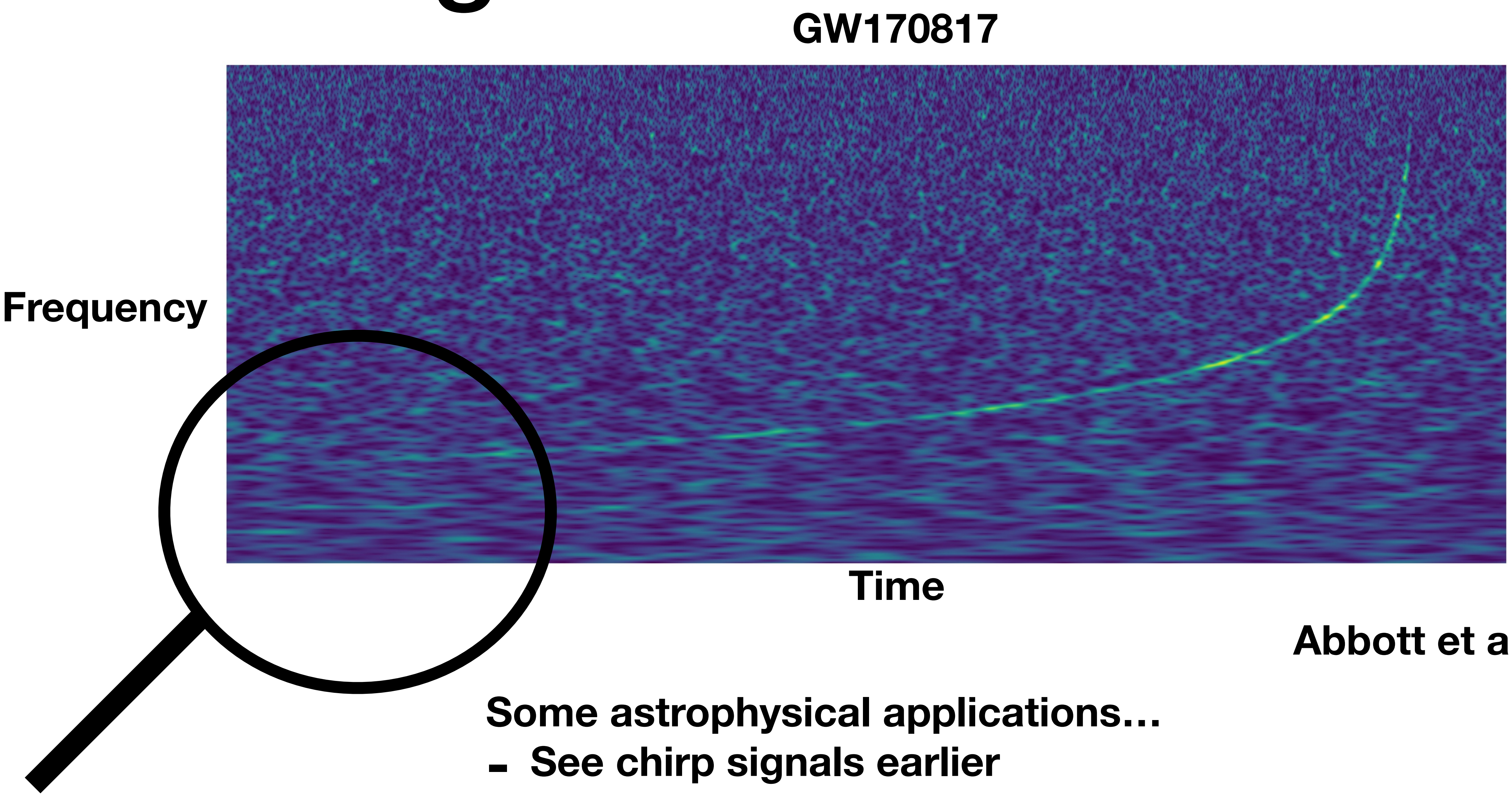
Newtonian noise estimates with the Homestake Array

Andrew Matas
AEI-Potsdam
Sardinia Conference, 2 May 2019
in collaboration with Jan Harms, Vuk Mandic, Pat Meyers

