# Numerical Simulation of Slow Slip Triggered Tremor Migration and Rapid Tremor Reversals

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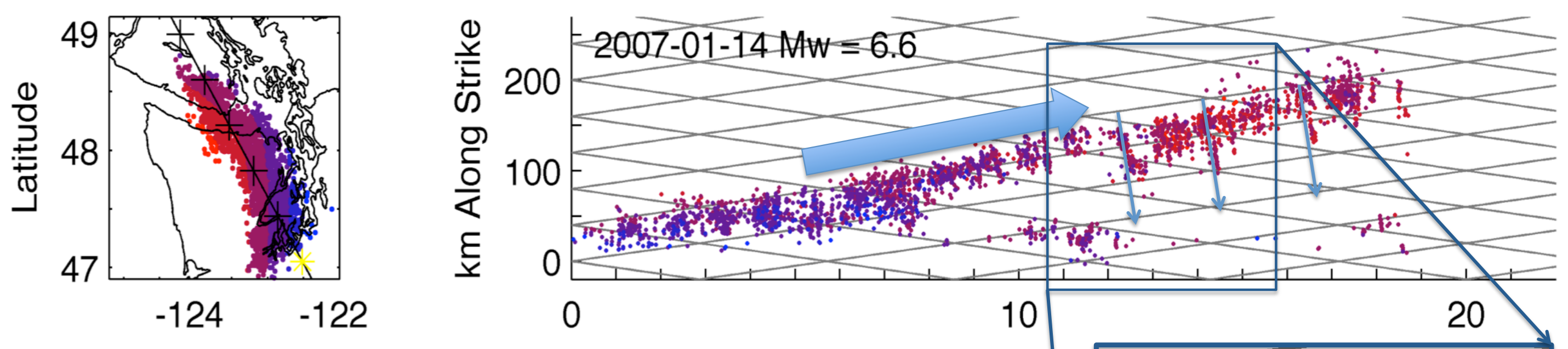
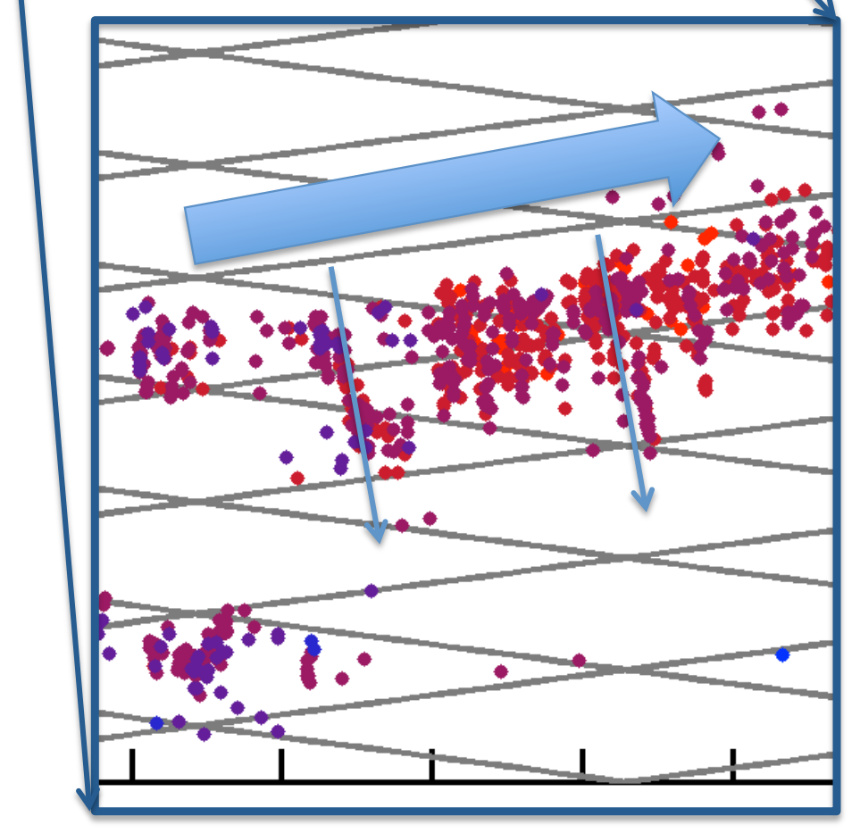
## I. Introduction

