The W Phase

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Jennifer Nealy (NEIC)

The W Phase

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(Gavin Hayes
U.S. Geological Survey, National Earthquake Information Center)

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What is the W Phase?

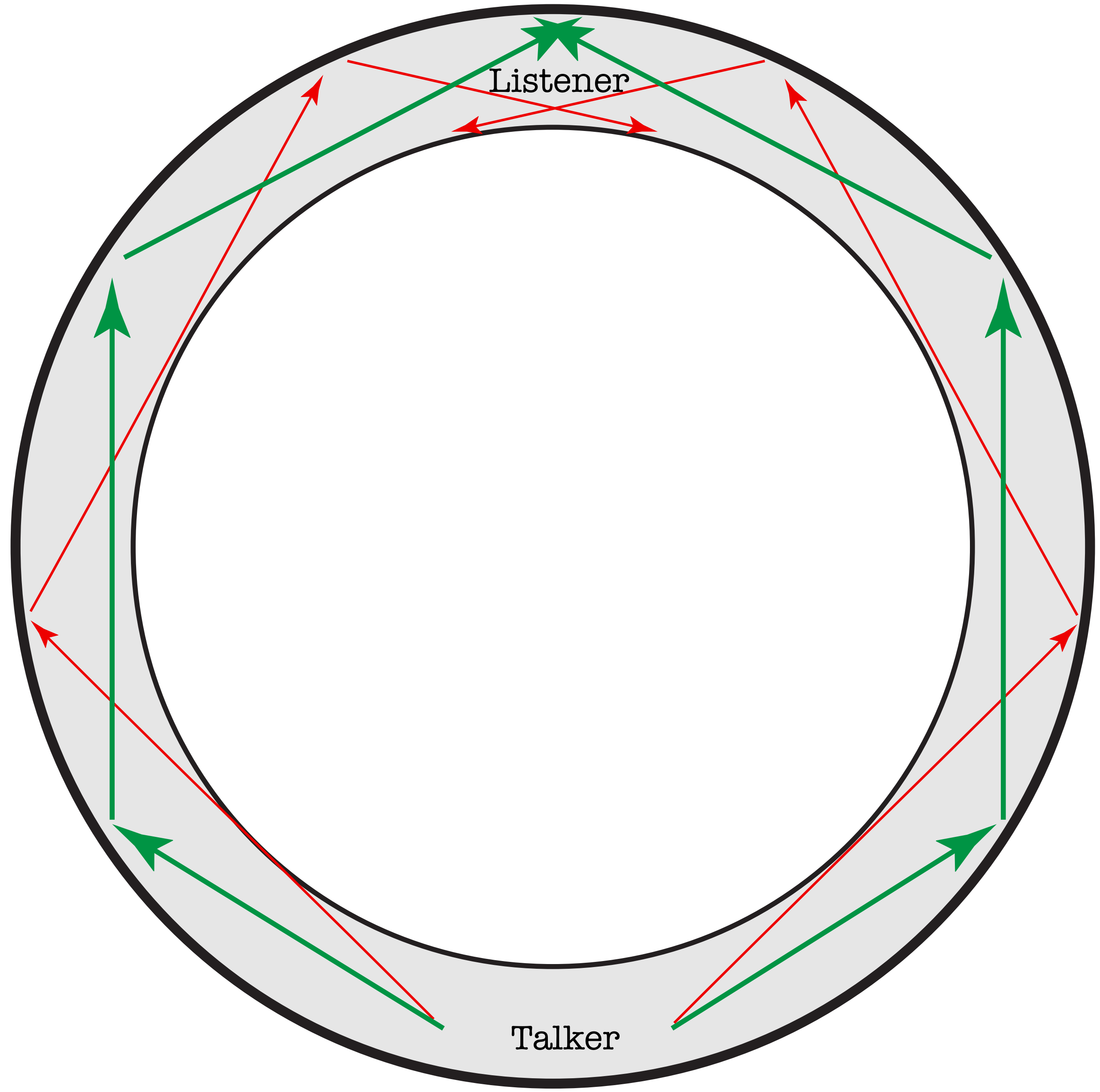
Complex interference of body waves at very long periods.

Arrives between the P- and surface-waves ==> fast.

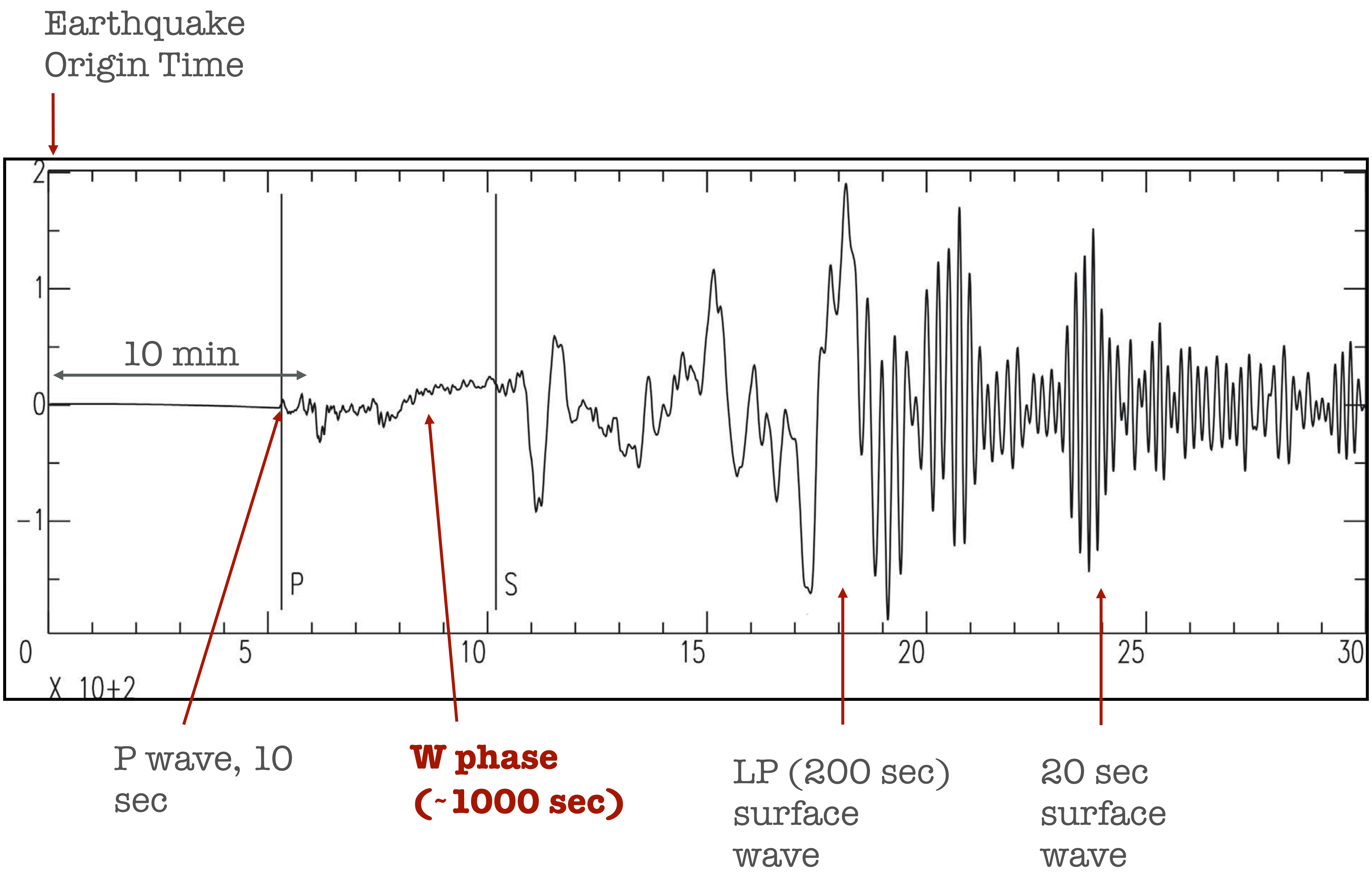
Travels in the upper mantle ==> stable (unaffected by shallow heterogeneity).

Analogous to a whispering gallery effect - hence ‘W’ phase.

Can be synthesized by the superposition of normal modes.



What is the W Phase?



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W PHASE

Hiroo Kanamori

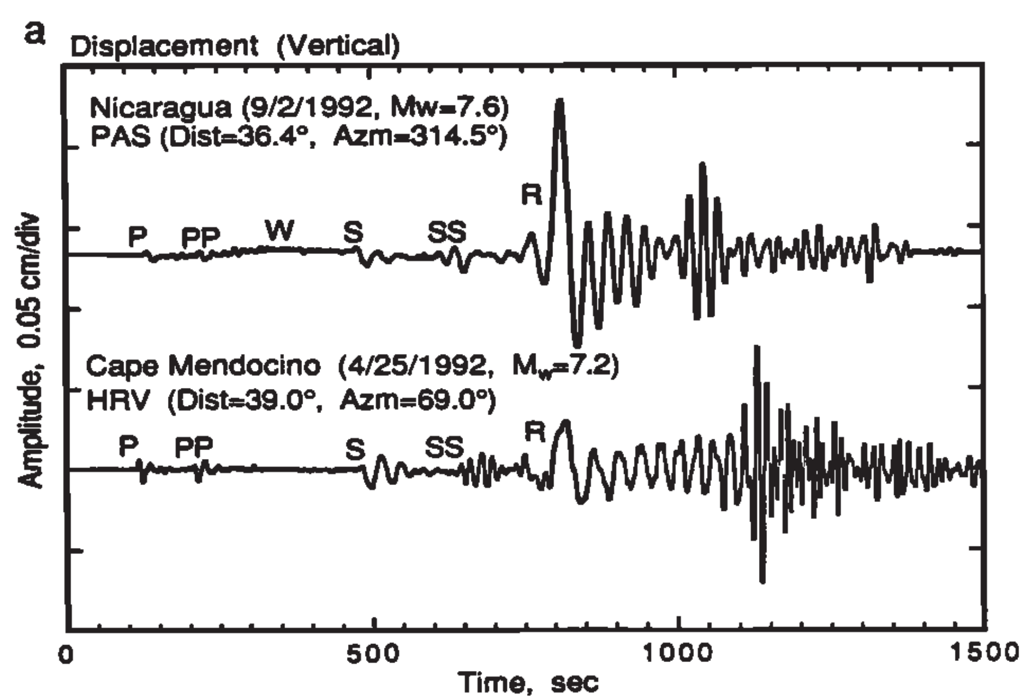
Seismological Laboratory, California Institute of Technology

Abstract. The recent Nicaragua tsunami earthquake (September 2, 1992) produced a distinct ramp-like long-period (up to 1000 sec) phase which begins between *P* and *S* waves on displacement seismograms. In terms of ray theory, this phase consists of long-period *P*, *PP*, *S*, *SS*, *SP*, *PS*, etc and its propagation mechanism is similar to that of a whispering gallery. In terms of normal-mode theory, it represents a group of higher-mode Rayleigh waves with a group velocity close to, but slower than, that of *P* wave. This phase has not been recognized as a distinct phase in the seismological practice because of clipping of seismograms for very large earthquakes. With the advent of modern wide-dynamic range seismographs, this phase can be easily identified for all large earthquakes. In view of its use for identifying slow earthquakes, determining whether slow deformation is precursory or coseismic to the regular short-period energy release, and determining velocity structures between the source and the station, we propose that this phase be called the "*W* phase".

Typical seismograms exhibit distinct short-period (up to 30 sec) body-wave phases, such as *P*, *PP*, *S*, *SS*, *SP*, *PS*, etc, which are followed by longer period (typically 10 to 250 sec) surface waves. Since both body and surface waves originate from the same source, the body-wave part of the seismogram must also contain long-period energy. However, because of the combined effect of seismic source spectrum of ordinary dislocation sources and the conventional instrument response, the long-period wave is usually not visible in the body-wave part of the seismogram and has been seldom used for research. Here, we use the term "body wave" to refer to the phase that arrives before the regular surface waves.

To extract very long-period body waves from a seismogram, short-period waves which dominate the record must be filtered out. Unfortunately, this was not possible until recently because of clipping of records for large earthquakes. With modern broadband wide-dynamic-range seismographs, we can now easily filter out short-period waves to extract long-period body waves. Although at short period, various body-wave phases such as *P*, *PP*, *S*, *SS*, *PS*, *SP*, etc, these phases interfere in a complex fashion and cannot be identified as distinct phases. At long period, these phases interfere with each other to produce a distinct long-period phase. Here we call this long-period phase the "*W* phase". *W* phase can be identified easily for large earthquakes, and can be used effectively for studies of long-period source characteristics and regional Earth structure.

The recent slow tsunami earthquake which occurred in Nicaragua on September 2, 1992, produced a clear *W* phase, because of its anomalously long-period character of the source [Kanamori and Kikuchi, 1993]. The source preferentially excited very long-period waves so that *W* phase was clearly visible on displacement seismograms at many stations. Figure 1a shows the displacement record of the Nicaragua earthquake recorded at Pasadena. For comparison, the record of an ordinary earthquake (April 25, 1992 Cape Mendocino,

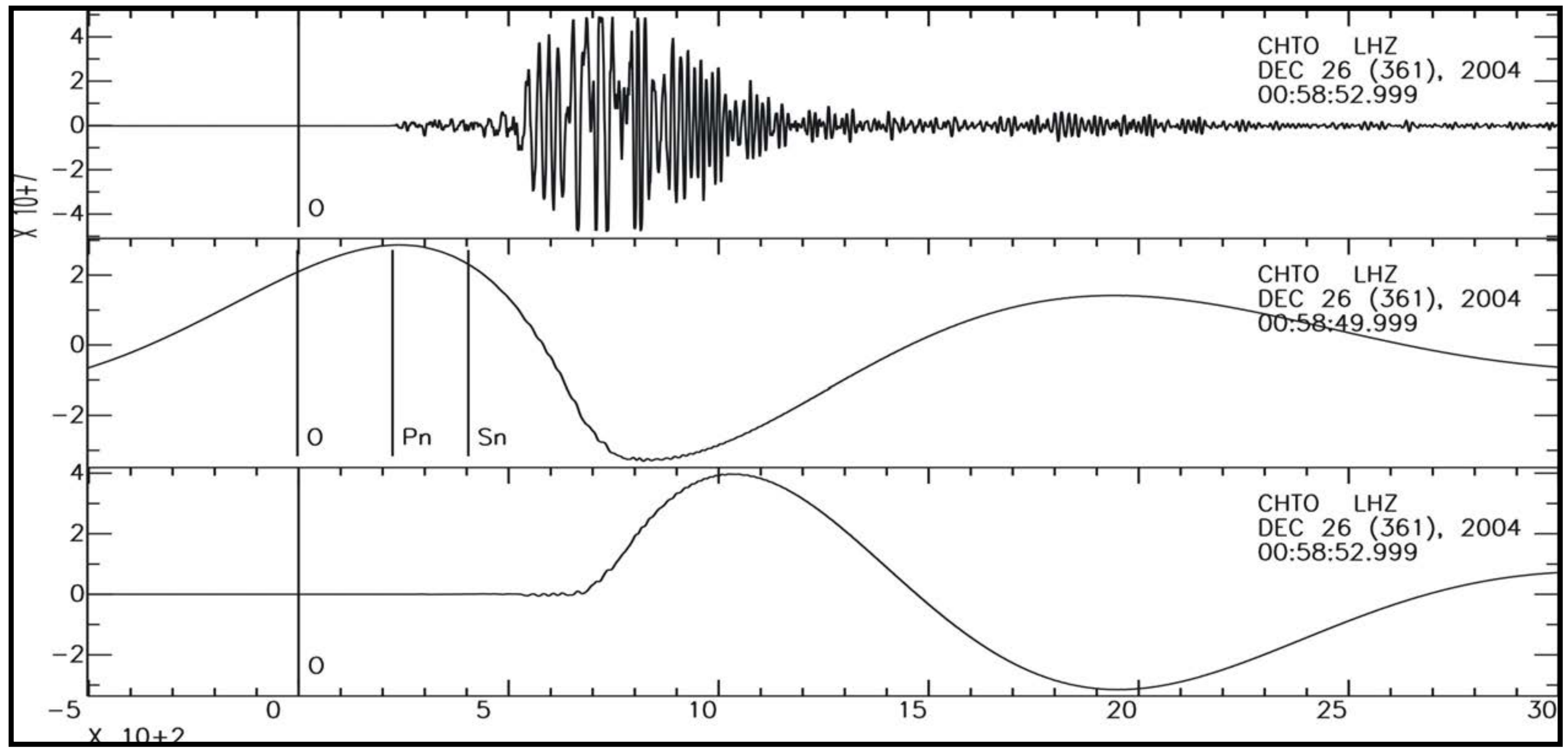


Inversion Challenges

Large earthquakes...

==> clipped surface wave records, even at moderate distances.

==> difficult to deconvolve and focus on low freq. WP signal.



Inversion Challenges

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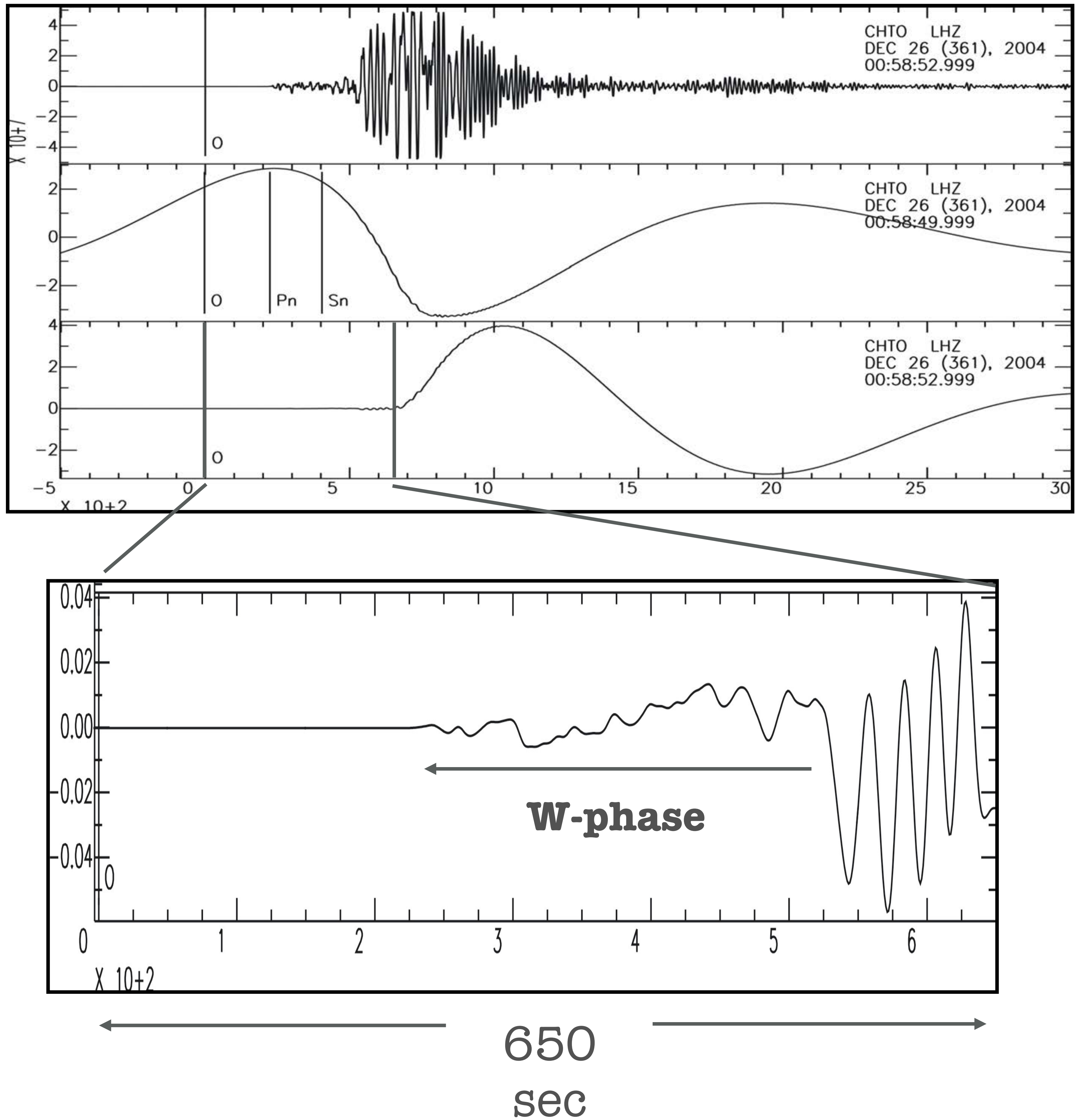

Time domain, causal deconvolution (iterative) retains signal up until time of clip

==> W phase can be extracted

Source inversion of W phase: speeding up seismic tsunami warning

Hiroo Kanamori[1] and Luis Rivera[2]

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[2]Institut de Physique du Globe de Strasbourg, CNRS-ULP,5 rue René Descartes, Strasbourg Cedex,67084 France

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SUMMARY

W phase is a long period phase arriving before *S* wave. It can be interpreted as superposition of the fundamental, first, second and third overtones of spheroidal modes or Rayleigh waves and has a group velocity from 4.5 to 9 km s^{-1} over a period range of 100–1000 s. The amplitude of long period waves better represents the tsunami potential of an earthquake. Because of the fast group velocity of W phase, most of W phase energy is contained within a short time window after the arrival of the *P* wave. At a distance of 50, W phase energy is contained within 23 min after the origin time which is the distinct advantage of using W phase for rapid tsunami warning purposes. We use a time domain deconvolution method to extract W phases from the broad-band records of global seismic networks. The bandwidth of W phase is approximately from 0.001 to 0.01 Hz, and we bandpass filter the data from 0.001 to 0.005 Hz in most cases. Having extracted W phase from the vertical component records, we perform a linear inversion using a point source to determine M_w and the source mechanism for several large earthquakes including the 2004 Sumatra–Andaman earthquake, the 2005 Nias earthquake, the 2006 Kuril Is. earthquake and the 2007 Sumatra earthquake. W phase inversion yields reliable solutions and holds promise of the use of W phase for rapid assessment of tsunami potential.

Key words: Tsunamis; Earthquake source observations; Surface waves and free oscillations; Wave propagation, Early warning.

GJI Seismology

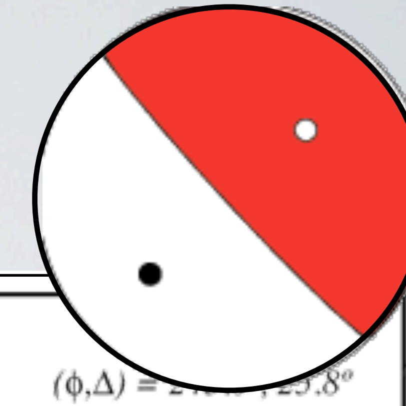
1 INTRODUCTION

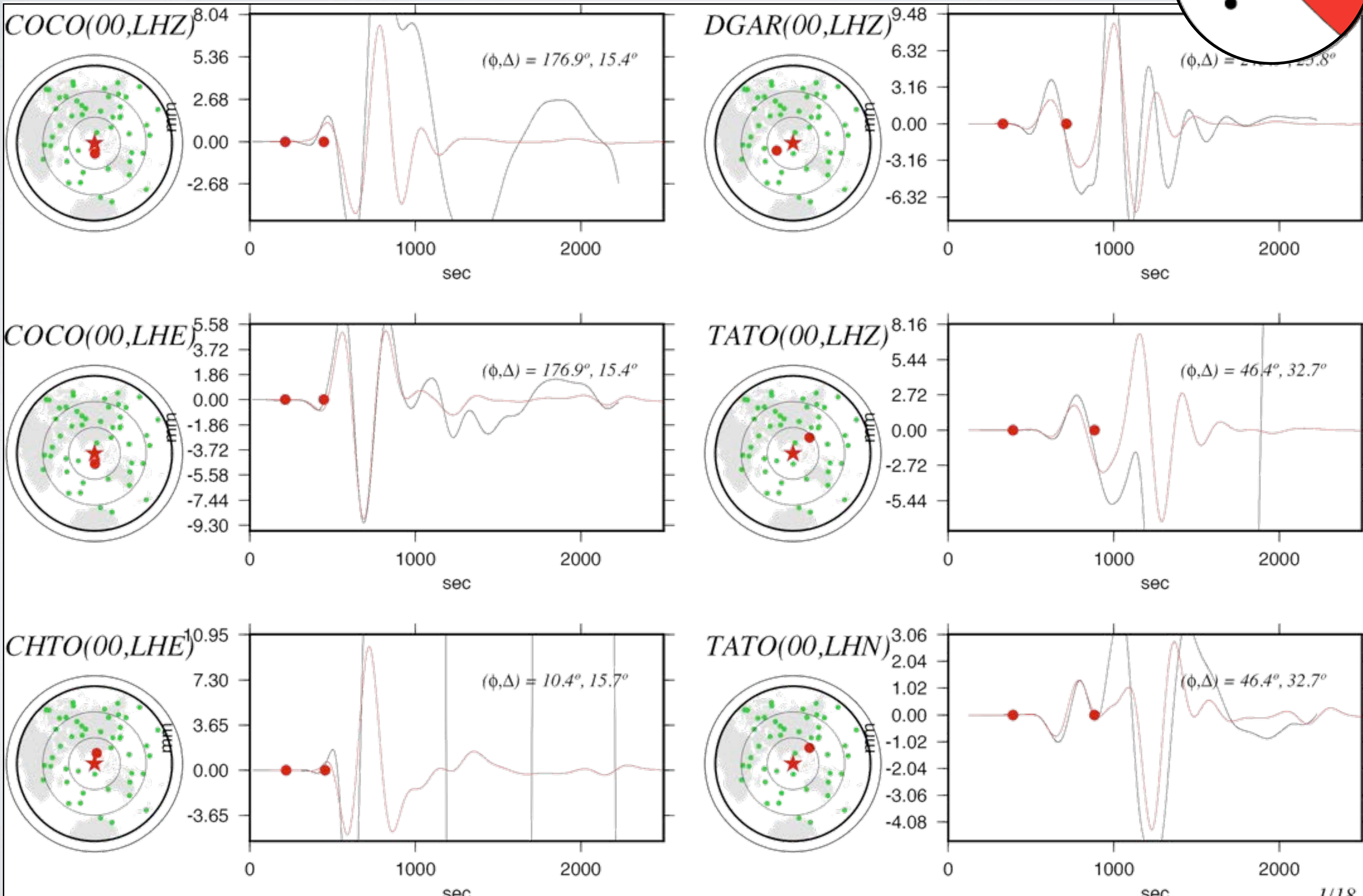
The 2004 Sumatra–Andaman Is. Earthquake (M_w = 9.2) excited Indian ocean wide tsunamis and caused widespread damage with an unprecedented magnitude with more than 283 000 casualties. This event motivated a renewed interest in developing effective tsunami warning systems which can help mitigate tragic tsunami damage in the future. Effective tsunami warning must have at least four elements: (1) detection of events, usually earthquakes, (2) detection of tsunami, (3) infrastructure for tsunami warning and (4) education and training of the public. In recent years, many new methodologies since seismograms can be used in many different ways, seismic warning methods can be made very versatile. In view of the recent extensive deployments of modern global seismic stations, we can now significantly improve the seismic warning method with introduction of novel concepts and methodology. In this paper, we use seismic W phase which carries long period information of the source at a much faster speed than the traditional surface waves. This wave has not been utilized because its suitability for rapid warning purposes has not been fully recognized. We will show that W phases can be retrieved on the time domain and used for rapid and robust determination of seismic source parameters with suffi-

Designed for the Largest EQs...