Low frequency sensitivity for gravitational waves



Abbott et al, 2017

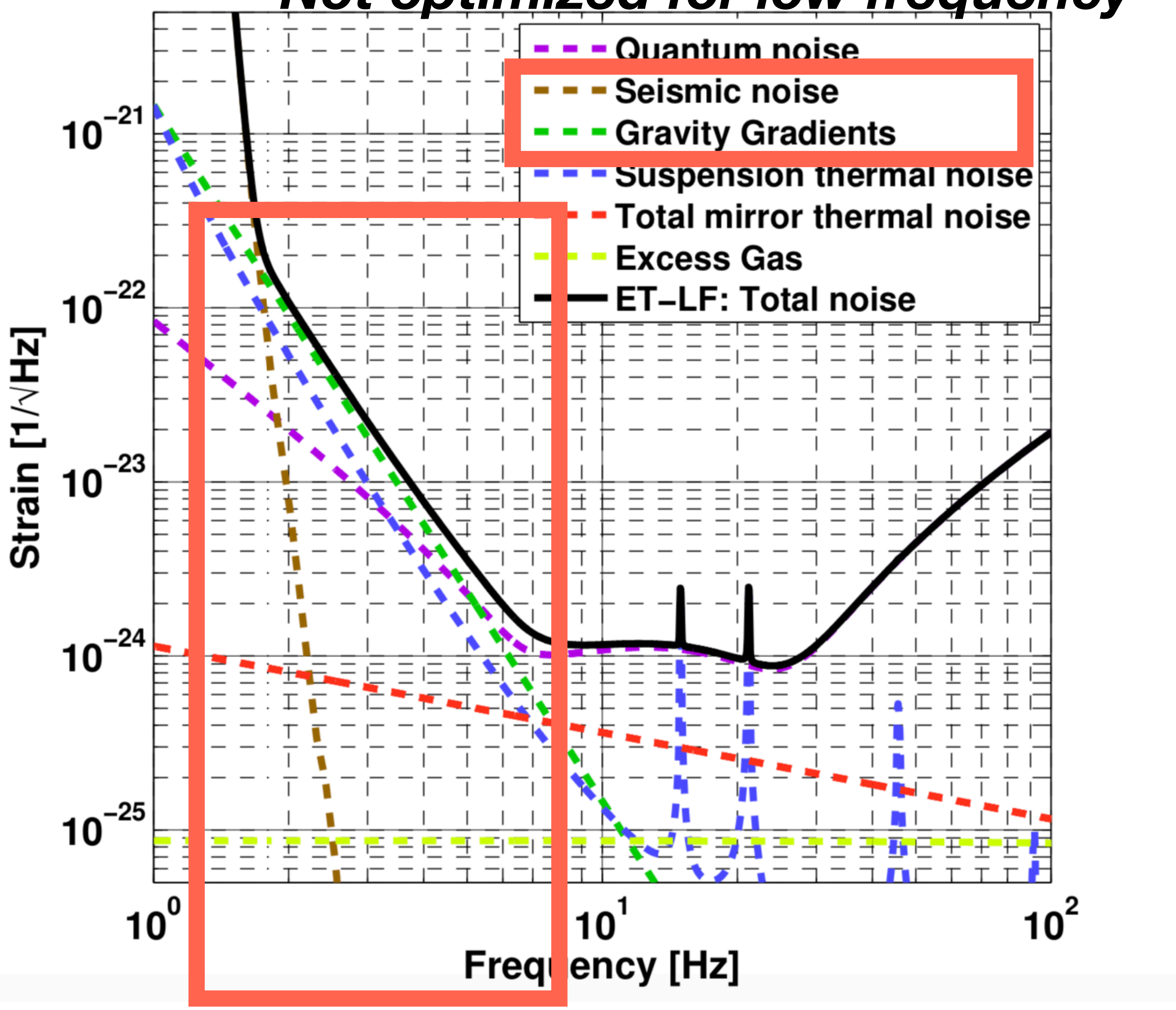
Some astrophysical applications…

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

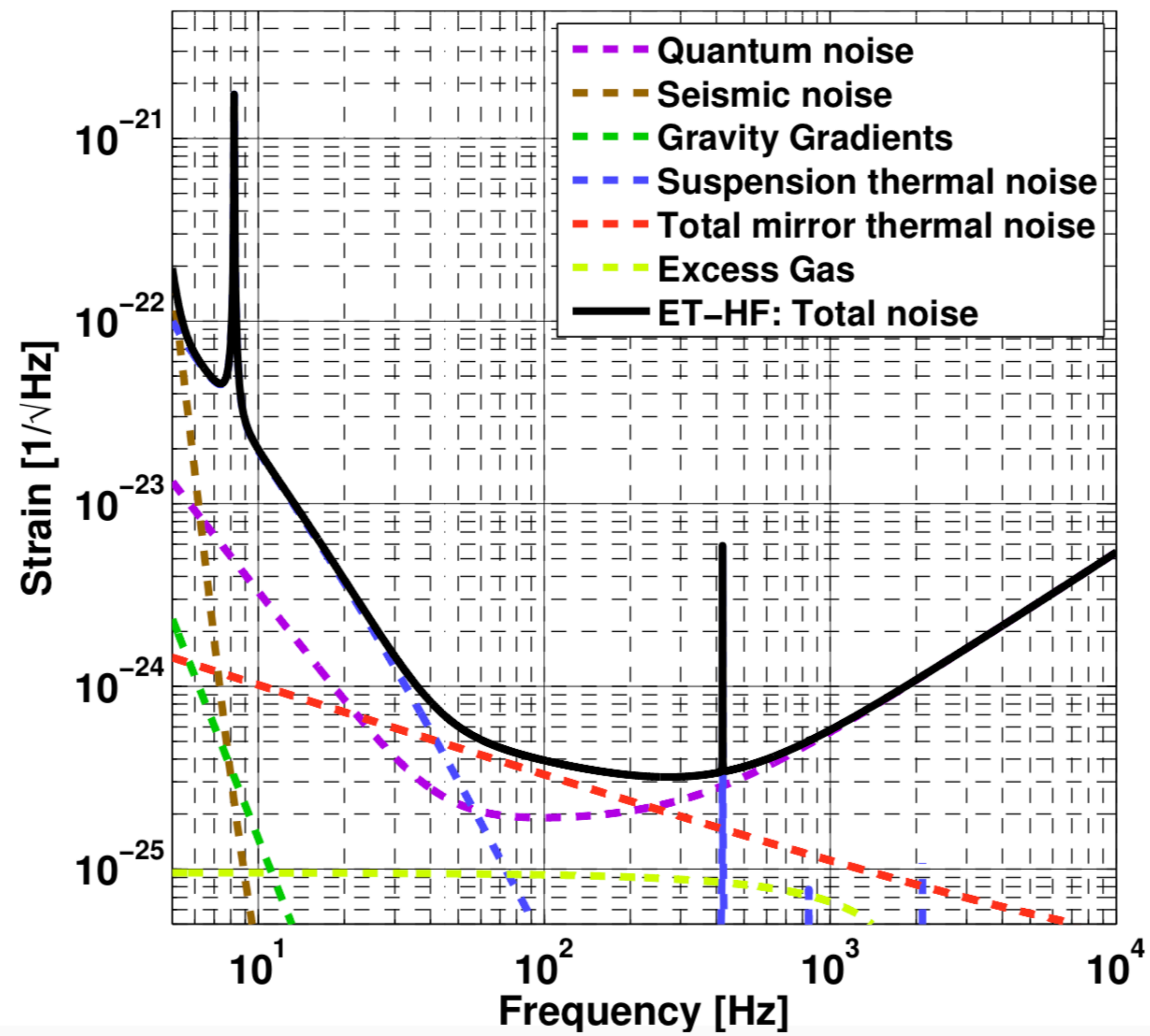
Challenges to improving sensitivity

ET Design Document

Not optimized for low frequency

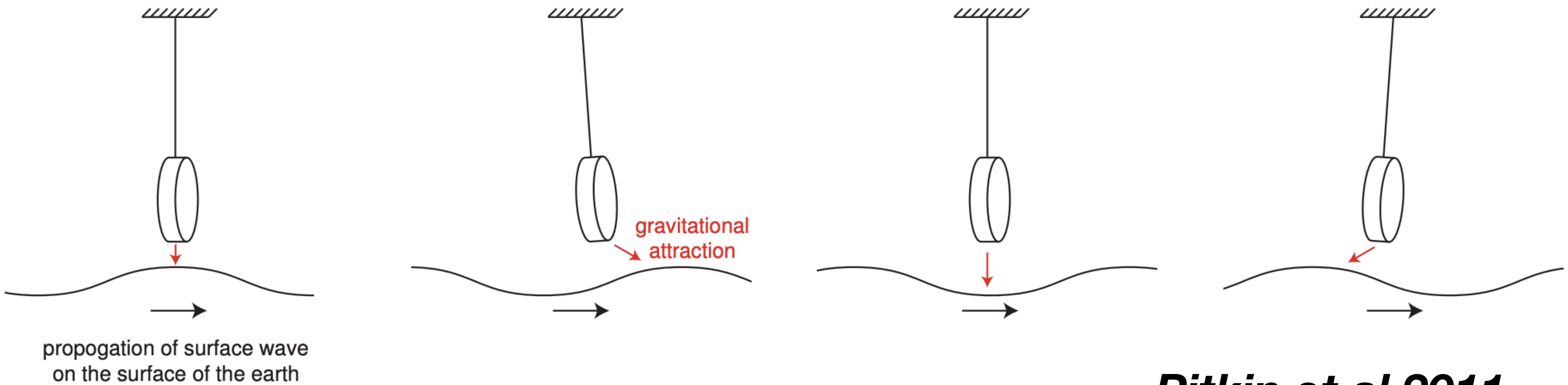


Optimized for low frequency

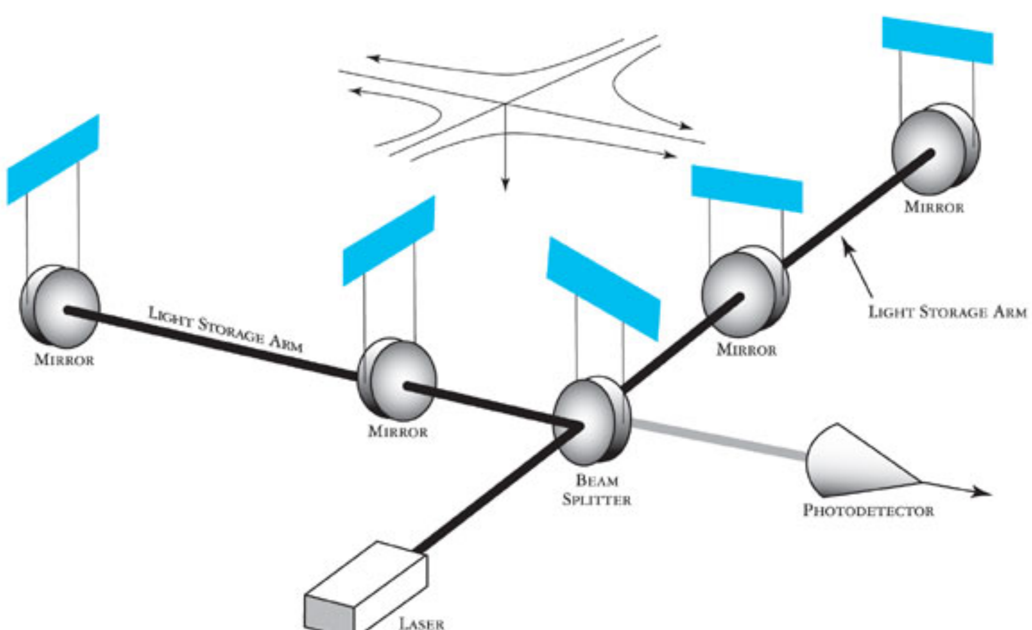


Optimizing detector for low frequencies crucially involves reducing seismic and Newtonian noise

