Newtonian noise estimates with the Homestake Array

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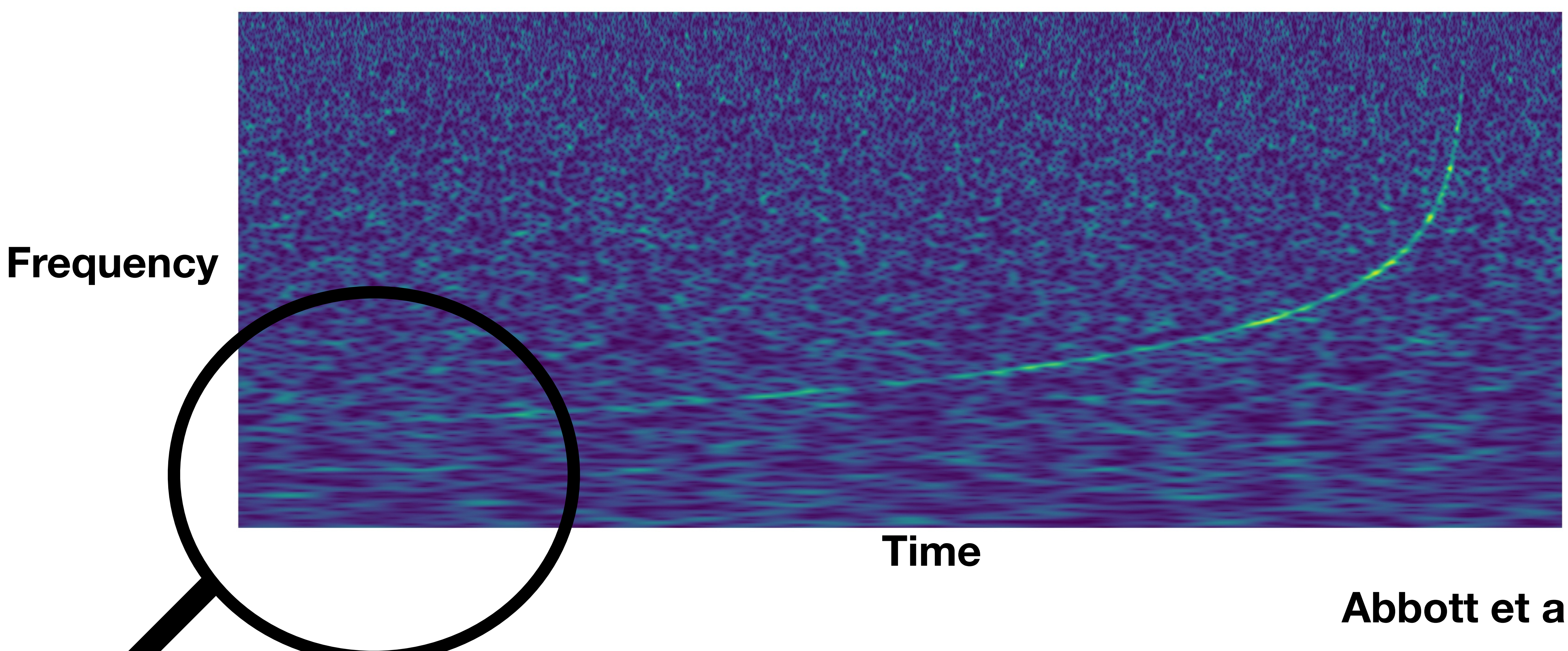
in collaboration with Jan Harms, Vuk Mandic, Pat Meyers

Vacuum Fluctuations at Nanoscale and Gravitation: theory and experiments
2 May 2019

Low frequency sensitivity for gravitational waves

GW170817



Abbott et al, 2017

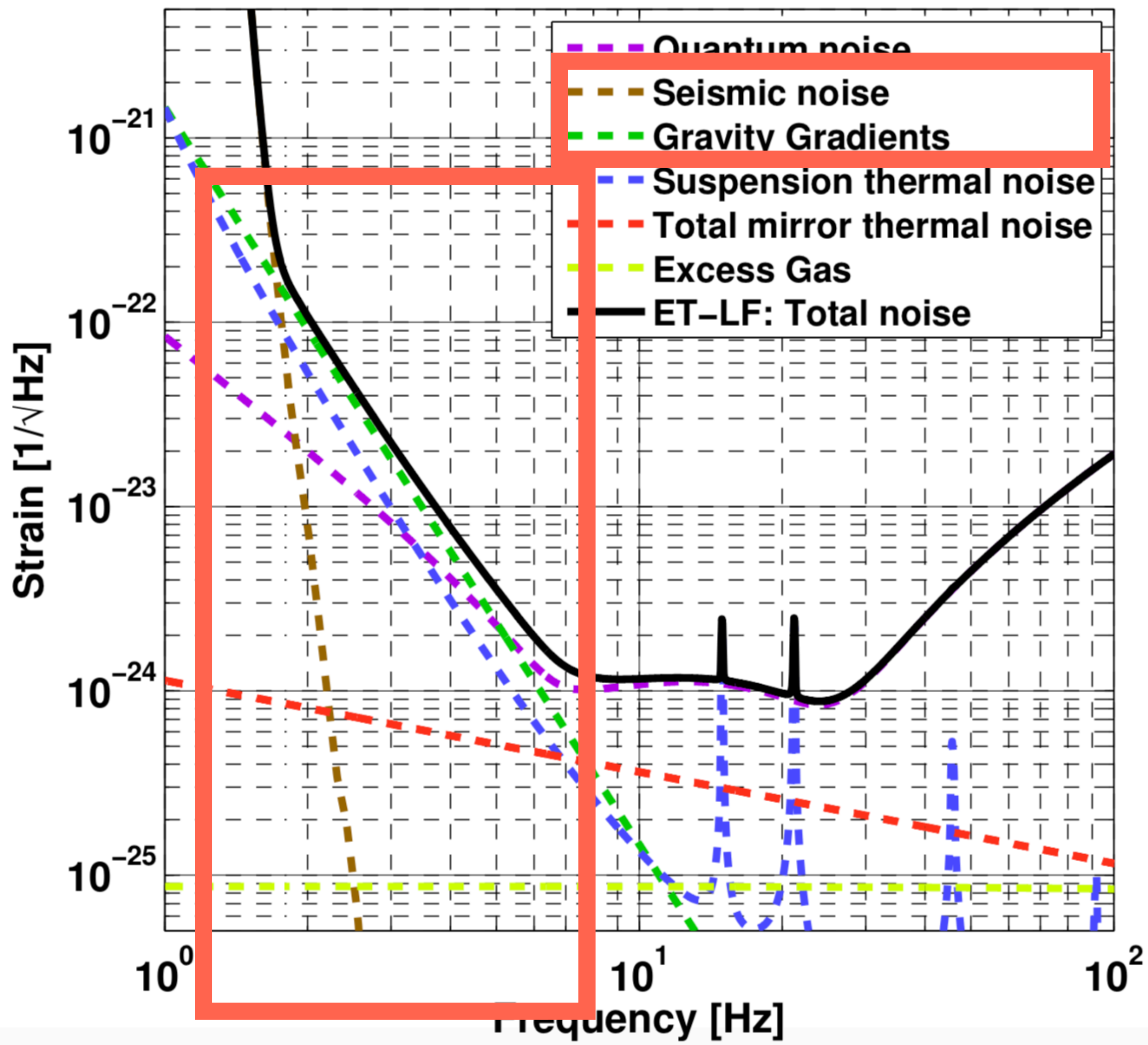
Some astrophysical applications…

- **See chirp signals earlier**
- **Neutron star *r*-modes**
- **Beat spin-down limit of CW signals**
- **Increased sensitivity to stochastic background**