(e.g., Sumatra 12-26-2004)

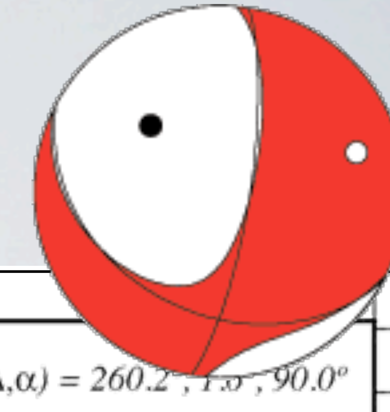
Mww 9.2

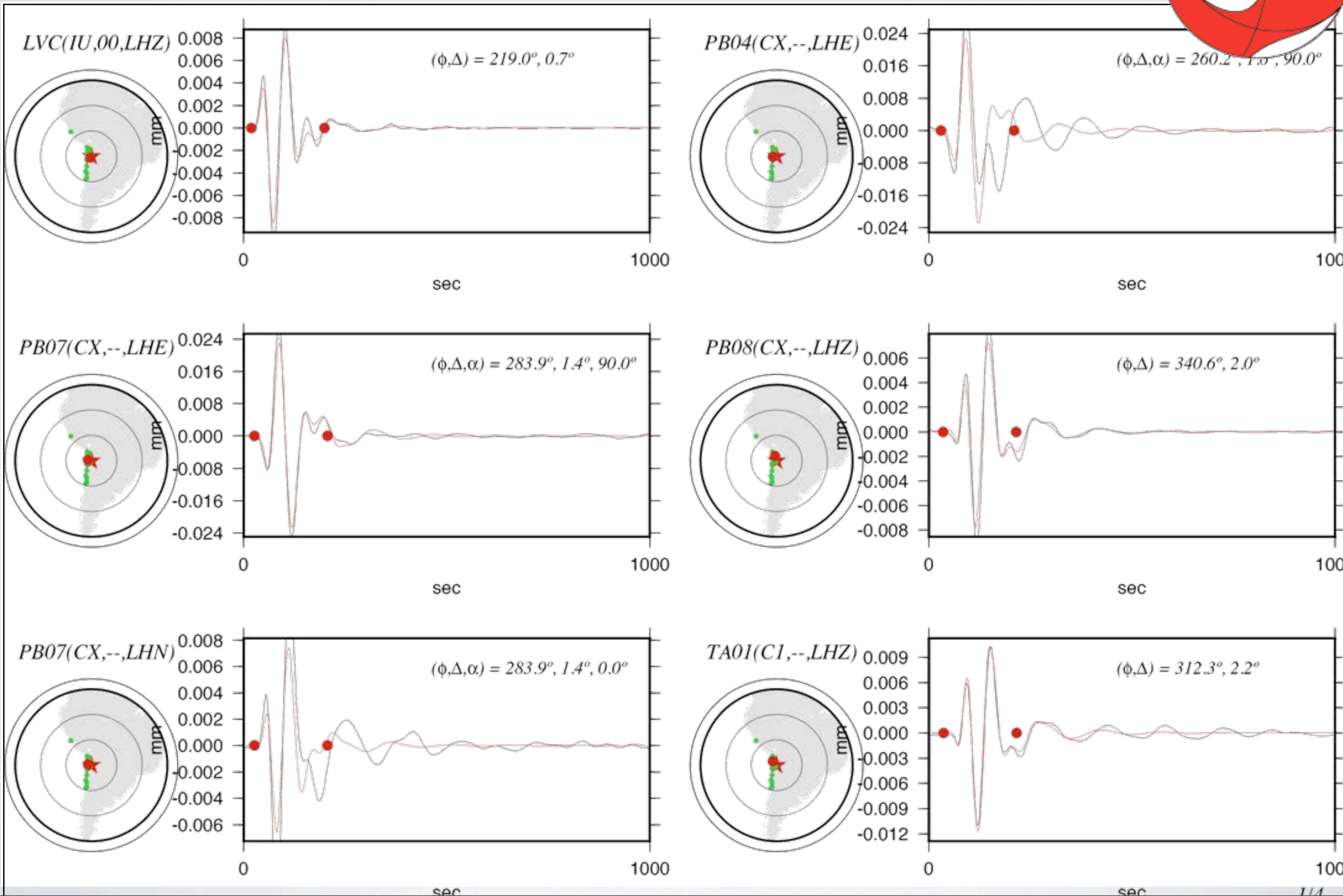




Shown Applicable down to M5 (e.g., Antofagasta 05-26-2015)

Mww 5.6





Ⓔ

Source Inversion of the W-Phase: Real-time Implementation and Extension to Low Magnitudes

Gavin P. Hayes,[1] Luis Rivera,[2] and Hiroo Kanamori[3]

Online material: Results for *W*-phase inversions for 498 events with M ≥ 5.8 in 2007–2008, compared to results from the global Centroid Moment Tensor catalog.

INTRODUCTION

We assess the use and reliability of a source inversion of the *W*-phase in real-time operations at the U.S. Geological Survey National Earthquake Information Center. The three-stage inversion algorithm produces rapid and reliable estimates of moment magnitude and source mechanism for events larger than M_w 7.0 within 25 minutes of the earthquake origin time, often less, and holds great promise for vastly improving our response times to such earthquakes worldwide. The method also produces stable results (within ±0.2 units of Global Centroid Moment Tensor project estimates) for earthquakes as small as M_w 5.8 when using stations out to distances of 90°. These applications extend the use of *W*-phase far beyond the higher magnitude events for which the inversion was originally intended, facilitating its use as a complementary approach to traditional body- and surface-wave methods for assessing the source properties of an earthquake.

Kanamori and Rivera (2008) introduced the use of

The U.S. Geological Survey (USGS) National Earthquake Information Center (NEIC) began implementation of *W*-phase inversion in real-time operations for testing purposes in July 2008. Here we assess the performance of this method in real time and show that *W*-phase not only provides rapid and accurate results for large earthquakes but also that this inversion can be applied successfully to earthquakes as small as M_w ~5.8. Such applications extend the magnitude range of the inversion far beyond that from which accurate results were previously expected (M_w > ~7.0) and facilitate the use of this method as a new moment tensor inversion algorithm for most damaging earthquakes worldwide.

W-PHASE

For information on the details of the wave-theory and modeling of *W*-phase, we refer readers to Kanamori and Rivera (2008); here we give just a brief overview. The *W*-phase is a long-period (approximately 100–1,000 s) phase arriving between the *P*- and *S*-wave phases of a seismic source, theoretically representing the total near- and far-field long-period wave-field. For modeling purposes, *W*-phase can be synthesized by a summation of normal modes (fundamental, 1st, 2nd, and 3rd overtones).

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W phase source inversion for moderate to large earthquakes (1990–2010)

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[2] *Institut de Physique du Globe de Strasbourg, IPGS - UMR 7516, CNRS and Université de Strasbourg (EOST), France*
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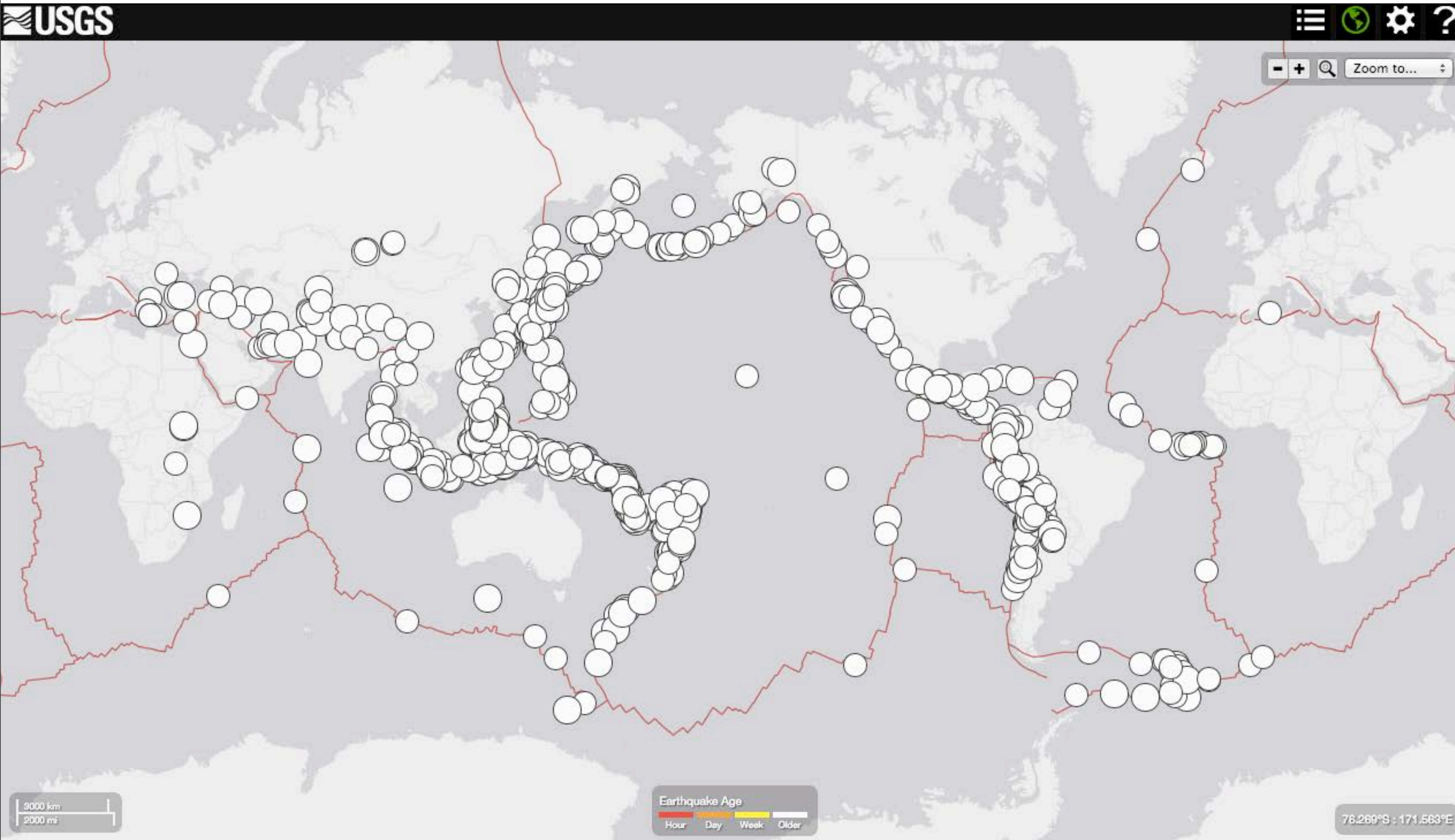
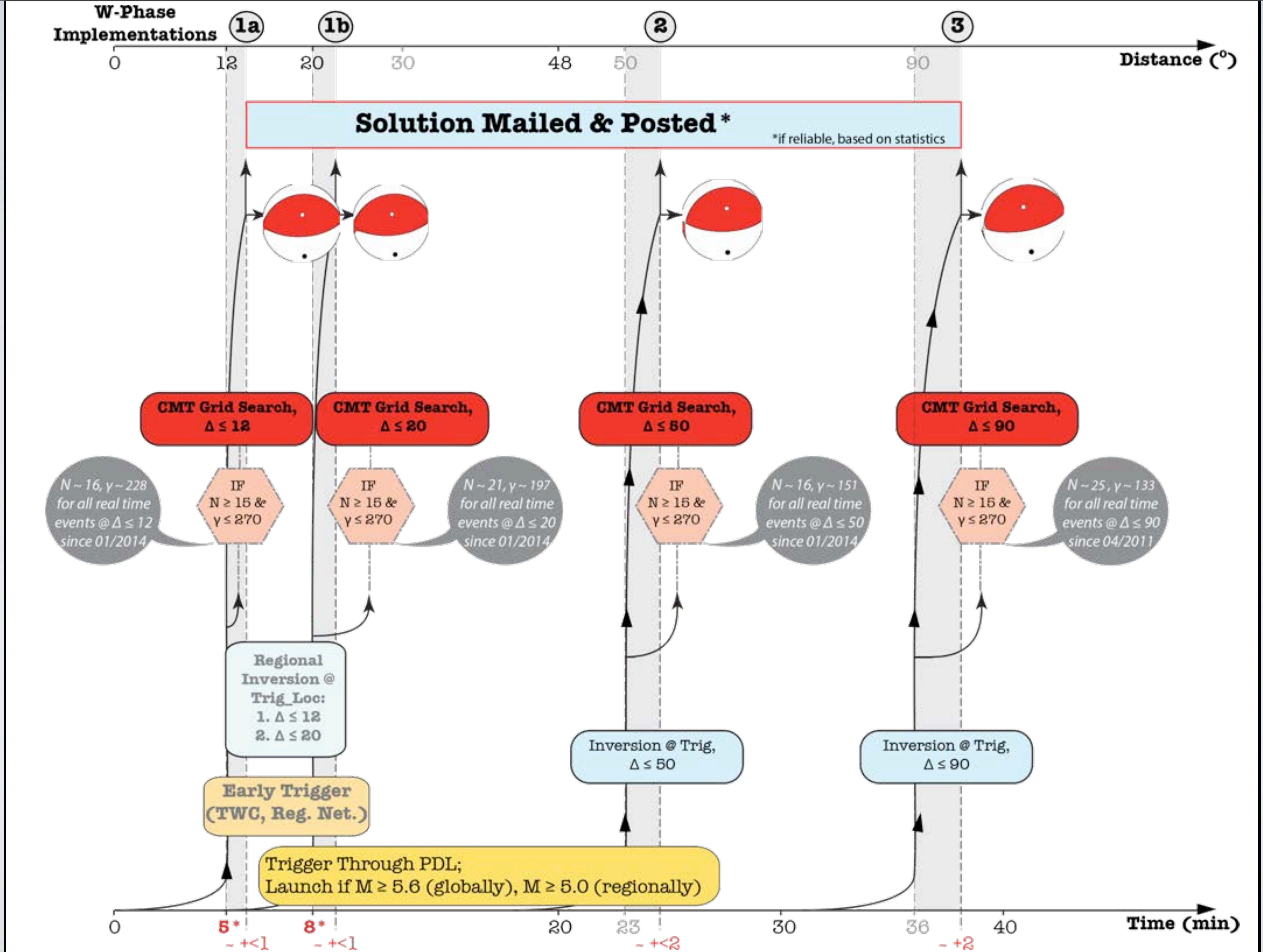
SUMMARY

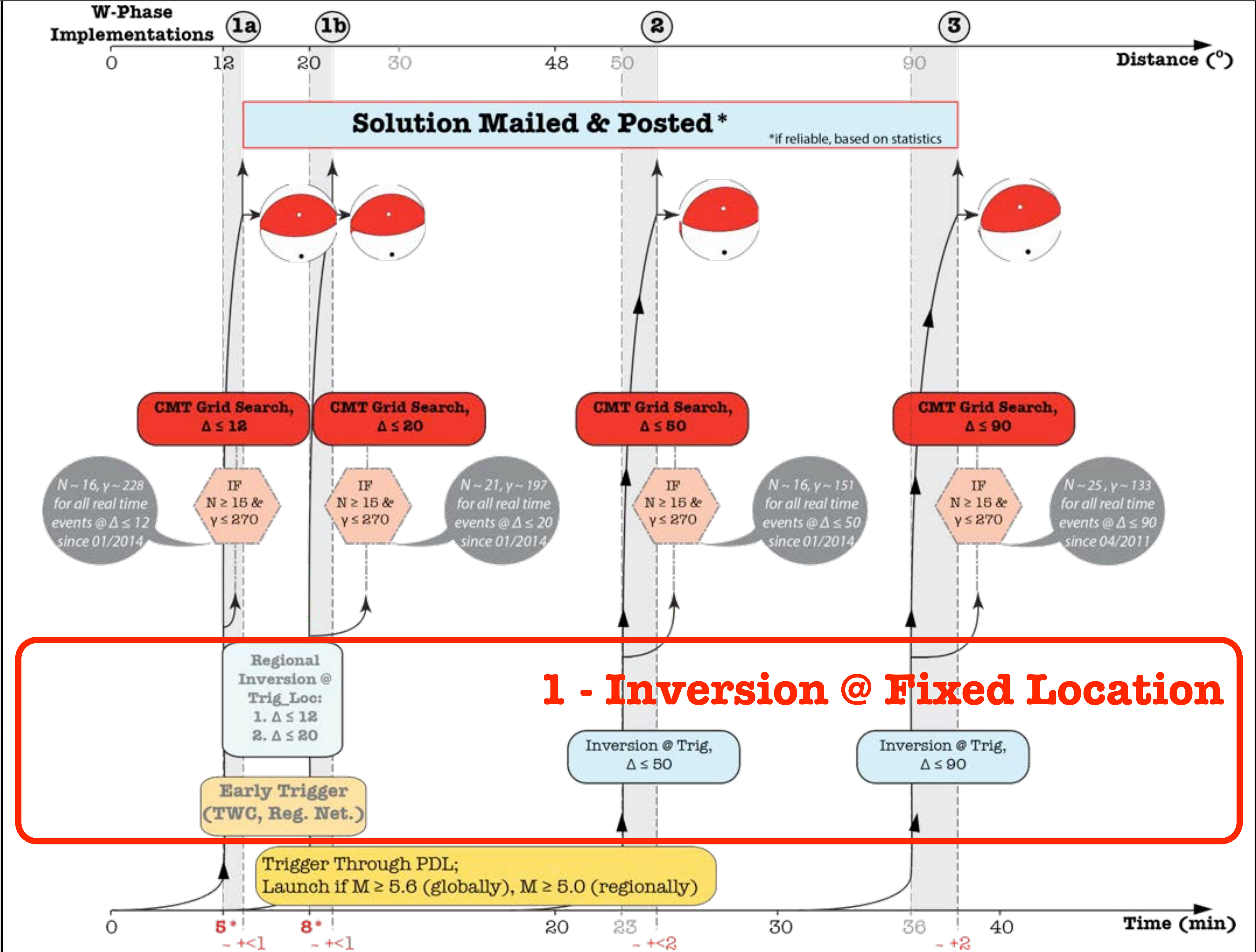
Rapid characterization of the earthquake source and of its effects is a growing field of interest. Until recently, it still took several hours to determine the first-order attributes of a great earthquake (e.g. $M_w \geq 7.5$), even in a well-instrumented region. The main limiting factors were data saturation, the interference of different phases and the time duration and spatial extent of the source rupture. To accelerate centroid moment tensor (CMT) determinations, we have developed a source inversion algorithm based on modelling of the W phase, a very long period phase (100–1000 s) arriving at the same time as the *P* wave. The purpose of this work is to finely tune and validate the algorithm for large-to-moderate-sized earthquakes using three components of W phase ground motion at teleseismic distances. To that end, the point source parameters of all $M_w \geq 6.5$ earthquakes that occurred between 1990 and 2010 (815 events) are determined using Federation of Digital Seismograph Networks, Global Seismographic Network broad-band stations and STS1 global virtual networks of the Incorporated Research Institutions for Seismology Data Management Center. For each event, a preliminary magnitude

A Global Catalog - now in ComCat



M6+ EQs from 1990-2012 from Duputel et al., 2012.
Real Time W Phase inversions 2009-present.


W-Phase Implementations
1a
1b
2
3
Distance (°)
0
12
20
30
48
50
90
Solution Mailed & Posted *
*if reliable, based on statistics
CMT Grid Search, Δ ≤ 12
CMT Grid Search, Δ ≤ 20
CMT Grid Search, Δ ≤ 50
CMT Grid Search, Δ ≤ 90
N ~ 16, γ ~ 228 for all real time events @ Δ ≤ 12 since 01/2014
IF N ≥ 15 & γ ≤ 270
IF N ≥ 15 & γ ≤ 270
N ~ 21, γ ~ 197 for all real time events @ Δ ≤ 20 since 01/2014
IF N ≥ 15 & γ ≤ 270
N ~ 16, γ ~ 151 for all real time events @ Δ ≤ 50 since 01/2014
IF N ≥ 15 & γ ≤ 270
N ~ 25, γ ~ 133 for all real time events @ Δ ≤ 90 since 04/2011
Regional Inversion @ Trig_Loc: 1. Δ ≤ 12 2. Δ ≤ 20
Inversion @ Trig, Δ ≤ 50
Inversion @ Trig, Δ ≤ 90
Early Trigger (TWC, Reg. Net.)
Trigger Through PDL; Launch if M ≥ 5.6 (globally), M ≥ 5.0 (regionally)
0
5*
8*
20
23
30
36
40
Time (min)
~ +<1
~ +<1
~ +<2
~ +2


W-Phase Implementations
1a
1b
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3
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12
20
30
48
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90
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CMT Grid Search, Δ ≤ 20
CMT Grid Search, Δ ≤ 50
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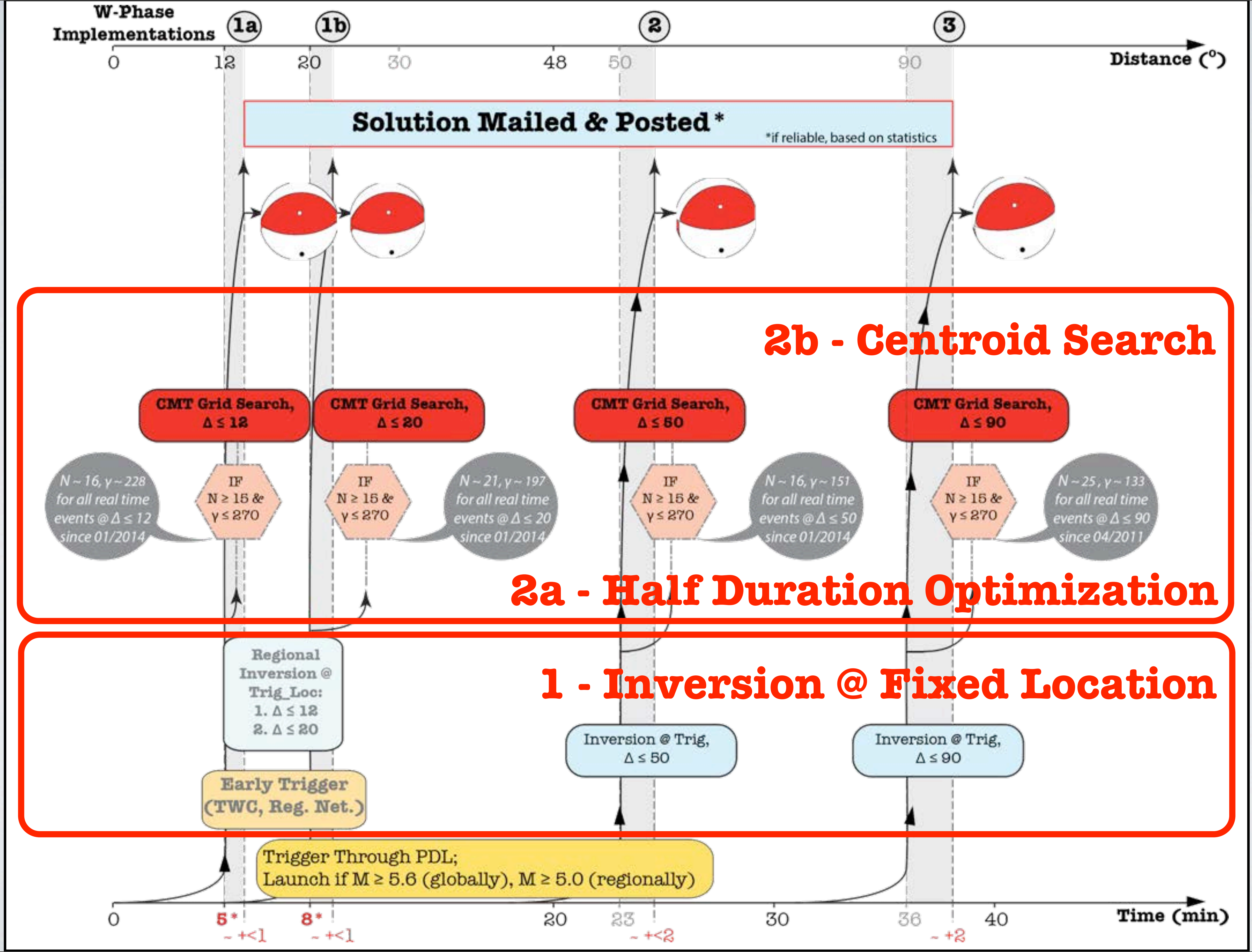
IF N ≥ 15 & γ ≤ 270
N ~ 16, γ ~ 151 for all real time events @ Δ ≤ 50 since 01/2014
IF N ≥ 15 & γ ≤ 270
N ~ 25, γ ~ 133 for all real time events @ Δ ≤ 90 since 04/2011
Regional Inversion @ Trig_Loc: 1. Δ ≤ 12 2. Δ ≤ 20
1 - Inversion @ Fixed Location
Inversion @ Trig, Δ ≤ 50
Inversion @ Trig, Δ ≤ 90
Early Trigger (TWC, Reg. Net.)
Trigger Through PDL; Launch if M ≥ 5.6 (globally), M ≥ 5.0 (regionally)
0
5*
~ +<1
8*
~ +<1
20
23
~ +<2
30
36
~ +2
40
Time (min)



