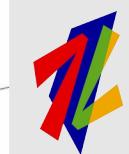
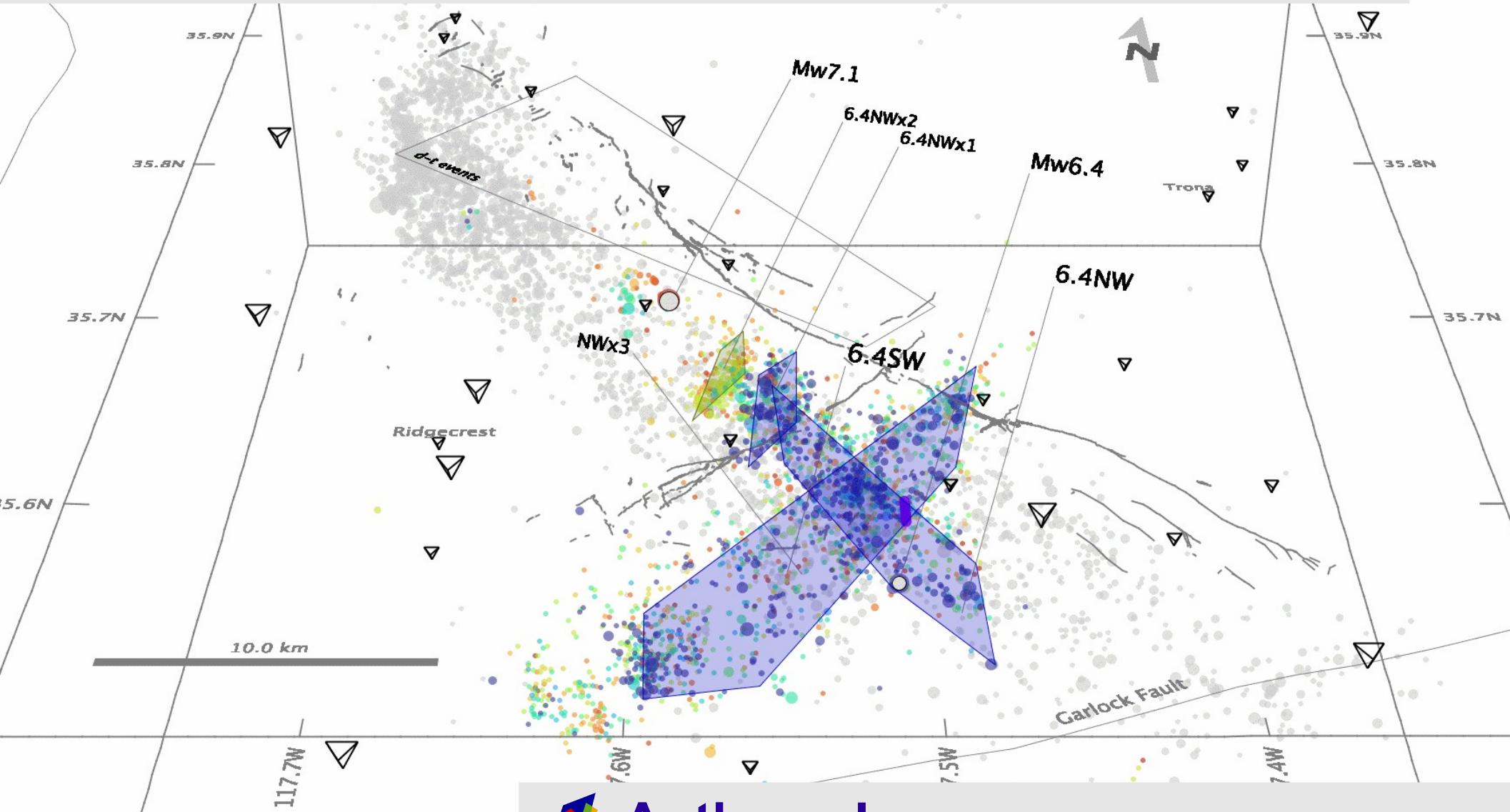


NonLinLoc Earthquake Location



Anthony Lomax
ALomax Scientific, Mouans-Sartoux, France

NonLinLoc Earthquake Location

Outline:

- Introduction – Seismic sources and Earthquake location**
- 1. Phase picking, phase association and event detection**
- 2. Probabilistic, global-search earthquake location**
- 3. NonLinLoc earthquake location**
- 4. Illustrative examples of NonLinLoc global-search earthquake location**

More information: <http://alomax.net/science.html>, <http://alomax.net/nlloc>

Anthony Lomax - ALomax Scientific, Mouans-Sartoux, France - anthony@alomax.net, www.alomax.net

Introduction – Seismic sources and Earthquake location

Anthony Lomax
ALomax Scientific, Mouans-Sartoux, France

Seismic Sources

earthquake

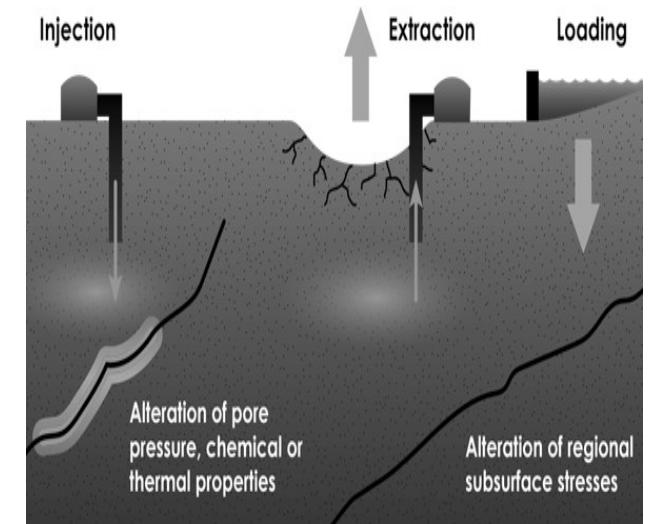


San Andreas Fault, 1906 quake. G.K. Gilbert.

explosion



induced

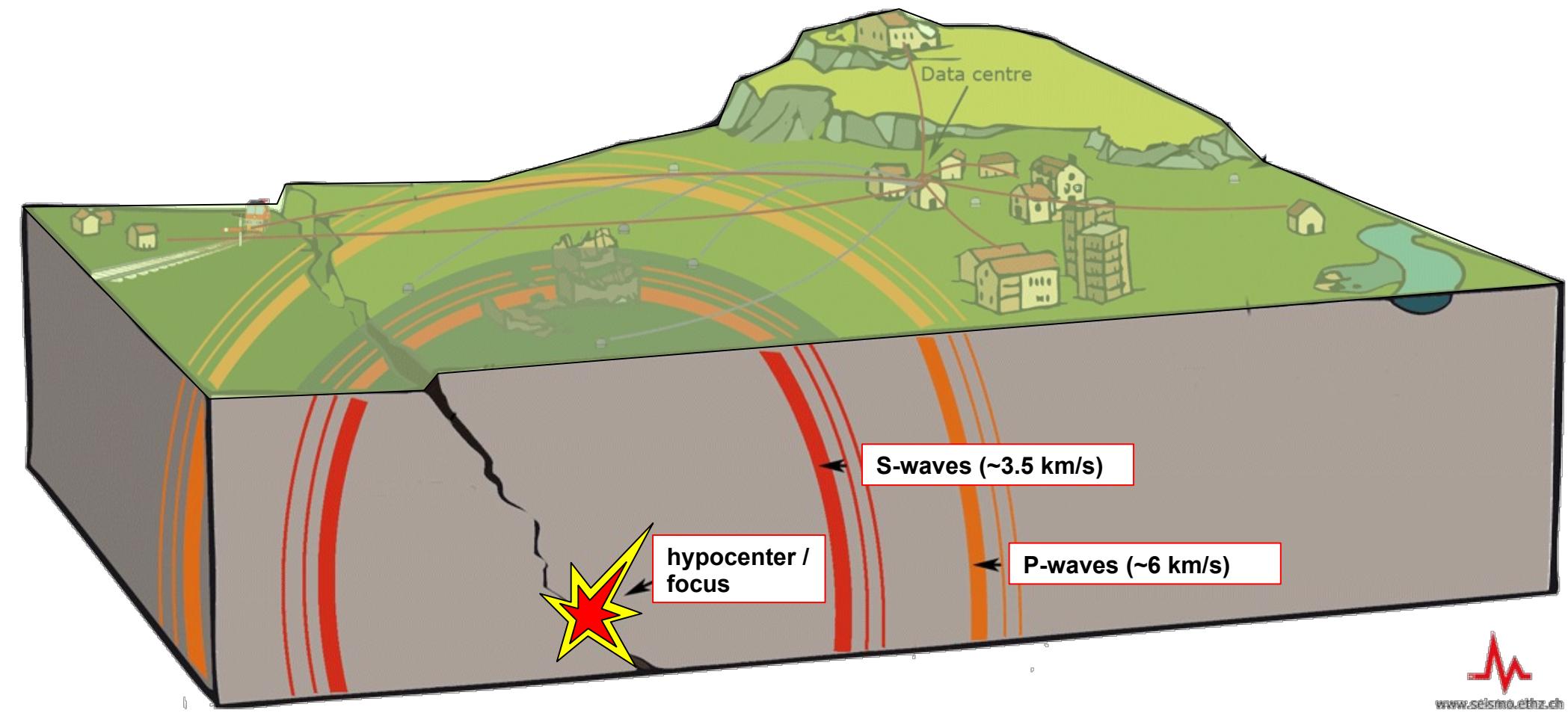


K. Cantner, AGI, after Ellsworth et al., Science, 2013

volcanic

...

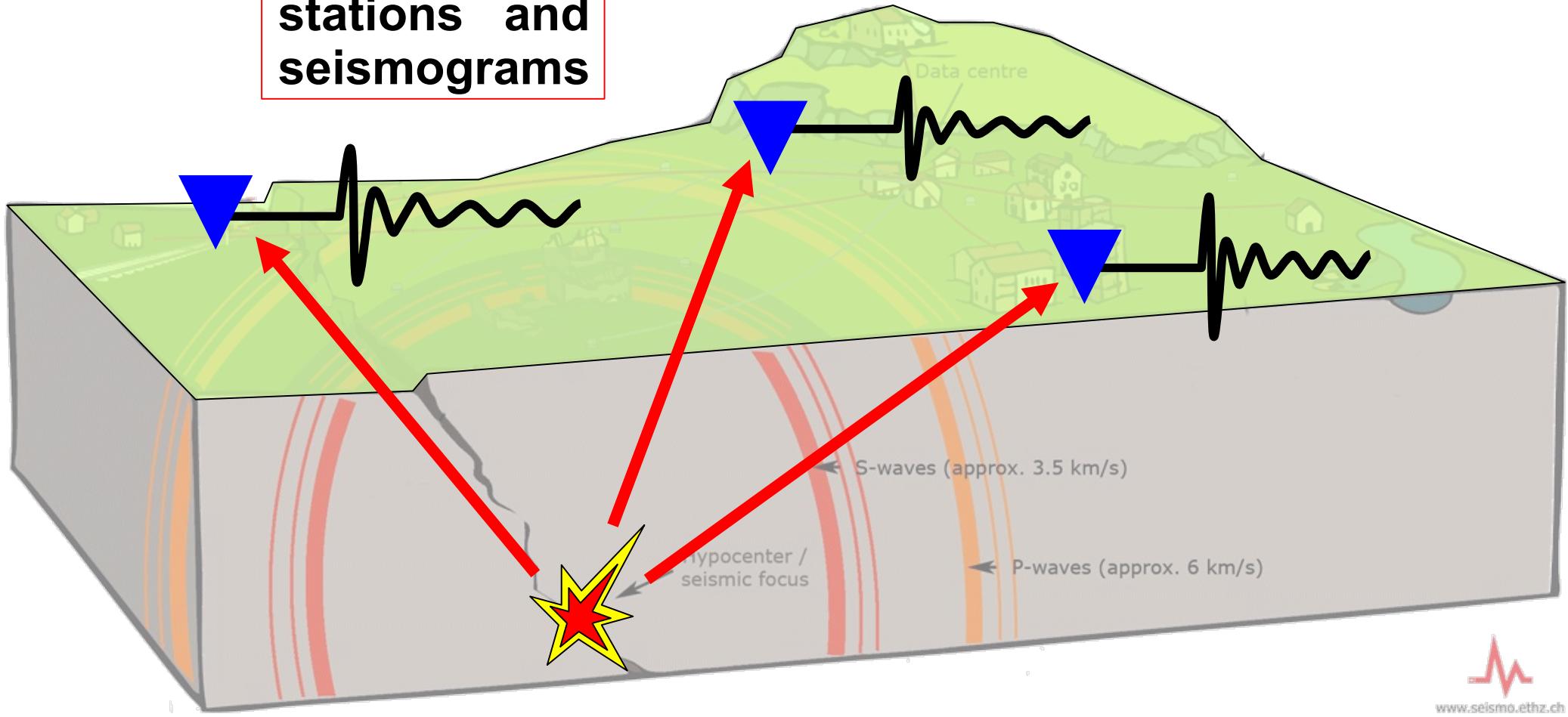
Seismic Sources



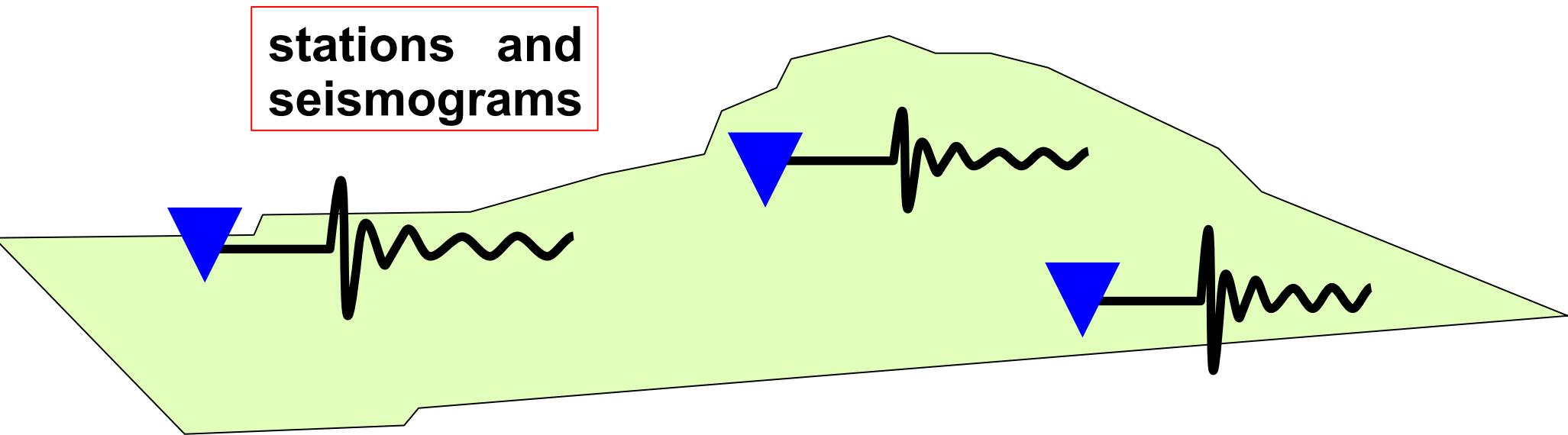
www.seismo.ethz.ch

Seismic Sources

stations and seismograms

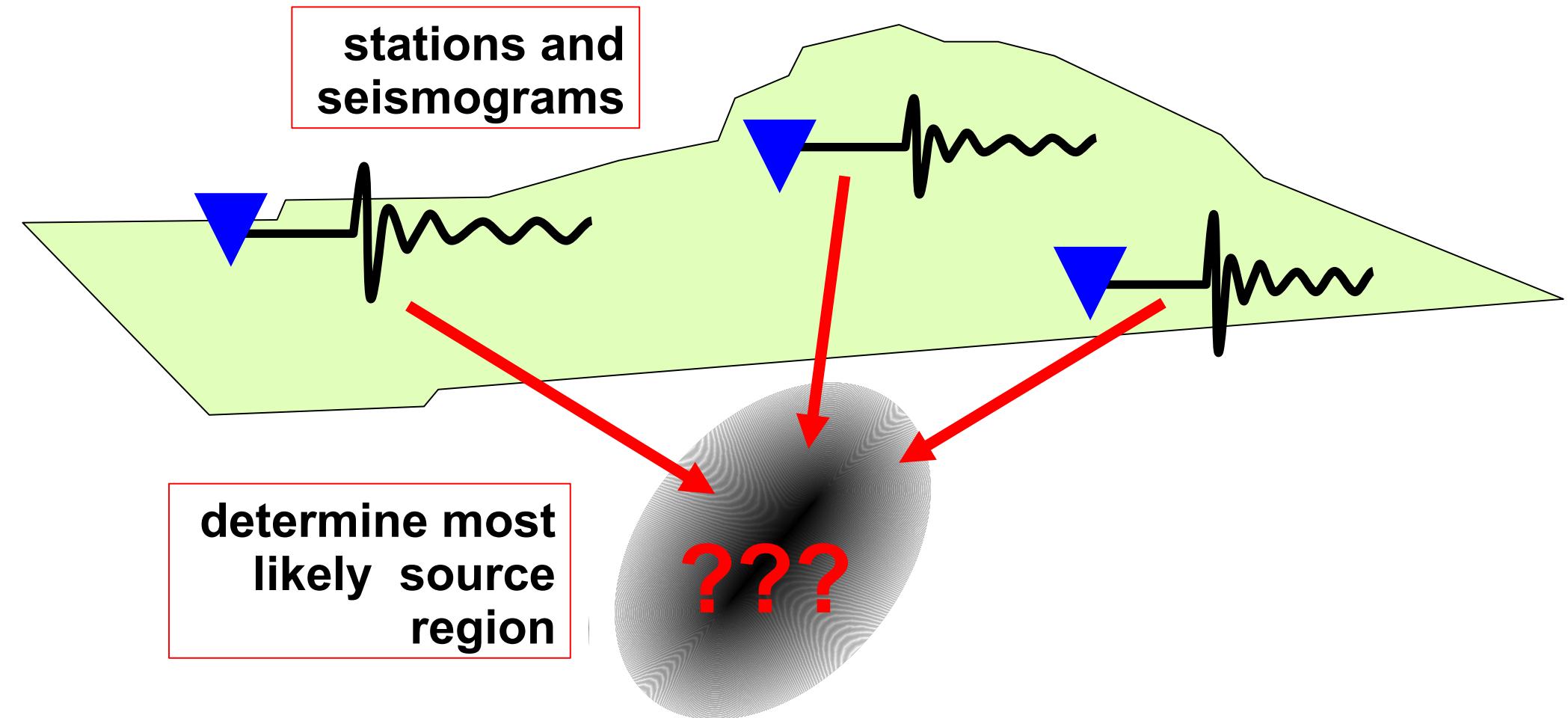


Seismic Sources



???
source location

Earthquake Location



NonLinLoc Earthquake Location

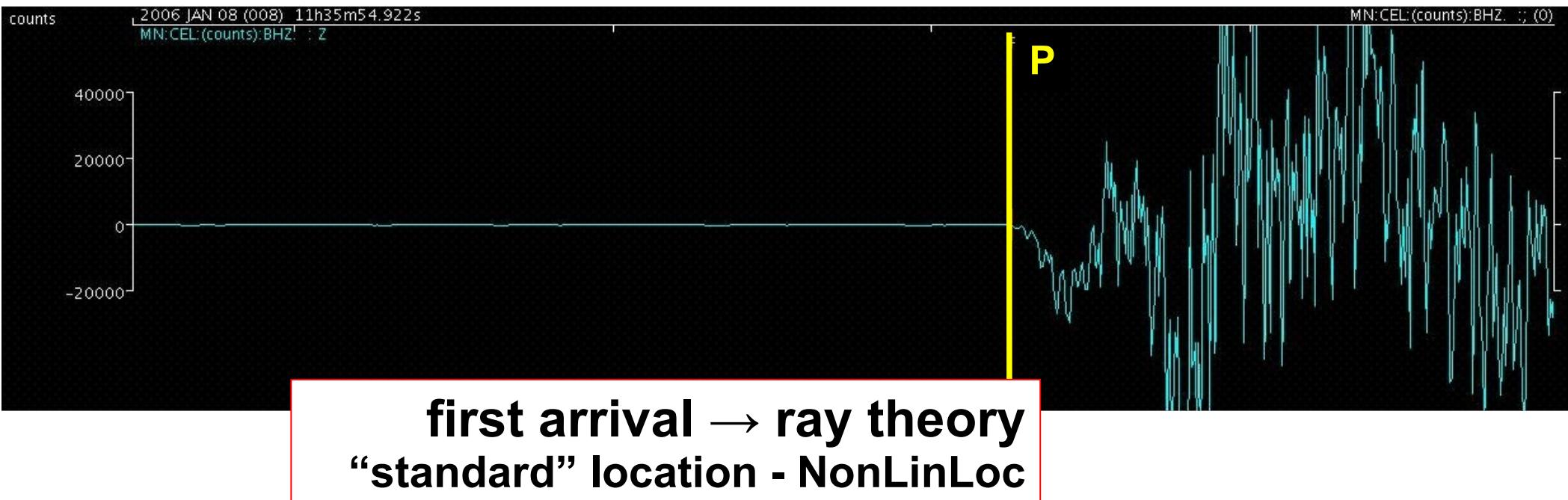
1. Phase picking, phase association and event detection

Anthony Lomax
ALomax Scientific, Mouans-Sartoux, France

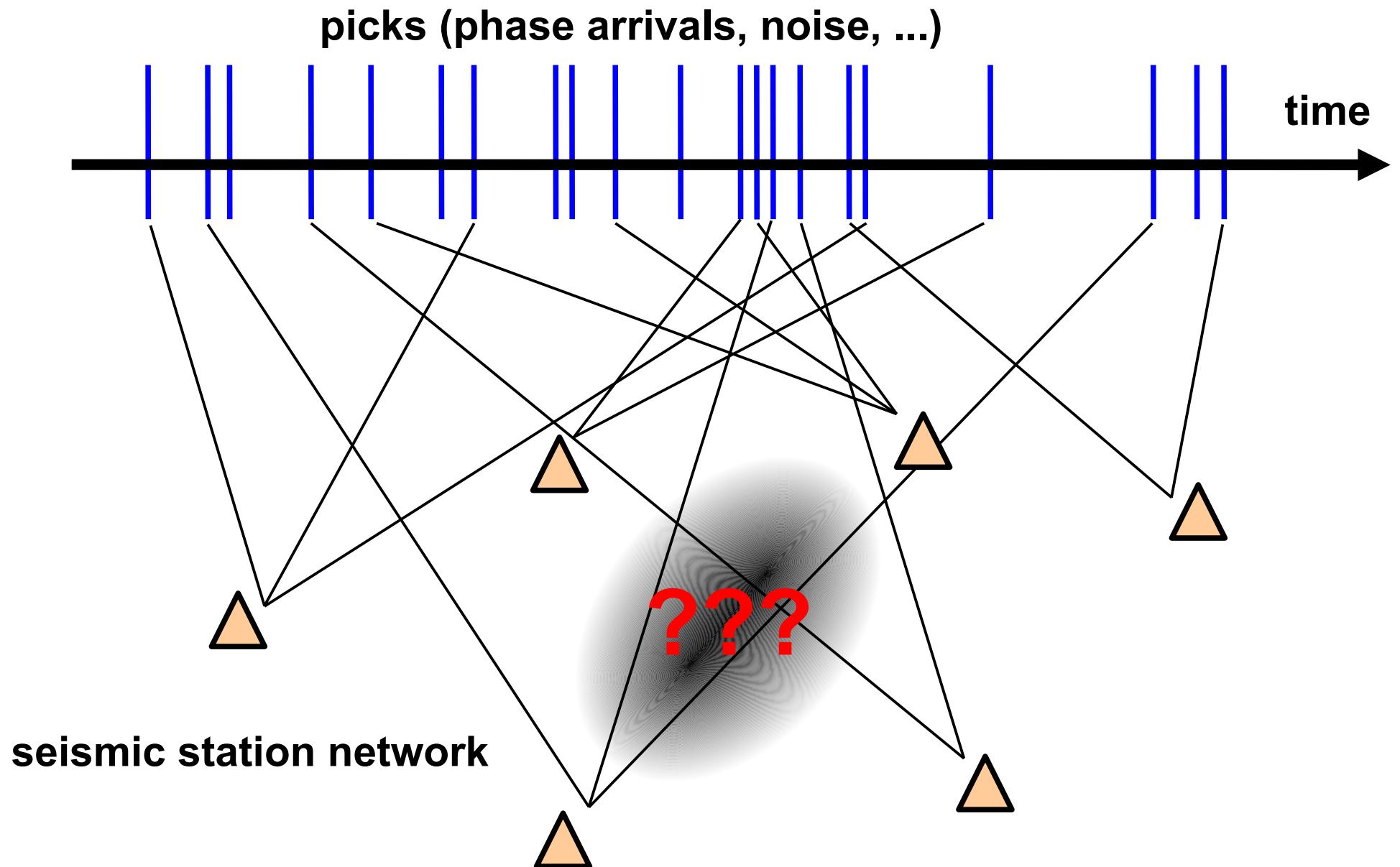
1. Phase picking, phase association and event detection

