Laboratory Earthquakes:
From Lab-Scale Experiments to Global-Scale Seismic Events

The Aurel Stodola Lecture

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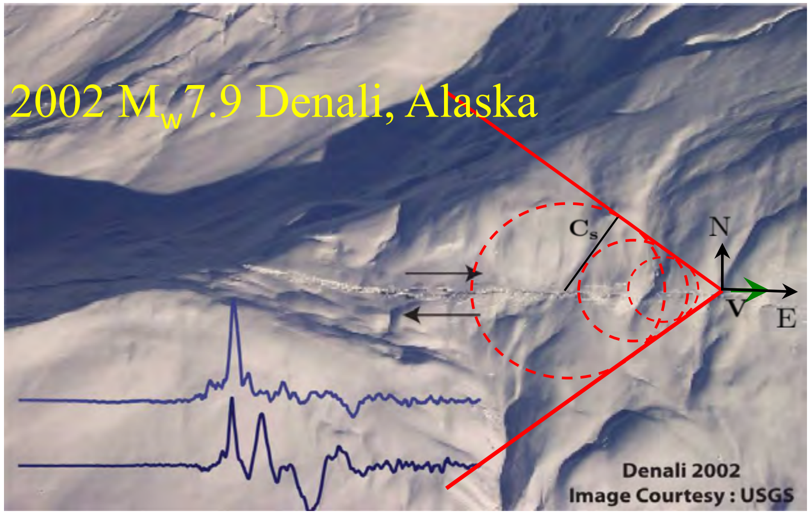
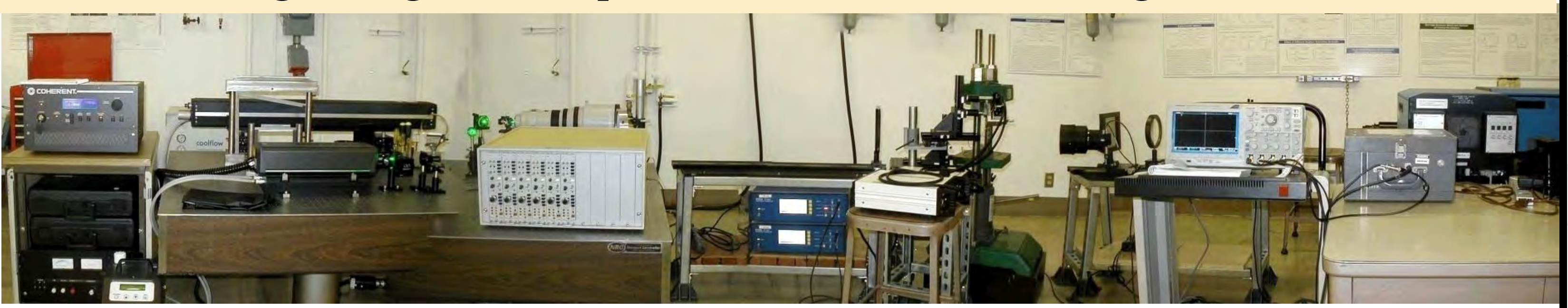


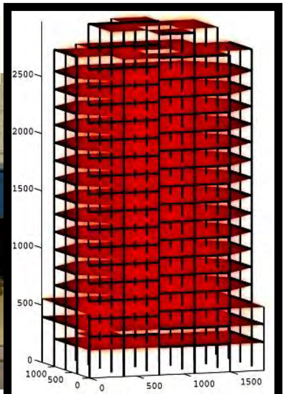
2002 M_w7.9 Denali, Alaska

Denali 2002
Image Courtesy : USGS

1999 M 7.5, Izmit ,Asia Minor , Turkey .

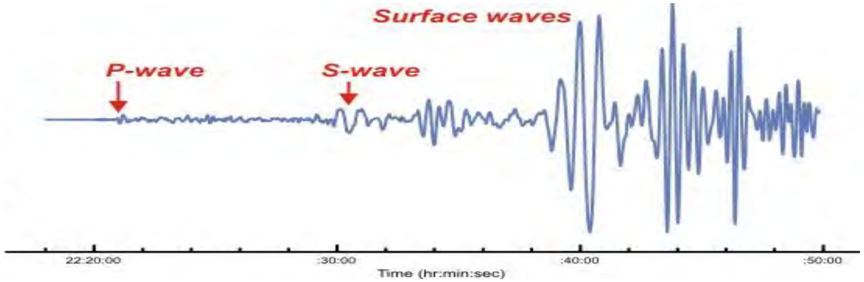
Producing surrogate earthquakes in GALCIT s seismological wind tunnel





What Is a crustal Earthquake ?

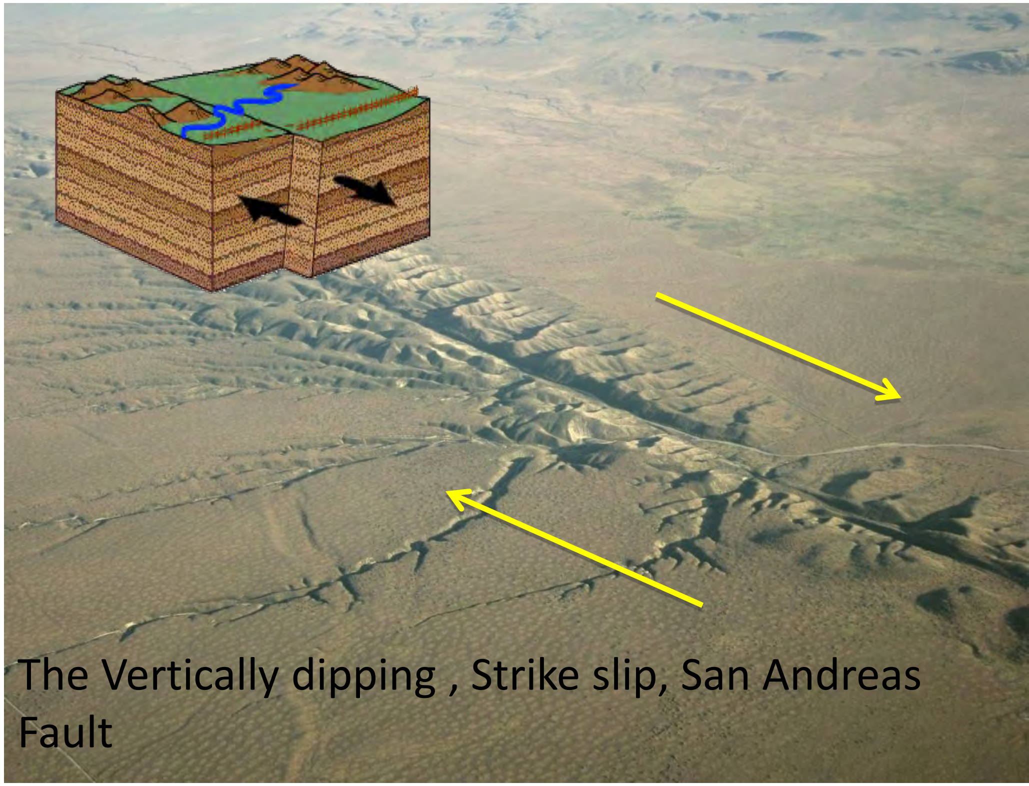
Time history of Ground shaking



Earthquake is a term used to describe both sudden slip on a fault, and the resulting ground shaking and radiated seismic energy caused by the slip.

Earthquakes are generated by spontaneous , frictional (shear), ruptures occurring along weak planes (faults) in the crust :

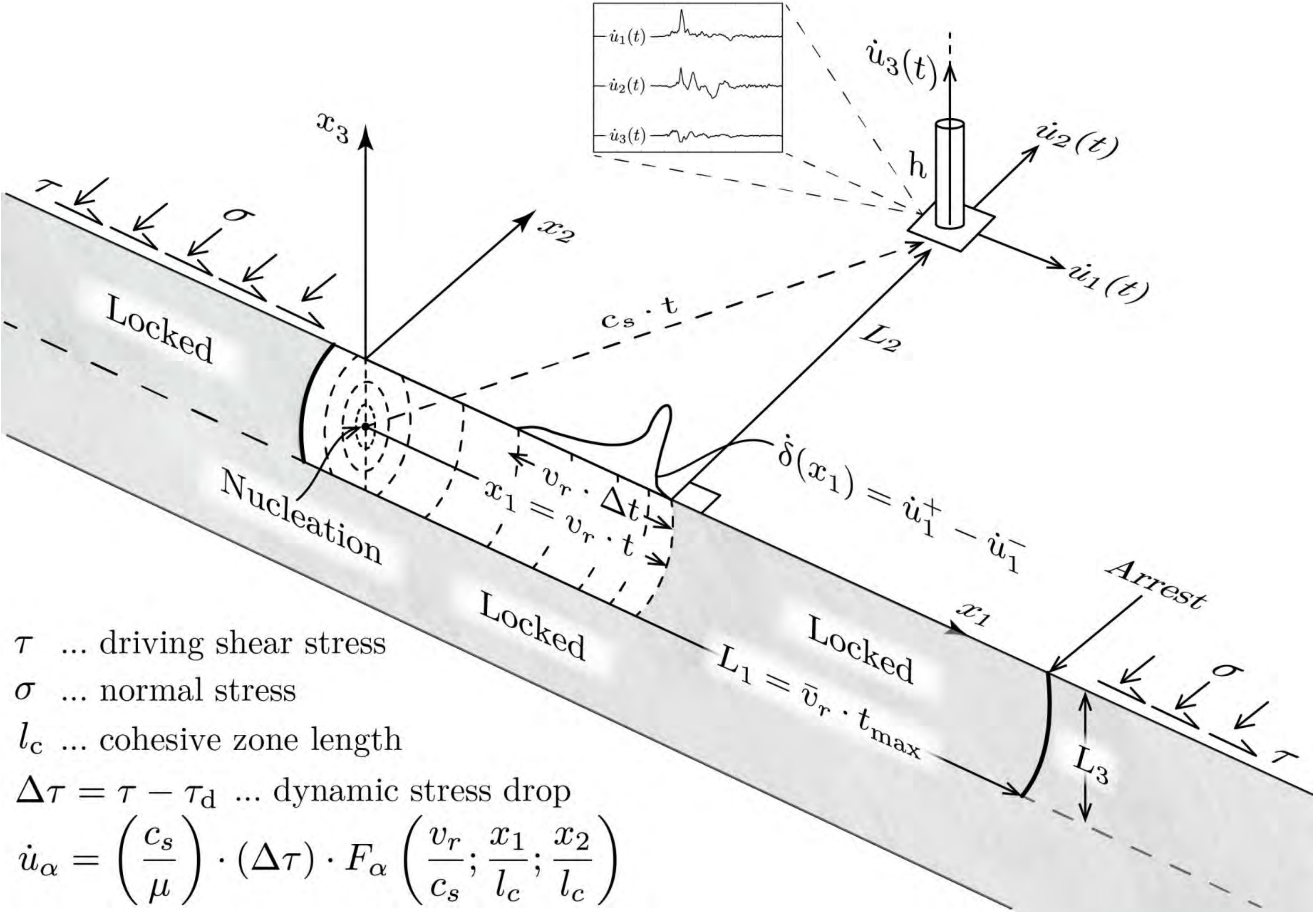
"Ruptures" are areas of sliding (Slip) propagating with very high speeds along a frictional (incoherent) interface (Fault).
The rupture speed is the speed of dynamic unzipping and governs the nature of near-fault ground shaking.
It is comparable to the wave speeds of rock



The Vertically dipping , Strike slip, San Andreas Fault

Rate of Relative Plate motion ~ 20mm/ year

“Ruptures”are areas of sliding (Slip) propagating with very high speeds along a frictional (incoherent) interface (Fault). - Equivalent to fast unzipping of the fault

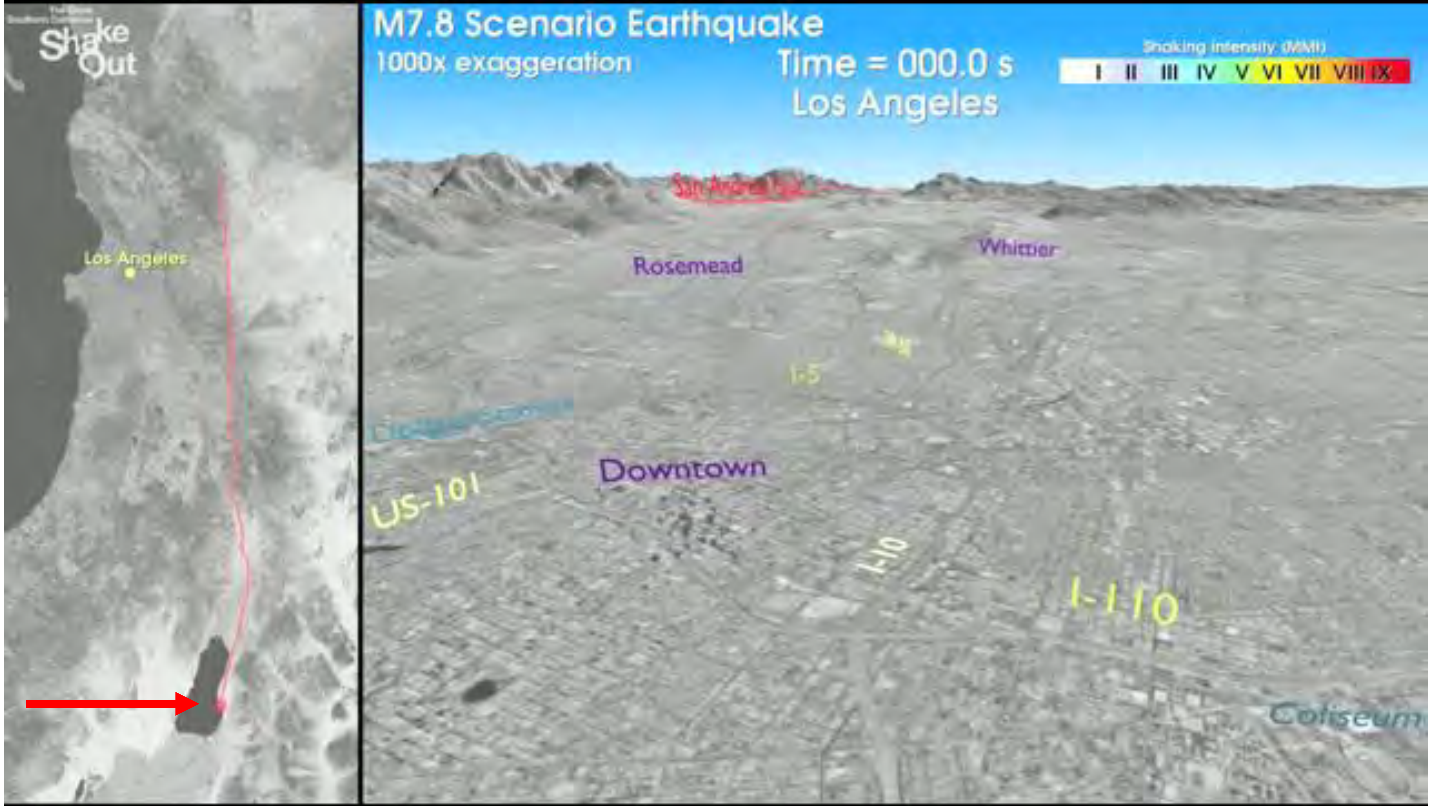


GENERIC STRIKE-SLIP FAULT RUPTURE GEOMETRY AND DYNAMICS

“Ruptures”are areas of sliding (Slip) propagating with very high speeds along a frictional (incoherent) interface (Fault). - Equivalent to fast unzipping of the fault

Brad Aagaard (CE Ph.D, 2000)
Robert Graves (GPS PhD, 1990)

Pressure Wave (~ 5.9km/s), Shear (~ 3.2km/s), Rayleigh (~ 2.9km/s)



Numerical simulation of an earthquake rupture propagating dynamically from the EPICENTER North, towards Los Angeles.

- The ground-shaking intensity and radiated energy are related to rupture speed

How high could the Rupture Speed (v)be ? Can v be Super-Shear ($c_S < v < c_P$)?

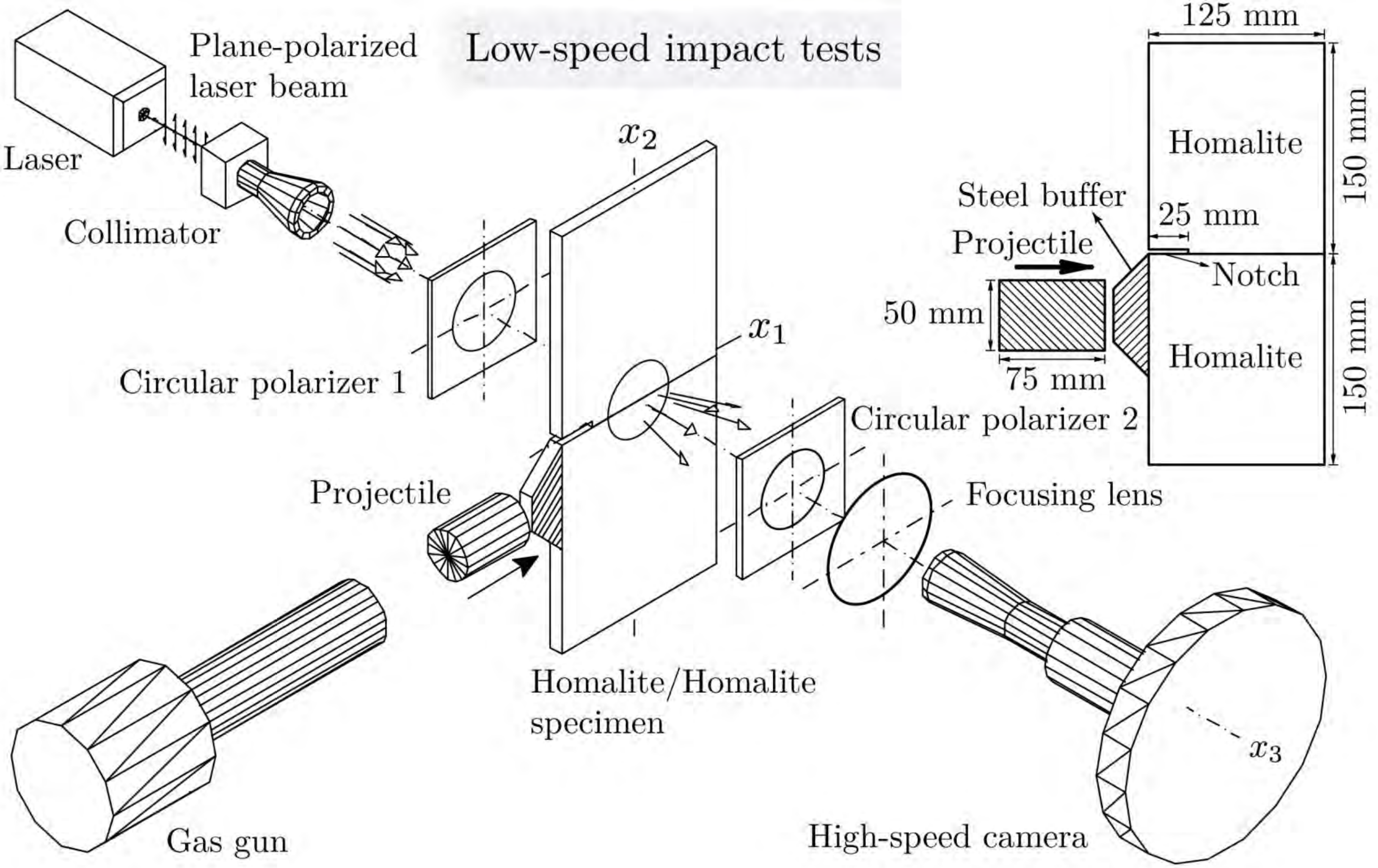
SECTION 1

THE FIRST SUPER-SHEAR RUPTURES TO BE OBSERVED IN THE LAB

A Brief Historical Introduction
and
Connections of Crustal Fault Mechanics to Engineering Fracture Mechanics (EFM) of Jointed Structures, Layered Solids and Composites

Capturing super-shear ruptures in the laboratory

Low-speed impact tests



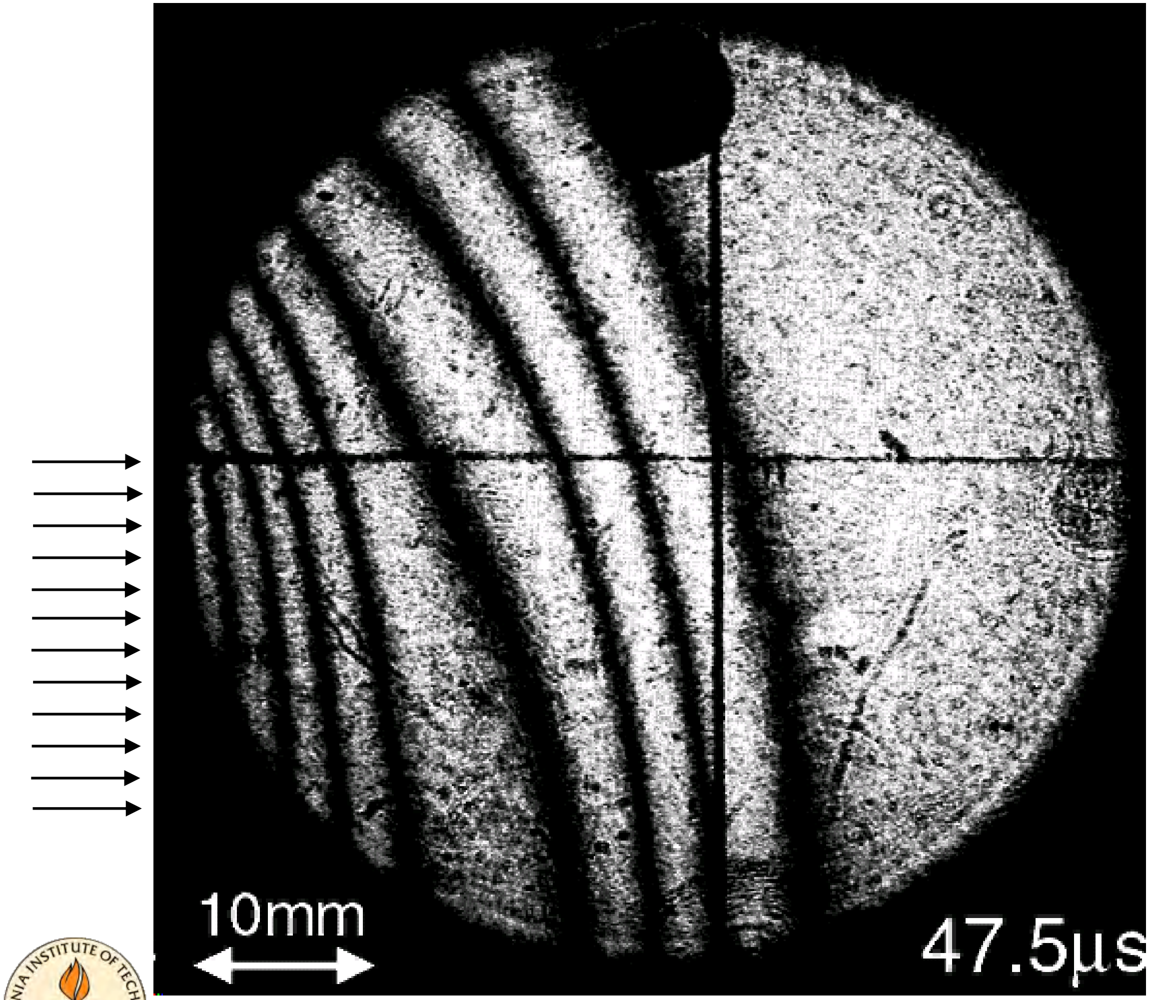
[1] A. J. Rosakis, O. Samudrala, and D. Coker. "Cracks faster than the shear wave speed." Science, 284(5418):1337-1340, 1999.

[2] A. J. Rosakis, O. Samudrala, and D. Coker. "Intersonic shear crack growth along weak planes." Mater. Res. Innov., 3:236-243, 2000.

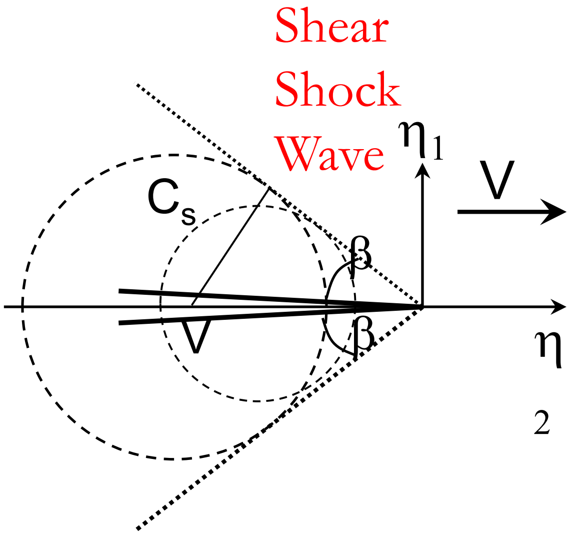
DEMONSTRATING THAT SUPERSHEAR CRACKS EXIST

(Rosakis, Samudrala and Coker, Science 1999)

Motivation: Design of Composite(ONR) and Bi-Material structures (ARO)



Super-Shear ($c_S < v < c_P$)



$V=C_S/\sin\beta$

Ruptures are:

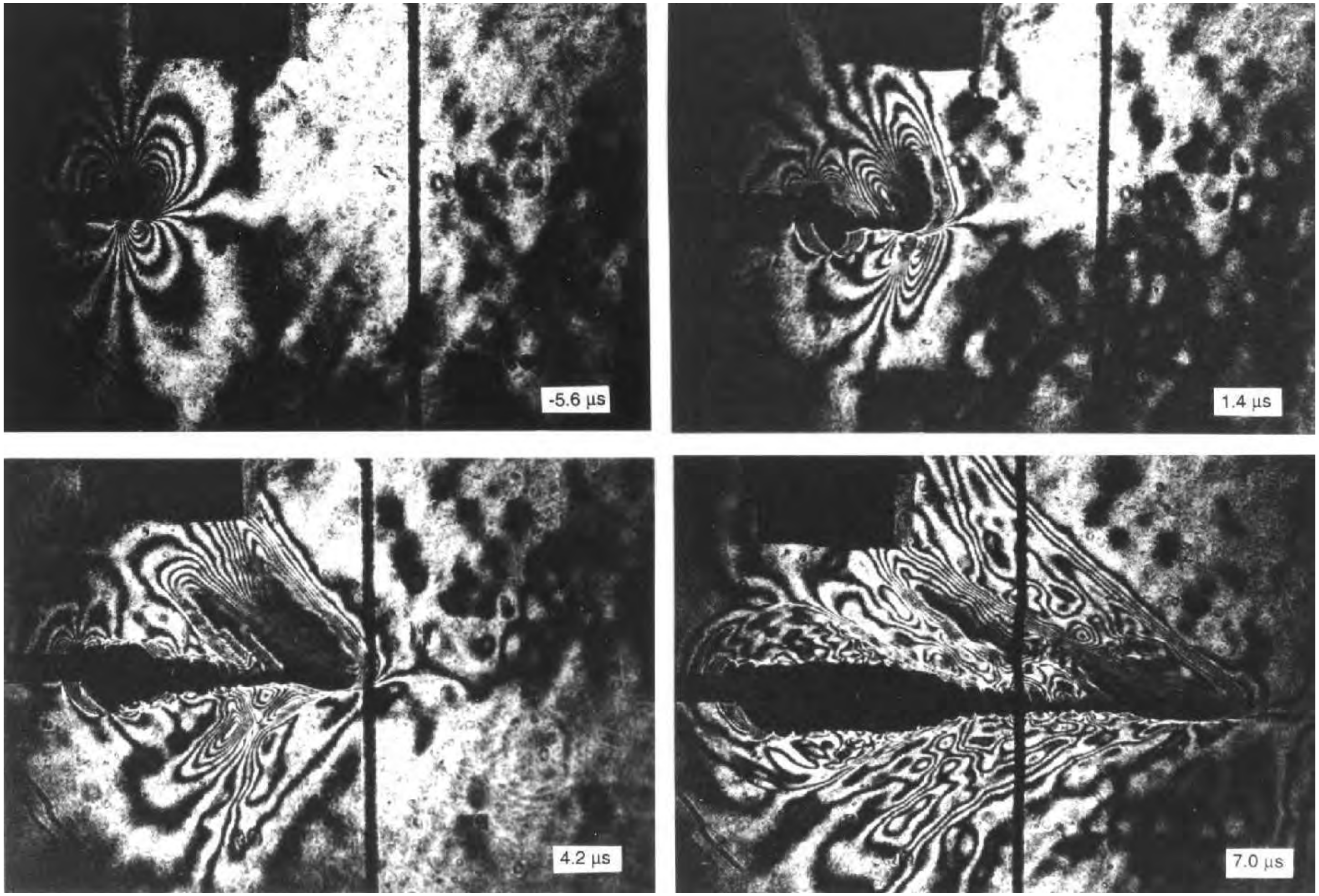
1)Impact-induced, non-spontaneous.

2)Interfaces are Coherent.

DISCOVERY OF THE FASTEST CRACKS IN THE WORLD

Breaking The Speed Limit of Crack Growth in Composites subjected to Impact

(Unidirectional , Carbon–Fiber Reinforced Composite, CGS Inrerferometry)



Rosakis , Coker &
Samudrala,
Science (1999)
Coker & Rosakis,
Phil. Mag A., 2001

Super-Shear Rupture

($c_S < v \sim c_P$)

← *7.5km/s!*

=22 Mach

BET WITH THE CALTECH SEISMOLAB DIRECTOR

WHAT WAS THE BET:

Is it possible to generate Super-Shear ($c_S < v < c_P$) ruptures in frictional interfaces and faults under conditions of simple static tectonic loading and NOT impact.

•Within resolution of the inversion process the majority of field evidence suggests rupture speeds, *v*, between 0.8 c_R to c_R of crustal rock (~2.9Km/s)
Venkataraman and Kanamori , *JGR* (2004)

•These ruptures ate called Sub-Rayleigh ($v < c_R = 0.93\, c_s$) and are also sub-shear.

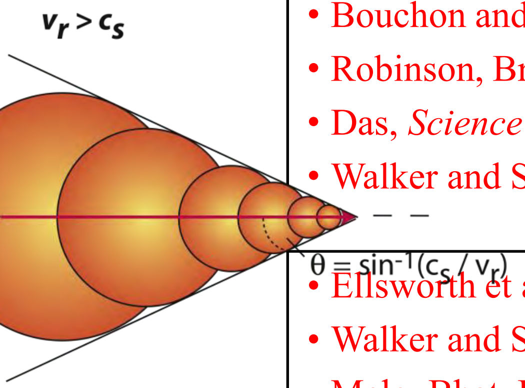
Until 1999 there were only ***indirect*** evidence of ***Super-Shear ($c_S < v < c_P$)*** rupture speeds along small fault segments.

References	*Events*
• R. Archuleta, *JGR* (1984) • Spudich and Kranswick, *BSSA* (1984)	1979 Imperial Valley, CA; M_w 6.5

After the discovery of Super-Shear ruptures in composite materials, , our laboratory, begun to look for experimental proof for the existence of Super-shear rupture under conditions mimicking tectonic, far-field loading.

Direct Evidence of Super-shear ($c_S < v < c_P$) Rupture Speeds from the Field in three large Earthquakes after 1999.

In parallel and together with our collaborators from Seismology, we begun seeking for direct field evidence of super-shear occurrences in both past (Historic) and new Earthquakes around the world.



