Initiation of Dynamic Ruptures in Numerical Simulations

Martin GALIS [1], **Jean-Paul AMPUERO** [2], **P. Martin MAI** [1],
Jozef KRISTEK [3,4], **Peter MOCZO** [3,4]

[1] KAUST, Thuwal, Saudi Arabia
[2] California Institute of Technology, Pasadena, USA
[3] Comenius University Bratislava, Slovakia
[4] Slovak Academy of Sciences, Bratislava, Slovakia

e-mail: martin.galis@kaust.edu.sa

NMEM 2015
Smolenice castle | Slovakia | 5 – 9 July 2015

outline

- introduction
- critical parameters of the initiation zone (IZ) and their estimates
- effects of shape/aspect ratio on the IZ
- verification
- influence of material parameters of the IZ
- optimal parameters of the IZ
- summary

introduction

artificial procedures are used
to initiate dynamic ruptures
under linear slip-weakening friction law

the artificial initiation may have significant impact
on the resulting dynamic rupture propagation

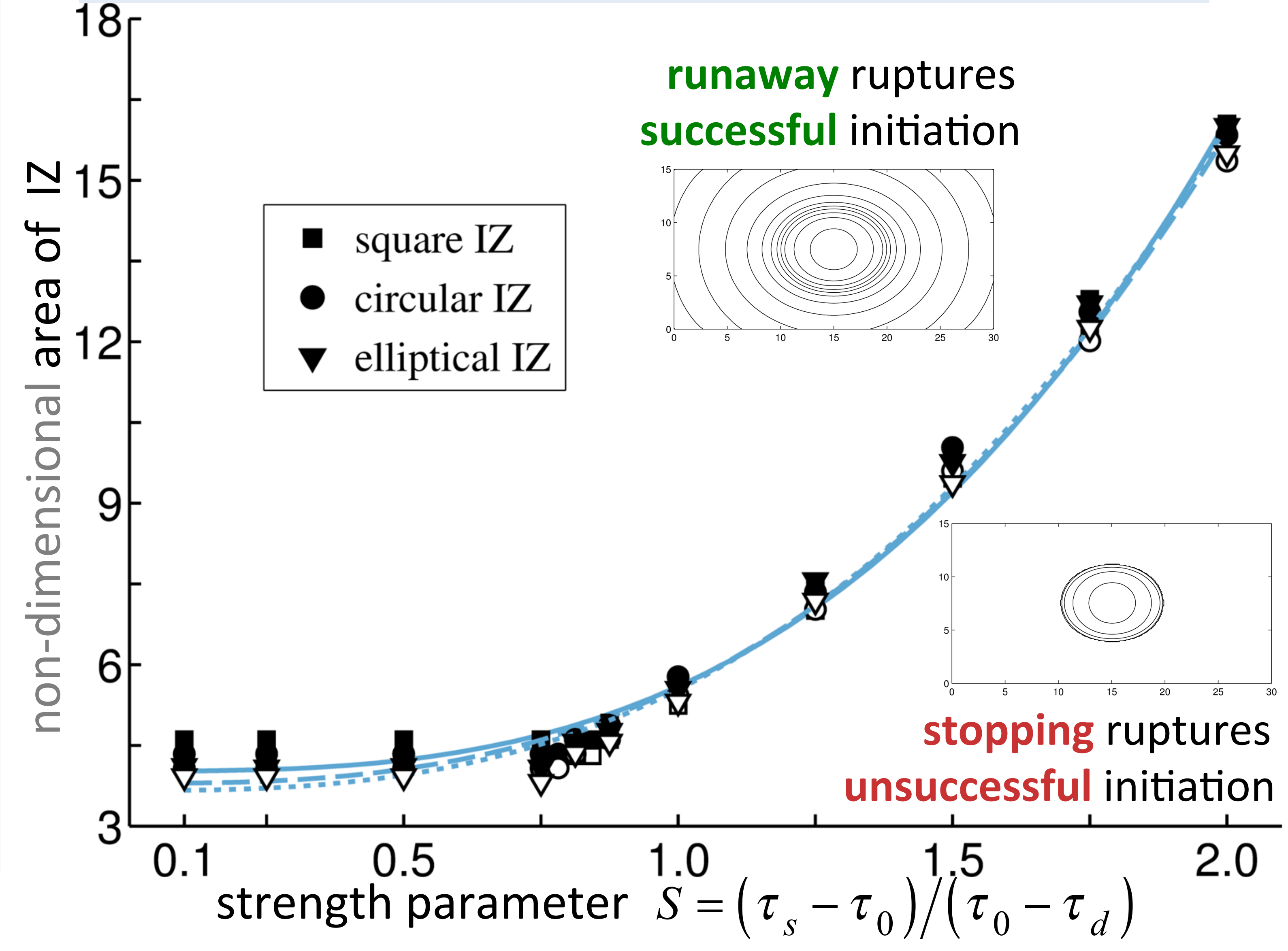
therefore,
it is desirable to understand and then minimize
side effects of the initiation

here we discuss initiation
using an overstressed asperity,
i.e., region with initial traction higher than static traction

outline

- introduction
- **critical parameters of the initiation zone (IZ) and their estimates**
- effects of shape/aspect ratio on the IZ
- verification
- influence of material parameters of the IZ
- optimal parameters of the IZ
- summary

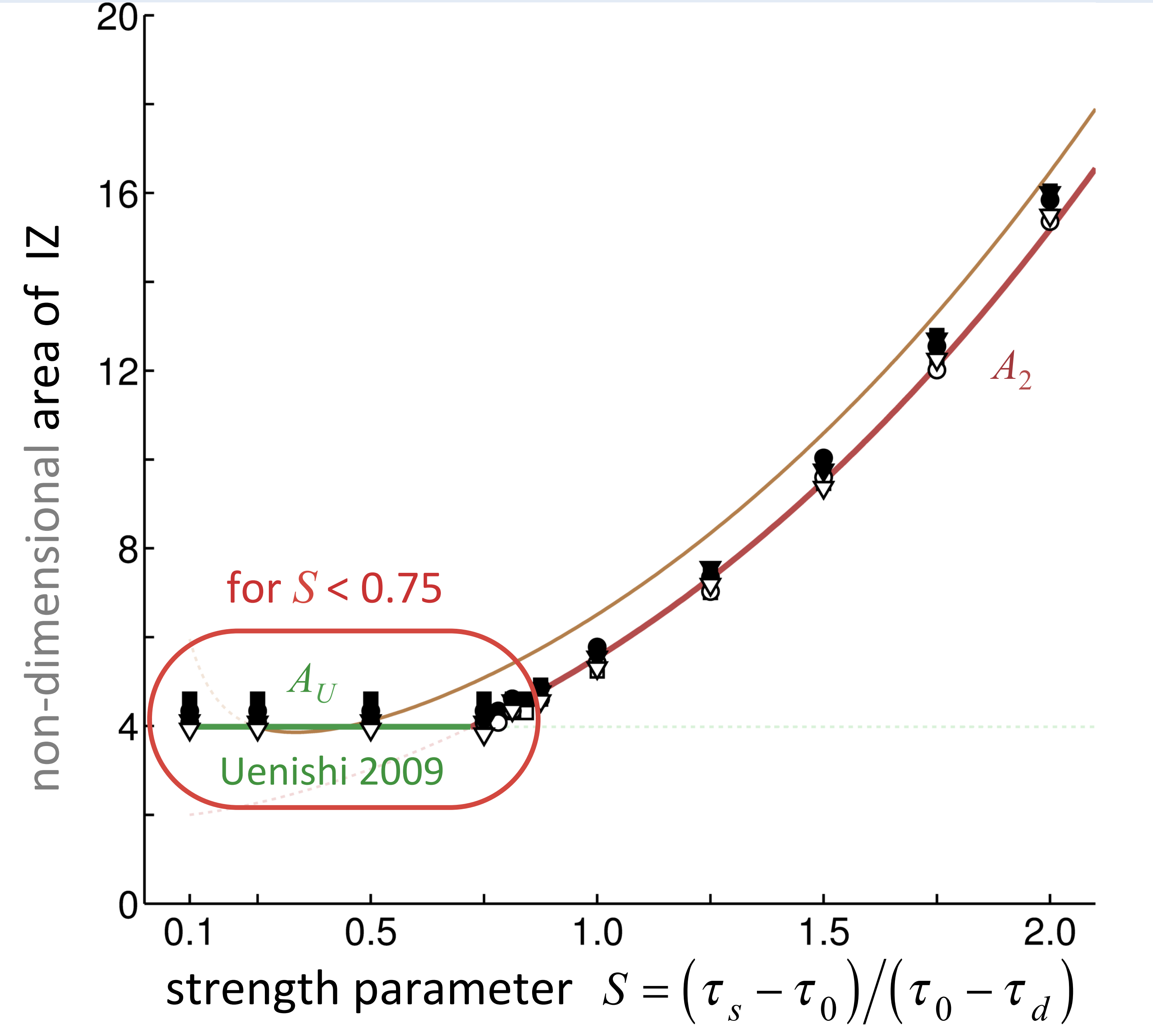
critical parameters | the critical area of the IZ (Galis et al. 2015)



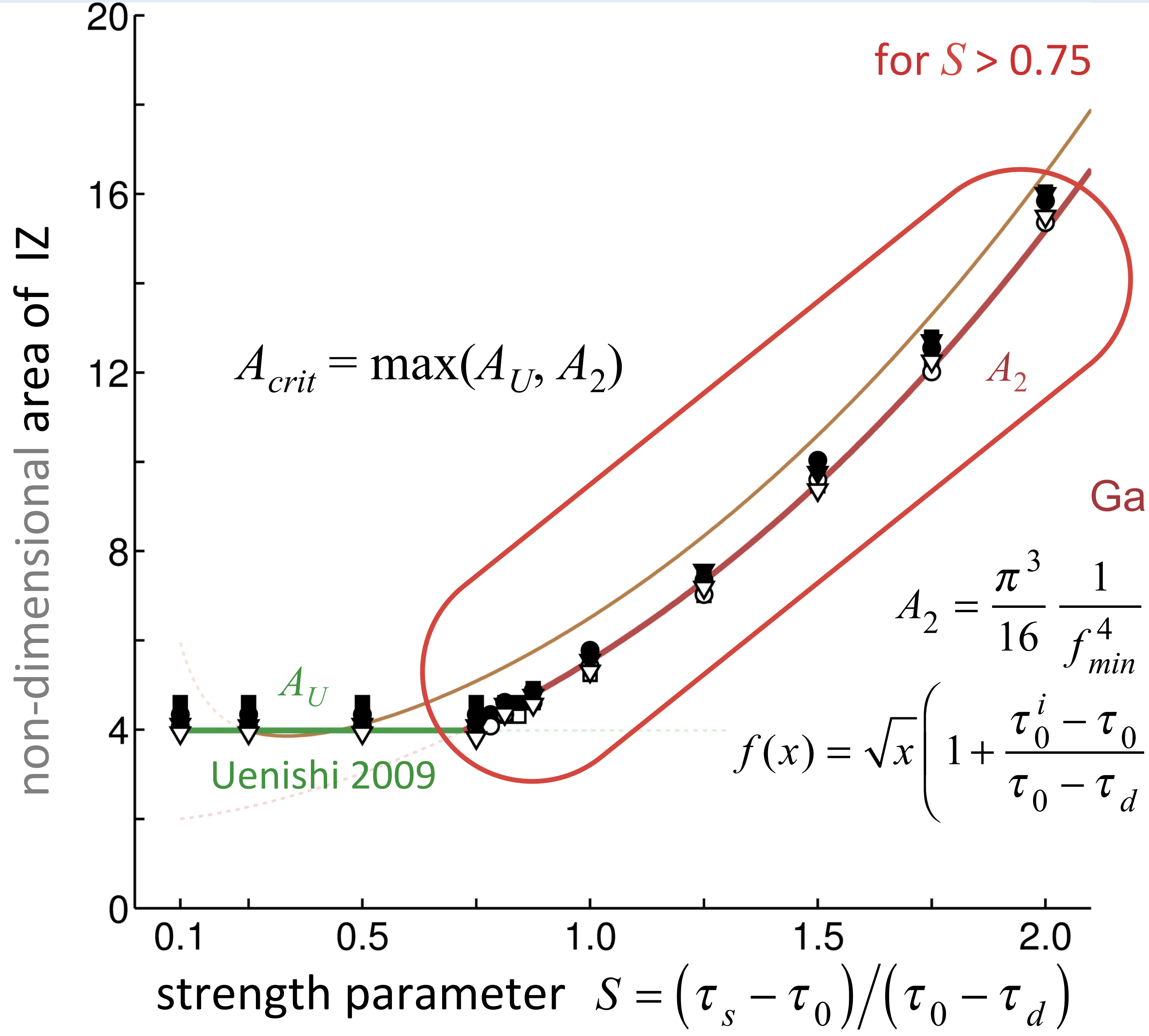
the initiation is controlled by the area of the initiation zone

