Monitoring induced seismicity with a single station combining CWI with DGS

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Coda Wave Interferometry (CWI)

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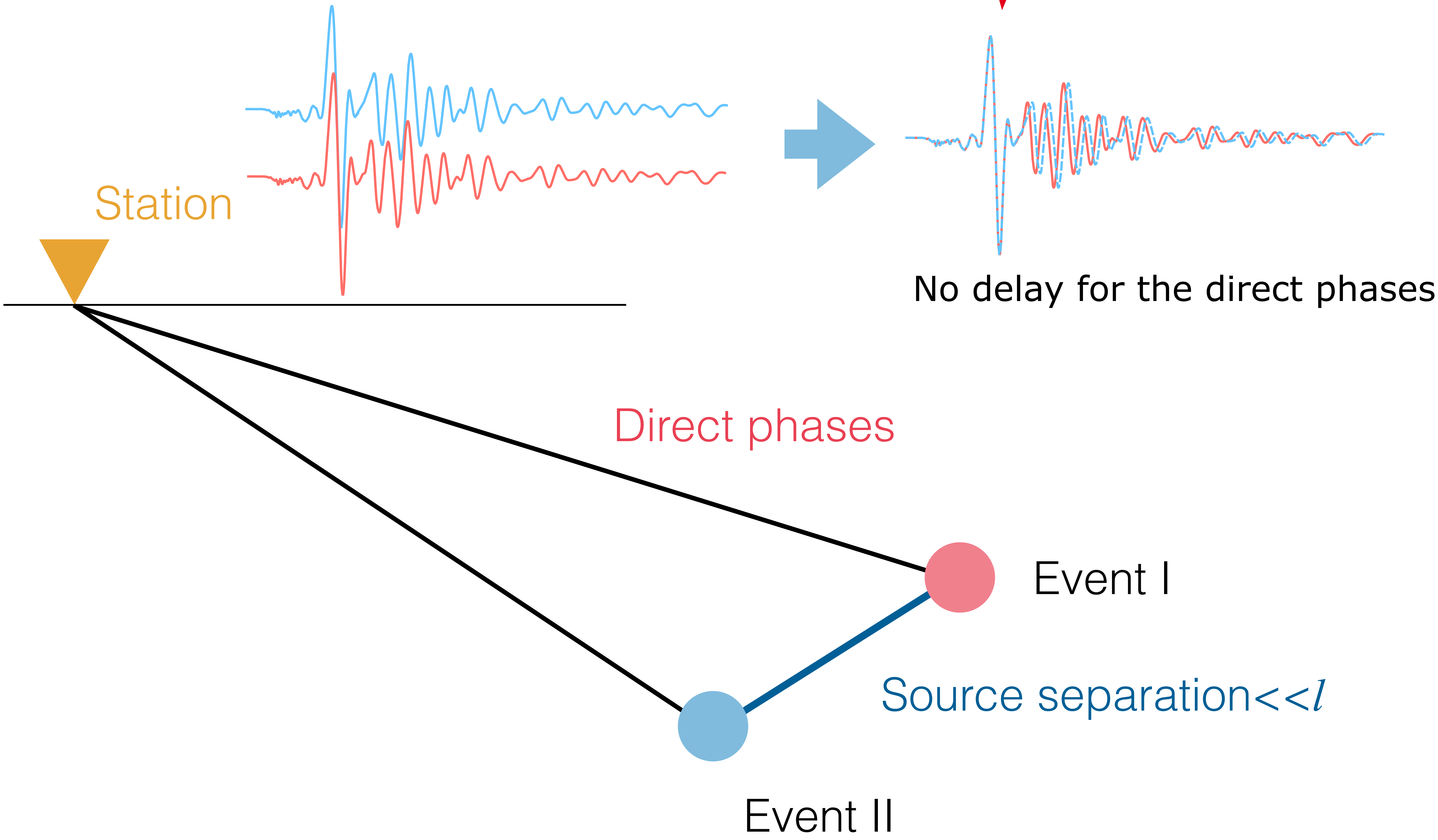
Coda Wave Interferometry (CWI) is a technique that exploits the change in coda waves between similar seismic events (Snieder et al. 2006).

It can be used to:
Monitor spatio-temporal changes in the medium (Snieder et al. 2002)

Estimate the inter-event distance between two seismic events (Snieder and Vrijlandt 2005, Snieder et al. 2006, Zhao et al. 2017)

It can be used if we satisfy three main conditions
Very similar source mechanism
No changes in the medium
Interevent distance << than the average source-station distance

Direct and Scattered Waves



Direct and Scattered Waves

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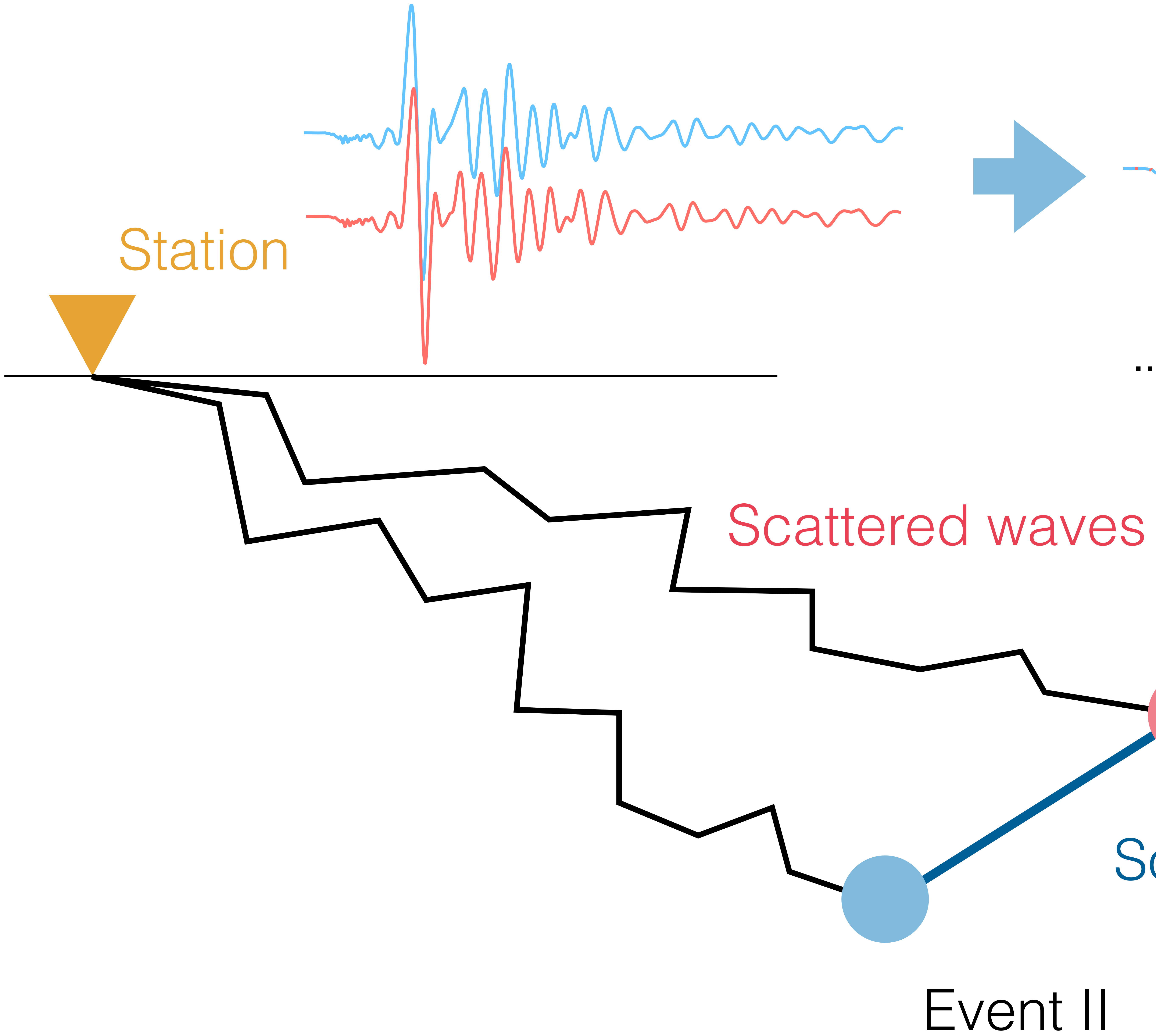

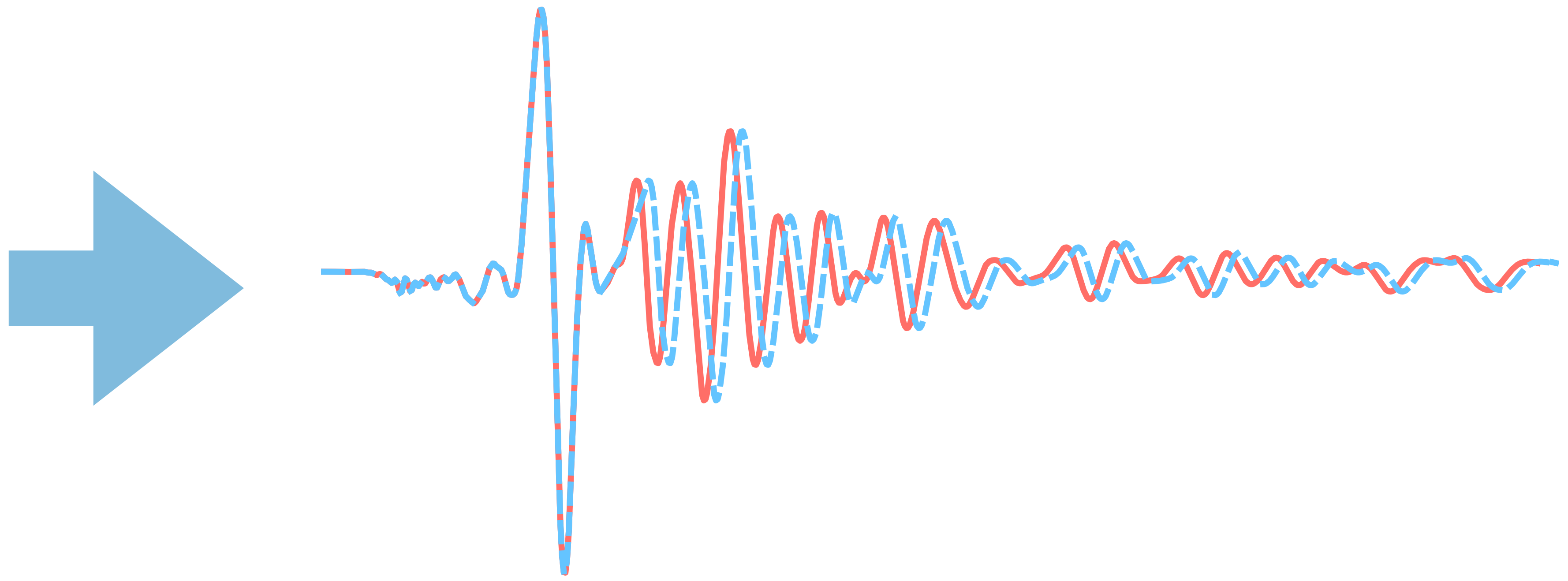

… but we can observe delay in the coda

Solving a Distance Geometry Problem

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- **Using CWI we obtain the inter-event distance for a cluster of earthquakes, but to locate them we need to solve a Distance Geometry Problem.**

- **Distance geometry is the characterization and study of sets of points based *only* on given values of the distances between member pairs.**

- **The Distance Geometry Problem (DGP) is the one of finding the coordinates of a set of points by using the distances between some pairs of such points.**

- **Combining the Coda Wave Interferometry method with a distance geometry algorithm we are able to locate seismic events using only a single station**

