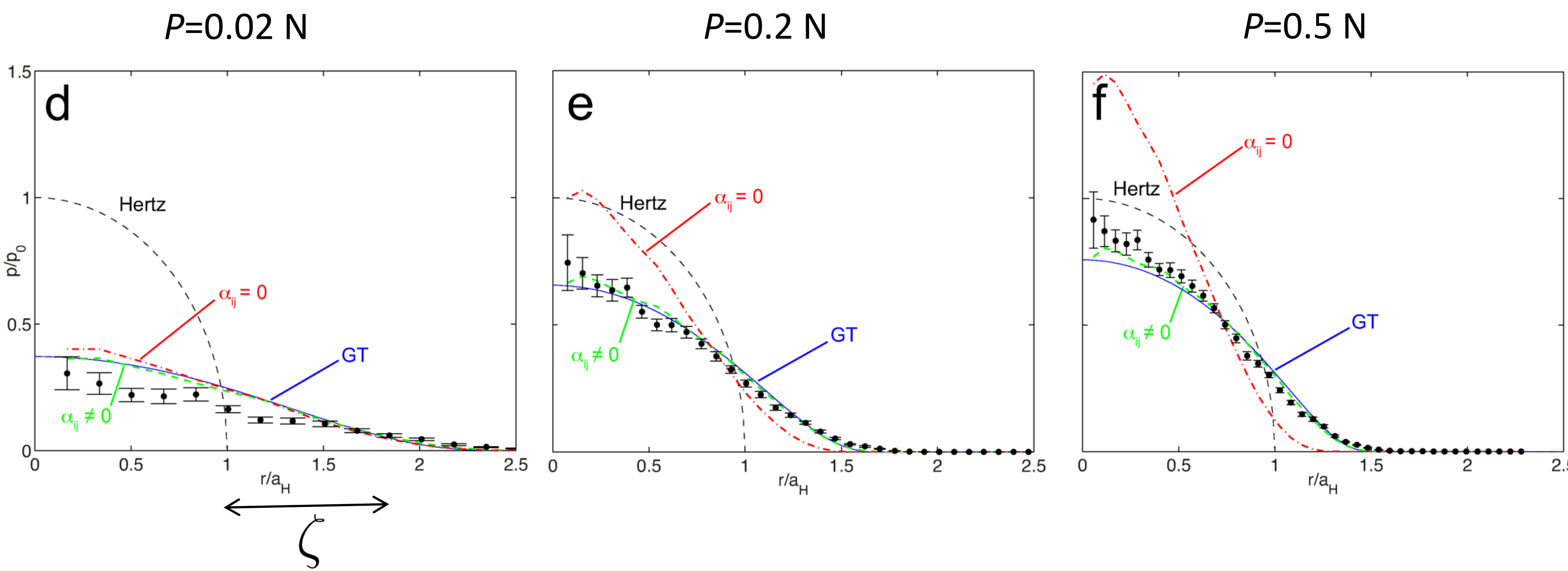
  → Ciavarella's model

  → **Extension of the GW model to the contact of rough spheres**
  Greenwood and Tripp (1967)



- **No short range elastic interaction** between neighboring micro-asperities
- **Long range elastic coupling** coming from the curvature of the nominal surfaces