References	*Events*
- Bouchon, Bouin, Karabulet, Toksöz, Dietrich and Rosakis, *GRL* (2001) - Xia , Rosakis and Kanamory ,Science, 2004. - K. Xia, A.J. Rosakis, H. Kanamori and J.R. Rice, Science 2005)	1999 Izmit (Νικομήδια), Turkey; M_w 7.4
- Bouchon and Vallee, *Science* (2003) - Robinson, Brough and Das, *JGR* (2006) - Das, *Science* (2007) - Walker and Shearer, *JGR* (2009)	2001 Kunlunshan, Tibet ,China; M_w 7.8 (Transition)
- Ellsworth et al., (2004) - Walker and Shearer, *JGR* (2009) - Melo, Bhat, Rosakis and Kanamori , *Earth and Planetary, Science (20013)*	2002 Denali, Alaska; M_w 7.9 (Transition and near-fault record)
- Amlani, Bhat, Simons, Schubnel, Vigny, Rosakis, Efendi, Elbanna, Abidin *work in Progress* (2019)	2018 Sulawesi-Palu earthquake in Indonesia; M_w 7.5

All large

SECTION 2

THE SEISMOLOGICAL WIND TUNEL:

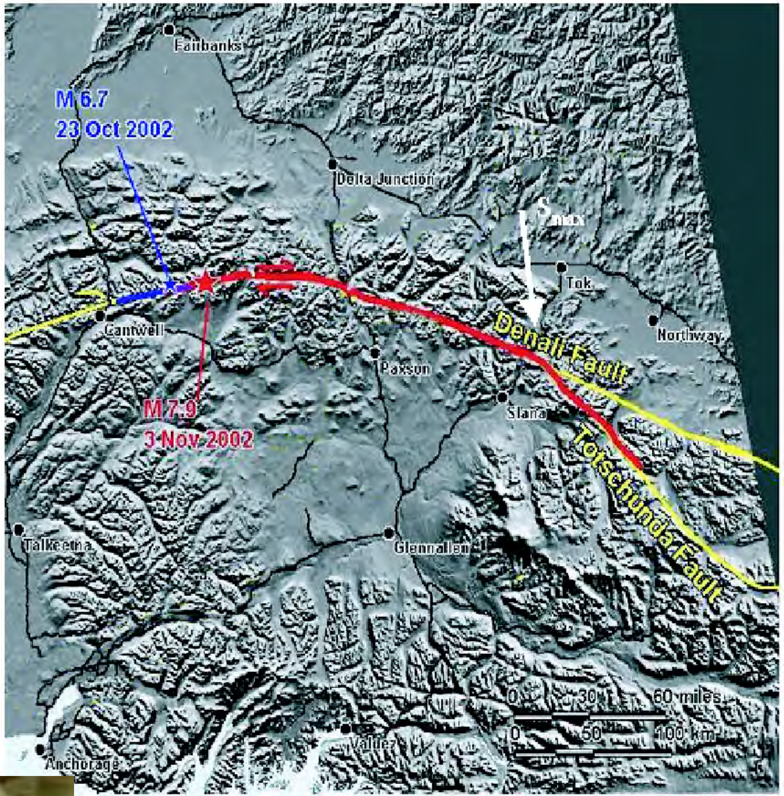
Creating model “Laboratory Earthquakes” in a controlled environment allow us to study real ones
Just like models in Wind Tunnels were used to design airplanes

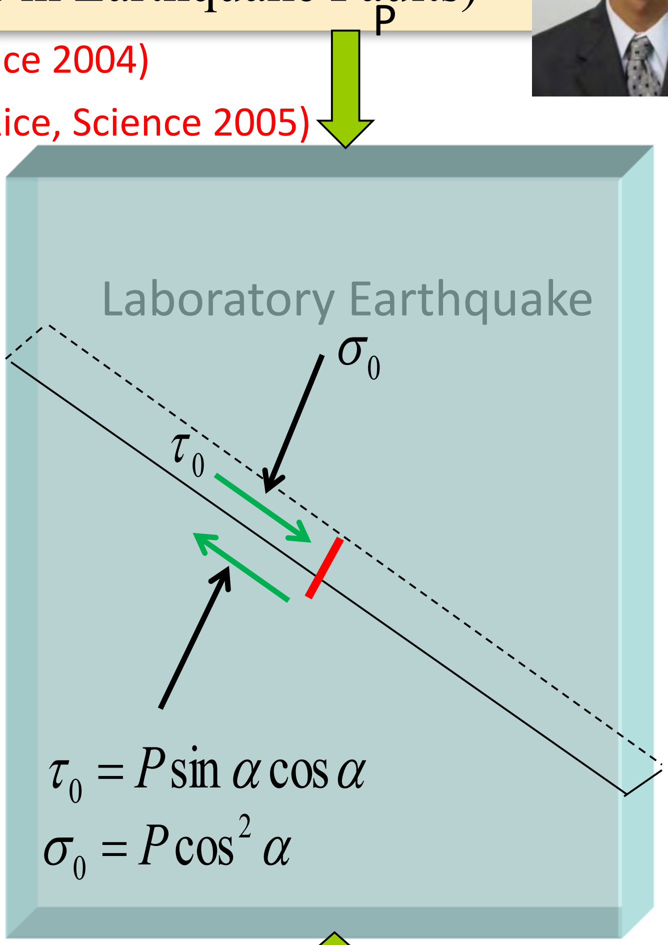
From Real to Laboratory Earthquakes

(Mimicking Spontaneous Rupture Events in Earthquake Faults)

(K. Xia, AJ. Rosakis and H. Kanamori, Science 2004)

(K. Xia, A.J. Rosakis, H. Kanamori and J.R. Rice, Science 2005)





$$\tau_0 = P \sin\alpha \cos\alpha$$

$$\sigma_0 = P \cos^2\alpha$$

- **Rock** → **Photoelastic Polymer**
- **Fault** → **Inclined Contact Interface**
- **Tectonic stress** → **Far Field Load**
- **Hypocenter** → **Triggering Site**

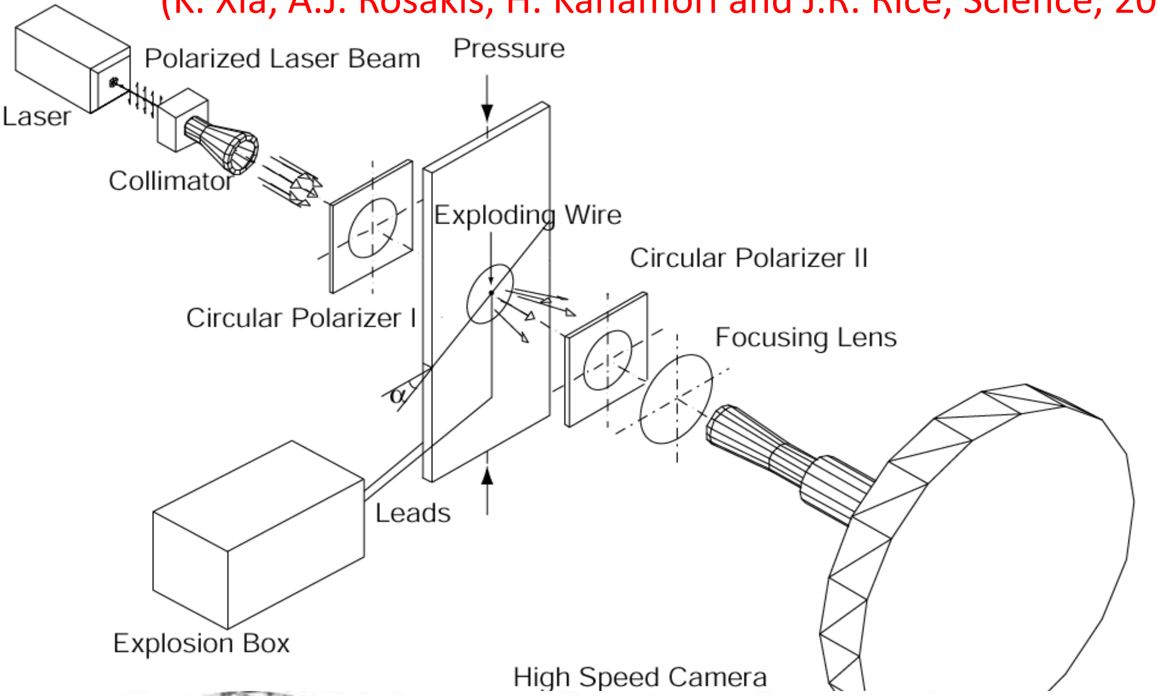
Experimental Setup

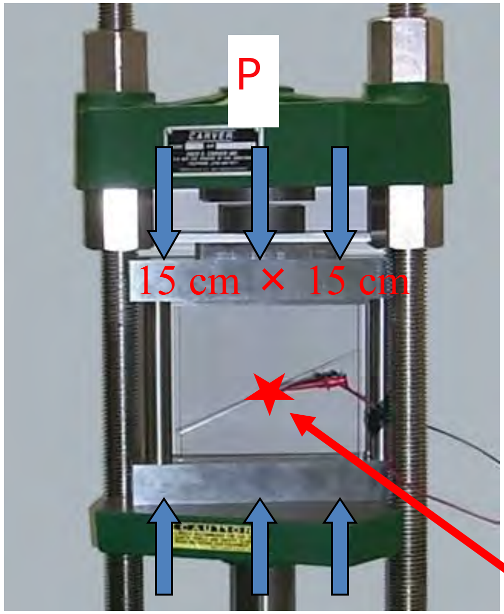
(Far-Field Loading and Local Release of Pressure: Spontaneous Rupture)

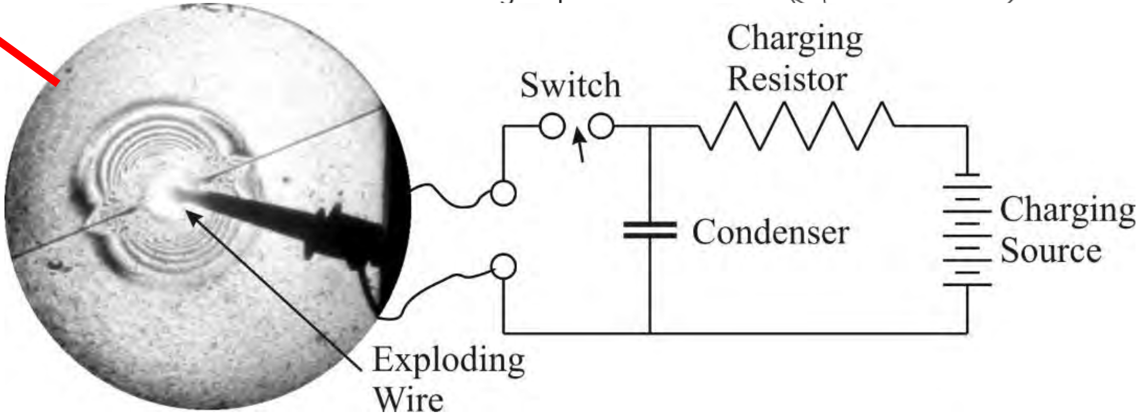
Non-dimensional shear prestress $= \tau_0 / \sigma_0 = f_0 = \tan\alpha$

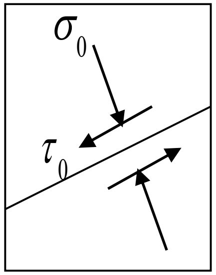
(K. Xia, AJ. Rosakis and H. Kanamori, Science, 2004)

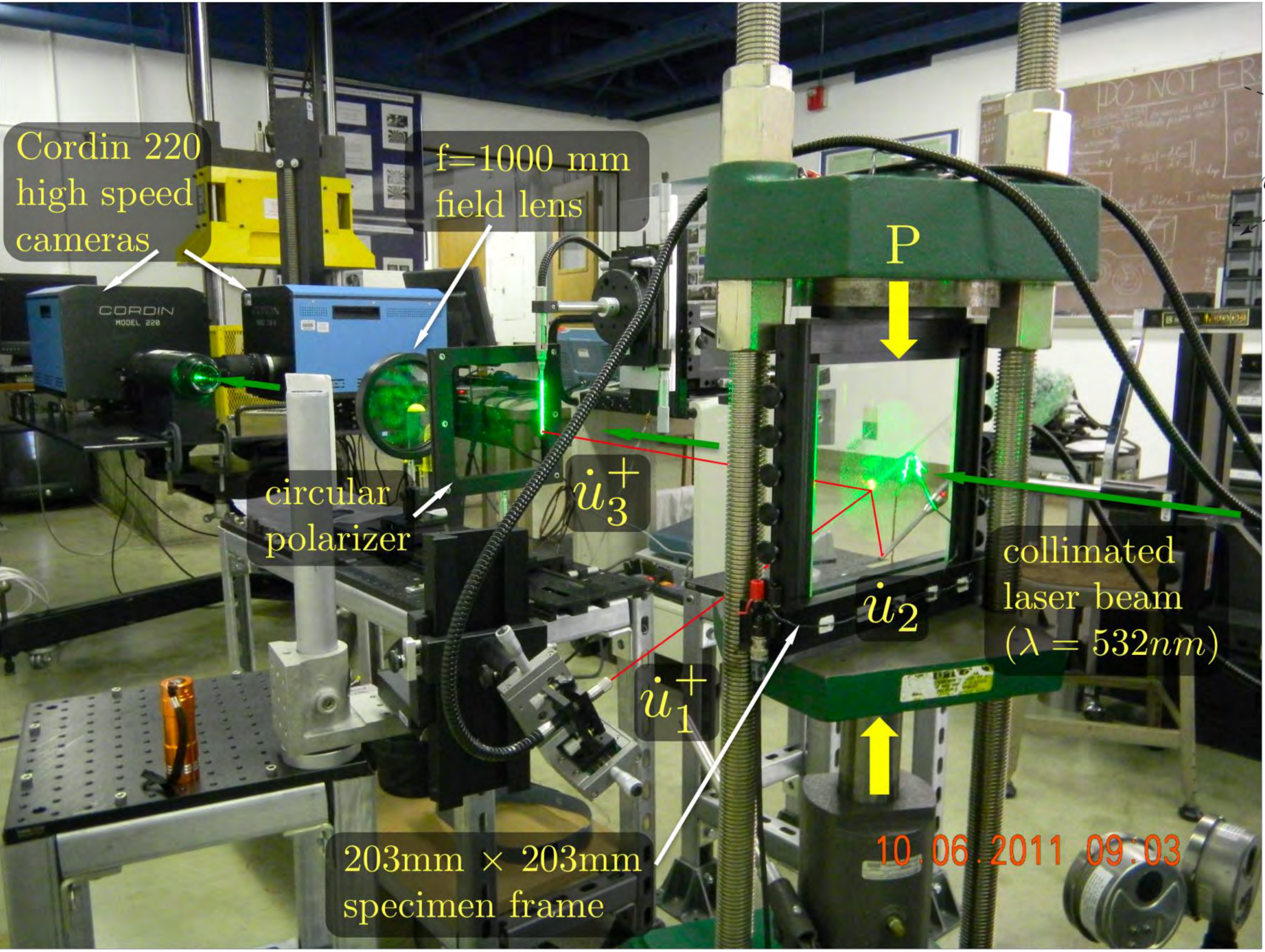
(K. Xia, A.J. Rosakis, H. Kanamori and J.R. Rice, Science, 2005)

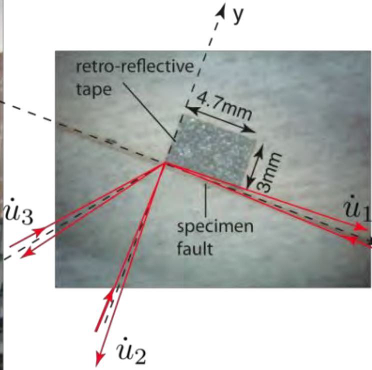






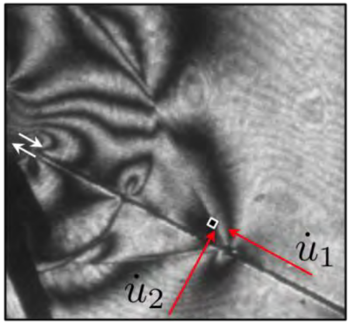






temporal resolution:

- ***BW = 1.5MHz,2.5MHz***
- ***t^{rise} = 140-233 nsec***
- ***spot size: 100-150 μm***



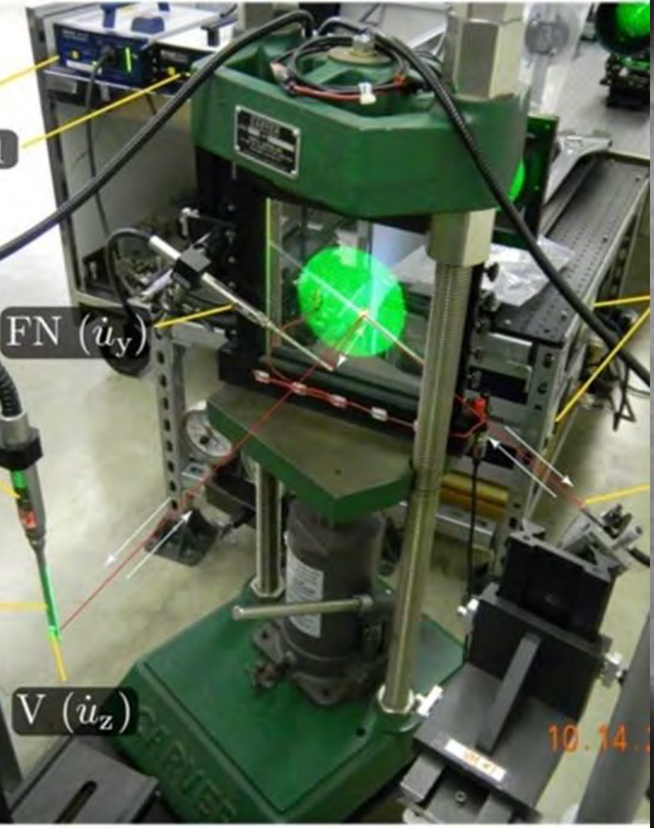
✧ Fiber optic heterodyne laser interferometers enable continuous particle velocity records at a fixed location with high temporal resolution. All three components measured.

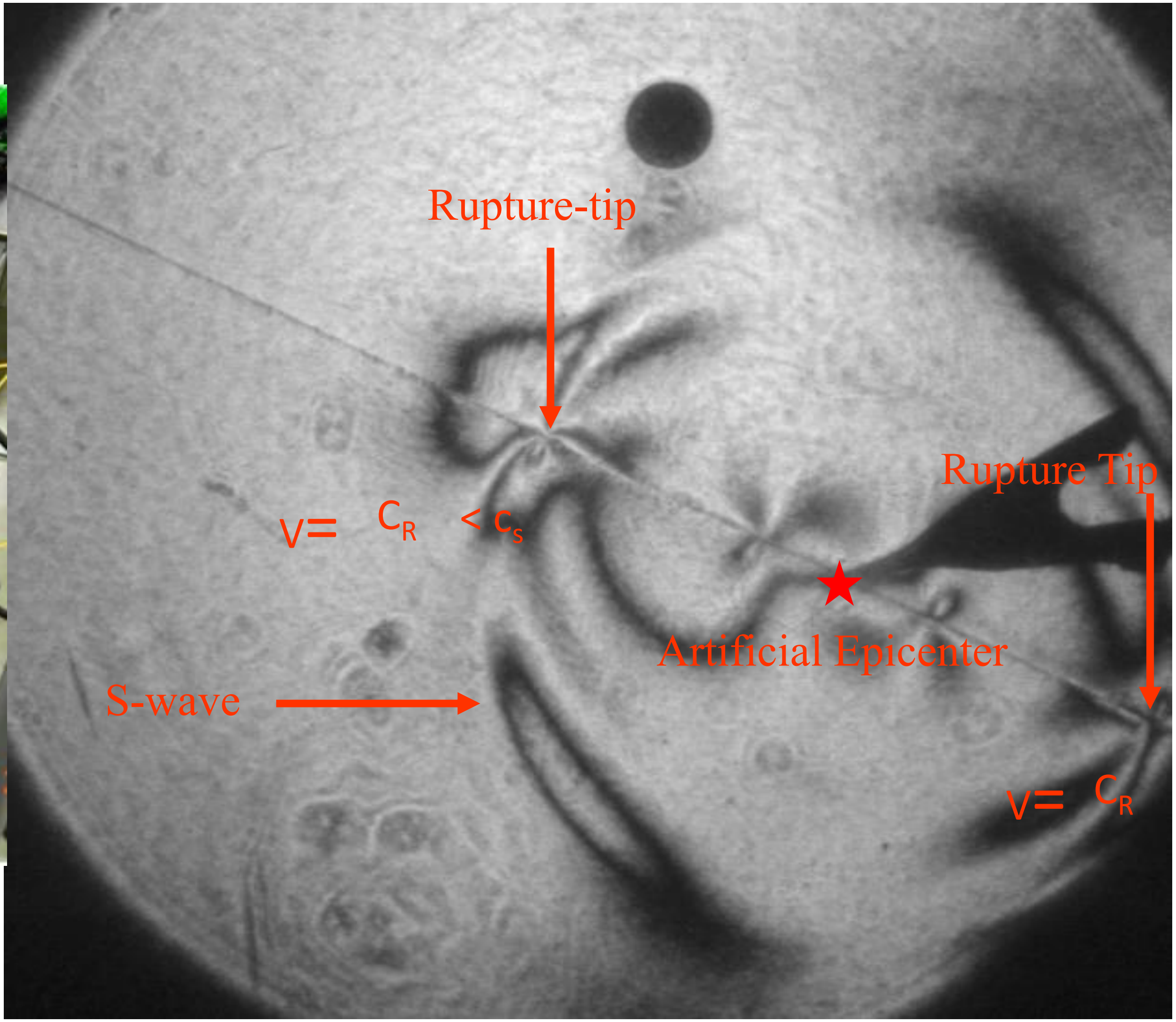
✧ Photo-elastic interferometer with high speed cameras: Interference fringes correspond to iso-contours of $\sigma_1 - \sigma_2 = 2\tau_{max}(x_1,x_2)$,camera operated at 1Million frames per second.

Classical , Bi-lateral, sub-Raleigh , rupture

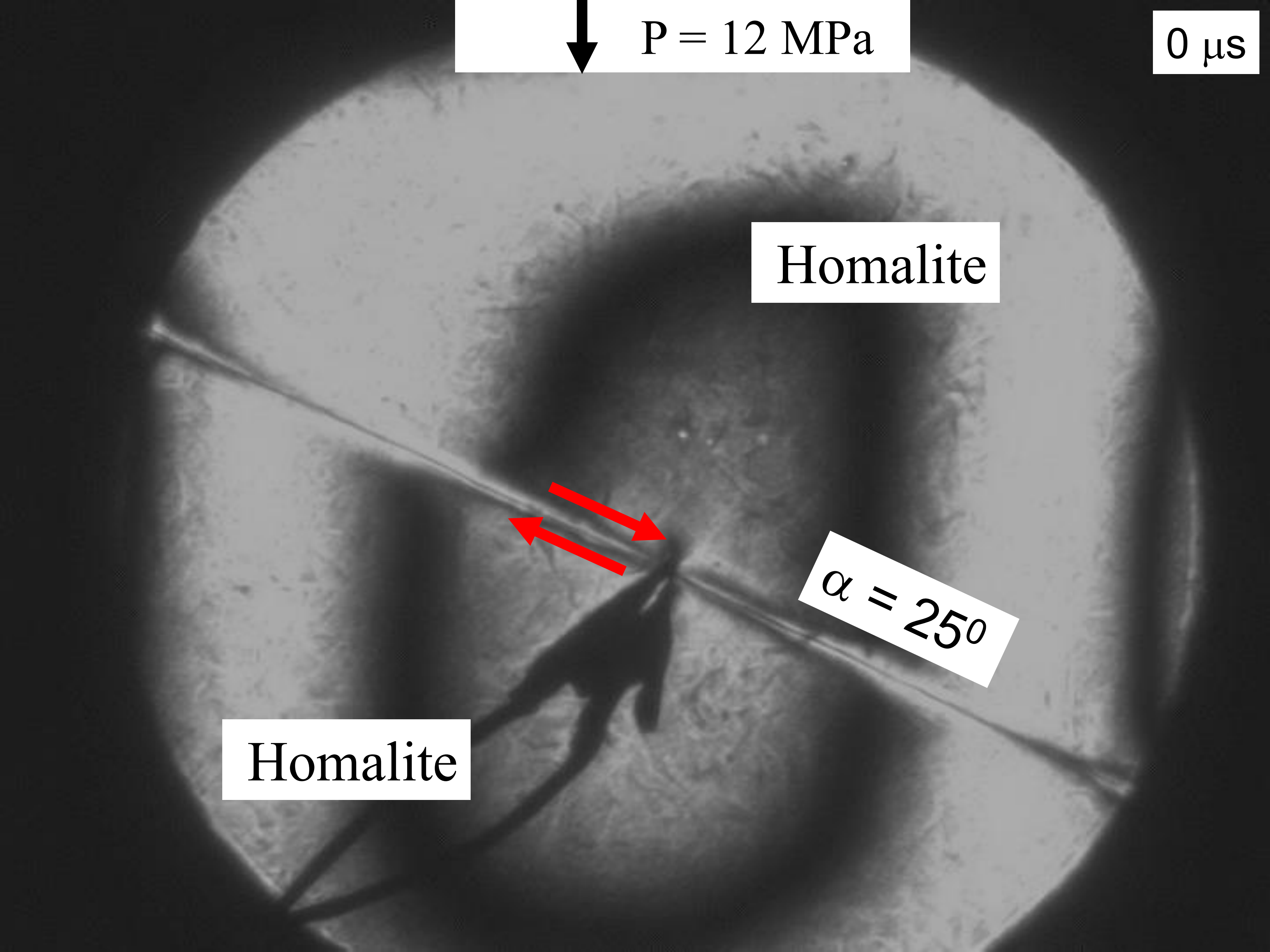
Angle=25°, Pressure(P)=7MPa T=30µs

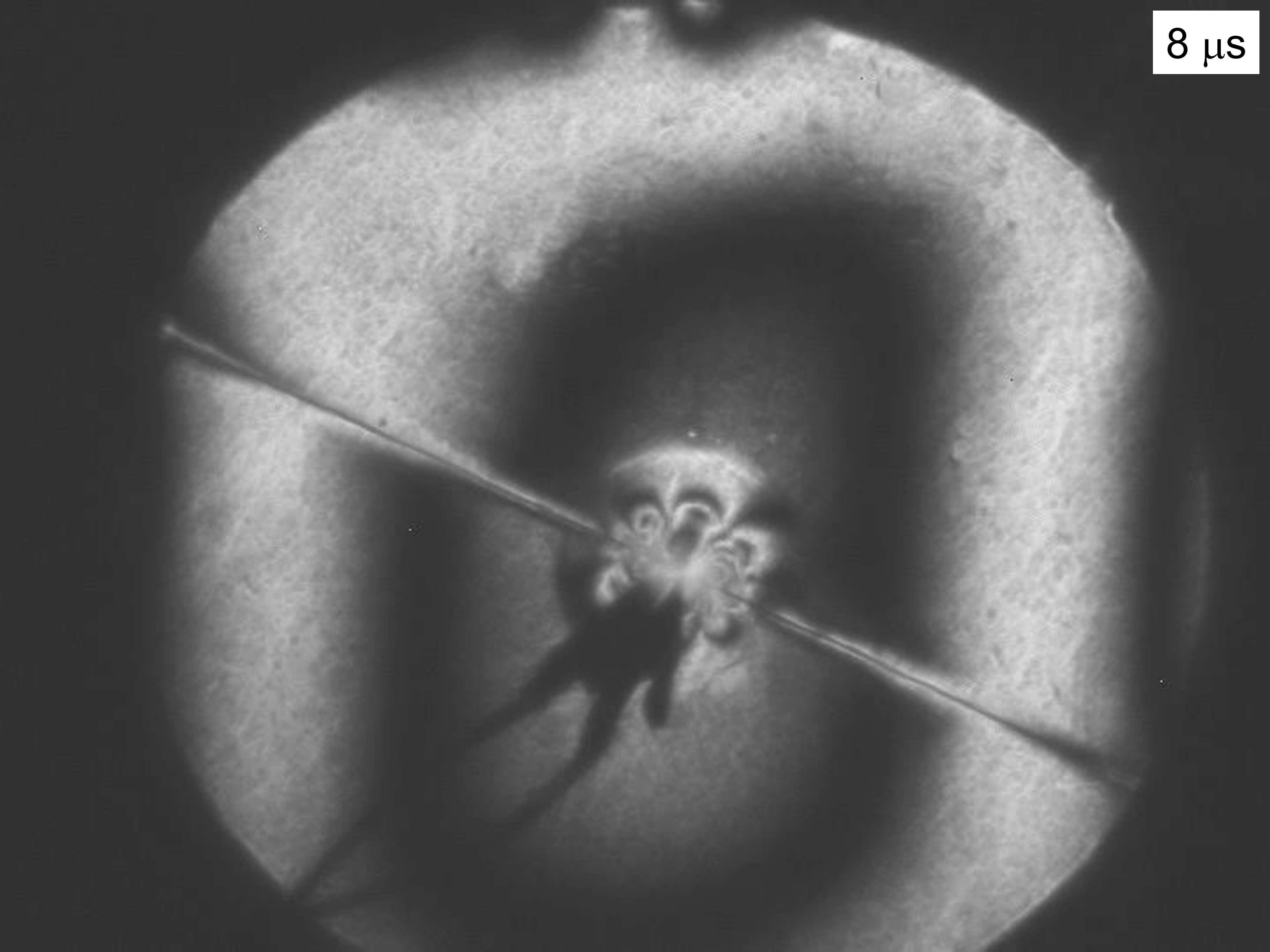
(Xia, Rosakis and Kanamori, Science, March 2004)



