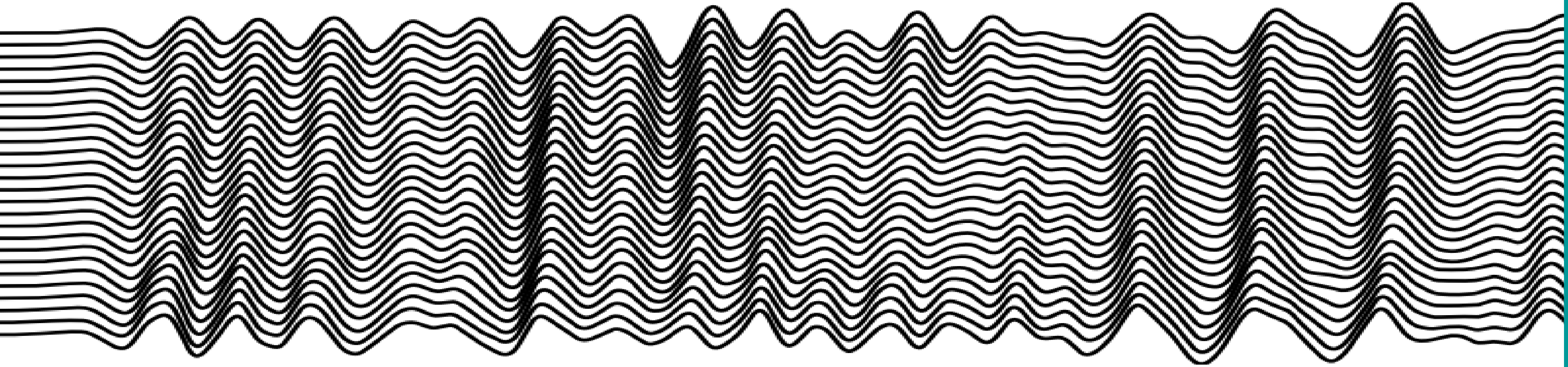
Martijn van den Ende Jean-Paul Ampuero

What’s that wiggle?



The challenges (and solutions) of using fibre-optic cables as seismological antennas

UNIVERSITÉ CÔTE D’AZUR

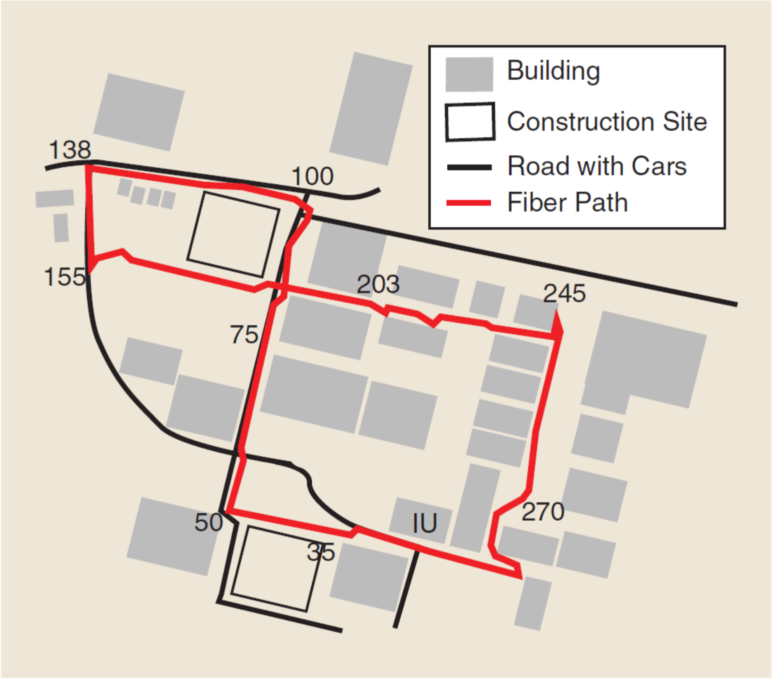
3iA Côte d’Azur
Institut interdisciplinaire d’intelligence artificielle

van den Ende & Ampuero (2021), *Evaluating seismic beamforming capabilities of distributed acoustic sensing arrays*, Solid Earth 12

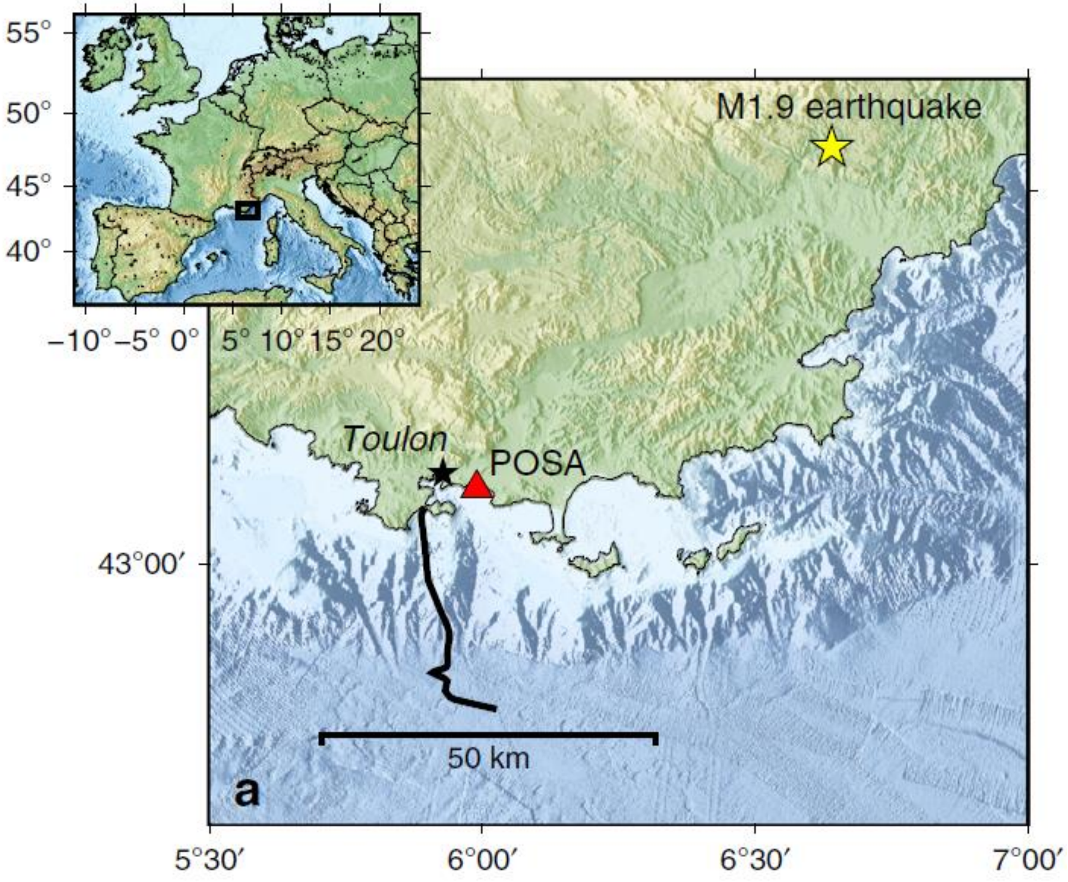
DAS arrays are the future (?)

