Kaila Nathaniel

Virginia Polytechnic Institute and State University

Brittany Kamai
Rana X. Adhikari
Ayooluwa Odemuyiwa

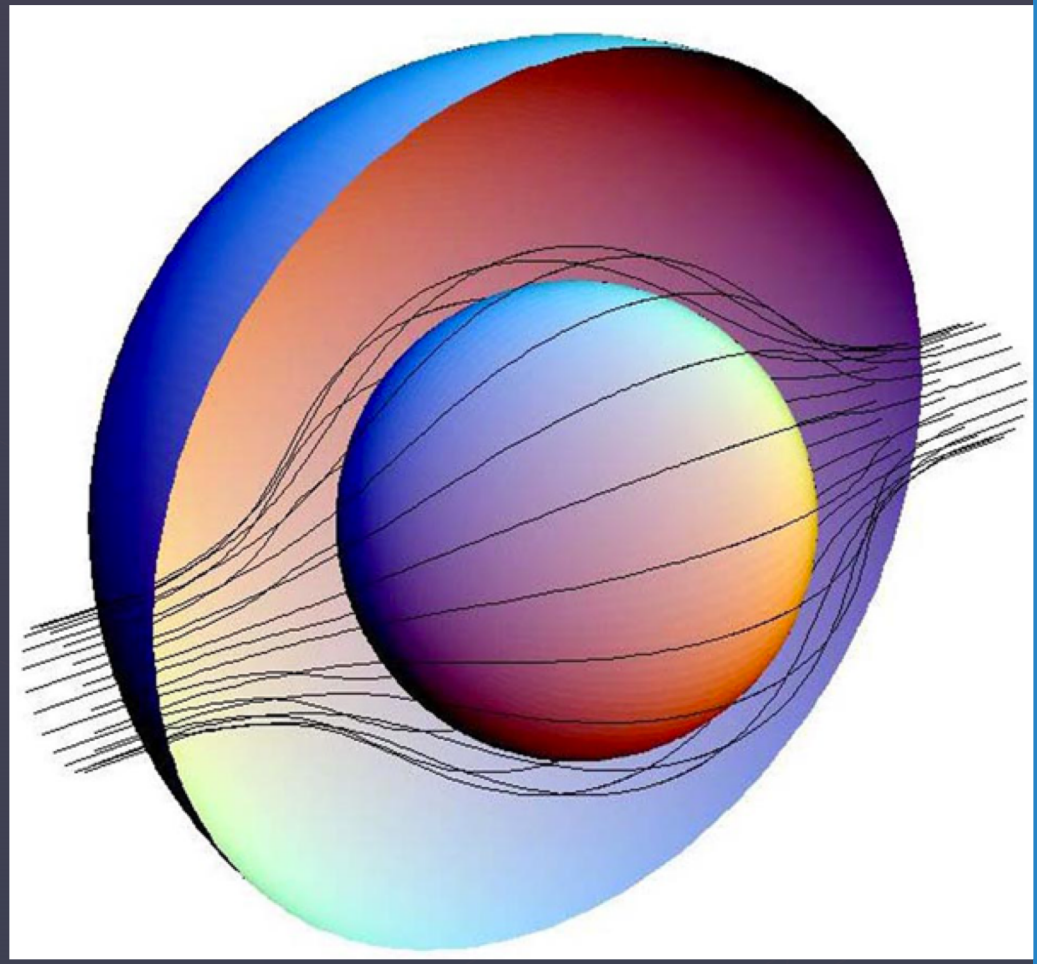
California Institute of Technology

Seismic Cloaking for LIGO

LIGO SURF 2018

Cloaking

- Manipulating waves around an object, making it appear invisible to certain types of waves
- Original concept was invisibility cloaks for electromagnetic waves
  - Experimentally verified in 2006 by Schurig et al.
- Research now underway for thermodynamic, acoustic, and elastodynamic cloaking



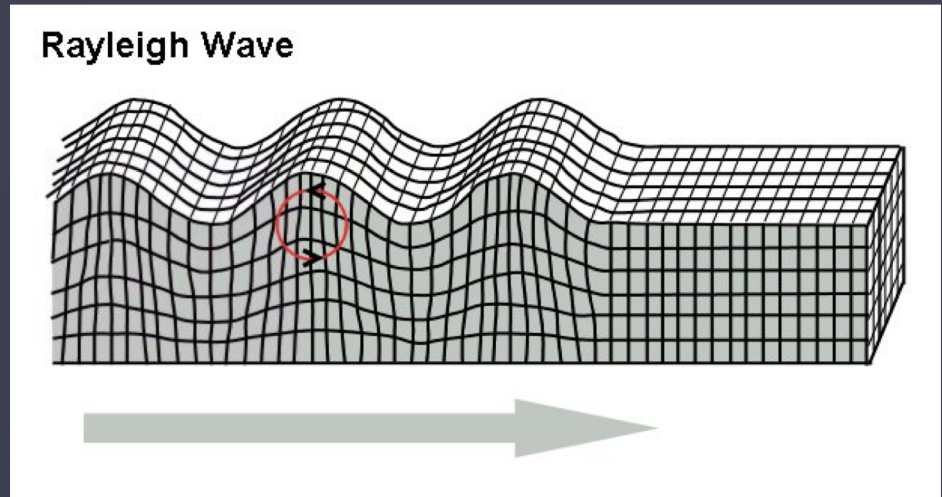
J. B. Pendry, D. Schurig, and D. R. Smith, Science 312, 1780 (2006)

Metamaterials

- Acoustic, thermodynamic, and elastodynamic cloaking is done with metamaterials
- Carefully designed building blocks packed into a dense periodic structure
- Usually artificially made, but some natural materials can be manipulated into metamaterials via spacing or other techniques

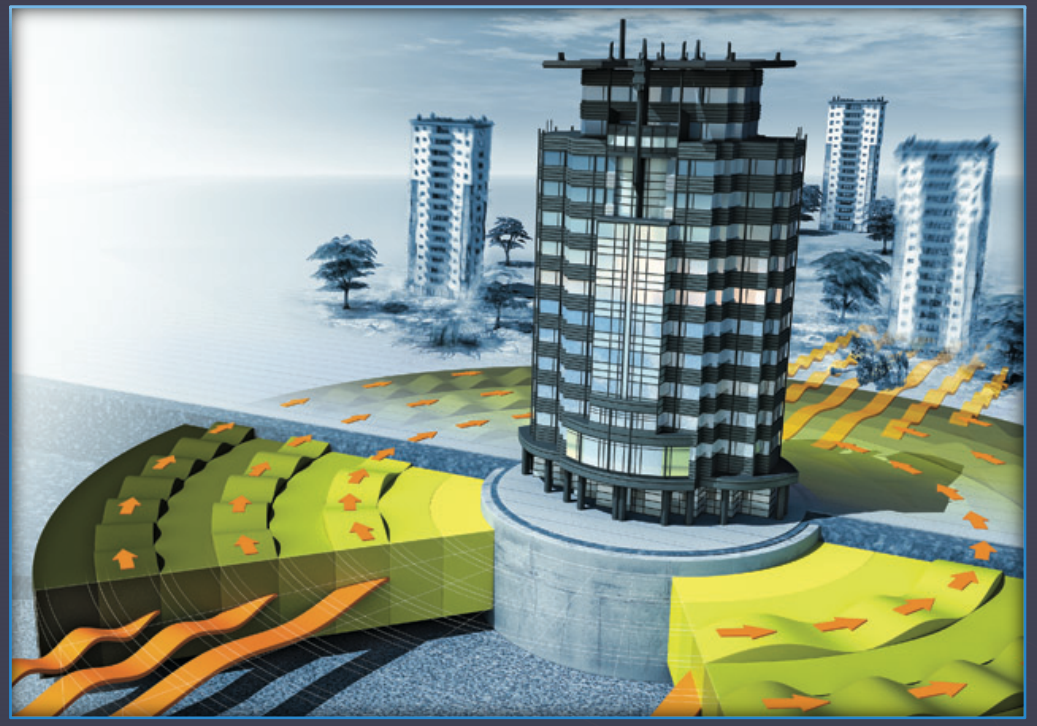
Seismic cloaking

- This field is less than 10 years old
- Subset of elastodynamic cloaking
- Interacts with surface (Rayleigh) waves
  - Wavelengths that match the dimensions of houses and other infrastructure



Seismic cloaking

- Seismic metamaterials manipulate waves to attenuate and reflect energy away from the cloaked object
- Seismic cloaking could protect valuable infrastructure from earthquakes



Graham Murdock, Popular Science

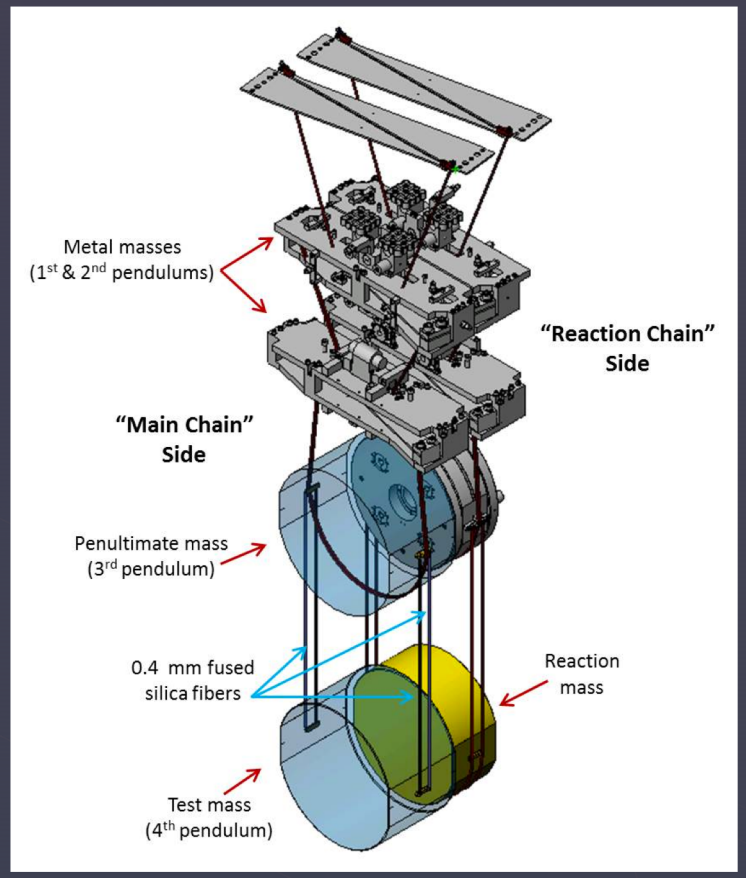
Can we apply the concept of seismic cloaking to LIGO?

