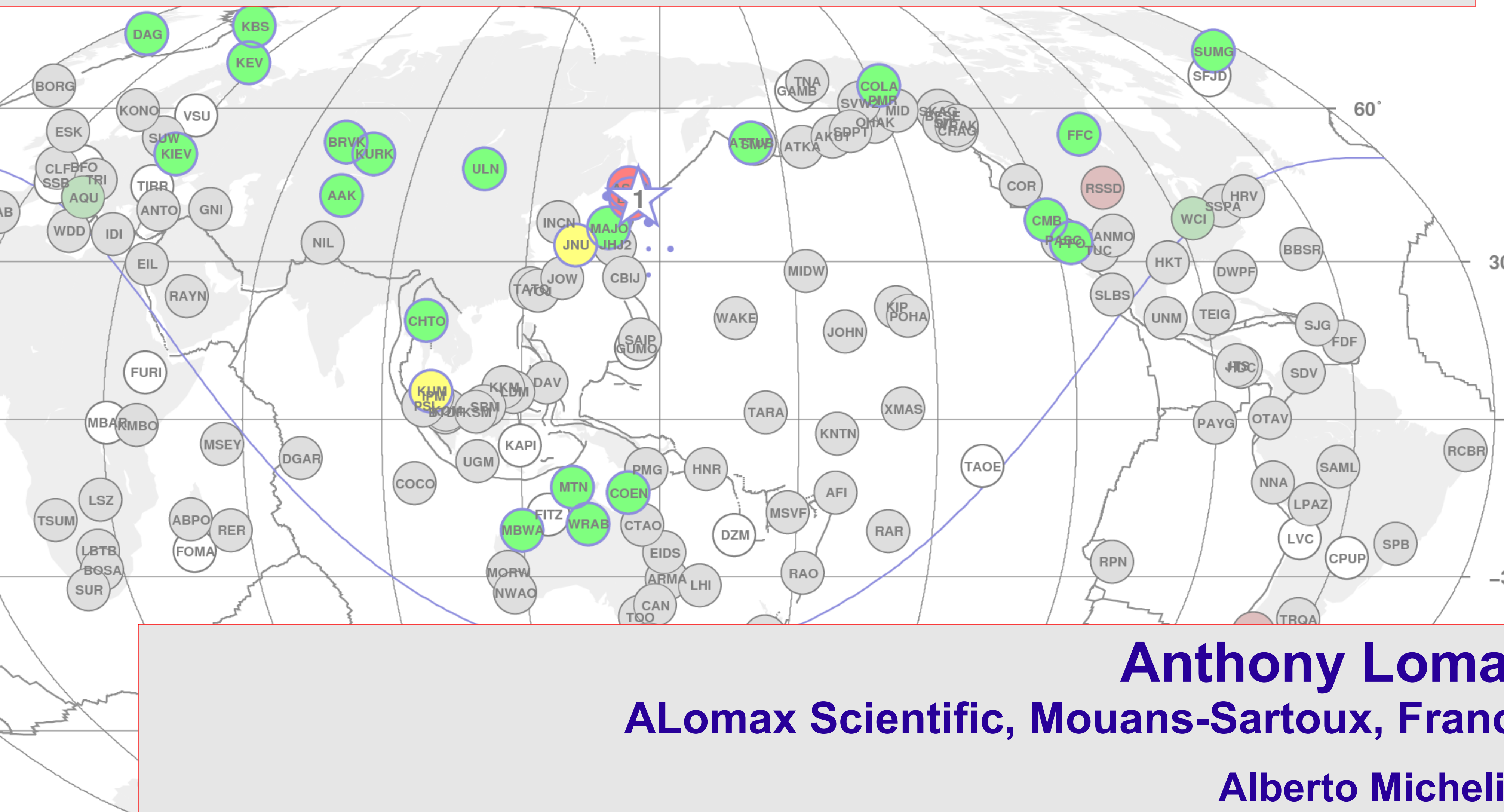
Real-Time Earthquake Location



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Outline:

Introduction

1. Phase picking, phase association and event detection
2. Earthquake location at local, regional and teleseismic distances: Probabilistic, global-search earthquake location
3. New perspectives in observatory analysis: Illustrative examples of global-search earthquake location

More information: http://alomax.net/science.html

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Introduction – Earthquake location

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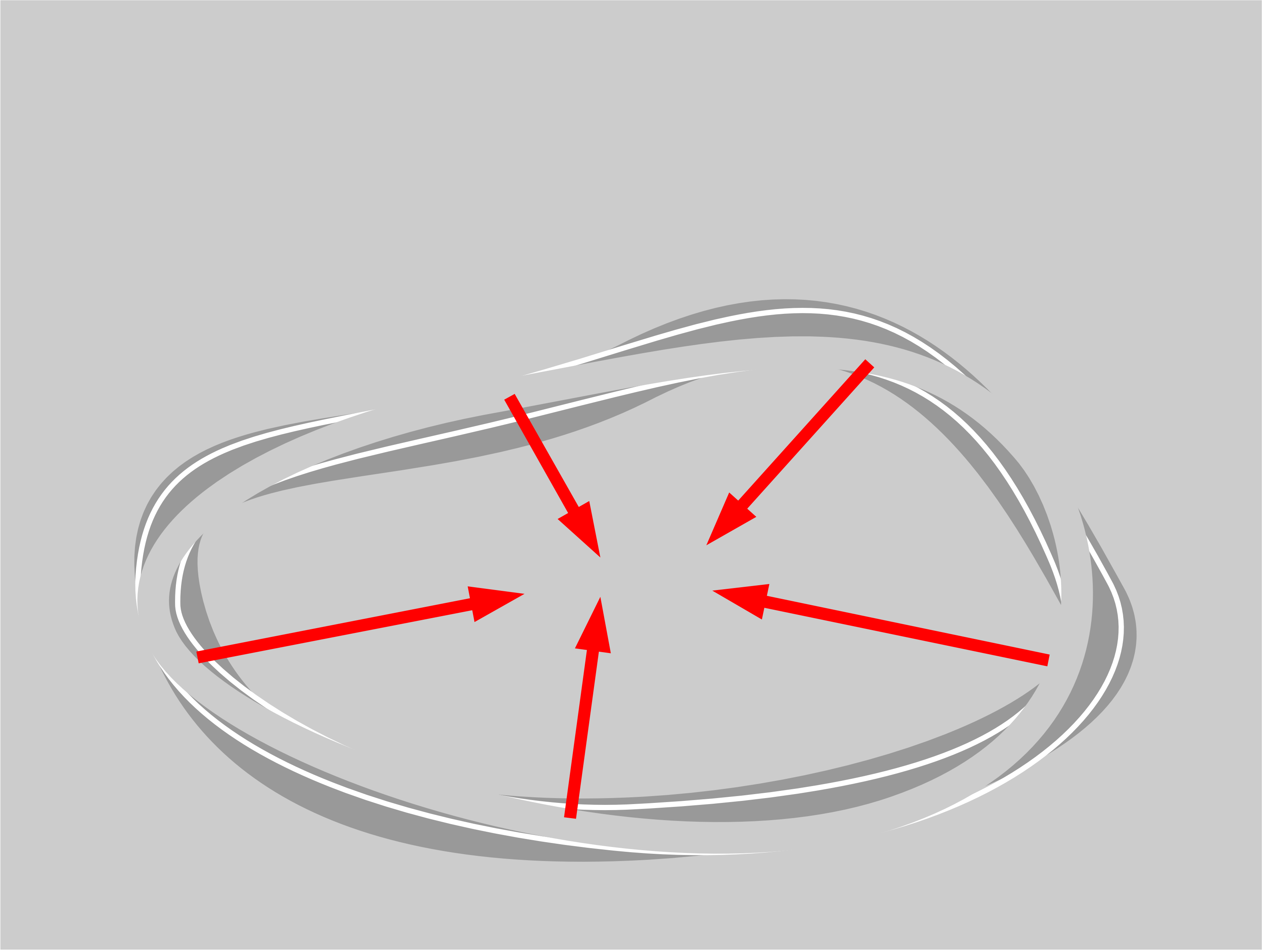
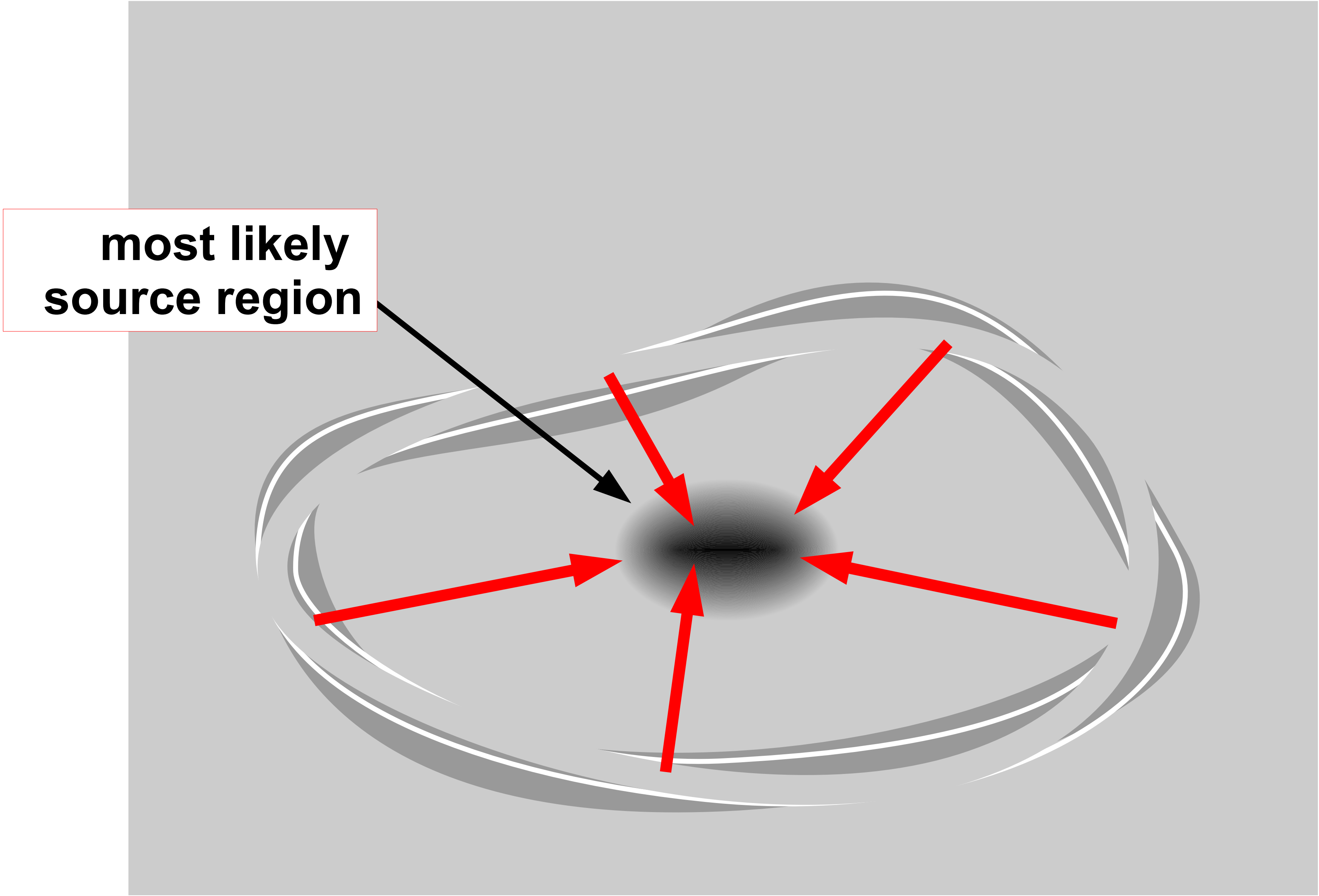
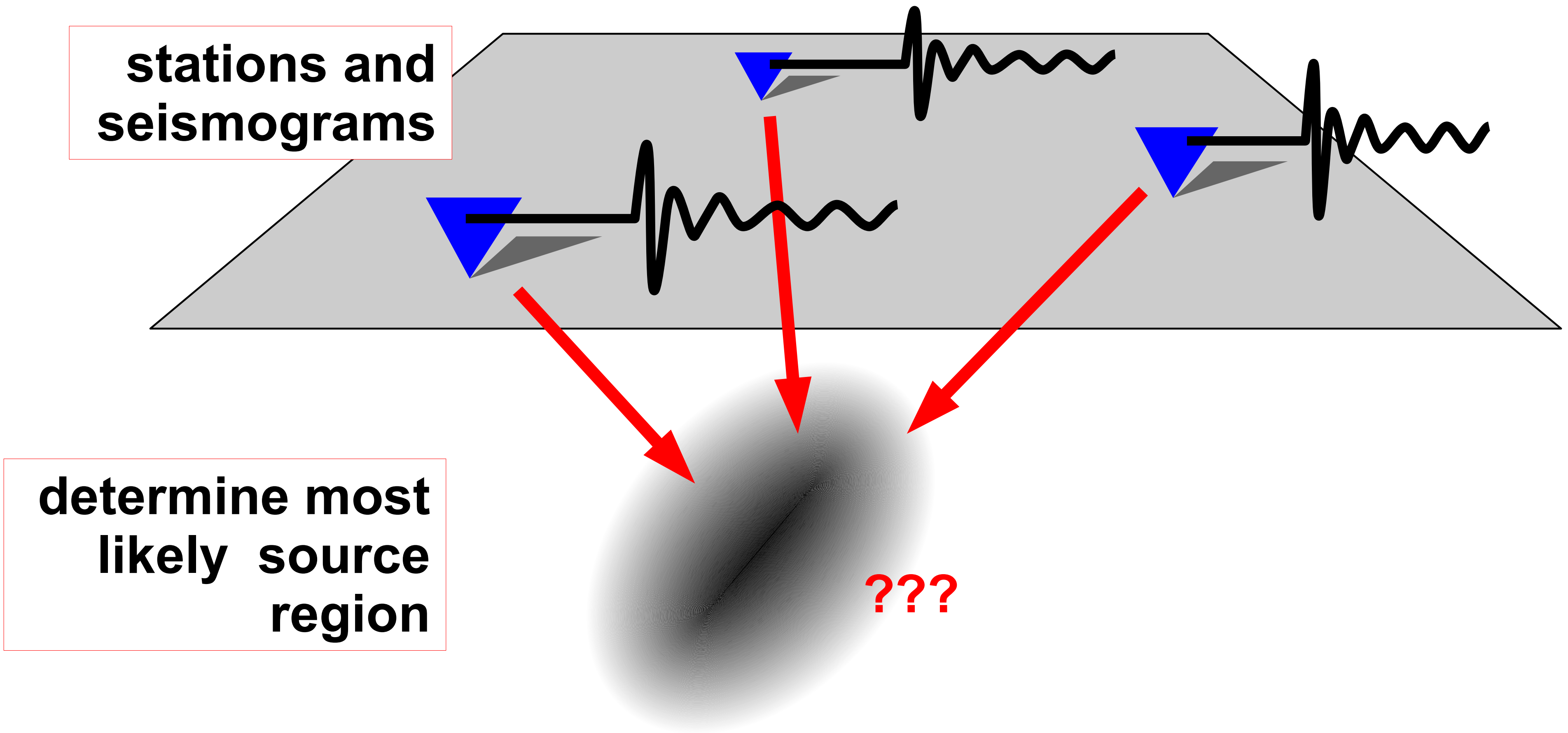
Earthquake Location




most likely
source region

Earthquake Location



1. Phase picking, phase association and event detection

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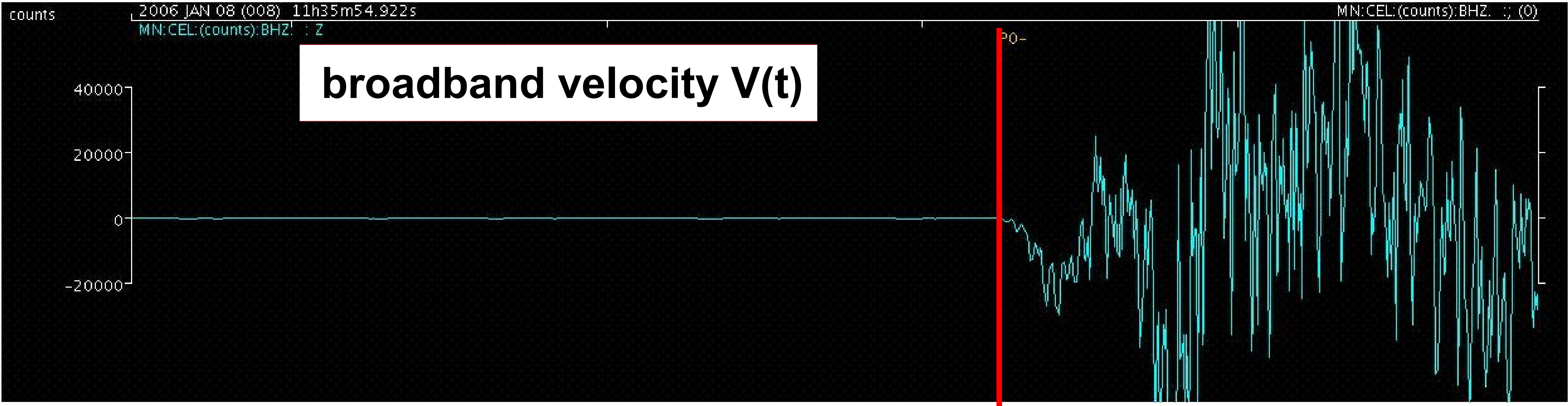
1. Phase picking, phase association and event detection

Phase picking

Phase picking – theory

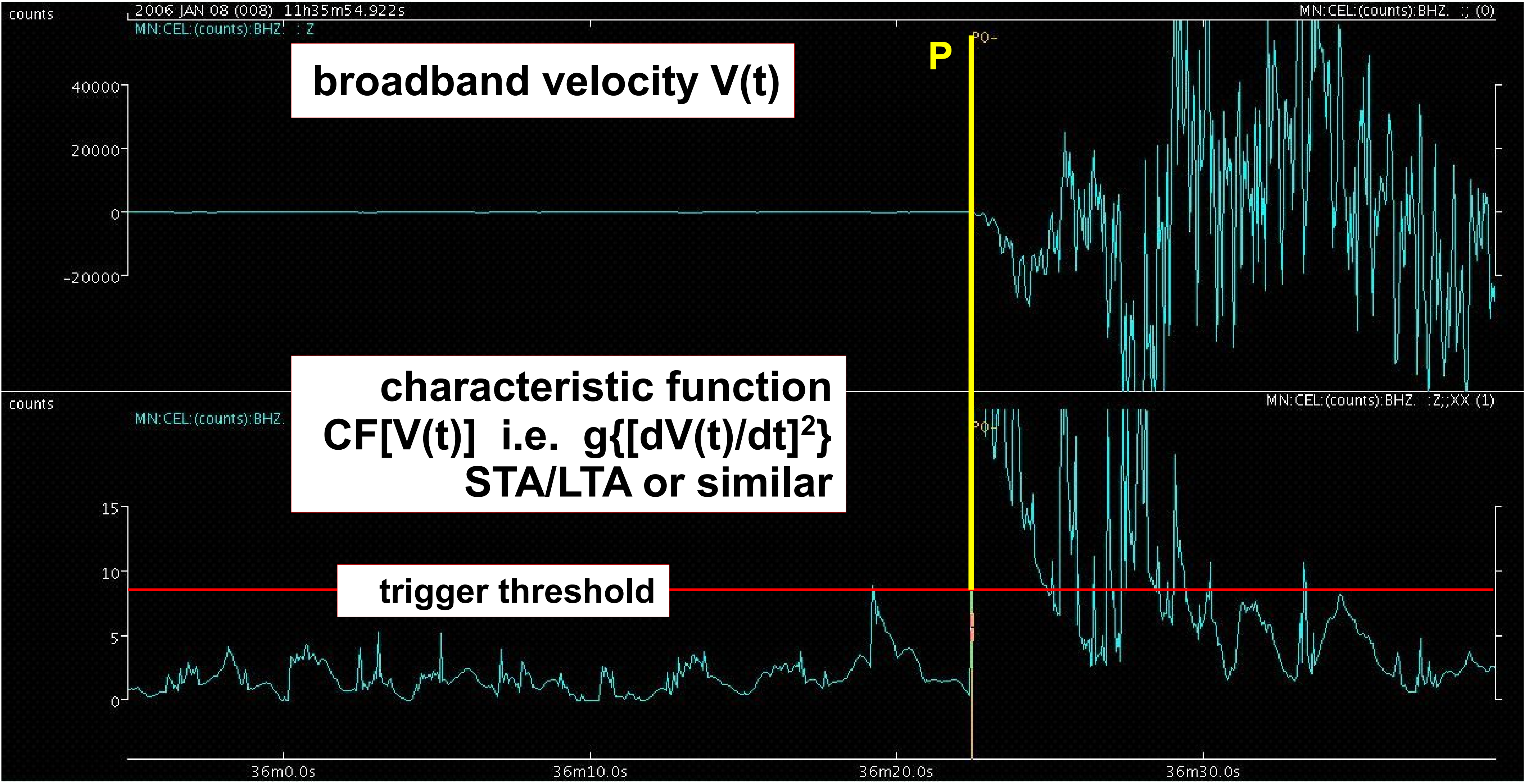


broadband velocity V(t)

first arrival → ray theory
"standard" location

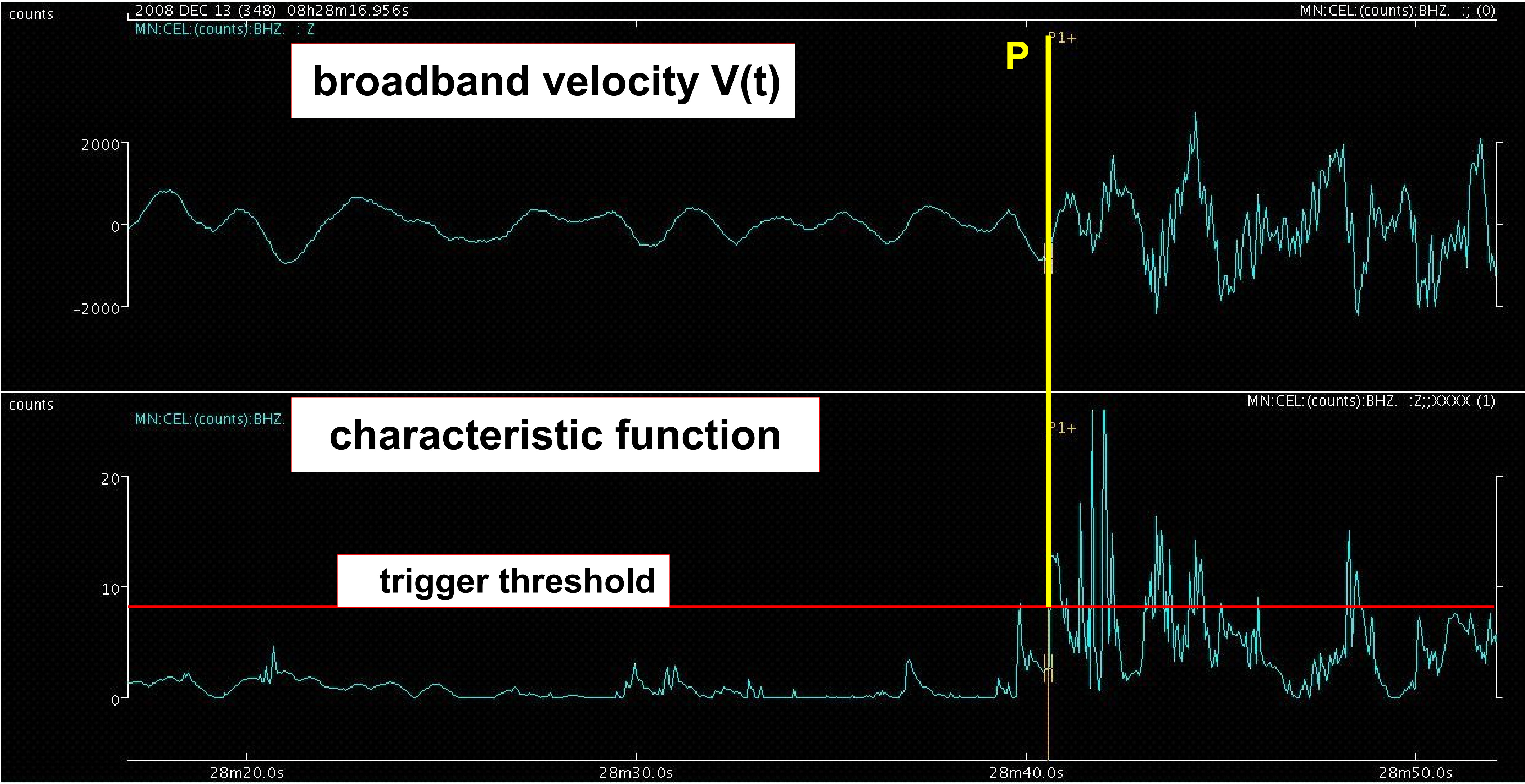
full waveform → wave propagation
waveform location
centroid moment tensor (CMT)
etc..

Phase picking – Automatic pickers - algorithm

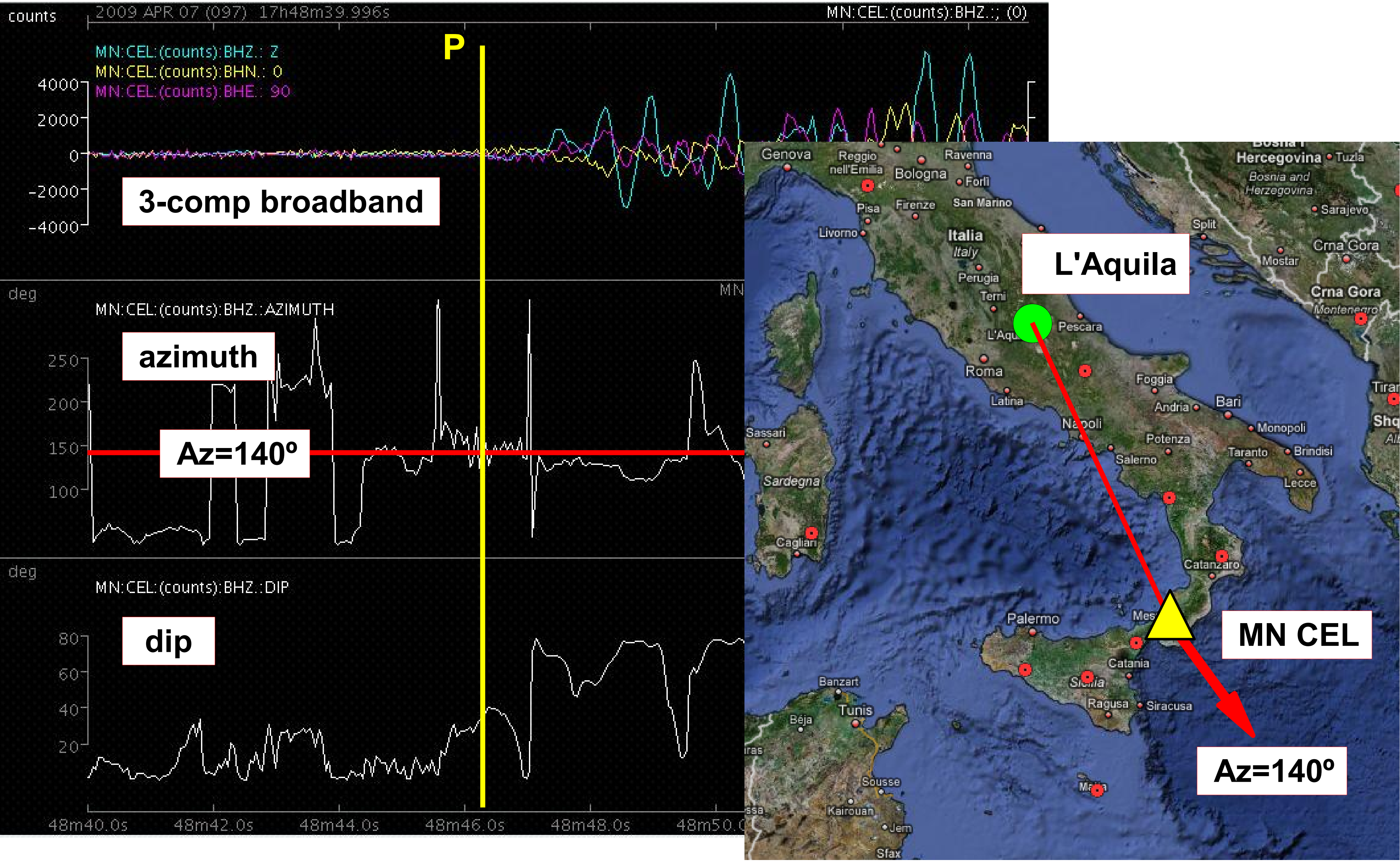


e.g. Allen, R.V. (1982) - Baer, M., and U. Kradolfer (1987) - Sleeman, R., and T. van Eck (1999) - etc...

