SPIN workshop, Pitlochry, Scotland, 25th March 2023

Wave-induced rockfall triggering

Unexpected effect of low seismicity

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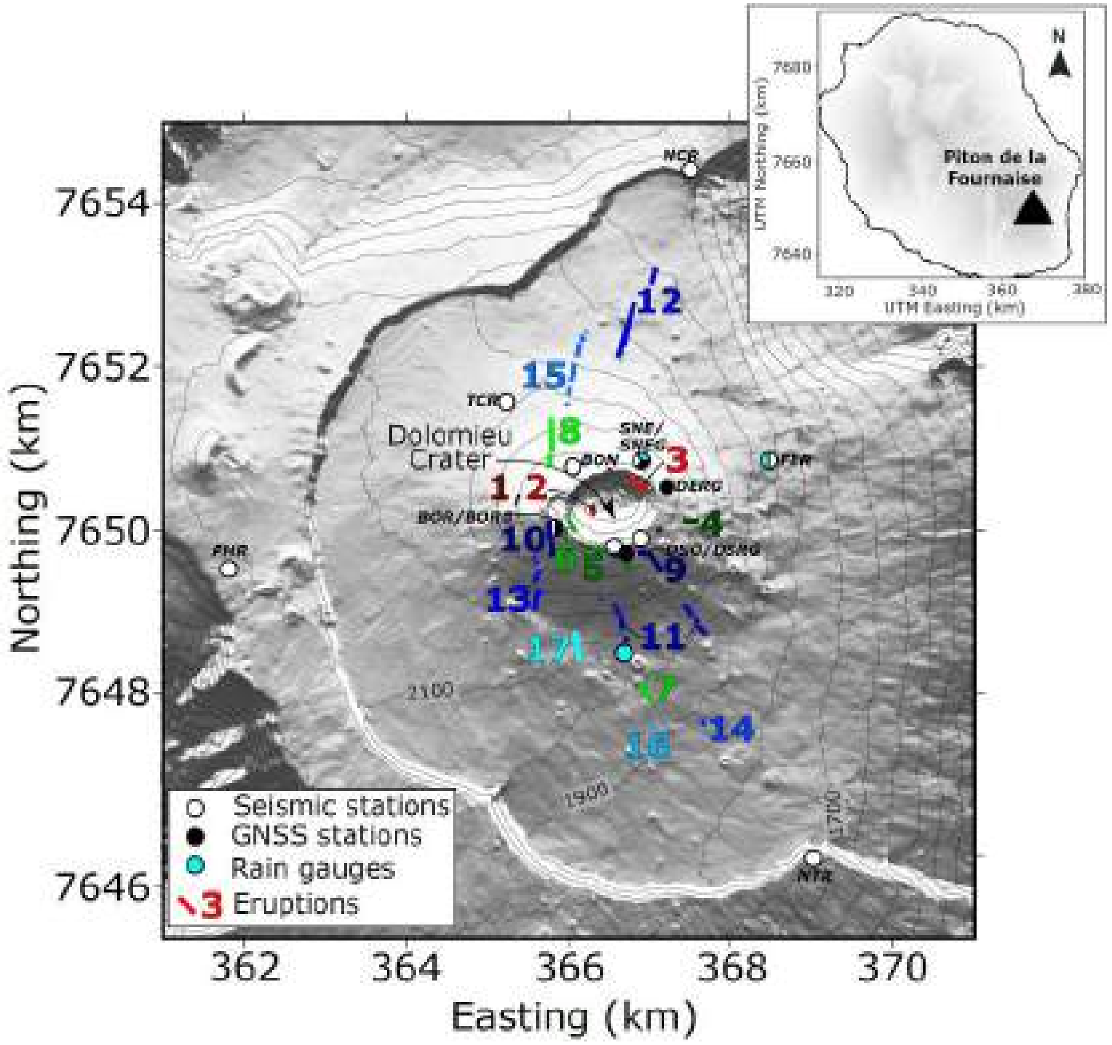
Natural field lab for rockfalls: Piton de la Fournaise

Permanent seismic network, cameras

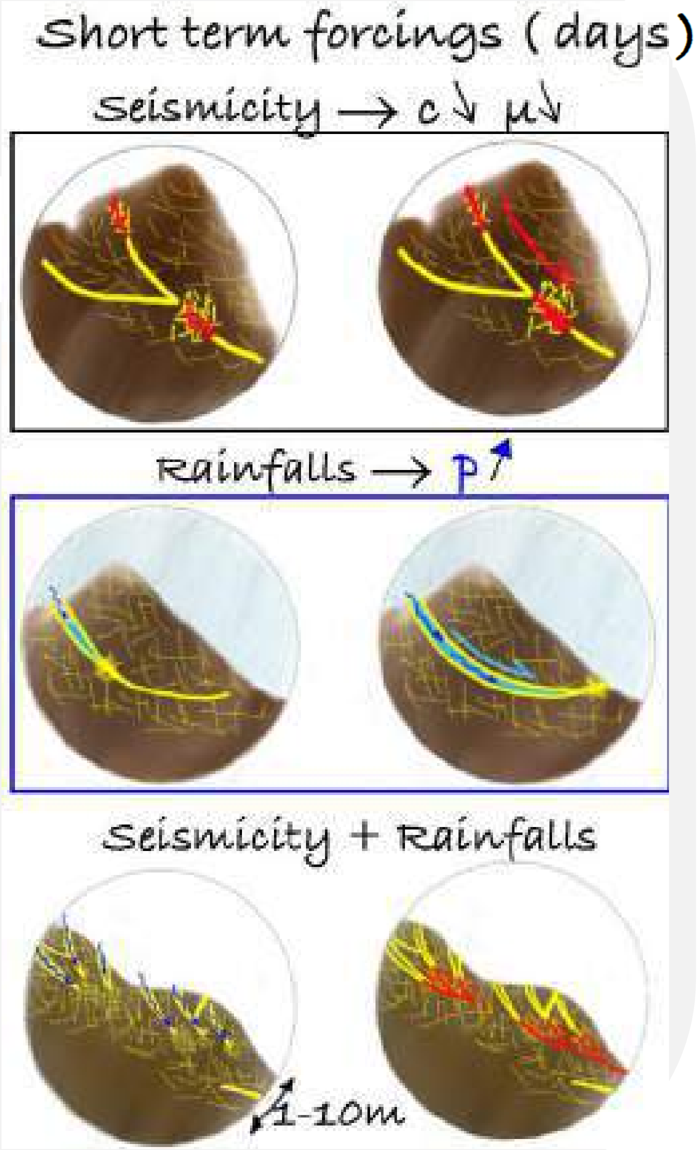
One eruption very 8 months ➡ Volcano-tectonic seismicity (VT), Heavy rain

SLIDEQUAKES



Hibert et al. 2011, 2014, 2017, Durand et al. 2018

What triggers slope instabilities ?



Yield stress

Friction coefficient

Cohesion

$$\tau = \mu\,(\sigma - p) + c$$

Fluid pore pressure

Cumulative forcings

$\tau \searrow$

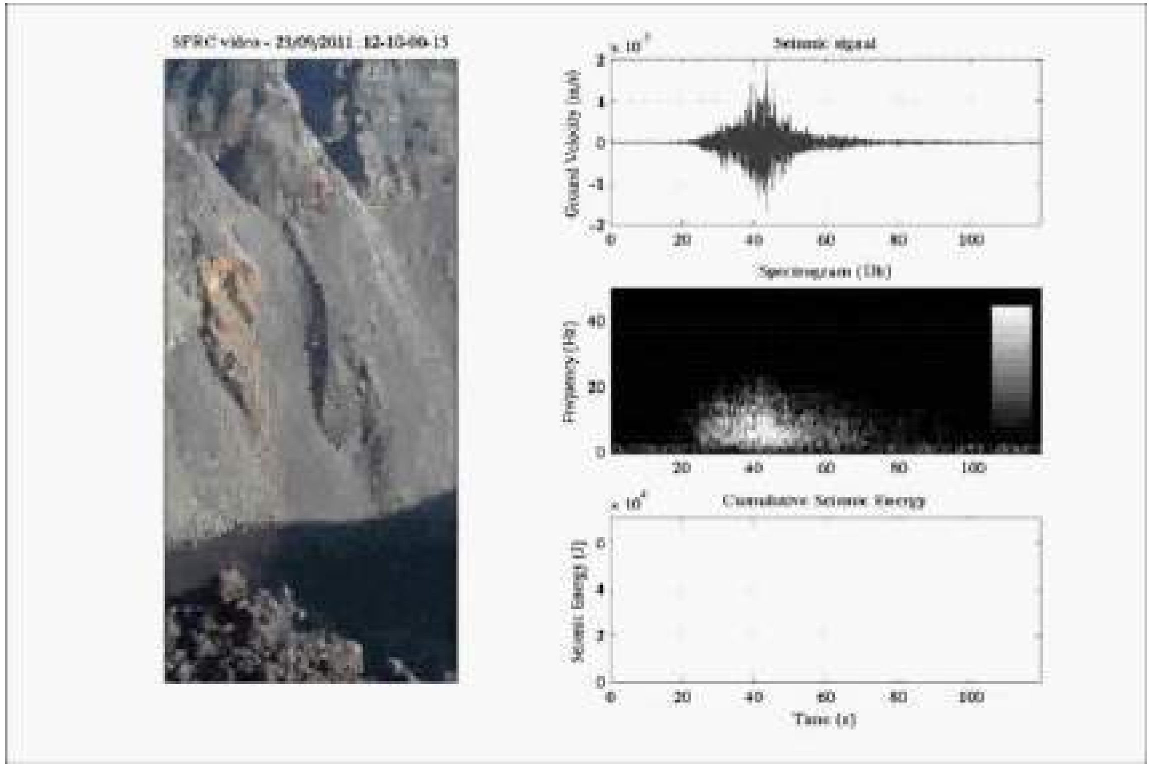
➡ **Metastable slopes**

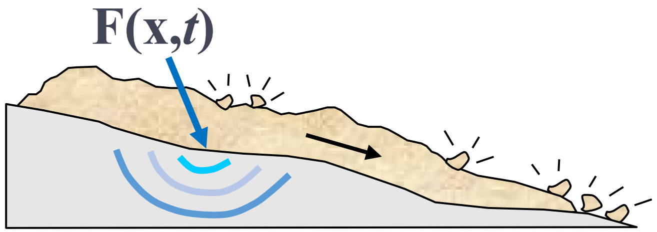
Instantaneous or delayed triggering by **Low** seismicity + Rainfalls

Tatard et al. 2010, Dietze et al. 2017, Bontemps et al. 2020, Durand et al. 2023

10-year rockfall's catalogue

Piton de la Fournaise, Dolomieu crater



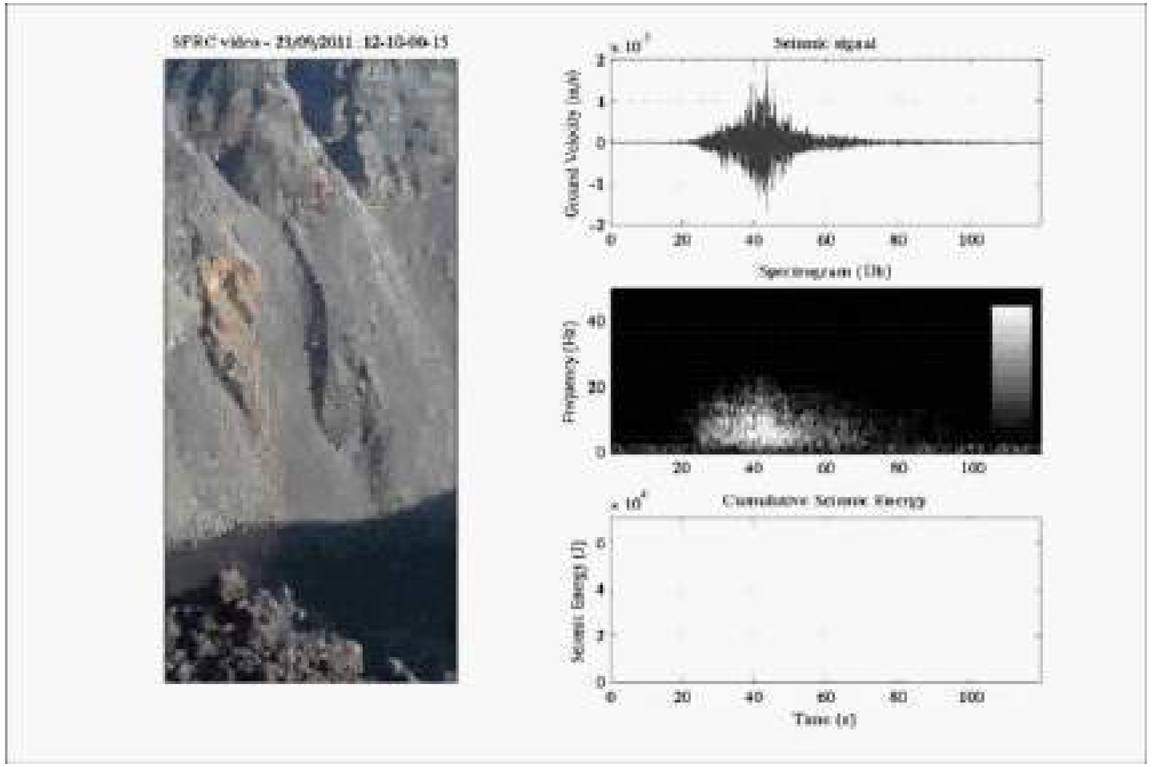


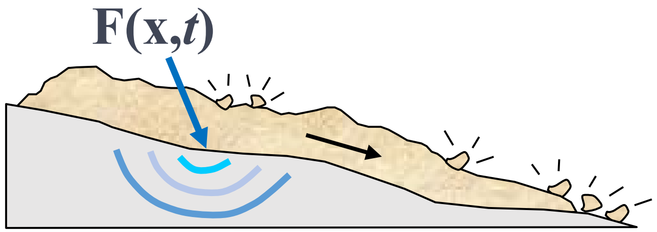
Hibert et al. 2011, 2014, 2017, Durand et al. 2018

