Contact mechanics and elements of tribology

Lecture 5.
Micromechanical contact: mechanics

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February 26, 2020

Outline

1. **True contact area**

   How does it grow with the squeezing force?

2. **Interfacial fluid flow**

   How does the permeability decay with the squeezing force?

3. **Conclusions & perspectives**

   How physical are the assumptions and results?

Objective:

link **roughness** parameters with the evolution of the true **contact area** and interface **permeability** with external pressure.

Contact between rough surfaces

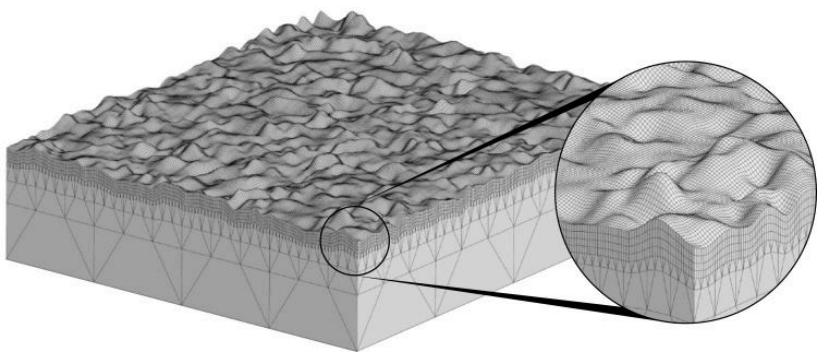
Problem statement & methods

Problem

- Solve contact problem for two elastic half-spaces E_1, ν_1 and E_2, ν_2
- With surface roughnesses $z_1(x, y)$ and $z_2(x, y)$
- Balance of momentum $\nabla \cdot \underline{\underline{\sigma}} = 0$,
- Boundary conditions $-\sigma_z^\infty = p_0$
- Contact constraints $g \geq 0, \quad p \geq 0, \quad g\,p = 0$,
  where $g(x, y)$ is the gap between surfaces,
  $p = -\underline{n} \cdot \underline{\underline{\sigma}} \cdot \underline{n}$ is the contact pressure.

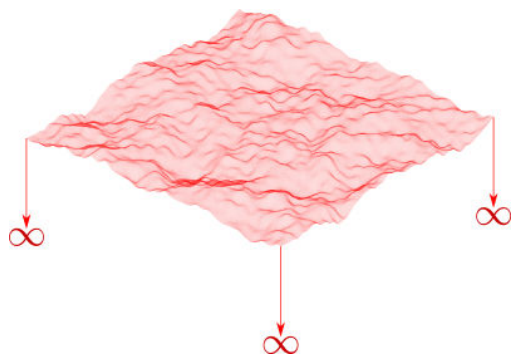
Methods

- Finite element method



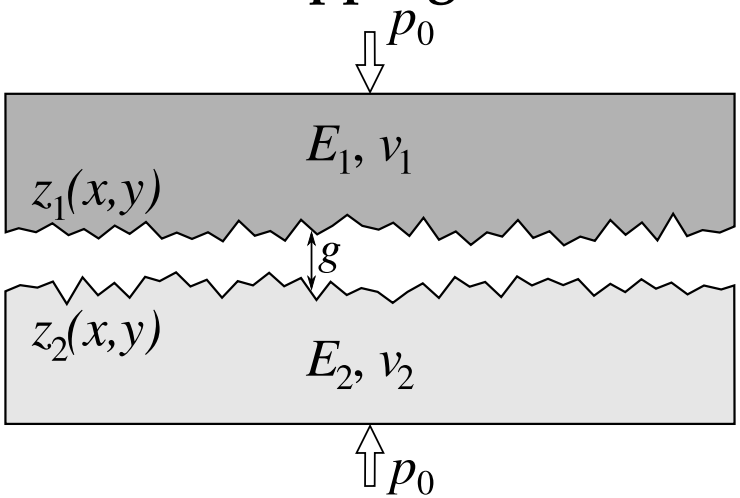
[1] Yastrebov, Wiley/ISTE (2013)

- Boundary element method



[2] Stanley & Kato, J Tribol 119 (1997)

Problem mapping



- **Flat** elastic[1] half-space with $E^* = \dfrac{E_1 E_2}{E_2(1-\nu_1^2) + E_1(1-\nu_2^2)}$
- **Rough** rigid[1] surface with $z^* = z_2 - z_1$
- Optimization problem[2]: $\min \mathcal{F}$

  under constraints $p \geq 0$ and $\frac{1}{A_0} \int\limits_A p dA = p_0$,

  with $\mathcal{F} = \int\limits_A p[u_z/2 + g] dA$

[1] Barber, Bounds on the electrical resistance between contacting elastic rough bodies, PRSL A 459 (2003)
[2] Kalker, Variational Principles of Contact Elastostatics, J Inst Maths Applics (1977)

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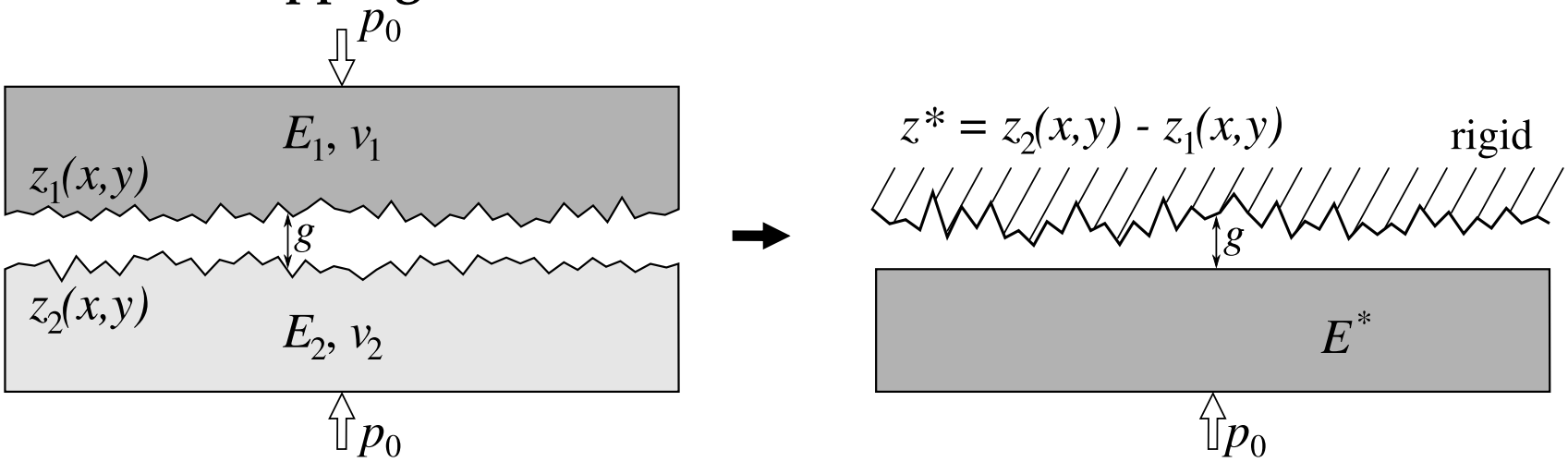

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Analytical models

Asperity based models

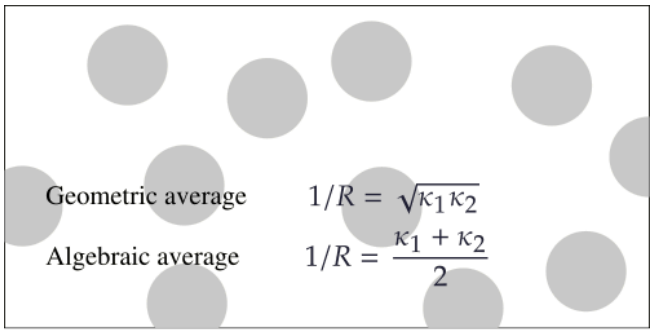
[1] Greenwood, Williamson. *P Roy Soc Lond A Mat* (1966)
[2] Bush, Gibson, Thomas. *Wear* (1975)
[3] Mc Cool. *Wear* (1986)
[4] Thomas. *Rough Surfaces* (1999)
[5] Greenwood. *Wear* (2006)
[6] Carbone. *J. Mech. Phys. Solids* (2009)
[7] Ciavarella, Greenwood, Paggi. *Wear* (2008)

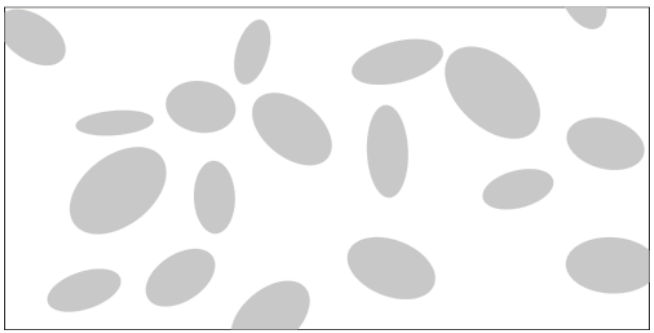
Persson's model

[8] Persson. *J. Chem. Phys.* (2001)
[9] Persson. *Phys. Rev. Lett.* (2001)
[10] Persson, Bucher, Chiaia. *Phys. Rev. B* (2002)
[11] Müser. *Phys. Rev. Lett.* (2008)

Cross-link studies

[12] Manners, Greenwood. *Wear* (2006)
[13] Carbone, Bottiglione. *J. Mech. Phys. Solids* (2008)
[14] Paggi, Ciavarella. *Wear* (2010)





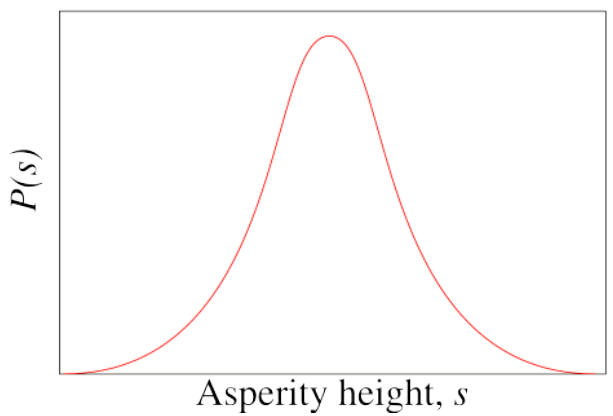


Fig. Asperity based models

Analytical models

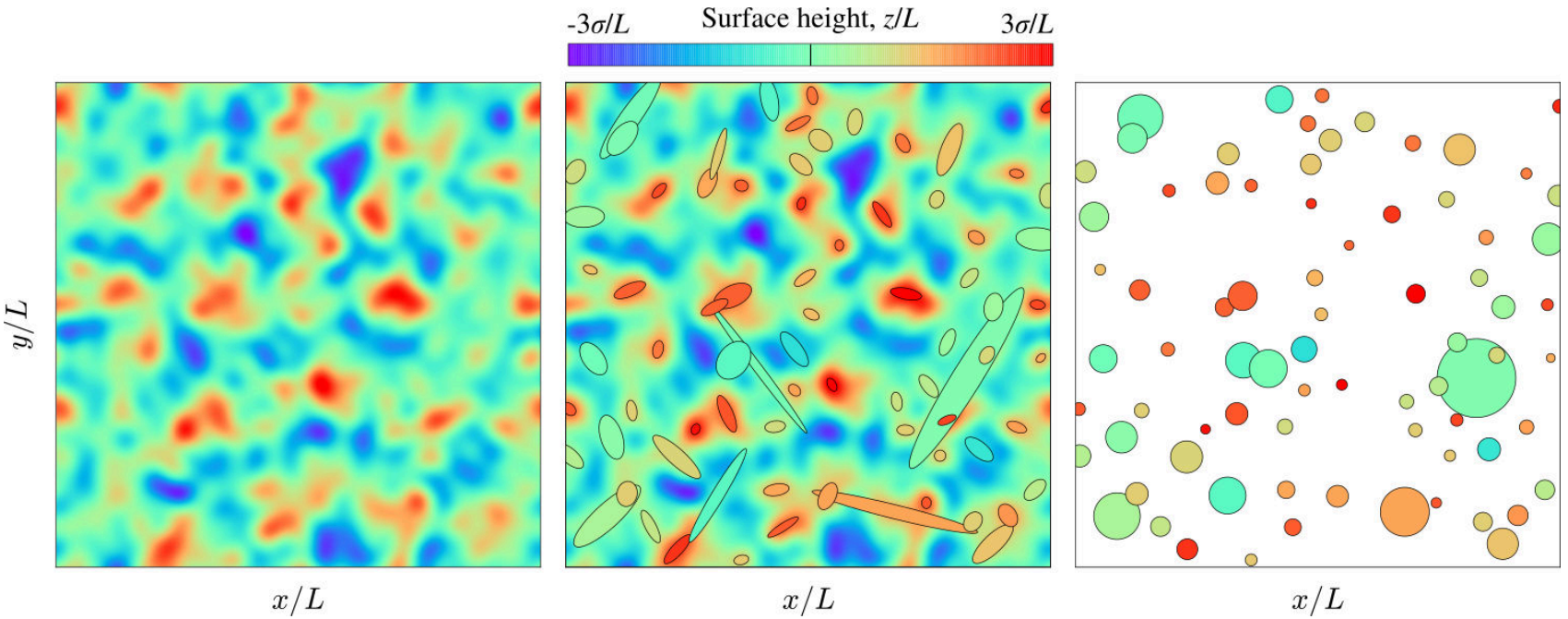


Fig. Roughness and detected asperities for $L/\lambda_l = 4$ and $L/\lambda_s = 16$

Analytical models

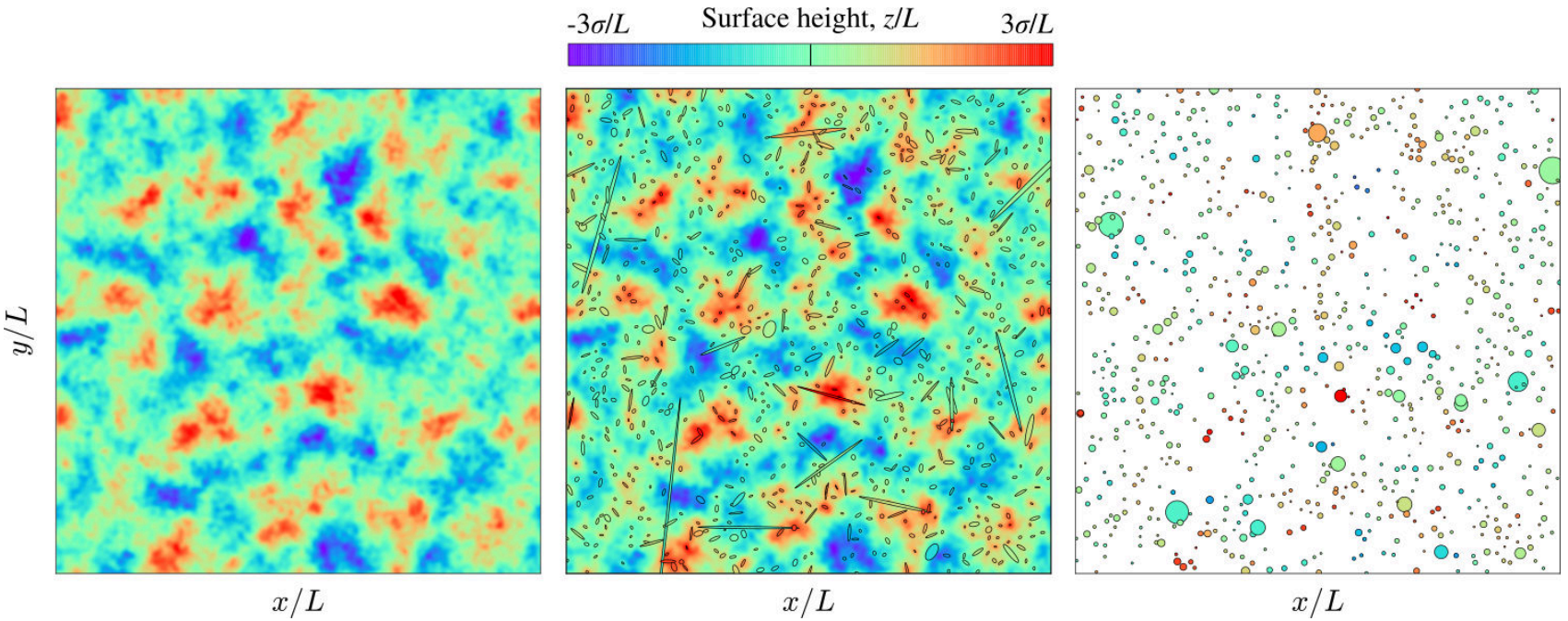


Fig. Roughness and detected asperities for $L/\lambda_l = 4$ and $L/\lambda_s = 64$

Analytical models

contact radius: $a = \left(\frac{3RF}{4E^*}\right)^{1/3}$ contact force: $F = \frac{4}{3} R^{1/2} E^* \delta^{3/2}$

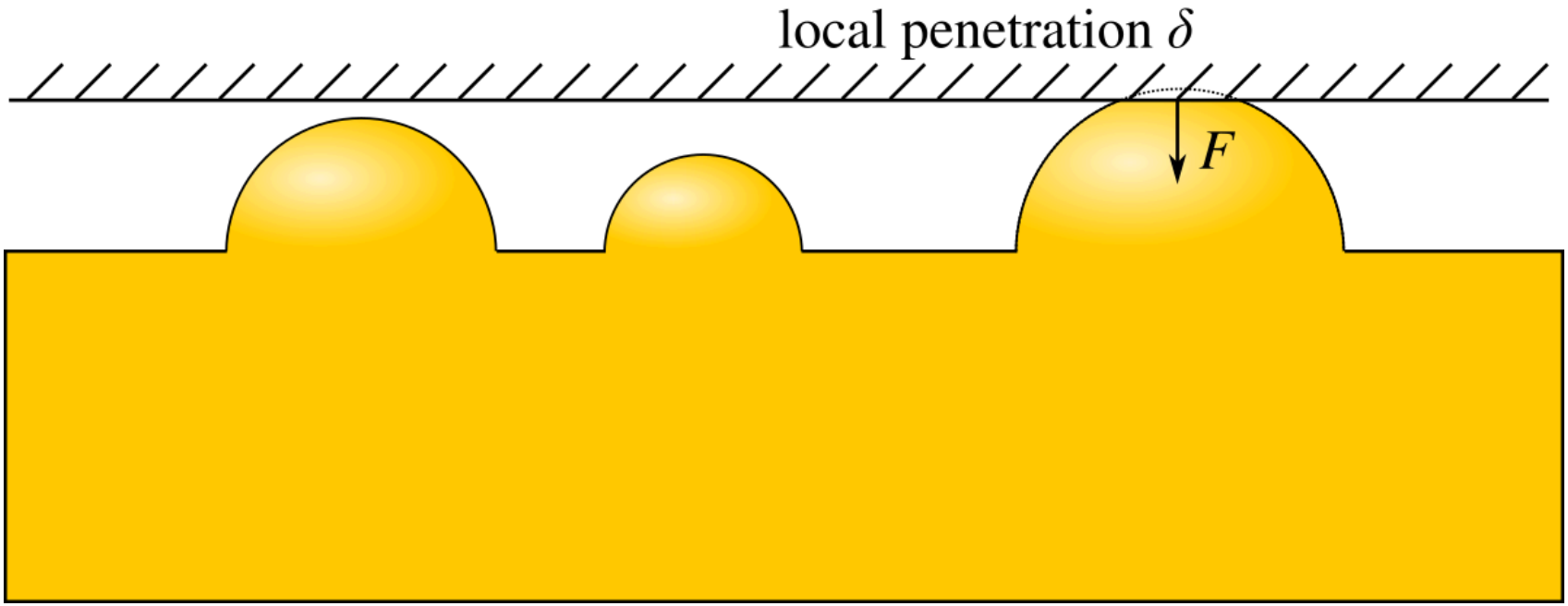


Fig. Hertz's theory of contact

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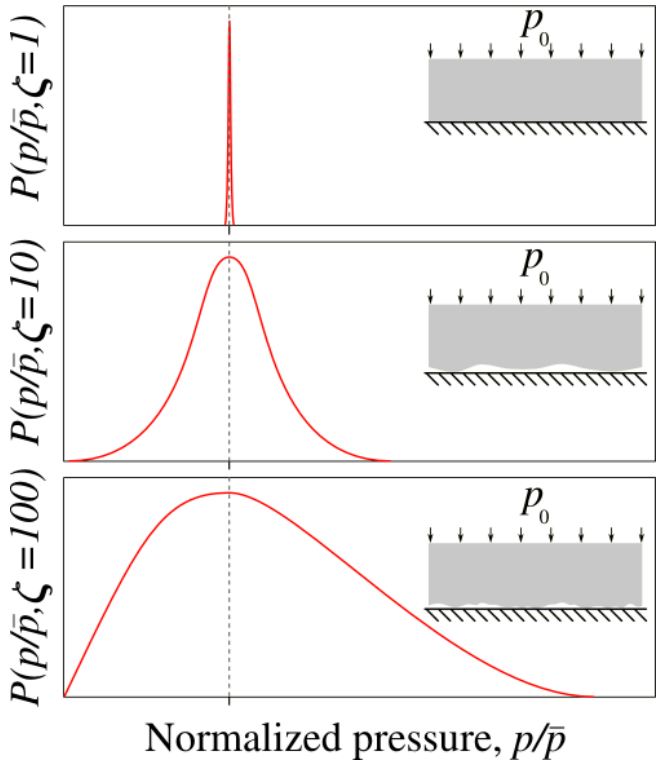


Fig. Persson's model

$$\boxed{\frac{\partial P(p,\zeta)}{\partial V(\zeta)} = \frac{1}{2}\frac{\partial^2 P(p,\zeta)}{\partial p^2}} \quad P(0,\zeta) = 0$$

$$V(\zeta) = \tfrac{1}{2}E^* m_2(\zeta) = \tfrac{\pi E^*}{2}\int_{k_l}^{\zeta k_l} k^3 \Phi^p(k) dk$$

Comparison of models

Asperity based models **Persson's model**

1. Evolution of the real contact area $A(p_0)$ for $A/A_0 \to 0$

$$\frac{A}{A_0} = \frac{\kappa}{\sqrt{\langle |\nabla z|^2 \rangle}} \frac{p_0}{E^*}$$

$\kappa_{\mathrm{BGT}} = \sqrt{2\pi} \approx 2.5$ *according to* [2-5]

$\kappa_{\mathrm{P}} = \sqrt{8/\pi} \approx 1.6$ *according to* [6-7]

2. Evolution of the real contact area $A(p_0)$ for $\forall A/A_0$

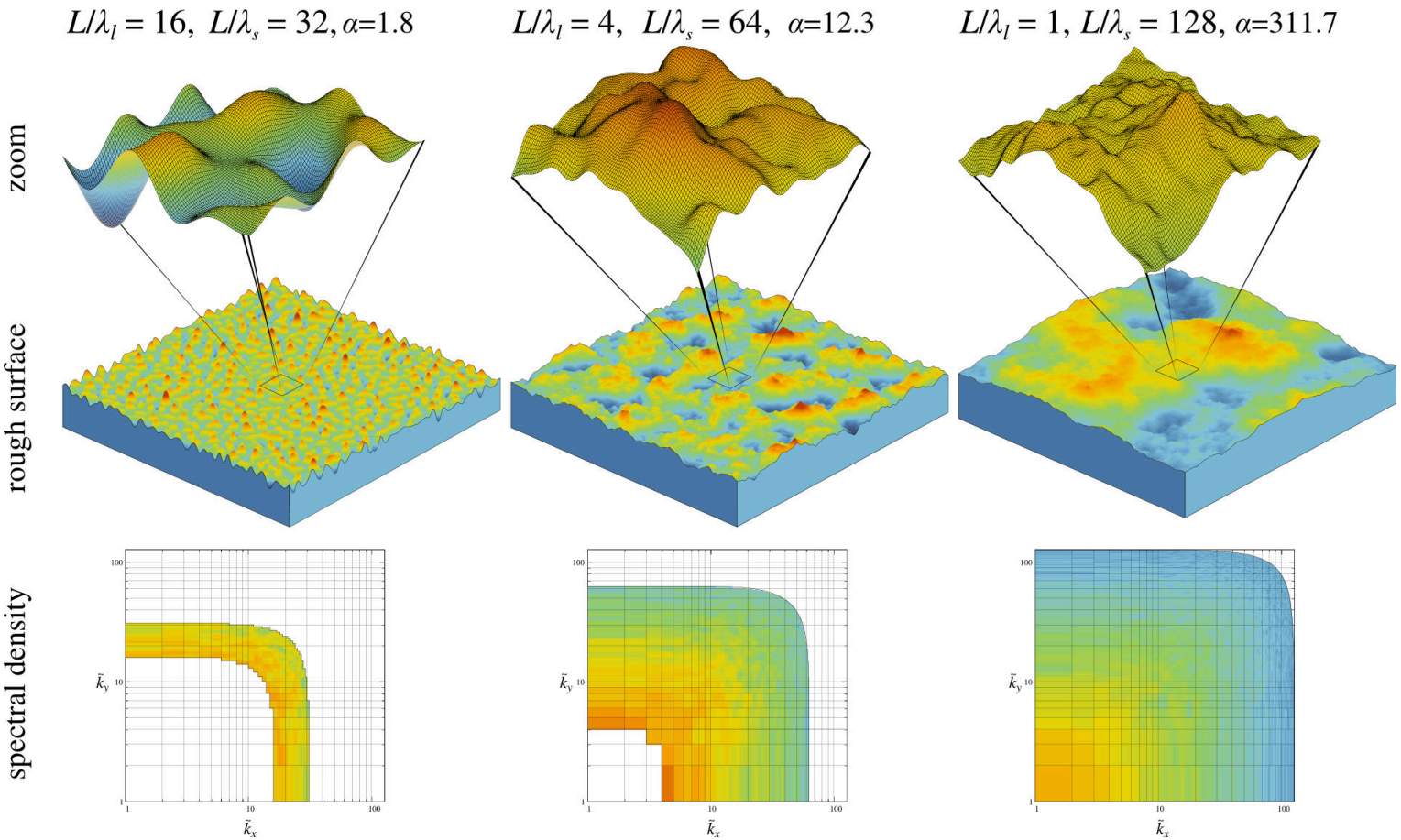
$\frac{A}{A_0} = A(p_0, \alpha)/A_0$ *according to* [2-5]

$\frac{A}{A_0} = \mathrm{erf}\left(\sqrt{\frac{2}{\langle |\nabla z|^2 \rangle}} \frac{p_0}{E^*} \right)$ *according to* [6-7]

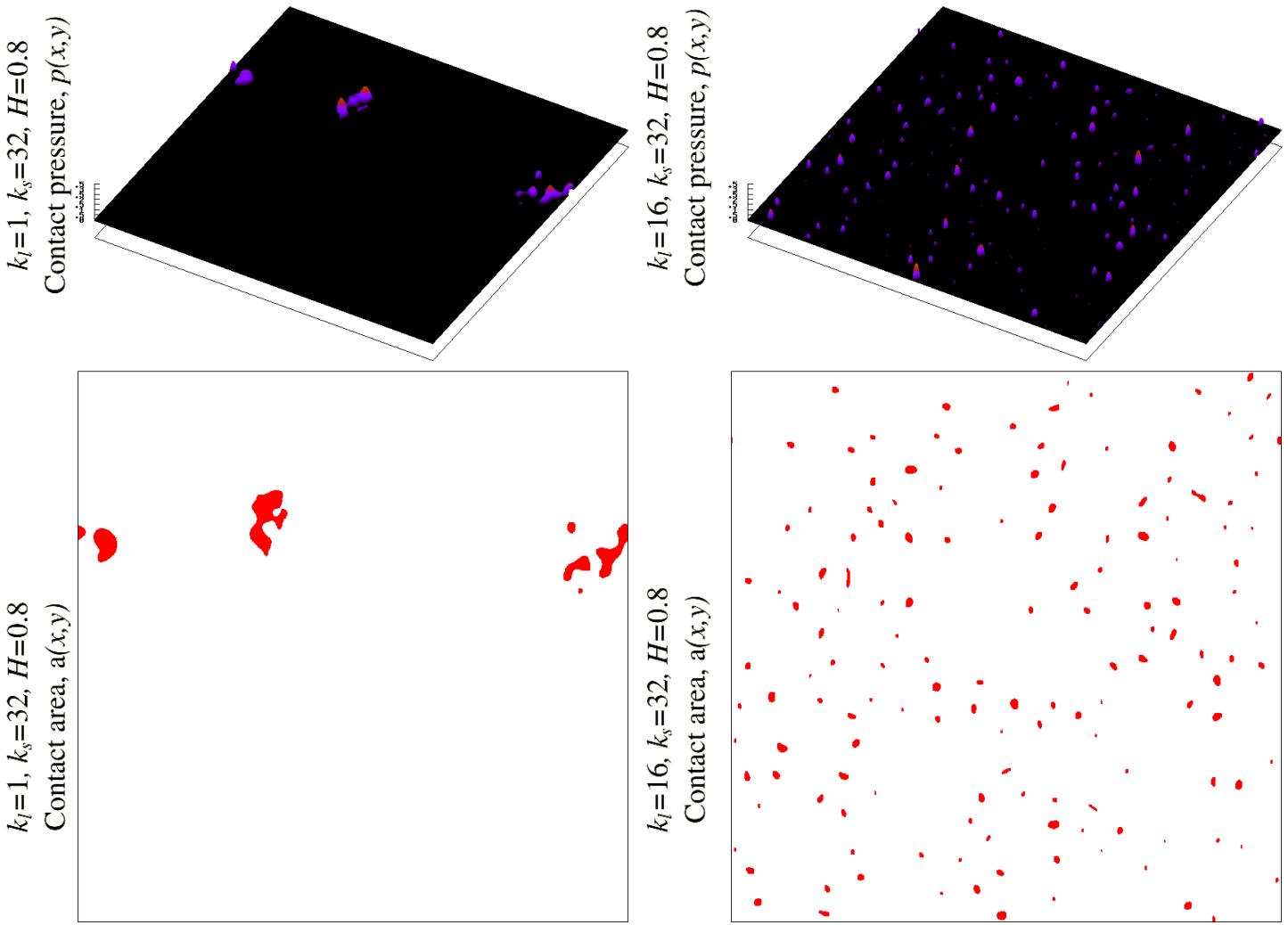
[1] Greenwood, Williamson, P Roy Soc Lond A Mat 295 (1966)
[2] Bush, Gibson, Thomas, Wear 35 (1975)
[3] Mc Cool, Wear 107 (1986)
[4] Thomas, Rough Surfaces (1999)
[5] Greenwood, Wear 261 (2006)
[6] Persson, J. Chem. Phys. 115 (2001)
[7] Persson, Phys. Rev. Lett. 87 (2001)
[8] Persson, Bucher, Chiaia, Phys. Rev. B 65 (2002)
[9] Müser, Phys. Rev. Lett. 100, (2008)

Simulations set-up

- Cut-off parameters: $L/\lambda_l \otimes L/\lambda_s = \{1, 2, 4, 8, 16\} \otimes \{32, 64, 128, 256, 512\}$
- Hurst exponent $H = \{0.4, 0.8\}$
- 10 random surface realizations per combination of parameters
- Discretization: $\{L/\Delta x\} \times \{L/\Delta x\} = 2048 \times 2048$
- Search for contact area A', gap field $g(x, y)$ and gap PDF $P(g)$



Contact area and contact pressure evolution



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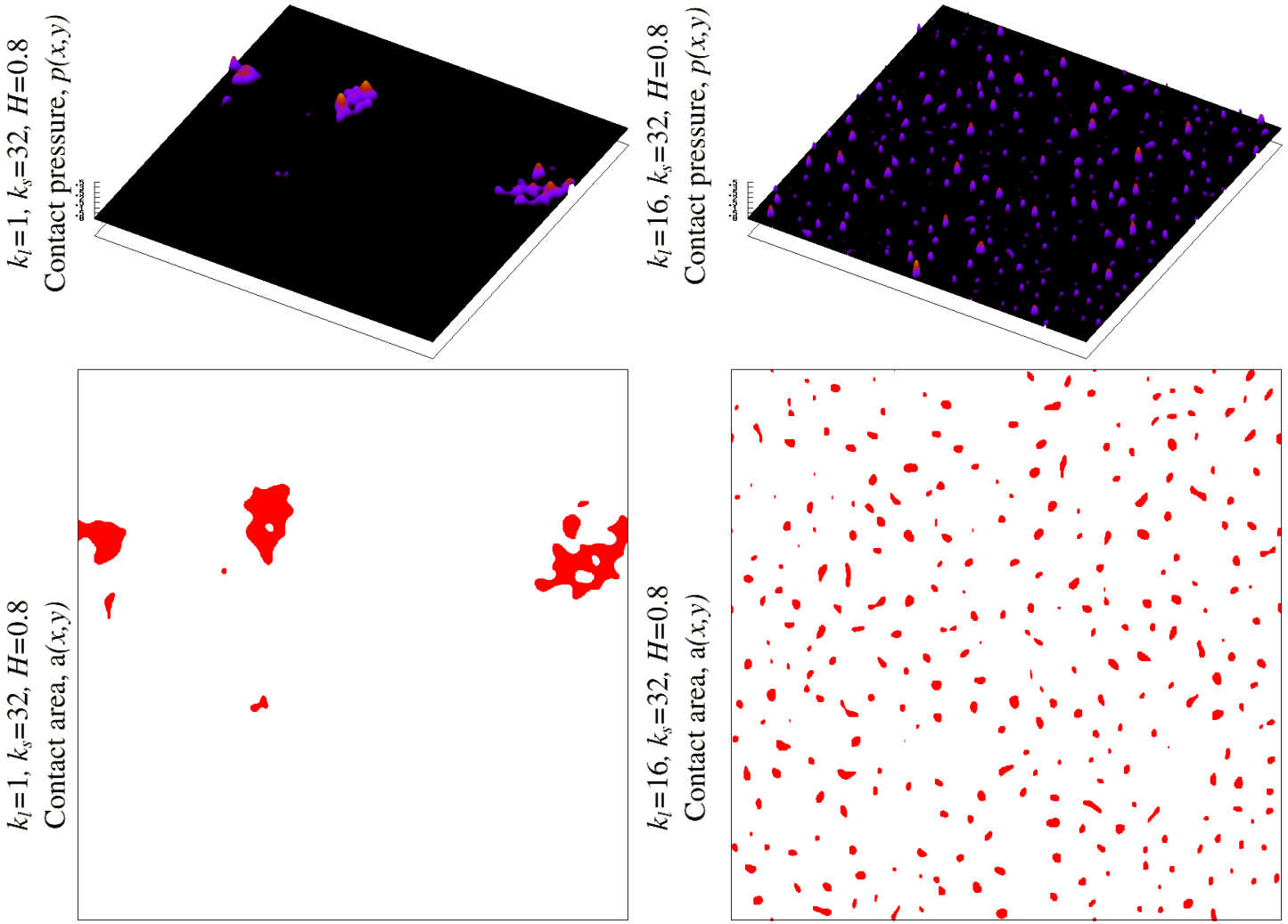

