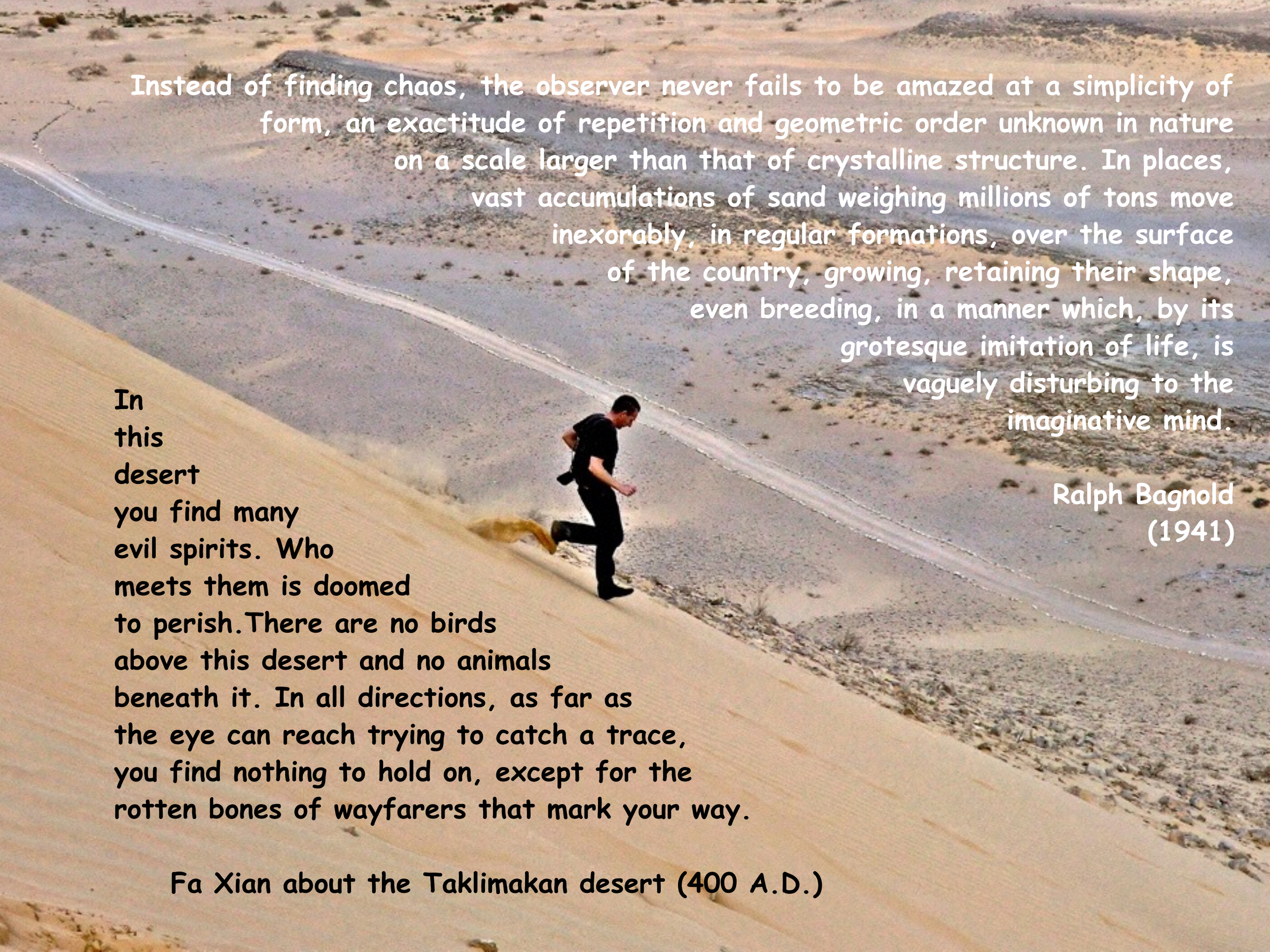
Why is the desert not flat?

The interesting physics of windblown sand

Klaus Kroy–Universität Leipzig



Instead of finding chaos, the observer never fails to be amazed at a simplicity of form, an exactitude of repetition and geometric order unknown in nature on a scale larger than that of crystalline structure. In places, vast accumulations of sand weighing millions of tons move inexorably, in regular formations, over the surface of the country, growing, retaining their shape, even breeding, in a manner which, by its grotesque imitation of life, is vaguely disturbing to the imaginative mind.

Ralph Bagnold
(1941)

In this desert you find many evil spirits. Who meets them is doomed to perish.There are no birds above this desert and no animals beneath it. In all directions, as far as the eye can reach trying to catch a trace, you find nothing to hold on, except for the rotten bones of wayfarers that mark your way.

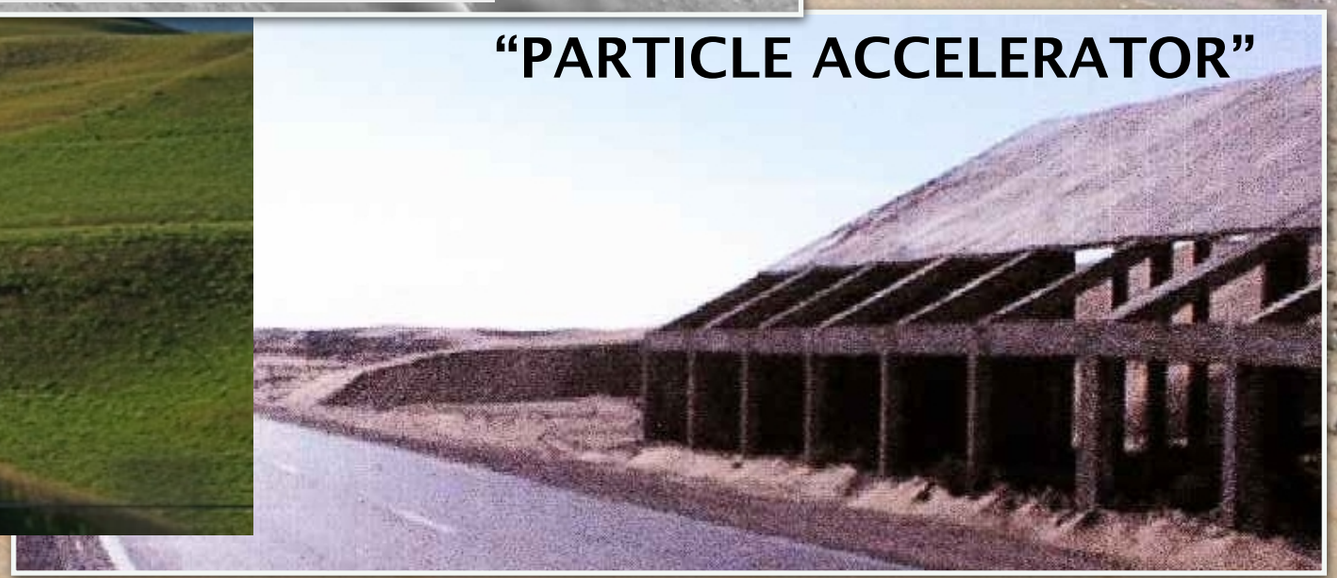
Fa Xian about the Taklimakan desert (400 A.D.)


Juli 1987, Niger bei Tahoua; Foto : Barth
DUST

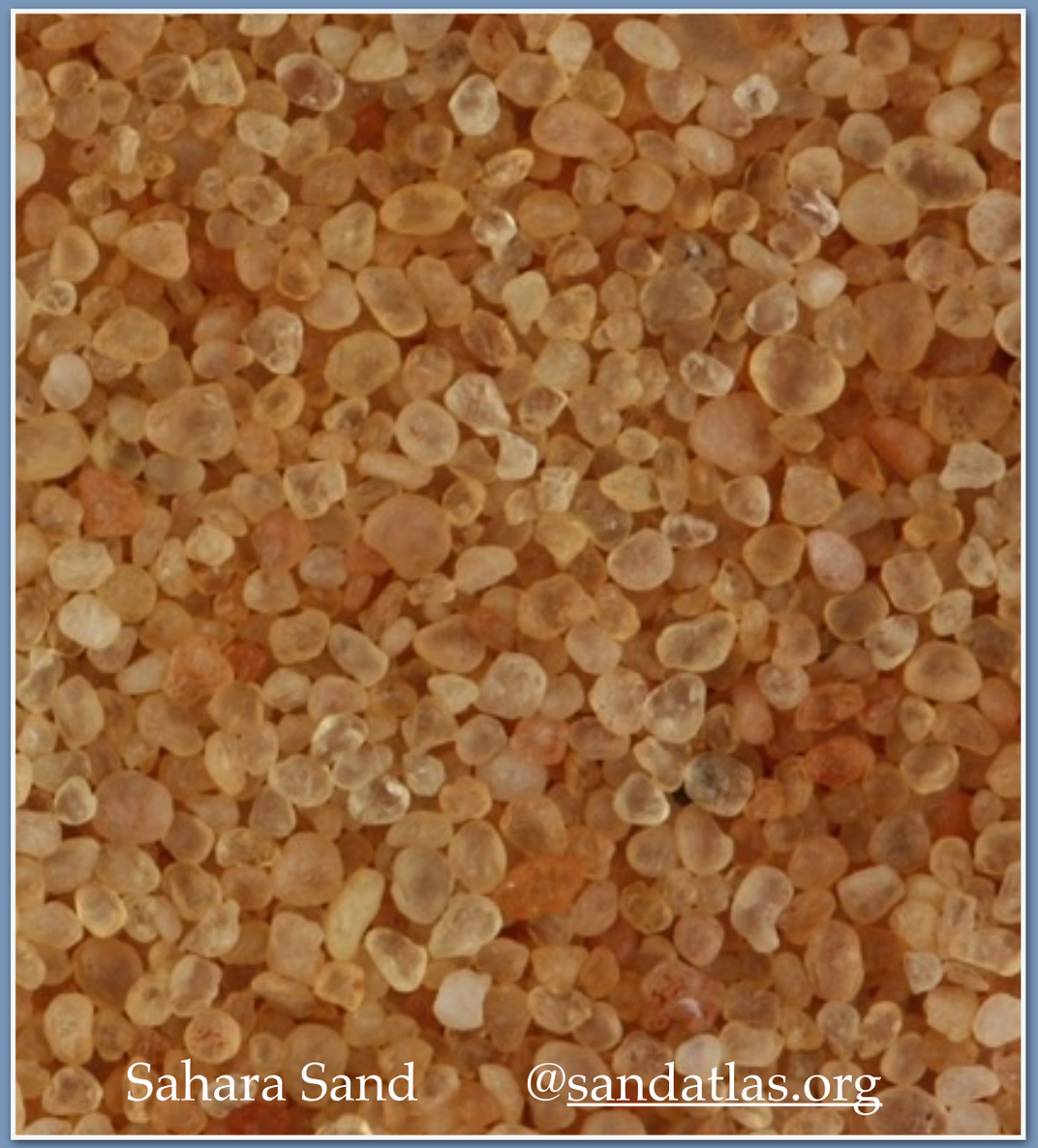

“SNOWPLOW”


MARS
DUNES
NASA/JPL-CALTECH/UNIVERSITY OF ARIZONA


LANDSCAPE


“PARTICLE ACCELERATOR”