Glacier
Walter et al. (2020)

Stanford Campus
Martin et al. (2018)

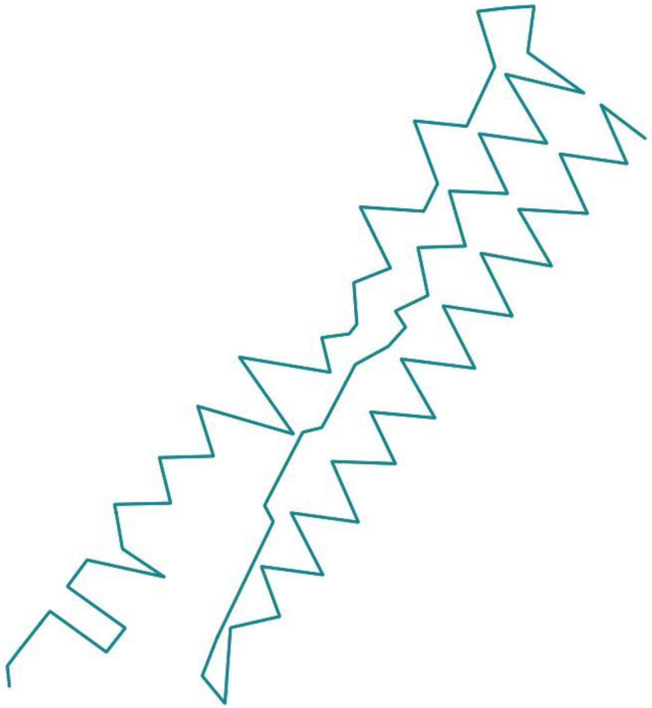


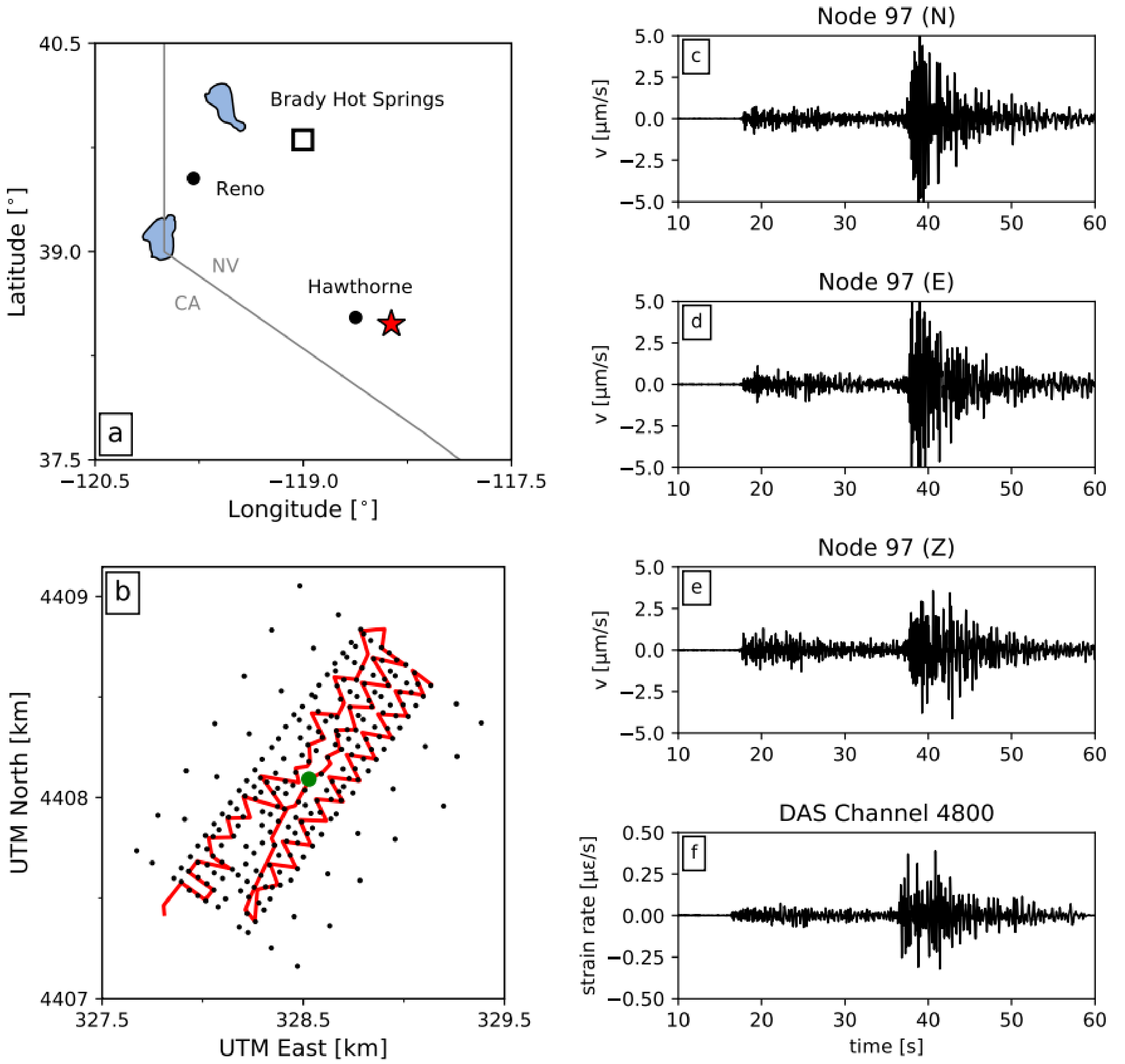
Offshore telecommunication cable
Sladen et al. (2019)



Hawthorne M4.3 earthquake

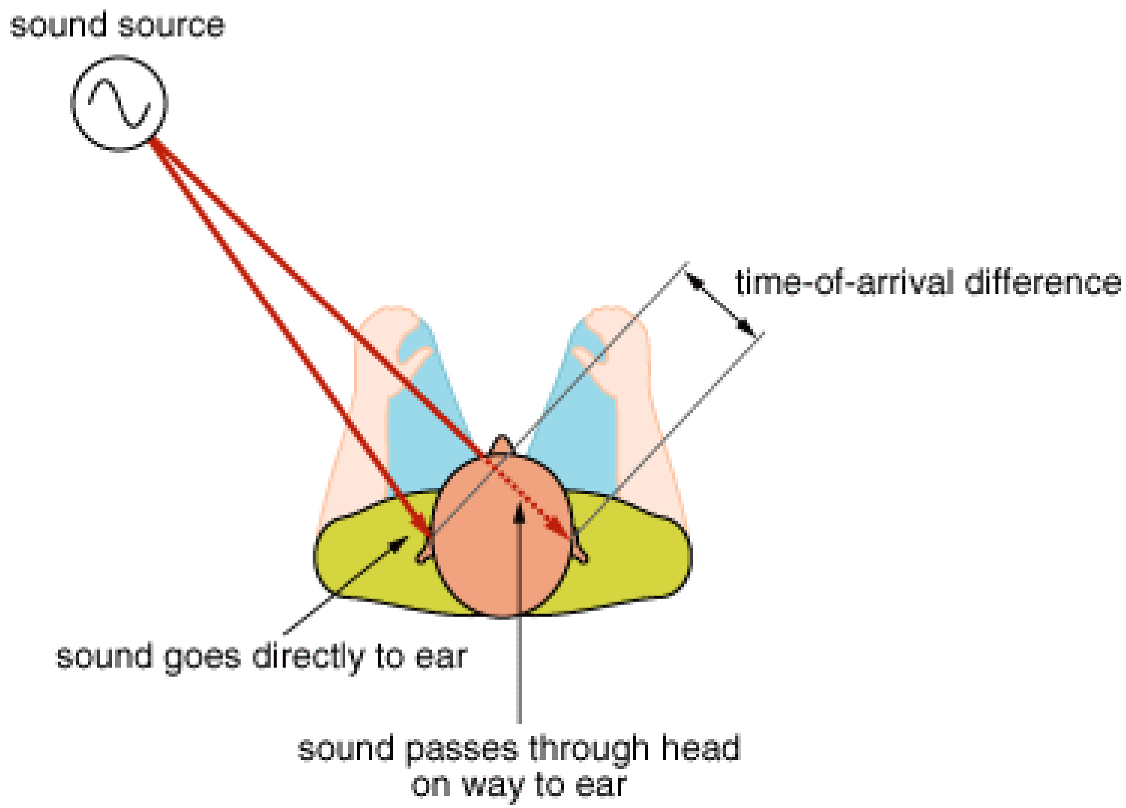
See: Feigle & the PoroTomo team (2018)
Wang et al. (2018)