(not by the half-length or shape)

critical parameters | estimates of the critical area (Galis et al. 2015)



critical parameters | estimates of the critical area (Galis et al. 2015)



for $S > 0.75$

$$A_{crit} = \max(A_U, A_2)$$

Galis et al., 2015

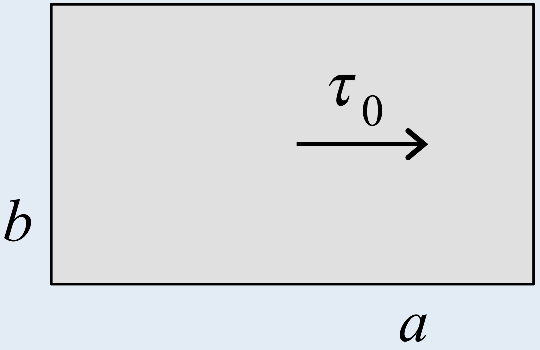
$$A_2 = \frac{\pi^3}{16} \frac{1}{f_{min}^4} \frac{(\tau_s - \tau_d)^2}{(\tau_0 - \tau_d)^4} \mu^2 D_c^2$$

$$f(x) = \sqrt{x}\left(1 + \frac{\tau_0^i - \tau_0}{\tau_0 - \tau_d}\left(1 - \sqrt{1 - 1/x^2}\right)\right)$$

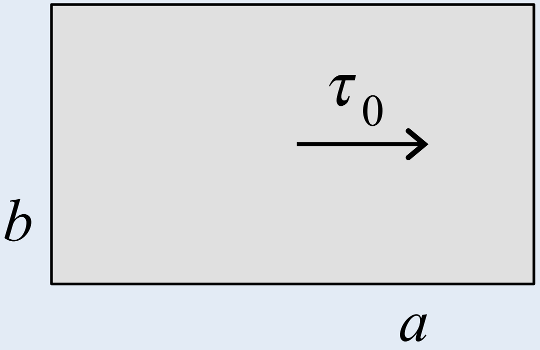
outline

- introduction
- critical parameters of the initiation zone (IZ) and their estimates
- **effects of shape/aspect ratio on the IZ**
- verification
- influence of material parameters on the IZ
- optimal parameters of the IZ
- summary

effects of shape/aspect ratio on the IZ



effects of shape/aspect ratio on the IZ



transition

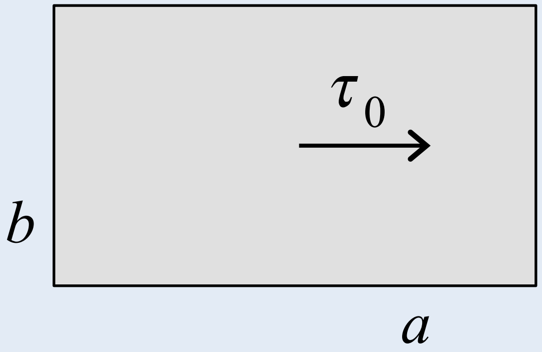
from 3D

(init. controlled by area)

to 2D

(init. controlled by length)

effects of shape/aspect ratio on the IZ



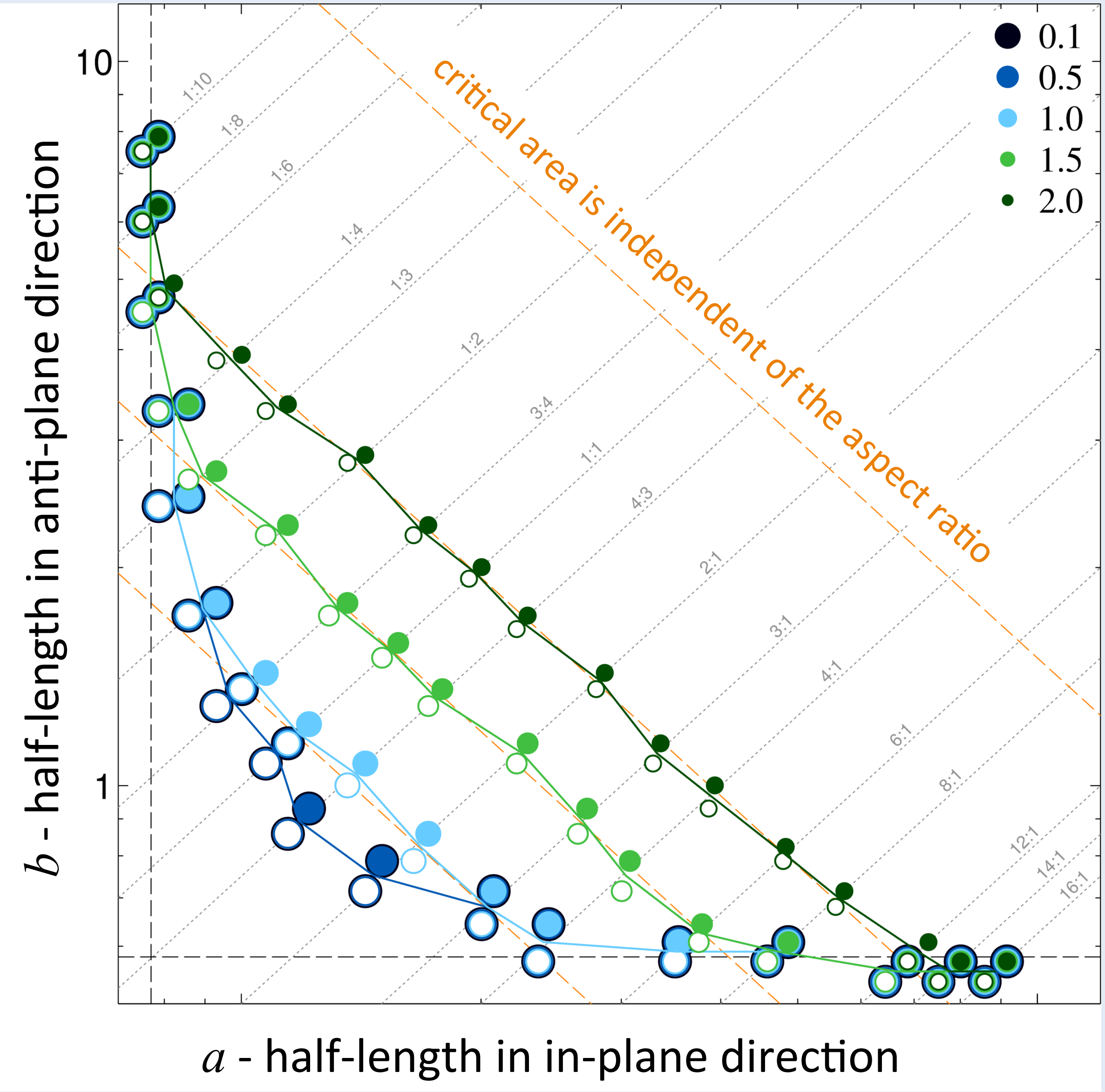
transition

from 3D

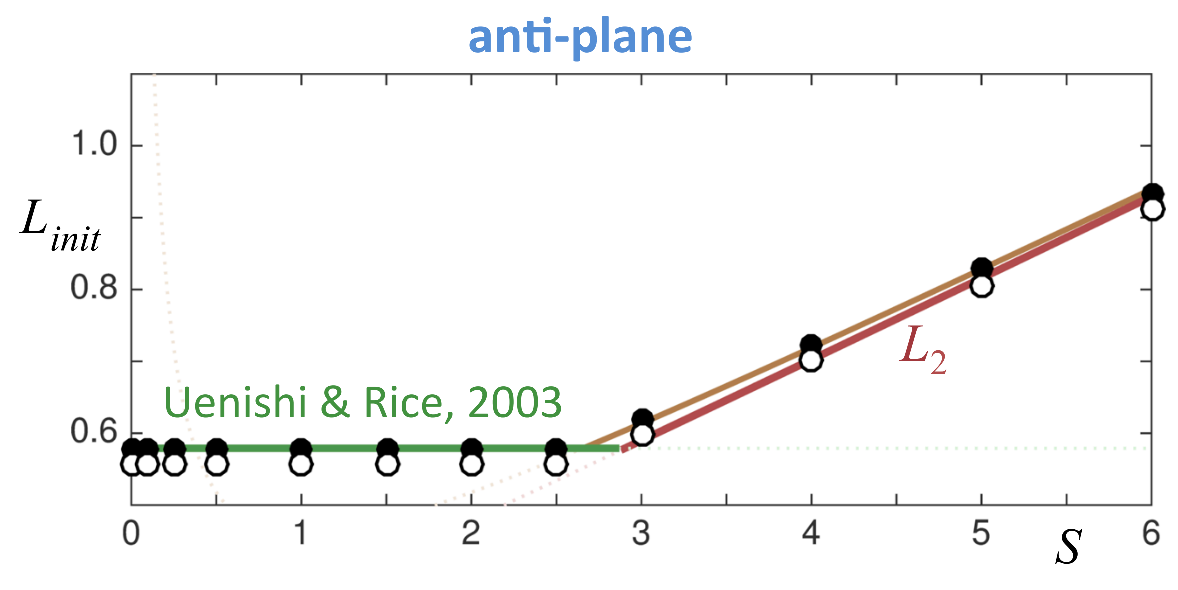
(init. controlled by area)

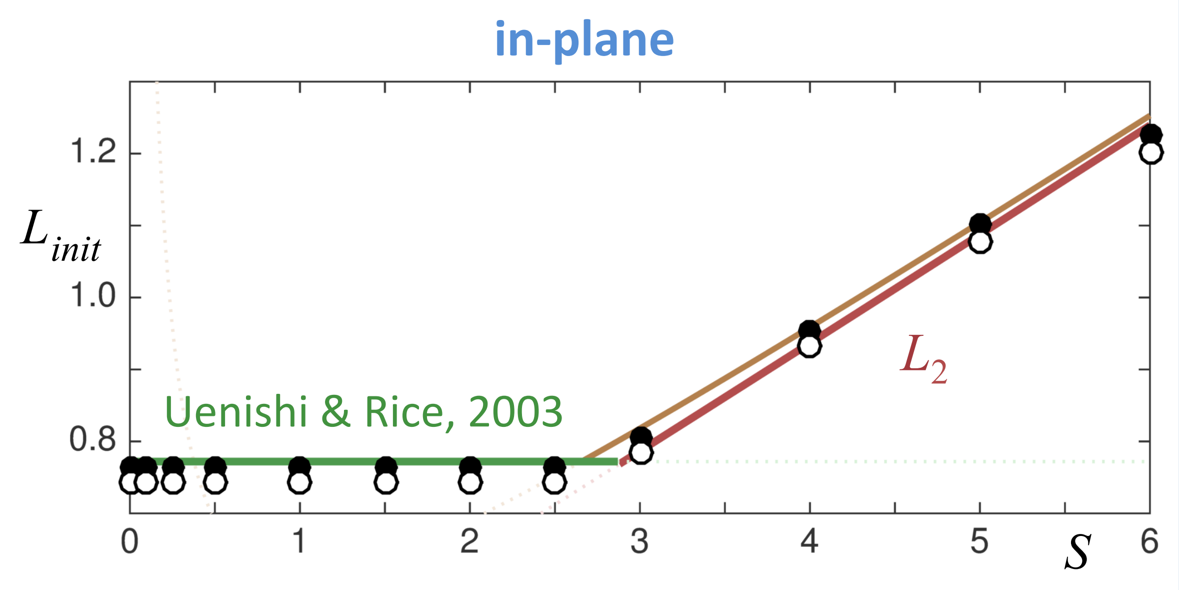
to 2D

(init. controlled by length)



effects of shape/aspect ratio on the IZ





outline

- introduction
- critical parameters of the initiation zone (IZ) and their estimates
- effects of shape/aspect ratio on the IZ
- **verification**
- influence of material parameters of the IZ
- optimal parameters of the IZ
- summary

to demonstrate that
our results and conclusions are not biased
by the choice of the numerical method,
we verify our results using

- **FESD**

2nd order finite-element method
Galis et al. (2008, 2010); Moczo et al. (2014)

- **SeisSol**

ADER-DG: arbitrary high-order derivative – discontinuous Galerkin method
Käser and Dumbser (2006), De la Puente et al. (2009), Pelties et al. (2012)