LIGO and seismic noise

- The gravitational wave strain amplitude of GW170817 (the binary neutron star merger) was ~10^{-22}
- Average seismic activity at LIGO-Livingston and LIGO-Hanford is ~10^{-9} at 10 Hz

LIGO seismic isolation

- Quadruple pendulum system isolates test masses from seismic noise
- Dampens up to 10 orders of magnitude
- Pendulum system shields at 10 Hz and below



Newtonian noise

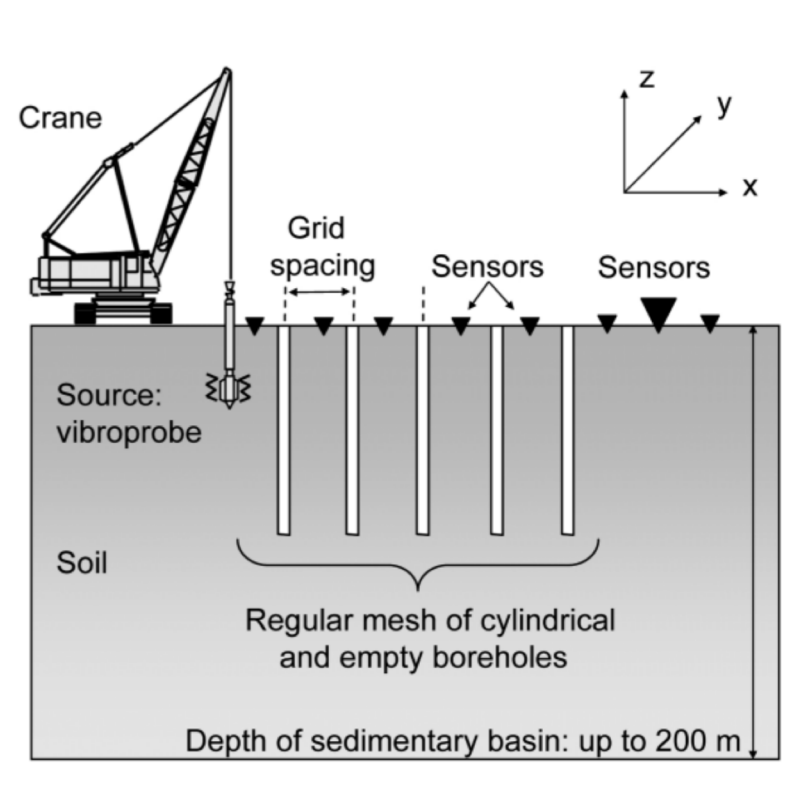
- Mass density fluctuations in soil due to surface waves can create changes in the gravitational potential around the test masses
- Affects LIGO at mostly 10 Hz and below
- Advantages of seismic cloaking
  - Reduce the amount of terrestrial noise
  - Improve LIGO operation

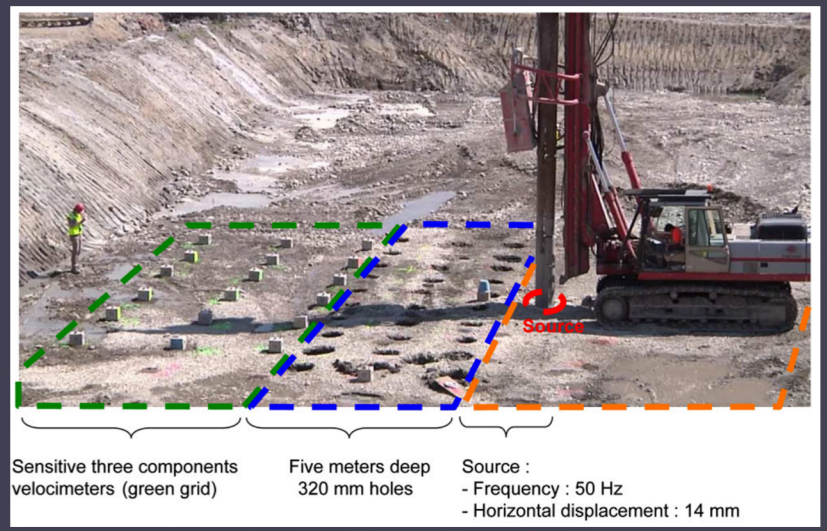
Seismic cloaking experiments

Seismic cloaking experiments: Brûle

- An early seismic cloaking experiment was conducted by Brûle et al.
  - Published March 2014
- Created a seismic metamaterial with a grid of 5 m deep self-stable holes, with a diameter of 0.32 m, and spaced 1.73 m apart
- Tested with a 50 Hz source
  - Previous cloaking experiments have been at 1 kHz and 600 Hz

Seismic cloaking experiments: Brûle





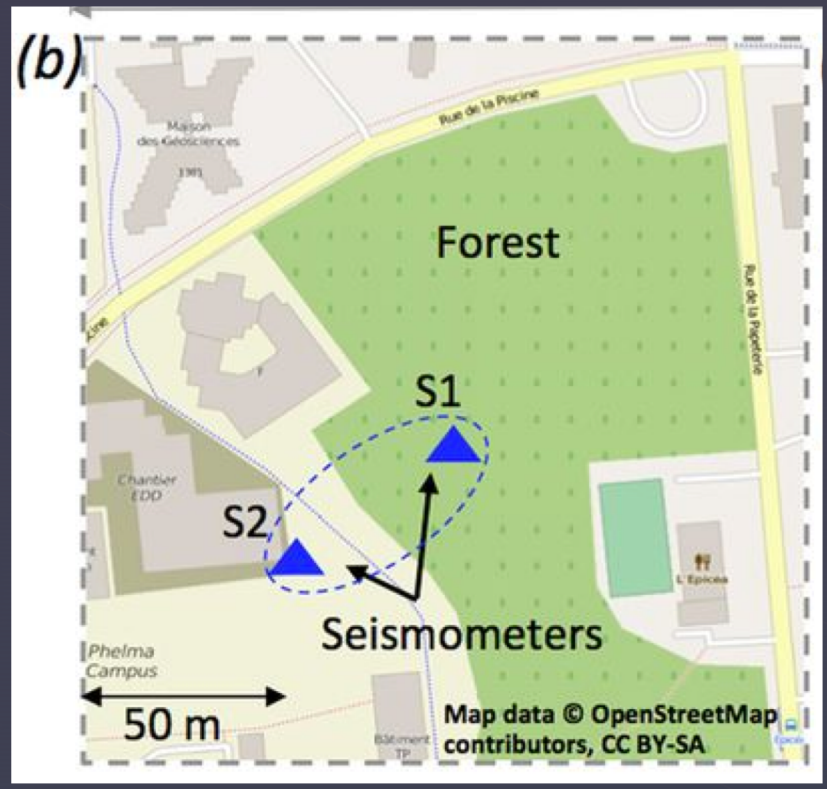
- Elastic energy was 2.3 times larger at the source than in the metamaterial
- Suggests that the seismic metamaterial has a significant effect on energy dissipation

Seismic cloaking experiments: Colombi

PROJECT GENESIS!

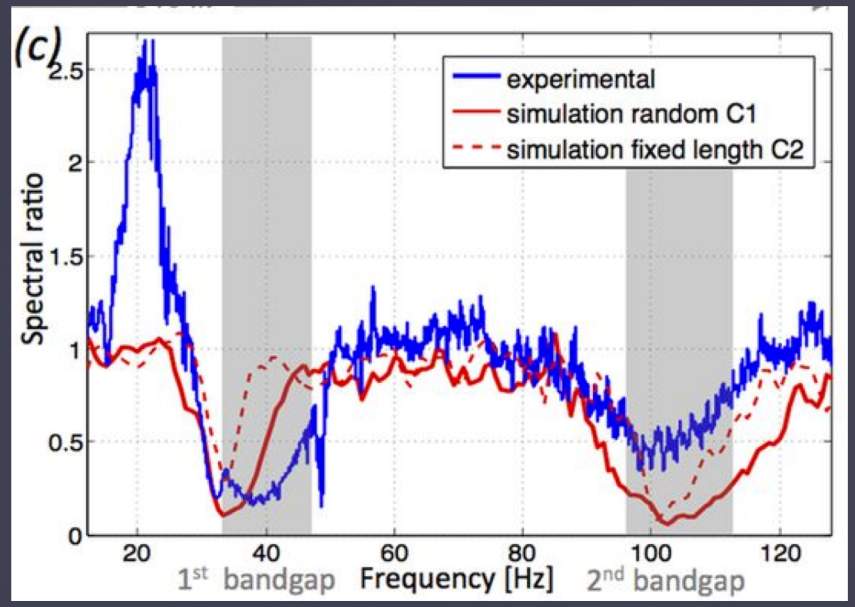
- What's the opposite of a borehole? What about something sticking out of the ground?
- Colombi et al. tested trees as a seismic metamaterial
  - Published January 2016
- Geophysical survey on a ~6000 m^2 forest of mainly pine trees in Grenoble, France

Seismic cloaking experiments: Colombi



Seismic cloaking experiments: Colombi

- Found that the longitudinal resonance inside the trees created two highly attenuating regions around 40 Hz and 110 Hz
- The various sizes and random spacing of the trees produced larger band-gaps than for a uniform configuration
- Theorized that cloaking could be achieved for frequencies ≤ 10 Hz with trees of longitudinal resonant frequencies of ≤ 10 Hz