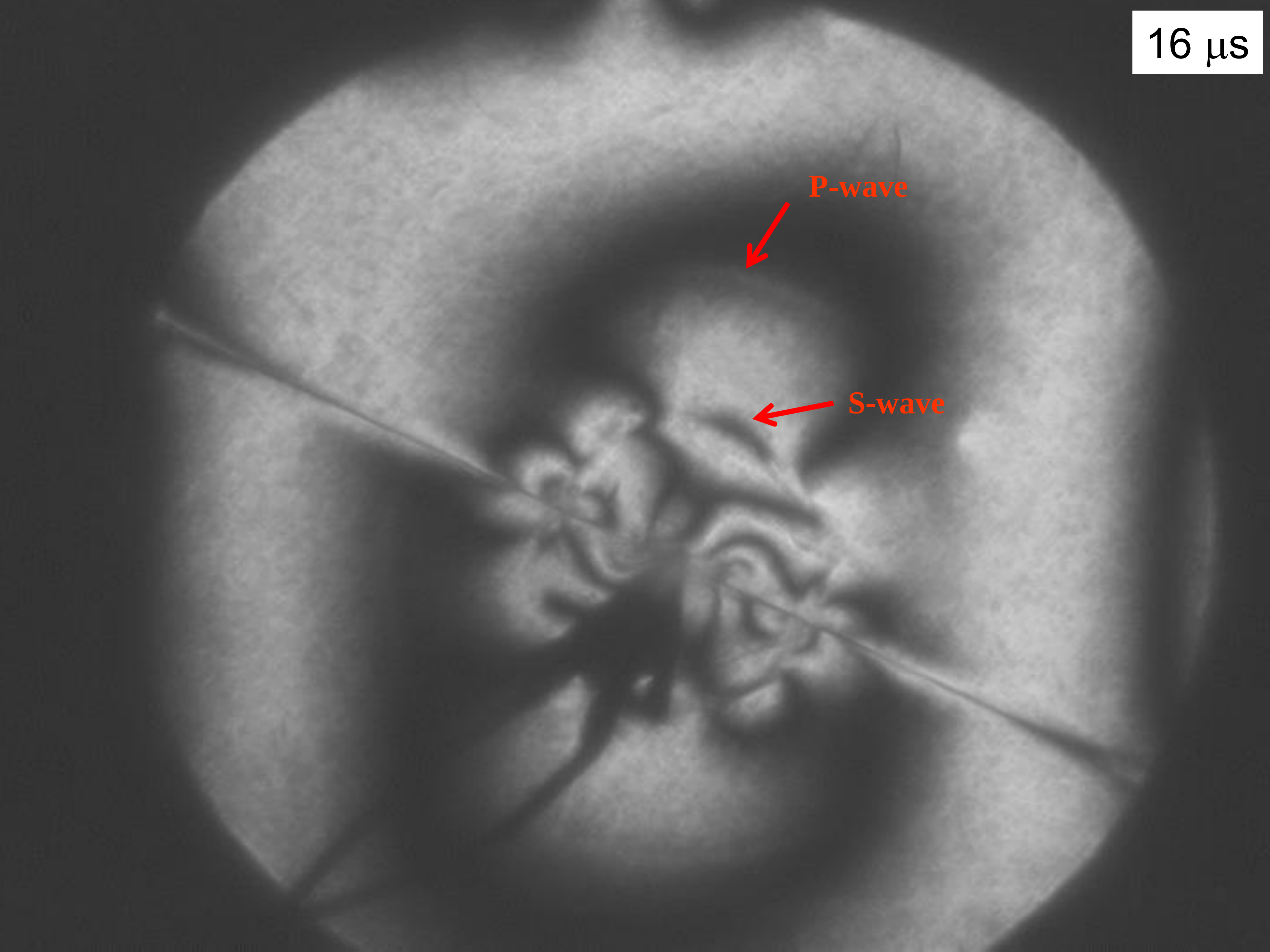


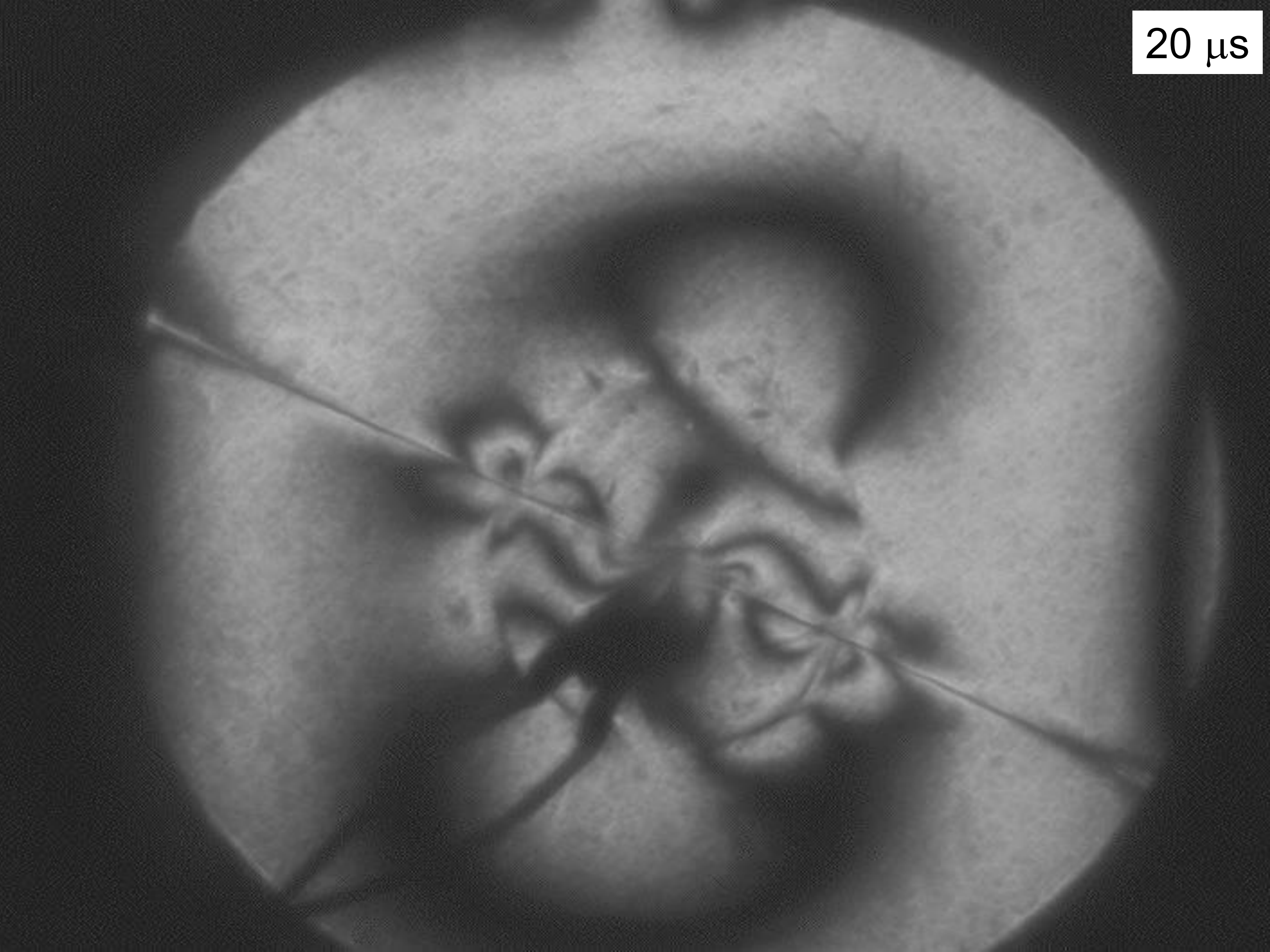
Non-dimensional shear prestress $= \tau_0 / \sigma_0 = f_0 = \tan\alpha$

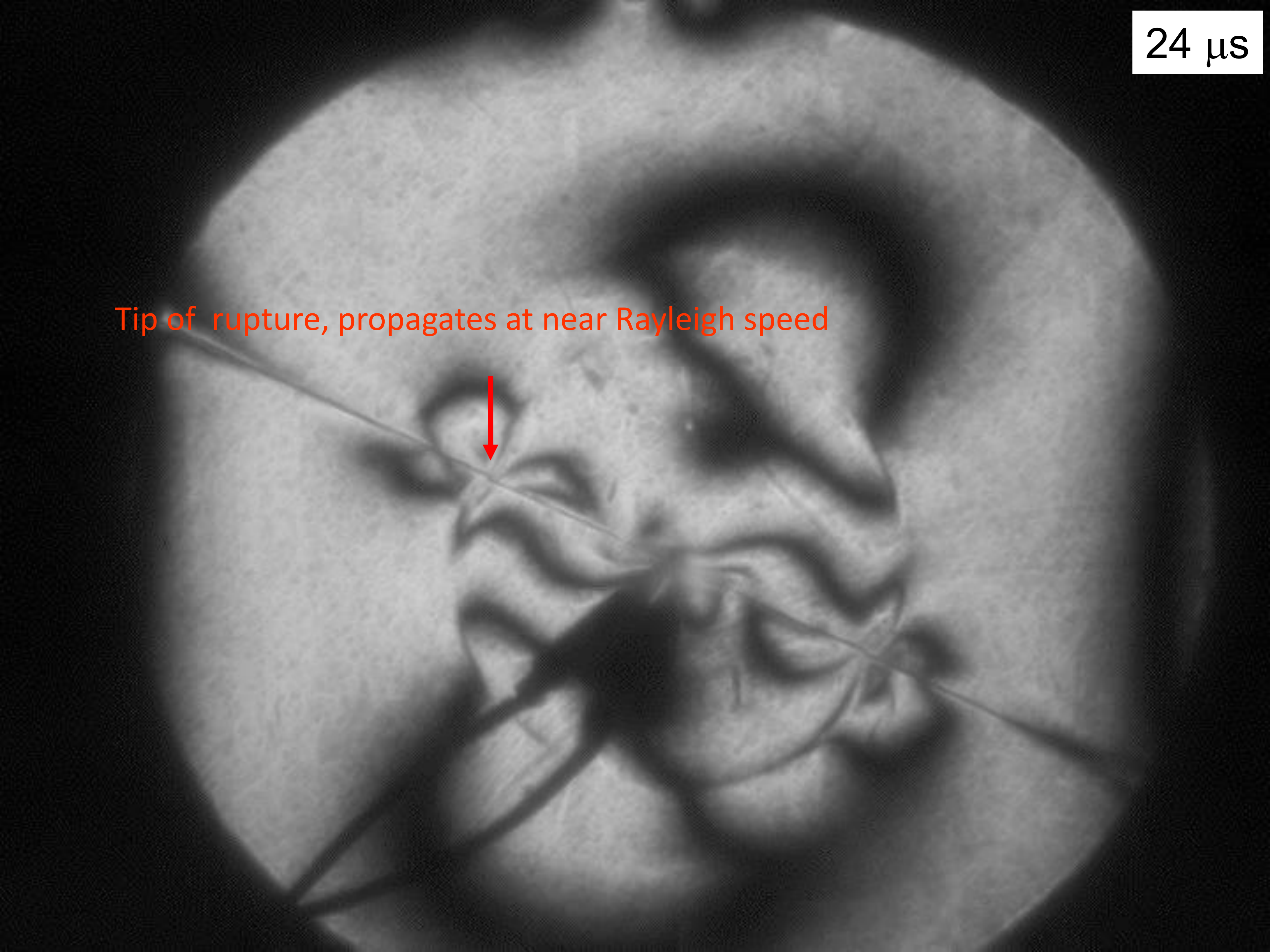

P = 12 MPa
0 μs
Homalite
α = 25°
Homalite



8 μs

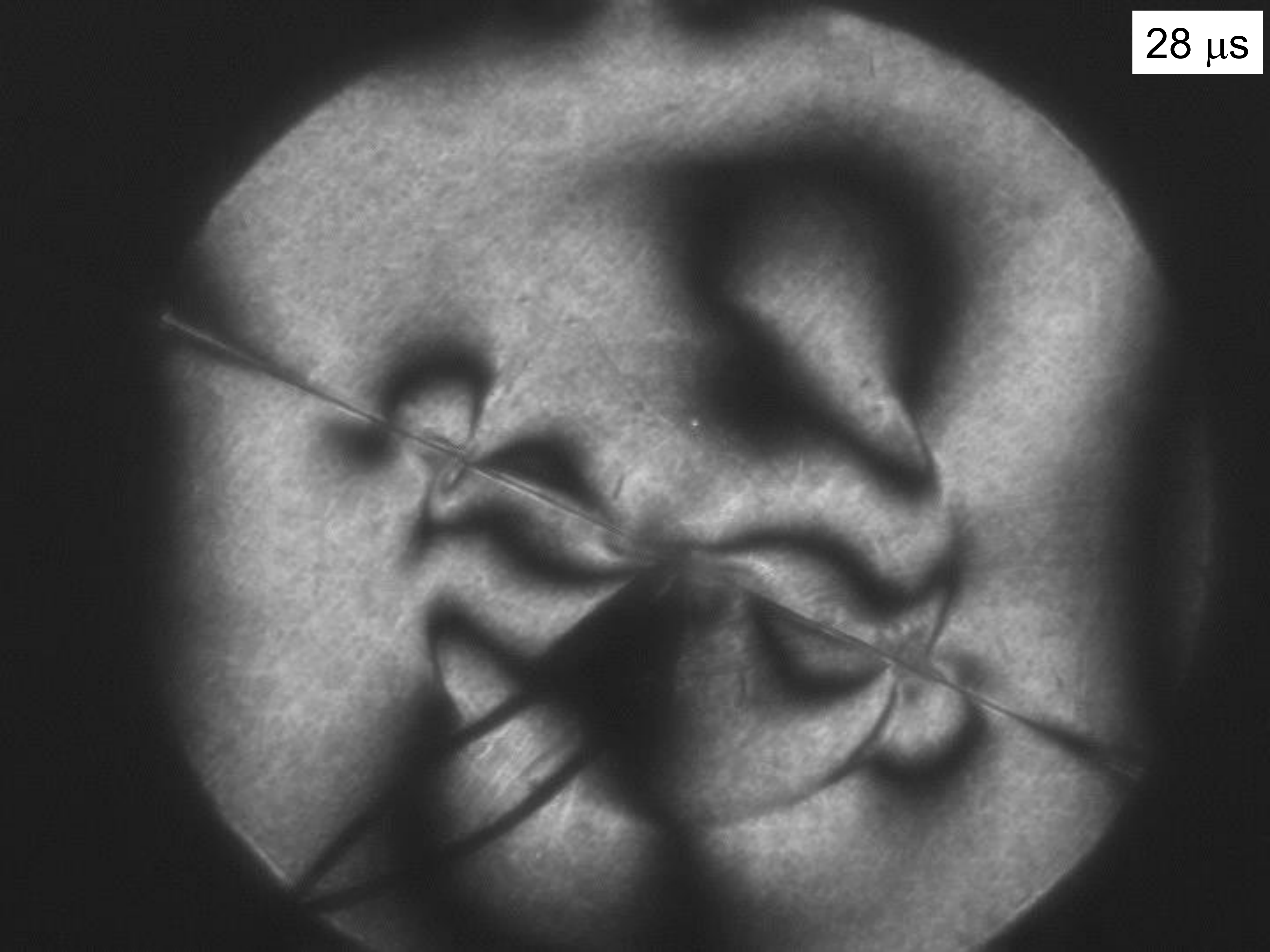

16 μs
P-wave
S-wave


20 μs

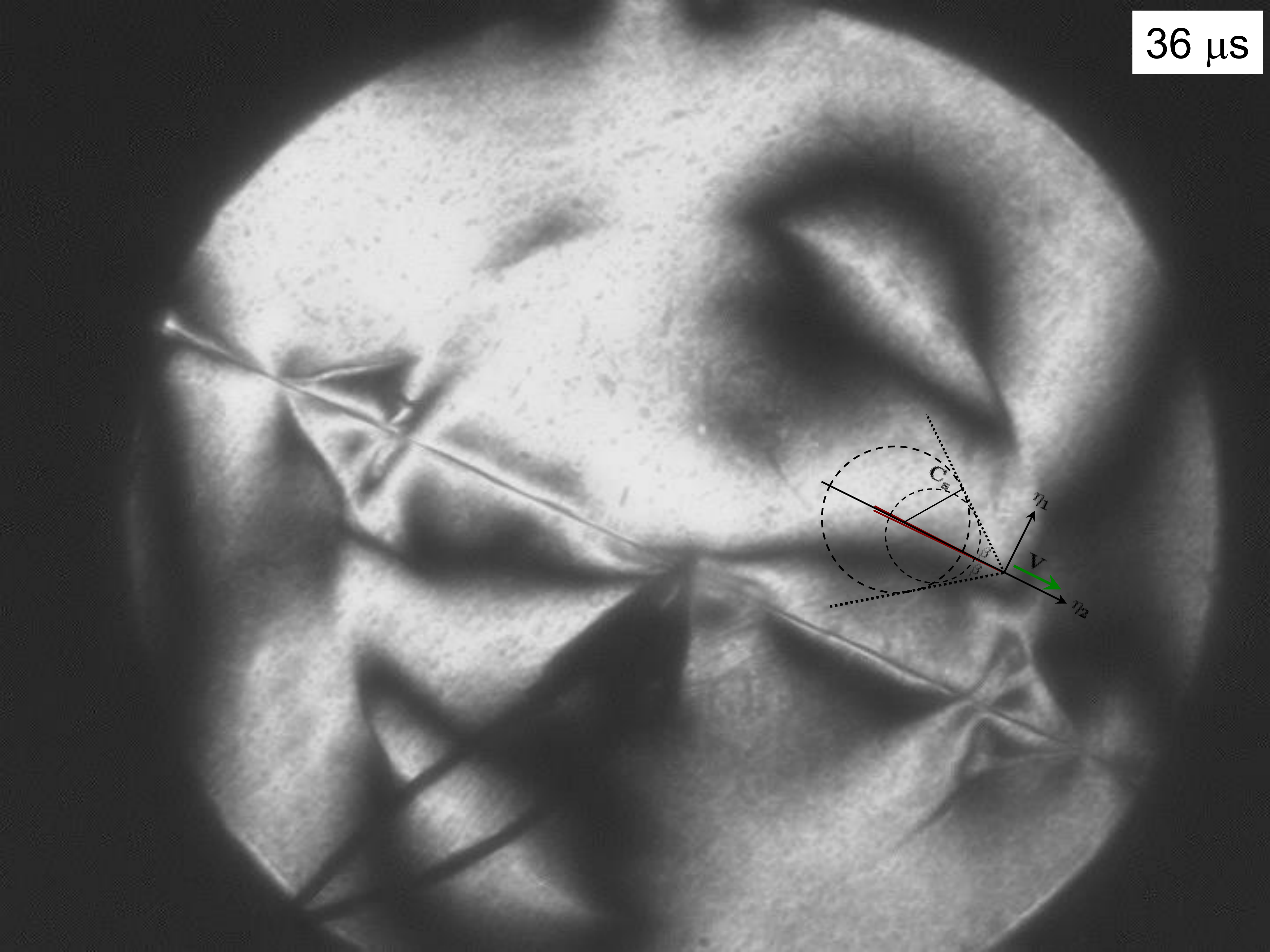


24 μs

Tip of rupture, propagates at near Rayleigh speed


28 μs

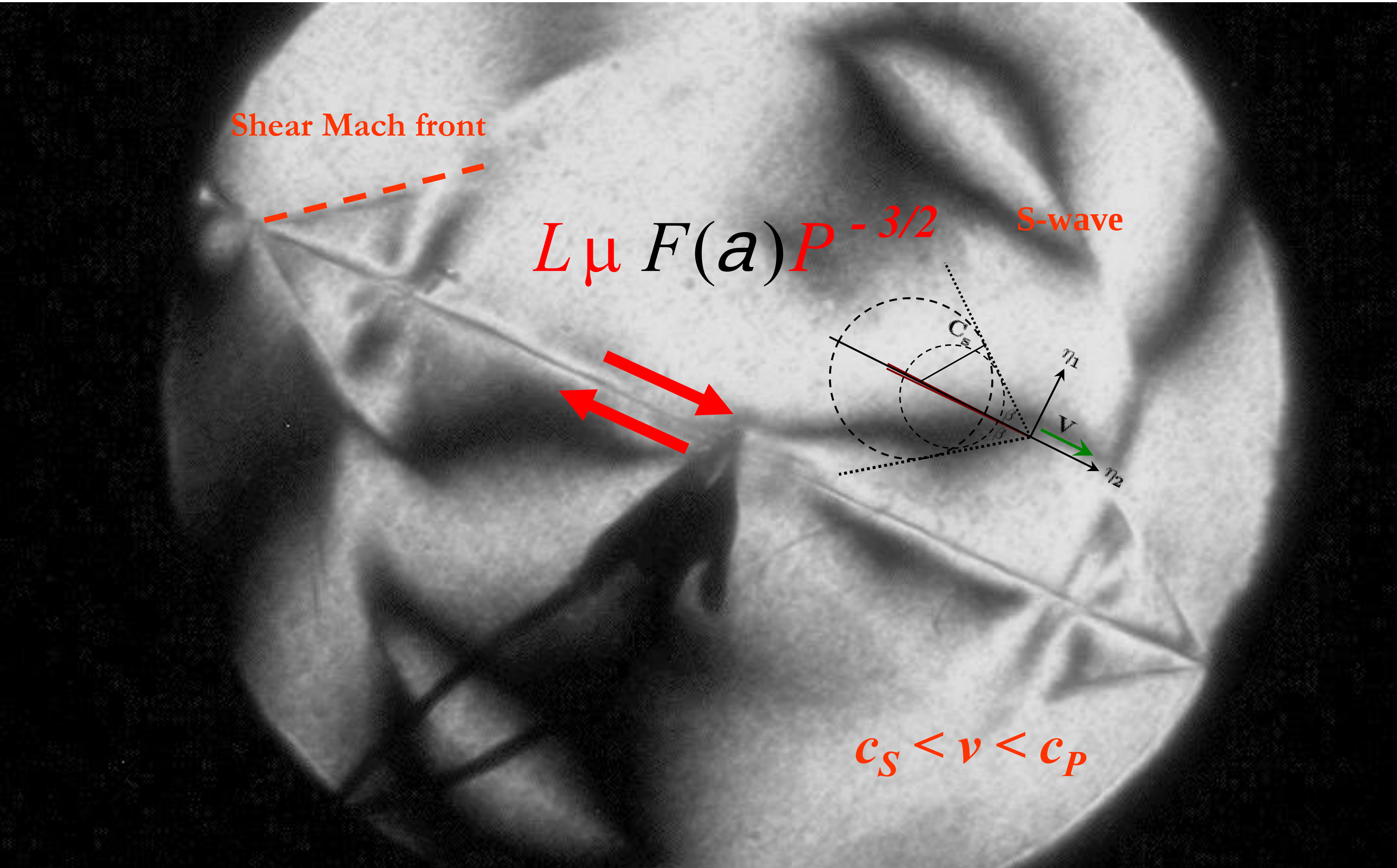

32 μs
C_s
η_1
$\mathbf{V}$
β
β
η_2


36 μs
C_s
η_1
β
β
V
η_2

40 μs

Transition: From Sub-Rayleigh to Supershear

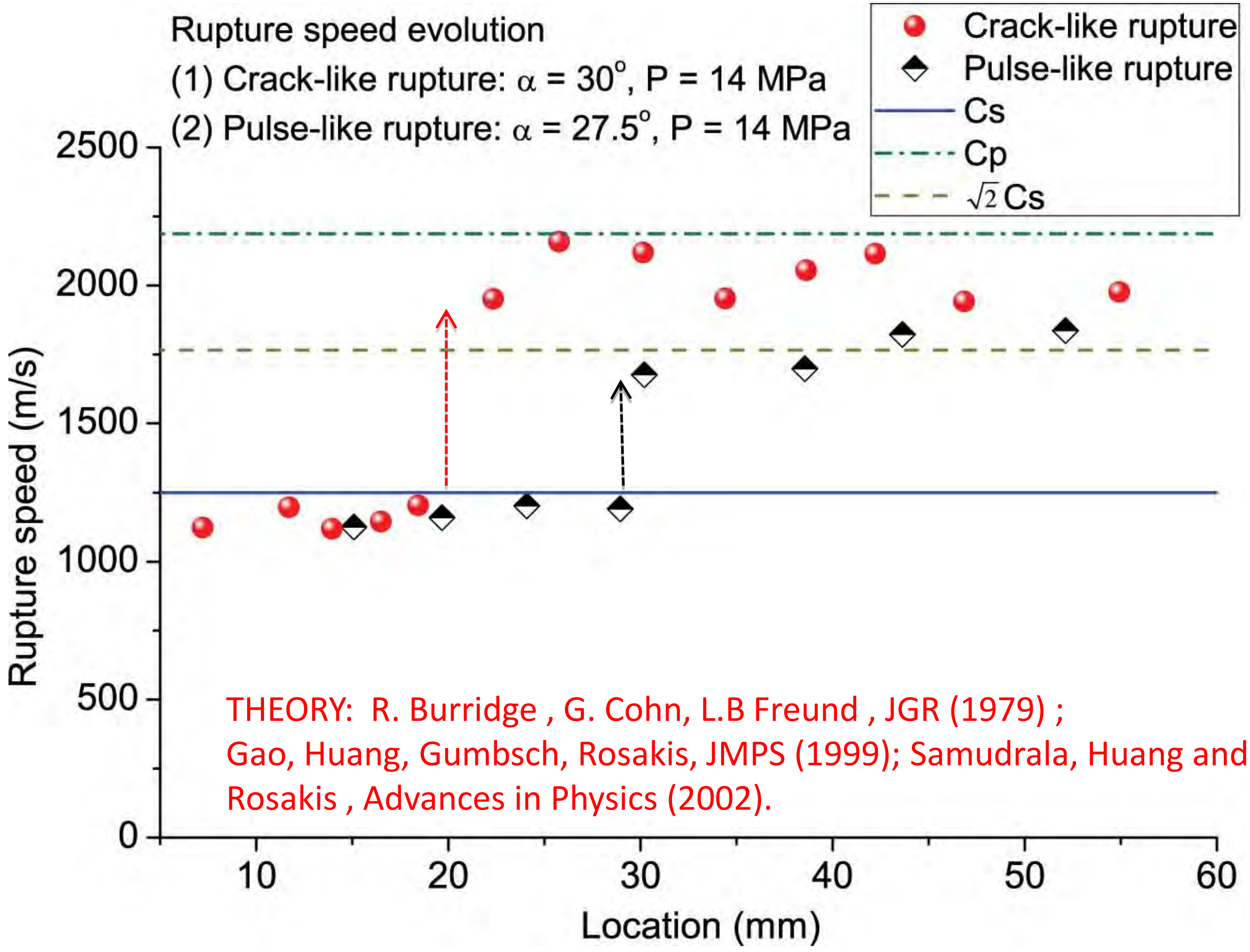
(Xia, Rosakis and Kanamori, Science 2004)



$L \mu F(a) P^{-3/2}$

$c_S < v < c_P$

Evolution of Rupture Speed for transitioning Ruptures



Stable supershear speed regime

THEORY: R. Burridge , G. Cohn, L.B Freund , JGR (1979) ;
Gao, Huang, Gumbsch, Rosakis, JMPS (1999); Samudrala, Huang and Rosakis JGR (2002);
Rosakis , Advances in Physics (2002).

1. $\left[\sqrt{2}c_s, c_p\right]$ is the stable supershear rupture speed regime
2. Higher interface pre-stress results in higher super-shear speeds

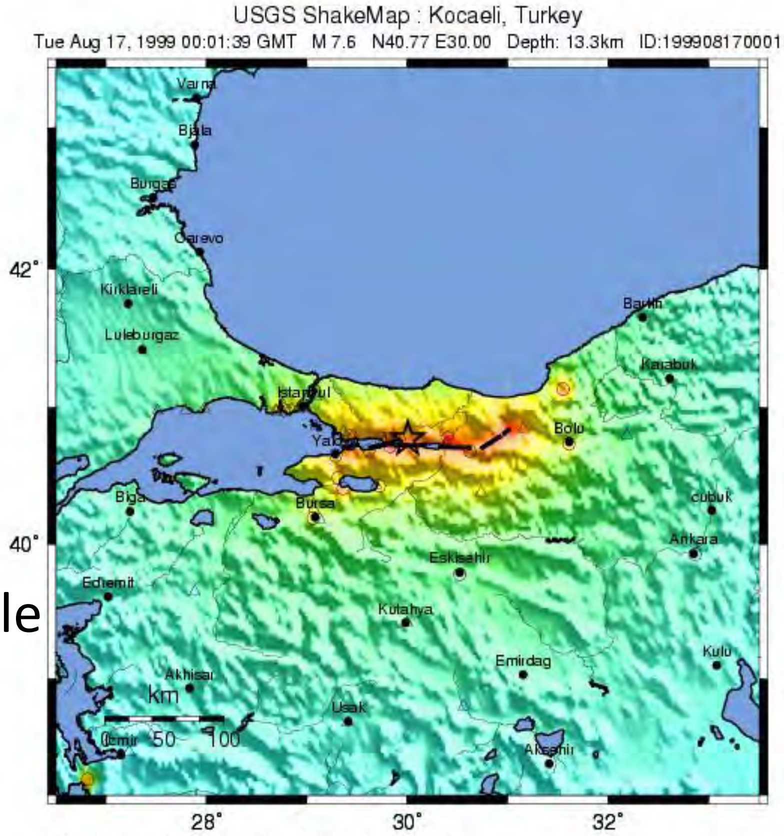
Xiao Lu, Nadia Lapusta, and Ares Rosakis, PNAS, 104(48), 2007

The 1999 (M7.5) Earthquake in IZMIT ruptured 150 km of the North Anatolian Fault.

The Maximum Slip Along the ruptured part of the fault was 5,7 meters .
The fault, starts near the boarder of Turkey with Iran , extends parallel to the Black sea, και continues underwater the sea of Marmara towards Istanbul (Constantinople) and the Aegean sea , to Greece .

The Earthquake lasted 37s, killed 17.000 people and left half a million homeless.

Why was it so destructive?



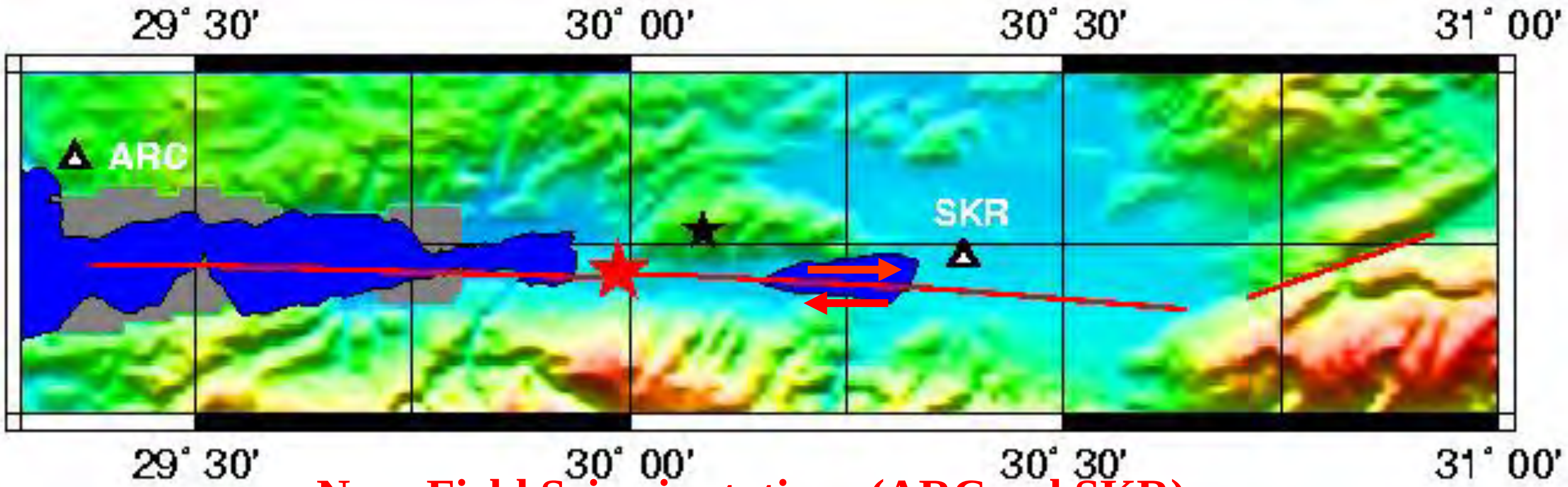
USGS ShakeMap : Kocaeli, Turkey
Tue Aug 17, 1999 00:01:39 GMT M 7.6 N40.77 E30.00 Depth: 13.3km ID:199908170001

Direct Indications of Super-shear Rupture during the 1999 (M7.5) Earthquake in IZMIT explains extensive damage to the East

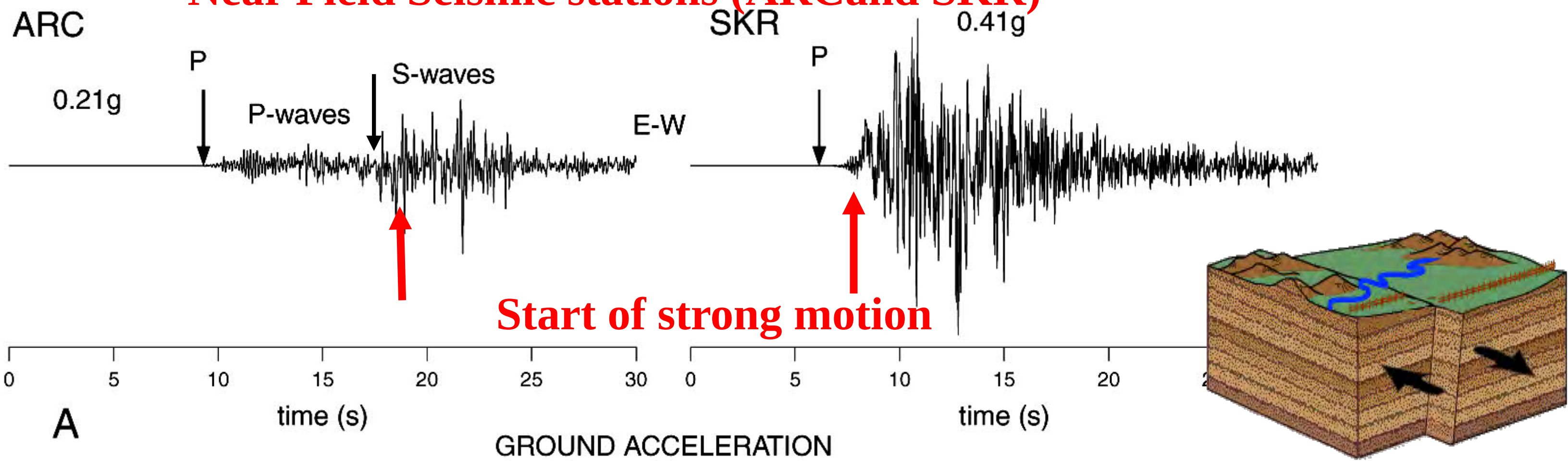
M. Bouchon, M. Bouin, H. Karabulet, M. Toksöz, M. Dietrich and A. Rosakis

Geophysical Research Letters, 2001

Bilateral rupture. Rupture speed(West : Rayleigh, East: $\sqrt{2}\ C_S = 4.9$ km/s)

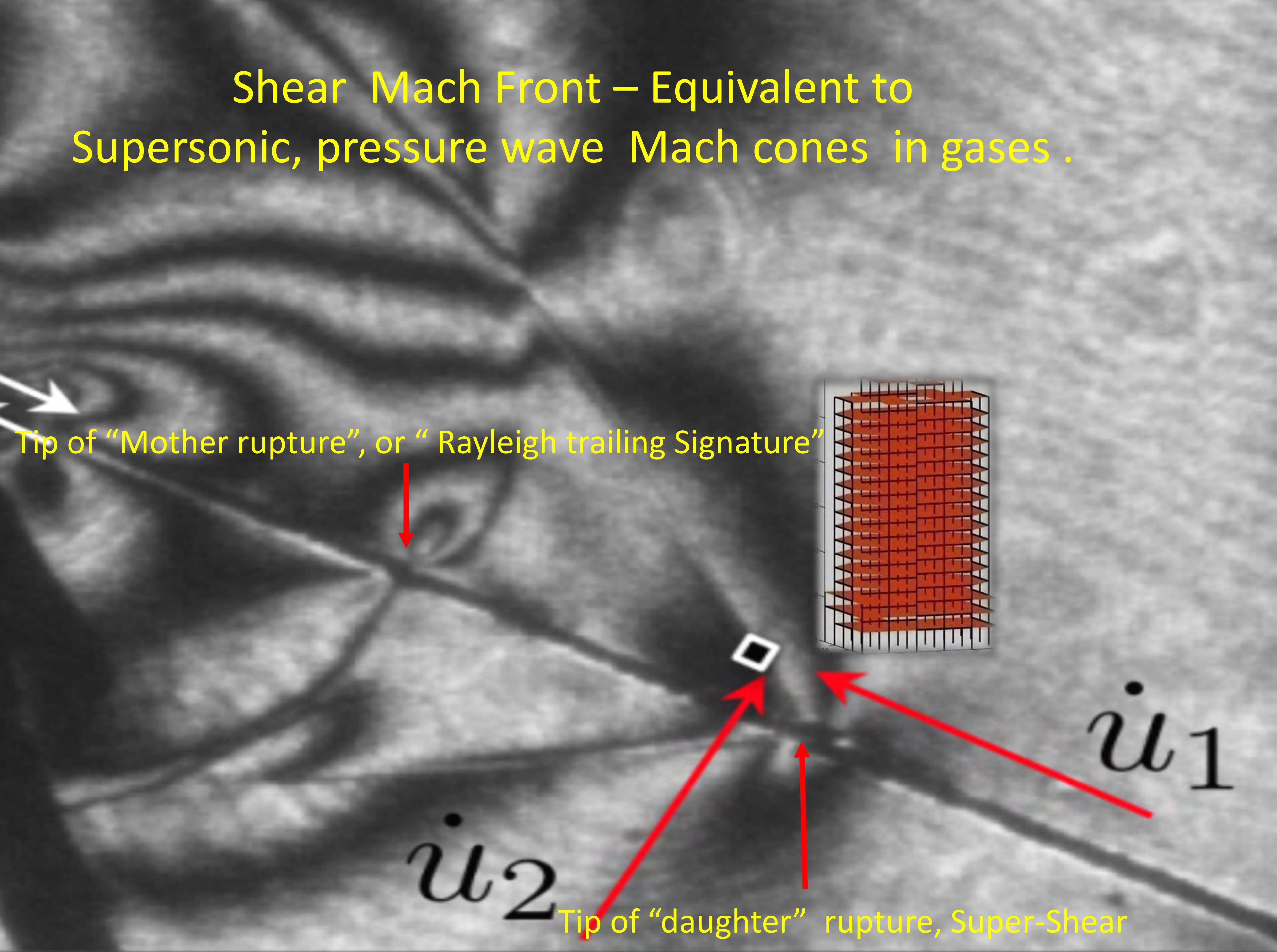


Near Field Seismic stations (ARCand SKR)



Start of strong motion

Shear Mach Front – Equivalent to Supersonic, pressure wave Mach cones in gases .



