Controlling the COF in CMP

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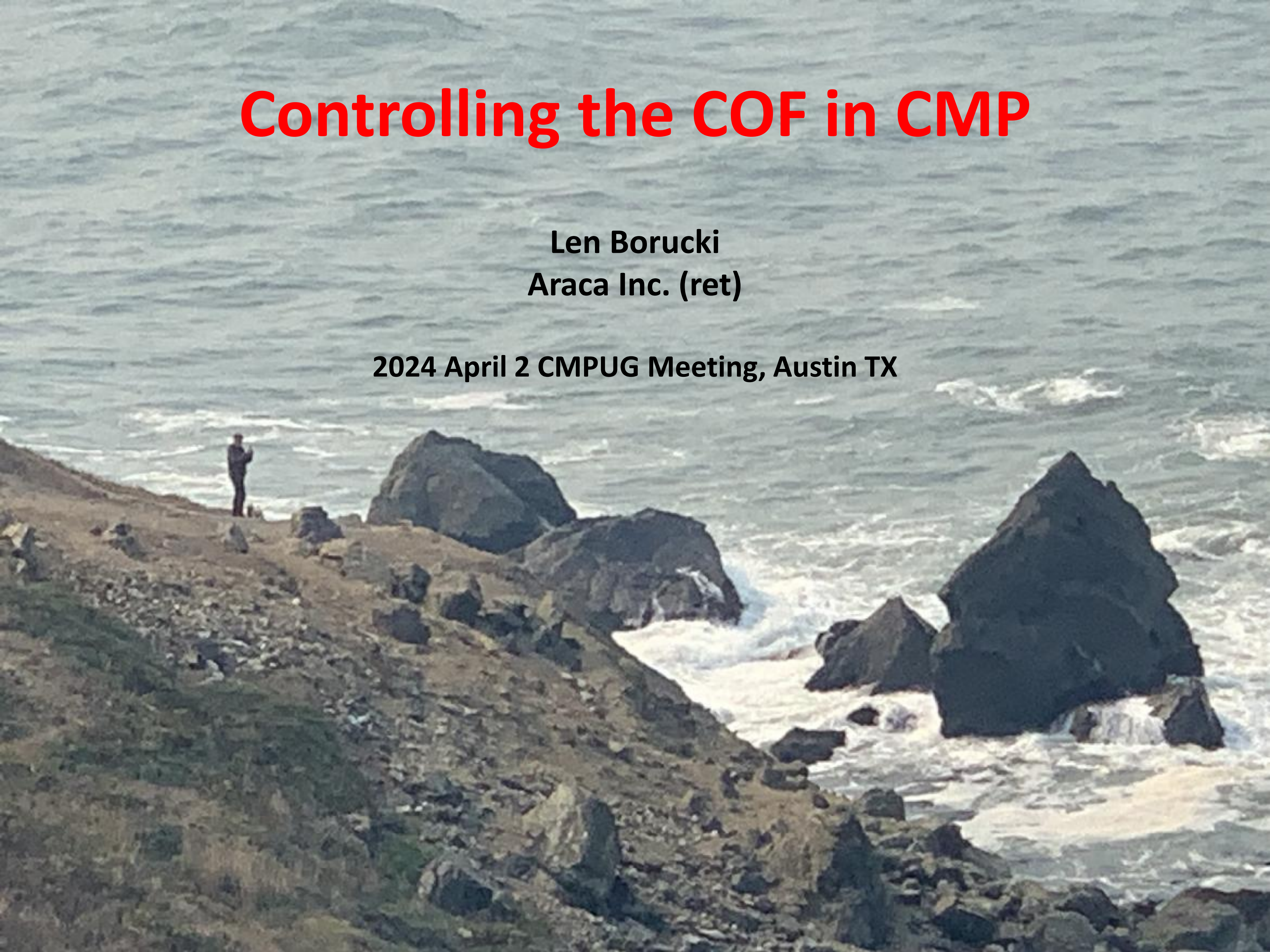
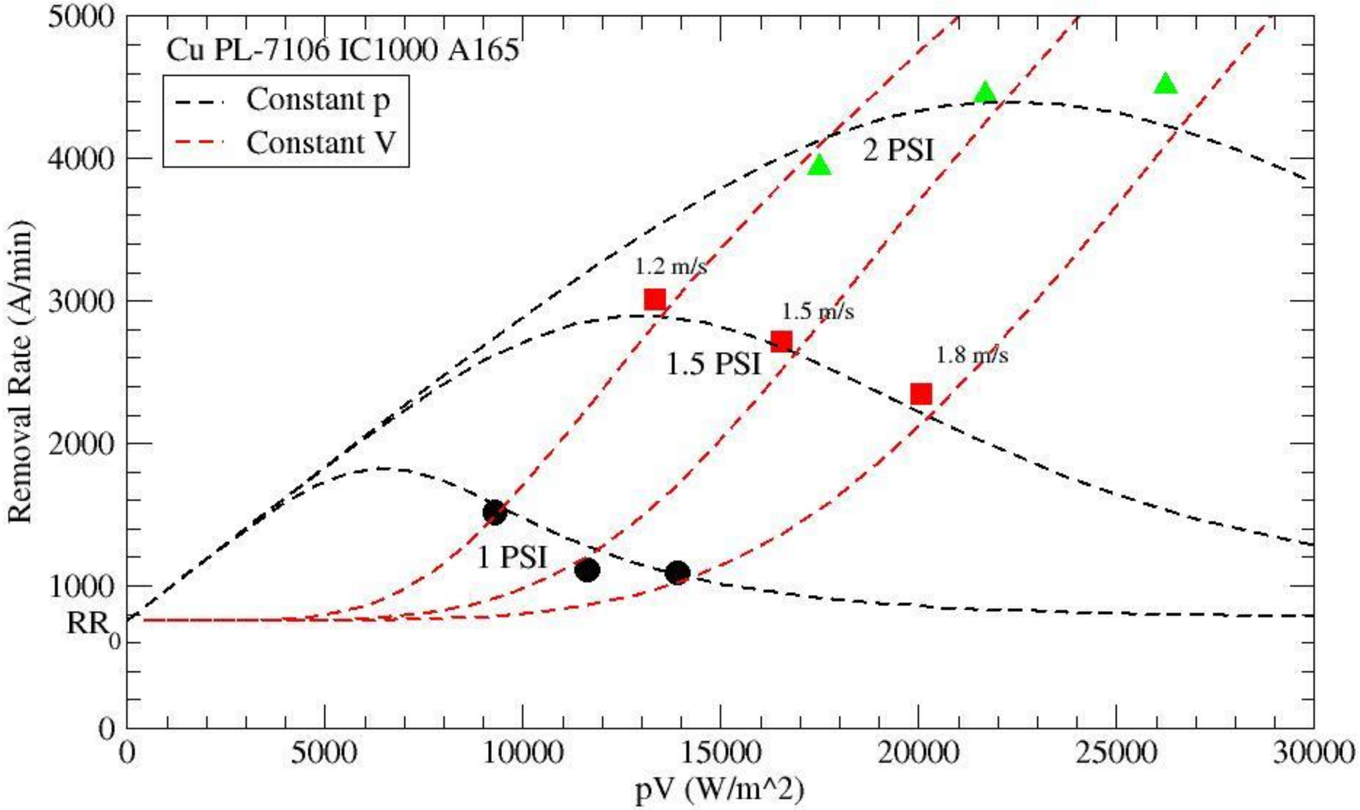


Significance of Friction in CMP

Accurate, explanatory RR models are possible if we take the pad/wafer COF into account.

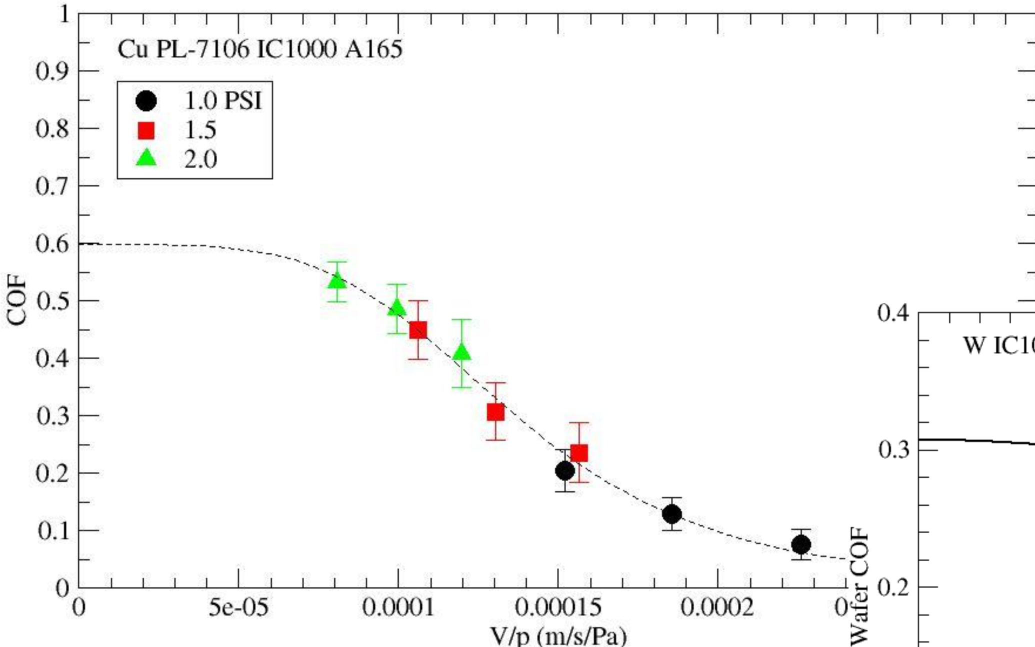
$$RR = RR_0 + c_p(V) \cdot \boldsymbol{COF(p,V)} \cdot p$$