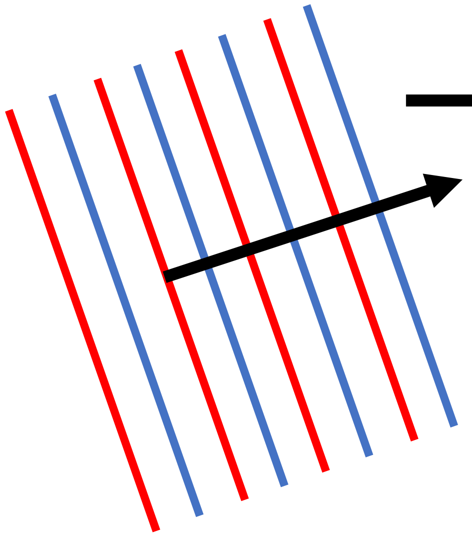
Quick primer on beamforming

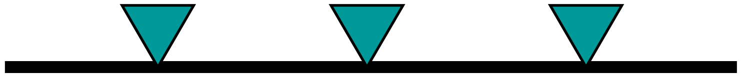
- Arrival time of signals depends on source-receiver distance
- Array of sensors (your ears): time delay caused by offset between sensors, dependent on azimuth
- Beamforming: use sensor array to estimate direction-of-arrival and apparent phase velocity
- Frequency-domain **MU**ltiple **SI**gnal **C**lassification (MUSIC) beamforming



