Newtonian noise studies for future generation gravitational-wave detectors

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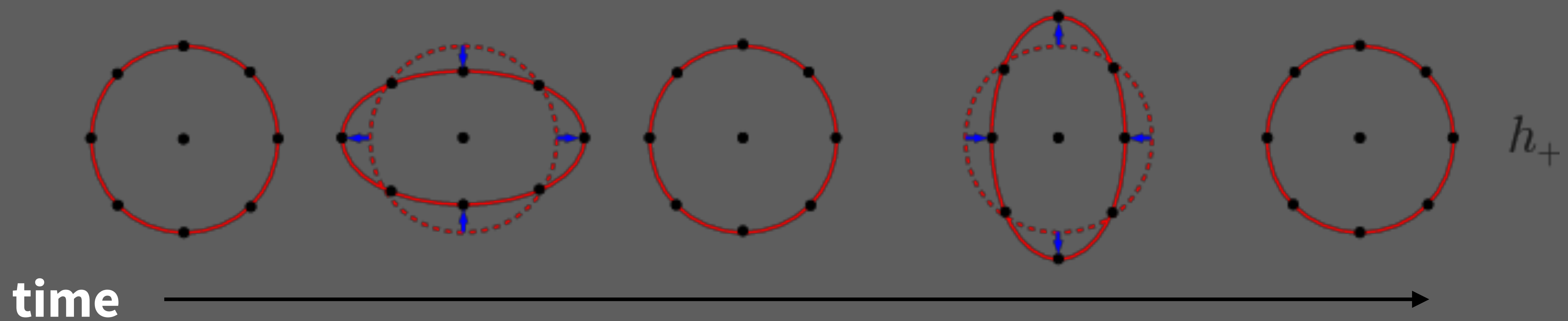
University of Melbourne
OzGrav
November 14th, 2018

Outline

- Gravitational waves (GWs) and LIGO
- The case for low frequency sensitivity
- Proposed low frequency detectors
- Newtonian noise
- Basic seismology
- Newtonian noise studies with Homestake 3D seismometer array
- Seismologically useful results

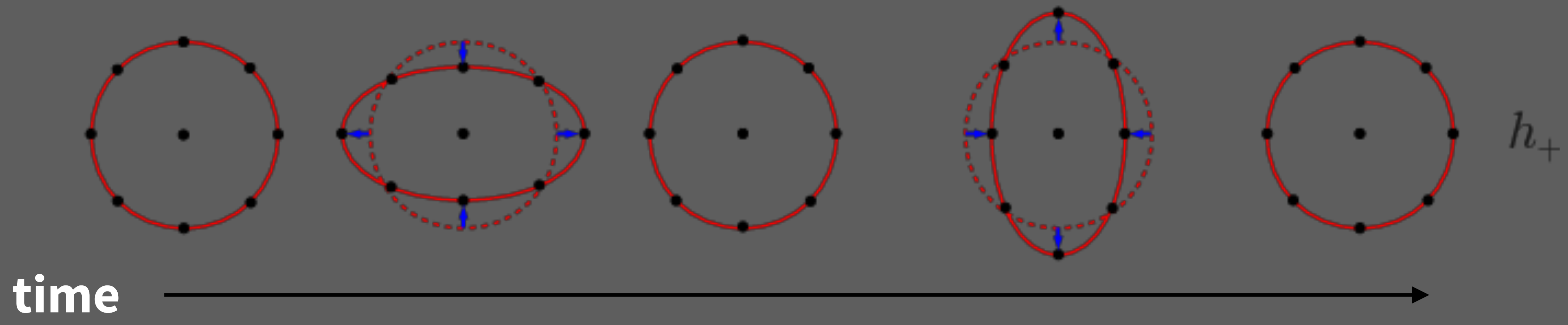
GW Polarization

"Plus" Polarization

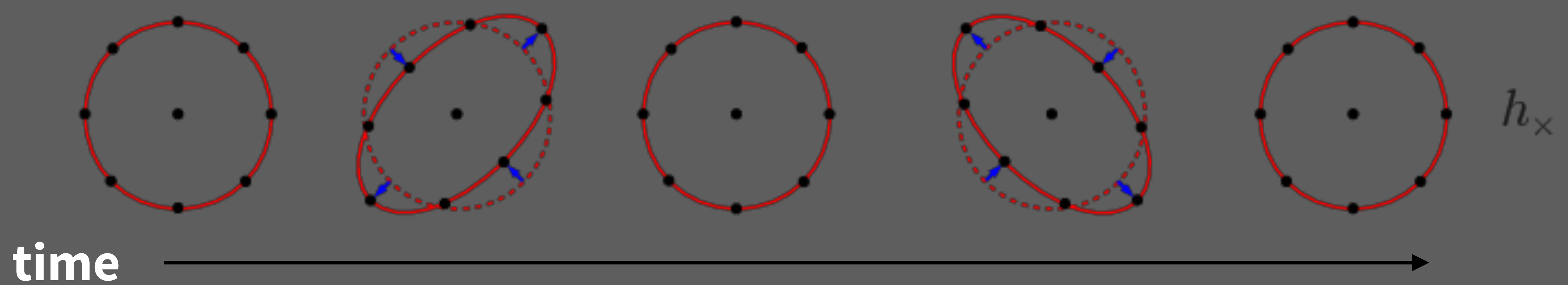


GW Polarization

“Plus” Polarization



“Cross” Polarization



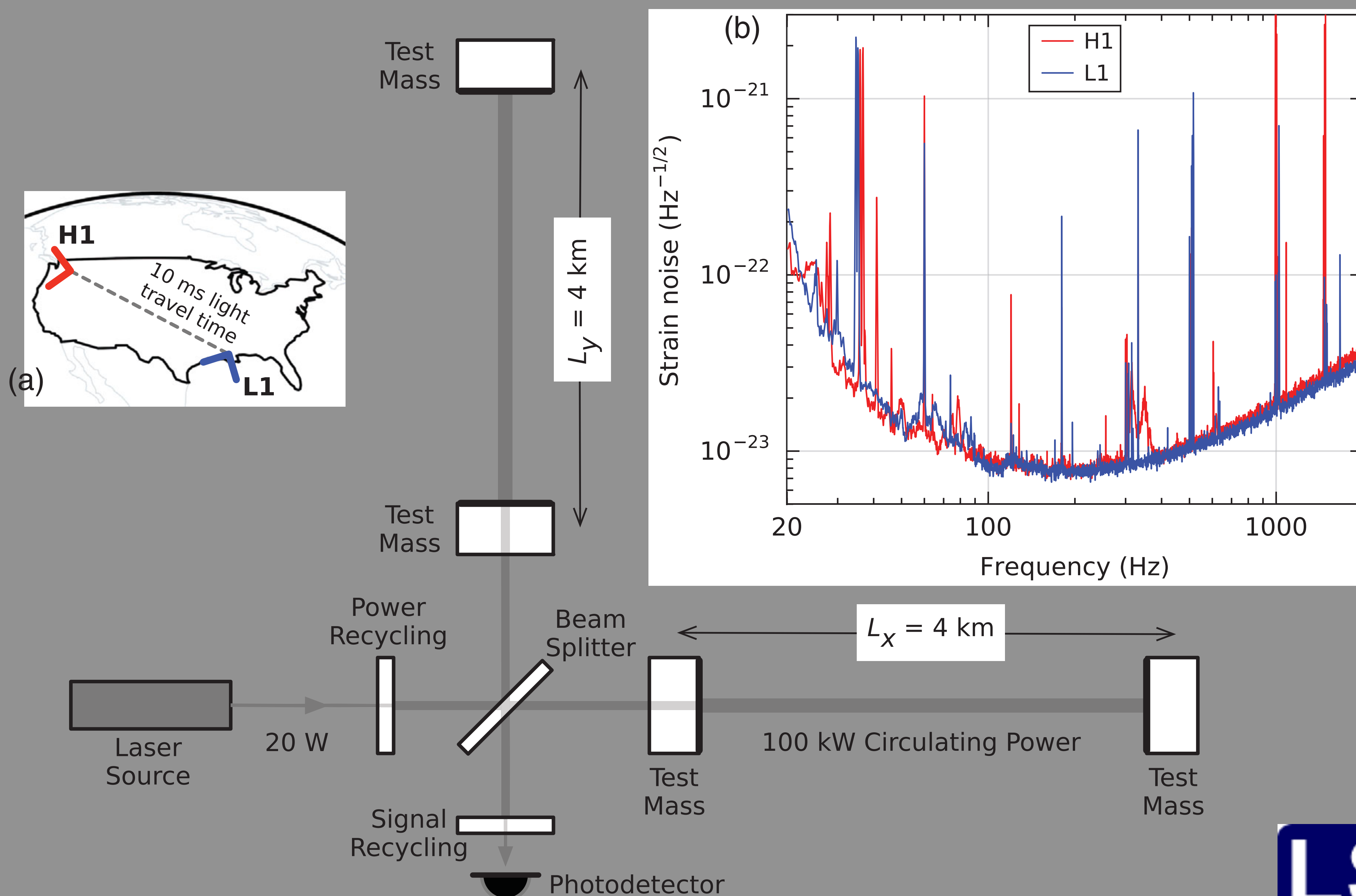
GW Amplitude

GW amplitude is measured in **strain**:

$$h = \Delta L / L$$

Blue arrows divided by radius of ring (from previous slide)

Advanced LIGO/Advanced Virgo

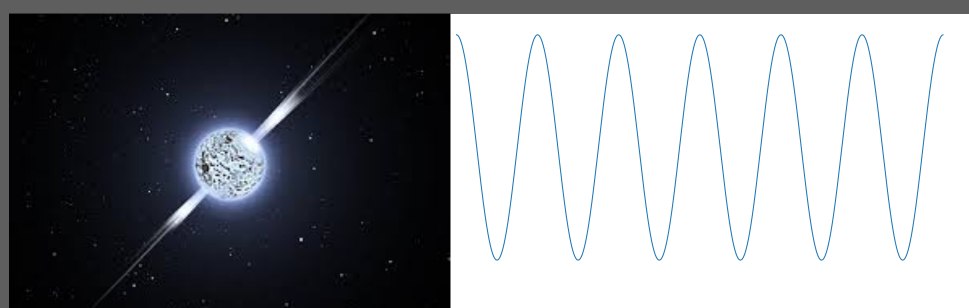


Martynov, D. V., et al. (2016). *Phys. Rev. D*, *93*(11), 433. http://doi.org/10.1103/PhysRevD.93.112004

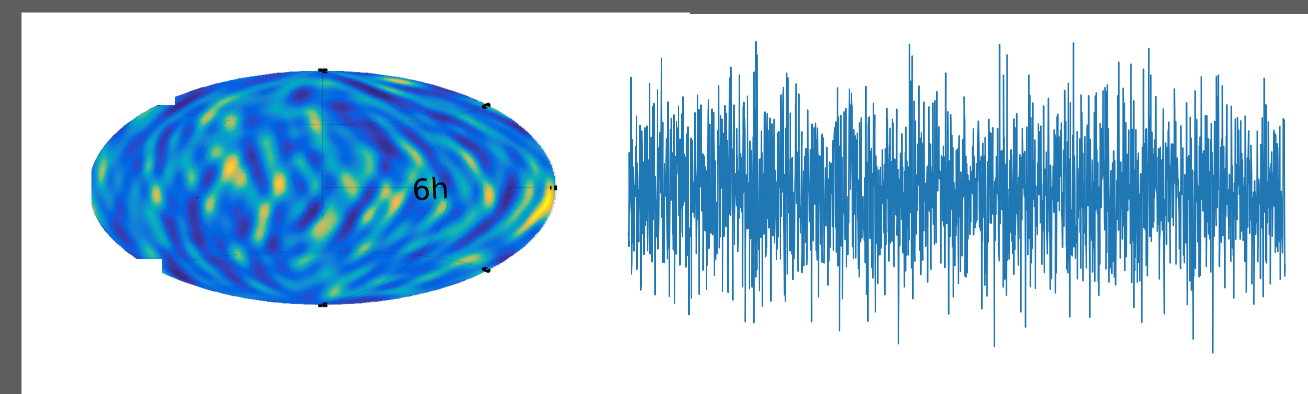
GW sources

targeted by LIGO

rotating neutron stars

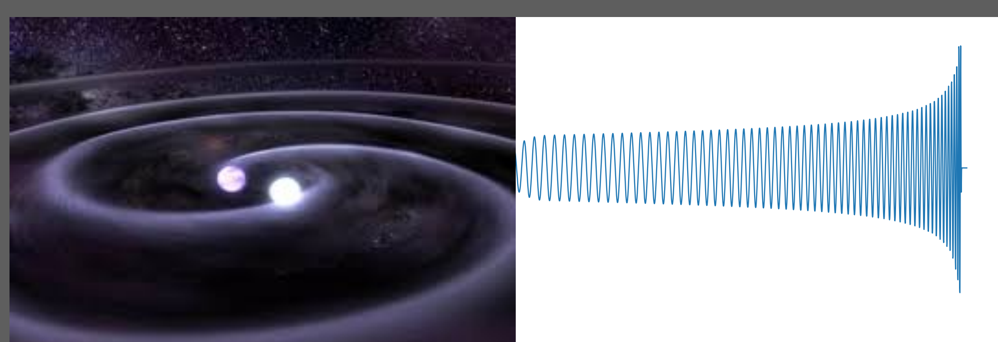


stochastic background

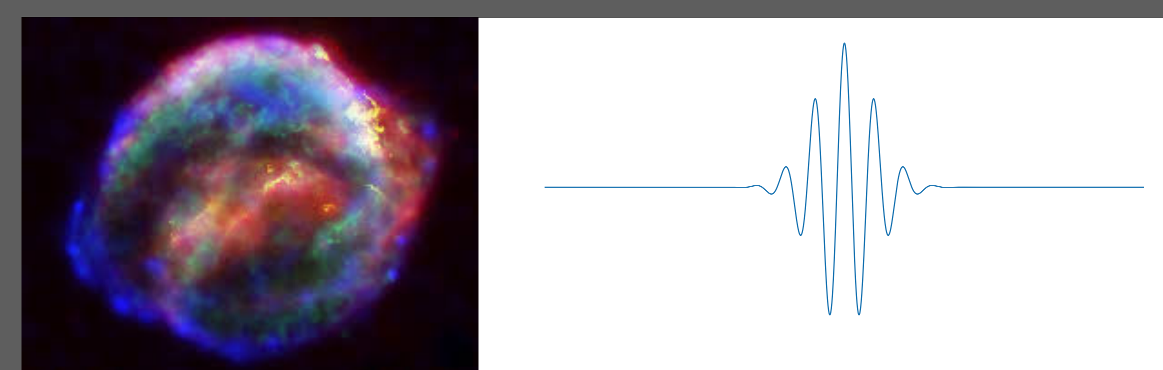


Long

Short



compact binary mergers



supernovae

Well-modeled

Poorly-modeled

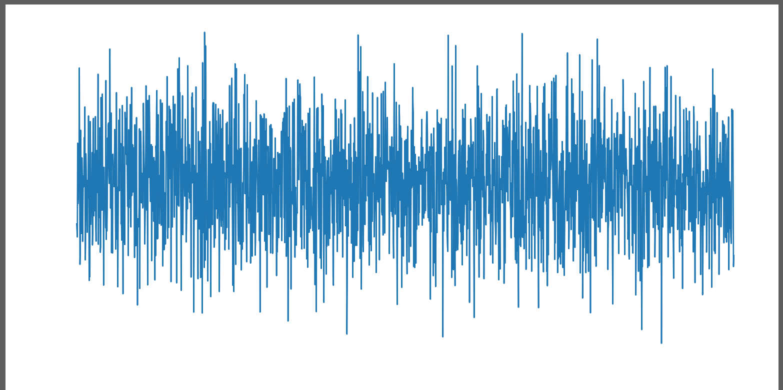
Stochastic Gravitational-wave Background

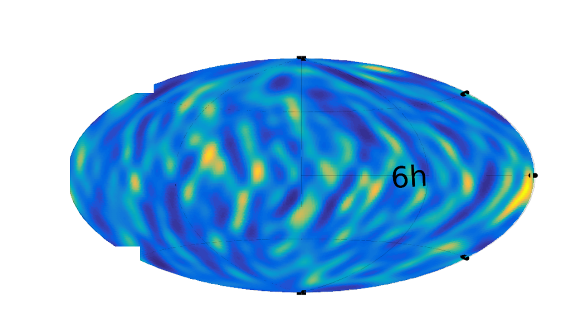
Sources

- Unresolved astrophysical sources
  - CBCs
  - Rotating neutron stars
- Early universe models
- cosmic strings

SGWB Properties/Assumptions

- Gaussian
- unpolarized
- stationary
- Isotropic
- **In some searches (not discussed here) we relax one or more of these assumptions**