From Biochemistry to Seismology

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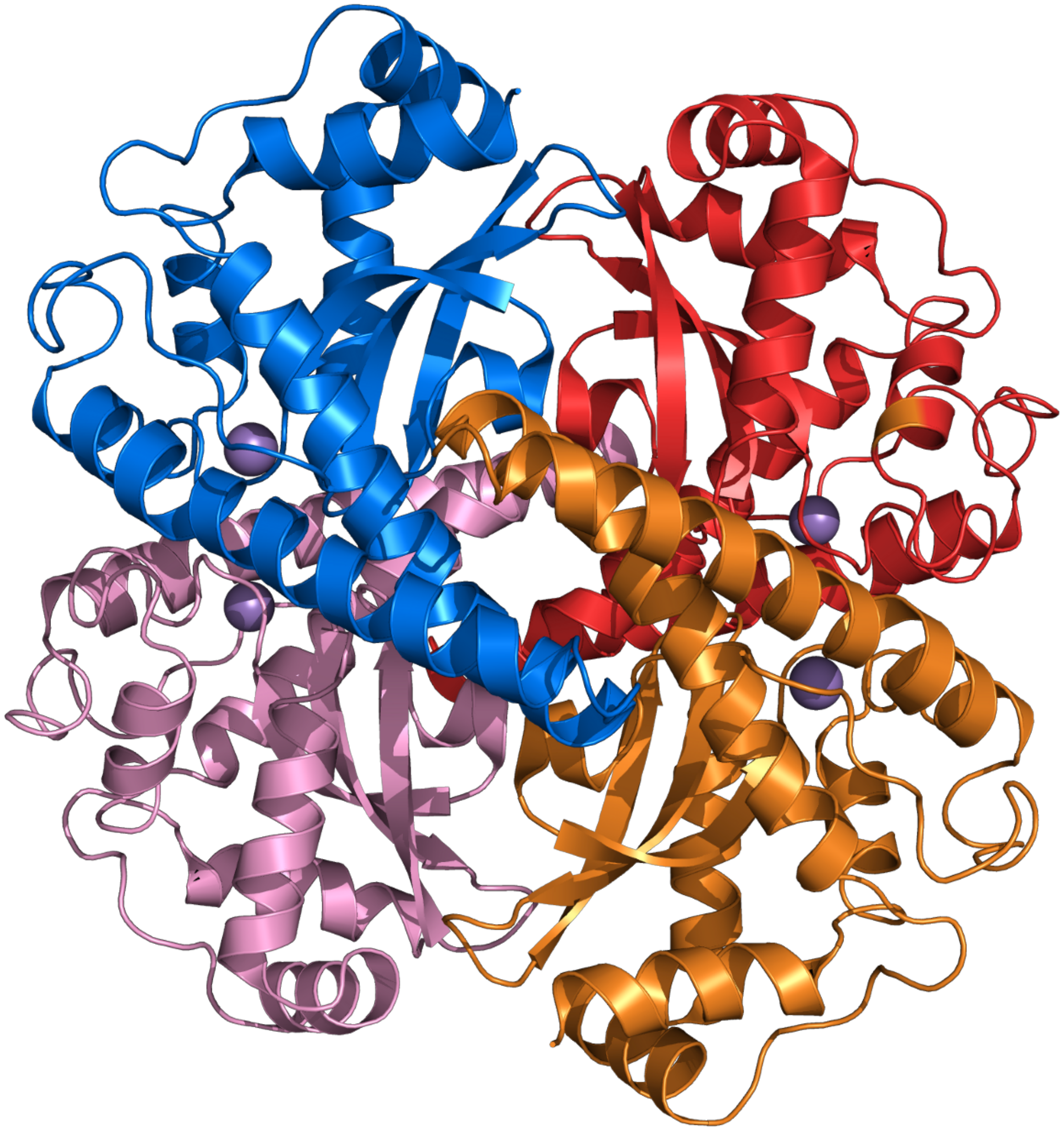


To locate earthquakes we modified a technique used in Biochemistry to determine the molecular structure of proteins.

These techniques are based on the iterative solution of linear systems and have been applied to determine the structure of complex proteins.

References:

A linear-time algorithm for solving the molecular distance geometry problem with exact inter-atomic distances (Dong and Wu 2002)

Solving the molecular distance geometry problem with inaccurate distance data (Souza et al 2013)

Location approach (2D example)

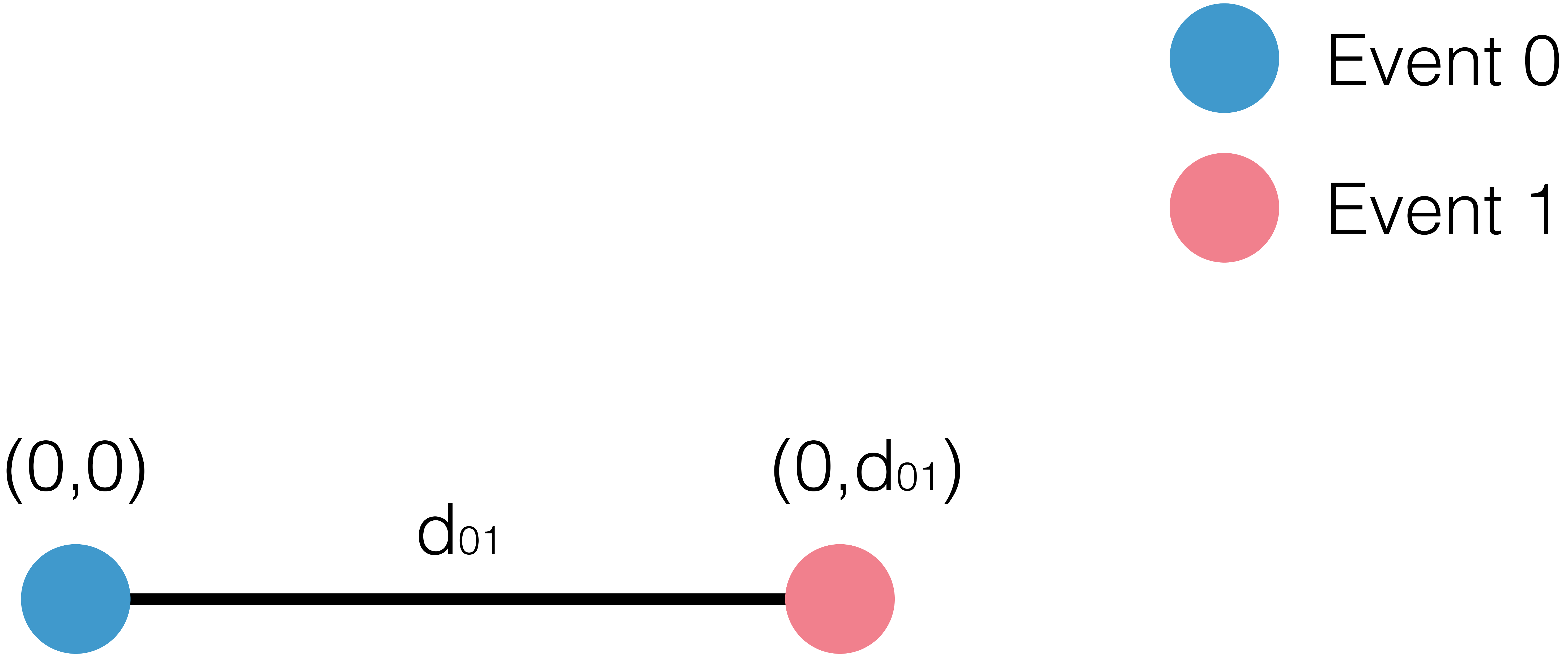
First step: Setting up the reference frame (Relative reference frame)

For the construction of the reference frame we use the events that show high correlation (typically >0.9) with the largest number of events

Location approach (2D example)

First step: Setting up the reference frame (Relative reference frame)

For the construction of the reference frame we take the events showing high correlation with the largest number of events



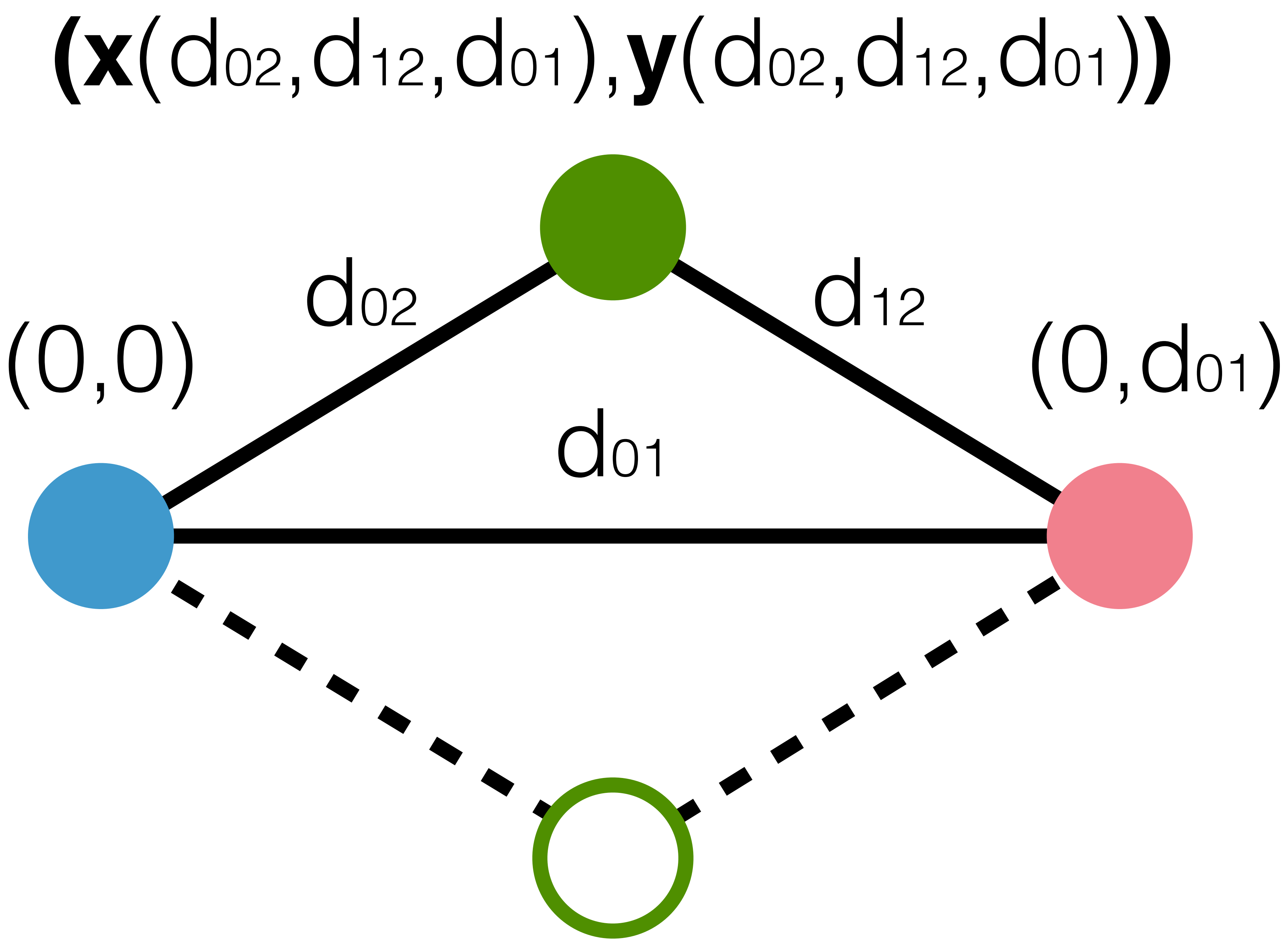
Event 1 and Event 0 are separated by a distance of d01 (obtained using CWI)

These two event form a reference axis (relative).