10-year rockfall's catalogue

Seismic energy loss of potential energy

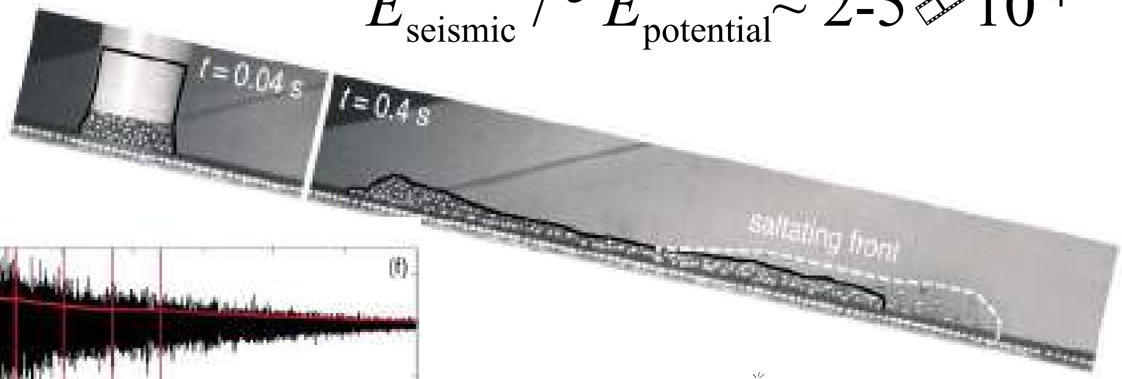
Piton de la Fournaise, Dolomieu crater

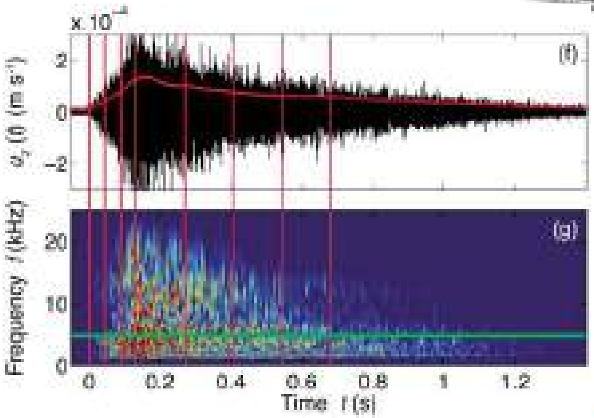




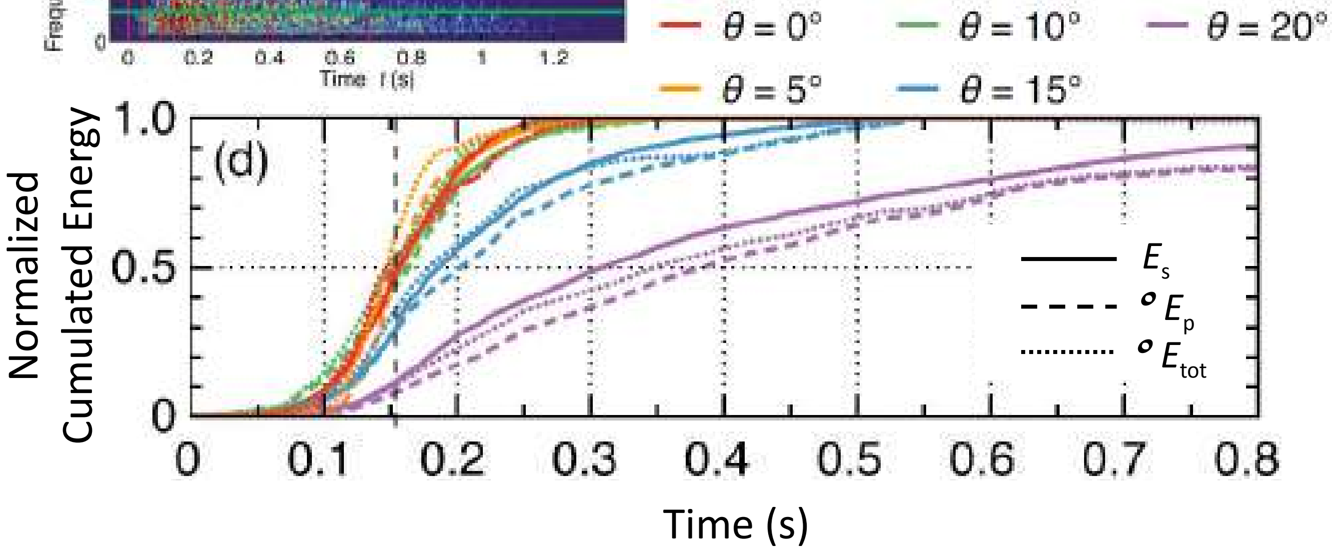
Lab-scale granular flow experiments

$E_{seismic} / ° E_{potential} \sim 2\text{-}5 \times 10^{-4}$





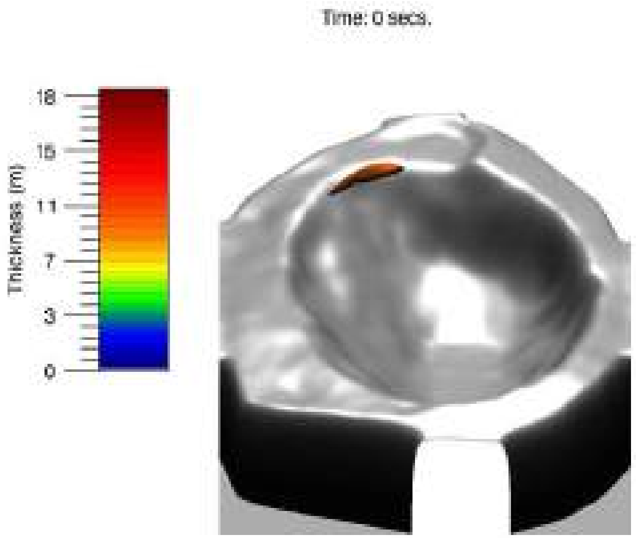
$t_{seismic}$ t_{flow}



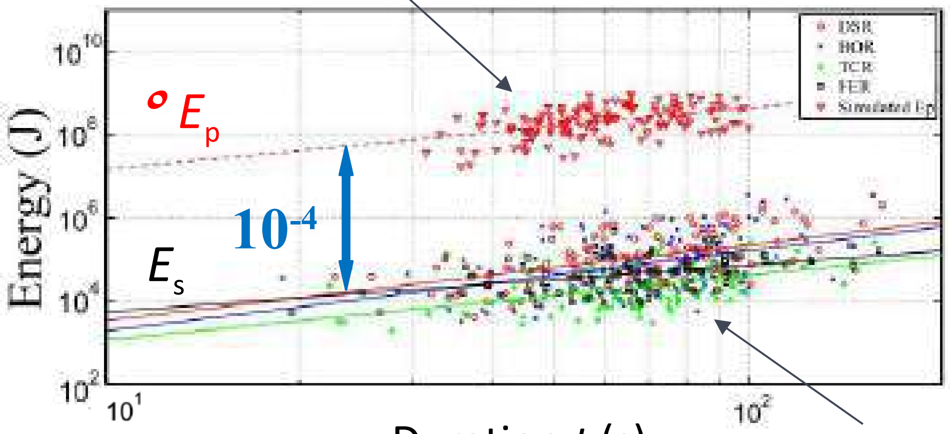
Hibert et al. 2011, 2014, 2017, Durand et al. 2018

Farin, Mangeney et al. 2018, 2019

From seismic energy to rockfall volume



Granular flow simulation



Duration t (s)

seismic data

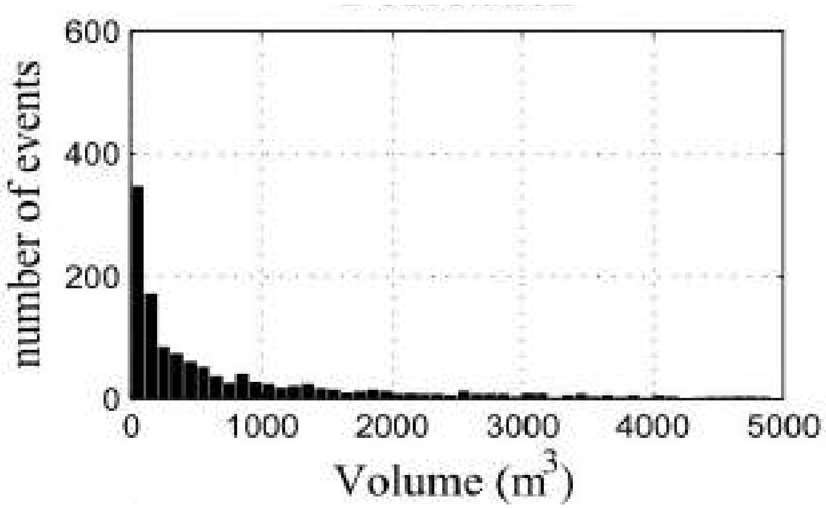
Power law:
energy - duration

$Energy \propto t^{\beta}$

$$R_{s/p} = E_{seismic} / \Delta E_{potential} \sim 10^{-3} \text{-} 10^{-4}$$

Rockfall volume

$$V = \frac{3E_s}{R_{s/p}.\rho g L(\tan\alpha\cos\theta - \sin\theta)}$$



Hibert et al. 2011, 2014, 2017, Levy et al. 2015

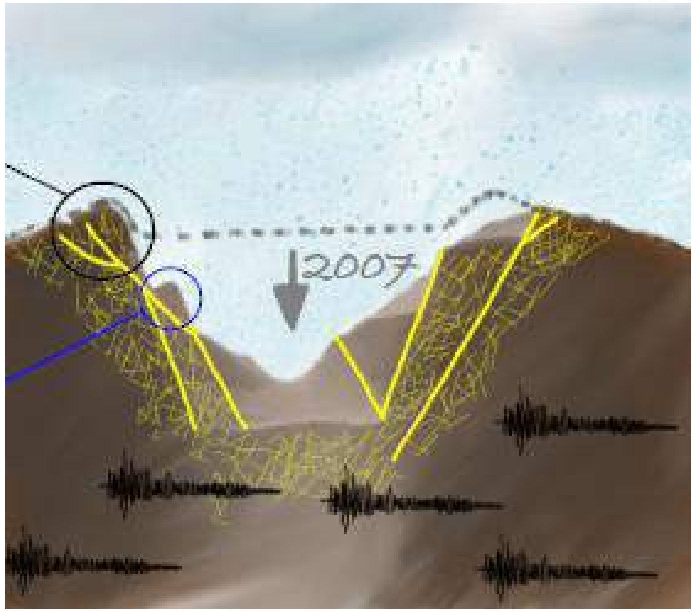
10-year rockfalls + seismicity (VT) + rainfall

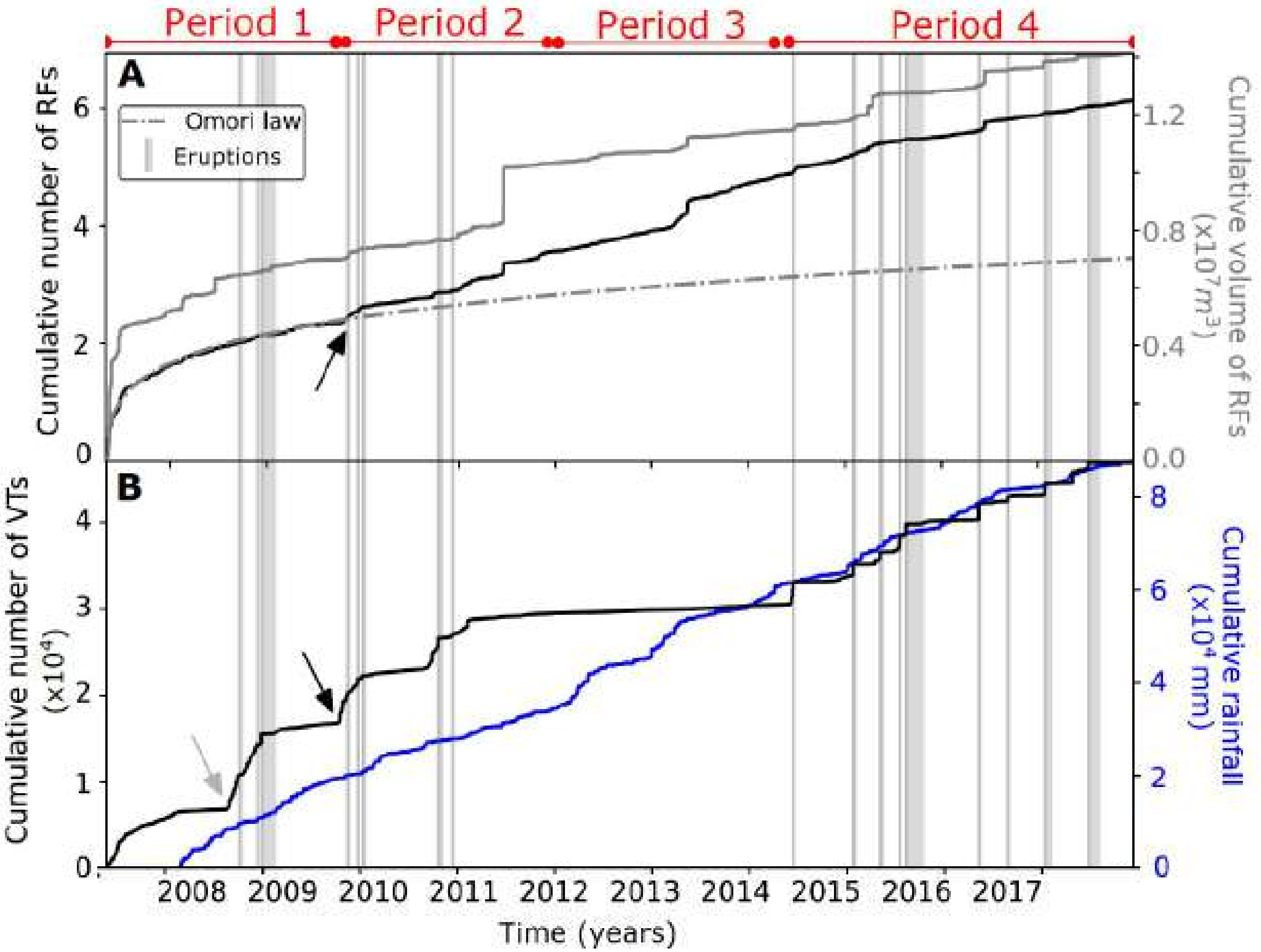
Period 1 : crater collapse (VT + rain)