L. Borucki, Y. Sampurno, A. Philipossian, ECS J. Solid State Sci. Technol. **12** 044003 (2023)

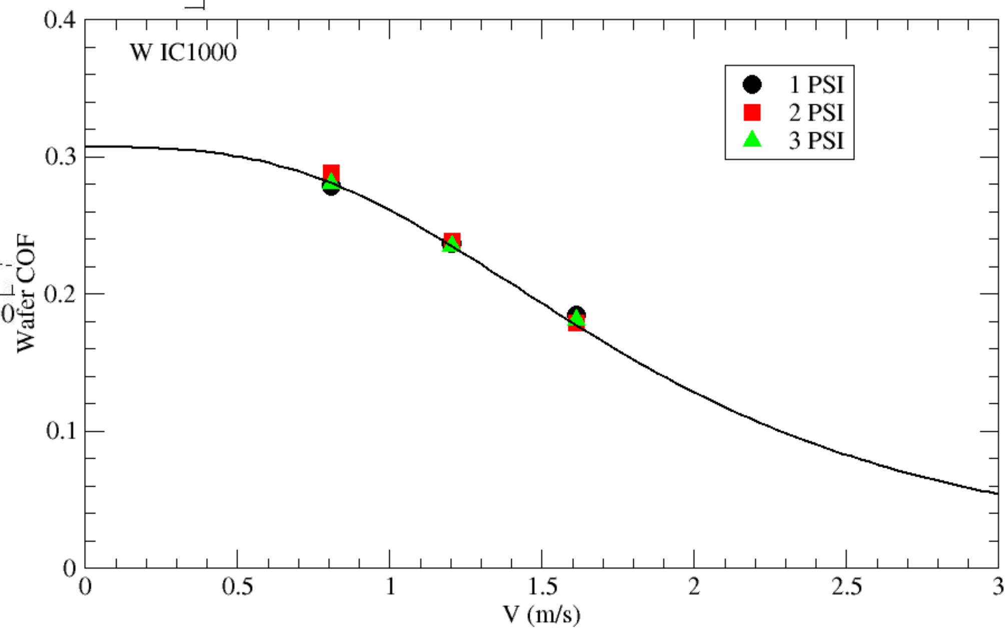
Measured Friction Coefficients

The COF often follows a Stribeck lubrication curve, but with quirks that are poorly understood.



$$\text{COF} = \frac{c_0}{1 + \left(b\,\frac{V}{p}\right)^{a}}$$

$$\text{Sommerfeld Number} = \frac{\mu_0 V}{\delta_0 p}$$



Independent of p!

Motivations for this Study

Understand how Stribeck curves work in CMP and how they relate to the process and consumables.

Explain the quirky behaviors.

Understand what we can do to change the COF if we need to.

What Kind of Tribological Problem is CMP?

Because there is slurry and the surfaces are wetted, it is a **lubrication problem**.

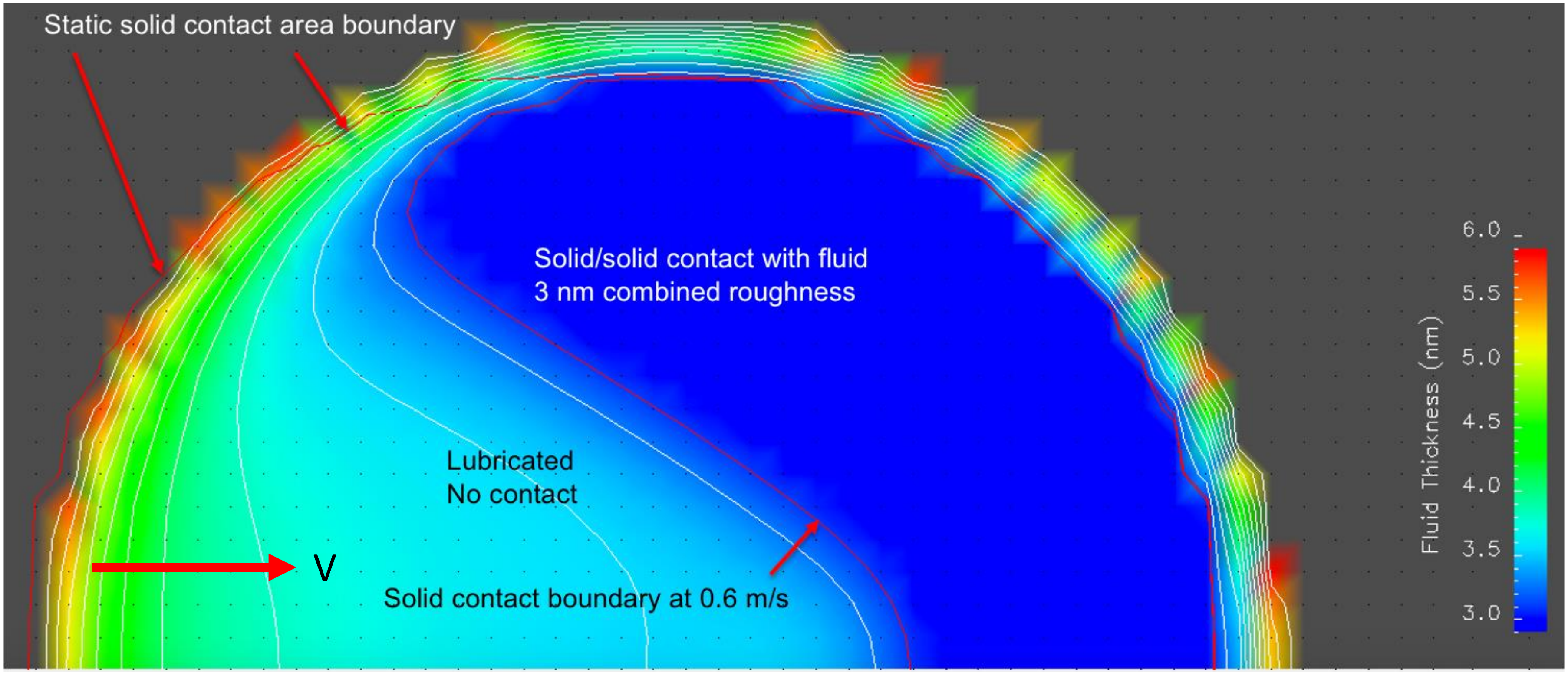
We know, experimentally, that there is pad-wafer contact, so it is then a **mixed lubrication problem**.

Both the pad and wafer surface change significantly during polishing (intentionally!), making it a **time-dependent mixed lubrication problem**.

And then it gets worse ….

