Mapping the subglacial hydrology network with a dense seismic array

A multi-method approach.

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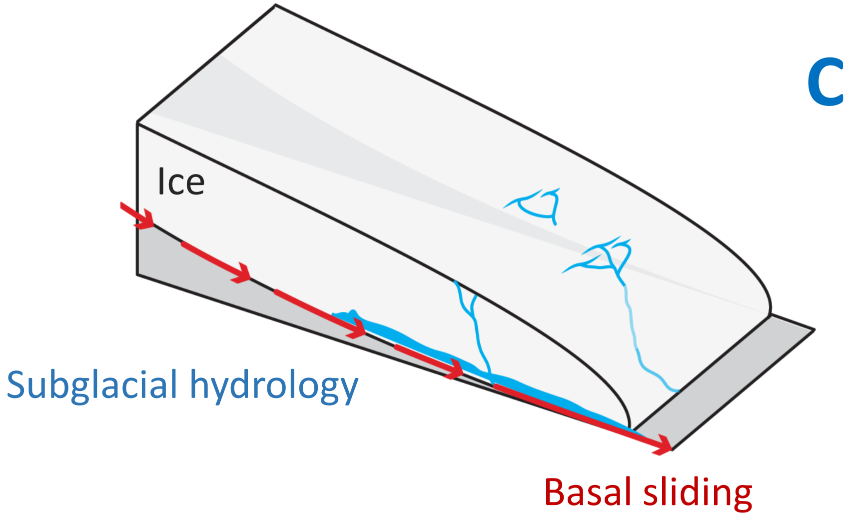
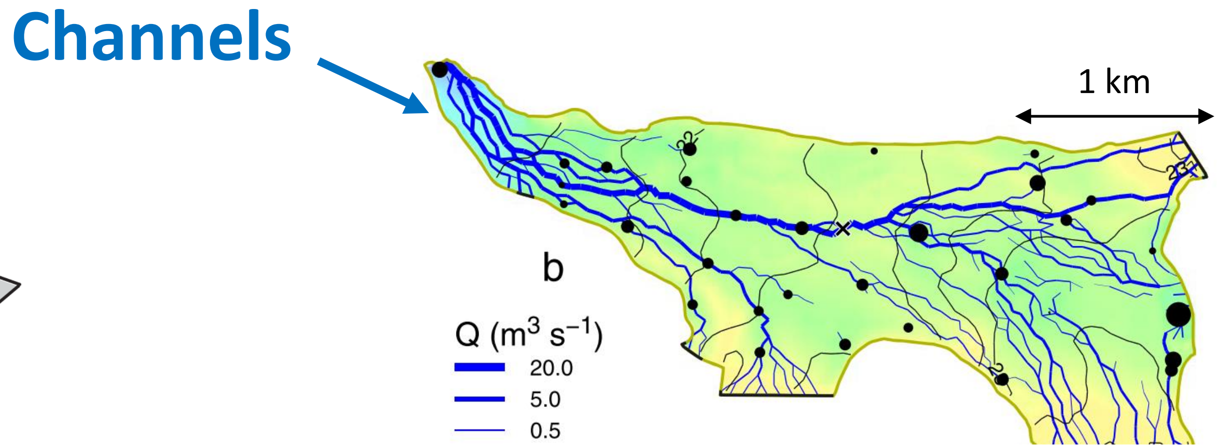
About subglacial hydrology

- <u>Subglacial water conditions</u> :
  - Control sliding by lubrication



- <u>Complex drainage system</u>:
  - **Channels** : spatially discrete
  - Cavities : spatially distributed

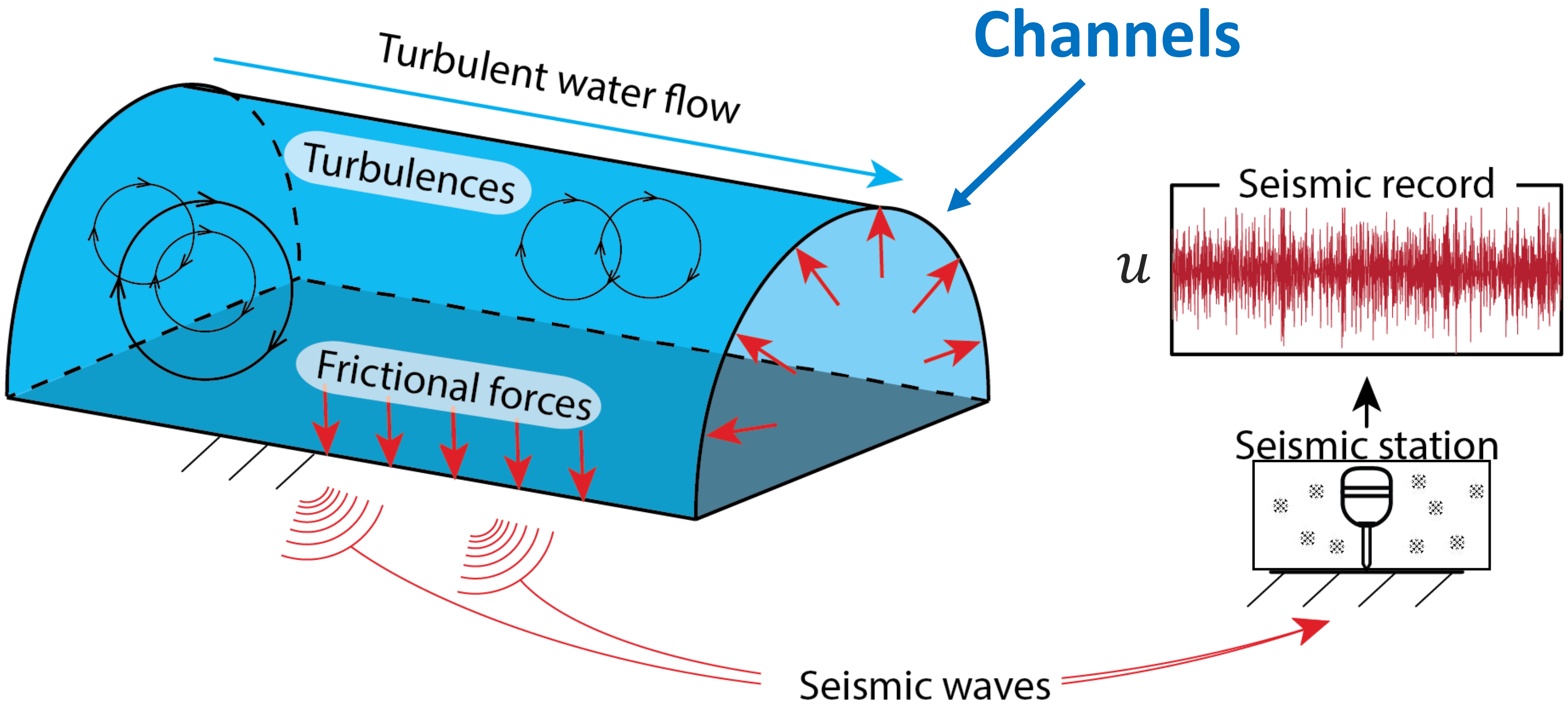


Subglacial drainage system as modelled by Werder et al., 2013

→ Complex physical process but **limited observations**

Subglacial channel flow induced noise

- Subglacial turbulent water flow generates **continuous seismic noise** (~ [2-20] Hz)



Ground displacement

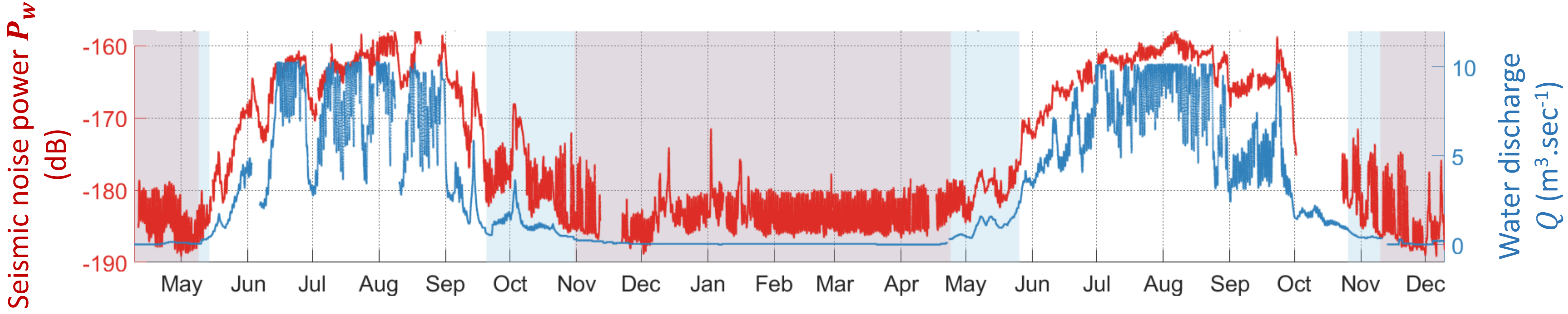
$$u(t) = Ae^{i\omega t}$$

Amplitude Phase

(Bartholomaus et al., 2015; Gimbert et al.,2016;)

Seismic power in the $[3 - 10]\ Hz$ band

- Good sensitivity to subglacial water discharge:
  - Continuous signal over melt season



(Nanni et al., 2019)

(See also Bartholomaus et al., 2015; Röösli et al., 2014; Lindner et al.,2019;)

→ Lacking **spatial** and **phase** information

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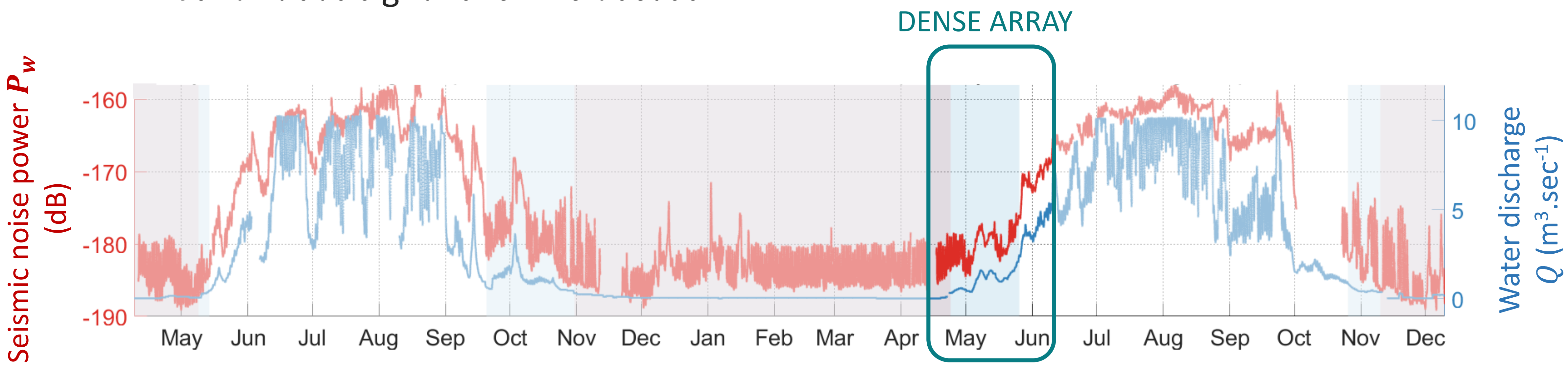

