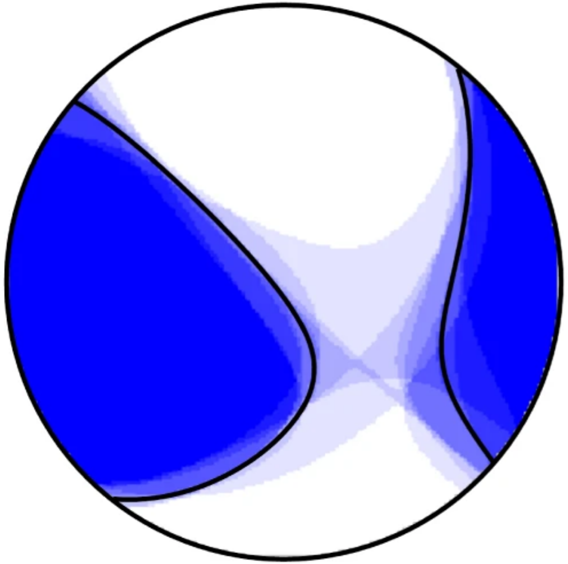
Source inversion in seismology



Simone Cesca[1], Sebastian Heimann[2], Gesa Petersen[1],

Pinar Büyükakpinar[1,2], Daniela Kühn[1,3]

1. GFZ Potsdam, 2. University of Potsdam, 3. NORSAR, Norway

Potsdam, 29.6.2023

Source inversion team

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GFZ, Univ. Potsdam

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GFZ Potsdam

Our task

Source inversion in seismology: how to determine geometry and properties of the earthquake source based on the modeling of the earthquake effects?

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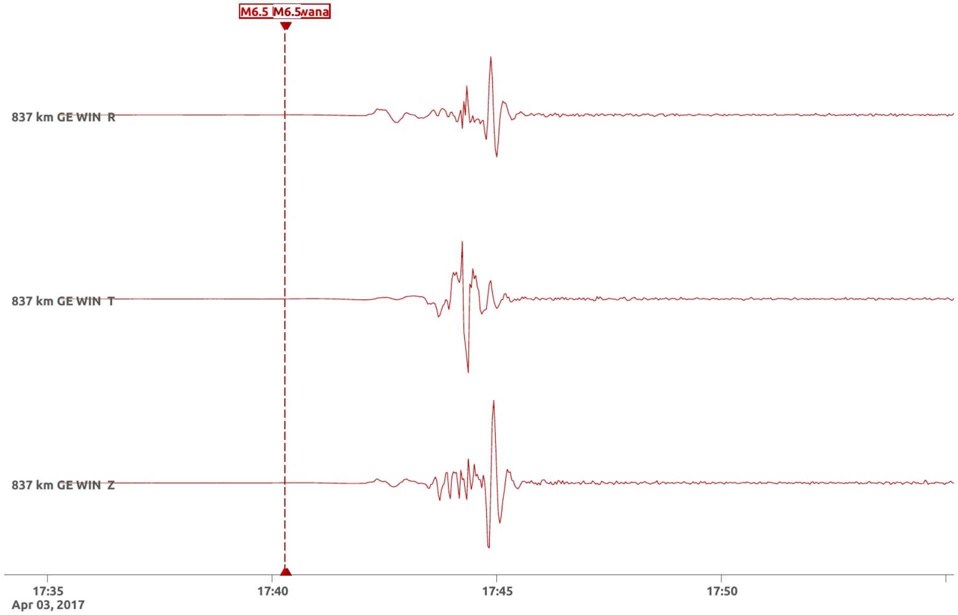
Source inversion in seismology: how to determine geometry and properties of the earthquake source based on the modeling of the **earthquake effects**?



GFZ Helmholtz Centre Potsdam

HELMHOLTZ

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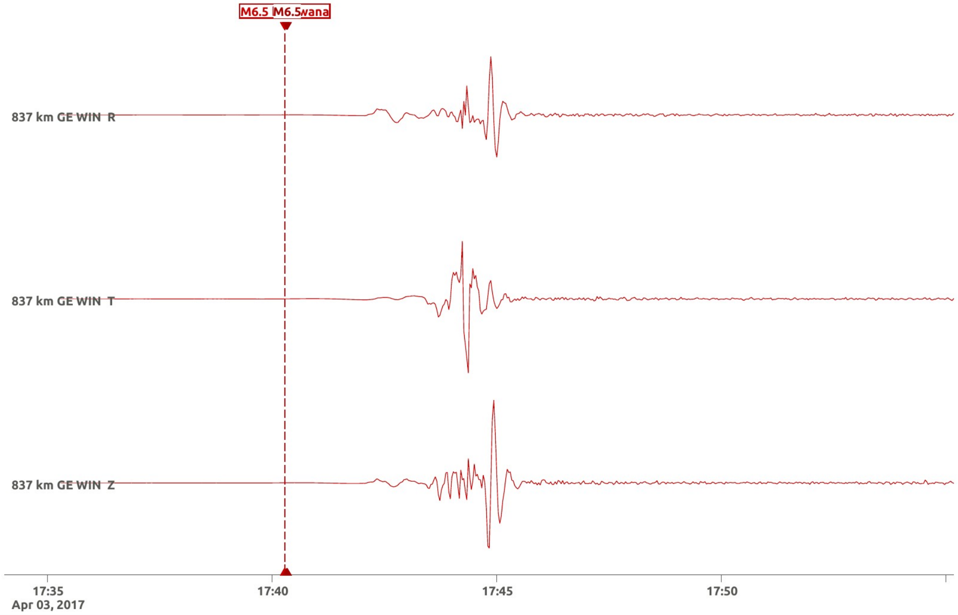
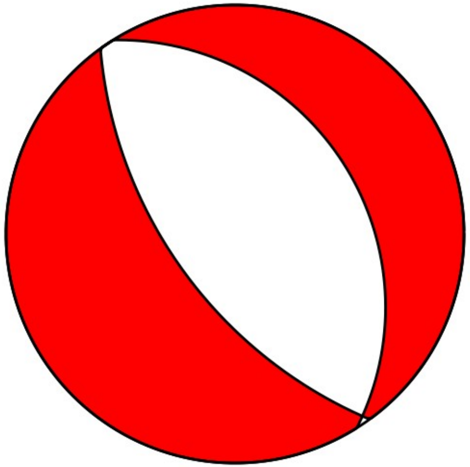
Source inversion in seismology: how to determine geometry and properties of the **earthquake source** based on the modeling of the earthquake effects?





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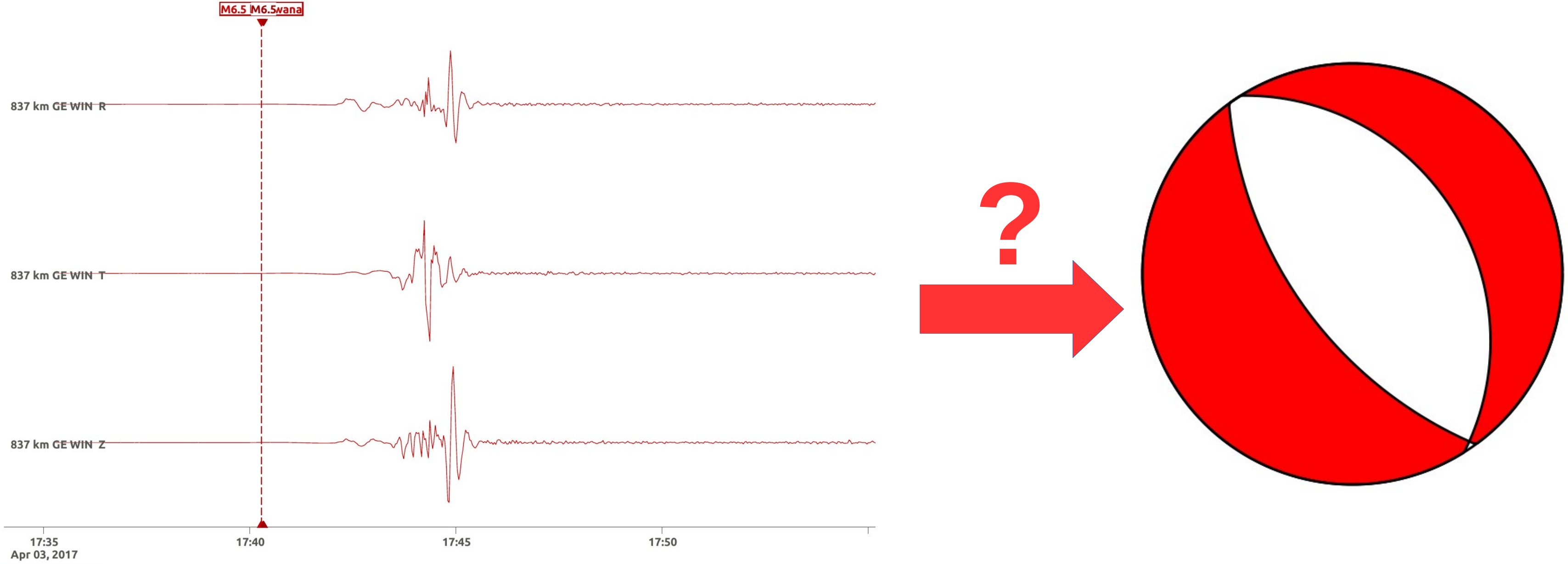
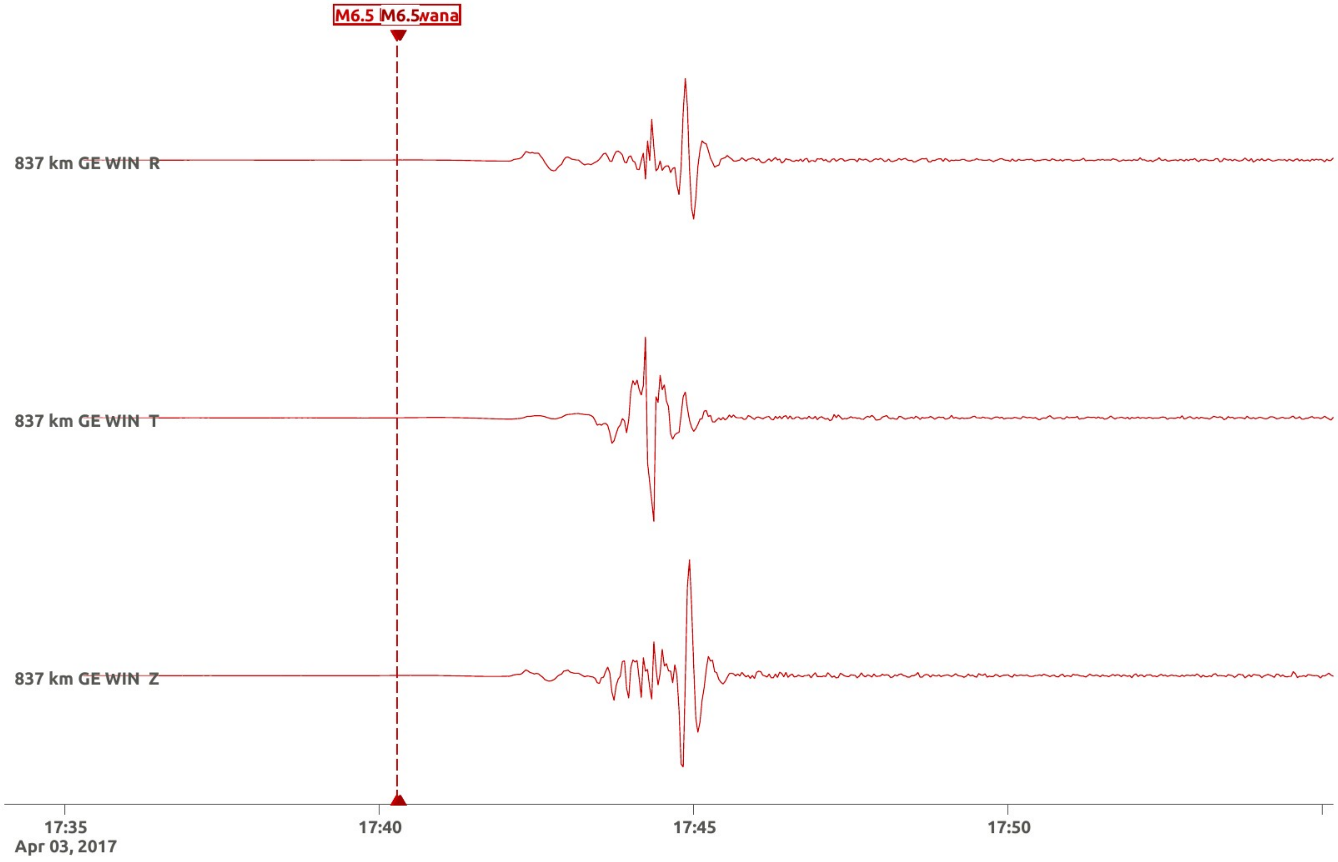


From seismograms to the earthquake source



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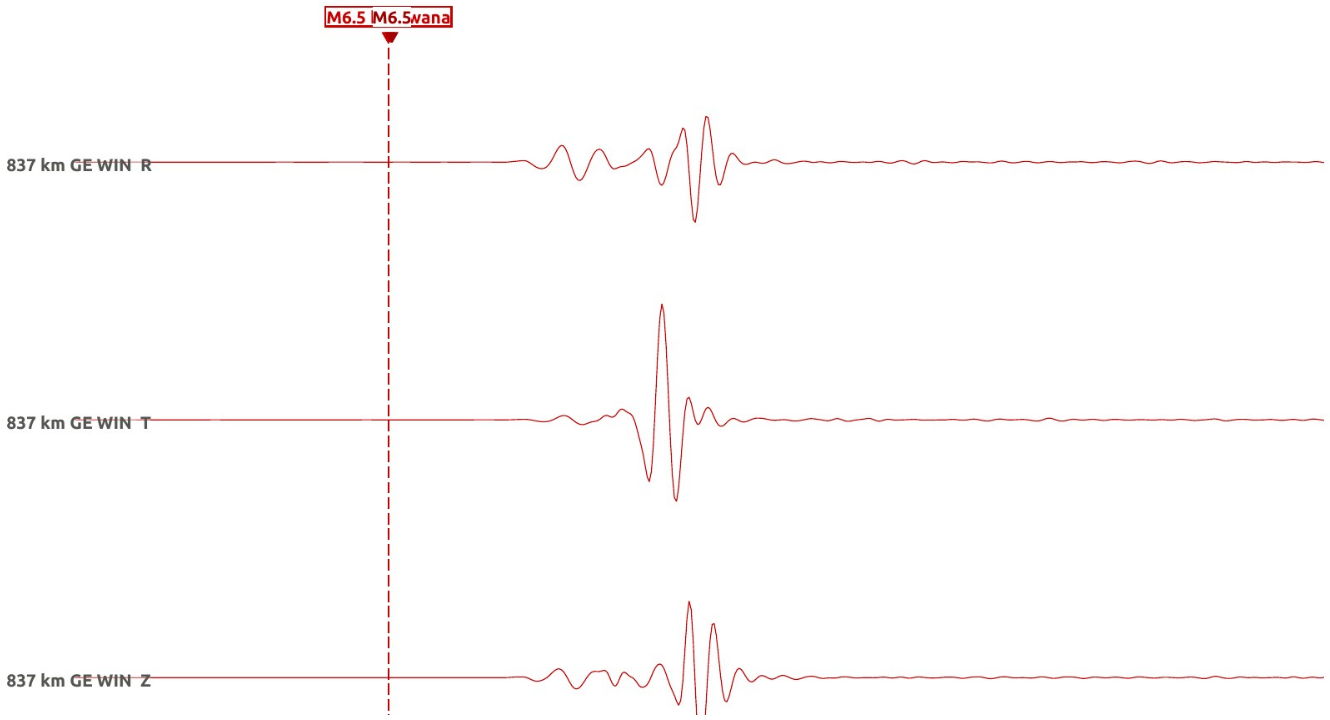

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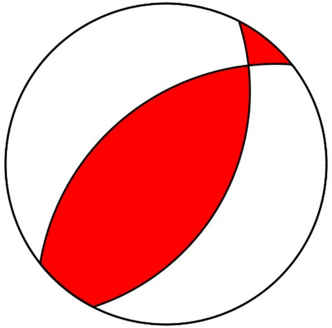

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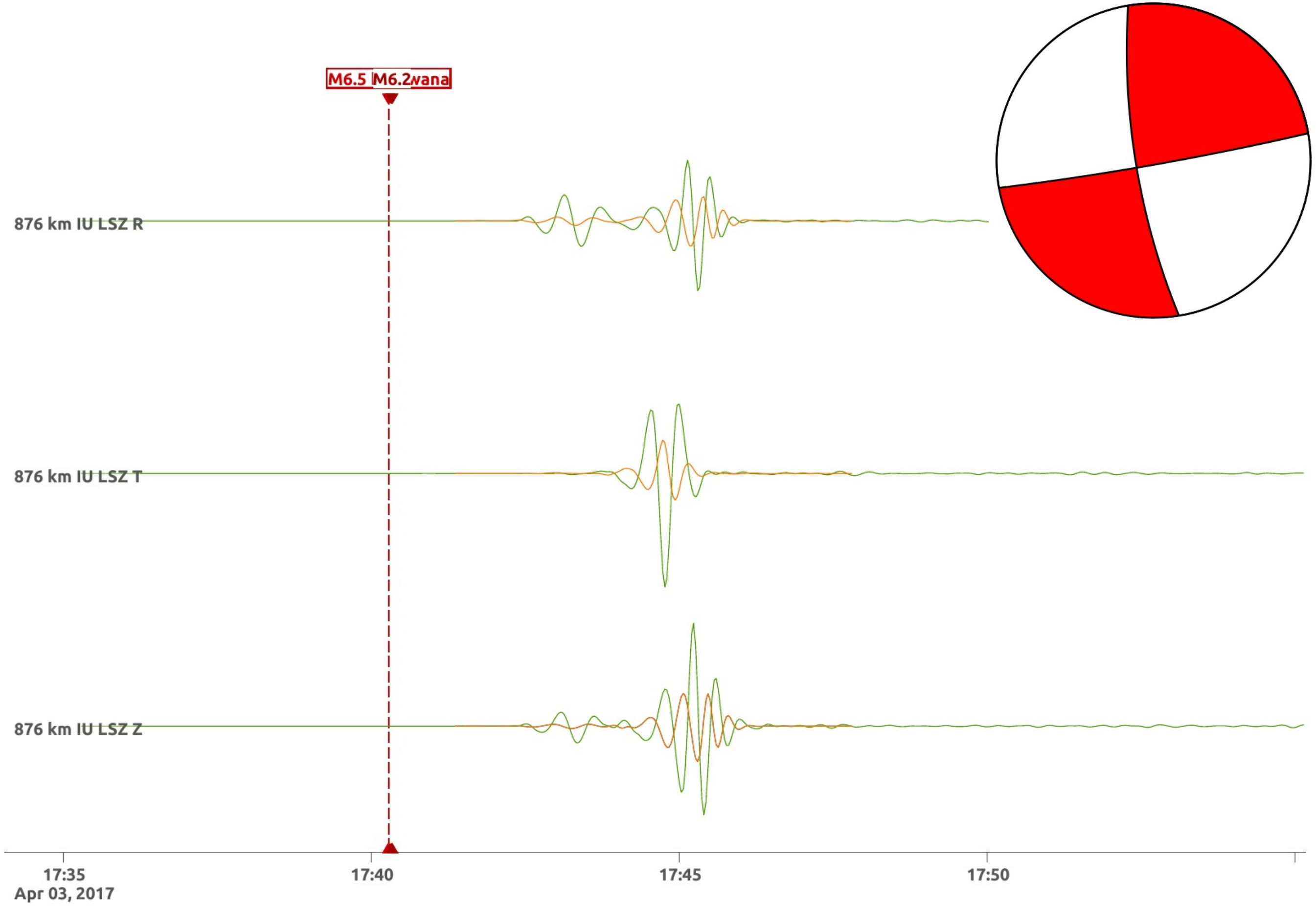

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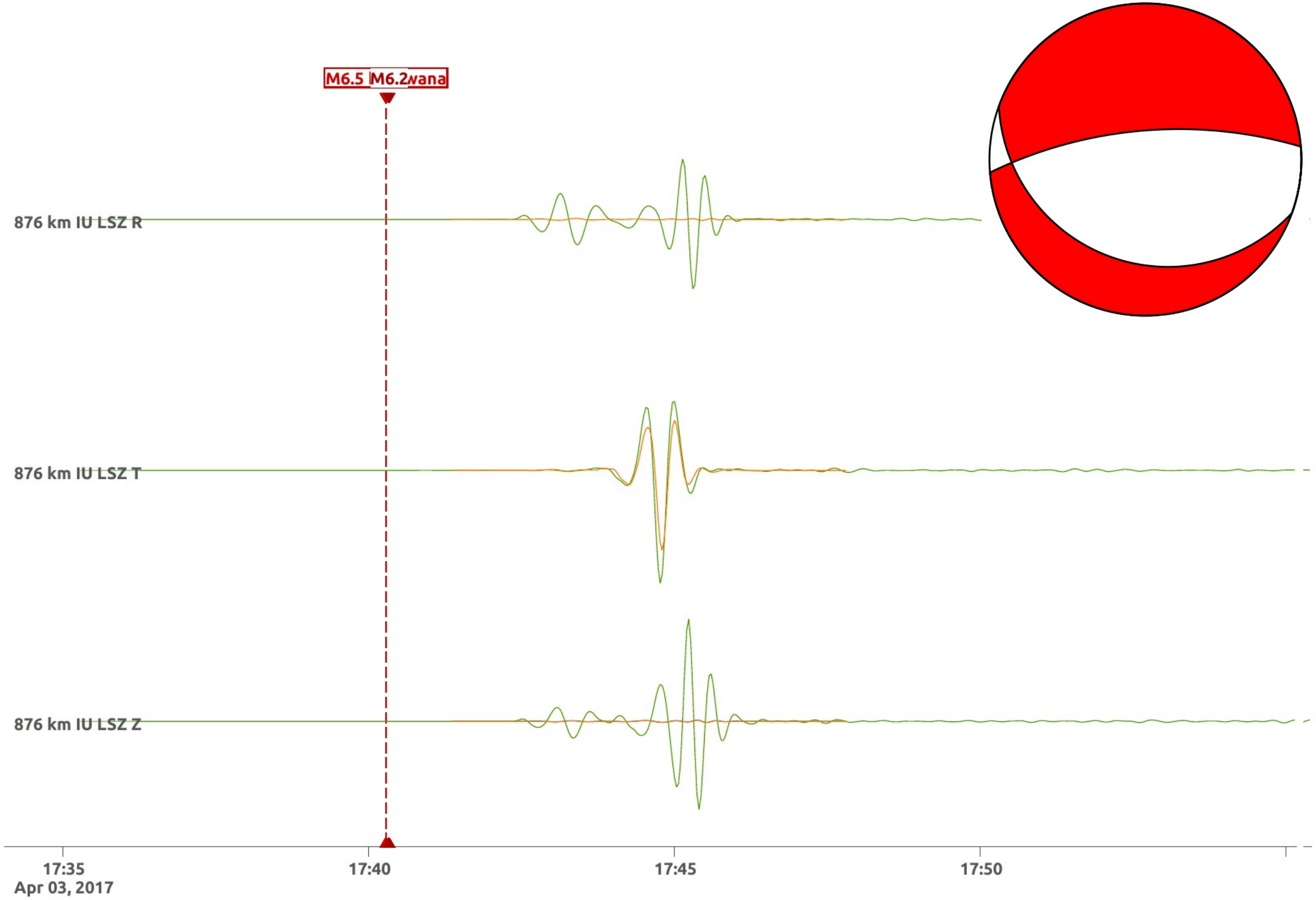

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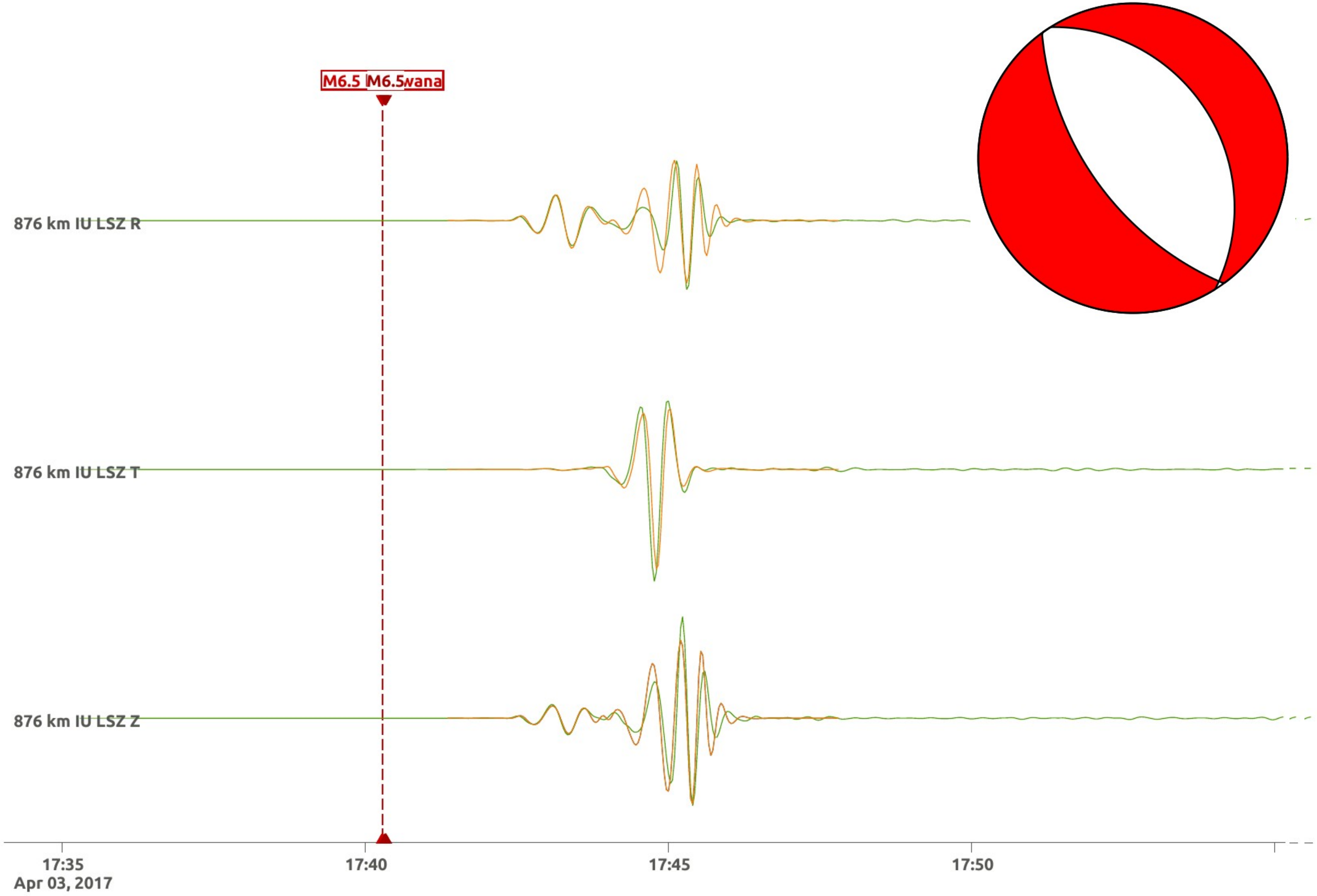
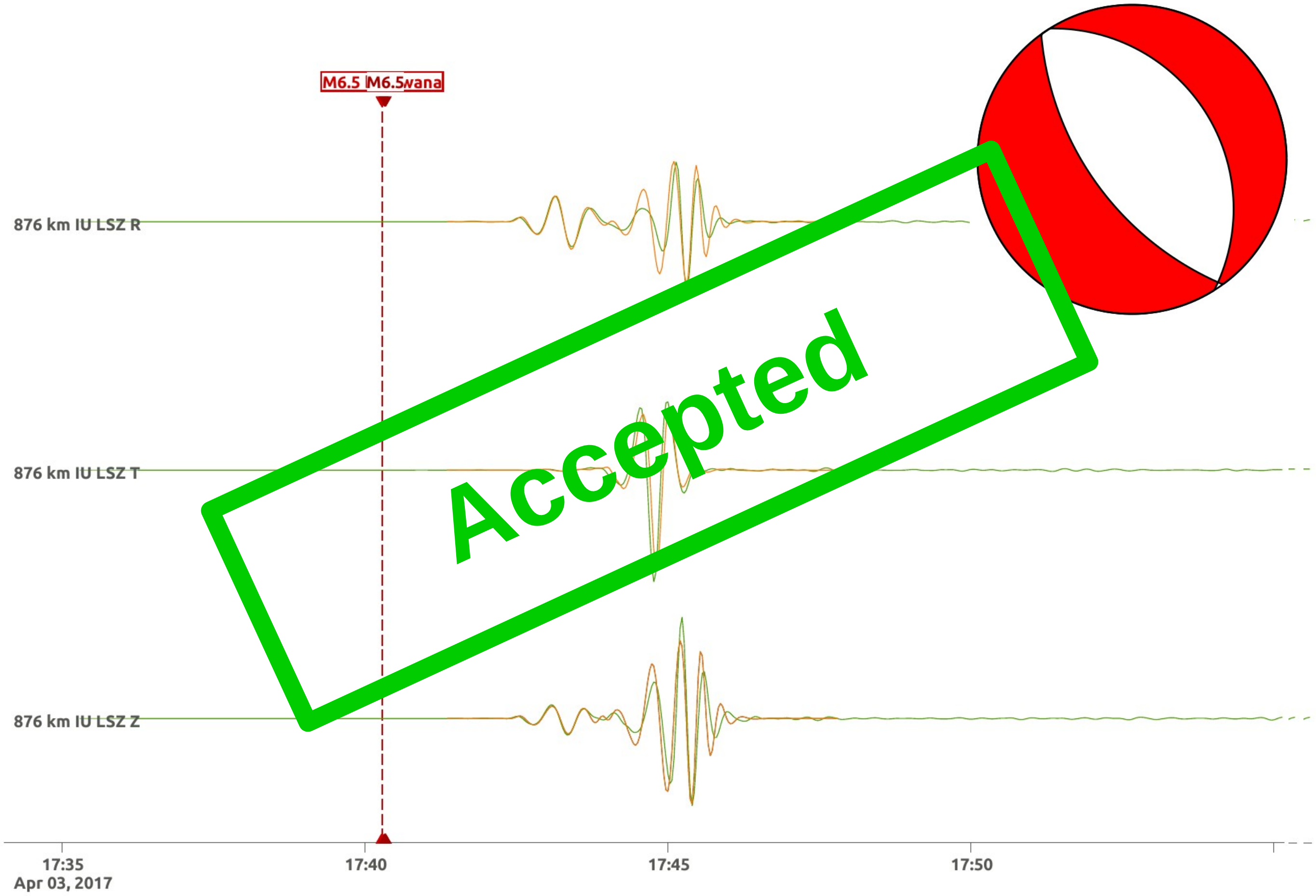


From seismograms to the earthquake source



Our task

Source inversion in seismology: how to determine geometry and properties of the earthquake source based on the modeling of the earthquake effects?

Our task, what do we need?

SOURCE MODEL

We need to define an earthquake source model (or more than one), and the parameters which describe it

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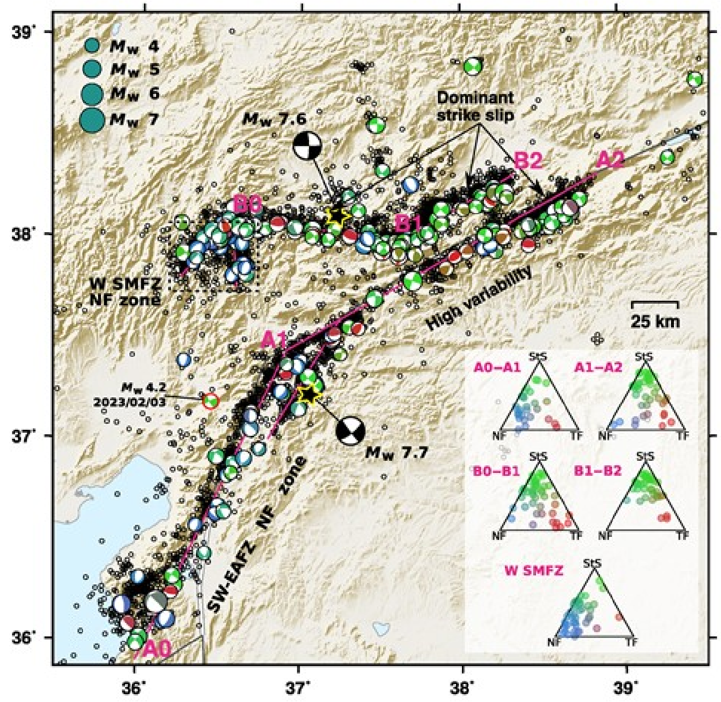
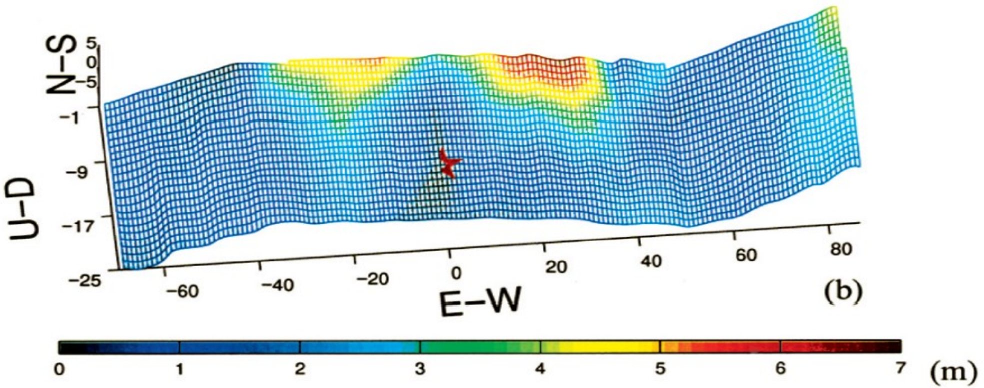


Moment tensors
(2023 Turkey-Syria earthquake sequence)
Petersen et al. 2023

Slip map
1977 Izmit, Turkey, earthquake)
Li et al. 2002



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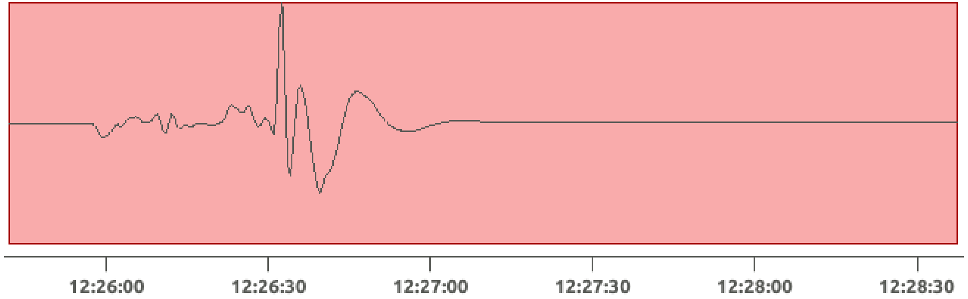
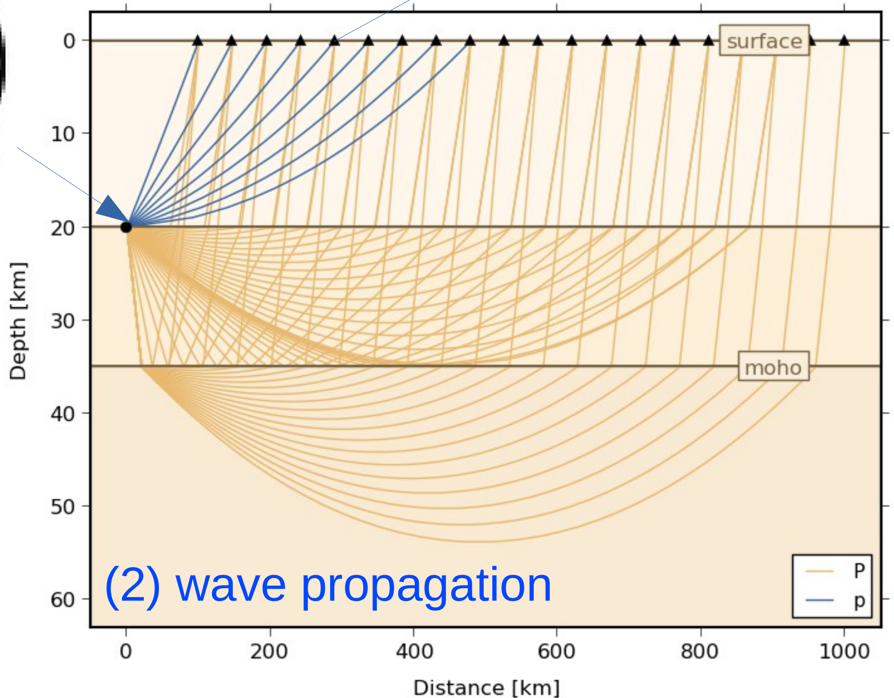
SYNTHETIC SEISMOGRAMS (FORWARD MODEL)
We need to establish how to simulate the effects of a given source model; for example, to compute synthetic seismograms at the Earth's surface