Mixed Elastohydrodynamic Lubrication (EHL) Model

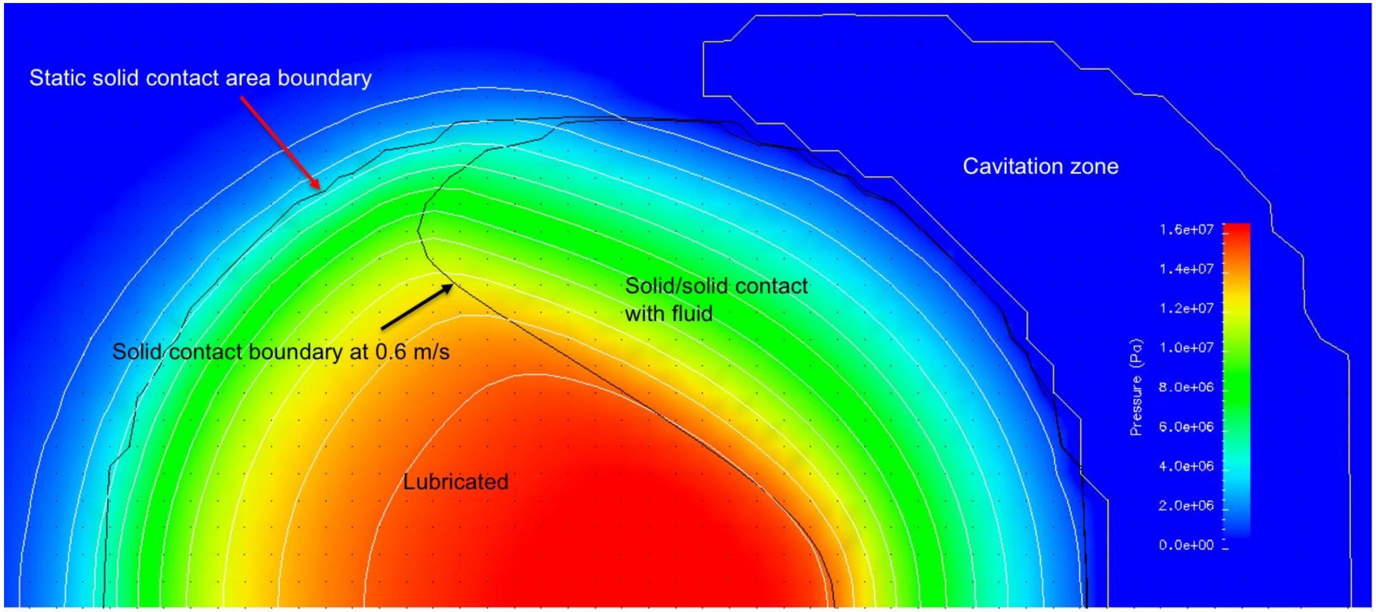
Example results from a coupled solution of the Reynolds and linear elasticity equations with CMP-relevant contact conditions and load balance.

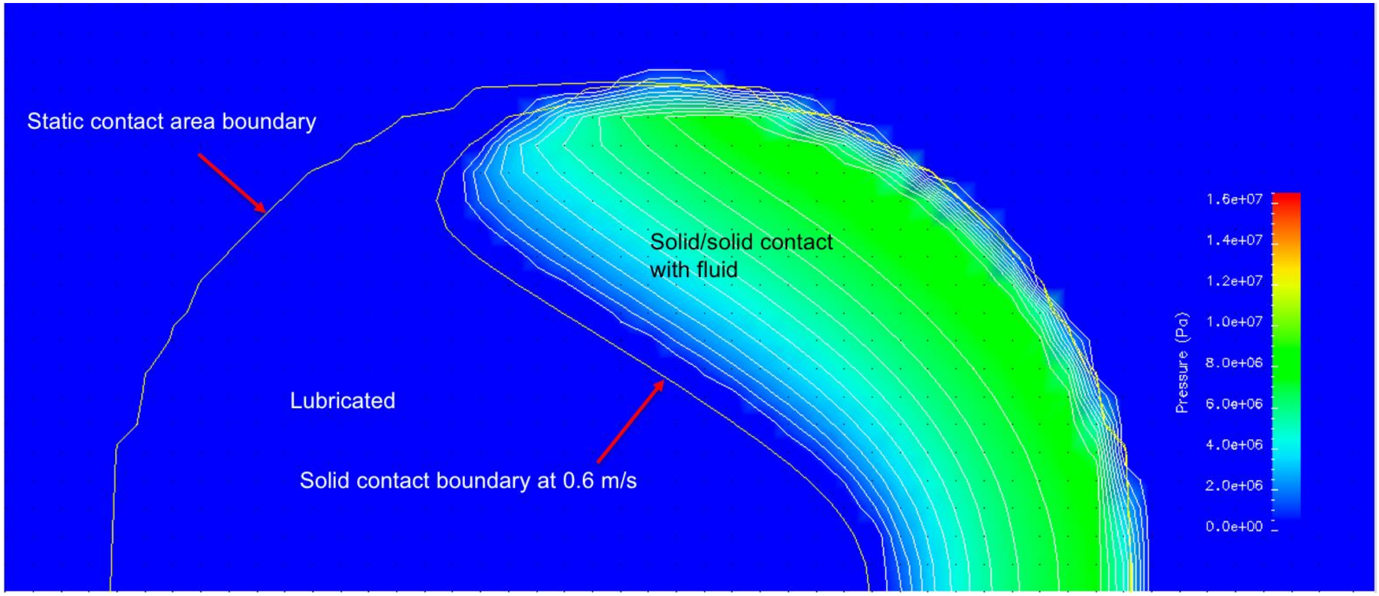


This example:

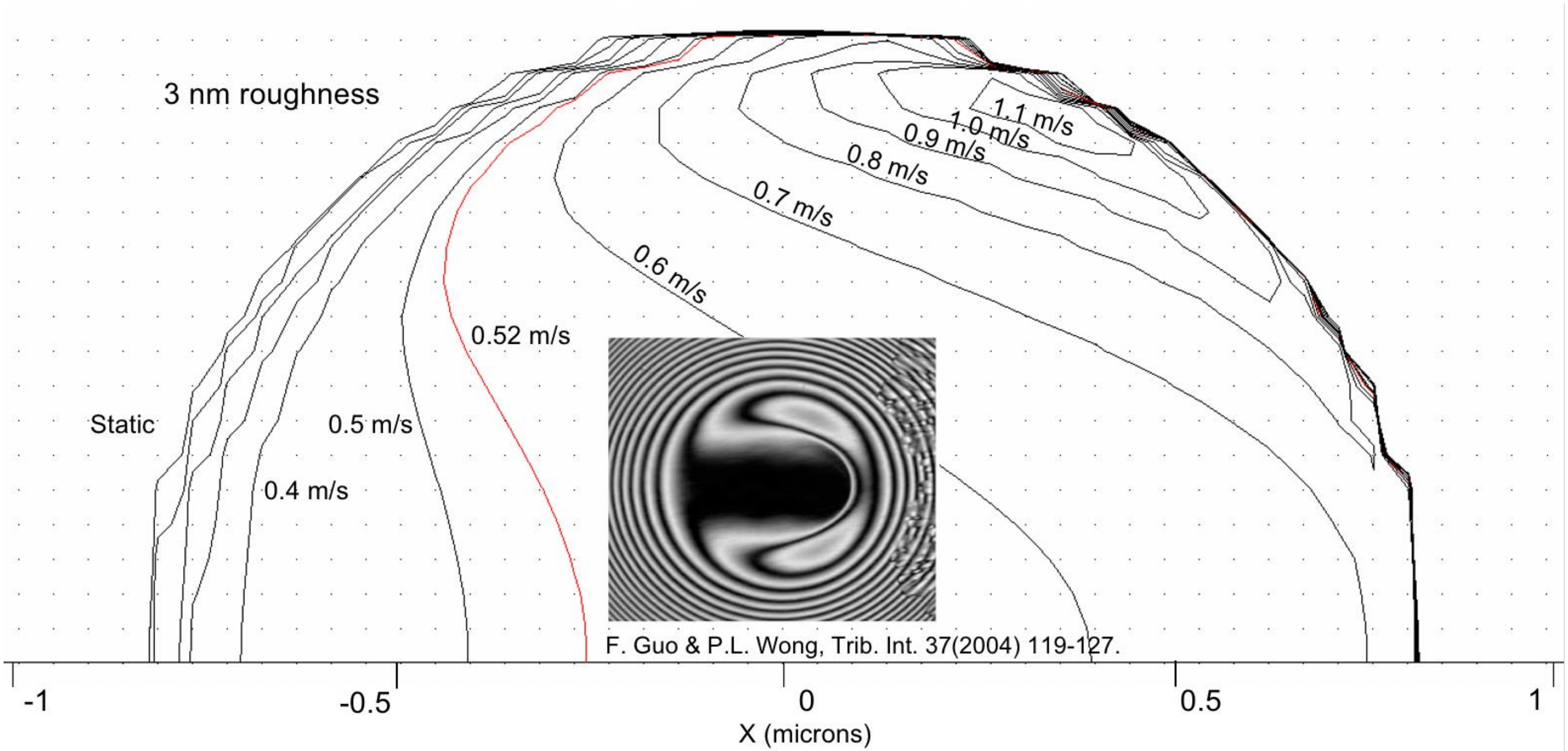
V = 0.6 m/s	50 μm tall parabolic (Hertzian) asperity
p = 0.4 PSI.	5 μm summit radius of curvature
Viscosity of water.	120 MPa elastic modulus, $\nu=0.25$