W-Phase Implementations
1a
1b
2
3
0
12
20
30
48
50
90
Distance (°)
Solution Mailed & Posted *
*if reliable, based on statistics
2b - Centroid Search
CMT Grid Search, Δ ≤ 12
CMT Grid Search, Δ ≤ 20
CMT Grid Search, Δ ≤ 50
CMT Grid Search, Δ ≤ 90
N ~ 16, γ ~ 228 for all real time events @ Δ ≤ 12 since 01/2014
IF N ≥ 15 & γ ≤ 270
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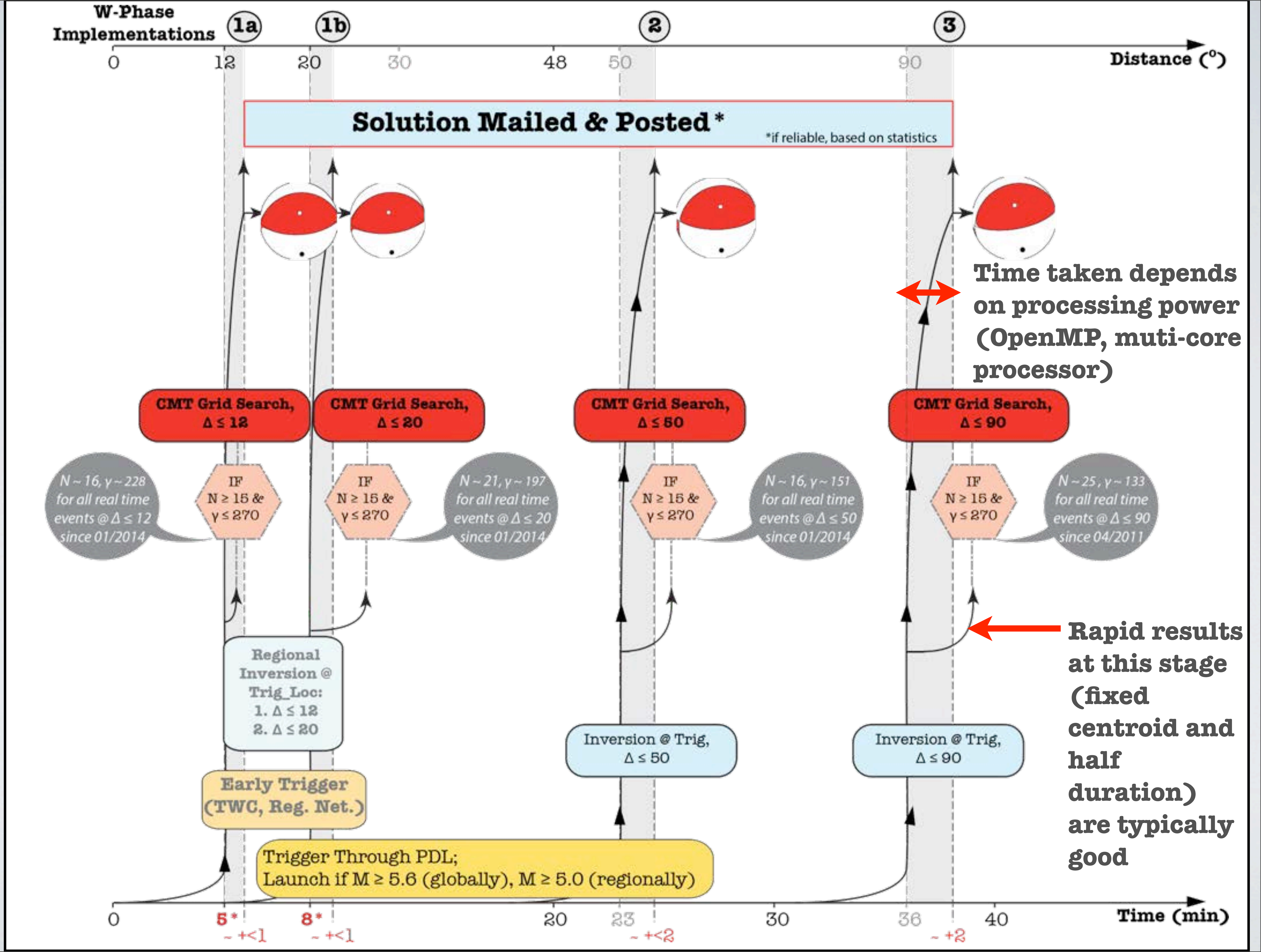
N ~ 21, γ ~ 197 for all real time events @ Δ ≤ 20 since 01/2014
IF N ≥ 15 & γ ≤ 270
N ~ 16, γ ~ 151 for all real time events @ Δ ≤ 50 since 01/2014
IF N ≥ 15 & γ ≤ 270
N ~ 25, γ ~ 133 for all real time events @ Δ ≤ 90 since 04/2011
2a - Half Duration Optimization
Regional Inversion @ Trig_Loc: 1. Δ ≤ 12 2. Δ ≤ 20
1 - Inversion @ Fixed Location
Inversion @ Trig, Δ ≤ 50
Inversion @ Trig, Δ ≤ 90
Early Trigger (TWC, Reg. Net.)
Trigger Through PDL; Launch if M ≥ 5.6 (globally), M ≥ 5.0 (regionally)
0
5*
8*
20
23
30
36
40
Time (min)
~ +<1
~ +<1
~ +<2
~ +2



W-Phase Implementations
1a
1b
2
3
Distance (°)
0
12
20
30
48
50
90
Solution Mailed & Posted *
*if reliable, based on statistics
Time taken depends on processing power (OpenMP, muti-core processor)
CMT Grid Search, Δ ≤ 12
CMT Grid Search, Δ ≤ 20
CMT Grid Search, Δ ≤ 50
CMT Grid Search, Δ ≤ 90
N ~ 16, γ ~ 228 for all real time events @ Δ ≤ 12 since 01/2014
IF N ≥ 15 & γ ≤ 270
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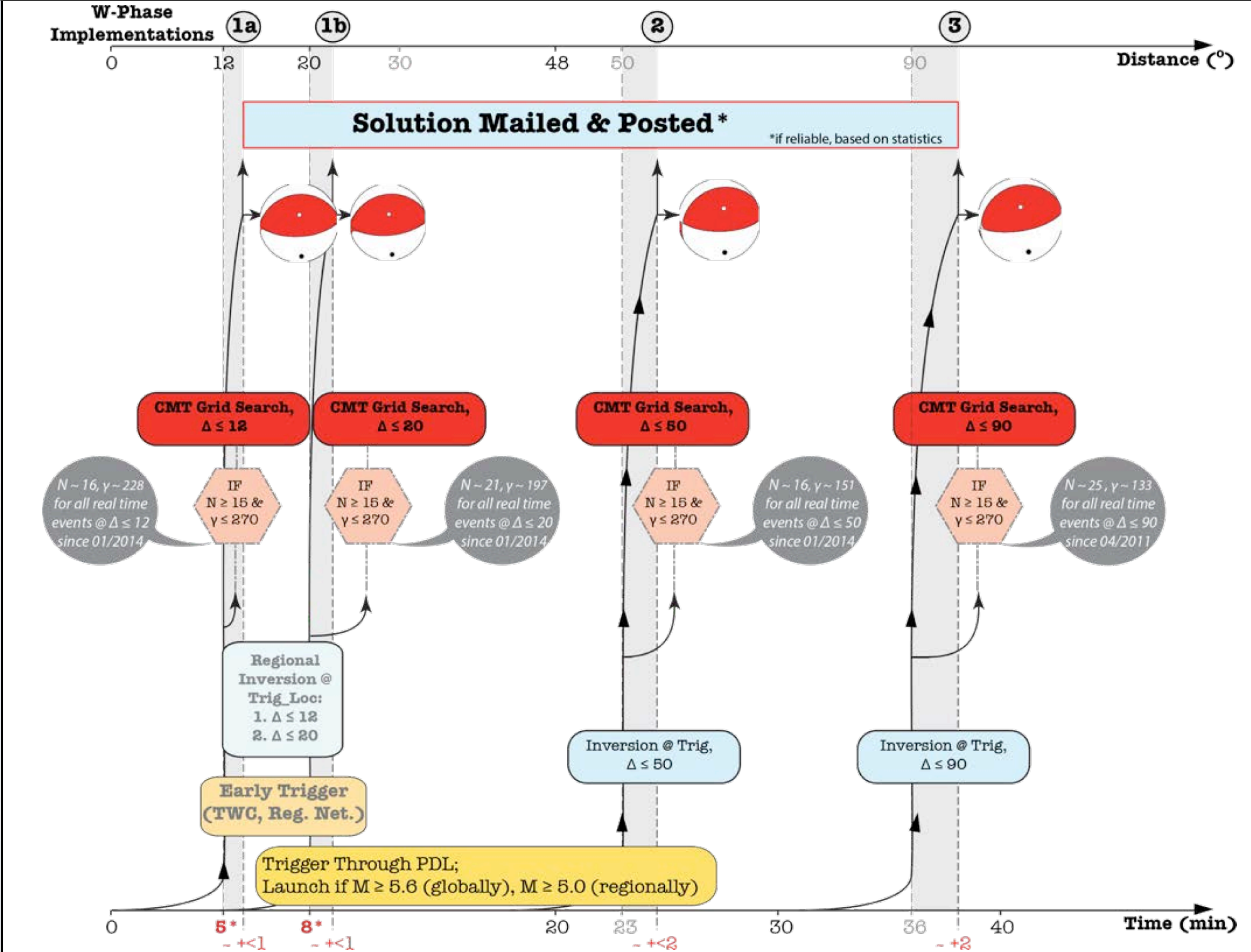
IF N ≥ 15 & γ ≤ 270
N ~ 16, γ ~ 151 for all real time events @ Δ ≤ 50 since 01/2014
IF N ≥ 15 & γ ≤ 270
N ~ 25, γ ~ 133 for all real time events @ Δ ≤ 90 since 04/2011
Rapid results at this stage (fixed centroid and half duration) are typically good
Regional Inversion @ Trig_Loc: 1. Δ ≤ 12 2. Δ ≤ 20
Inversion @ Trig, Δ ≤ 50
Inversion @ Trig, Δ ≤ 90
Early Trigger (TWC, Reg. Net.)
Trigger Through PDL; Launch if M ≥ 5.6 (globally), M ≥ 5.0 (regionally)
0
5 *
8 *
20
23
30
36
40
Time (min)
~ +<1
~ +<1
~ +<2
~ +2



W-Phase
Implementations
1a
1b
2
3
0
12
20
30
48
50
90
Distance (°)
Solution Mailed & Posted *
*if reliable, based on statistics
CMT Grid Search, Δ ≤ 12
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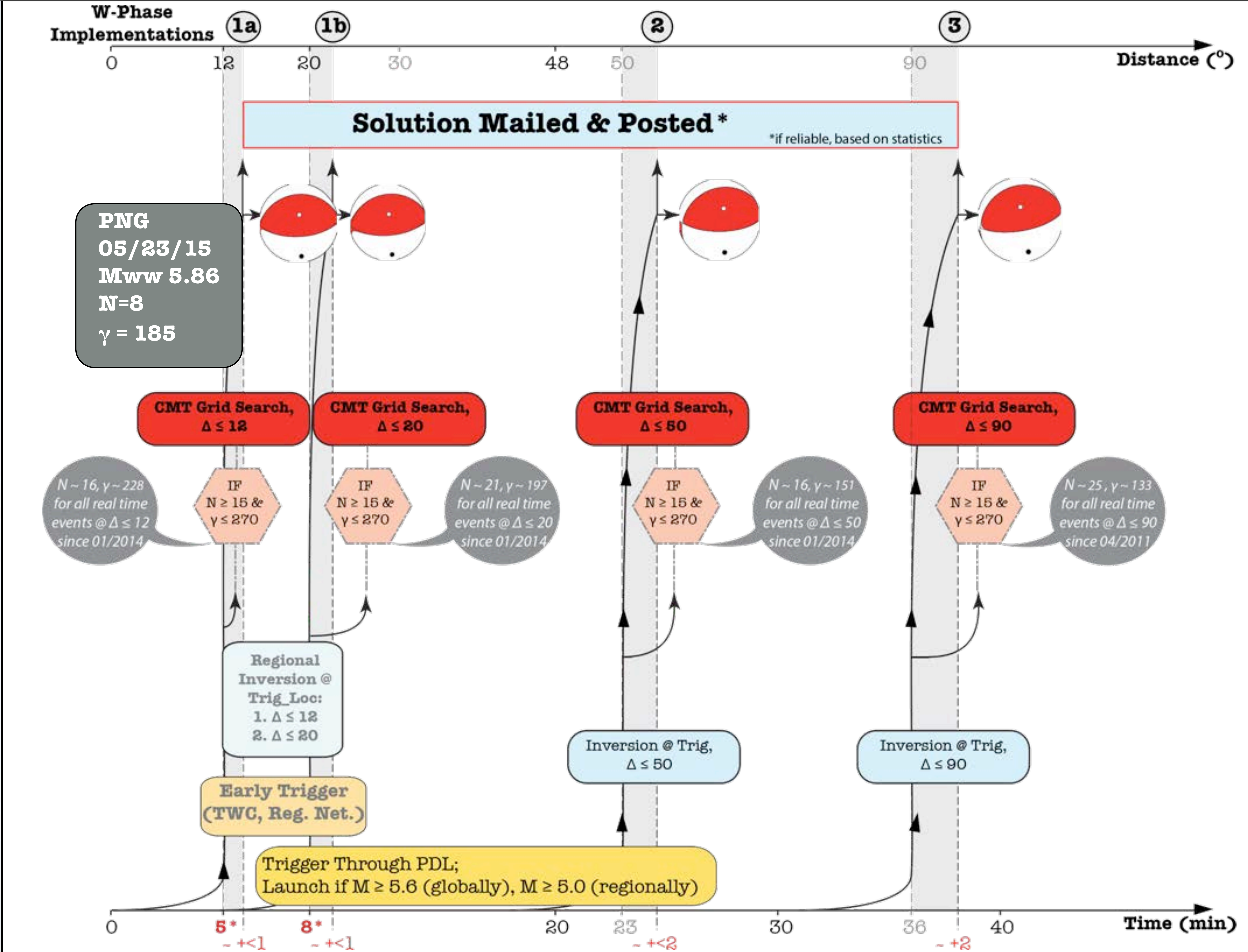
Inversion @ Trig, Δ ≤ 50
Inversion @ Trig, Δ ≤ 90
Early Trigger (TWC, Reg. Net.)
Trigger Through PDL; Launch if M ≥ 5.6 (globally), M ≥ 5.0 (regionally)
0
5*
8*
20
23
30
36
40
Time (min)
~ +<1
~ +<1
~ +<2
~ +2


W-Phase Implementations
1a
1b
2
3
Distance (°)
0
12
20
30
48
50
90
Solution Mailed & Posted *
*if reliable, based on statistics
PNG
05/23/15
Mww 5.86
N=8
γ = 185
CMT Grid Search, Δ ≤ 12
CMT Grid Search, Δ ≤ 20
CMT Grid Search, Δ ≤ 50
CMT Grid Search, Δ ≤ 90
N ~ 16, γ ~ 228 for all real time events @ Δ ≤ 12 since 01/2014
IF N ≥ 15 & γ ≤ 270
IF N ≥ 15 & γ ≤ 270
N ~ 21, γ ~ 197 for all real time events @ Δ ≤ 20 since 01/2014
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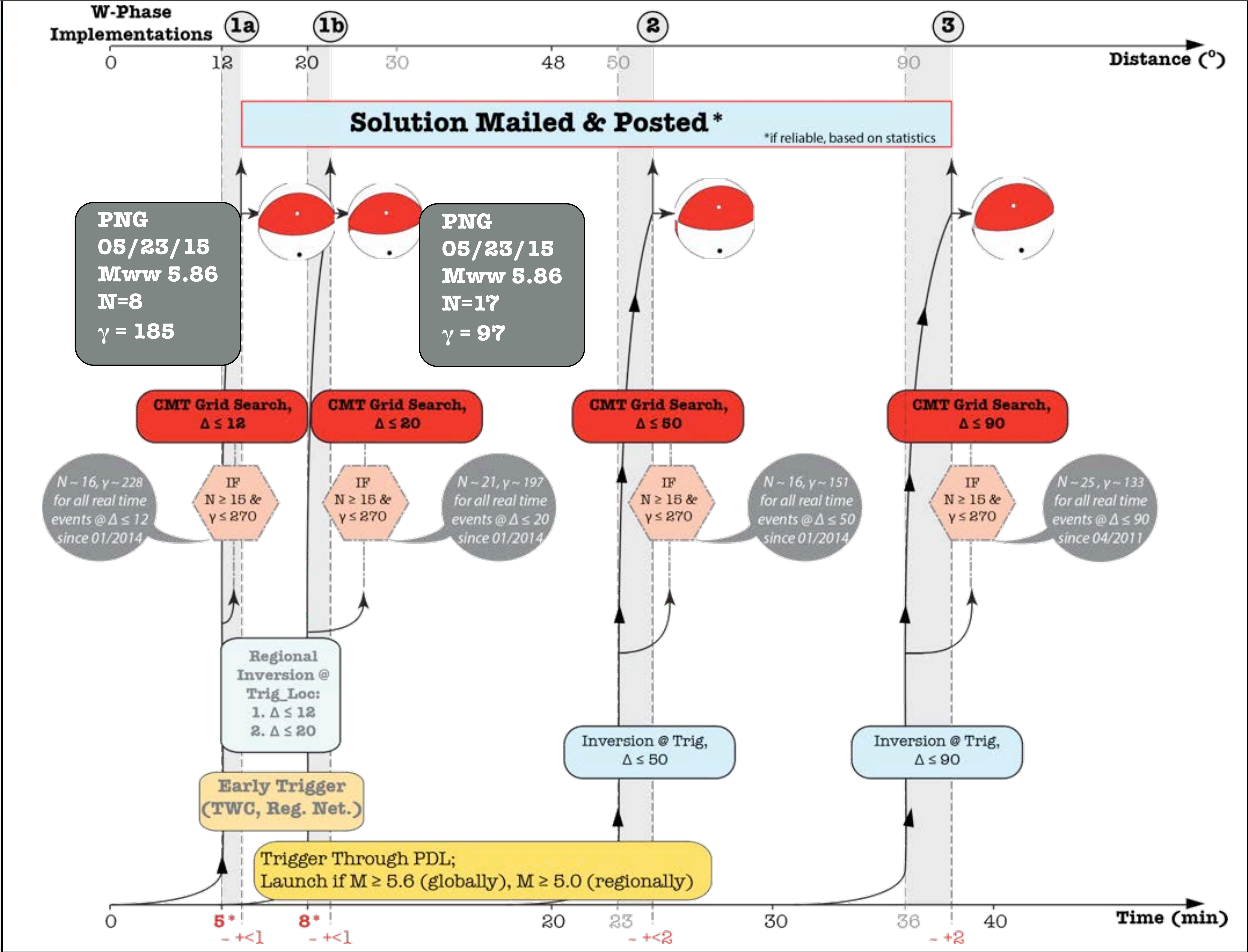
Regional Inversion @ Trig_Loc:
1. Δ ≤ 12
2. Δ ≤ 20
Inversion @ Trig, Δ ≤ 50
Inversion @ Trig, Δ ≤ 90
Early Trigger (TWC, Reg. Net.)
Trigger Through PDL;
Launch if M ≥ 5.6 (globally), M ≥ 5.0 (regionally)
0
5 *
8 *
20
23
30
36
40
Time (min)
~ +<1
~ +<1
~ +<2
~ +2


W-Phase Implementations
1a
1b
2
3
0
12
20
30
48
50
90
Distance (°)
Solution Mailed & Posted *
*if reliable, based on statistics
PNG
05/23/15
Mww 5.86
N=8
γ = 185
PNG
05/23/15
Mww 5.86
N=17
γ = 97
CMT Grid Search, Δ ≤ 12
CMT Grid Search, Δ ≤ 20
CMT Grid Search, Δ ≤ 50
CMT Grid Search, Δ ≤ 90
N ~ 16, γ ~ 228 for all real time events @ Δ ≤ 12 since 01/2014
IF N ≥ 15 & γ ≤ 270
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Inversion @ Trig, Δ ≤ 90
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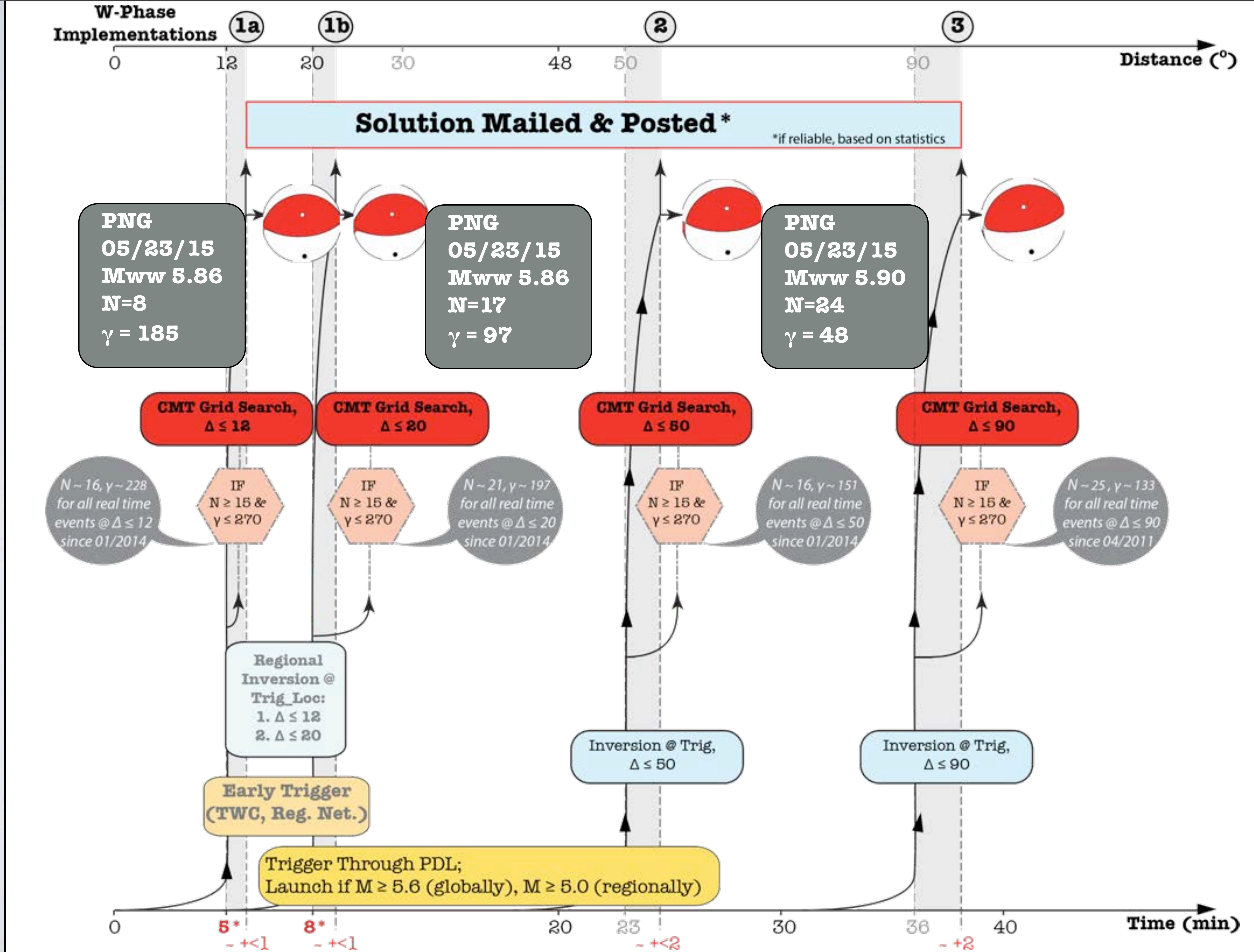
Launch if M ≥ 5.6 (globally), M ≥ 5.0 (regionally)
0
5 *
8 *
20
23
30
36
40
Time (min)
~ +<1
~ +<1
~ +<2
~ +2