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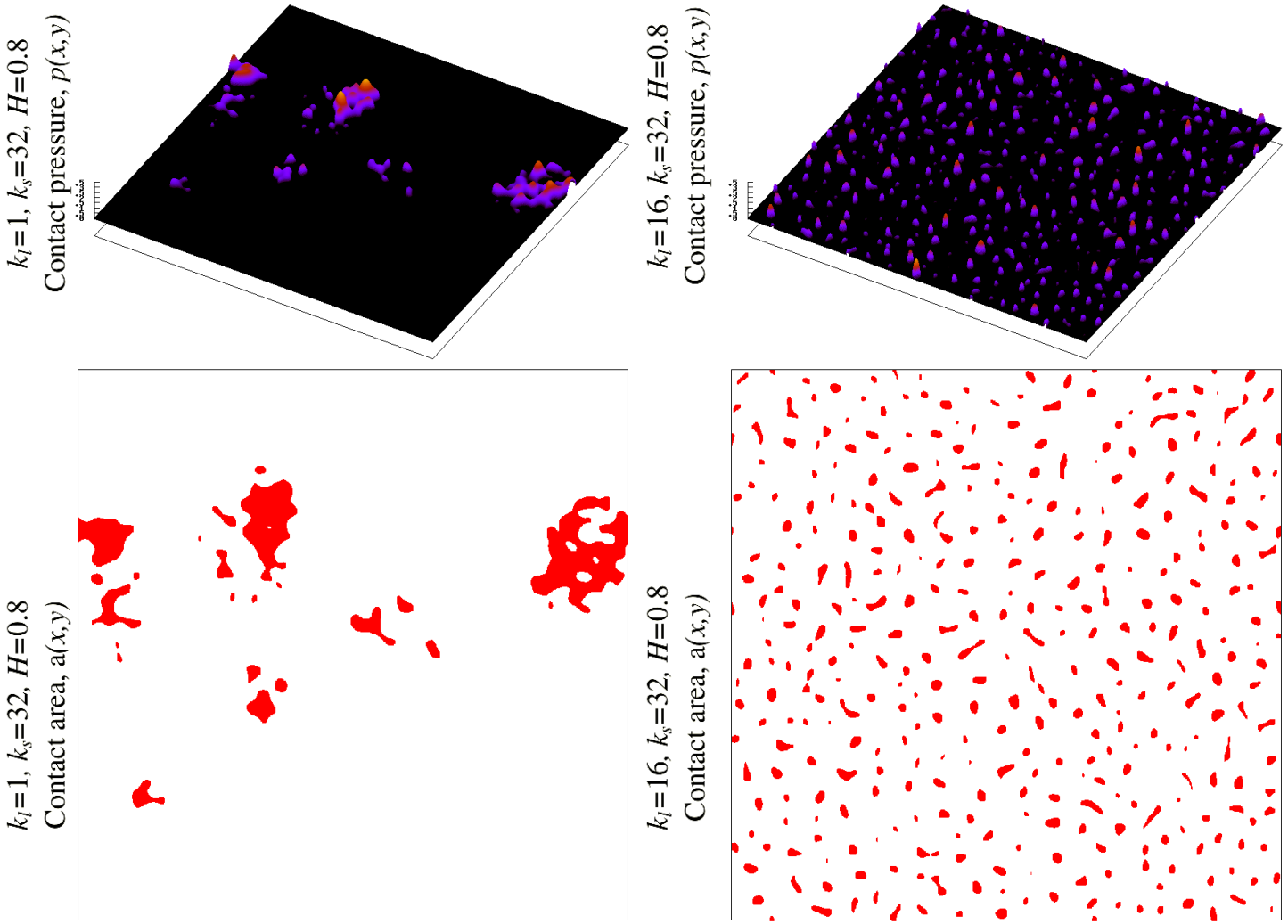

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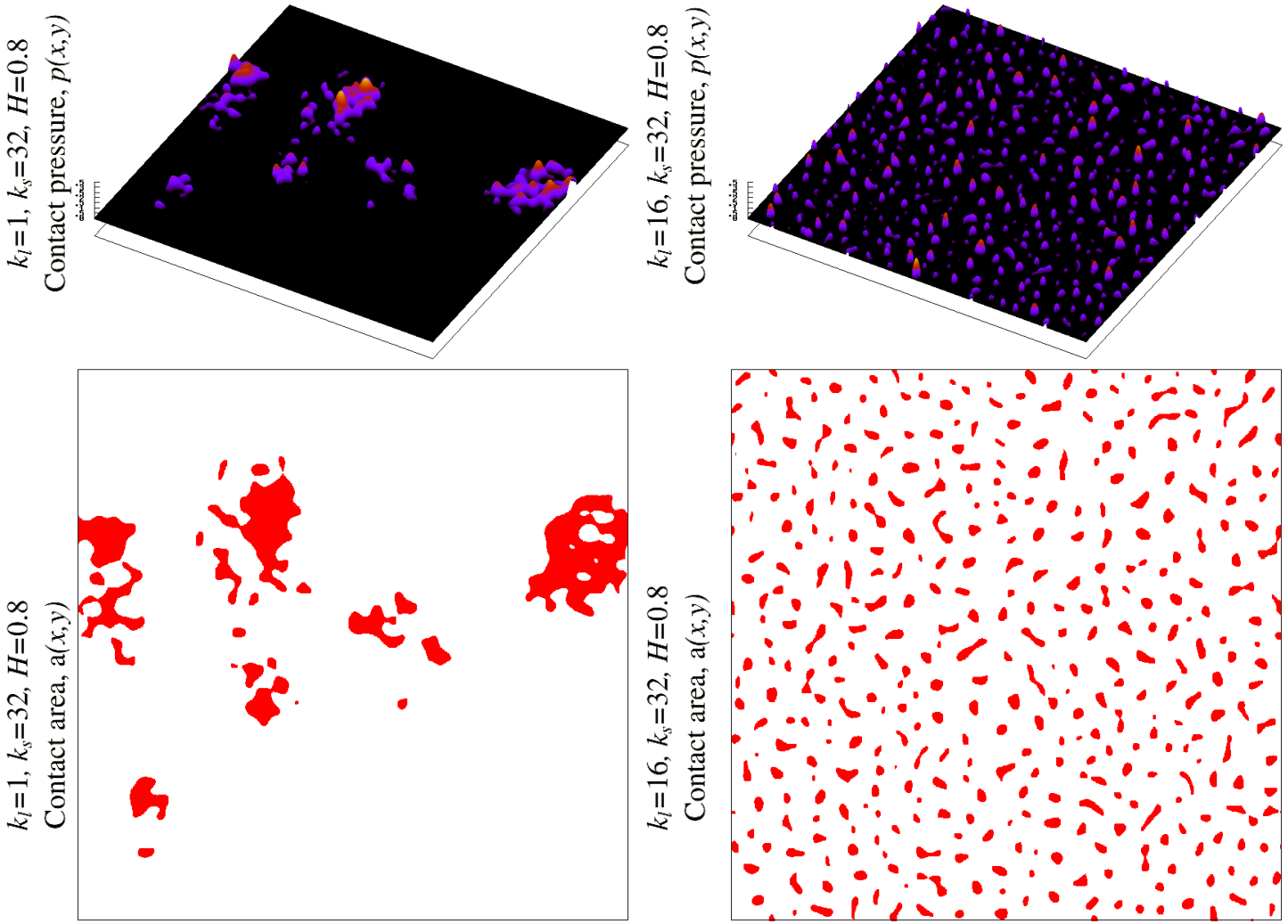

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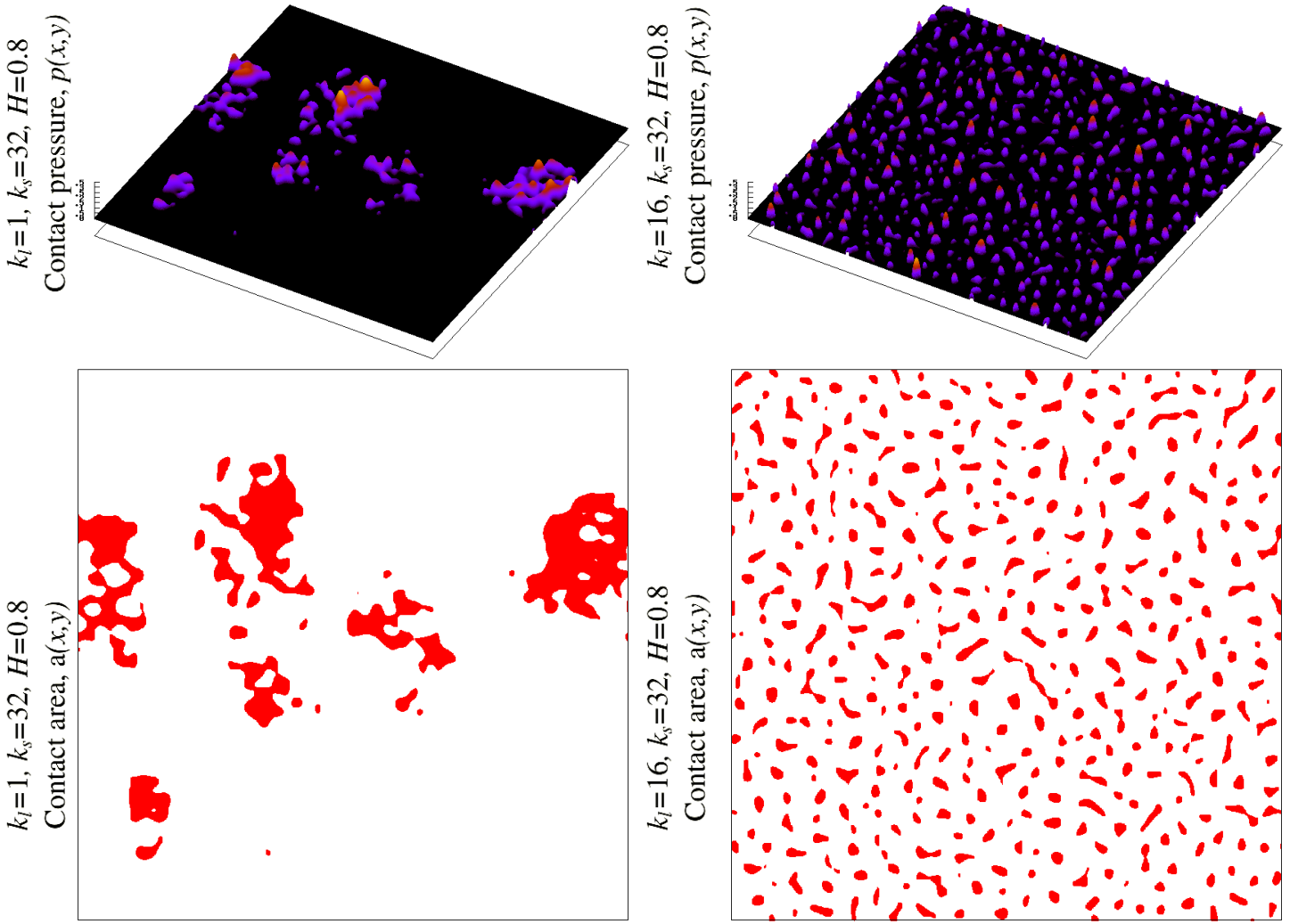

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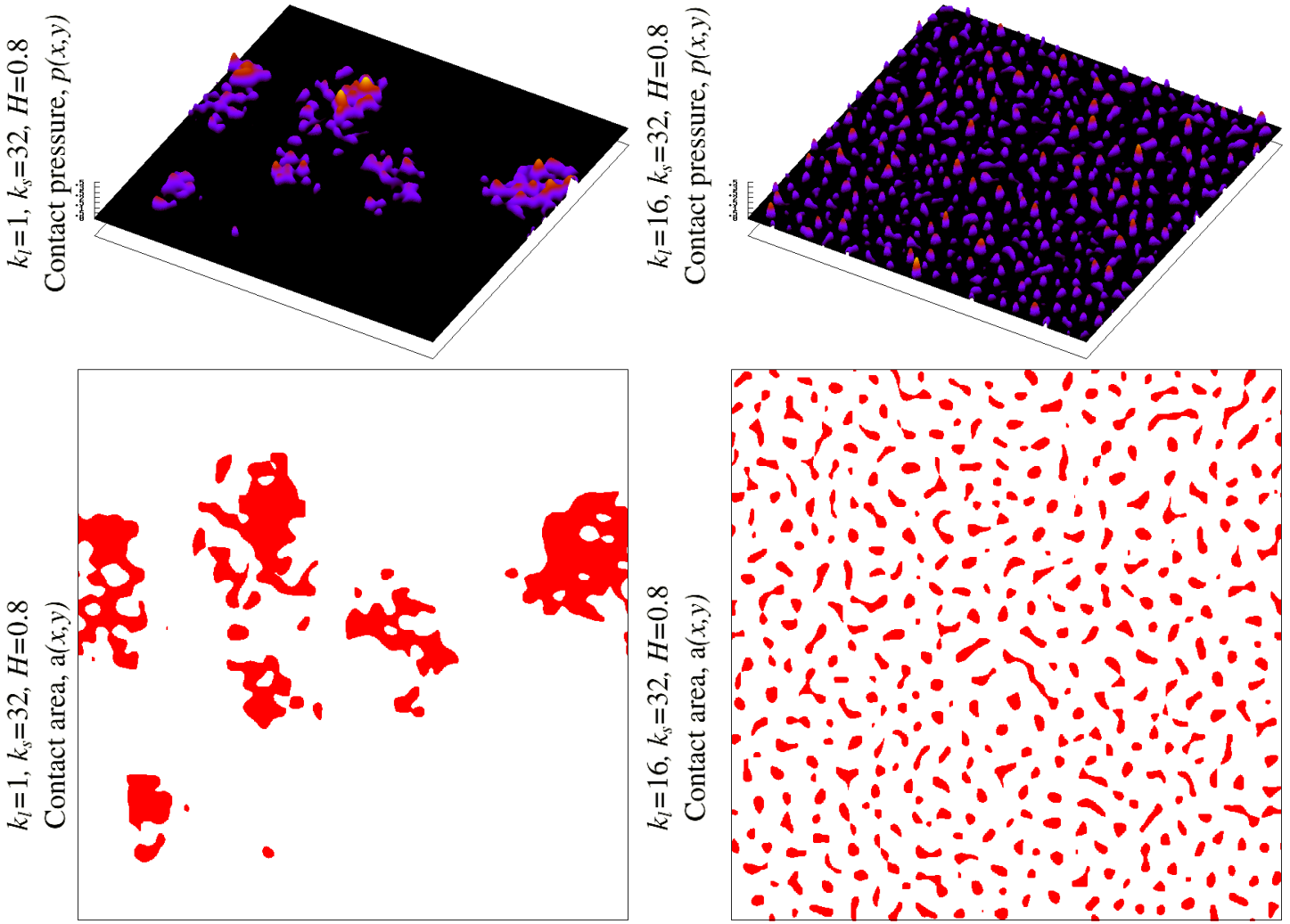

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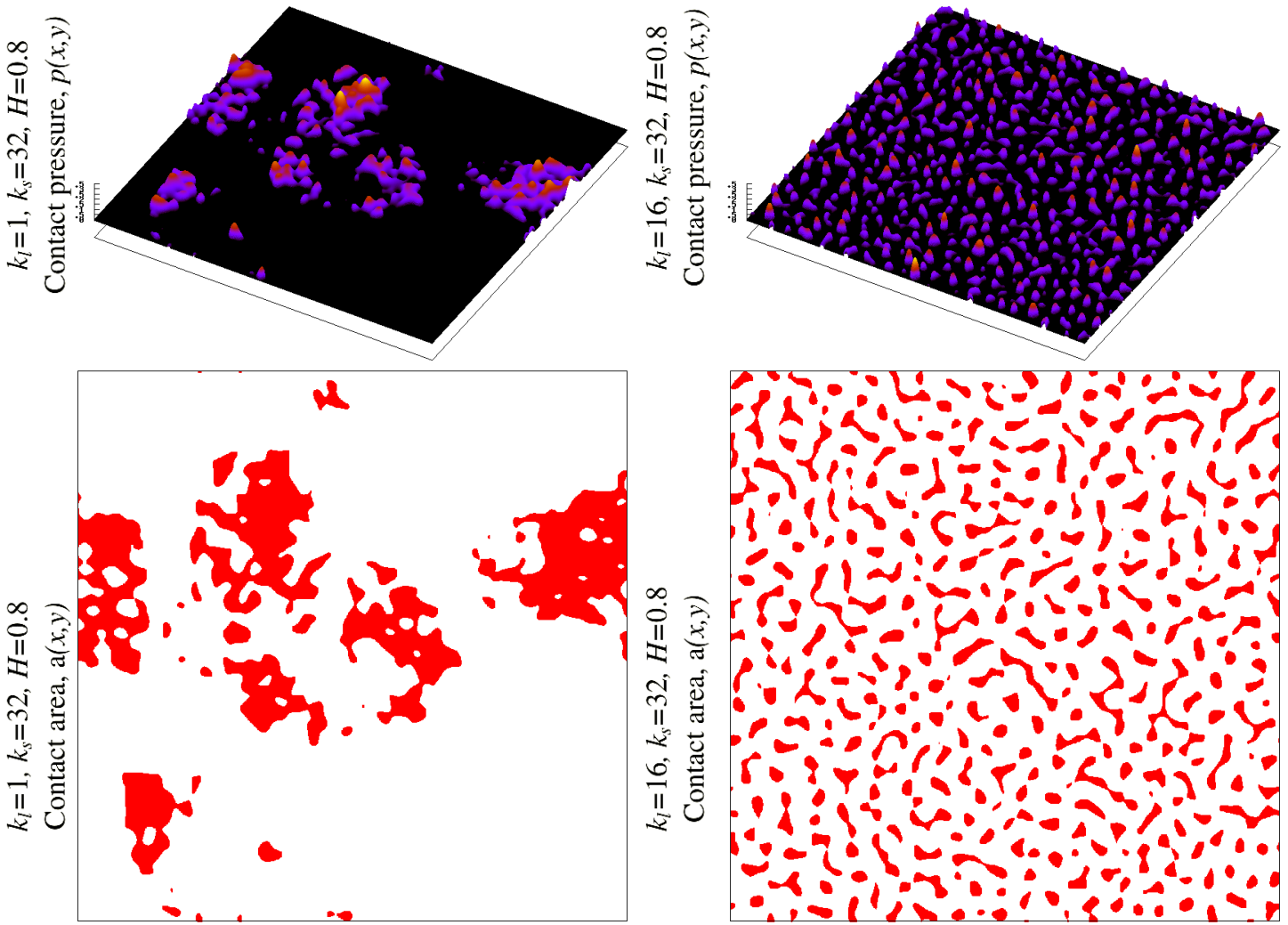

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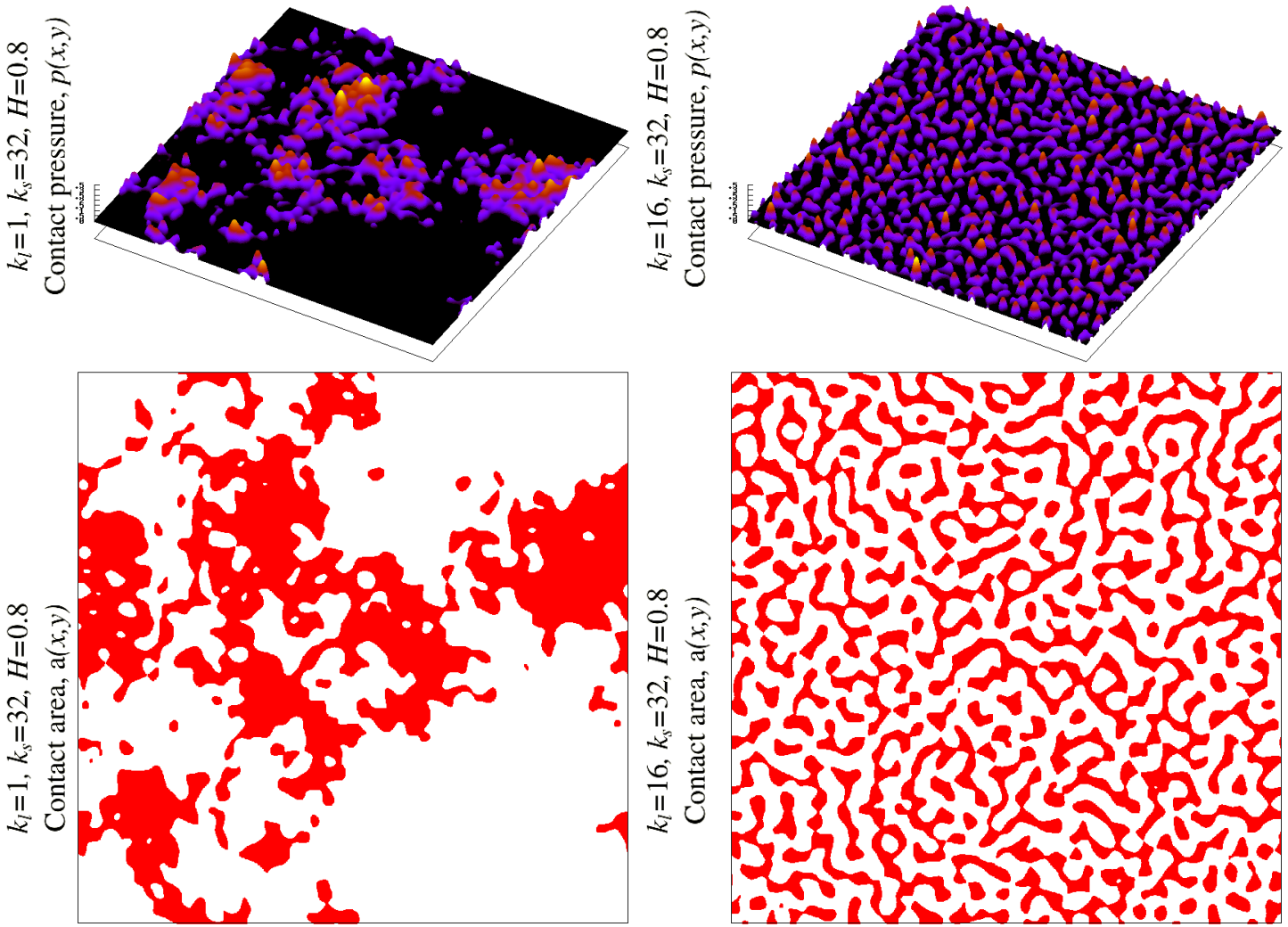

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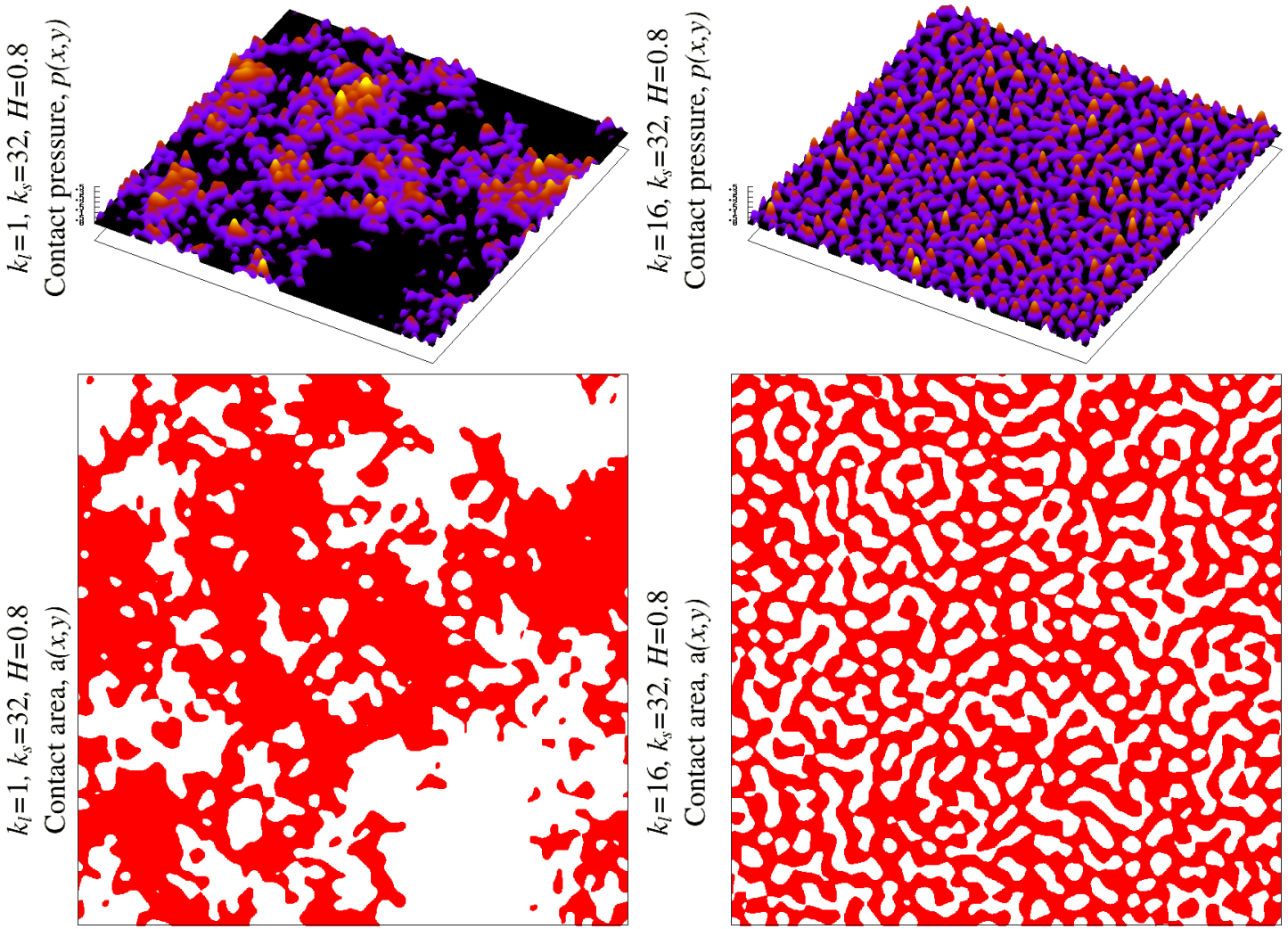

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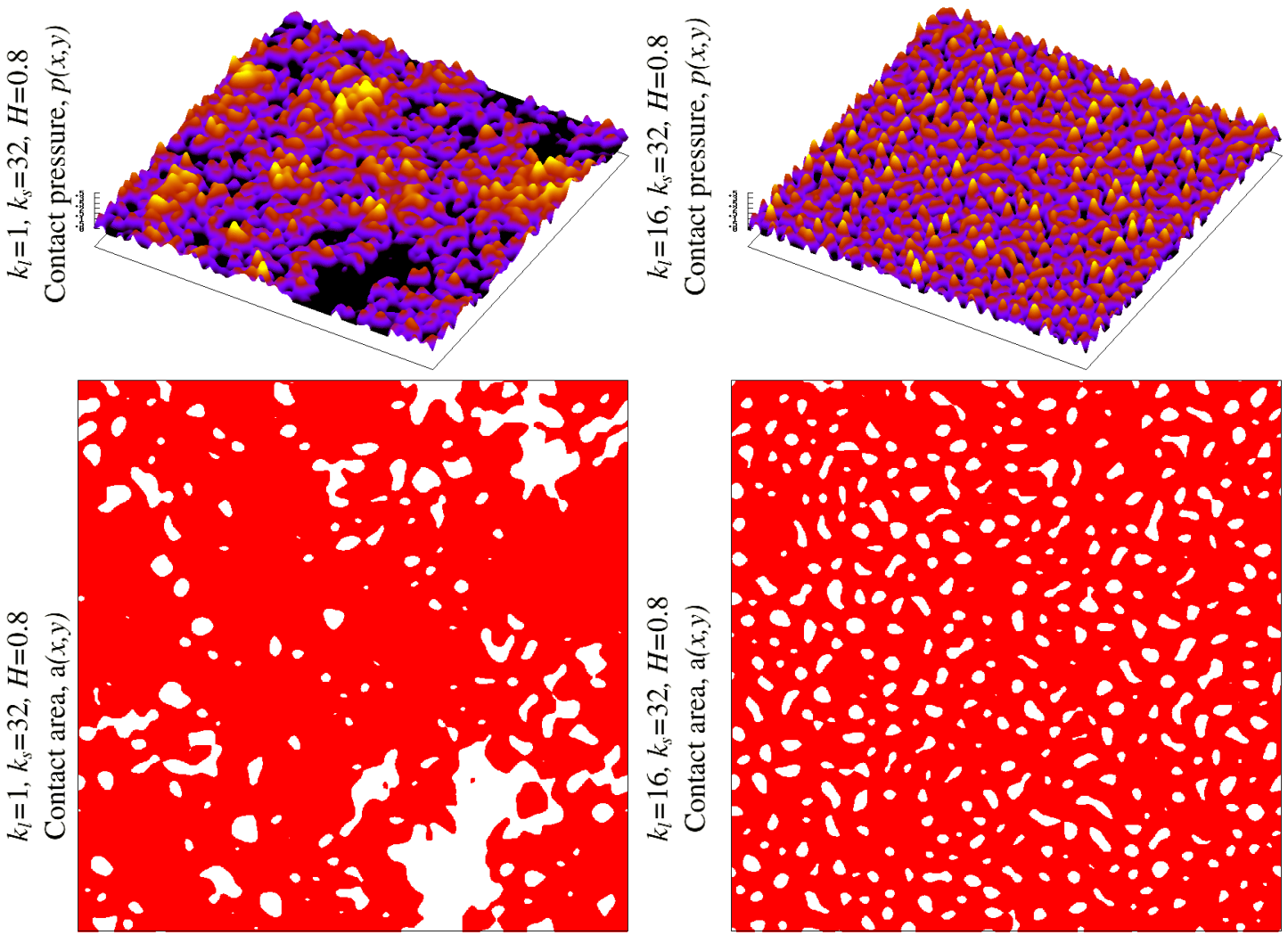

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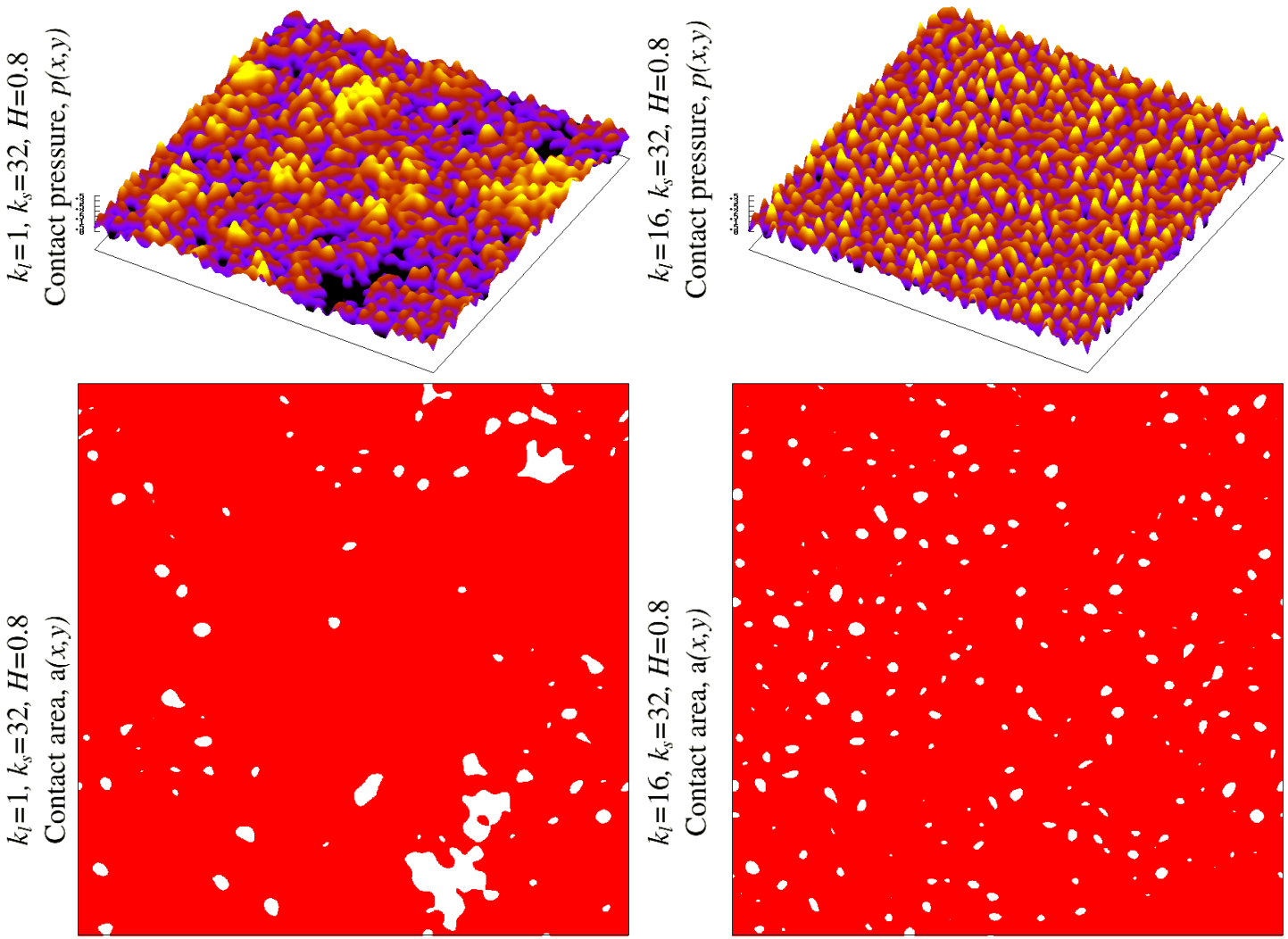

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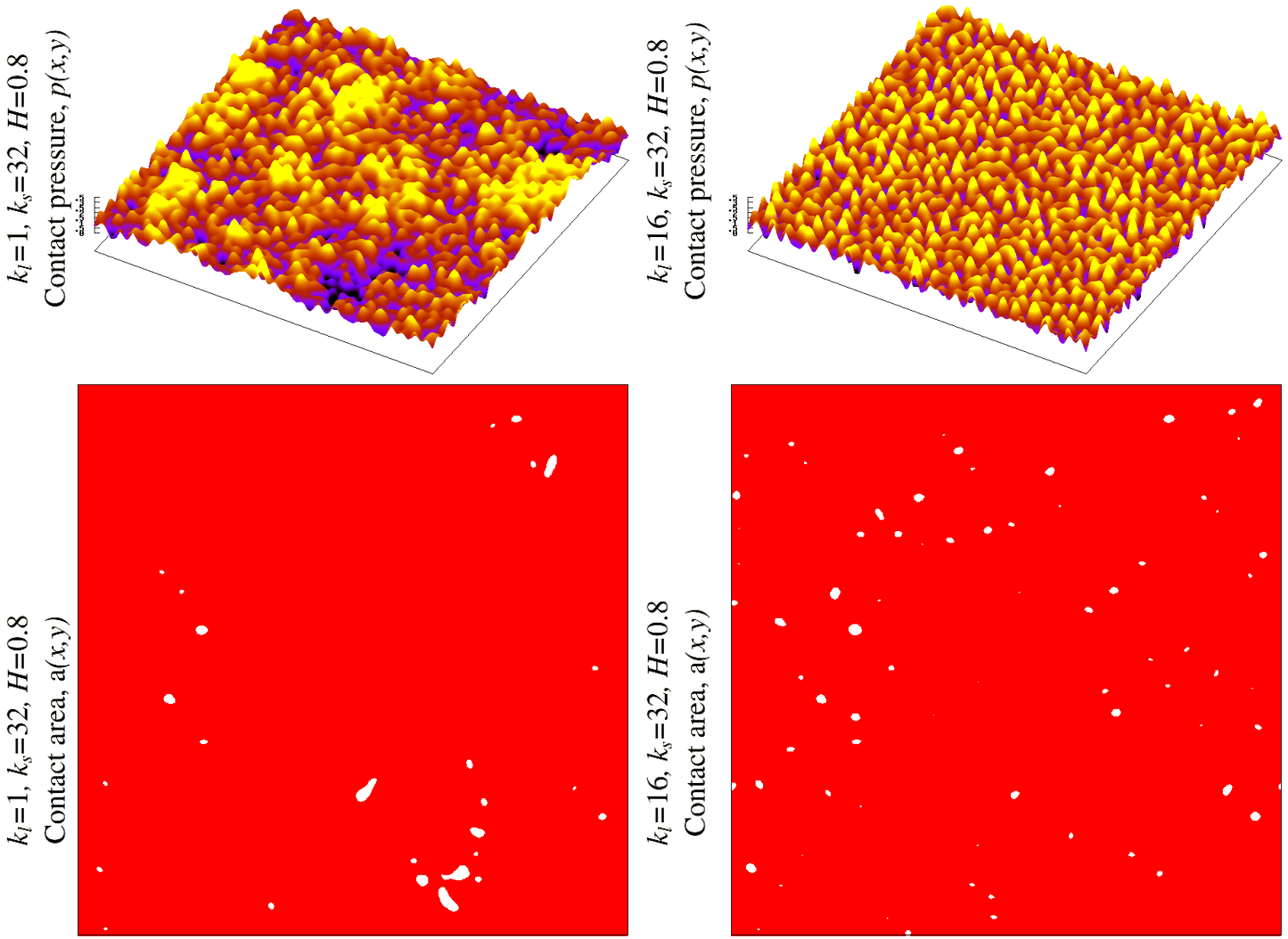