Fluid and Solid Contact Pressures



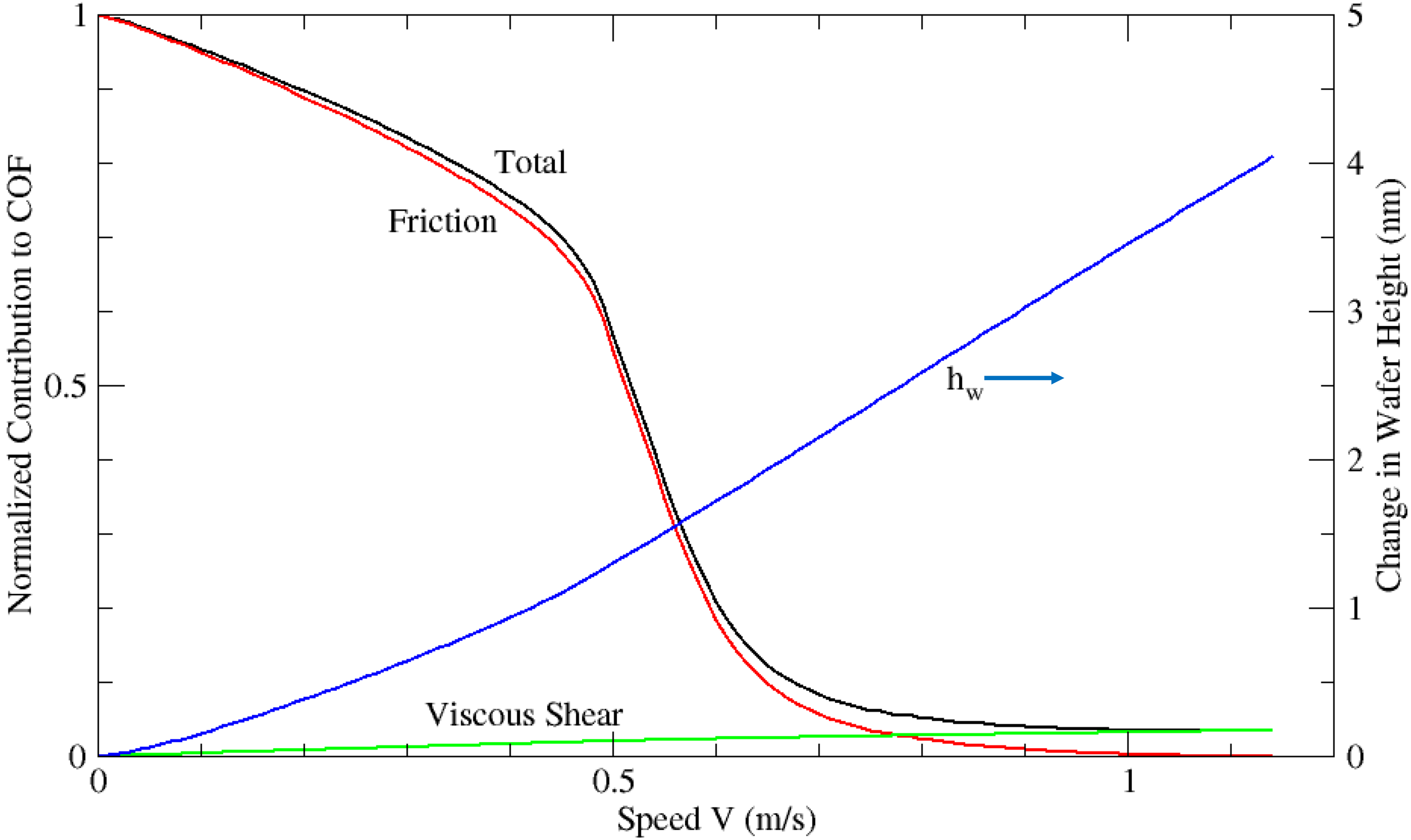


Variation of Contact Region C with Speed



Normalized Stribeck Curve

Normalized *frictional* contribution to the COF $= \dfrac{\iint_C \; p_s dA}{F}$ where $F = \dfrac{p}{\eta_c}$



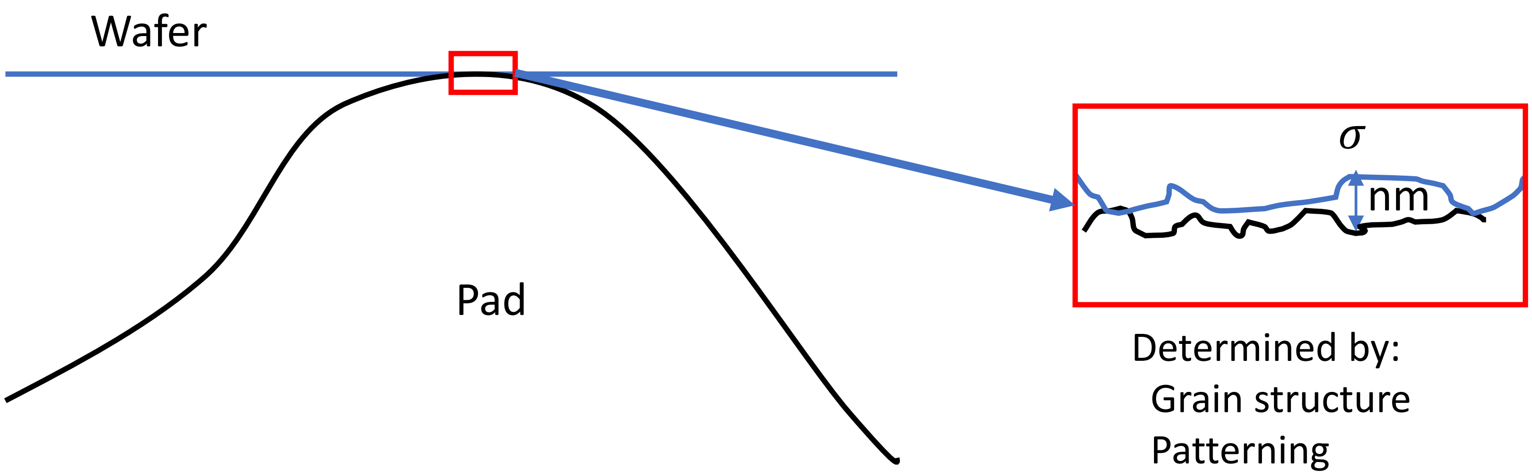
Physical Parameters

The model has six *physical* parameters, two of which are held constant here:

$\mu_0 = 10^{-3}$ Pa-s	Slurry viscosity (Newtonian).
$\nu = 0.25$	Pad Poisson ratio.
$E^* = E/(1-\nu^2)$	Effective pad modulus.
R	Contacting pad asperity radius of curvature.
σ	Combined roughness (minimum contact fluid thickness)
$F = \frac{p}{\eta_c}$	Applied force (or contact density) at pressure p.

Combined Roughness

Contacts contain fluid assumed to have a minimum thickness σ determined by the pad & wafer *nanoscale combined roughness*.



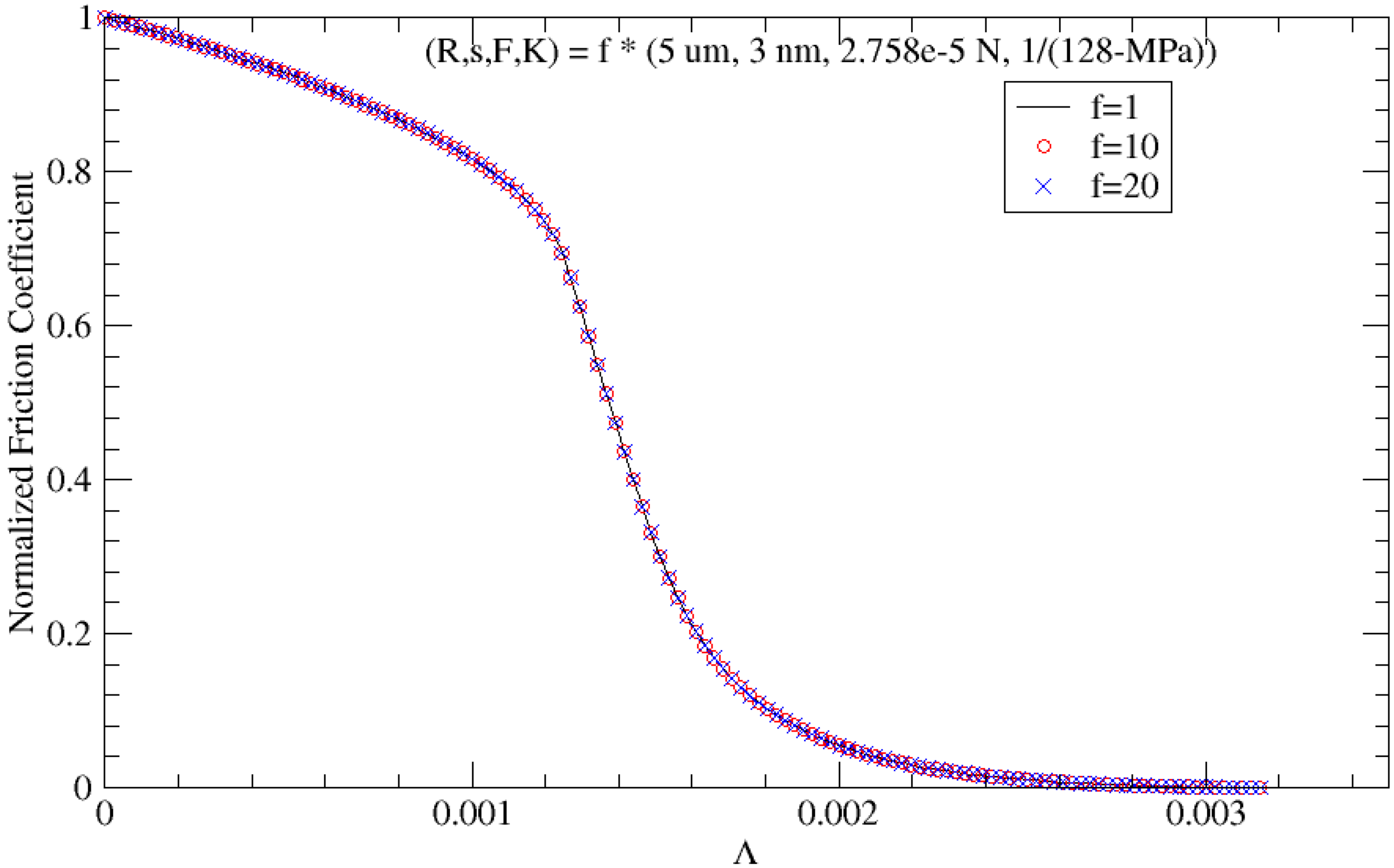
Determined by:
- Grain structure
- Patterning
- Wafer surface quality
- Pad plastic deformation
- Wear
- Conditioning
- Slurry particles

