A comparative study of robust algorithms for rapid, automatic earthquake location

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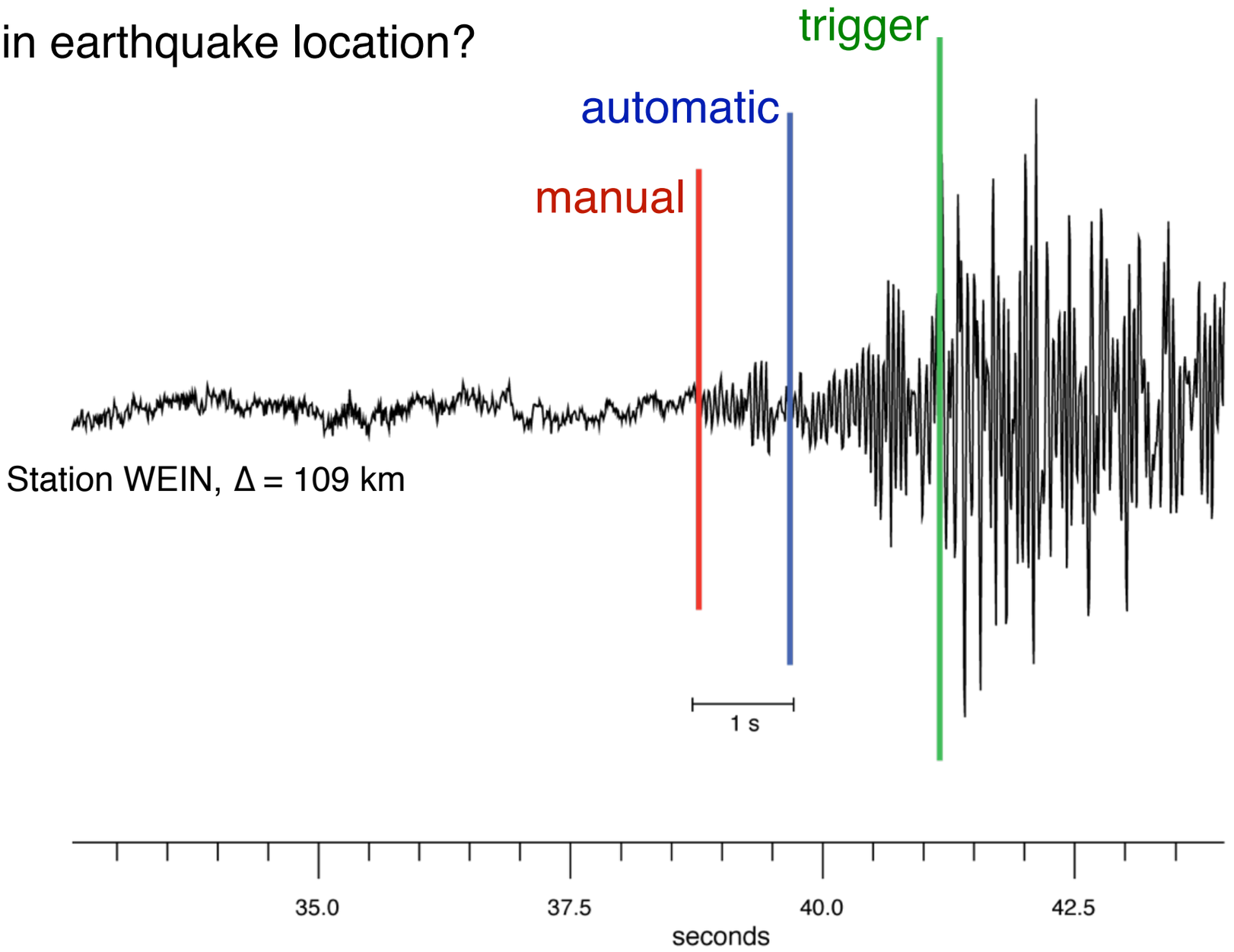
Different qualities of arrival times

How to deal with them in earthquake location?