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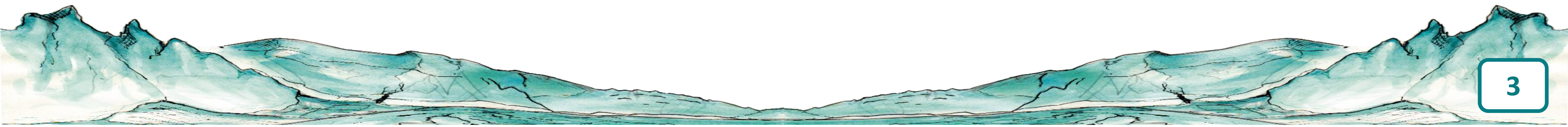
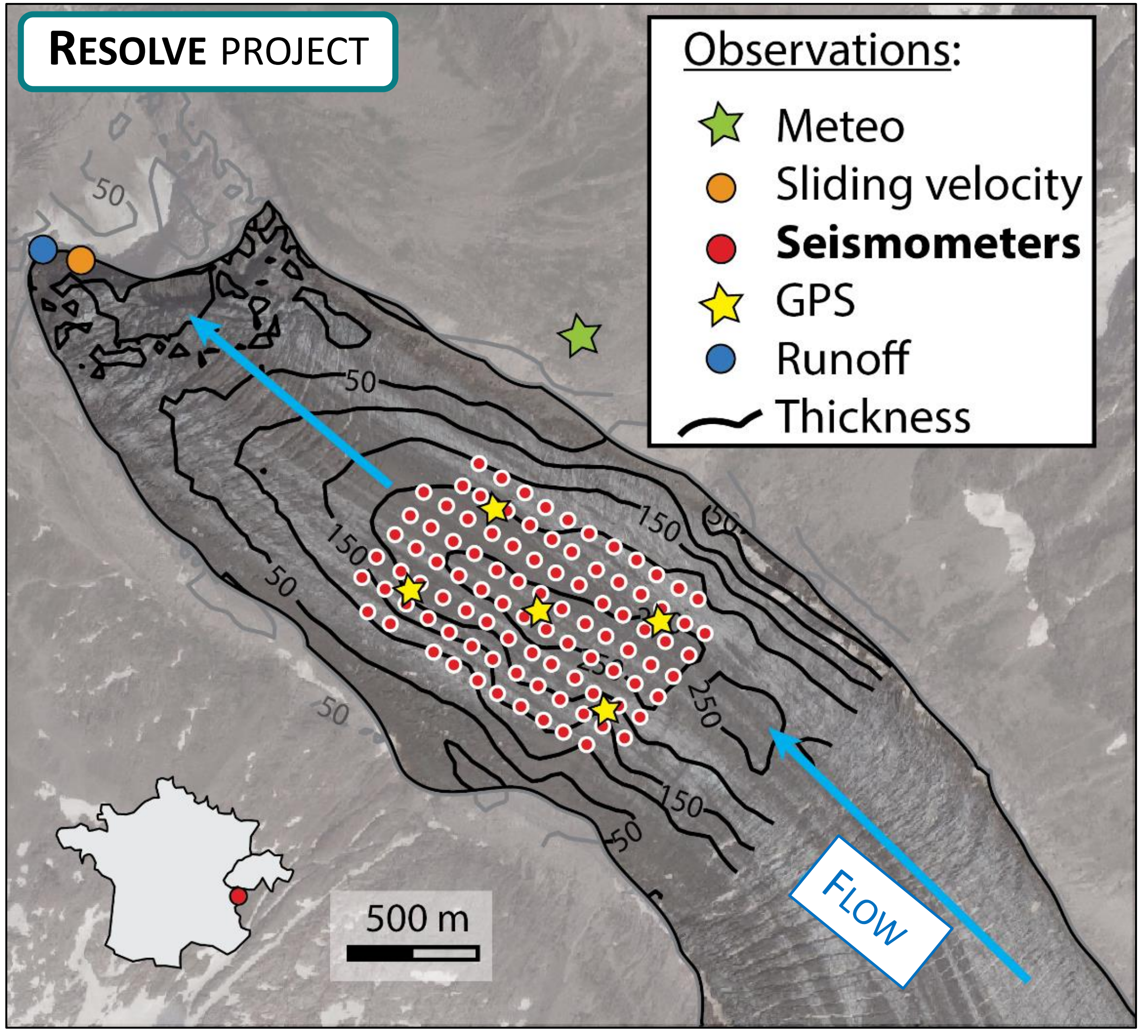
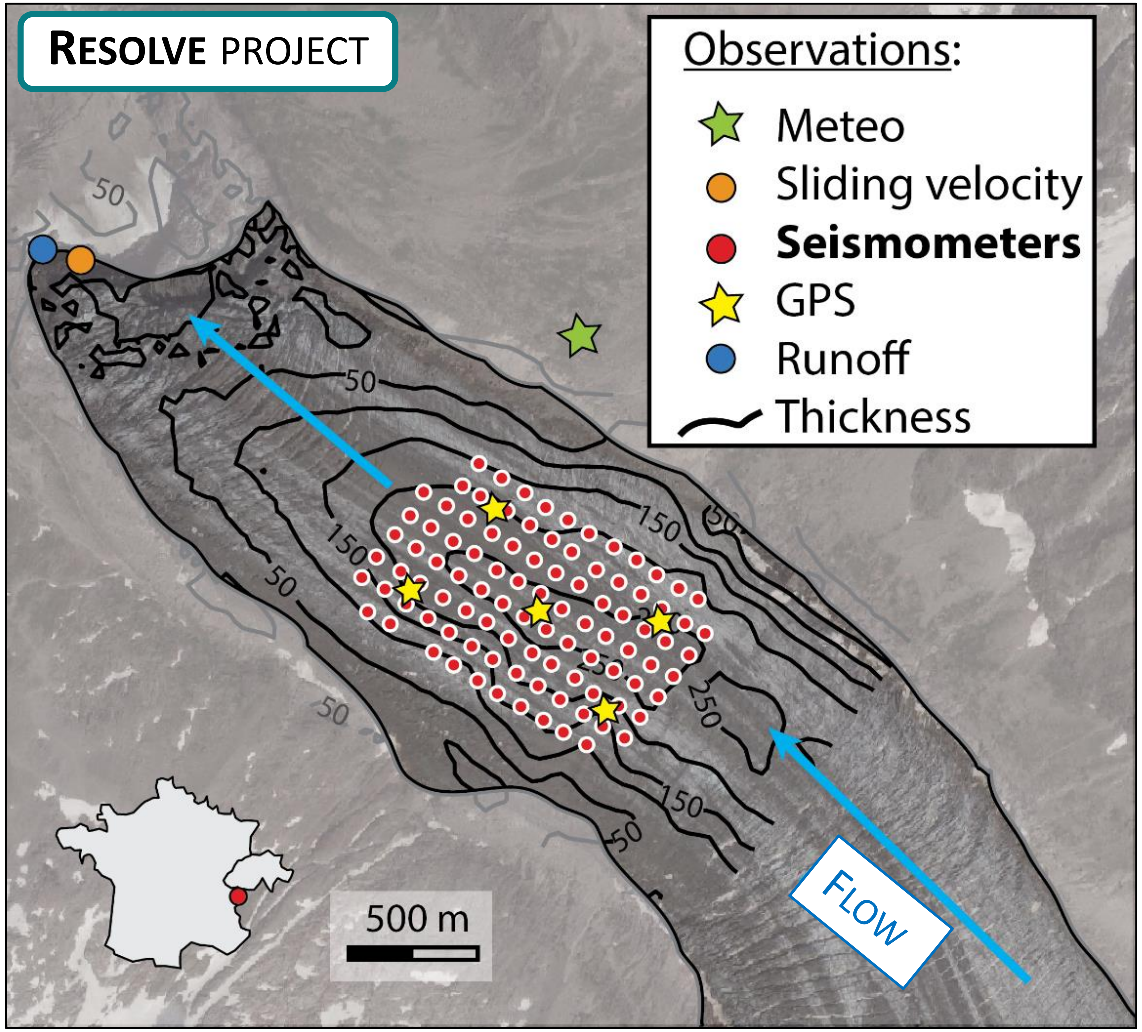


Challenge: locate continuous noise source(s)



- 1 month when channels develop
- 100 seismometers

Challenge: locate continuous noise source(s)



- Typical frequencies : $[3 - 20]Hz$
- Typical wavelengths : $\lambda \sim [500 \ - \ 75]\ m$

- Inter-stations distance: $40\ m$
- Glacier thickness: $\sim 250\ m$

→ Sub-wavelength array

→ Near-field propagation

UNIQUE SETUP !

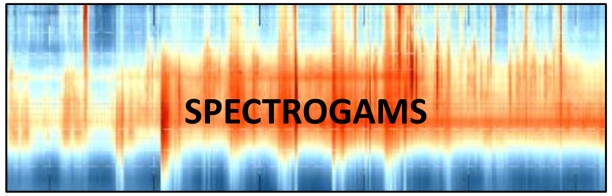
Methods: locate continuous noise source(s)

$$u(t) = Ae^{i\omega t}$$

Amplitude — Phase

1 Amplitude analysis

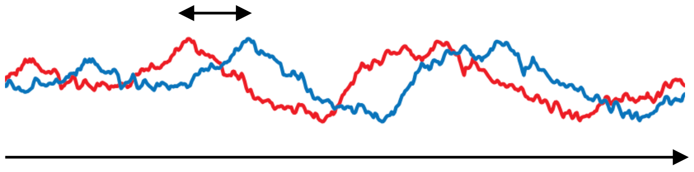
~ energy differences



- Seismic power P_w spatial variability:
  - Source surface signature
  - **Dominant** sources in time

2 Phase analysis

~ time delays



- Phase difference averaging (> 1 h) prior to locating:
  - Stack phase differences: keep **coherent** signal

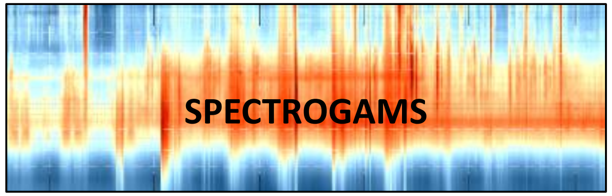
Methods: locate continuous noise source(s)

$$u(t) = Ae^{i\omega t}$$

Amplitude — Phase

1 **Amplitude analysis**

~ energy differences



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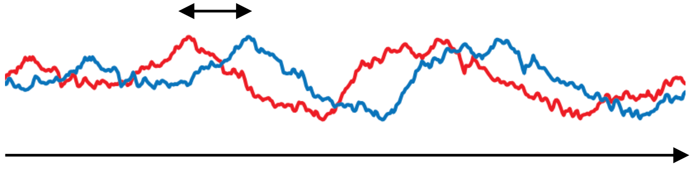
Phase analysis 2

~ time delays



- ~~Use long-term period (> 1 h) :~~
  - ~~Stack phase differences: keep **coherent** signal~~

NOT SUITABLE

Methods: locate continuous noise source(s)

$$u(t) = Ae^{i\omega t}$$

Amplitude — Phase

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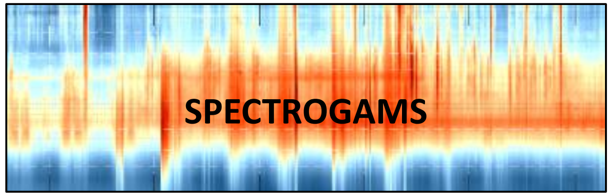

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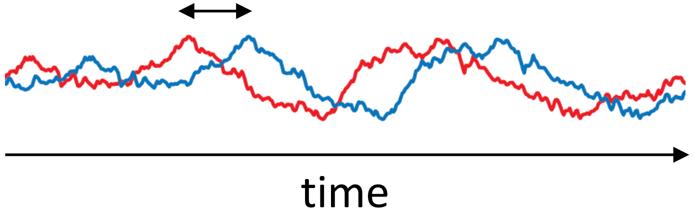
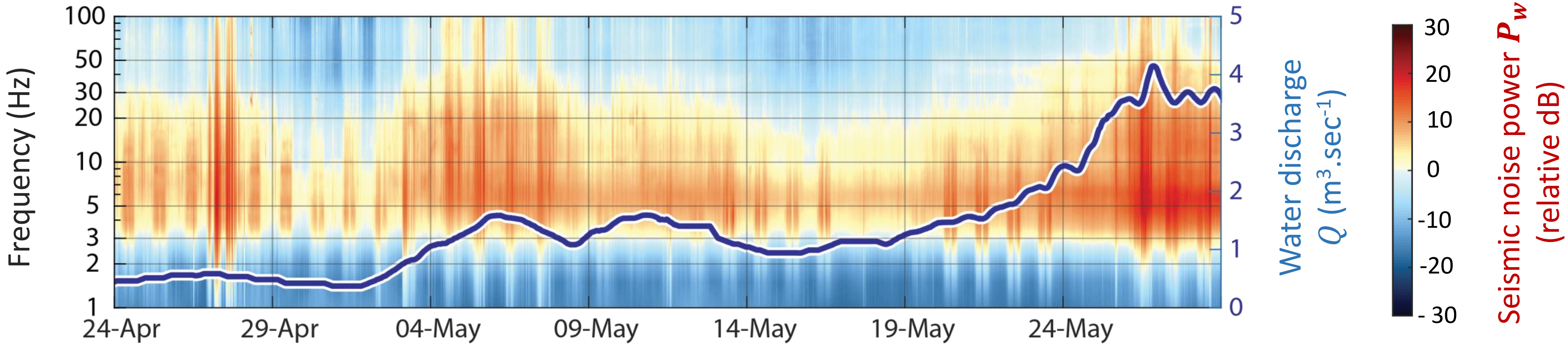