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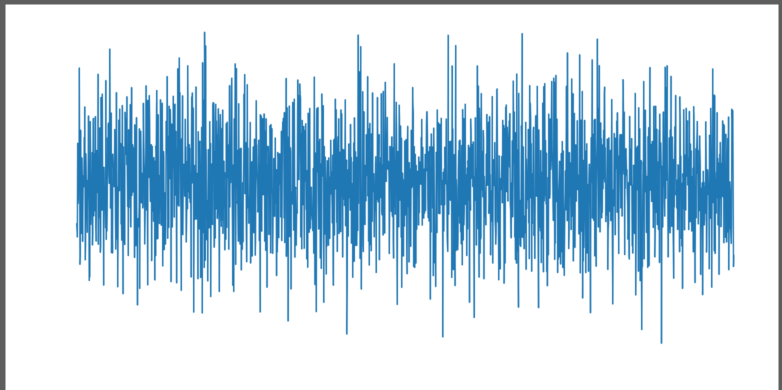
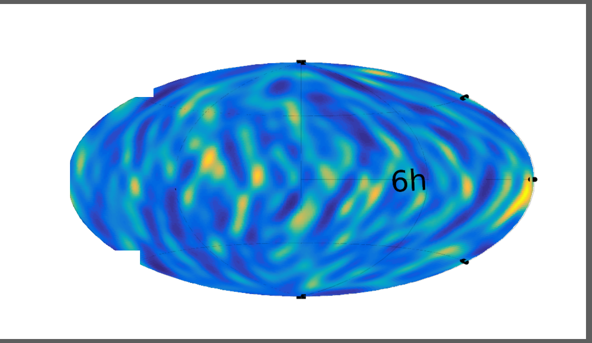
Energy density of GWs

$$\Omega_{\mathrm{GW}}(f) = \frac{f}{\rho_c}\frac{d\rho_{\mathrm{GW}}}{df}$$

Critical energy density to close the universe





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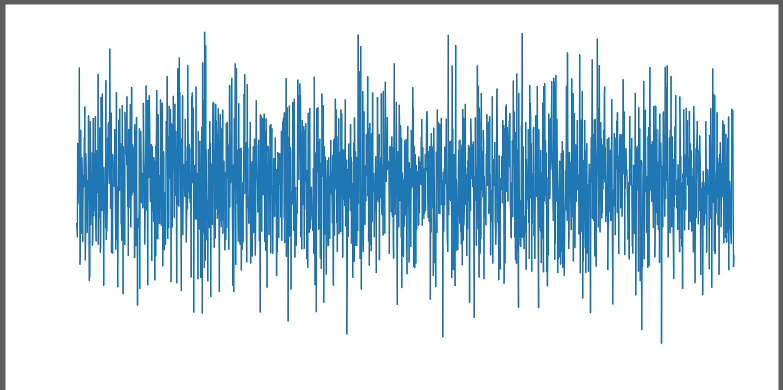
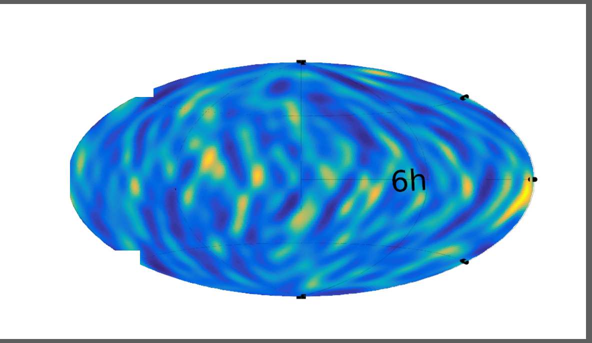
$$\rho_{GW} \propto \langle \dot{h}\dot{h} \rangle$$

$$\Rightarrow \Omega_{\rm GW}(f) \propto f^3 \langle hh \rangle$$





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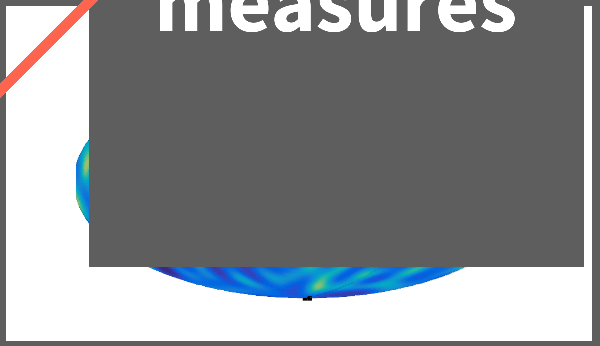


What LIGO measures

Another case for low frequencies: BBH systems

- Higher-mass BBH systems coalesce at (much) lower frequencies

- Cosmological red shift —> further-away systems get redshifted

- Higher-mass —> inspiral faster at a given frequency (i.e. fdot at a given f is higher for higher mass systems)

- Lower frequencies —>get more cycles —> more likely to see higher-mass (and more distance) black hole systems

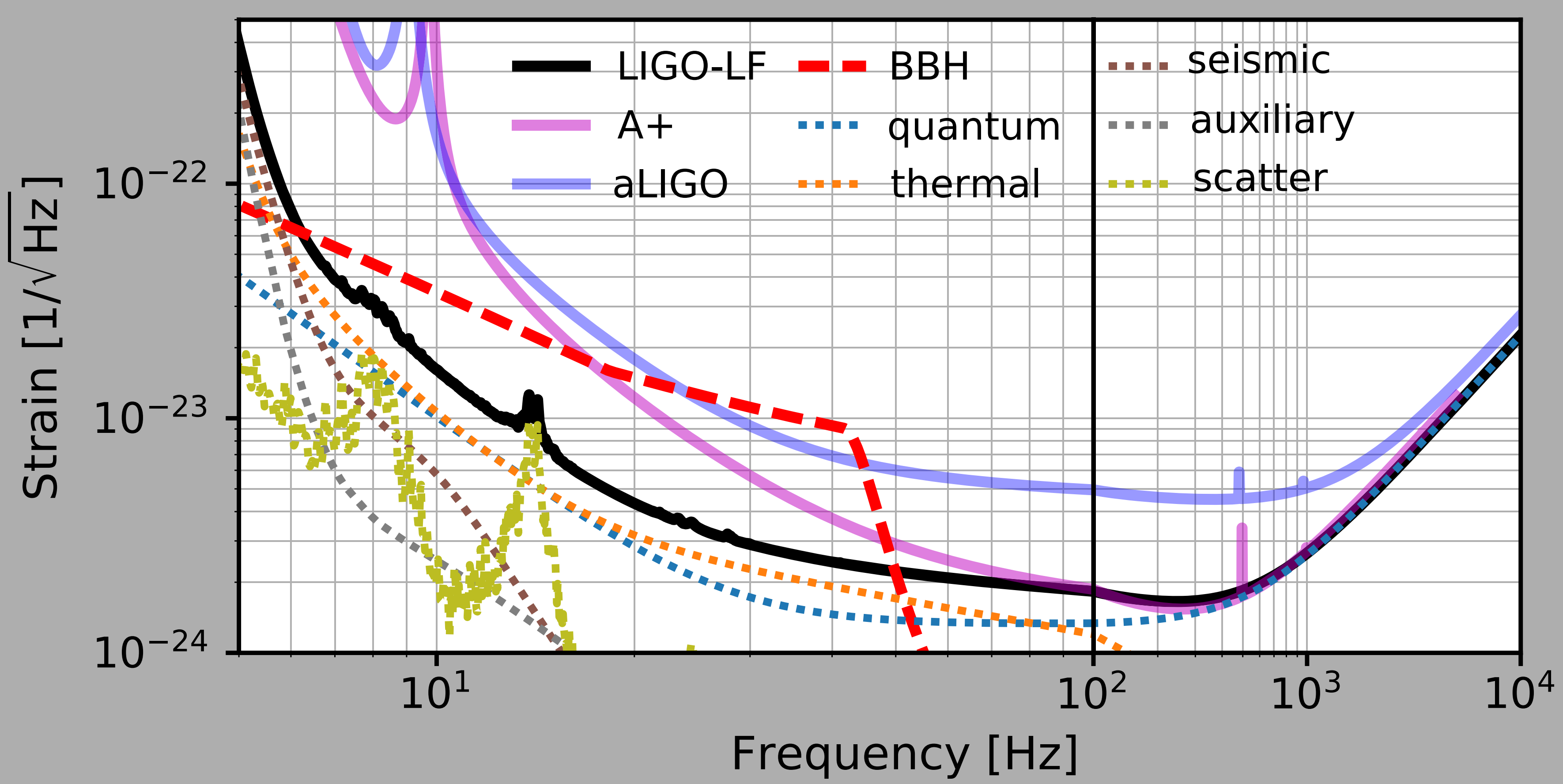
Abbott, B. P., et al. (2017). *Annalen Der Physik*, *529*(1–2), 1600209. https://doi.org/10.1002/andp.201600209

Proposed low frequency

current state

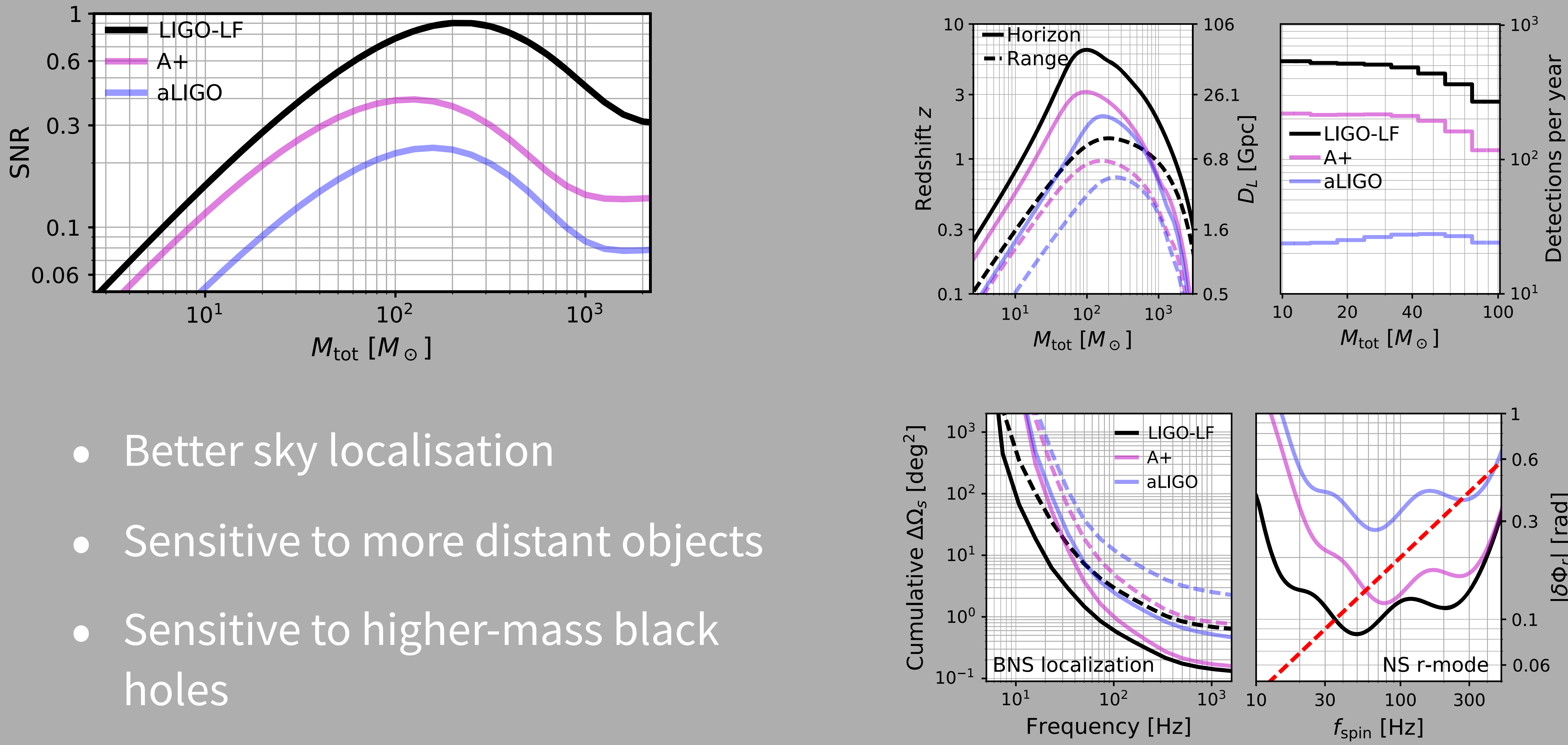
LIGO-LF

- "Use current facilities, but max out all of the current technology"
- Better auxiliary sensors —> better damping/angular controls
- Double pendulum length in suspensions
- Increase fibre tensions
- Larger test masses
    - (40 kg —> 200 kg)
- More squeezing



Yu, H., et al. (2018). https://doi.org/10.1103/PhysRevLett.120.141102

BBH improvements

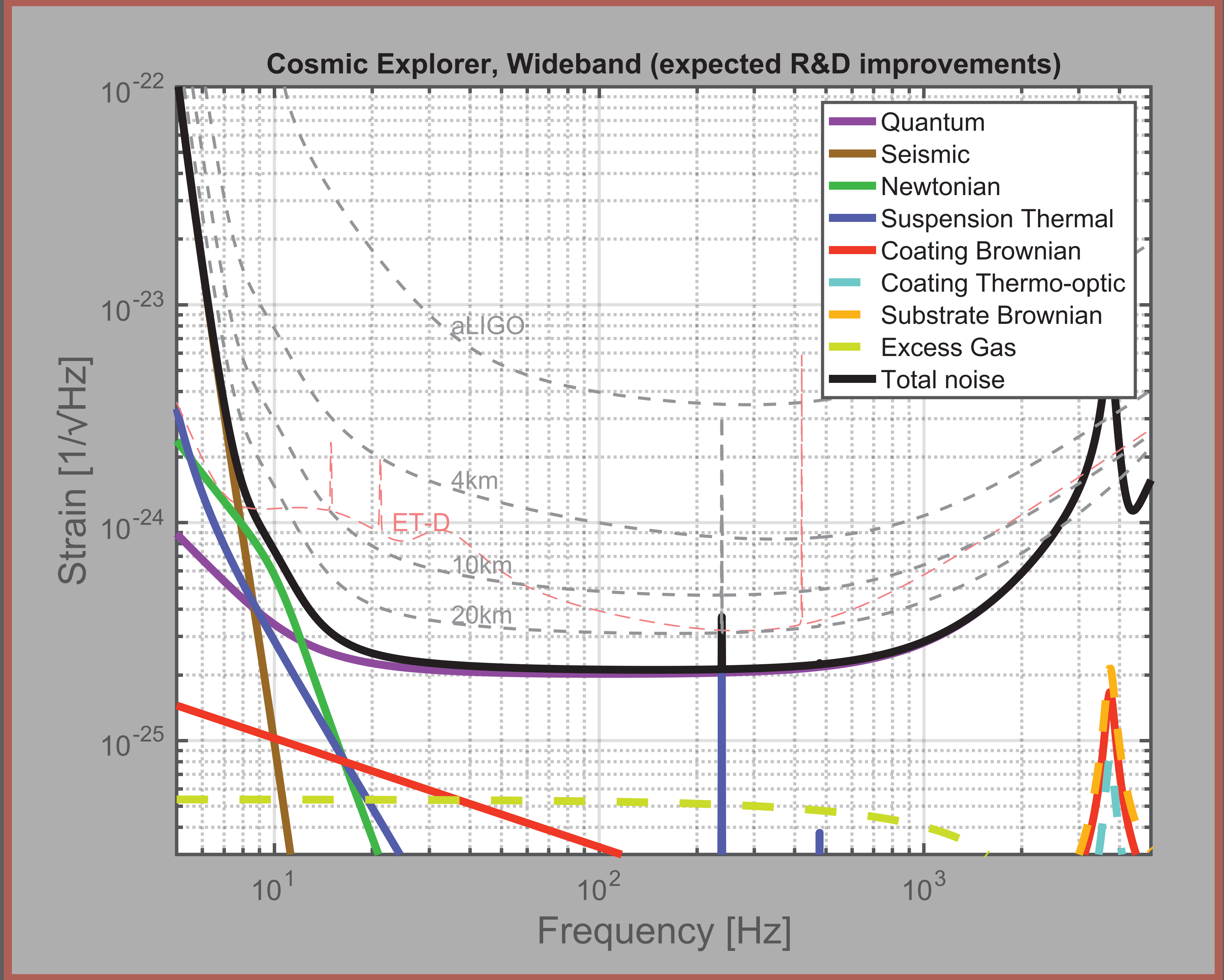


- Better sky localisation
- Sensitive to more distant objects
- Sensitive to higher-mass black holes

Yu, H., et al. (2018). https://doi.org/10.1103/PhysRevLett.120.141102

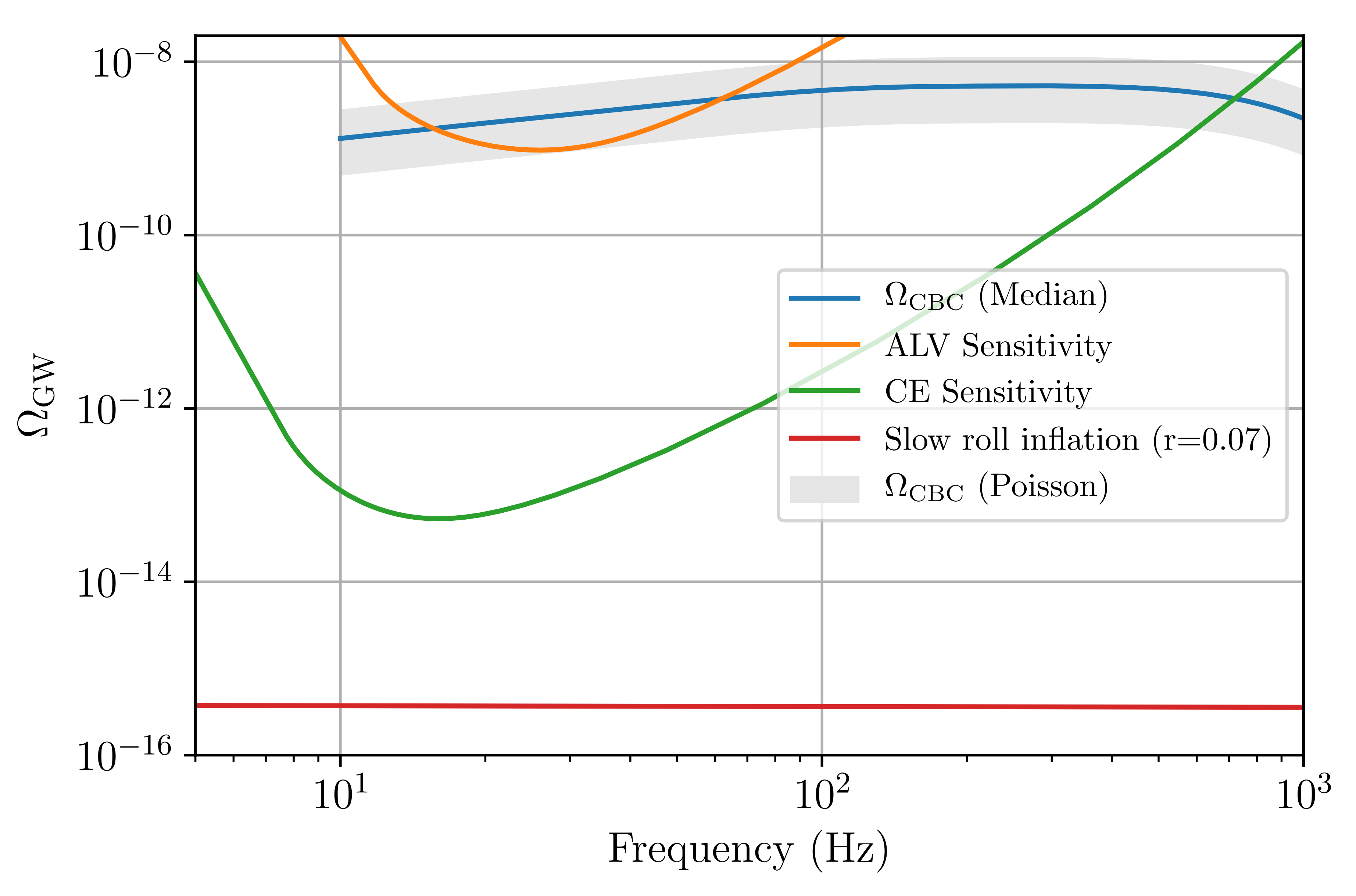
Cosmic Explorer

- **40 km arms**
- **T = 123 K**
- **m_{TM} = 320 kg**
- **λ=1550 nm**
- **P=2 MW**



