E-GRAAL (Earthquake GRAvity ALerts) kick-off meeting
March 9, 2015

Status Review of Earthquake Early Warning and Future Prospects

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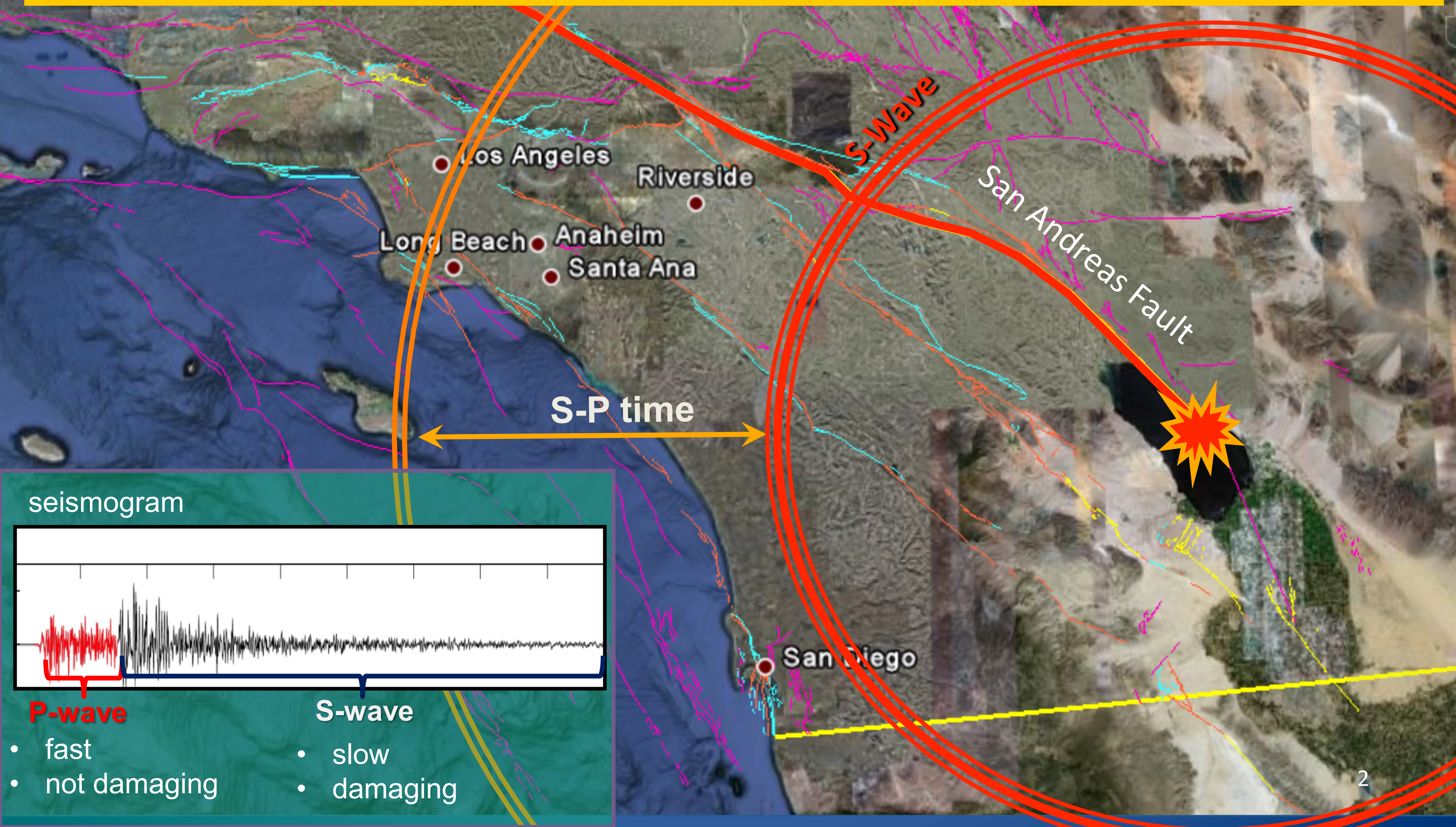
What is Earthquake Early Warning ?

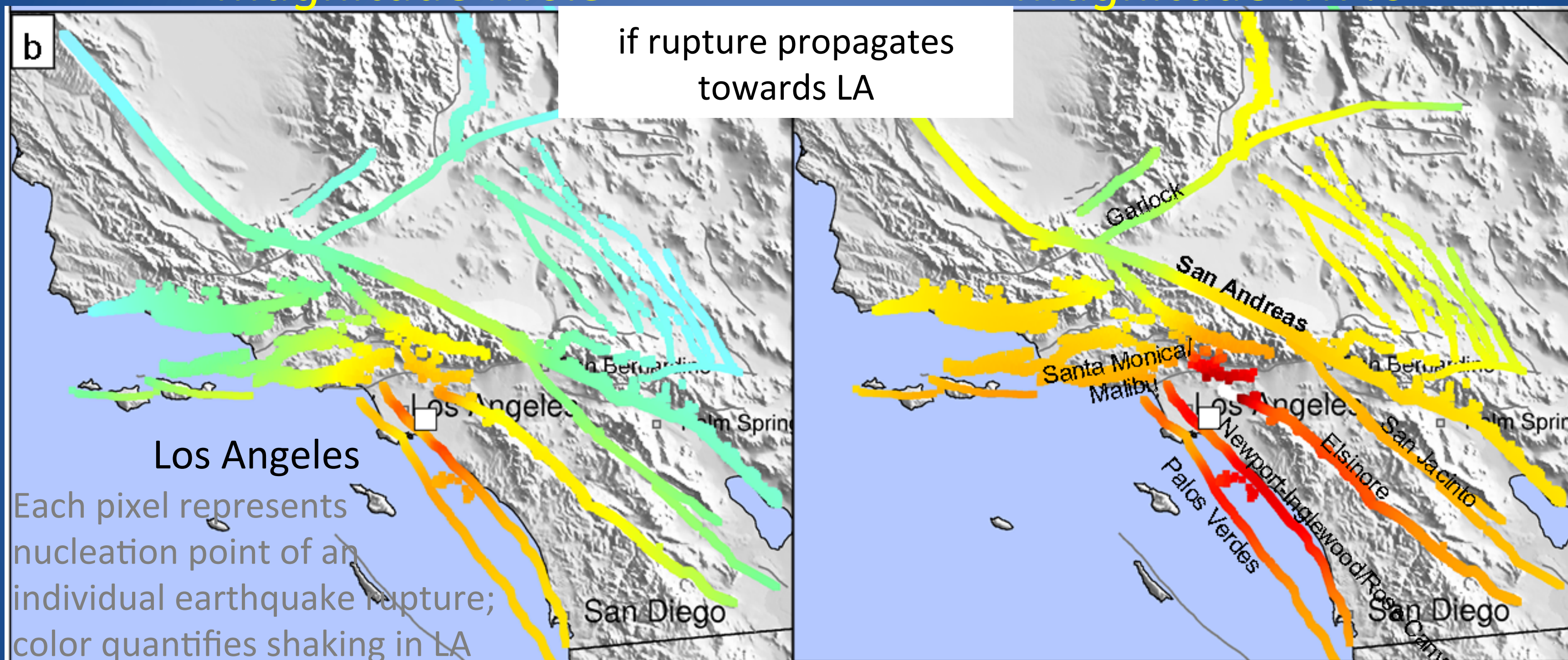
ability to provide a few to tens of seconds of warning before damaging seismic waves arrive



Why do we need Early Warning ?

Expected ground shaking in the Los Angeles basin
if we had an earthquake of

magnitude M6.5 | *magnitude M7.0*



if rupture propagates towards LA

Los Angeles

Each pixel represents nucleation point of an individual earthquake rupture; color quantifies shaking in LA

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

For many dangerous earthquake scenarios warning times of **>30 seconds** are likely.

Böse et al., 2014

How can we use Early Warning ?

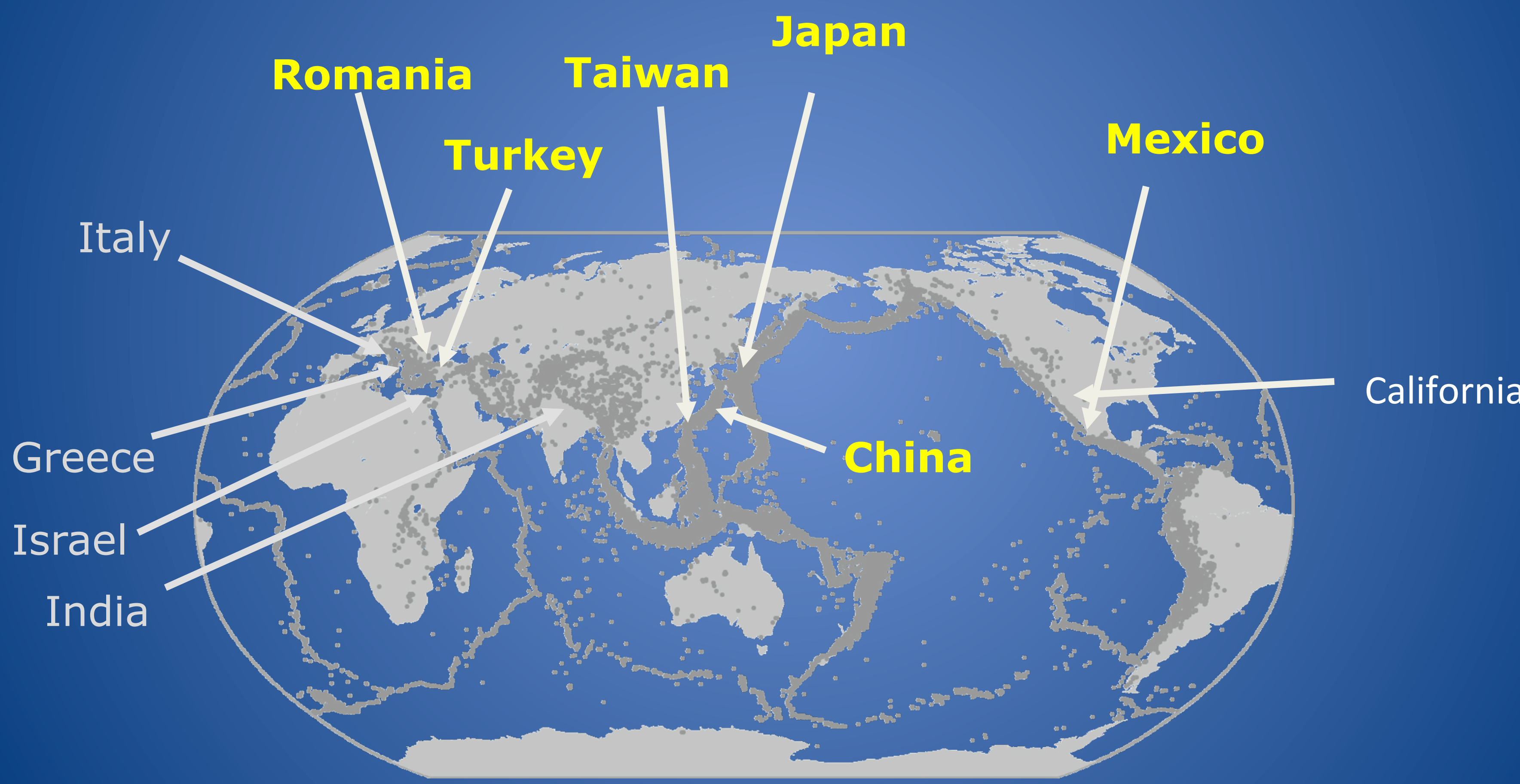
1. **Public Alert**
   - warn people to take protective measures (drop-cover-hold on)
   - move people to safe positions
   - warn school children
   - warn people to prepare physically and psychologically for the impending shaking
2. **Trigger Automatic Responses** in places like factories
   - slow down/stop trains
   - control traffic by turning signals red on bridges, freeway entrances
   - close valves and pipelines
   - stop elevators
   - save vital computer information
   - …

Limitations: chance of false alerts, warnings can be too late; no warning in blindzone (~20 miles around epicenter)

Early Warning Activities

Operational systems

Systems under development



Early Warning Activities

Japan Meteorological Agency (JMA)

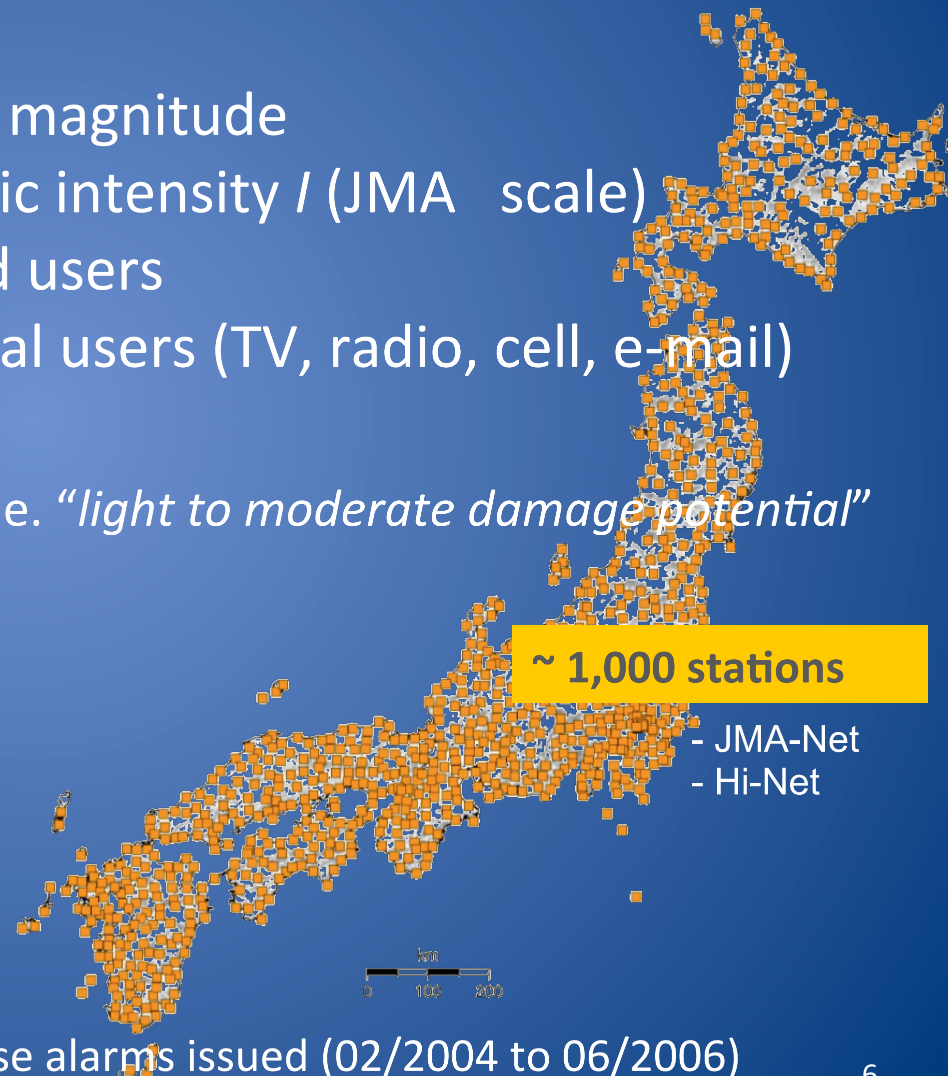
- Public since Oct. 2007
- Output: hypocenter location & magnitude

  → S-wave arrivals & seismic intensity *I* (JMA scale)

  I>=4+ : warning to limited users

  I>=5- * : warning to general users (TV, radio, cell, e-mail)

* =VI-VII on MSK scale, i.e. *"light to moderate damage potential"*



Testing period: 855 warnings & 26 false alarms issued (02/2004 to 06/2006)

Early Warning Activities

Japan Meteorological Agency (JMA)

1995 Kobe earthquake (*before* EEW)

0min	Earthquake
14min	Seismic intensity 6 in Kobe
23min	Seismic intensity in Kobe was corrected to 5
29min	Seismic intensity in Kobe was corrected to 6
3days	Seismic intensity in Kobe was corrected to 7

J Mori

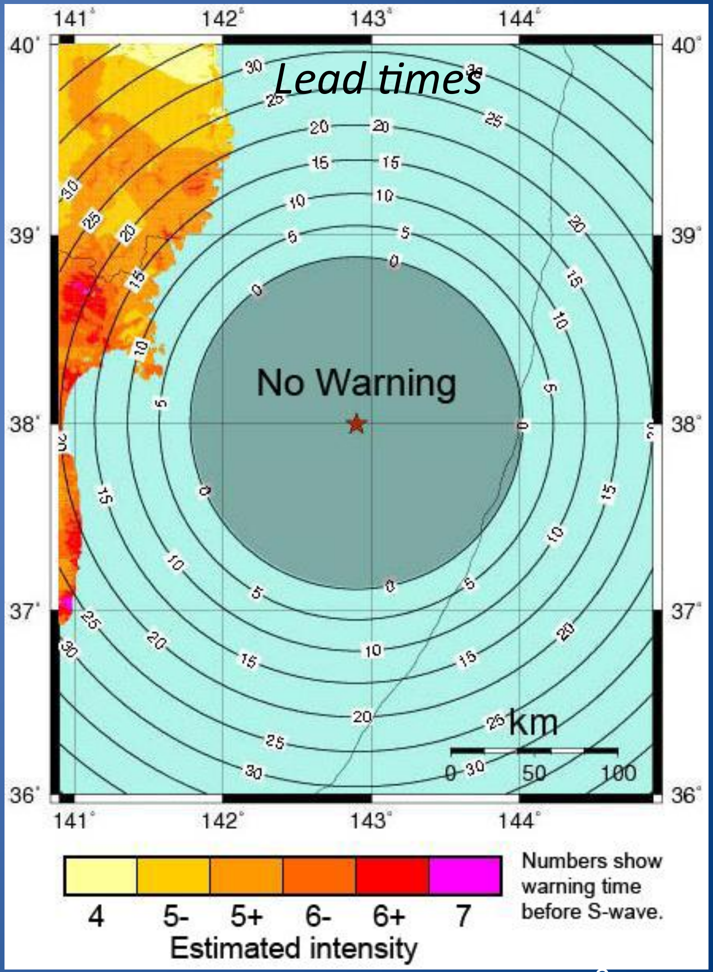
M. Böse

Early Warning Activities

Japan Meteorological Agency (JMA)

2011 Tohoku earthquake (*with* EEW)

0sec	Earthquake
19sec	P-wave detected
27sec	Location and Magnitude determined; EEW issued
3min	Observed Seismic Intensity reported
3.5min	Tsunami Warning issued



M Yamada

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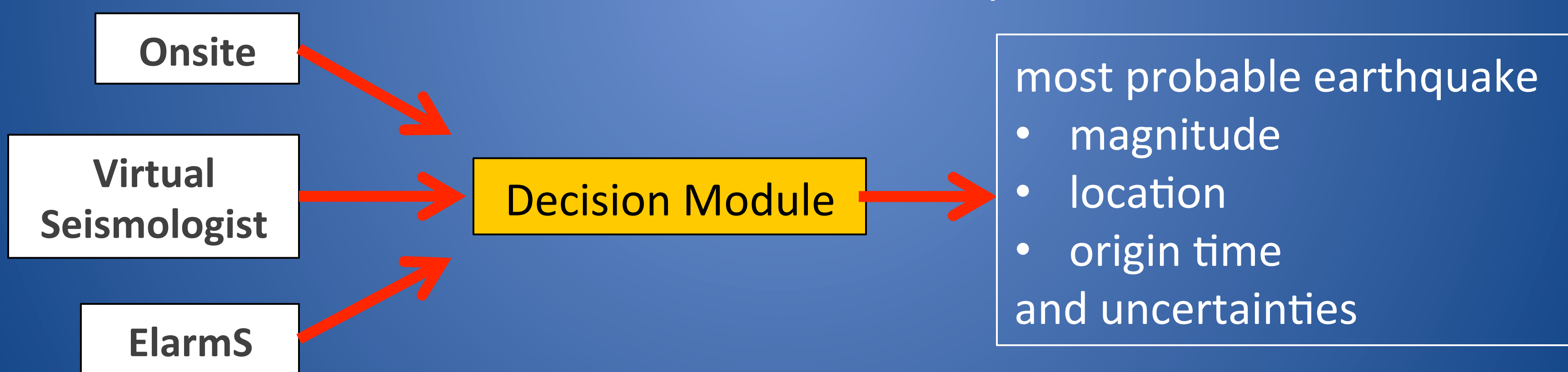
Early Warning Activities

California (ShakeAlert)

CISN ShakeAlert is a **hybrid system** that combines single sensor and network approaches. Single sensor algorithms are faster, but less reliable than network approaches. Estimates are up-dated with time.

