From Single-Station Prediction to Finite-Fault Detection:
the Large Spectrum of EEW Algorithms and the Question of How to Combine Them

- Keynote -

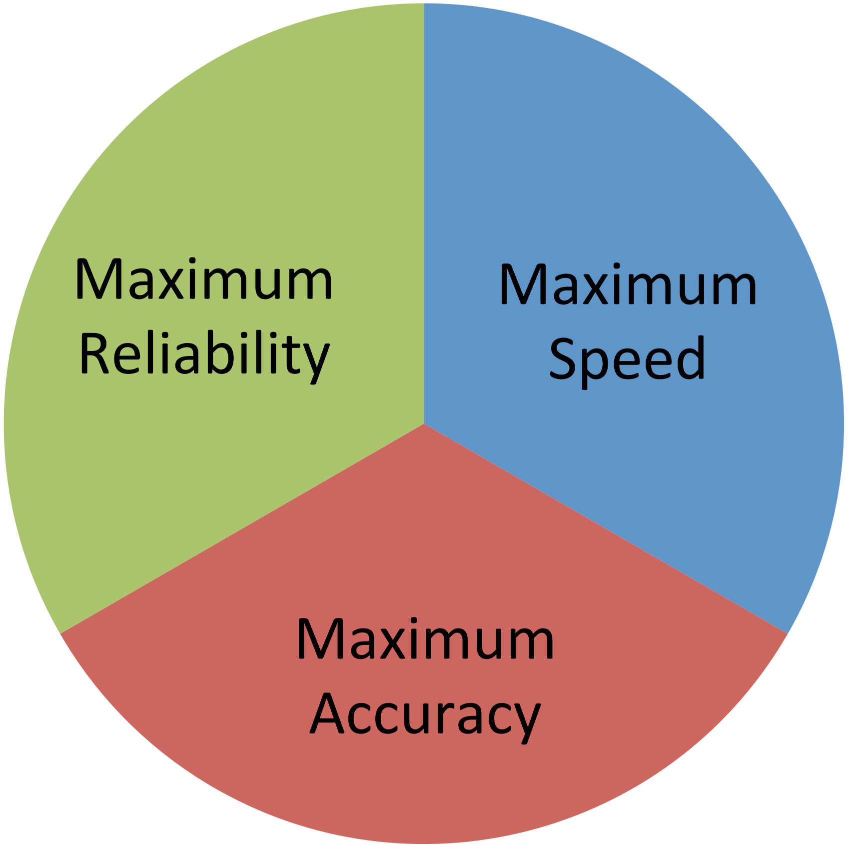
Maren Böse mboese@sed.ethz.ch

Y. Behr, T. Heaton, J. Clinton, D. Smith, S. Minson

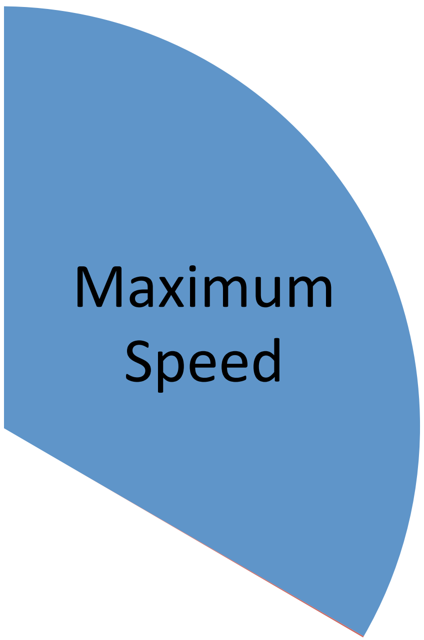
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Schweizerischer Erdbebendienst
Service Sismologique Suisse
Servizio Sismico Svizzero
Swiss Seismological Service

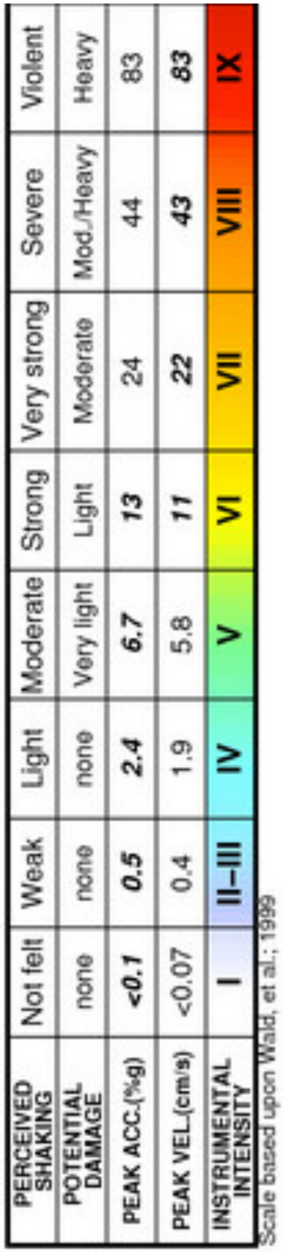
Early Warning: Objectives



Early Warning: Objectives

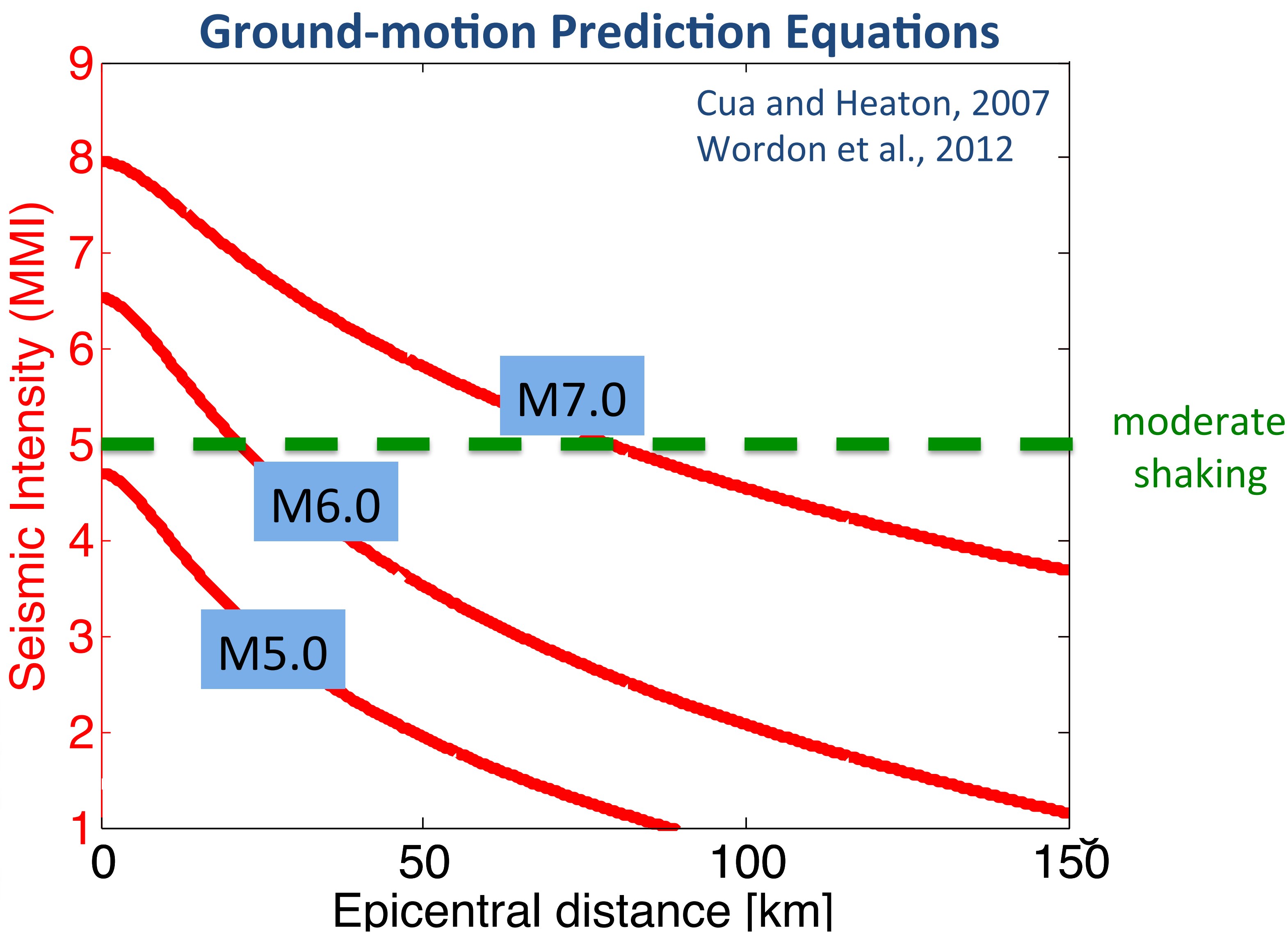


Speed



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy
PEAK ACC.(%g)	<0.1	0.5	2.4	6.7	13	24	44	83
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	11	22	43	83
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX

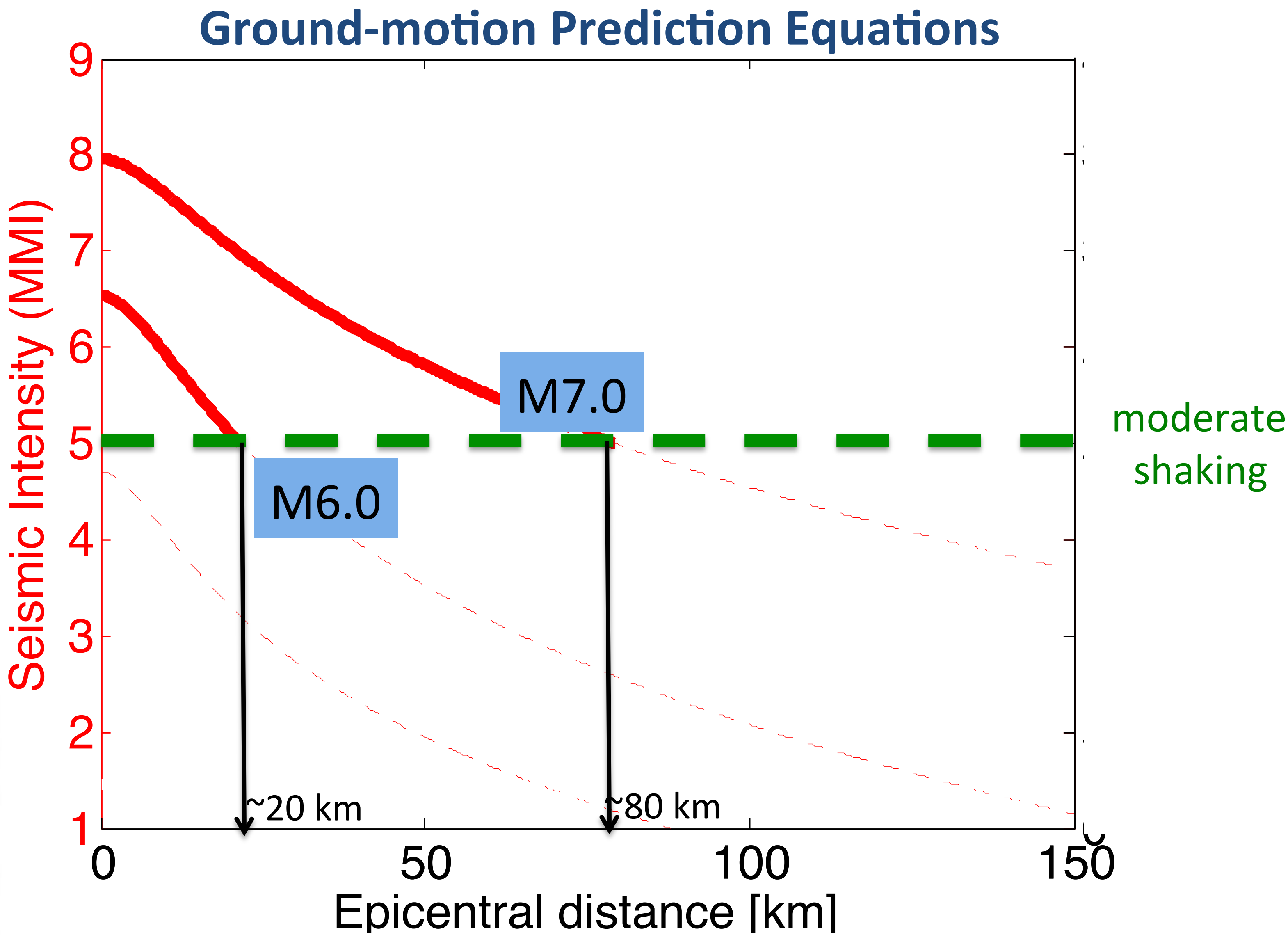
Scale based upon Wald, et al.; 1999



Speed

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy
PEAK ACC.(%g)	<0.1	0.5	2.4	6.7	13	24	44	83
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	11	22	43	83
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX

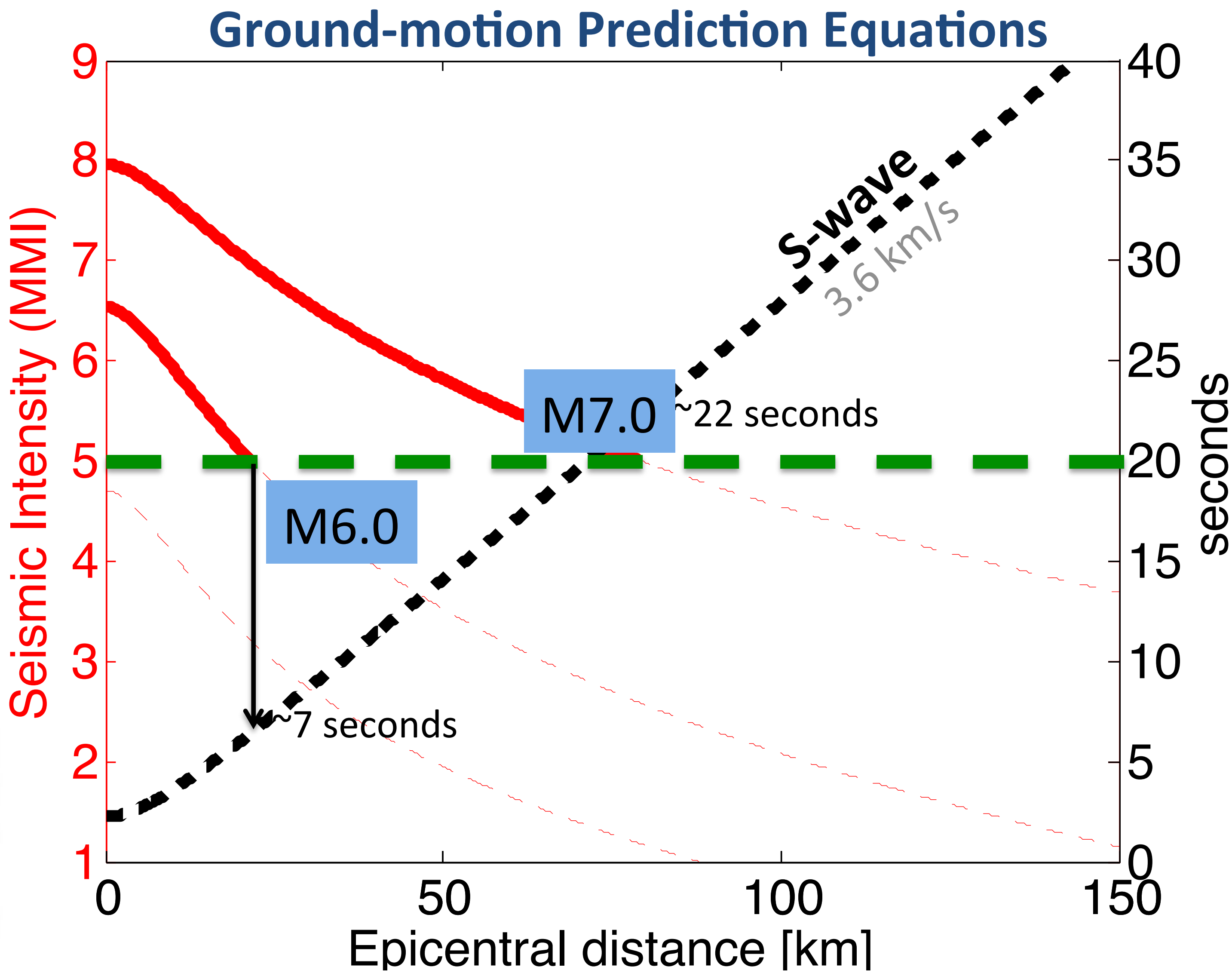
Scale based upon Wald, et al.; 1999



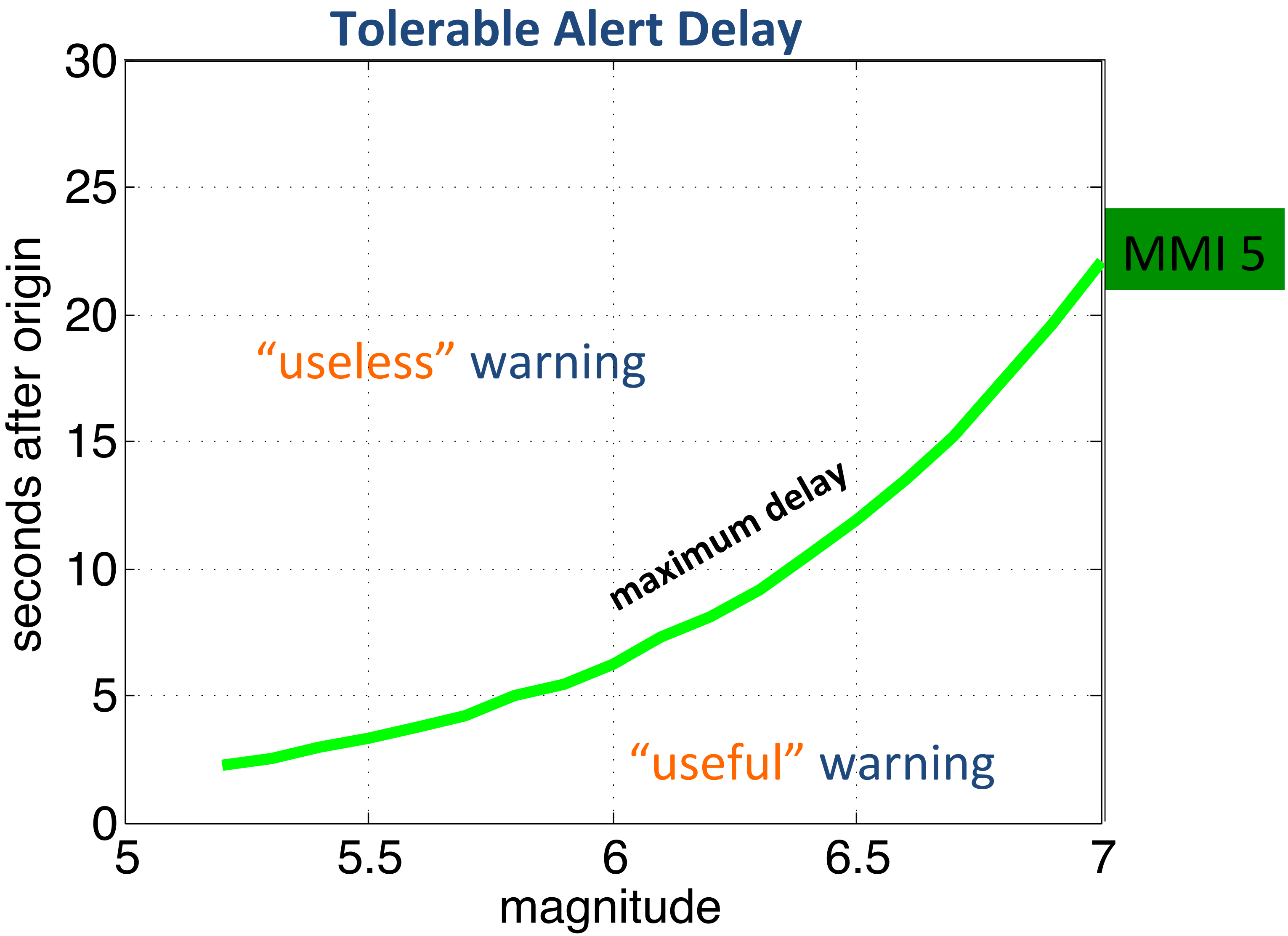
Speed

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy
PEAK ACC.(%g)	<0.1	0.5	2.4	6.7	13	24	44	83
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	11	22	43	83
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX

Scale based upon Wald, et al.; 1999

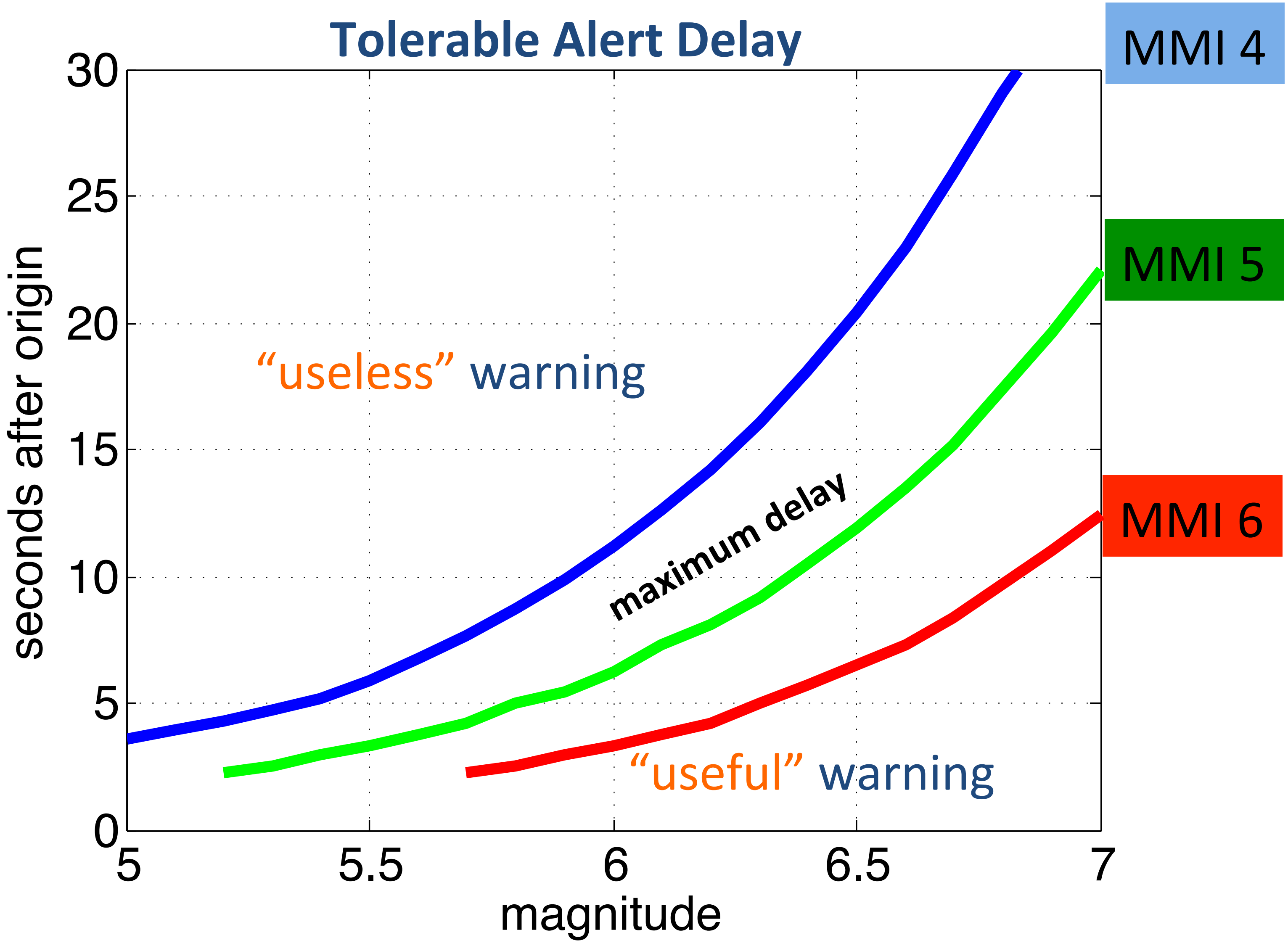


Speed



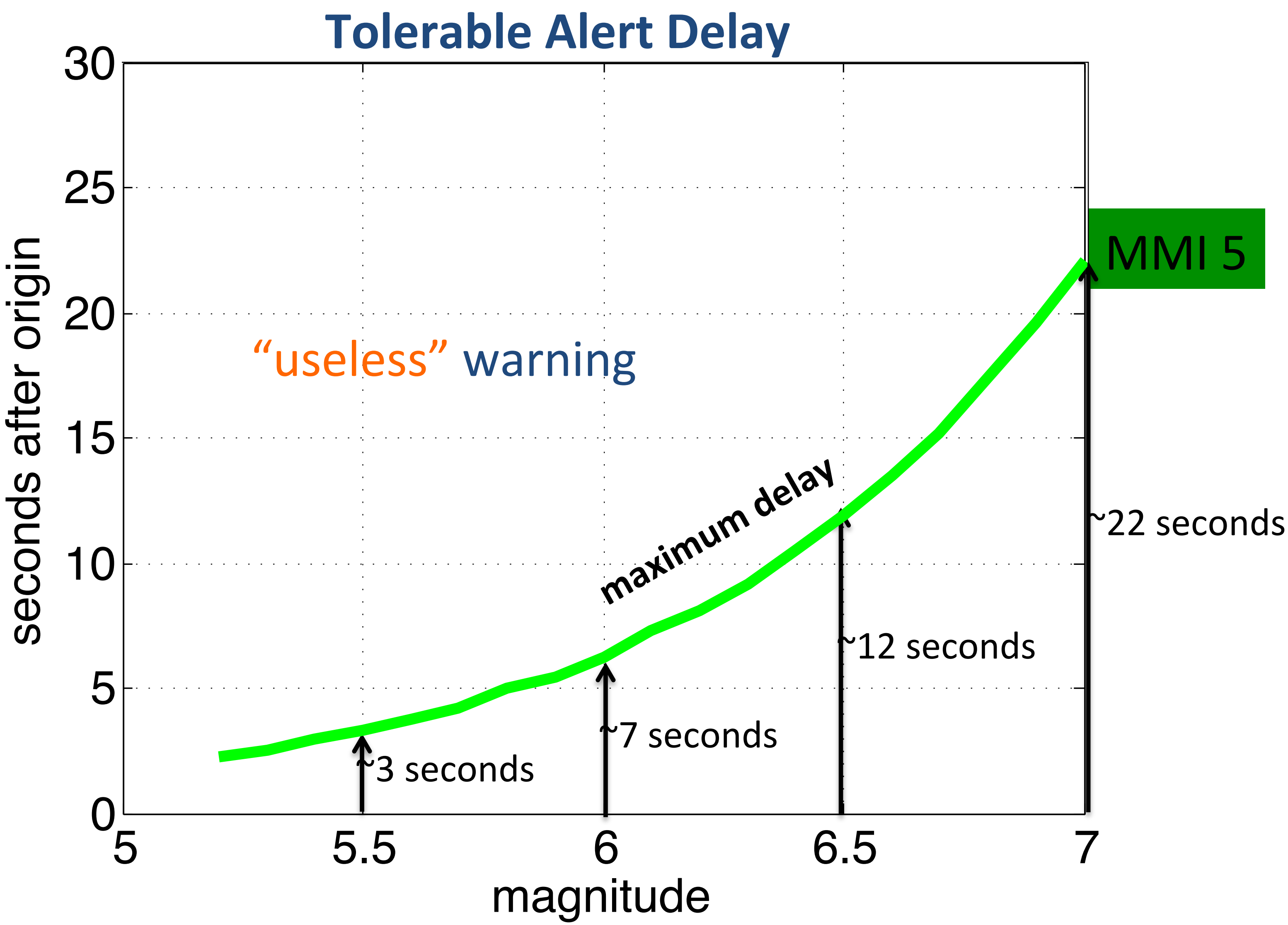
Tolerable Alert Delay
30
25
20
15
10
5
0
seconds after origin
5
5.5
6
6.5
7
magnitude
MMI 5
"useless" warning
maximum delay
"useful" warning

Speed



Tolerable Alert Delay
MMI 4
MMI 5
MMI 6
"useless" warning
maximum delay
"useful" warning
seconds after origin
magnitude
30
25
20
15
10
5
0
5
5.5
6
6.5
7

Speed



Tolerable Alert Delay
30
25
20
15
10
5
0
seconds after origin
5
5.5
6
6.5
7
magnitude
“useless” warning
maximum delay
MMI 5
~3 seconds
~7 seconds
~12 seconds
~22 seconds

Example: ShakeAlert (California)