Phase picking – Automatic pickers – noisy signal

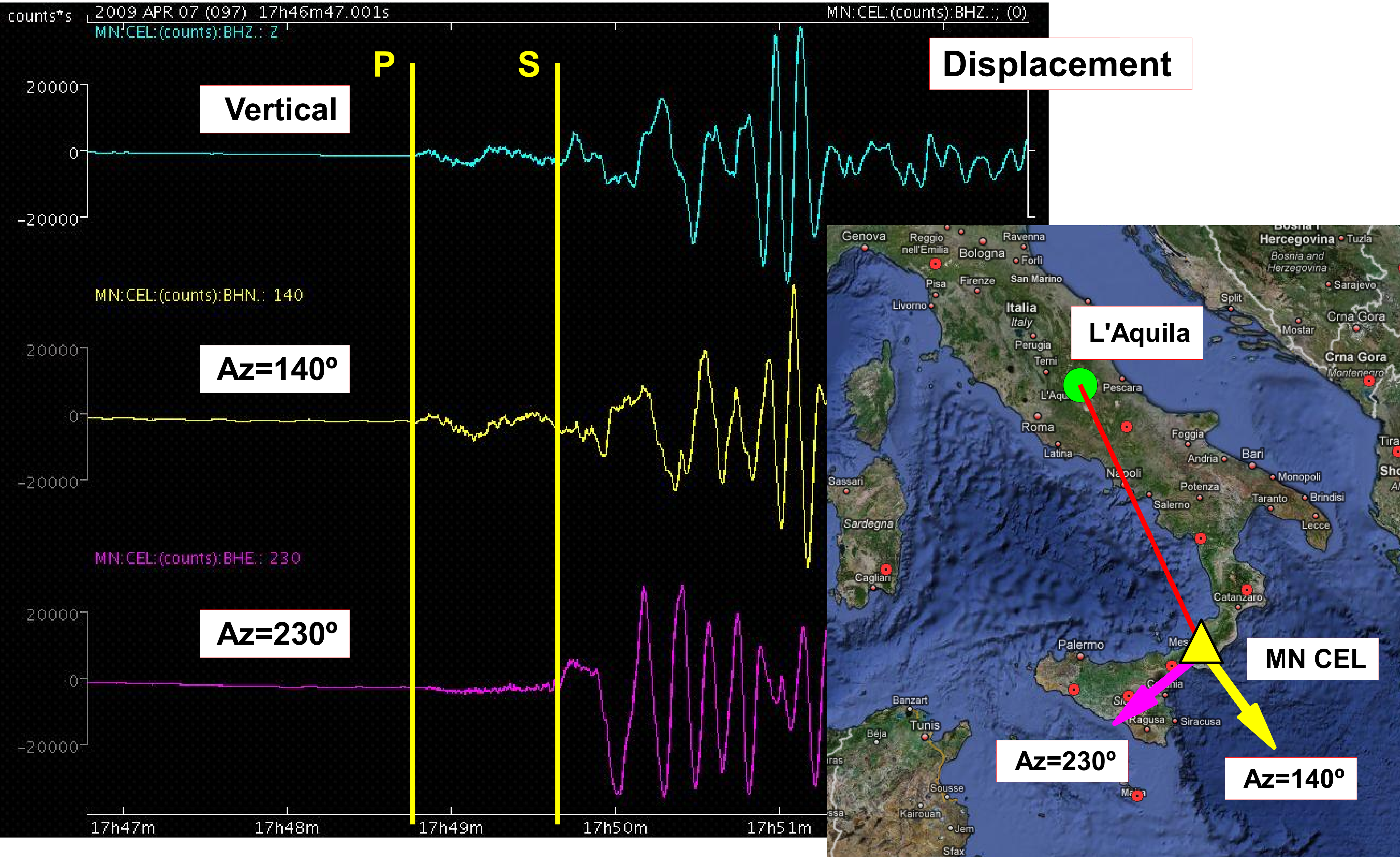


Phase picking – 3-component broadband – polarisation



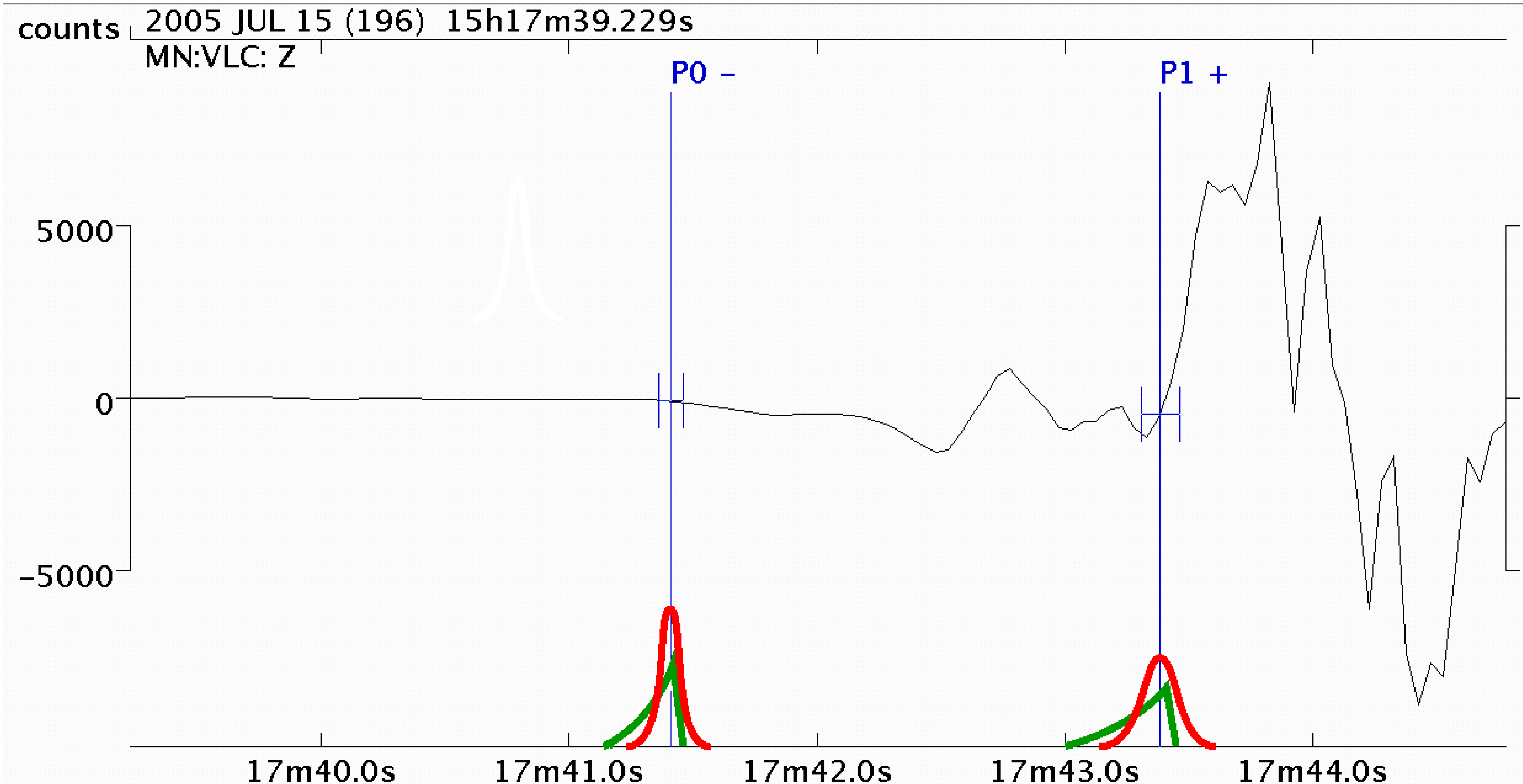
e.g. Magotra, N., N.Ahmed, and E.Chael (1987) - Cichowicz, A. (1993) - Oye, V. and W.L. Ellsworth (2005) - etc...

Phase picking – 3-component broadband



e.g. Magotra, N., N.Ahmed, and E.Chael (1987) - Cichowicz, A. (1993) - Oye, V. and W.L. Ellsworth (2005) - etc...

Phase picking - Arrival times and pick uncertainty

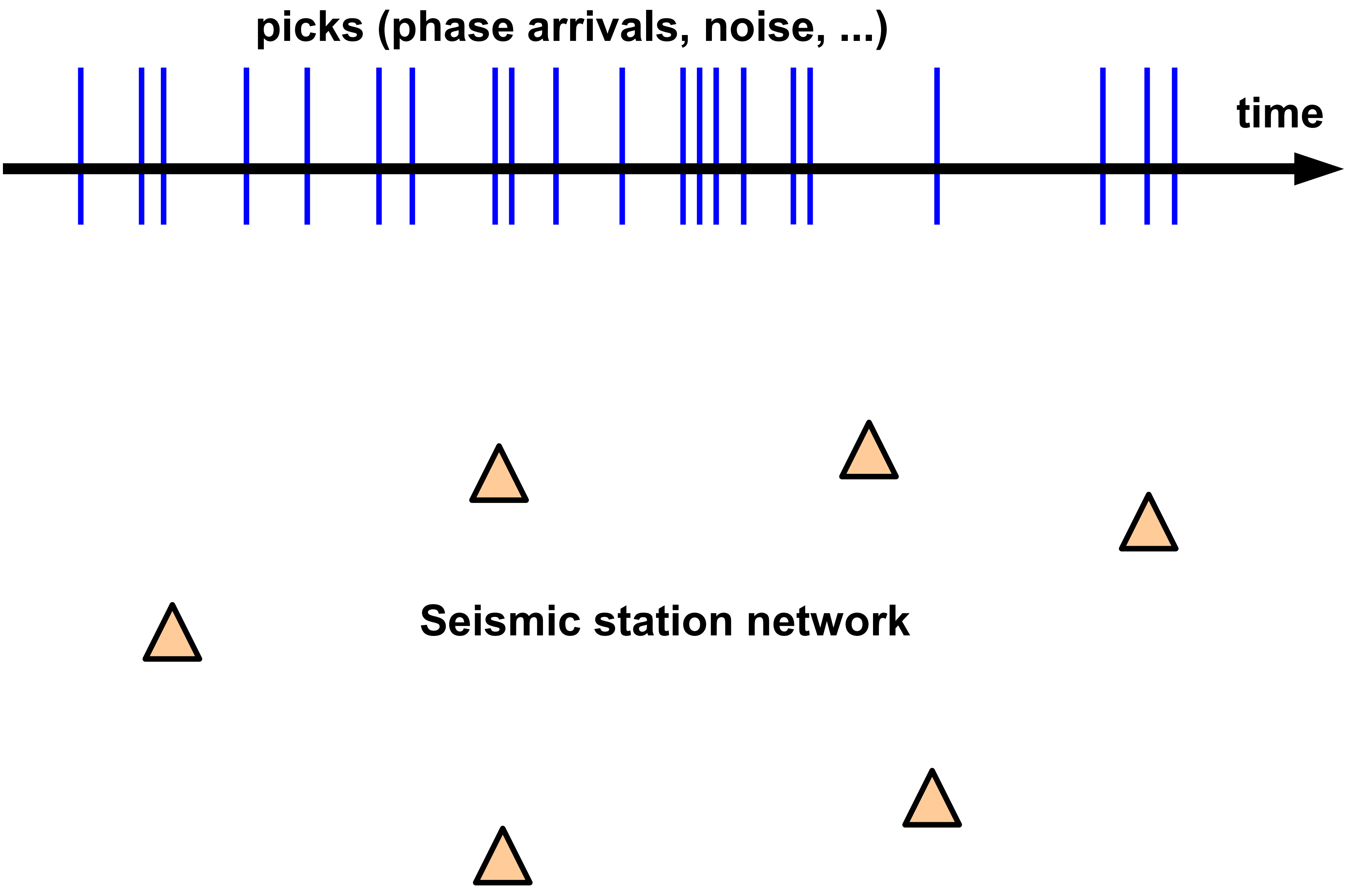


e.g. Tarantola, A. (1987) - refs in Lomax, A., A. Michelini, A. Curtis (2009) - etc...

1. Phase picking, phase association and event detection

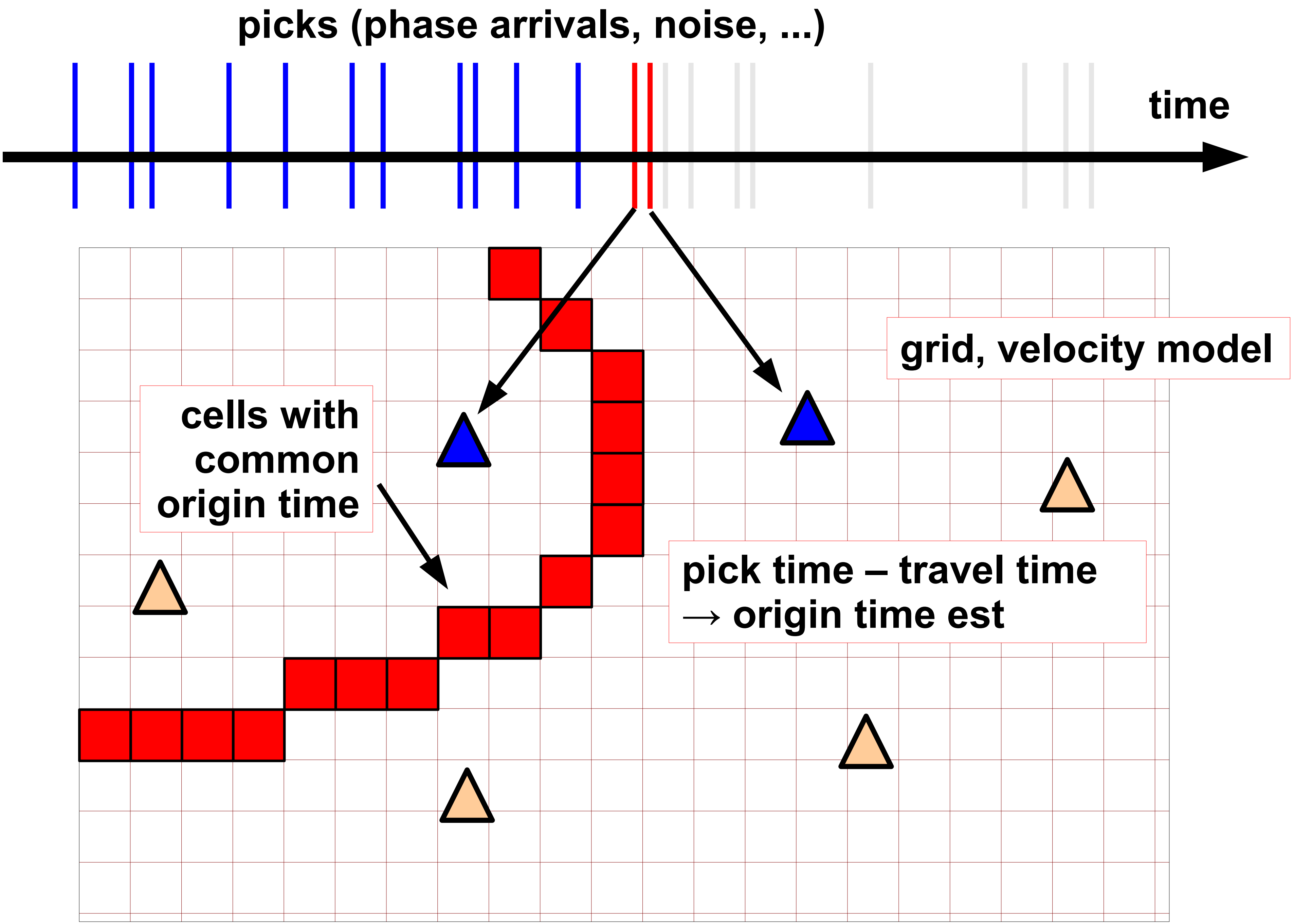
Phase association and event detection

Phase association and event detection

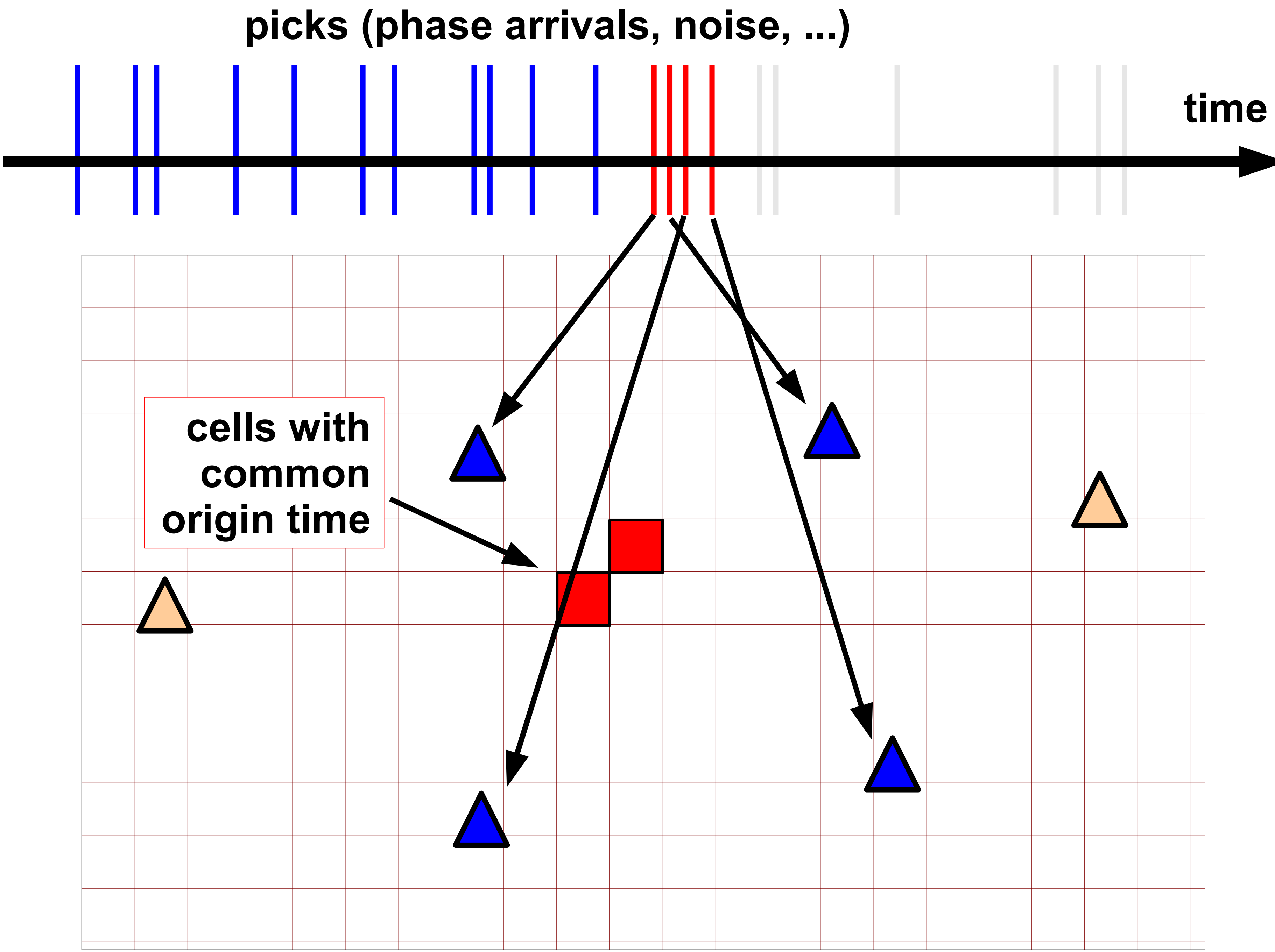


e.g. Johnson, C. E., A. Lindh, B. Hirshorn (1994) - Earthworm - SeisComP3 - etc...

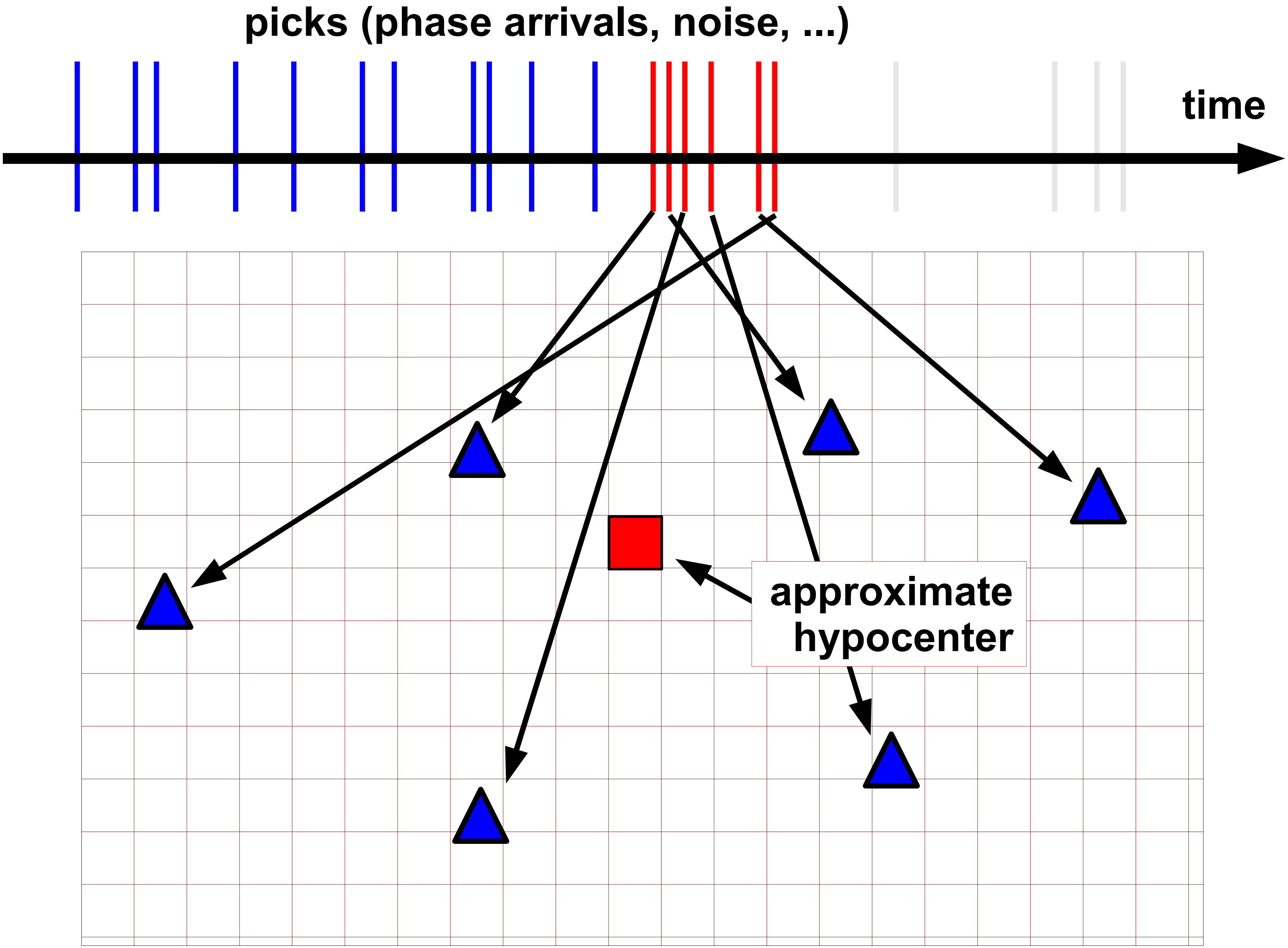
Phase association and event detection



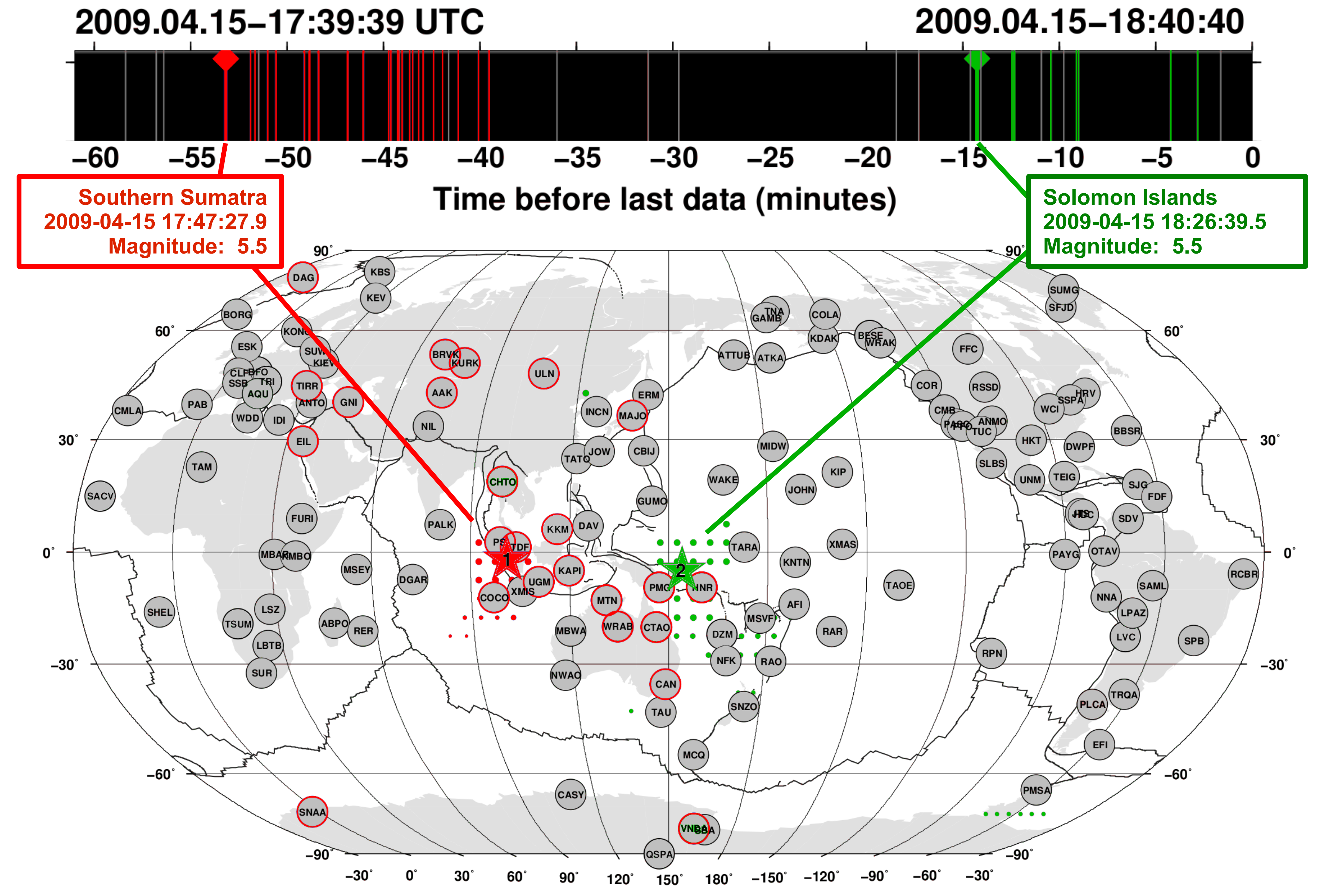
Phase association and event detection



Phase association and event detection



Phase association and event detection



Difficulties for picking, association, location

- False picks (noise, signal problems, ...)
- Small, pre-cursor events (foreshocks, noise, ...)
- Simultaneous events
- Poor network geometry or station coverage around event
- ...

e.g. refs in Lomax, A., A. Michelini, A. Curtis (2009)

2. Earthquake Location at local, regional and teleseismic distances: Probabilistic, global-search earthquake location

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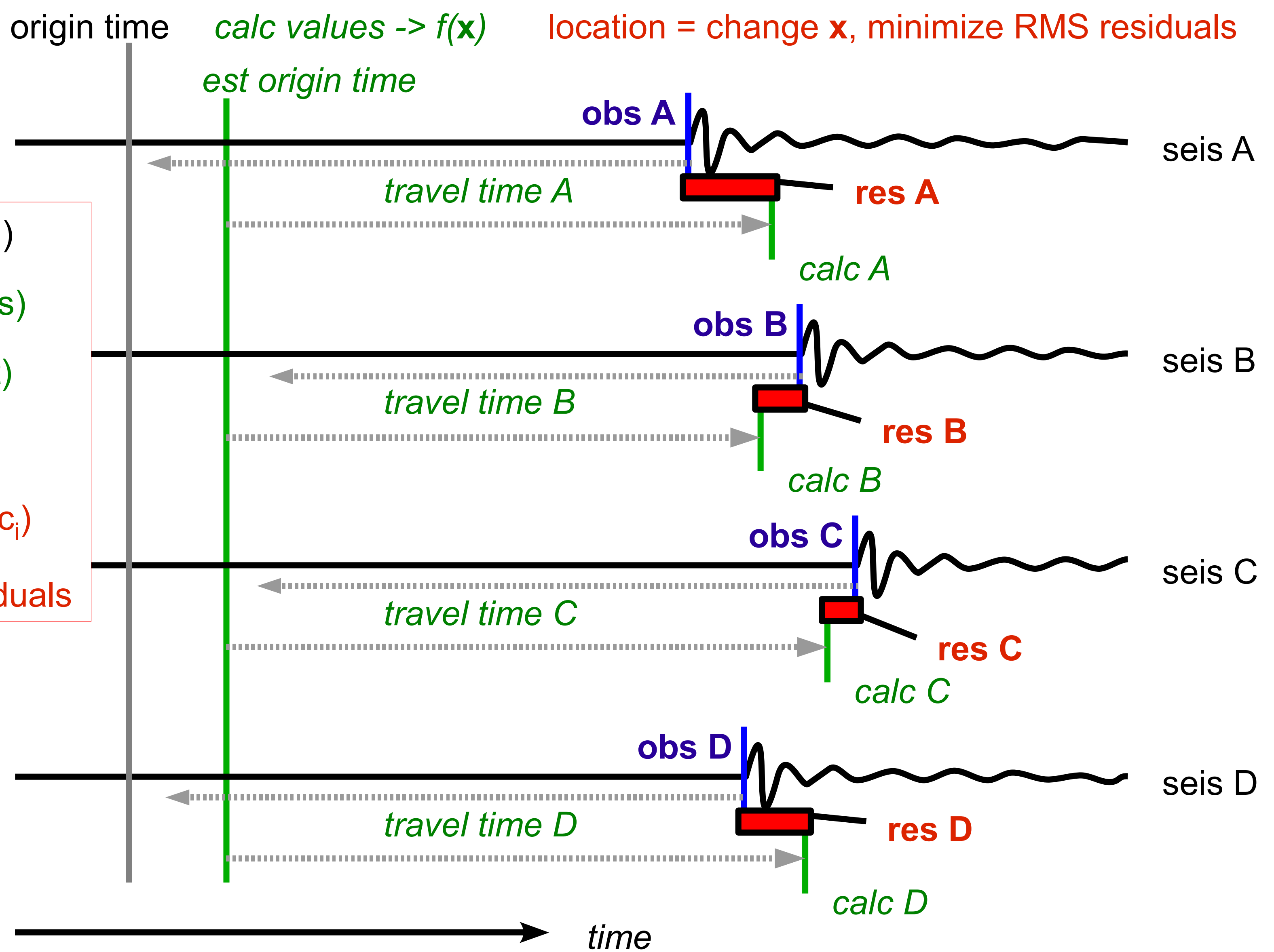
Real-Time Earthquake Location

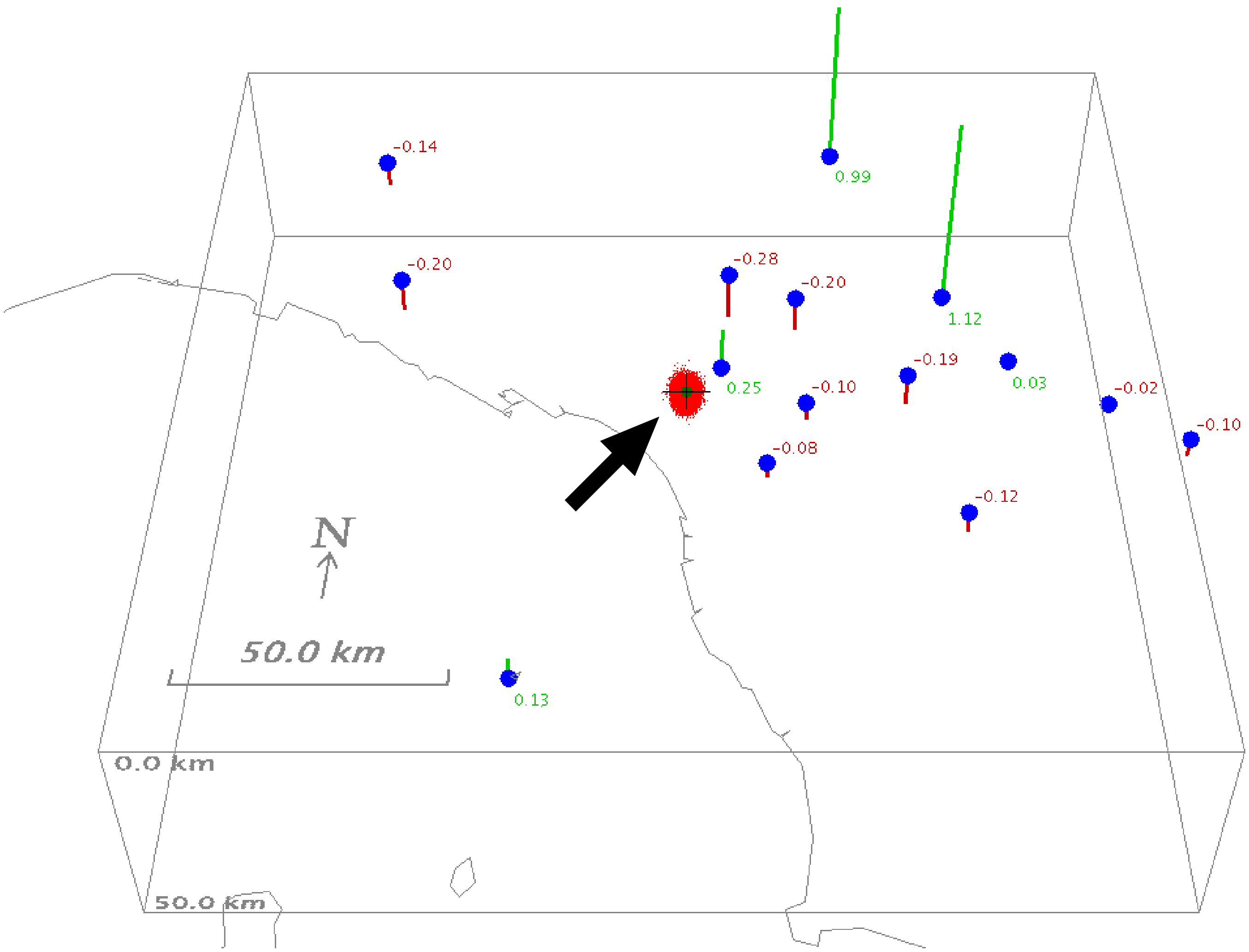
basic least-squares location

1. choose **x** (linear, global)
٢. calc travel times tt(**x**,obs)
٣. est origin time ot(obs, tt)
٤. calc arrivals $calc_i(ot, tt_i)$
٥. calc residuals (obs_i, $calc_i$)
٦. repeat to minimize residuals



