Bridging Length-Time Scales in a Brittle-Ductile Process : evolution of "defects" in fast-slow time space

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In collaboration with :

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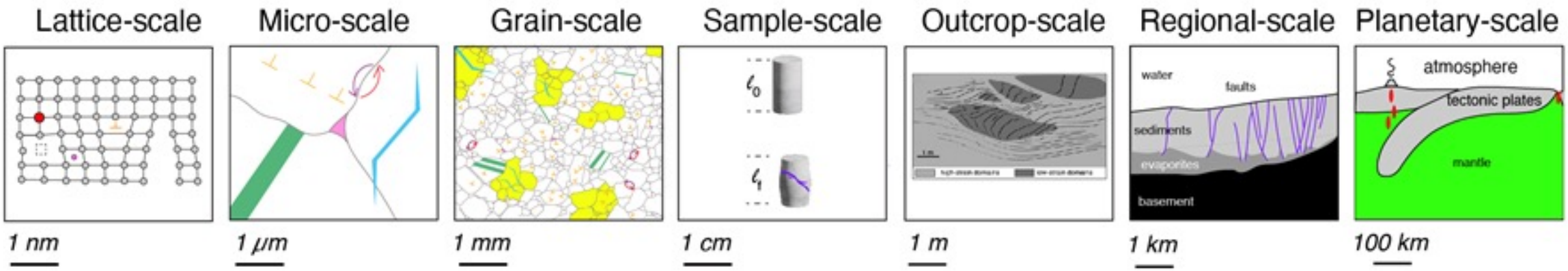
- *Length scales which control deformation processes in geomaterials...*



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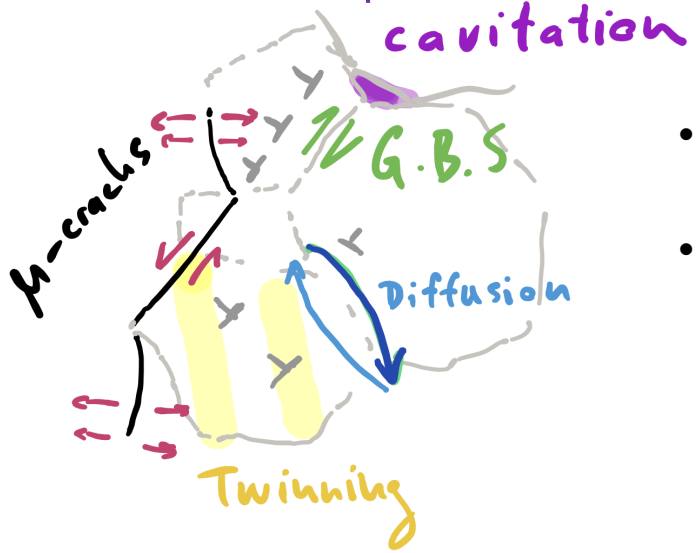
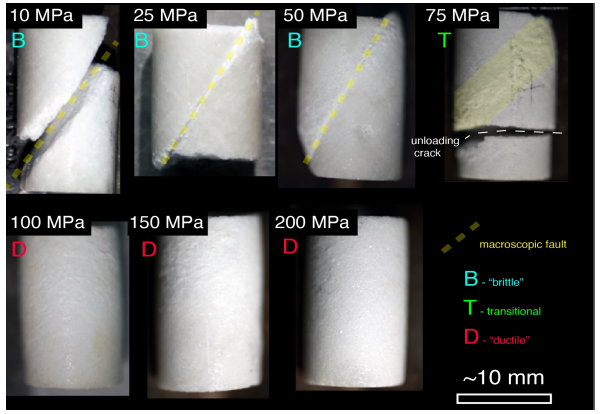


Courtesy of M.Pec,2022

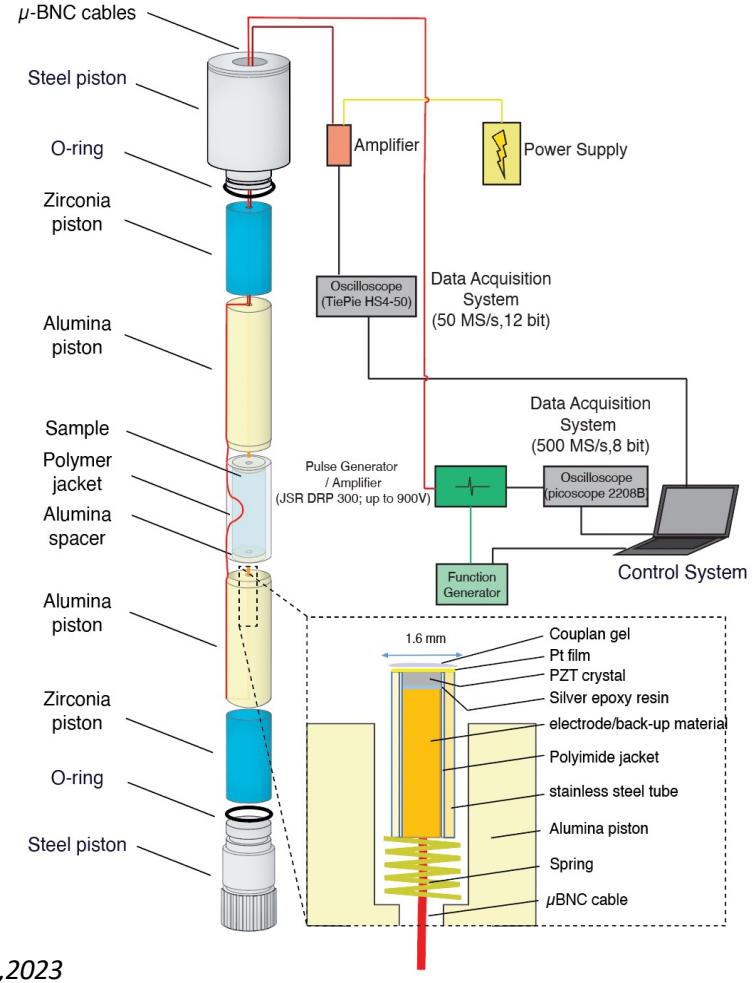
- Rise and *freeze-out* of defects
- Interactions of defects gives rise to complexity of deformation modes [brittle/Ductile//semi-brittle…]: *Probing Deformation phase in micro/macro-scales*

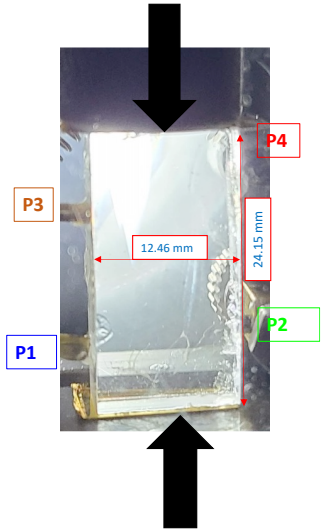
Marble Samples &Calcite Single Crystal :

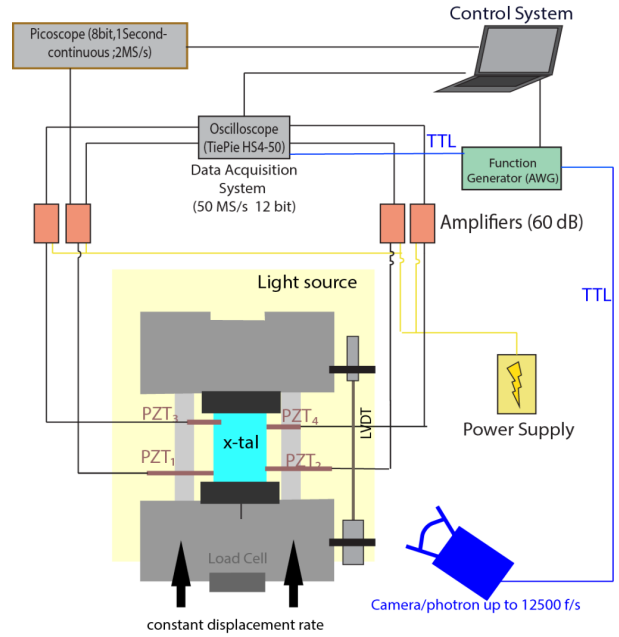
Active &Passive in fast-slow time space



Marble Samples







Calcite Samples

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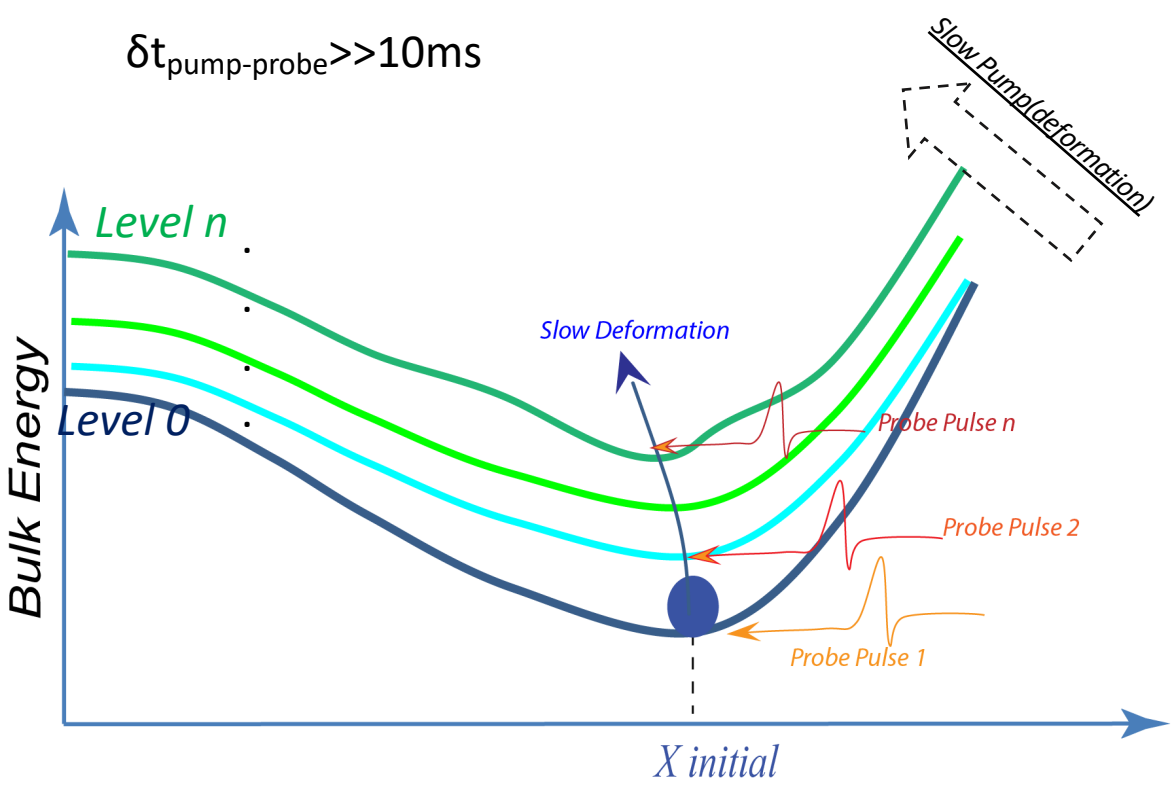
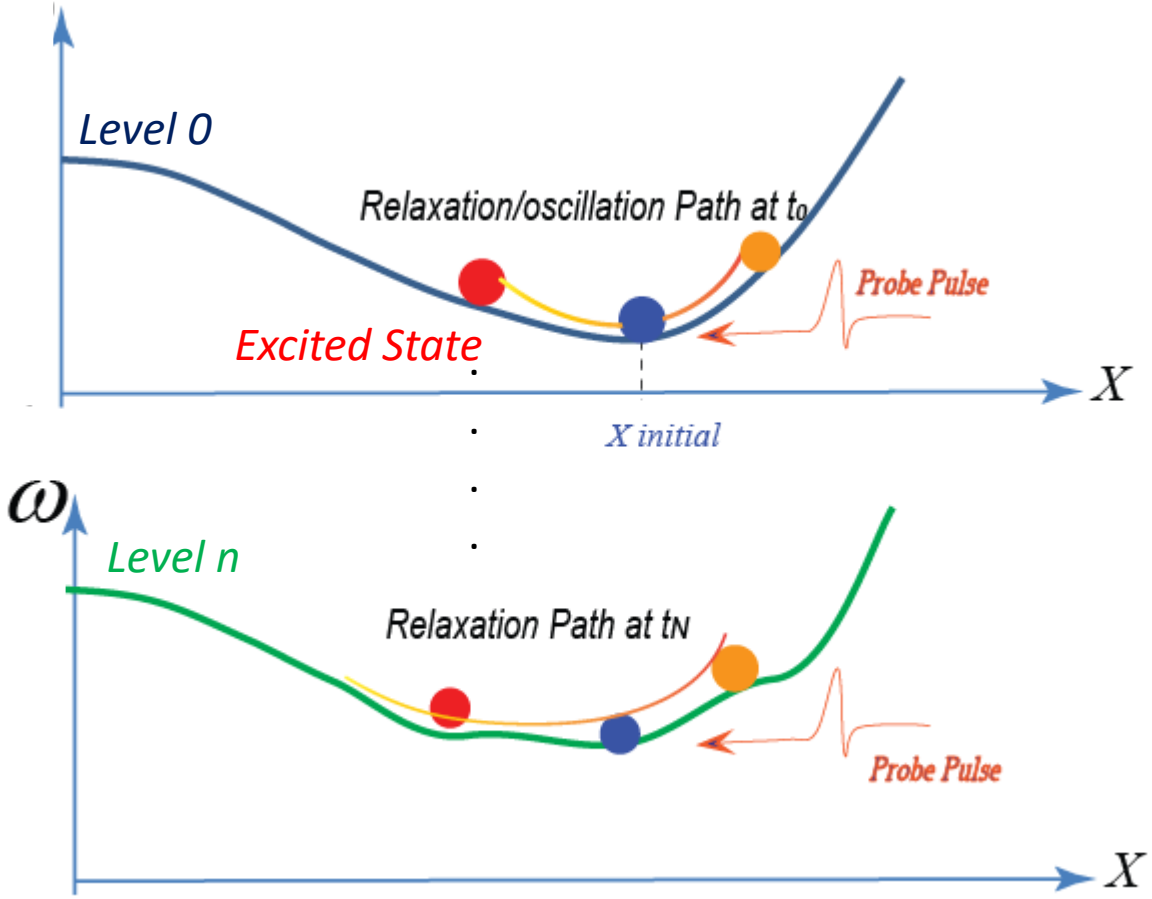
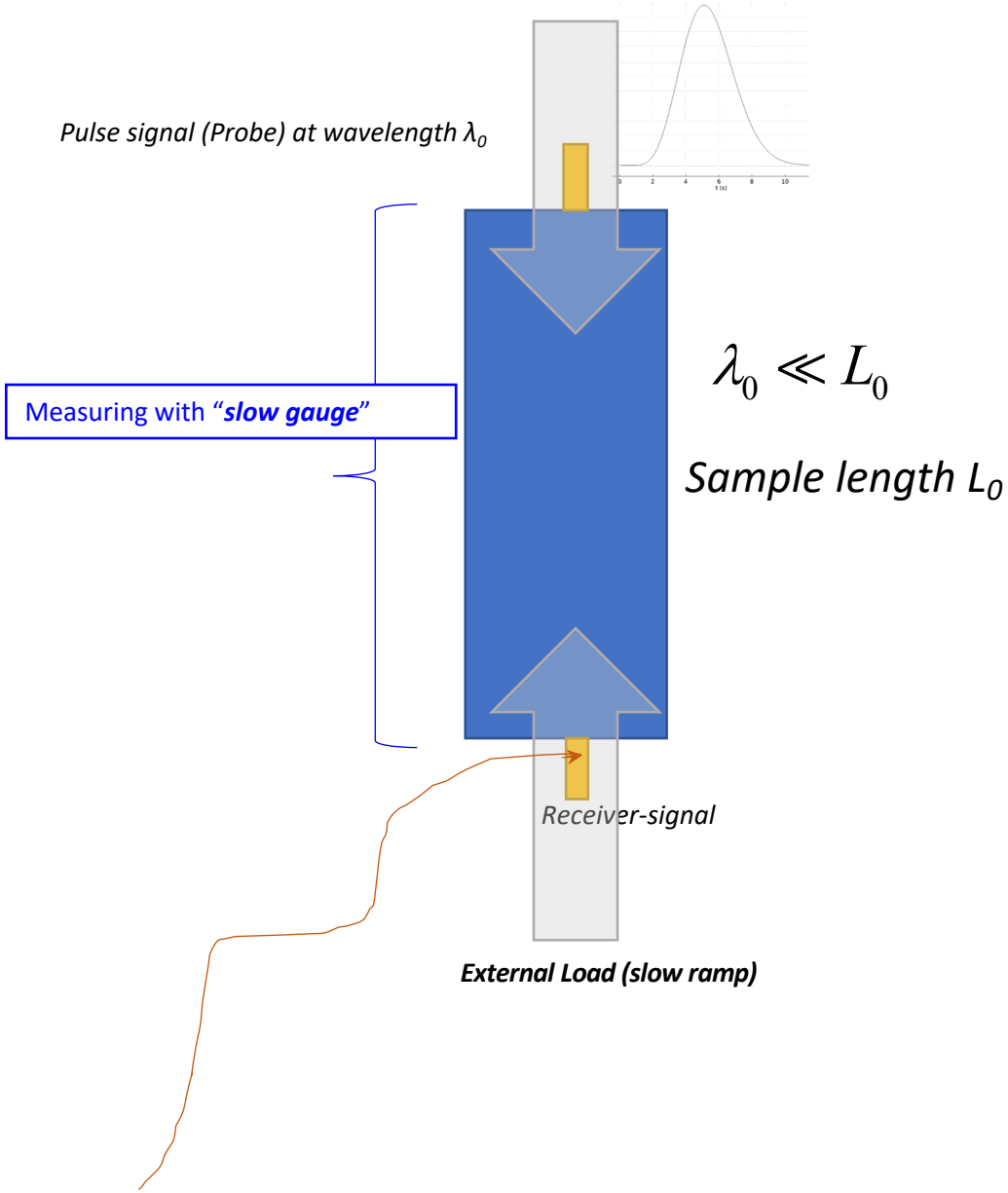
- *Probing slow deforming energy landscape : **Active (external)probe***