Algorithms

Every second after event detection:



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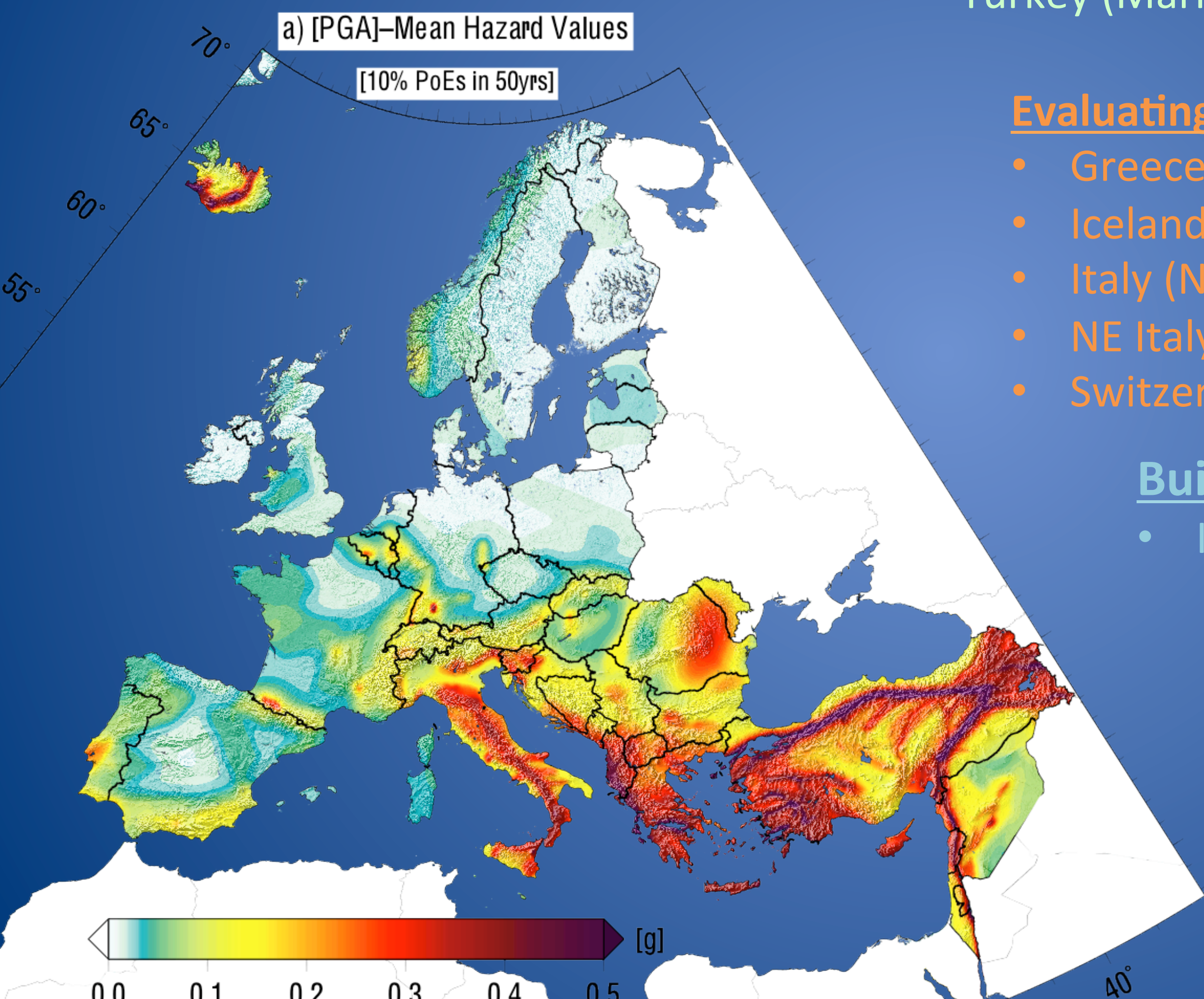
Early Warning Activities

Europe



Map: European Seismic Hazard Model, 2013

Operational Systems

- Romania
- Turkey (Marmara Area)

Evaluating EEW implementation

- Greece
- Iceland
- Italy (Naples)
- NE Italy/Slovenia/Austria
- Switzerland

Building EEW

- Israel

Algorithm Development

- Germany (GFZ)
- Italy (U. Naples)
- Romania (NIEP)
- Spain (UCM)
- Switzerland (SED)
- Turkey (KOERI)

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Early Warning Activities

Europe

European Funding for EEW in Europe

SAFER → REAKT → ??? <EPOS>

SAFER: 2006-2010

REAKT: 2011-2014

- With > €7m SAFER / REAKT funded >20 institutions in >10 nations

  >50 man-years were funded

- Focus on science, evaluation and implementation of test EEW systems, fostering key End User interactions

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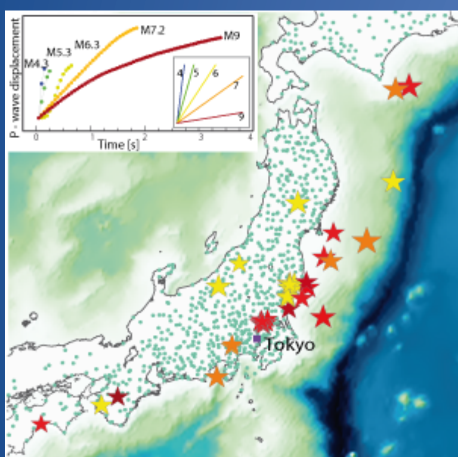
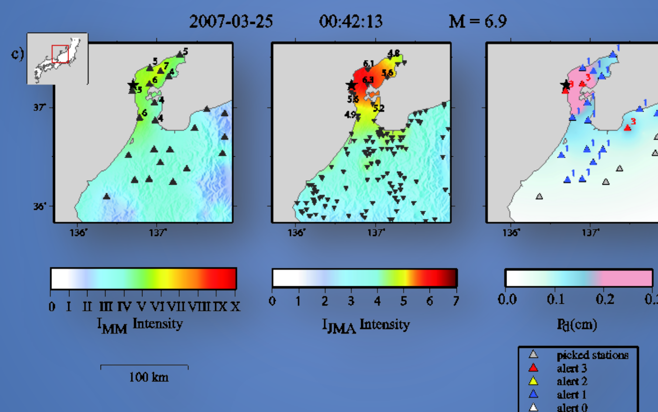
Early Warning Activities

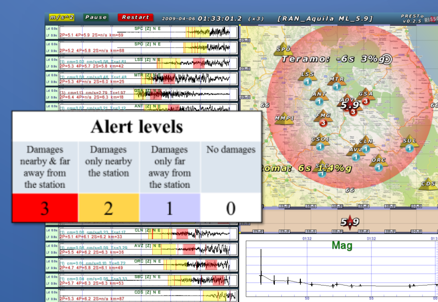
Europe (U. Naples)

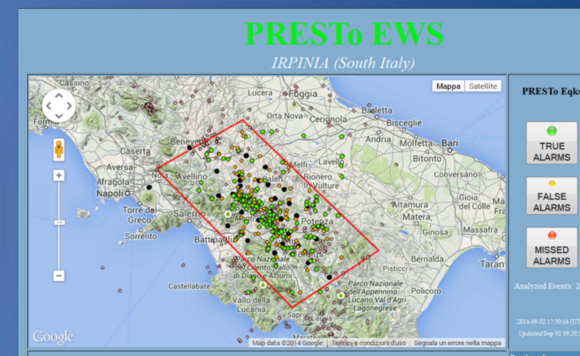
Scientific results	Method Updates	Applications
Rupture initiation of small and large events	The concepts of alert levels and Potential Damage Zone	Testing PRESTo in Southern Italy and elsewhere



Colombelli et al., 2014, Nature Communications







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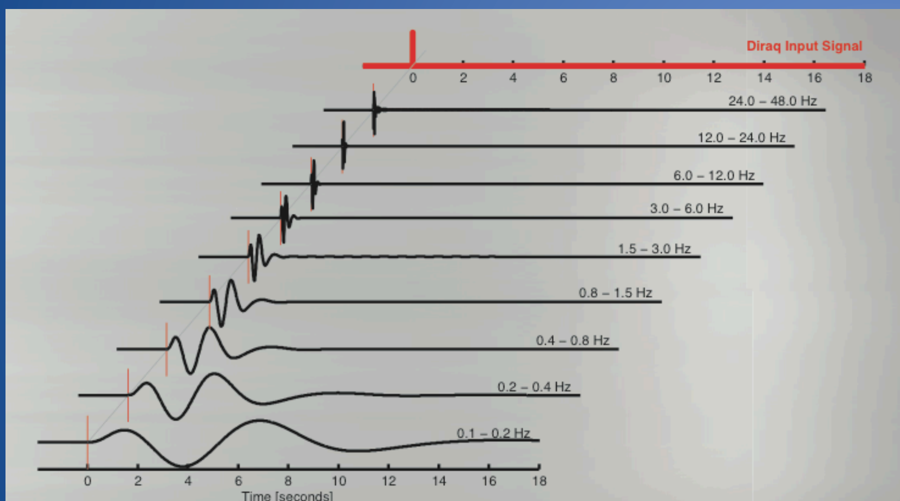
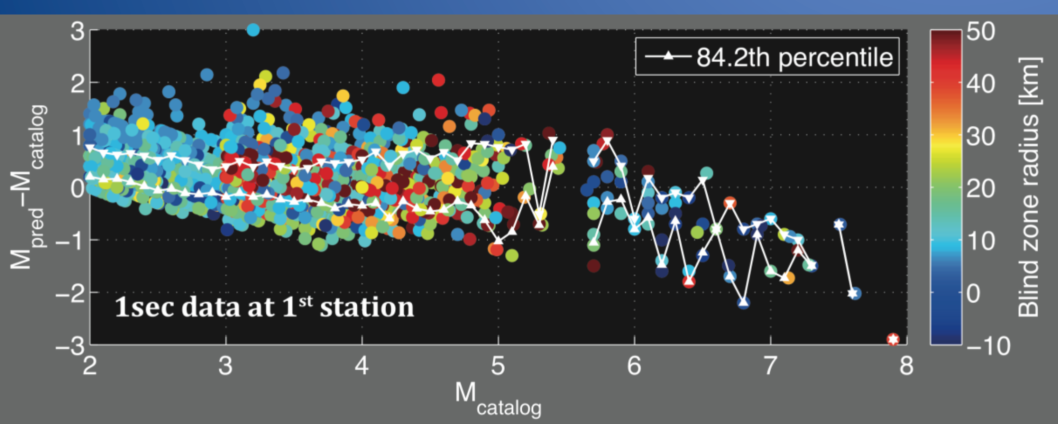
Early Warning Activities

Europe (SED@ ETHZ)

ETHZ maintains and develops the **Virtual Seismologist** (VS) regional EEW algorithm (Cua and Heaton, 2006)

VS is part of the *ShakeAlert* System in CA





<u>Faster EEW to minimise the blind zone:</u>

Using filter banks to characterise magnitude / location using 0.5 s updates at a single station

Combining single station event information with increasing network awareness (multiple picks, NYAD)

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Early Warning Activities

Europe

Lessons Learned

- A major investment in seismic networks is required for most regions to be EEW-capable
- Networks do not share real time data across different networks / nations
- ***Small events <M6.5 dominate hazard in majority of European countries***:
    - damage zones are currently inside the blind zone
    - EEW community need to demonstrate the blind zone can be reduced

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Performance

Speed

Accuracy

Reliability

Utilization

Performance

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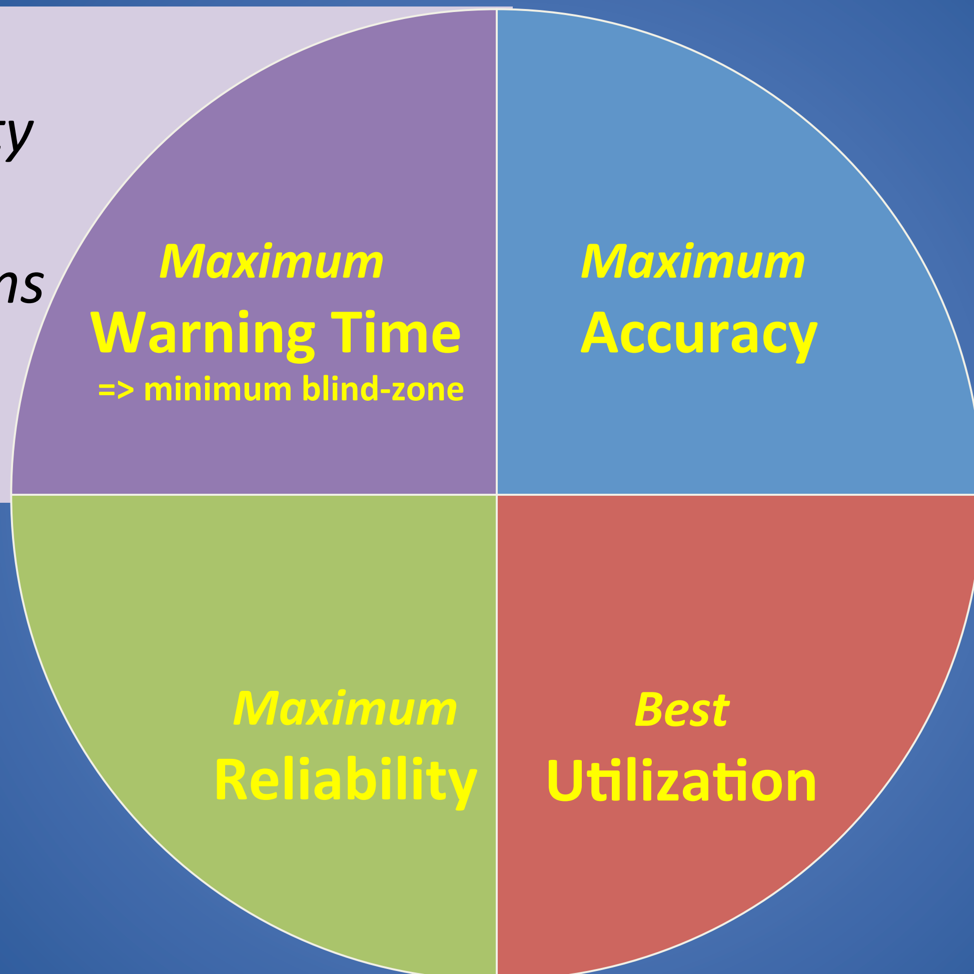
1. *station density*