Real-Time Earthquake Location

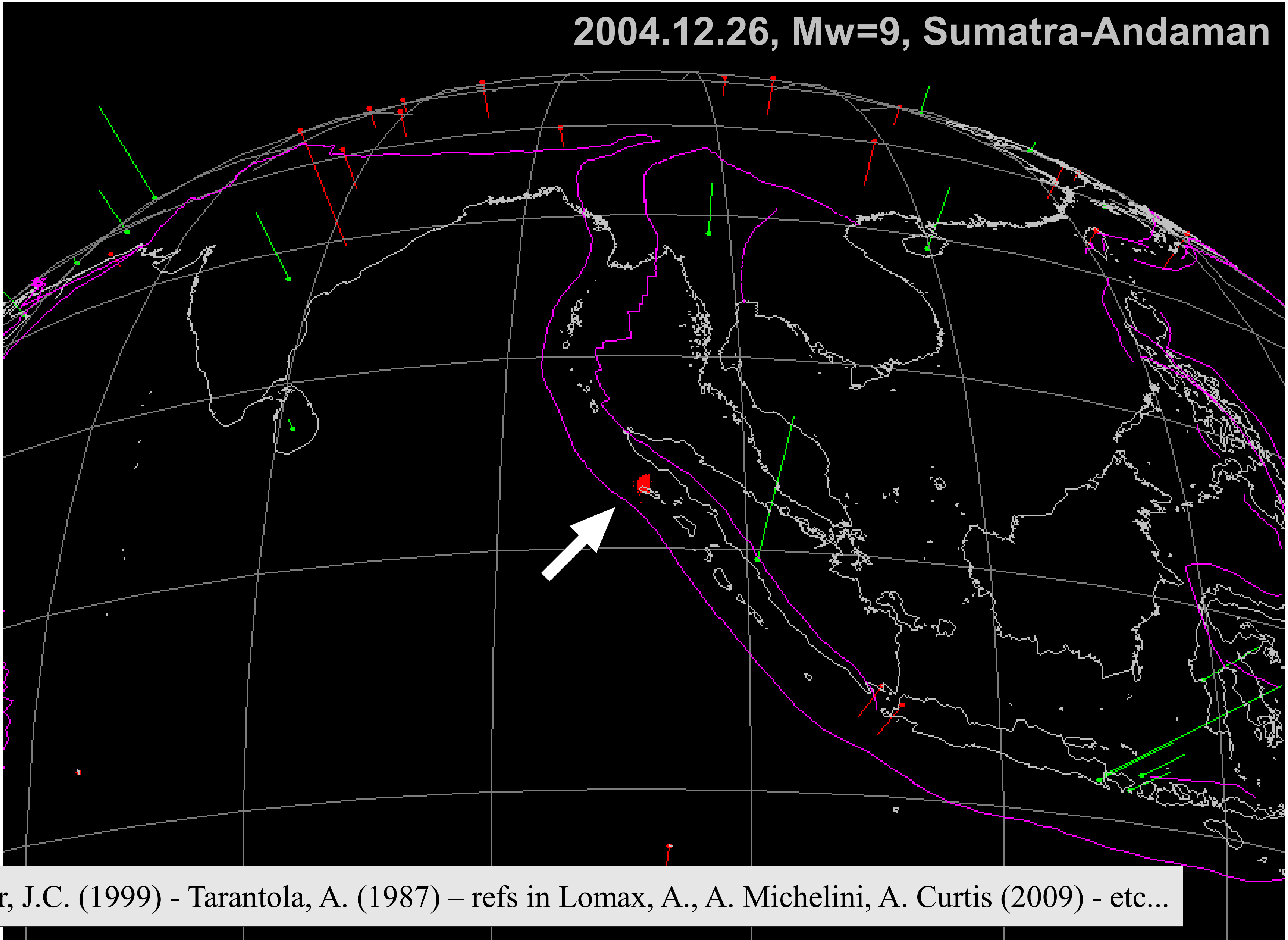
basic least-squares location – local/regional – Cartesian coordinates



e.g. Lahr, J.C. (1999) - Tarantola, A. (1987) – refs in Lomax, A., A. Michelini, A. Curtis (2009) - etc...

Real-Time Earthquake Location

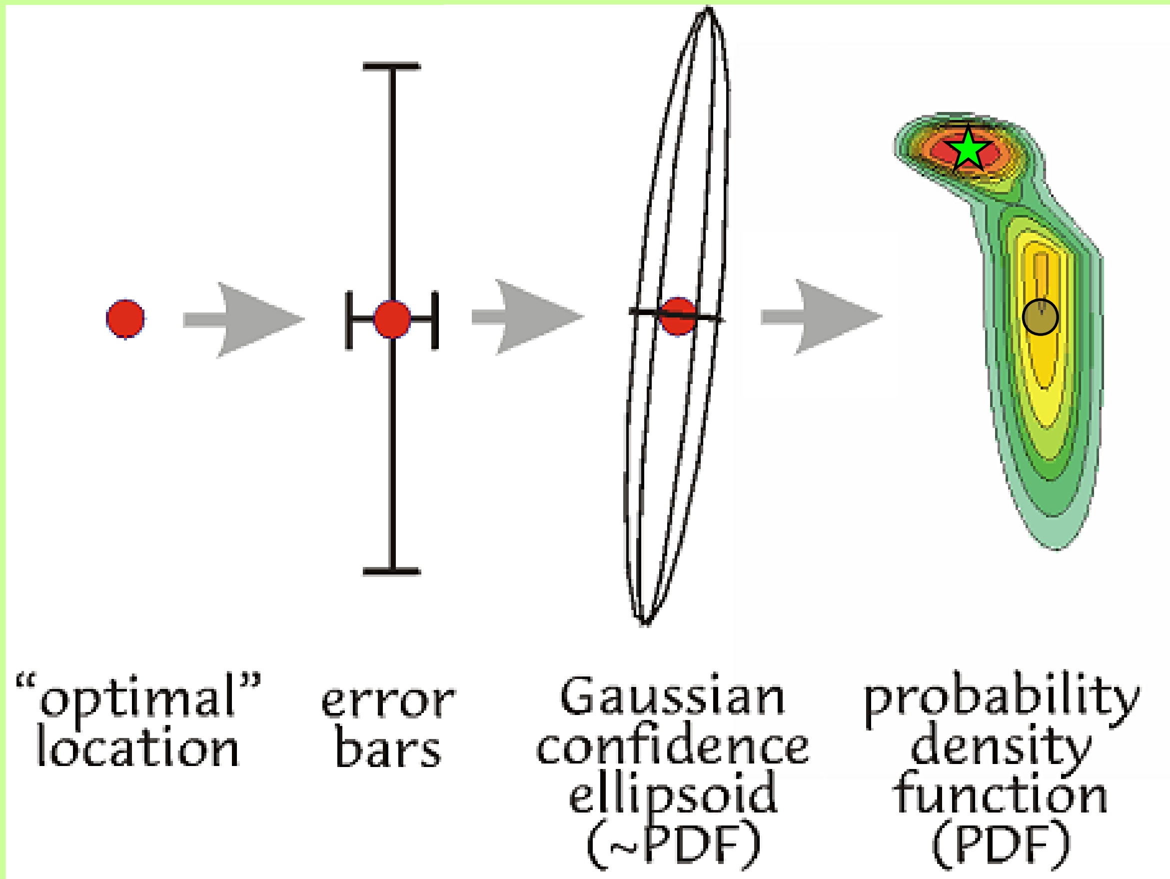
basic least-squares location – teleseismic – spherical coordinates



e.g. Lahr, J.C. (1999) - Tarantola, A. (1987) – refs in Lomax, A., A. Michelini, A. Curtis (2009) - etc...

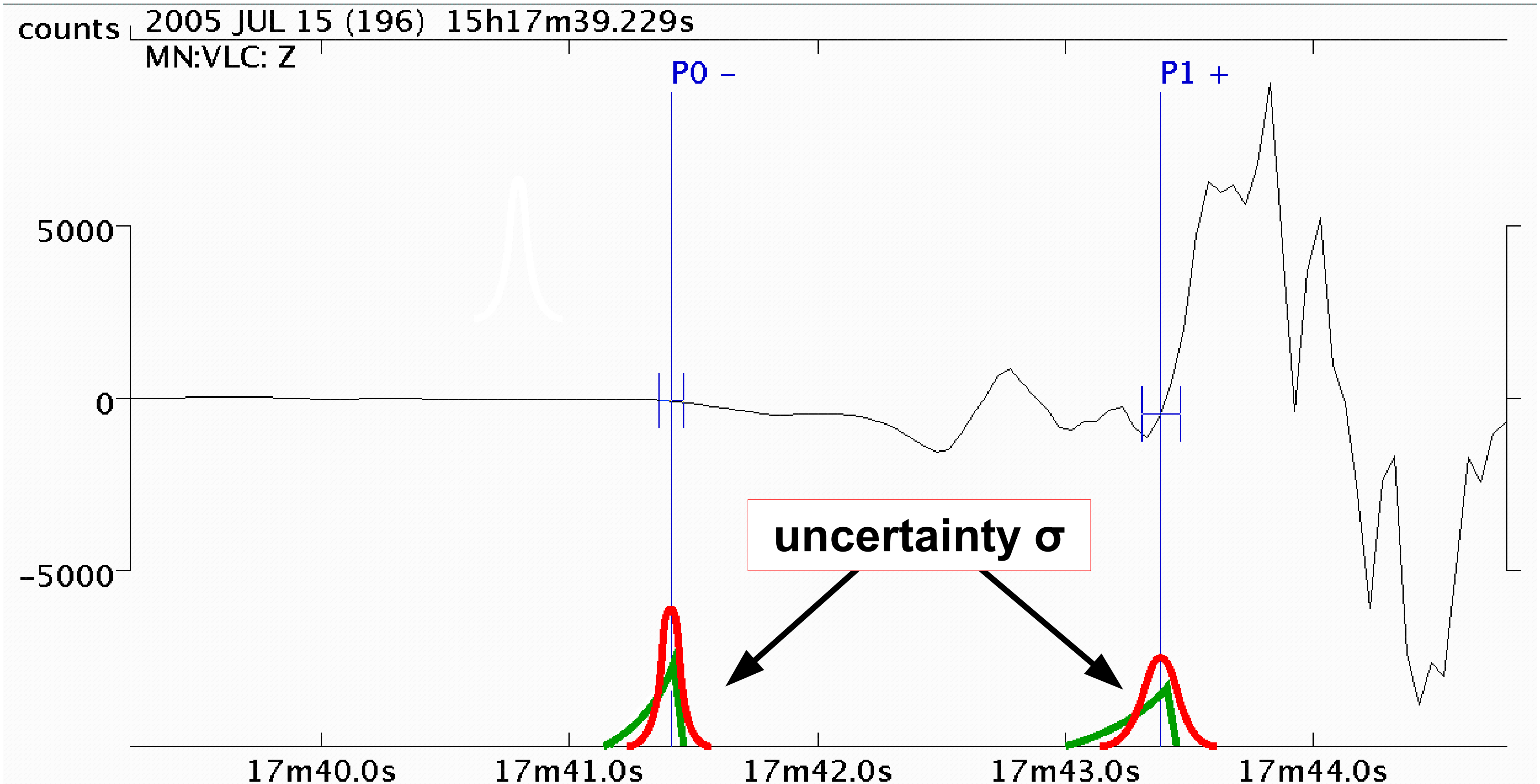
Probabilistic event location

global methods



linear methods

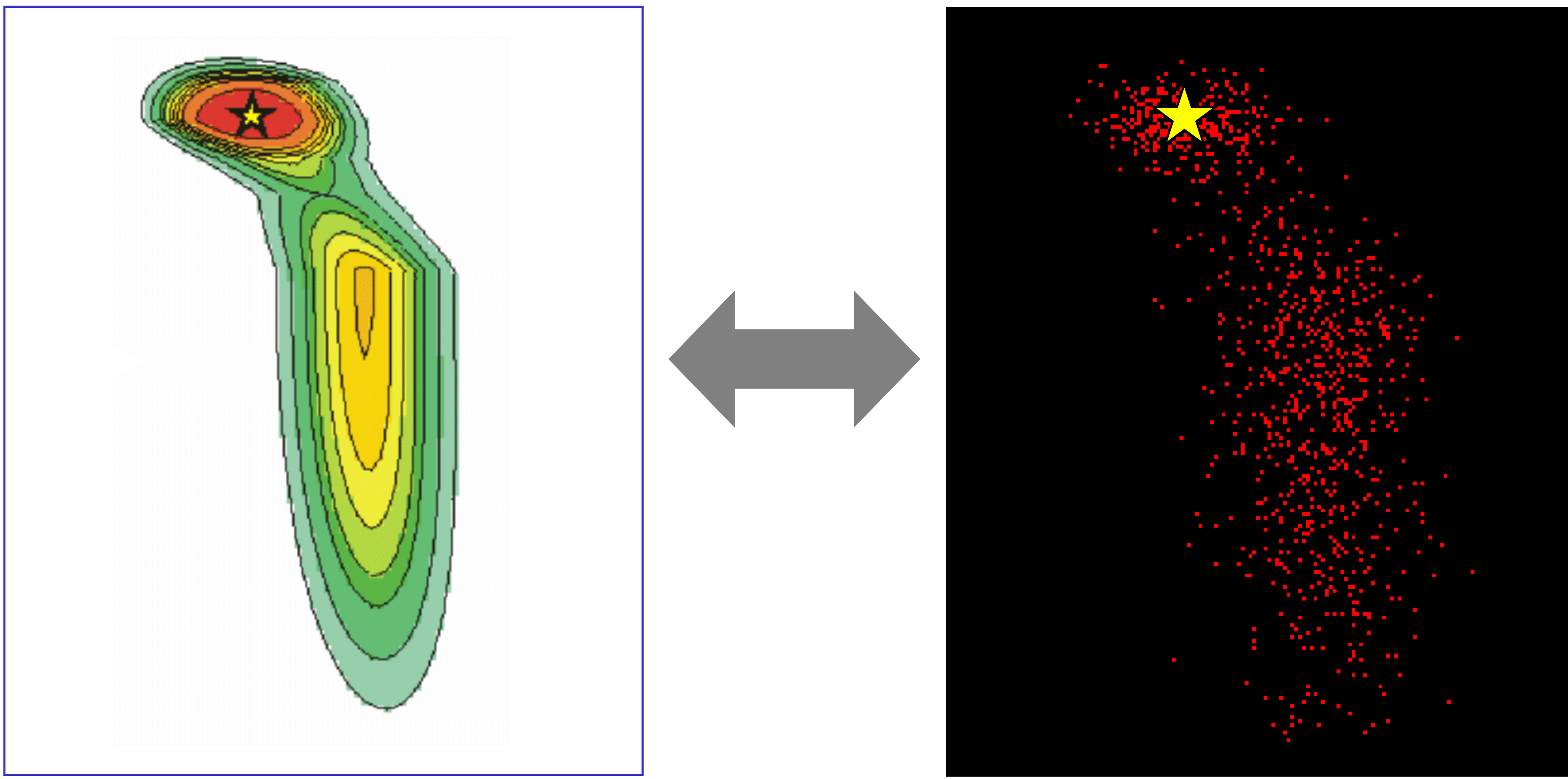
Arrival times and pick uncertainty



e.g. Tarantola, A. (1987) - refs in Lomax, A., A. Michelini, A. Curtis (2009) - etc...

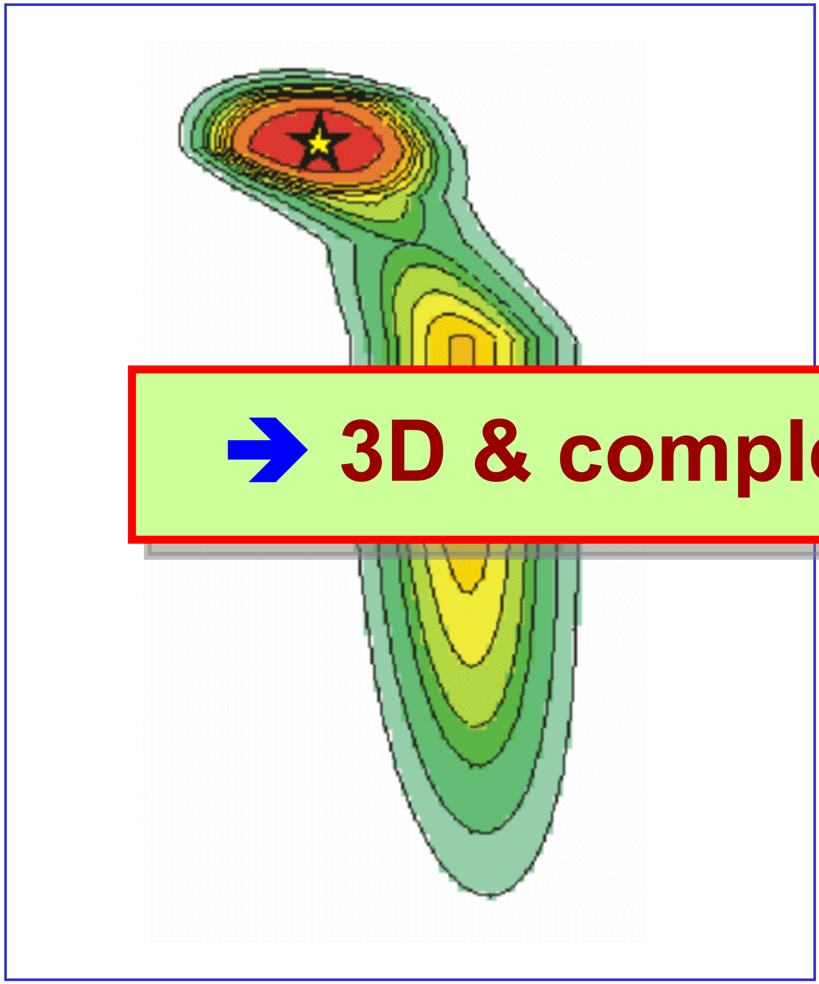
Probabilistic, global-search event location

Probability Density Function: $$pdf\left(\mathbf{x}\right) = k\,\mathrm{e}^{-f\left(\mathrm{misfit}\left(\mathbf{x}\right)/\sigma\right)}$$