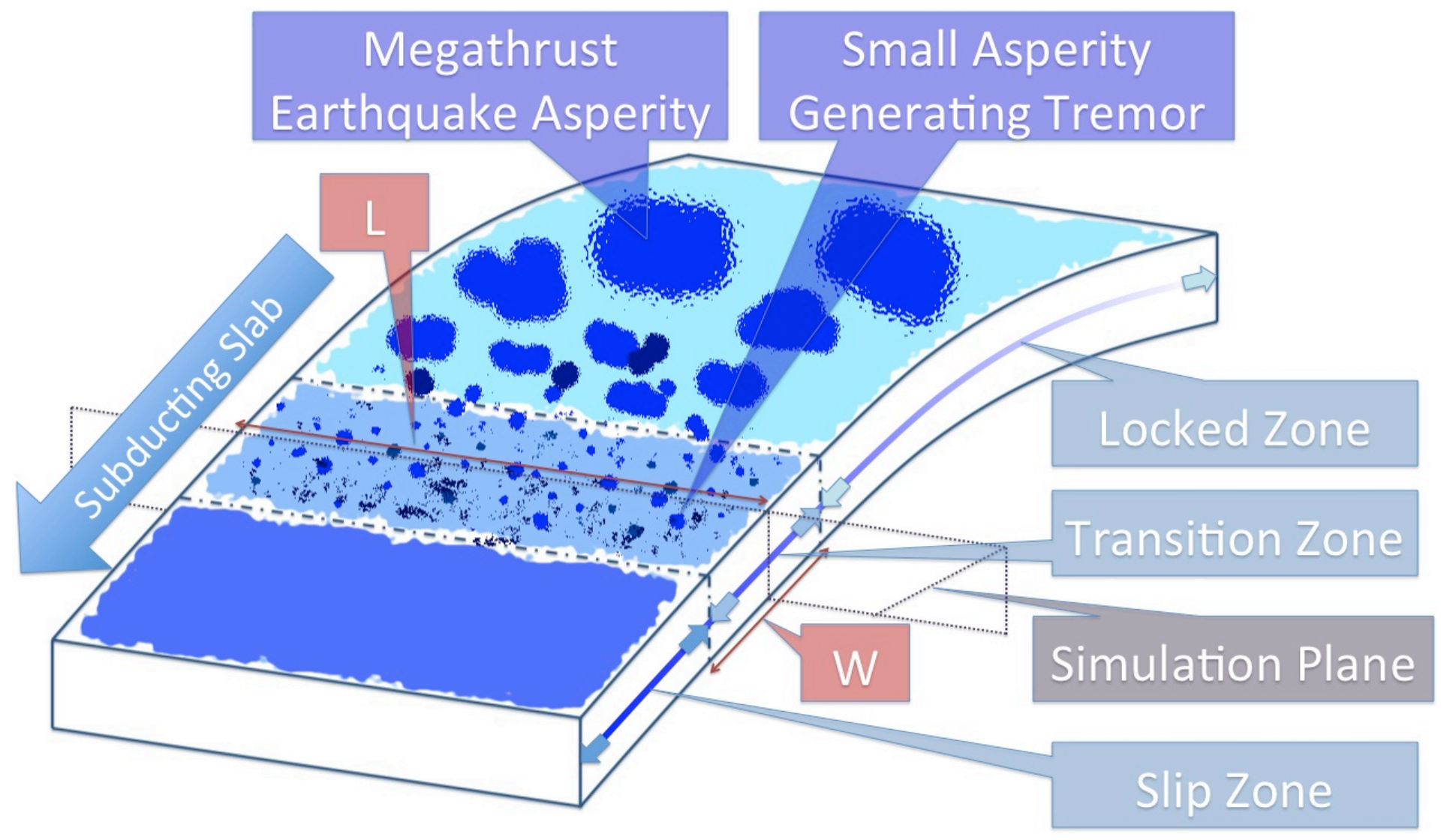
Slow-slip events (SSE) and non-volcanic tremors unveil a broad spectrum of earthquake behavior and offer a unique window into fault mechanics at the bottom of seismogenic zones. A hierarchy of migration patterns of tremors has been observed in the Cascadia subduction zone (Houston et al, 2011) :





1. ( ➡ ) Large-scale, along-strike tremor propagation at about 10 km/day. Likely triggered by to the migrating front of the slow slip event.
2. ( → ) Rapid Tremor Reversals (RTRs): smaller-scale swarms migrating along-strike in the opposite direction, at about 100 km/day. Their origin is less obvious.
3. Along-dip streaky tremor swarms, migrating at about 1000 km/day (not addressed here)