Period 2 : long duration VT + rain

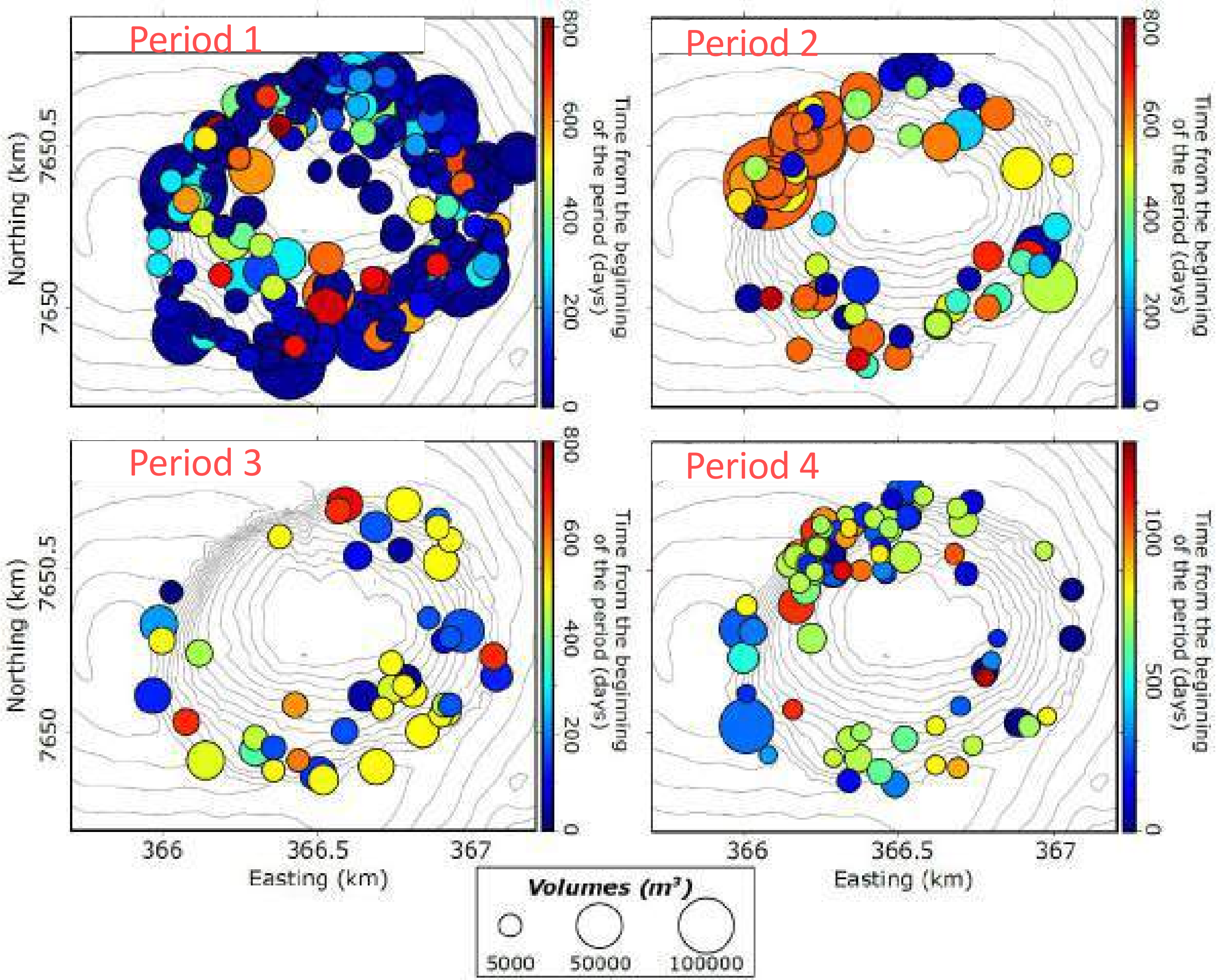
Period 3 : ~no VT + rain

Period 4 : short duration VT + rain



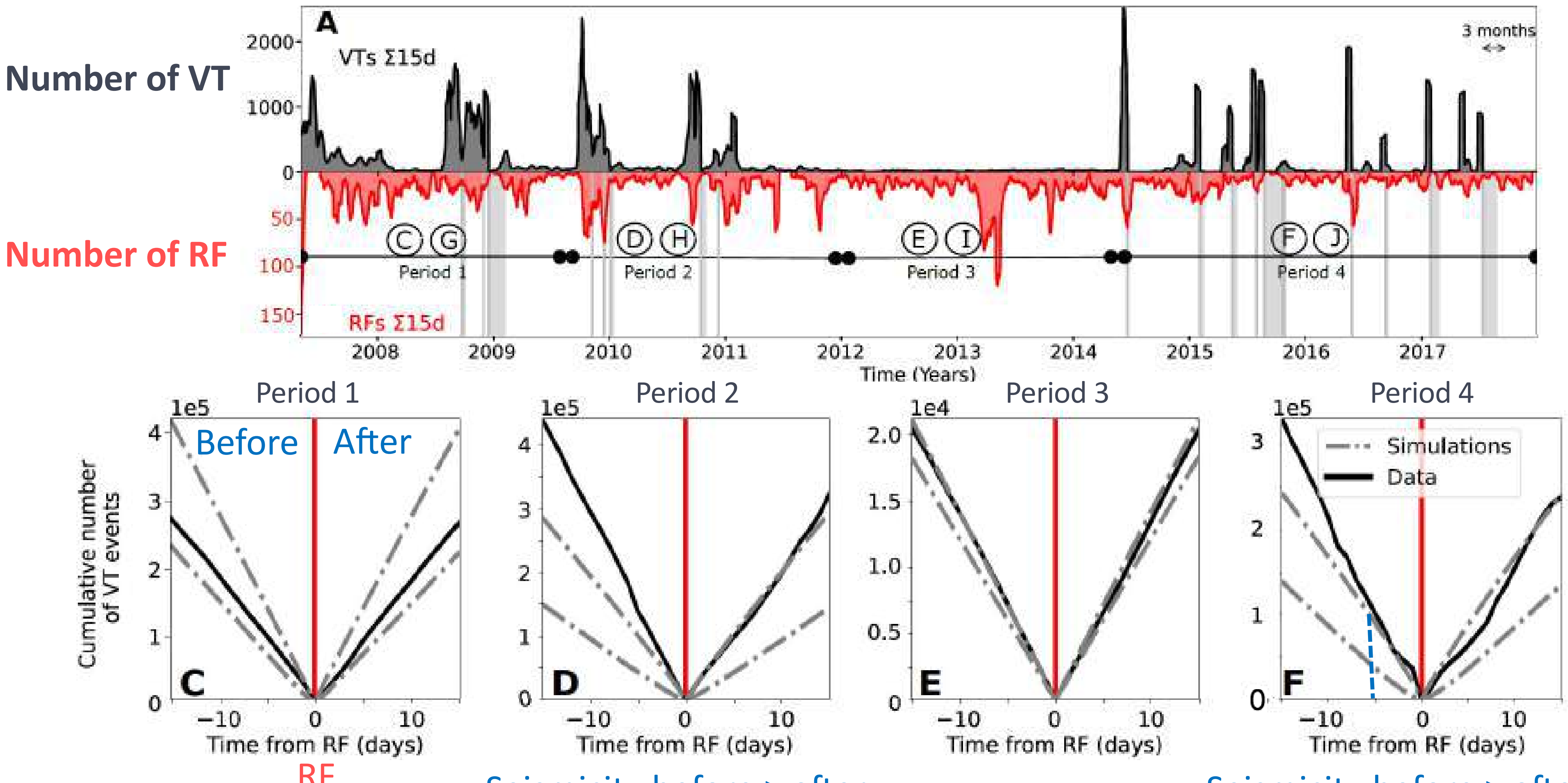


Spatio-temporal distribution of rockfalls



Low seismicity may trigger rockfalls

Tatard et al. 2010, Keefer et al. 1984



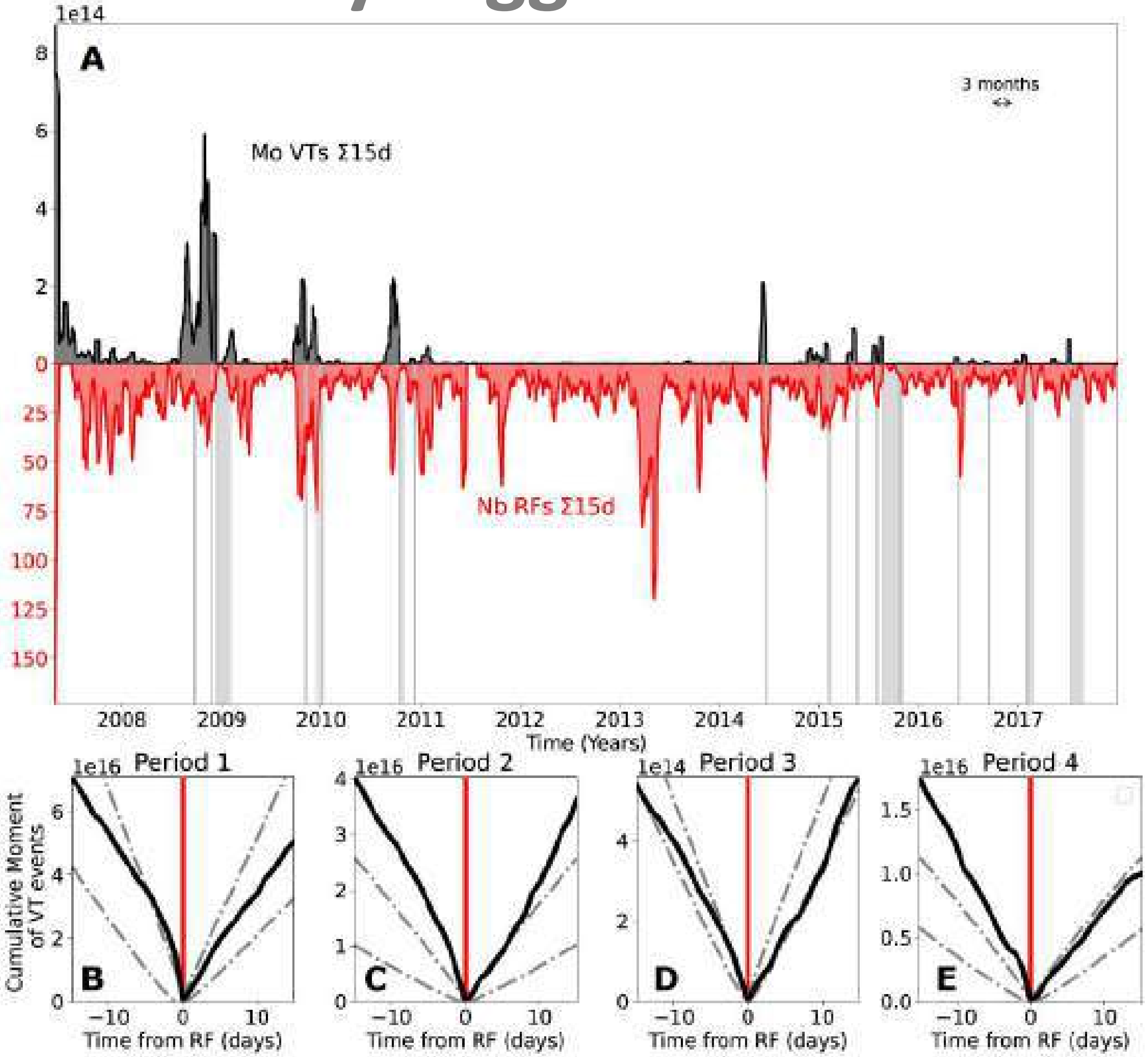
Seismicity before > after

Seismicity before > after
~ 5 days time delay

Does low seismicity trigger rockfalls ?

Moment of VT

Number of RF

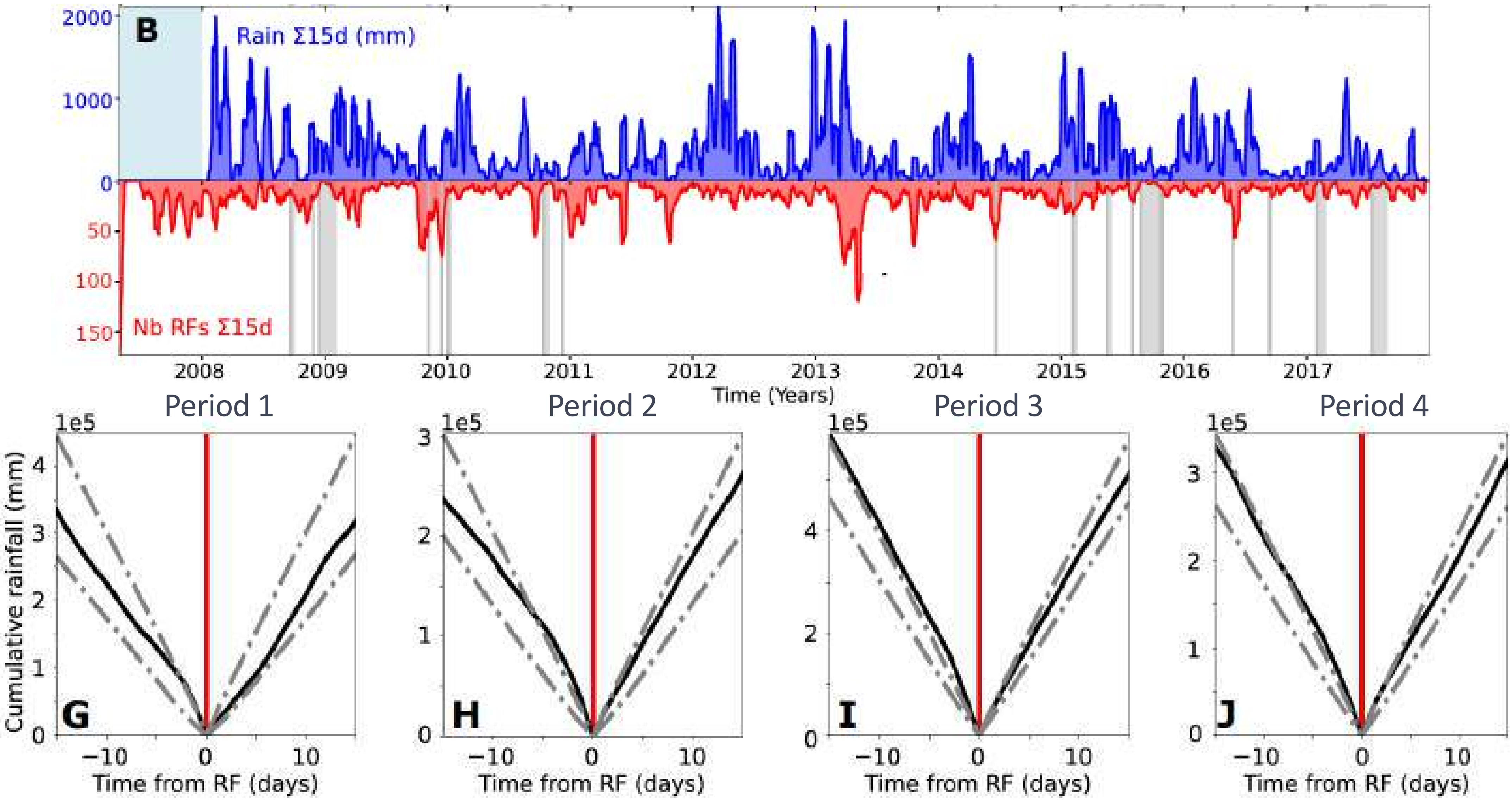


Moment dominated by strong VT events

Number dominated by small VT events

No delay for strong VT

Does rain trigger rockfalls ?

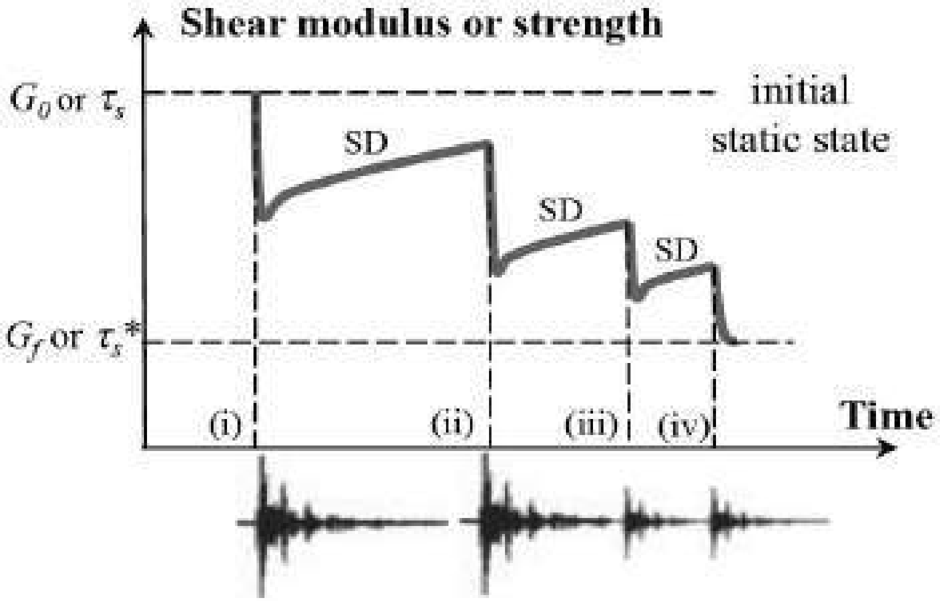


Rain before slightly > after

Seismicity induced yield weakening

Long term story of crater Dolomieu slopes

$$\tau = \mu\,(\sigma - p) + c$$



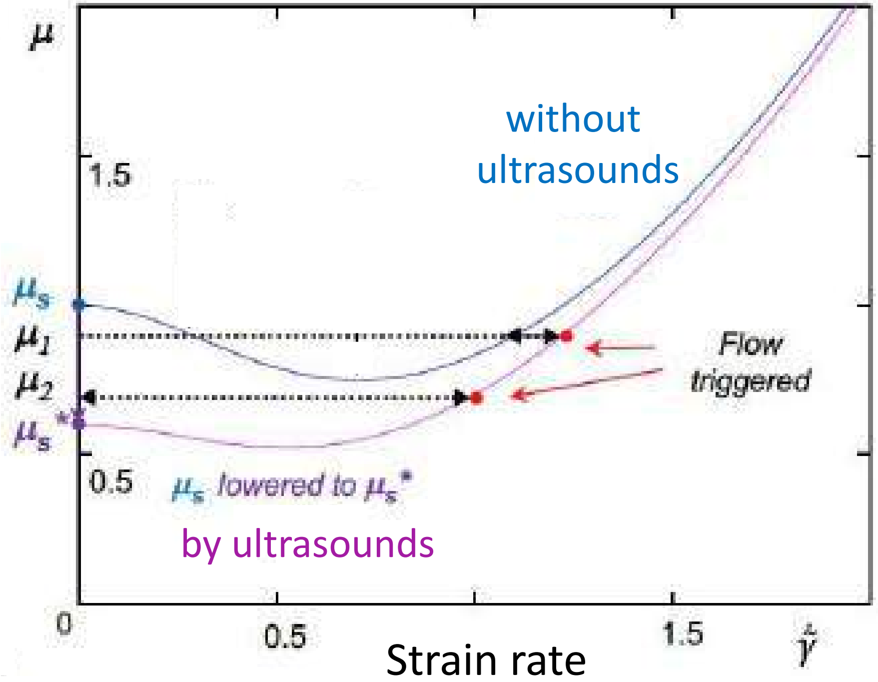
Lab-scale avalanche triggering with ultrasounds

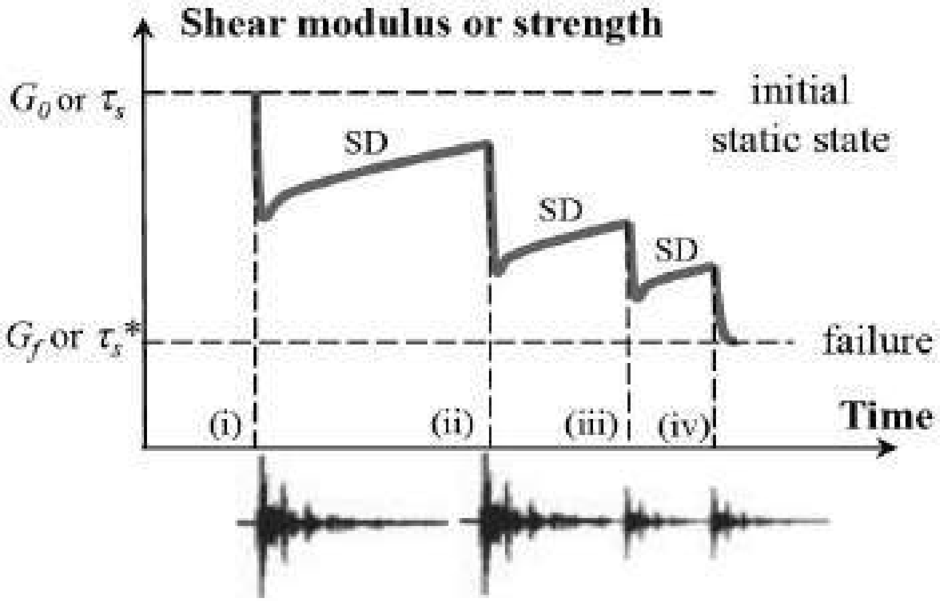
Long term story of crater Dolomieu slopes