Newtonian noise



Pitkin et al 2011

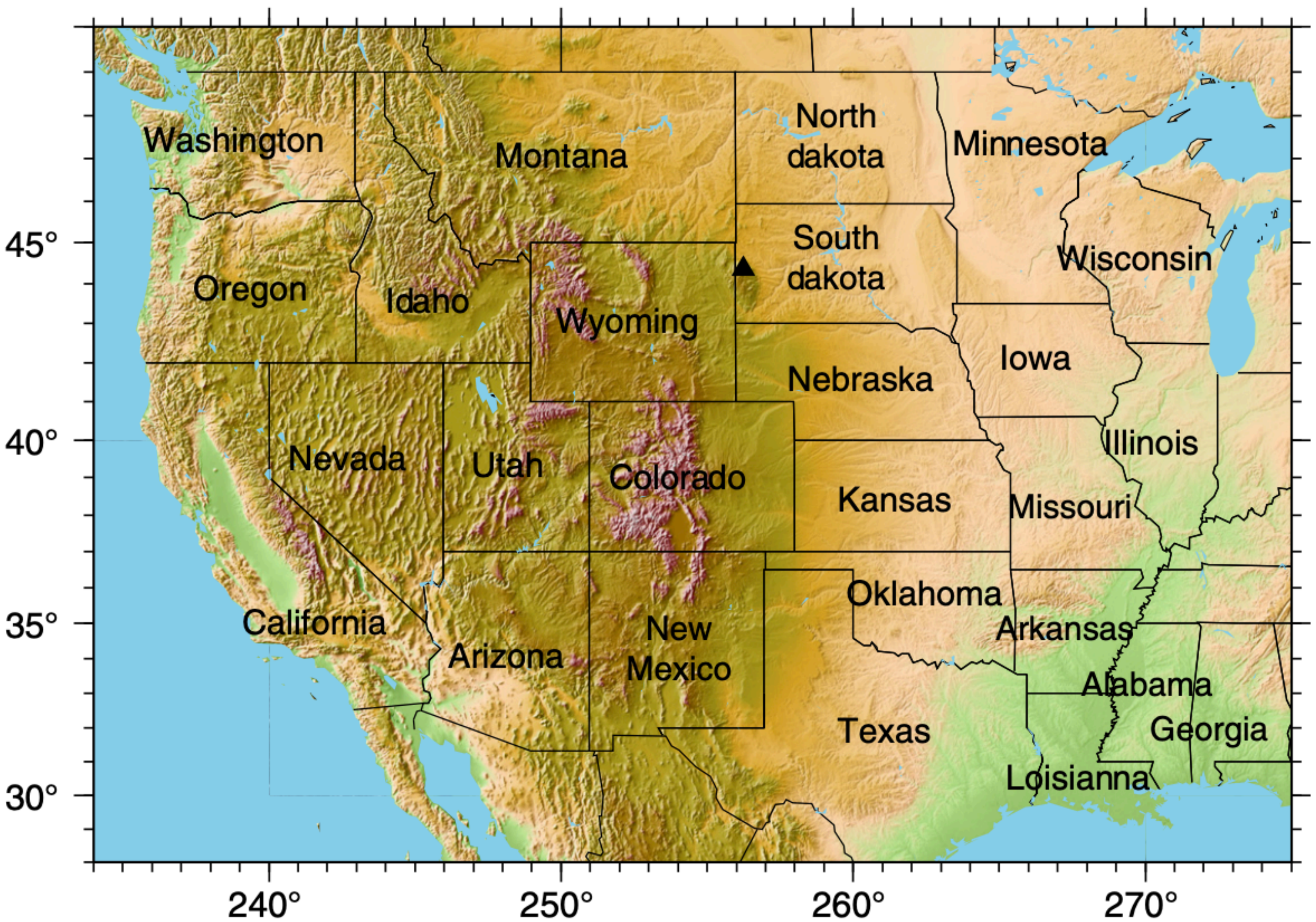


ligo.org

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

Important to accurately characterize newtonian noise underground

Homestake mine

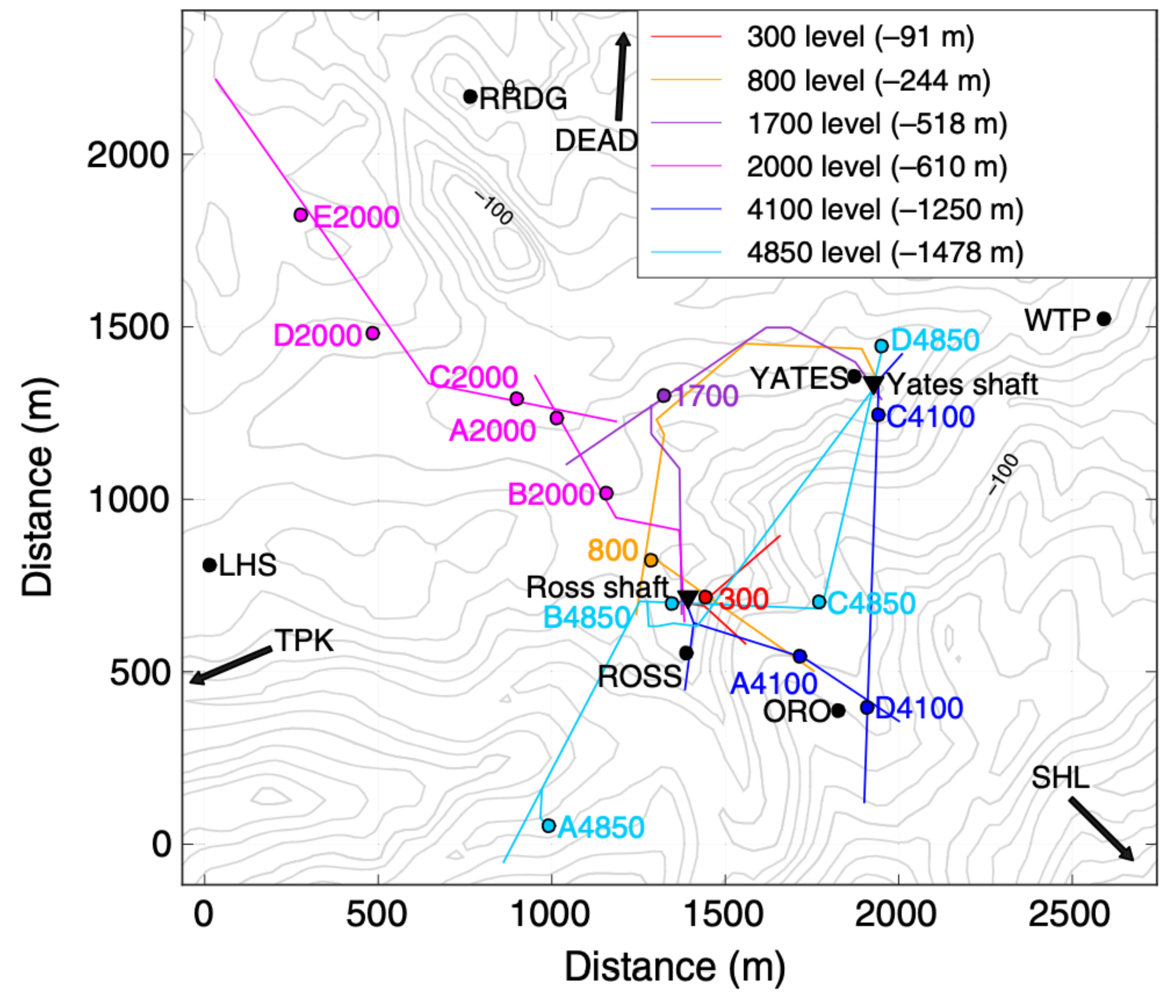


Sanford Lab

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
Michael Coughlin

Indiana University

Gary Pavlis*
Ross Canton

Gran Sasso

Jan Harms

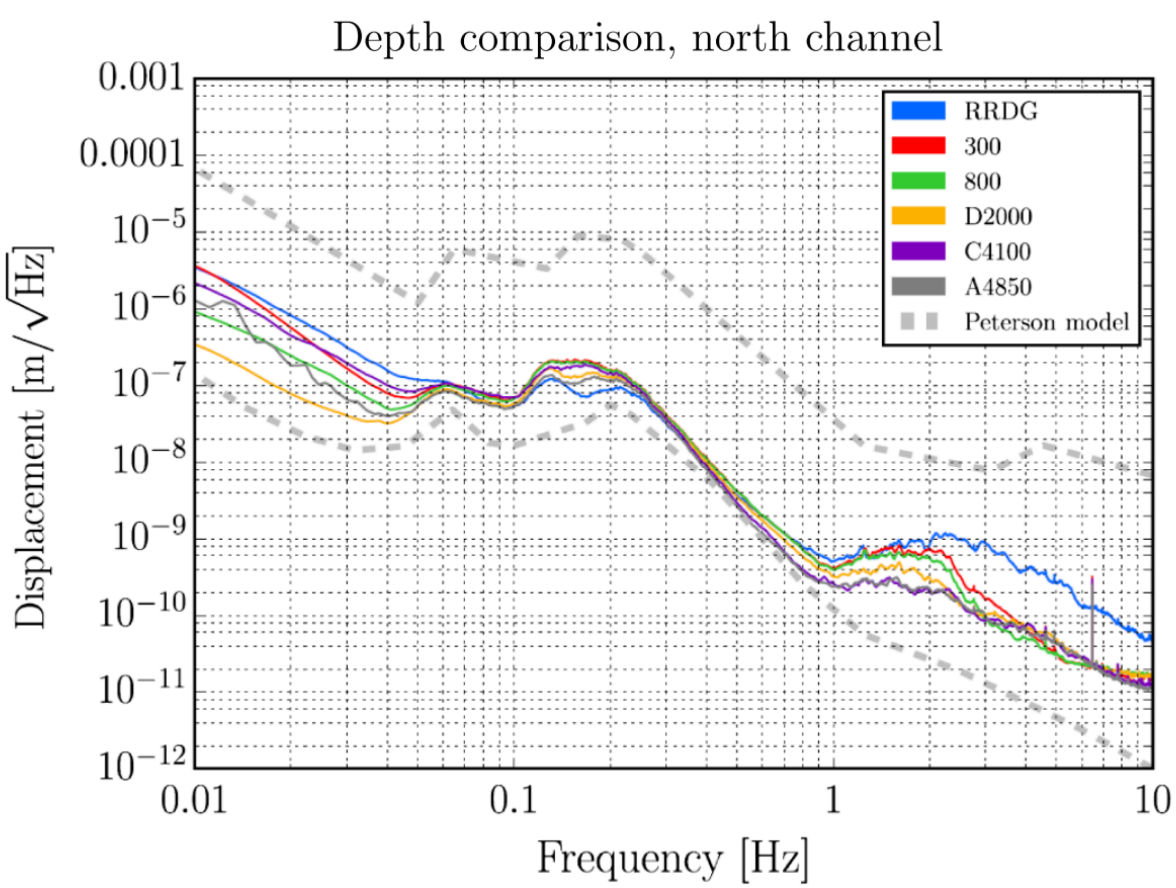
SURF@Homestake

Papers covering a variety of topics

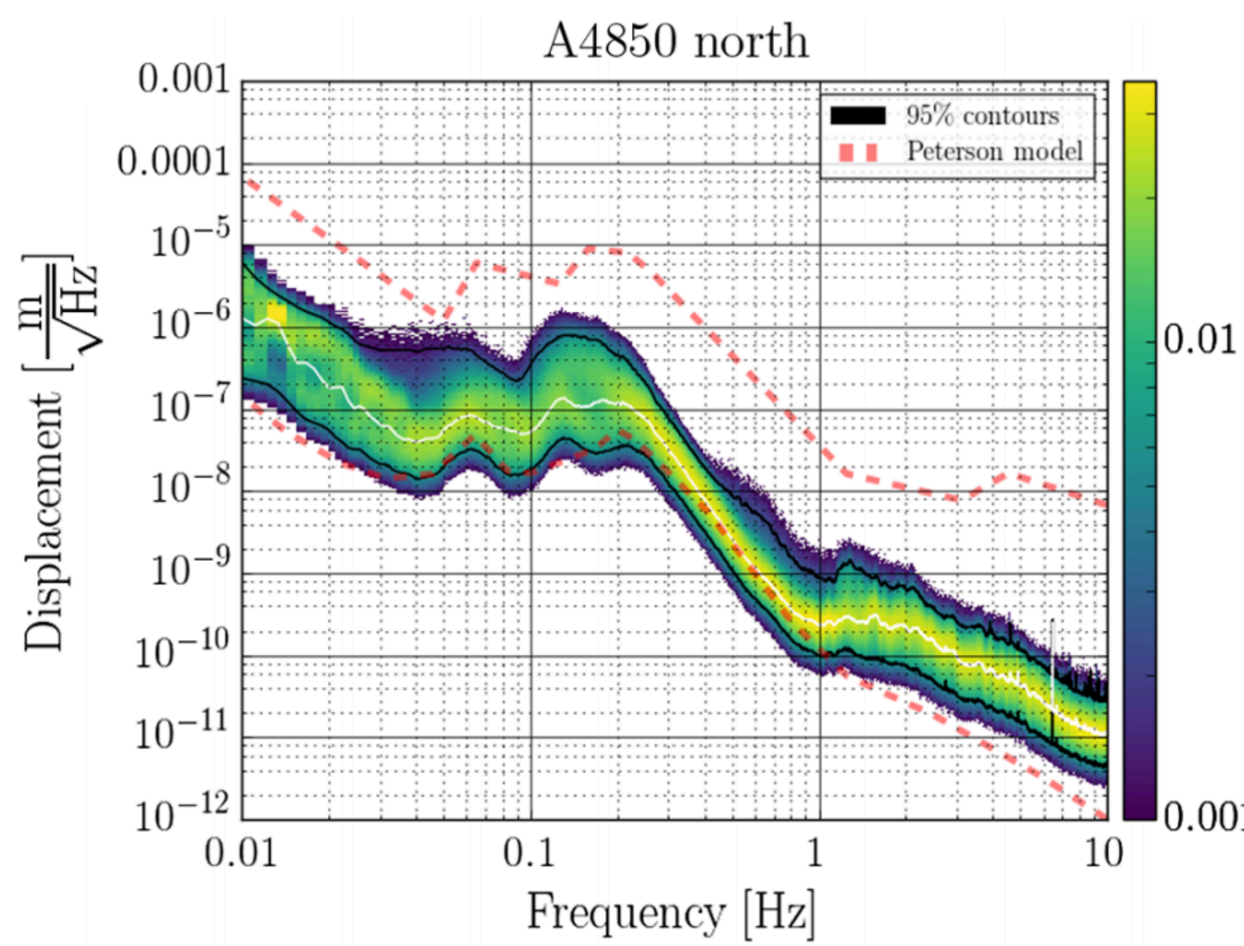
A 3D Broadband Seismometer Array Experiment at the Homestake Mine, Mandic et al, Seismological Research Letters 2018
Coherence-Based Approaches for Estimating the Composition of the Seismic Wavefield, Coughlin et al, JGR Solid Earth 2018
Future papers planned on surface wave measurements, newtonian noise,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