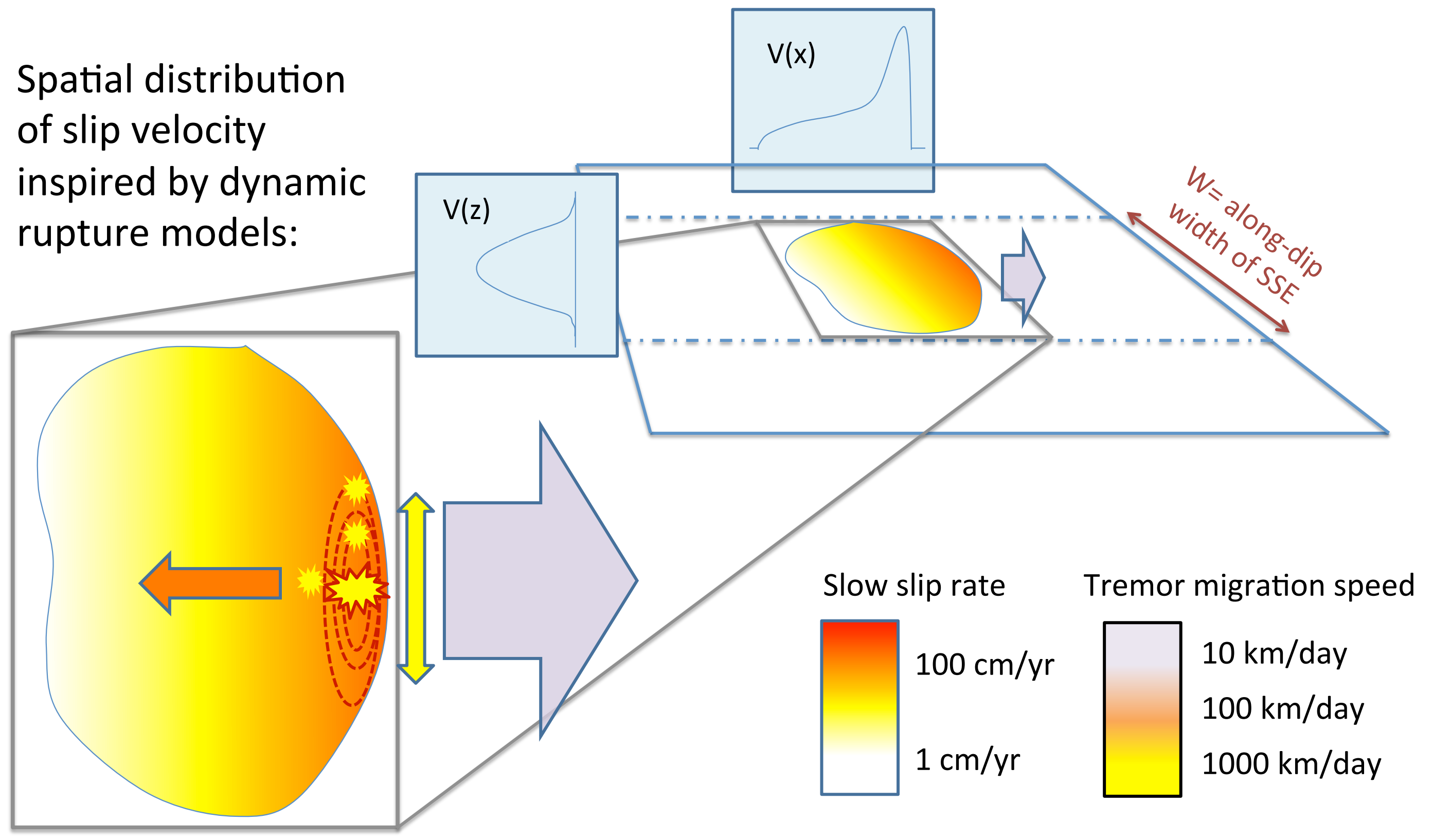
## II. Conceptual model



In an emergent view, the deep seismic/aseismic transition region of a fault has heterogeneous friction properties and is composed of frictionally unstable patches ('asperities') embedded in a more frictionally stable fault matrix.

Ariyoshi et al (2011) modeled tremor swarms as a cascade of asperity ruptures mediated by transient aseismic slip. The post-seismic slip induced locally by each asperity break propagates at a speed that correlates with the background slip velocity. RTRs propagate into the high background slip velocity areas inside a SSE pulse, resulting in fast backwards migration. Along-dip swarms are even faster because they propagate along the leading edge of the SSE front (high background slip velocity).

Spatial distribution of slip velocity inspired by dynamic rupture models:



## III. Model

### Rate and State Friction

$$\tau = \sigma\left[f^* + a\ln\frac{V}{V^*} + b\ln\frac{V^*\theta}{D_c}\right]$$

| | |
|---|---|
| τ | fault shear stress |
| σ | effective normal stress |
| f * | reference value of the friction coefficient |
| V* | reference value of the slip velocity |
| V | sliding velocity |
| a | constitutive parameter: direct effect |
| b | constitutive parameter: evolution effect |
| $D_c$ | characteristic slip distance |
| θ | state variable |