La Habra

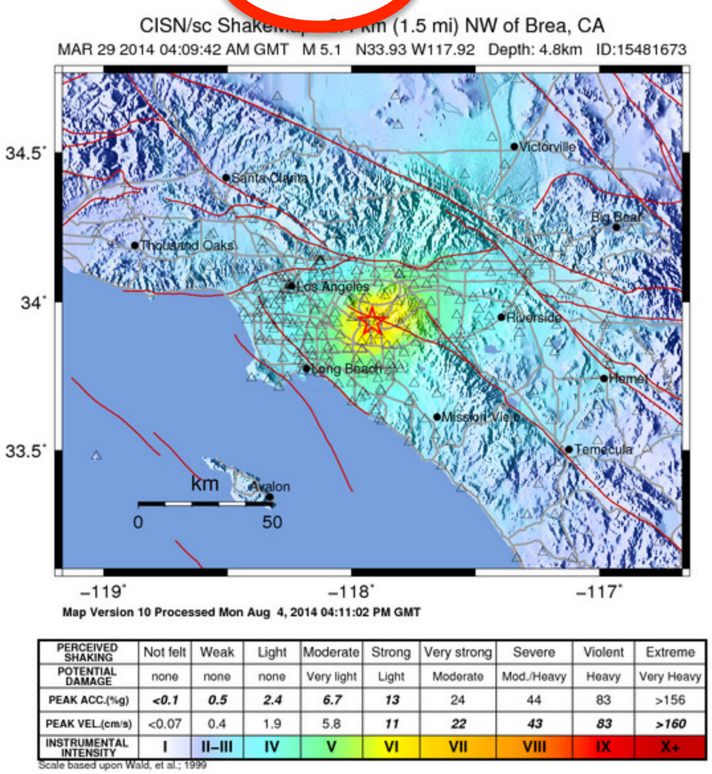
M 5.1, March 28, 2014. 9:09 pm PDT

ShakeAlert Timeline

09:09:42.3 Origin time

09:09:43.3 (+1.0s) 1st P-wave

09:09:46.3 (+4.0s) 1st Alert



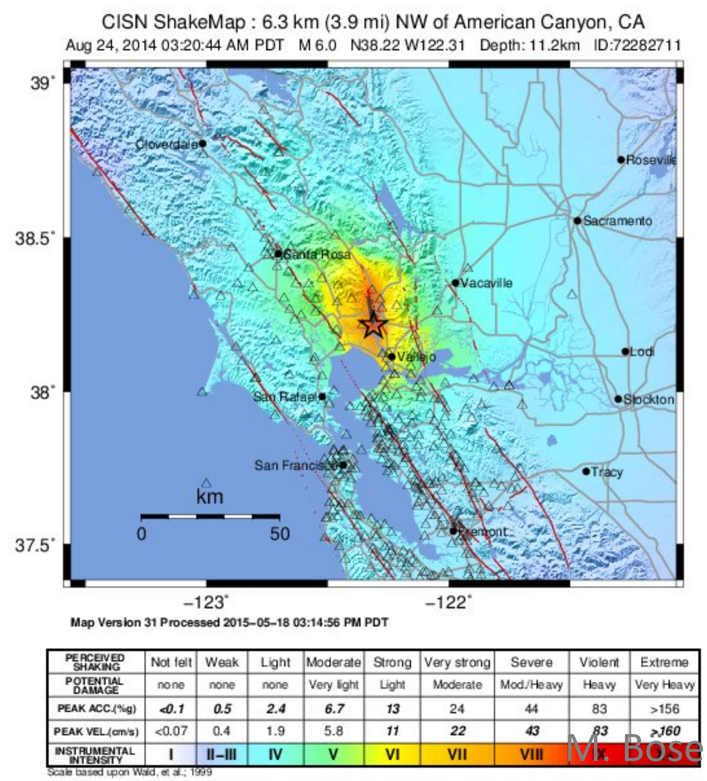
South Napa

M 6.0, Aug. 24th, 2014. 3:20am PDT

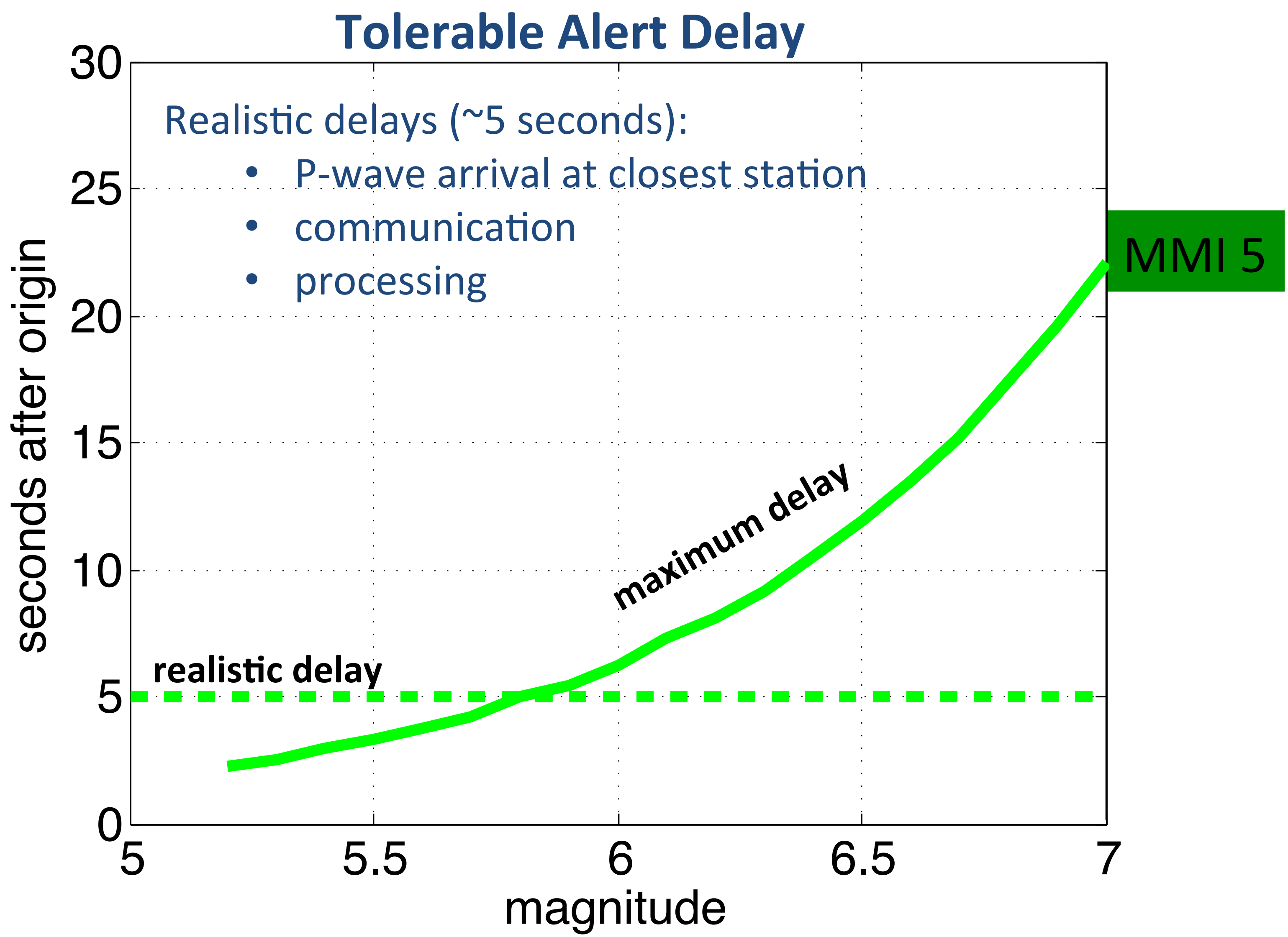
ShakeAlert Timeline

10:20:44.4 Origin time

10:20:49.5 (+5.1s) 1st Alert

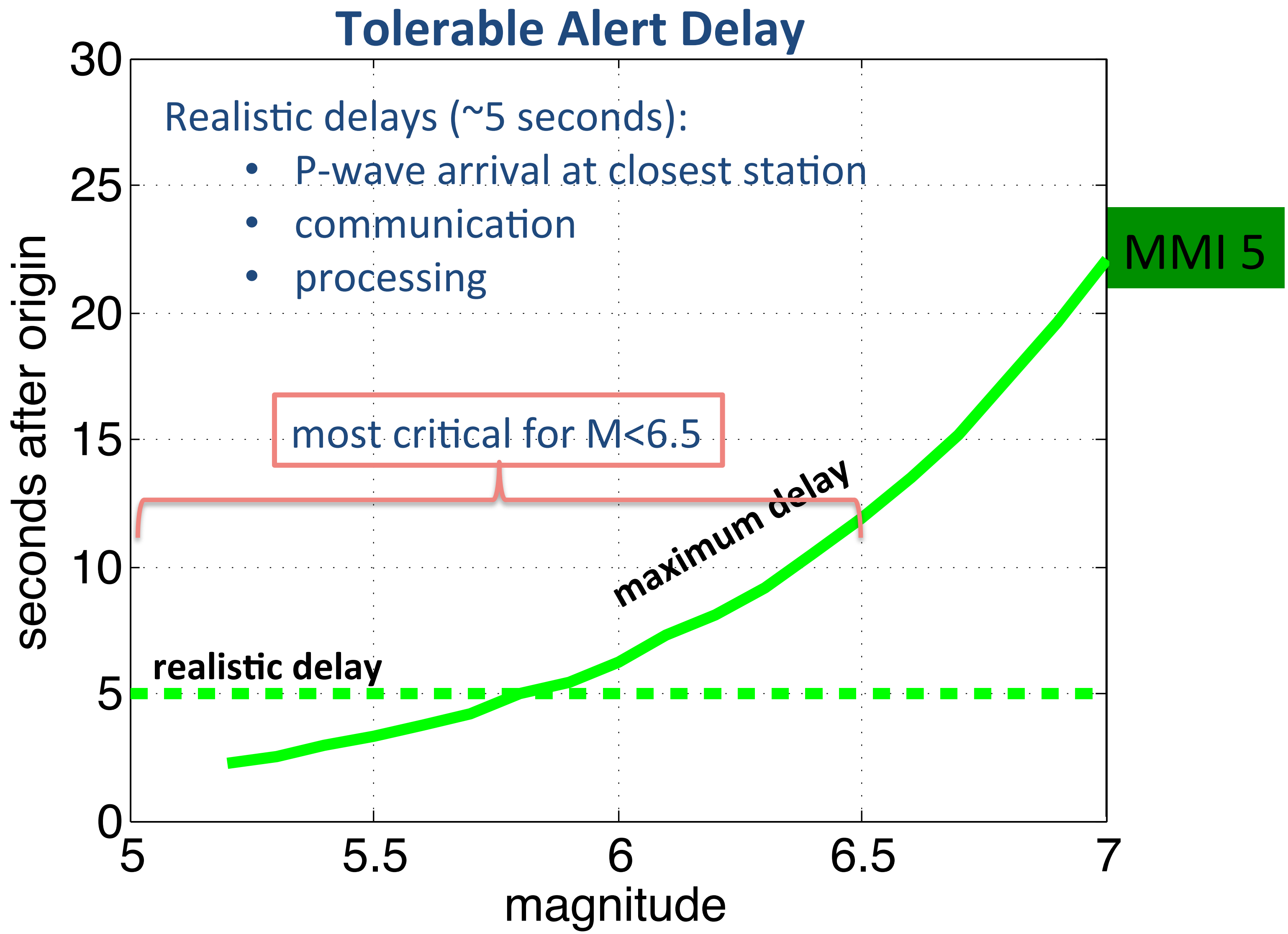


Speed



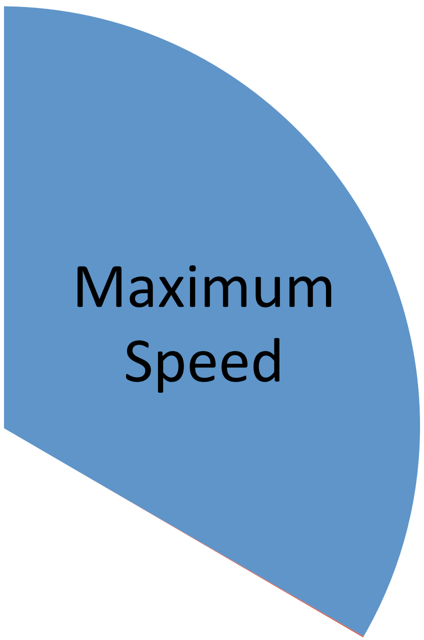
Tolerable Alert Delay
Realistic delays (~5 seconds):
• P-wave arrival at closest station
• communication
• processing
MMI 5
maximum delay
realistic delay
seconds after origin
magnitude
30
25
20
15
10
5
0
5
5.5
6
6.5
7

Speed

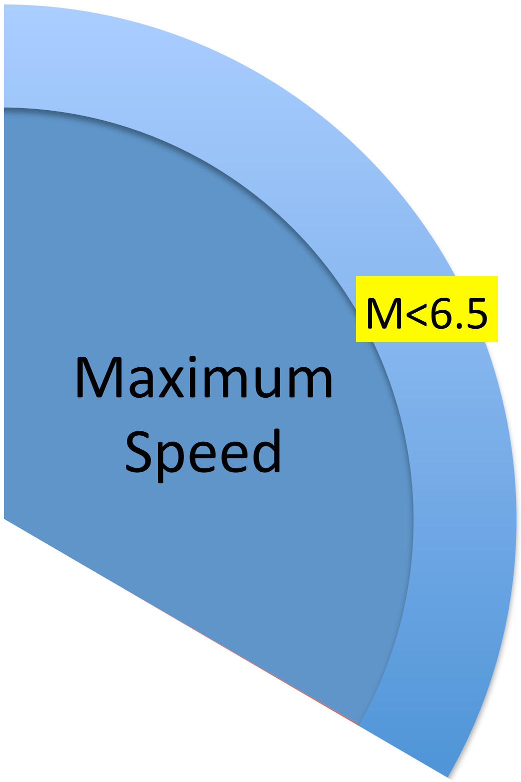


Tolerable Alert Delay
Realistic delays (~5 seconds):
• P-wave arrival at closest station
• communication
• processing
most critical for M<6.5
maximum delay
realistic delay
MMI 5
seconds after origin
magnitude
0
5
10
15
20
25
30
5
5.5
6
6.5
7

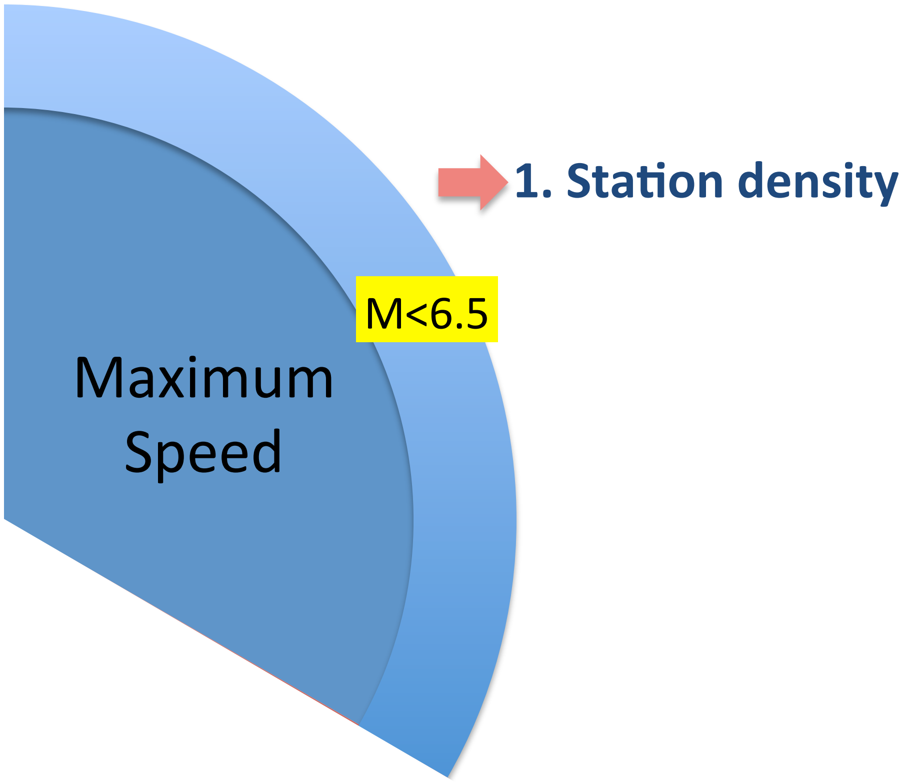
Speed



Speed

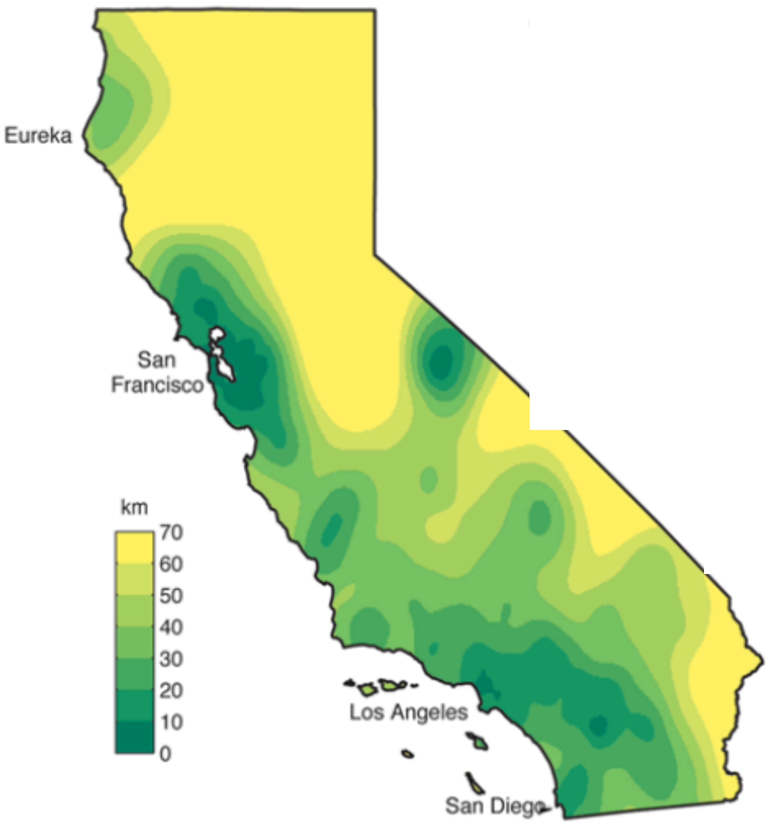


Speed

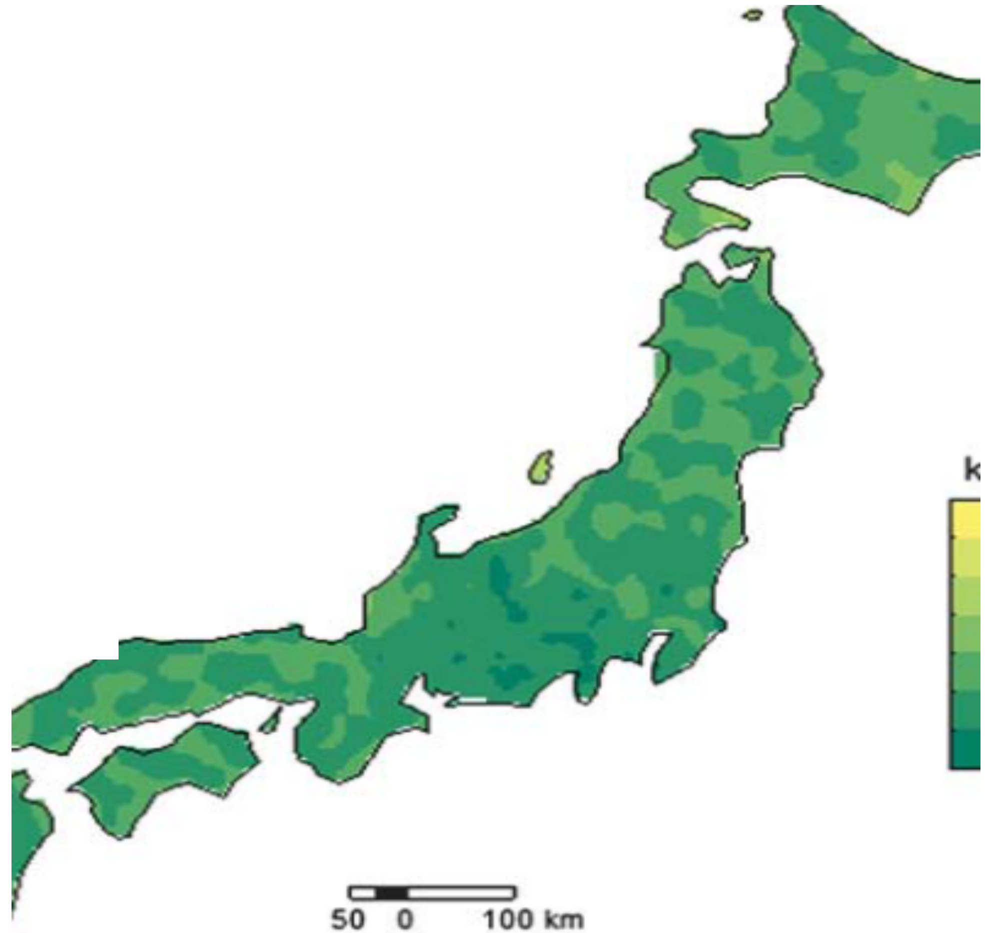


Speed

1. Station density



California

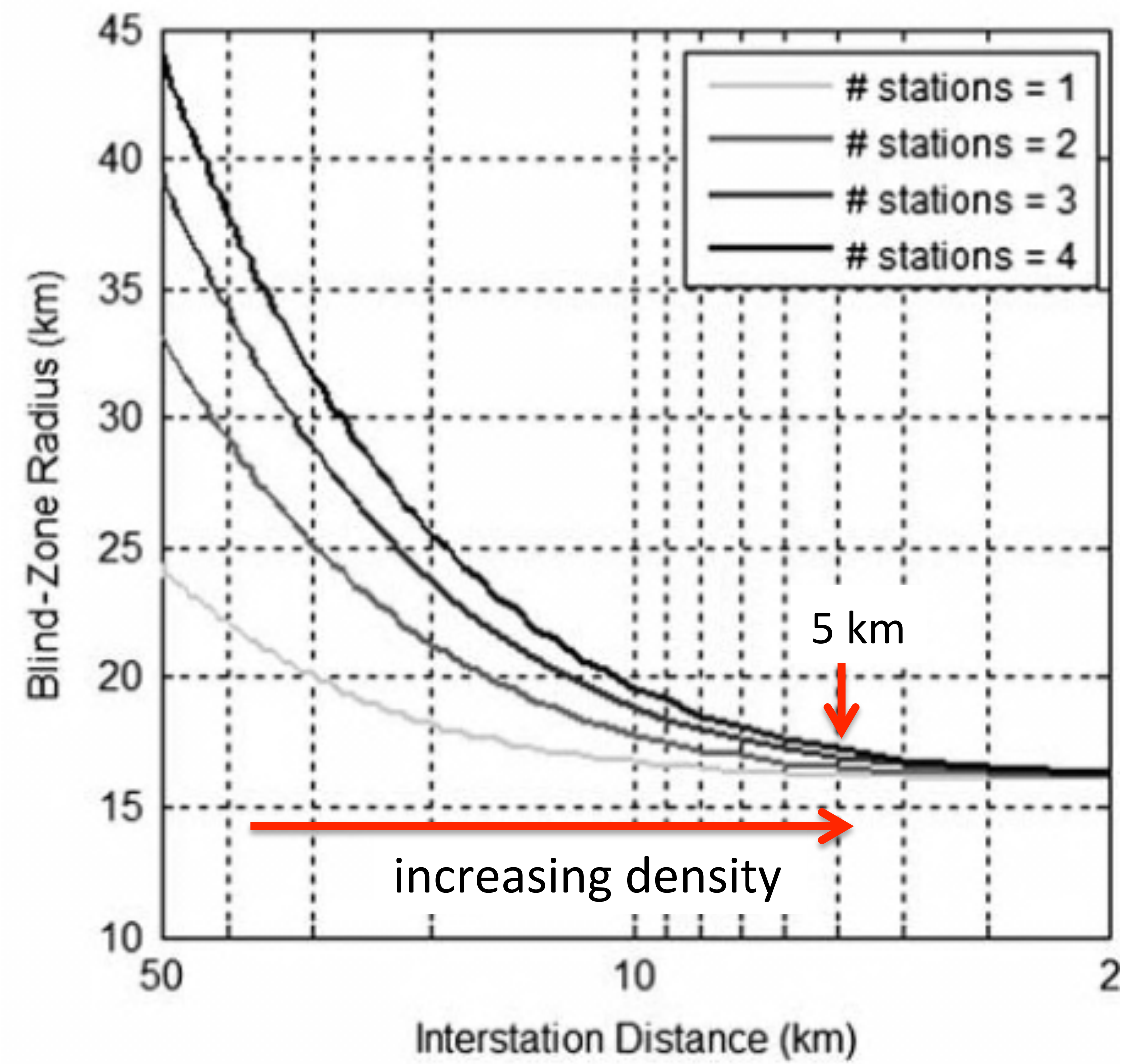


Japan

Kuyuk & Allen, 2013

Speed

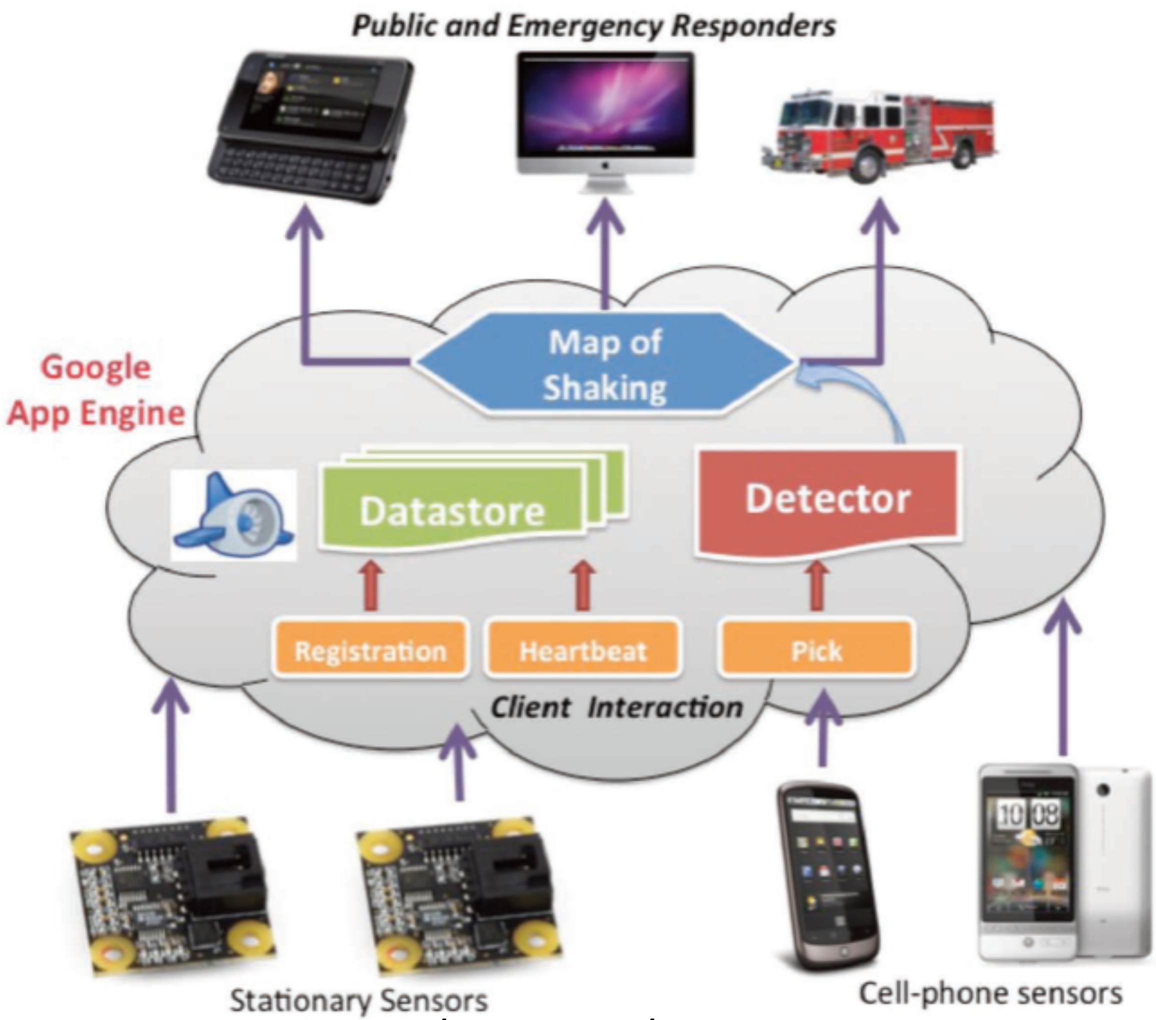
1. Station density



Kuyuk & Allen, 2013

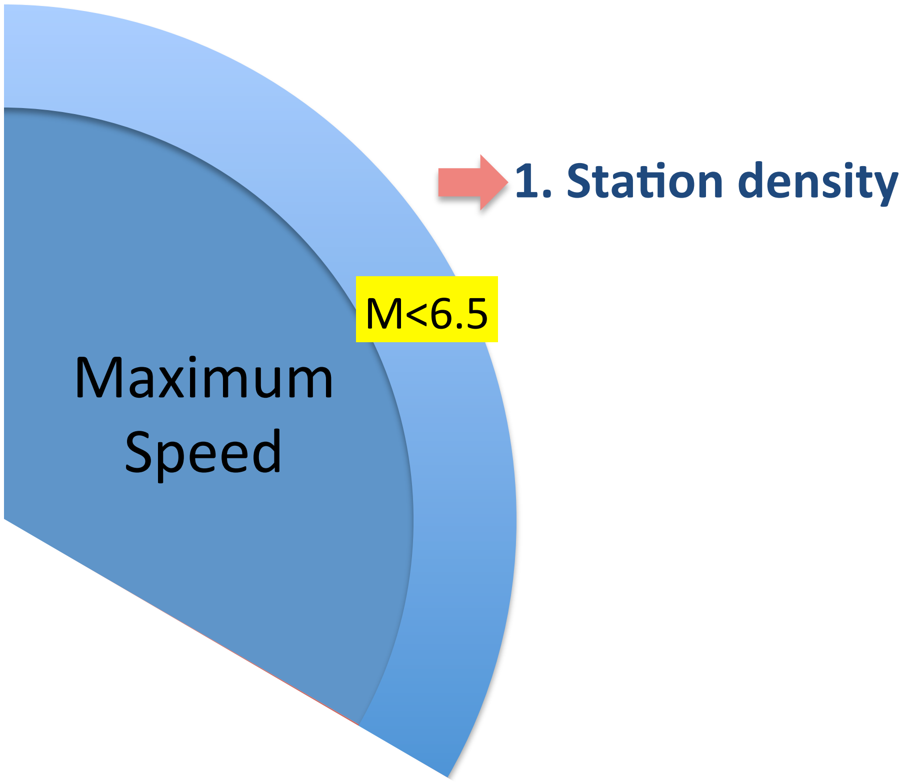
1. Station density

Crowd-Sourcing (e.g. Community Seismic Network)