Seismic environment at homestake

Depth comparison



Time comparison



Mandic et al, 2018

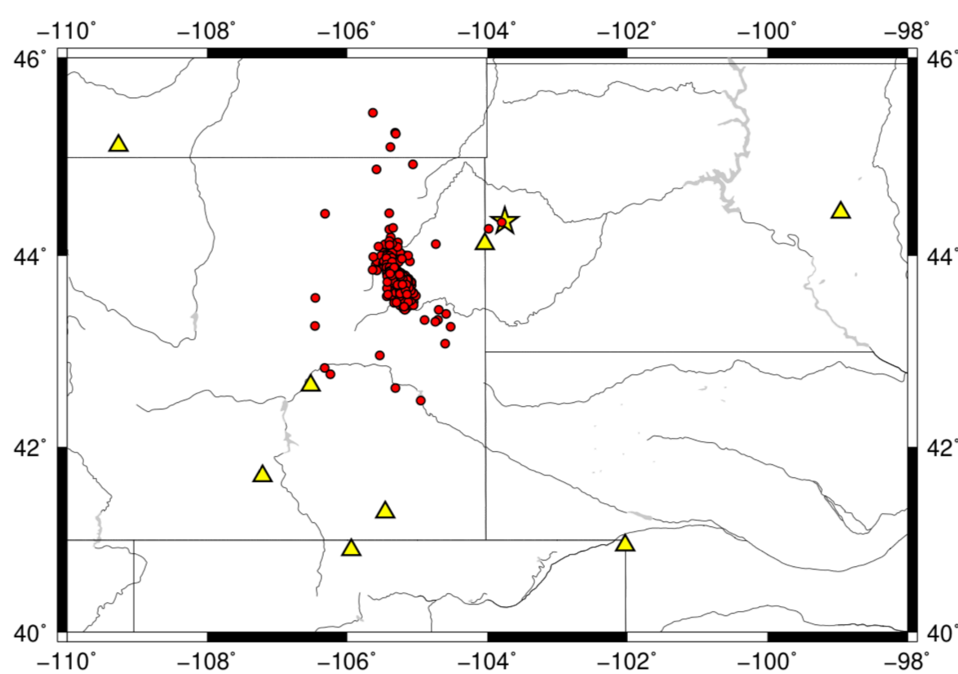
R wave eigenfunction measurements

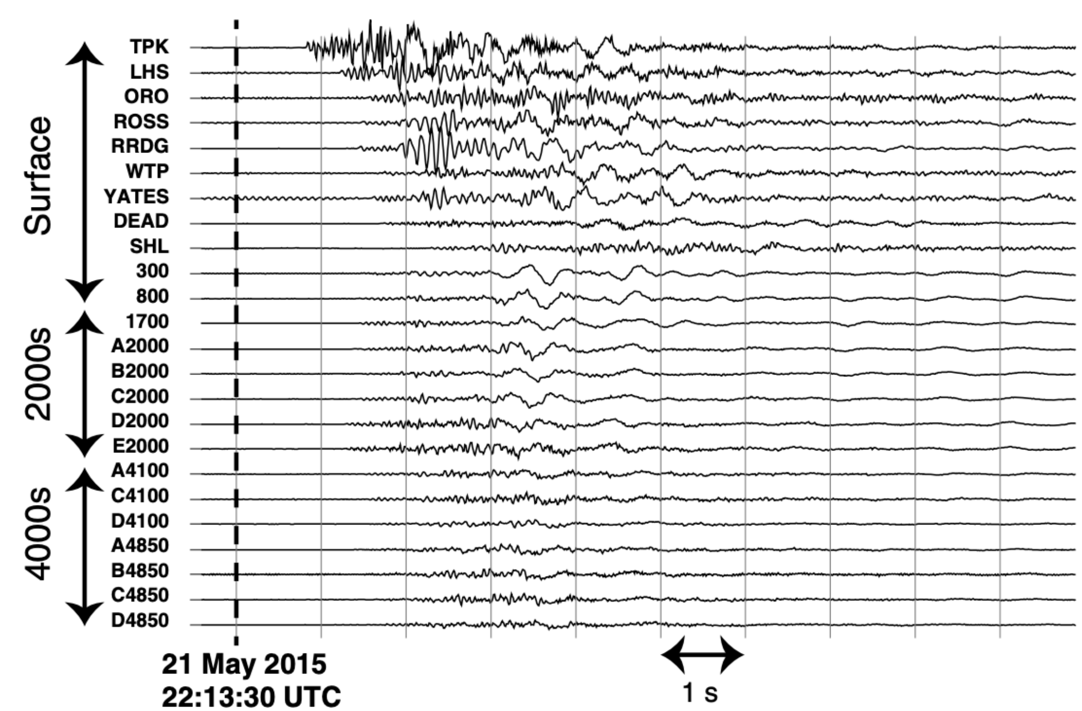
Mandic et al, 2018
Meyers Thesis

Bi-exponential form

$$r_H(f,z;\vec{\theta}) = \left(e^{-2\pi f z \frac{a_1}{v_R(f)}} + c_2 e^{-2\pi f z \frac{a_2}{v_R(f)}}\right) \times \frac{1}{1+c_2}$$
$$r_V(f,z;\vec{\theta}) = \left(e^{-2\pi f z \frac{a_3}{v_R(f)}} + c_4 e^{-2\pi f z \frac{a_4}{v_R(f)}}\right) \times \frac{N_{vh}}{1+c_4}$$
$$v_{\mathrm{R}}(f) = v_{1\mathrm{Hz}} f^{\alpha}$$

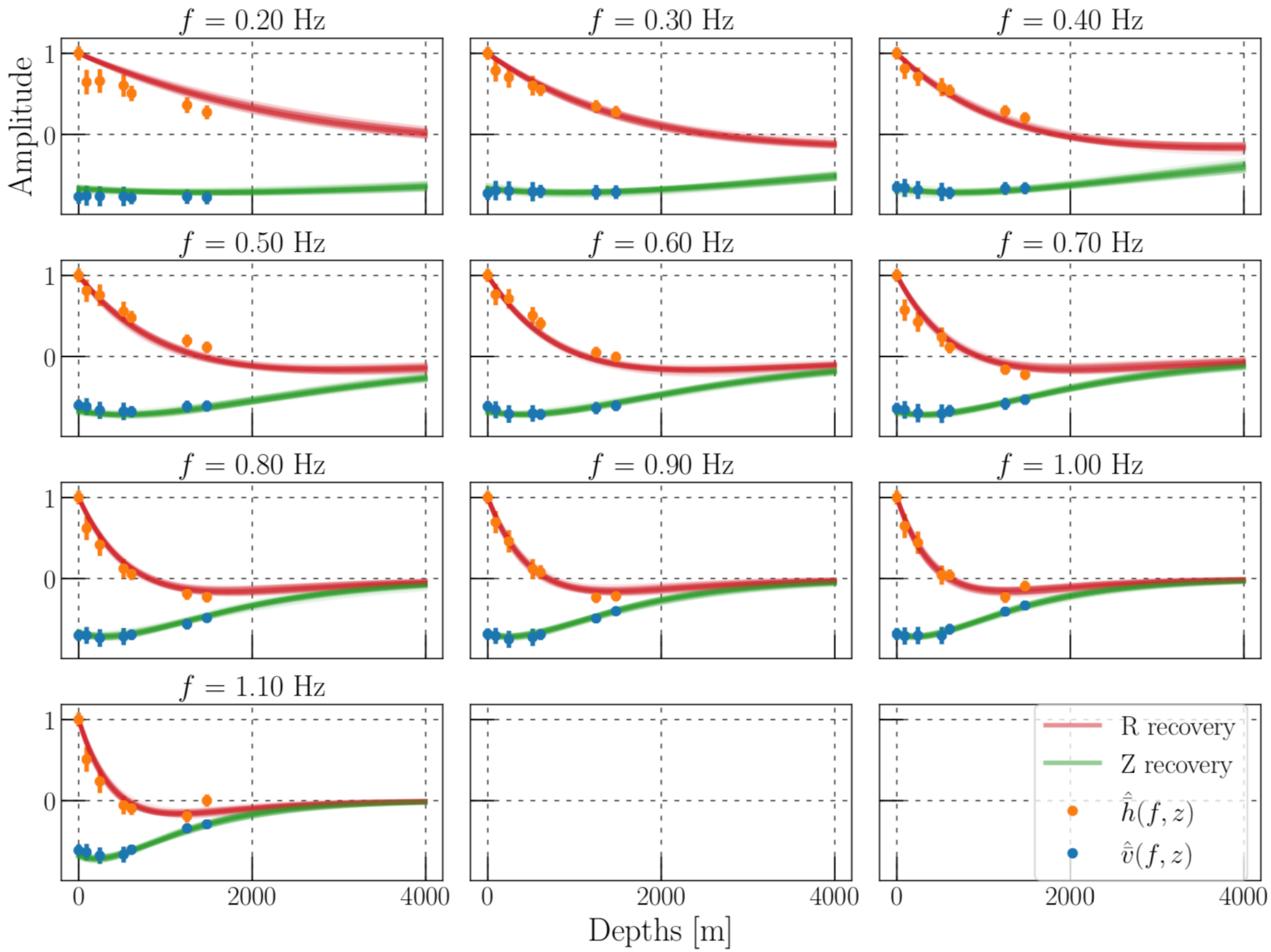
Transient events





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**

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

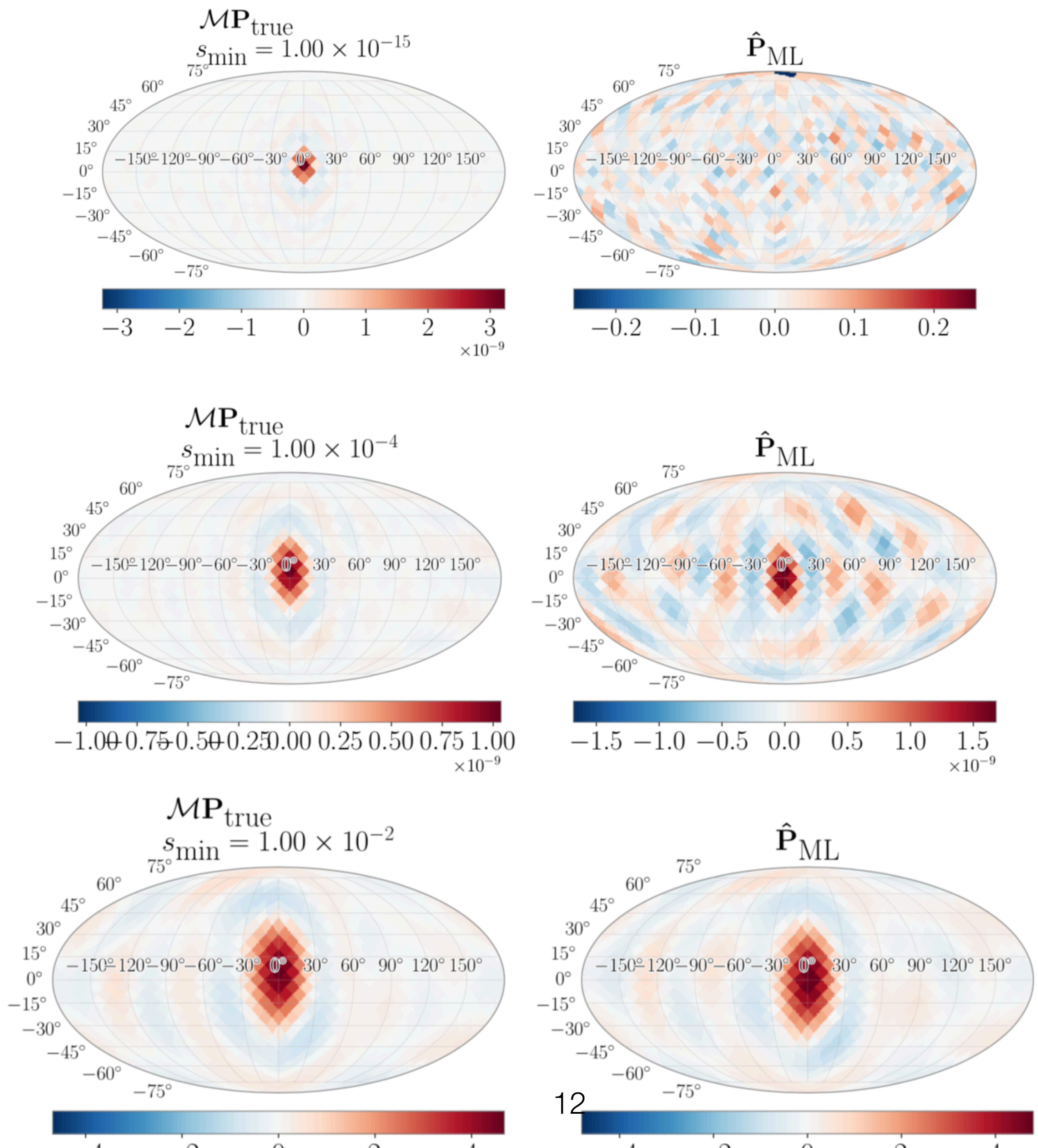
Simple idea: to get sky map, invert the kernel
In practice, this is an ill-conditioned matrix so this needs to be done with care