2. *fast algorithms*

   <u>Challenge:</u>
   small to moderate EQs M<6.5



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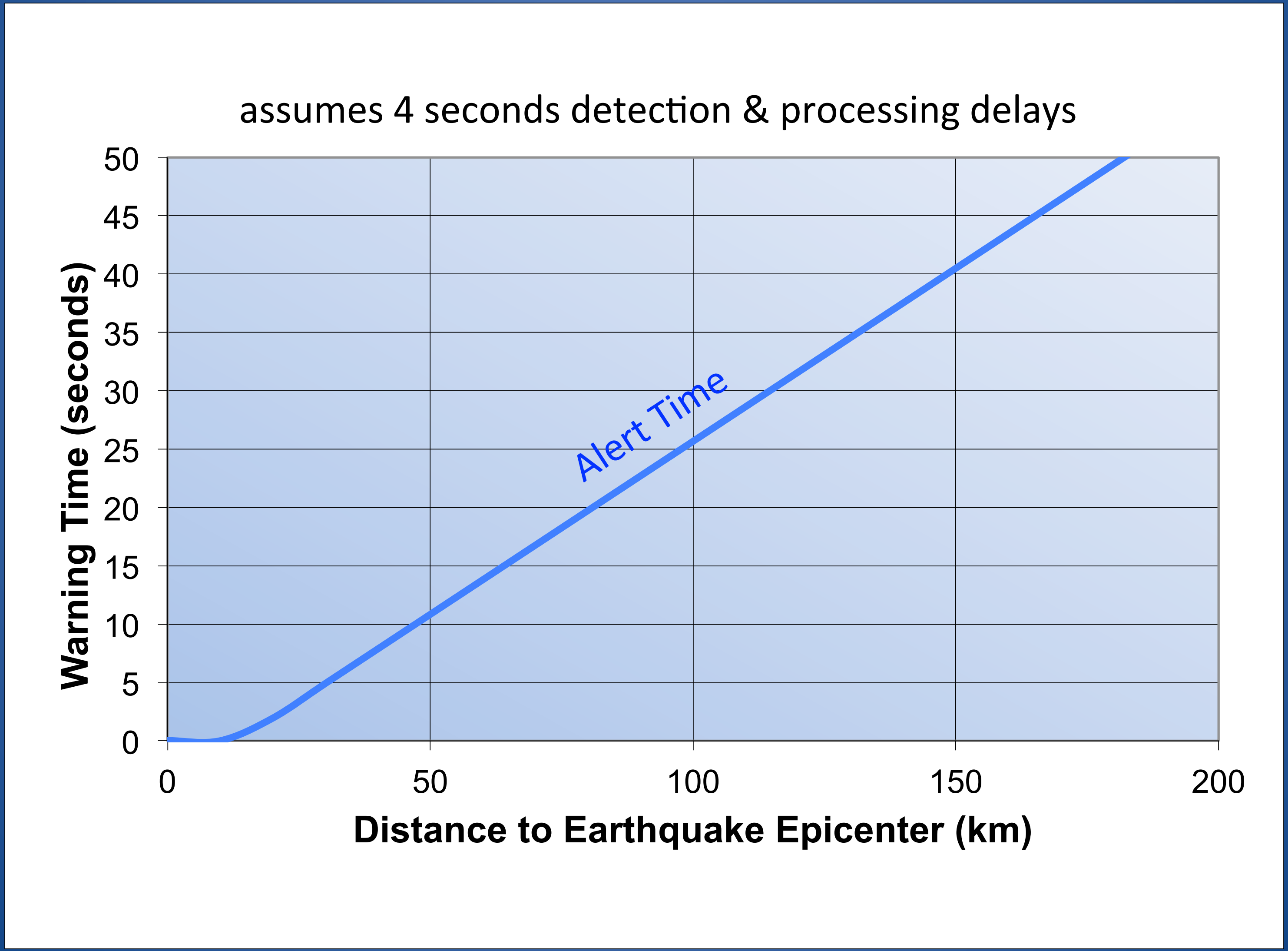
Performance

Warning Times/Blind-Zone



D Given

Performance

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Warning Times/Blind-Zone

Example: ShakeAlert

La Habra:

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

ShakeAlert Timeline

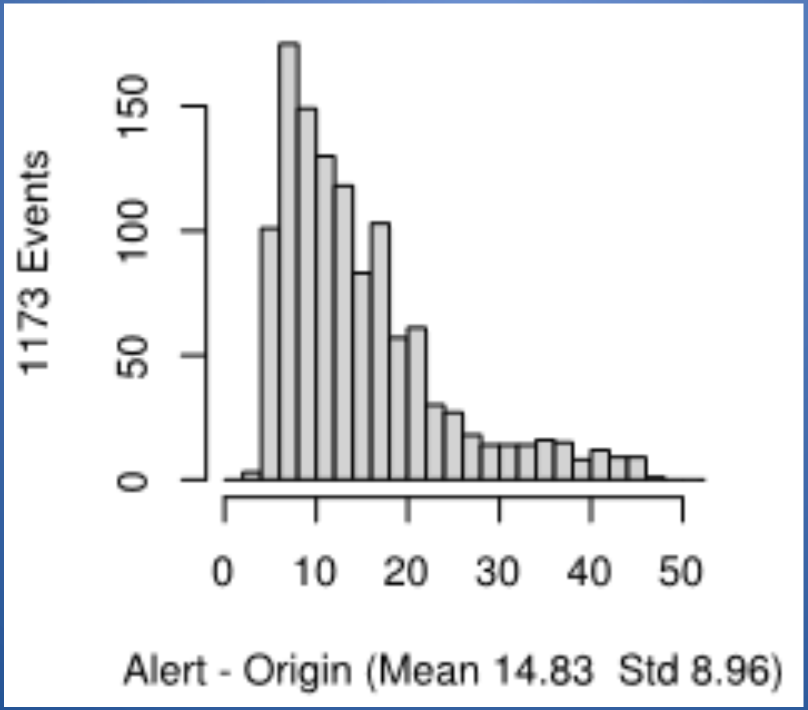
09:09:42.3		Origin time
09:09:43.3	(+1.0s)	1st P-wave
09:09:46.3	**(+4.0s)**	1st Alert

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



Performance

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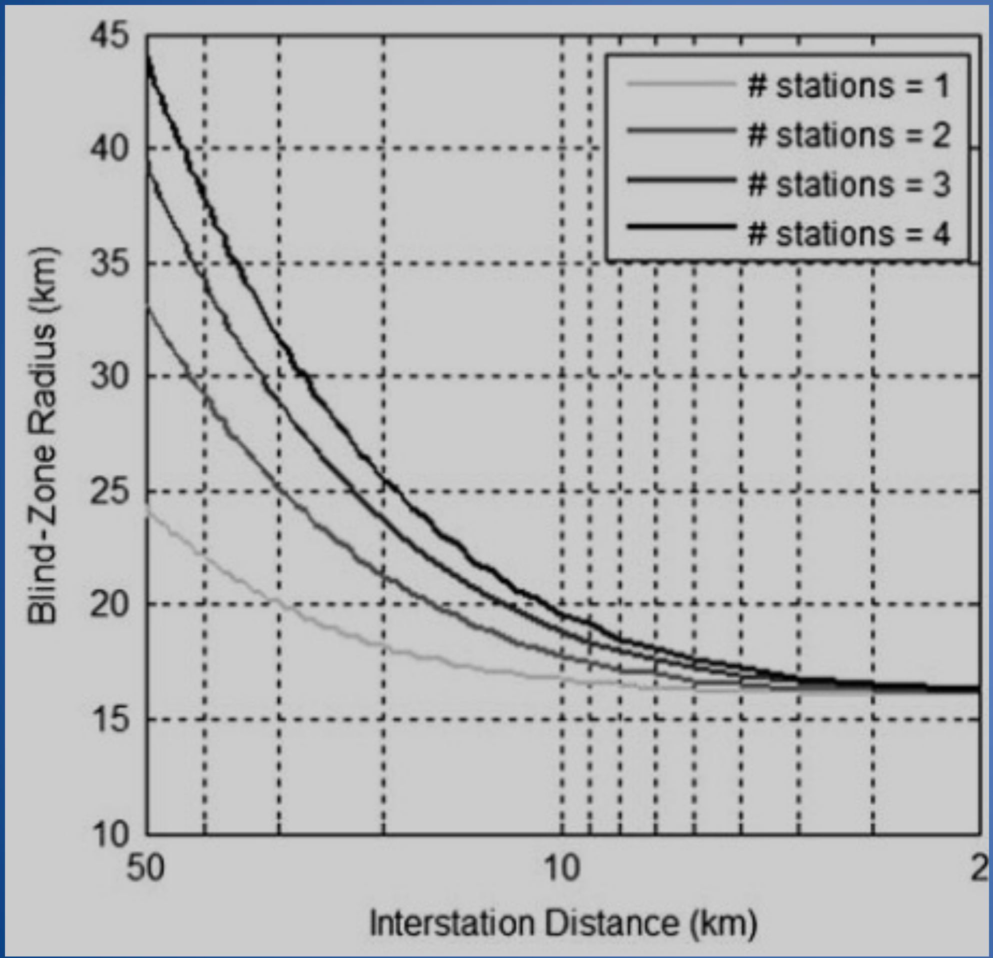
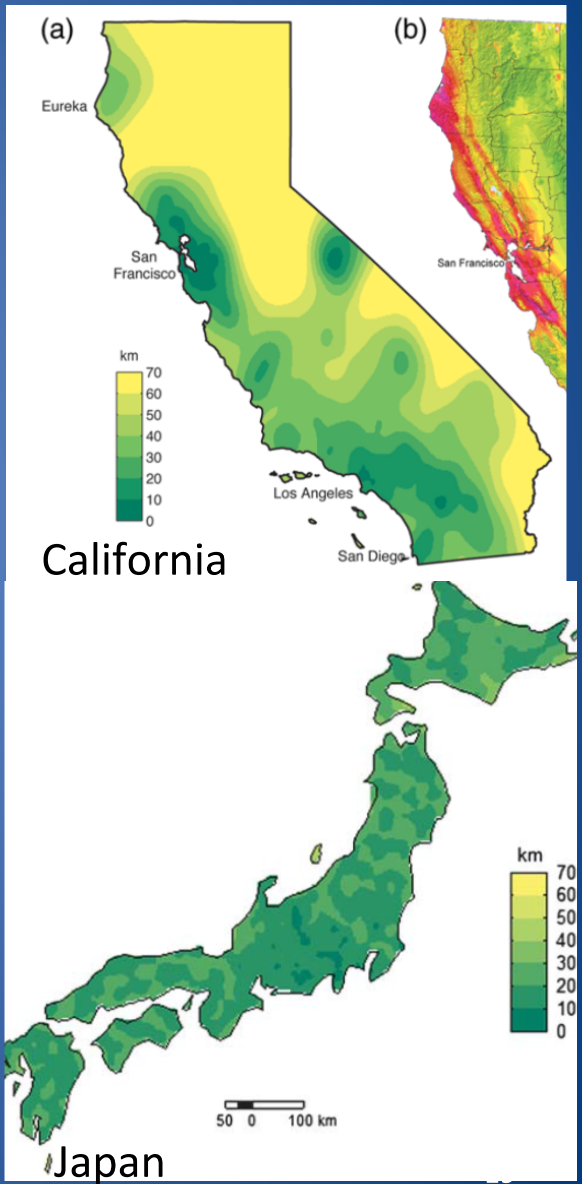
Warning Times/Blind-Zone

1. Station Density



$v_p = 6.1$ km/s
$V_s = 3.6$ km/s

Seismic station density



Kuyuk and Allen, 2013

Performance

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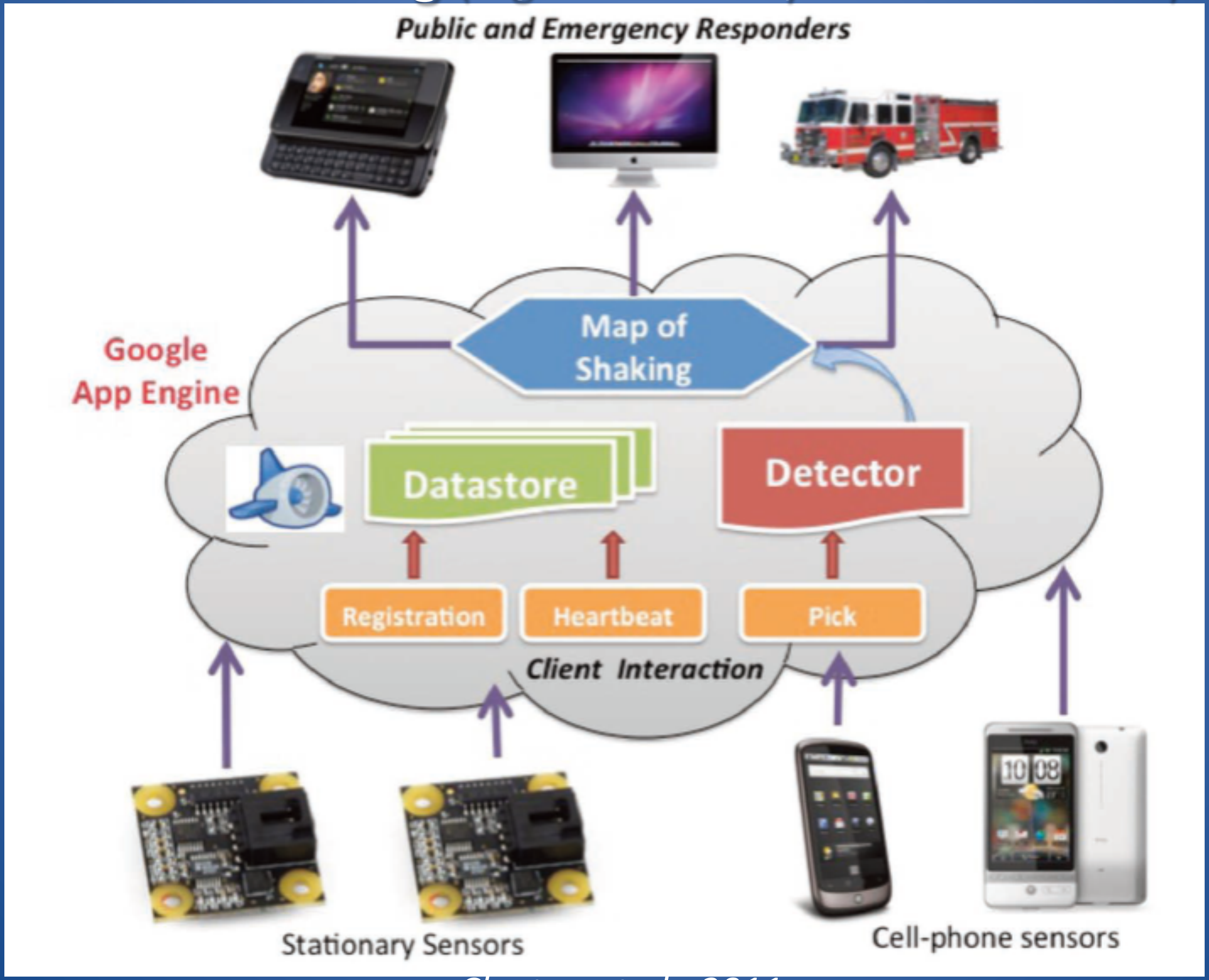
Warning Times/Blind-Zone

1. Station Density

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



Clayton et al., 2011

Performance

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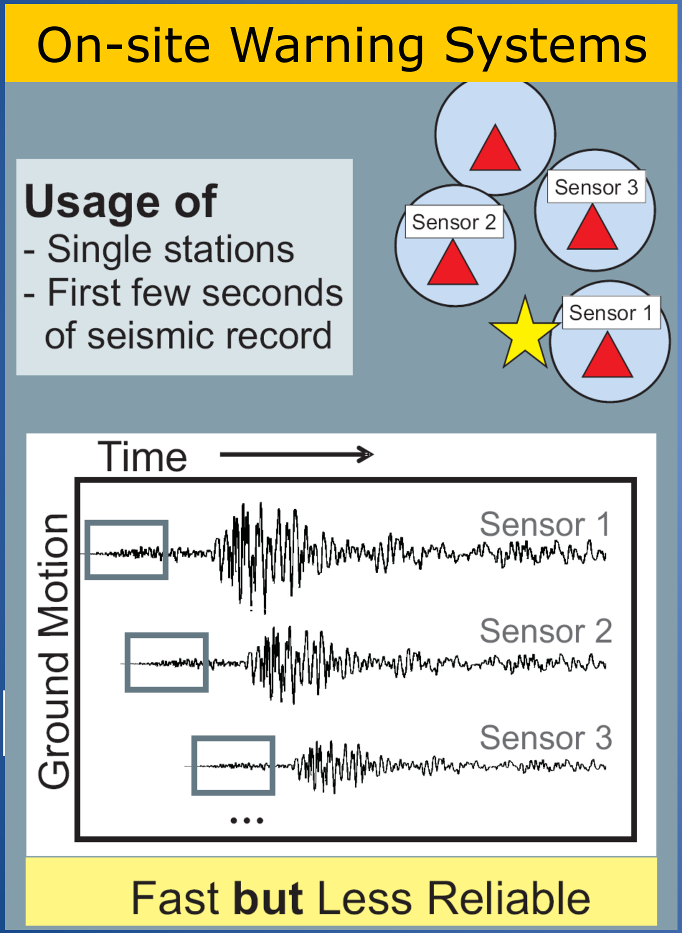
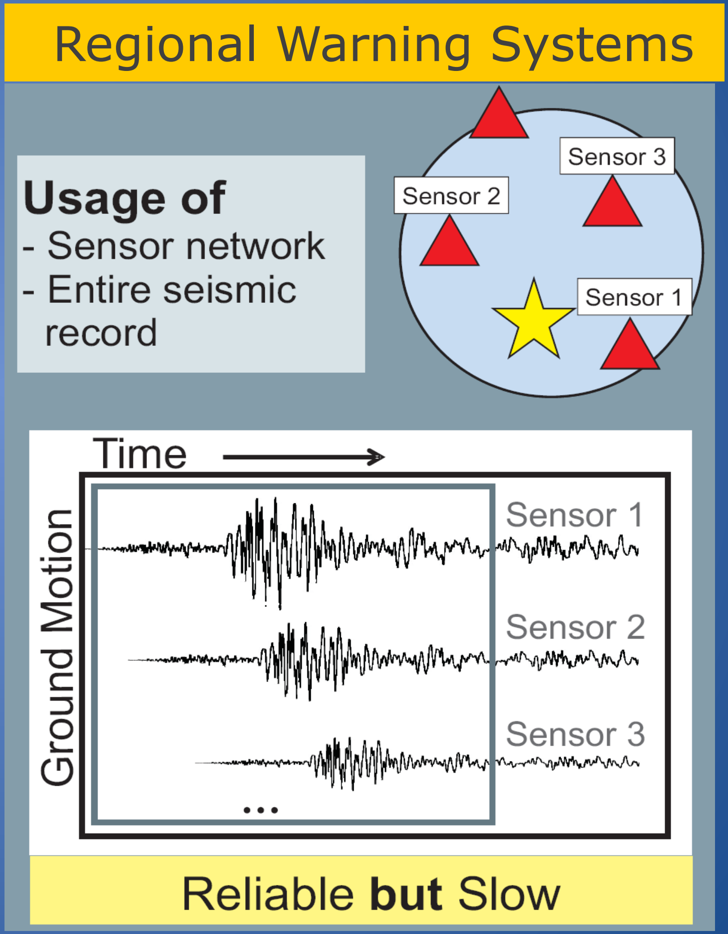
Warning Times/Blind-Zone