- ~~Use long-term period (> 1 h) :~~ NOT SUITABLE
  - ~~Stack phase differences: keep **coherent** signal~~
- Perform location analysis at short timescales (1 sec), and then look at location density maps :
  (e.g. Corciulo et al., 2012)
  - Phase coherence = **individual** source location

$u(t) = \boldsymbol{A} e^{i\omega t}$

Median amplitude evolution

- High P_w in the $[3 - 20]\ Hz$ frequency range concomitant with increasing Q



→ Amplitude dominated by turbulent water flow induced noise

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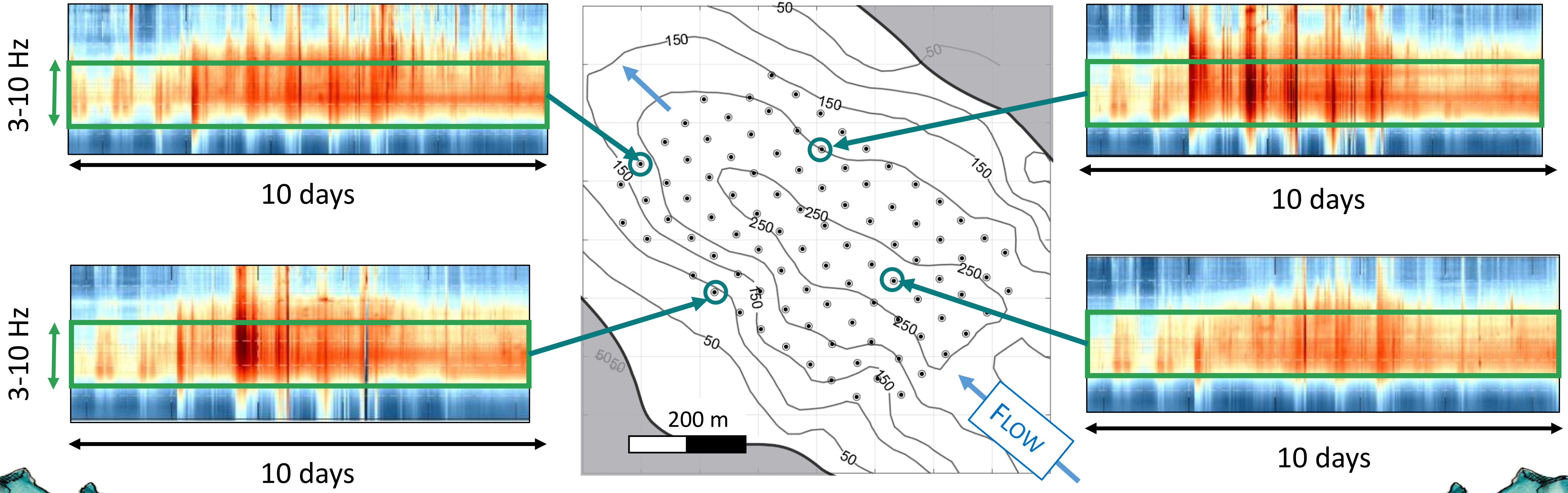
Amplitude analysis

- Compute P_w spatial anomaly **over 2 hours**

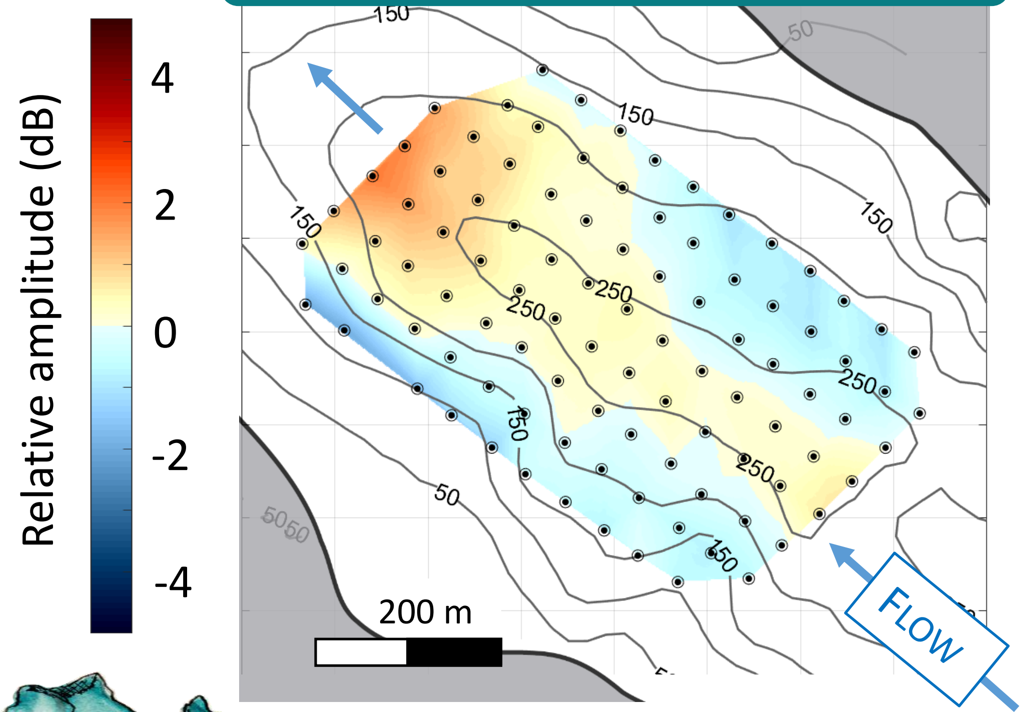


$u(t) = \boldsymbol{A} e^{i\omega t}$

Amplitude spatial variations

- Compute 2 hour-P_w spatial anomaly: stack over the whole period **whole period**

Median anomaly over 30 days

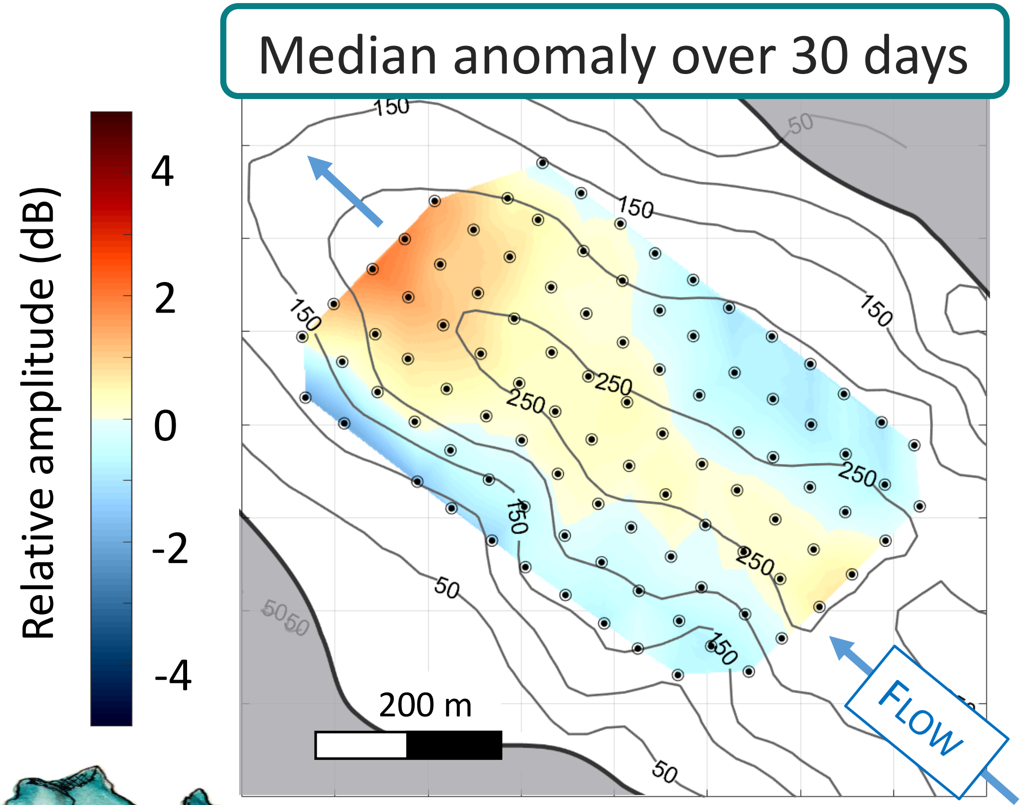


- Higher *power* downstream
- Higher *power* in the middle
- $\sim 100\ m$ variations