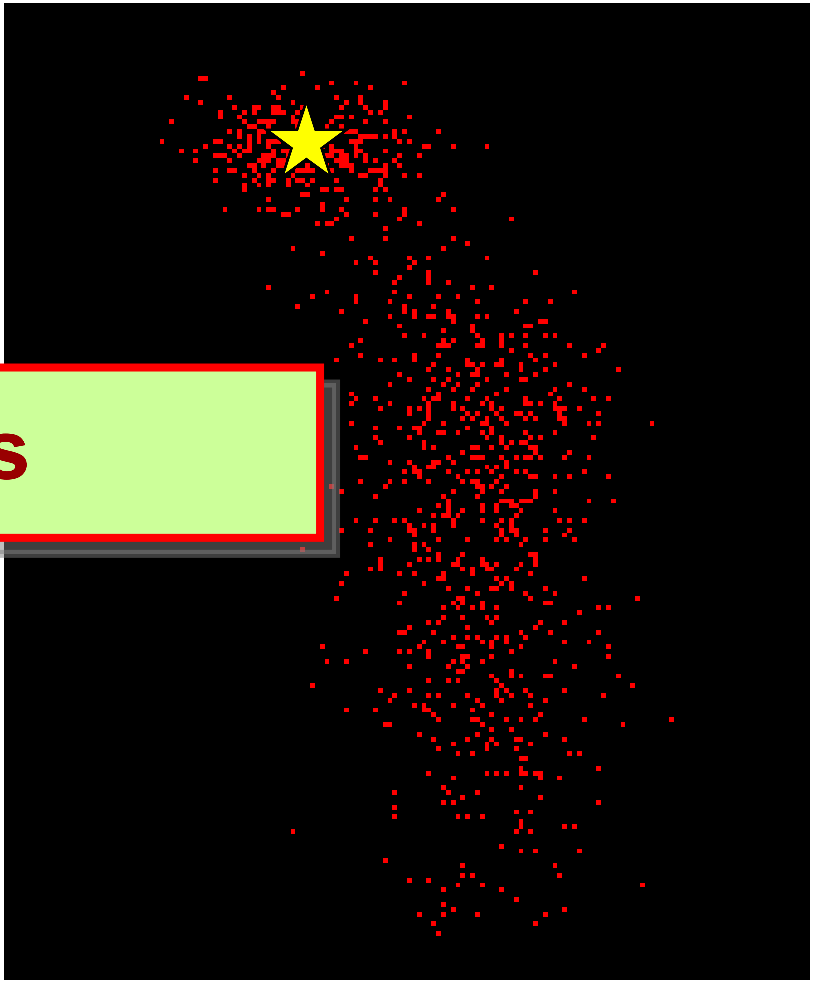


Probabilistic, global-search event location

- PDF image
- multiple minima
- efficiency

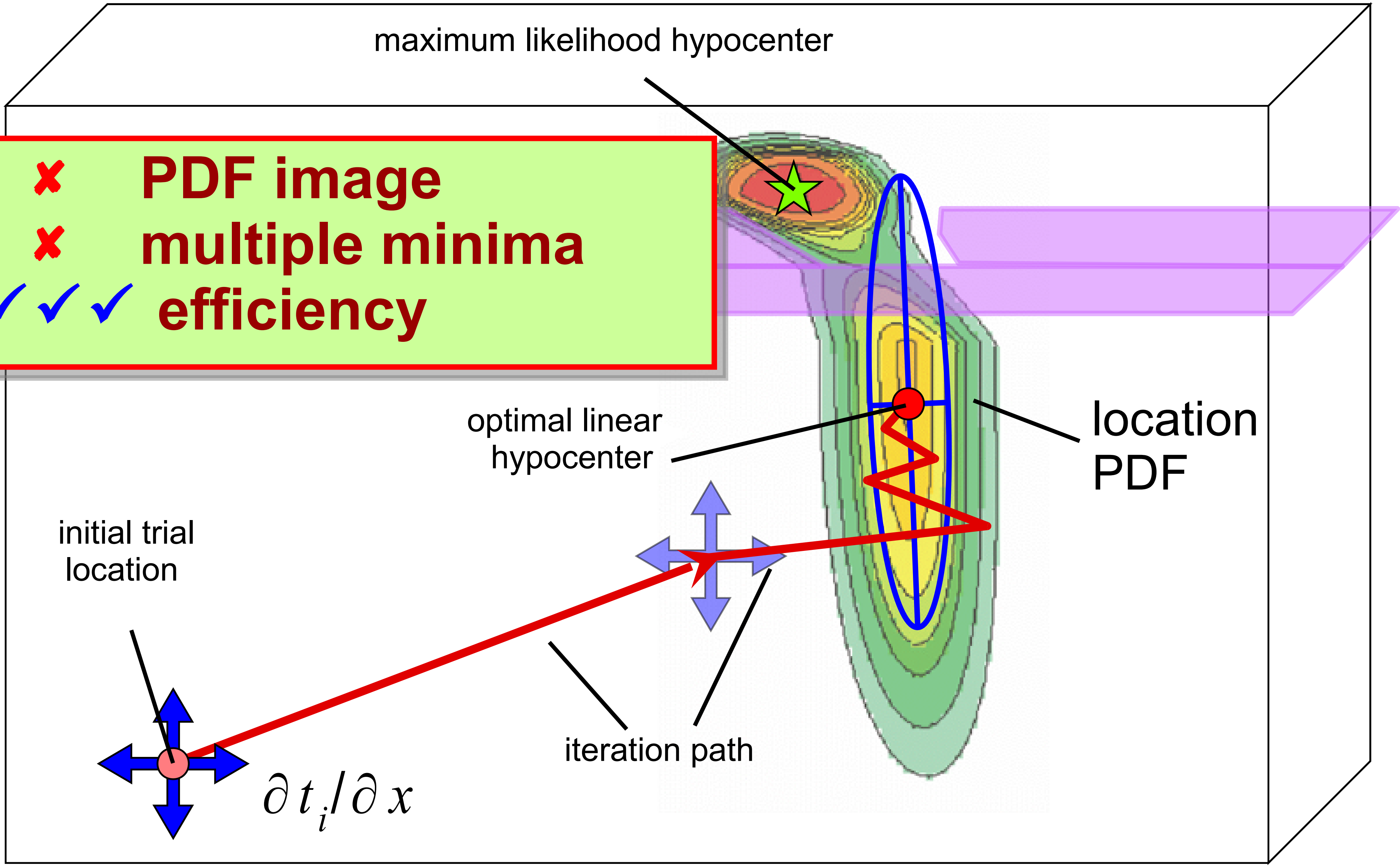


- 3D & complex models

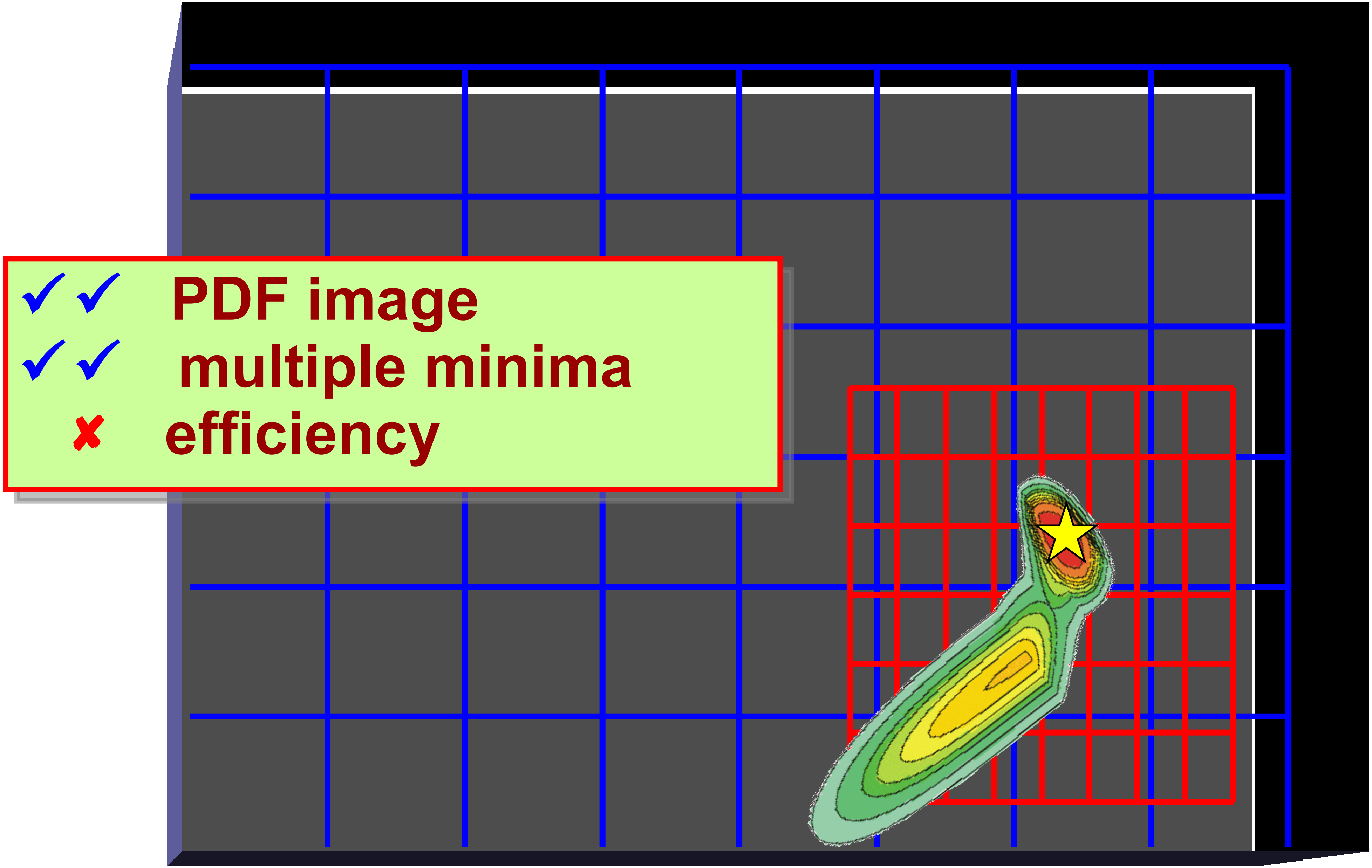


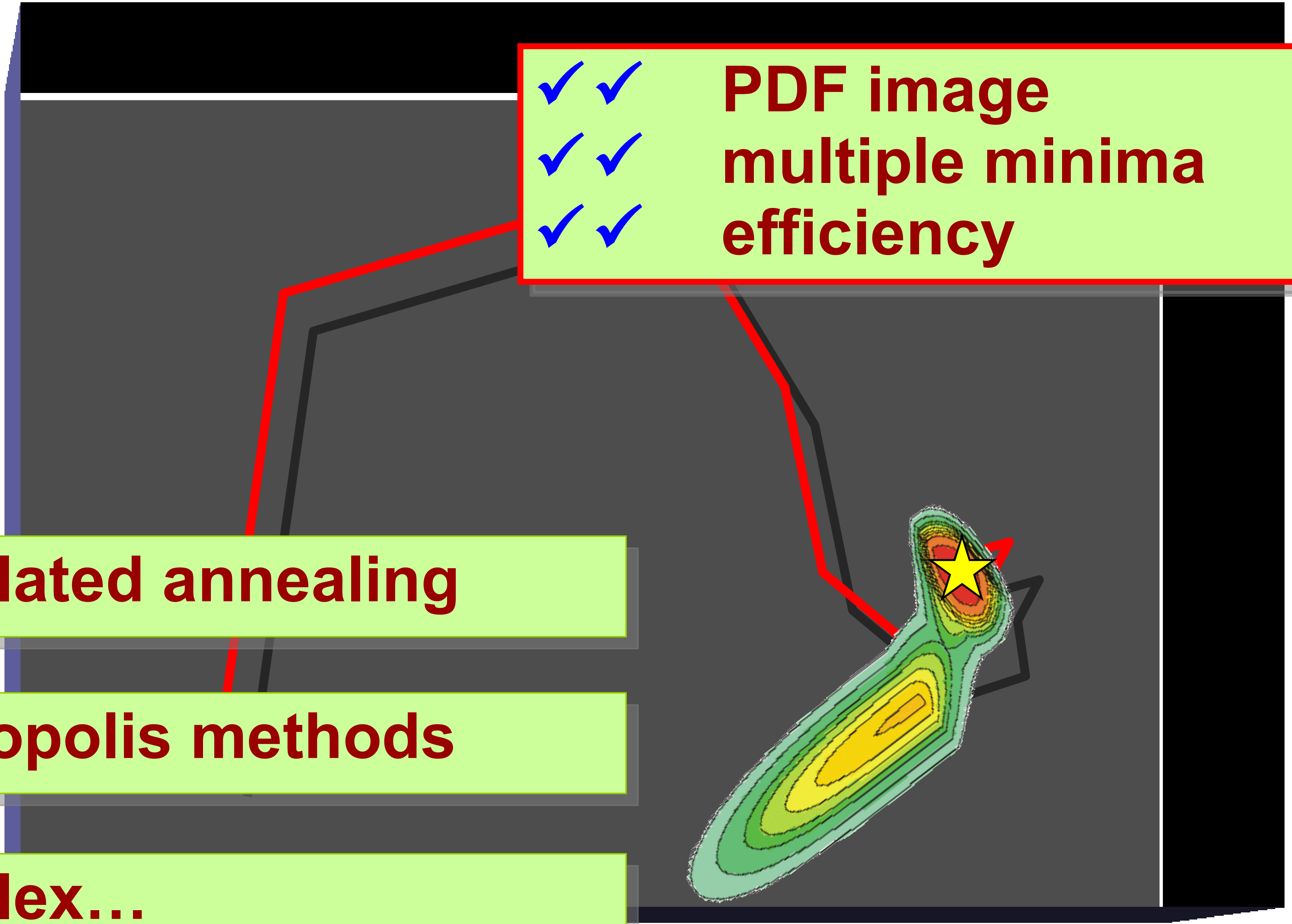
Iterative-linearized location

✘ PDF image
✘ multiple minima
✓✓✓ efficiency



Global-Search methods: Grid search





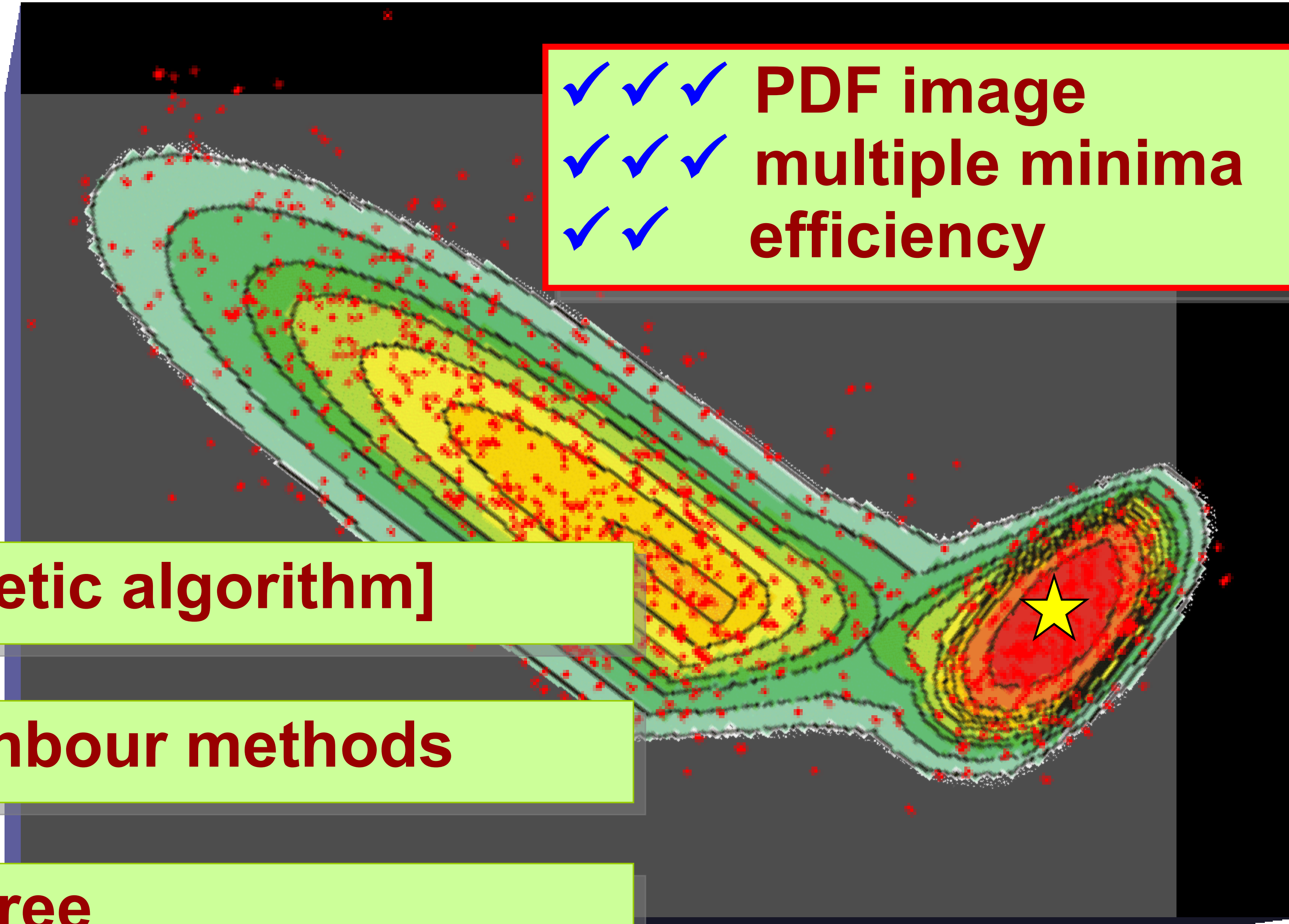
✓✓ PDF image
✓✓ multiple minima
✓✓ efficiency

simulated annealing

metropolis methods

simplex…

Search methods: Importance sampling



- ✓✓✓ PDF image
- ✓✓✓ multiple minima
- ✓✓ efficiency

[Genetic algorithm]

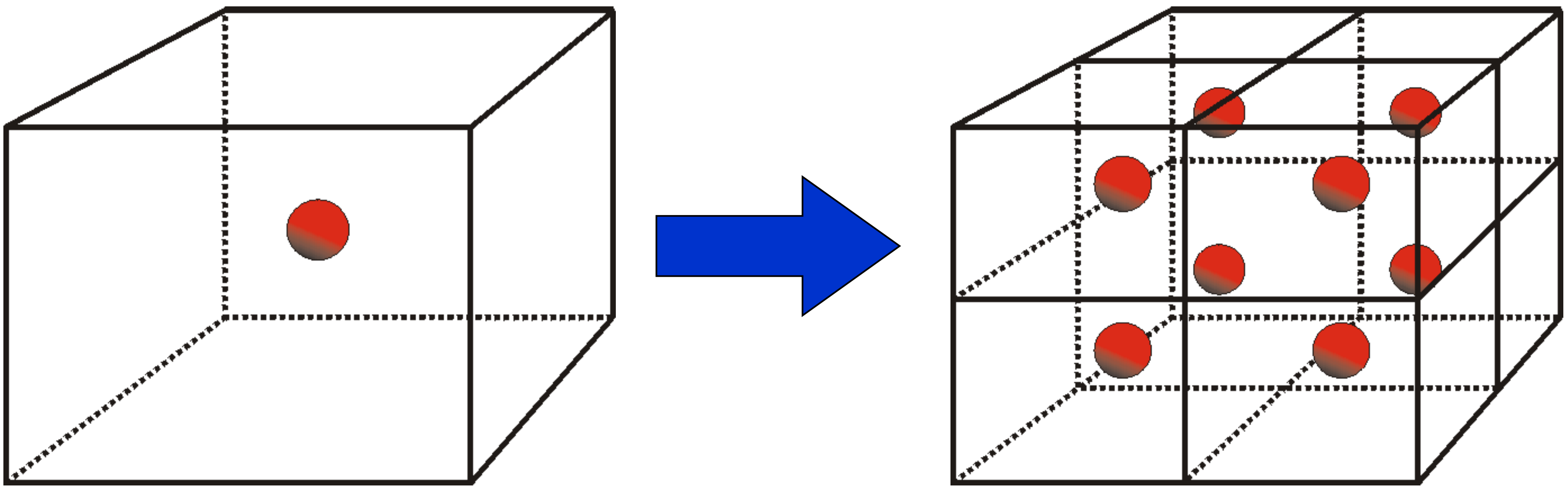
Neighbour methods

Oct-tree

2. Probabilistic, global-search earthquake location

The Oct-tree importance sampling method

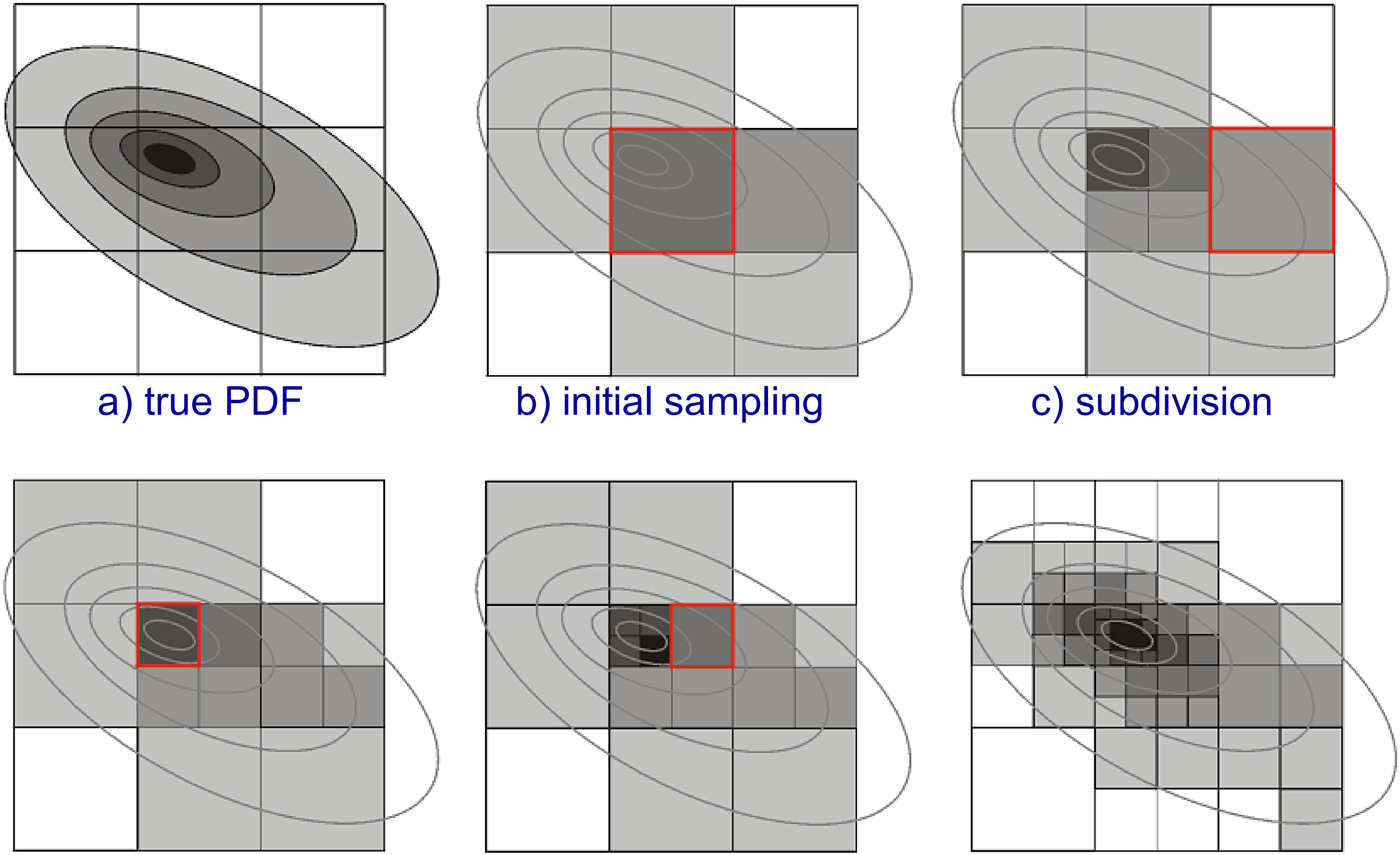
Sub-division of highest probability cell:



1 sample → 8 new samples

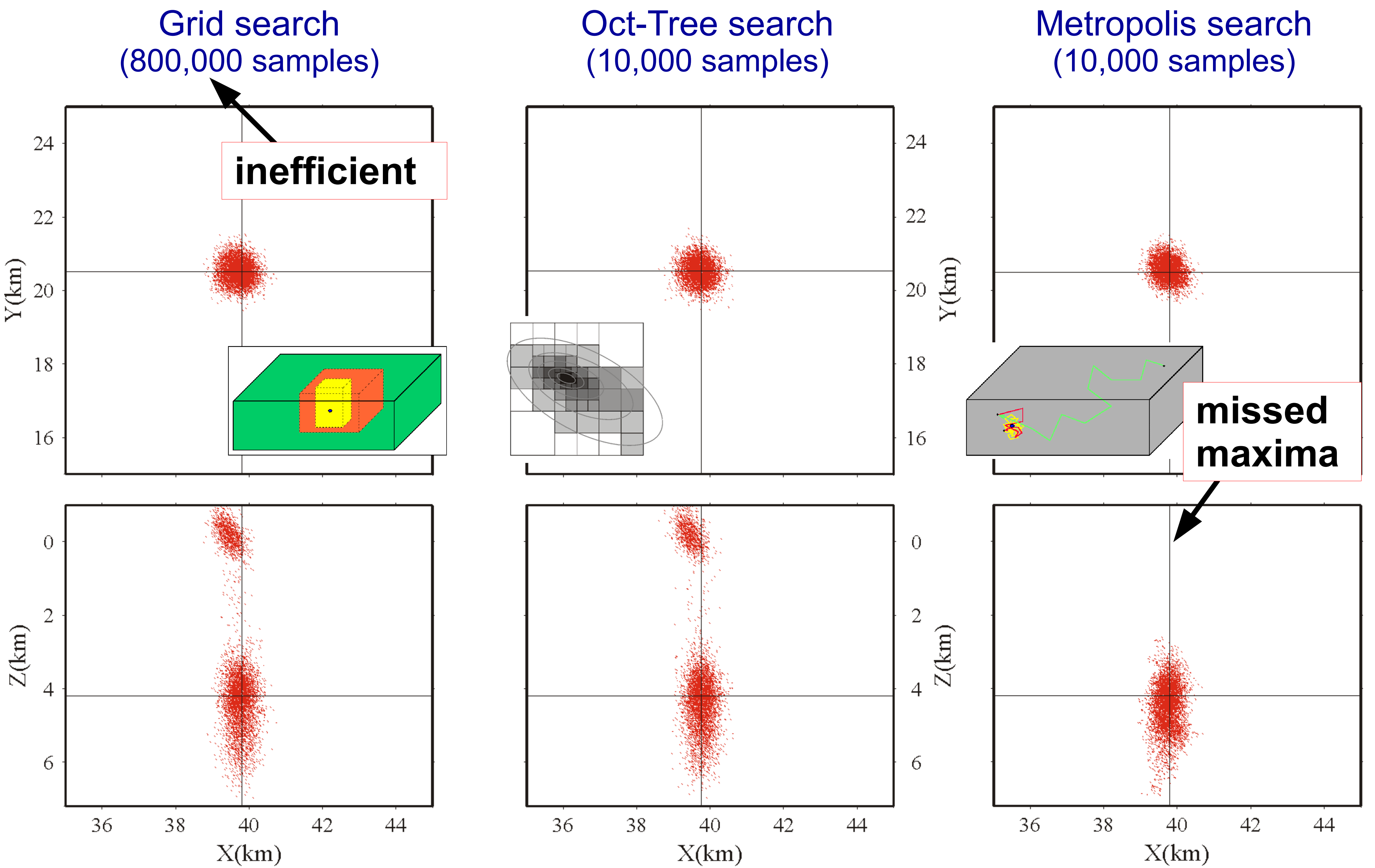
cell volume → cell volume / 8

Oct-Tree sampling procedure



a) true PDF
b) initial sampling
c) subdivision
d) subdivision
e) subdivision
f) many subdivisions

Example: PDF with two maxima



2. Probabilistic, global-search earthquake location

The EDT Probability Density Function

RMS/L2-norm vs EDT Probability Density Function

RMS/L2-norm

$$pdf(x, t_0) \propto e^{-\frac{1}{2}\sum_{obs_i} \frac{[Tobs_i(x) - Tcalc_i(x)]^2}{\sigma^2}}$$

"satisfy ***all*** the observations"

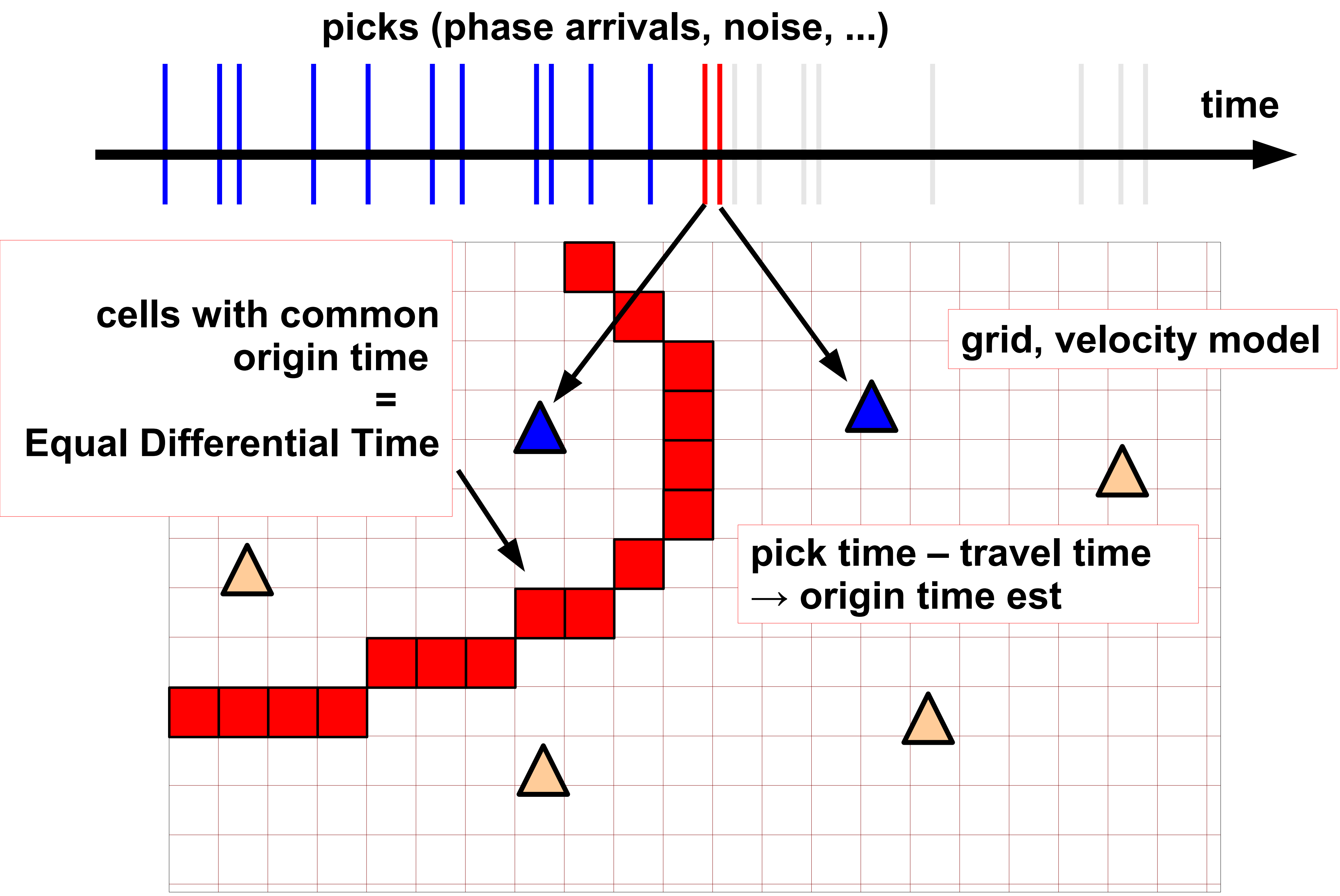
EDT (Equal Differential Time)

$$pdf(x) \propto \sum_{obs_a, obs_b} e^{-\frac{\{[Tobs_a(x) - Tobs_b(x)] - [TTcalc_a(x) - TTcalc_b(x)]\}^N}{\sigma^2}}$$

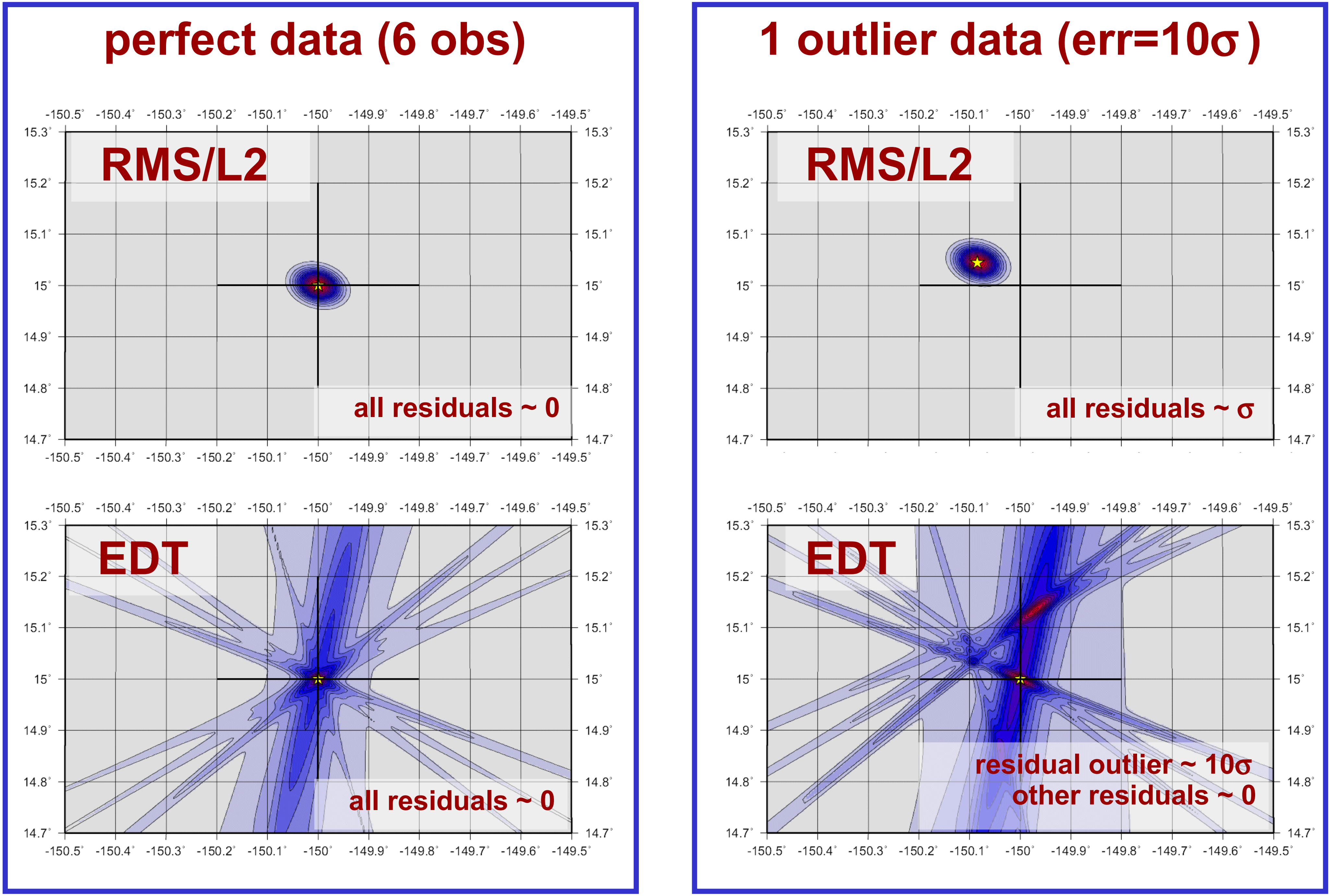
"satisfy ***the most pairs*** of observations"

- independent of origin time

Phase association and event detection → EDT



RMS/L2 vs EDT with outlier data



3. New perspectives in observatory analysis: Illustrative examples of global-search earthquake location

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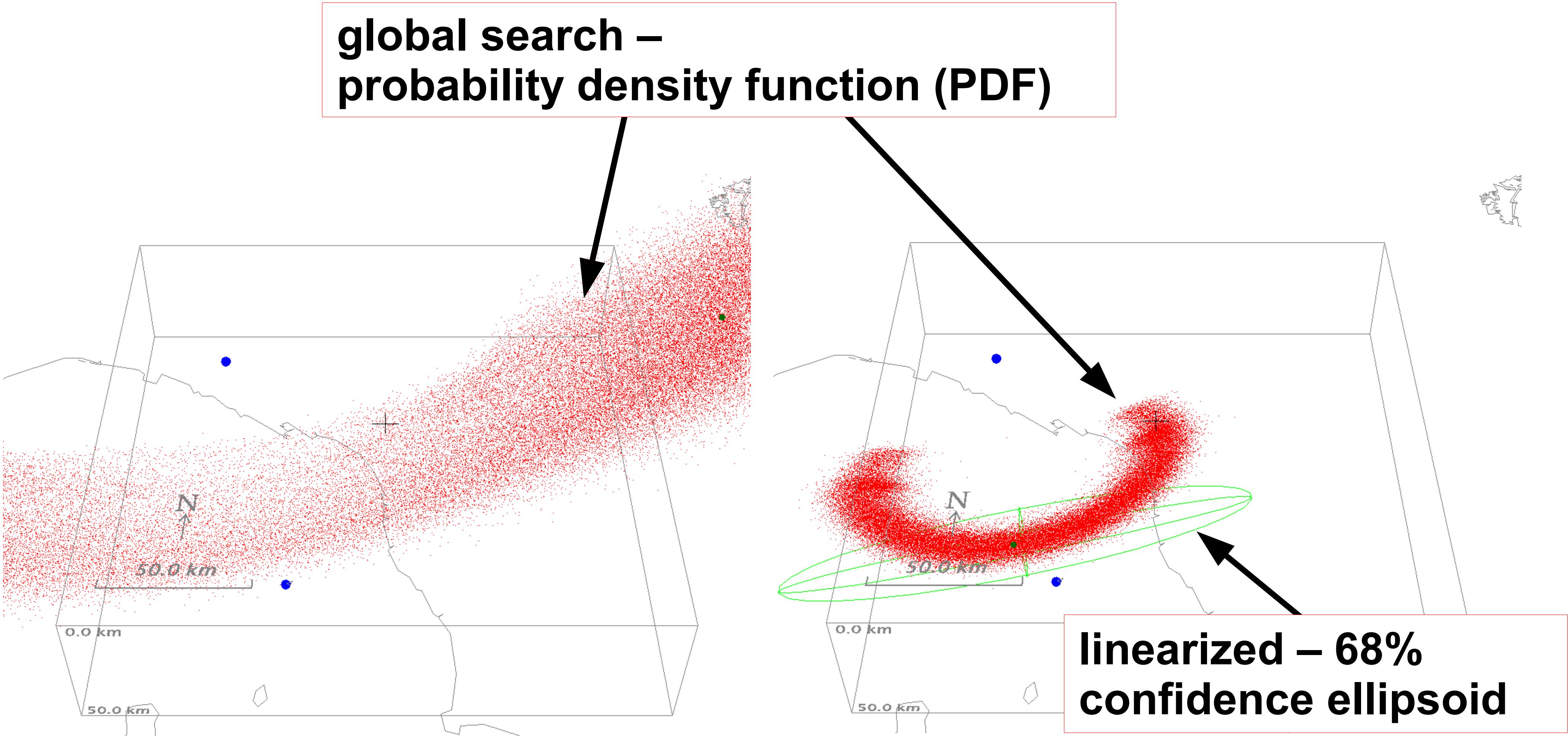
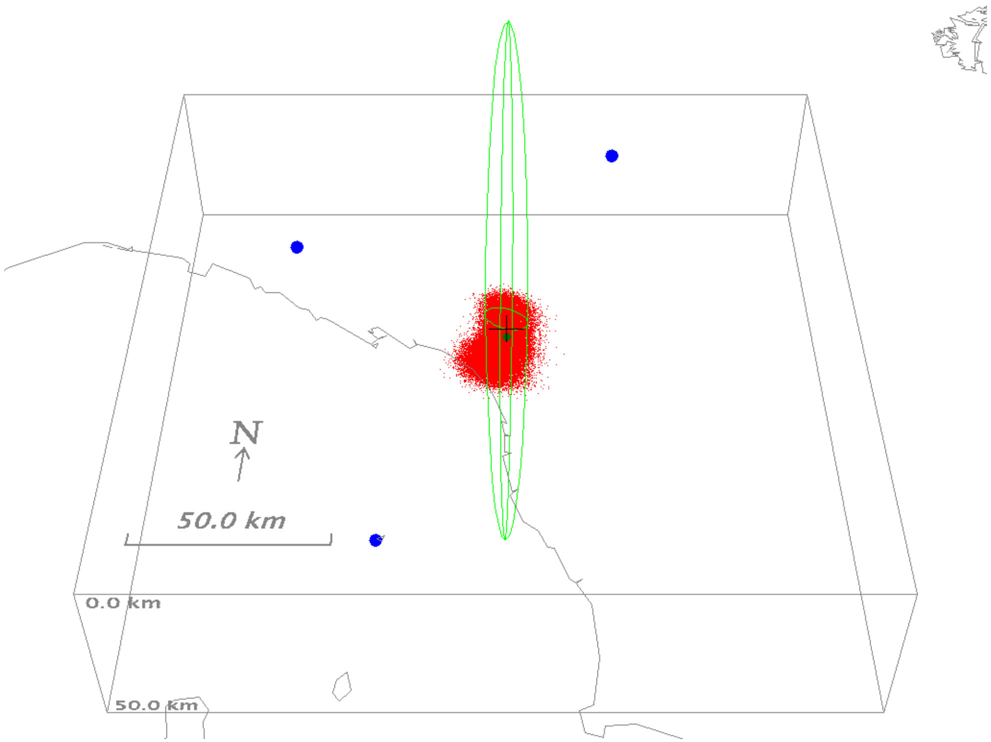
Few available stations

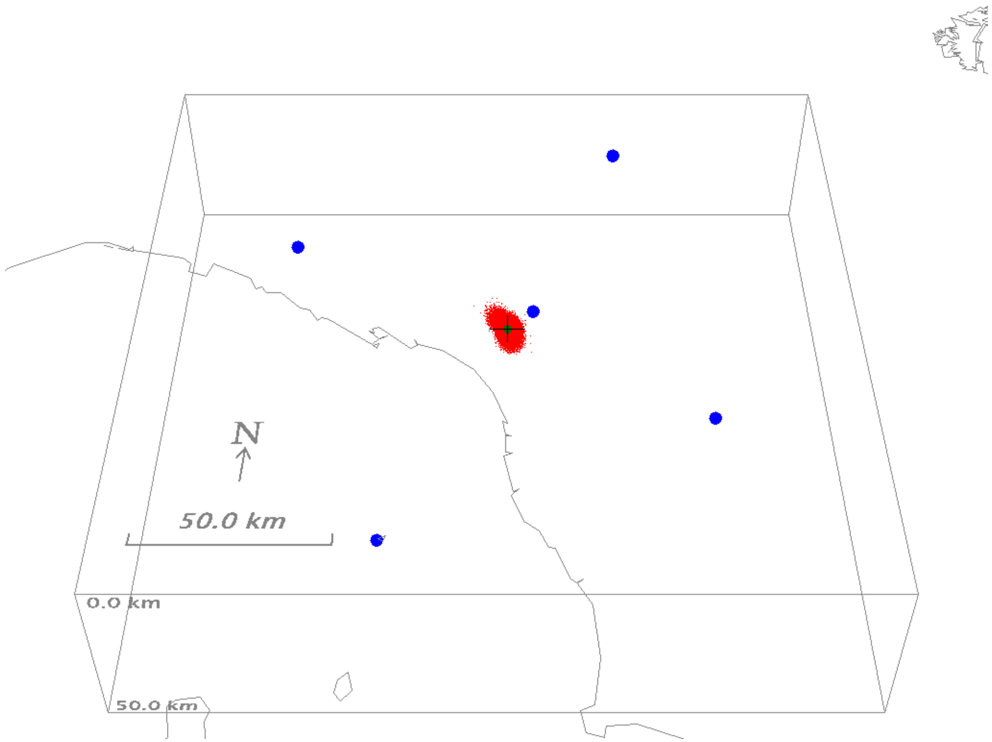


2P phases (2 stations)   2P and 2 S phases (2 stations)