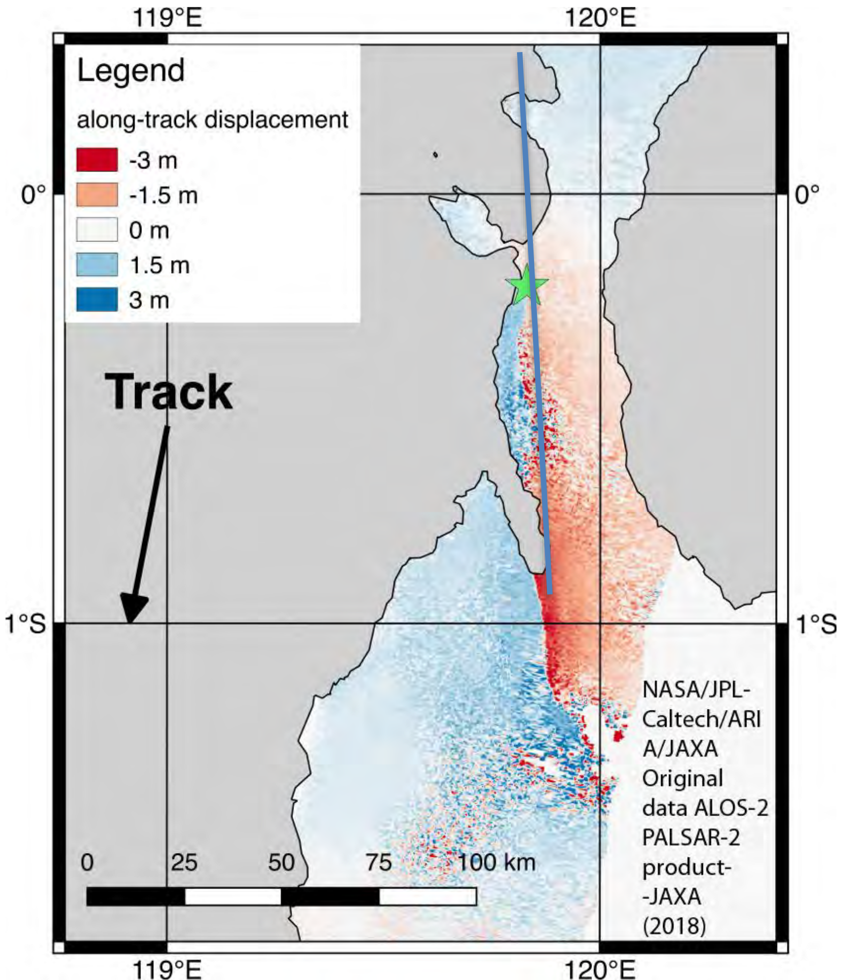
Tip of “Mother rupture”, or “ Rayleigh trailing Signature”

Tip of “daughter” rupture, Super-Shear

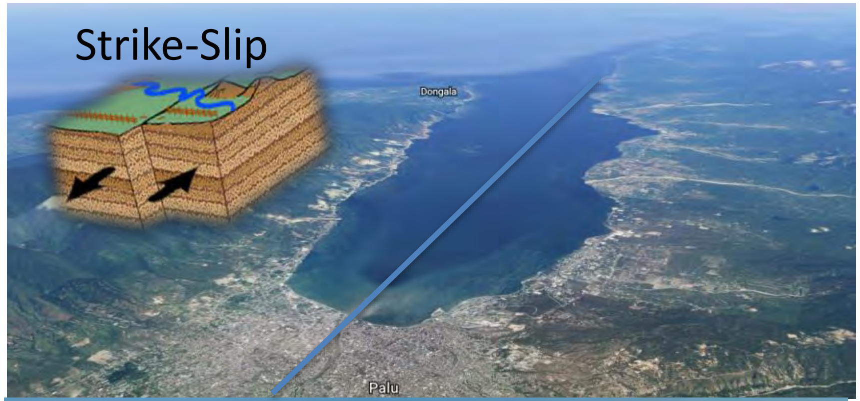
Strong evidence of Super-shear, with the exact rupture speed still being debated in the literature

The September 28th, 2018 Mw7.5 Sulawesi-Palu earthquake in Indonesia, generated a Tsunami, killed 4,300people, and mystified Scientists. Its epicenter was just off the central Island of Sulawesi at a shallow depth of 10 km

Amlani, Bhat, Simons, Schubnel, Vigny, Rosakis, Efendi, Elbanna, Abidin *work in Progress* (2019)



NASA/JPL-Caltech/ARIA/JAXA Original data ALOS-2 PALSAR-2 product--JAXA (2018)



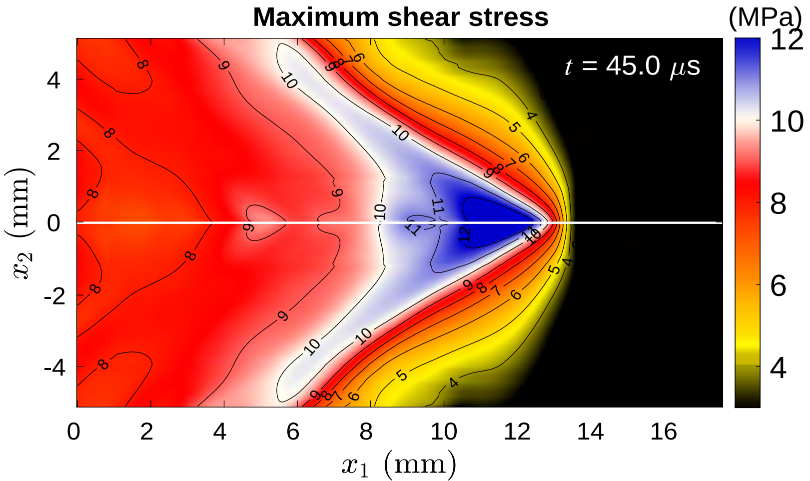
SECTION 3

THE SEISMOLOGICAL WIND TUNEL PHASE II:

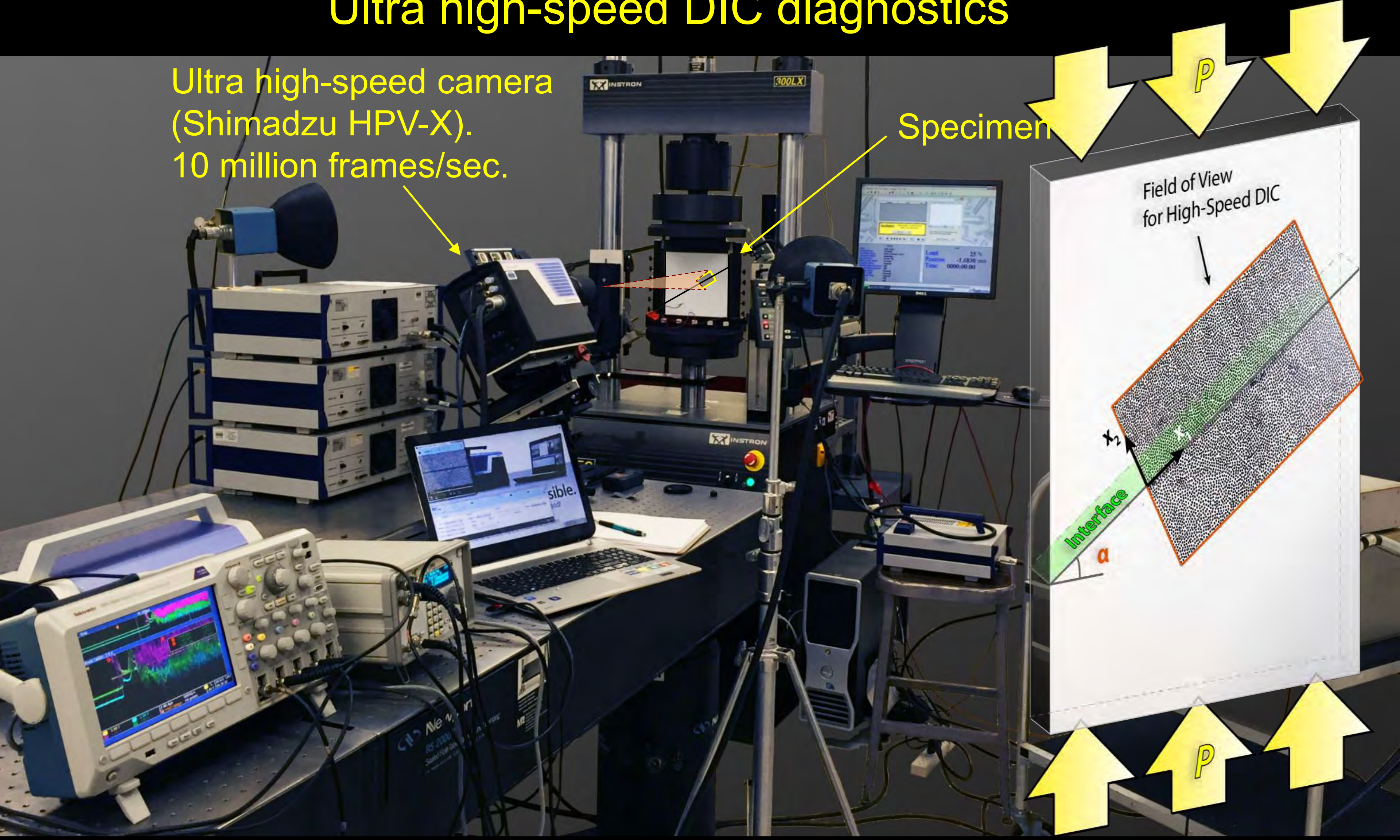
IN SEARCH OF QUANTITATIVE FULL-FIELD VISUALIZATION OF THE EATRHQUAKE RUPTURE PHENOMENA, ON AND OFF FAULT

Dynamic DIC has enabled high resolution laboratory earthquake measurements as a tool for hazard mitigation.

Can we compete with numerical resolution in predicting ground shaking?



New Laboratory earthquake setup with Ultra high-speed DIC diagnostics

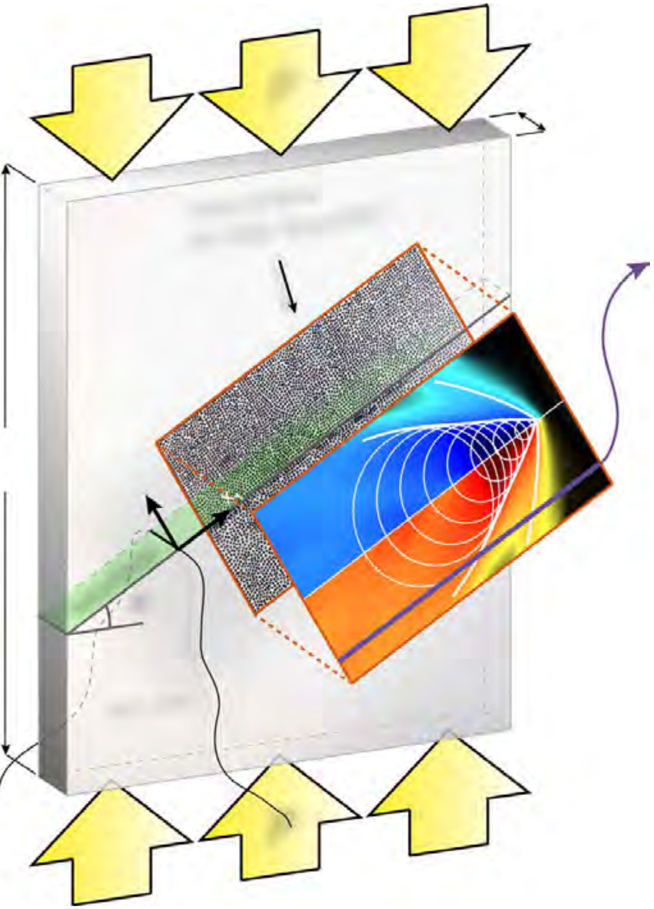


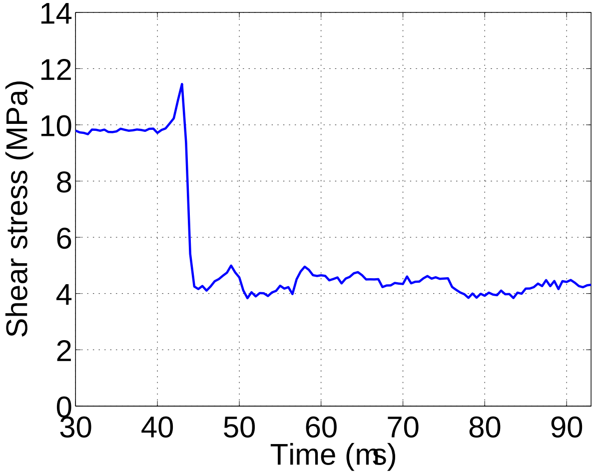
Ultra high-speed camera (Shimadzu HPV-X). 10 million frames/sec.

Specimen

Speckle pattern is deposited on specimen. DIC identifies the gray level patterns in small **pixel subsets** and tracks their motion during deformation

Speckle pattern displacement fields are computed via DIC. They are used to obtain displacement gradients fields, strains and to infer stress fields. Particle velocity fields are also computed.





Field quantity evolution with time

V. Rubino, A. J. Rosakis, N. Lapusta
Understanding dynamic friction through spontaneously evolving laboratory earthquakes *Nature Communications, 2017*

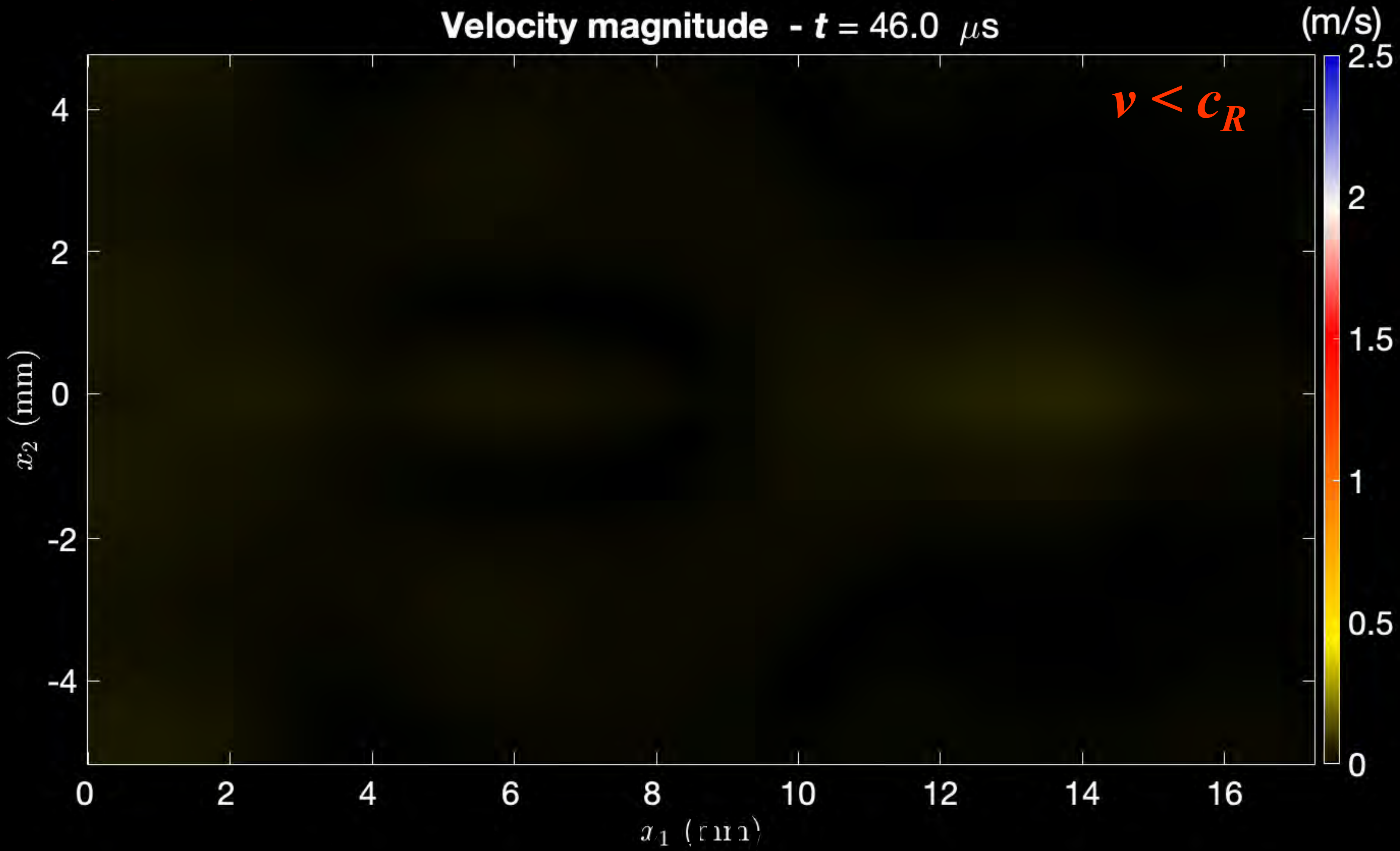
M. Gori , V. Rubino A.J. Rosakis1 & N. Lapusta
Pressure shock fronts formed by ultra-fast shear cracks in viscoelastic materials, *Nature Communications , 2018.*

$$c_R = 1170m/s \quad c_s = 1290m/s \quad c_p = 2600m/s$$

HOW DO INDIVIDUAL RUPTURE EVENTS LOOK WITH DYNAMIC DIC?

Classical Sub-Rayleigh, sliding "Rice-Heaton" pulse (Zheng & Rice)

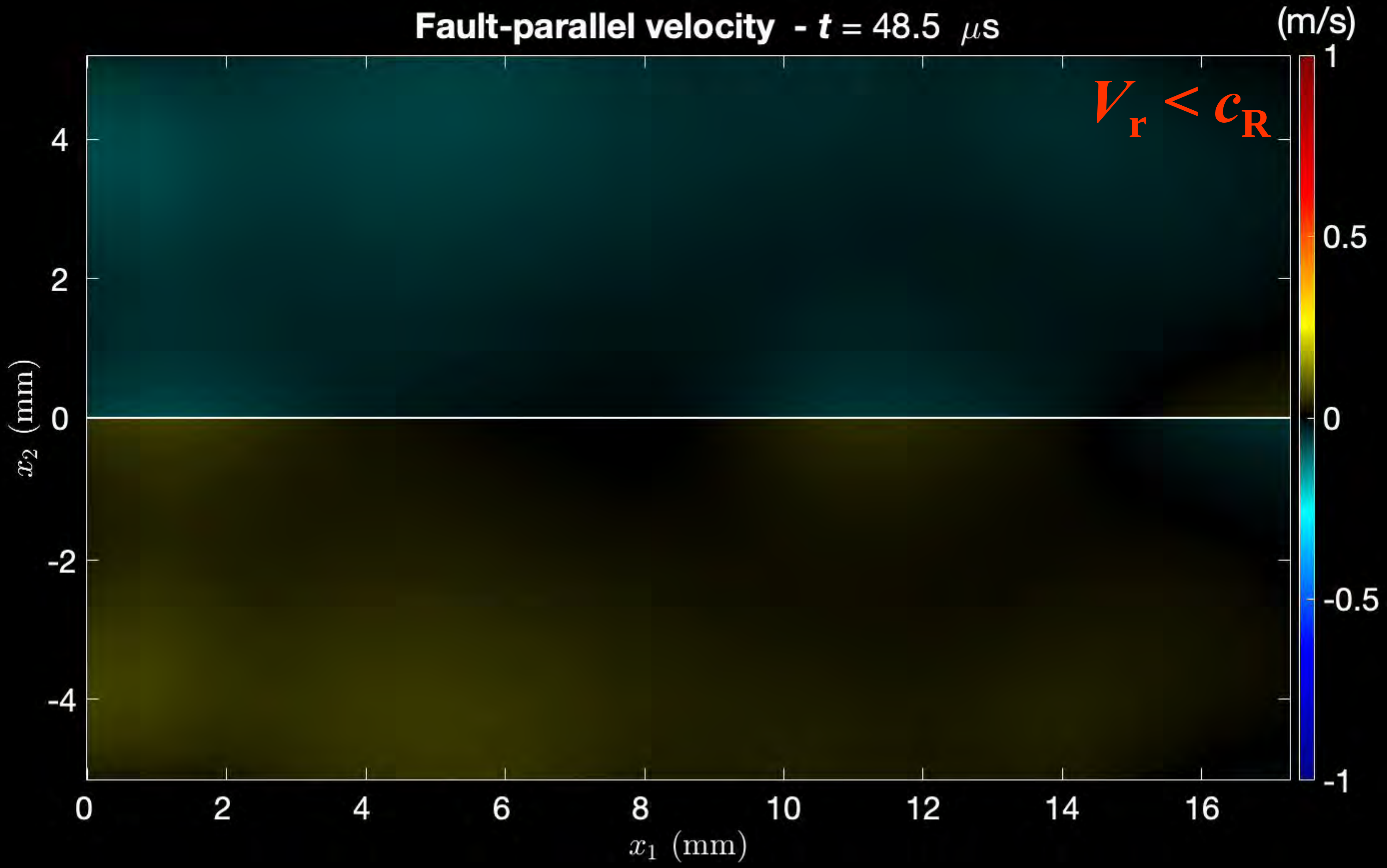
Rupture speed: 1150m/s



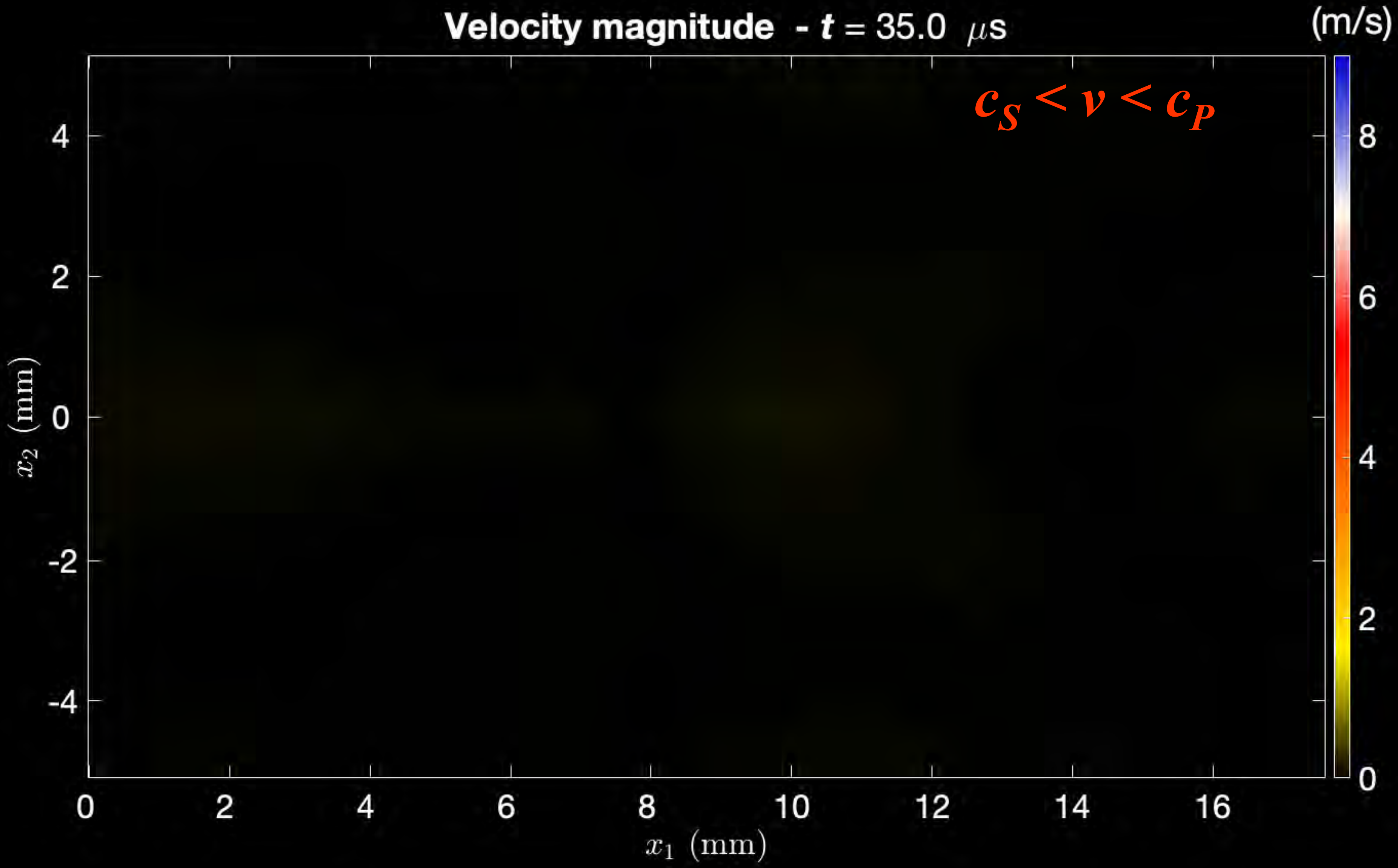
DIC identifies gray level patterns in small **pixel subsets** and tracks their motion during deformation

Classical Sub-Rayleigh rupture

Rupture speed: 1145 m/s



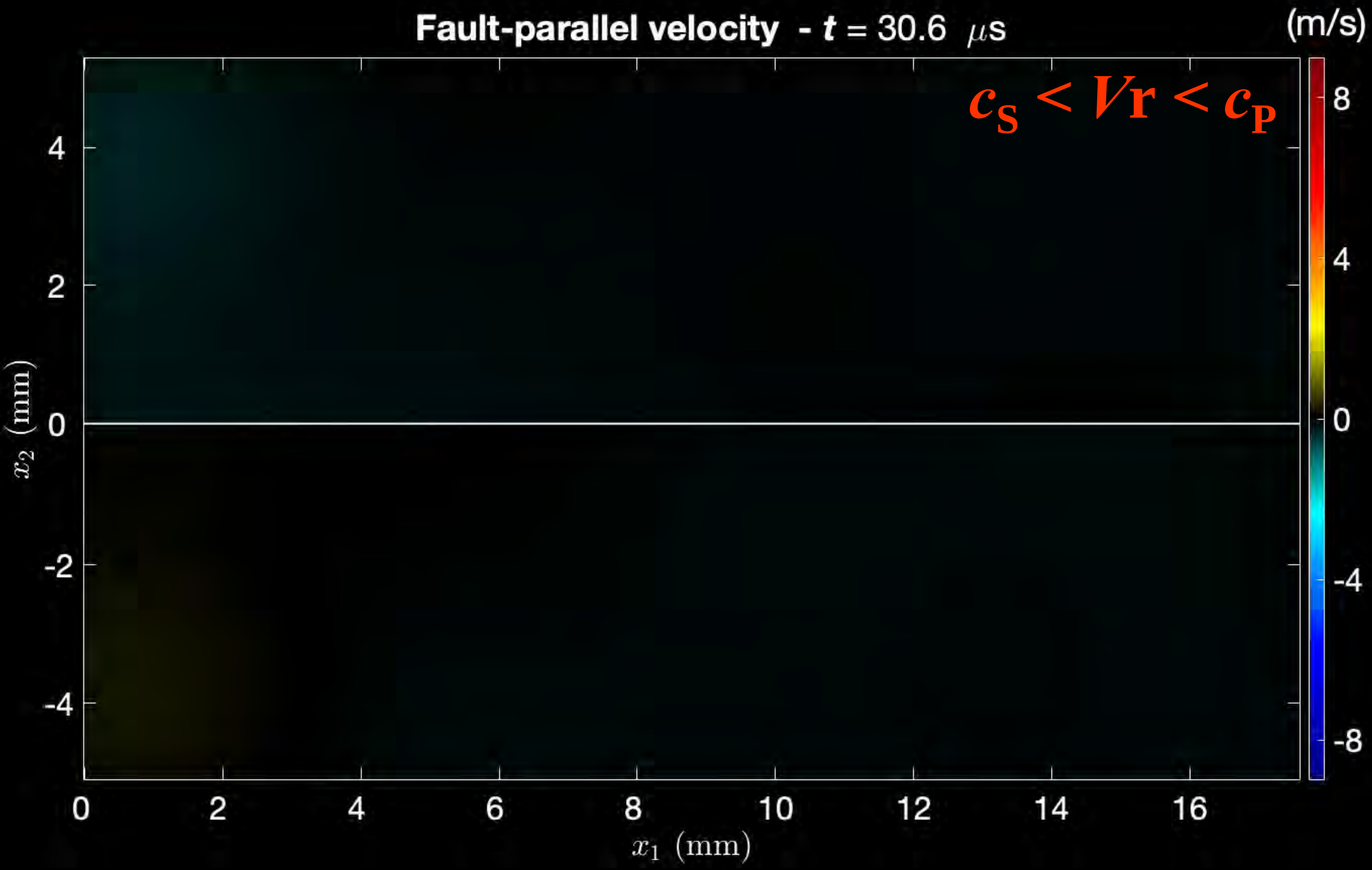
Supershear crack, Rupture speed: 2368m/s