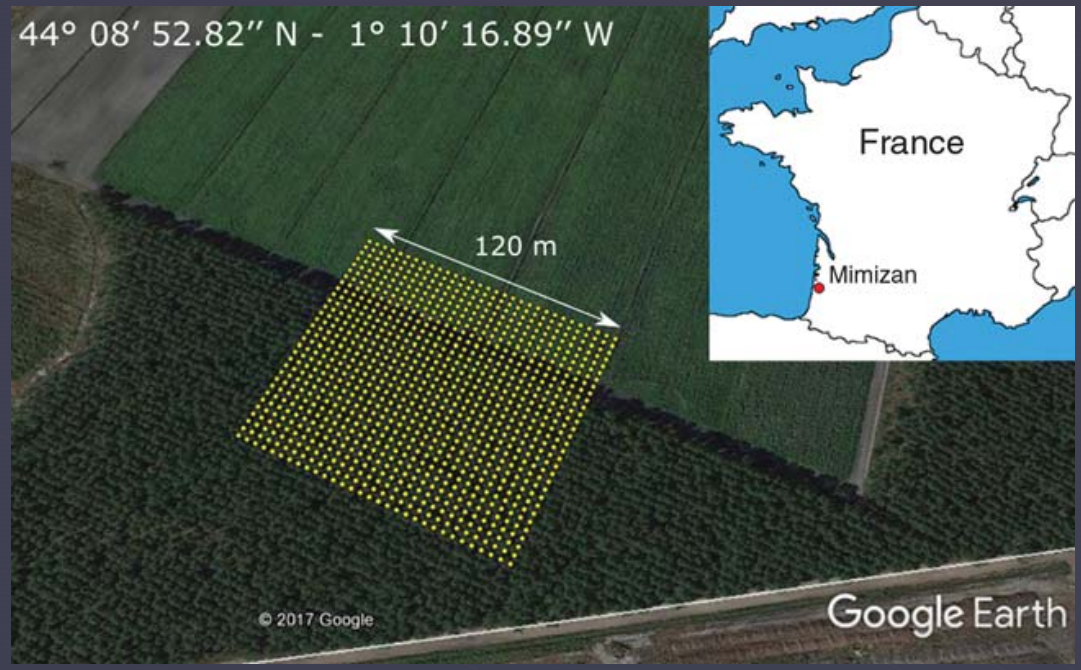


Seismic cloaking experiments: Roux

- The METAFORET project, by Roux et al. expanded upon Colombi's work
  - Published January 2018
- Demonstrated that a dense forest of trees can behave as a locally resonant metamaterial for seismic surface waves

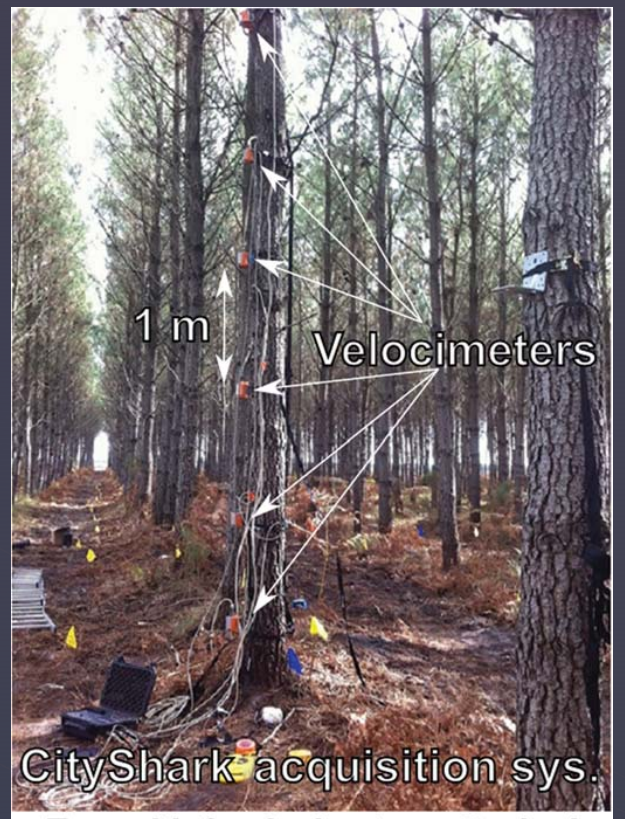
Seismic cloaking experiments: Roux

- Data collection in Mimizan, France
- Used a forest and a canola field
- Took data with geophones and velocimeters



Seismic cloaking experiments: Roux

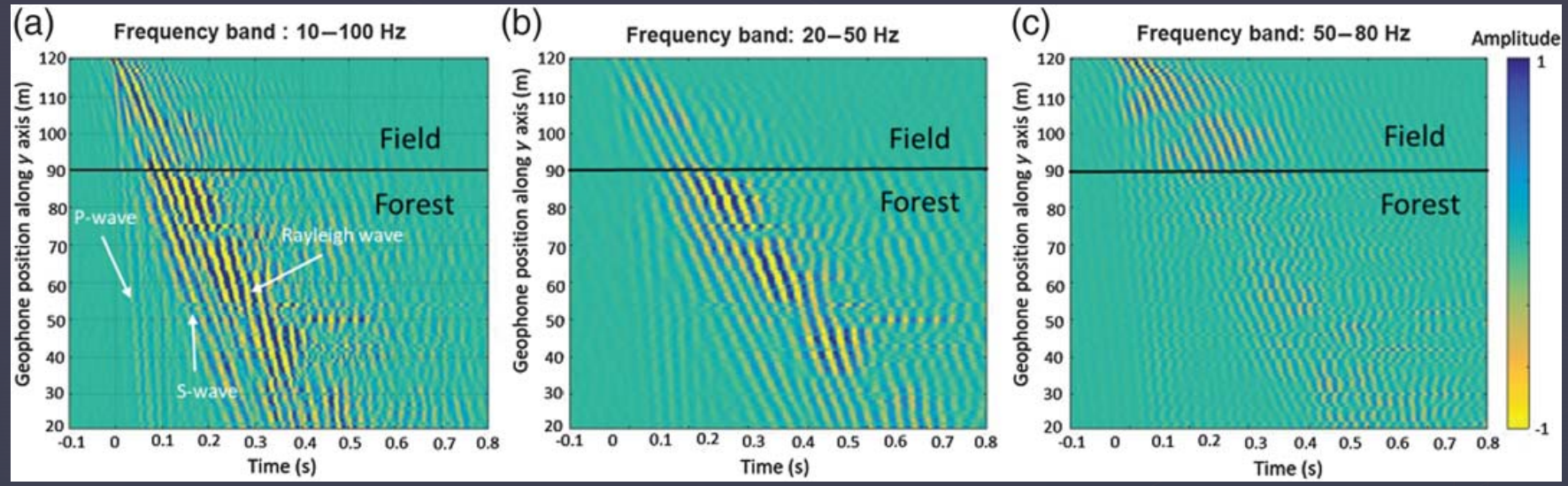
- Measured flexural and compressional resonance in the trees
- Found that compressional resonance is what provides filtering for the waves
- Measured ambient noise and noise from a 70 kg shaker that excited a 60 s long 10-100 Hz frequency-modulated sweep



Tree with 6 velocimeters attached

Seismic cloaking experiments: Roux

- Compressional resonances were ~50 Hz (cutoff frequency)
- At 50 Hz the trees responded best with compressional resonance
- Above 50 Hz a lot of waves get filtered out and cloaked



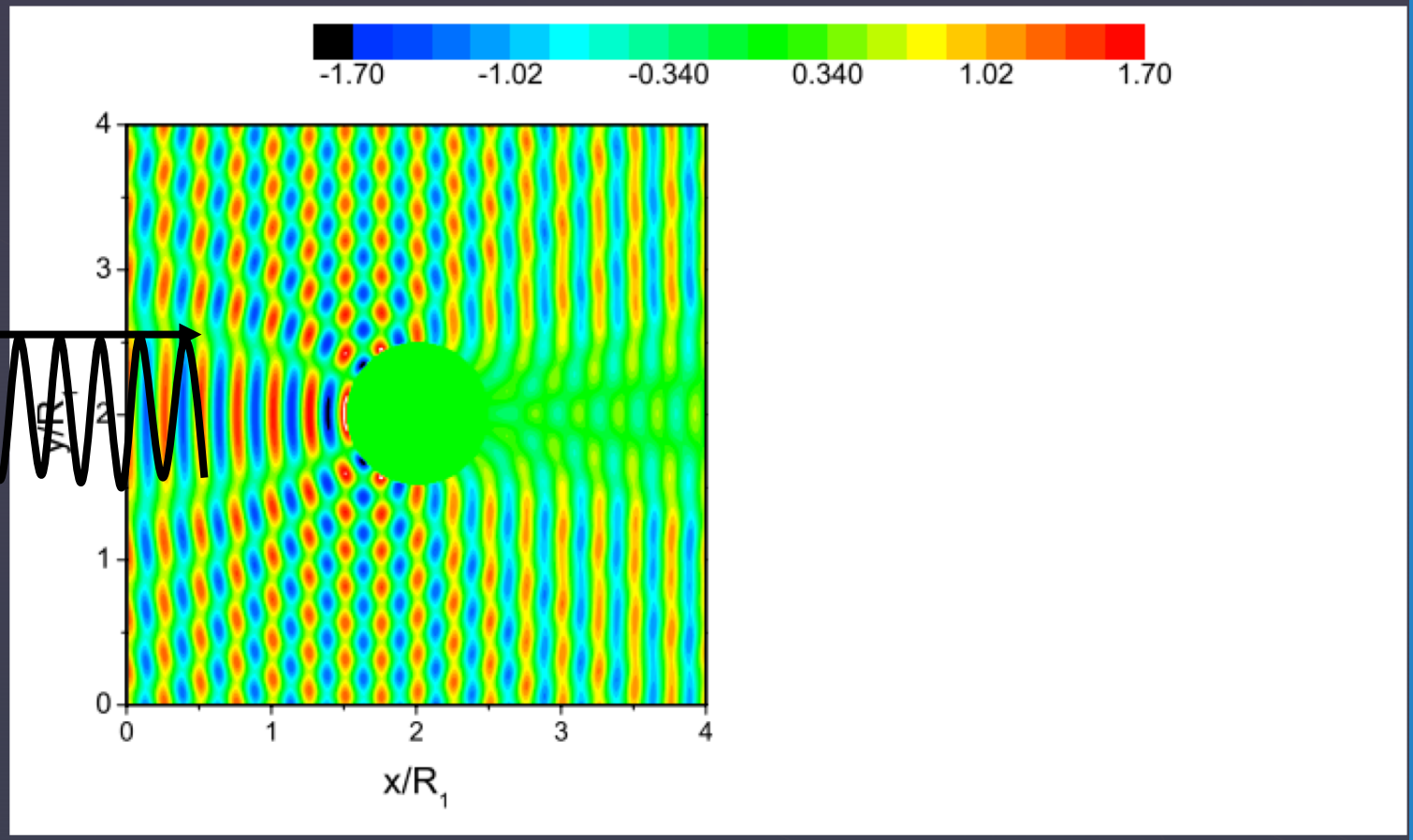
Our work: modeling cloaking

Modeling acoustic cloaking

- Wanted an intuitive understanding of cloaking
  - Does not require a full-scale seismic model
- Acoustic cloaking is a simpler 2D analog of seismic cloaking
- Similar types of waves, but don’t need to account for soil density or speed of sound in soil
- Future work in seismic cloaking will require full solutions of elastodynamic equations