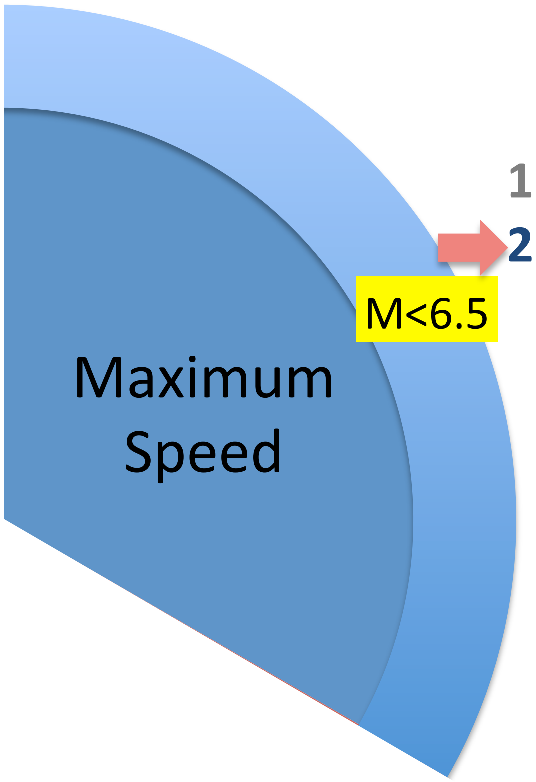


Clayton et al., 2011

Speed

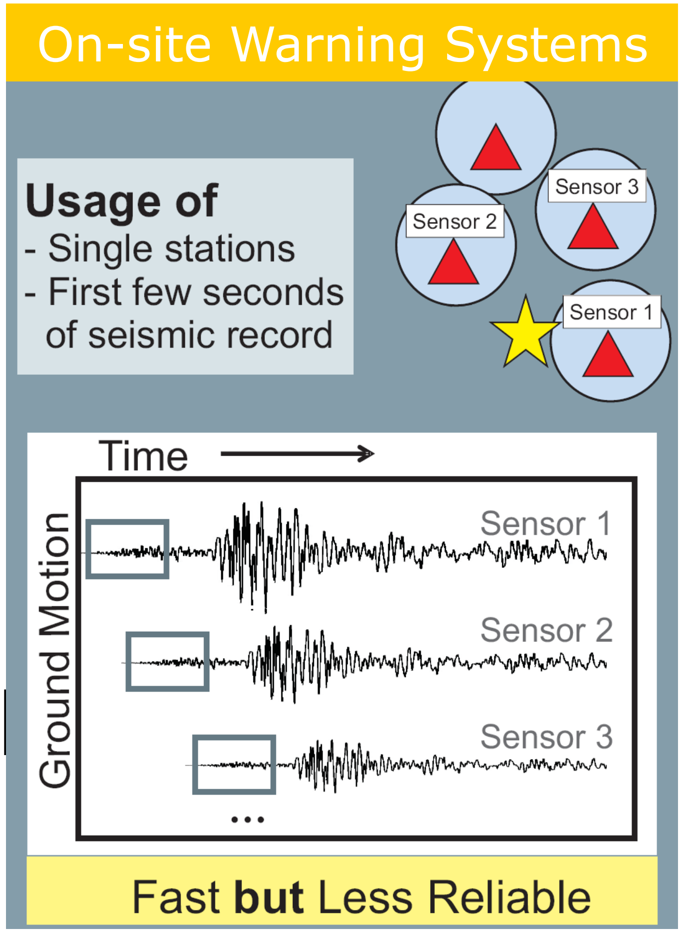


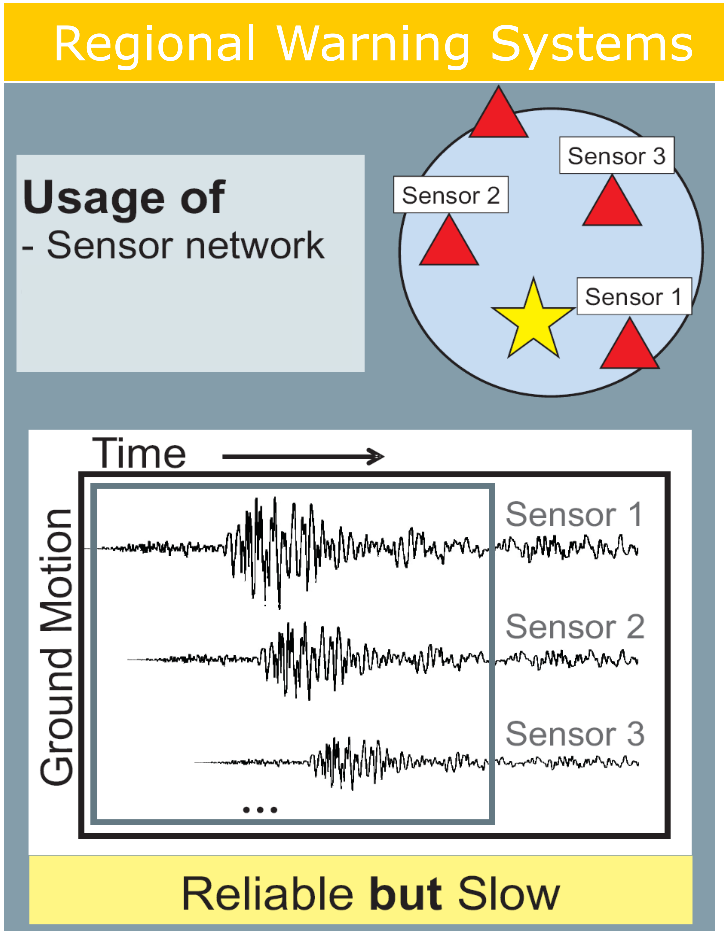
Speed



1. Station density
2. **Fast algorithms**

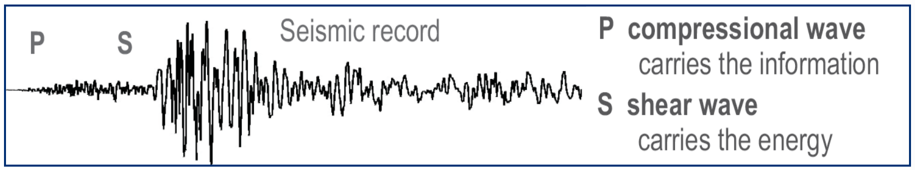
2. Fast algorithms



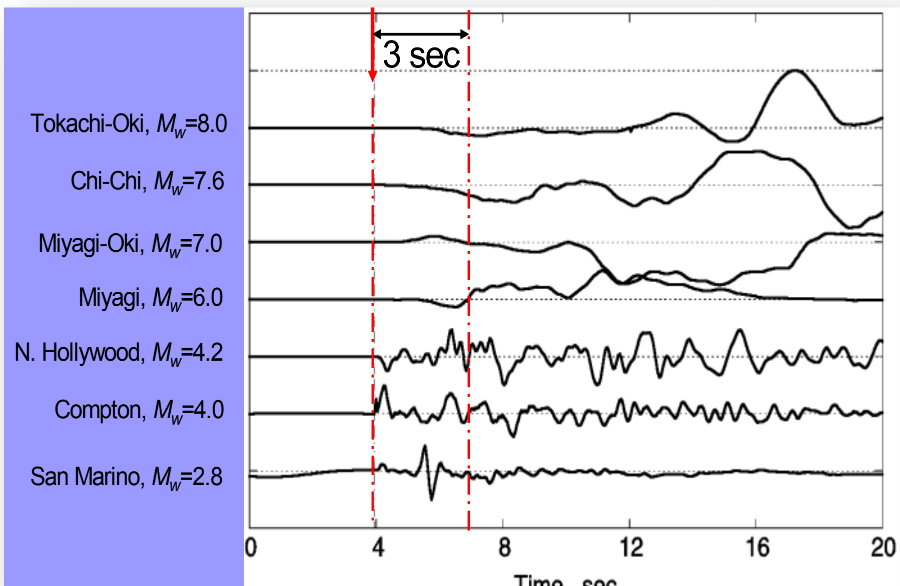


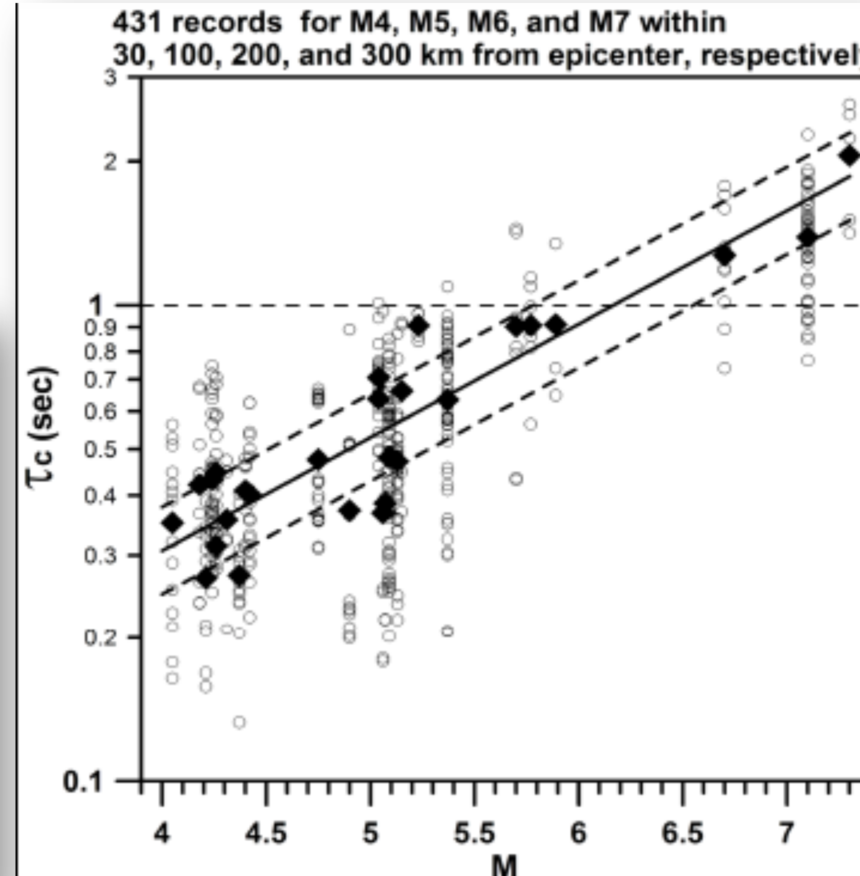
2. Fast algorithms

Tauc-Pd Onsite algorithm   Kanamori, Wu



predominant period ~ earthquake magnitude:





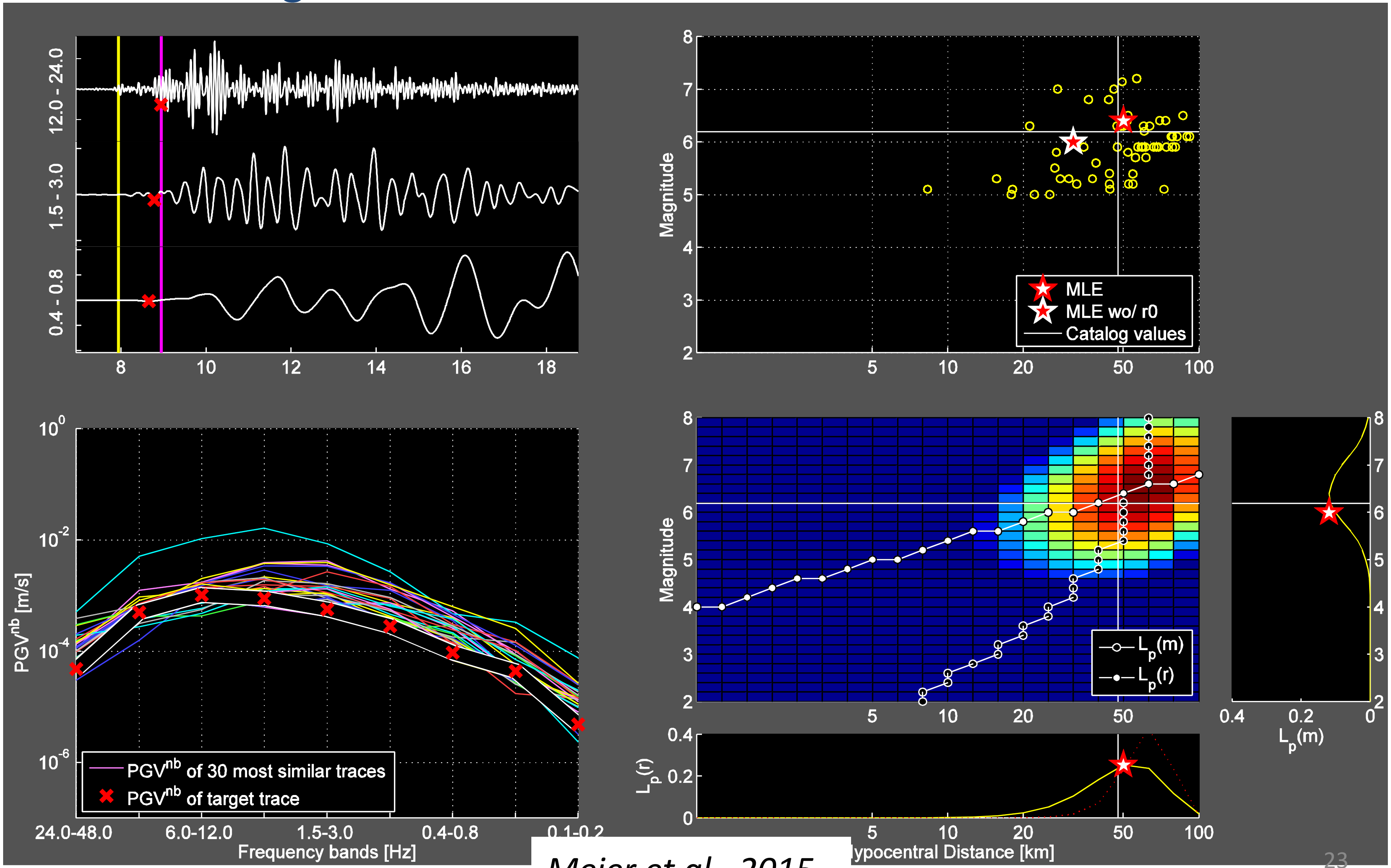
Kanamori, 2005

Speed

2. Fast algorithms

Filterbank algorithm

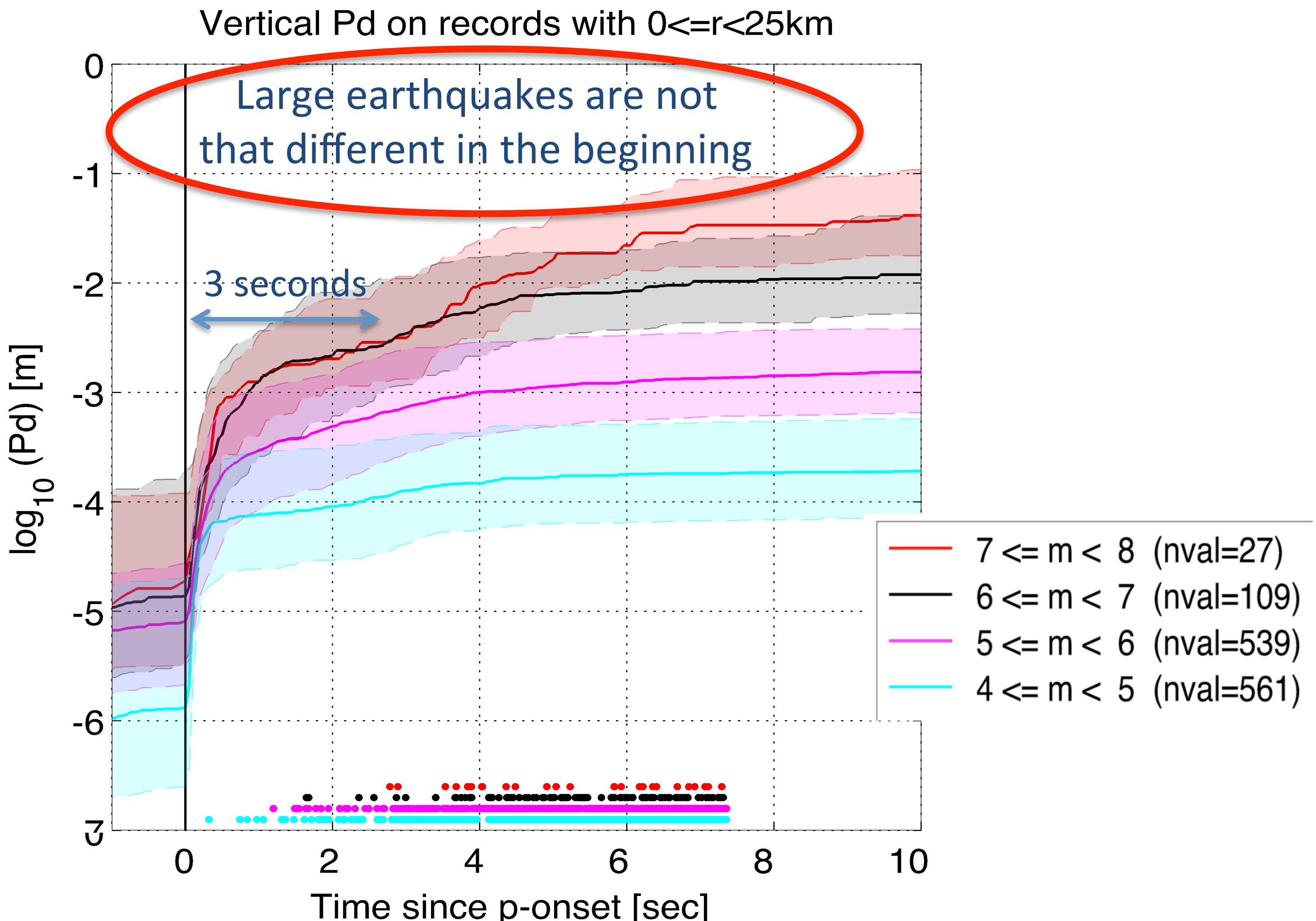
Meier, Heaton, and Clinton



Meier et al., 2015

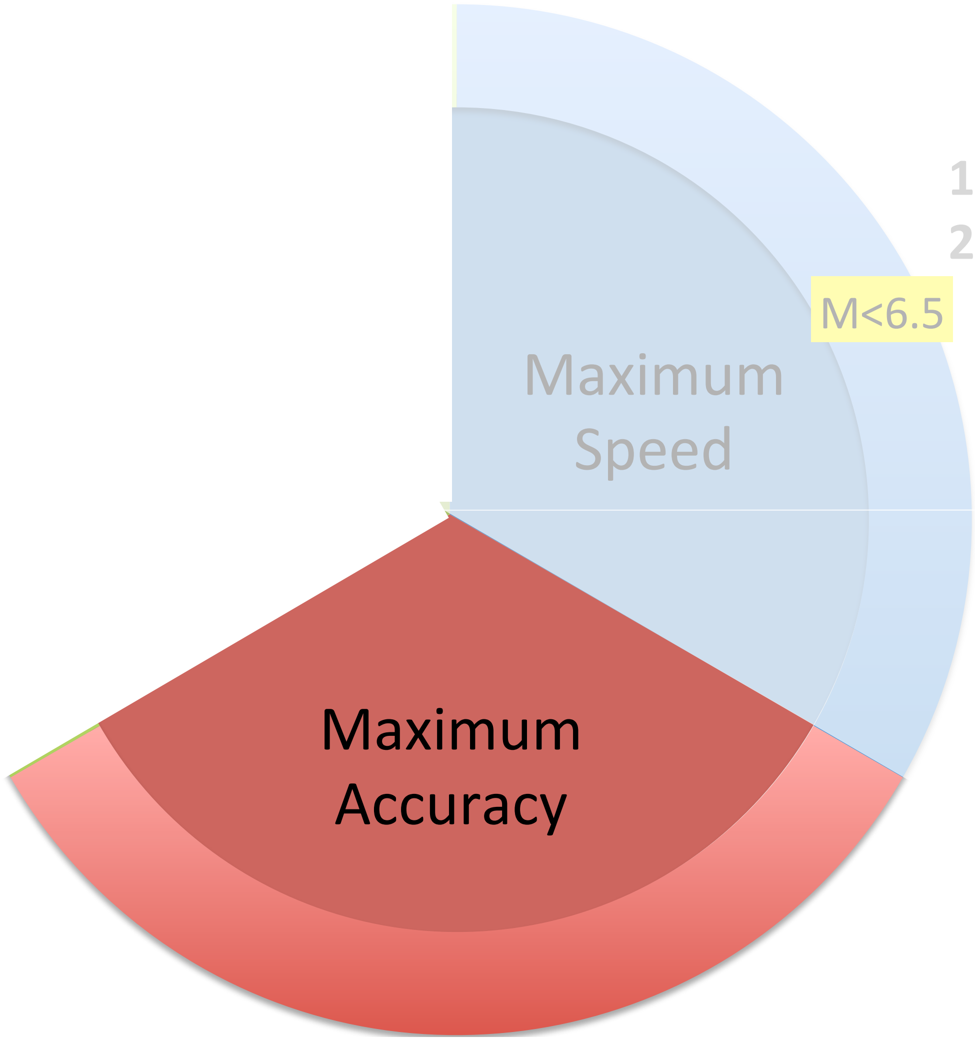
2. Fast algorithms

Limitation



Meier, 2015

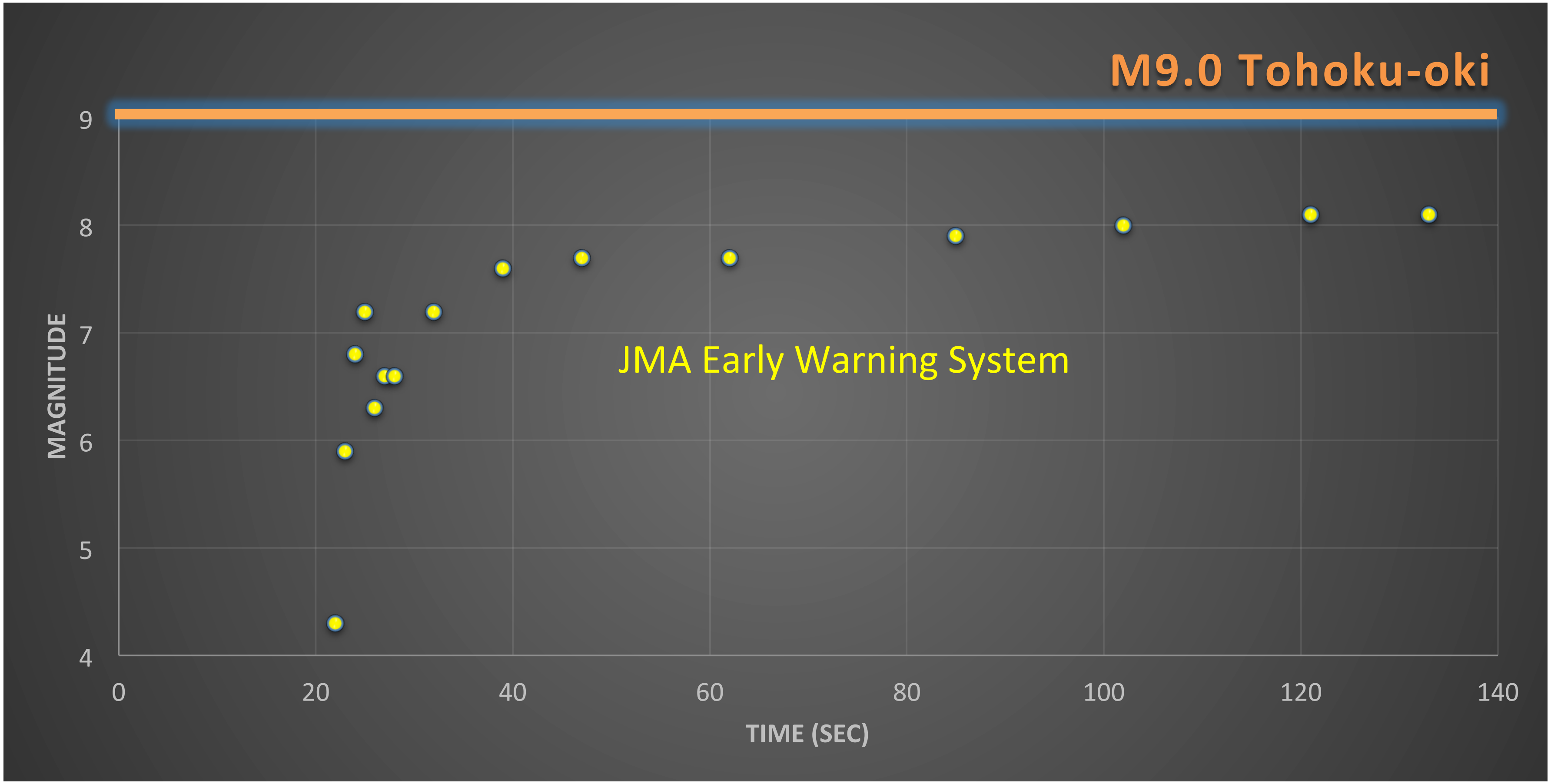
Accuracy



1. Station density
2. Fast algorithms

Magnitude Saturation

… in large earthquakes

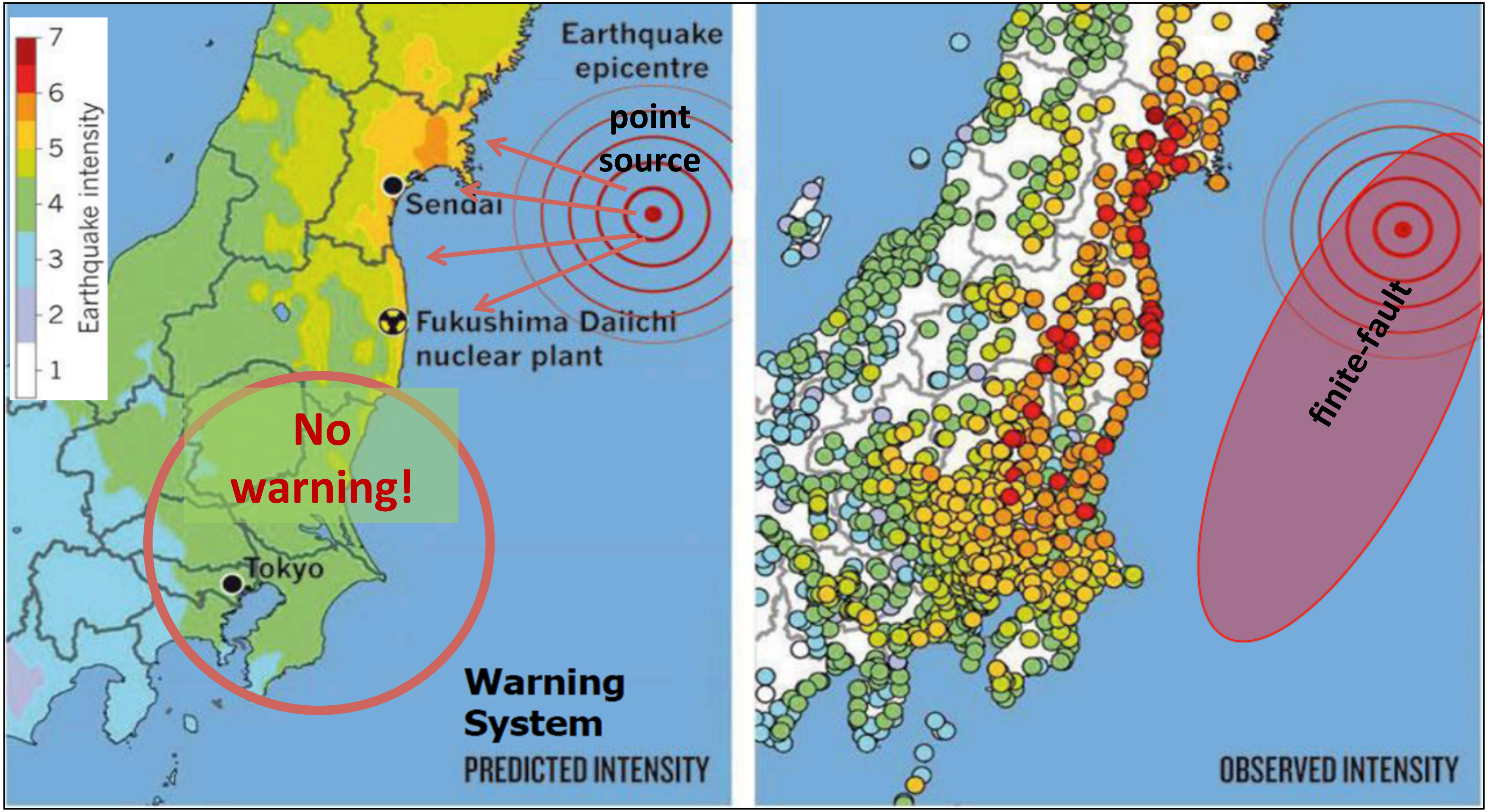


Minson

Finite-Fault Ruptures

… in large earthquakes

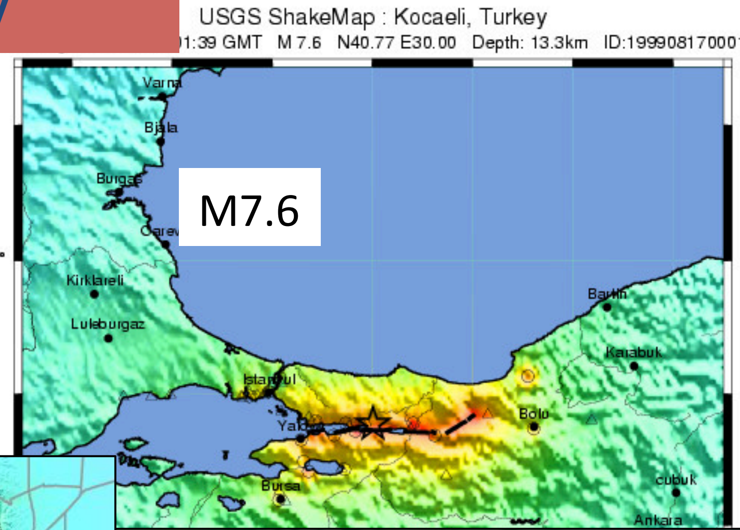
M9 Tohoku-Oki, Japan

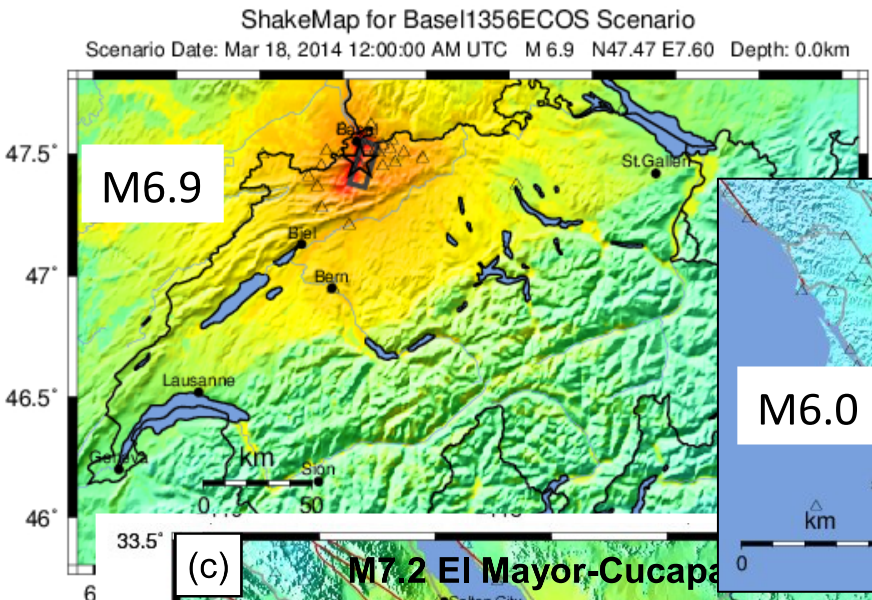


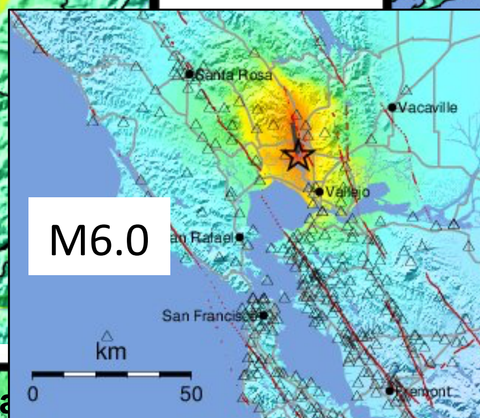
Yamada

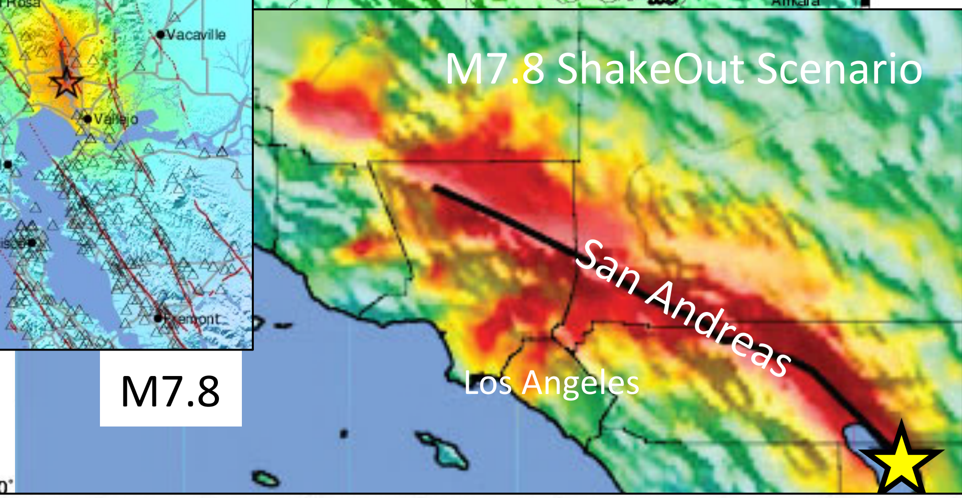
Finite-Fault Ruptures

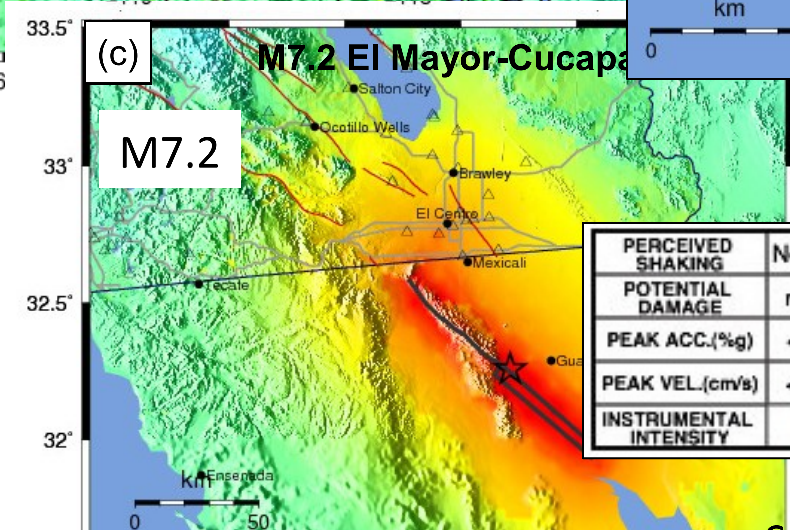
… in large earthquakes







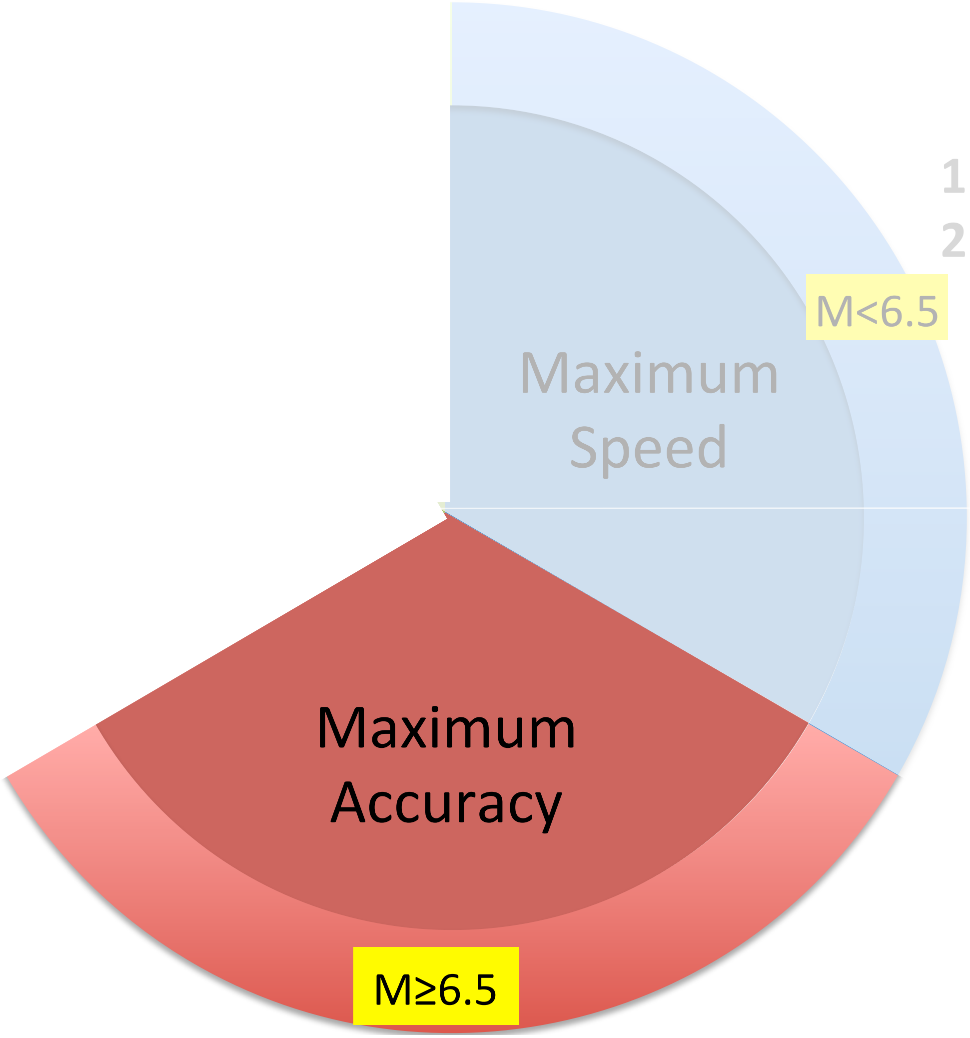




PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

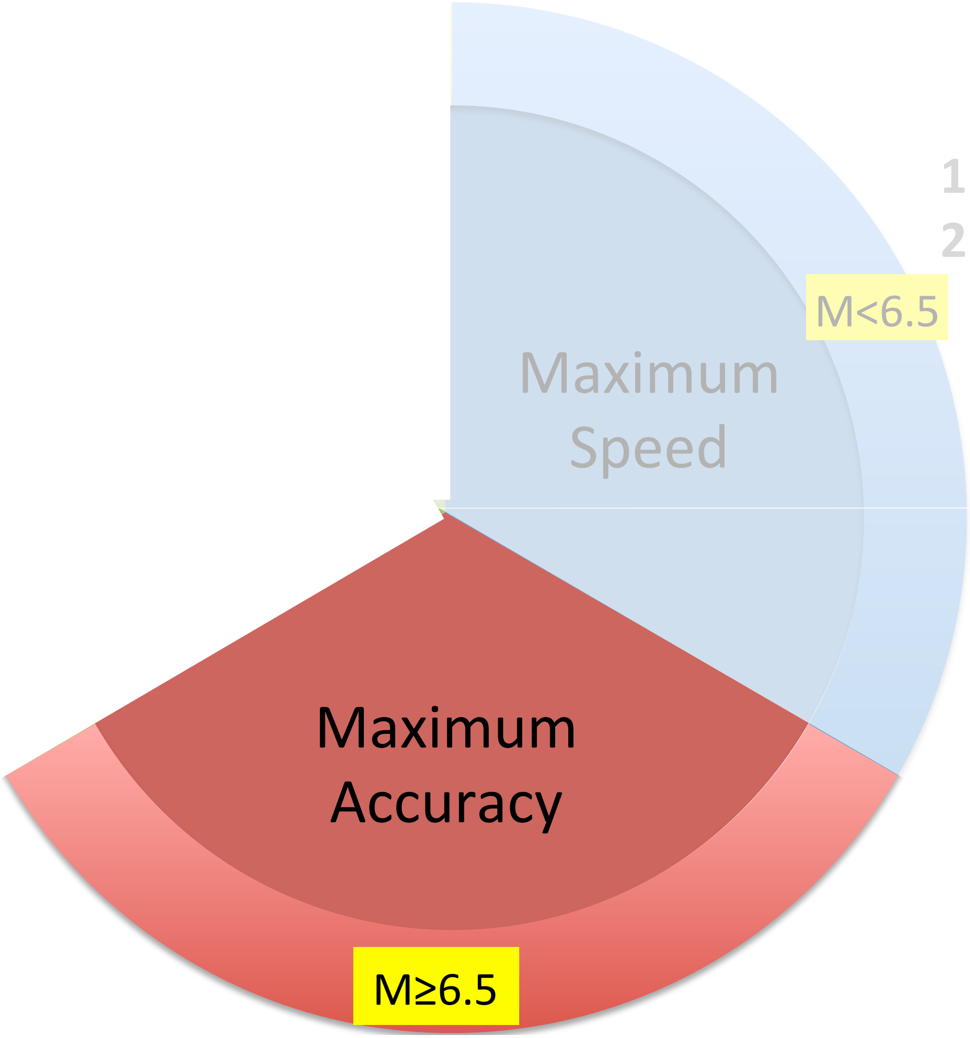
Shakemaps.org

Accuracy



1. Station density
2. Fast algorithms

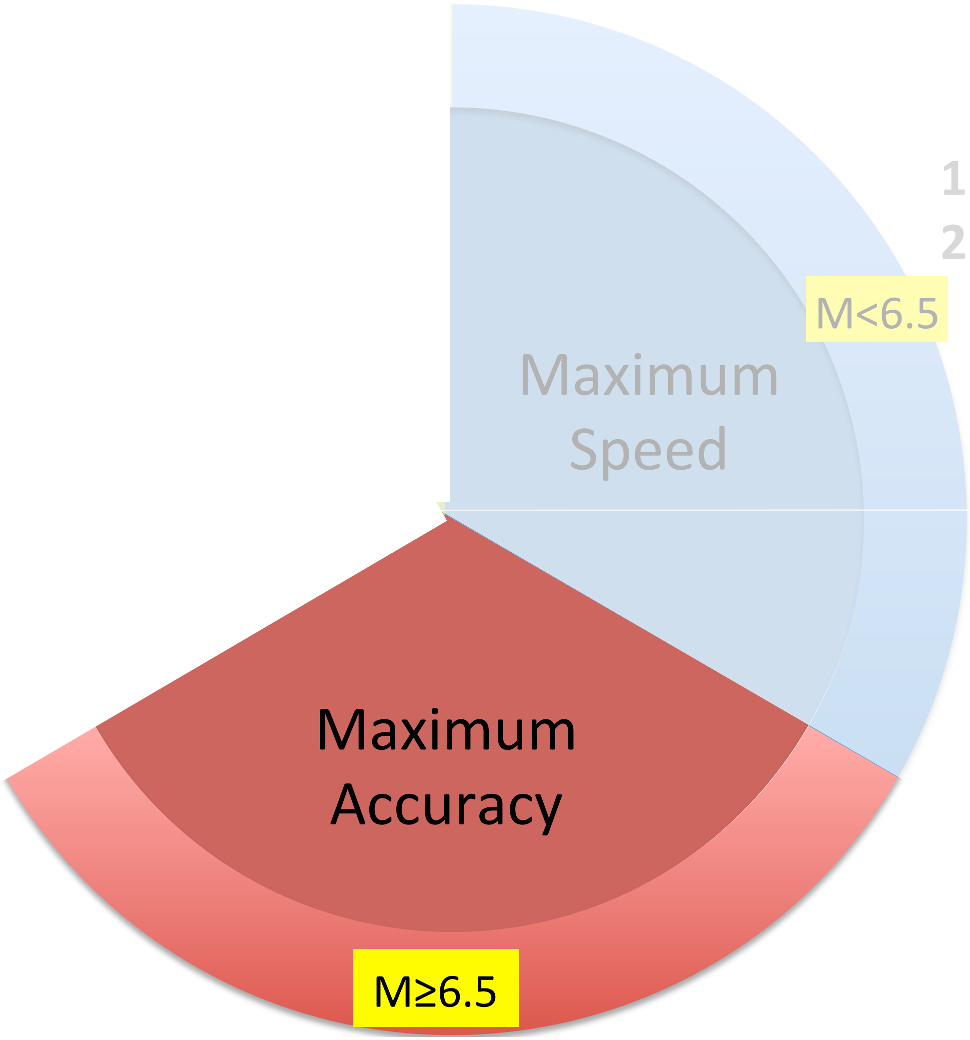
Accuracy



1. Station density
2. Fast algorithms

1. **Geodetic algorithms**

Accuracy

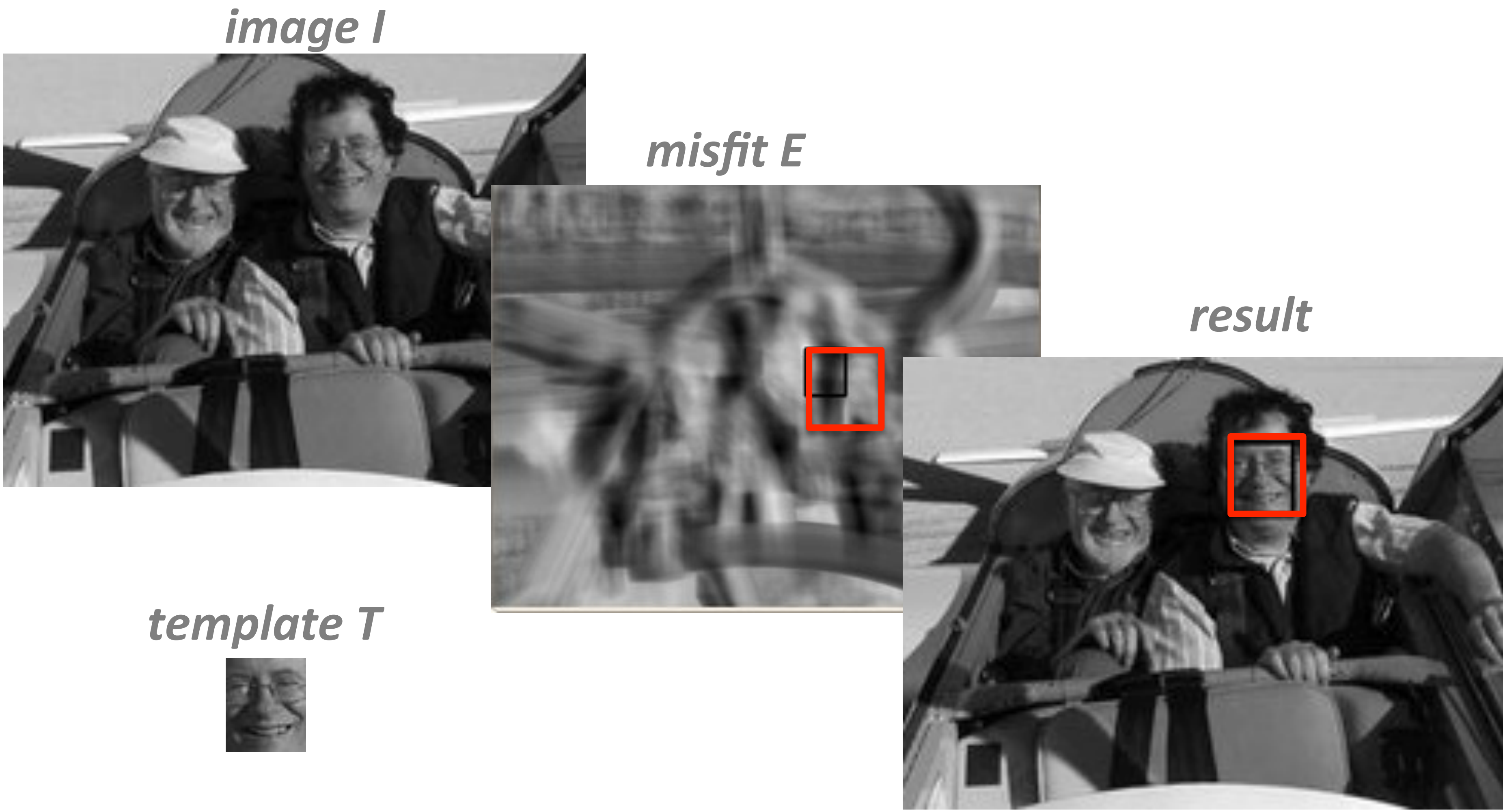


1. Station density
2. Fast algorithms

1. Geodetic algorithms
2. **Finite-fault detector**

FinDer (Finite-Fault Rupture Detector)

Template Matching

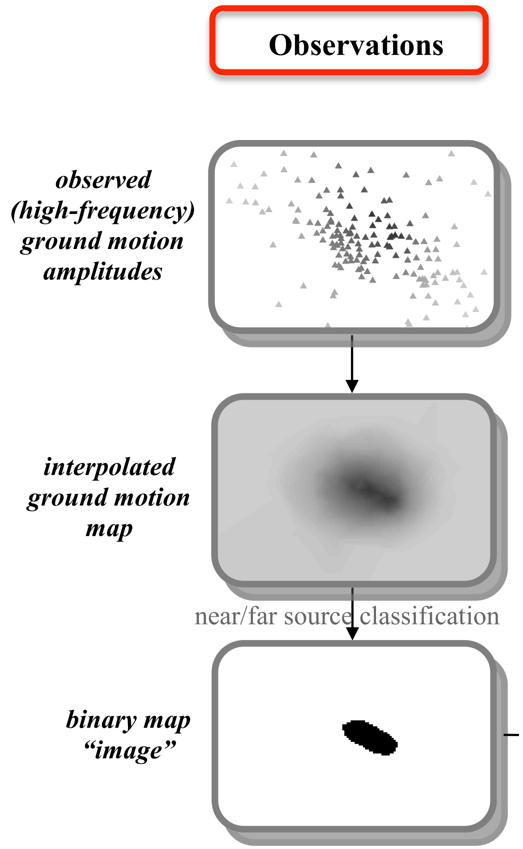


opencv.org

FinDer (Finite-Fault Rupture Detector)

… estimates rupture centroid, dimensions & orientation

(with uncertainties) from seismic real-time data



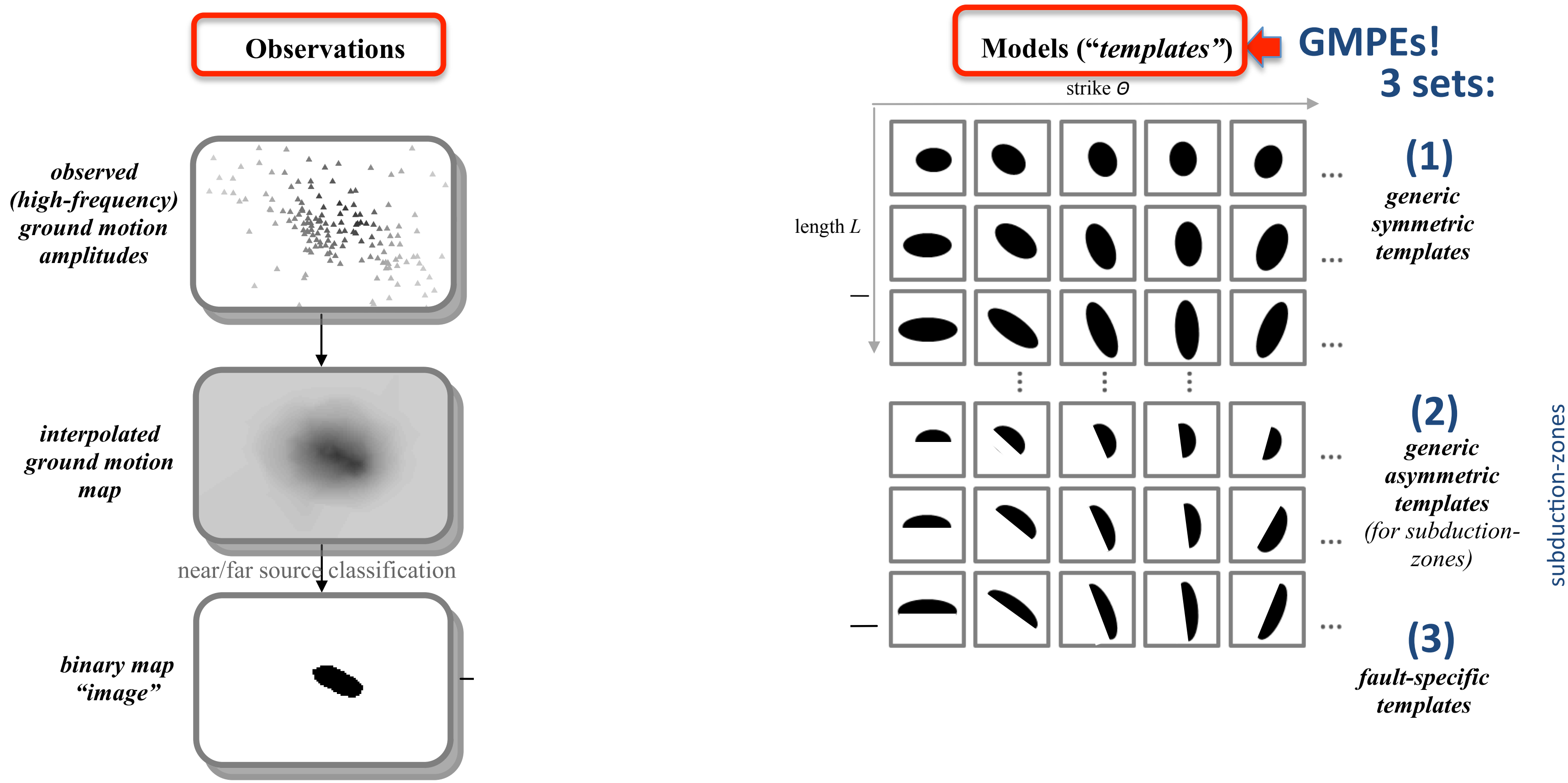
Peak Ground Acceleration (PGA):

- little directivity effects
- mainly controlled by distance to rupturing fault

Böse et al., 2012

FinDer (Finite-Fault Rupture Detector)

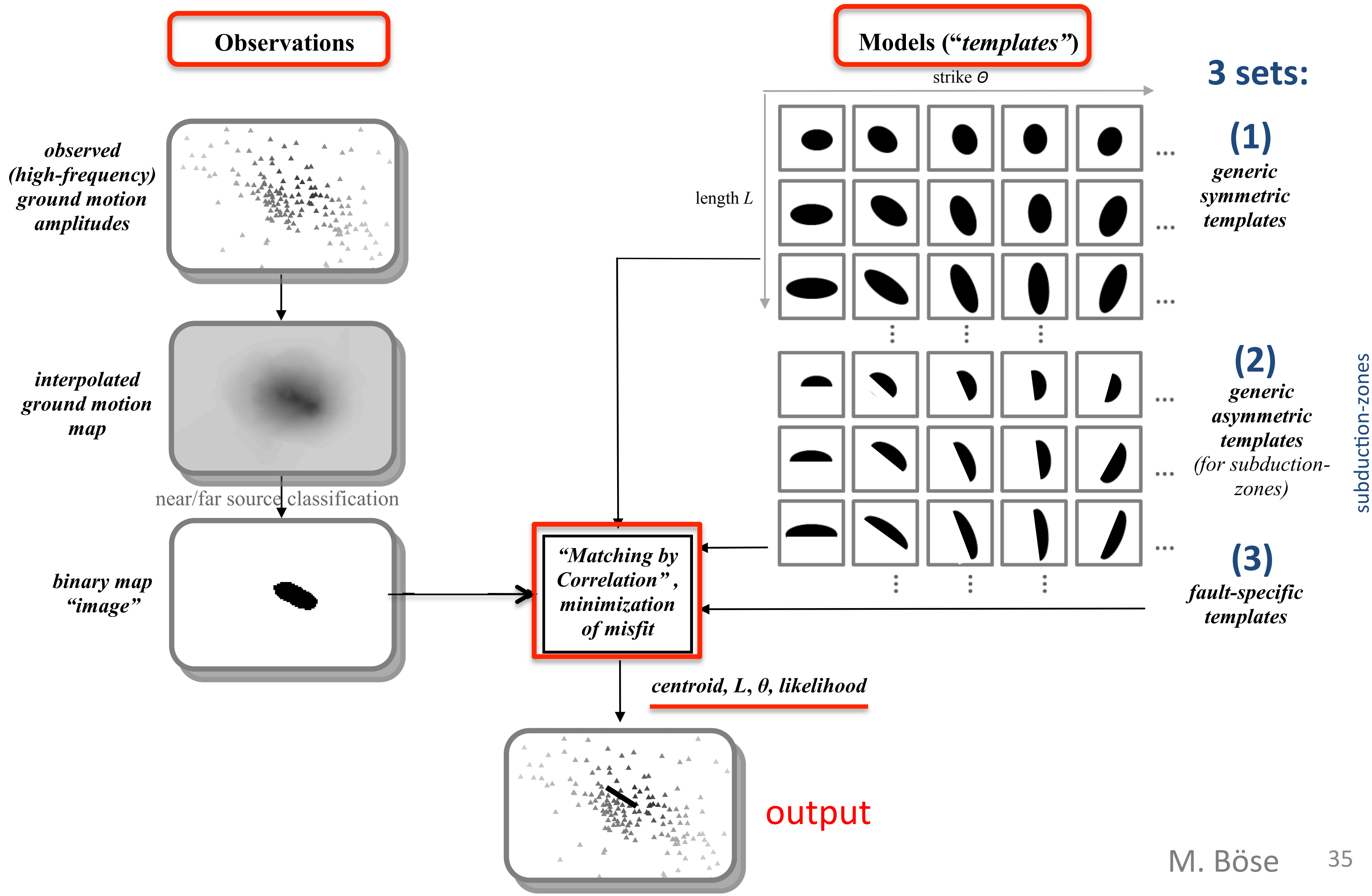
… estimates rupture centroid, dimensions & orientation