Challenges to improving sensitivity

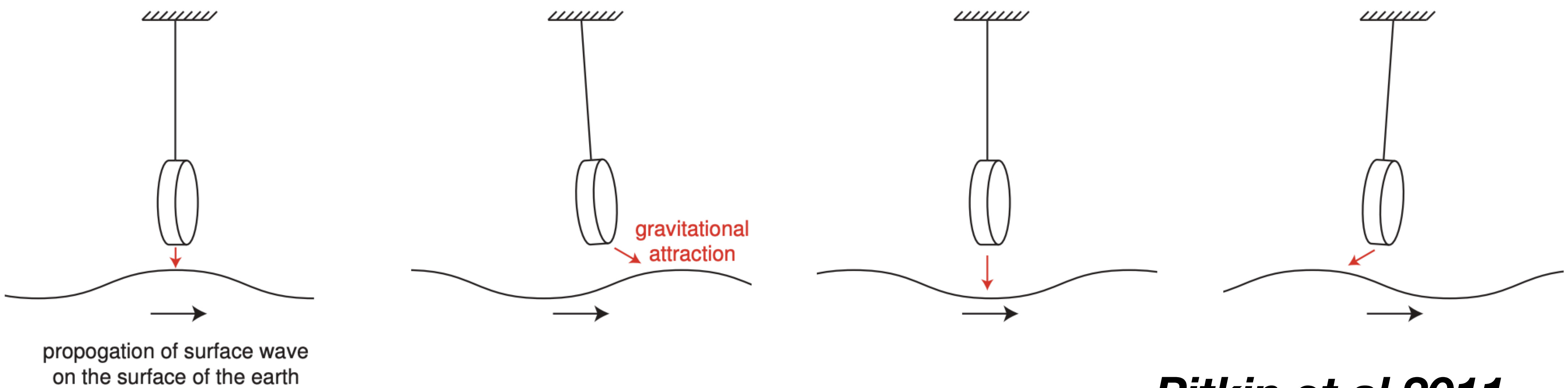
ET Design Document

ET design, optimized for low frequency

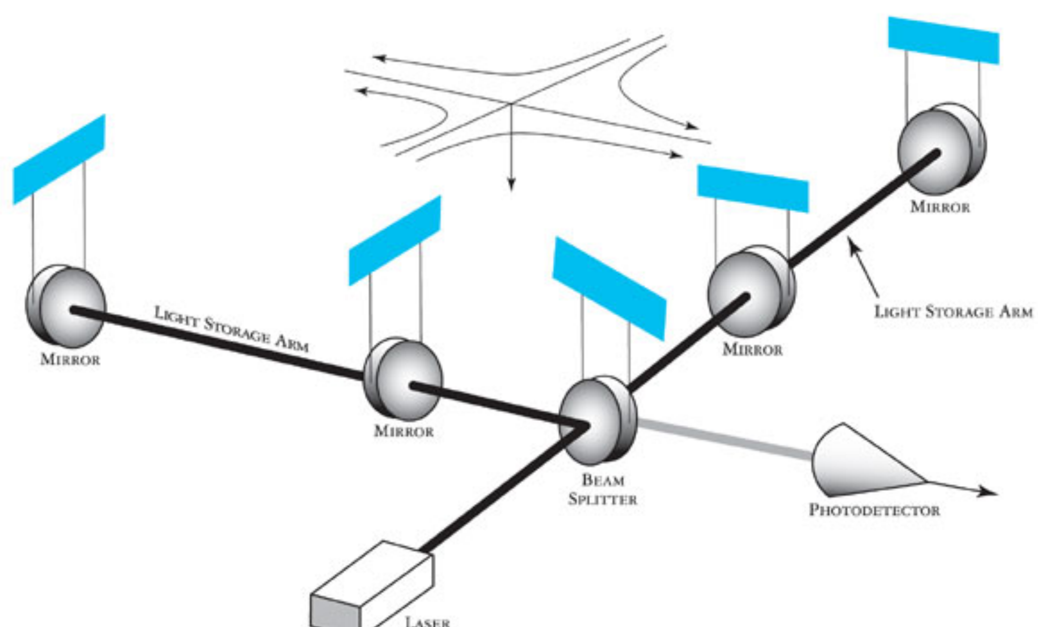


Low frequency sensitivity limited by seismic and Newtonian noise

Newtonian noise



Pitkin et al 2011

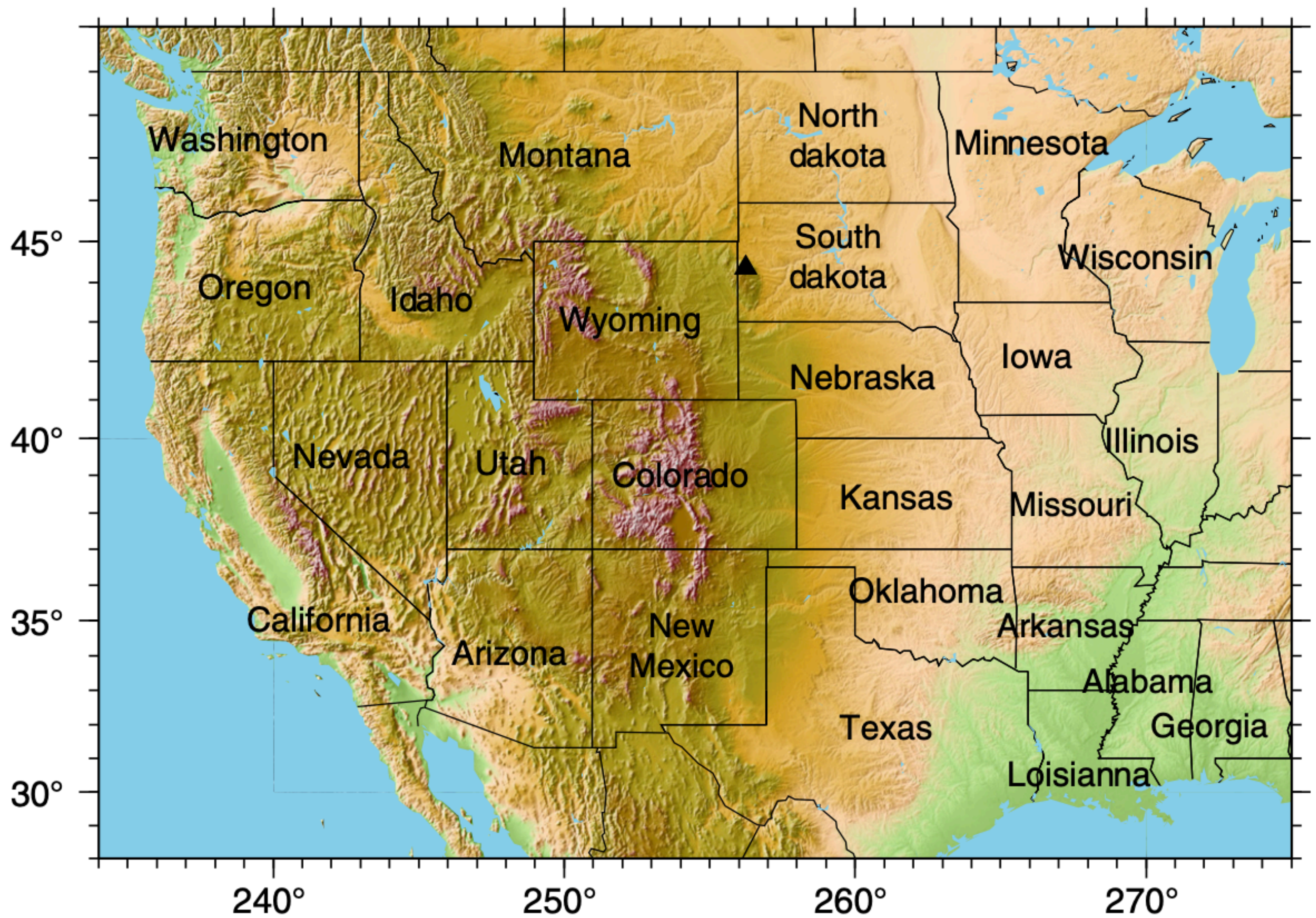


ligo.org

$$h = \frac{\delta x - \delta y}{L} = \frac{\delta a_x - \delta a_y}{(2\pi f)^2 L}$$

Important to accurately characterize newtonian noise underground

Homestake mine

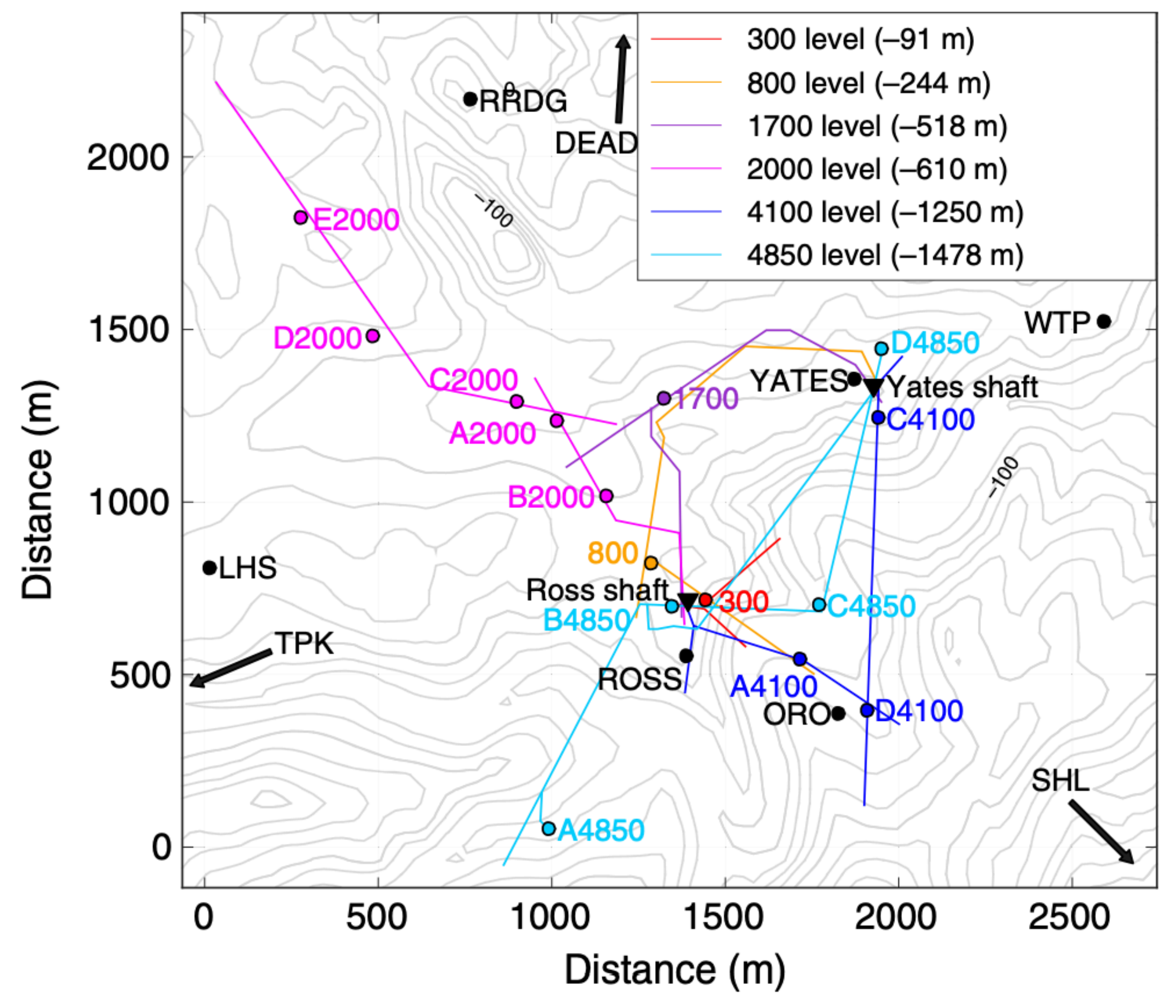


Sanford Lab

Mine in South Dakota, converted into physics research facility

Homestake array

Mandic et al, 2018



Array spans ~ cubic mile
Broadband seismometers (STS-2, Gurlap)
GPS-synchronized stations
Data collected May 2015-September 2016

Collaboration

Collaboration with geophysicists and gravitational-wave scientists

University of Minnesota

Vuk Mandic*
Patrick Meyers (now at Melbourne)
Tanner Prestegard (now at UWM)
Andrew Matas (now at AEI)