2. Fast Algorithms





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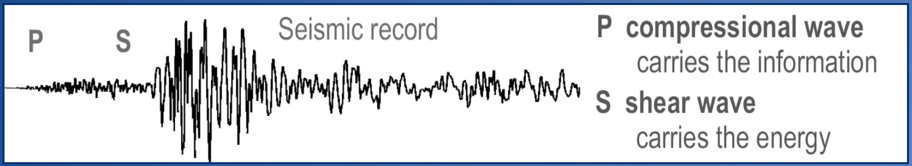
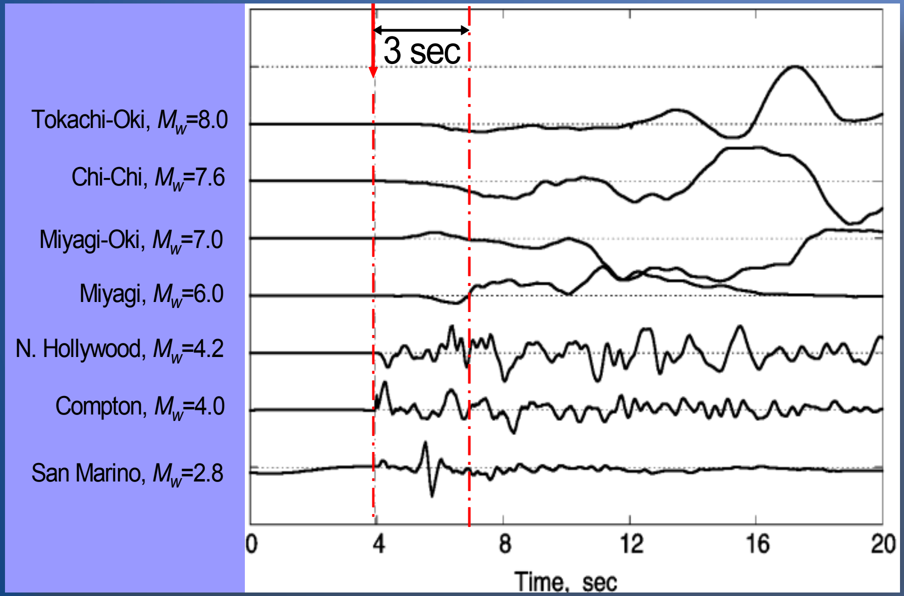
Performance

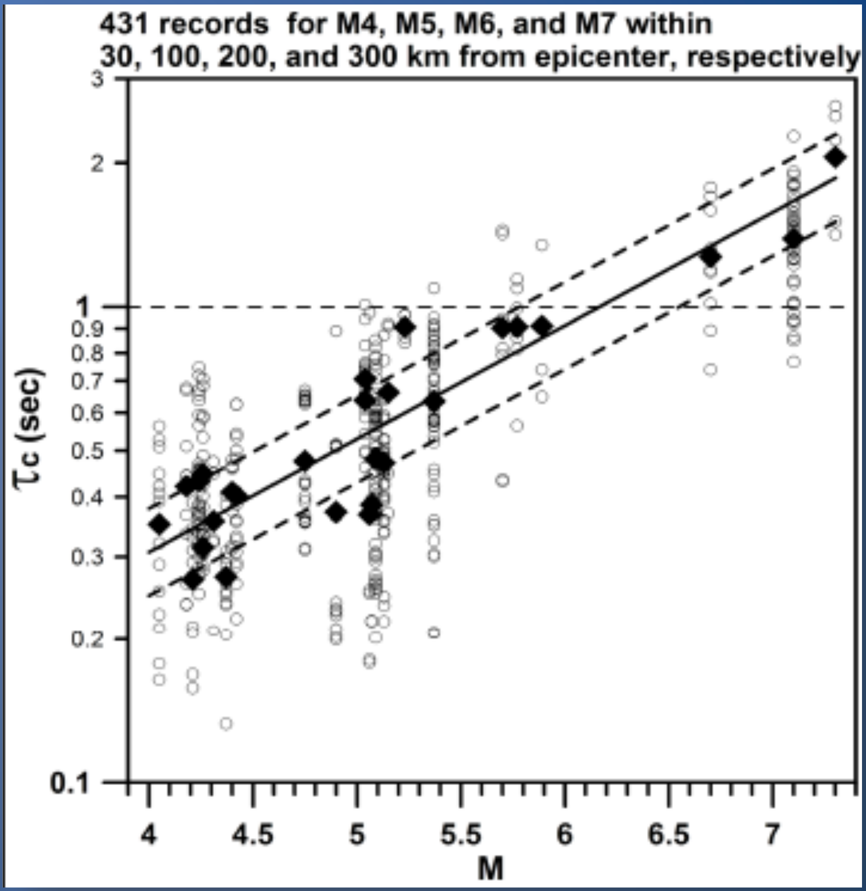
Warning Times/Blind-Zone

2. Fast Algorithms - Tc-Pd Onsite



predominant period ~ earthquake magnitude:





Kanamori, 2005

Speed

Performance

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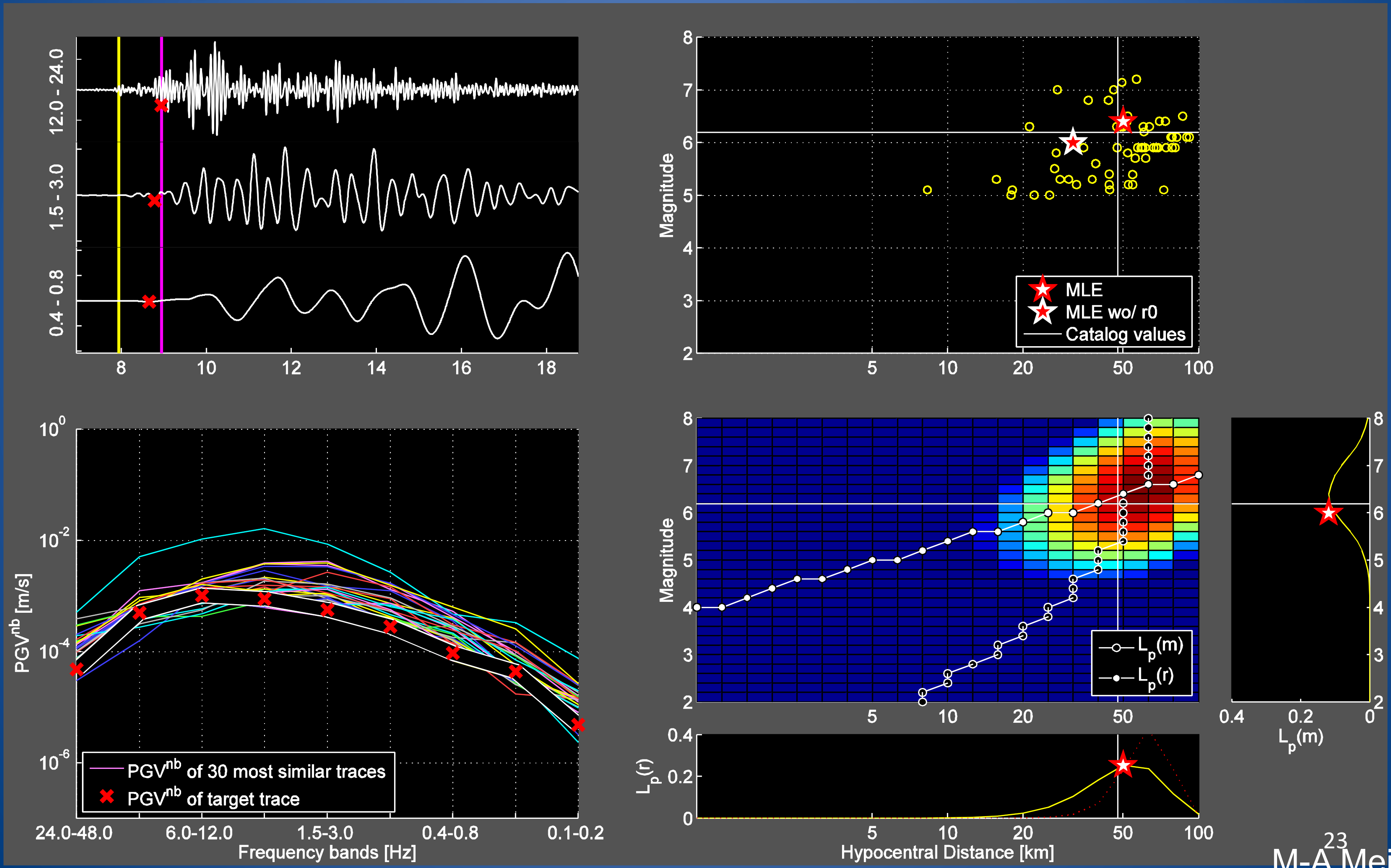
Warning Times/Blind-Zone

2. Fast Algorithms - **Filterbank**



M-A Meier

Performance

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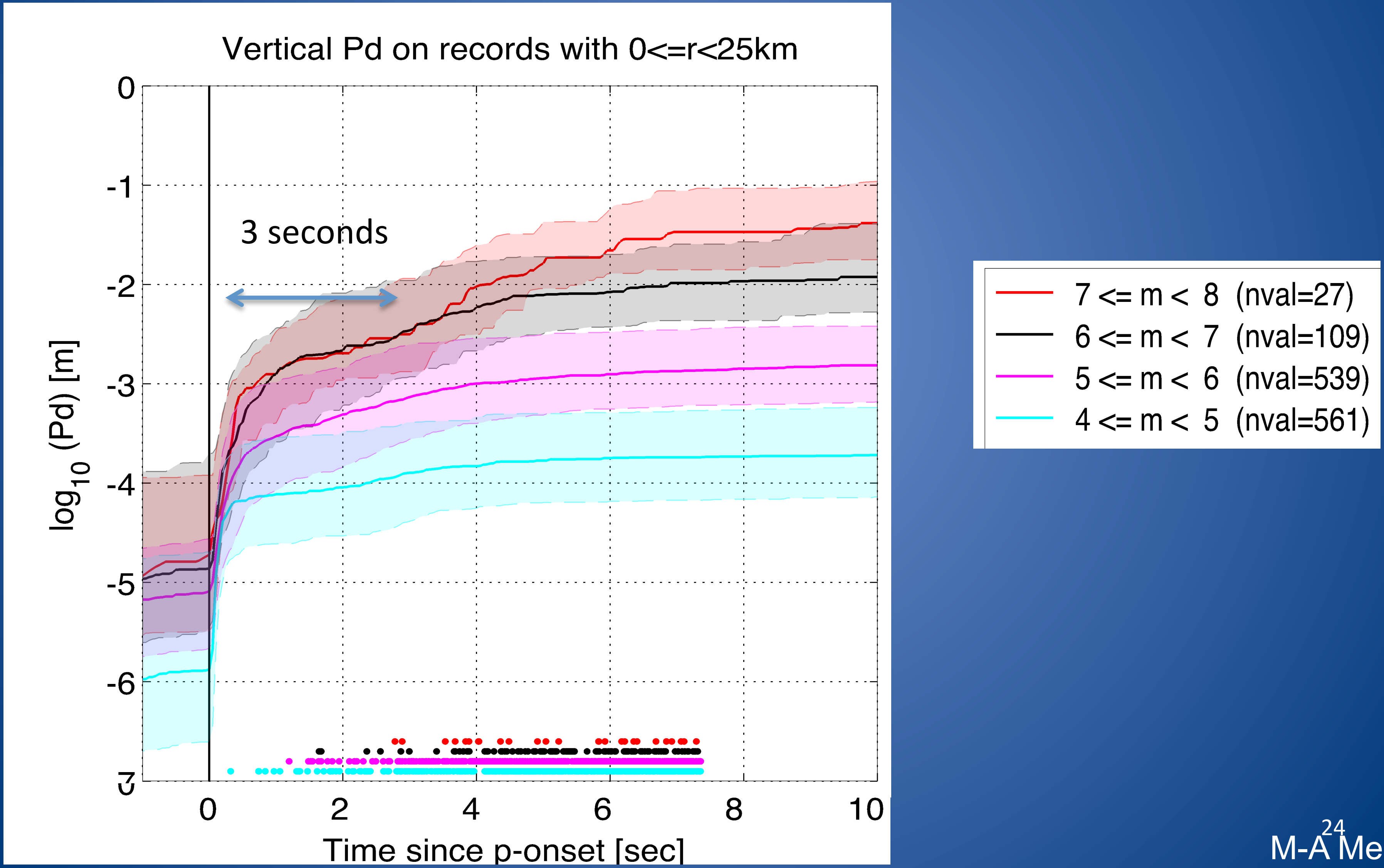
Warning Times/Blind-Zone

2. Fast Algorithms - **Limitations**



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Speed

Challenge

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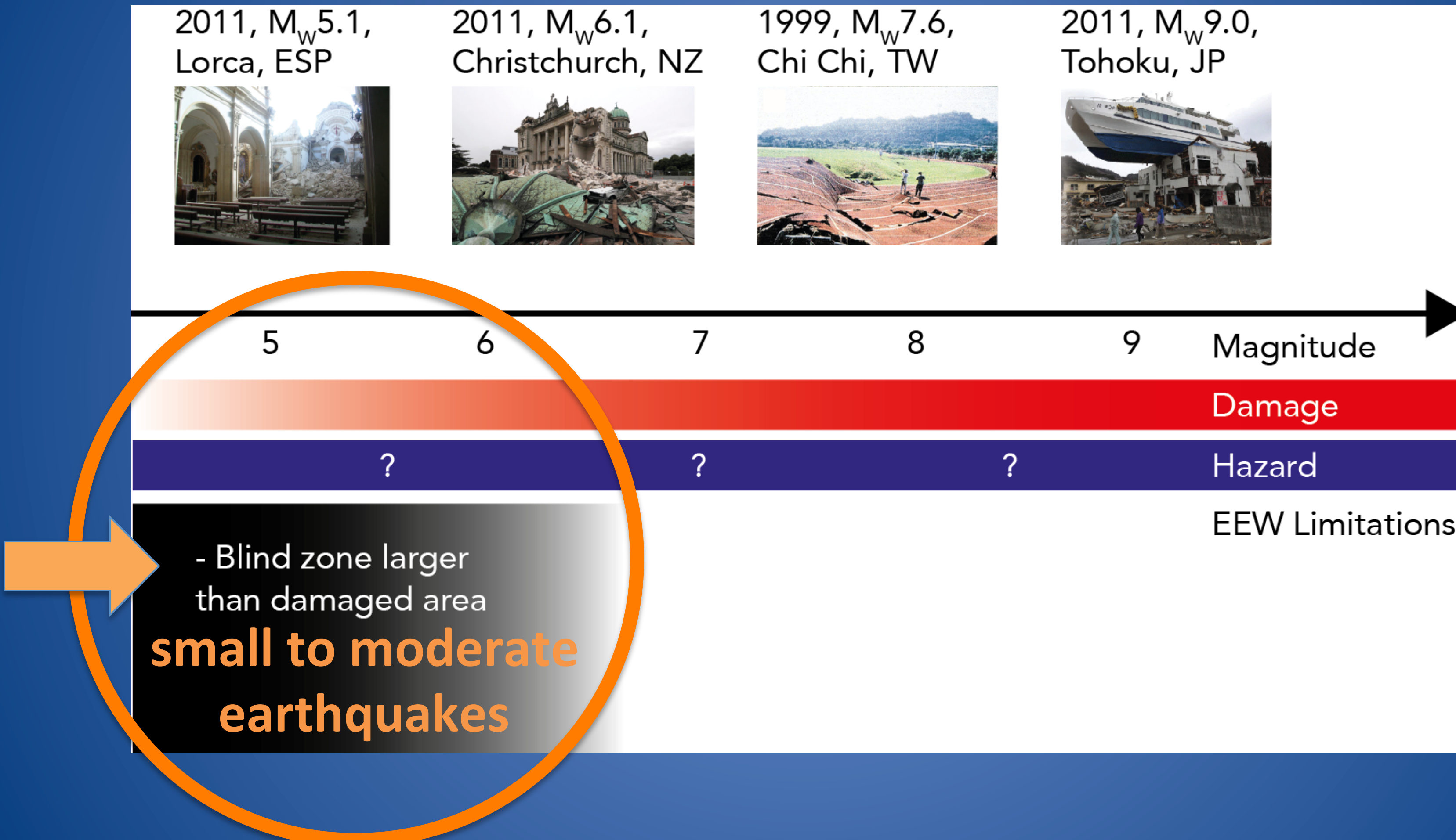
Warning Times/Blind-Zone

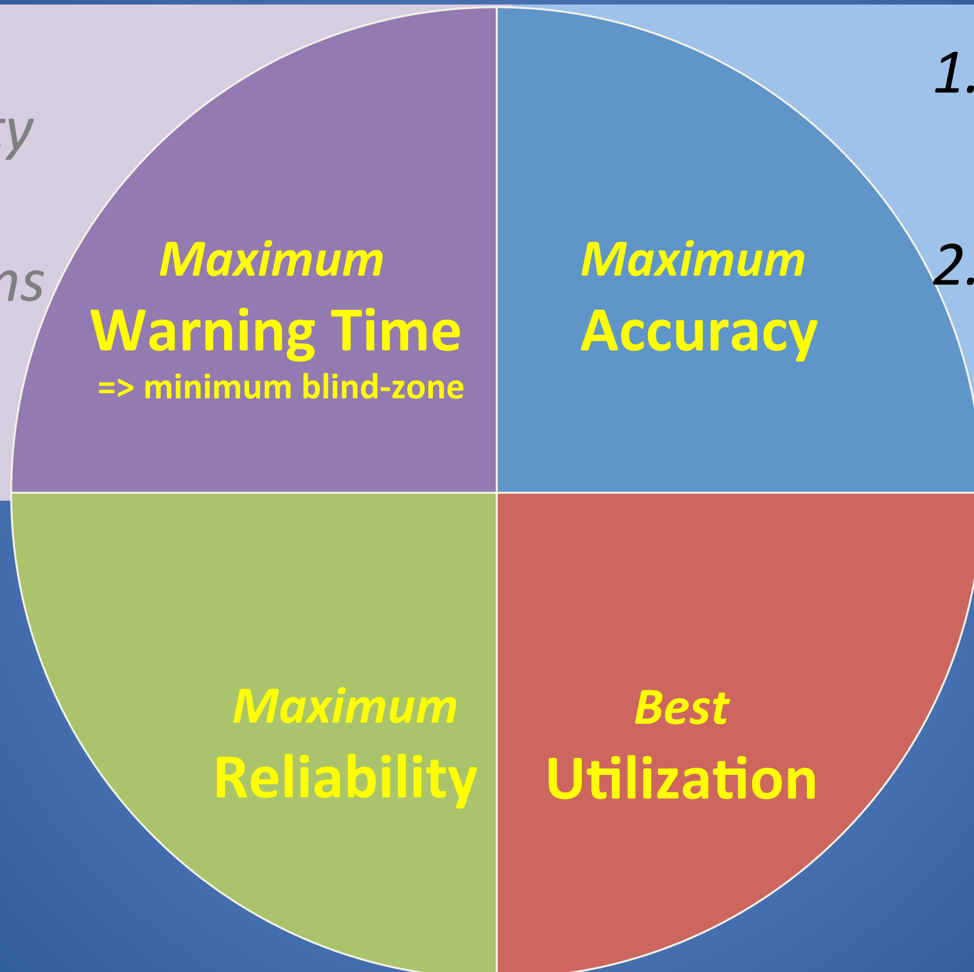


seismic waves are too slow!