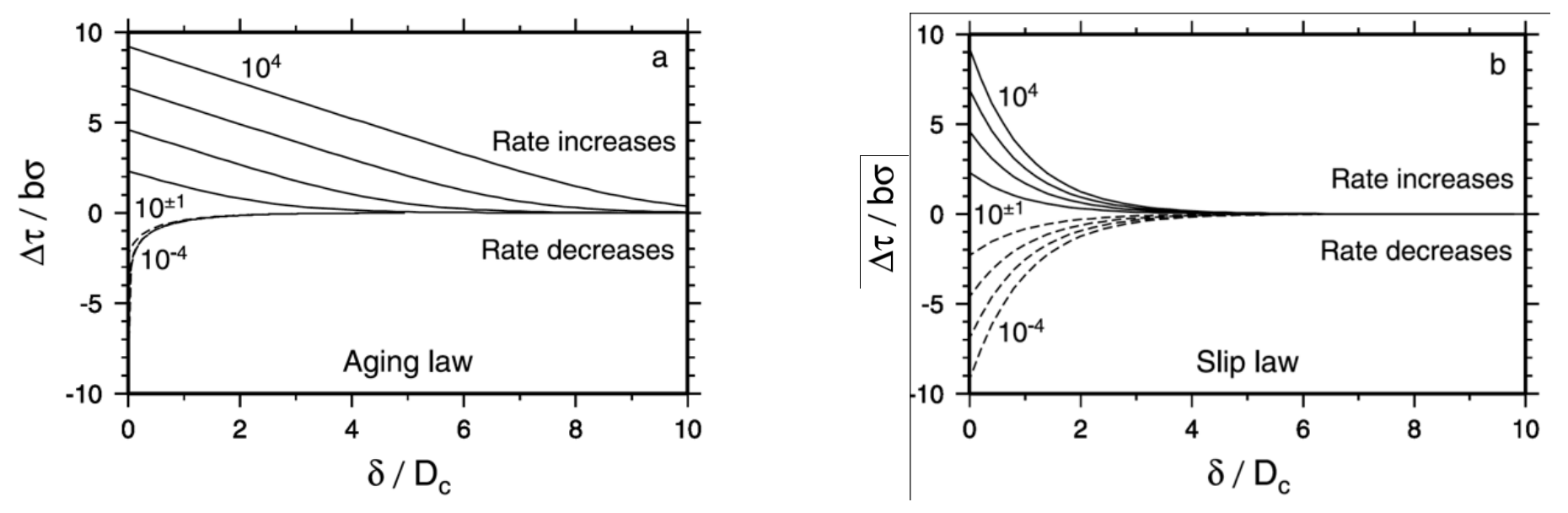
### Empirical Equations for State Variable