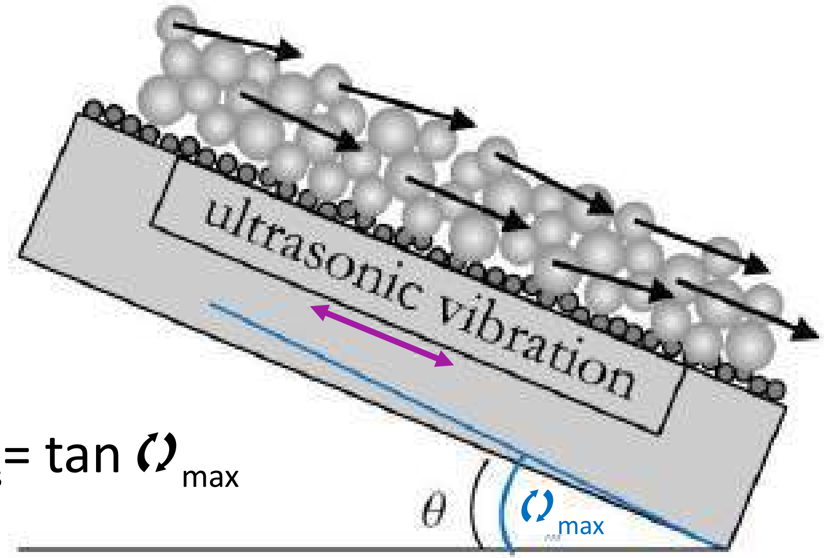
Dry granular flows experiments

$$\tau = \mu\,(\sigma - p) + c$$

$\mu = \tan\theta$ **Friction weakening**



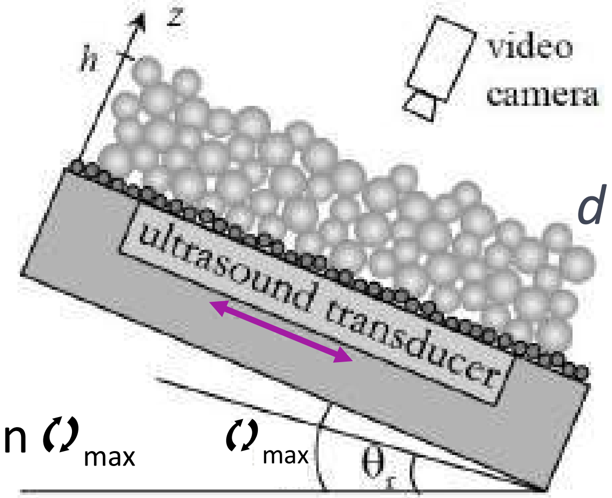




$\mu_s = \tan\theta_{max}$

Leopoldes et al., 2020

Lab-scale avalanche triggering with ultrasounds



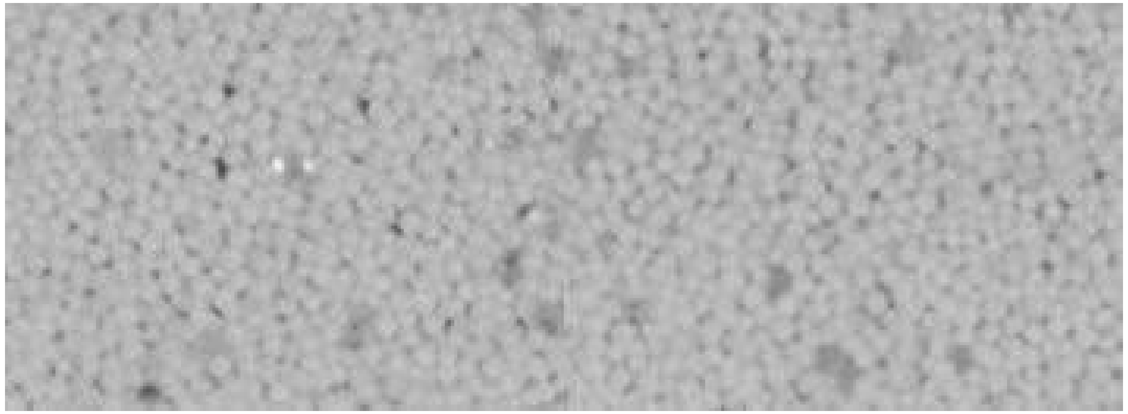
μ_s= tan θ_{max} θ_{max}

$d \approx$ 0.1mm

f_{US} = 100 kHz

U_0 ~ 10 nm

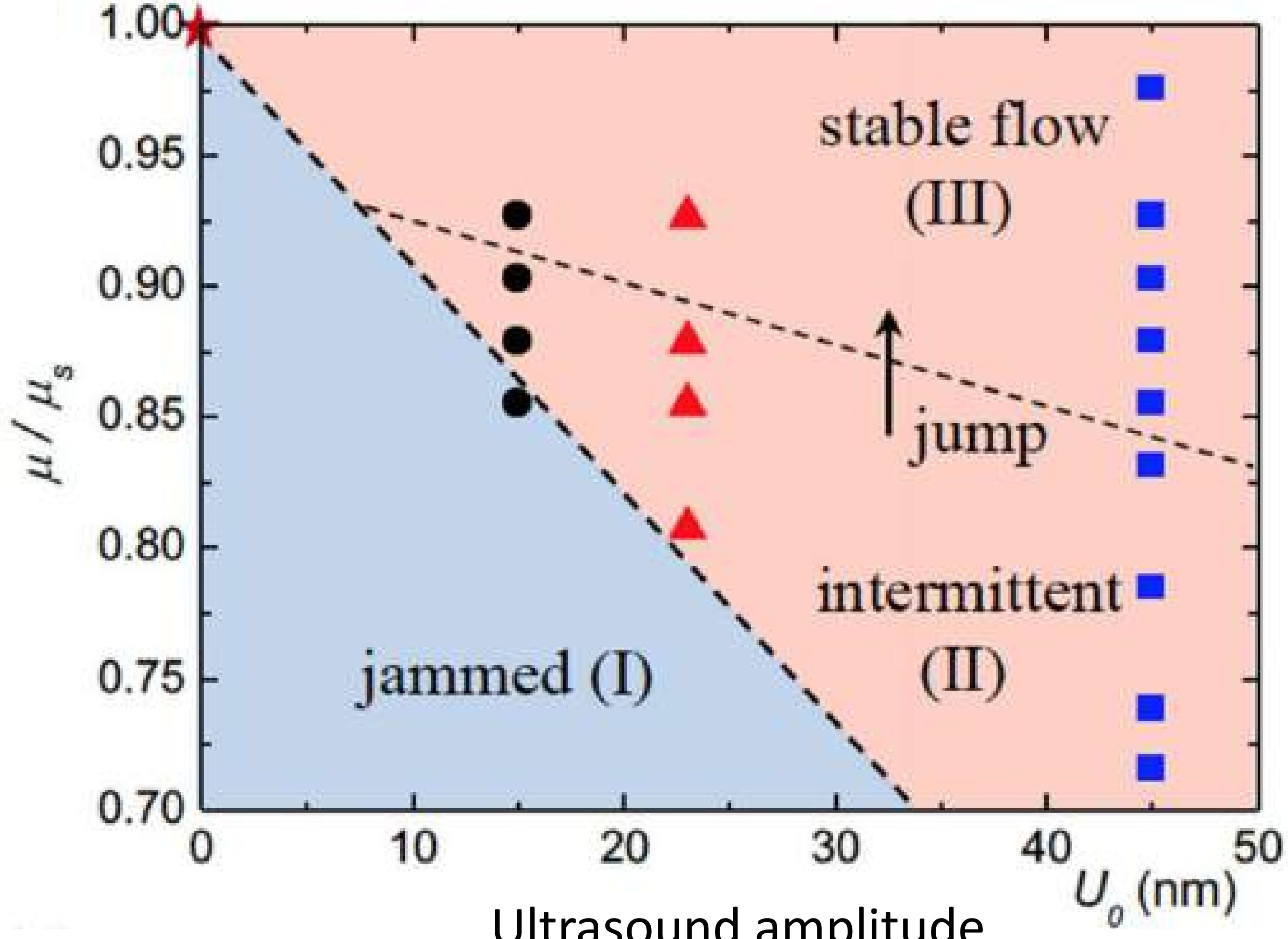
θ = 18°< θ_{max} = 20° θ = 15°< θ_{repose}



triggered inertial flow (continuous)

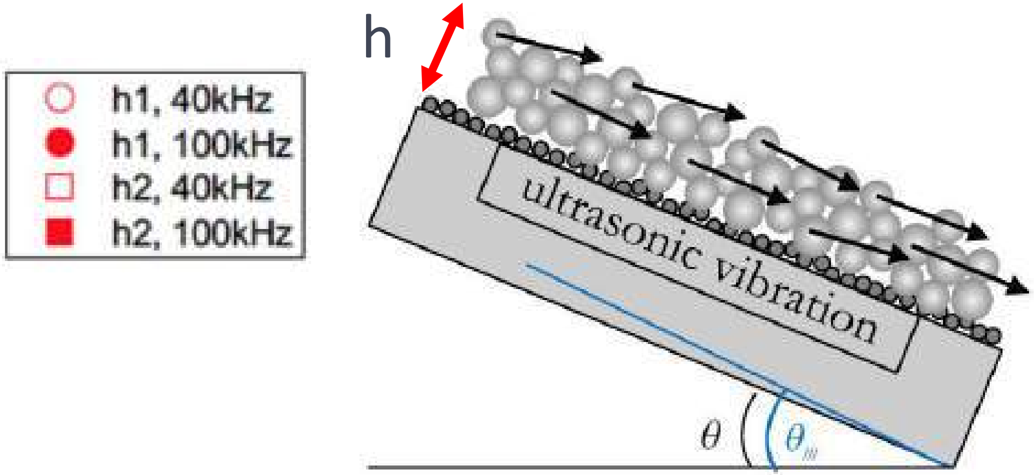
triggered slower flow (intermittent)

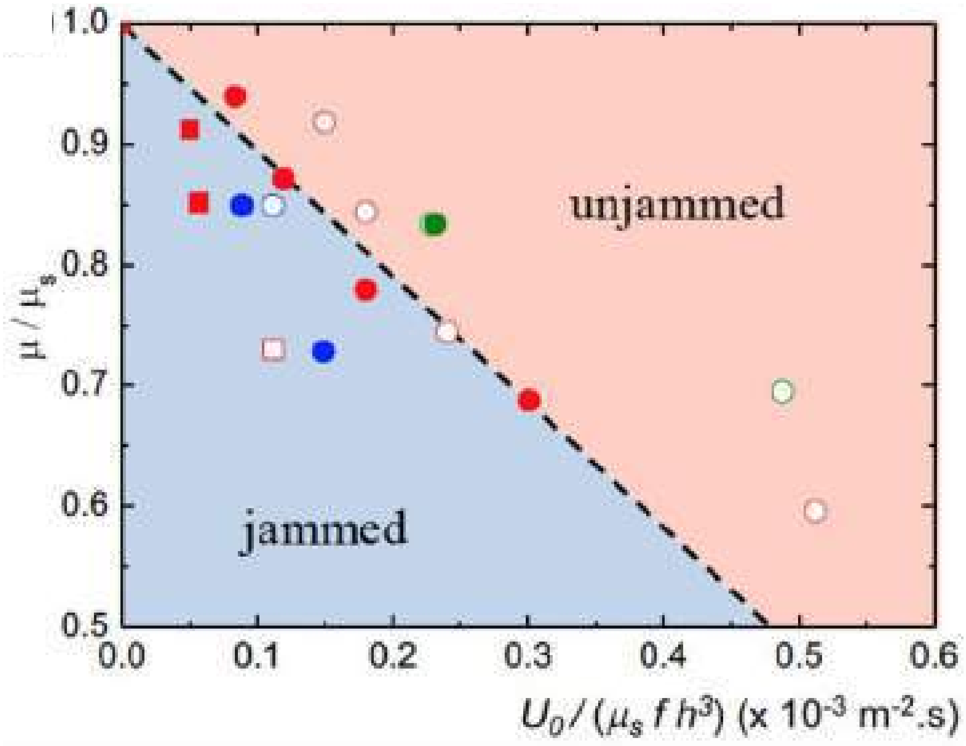
μ= tan θ



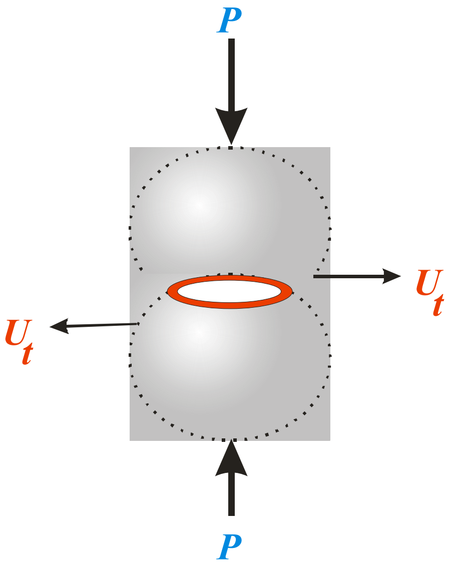
Ultrasound amplitude

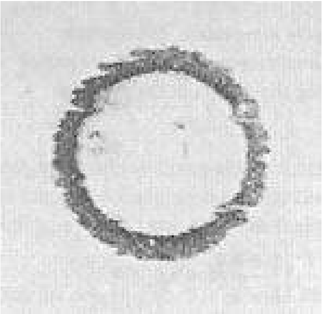
Ultrasound triggered avalanche





Acoustic lubrication of the stuck area Mindlin model





Jia et al., 2011
Leopoldes et al., 2020

Friction weakening

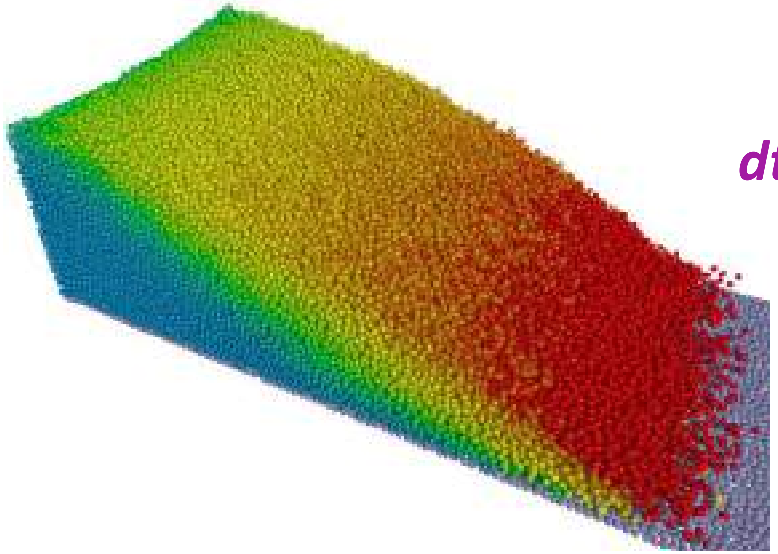
$$\mu_s^* / \mu_s \sim 1 - (c^3/g)[U_0/(\mu_s f h^3)]$$

c sound speed

Simulation of wave effects on granular motion

Decouple grain motion wave propagation

Discrete Element Method for grain motion



dt_{grains} ms

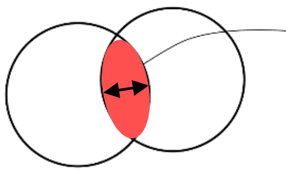
Very different time scales !

Wave propagation on force chains

on the graph of contacts

Hertz's contact law

dt_{waves} µs



normal stiffness

$$\mathbf{f}_{i,j} \cdot \mathbf{n}_{i,j} = \kappa \; \delta_{i,j}{}^{\frac{3}{2}}$$

Friction weakening

$$\mu_s^*/\mu_s \sim 1 - (c^3/g)[U_0/(\mu_s f h^3)]$$

wave frequency (~70 kHz)

wave amplitude (~nm)

Martin et al. 2023

Discrete Element Method

Grain motion time scale

Contact Dynamics

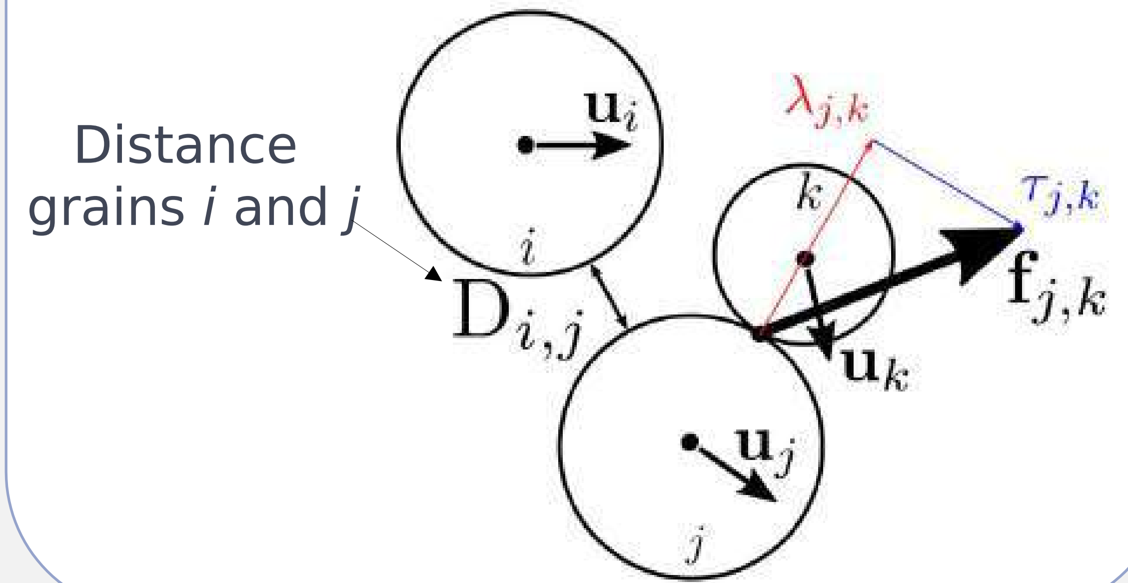
$$m_i \frac{\mathrm{d}\,\mathbf{u}_i}{\mathrm{d}\,t} = m_i\,\mathbf{g} + \sum_{j=i}^{N} \mathbf{f}_{i,j}$$

← contact forces

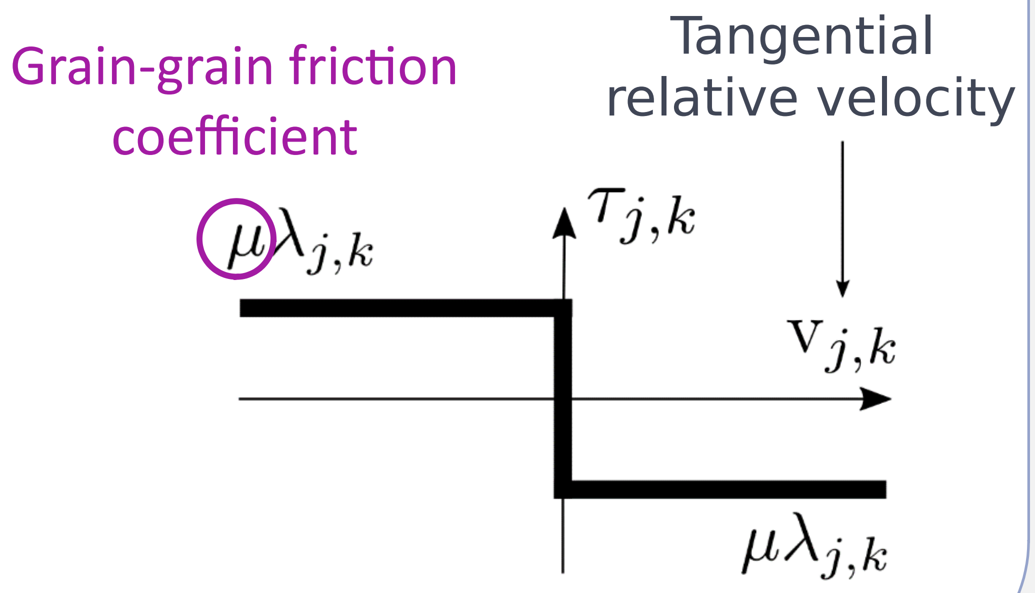
Constrained optimization problem ➡ Contact forces verify contact laws