Phase association and event detection

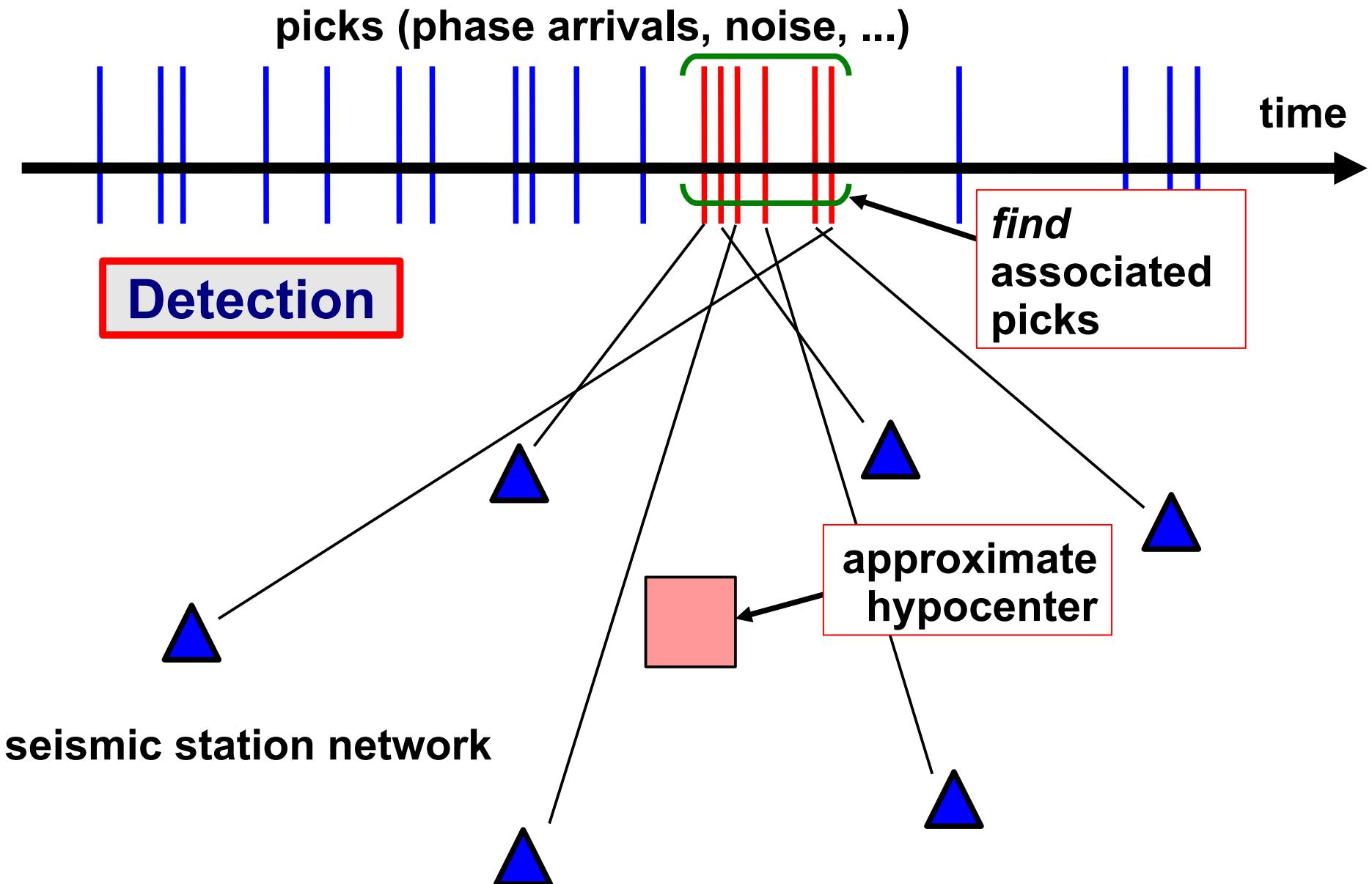
Phase picking



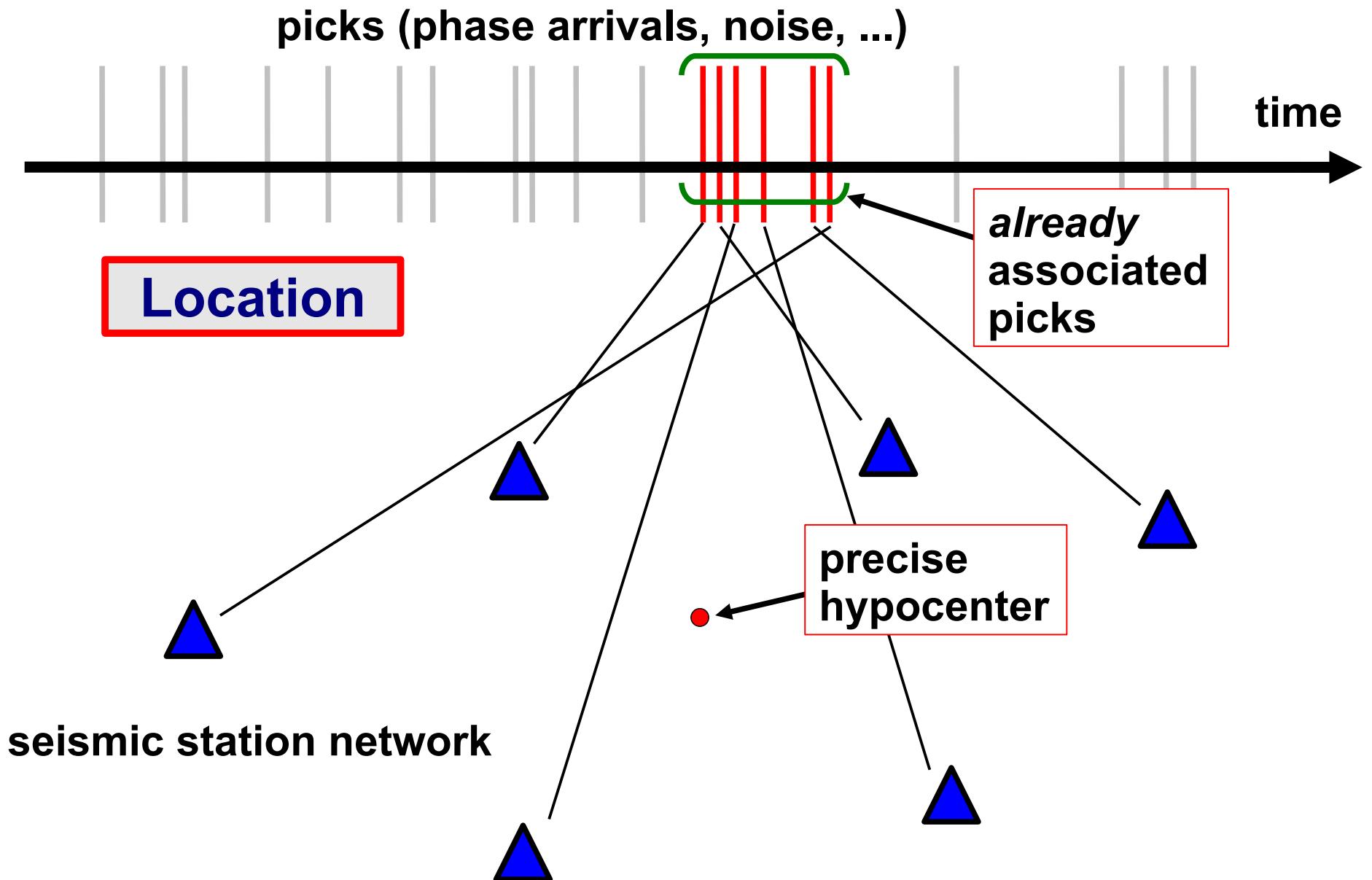
Detection vs. Location



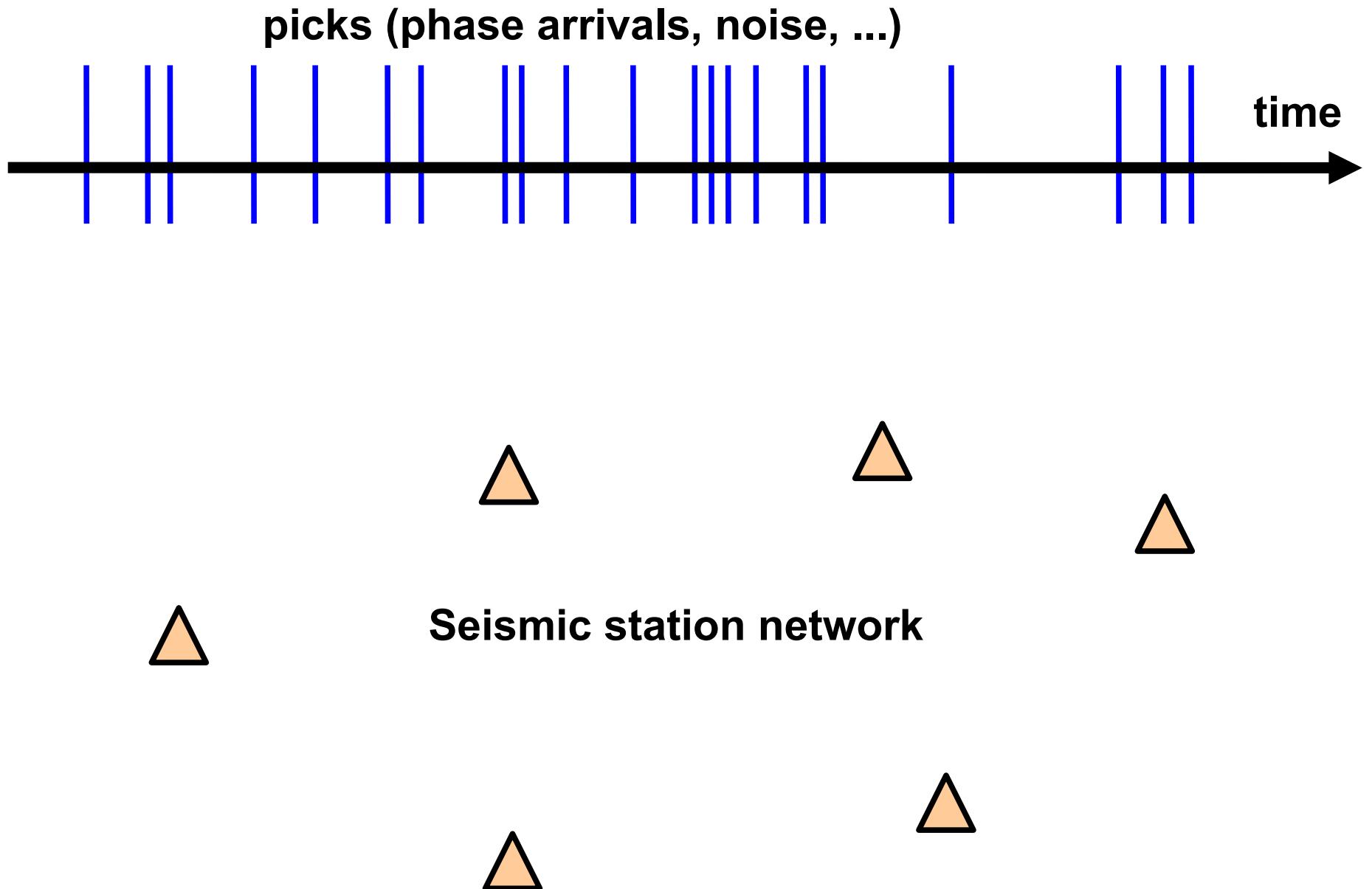
Detection vs. Location



Detection vs. Location

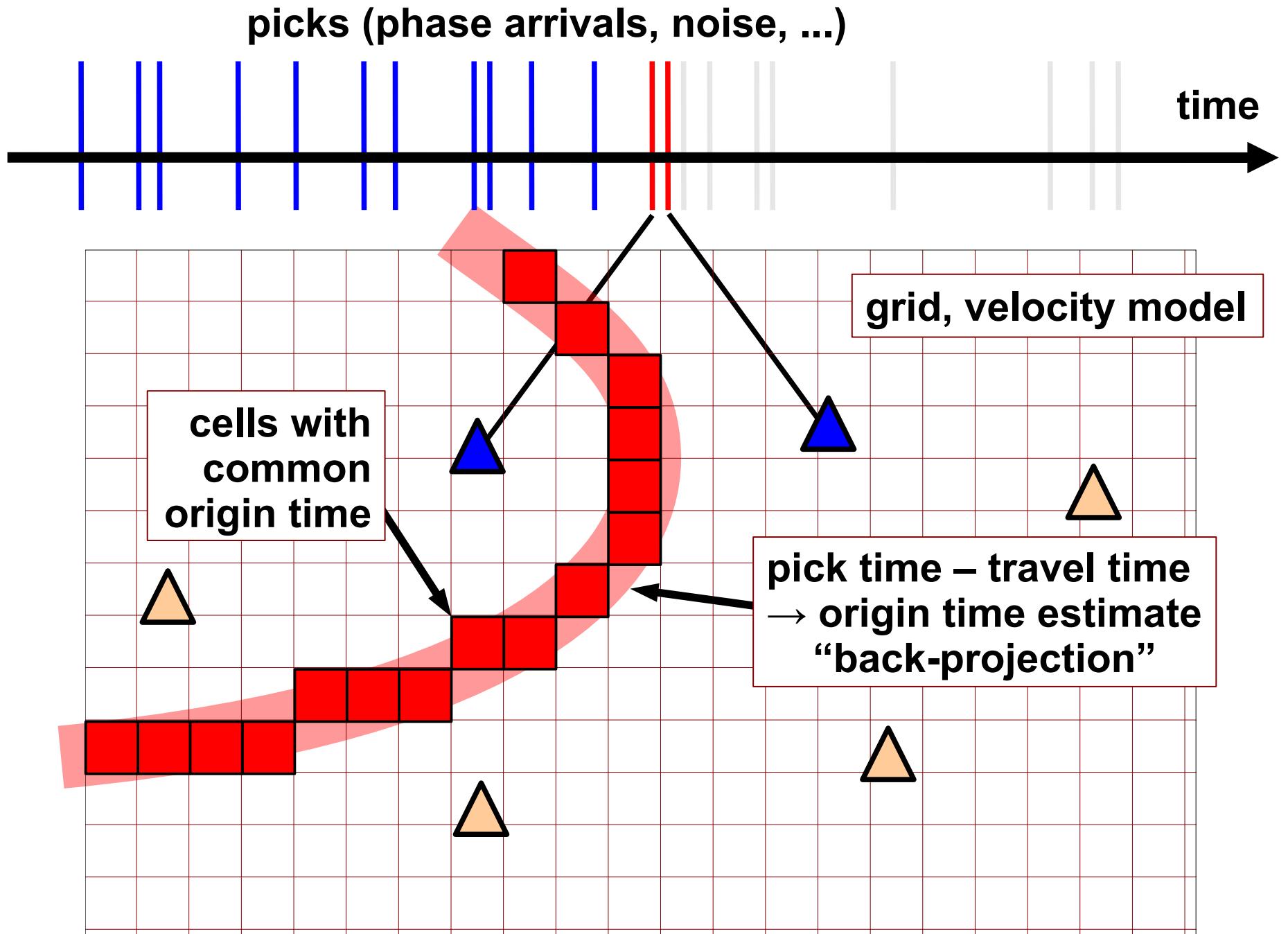


Phase association and event detection

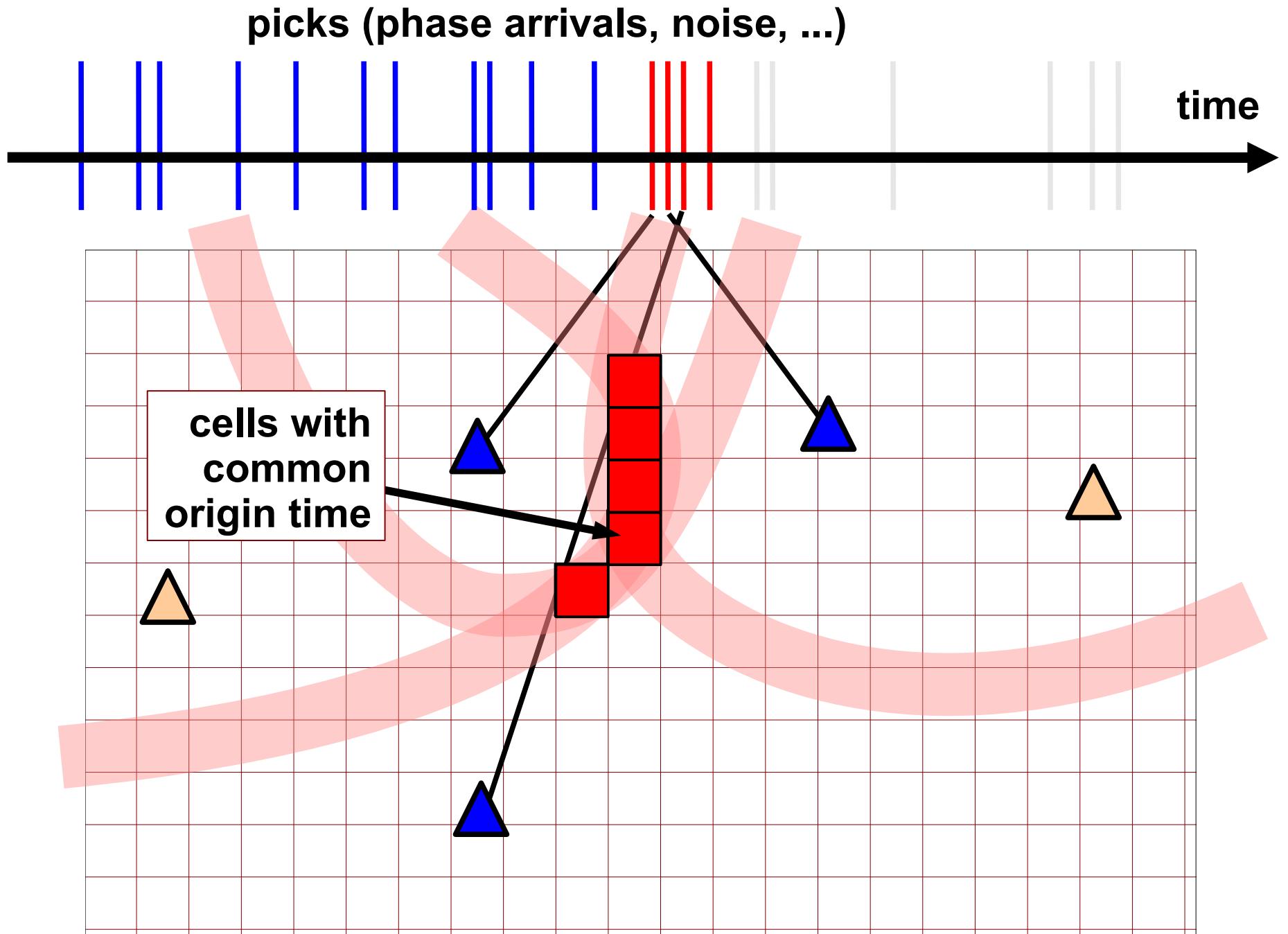


e.g. Johnson, C. E., A. Lindh, B. Hirshorn (1994) - Earthworm - SeisComP3 – USGS Glass, etc...

Phase association and event detection

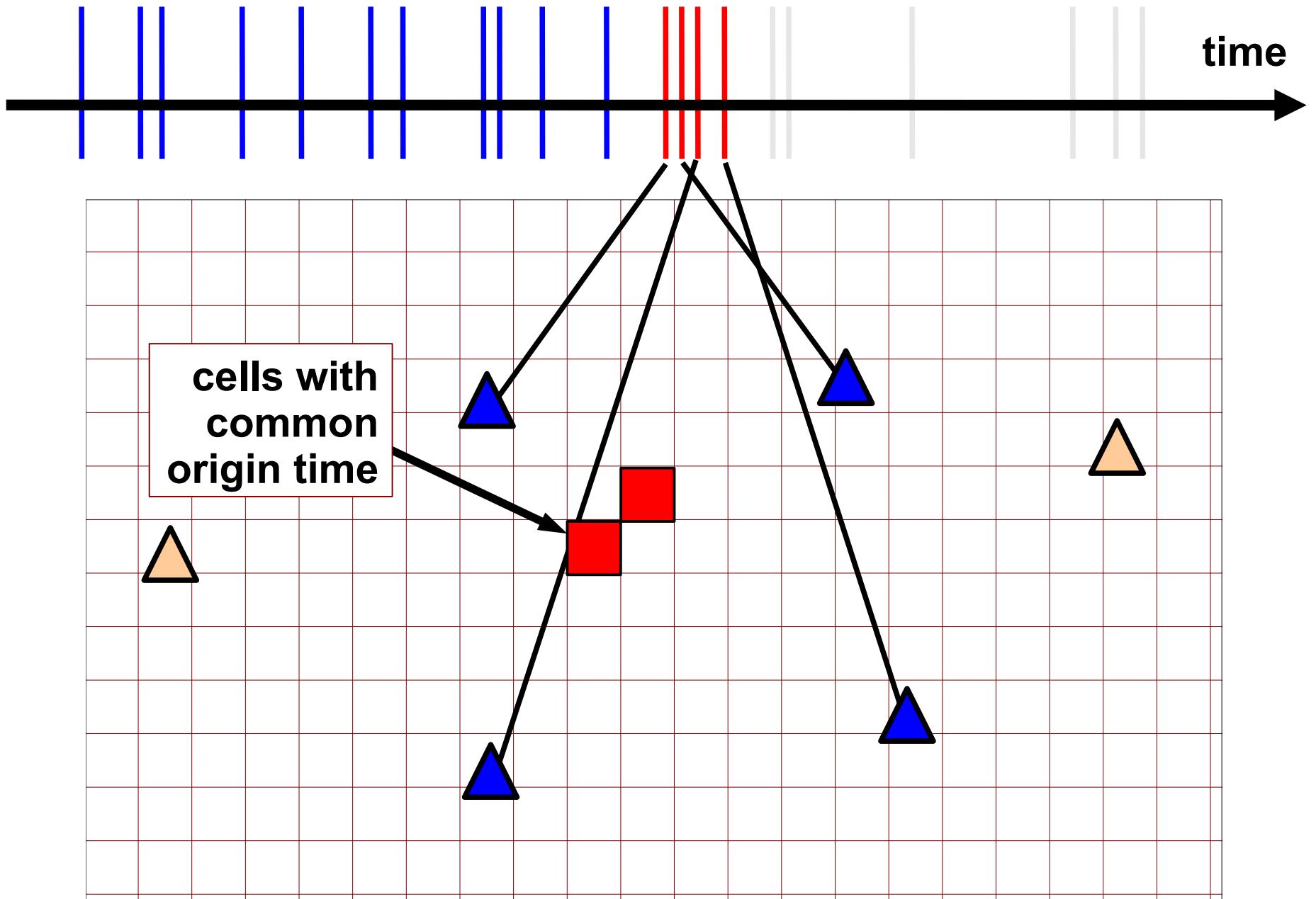


Phase association and event detection

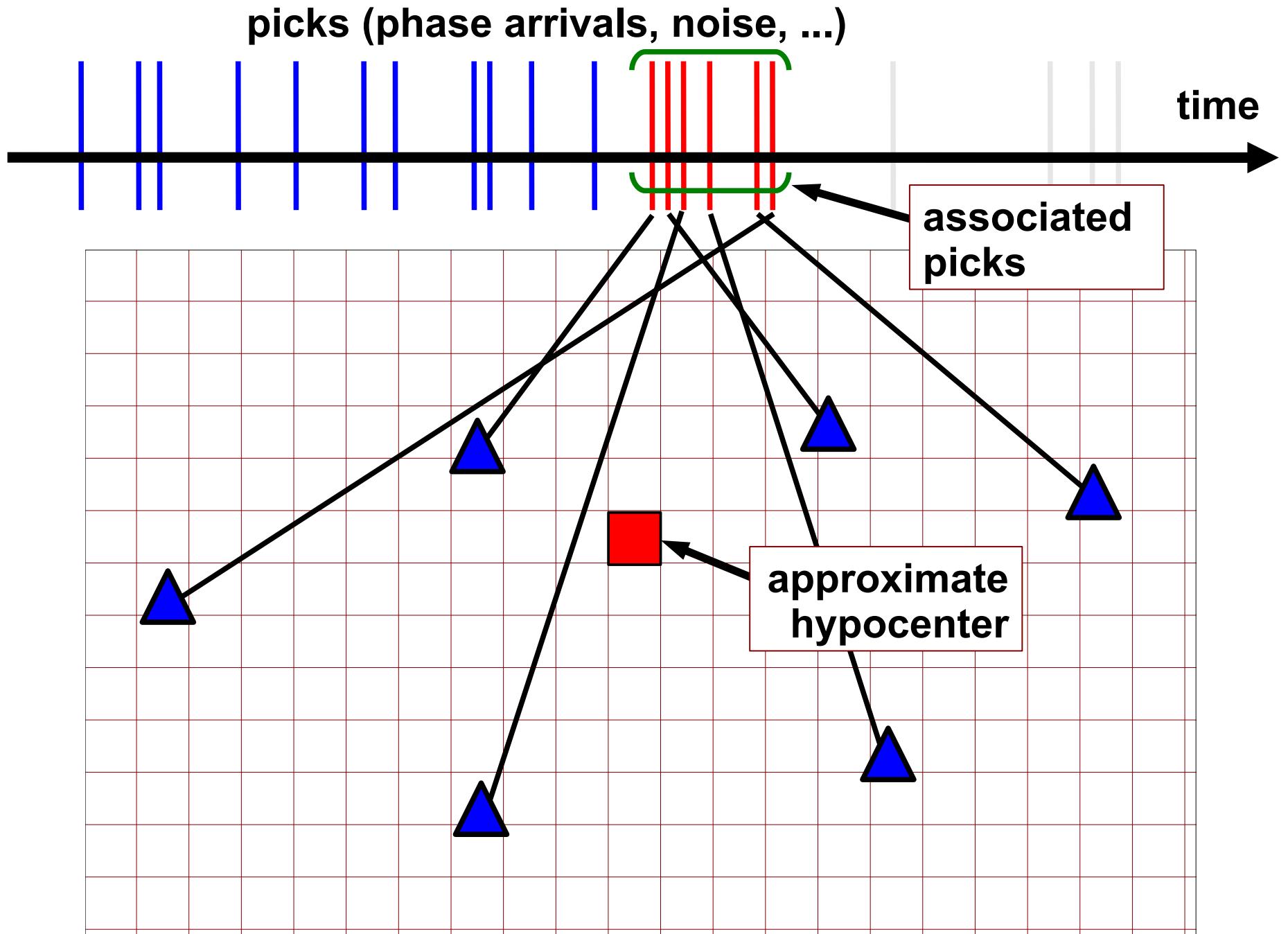


Phase association and event detection

picks (phase arrivals, noise, ...)



Phase association and event detection



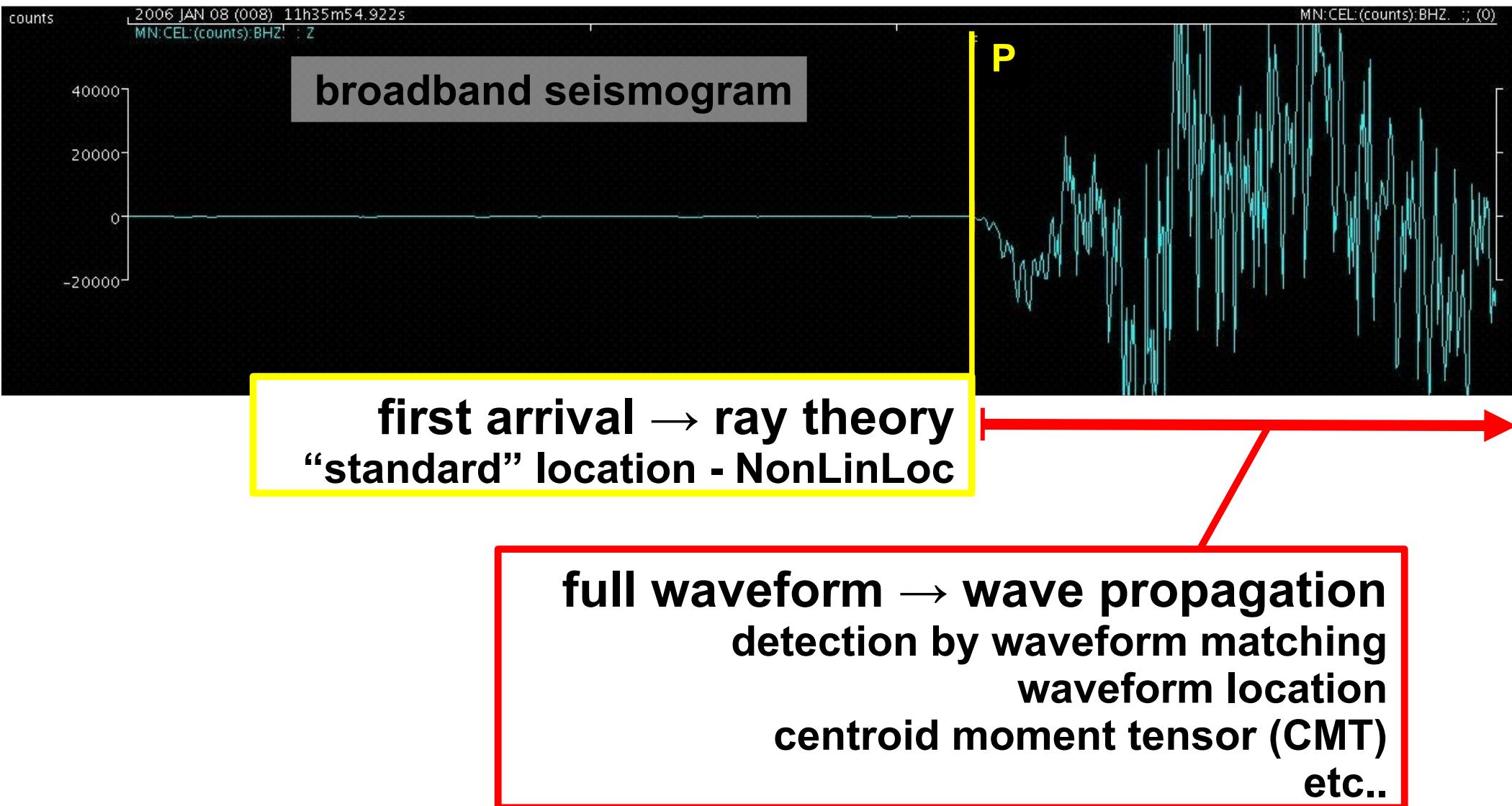
Difficulties for picking, association, location

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

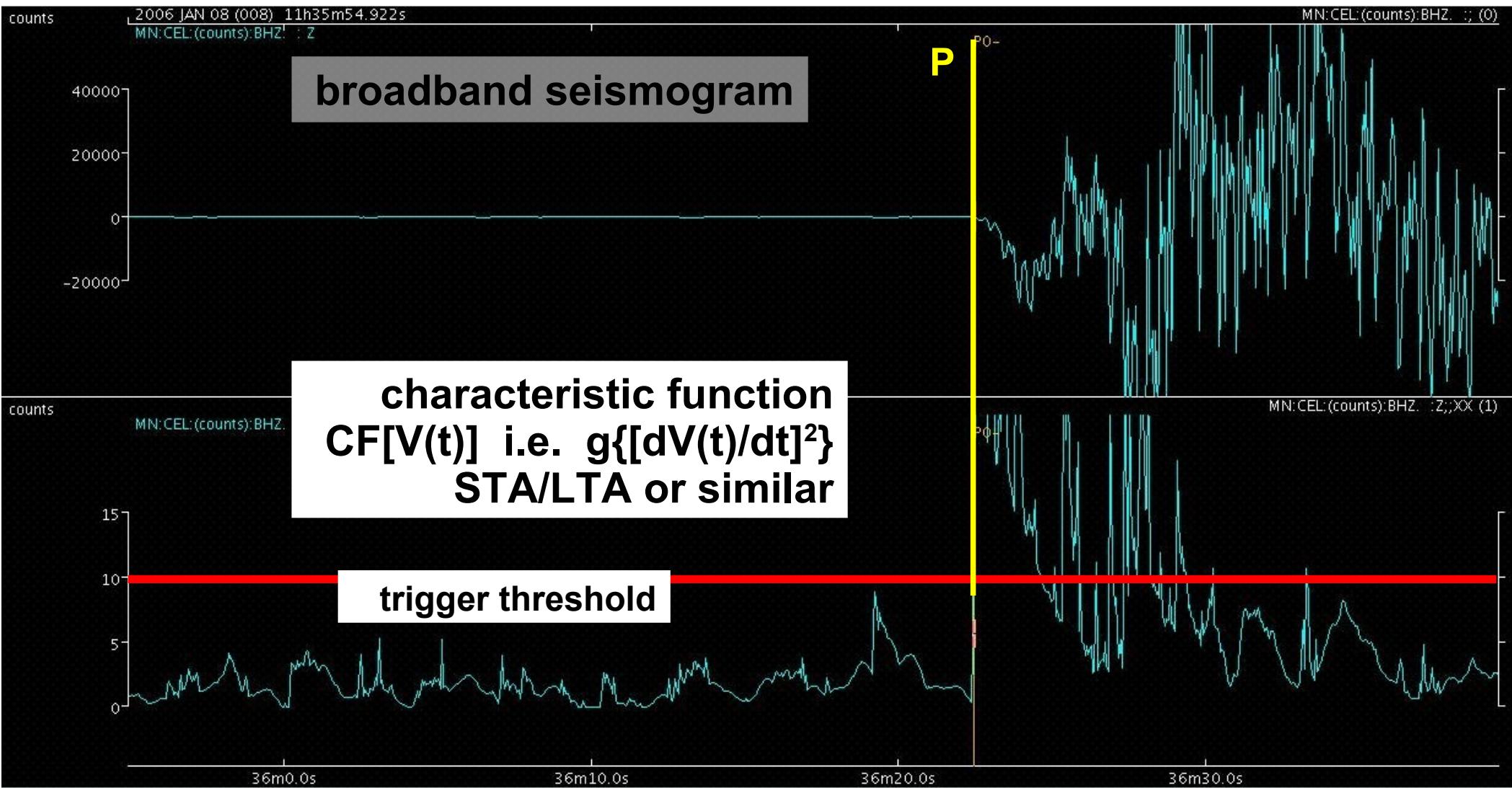
1. Phase picking, phase association and event detection