- **SORD**

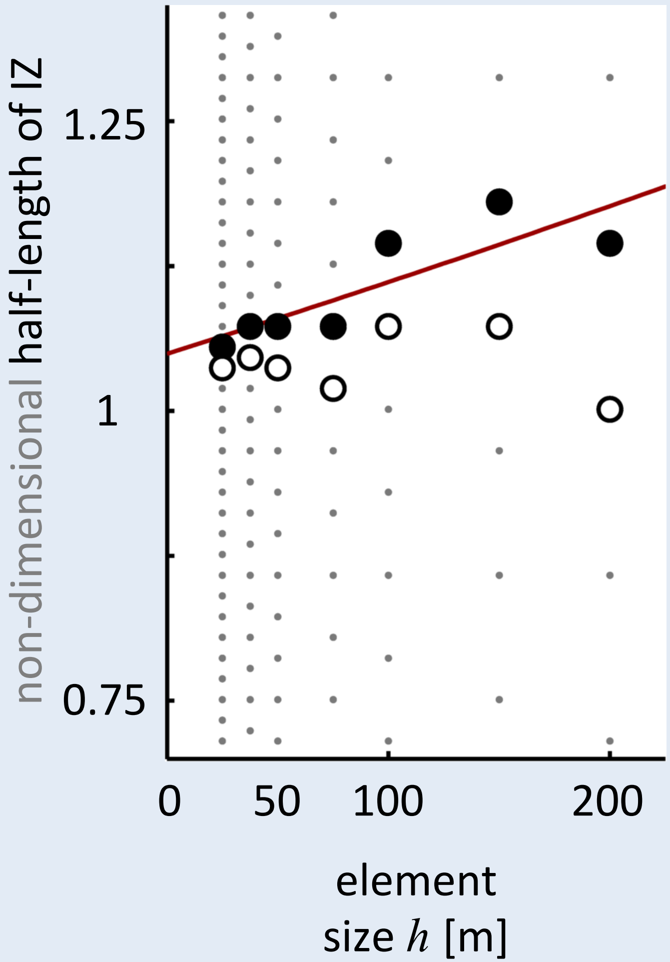
2nd-order support operator method
Ely et al. (2008, 2009)

- **WaveQLab3D**

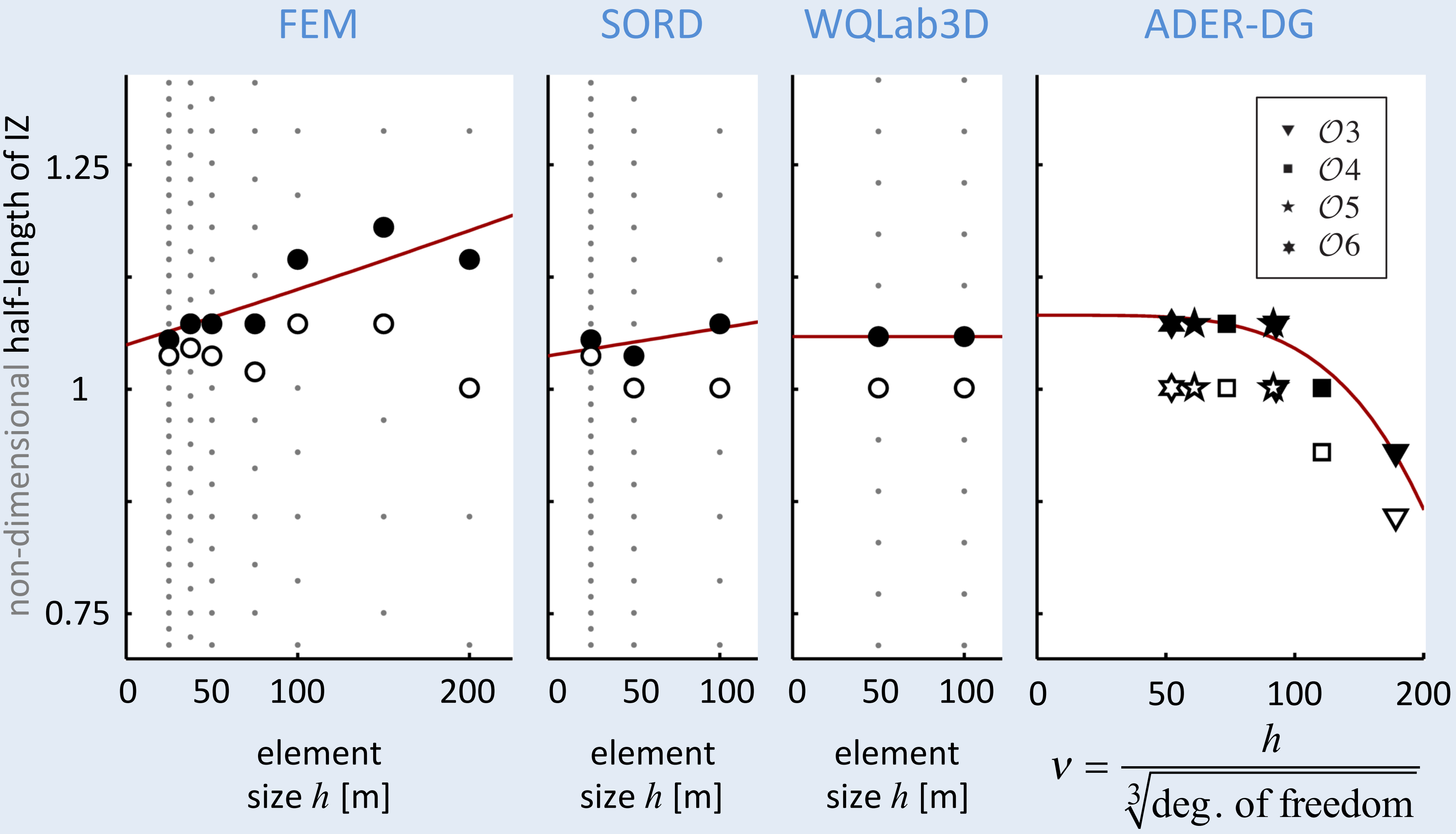
6th-order summation-by-parts finite-difference method
Duru and Dunham (2015)

verification | high background stress, **S = 0.1**

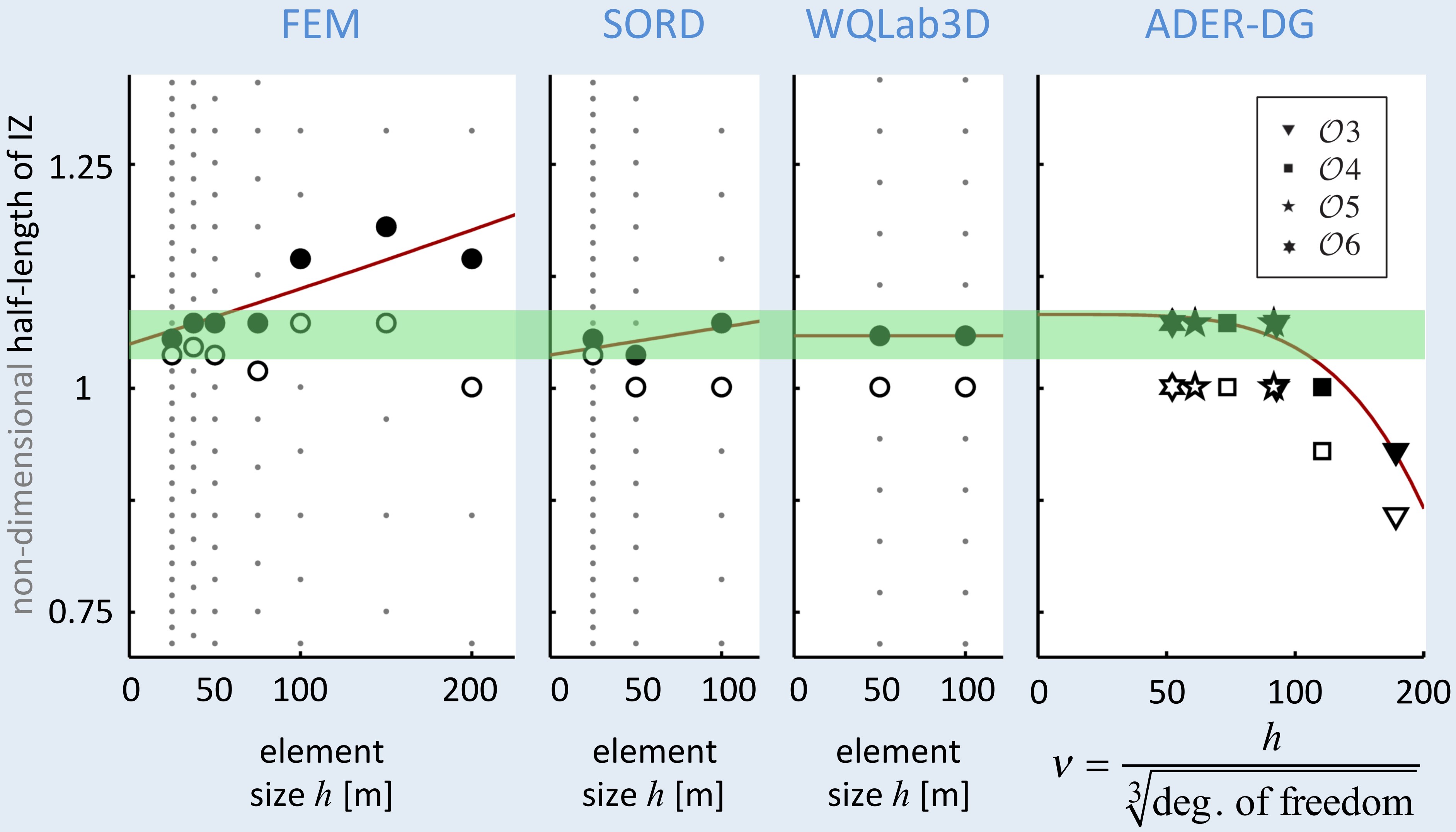
FEM



verification | high background stress, **S = 0.1**



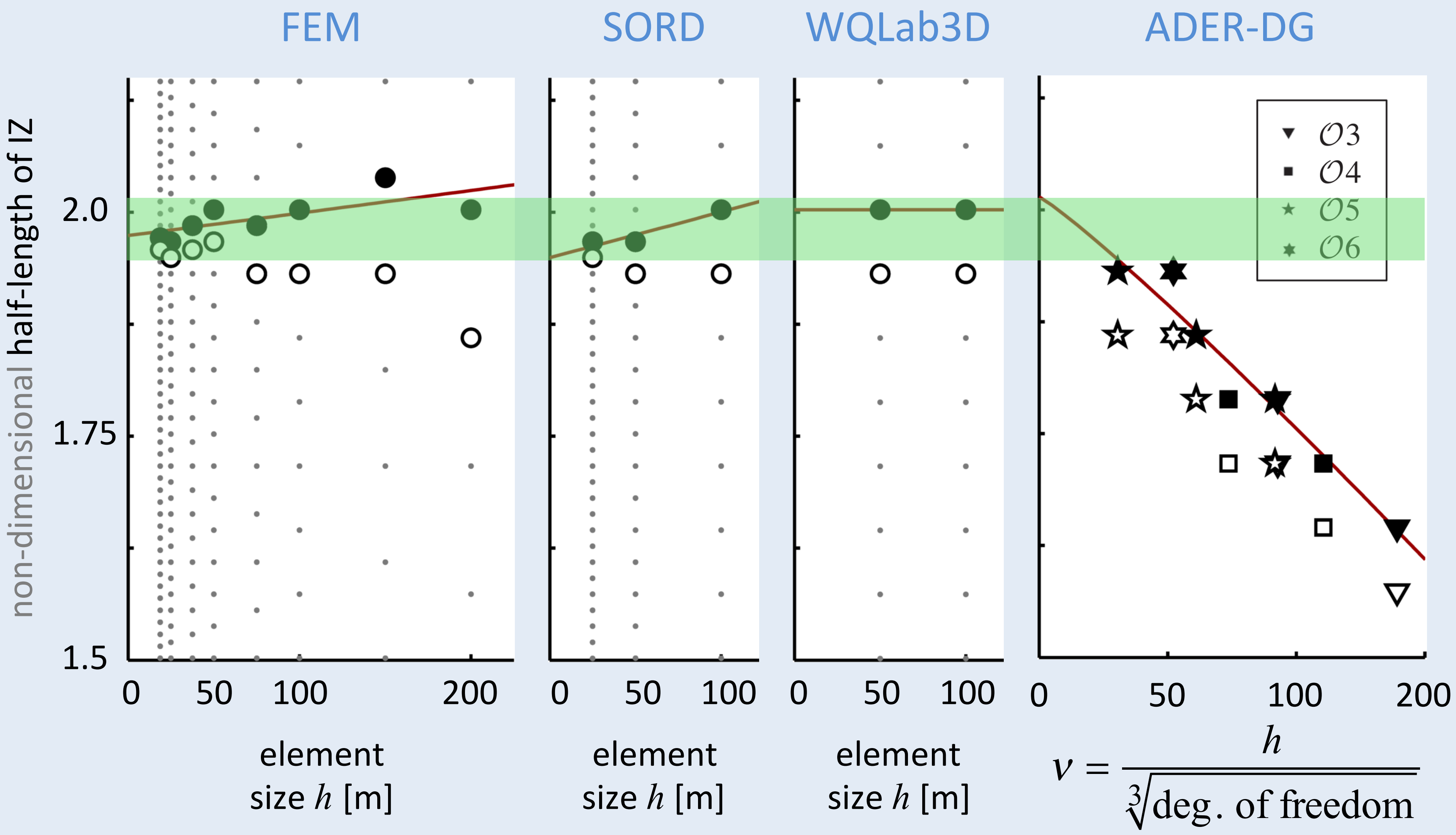
verification | high background stress, **S = 0.1**



the critical size of IZ converge systematically to consistent values in all 4 considered numerical methods