CalTech

Victor Tsai*
Daniel Bowden
(now at ETH-Zurich)
Michael Coughlin

Indiana University

Gary Pavlis*
Ross Caton

Gran Sasso

Jan Harms

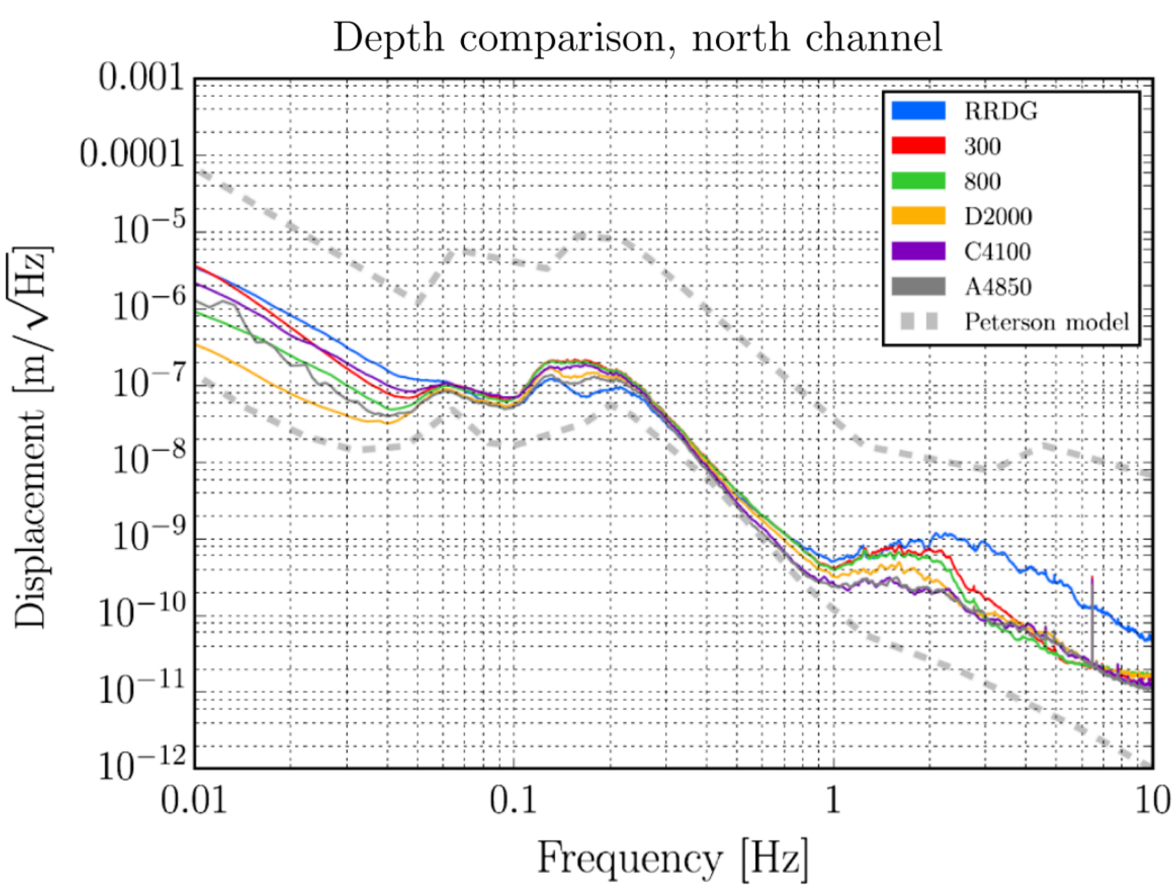
SURF@Homestake

Papers covering a variety of topics

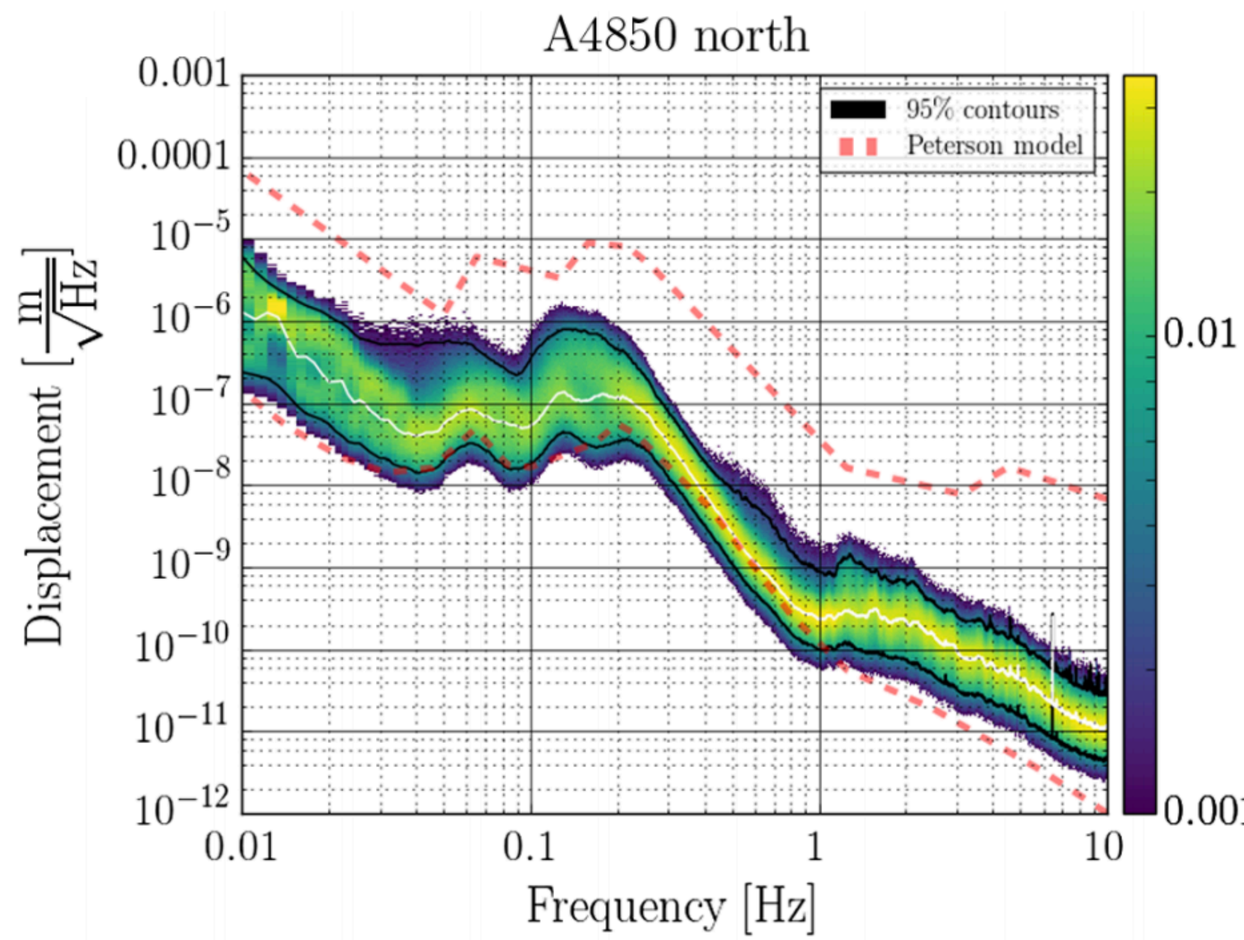
A 3D Broadband Seismometer Array Experiment at the Homestake Mine, Mandic et al, Seismological Research Letters 2018
Coherence-Based Approaches for Estimating the Composition of the Seismic Wavefield, Coughlin et al, JGR Solid Earth 2019
R-wave eigenfunction paper in review at BSSN
Future papers planned on surface wave measurements, newtonian noise, …

Seismic environment at homestake

Depth comparison



Time comparison



Mandic et al, 2018

R wave eigenfunction measurements

Mandic et al, 2018
Meyers Thesis

Bi-exponential form

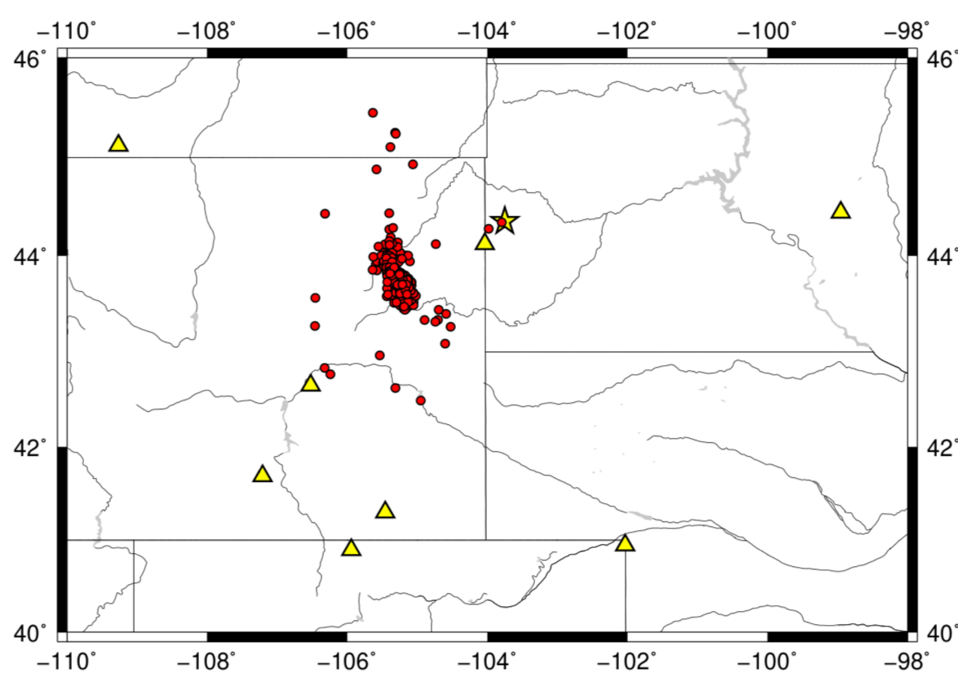
$$r_H(f,z;\vec{\theta}) = \left(e^{-2\pi f z \frac{a_1}{v_R(f)}} + c_2 e^{-2\pi f z \frac{a_2}{v_R(f)}}\right) \times \frac{1}{1+c_2}$$

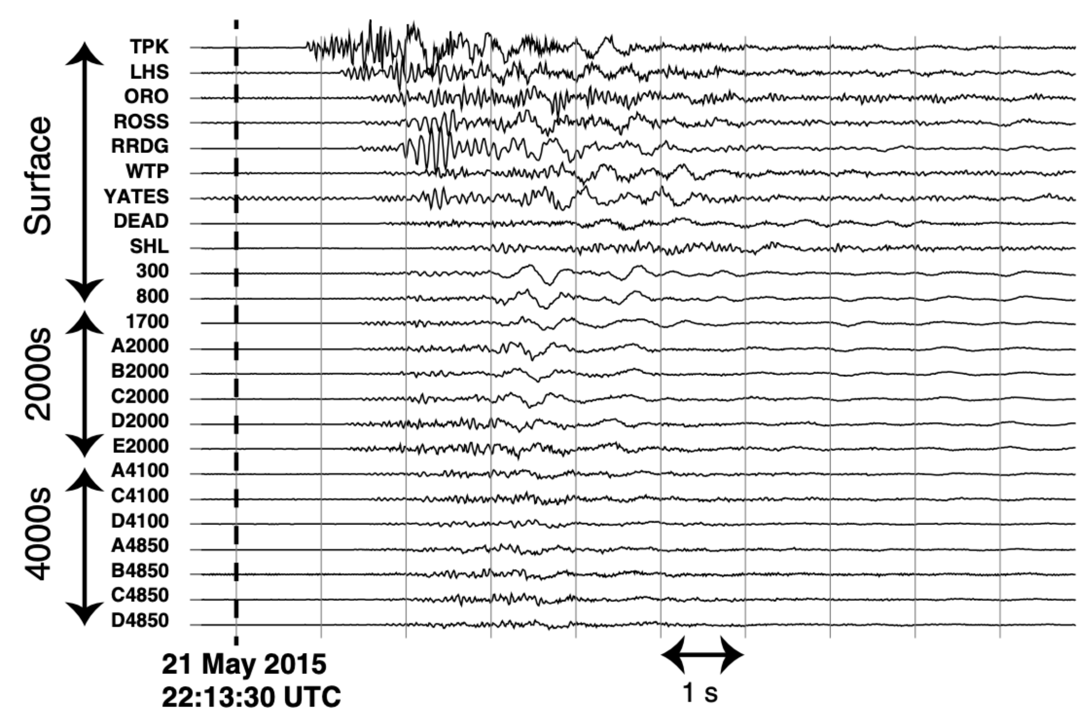
$$r_V(f,z;\vec{\theta}) = \left(e^{-2\pi f z \frac{a_3}{v_R(f)}} + c_4 e^{-2\pi f z \frac{a_4}{v_R(f)}}\right) \times \frac{N_{vh}}{1+c_4}$$

$$v_{\mathrm{R}}(f) = v_{1\mathrm{Hz}} f^{\alpha}$$

other velocity models considered in upcoming dedicated paper

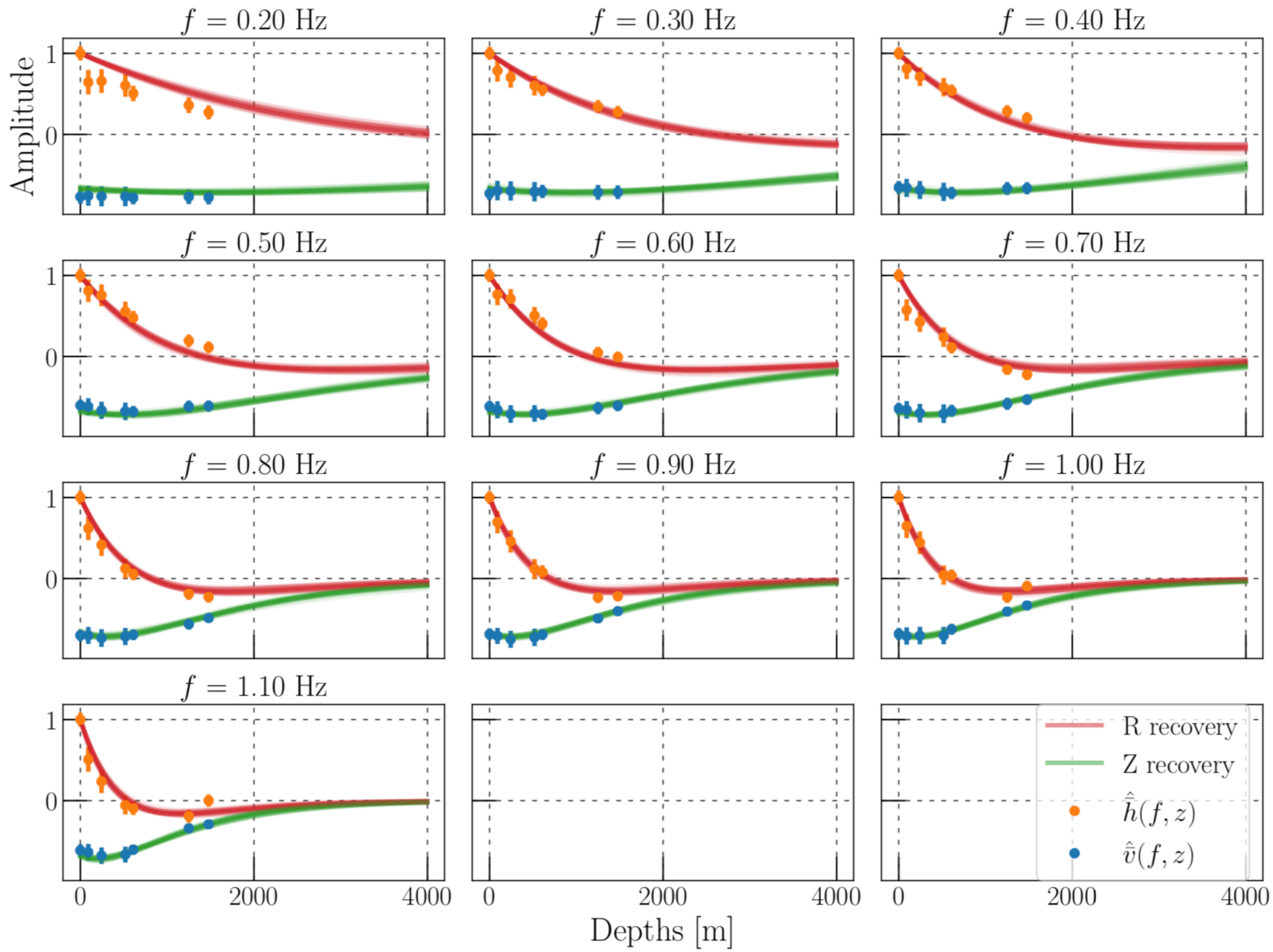
Transient events





R wave eigenfunction measurements

Meyers Thesis



Radiometer method

"Synergy": method inspired by GW applications, generalized to geophysics

Cross-correlation ~ Sky maps for each polarization x Kernel

$$\langle Y_{i\alpha,j\beta}(f)\rangle = 2T\Delta f \sum_m \sum_A \sum_a S_{m,A,a}\gamma^{i\alpha,j\beta}_{m,A,a}$$