Aging Law

$$\dot{\theta} = 1 - \frac{V\theta}{D_c}$$

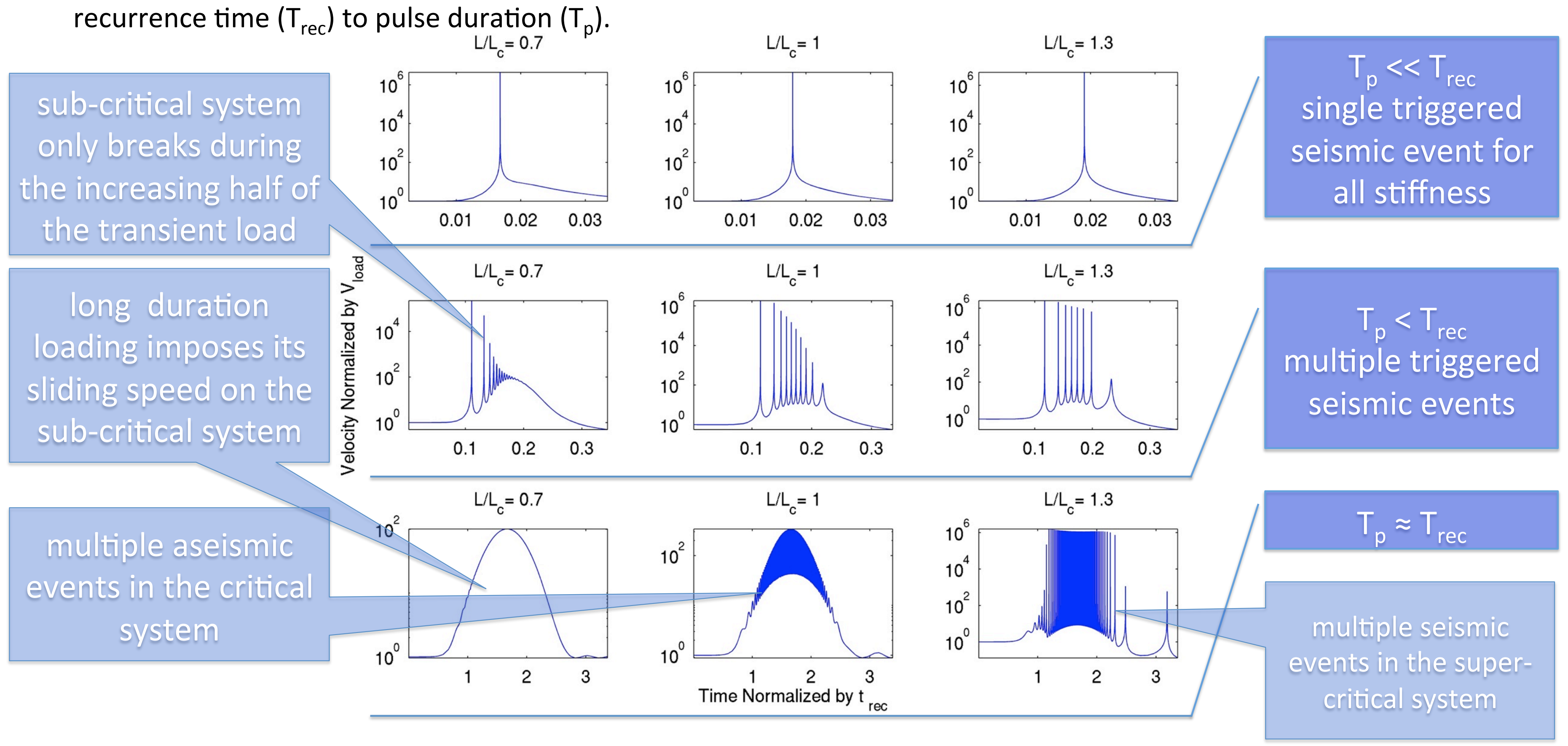
Slip Law

$$\dot{\theta} = -\frac{V\theta}{D_c}\ln\frac{V\theta}{D_c}$$



### Single Degree of Freedom Spring-Block System

Response of a spring-block system to an external transient loading (a Gaussian pulse). The slip law is assumed. Each row has a different characteristic pulse duration: $T_{rec}$ /100, $T_{rec}$ /10 and $T_{rec}$ (top to bottom). Each column has different stiffness: sub-critical, critical and super-critical (left to right). The response highly depends on the ratio of recurrence time ($T_{rec}$) to pulse duration ($T_p$).



sub-critical system only breaks during the increasing half of the transient load

long duration loading imposes its sliding speed on the sub-critical system

multiple aseismic events in the critical system

$T_p << T_{rec}$ single triggered seismic event for all stiffness

$T_p < T_{rec}$ multiple triggered seismic events

$T_p \approx T_{rec}$

multiple seismic events in the super-critical system

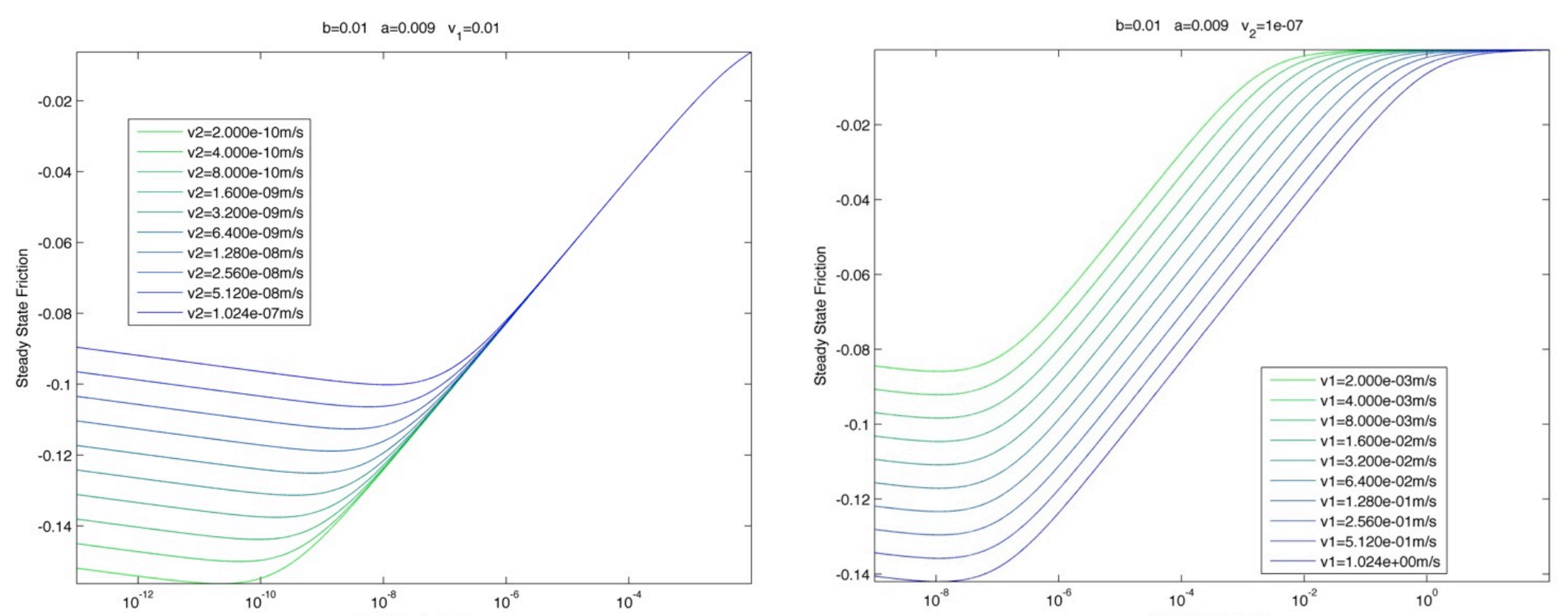
Henceforth we consider sub-critical asperities with recurrence time smaller than the transient load (SSE) so they can be triggered by SSE seismically and then interact with each other to generate RTRs.