Abbott, B. P., et al. (2017). 34(4), 44001. https://doi.org/10.1088/1361-6382/aa51f4

CE SGWB Sensitivity



Plot courtesy of Andrew Matas

Other proposed (ground-based) detectors

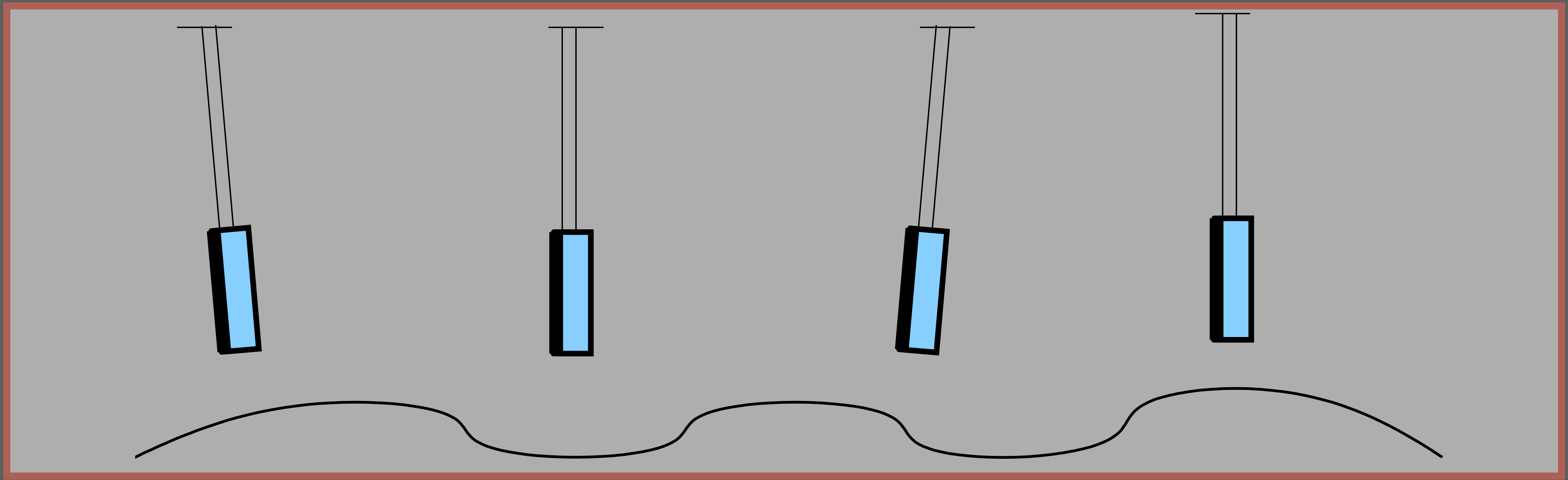
- Einstein Telescope — 10 km triangular configuration (European proposal) (O(1 Hz) — ***O***(1 kHz)) [http://www.et-gw.eu/]
- **MANGO** — laser & atom interferometer (.01 Hz — 1 Hz)
- **TOBA** — "Torsion bar antenna" (1e-3 Hz — 10 Hz)
- **TorPeDO** — torsion bar, ANU, (1e-3 Hz — 10 Hz)
  - Could also be useful for directly measuring Newtonian Noise

Harms, J., et al. (2013) https://doi.org/10.1103/PhysRevD.88.122003
McManus, D. J., et al. https://doi.org/10.1088/1361-6382/aa7103

Newtonian Noise

Newtonian Noise

- Gravitational fluctuations at the test mass
  - Density/temperature perturbations in atmosphere
  - Seismic waves
- Likely to become a limiting noise source for advanced detectors at lower frequencies



Newtonian Noise

from seismic fields

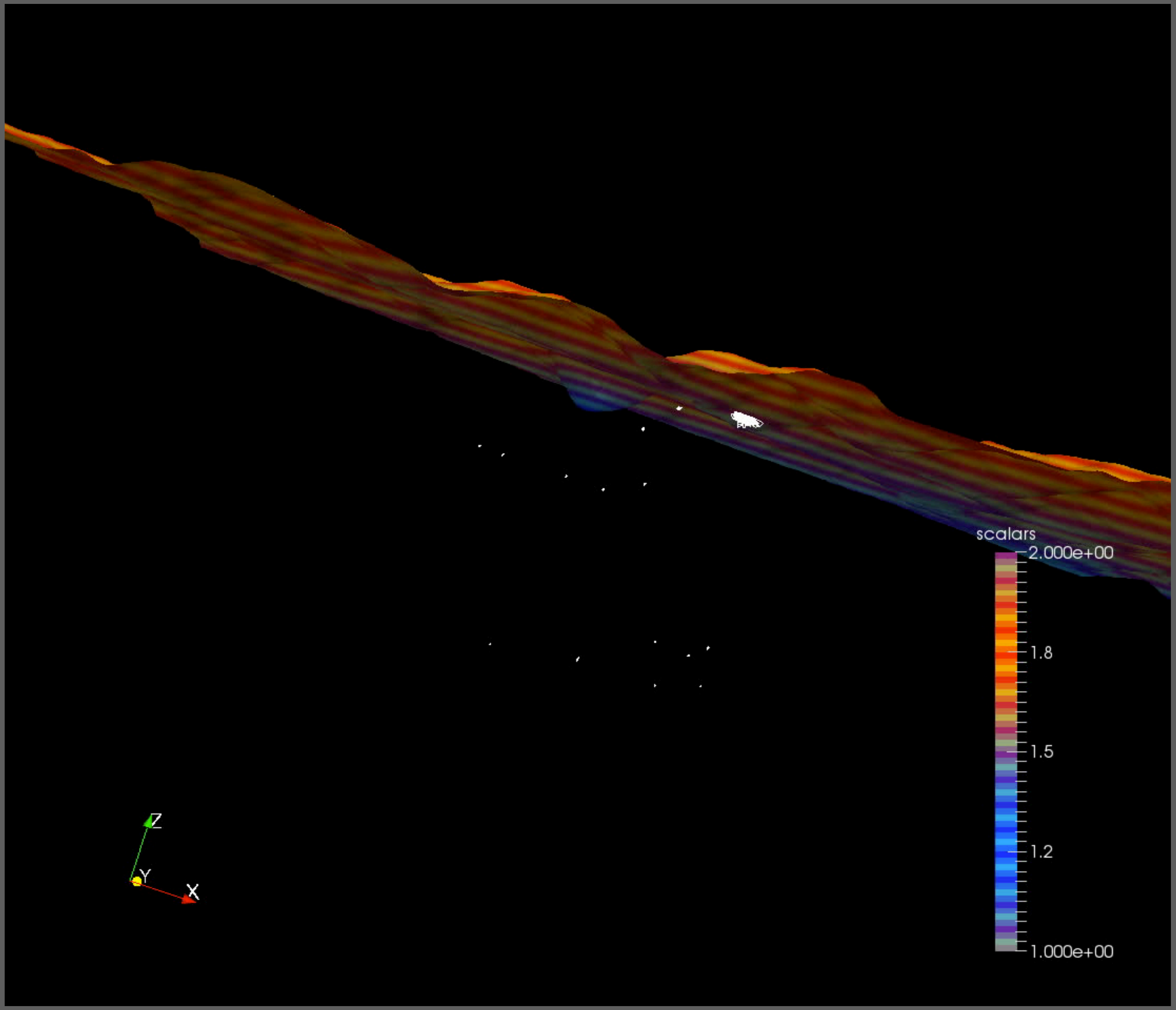
- Perturbation to gravitational field related by displacement field, **ξ**
- **ξ** is different for different types of seismic waves
- Name of the game: estimate **ξ** for different types of seismic waves

$$\delta\vec{a}(\vec{r}_0, t) = -G \int dV \rho(\vec{r})(\vec{u}(\vec{r}, t) \cdot \nabla_0) \frac{\vec{r} - \vec{r}_0}{|\vec{r} - \vec{r}_0|^3}$$

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

Seismic waves

- **P**, **S**, and **R**-waves
  - **P** — “primary” or “pressure” waves. Longitudinal wave
  - **S** — “secondary” or “shear” waves. Transverse wave
  - **R** — “Rayleigh” waves. Superposition of **P** and **S** waves. Characterized by **retrograde** particle motion
- Visualization of transient is courtesy of Gary Pavlis at IU.
- [Link to video]



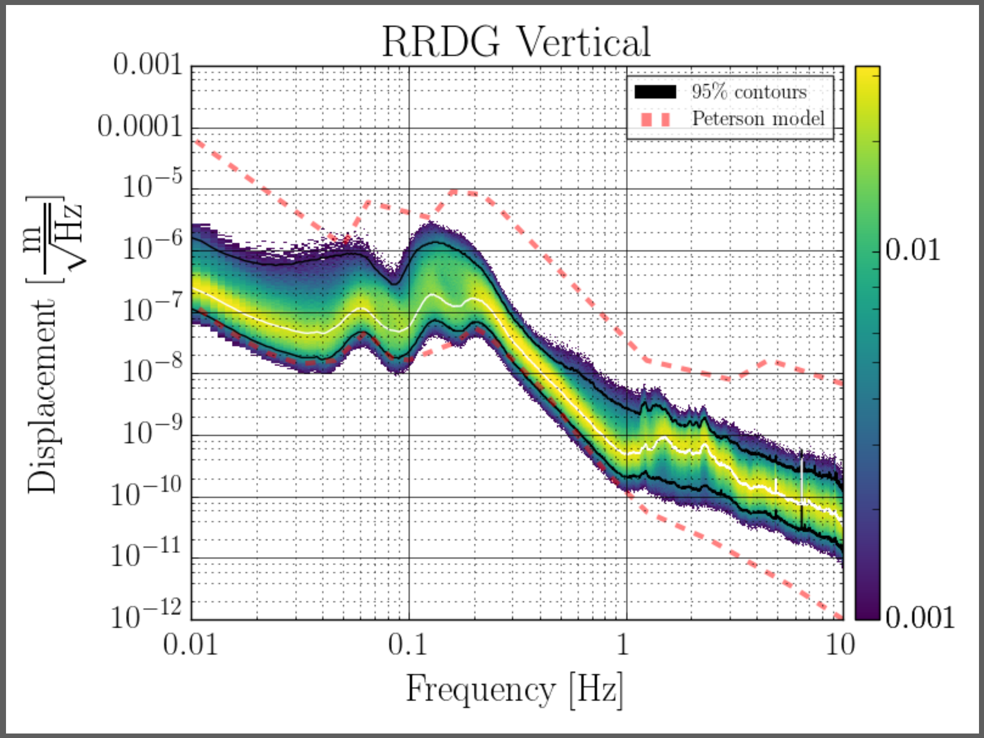
GOALS:

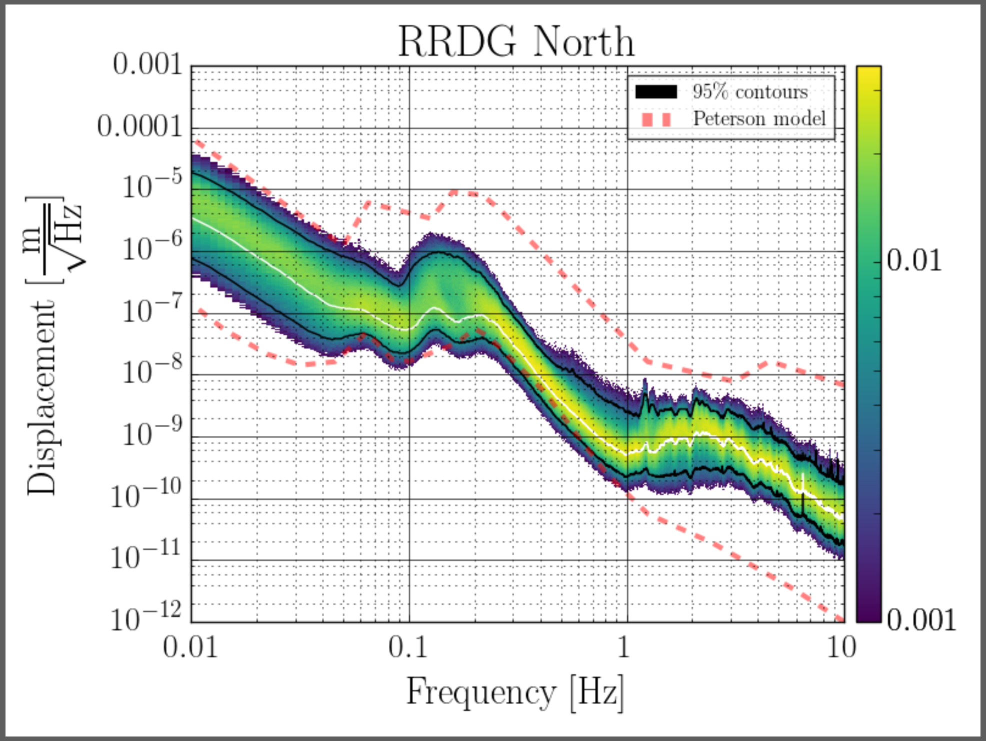
- Estimate amplitude of different seismic waves simultaneously
- From this, estimate Newtonian Noise

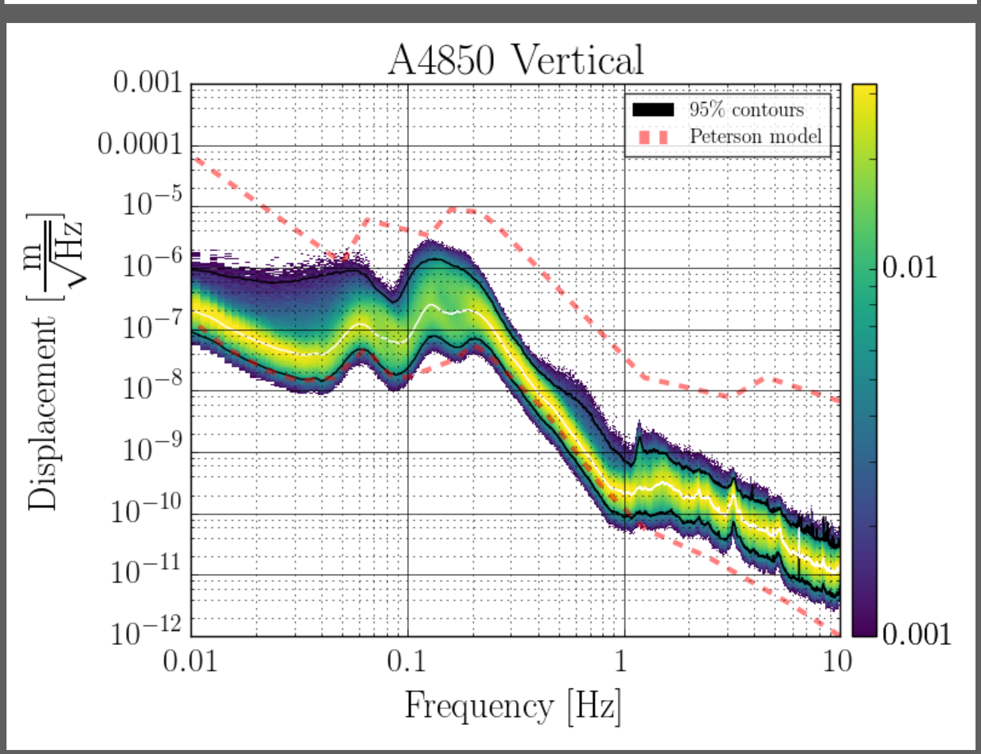
Homestake array

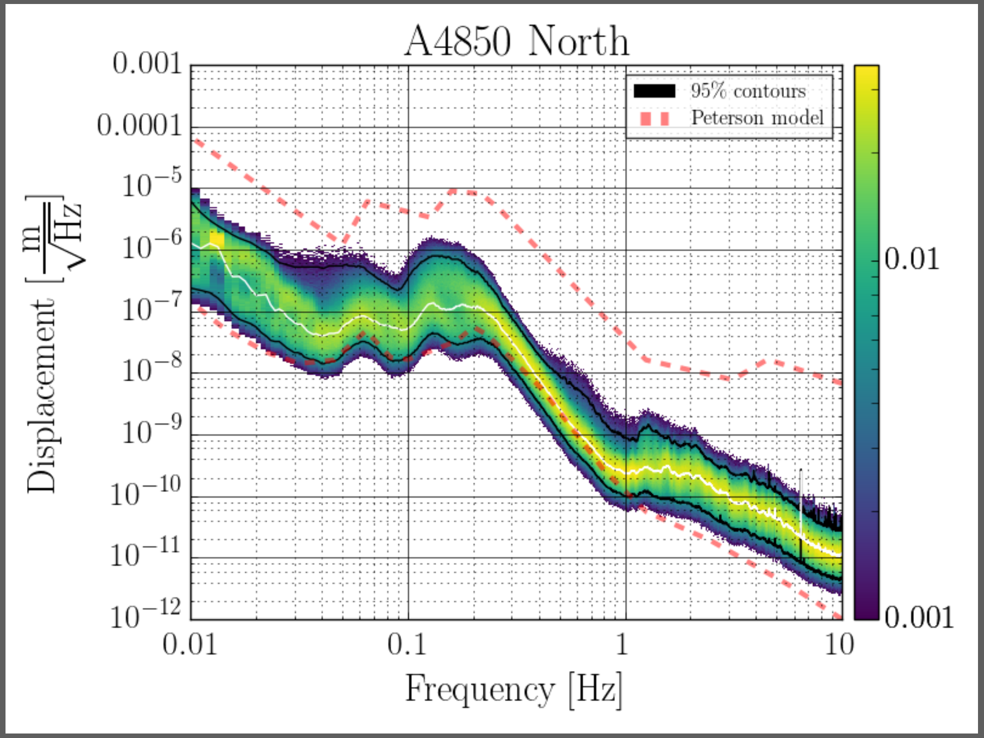
- Located at Sanford Underground Research Facility in Lead, SD.
- Collaborators at CIT, Indiana University, University of Minnesota
- 24 seismometers
  - 15 underground
  - 9 surface
  - STS2 and Guralp 3T
- Ran from November 2014 - December 2016
- Roughly 1 cubic mile
- Data set is now public on IRIS

World class data









Seismic radiometer

- Try to decouple different wave types
- Reconstruct propagation direction and amplitude for each type

Correlation of i[th] channel pair

Field amplitude in direction d (or basis element for sky decomposition)

$$\log(\mathcal{L}) \propto -\frac{1}{2}\left(\left(Y_i^* - \gamma_{i,d}^* S_d\right) N^{-1} \left(Y_i - \gamma_{i,d} S_d\right)\right)$$

Direction, d: **ϕ,θ**

$$S_d = (\gamma^T \gamma)^{-1} \gamma^T Y_i$$

maximum likelihood estimator

- **Eventual goal**: Use maps to get NN estimates

Brief aside:

Gamma matrices

- α=channel of detector "i" (i.e., N, E, V)
- β=channel of detector "j"
- a=basis function label

$$\gamma_{R,a}^{i\alpha,j\beta} = \int d\hat{\Omega} \, \Big[Q_a(\hat{\Omega}) \left(r_H(z)\hat{\Omega}\cdot\hat{\alpha} - e^{i\pi/2} r_V(z)\, \hat{z}\cdot\hat{\alpha} \right) \times \left(r_H(z)\hat{\Omega}\cdot\hat{\beta} - e^{-i\pi/2} r_V(z)\, \hat{z}\cdot\hat{\beta} \right) e^{2\pi i f \hat{\Omega}\cdot\Delta\vec{x}/v_R} \Big] \, .$$

Brief aside:

Gamma matrices

Basis function (delta functions)

$$\gamma^{i\alpha,j\beta}_{R,a} = \int d\hat{\Omega} \left[Q_a(\hat{\Omega}) \left(r_H(z)\hat{\Omega}\cdot\hat{\alpha} - e^{i\pi/2} r_V(z)\, \hat{z}\cdot\hat{\alpha} \right) \times \right.$$
$$\left. \left(r_H(z)\hat{\Omega}\cdot\hat{\beta} - e^{-i\pi/2} r_V(z)\, \hat{z}\cdot\hat{\beta} \right) e^{2\pi i f \hat{\Omega}\cdot\Delta\vec{x}/v_R} \right].$$

Brief aside:

Gamma matrices

Propagation direction

$$\gamma_{R,a}^{i\alpha,j\beta} = \int d\hat{\Omega}\, \Big[Q_a(\hat{\Omega}) \left(r_H(z)\hat{\Omega}\;\hat{\alpha} - e^{i\pi/2} r_V(z)\,\hat{z}\cdot\hat{\alpha}\right) \times$$
$$\left(r_H(z)\hat{\Omega}\cdot\hat{\beta} - e^{-i\pi/2} r_V(z)\,\hat{z}\cdot\hat{\beta}\right) e^{2\pi i f \hat{\Omega}\cdot\Delta\vec{x}/v_R}\Big].$$

Brief aside:

Gamma matrices

alpha/beta Phase difference (retrograde motion)

$$\gamma_{R,a}^{i\alpha,j\beta} = \int d\hat{\Omega}\, \left[Q_a(\hat{\Omega}) \left(r_H(z)\hat{\Omega}\cdot\hat{\alpha} - e^{i\pi/2} r_V(z)\,\hat{z}\cdot\hat{\alpha} \right) \times \right.$$
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Phase difference between I and j

Brief aside:

Gamma matrices

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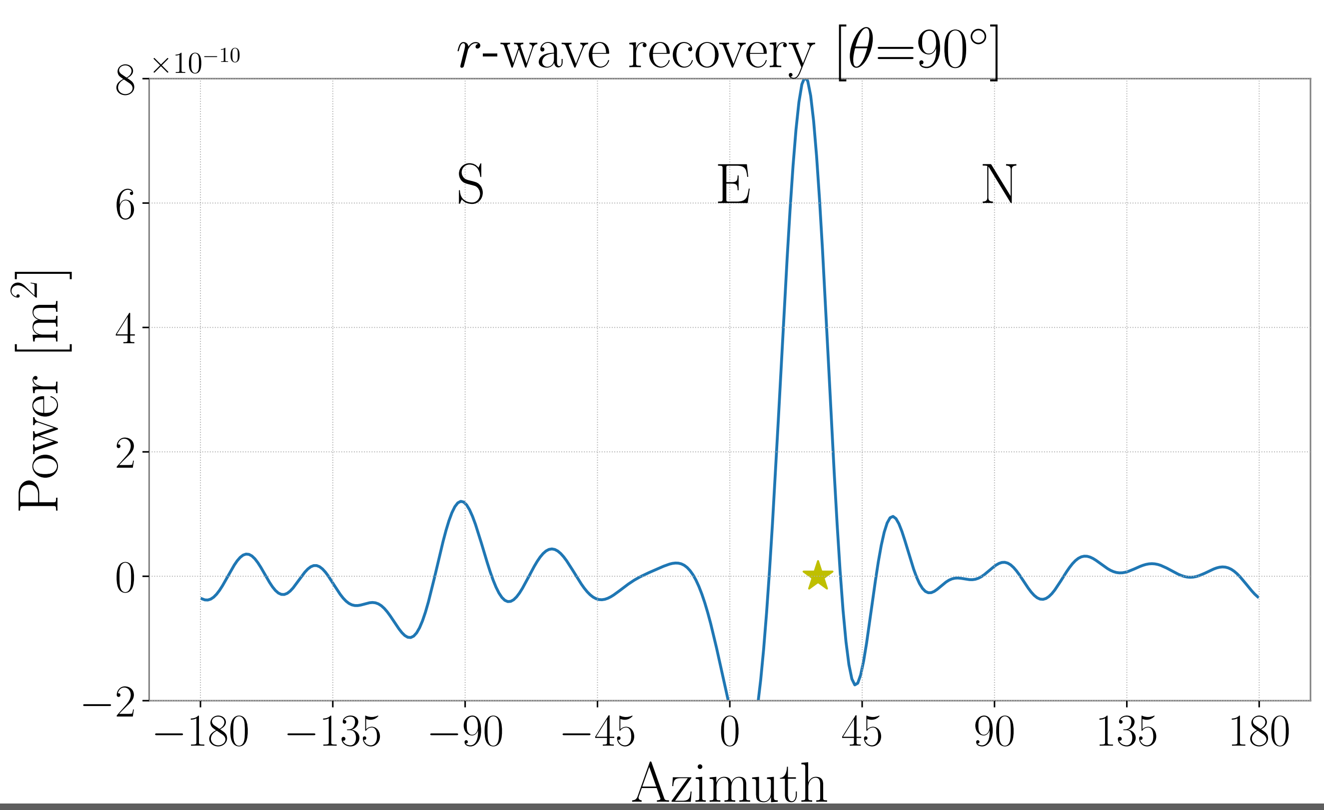
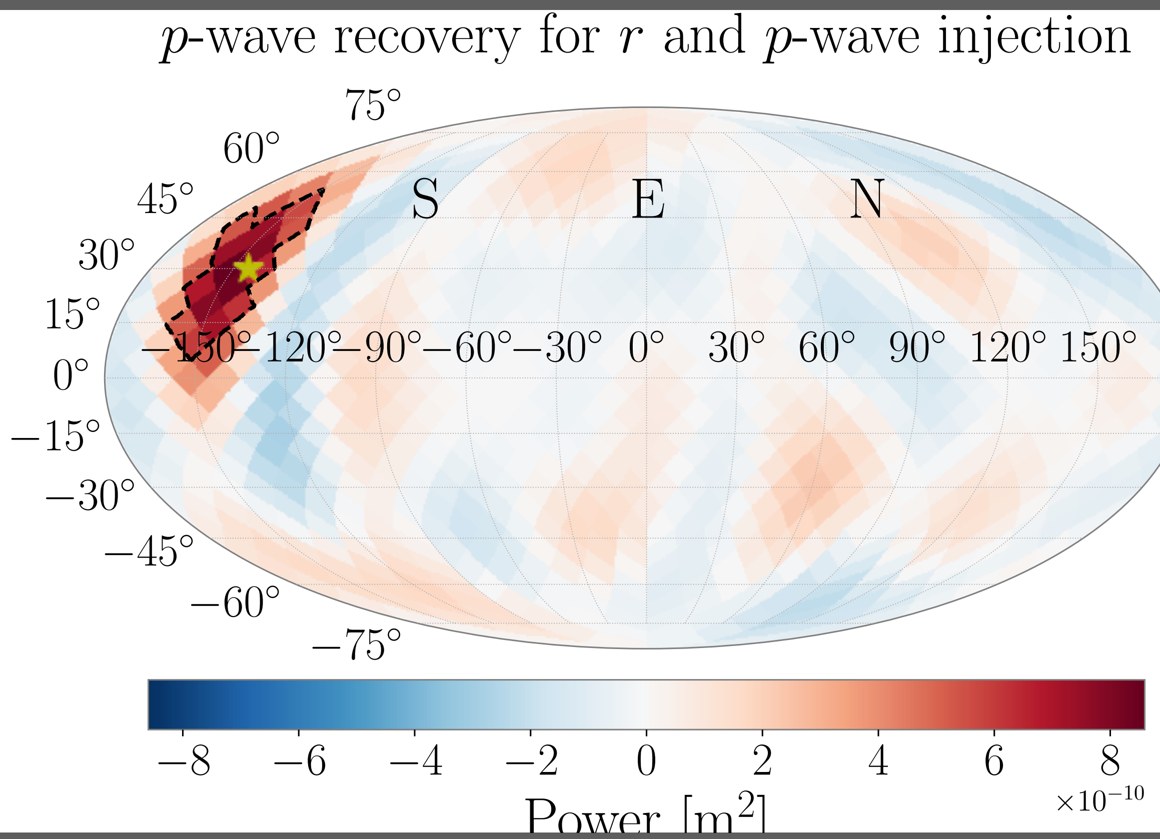
Govern how R-wave amp fall with depth (measured later)

Seismic radiometer

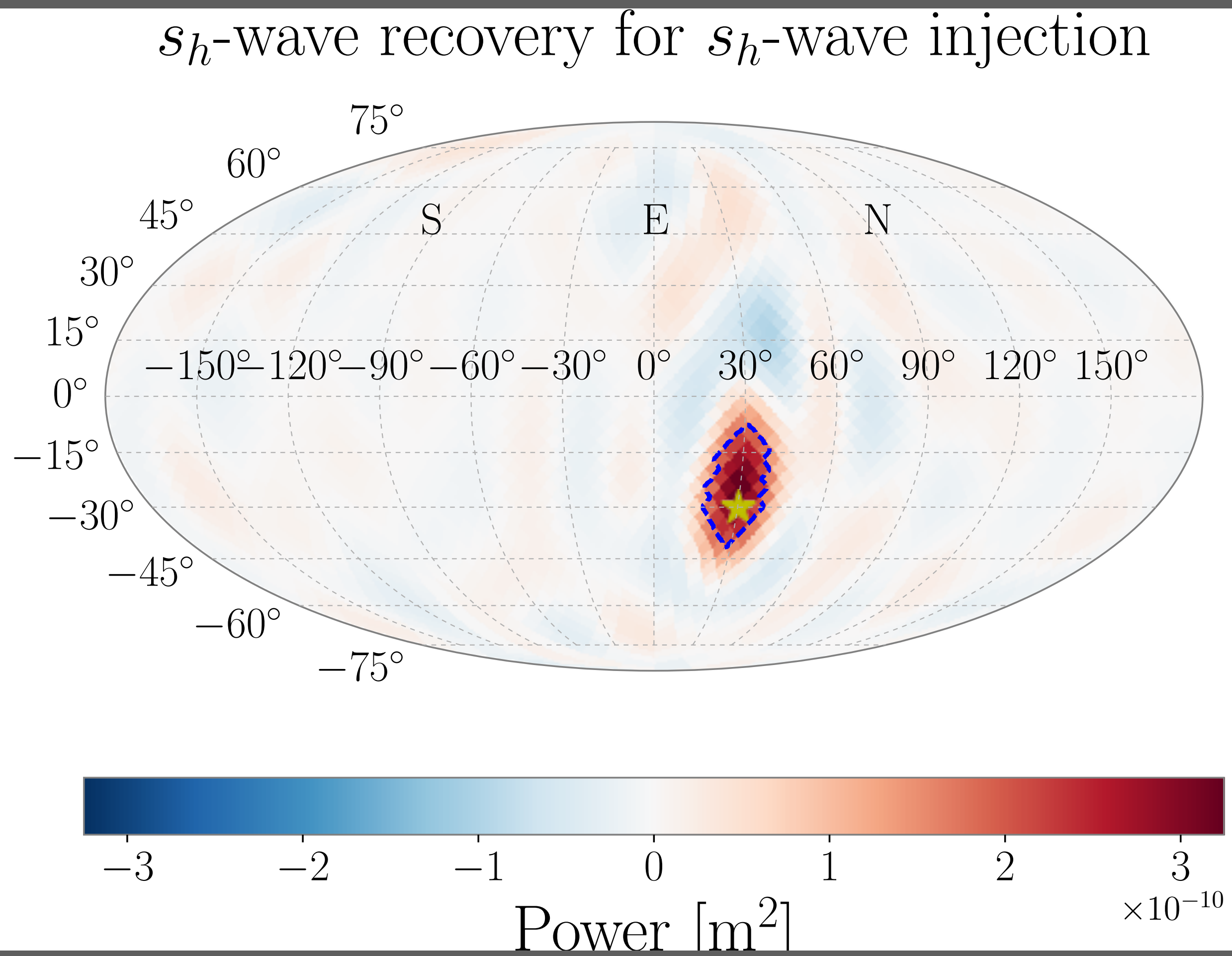
- Rayleigh and P-waves both injected
- Recovered in proper direction
- Amplitudes not quite right when 2 sources are present
  - (injections violate one assumption of search)

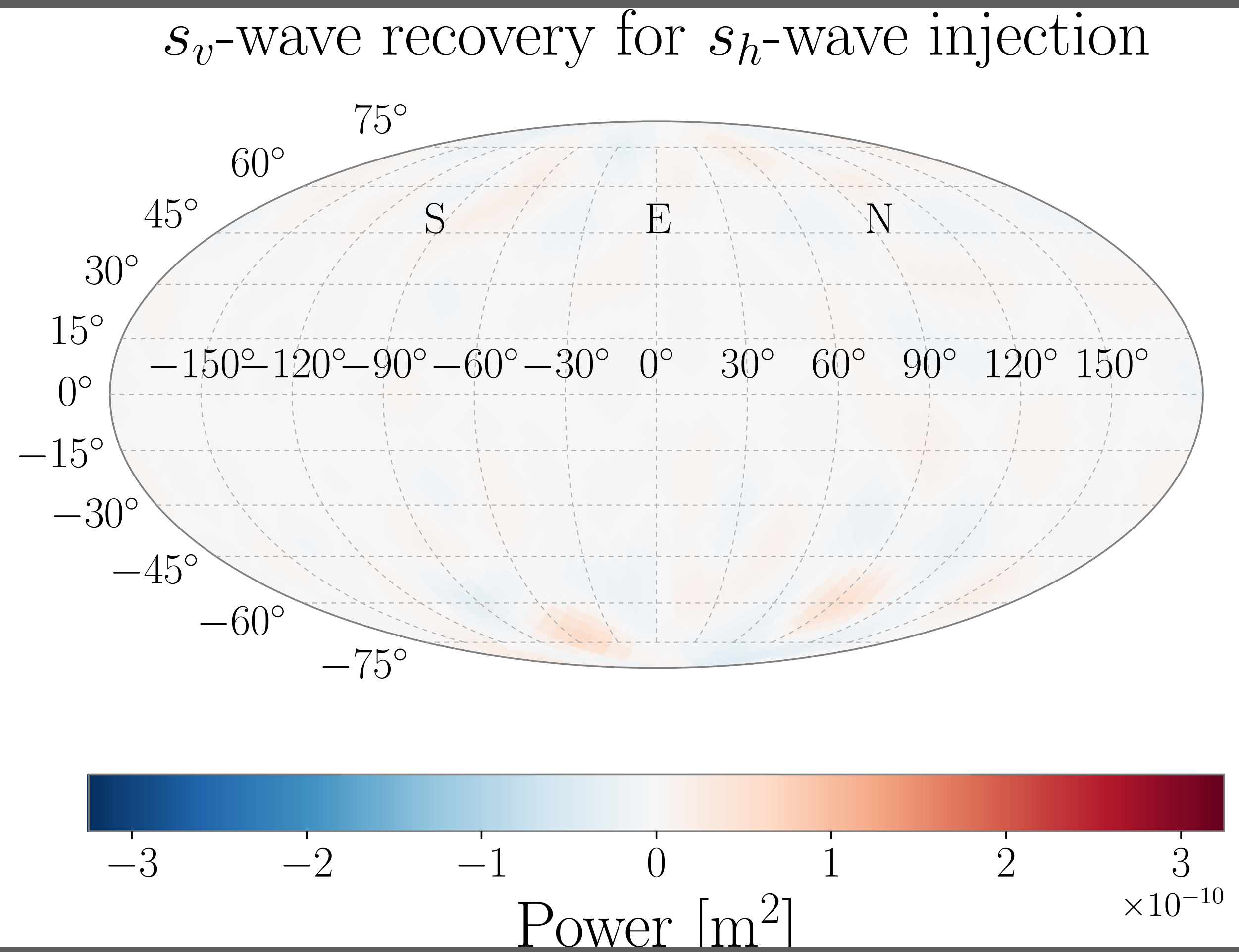




Seismic radiometer

- S-wave injection/recovery

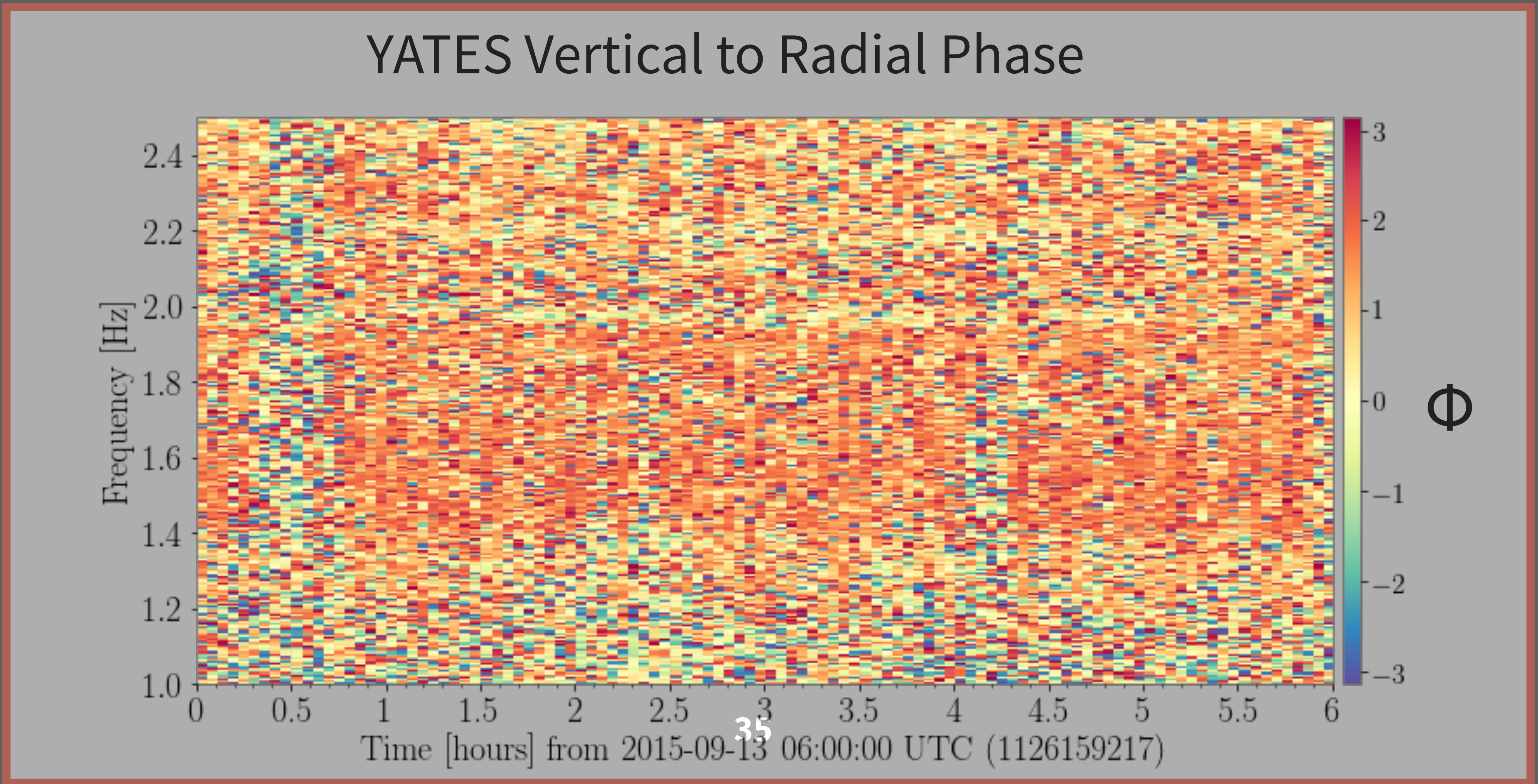




Seismic Radiometer

1.5 - 2 Hz Source

- There is a source of (presumably) R-waves at 1.5 Hz
- Turns on and off at certain times of the day
- Would like to use Radiometer to resolve direction
- Will compare to a pure plane-wave model