Sand & Wind

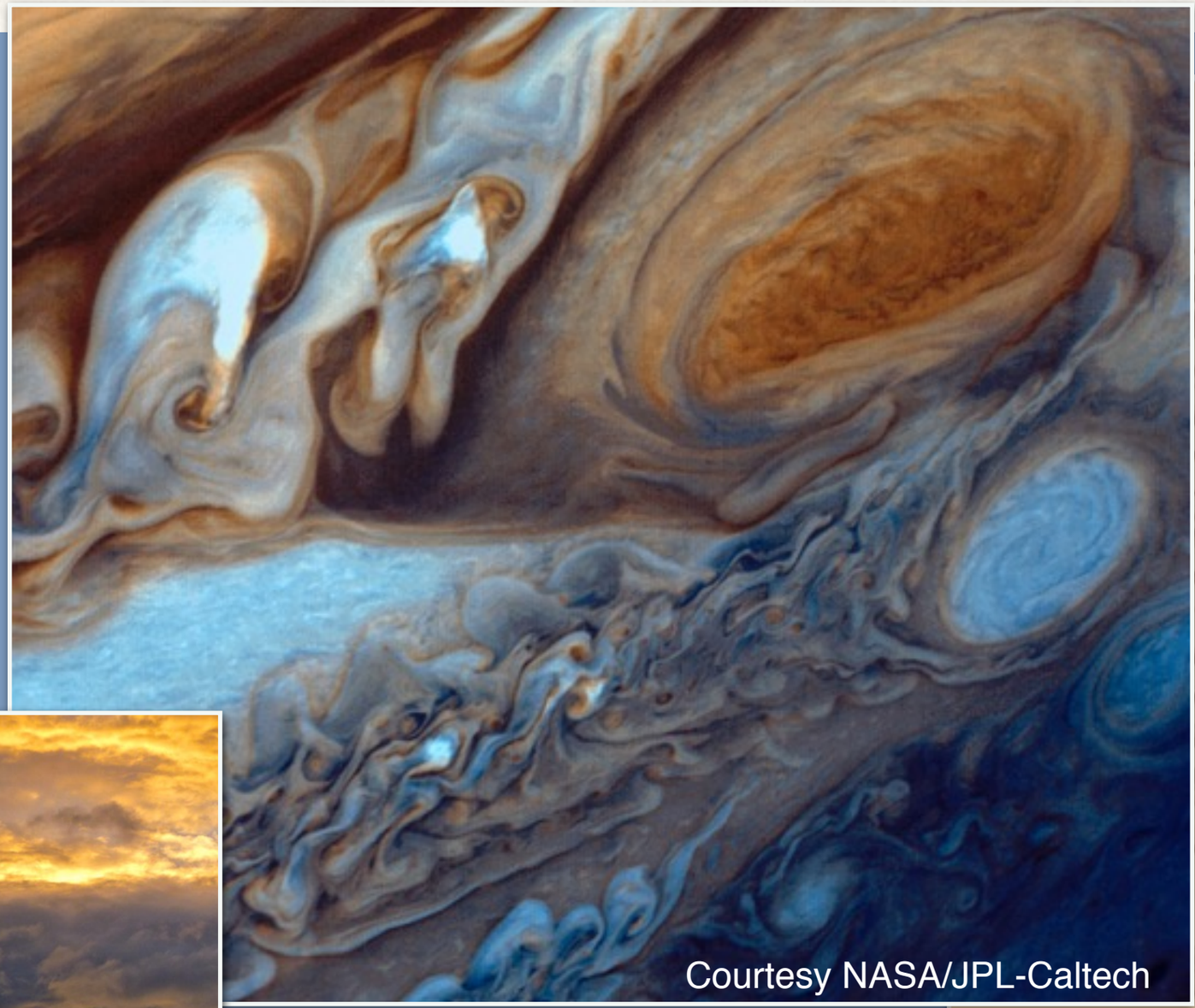


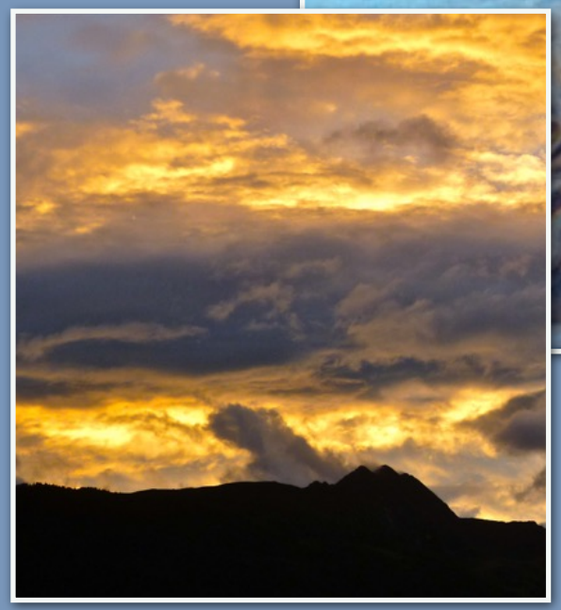
Sand: ∅ ~ 0.2 mm

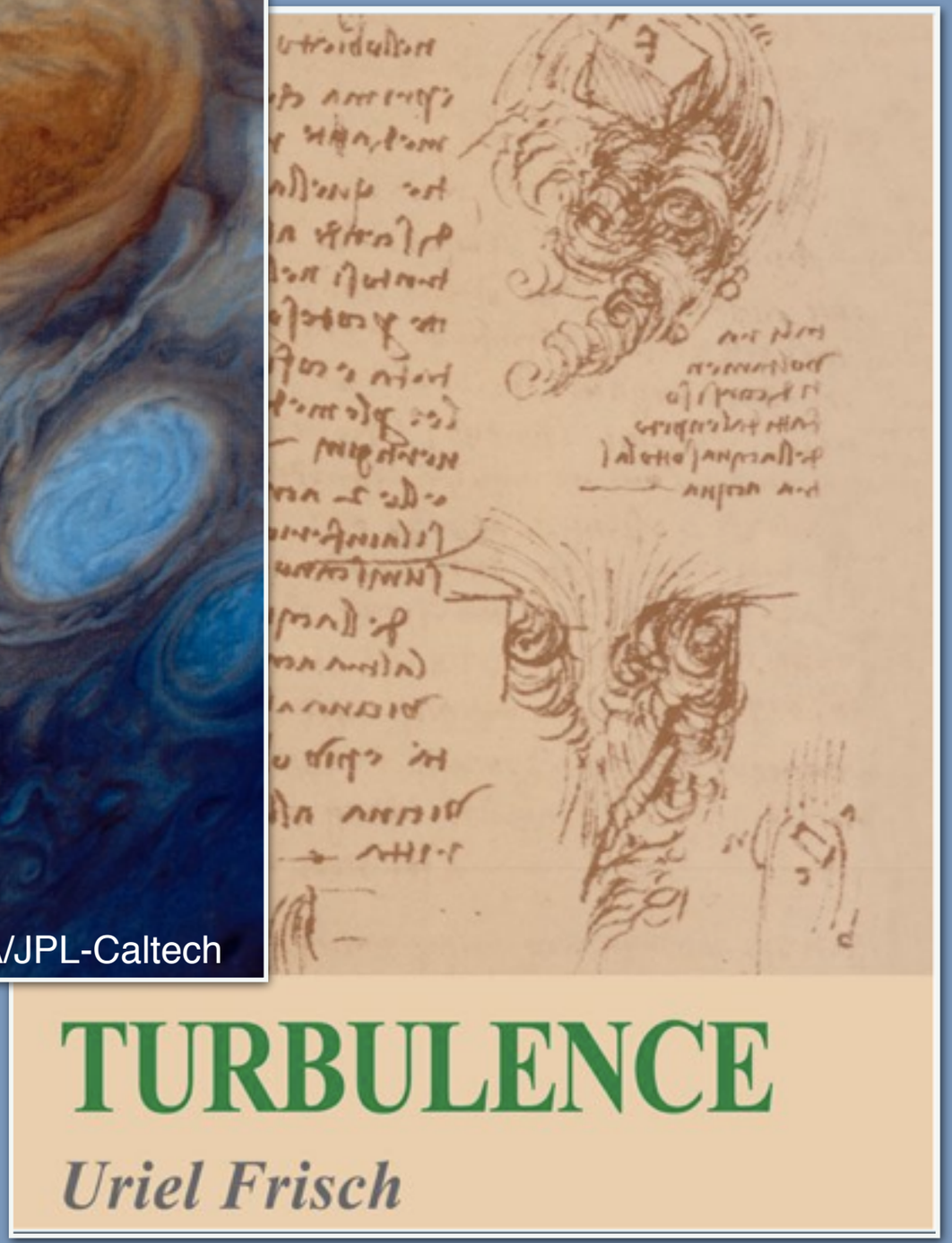
Sahara (Erg Murzug), Lybia @sandatlas.org

Gobi Desert, Mongolia @sandatlas.org

Wind: Self-Similarity







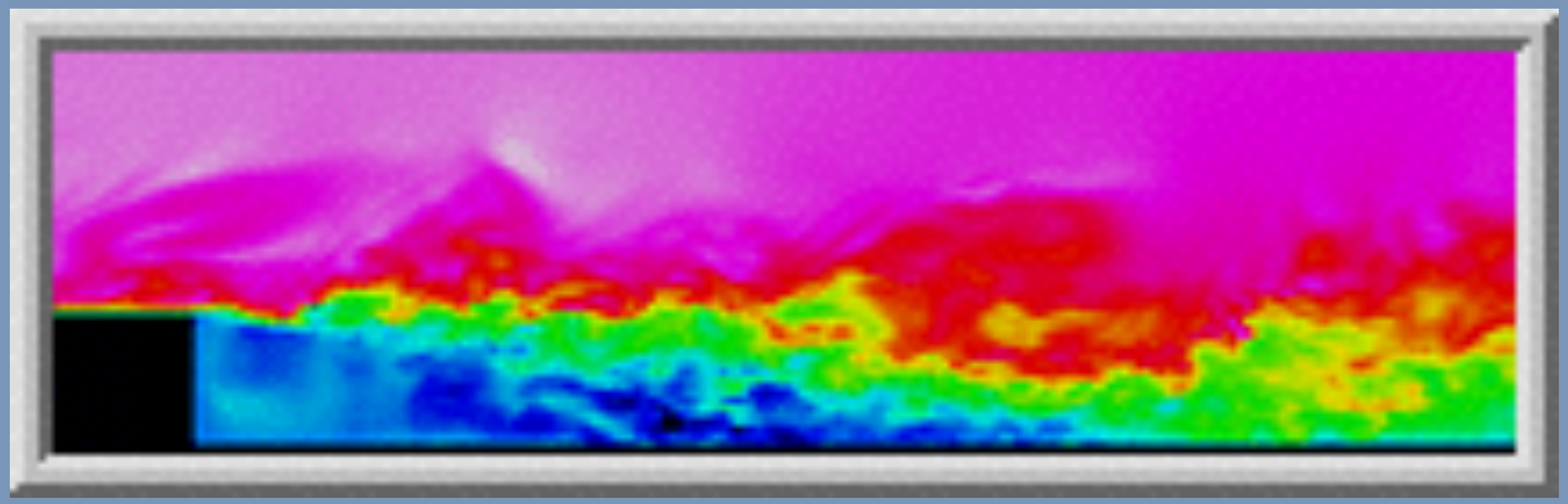
Sand

Sand & Wind: Saltation

Sand & Wind: Saltation

So, why is the desert not flat?