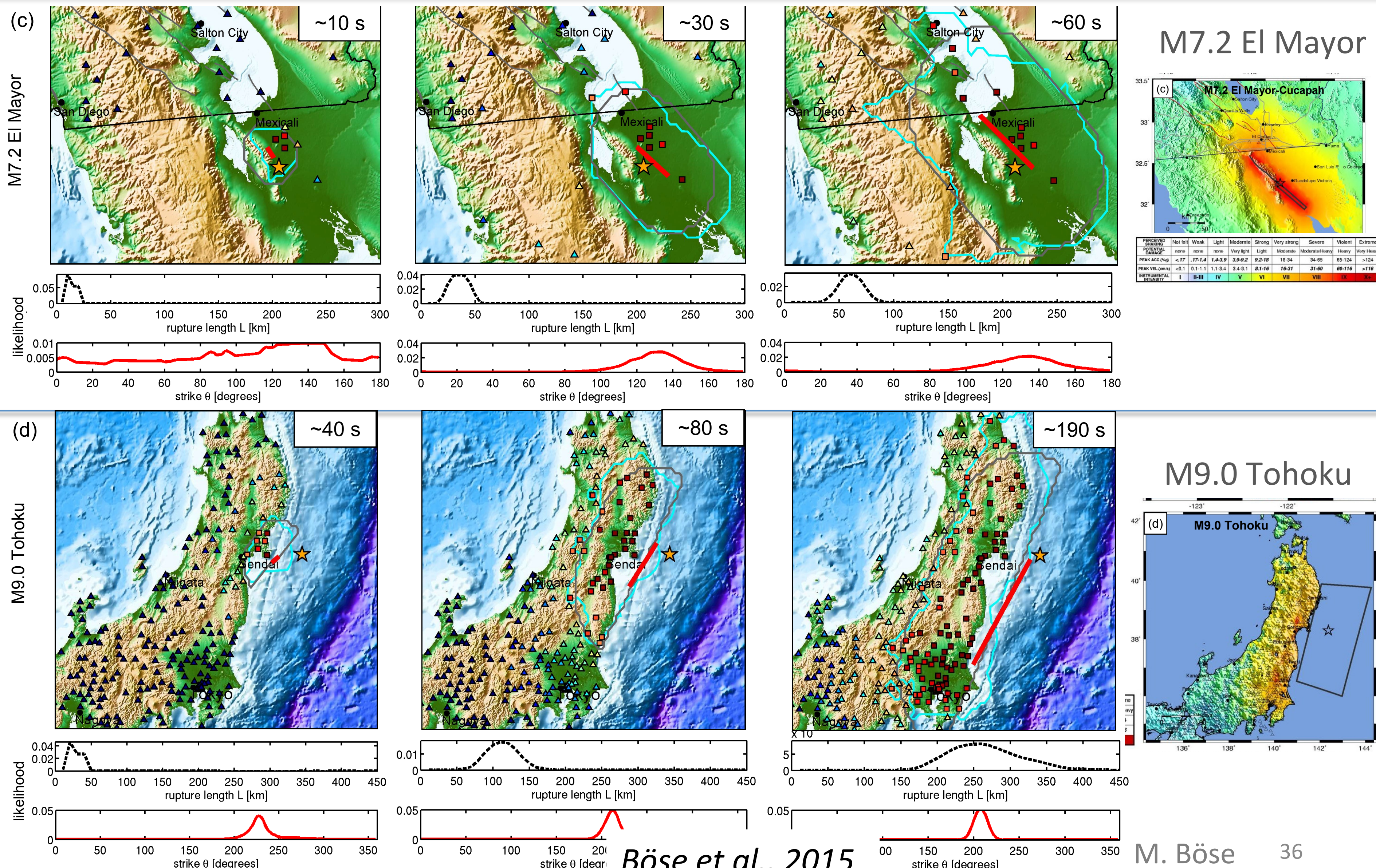
Böse et al., 2012

FinDer (Finite-Fault Rupture Detector)

… estimates rupture centroid, dimensions & orientation



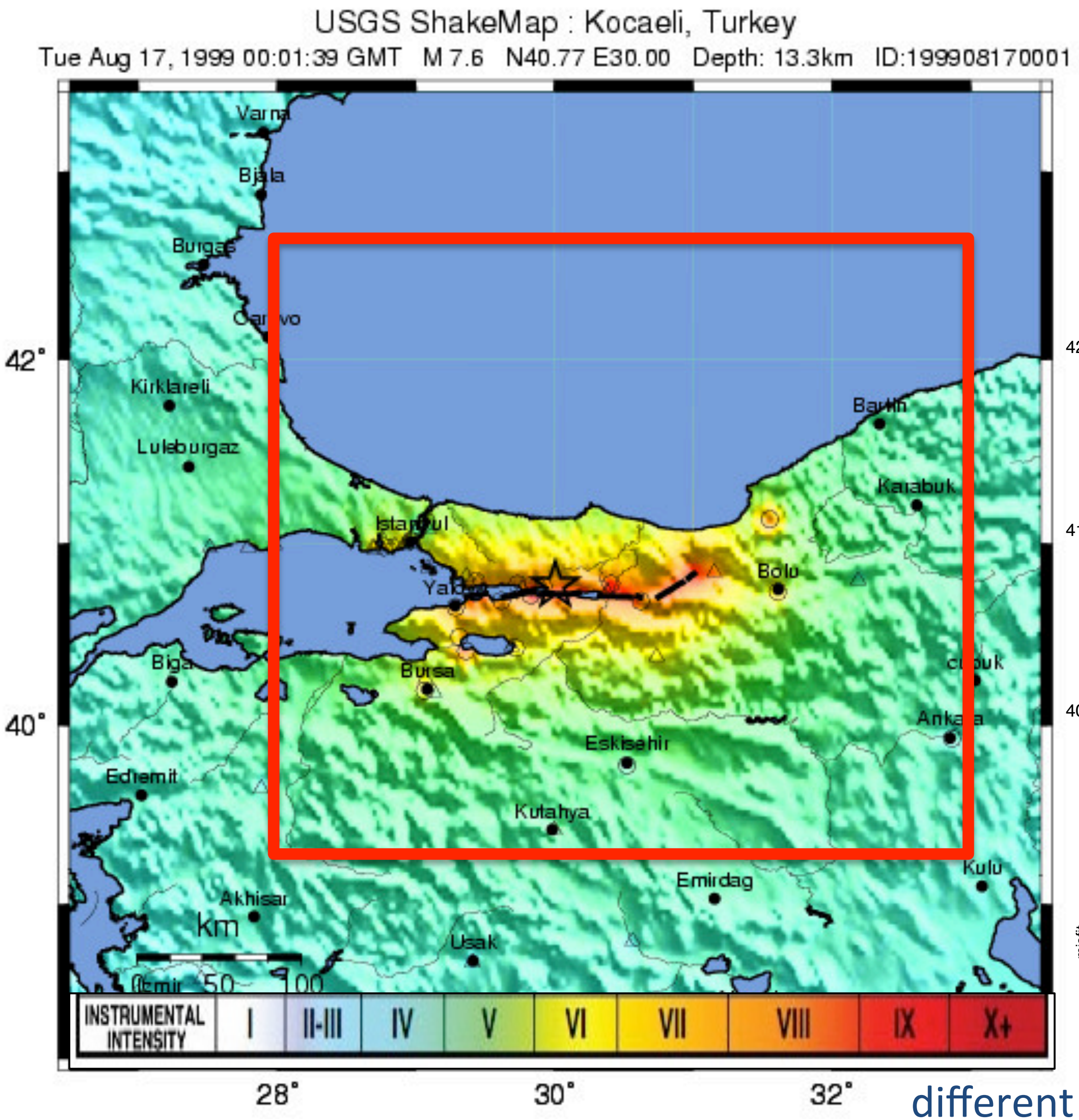
FinDer (Finite-Fault Rupture Detector)



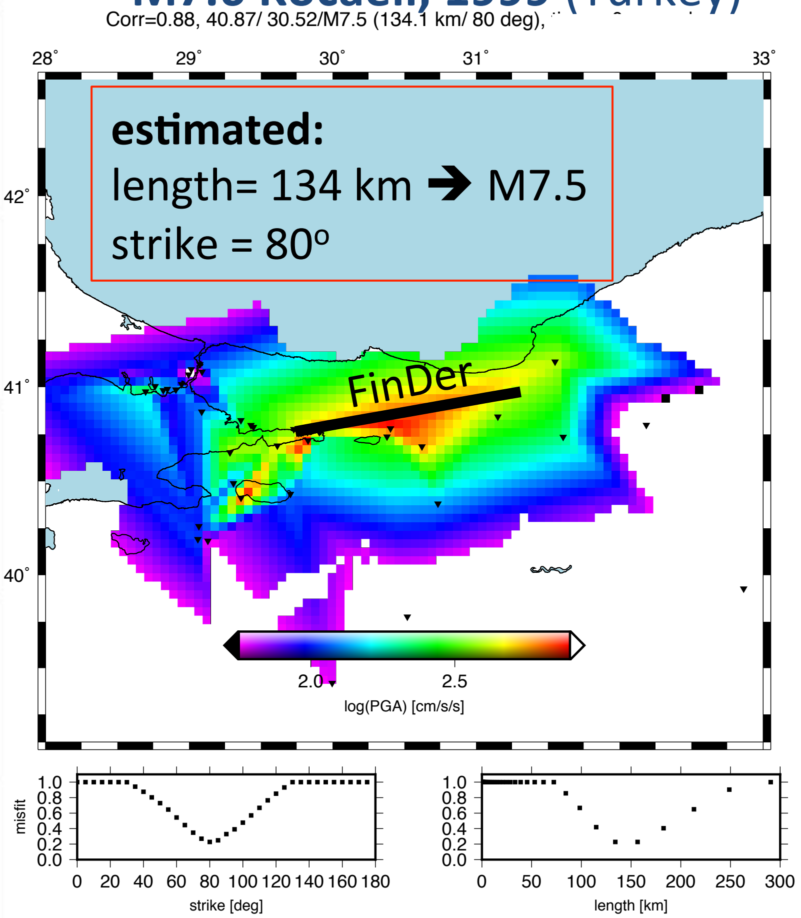
Böse et al., 2015

M. Böse

FinDer (Finite-Fault Rupture Detector)



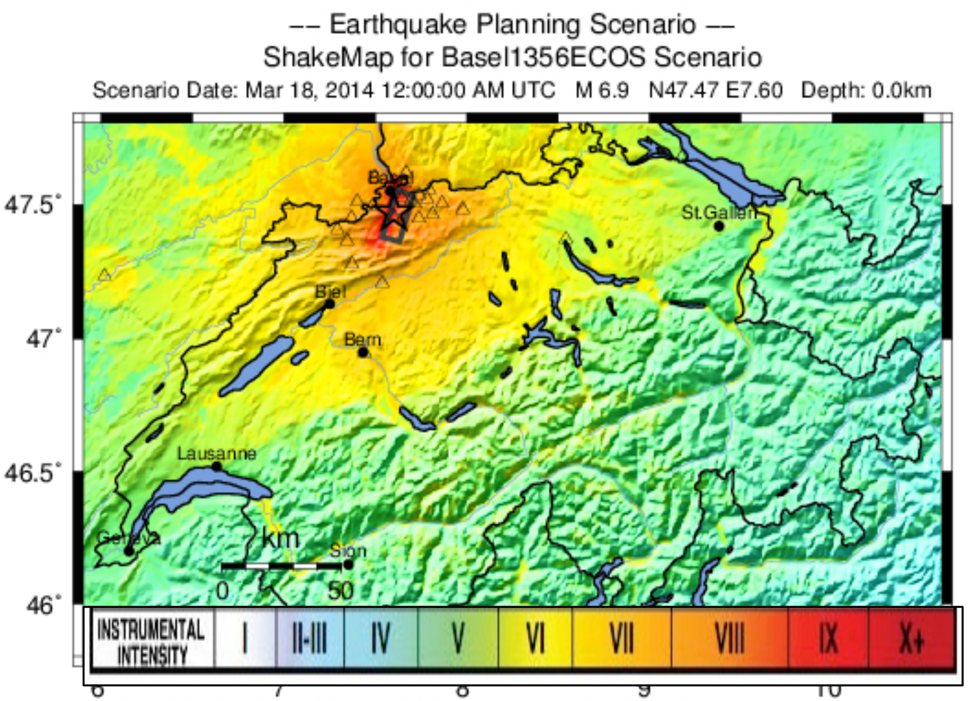
M7.6 Kocaeli, 1999 (Turkey)

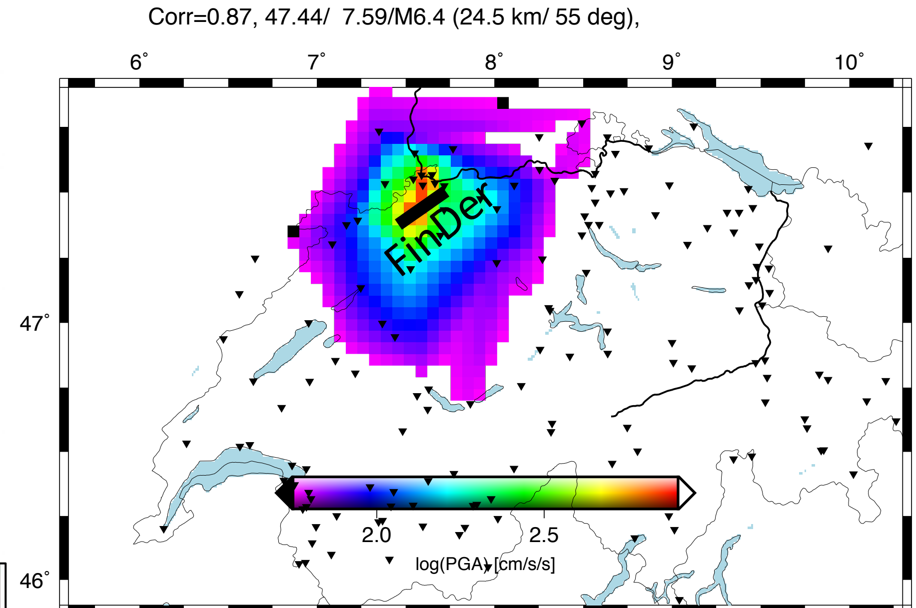


different color scales!

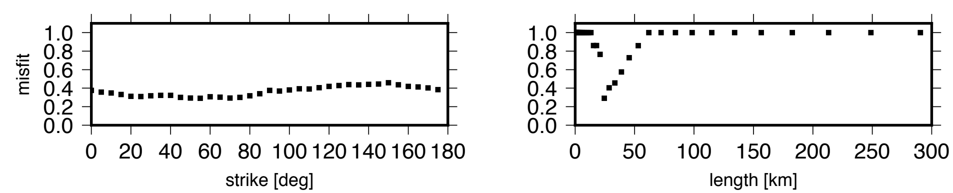
FinDer (Finite-Fault Rupture Detector)

M6.9 Basel 1356 (ECOS) Scenario (Switzerland)





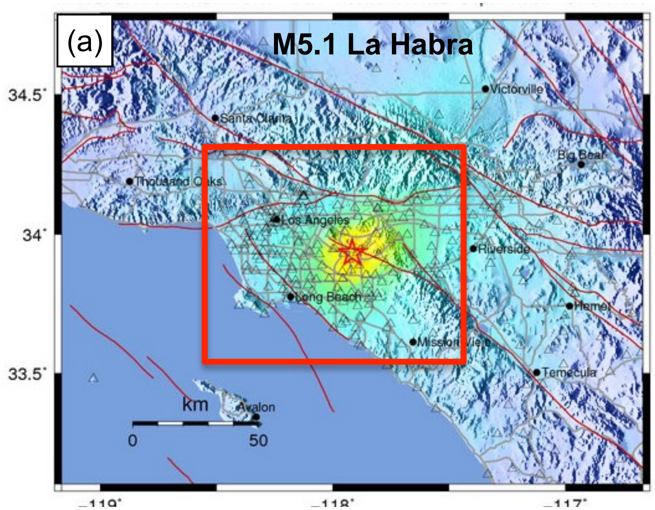
estimated:
length= 25 km ➔ M6.4
strike = 55°

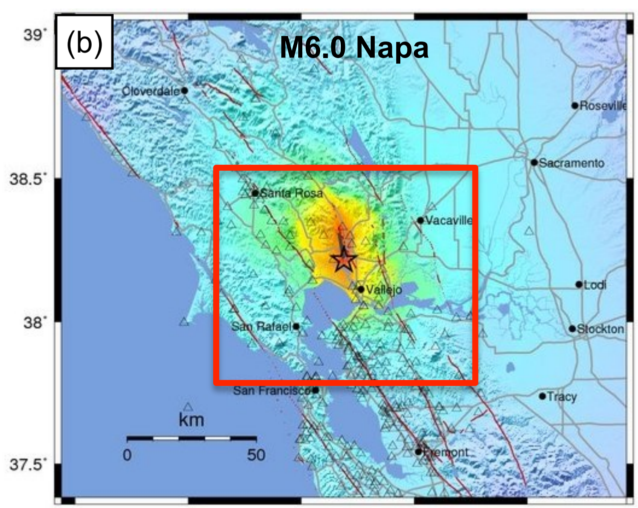


different color scales!

FinDer (Finite-Fault Rupture Detector)

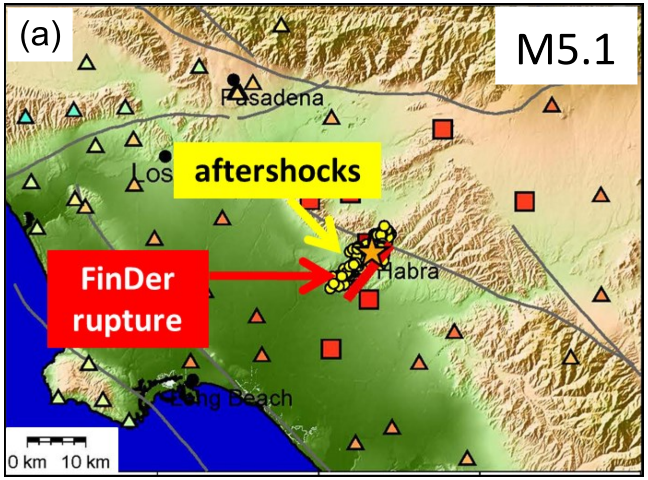
… is actively contributing to ShakeAlert since 04-2015



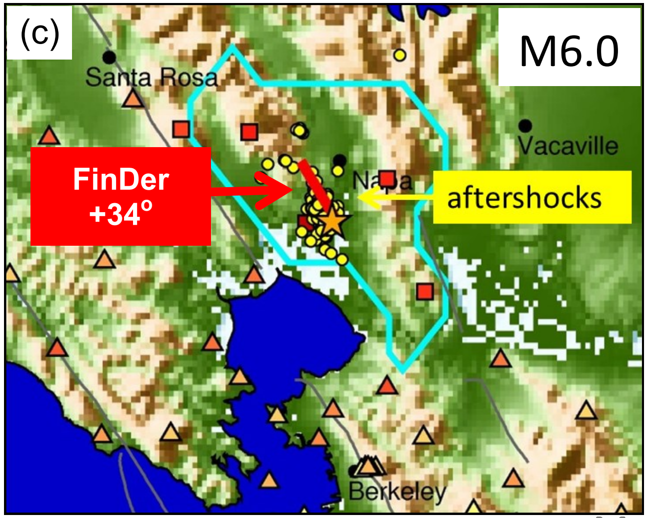


FinDer Real-Time Performance

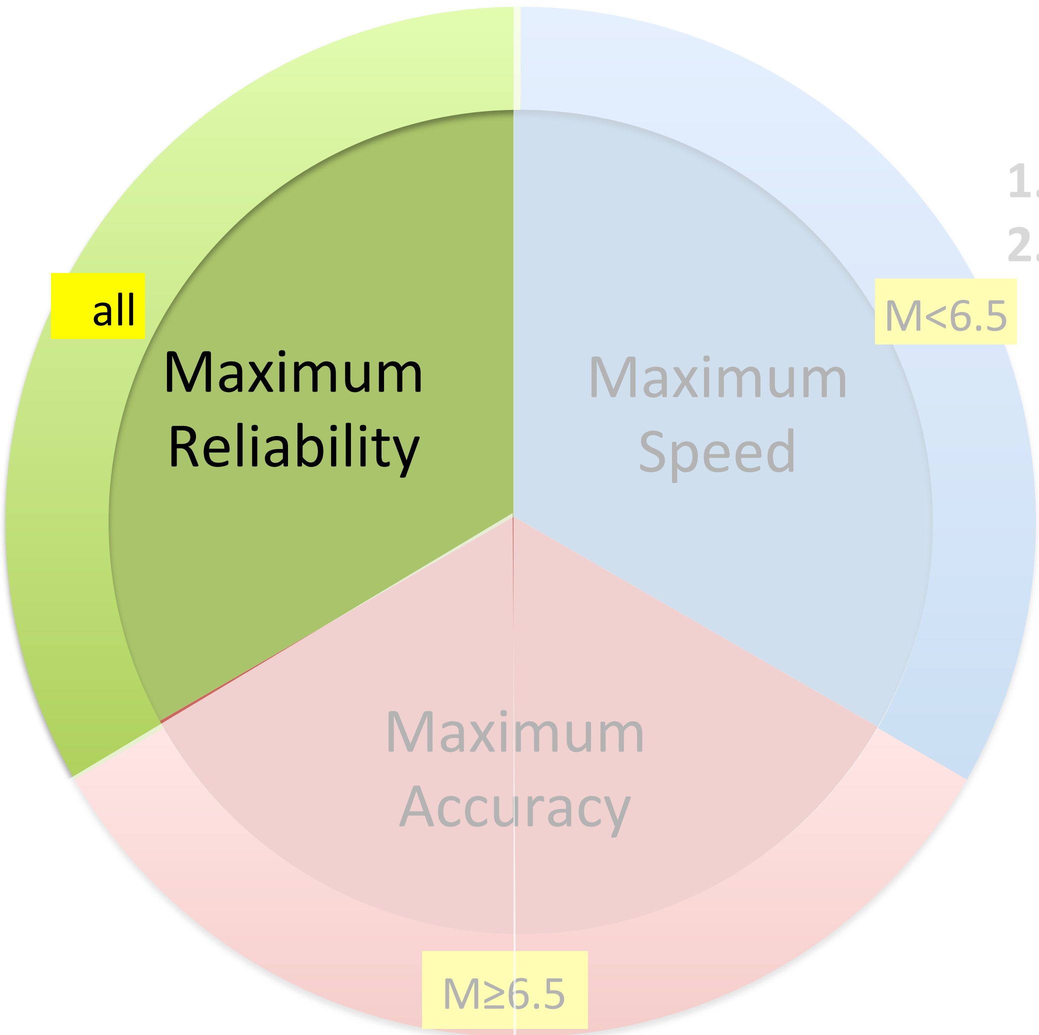
2014 M5.1 La Habra



2014 M6.0 South Napa



Böse et al., 2015



1. Station density
2. Fast algorithms

1. Geodetic algorithms
2. Finite-fault detector

Algorithms

point-source (M<6.5)

- single sensor-based
- network-based

finite-source (M≥6.5)

Data

high-quality

- seismic
- geodetic
- gravity
- …

Algorithms

point-source (M<6.5)

- single sensor-based
- network-based

finite-source (M≥6.5)

Data		Algorithms
high-quality	• seismic • geodetic • gravity • …	**point-source** (M<6.5) • single sensor-based • network-based
low-quality	• seismic • geodetic • gravity • …	**finite-source** (M≥6.5)

How to combine?

Data	Algorithms	Warning
high-quality • seismic • geodetic • gravity • …	**point-source** (M<6.5) • single sensor-based • network-based	ground-shaking
low-quality • seismic • geodetic • gravity • …	**finite-source** (M≥6.5)	

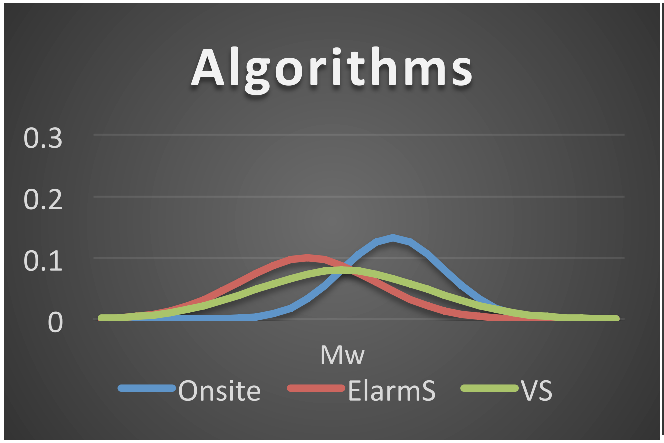
How to combine?

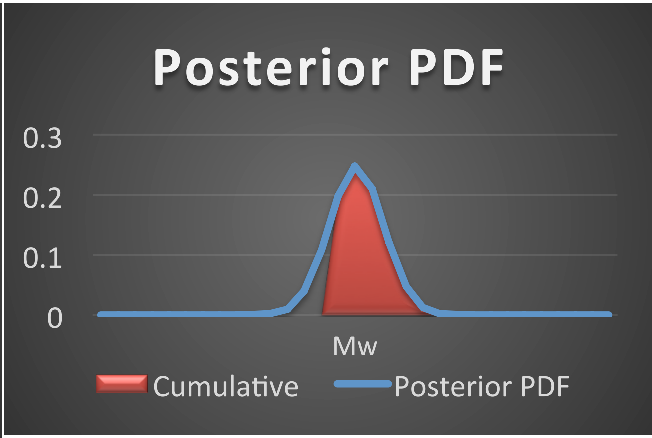
Data	Algorithms	Warning
incomplete	*optimized for event-class*	*uncertain*
high-quality: • seismic • geodetic • gravity • …	**point-source** (M<6.5) • single sensor-based • network-based	ground-shaking
low-quality: • seismic • geodetic • gravity • …	**finite-source** (M≥6.5)	

How to combine?

Data	Algorithms	Warning
incomplete	*optimized for event-class*	*uncertain*
high-quality: • seismic • geodetic • gravity • …	**point-source** (M<6.5) • single sensor-based • network-based	ground-shaking
low-quality: • seismic • geodetic • gravity • …	**finite-source** (M≥6.5)	

Probabilistic approach





How to combine?