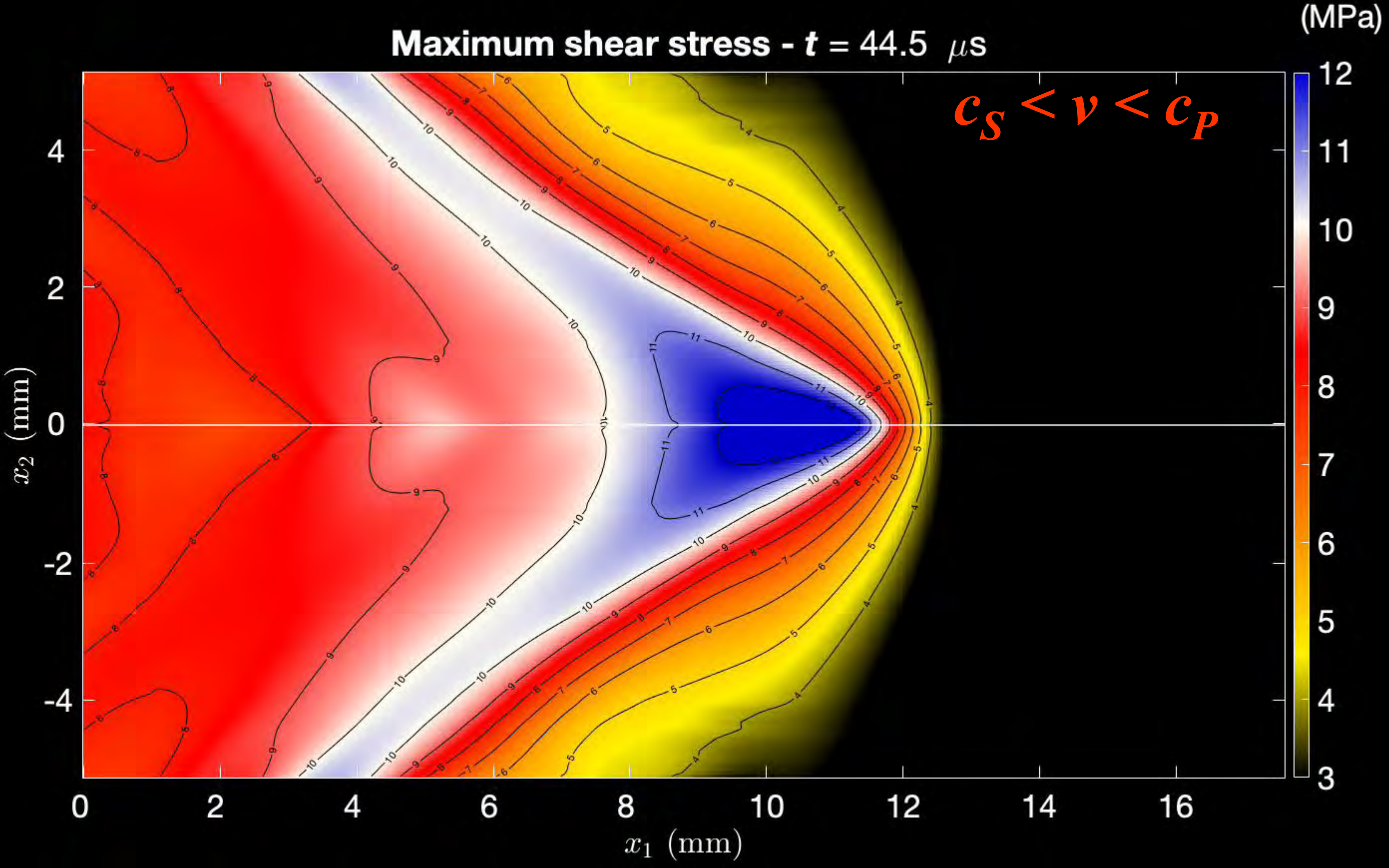
DIC identifies gray level patterns in small **pixel subsets** and tracks their motion during deformation

Supershear crack

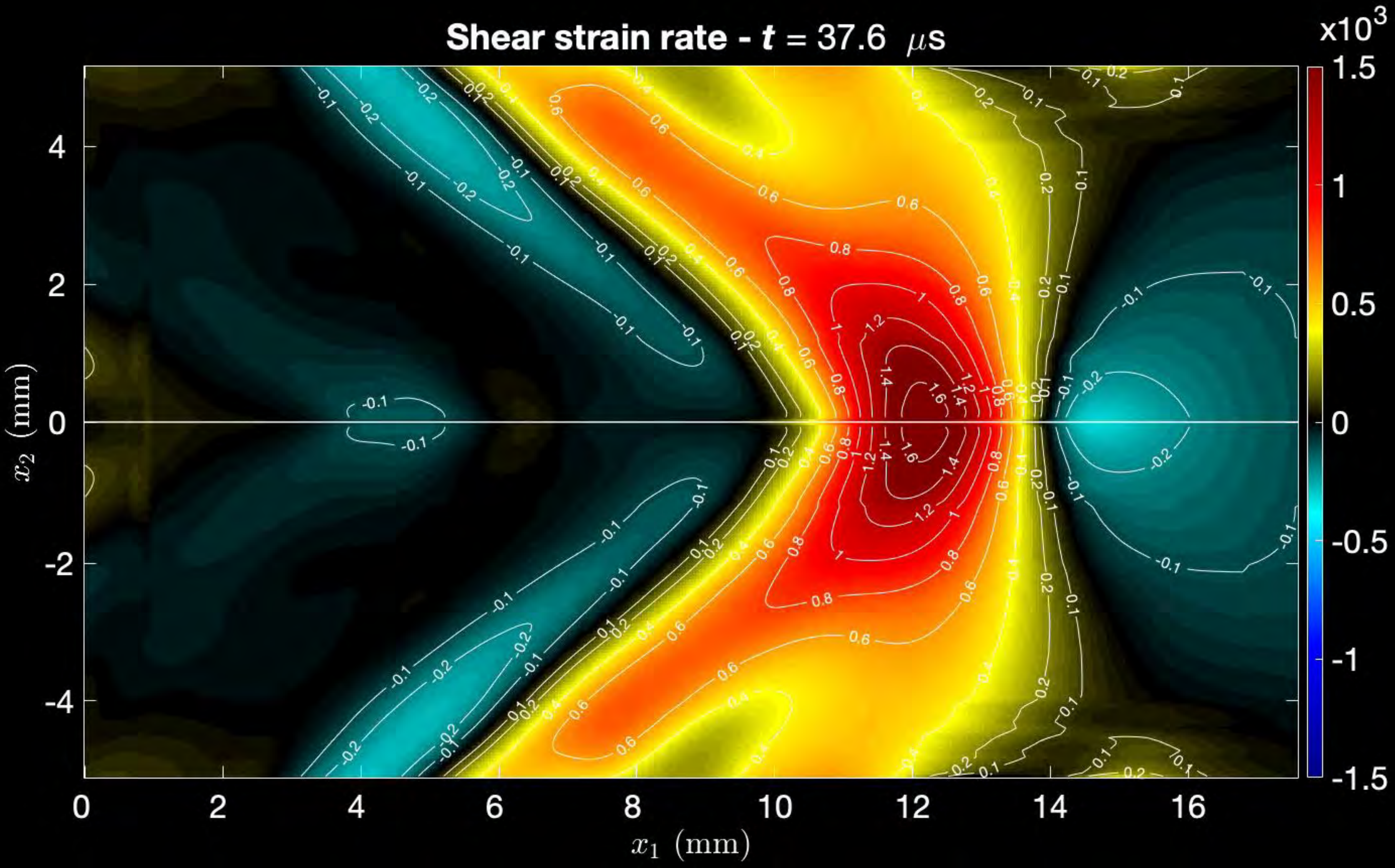
Rupture speed: 2285 m/s



Stresses from DIC



Super-shear rupture $c_S < v < c_P$



SECTION 4

CONNECTIONS WITH EARTHQUAKE SOURCE PHYSICS: USING INDIVIDUAL RUPTURES TO STUDY TRANSIENT FRICTION AT SEISMIC SLIP RATES

The nature of dynamic friction at sliding rates up to 20m/s is investigated by visualizing and measuring it during sliding at the tip a particular laboratory earthquake rupture

V. Rubino, A. J. Rosakis,N. Lapusta
Understanding dynamic friction through spontaneously evolving laboratory earthquakes
Nature Communications, 2017

Why is dynamic friction important in earthquake ruptures?

- Friction plays a key role in how ruptures unzip faults in the earth's crust

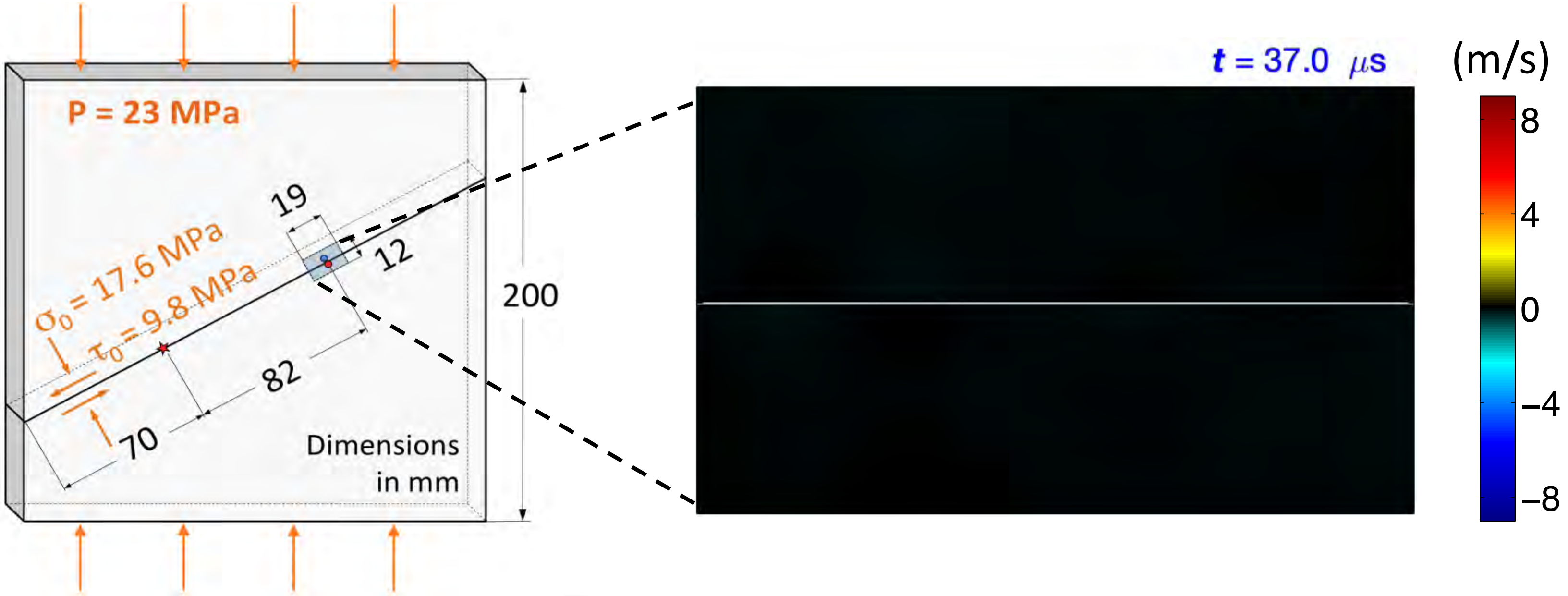
- In theoretical modeling , the assumed frictional law effects a wide range of earthquake science predictions, including: Energy partitioning, rupture speed , rupture mode selection, the nature of ground shaking , residual stress levels on faults, and patterns of seismic/aseismic slip. Yet the detailed nature of dynamic friction laws remains one of the biggest unknowns in earthquake science.

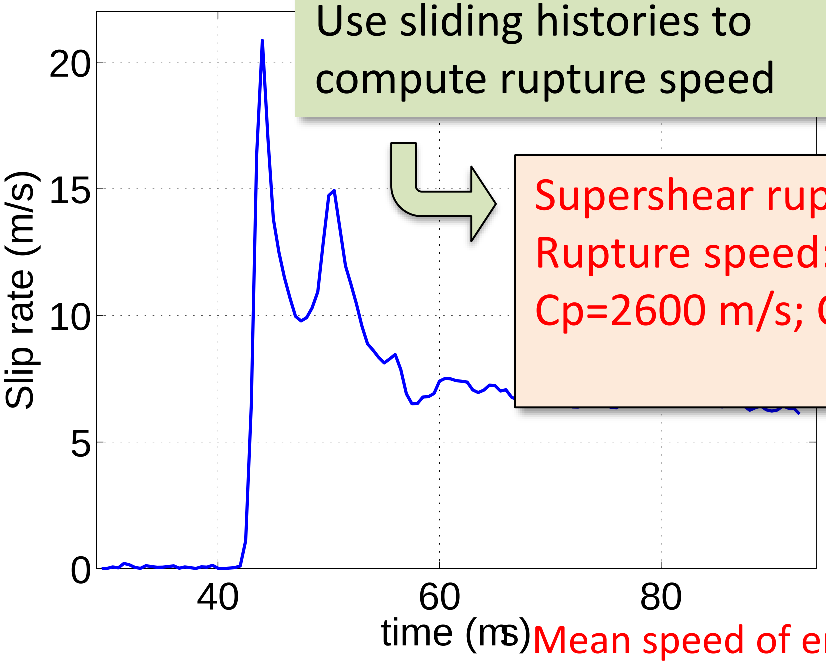
- Here we present a new way of inferring dynamic friction laws at ***seismic slip rates*** in a ***non-traditional setting***. Unlike classical dynamic friction experiments, we do not invoke the assumption of uniform sliding at the interface and do not impose sliding speed histories.

- Instead we welcome the presence of non-uniform sliding and infer dynamic friction (sliding rates up to 20m/s) by following individual laboratory earthquake rupture events with ultra-high-speed Photography and Digital Image Correlation (DIC)

Rubino, Rosakis, Lapusta, *Nature Communications*, 2017

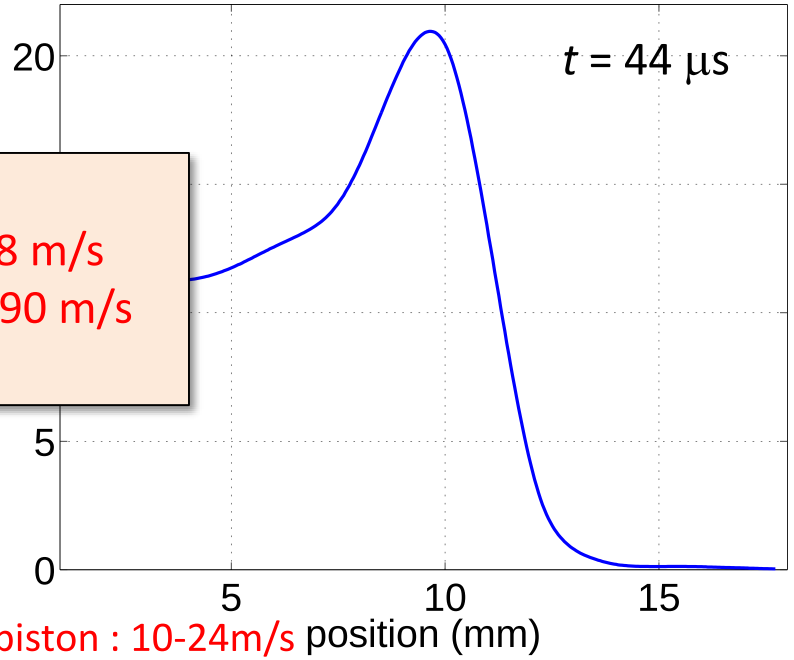
Fault-parallel velocity fields and sliding histories





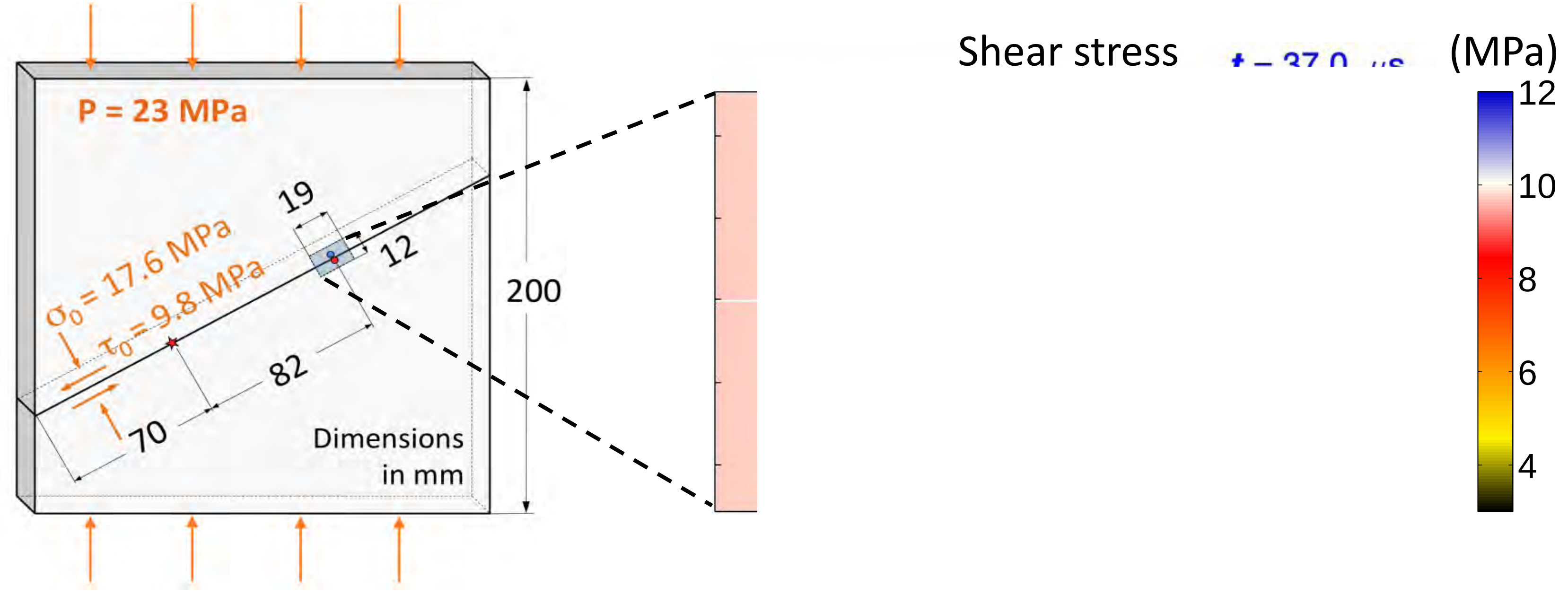
Use sliding histories to compute rupture speed

Supershear rupture.
Rupture speed: 2,368 m/s
Cp=2600 m/s; Cs=1290 m/s

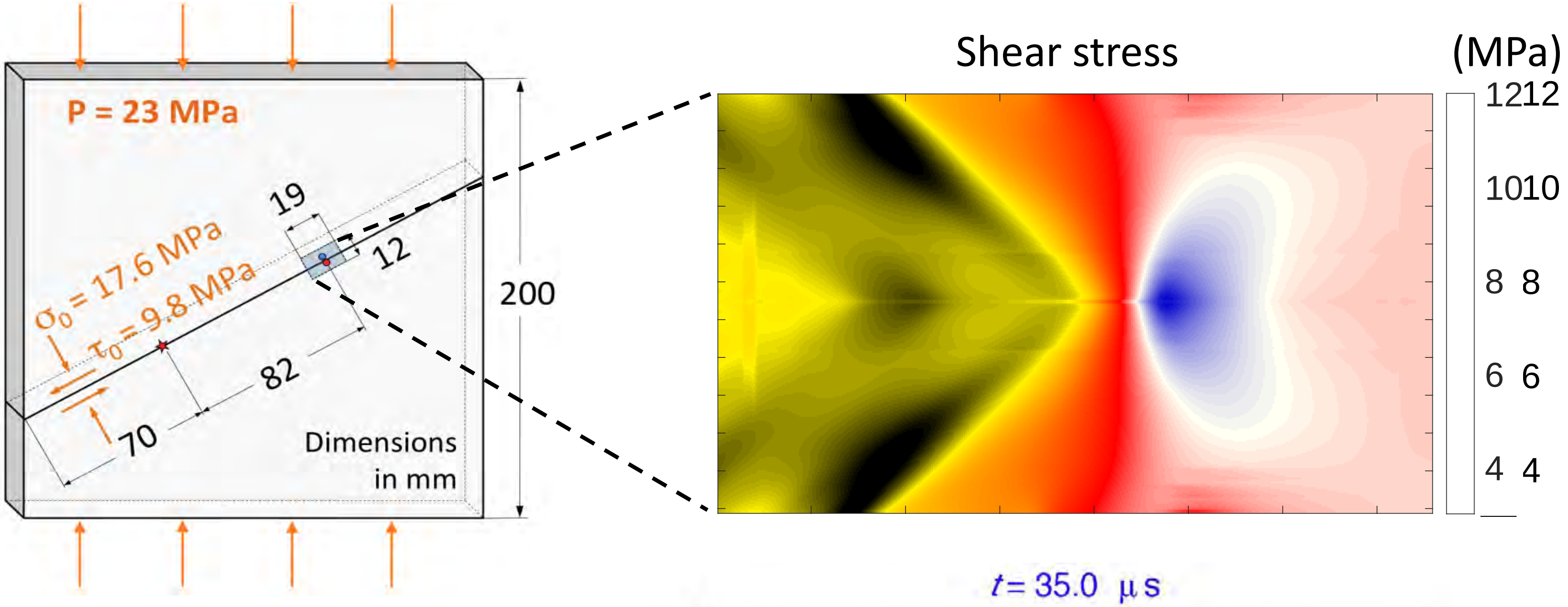


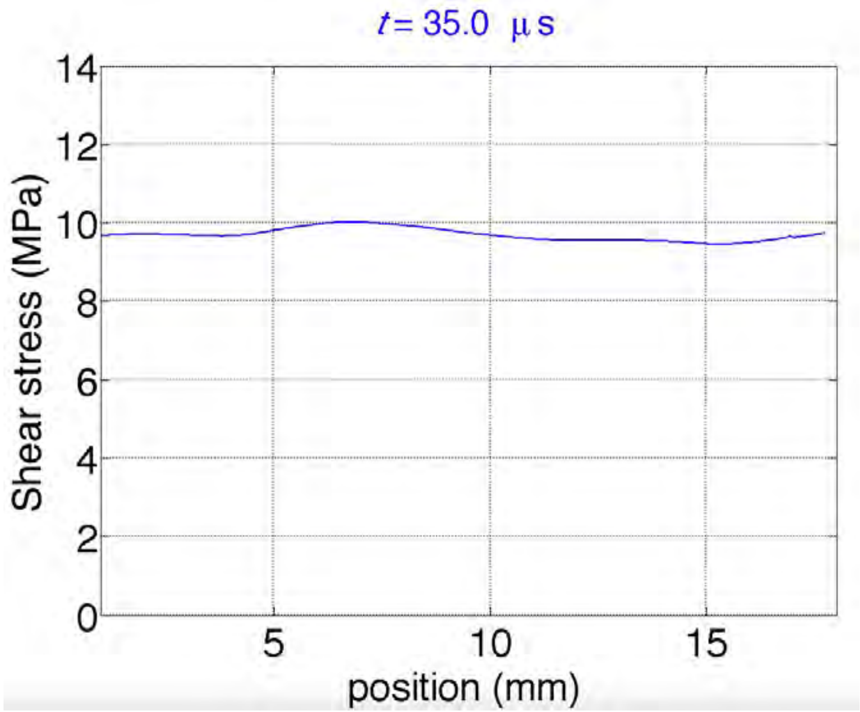
Mean speed of engine piston : 10-24m/s

Shear Stress fields

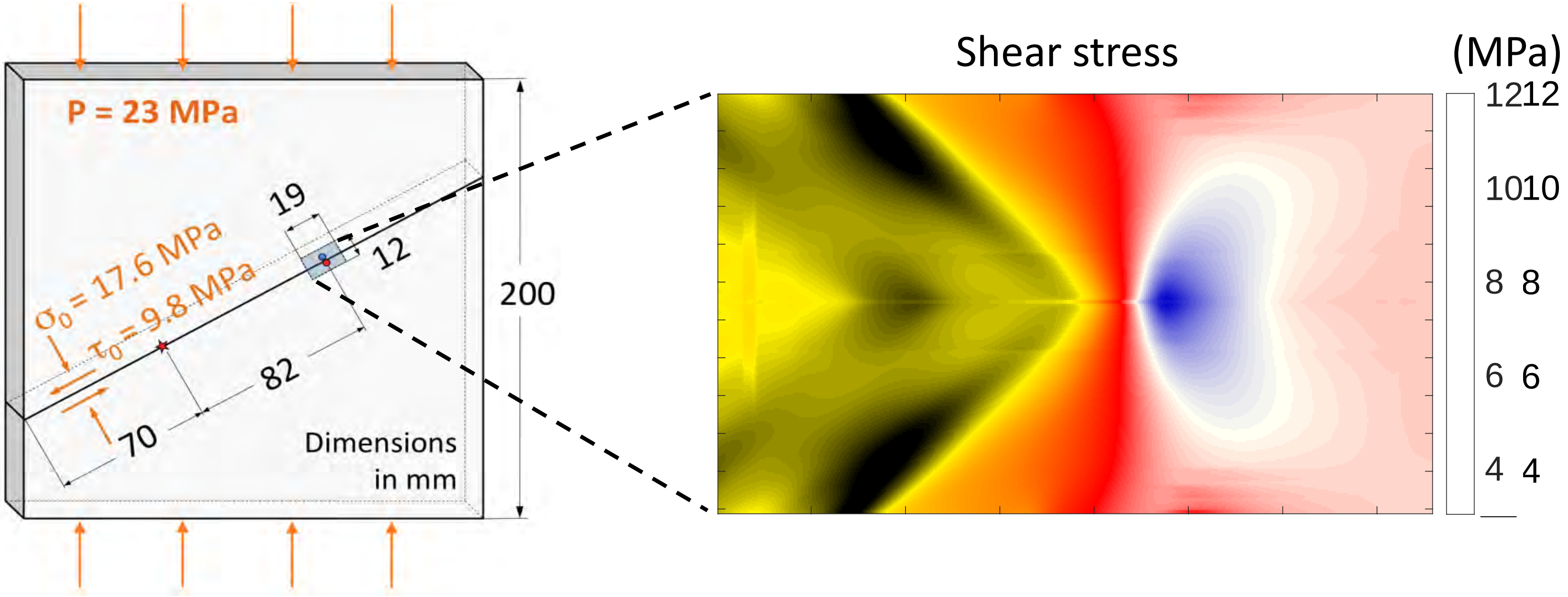


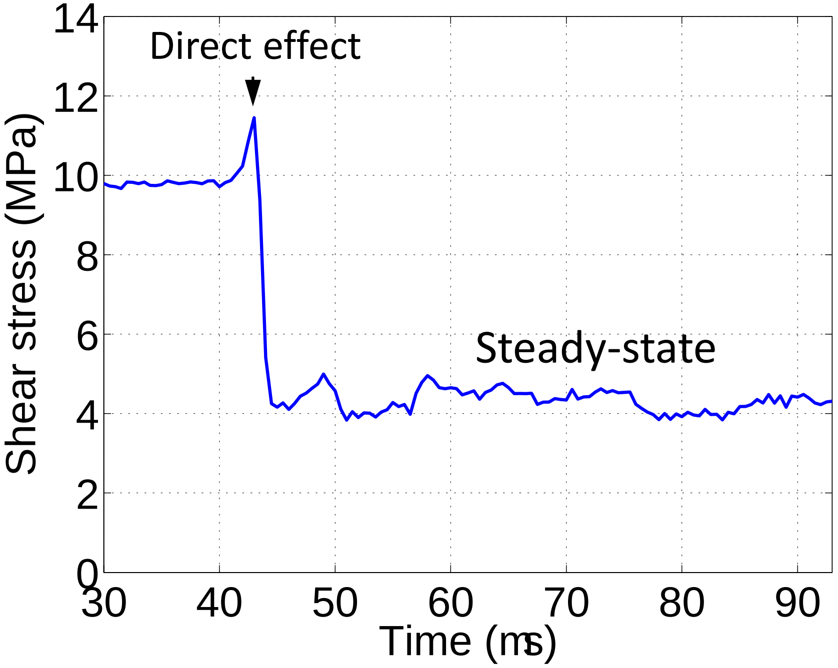
Shear Stress fields

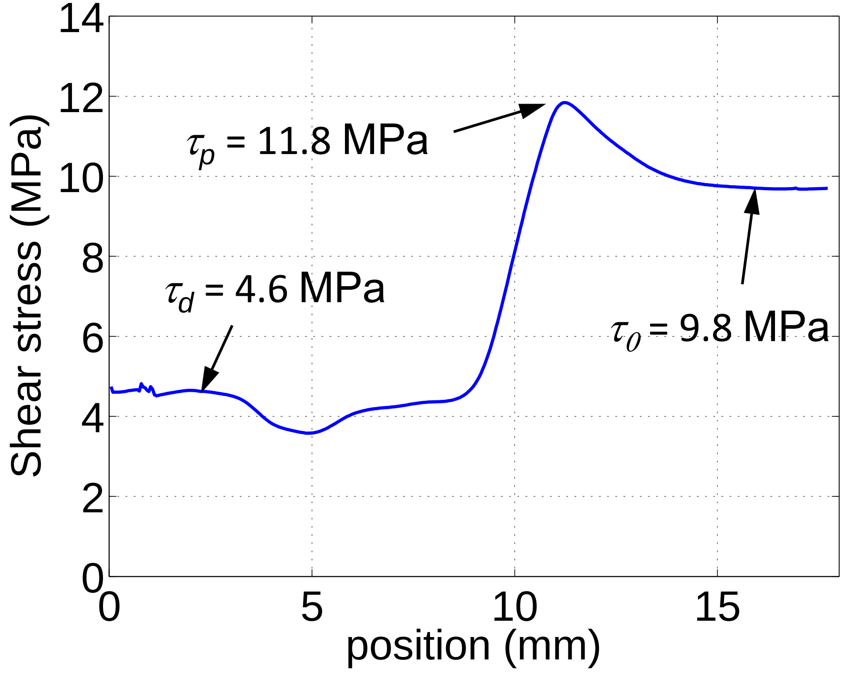




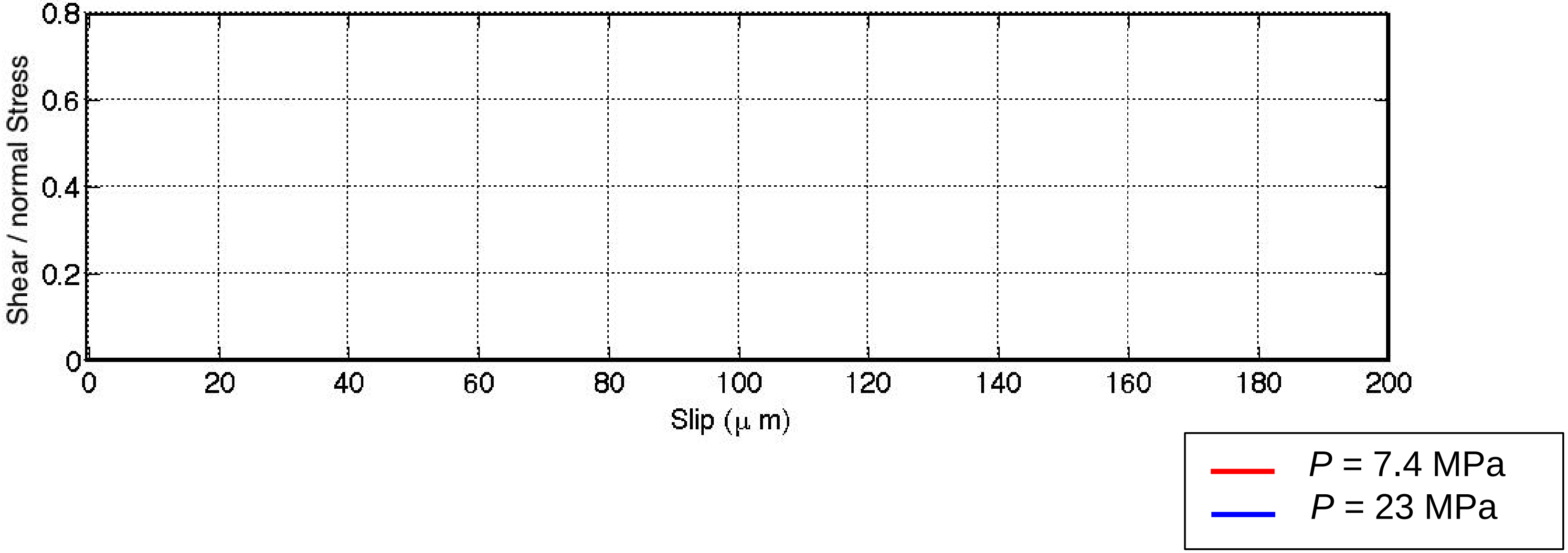
Shear Stress fields





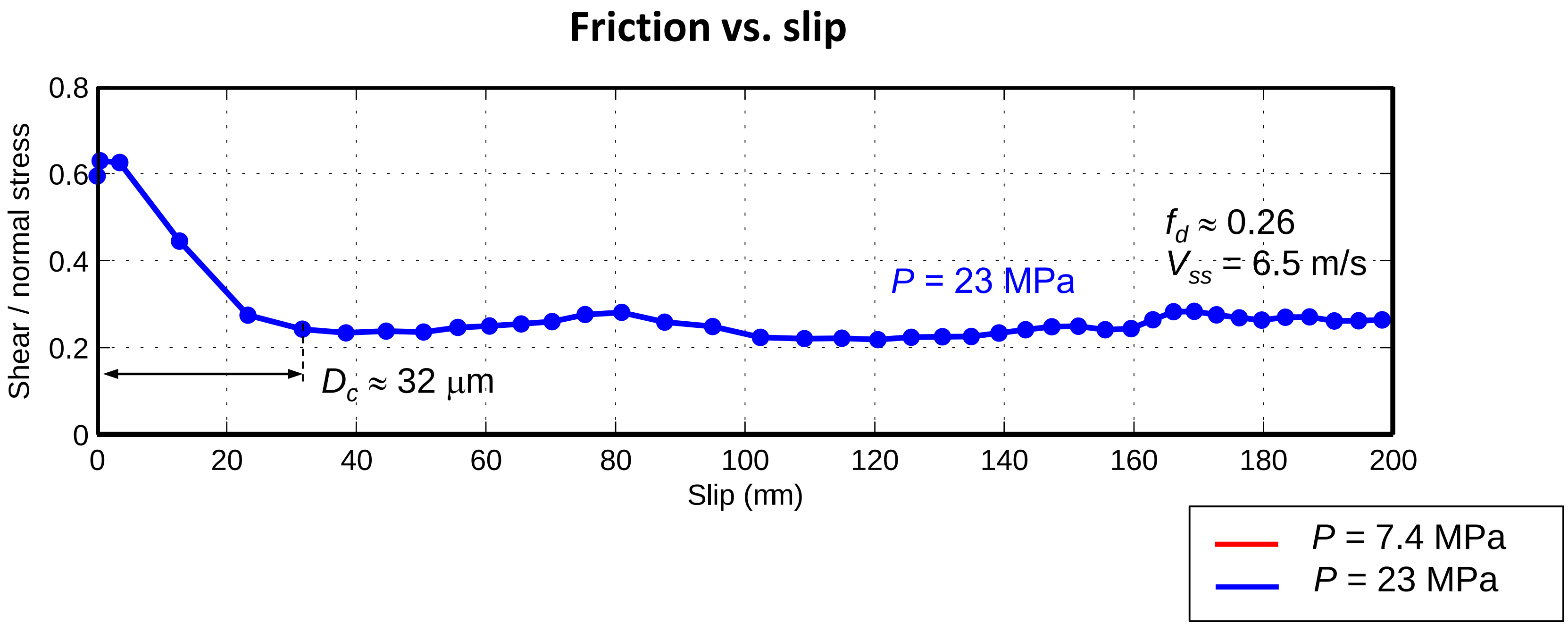


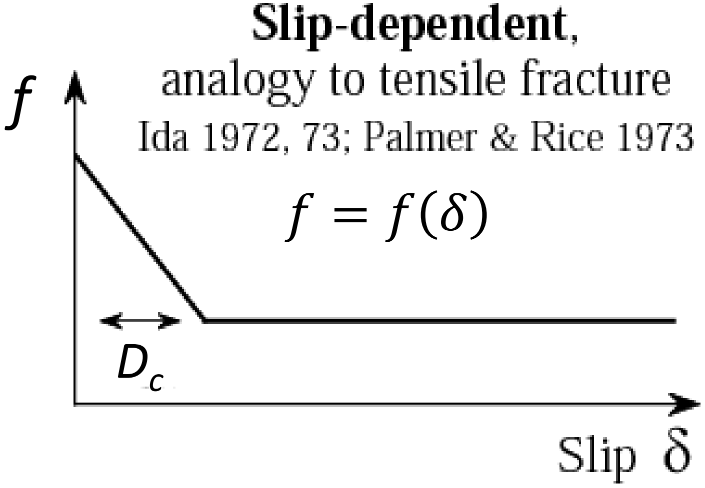
Evolution of dynamic friction f.