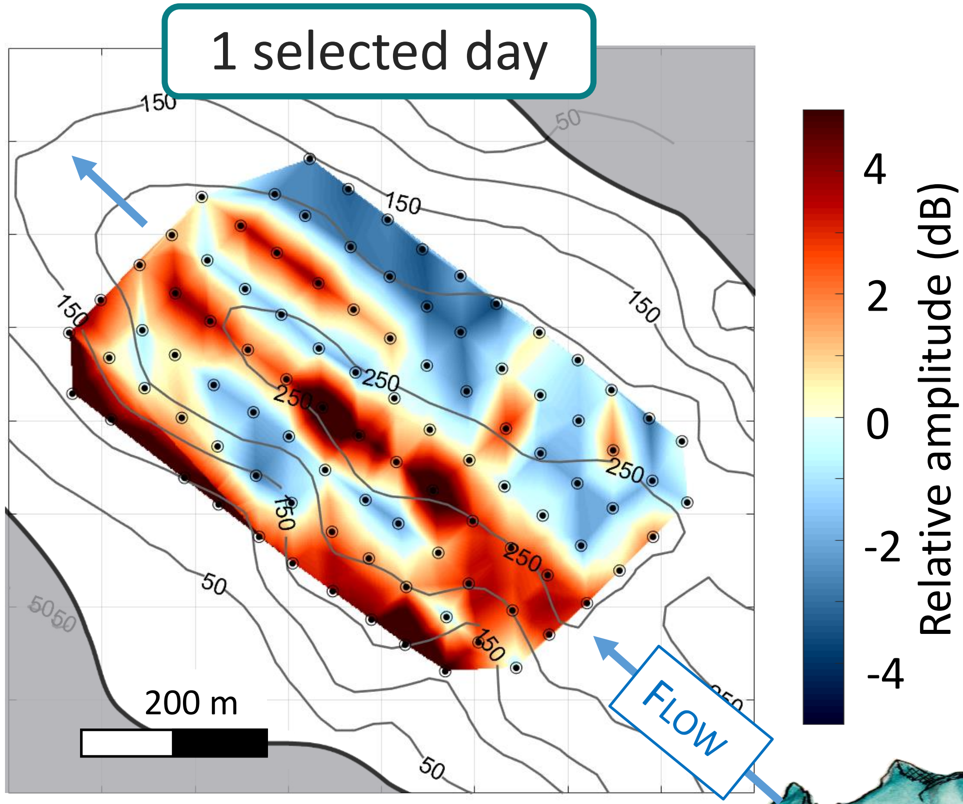
$u(t) = \boldsymbol{A}e^{i\omega t}$

Amplitude spatial variations

- Compute P_w spatial anomaly: stack over the **whole period / 1 day**



- Distinct pattern
- Strong heterogneity
- Source effect
- **Channels ?**



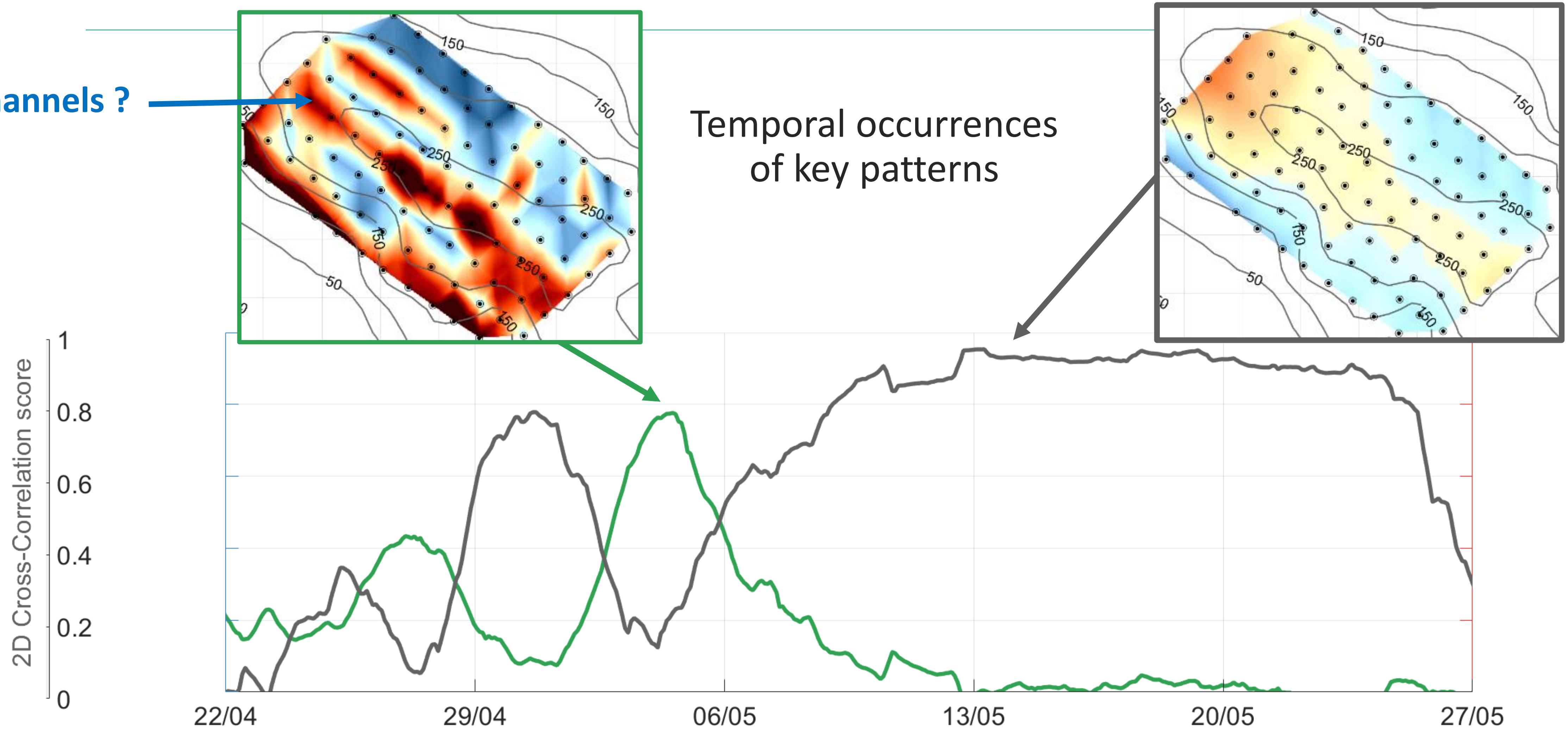
(Nanni et al., in prep.)

$u(t) = \boldsymbol{A}e^{i\omega t}$

Amplitude spatio-temporal variations

Channels ?

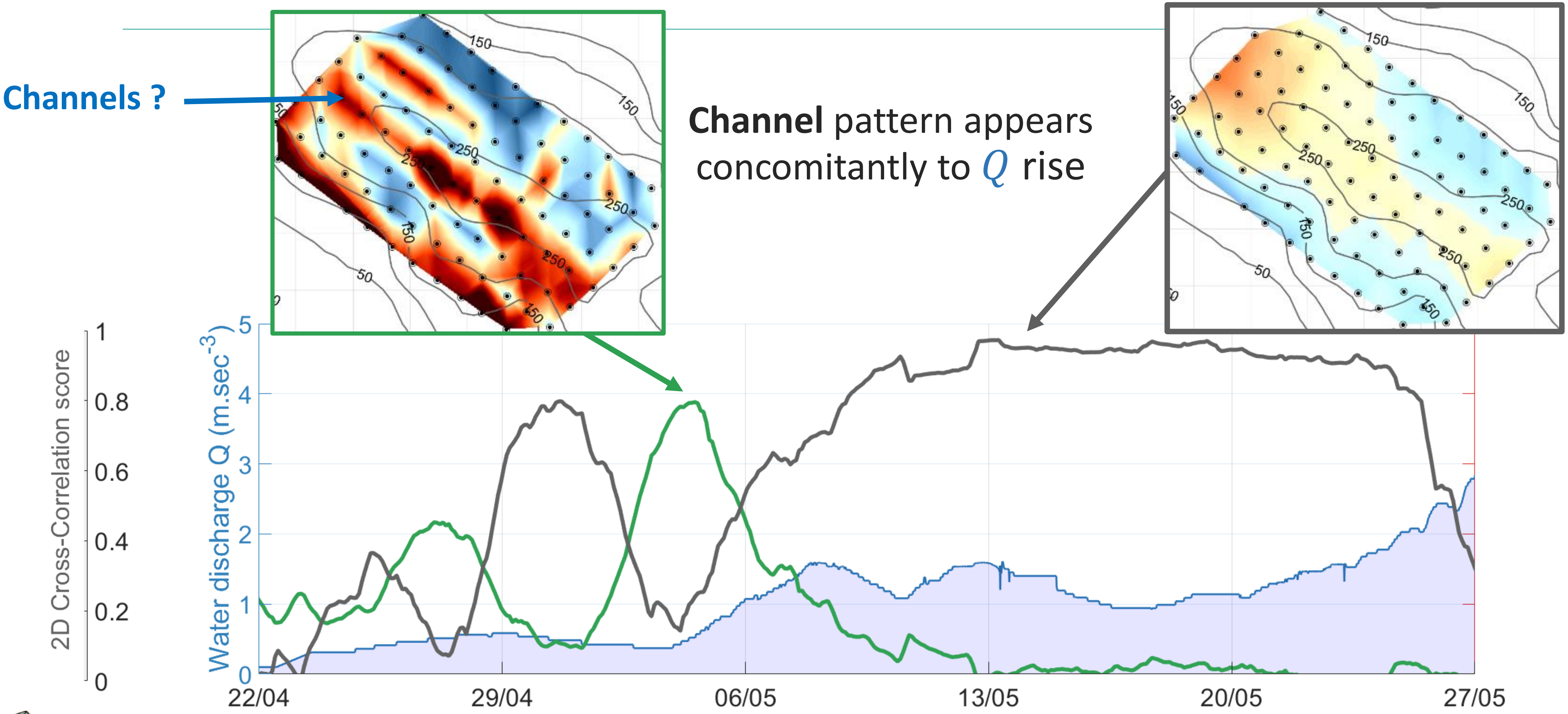
Temporal occurrences of key patterns



$u(t) = \boldsymbol{A}e^{i\omega t}$

#1 Capable to capture channels development

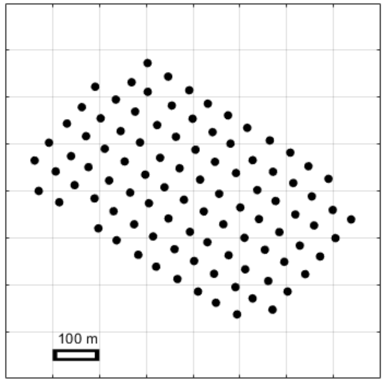
Channel pattern appears concomitantly to Q rise



$u(t) = Ae^{i\omega t}$

The beam former method

Source location

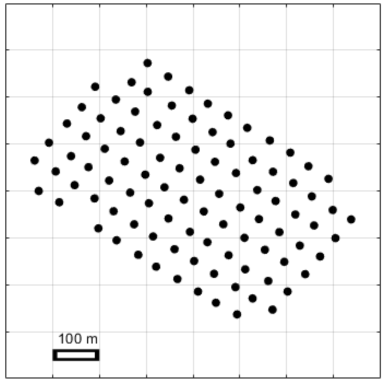


$u(t) = Ae^{i\omega t}$

The beam former method

- Assume a unique source over 1 second-signal
- Minimize misfit $|\mathrm{Phase}_{\mathrm{model}} - \mathrm{Phase}_{\mathrm{observed}}|$ (*gradient-based minimization*)

Source location



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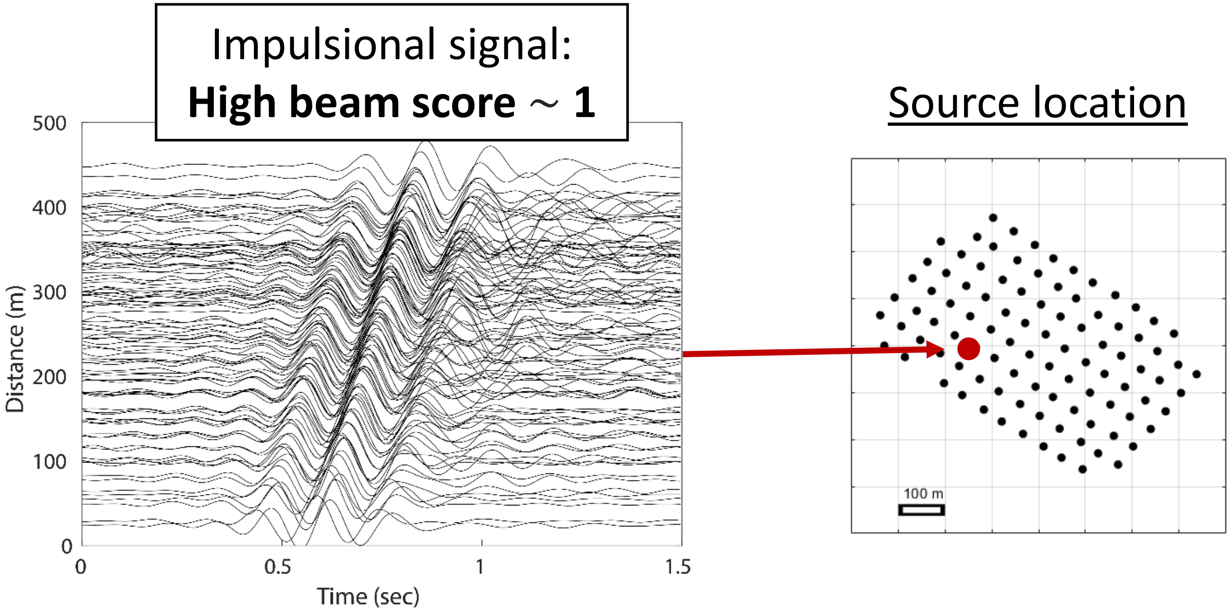
- Beam score $\propto$ phase coherency $\sim$ location accuracy