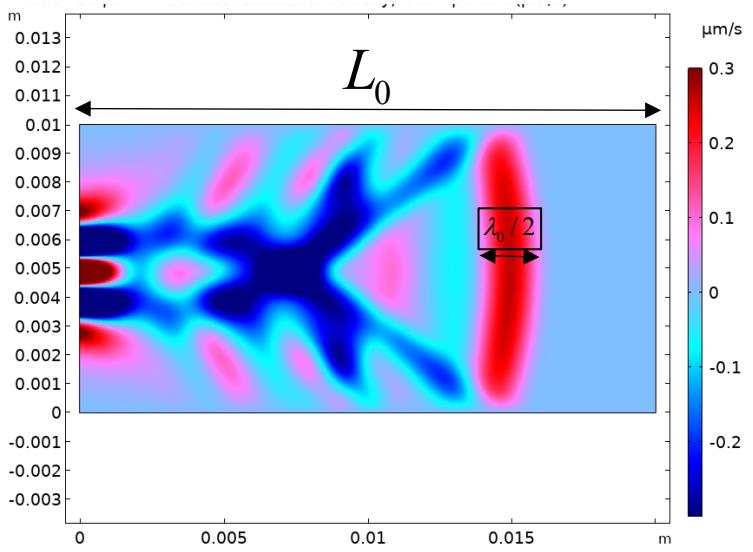




- *Special case : **slow deformation** ;non-destructive measure with **fast-probe***

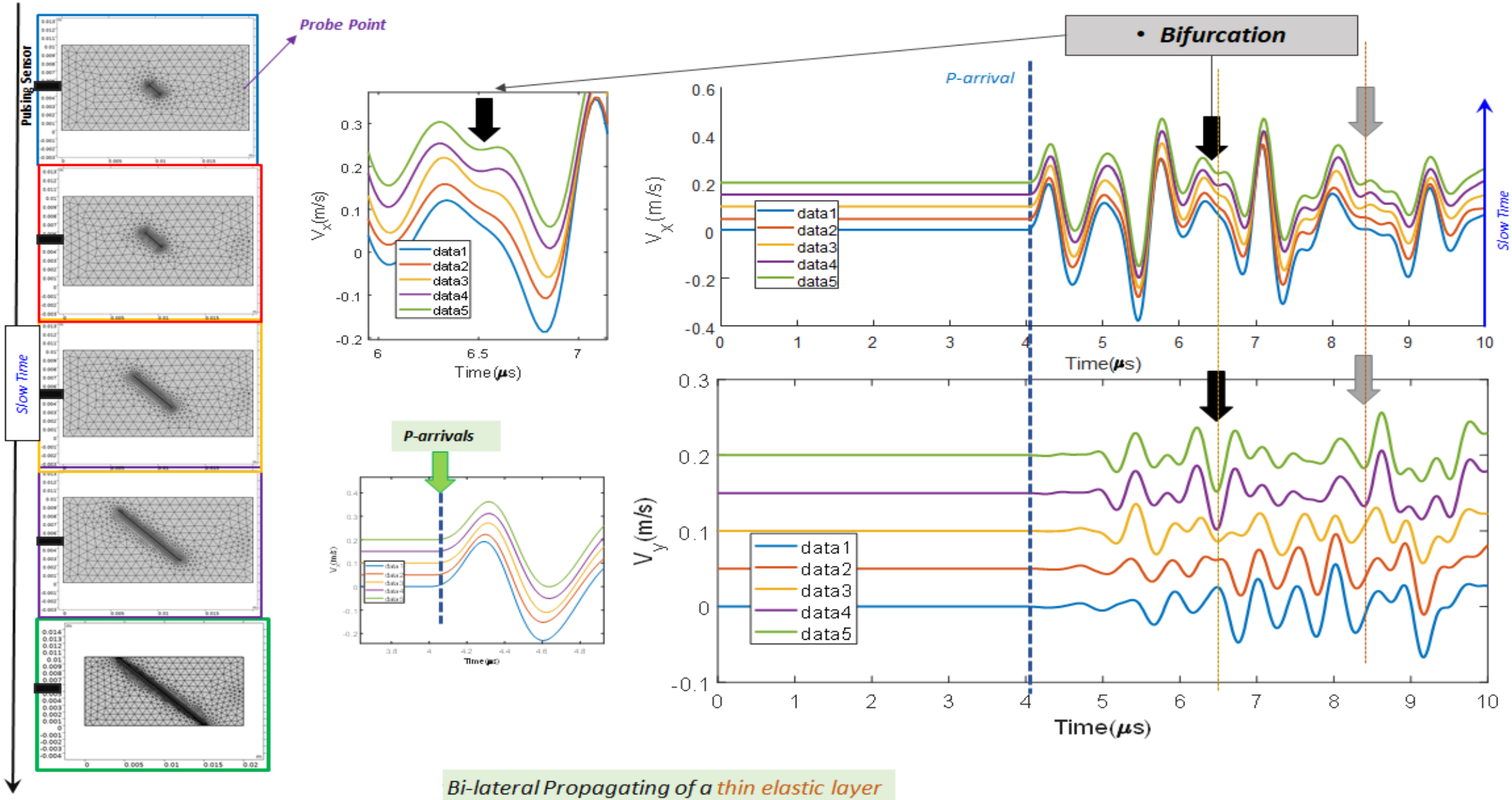
- *An example of "fast-slow" time space or "Wave-field" ["**Rug Patterns**"]*





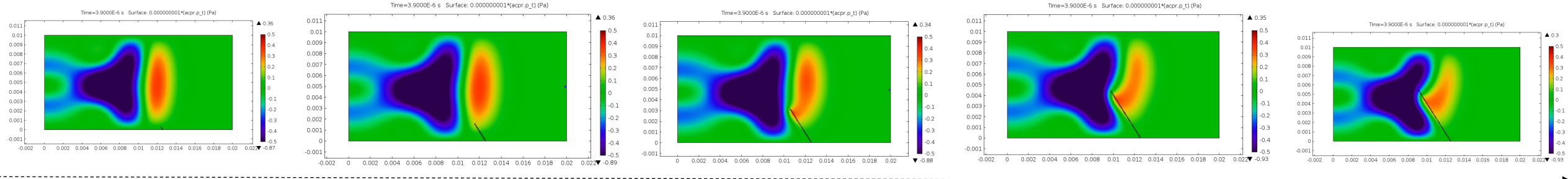
- *Fast gauge [=fast response=short response time]*

Let’s consider synthetic waves...