Synthetic seismograms

(1) source model



(3) synthetic seismograms



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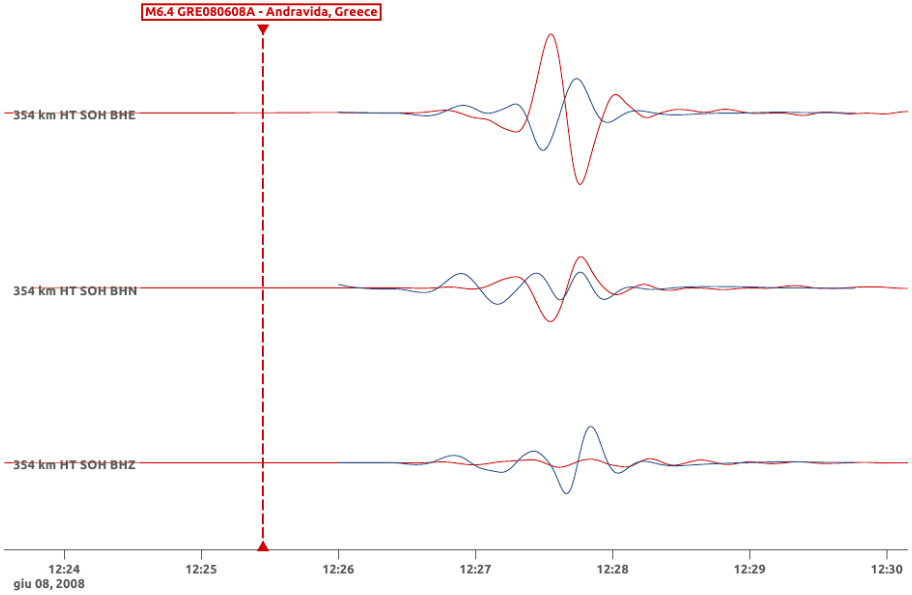
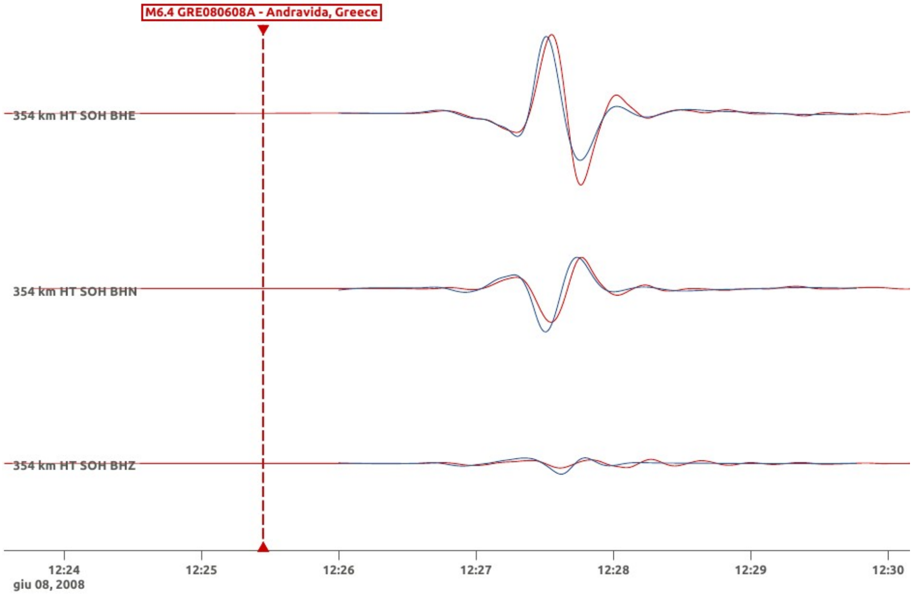
INVERSION FRAMEWORK (INVERSE PROBLEM)
We need to choose how to compare modeled and observed effects (e.g. synthetic and observed waveforms) and how to use this information to retrieve the most likely source model

Inversion framework



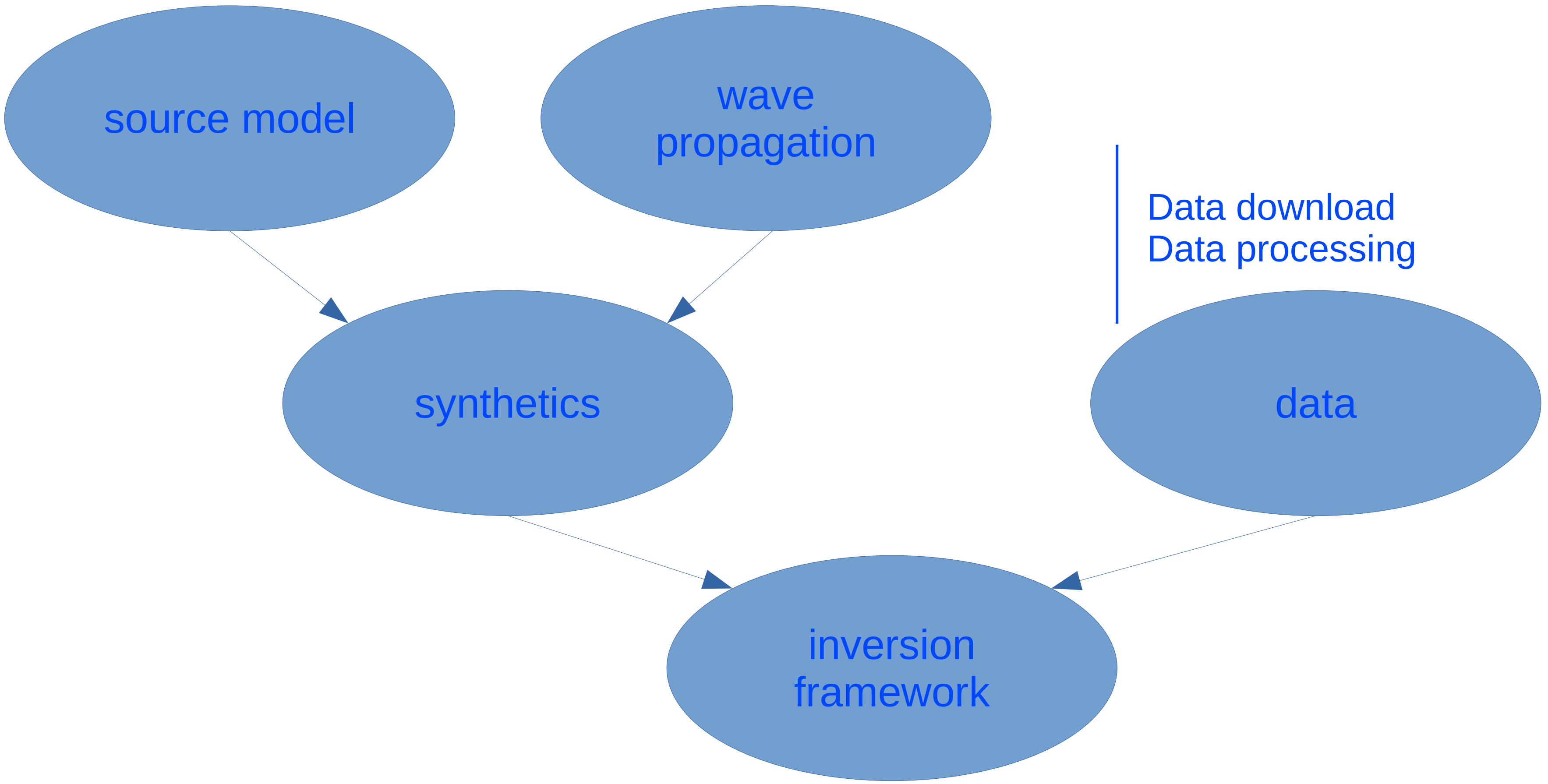


data* *vs.* *synthetics

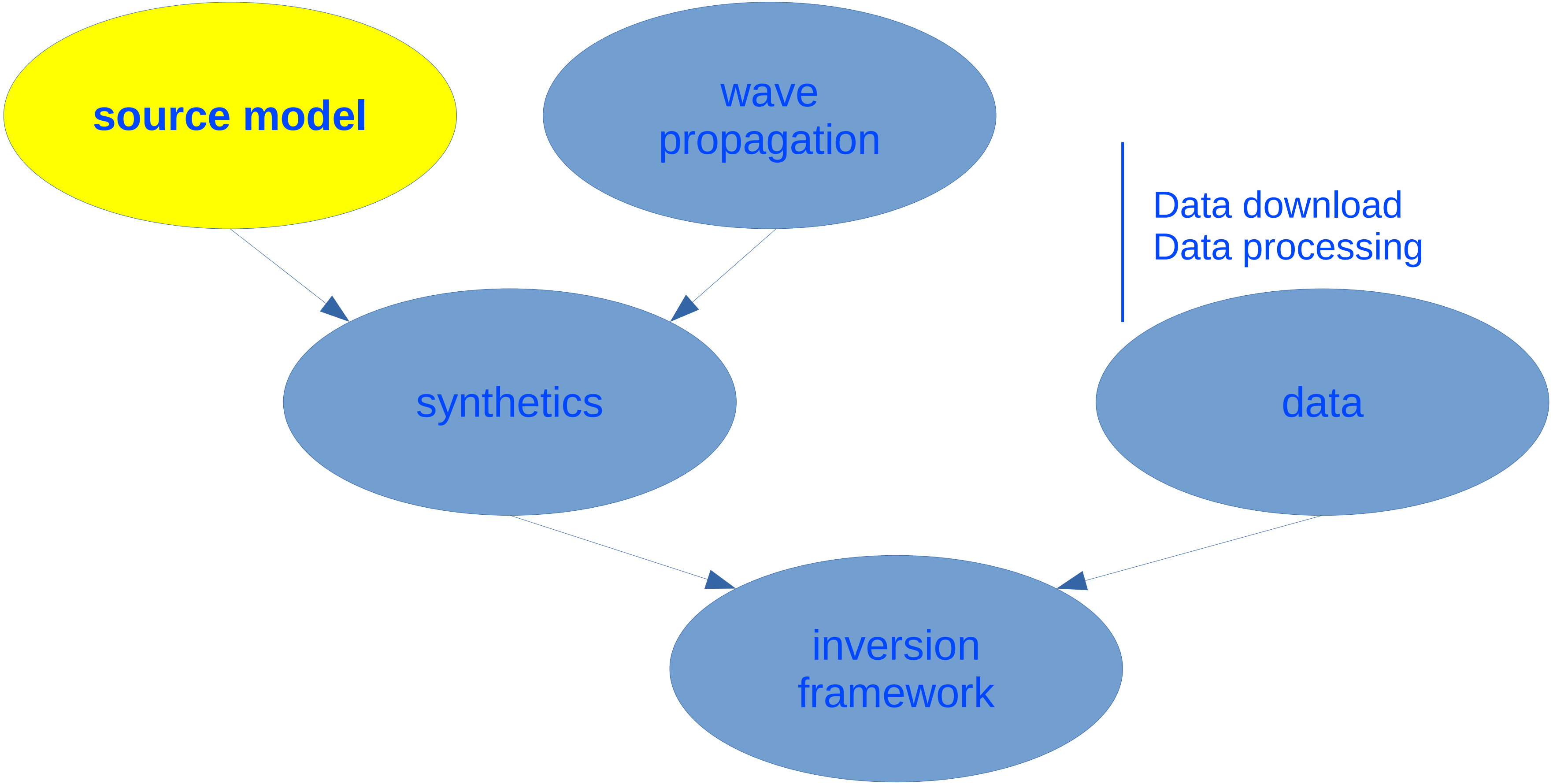
Bad fit (bad solution)

Good fit (good solution)

Source inversion layout



Source inversion layout



The seismic source, point source models

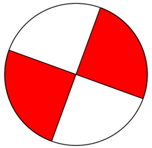
A point source model is justified in the far field approximation:

Source-Receiver distance >> Rupture size

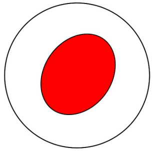
Considered wavelength >> Rupture size

Two types of point sources are most commonly used

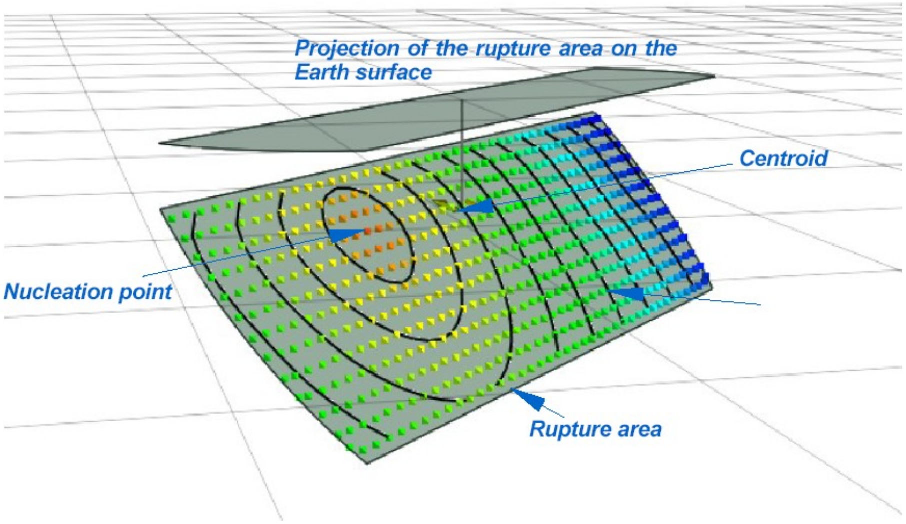
The double couple (DC) source model



The moment tensor (MT) source model



Source & source parameters



Heimann 2011

Centroid location (Lat, Lon, Depth)

Scalar moment and magnitude

Strike, Dip, Rake

Non-shear and Isotropic components

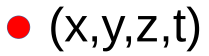
Rupture Duration

Source Time Function

Shape and size of the rupture area

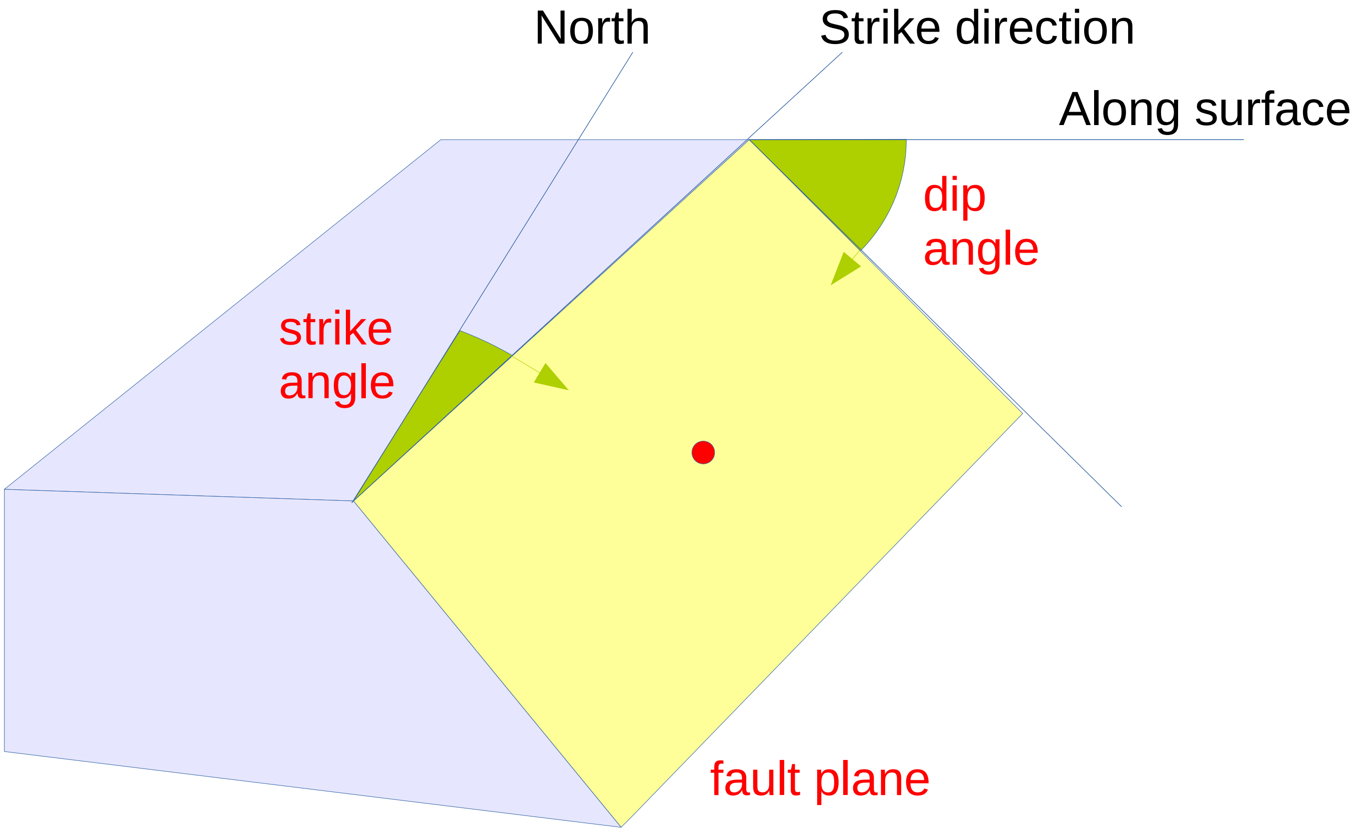
Rupture Velocity

DC model, source parameters



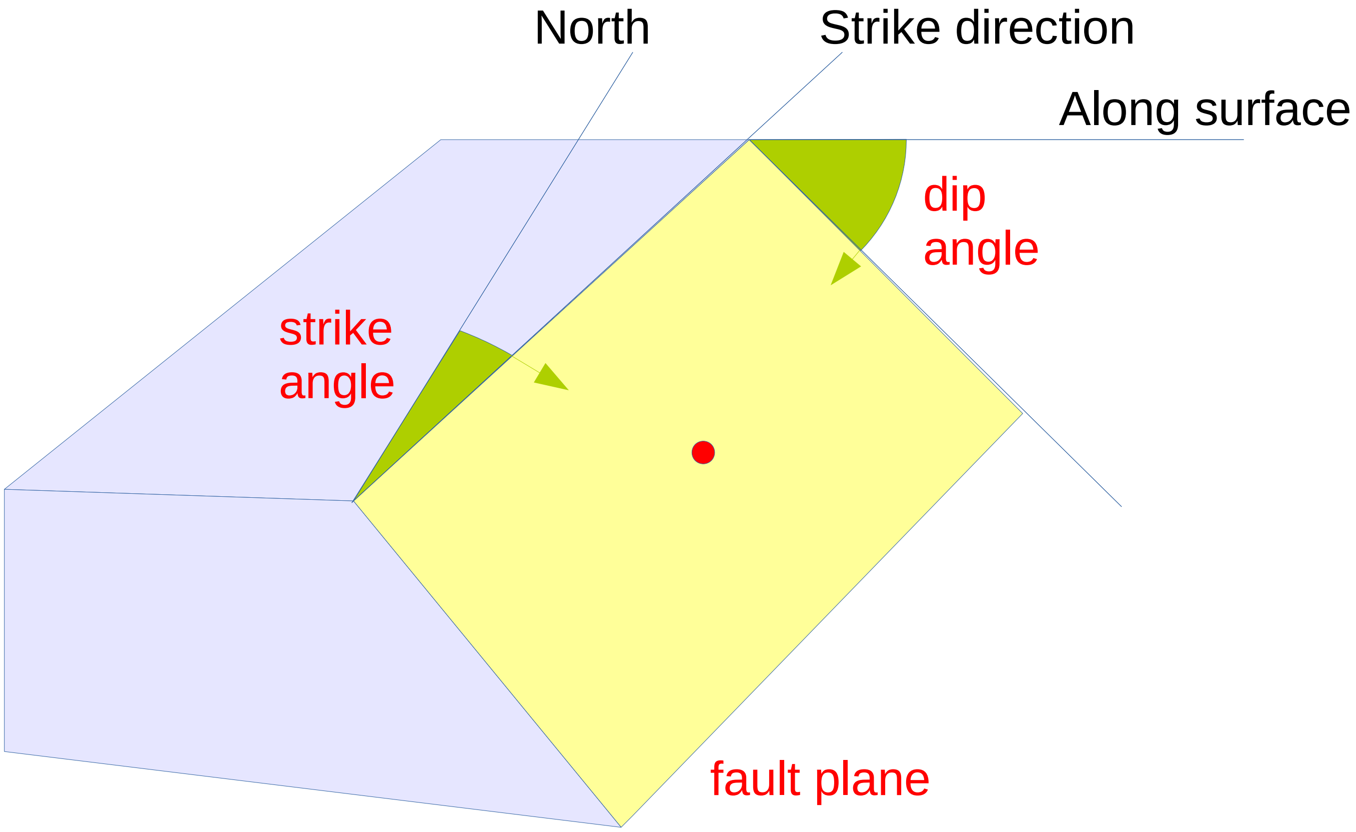
Source parameters: Lat, Lon, Depth, Origin time

DC model, source parameters



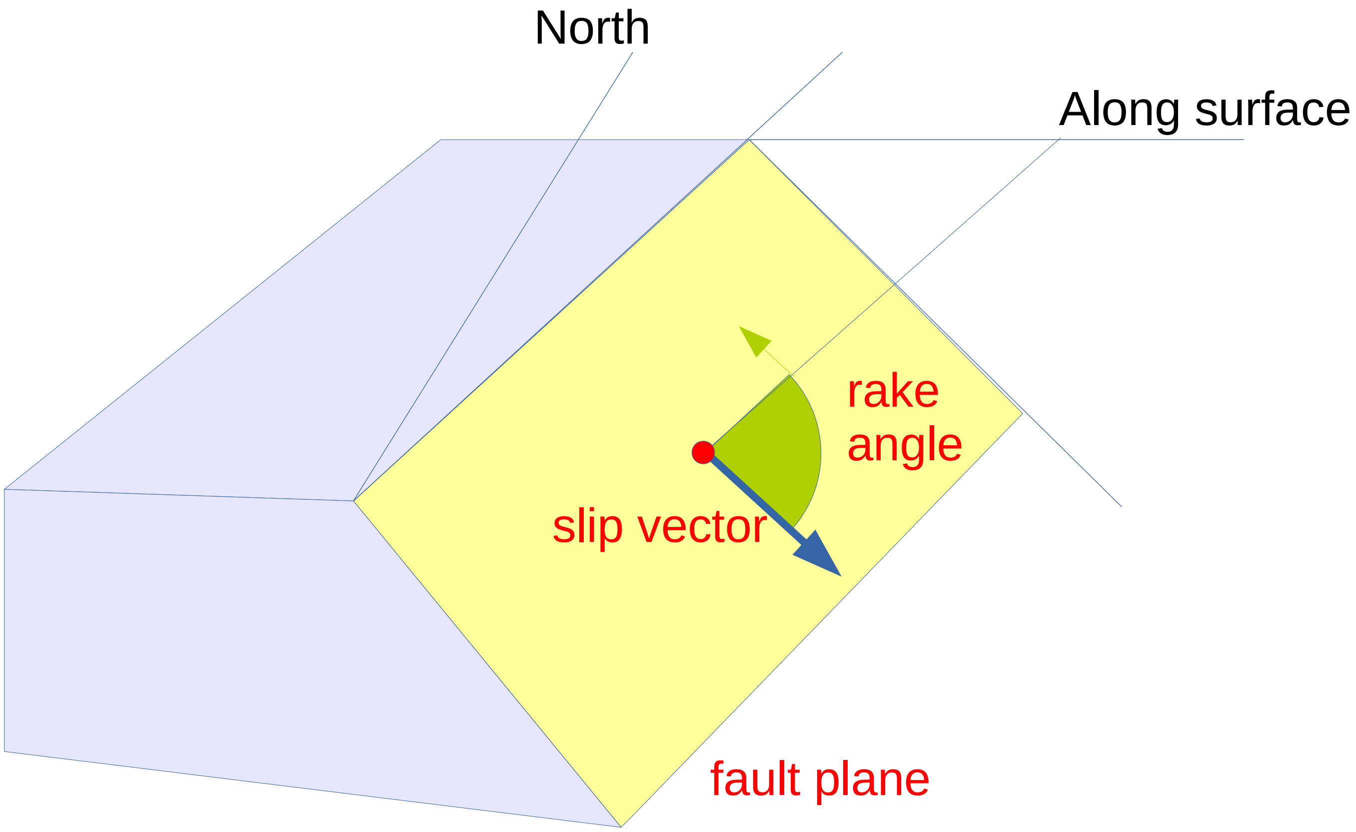
Source parameters: Lat, Lon, Depth, Origin time, Strike, Dip

DC model, source parameters



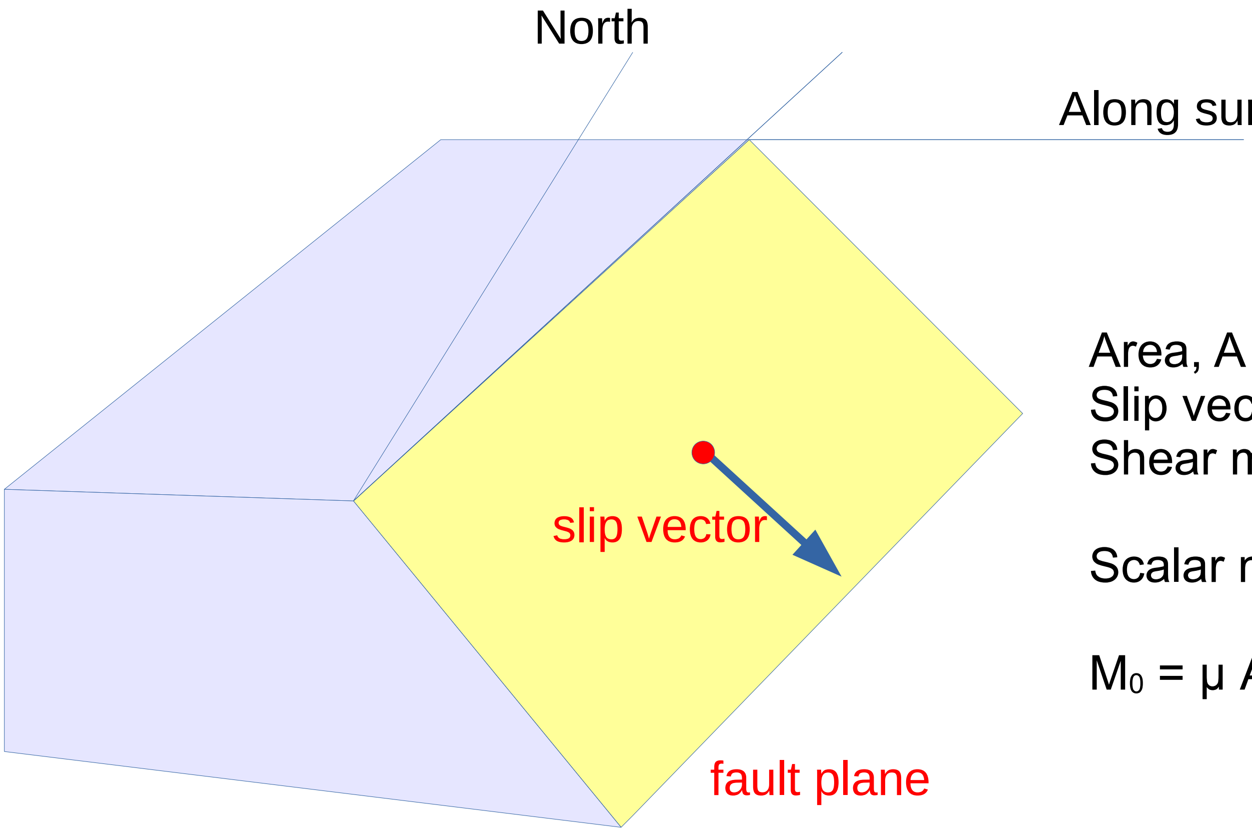
Source parameters: Lat, Lon, Depth, Origin time

DC model, source parameters



Source parameters: Lat, Lon, Depth, Origin time, Strike, Dip, Rake

DC model, source parameters



Area, A
Slip vector, λ
Shear modulus, μ

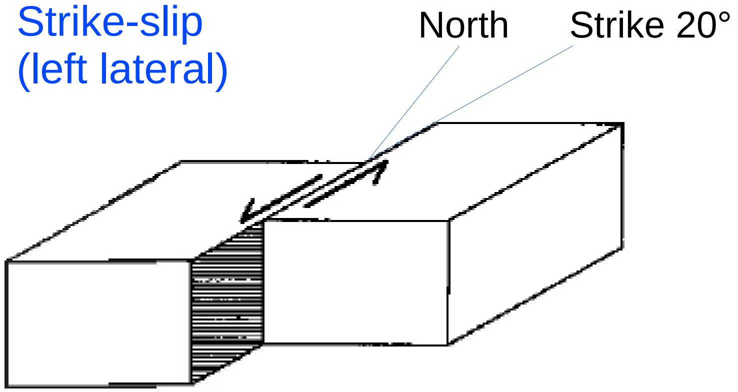
Scalar moment [Nm]:

$M_0 = \mu A \lambda$

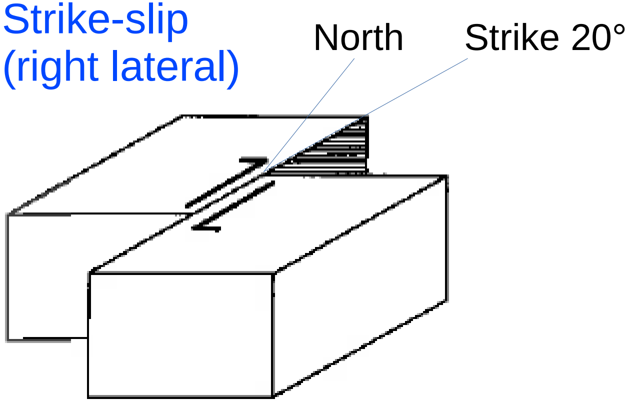
Source parameters: Lat, Lon, Depth, Origin time, Strike, Dip, Rake, Scalar Moment

DC model, shear faulting

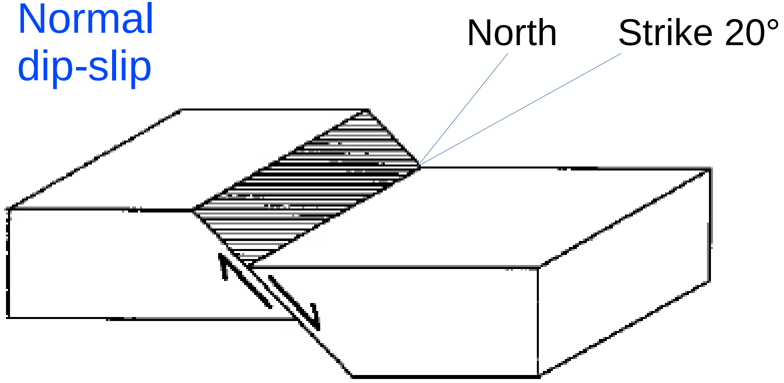
Strike-slip
(left lateral)



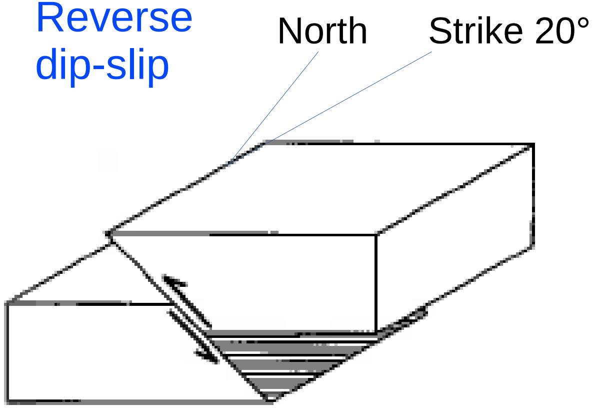
Strike-slip
(right lateral)



Normal
dip-slip

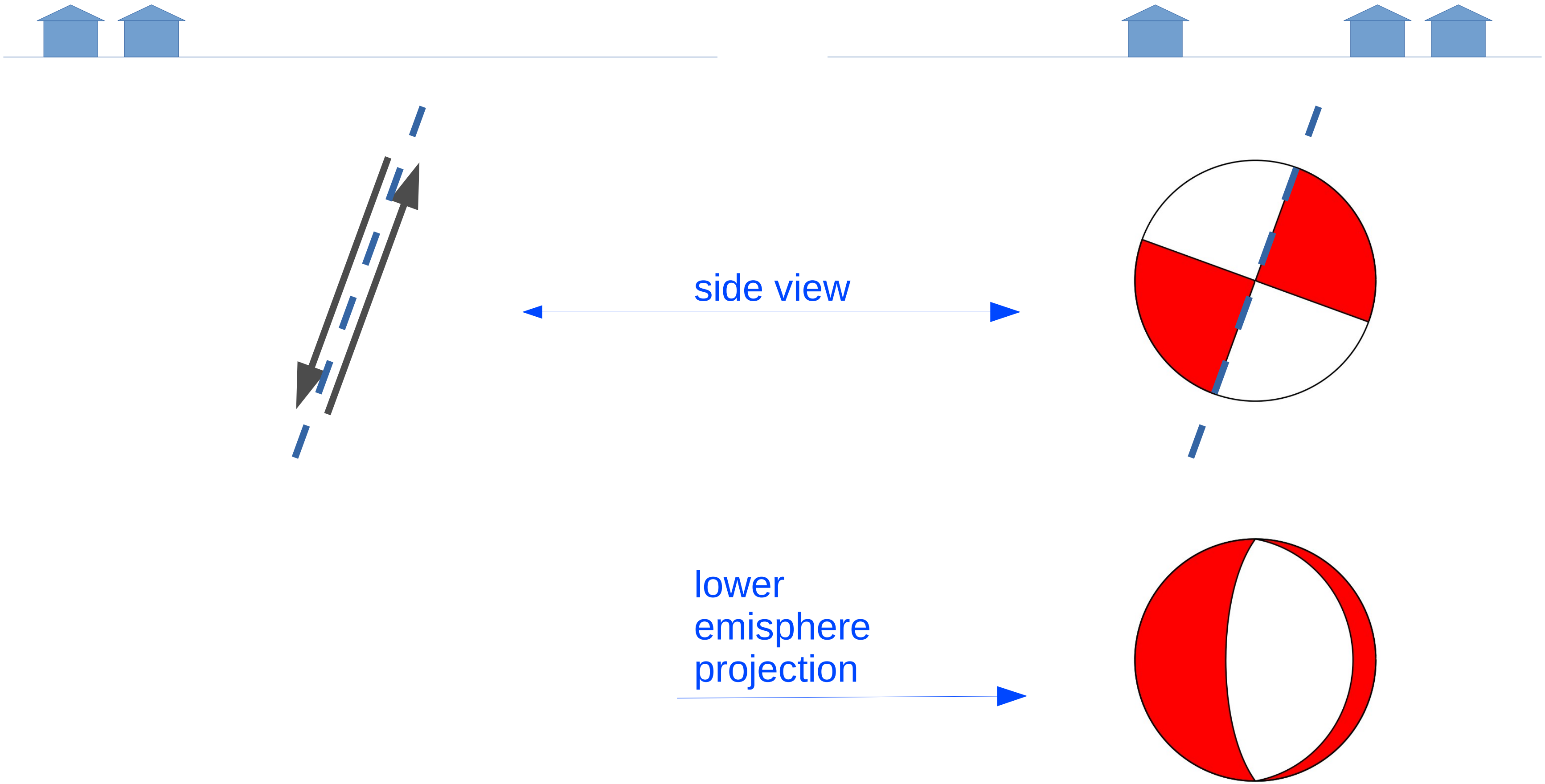


Reverse
dip-slip



After Stein & Wysession 2003

DC model, focal sphere



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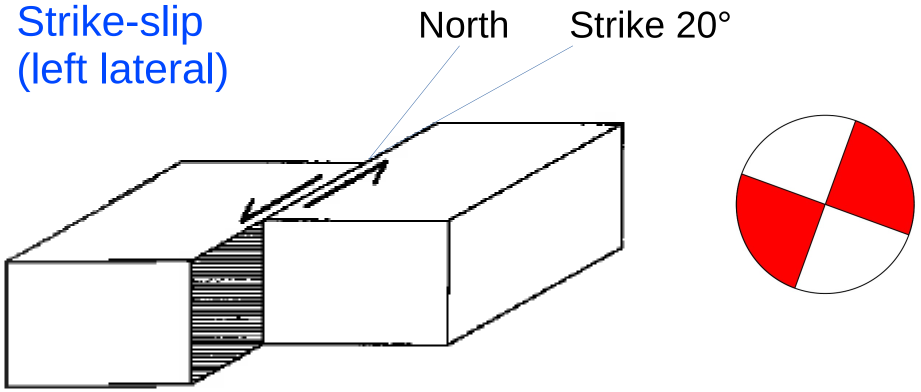