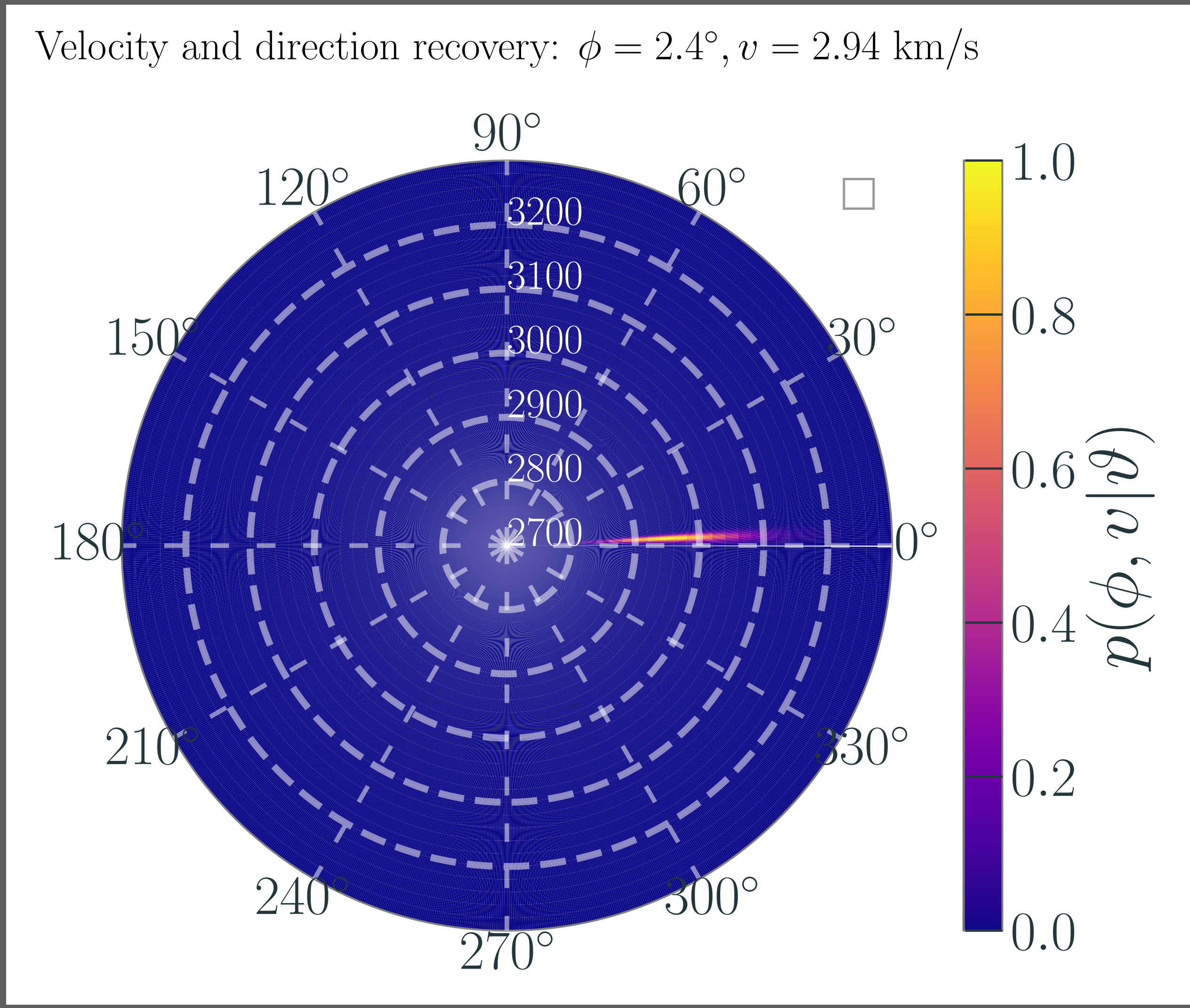


1.5 Hz source

timing-only analysis

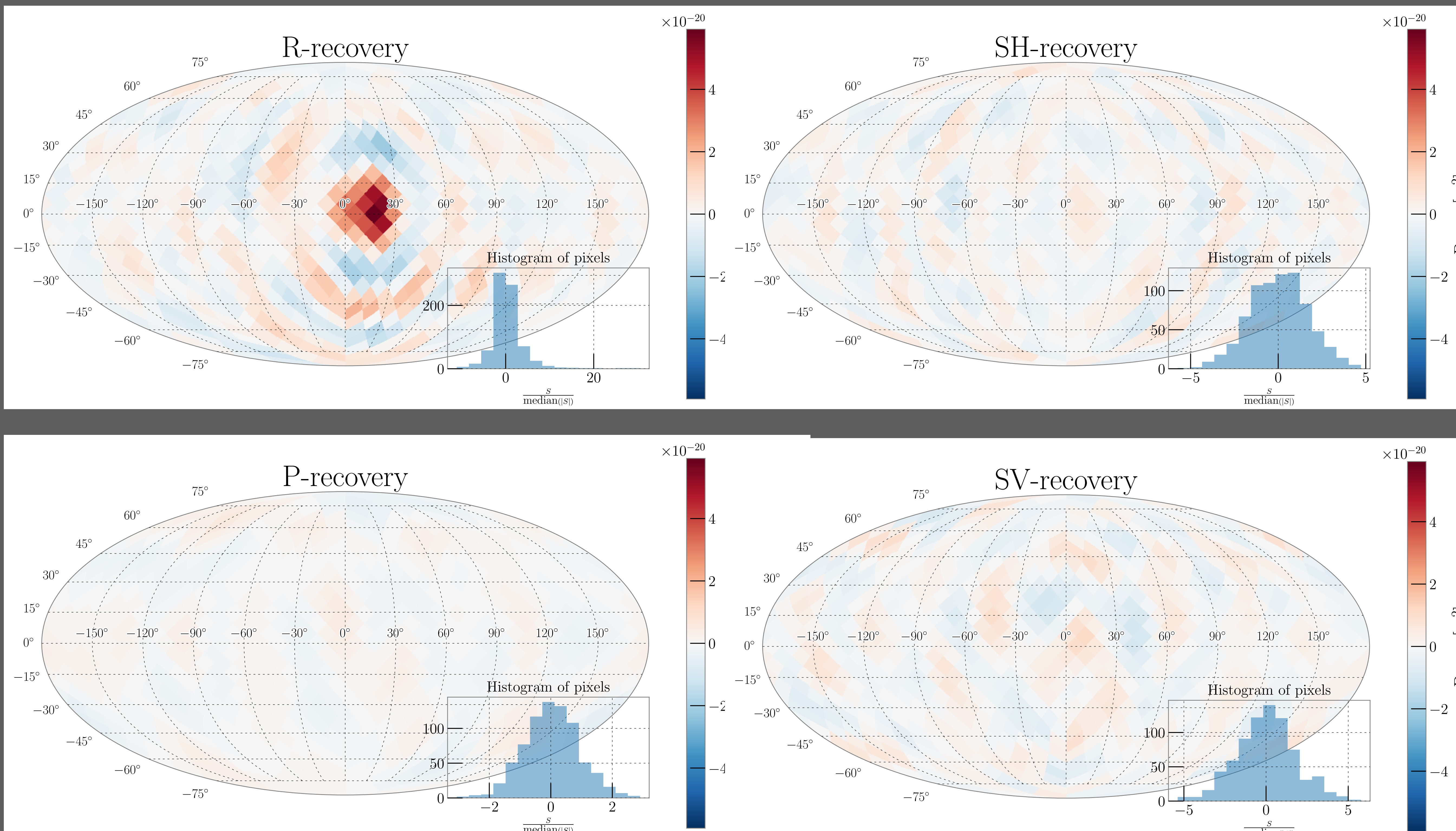
- Use phase-delay between stations to estimate velocity, **v**, and direction, **Ω**.
- Assuming pure-plane-wave, the phase delay should be:

$$\vartheta_{ij} = \frac{2\pi f \hat{\Omega} \cdot \Delta\vec{x}_{ij}}{v}$$



1.5 Hz source

seismic radiometer



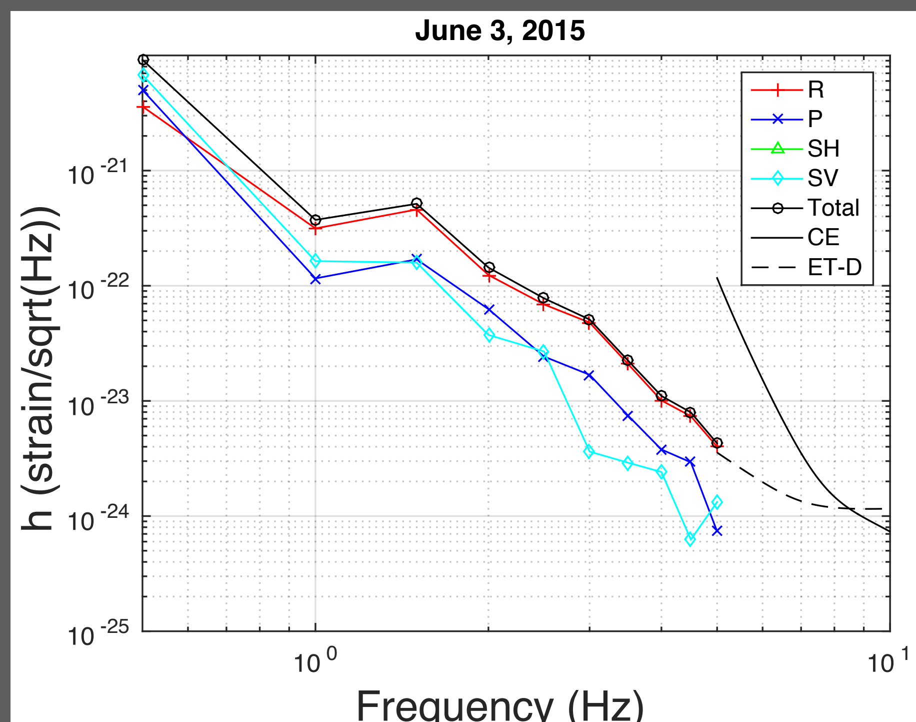
Estimate NN from maps

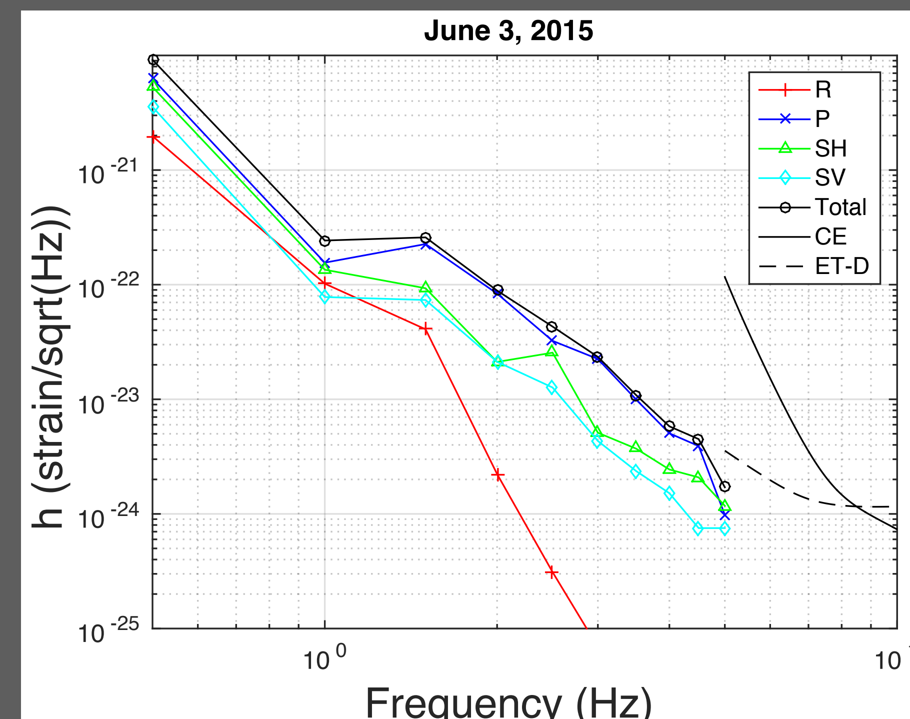
- We can now try to estimate the Newtonian noise from our recovery maps
- Run radiometer from **0.5 - 5 Hz** in **0.5 Hz** increments
- Assume “CE-like” detector (i.e. **40 km** arms)

Estimating Newtonian noise

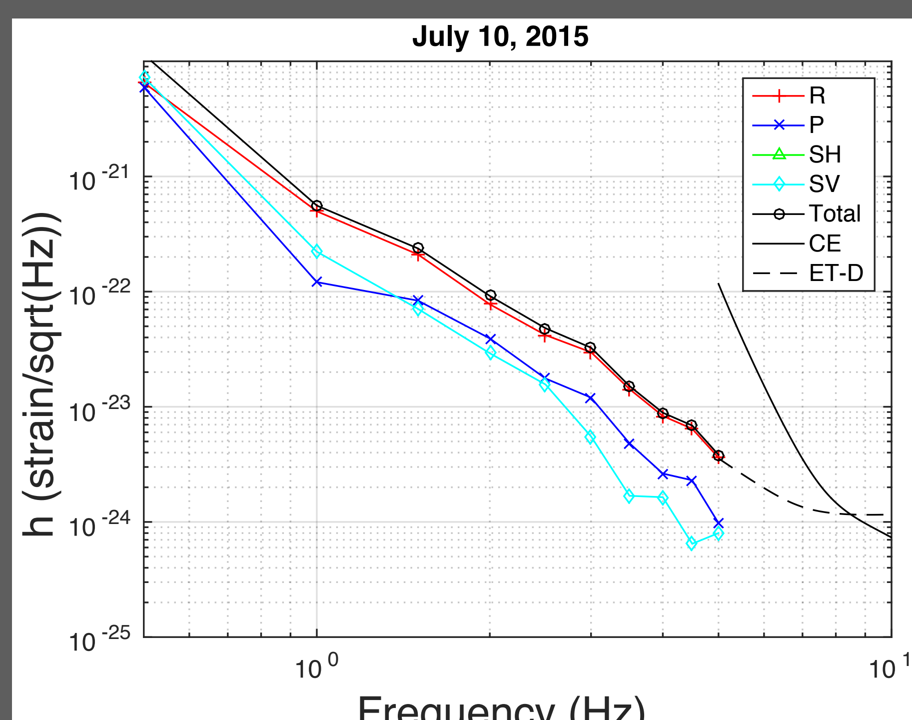
Surface Detector | **4850 ft. Detector**

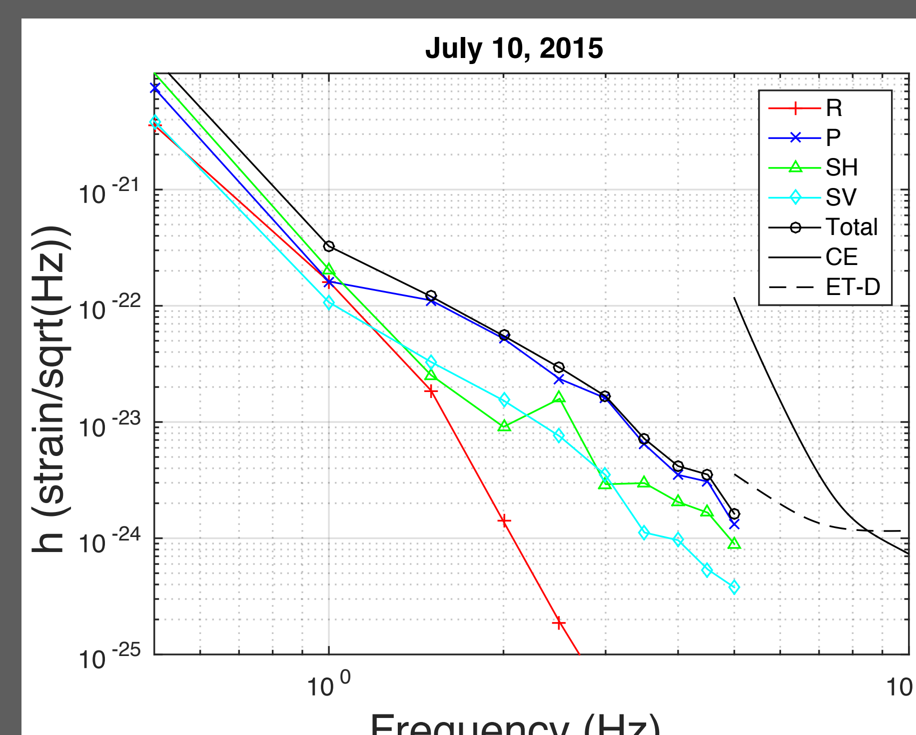
June 3, 2015





July 10, 2015





Plots made by Andrew Matas

Newtonian noise estimates

caveats

- Need better testing/assurance that recovered amplitudes make sense
  - Currently we normalise the maps by the average total power in the surface stations across all three directions
  - This should work “effectively” but is not ideal
- Need to figure out how to properly deal with “negative” power
- We’ve made some “estimates”