The minimum fluid-containing layer is treated as **incompressible**.

$\delta_0^E + \sigma \approx \delta_0$ (deformation with smooth surfaces)

Equivalent Sets of Parameters

Stribeck curves have a degeneracy – many sets of parameters produce the same curve!



Dimensionless Parameters

$$\Lambda = 6\sqrt{2}\frac{\mu_0 R^{1/2}}{(\delta_0^E)^{3/2}E^*}V \equiv \Lambda_1 V$$

Analog of the Sommerfeld number. Independent variable used for plotting.

$$\gamma = \frac{\delta_0^E}{R}$$

Ratio of elastic displacement to the radius of curvature

$$\chi = \frac{\sigma}{\delta_0^E}$$

Ratio of the combined roughness to the elastic displacement

$$\varphi = \frac{F}{\delta_0^E R E^*}$$

Normalized load

The last three parameters are *not independent* because δ_0^E depends on the other physical parameters.

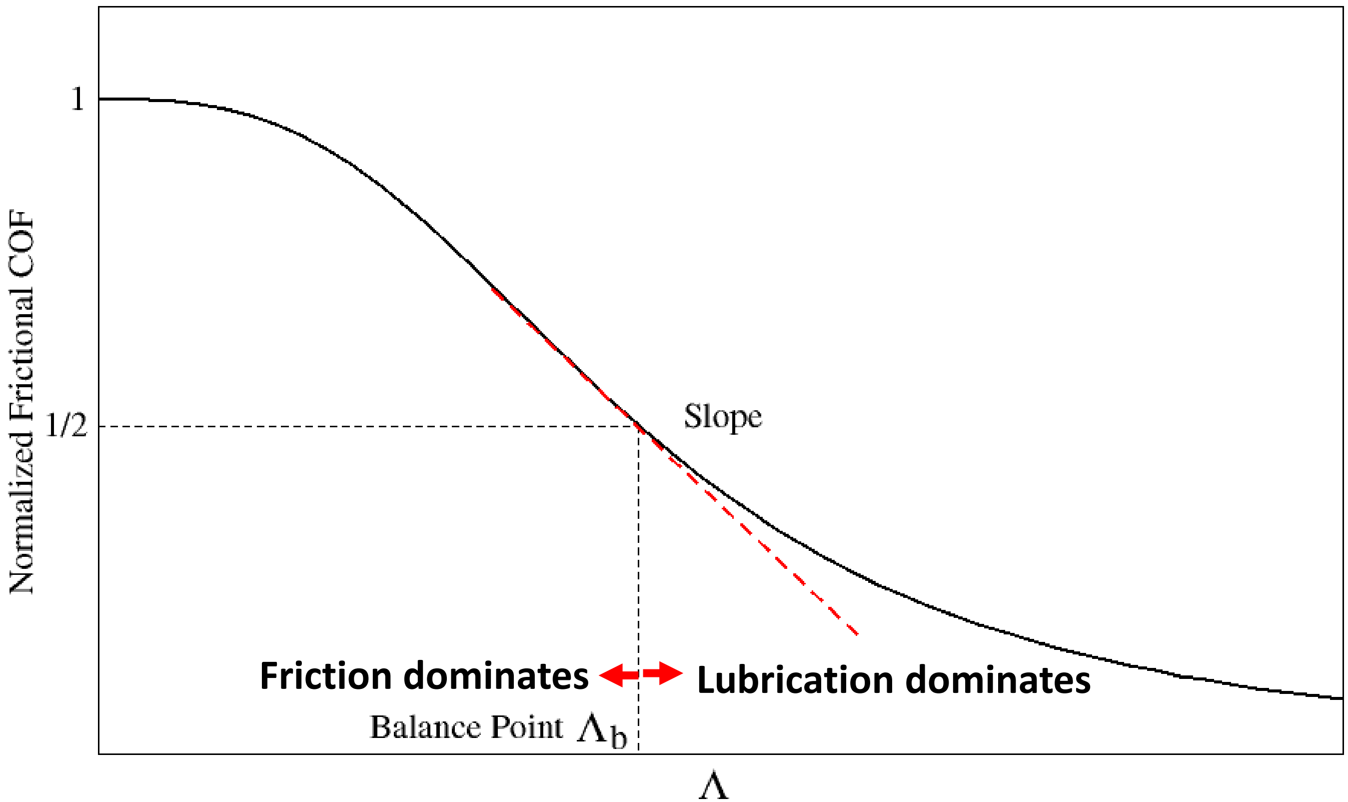
$$\chi = \left(\frac{3}{4}\gamma^{-1/2}\varphi\right)^{2/3} - 1$$

Stribeck Curve Characterization Method

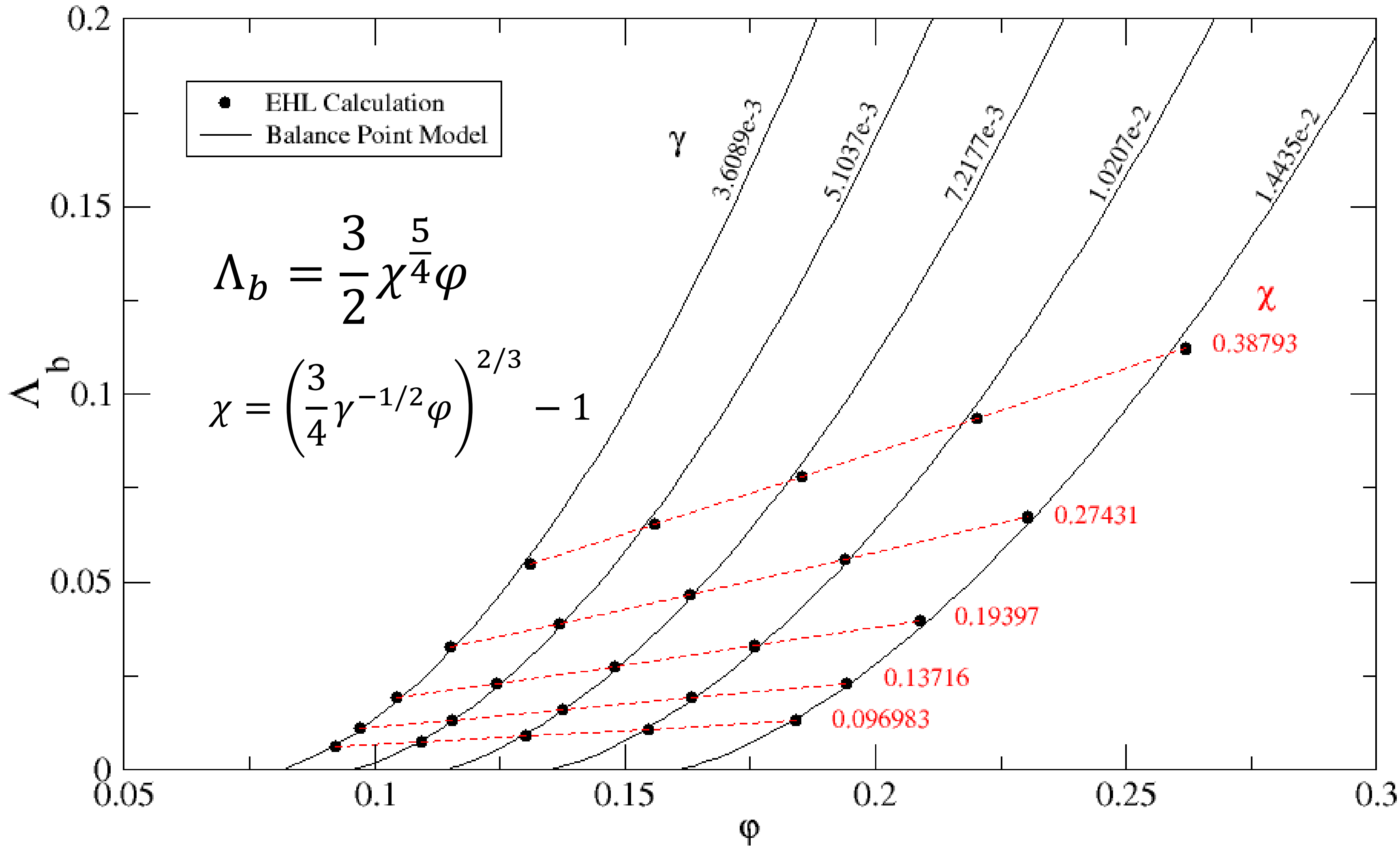
Construct a 5x5 point lattice (γ_i, χ_j) by varying two independent parameters.