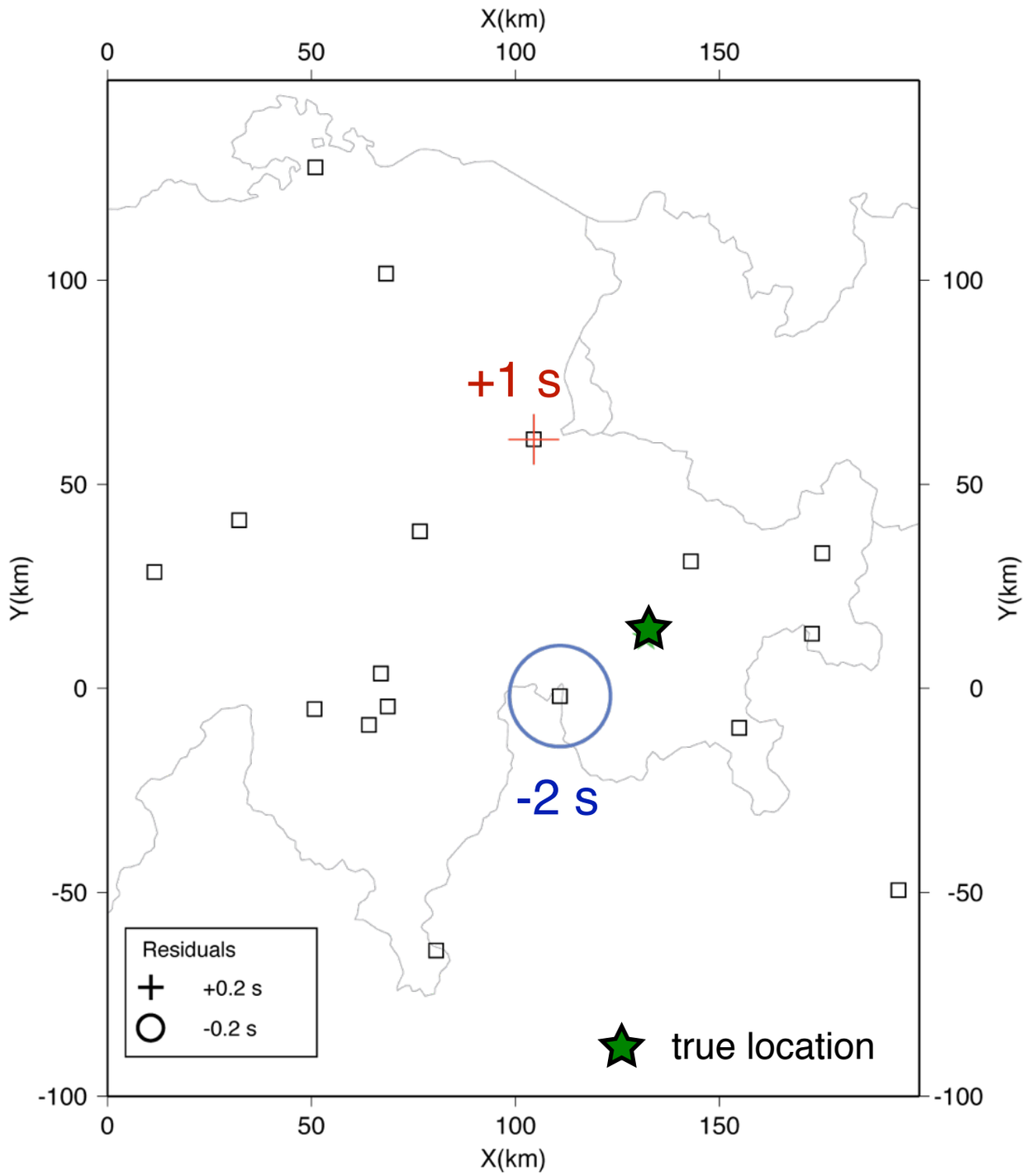
Synthetic example

Realistic station distribution

GAP: 78 deg

nobs: 17

synthetic travel times
plus two outliers

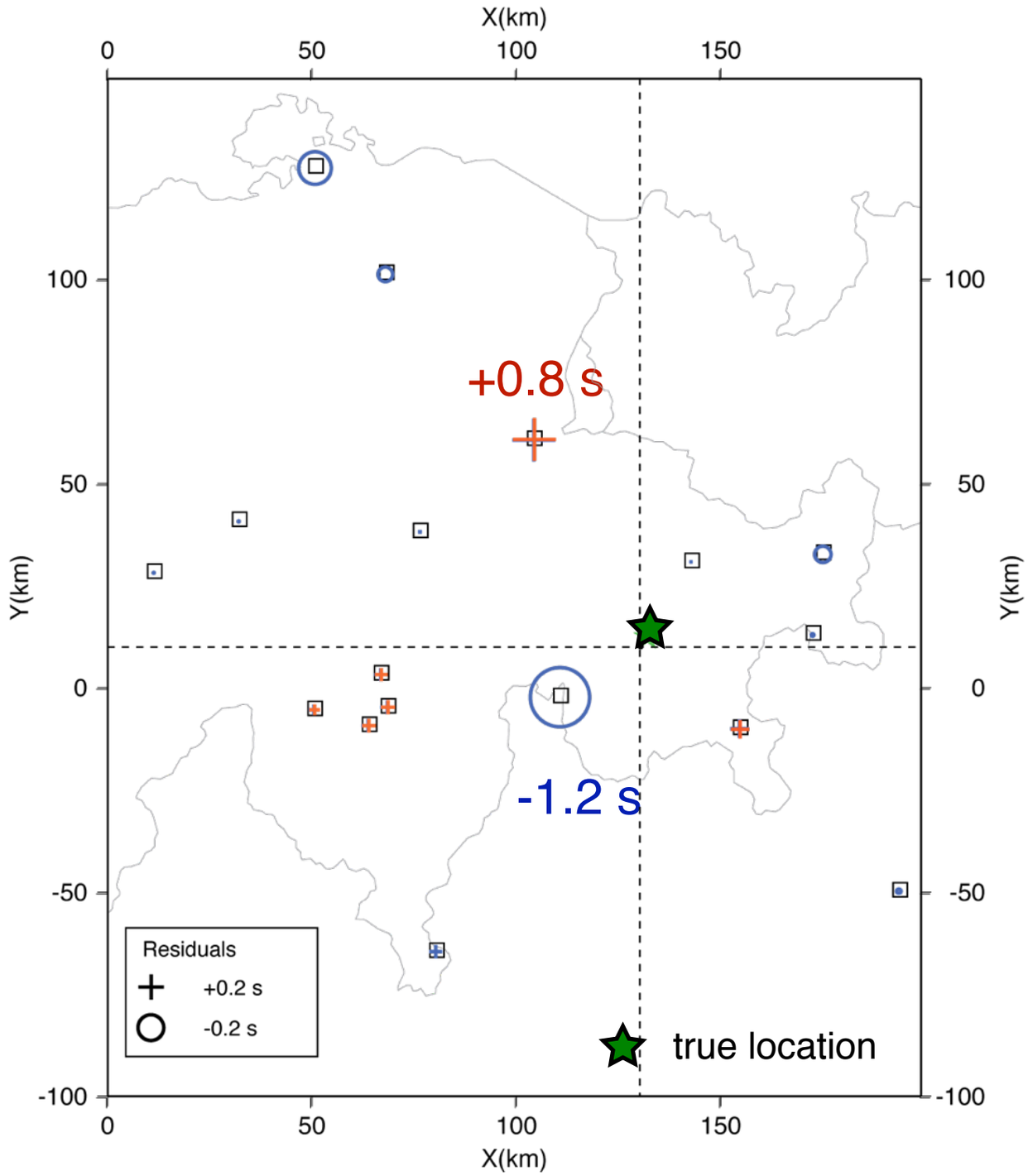


Synthetic example

Relocation using L2 norm

GAP: 80 deg
nobs: 17

RMS: 0.4 s
mislocation: dx=1.5 km, dy=1.8 km



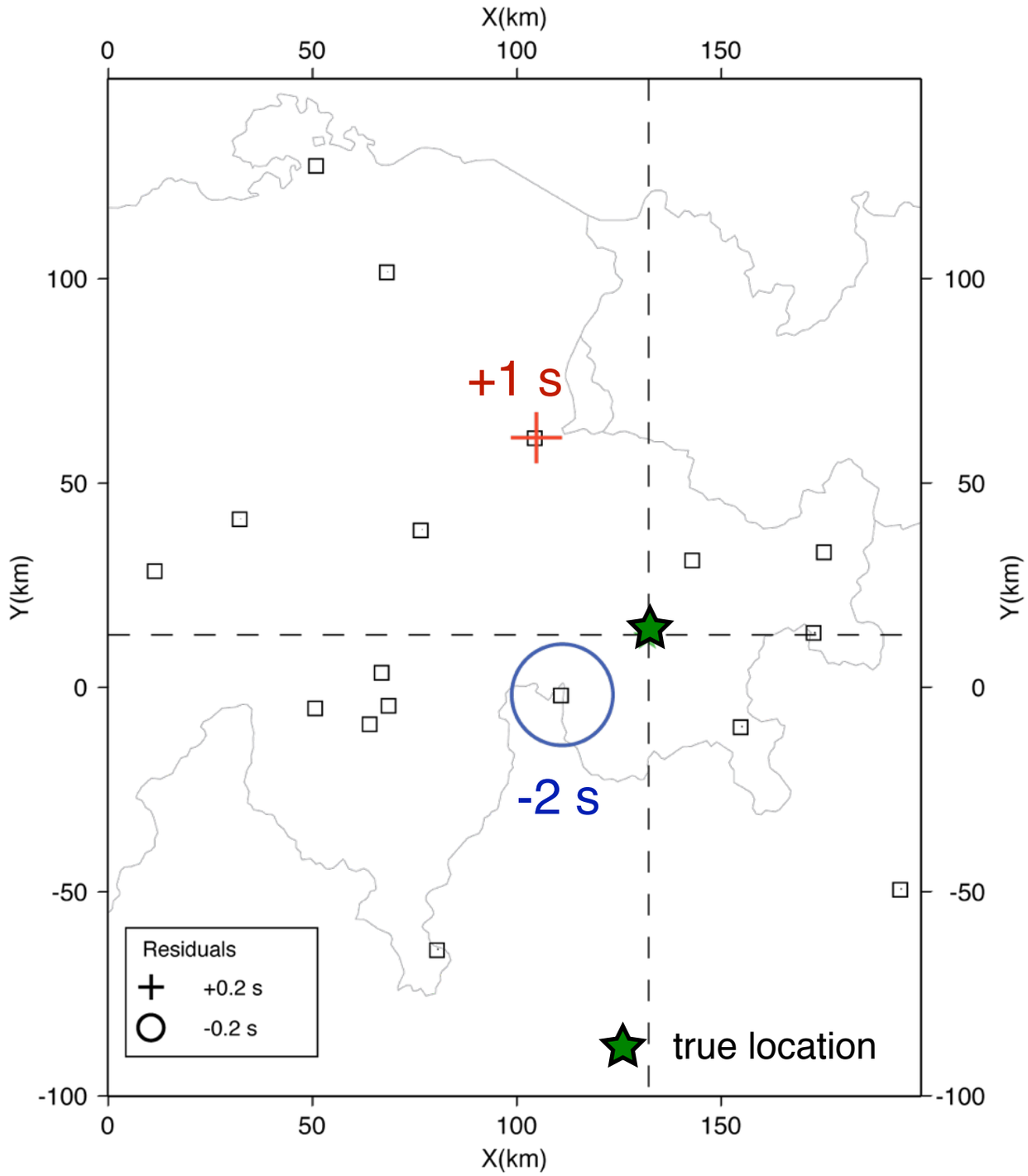
Synthetic example

Relocation using EDT misfit function

GAP: 78 deg
nobs: 17

RMS: 0.55 s

mislocation: dx=0.1 km, dy=0.1 km



Non-linear Probabilistic Earthquake location (NonLinLoc)