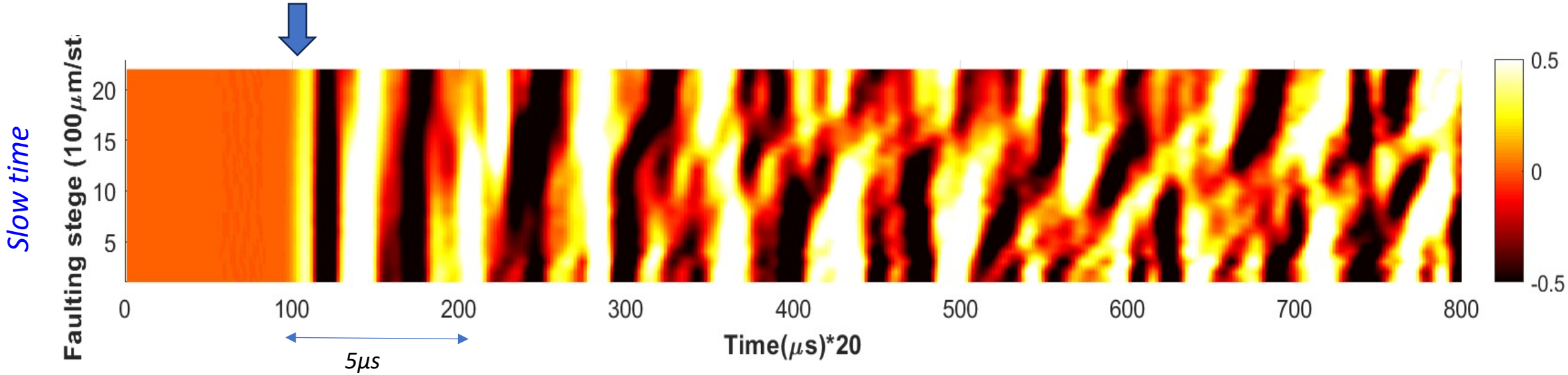


Bi-lateral Propagating of a thin elastic layer

- *Pressure Distribution at t=3.9μs*



Stage 1 **Stage 6** **Stage 11** **Stage 16** **Stage 21**



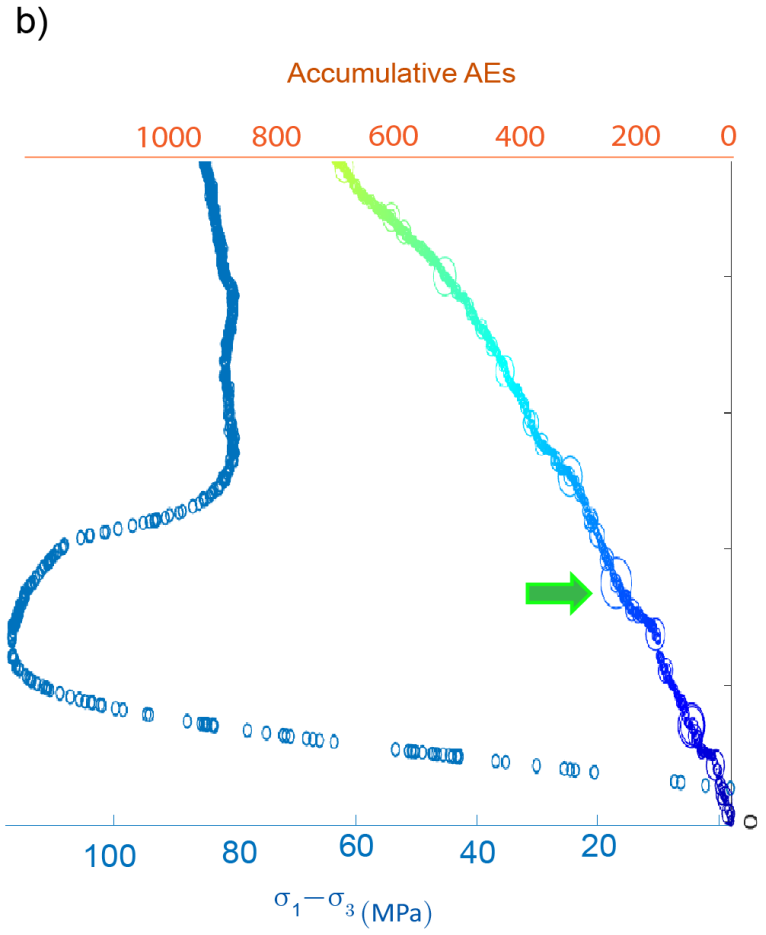
Experimental Observations

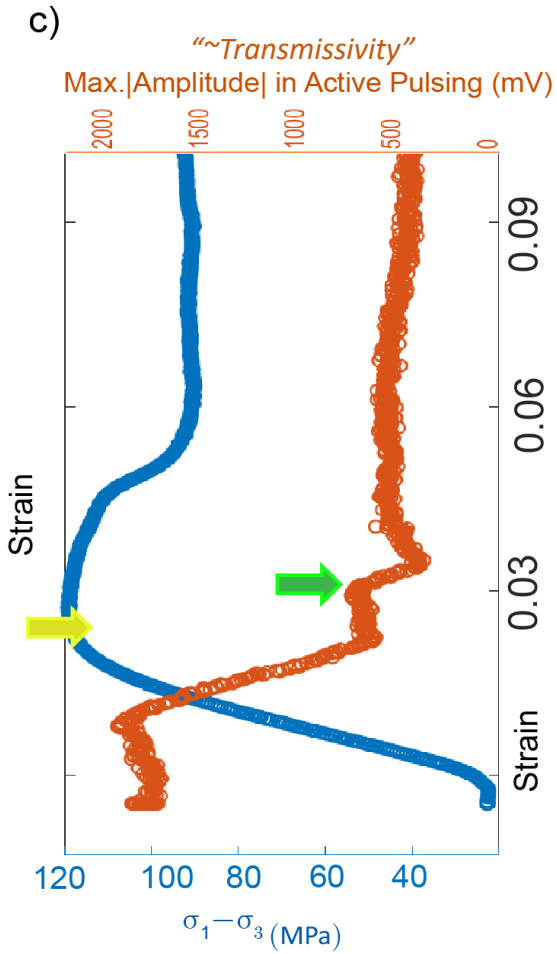
Carrara Marble & Brittle-Ductile transition:

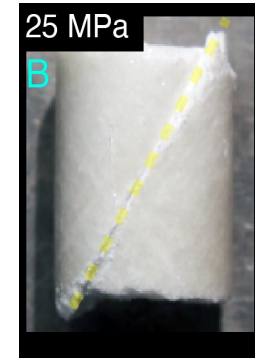
Active fast-slow time space

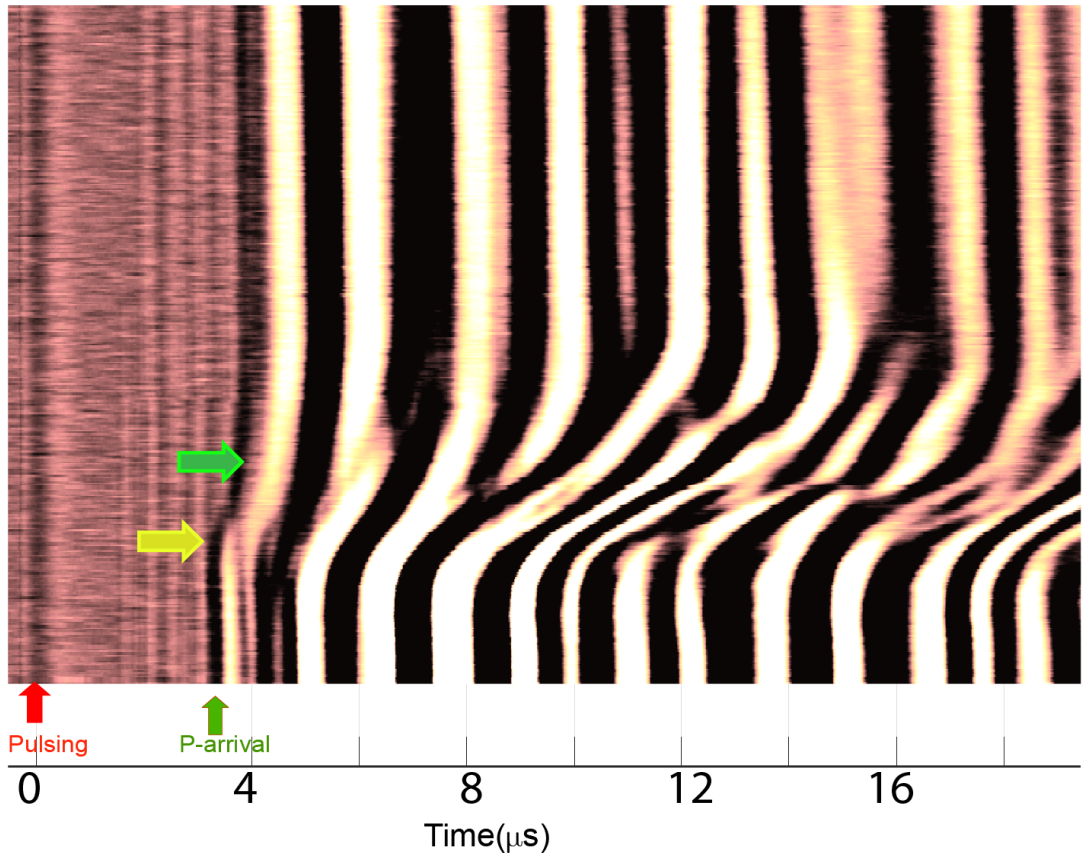
- *The configuration of wavefield("rug patterns of active pulsing")*

Brittle









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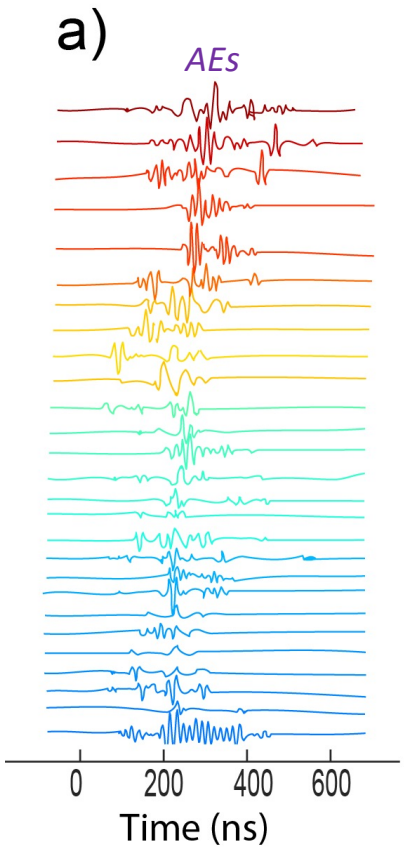
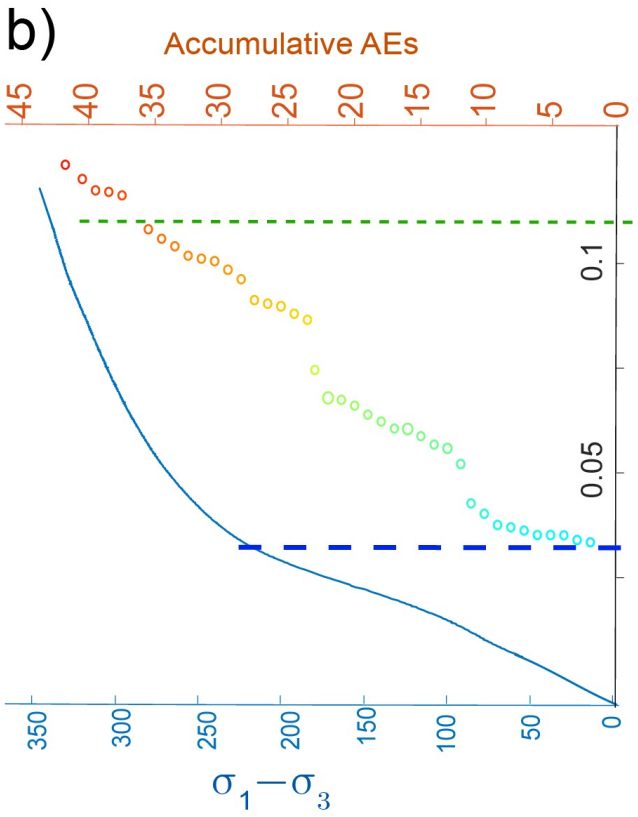
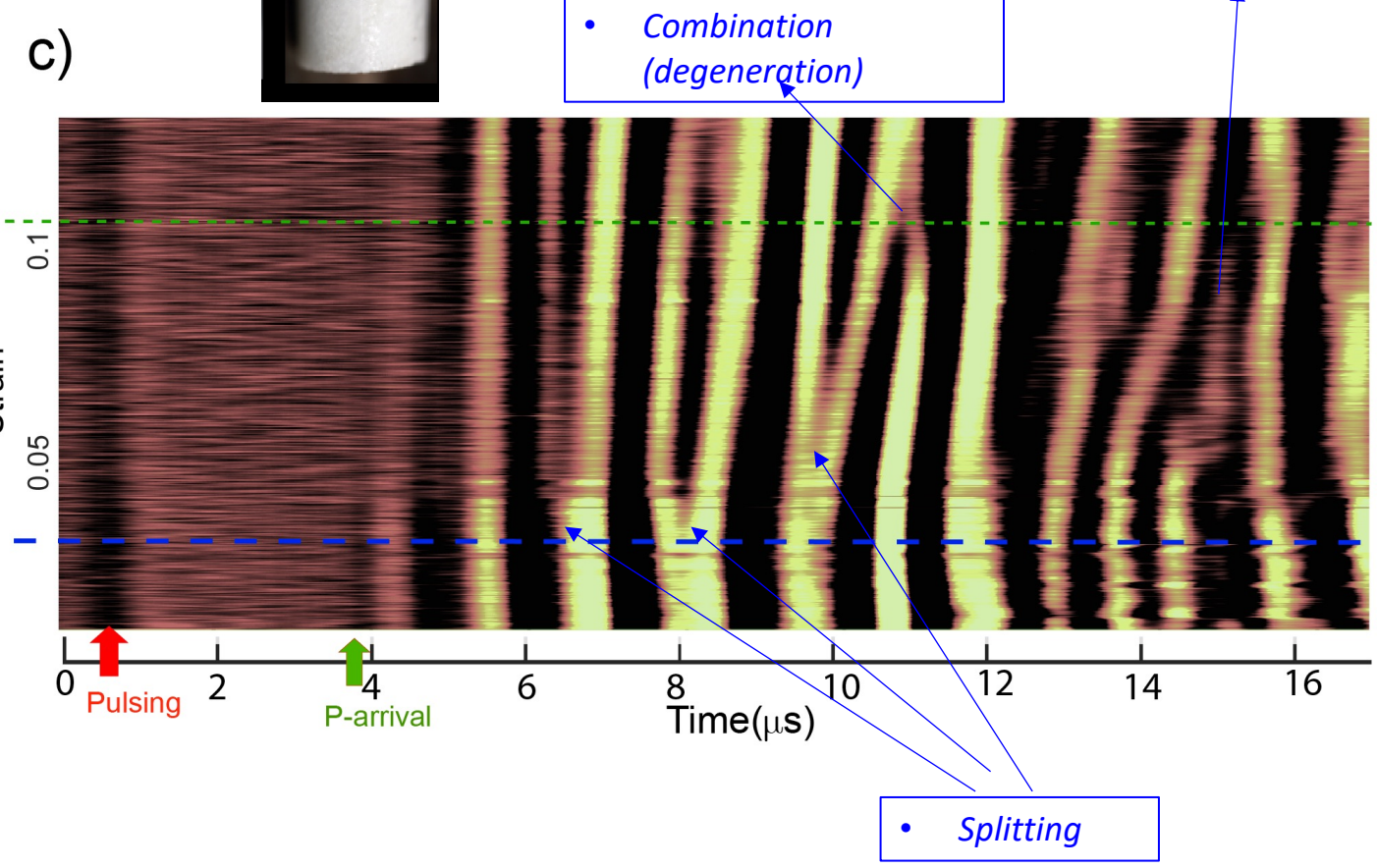
Ductile