(within resolution of the discrete models)

verification | low background stress, **S = 2.0**



the critical size of IZ converge systematically to consistent values in all 4 considered numerical methods

(within resolution of the discrete models)

outline

- introduction
- critical parameters of the initiation zone (IZ) and their estimates
- effects of shape/aspect ratio on the IZ
- verification
- **influence of material parameters of the IZ**
- optimal parameters of the IZ
- summary

critical parameters | influence of material parameters

Uenishi 2009

$$L_{U3}^{a} \cong 0.624\, C(\nu) \frac{1}{1-\nu} \frac{\mu.D_c}{\tau_s - \tau_d}$$

$$L_{U3}^{b} \cong 0.624\, C(\nu) \frac{\mu.D_c}{\tau_s - \tau_d}$$

$$C(\nu) = \frac{E(k) + (1-\nu)K(k)}{2-\nu}$$

$$k = \sqrt{\nu(2-\nu)}$$

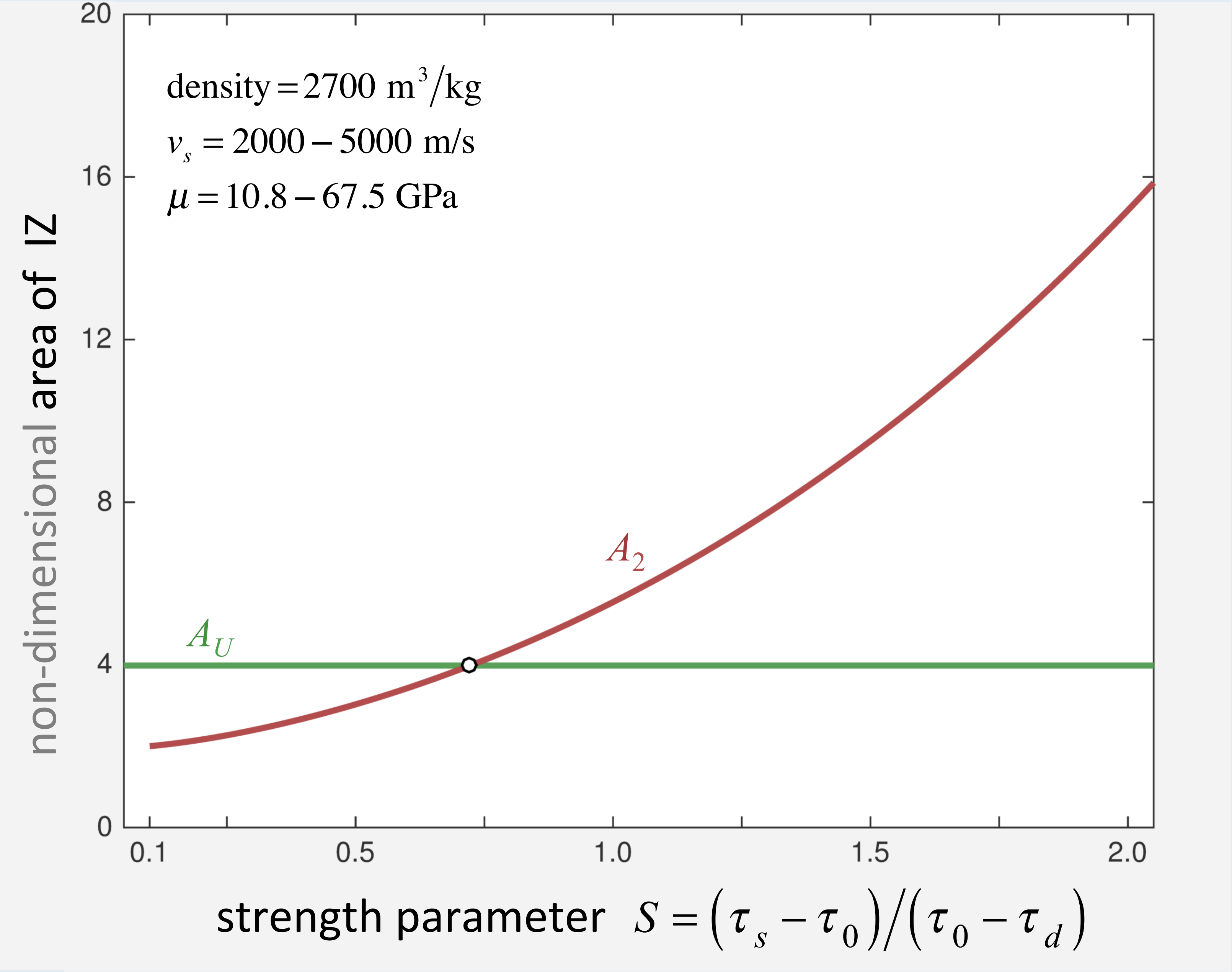
$E(k)$ and $K(k)$
are complete elliptic integrals
of the first and second kind

Galis et al., 2015

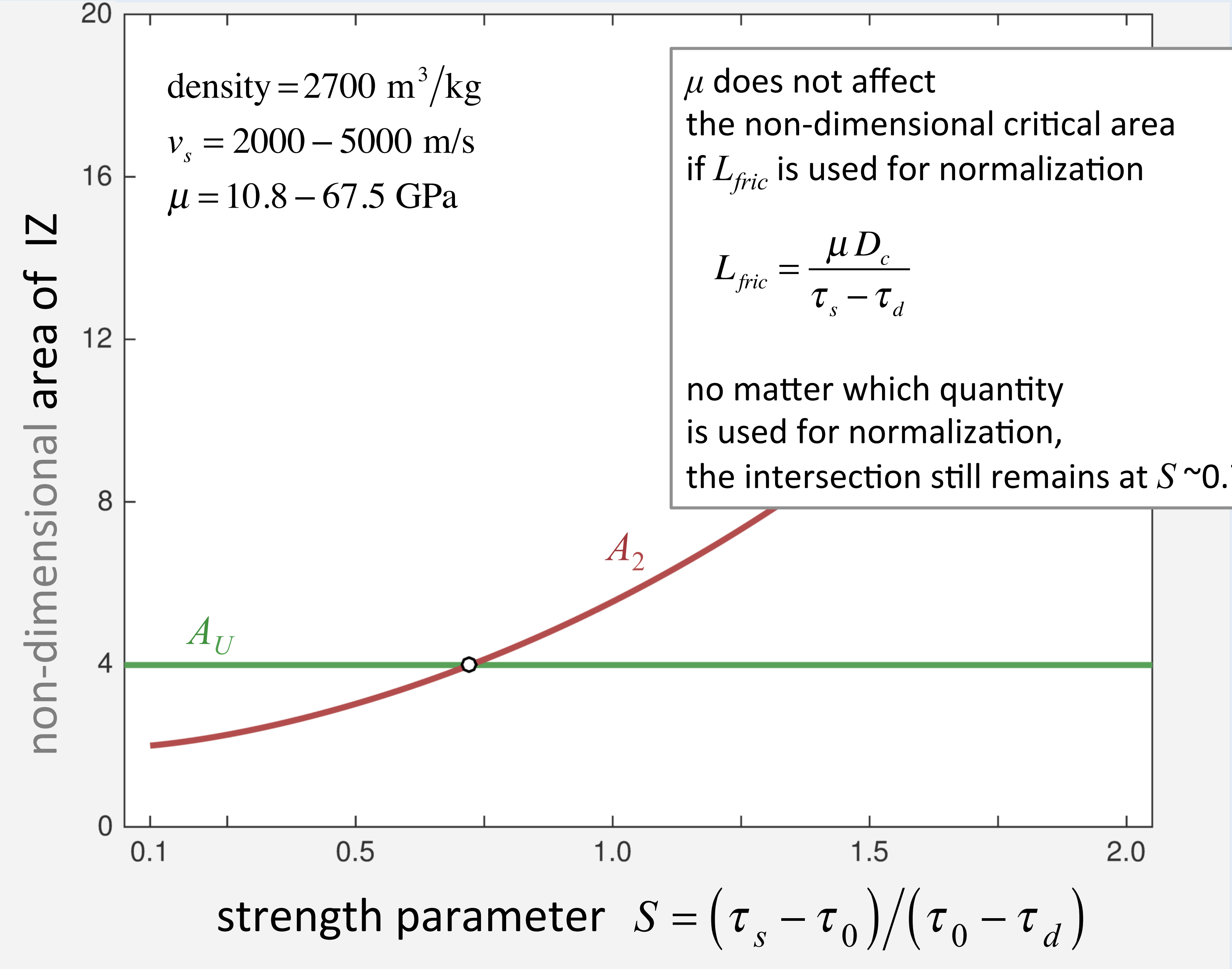
$$A_2 = \frac{\pi^3}{16} \frac{1}{f_{min}^4} \frac{(\tau_s - \tau_d)^2}{(\tau_0 - \tau_d)^4} \mu^2 D_c^2$$

$$f(x) = \sqrt{x}\left(1 + \frac{\tau_0^i - \tau_0}{\tau_0 - \tau_d}\left(1 - \sqrt{1 - 1/x^2}\right)\right)$$

critical parameters | influence of material parameters



critical parameters | influence of material parameters



$\text{density} = 2700\ \text{m}^3/\text{kg}$

$v_s = 2000 - 5000\ \text{m/s}$

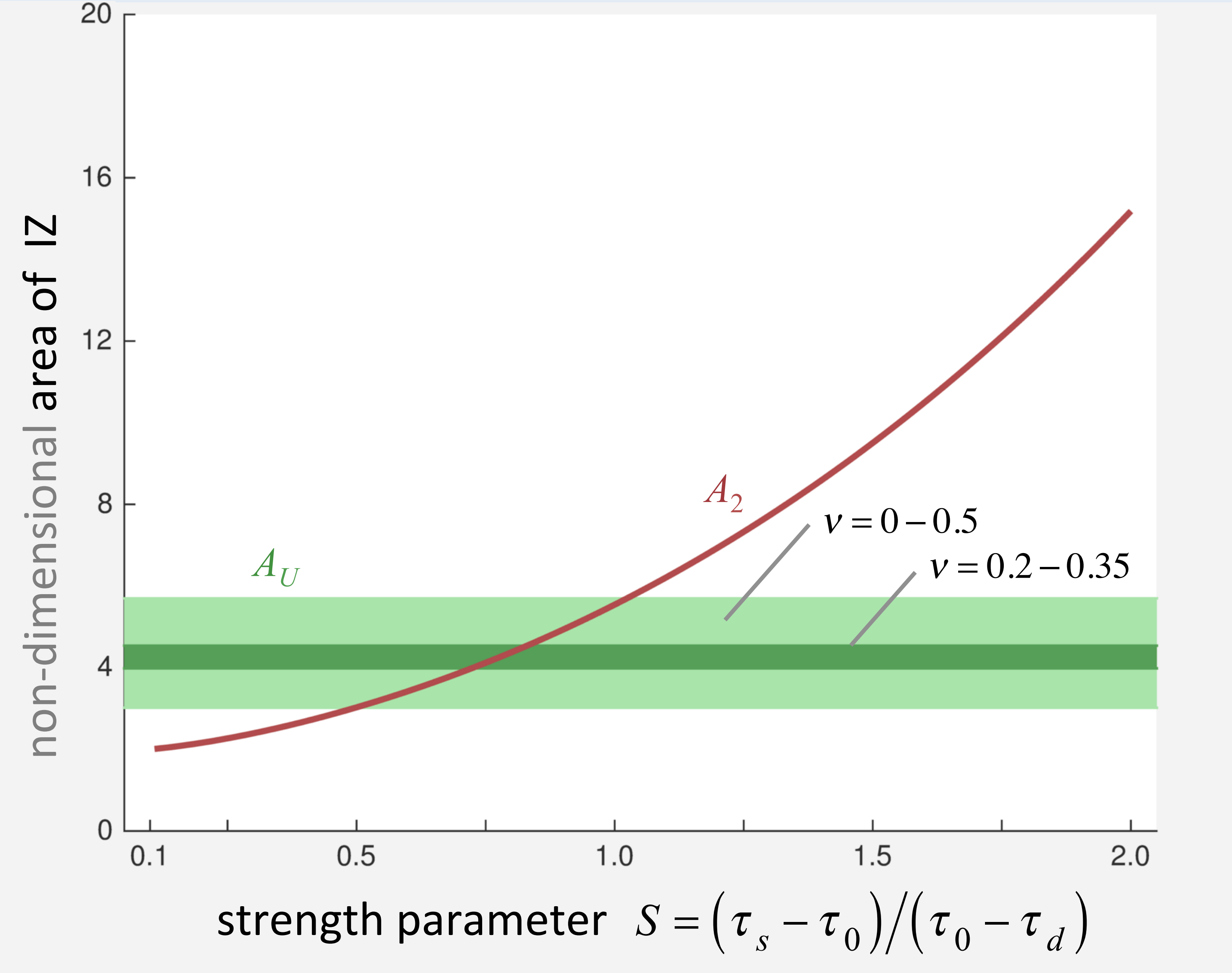
$\mu = 10.8 - 67.5\ \text{GPa}$

μ does not affect
the non-dimensional critical area
if L_{fric} is used for normalization