Polarization **Time delay**

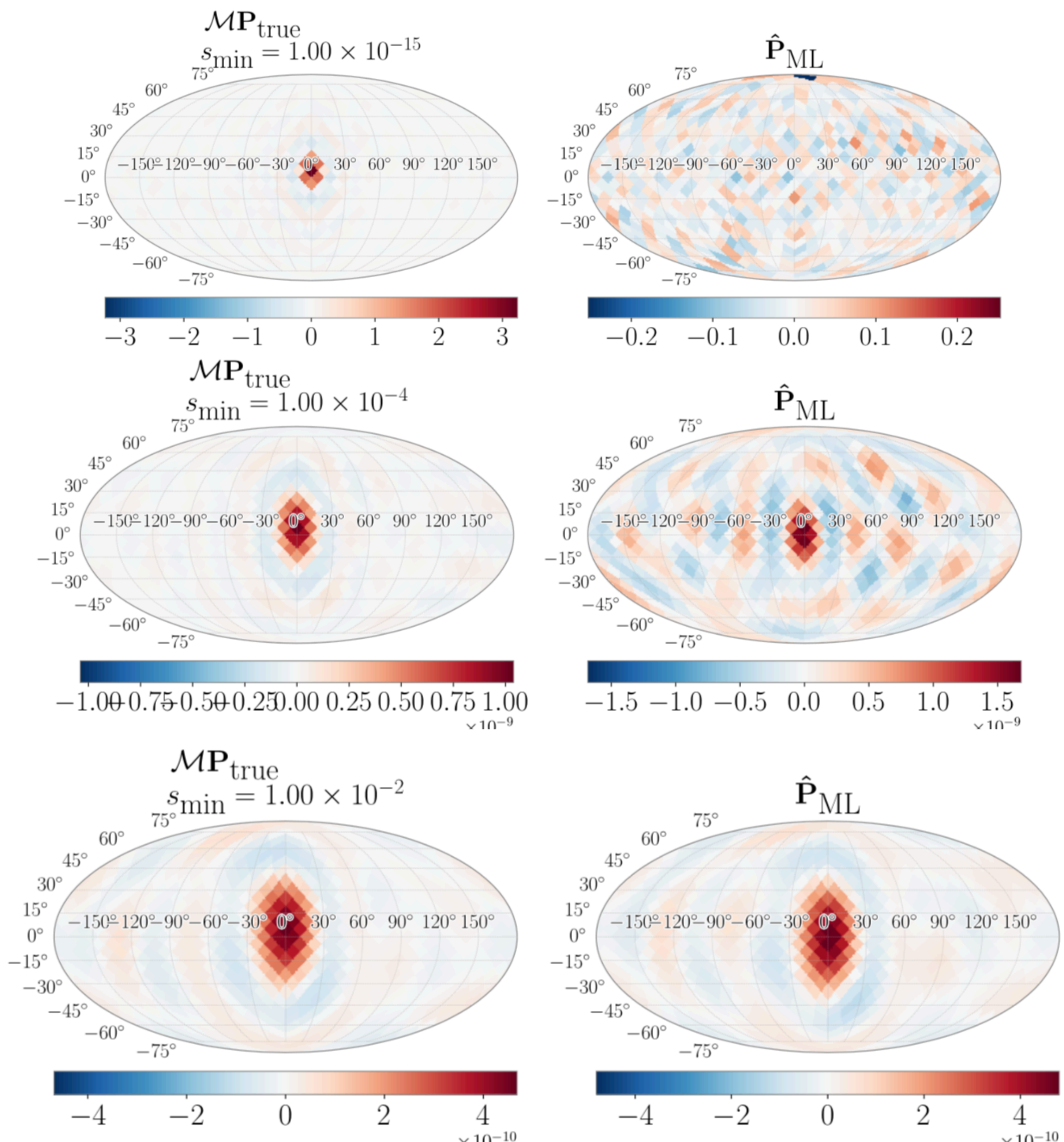
$$\gamma^{i\alpha,j\beta}_{m,a,A} = \int d\hat{\Omega}\, Q_a(\hat{\Omega}) \boxed{\left(\vec{e}_{m,A}(\hat{\Omega})\cdot\hat{\alpha}\right)\left(\vec{e}_{m,A}(\hat{\Omega})\cdot\hat{\beta}\right)}\, \boxed{e^{2\pi i f\hat{\Omega}\cdot\Delta\vec{x}/v_m}}$$

Simple idea: to get sky map, invert the kernel
In practice, this is an ill-conditioned matrix so this needs to be done with care

Meyers Thesis

Tradeoff

Better angular resolution



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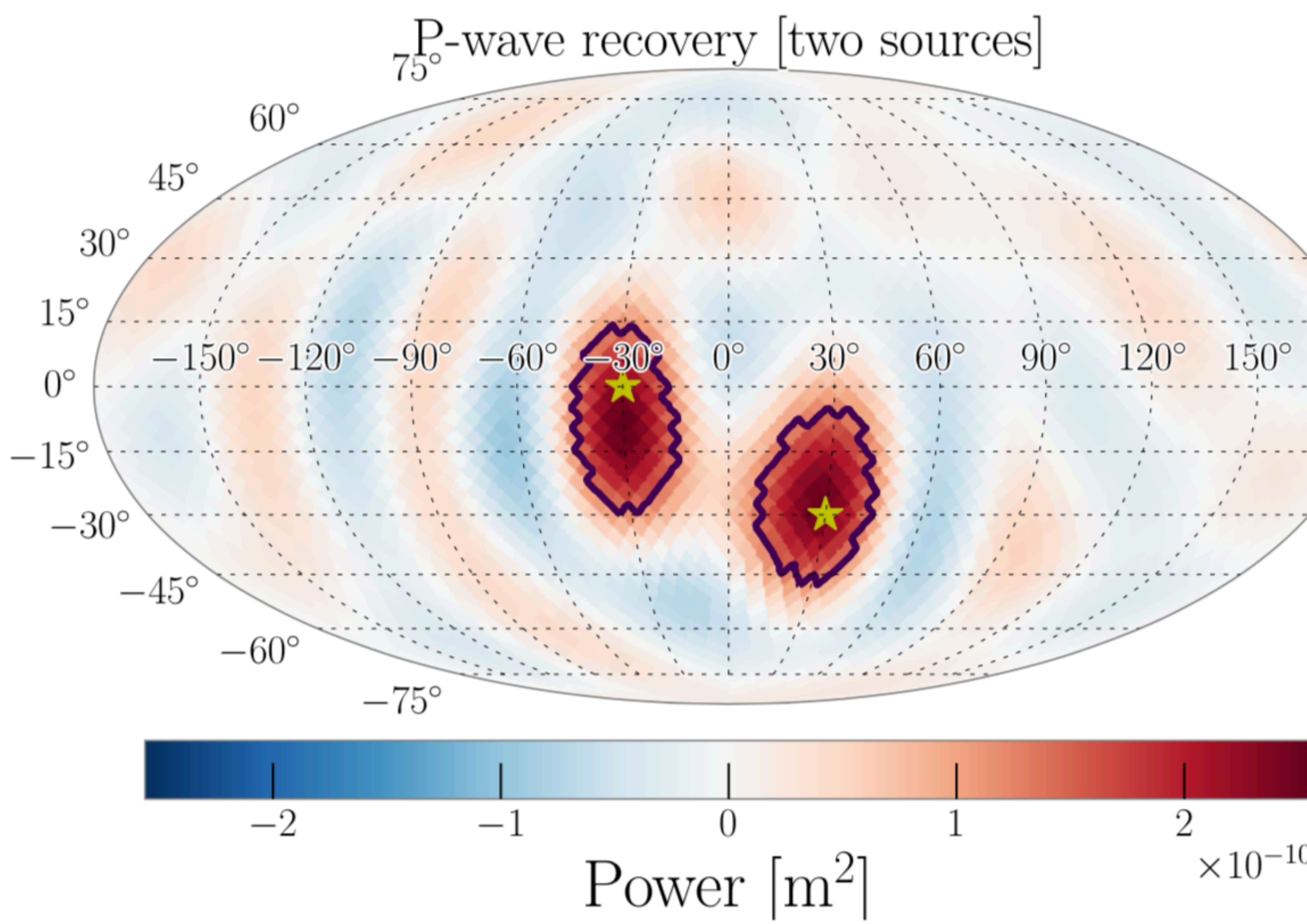
Less covariance between pixels