Data	Algorithms	Warning
incomplete	*optimized for event-class*	*uncertain*
high-quality: • seismic • geodetic • gravity • …	**point-source** (M<6.5) • single sensor-based • network-based	ground-shaking
low-quality: • seismic • geodetic • gravity • …	**finite-source** (M≥6.5)	

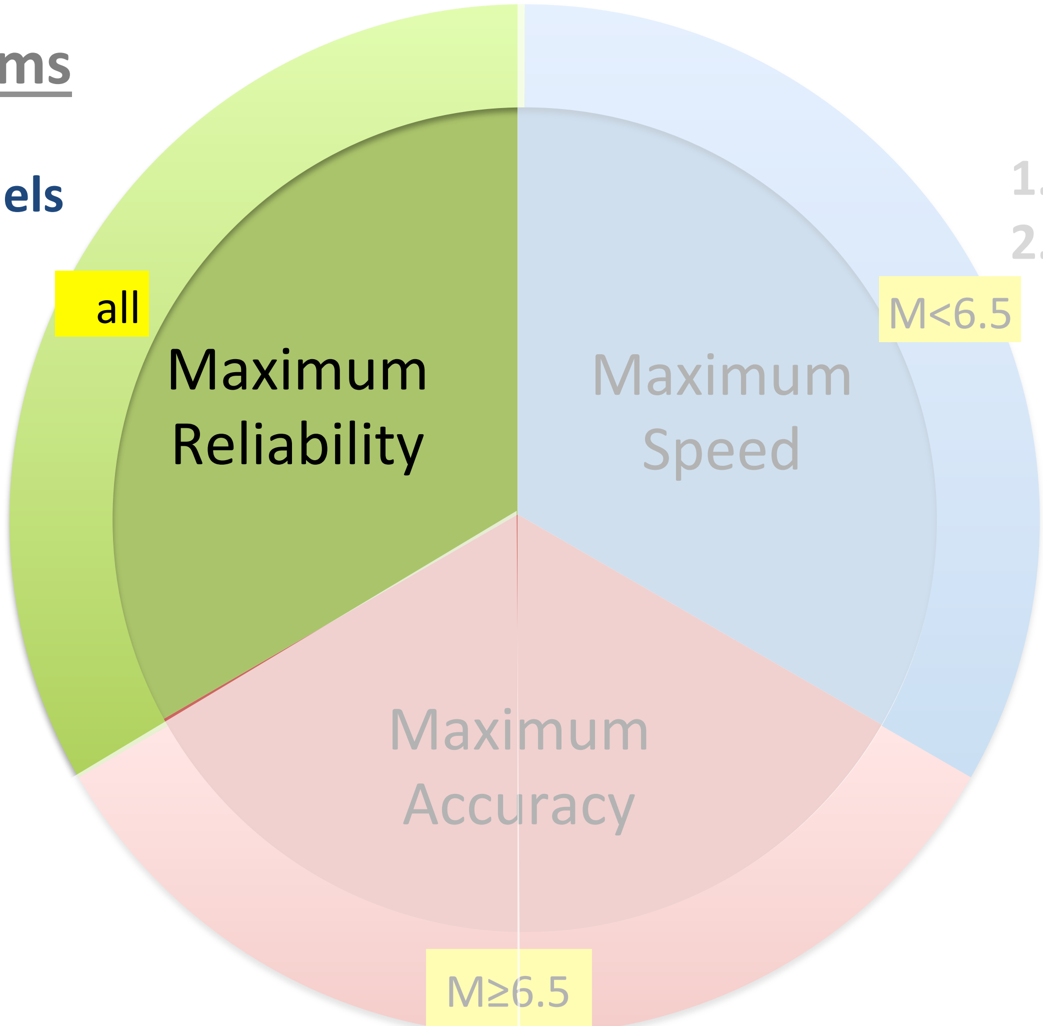
Probabilistic approach

But:
Output parameters and uncertainty estimates from various algorithms/models are usually **inconsistent**!

Combined Systems

require

1. **Consistent models**



1. Station density
2. Fast algorithms

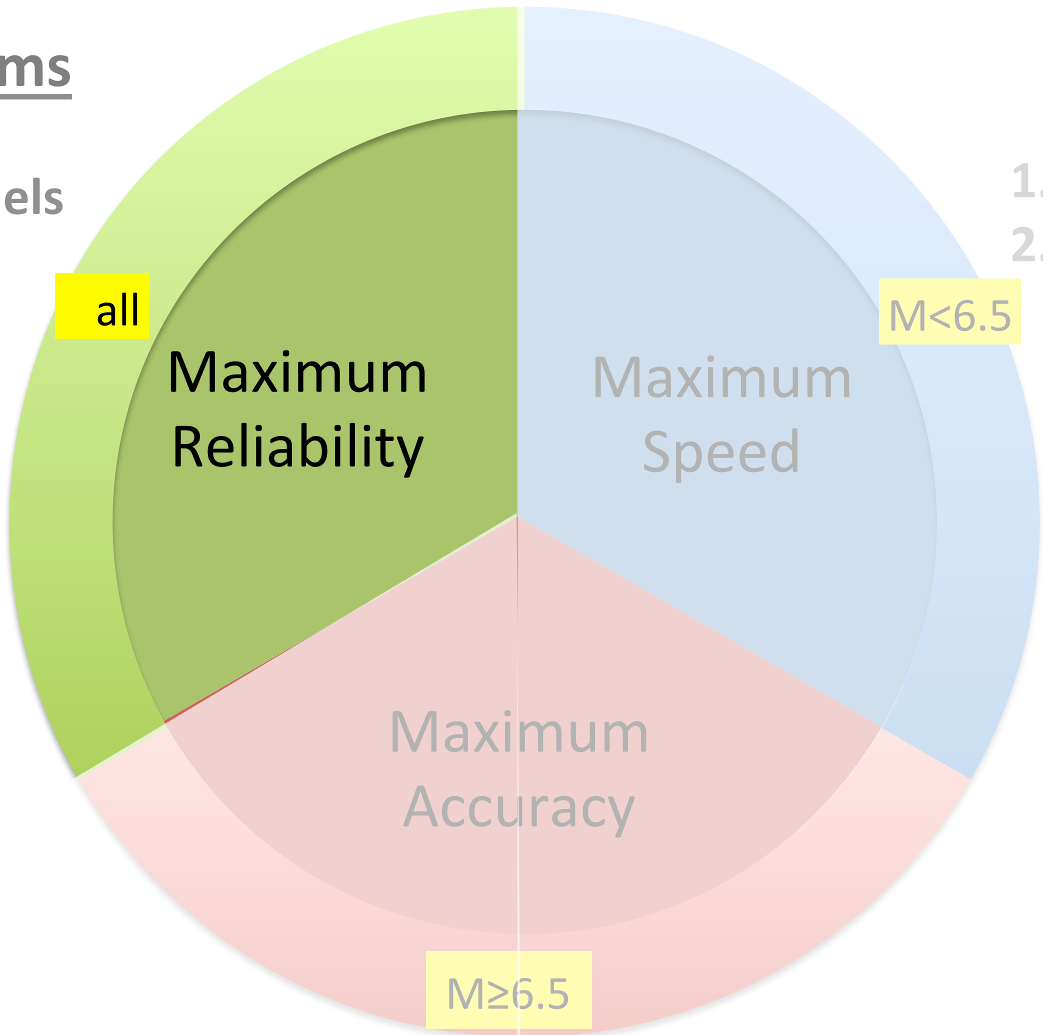
1. Geodetic algorithms
2. Finite-fault detector

<u>Combined Systems</u>

require

1. **Consistent models**

   FinDer2



1. **Station density**
2. **Fast algorithms**

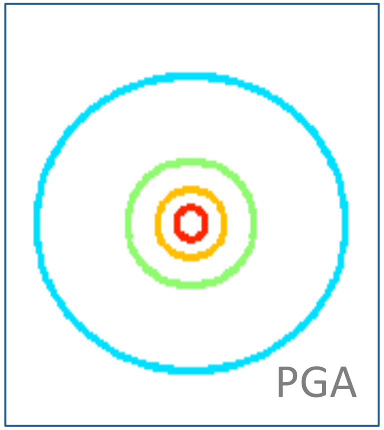
1. **Geodetic algorithms**
2. **Finite-fault detector**

1. Consistent Models

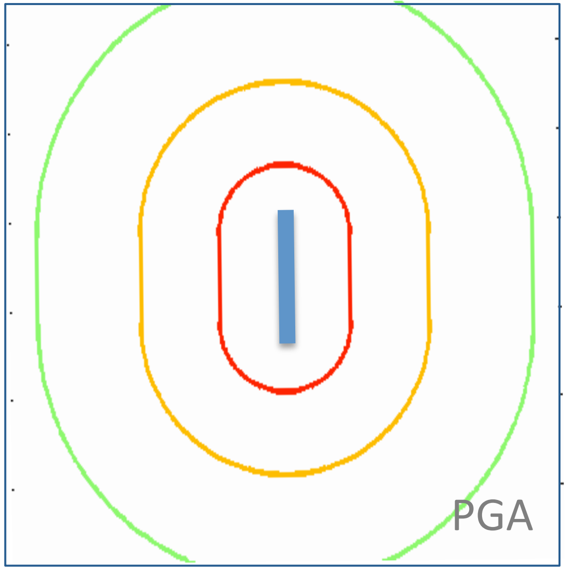
FinDer2 algorithm Böse, Smith, Heaton

- extension of FinDer (Finite-fault Rupture Detector) from finite-fault to point-source events (entire magnitude range)
- **smooth transition** from small to large event with consistent (normalized) output and misfit values

point-source template



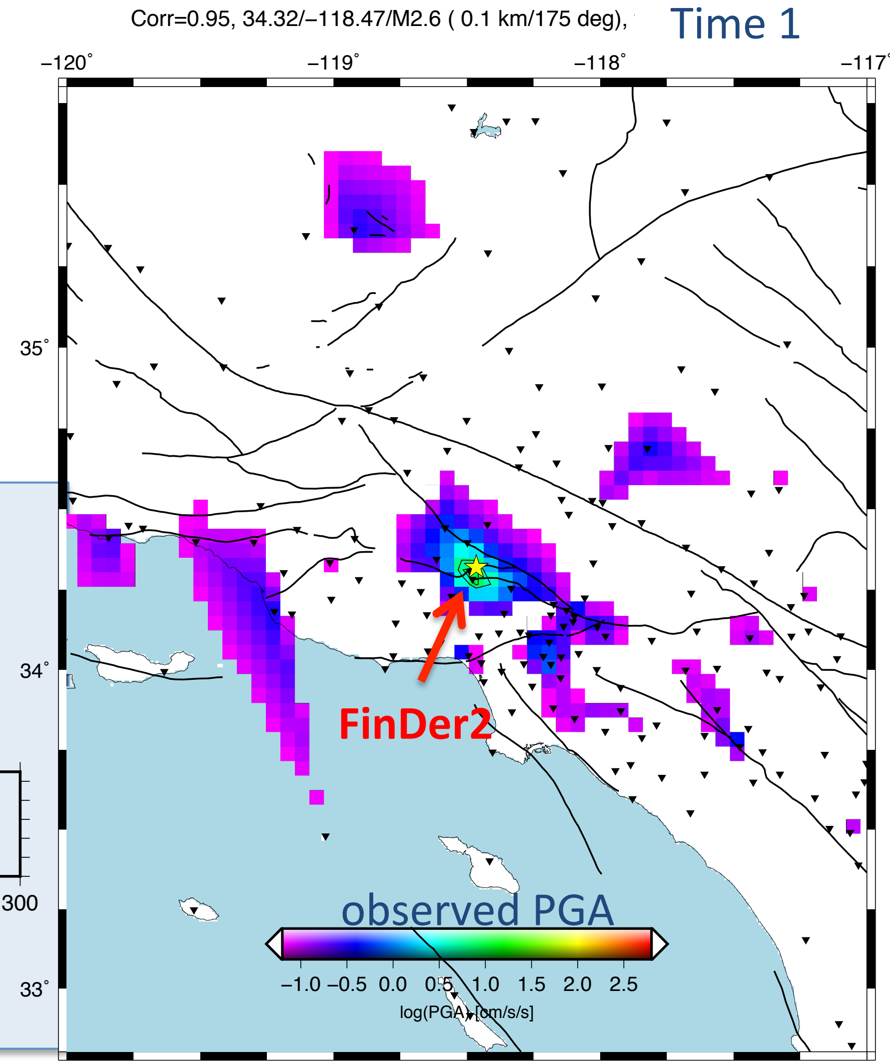
finite-source template



1. Consistent Models

FinDer2 algorithm Böse, Smith, Heaton

Time 1



M3.4 Pacoima, Southern CA

2015-11-06

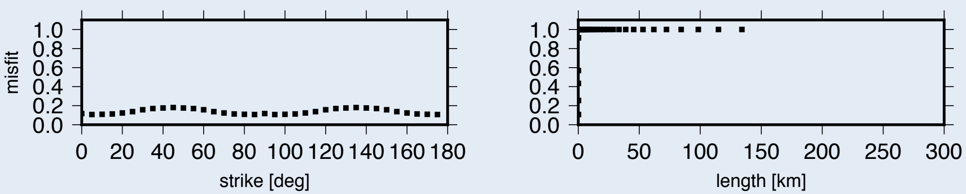
point-source

FinDer2:

R = 0.95 (correlation with best template)

M_{est}2.6

Misfit values for strike and length:



1. Consistent Models

FinDer2 algorithm Böse, Smith, Heaton

M3.4 Pacoima, Southern CA

2015-11-06

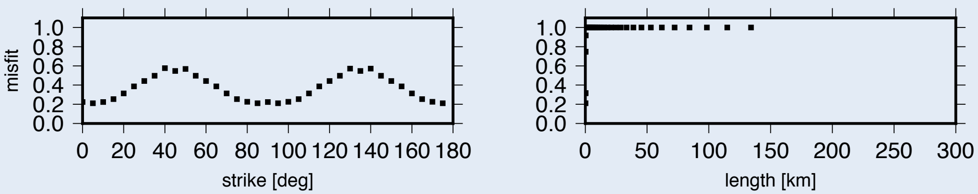
point-source

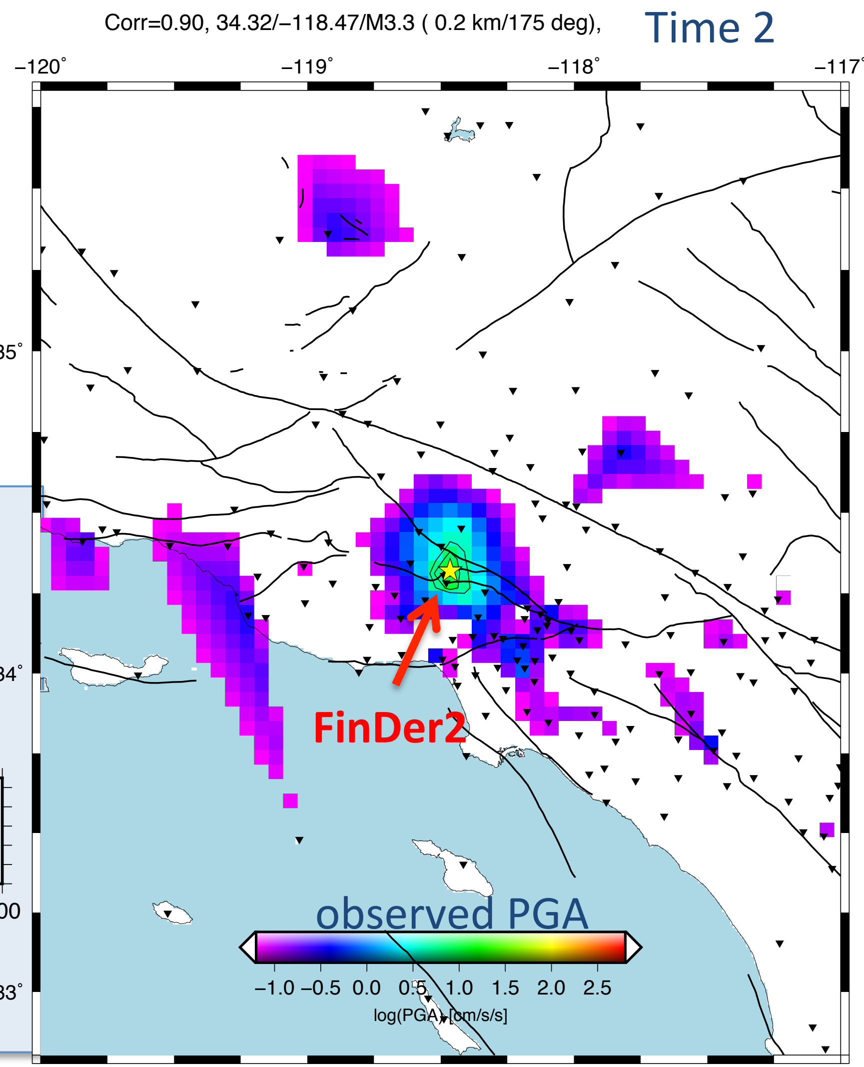
FinDer2:

R = 0.90 (correlation with best template)

M_{est}3.3

Misfit values for strike and length:





1. Consistent Models

FinDer2 algorithm Böse, Smith, Heaton

M3.4 Pacoima, Southern CA

2015-11-06

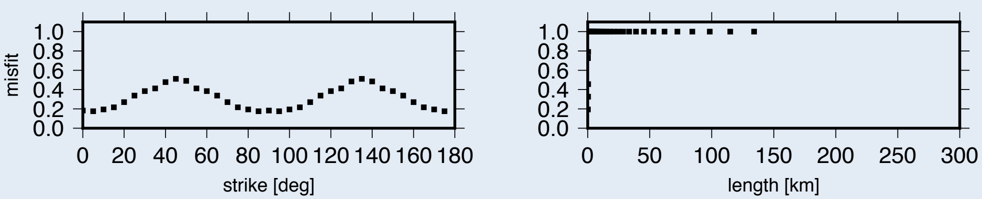
point-source

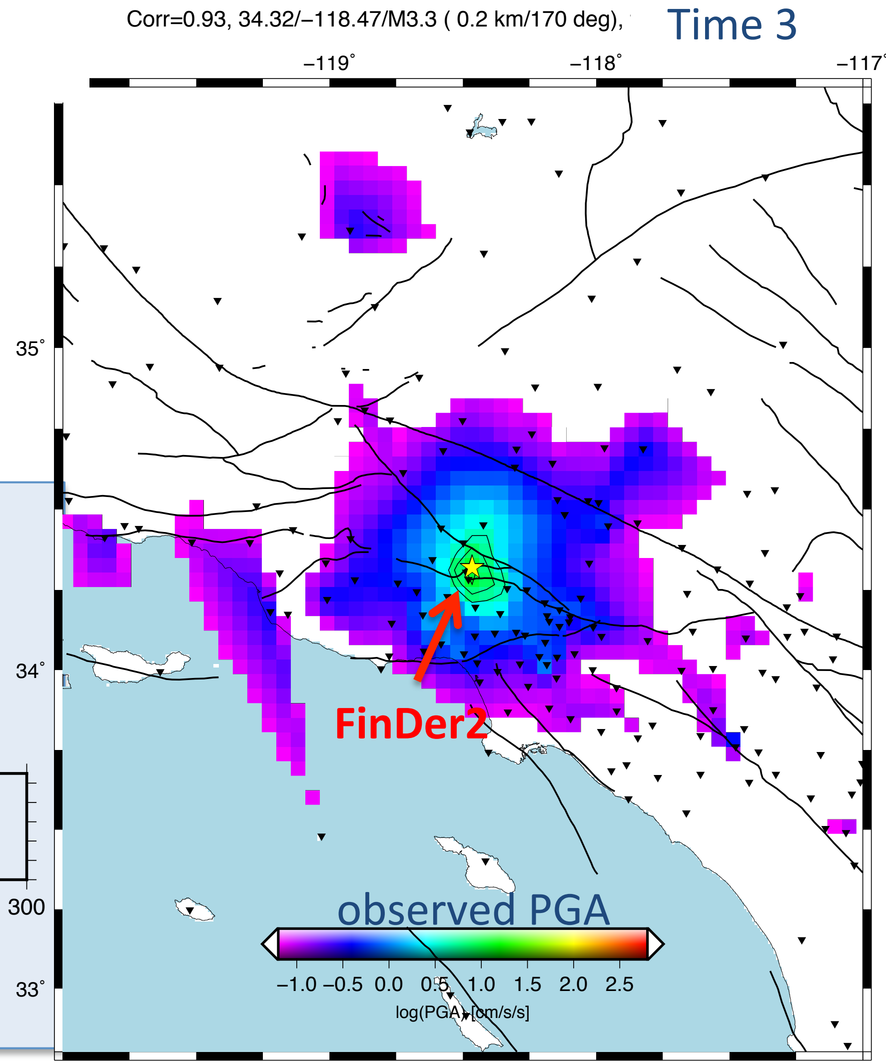
FinDer2:

R = 0.93 (correlation with best template)

M_{est}3.3

Misfit values for strike and length:



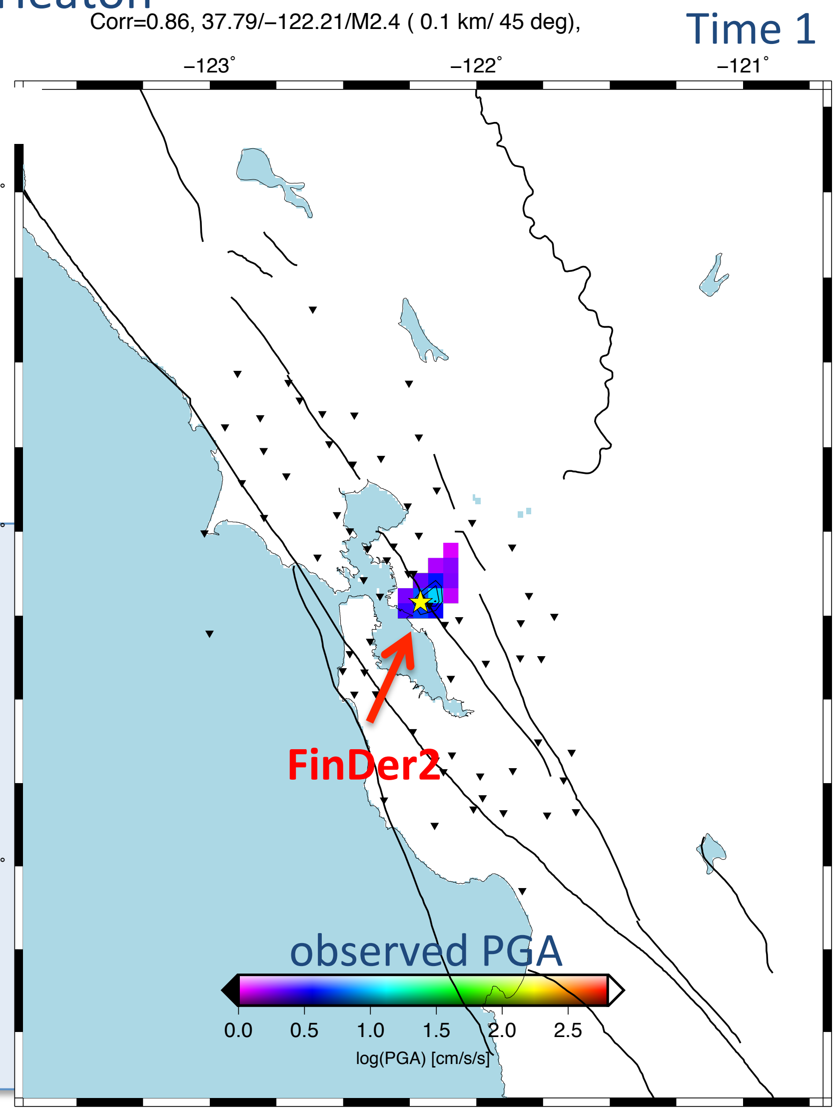


1. Consistent Models

FinDer2 algorithm Böse, Smith, Heaton

M7.1 Hayward Scenario, Northern CA

point-source

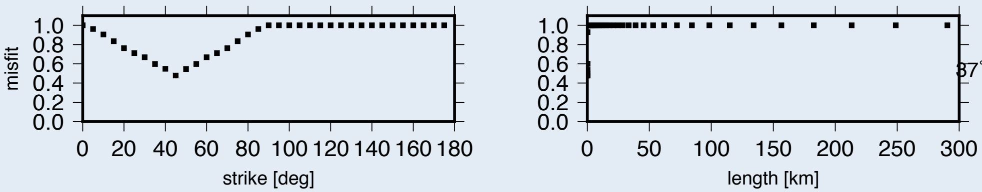


FinDer2:

R = 0.86 (correlation with best template)

M_{est}2.4

Misfit values for strike and length:



1. Consistent Models

FinDer2 algorithm Böse, Smith, Heaton

M7.1 Hayward Scenario, Northern CA

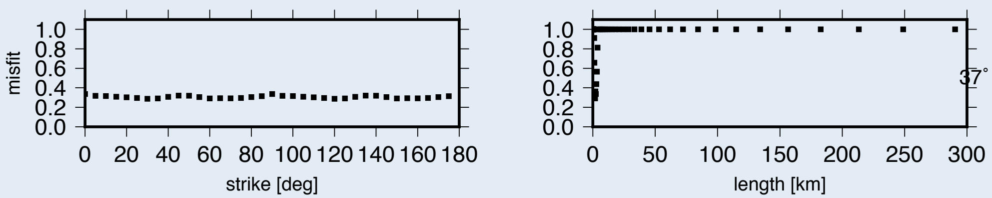
point-source

FinDer2:

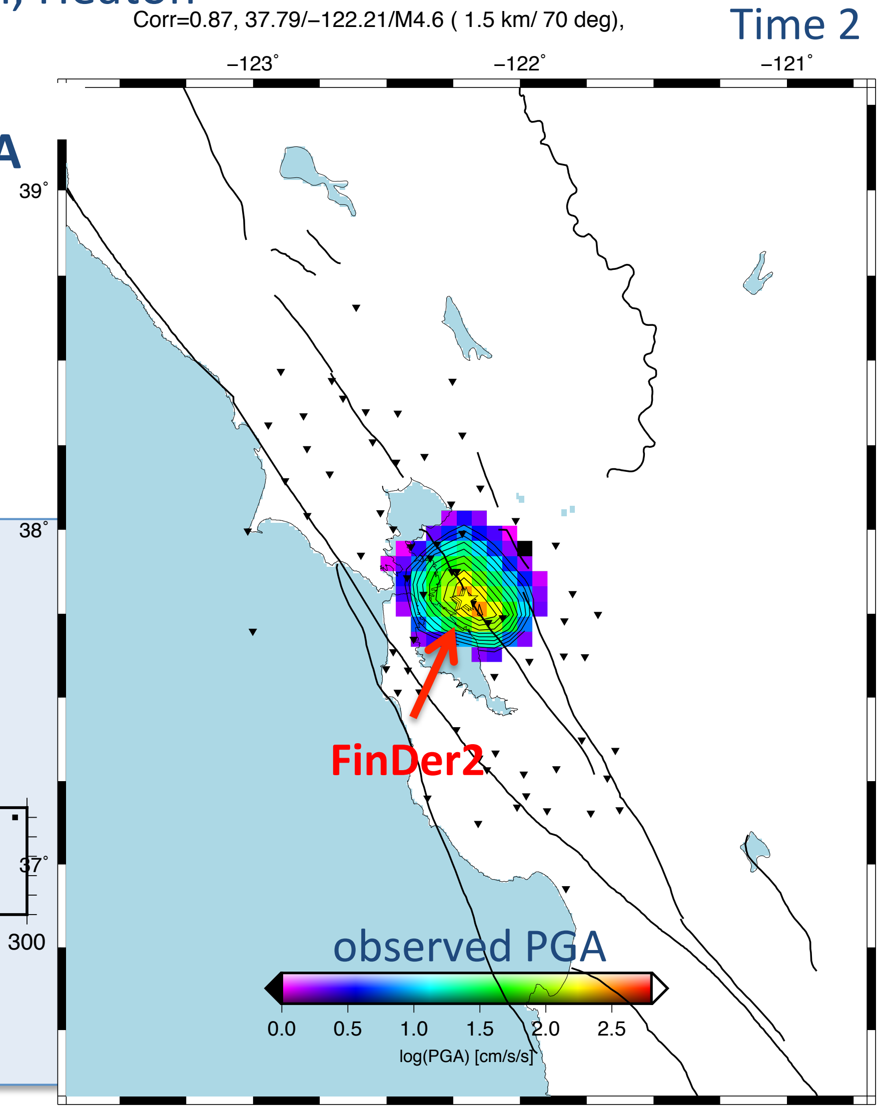
R = 0.87 (correlation with best template)

M_{est}4.6

Misfit values for strike and length:



Time 2



1. Consistent Models

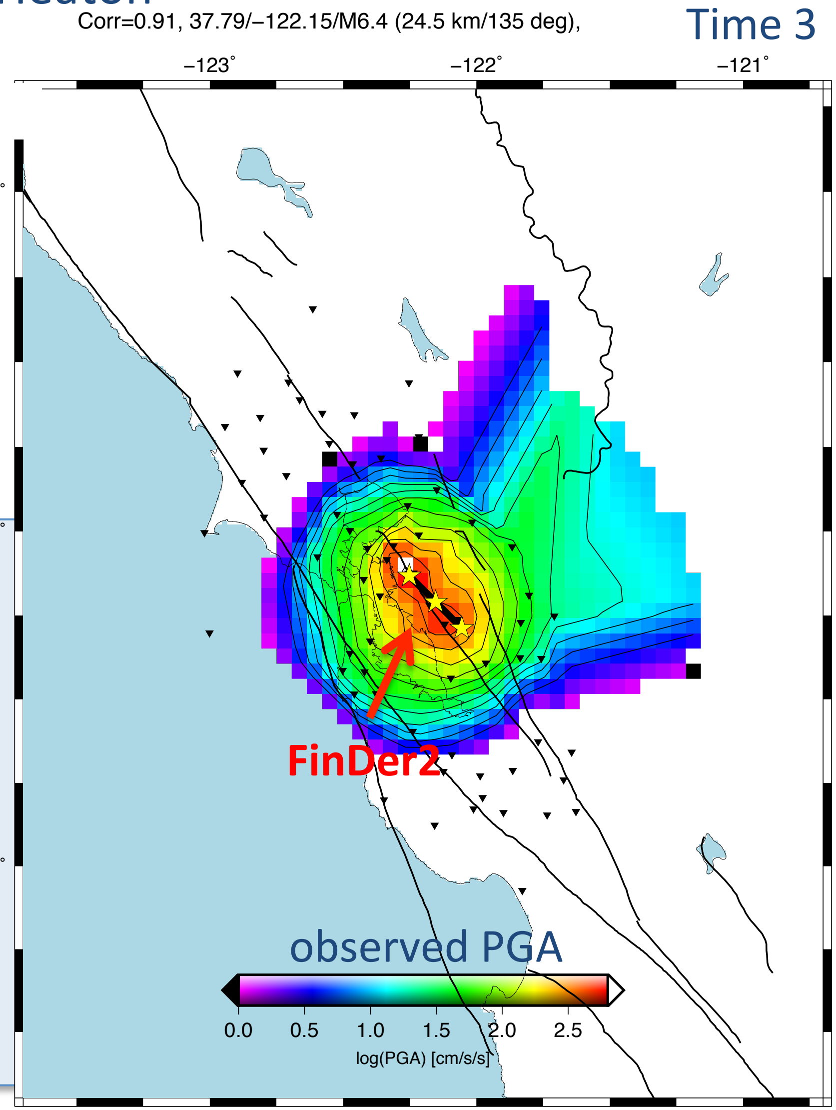
FinDer2 algorithm Böse, Smith, Heaton

M7.1 Hayward Scenario, Northern CA

finite-source

smooth transition!!!