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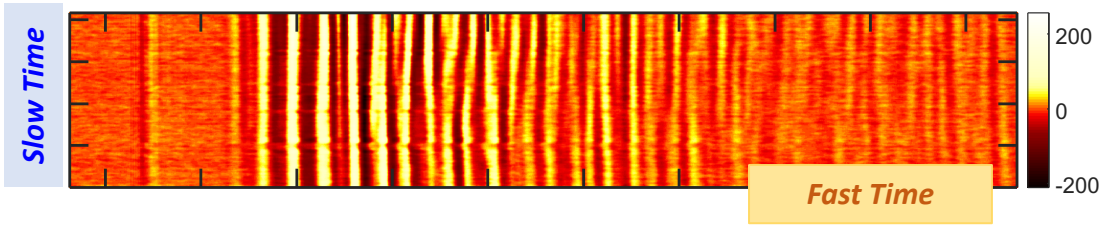
Patterns in fast-slow time: Clustering (unsupervised learning)

- ✓ *Clusters of **f-s** space unravel the deformation stages (faulting , strain hardening phase)*

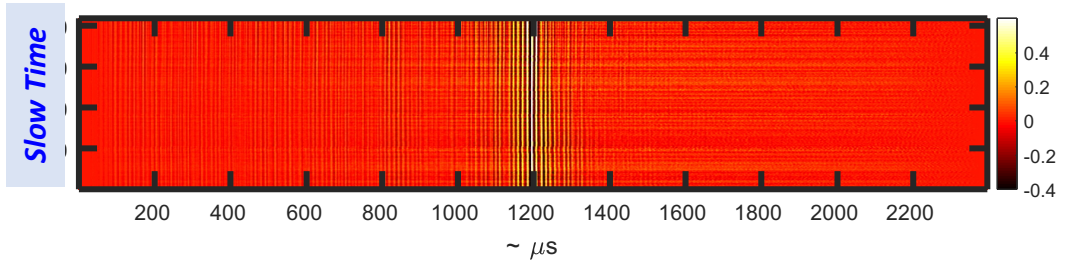
- *Deformation of Marble Sample: clusters on "Transformed Rug space"*

Ductile-250MPa Confining pressure



Step1

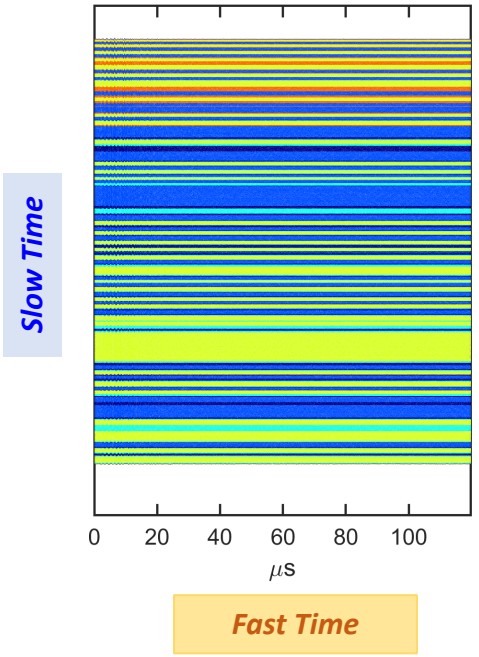
CROSS-CORRELATION



Step2

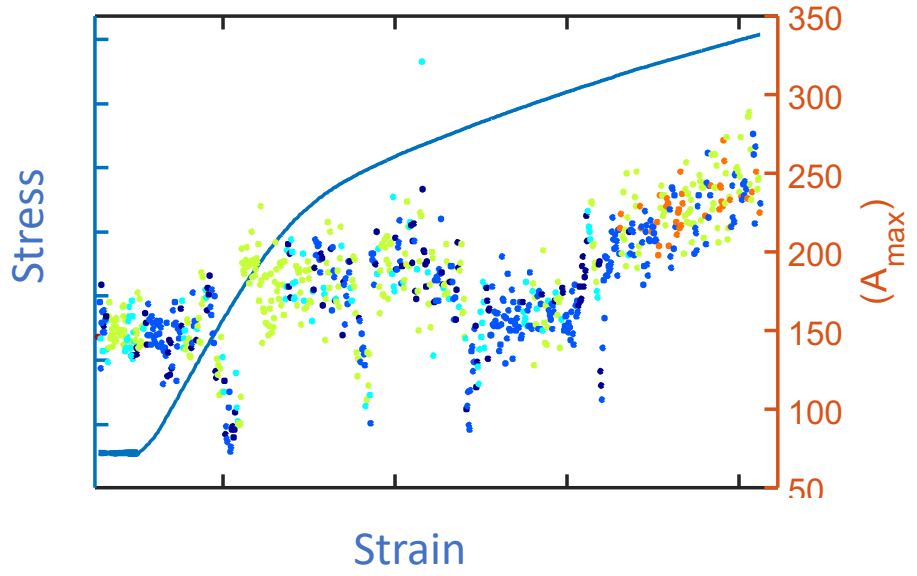
DTW *on cross-correlation space*

Dynamic Time Warping



Step3

Temporal-Clusters

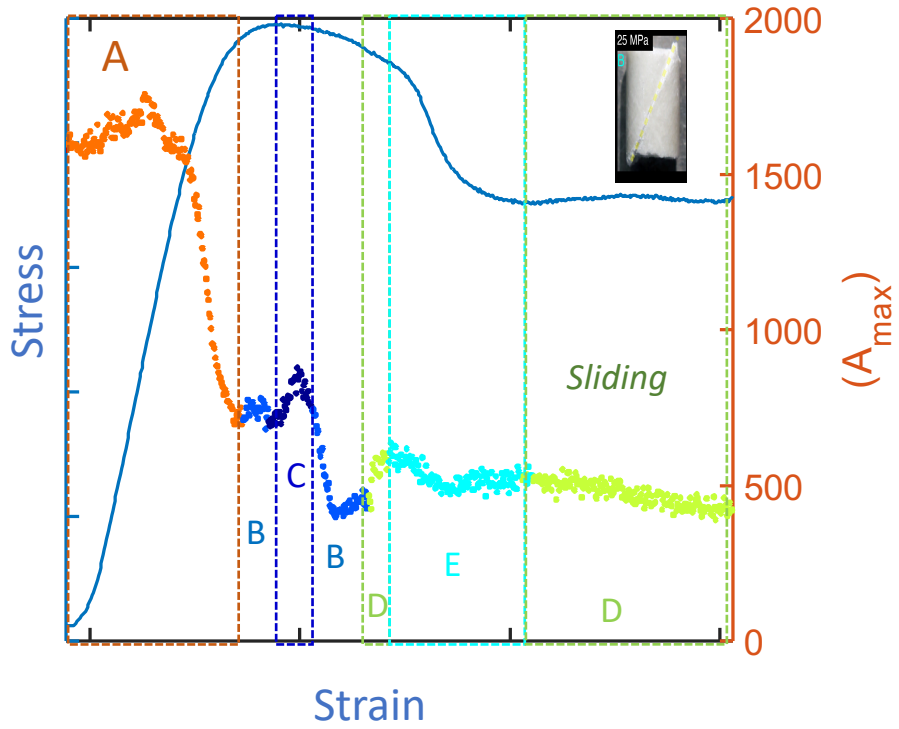


- *Clustering (Temporal or spatial) is another manifestation of fast-time*
- *Evolution of clusters =coupling of fast-slow relaxation times*