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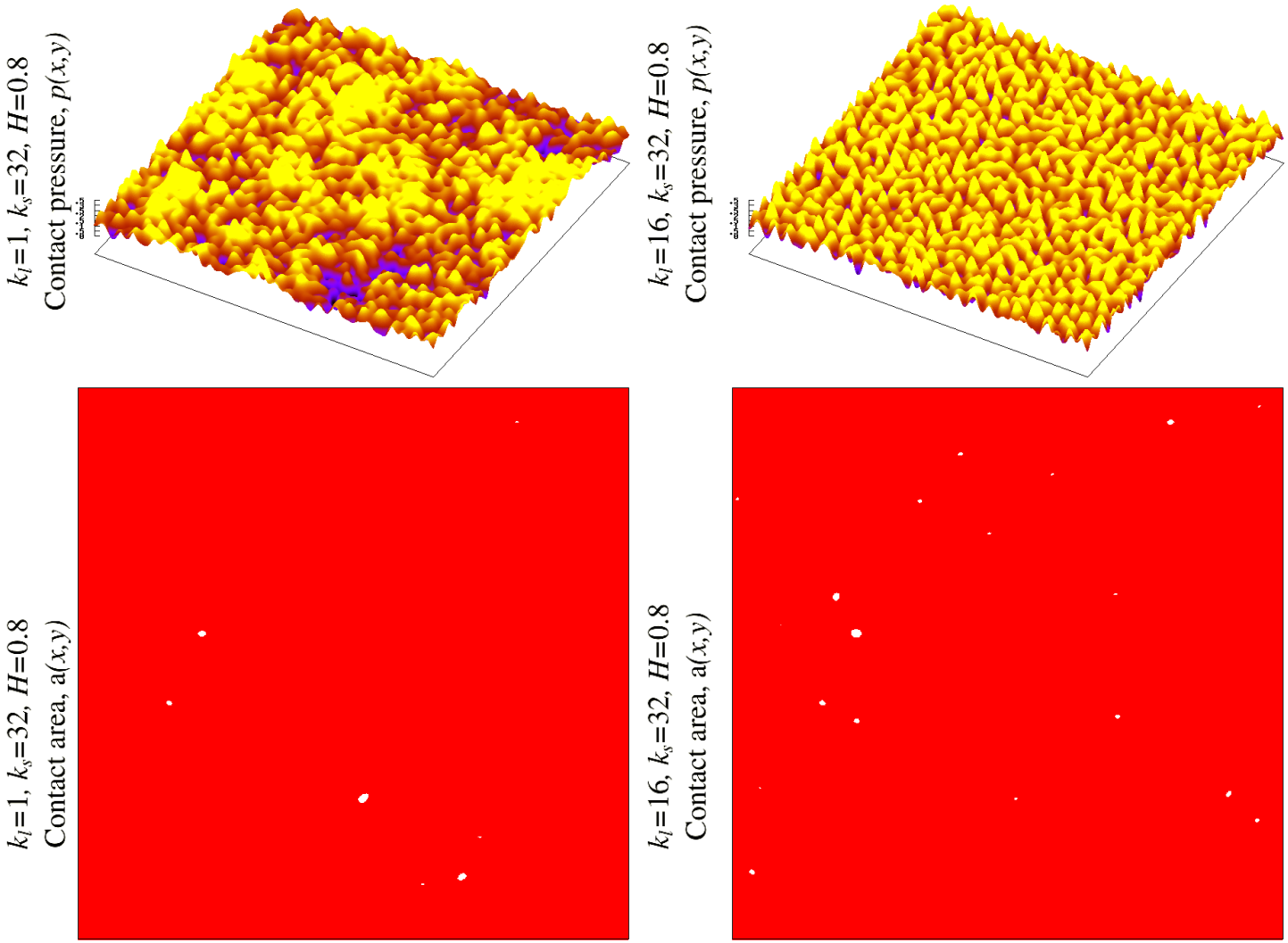

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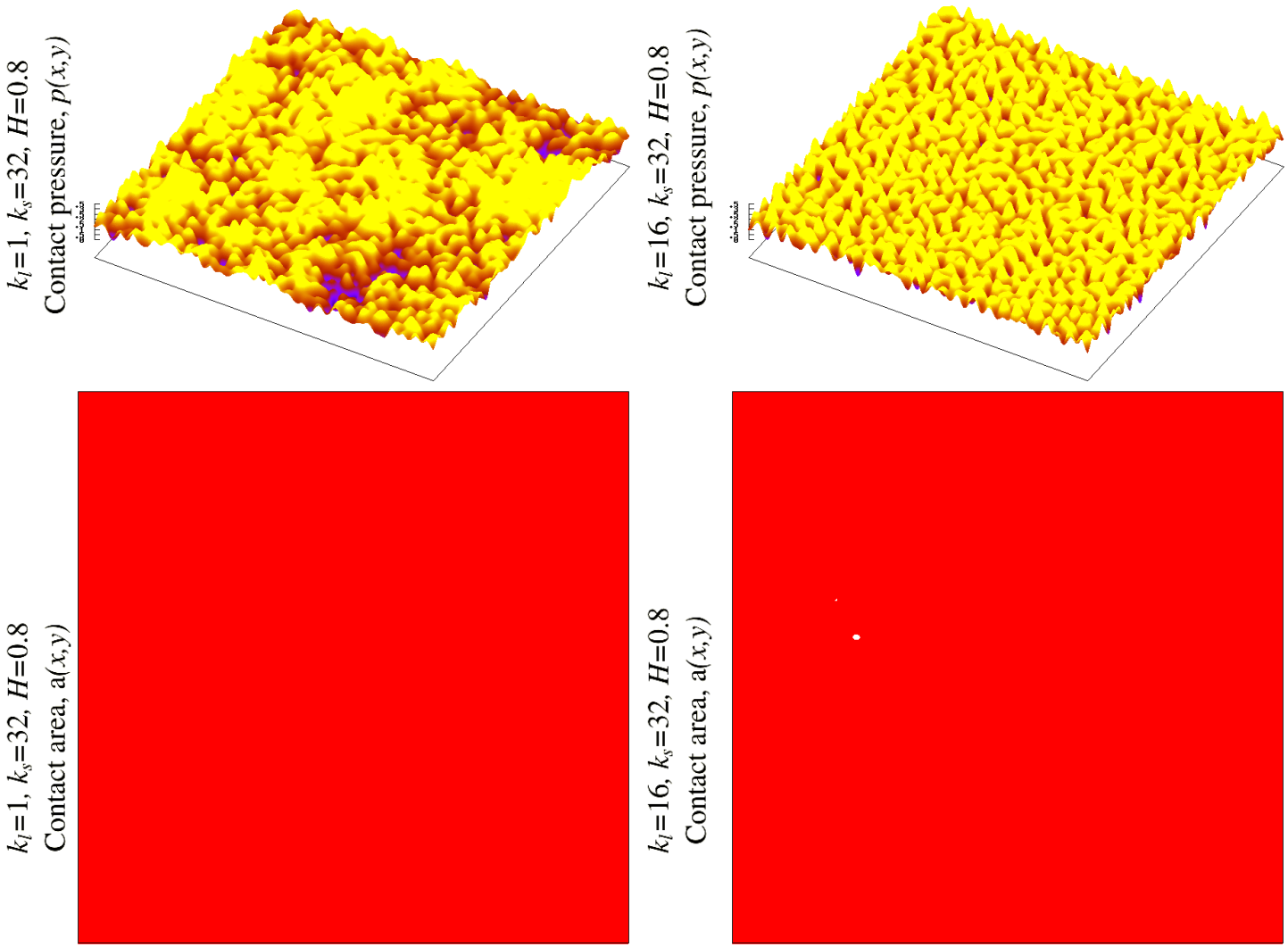
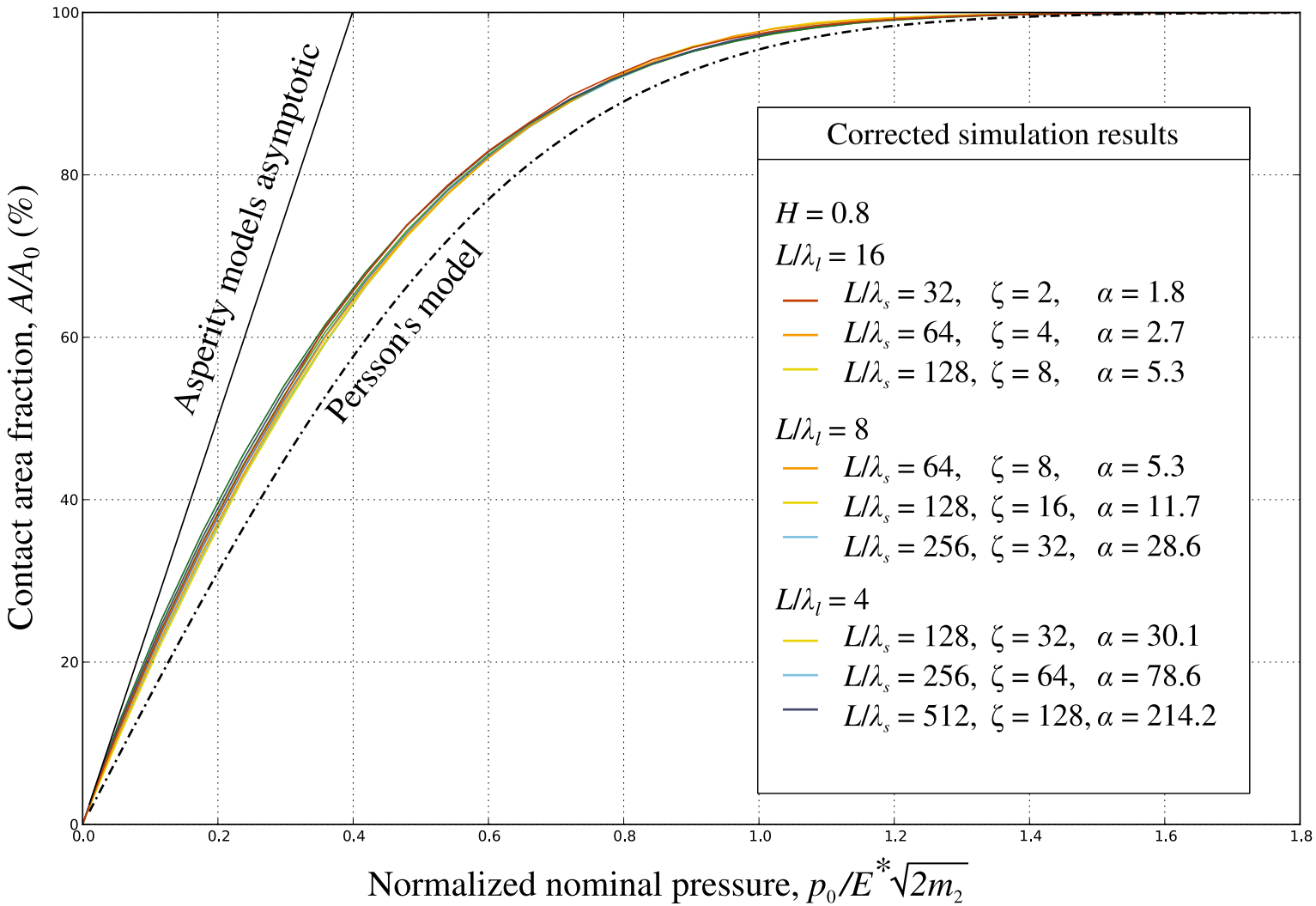


Results: contact area



Multi-asperity models asymptotic[1,2], Persson's model[3]

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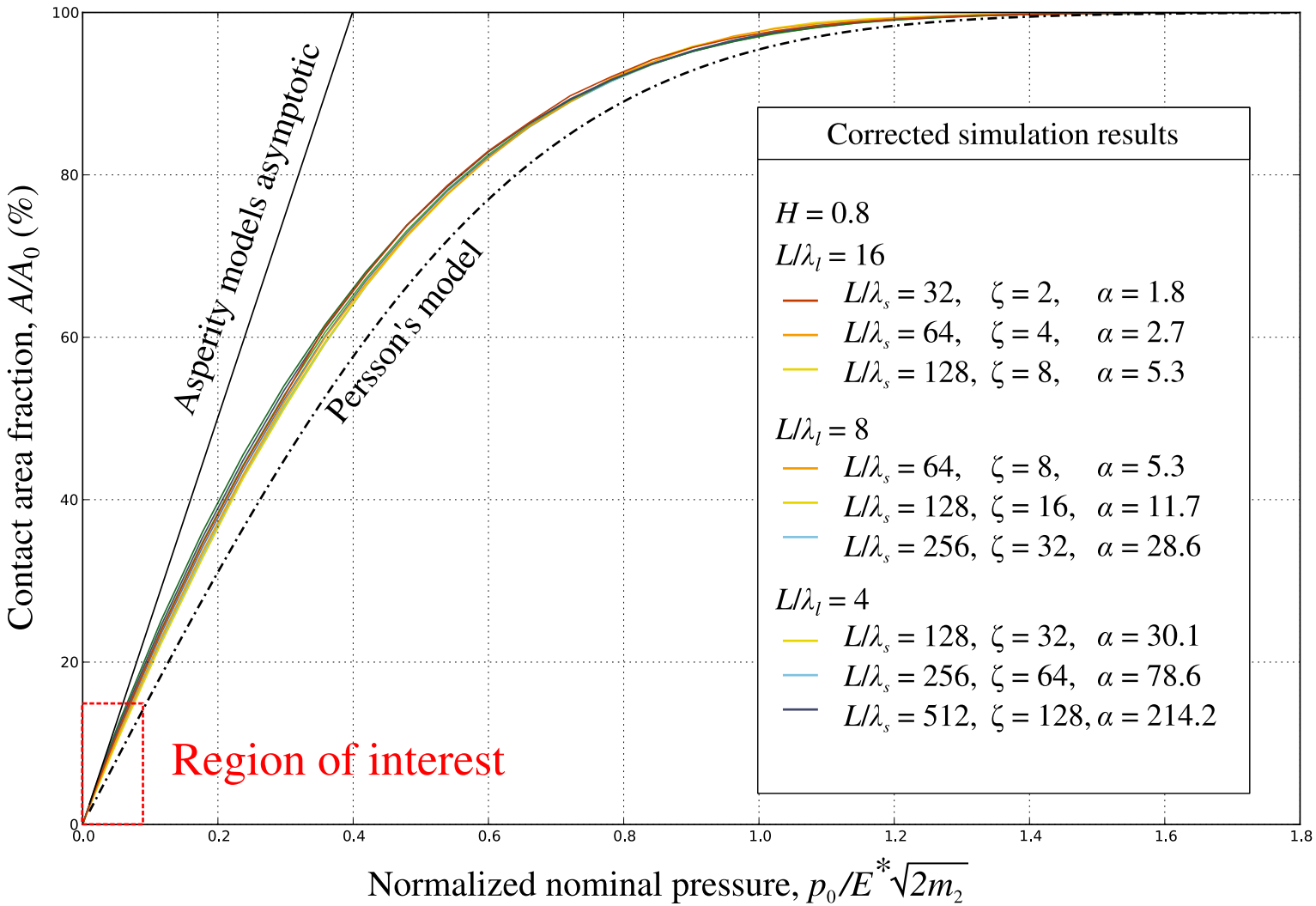

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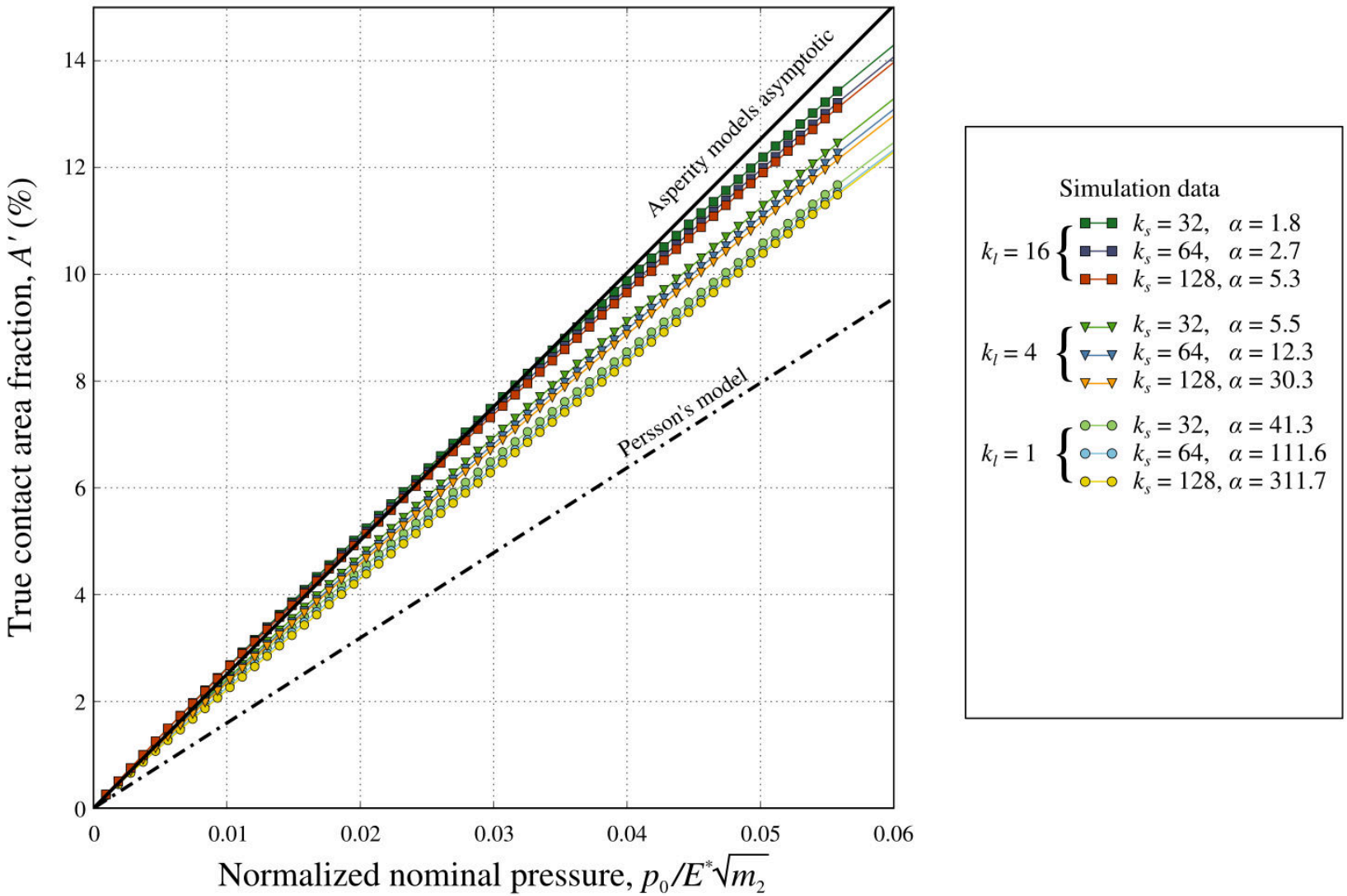
Real contact area: interpretation of results?



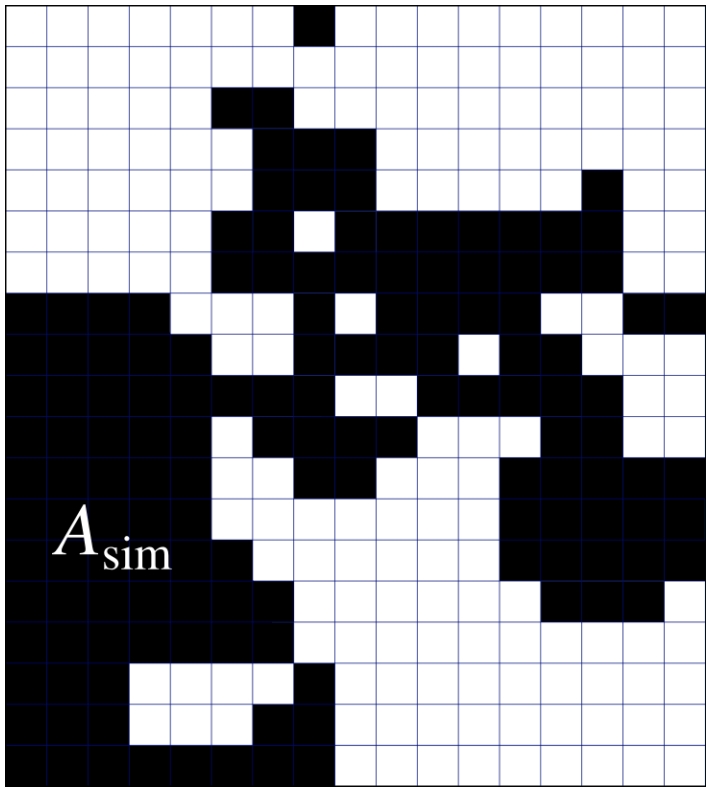
Raw data

[1] Yastrebov, Anciaux, Molinari, Int J Solids Struct 52 (2015)

Numerical error correction

- Contact area is overestimated in simulations:

$$A_{\text{sim}} > A_*$$



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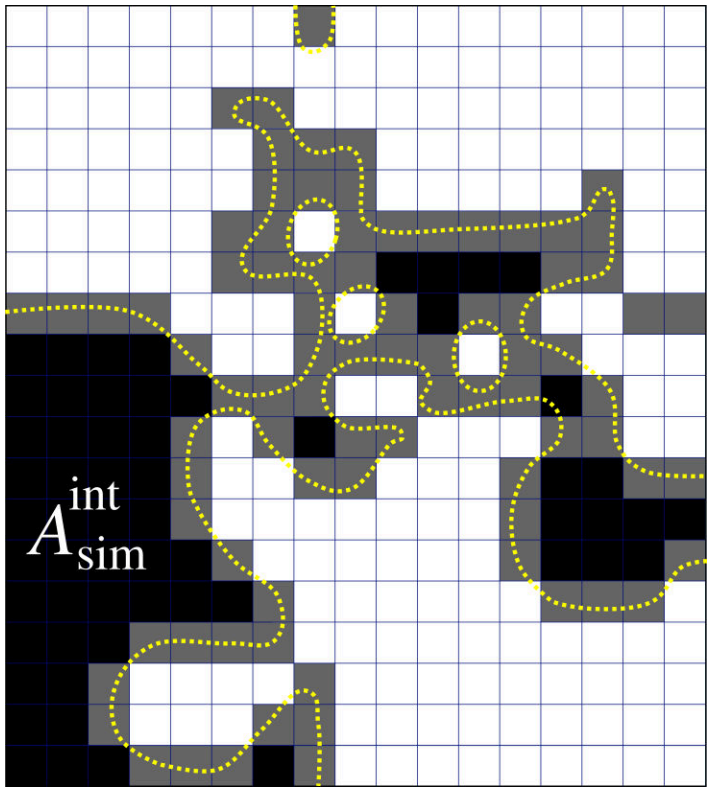

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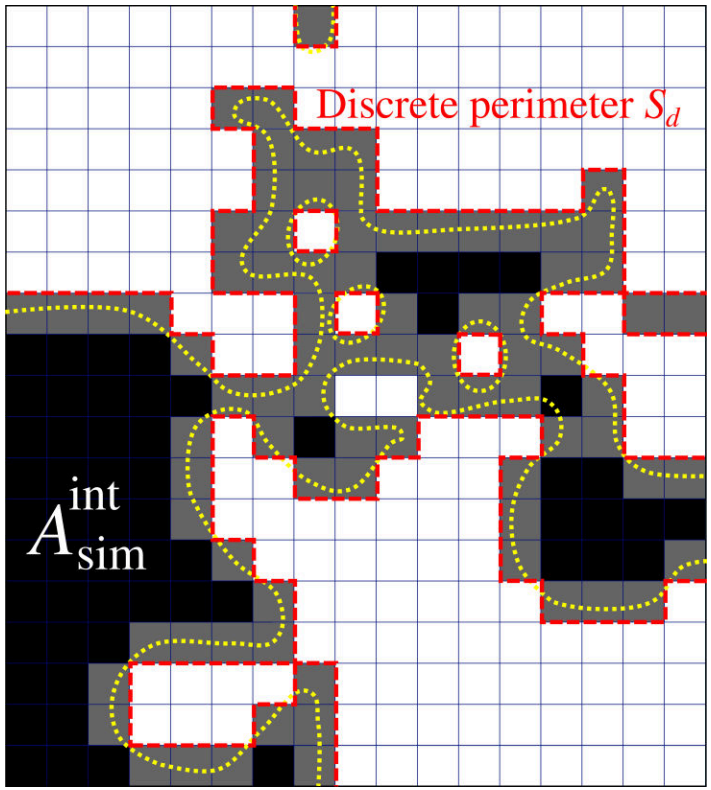
- Boundary area ~ perimeter S_d:

$$A_{\text{sim}} - A_{\text{sim}}^{\text{int}} = S_d \Delta x$$



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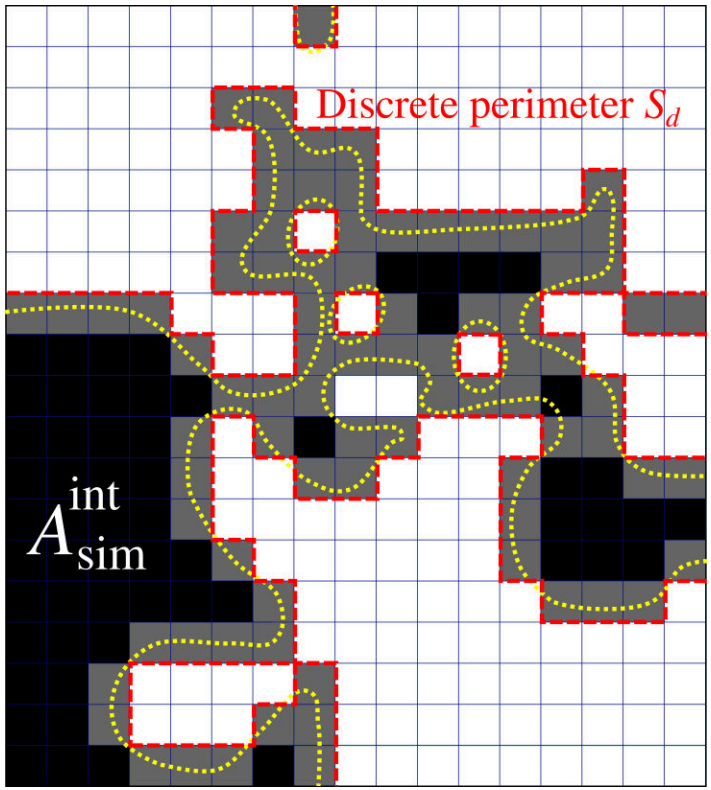
- Manhattan S_d vs Euclidean metric S:

  $$\langle S \rangle = \frac{\pi}{4} \langle S_d \rangle$$



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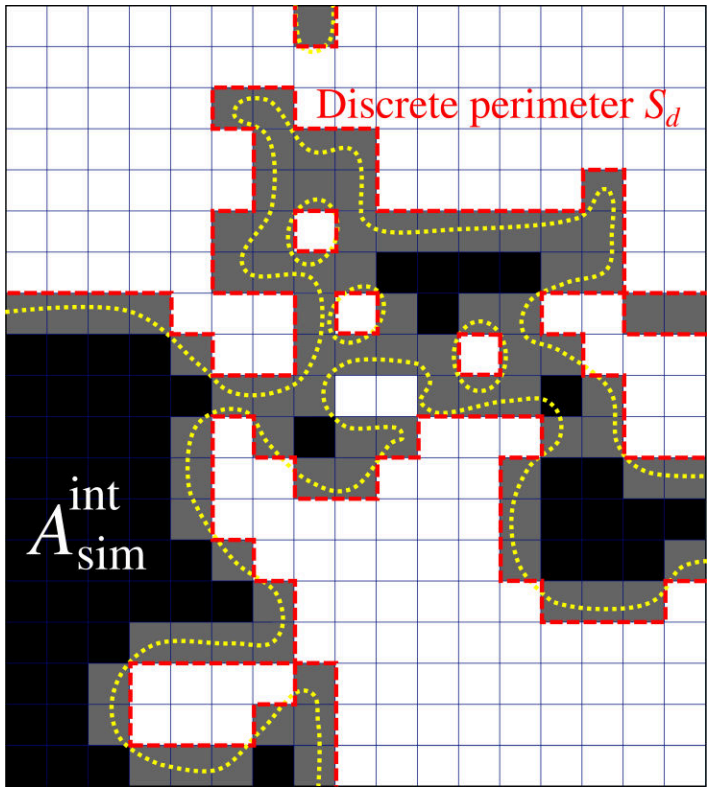
- Manhattan S_d vs Euclidean metric S:

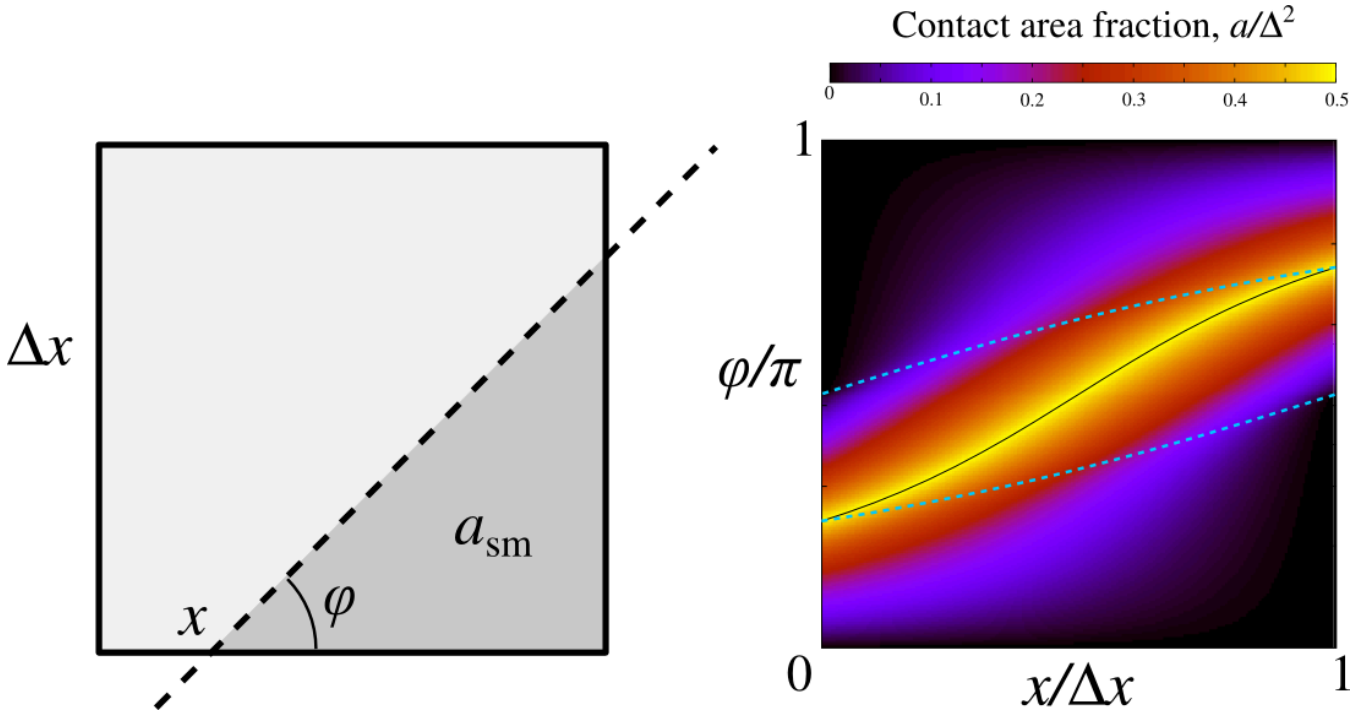
$$\langle S \rangle = \frac{\pi}{4} \langle S_d \rangle$$

- True contact area estimation:

$$\boxed{A_* \approx A_{\text{sim}} - \beta \frac{\pi}{4} S_d \Delta x}$$



Numerical error correction: corrective factor

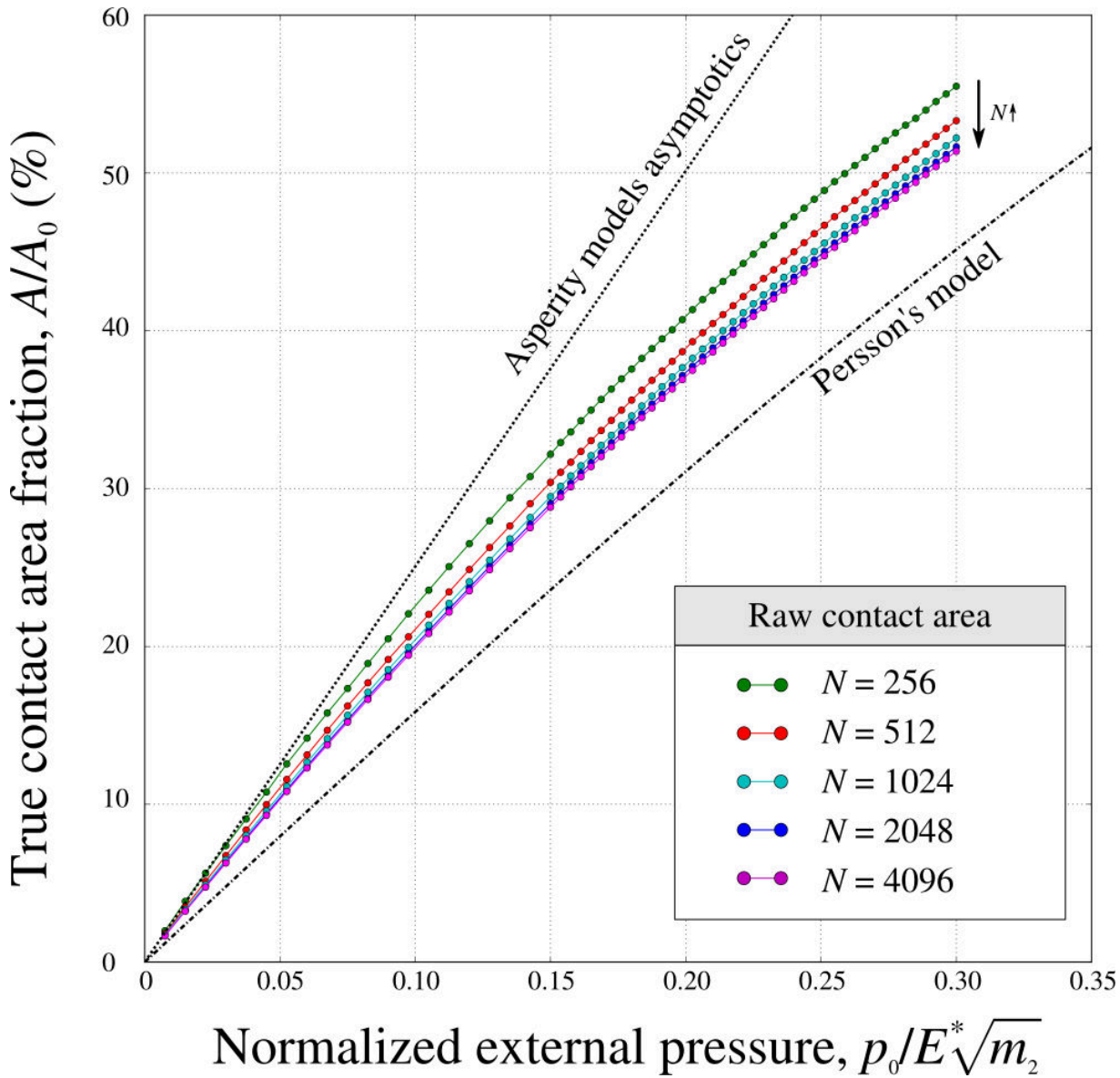


Corrective factor $\beta = \dfrac{\langle a_{\mathrm{sm}} \rangle}{\Delta x^2} = \dfrac{1}{\Delta x^2} \int_0^h \int_0^\pi a_{\mathrm{sm}} P(x, \phi)\, dx d\phi = \dfrac{\pi - 1 + \ln 2}{6\pi}$

$$\beta = 0.150387618994810151606955\ldots$$

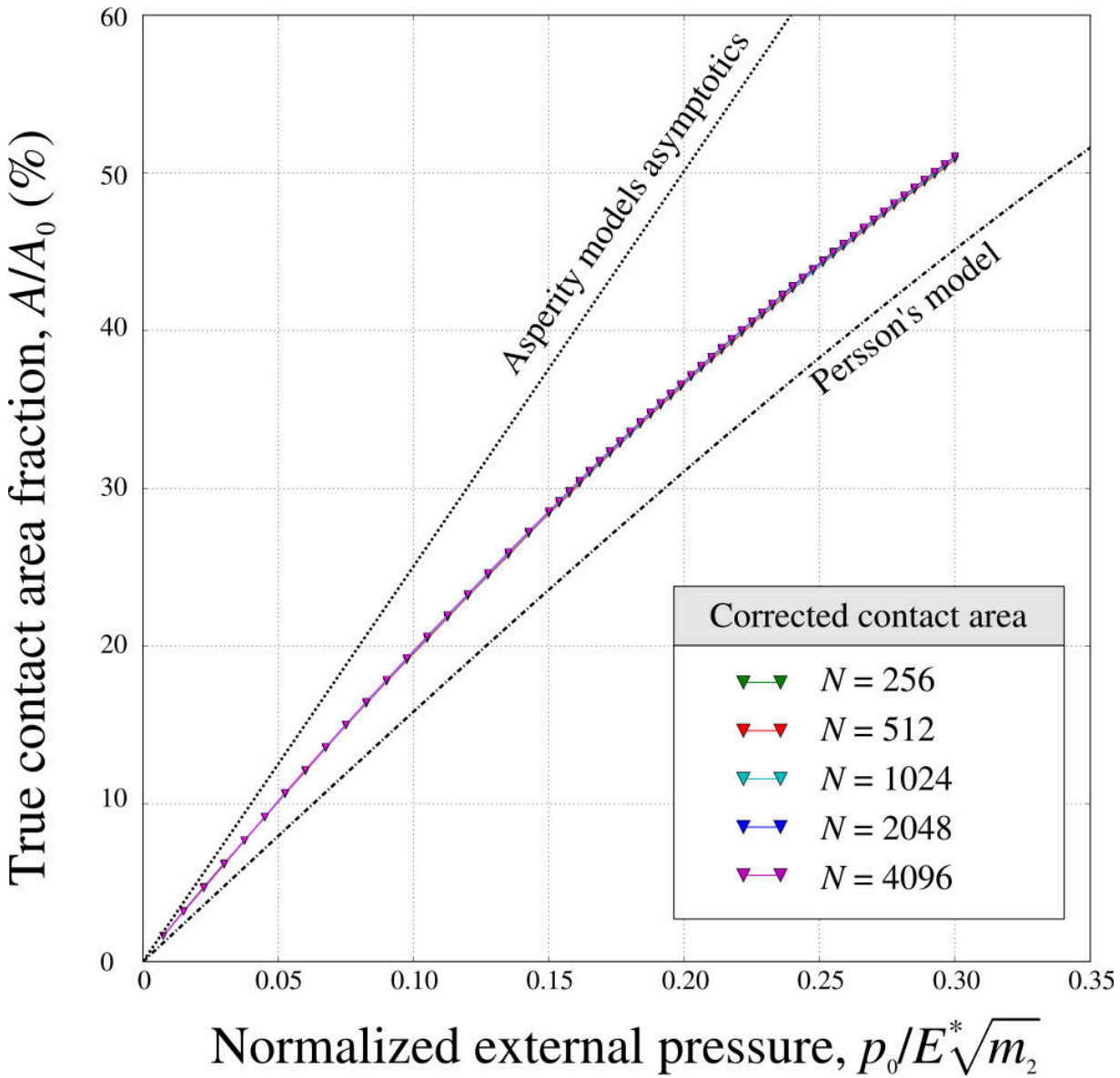
True area estimation: $\boxed{A_* \approx A_{\mathrm{sim}} - \dfrac{\pi - 1 + \ln 2}{24} S_d \Delta x}$