Strike-slip
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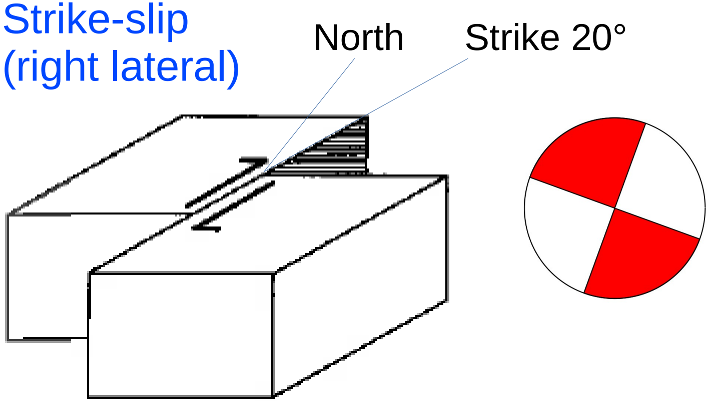
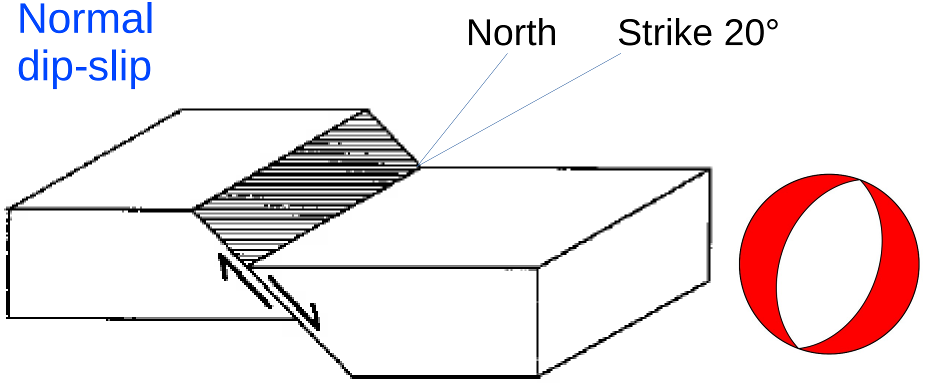
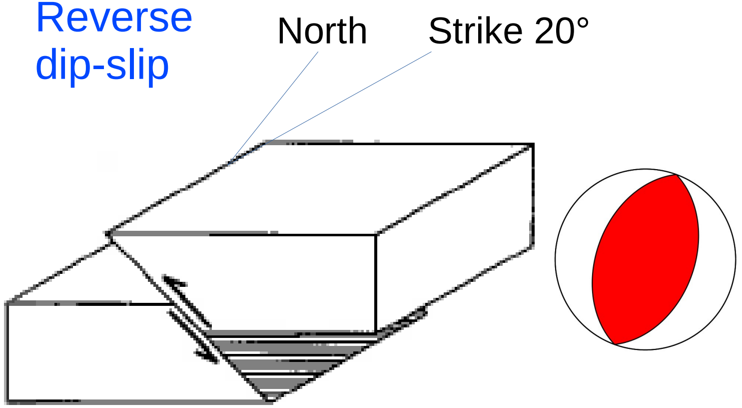


Normal
dip-slip



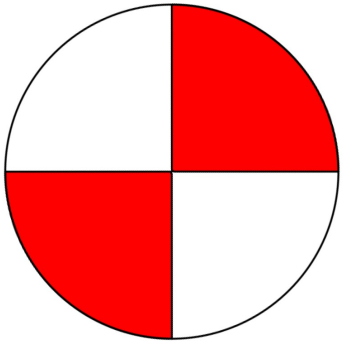
Reverse
dip-slip



After Stein & Wysession 2003

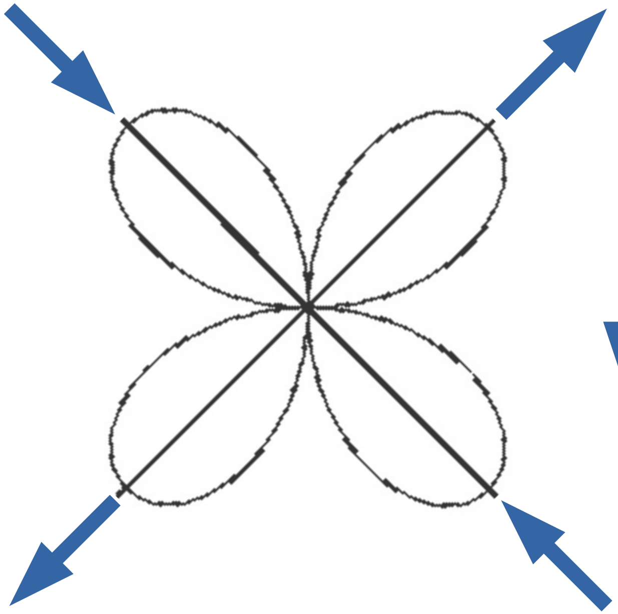
DC model, radiation pattern

Focal sphere

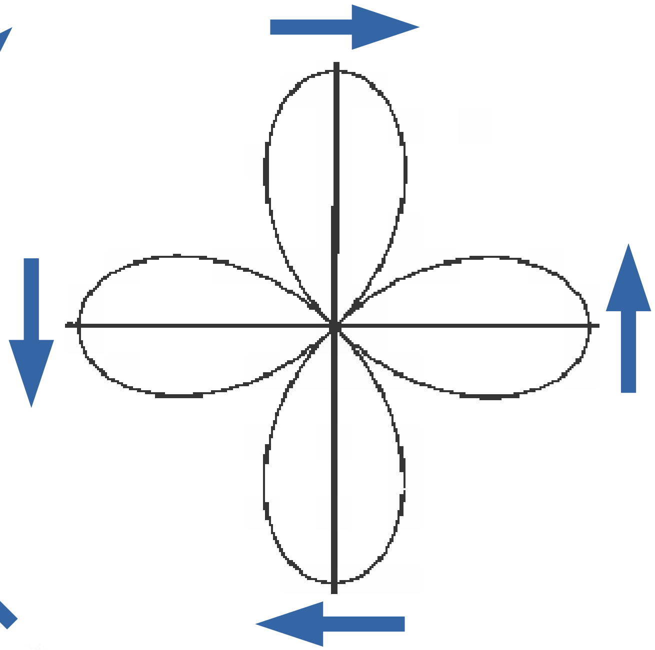


Radiation pattern

P waves

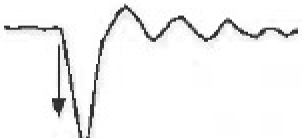


S waves



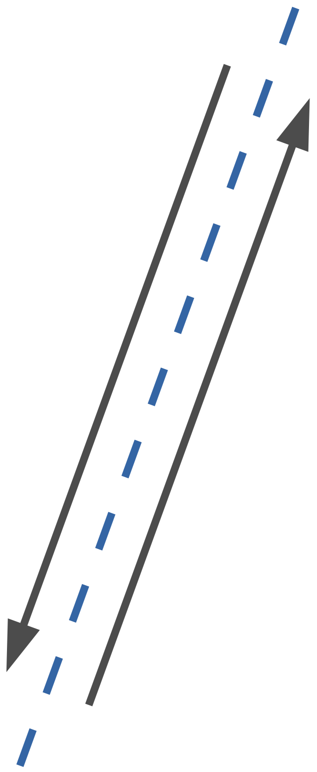
Positive onset

Negative onset

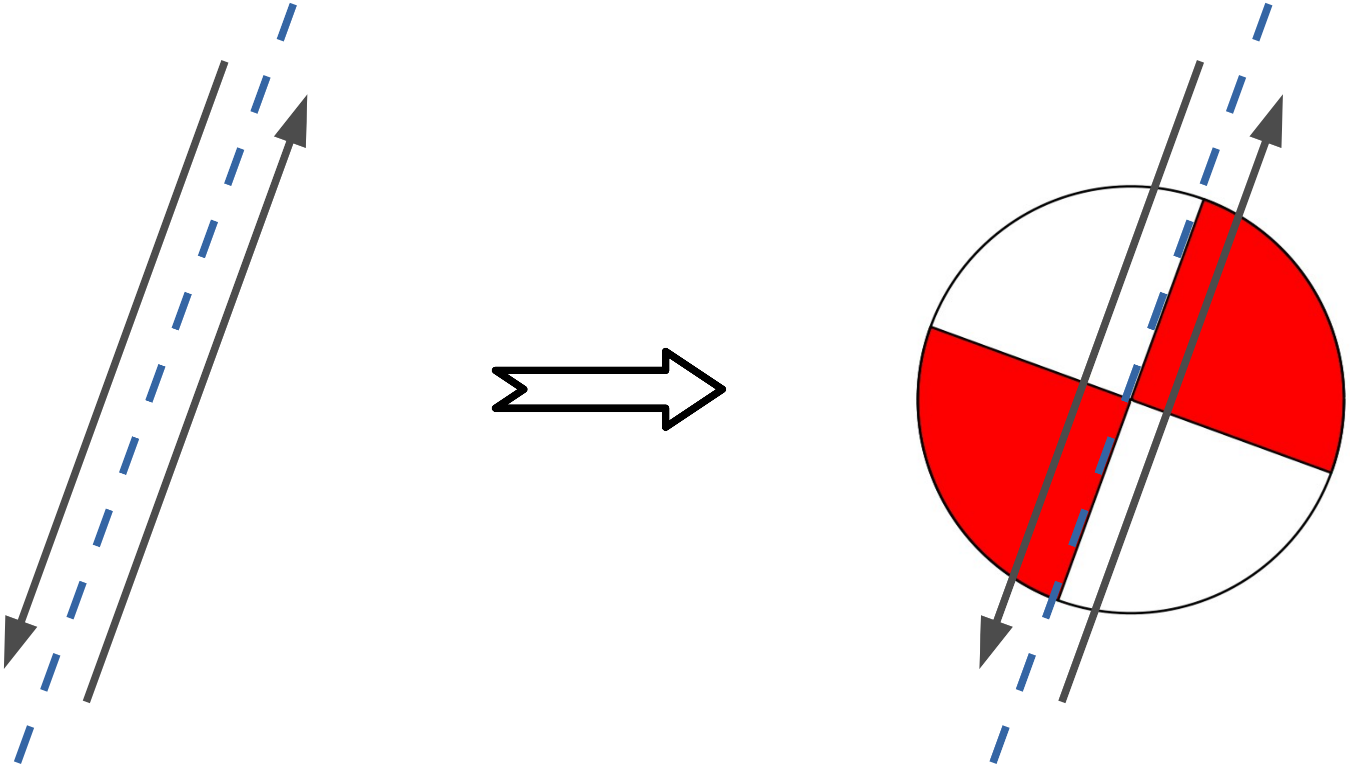


After Stein & Wysession 2003

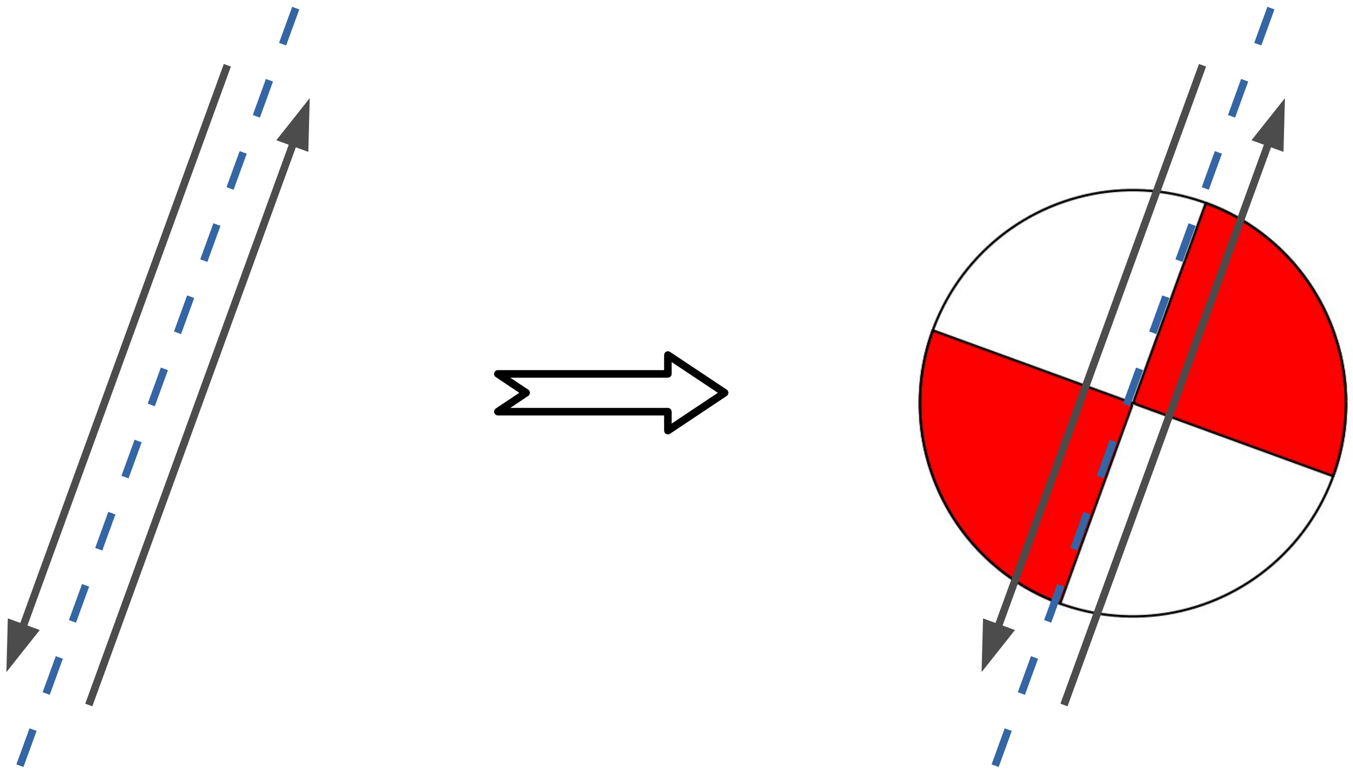
DC source, rupture plane ambiguity



DC source, rupture plane ambiguity



DC source, rupture plane ambiguity



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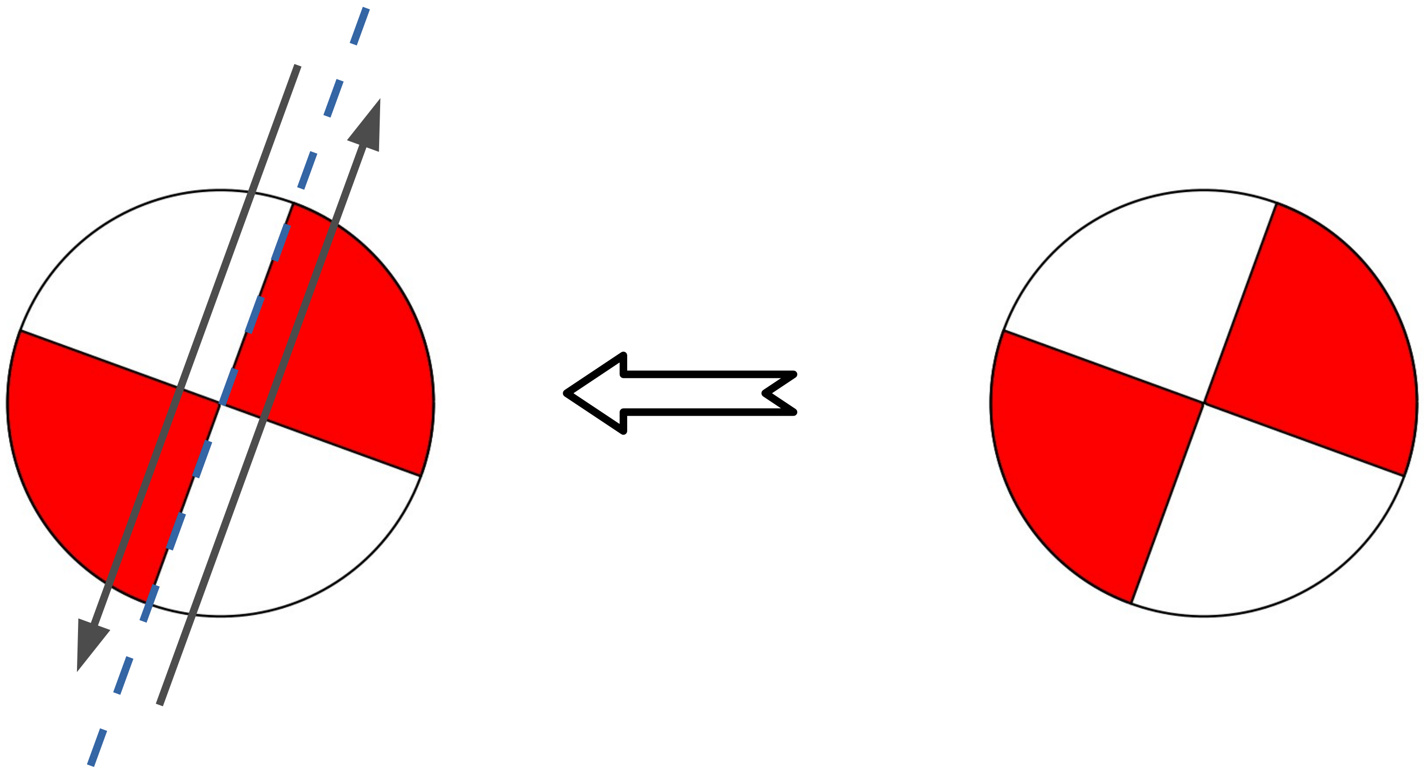
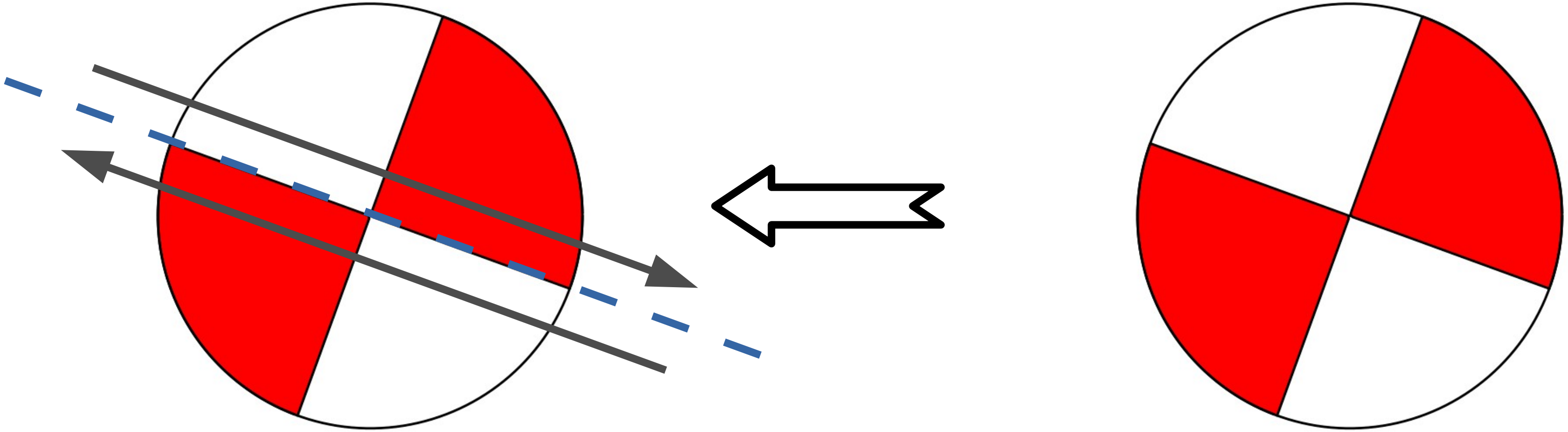
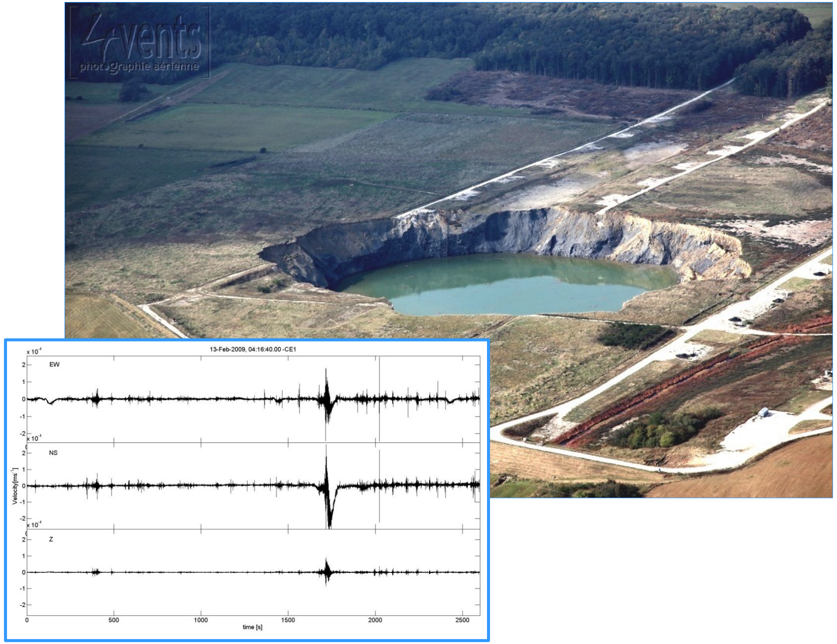


DC source, rupture plane ambiguity

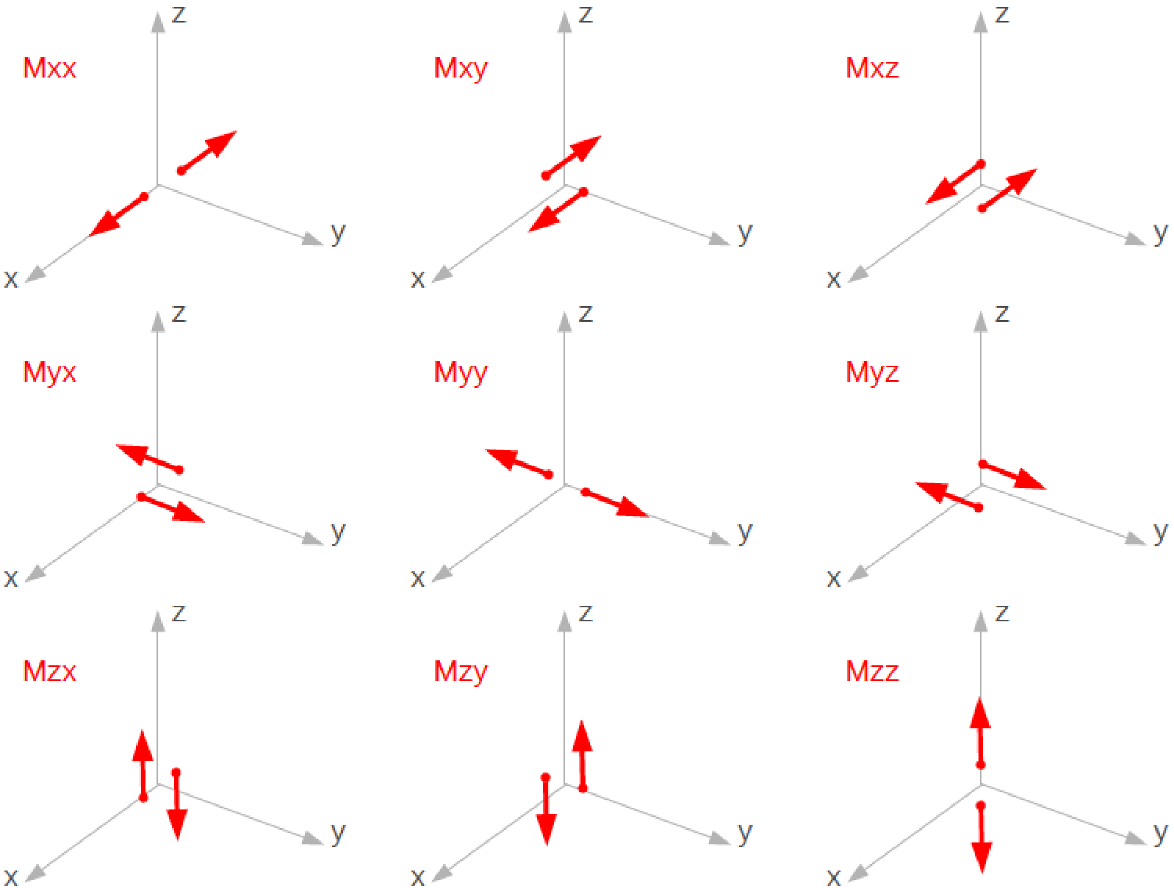


From DC to MT source



Volcanic and induced earthquakes, explosions, deep earthquakes, as well as complex tectonic earthquake ruptures require a more general source model

The seismic moment tensor (MT) source



- Symmetric tensor
- 6 independent parameters M_{ij}
- Relation with scalar moment:

$$M_{ij} = M_0 \, m_{ij}$$

On moment tensor decomposition

Full MT
6 parameters (Mij)

Mxx	Mxy	Mxz
Myx	Myy	Myz
Mzx	Mzy	Mzz

On moment tensor decomposition

Full MT
6 parameters (Mij)

Iso MT
1 parameter (Mi)

Deviatoric MT
5 parameters (Mij)

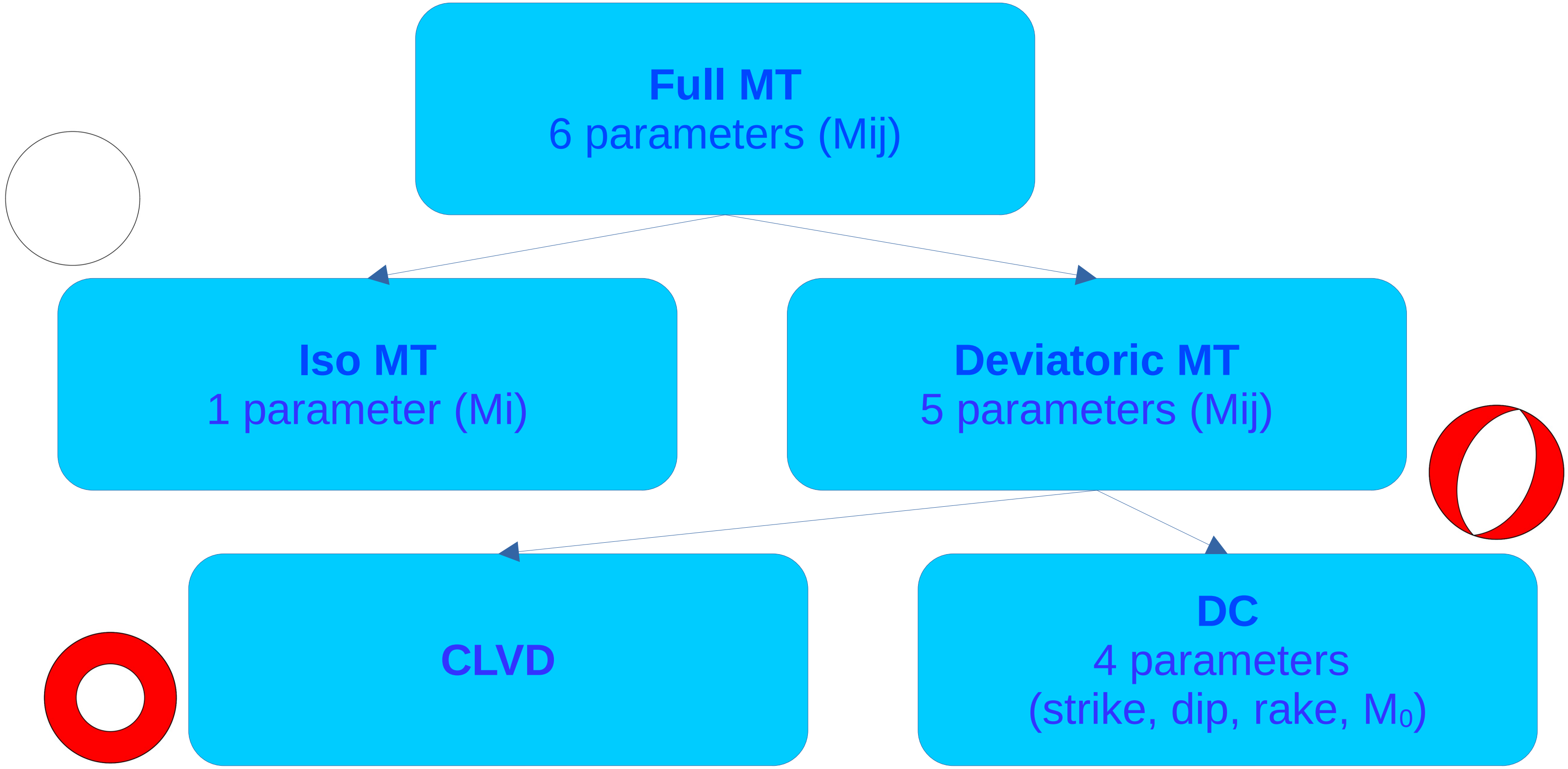
Mi	0	0
0	Mi	0
0	0	Mi

Volumetric change at the source

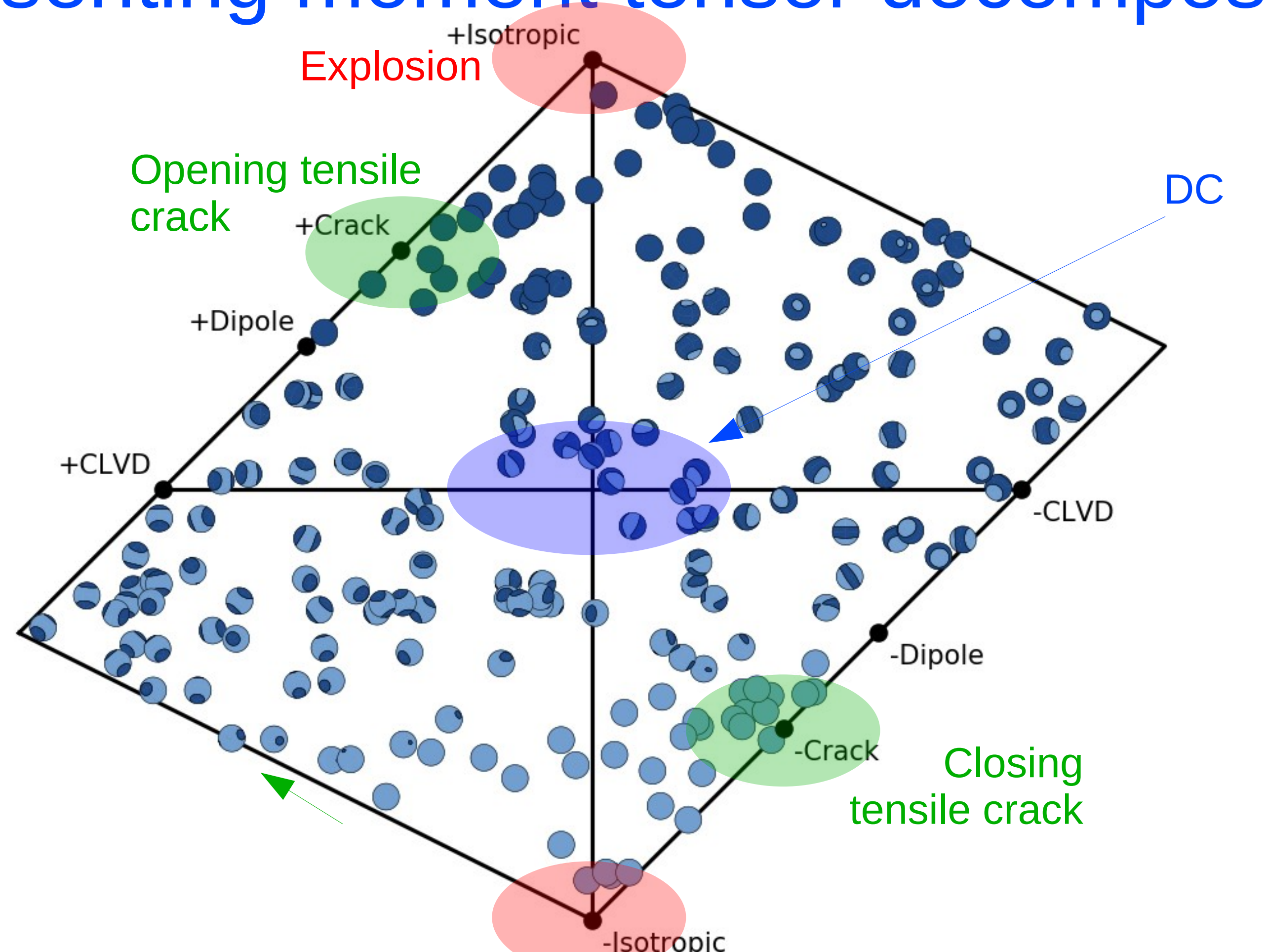
Mxx	Mxy	Mxz
Mxy	Myy	Myz
Mxz	Mxz	-(Mxx+Myy)

No net volume change

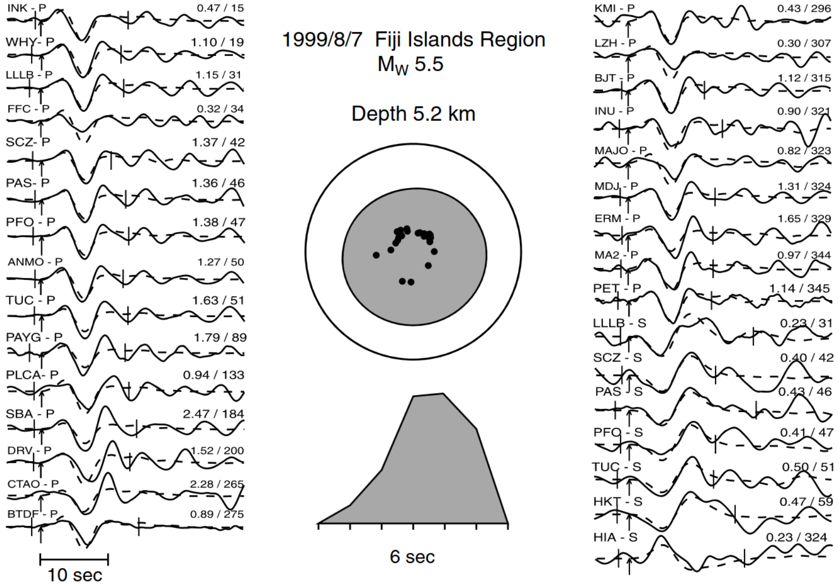
On moment tensor decomposition

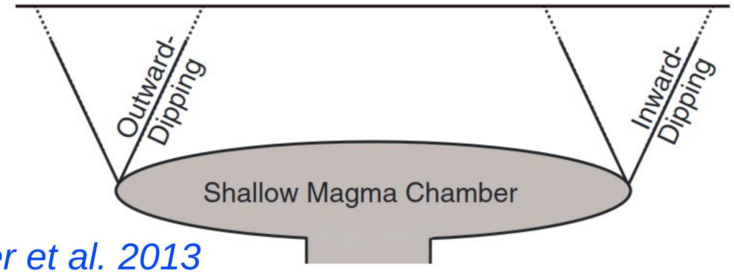


Representing moment tensor decomposition

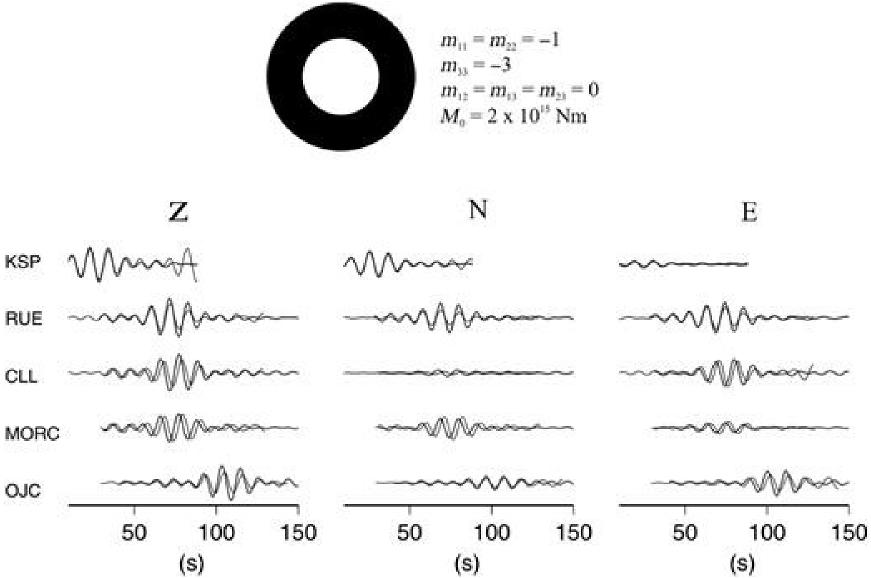


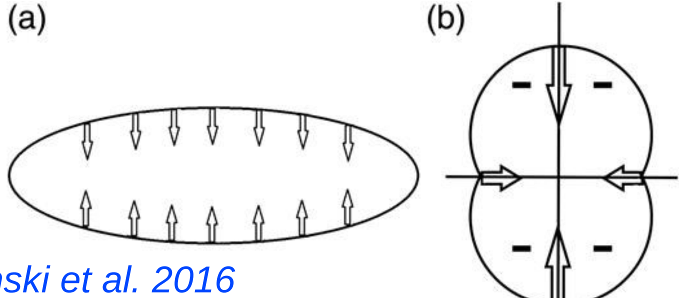
Examples of non-DC components





Shuler et al. 2013





Rudzinski et al. 2016

Origin of non-DC components

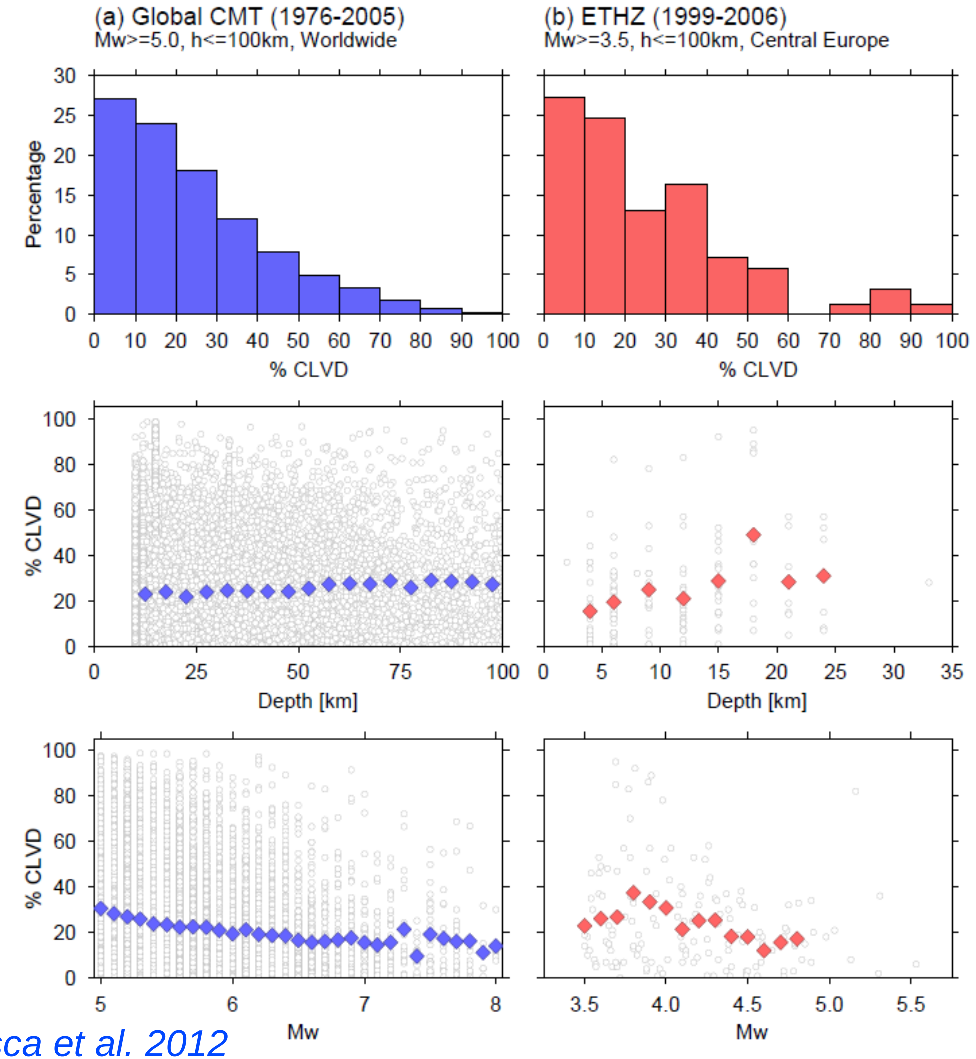
Common ISO=0 constraint for natural earthquakes (e.g. Global CMT)

non-DC terms:

Waveform propagation mismodeling

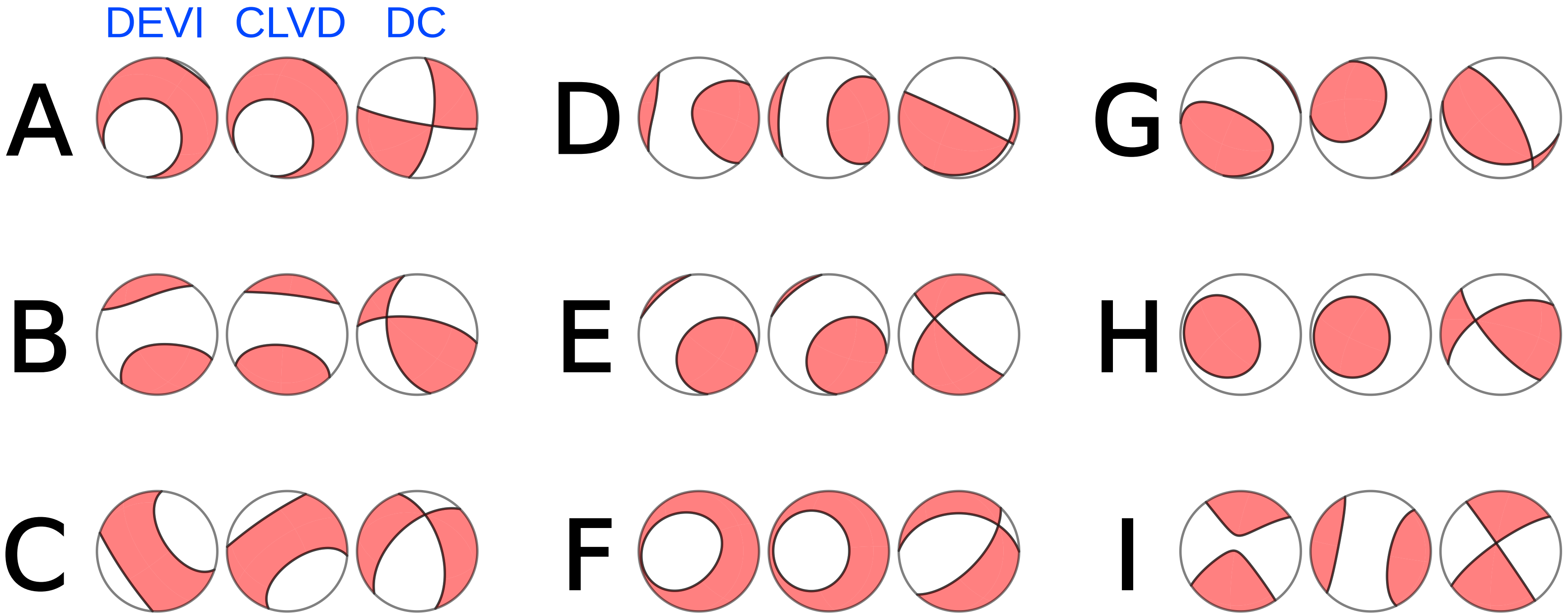
Poor network configurations and data quality

Complex source process



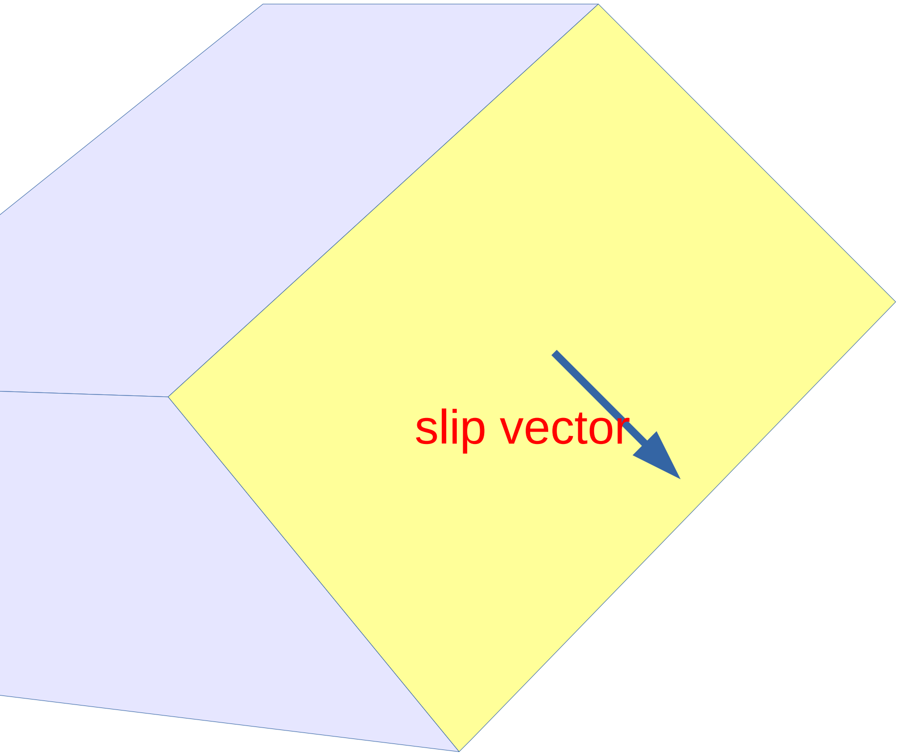
Cesca et al. 2012

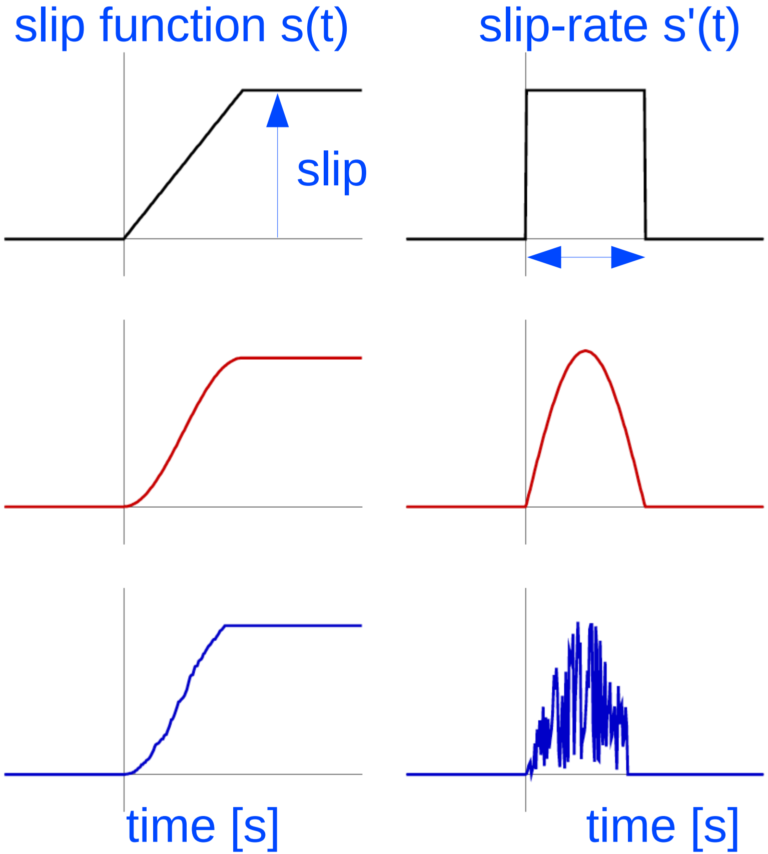
Challenges of moment tensor interpretation



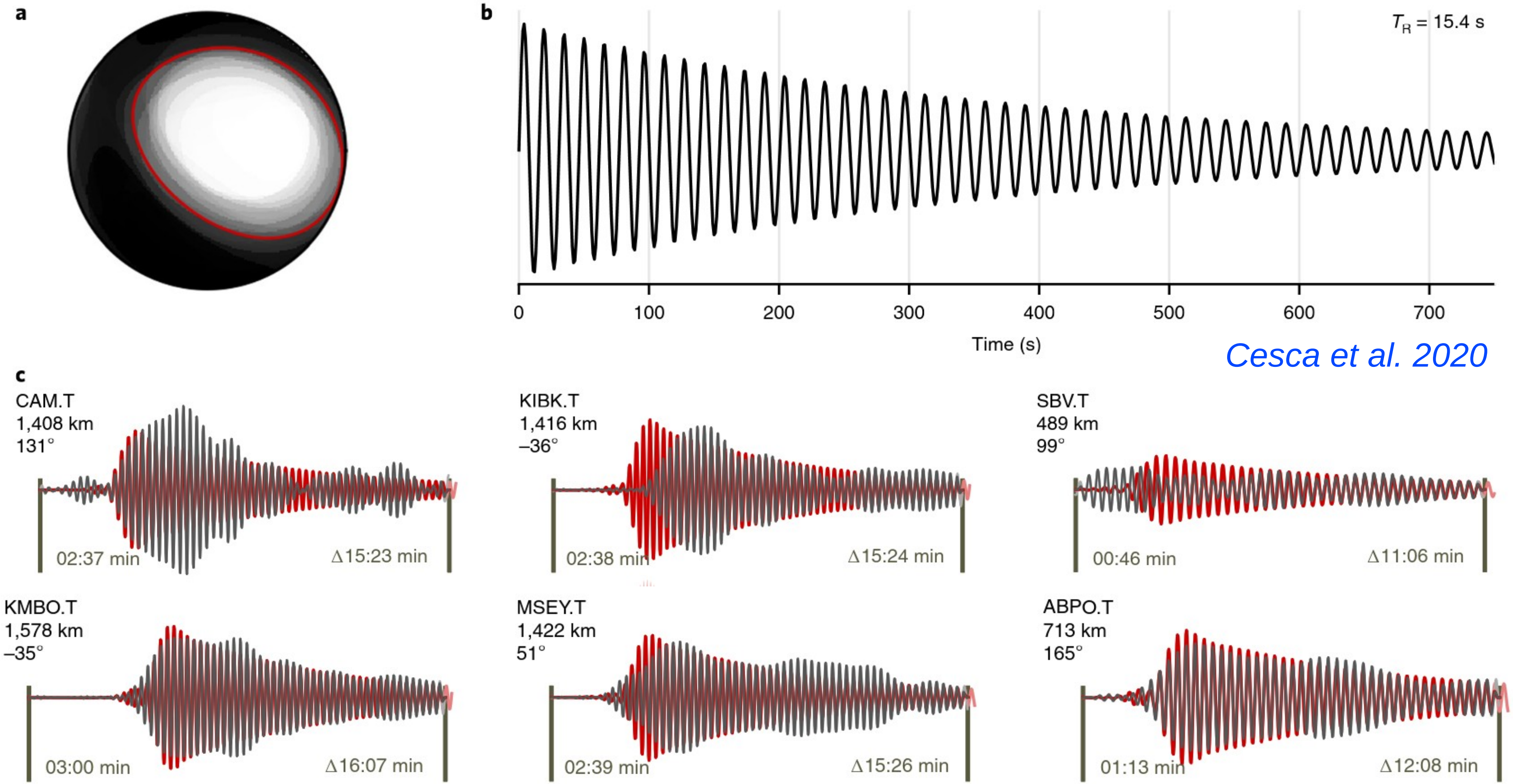
Find the correct decomposition

Beyond point sources, source time function (STF)



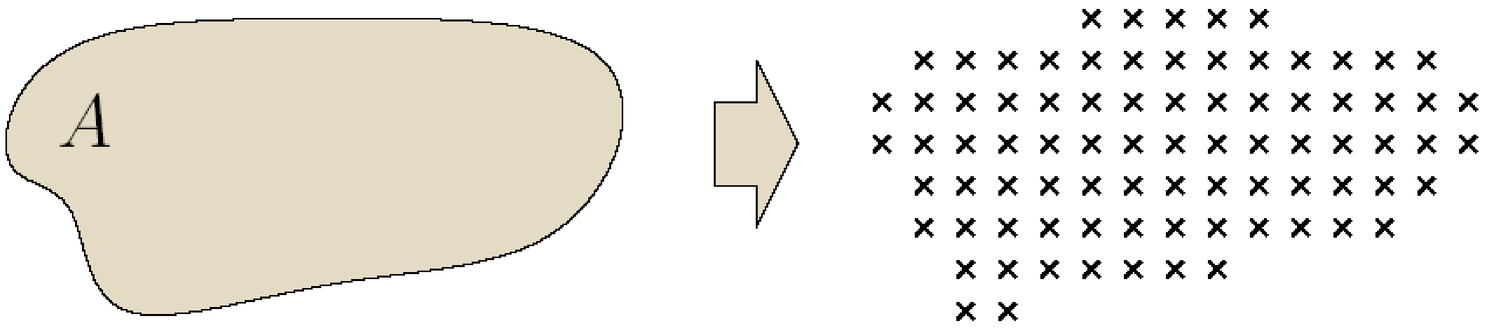


Implementing unusual STFs



Cesca et al. 2020

Beyond point sources, finite sources

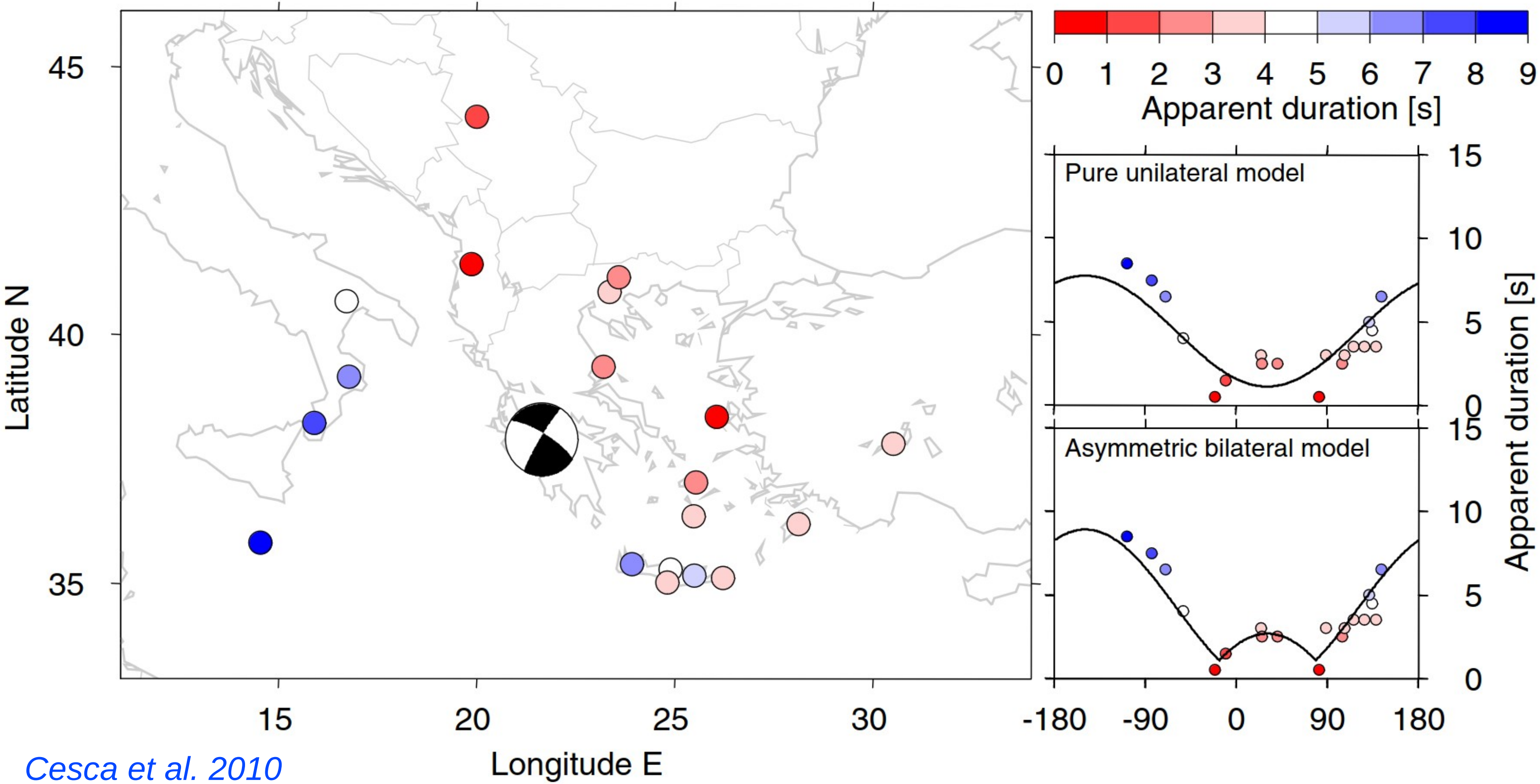


after Heimann 2011

A finite source model along a surface A can be represented by means of point sources (DC or MT) distributed along that surface

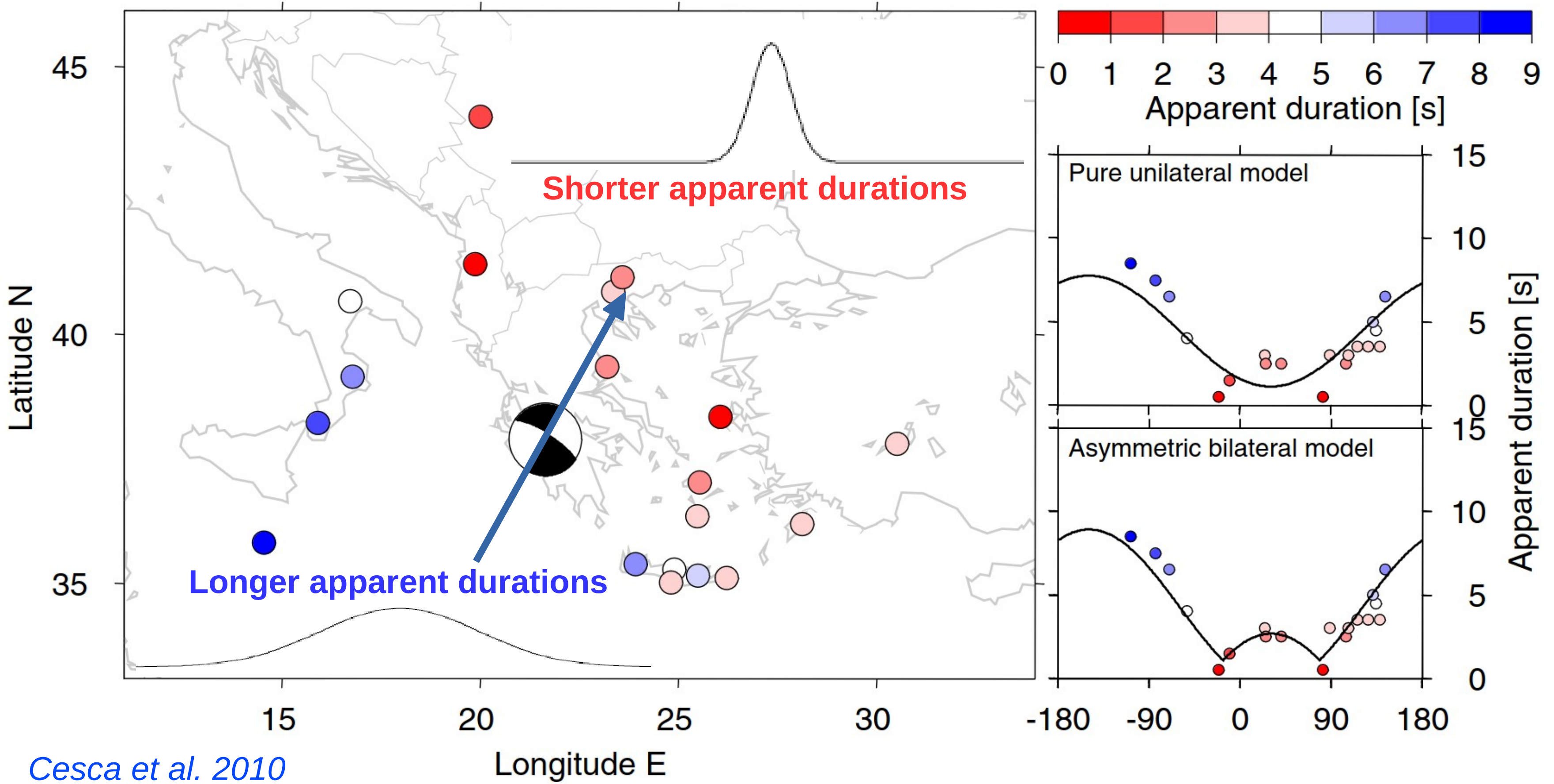
To reproduce rupture propagation effects, each point source is activated at its own time (i.e. when the rupture front reach that point)

Apparent STF, earthquake directivity



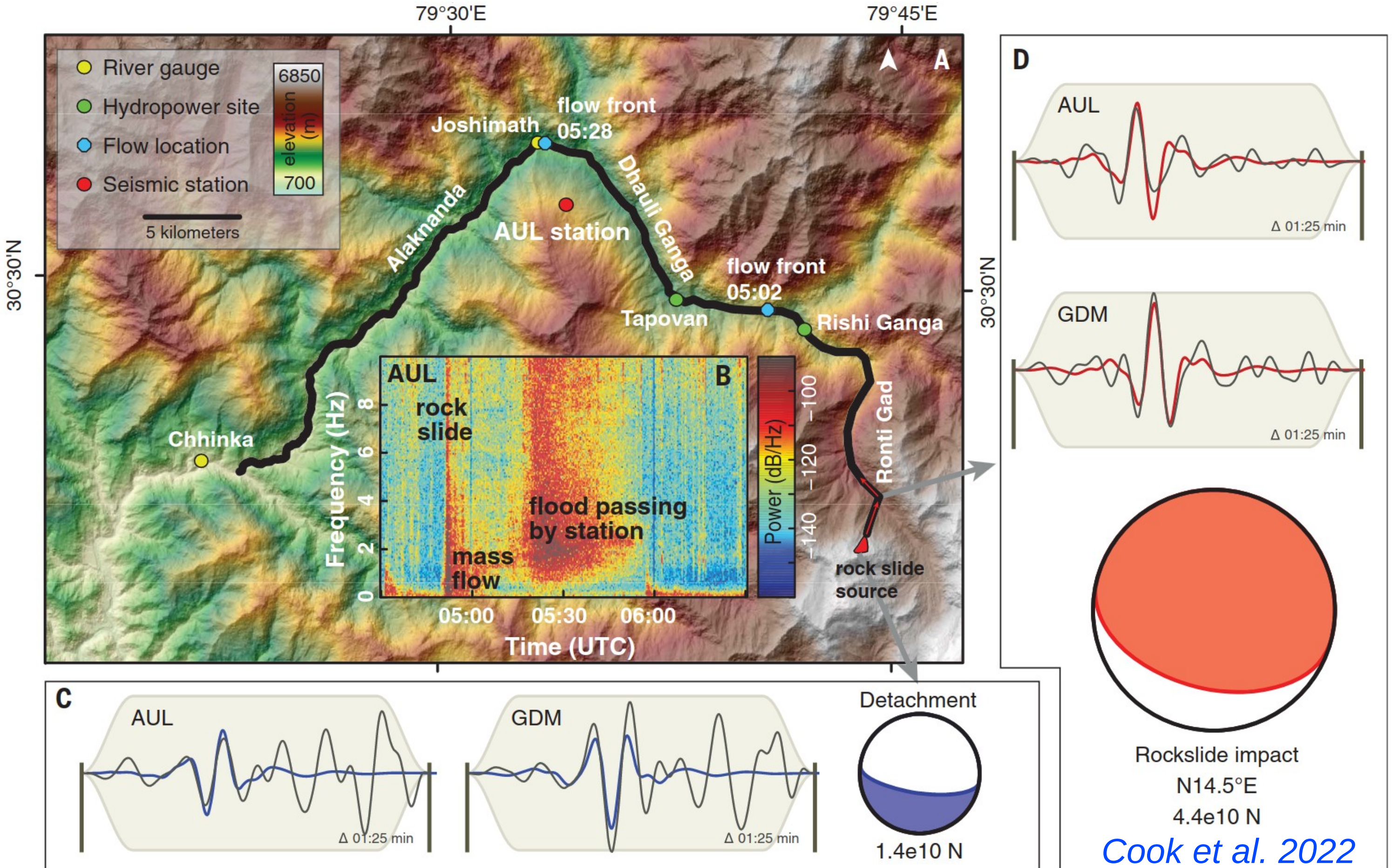
Cesca et al. 2010

Apparent STF, earthquake directivity



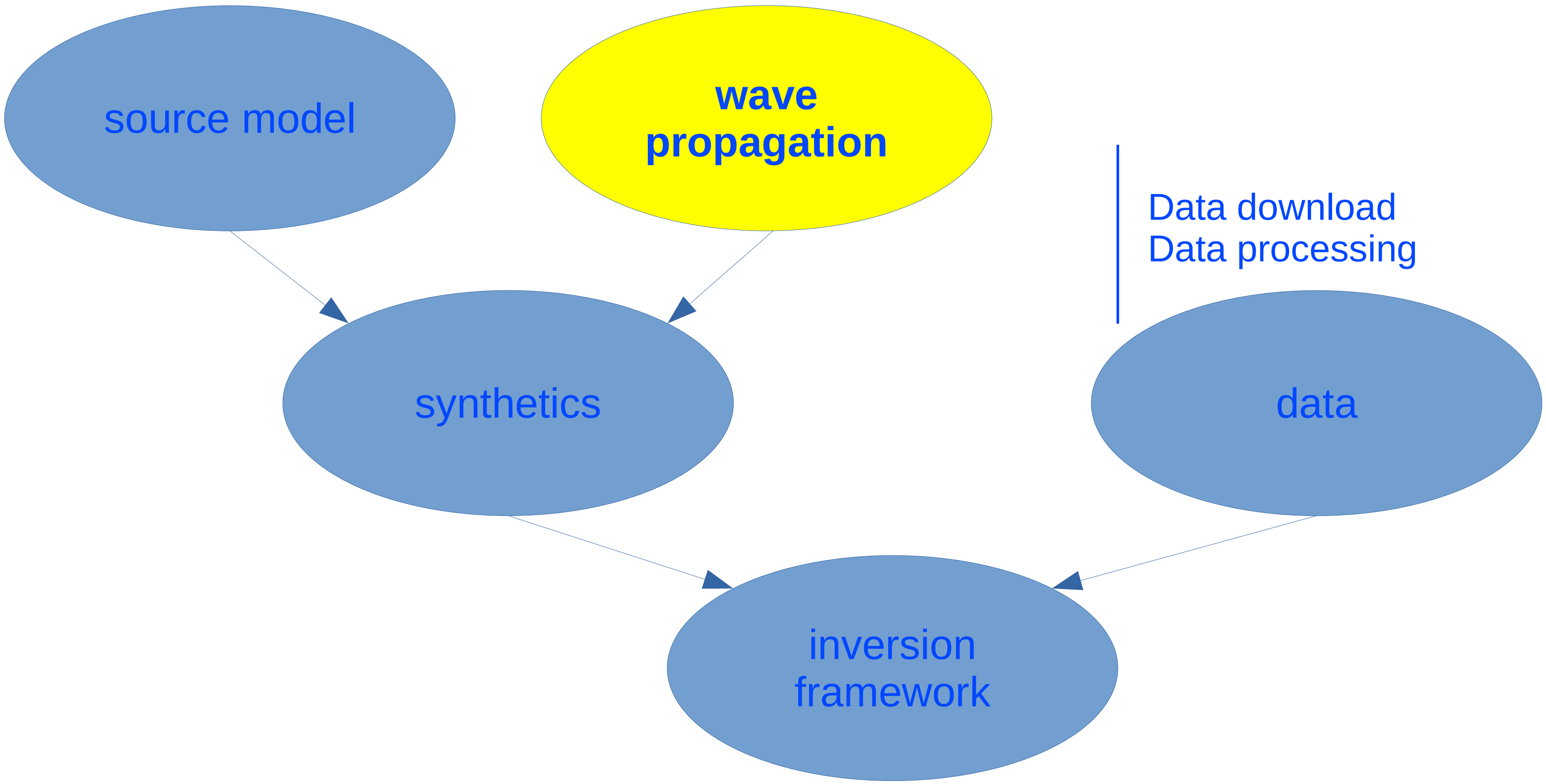
Cesca et al. 2010

Beyond usual sources...



Cook et al. 2022

Source inversion layout

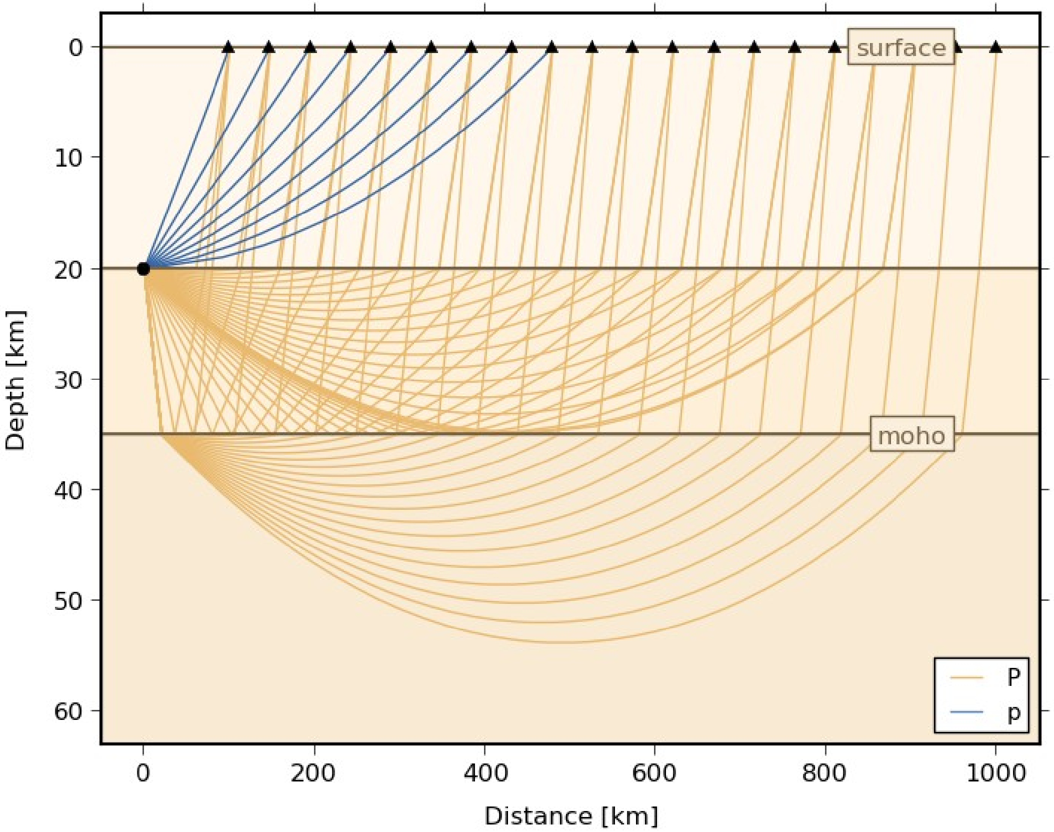


Green’s functions (GFs) and databases (GFDB)

GFs are the Earth response at a receiver to a simple excitation at the earthquake source.