Probability Density Function (PDF)
(Tarantola and Valette, 1982)

$$pdf\left(\mathbf{x}\right) = f\left(misfit\left(\mathbf{x}\right)\right)$$

L2 misfit function

satisfies all observations

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

Equal Differential Time (EDT) misfit function

satisfies the most pairs of observations

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

coded into NonLinLoc software:
www.alomax.net/nlloc

Network Beamforming (NB)
(Pinsky, 2006)

T_k : arrival time

$TT_k(xyz)$: predicted travel time

σ: empirical scaling factor

origin time T_{0k} for station k:

$$T_{0k} = T_k - TT_k(xyz)$$

expressed by means of complex exponents:

$$\exp(iT_{0k}/\sigma) = \exp\{i\,[T_k - TT_k(X,Y,Z)]/\sigma\}$$

L2 solution of this set of equations:

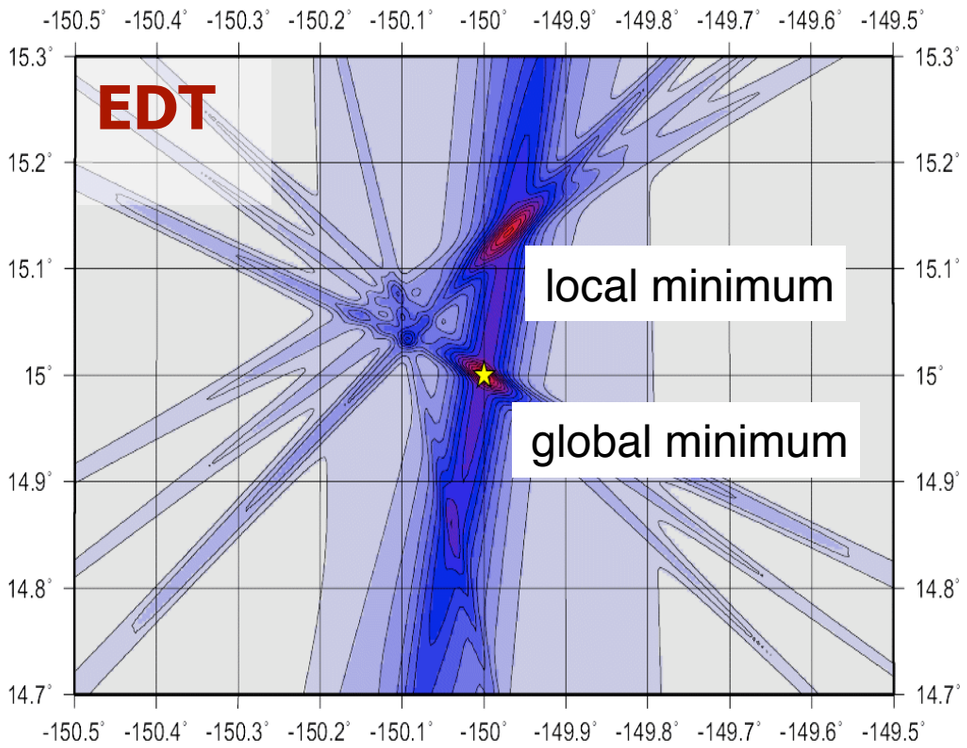
$$S(X, Y, Z) = \max(|\Sigma \exp(iT_{0k}/\sigma)|)/N$$

maximum of the absolute value of the average of complex exponents

The use of complex exponents allows easier separation of outliers!

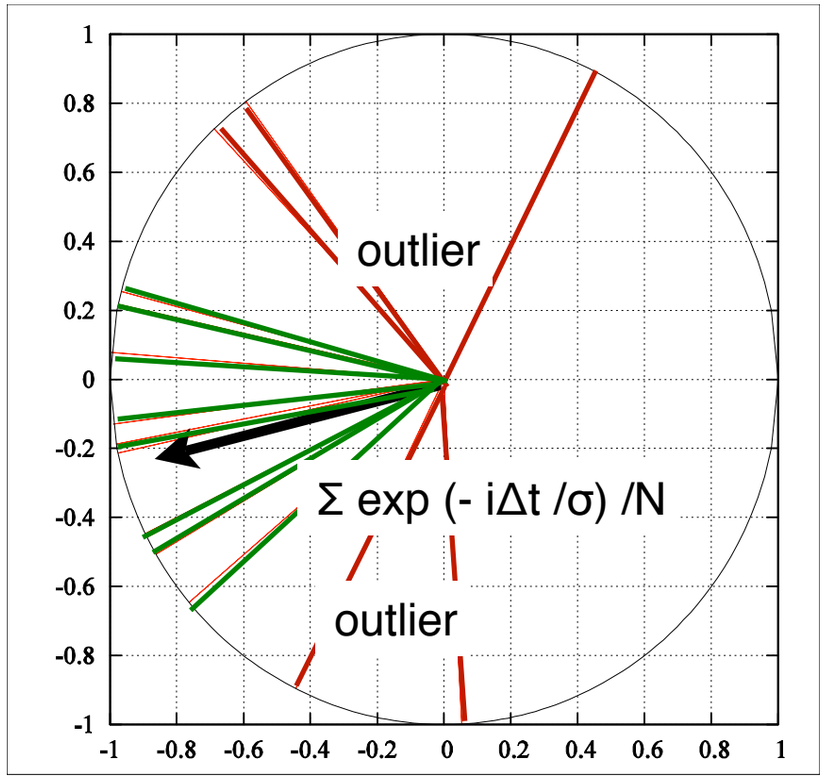
Graphical interpretation

NonLinLoc + EDT



Inconsistent pairs of observations form local minimum in the PDF.