Phase picking

Phase picking – theory

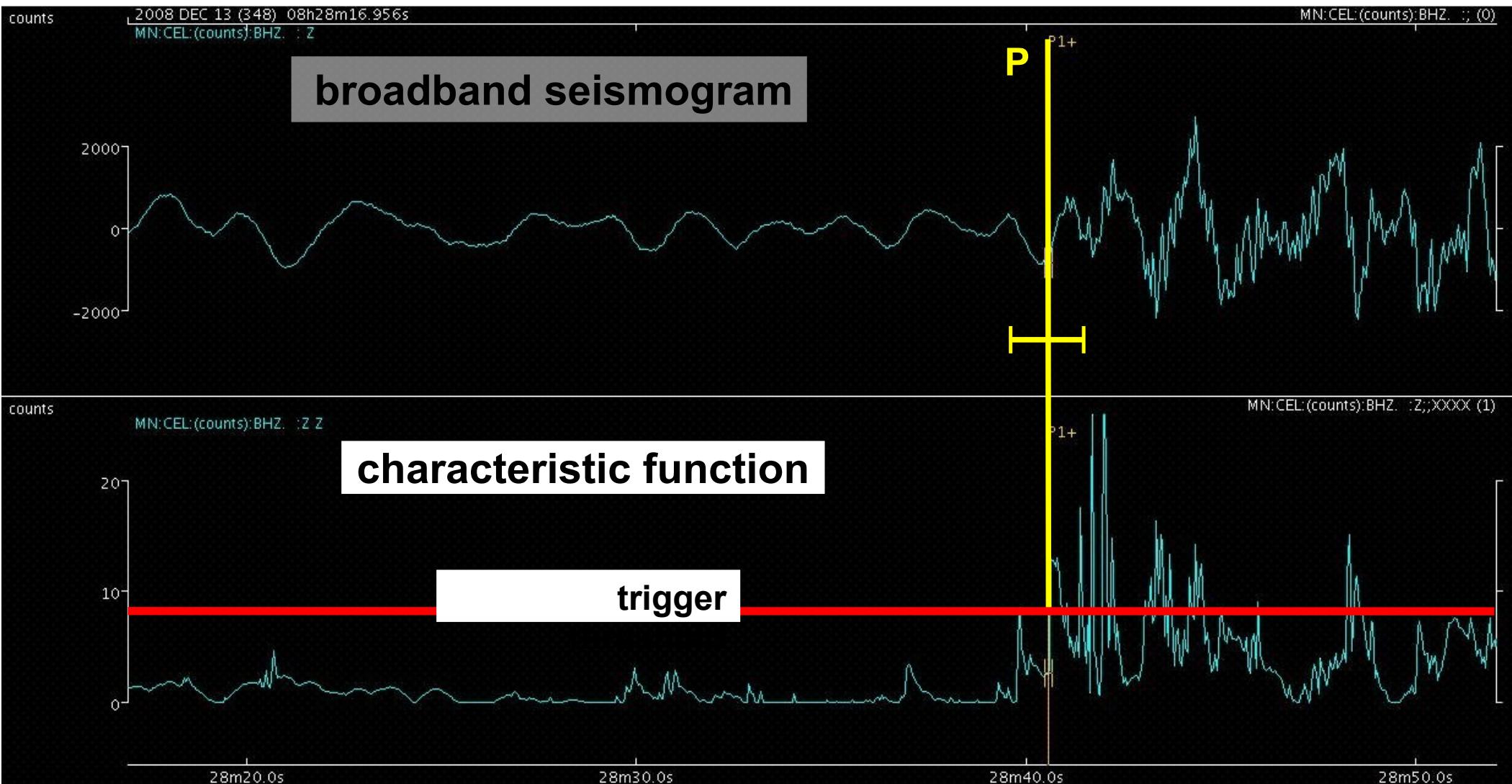


Phase picking – Automatic pickers - algorithm

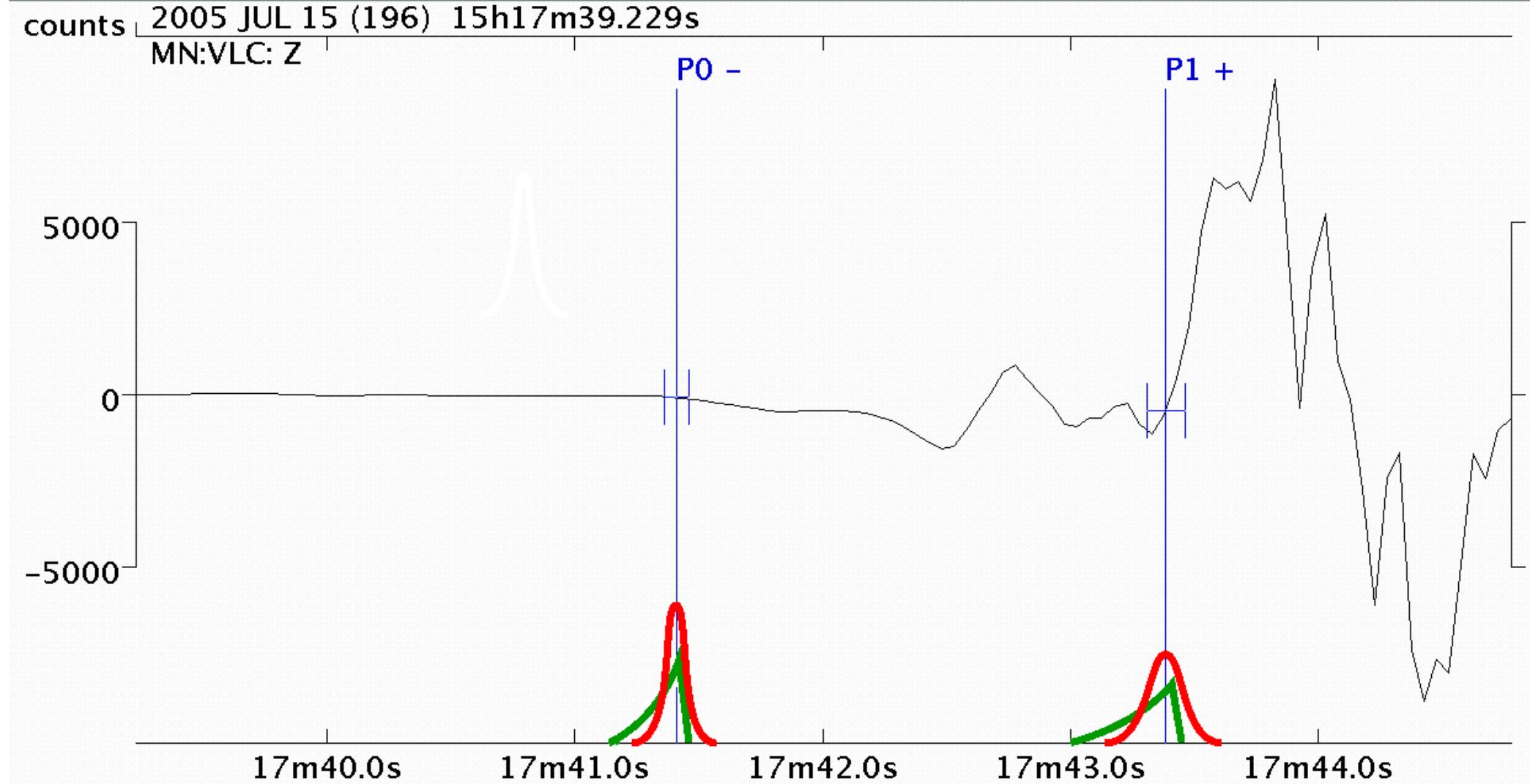


e.g. Allen, R.V. (1982) - Baer, M., and U. Kradolfer (1987) - Sleeman, R., and T. van Eck (1999) - etc...

Phase picking – Automatic pickers – noisy signal



Phase picking - Arrival times and pick uncertainty



e.g. Tarantola, A. (1987) - refs in Lomax, Michelini, Curtis (2014) - etc...

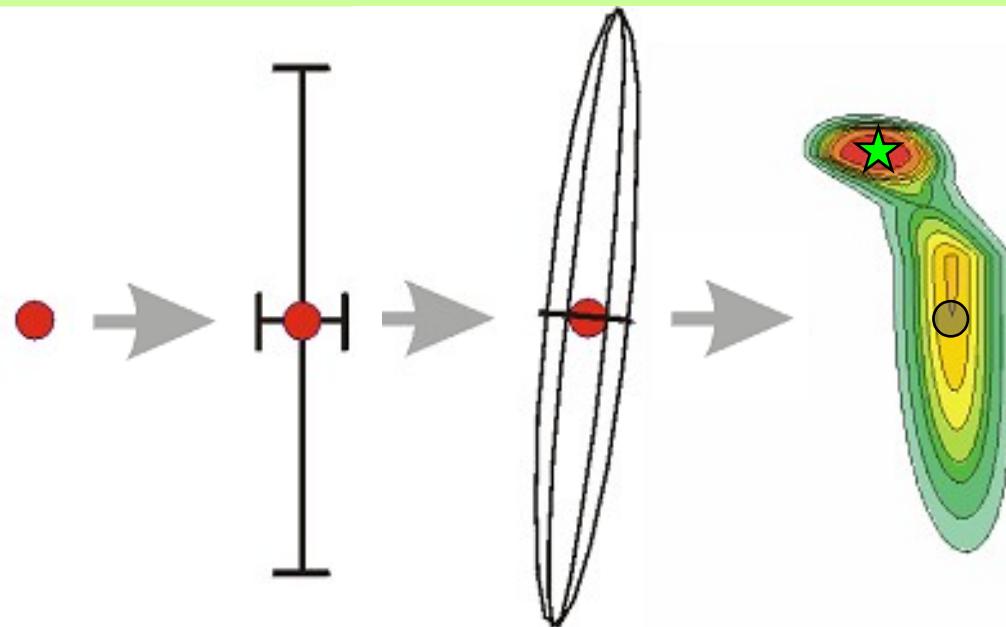
NonLinLoc Earthquake Location

2. Probabilistic, global-search earthquake location

Anthony Lomax
ALomax Scientific, Mouans-Sartoux, France

Uncertainty → Probabilistic event location

global methods (NonLinLoc)



"optimal"
location

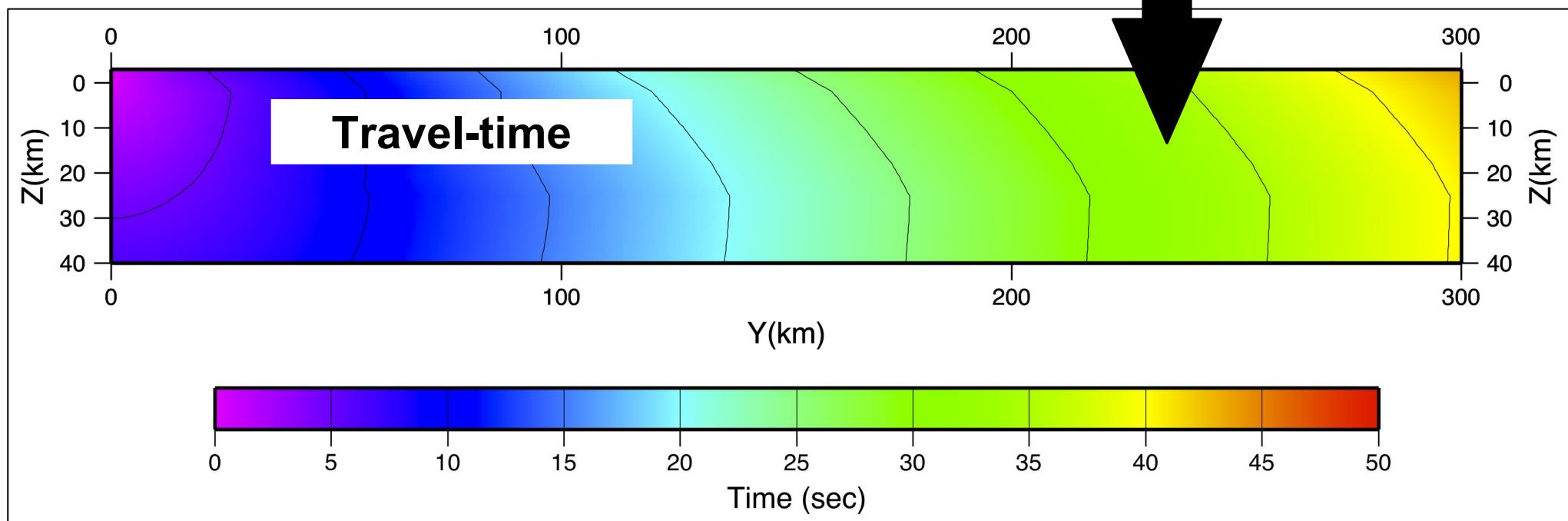
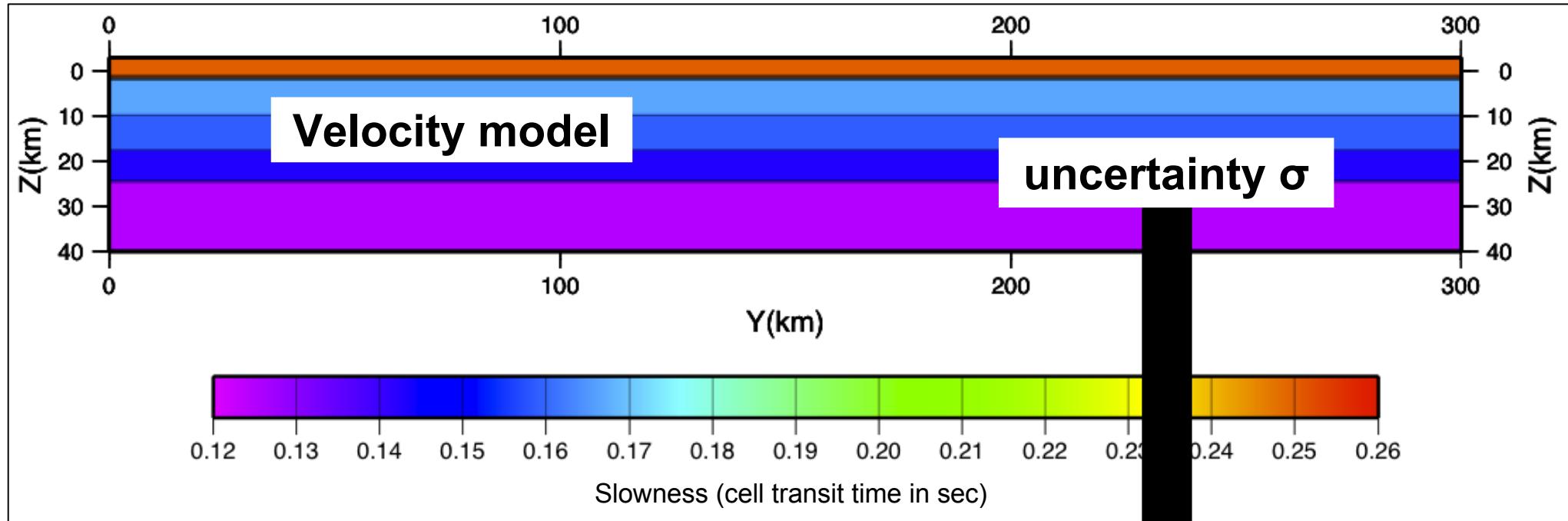
error
bars

Gaussian
confidence
ellipsoid
(~PDF)

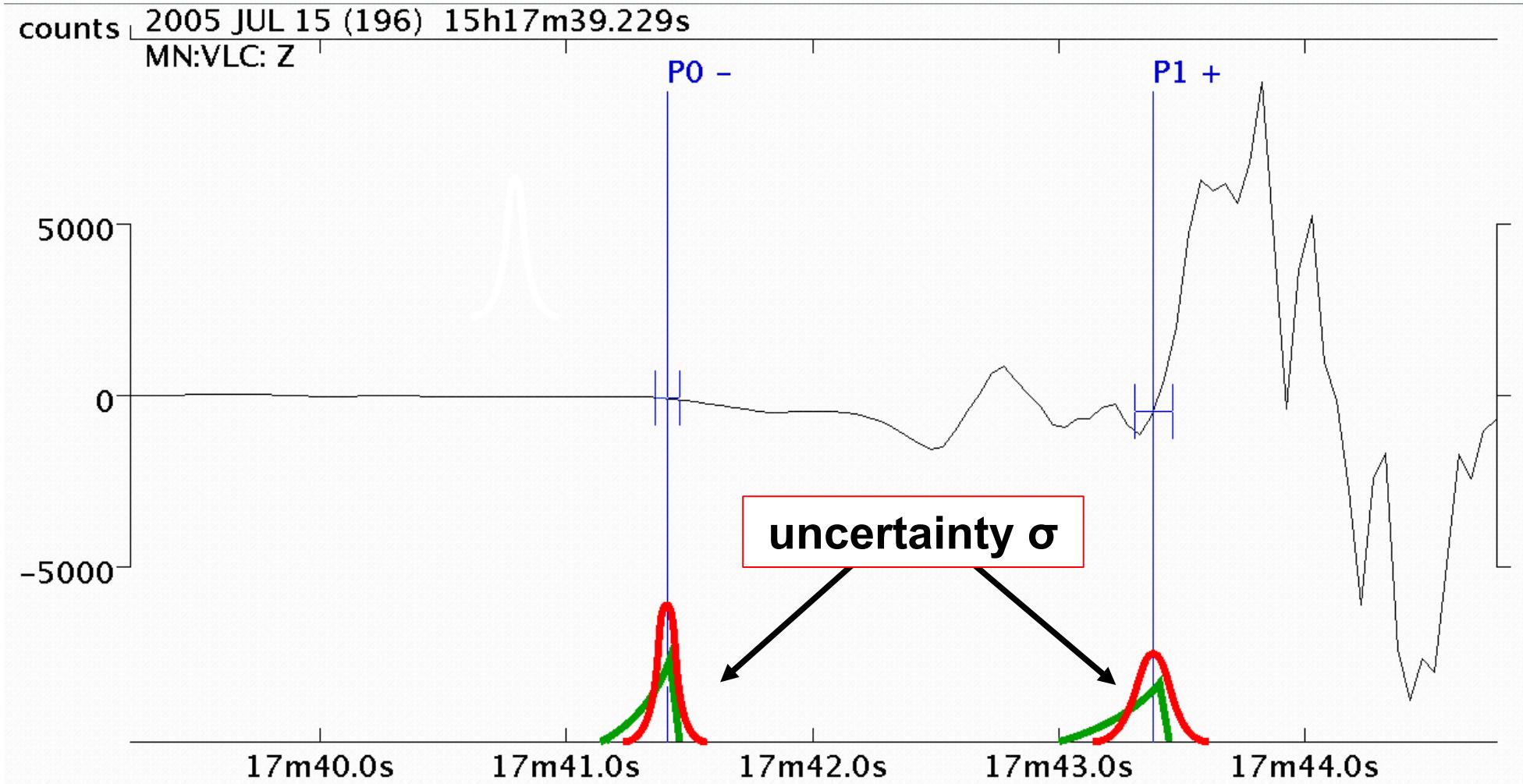
probability
density
function
(PDF)

linear methods (LocSat)

Velocity model and travel-time uncertainty



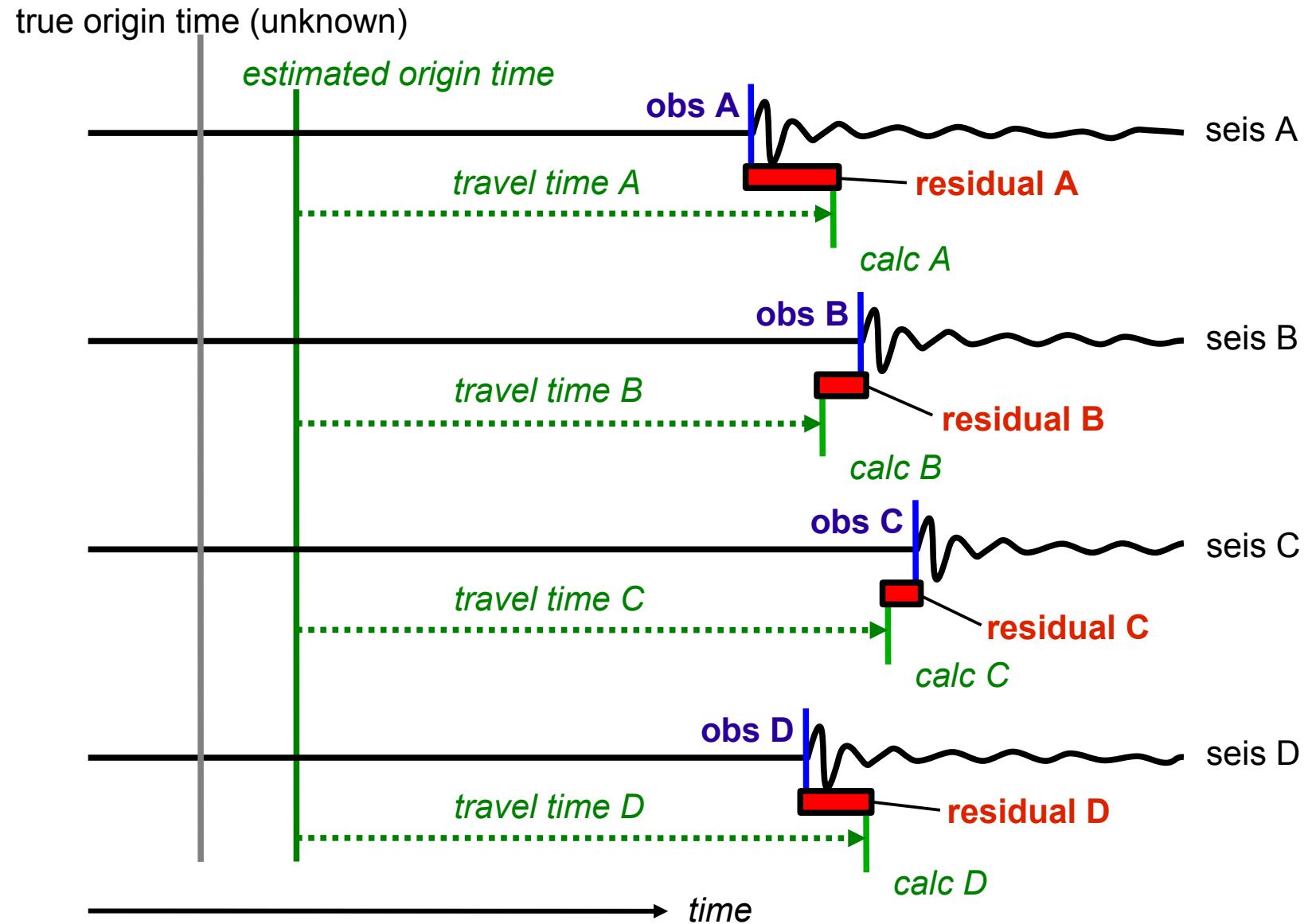
Arrival times and pick uncertainty



e.g. Tarantola, A. (1987) - refs in Lomax, Michelini, Curtis (2014) - etc...

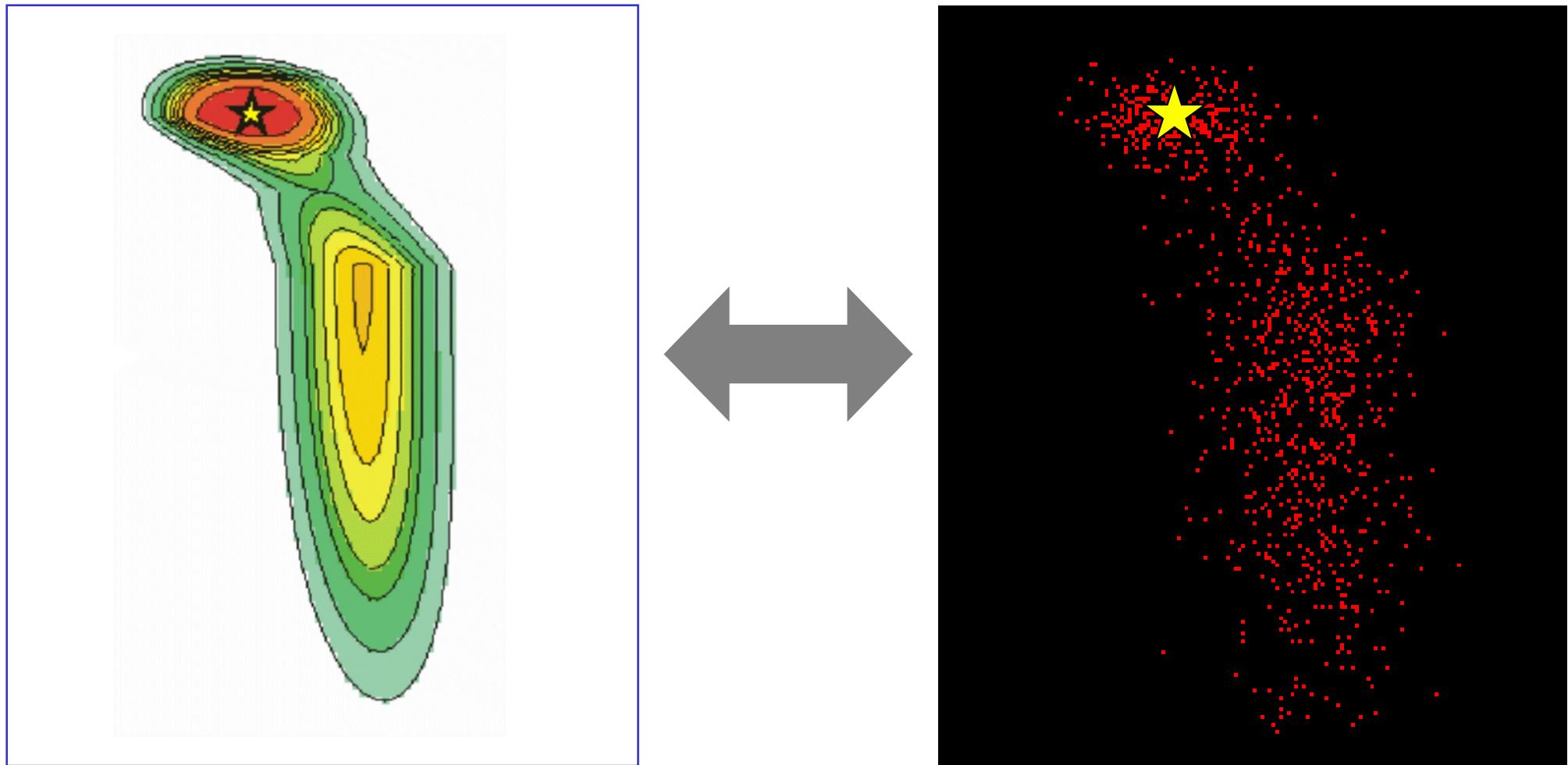
Phase pick based event location - misfit

misfit based on residual (obs-calc) values for trial location x



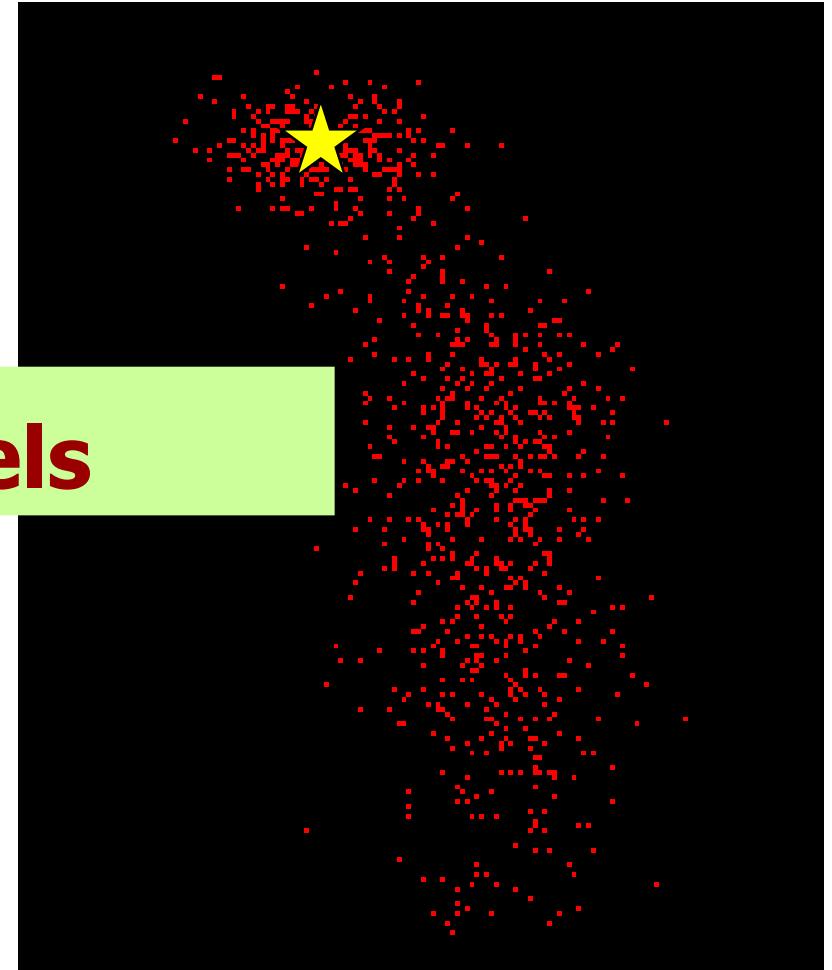
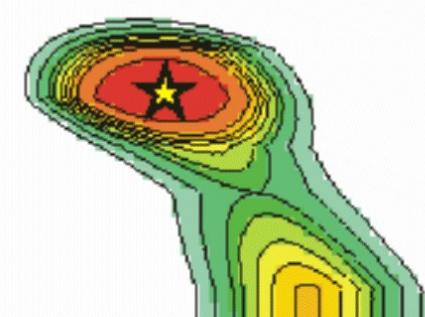
Probabilistic, global-search event location

Probability Density Function: $pdf(\mathbf{x}) = k e^{-f[misfit(\mathbf{x})/\sigma]}$