GFs can be seen as elementary seismograms

GFs describe the seismic wave propagation from source to receiver and depend on the velocity model



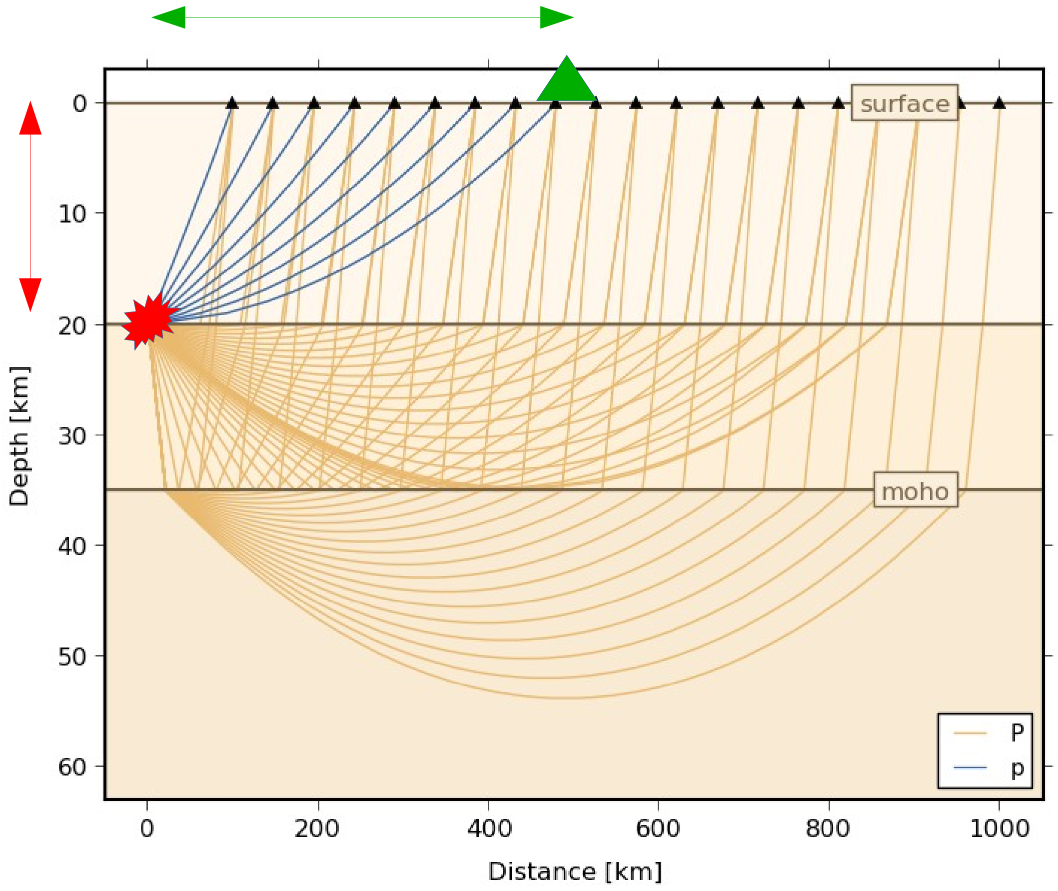
Green’s functions in 1D media

Symmetry of the 1D velocity model:

GFs only depend on
source depth (z) and
source-receiver distance (x)

The response of any MT source can be computed as lineal combination of 10 Gfs

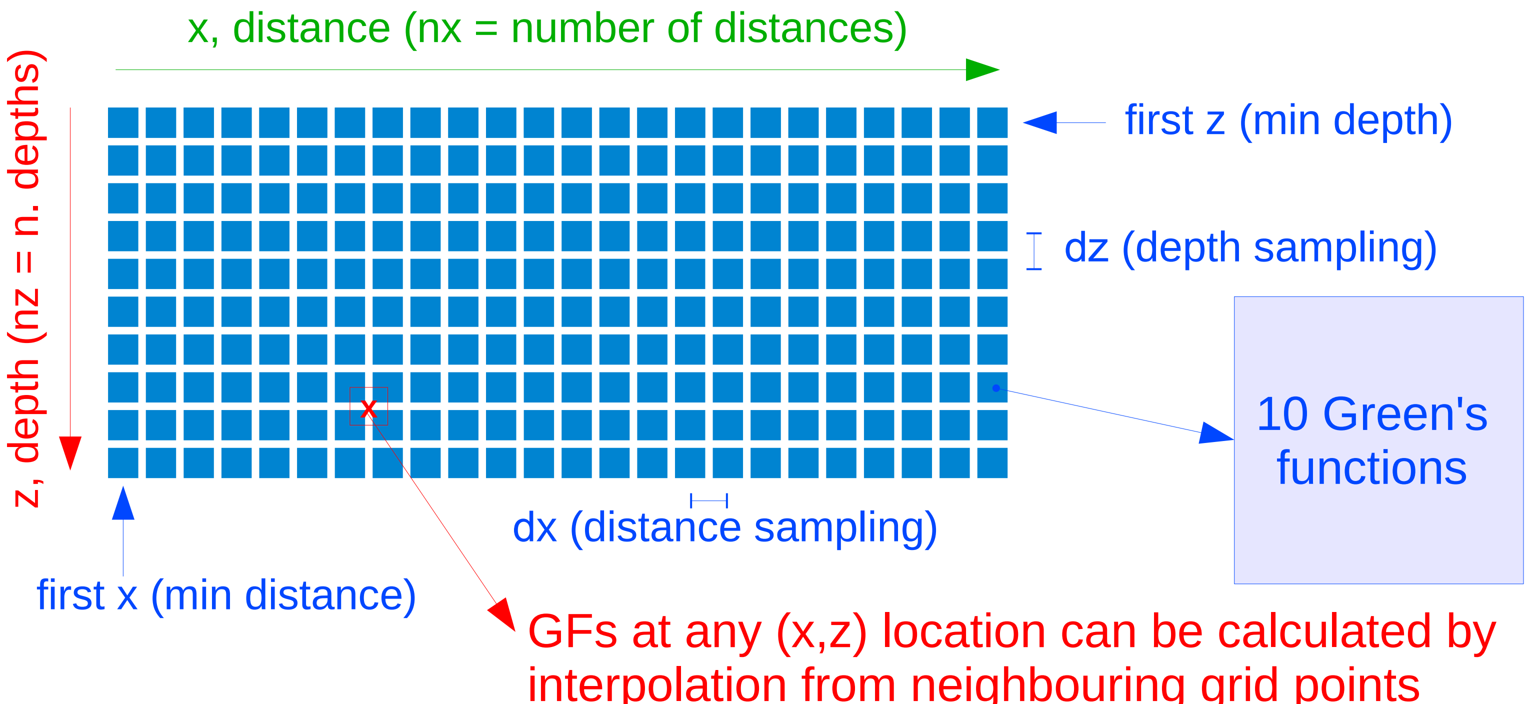
We can calculate those in advance, and store them in a database



Green's functions database

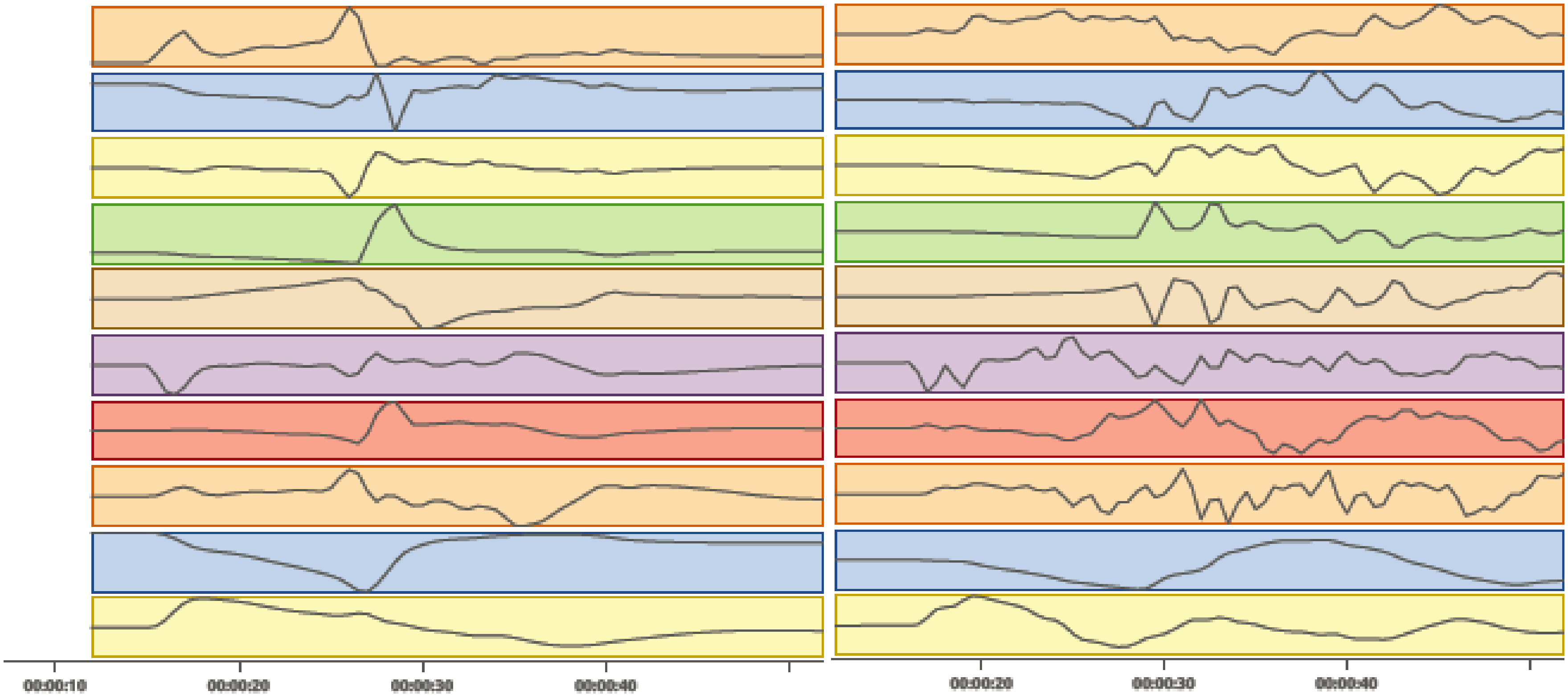
The 1D model symmetry allow to develop a GF database concept

GFs are pre-calculated and ready to use for the inversion

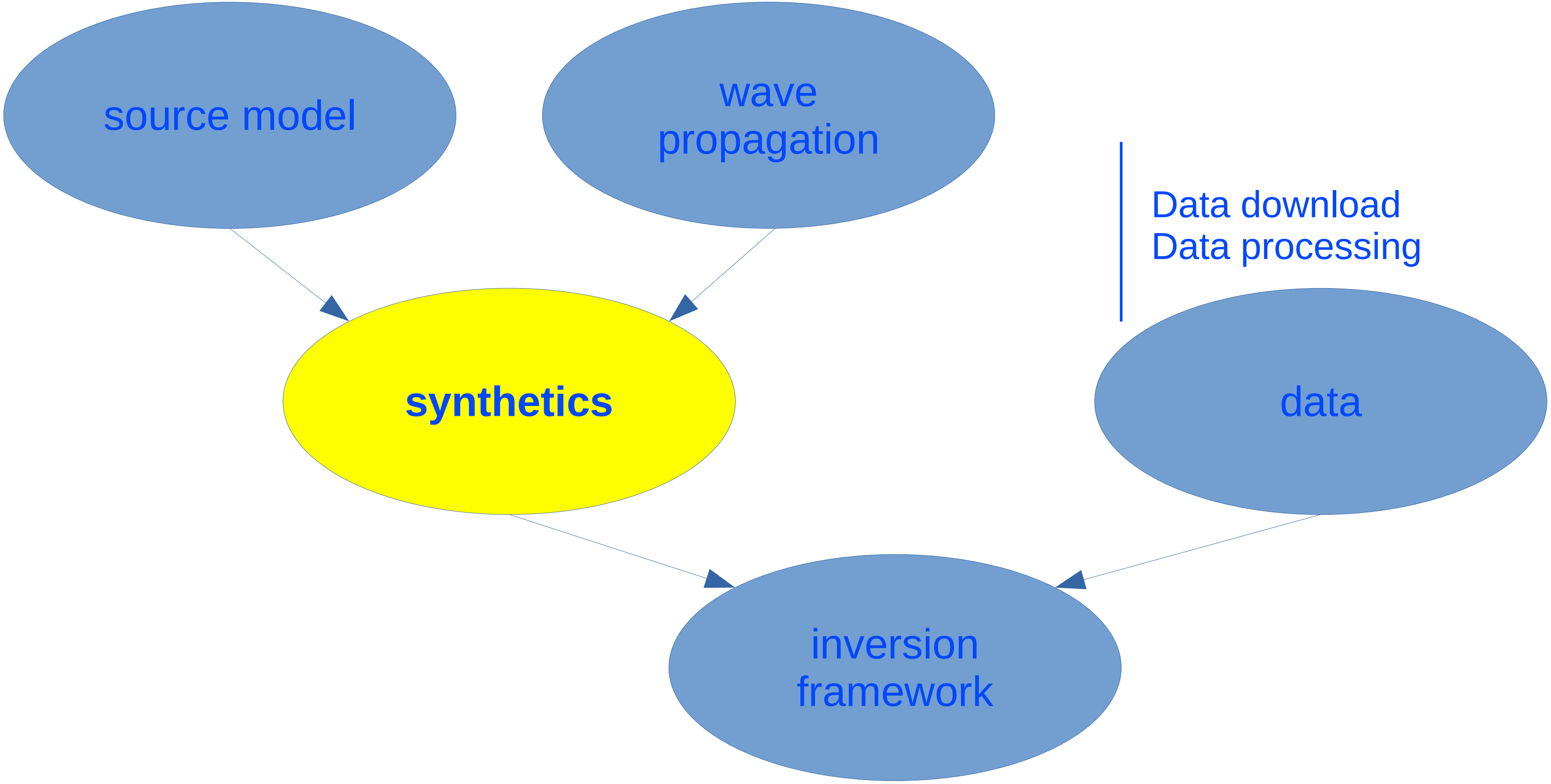


Green’s functions example

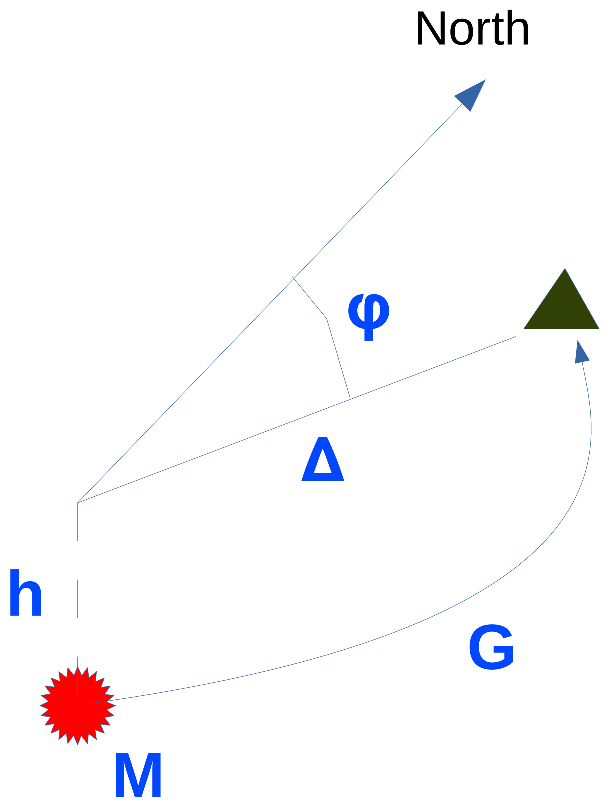
How do GFs look like?
Offshore SW Portugal, z = 40 km, d = 100 km, 2 velocity models



Source inversion layout



From GFs to Synthetic seismograms



$$u_n(\bar{x},t) = M_{pq}(\bar{\xi},\tau) * G_{np,q}(\bar{\xi},\tau,\bar{x},t)$$

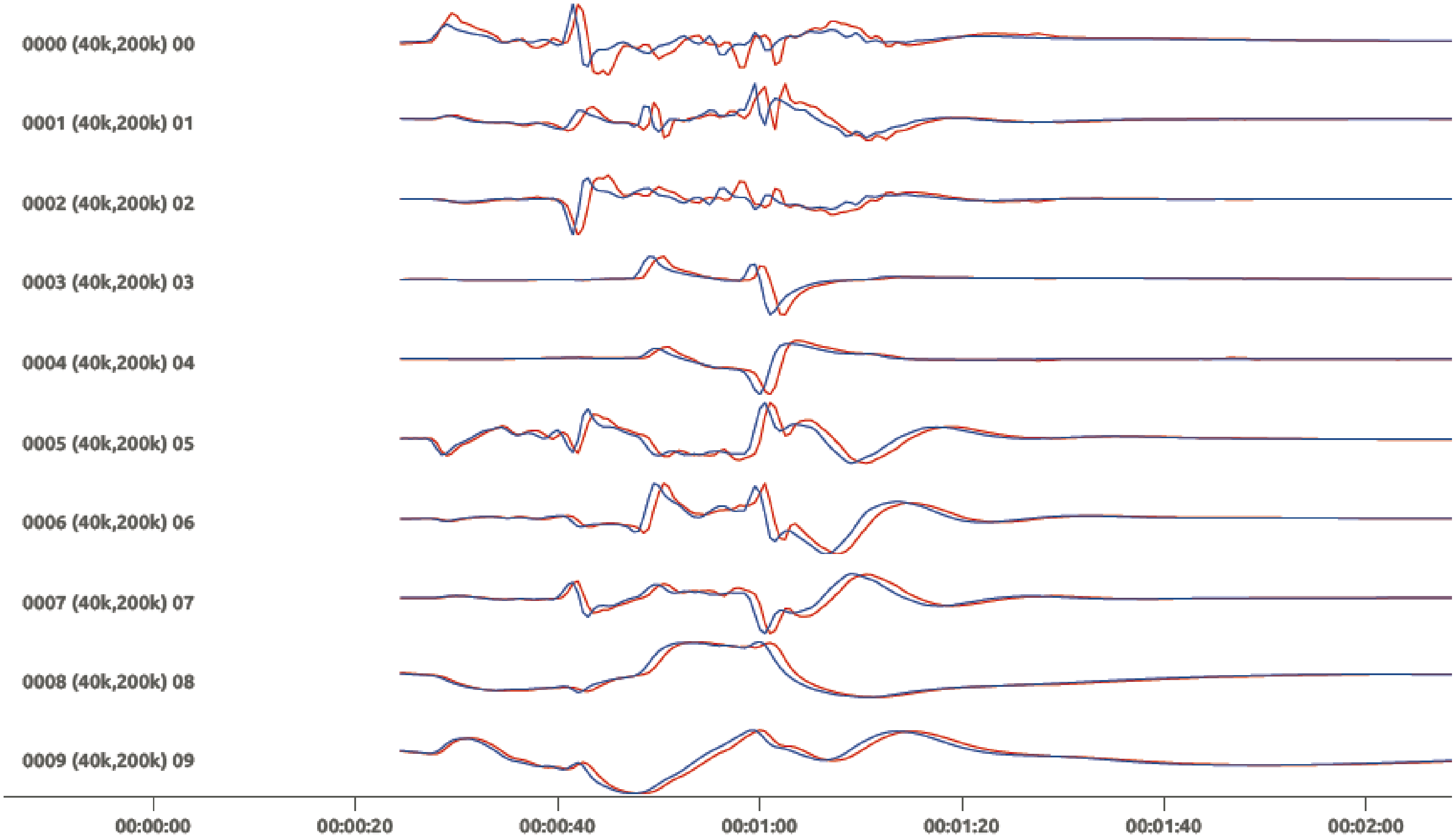
$$u_z = \sum_{i=1,4} \tilde{M}(M_{ij},\phi)\tilde{G}_i(\Delta,h)$$

$$u_r = \sum_{i=5,8} \tilde{M}(M_{ij},\phi)\tilde{G}_i(\Delta,h)$$

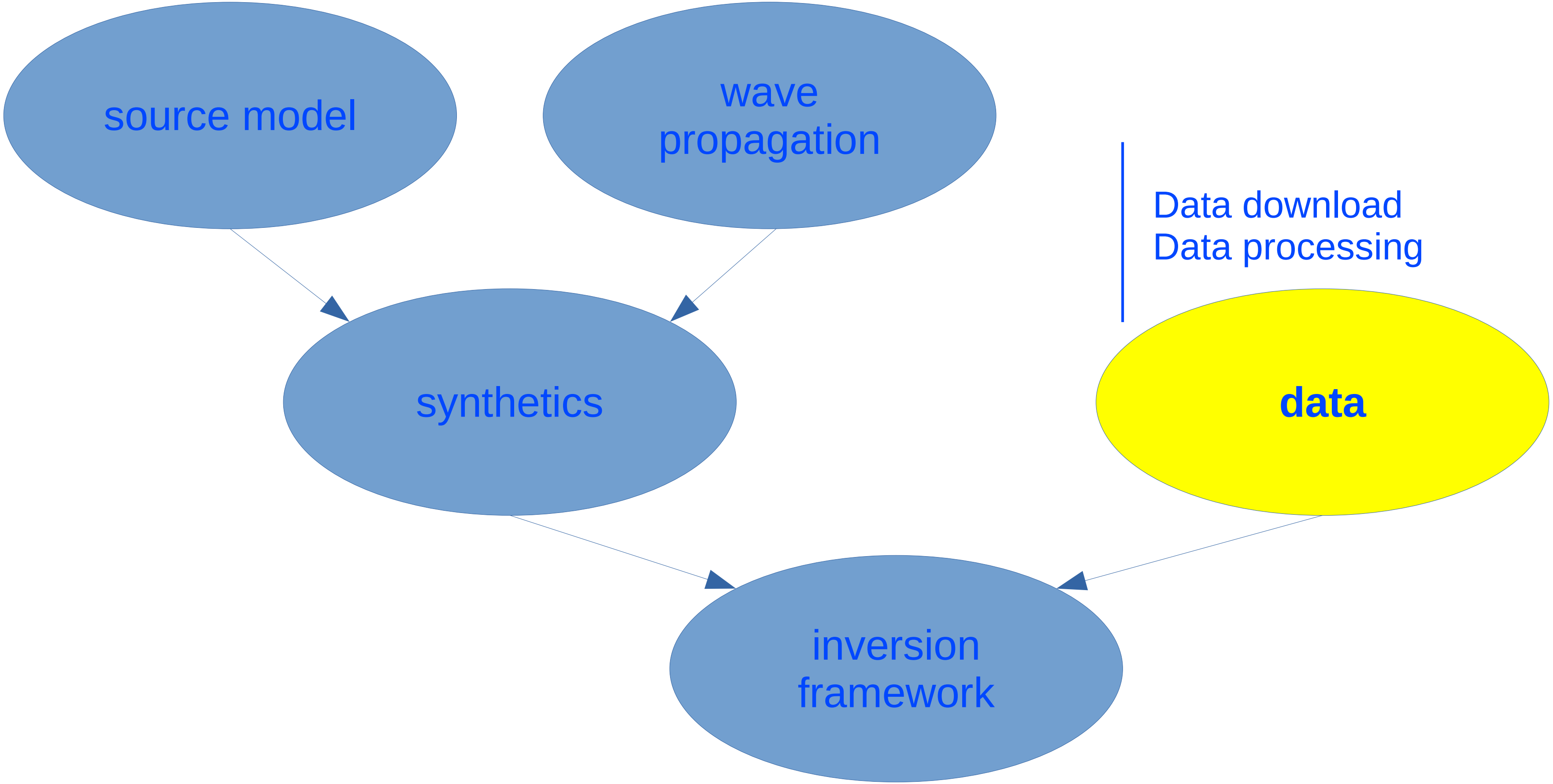
$$u_t = \sum_{i=9,10} \tilde{M}(M_{ij},\phi)\tilde{G}_i(\Delta,h)$$

$note: u_n(\bar{x},t)\ linear\ dependent\ on\ M_0$

Synthetic seismograms, example



Source inversion layout



Data access and data processing

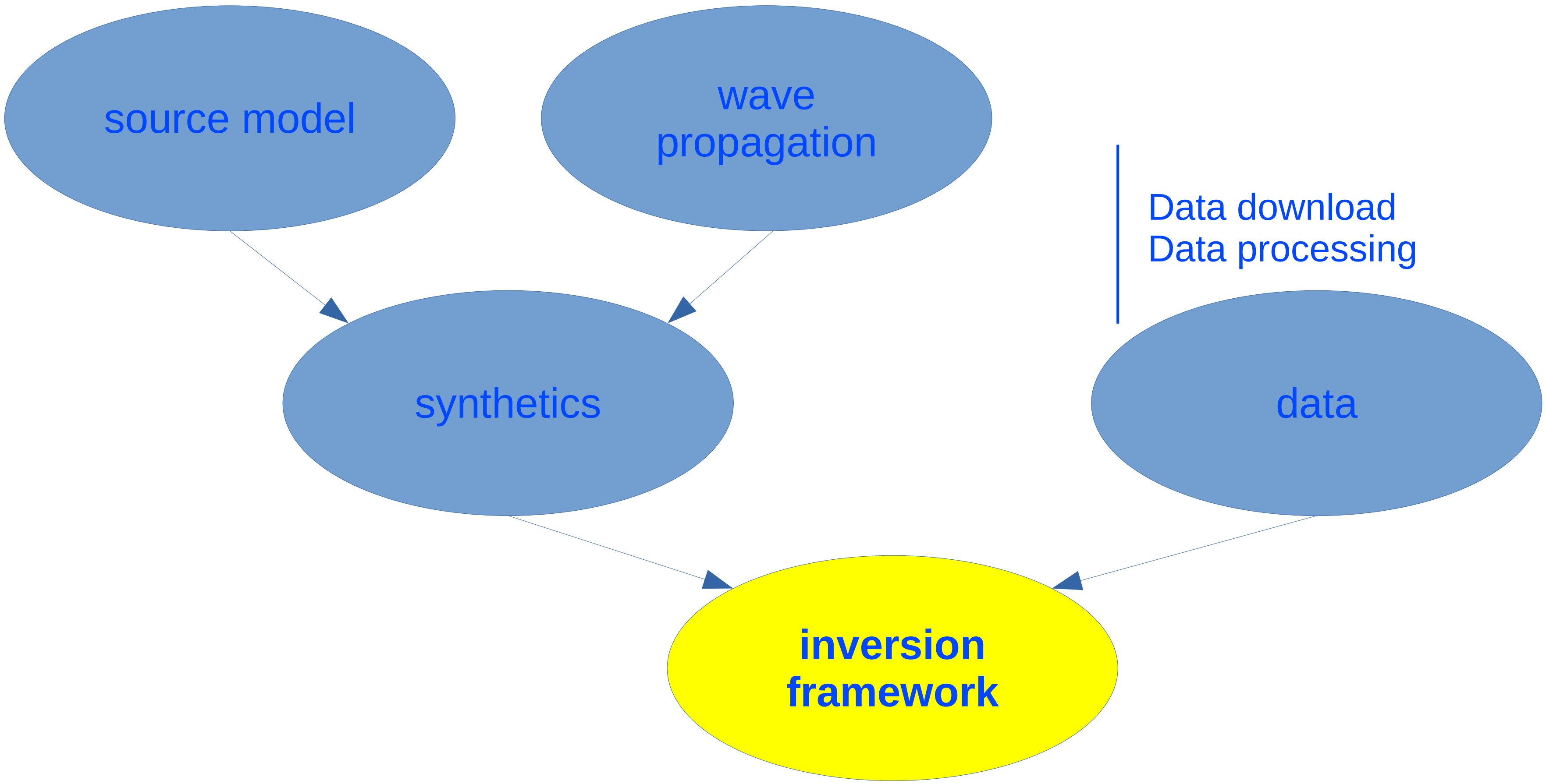
data download

- Data search
  (event, stations, waveform selection)
- Data download/access
- Metadata download/access
  (station and instrument information)

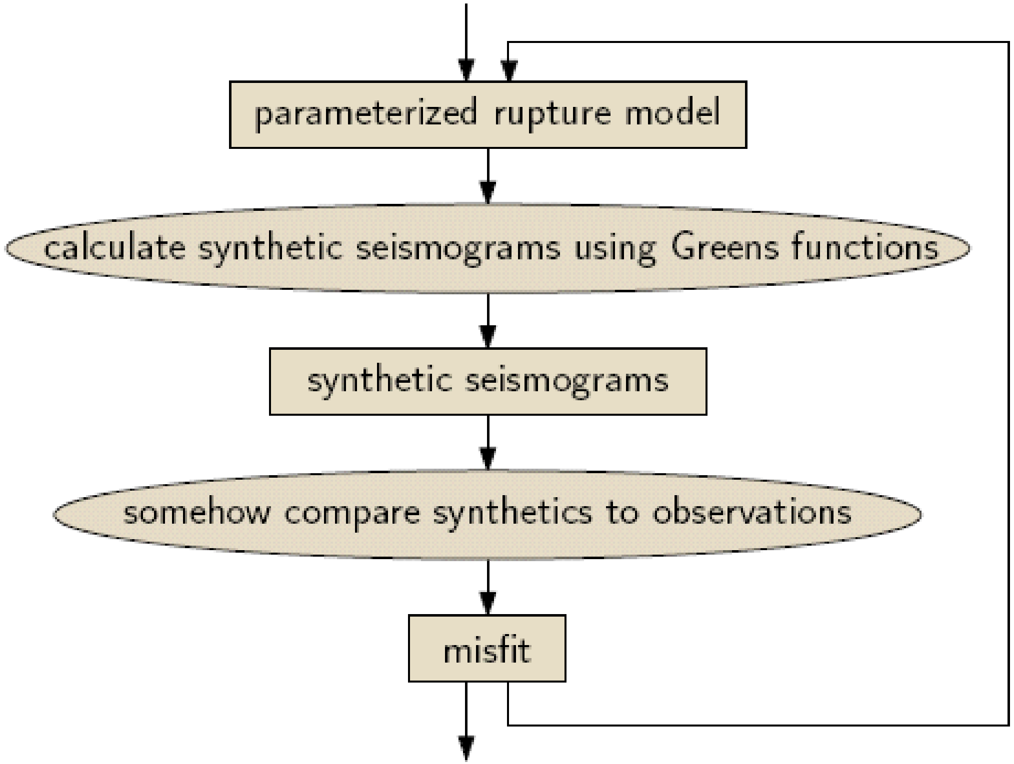
data processing

- Demean, detrend, filter
- Deconvolution of instrumental response
  (→ true velocities or displacements)
- Data quality assessment