W-Phase Implementations
1a
1b
2
3
Distance (°)
0
12
20
30
48
50
90
Solution Mailed & Posted *
*if reliable, based on statistics
PNG 05/23/15 Mww 5.86 N=8 γ = 185
PNG 05/23/15 Mww 5.86 N=17 γ = 97
PNG 05/23/15 Mww 5.90 N=24 γ = 48
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CMT Grid Search, Δ ≤ 20
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Inversion @ Trig, Δ ≤ 90
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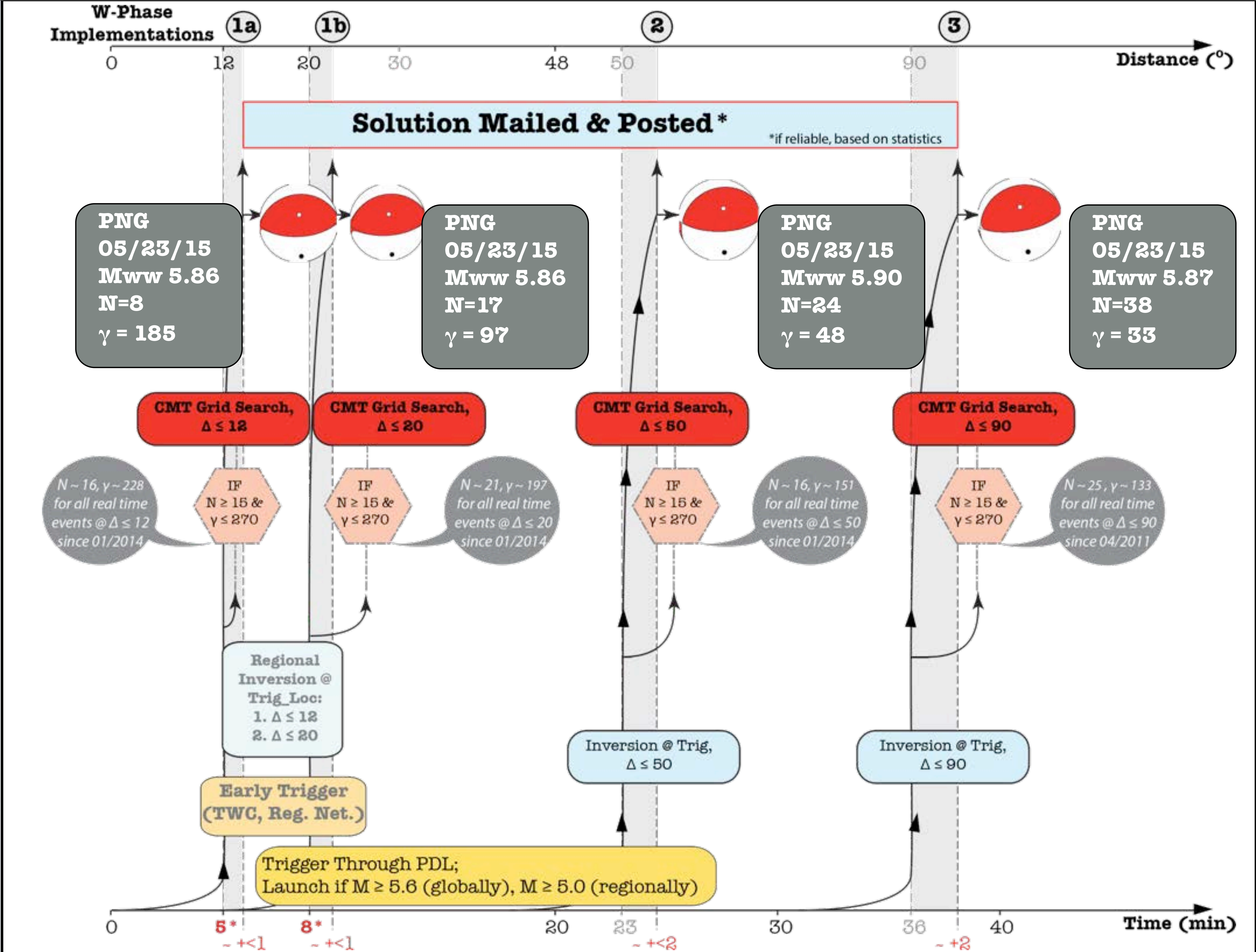
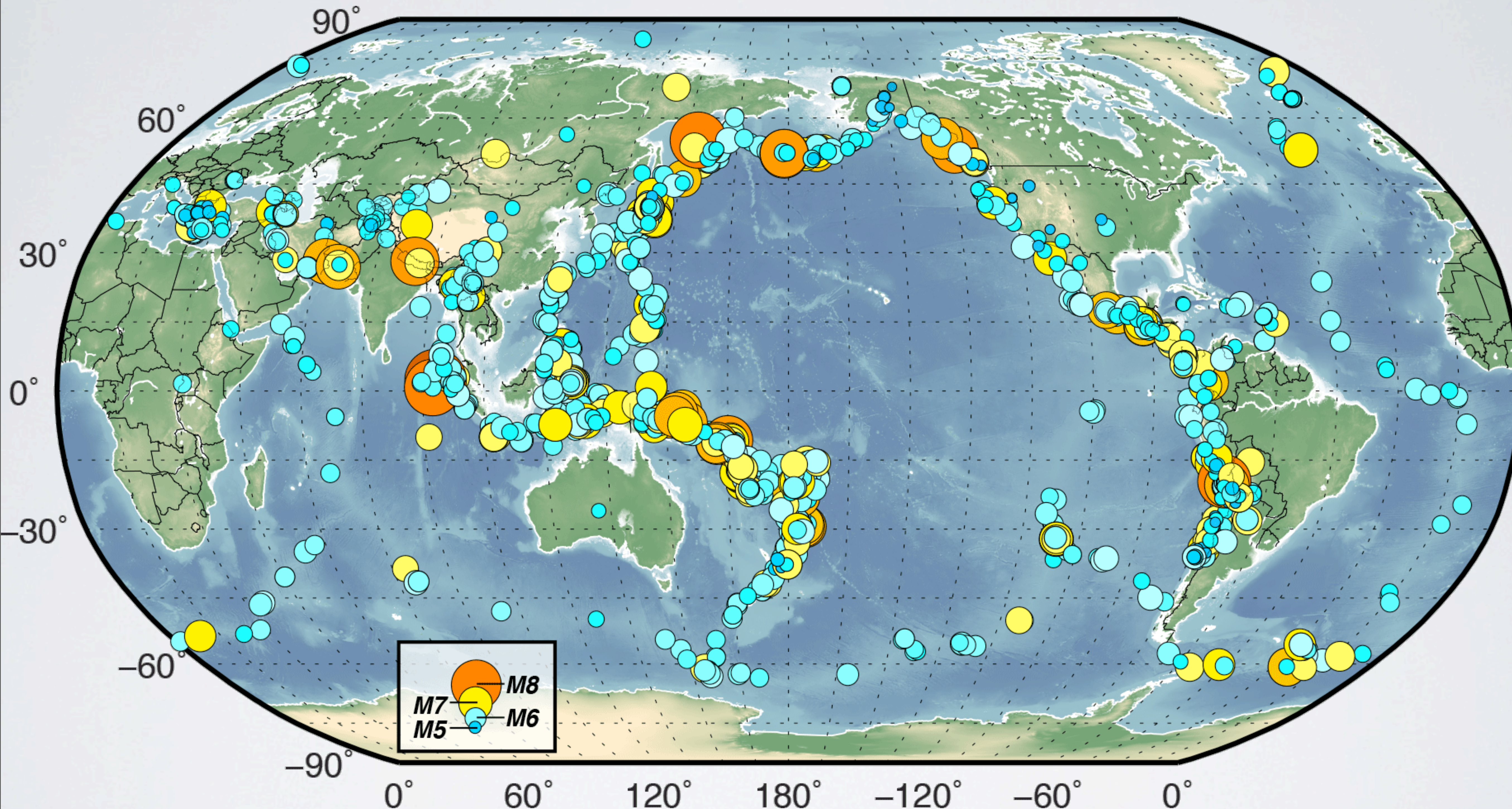
Trigger Through PDL; Launch if M ≥ 5.6 (globally), M ≥ 5.0 (regionally)
0
5 *
8 *
20
23
30
36
40
Time (min)
~ +<1
~ +<1
~ +<2
~ +2

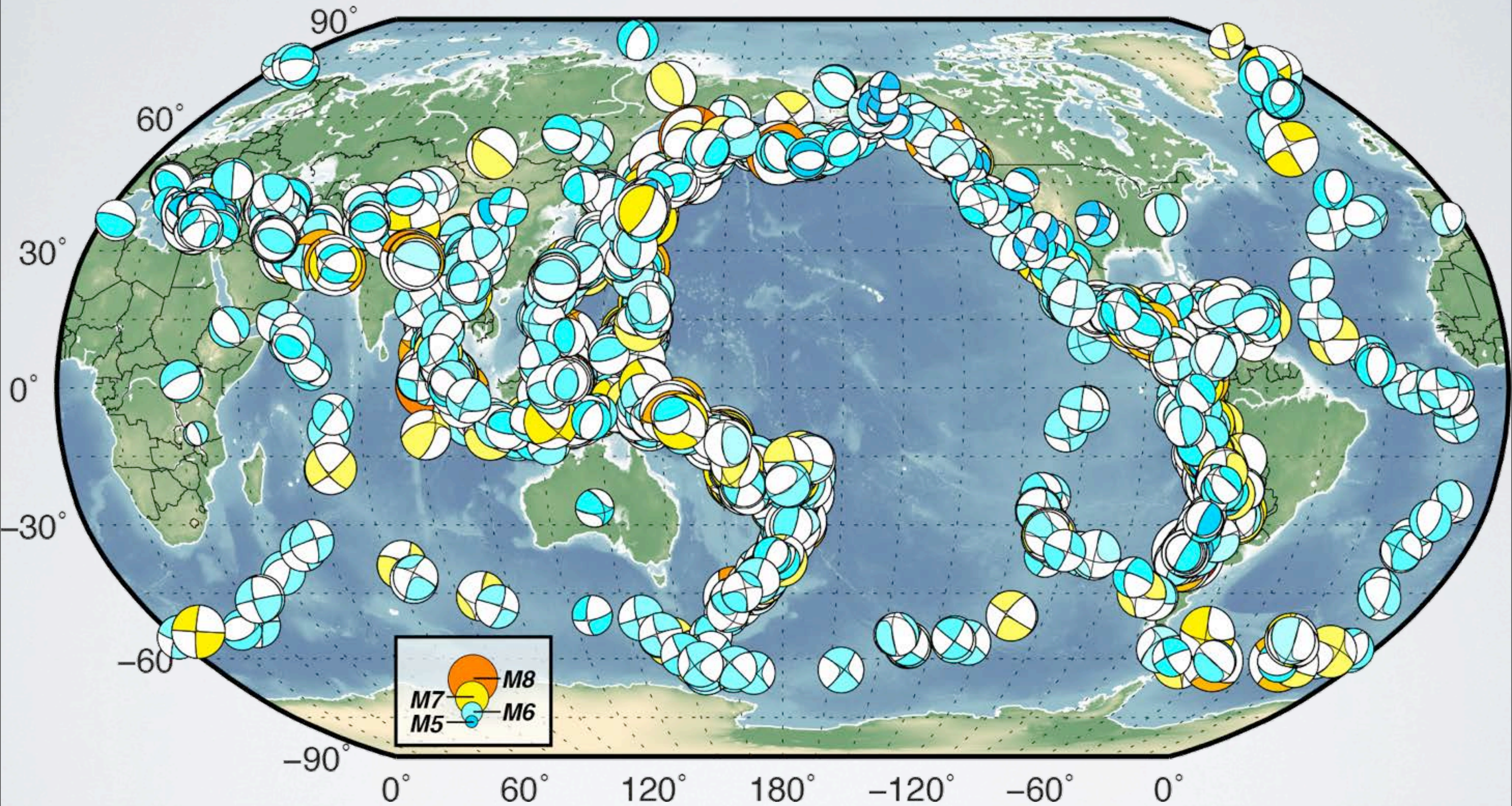

W-Phase Implementations
1a
1b
2
3
Distance (°)
0
12
20
30
48
50
90
Solution Mailed & Posted *
*if reliable, based on statistics
PNG 05/23/15 Mww 5.86 N=8 γ = 185
PNG 05/23/15 Mww 5.86 N=17 γ = 97
PNG 05/23/15 Mww 5.90 N=24 γ = 48
PNG 05/23/15 Mww 5.87 N=38 γ = 33
CMT Grid Search, Δ ≤ 12
CMT Grid Search, Δ ≤ 20
CMT Grid Search, Δ ≤ 50
CMT Grid Search, Δ ≤ 90
N ~ 16, γ ~ 228 for all real time events @ Δ ≤ 12 since 01/2014
IF N ≥ 15 & γ ≤ 270
IF N ≥ 15 & γ ≤ 270
N ~ 21, γ ~ 197 for all real time events @ Δ ≤ 20 since 01/2014
IF N ≥ 15 & γ ≤ 270
N ~ 16, γ ~ 151 for all real time events @ Δ ≤ 50 since 01/2014
IF N ≥ 15 & γ ≤ 270
N ~ 25, γ ~ 133 for all real time events @ Δ ≤ 90 since 04/2011
Regional Inversion @ Trig_Loc: 1. Δ ≤ 12 2. Δ ≤ 20
Inversion @ Trig, Δ ≤ 50
Inversion @ Trig, Δ ≤ 90
Early Trigger (TWC, Reg. Net.)
Trigger Through PDL; Launch if M ≥ 5.6 (globally), M ≥ 5.0 (regionally)
Time (min)
0
5 *
~ +<1
8 *
~ +<1
20
23
~ +<2
30
36
~ +2
40

Global W Phase: Teleseismic Mww Inversion



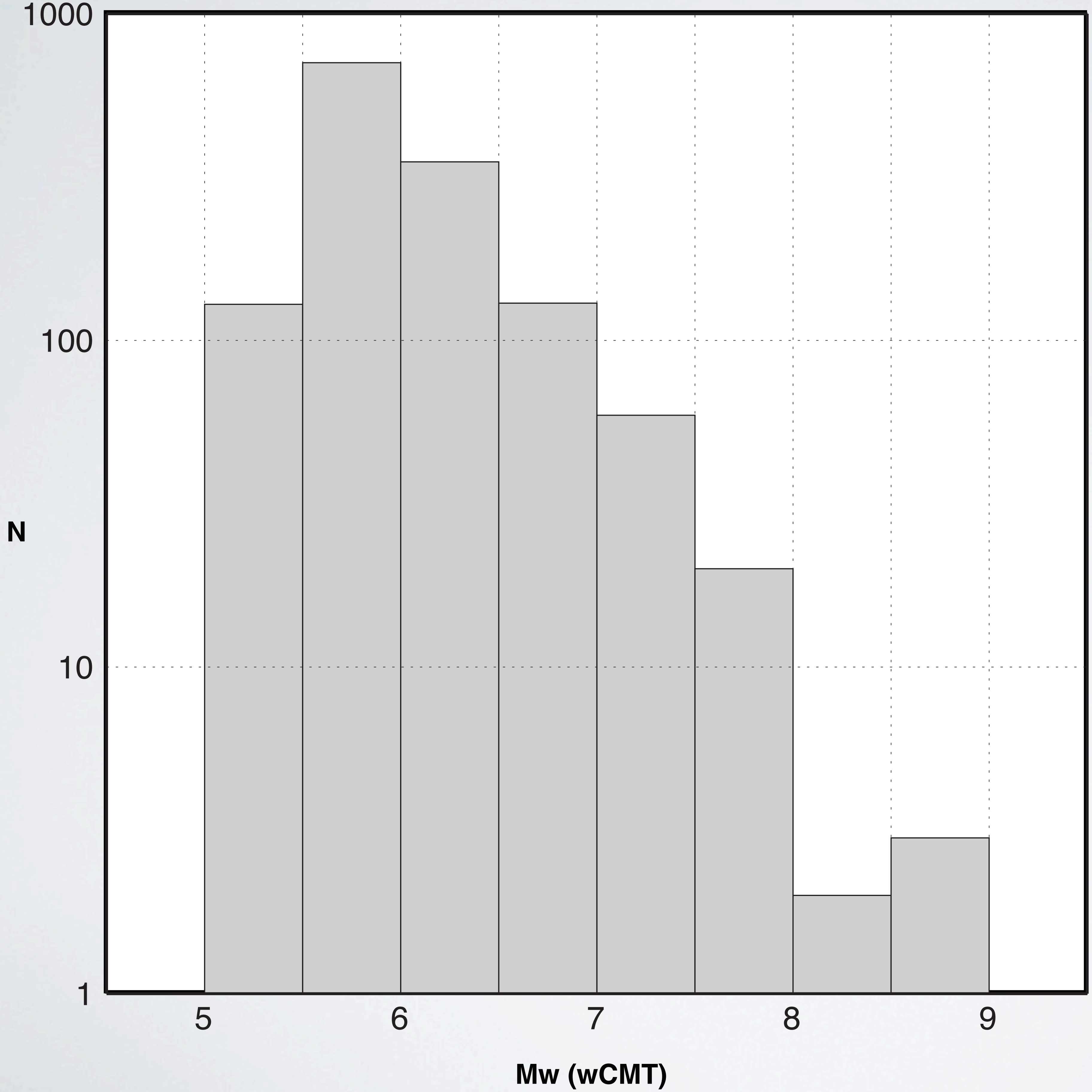
1920+ events published since July 2009.
Approximately complete above M6.
Authoritative NEIC magnitude for M6+ EQs in response, and for PDE.

Global W Phase: Teleseismic Mww Inversion



1920+ events published since July 2009.
Approximately complete above M6.
Authoritative NEIC magnitude for M6+ EQs in response, and for PDE.

Global W Phase: Teleseismic Mww Inversion



Completeness levels approaching M5.5.

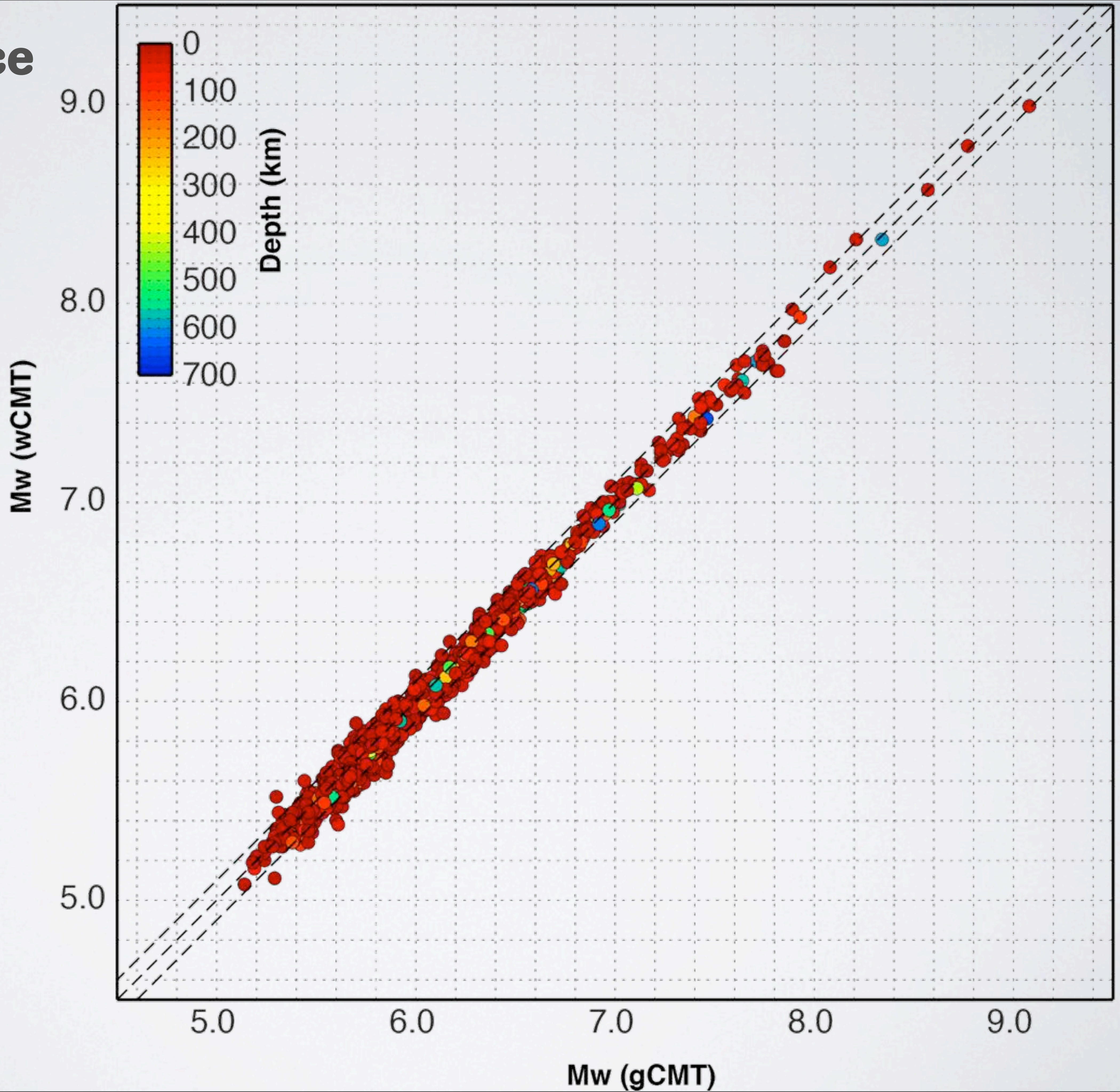
Applicable to even smaller magnitudes (smallest published Mww = 4.45)

=> Regional applications cover almost the complete magnitude range of interest for typical moment tensor analyses.

Performance

gCMT is the benchmark for modern source inversion and magnitude. W phase consistently comparable across the whole magnitude range.

Also published much more quickly...



Performance

gCMT is the benchmark for modern source inversion and magnitude. W phase consistently comparable across the whole magnitude range.