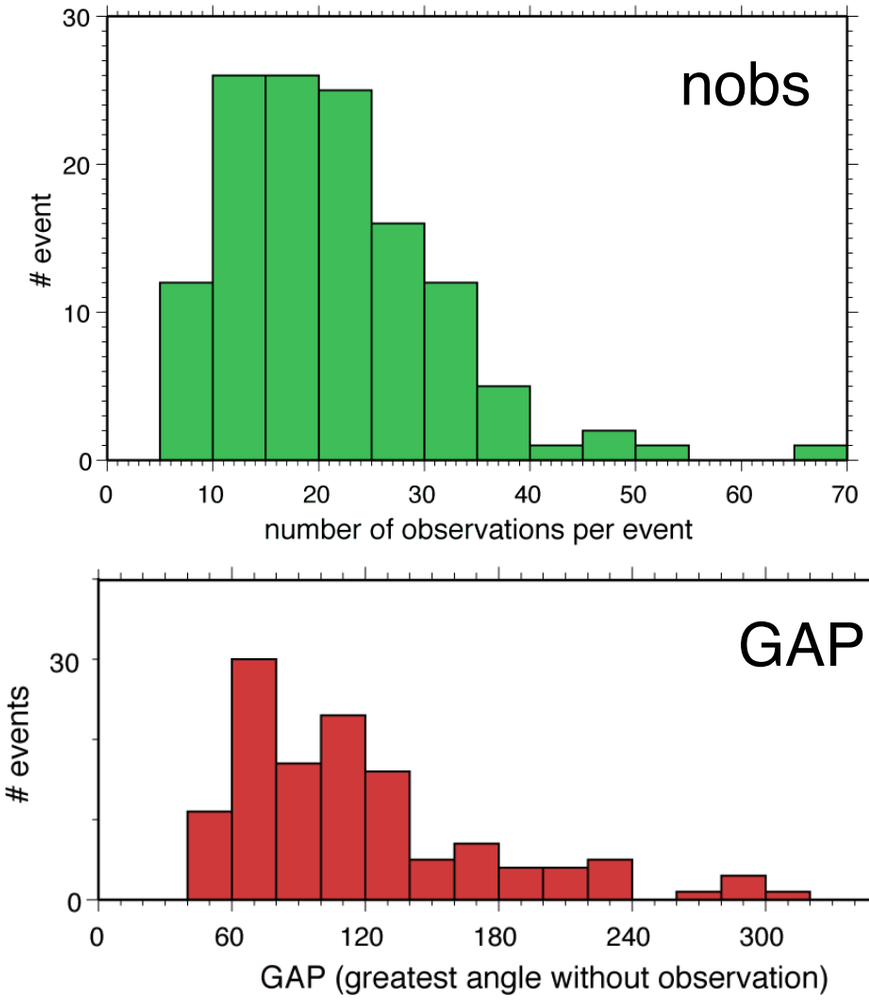
NB

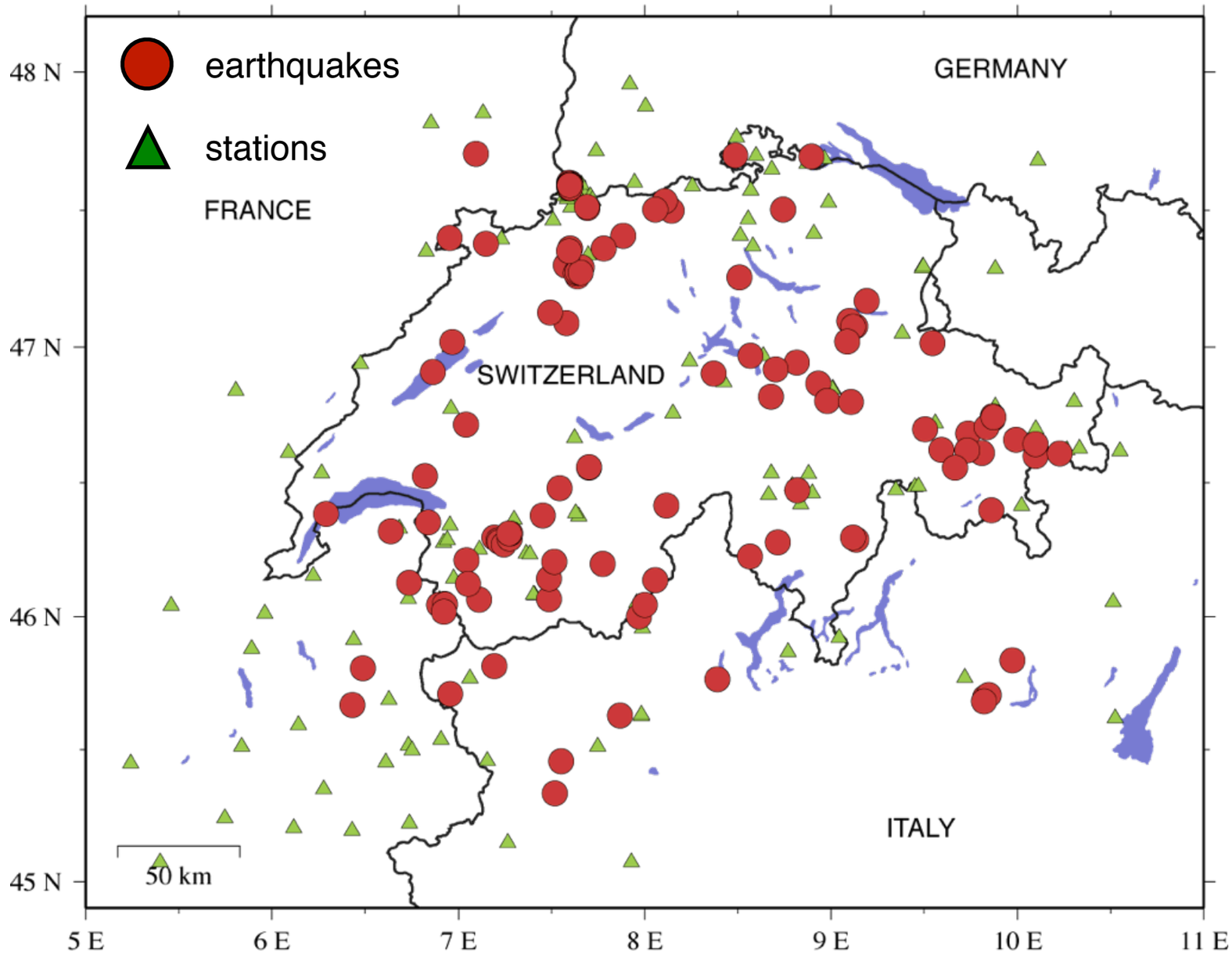


Average of a set of radius vectors, which becomes the longest, when the set is the most dense.

Data set for comparison

127 earthquakes 2004 - 2007 (M>2.0)