Verification: direction

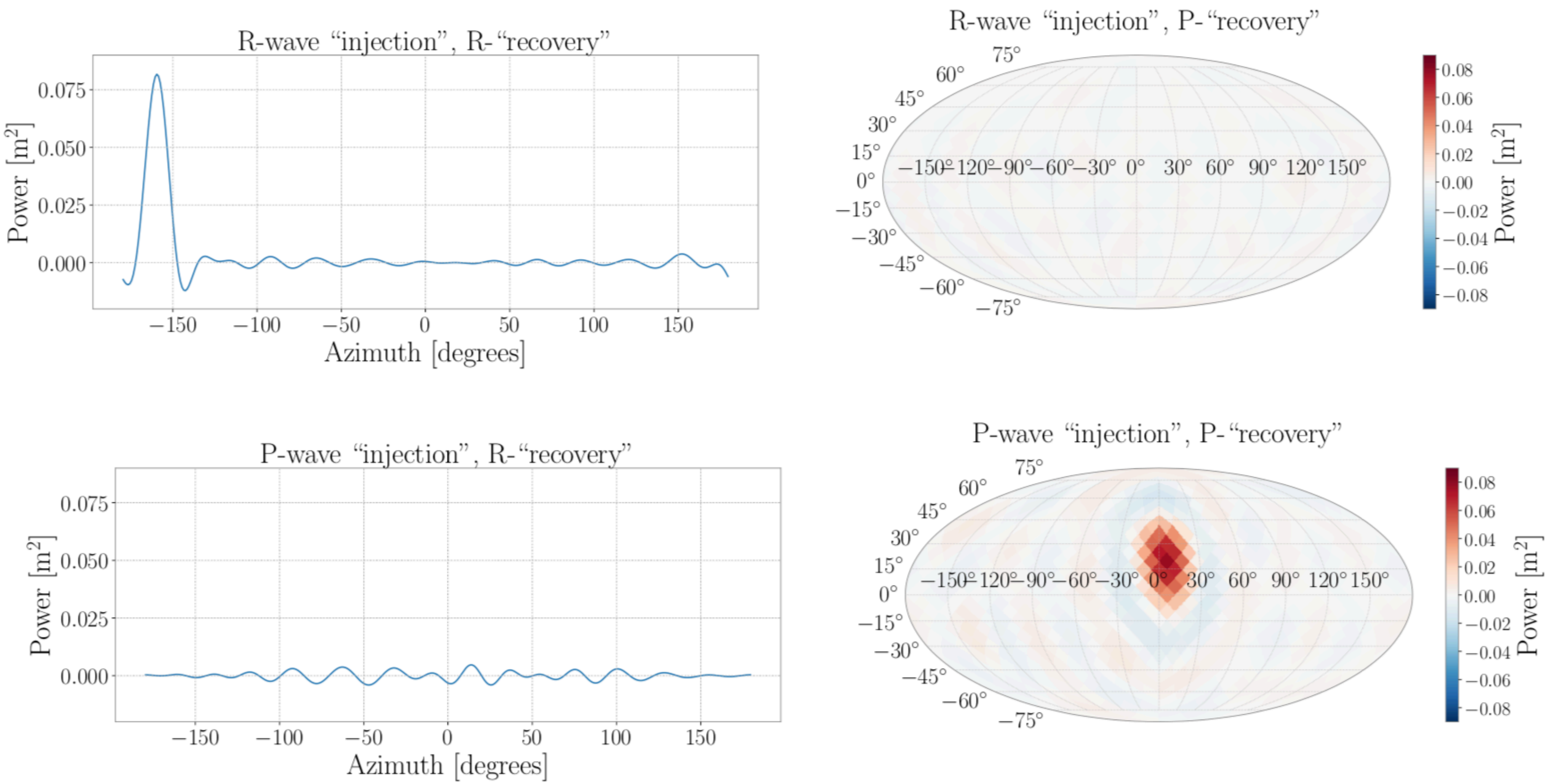
Meyers Thesis



Can resolve point sources

Verification: Polarization

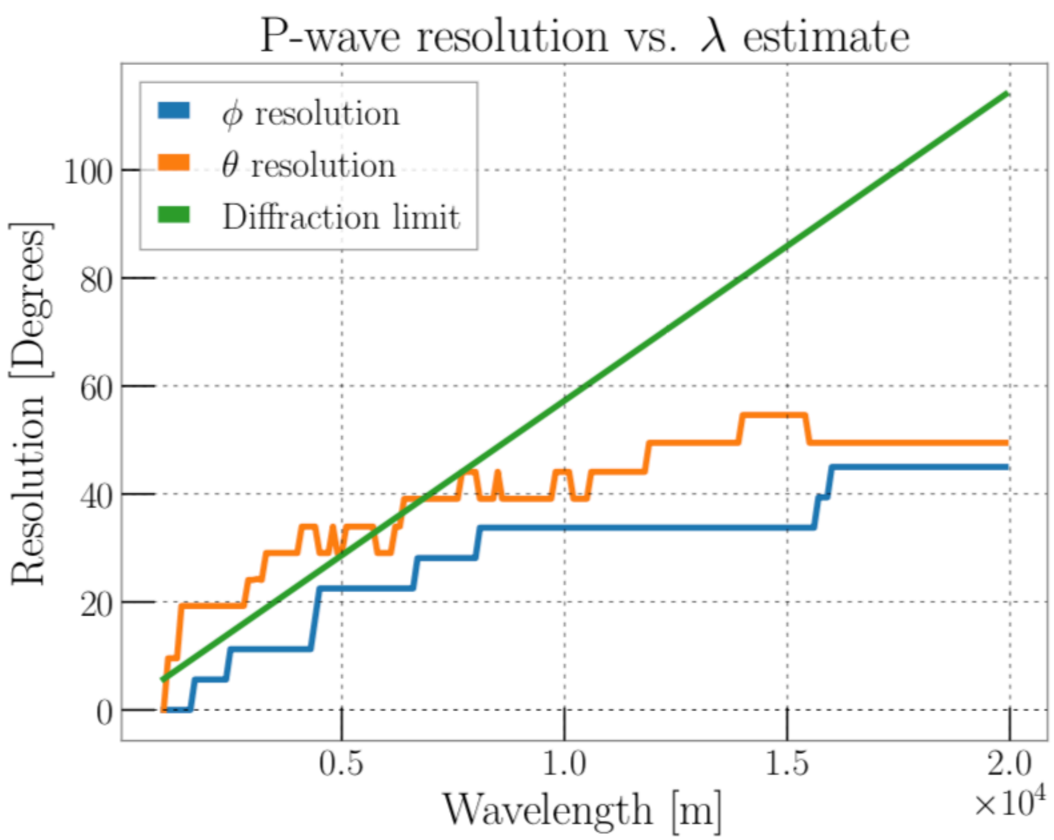
Meyers Thesis

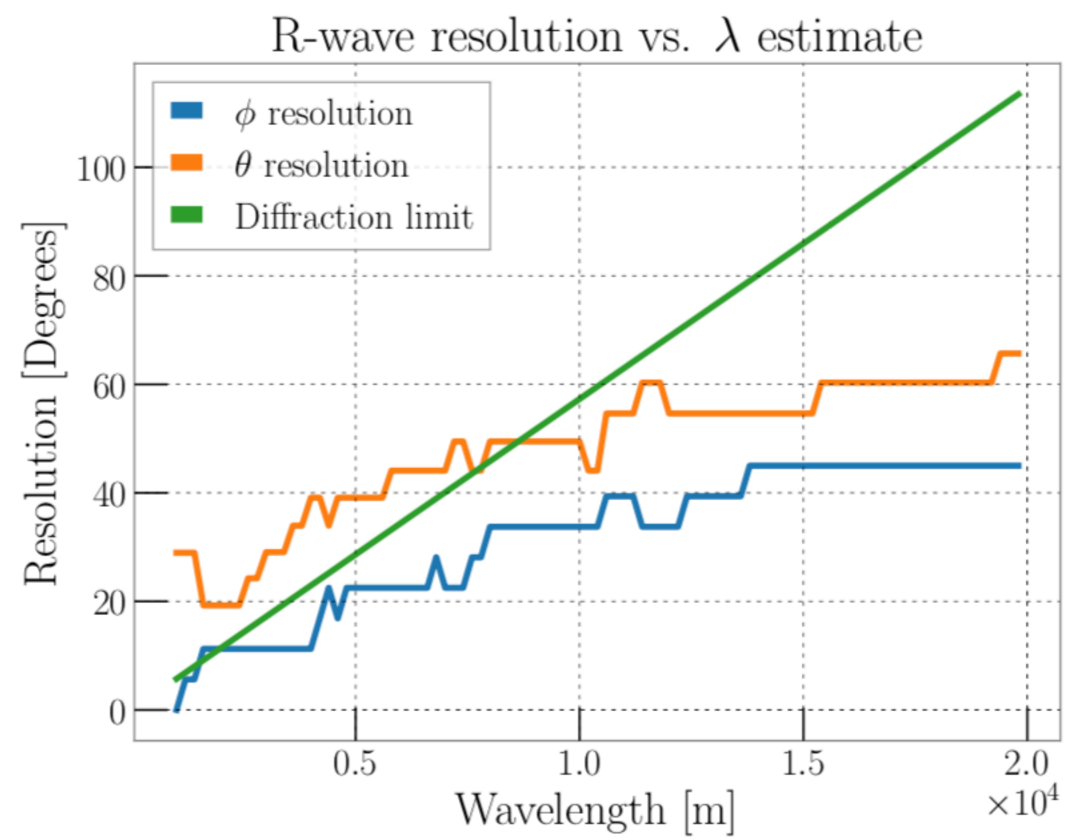


Check both for false positives and false negatives

Angular resolution

Meyers Thesis





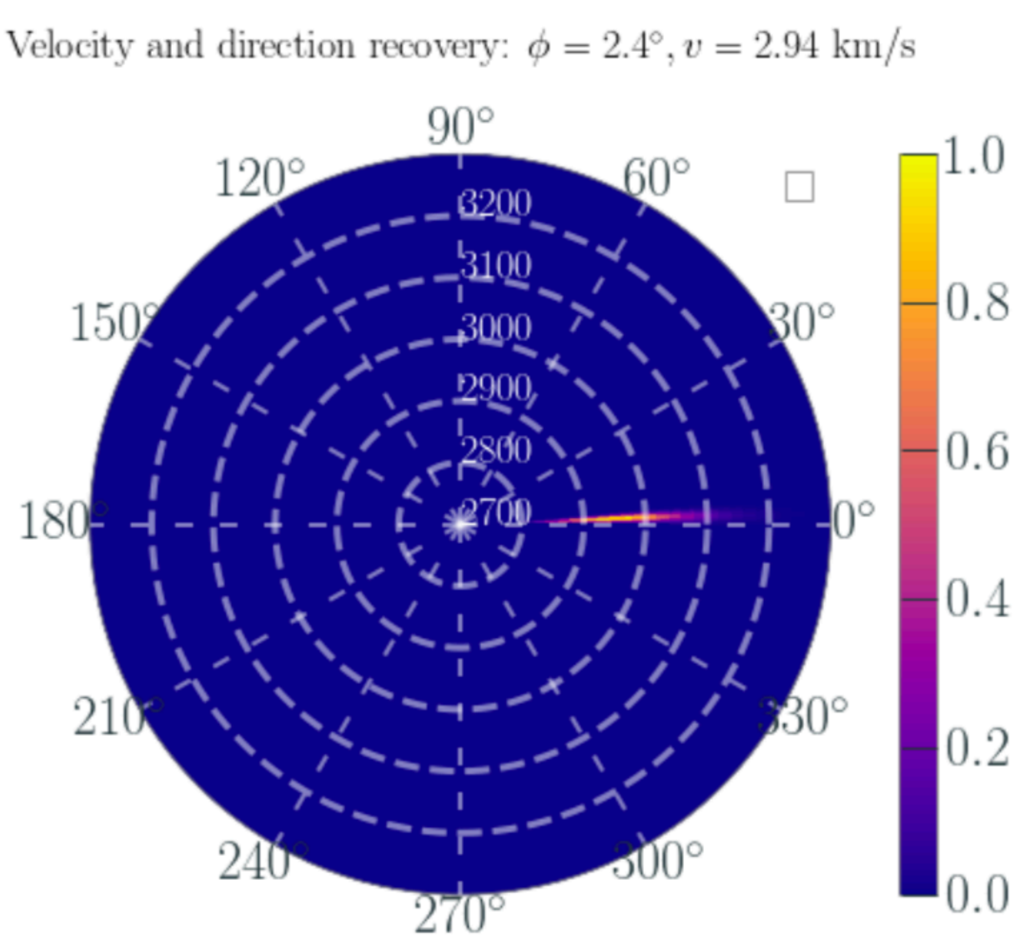
Diffraction limit $$\Delta\theta \sim \frac{\lambda}{D}$$

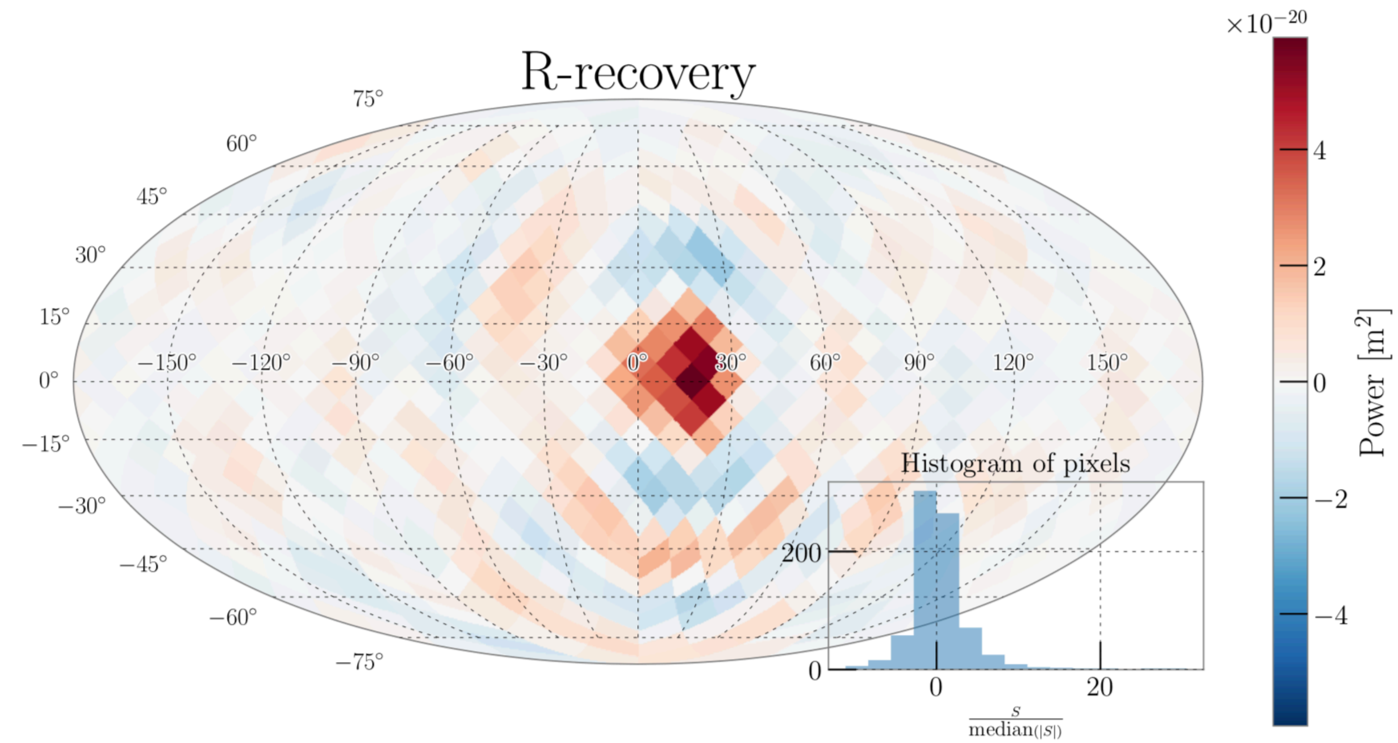
Polarization also provides direction information