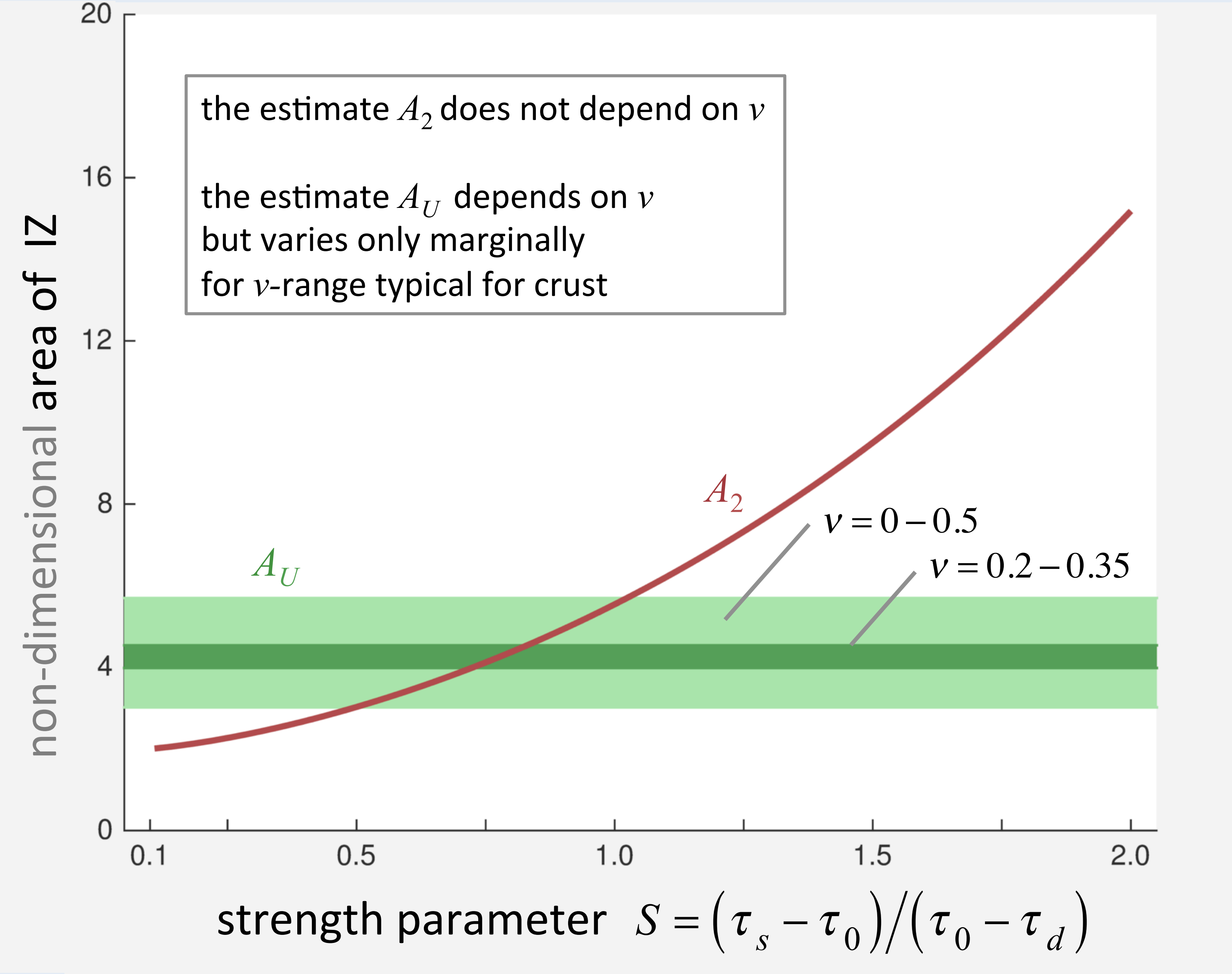
$$L_{fric} = \frac{\mu D_c}{\tau_s - \tau_d}$$

no matter which quantity
is used for normalization,
the intersection still remains at S ~0.75.

critical parameters | influence of material parameters



critical parameters | influence of material parameters



the estimate A_2 does not depend on ν

the estimate A_U depends on ν
but varies only marginally
for ν-range typical for crust

outline

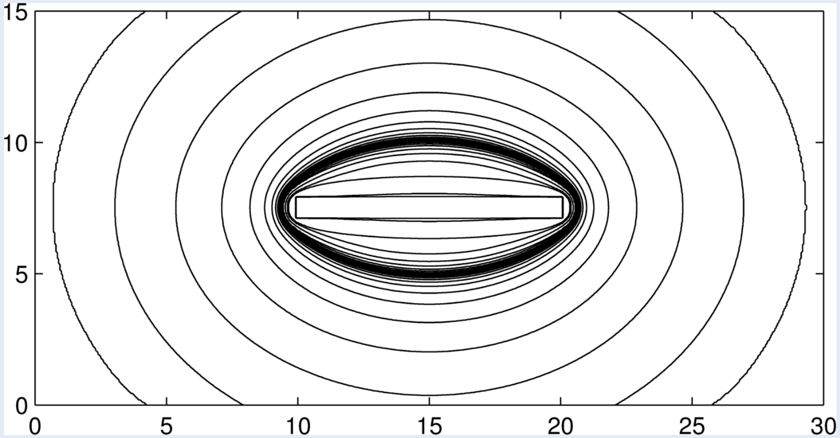
- introduction
- critical parameters of the initiation zone (IZ) and their estimates
- effects of shape/aspect ratio on the IZ
- verification
- influence of material parameters of the IZ
- **optimal parameters of the IZ**
- summary

optimal parameters | introduction

an illustrative example

rupture initiatiated by

slightly over-critical parameters



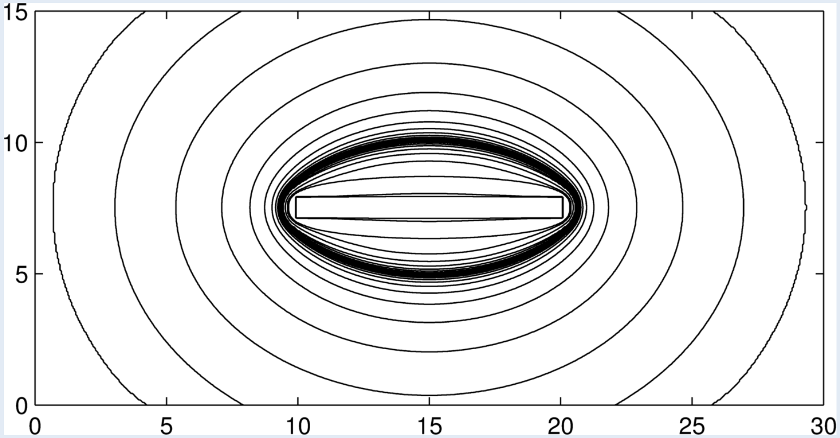
- initiation with
  slightly over-critical parameters
  may take long time

optimal parameters | introduction

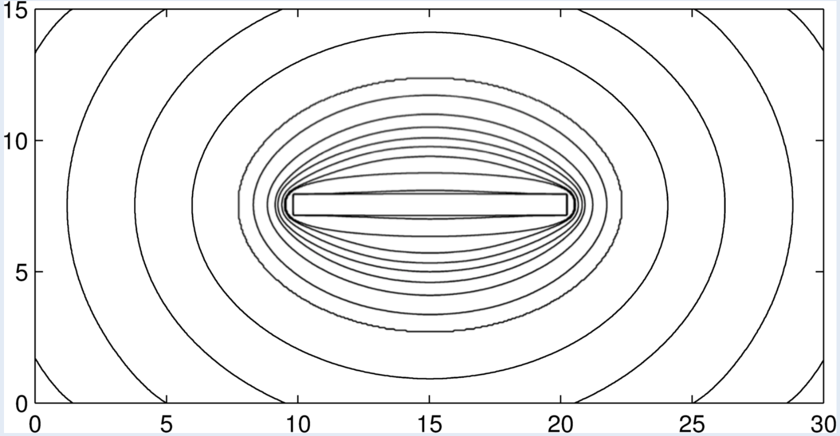
an illustrative example

rupture initiatiated by

slightly over-critical parameters



optimal parameters



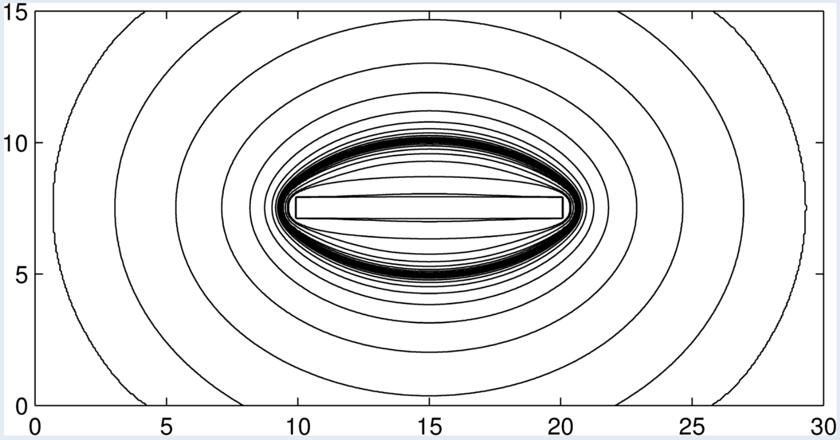
- initiation with slightly over-critical parameters may take long time