Few available stations (cont)

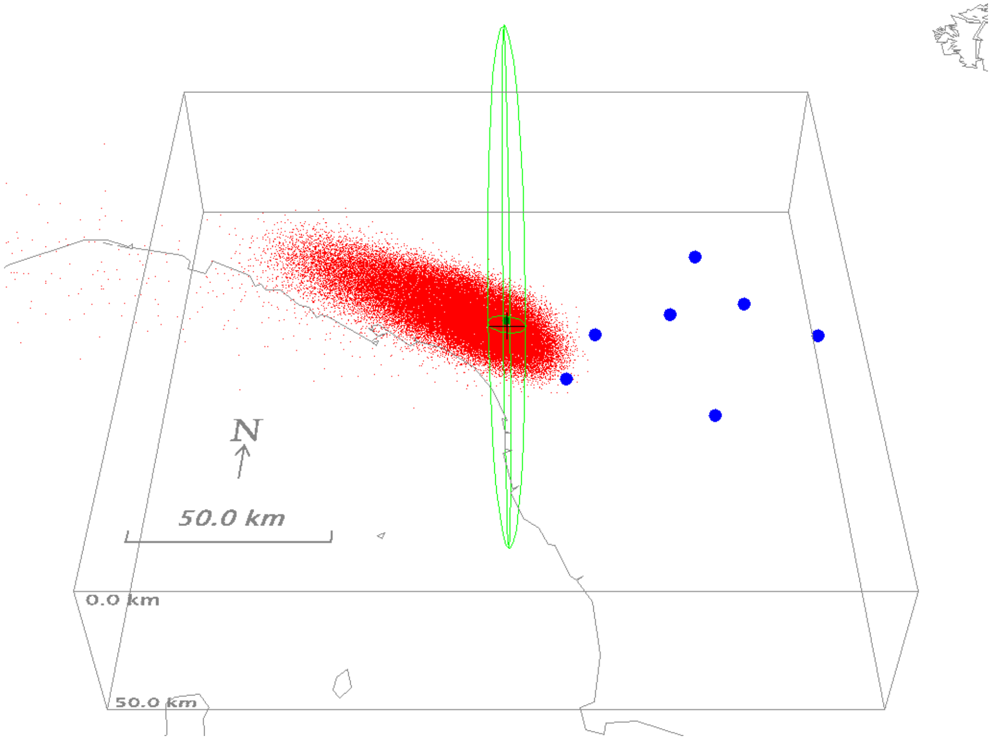


3P phases (3 stations)



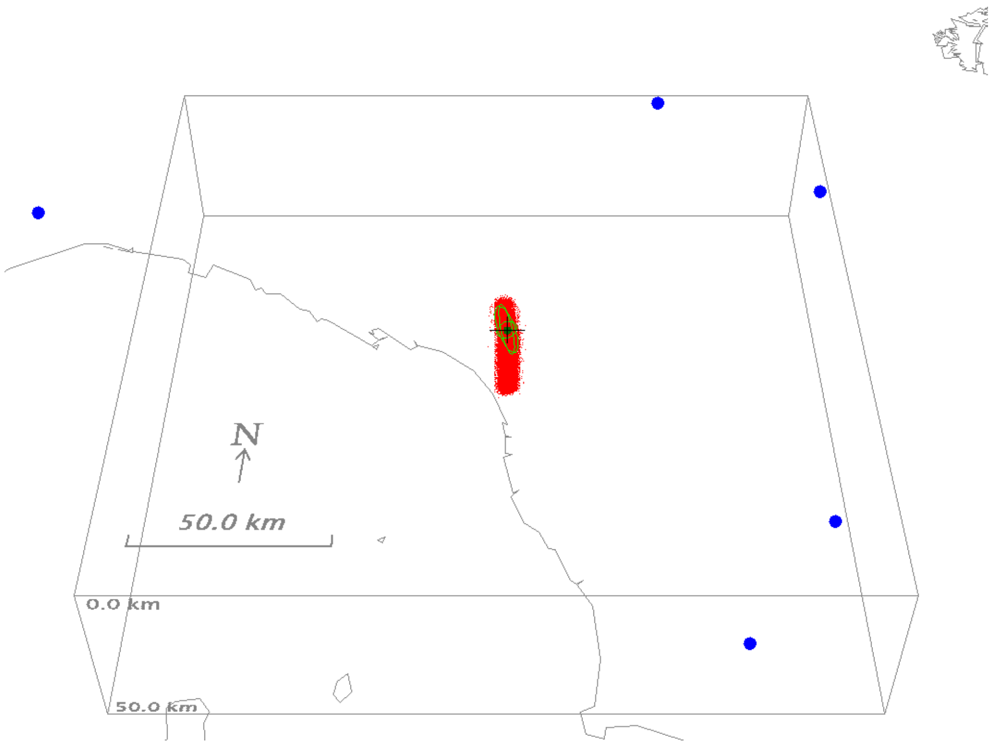
5P and 3S phases (5 stations)

Stations to one side of the event

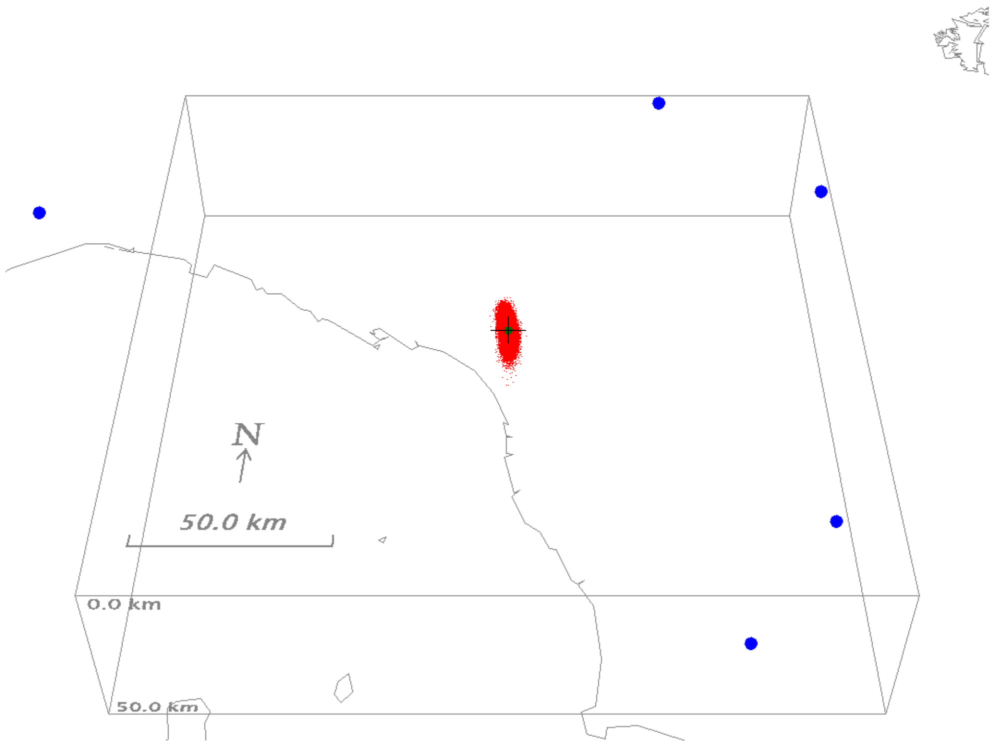


P-wave arrival times at 7 stations

Stations far from the event

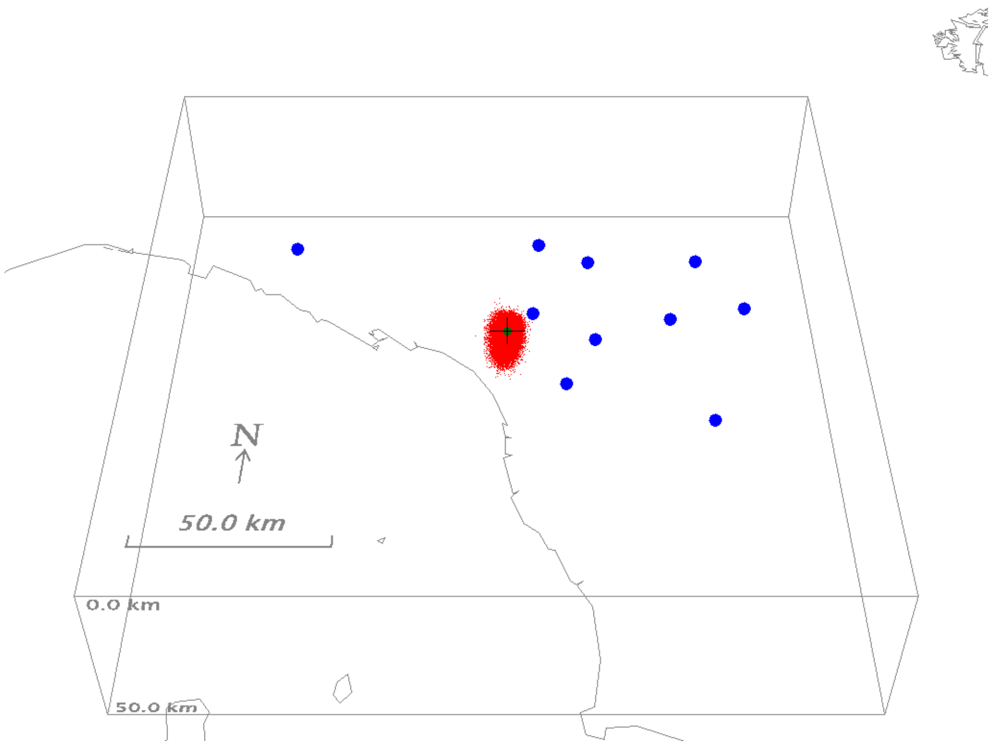


P arrival times only

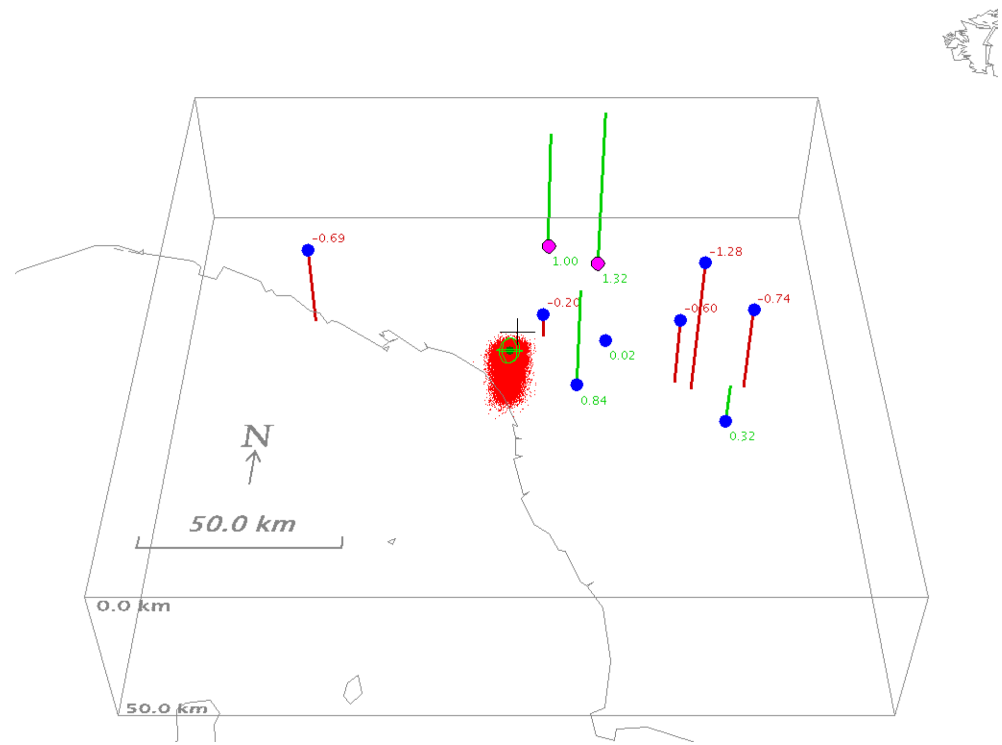


P and S arrival times

Incorrect picks and phase id - outlier data: L2-norm

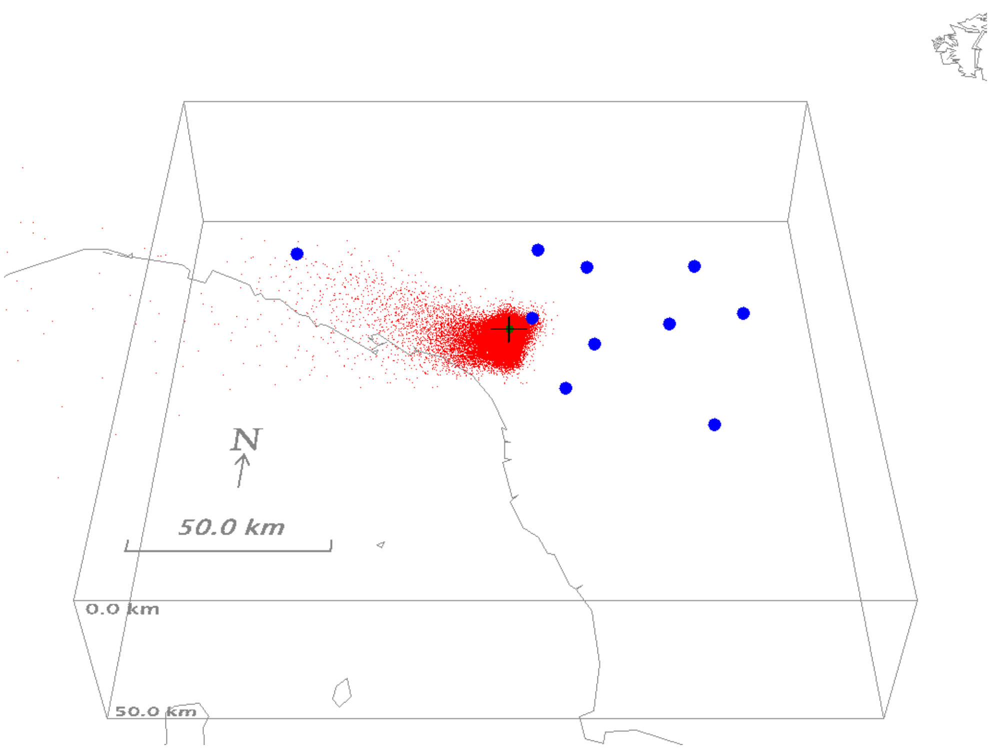


no outliers

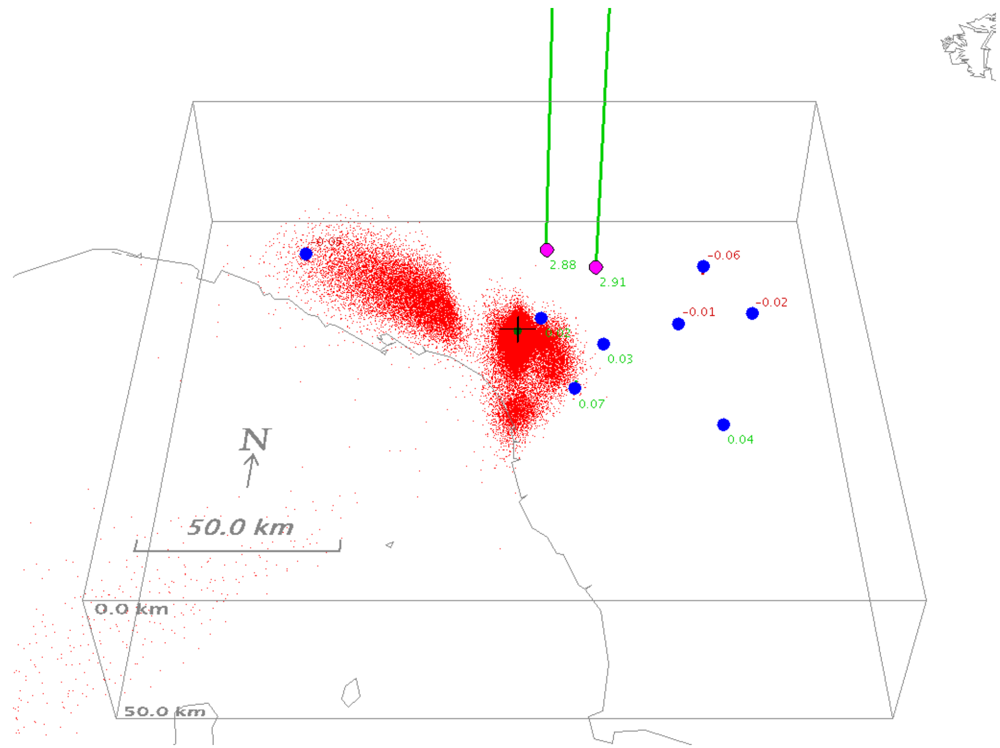


two arrival-time outliers

Incorrect picks and phase id - outlier data: EDT

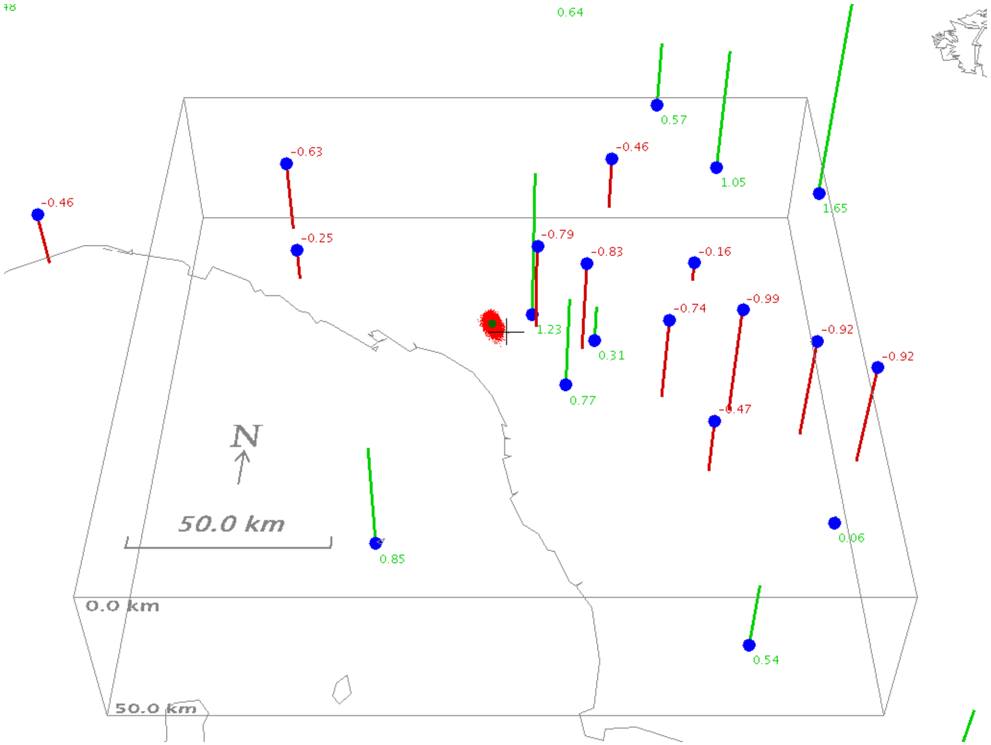


no outliers

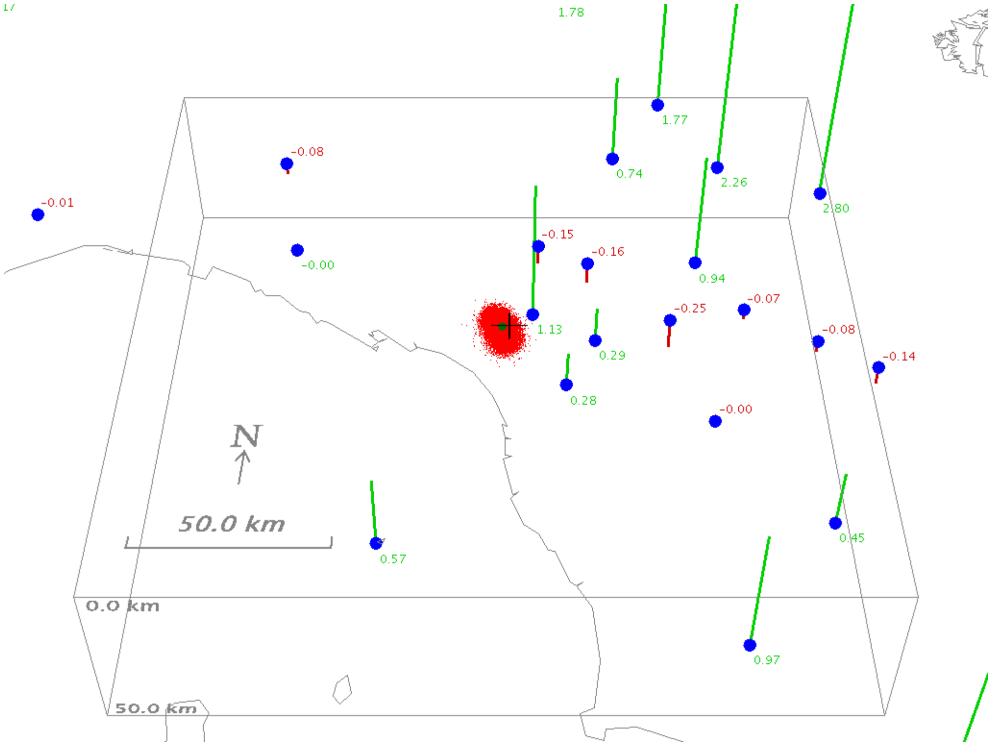


two arrival-time outliers

Incorrect velocity model

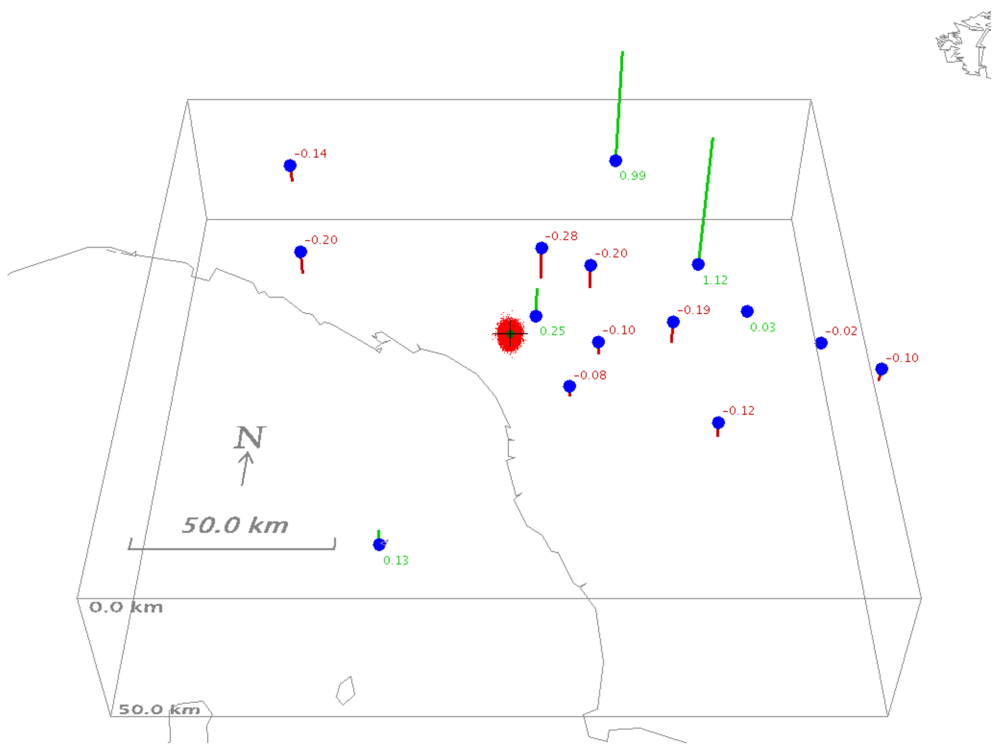


L2-norm

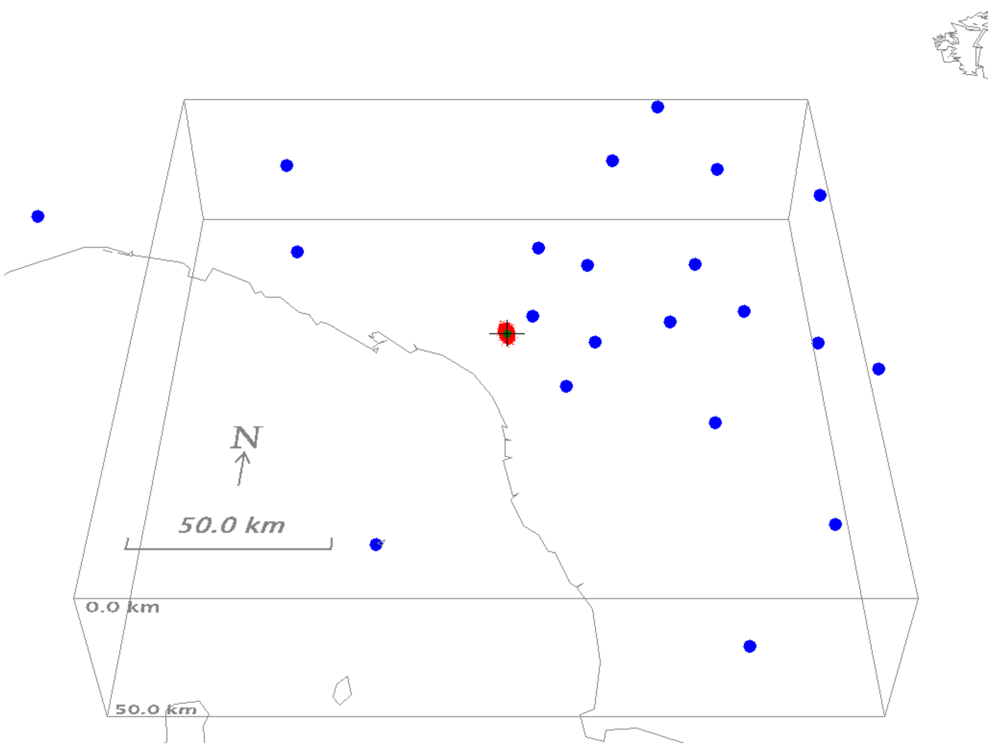


EDT

Station corrections



Original location



Location with corrected times

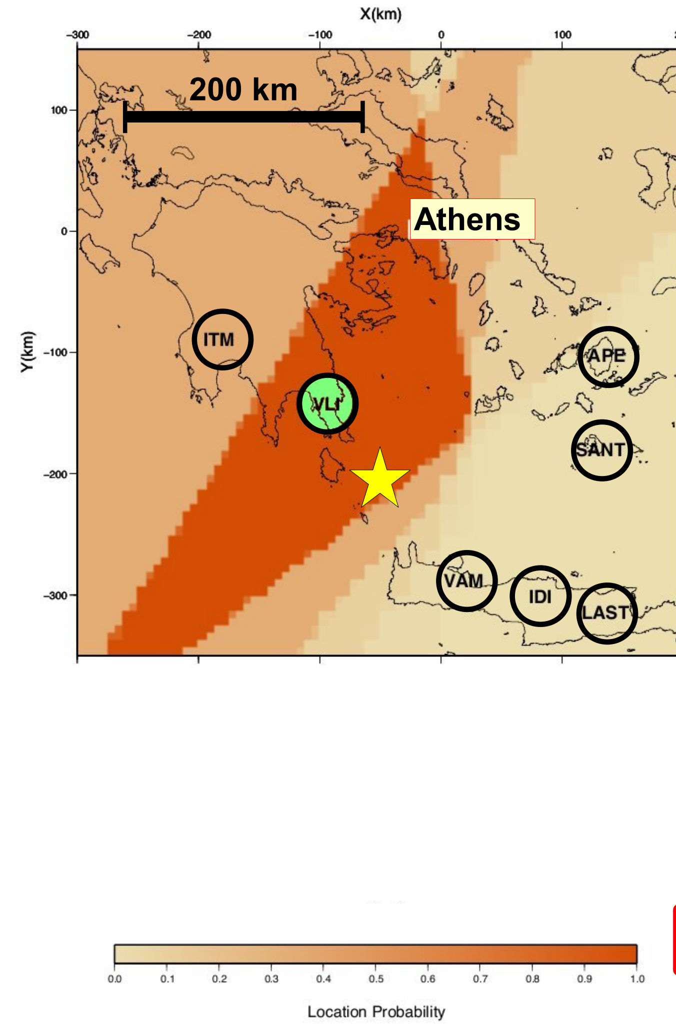
3. New perspectives in observatory analysis: Illustrative examples of global-search earthquake location

Evolutionary, early-warning location

Evolutionary Location – 2006.01.08 M6.8 Greece

Early warning scenario:

How early before S wave arrival in Athens (t^S) can the location be determined?