### Friction Law with cut-off Velocity

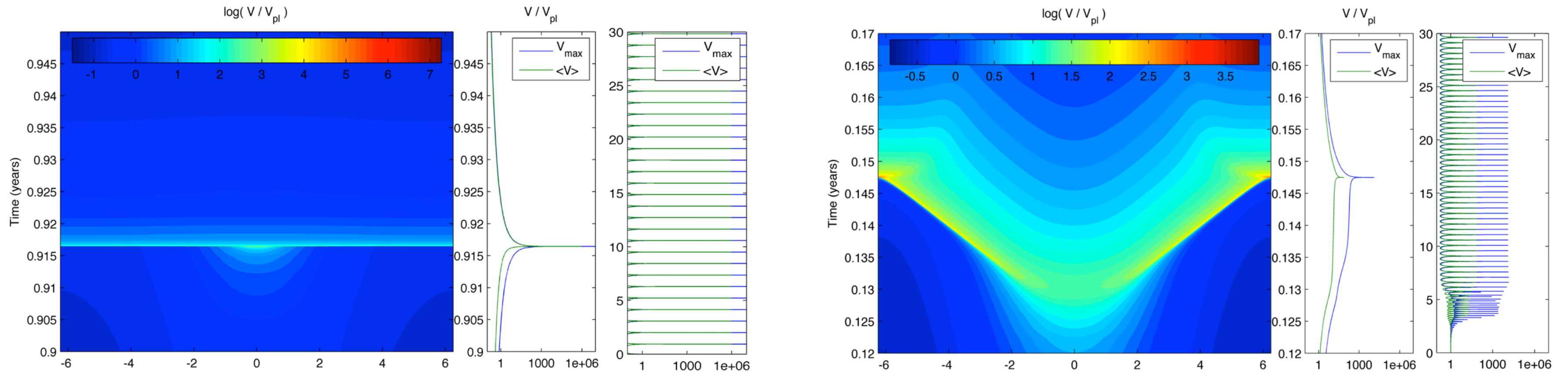
Because we focus on modeling tremor migration, we conveniently generate the underlying SSE by adopting a friction law with transition from velocity-weakening to strengthening. We adjust model parameters to obtain a SSE propagation speed of ~10 km/day.

$$\mu = \mu_* - a\ln\left(\frac{v_1}{v}+1\right) + b\ln\left(\frac{v_2\theta}{D_c}+1\right)$$

$v_1$ Cut-off velocity of direct effect
$v_2$ Cut-off velocity of evolution effect:
Velocity weakening to strengthening transition