optimal parameters | introduction

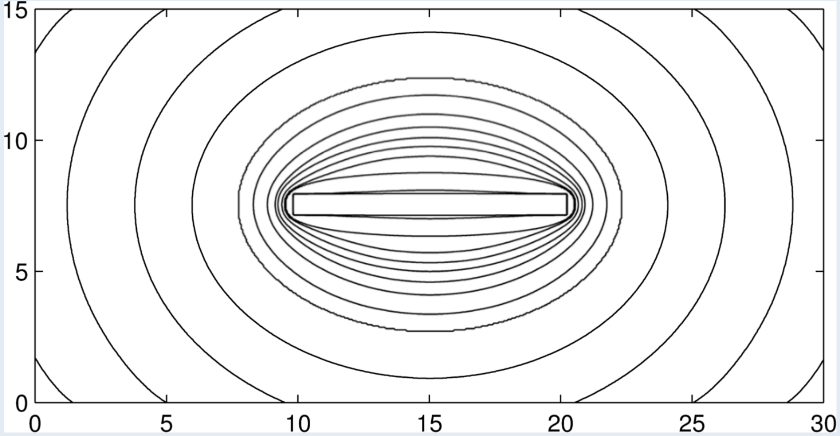
an illustrative example

rupture initiatated by

slightly over-critical parameters



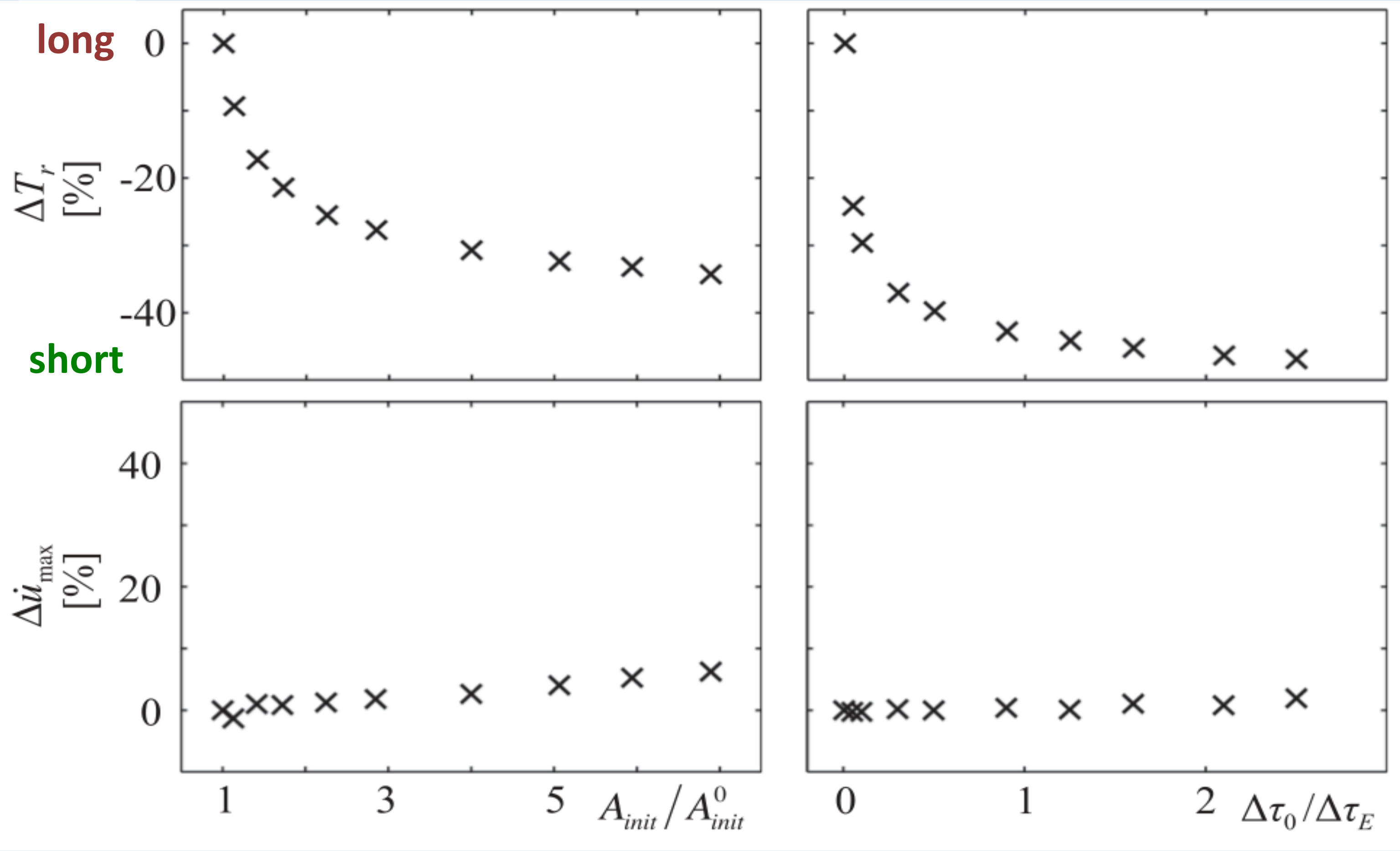
optimal parameters



- initiation with slightly over-critical parameters may take long time
- shorter duration of initiation can be achieved by **higher overstress** and/or **larger initiation area**
- if they are **too large** they can **affect resulting** self-sustained **dynamic rupture**
- we examine relations between the initiation area, overstress and duration of the initiation to find optimal parameters

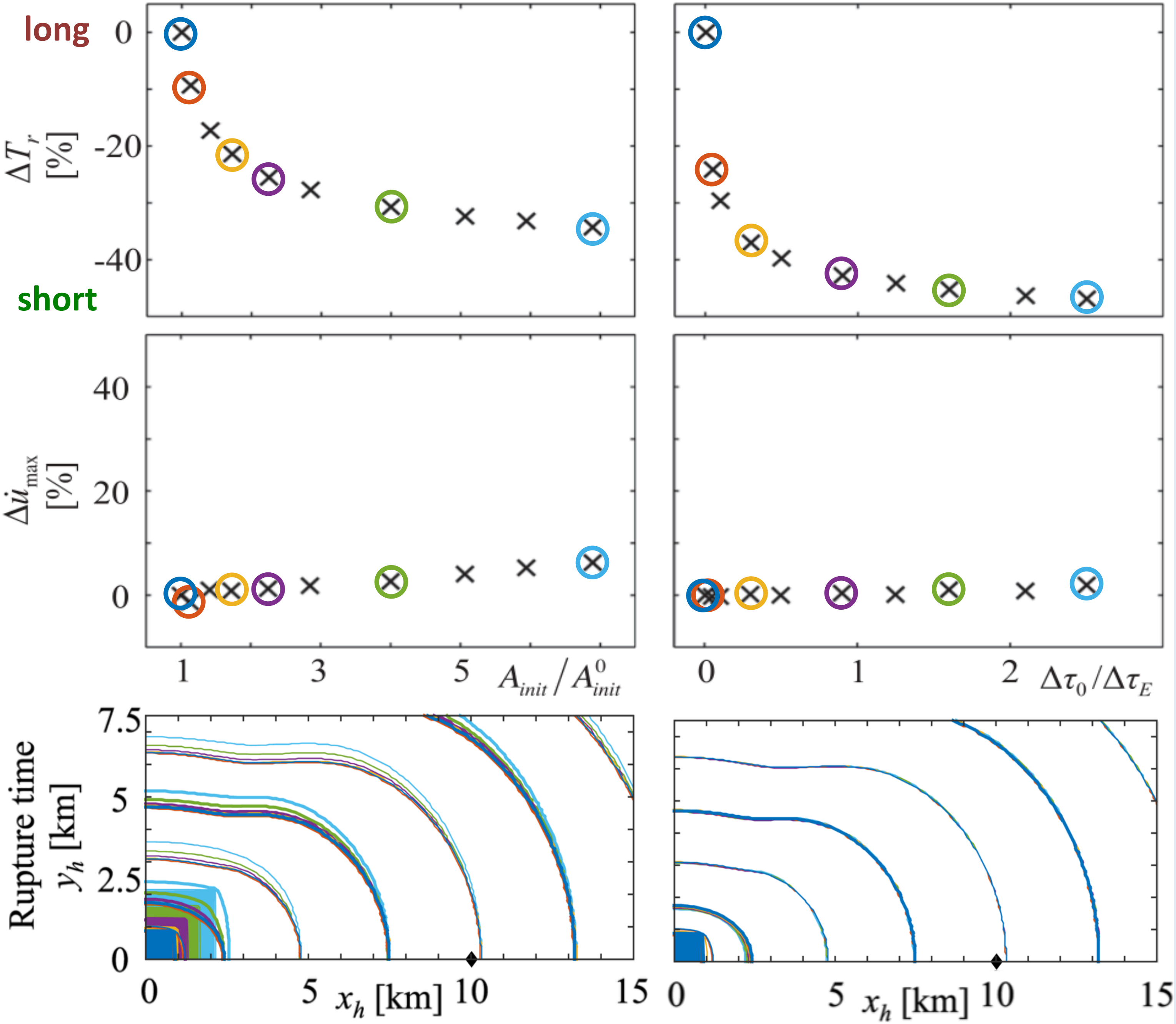
optimal parameters | high background stress, **S = 0.1**