Numerical error correction: convergence study



[1] Yastrebov, Anciaux, Molinari, Tribol Int 114 (2017)

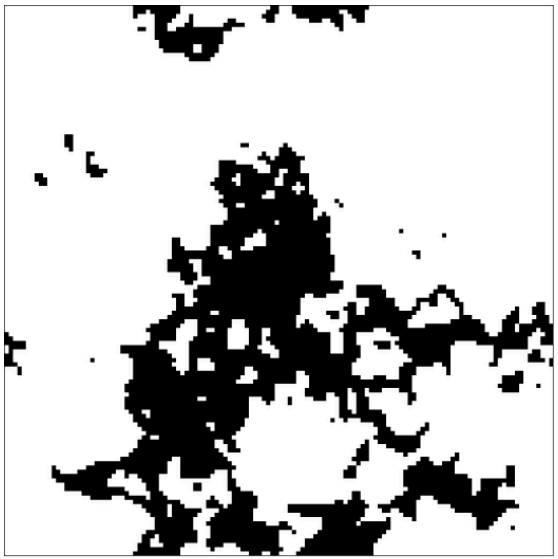
Numerical error correction: convergence study



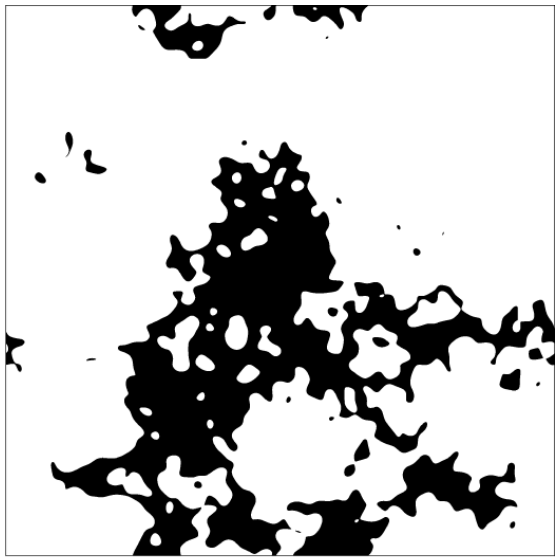
[1] Yastrebov, Anciaux, Molinari, Tribol Int 114 (2017)

Morphological correction

- Morphology of contact clusters



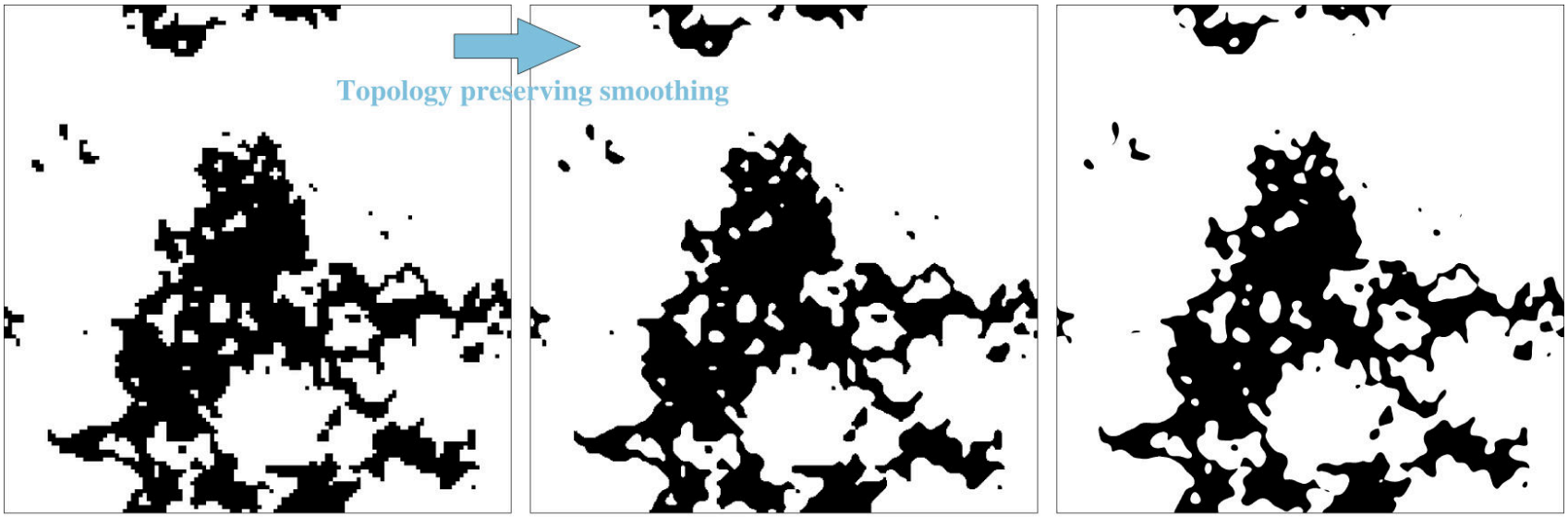
N=128, raw



N=2048, raw

Morphological correction

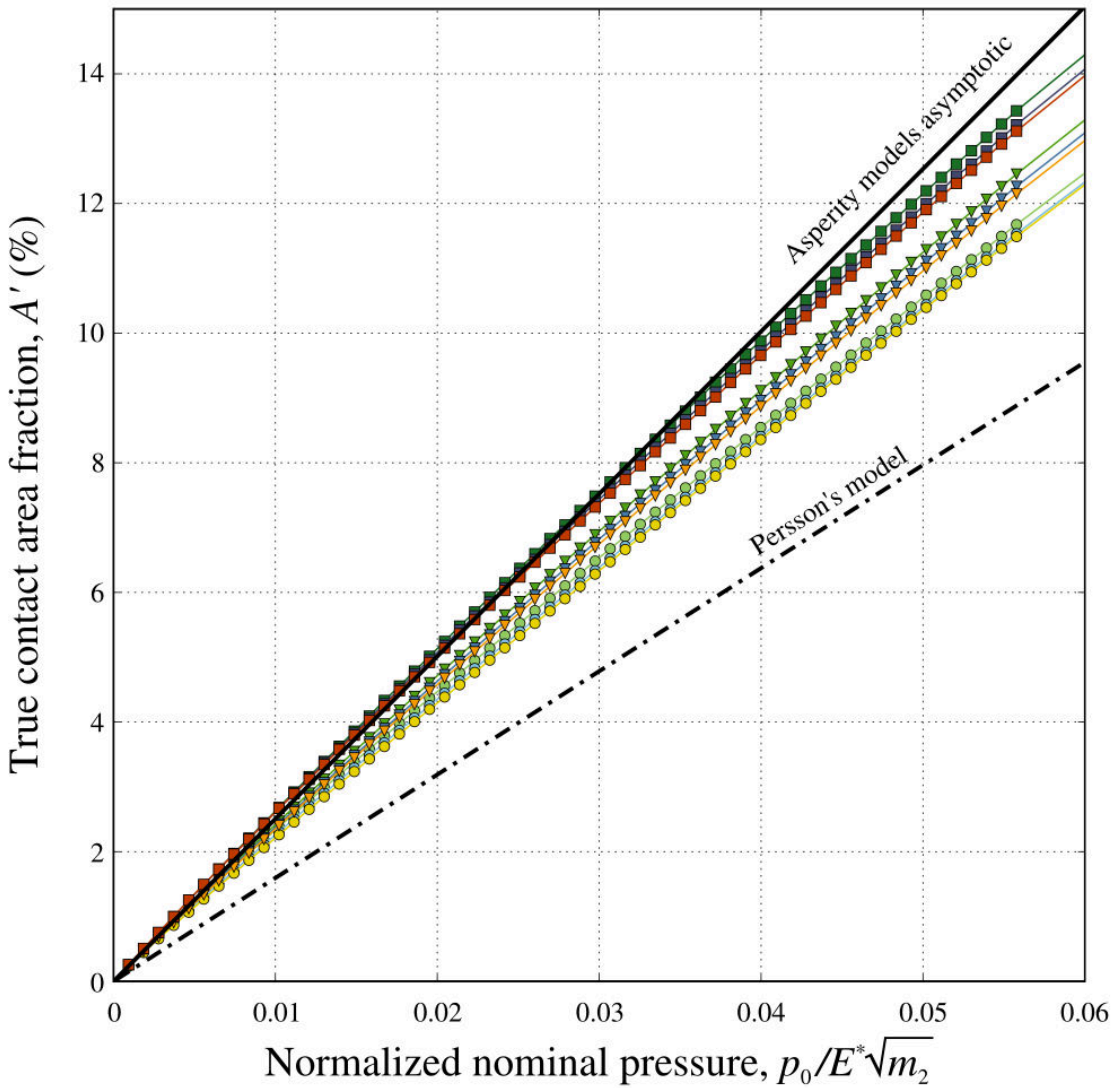
- Morphology of contact clusters

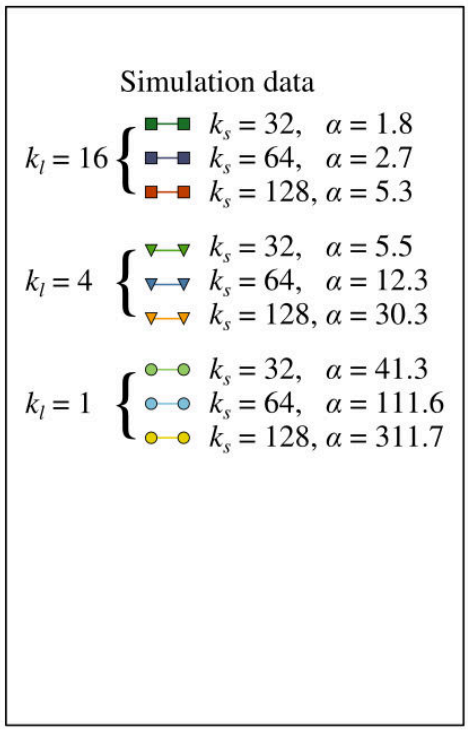


Topologically preserving smoothing results in realistic cluster geometry

[1] Couprie & Bertrand, *J Electr Imag* 13 (2004)

Real contact area: accurate results

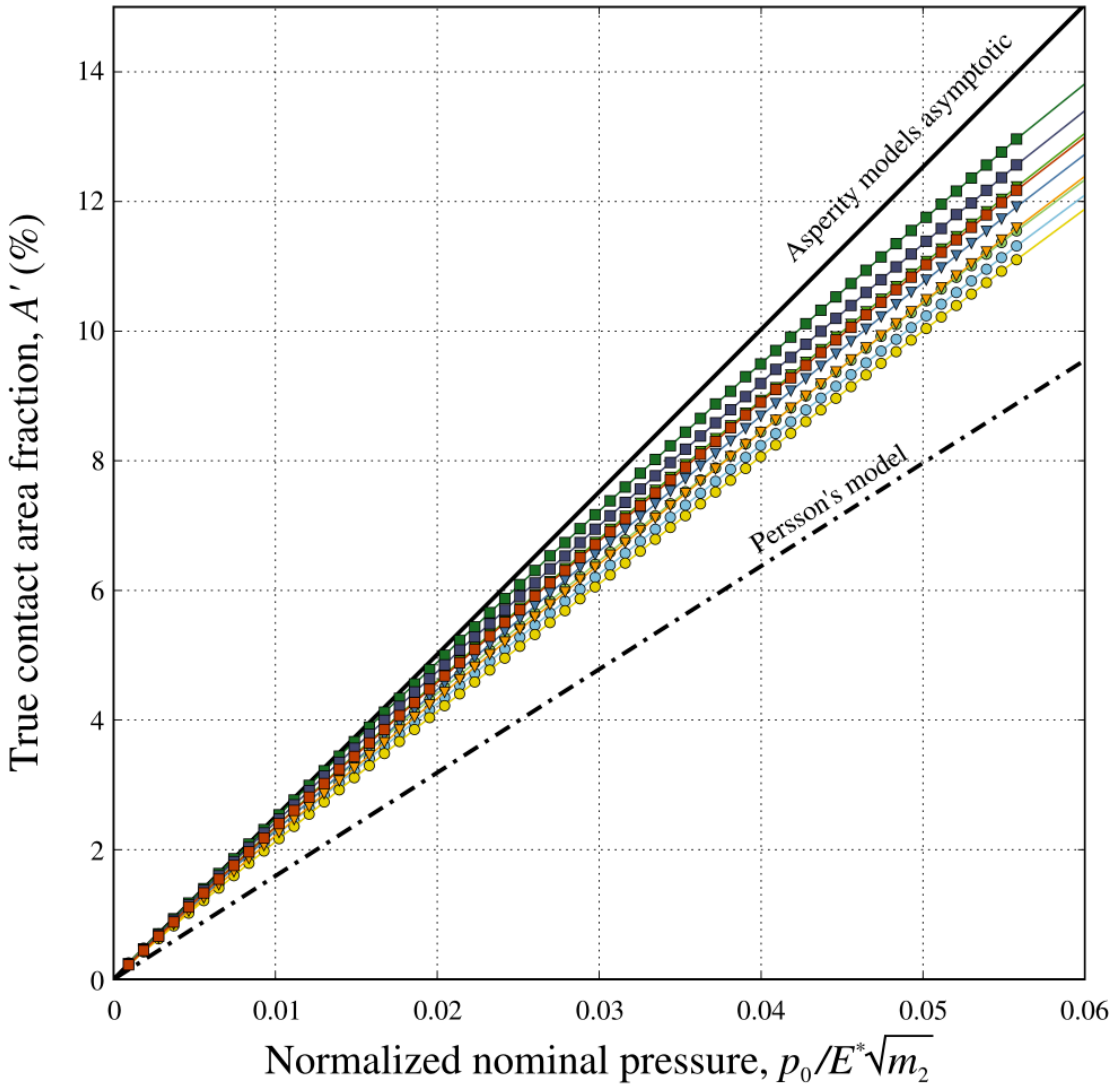




Raw data

[1] Yastrebov, Anciaux, Molinari, Int J Solids Struct 52 (2015)

Real contact area: accurate results



Corrected simulation data

$k_l = 16$: $k_s = 32$, $\alpha = 1.8$; $k_s = 64$, $\alpha = 2.7$; $k_s = 128$, $\alpha = 5.3$

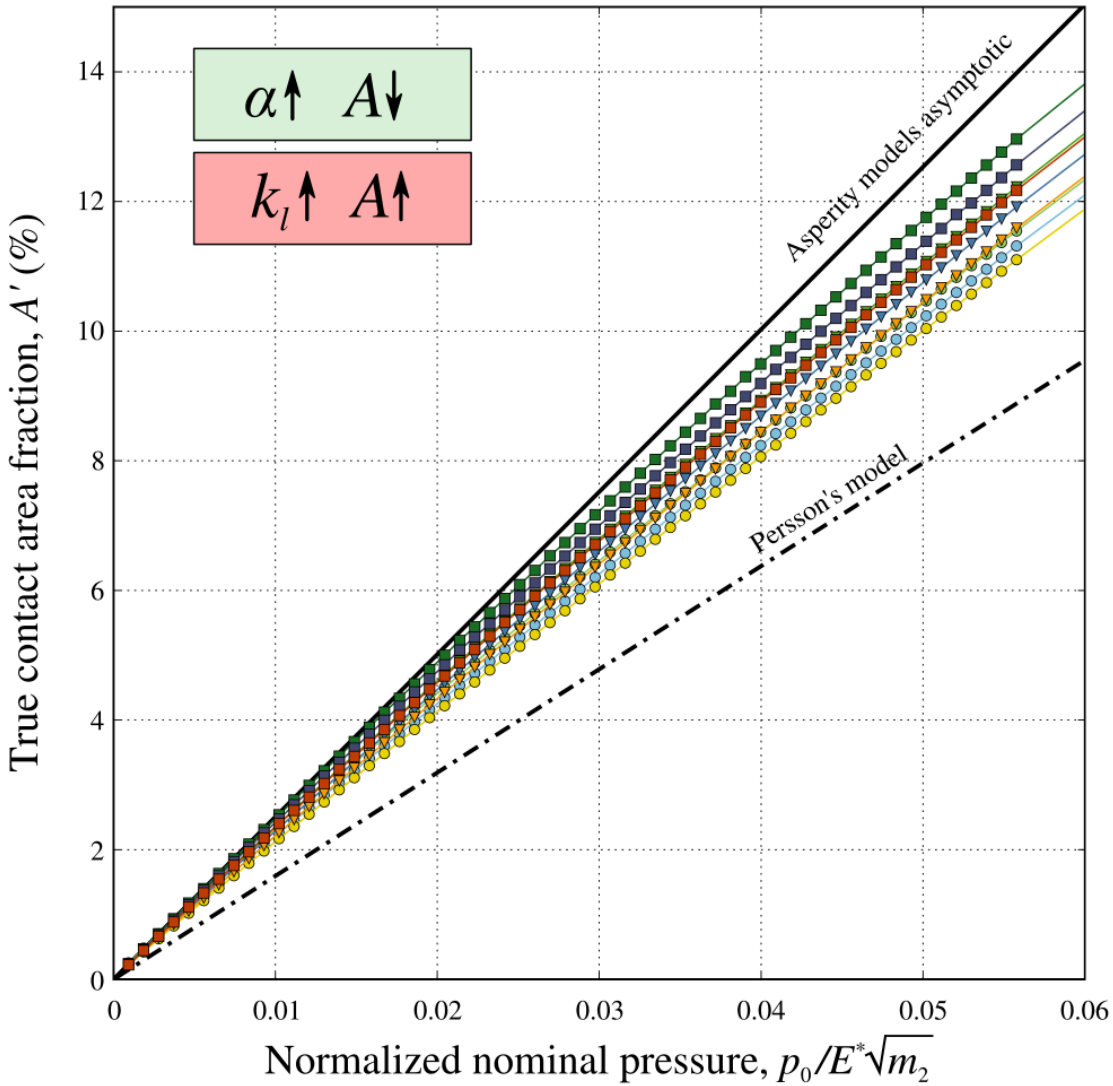
$k_l = 4$: $k_s = 32$, $\alpha = 5.5$; $k_s = 64$, $\alpha = 12.3$; $k_s = 128$, $\alpha = 30.3$

$k_l = 1$: $k_s = 32$, $\alpha = 41.3$; $k_s = 64$, $\alpha = 111.6$; $k_s = 128$, $\alpha = 311.7$

Corrected data

[2] Yastrebov, Anciaux, Molinari, *J Mech Phys Solids* 107 (2017)

Real contact area: accurate results



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$k_l = 16$ { $k_s = 32$, $\alpha = 1.8$; $k_s = 64$, $\alpha = 2.7$; $k_s = 128$, $\alpha = 5.3$ }

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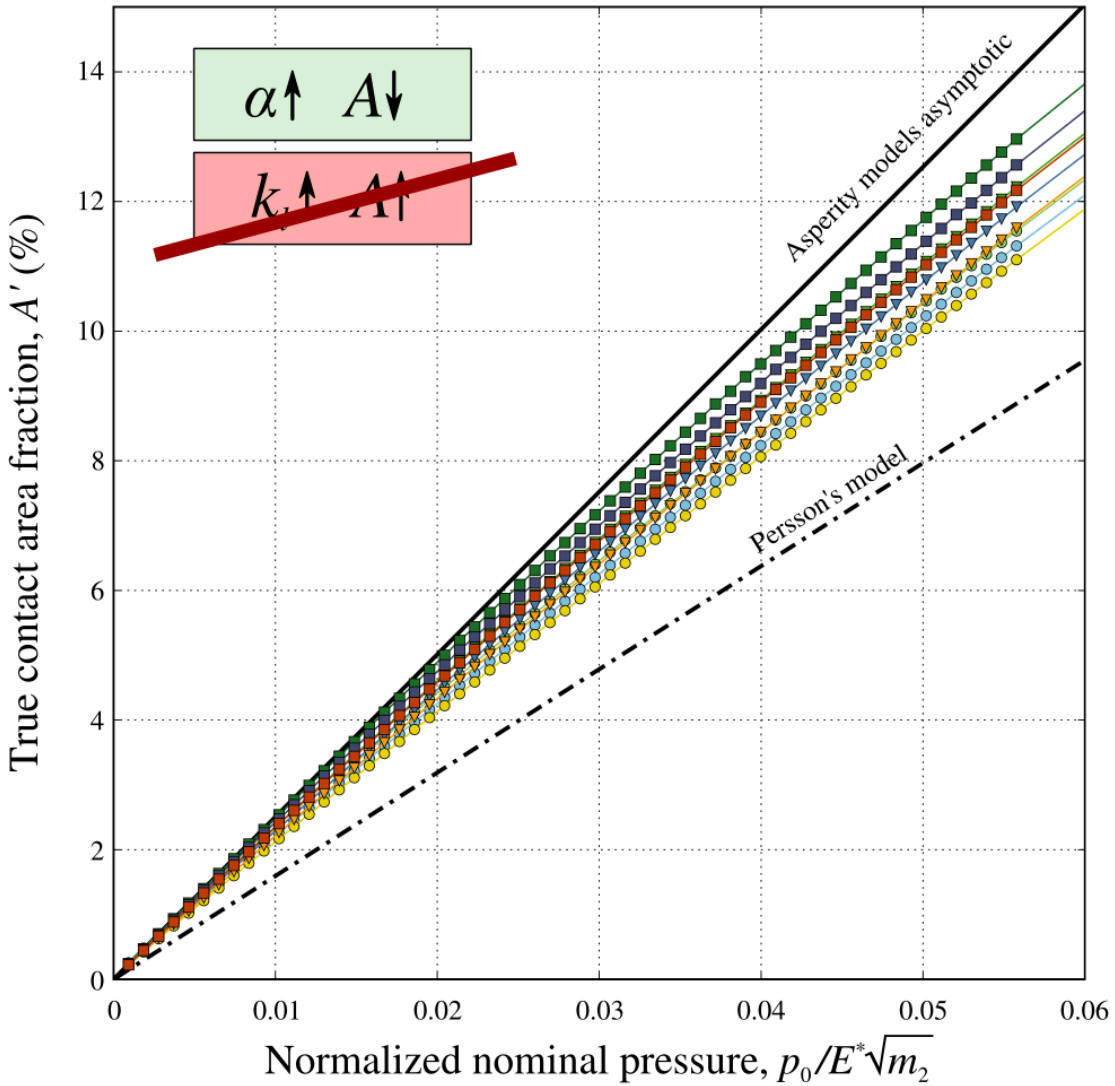

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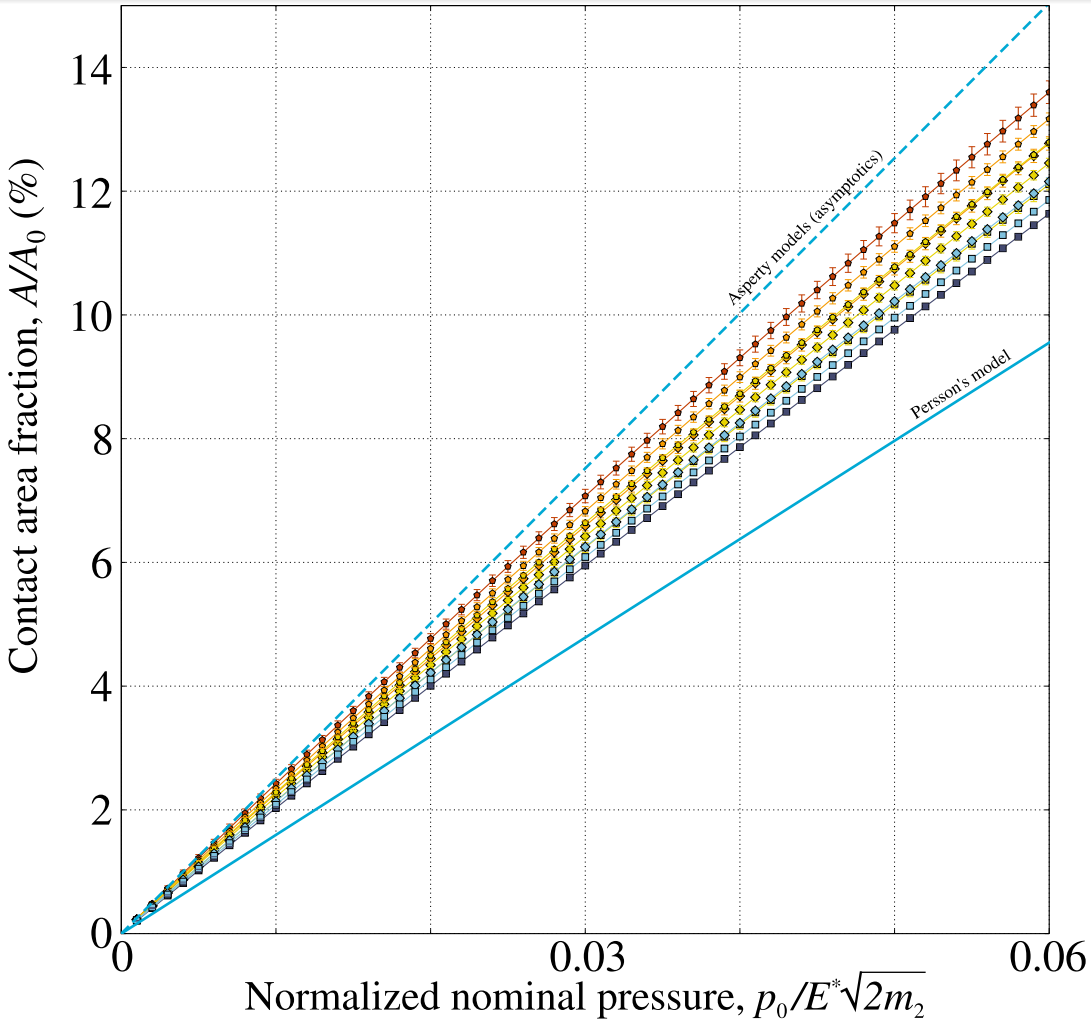
Corrected data

[2] Yastrebov, Anciaux, Molinari, *J Mech Phys Solids* 107 (2017)

Results: contact area



Corrected simulation results

$H = 0.8$

$L/\lambda_l = 16$

- $L/\lambda_s = 32,\ \zeta = 2,\ \alpha = 1.8$
- $L/\lambda_s = 64,\ \zeta = 4,\ \alpha = 2.7$
- $L/\lambda_s = 128,\ \zeta = 8,\ \alpha = 5.3$

$L/\lambda_l = 8$

- $L/\lambda_s = 64,\ \zeta = 8,\ \alpha = 5.3$
- $L/\lambda_s = 128,\ \zeta = 16,\ \alpha = 11.7$
- $L/\lambda_s = 256,\ \zeta = 32,\ \alpha = 28.6$

$L/\lambda_l = 4$

- $L/\lambda_s = 128,\ \zeta = 32,\ \alpha = 30.1$
- $L/\lambda_s = 256,\ \zeta = 64,\ \alpha = 78.6$
- $L/\lambda_s = 512,\ \zeta = 128,\ \alpha = 214.2$

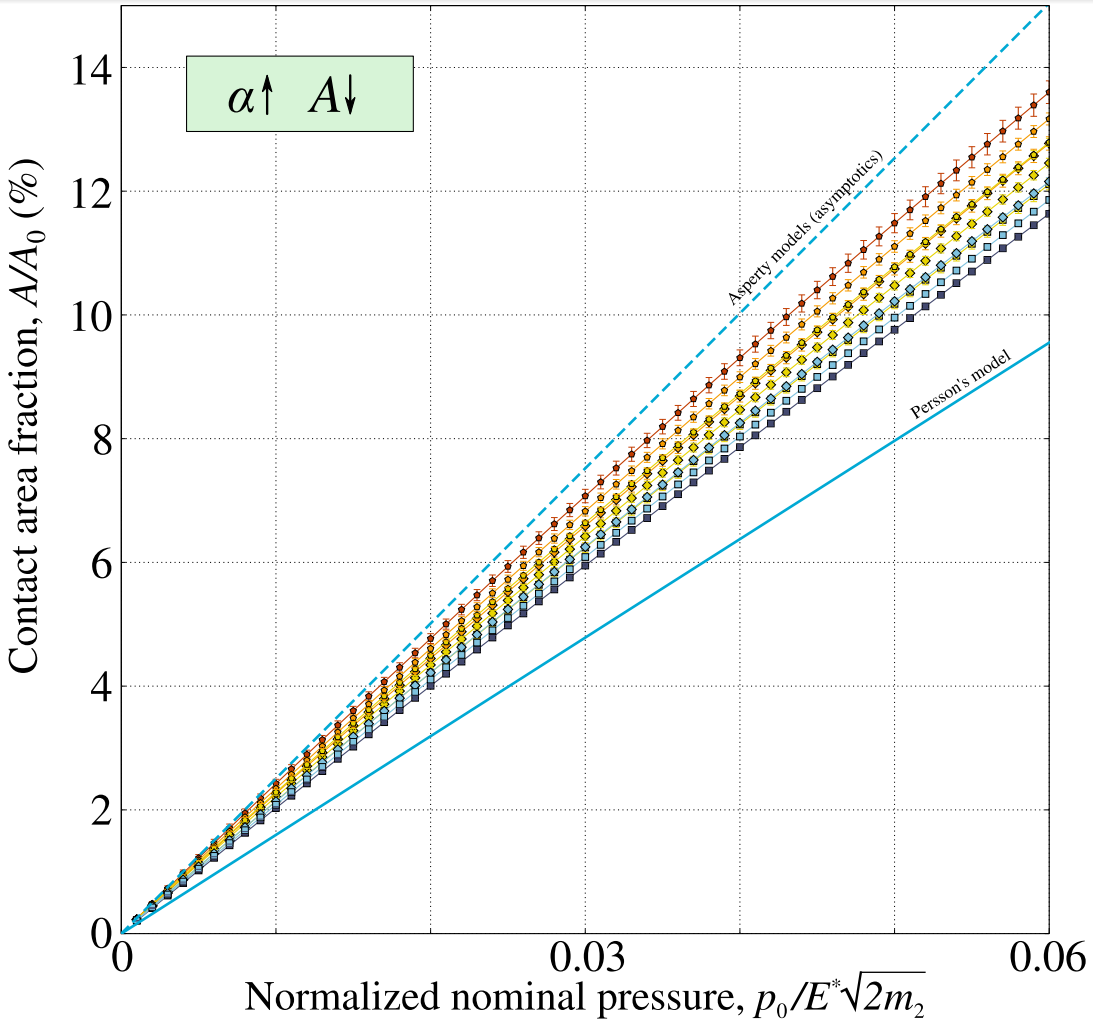
Corrected contact area (discretization independent): "magic" formula[1,2]

$$A_* \approx A_{\text{sim}} - \frac{\pi - 1 + \ln 2}{24} S_d \Delta x,$$

where S_d is the integral **perimeter** of the contact zones.