Right: Steady state friction for different cut-off velocities $v_1$ and $v_2$



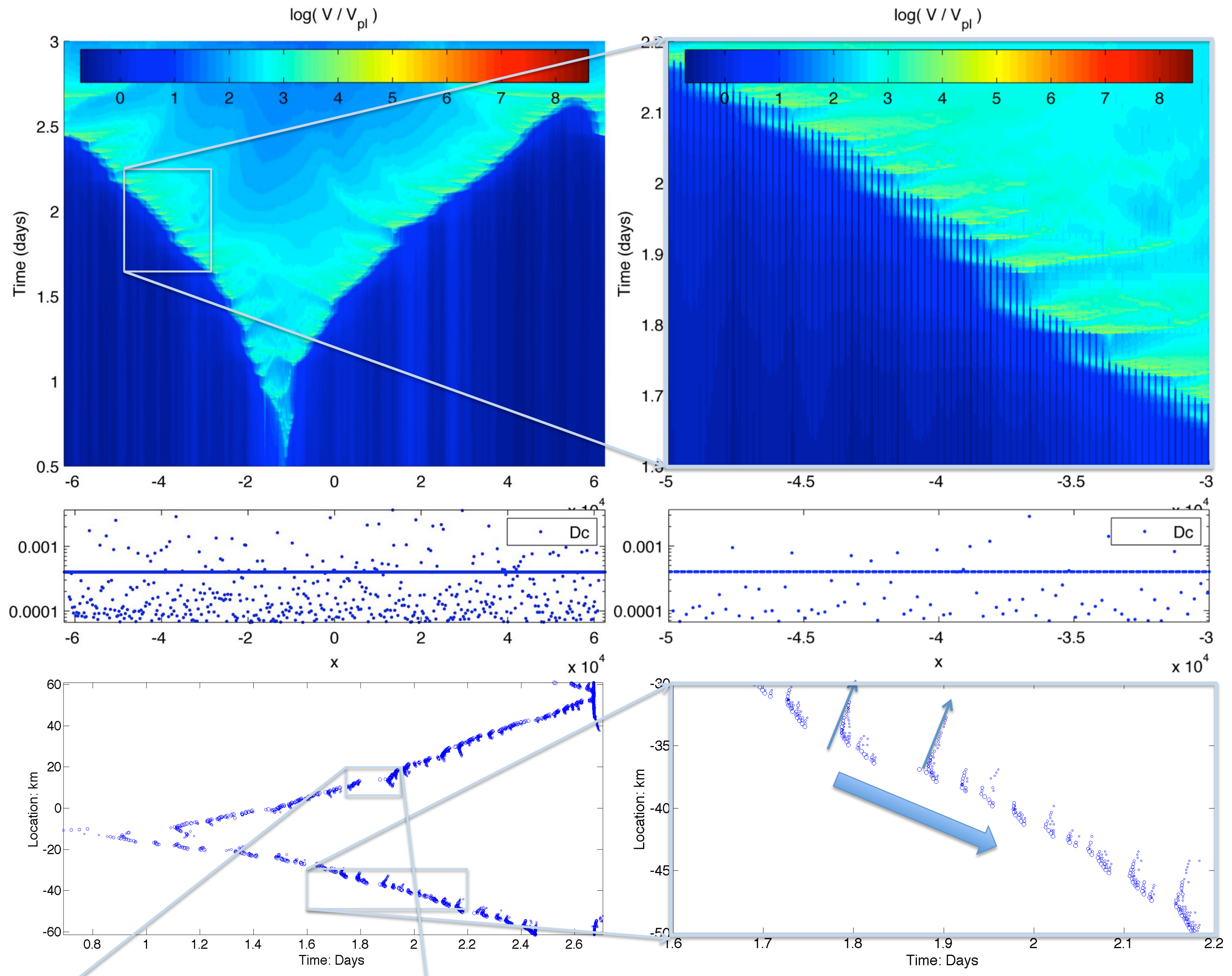
Velocity-weakening 2D simulation with fault length L=125 km and along-dip width W=110 km.
Left: without cut-off velocity produces recurrent seismic events unless W is finely tuned.
Right: with cut-off velocity $v_2 = 10^{-7}$ m/s produces episodic slow slip events.

## IV. Numerical simulations

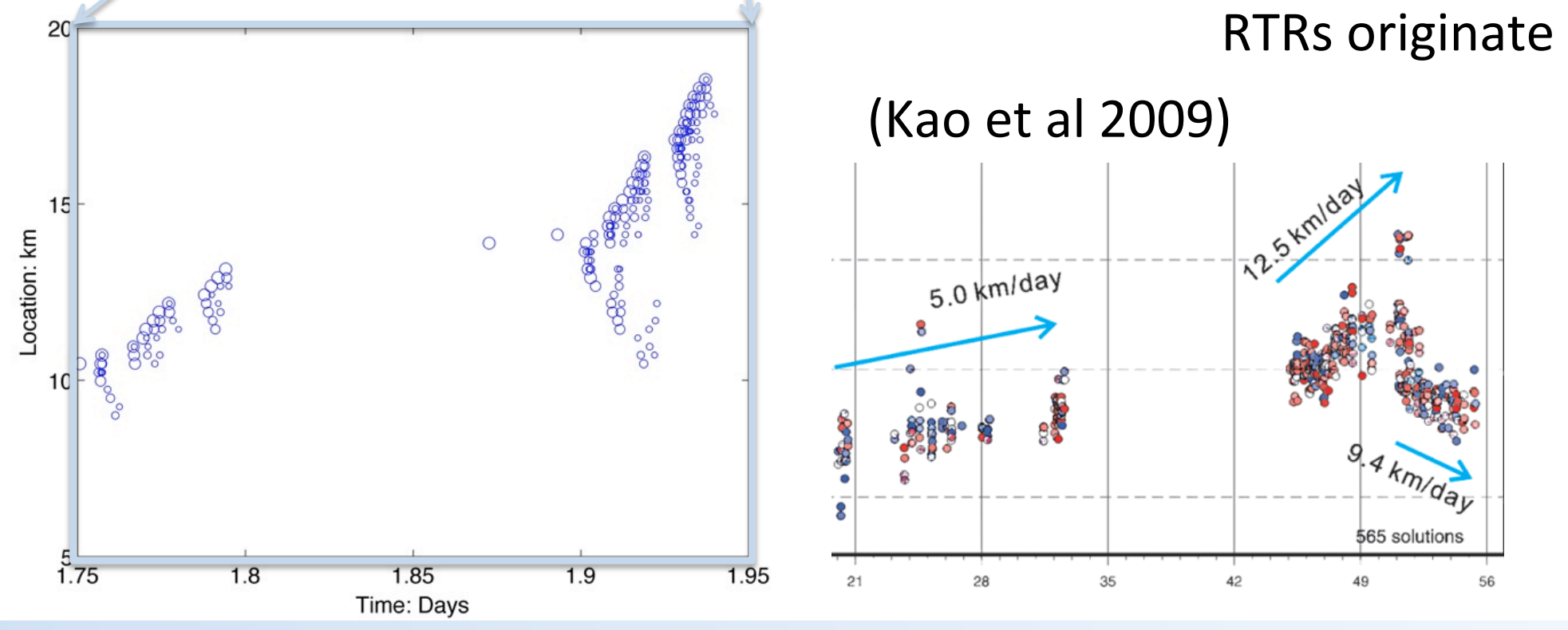
We conduct 2D numerical simulations of heterogeneous rate-and-state faults under the quasi-dynamic approximation with a spectral Boundary Element Method. We first simulate several SSE cycles on a homogeneous fault. We then add a collection of small asperities defined as patches of velocity-weakening friction (no velocity cut-off, to allow seismic slip) with shorter Dc and larger aσ and bσ than their surroundings.