Modeling acoustic cloaking

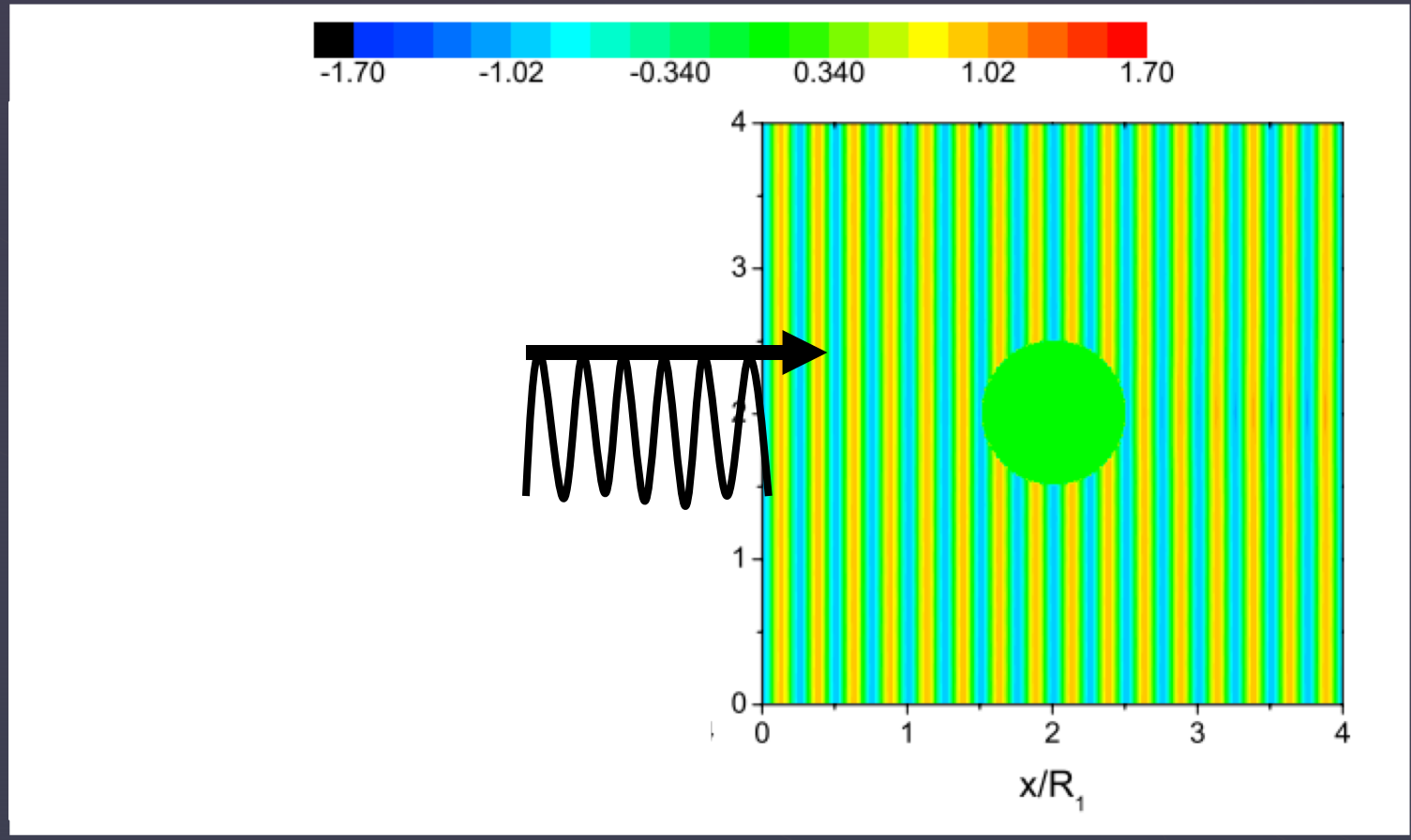
- Wave interacts with a boundary, which creates higher amplitude and pressure buildup



Torrent, D., & Sánchez-Dehesa, J. (2008). New Journal of Physics, 10(6), 063015.

Modeling acoustic cloaking

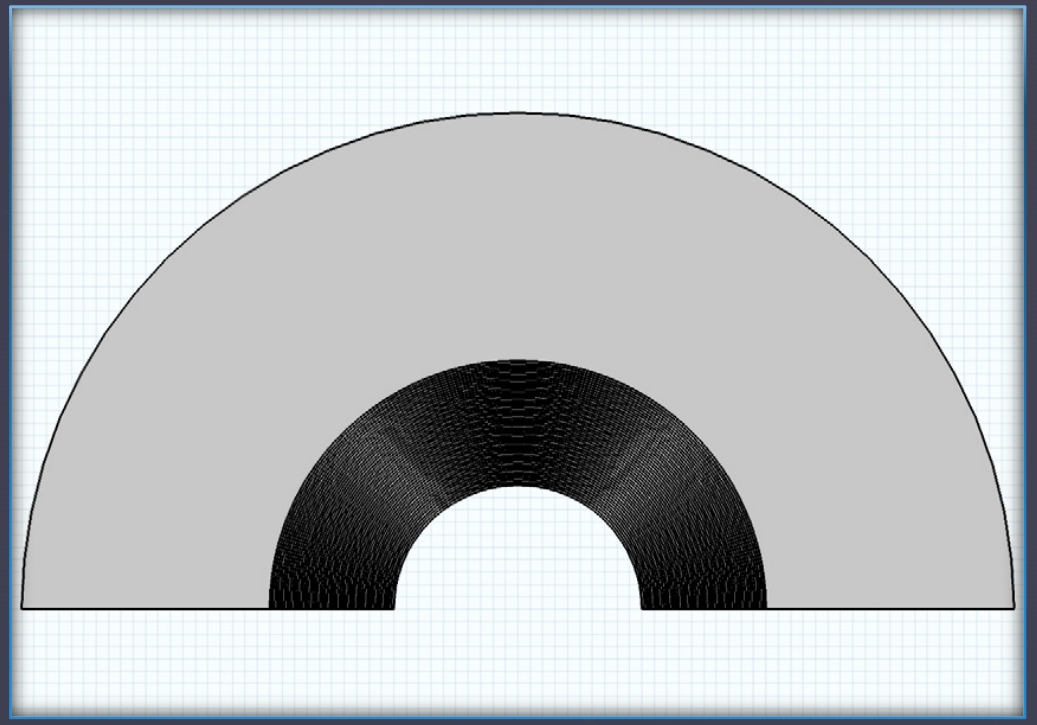
- With a cloak, there is no pressure buildup and the wave just moves through
- Cloaking requires both a negative bulk modulus and a negative mass density
- Creates a negative phase velocity → negative refractive index



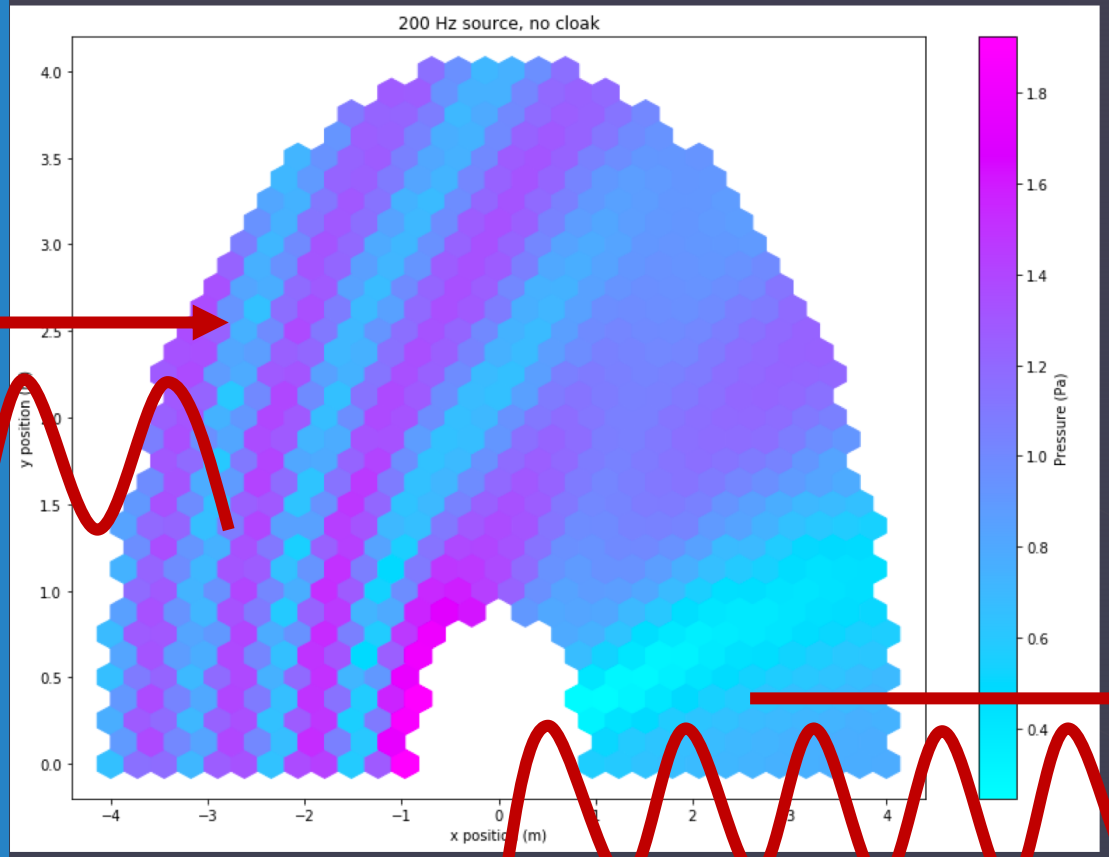
Torrent, D., & Sánchez-Dehesa, J. (2008). New Journal of Physics, 10(6), 063015.