Mathematical Modelling



@ Stanford Supercomputer

Man-in-the-street's Supercomputer

Simulations

PNAS

Direct numerical simulations of aeolian sand ripples

Orencio Durán[a,b,1], Philippe Claudin[a], and Bruno Andreotti[a]

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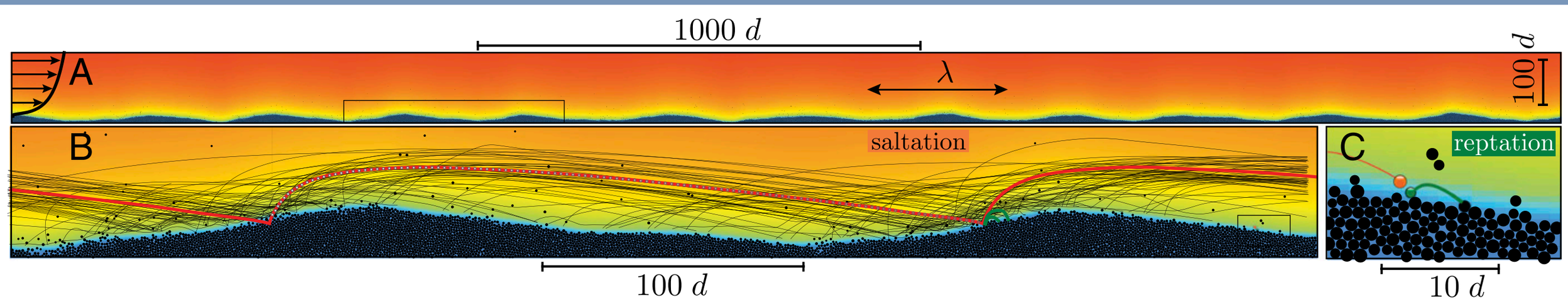
Edited by Harry L. Swinney, The University of Texas at Austin, Austin, TX, and approved September 17, 2014 (received for review July 10, 2014)

Aeolian sand beds exhibit regular patterns of ripples resulting from the interaction between topography and sediment transport. Their characteristics have been so far related to reptation transport caused by the impacts on the ground of grains entrained

presented in ref. 26, we explicitly implement a two-way coupling between a discrete element method for the particles and a continuum Reynolds averaged description of hydrodynamics, coarse-grained at a scale larger than the grain size. This coupling



$1000000 Millenium Problem

"Fearless engineers write gigantic codes that are supposed to produce solutions to the equations: they do not care the least (when they are conscious of the problem, which unfortunately seldom seems to be the case) that what they study are *not* the Navier-Stokes equations, but just the computer code they produced. […] Statements to the contrary are not rare, and they may appear even on the news: but they are wrong."

G. Gallavotti (2004)

$$\partial_t \vec{v} + \vec{v} \cdot \nabla \vec{v} = -\nabla \tilde{P} + \nu \nabla^2 \vec{v}\,, \qquad \nabla \cdot \vec{v} = 0$$

What matters

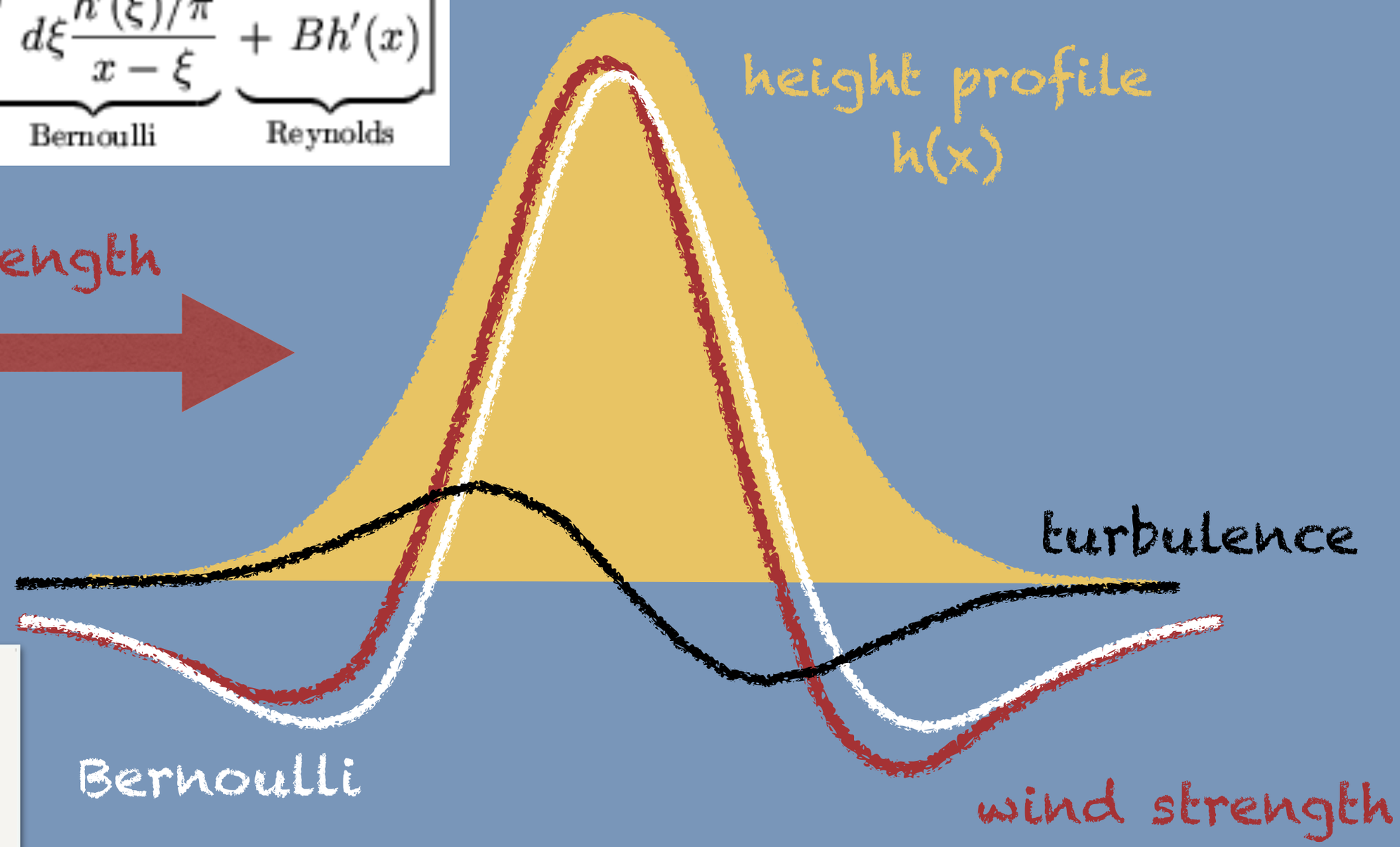
Fundamental Physical Principles

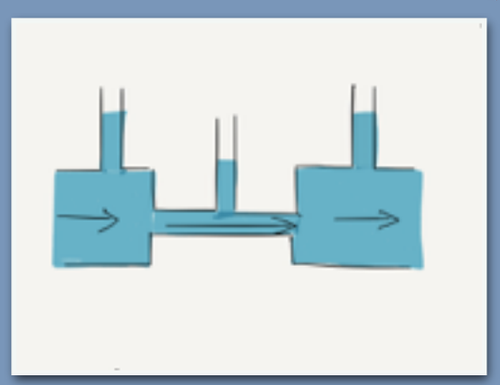
- Structurally Robust:
  Symmetries → Conservation Laws
- Structurally Critical:
  Symmetry Breaking → Emergence
- turbulent SB, broken scale-invariance, sorting

Turbulent Symmetry Breaking

J. C. R. Hunt & coworkers, 1975–90

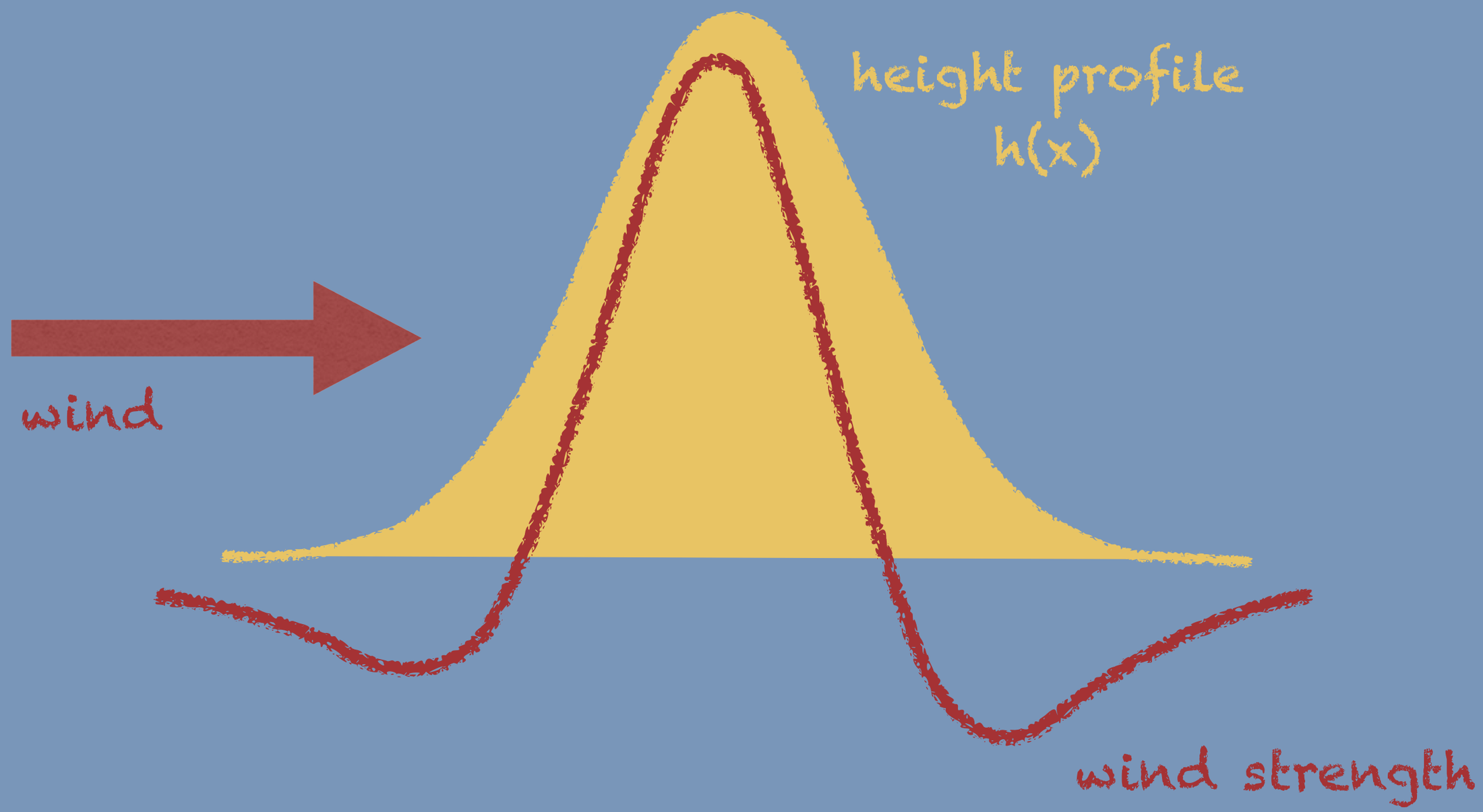
$$\Delta\tau(x) \approx A\left[\underbrace{\int d\xi \frac{h'(\xi)/\pi}{x-\xi}}_{\text{Bernoulli}} + \underbrace{Bh'(x)}_{\text{Reynolds}}\right]$$