Signorini law : no overlap between grains

$$\mathrm{D}_{i,j} \geq 0$$

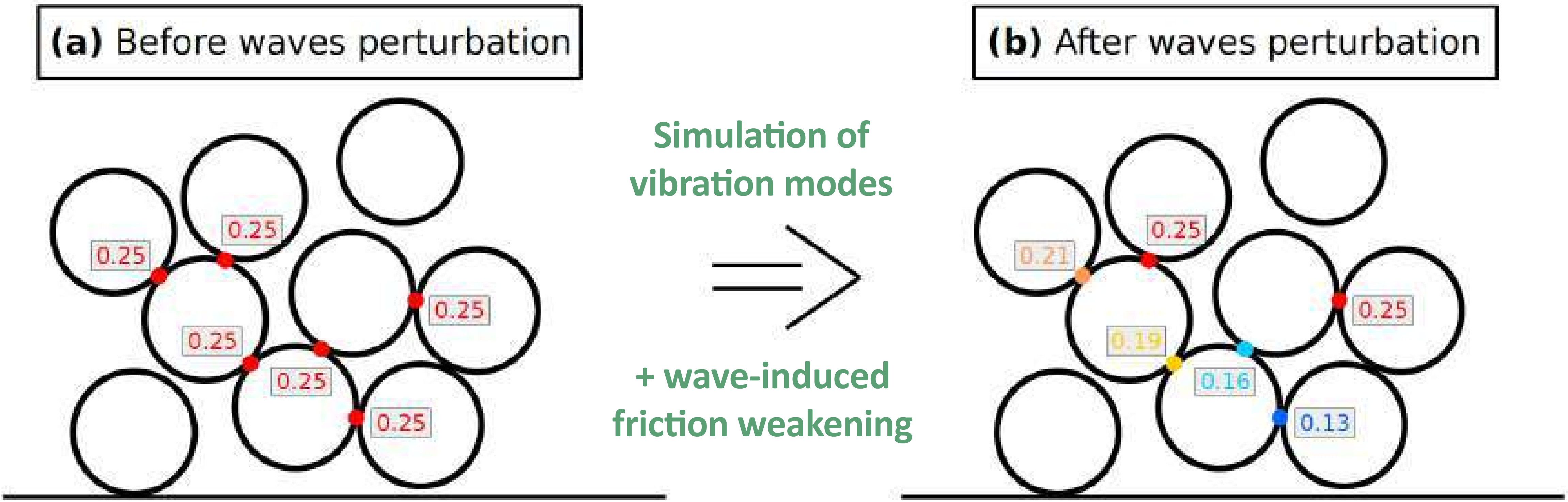


Coulomb friction law



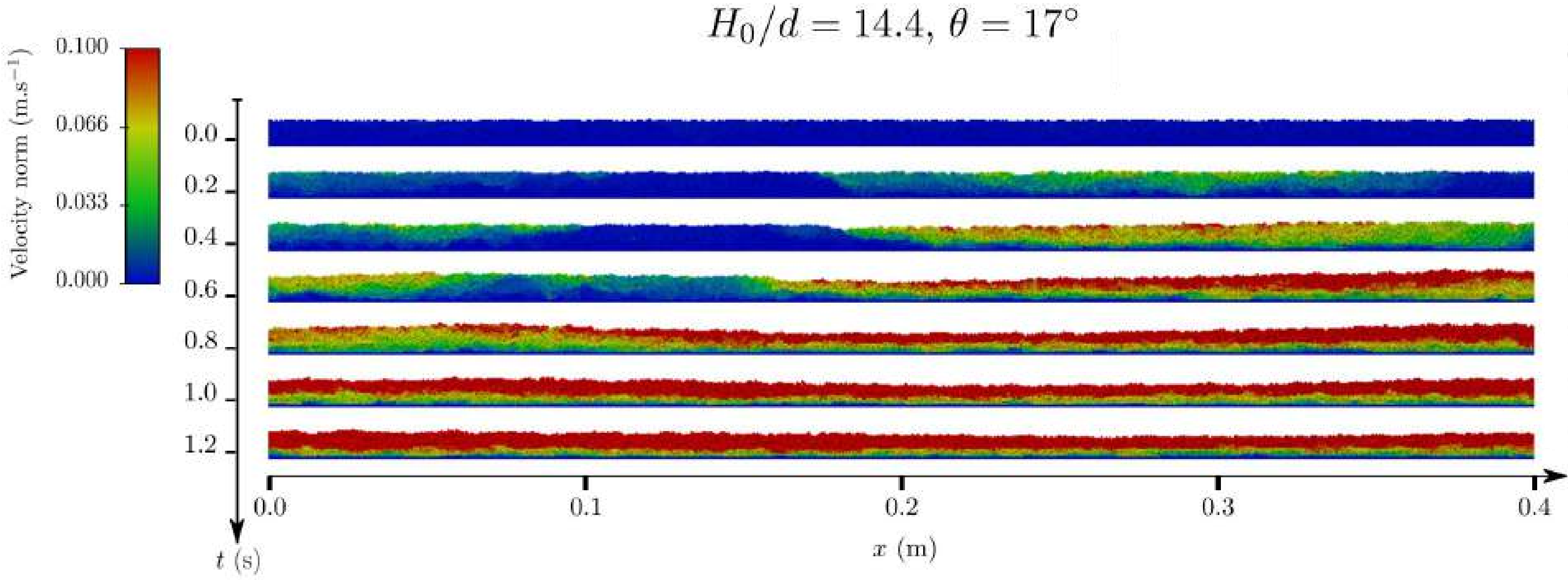
Wave induced weakening of grain-grain friction

Schematic view



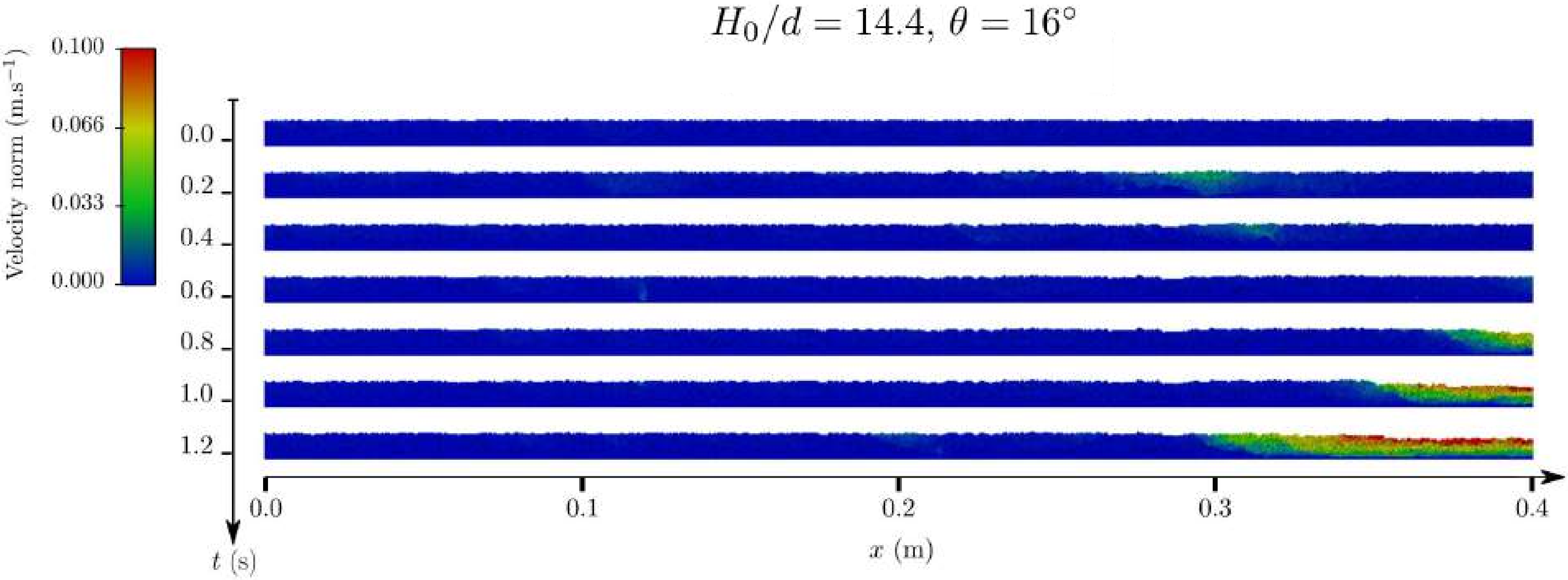
➡ Friction coefficient μ decreases down to ~0

Granular avalanche without waves



After a time delay, fully developped granular flow

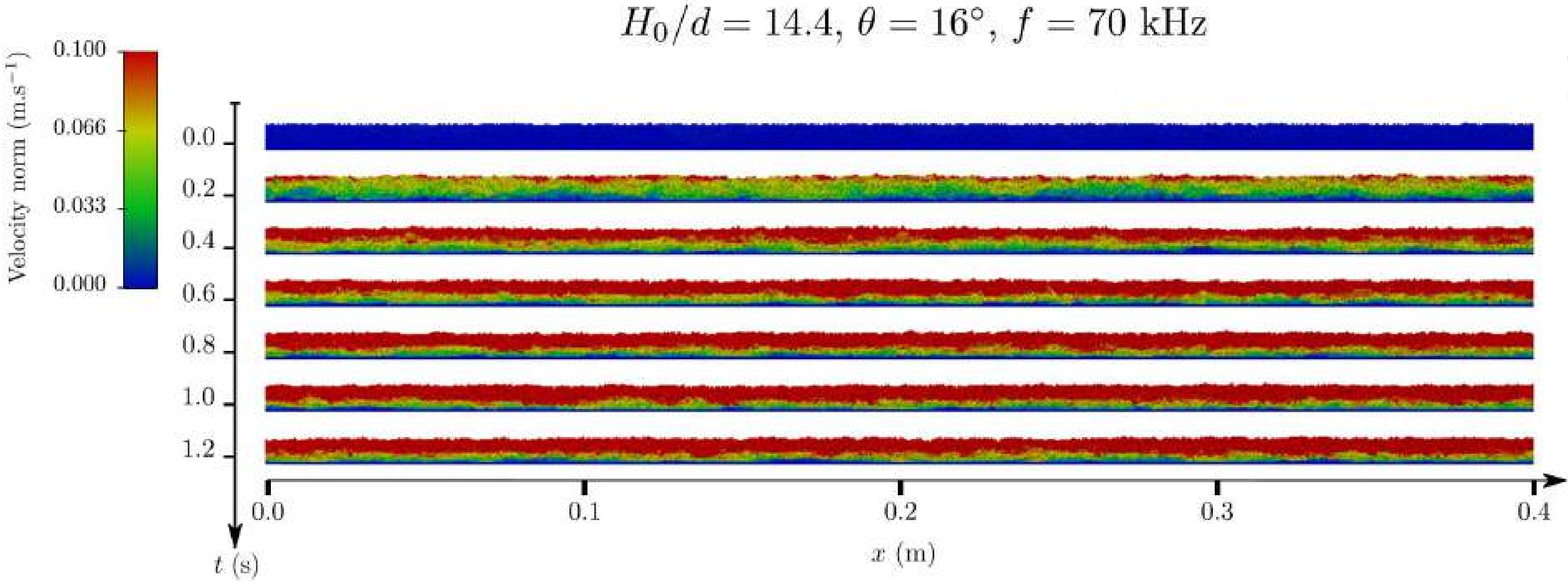
Granular avalanche without waves



Granular flow generated at the right boundary condition

Martin et al. 2023

Avalanche triggering with waves



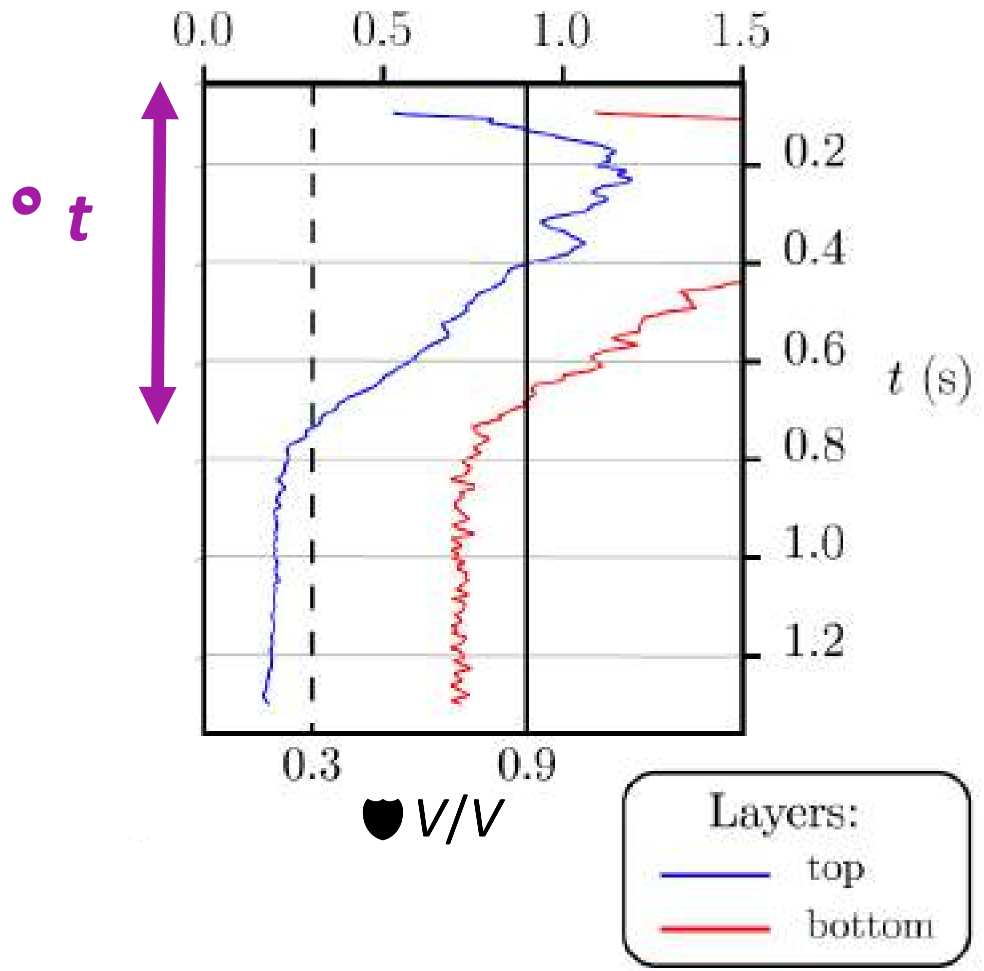
Very shortly, fully developped granular flow even at θ = 16°

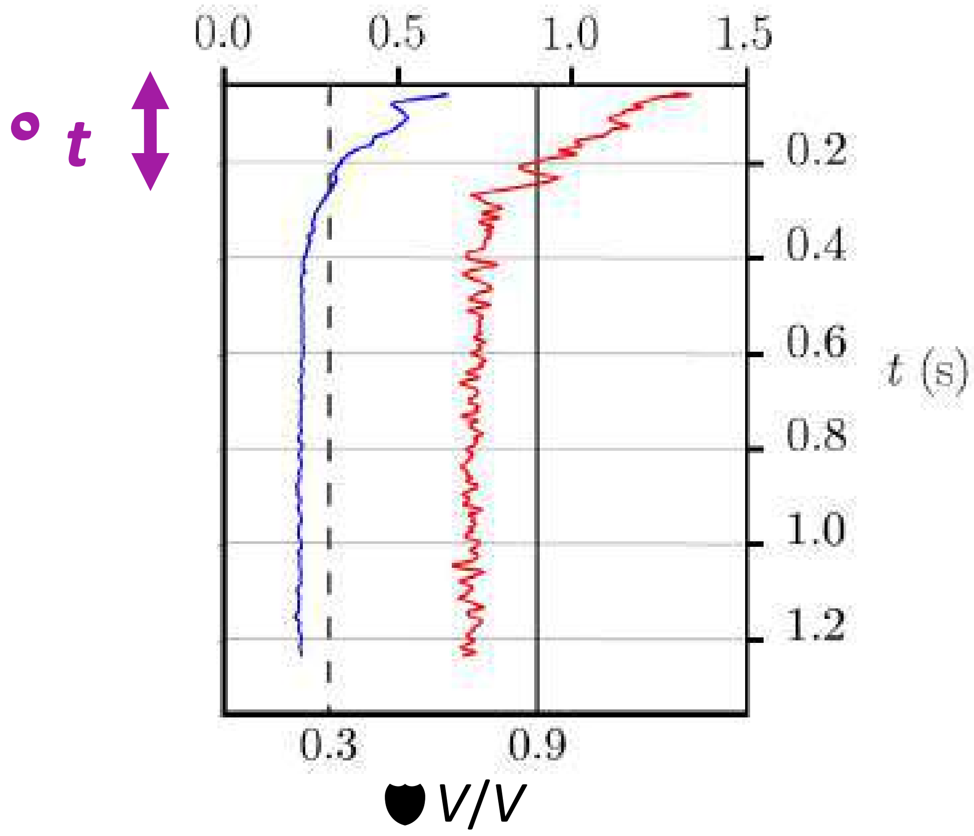
Wave-induced change in avalanche ‘nucleation’ time