Contact pressure profiles $p(r)$



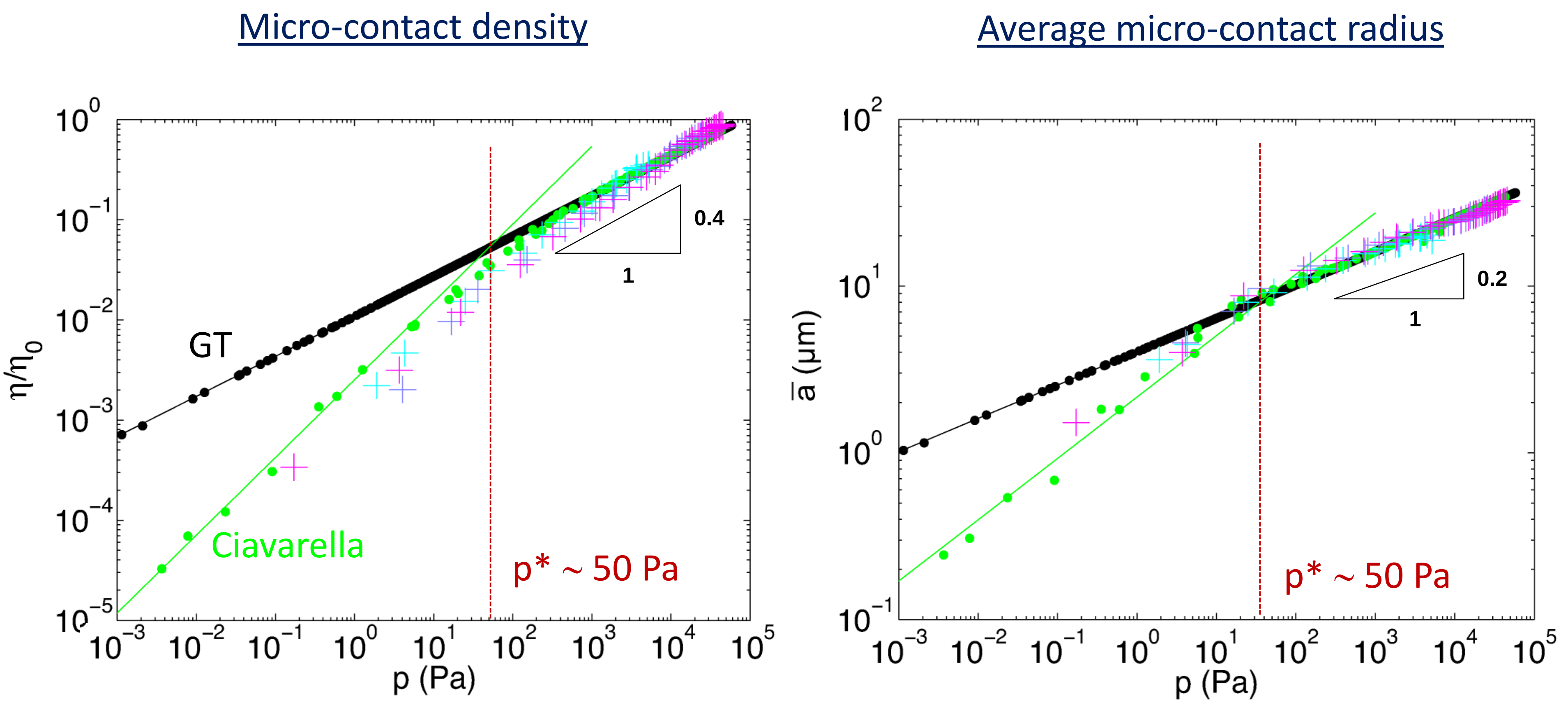
- Added tail to the Hertzian pressure distribution $\zeta \propto R^{5/9}\sigma^{2/3} \sim \sqrt{R\sigma}$

No significant difference between Ciavarella's and GT model

Short range elastic interactions does not affect the radial pressure distribution

What about the distribution of quantities from which $p(r)$ derives?