[1] Yastrebov, Anciaux, Molinari, *Tribol. Int.* 114 (2017)
[2] Yastrebov, Anciaux, Molinari, *J Mech Phys Solids* 107 (2017)

Results: contact area



Corrected simulation results		
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$L/\lambda_l = 16$		
$L/\lambda_s = 32$,	$\zeta = 2$,	$\alpha = 1.8$
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$L/\lambda_l = 8$		
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$L/\lambda_l = 4$		
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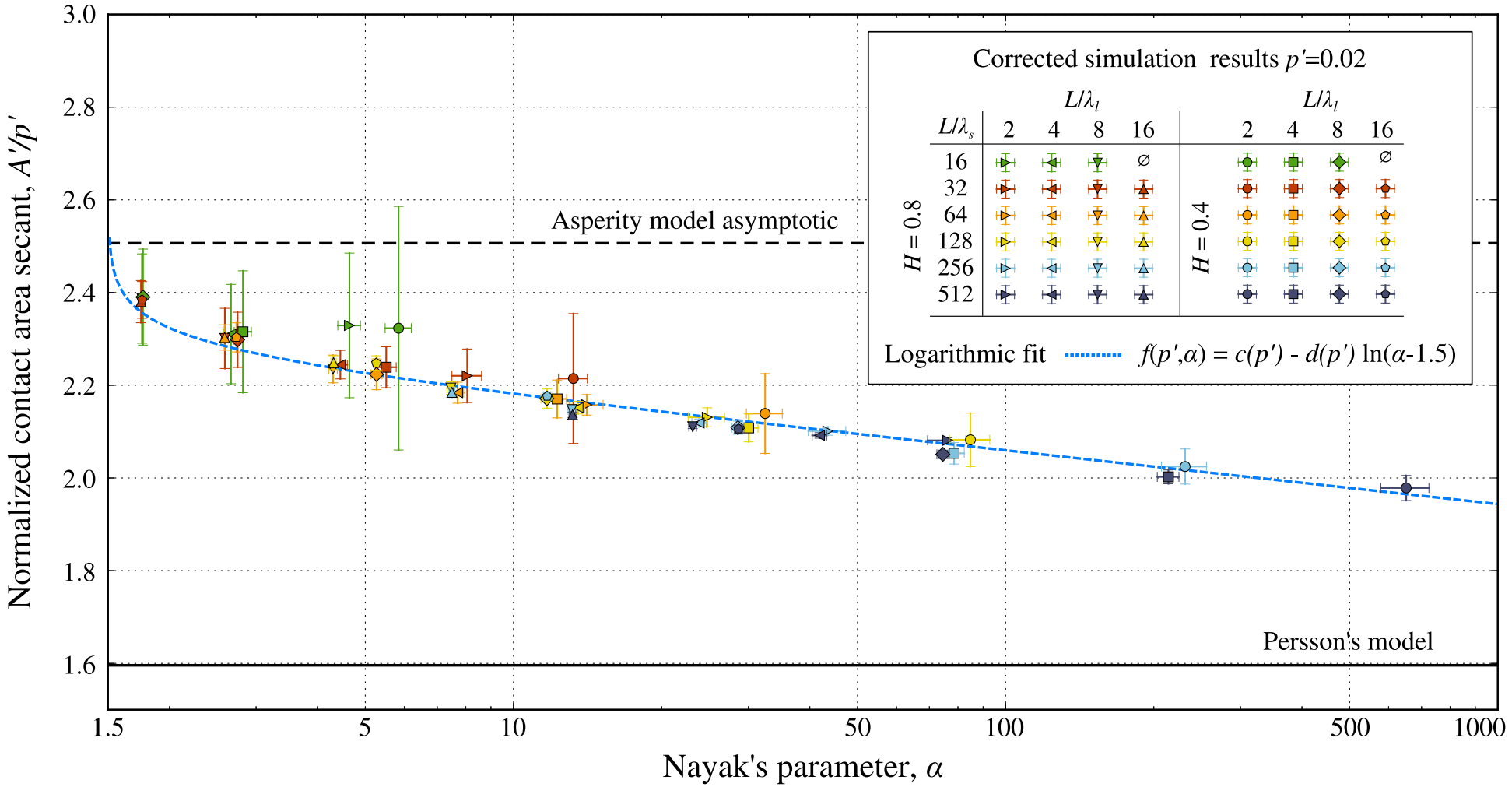
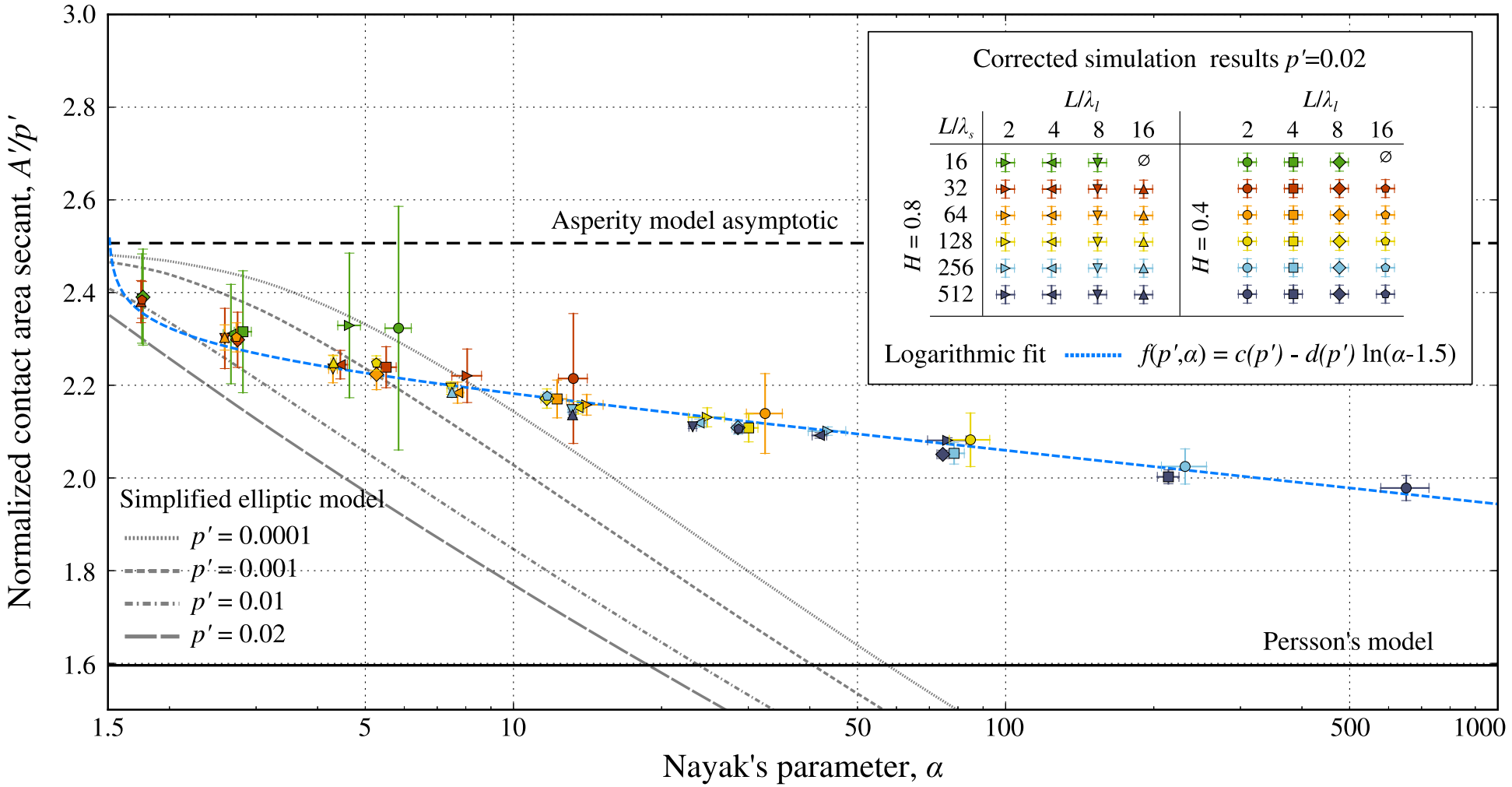
Role of Nayak parameter α



Numerical results: [1] Yastrebov, Anciaux, Molinari, J Mech Phys Solids 107 (2017)

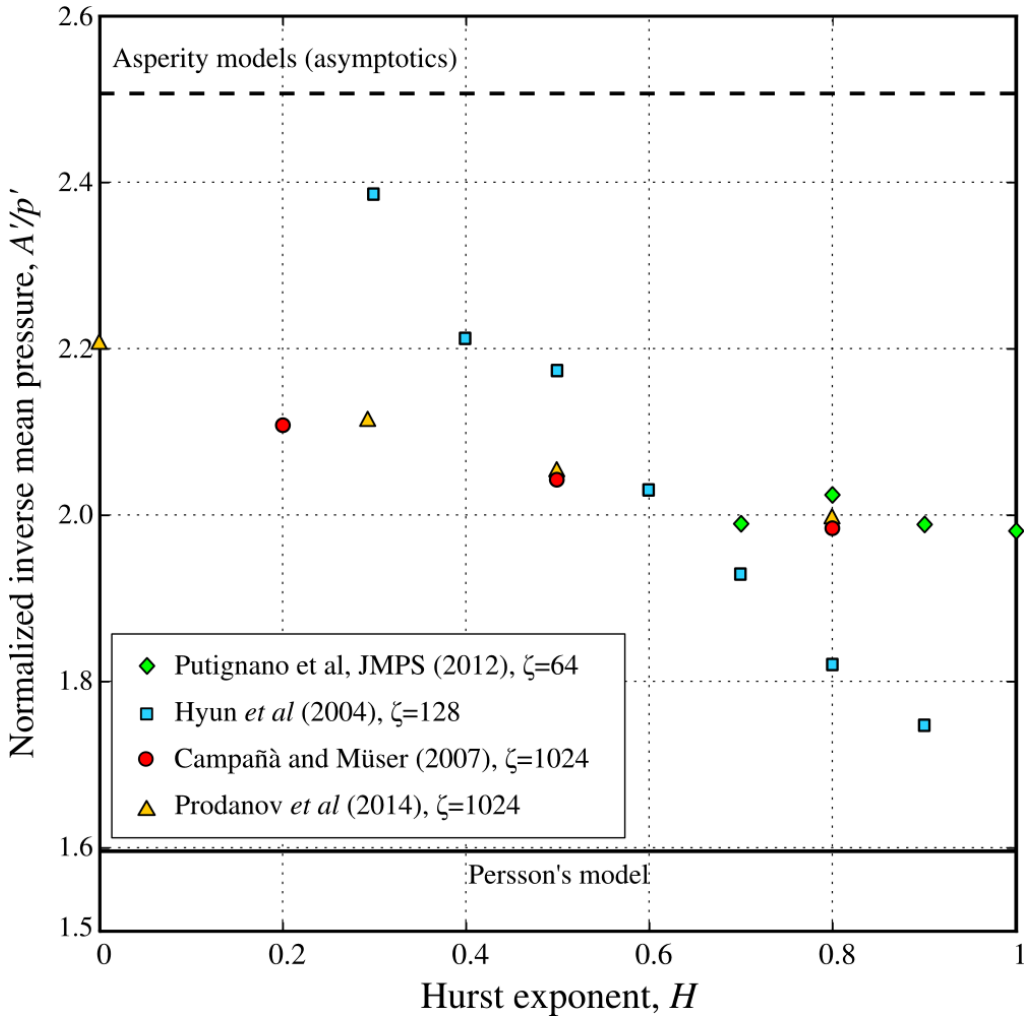
Role of Nayak parameter α



Numerical results: [1] Yastrebov, Anciaux, Molinari, J Mech Phys Solids 107 (2017)

Simplified elliptic model: [2] Greenwood, Wear (2006)

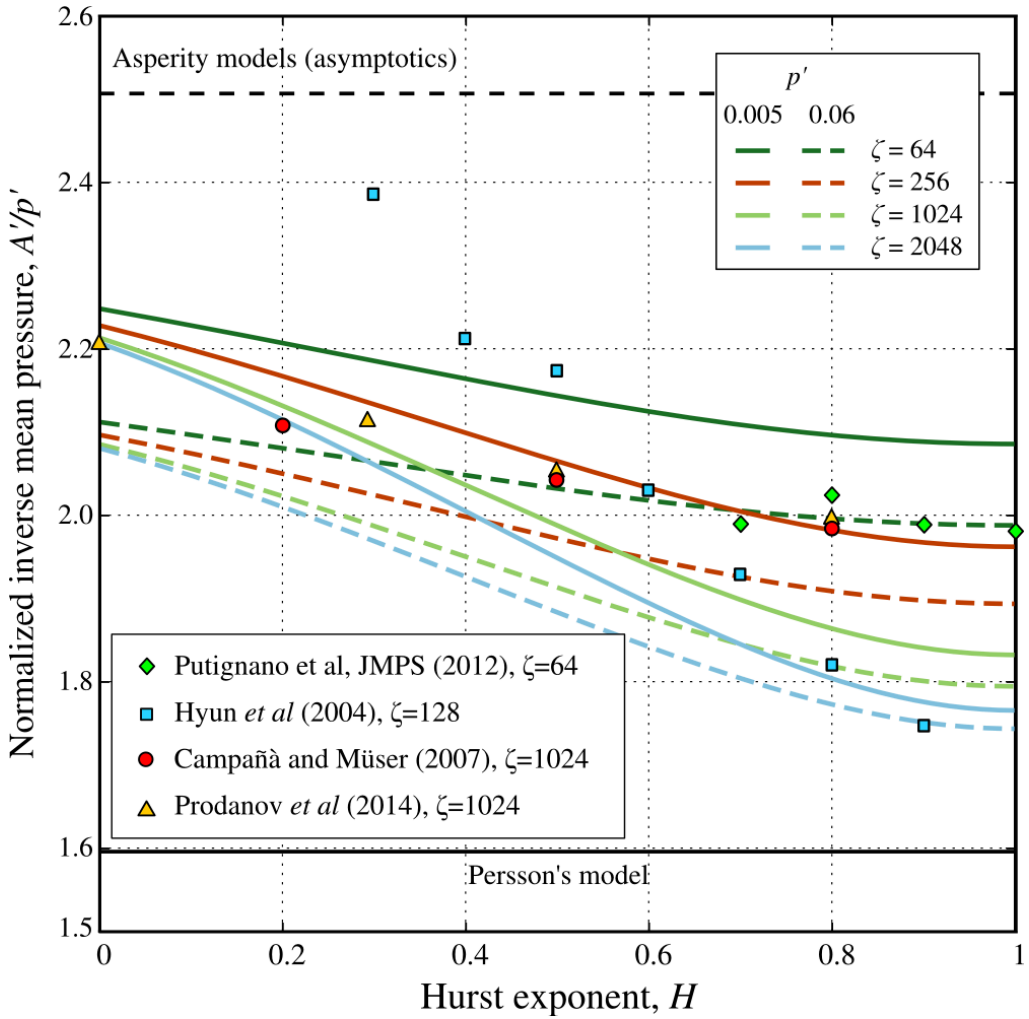
Role of Nayak parameter α



Comparison with other numerical studies
Nayak-Hurst relationship

$$\alpha(H,\zeta) = \frac{3}{2}\frac{(1-H)^2}{H(H-2)}\frac{(\zeta^{-2H}-1)(\zeta^{4-2H}-1)}{(\zeta^{2-2H}-1)^2}$$

Role of Nayak parameter α



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Phenomenological relationship

- Contact area A grows with applied pressure p_0 as

$$\frac{A}{A_0} = a(\alpha)\frac{p_0}{E^*\sqrt{2m_2}} - b(\alpha)\left[\frac{p_0}{E^*\sqrt{2m_2}}\right]^2$$

- Contact area fraction $A' = A/A_0$ grows with normalized applied pressure $p' = p_0/E^*\sqrt{2m_2}$

$$\boxed{A' = a(\alpha)p' - b(\alpha)p'^2}$$

- With ≈universal adimensional constants:

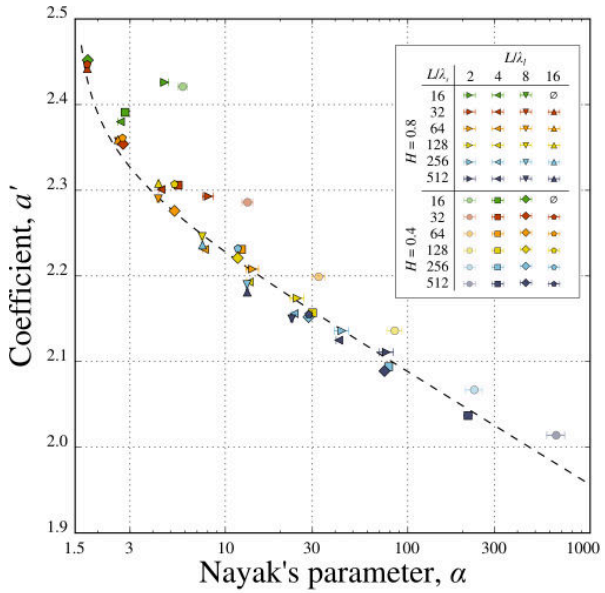
$$a(\alpha) = 2.35 - 0.057\ln(\alpha - 1.5)$$

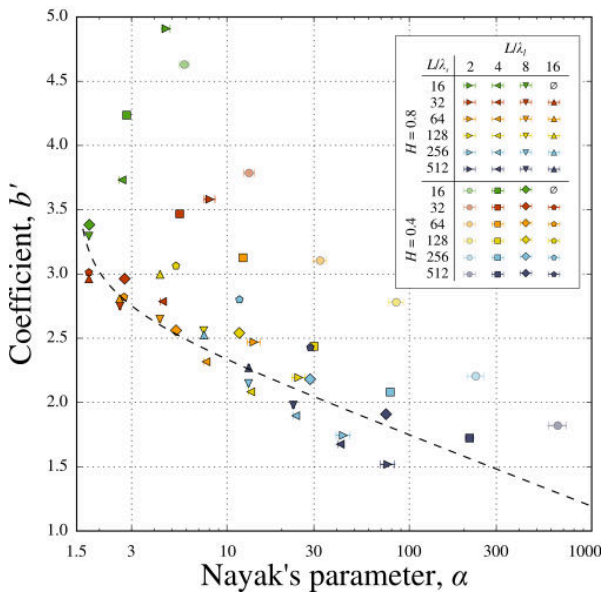
$$b(\alpha) = 2.85 - 0.24\ln(\alpha - 1.5)$$

- Pressure dependent friction coefficient:

$$\mu(p') = \mu_0\left[1 - \frac{b(\alpha)}{a(\alpha)}p'\right]$$

with $\mu_0 = a(\alpha)\tau_{\max}/E^*\sqrt{2m_2}$,
$\tau_{\max}$ is the maximum shear traction the contact interface can bear.





Conclusions

- Contact area growth almost linearly for small pressures and saturates at bigger pressure
- The key parameter of the contact area growth is the RMS slope or its variance $2m_2$
- Contact area depends weakly on Nayak parameter $\alpha = m_0 m_4 / m_2^2$

$$\boxed{A' = a(\alpha)p' - b(\alpha)p'^2}$$

with $a(\alpha) = 2.35 - 0.057 \ln(\alpha - 1.5)$, $\quad b(\alpha) = 2.85 - 0.24 \ln(\alpha - 1.5)$

- No effect of fractal dimension D_f *per se* on the contact area
  it affects the contact area only through the Nayak parameter

Flow through the contact interface

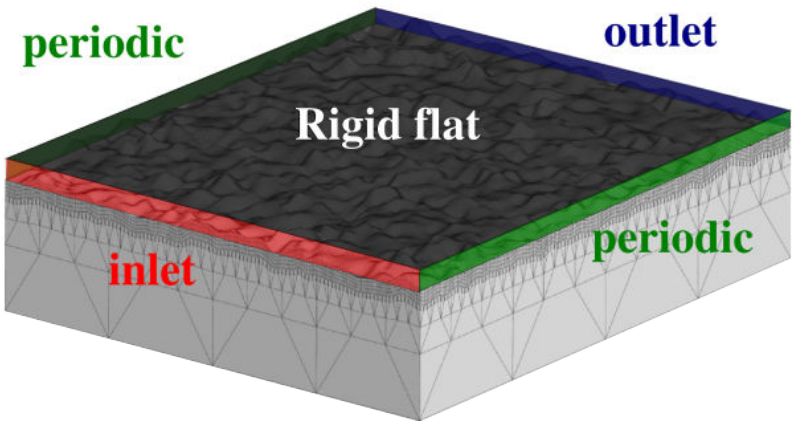
Problem statement

Problem

- **Thin creeping** flow in contact interface:
  Navier-Stokes → Stokes → Reynolds equation
- In addition: incompressible fluid, immobile walls:

$$\nabla \cdot \underline{q} = 0, \quad \underline{q} = -\frac{g^3}{12\mu} \nabla p_f$$

$\underline{q}(x, y)$ is the fluid flux,
$g(x, y)$ is the gap (opening) fields,
$p_f(x, y)$ hydrostatic fluid pressure,
μ is the dynamic viscosity.



- Gap profile $g(x, y)$ for $x, y \in (0, L)$
- At inlet: $p_f = p_{\text{in}}$
- At outlet: $p_f = p_{\text{out}}$
- At lateral sides: periodic
  $q_n(y = L) = -q_n(y = 0)$
- Linear problem: use FEM

Analytical approach

Effective flow estimation

- Averaging over surface $\langle x \rangle = 1/A_0 \int_{A_0} x\, dA$ gives:

$$\langle \underline{q} \rangle = -\underline{\underline{K}}_{\text{eff}} \cdot \langle \nabla p_f \rangle$$

- For isotropic case, normalized scalar **effective transmissivity** along pressure drop OX:

$$K'_{\text{eff}} = -\frac{12\mu \langle q_x \rangle L}{m_0^{3/2}(p_{\text{in}} - p_{\text{out}})}$$

- Using effective medium[1,2] approach

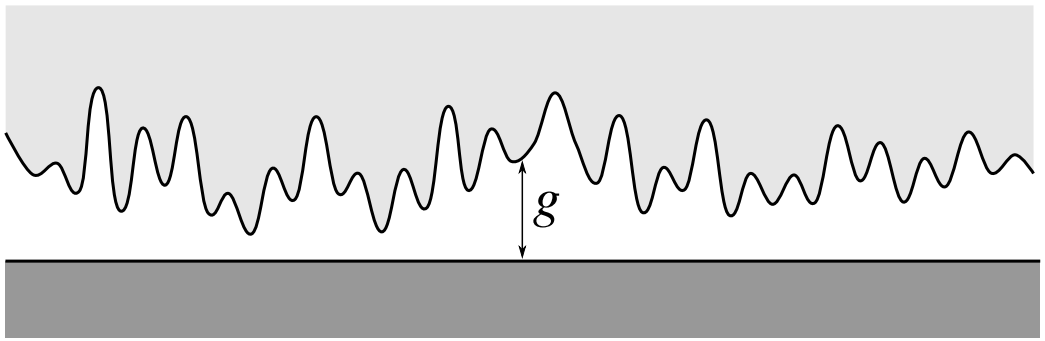
$$(1 - A') \int_0^\infty \frac{g^3 P(g)}{g^3 + K'_{\text{eff}} m_0^{3/2}}\, dg = \frac{1}{2}$$

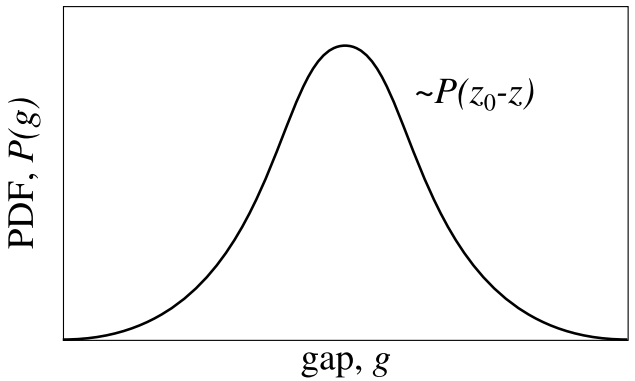
$A' = A/A_0$ is the contact area fraction, $P(g)$ is the gap probability density.

[1] Kirkpatrick. Rev Modern Phys, 45 (1973)
[2] Lorenz & Persson. Europ Phys J E: Soft Matter, 31 (2010)

Danger: geometrical overlap

- Geometrical overlap model is highly inaccurate





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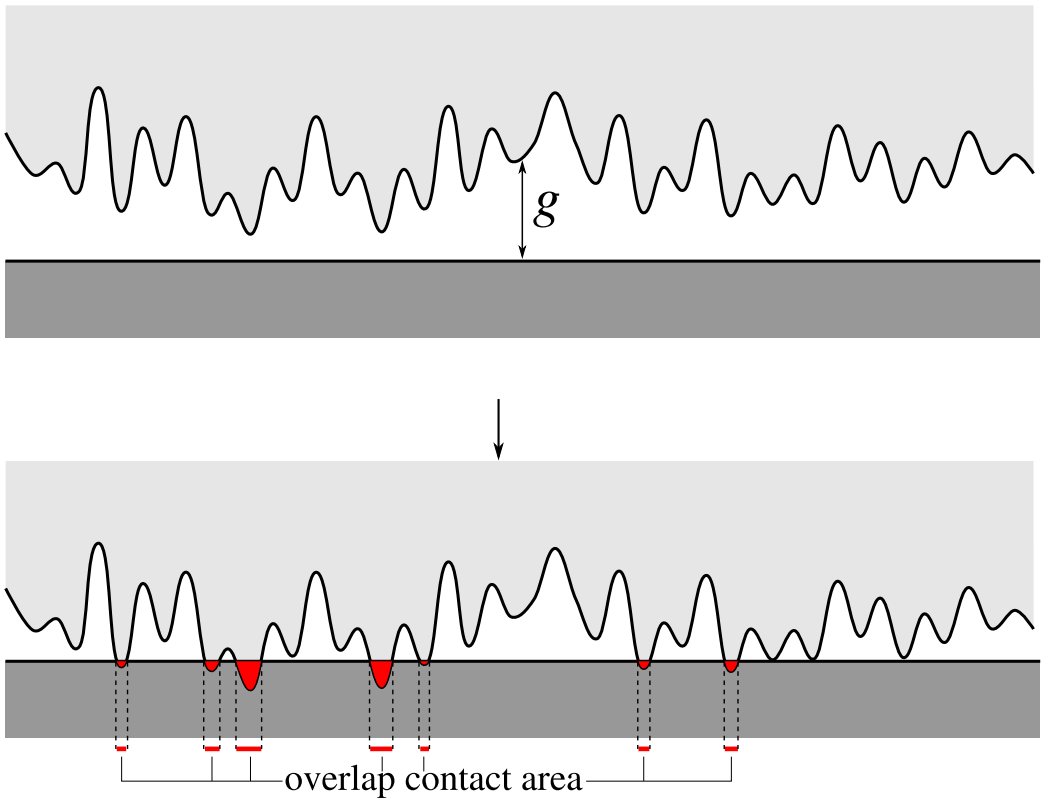
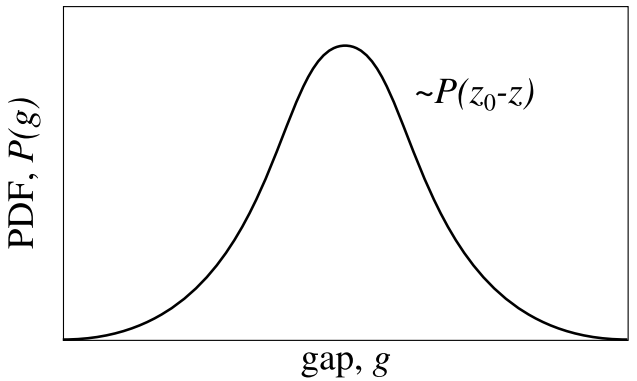
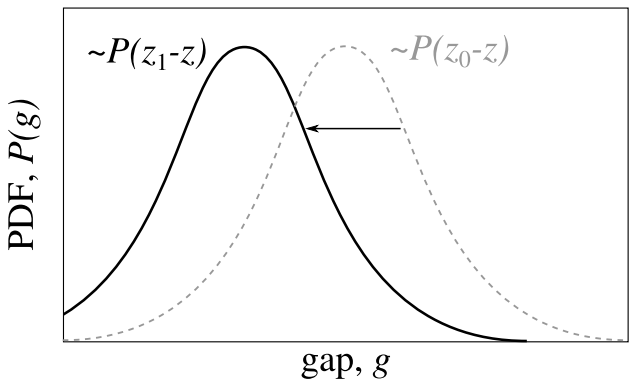
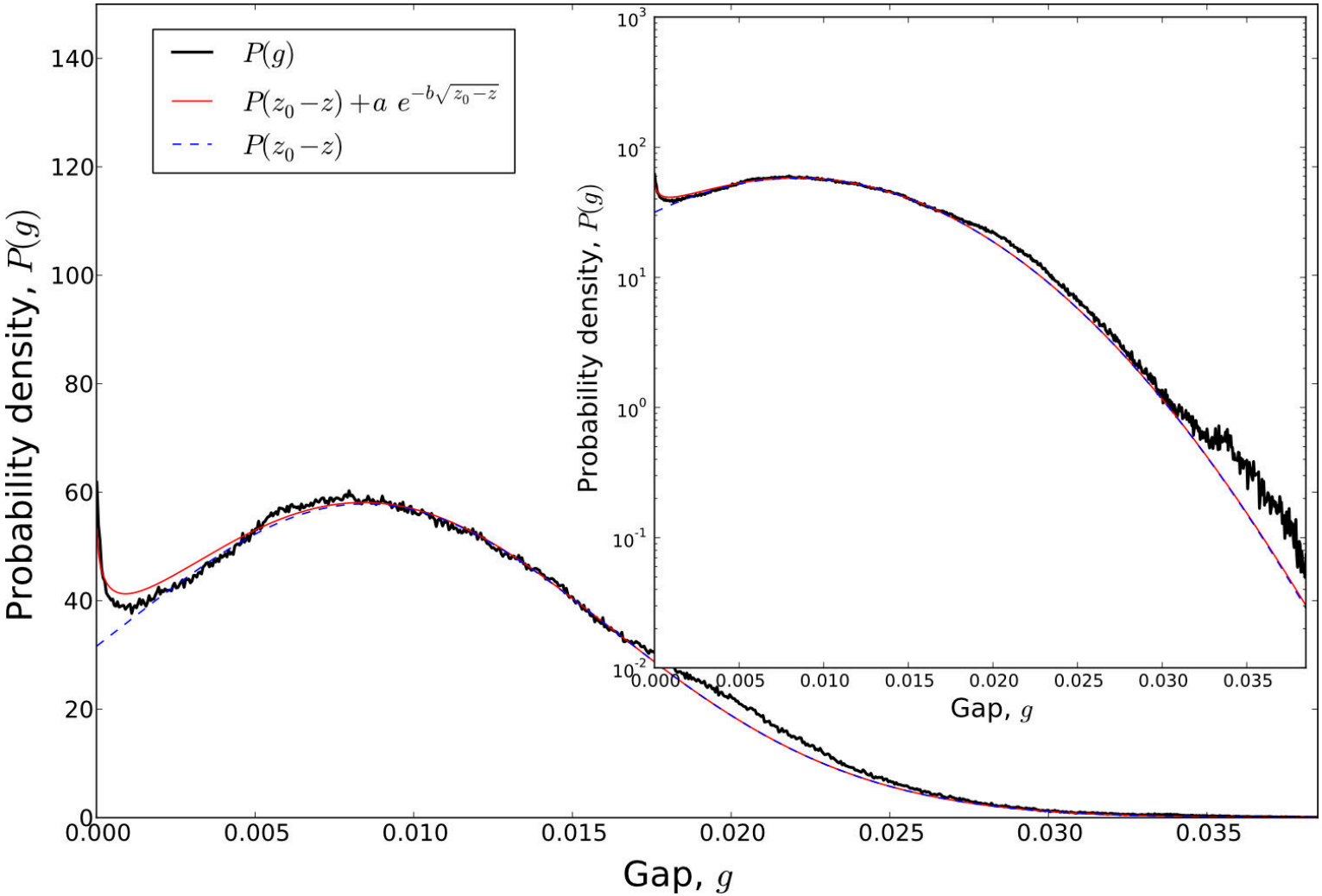






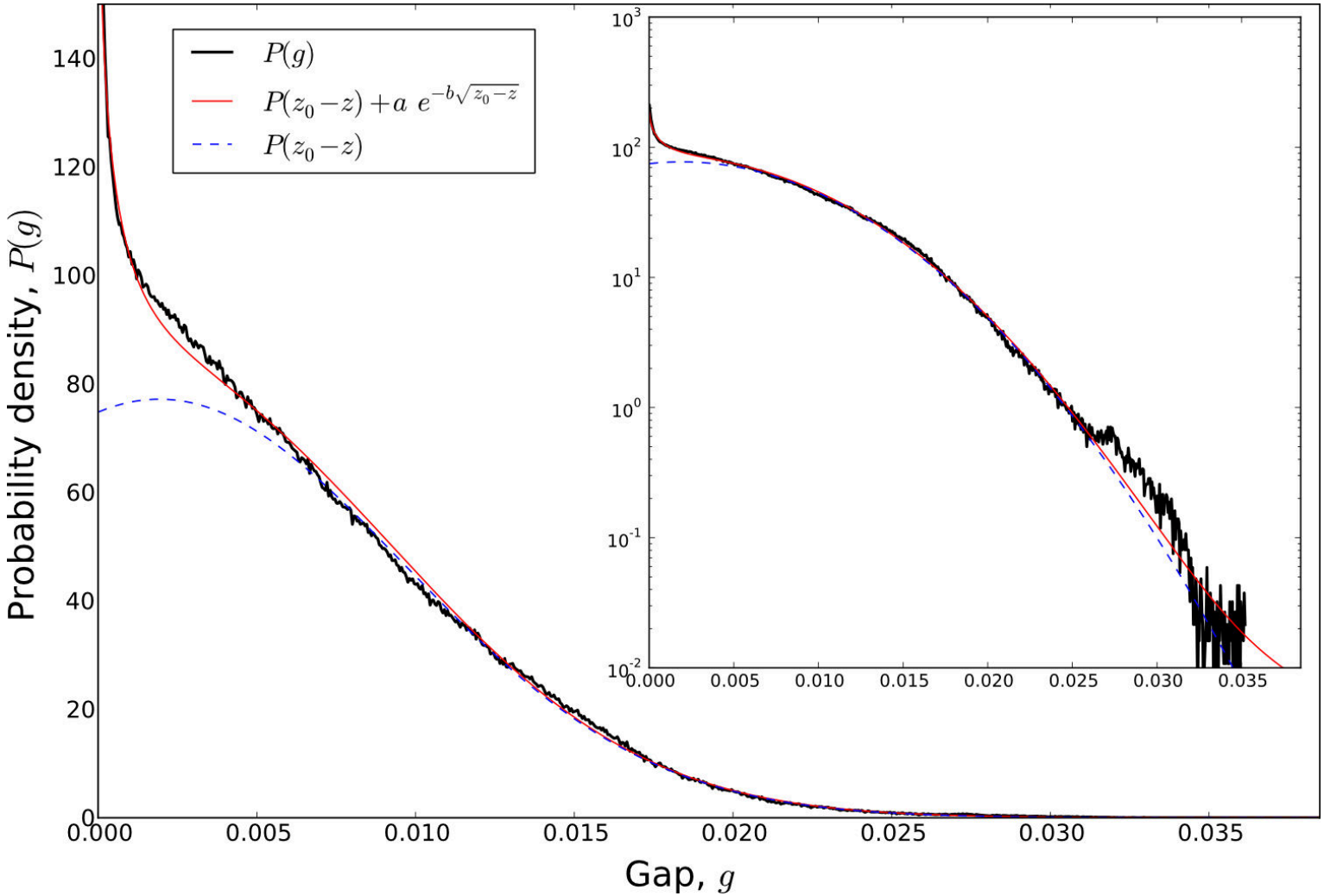
Solid contact results: gap distribution



Area fraction $A' = 1.6\%$

Gap probability density VS geometrical overlap model (dashed line)
Near contact interface $P(g) \sim P(z_0 - z) + a \exp(-b\sqrt{z_0 - z})$

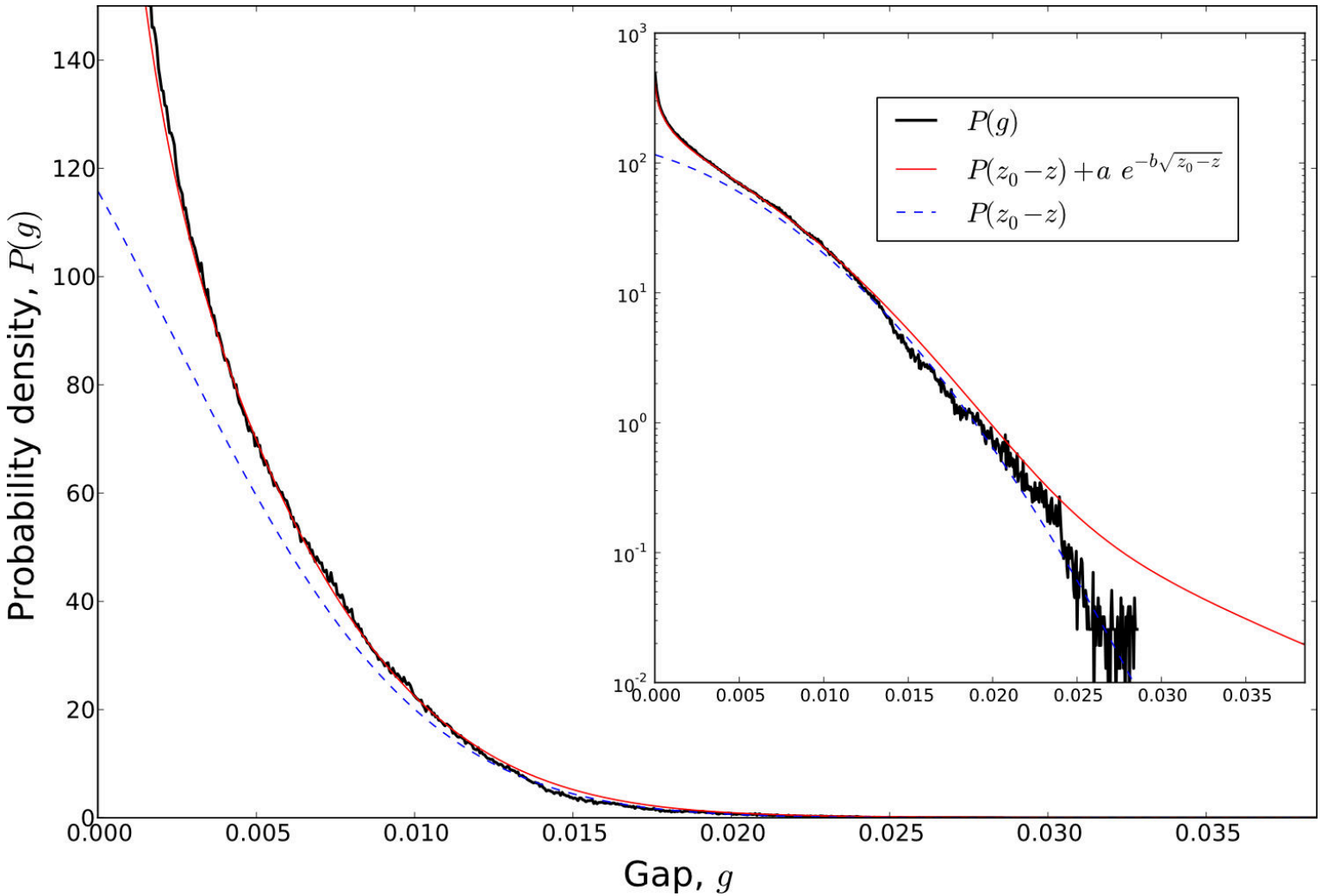
Solid contact results: gap distribution



Area fraction $A' = 9.5\%$

Gap probability density VS geometrical overlap model (dashed line)
Near contact interface $P(g) \sim P(z_0 - z) + a \exp(-b\sqrt{z_0 - z})$