Performance

1. *station density*
2. *fast algorithms*

Challenge:
small to moderate EQs M<6.5



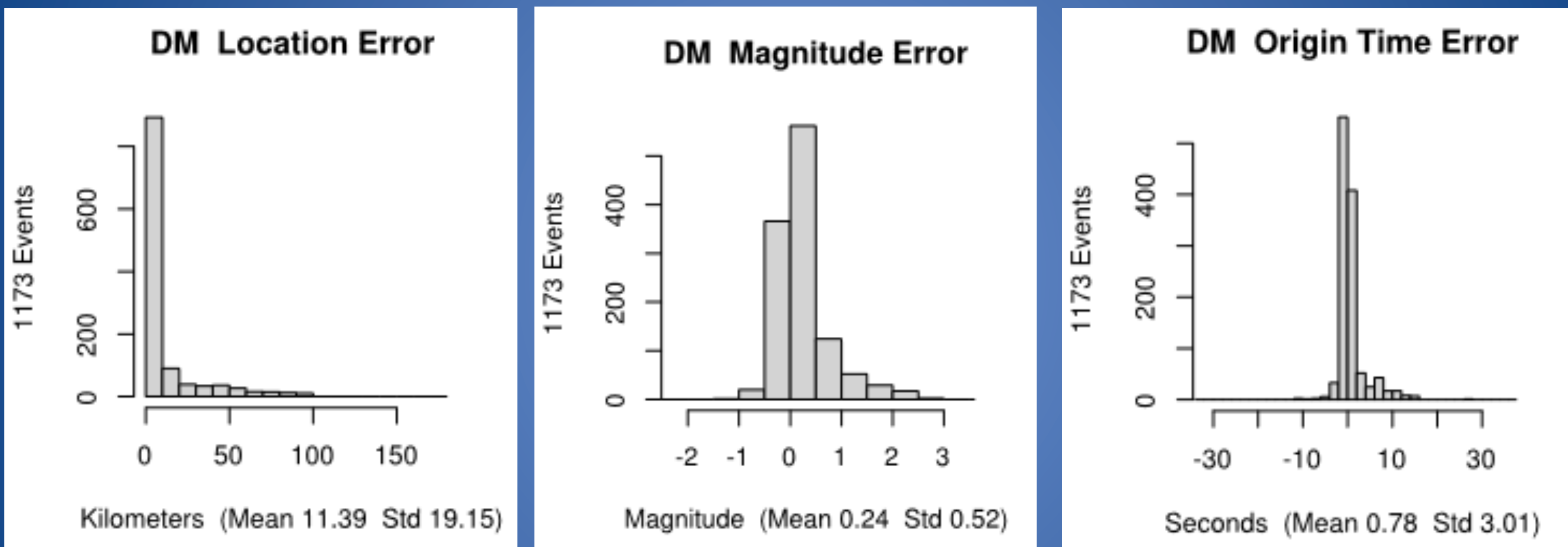
1. *source characterization*
2. *ground-motion prediction*

Challenge:
large EQs M>=6.5

Performance

Accuracy: 1. Earthquake Source Characterization

ShakeAlert:



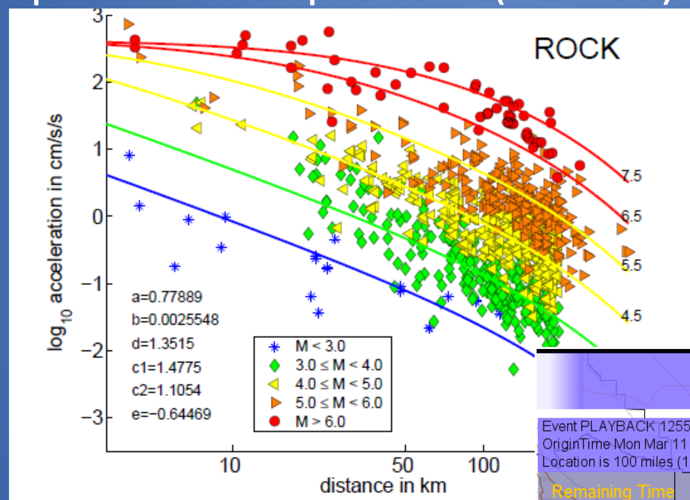
Depend on event size
and location
->station density

Performance

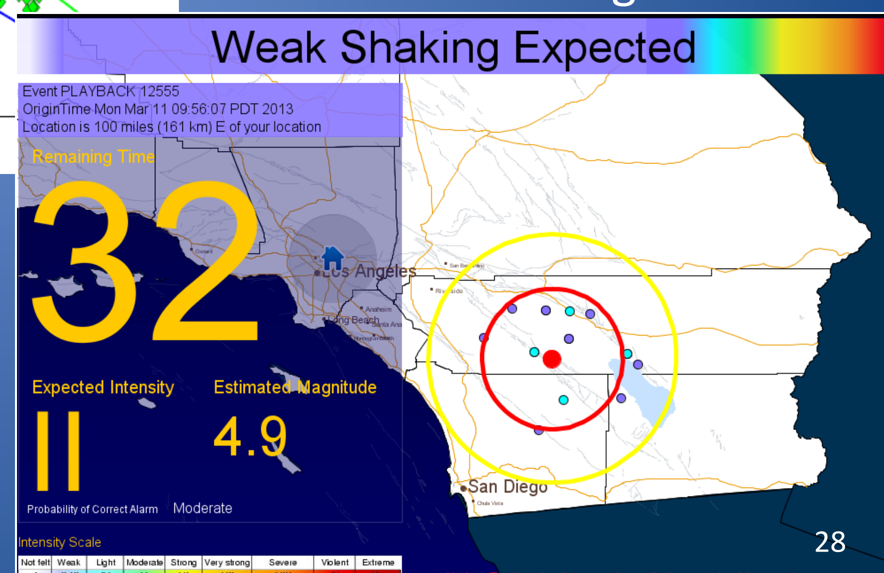
Accuracy: 2. Ground-Motion Prediction

source parameters:
- magnitude
- hypocenter

ground-motion
prediction equations (GMPEs)

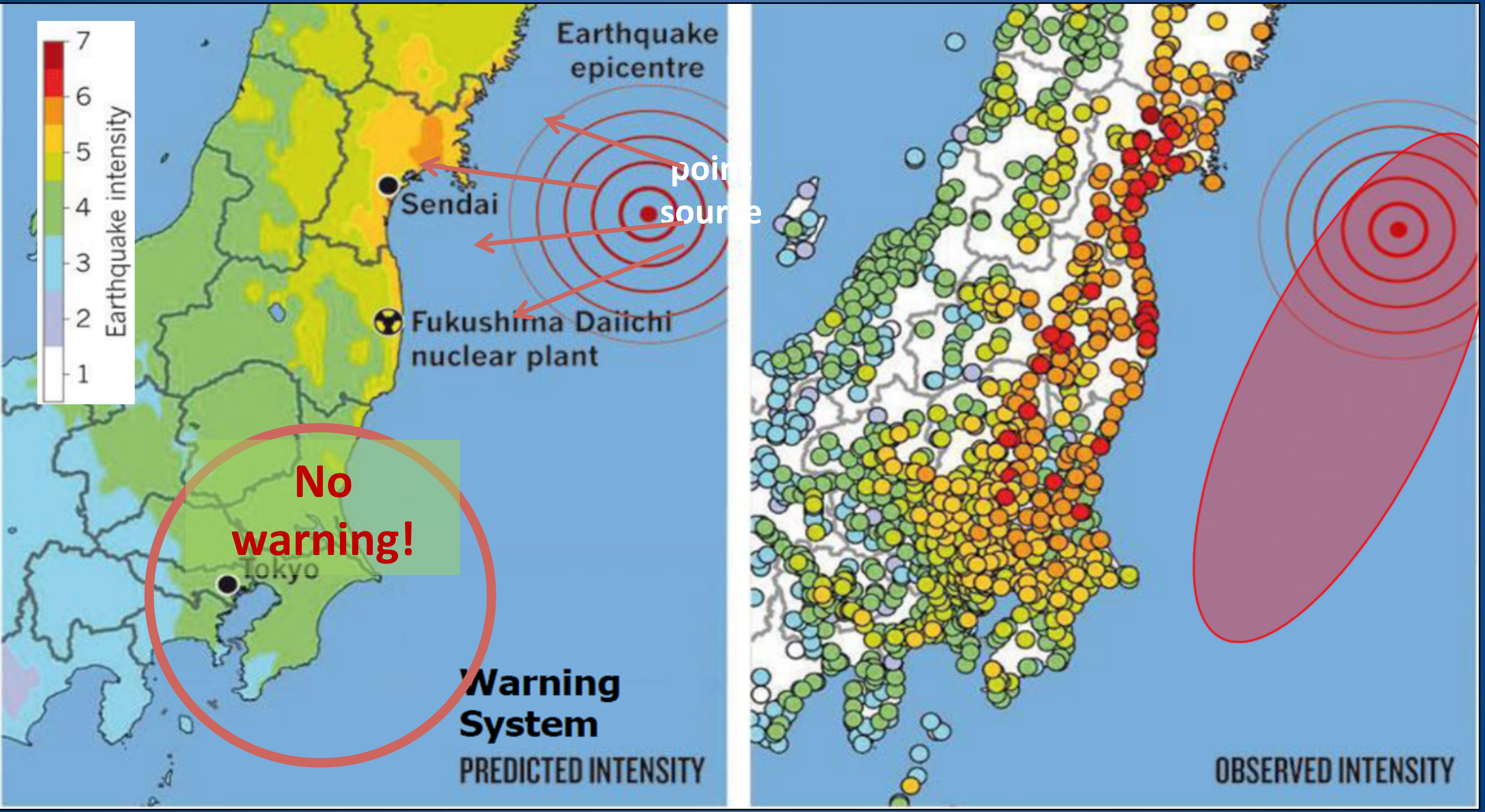


site-dependent
shaking



Challenge

Large Earthquakes: 1. Finite-Fault Ruptures



M9 Tohoku-Oki, Japan

M Yamada

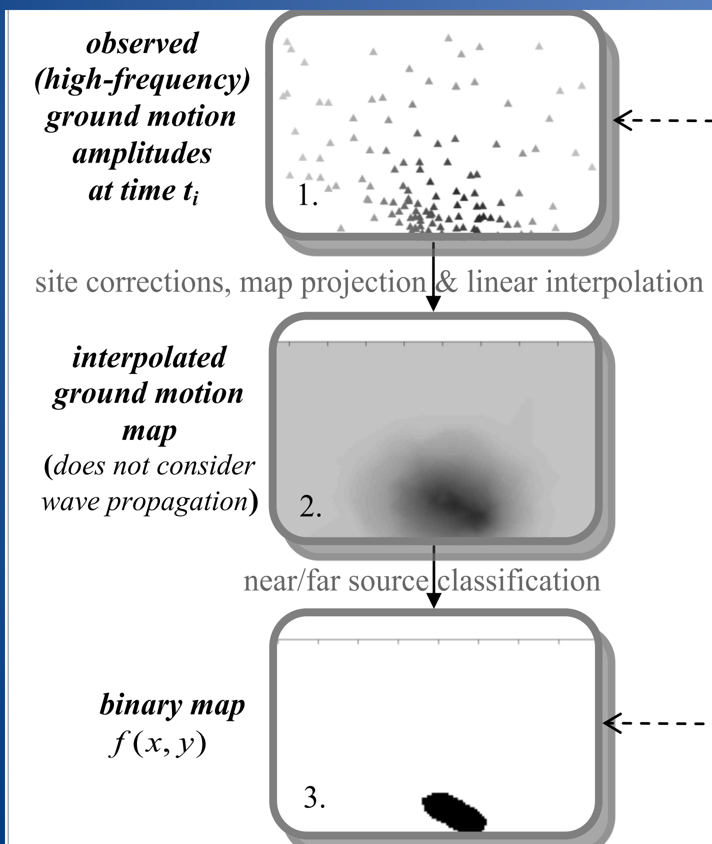
Large Earthquakes: 1. Finite-Fault Ruptures

Finite-Fault Rupture Detector (FinDer)

Böse *et al.*, 2012

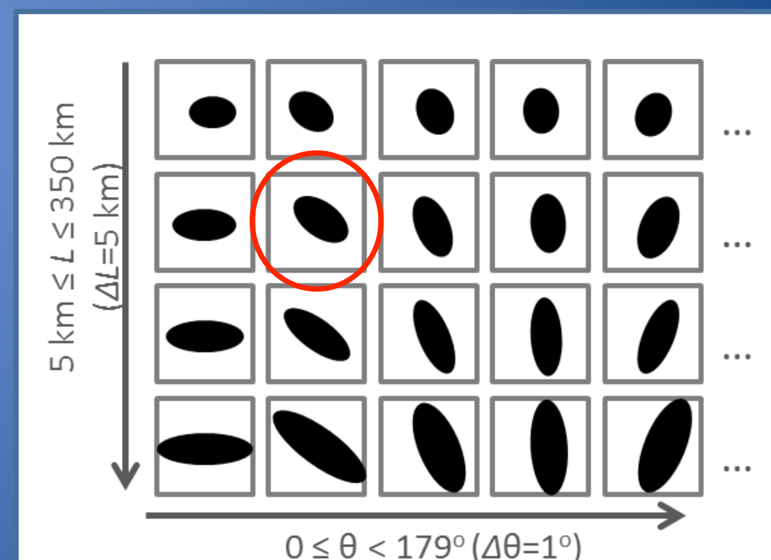
use spatial distribution of PGA observations to find best line source

observations



templates

generic templates

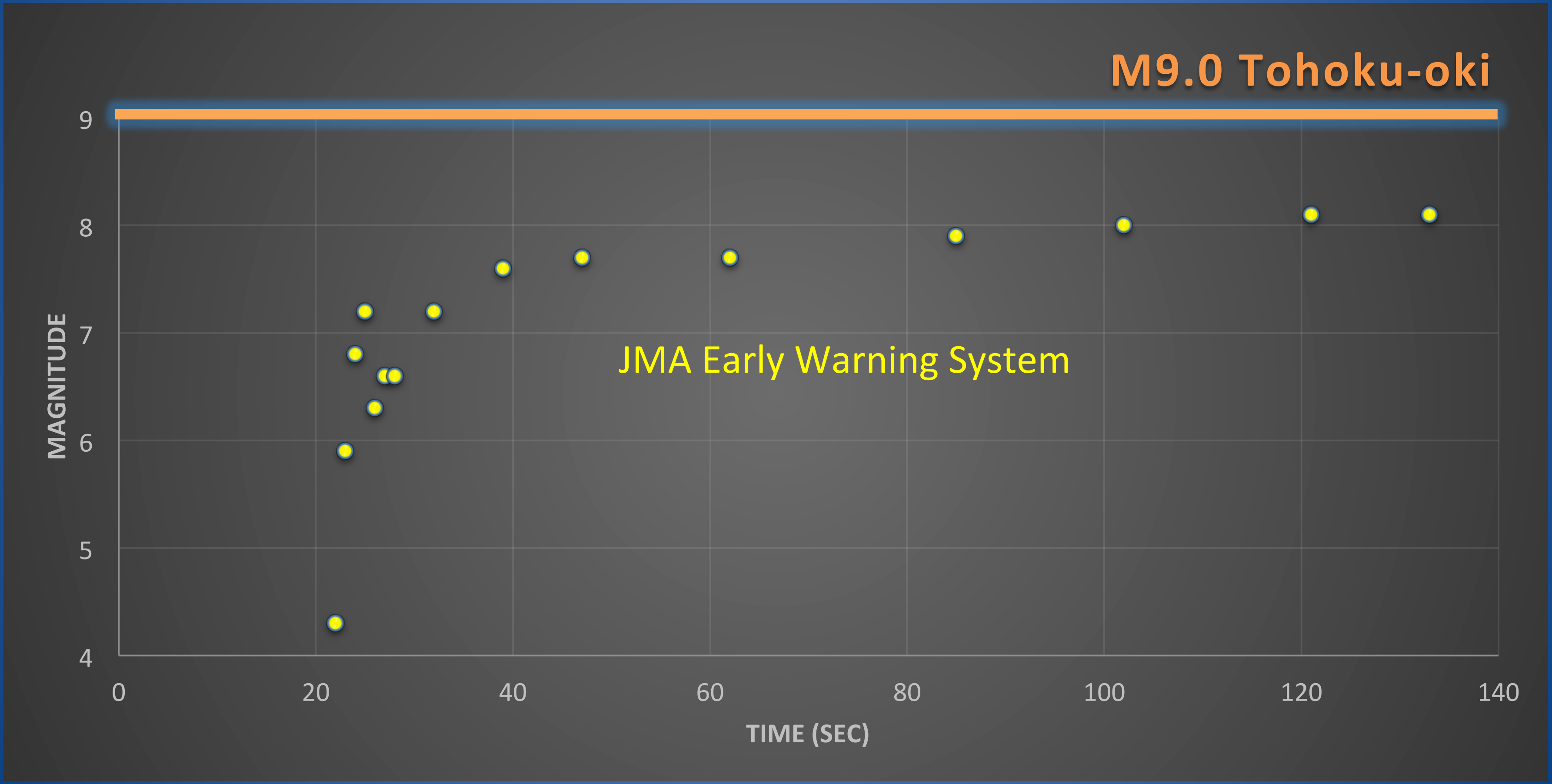


+

fault-specific templates

Challenge

Large Earthquakes: 2. Magnitude Saturation



Large Earthquakes: 2. Magnitude Saturation

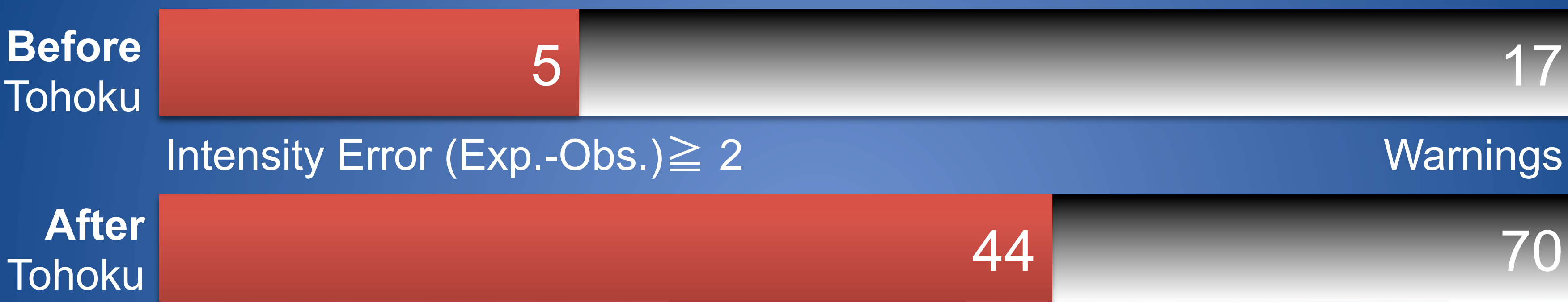
Real-time GPS/GNSS (GPSlip, BEFORES, G-larmS)