Meyers Thesis

Tradeoff

Better angular resolution

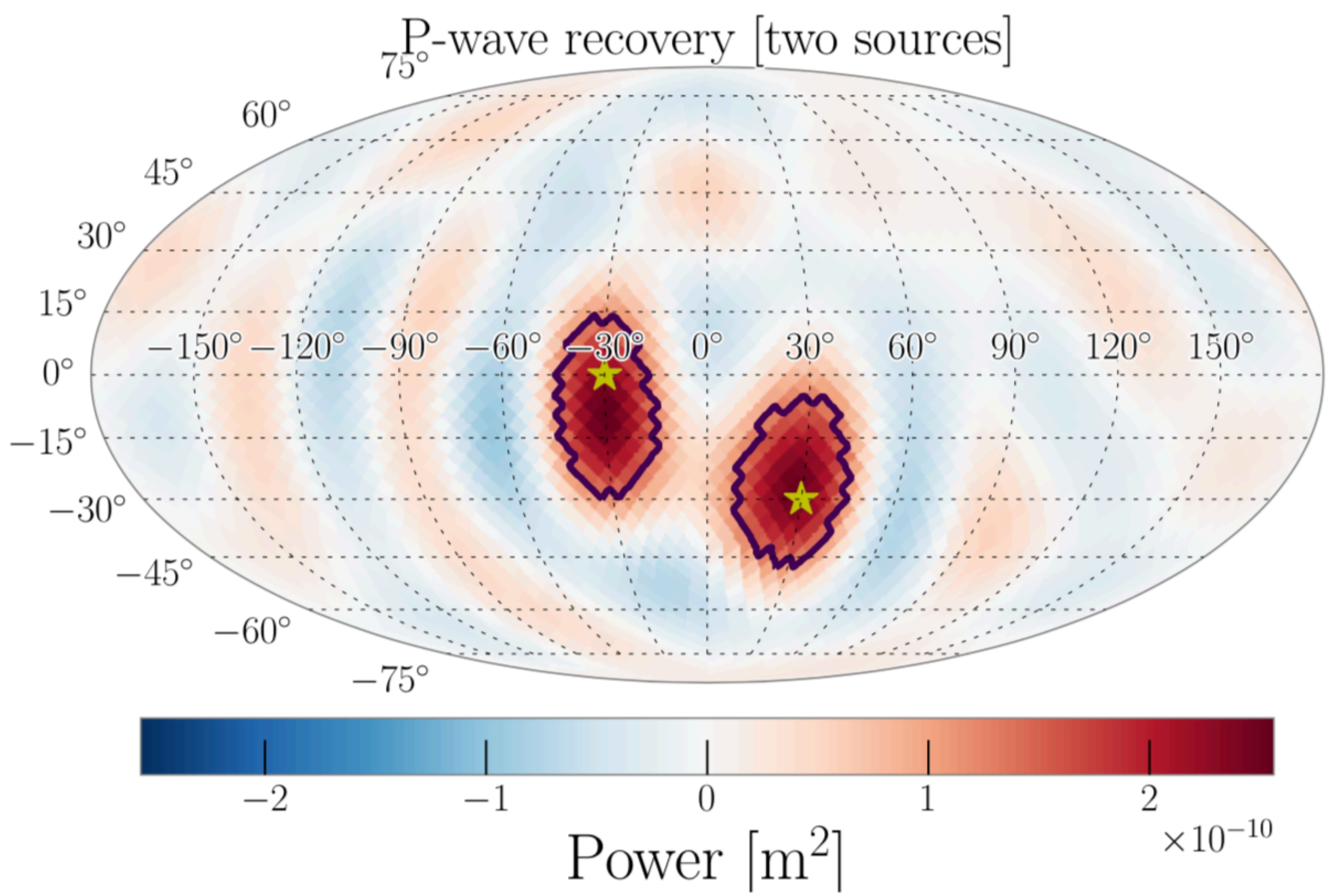
Meyers Thesis



Less covariance between pixels

Verification: direction

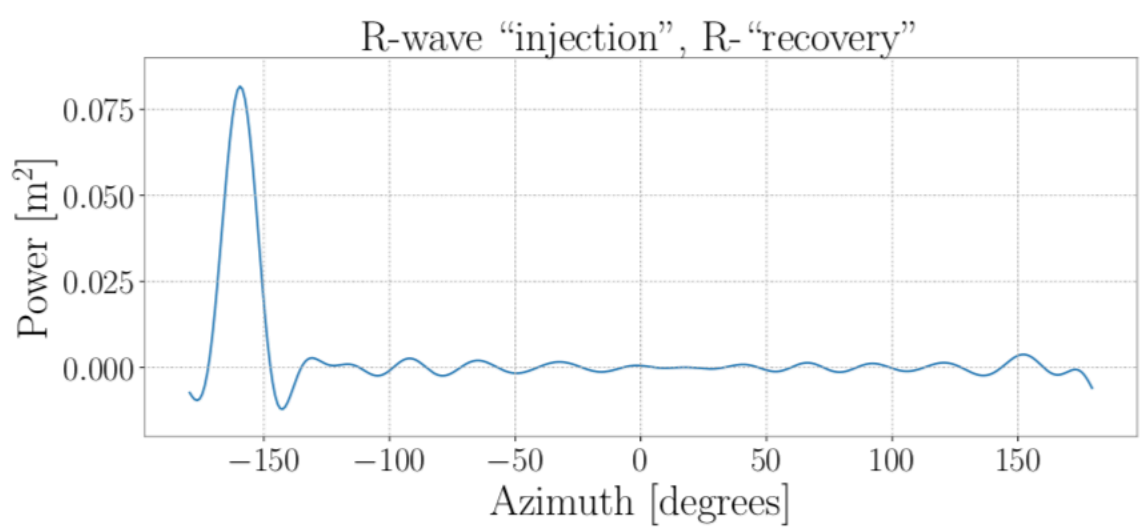
Meyers Thesis

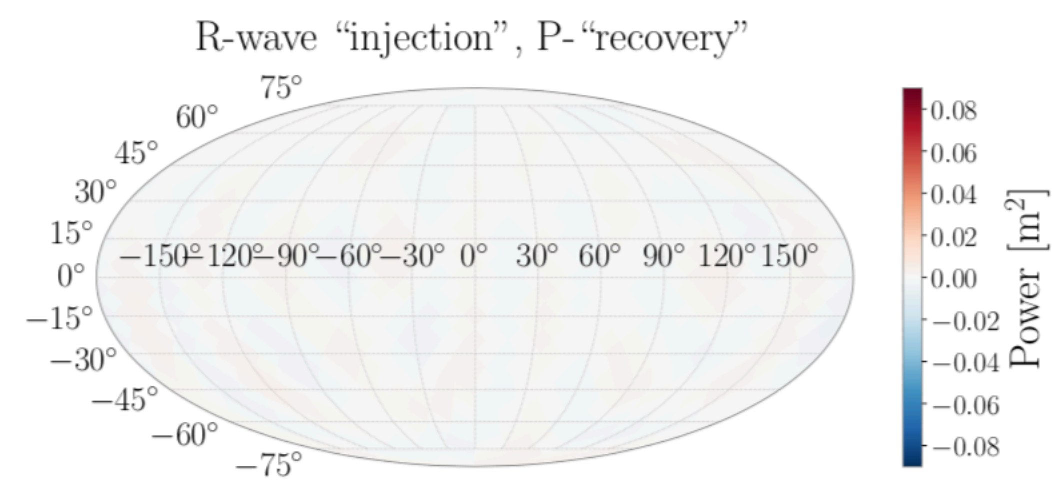


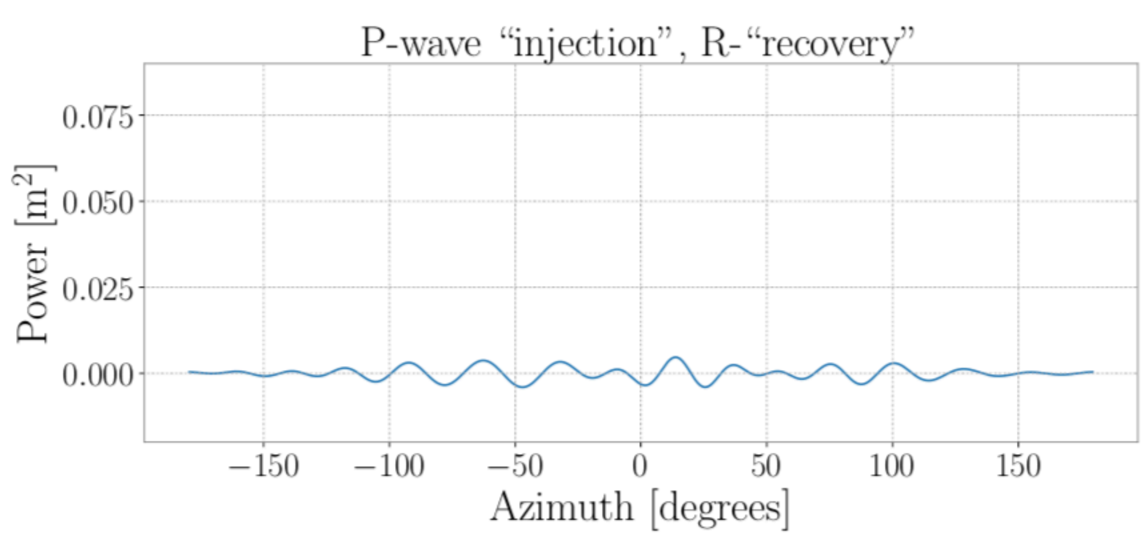
Can resolve point sources