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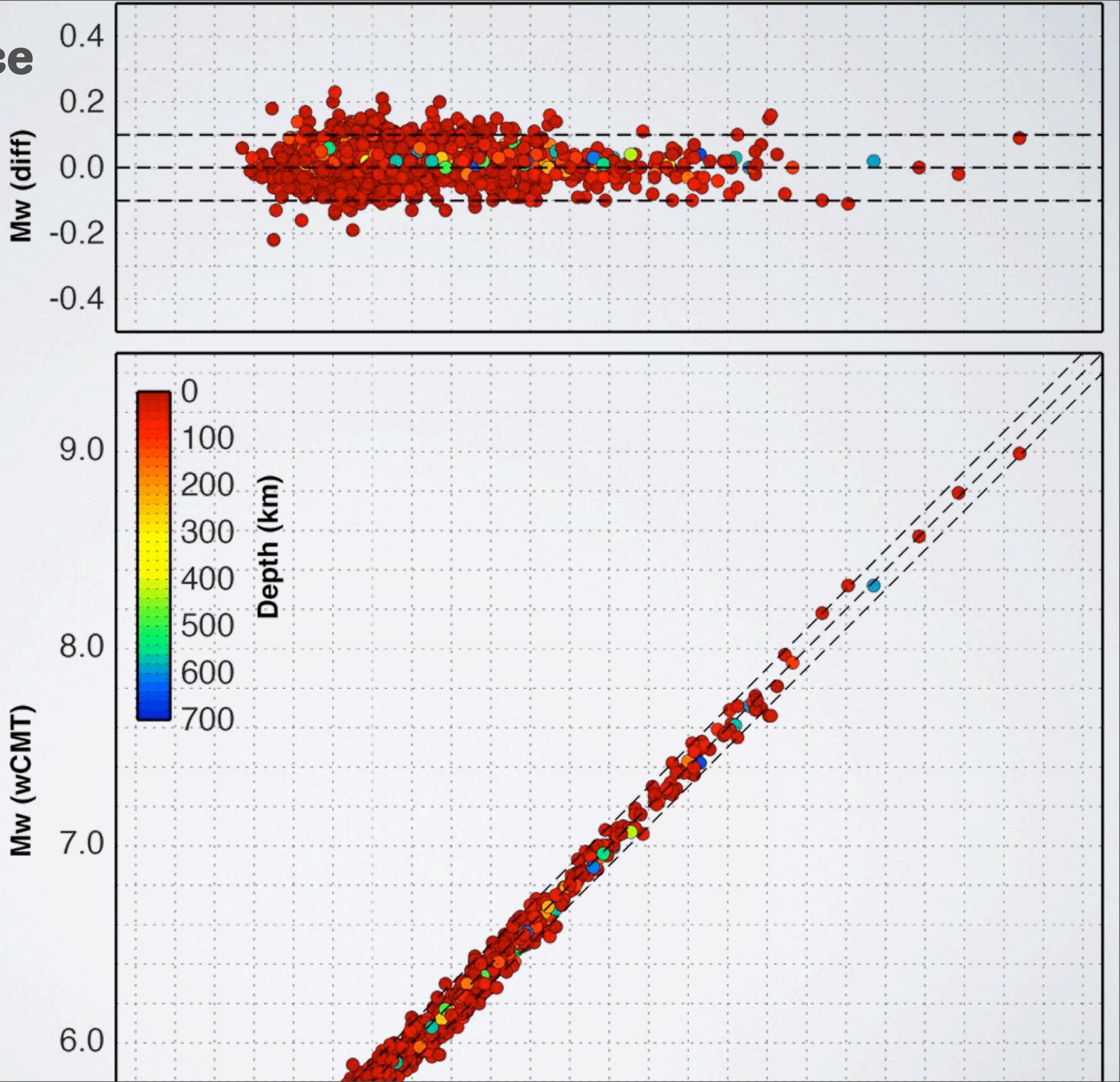
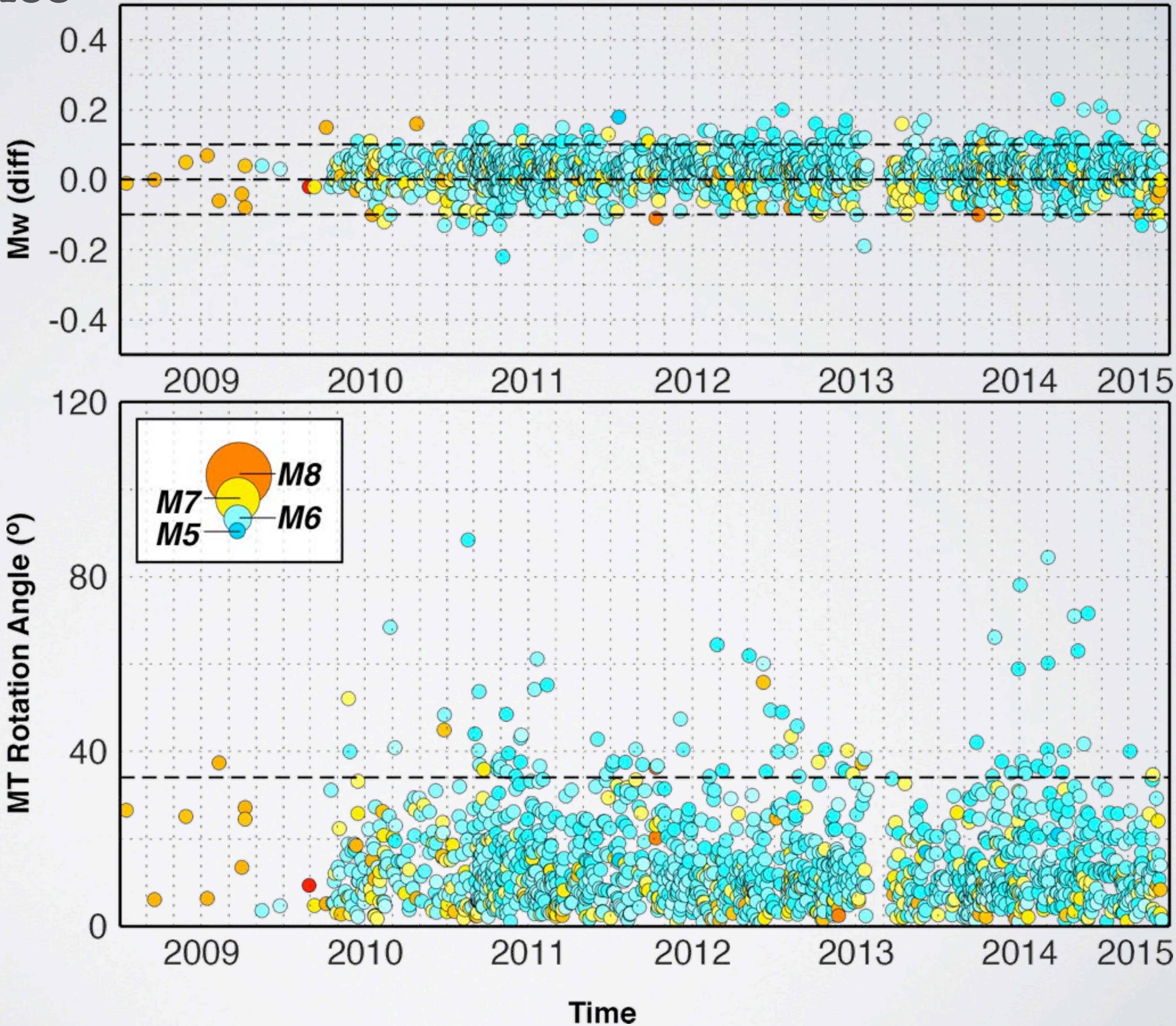
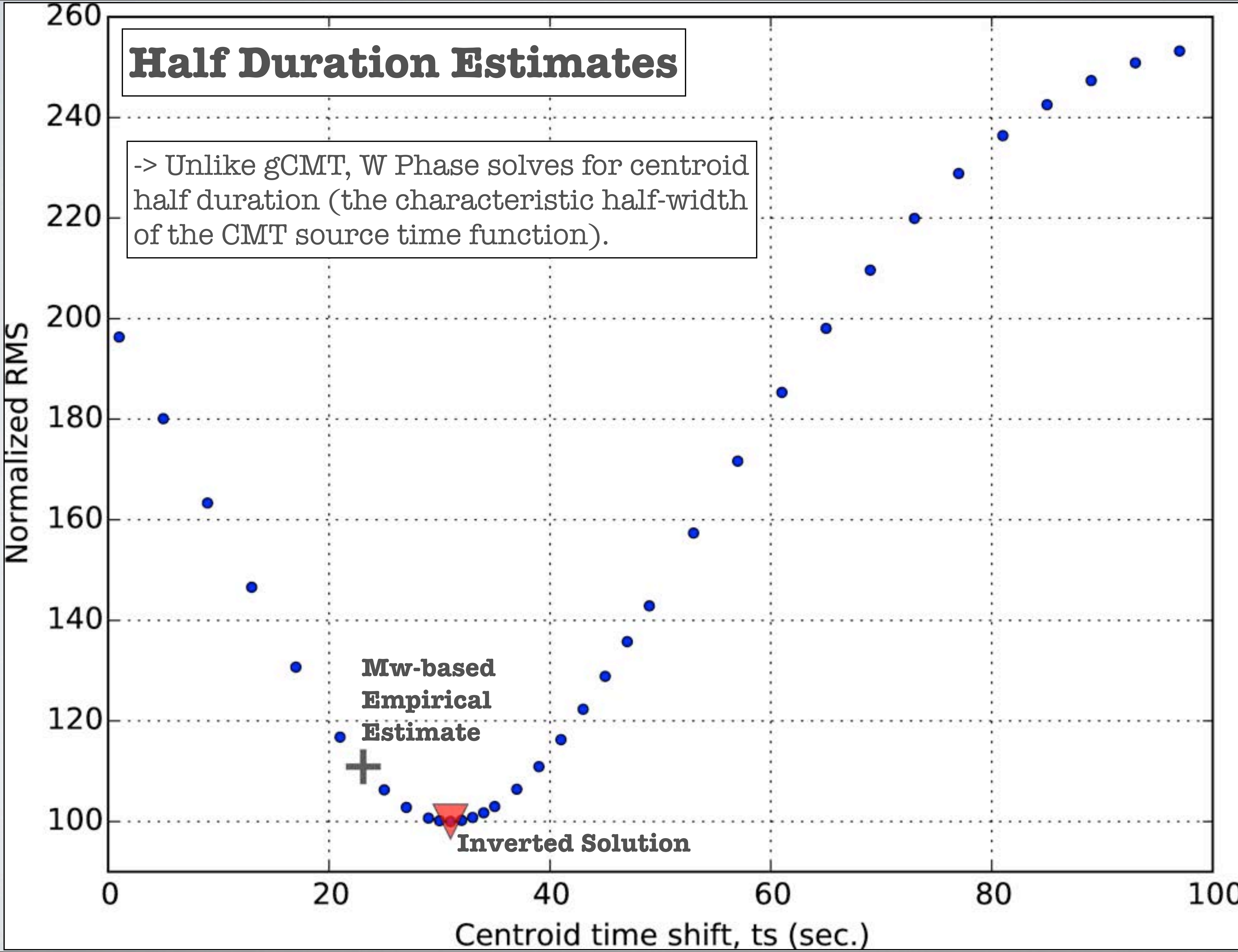


Performance

Angular rotation quantifies the difference between two tensors; less than ~ 35º is similar.

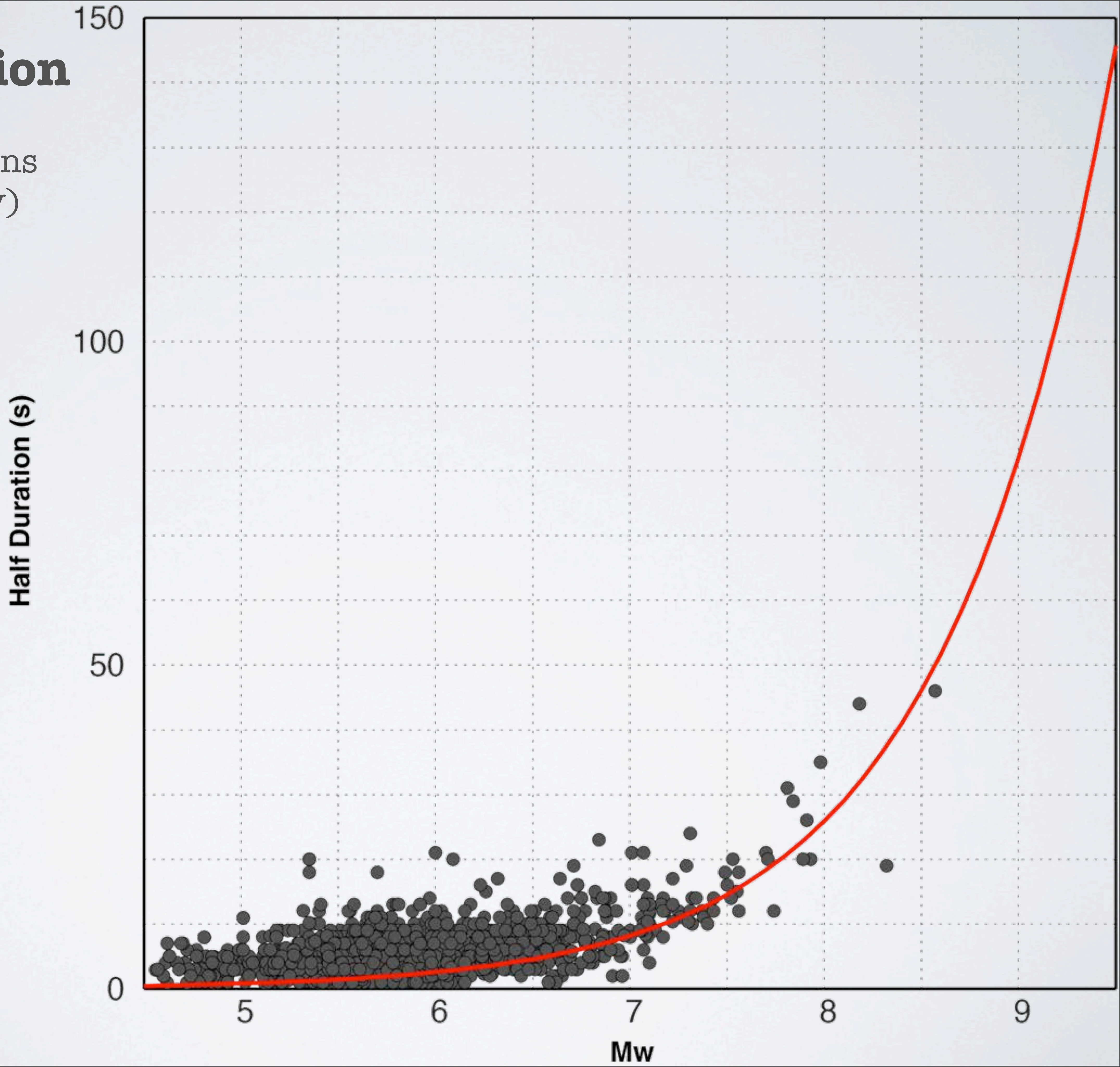
Difference in Mww also consistent through time.




Half Duration Estimates
-> Unlike gCMT, W Phase solves for centroid half duration (the characteristic half-width of the CMT source time function).
Mw-based Empirical Estimate
Inverted Solution
Normalized RMS
Centroid time shift, ts (sec.)
260
240
220
200
180
160
140
120
100
0
20
40
60
80
100

Half Duration

Real time solutions since 2009 (gray) show broad agreement with empirical estimate (red).



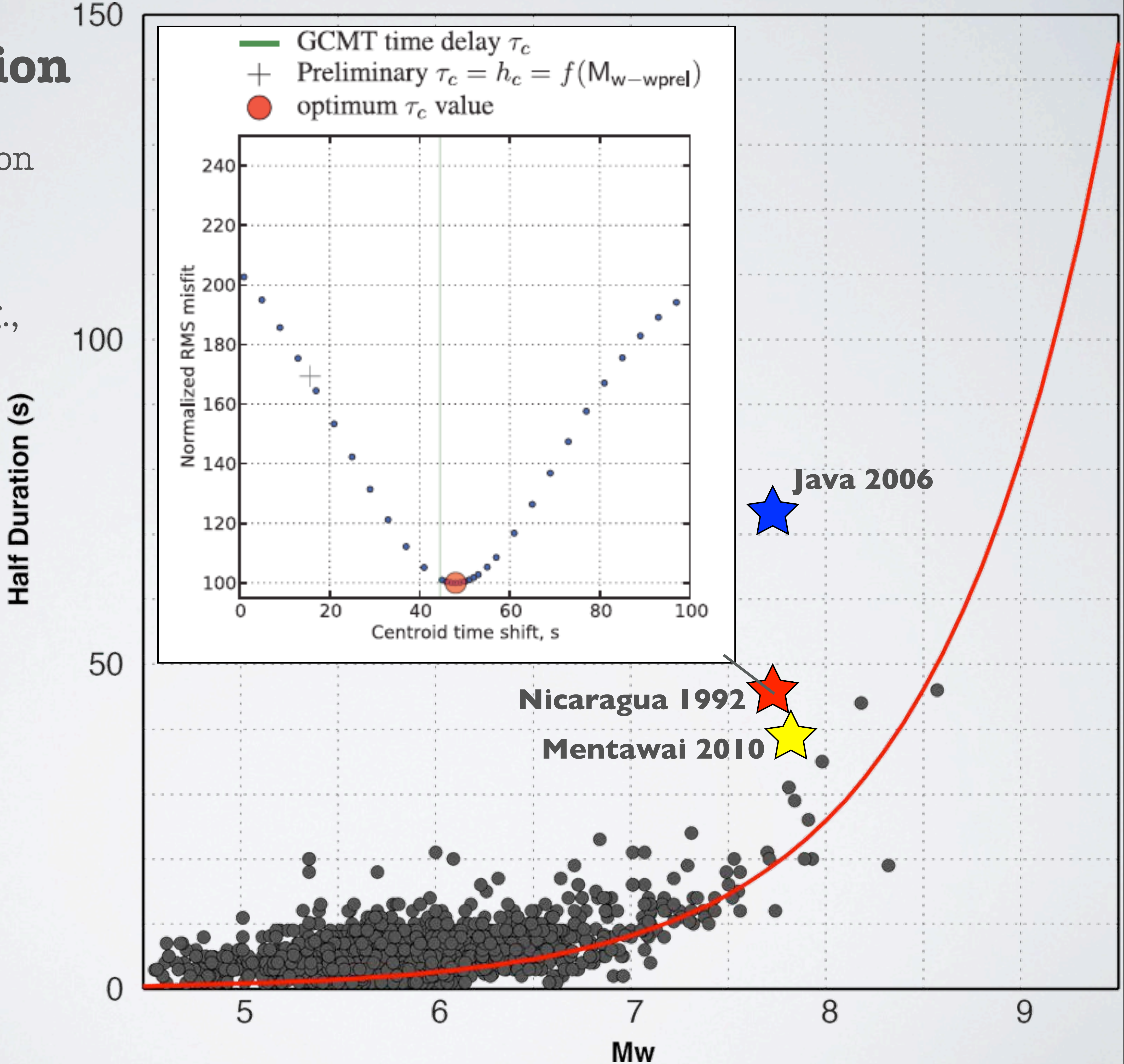
Half Duration

BUT - half duration estimates can be diagnostic of 'unusual' earthquakes - e.g., tsunami EQs.

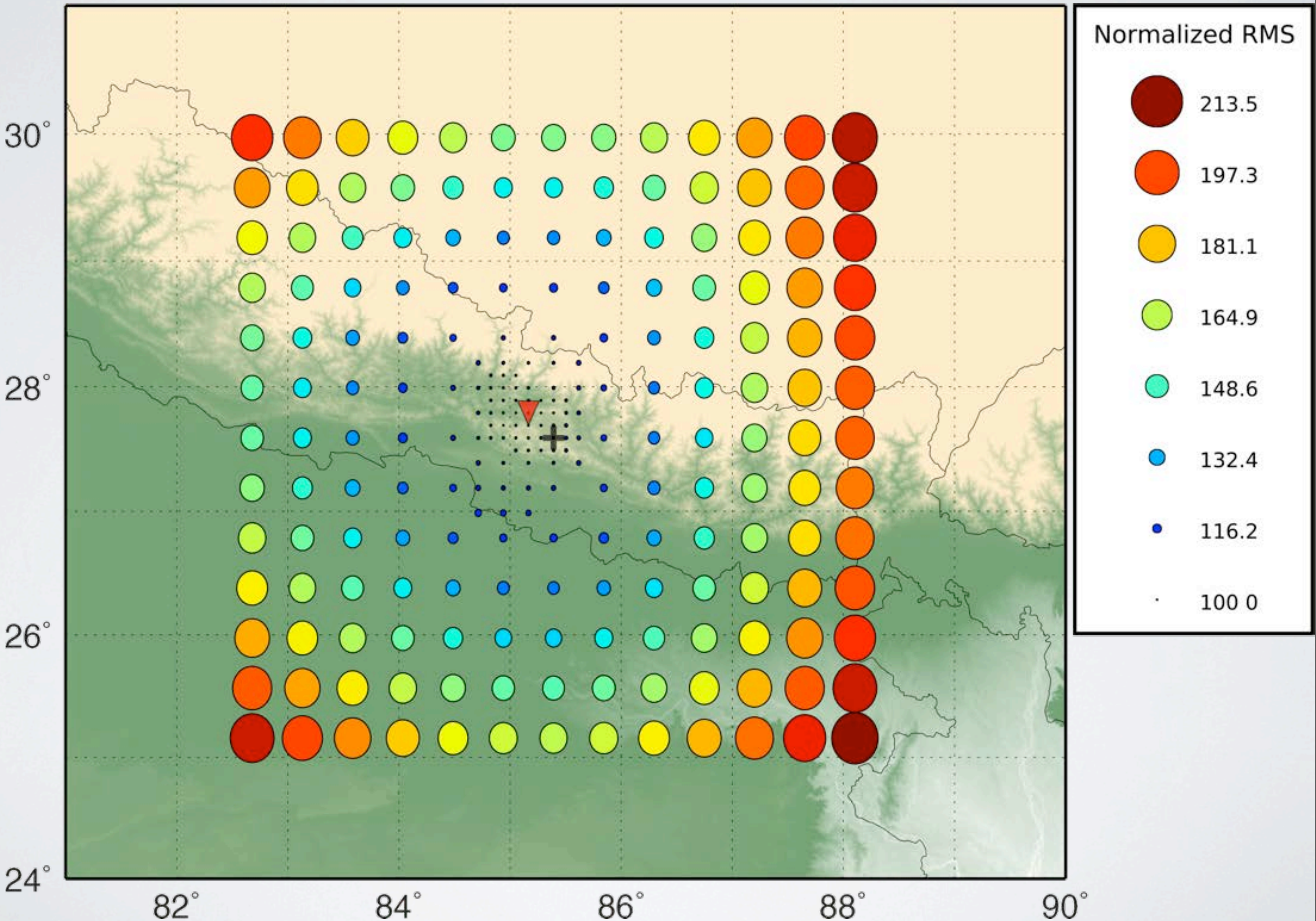
This example shows the extended duration of the 1992 Nicaragua tsunami EQ.

Yellow star = 2010 Mentawai tsuanami EQ.

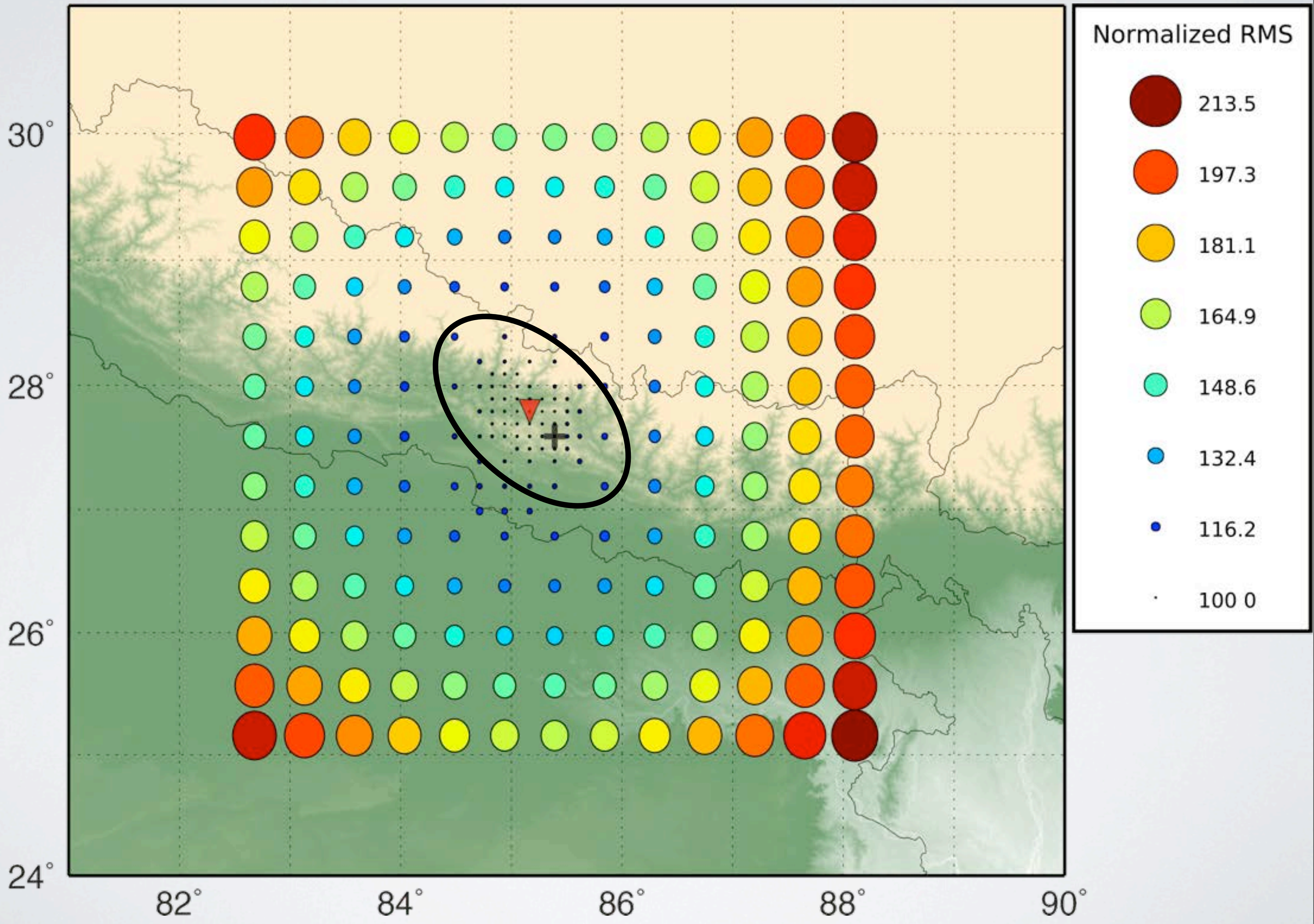
Blue = 2006 Java tsunami EQ.



Centroid Search



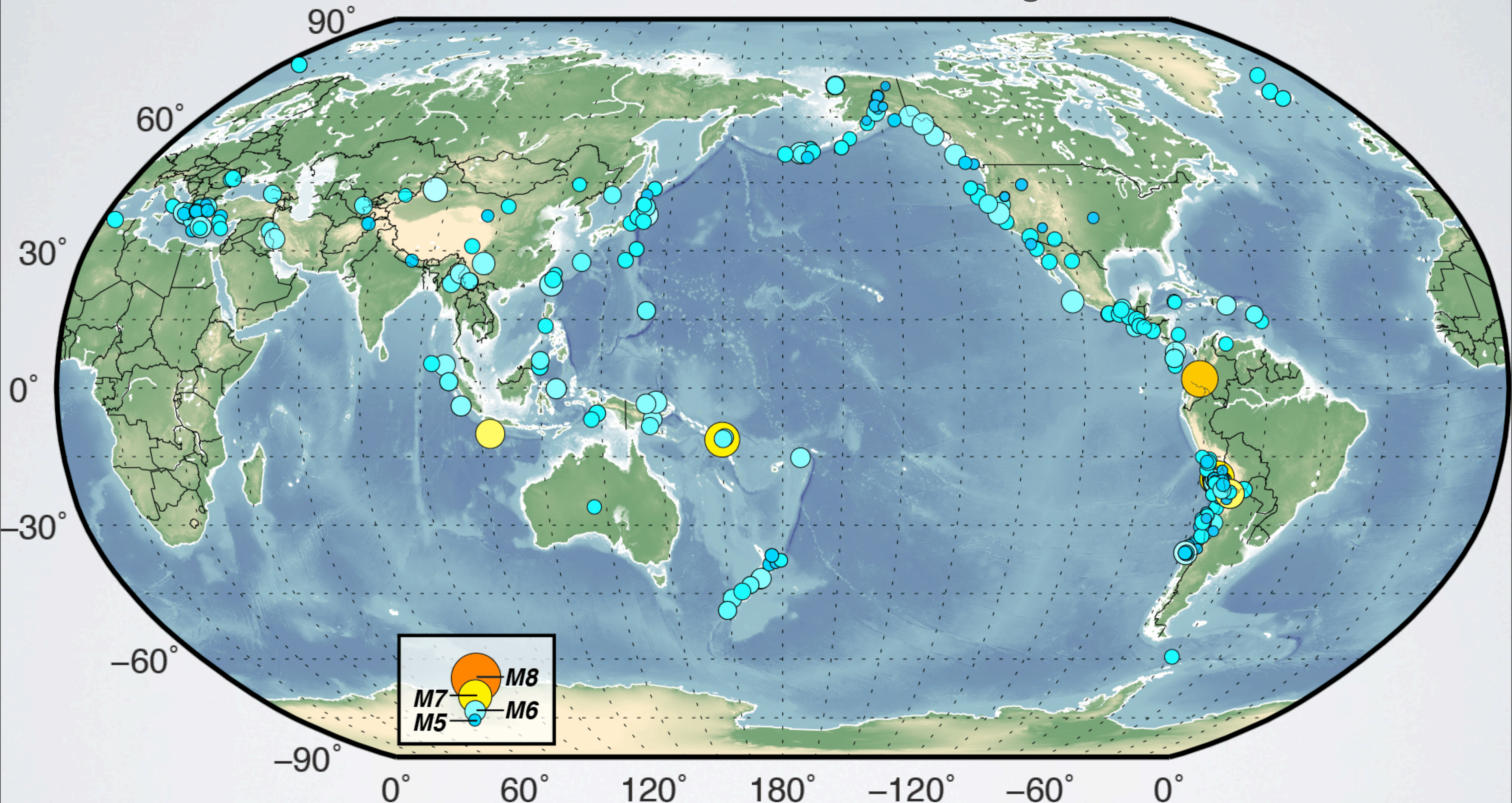
Centroid Search - Diagnostic of Source Area?



Regional Applications

Global W Phase: Regional Mww Inversion (<12 mins)

Event-station distances of <20 deg.



405 events published since June 2012

Smallest Mww published = M 4.45 (11-2014 Oregon, US EQ)

% of Mww's published at regional distances - 12% in 2013; 47% in 2015.