Turbulent Symmetry Breaking

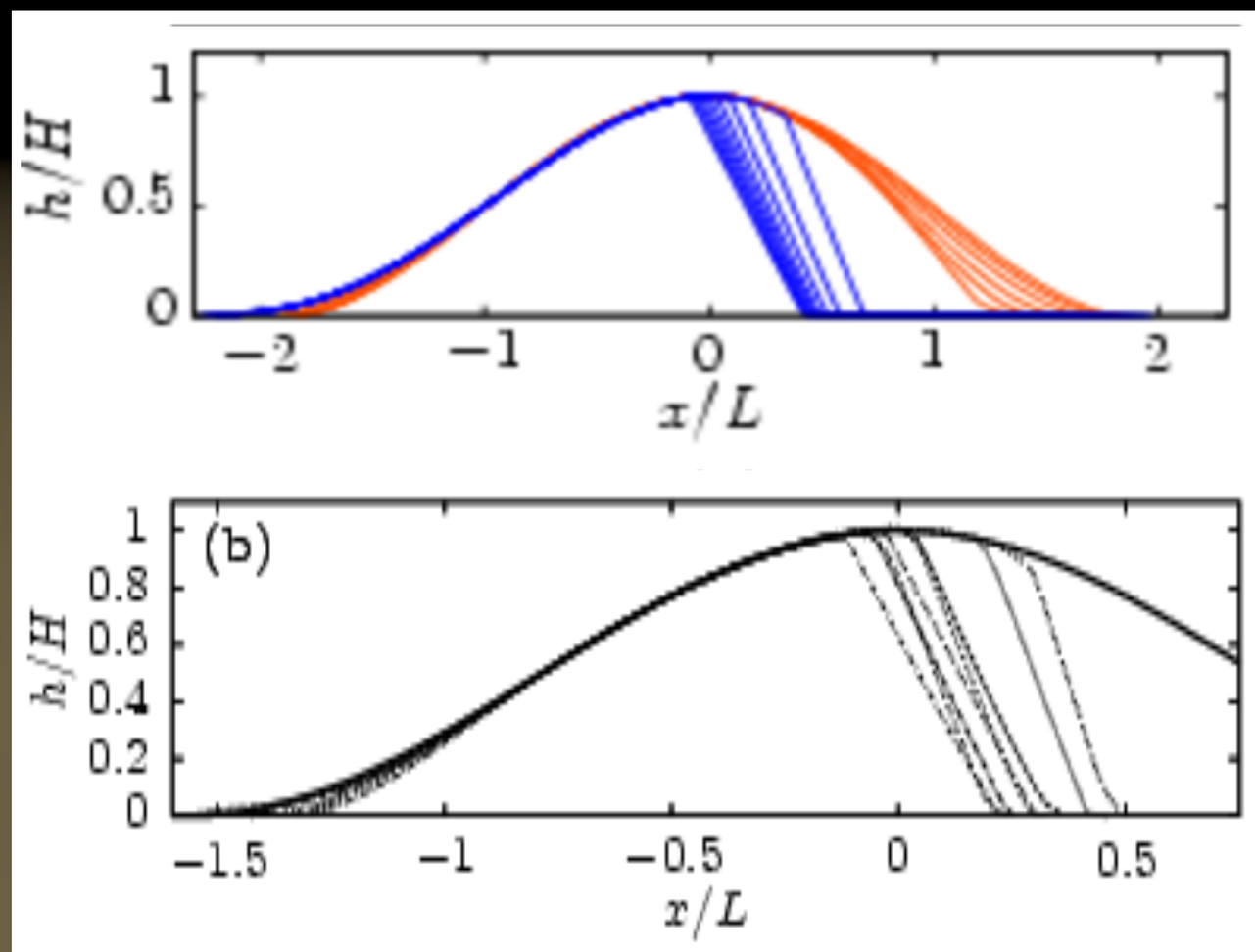
deposition @ crest —> growth instability

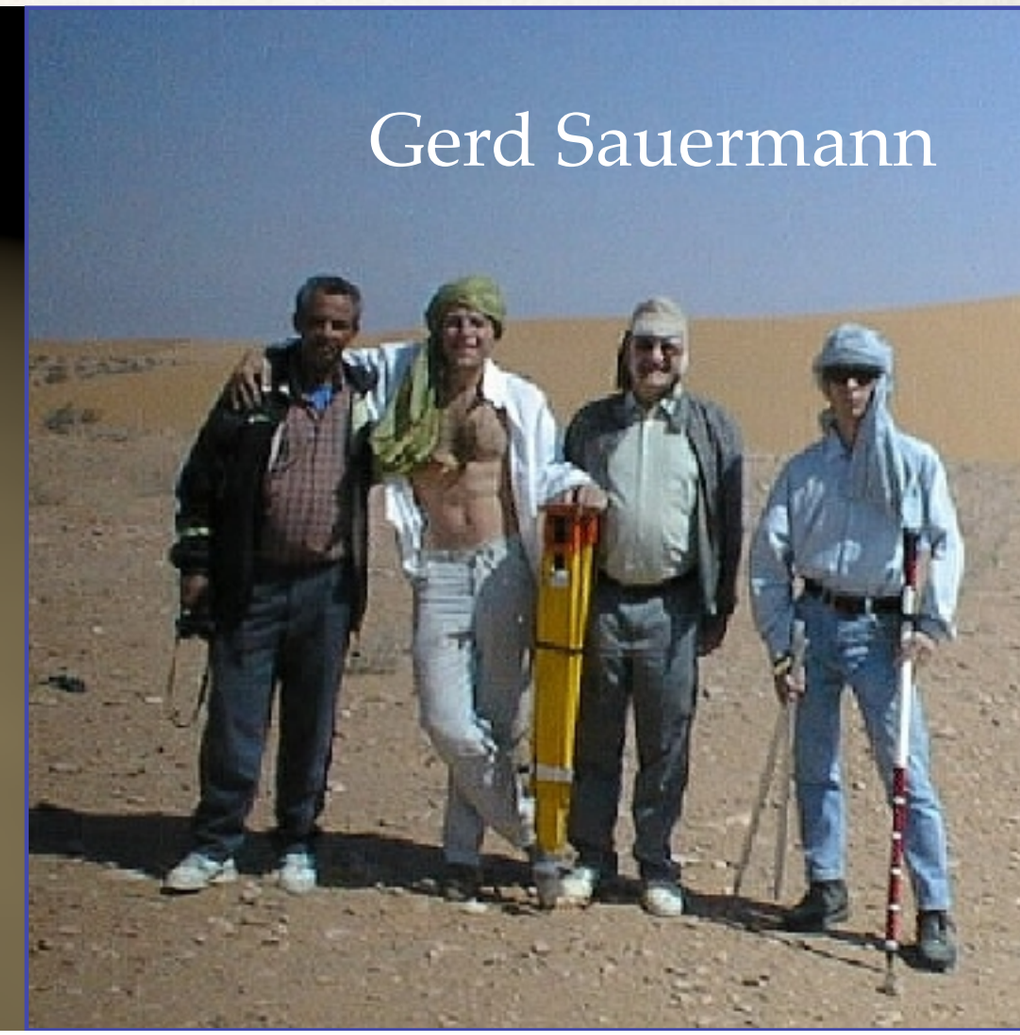


Are all wavelengths unstable?

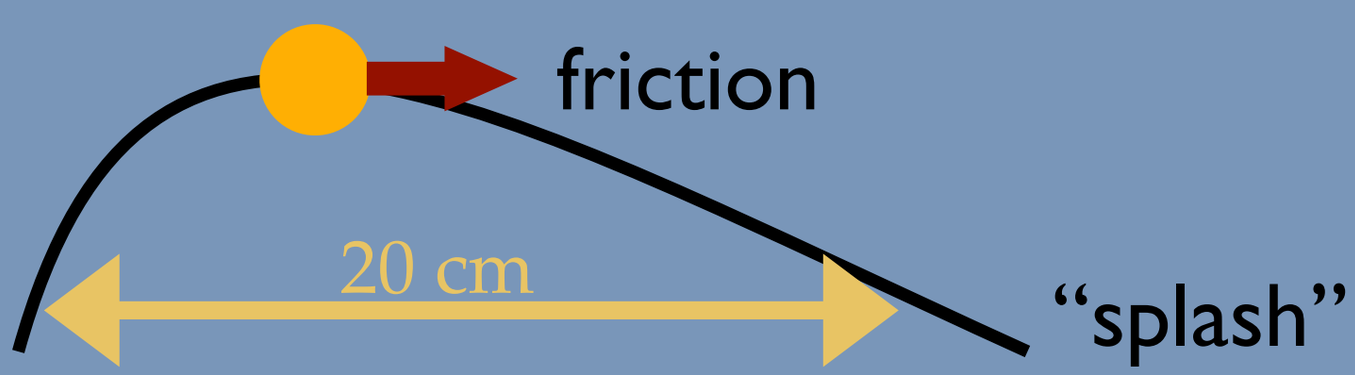
Are All Dunes Alike?