Different sets of arrival times

TRIGGER

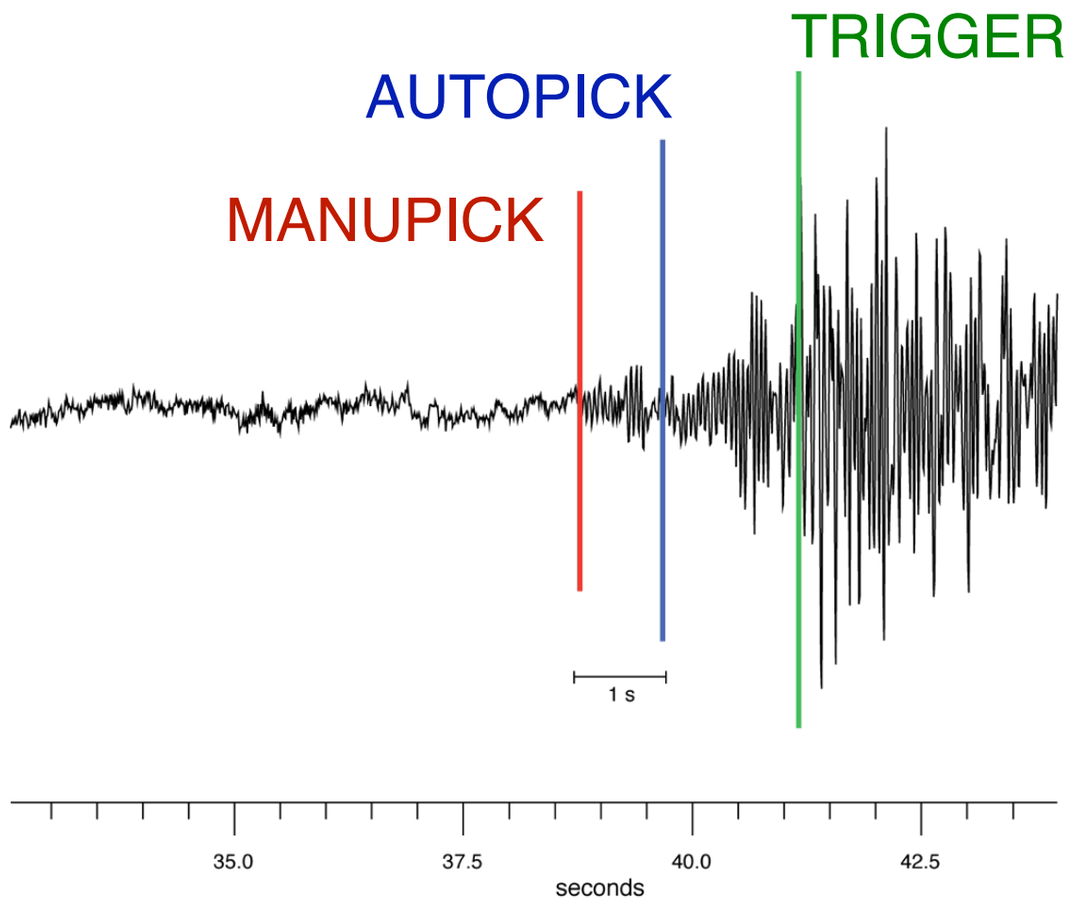
Based on simple STA/LTA

AUTOPICK

Based on Baer & Kradolfer (1992) automatic picker

MANUPICK

Manually reviewed by experienced analyst



Testing procedure

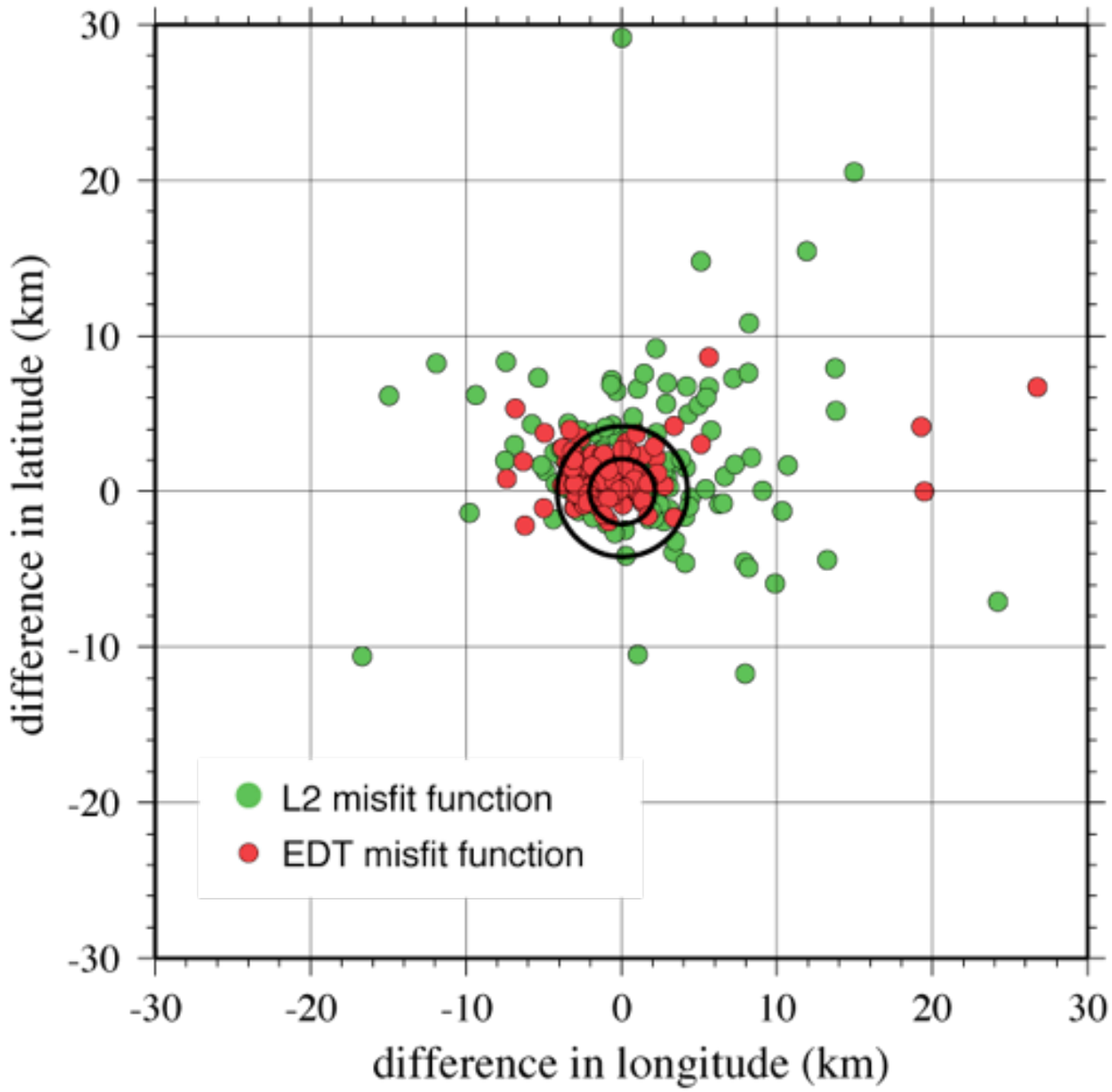
- Locate events using different sets of arrival times (AUTOPICK & TRIGGER) and each locator (NonLinLoc & NB).

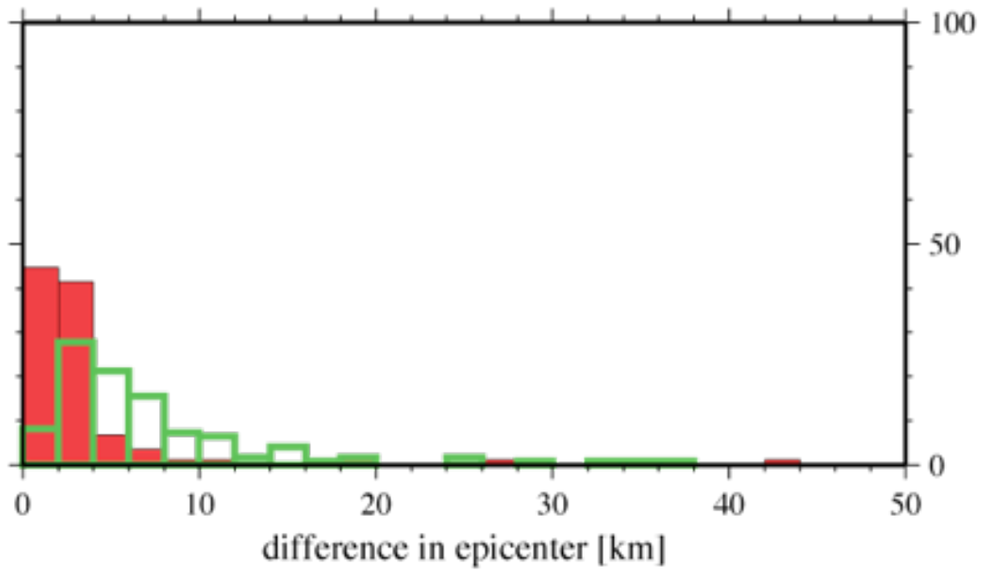
- Compare locations (mislocation in epicenter) against reference locations computed using MANUPICK and NonLinLoc-EDT.

- All locations are computed using the same minimum 1D model velocity model.