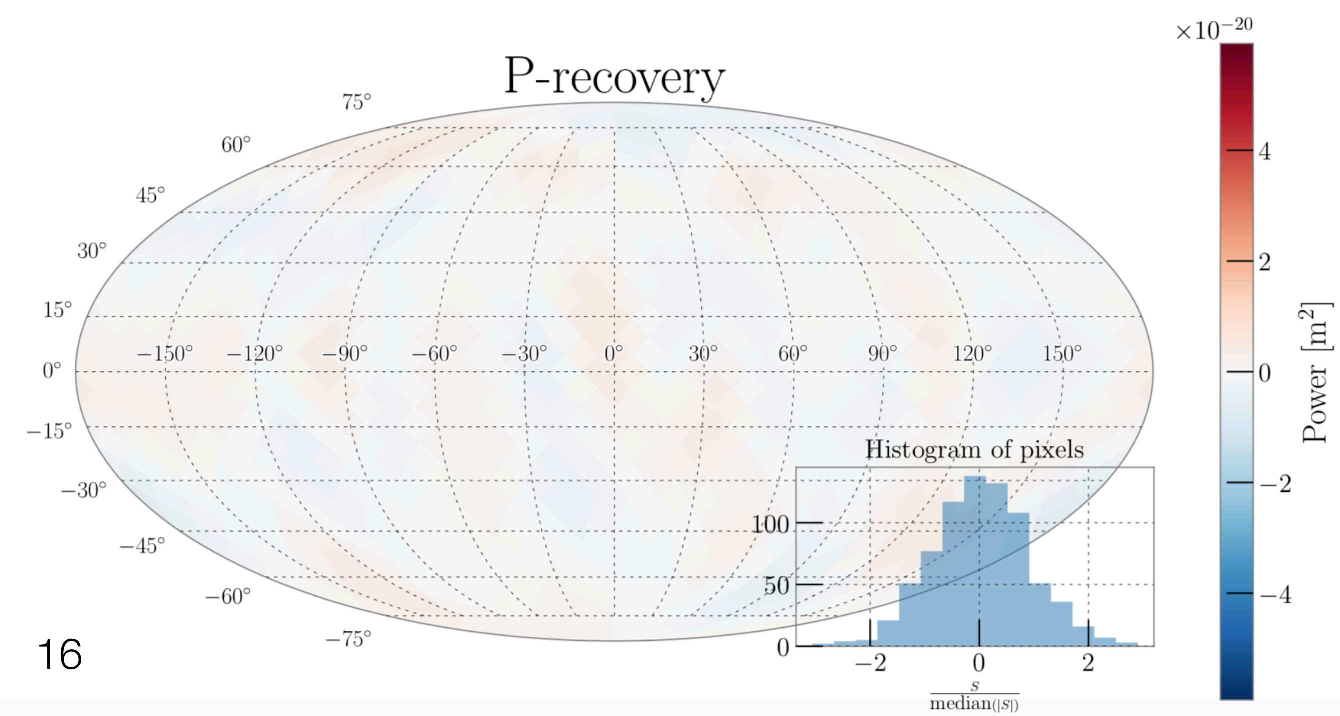
Application to real data: Regular source

Meyers Thesis

Point source, originating from nearby town
Radiometer direction agrees with location



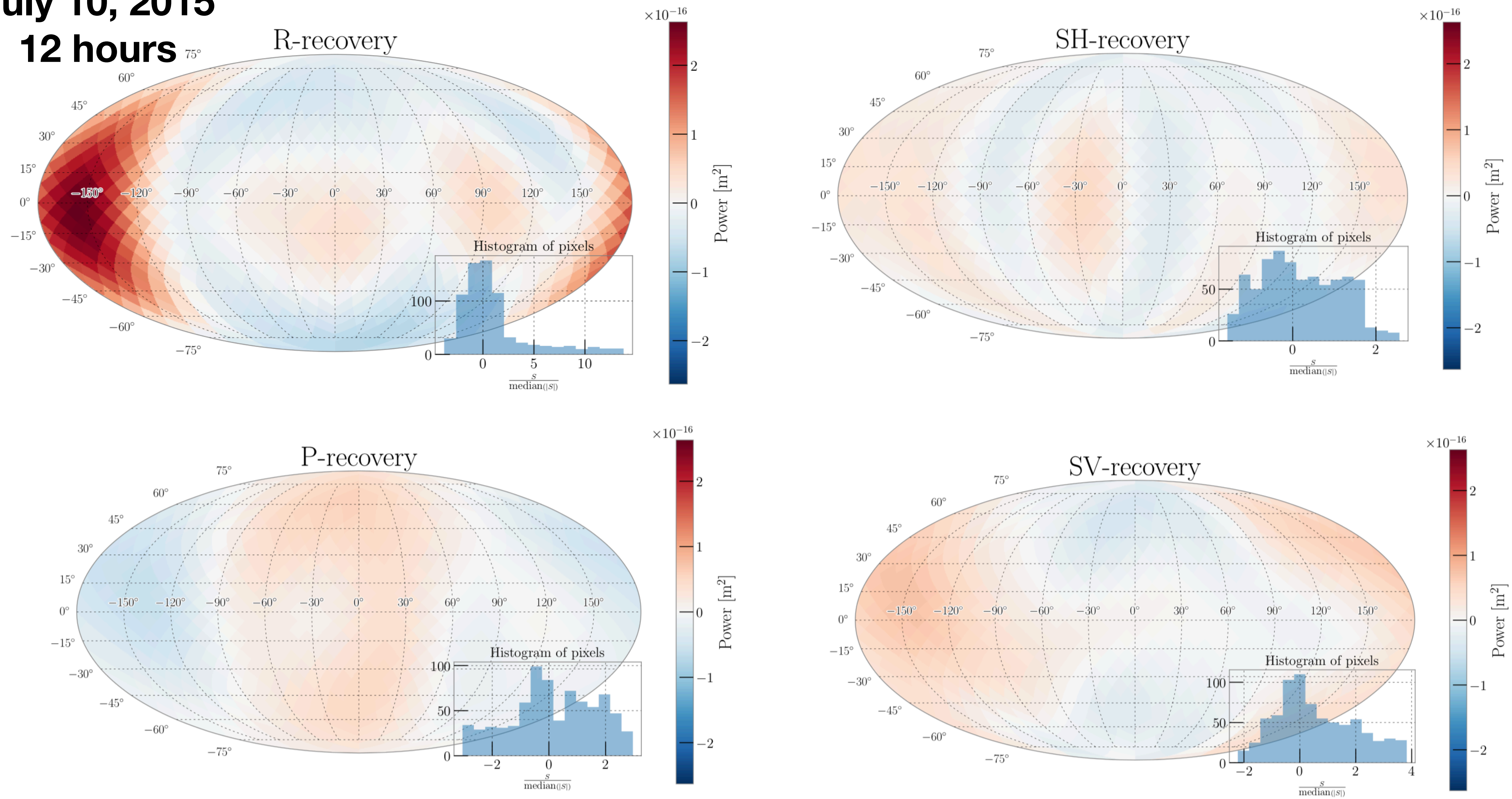




Application to real data: Loud microseism

Meyers Thesis

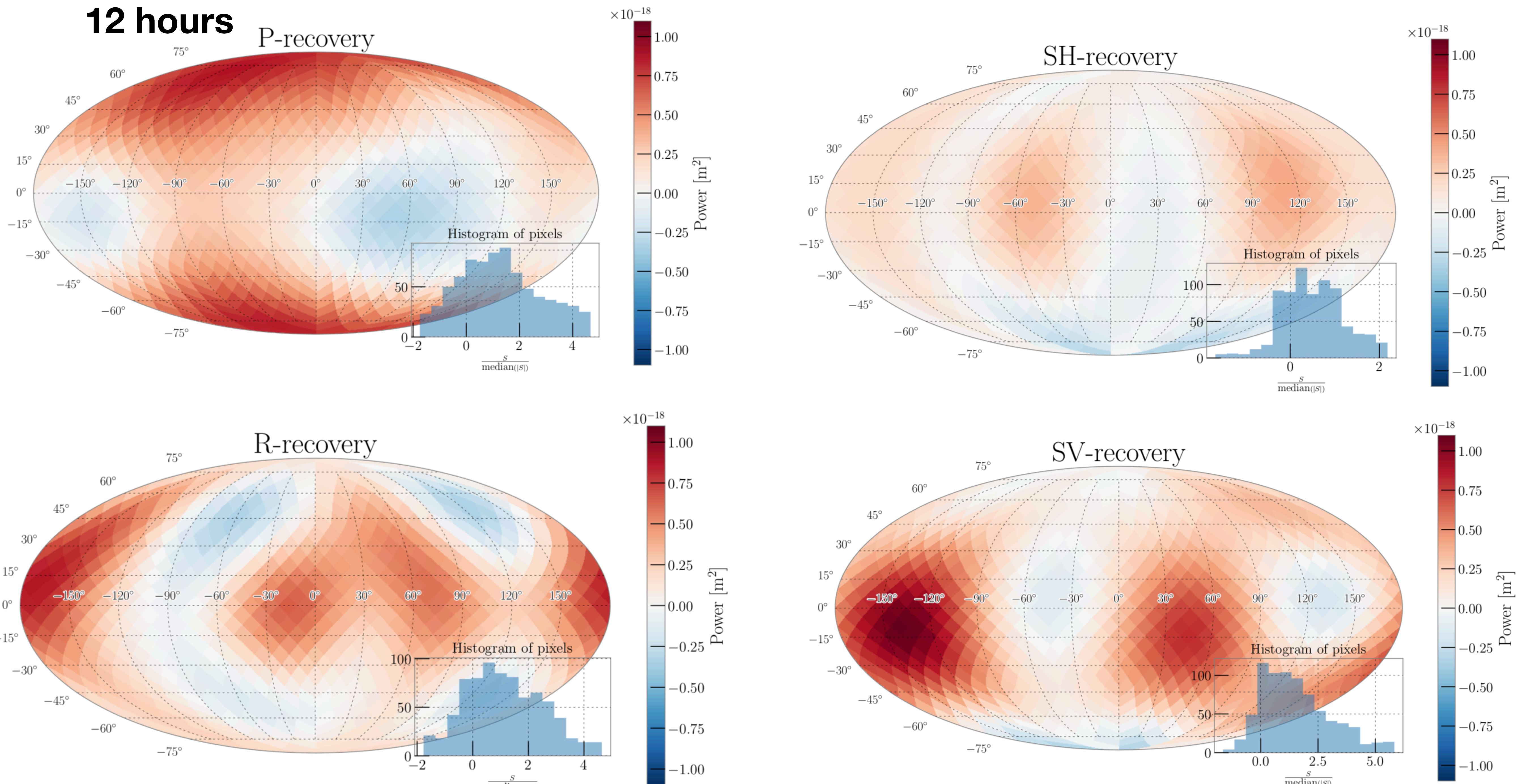
July 10, 2015
12 hours



Application to real data: Quiet microseism

Meyers Thesis

June 3, 2015
12 hours



Newtonian noise: estimation method

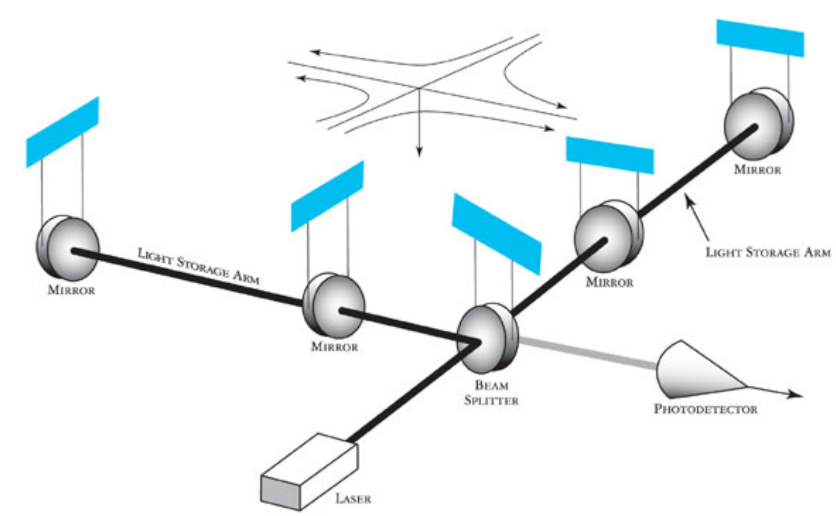
Harms, 2015

Account for different mechanisms…

- **Different polarizations induce different NN perturbations**
- **Interactions of seismic waves with surface**
- **Reflection with cavity walls for underground masses (assume small cavity)**

$$h = \frac{\delta x - \delta y}{L} = \frac{\delta a_x - \delta a_y}{(2\pi f)^2 L}$$