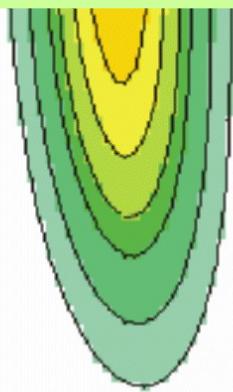


Probabilistic, global-search event location

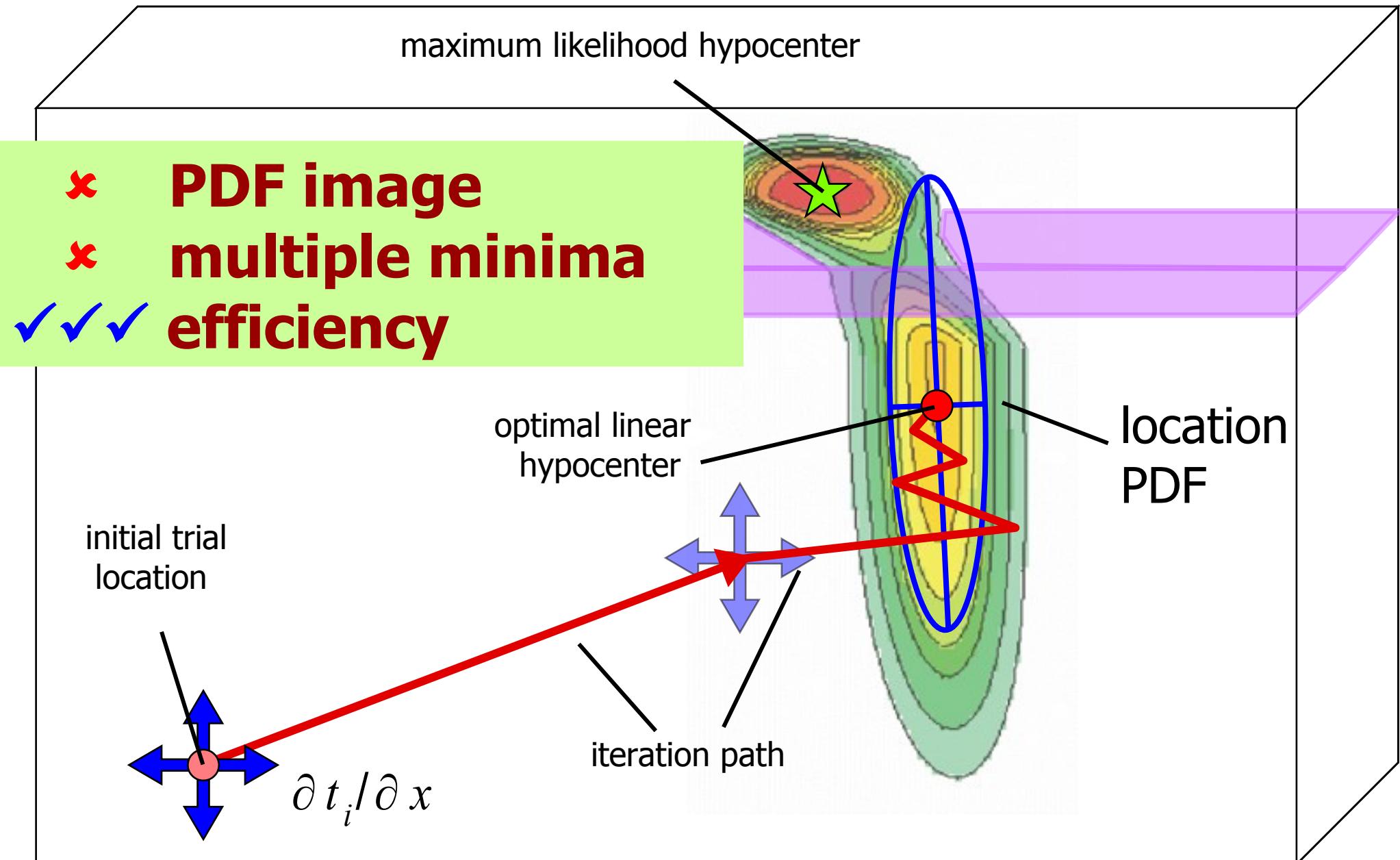
- PDF image
- multiple minima
- efficiency



→ 3D & complex models



Iterative-linearized location

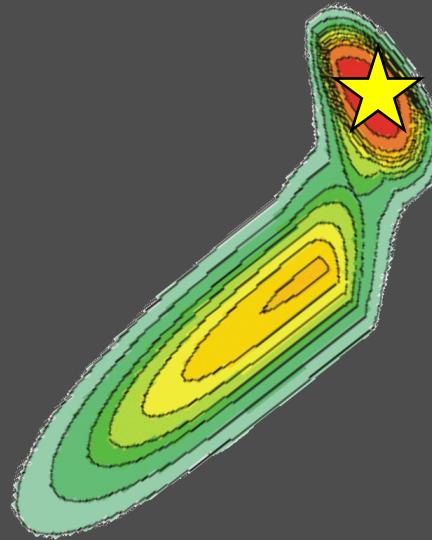


Global-Search methods: Grid search

✓✓ PDF image

✓✓ multiple minima

✗ efficiency



Global-Search methods: Directed walk

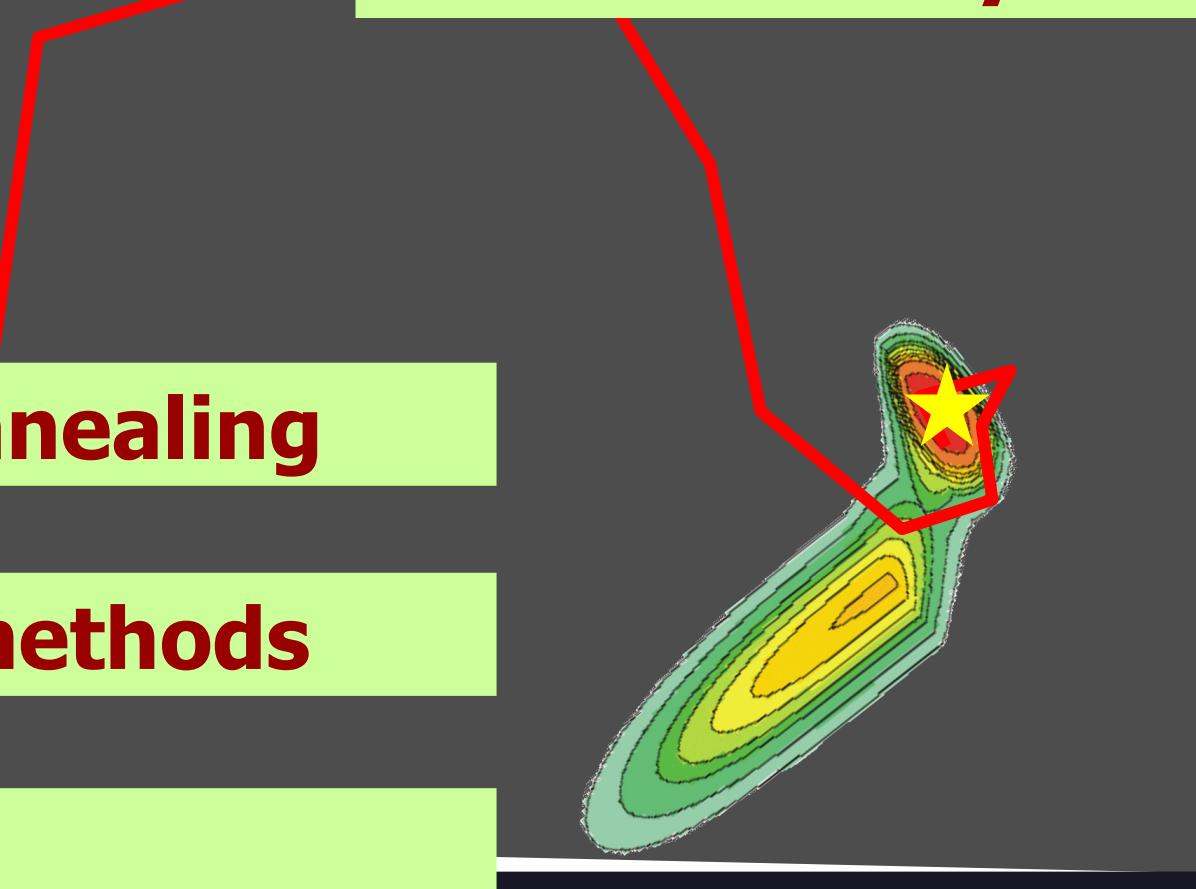


**PDF image
multiple minima
efficiency**

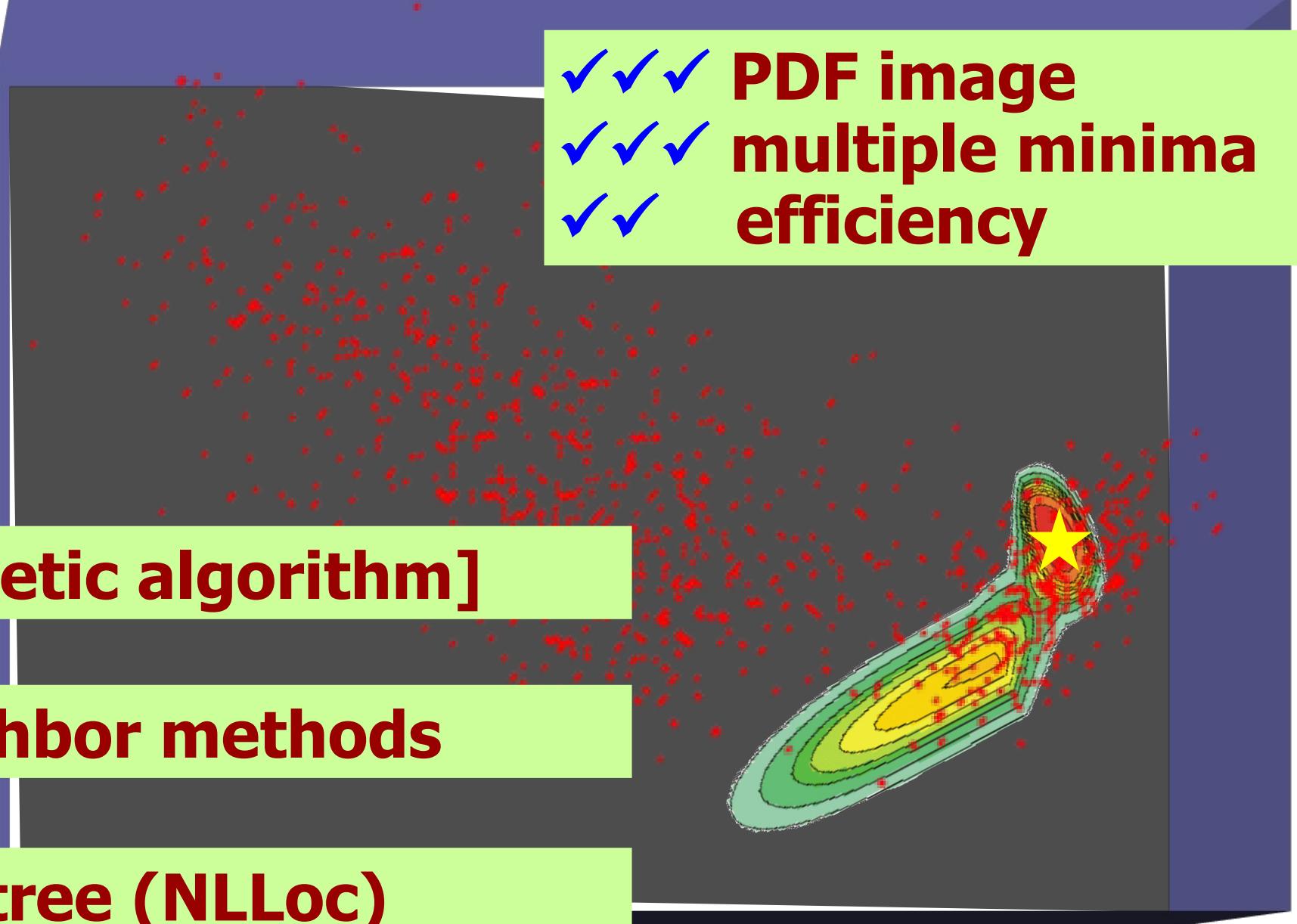
simulated annealing

metropolis methods

simplex...



Search methods: Importance sampling



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

[Genetic algorithm]

Neighbor methods

Oct-tree (NLLoc)

Break or questions?

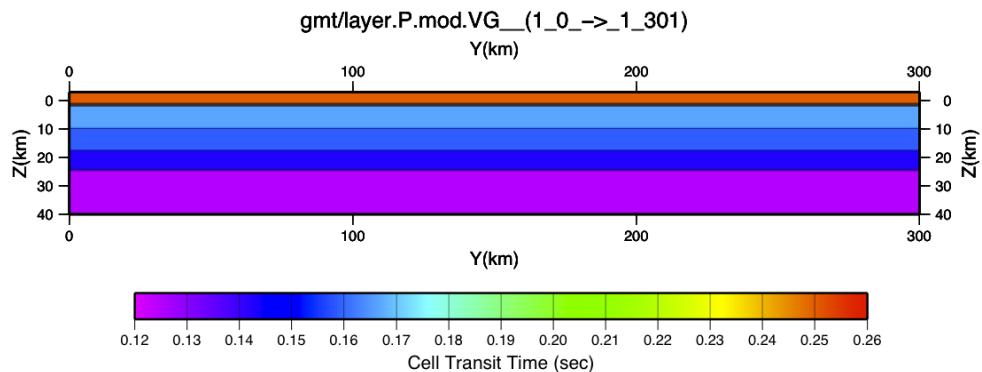
3. NonLinLoc earthquake location

Basic tools

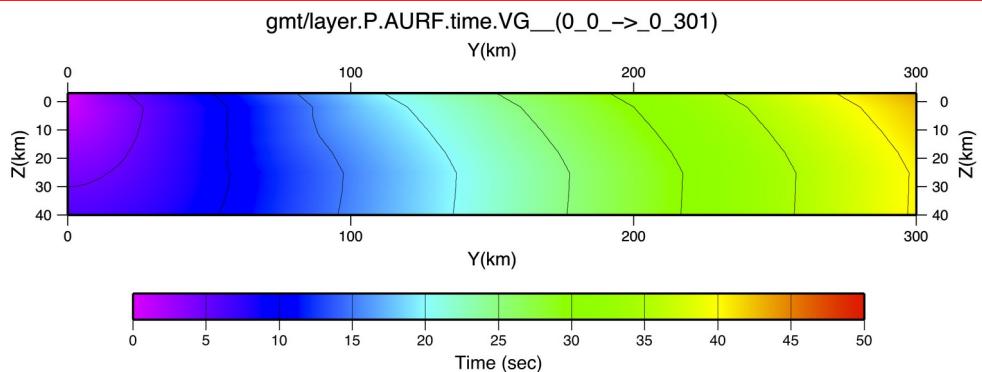
NonLinLoc Software Guide (<http://alomax.net/nlloc>)

NonLinLoc Earthquake Location – Basic Tools

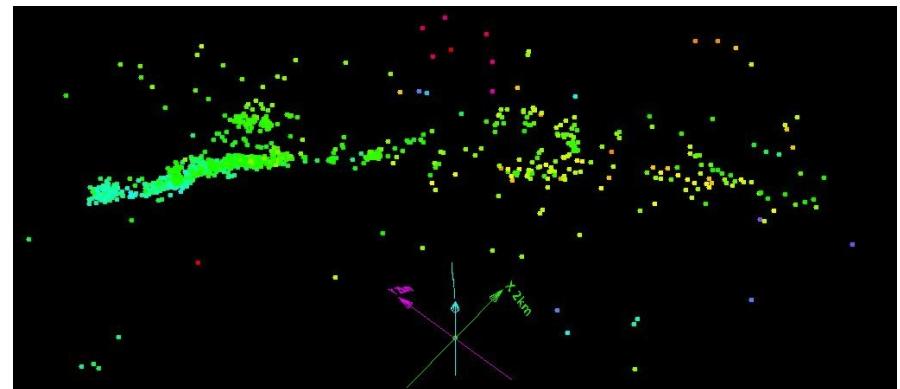
- **Vel2Grid** - velocity model description to 2D or 3D model grid



- **Grid2Time** - 3D model grid to travel-time and angles grids

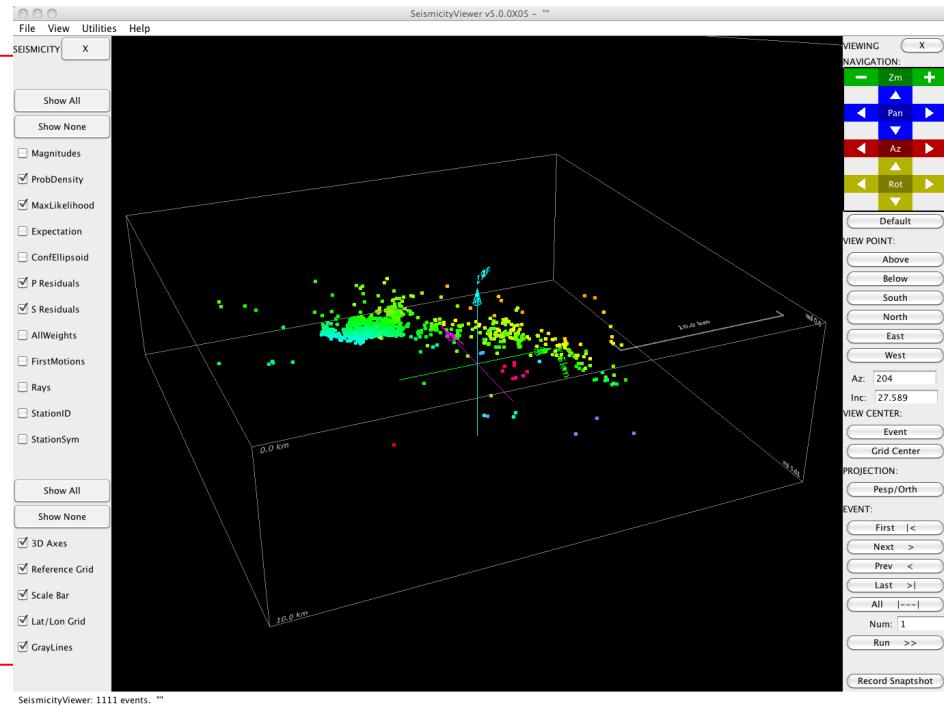


- **NLLoc** - Global-search earthquake location

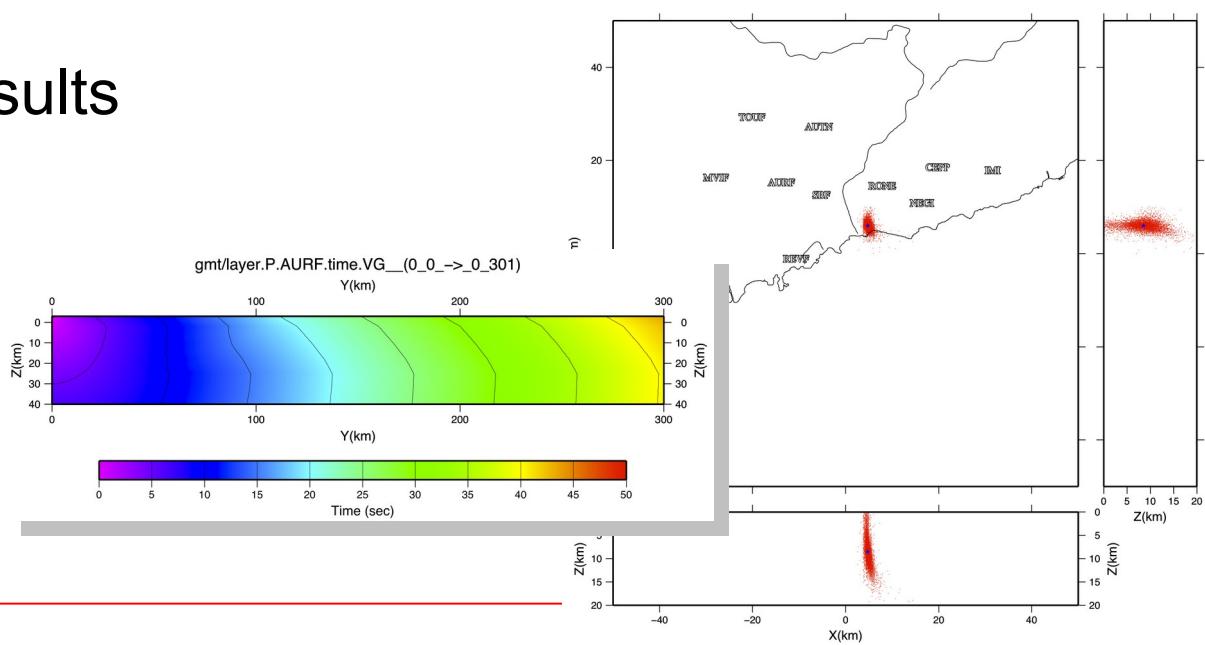


NonLinLoc – Basic Visualization Tools

- **Seismicity Viewer** - Java program for interactive viewing of earthquake locations and geographic information in a 3D space



- **Grid2GMT** - location results or 3D grid data to GMT command script and plot



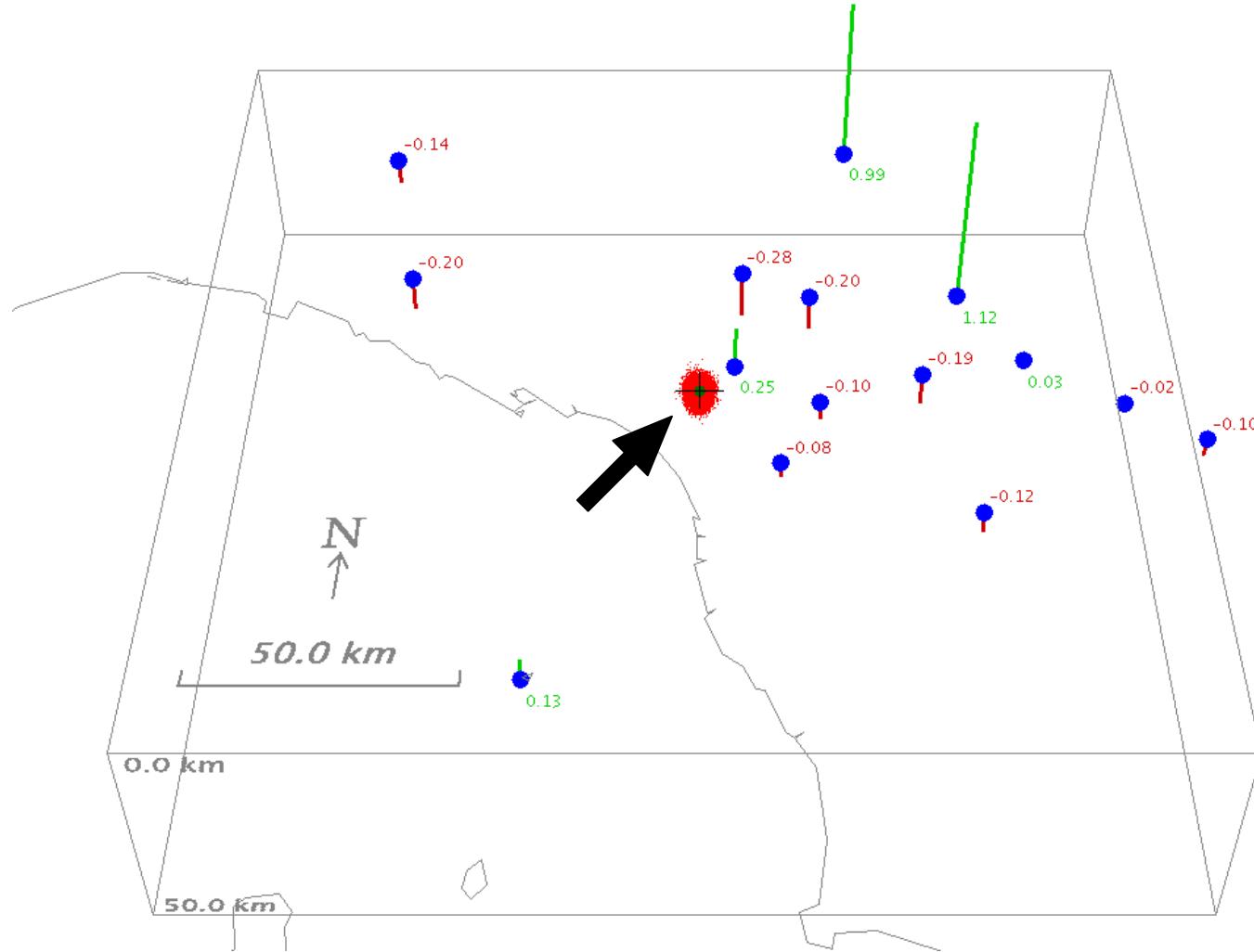
3. NonLinLoc earthquake location

Geography and geometry

NonLinLoc Software Guide (<http://alomax.net/nlloc>)

Earthquake Location

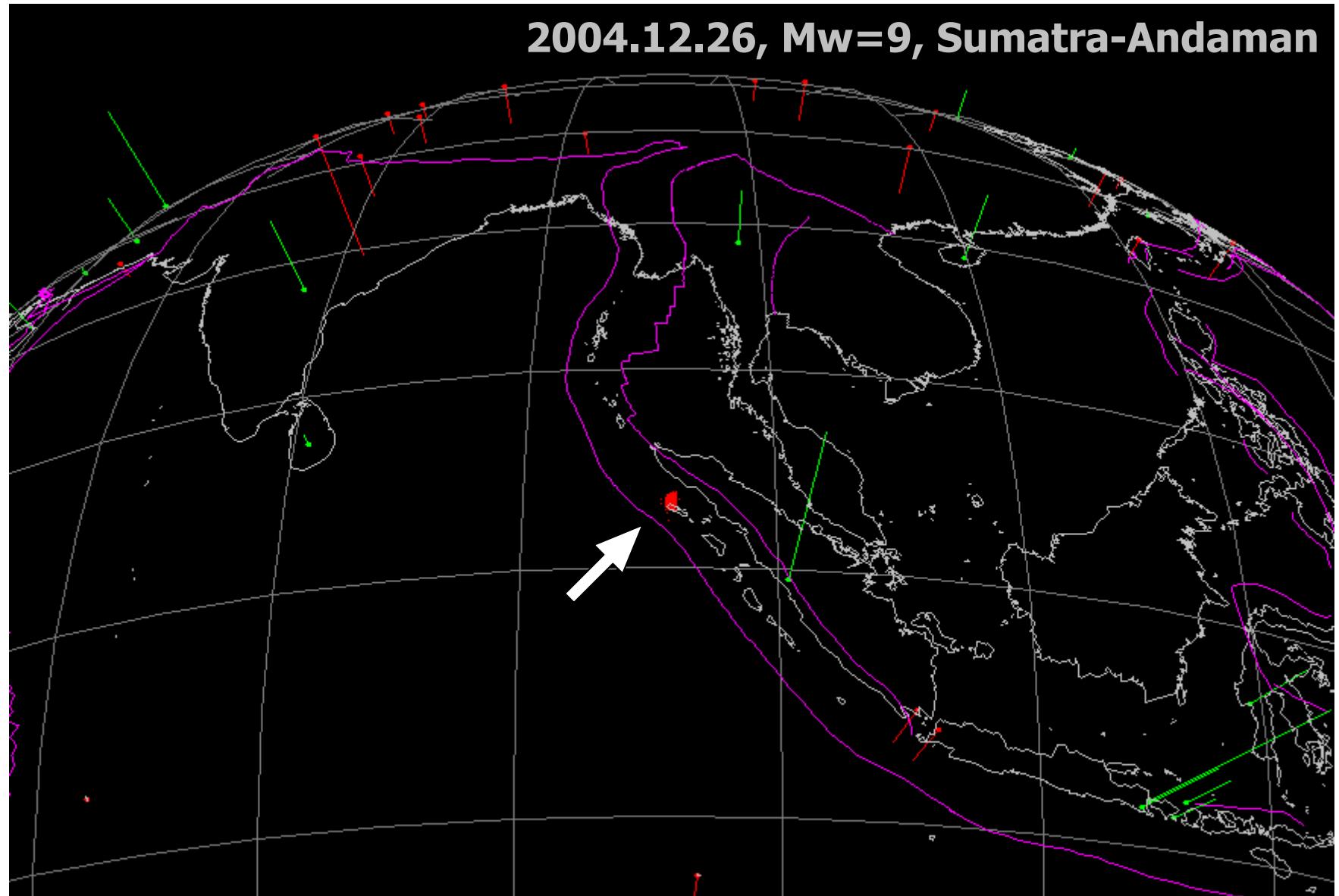
local/regional – Cartesian / rectangular coordinates



e.g. Lahr, J.C. (1999) - Tarantola, A. (1987) – refs in Lomax, Michelini, Curtis (2014) - etc...