EDT vs L2 (AUTOPICK)

Difference relative to locations with MANUPICK and EDT misfit function



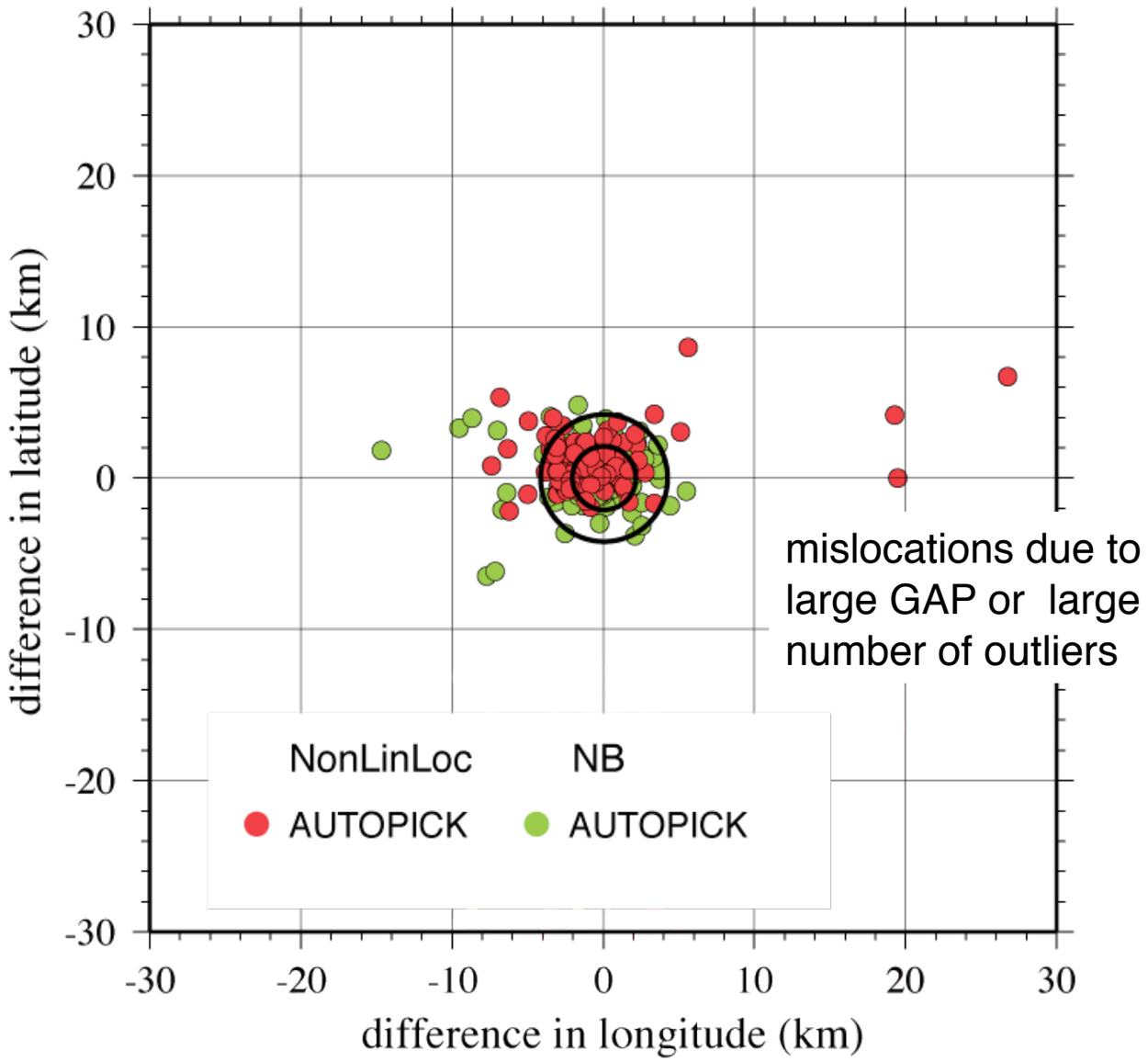


L2: 38% of events within 4 km radius of reference location

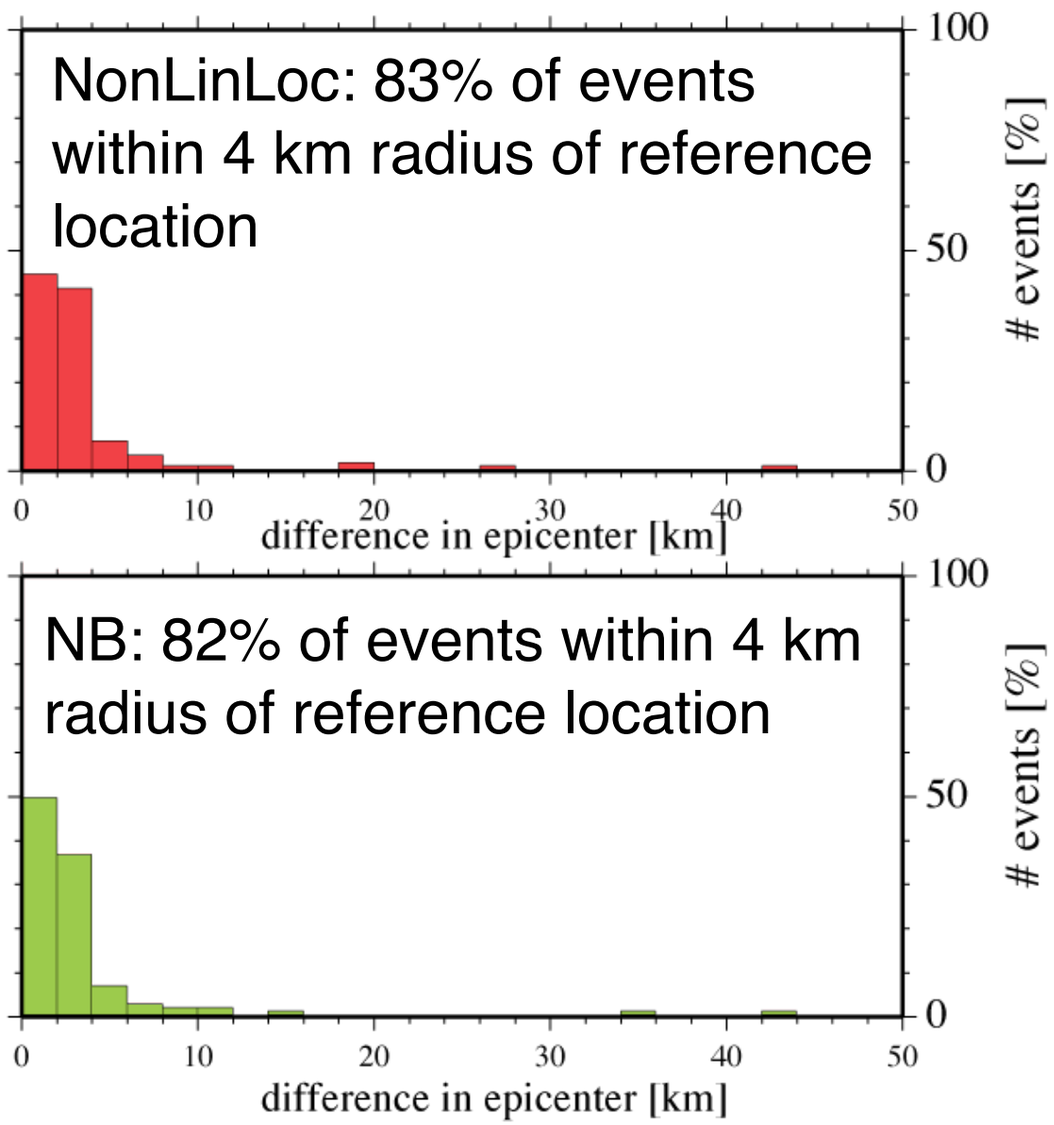
EDT: 83% of events within 4 km radius of reference location

NB vs NonLinLoc (AUTOPICK)