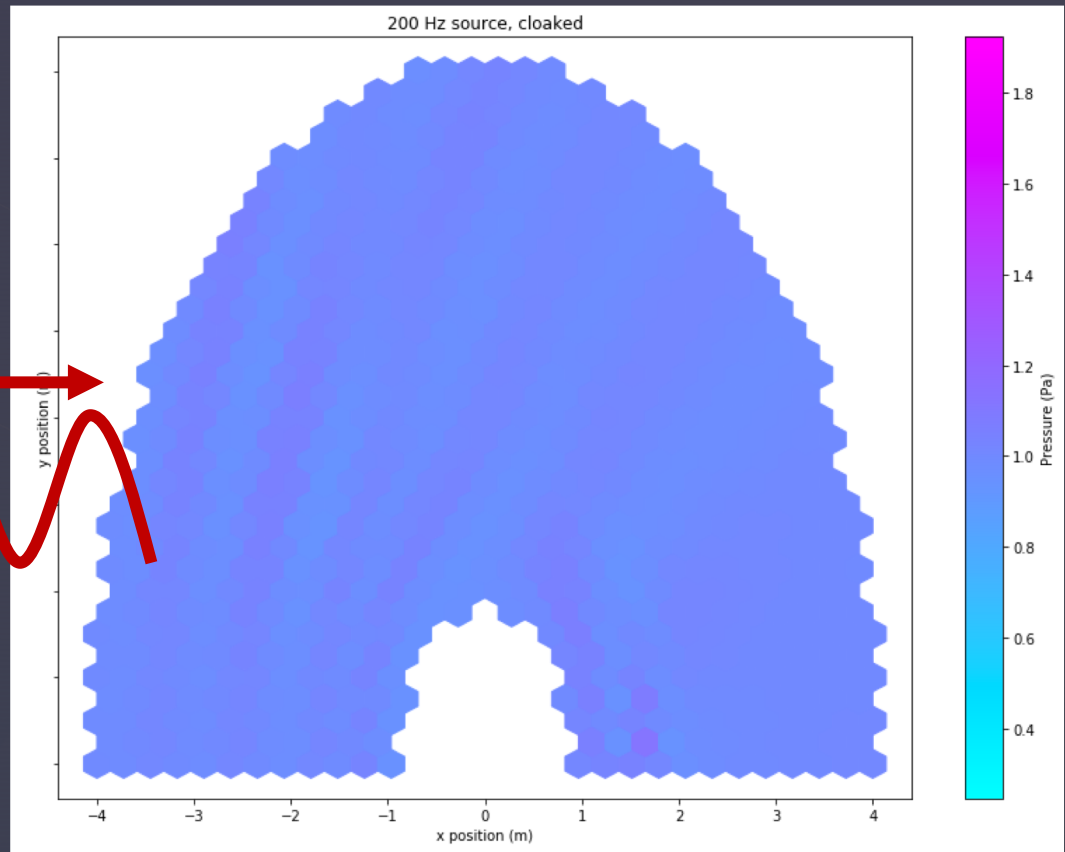
Modeling acoustic cloaking

- Created cylinder model
  - 1 m radius
- 50-layer metamaterial cloak of two alternating fluid-like materials
  - Each layer 2 cm thick