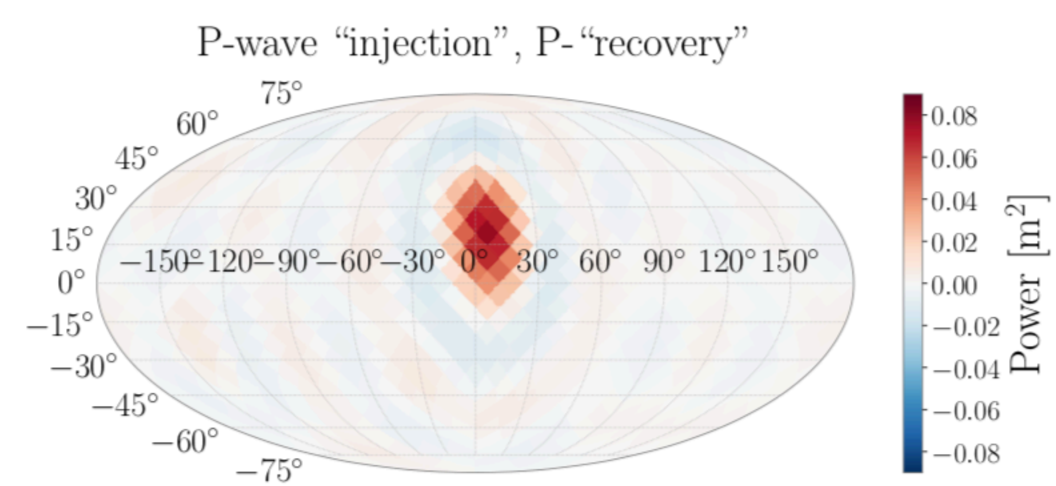
Verification: Polarization

Meyers Thesis





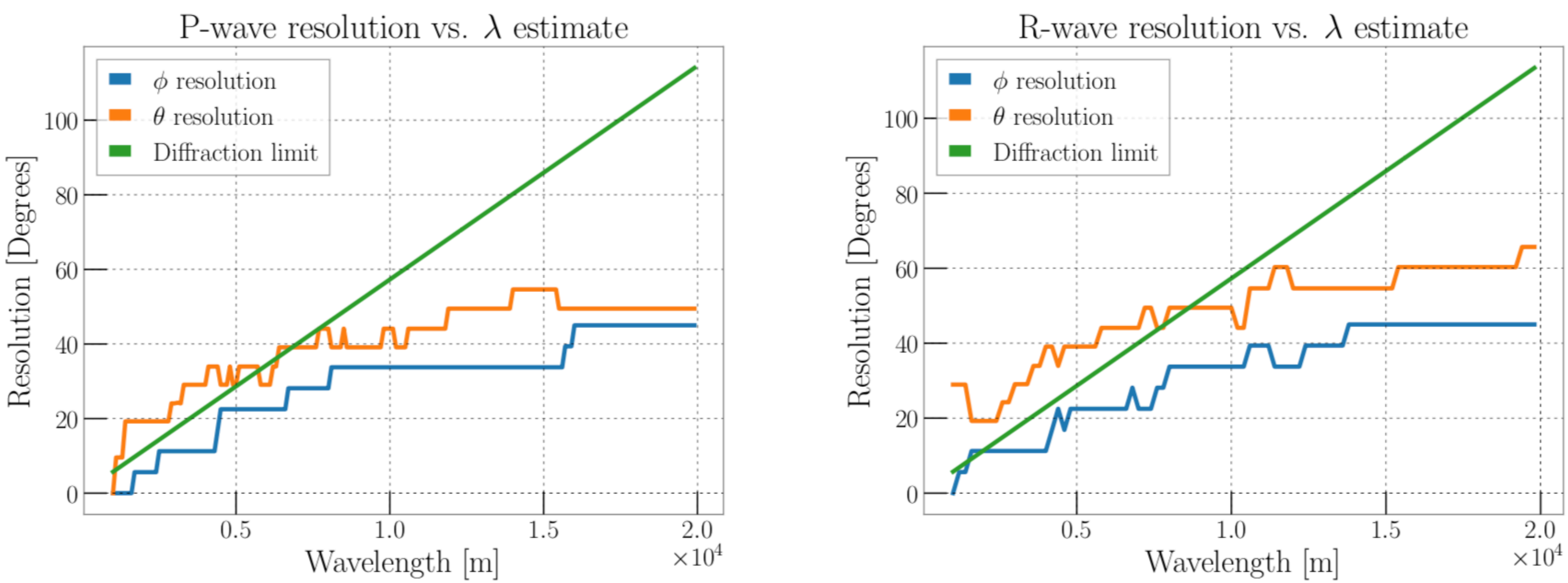




Check both for false positives and false negatives

Angular resolution

Meyers Thesis

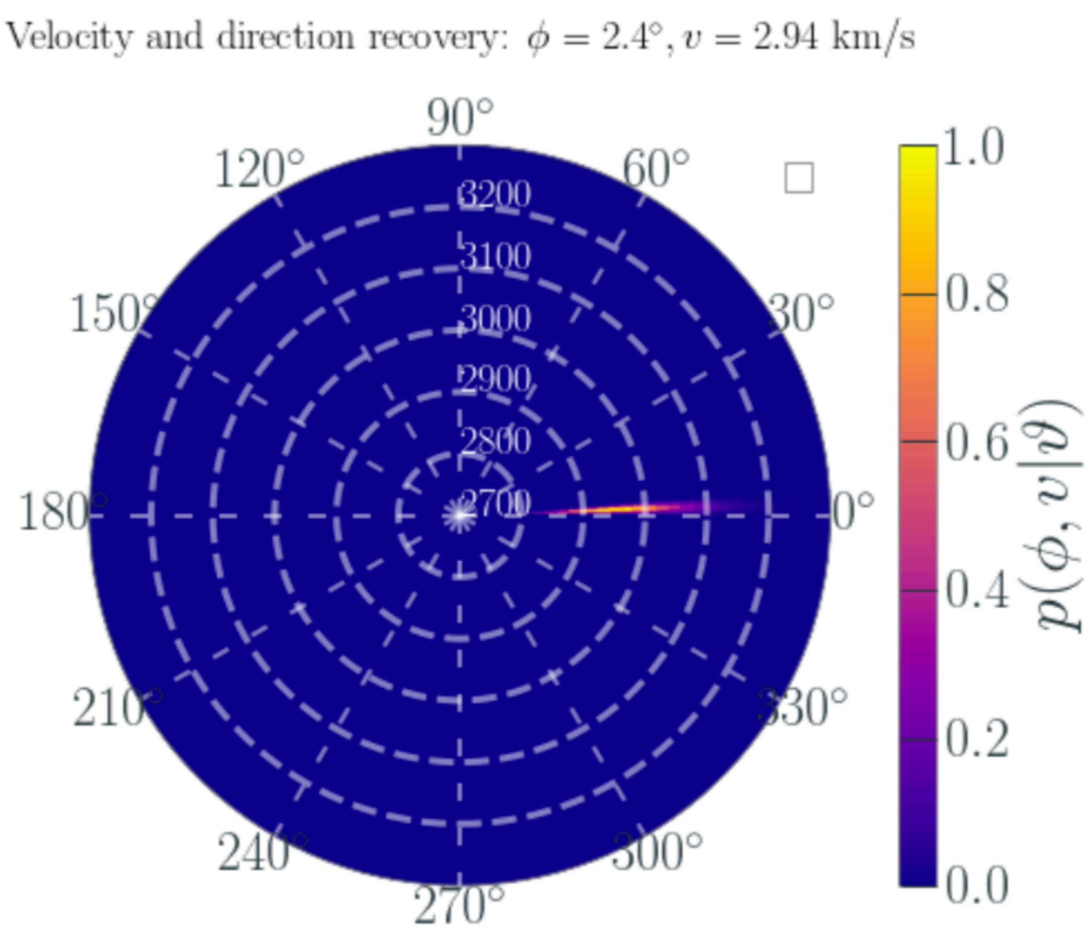


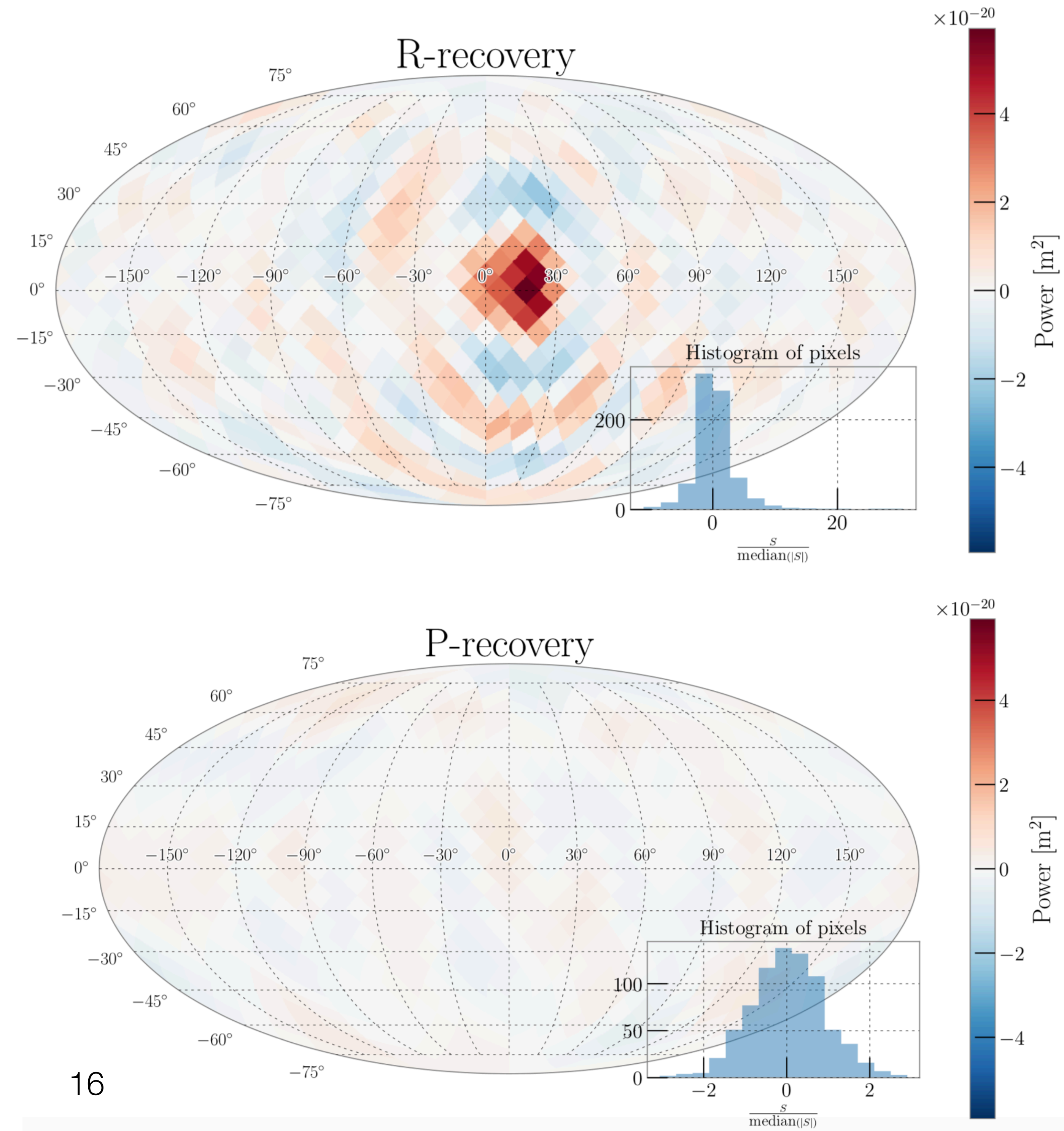
Diffraction limit $$\Delta\theta \sim \frac{\lambda}{D}$$