Source inversion layout

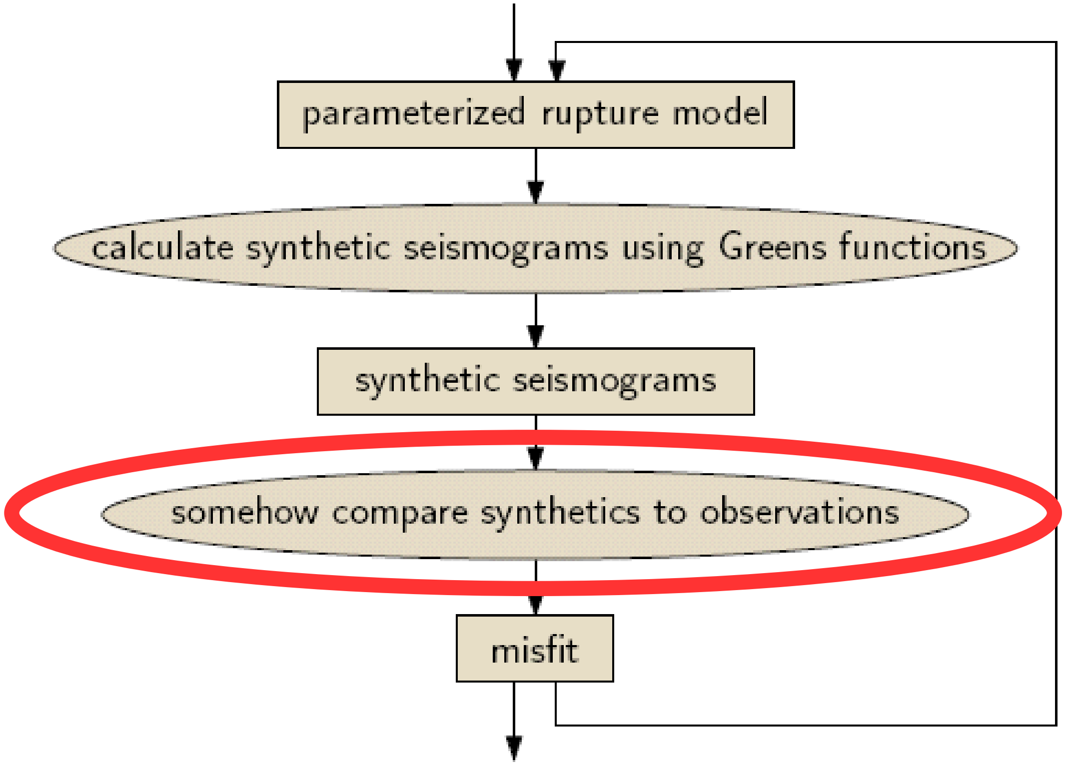


Inversion, general concept



Heimann 2011

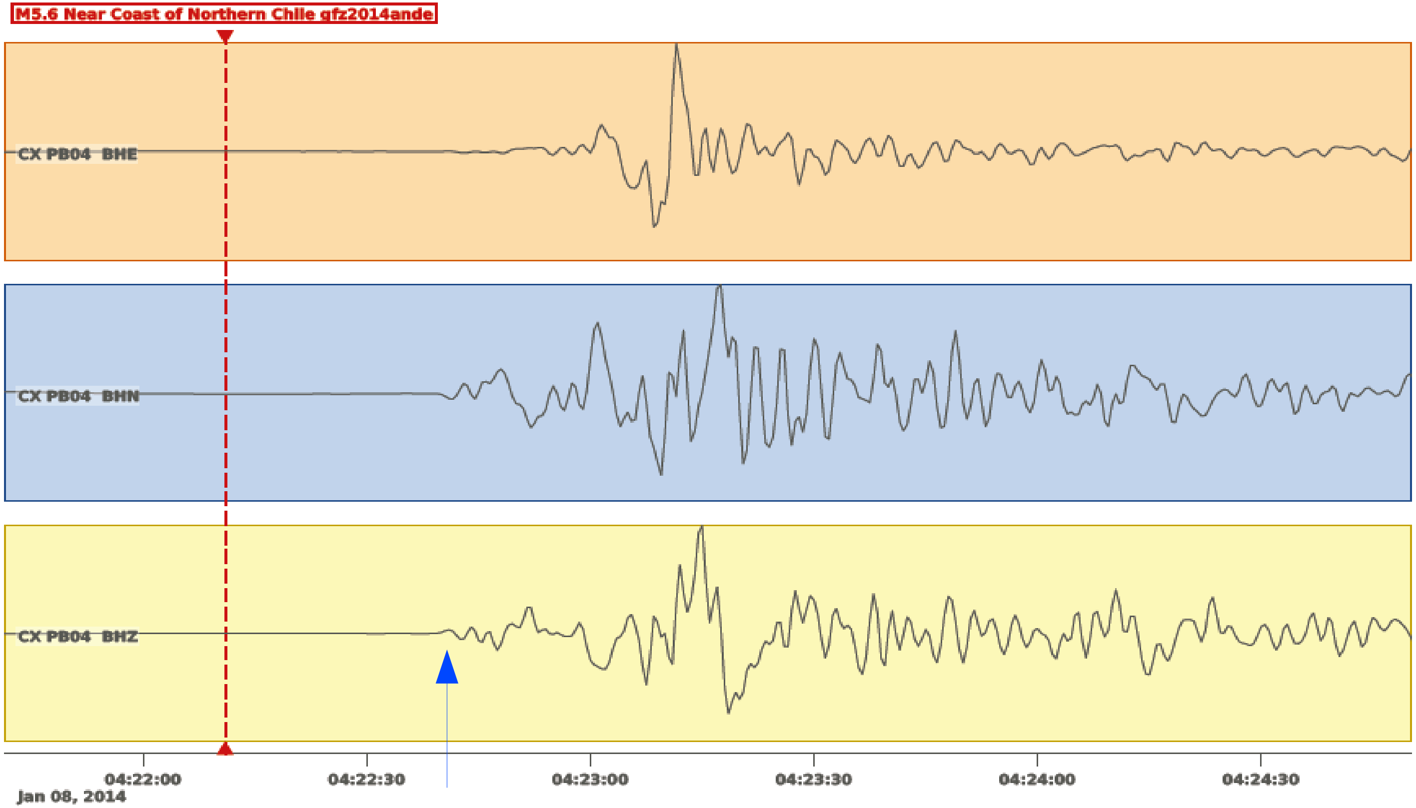
Inversion, general concept



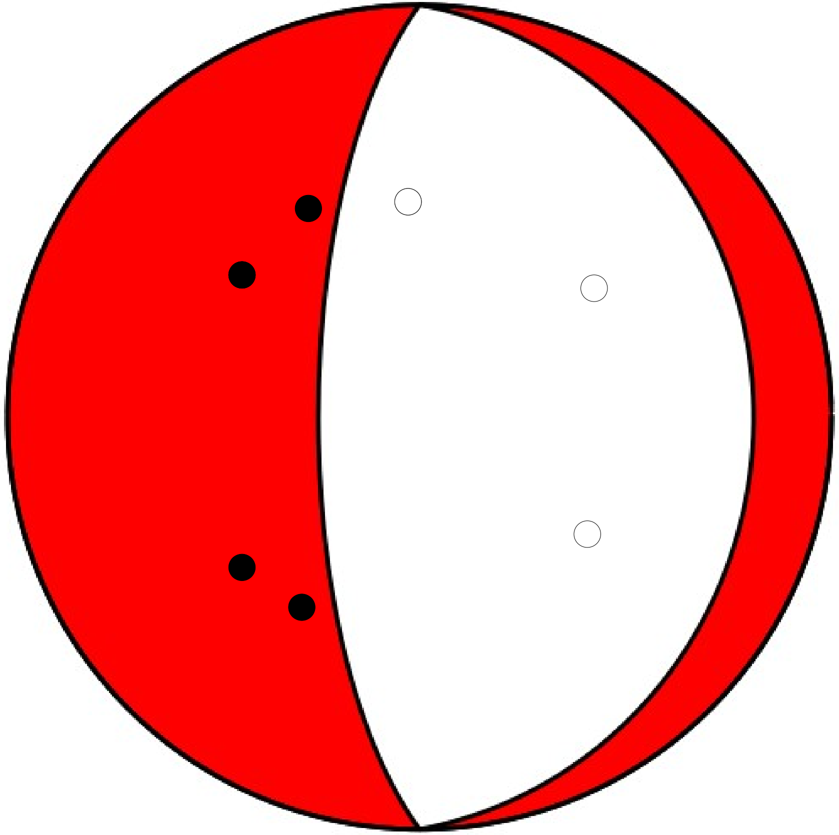
Heimann 2011

Inversion, first motion polarity

Only sign of first motion P

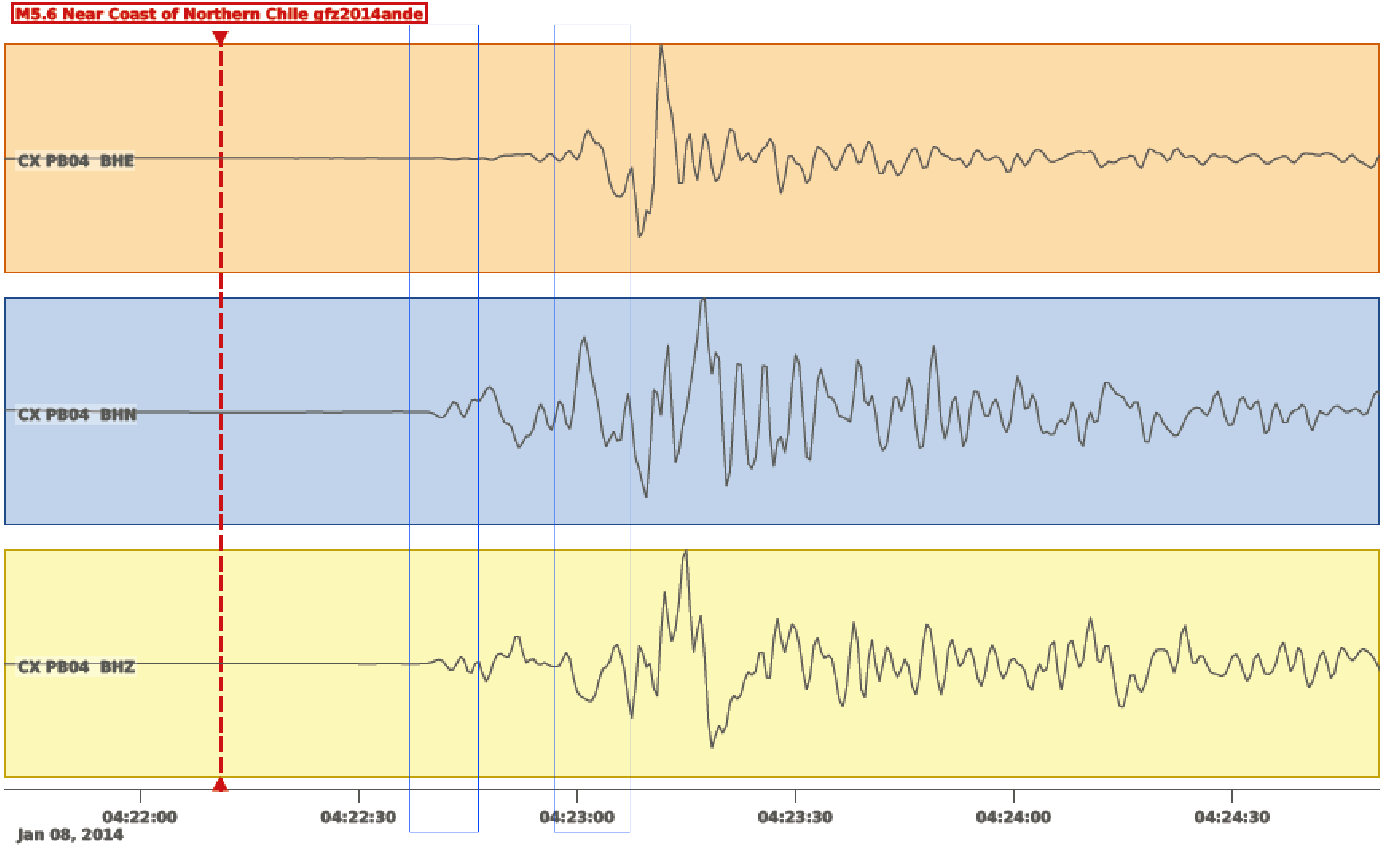


Inversion, first motion polarity

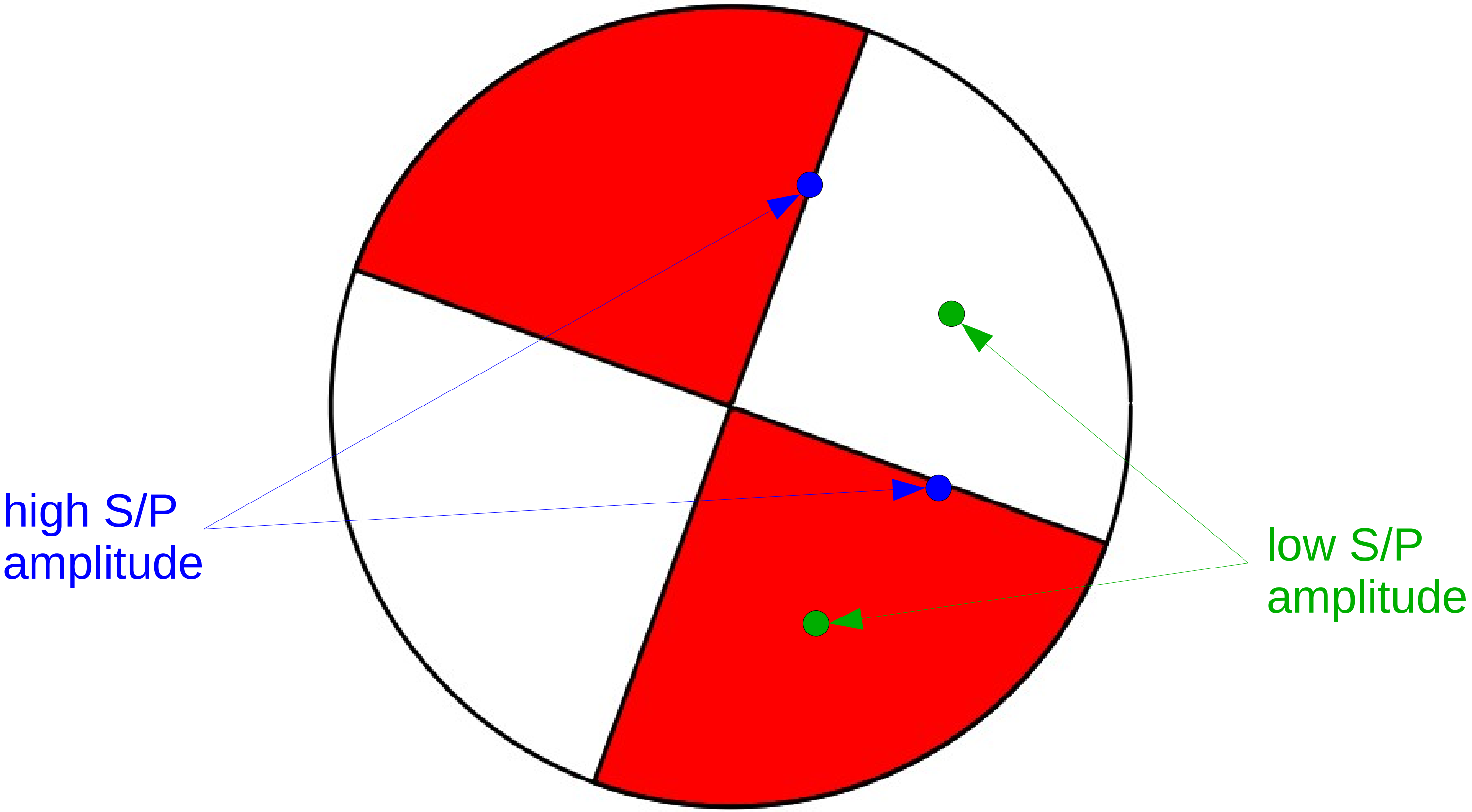


Inversion, bodywave amplitudes

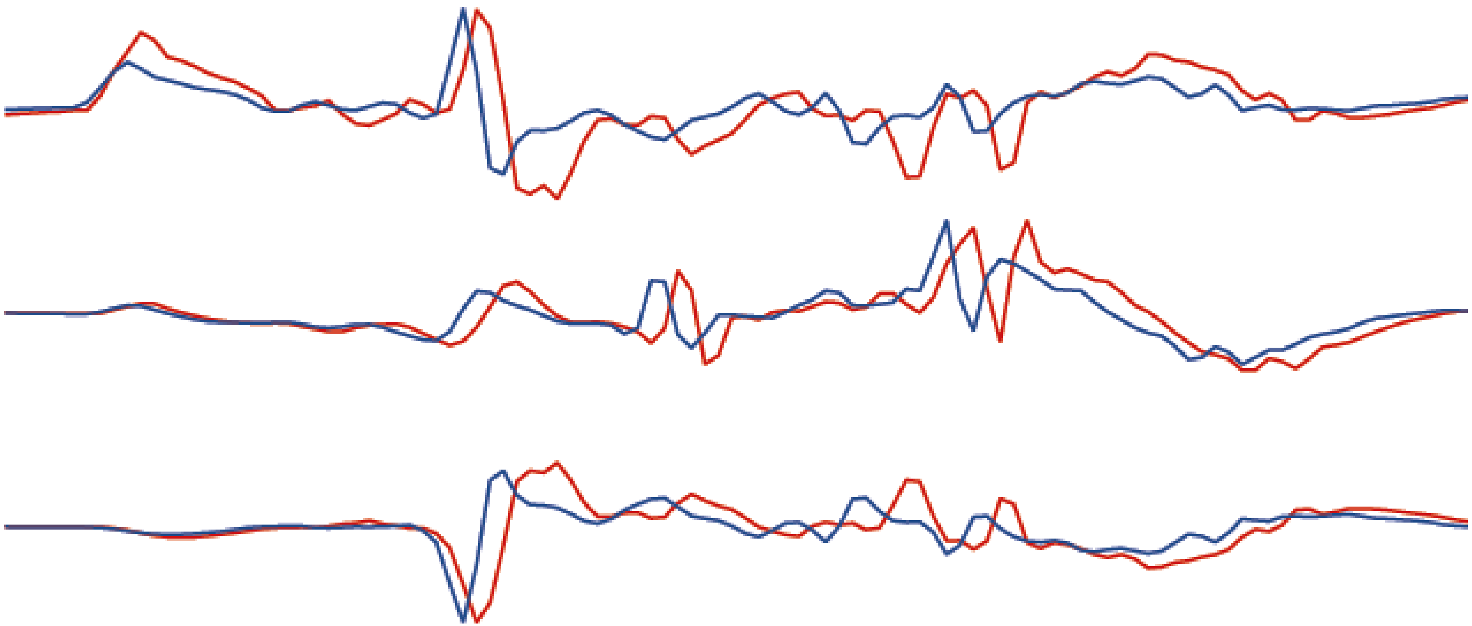
P amplitudes, S amplitudes, and S/P amplitudes ratio



Inversion, bodywave amplitudes and ratios

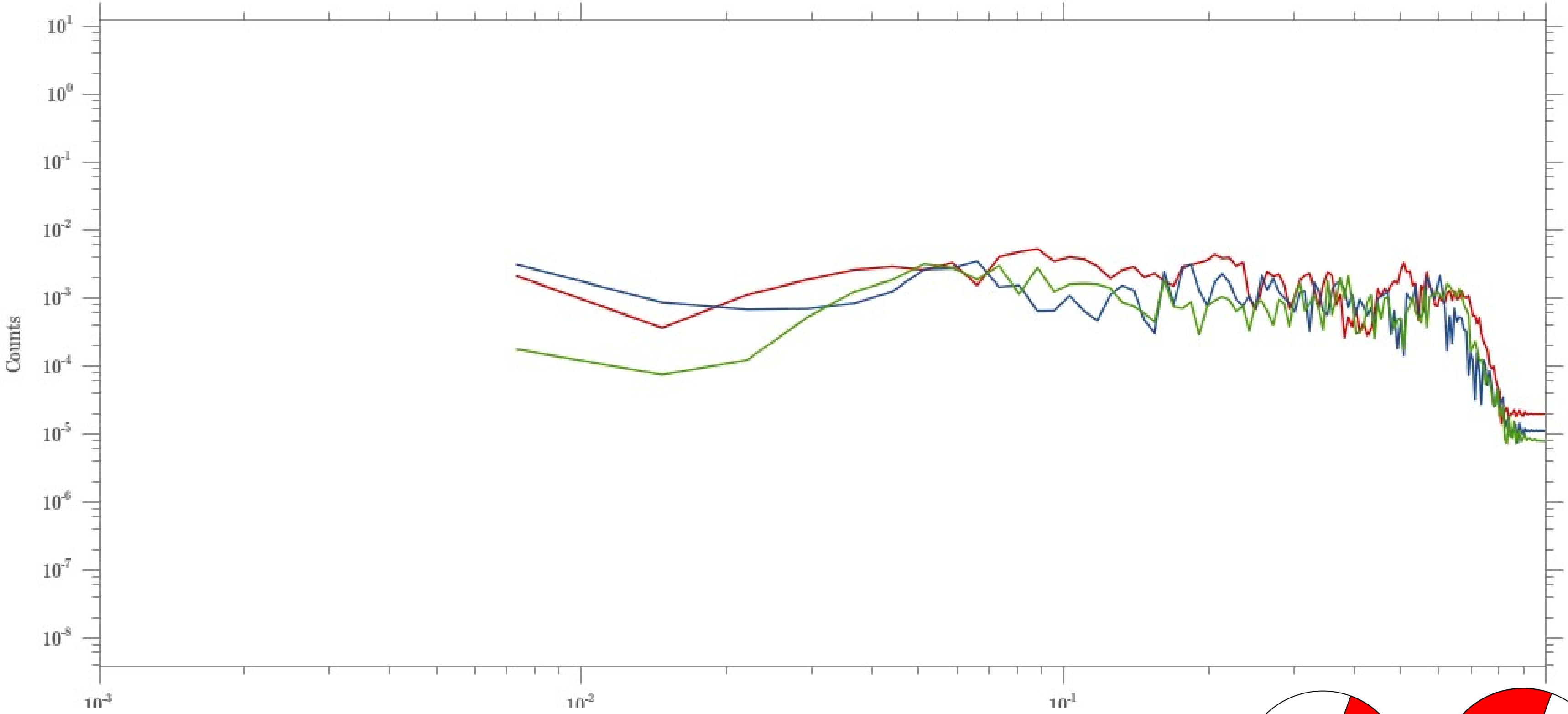


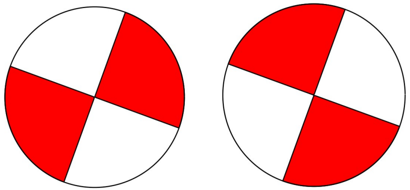
Full waveforms



→ consider full data information
→ fitting require good velocity model, or fit low frequency waveforms
→ trace alignment may be needed

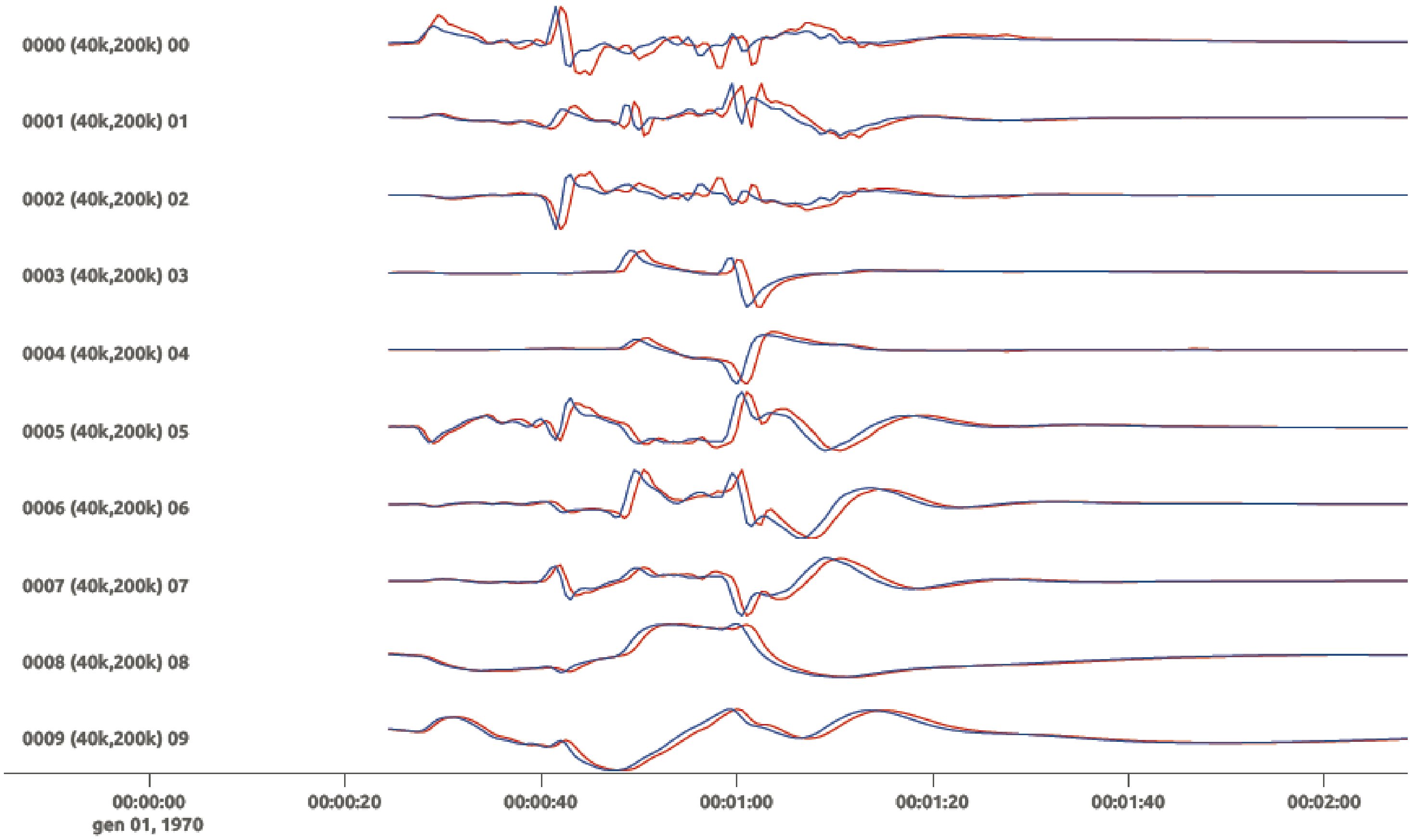
Amplitude spectra



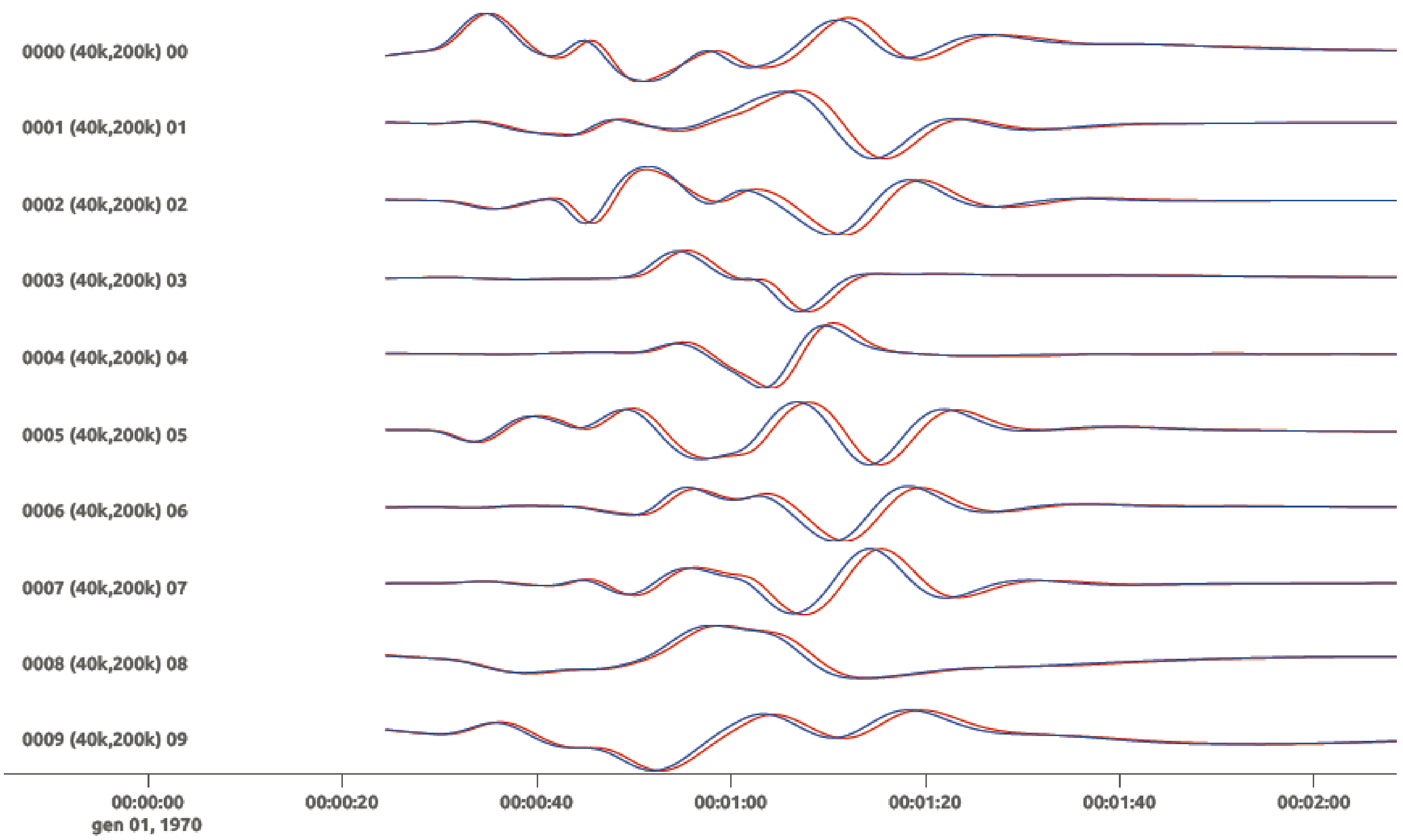


→ robust against alignment and velocity model approximation
→ loose information on phases (P-T quadrant ambiguity)

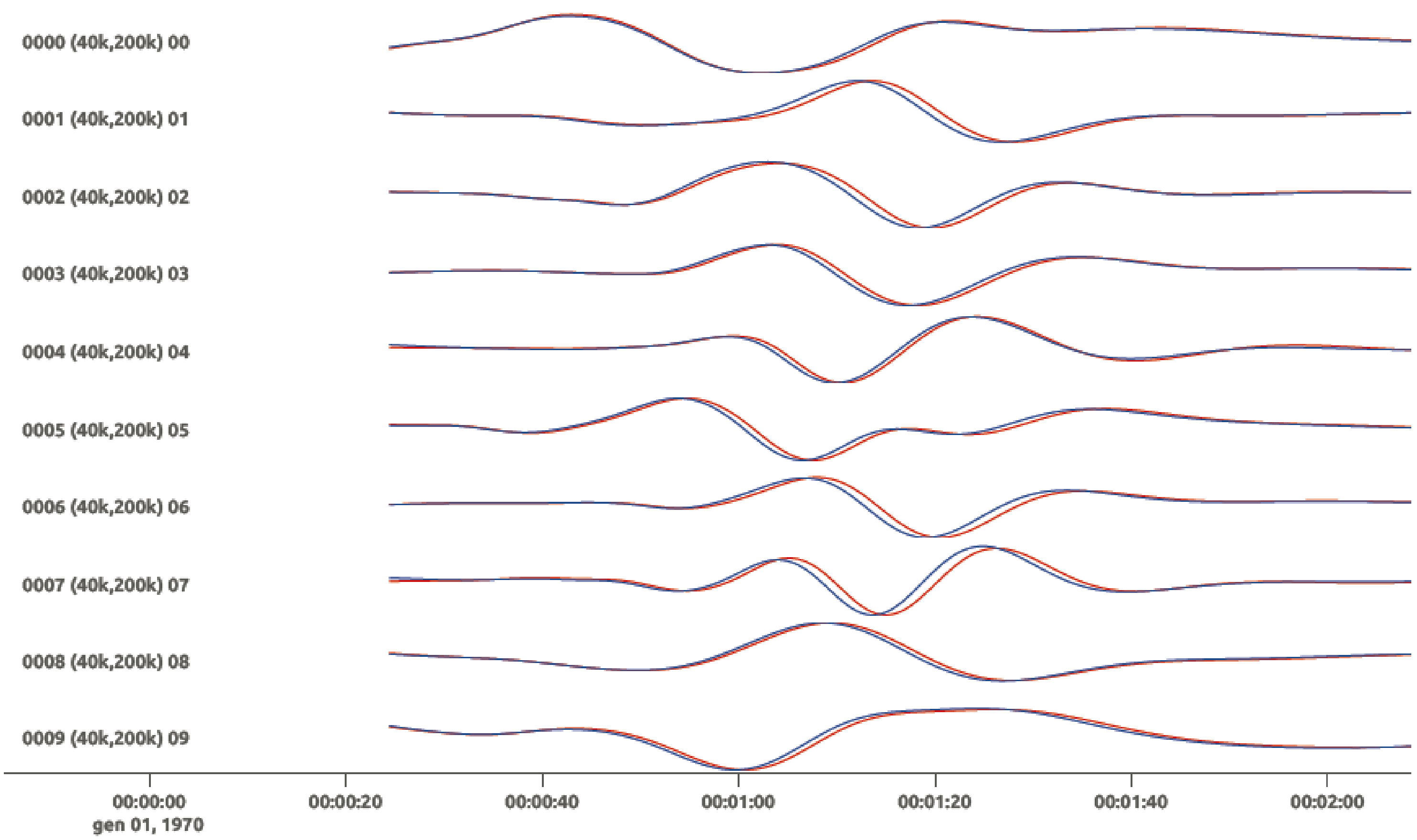
Full waveform inversion, no filter



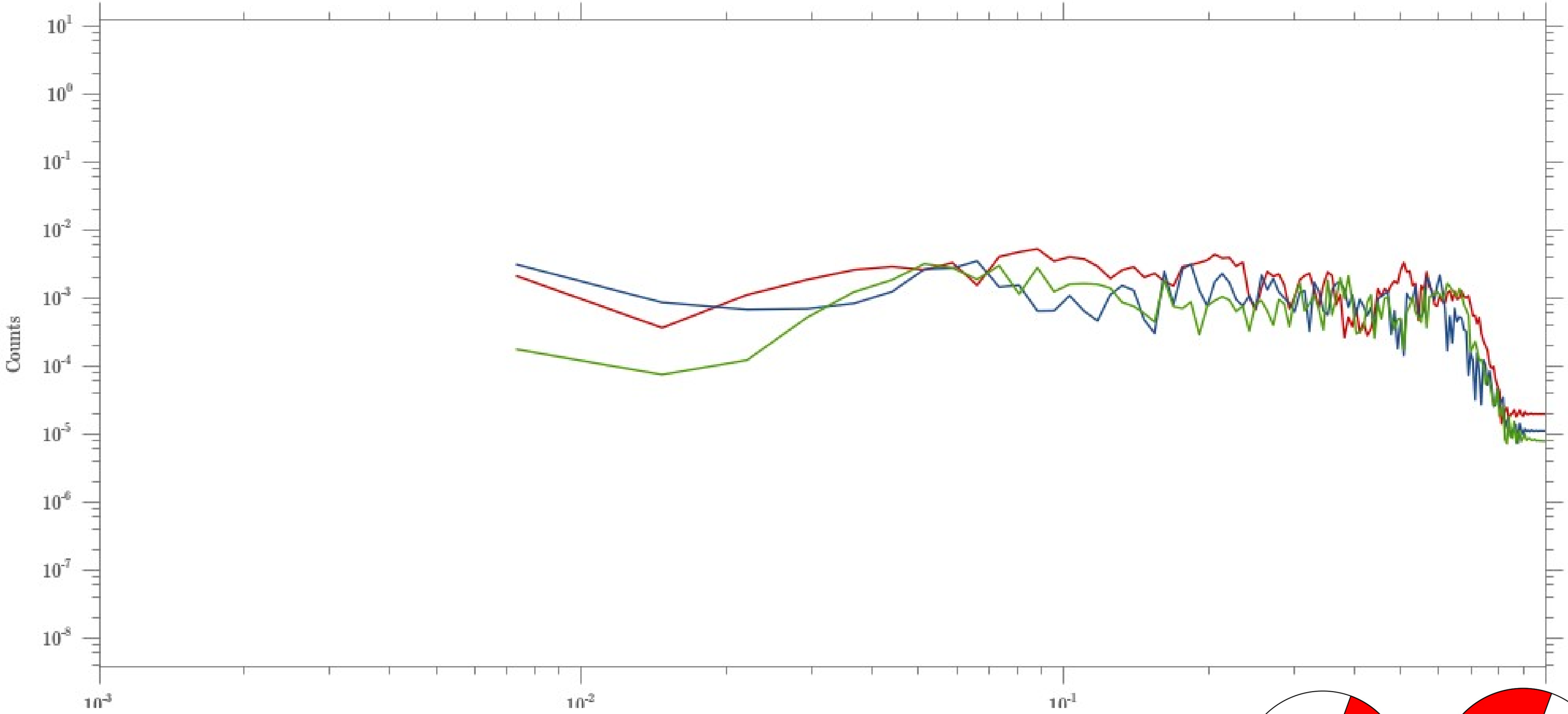
Full waveform inversion, filter 10-100 s

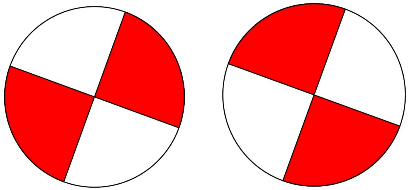


Full waveform inversion, filter 30-100 s



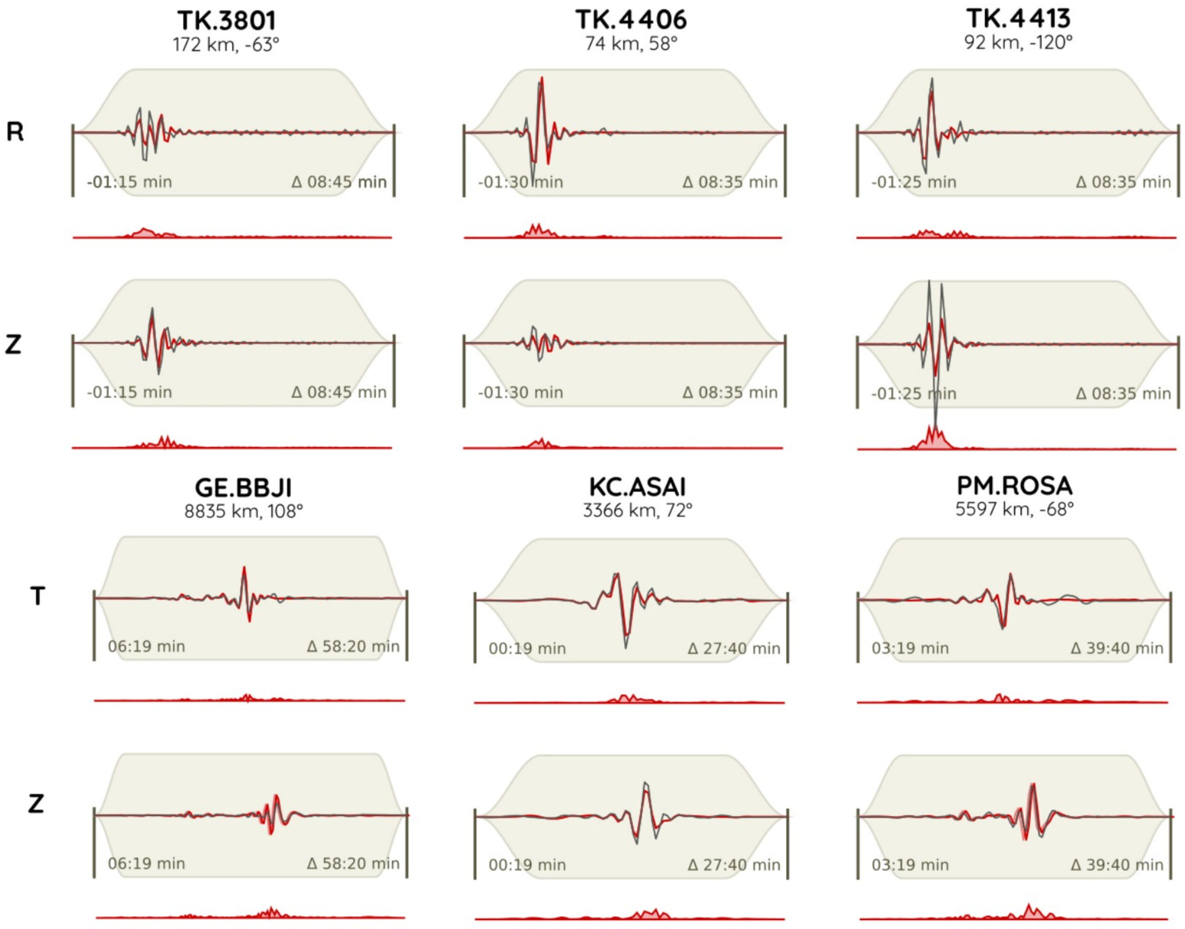
Amplitude spectra





→ robust against alignment and velocity model approximation
→ loose information on phases (P-T quadrant ambiguity)