Friction vs. slip

Evolution of dynamic friction f.



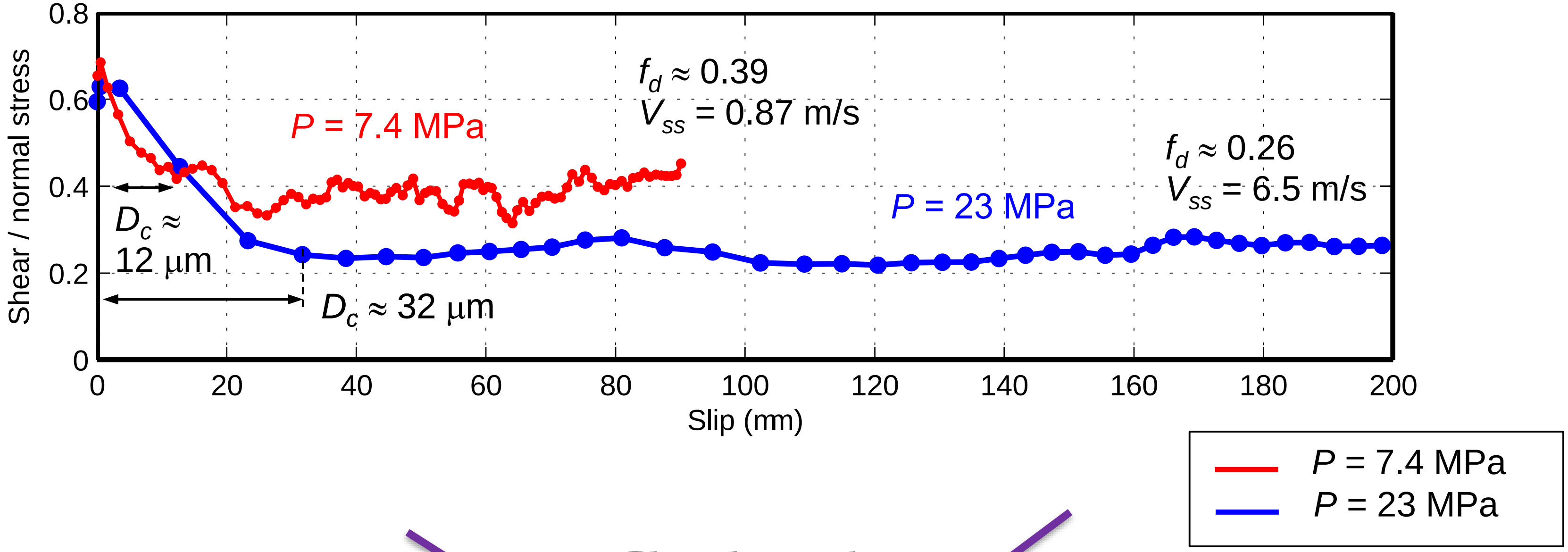

Slip-dependent, analogy to tensile fracture
Ida 1972, 73; Palmer & Rice 1973

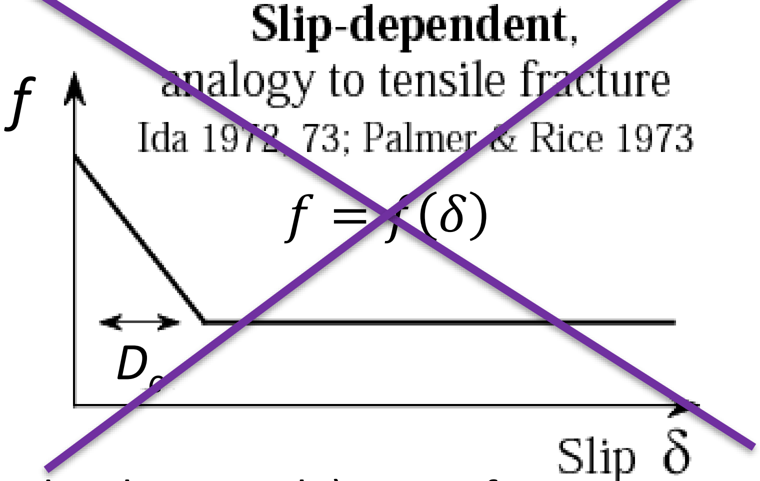
$$f = f(\delta)$$

Rubino, Rosakis, Lapusta, *Nature Communications*, 2017

Evolution of dynamic friction f.

Friction vs. slip

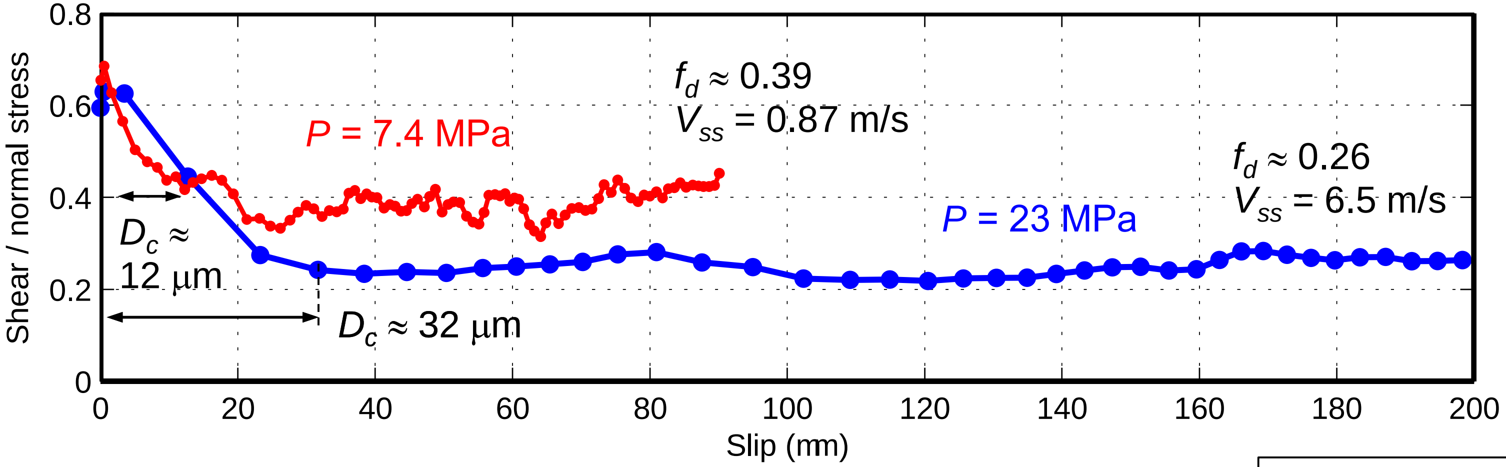




G, Energy release rate (Area under the triangle) varies from rupture scenario to rupture scenario. The analogy to fracture brakes down.

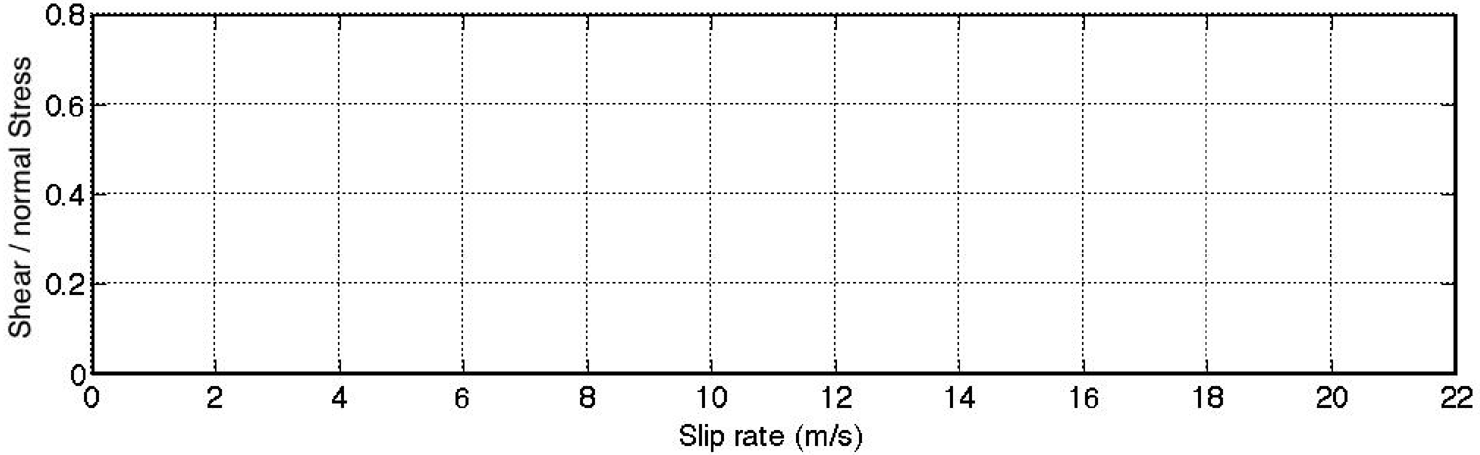
Evolution of dynamic friction f.

Friction vs. slip



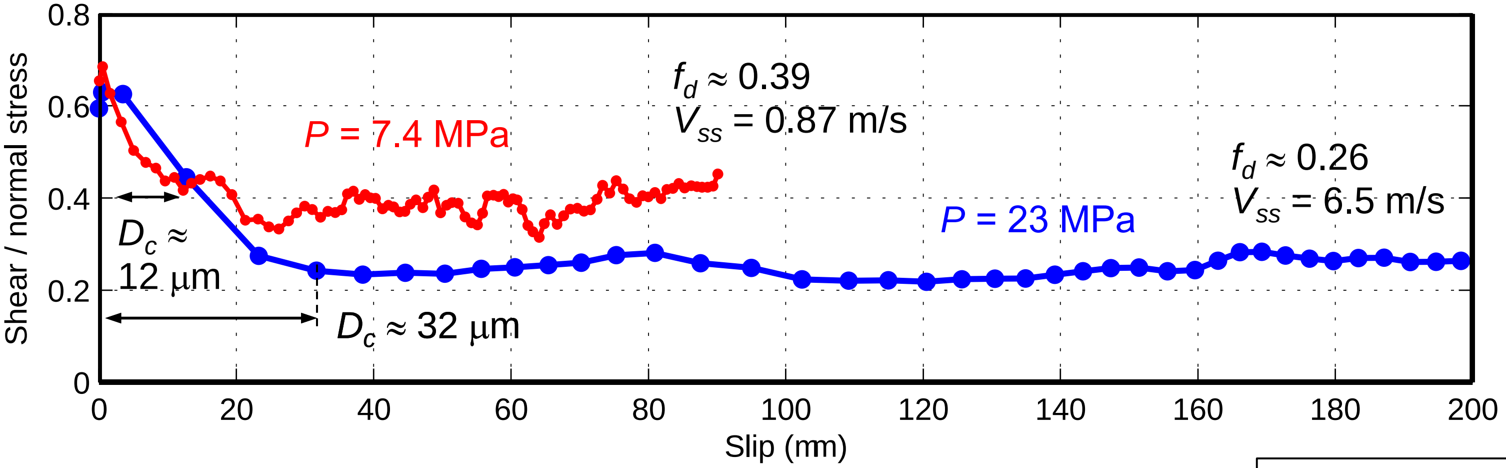
Friction depends STRONGLY on slip rate and its history

Friction vs. slip rate



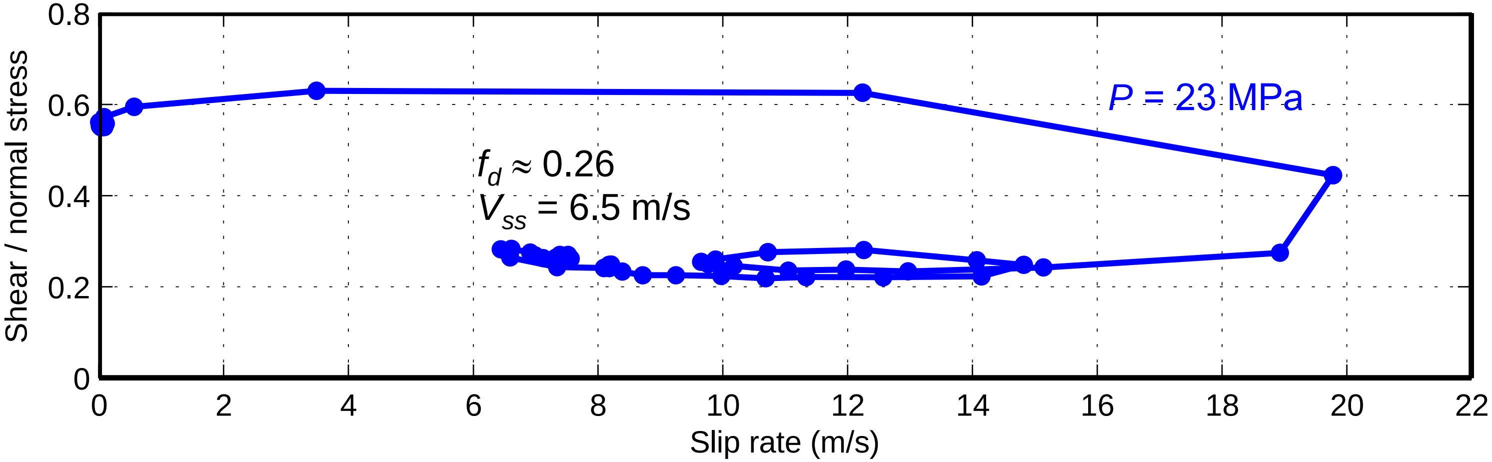
Evolution of dynamic friction f.

Friction vs. slip

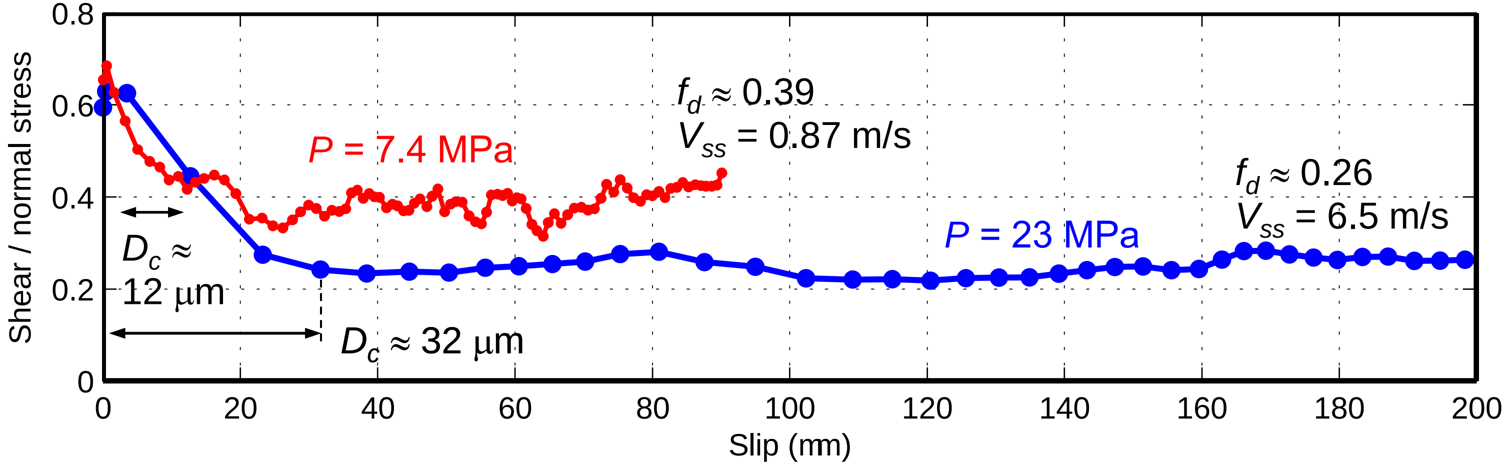


Friction depends STRONGLY
on slip rate and its history

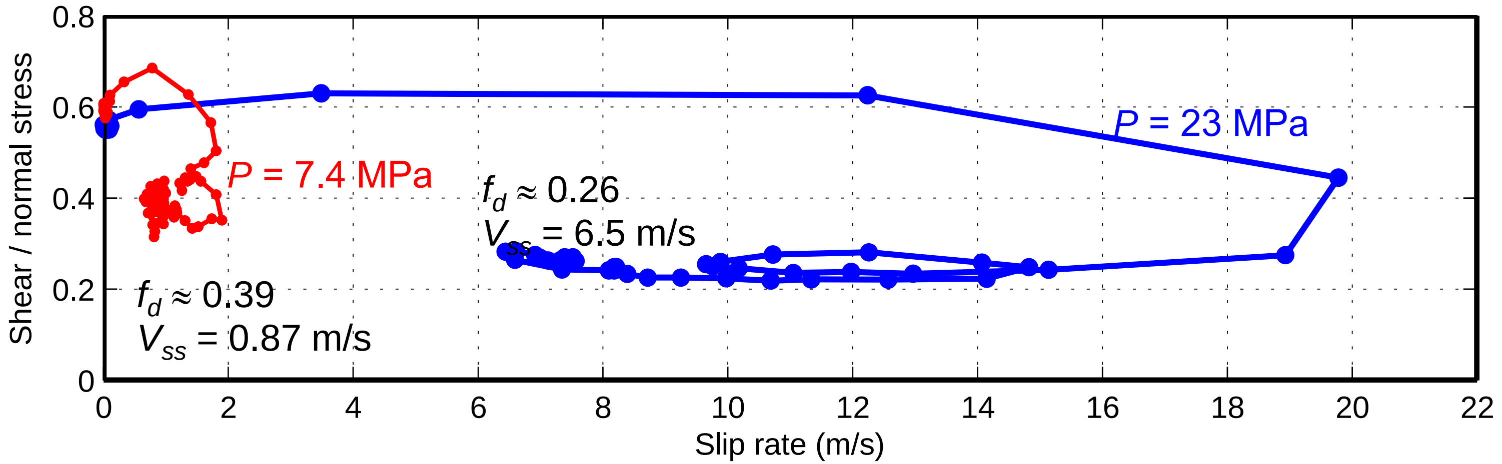
Friction vs. slip rate



Evolution of dynamic friction f.


Friction vs. slip

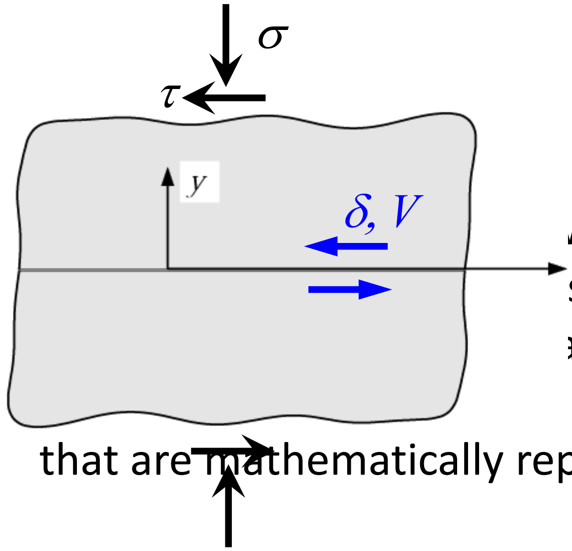
Friction depends STRONGLY on slip rate and its history


Friction vs. slip rate

We need a history dependent law to model this phenomenon (e.g. Dietrich 1979; Ruina 1980; Rice, EOS Trans AGU 1999 ; Rice JGR 2006)

Friction,f, and sliding: slip vs. velocity dependent laws

$\tau = f\,\sigma$

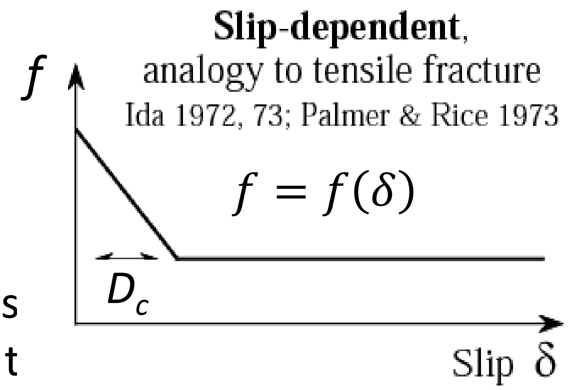


- ws
- s t

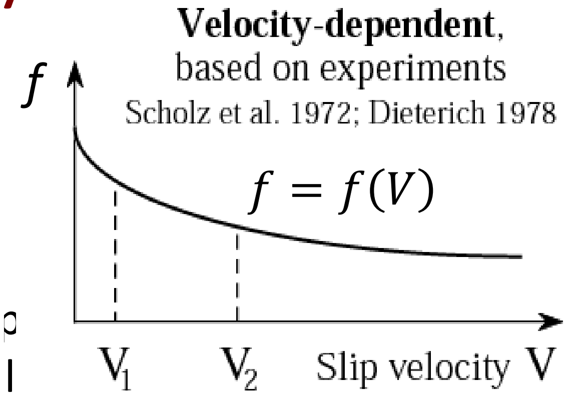
after sufficient slip

transient effects d

that are mathematically represented by the e


Slip-dependent, analogy to tensile fracture

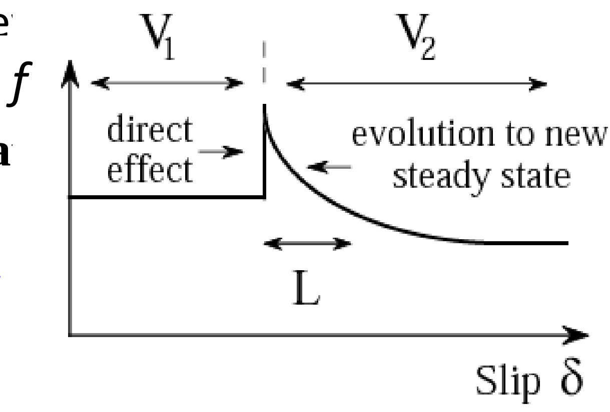
Ida 1972, 73; Palmer & Rice 1973


Velocity-dependent, based on experiments

Scholz et al. 1972; Dieterich 1978

More detailed experiments

Dieterich 1979, 81; Ruina 1980, 83



Flash heating supplemented with rate-and-sta

Rate-and-state dependent friction exhibits a history dependent direct effect

$$\tau = f\,\sigma$$

$$f = f_w + \frac{\left(f_* + a\ln\frac{V}{V_*} + b\ln\frac{V_*\theta}{L}\right) - f_w}{1 + \frac{\theta V_w}{L}};$$

$$f = f_* + a\ln\frac{V}{V_*} + b\ln\frac{V_*\theta}{L};$$

$$\frac{d\theta}{dt} = 1 - \frac{V\theta}{L}$$ (Aging law)

w

$f = f_* + (a$

$$f = f_w + \frac{\left(f_* + (a-b)\ln\left(\frac{V}{V_*}\right)\right) - f_w}{1 + \frac{V}{V_w}}$$

or

tion

Friction,f, and sliding: slip vs. velocity dependent laws

- Flash heating is a type of shear weakening mechanism. Tips of contacting microscopic asperities heat up and weaken. At high slip rates this is activated adiabatically even at low values of slip, of the order of tens to hundreds of microns.
- Flash heating has received ample theoretical and experimental support (e.g. Rice, *EOS Trans AGU* 1999; Beeler, Tullis, Goldsby, *JGR* 2008; Rice, *JGR* 2006)

Flash heating supplemented with rate-and-state dependent friction

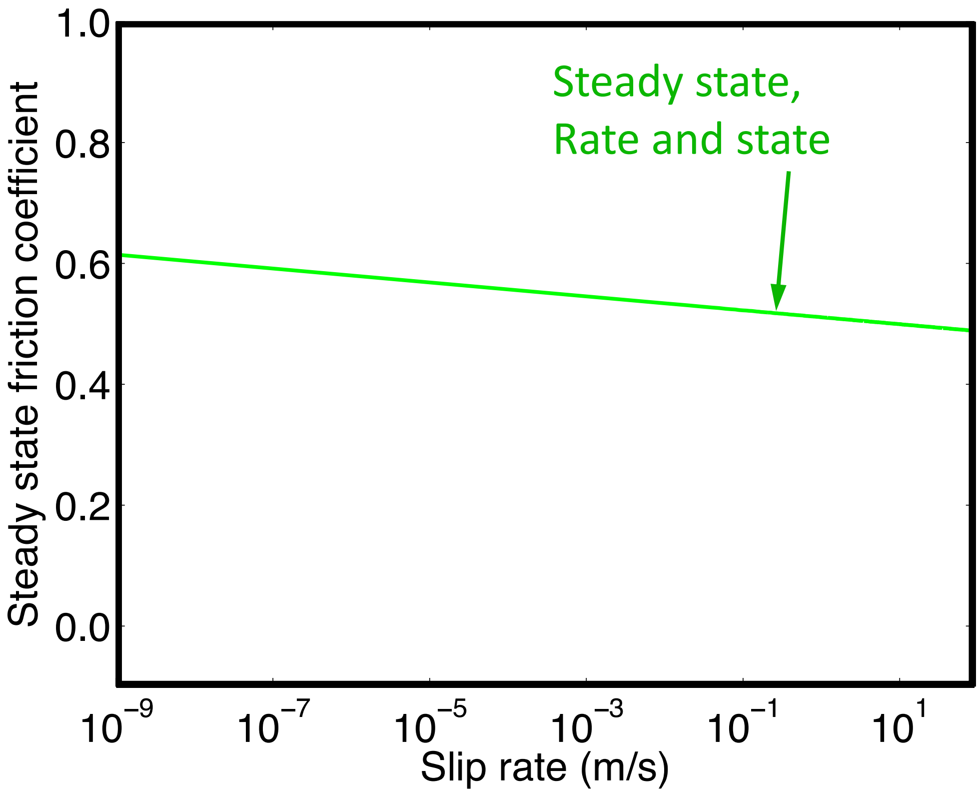
$$\left.\begin{aligned} f &= f_w + \frac{\left(f_* + a\ln\dfrac{V}{V_*} + b\ln\dfrac{V_*\theta}{L}\right) - f_w}{1 + \dfrac{L}{\theta V_w}}; \\[2ex] \frac{d\theta}{dt} &= 1 - \frac{V\theta}{L} \qquad \text{(Aging law)} \end{aligned}\right\}$$

Steady state behavior of combined friction law

$$\boxed{f = f_w + \frac{\left(f_* + (a-b)\ln\left(\dfrac{V}{V_*}\right)\right) - f_w}{1 + \dfrac{V}{V_w}}}$$

Steady state behavior (V = constant)

Rate-and-state dependent friction

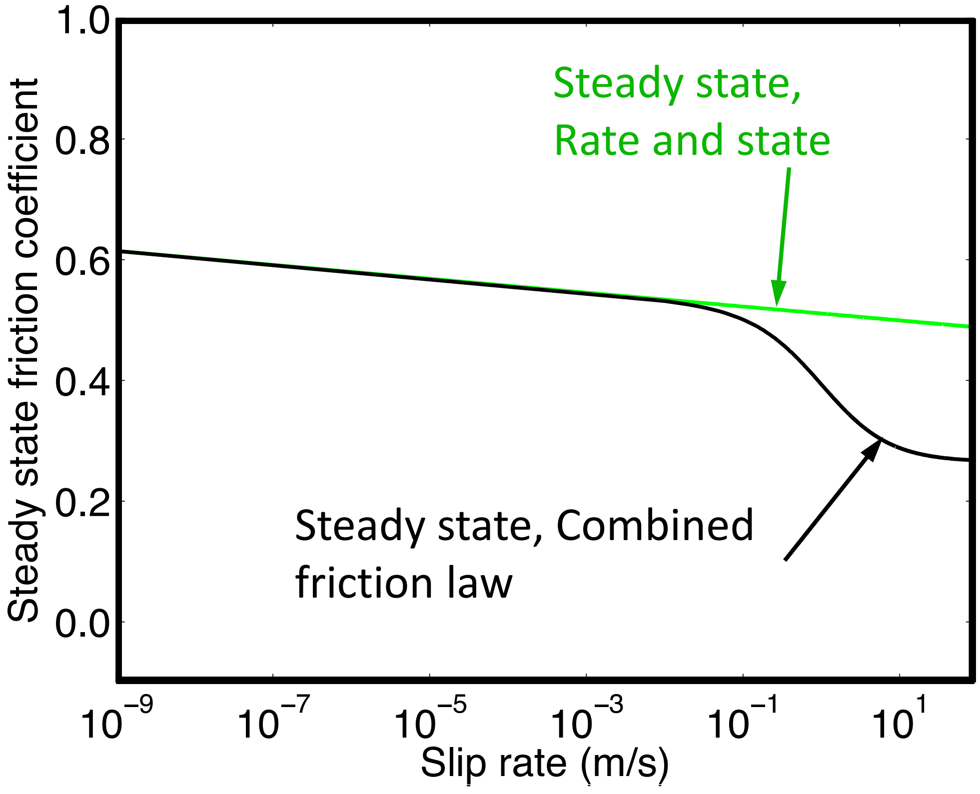


Steady-state behavior of **rate-and-state friction**

$$f = f_* + (a - b)\ln\frac{V}{V_*}$$

- In rate-and-state friction laws, friction is function of the slip rate and a state variable that describes the evolution of contact population.
- Friction is rate-dependent after sufficient slip at a constant slip rate, but exhibits history-dependent transient effects during changes of velocity that are mathematically represented by the evolving state variable.