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The beam former method

- Assume a unique source over 1 second-signal
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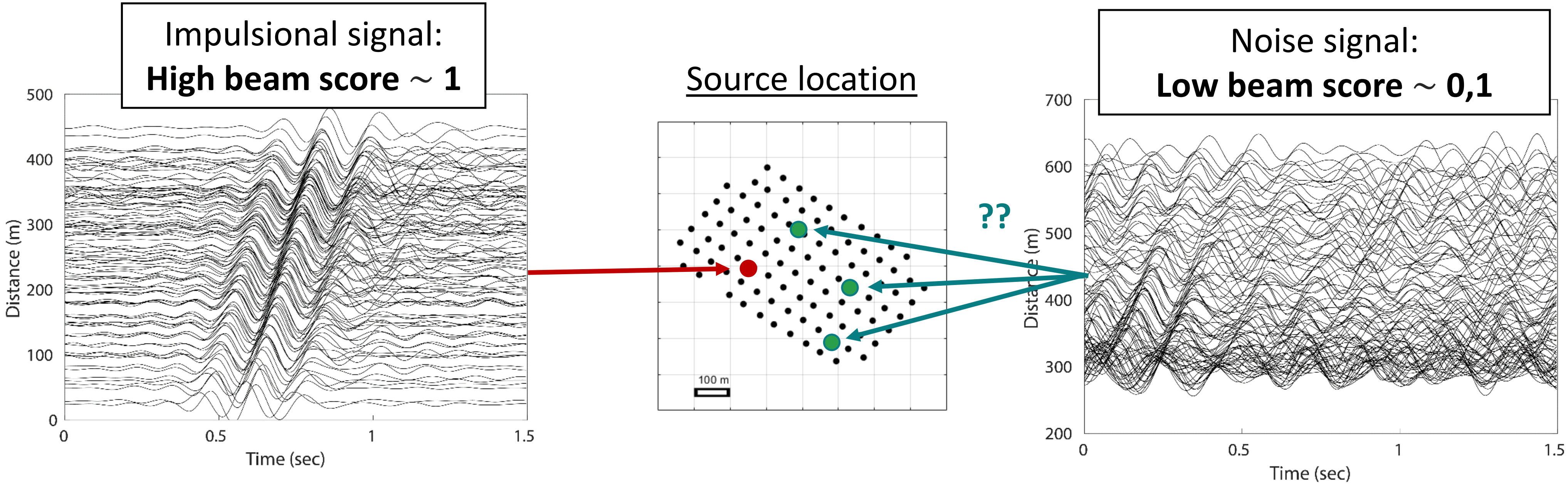
- Beam score $\propto$ phase coherence $\sim$ location accuracy

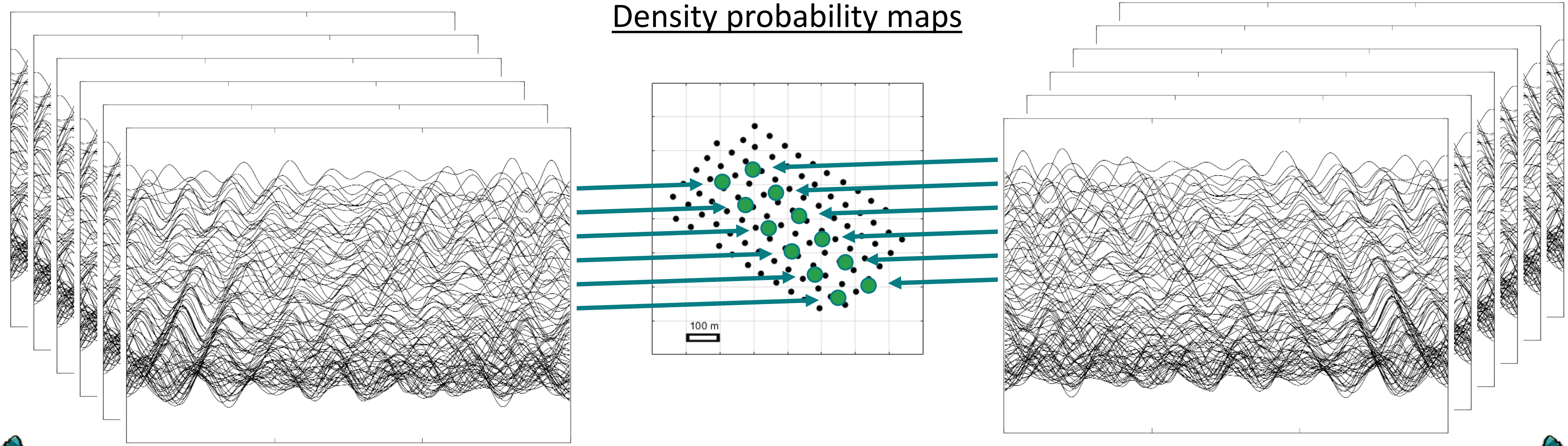


$u(t) = Ae^{i\omega t}$

Increasing location precision

- Subglacial water flow: **low beam** score (several sources are active simultaneously)
- We stack 1 second-location over long time periods (∼ days)

Density probability maps



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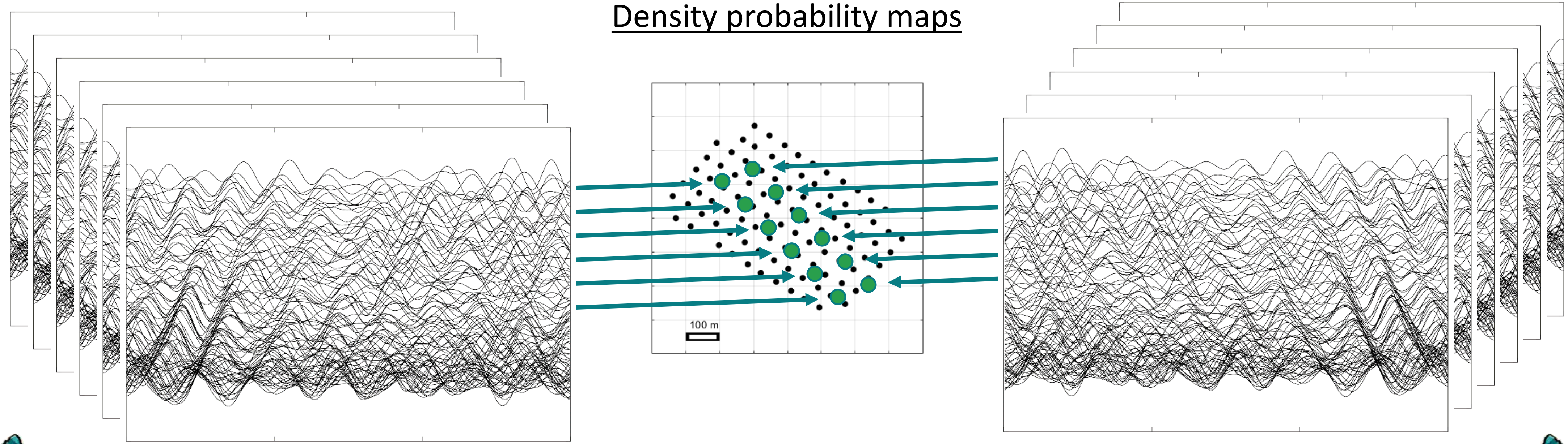

$u(t) = A\boldsymbol{e}^{\boldsymbol{i\omega t}}$

Increasing location precision

- Subglacial water flow: **low beam** score (noise)
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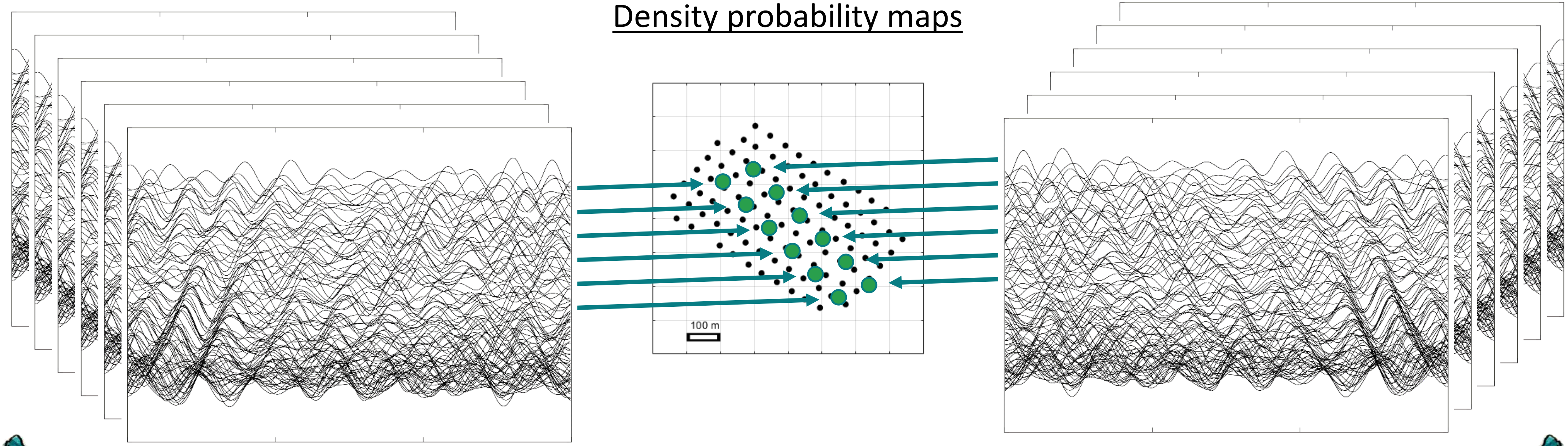
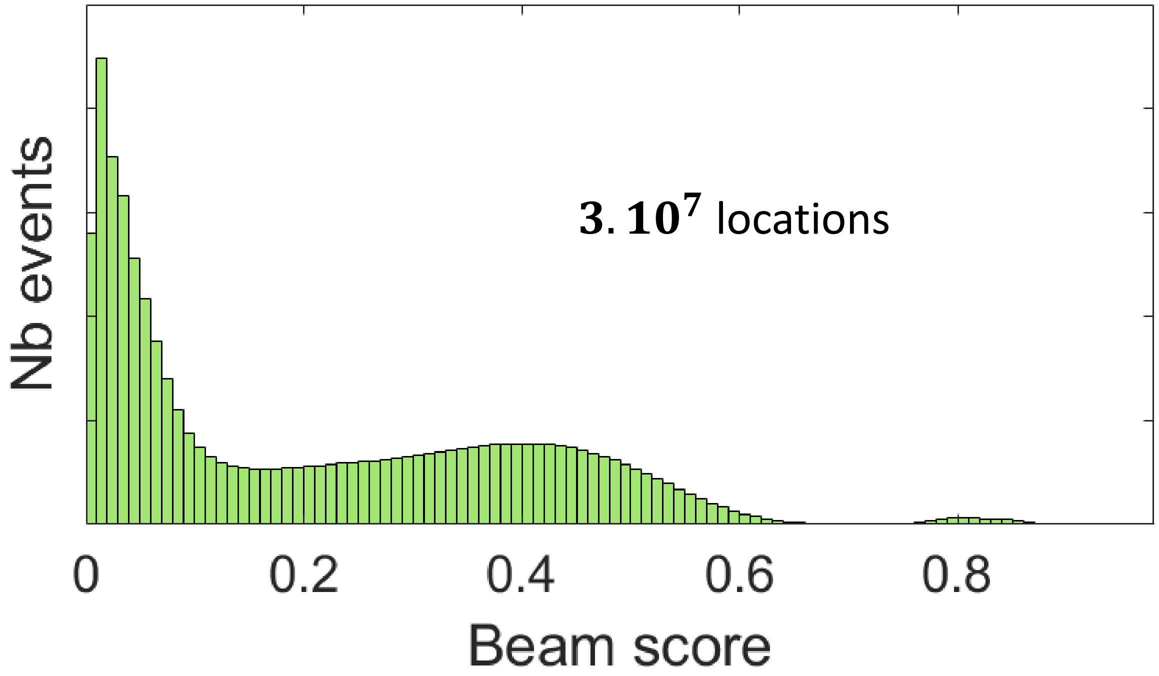


Beam score ranges over 10 days (5 Hz)