Earthquake Location

teleseismic – spherical coordinates



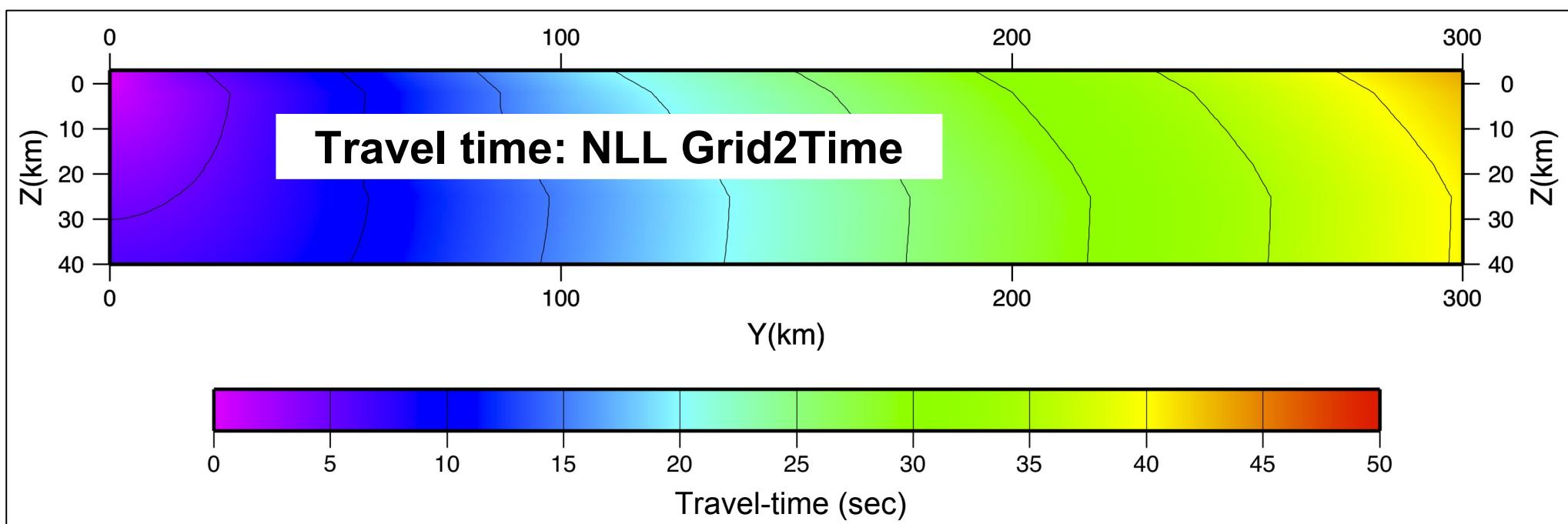
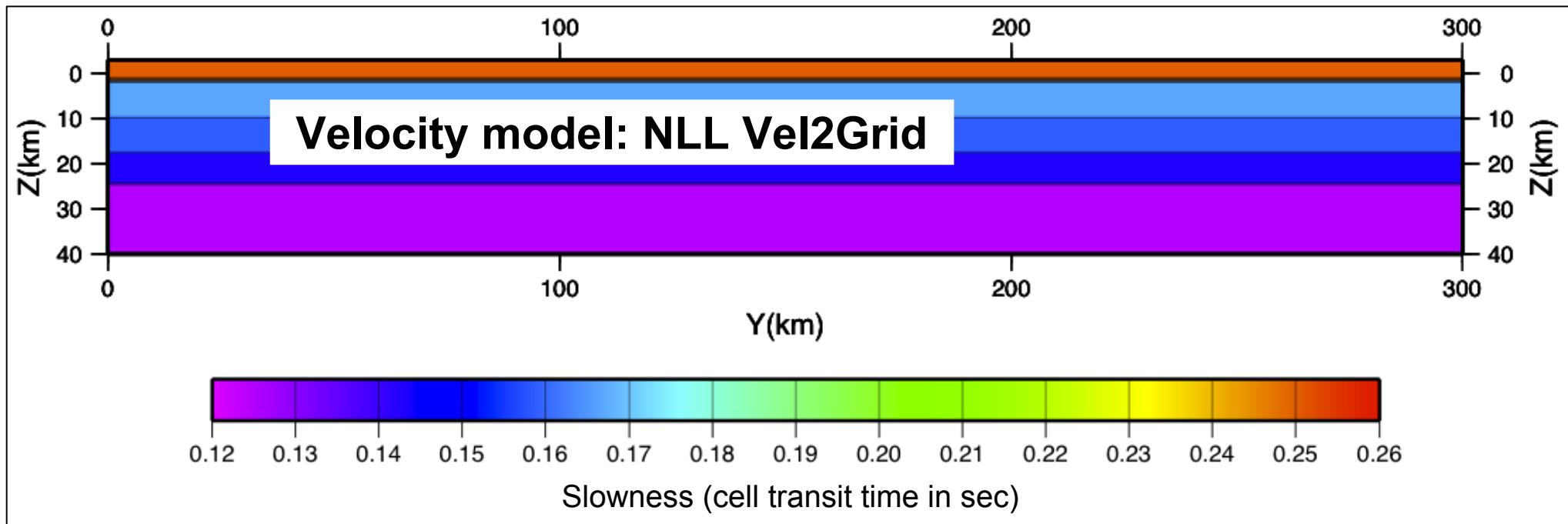
e.g. Lahr, J.C. (1999) - Tarantola, A. (1987) – refs in Lomax, Michelini, Curtis (2014) - etc...

3. NonLinLoc earthquake location

Velocity Model and Travel-time Calculations

NonLinLoc Software Guide (<http://alomax.net/nlloc>)

Velocity Model and Podvin-Lecomte Travel-time



Podvin-Lecomte Finite-Differences Travel-time Calculation



Figure 2. Sketch of wavelets emitted by an interface in 2-D.

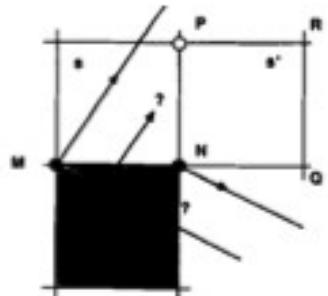


Figure 3. Transmission in 2-D. When only points



Figure 5. Local shadow zone in 2-D. Corner M acts as a secondary source.

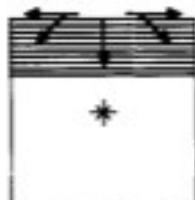
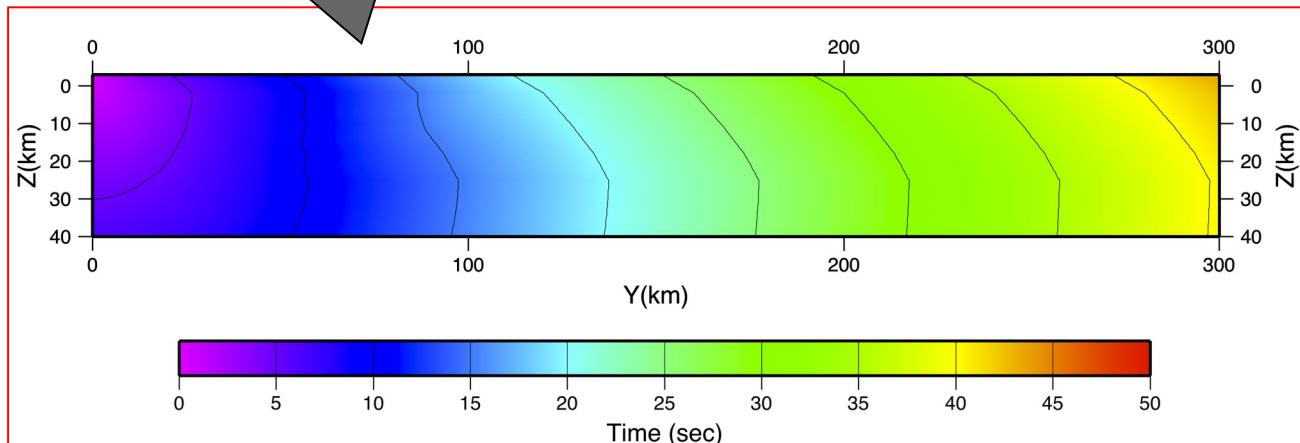


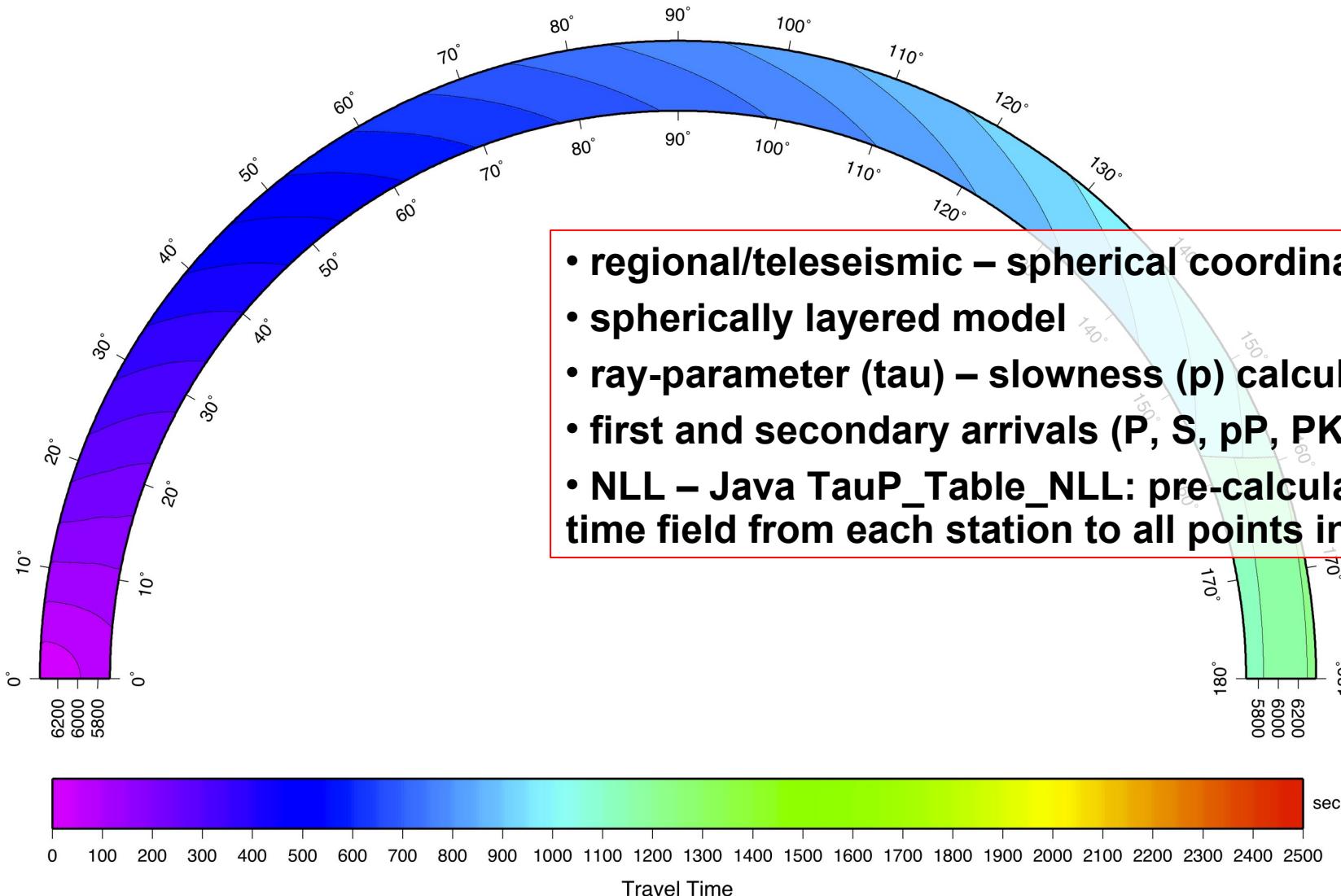
Figure 11. Reverse propagation. When head waves are generated

- local/regional – Cartesian coordinates
- square (2D) or cubic (3D) grid: $dx=dy=dz$
- rule and template based calculation
- first-arrivals (direct or head-waves)
- NLL – Grid2Time: pre-calculate and store time field from each station to all points in model

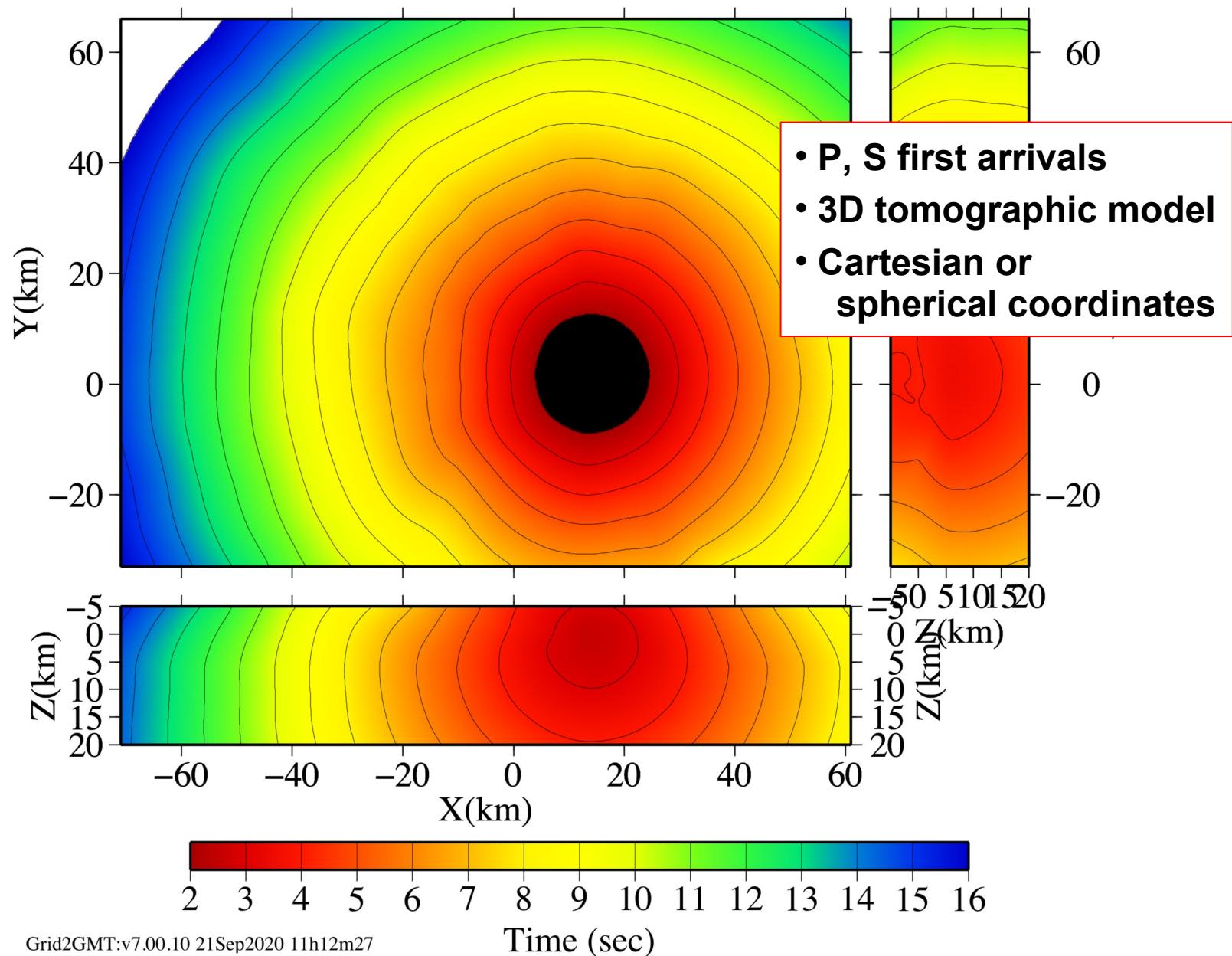


Tau-P Toolkit Travel-time calculation

./ak135/ak135.P.DEFAULT.time



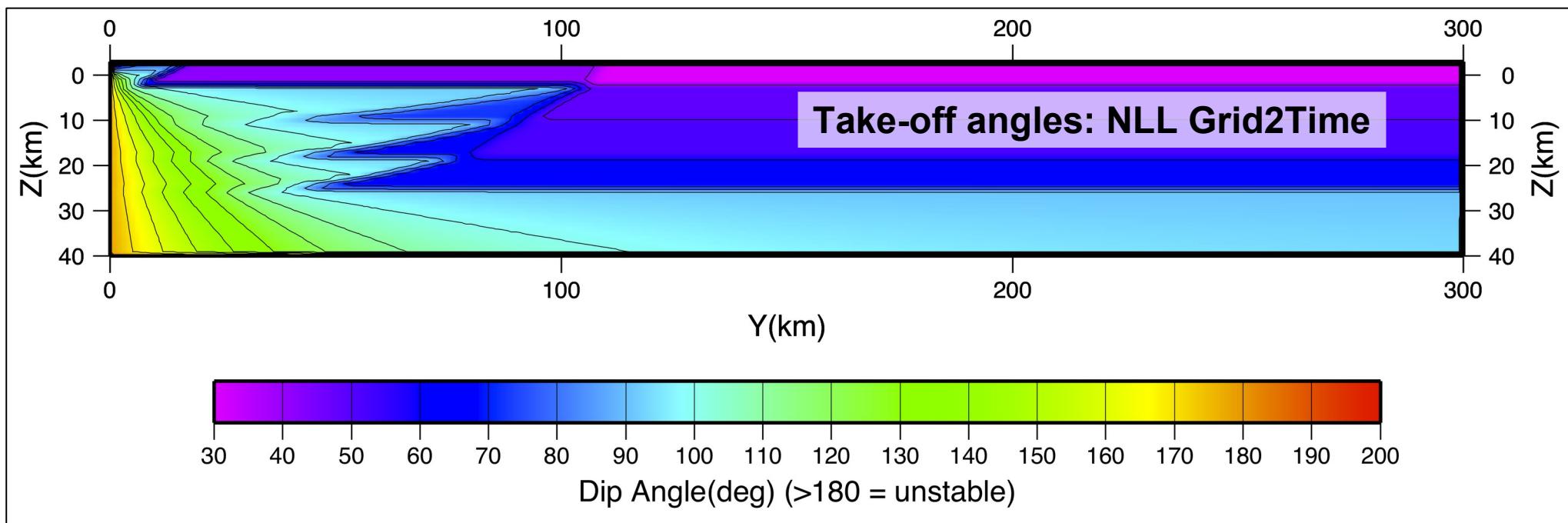
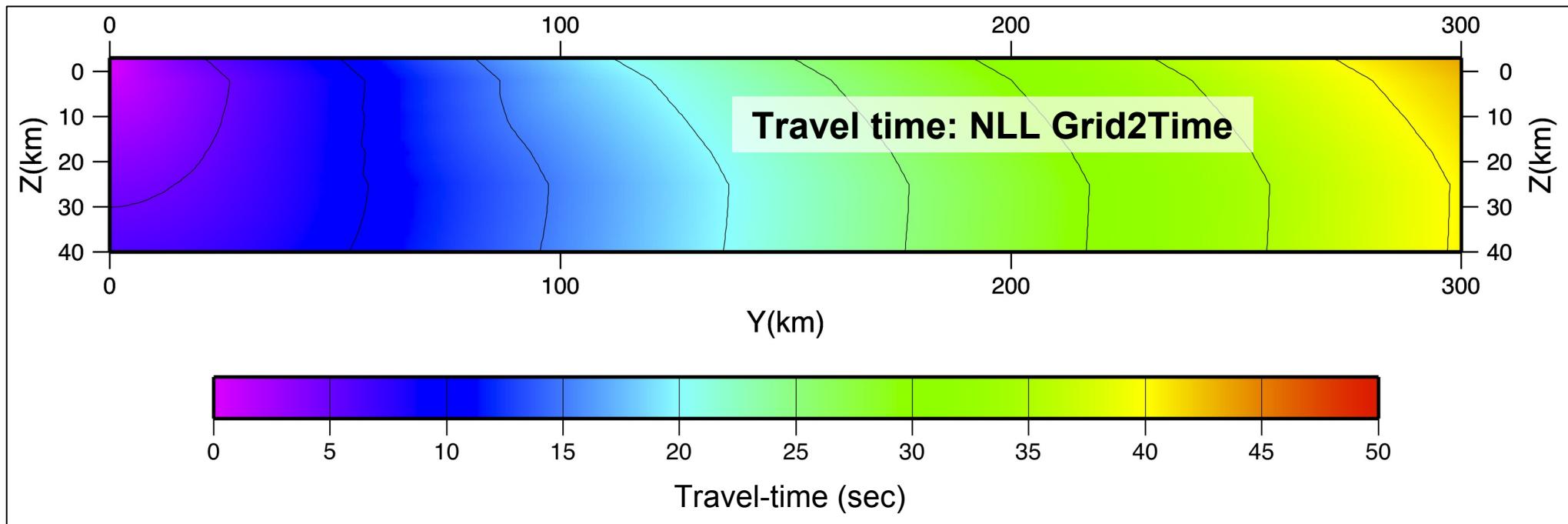
3D Travel-time calculation



Grid2GMT:v7.00.10 21Sep2020 11h12m27

(Travel-time grid from Lomax, 2020)

Travel-times → Take-off angles



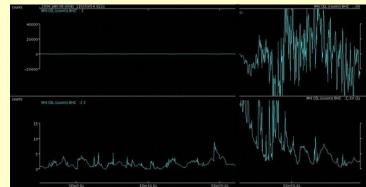
Location → NLLoc

Read control file

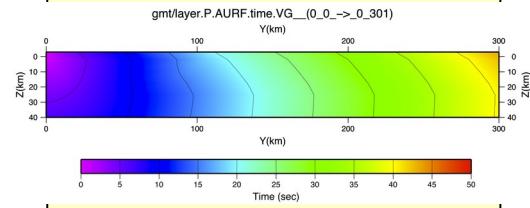
```
# nmlloc control file statements  
#  
#  
# LOCsig -- Signature text  
# optional, non-repeatable  
#  
# signature  
# (LOCsig signature)  
  
LOCSIG Anthony Lomax - INGV Alta Valle del Tevere  
#  
# LOCcom -- Comment text  
# optional, non-repeatable  
#  
# comment  
# (LOCcom comment)  
  
LOCCKM 2010-2011 AVT Experiment (NonLinLoc Location)  
  
#  
# Input/Output files  
# required, non-repeatable  
# input grid filenames root, output filename  
# (LOCFILES .vobs File: obs_type, travel-time grid files path/n  
# (char!) obs_type : (NLLOC_000, HYPO72, HYPOLINE, RSEA  
#  
LOCFILES ./PM5_HAN0/*.spo HYPOELLIPE /tmp/nlloc_tmp/INV_AVT.
```

first event

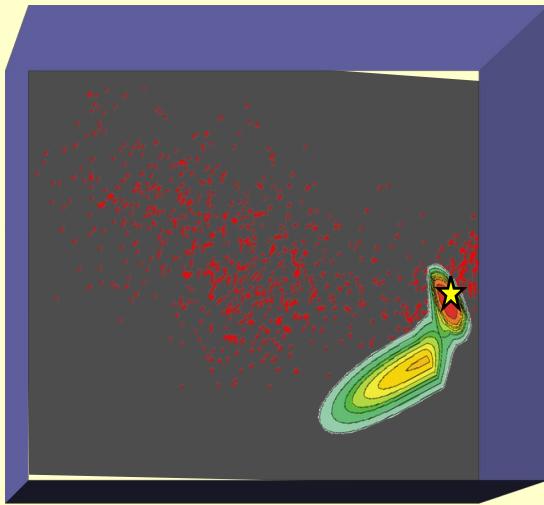
Read phases



Read travel-time grids, etc.



Global-search location



Calculate:
location statistics,
take-off angles,
corrections,
etc.



Output
location
to files

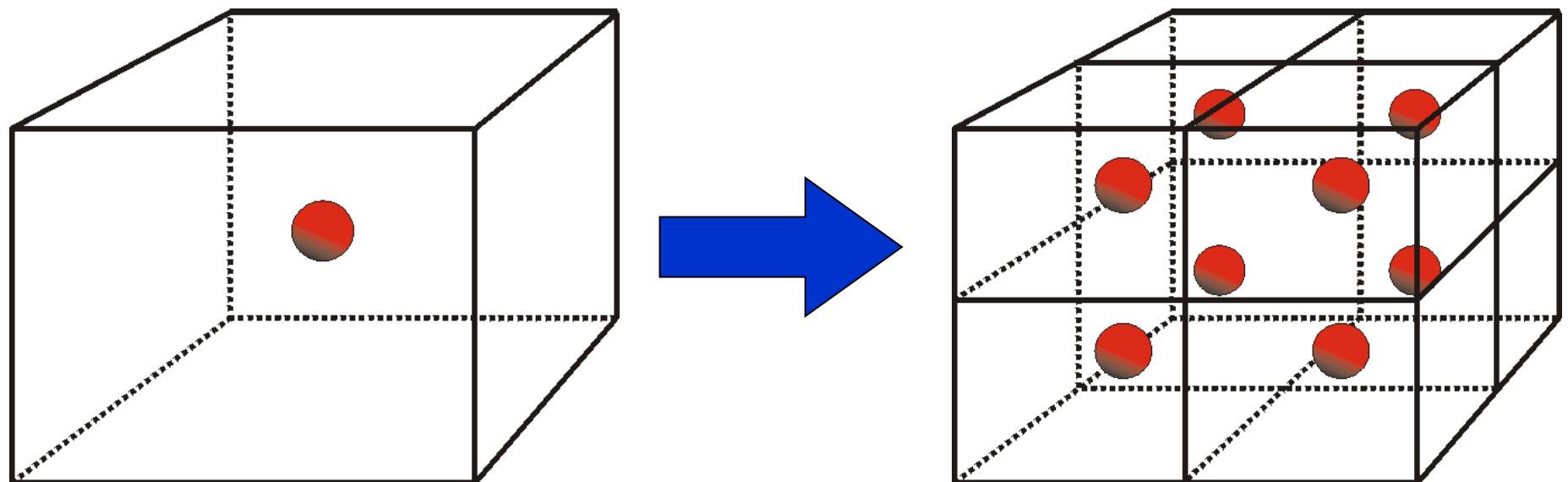


3. NonLinLoc earthquake location

NLLoc - The Oct-tree importance sampling method

NonLinLoc Software Guide (<http://alomax.net/nlloc>)

Sub-division of highest probability cell:



1 sample



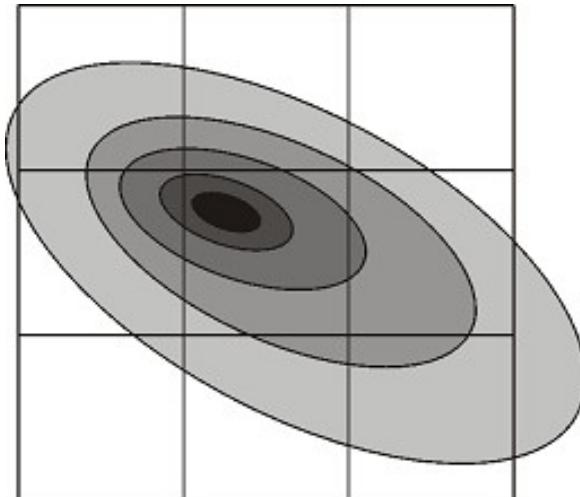
8 new samples

cell volume

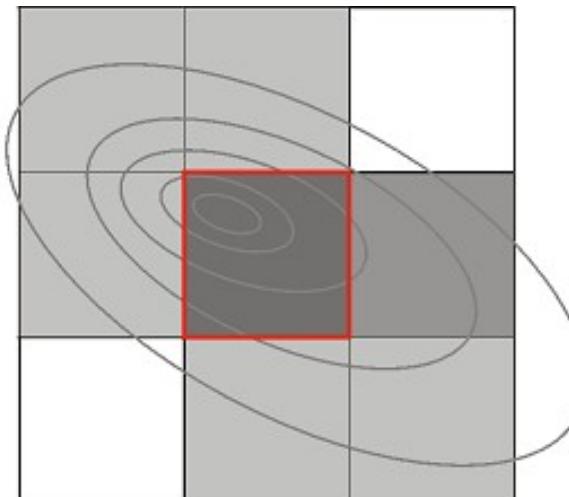


cell volume / 8

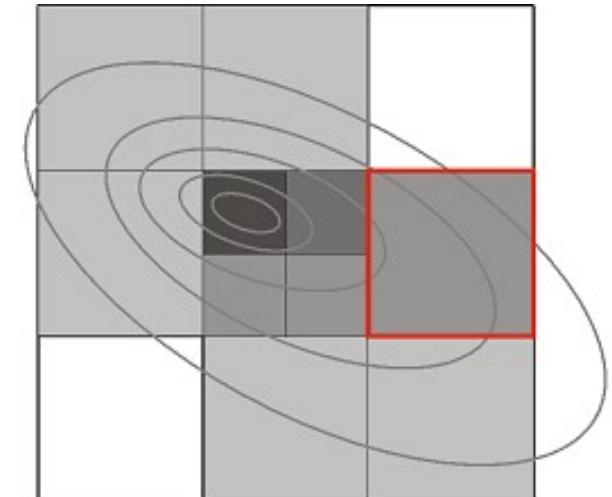
Oct-Tree sampling procedure



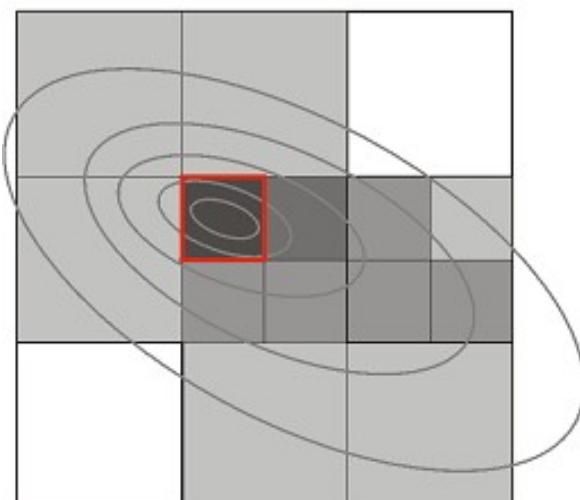
a) true PDF



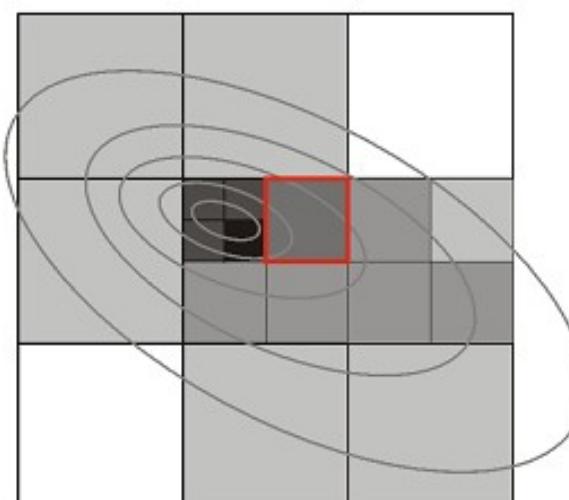
b) initial sampling



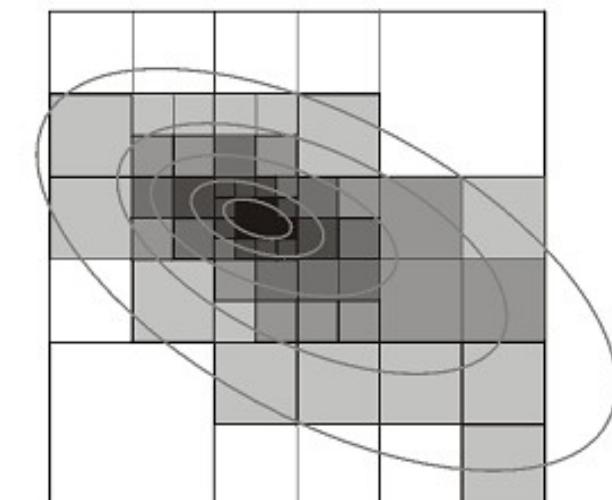
c) subdivision



d) subdivision



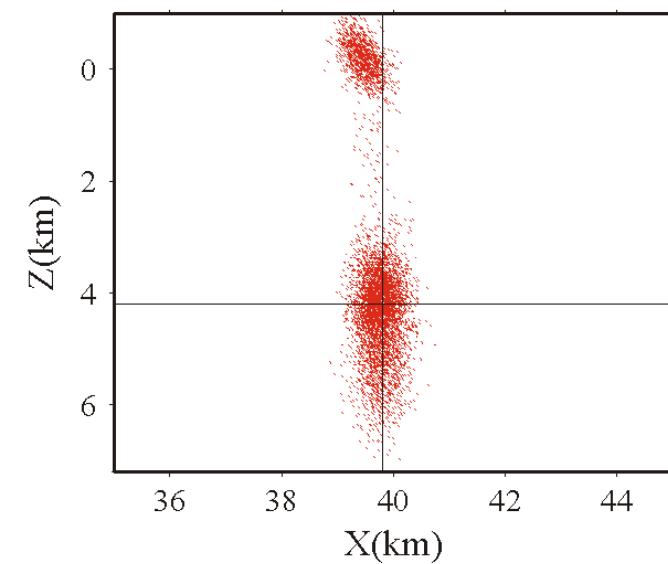
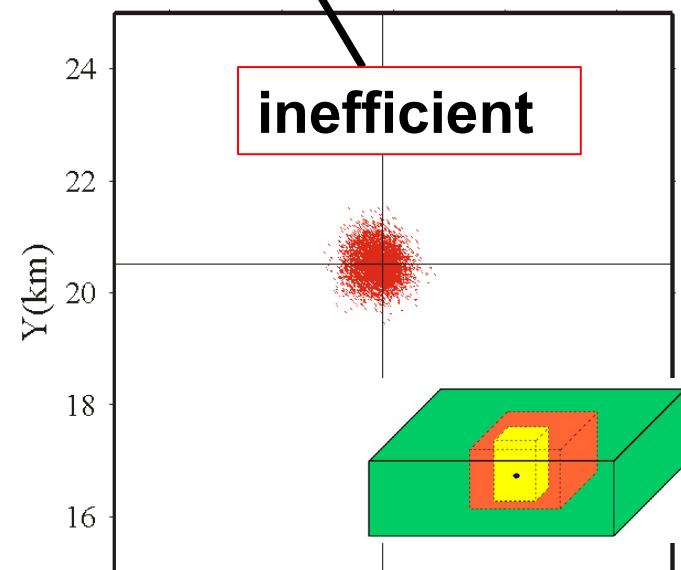
e) subdivision