Broken Scale Invariance



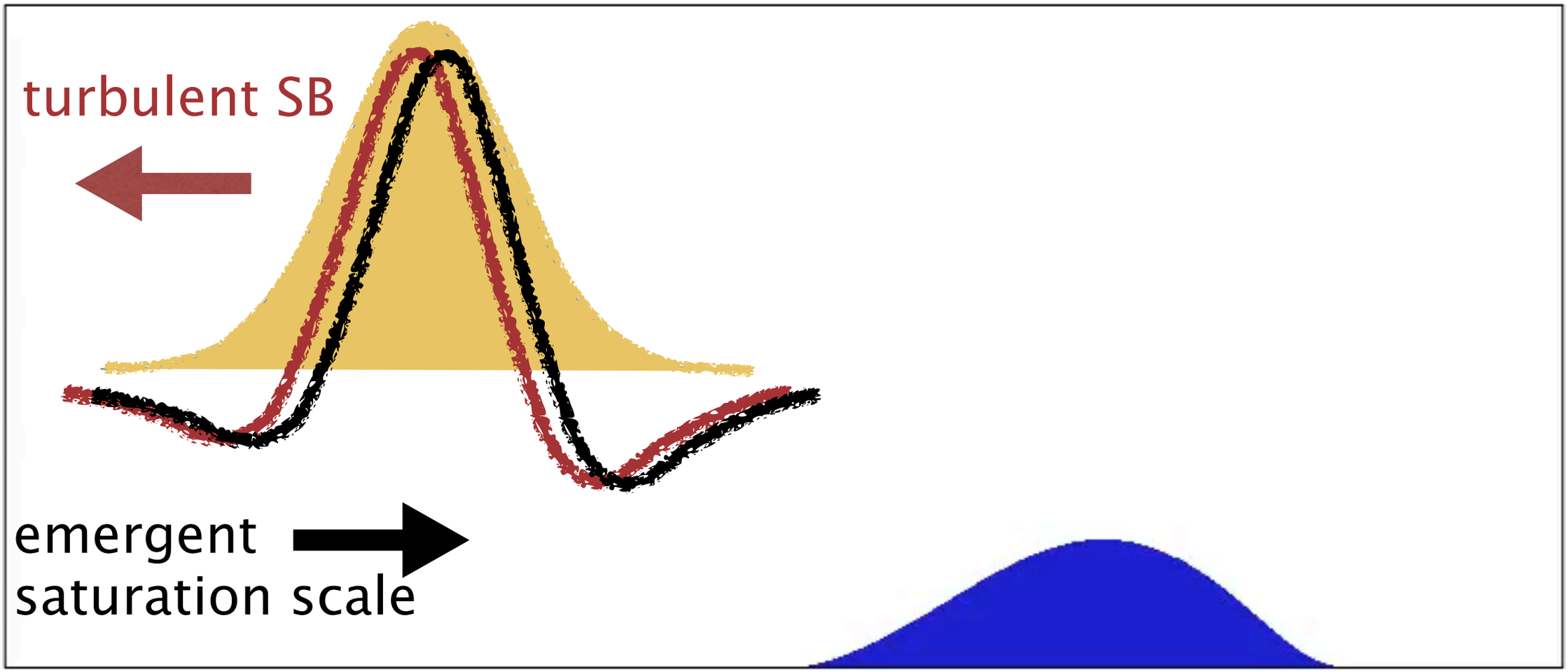


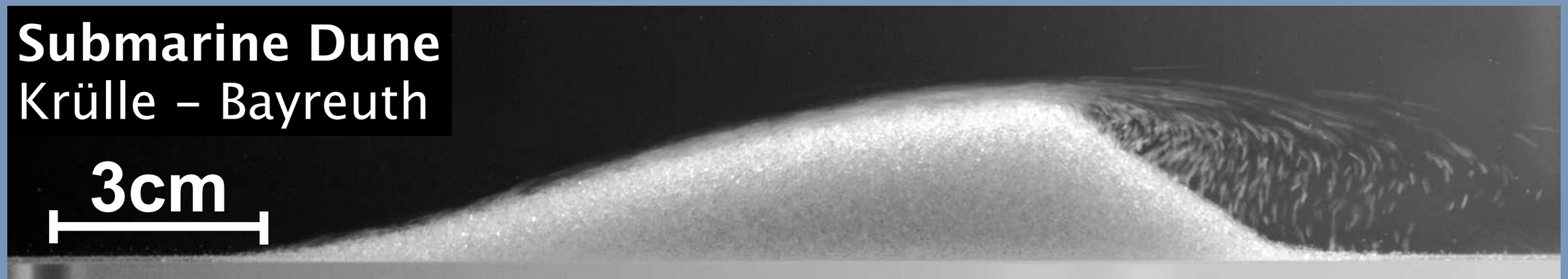
Sauermann, Rognon, Poliakov, Herrmann, Geomorphology 36, 47 (2000)



Emergent Mesoscale: "SATURATION LENGTH" ~ grain-size x density-ratio

Critical Size & Shape Transition



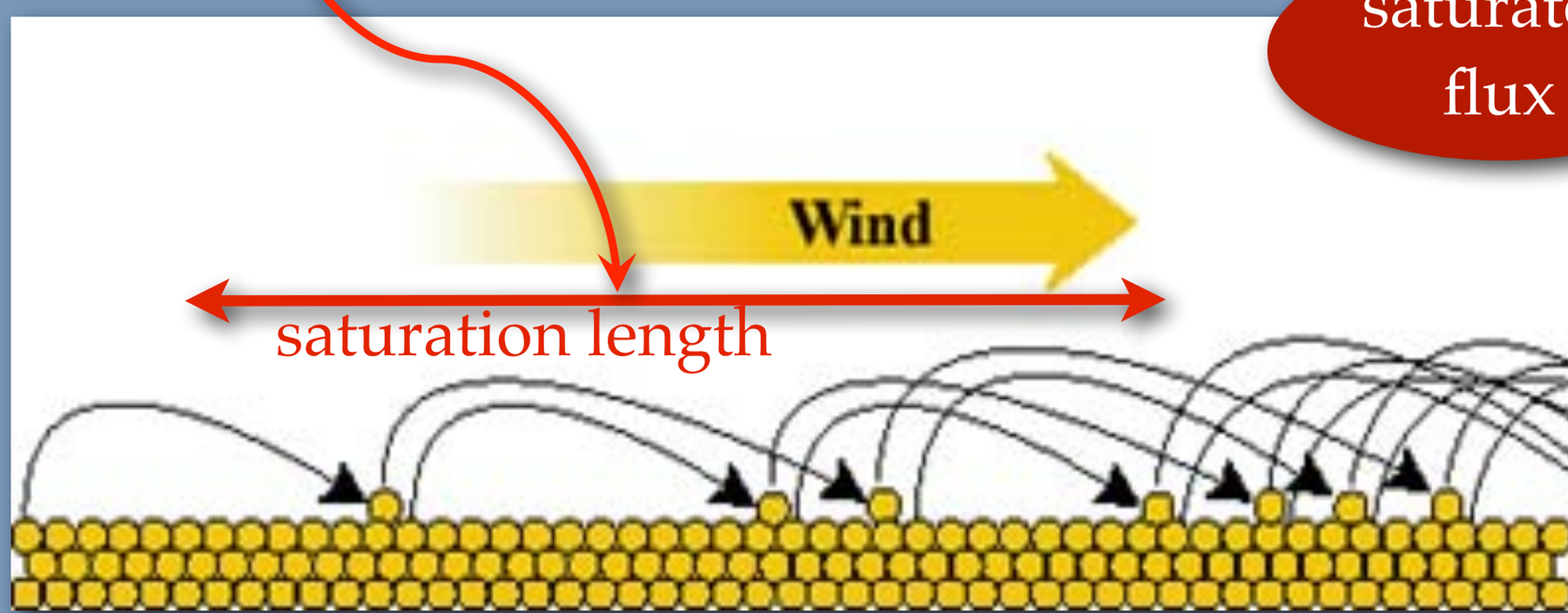


Emergent length

sand flux

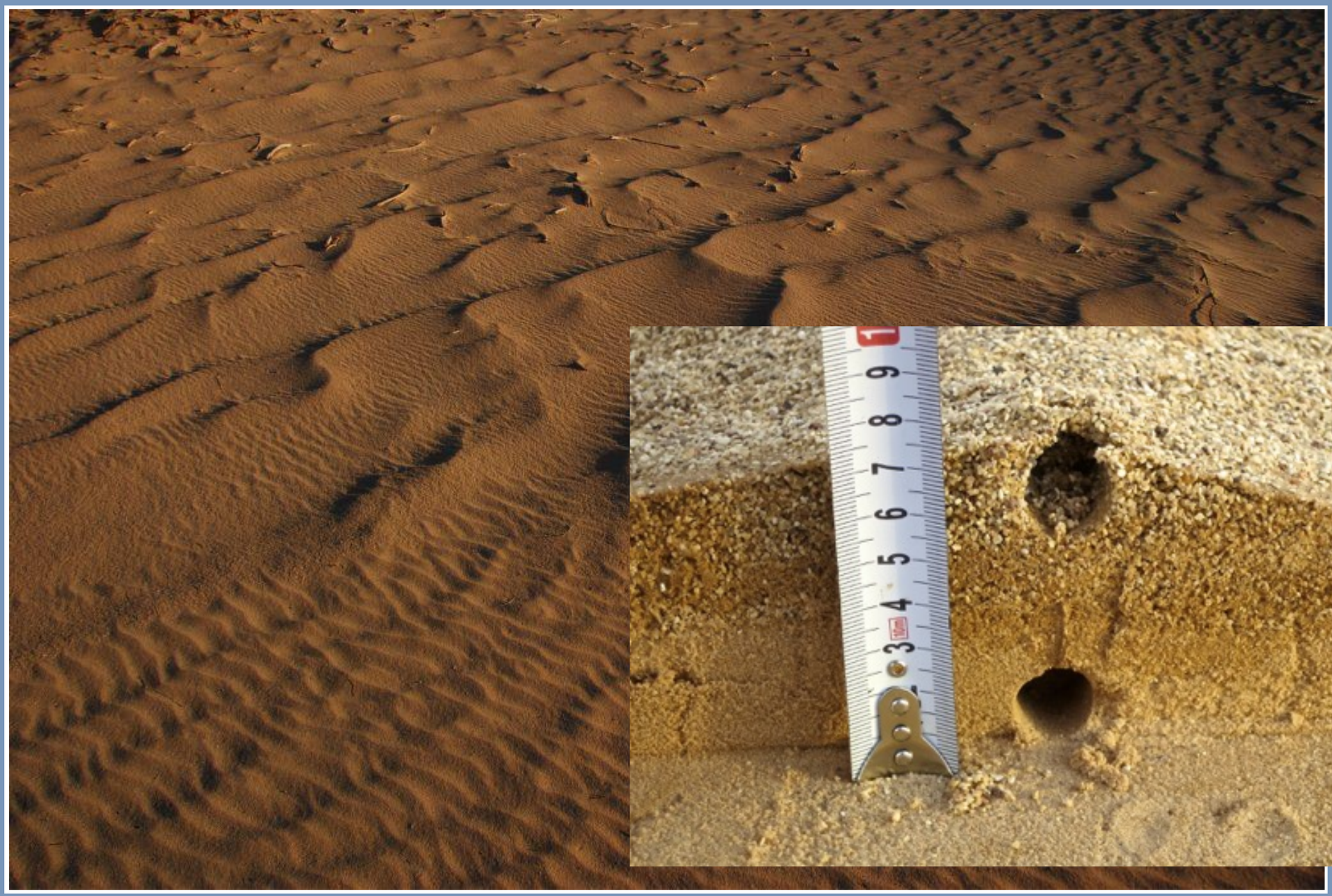
$$\ell_s \frac{\mathrm{d}}{\mathrm{d}x} q(x) = q(x) \left(1 - \frac{q(x)}{q_s(\tau(x))} \right)$$