Steady State, Rate-and-State dependent friction enhanced with flash heating weakening



- Flash heating is a type of shear weakening mechanism. Tips of contacting microscopic asperities heat up and weaken. At high slip rates this is activated adiabatically even at low values of slip, of the order of tens to hundreds of microns.
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Steady-state behavior of **rate-and-state friction**

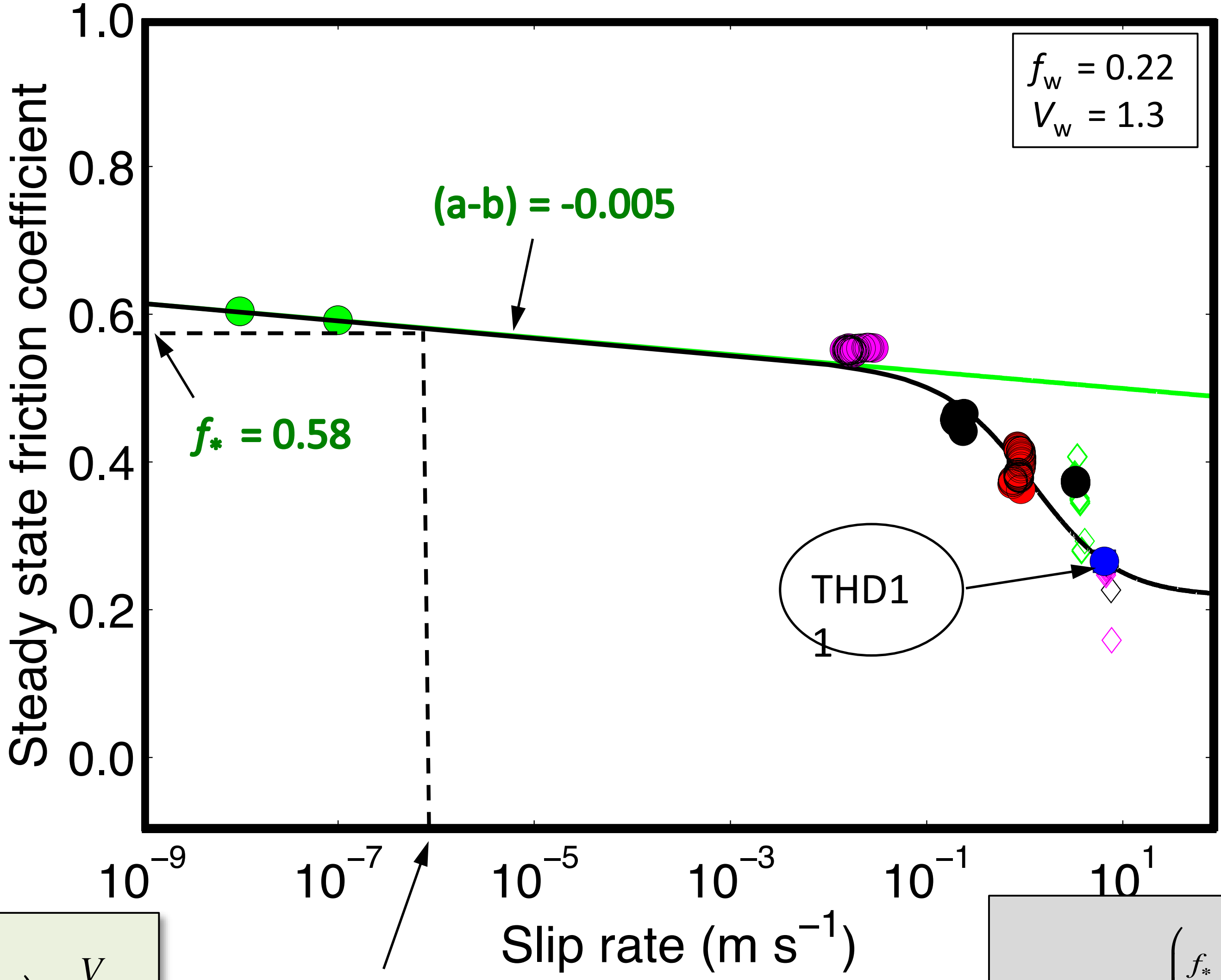
$$f = f_* + (a-b)\ln\frac{V}{V_*}$$

Steady-state behavior of **combined friction law**

$$f = f_w + \frac{\left(f_* + (a-b)\ln\left(\frac{V}{V_*}\right)\right) - f_w}{1 + \frac{V}{V_w}}$$

Getting parameters from ‘Steady state’ behavior

Rubino, Rosakis, Lapusta, *Nature Communications*, 2017

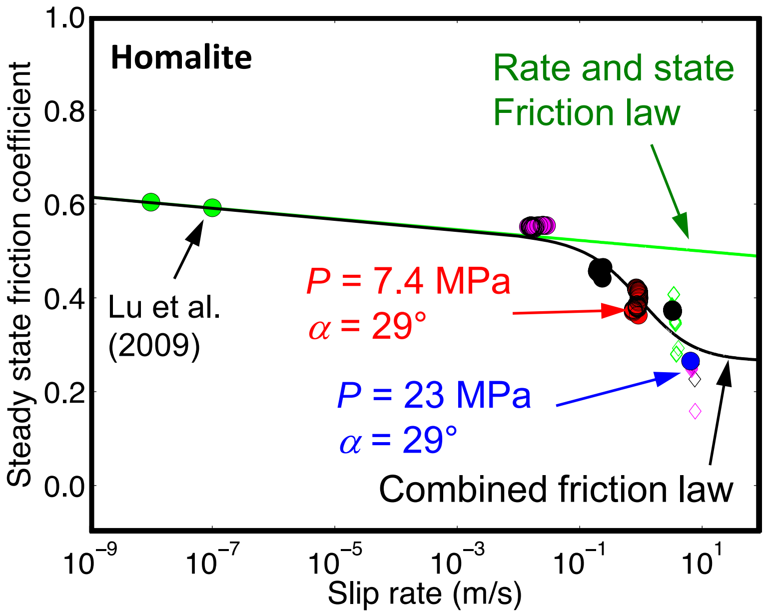


V_* = 10^{-6} m/s

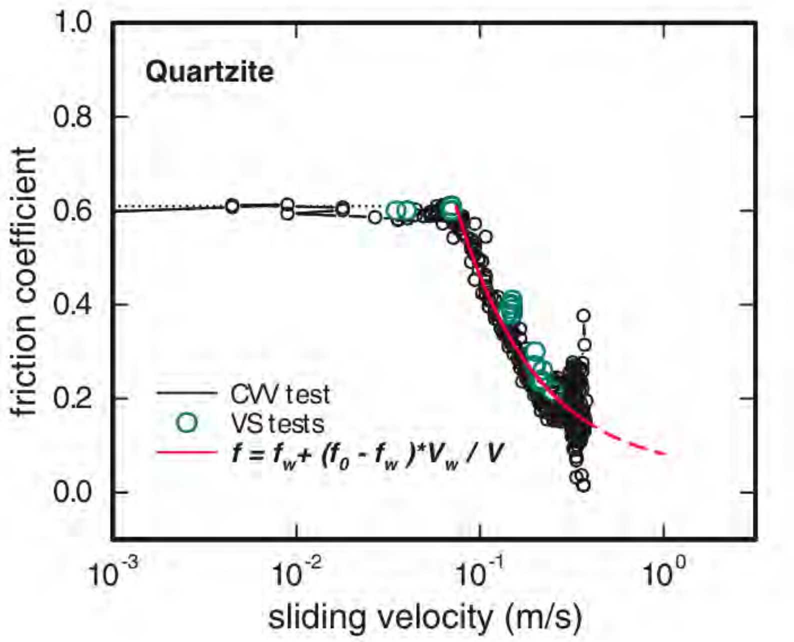
$$f = f_* + (a-b)\ln\frac{V}{V_*}$$

$$f = f_w + \frac{\left(f_* + (a-b)\ln\left(\frac{V}{V_*}\right)\right) - f_w}{1 + \frac{V}{V_w}}$$

Comparison with flash heating formulation at seismic slip rates



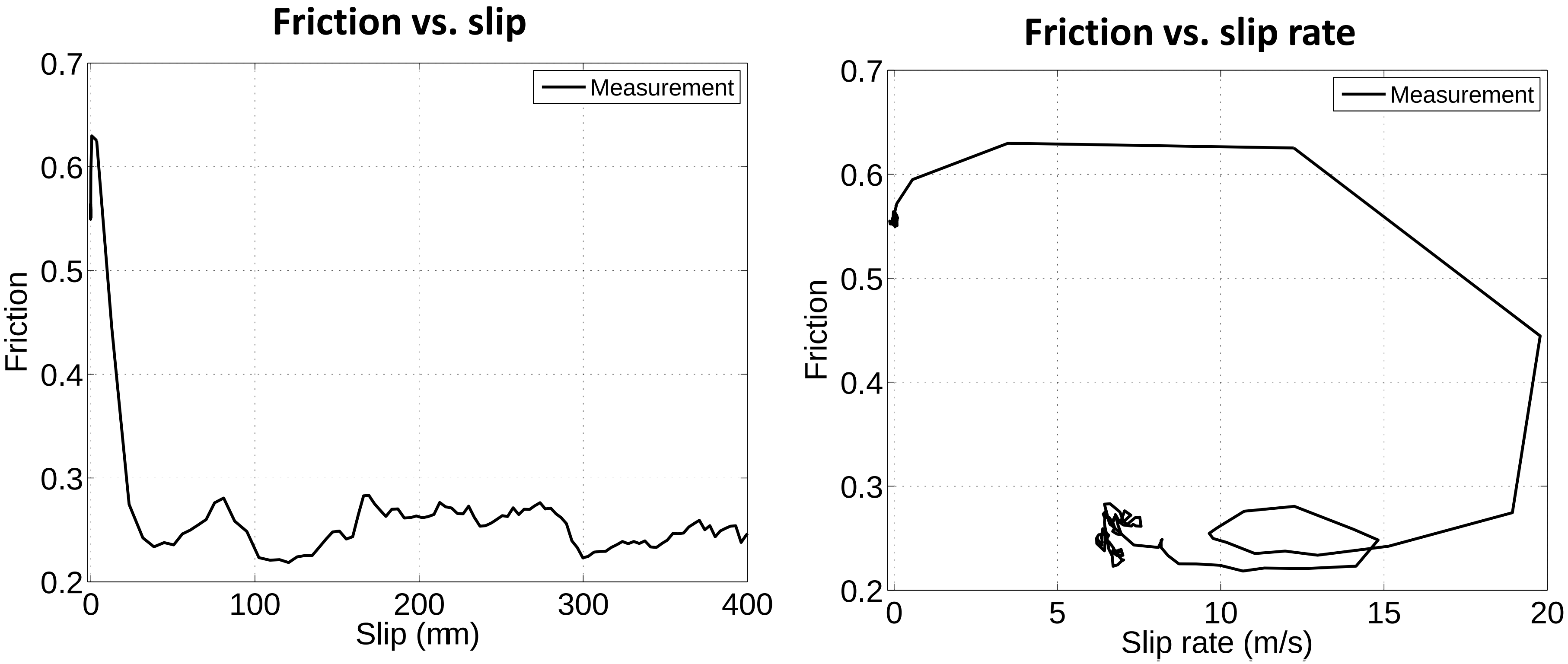
Our tests on spontaneous ruptures
(Rubino, Rosakis, Lapusta,
Nature Communications, 2017)



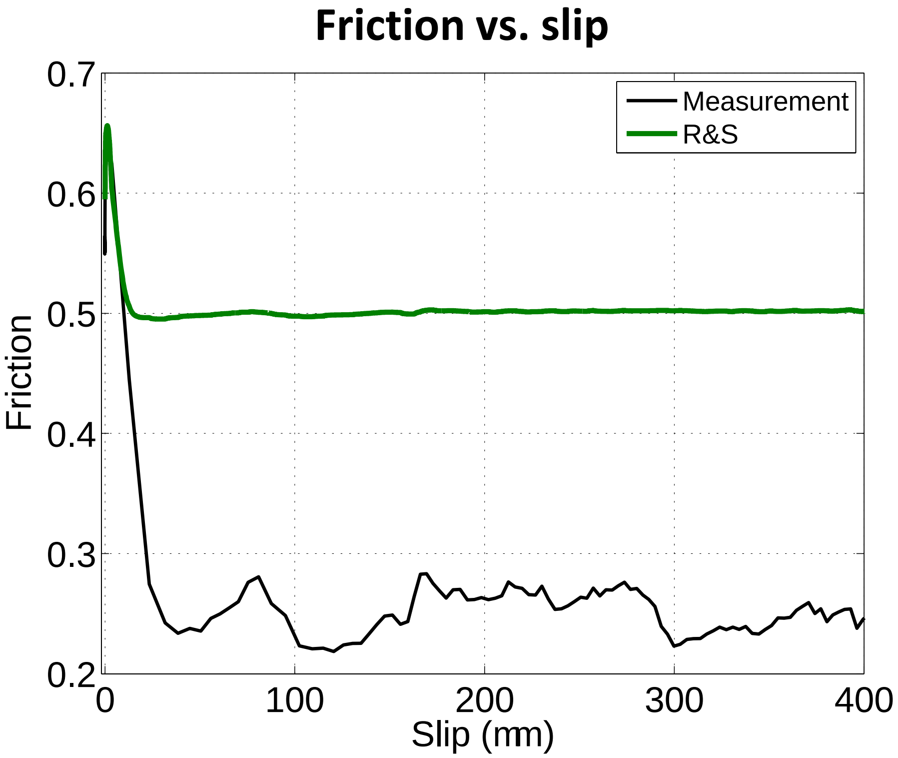
Goldsby and Tullis, *Science* 2011

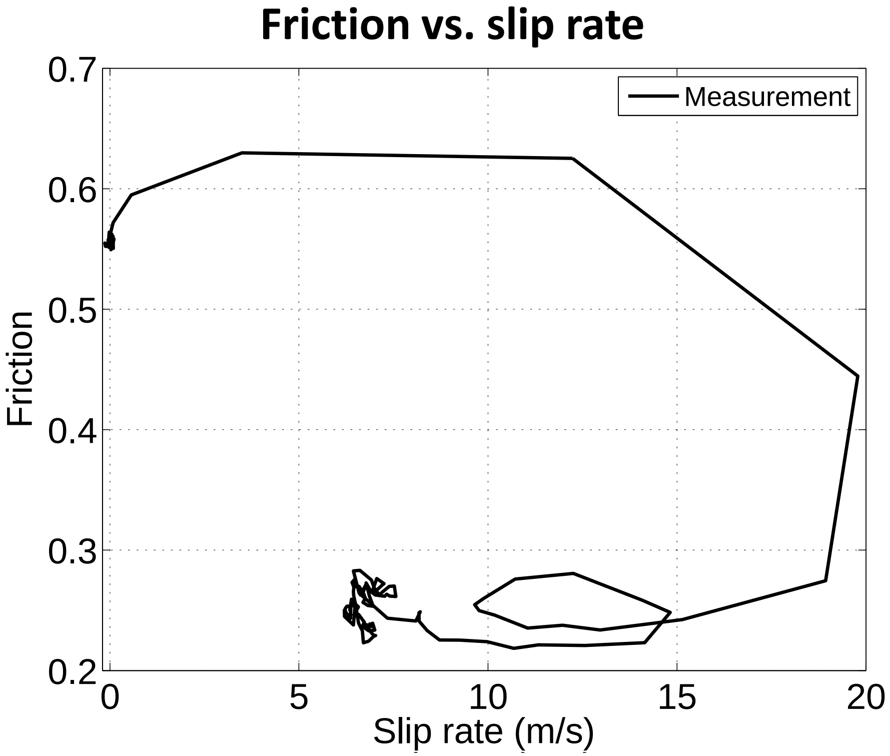
- Similar to Rocks, flash heating in Homalite-100 reduces the steady state dynamic friction coefficient to values of ≈ 0.2 at seismic slip rates.

Matching friction evolution with fitted friction laws

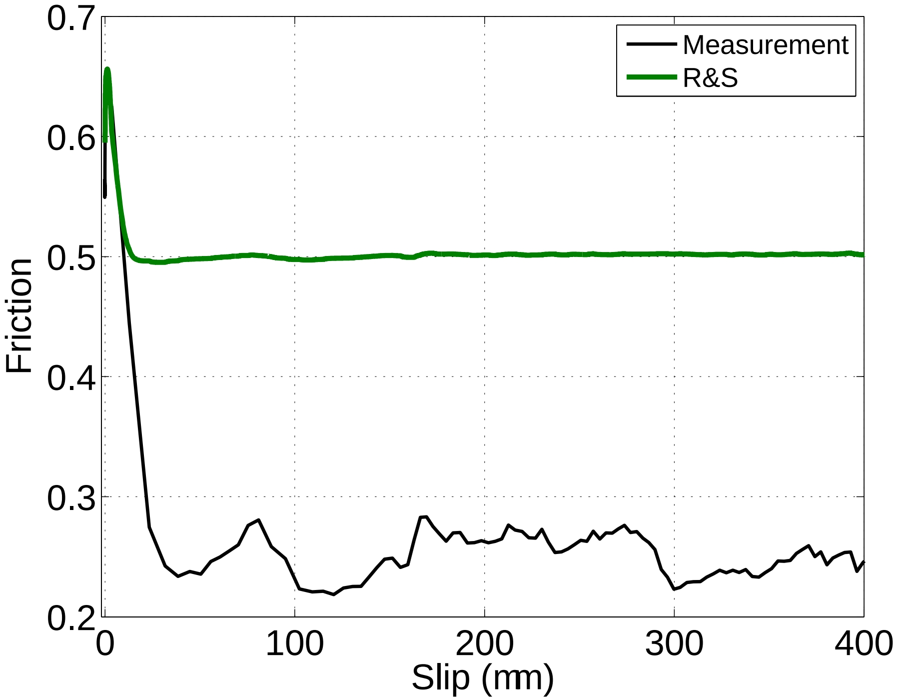


Matching dynamic friction evolution of a single rupture with fitted friction laws

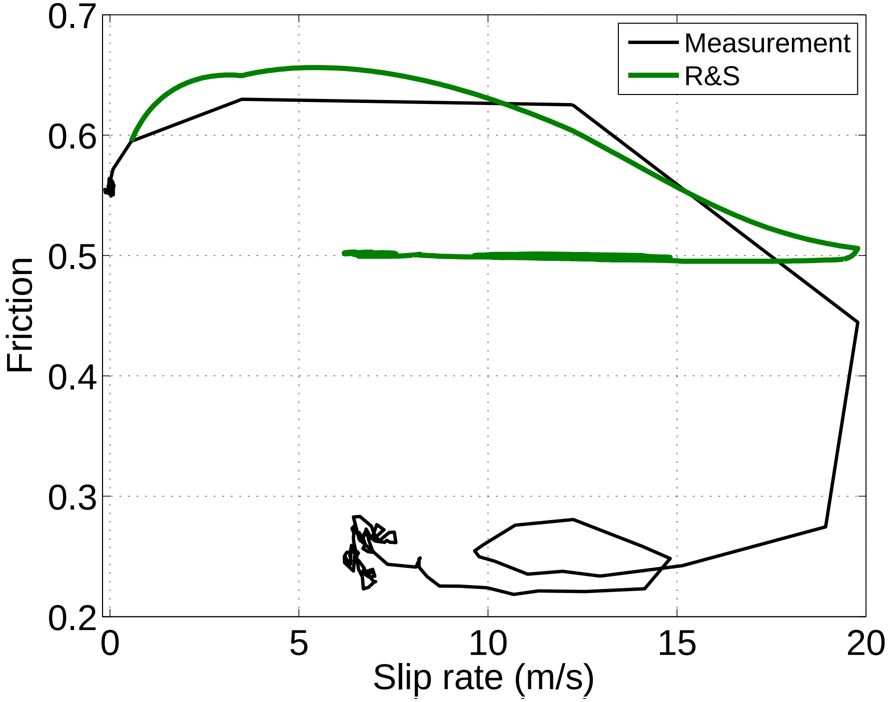




Matching friction evolution with fitted friction laws



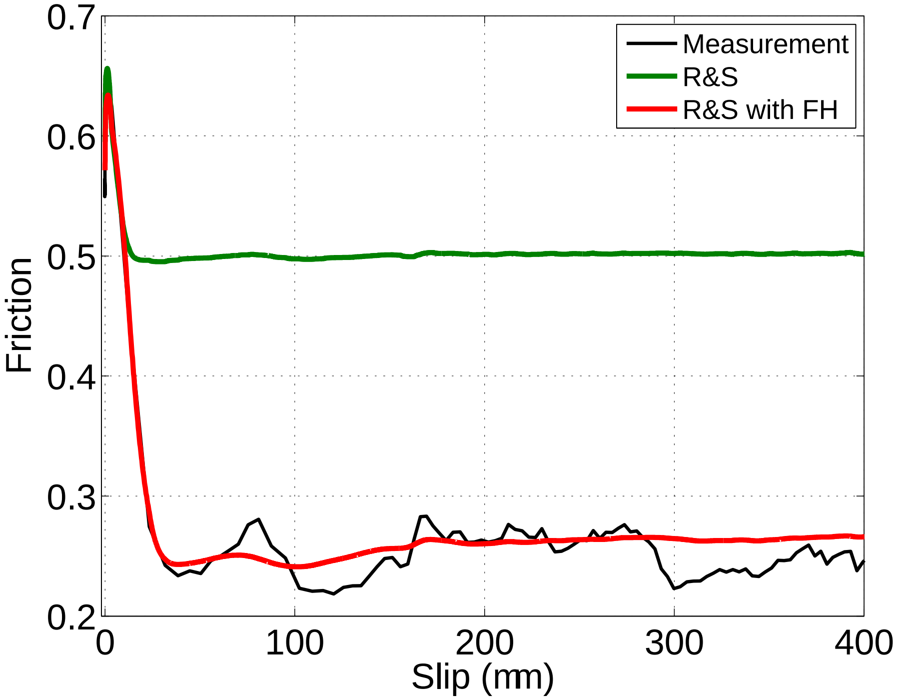
Friction vs. slip



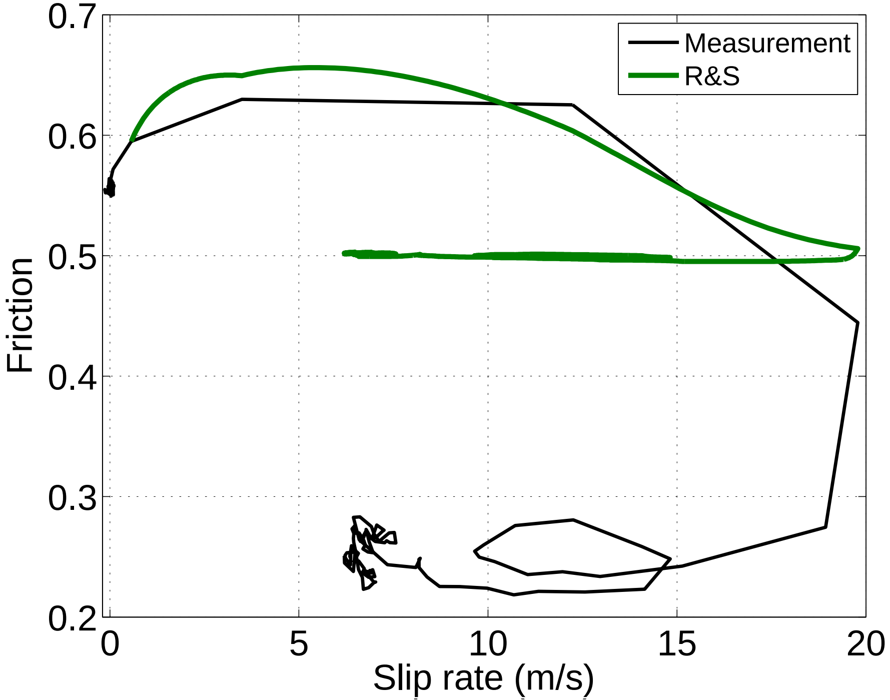
Friction vs. slip rate

Matching friction evolution with fitted friction laws

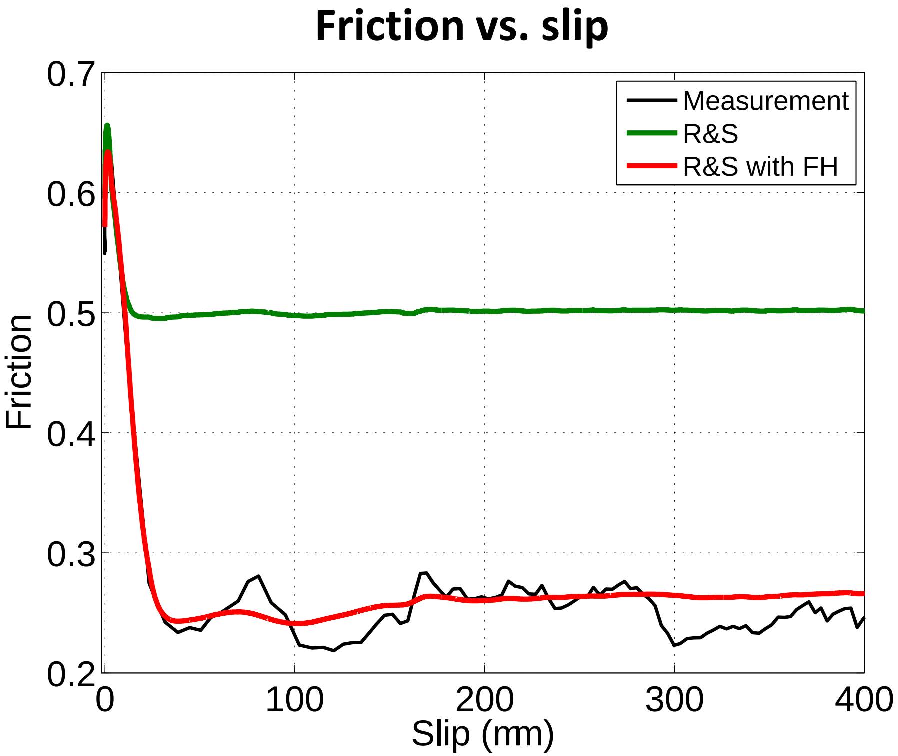
Friction vs. slip

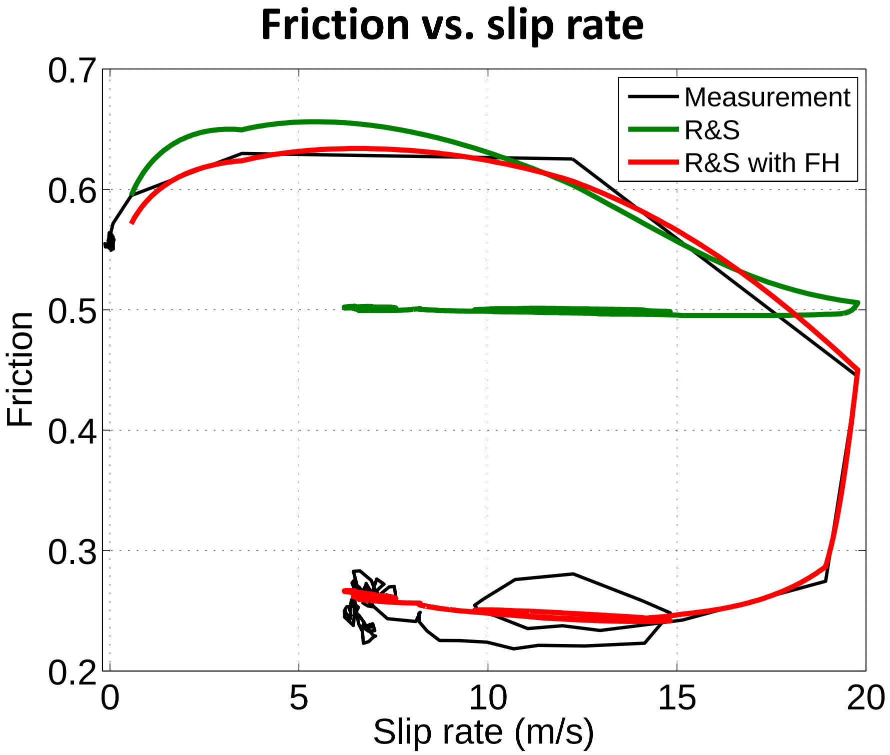


Friction vs. slip rate



Matching friction evolution with friction laws





$\tau = f\,\sigma$ where: $$f = f_w + \frac{\left(f_* + a\ln\frac{V}{V_*} + b\ln\frac{V_*\theta}{L}\right) - f_w}{1 + \frac{L}{\theta V_w}}; \qquad \frac{d\theta}{dt} = 1 - \frac{V\theta}{L}$$

Rate and State with Flash Heating captures trends well

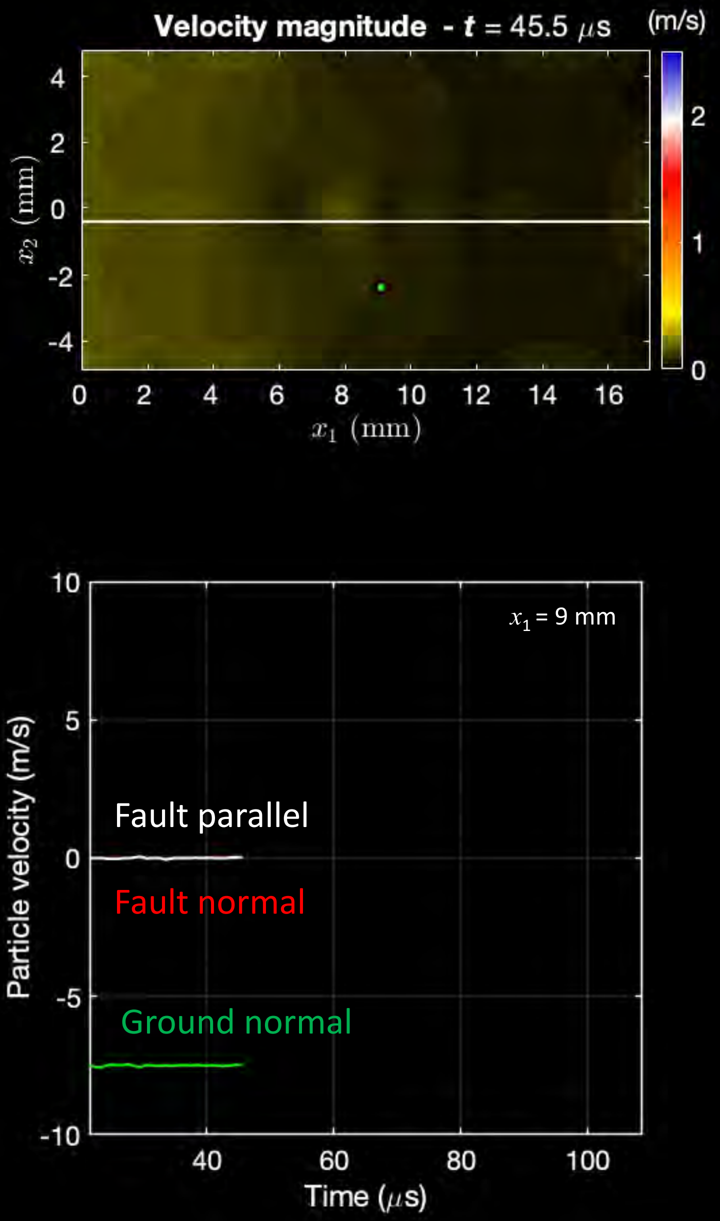
SECTION 5

CONNECTIONS WITH ENGINEERING SEISMOLOGY

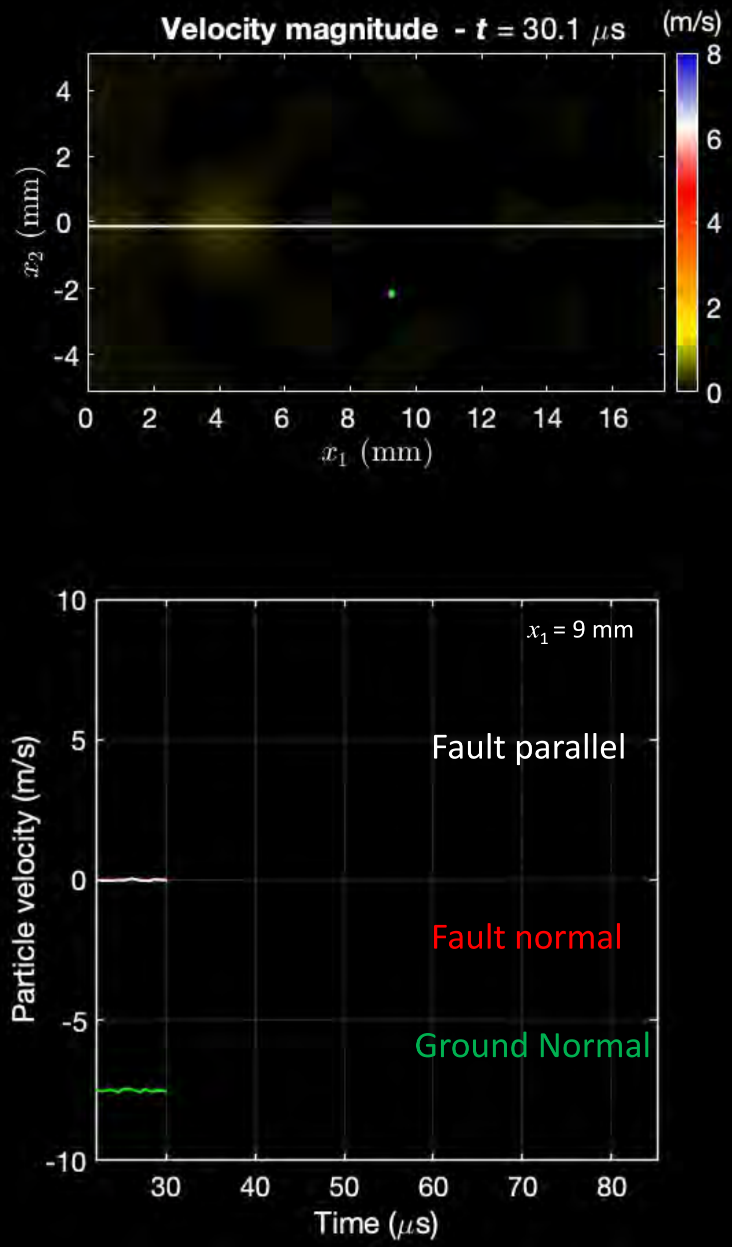
Using DIC and Laboratory ruptures to study near fault ground shaking signatures of both sub-Rayleigh and super-Shear Ruptures and to evaluate near fault hazards

Mello, Bhat, Rosakis and Kanamori, Tectonophysics, Special Volume on Supershear 2010.