Time 3

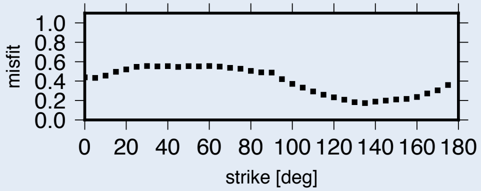


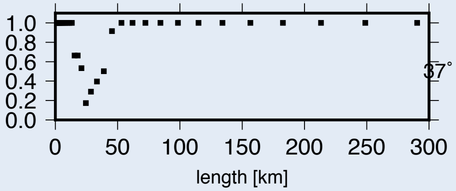
FinDer2:

R = 0.91 (correlation with best template)

M_{est}6.4

Misfit values for strike and length:





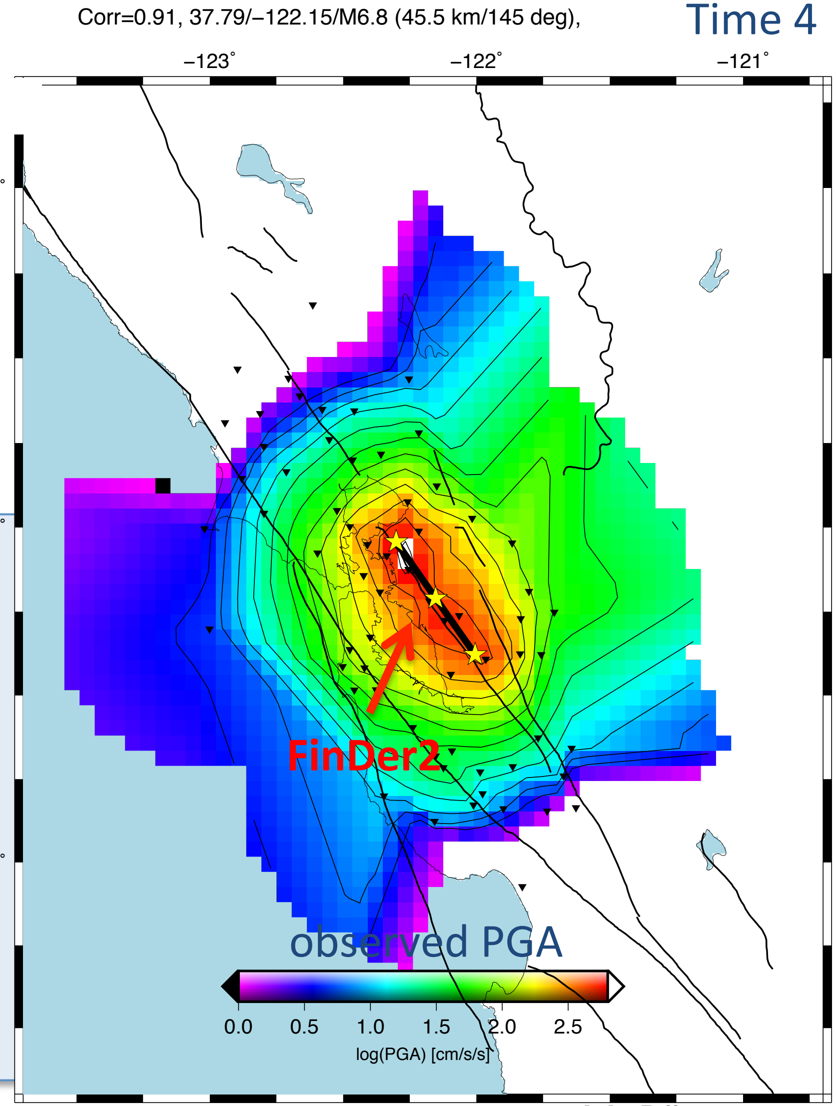
1. Consistent Models

FinDer2 algorithm Böse, Smith, Heaton

Time 4

M7.1 Hayward Scenario, Northern CA

finite-source

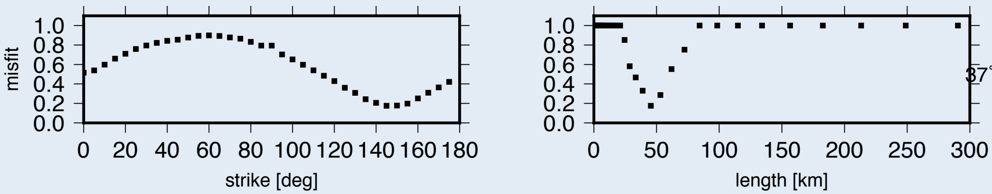


FinDer2:

R = 0.91 (correlation with best template)

M_{est} 6.8

Misfit values for strike and length:



1. Consistent Models

FinDer2 algorithm Böse, Smith, Heaton

M7.1 Hayward Scenario, Northern CA

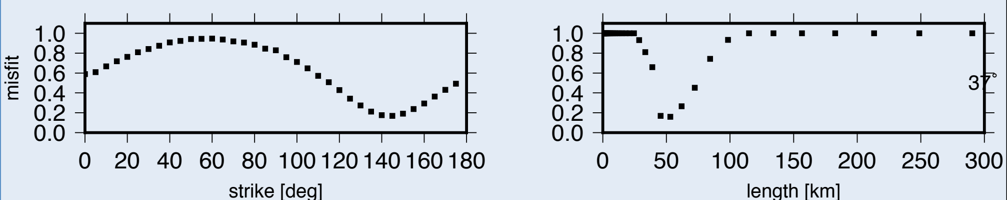
finite-source

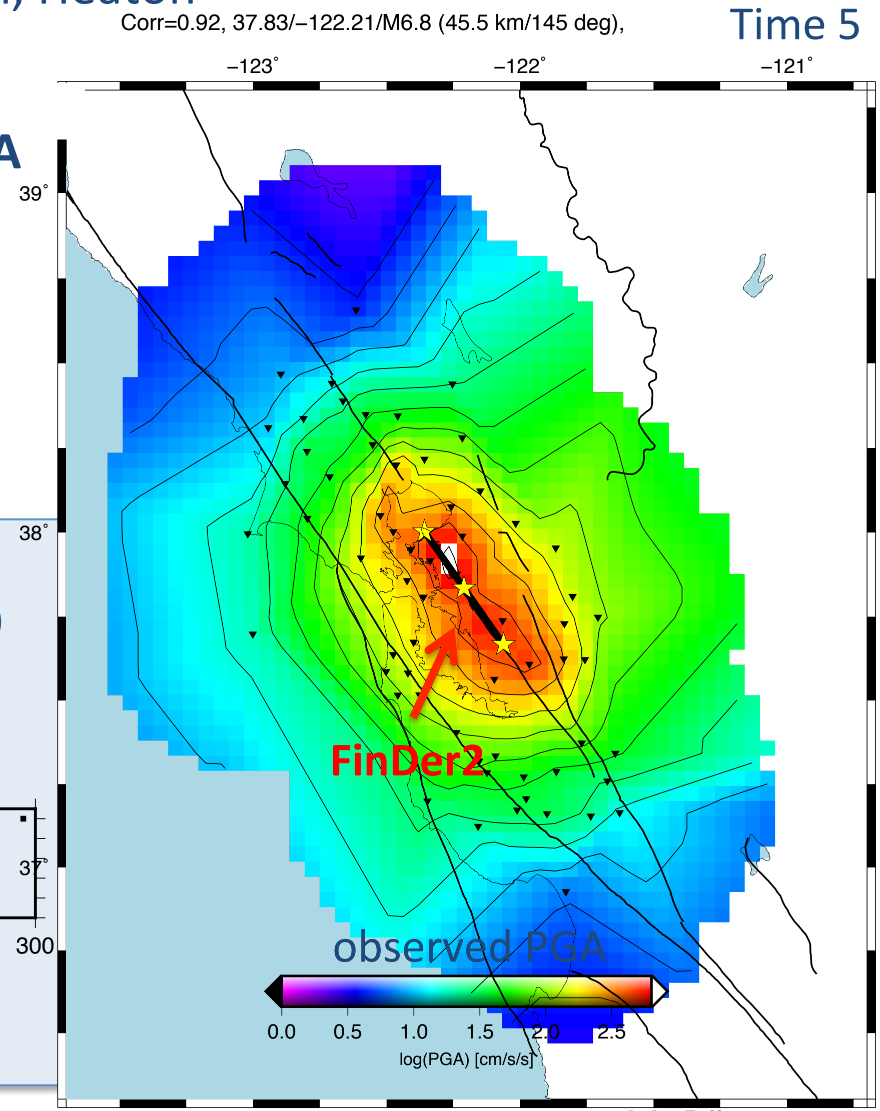
FinDer2:

R = 0.92 (correlation with best template)

M_{est} 6.8

Misfit values for strike and length:





1. Consistent Models

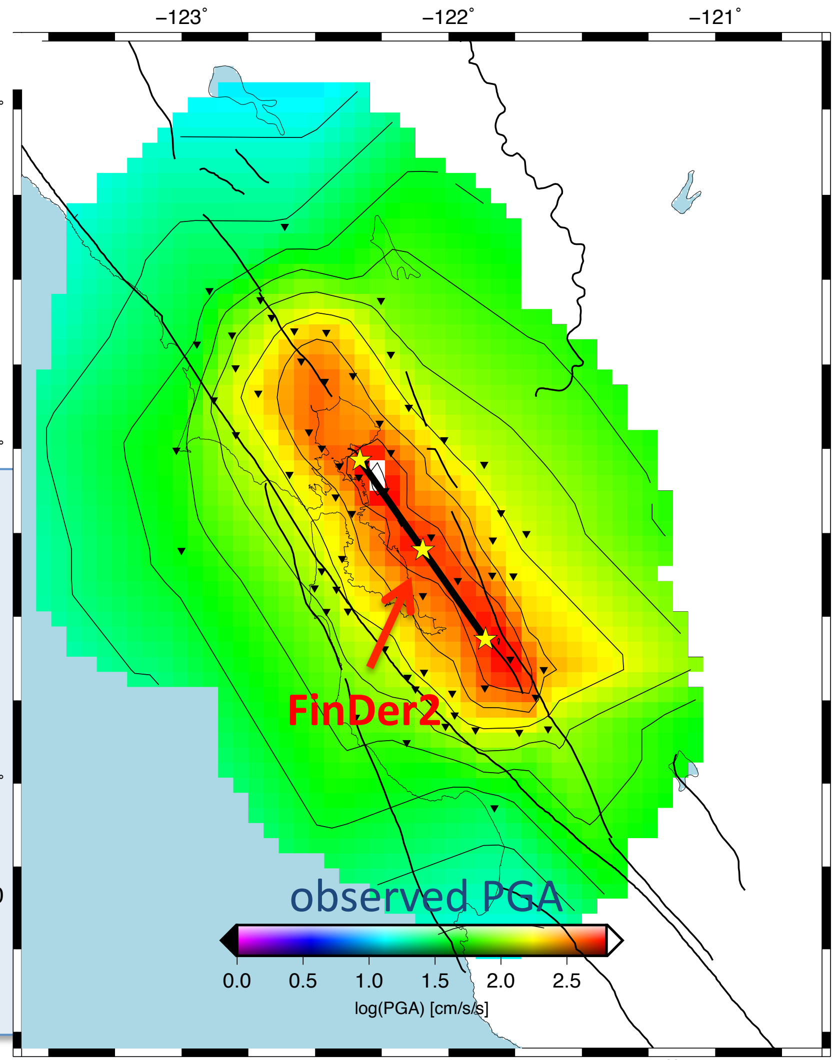
FinDer2 algorithm Böse, Smith, Heaton

M7.1 Hayward Scenario, Northern CA

finite-source

Corr=0.89, 37.70/–122.10/M7.1 (72.3 km/145 deg),

Time 6

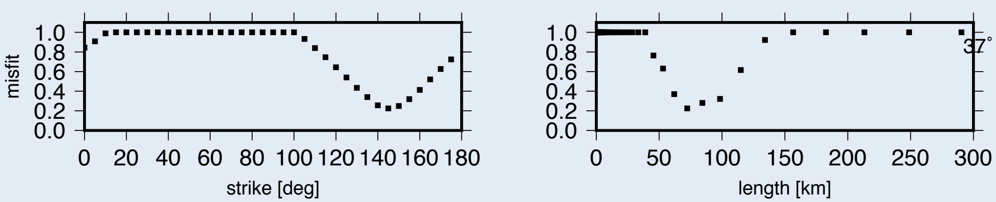


FinDer2:

R = 0.89 (correlation with best template)

M_{est} 7.1

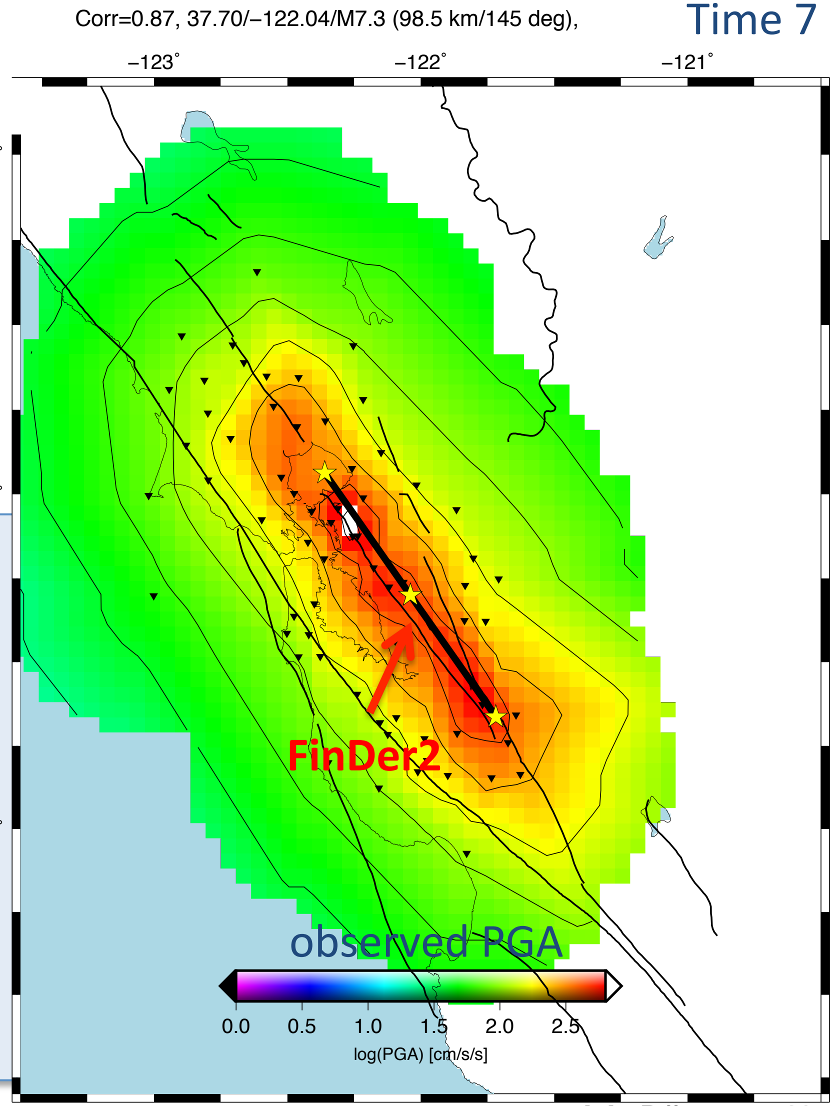
Misfit values for strike and length:



1. Consistent Models

FinDer2 algorithm Böse, Smith, Heaton

Time 7



M7.1 Hayward Scenario, Northern CA

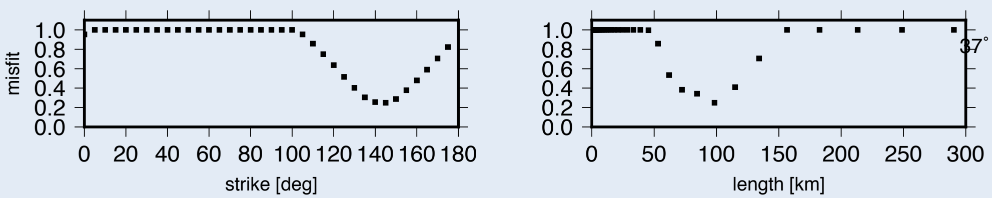
finite-source

FinDer2:

R = 0.87 (correlation with best template)

M_{est} 7.3

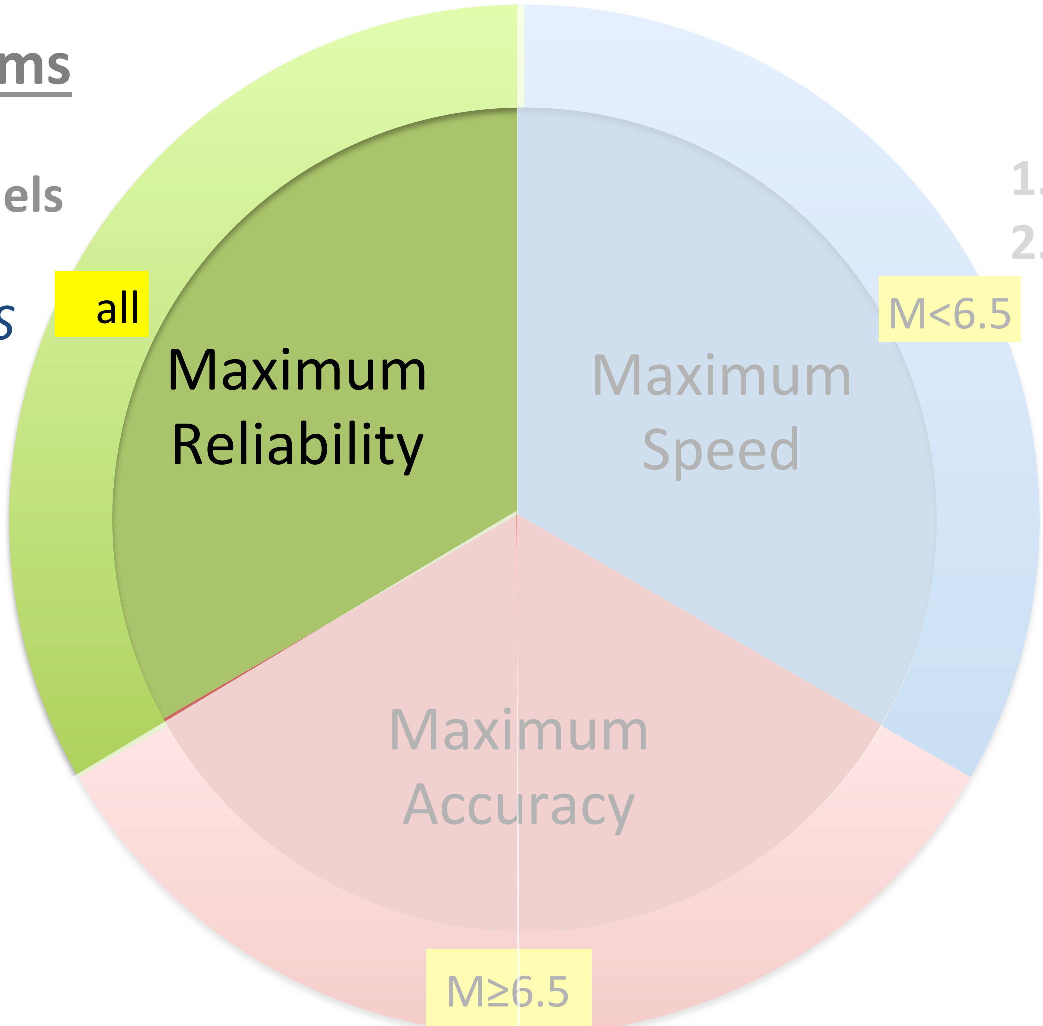
Misfit values for strike and length:



Combined Systems

require

1. **Consistent models**
   FinDer2
   FinDer-BEFORES



1. **Station density**
2. **Fast algorithms**

1. **Geodetic algorithms**
2. **Finite-fault detector**

1. Consistent Models

FinDer-BEFORES Minson, Böse, Smith, Heaton et al.

Seismic and geodetic data observe complementary parts of the earthquake. Combining the two datasets constrains rupture dimensions, slip and magnitudes **without saturation in large earthquakes**.

seismic observations → FinDer →
- rupture location and length
- fault strike θ

dynamic acceleration

Böse *et al.*, 2012 & 2015

GPS observations → BEFORES →
- fault strike θ
- fault dip
- spatial slip distribution (magnitude)

static displacement

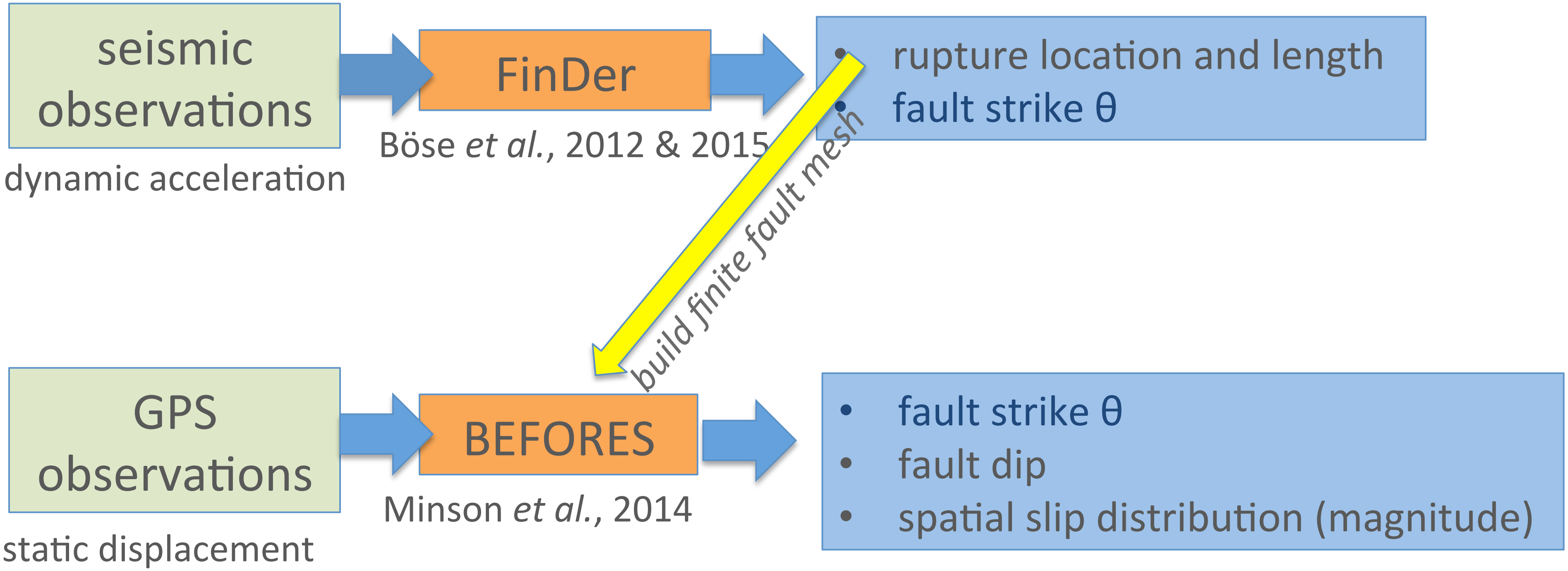
Minson *et al.*, 2014

Minson et al., under review

1. Consistent Models

FinDer-BEFORES Minson, Böse, Smith, Heaton et al.

Seismic and geodetic data observe complementary parts of the earthquake. Combining the two datasets constrains rupture dimensions, slip and magnitudes **without saturation in large earthquakes**.

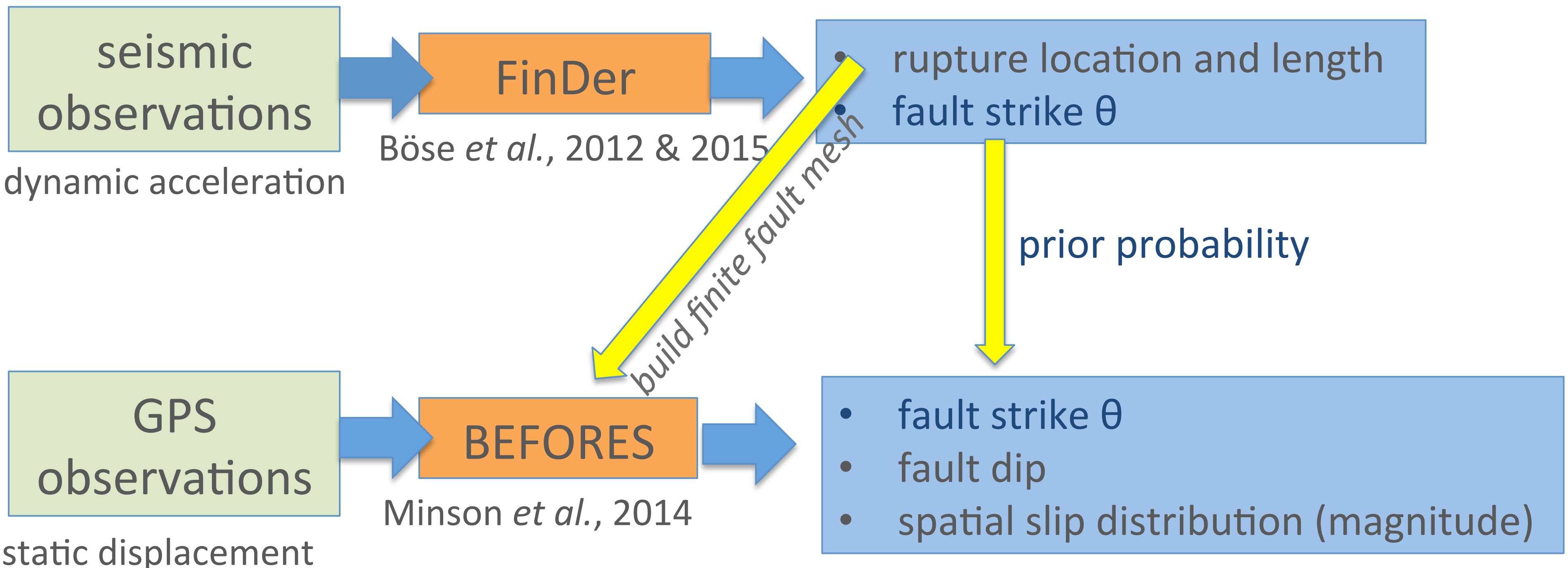


Minson et al., under review

1. Consistent Models

FinDer-BEFORES Minson, Böse, Smith, Heaton et al.

Seismic and geodetic data observe complementary parts of the earthquake. Combining the two datasets constrains rupture dimensions, slip and magnitudes **without saturation in large earthquakes**.



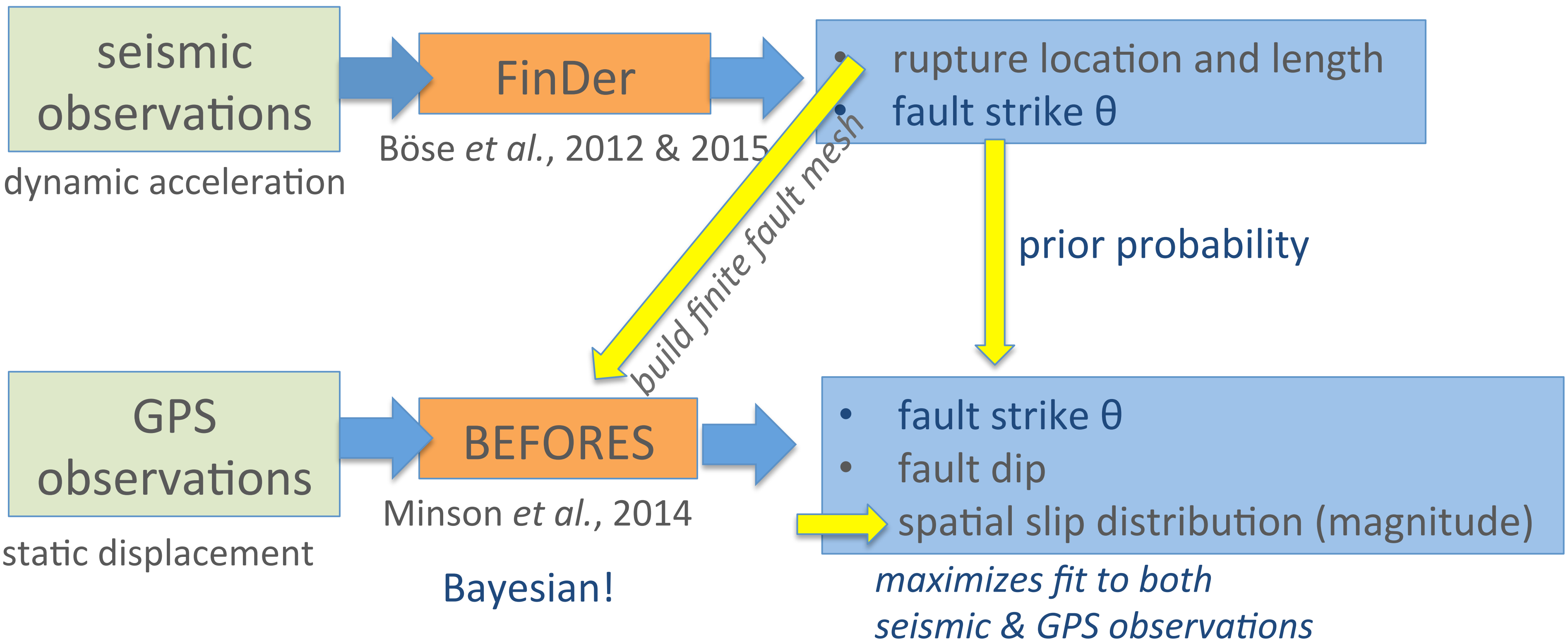
Bayesian!