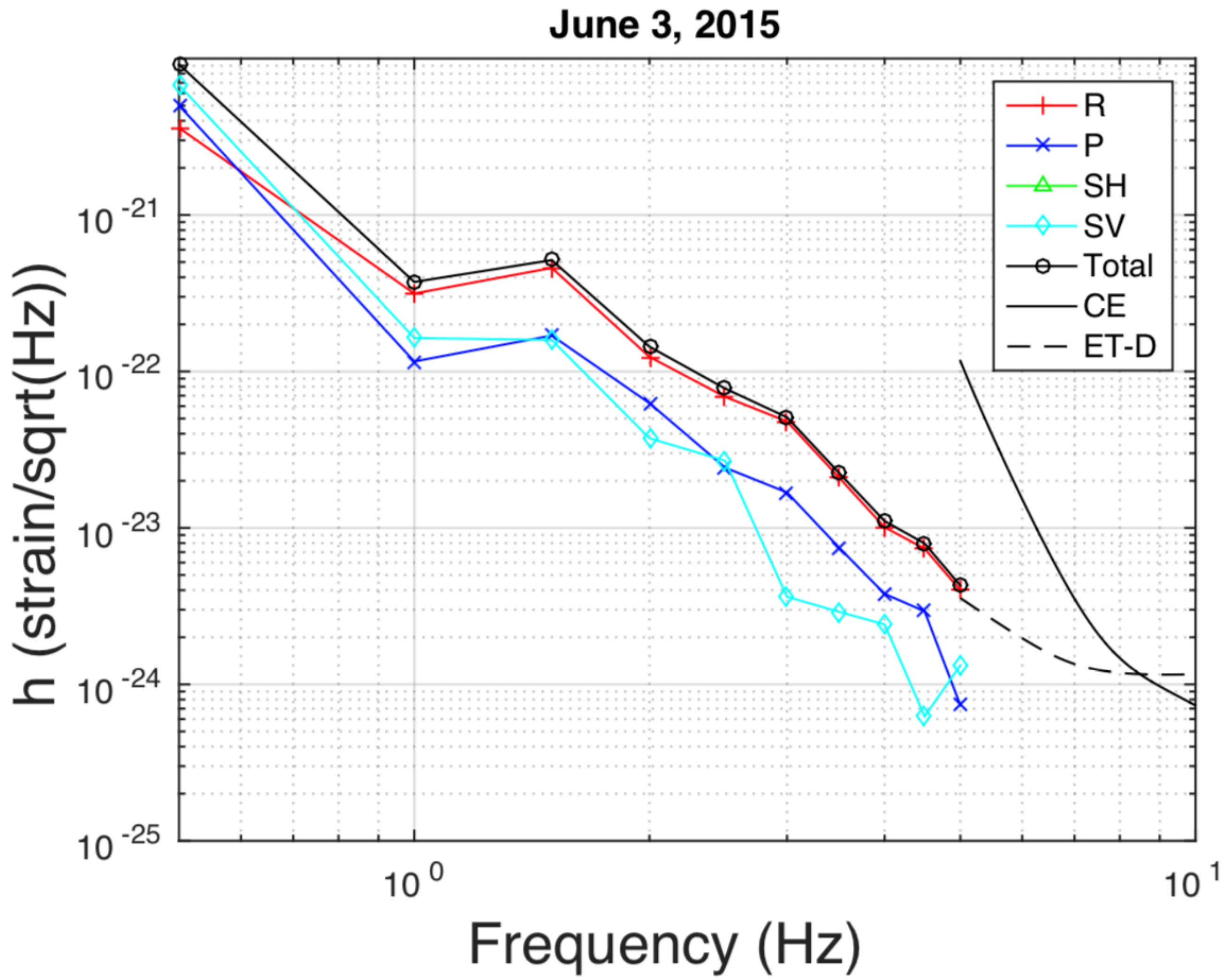
$$h_{\mathrm{NN}} = \frac{\sqrt{2\left(\delta a_{x,\mathrm{rms}}^2 + \delta a_{y,\mathrm{rms}}^2\right)}}{(2\pi f)^2 L}$$