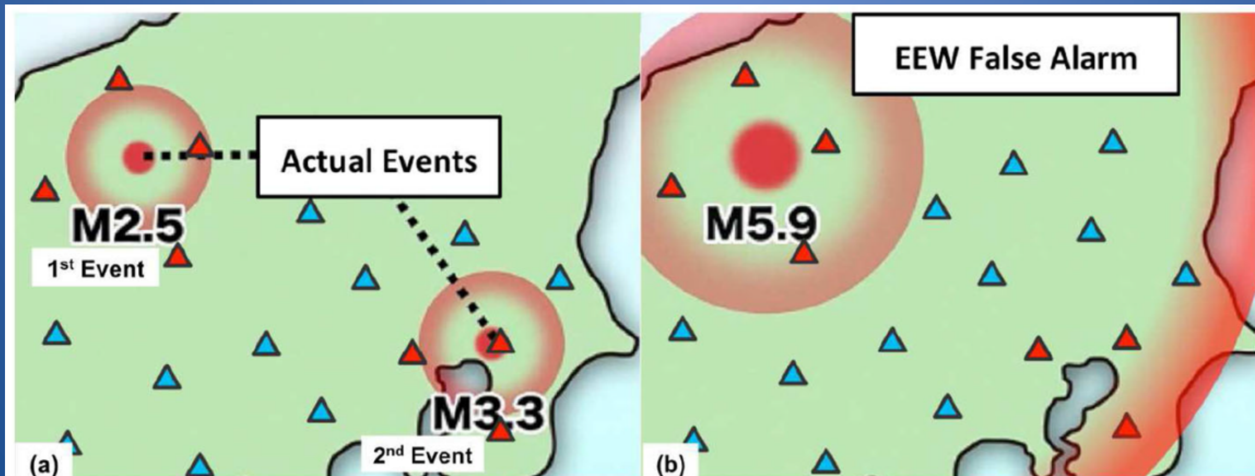
use spatial distribution of static and dynamic displacement to find best slip model

- -> no magnitude saturation
- essential for tsunami warning

Large Earthquakes: 3. Aftershocks

False Alert Rates





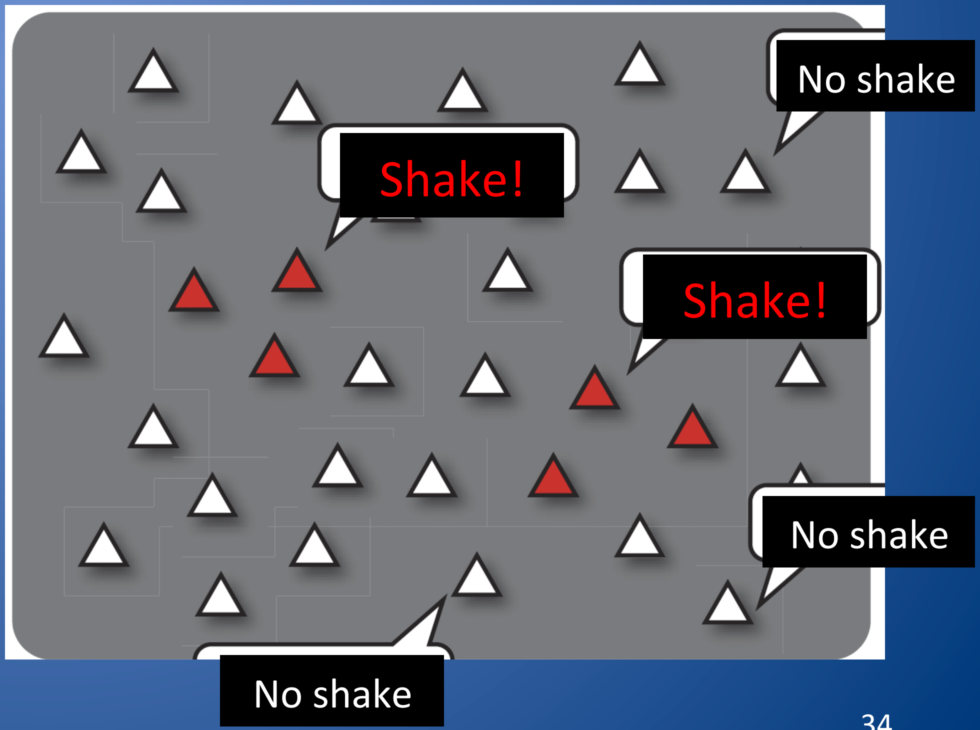
http://www.jma.go.jp/jma/press/1104/28b/eew_hyouka_2.pdf

Large Earthquakes: 3. Aftershocks

Integrated Particle Filter Approach

Wu *et al.*, 2014

- *use of NON triggered data (amplitude & trigger time)*
- *probabilistic scheme for a quick optimization using a Bayesian approach*
- *90% less false alarms (2 month after Tohoku)*



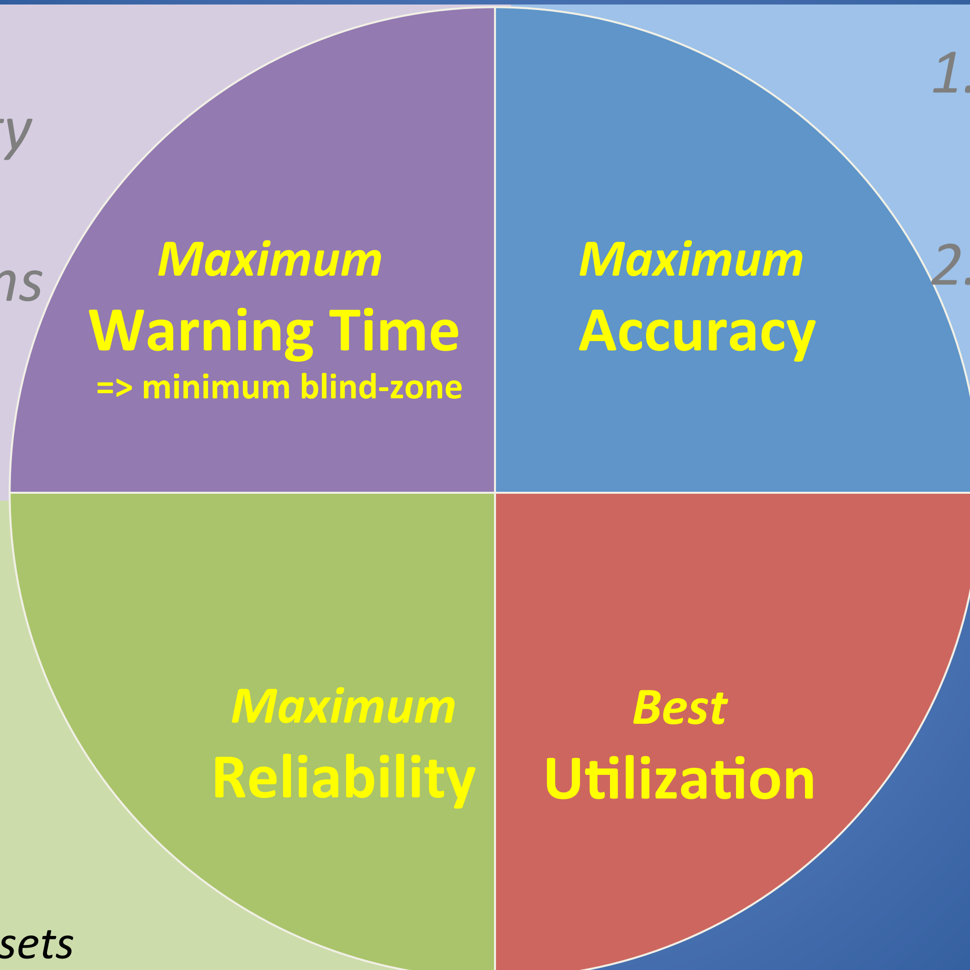
Performance

1. *station density*
2. *fast algorithms*

<u>Challenge:</u>
small to moderate EQs M<6.5

1. *source characterization*
2. *ground-motion prediction*

<u>Challenge:</u>
large EQs M>=6.5



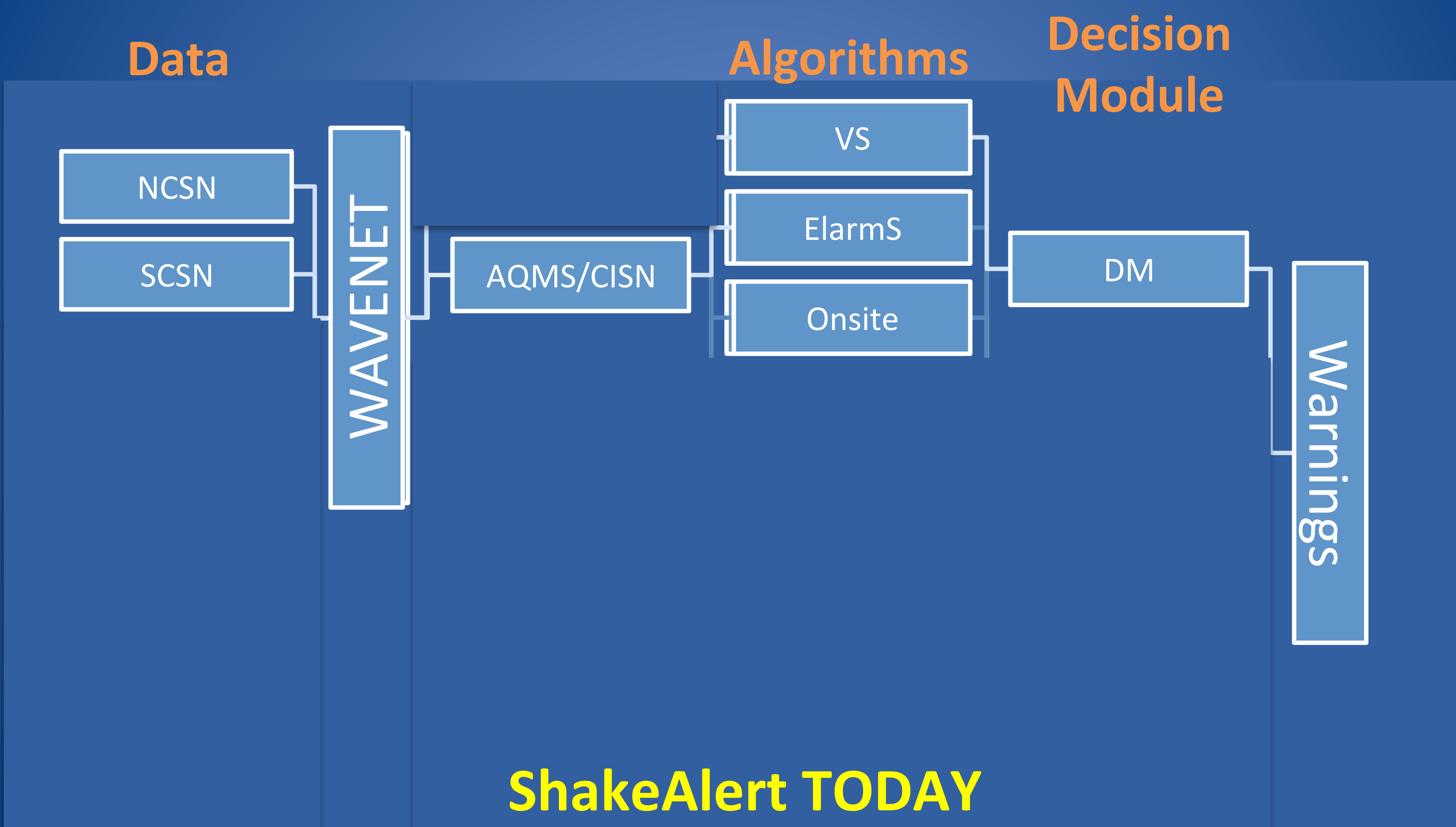
1. *redundancy*
2. *integration*

<u>Challenge:</u>
combining multiple algorithms and datasets

Reliability

Challenge

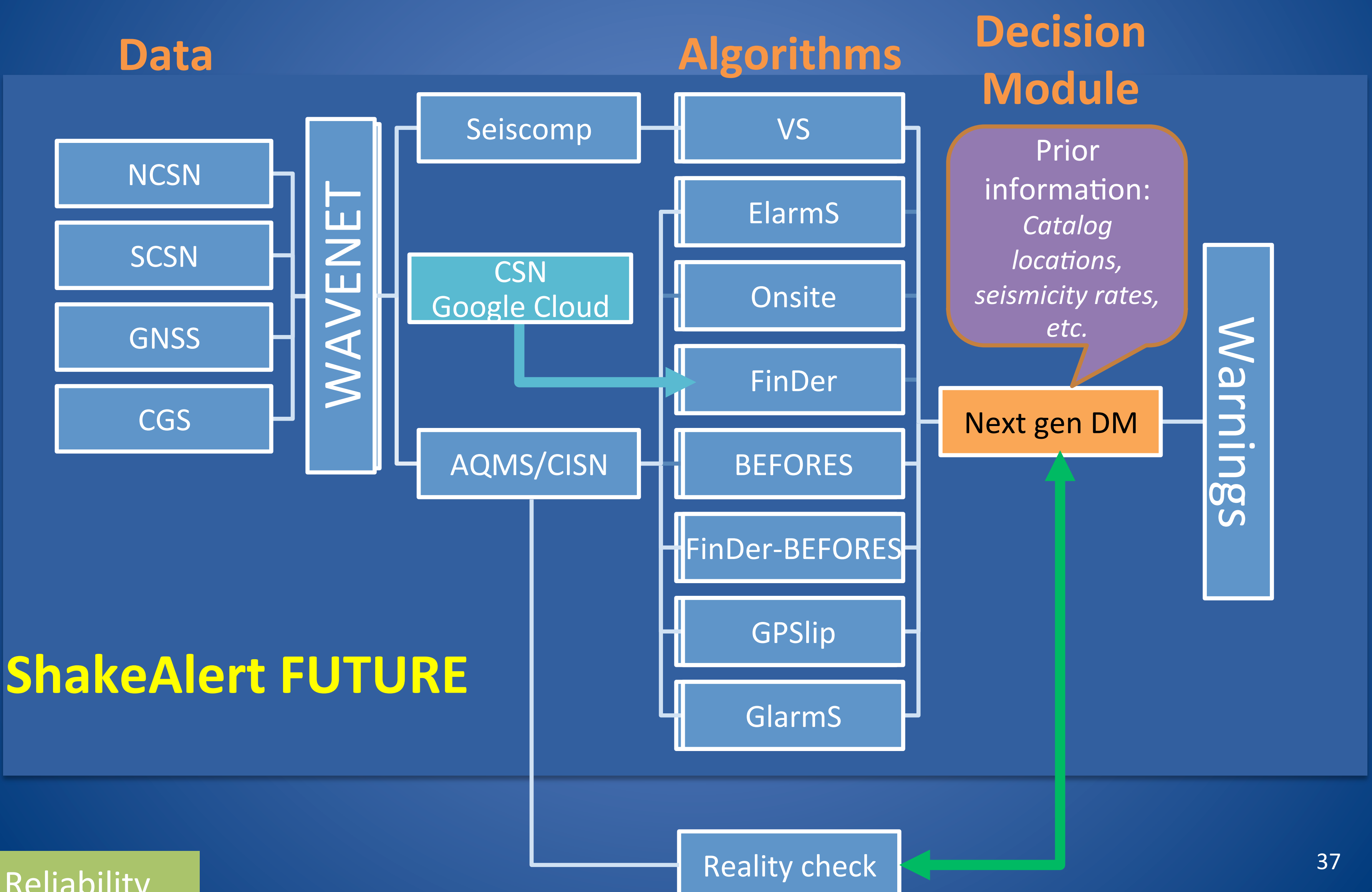
Combining Multiple Algorithms & Datasets