Location approach (2D example)

First step: Setting up the reference frame (Relative reference frame)

We arbitrarily set the Event 2
below or above or reference axis



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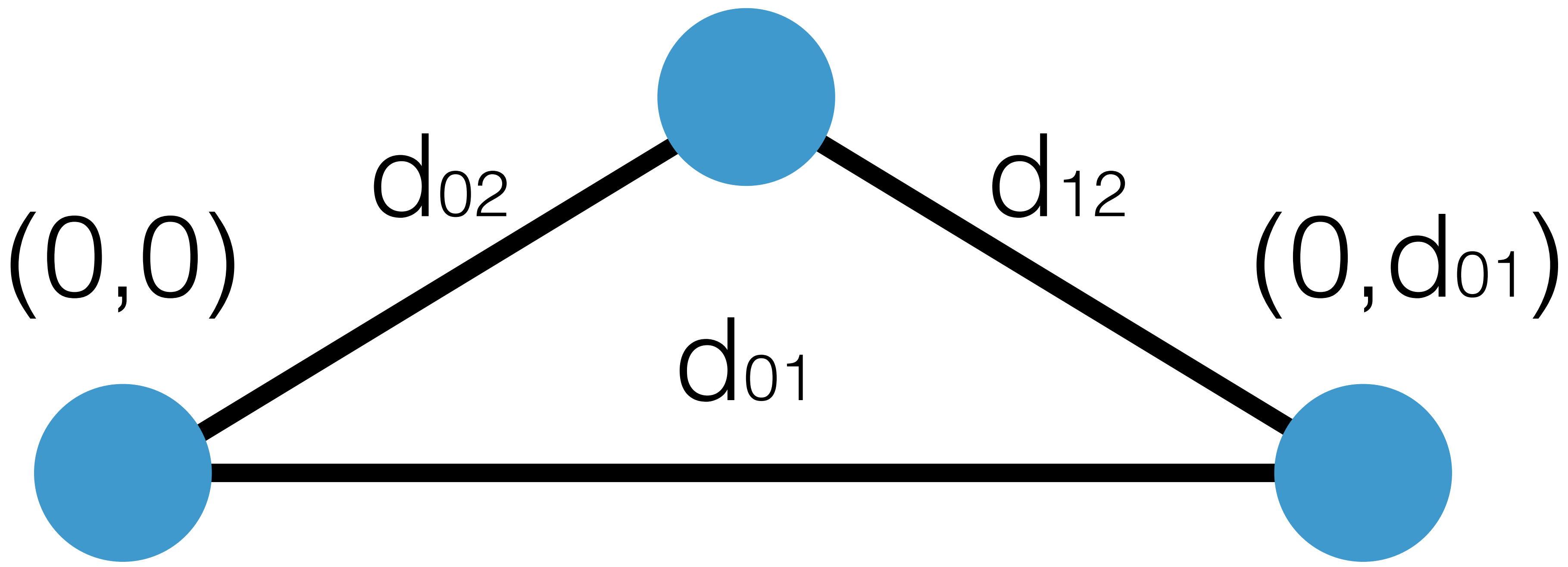
First step: Setting up the reference frame (Relative reference frame)

The reference frame is now completed

$(\mathbf{x}(d_{02},d_{12},d_{01}),\mathbf{y}(d_{02},d_{12},d_{01}))$



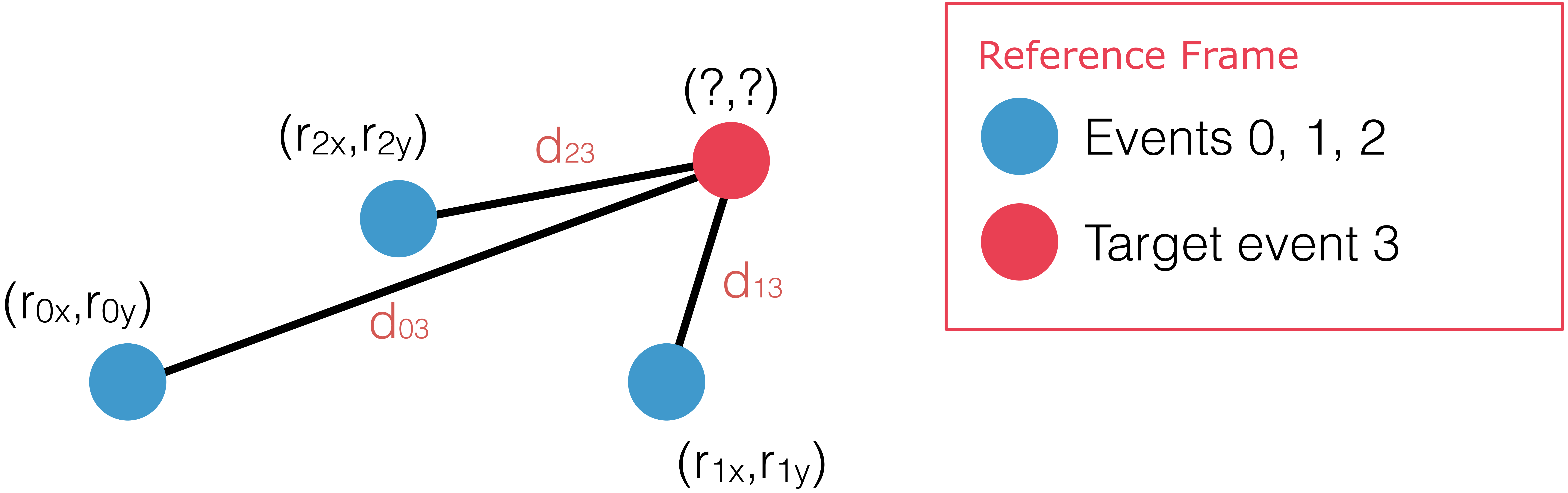
Reference Frame

Events 0, 1, 2

In two-dimensional space, if we know the distances among three events, we can find the coordinates for the event by solving a simple algebraic equation.

Location approach (2D example)

Second step: location of the remaining events



If the three events are not in the same line, the coordinates for any of the remaining events can then be determined uniquely with its distances to the three events

Location approach (2D example)

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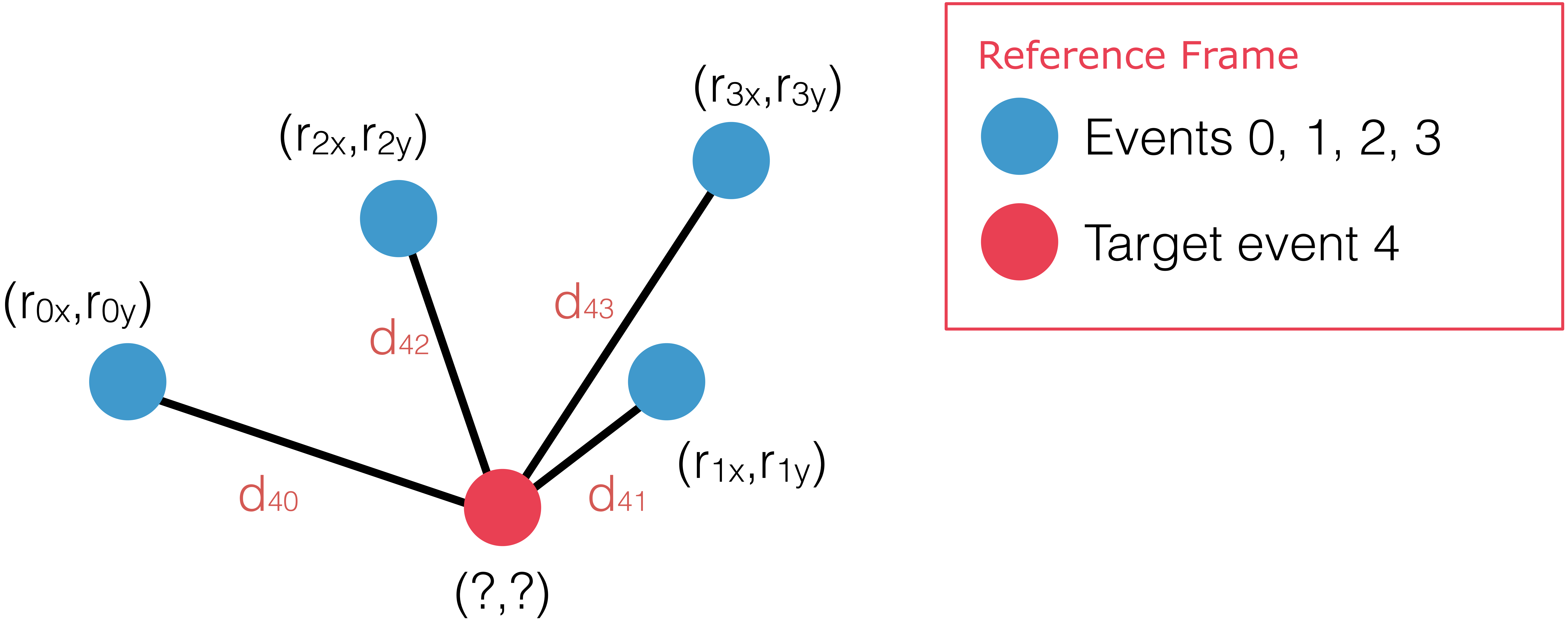
Second step: location of the remaining events

Previously located events contribute the the location of the new ones



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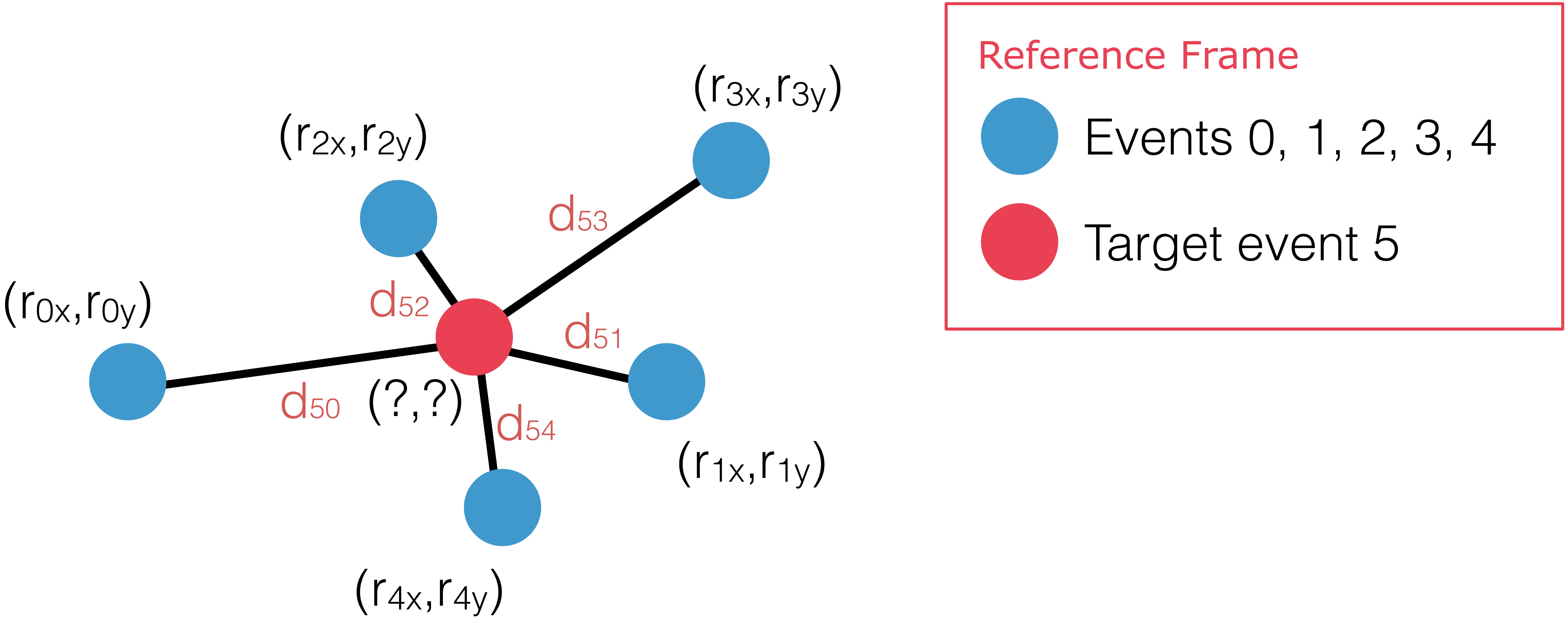