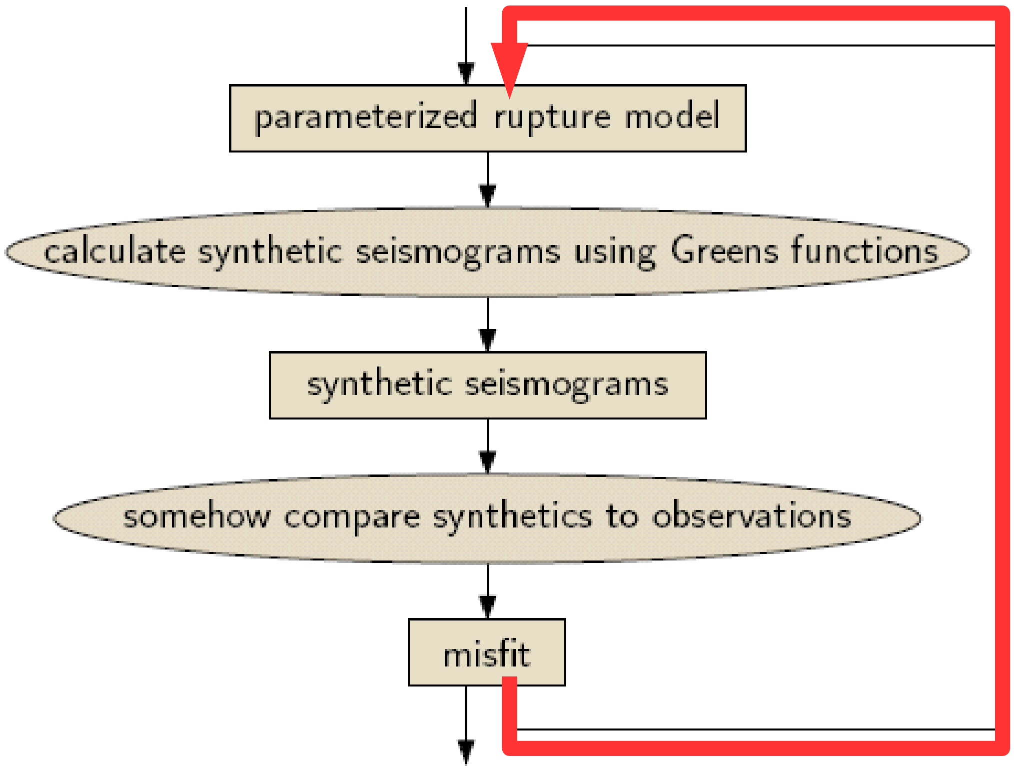
Joint data inversion



Strong motion

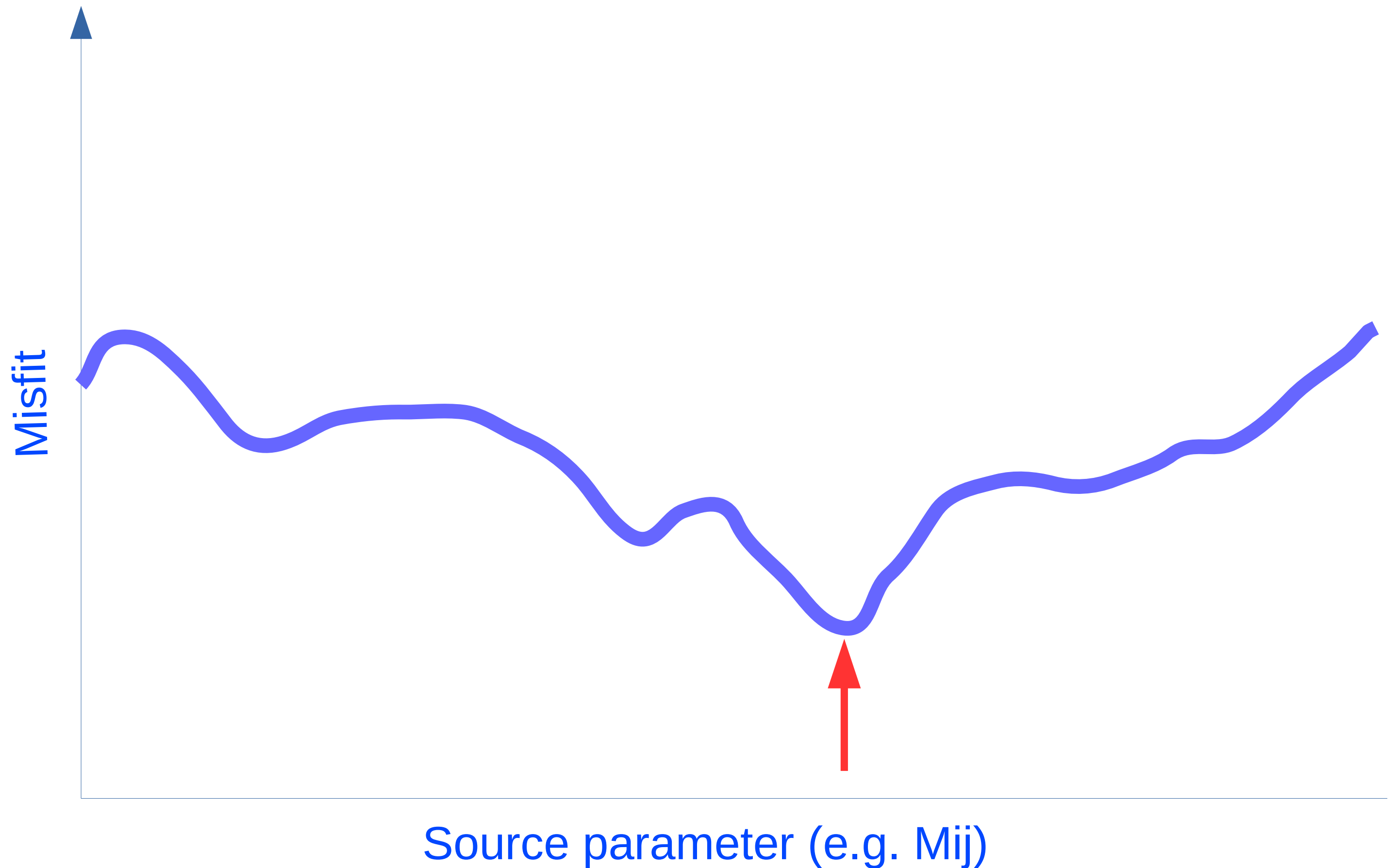
Broadband

Inversion, general concept

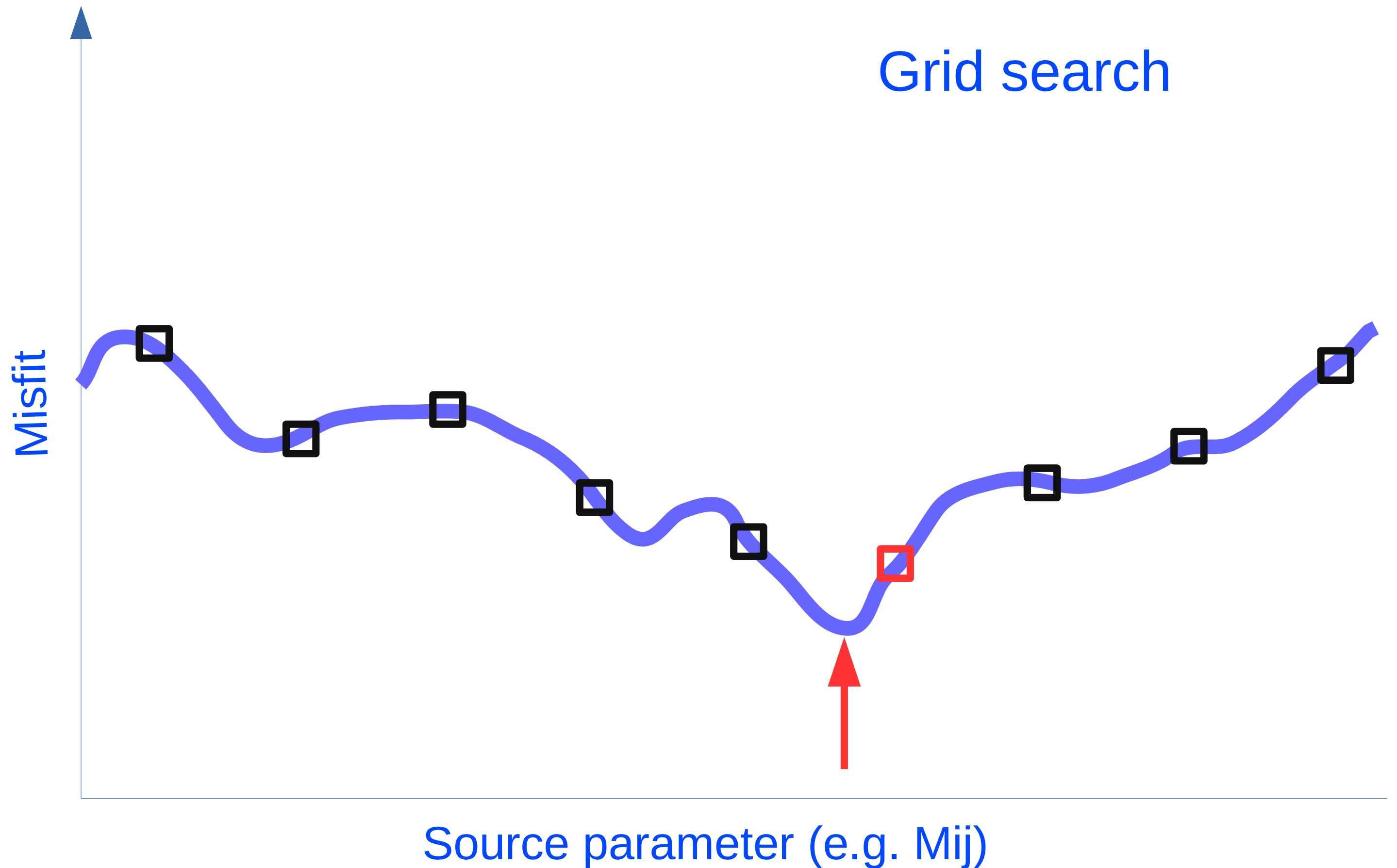


Heimann 2011

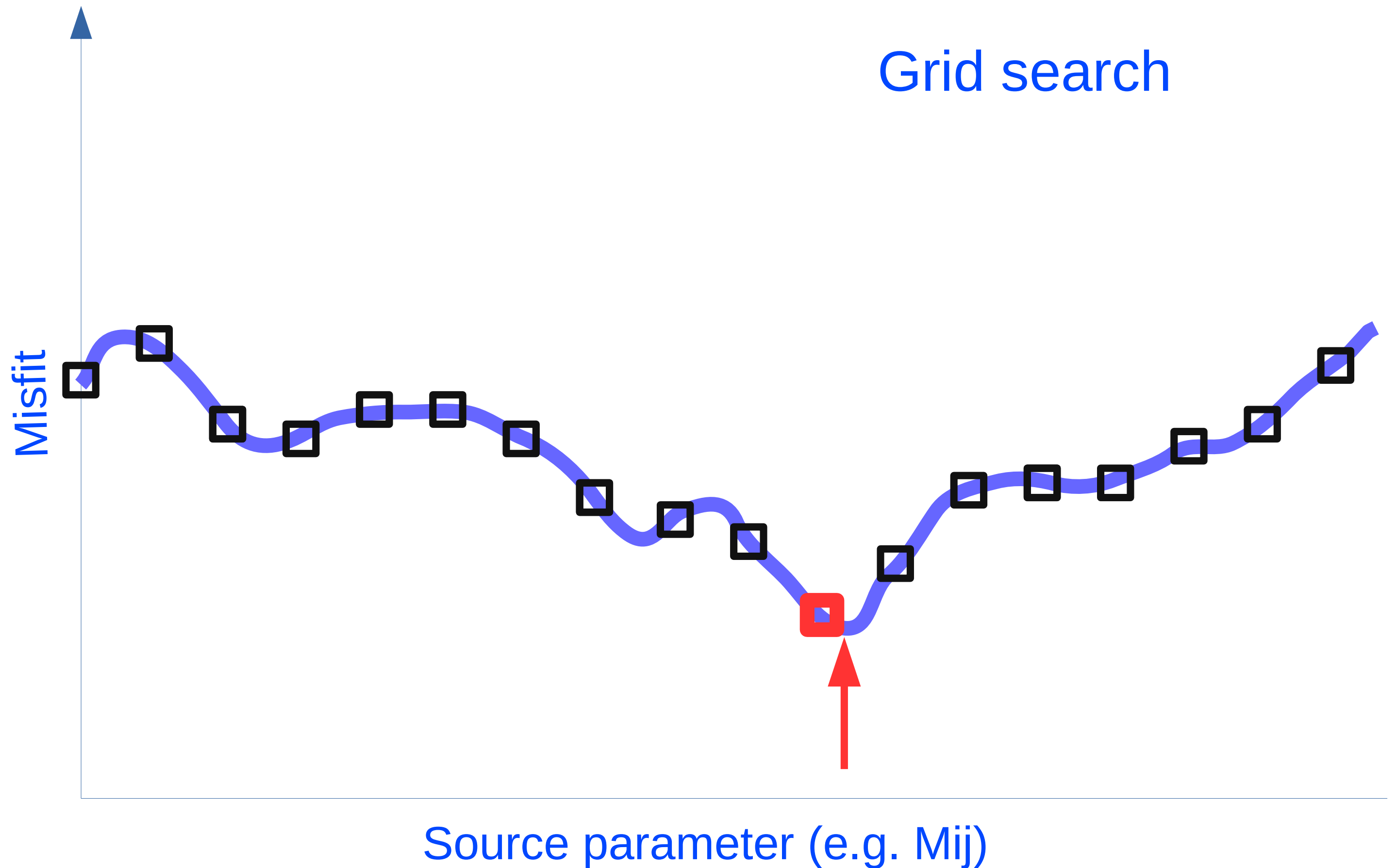
Exploring the parameter space



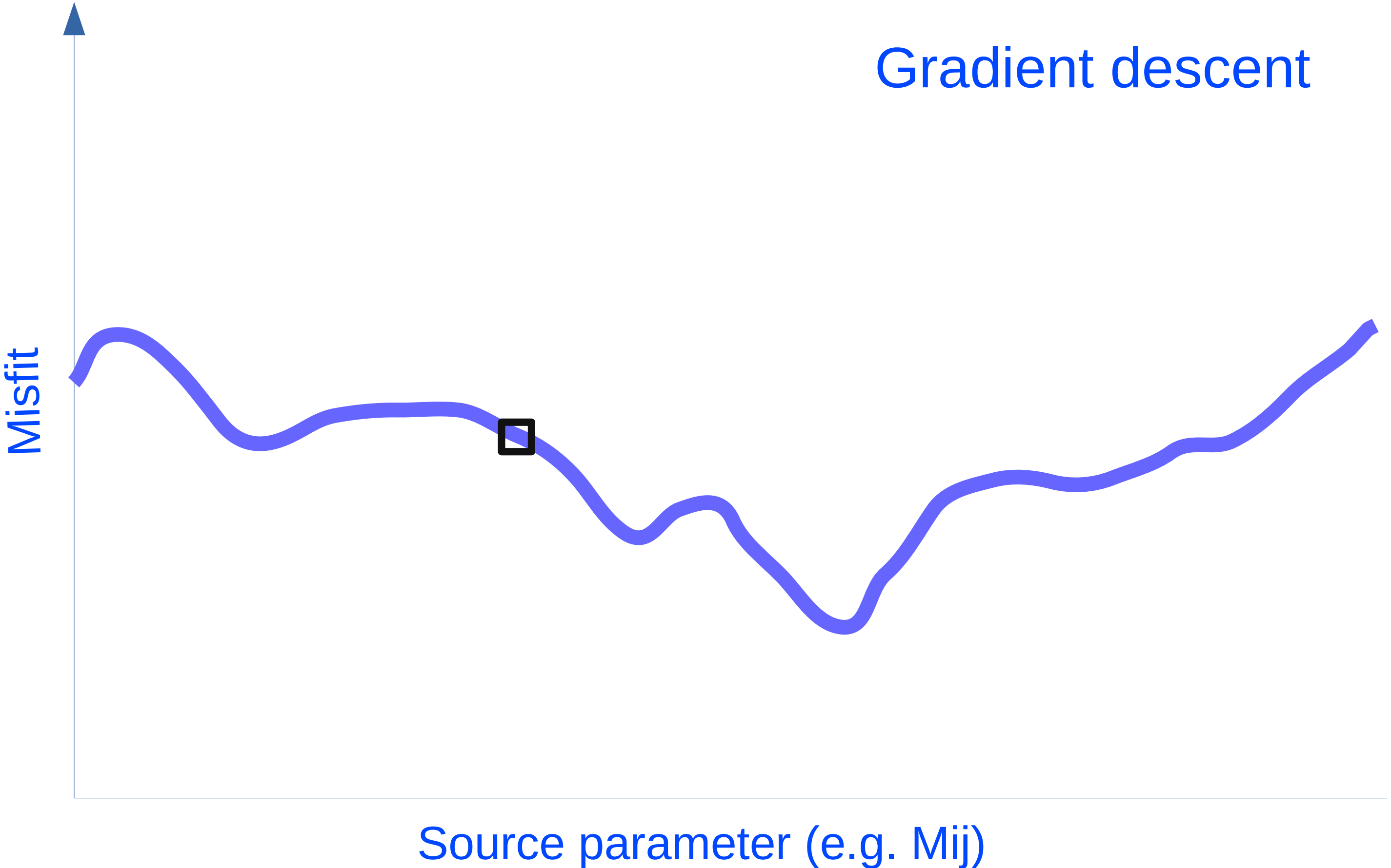
Exploring the parameter space



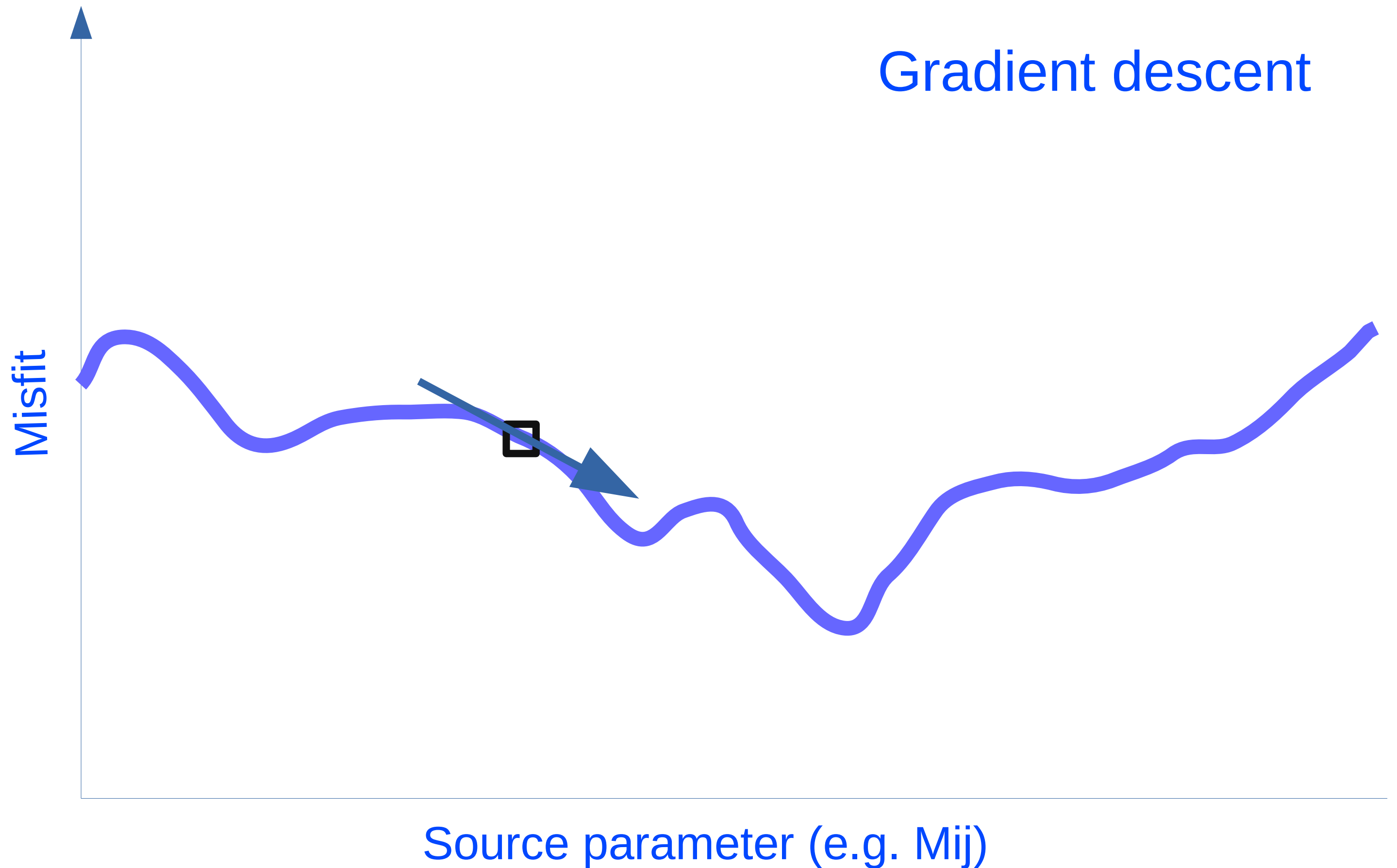
Exploring the parameter space



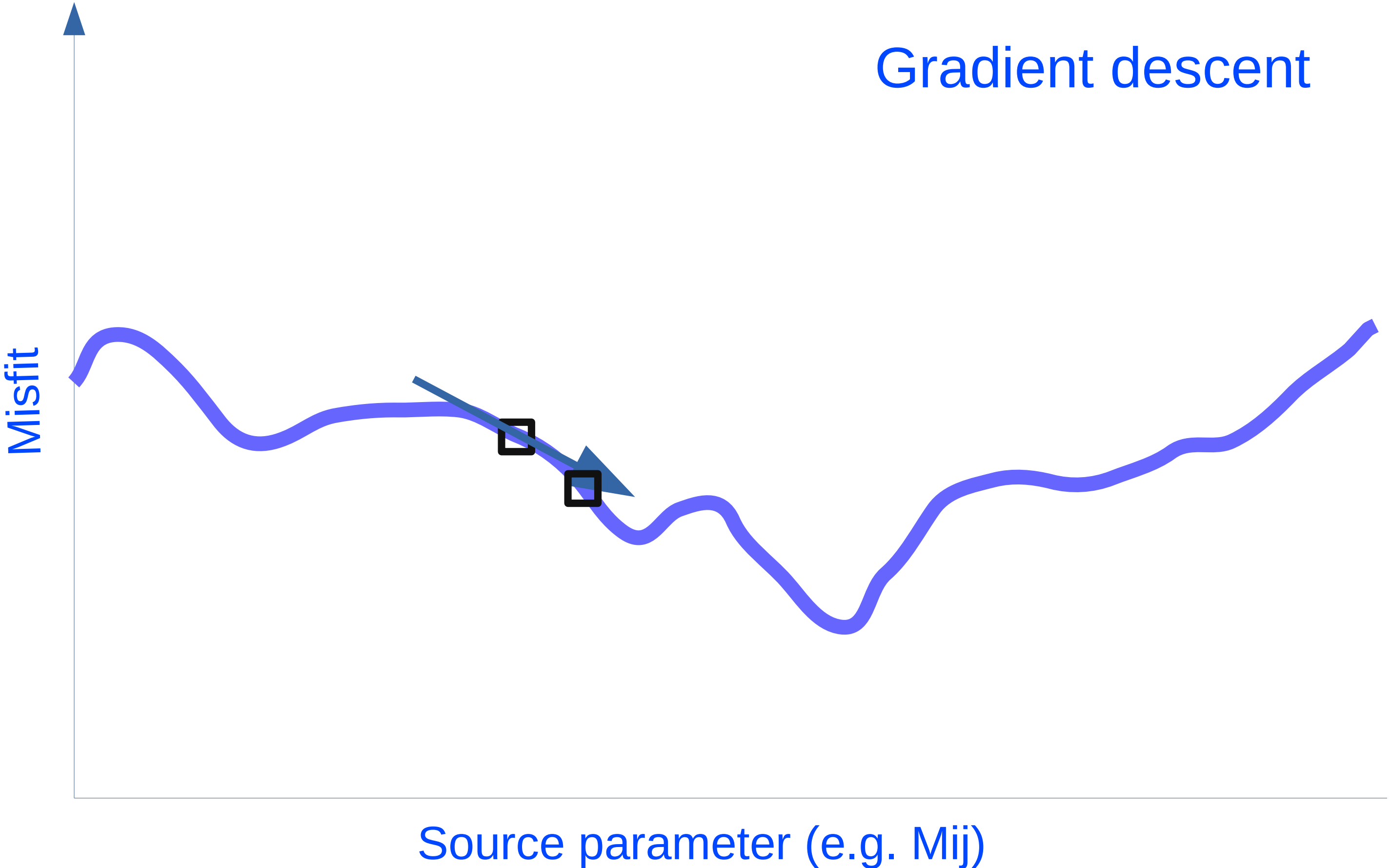
Exploring the parameter space



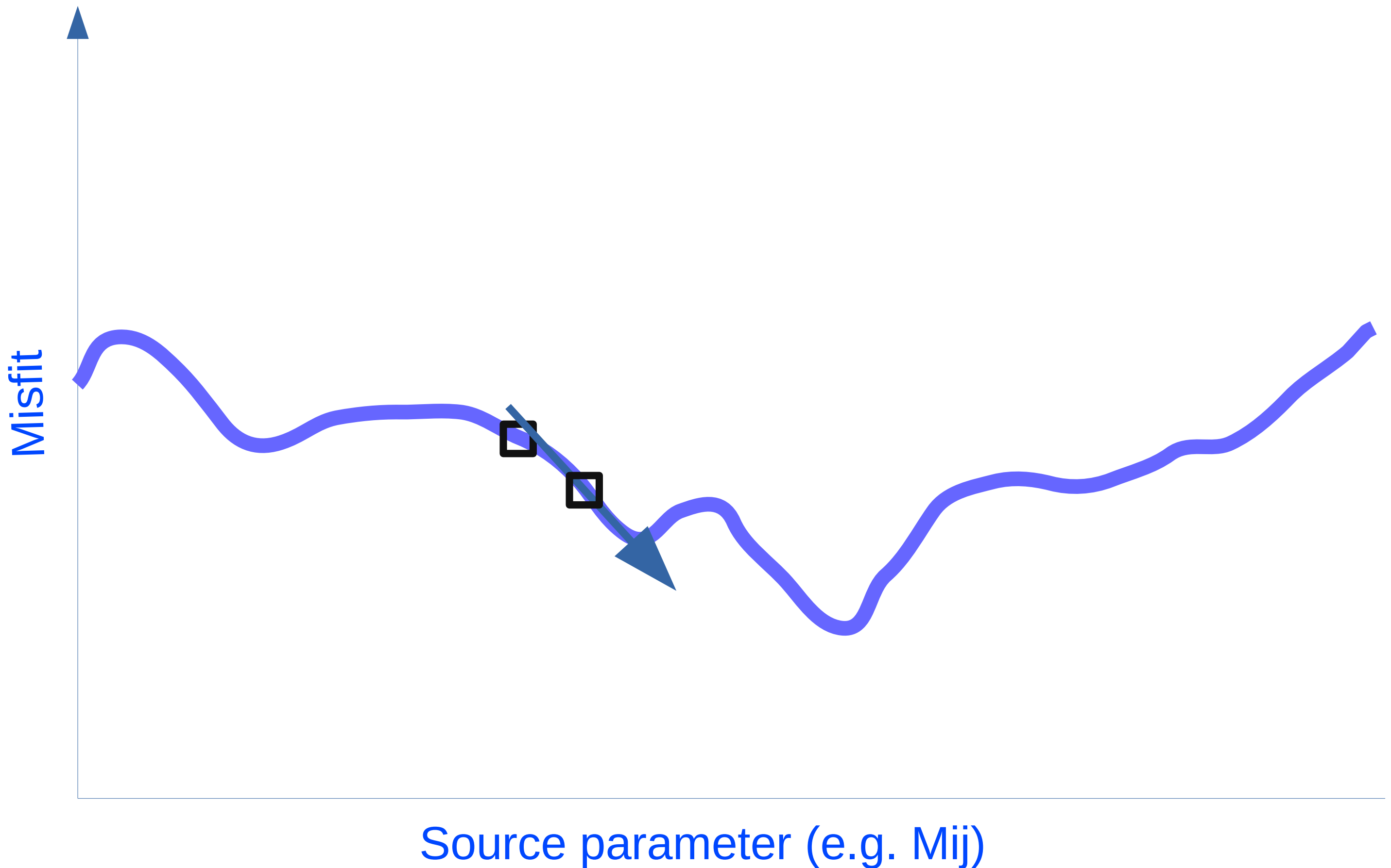
Exploring the parameter space



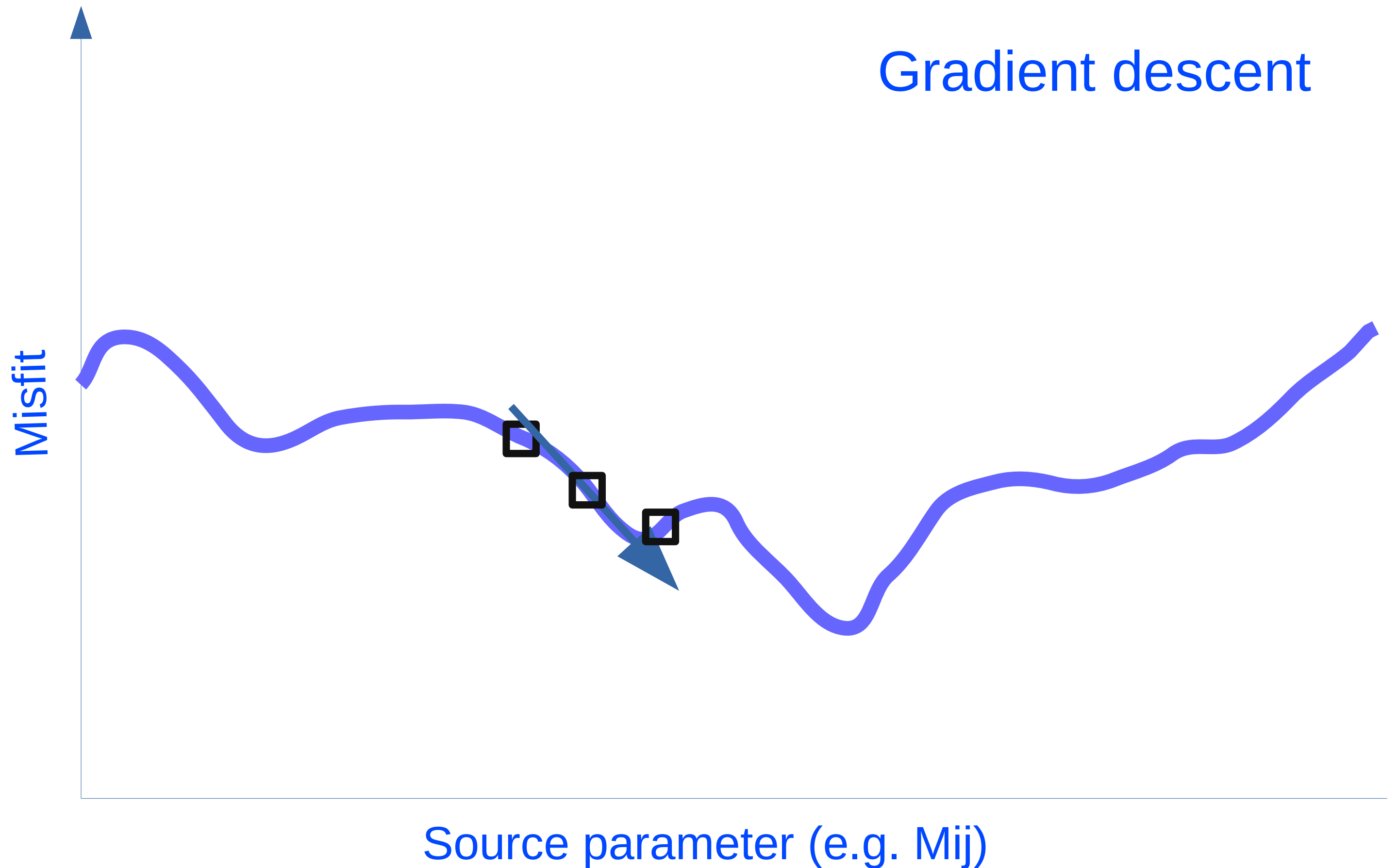
Exploring the parameter space



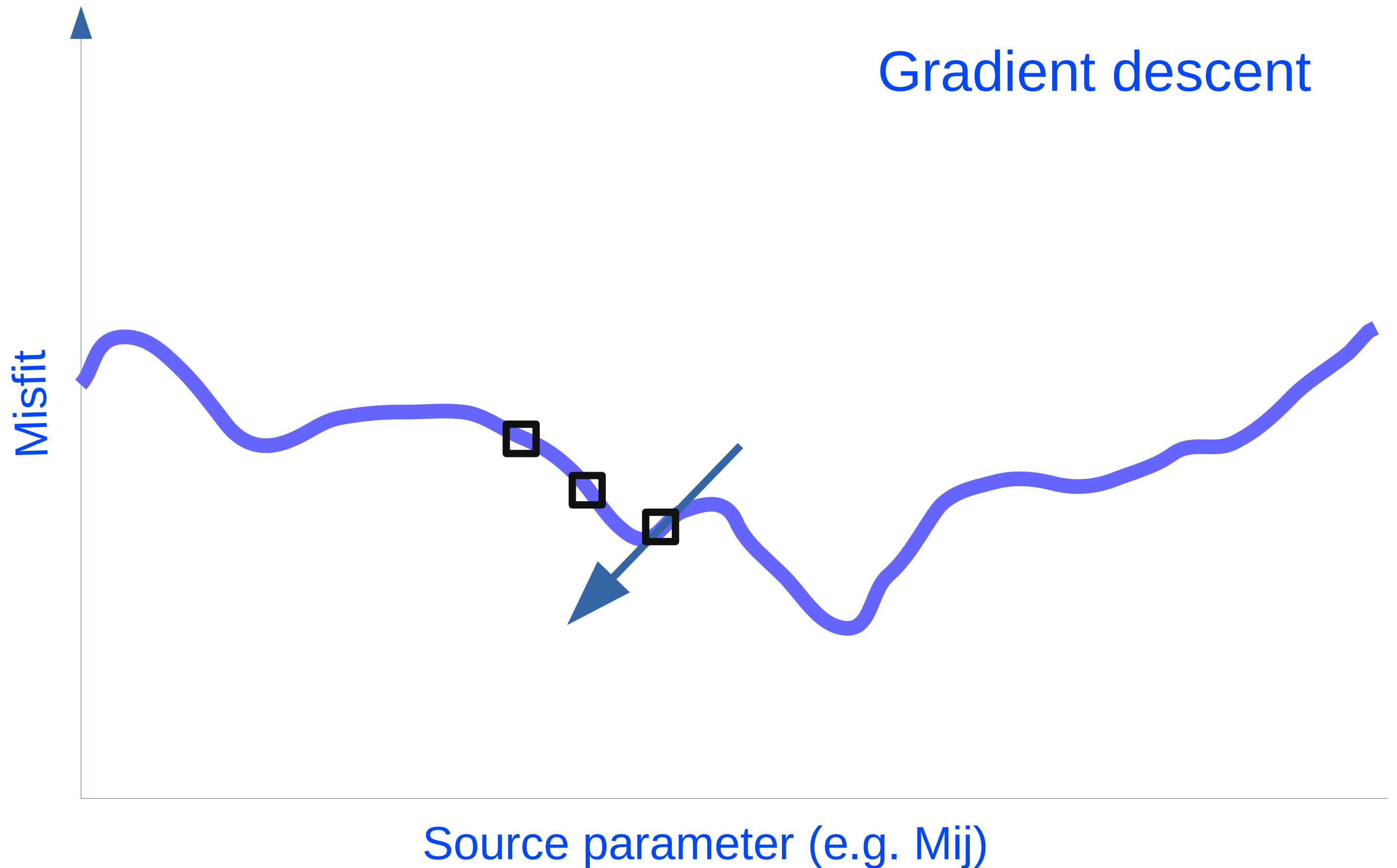
Exploring the parameter space



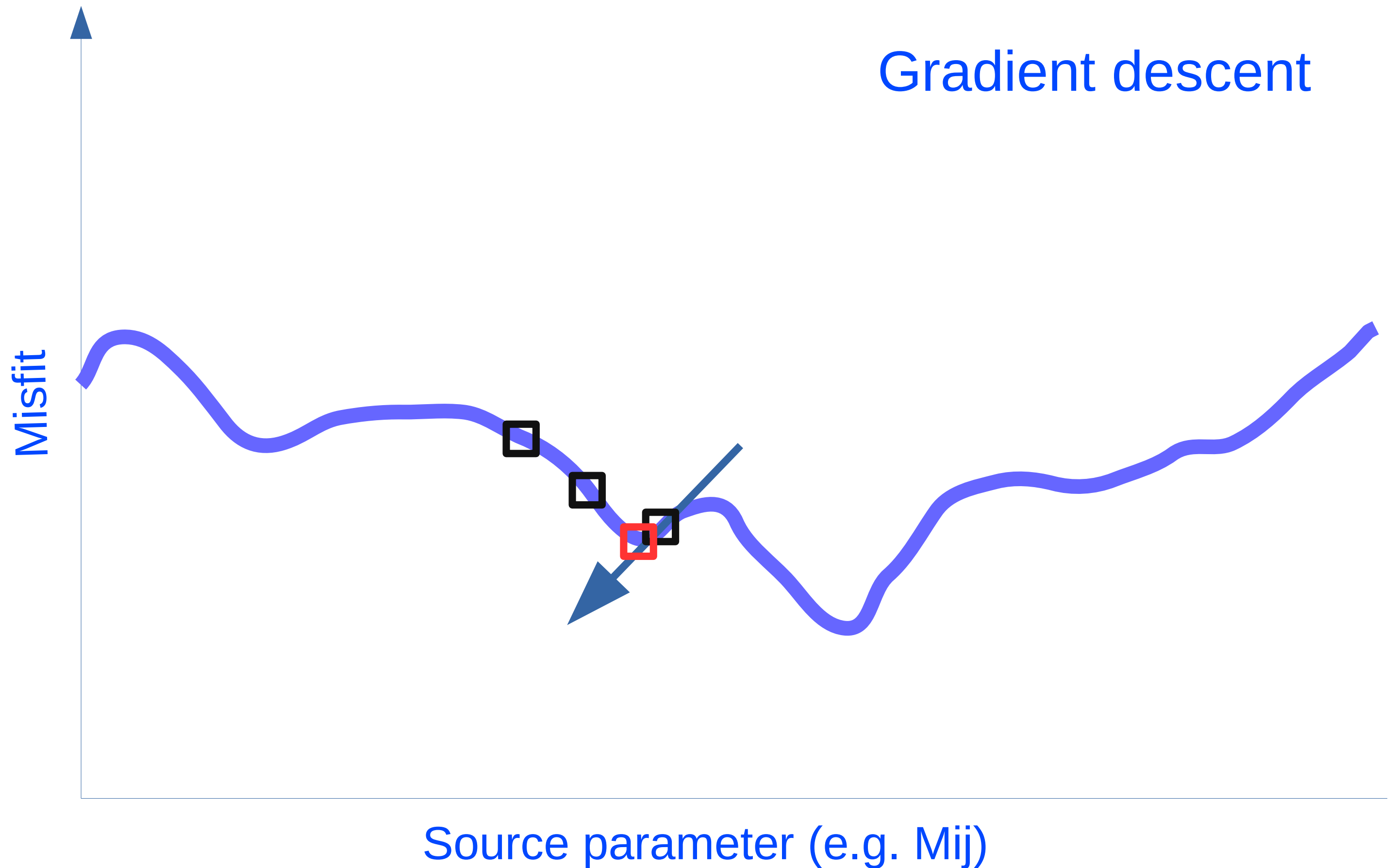
Exploring the parameter space



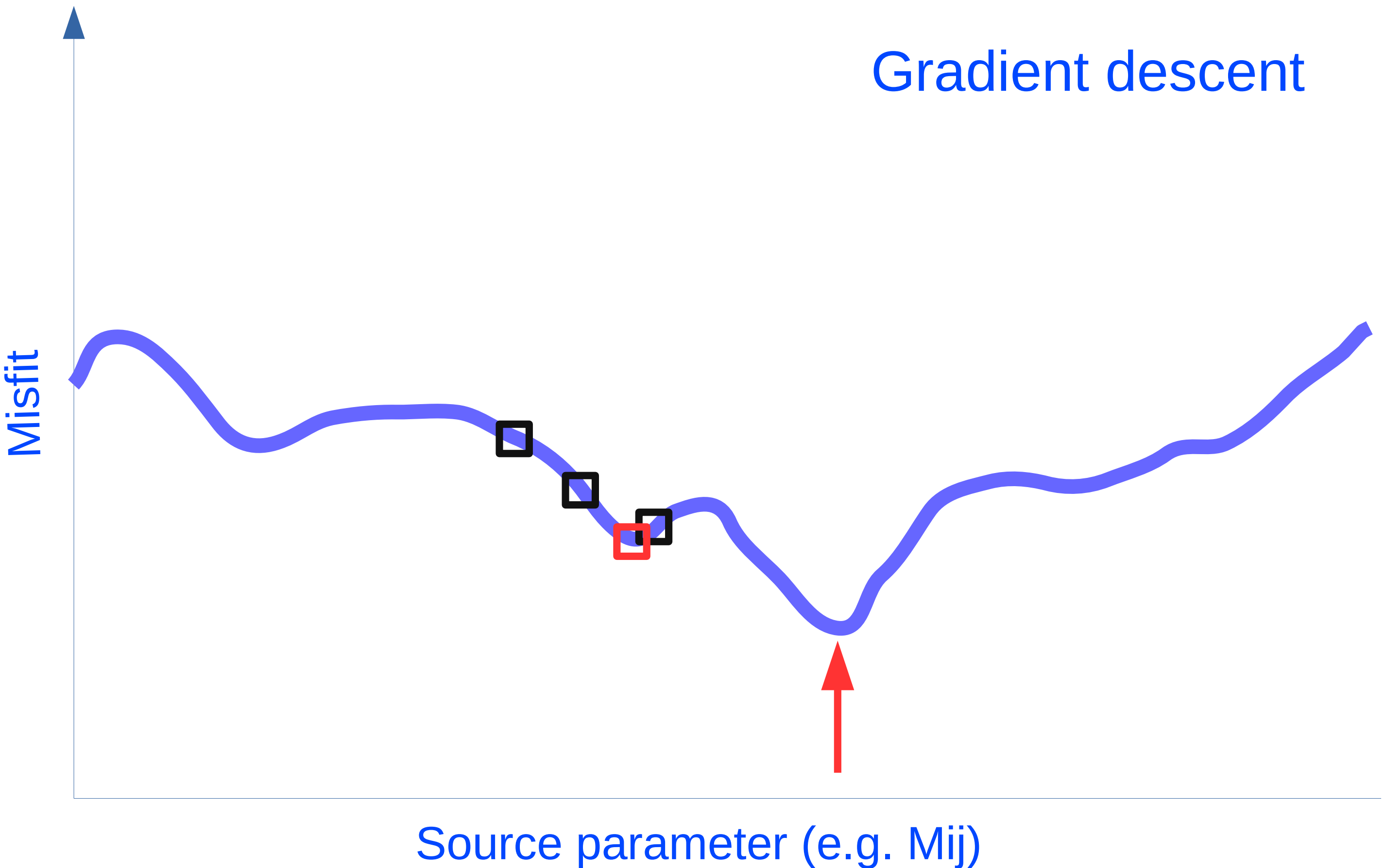
Exploring the parameter space



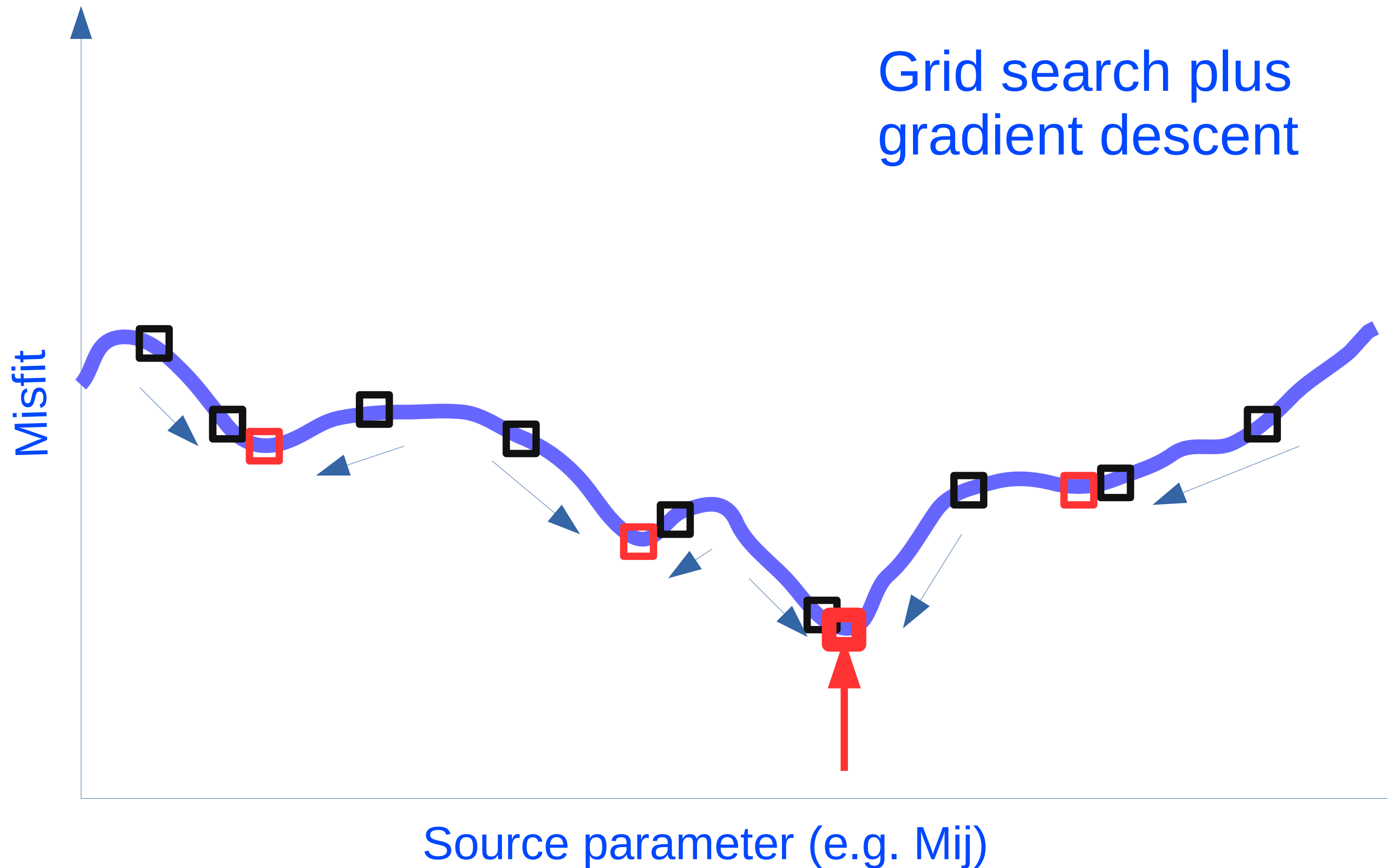
Exploring the parameter space



Exploring the parameter space

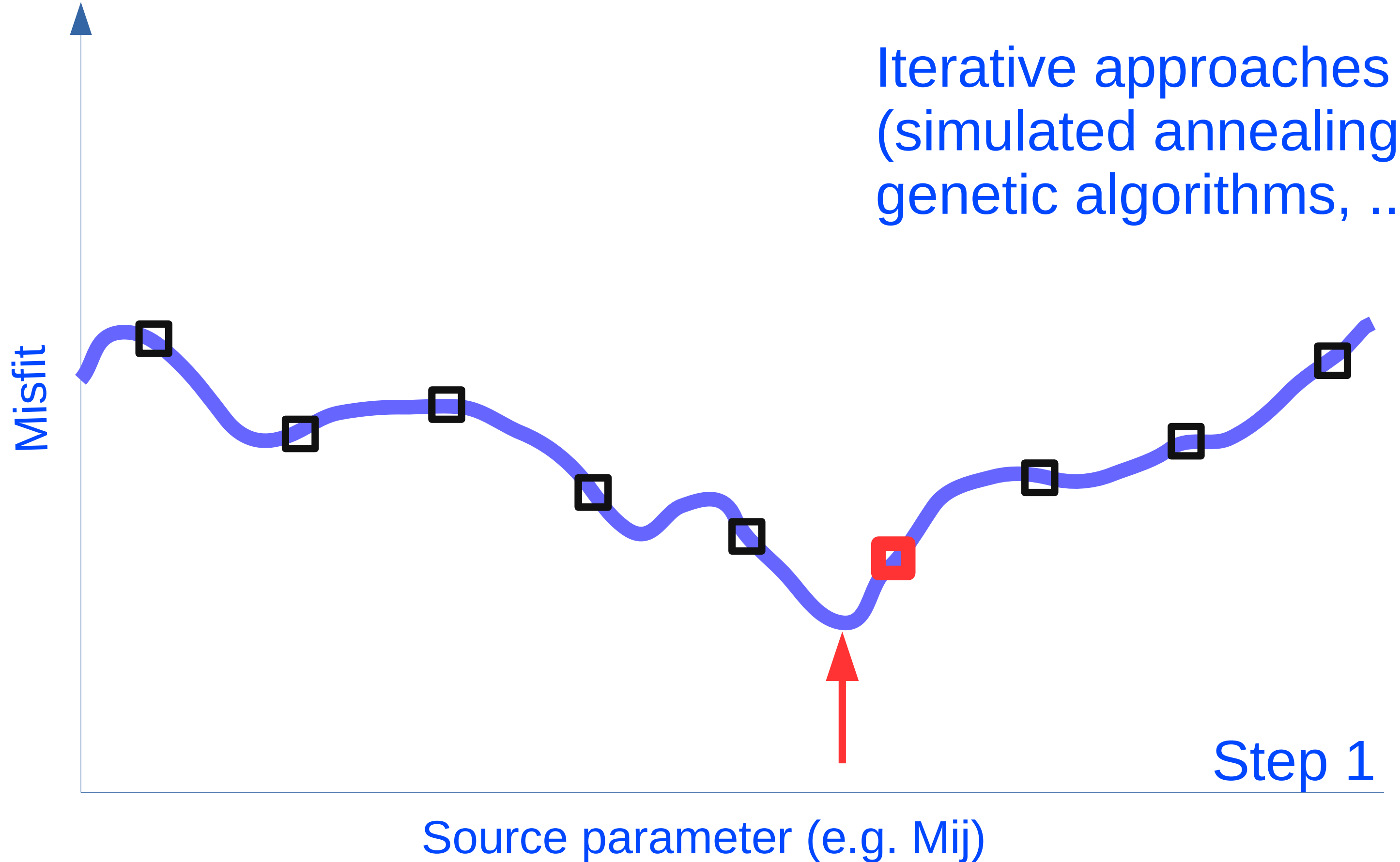


Exploring the parameter space

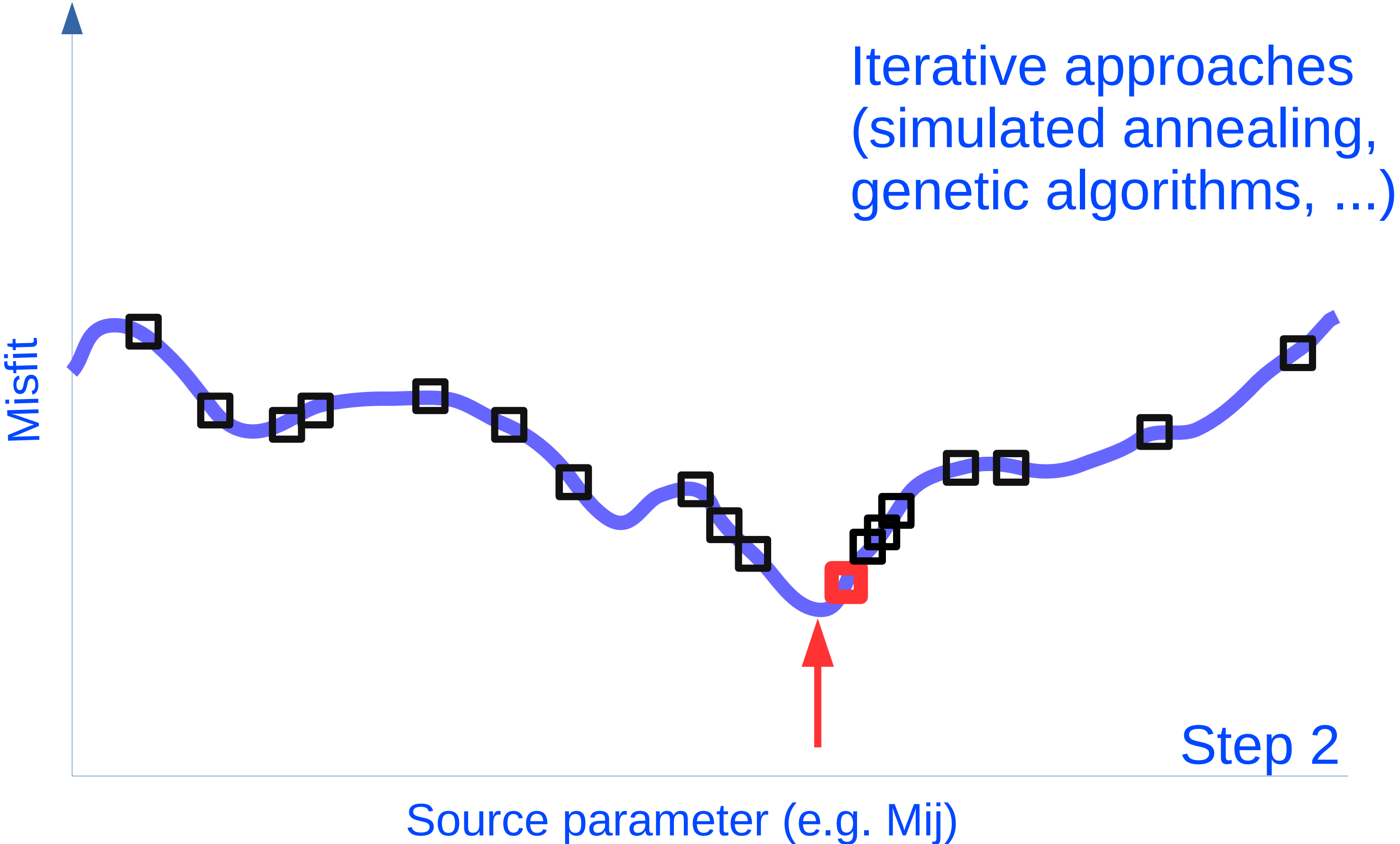


Exploring the parameter space

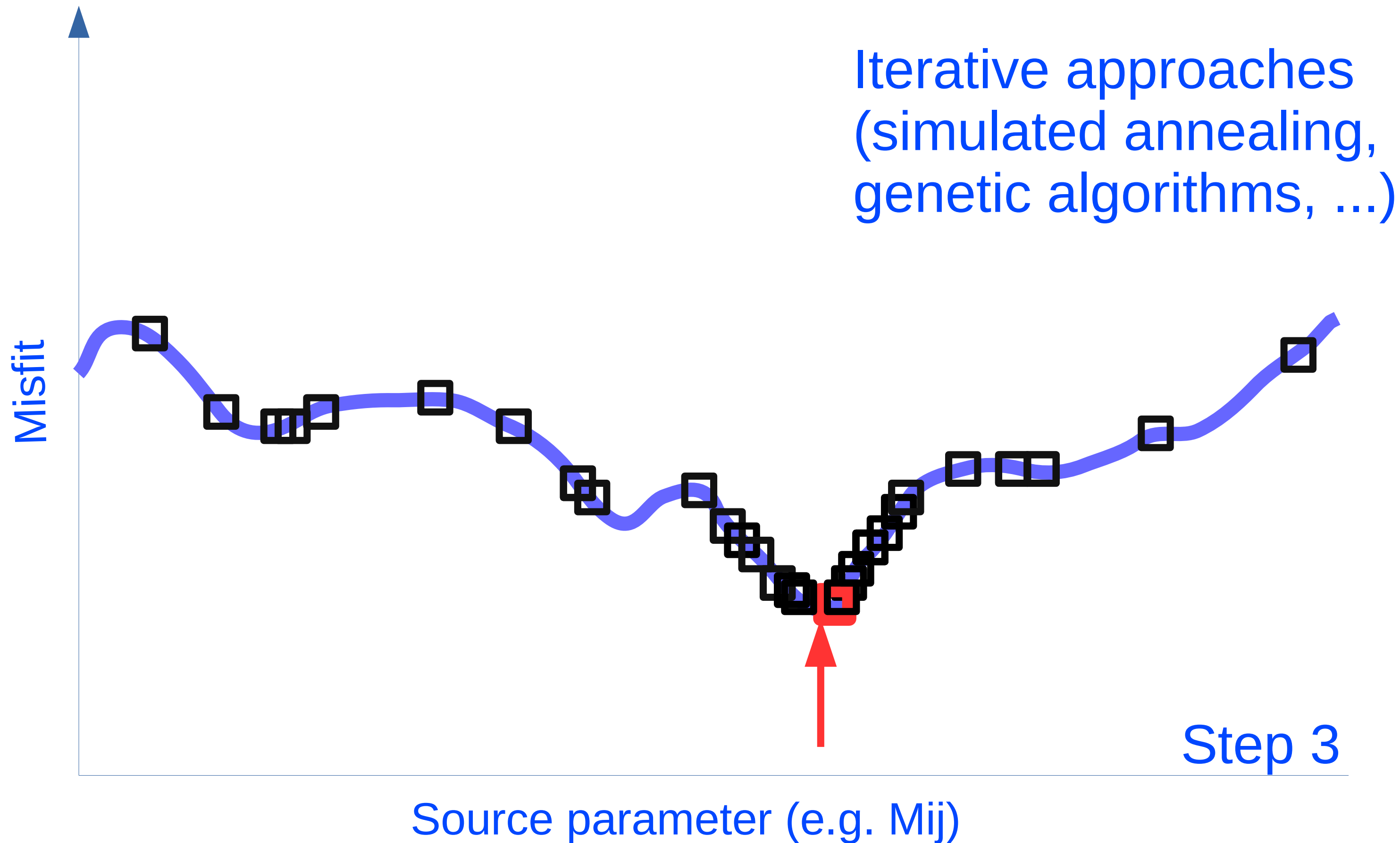
Iterative approaches (simulated annealing, genetic algorithms, ...)



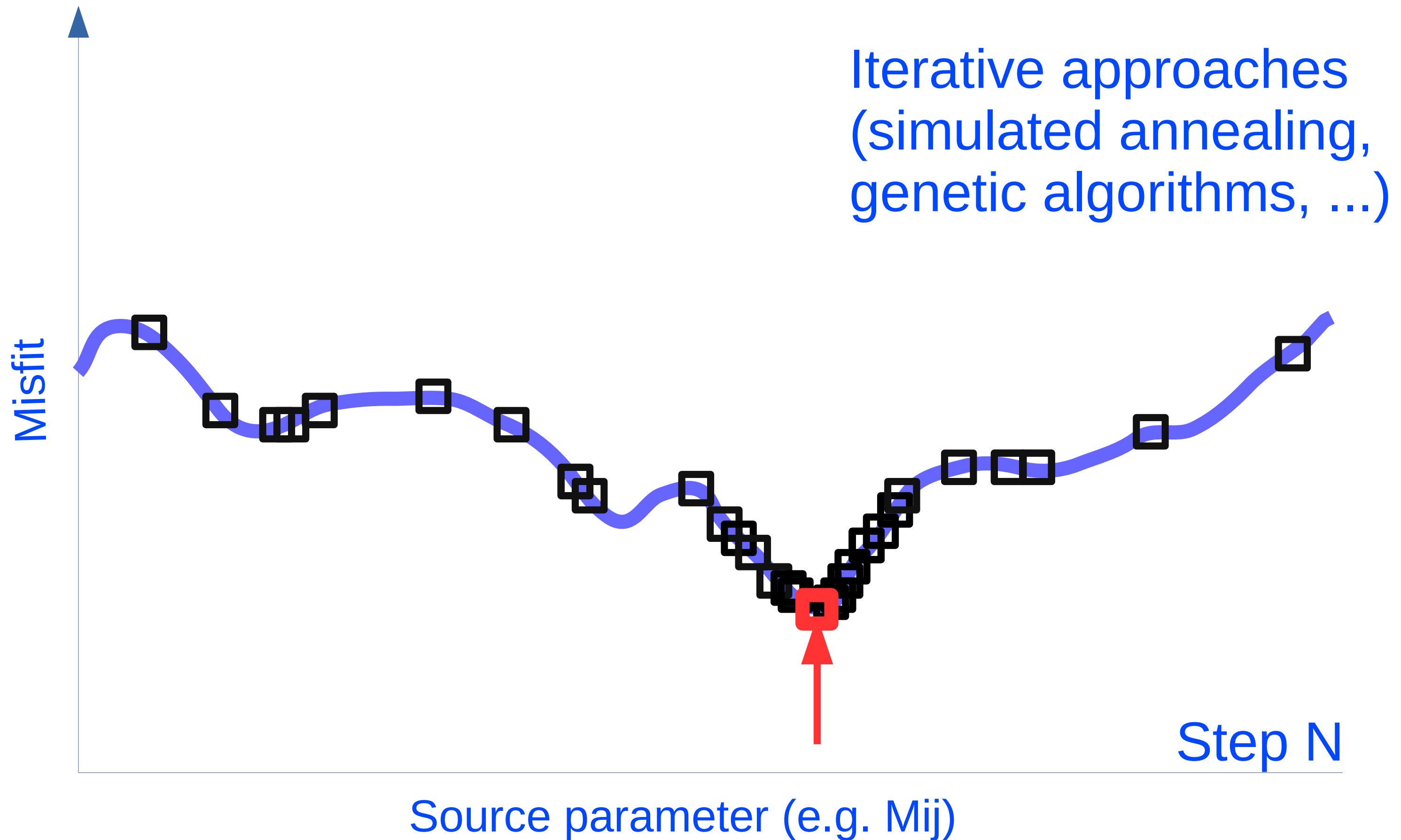
Exploring the parameter space



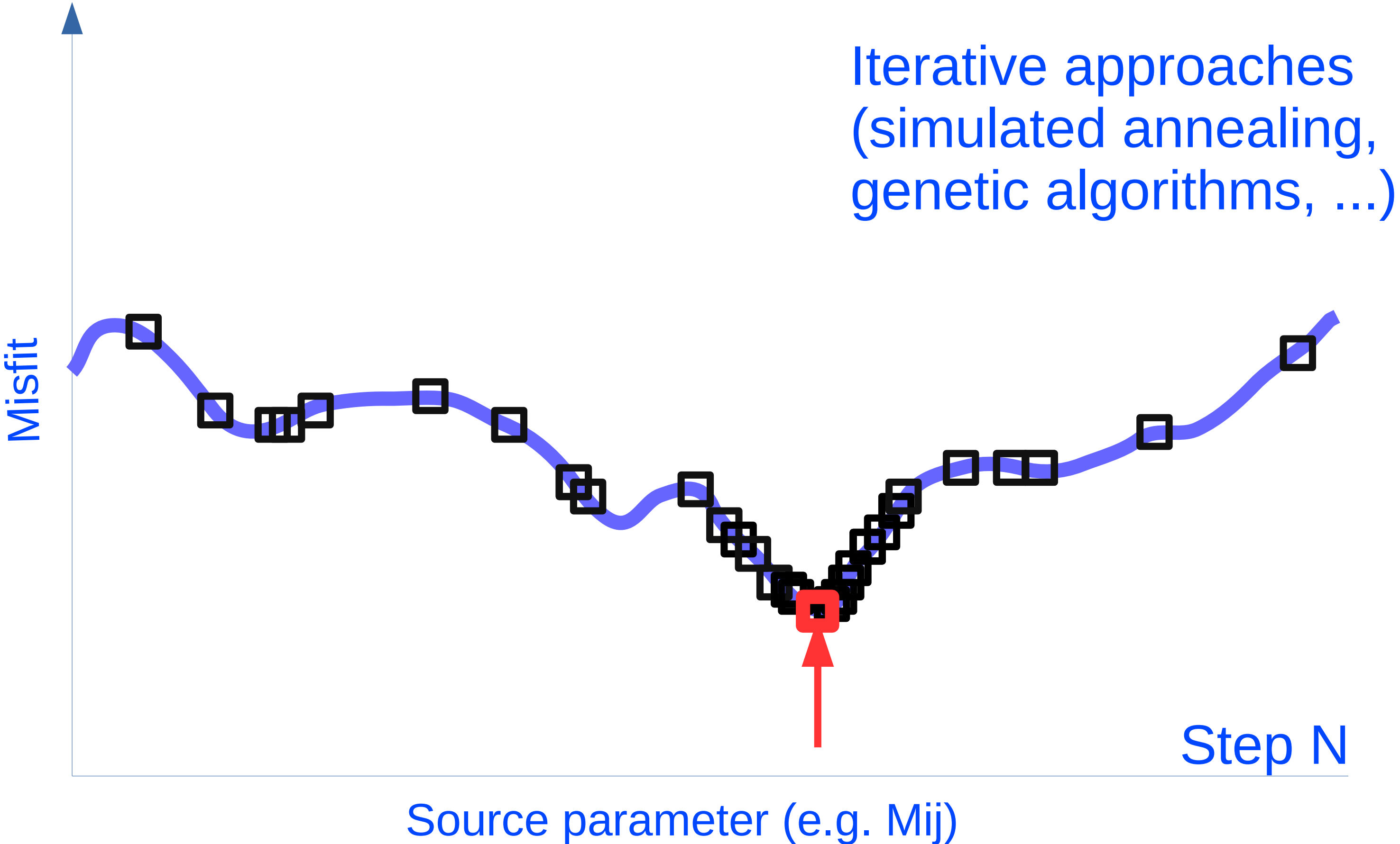
Exploring the parameter space



Exploring the parameter space



Exploring the parameter space

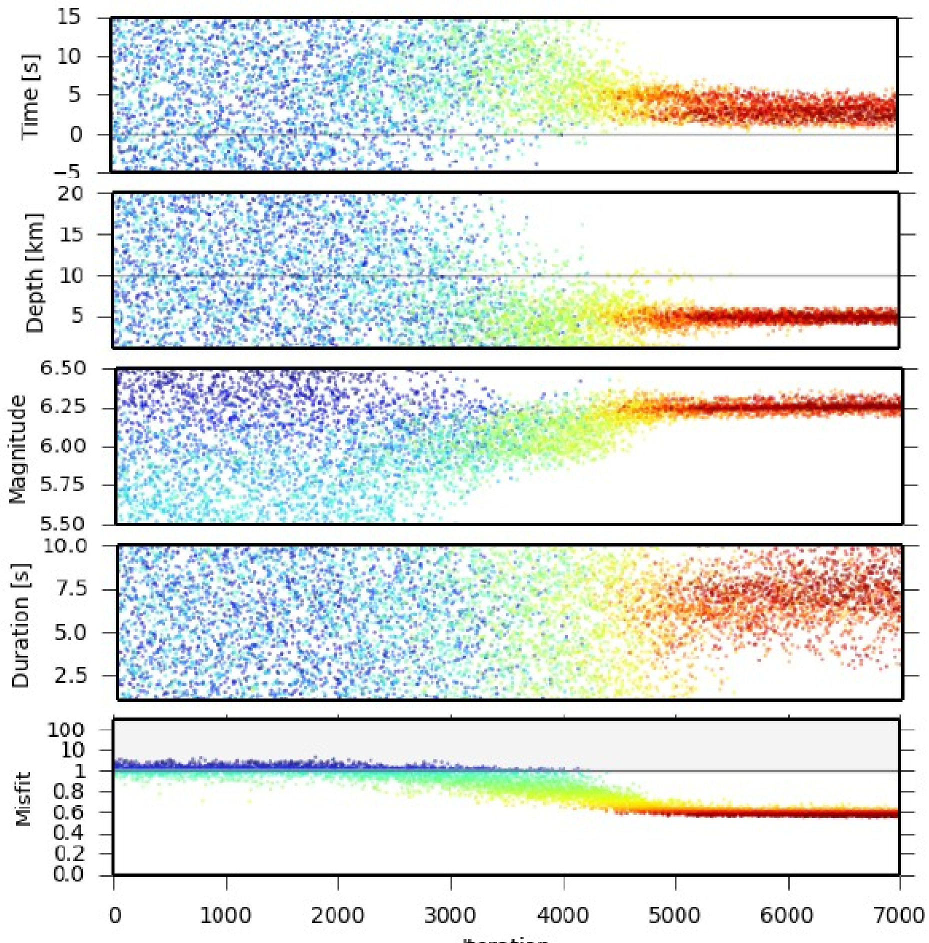


Source inversion using Grond

https://pyrocko.org/

doi:10.5880/GFZ.2.1.2018.003

Grond



Source inversion algorithm
(S. Heimann, Uni Potsdam)

Simultaneous determination of multiple source parameters

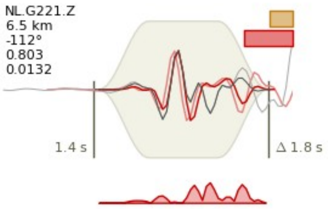
Flexible
→ Source model
→ (Joint) datasets
→ Fitting procedure
→ Weighting
→ Iterative approach

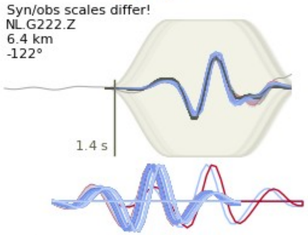
Uniform phase (random search)
Transition phase (mixed search)
Explorative phase (guided search)

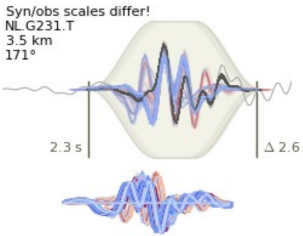
Simultaneous bootstrap simulation

Flexible data fitting