f) many subdivisions

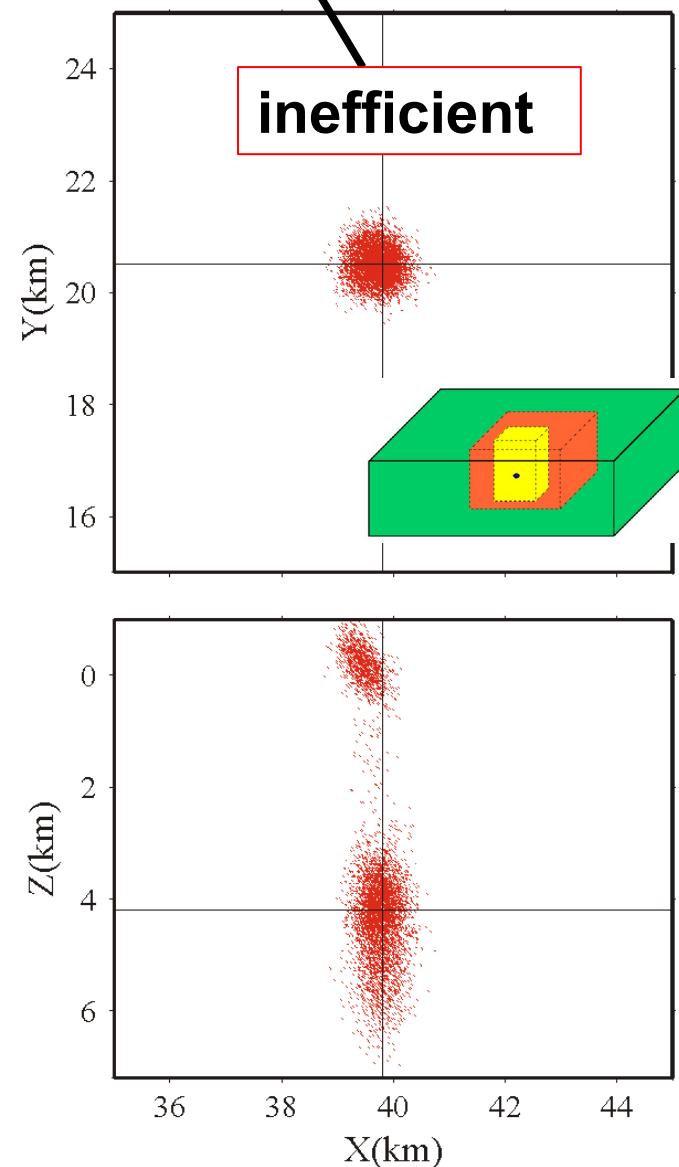
Example: PDF with two maxima

Grid search
(800,000 samples)

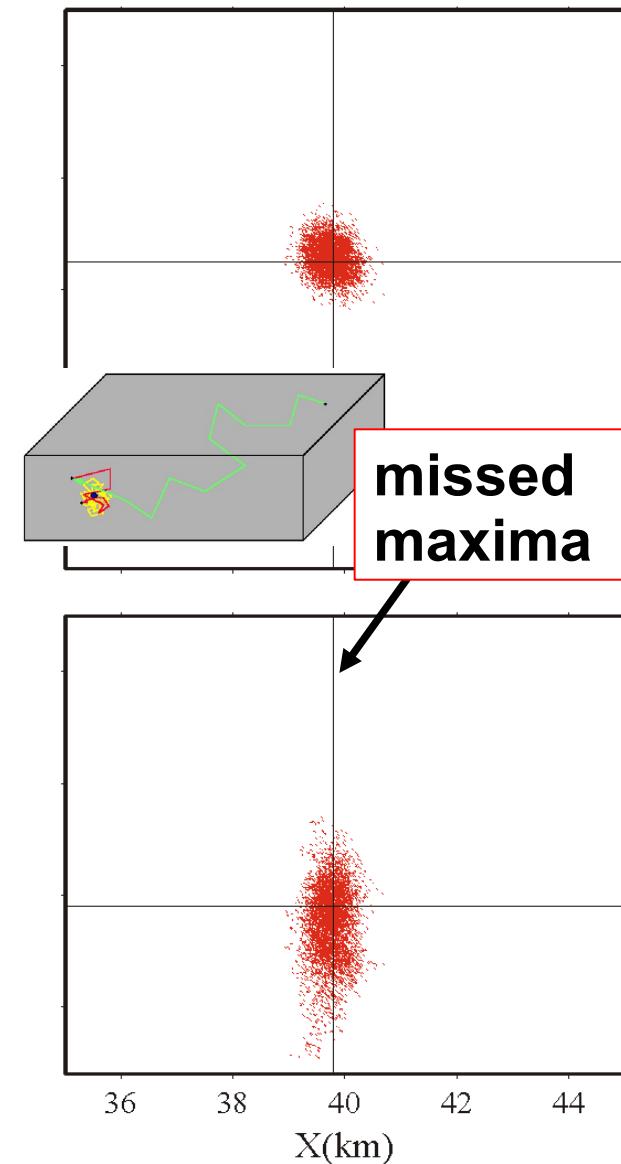


Example: PDF with two maxima

Grid search
(800,000 samples)

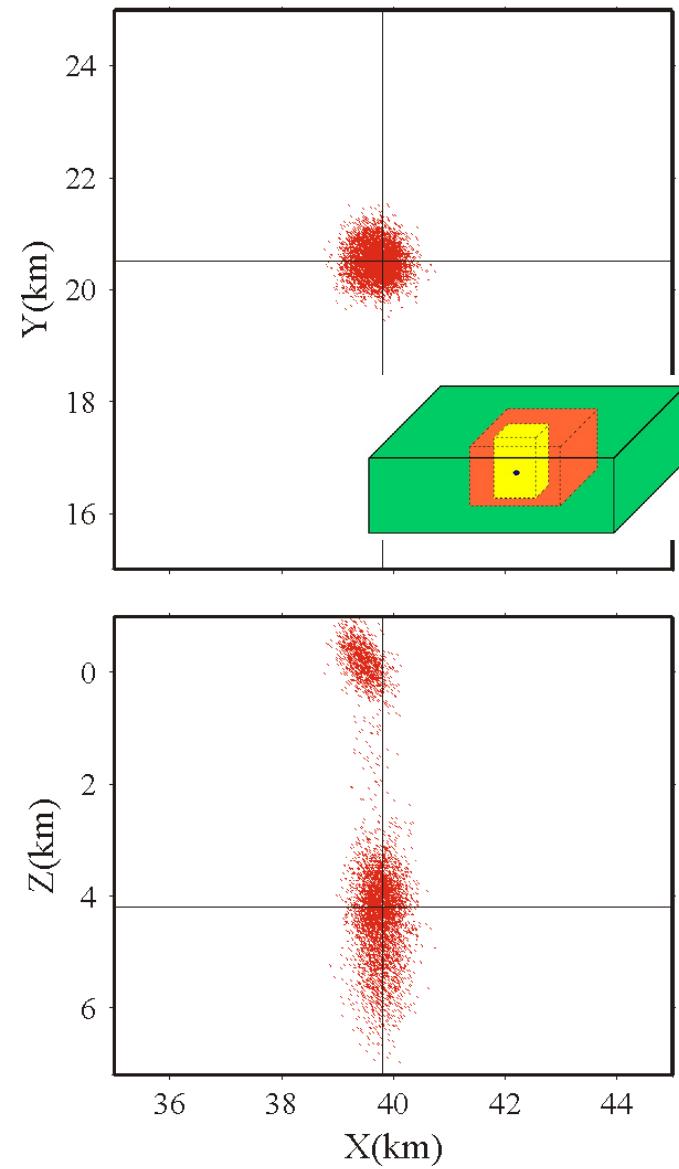


Metropolis search
(10,000 samples)



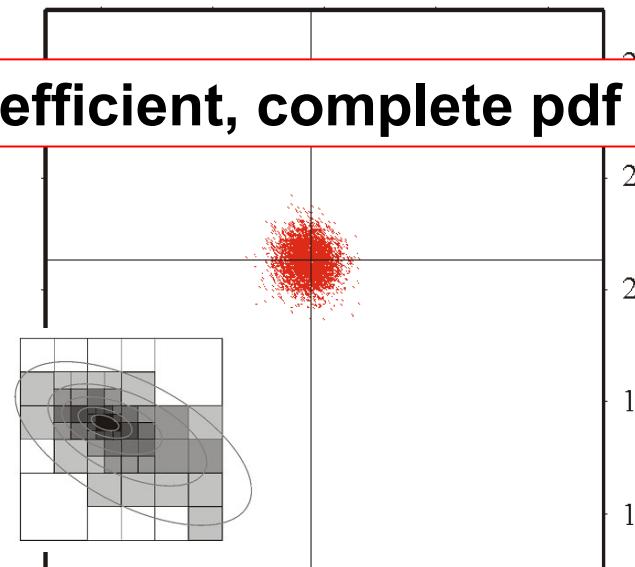
Example: PDF with two maxima

Grid search
(800,000 samples)

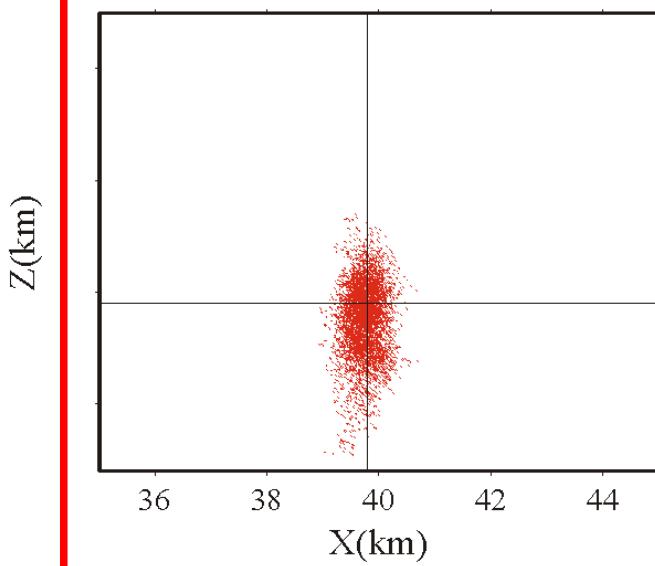
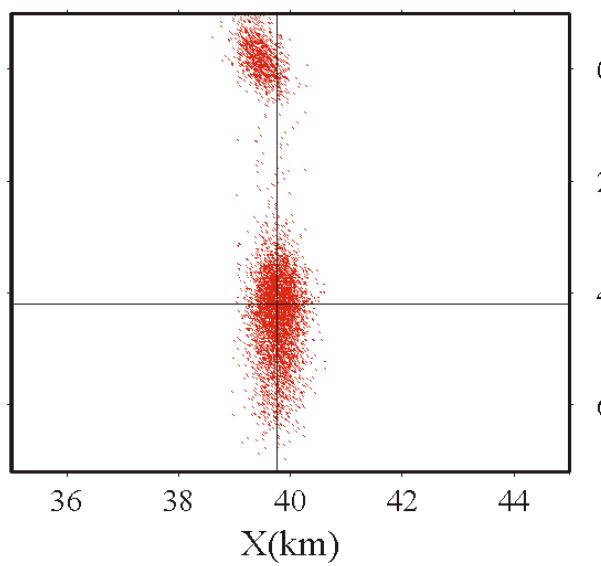
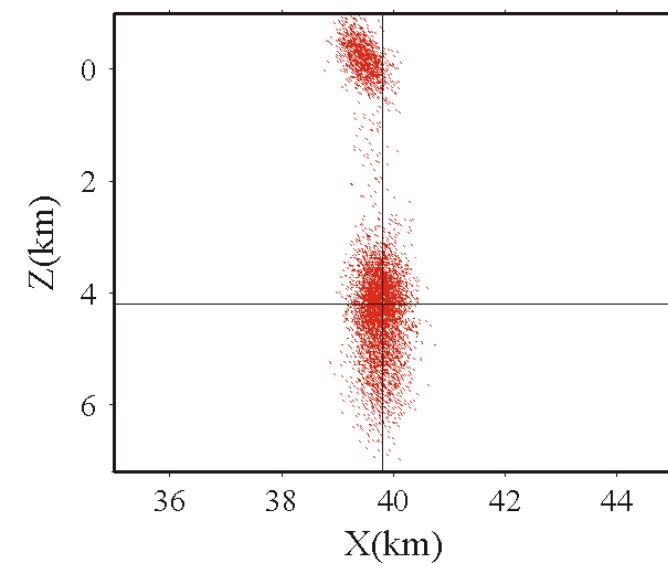
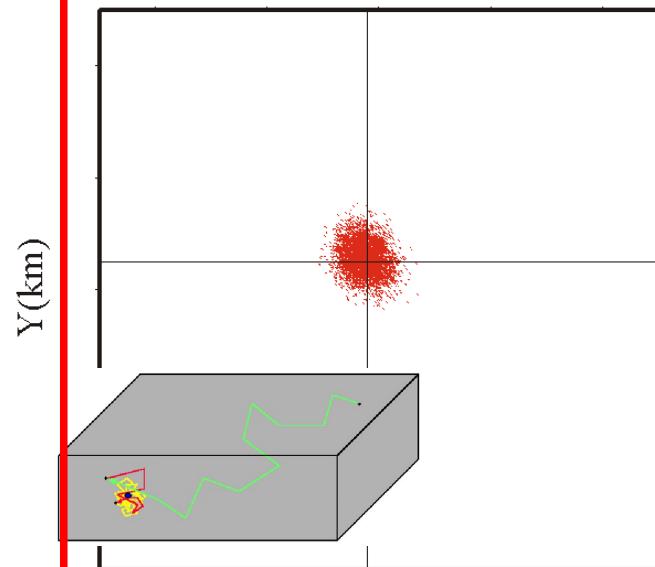


Oct-Tree search
(10,000 samples)

efficient, complete pdf



Metropolis search
(10,000 samples)



3. NonLinLoc earthquake location

NLLoc - The EDT Probability Density Function

NonLinLoc Software Guide (<http://alomax.net/nlloc>)

RMS/L2-norm vs EDT Probability Density Function

RMS/L2-norm

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

“satisfy **all** the observations”

- requires origin time estimate to get T_{calc}

RMS/L2-norm vs EDT Probability Density Function

RMS/L2-norm

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

“satisfy **all** the observations”

- requires origin time estimate to get T_{calc}

EDT (Equal Differential Time)

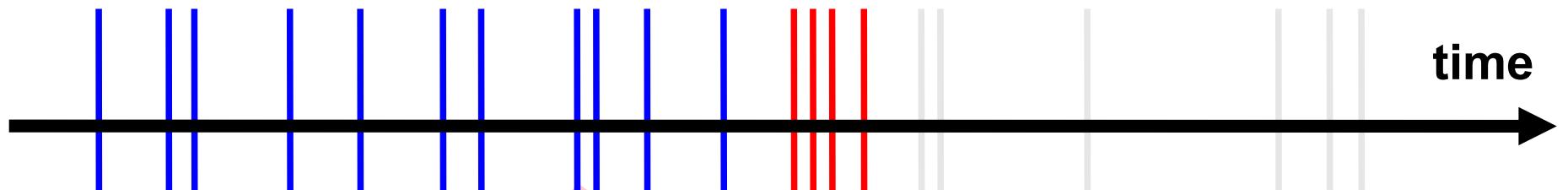
$$pdf(x) \propto \left[\sum_{obs_a, obs_b} e^{-\frac{[(T_{obs_a}(x) - T_{obs_b}(x)) - (TT_{calc_a}(x) - TT_{calc_b}(x))]^2}{\sigma^2}} \right]^N$$

“satisfy **the most pairs** of observations”

- no origin time estimate required

Phase association and event detection → EDT

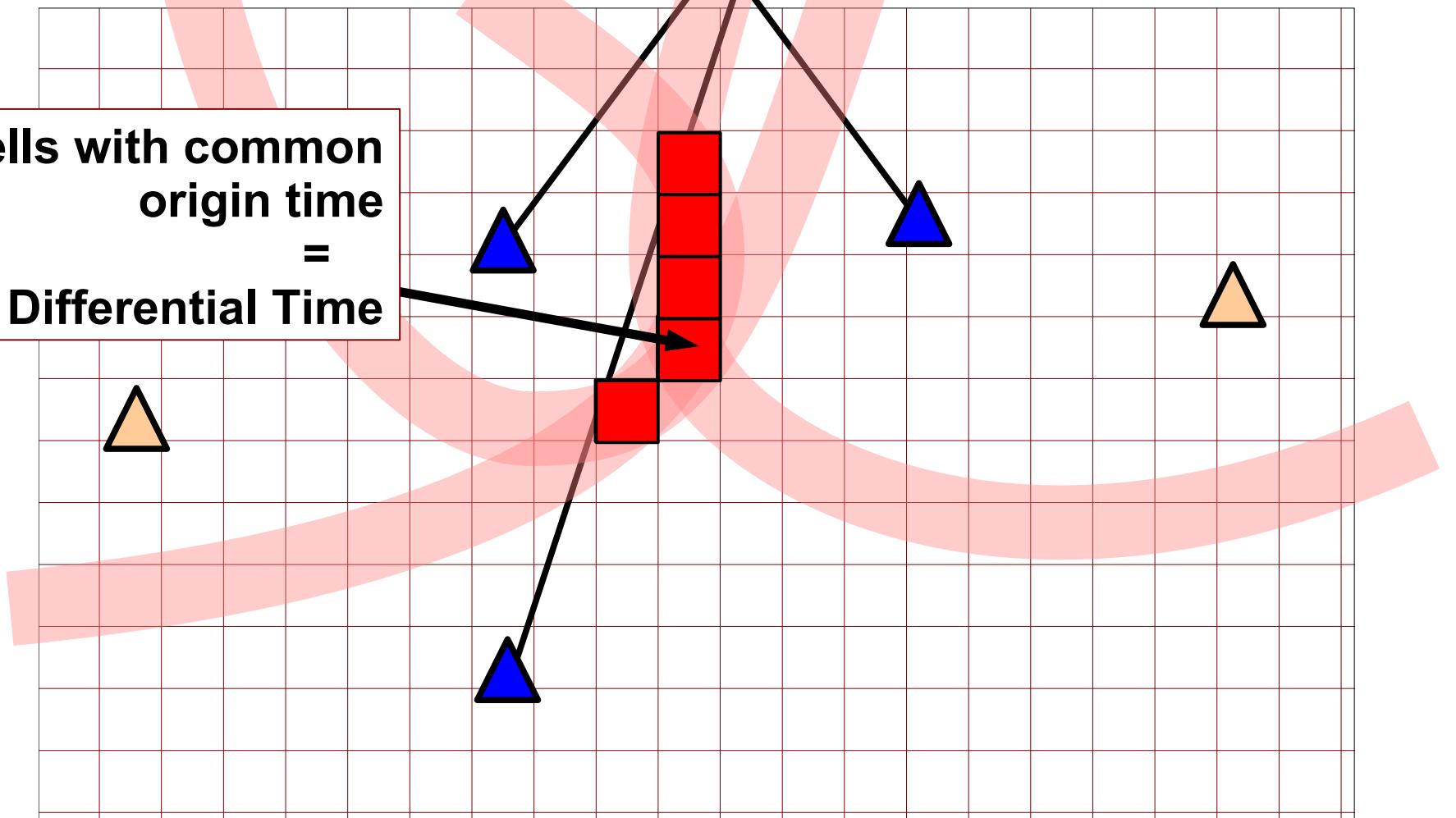
picks (phase arrivals, noise, ...)



cells with common
origin time

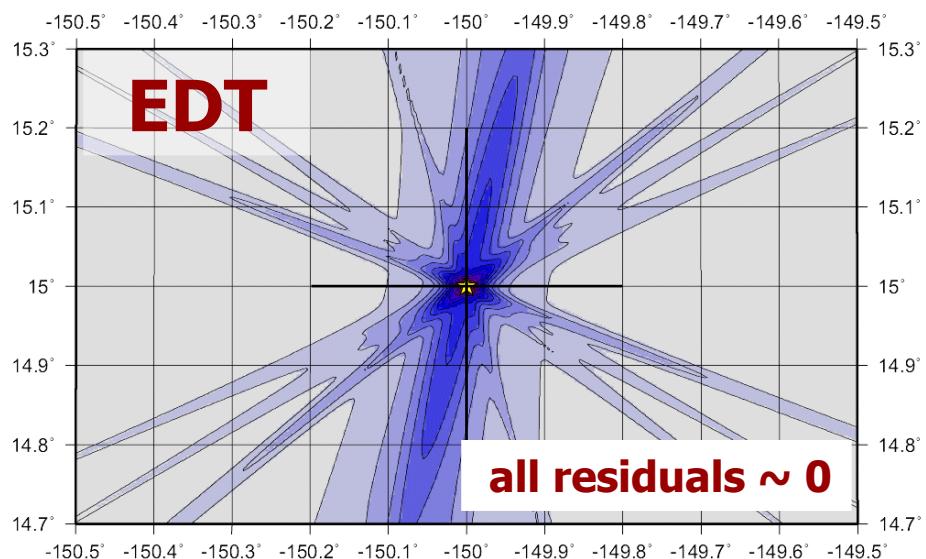
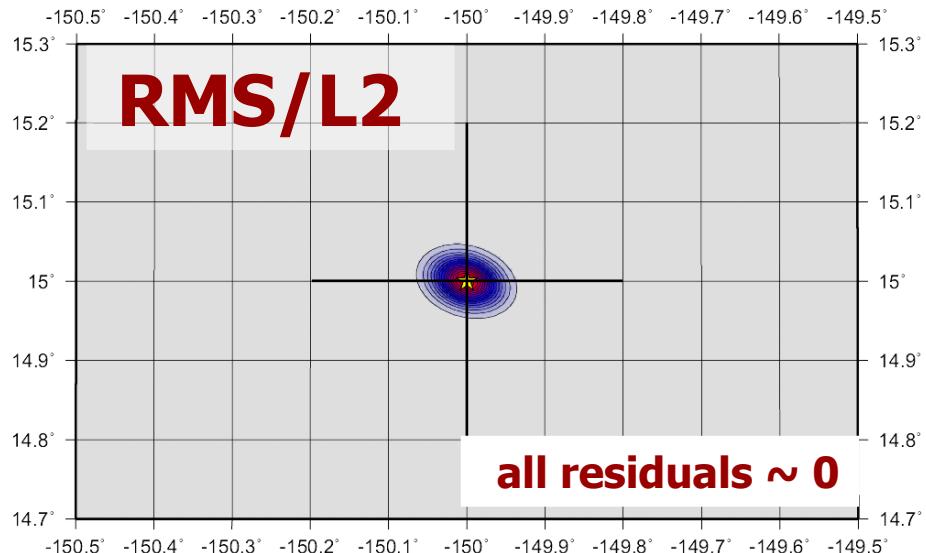
=

Equal Differential Time



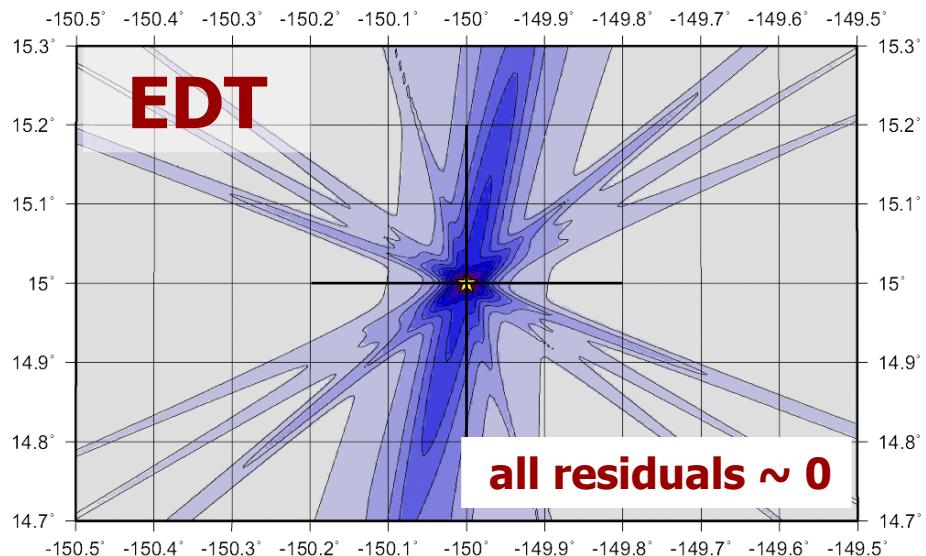
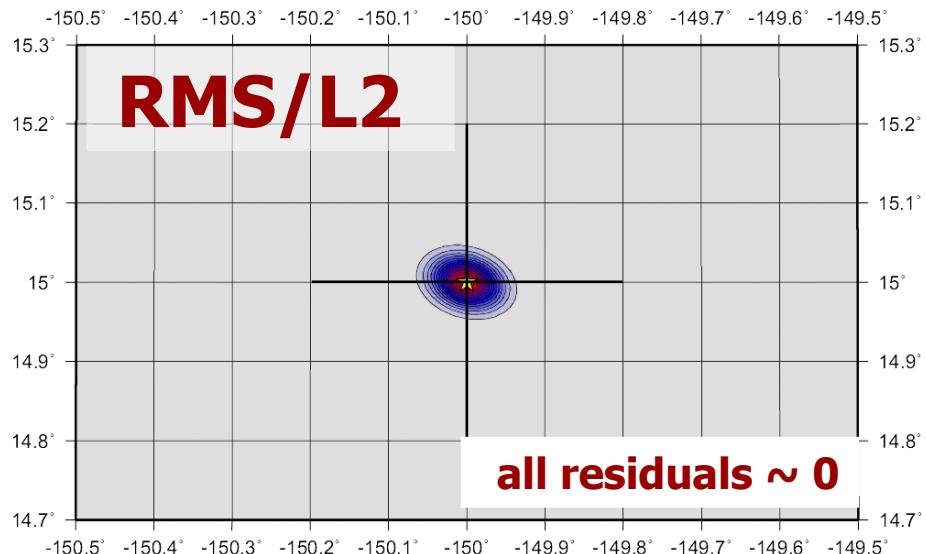
RMS/L2 vs EDT with outlier data

perfect data (6 obs)

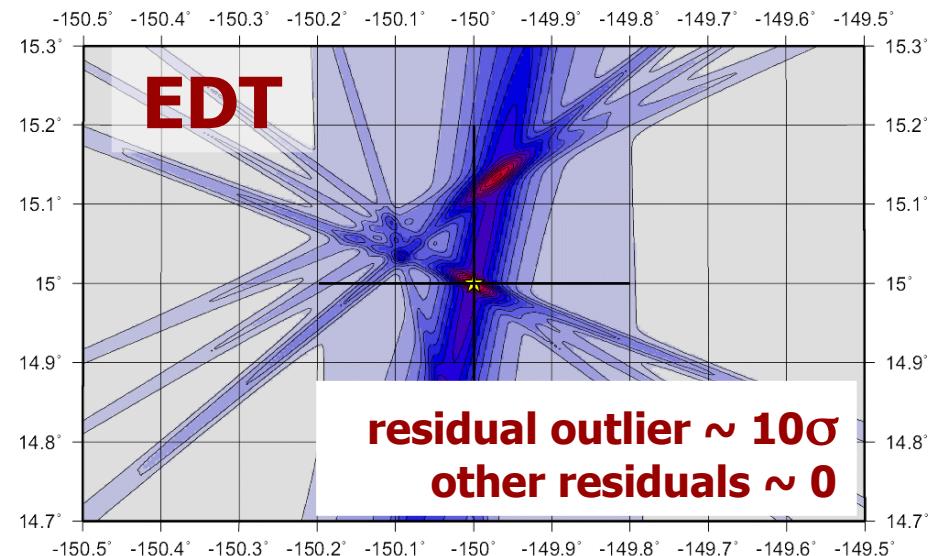
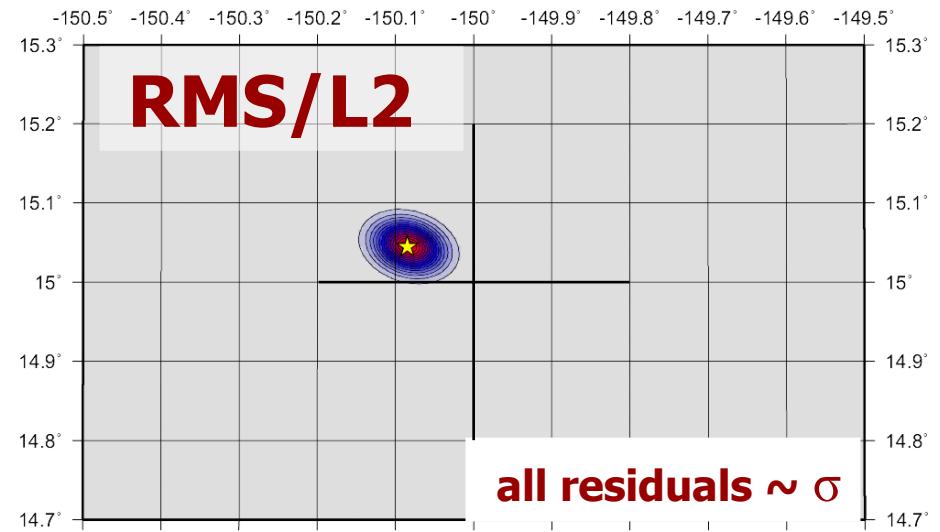