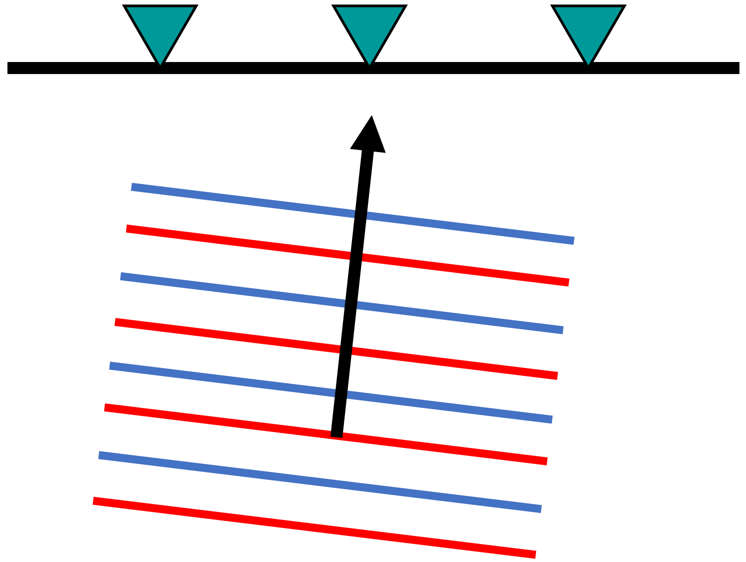
http://sites.music.columbia.edu

Quick primer on beamforming



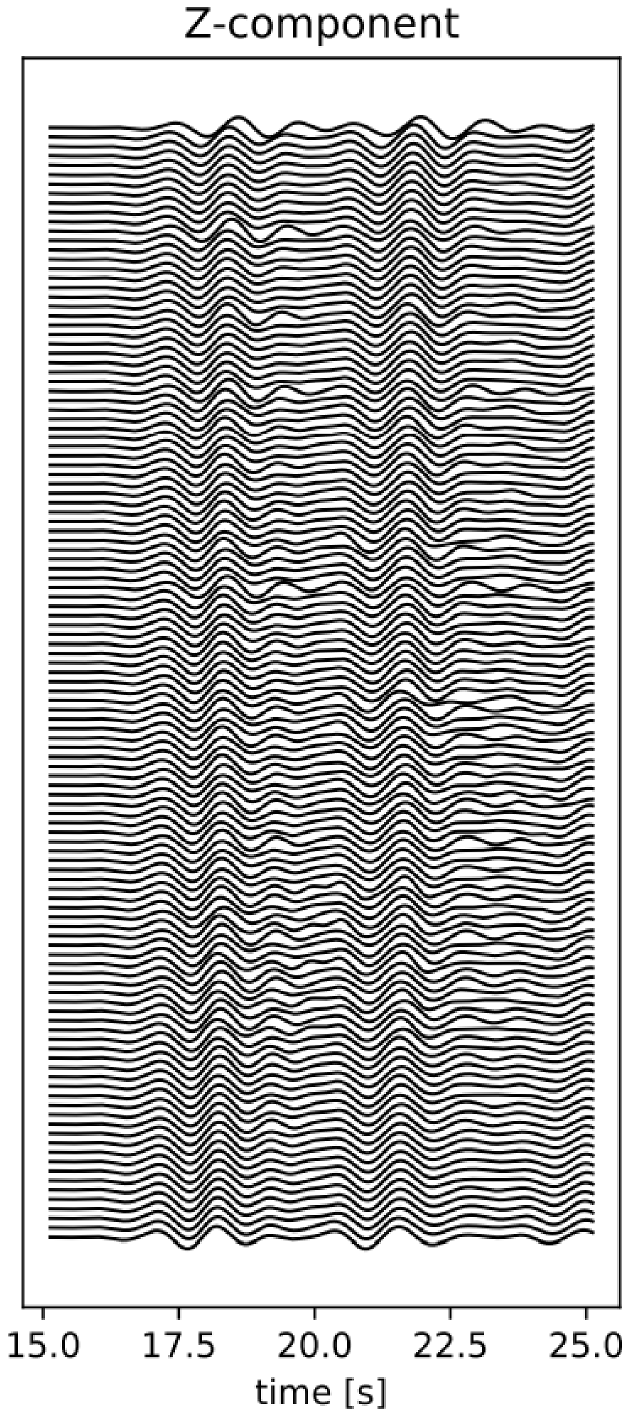


Shallow source:
Apparent velocity ~ true velocity

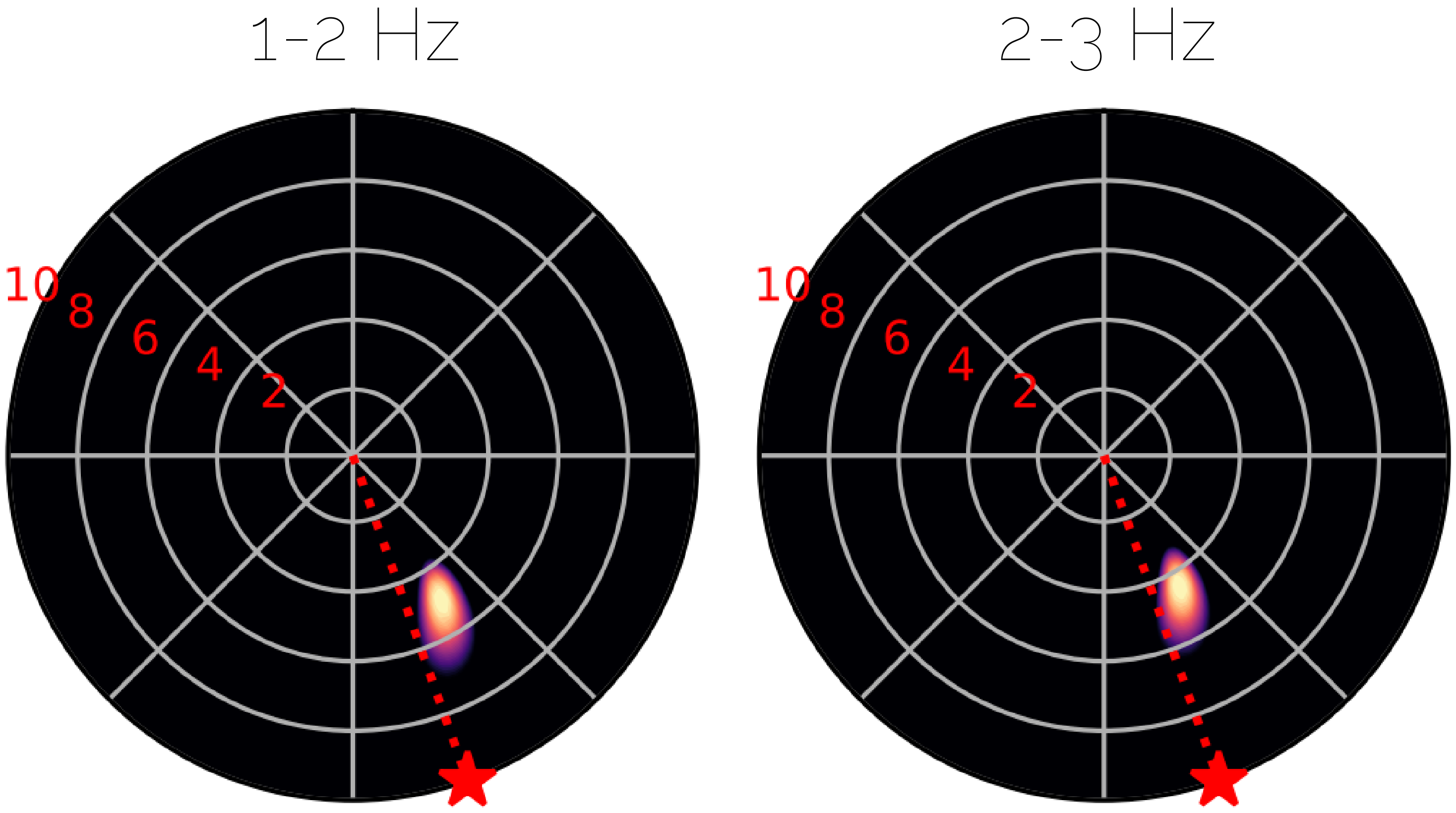


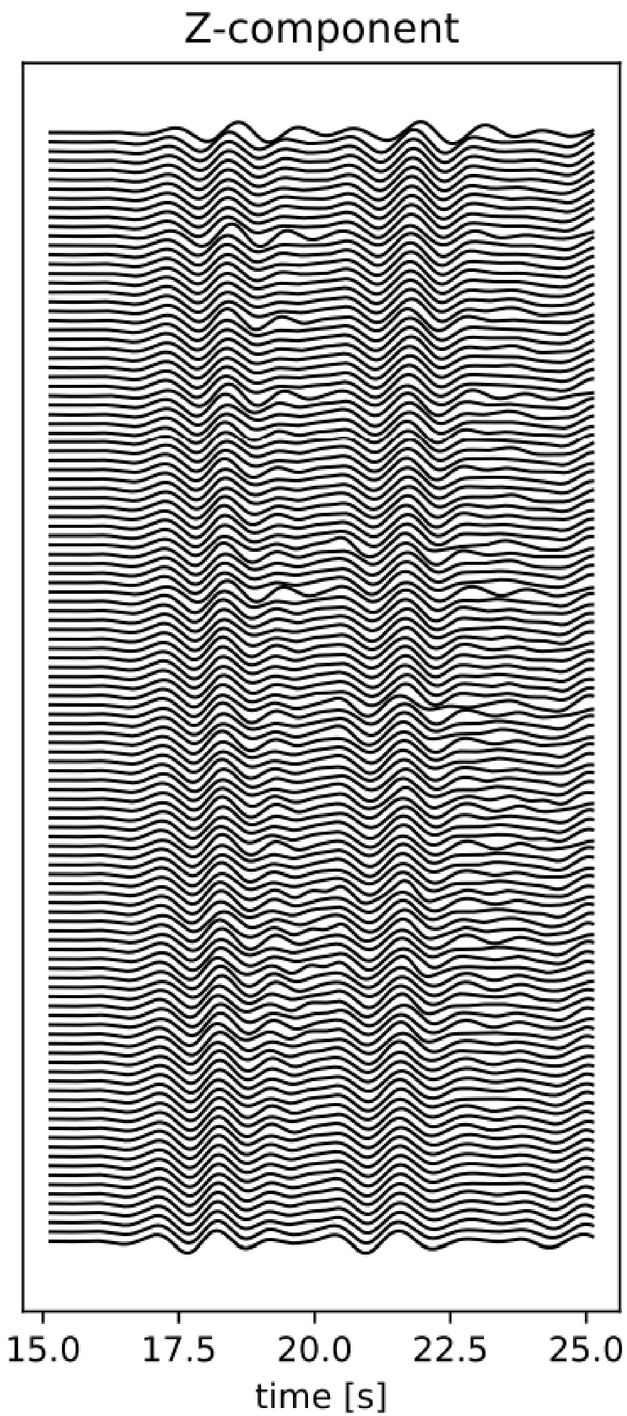
Deep/ distant source :
Apparent velocity >> true velocity