Micro-contacts density and average micro-contact radius



GW model for uniform random height distribution

$$\eta \propto p^{2/5}$$

$$\bar{a} \propto p^{1/5}$$

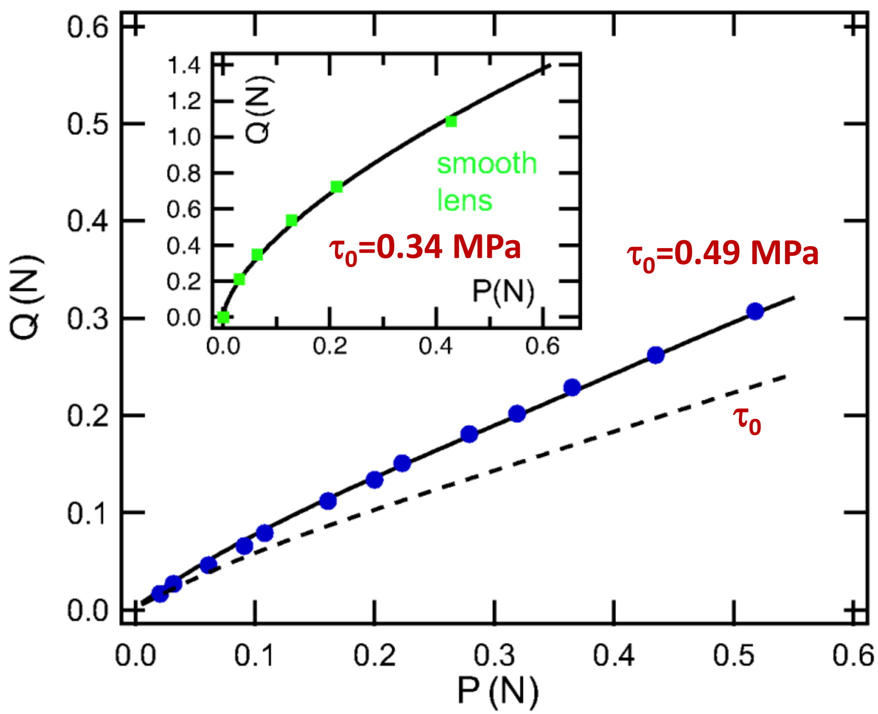
GW model obeyed over most of the contact pressure range

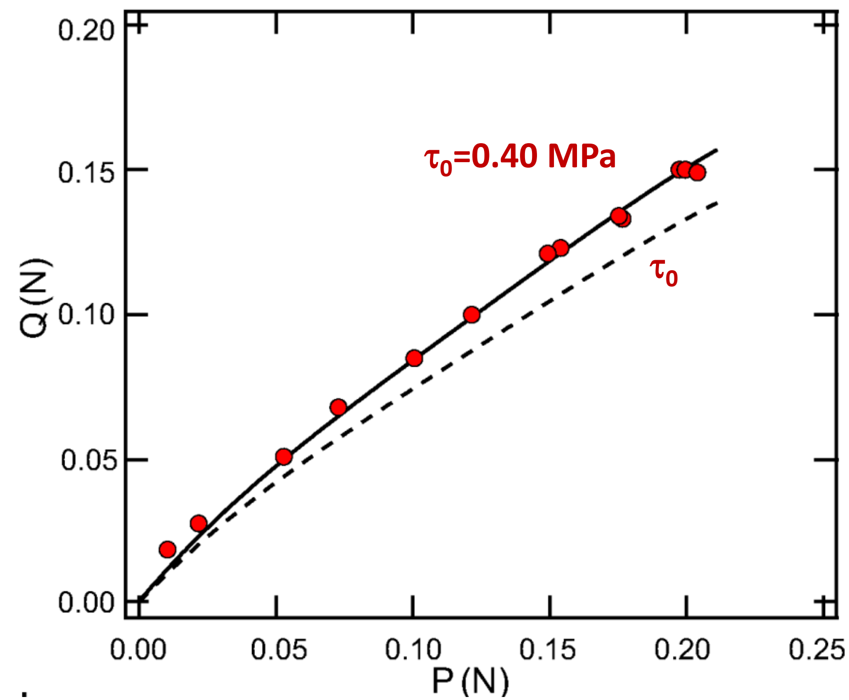
Frictional properties of RA surfaces

$\overline{R} = 64.4\ \mu m$

V =0.5 mm/s

$\overline{R} = 49.6\ \mu m$





Smooth lens : $F = \tau_0 A$ τ_0 pressure independent

Patterned lens: $F \neq \tau_0 A$ with $A = \sum_i (\pi a_i^2)$

Interface shear stress cannot simply be transposed at all length scales

Conclusion / Outlook

- **Normal contact** of model randomly rough surfaces reminiscent to GW model

→ Long range elastic interactions coming from the curved profile of the indenter
→ Short range interactions between neighboring micro-contacts negligible

Experimental validation of the GW Williamson model

Extension to more realistic surface roughness including fractal surfaces ??

→ Experiments with hierarchical surface roughness

- Preliminary **friction** results show that frictional stress measured at macroscopic length scales cannot simply be transposed to multi-contact interfaces

→ Dependence of rubber friction on surface stretching ??