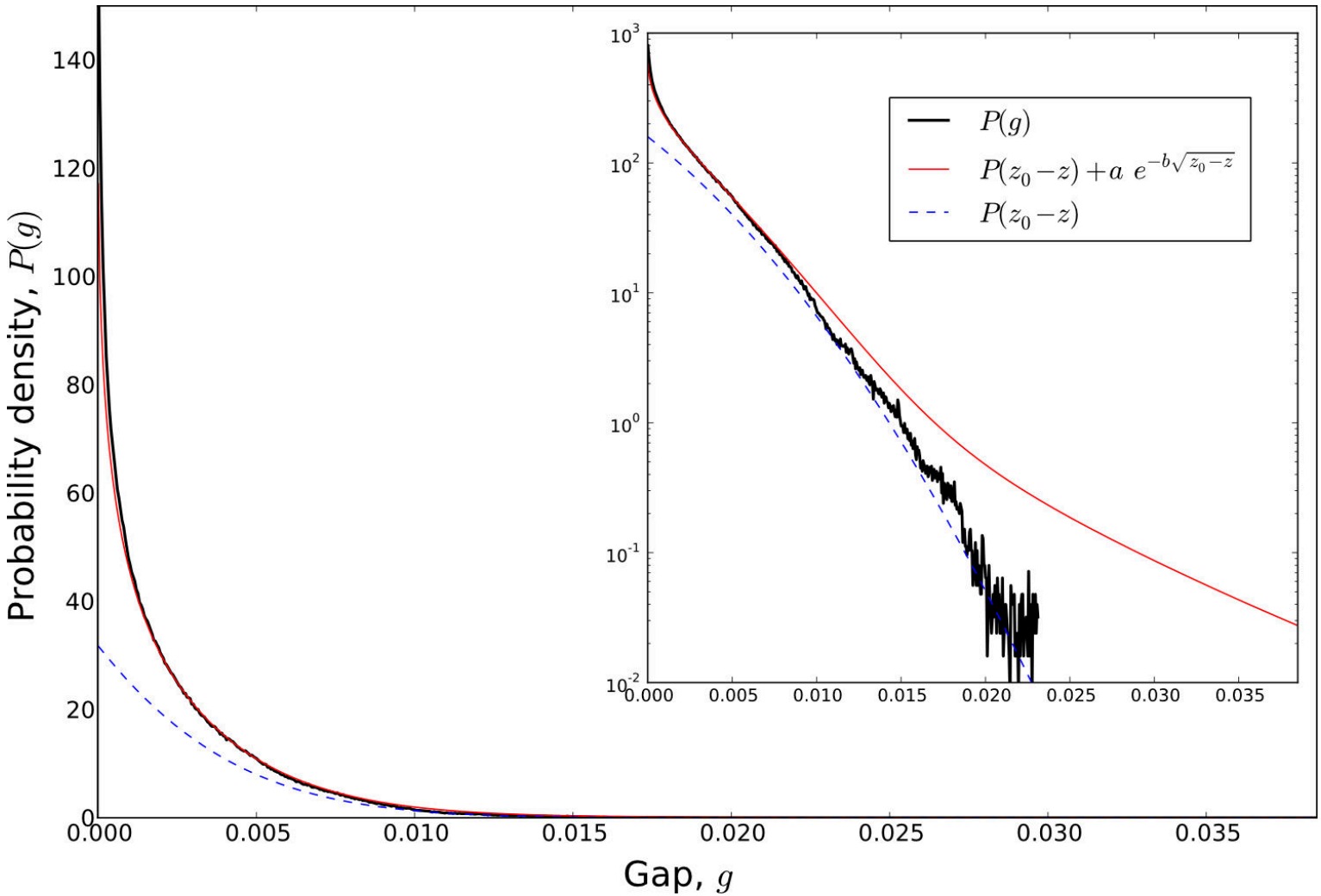
Solid contact results: gap distribution



Area fraction $A' = 24\%$

Gap probability density VS geometrical overlap model (dashed line)
Near contact interface $P(g) \sim P(z_0 - z) + a \exp(-b\sqrt{z_0 - z})$

Solid contact results: gap distribution

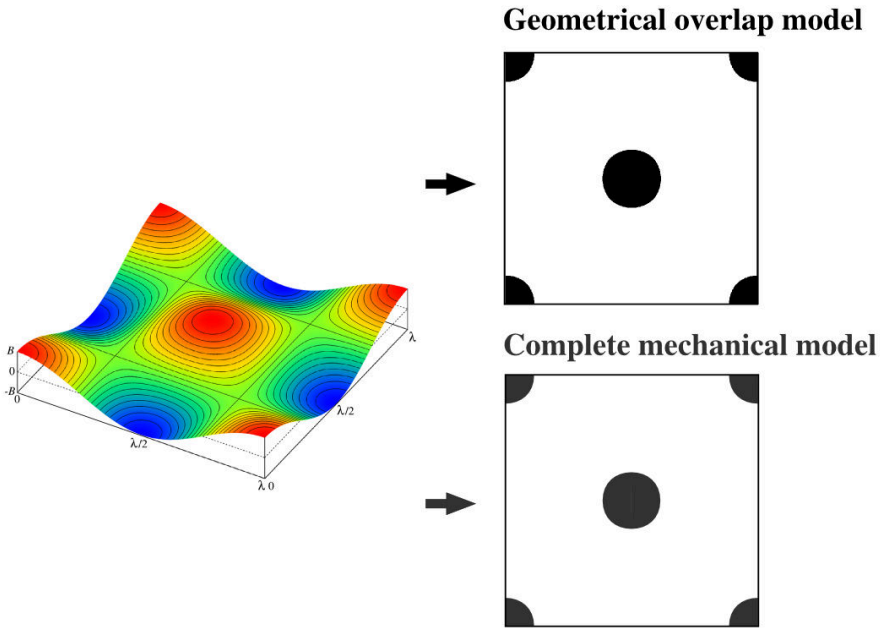


Area fraction $A' = 39\%$

Gap probability density VS geometrical overlap model (dashed line)
Near contact interface $P(g) \sim P(z_0 - z) + a \exp(-b\sqrt{z_0 - z})$

Geometrical overlap: morphology and percolation

- Geometrical overlap model is highly inaccurate[1,2]



[1] Dapp, Lücke, Persson, Müser, *Phys. Rev. Lett.* 108 (2012)

[2] Yastrebov, Anciaux, Molinari. *Tribol Lett*, 56 (2014)

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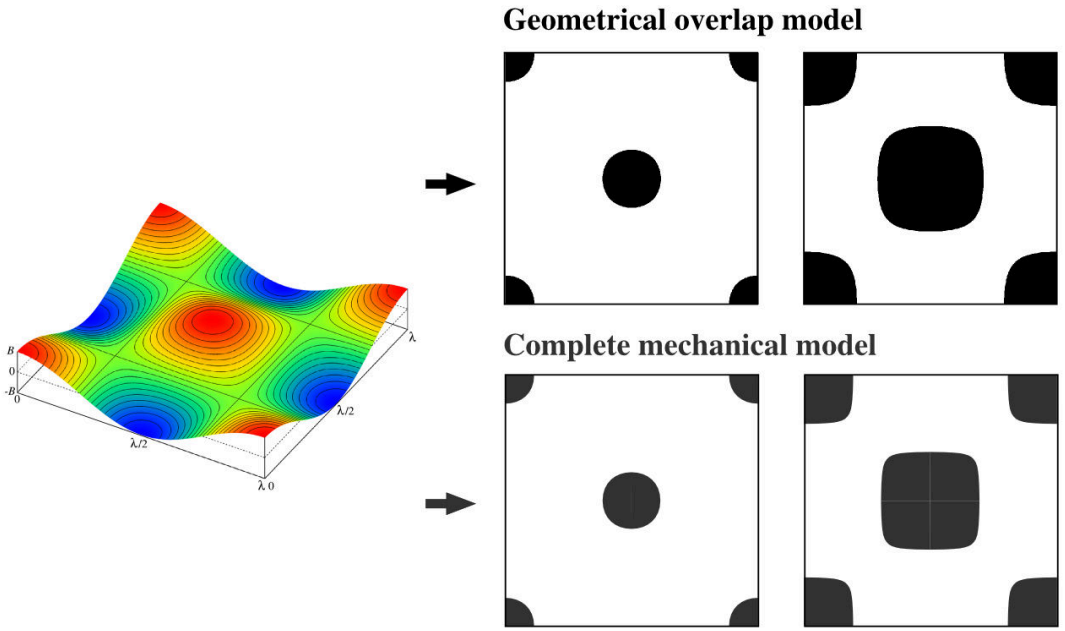

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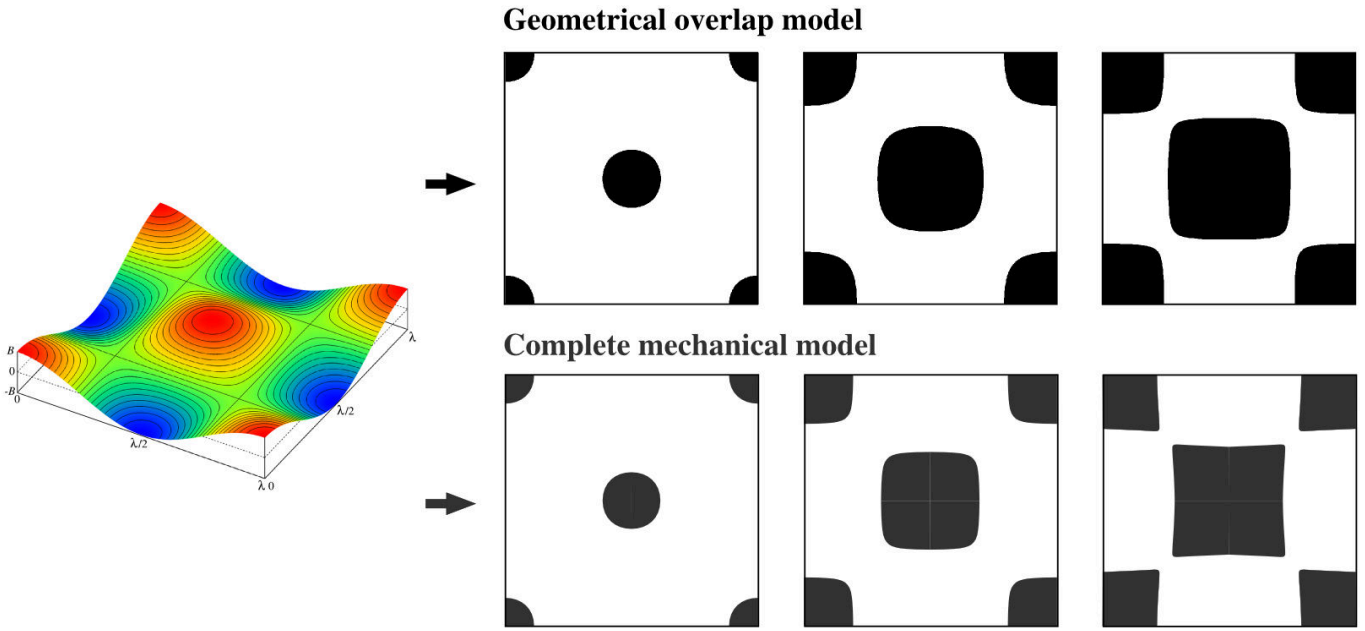

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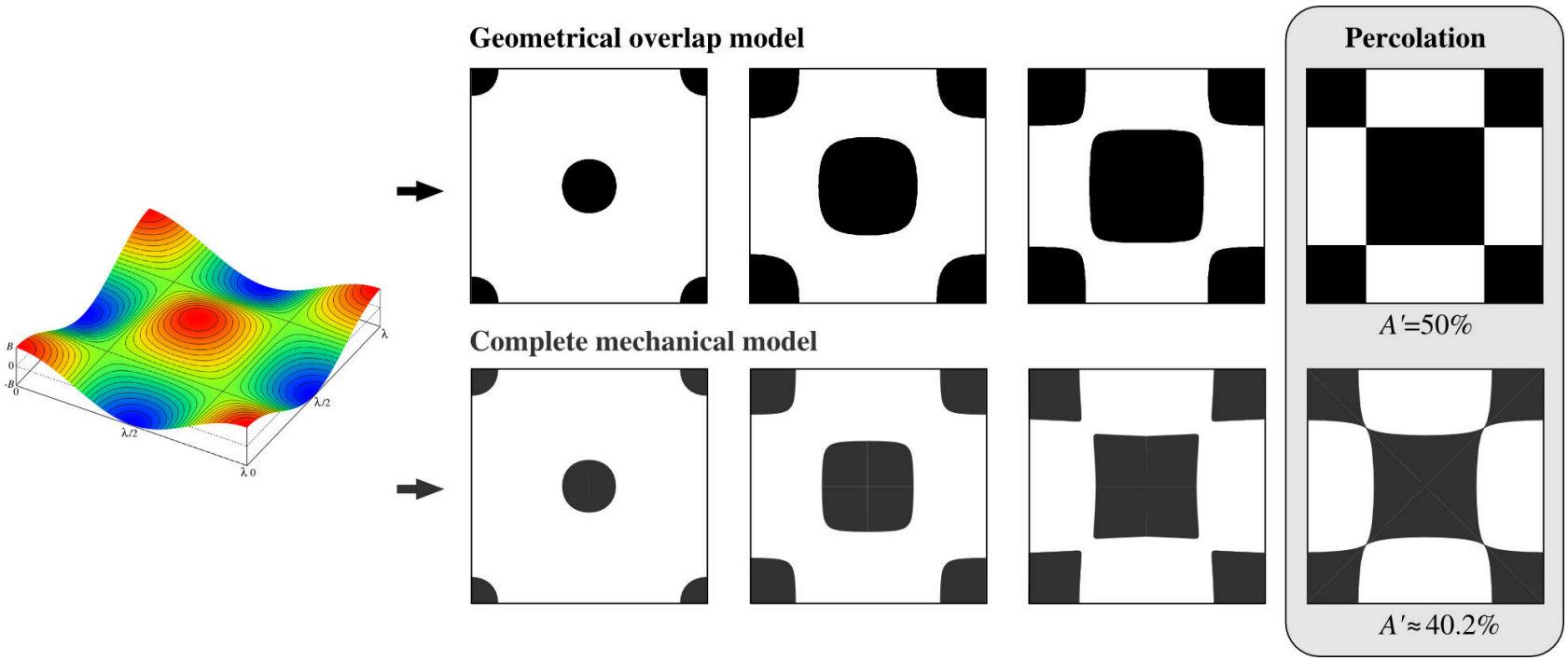
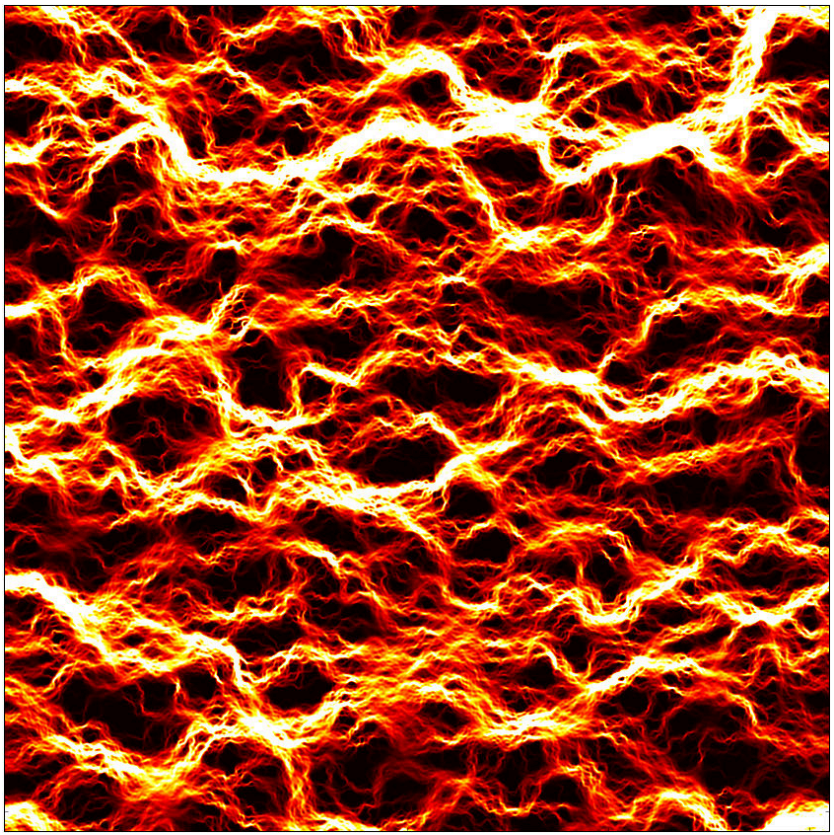
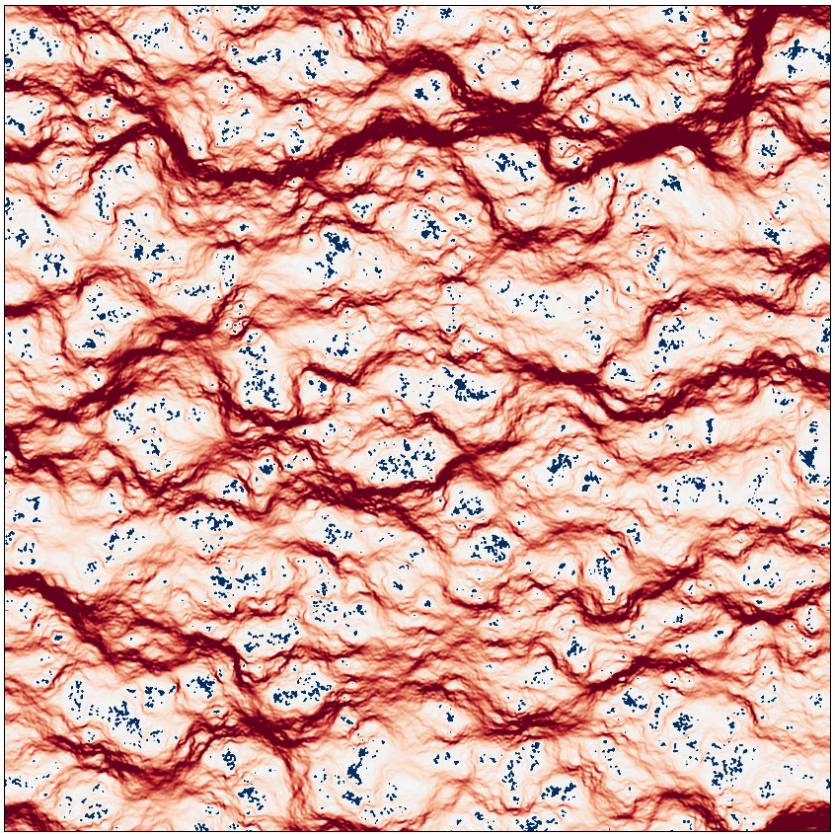


[1] Dapp, Lücke, Persson, Müser, *Phys. Rev. Lett.* 108 (2012)

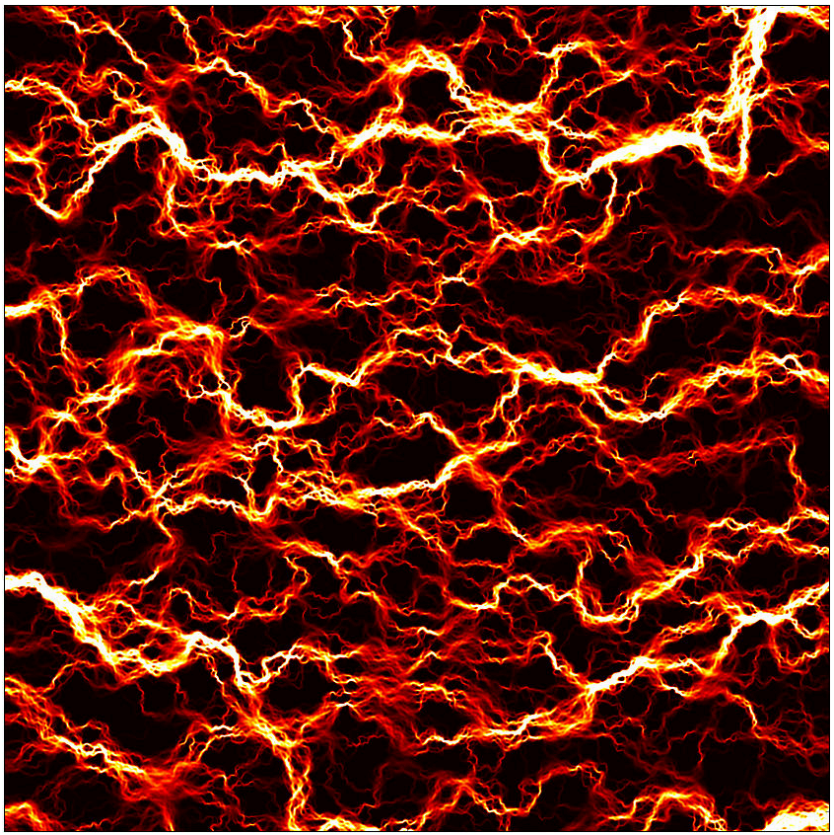
[2] Yastrebov, Anciaux, Molinari. *Tribol Lett*, 56 (2014)

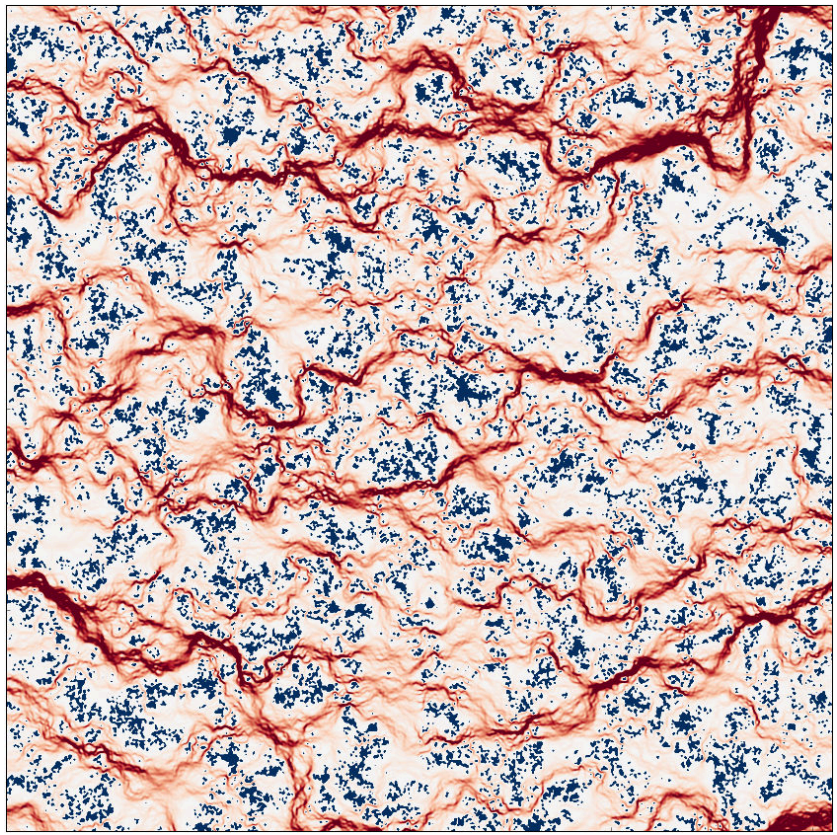
Creeping fluid transport





Creeping fluid transport





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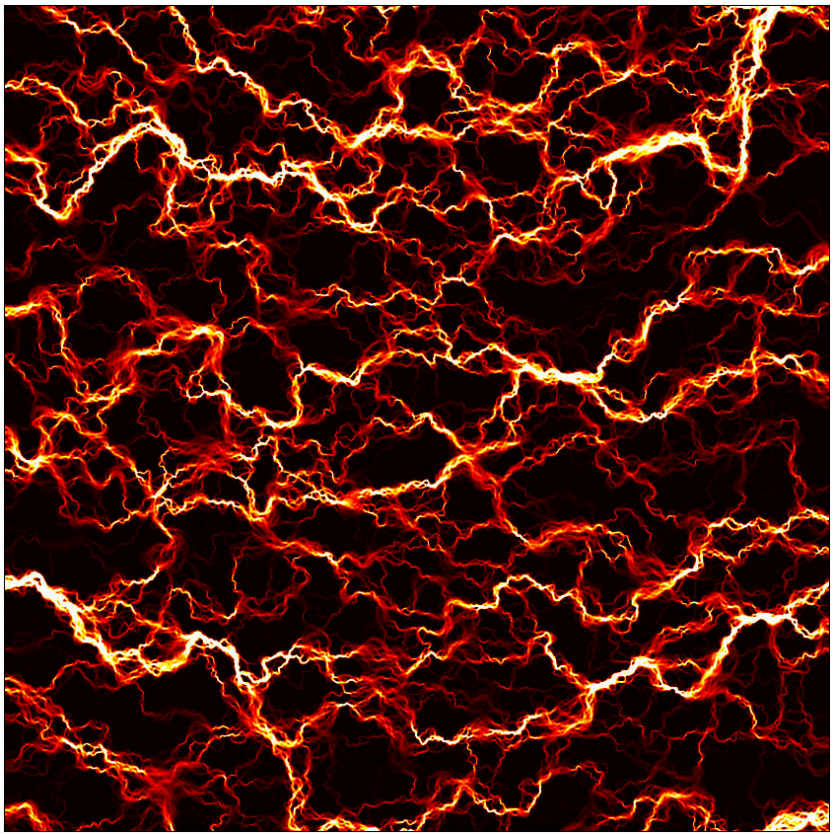

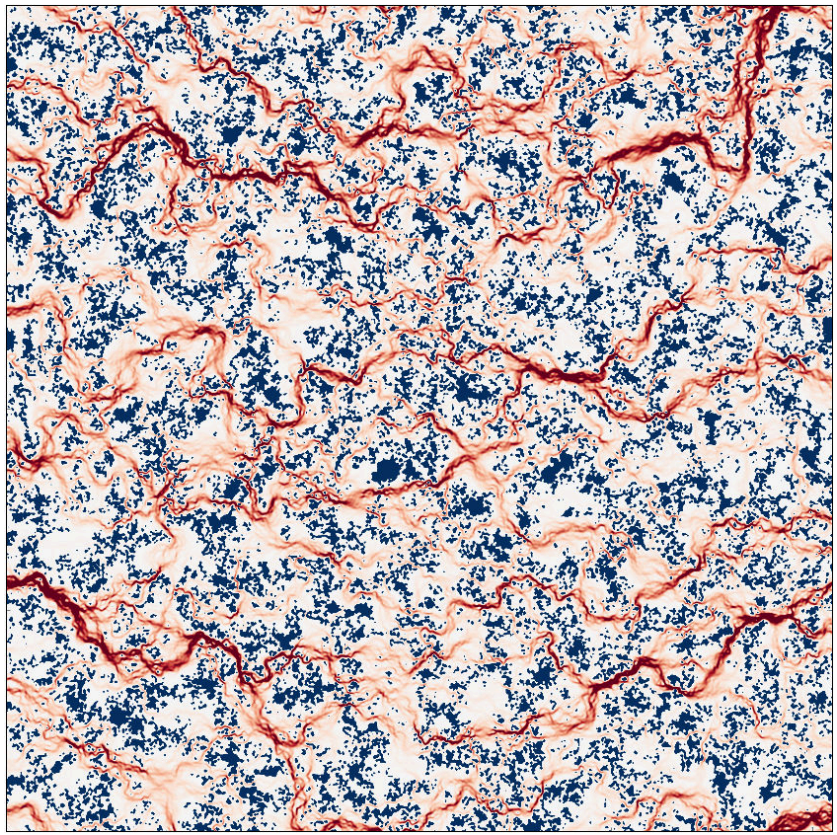

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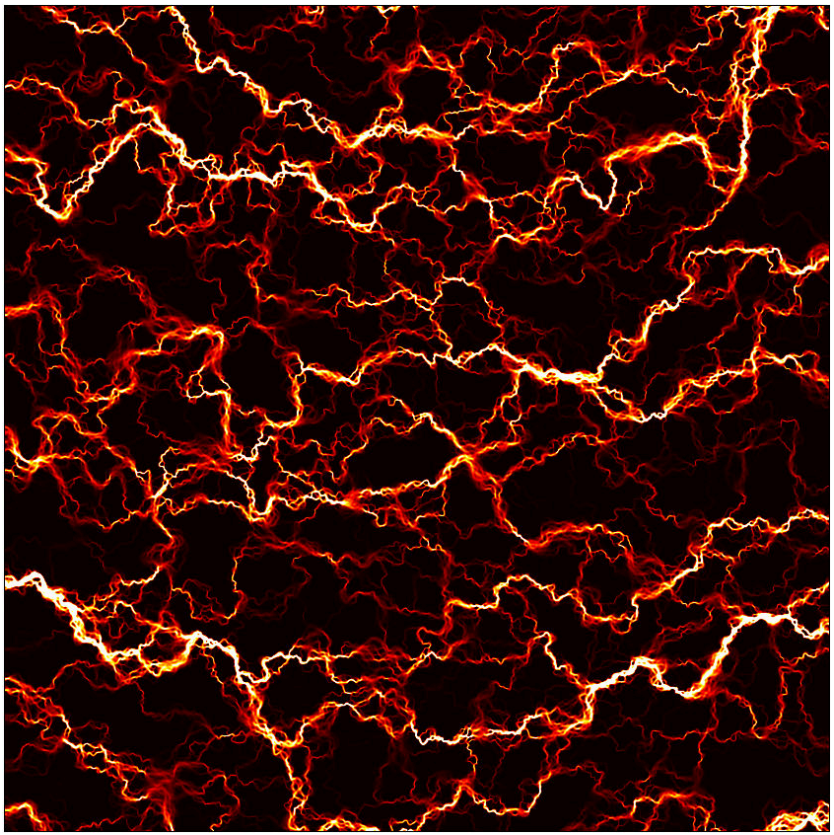

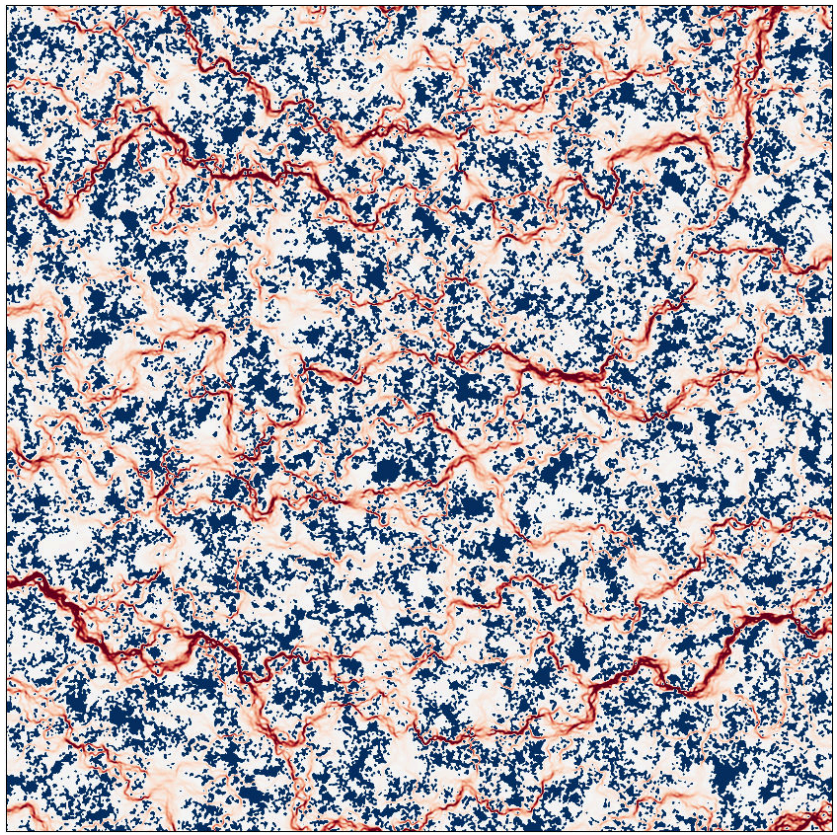

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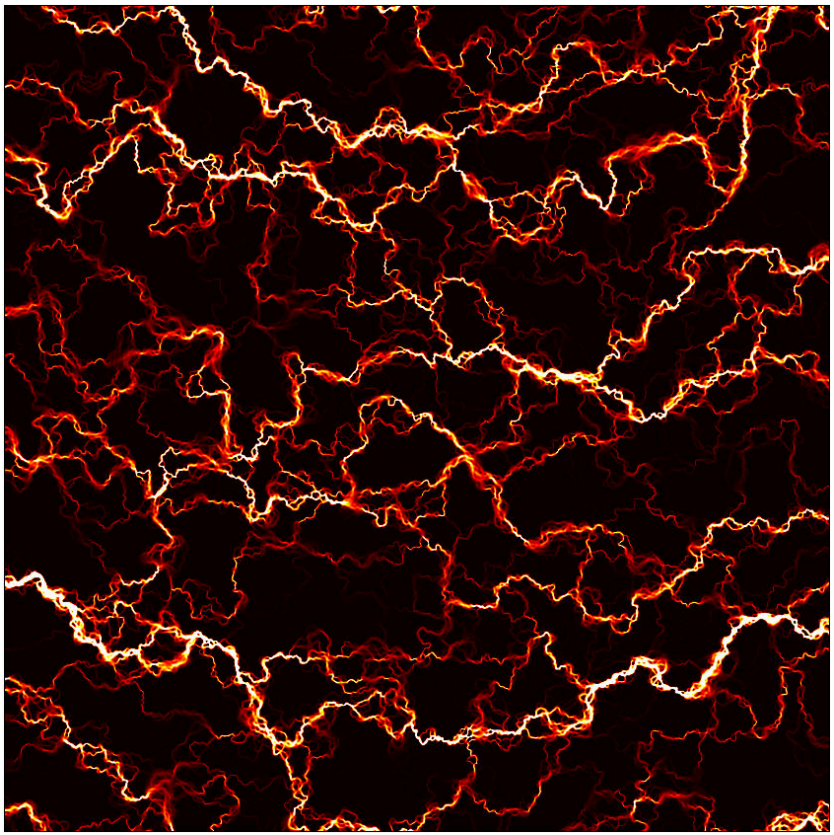