Nodal seismometer beamforming



Nodal seismometer beamforming

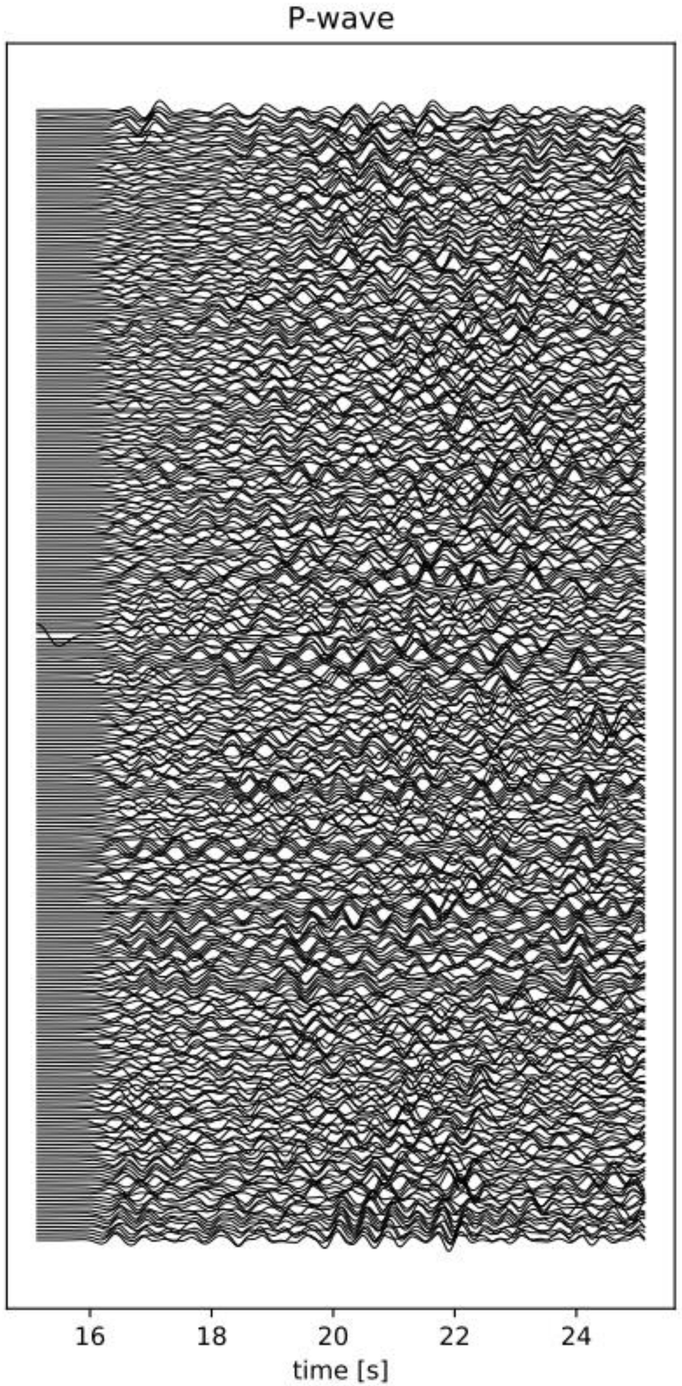




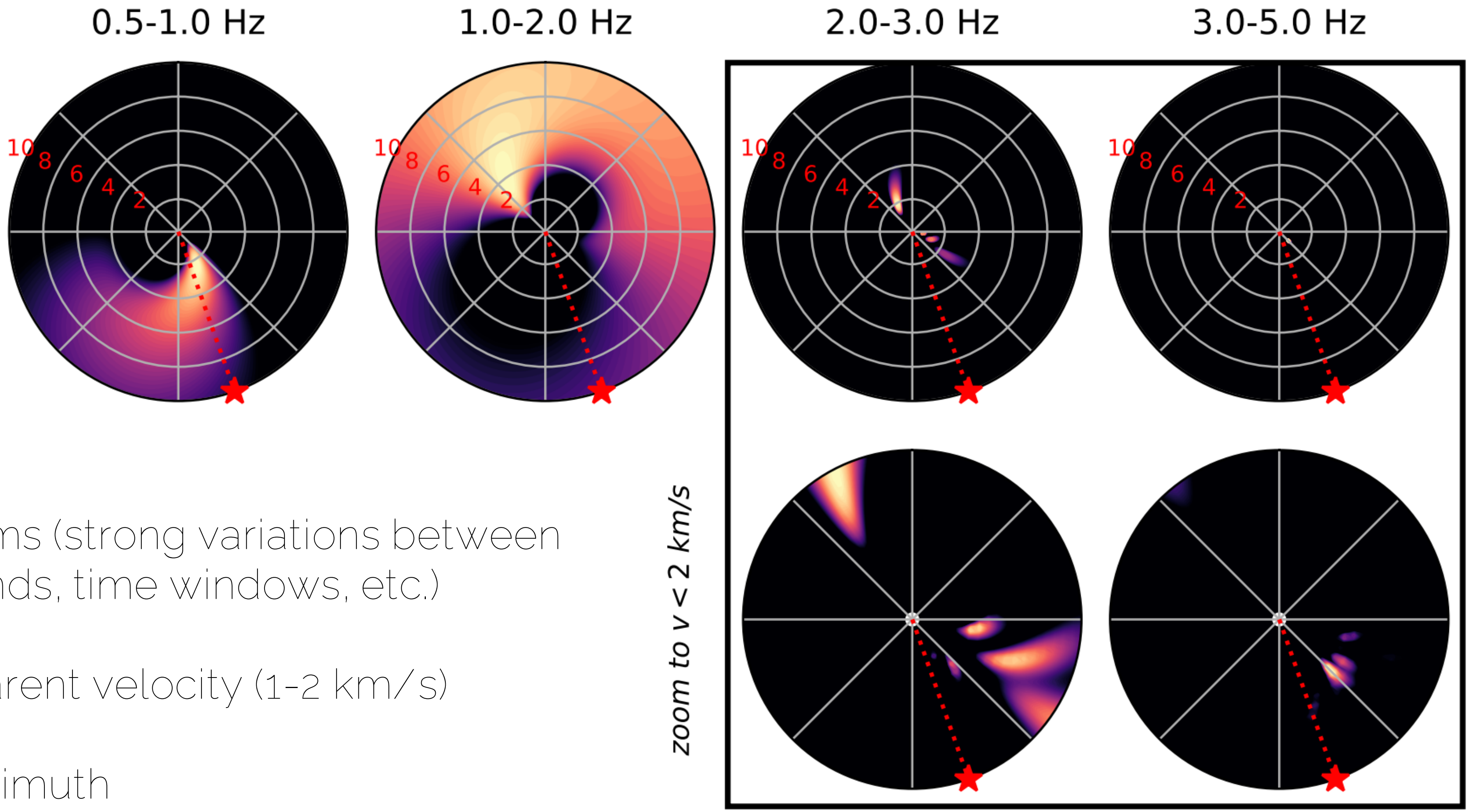
Apparent wave speed: 5 km/s   Back-azimuth: SSE

DAS beamforming

- Poor waveform coherence P- and S-phases
- Some local waveform coherence in individual segments, but not at array-scale
- Good SNR ≠ good coherence



DAS beamforming



Unstable beams (strong variations between frequency bands, time windows, etc.)

Very low apparent velocity (1-2 km/s)

Ambiguous azimuth

DAS vs. nodal array beamforming

- DAS array beamforming gives very different results than for the nodal array beamforming. Why?
- If the signal sources sensed by the DAS array are real, then what do we measure? (*what's that wiggle?*)

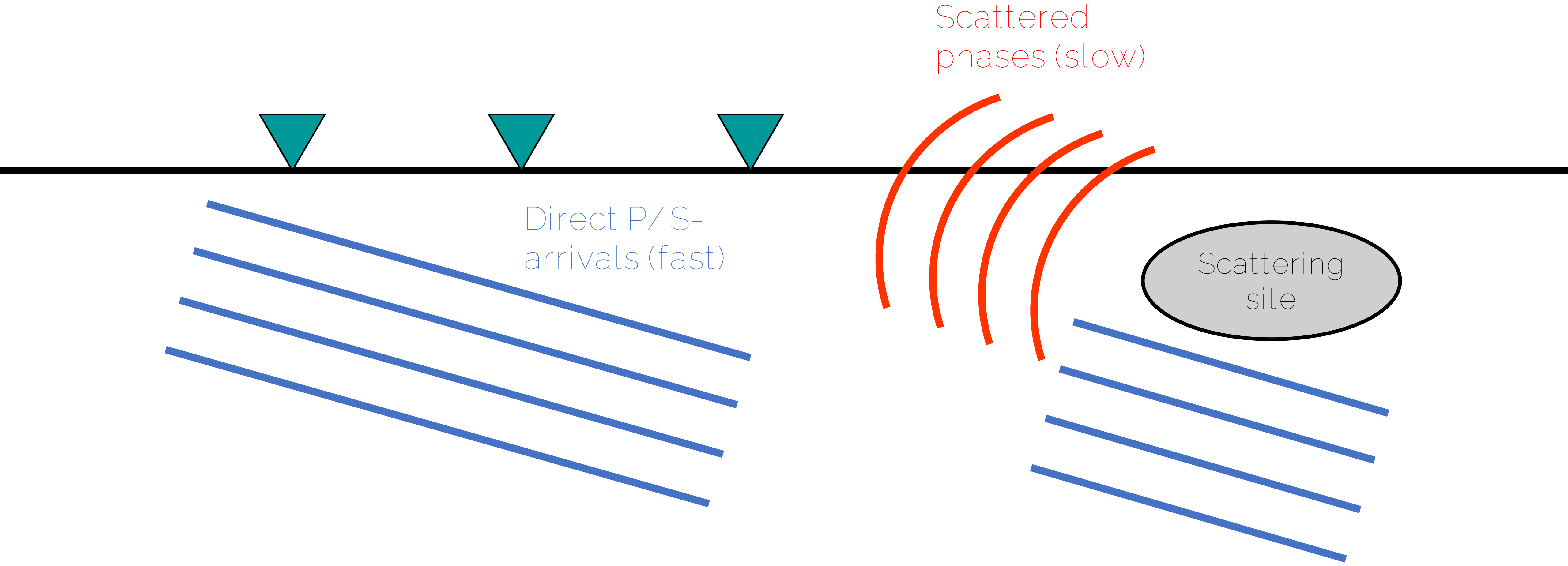
DAS slowness sensitivity

- Strain amplitudes are inversely proportional to phase velocity:

$$\varepsilon \equiv \frac{\partial u}{\partial x} = \pm \frac{\partial t}{\partial x}\frac{\partial u}{\partial t} = \pm \frac{1}{c}\dot{u}$$