- *Classification based on Convolution(cross- correlation)*

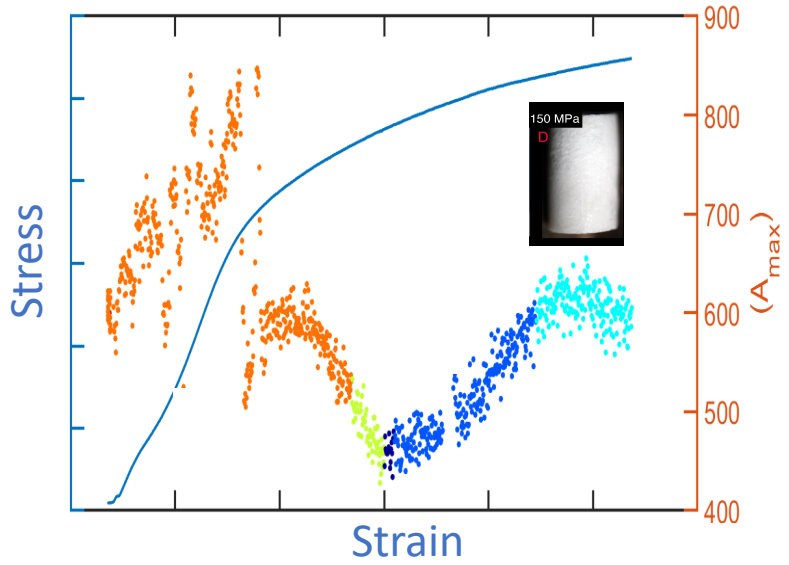
- *clusters of **f-s space***

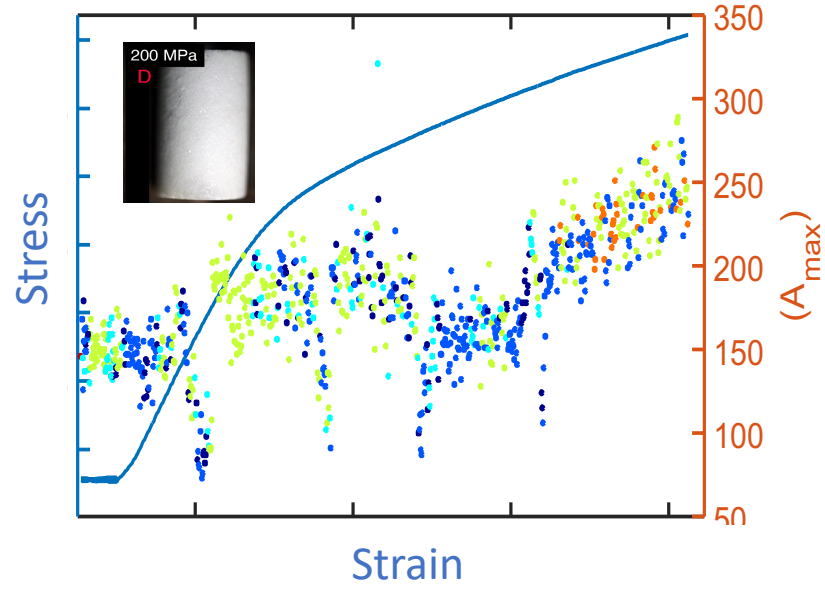
Brittle: Faulting



Brittle-Ductile Transition

Ductile: Strain- hardening



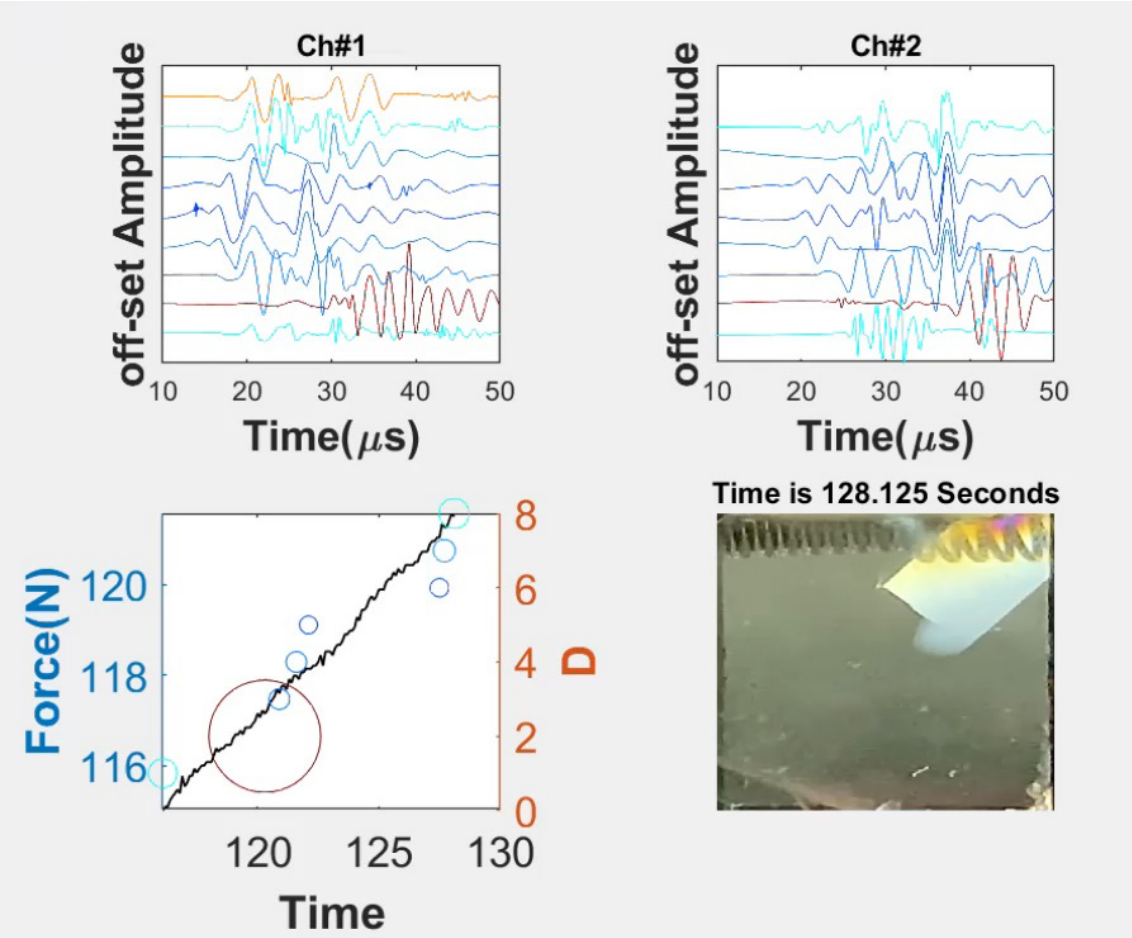


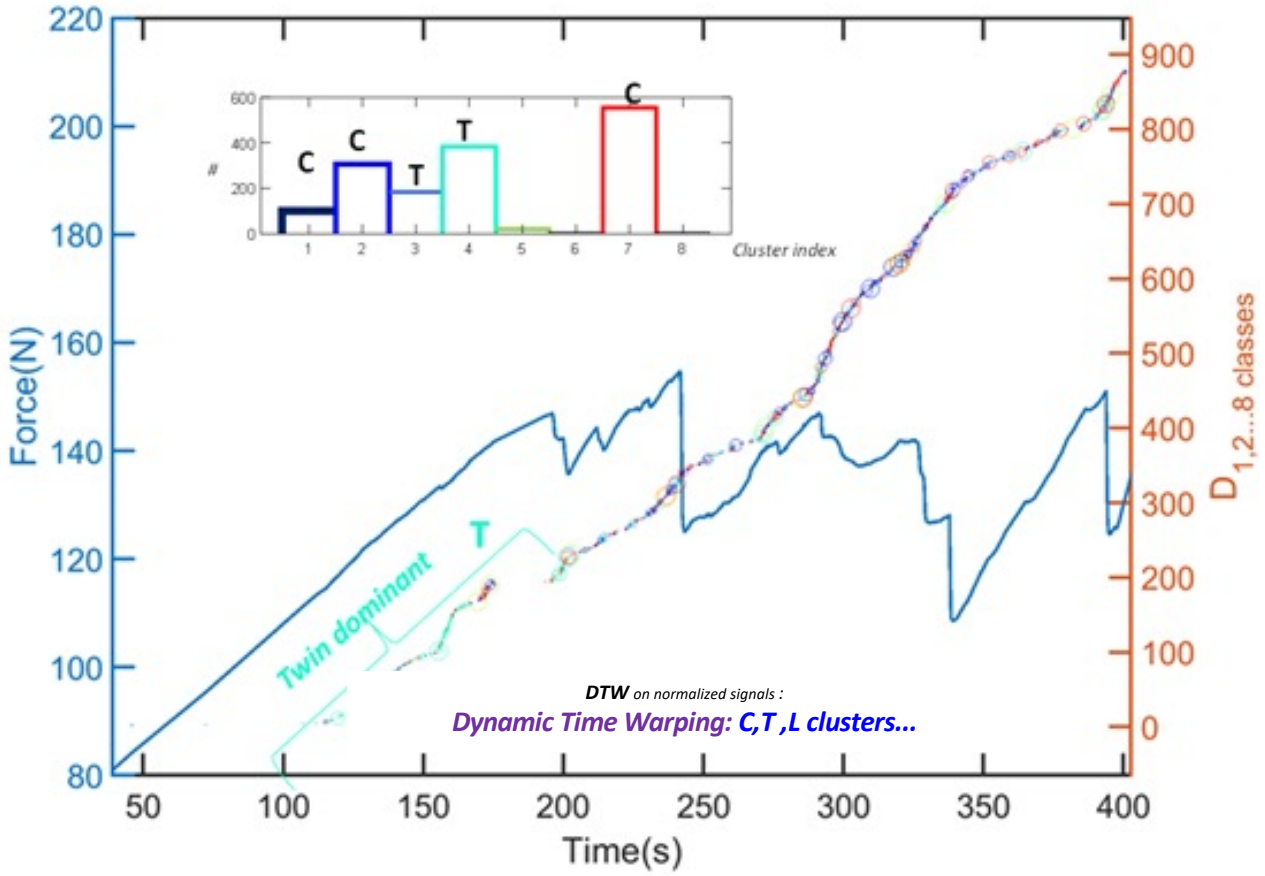
- *Clusters of **f-s** space might indicate the deformation stages (**faulting , strain hardening phase**)*

Do we have fast-slow spaces in “passive” excitations(i.e.,AEs)?...

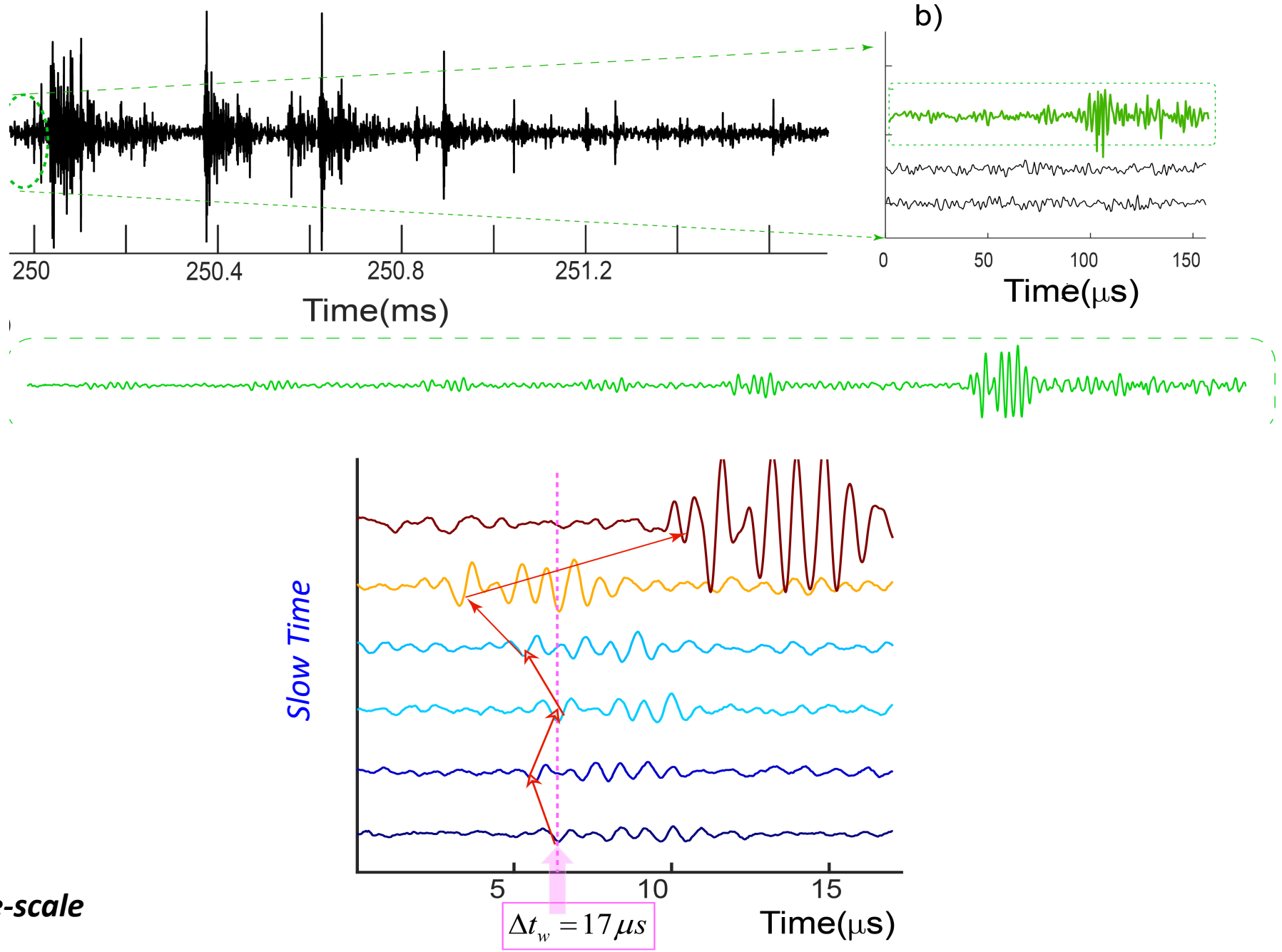
- ***Clusters of AEs (passive probe)*** *-in slow time (strain, load, etc):*

❑ *Each cluster is a* ***flavor*** *of fast-time* : ***sequence of clusters*** **in time or space is an indication** ***of spatio-temporal interactions of defects , stress-field evolution and relaxation parameters of the rock***



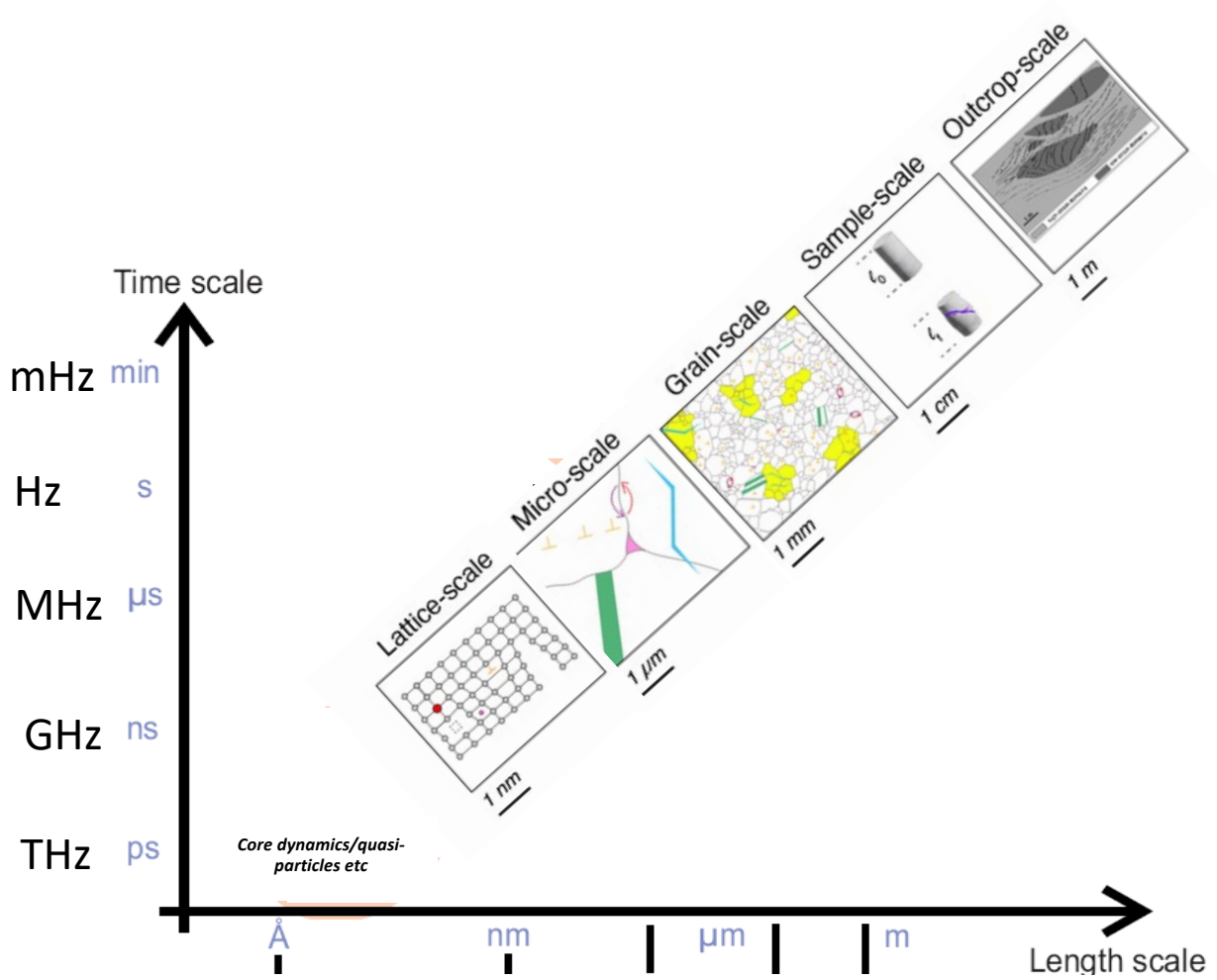


- *Slow Time – ms- from fast time -μs-: pump is dynamic (source)*



- ***Rise of ~constant time-scale***

- *Length scales ....Time scales : Ladder of scales and building macro from micro*