No waves $H_0/d = 14.4,\ \theta = 17°$

Waves $H_0/d = 14.4,\ \theta = 16°,\ f = 70\ \text{kHz}$

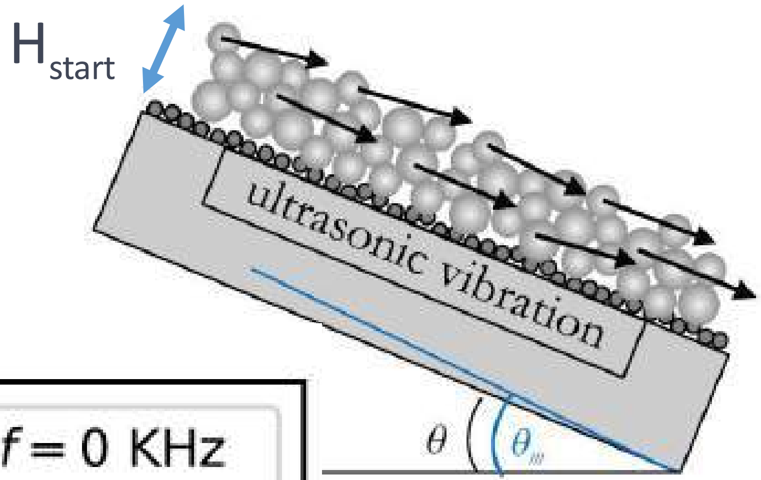
Normalized velocity fluctuations

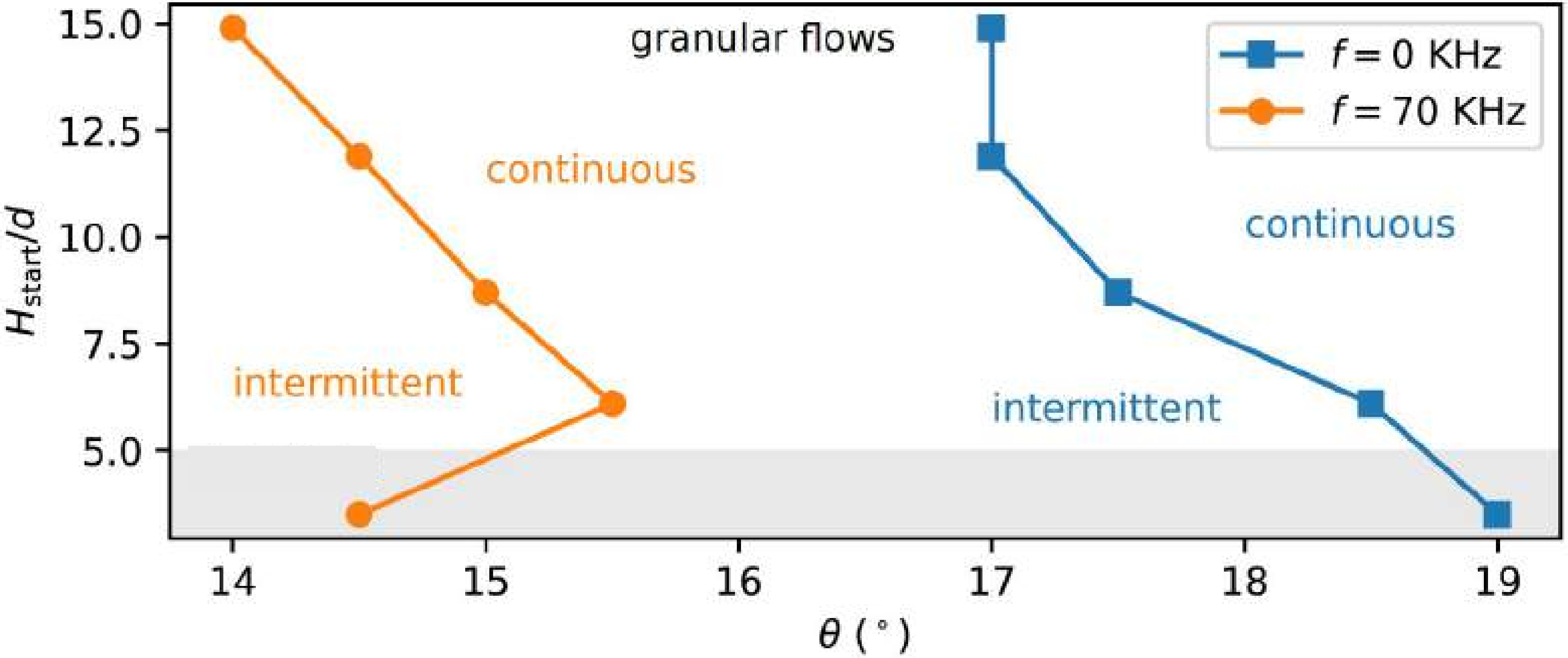




Waves reduce ‘nucleation’ time

Wave impact on avalanche triggering





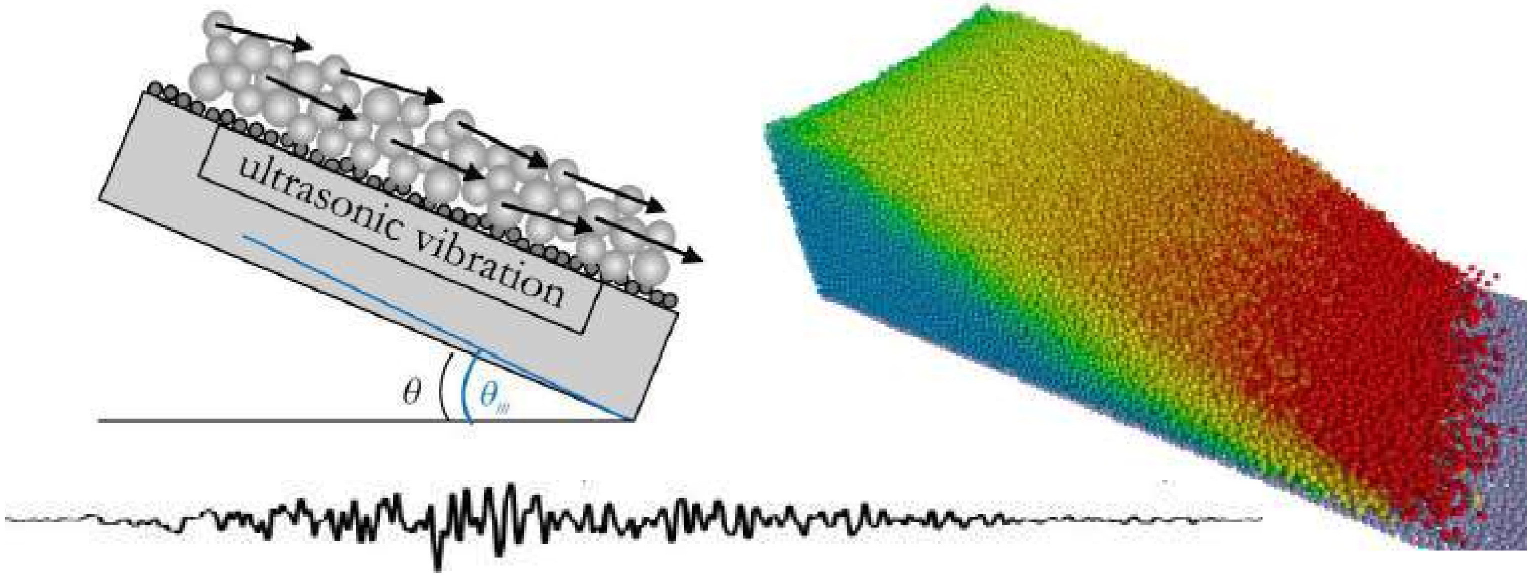
Small amplitude high frequency waves ➡ **Avalanche triggering at angles 2-3° lower !**

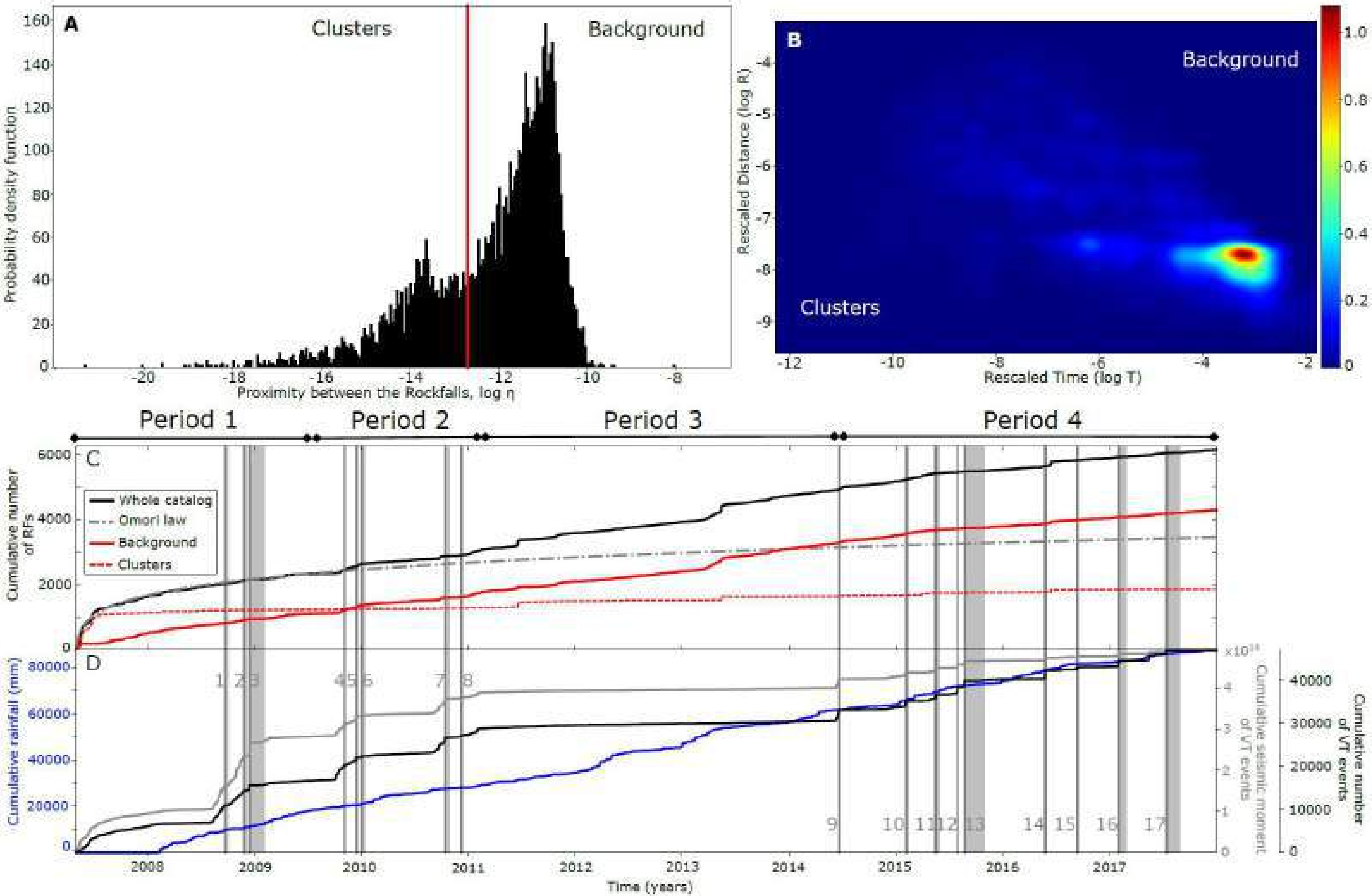
Wave impact on avalanche triggering

- **Low amplitude high frequency** waves may trigger slope instabilities
- Rockfall response to low seismicity and time delay depend on the stability state of the slope
- Quantification of physical processes requires field data, lab experiments and simulations

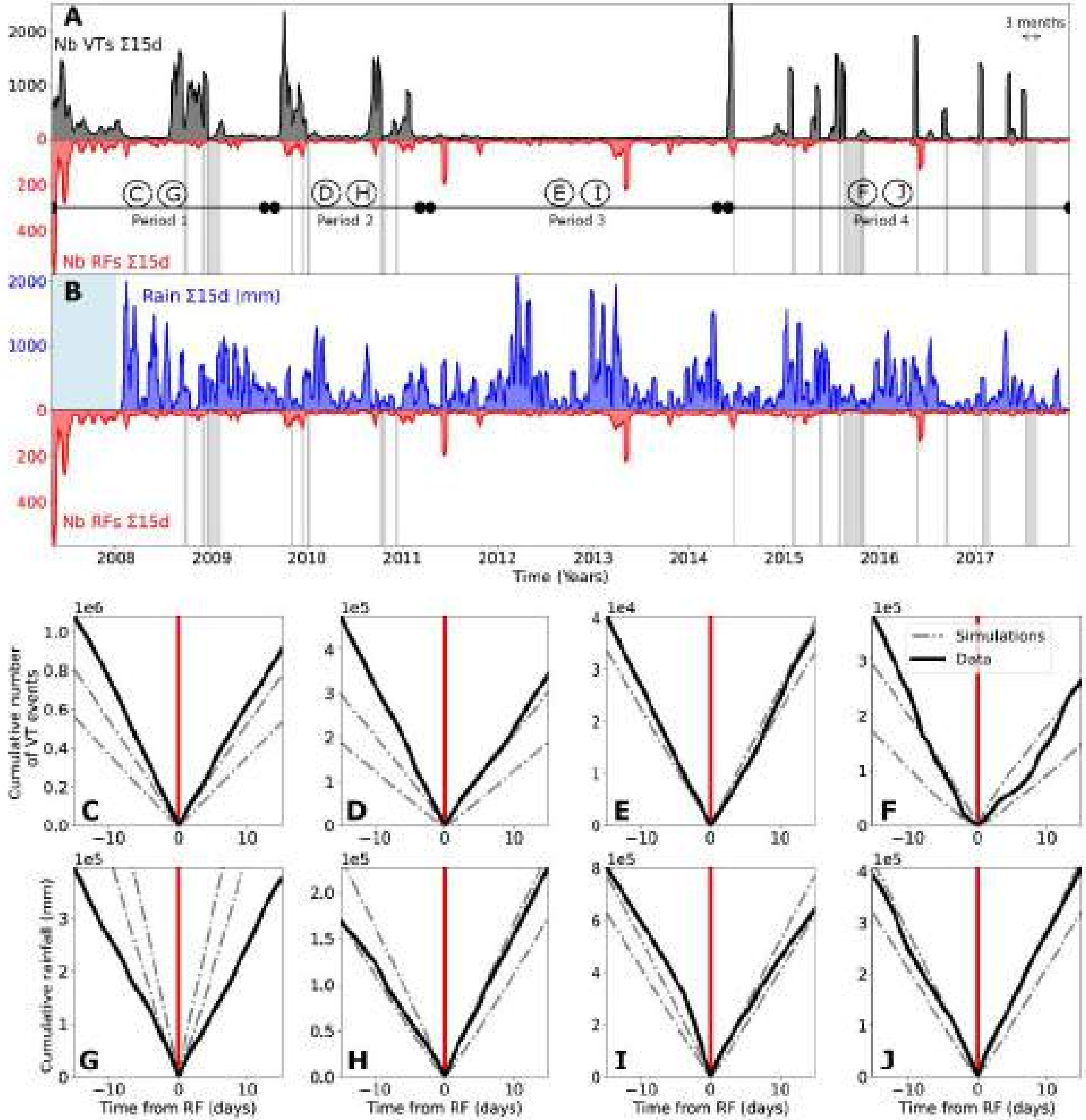
SLIDEQUAKES

➡ Need to **account for long-term swarm-type seismic activity for hazard assessment**



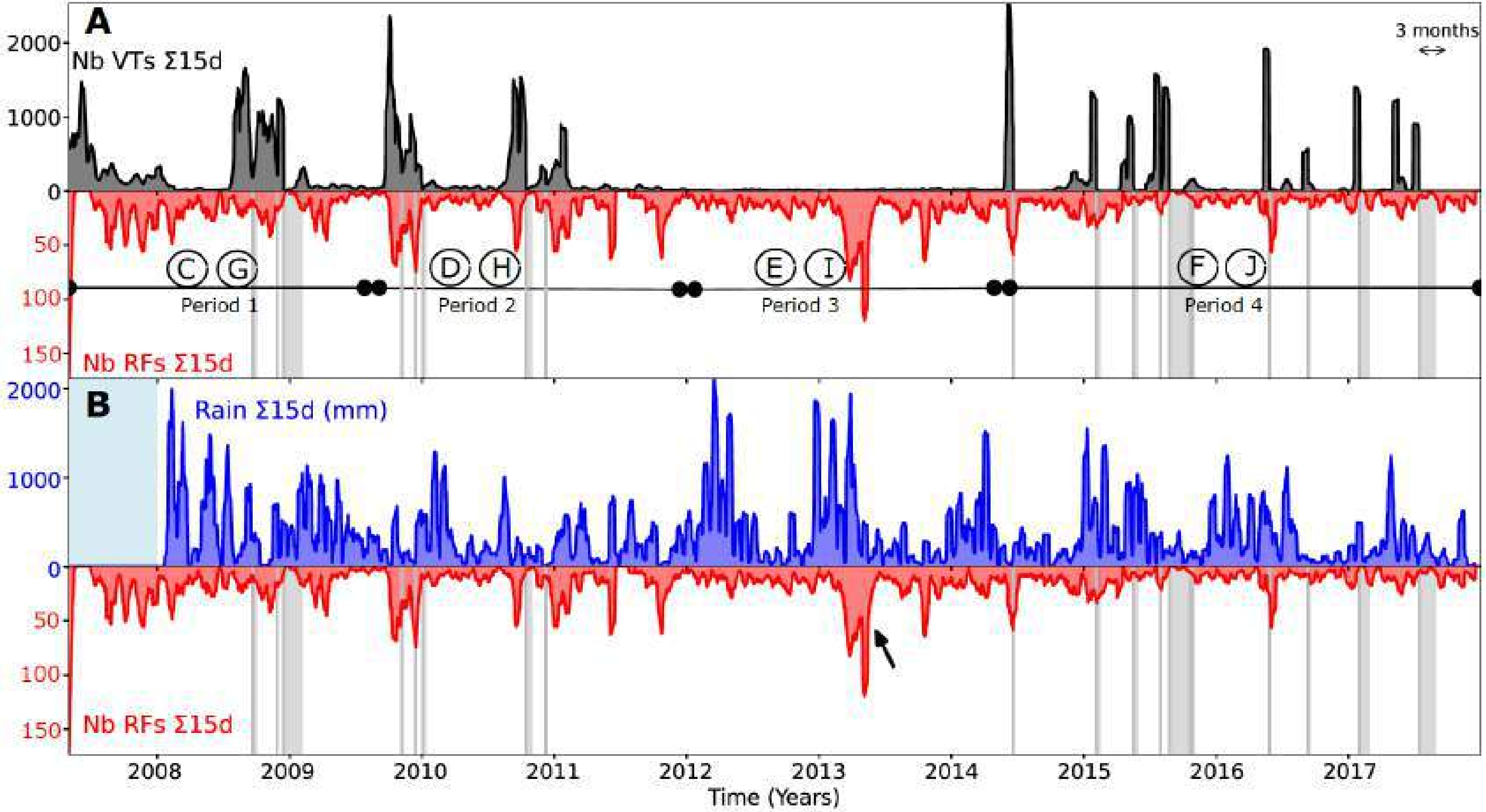


A
Clusters
Background
Probability density function
Proximity between the Rockfalls, log η
B
Background
Clusters
Rescaled Distance (log R)
Rescaled Time (log T)
Period 1
Period 2
Period 3
Period 4
C
Cumulative number of RFs
Whole catalog
Omori law
Background
Clusters
D
Cumulative rainfall (mm)
Cumulative seismic moment of VT events
Cumulative number of VT events
1 2 3
4 5 6
7 8
9
10
11
12
13
14
15
16
17
Time (years)