Dealing with Newtonian noise

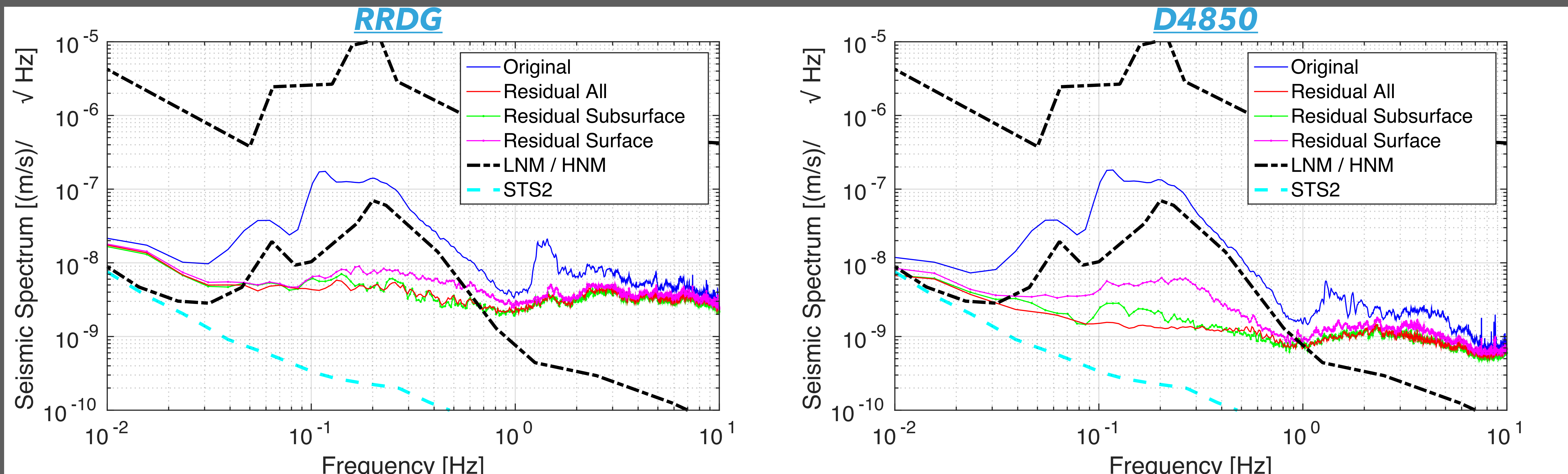
- Can’t shield
- Wiener filter?
- Budget?
- Site selection?

Wiener filter

- Coughlin + Harms
  - Results for “cleaning” seismometer data using other seismometers is impressive
  - Goal is to eventually use something like this for NN
    - Geophone array and tilt-meters are installed at Virgo for explicit testing once we start to measure NN
  - Might be difficult because filters likely need to change as a function of time
    - Kalman filter?
    - Adaptive filter?

Wiener filter results

- **Day 154 of 2015**



Plots made by Michael Coughlin/Jan Harms

Recap

Seismology sidetracks

REMEMBER THIS?!

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Seismology sidetracks

REMEMBER THIS?!

$$\gamma_{R,a}^{i\alpha,j\beta} = \int d\hat{\Omega} \left[Q_a(\hat{\Omega}) \left(r_H(z)\hat{\Omega}\cdot\hat{\alpha} - e^{i\pi/2} r_V(z)\,\hat{z}\cdot\hat{\alpha} \right) \times \left(r_H(z)\hat{\Omega}\cdot\hat{\beta} - e^{-i\pi/2} r_V(z)\,\hat{z}\cdot\hat{\beta} \right) e^{2\pi i f \hat{\Omega}\cdot\Delta\vec{x}/v_R} \right].$$

Govern how R-wave amp fall with depth (measured later)

"Rayleigh-wave eigenfunctions"

Surface-wave eigenfunctions

- Two types of surface waves — “**Rayleigh**” and “**Love**”
- **Rayleigh**—
  - superposition of P- and S-waves
  - Travel along surface
  - Elliptical particle motion

Surface-wave eigenfunctions

- Two types of surface waves — “**Rayleigh**” and “**Love**”
- **Love**—
  - Superposition of *multiply reflected S-waves*
  - Needs S-wave velocity profile that increases with depth
  - S-waves get refracted in this profile, turn around, and reflect off of the surface again

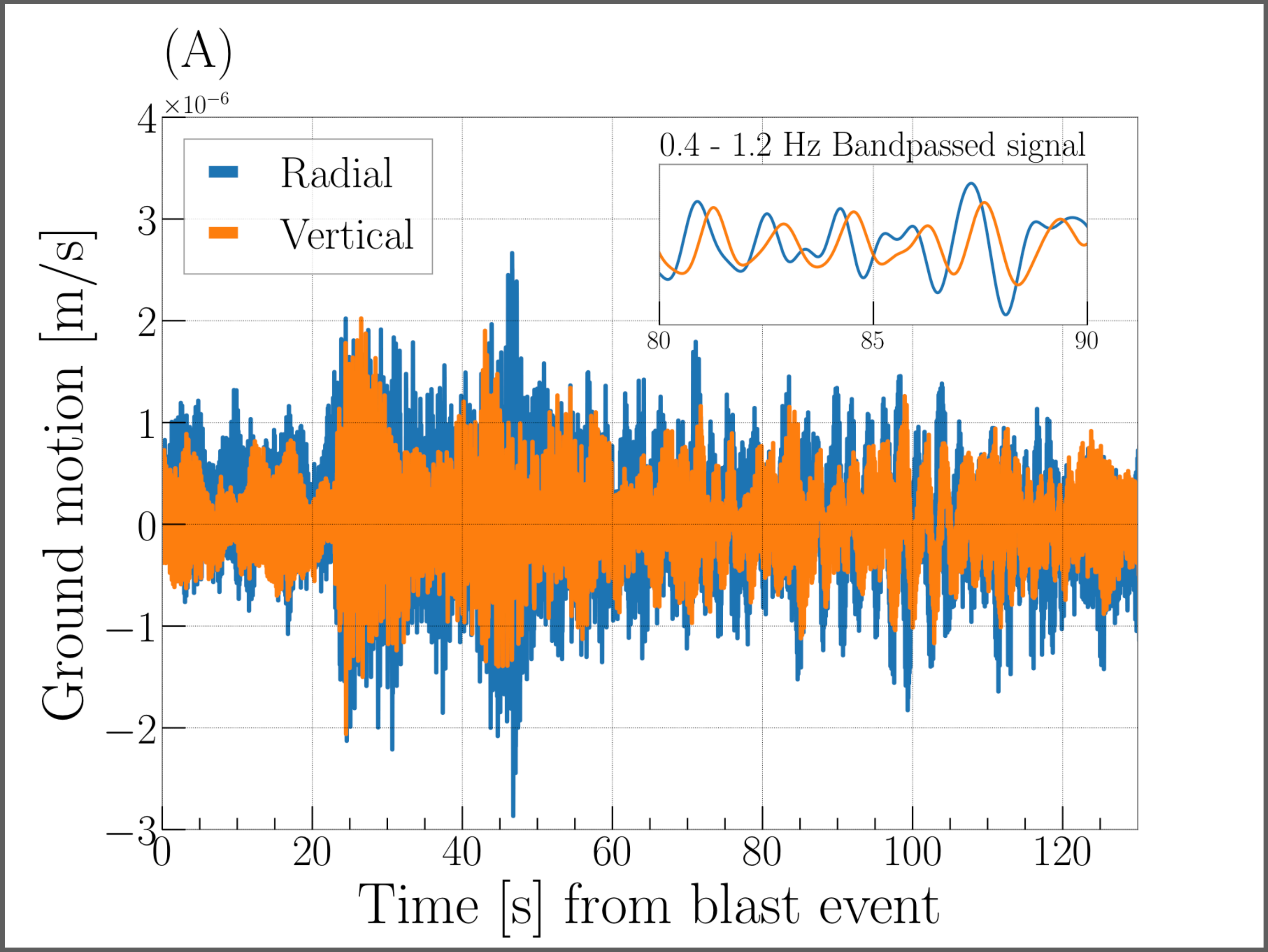
- Both types of surface wave have amplitudes that fall off with depth (“surface-wave eigenfunctions”)

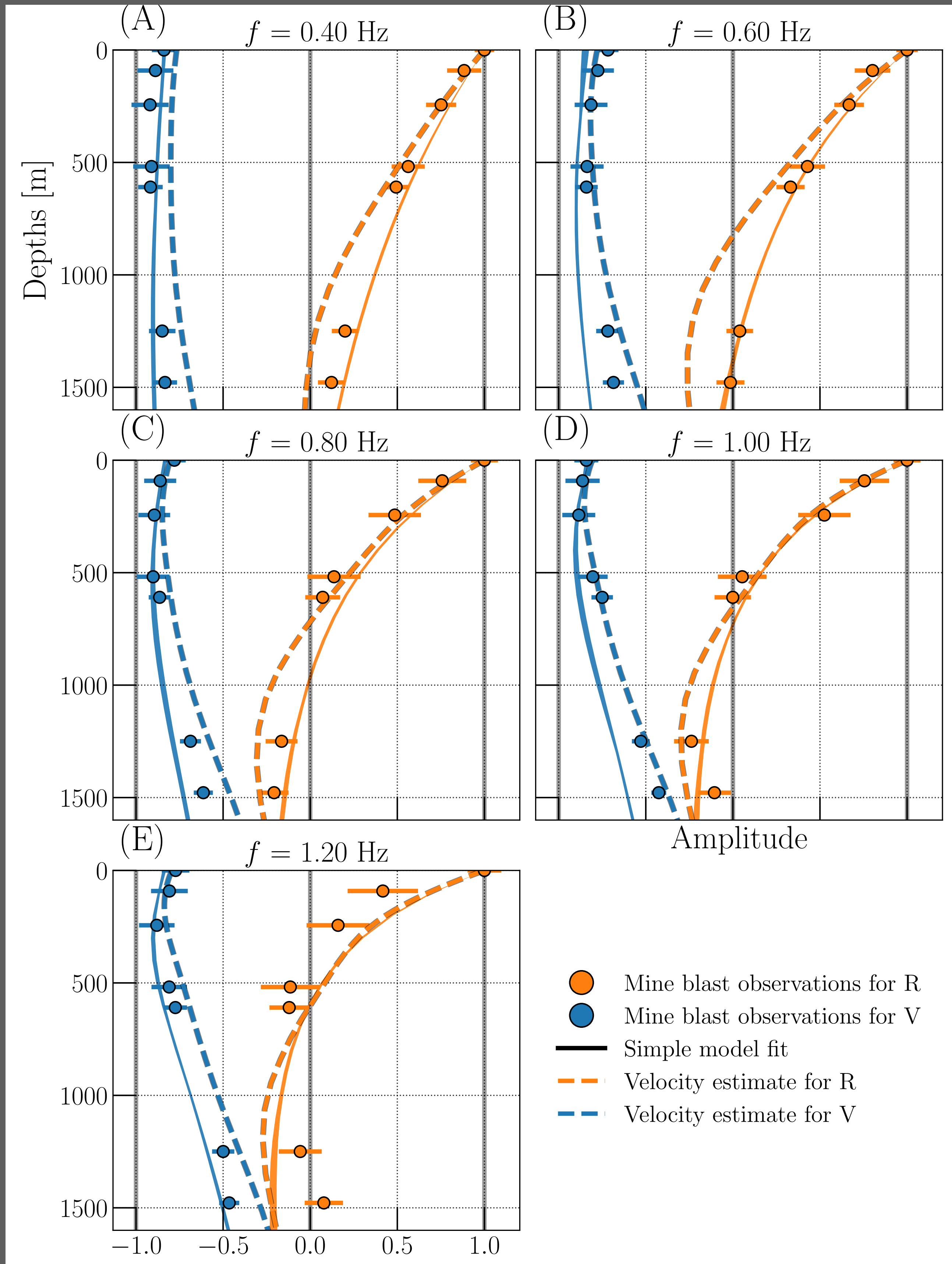
Homestake is special

- There are not many 3D arrays
  - There are borehole arrays — usually smaller scale, often use single-component sensors
- Usually experiments are confined to the surface
- **With Homestake we can *explicitly* measure how amplitude changes with depth for these waves — not something that has been done before**

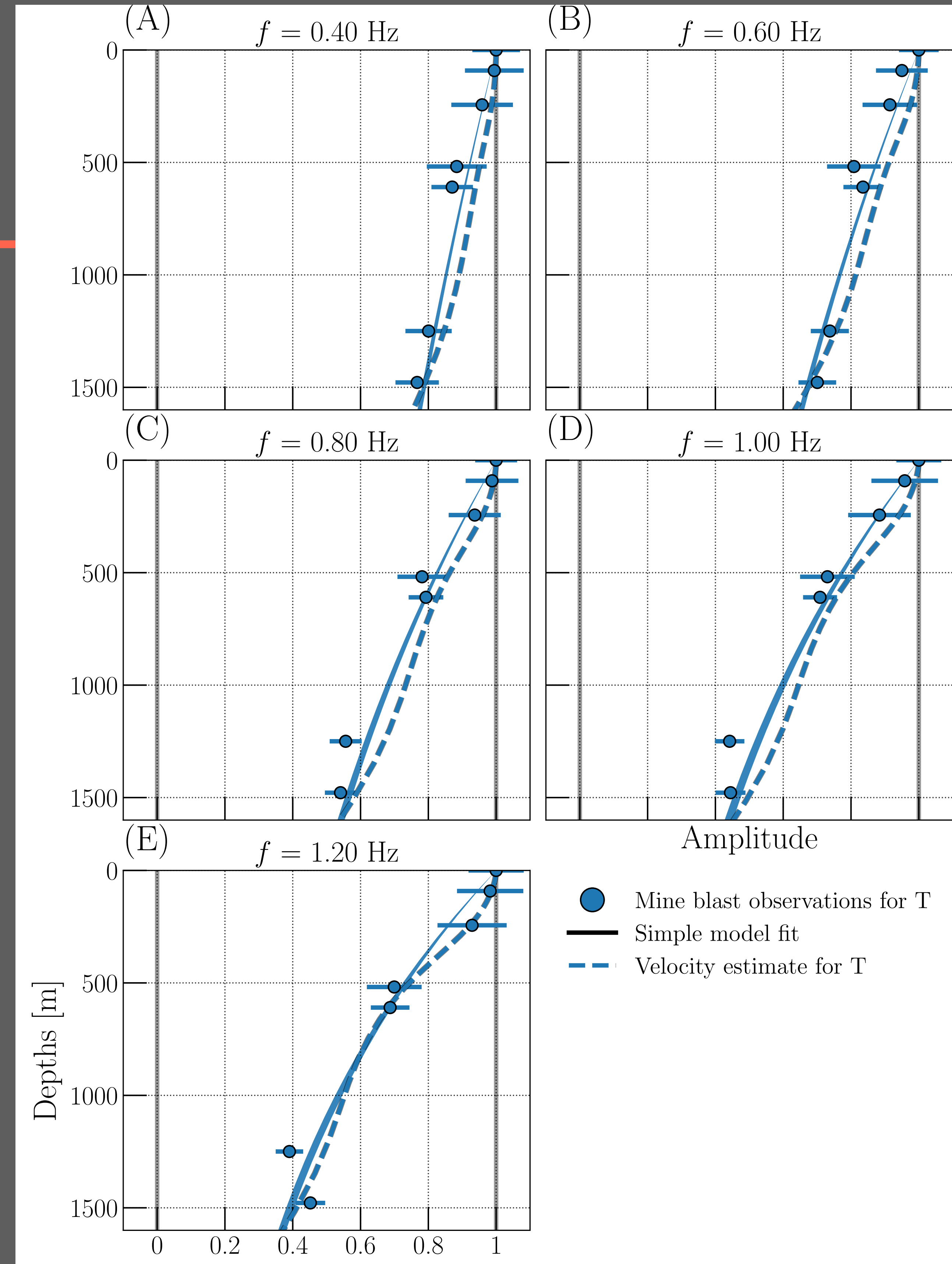
Measuring eigenfunctions

- Use the amplitude of the Rayleigh-wave part of a signal from mine blasts





(A) f = 0.40 Hz
(B) f = 0.60 Hz
(C) f = 0.80 Hz
(D) f = 1.00 Hz
(E) f = 1.20 Hz
Depths [m]
0
500
1000
1500
−1.0
−0.5
0.0
0.5
1.0
Amplitude
Mine blast observations for R
Mine blast observations for V
Simple model fit
Velocity estimate for R
Velocity estimate for V