saturated flux



Forbidden wavelength gap

Quibble: Megaripples



Bimodal grain-size distribution

Contents lists available at SciVerse ScienceDirect

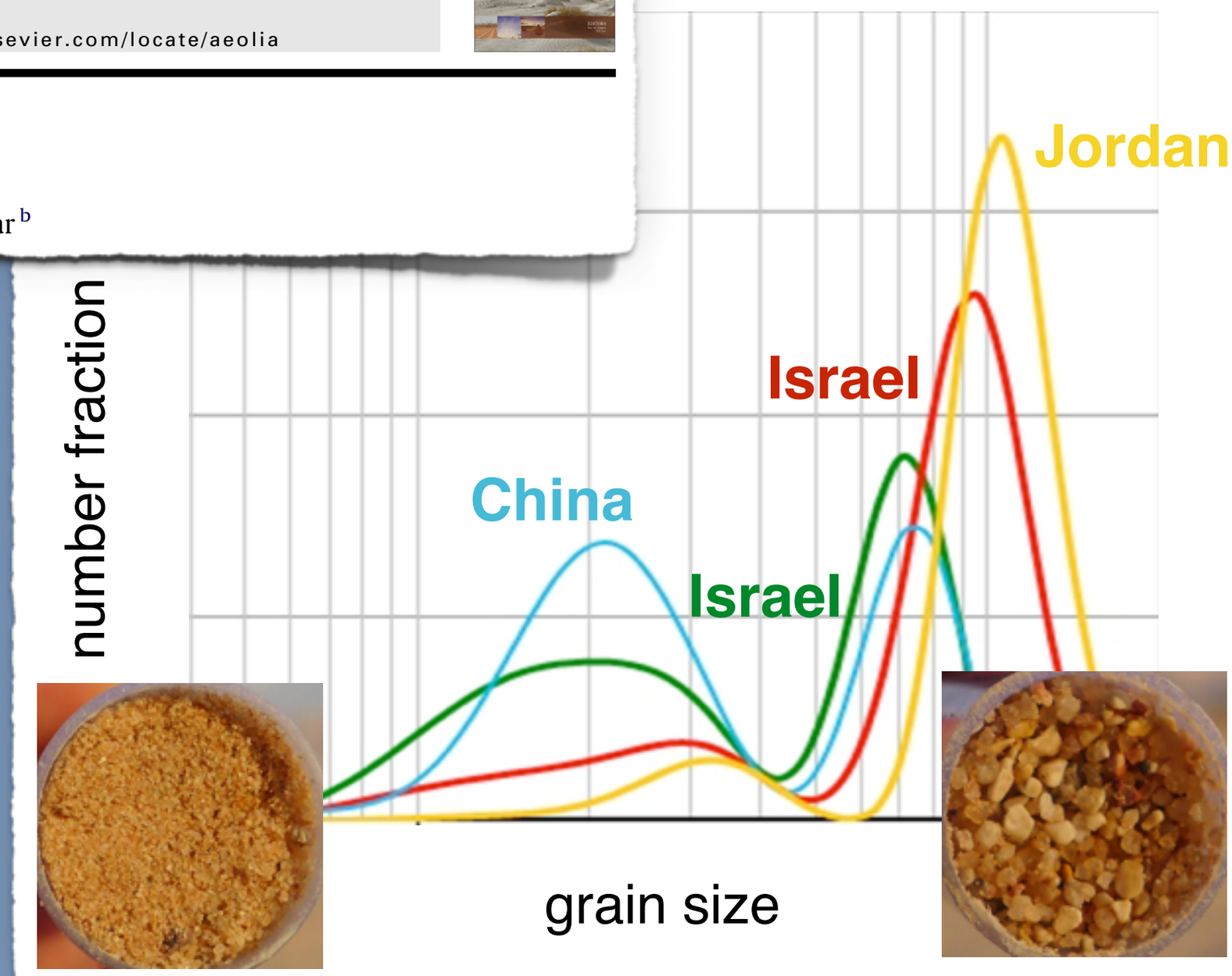
Aeolian Research

journal homepage: www.elsevier.com/locate/aeolia

Evolution of megaripples from a flat bed

Hezi Yizhaq [a,*], Itzhak Katra [b], Ori Isenberg [a], Haim Tsoar [b]

sand sorting



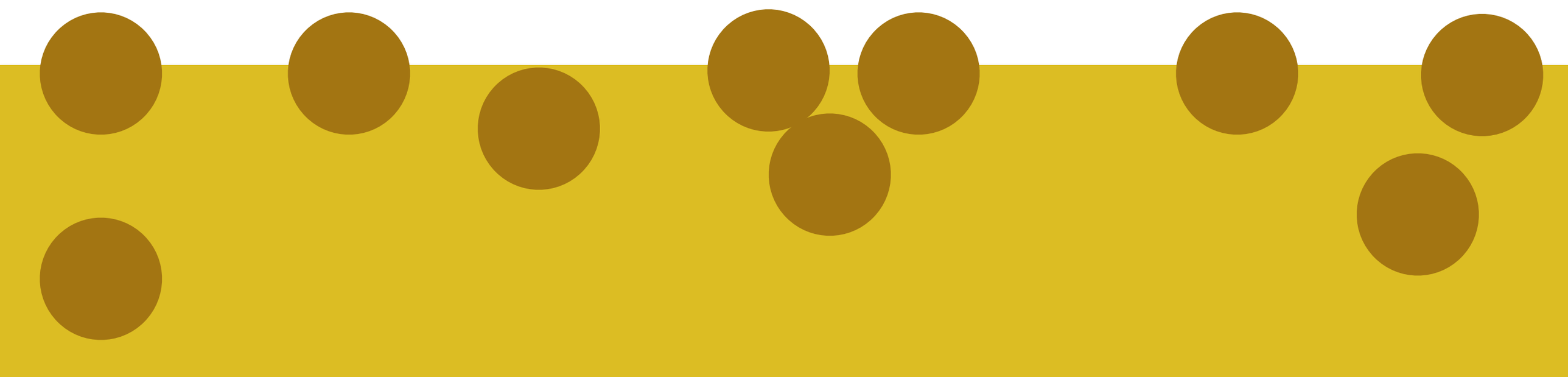
erosive sand sorting

erosive sand sorting

erosive sand sorting

erosive sand sorting

erosive sand sorting



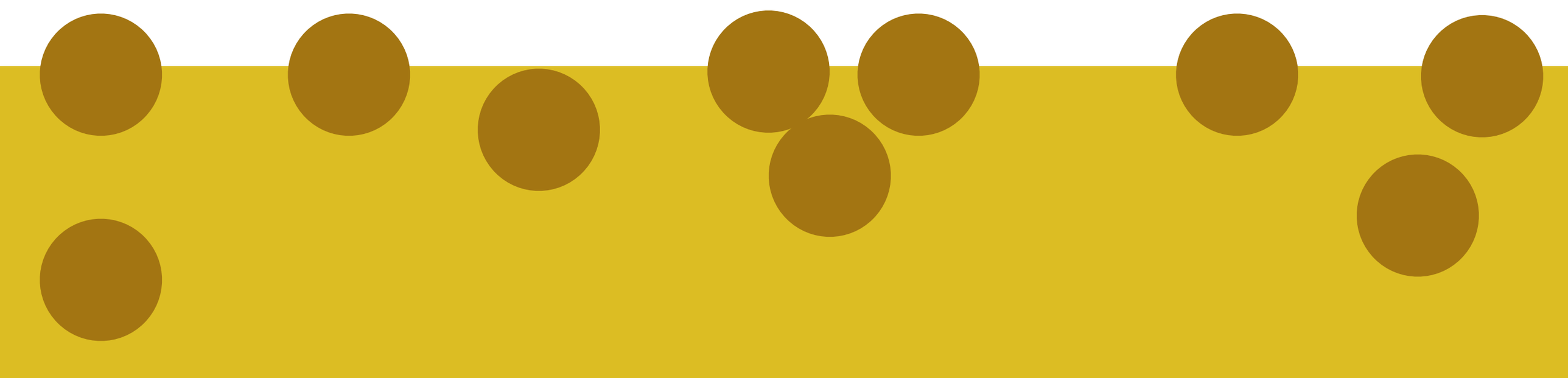
erosive sand sorting

erosion kernel

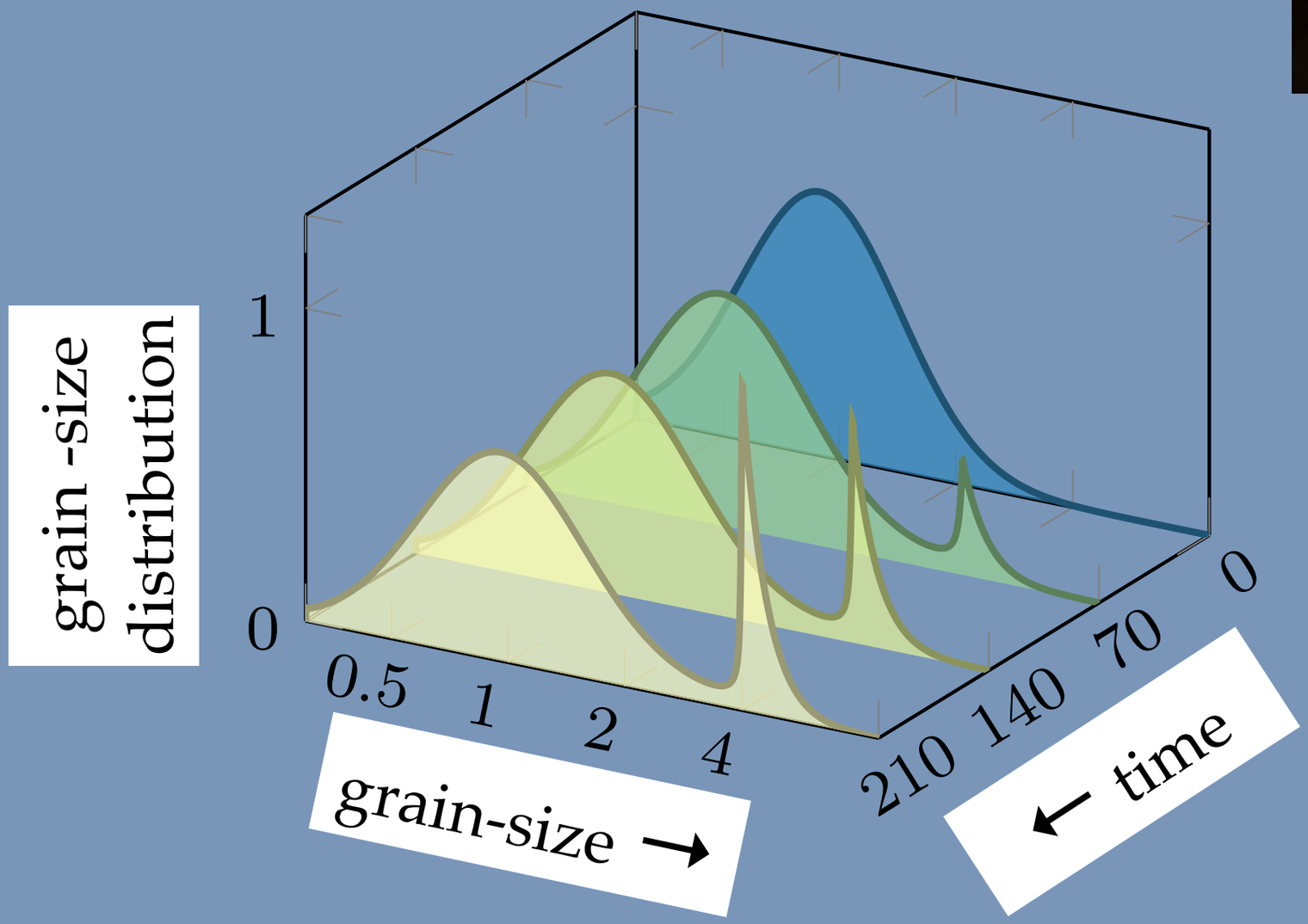
$$\partial_t P_{\mathrm{s}}(d,t) = -\phi(d) P_{\mathrm{s}}(d,t) + \overline{\phi} P_{\mathrm{b}}(d)$$