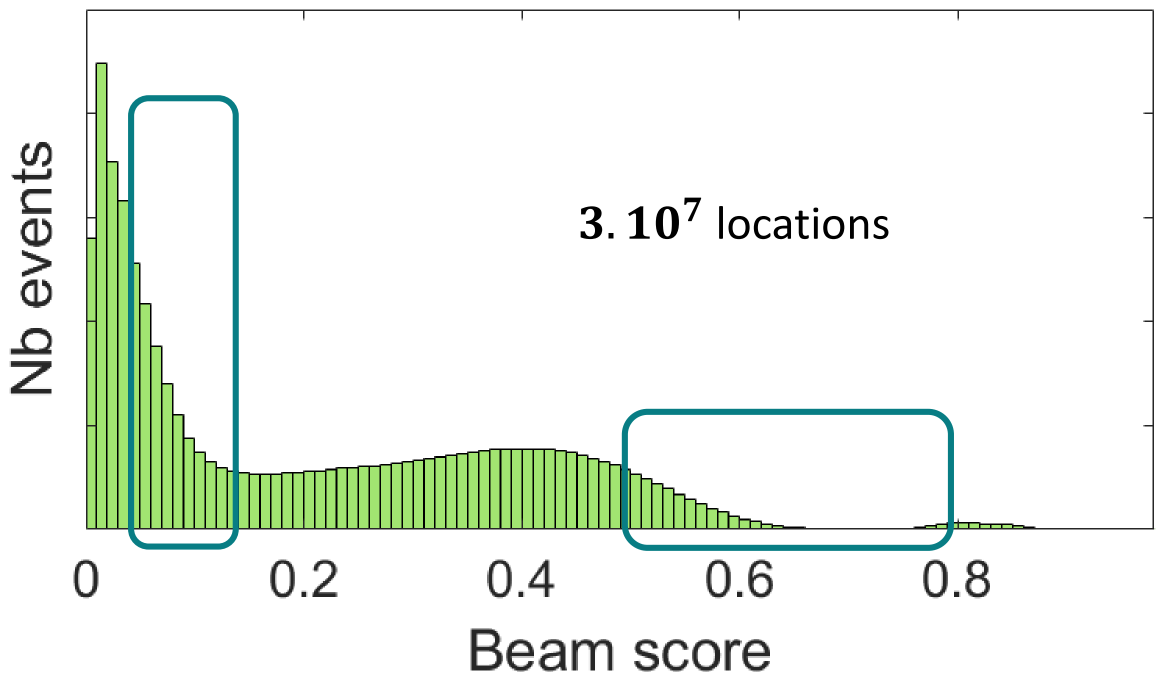
- Most location are associated with low beam scores ($< 0{,}2$)



$u(t) = Ae^{i\omega t}$

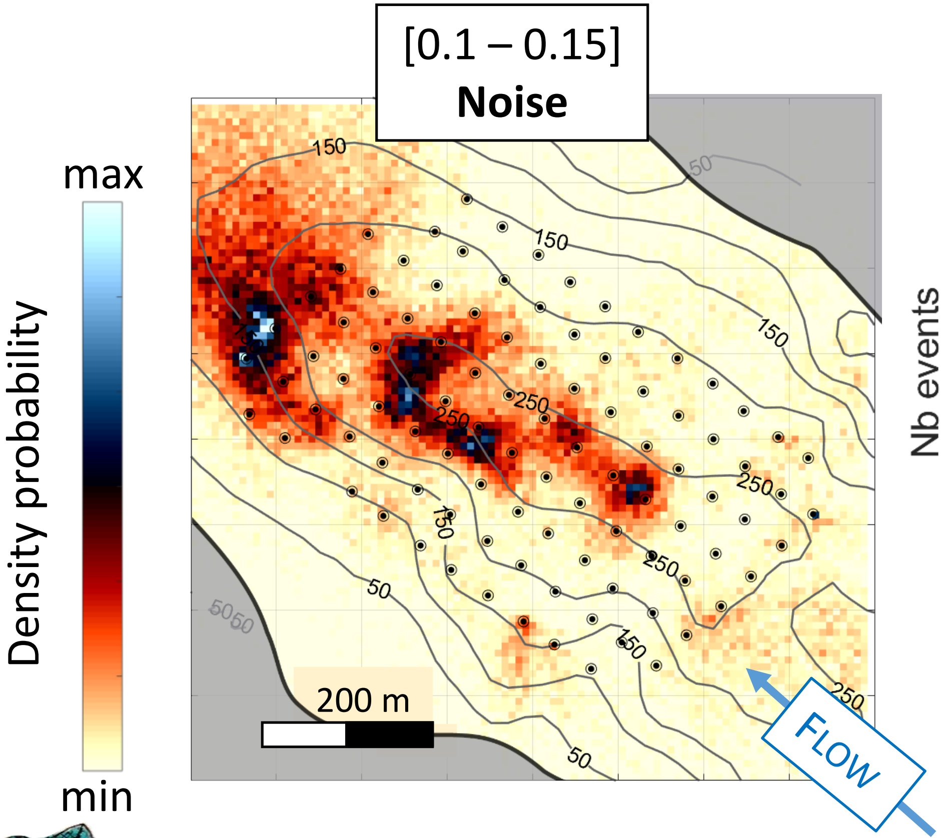
Beam score ranges over 10 days (5 Hz)

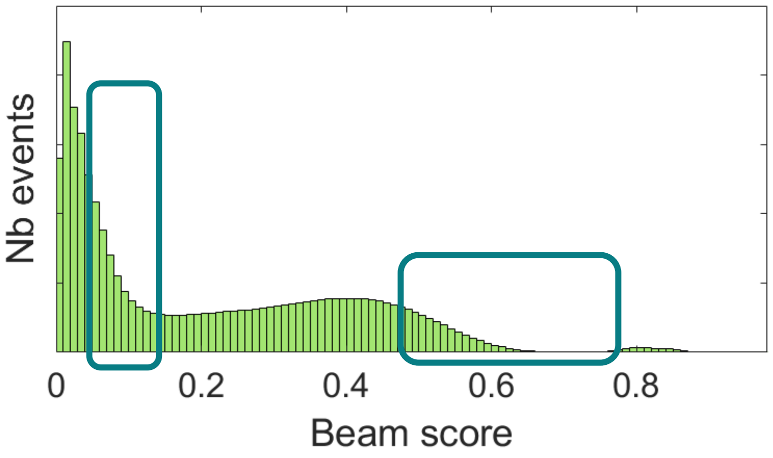
- Most location are associated with low beam scores ($<$ 0,2)
  - Select 2 beam score ranges
  - Select coherent phase velocities [$1400 - 2400\ m.sec^{-1}$] and depth

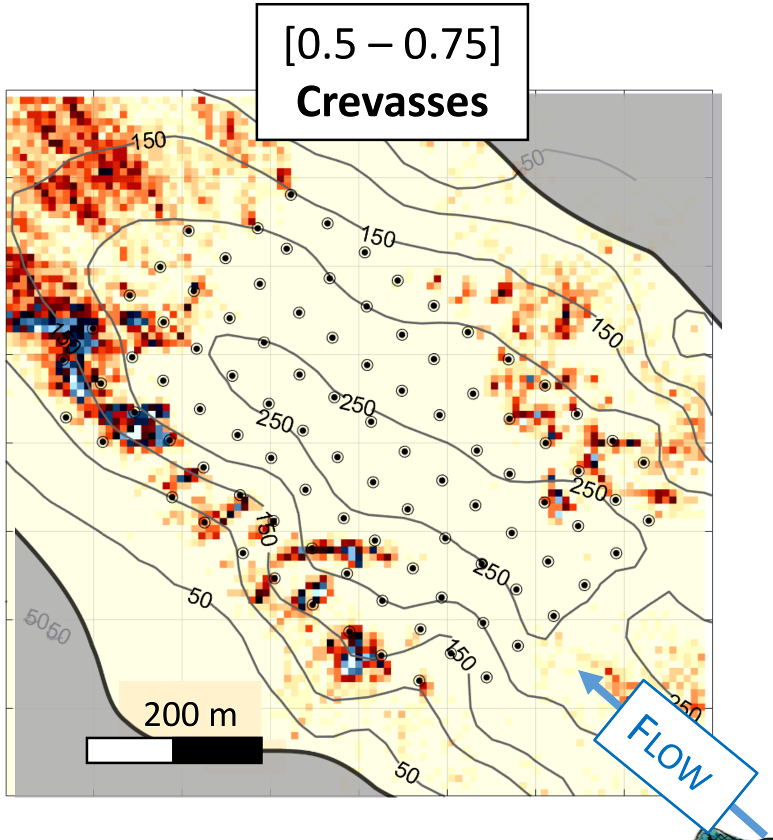


$u(t) = Ae^{i\omega t}$ Beam score ranges over 10 days $(5\ Hz)$

- Distincts features with coherent phase velocities $[1400 - 2400\ m.sec^{-1}]$ and depths







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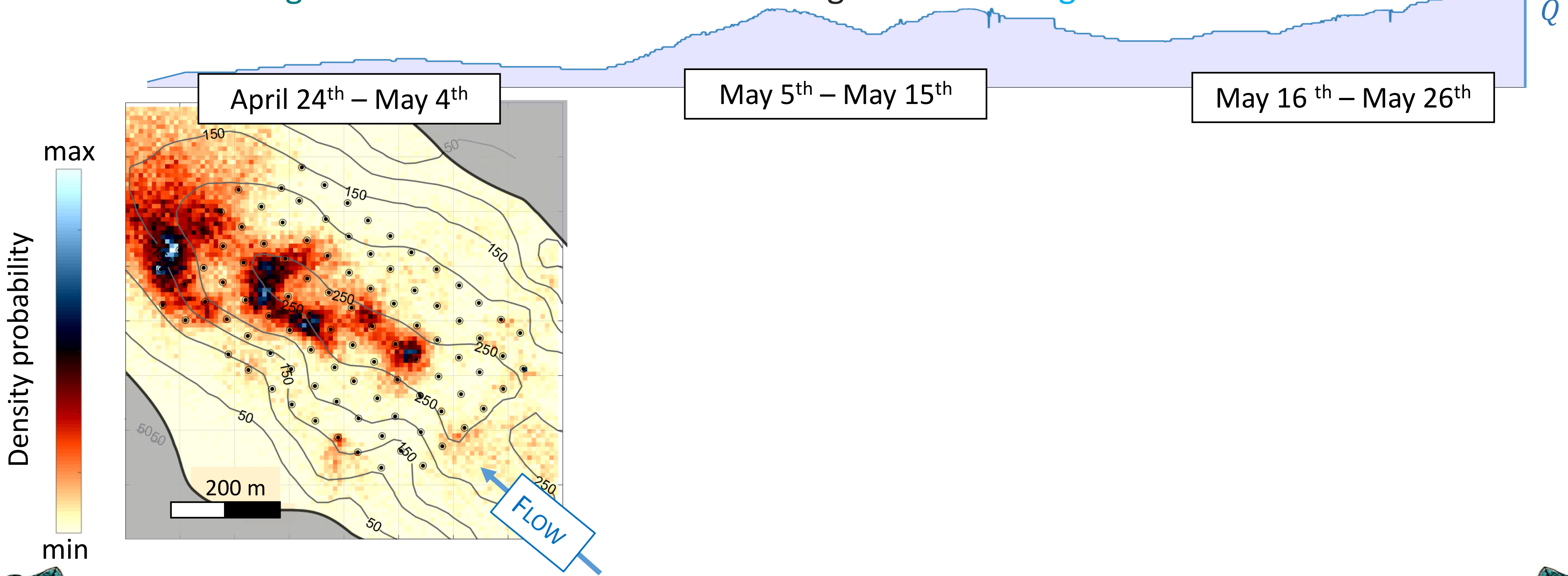
Spatial patterns at **low beam score**