rupture propagation



optimal parameters | high background stress, **S = 0.1**

rupture propagation

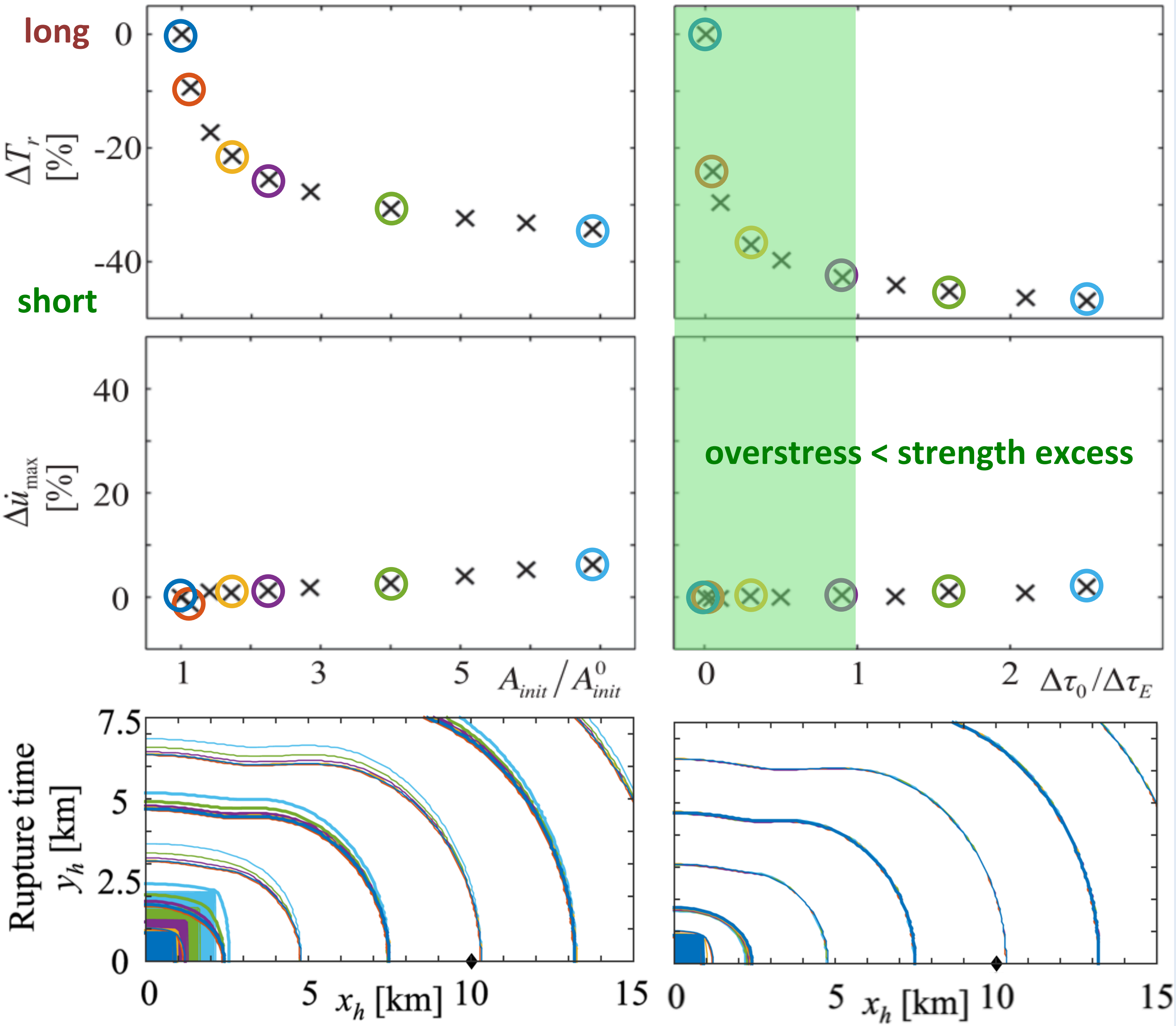


A_{init}/A^0_{init}	
1.0	2.2
1.1	3.9
1.4	6.8

$\Delta\tau_0/\Delta\tau_E$	
0.005	0.9
0.05	1.6
0.3	2.5

optimal parameters | high background stress, **S = 0.1**

rupture propagation


long

short

overstress < strength excess

A_{init}/A_{init}^0

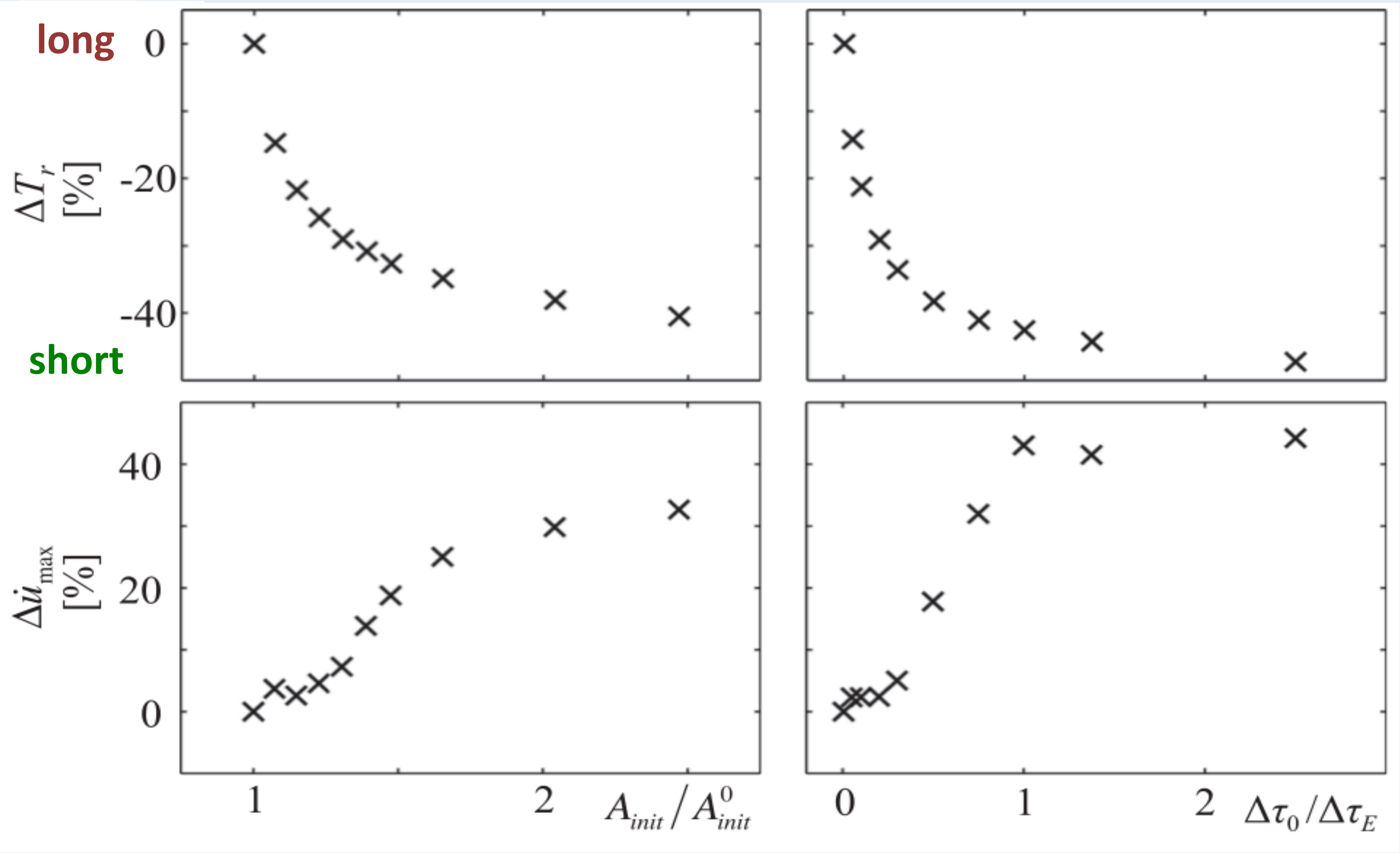
1.0 **2.2**
1.1 **3.9**
1.4 **6.8**

$\Delta\tau_0/\Delta\tau_E$

0.005 **0.9**
0.05 **1.6**
0.3 **2.5**

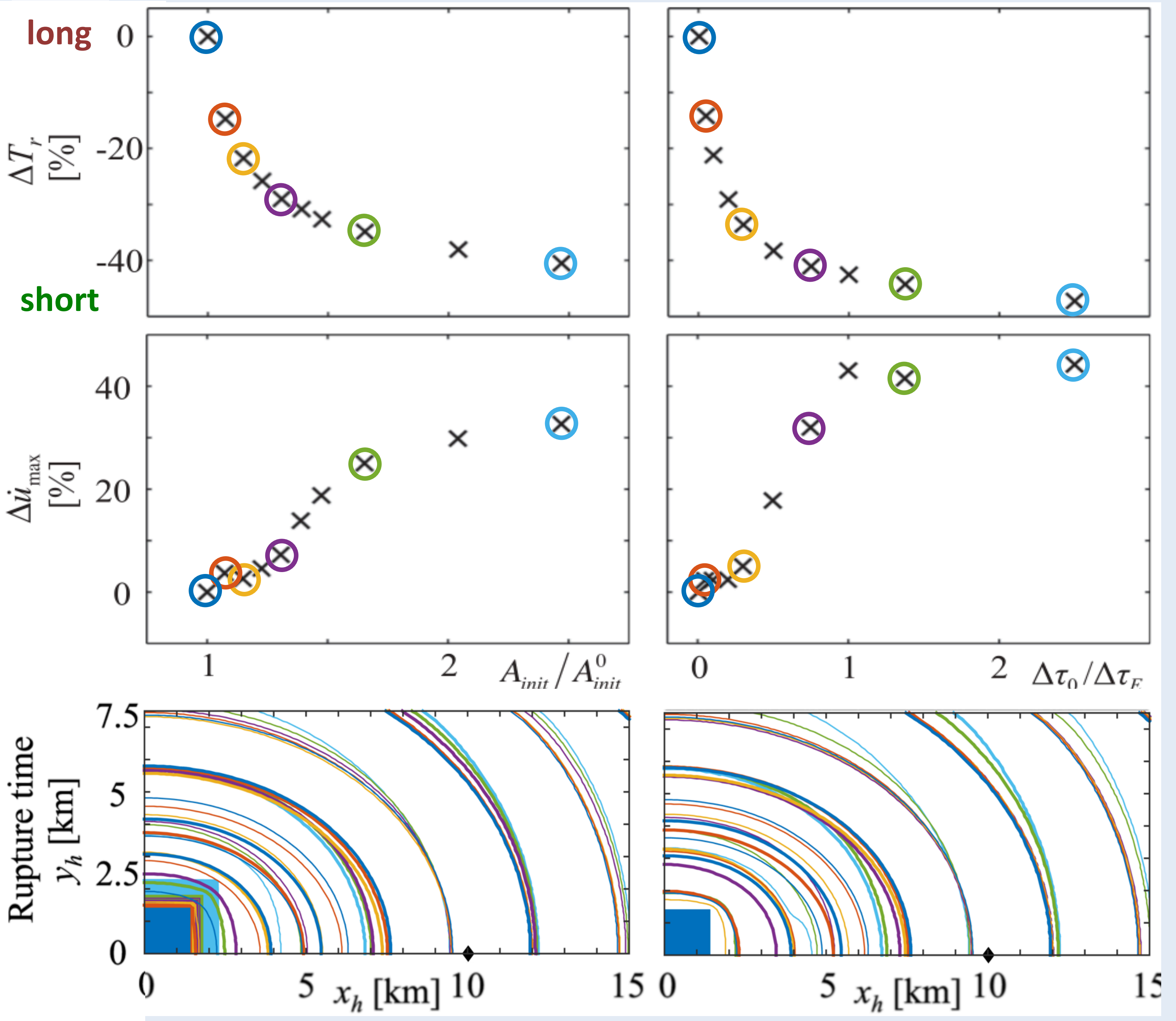
optimal parameters | low background stress, **S = 2.0**