Δt = 0.00 s

t_{now} = 14.90 s

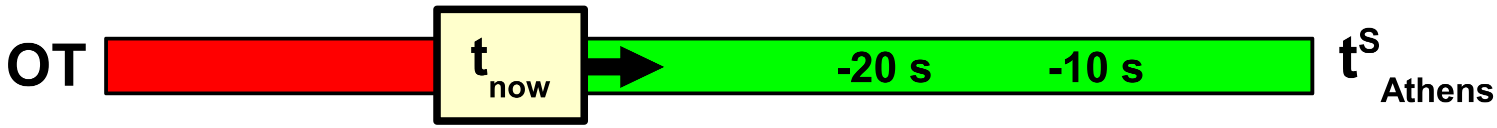
t^S_{Athens} = –40.00 s

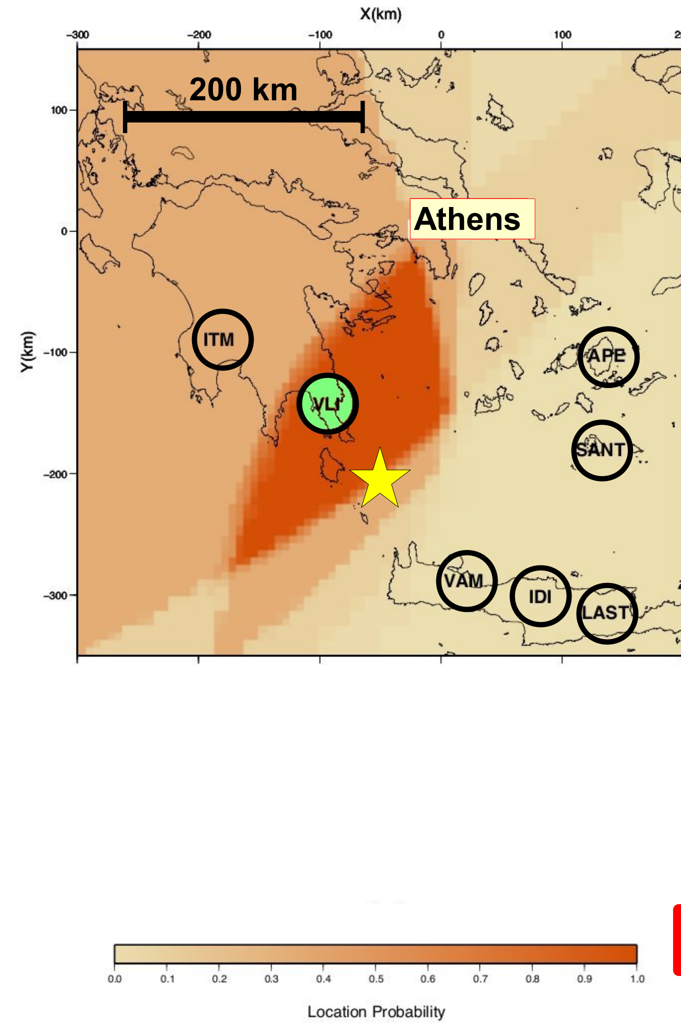
RTLoc

Satriano, C., A. Lomax and A. Zollo (2008)

C. Satriano - 2007/07/11

Evolutionary Location – 2006.01.08 M6.8 Greece





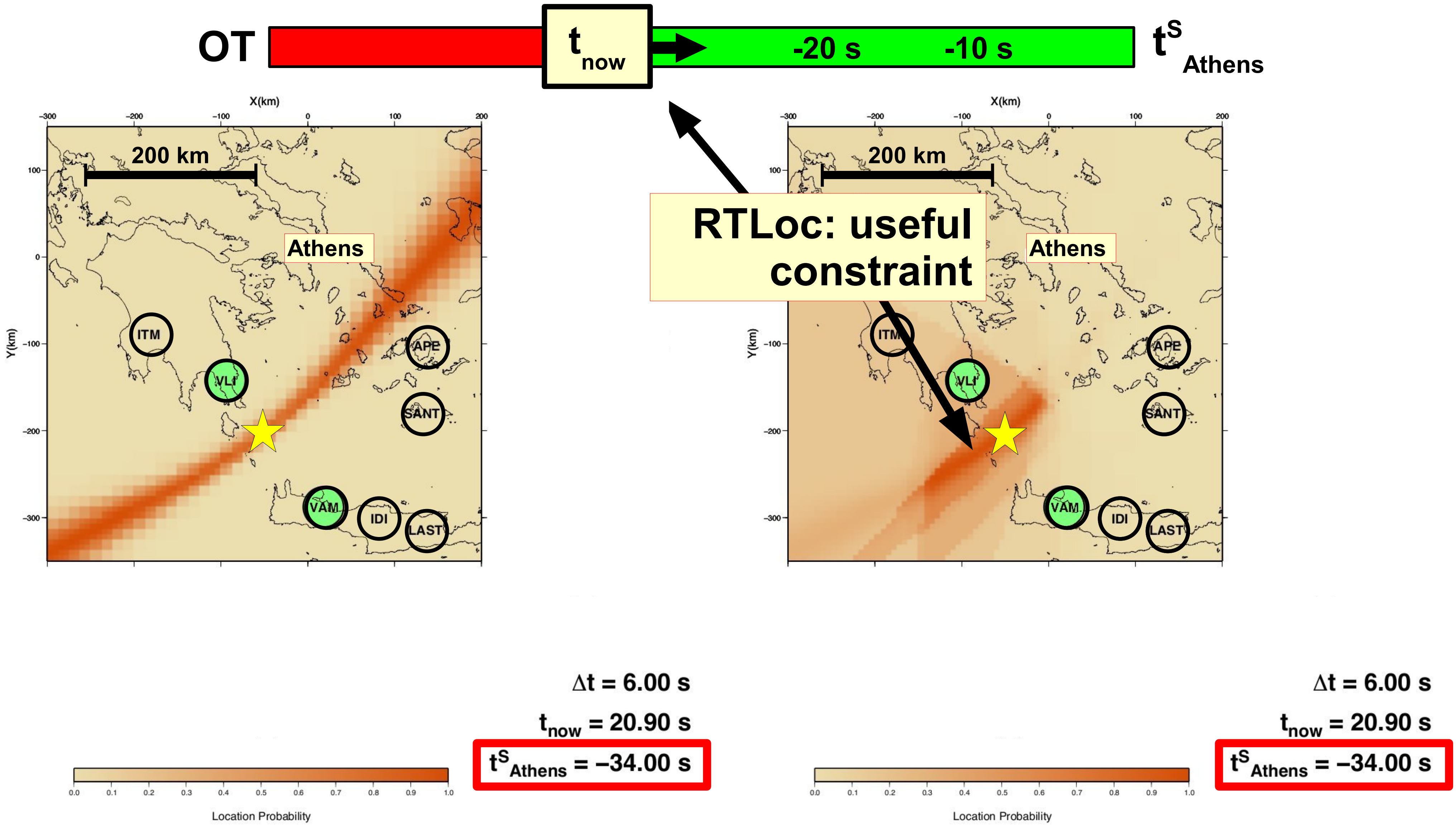
$\Delta t = 4.00$ s

$t_{now} = 18.90$ s

$t^{S}_{Athens} = -36.00$ s

RTLoc

Evolutionary Location – 2006.01.08 M6.8 Greece



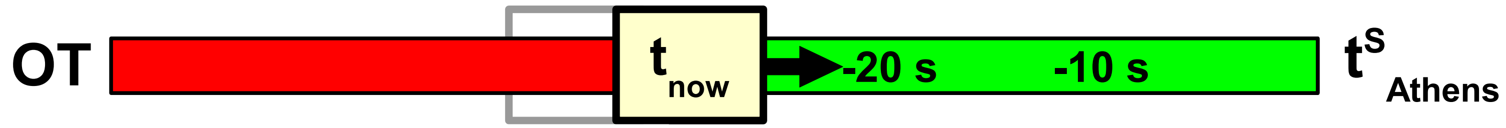
NLLoc

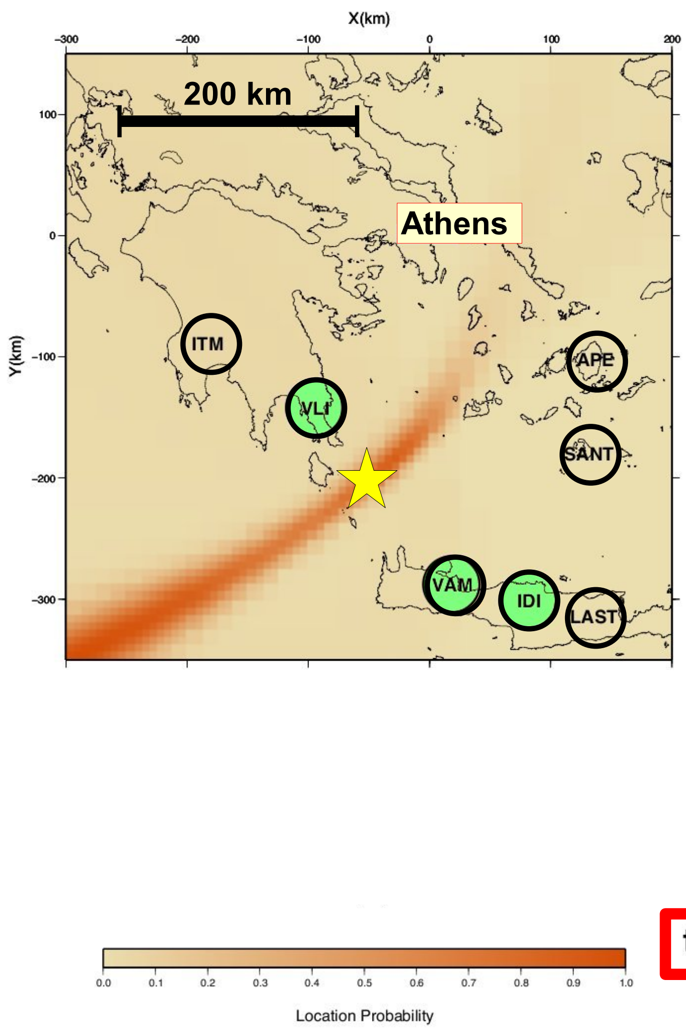
Lomax, et al., 2000

RTLoc

C. Satriano - 2007/07/11

Evolutionary Location – 2006.01.08 M6.8 Greece



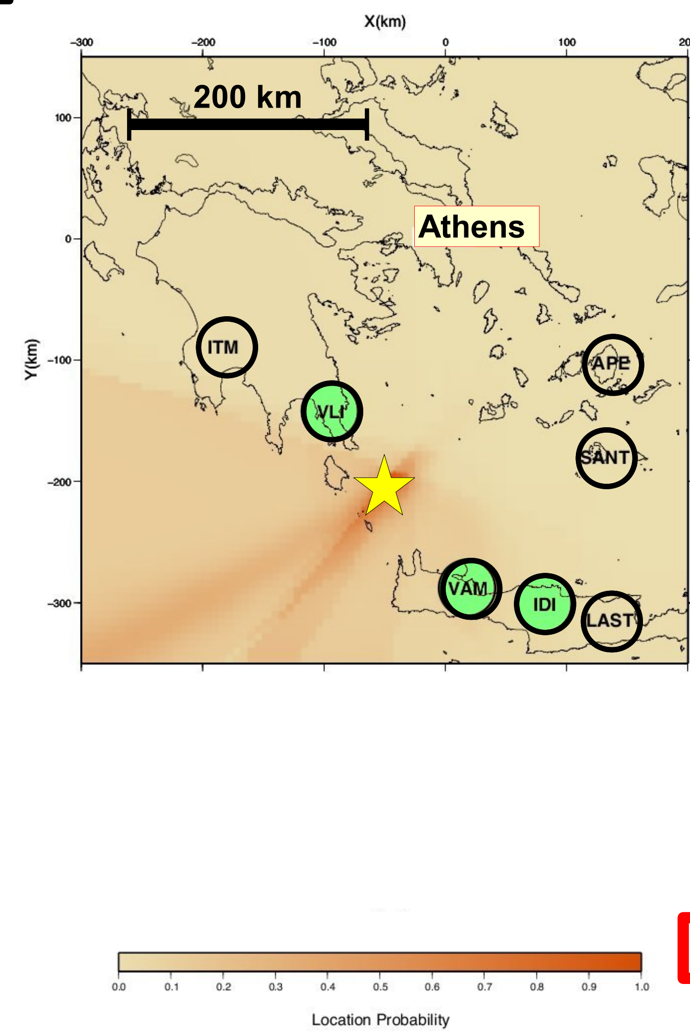


Δt = 12.00 s

t_{now} = 26.90 s

t^S_{Athens} = –28.00 s

NLLoc



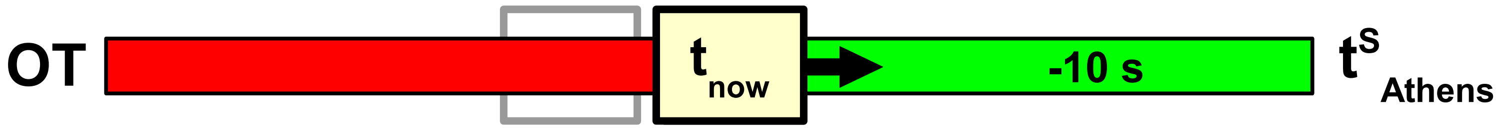
Δt = 12.00 s

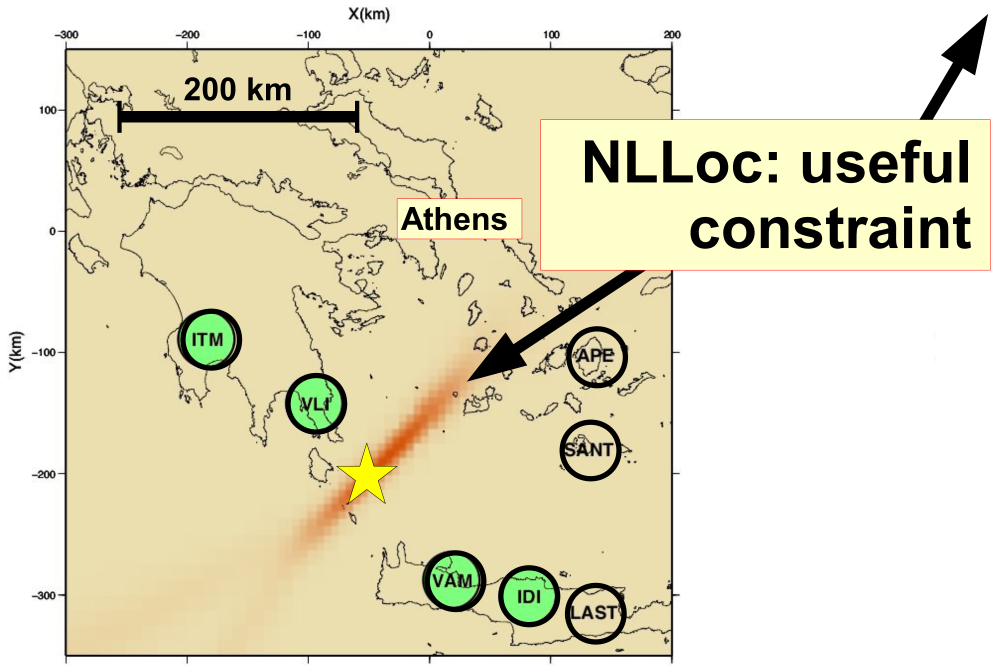
t_{now} = 26.90 s

t^S_{Athens} = –28.00 s

RTLoc

Evolutionary Location – 2006.01.08 M6.8 Greece

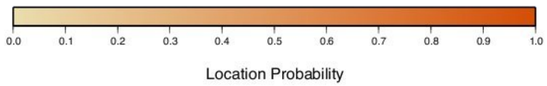




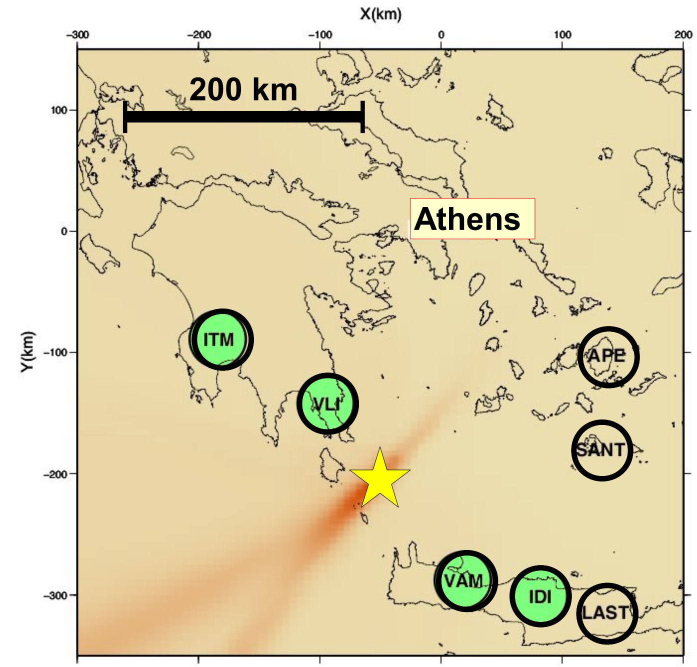
$\Delta t = 14.00$ s

$t_{now} = 28.90$ s

$t^S_{Athens} = -26.00$ s



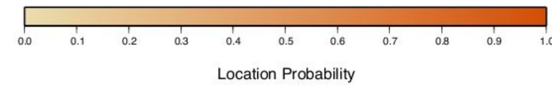
NLLoc



$\Delta t = 14.00$ s

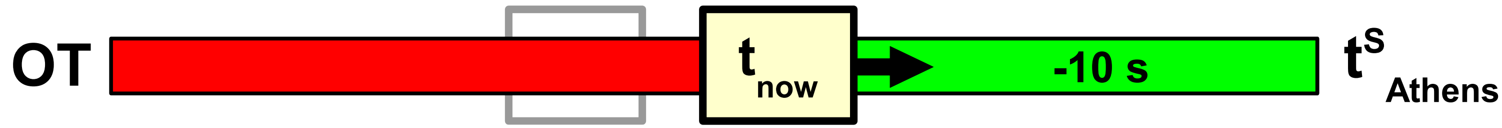
$t_{now} = 28.90$ s

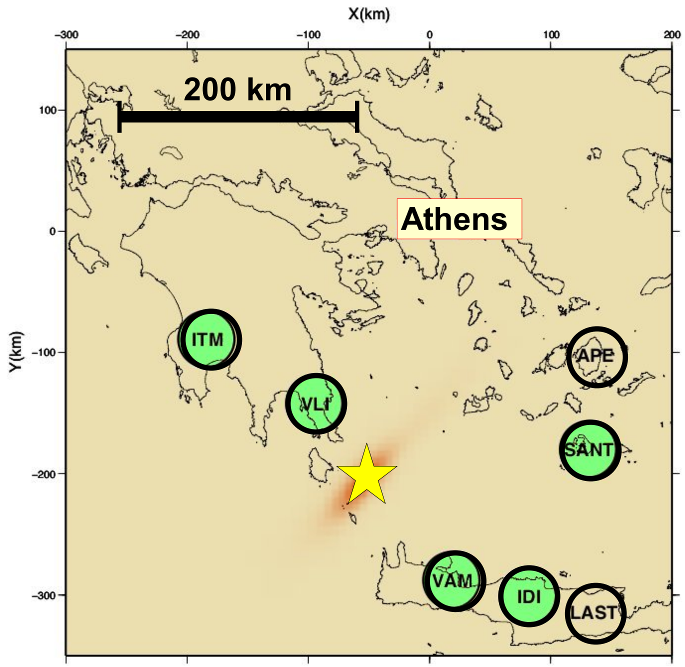
$t^S_{Athens} = -26.00$ s

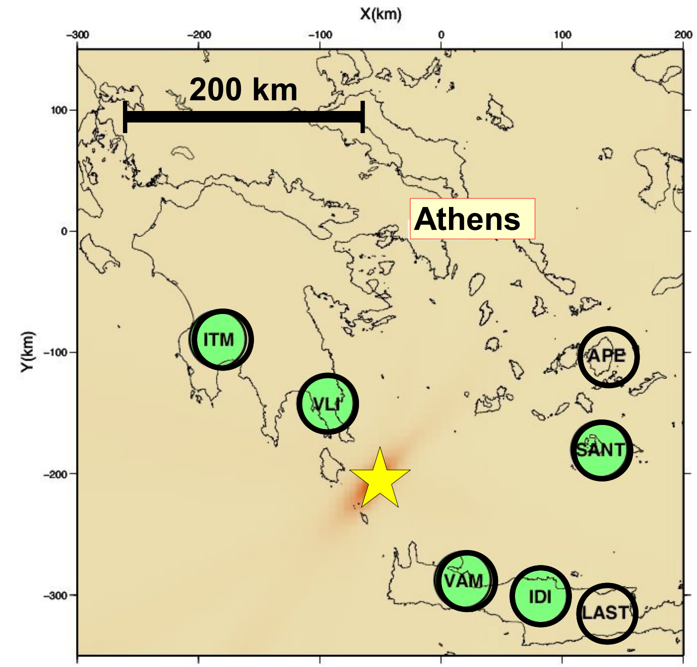


RTLoc

Evolutionary Location – 2006.01.08 M6.8 Greece



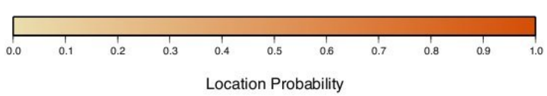




$\Delta t = 16.00$ s

$t_{now} = 30.90$ s

$t^{S}_{Athens} = -24.00$ s

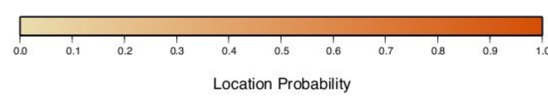


NLLoc

$\Delta t = 16.00$ s

$t_{now} = 30.90$ s

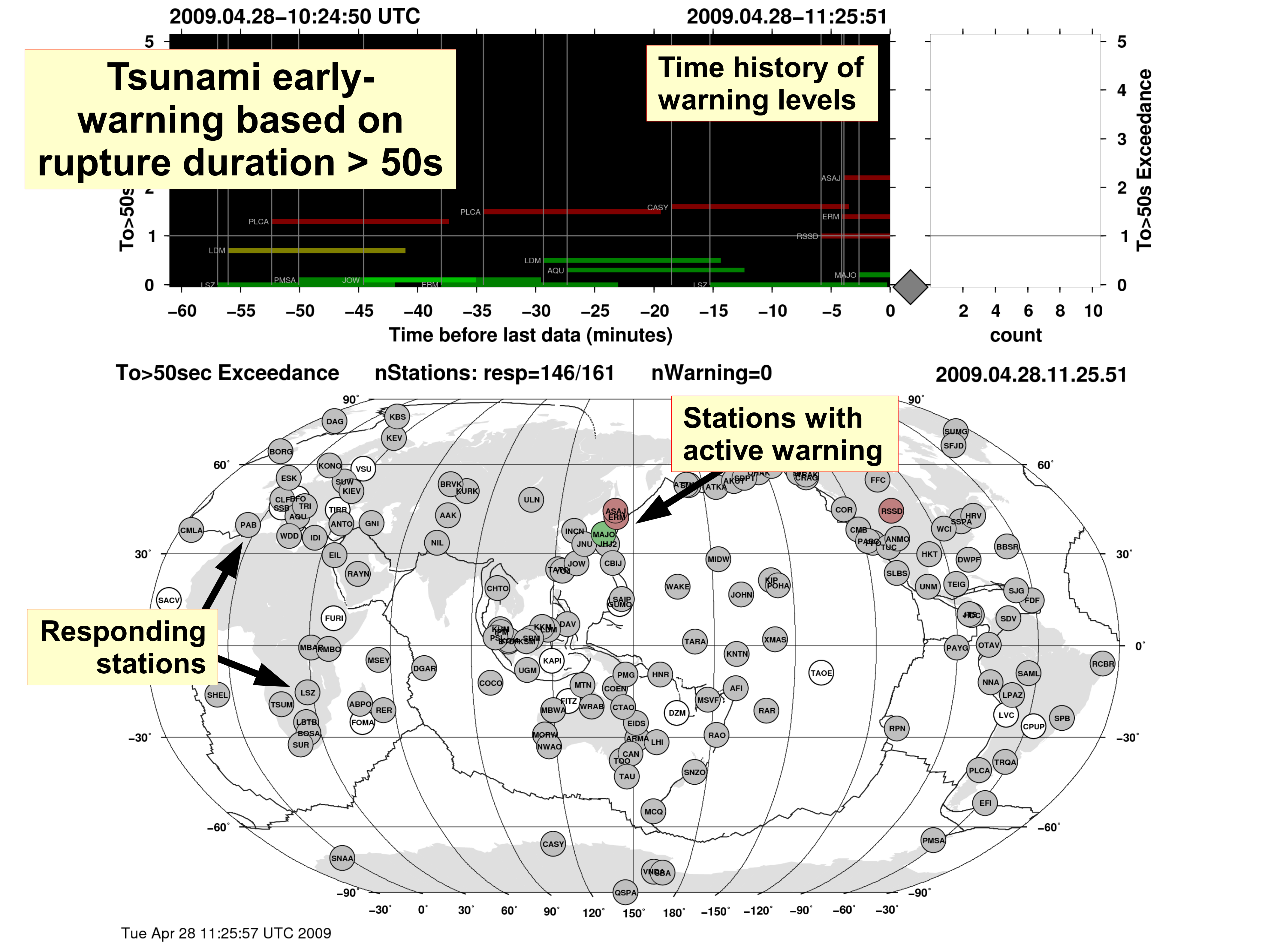
$t^{S}_{Athens} = -24.00$ s



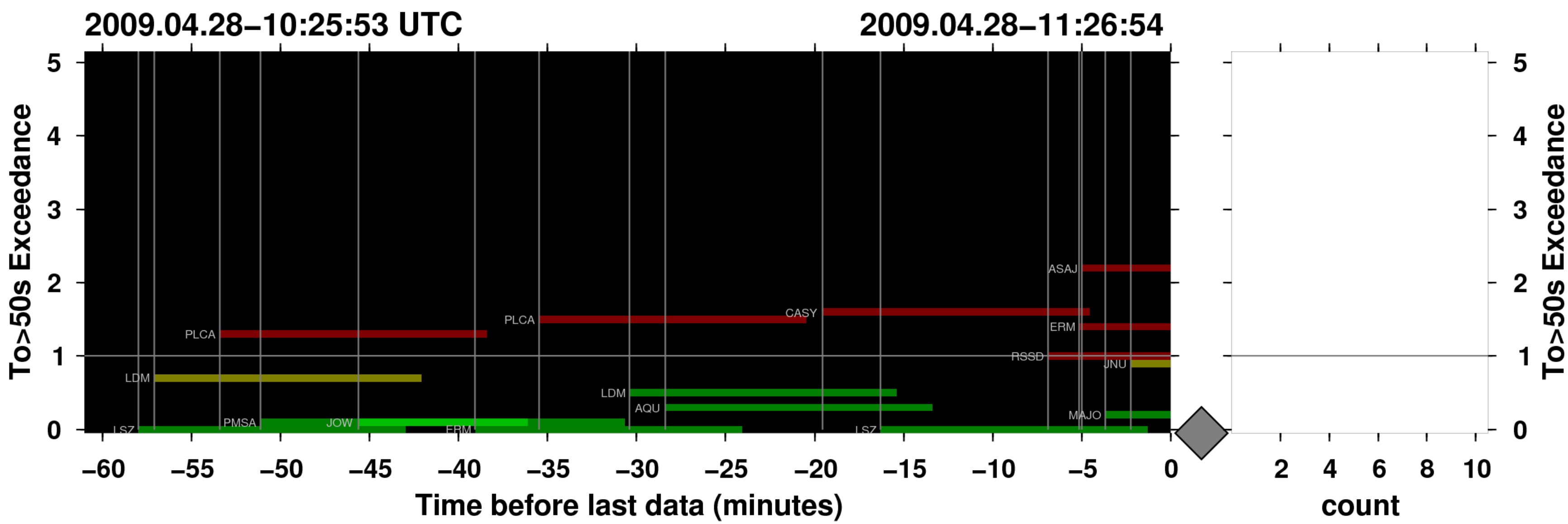
RTLoc

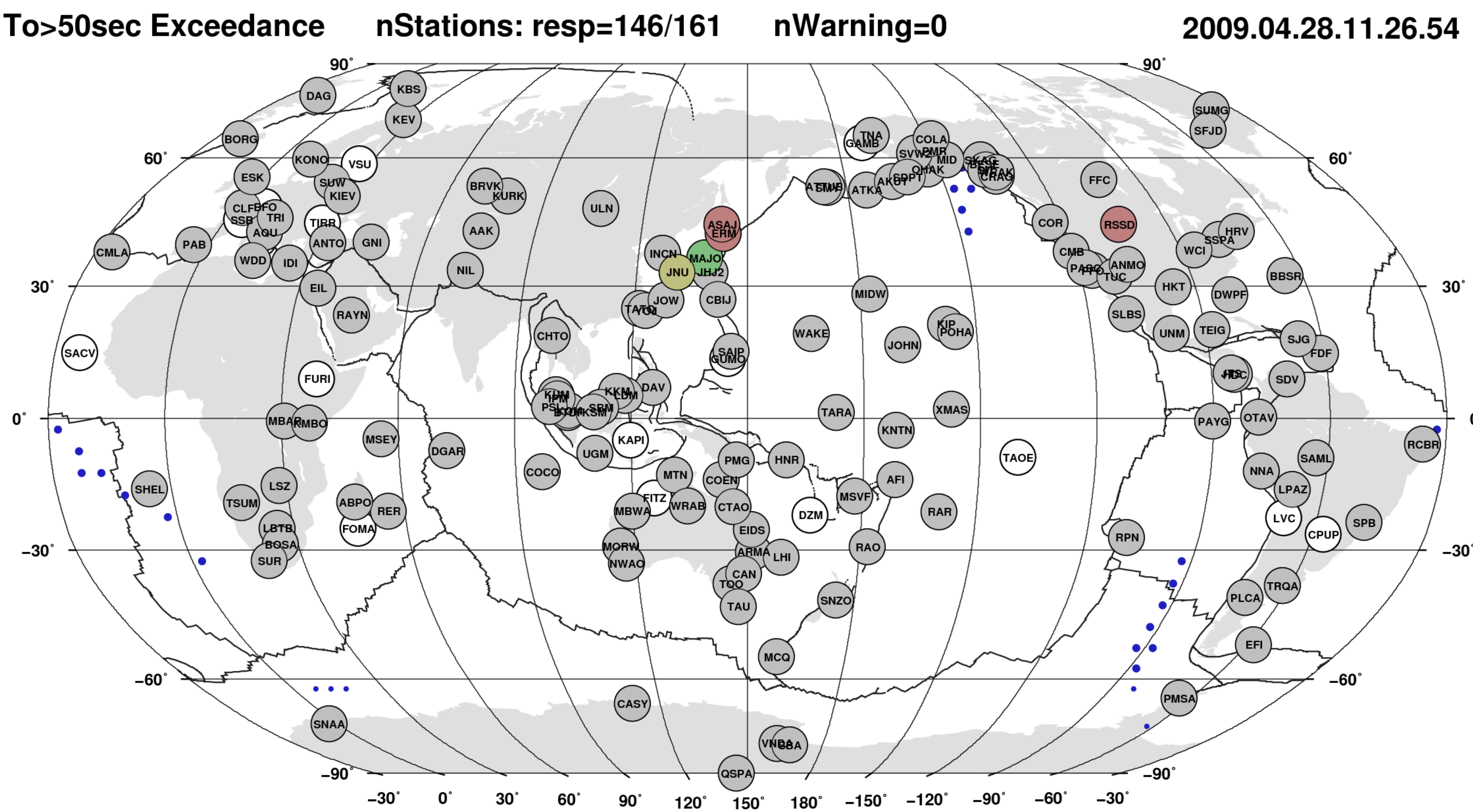
3. New perspectives in observatory analysis: Illustrative examples of global-search earthquake location