Sub-Rayleigh rupture

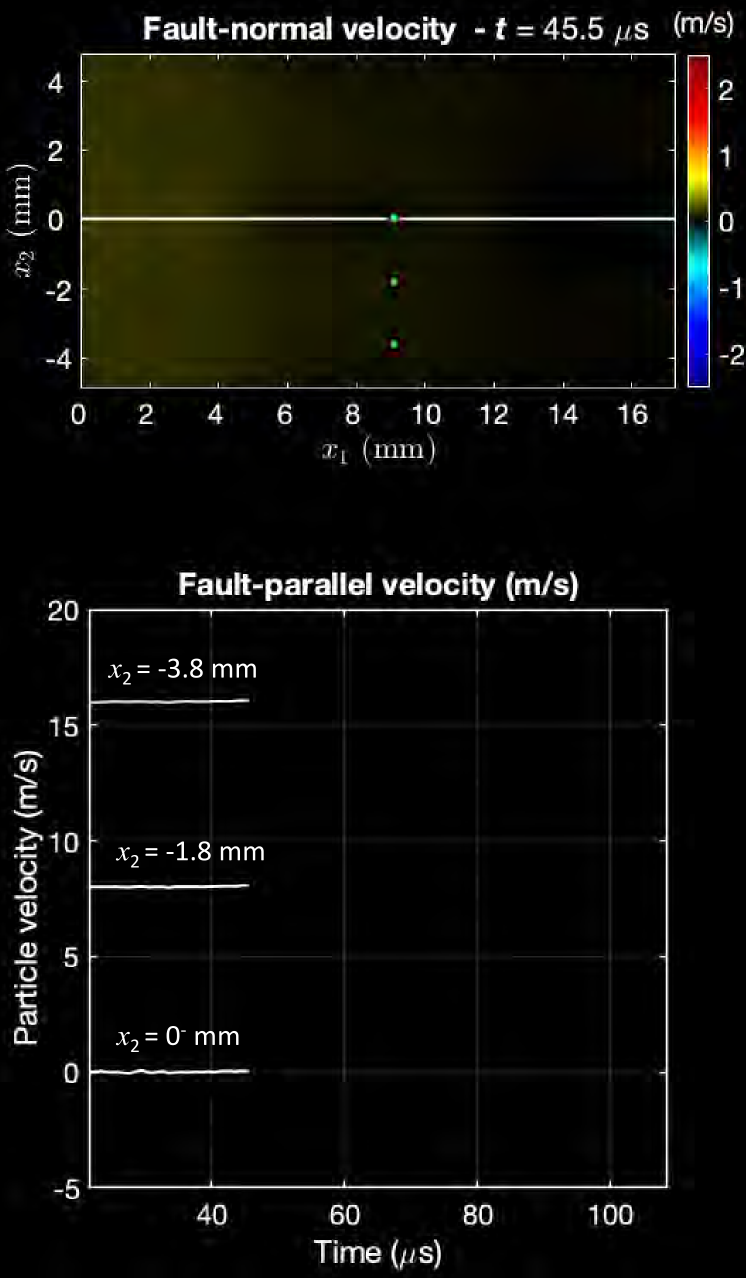


Supershear rupture

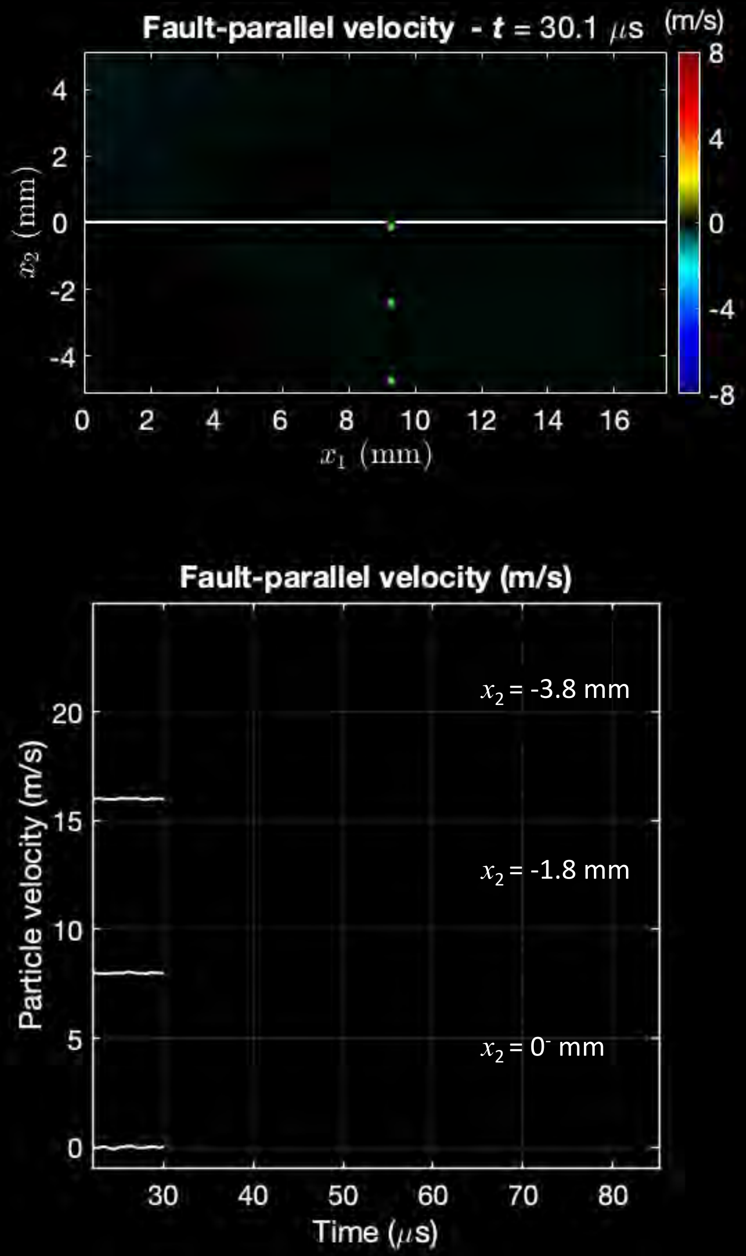


Near Fault Ground shaking

Sub-Rayleigh rupture

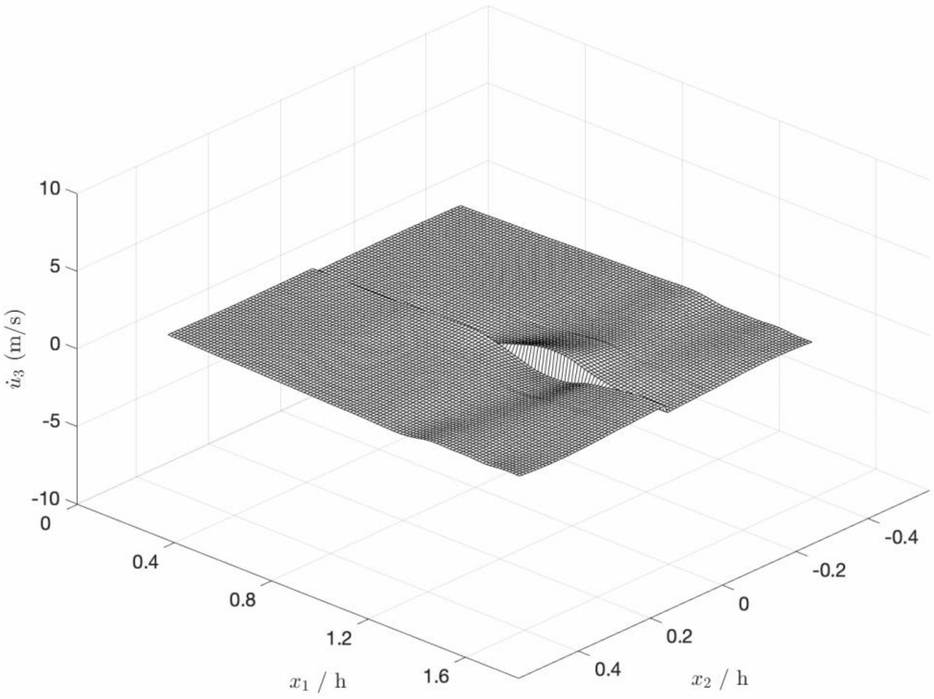


Supershear rupture

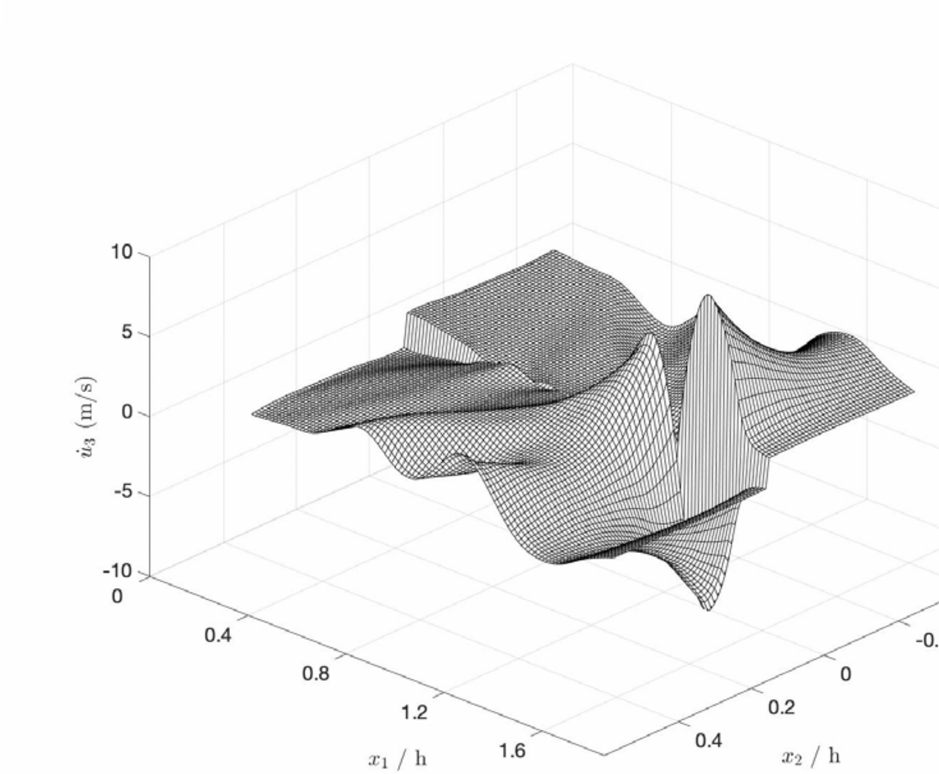


Comparison of out of plane ground surface velocities

Sub-Rayleigh rupture



Super-shear rupture



SECTION- 5

EFFECT OF SUPR-SHEAR EARTHQUAKES ON BULDINGS

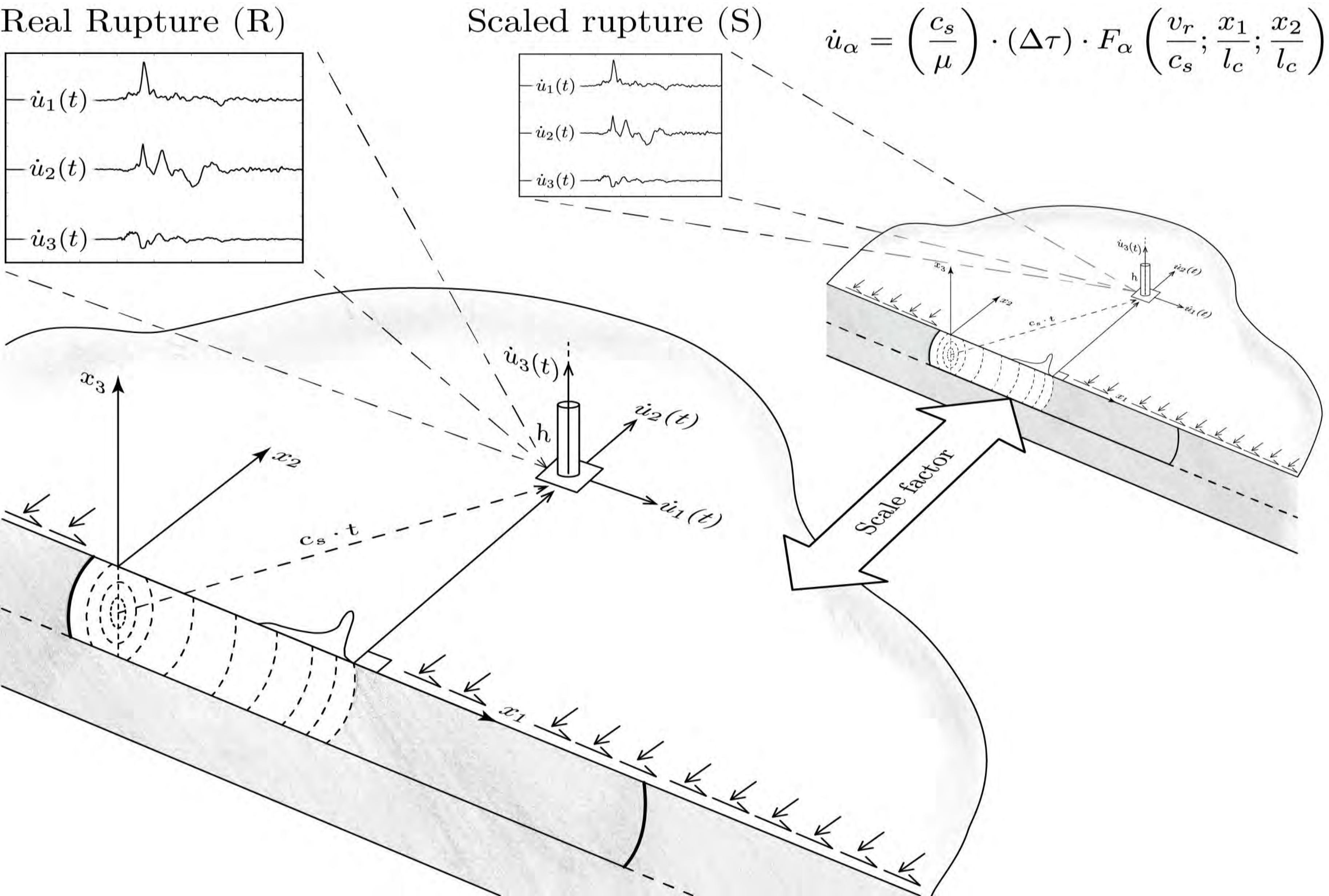
Maximum Slip
was 5,7 meters

The 1999 (M7.5) Earthquake in IZMIT ruptured 150 km of the North Anatolian Fault. It lasted 37s, killed 17.000 people and left half a million homeless.

Mello, Bhat, Rosakis and Kanamori, Tectonophysics, Special Volume on Supershear 2010.
M. Bouchon, M. Bouin, H. Karabulet, M. Toksöz, M. Dietrich and A. Rosakis Geophys. Res. Letters, 2001

FROM THE LAB TO THE REAL EARTH:

SCALING OF SIZE AND MATERIAL, TO OBTAIN TIME AND GROUND VELOCITY HISTORY



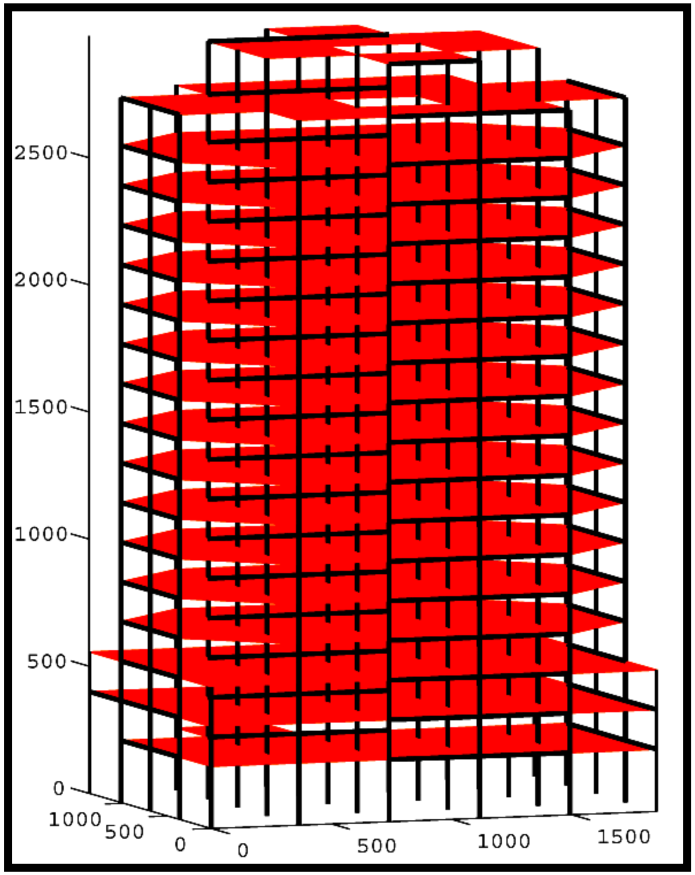
$$\dot{u}_\alpha = \left(\frac{c_s}{\mu}\right) \cdot (\Delta\tau) \cdot F_\alpha\left(\frac{v_r}{c_s}; \frac{x_1}{l_c}; \frac{x_2}{l_c}\right)$$

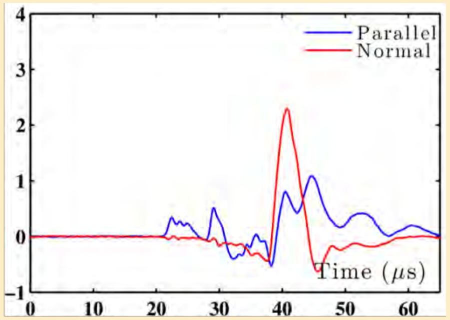
Implications of Super-shear Ruptures on Buildings

Building Studied : Existing, steel moment-frame building of the 20-story class

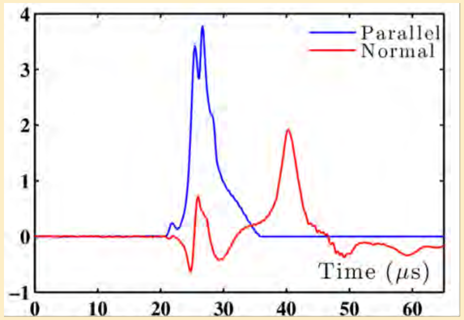
- 3D Finite Element simulations using FRAME3D
- Developed at Caltech by Prof. Swaminathan Krishnan

Swaminathan Krishnan
CE/GPS Caltech





Sub-Rayleigh Earthquake Rupture



Super-shear Earthquake Rupture

Existing Building (Woodland Hills), isometric view

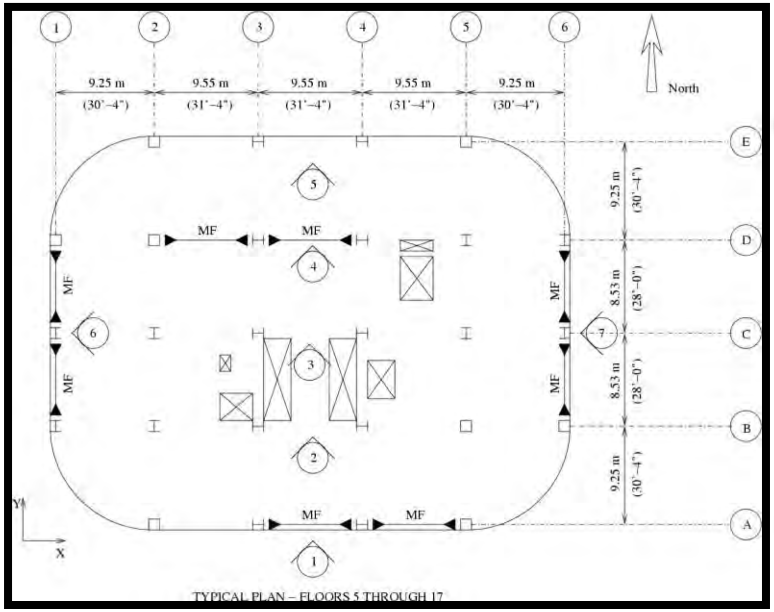
(designed according to UBC82 provisions)

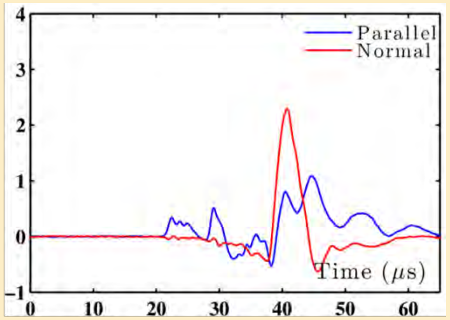
$T_1 = 4.43s$; $T_2 = 4.22s$; $T_3 = 2.47s$

Asymmetric placement of Moment Frames (Center of resistance and Center of Mass don't coincide)

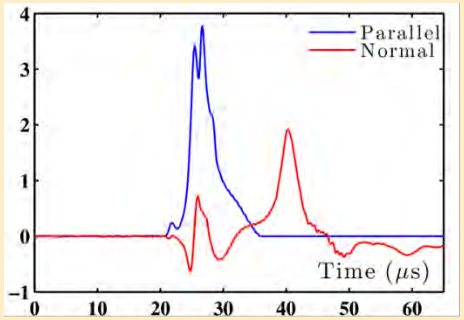
Building Studied : Existing steel moment-frame building of the 20-story class

- 3D Finite Element simulations using FRAME3D
- Developed at Caltech by Professor Swaminathan Krishnan





Sub-Rayleigh Earthquake Rupture



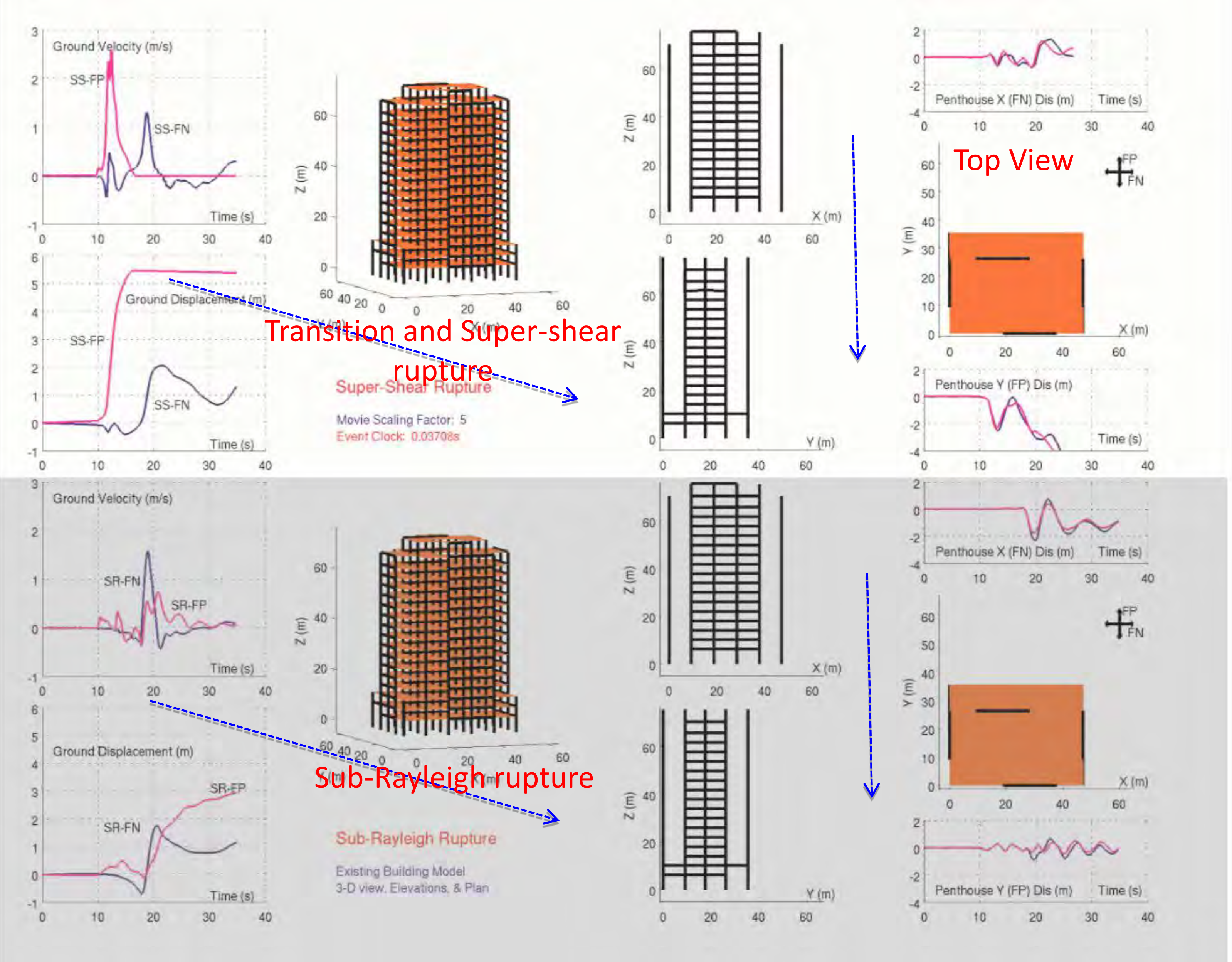
Super-shear Earthquake Rupture

Existing Building (Woodland Hills), isometric view

(designed according to UBC82 provisions)

$T_1 = 4.43s$; $T_2 = 4.22s$; $T_3 = 2.47s$

Identical Buildings at 3Km from the fault subjected to excitation from Super-shear or Sub-Rayleigh ruptures



Transition and Super-shear rupture

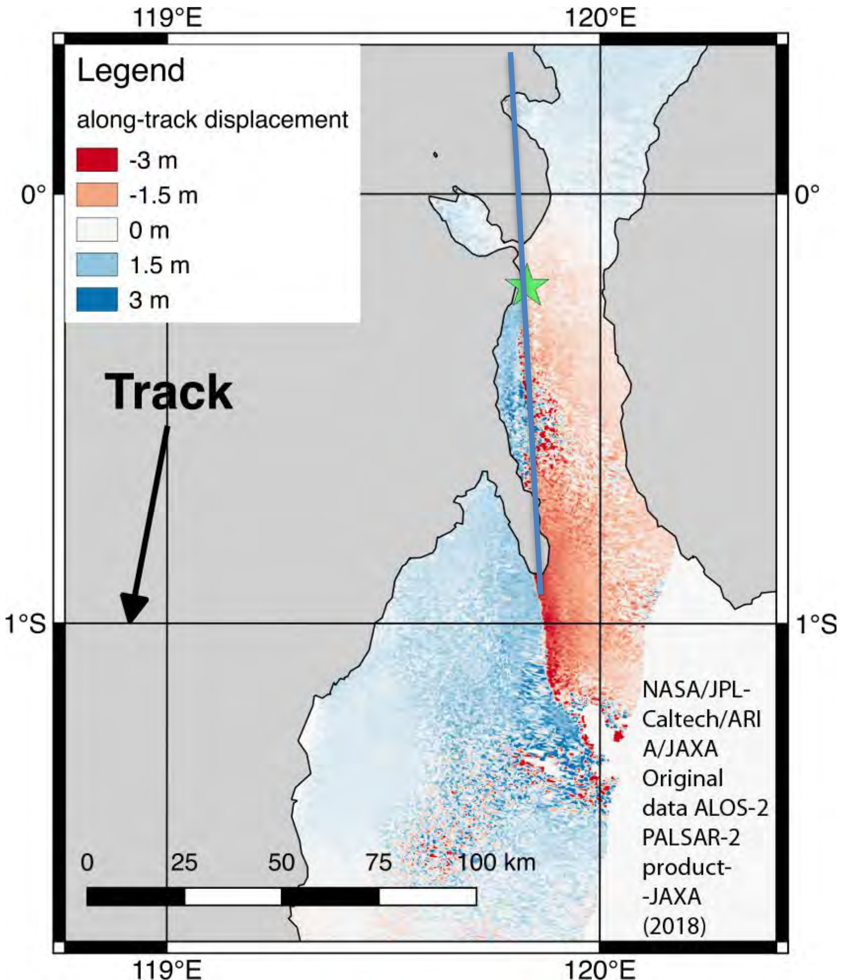
Top View

Sub-Rayleigh rupture

Strong evidence of Super-shear, with the exact rupture speed still being debated in the literature

The September 28th, 2018 Mw7.5 Sulawesi-Palu earthquake in Indonesia, generated a Tsunami, killed 4,300people, and mystified Scientists. Its epicenter was just off the central Island of Sulawesi at a shallow depth of 10 km

Amlani, Bhat, Simons, Schubnel, Vigny, Rosakis, Efendi, Elbanna, Abidin *work in Progress* (2019)



NASA/JPL-Caltech/ARIA/JAXA Original data ALOS-2 PALSAR-2 product--JAXA (2018)