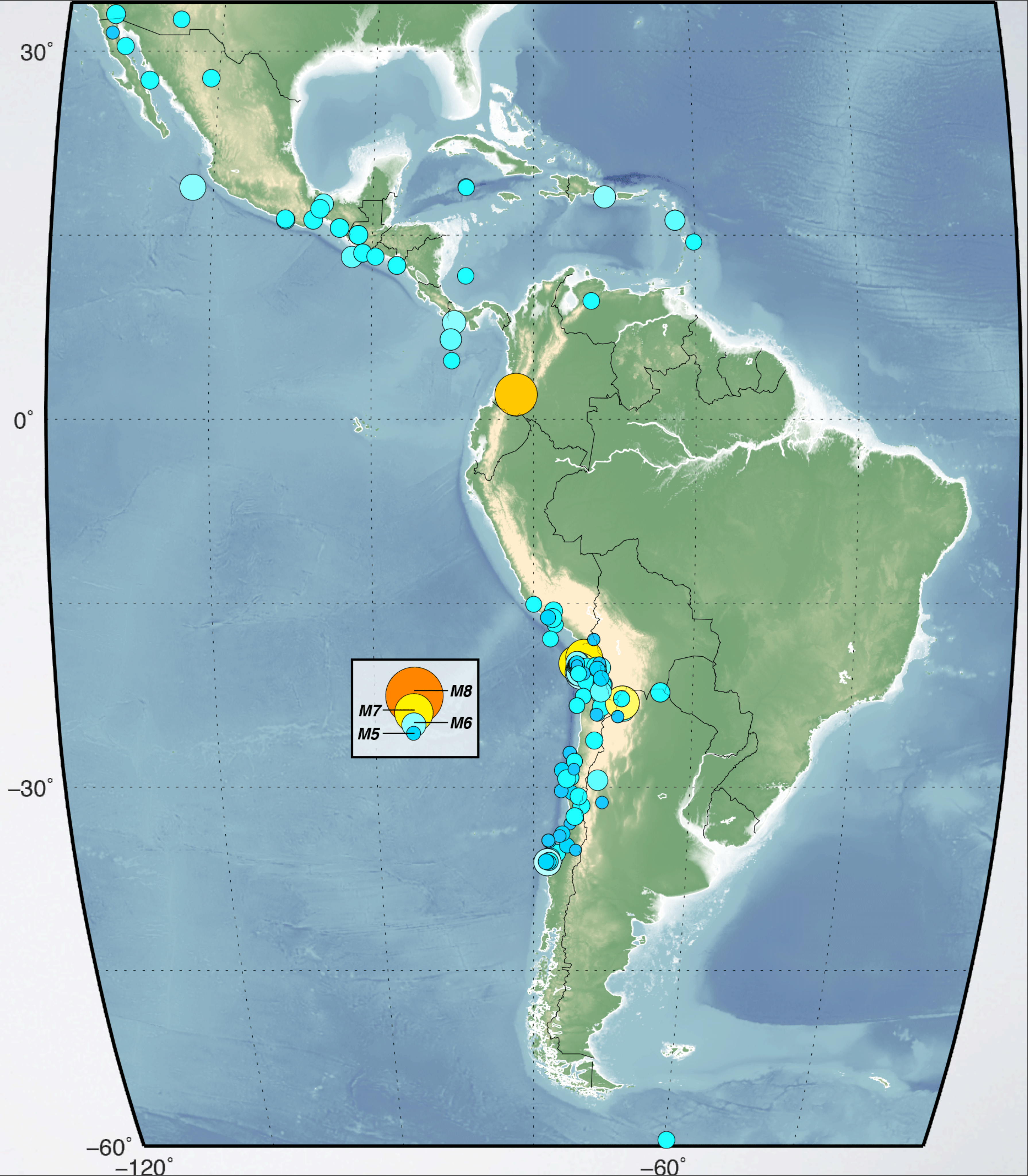
Regional Mww, Central/South America

211 events since 2013 (plus one Mw7.2 EQ in Colombia, 09-2012)

Mw 4.56-7.22

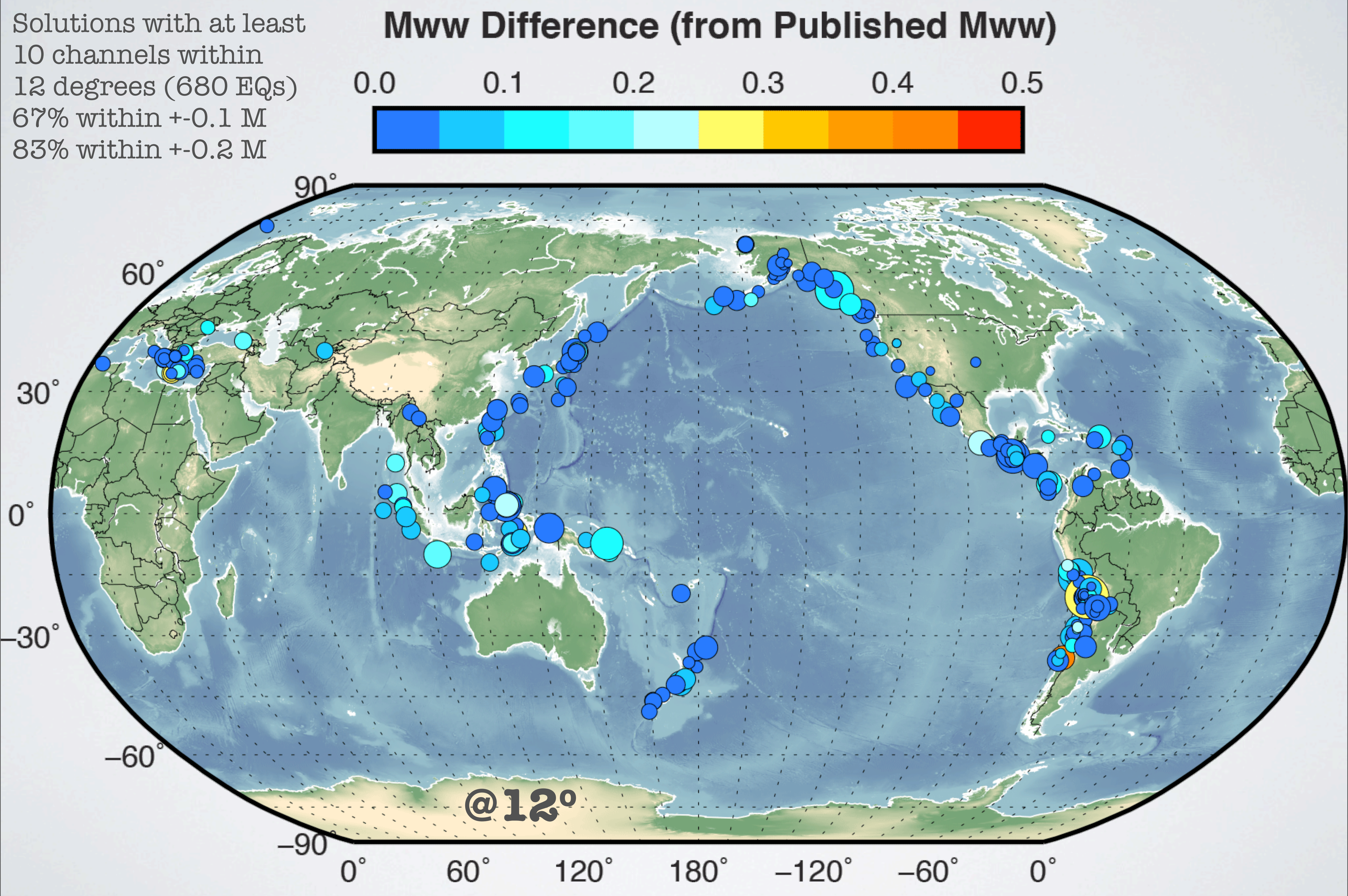
Most in Chile (170).

Mww catalog complete at the M5 level in Chile (All of 131 EQs in PDE; 95 with regional Mww).



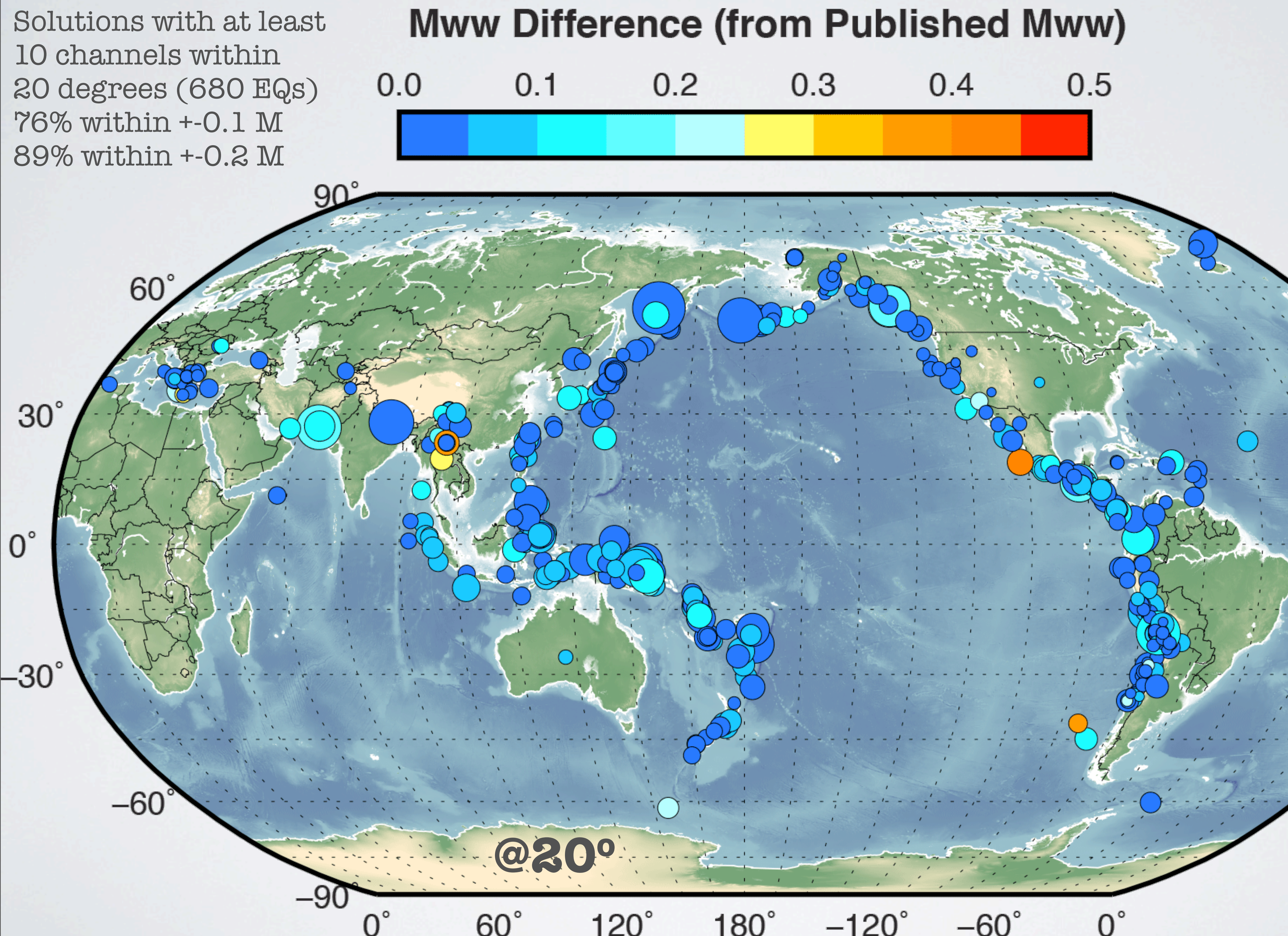
Global W Phase: Rapid Mww Vs Published Solution

Solutions with at least
10 channels within
12 degrees (680 EQs)
67% within +-0.1 M
83% within +-0.2 M



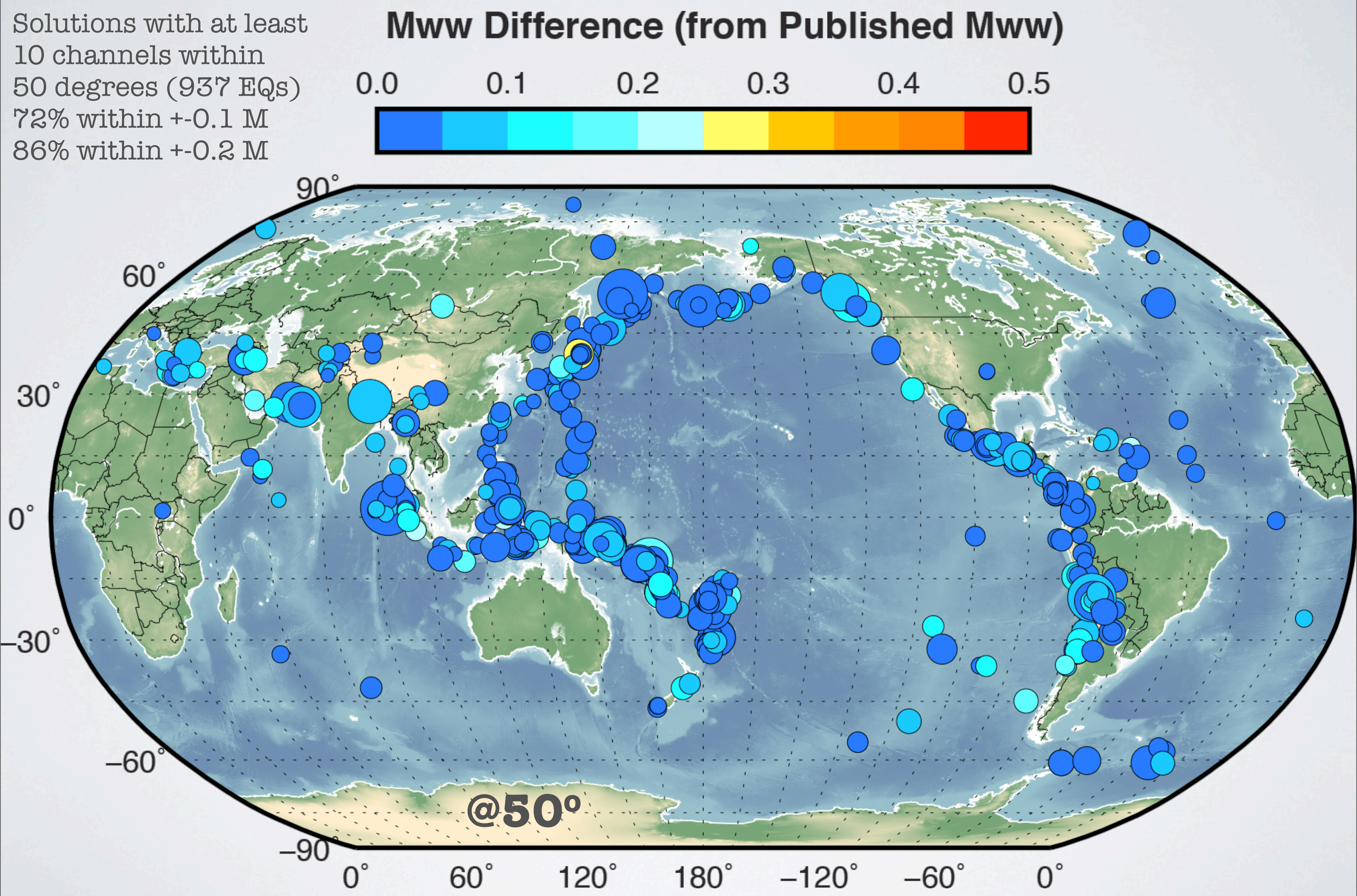
Global W Phase: Rapid Mww Vs Published Solution

Solutions with at least
10 channels within
20 degrees (680 EQs)
76% within +-0.1 M
89% within +-0.2 M



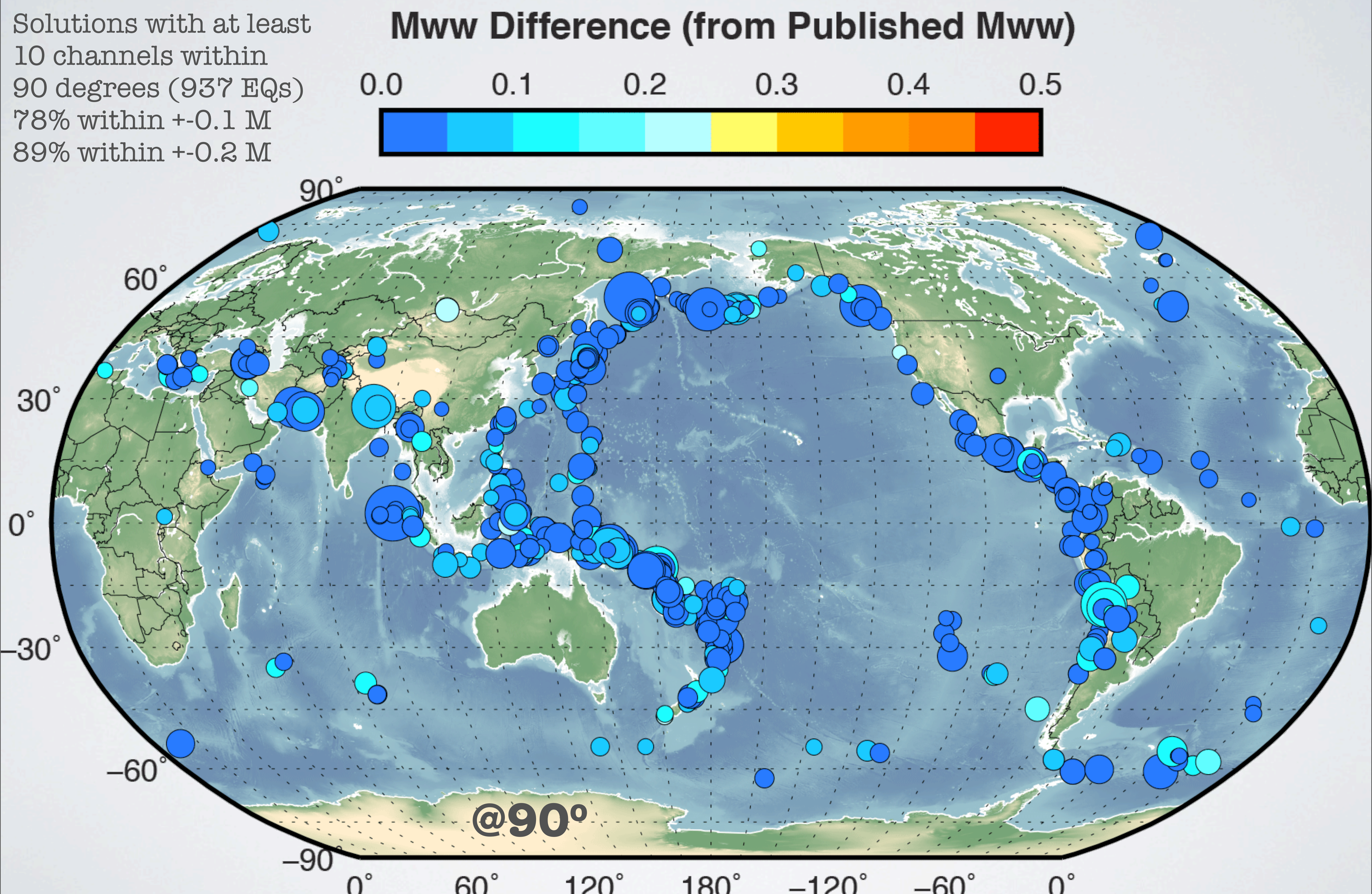
Global W Phase: Rapid Mww Vs Published Solution

Solutions with at least
10 channels within
50 degrees (937 EQs)
72% within +-0.1 M
86% within +-0.2 M

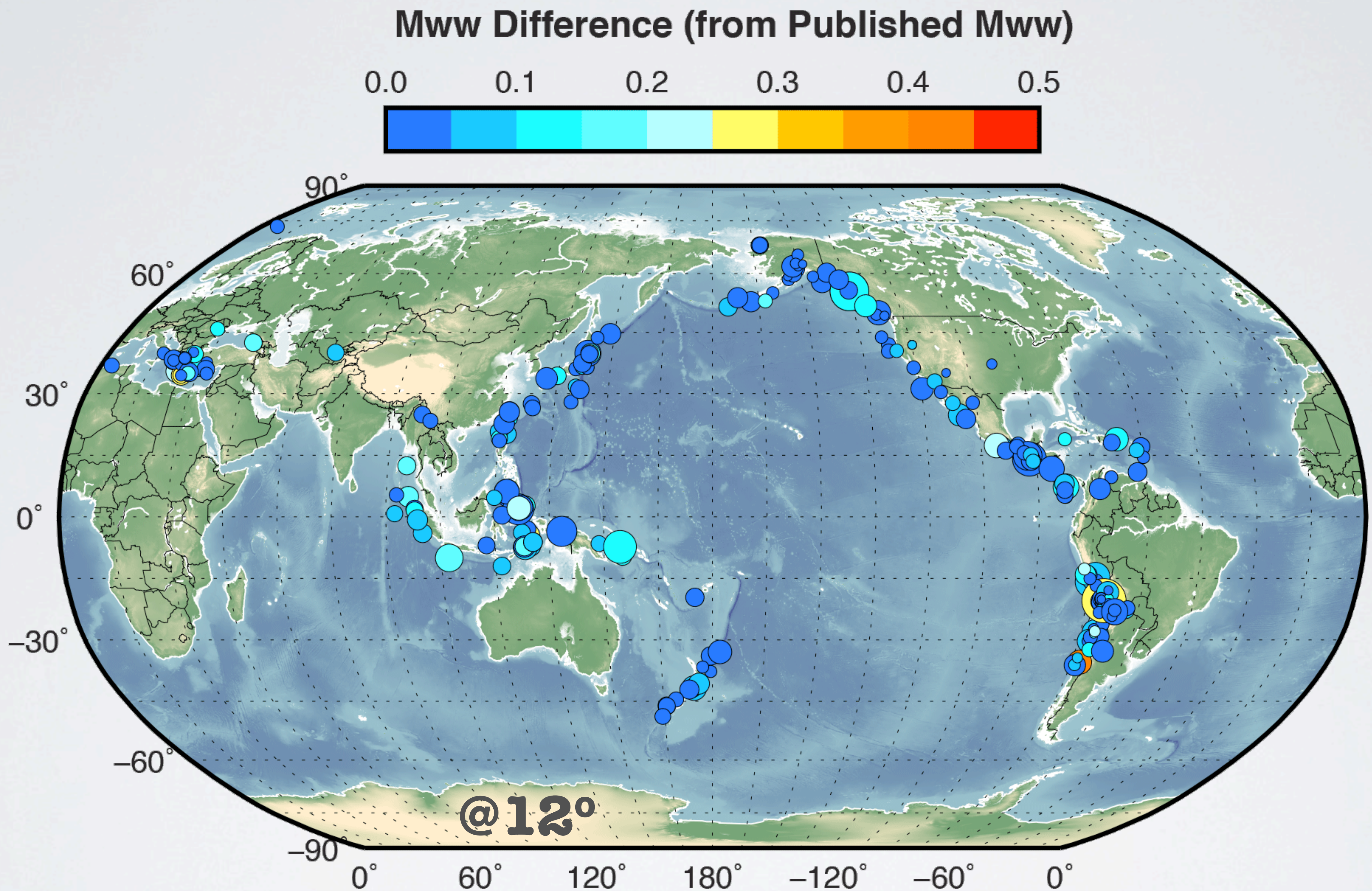


Global W Phase: Rapid Mww Vs Published Solution

Solutions with at least
10 channels within
90 degrees (937 EQs)
78% within +-0.1 M
89% within +-0.2 M

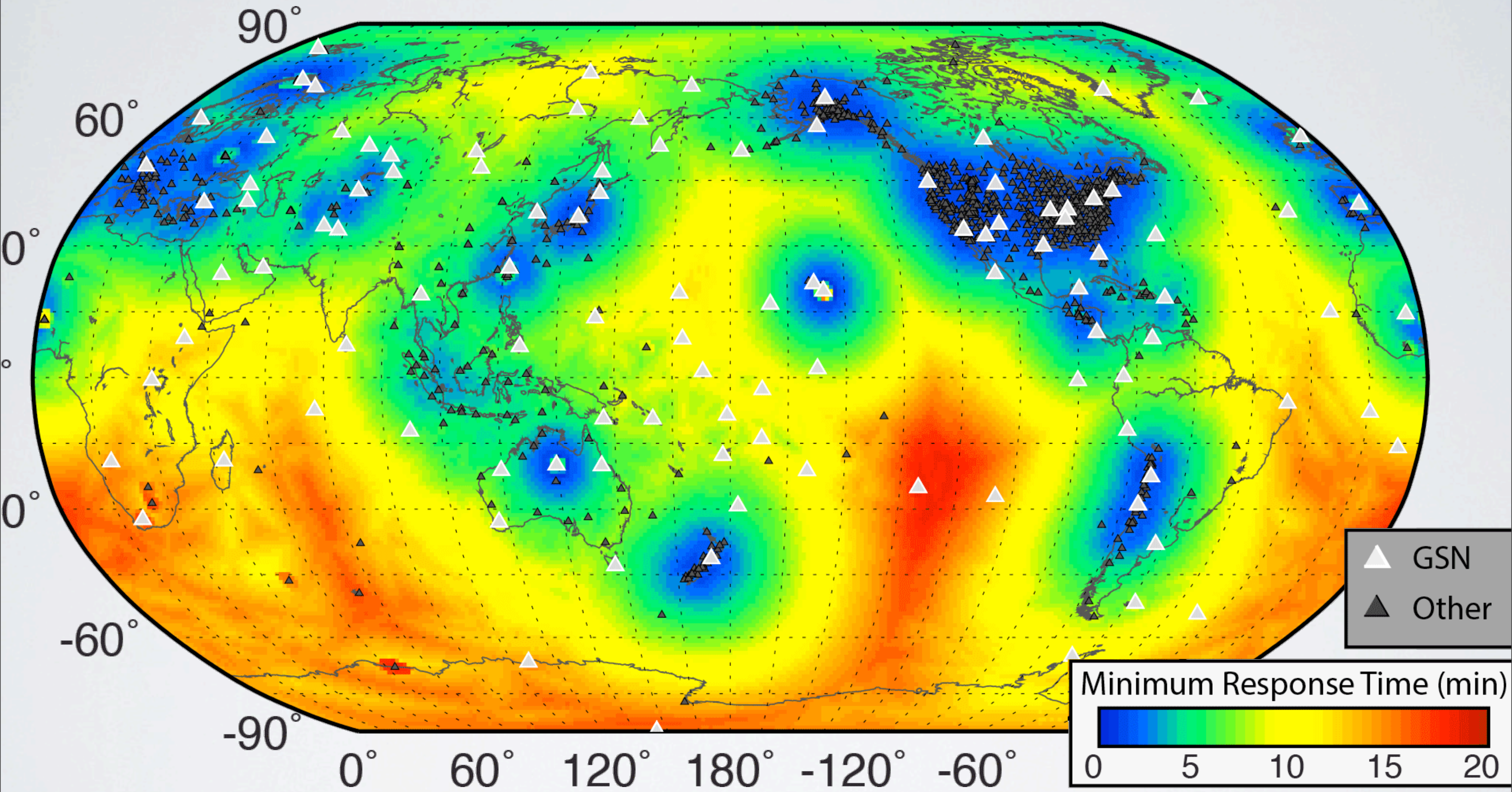


Global W Phase: Rapid Mww Vs Published Solution



These results imply that, for response purposes, we can accurately characterize magnitude very rapidly, given a locally dense distribution of stations (i.e., a regional network).