Real-time display of derived quantities: Tsunami early-warning

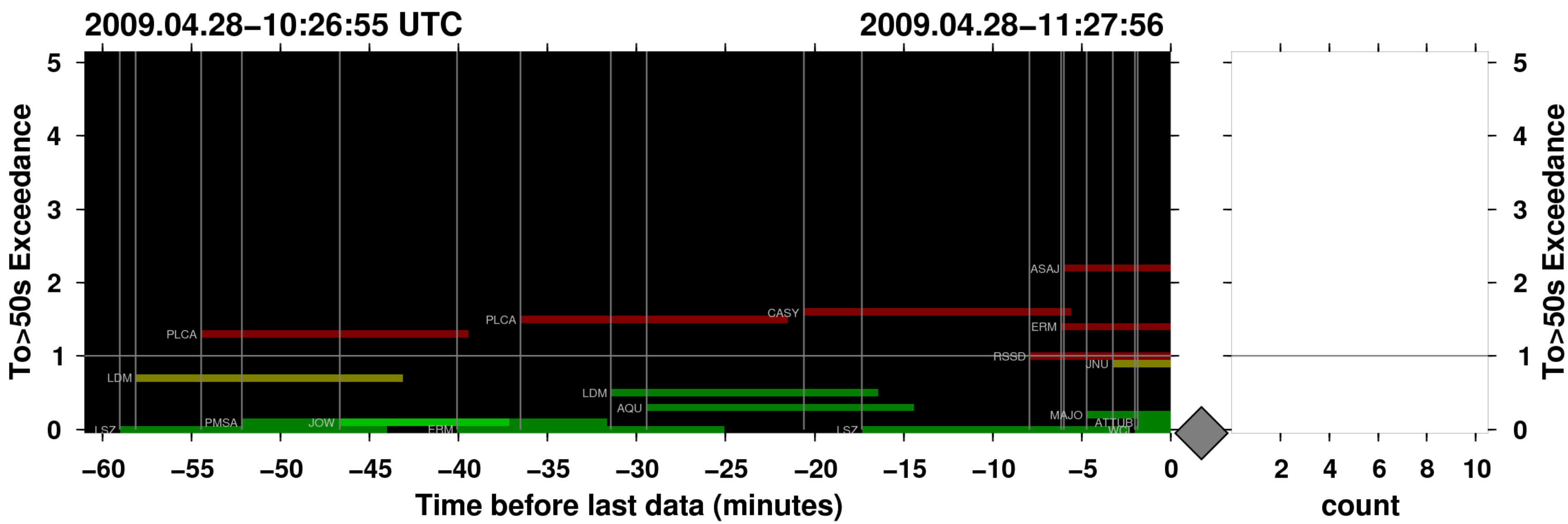


Tsunami early-warning based on rupture duration > 50s
Time history of warning levels
Stations with active warning
Responding stations
2009.04.28–10:24:50 UTC
2009.04.28–11:25:51
To>50s
Time before last data (minutes)
count
To>50s Exceedance
To>50sec Exceedance
nStations: resp=146/161
nWarning=0
2009.04.28.11.25.51
Tue Apr 28 11:25:57 UTC 2009

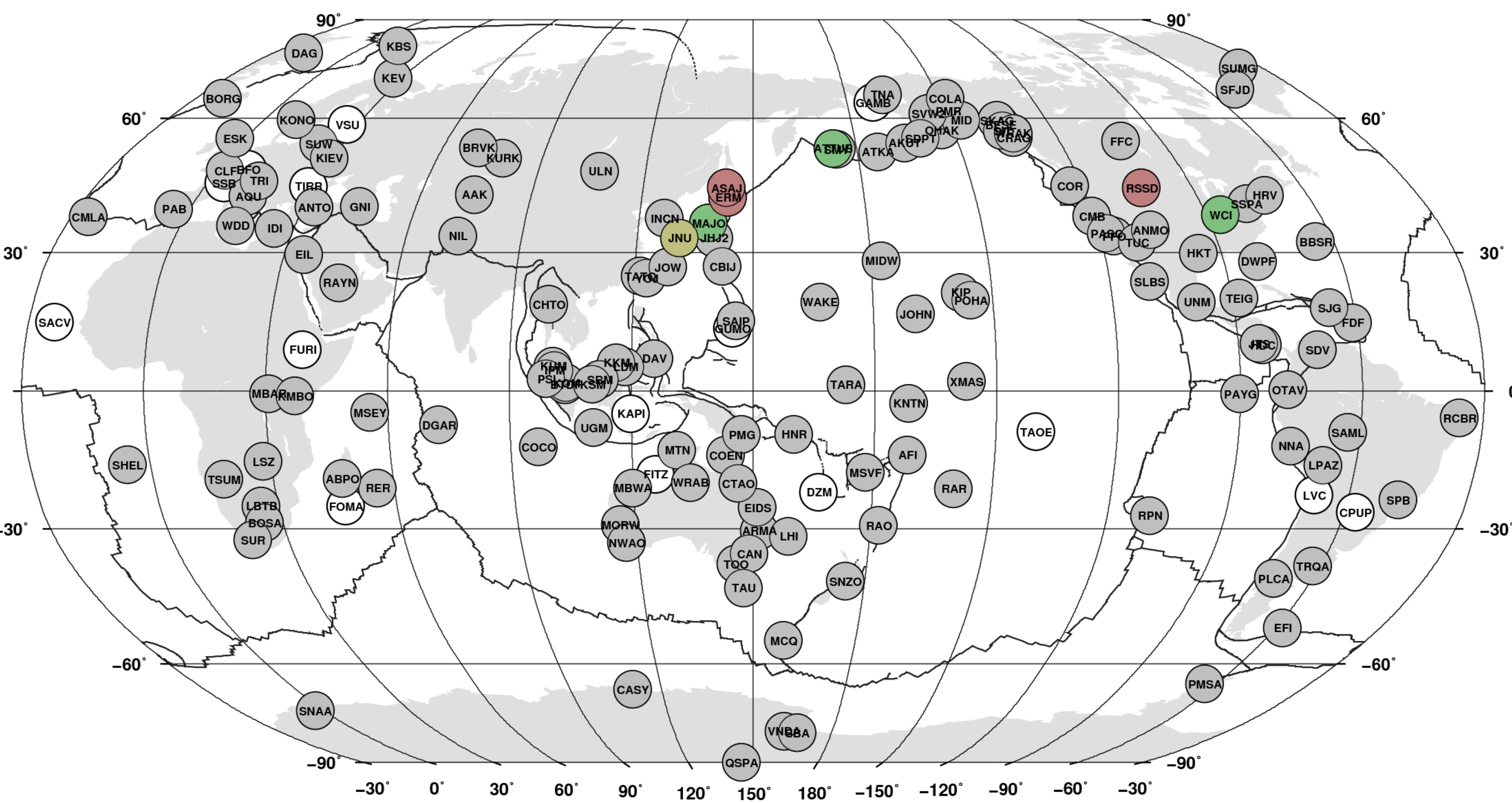




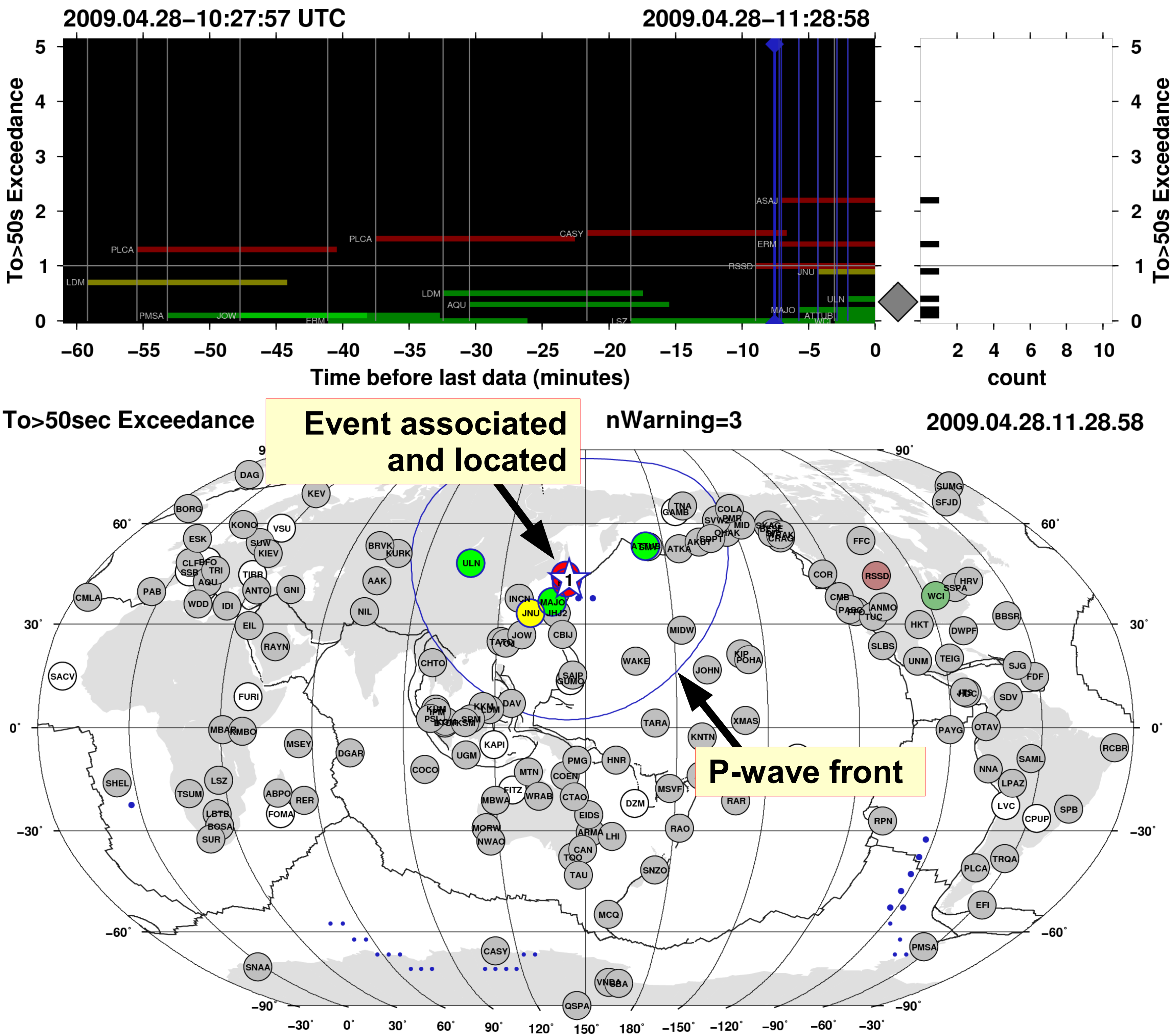
Tue Apr 28 11:27:00 UTC 2009



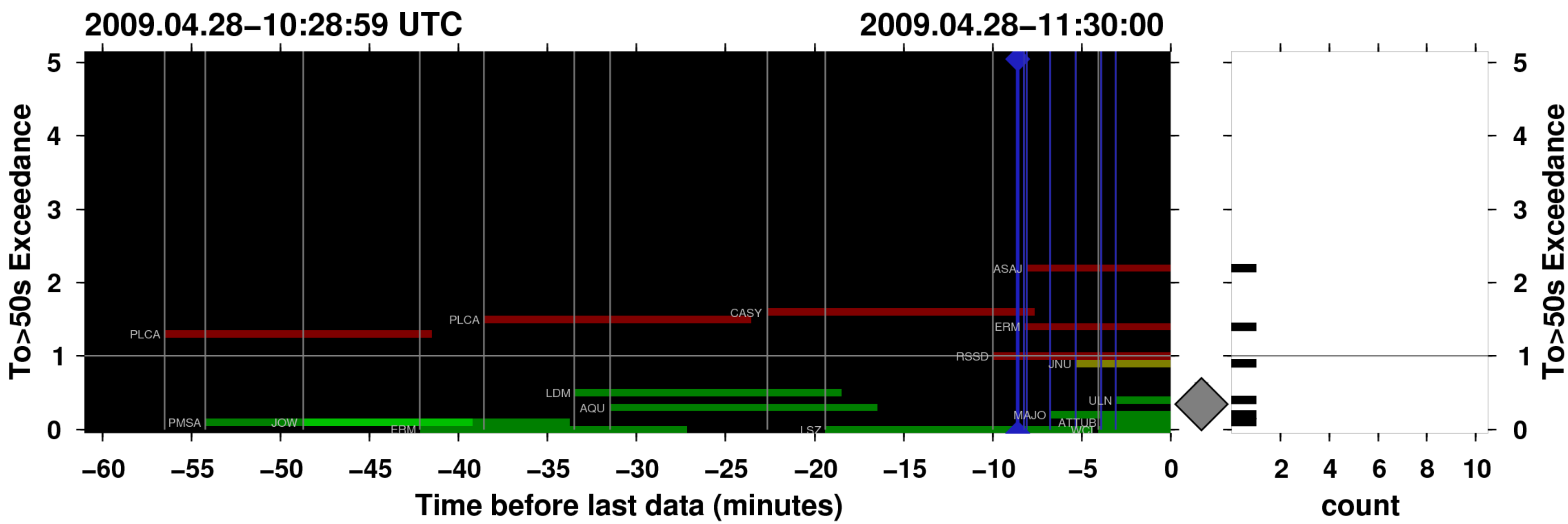
To>50sec Exceedance nStations: resp=146/161 nWarning=0 2009.04.28.11.27.56



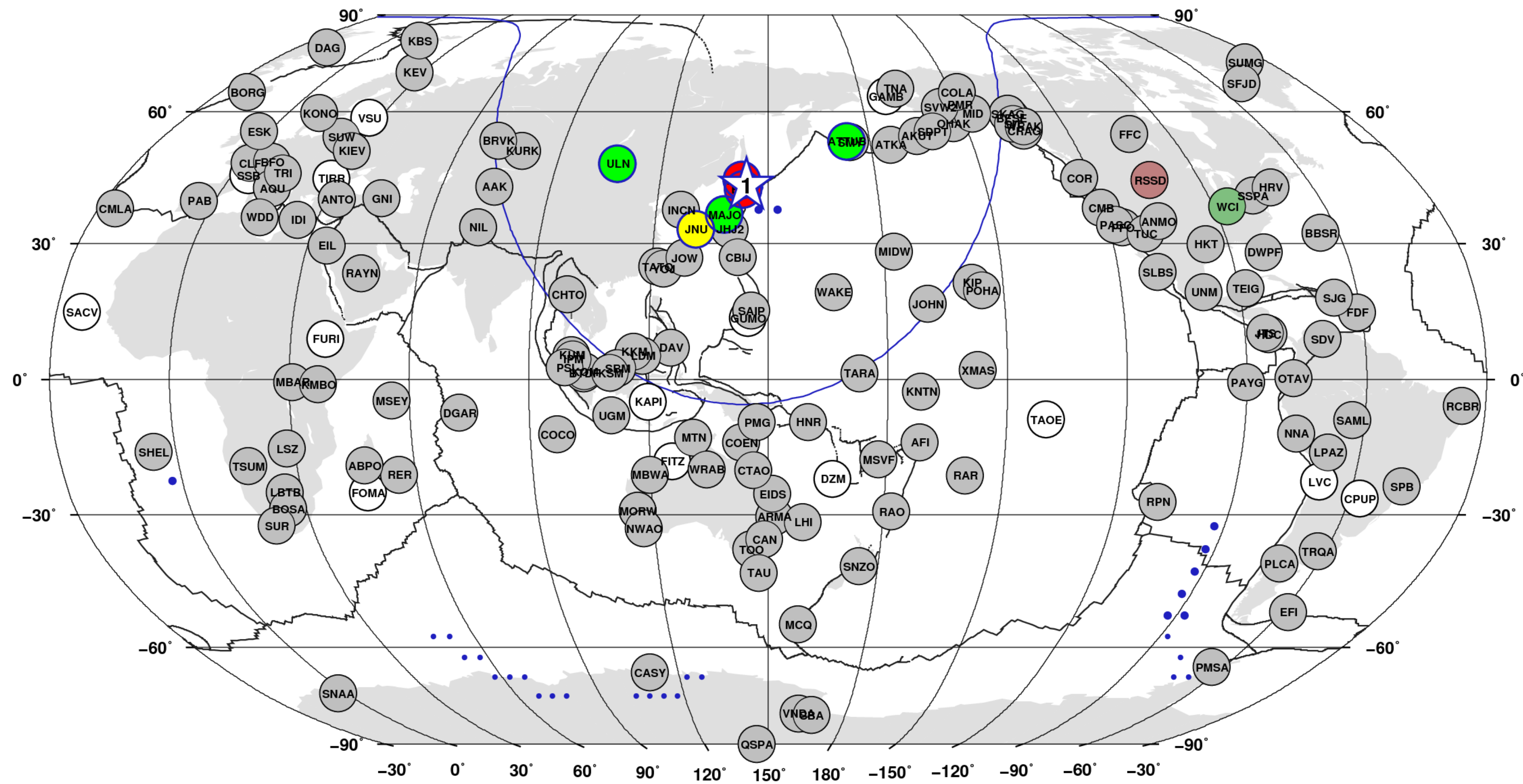
Tue Apr 28 11:28:02 UTC 2009



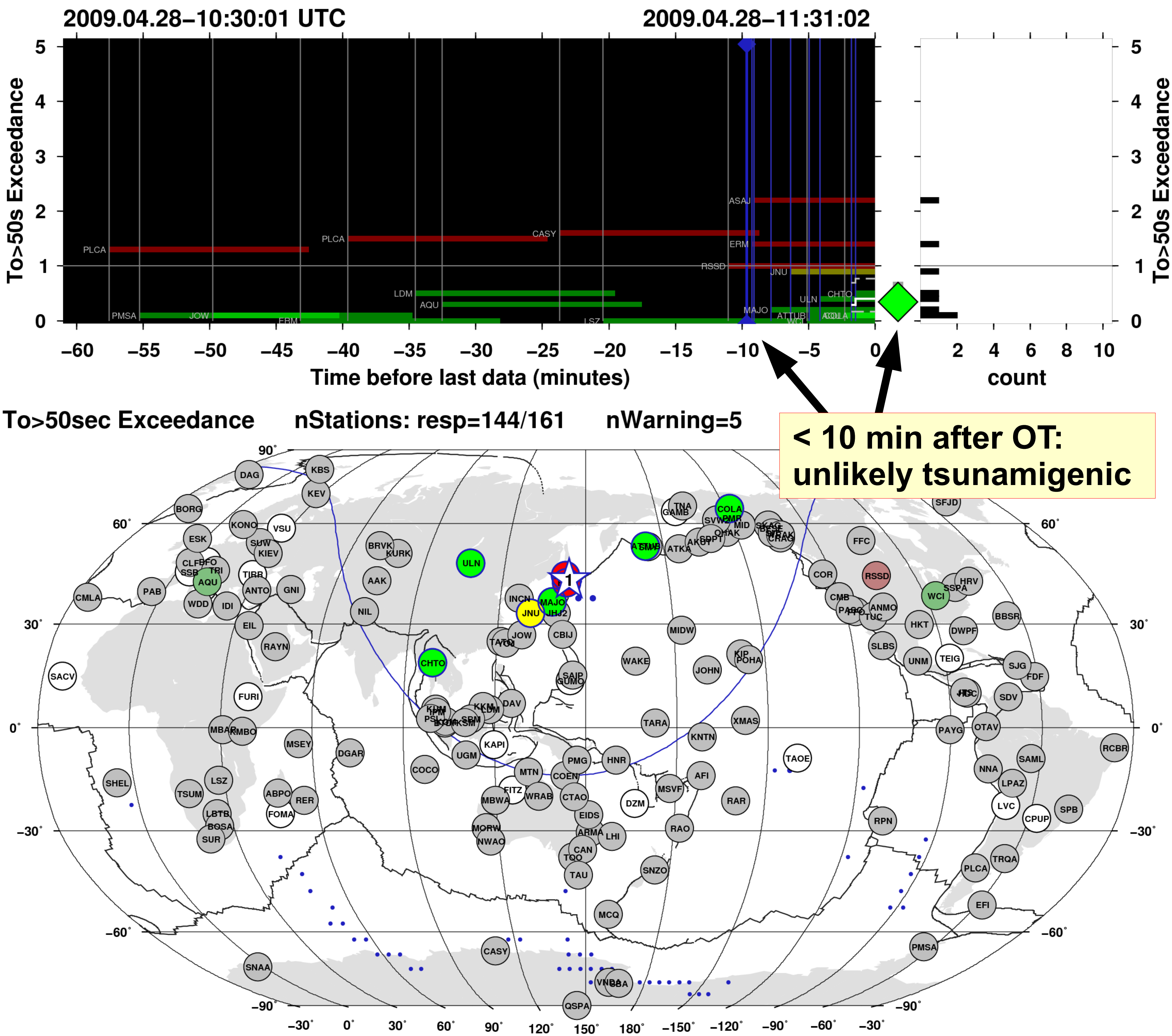
Tue Apr 28 11:29:06 UTC 2009



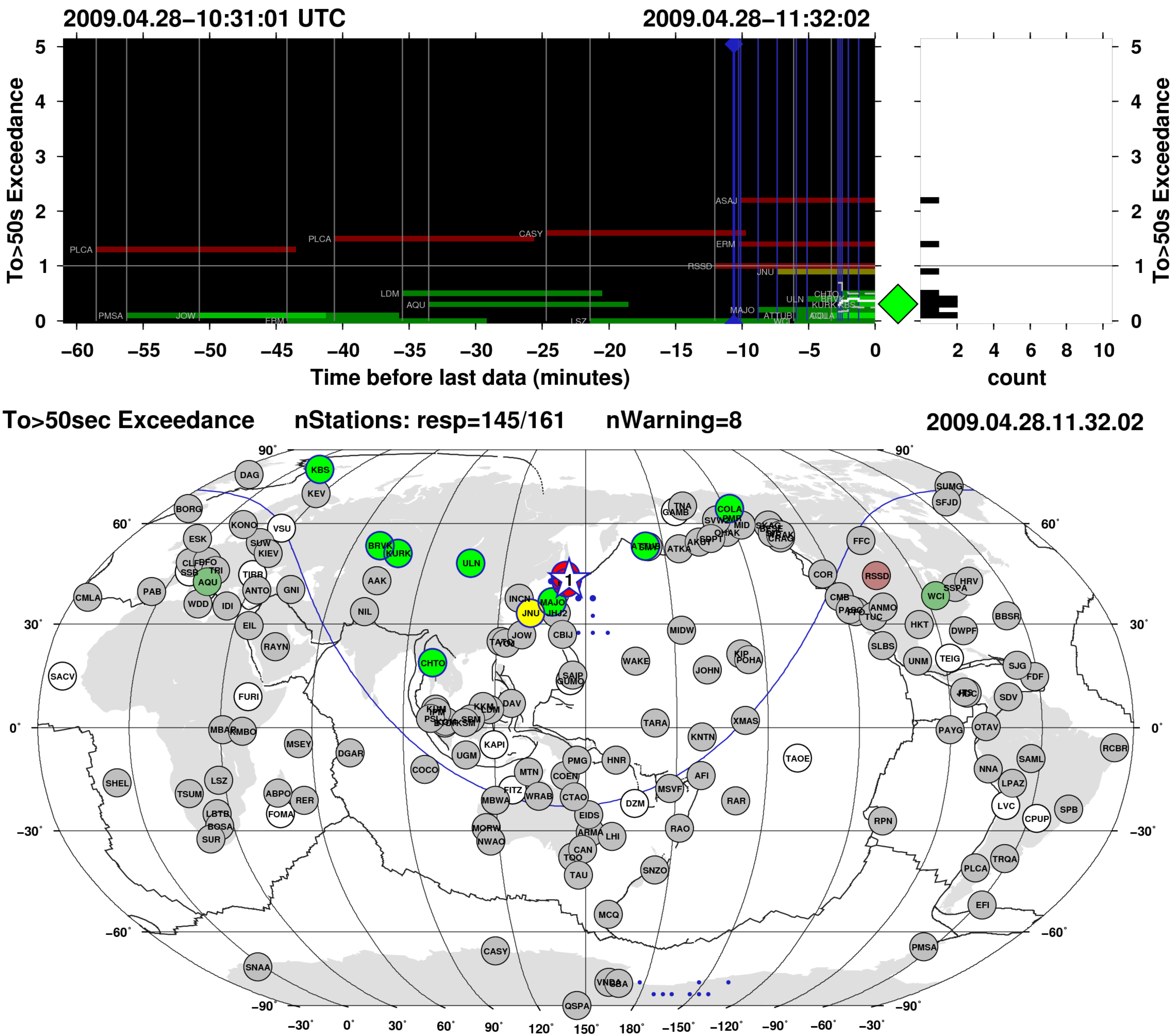
To>50sec Exceedance nStations: resp=146/161 nWarning=3 2009.04.28.11.30.00



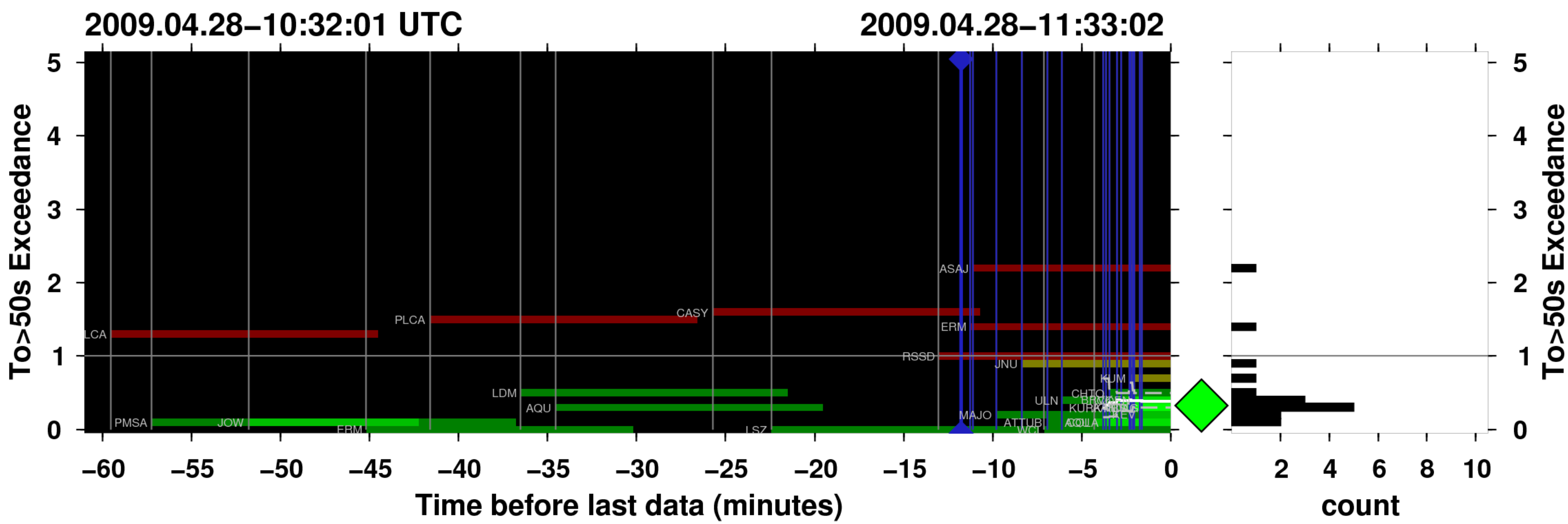
Tue Apr 28 11:30:05 UTC 2009



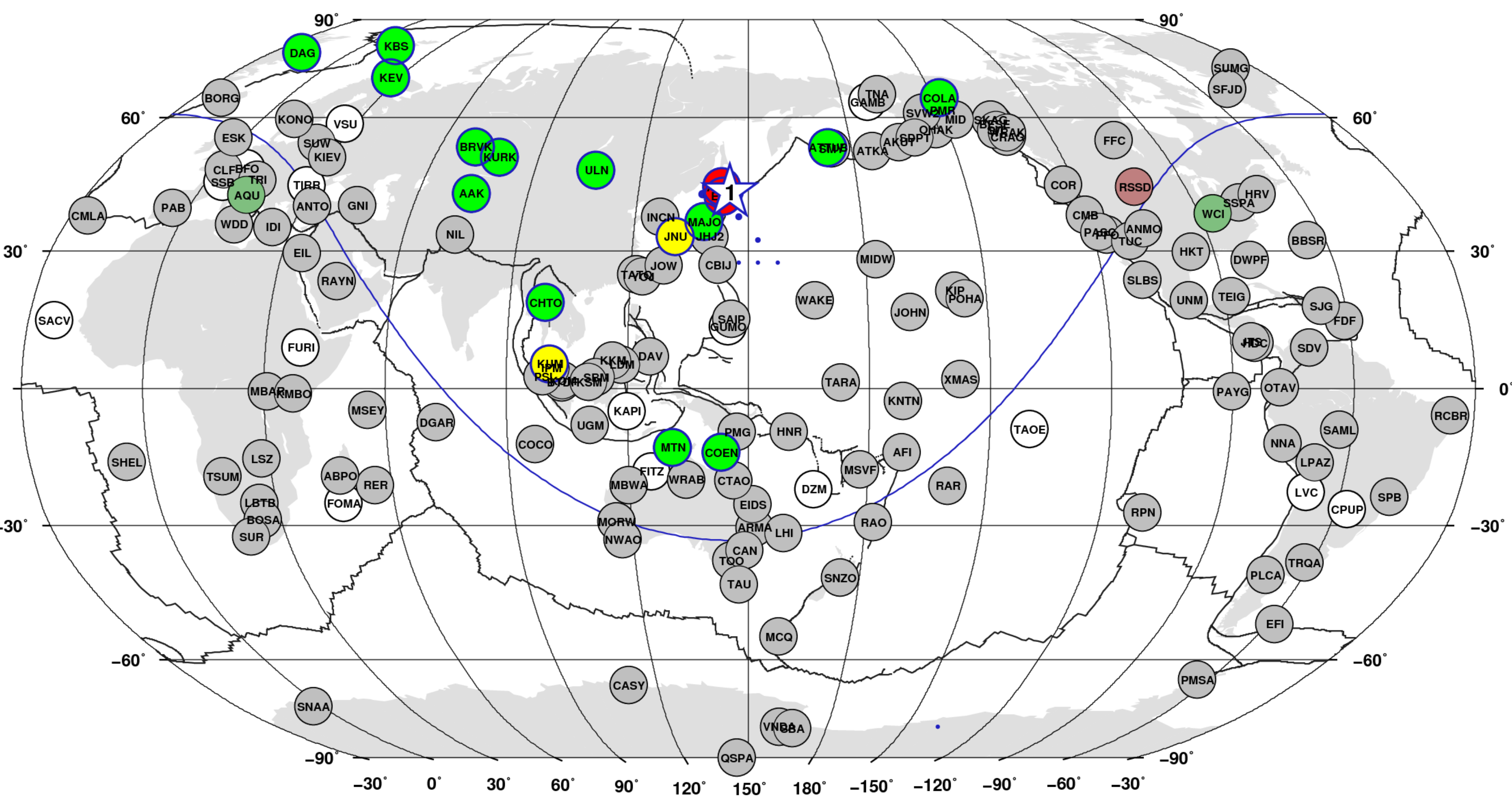
Tue Apr 28 11:31:10 UTC 2009



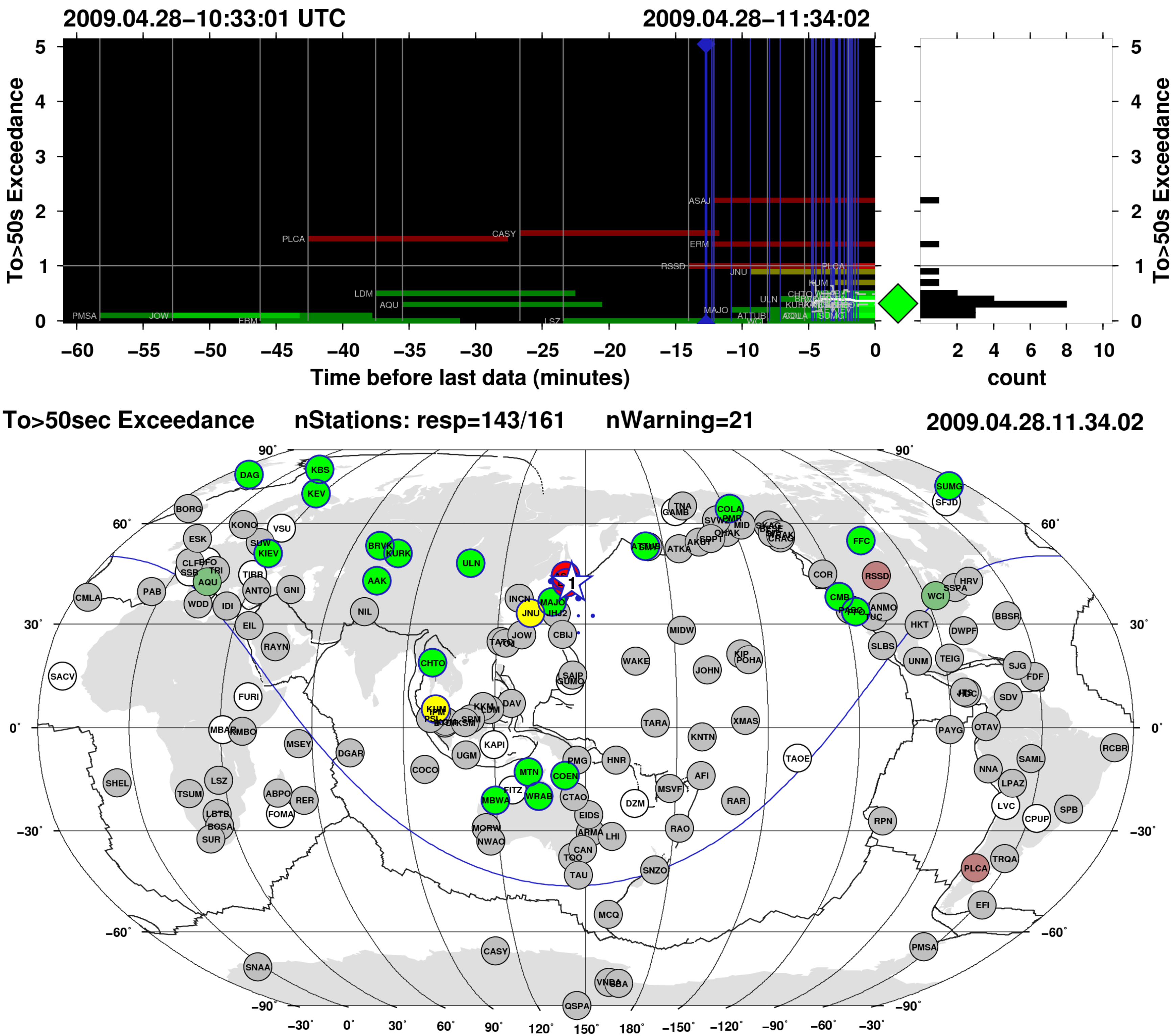
Tue Apr 28 11:32:10 UTC 2009



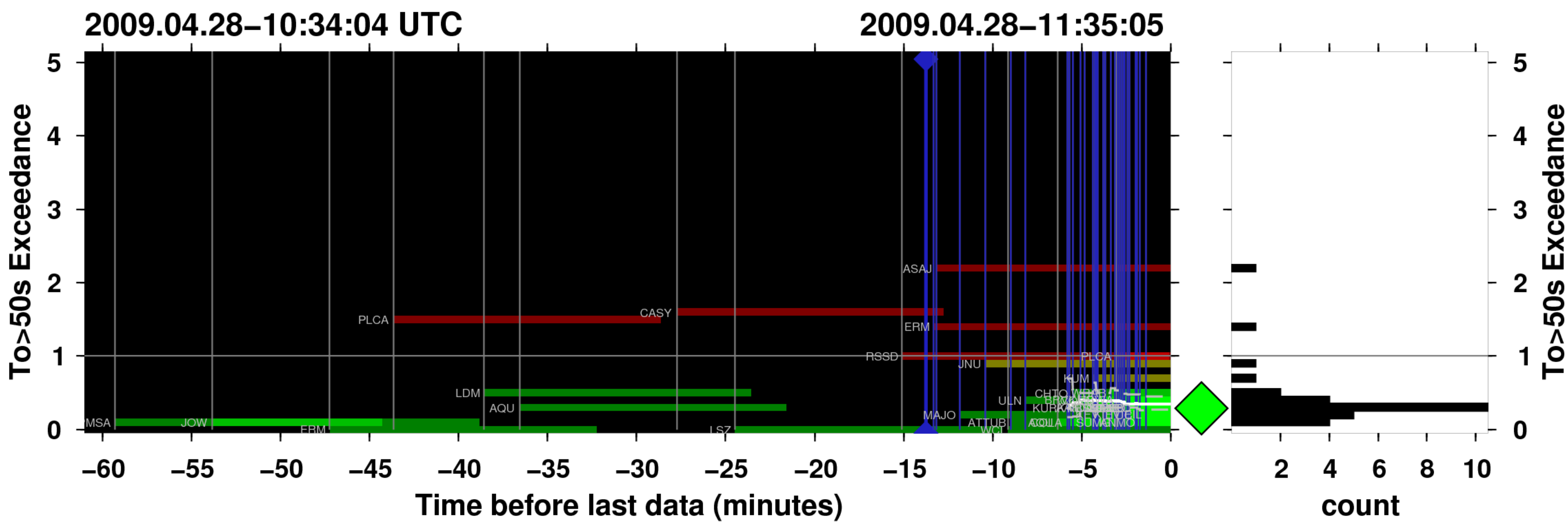
To>50sec Exceedance nStations: resp=145/161 nWarning=14 2009.04.28.11.33.02