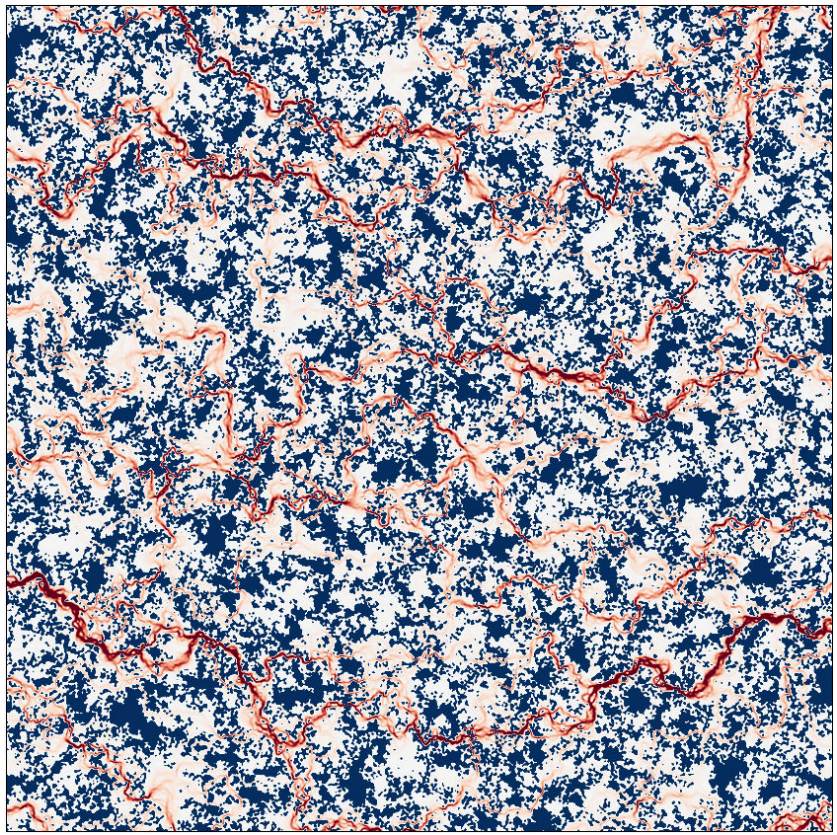

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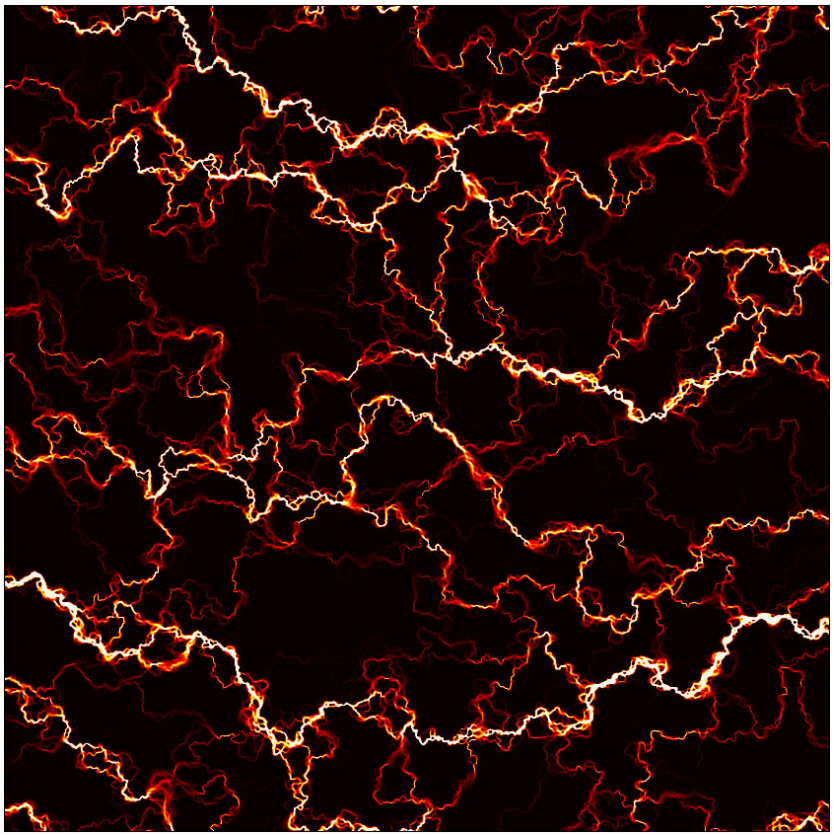

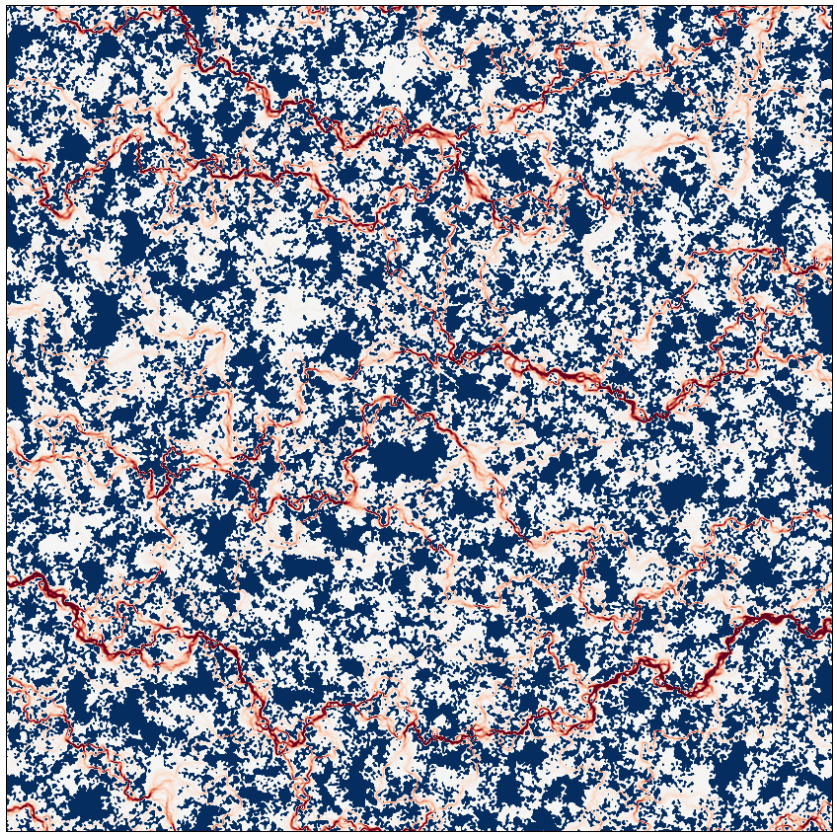

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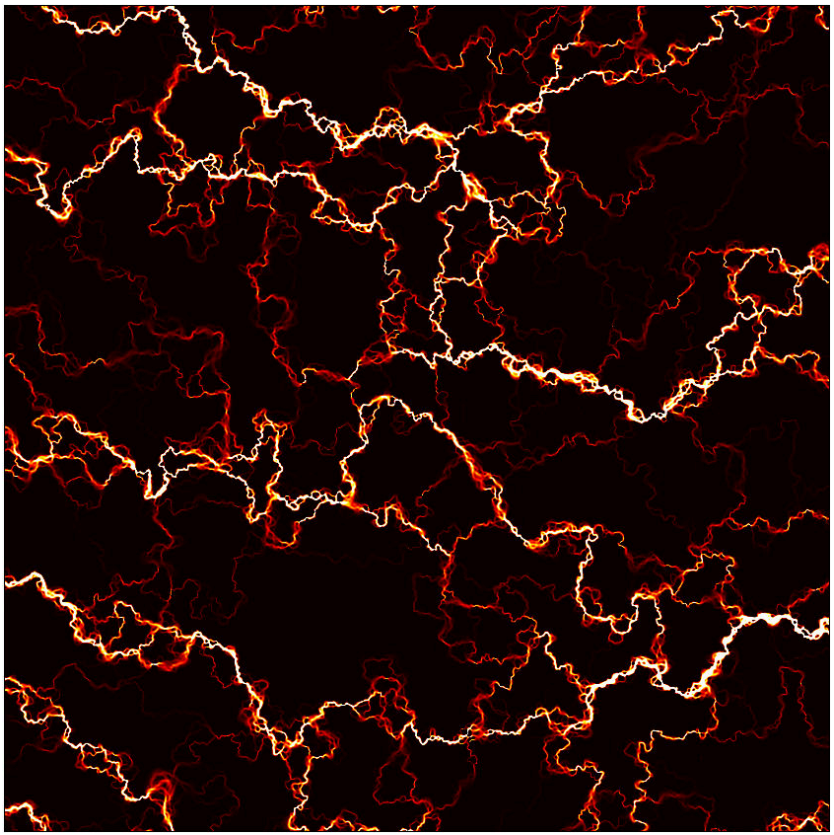

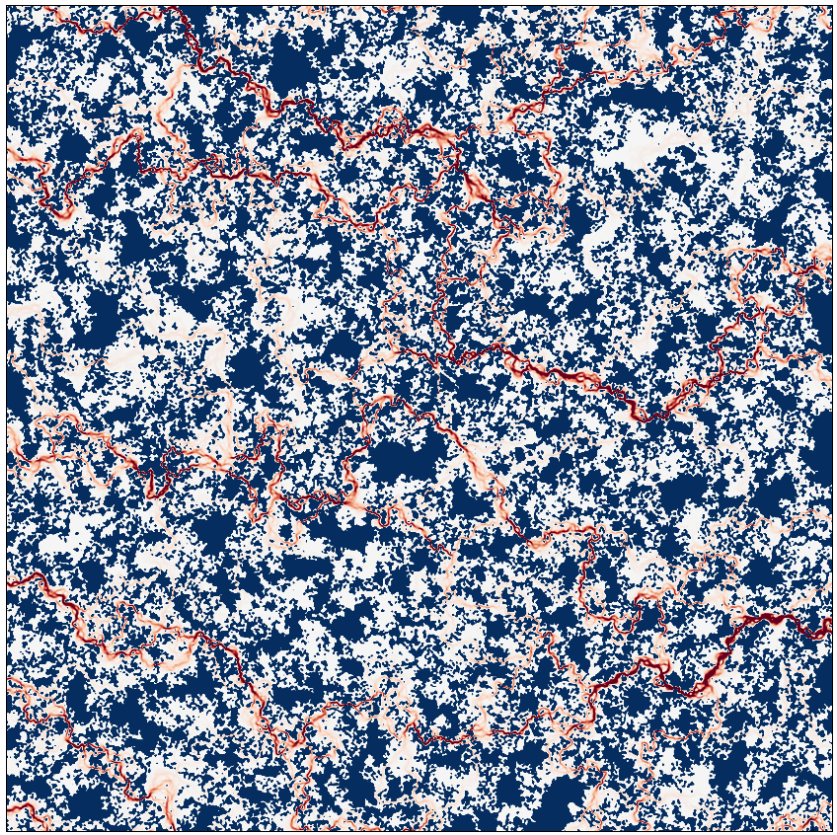

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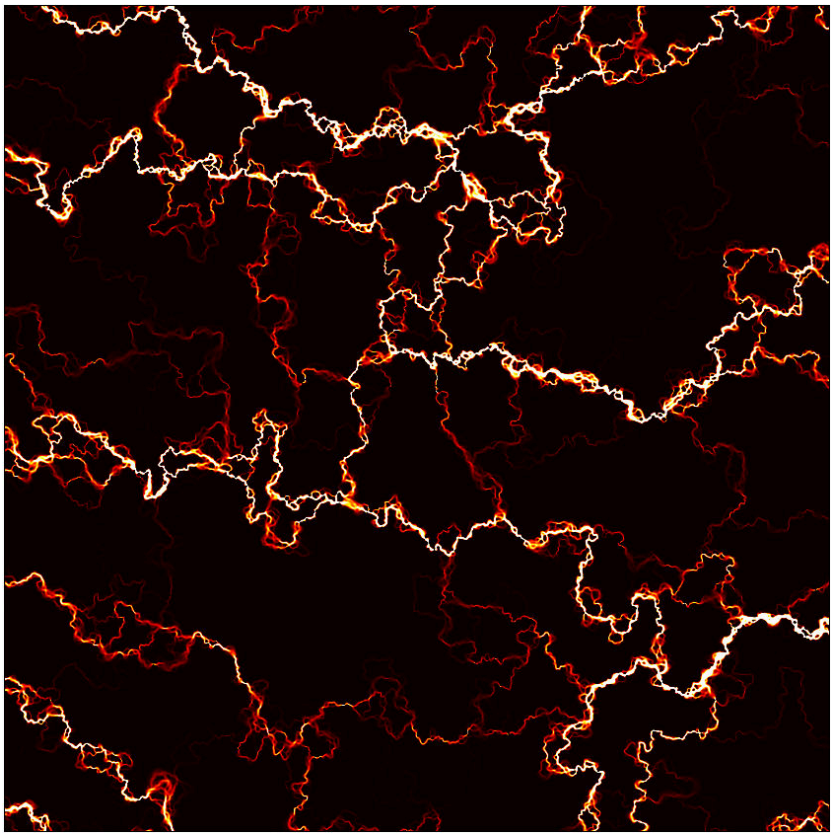

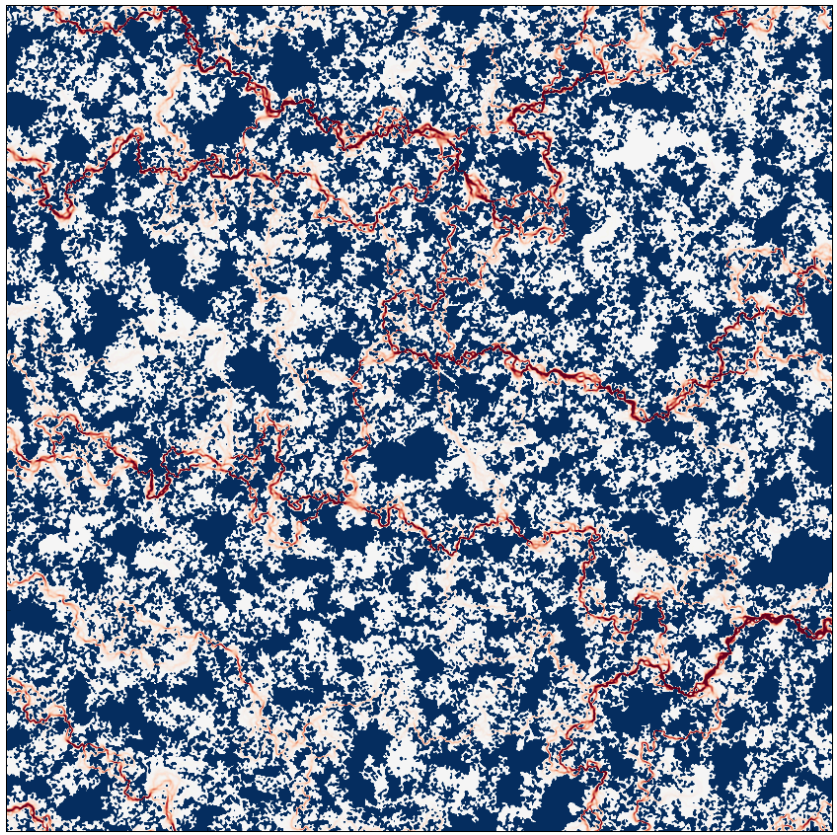

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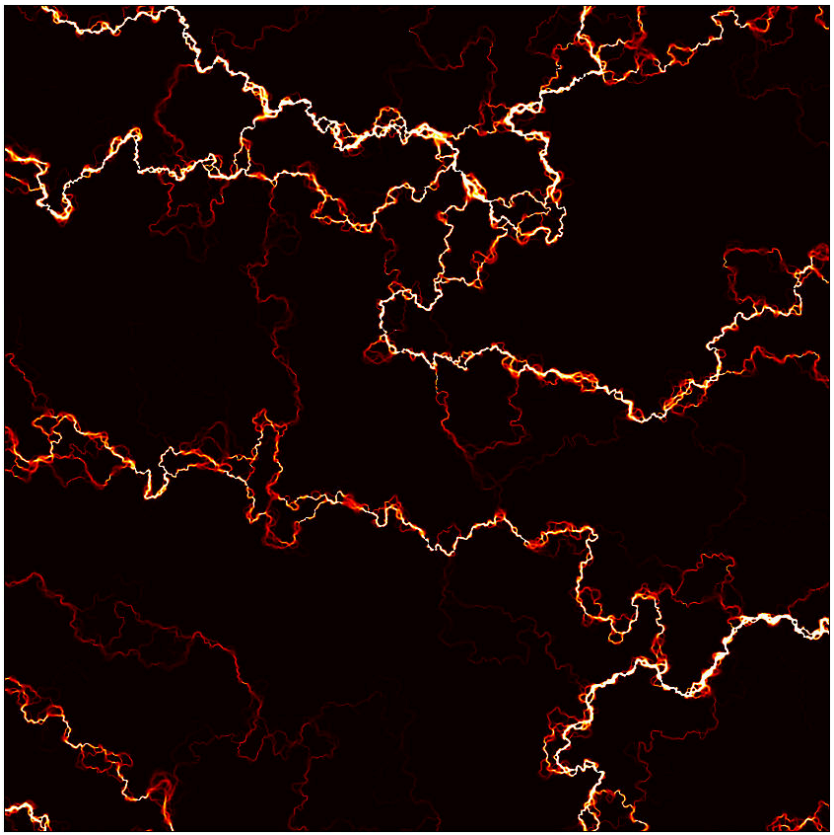

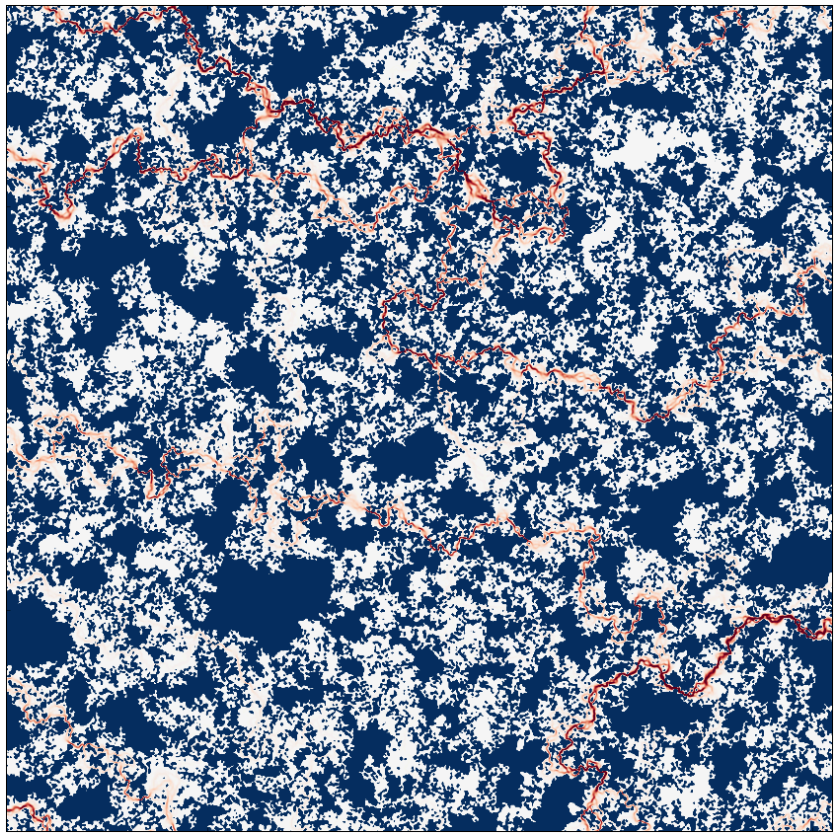

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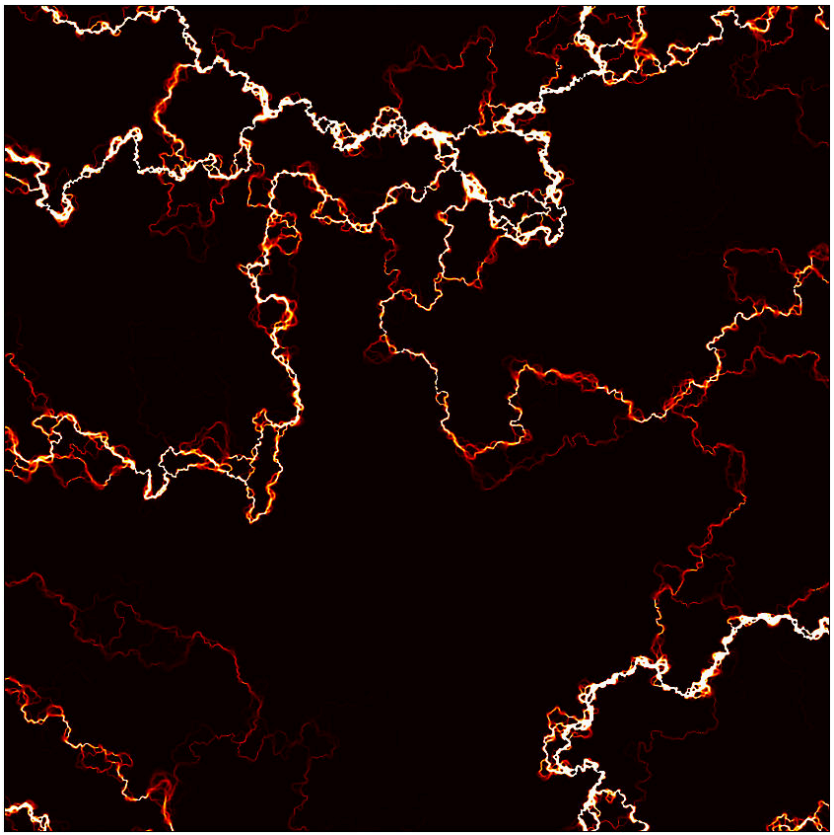

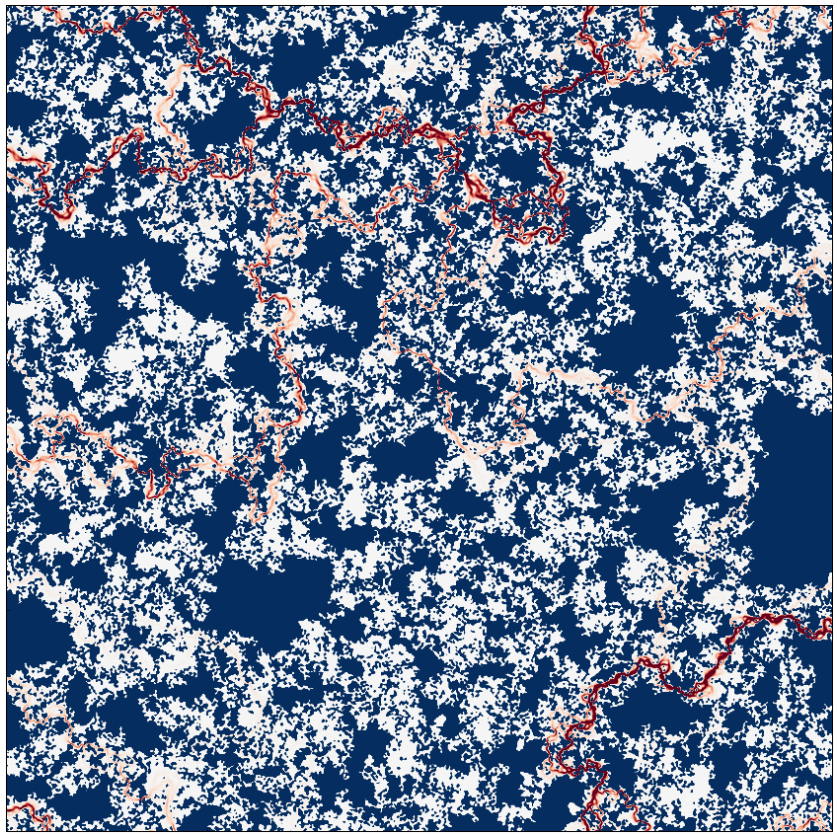

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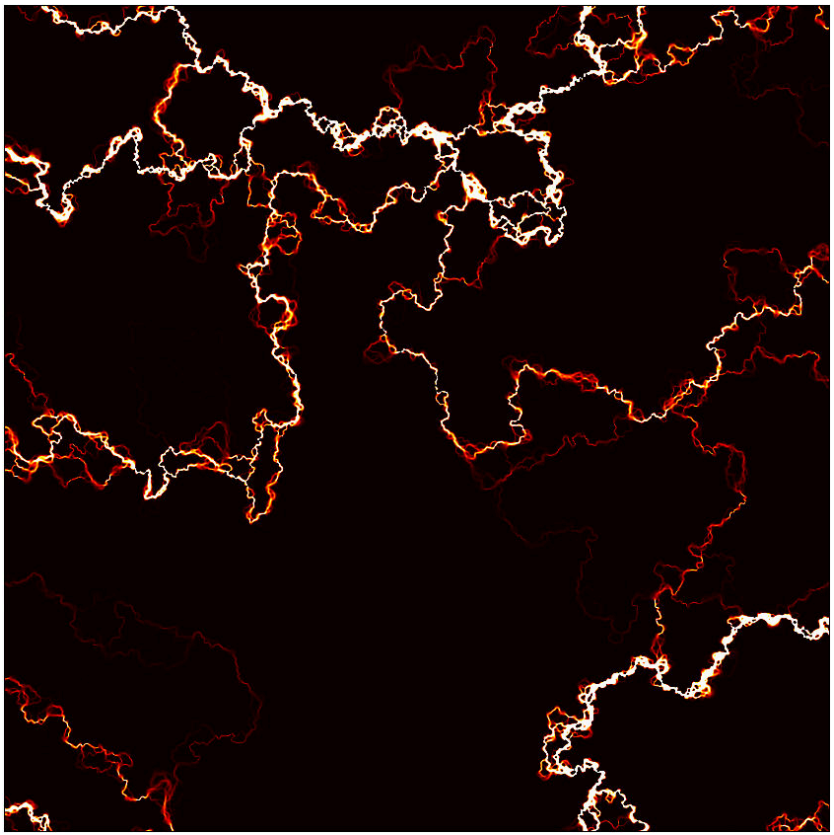

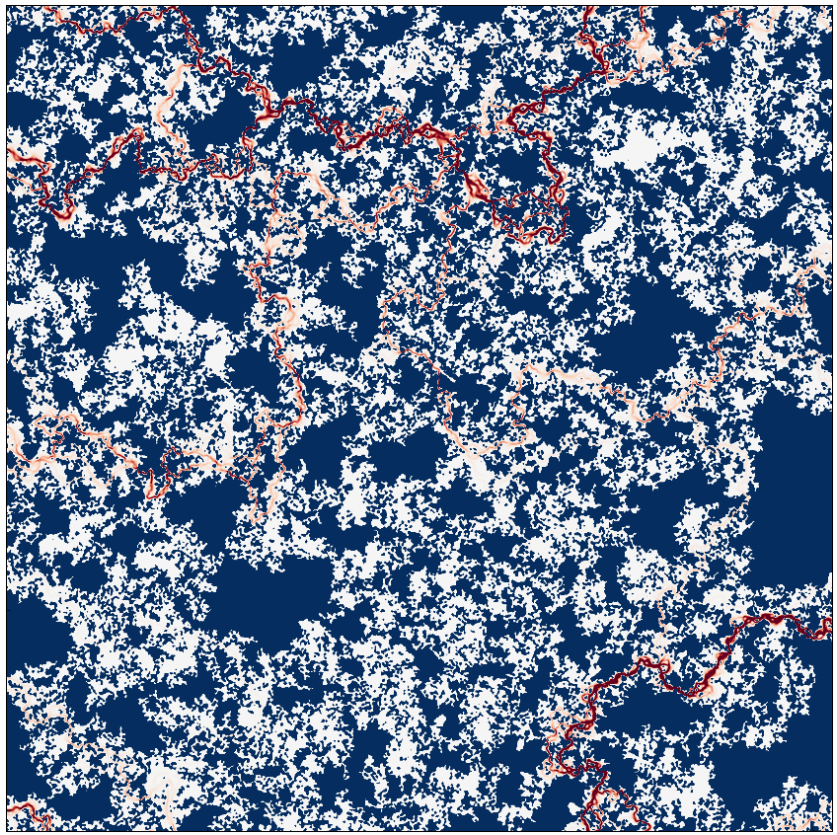

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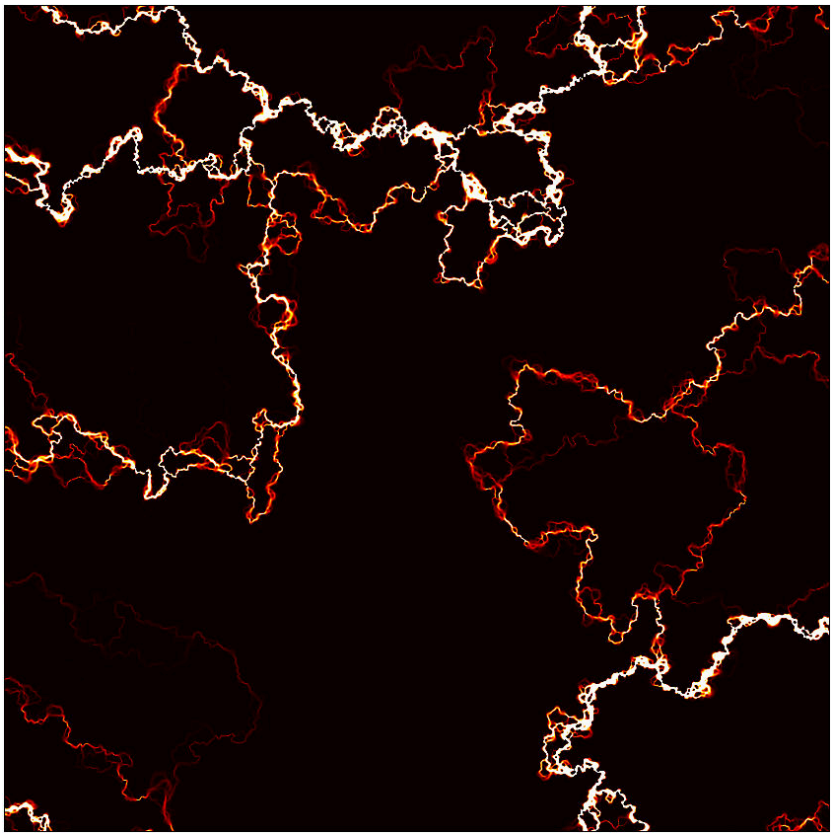

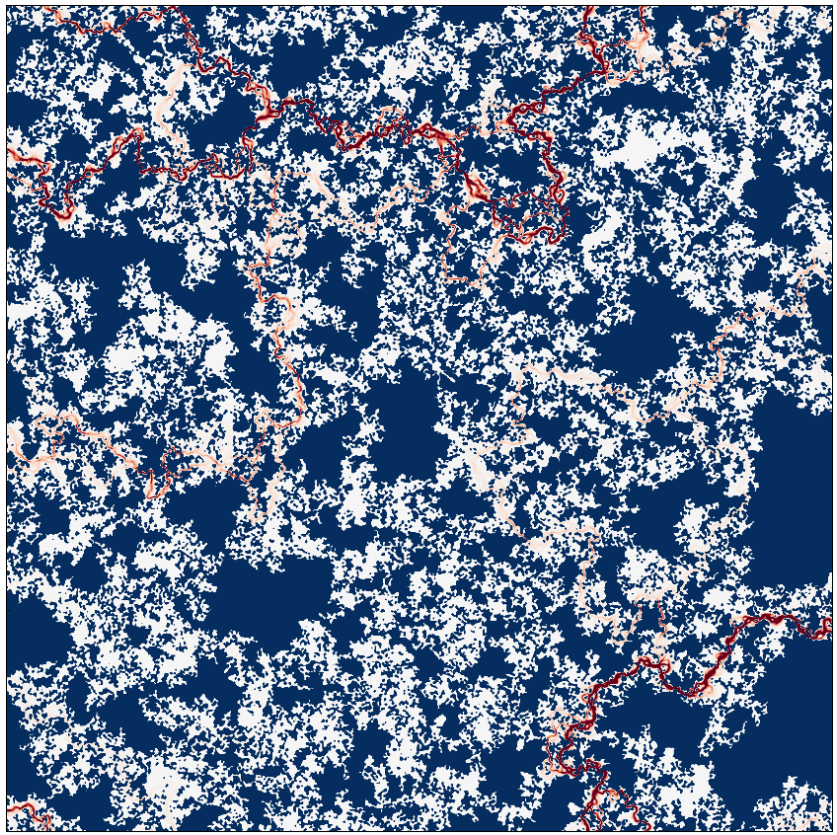

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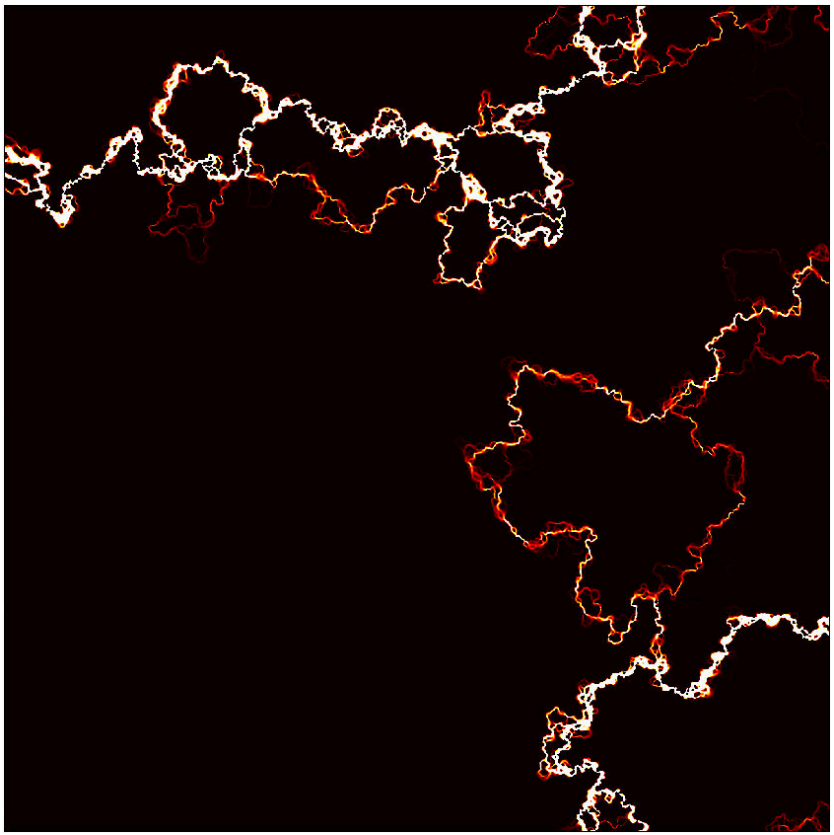

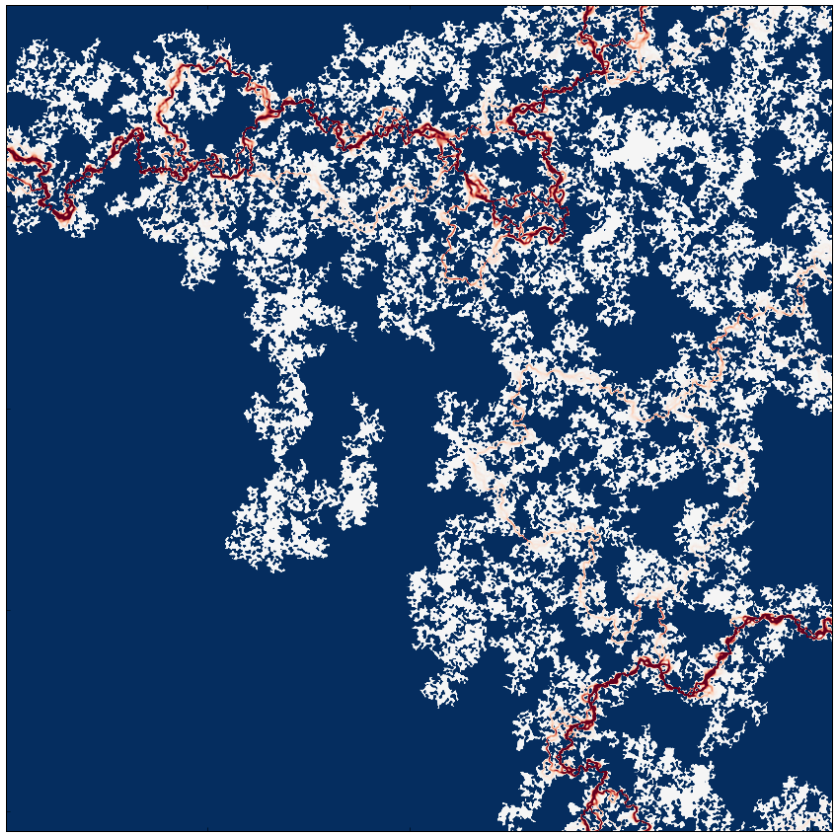

Contact area & trapped fluid

- Contact area does not conduct flow

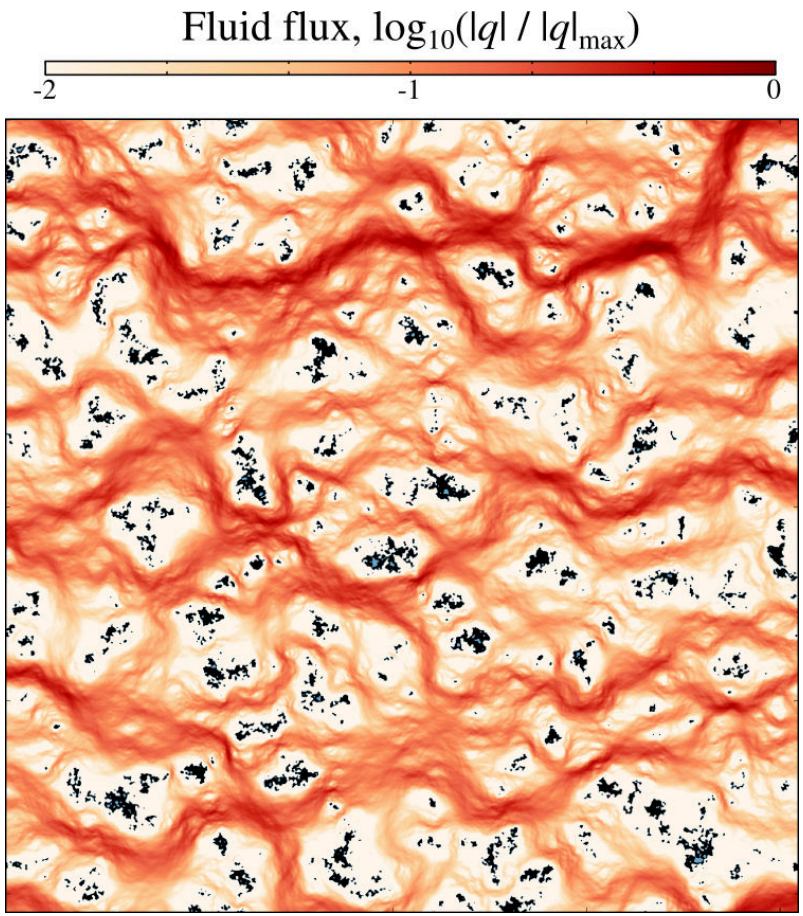

Fig. Fluid flux

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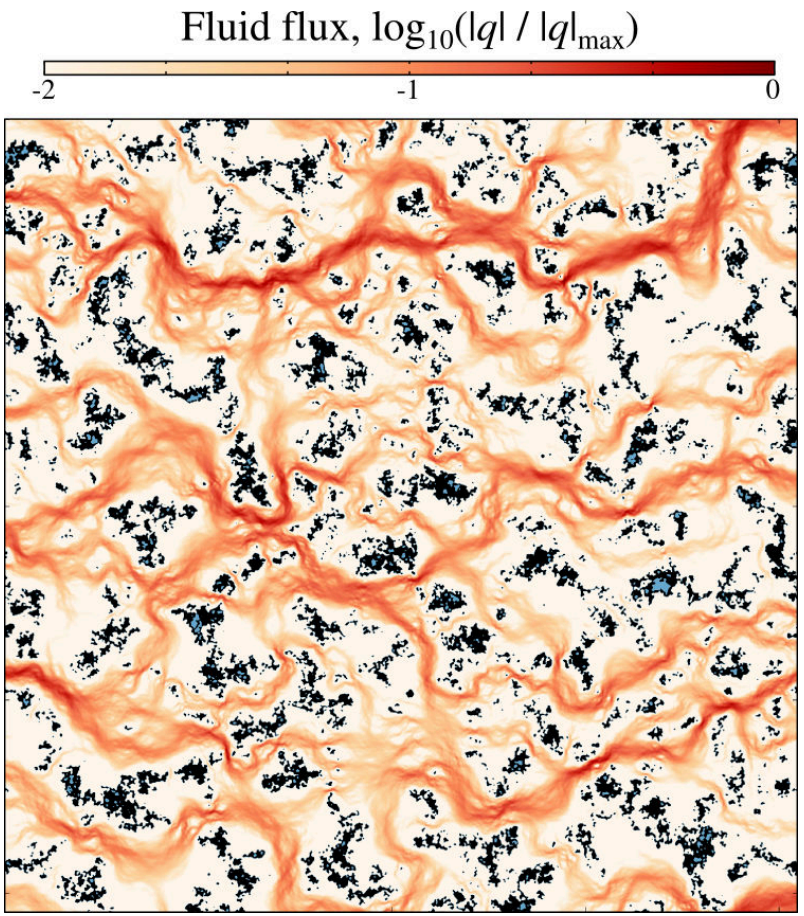