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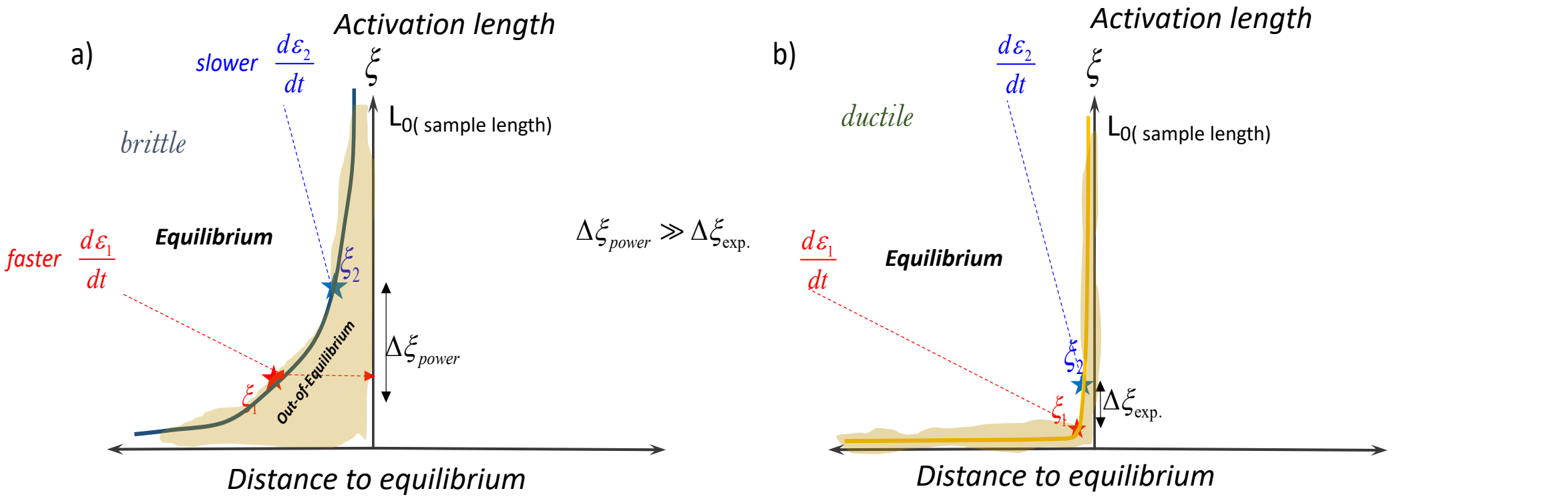
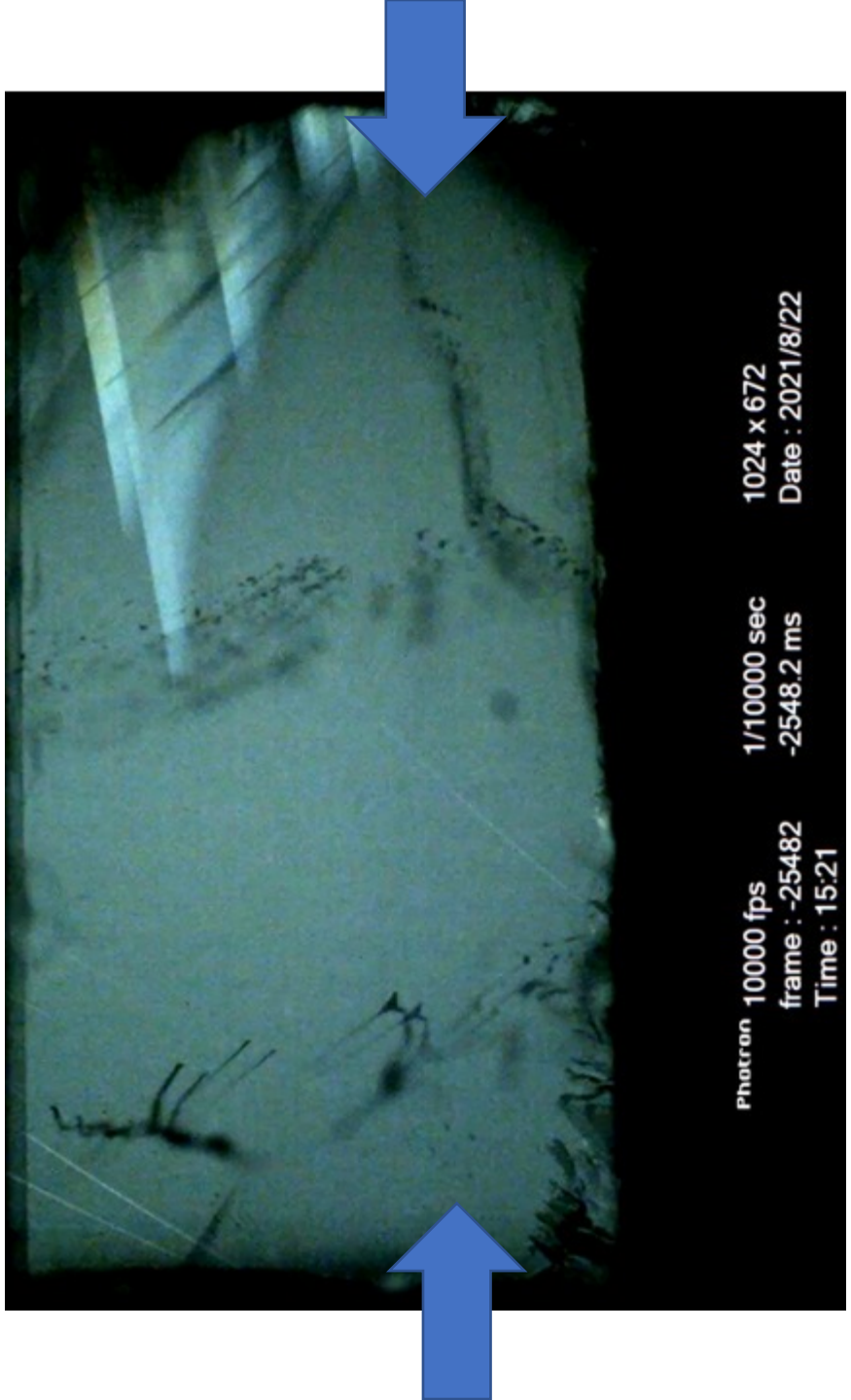
- ***Rise and Evolution of Defects*** *in different length/time scales :* ***Dynamic Relaxation Process***



Modified from O'Ghaffari et al, 2016, Scientific Reports
Zurek,1985,Nature; Kibble,1976

- *To have any excitation: one must push the "system" into the out-of-equilibrium phase (Zurek-Kibble Theory)*
- *Energy rate or ramp rate* ***competes*** *with equilibrium relaxation*
- *Time in impulse state (out-of- equilibrium) ~duration of an event*
- *More resilient relaxation results more uniform impulses states for a given range of energy rates*

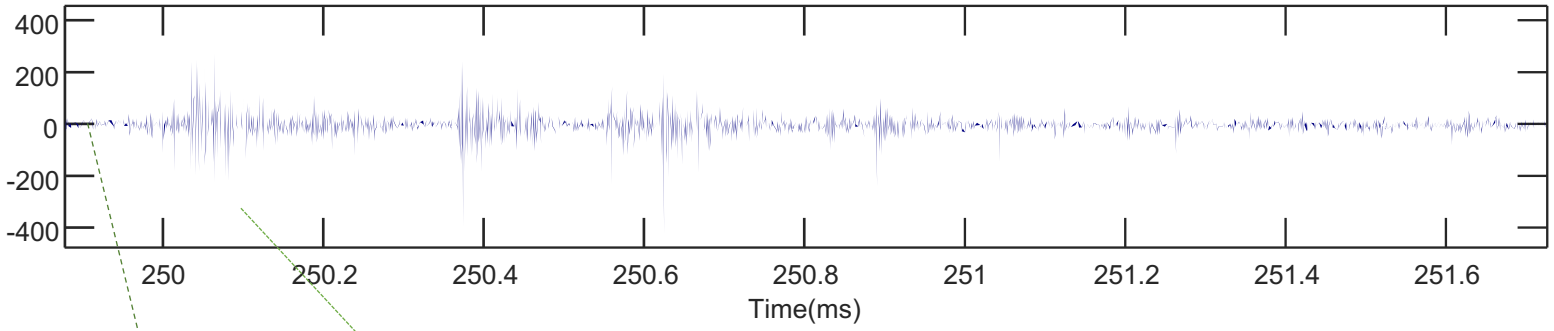
Questions?

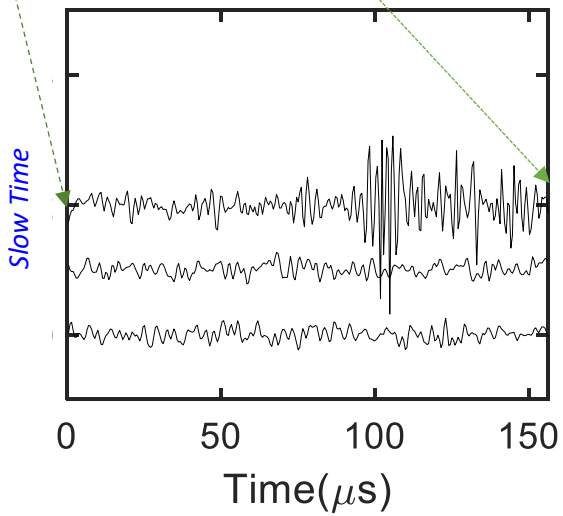


- *Twin propagation co-evolving with Thickening process:*

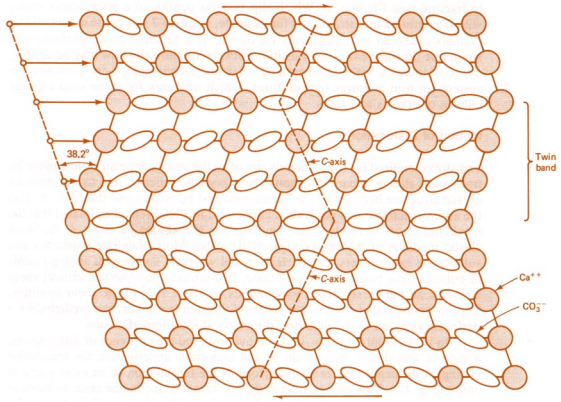
- *Shape of a twin (thickness versus length) == fast-slow time manifestation*

*Now slow Time is ms and fast time is μs.

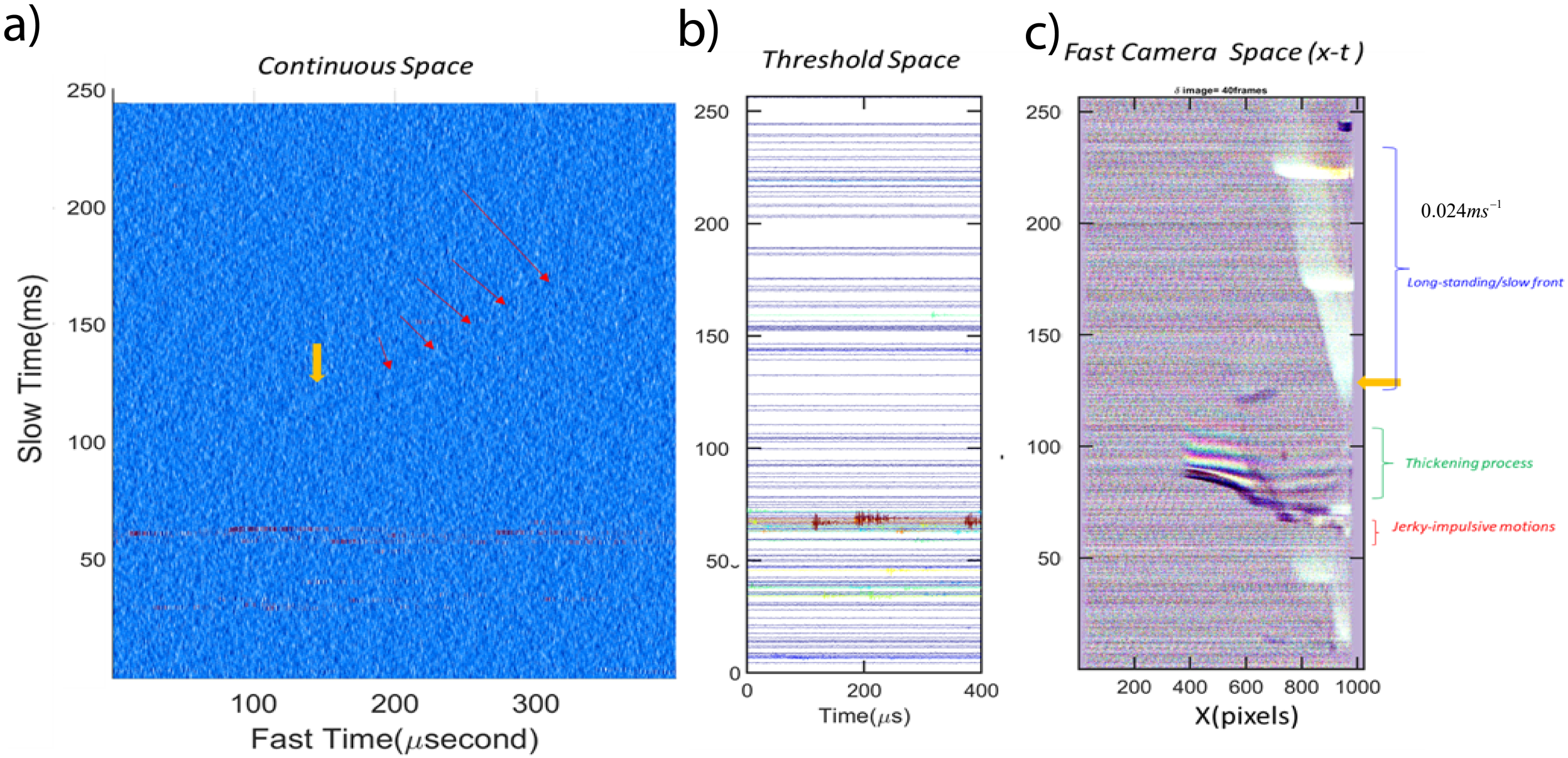




Twin gliding in calcite…



- *Thickening + developing Twin process :* ***The shape of the twin is a manifestation of fast-slow time scales….***