Polarization also provides direction information

Application to real data: Regular source

Meyers Thesis

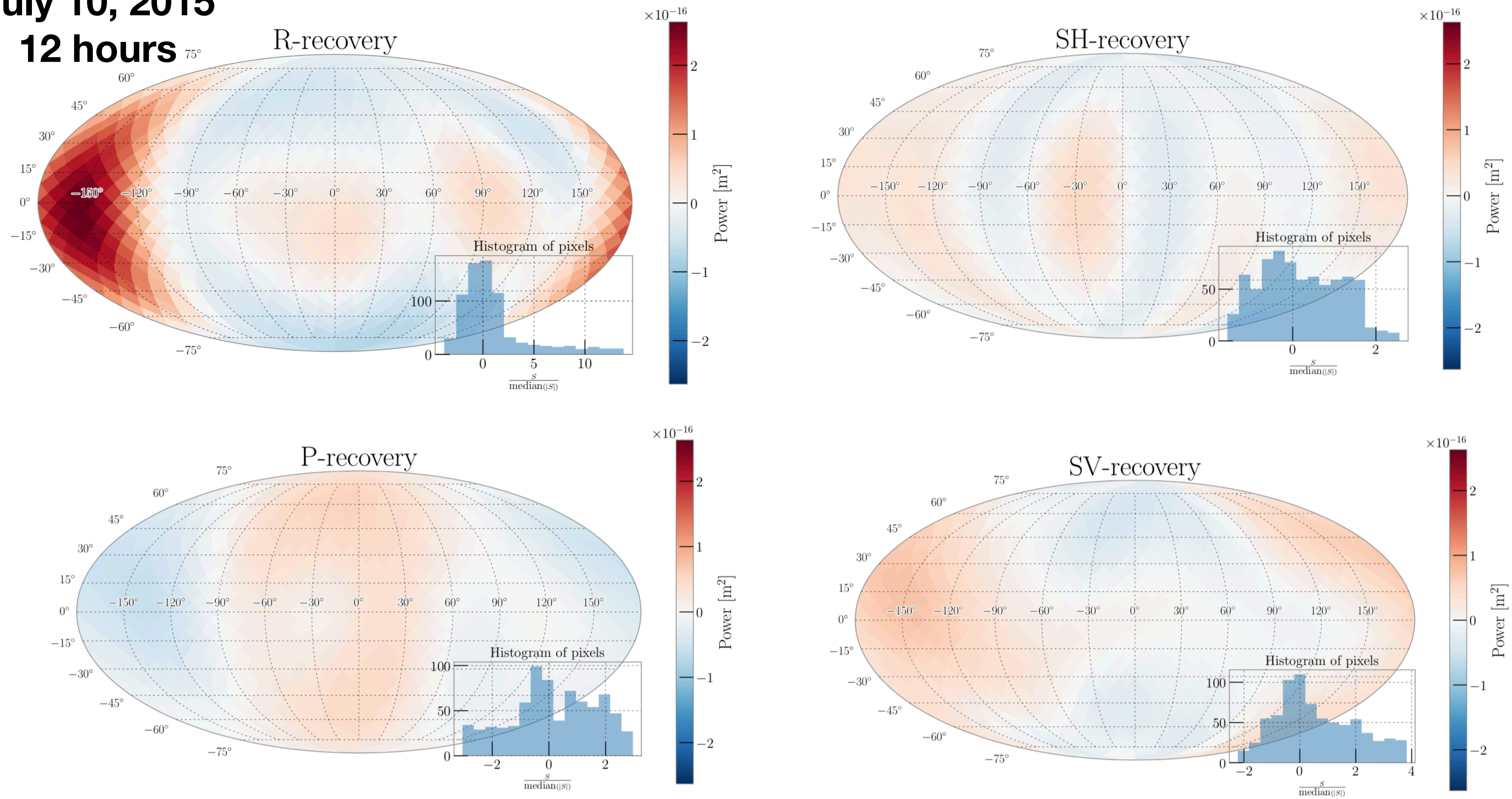




Application to real data: Loud microseism

Meyers Thesis

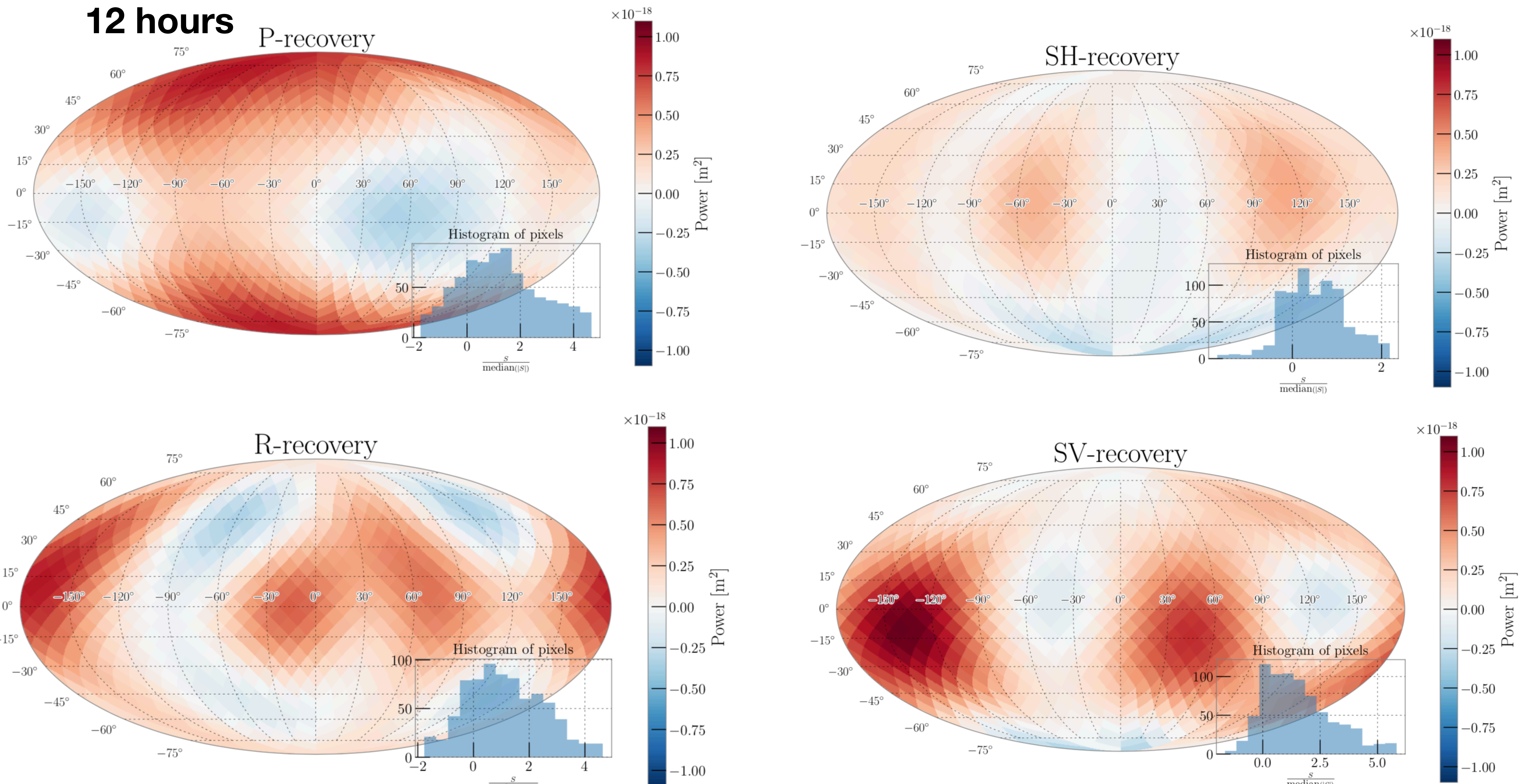
July 10, 2015
12 hours



Application to real data: Quiet microseism

Meyers Thesis

June 3, 2015
12 hours



Newtonian noise: estimation method

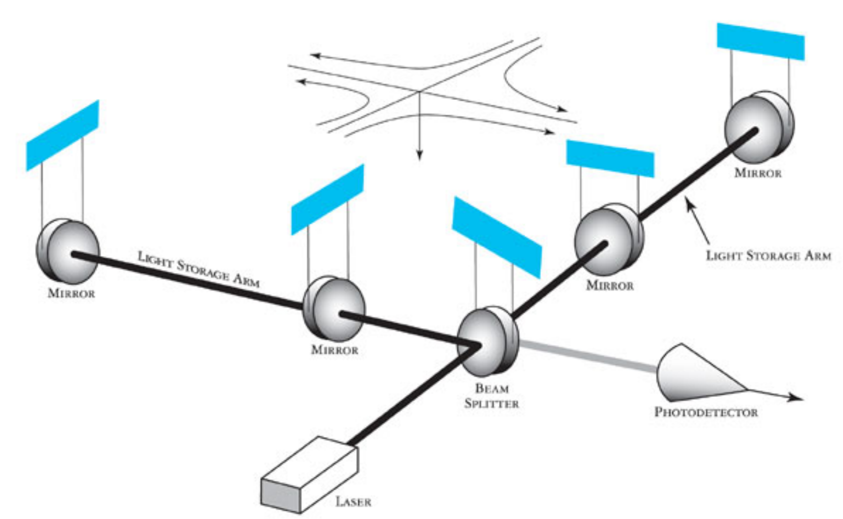
Harms, 2015

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)**

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

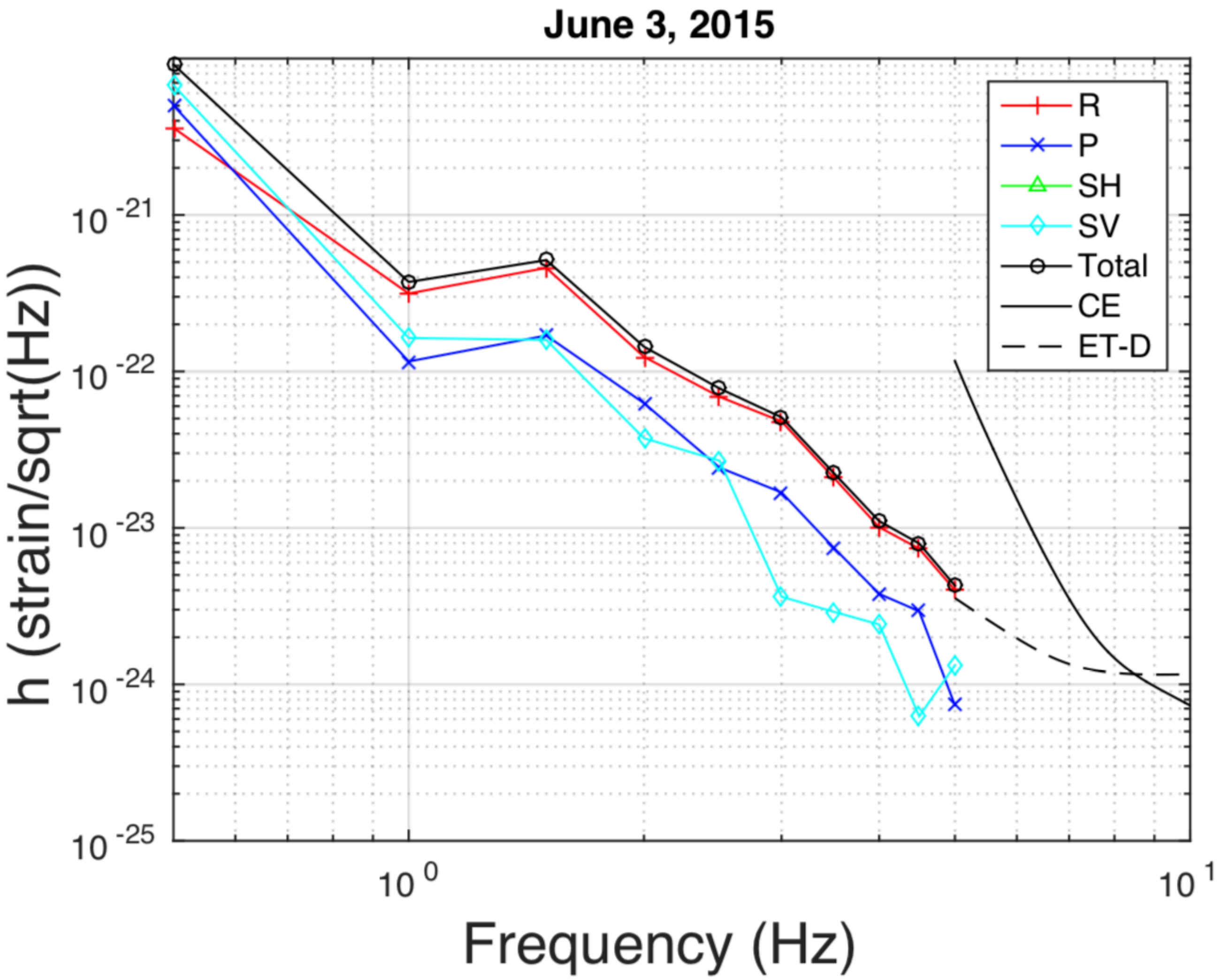
$$h_{\rm NN} = \frac{\sqrt{2\left(\delta a_{x,\rm rms}^2 + \delta a_{y,\rm rms}^2\right)}}{(2\pi f)^2 L}$$