Location approach (2D example)

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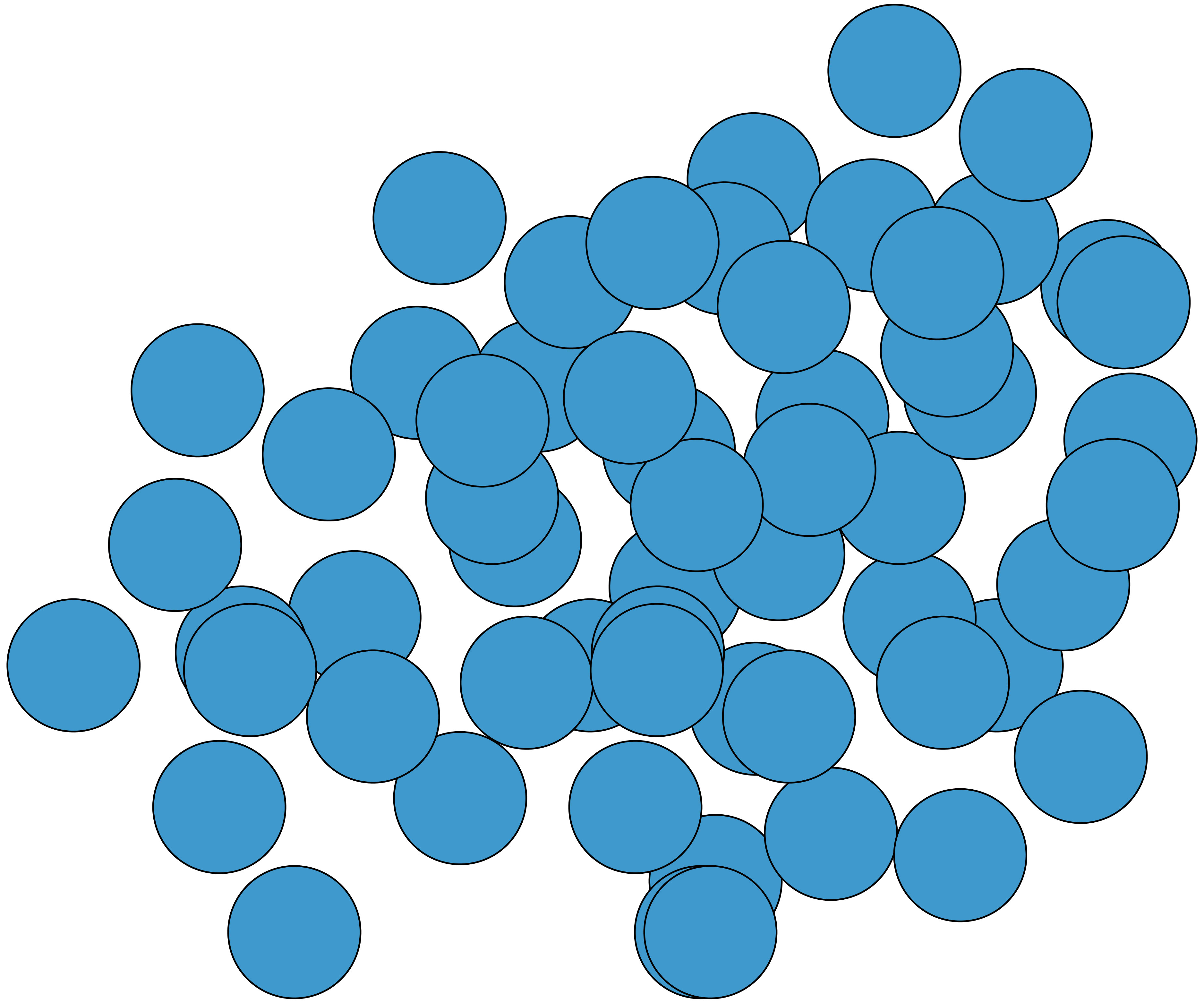
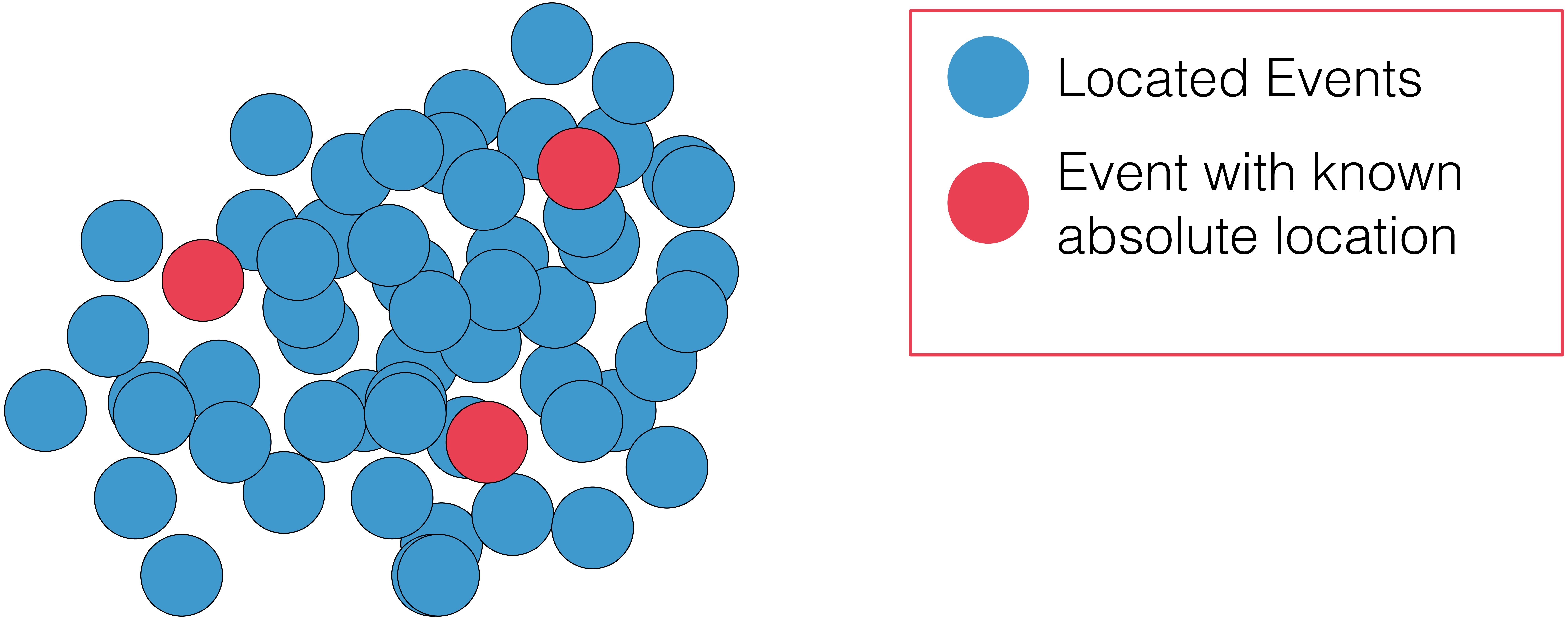


Located Events

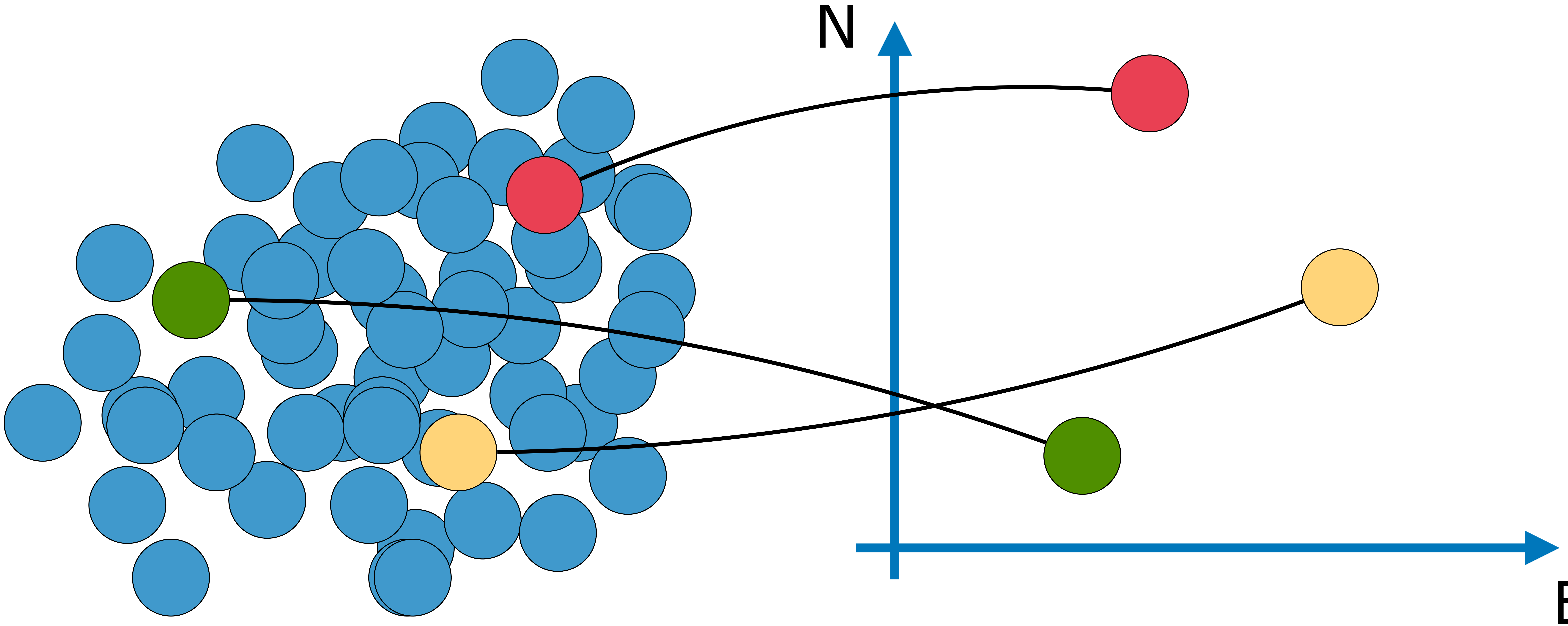
Location approach (2D example)

Third step: finding events which have absolute locations, or find event that is possible to locate with an absolute location method