Calculate the normalized frictional Stribeck curves $c_{ij}(\Lambda)$.

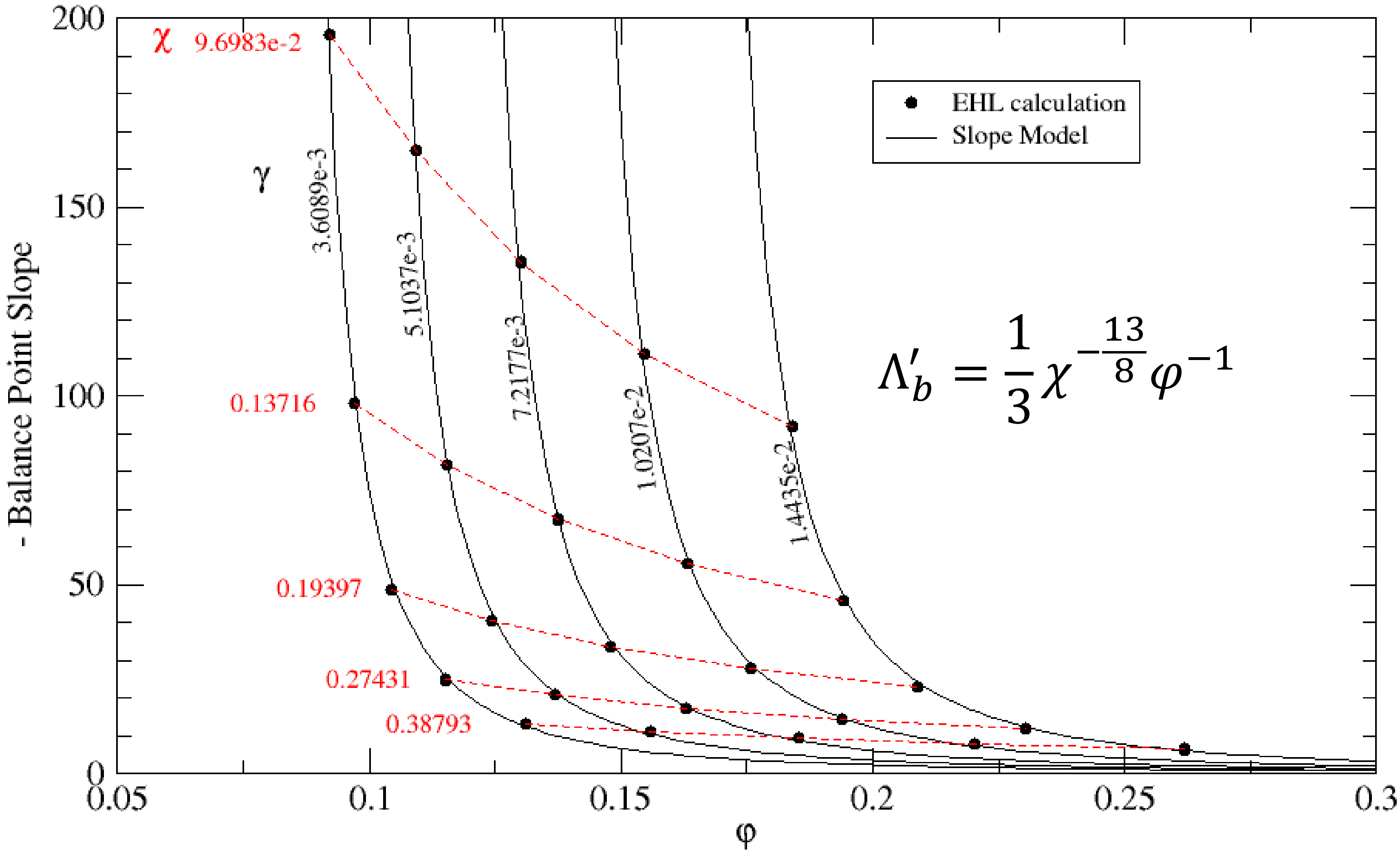
Extract the "balance point" in the tail and the slope at the balance point and characterize with compact formulas.



The Balance Point



The Balance Point Slope Magnitude



$$\Lambda_b' = \frac{1}{3}\chi^{-\frac{13}{8}}\varphi^{-1}$$

An Important Implication

The product of the balance point and the slope magnitude depends only on χ:

$$\Lambda_b \, \Lambda'_b = \frac{1}{2} \chi^{-\frac{3}{8}}$$

Furthermore, this also holds for the **physical** speed and slope since

$$V_b \, V'_b = \Lambda_b \, \Lambda'_b$$

Parameter Extraction

If we know the balance point speed and slope and know two other physical parameters, we can calculate *all* of the parameters for a Stribeck curve

$$V_b\, V_b' = \frac{1}{2}\chi^{-\frac{3}{8}}$$

$$\Lambda_b' = \frac{1}{3}\chi^{-\frac{13}{8}}\varphi^{-1} \quad \longleftrightarrow \quad \Lambda_1 = 3V_b'\chi^{\frac{13}{8}}\varphi$$

$$\Lambda_1 = 6\sqrt{2}\,\frac{\mu_0 R^{1/2}}{(\delta_0^E)^{3/2}E^*}$$

Consistency requires that $\gamma = 8\left(\frac{R}{F}\frac{\mu_0}{V_b'}\right)^2 \chi^{-13/4} \longrightarrow \varphi = \frac{4}{3}\gamma^{1/2}(1+\chi)^{3/2}$