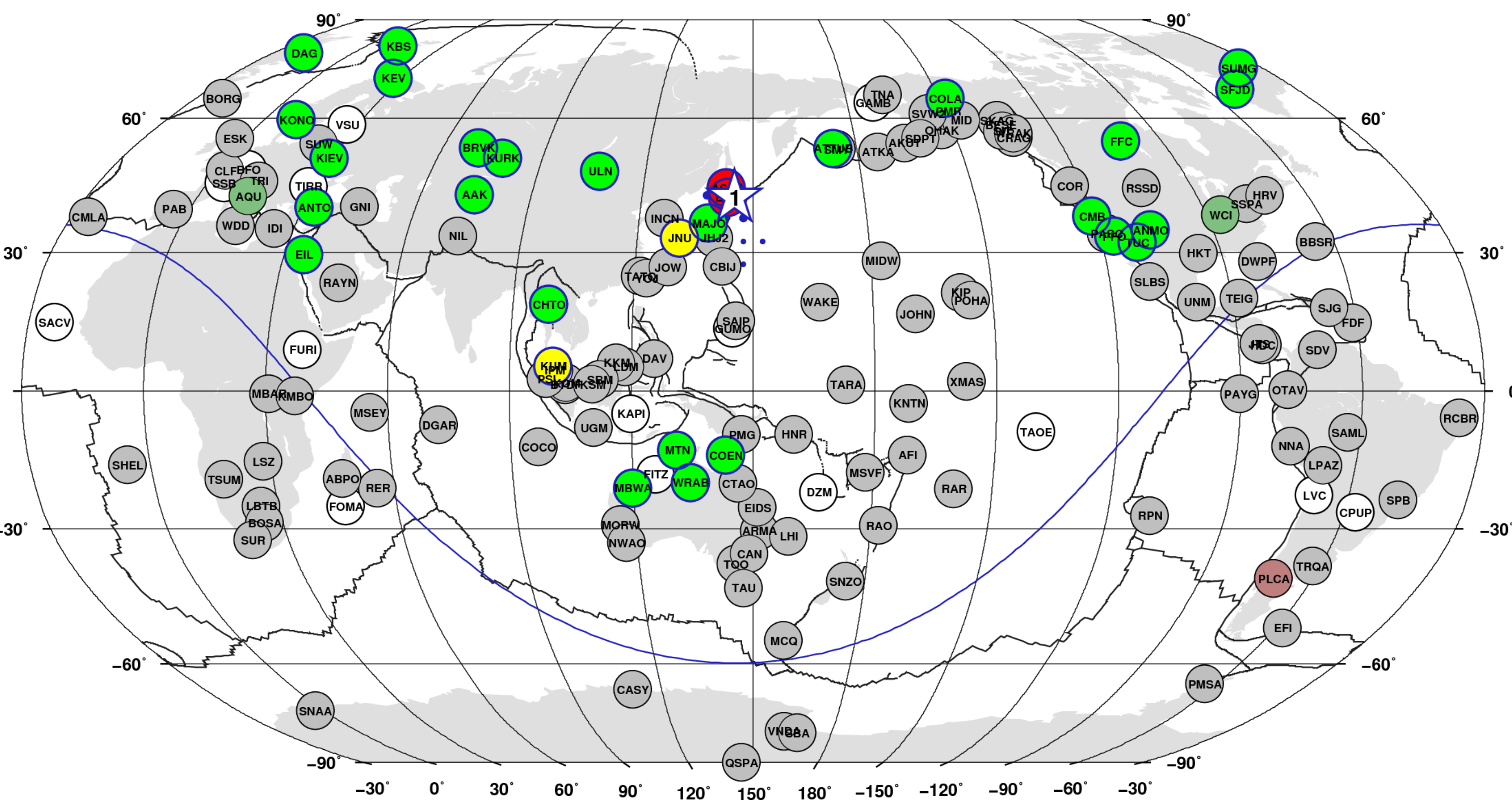
Tue Apr 28 11:33:10 UTC 2009



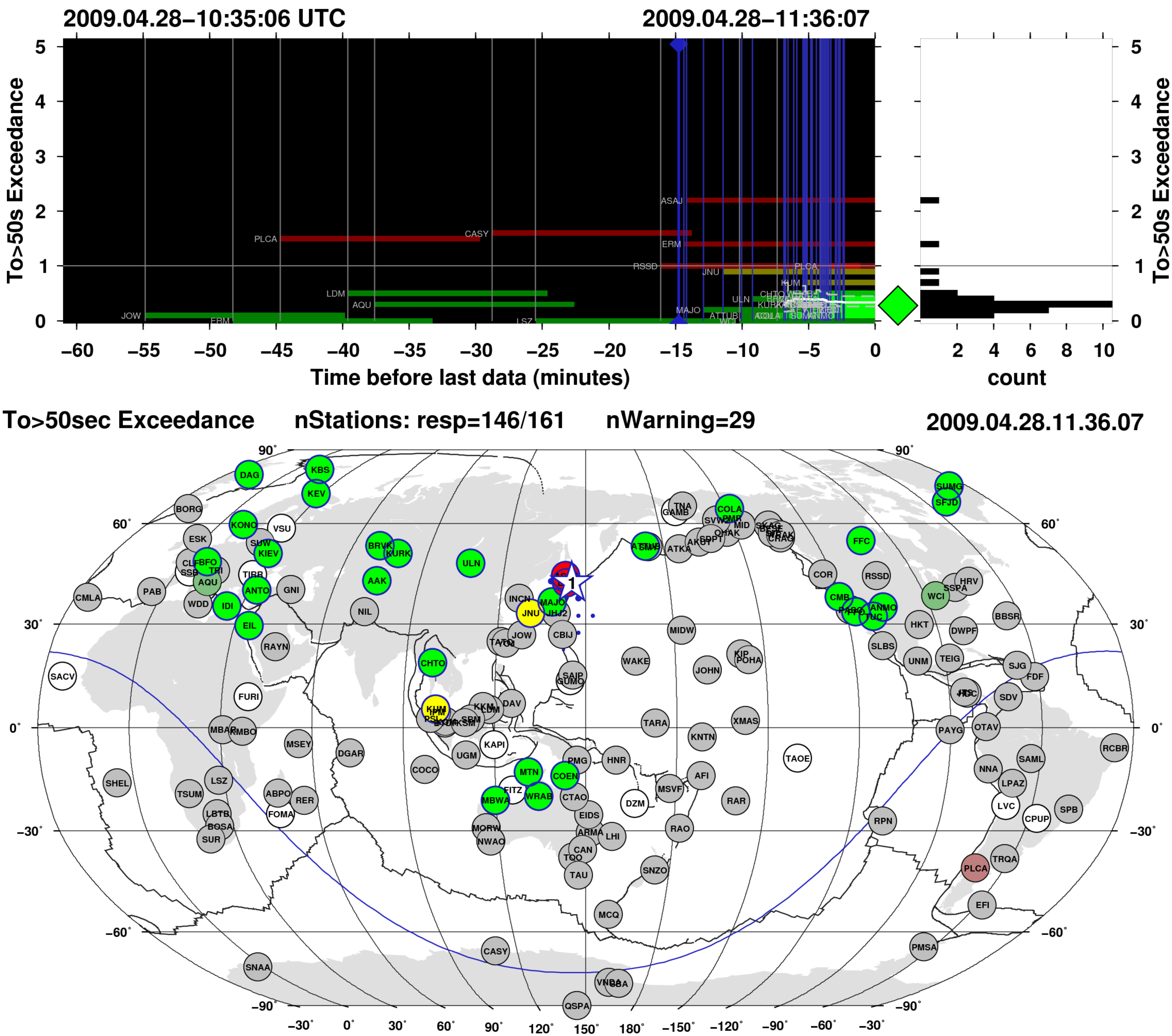
Tue Apr 28 11:34:10 UTC 2009



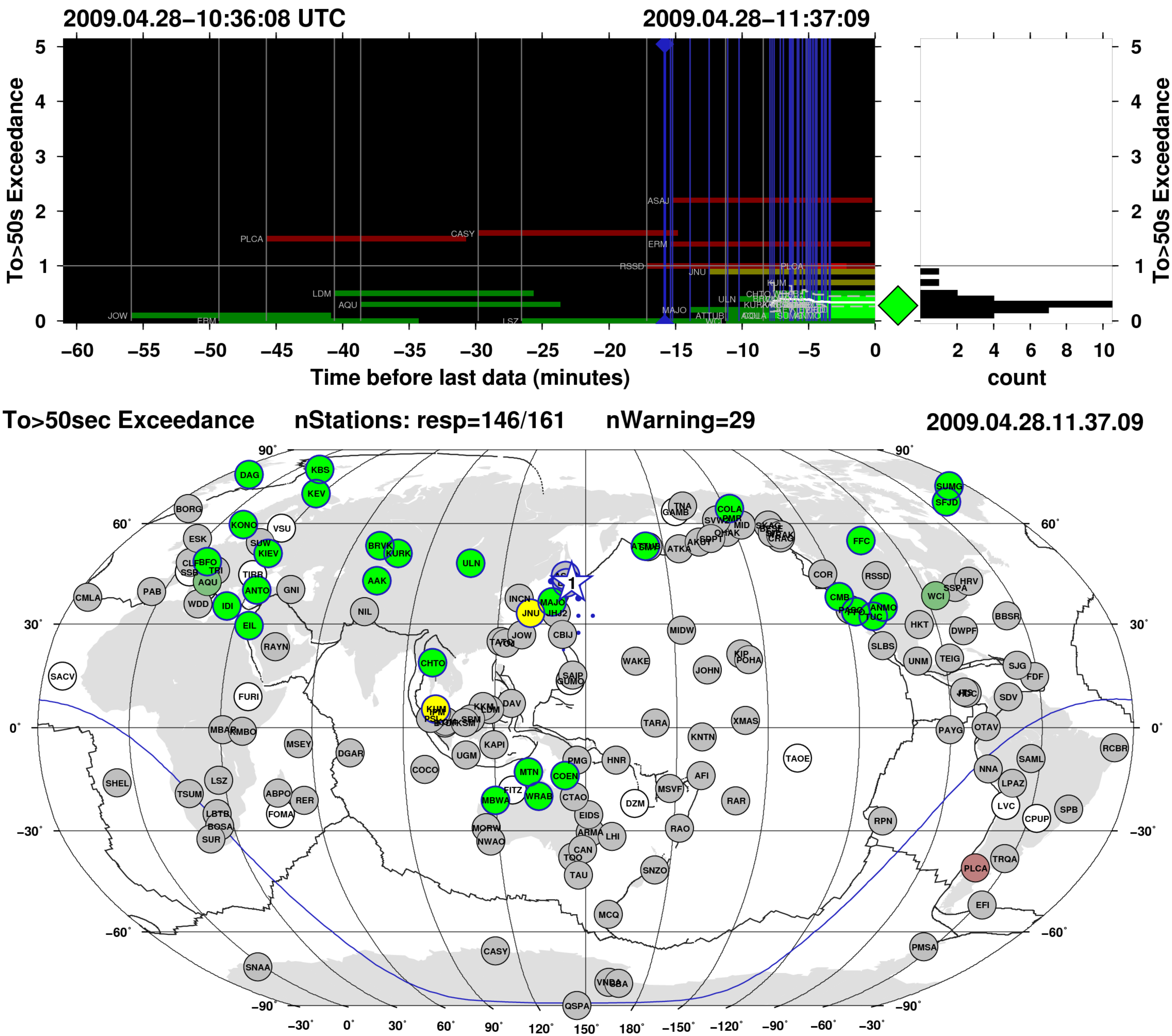
To>50sec Exceedance nStations: resp=144/161 nWarning=27 2009.04.28.11.35.05



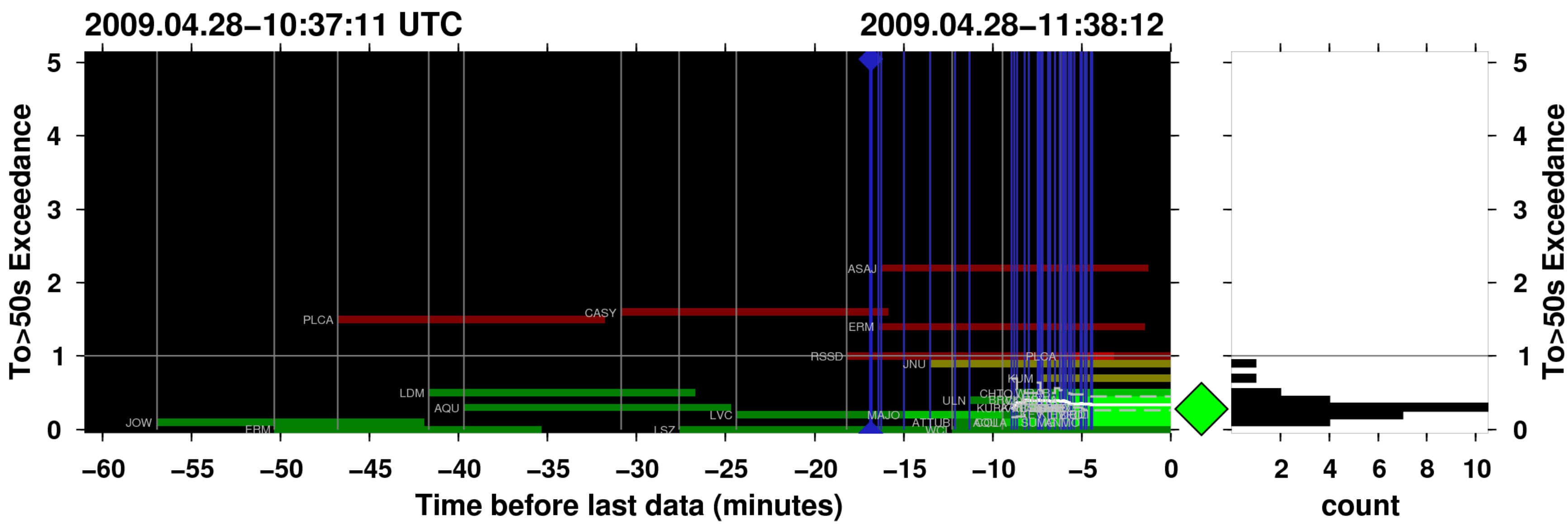
Tue Apr 28 11:35:11 UTC 2009



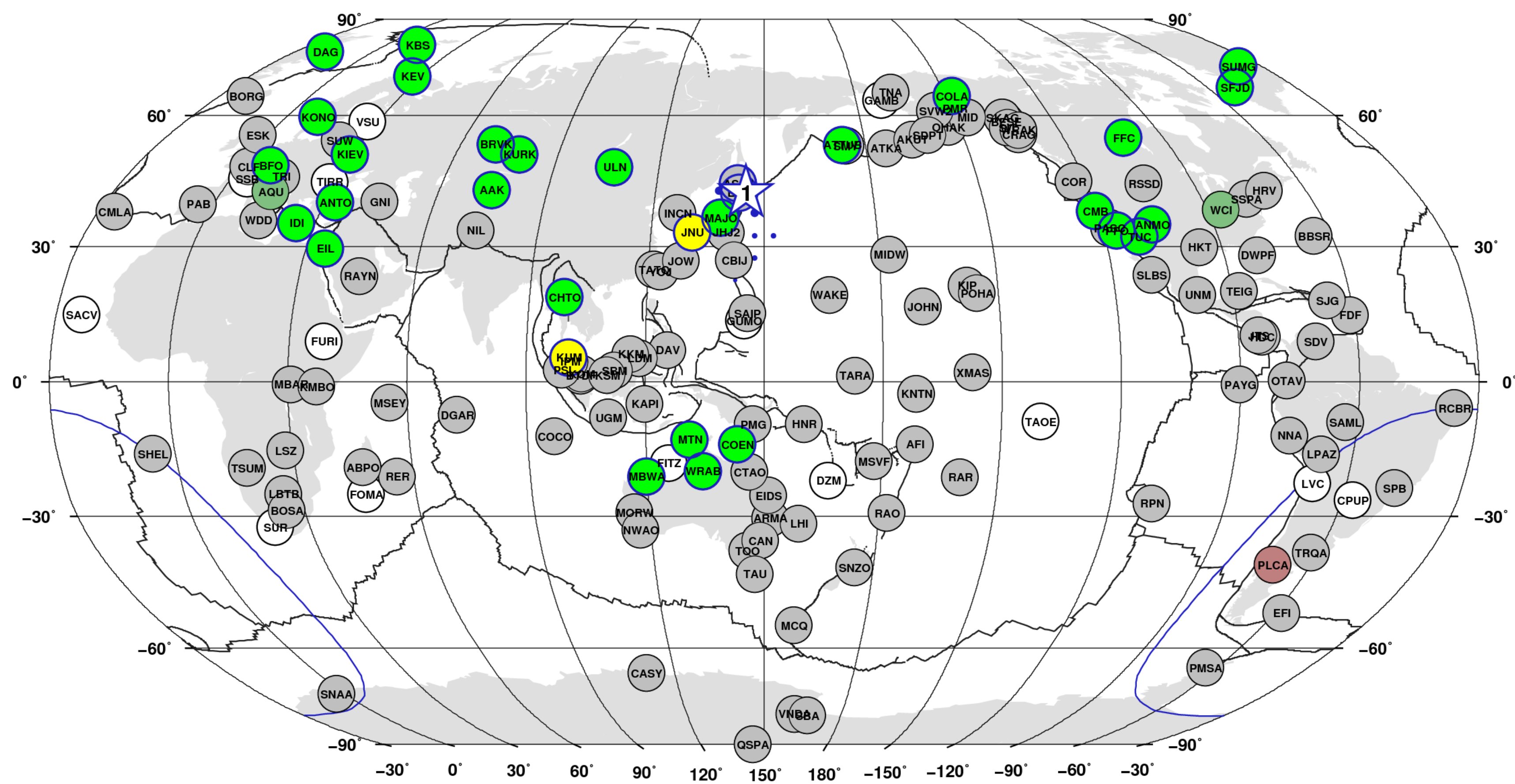
Tue Apr 28 11:36:13 UTC 2009



Tue Apr 28 11:37:16 UTC 2009

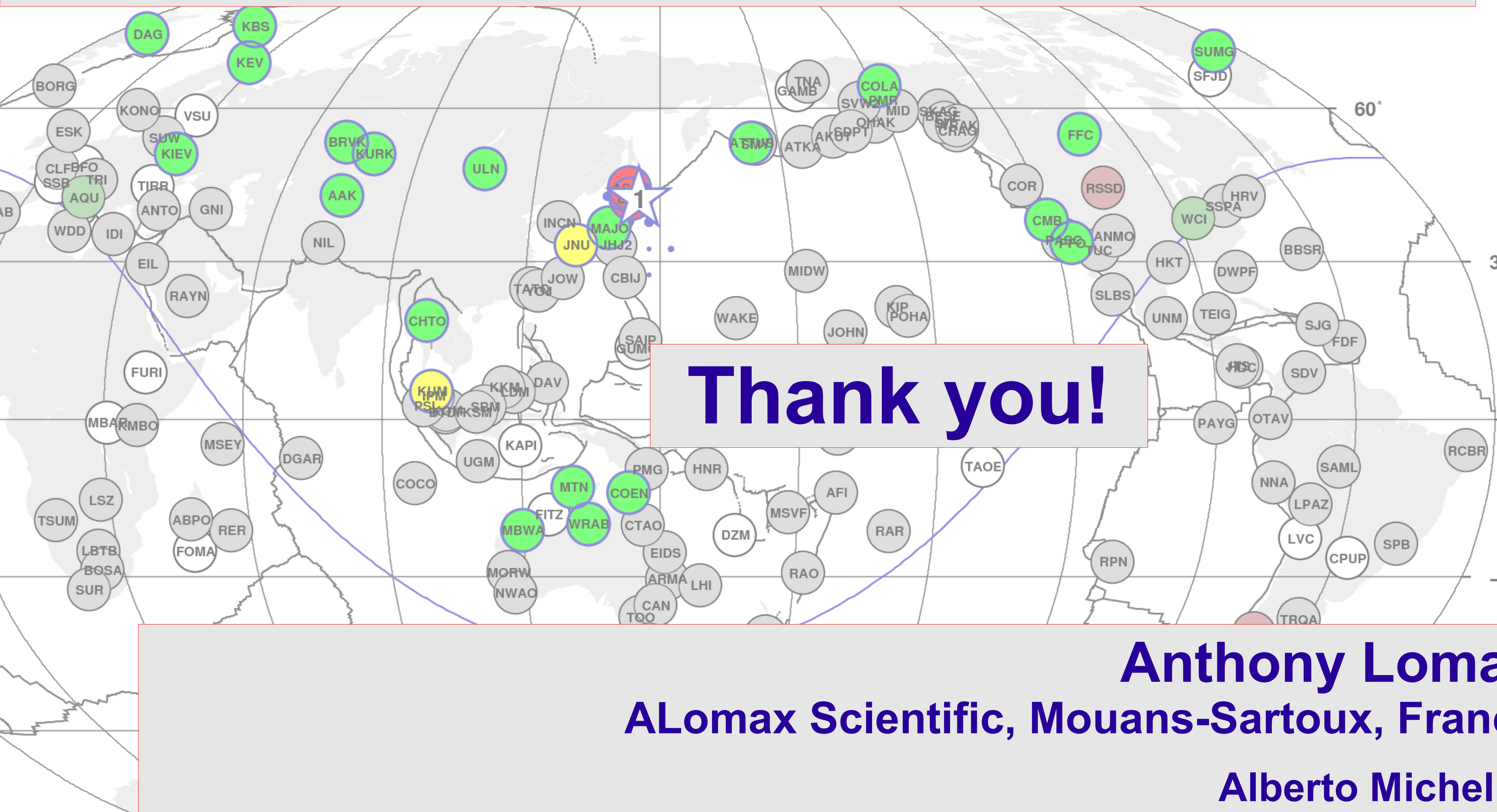


To>50sec Exceedance nStations: resp=146/161 nWarning=29 2009.04.28.11.38.12



Tue Apr 28 11:38:16 UTC 2009

Real-Time Earthquake Location



Thank you!

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Alberto Michelini
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References

- Lomax, A., A. Michelini, A. Curtis (2009), Earthquake Location, Nonlinear, in *Complexity In Earthquakes, Tsunamis And Volcanoes And Forecasting And Early Warning Of Their Hazards*, W.H.K. Lee, ed., Encyclopedia of Complexity and System Science, Springer, Heidelberg. EarthqkLoc-Direct-Search_v2.0.pdf

Allen, R.V. (1978), Automatic earthquake recognition and timing from single traces. *Bull. Seism. Soc. Am.*, **68**,1521-1531.

Allen, R.V. (1982), Automatic phase pickers: their present use and future prospects. *Bull. Seism. Soc. Am.*, **72**, S225-S242.

Bai C-Y and Kennett B.L.N. (2000), Automatic phase-picking and identification by full use of a single three-component broadband seismogram, *Bull. Seism. Soc. Am.*, **90**, 187-198.

Baer, M., and U. Kradolfer (1987), An automatic phase picker for local and teleseismic events. *Bull. Seism. Soc. Am.*, **77**, 1437-1445.

Cichowicz, A. (1993), An automatic s phase picker, *Bull. Seism. Soc. Am.*, **83**, 180-189.

Greenhalgh, S., I. M. Mason and B. Zhou (2005), An analytical treatment of single station triaxial seismic direction finding, *J. Geophys. Eng.*, **2**, 8–15, doi:10.1088/1742-2132/2/1/002.

Hendrick, N. and S. Hearn (1999), Polarisation Analysis: What is it? Why do you need it? How do you do it?, *Explor. Geophys*., **30**, 177-190.

.Johnson, C. E., A. Lindh, B. Hirshorn (1994), Robust regional phase association, U.S. Geol. Surv. Open-File Rept. 94-621.

Leonard, M. (2000), Comparison of Manual and Automatic Onset Time Picking, *Bull. Seism. Soc. Am.*, **90**, 1384-1390.

Lahr, J.C. (1984), Description of the weighted regression and quality estimation used in the earthquake location program hypoellipse, *U.S. Geological Survey Open-File Report* 84-766, http://jclahr.com/science/software/hypoellipse/of84-766.pdf.

Lahr, J.C. (1999), HYPOELLIPSE: A Computer Program for Determining Local Earthquake Hypocentral Parameters, Magnitude, and First-Motion Pattern (Y2K Compliant Version), *U.S. Geological Survey Open-File Report* 99-23, http://pubs.usgs.gov/of/1999/ofr-99-0023/.

Lomax, A. (2005), A Reanalysis of the Hypocentral Location and Related Observations for the Great 1906 California Earthquake, *Bull. Seism. Soc. Am.*, **91**, 861-877.

Lomax, A.J. and A. Michelini (1988), The use of spherical coordinates in the interpretation of seismograms, *Geophys. J. R. astr. Soc.*, **93**, 405-412.

Magotra, N., N.Ahmed, and E.Chael (1987), Seismic event detection and source location using single station (three-component) data, *Bull. Seism. Soc. Am.*, **77**, 958-971.

Montalbetti, J. F., and E. R. Kanasewich (1970), Enhancement of teleseismic body phases with a polarization filter, *Geophys. J. R. Astr. Soc*. **21**, 119–129.

Nguyen, D. T., R. J. Brown, D. C. Lawton, (1989), Polarization filter for multi-component seismic data, in *CREWES Research Report 1989*, chap. 7, 93-101, http://www.crewes.org/Reports/1989/1989-07.pdf.

Oye, V. and W.L. Ellsworth (2005), Orientation of Three-Component Geophones in the San Andreas Fault Observatory at Depth Pilot Hole, Parkfield, California, *Bull. Seism. Soc. Am.*, **95**, 751–758

Samson, J. C. (1983), The spectral matrix, eigenvalues, and principal components in the analysis of multichannel geophysical data, *Ann. Geophys*. **1**, 115–119.

Samson, J. C., and J. V. Olson (1980), Some comments on the descriptions of the polarization states of waves, *Geophys. J. R. Astr. Soc*. **61**, 115–130.

Satriano, C., A. Lomax and A. Zollo (2008), Real-time evolutionary earthquake location for seismic early warning, *Bull. Seism. Soc. Am.*, **98**, 1482-1494

Schimmel, M. and J. Gallart (2004), Degree of Polarization Filter for Frequency-Dependent Signal Enhancement Through Noise Suppression, *Bull. Seism. Soc. Am.*, **94**, 1016–1035.

Sleeman, R., and T. van Eck (1999), Robust automatic P-phase picking: an on-line implementation in the analysis of broadband seismogram recordings, *Phys. of the Earth and Planet. Int*, **113**, 265-275.

Tarantola, A. (1987), *Inverse problem theory: Methods for data fitting and model parameter estimation*, Elsevier, Amsterdam, 613p.

Tarantola, A. and Valette, B., (1982), Inverse problems = quest for information., *J. Geophys*., **50**, 159-170.

Vidale, J. E. (1986), Complex polarization analysis of particle motion, *Bull. Seism. Soc. Am*. **76**, 1393–1405.

Withers, M., R. Aster, C. Young, J. Beiriger, M. Harris, S. Moore and J. Trujillo (1998), A comparison of select trigger algorithms for automated global seismic phase and event detection, *Bull. Seism. Soc. Am.*, **88**, 95–106.