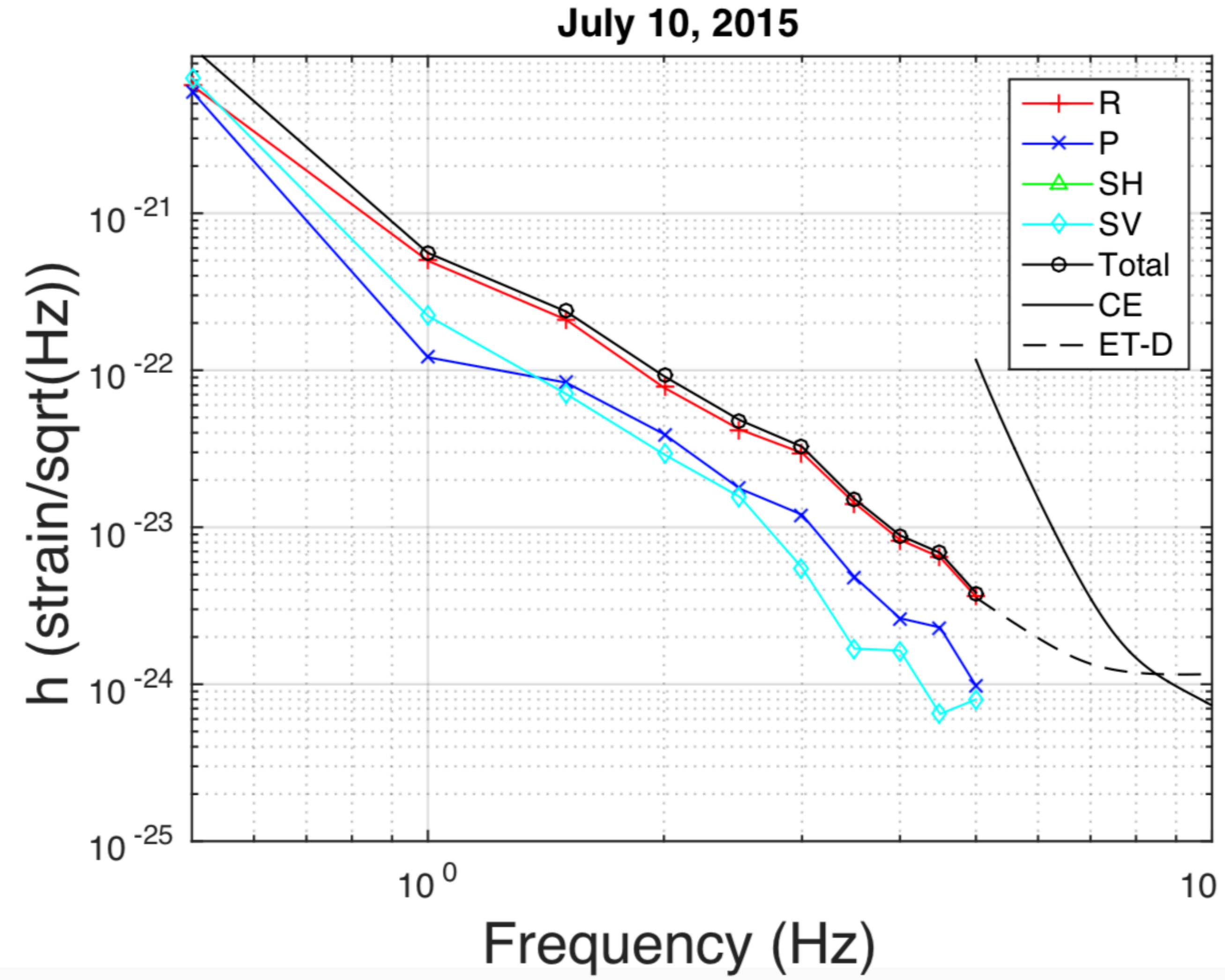


Expect radiometer to capture reflections from surface

Newtonian noise, surface

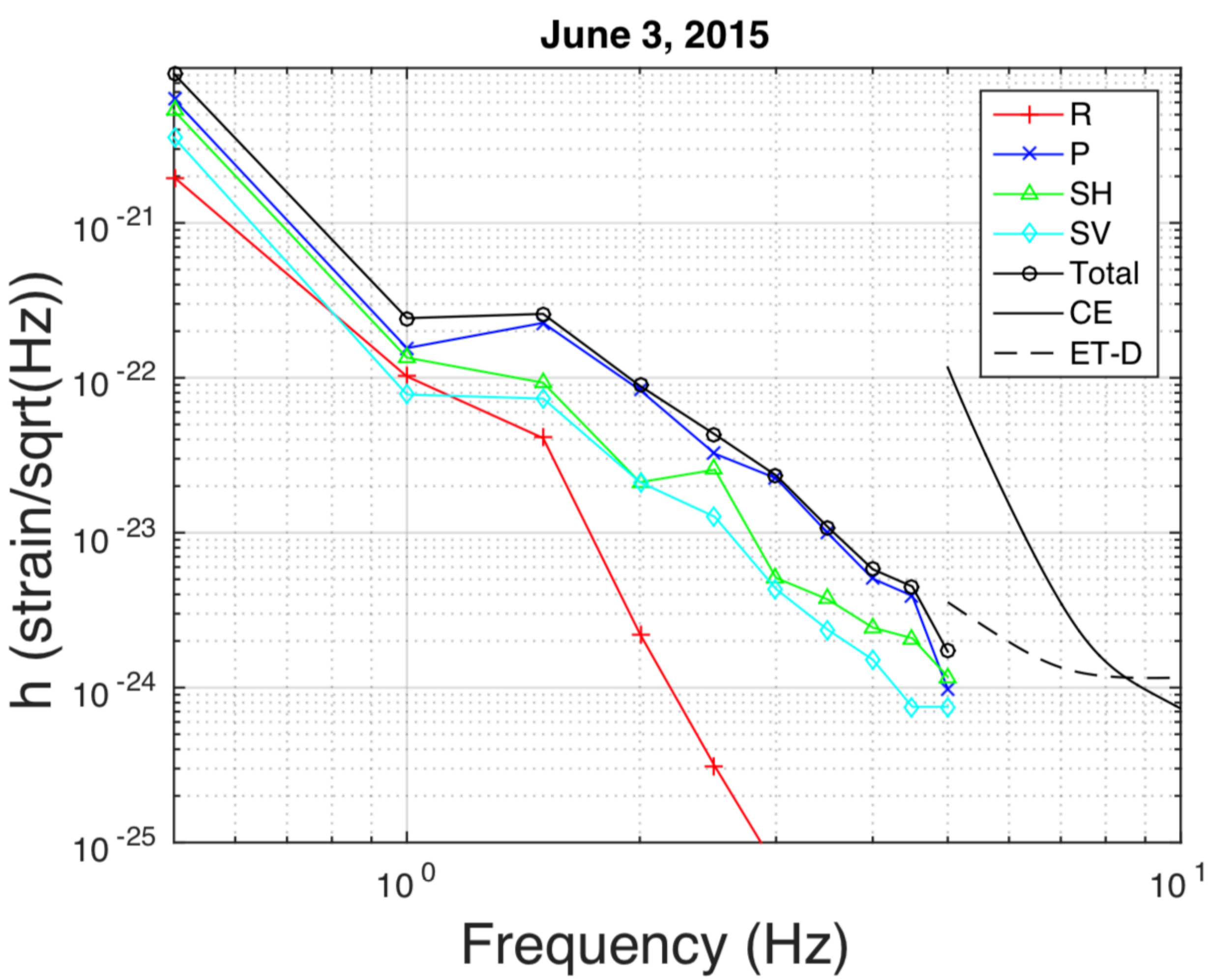
Meyers Thesis

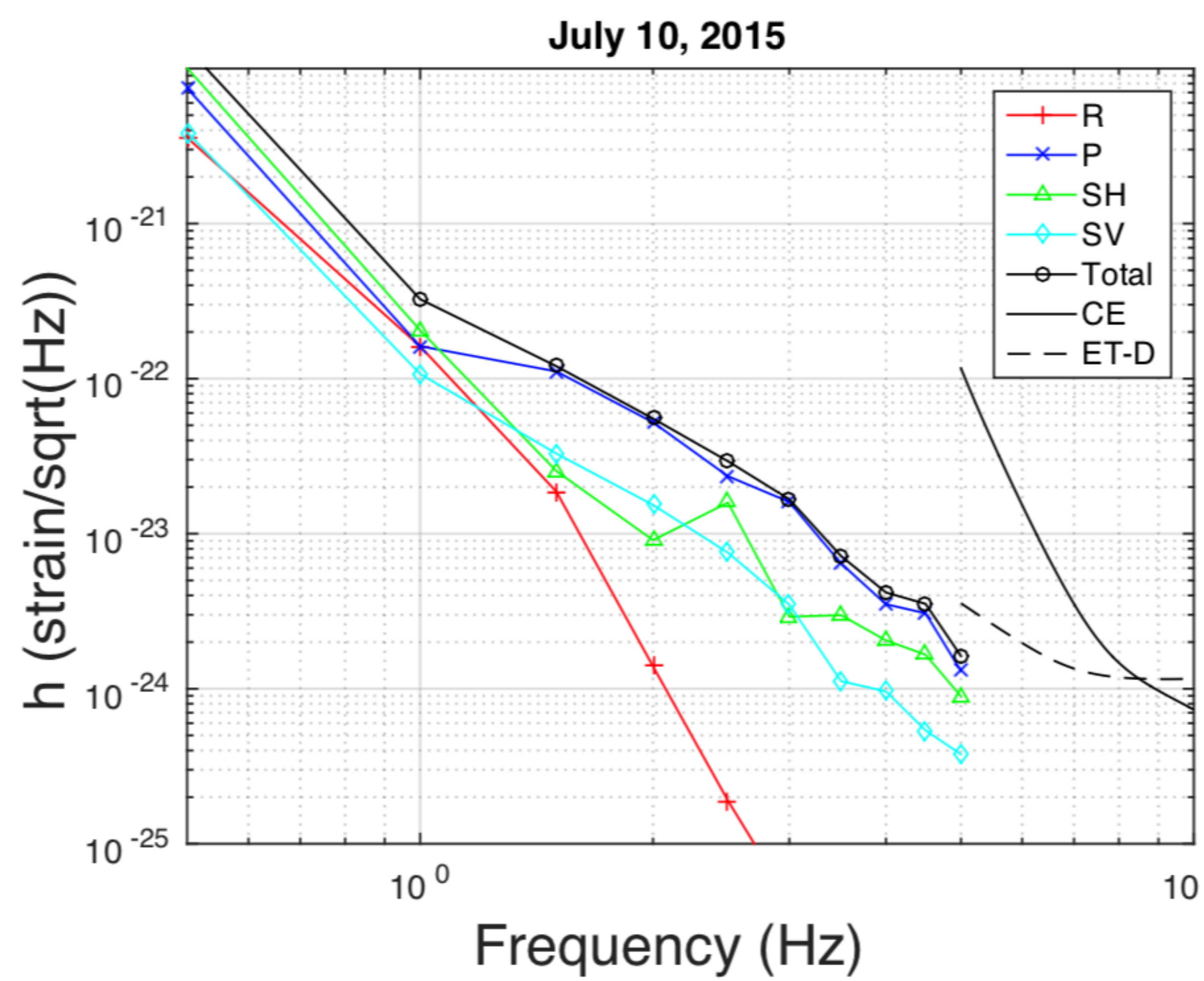




Newtonian noise results, depth

Meyers thesis





Not as much improvement as expected — Homestake is relatively quiet, leading to large body wave content

Summary

- Reducing the impact of seismic and Newtonian noise is crucial for improving low frequency sensitivity of future ground-based gravitational-wave detectors —> many benefits for astrophysics

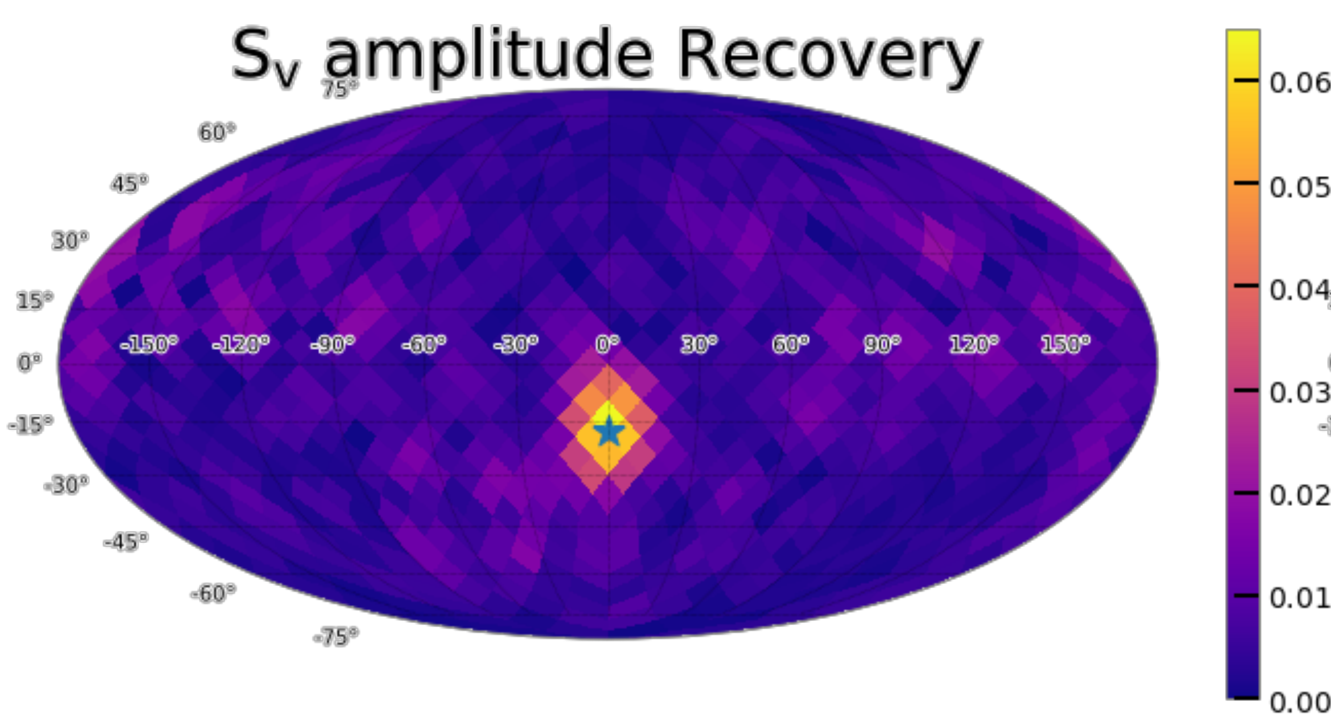
- Homestake array is a unique seismic array allowing for interdisplinary studies in geophysics and gravitational-wave instrument science

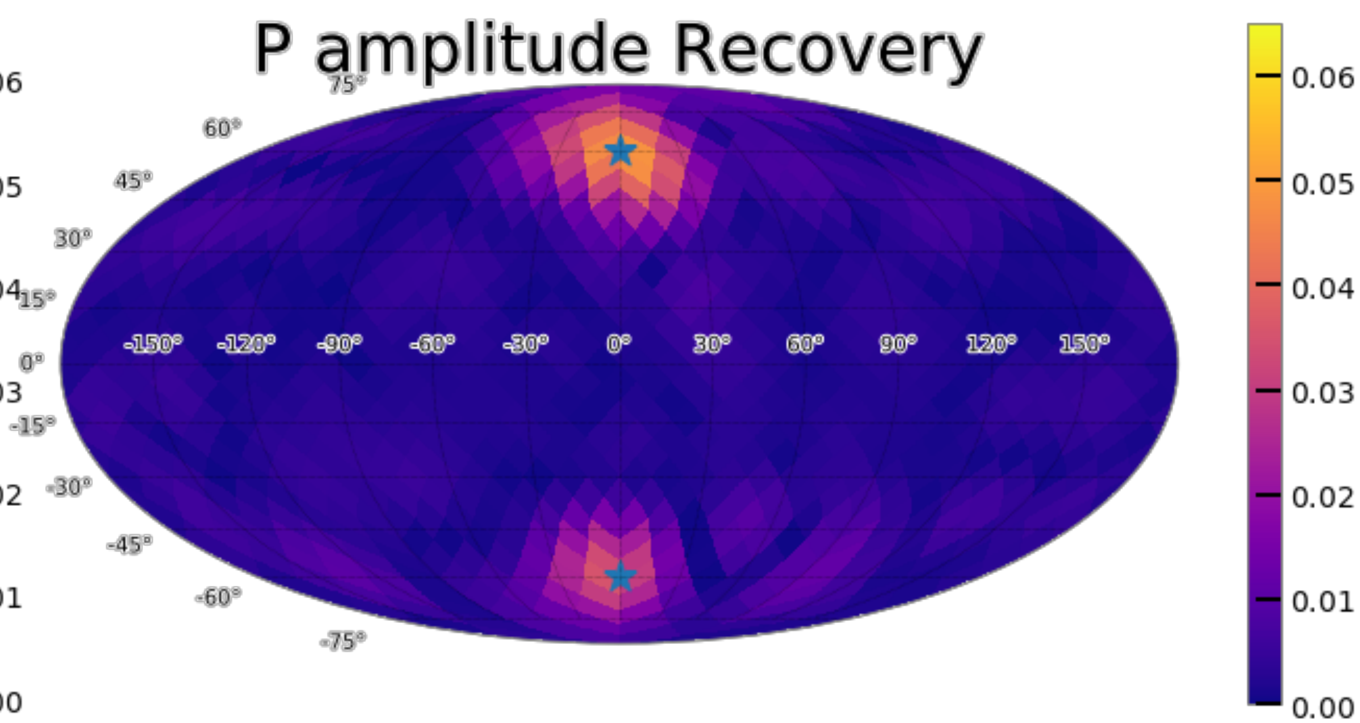
- First estimates of Newtonian noise have been made with Homestake data

Extra slides

Phase coherent mapping

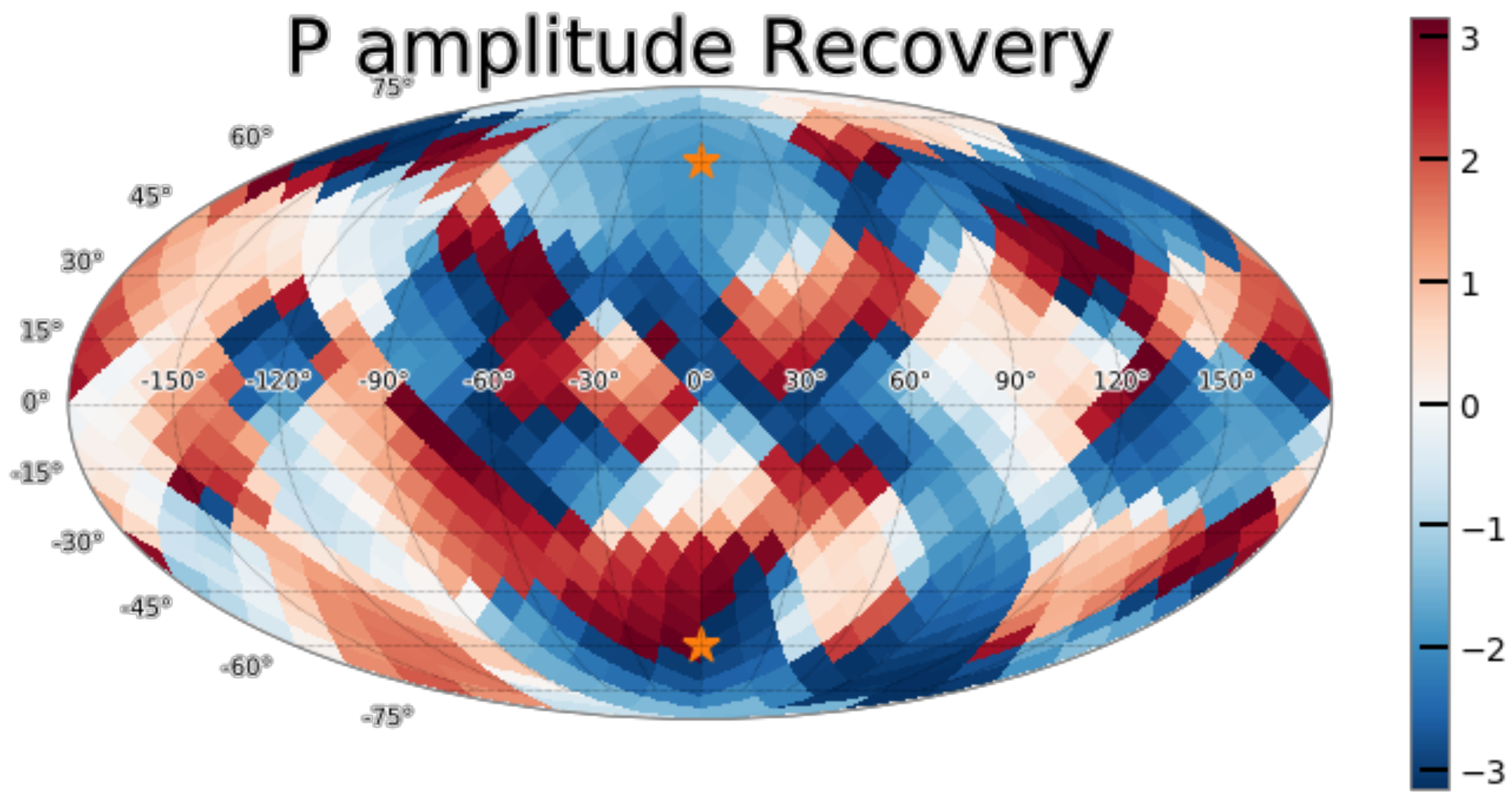
- Mathematically similar to radiometer method, but obtain maps of **amplitude and phase** (not just power)
- Example recovery





This example also shows recovery of reflection (P->P+SV)

Phase coherent mapping — P wave phase



Can use phase coherent mapping to coherently sum contributions to Newtonian noise