RMS/L2 vs EDT with outlier data

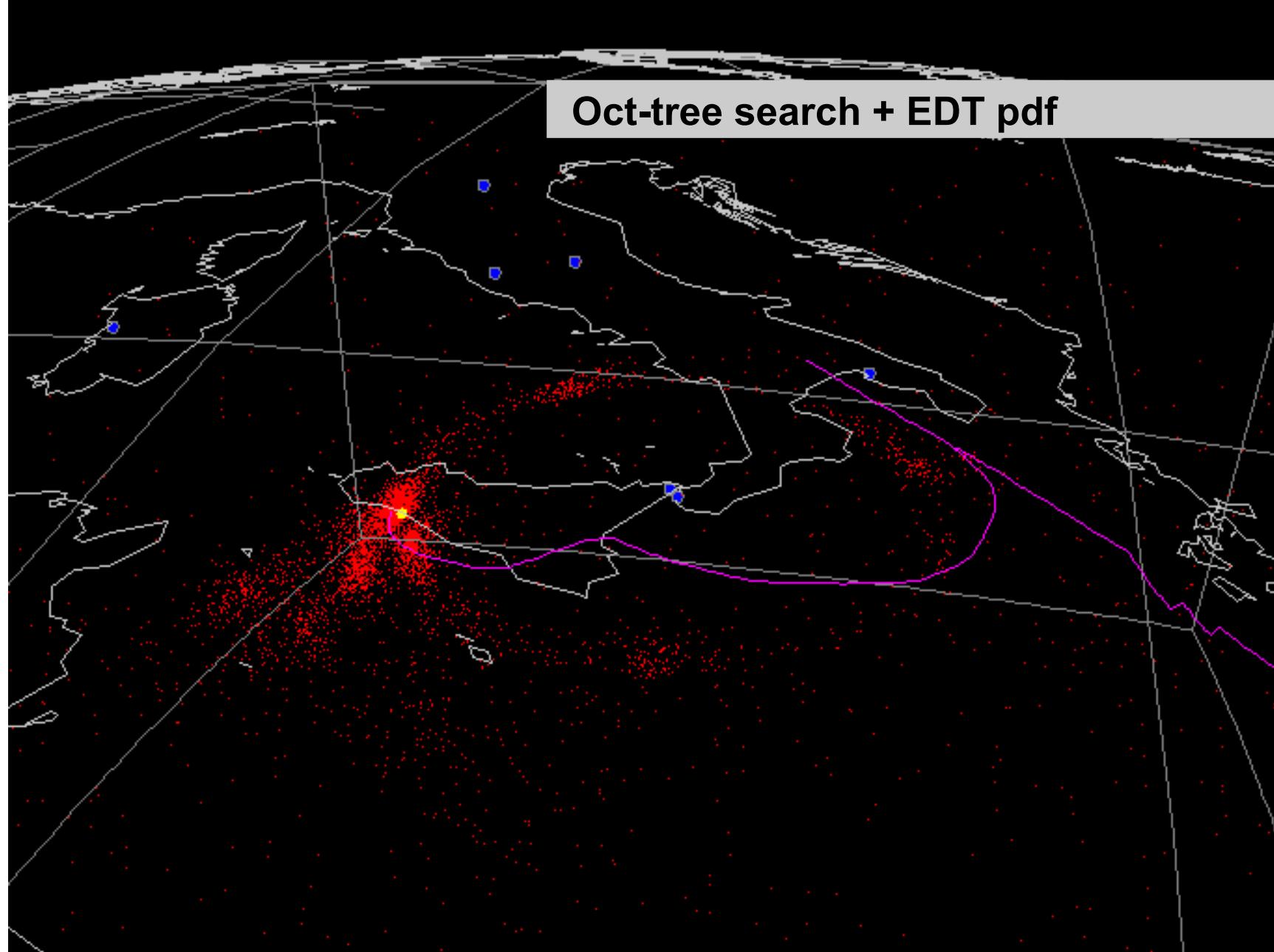
perfect data (6 obs)



1 outlier data ($\text{err}=10\sigma$)



Example: 1905 Italian historical event location



Michelini, Lomax, Nardi, Rossi (2006)

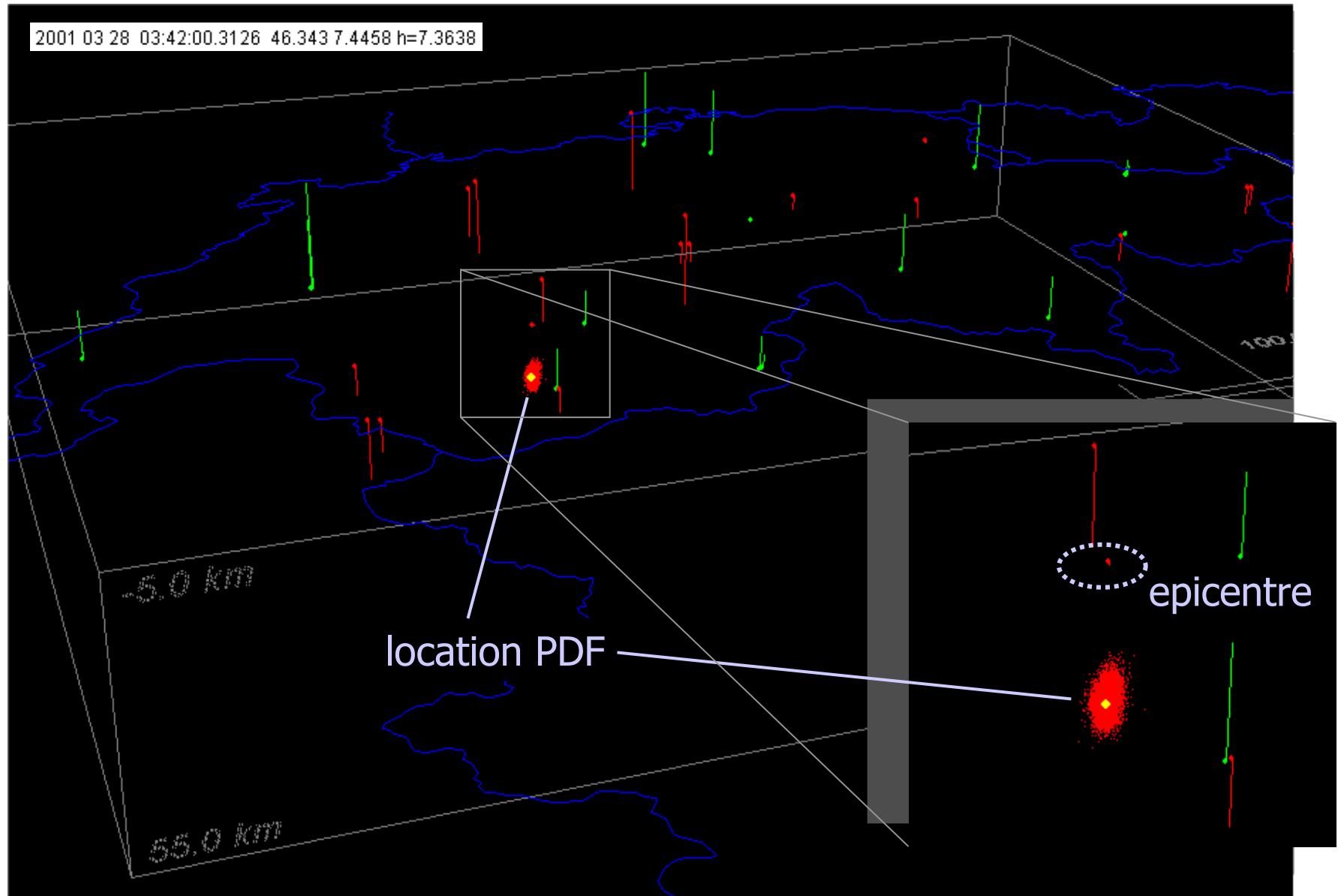
La localizzazione del terremoto della Calabria dell'8 settembre 1905 da dati strumentali

4. Illustrative examples of NonLinLoc global-search earthquake location

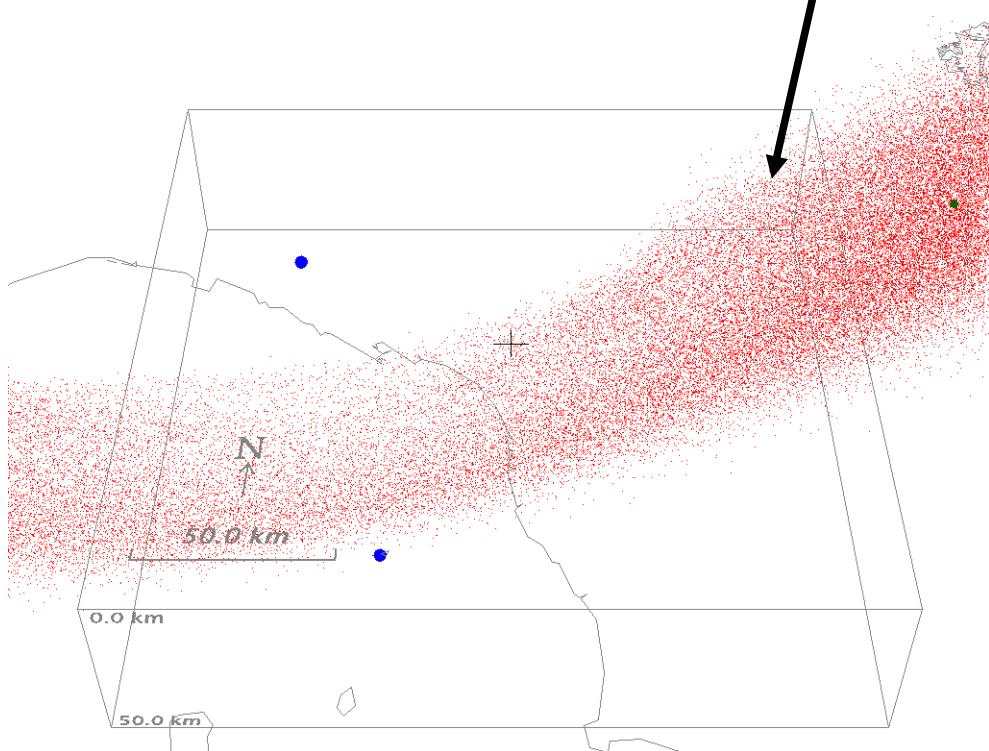
Anthony Lomax
ALomax Scientific, Mouans-Sartoux, France

NonLinLoc Software Guide (<http://alomax.net/nlloc>)

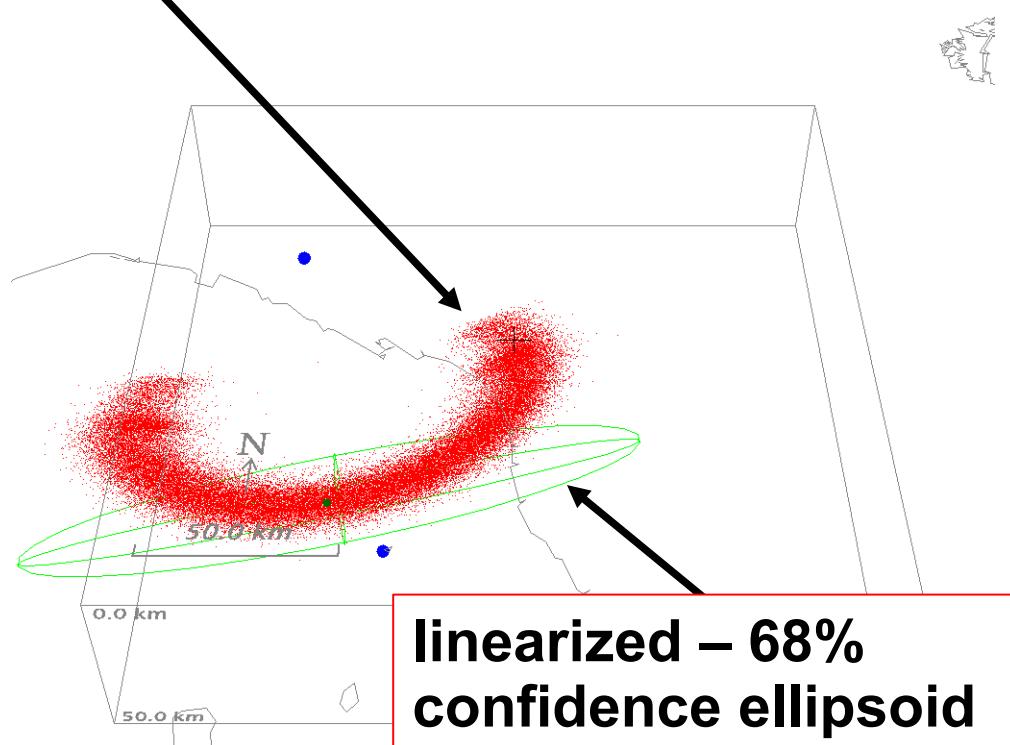
ETH Example: well located event



global search – probability density function (PDF)



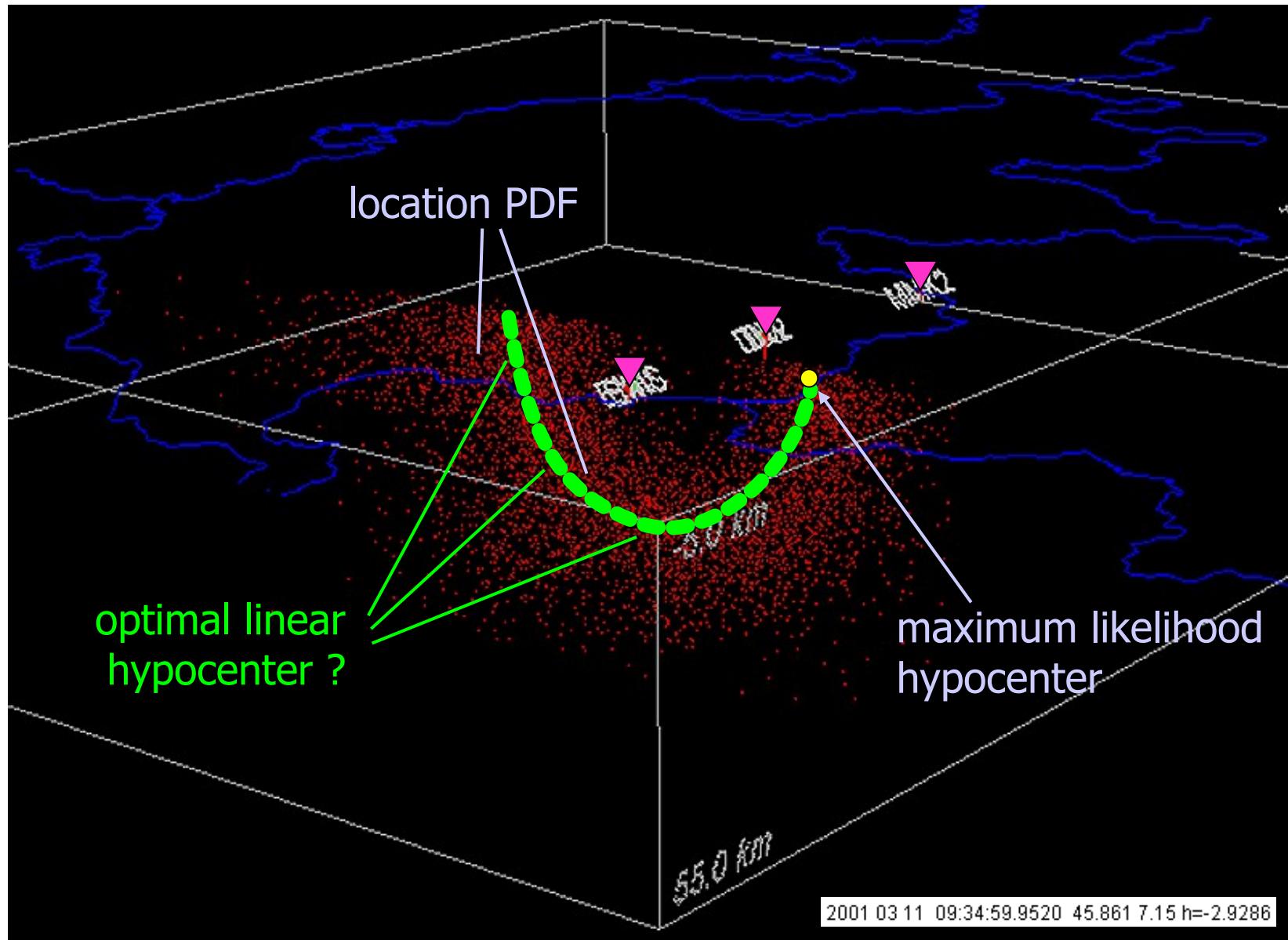
2P phases (2 stations)



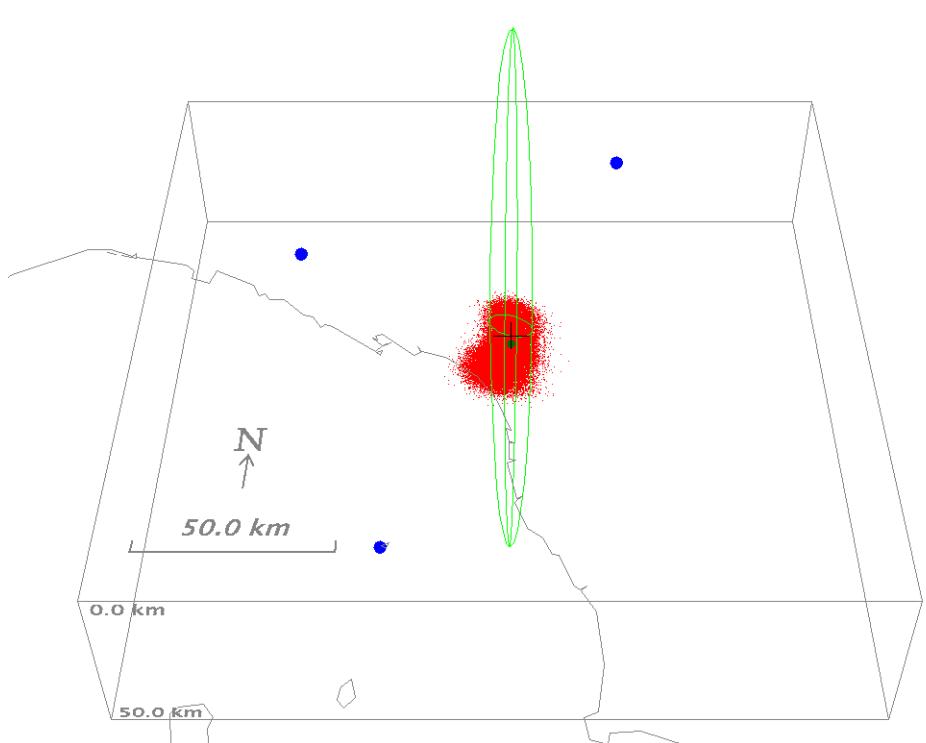
linearized – 68%
confidence ellipsoid

2P and 2 S phases (2 stations)

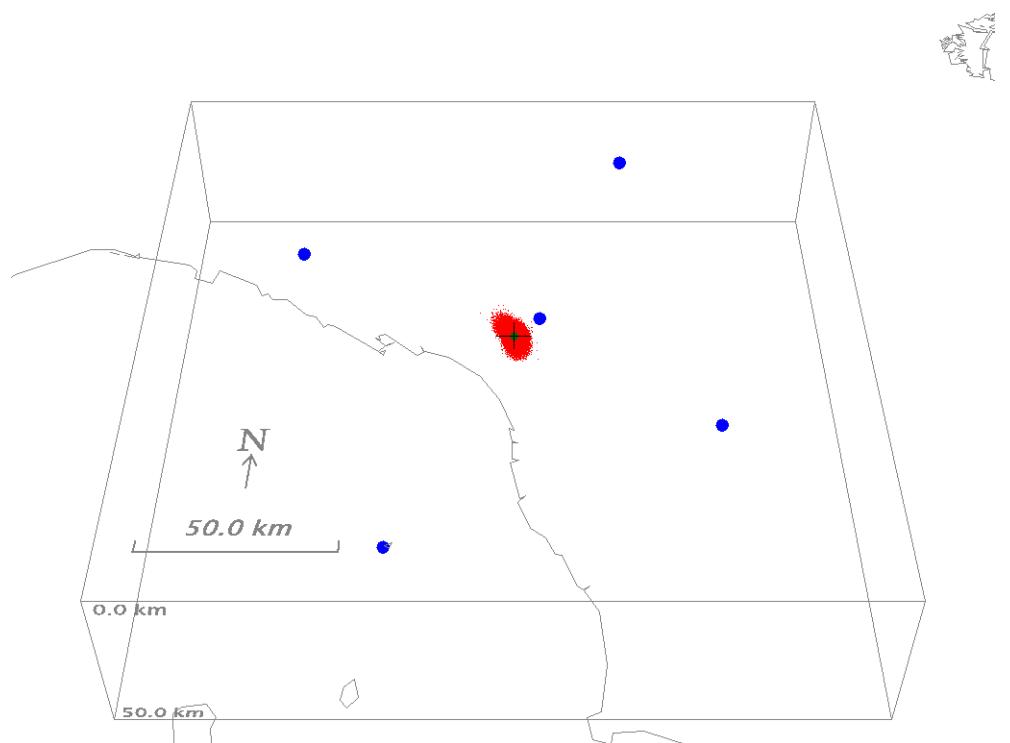
ETH Example: Few available stations



Few available stations (cont)

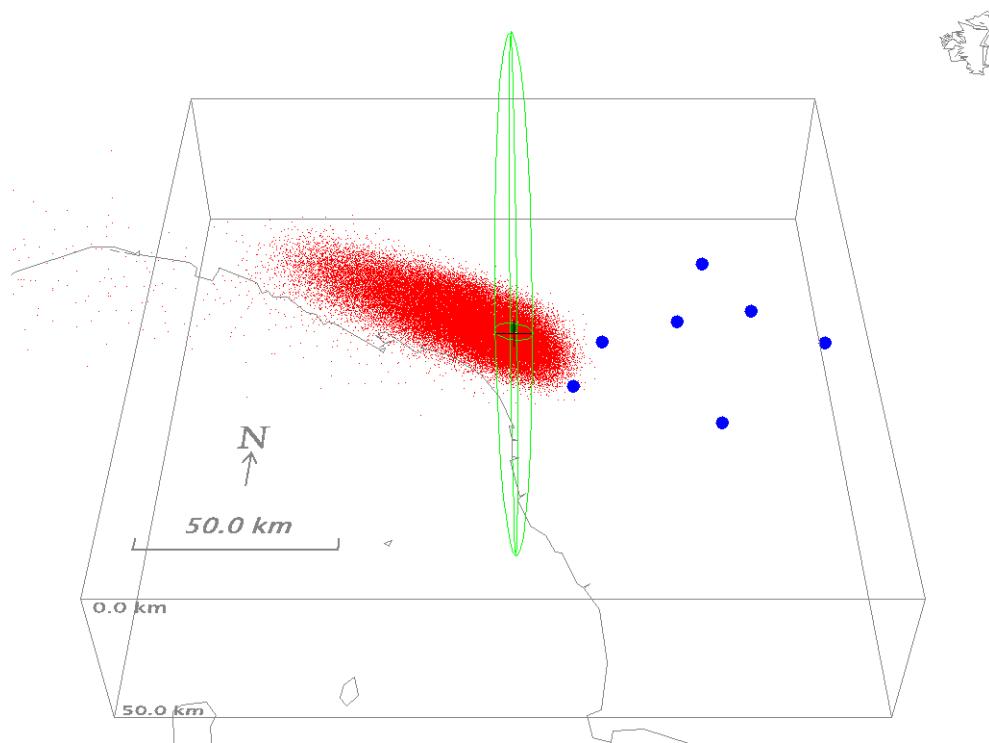


3P phases (3 stations)



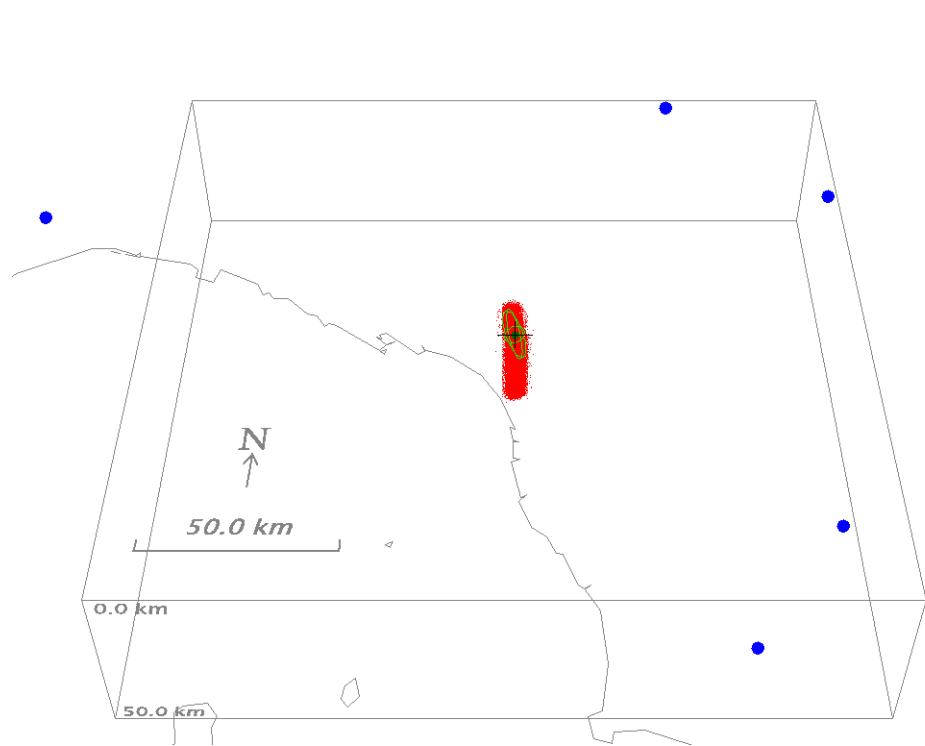
5P and 3S phases (5 stations)