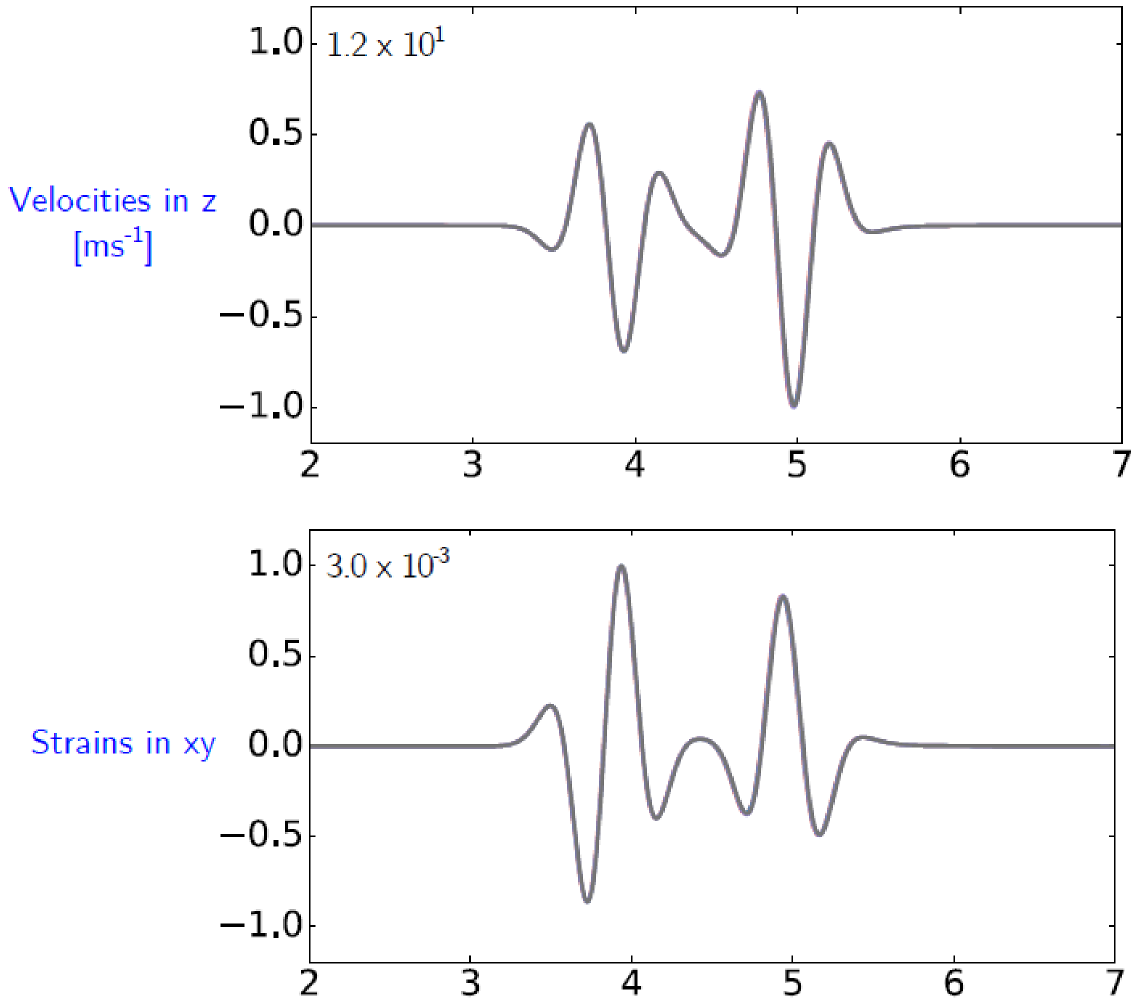
- Only horizontal components of strain are measured: highest signal amplitudes for <u>apparently</u> slow phases (e.g. shallow sources)

DAS slowness sensitivity

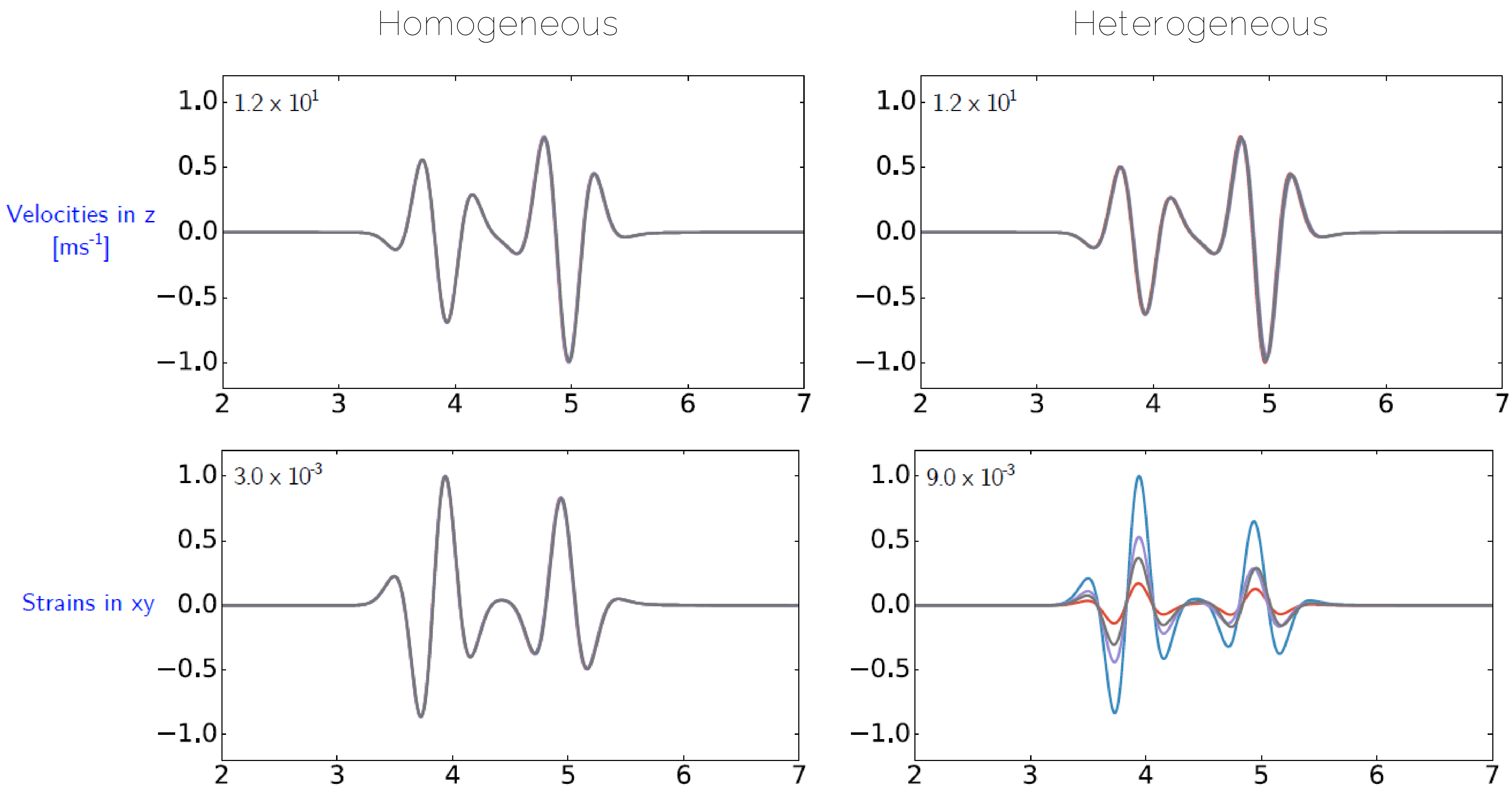


Phase velocity heterogeneities (Singh et al., 2020)

Homogeneous

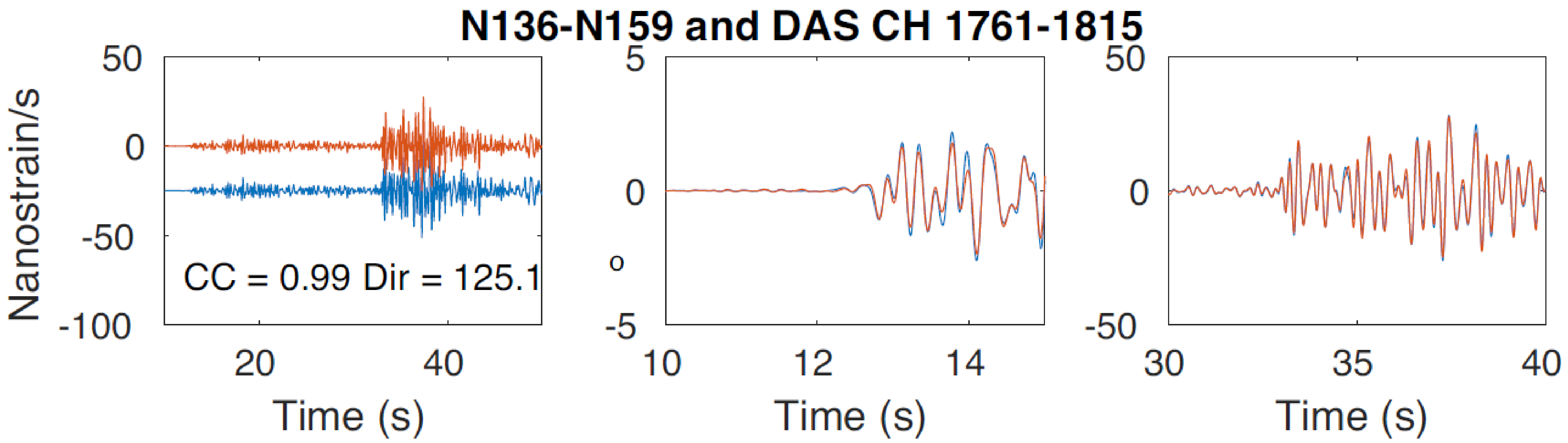


Phase velocity heterogeneities (Singh et al., 2020)