- Focusing on sources location with increasing water discharge



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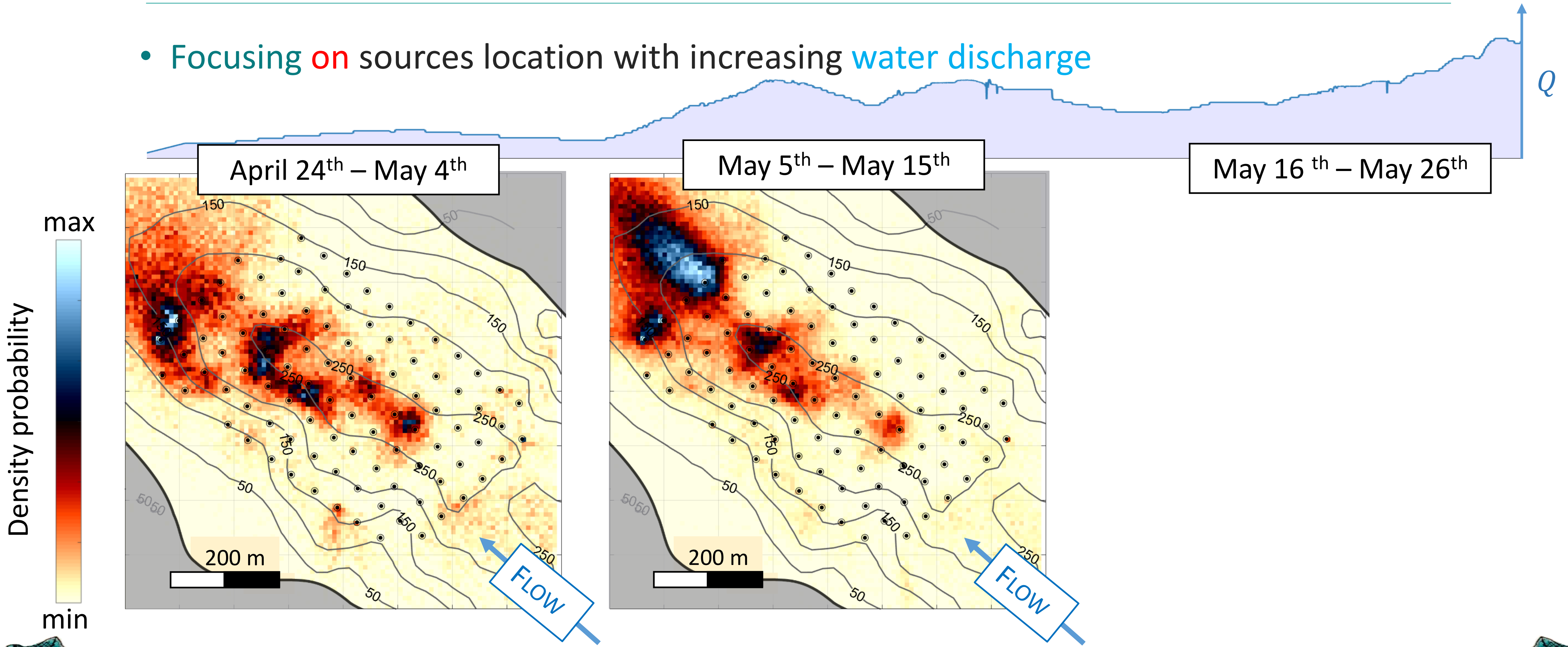

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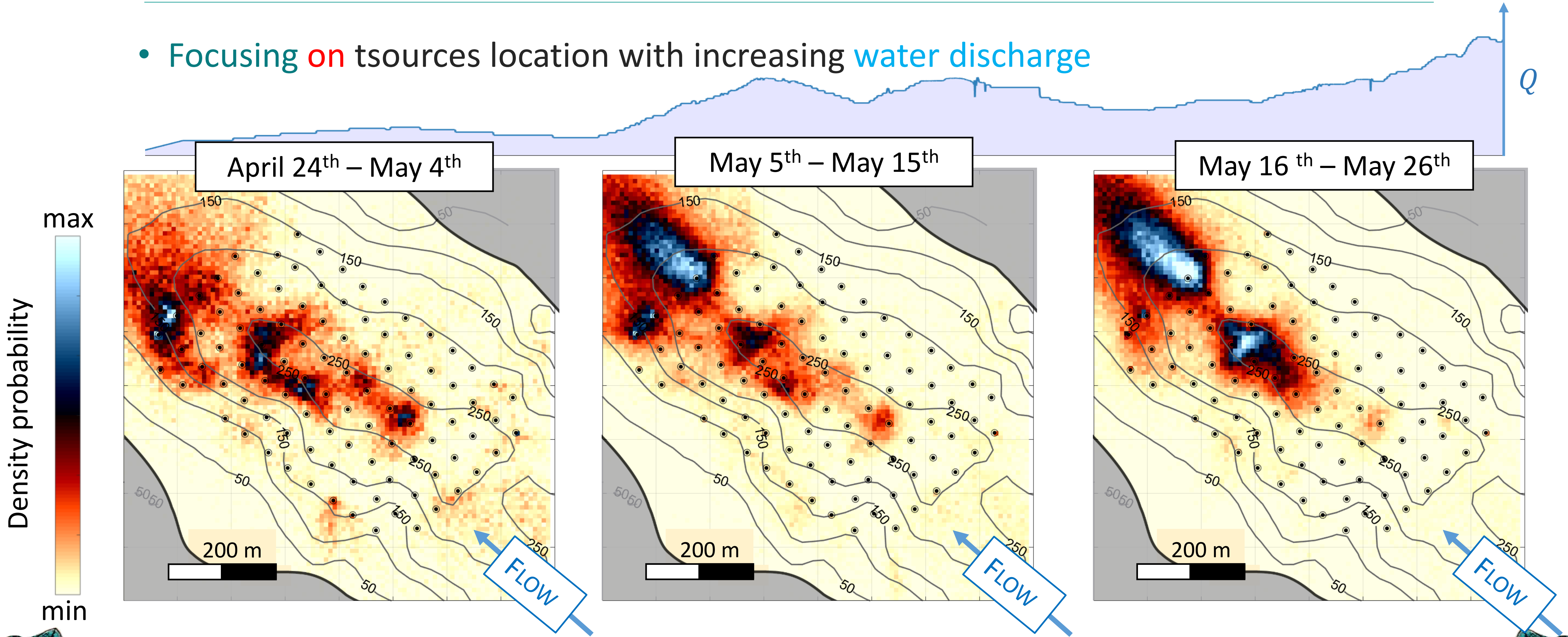
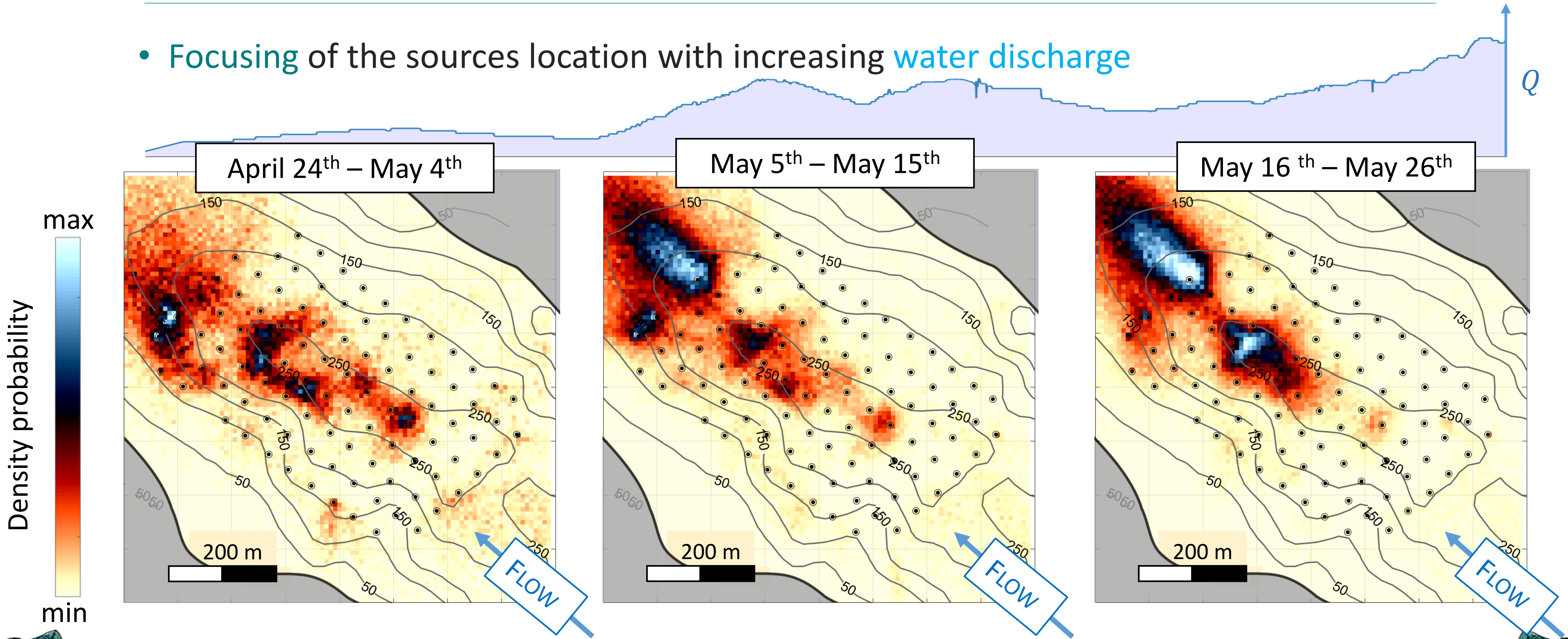


(Nanni et al., in prep.)

$u(t) = Ae^{i\omega t}$

#2 Capable to capture channels evolution

- Focusing of the sources location with increasing water discharge



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Conclusions

Complementary

Amplitude spatial anomaly

- ✓ Capture noise sources changes
- ✓ Capture **channelization onset**

Phase analysis *(1 sec-beamformer)*

- ✓ Allows retrieving multiple noise source
- ✓ Captures channels location continuously
- ✓ Capture **subglacial hydrology evolution**
- ✓ Allows for localization $< 20\ m$ resolution

Conclusions & Perspectives

Complementary

Amplitude spatial anomaly

- ✓ Capture noise sources changes
- ✓ Capture **channelization onset**

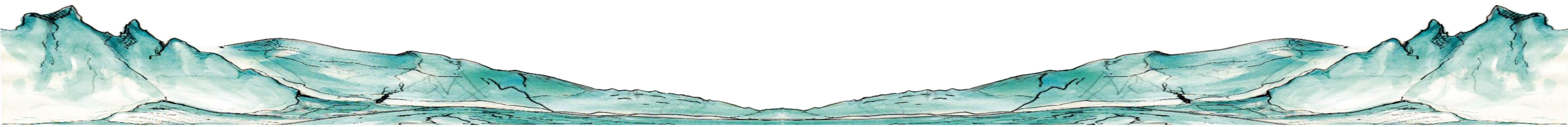
- ~ Channels not observed full-time
- ~ Influence of near field-propagation
- ~ Spatial heterogeneity of $\boldsymbol{\lambda/6}$

Phase analysis *(1 sec-beamformer)*

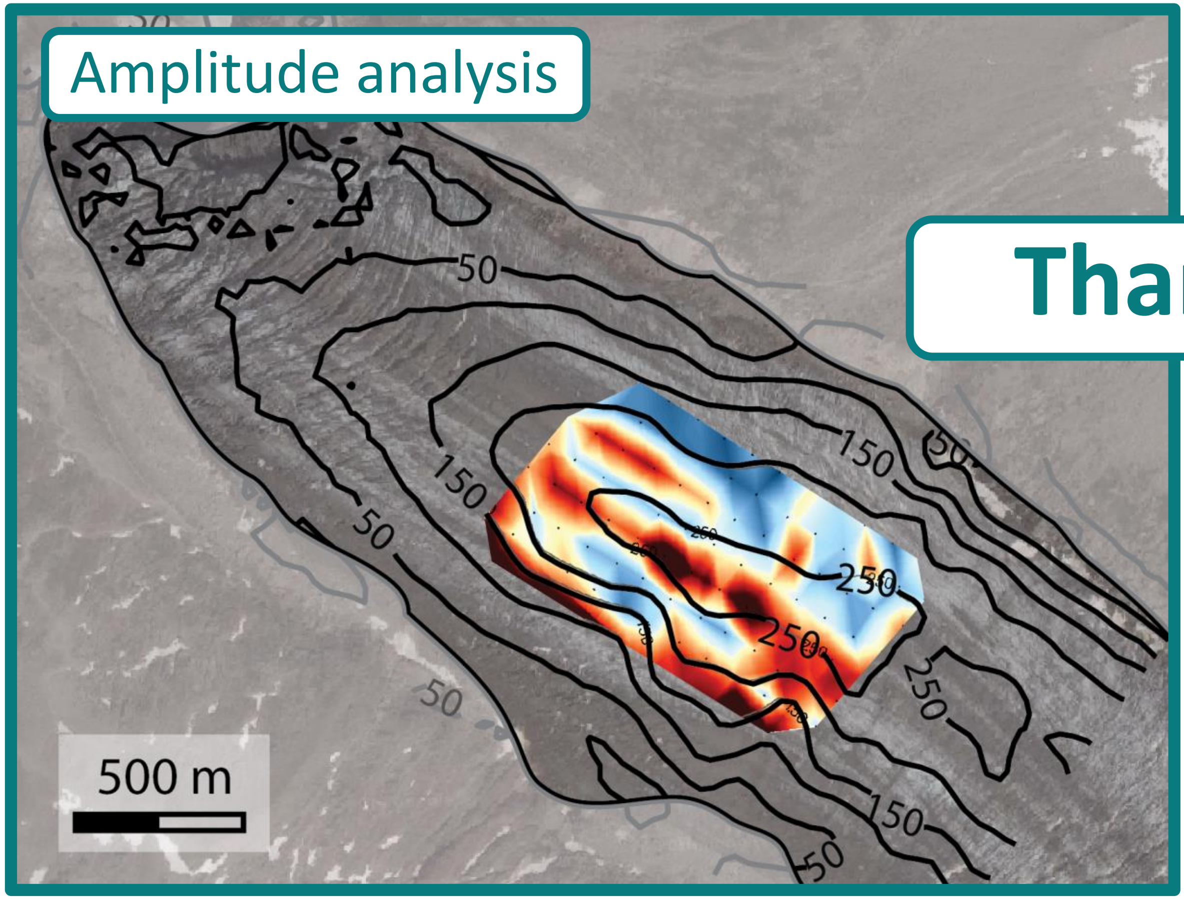
- ✓ Sensitive to multiple noise source
- ✓ Statistically capture channels location
- ✓ Capture **subglacial hydrology evolution**
- ✓ $< 20\ m$ resolution