surface grain distribution

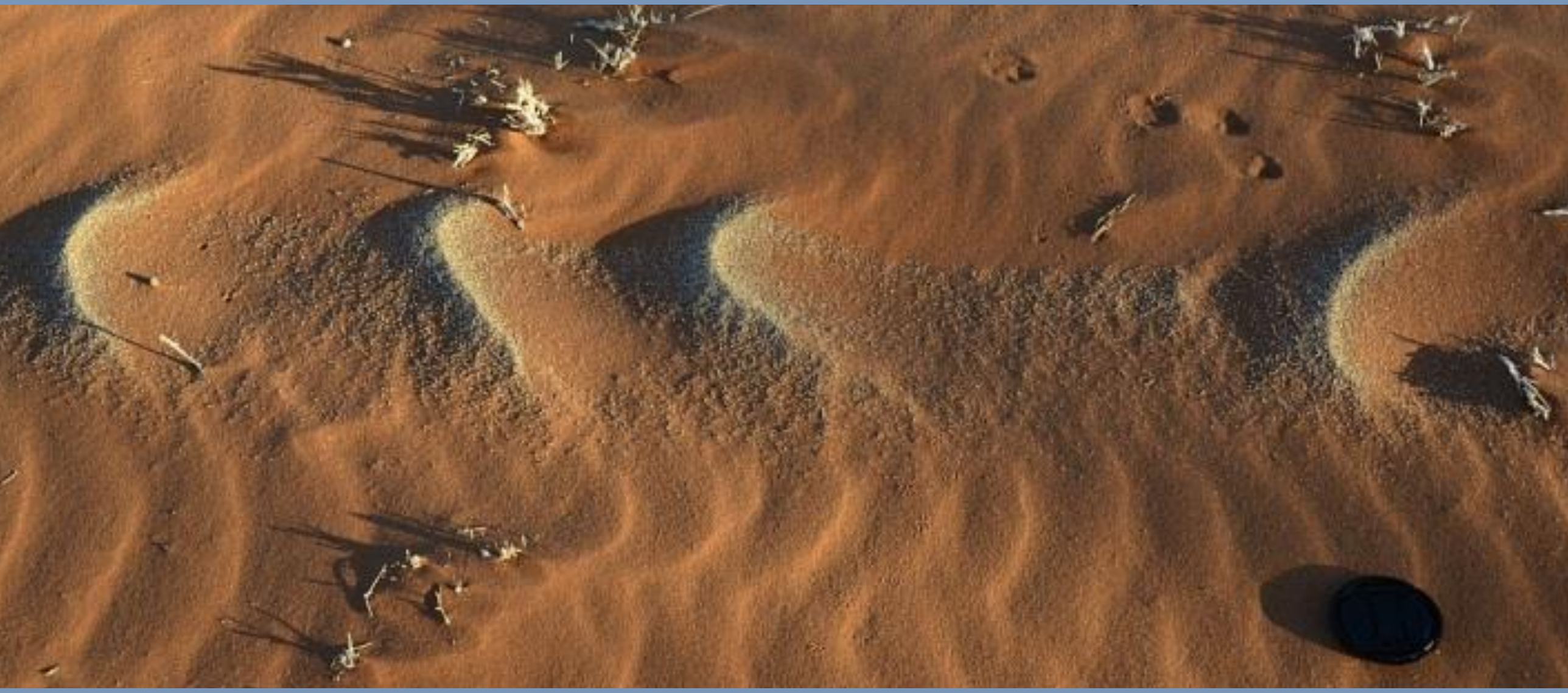
bulk grain distribution



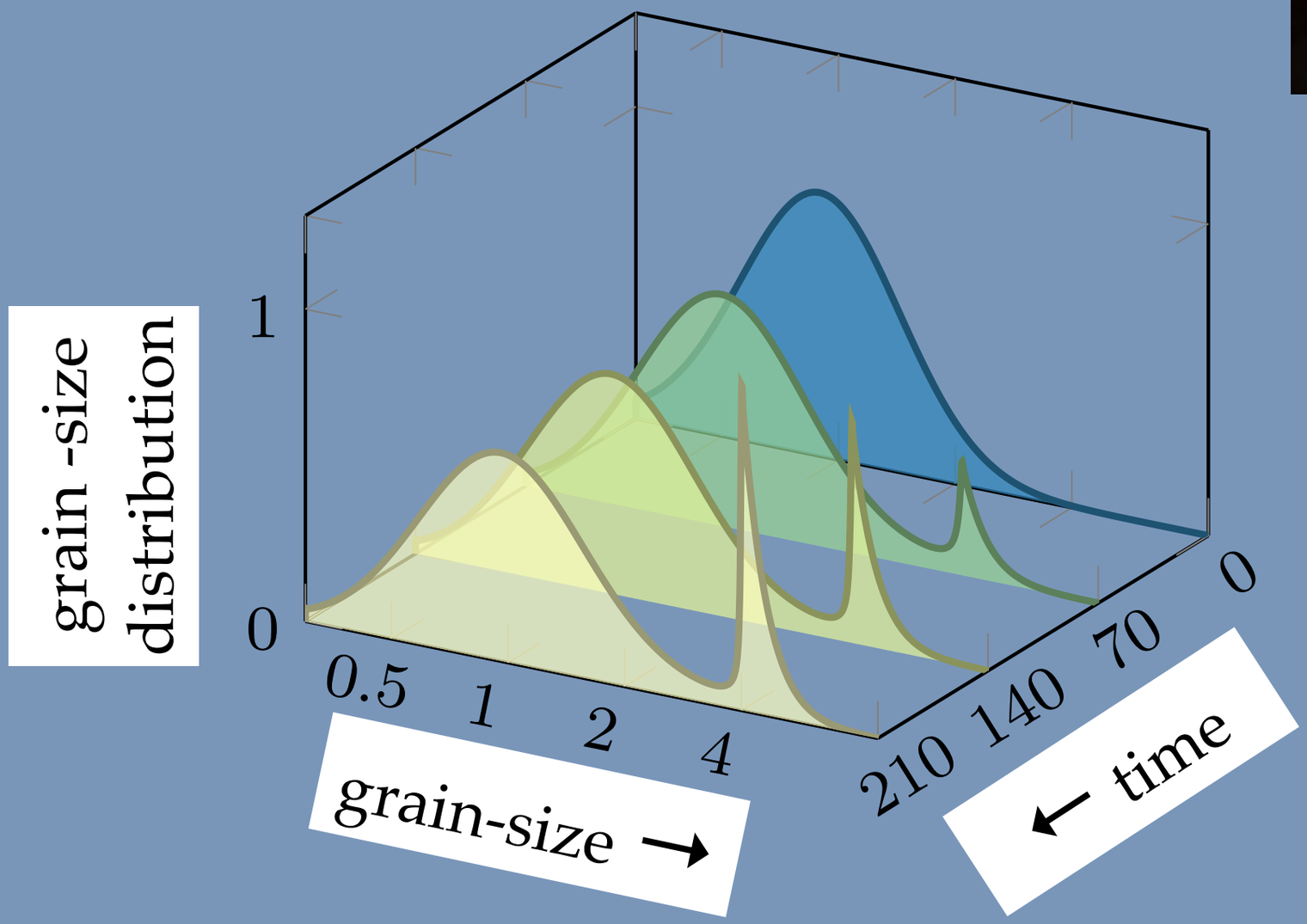
Sand Sorting

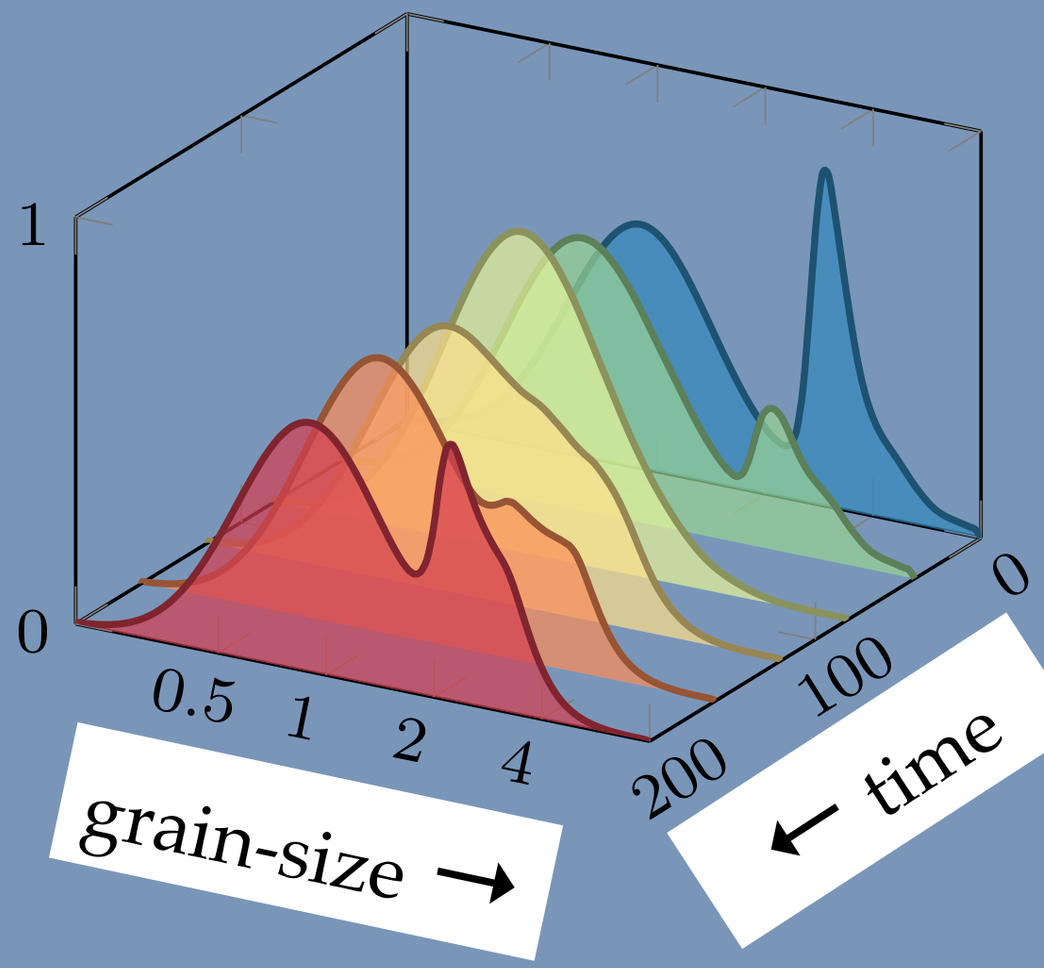


“Minidunes from Megagrains”