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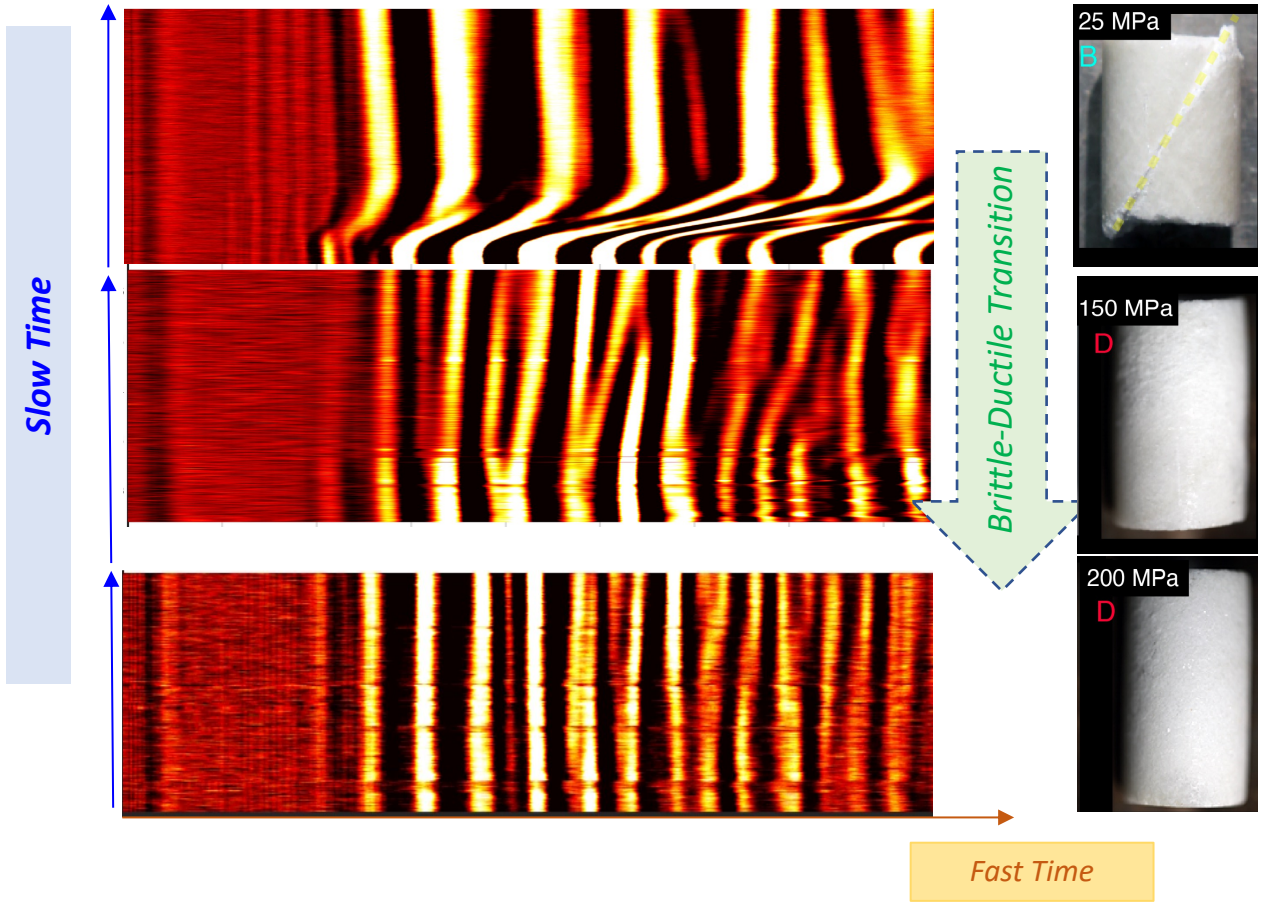
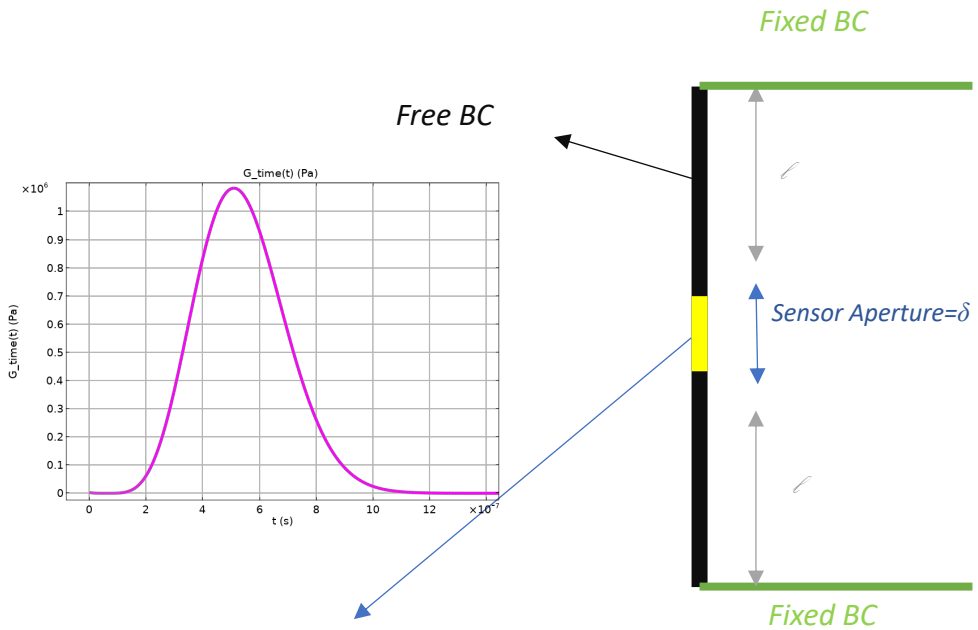
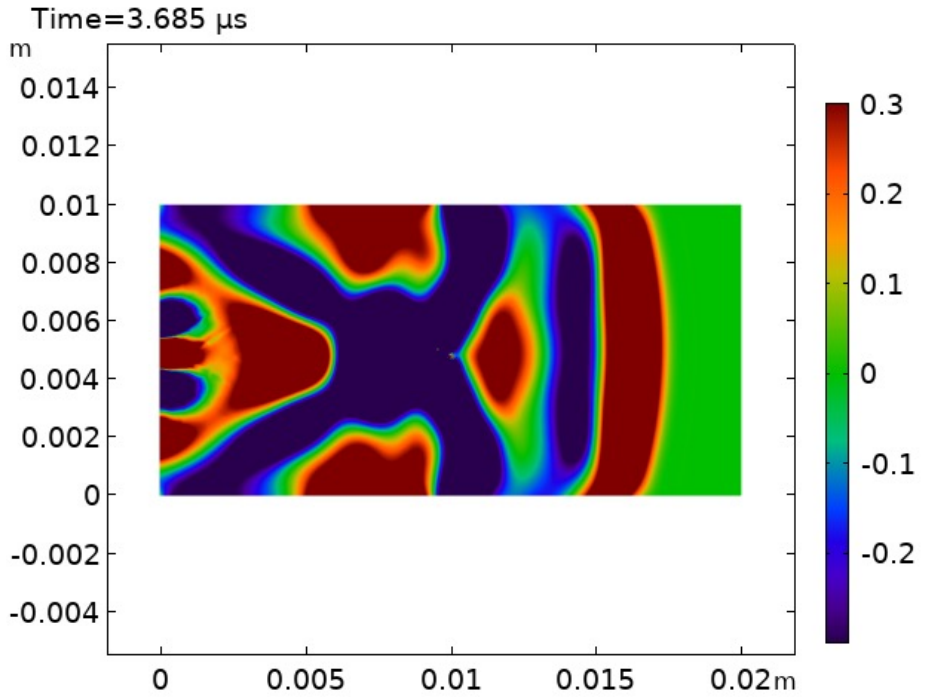
Patterns in fast-slow time...



Let's consider synthetic waves...



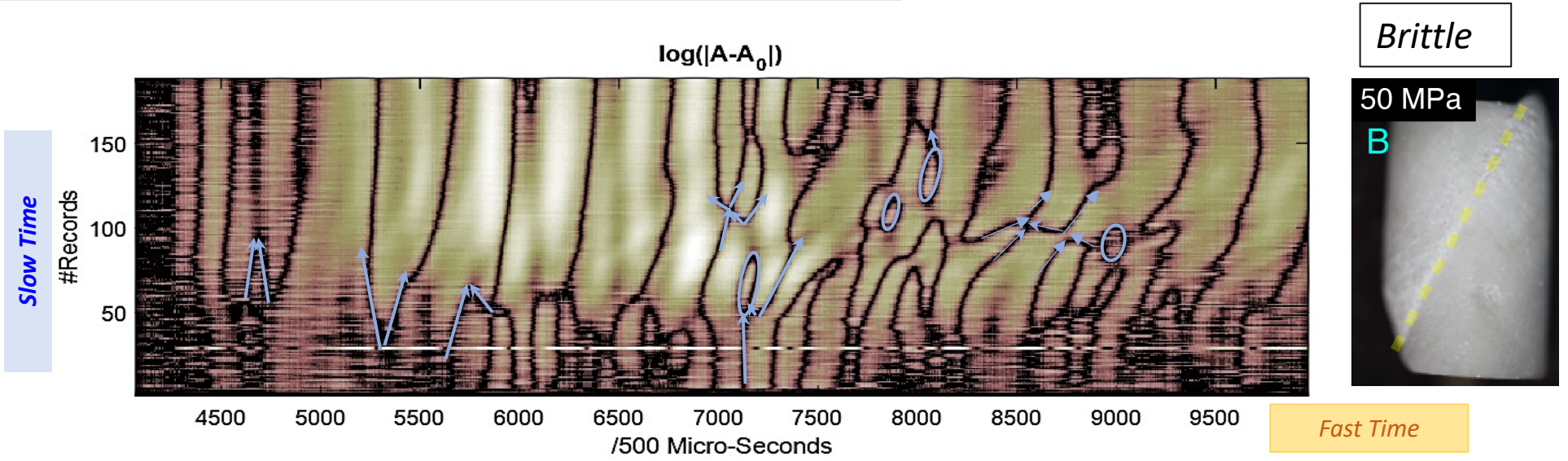


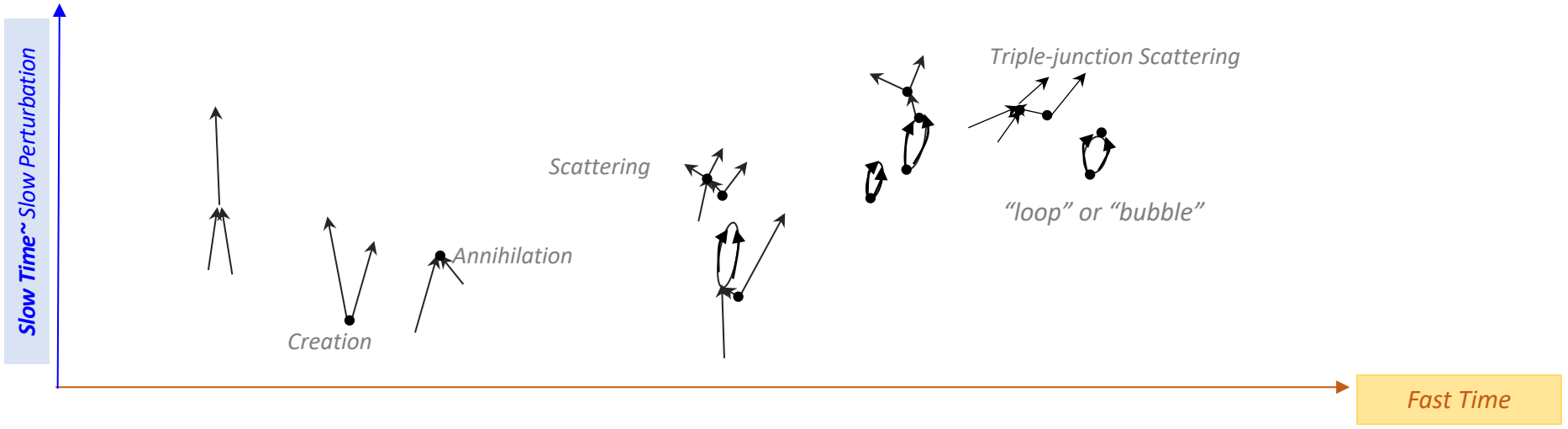
Vibrating Piezo-wafer(=single Gaussian impulse)