### SSE Triggered Tremor Migration and RTRs

About 500 single-cell ( ≈ 60m in actual size) small asperities embedded on the fault, 3-cells interval between asperities. Asperity size normalized by $L_c = GD_c / ((b-a)\sigma)$ and randomly distributed from 0.01 to 0.61.

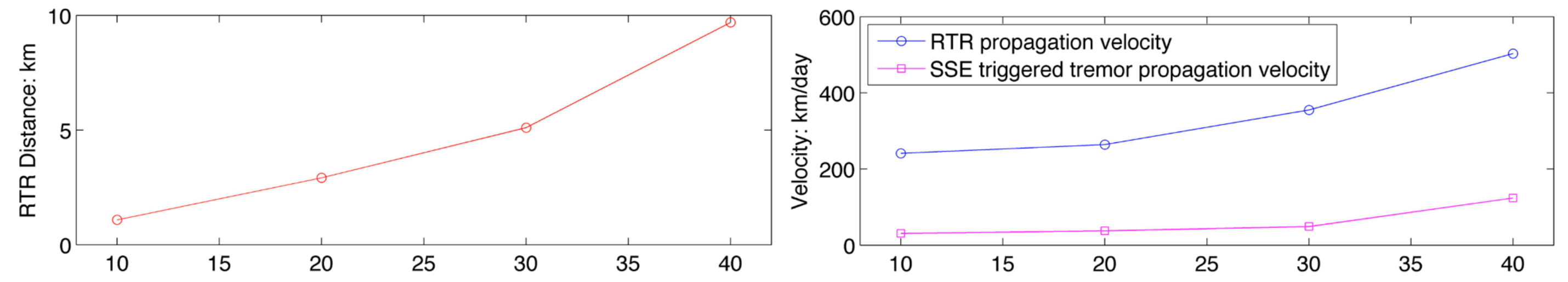


RTRs originate from asperities with large Dc



Simulation also reproduces observed 'halting' tremor migration pattern: tremor propagation halts, and then branches and accelerates

### RTR Migrating Distance and Velocity



Increasing aσ within the asperities increases the propagation distance reached by RTRs and reduces their relative migration speed.

## V. Future work

- Identify the factors controlling the propagation speed and distance of RTRs
- a more natural fault model with lower frictional contrasts by modifying the actual size of small asperities
- 3D simulations including tremor swarms propagating along-dip on narrow streaks at about 1000 km/day

## VI. References

- J.-P. Ampuero, and A. M. Rubin (2008), *Earthquake nucleation on rate and state faults - Aging and slip laws*, JGR, 113, B01302
- K. Ariyoshi,, T. Matsuzawa, J.-P. Ampuero, R. Nakata, T. Hori, Y. Kaneda, R. Hino and A. Hasegawa (2011), *Migration process of very low-frequency events based on a chain-reaction model and its application to the detection of preseismic slip for megathrust earthquakes* , EPS, in press
- H. Houston et al (2011), *Rapid Tremor Reversals in Cascadia generated by a weakened plate interface*, Nature Geo 4
- H. Kao et al (2009), *Northern Cascadia episodic tremor and slip: A decade of tremor observations from 1997 to 2007*, JGR, 144 B00A12