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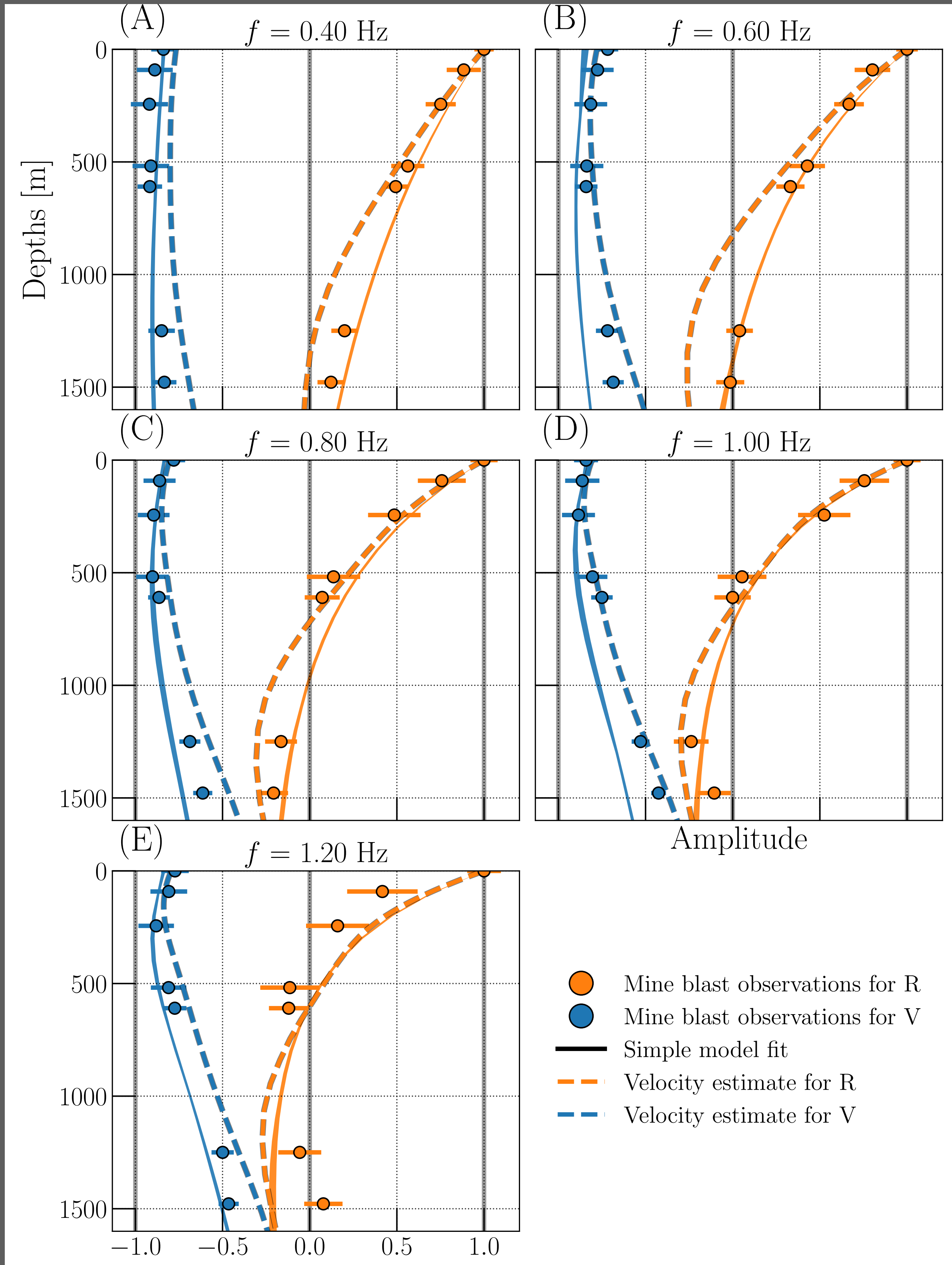
(D) f = 1.00 Hz
(E) f = 1.20 Hz
Depths [m]
0
500
1000
1500
0
0.2
0.4
0.6
0.8
1
Amplitude
Mine blast observations for T
Simple model fit
Velocity estimate for T

Two fits — theoretical and empirical

- On the results plot there are data points and two fits

- **FIT 1** — fits theory to the data points
  - Assume S-waves have a velocity depth profile that goes like a power law
  - This gives a functional form for R and L-wave eigenfunctions with some (frequency independent) free parameters
  - We fit those free parameters using a nested sampling technique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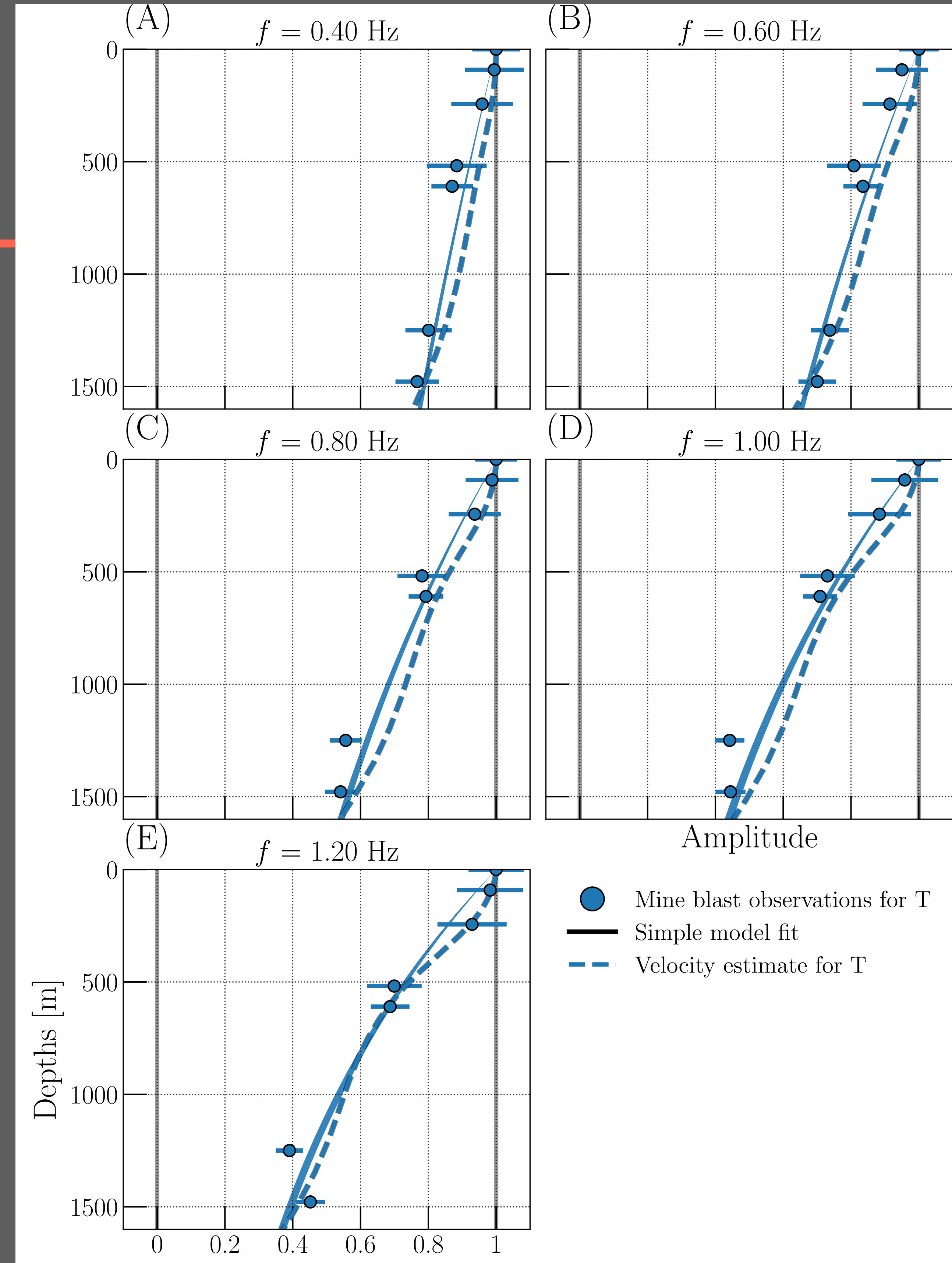
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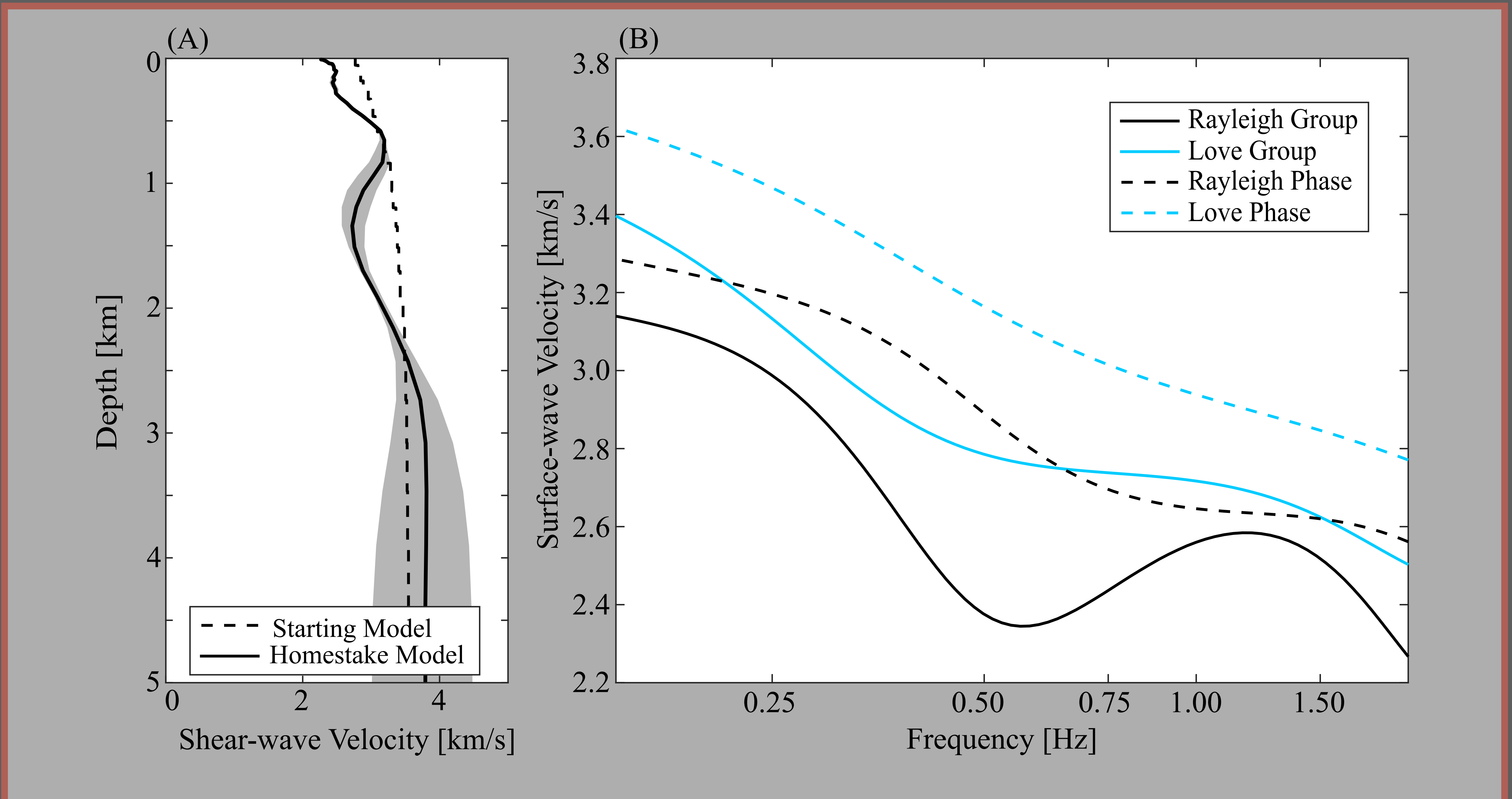
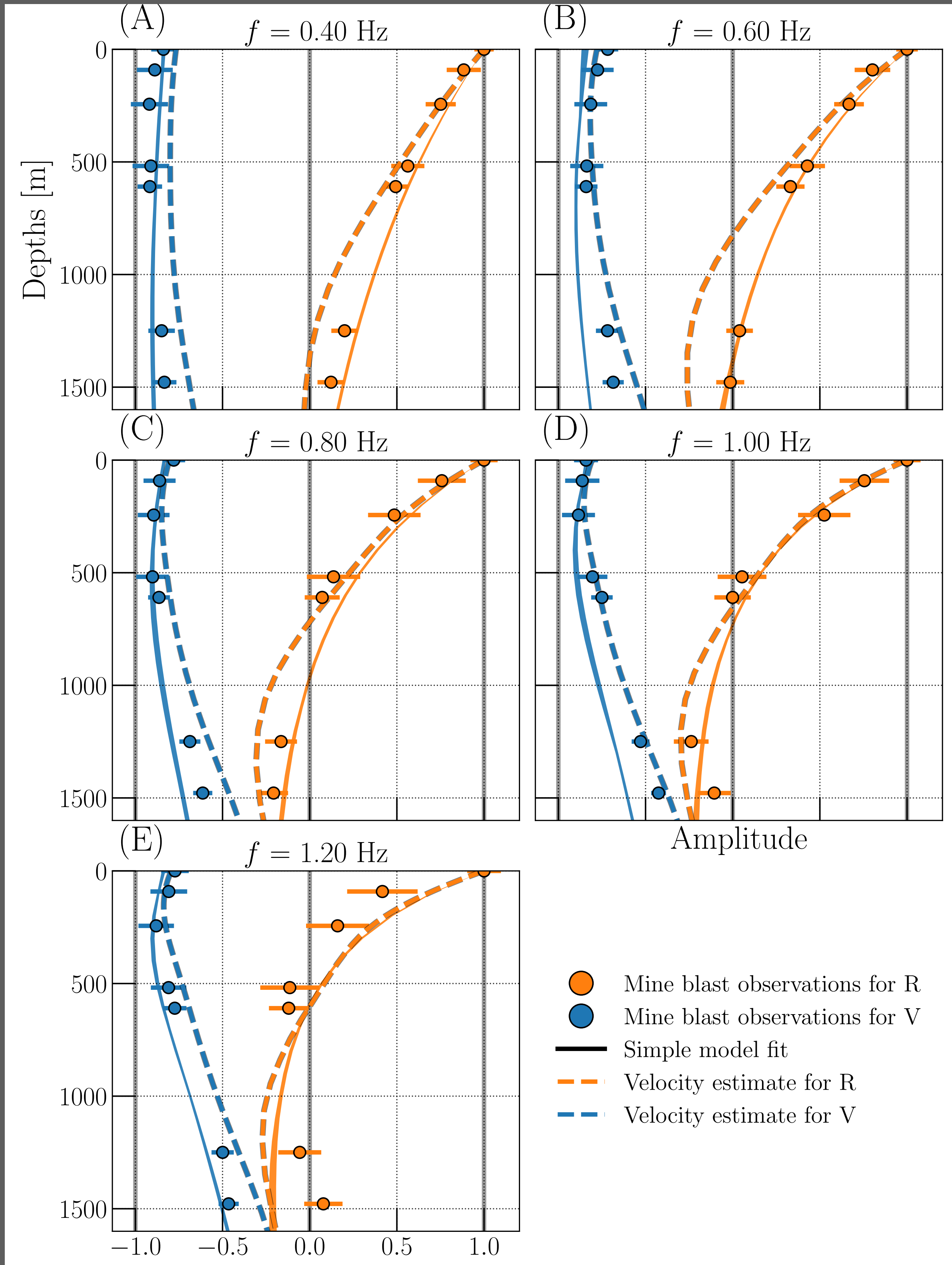
Two fits — theoretical and empirical

- On the results plot there are data points and two fits
- “**FIT” 2** — independent analysis that produces results based on a model
  - Assume S-waves have a velocity depth profile that goes like a power law
  - Use velocity dispersion of R- and L-waves to infer an S-wave velocity depth profile
  - Use this inferred velocity depth profile to estimate the R and L-wave eigenfunctions

Dispersion + Depth profile estimates



Plots made by Daniel Bowden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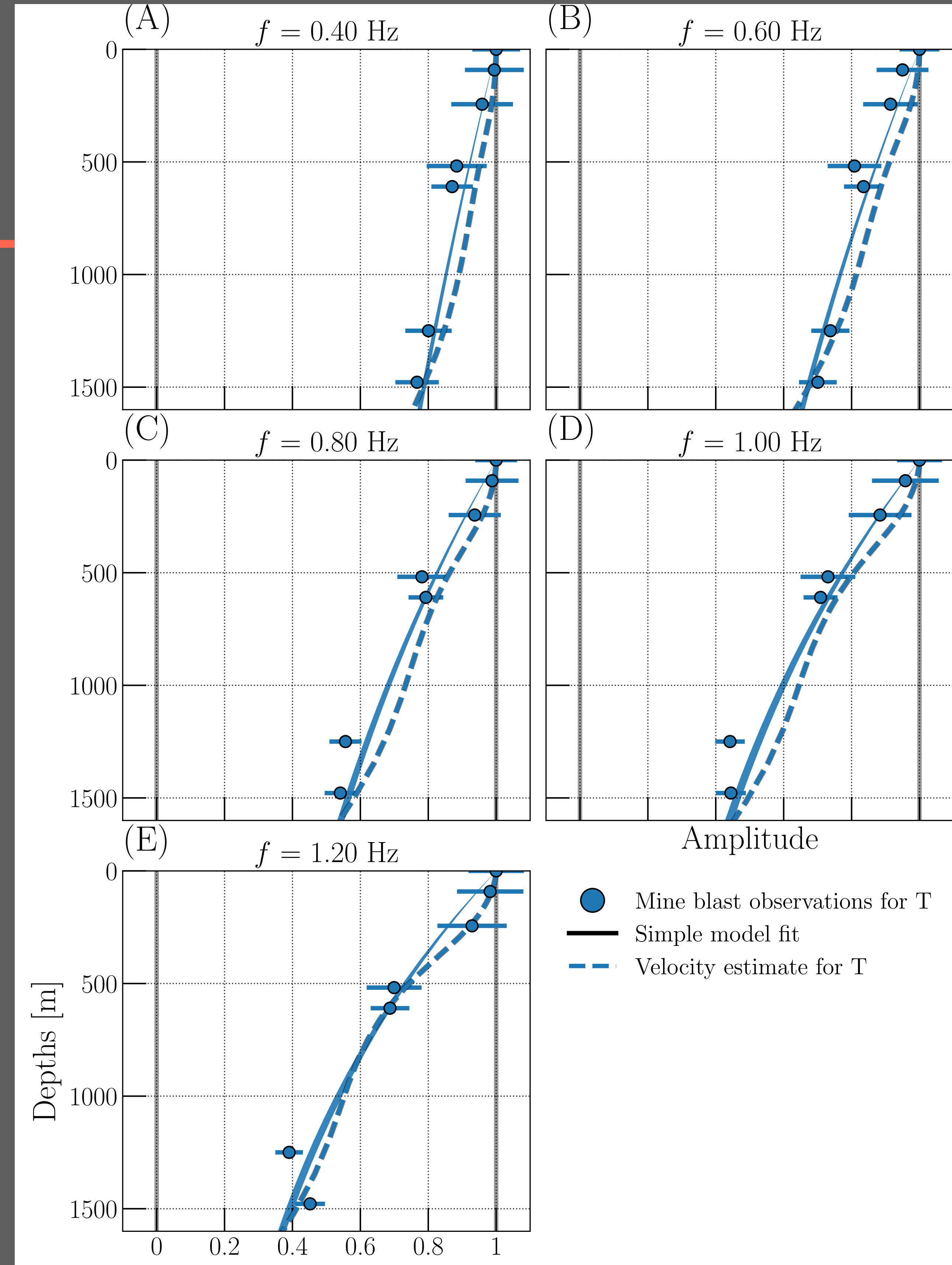
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Conclusions

seismology

- Useful verification of a classical seismological result
- Result of cross-disciplinary cooperation
  - This project likely doesn't happen without GW application
  - Seismological applications make it very compelling as a project with several purposes

Conclusions

General

- Lower frequencies —> interesting GW sources, cosmology, and astrophysics
- Newtonian noise will likely be an issue
- Initial estimates of NN from seismology indicate it could potentially be an issue
- Interesting cross-disciplinary work comes out as a natural byproduct of working on areas of mutual interest