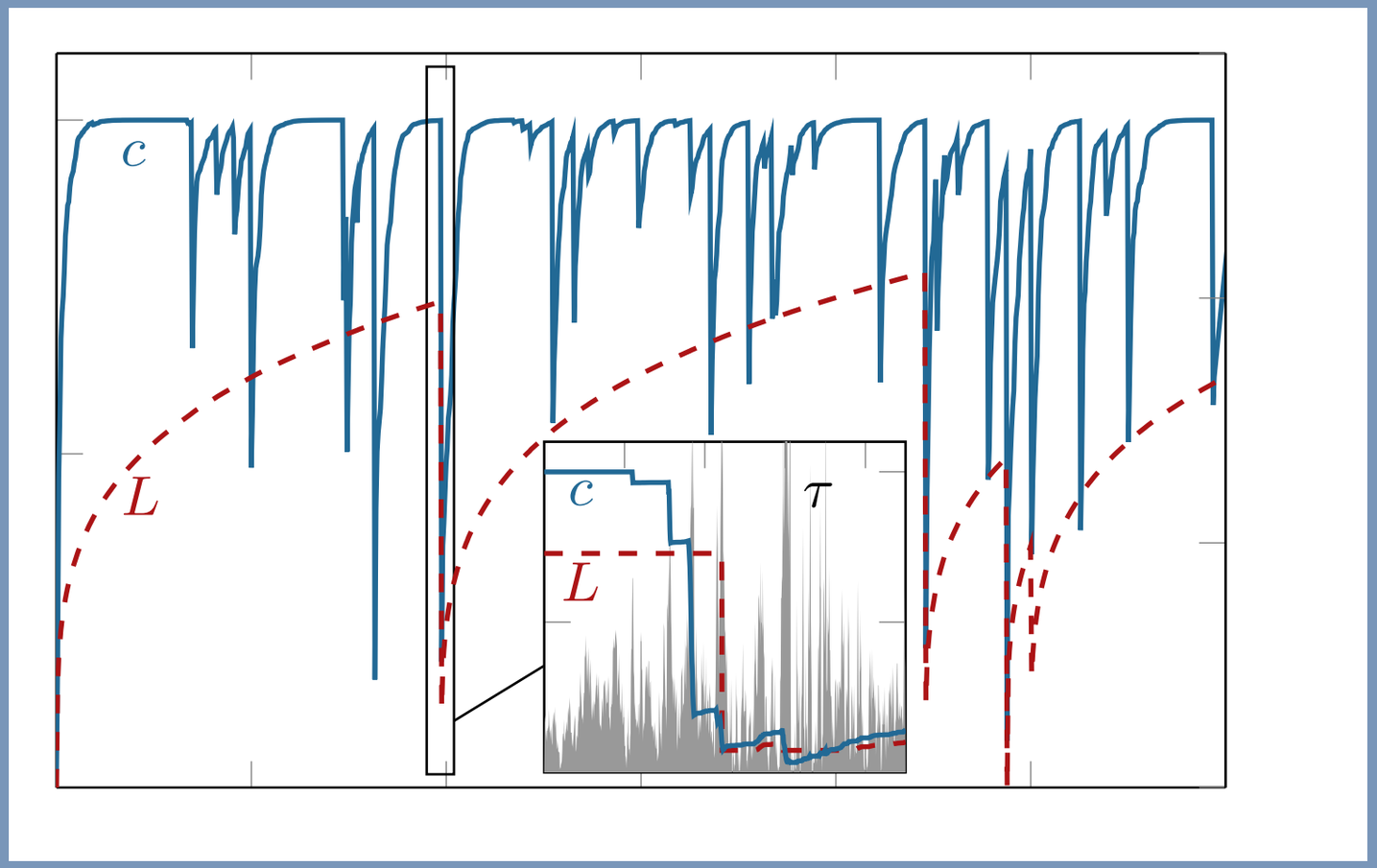
Sand Sorting

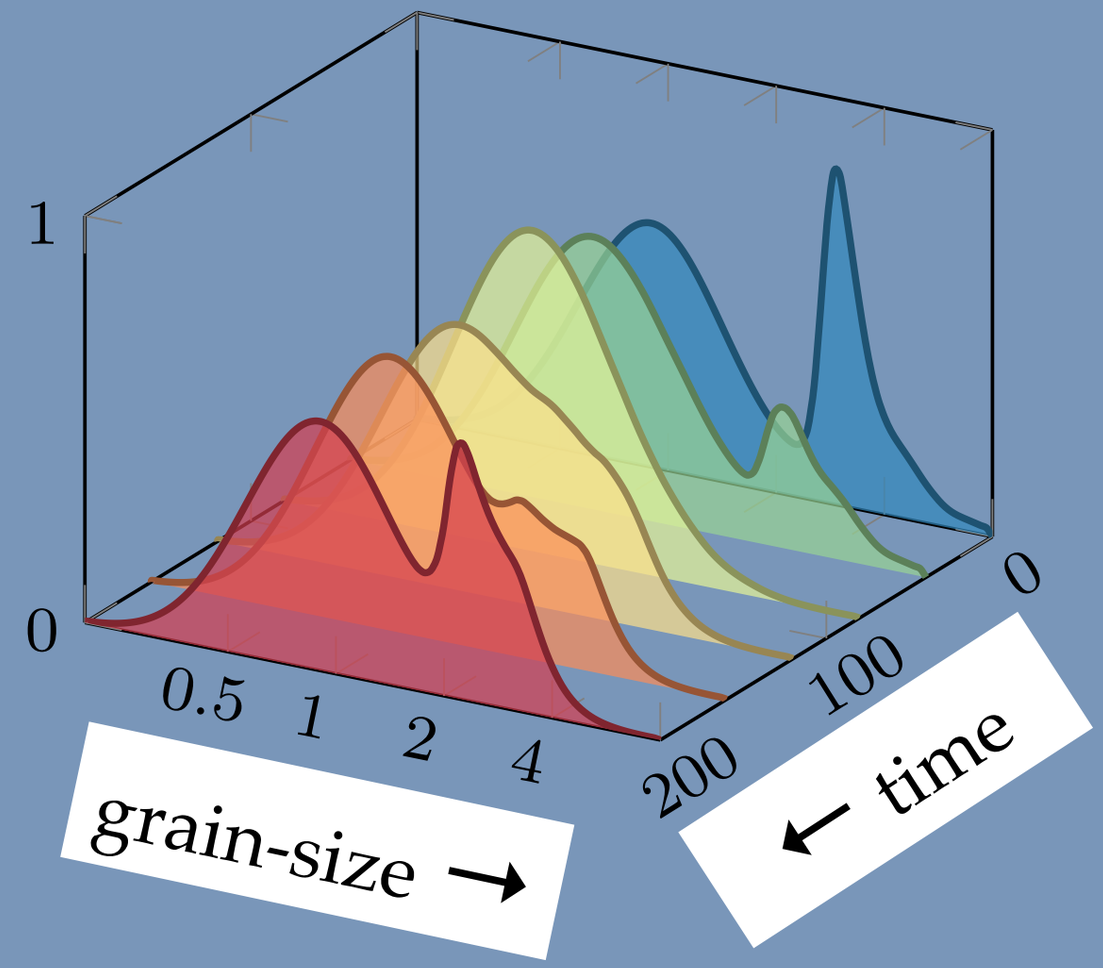




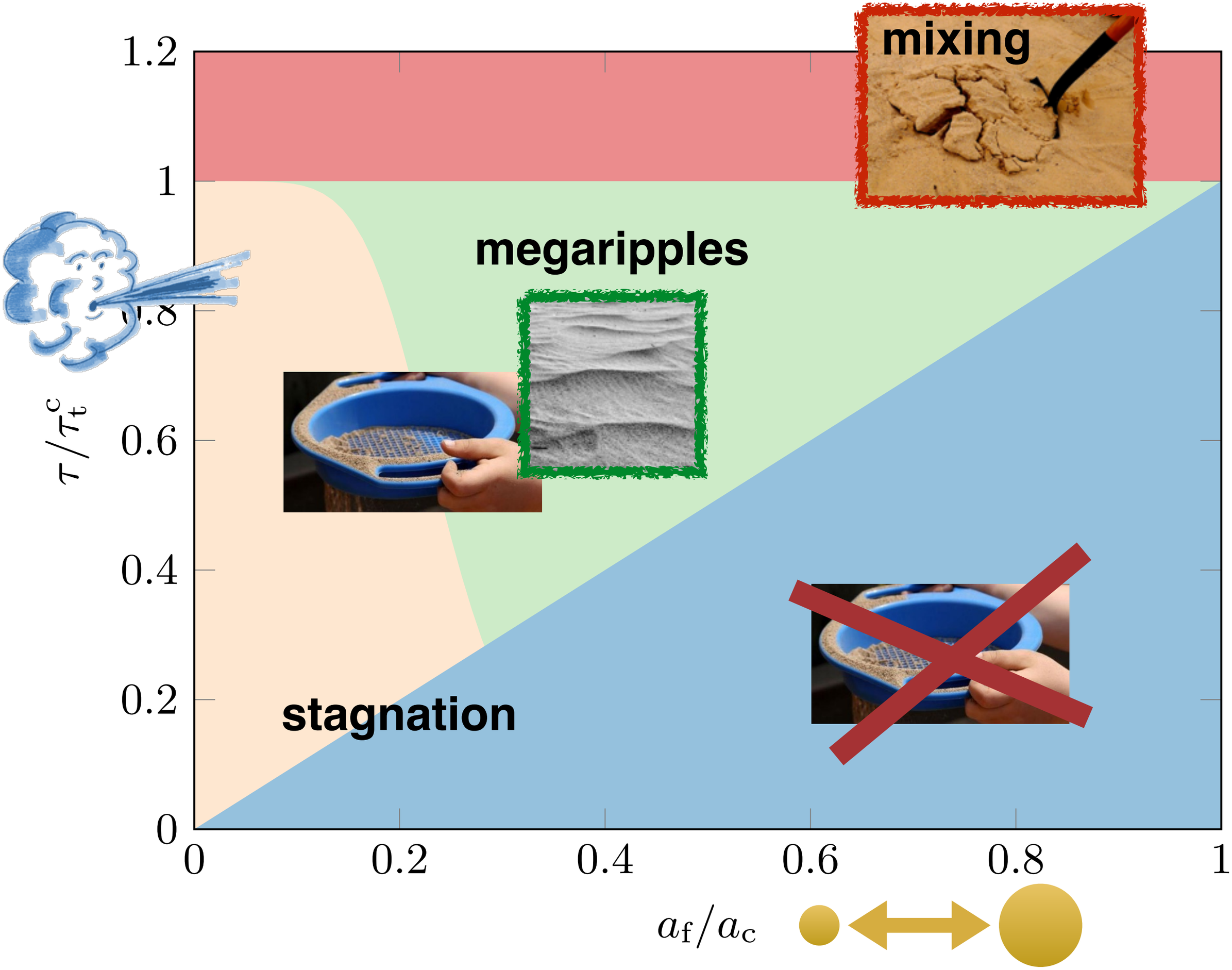
Megaripples formation hinges on sand sorting
But sand sorting hinges on the wind conditions

Intermittent wind fluctuations





Megaripples = transient bedforms
contingent on intermittent wind fluctuations


mixing
megaripples
stagnation
τ/τ_t^c
a_f/a_c
0
0.2
0.4
0.6
0.8
1
1.2

Summary

- wind -> saltation -> ripples
- turbulent symmetry breaking -> dunes
- broken scale invariance -> mesoscale, size selection, wavelength gap
- sand sorting -> megaripples = minidunes from megagrains in the forbidden wavelength gap
- contingent on intermittent wind fluctuations

Thank you for your attention!