- ~ Requires multi-day stacking

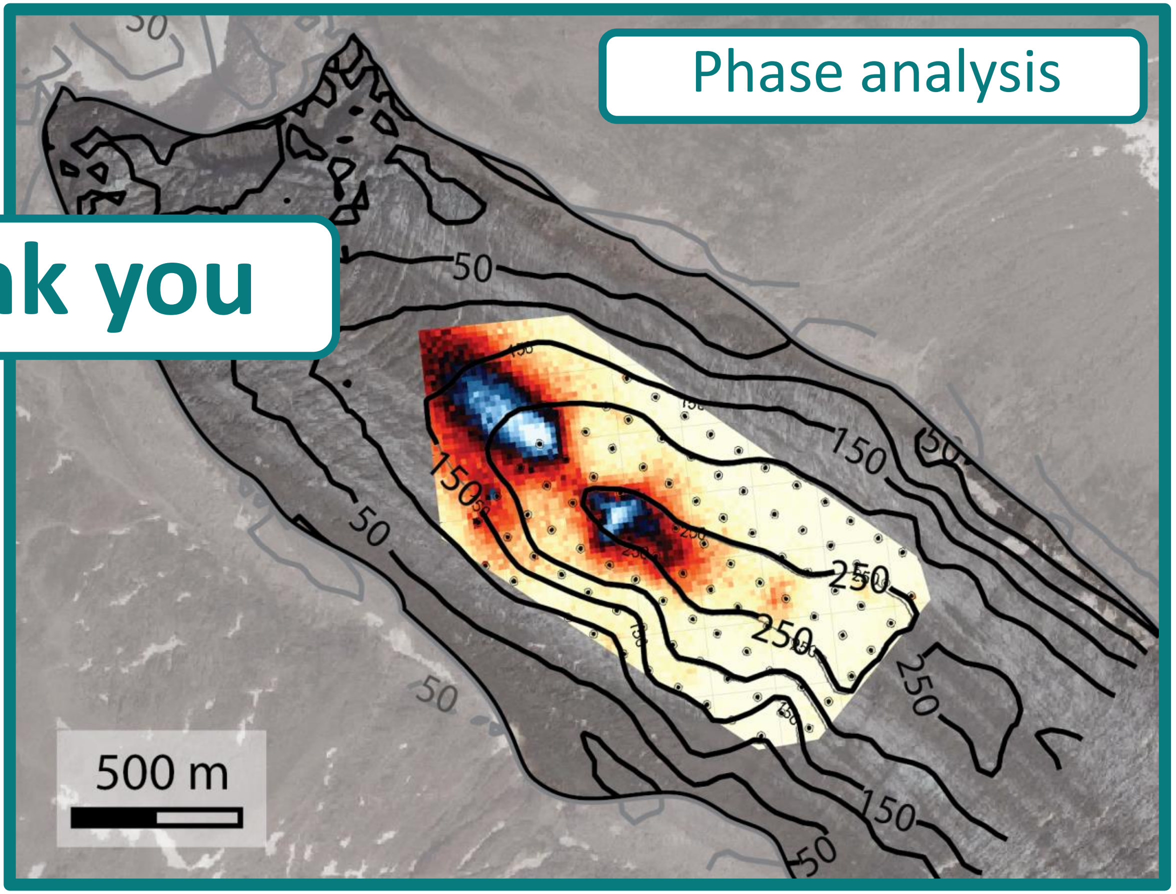
▶ Needs for full-waveform modelling (?)



We can map the subglacial hydrology network with dense array seismology



Thank you



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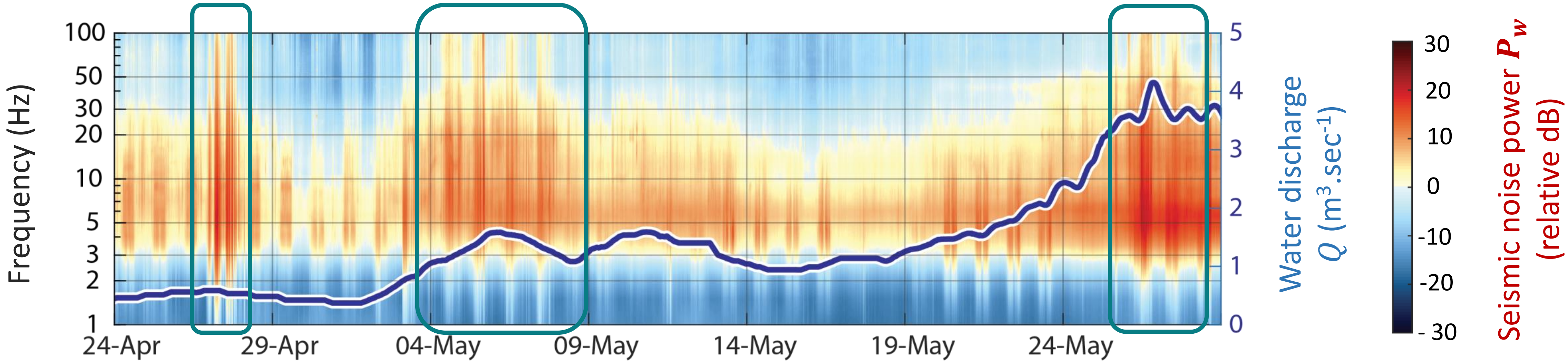

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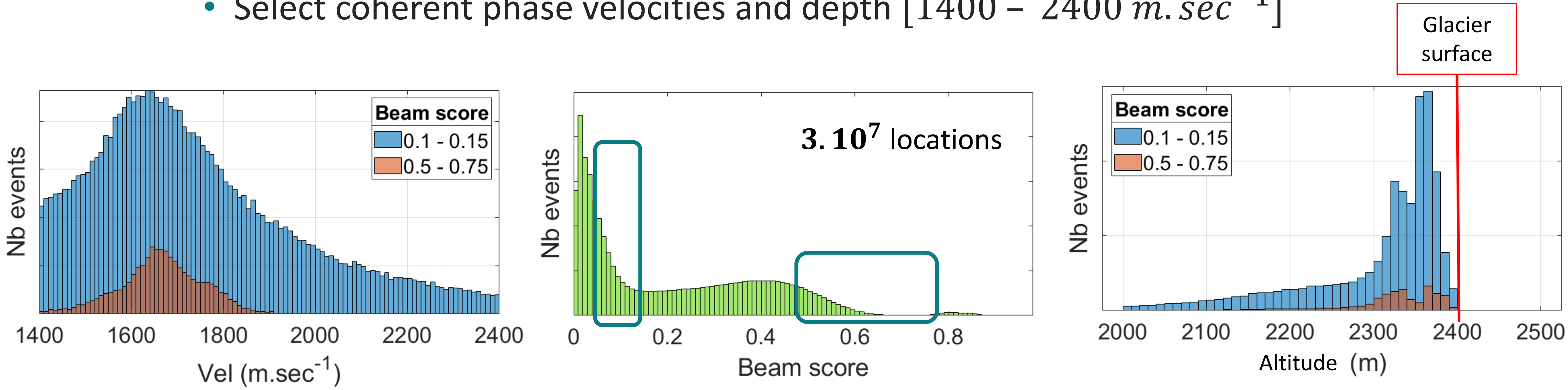
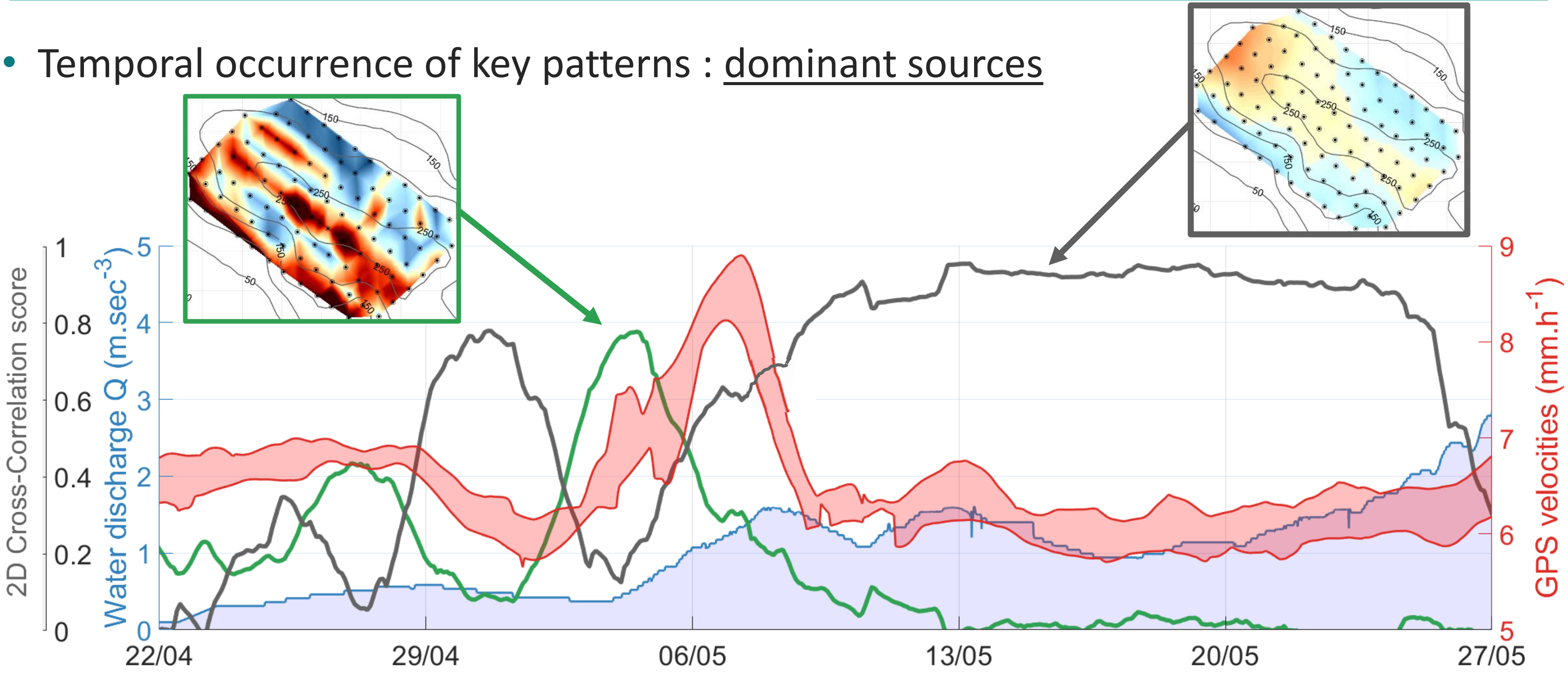


$u(t) = \boldsymbol{A}e^{i\omega t}$

Amplitude spatio-temporal variations

- Temporal occurrence of key patterns : dominant sources



(Nanni et al., in prep.)

- Concomitant to Q rise
- Concomitant to glacier acceleration