Difference relative to locations with MANUPICK and EDT misfit function

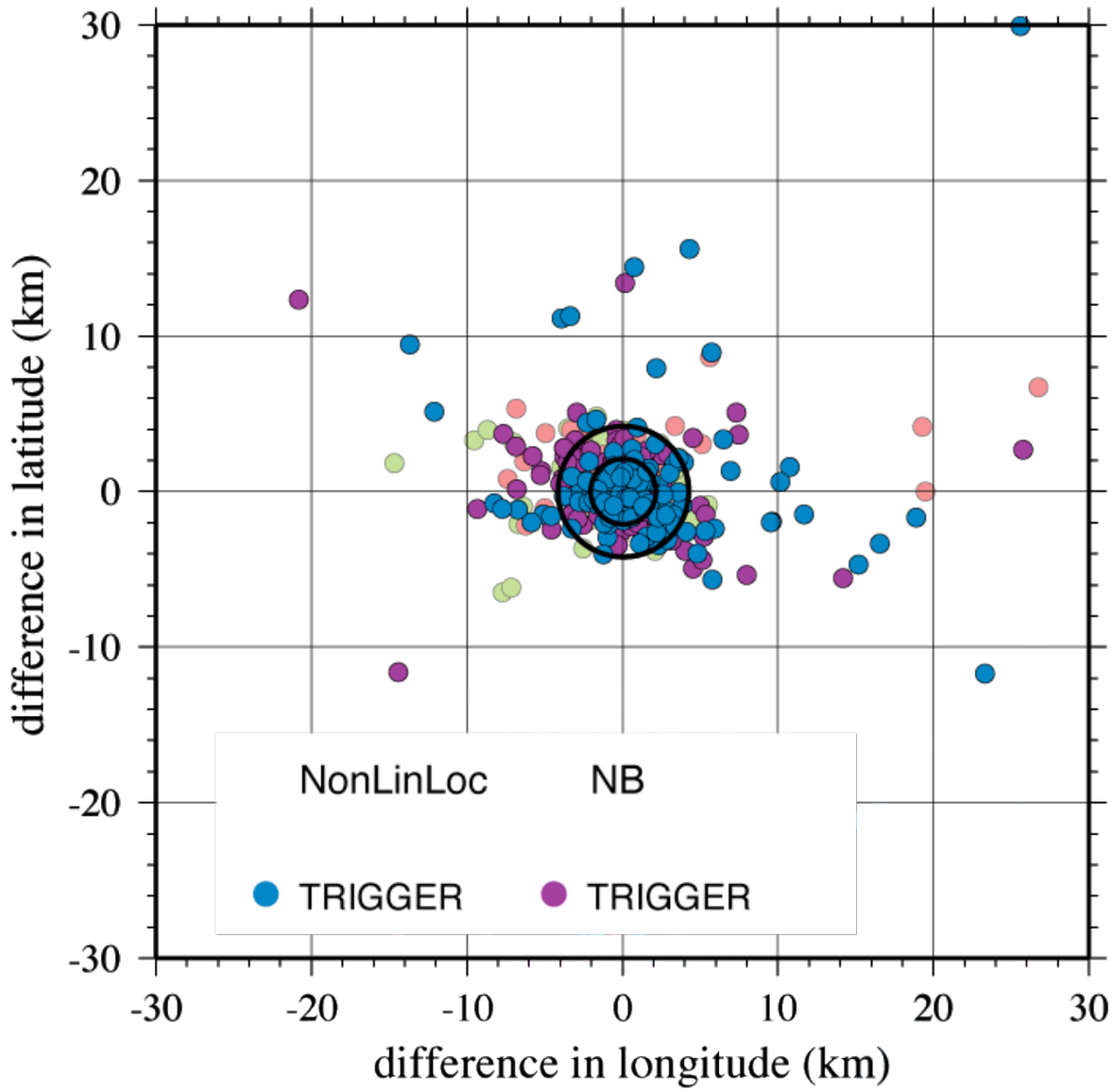


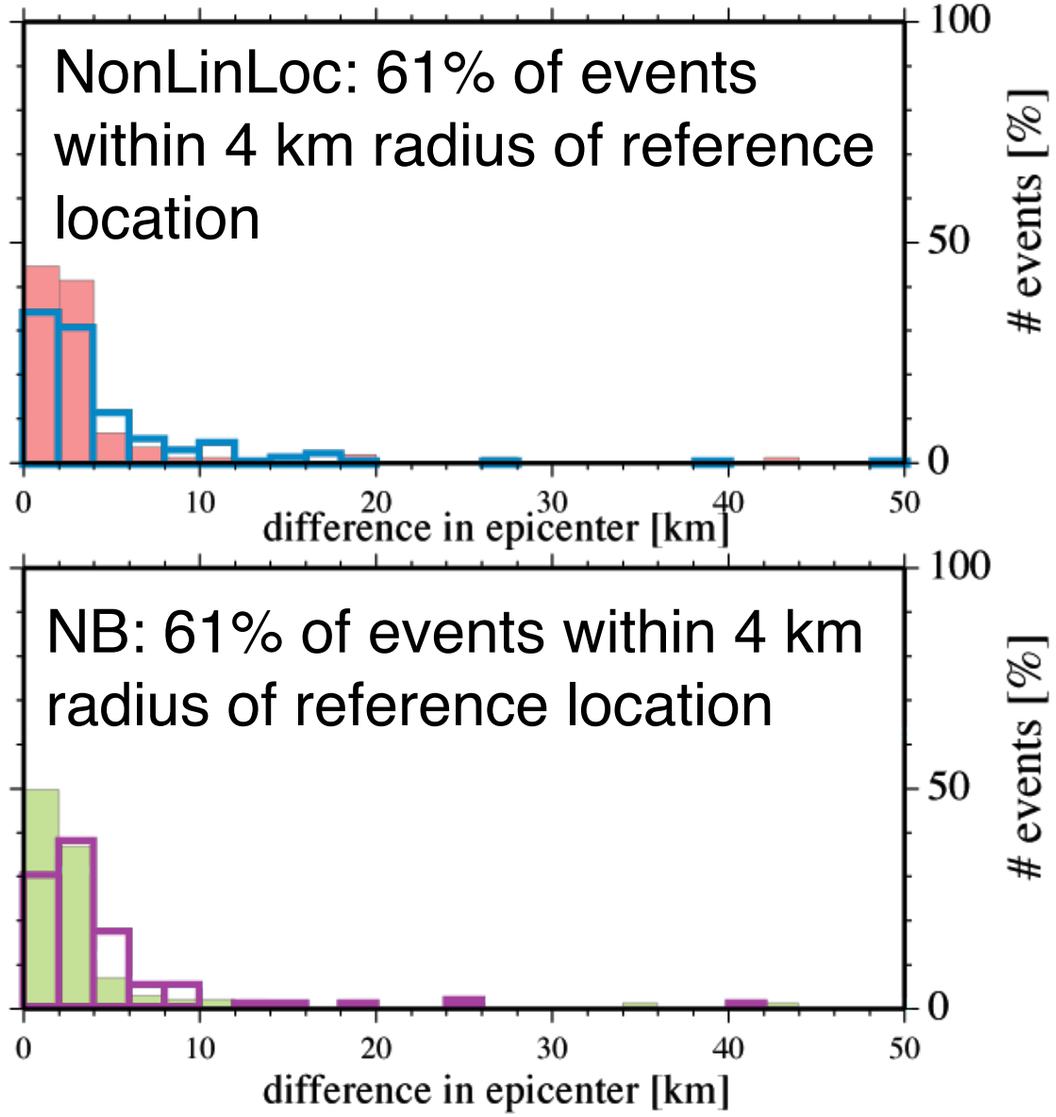
mislocations due to large GAP or large number of outliers



NB vs NonLinLoc (TRIGGER)