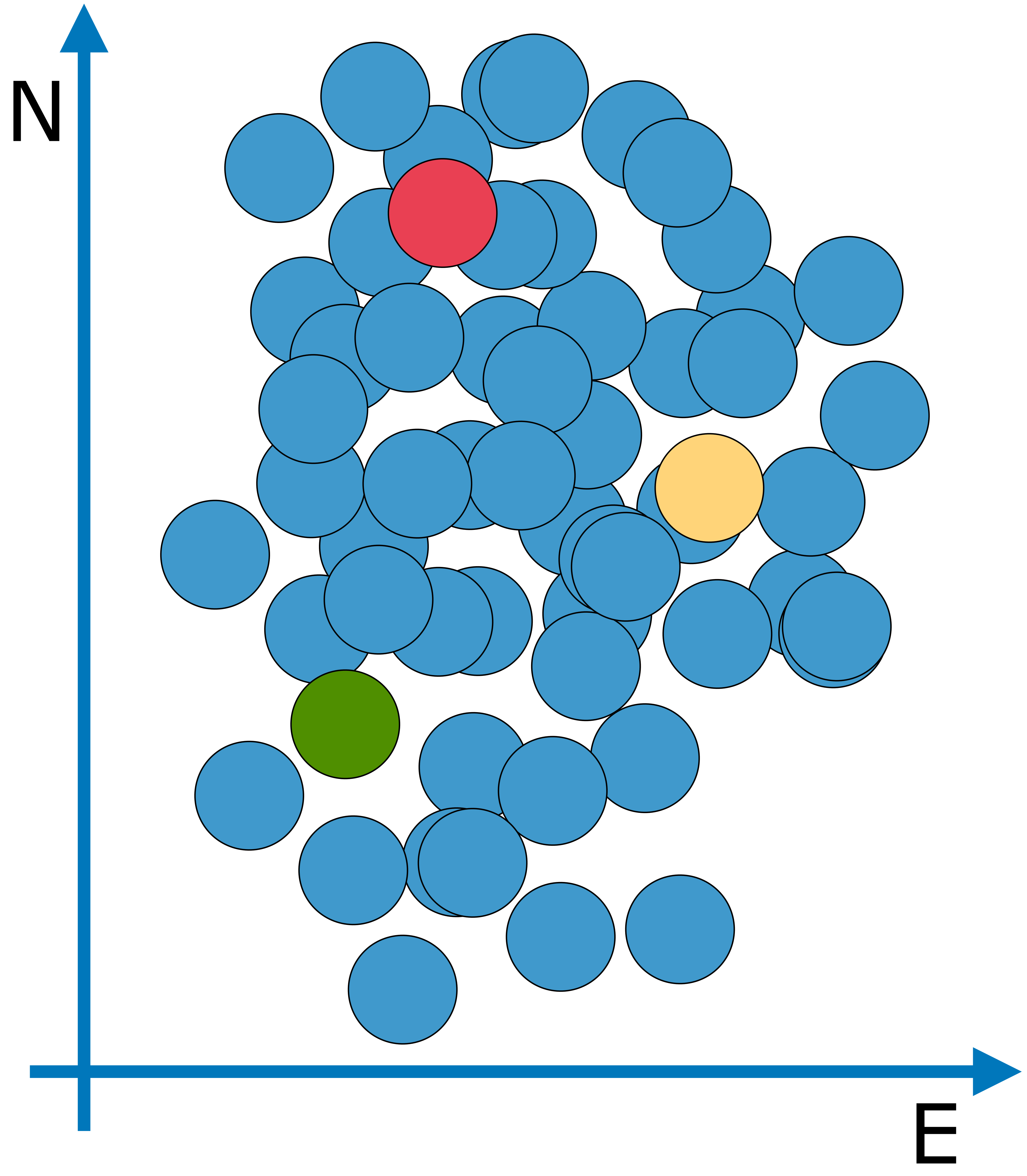


Location approach (2D example)

Final step: Find an absolute reference system using the events for which we know the absolute location



Location approach (2D example)



Final step: Fix the entire seismicity cloud to an absolute reference system

Noe we should have our locations….
…. In theory :)

Let us see if it works in practice….

The Castor Induced Seismic Sequence

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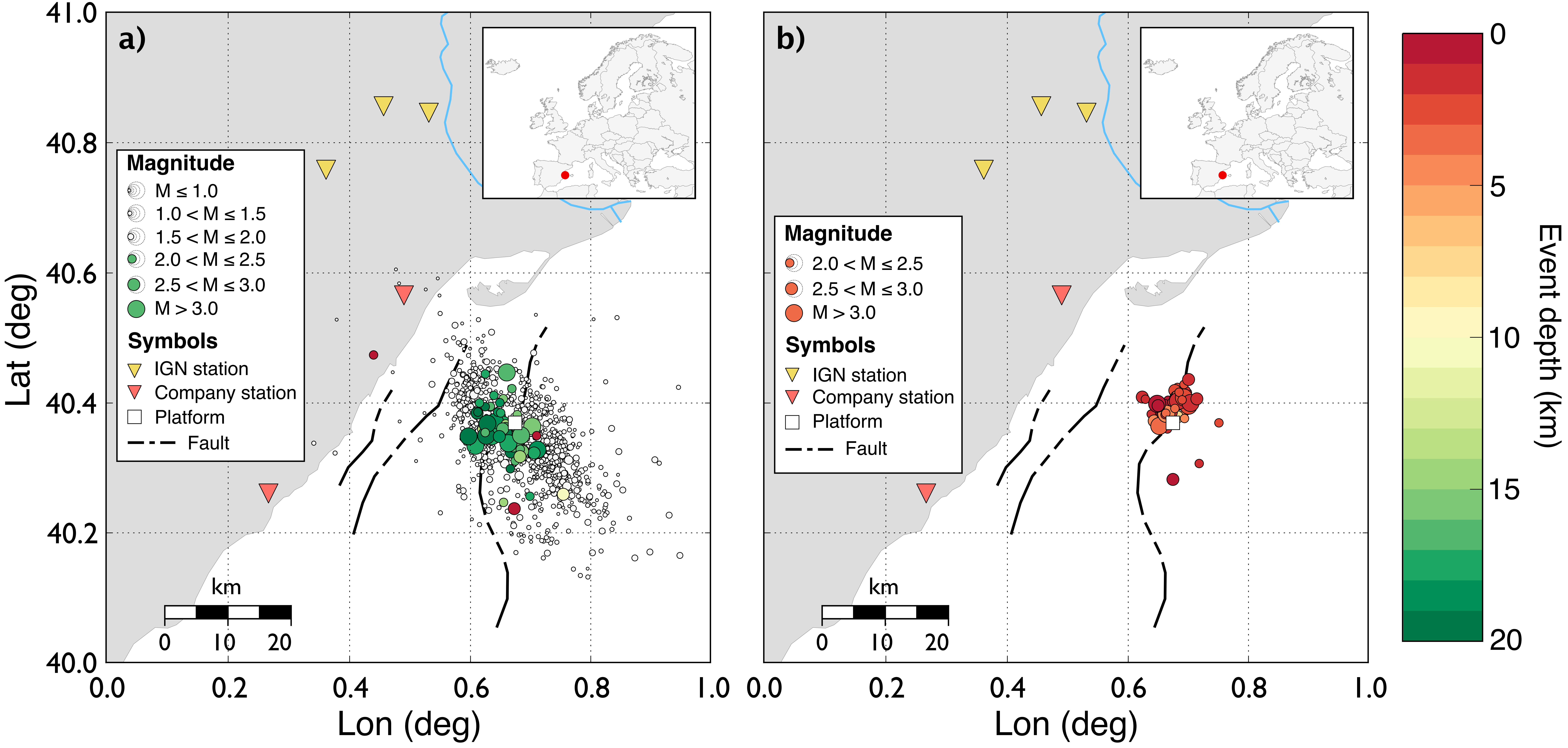
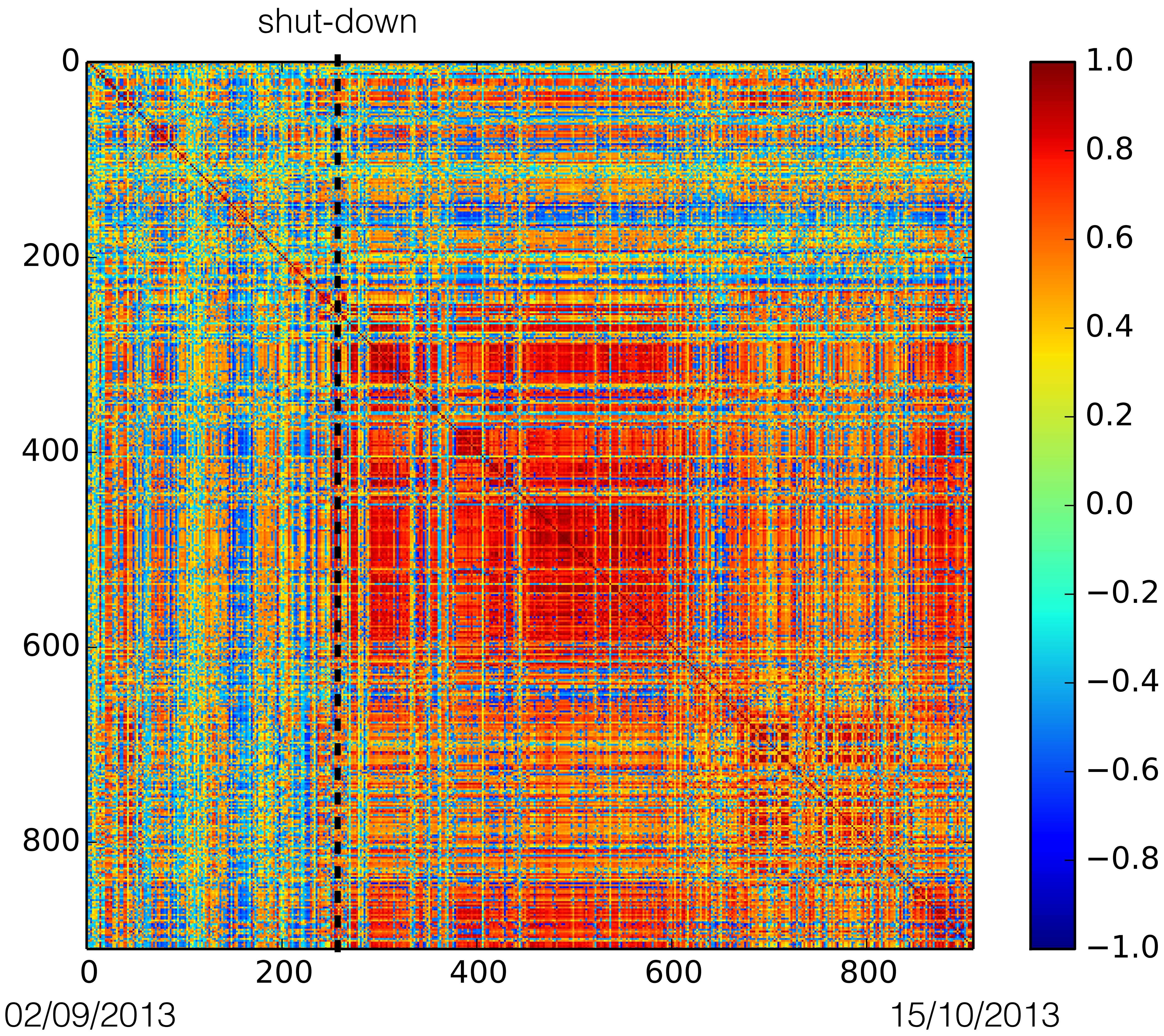


Waveform crosscorrelation



Waveform cross-correlation results

Events are sorted chronologically

Events with 0>Ml>2

Similarity matrices show waveform similarity for events couple, according to color table: red denotes similar traces, blue opposite traces (similar waveform, with opposite sign), green colors poor similarity. 4

We extracted all event showing a cross-correlation value higher than 0.9 with at least 4 other events

Total ~490 events

(Grigoli et al, in prep.)