Modeling acoustic cloaking

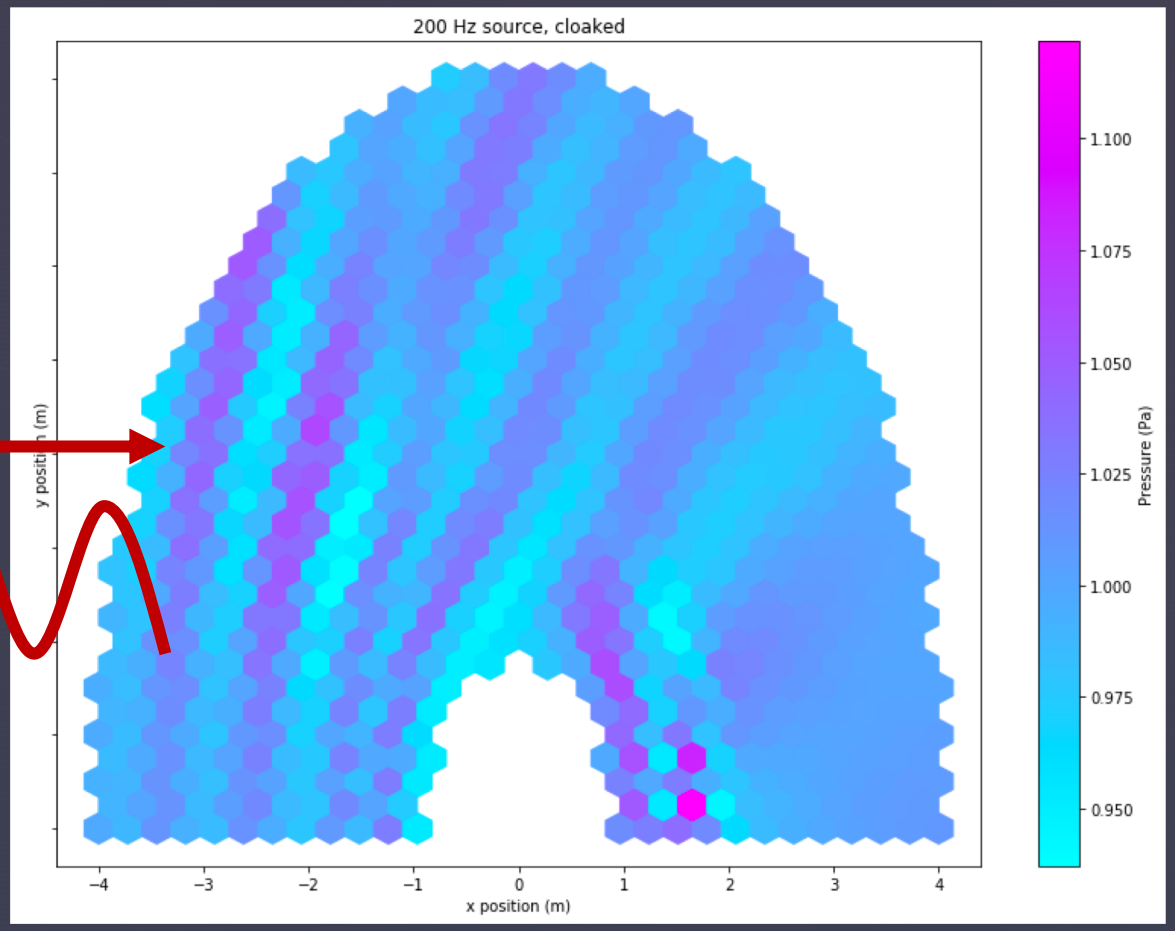




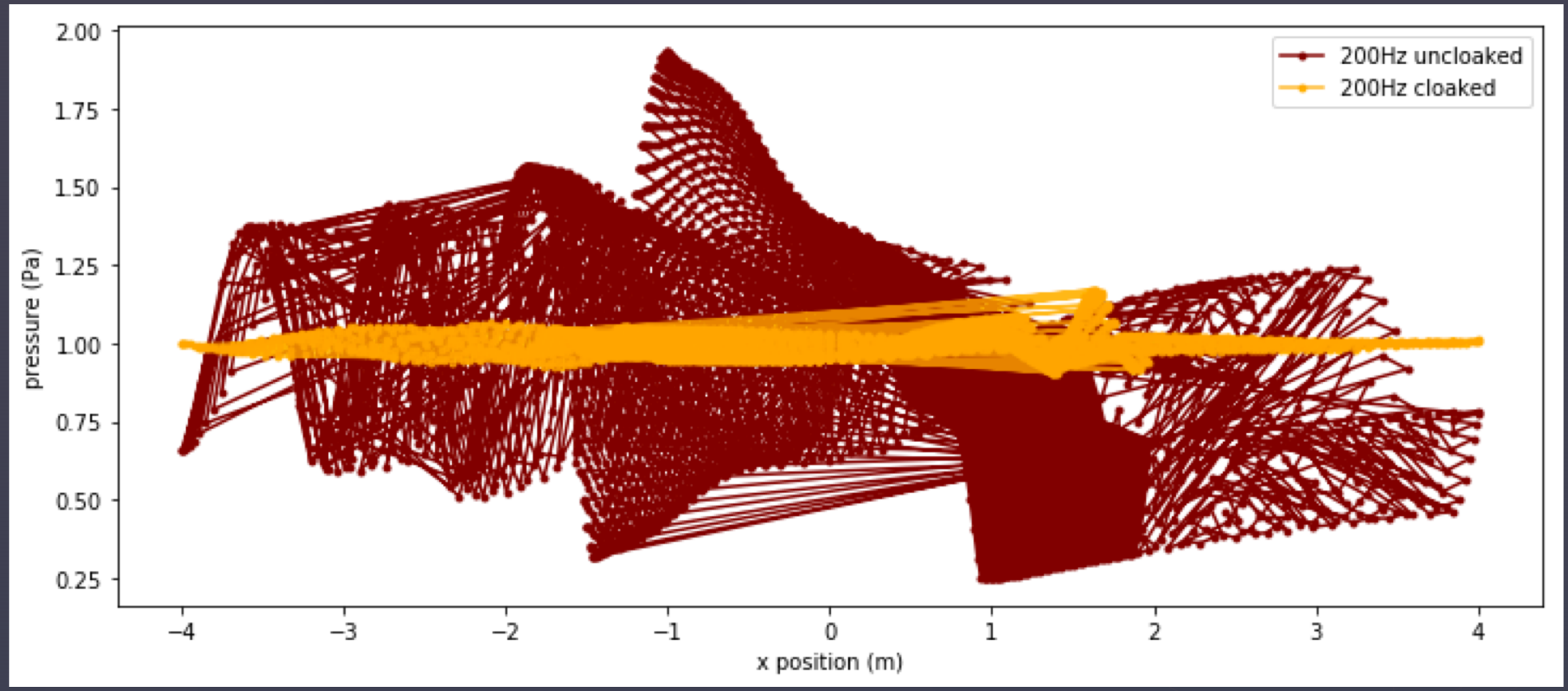
200 Hz incoming wave

Modeling acoustic cloaking

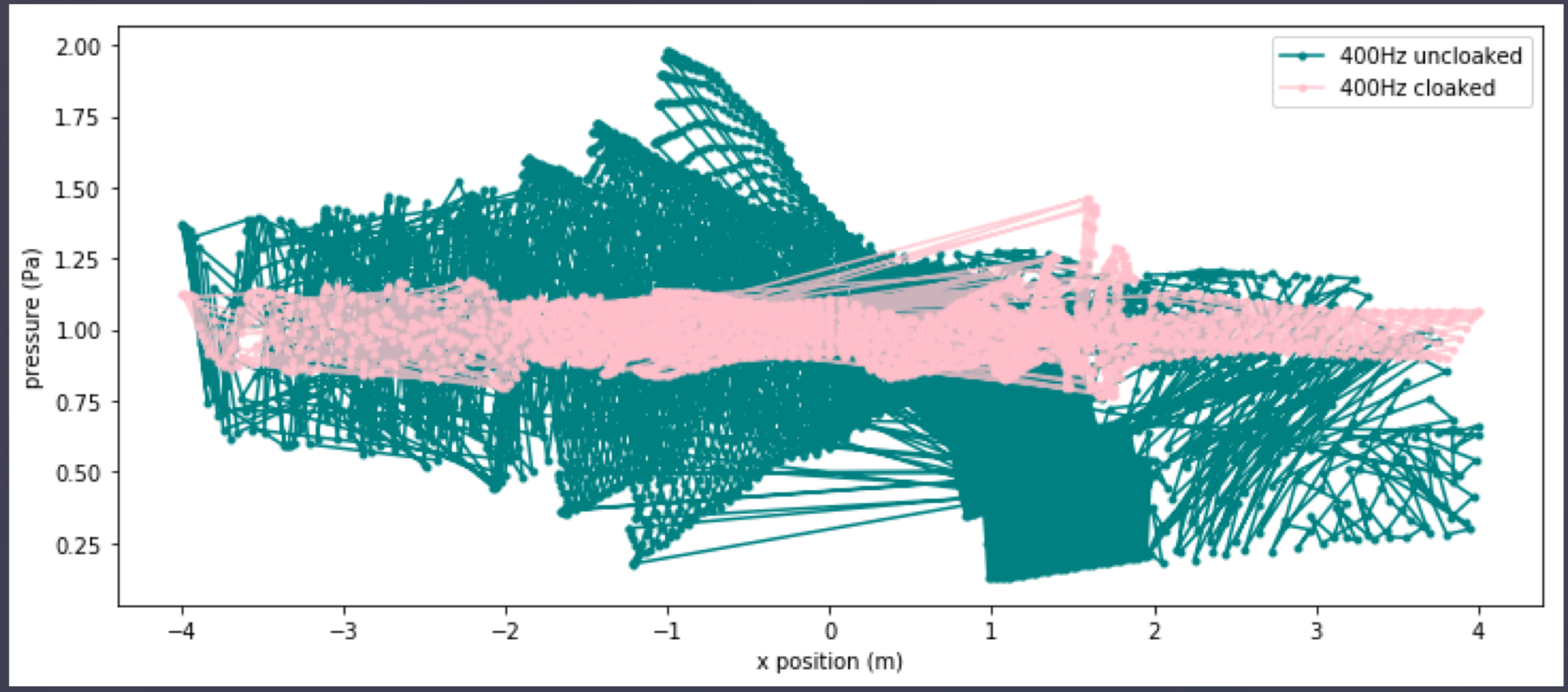
200 Hz



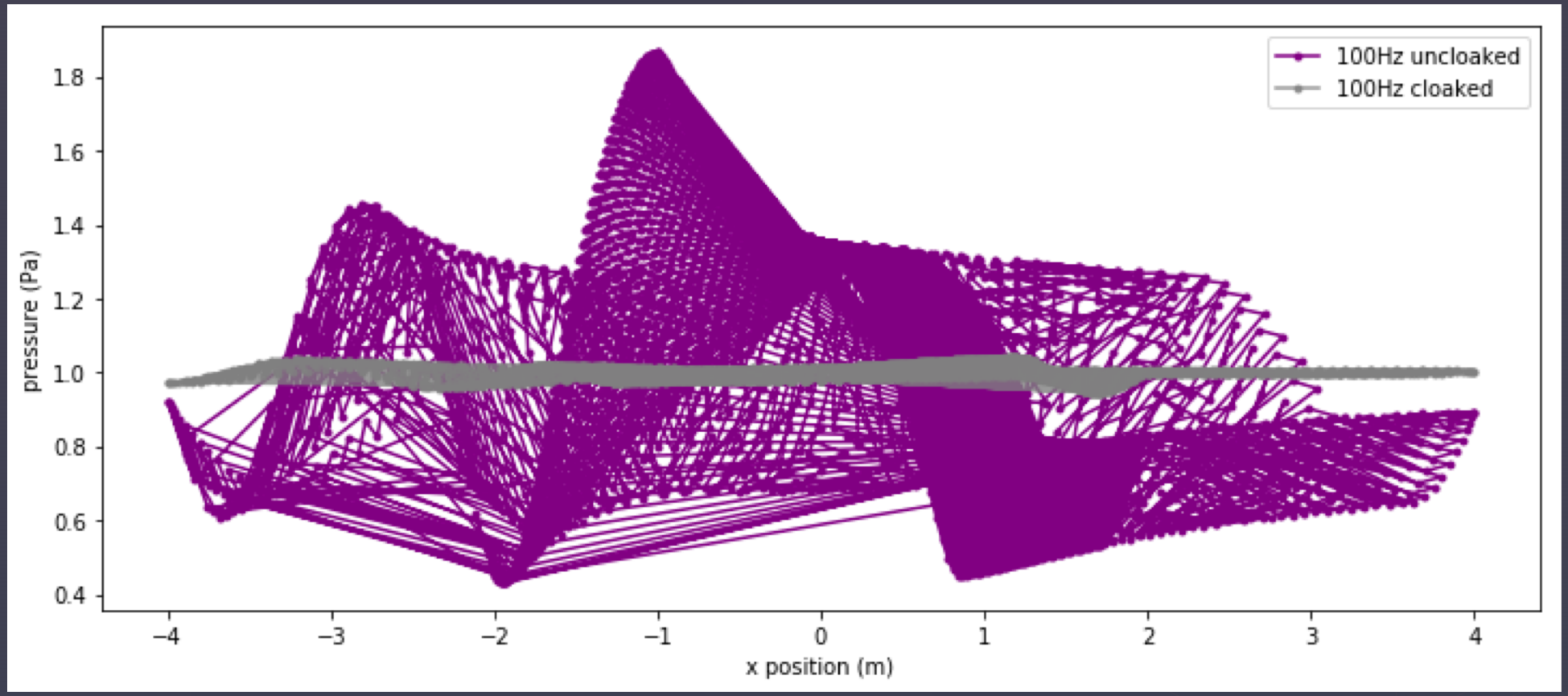
Modeling acoustic cloaking



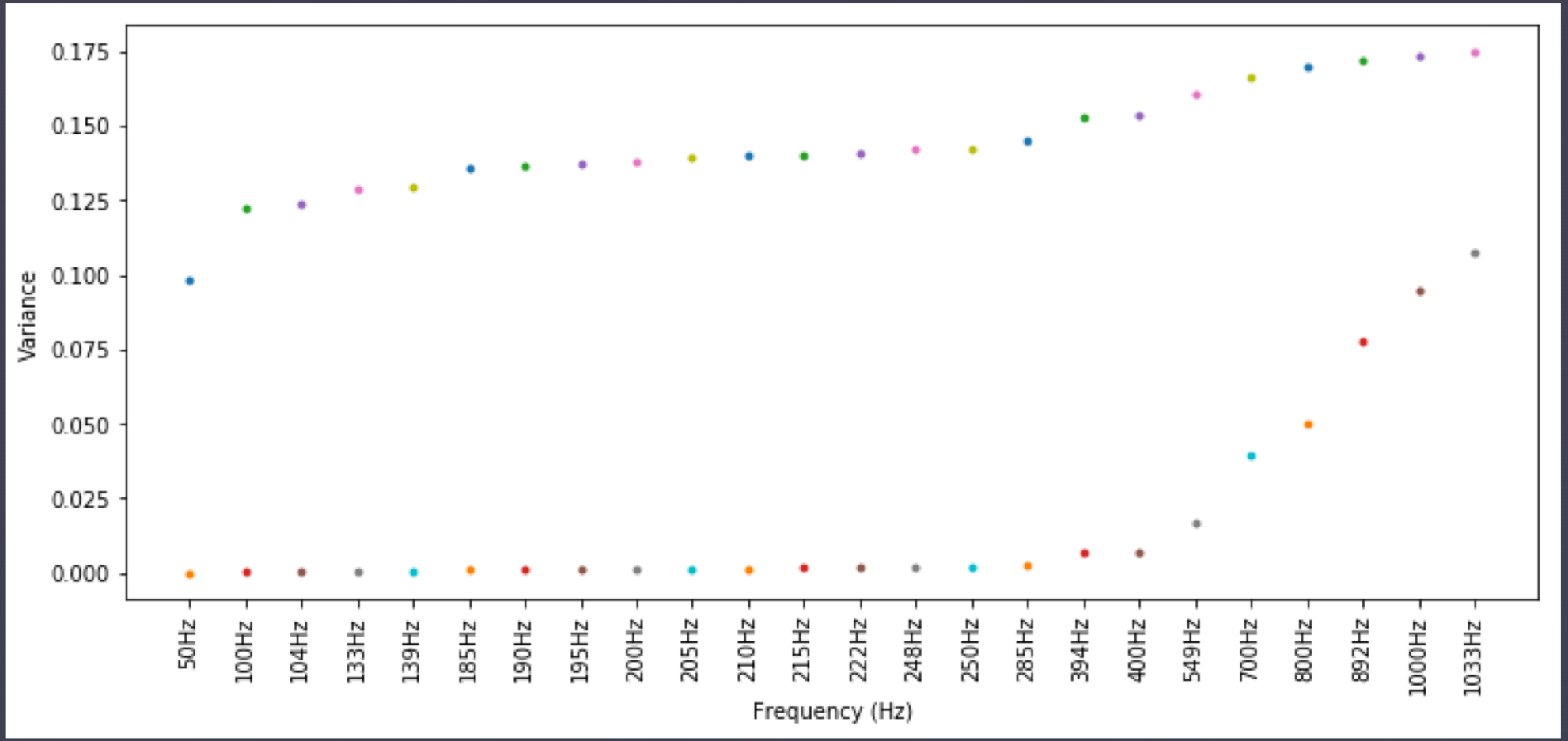
Modeling acoustic cloaking



Modeling acoustic cloaking



Modeling acoustic cloaking

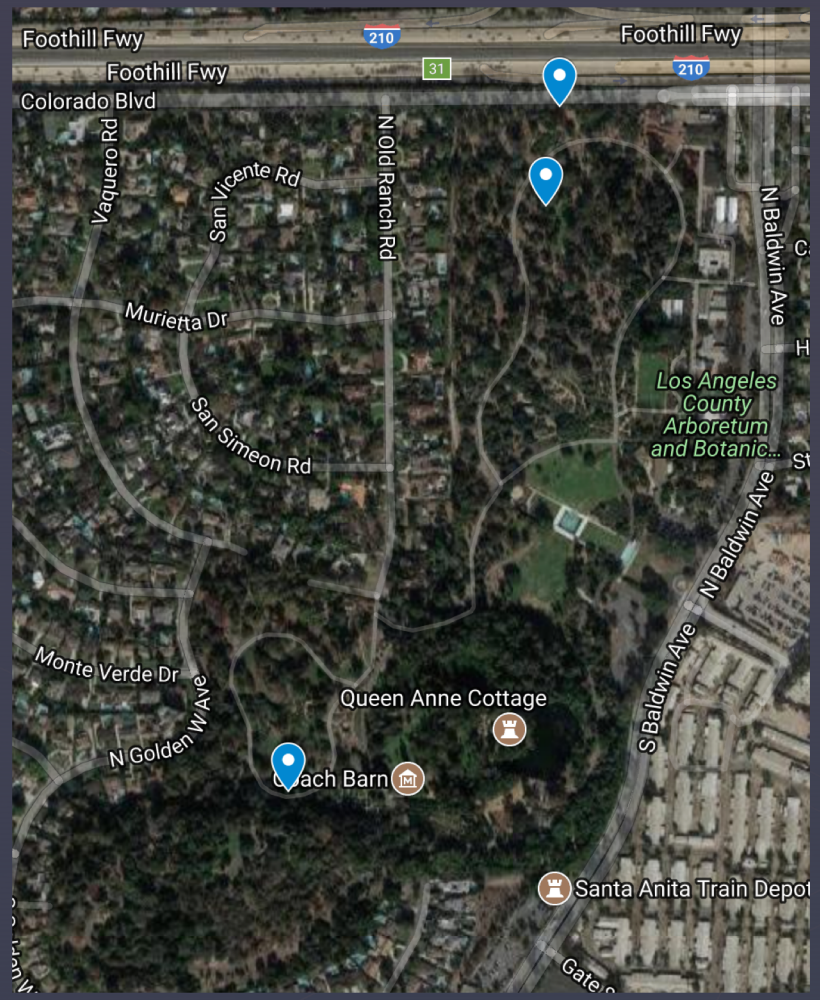


Measuring the effects of an existing seismic cloak

- Wanted to find trees and see if they acted similarly to Colombi's experiments
- Criteria: relatively dense trees, flat, near a noise source (i.e. a freeway)
- Most places in LA are either flat and full of houses or forested and mountainous