Reliability

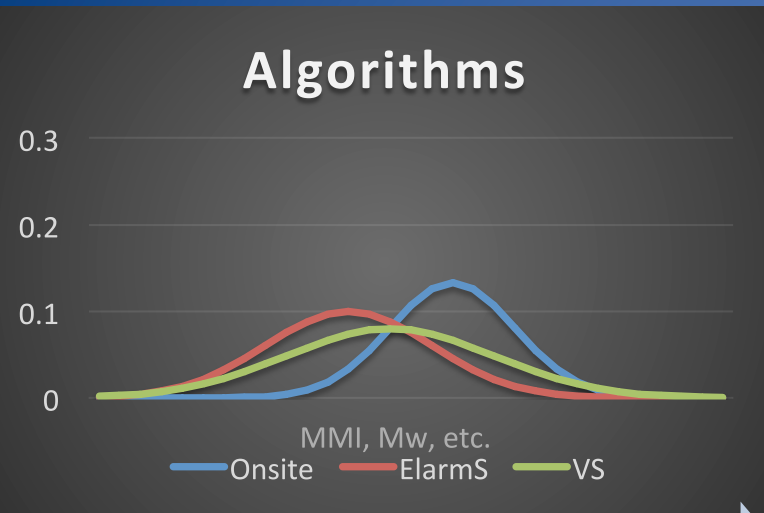
Accuracy

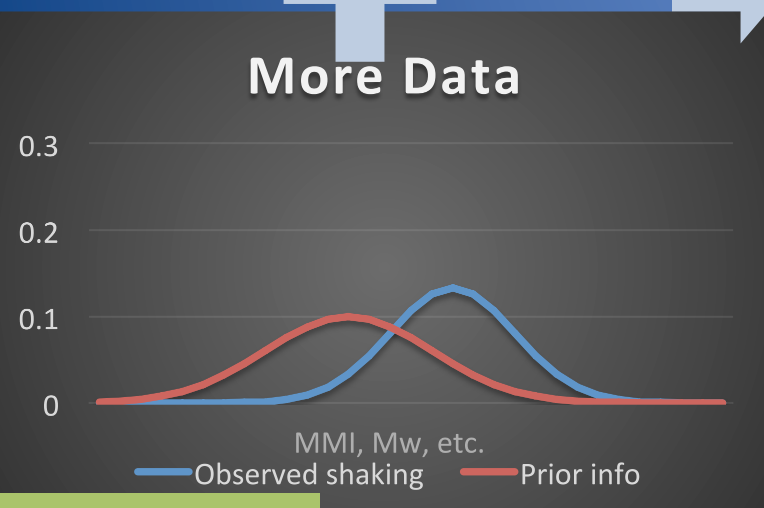
Combining Multiple Algorithms & Datasets

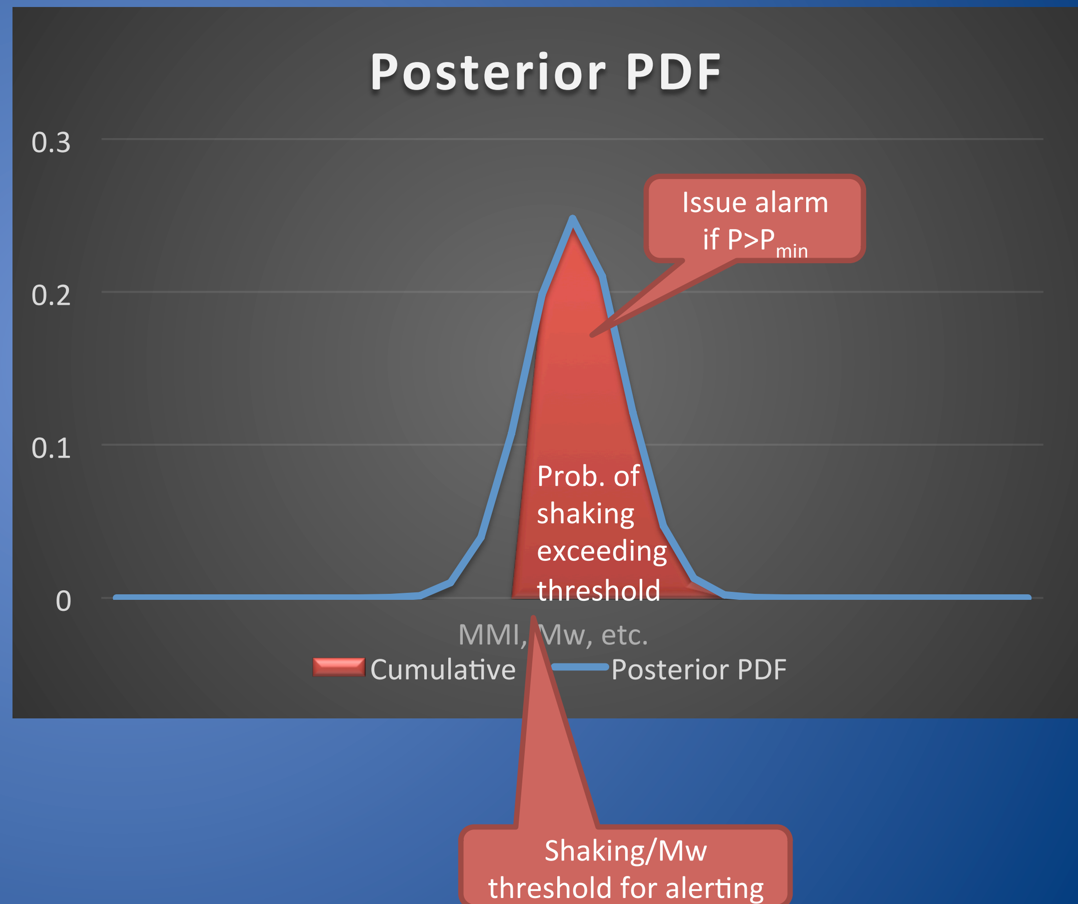


Reliability

Combining Multiple Algorithms & Datasets







Threshold and minimum probability for issuing alarms can be customized for each user.

Approach

Combining Multiple Algorithms & Datasets

Approach: Bayesian Framework

Bayes's theorem:

posterior *likelihood* *prior*

$$prob(X|Y,I) = \frac{prob(Y|X,I) \times prob(X|I)}{prob(Y|I)}$$

- Probability measures a *degree of belief*.
- Bayes's theorem then links the degree of belief in a proposition before and after accounting for evidence.

Approach

Accuracy

Combining Multiple Algorithms & Datasets

Example: FinDer (seismic) – BEFORES (geodetic)

seismic observations

dynamic acceleration

FinDer

Böse *et al.*, 2012

- rupture location and length
- fault strike θ

build finite fault mesh

GPS observations

static displacement

BEFORES

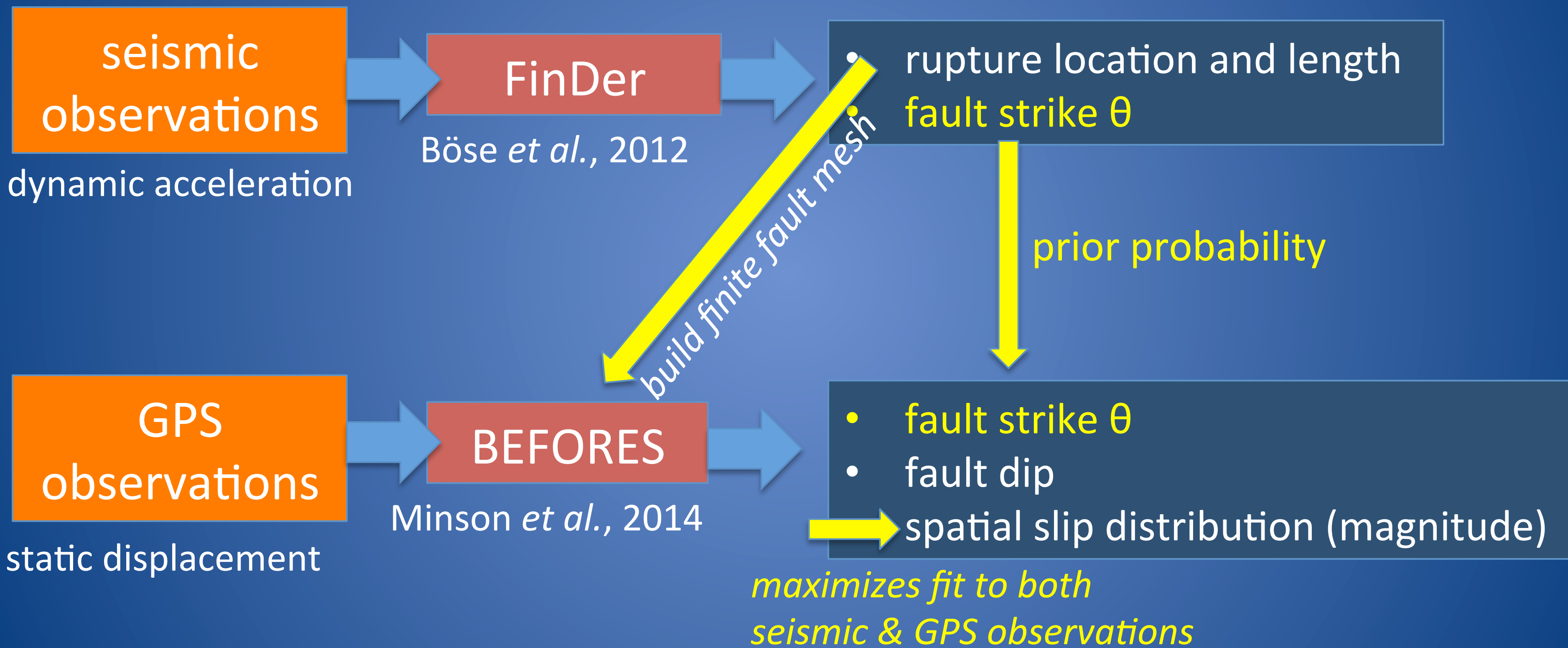
Minson *et al.*, 2014

- fault strike θ
- fault dip
- spatial slip distribution (magnitude)

Reliability

Combining Multiple Algorithms & Datasets

Example: FinDer (seismic) – BEFORES (geodetic)

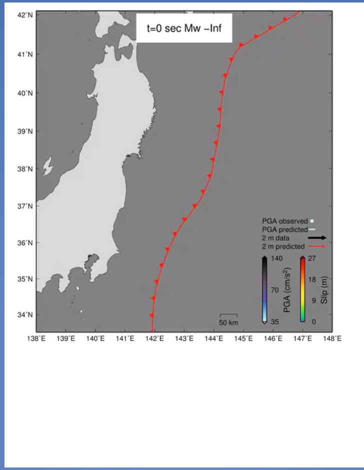


BEFORES is Bayesian. Any analysis of independent data (e.g., seismic) can be put into BEFORES' prior probability distribution and the resulting output is then the solution to the ***joint*** inversion of those data sets.

Performance

Combining Multiple Algorithms & Datasets

Example: FinDer (seismic) – BEFORES (geodetic)

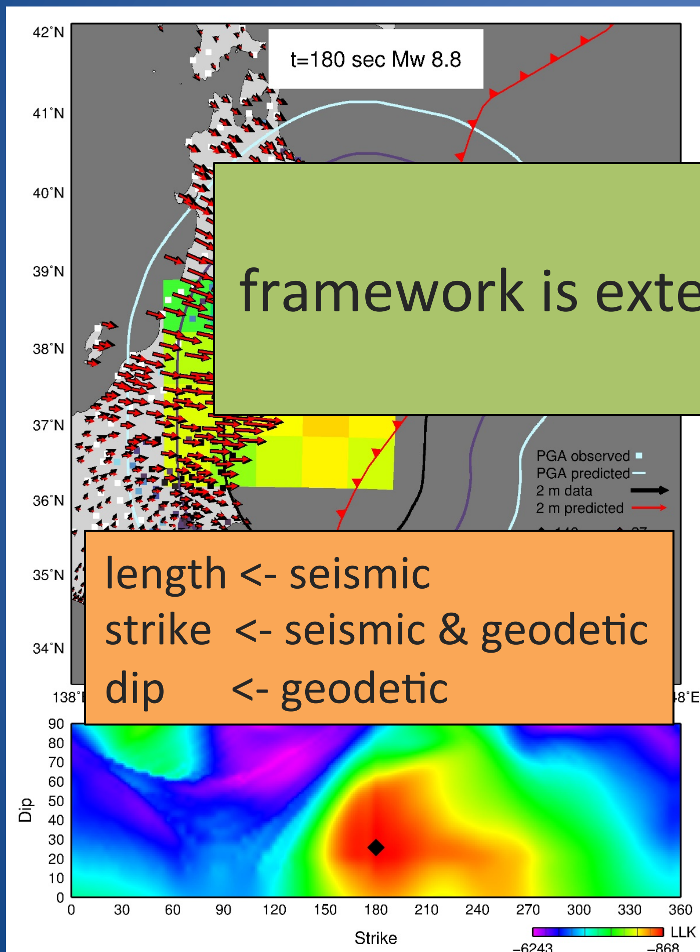


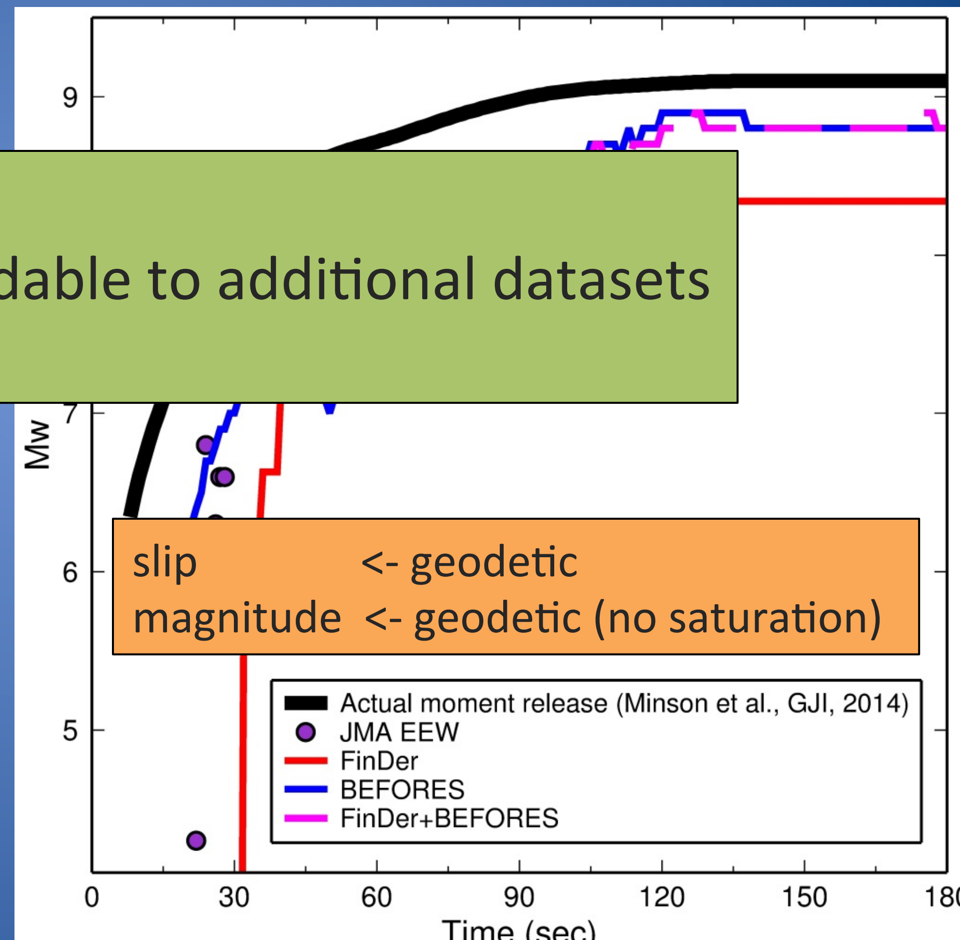
M9 Tohoku

Performance

Combining Multiple Algorithms & Datasets

Example: FinDer (seismic) – BEFORES (geodetic)





framework is extendable to additional datasets

length <- seismic
strike <- seismic & geodetic
dip <- geodetic

slip <- geodetic
magnitude <- geodetic (no saturation)