Stations to one side of the event

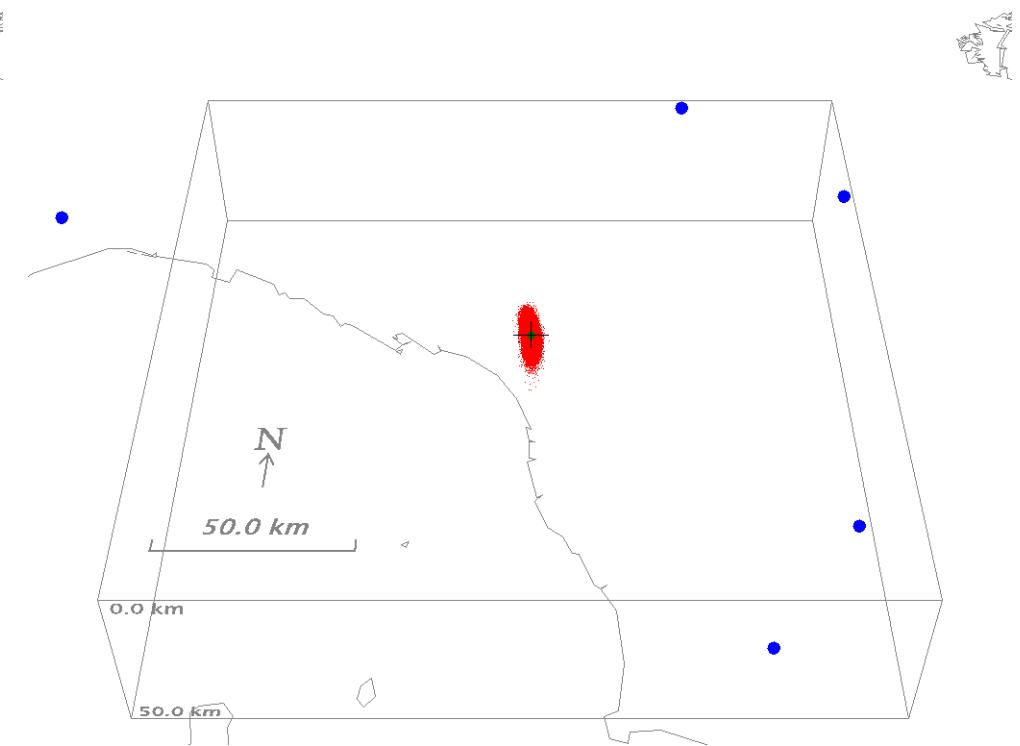


P-wave arrival times at 7 stations

Stations far from the event: Depth-origin time trade-off

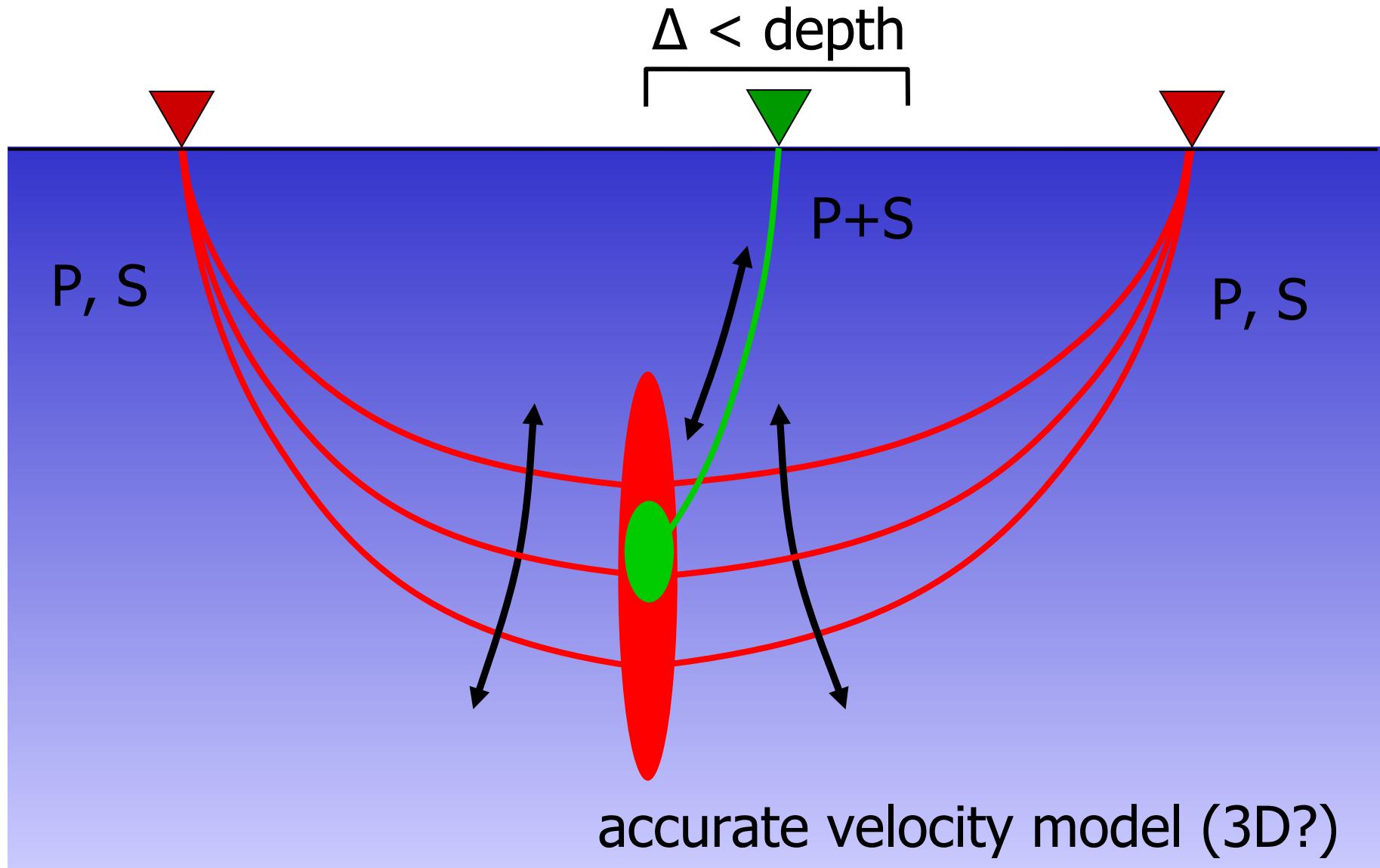


P arrival times only

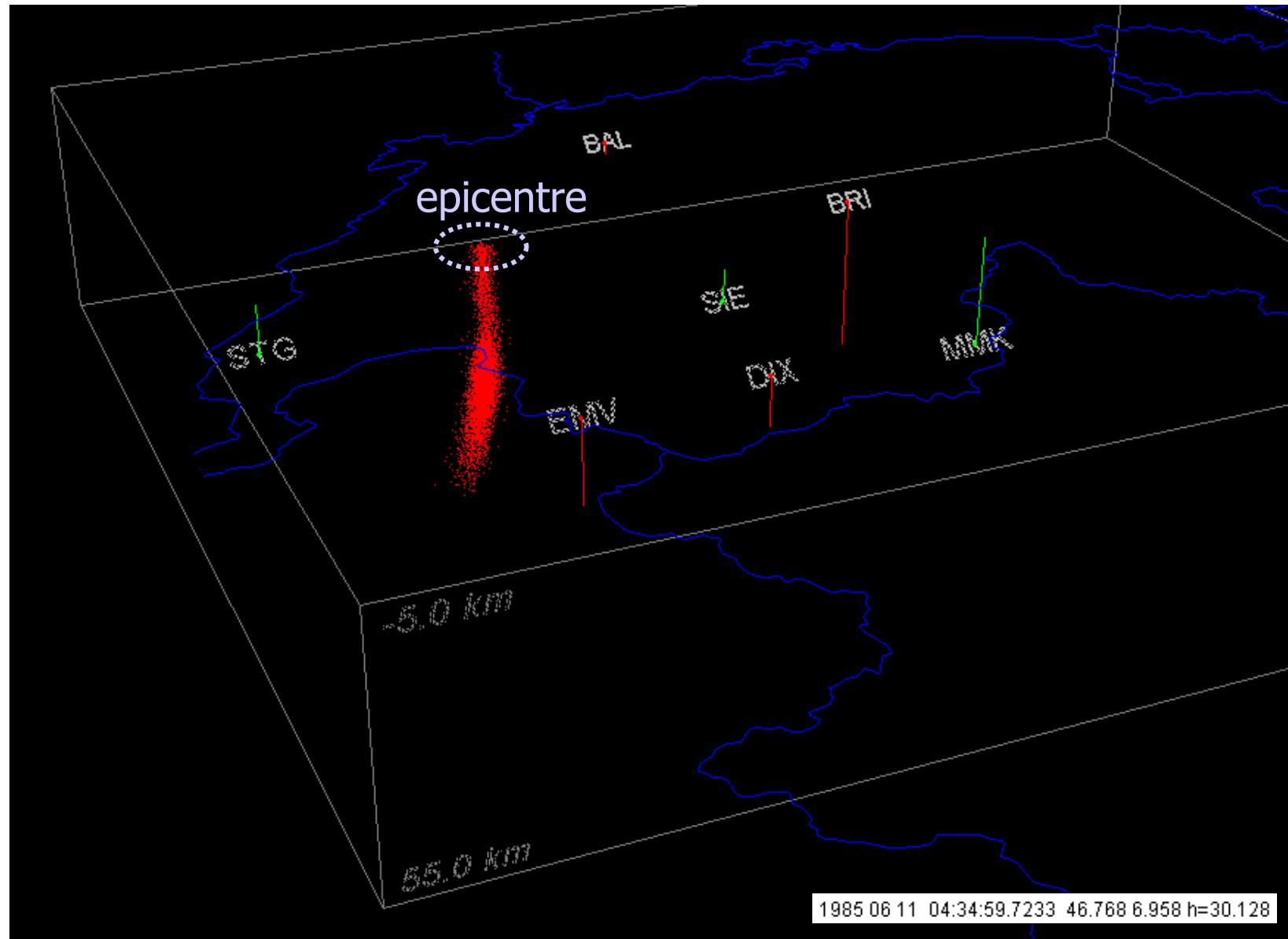


P and S arrival times

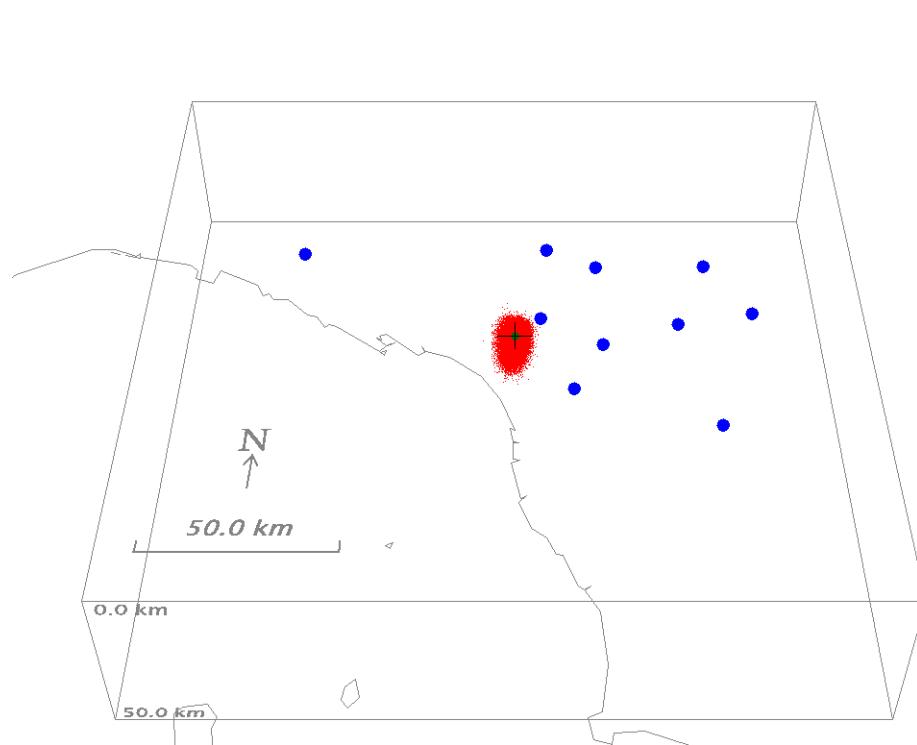
Stations far from the event: Depth-origin time trade-off



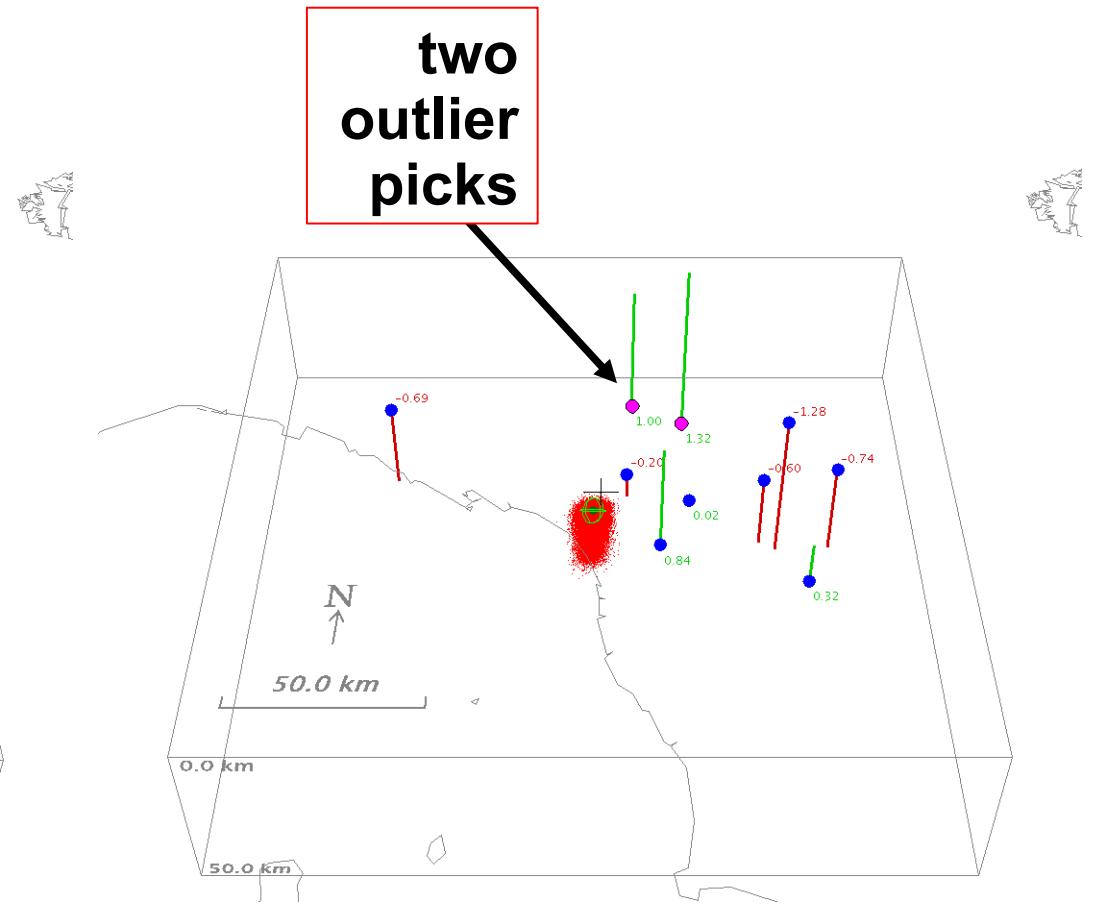
Stations far from the event: Depth-origin time trade-off



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

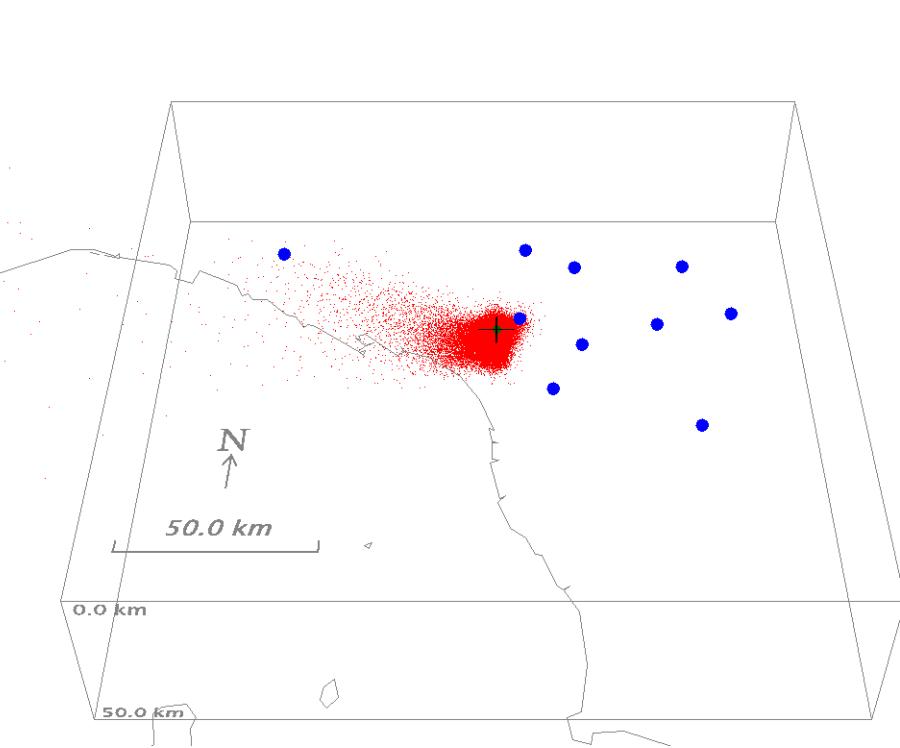


no outliers

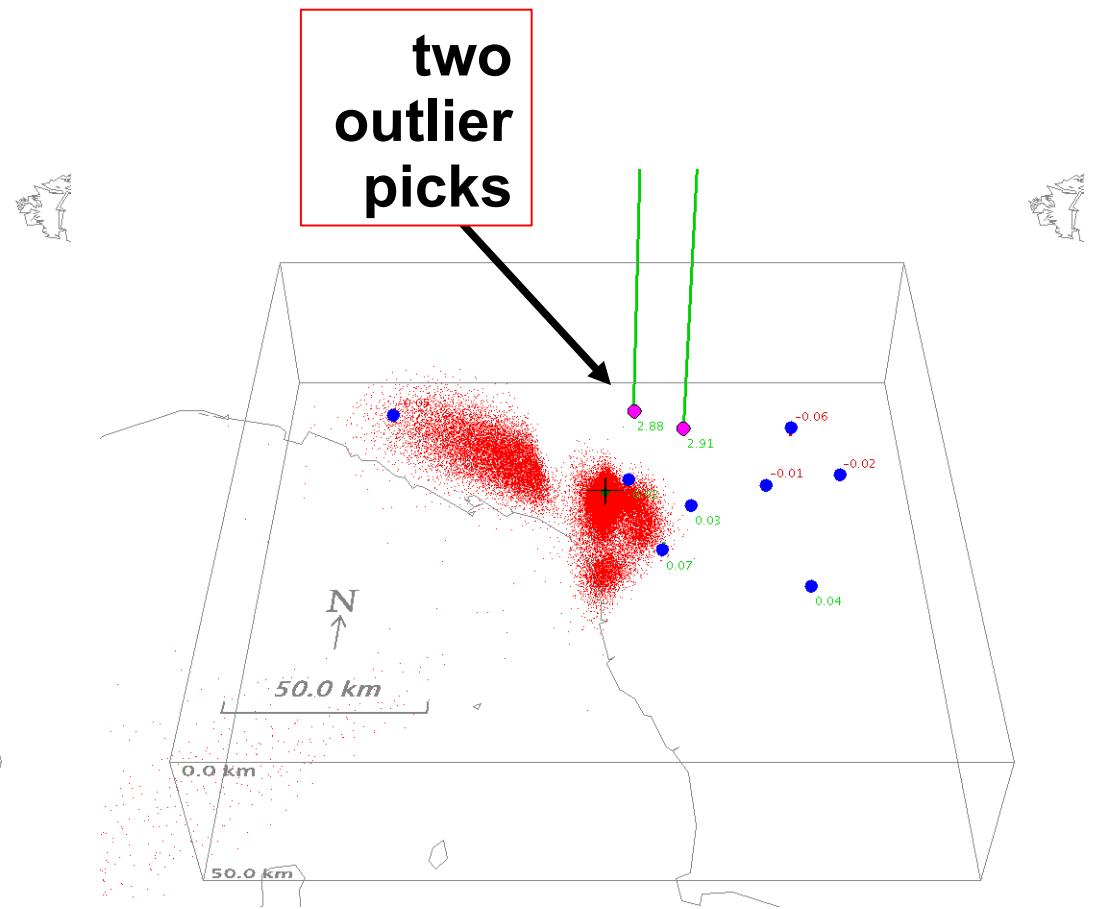


two arrival-time outliers

Incorrect picks and phase id - outlier data: EDT

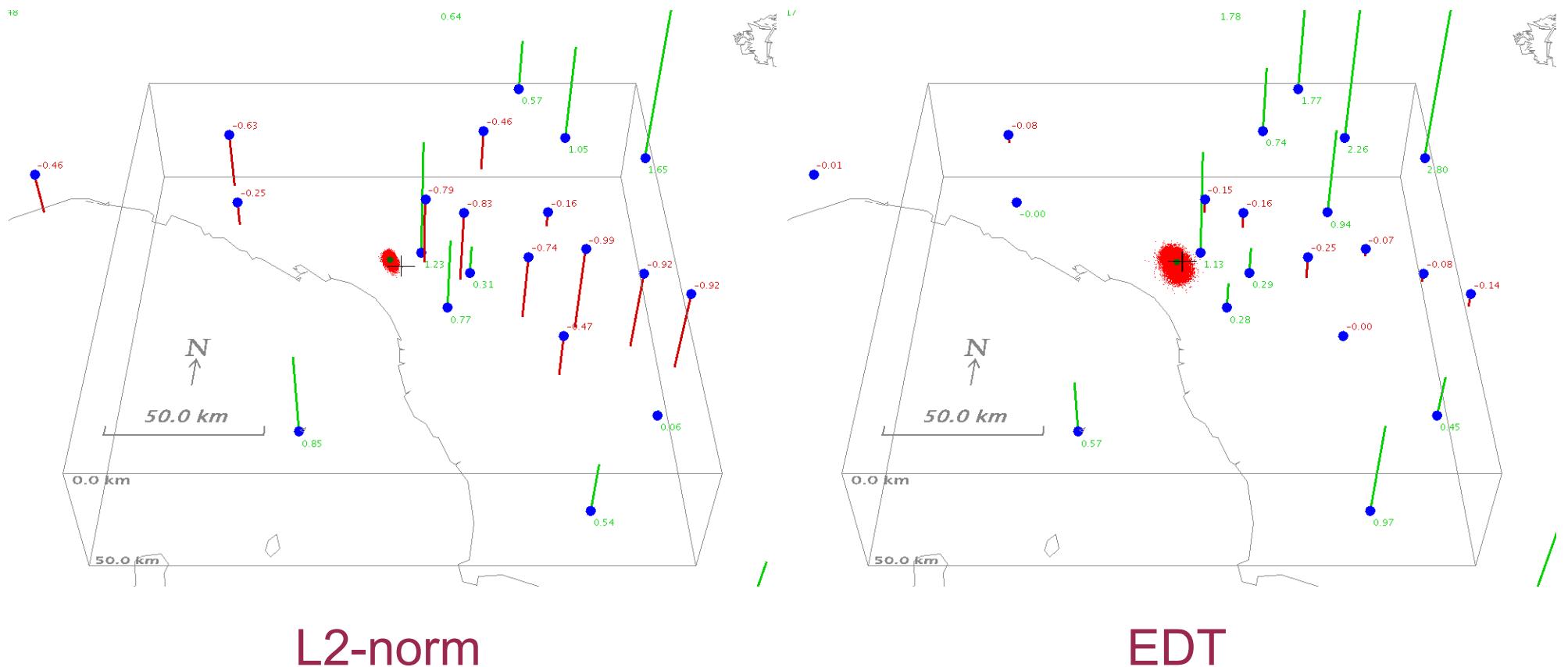


no outliers

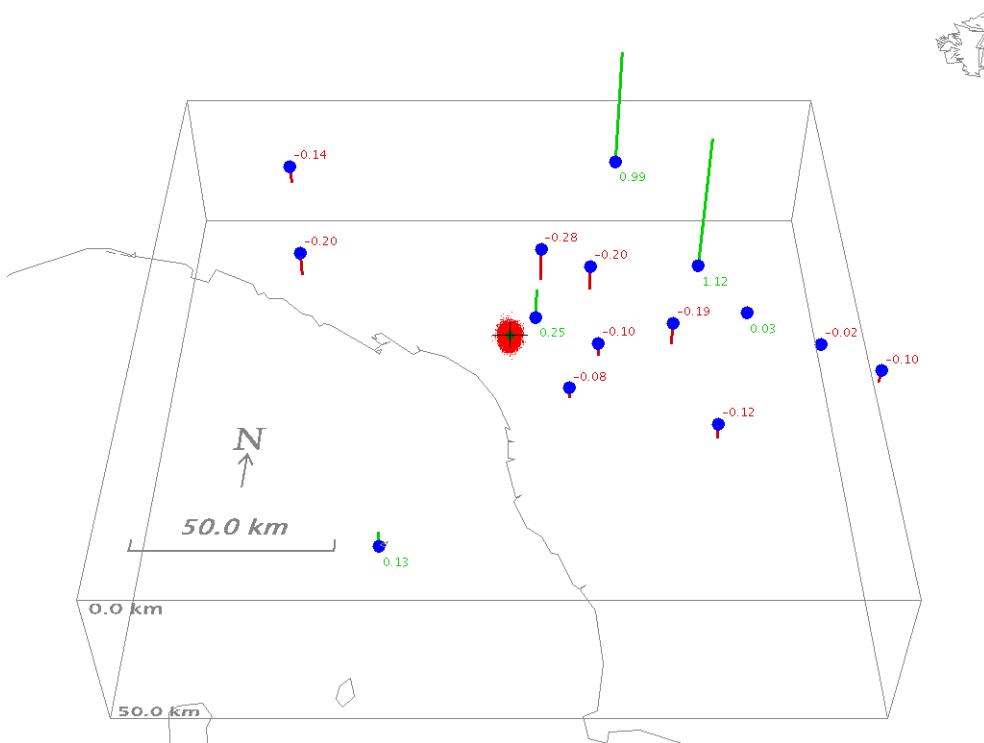


two arrival-time outliers

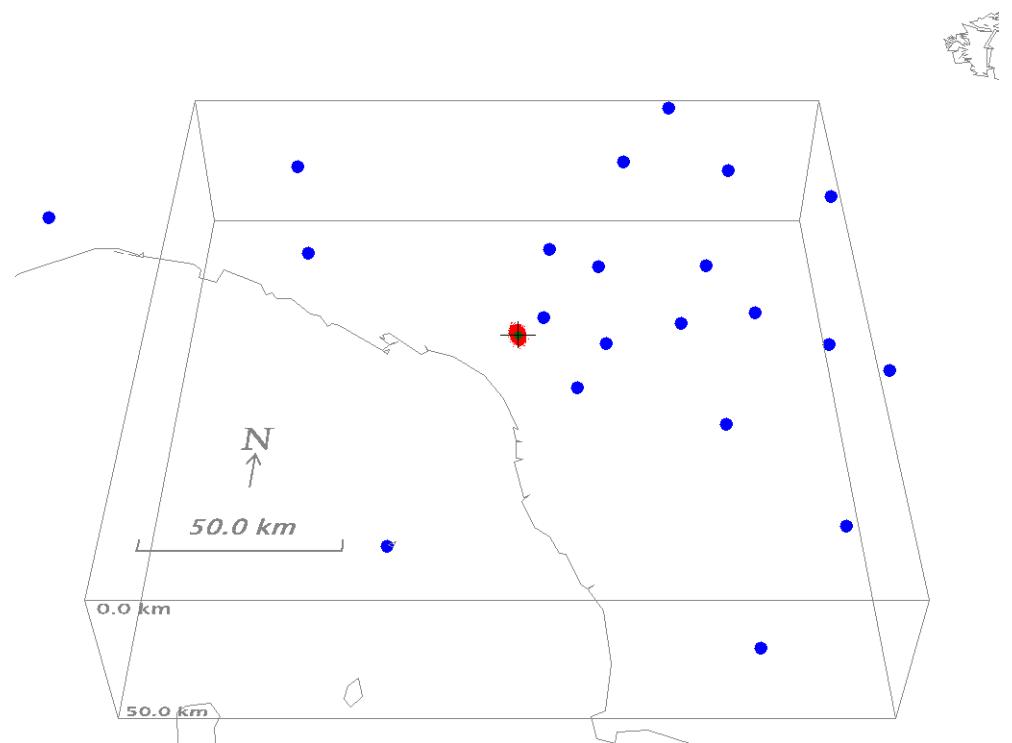
Incorrect velocity model



Station corrections (ideal case)



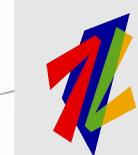
Original location



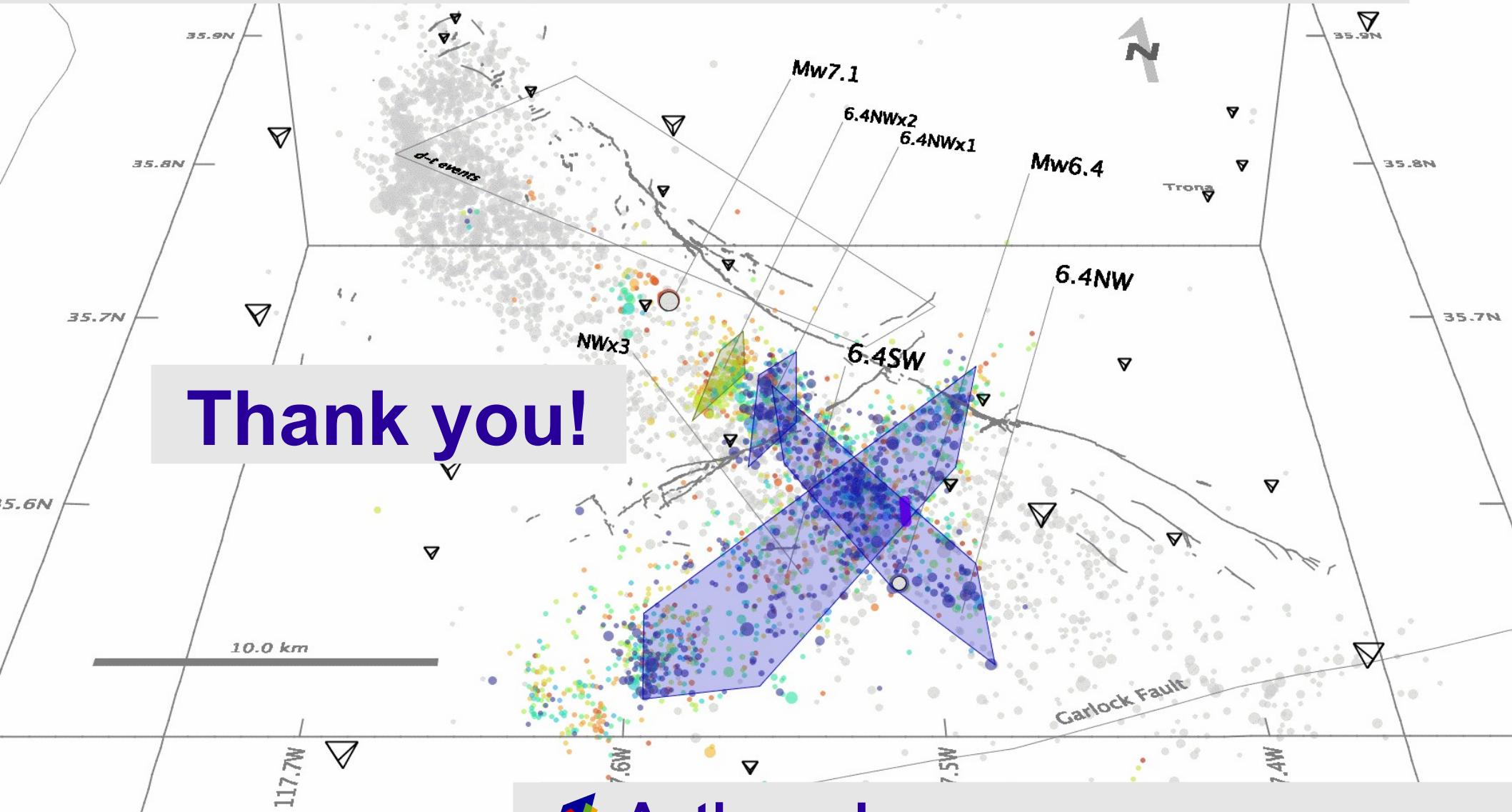
Location with corrected times

NonLinLoc Earthquake Location

Thank you!



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ALomax Scientific, Mouans-Sartoux, France



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NonLinLoc Software Guide (<http://alomax.net/nlloc>)

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