Idealized Response Times: Current Data Coverage



Given this information, and the current global distribution of broadband seismic stations providing data to the NEIC in real time, this map shows an idealized minimum response time anywhere on the global.

Beyond Realtime Applications...

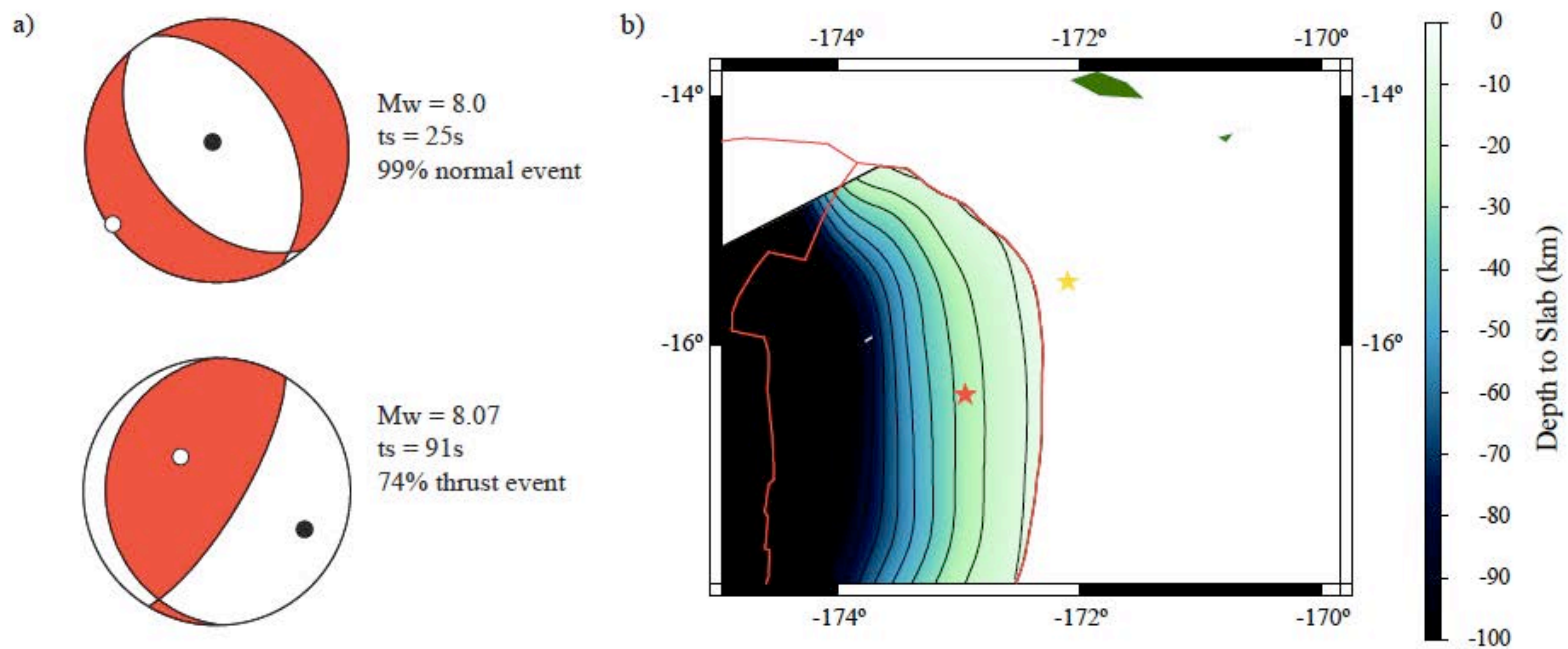
Inversion Challenges - Complex Earthquakes

Through an extension of the single point-source inversion, large earthquakes can be assessed for complexity with multiple sources.

=> Invert for multiple CMTs
-> Test whether improved solution fits are statistically significant.

Samoa EQ(s), 09-29-2009

Nealy & Hayes, in prep., 2015

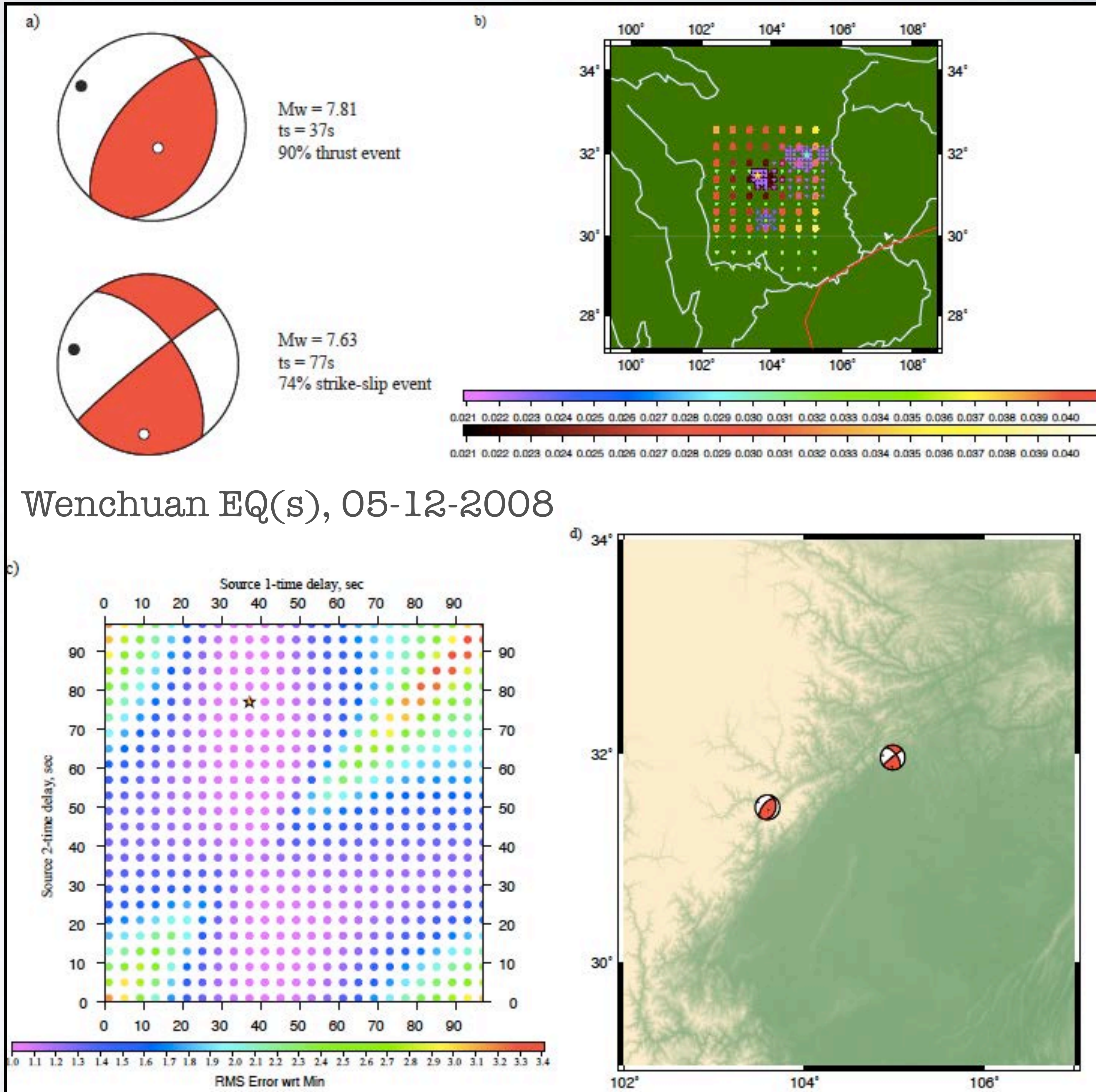


Inversion Challenges - Complex Earthquakes

Through an extension of the single point-source inversion, large earthquakes can be assessed for complexity with multiple sources.

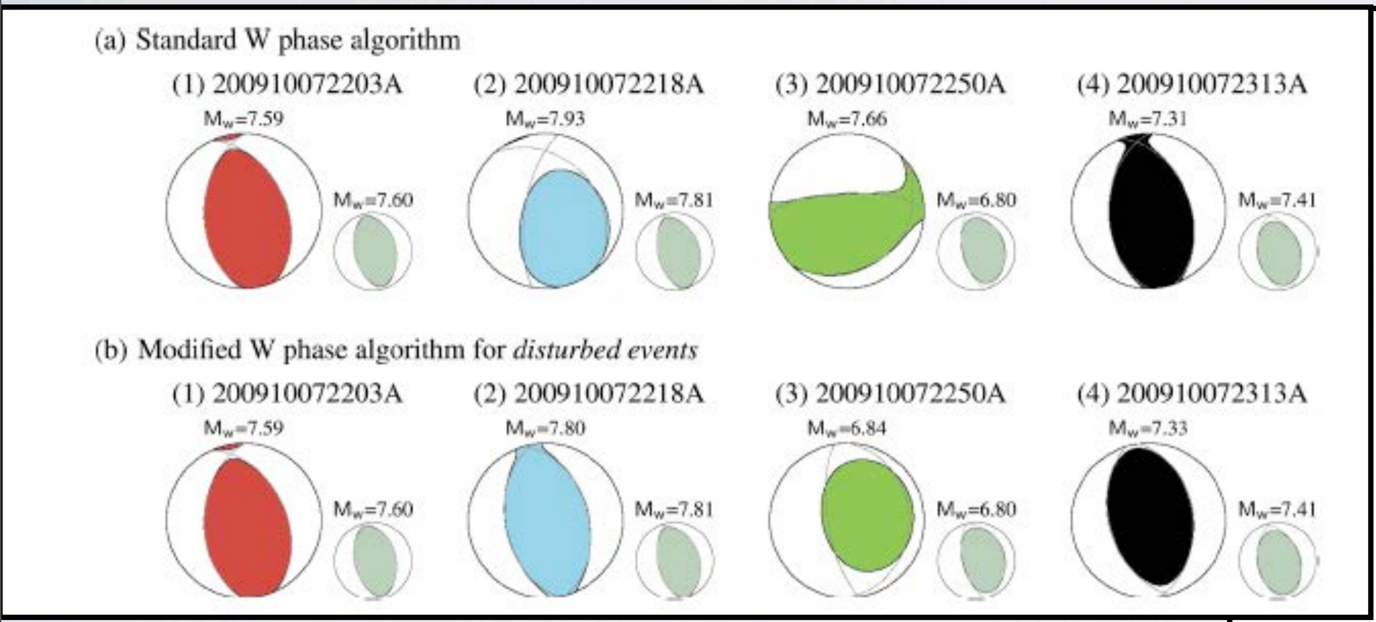
15% of M7.5+ EQs since 1990 demonstrate resolvable complexity.

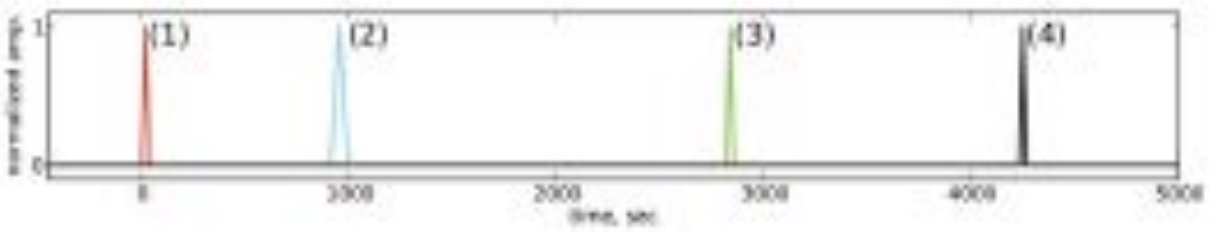
=> Can be used to improve single source fits rapidly; and identify 'missing' earthquakes.

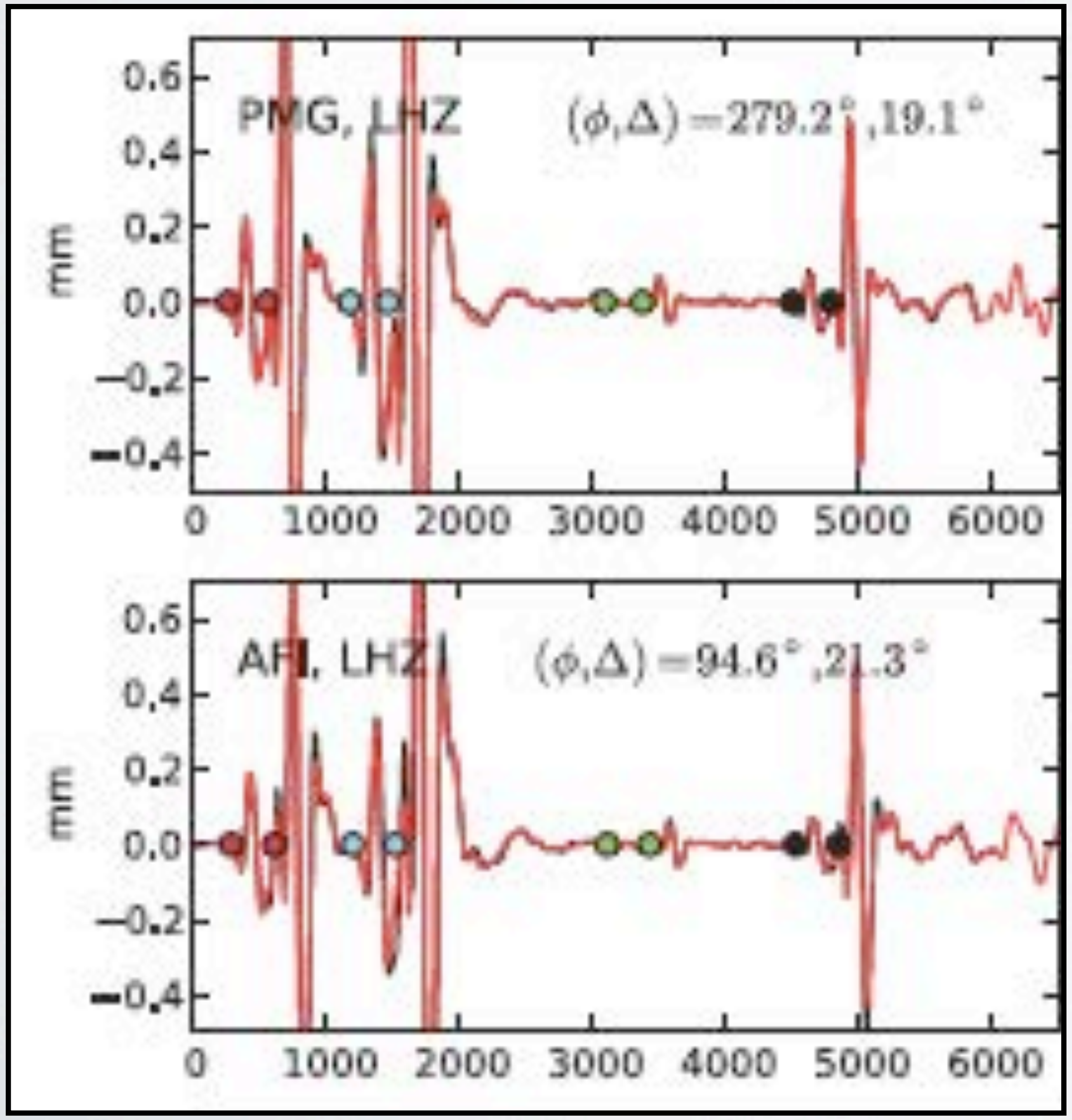


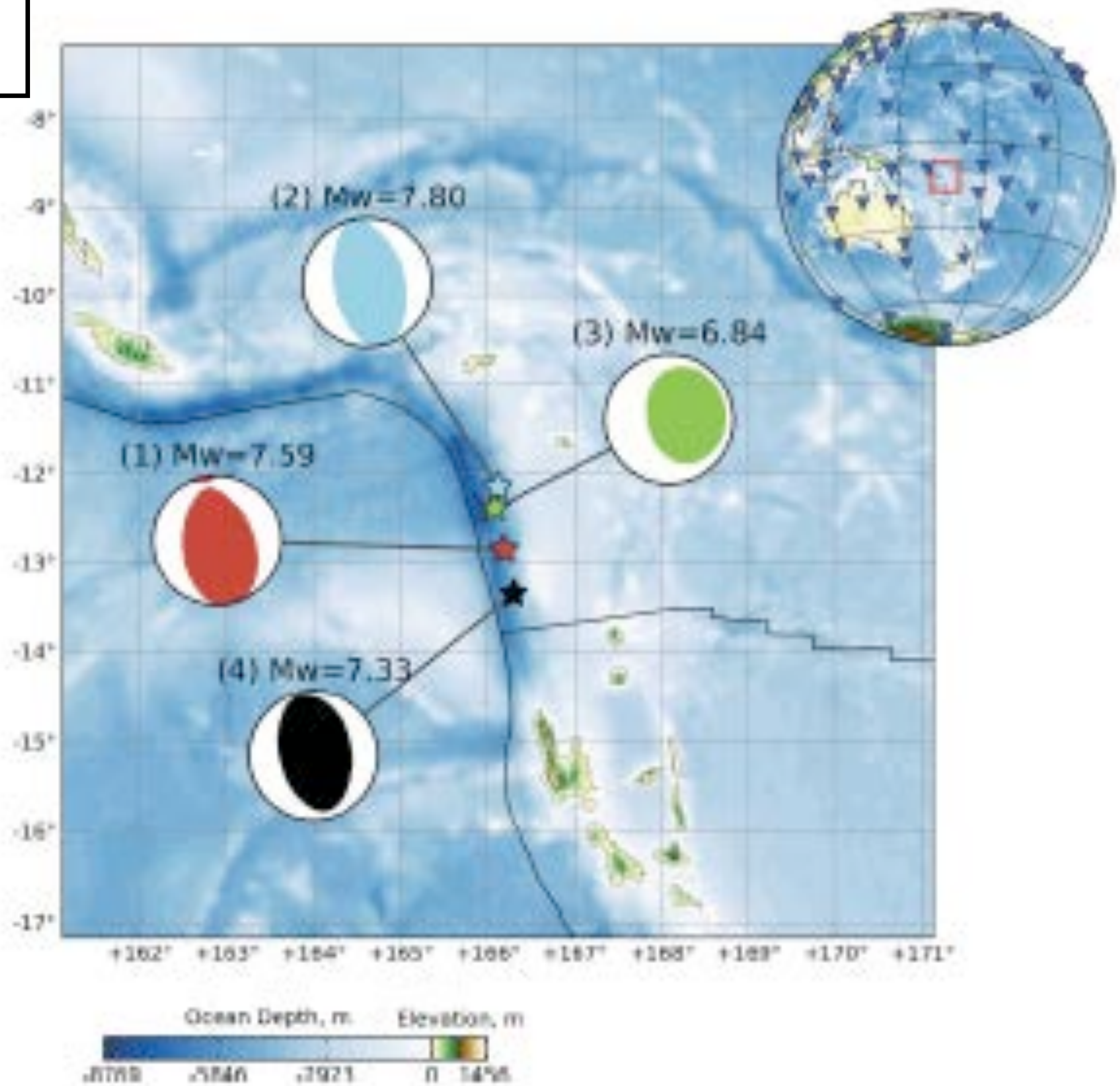
Wenchuan EQ(s), 05-12-2008

Inversion Challenges - 'Disturbed' Earthquakes









The Research Front

Resolving power for moment tensor & seismotectonic ambiguity.

Example for the 04-25-2015 Nepal earthquake shows the well-resolved near-horizontal dip of the causative fault.

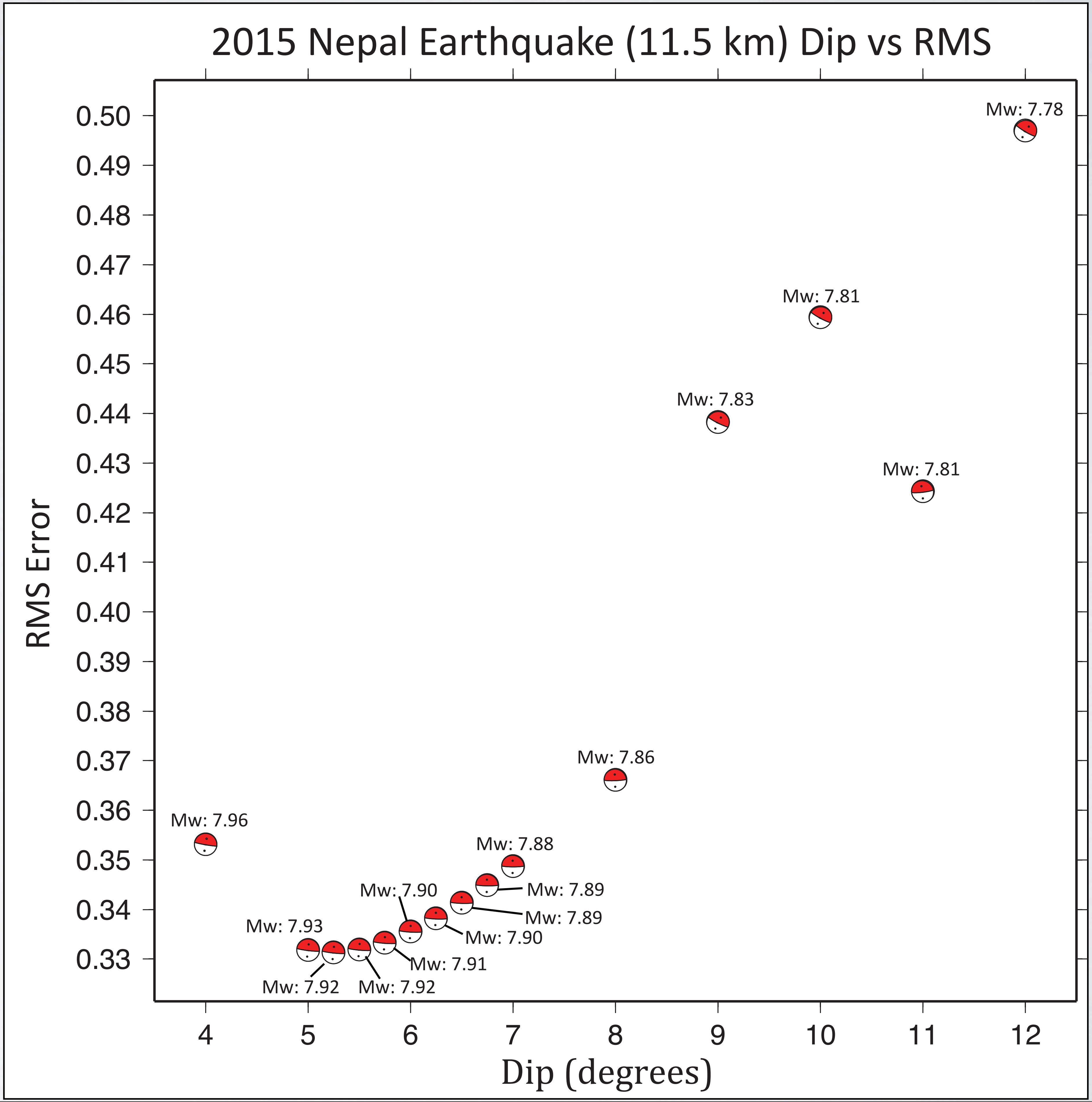
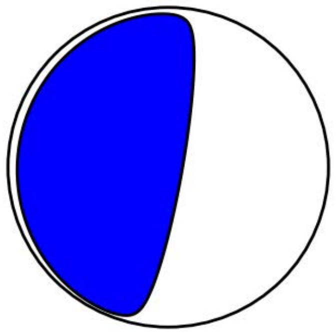


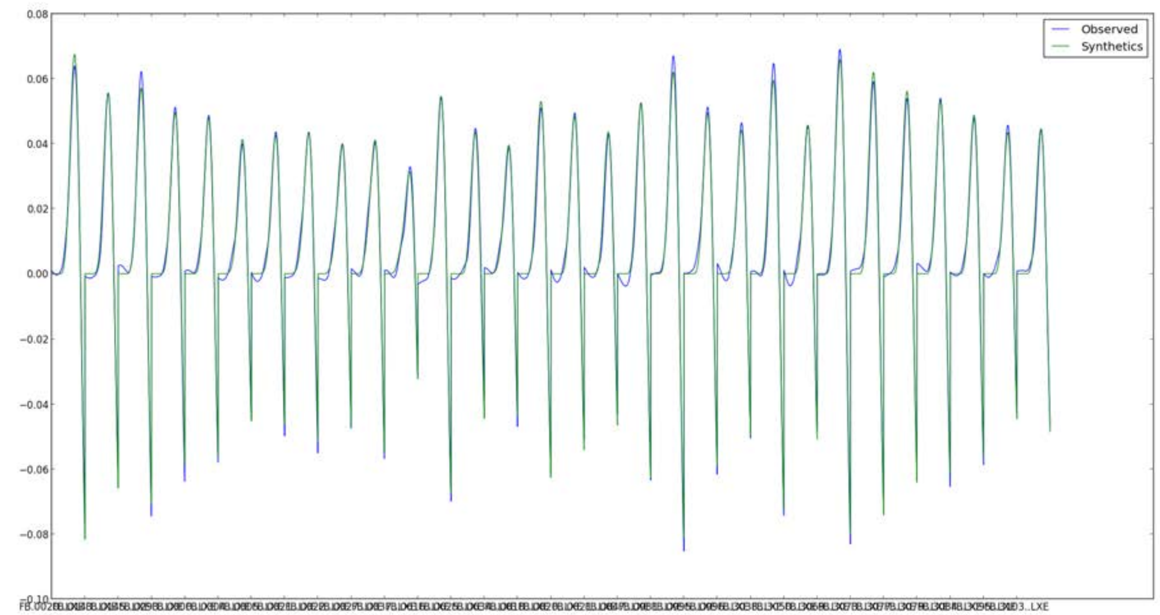
Figure from Jennifer Nealy.