EXTRA

SGWB searches

Isotropic

- We construct an estimator for the energy density in each small frequency bin (and its variance):

$$\hat{\Omega}_{\mathrm{GW}}(f) = \frac{10\pi^2}{3H_0^2} f^3 \frac{\mathrm{Re}(\hat{C}(f))}{\gamma(f)}$$

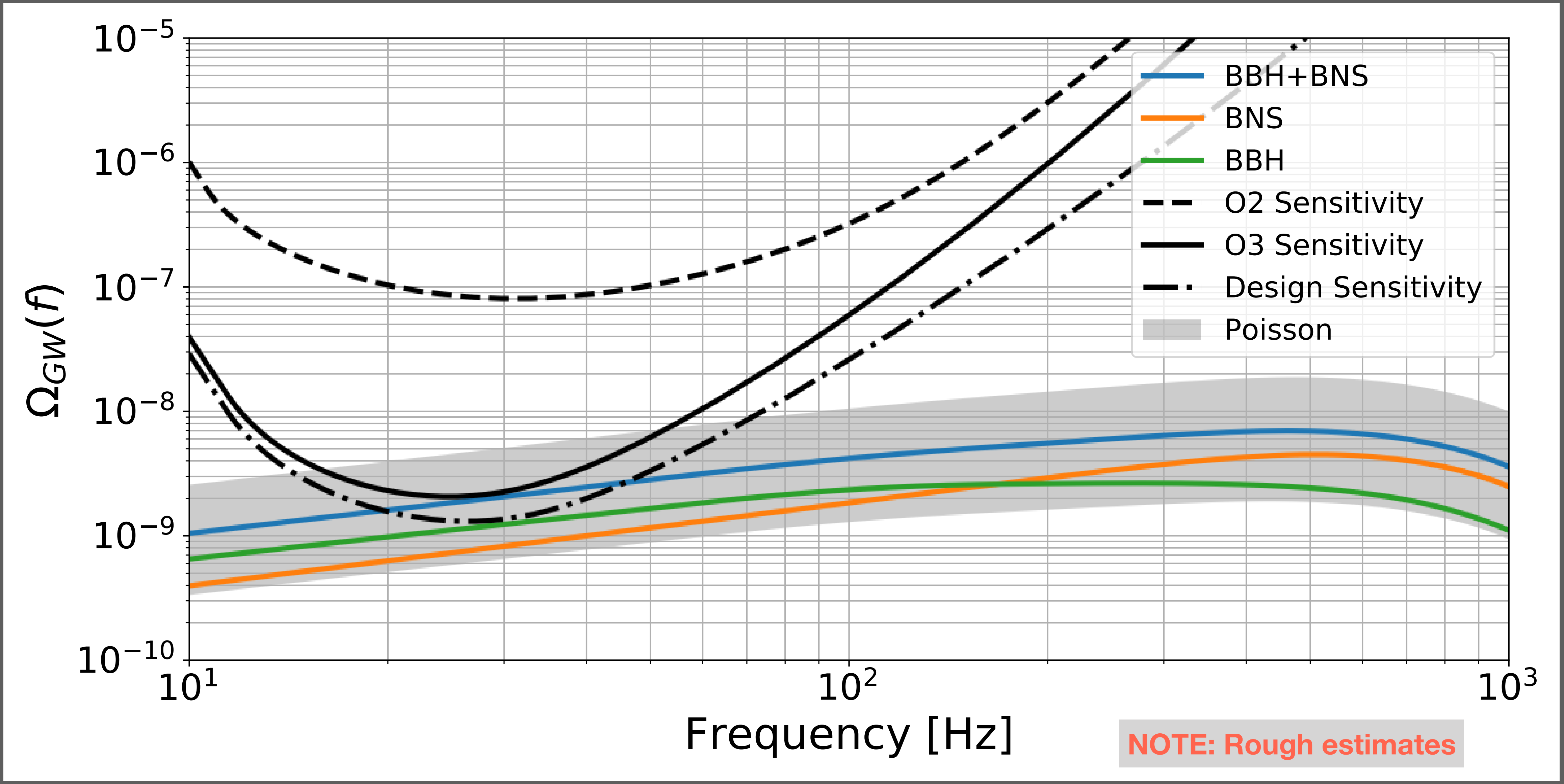
Assuming signal << typical noise level in the detector...

Power spectral density of the noise in each detector

$$\sigma^2_{\hat{\Omega}}(f) = \frac{1}{2\tau\Delta f}\left(\frac{10\pi^2}{3H_0^2}\right)^2 f^6 \frac{P_1(f)P_2(f)}{|\gamma(f)|^2}$$

SGWB Sources

- **Largest contribution:** unresolved compact binary mergers
  - **~15** binary neutron stars in LIGO frequency band at any one time
  - **1** binary black hole coalescence every **~250 s**



Abbott, B. P., et al. (2018). *Phys Rev Lett*, *120*(9), 091101. http://doi.org/10.1103/PhysRevLett.120.091101

GW Amplitude

$$h_{ij}^{\mathsf{TT}}(t,\vec{x}) = \left(\frac{1}{r}\right)\left(\frac{2G}{c^4}\right)\ddot{Q}_{ij}^{TT}(t-r/c)$$

GW Amplitude

Falls off as r^{-1}

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10^{-44} N^{-1}

GW Amplitude

Falls off as r^{-1}

Quadrupole moment

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10^{-44} N^{-1}

For LIGO detectors:

Cataclysmic events

$$h \approx 10^{-21} \text{ for } \mathcal{O}(\text{seconds})$$

GW Amplitude

Falls off as r^{-1}

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$$h_{ij}^{\mathrm{TT}}(t,\vec{x}) = \left(\frac{1}{r}\right)\left(\frac{2G}{c^4}\right)\ddot{Q}_{ij}^{TT}(t - r/c)$$

$10^{-44}\ N^{-1}$

For LIGO detectors:

Cataclysmic events

$$h \approx 10^{-21} \text{ for } \mathcal{O}(\text{seconds})$$

Look for a long time

$$h \approx 10^{-25} \text{ for } \mathcal{O}(\text{years})$$

SGWB searches

- There are not well-defined templates for the SGWB
  - So we **cross-correlate** data between detectors

$$\hat{C}(f) = \frac{2}{\tau}\tilde{s}_1^*(f)\tilde{s}_2(f)$$

SGWB searches

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noise

$$\tilde{s}_1(f) = \tilde{h}_1(f) + \tilde{n}_1(f)$$

GW signal

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GW signal

Substitute and take time average…

$$\langle\hat{C}(f)\rangle = \frac{2}{\tau}\left(\langle\tilde{h}_1^*(f)\tilde{h}_2(f)\rangle + \langle\tilde{n}_1^*(f)\tilde{h}_2(f)\rangle + \langle\tilde{h}_1^*(f)\tilde{n}_2(f)\rangle + \langle\tilde{n}_1^*(f)\tilde{n}_2(f)\rangle\right)$$

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ASSUMPTIONS!!!

Signal and noise are uncorrelated

SGWB searches

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GW signal

Substitute and take time average…

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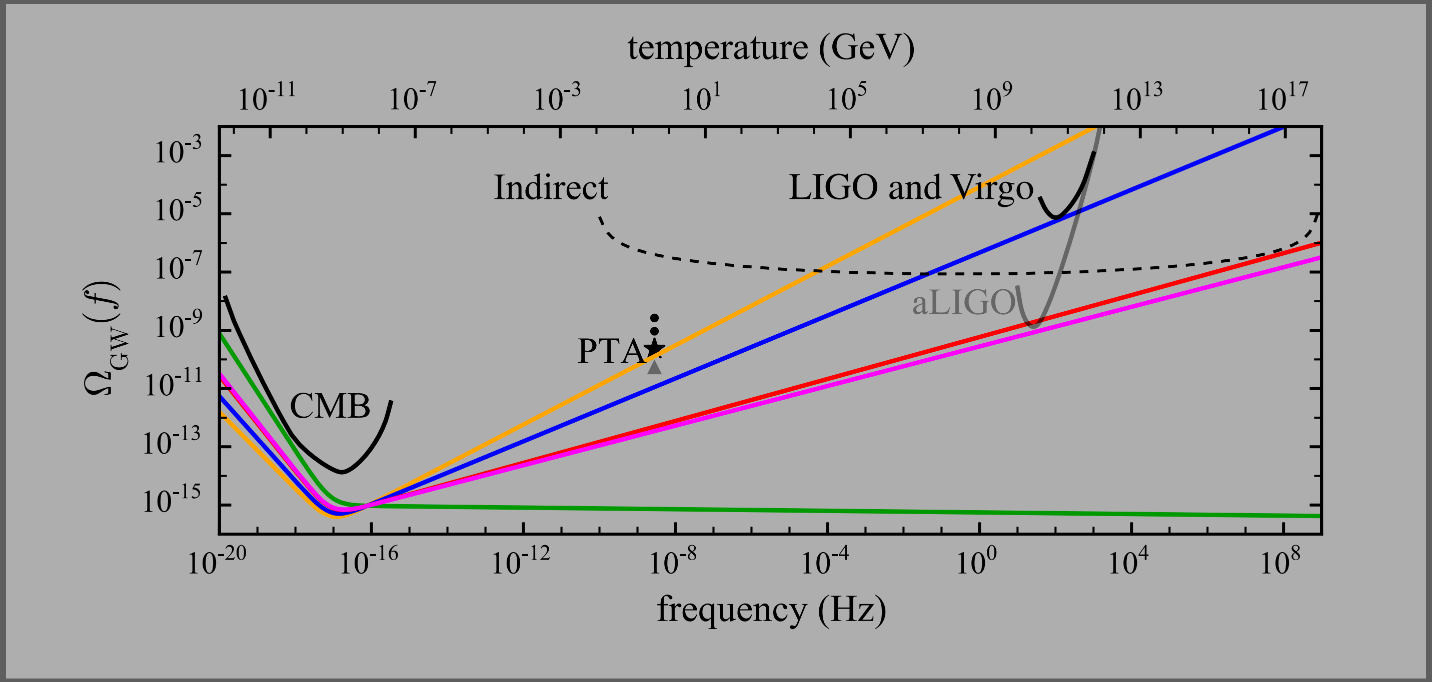
ASSUMPTIONS!!!

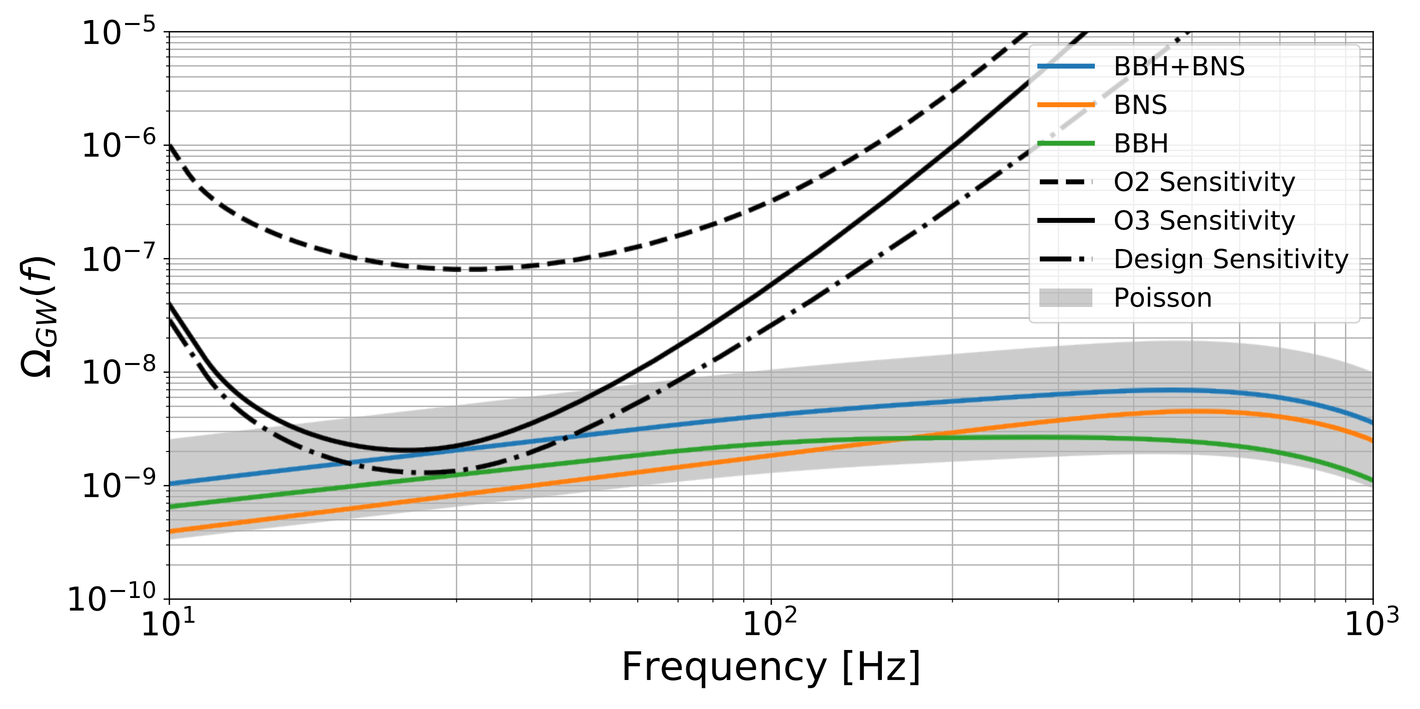
Signal and noise are uncorrelated

noise is uncorrelated between detectors

SGWB Sources/Detectors

Lasky, P. D., et al. (2016). PHYSICAL REVIEW X, 6(1), 11035. https://doi.org/10.1103/PhysRevX.6.011035





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CE facts

Table 1. Parameters used to produce the Cosmic Explorer (CE) target curve. The CE pessimistic and Einstein telescope, high- and low-frequency (HF and LF) parameters are included for comparison.

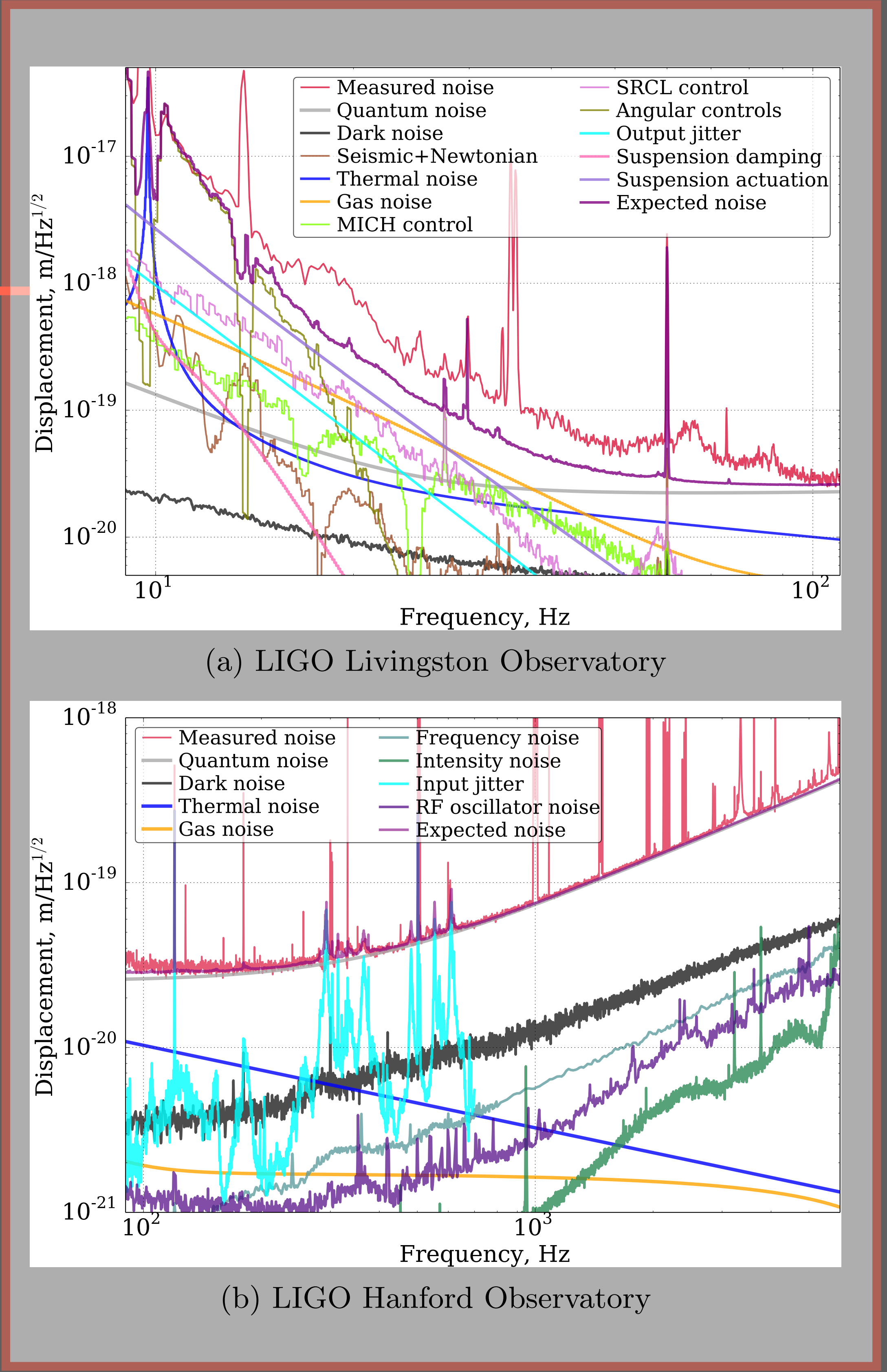
	CE	CE pess	ET-D (HF)	ET-D (LF)
L_{arm}	40 km	40 km	10 km	10 km
P_{arm}	2 MW	1.4 MW	3 MW	18kW
λ	1550 nm	1064 nm	1064 nm	1550 nm
r_{sqz}	3	3	3	3
m_{TM}	320 kg	320 kg	200 kg	200 kg
r_{beam}	14 cm	12 cm	9 cm	7 cm (LG_{33})
T	123 K	290 K	290 K	10 K
ϕ_{eff}	5×10^{-5}	1.2×10^{-4}	1.2×10^{-4}	1.3×10^{-4}

Abbott, B. P., et al. (2017). 34(4), 44001. https://doi.org/10.1088/1361-6382/aa51f4

LIGO Noise Curve

Low Frequency Noise:

- **Seismic noise** — moving platforms that hold suspensions
- **Angular controls** — controlling angular degrees of freedom of mirrors
- **Quantum noise** — radiation pressure



Martynov, D. V., et al. (2016). *Phys. Rev. D*, *93*(11), 433. http://doi.org/10.1103/PhysRevD.93.112004