$$\delta_0^E = \gamma R$$

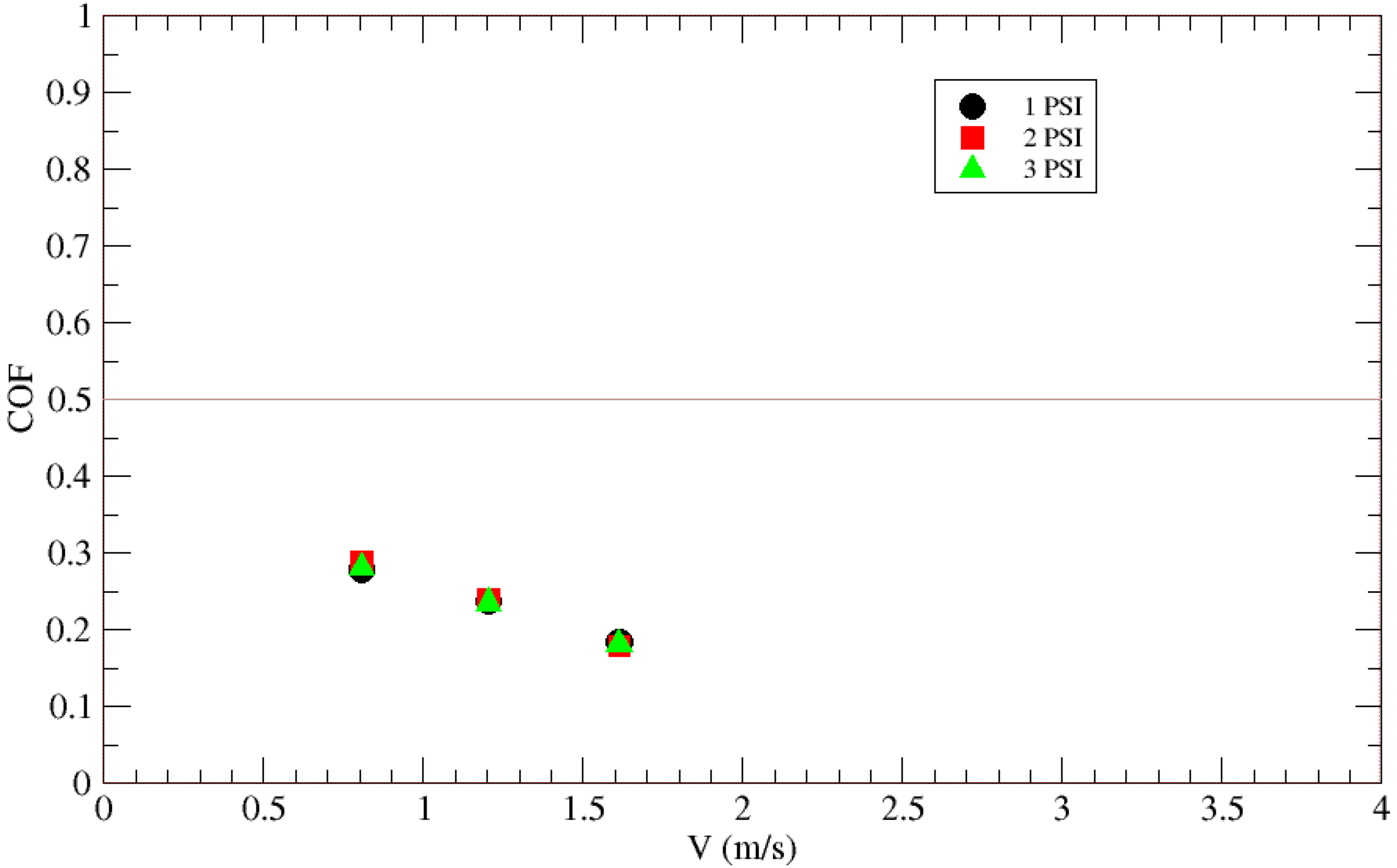
$$\sigma = \chi\gamma R$$

$$E^* = \frac{F}{\gamma\varphi R^2}$$

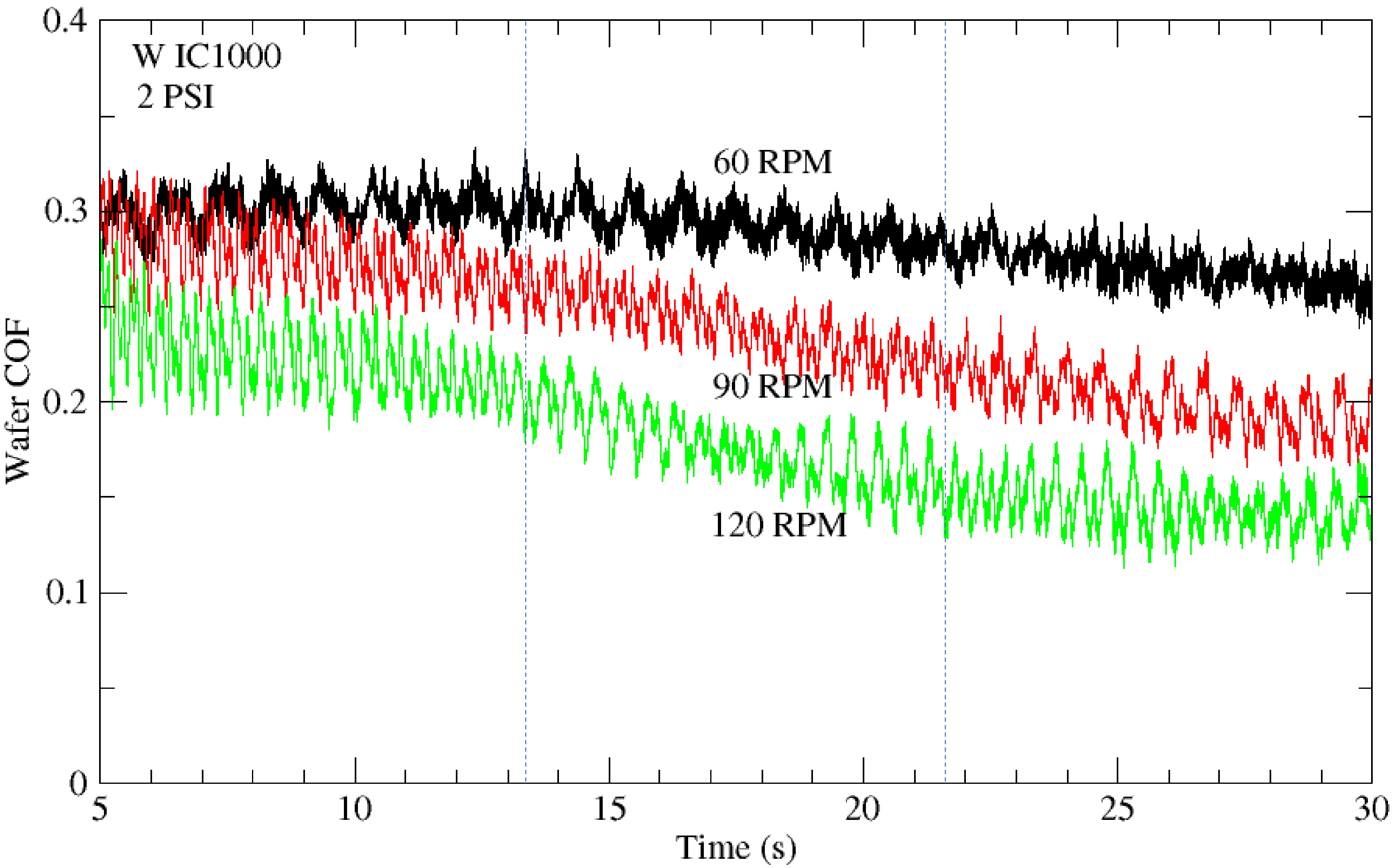
Thus, if we know E and F, we can solve for R and determine everything else.

Analysis of a Real Stribeck Curve

***Ex-situ* W buff**: pre-polished wafers, IC-1000, commercial slurry, 3p x 3V, 30 s, Araca RDP-500.



Time Dependence



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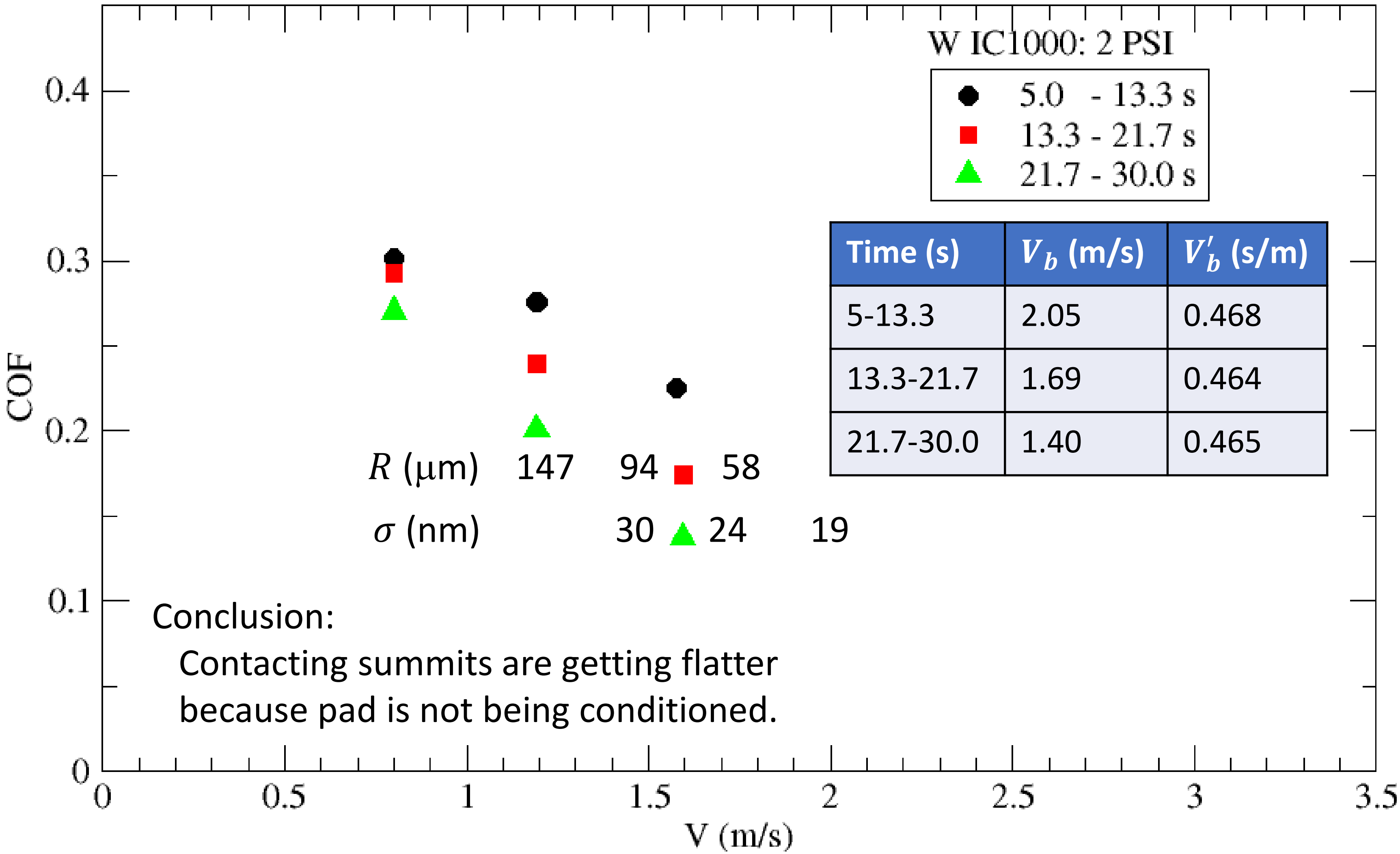


Time (s)	V_b (m/s)	V'_b (s/m)
5-13.3	2.05	0.468
13.3-21.7	1.69	0.464
21.7-30.0	1.40	0.465

Conclusion:

Contacting summits are getting flatter because pad is not being conditioned.