The Research Front W-phase using cGPS

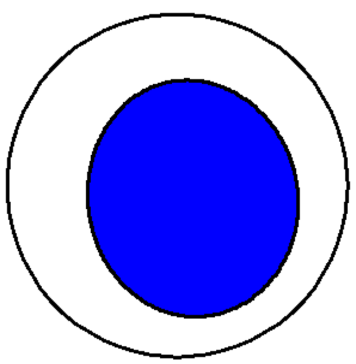
GPS: a Very LP green “function maker”, that doesn't saturate in the near-field

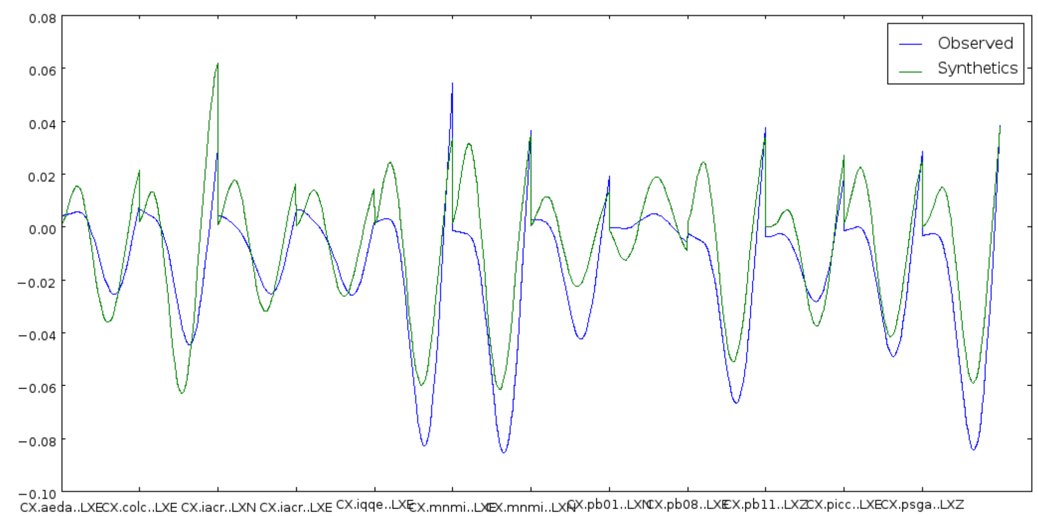
W-phase using cGPS 1 sps 2011
Mw 9.1 Tohoku Earthquake



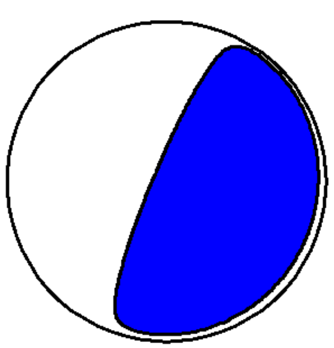


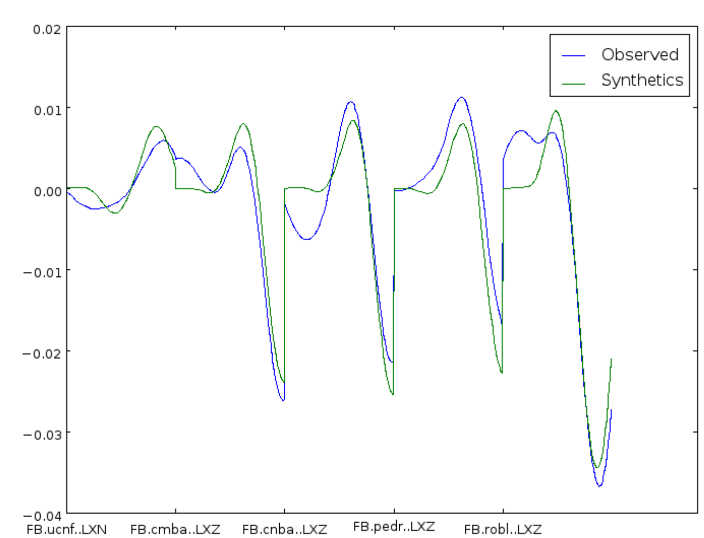
W-phase using cGPS 1 sps 2014
Mw 8.2 (8.35) Iquique Earthquake





W-phase using cGPS 1 sps 2010
Mw 8.8 (9.1)Maule Earthquake





The Research Front FFM W-phase using BB

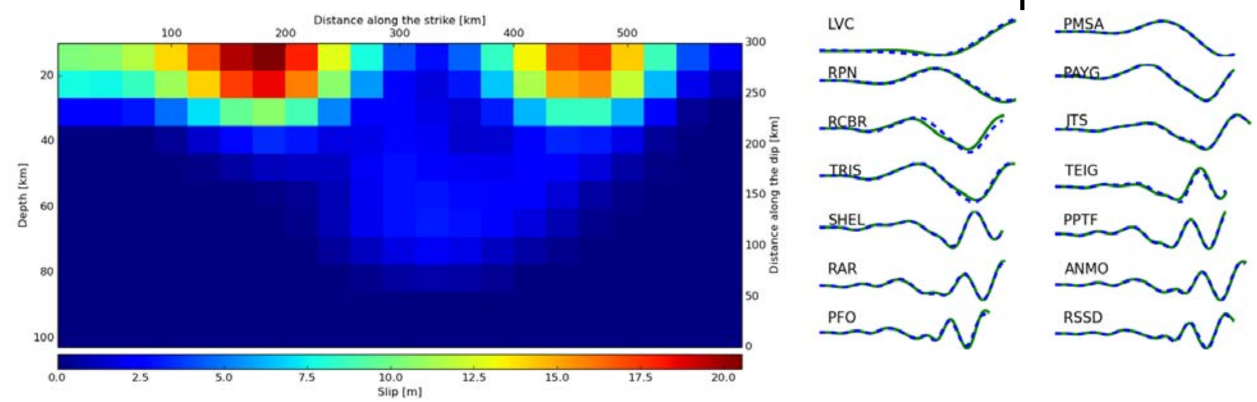
CSN CENTRO SISMOLÓGICO NACIONAL UNIVERSIDAD DE CHILE

- Next Steps: Include GPS signals.
- FFM from cGPS W-phase
- Hopefully from RTX technology
- Why FFM? provides a better estimation for run-up, pga, damage, economic losses and fatalities.

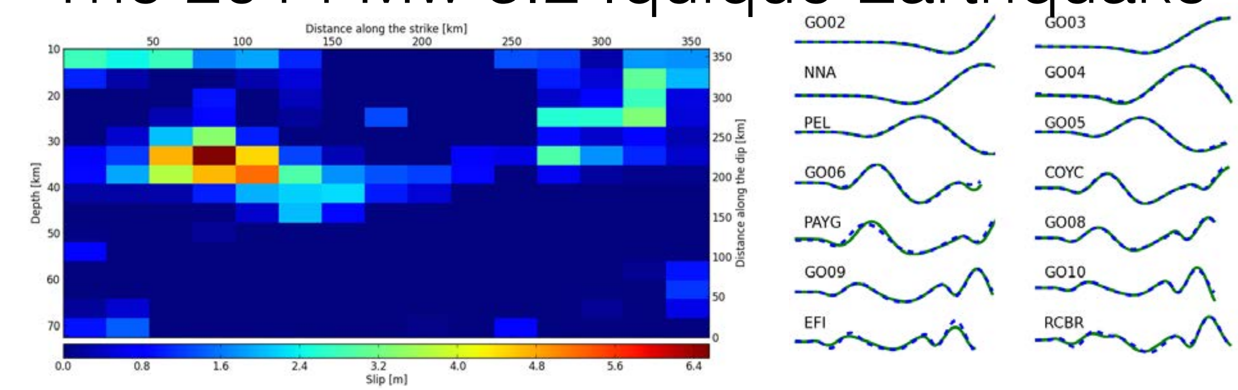
Possible Scheme for Mw > 8

- Hypocenter
- WCMT cGPS
- WCMT cGPS+BB
- WFFM cGPS
- WFFM cGPS+BB

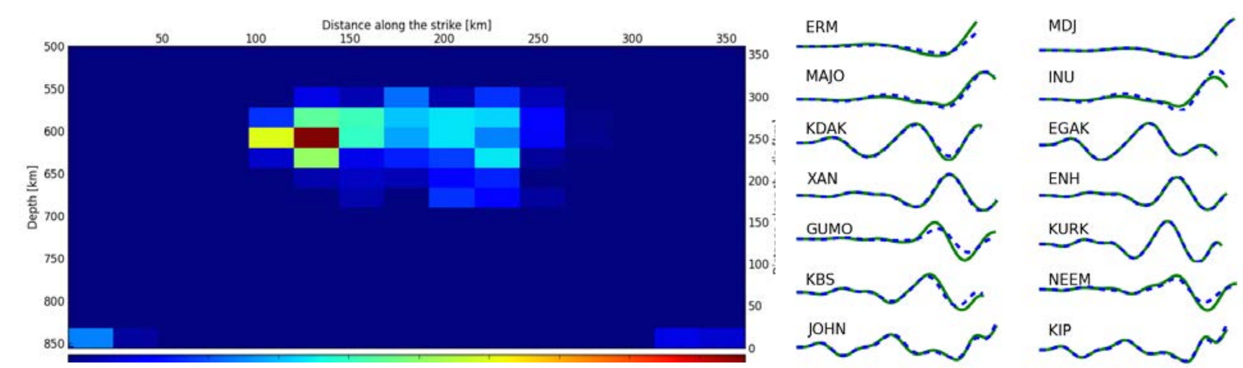
The 2010 Mw 8.8 Male Earthquake



The 2014 Mw 8.2 Iquique Earthquake



The 2013 Mw 8.3 Oshtok Earthquake



From Benavente R. & Cummins P., 2013

The Research Front FFM W-phase using BB

CSN CENTRO SISMOLÓGICO NACIONAL UNIVERSIDAD DE CHILE

GEOPHYSICAL RESEARCH LETTERS, VOL. 40, 3591–3595, doi:10.1002/grl.50648, 2013

Simple and reliable finite fault solutions for large earthquakes using the W-phase: The Maule (M_W = 8.8) and Tohoku (M_W = 9.0) earthquakes

Roberto Benavente[1] and Phil R. Cummins[1]

Received 6 May 2013; revised 5 June 2013; accepted 10 June 2013; published 22 July 2013.

[1] We explore the ability of W-phase waveform inversions to recover a first-order coseismic slip distribution for large earthquakes. To date, W-phase inversions for point sources provide fast and accurate moment tensor solutions for moderate to large events. We have applied W-phase finite fault inversion to seismic waveforms recorded following the 2010 Maule earthquake (M_w = 8.8) and the 2011 Tohoku earthquake (M_w = 9.0). Firstly, a W-phase point source inversion was performed to assist us in selecting the data for the finite fault solution. Then, we use a simple linear multiple-time-window method accounting for changes in the rupture velocity with smoothing and moment minimization constraints to infer slip and rake variations over the fault. Our results describe well the main features of the slip pattern previously found for both events. This suggests that fast slip inversions may be carried out relying purely on W-phase records. **Citation:** Benavente, R., and P. Cummins (2013), Simple and reliable finite fault solutions for large earthquakes using the W-phase: The Maule (M_w = 8.8) and Tohoku (M_w = 9.0) earthquakes, *Geophys. Res. Lett.*, *40*, 3591–3595, doi:10.1002/grl.50648.

1. Introduction

[2] Details of earthquake sources, such as fault orientation and the spatial variation of slip, are potentially useful in the first phases of disaster response. Understanding the proximity of fault rupture to population centers can be important for rapid casualty estimates [*Jaiswal and Wald*, 2011]. Understanding the spatial distribution of slip is especially important for large megathrust earthquakes, since tsunamigenicity is very sensitive to the amount of slip concentrated at shallow depth [*Satake and Tanioka*, 1999; *Hill et al.*, 2012]. These considerations have motivated recent work on the use of GPS data to estimate earthquake slip distributions in near real time [*Ohta et al.*, 2012; *Crowell et al.*, 2012]. These studies have demonstrated that dense GPS networks deployed in the near field of large earthquakes are able to obtain reliable estimates of slip distribution within minutes of an earthquake's occurrence, and are not prone to clipping, which plagues seismometer recordings in the near field.

Additional supporting information may be found in the online version of this article.

This article was originally published on line on 22 July 2013. Revised supporting information was supplied, and the article was reposted on 1 August 2013.

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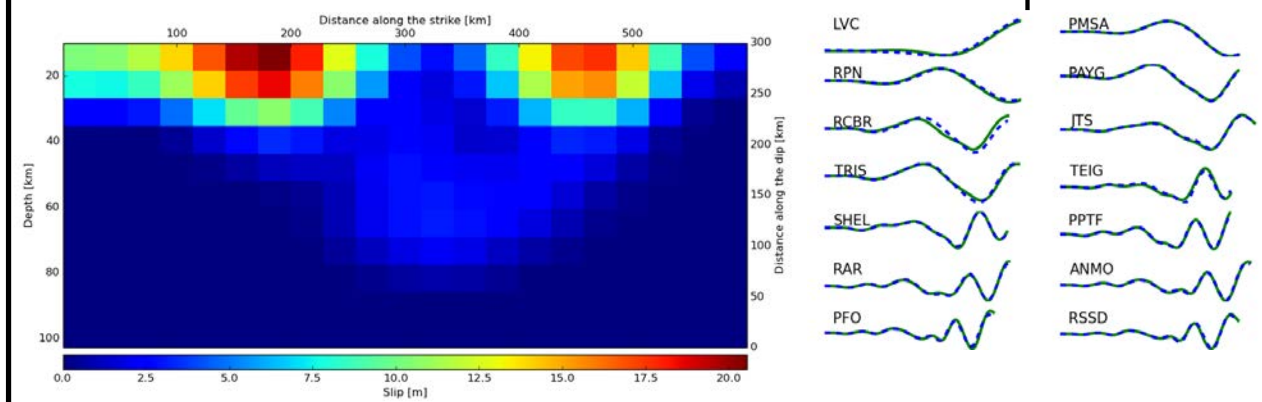
[3] However, because not all megathrust earthquakes occur adjacent to dense GPS networks providing near real-time positioning, it is important to consider alternative means of obtaining rapid and reliable earthquake slip distributions. Seismic waves have long been used in finite fault inversions to obtain slip distributions for large earthquakes [see, e.g., *Hartzell and Heaton*, 1983], and several studies have considered the rapid application of such techniques [*Mendoza and Hartzell*, 2013; *Mendoza*, 1996; *Ammon et al.*, 2006; *Dreger et al.*, 2005]. These studies either use regional seismic waveforms or teleseismic body and surface waves. However, these methods often require sophisticated processing and manual review and can be sensitive to 3-D earth structure. Here, we consider use of the W-phase [*Kanamori*, 1993] in finite fault inversion as an alternative that can potentially overcome some of the difficulties with using seismic body and surface waves in rapid finite fault inversions.

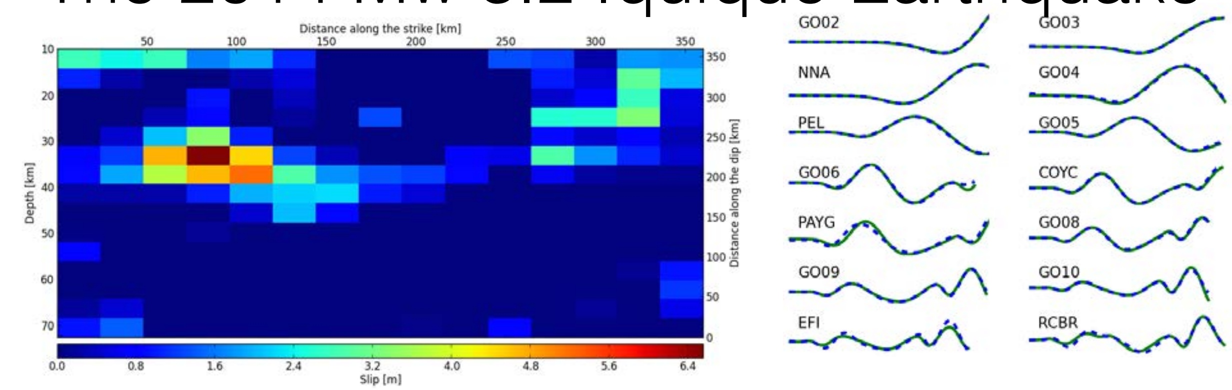
[4] The W-phase has gained special importance as a technique for point source inversions for large earthquakes. First reported by *Kanamori* [1993], the W-phase is a long period wave arriving at the recording station together with the *P* wave. Because of its small amplitude and the time window used (prior to *S* wave arrivals), the inversion of W-phase waveforms provides an effective method for rapid determination of the moment tensor. Moreover, if the instrument response is deconvolved in the time domain, the clipping in the records typical for large events can be avoided. Thus far, W-phase inversion has been shown to be a robust and reliable method for point source inversion for large earthquakes M_w > 6.5 [*Kanamori and Rivera*, 2008; *Duputel et al.*, 2012a], and it is a standard solution in the U.S. Geological Survey (USGS) catalog. In addition, multiple-point-source inversions of W-phase waveforms were introduced by *Duputel et al.* [2012b] in order to explain the source complexity of the 2012 Sumatra great strike-slip event (*Mw* = 8.6). These characteristics have led us to evaluate the use of the W-phase in the slip distribution problem.

[5] To recover the coseismic slip, different types of data can be used (geodetic, teleseismic, tsunami records, etc.), although far field seismic records play an important role because they are widely available within minutes after an earthquake occurs. The use of teleseismic data to constrain the spatial slip distribution was introduced by *Hartzell and Heaton* [1983]. They considered a predetermined fault plane divided into a number of subfaults and solved for their moment using constant rupture velocity. While many improvements have been made to this approach (a review

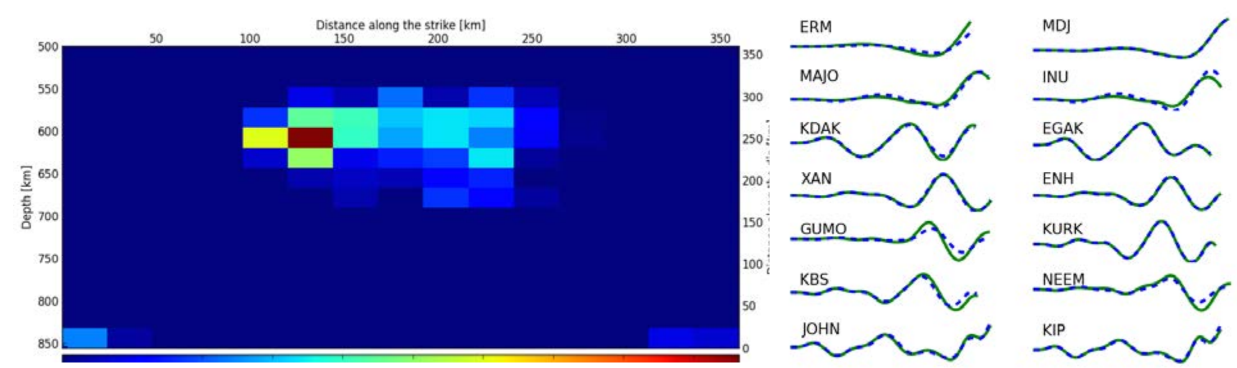
The 2010 Mw 8.8 Male Earthquake



The 2014 Mw 8.2 Iquique Earthquake



The 2013 Mw 8.3 Oshtok Earthquake



From Benavente R. & Cummins P., 2013

W Phase: Resources

GEOPHYSICAL RESEARCH LETTERS, VOL. 20, NO. 16, PAGES 1691-1694, AUGUST 20, 1993

W PHASE

Hiroo Kanamori

Abstract. The recent Nicar (September 2, 1992) produced a d (up to 1000 sec) phase which be on displacement seismograms. phase consists of long-period *P* its propagation mechanism is sir gallery. In terms of normal-mode of higher-mode Rayleigh waves w but slower than, that of *P* wave recognized as a distinct phase i because of clipping of seis earthquakes. With the advent of seismographs, this phase can be earthquakes. In view of its earthquakes, determining whe precursory or coseismic to the release, and determining velocity and the station, we propose that phase".

Typical seismograms exhibit sec) body-wave phases, such as which are followed by longer per surface waves. Since both body from the same source, the body- must also contain long-period e the combined effect of seismic dislocation sources and the conve the long-period wave is usually part of the seismogram and has be Here, we use the term "body wa arrives before the regular surface

To extract very long-per seismogram, short-period waves must be filtered out. Unfortunate recently because of clipping of r With the advent of digital wide- now it is possible to obtain o earthquakes, which allows seism period body waves for studying structure. A distinct merit of u studies is that the propagation pa for surface waves so that the s recovered from the observed rec advantageous for determinati earthquakes. For instance, wheth precedes or follows the onset of been a matter of great interest a source studies, long-period surf Rayleigh and Love waves) and long propagation paths were u source phase from which th determined. This procedure, how knowledge about the three-dimen

A difficulty in using very however, is that as the peri comparable to, or longer than, t

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Paper number 93GL01883
0094-8534/93/93GL-01883$03.0

Geophys. J. Int. (2008) 175, 222–238 doi: 10.1111/j.1365-246X.2008.03887.x

Source inversion of W phase: speeding up seismic tsunami warning

Hiroo Kanamori[1] and Luis Rivera[2]
[1]Seismological Lab., California Inst. of Technology, Pasadena, CA USA. E-mail: hiroo@gps.caltech.edu
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Accepted 2008 June

GJI Seismology

1 INTRODUCT

The 2004 Sumatra- Indian ocean wide unprecedented ma event motivated a warning systems w in the future. Effe elements: (1) detec of tsunami, (3) infra and training of the have been develop seismic networks, by Satake 2007; H tsunami warning m and global seismic

The seismic tsu sure tsunamis; ins an earthquake fro magnitude and me to false alarms. Ne of the most basic the Pacific Tsunam

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Source Inversion of the W-Phase: Real-time Implementation and Extension to Low Magnitudes

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Online material: Results for *W*-phase in with M ≥ 5.8 in 2007–2008, compar global Centroid Moment Tensor catalo

INTRODUCTION

We assess the use and reliability of a *W*-phase in real-time operations at the National Earthquake Information C inversion algorithm produces rapid an moment magnitude and source mecha than M_w 7.0 within 25 minutes of the e often less, and holds great promise fo response times to such earthquakes w also produces stable results (within Centroid Moment Tensor project esti as small as M_w 5.8 when using stations These applications extend the use of *W* higher magnitude events for which the i intended, facilitating its use as a comp traditional body- and surface-wave me source properties of an earthquake.

Kanamori and Rivera (2008) i *W*-phase as a reliable method to rap properties (M_w and mechanism) of ea ~M_w 7.5. They showed that the *W*-phas

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W phase source inversion for moderate to large earthquakes (1990–2010)

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SUMMARY

Rapid characterization of the earthquake source and of its effects is a growing field of interest. Until recently, it still took several hours to determine the first-order attributes of a great earthquake (e.g. $M_w \geq 7.5$), even in a well-instrumented region. The main limiting factors were data saturation, the interference of different phases and the time duration and spatial extent of the source rupture. To accelerate centroid moment tensor (CMT) determinations, we have developed a source inversion algorithm based on modelling of the W phase, a very long period phase (100–1000 s) arriving at the same time as the *P* wave. The purpose of this work is to finely tune and validate the algorithm for large-to-moderate-sized earthquakes using three

W Phase: Tutorial http://wphase.unistra.fr/wiki/doku.php/wphase

wphase

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W-phase

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Introduction

The W-phase package is an extensive source-inversion tool allowing rapid characterization of the seismic source and is a reliable and straightforward method to resolve first-order attributes of large earthquakes. Main contributors are Zacharie Duputel, Luis Rivera and Hiroo Kanamori.

Citation

If you use the W-phase package for your own research please cite the following articles:

- Z. Duputel, L. Rivera, H. Kanamori, and G. Hayes, 2012. W-phase fast source inversion for moderate to large earhquakes (1990 - 2010), Geophysical Journal International, v. 189, iss. 2, p. 1125-1147.
- G.P. Hayes, L. Rivera and H. Kanamori, 2009. Source inversion of the W phase: real-time implementation and extension to low magnitudes, Seismol. Res. Let., v. 3, 800-805.
- H. Kanamori and L. Rivera, 2008. Source inversion of W phase: speeding tsunami warning, Geophys. J. Int., v. 175, 222-238.

Questions?

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