Similarity between waveforms

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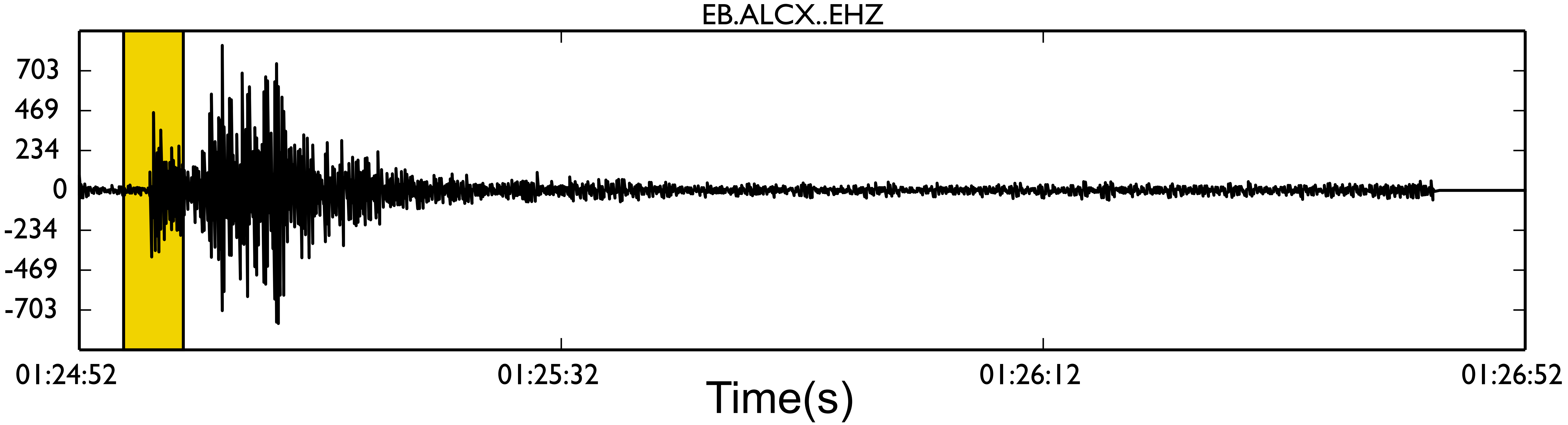
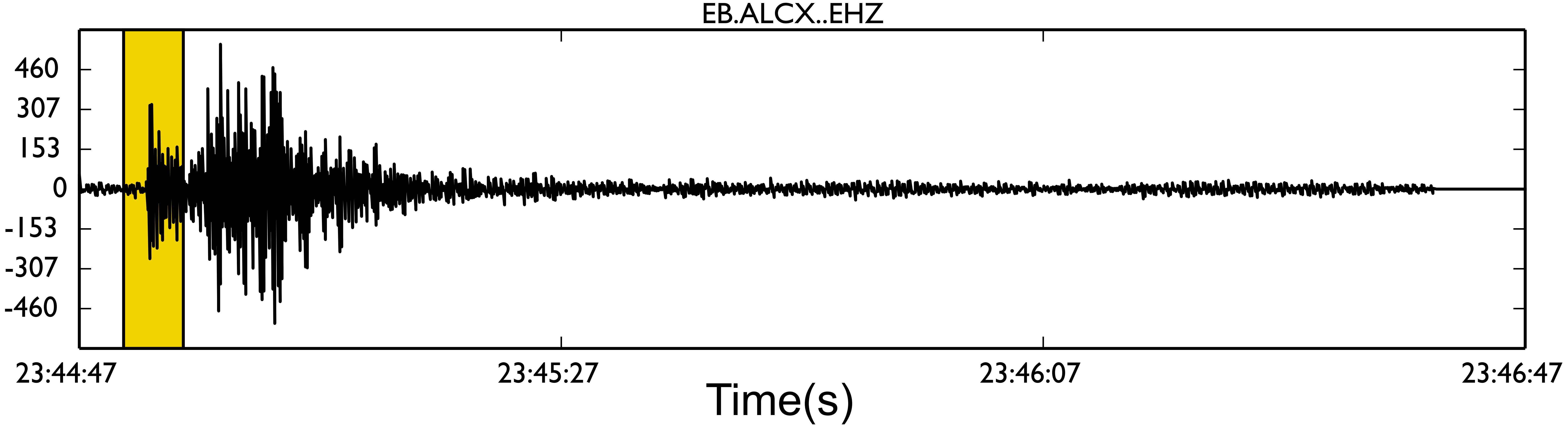
a) 2013-09-29T01:24:52Z - 2013-09-29T01:26:52Z

XCORR=0.93



Ml=1.1

b) 2013-09-29T23:44:47Z - 2013-09-29T23:46:47Z



Ml=1.0

Similarity between waveforms

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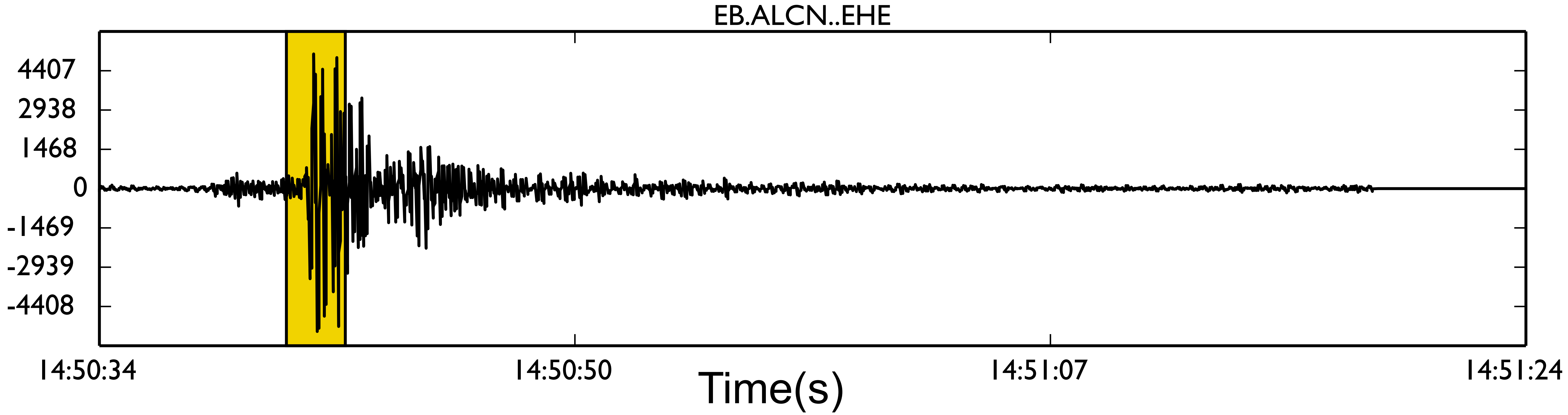
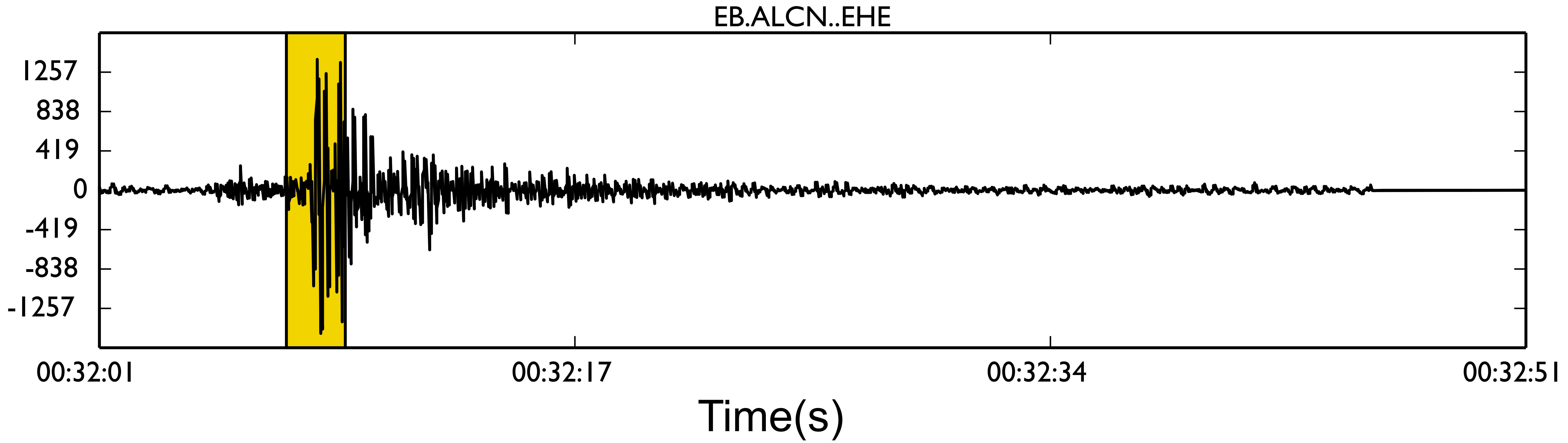
a) 2013-09-18T14:50:34Z - 2013-09-18T14:51:24Z