Measuring the effect of an existing seismic cloak

- Ended up taking data at the Los Angeles County Arboretum
- 3 data sites
  - Freeway – source of anthropogenic noise
  - Trees – quiet/cloaking
  - Waterfall – white noise

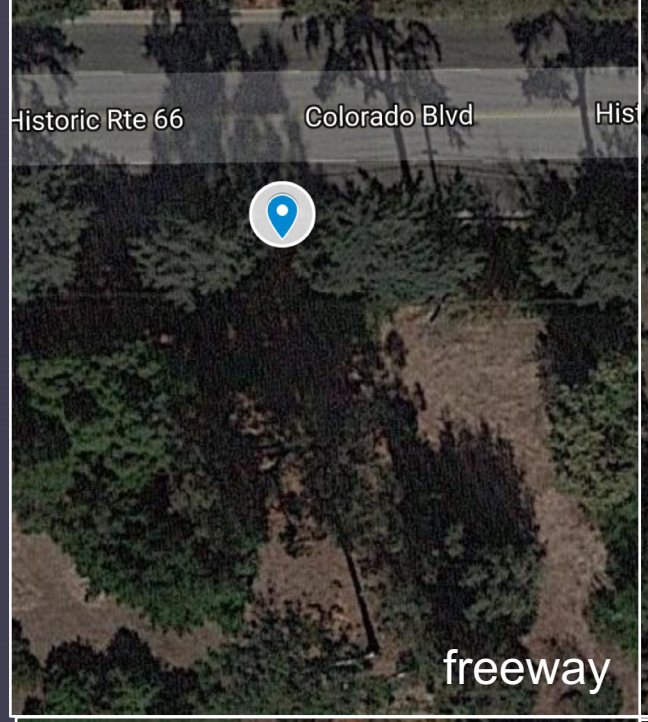


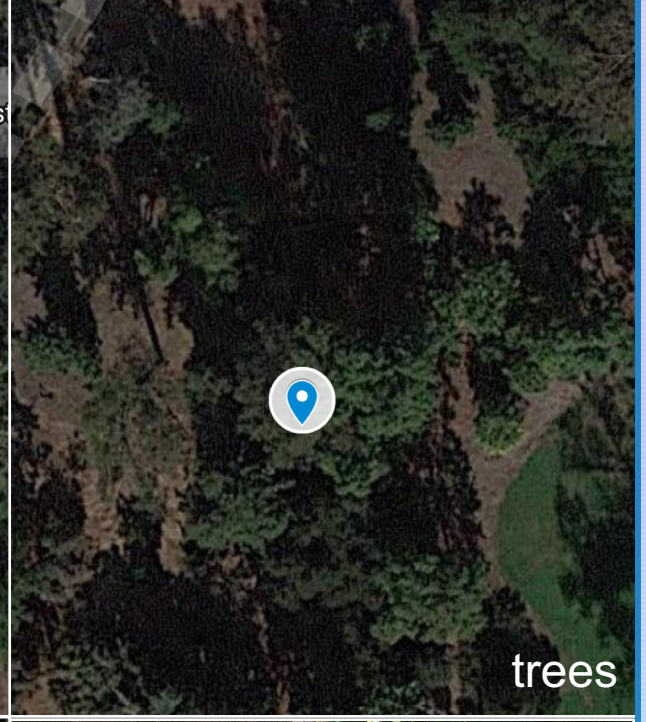
Measuring the effects of an existing seismic cloak

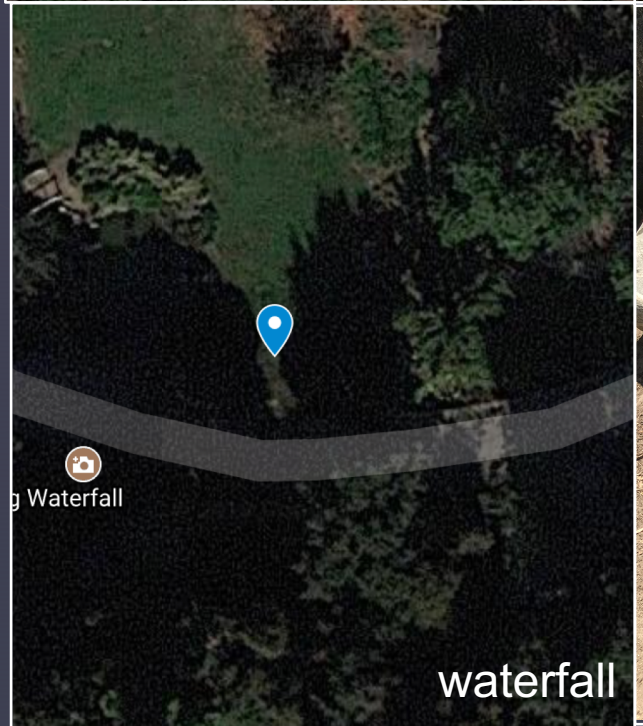
- Took data with geophones
  - Looked at Wilcoxn accelerometers, and laser vibrometers, but both required an external power source
  - Geophones do not require an amplifier or a power source
- Geophones convert ground movement into a voltage
- The voltage is the seismic activity due to the source