Minson et al., under review

1. Consistent Models

FinDer-BEFORES Minson, Böse, Smith, Heaton et al.

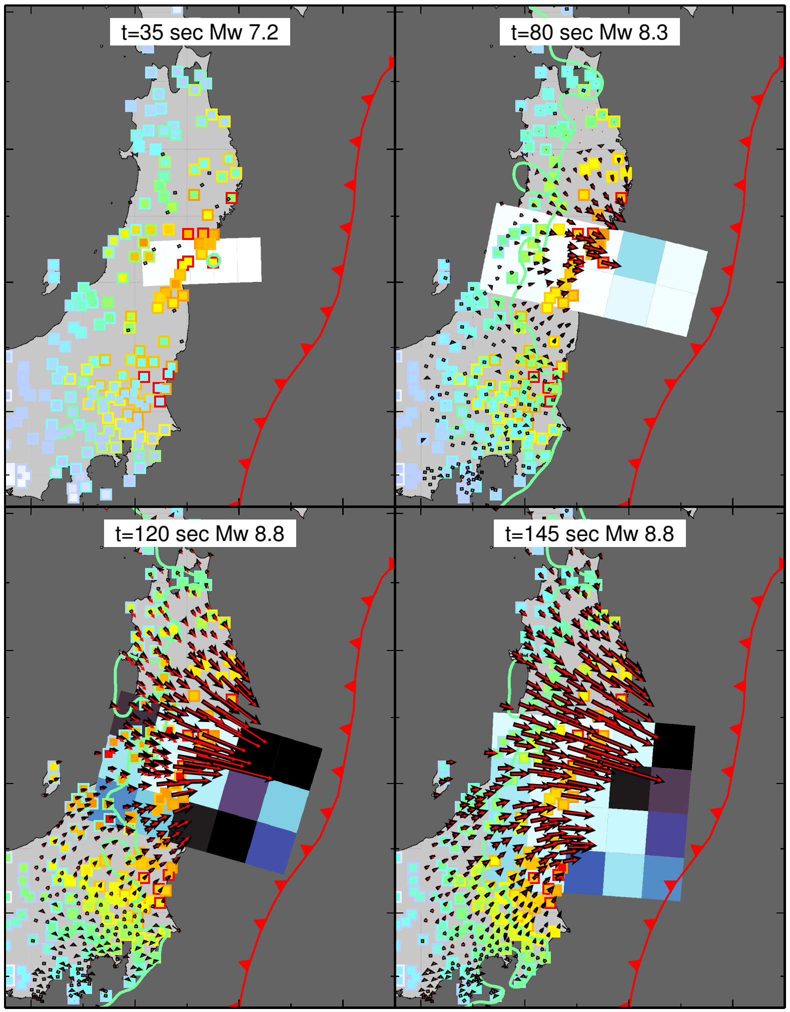
Seismic and geodetic data observe complementary parts of the earthquake. Combining the two datasets constrains rupture dimensions, slip and magnitudes **without saturation in large earthquakes**.



Minson et al., under review

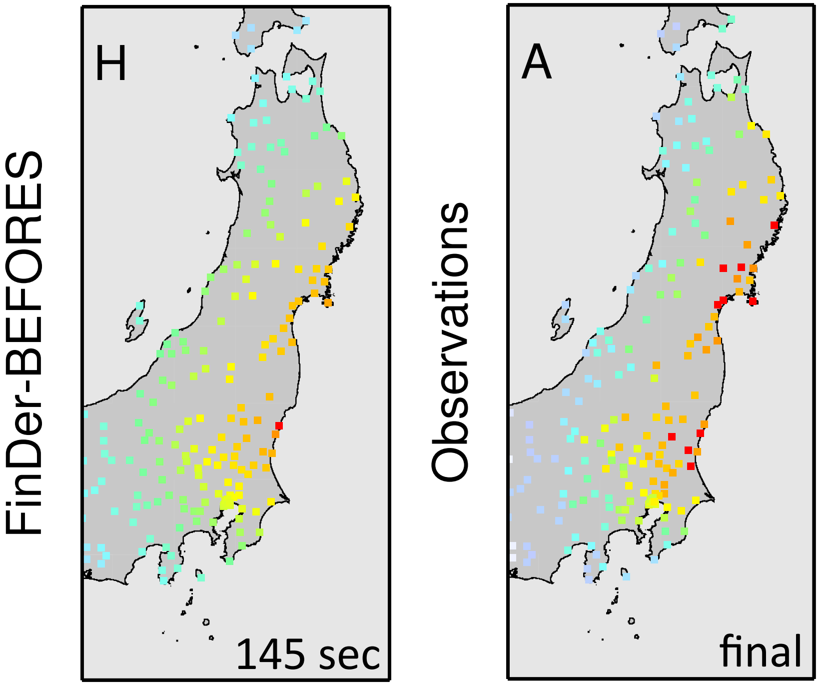
1. Consistent Models

FinDer-BEFORES Minson, Böse, Smith, Heaton et al.



M9.0 Tohoku-Oki

PGA

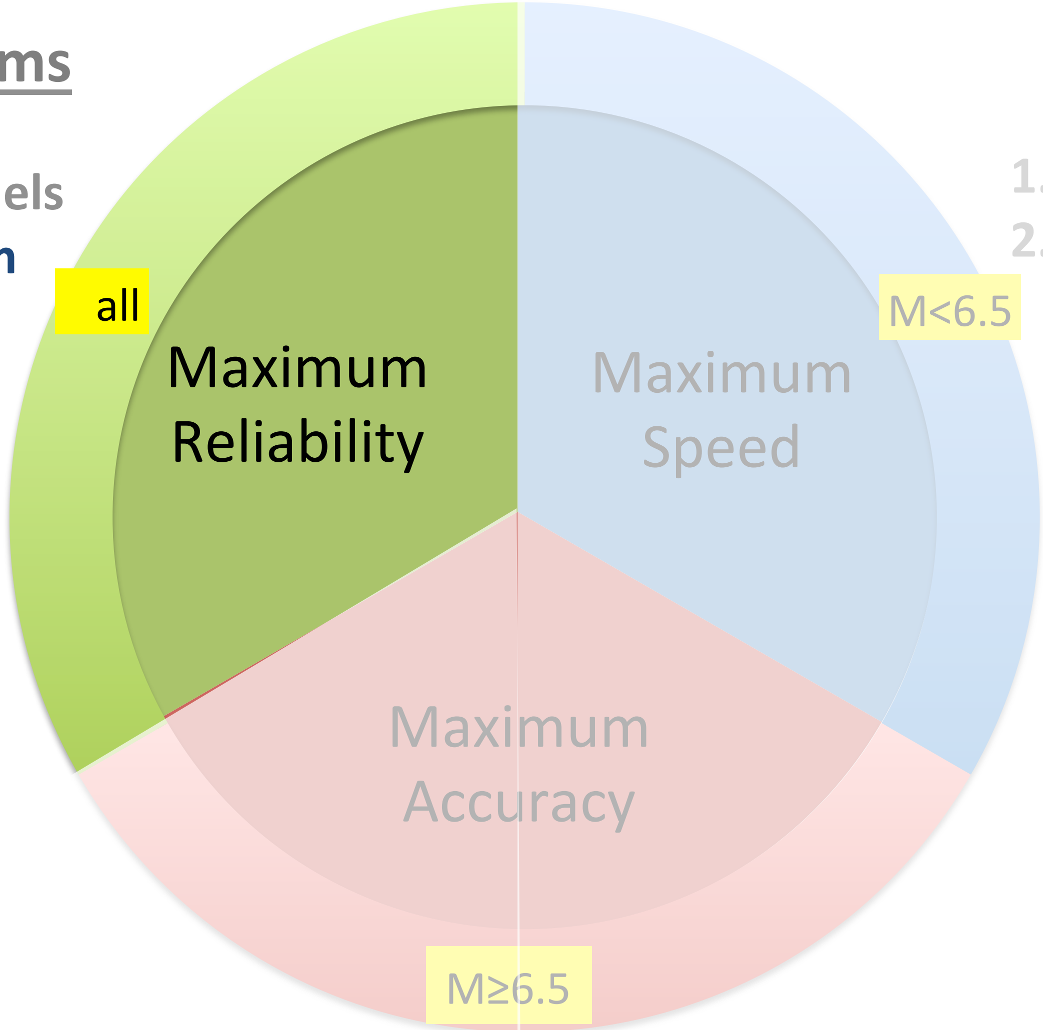


Minson et al., under review

Combined Systems

require

1. Consistent models
2. Robust platform



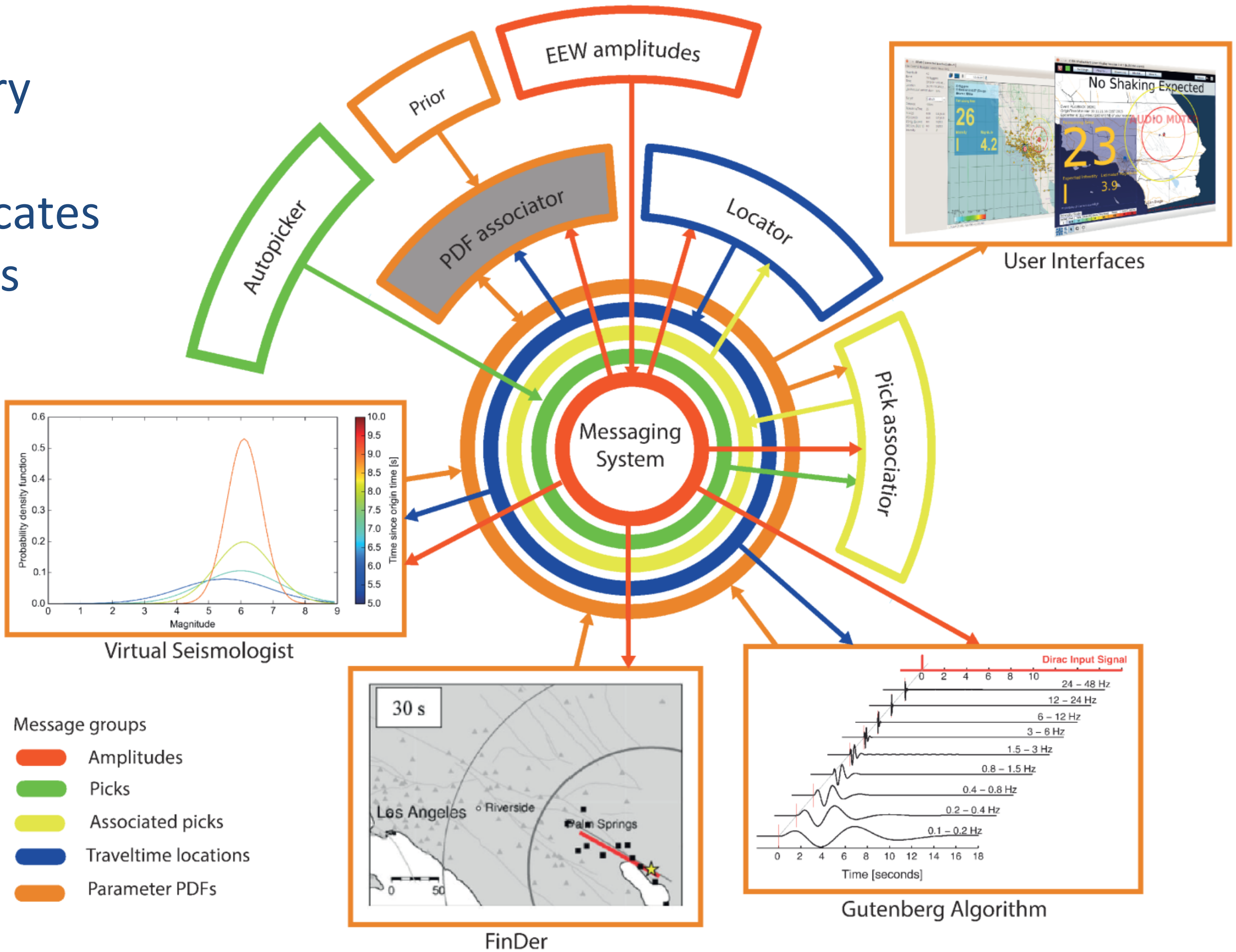
1. Station density
2. Fast algorithms

1. Geodetic algorithms
2. Finite-fault detector

2. Robust Platform/Modularity

ETH: Probabilistic combination Behr et al.

- Based on **SeisComP3**'s modular approach: every module is a standalone program that communicates through message groups
- EEW modules receive and send source parameter PDFs
- Modules can be easily replaced and more than one module can send and receive the same type of information



Behr

2. Robust Platform/Modularity
ETH: Probabilistic combination Behr et al.

- Tested with a large global dataset of local seismic records originally compiled by Meier (2015), which can be continuously extended.

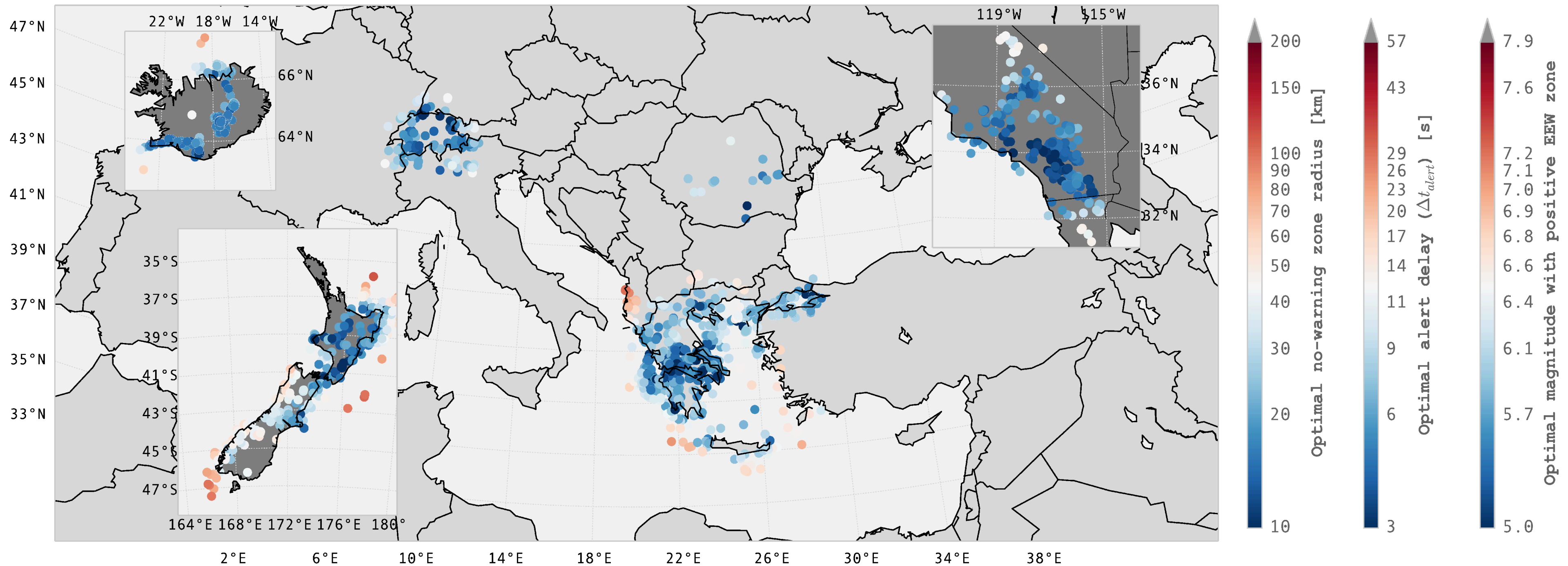
TO DO:
Map with test data

Behr

2. Robust Platform/Modularity

ETH: Testing the new system world-wide Behr et al.

- Virtual Seismologist in SeisComP3 (VS(SC3)) is already operating in real-time in Switzerland, Iceland, Romania, Greece, Turkey, California, and New Zealand
- Real-time testing the new system will be facilitated by the already existing SeisComP3 setup necessary to run VS(SC3)



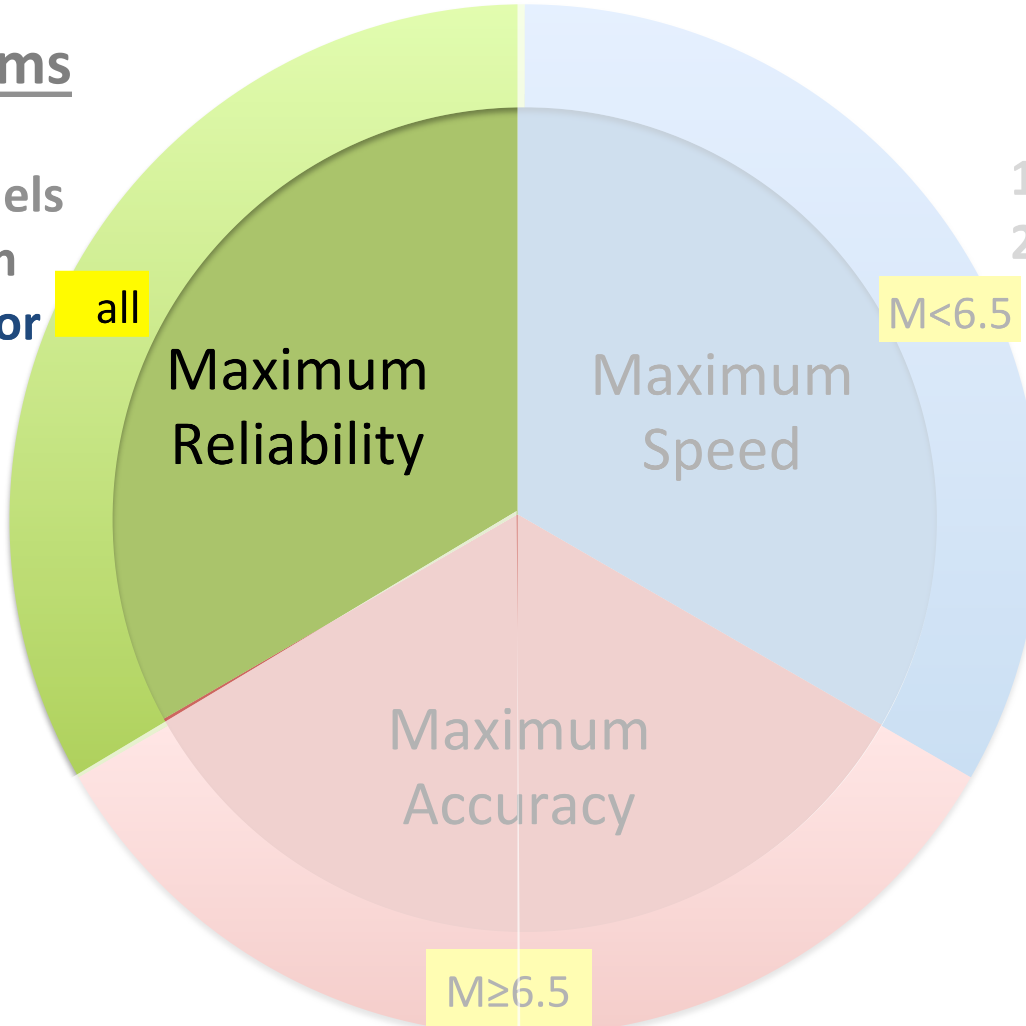
Behr

Reliability

Combined Systems

require

1. Consistent models
2. Robust platform
3. **Central mediator**



1. Station density
2. Fast algorithms

1. Geodetic algorithms
2. Finite-fault detector

3. Central Mediator/Reality Check

Posterior hyper-robust predictive PDF Minson, Wu, Beck, Heaton

Procedure

- For each algorithm report (+“No event”) compare the predicted and observed waveform envelopes (Cua, 2005)

waveform envelopes

- Compute probability in favor of each algorithm (+“No event”)

- Output hyper-robust predictive GM PDF (e.g. PGA) by appropriately weighting predictions from each algorithm (+“No event”) by their probabilities

Minson

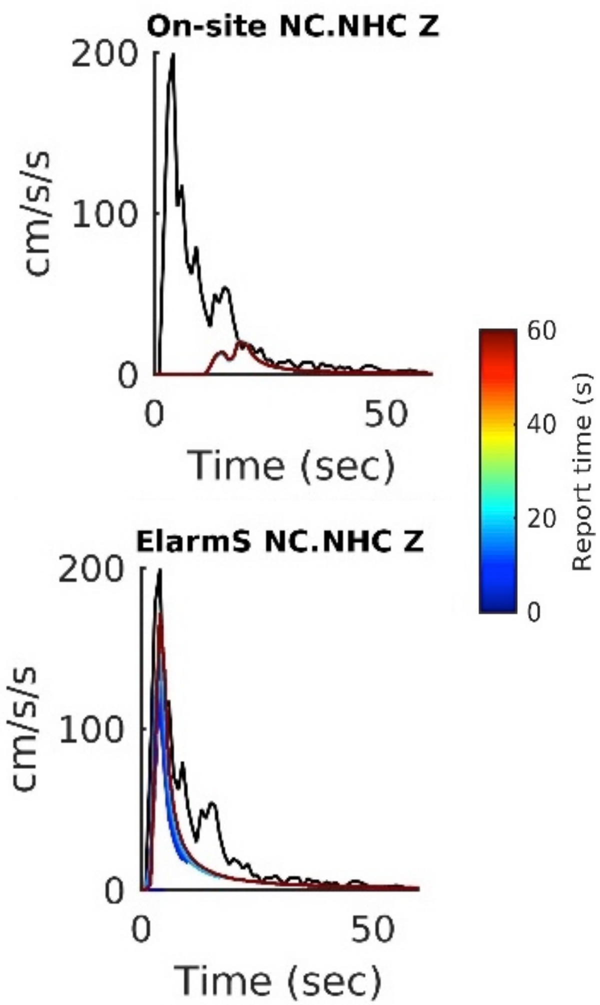
3. Central Mediator/Reality Check

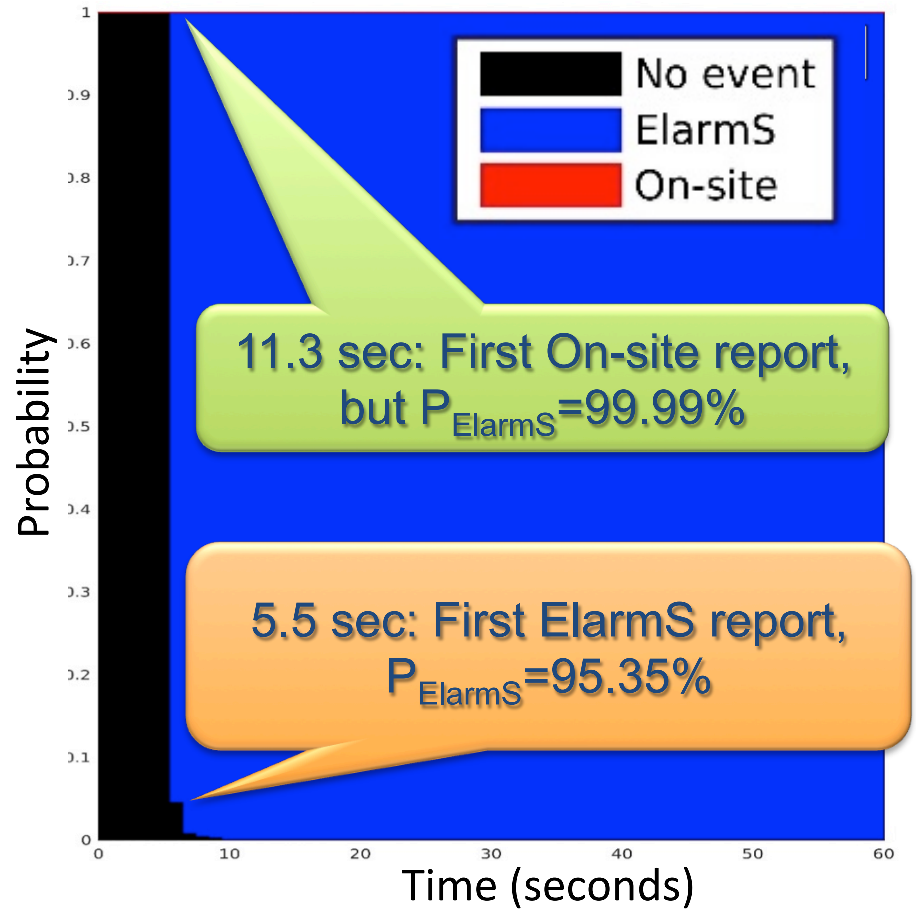
Posterior hyper-robust predictive PDF Minson, Wu, Beck, Heaton

Example: 2014 M6.0 Napa

Onsite Algorithm

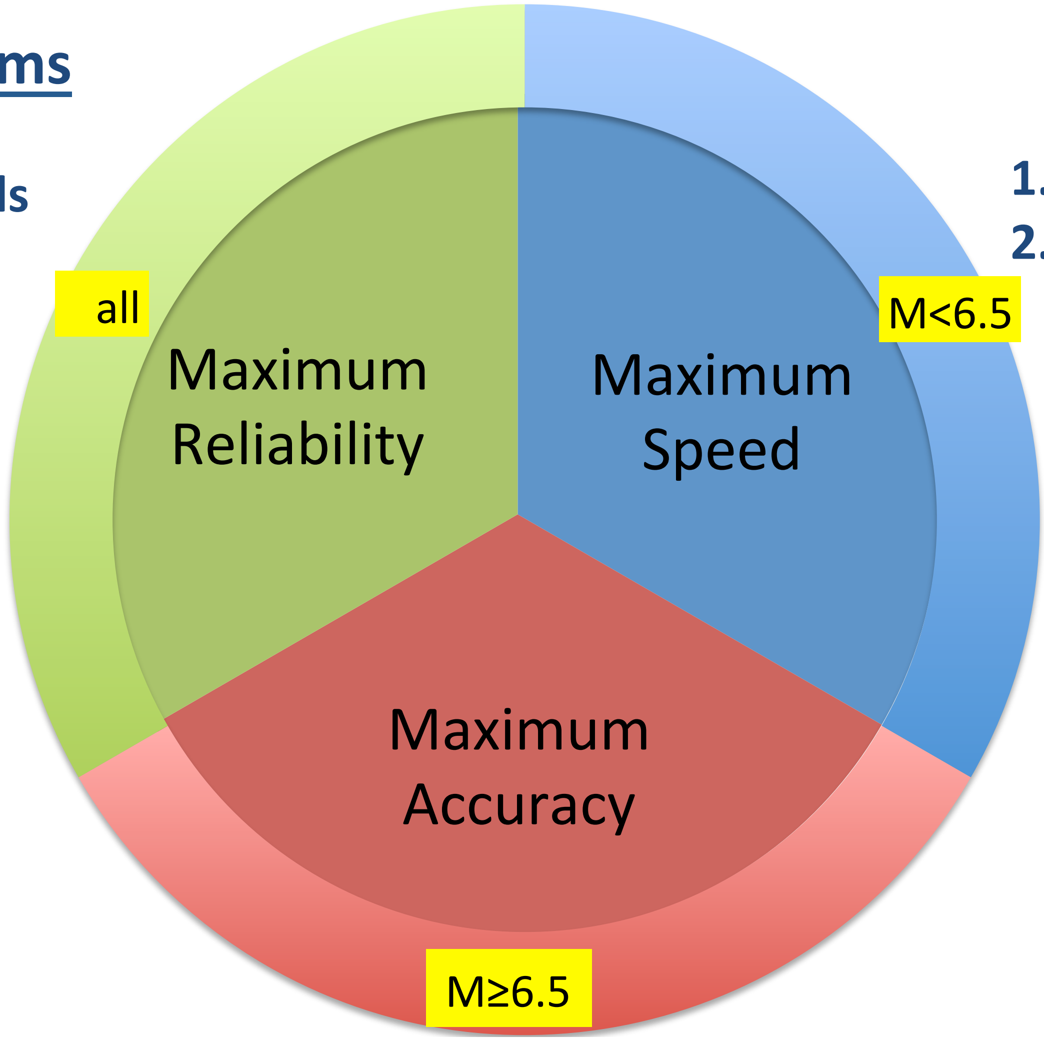
ElarmS Algorithm





Early Warning: Objectives, Challenges & Solutions

Combined Systems
require
1. Consistent models
2. Robust platform
3. Central mediator



1. Station density
2. Fast algorithms

1. Geodetic algorithms
2. Finite-fault detector