XCORR=0.95



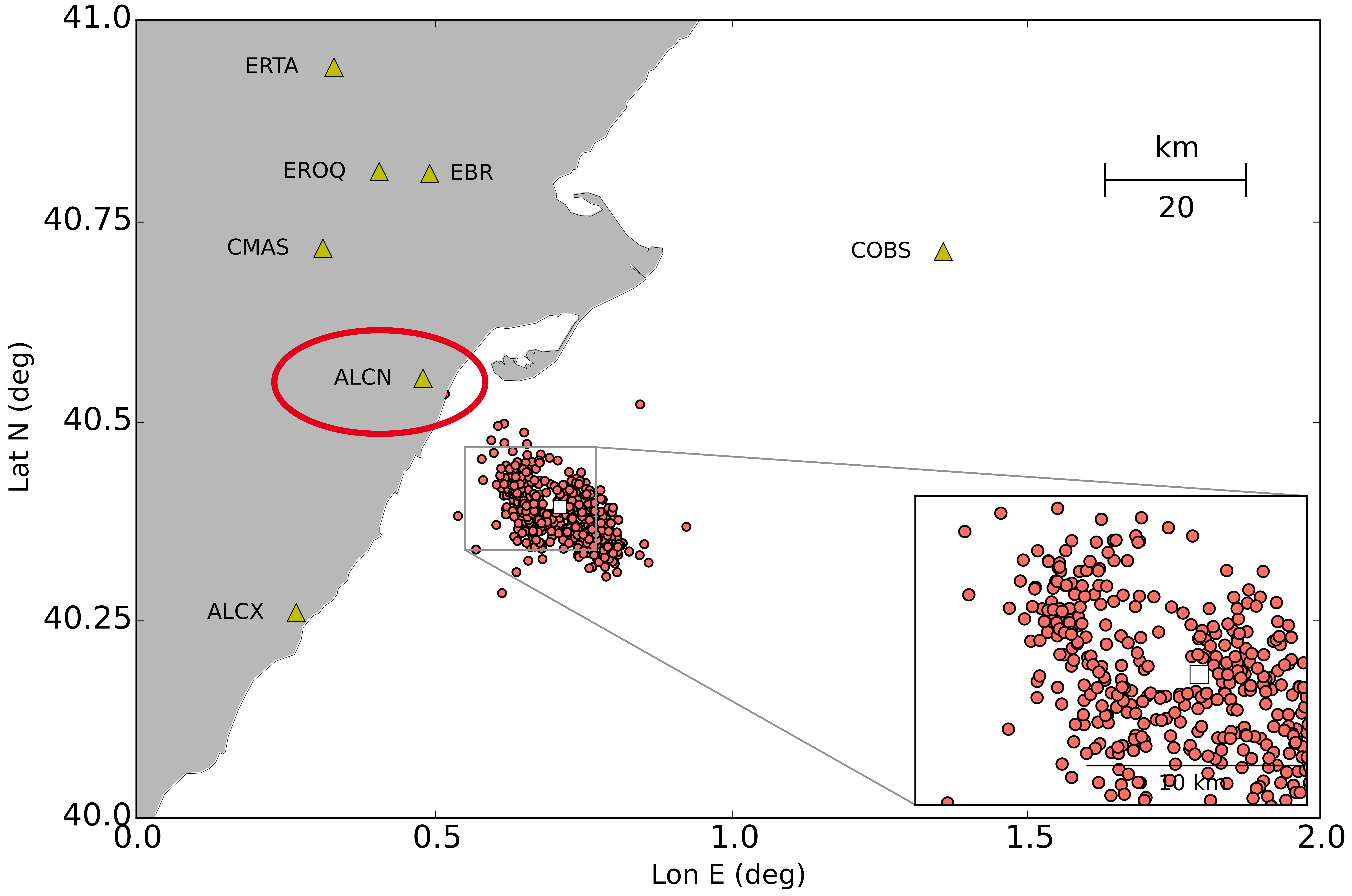
Ml=1.3

b) 2013-10-01T00:32:01Z - 2013-10-01T00:32:51Z



Ml=0.7

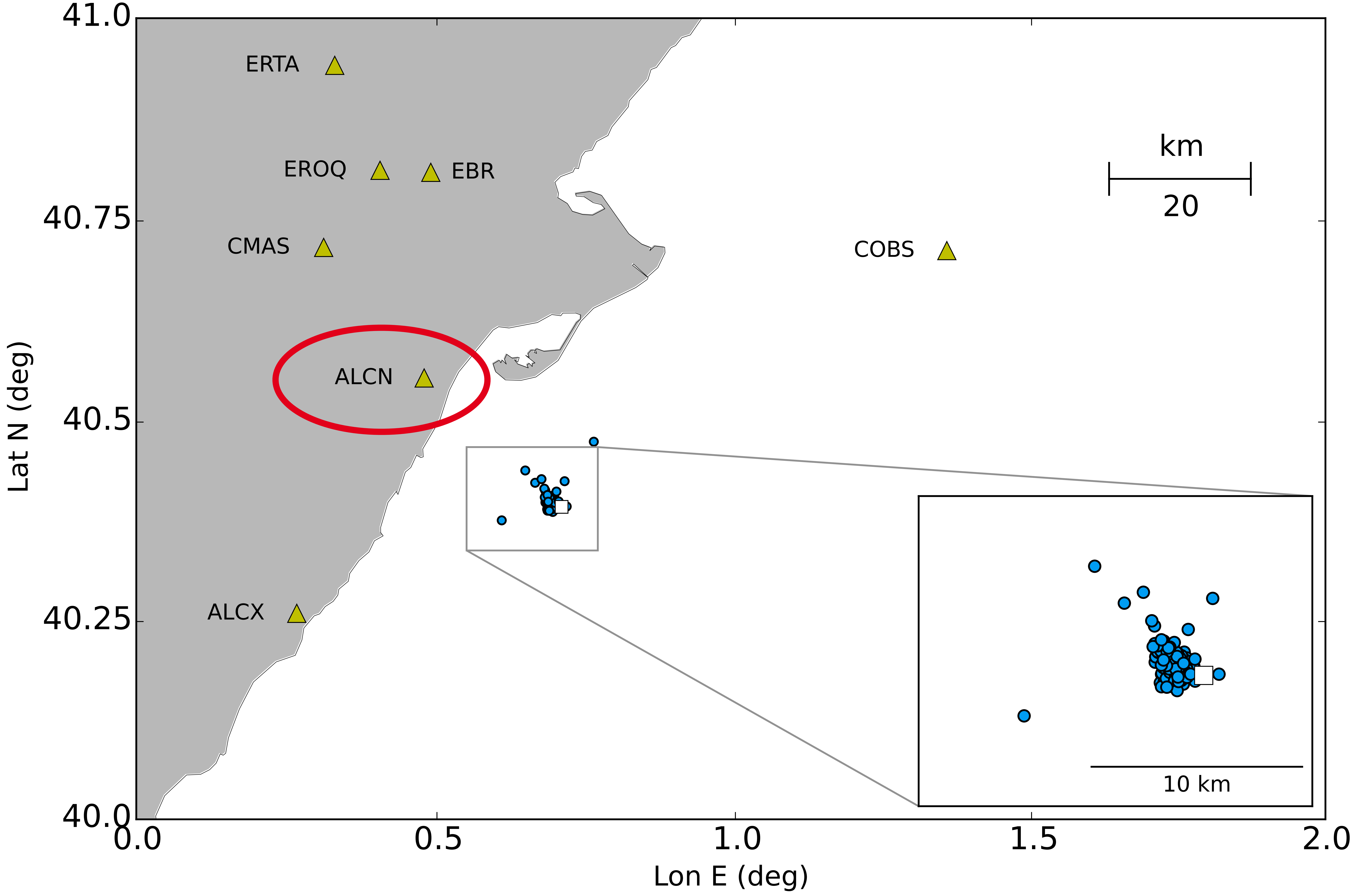
Locations from the Ebro Catalogue



492 events (Ml<2), cross-correlation value higher than 0.9

(Grigoli et al, in prep.)

Preliminary results



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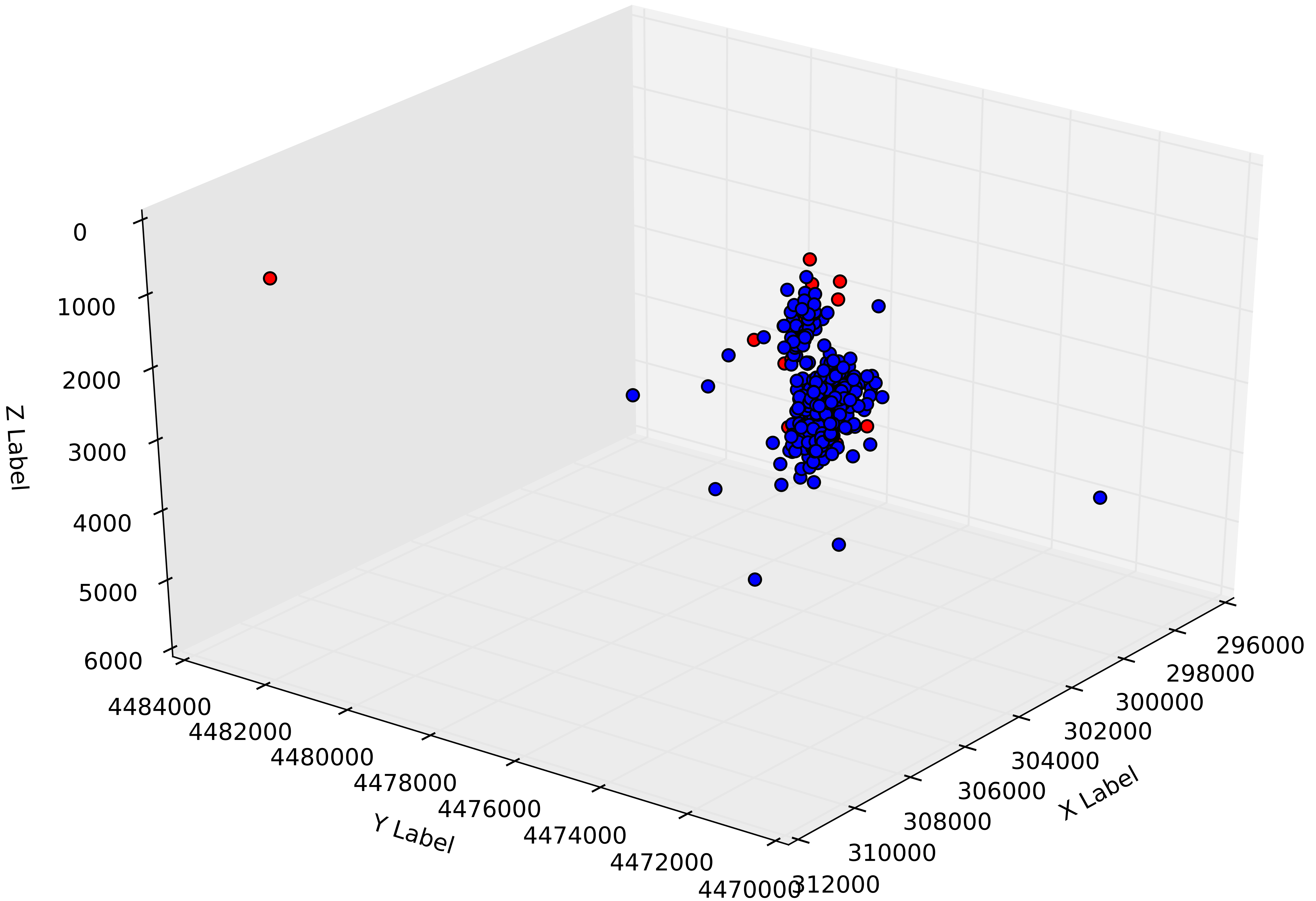


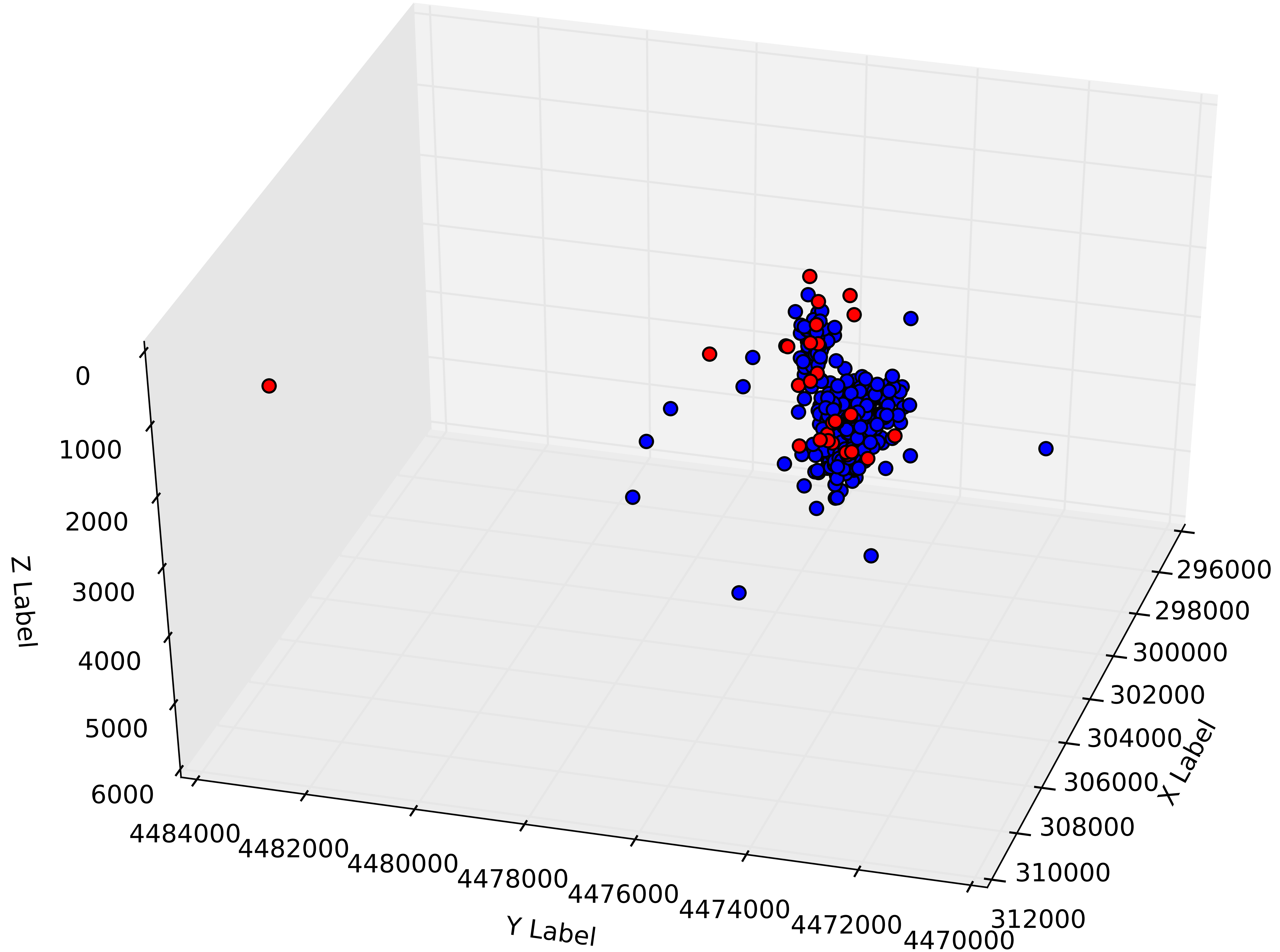
492 events (Ml<2), cross-correlation value higher than 0.9

Red dots (pre-injetion phase), Blue dots (post injection phase) dots (new locations)

Depths between 1.5 and 5.0 km

(Grigoli et al, in prep.)