Difference relative to locations with MANUPICK and EDT misfit function





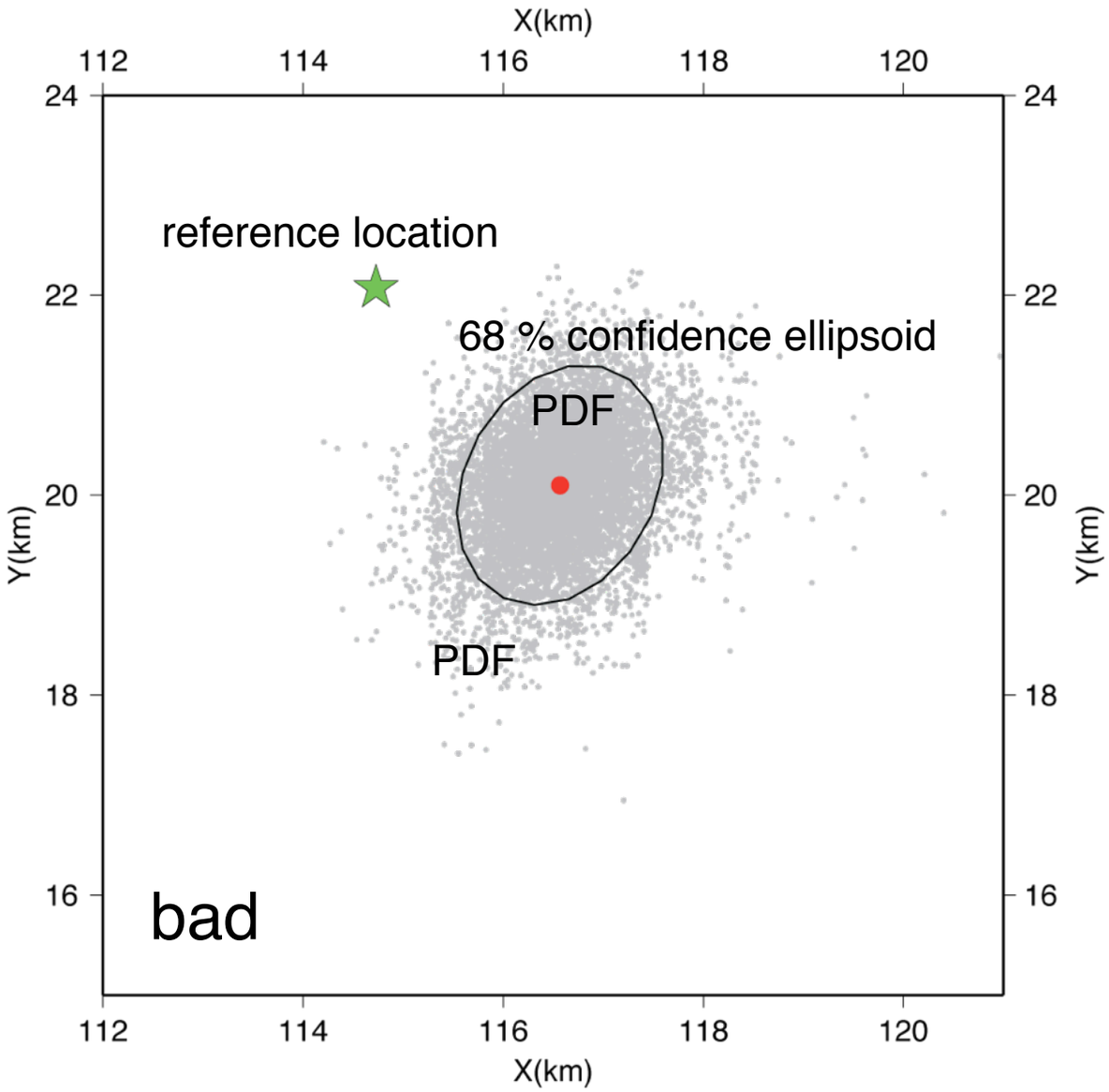
Conclusions

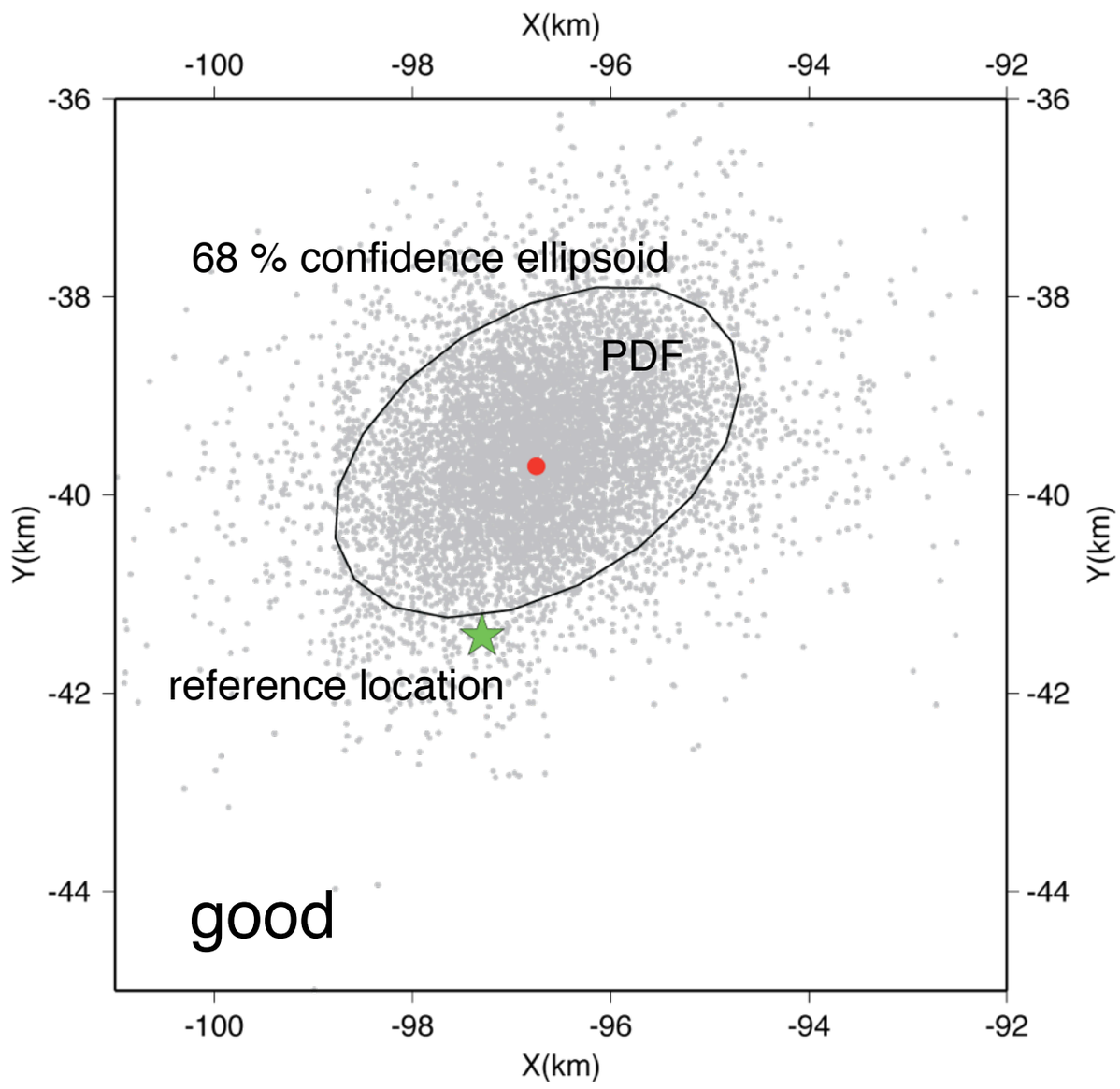
- The Equal Differential Time misfit function (EDT) and Network Beamforming (NB) can provide stable epicenter locations in the presence of outliers in the data.

- Arrival times of better quality (AUTOPICK) yield more reliable results then arrival times of lower quality (TRIGGER).

- Rapid earthquake locations, as needed in early earthquake warning, can be improved using robust earthquake location techniques such as NonLinLoc-EDT or NB.

Outlook


X(km)
112
114
116
118
120
24
22
20
18
16
Y(km)
reference location
68 % confidence ellipsoid
PDF
PDF
bad


X(km)
-100
-98
-96
-94
-92
-36
-38
-40
-42
-44
Y(km)
68 % confidence ellipsoid
PDF
reference location
good