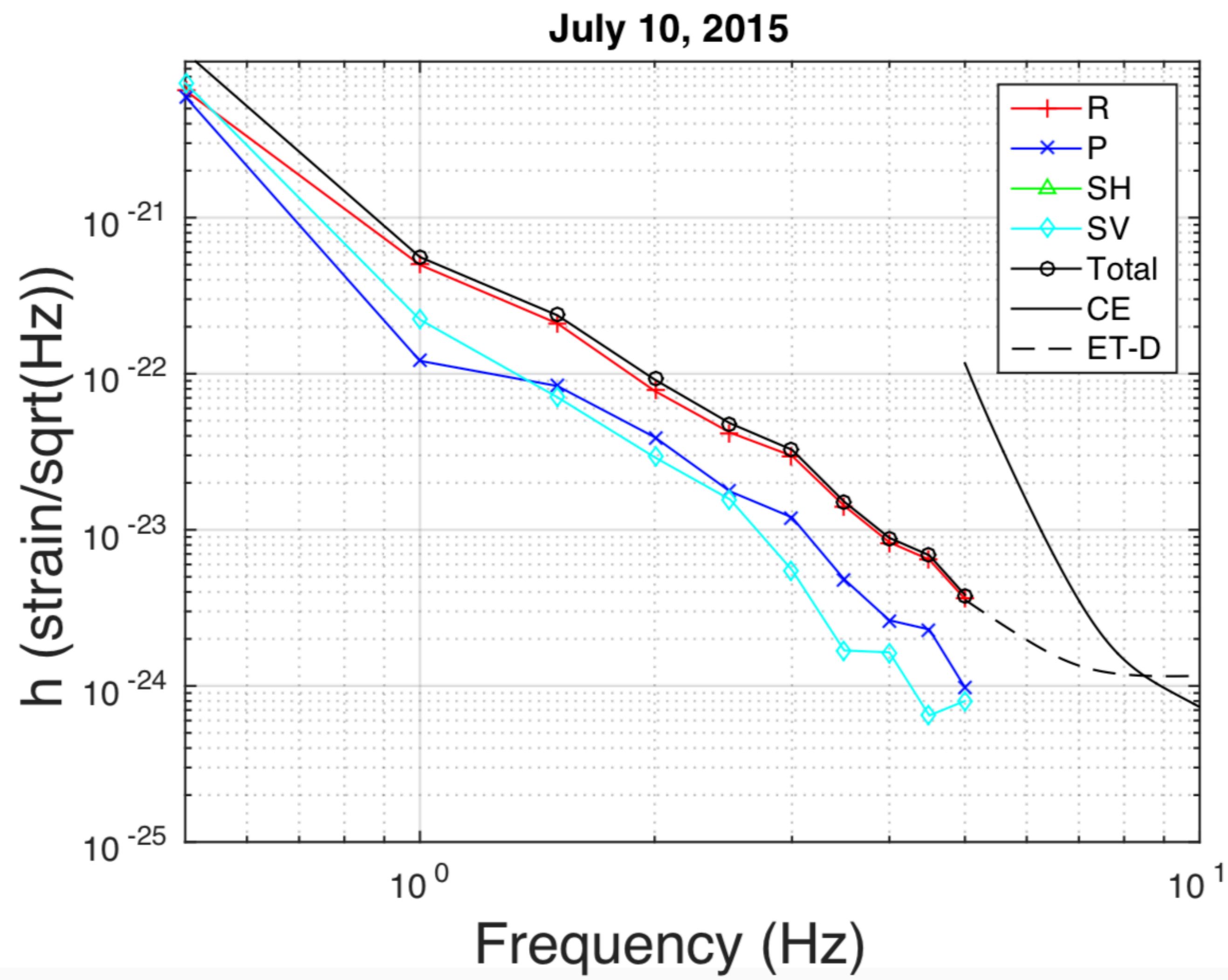


Expect radiometer to capture reflections from surface

Newtonian noise, surface

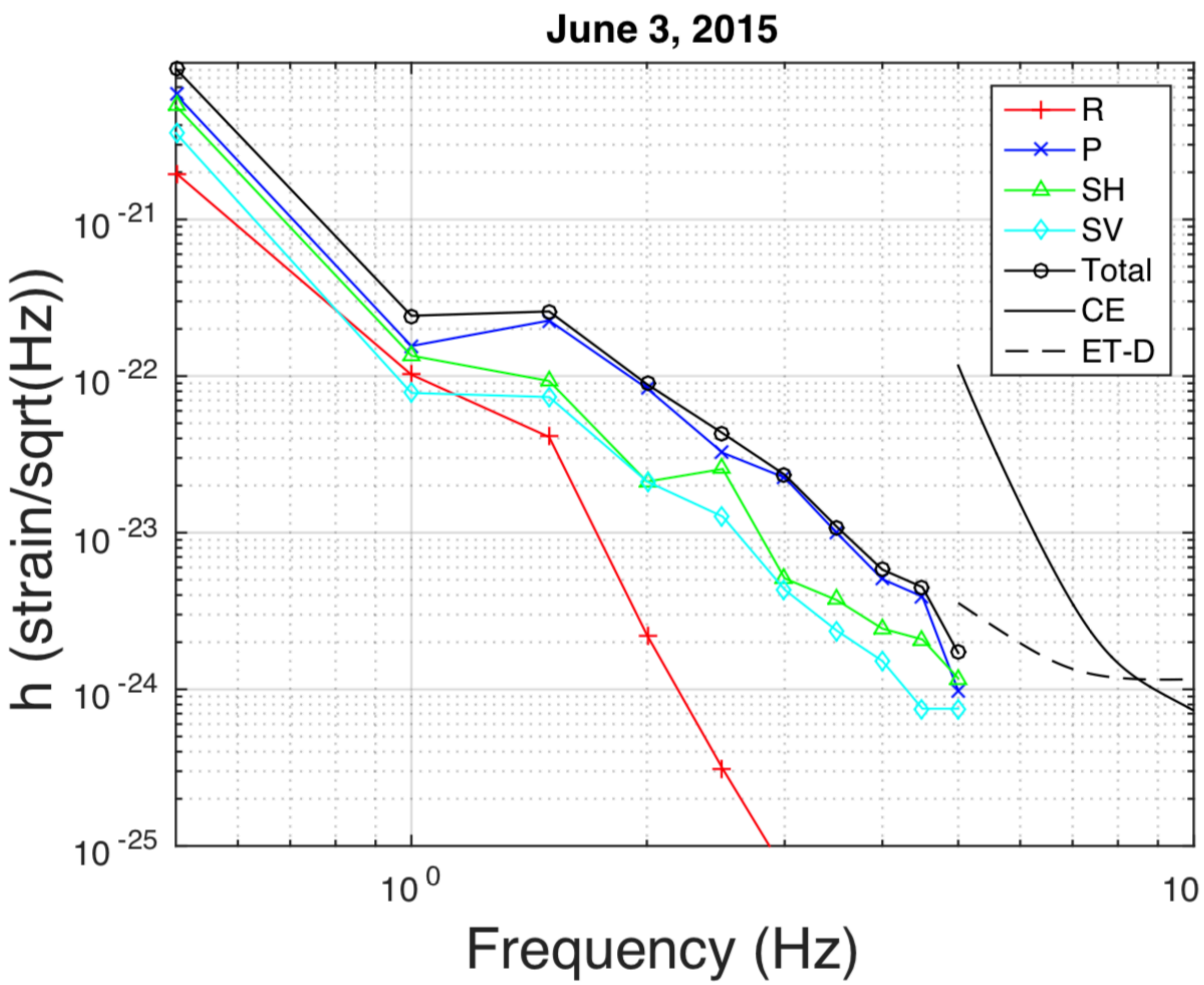
Meyers Thesis

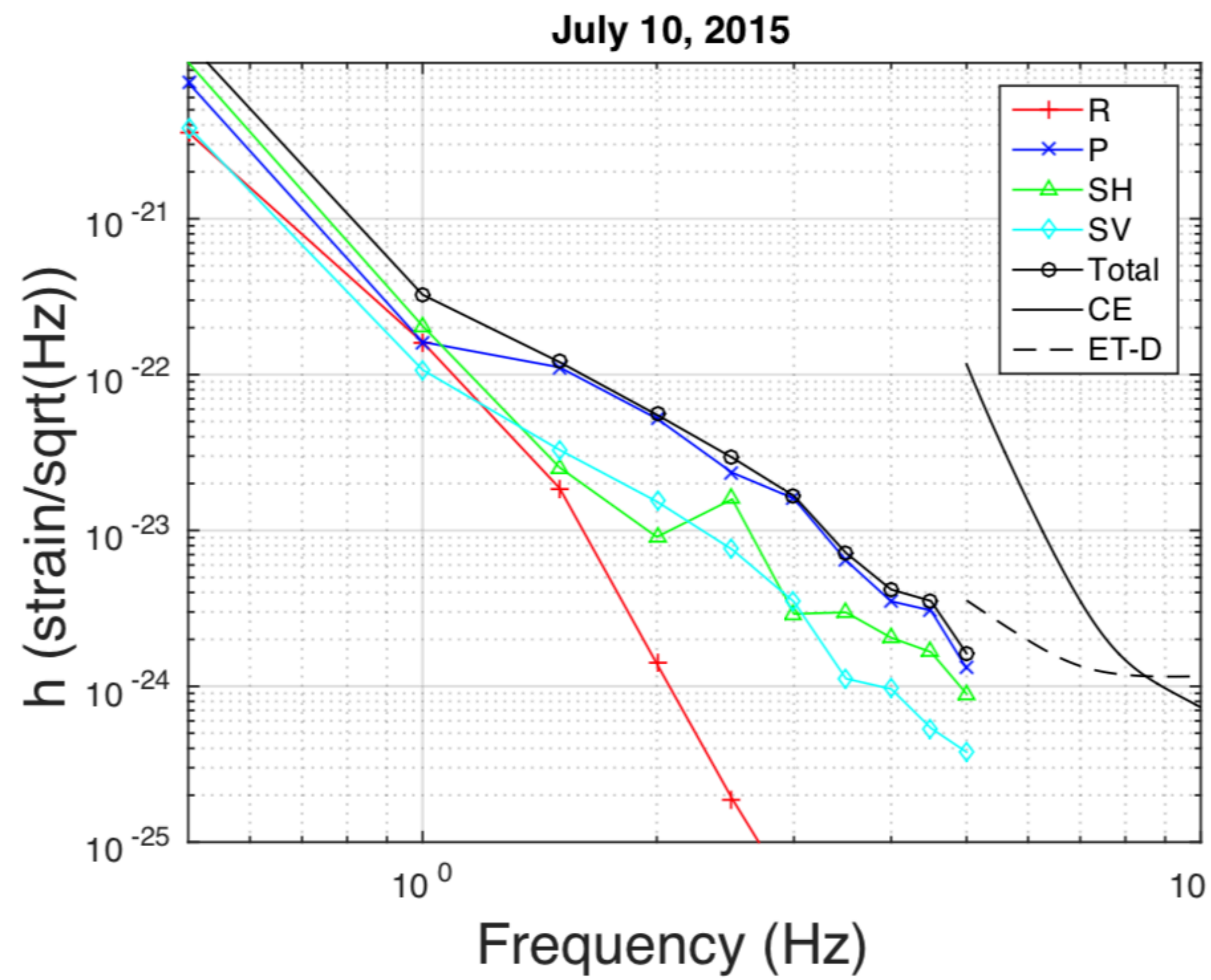




Newtonian noise results, depth

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

- Show method

Phase coherent mapping — recovery

- Plots with injections and recoveries

Phase coherent mapping — NN estimate

- NN estimate with coherent map

Reflections

- Show injection/recovery with a reflection