Preliminary results



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Conclusions

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- **We introduced a hybrid method that combines CWI with DGS that allow to locate seismic events using only a single station (single channel).**
- **Results seems promising... Since all the waveforms show very high crosscorrelation values we expect that seismicity cloud should not be larger than few kilometres. Our relocated events results much more clustered (within a radius of 2km) than the locations obtained using standard methods.**
- **The methods seems very useful in regions where poor monitoring networks, with only few stations are in operations (e.g. monitoring offshore operations).**
- **Working on robust uncertainty estimation**

THANK YOU!!!!

Synthetic Test

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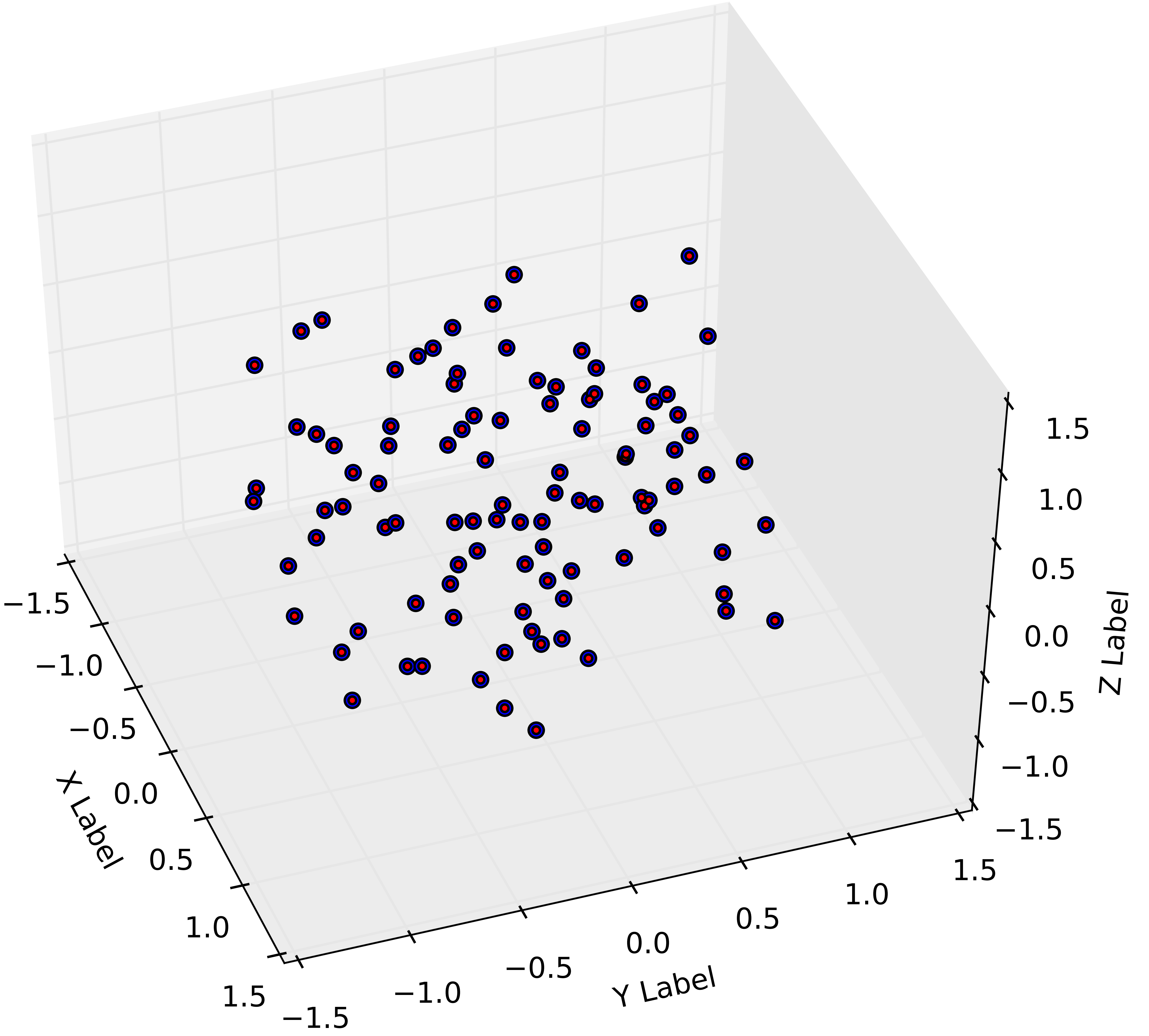

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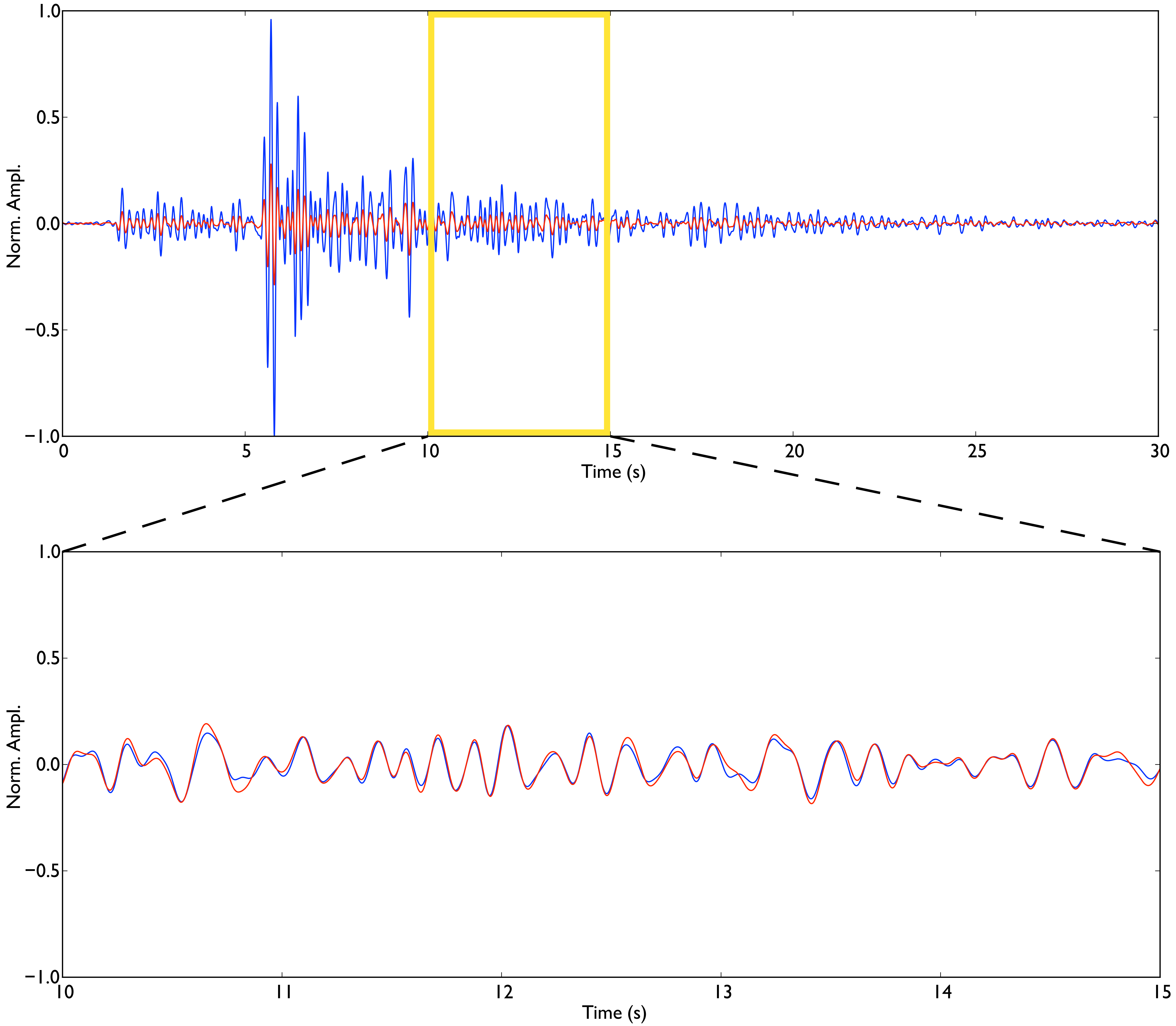

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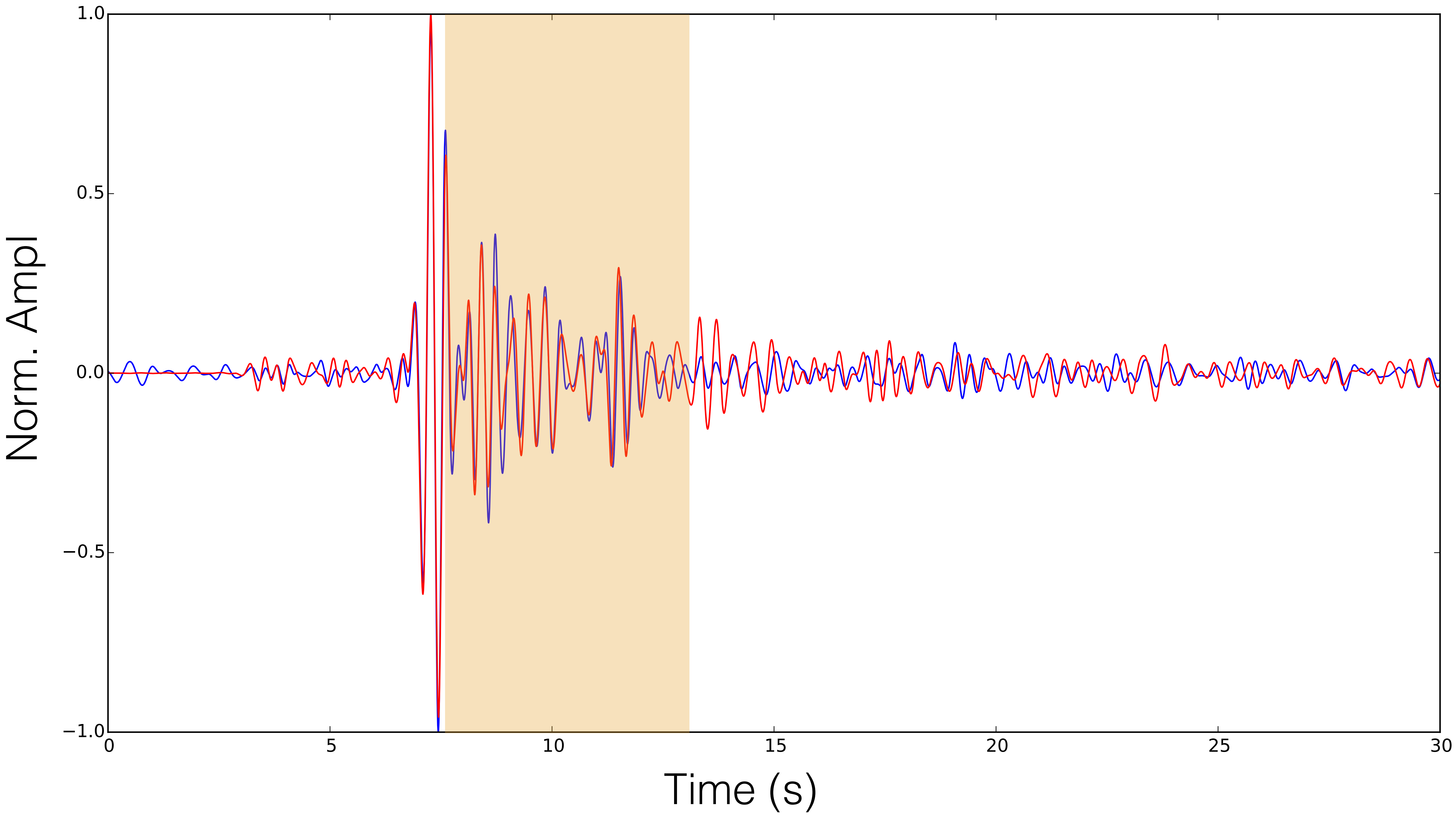

Inter-event distance about 800 m

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