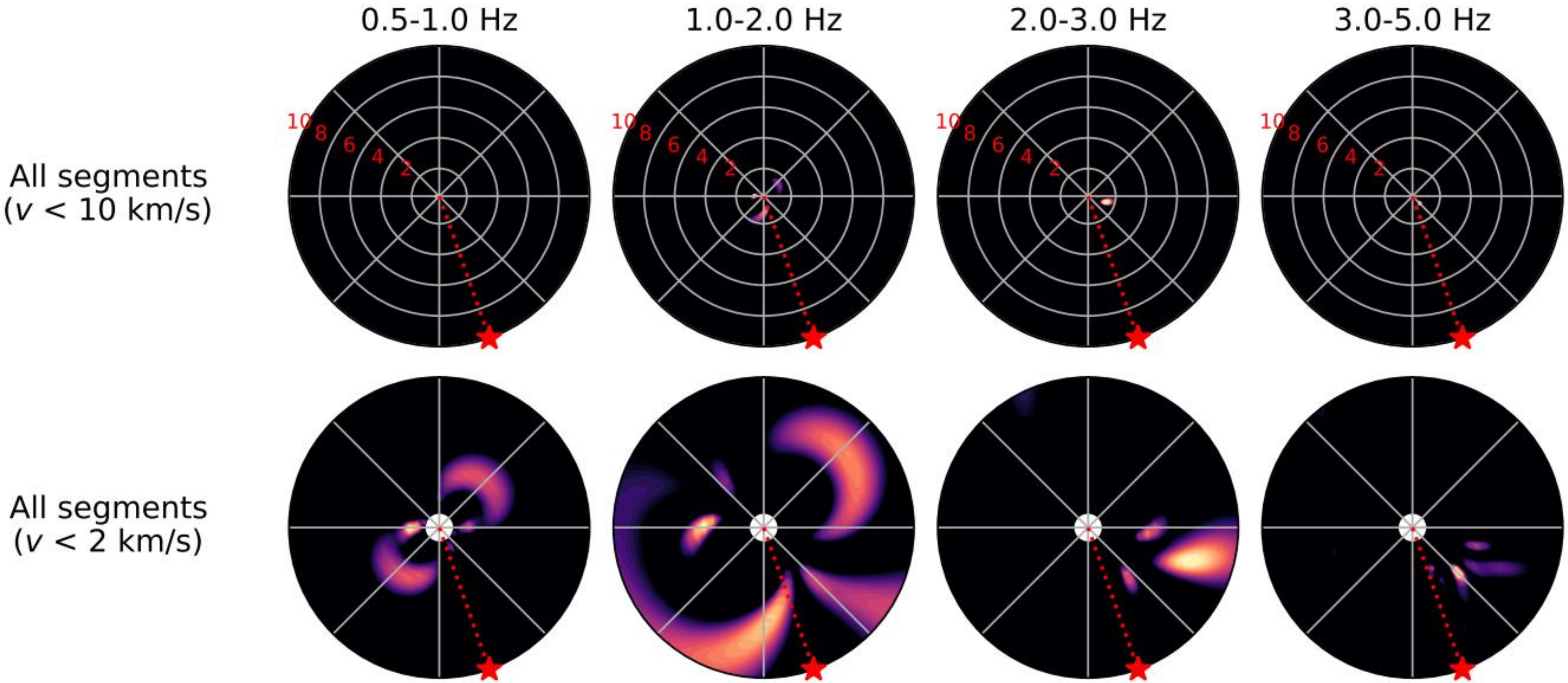
Testing hetero-sensitivity

- Wang et al. (2018): DAS waveforms can be reproduced wiggle-by-wiggle with a finite-difference stencil
- Take difference between particle velocity waveforms, divide by distance -> average strain rate between nodes



Wang et al. (2018)

Virtual DAS beamforming



Solution: integrate DAS data

- Beamforming of particle velocities: excellent results
- Beamforming of strain rates: poor results
- Strain rate can be computed from particle velocities -> can we go the other way around?
- Experiment: integrating DAS strain rates along the fibre

$$\dot{u}(x_0 + L) = \dot{u}(x_0) + \int_{x_0}^{x_0+L} \dot{\varepsilon}(x')\mathrm{d}x' = \dot{u}(x_0) + L\dot{\varepsilon}_{DAS}$$

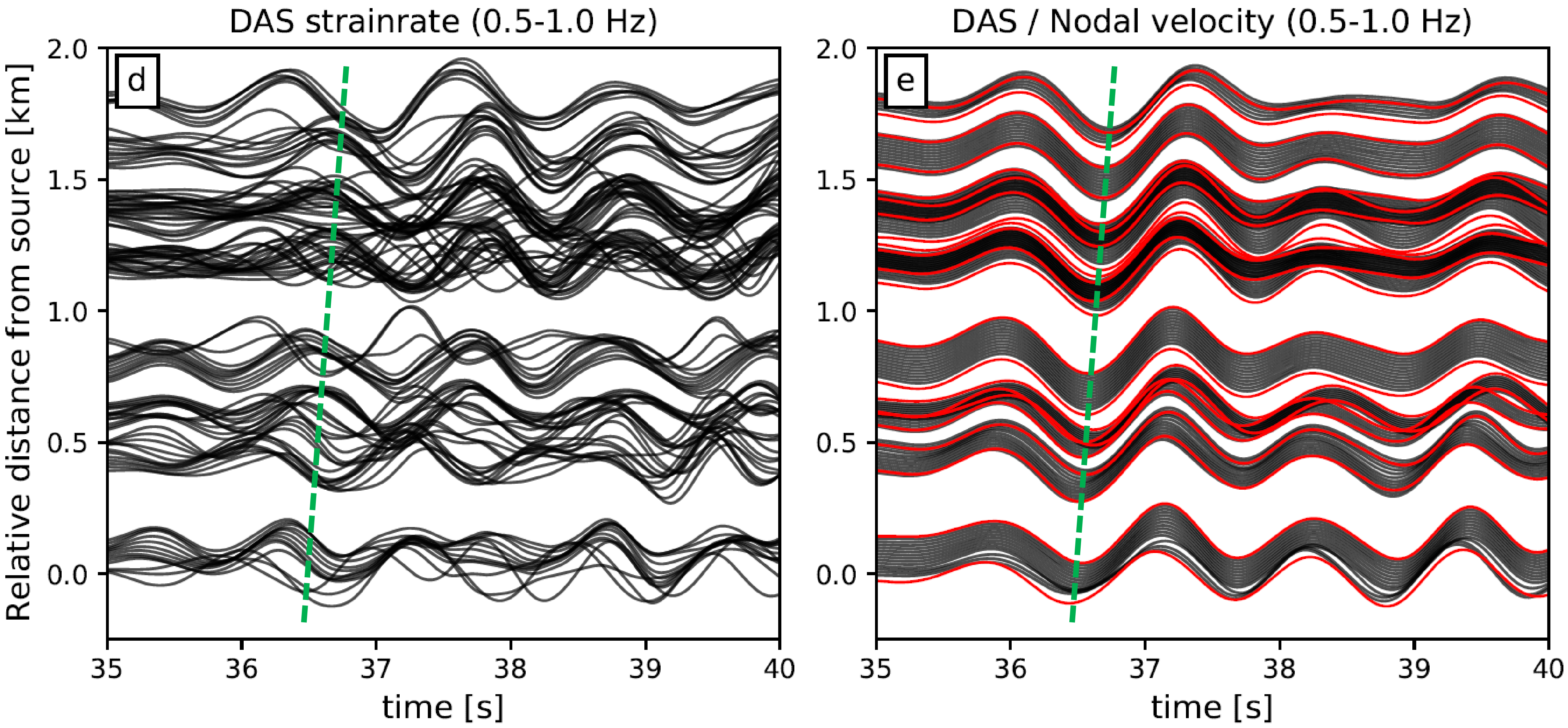
Solution: integrate DAS data

- For n DAS channels:

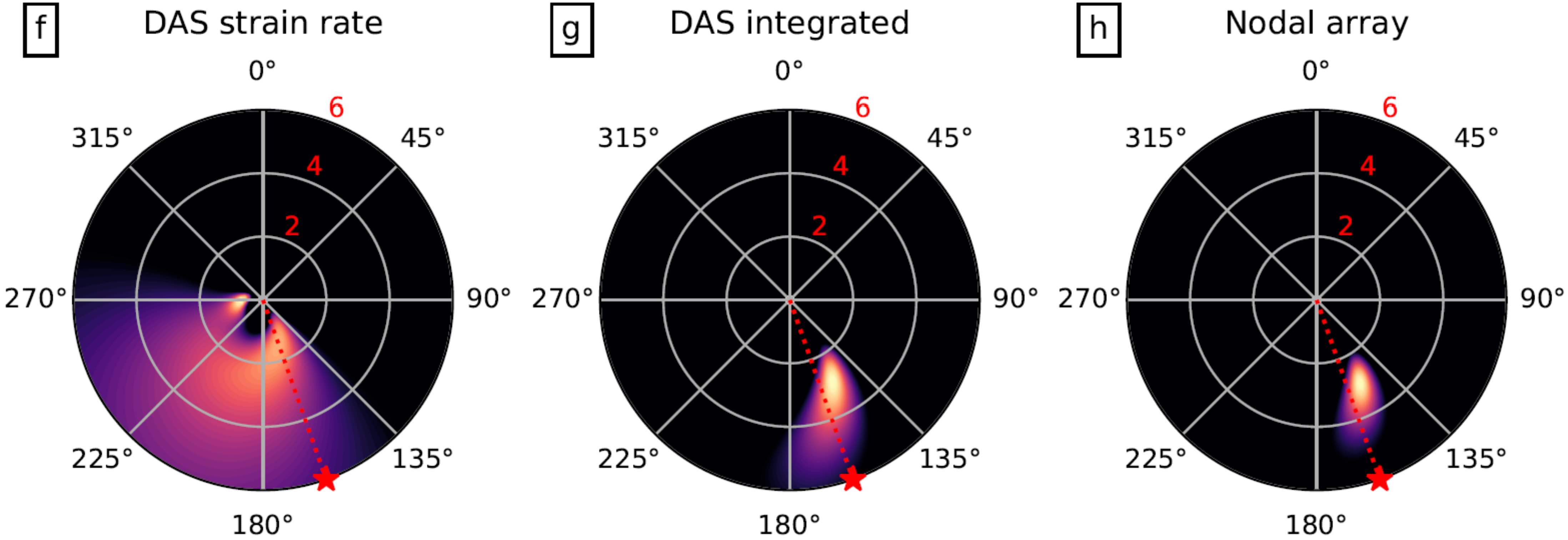
$$\dot{u}(x_0 + nL) = \dot{u}(x_0) + L \sum_{i=1}^{n} \dot{\varepsilon}_{DAS,i}$$

Requirements:

1. Straight DAS segments
2. Uniform coupling
3. One seismometer per segment

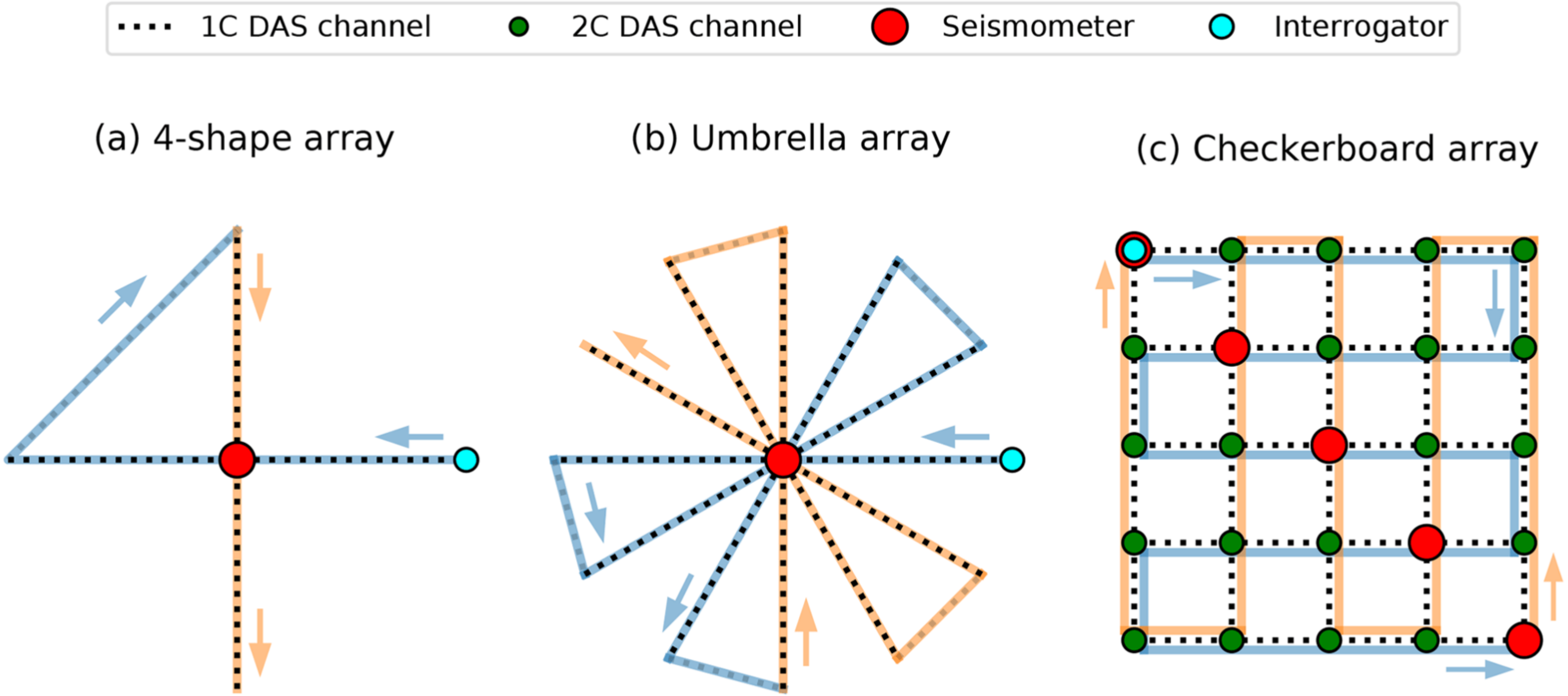


DAS strainrate (0.5-1.0 Hz)
DAS / Nodal velocity (0.5-1.0 Hz)
d
e
Relative distance from source [km]
2.0
1.5
1.0
0.5
0.0
35
36
37
38
39
40
time [s]



f
DAS strain rate
g
DAS integrated
h
Nodal array
0°
45°
90°
135°
180°
225°
270°
315°
2
4
6

Hybrid array design



Take-home messages

1. The measurement principle of DAS (strain/strain rate) highlights local scattering and is very sensitive to heterogeneities
2. Strain (rate) measurements are less coherent, and so DAS is not a good substitute for conventional seismometer arrays in terms of beamforming, template matching, etc.
3. By integrating the DAS strain (rate) using a seismometer as a reference, all of the issues can be resolved
4. To get the best of both worlds, we need to deploy hybrid seismometer-DAS arrays

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Data & Code

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Data & code available at *FigShare*:

https://doi.org/10.6084/m9.figshare.12899288