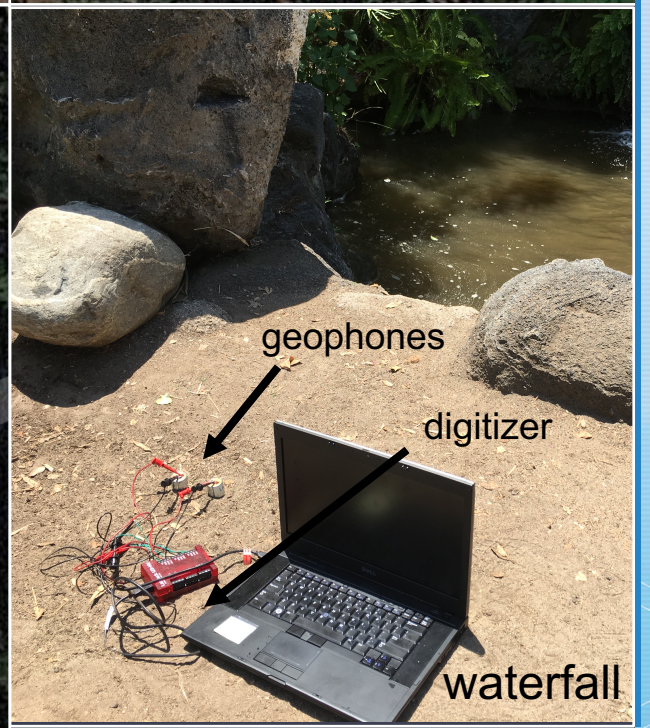
Measuring the effect of an existing seismic cloak

- Data collection with Ayooluwa Odemuyiwa
- Our three data collection sites
  - Freeway was very quiet
- Taking data at the waterfall

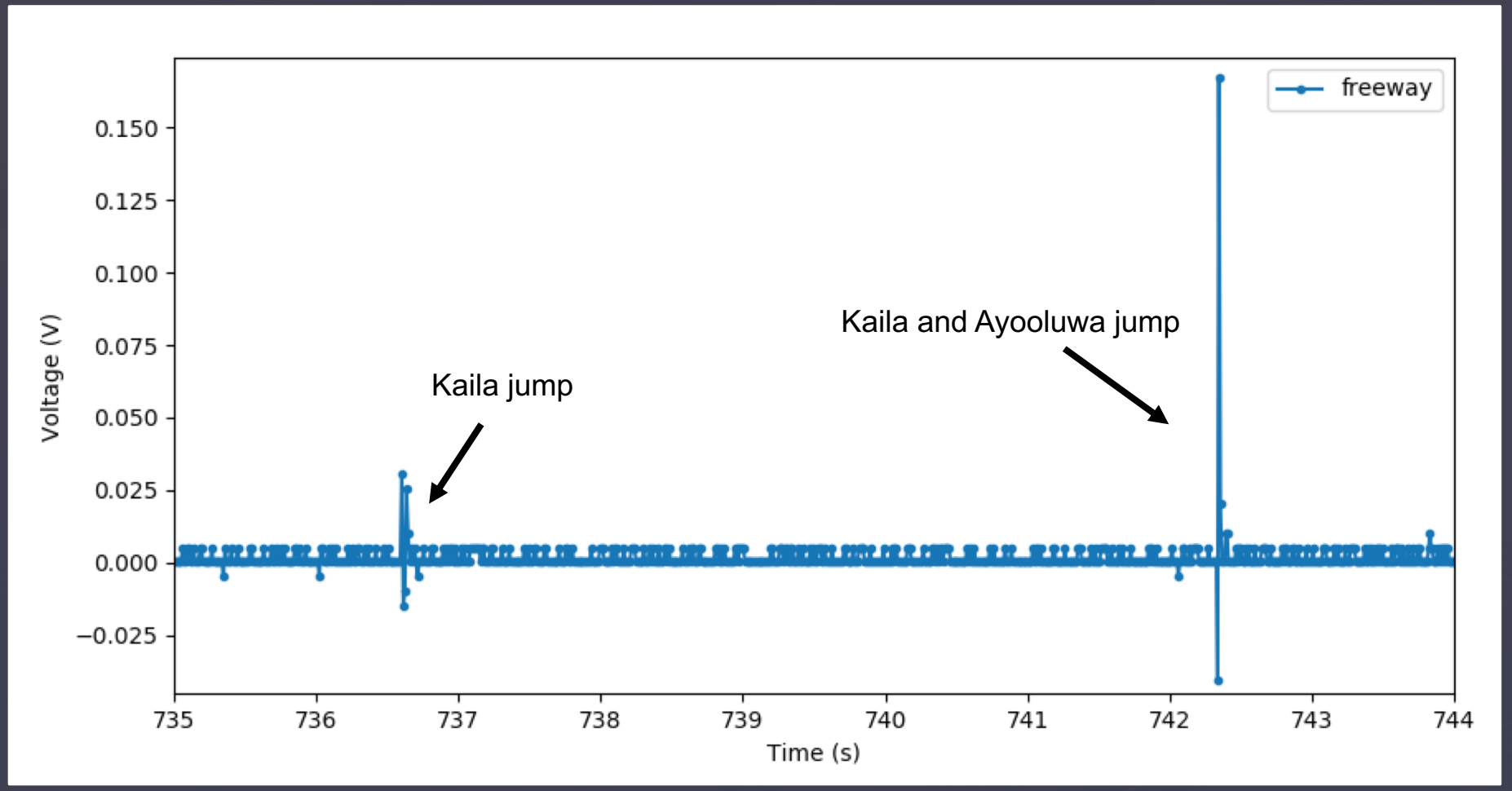




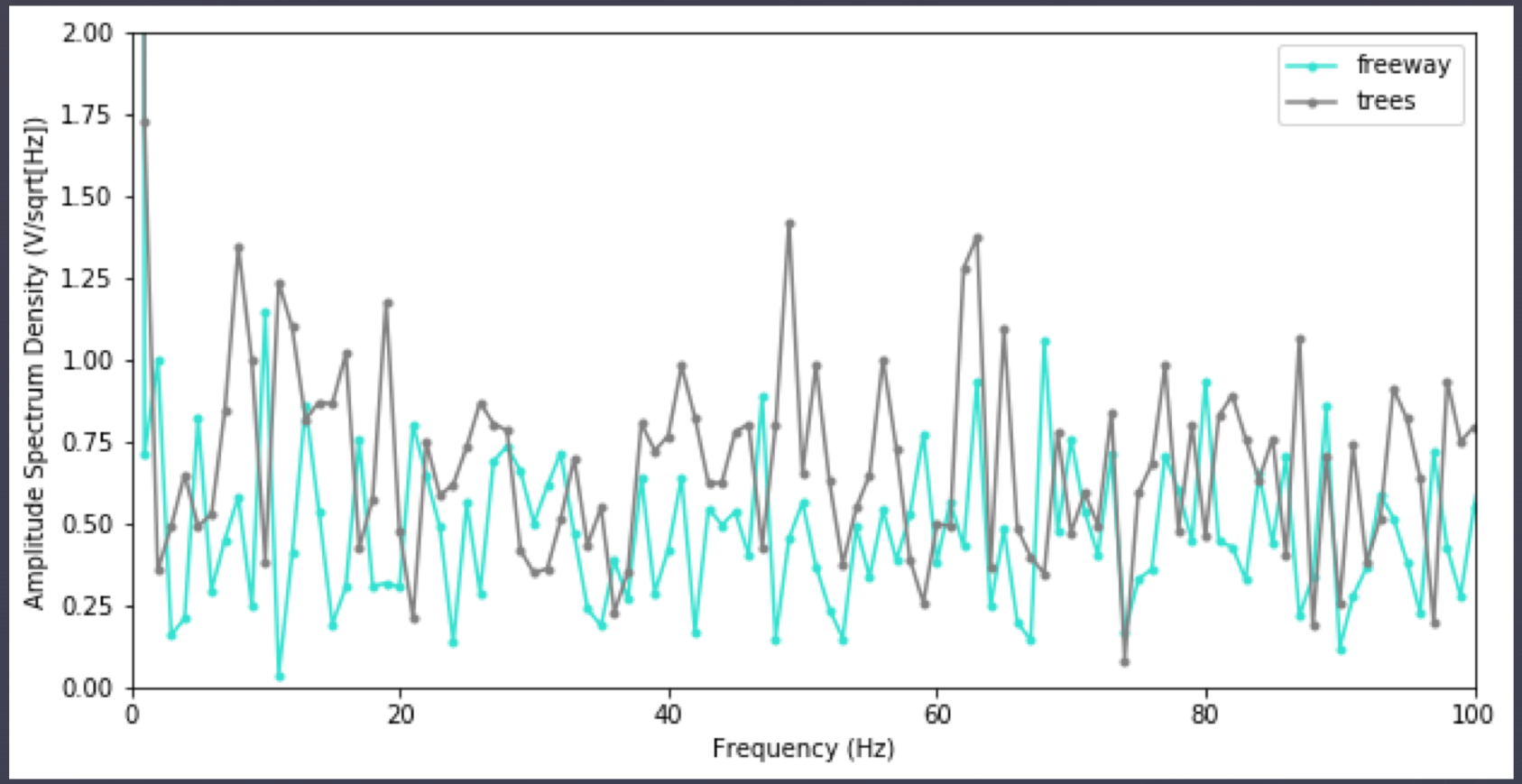




Measuring the effects of an existing seismic cloak



Measuring the effects of an existing seismic cloak



Future work

- Seismic cloaking has a lot of potential, but still needs work
  - Need to bring models down to 10 Hz and below
- Build a seismic cloaking model
- Take more data
  - More data sites around LA and central CA
  - Could LIGO Livingston already have an effective seismic cloak?
  - Go to France
- Seismic cloaking could factor into the location of future highly sensitive ground based detectors

Thank you!

Brittany Kamai
Ayooluwa Odemuyiwa
Rana X. Adhikari
Alan Weinstein
Alex Urban
Tom Callister
Caltech SFP
LIGO SURF
Cosmosis