rupture propagation



optimal parameters | low background stress, **S = 2.0**

rupture propagation



A_{init}/A^0_{init}

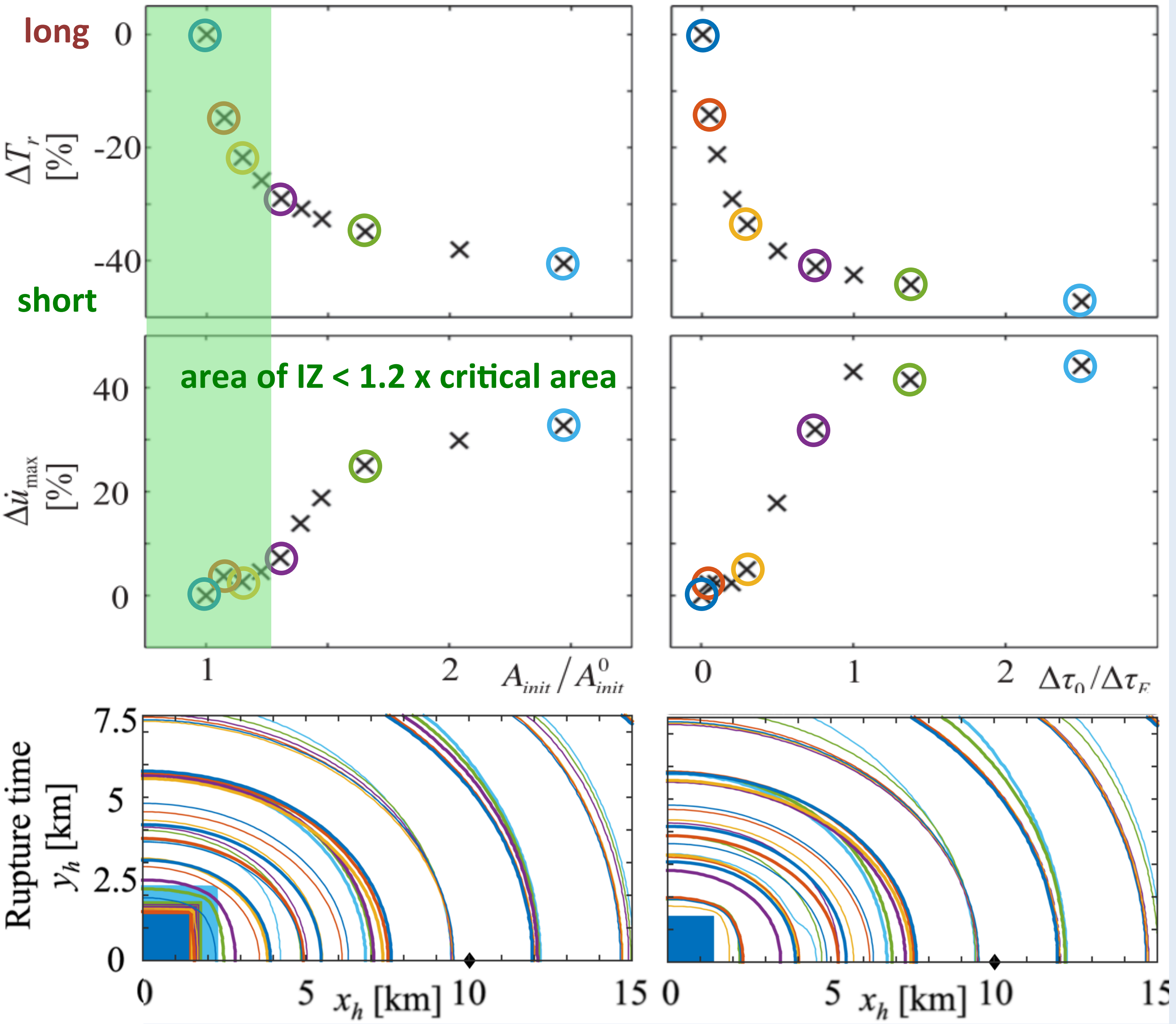
1.0 1.4
1.1 1.7
1.2 2.5

$\Delta\tau_0/\Delta\tau_E$

0.005 0.9
0.05 1.6
0.3 2.5

optimal parameters | low background stress, **S = 2.0**

rupture propagation



A_{init}/A^0_{init}

1.0	1.4
1.1	1.7
1.2	2.5

$\Delta\tau_0/\Delta\tau_E$

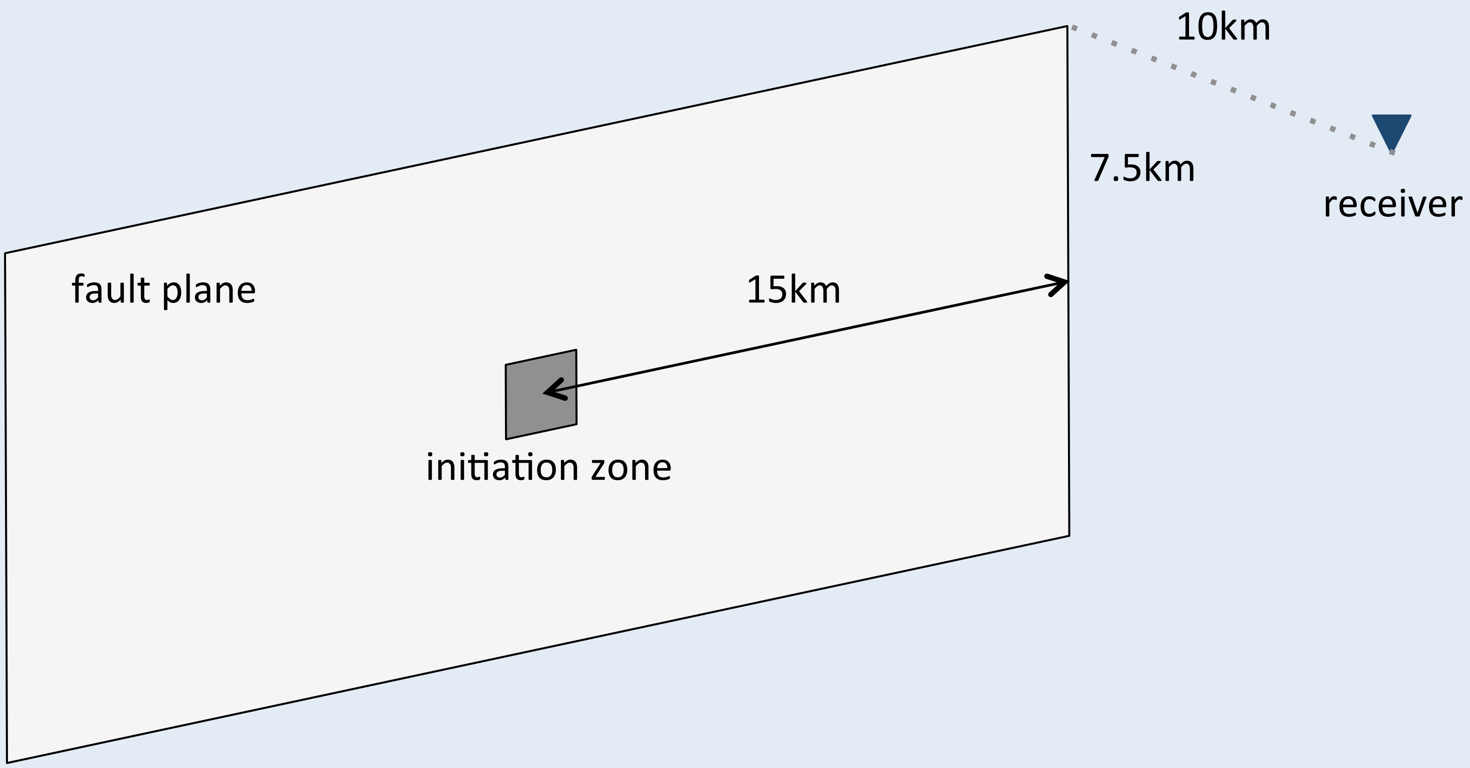
0.005	0.9
0.05	1.6
0.3	2.5

effects of initiation on ground motion | introduction

Galis et al., 2015

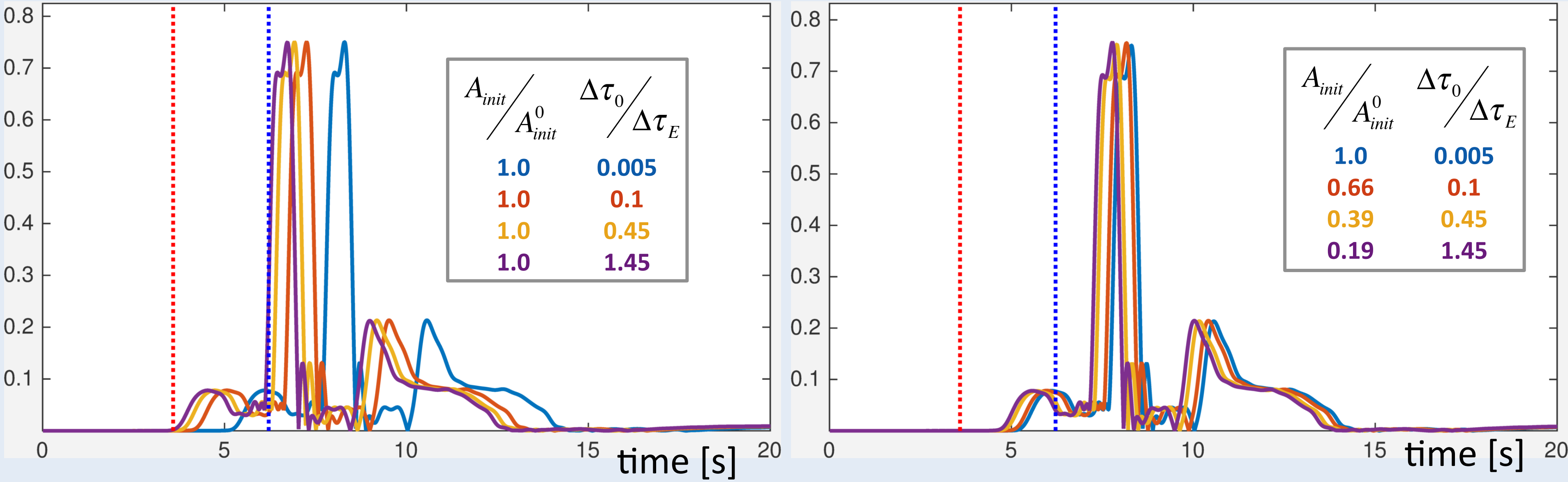
analyzed effects of initiation on rupture propagation

we now extend the analysis to effects on ground motion



effects of initiation on ground motion | high background stress, **S = 0.1**

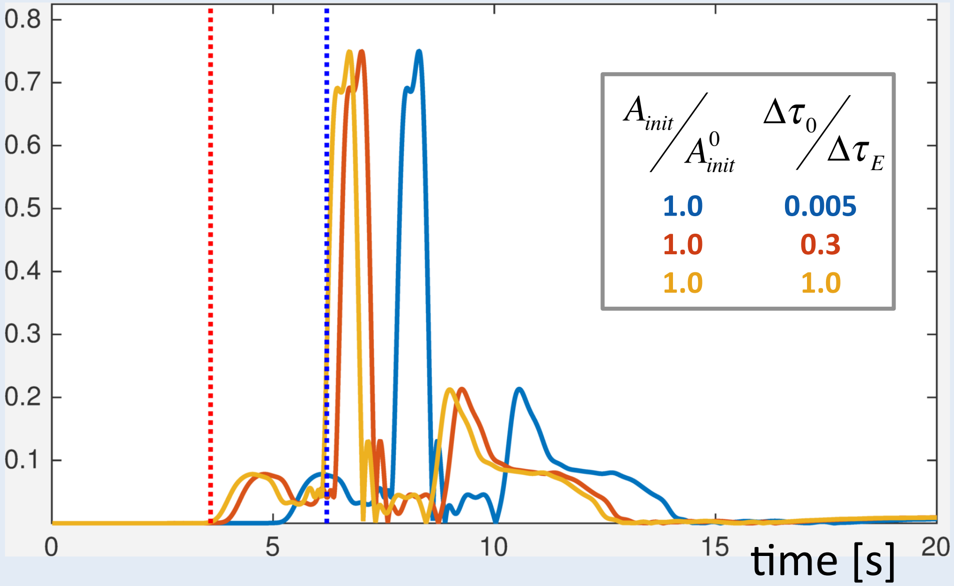
comparison of magnitude of particle velocity



super-critical initiation

slightly overcritical initiation

optimal initiation



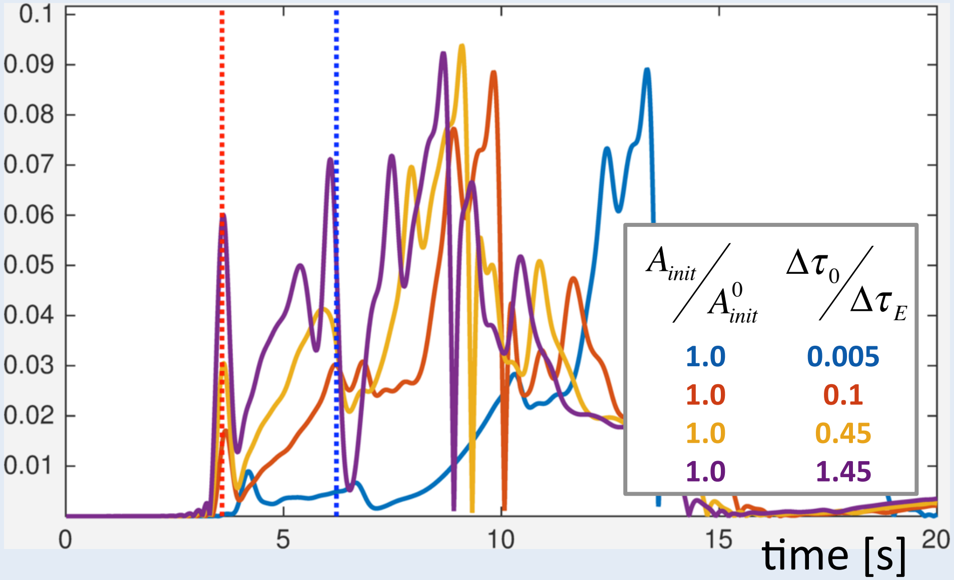
no observable
hypo-central P- or S- waves

optimal initiation:
ovestress < strength excess

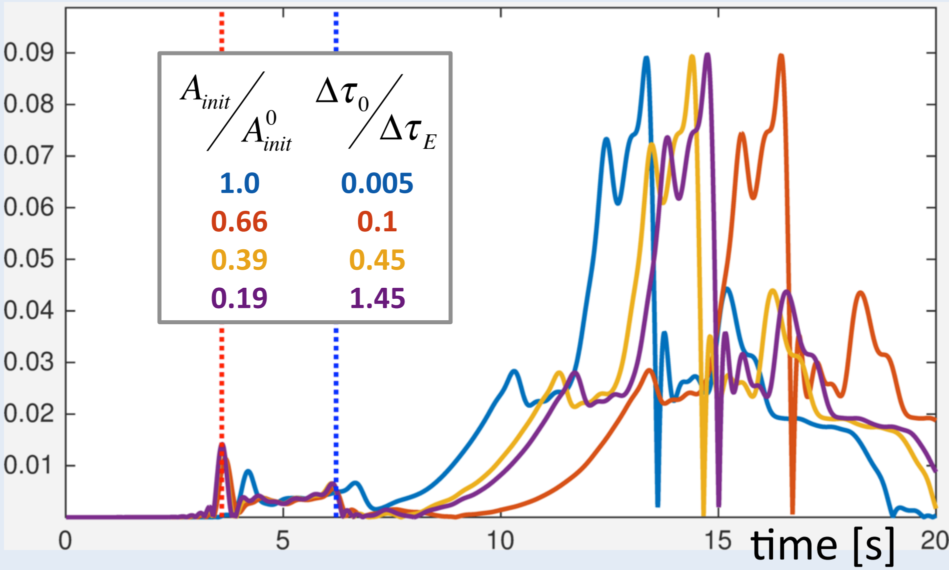
effects of initiation on ground motion | low background stress, **S = 2.0**

comparison of magnitude of particle velocity

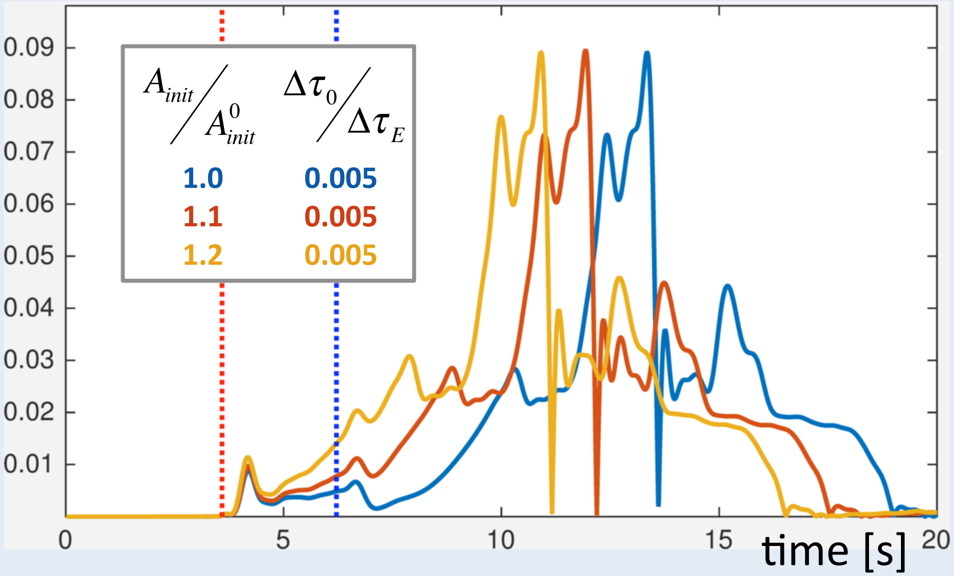
super-critical initiation



slightly overcritical initiation



optimal initiation



super-critical initiation:
strong hypo-central P- or S- waves

slightly overcritical and optimal initiation:
marginal variations in
hypo-central P- or S- waves

optimal initiation:
area < 1.2 x critical area

outline

- introduction
- critical parameters of the initiation zone (IZ) and their estimates
- effects of shape/aspect ratio on the IZ
- verification
- influence of material parameters on the IZ
- optimal parameters of the IZ
- **summary**

summary

- for a fixed overstress and aspect ratio close to 1

the initiation is controlled by the area of the initiation zone

however, if one side of IZ should be shorter than the corresponding critical half-length

initiation is controlled by half-length

- **the critical area** can be estimated by

$$A_{crit} = \max(A_U, A_2)$$

A_U : estimate by Uenishi, 2009

A_2 : estimate by Galis et al., 2015

- **efficient initiation with minimized side effects**

on rupture propagation and ground motion

can be achieved

high background stress (low S)	**low background stress (high S)**
overstress < strength excess	area of IZ < 1.2 x critical area

Thank you

e-mail: martin.galis@kaust.edu.sa