S Minson

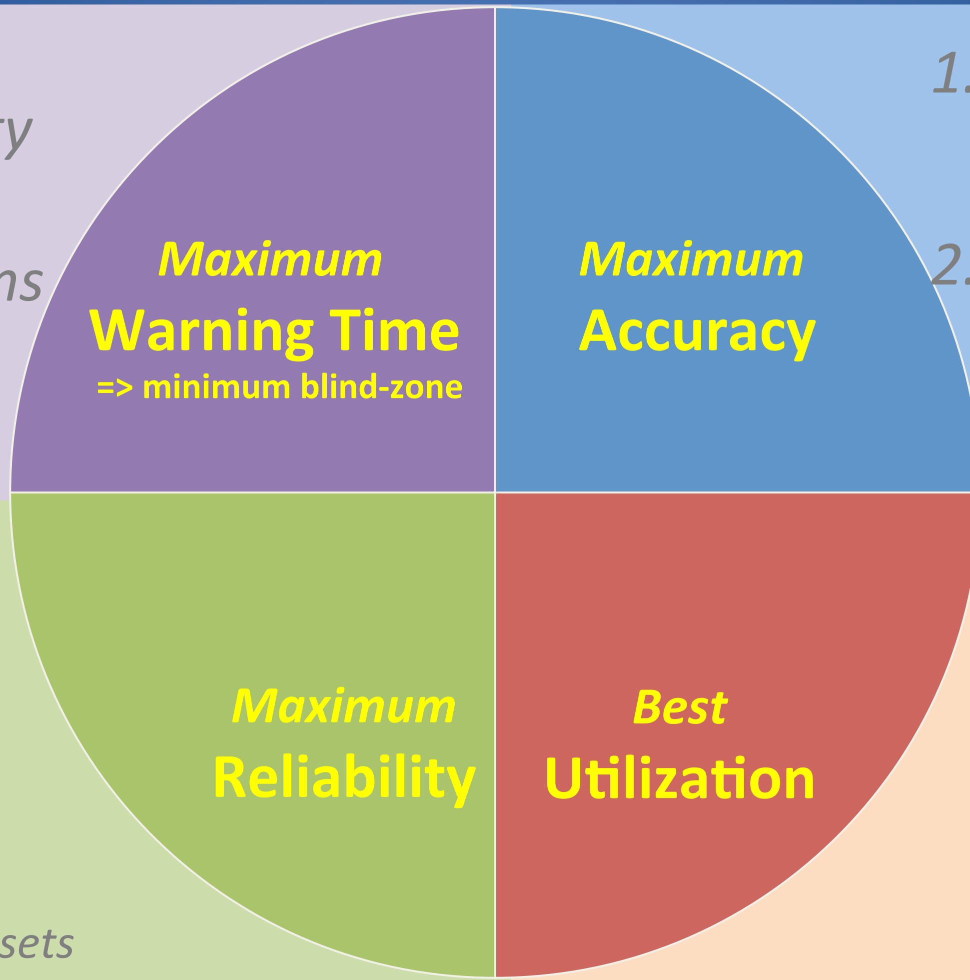
Performance

1. *station density*
2. *fast algorithms*

Challenge:
small to moderate EQs M<6.5

1. *source characterization*
2. *ground-motion prediction*

Challenge:
large EQs M>=6.5



1. *redundancy*
2. *integration*

Challenge:
combining multiple algorithms and datasets

communication

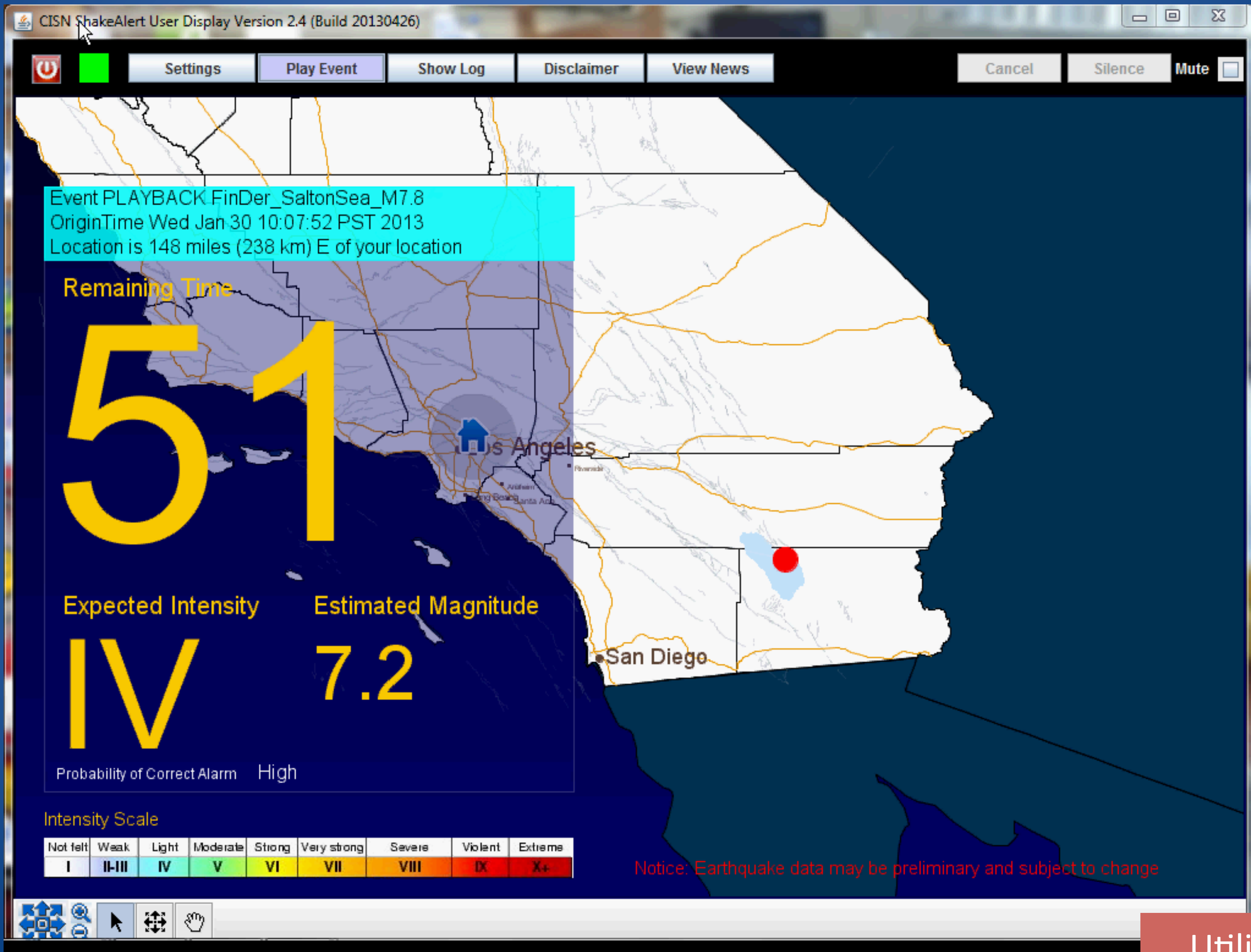
education

automated decision-making

M. Böse

Performance

Demonstration for the M7.8 ShakeOut Scenario Earthquake



Utilization

Summary

2011, M_w5.1, Lorca, ESP

2011, M_w6.1, Christchurch, NZ

1999, M_w7.6, Chi Chi, TW

2011, M_w9.0, Tohoku, JP

M-A Meier

5 6 7 8 9 Magnitude

Damage

? ? ? Hazard

EEW Limitations

- Blind zone larger than damaged area

small to moderate earthquakes

Challenge I

seismic waves are too slow!

large earthquakes

Challenge II-IV

- Magnitude saturation
- Fault finiteness
- Rupture directivity
- EEW relevant after-shocks sequence

Challenge V Combining information from multiple algorithms/datasets

Future ?

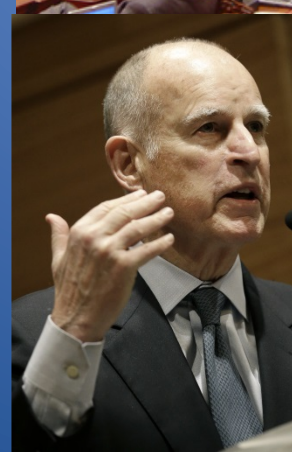
California Senate Bill 135

Statewide Public Earthquake Early Warning System

January 28, 2013
Bill announced by State Senator Alex Padilla at press conference at Caltech

May 28, 2013
Passes *unanimously* in Senate

September 24, 2013
Governor Jerry Brown signs bill



Installation costs:
installation /operation for 5 yrs: ~$80 M

Damage costs:

1994 M6.7 Northridge:	$ 20 billion
1995 M6.8 Kobe:	$200 billion
xxxx M7.8 ShakeOut:	$213 billion

OKI Engineering Co.,Ltd.

Miyagi, Japan

Semiconductor manufacturer

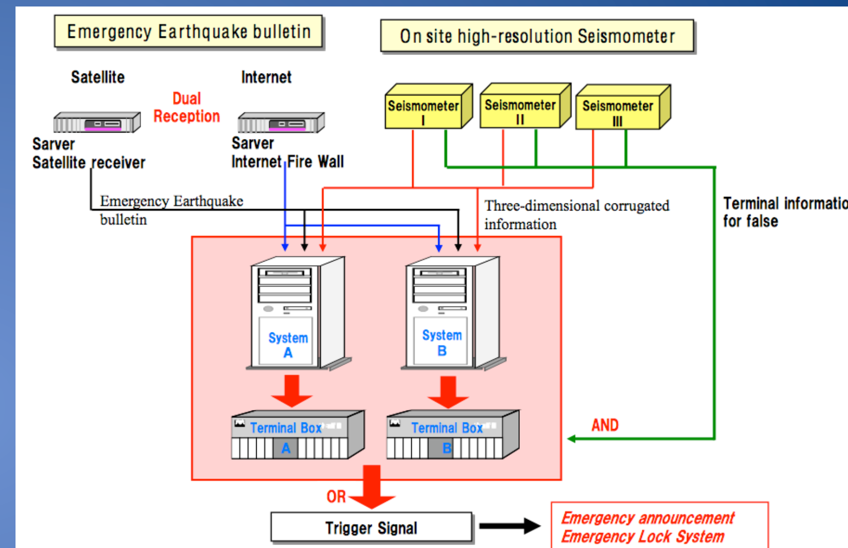
BEFORE EEW

2003: Two damaging earthquakes

- **$15 million in losses**
- fire, equipment damage
- 17 and 13 days loss of productivity

Spent $600K on early warning and shear walls in basement

- Sensitive equipment set down on floor to reduce shaking and damage

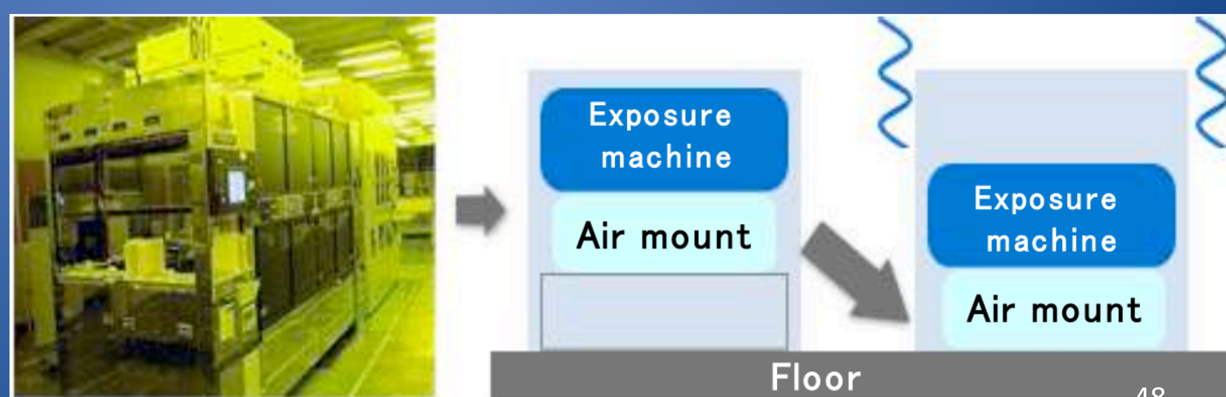


Both public and on-site systems work together

AFTER EEW

Two similar earthquakes

- **$200K in losses**
- 4.5 and 3.5 days loss of productivity

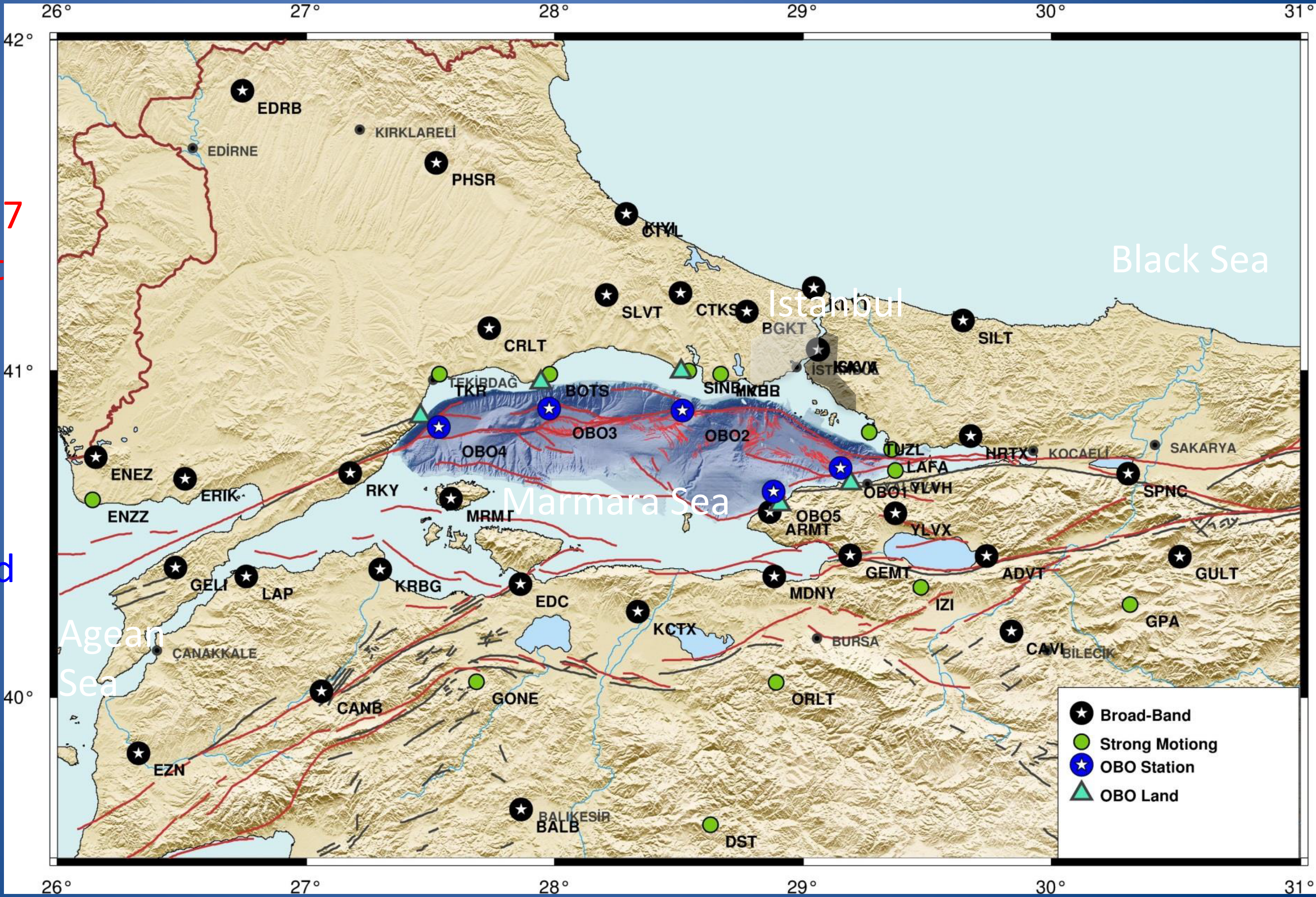


EEW in focus: Istanbul - IEEWS

- Istanbul megacity under high risk of M7.5+ event on NAF, 30km to South.
- KOERI maintain an **operational EEW system (IEEWS)** based on peak motion thresholds for Marmara sea stations. Operational since 2002 using 10 land sensors, upgrade using OBS in 2010.
- no location, magnitude: *just imminent strong shaking expected*

First IEEWS Alert issued for local M4.7 Marmara Sea event in 11/2013

Public alerts not available or planned



EEW in focus: Istanbul – Current End Users

IGDAS natural gas company

High pressure district regulators have local strong motion stations (100 of 700 currently instrumented), with EEW thresholds defined (combine PGA, PGV, intensities…)

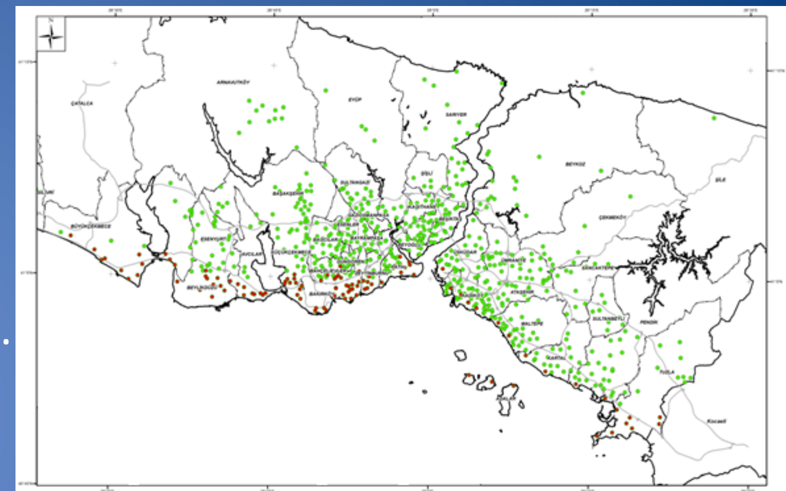
Automatic shutdown if

- IEEWS + low threshold
- No IEEWS + high threshold

Thresholds dependent on building stock served in district.

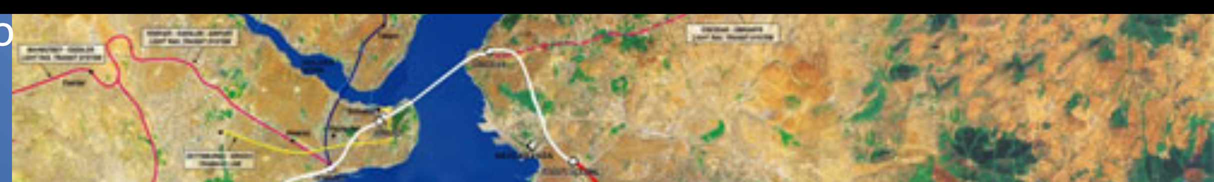
No shutdown as of yet activated

<poster by Zulfikar et al, this meeting>



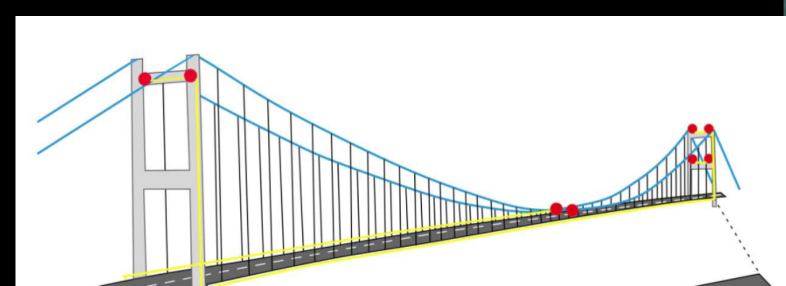
Other End Users receive alerts only for *situational awareness*:

Marmaray Tunnel: 1.4km tunnel under Bosphorus part of new metro line, with 22 strong motion sensors



Bosphorus Bridges / High Rise

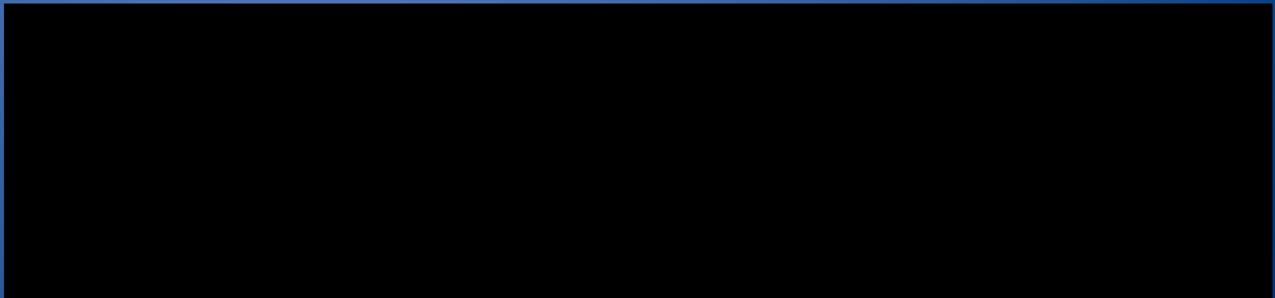
Active project to combine EEW messages with Structural Health Monitoring of critical infrastructures



EEW in focus: Istanbul – Towards Regional EEW

Critical Structures in Istanbul also at risk to large distant events with significant long period energy

KOERI test both VS(SC3) and Presto+ with a view to integration into IEEWS



<poster by Pinar et al, this meeting>