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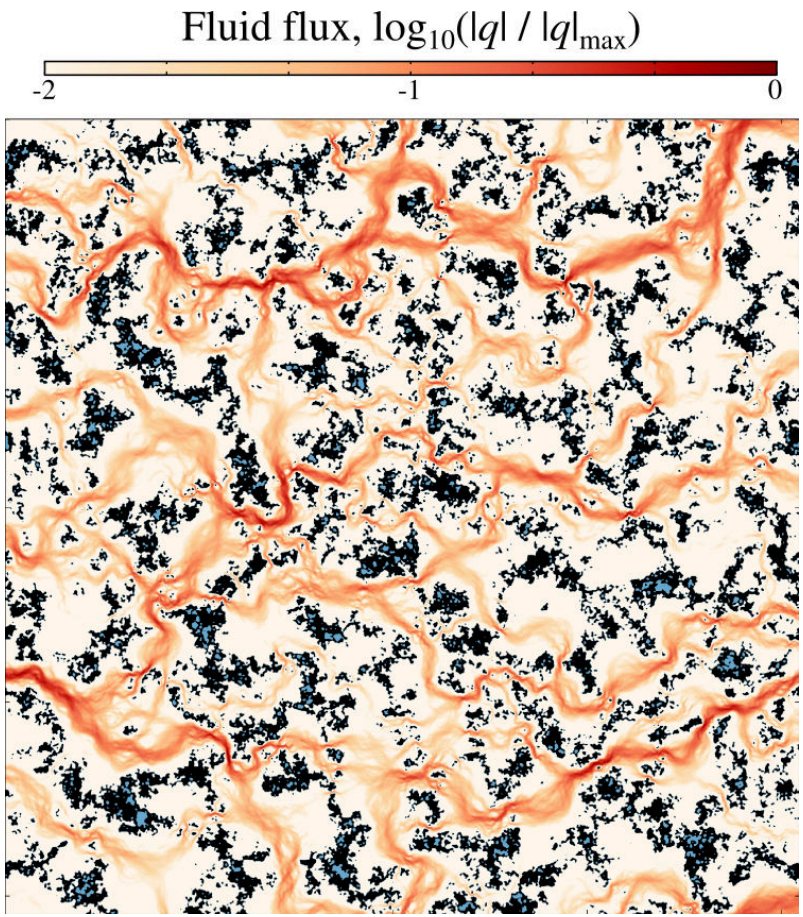

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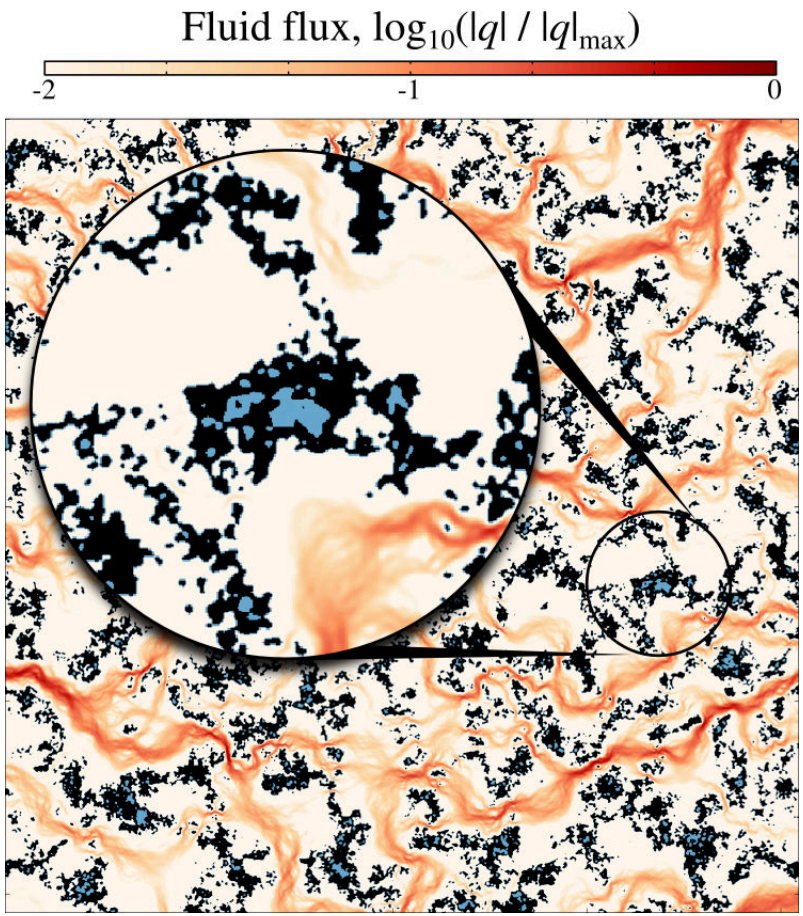

Fig. Fluid flux (zoom)

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- Thus the effective transmissivity depends on the **effective contact area**:

$$A'_{\text{eff}} = A' + A'_t$$

A' is the contact area fraction
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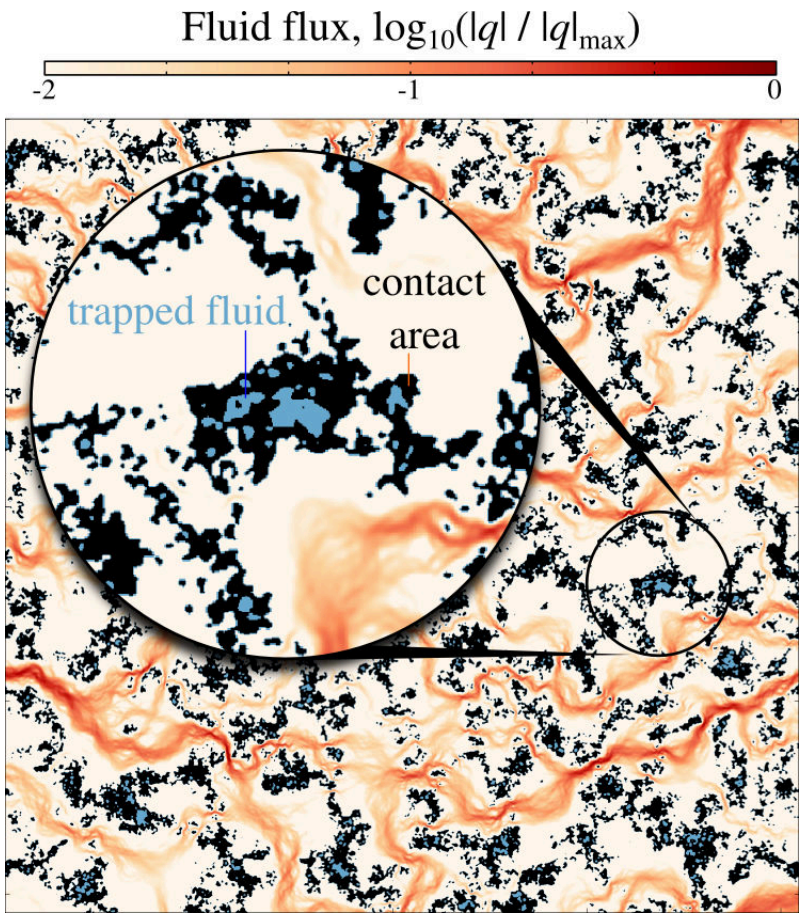
$$(1 - A') \int_0^\infty \frac{g^3 P(g)}{g^3 + K'_{\text{eff}} m_0^{3/2}} \, dg = \frac{1}{2}$$



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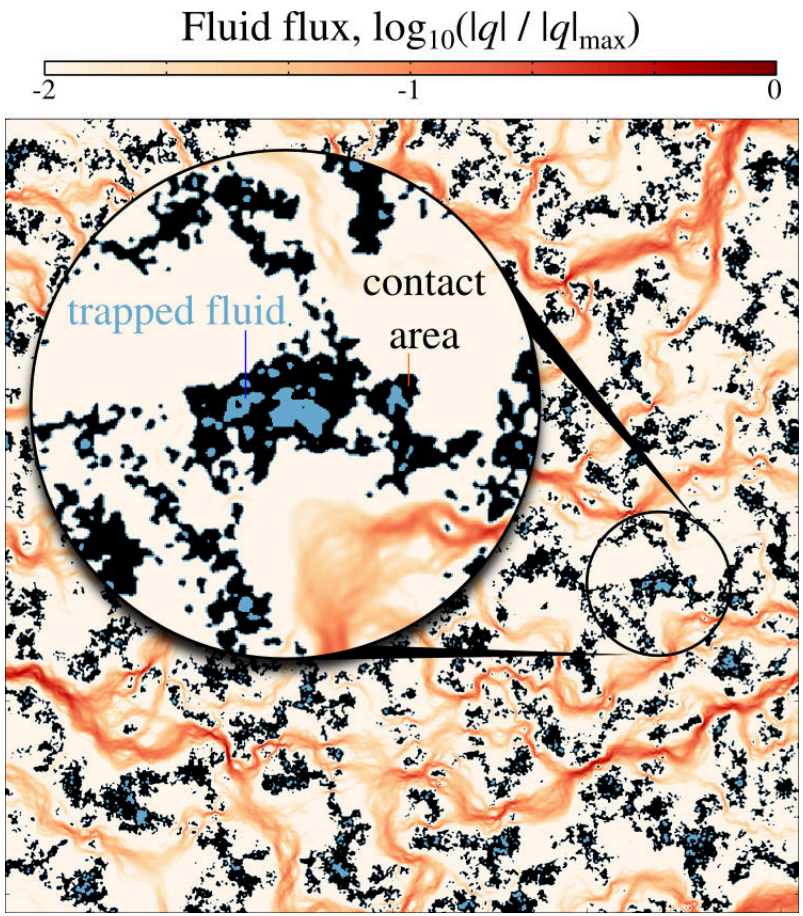

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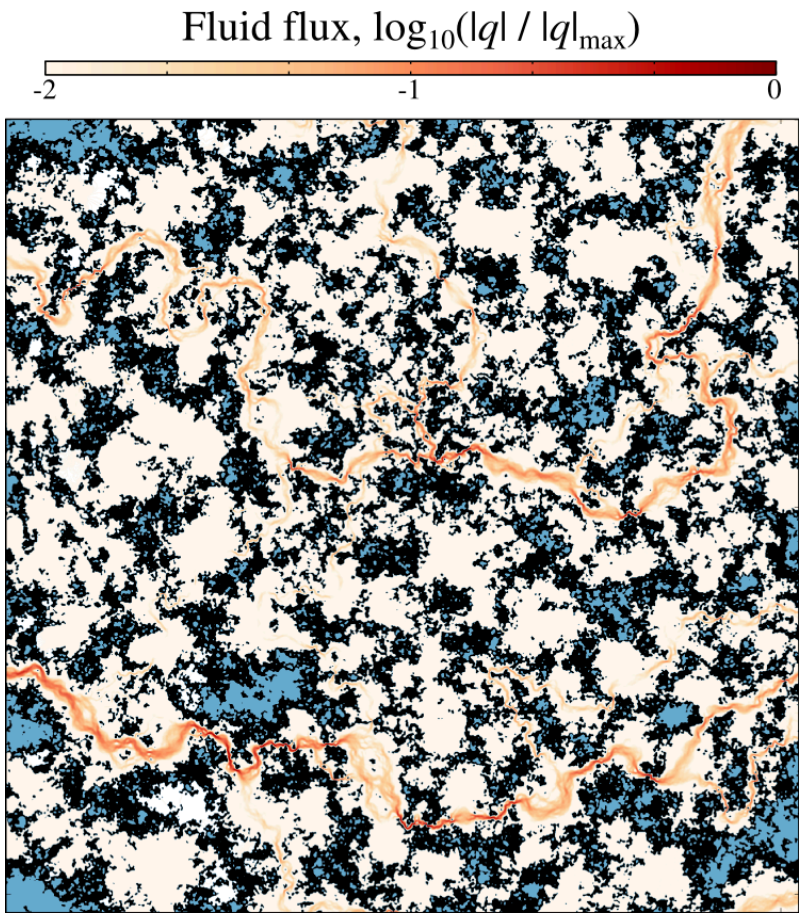

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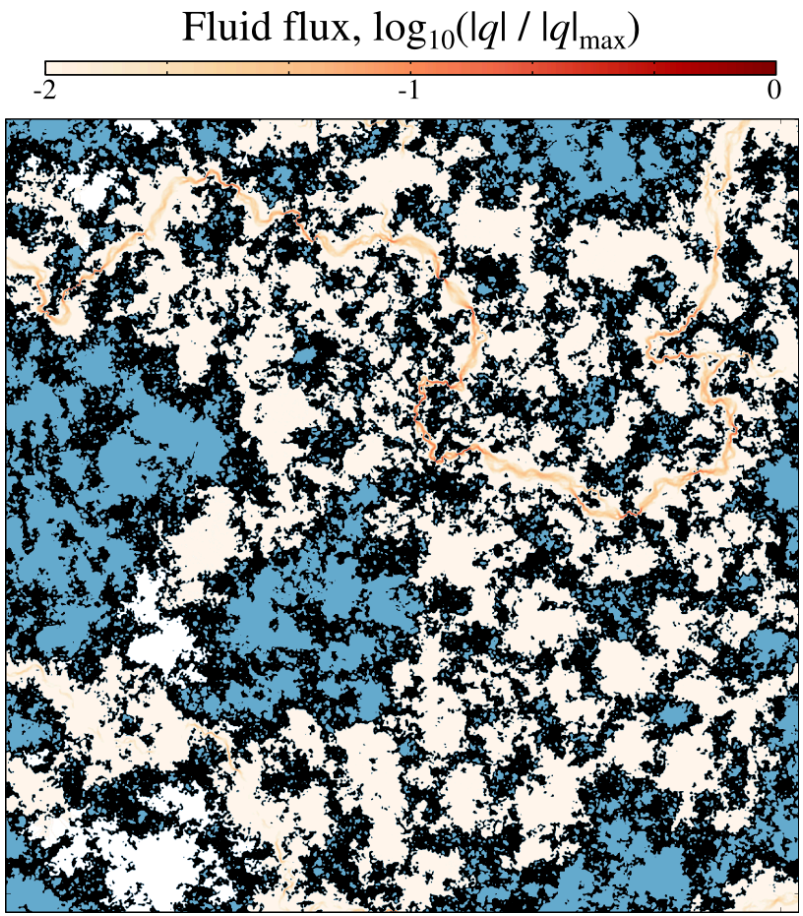

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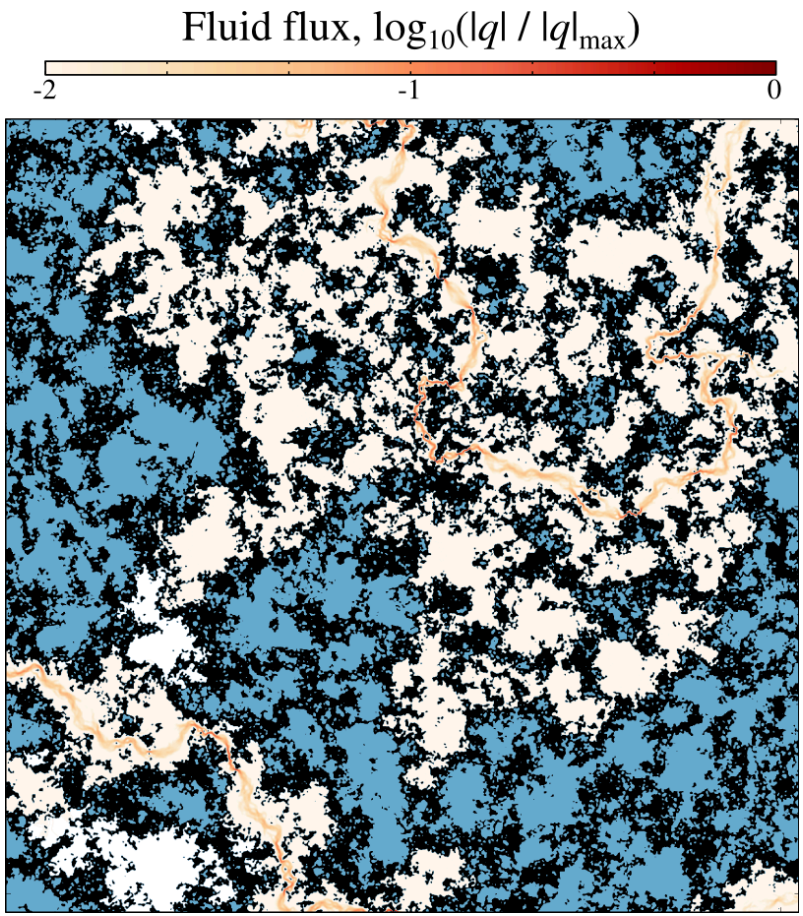

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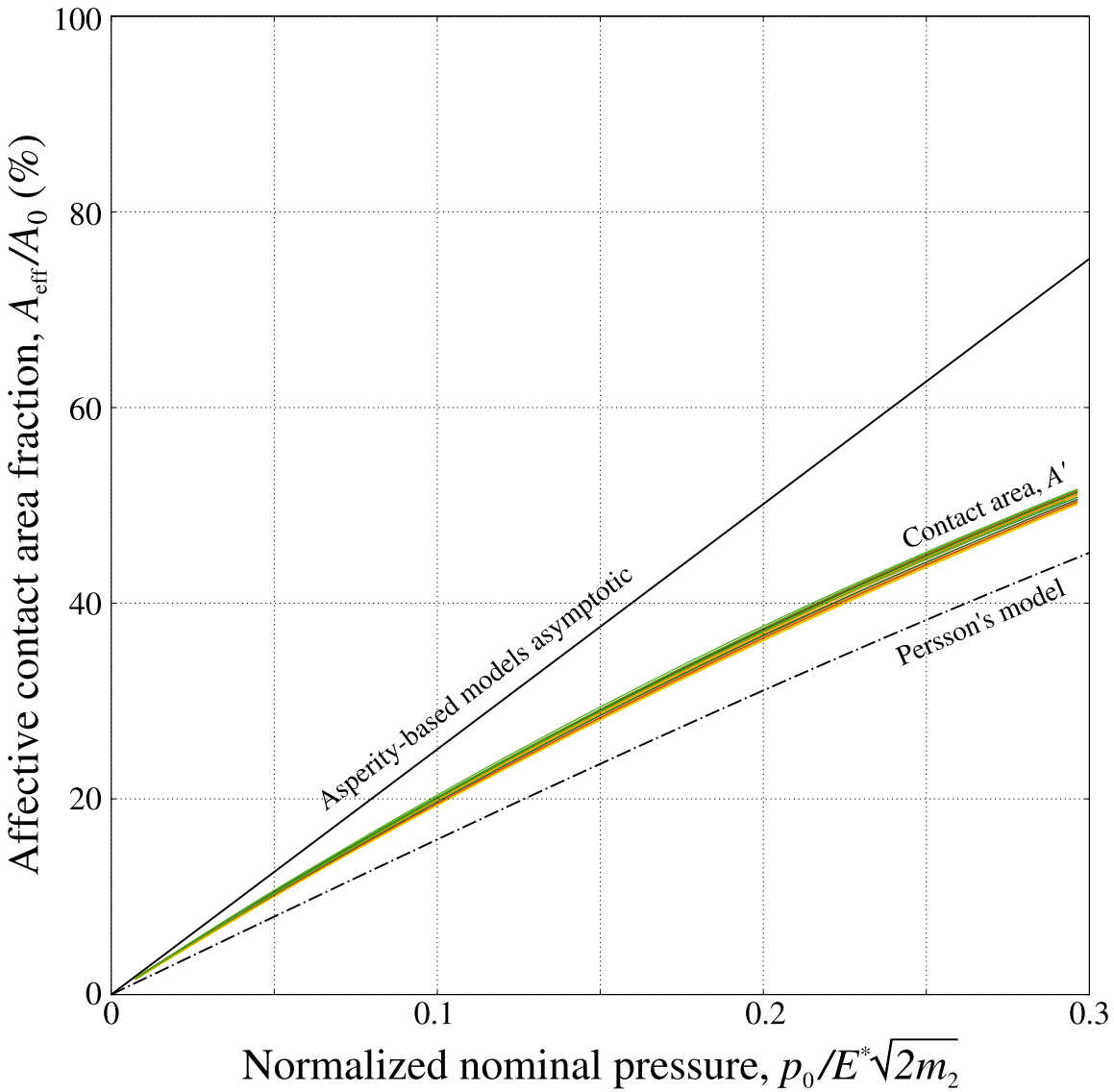

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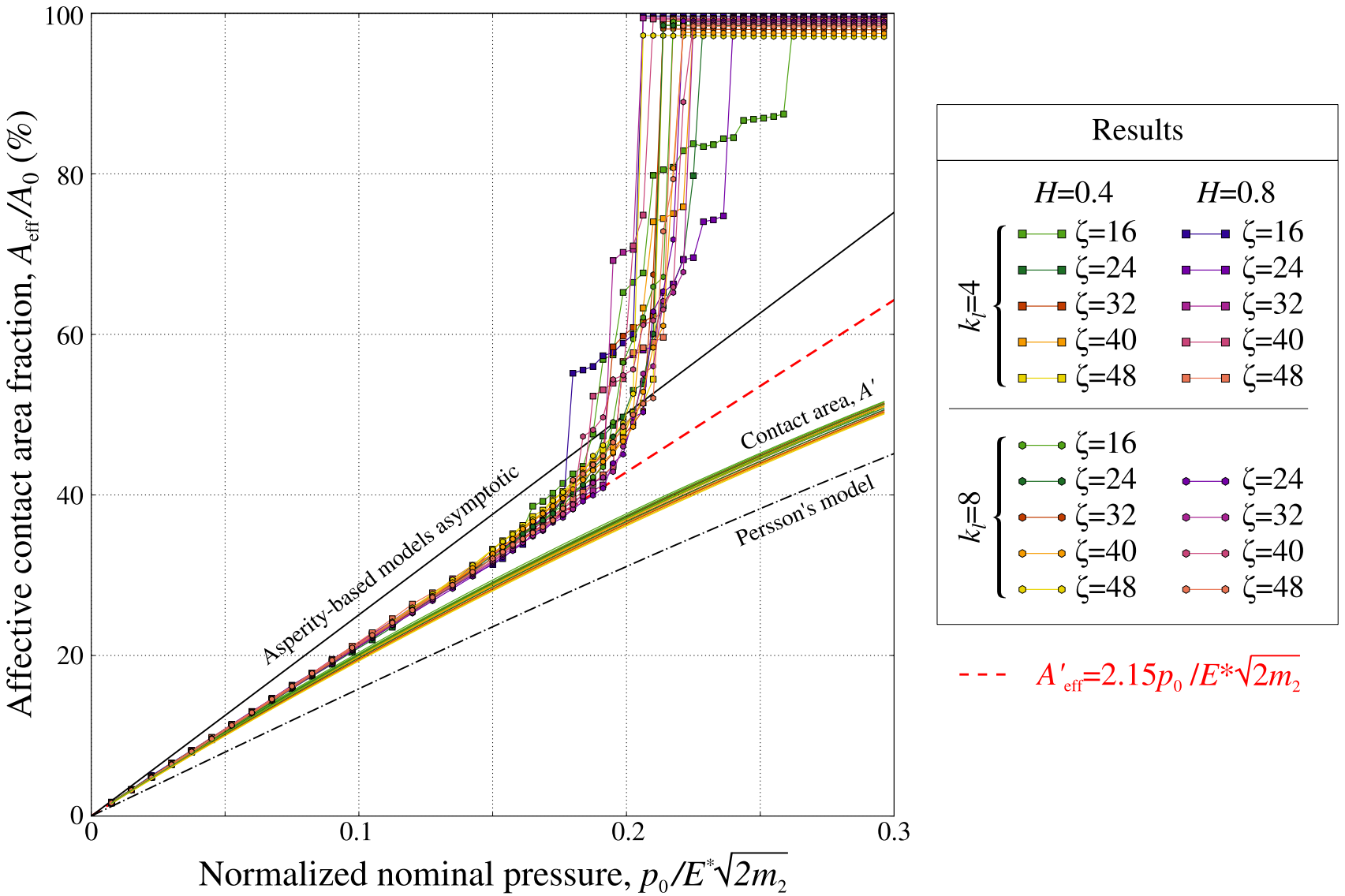
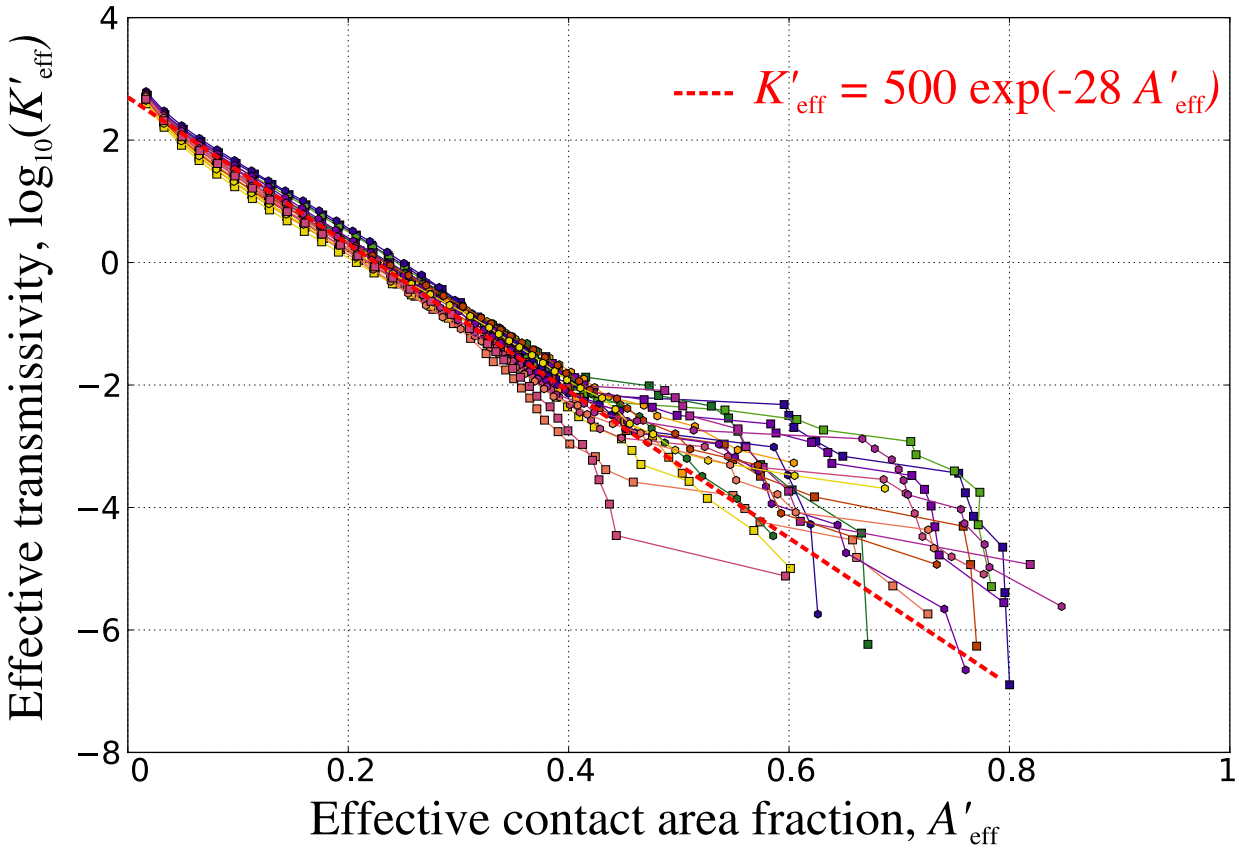


Normalized effective transmissivity



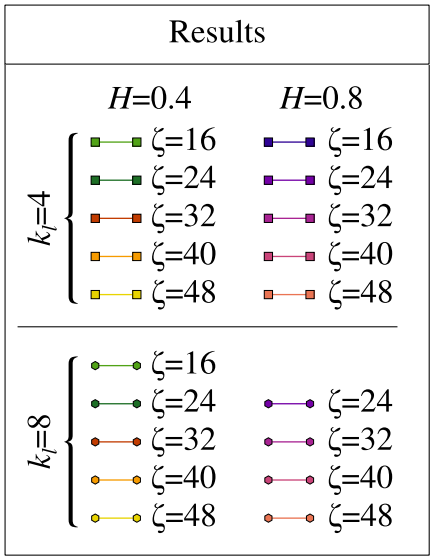


Fig. Evolution of the effective transmissivity

Effective transmissivity

- Effective area wrt load:

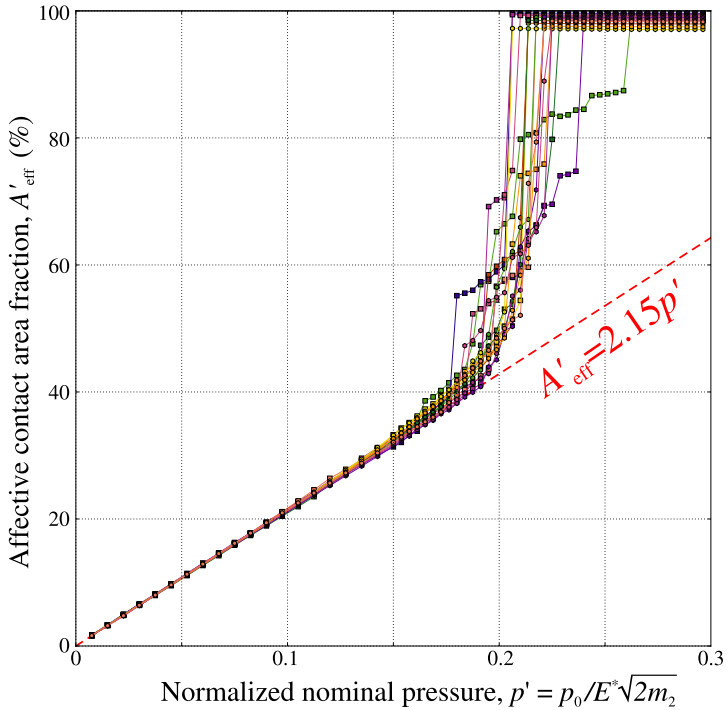
$$A'_{\text{eff}} \approx 2.15p'$$

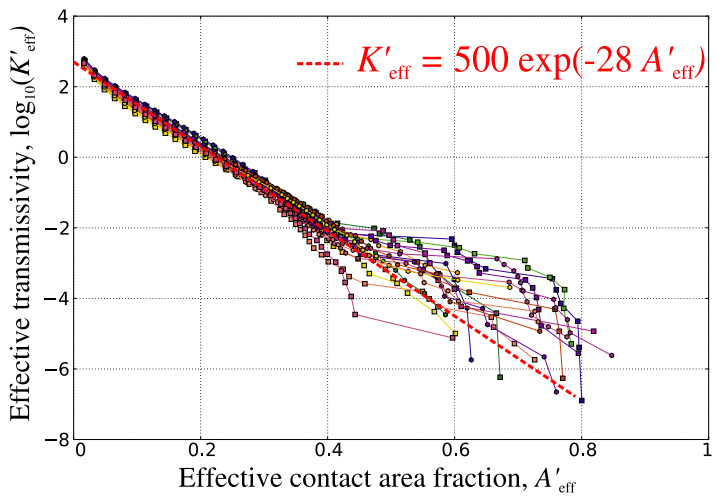
- Normalized load:

$$p' = p_0/E^* \sqrt{2m_2}$$

- Normalized effective transmissivity wrt effective area:

$$K'_{\text{eff}} \approx 500 \exp(-28A'_{\text{eff}})$$





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- Recall:

$$K'_{\text{eff}} = -\frac{12 \mu \langle\, q_x \,\rangle L}{m_0^{3/2} \Delta P_f}$$

- Express the mean flow:

$$\langle\, q_x \,\rangle = -\frac{K'_{\text{eff}} m_0^{3/2} \Delta P_f}{12 \mu L}$$

- Finally:

$$\boxed{\langle\, q_x \,\rangle \approx -\frac{41.7 \exp(-42.57 p_0 / E^* \sqrt{m_2}) m_0^{3/2} \Delta P_f}{\mu L}}$$

Conclusion & current work

Main result:

Mean flow[1] through contact of nominal area $L \times L$:

$$\langle\, q_x \,\rangle \approx -\frac{41.7 {m_0}^{3/2} \Delta P_f}{\mu L} \cdot \exp\left(-42.57 \frac{p_0}{E^* \sqrt{m_2}}\right)$$

μ is dynamic viscosity,
ΔP_f is the pressure drop between the inlet and the outlet,
p_0 is the nominal applied pressure,
E^* is the effective elastic modulus.

Roughness parameters:

m_0 is the variance of roughness,
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Beyond the one-way coupling:

- Monolithic two-way FEM scheme coupling solid and fluid equations (thin flow, Reynolds equation) with contacts including islands of non-linear compressible fluid

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General conclusion

The most critical assumption is the existence of the small wavelength cutoff

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  Let $\lambda_s \sim$ Å, then $m_2 < C < \infty$ and $\forall p_0 > 0, A' > 0$
- But, at Å-scales, continuum mechanics and especially continuum contact[1] do not work.
- Search for relevant physics that could justify $\lambda_s \gg$ Å.
- Candidates: plasticity (scale dependent), surface energy and adhesion, interaction potential.

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☺ Thank you for your attention!