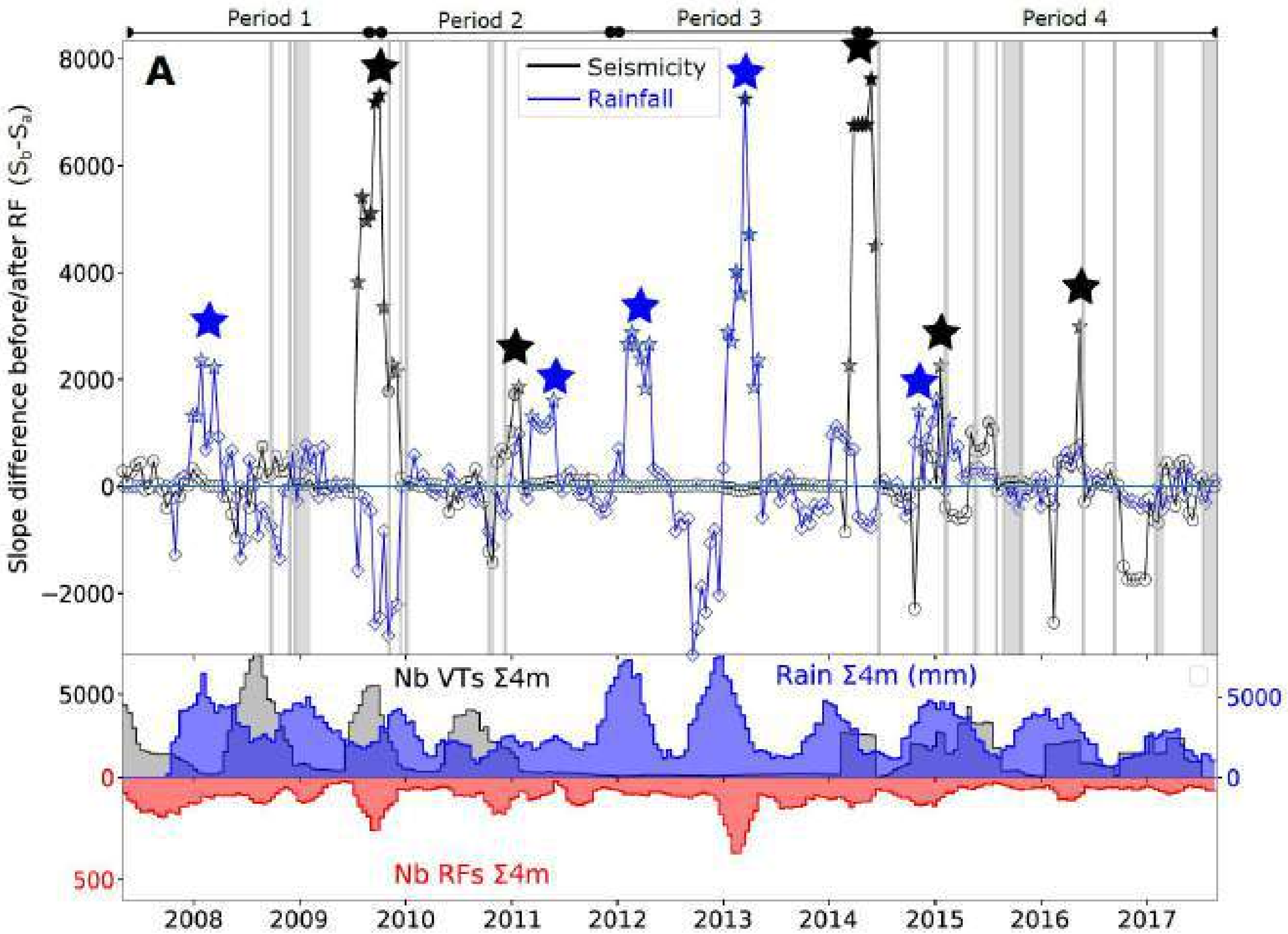


Whole catalogue

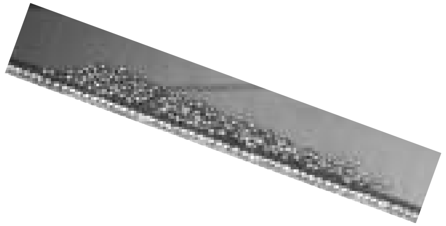
Do low seismicity rainfall trigger rockfalls ?



Do low seismicity rainfall trigger rockfalls ?



Laboratory/field for impacts/flows

	Single impacts: Laboratory	Single impacts: Field	Granular flows: Laboratory	Granular flows: Field
				
	Farin et al., 2014	*Farin et al., 2014*		
Characteristic Frequency	~ 100 kHz	~ 100 Hz	~ 5 - 20 kHz	~ 5 - 20 Hz
Seismic efficiency $W_{el} / \Delta E_p$	~ 0.2	10^{-3} - 10^{-2}	2.10^{-3} - 2.10^{-2}	10^{-5} - 10^{-3}

Laboratory to field (single impacts): frequency / 1000; seismic efficiency / 20 - 200

Laboratory to field (granular flows): frequency / 1000; seismic efficiency / 20 - 200

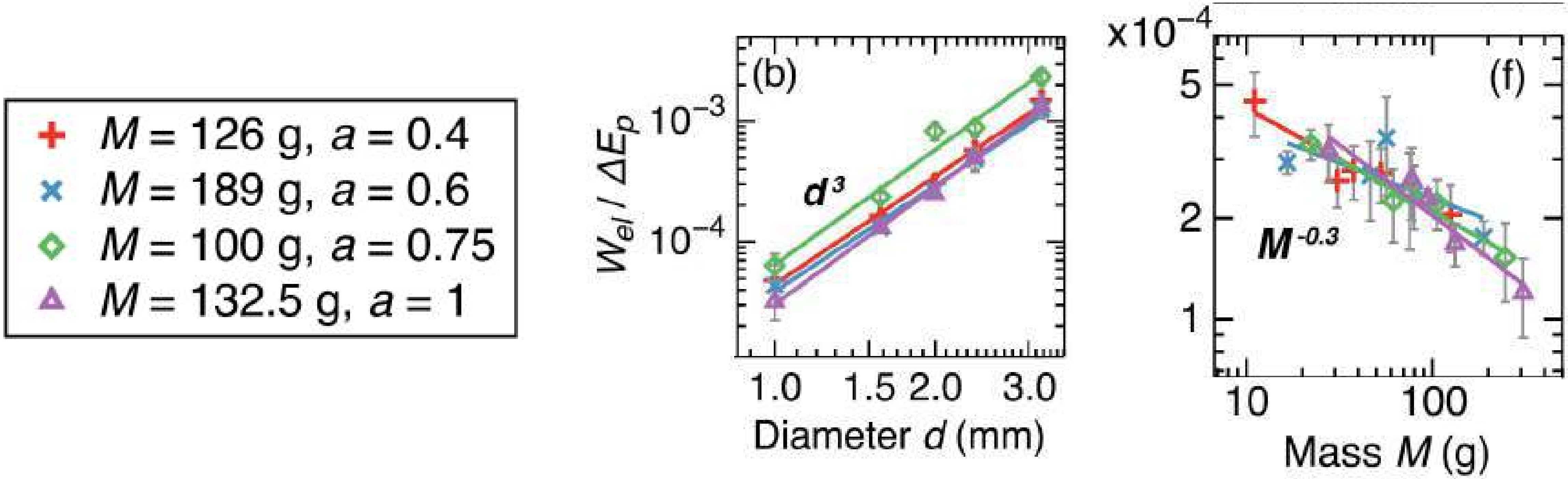
Single impacts to granular flows (laboratory): frequency / 5 - 20; seismic efficiency / 10-100

deduced values

in agreement with field studies

Hibert et al., 2011, 2014, Levy et al., 2015

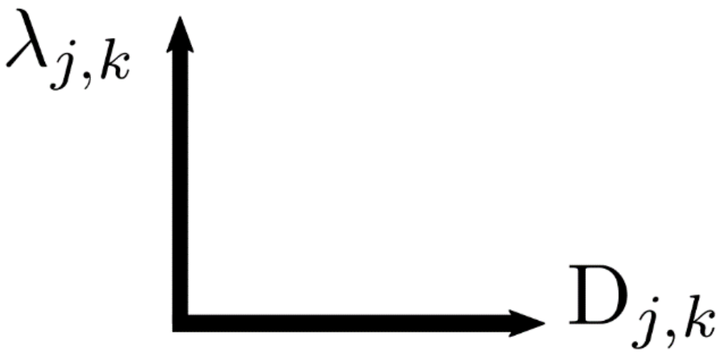
Granular collapse on inclined plates

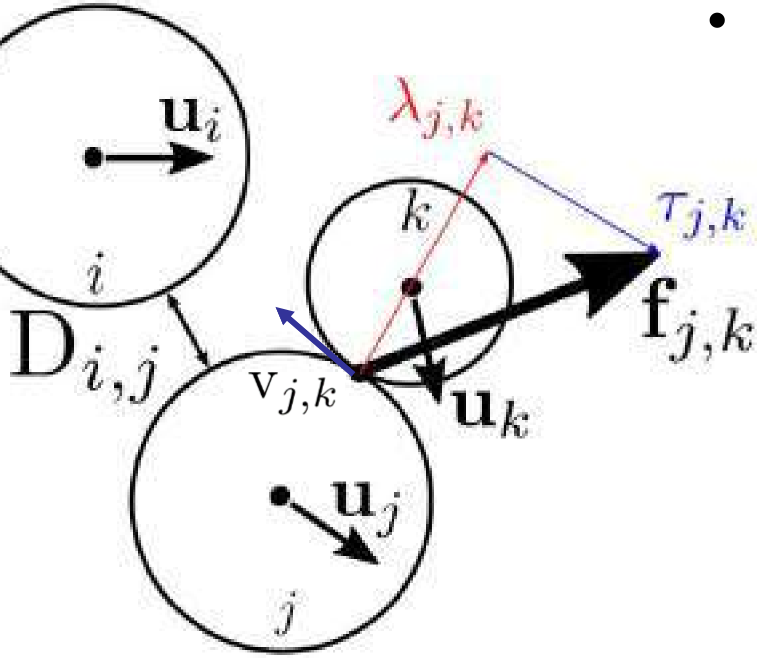


Signorini & Coulomb's contact laws

For each particle:

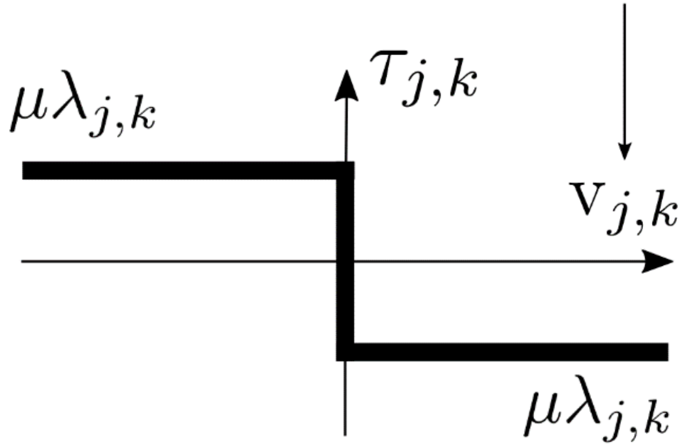
- Signorini's law





- Coulomb's law

Tangential relative velocity



Equivalent to the constrains :

$$\lambda_{j,k} \geq 0$$
$$D_{j,k} \geq 0$$
$$\lambda_{j,k} D_{j,k} = 0$$

Equivalent to maximize the dissipated power :

$$\max_{\tau_{j,k}} \; -\tau_{j,k}\, v_{j,k}$$

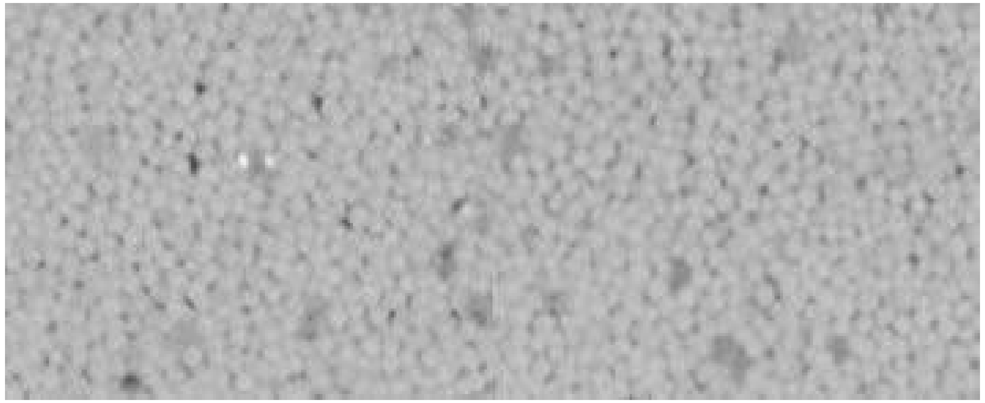
such that $|\tau_{j,k}| \leq \mu\lambda_{j,k}$

Roughness	Smooth	Intermediate			Rough
Thickness h/d	3	3	6	11.6	3
θ_m ($d \approx 0.5$ mm)	$16.5° \pm 1°$	$20.2 \pm 1°$	$16.5°$		$36° \pm 1°$
θ_m ($d \approx 0.1$ mm)				$22.5°$	

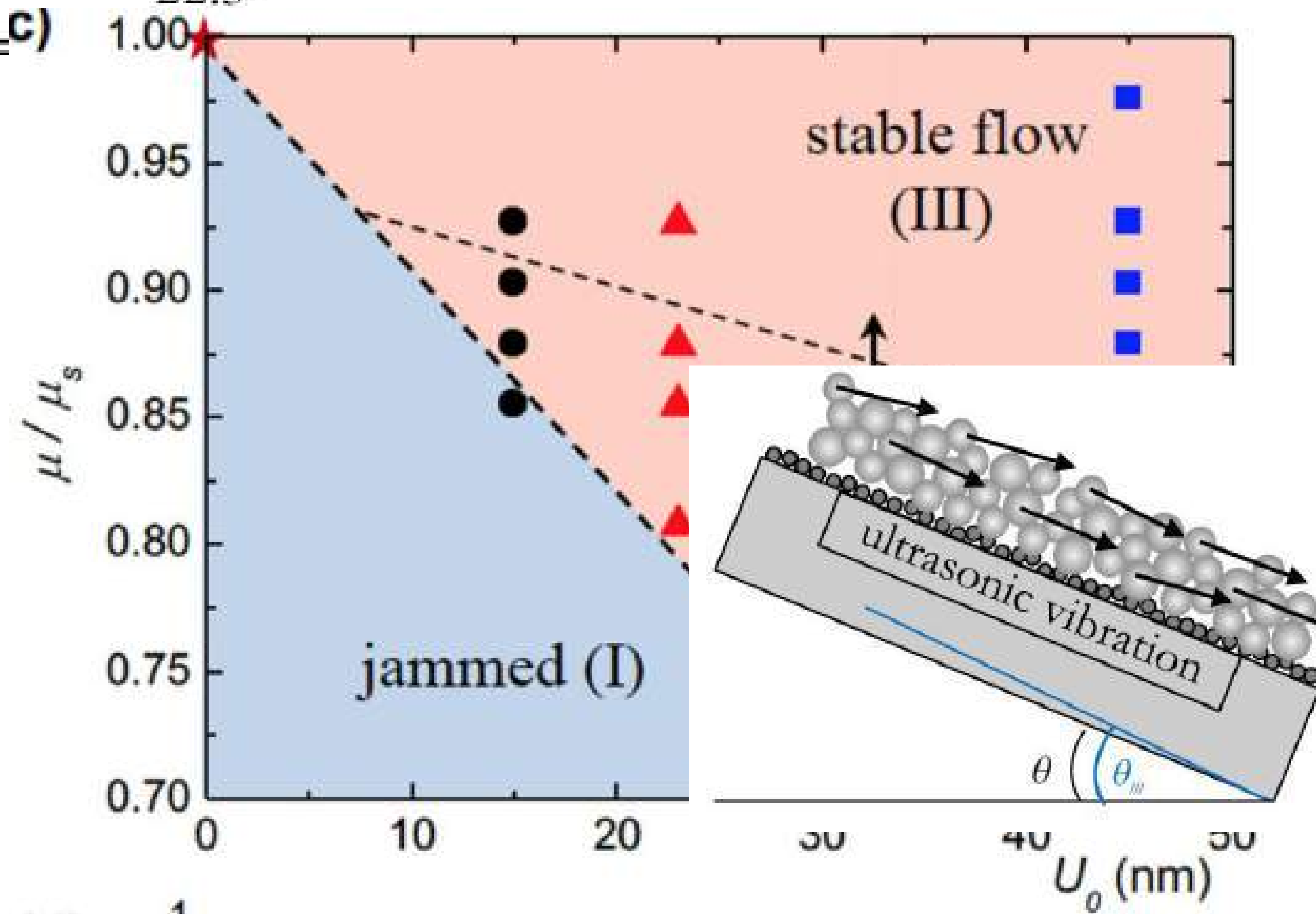
f_{US} = 100 kHz and U_0 ~ 5 nm

$\theta = 18° < \theta_{max} = 20°$ $\theta = 15° < \theta_r$

↓ ↓



triggered inertial flow (continuous) triggered slower flow (intermittent)