Final Remarks

It is difficult to model friction in CMP, but the theory is looking hopeful.

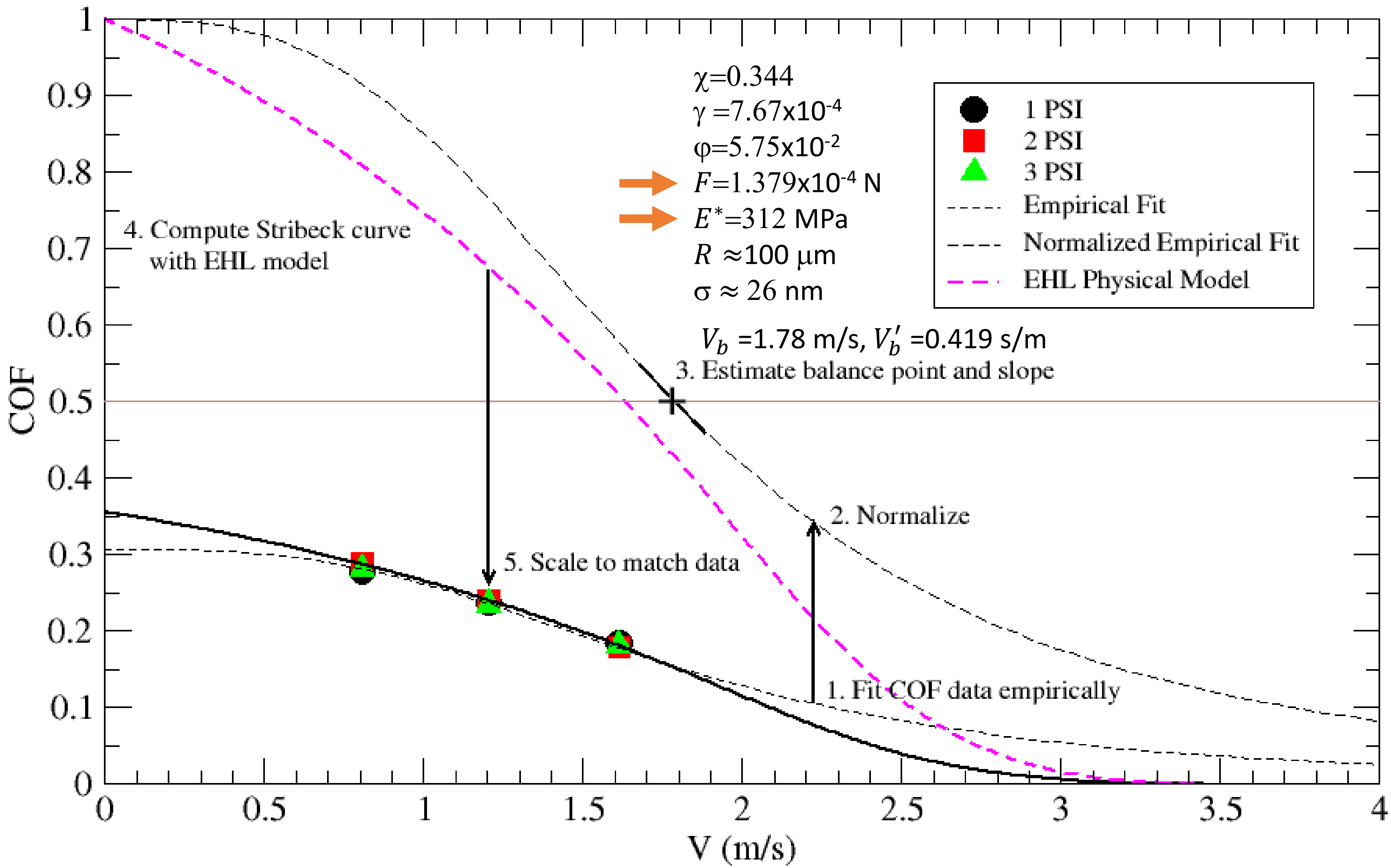
The approach presented here agrees with and explains some of the more basic friction observations.

While idealized asperities were used to model data from conventional pads, the EHL software is much more general and is particularly suited to studying friction for microreplicated pads.

Thank You!

Static Backup Slides

Analysis of Real COF Data



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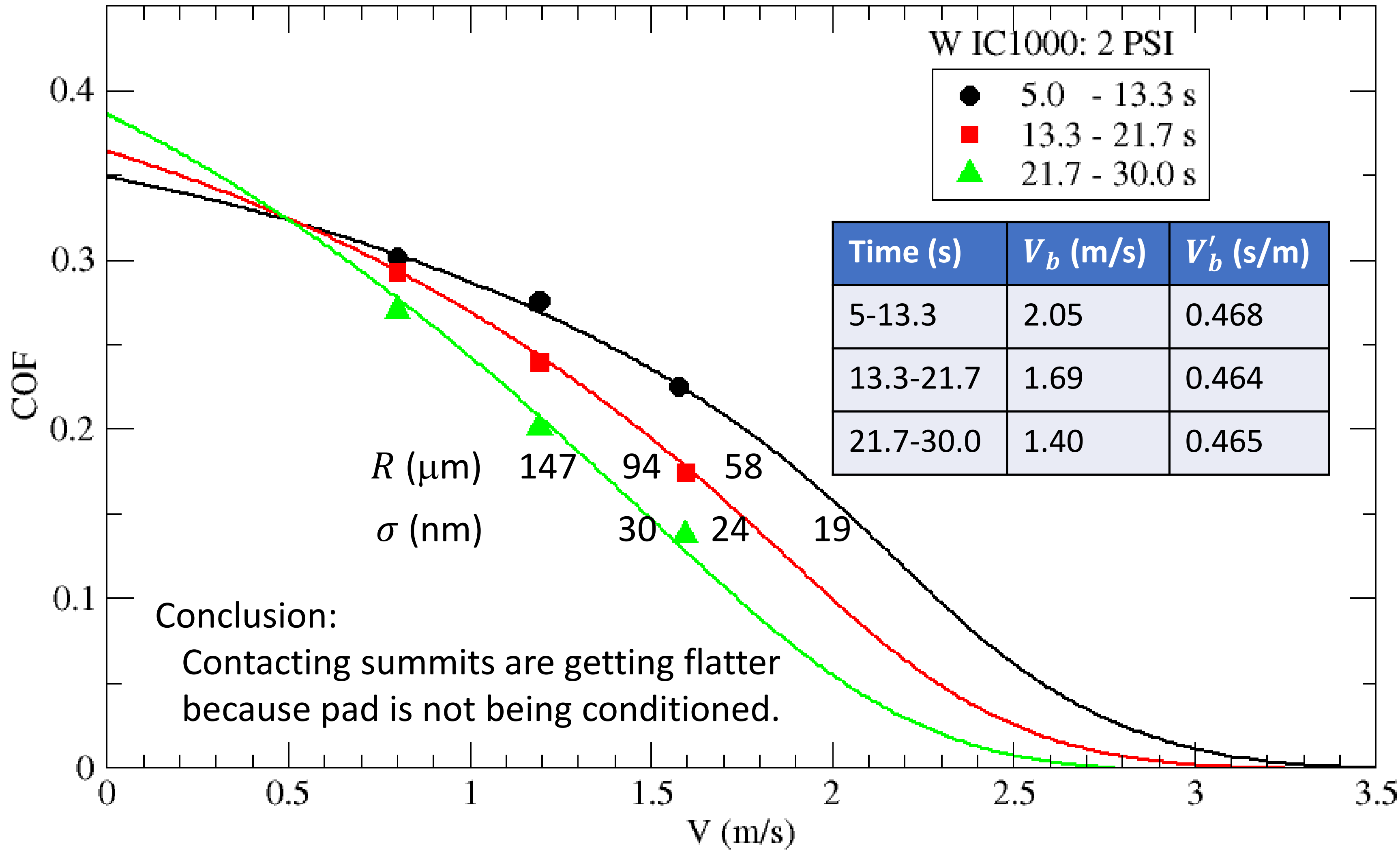

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