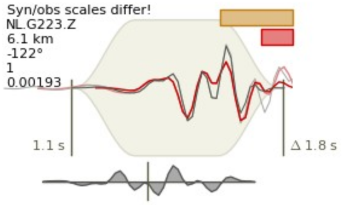
time traces



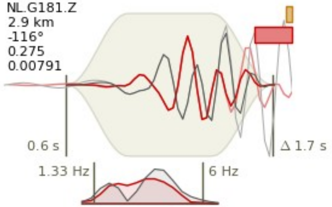




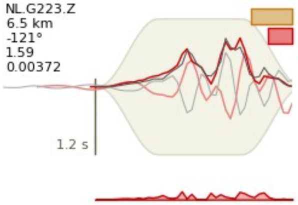
CC traces



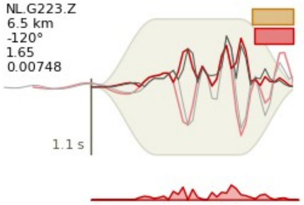
amplitude spectra



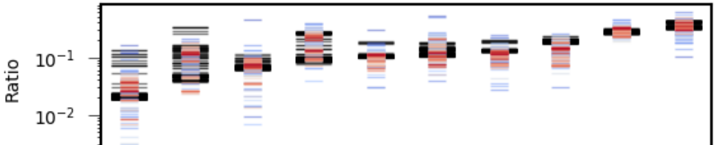
envelopes



absolute amplitudes



P/S amplitude ratios



Different source models

CMTProblem
It solves for a centroid moment tensor point source (DC, deviatoric, full MT).
This problem fits the very general earthquake source analysis.

DoubleDCProblem
It solves for two double-couple point sources.
Useful e.g. for complex, segmented earthquake sources.

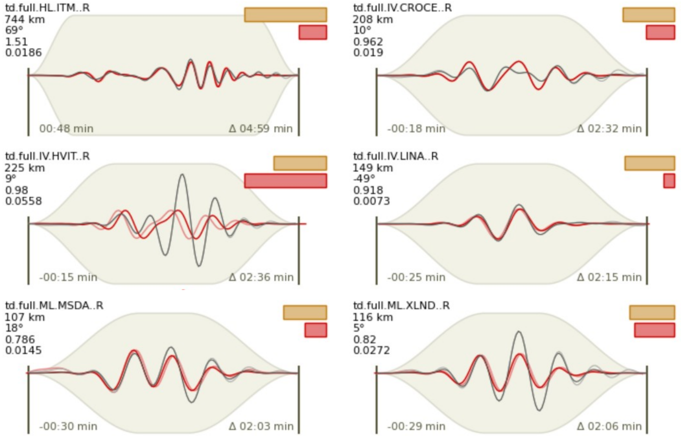
RectangularProblem
It solves for a rectangular finite source.
Analysis of large earthquakes and/or problems for which near-field surface displacement data (InSAR, GNSS, etc.) are available.

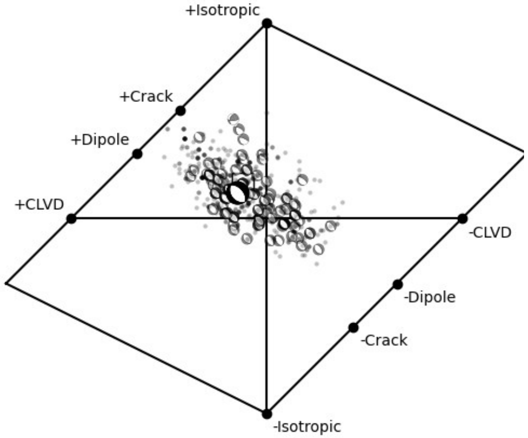
VolumePointProblem
It solves for a spherical volume point (infinite) to model magmatic or volcanic processes.
Only static targets (GNSS or InSAR) are supported.

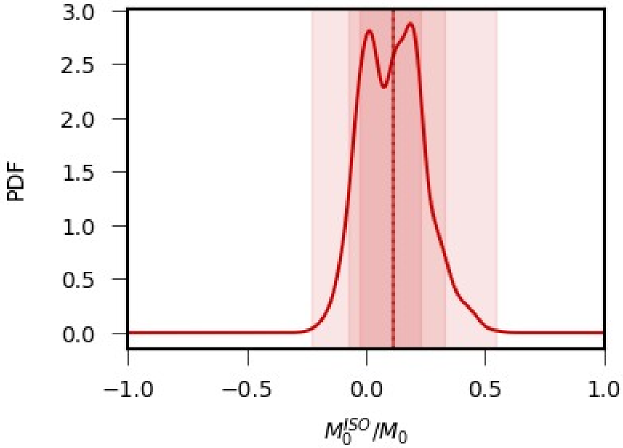
Other source models can be implemented
Double single force for landslides,
damped oscillator for resonating reservoirs/conduits, ...

Grond uncertainties

Data bootstrap → Solutions ensemble → Parameter uncertainty

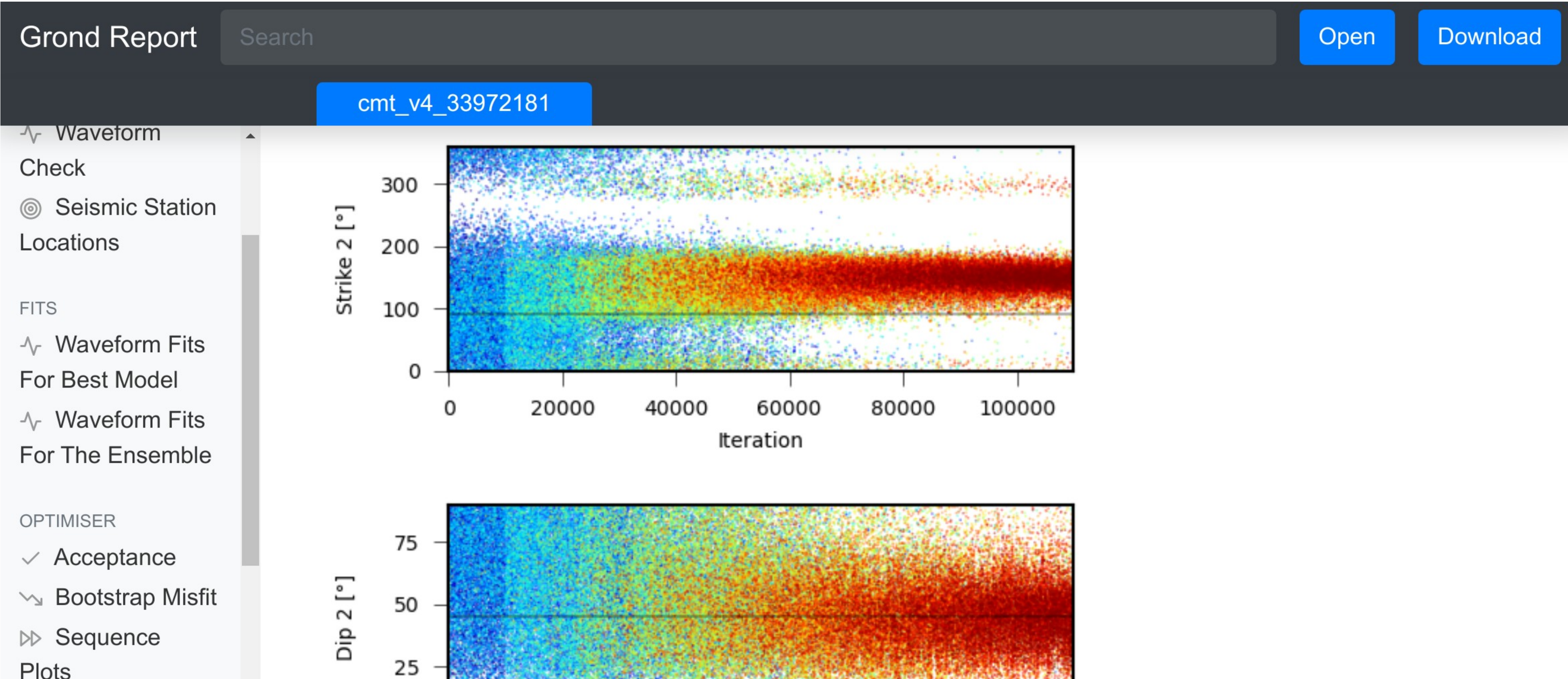






Grond graphical output

Grond graphical output



Grond graphical output

Grond Report | Search | Open | Download

cmt_v4_33972181

Sequence Plots

RUN

Problem Config

Parameter Results

Problem Info

SOLUTION

Target Contributions

Histogram

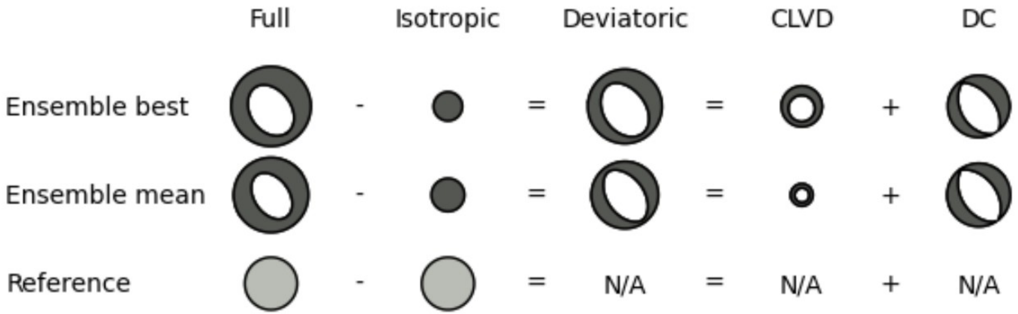
Hudson Plot

Jointpar Plot

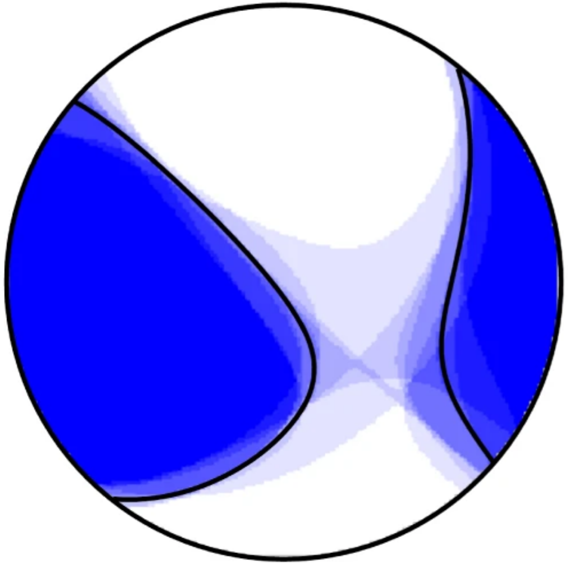
MT Decomposition

Moment tensor decomposition of the best-fitting solution into isotropic, deviatoric and best double couple components.

more...



Source inversion in seismology



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Pinar Büyükakpinar[1,2], Daniela Kühn[1,3]

1. GFZ Potsdam, 2. University of Potsdam, 3. NORSAR, Norway

Potsdam, 29.6.2023