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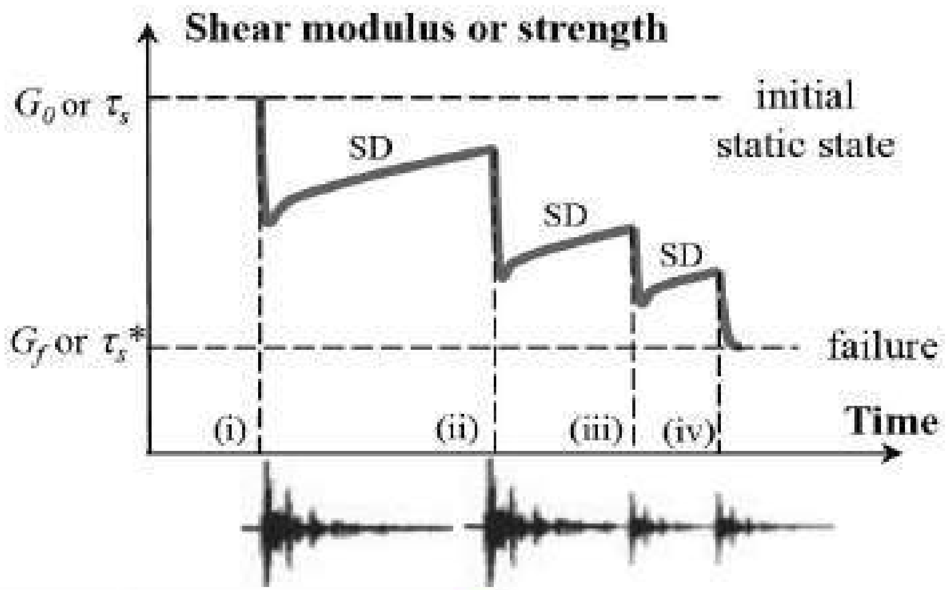
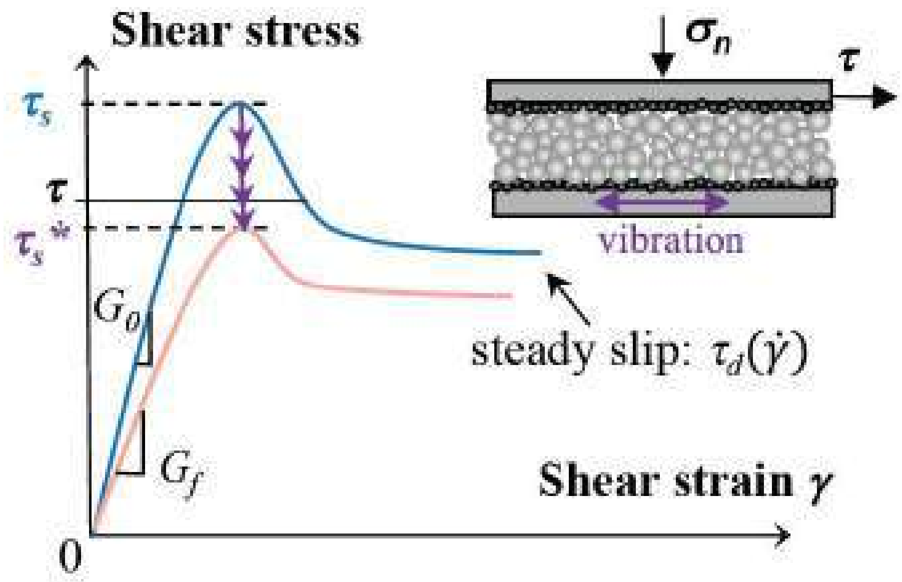
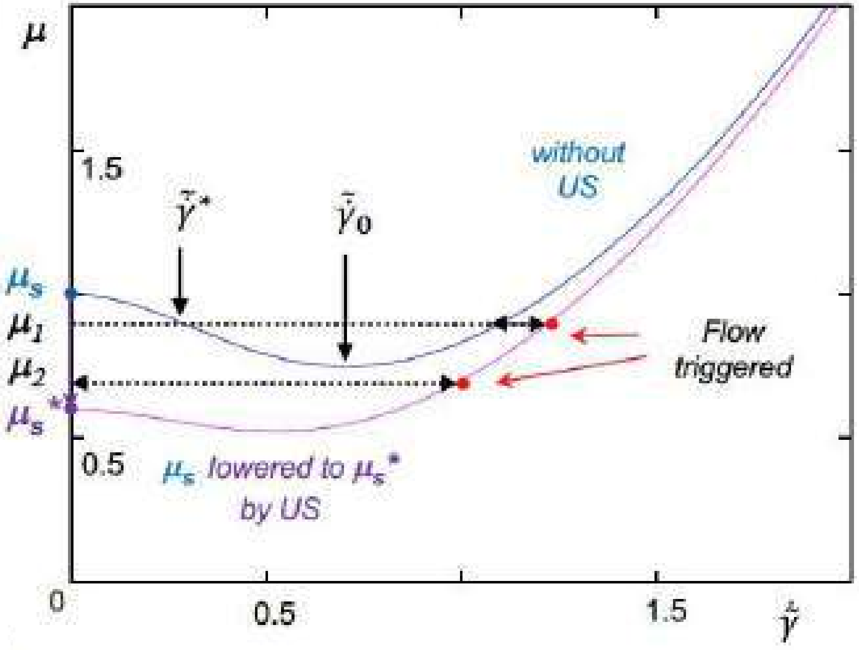
Dry granular flows experiments

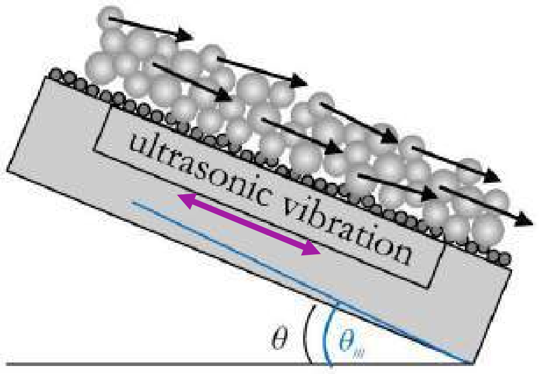
$$\tau = \mu(\sigma - p) + c$$



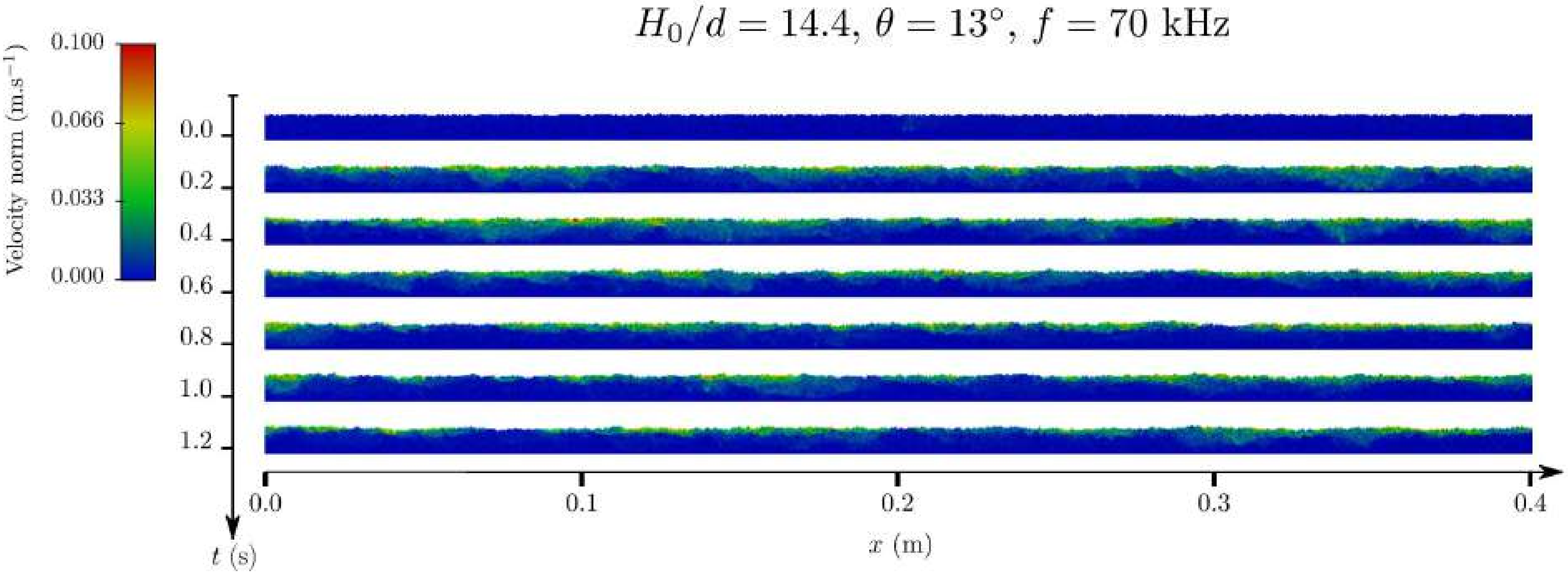
Friction weakening





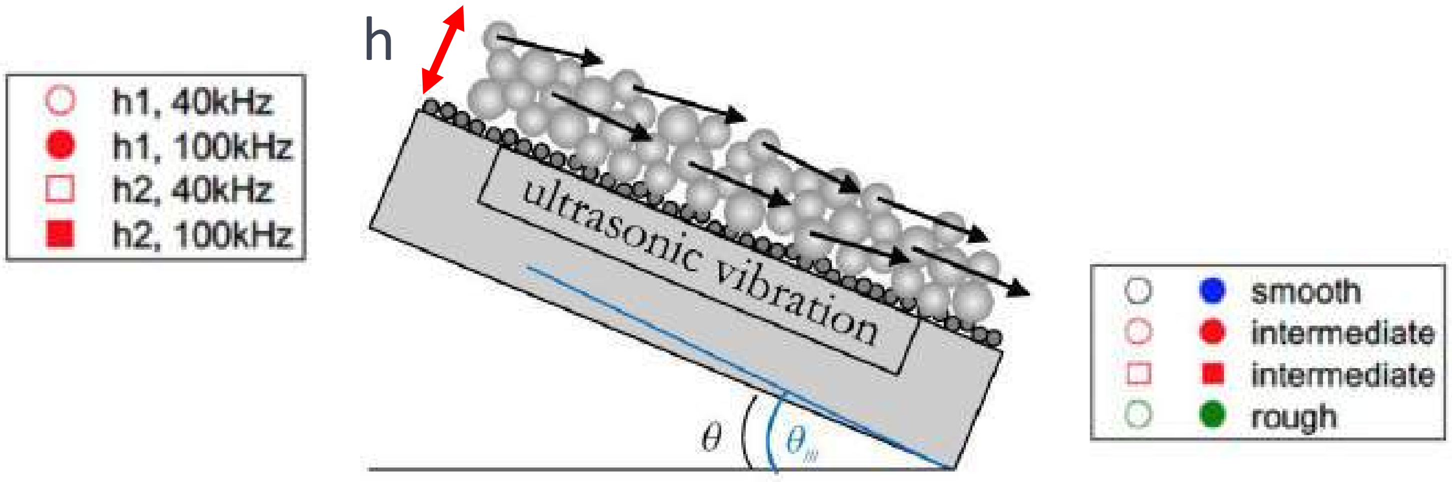


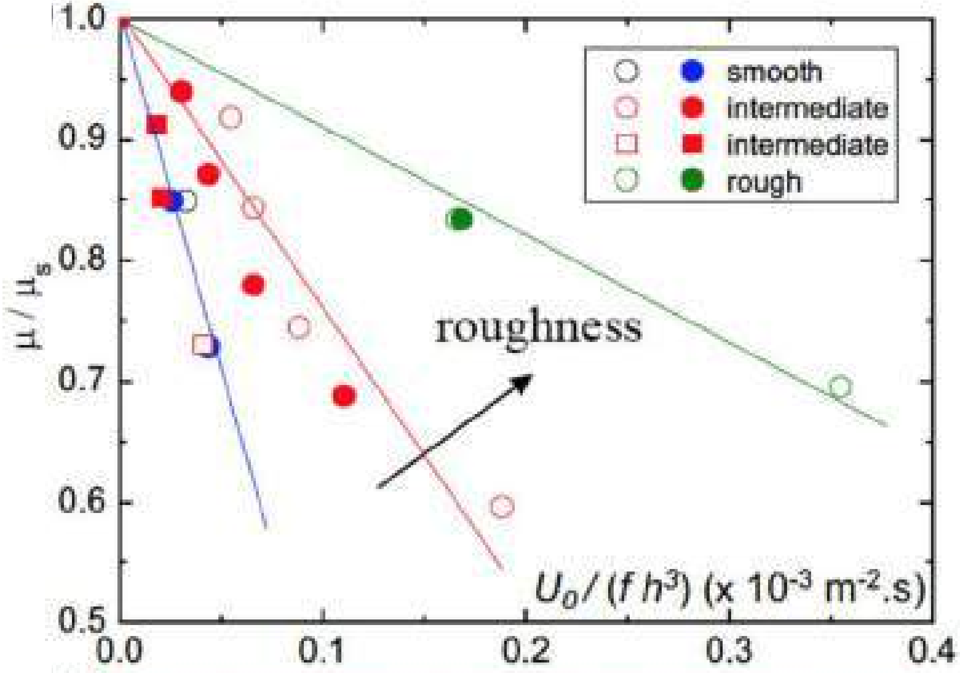
Avalanche triggering with waves



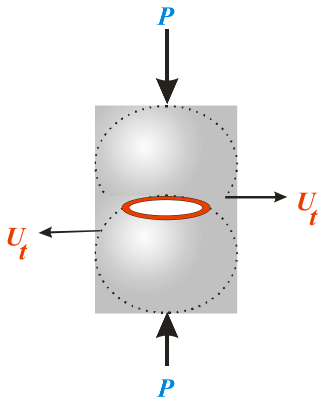
Already small motion at θ = 13° !

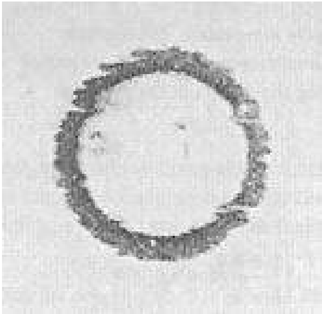
Ultrasound triggered avalanche



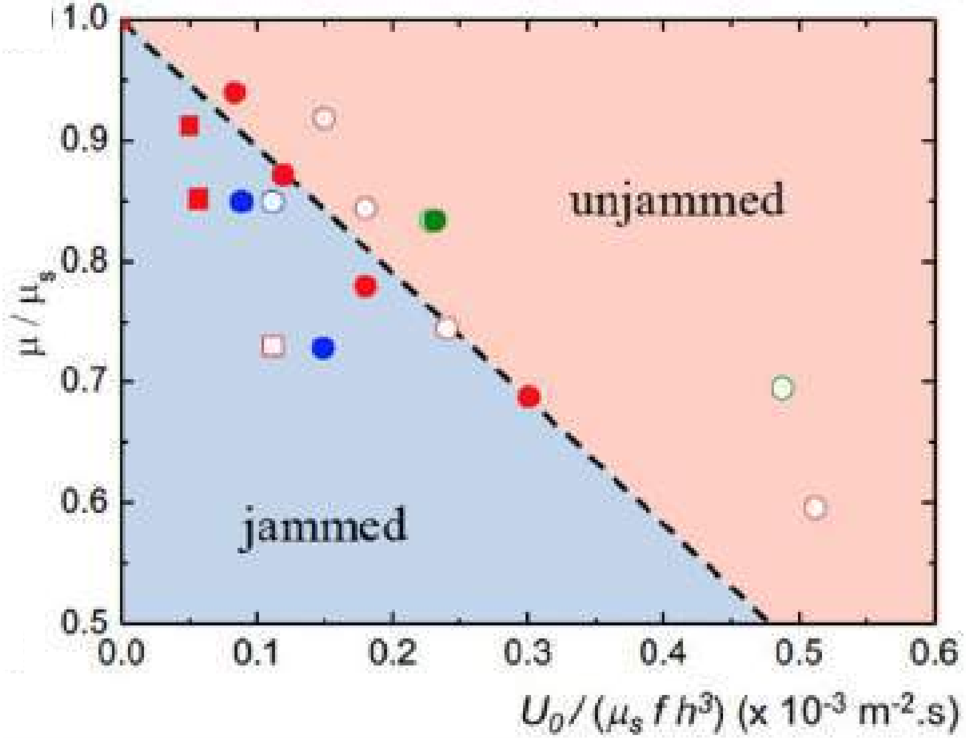


Acoustic lubrication of the stuck area Mindlin model





Jia et al., 2011
Leopoldes et al., 2020



Friction weakening

$$\mu_s^*/\mu_s \sim 1-(c^3/g)[U_0/(\mu_s f h^3)]$$

c sound speed