***Zero-crossing objects in f-s space :

Let's re-consider synthetic waves…

- *Deformation of Marble Sample: "Rug" space & **Interactions***



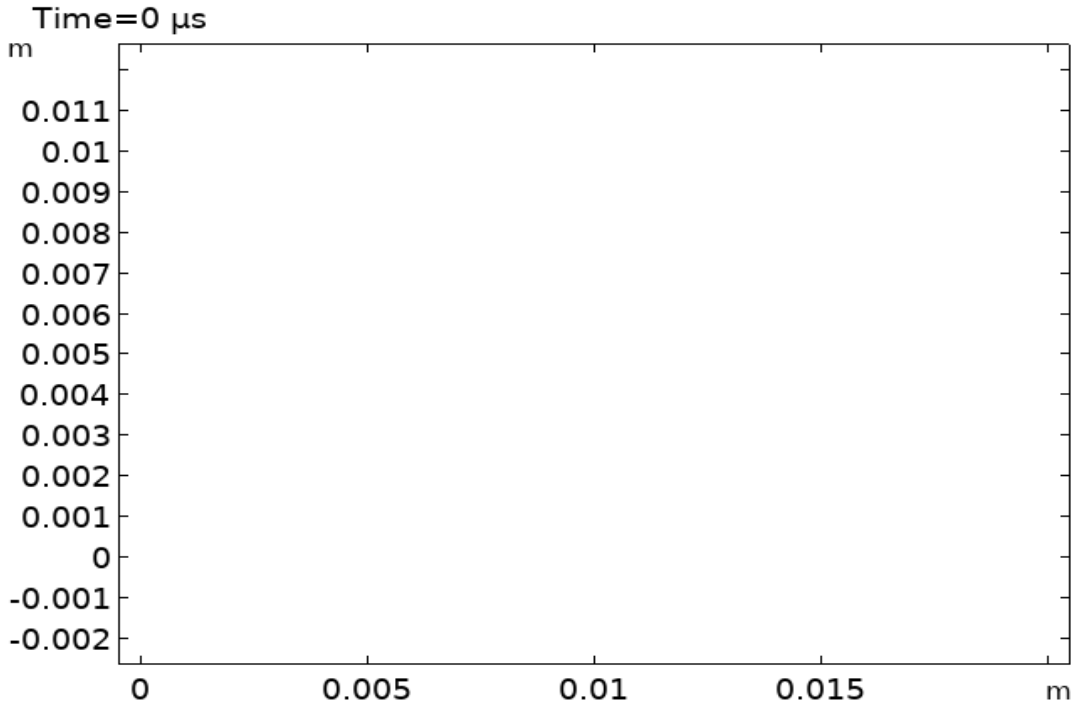


?

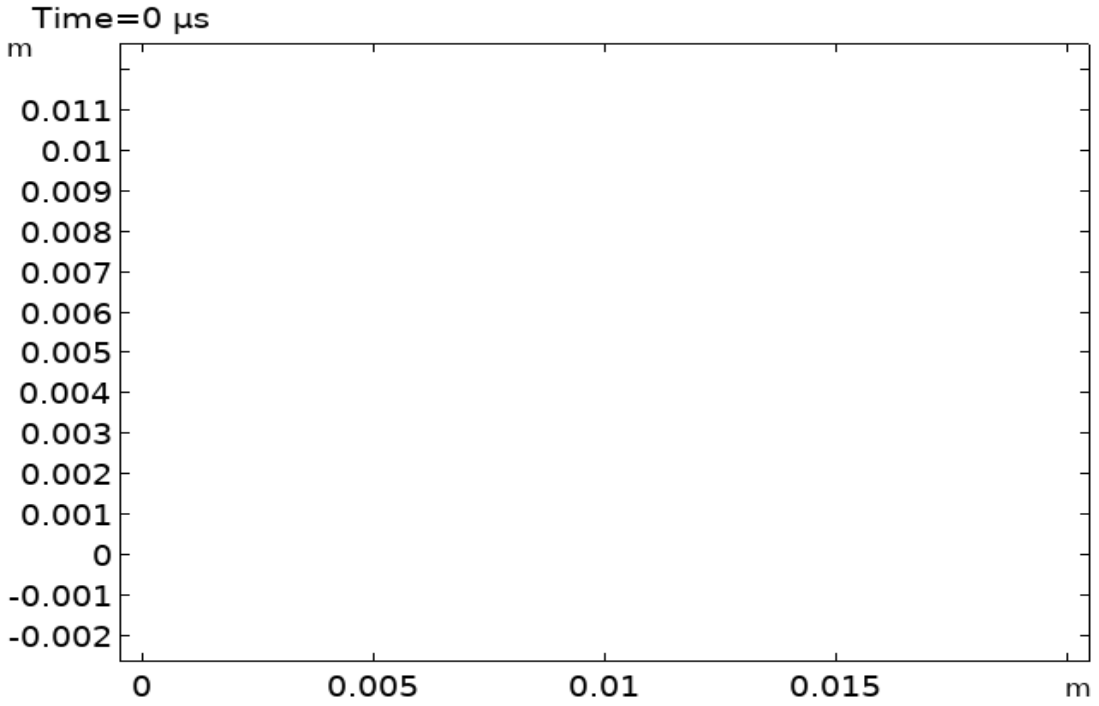
- *Rise of Interactions ("**Feynman-like Diagrams**" in fast-slow space): scattering and wave-wave interactions*

- *Zero-crossing domains in **X-Y** model of synthetic waveforms :Pressure field*

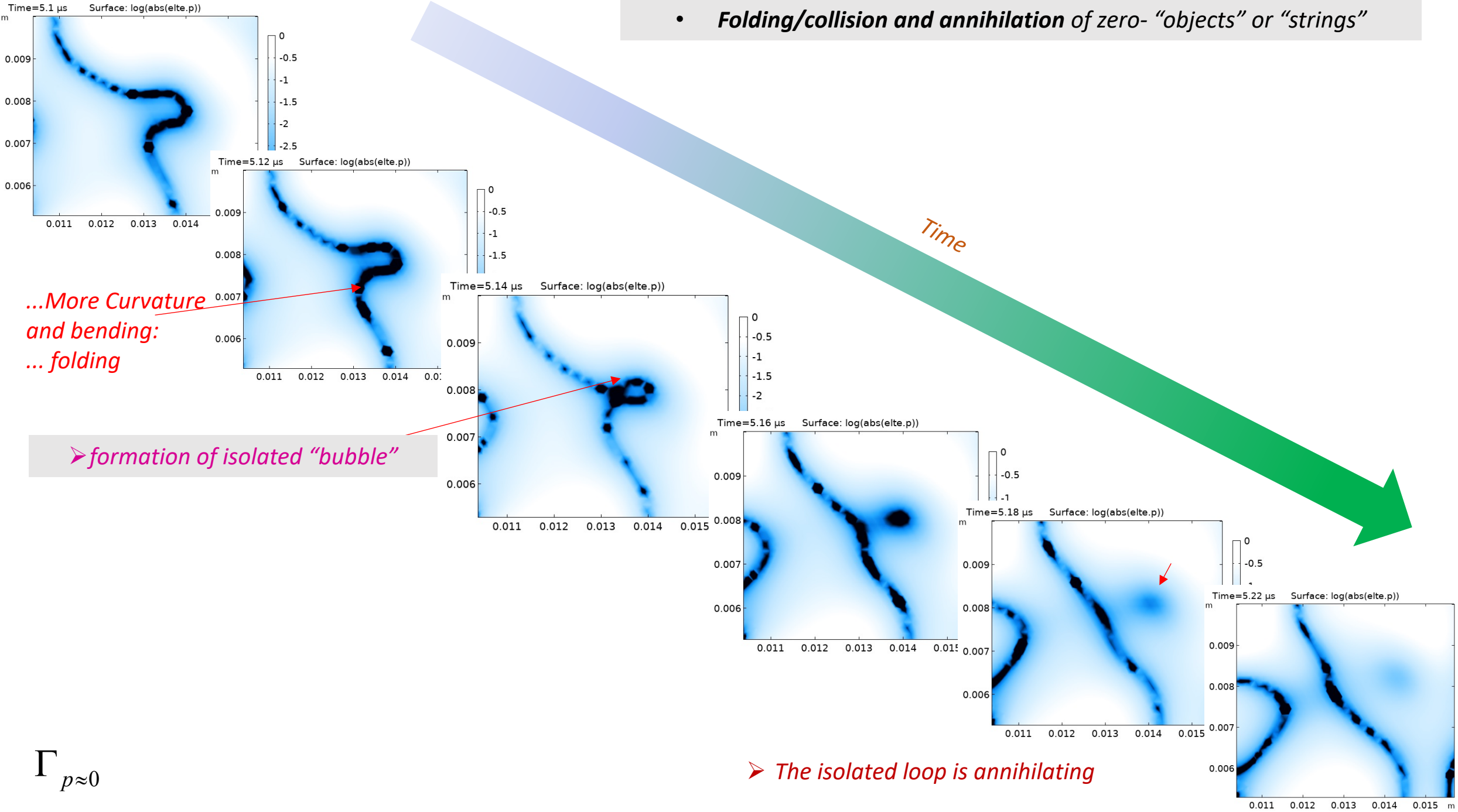
$$Z = \log|A(t_{[f=0-10\mu s]}, t_{slow} = Fault - stage2)|$$



$$Z = \log|A(t_{[f=0-10\mu s]}, t_{s} = stage3)|$$



- ***Folding/collision and annihilation*** *of zero- "objects" or "strings"*



Time

...More Curvature and bending: ... folding

➢ *formation of isolated "bubble"*

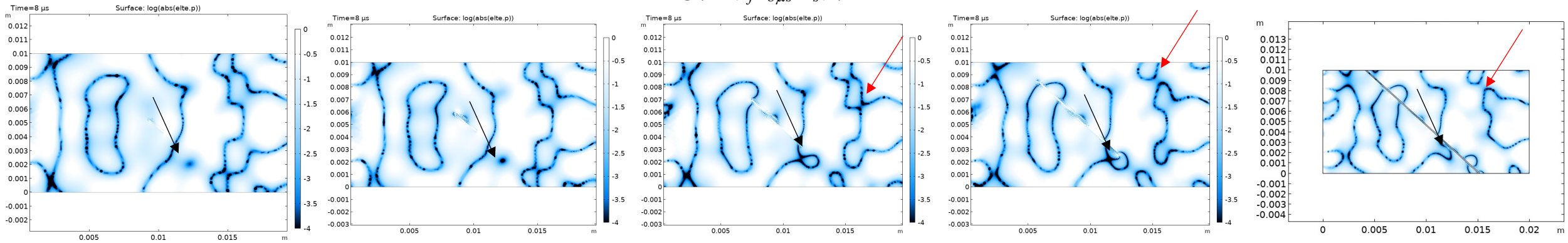
$\Gamma_{p\approx 0}$

➢ *The isolated loop is annihilating*

- *Interactions of Zero-pressure domains*

- *Example in **X-Y** model of synthetic waveforms :Pressure field*
- *..let's evolve the slow time with increasing fault length but **freeze "fast-time"***

$$Z = \log | A(t_{f=8\mu s}, t_s) |$$

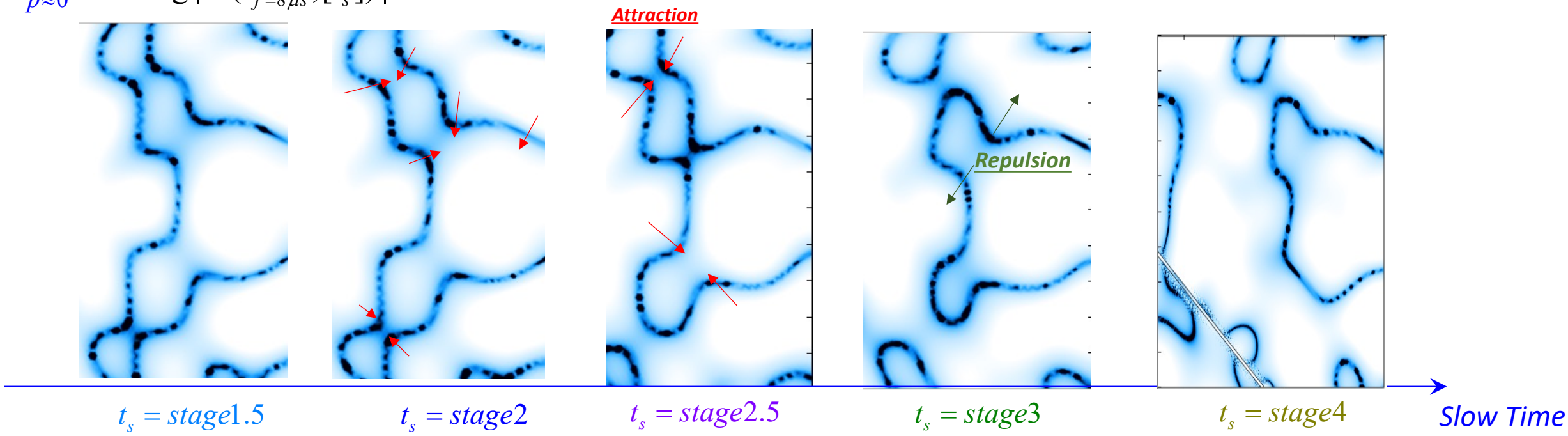


$t_s = stage1.5$ $t_s = stage2$ $t_s = stage2.5$ $t_s = stage3$ $t_s = stage4$

Slow Time=Faulting stages

- **Stages of faulting** *&Zero-crossing objects*

$\Gamma_{p\approx 0}$ $Z = \log|A(t_{f=8\mu s},[t_s])|$



Conjectures :

Zero-polarity objects are not stable in isolated forms ;

string objects are always ended in boundaries and no-isolated string is observed.

The bubble are stable but in short living forms