LIGO

Seismic Platform Interferometer (SPI) Pathfinder Update (GWANW 2025)

Joshua Freed, Jeff Kissel, Sina Koehlenbeck, Brian Lantz, Bram Slagmolen, Sheon Chua, Arnaud Pele, Eddie Sanchez, Jason Oberling, Matthew Heintze, Calum Torrie, Gabriele Vajente, Peter Fritschel, Michele Zanolin, …

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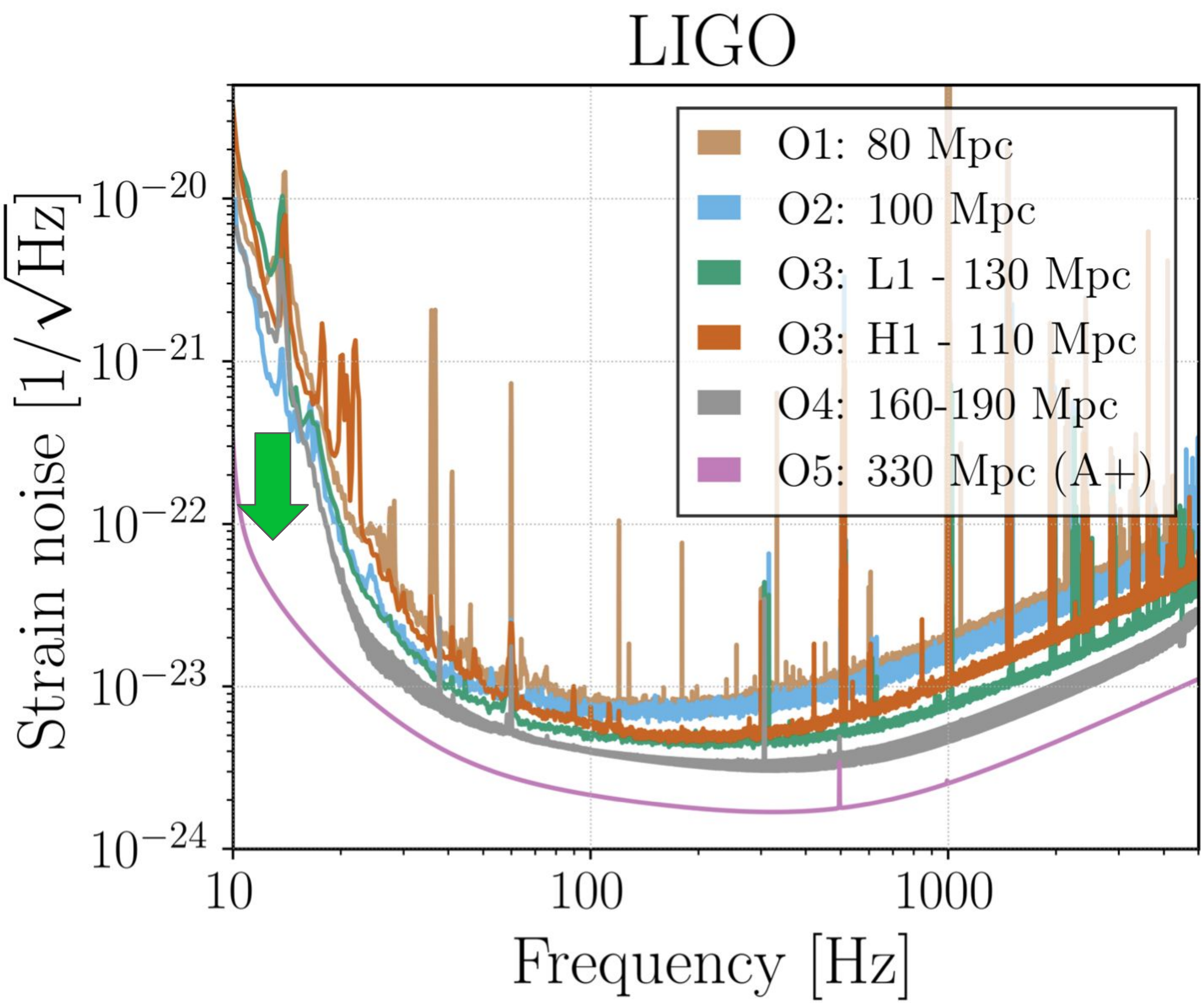
Australian National University

Outline

1. Motivation
2. SPI Pathfinder General Design
3. My work on characterizing SPI noise budget
4. Timeline

Motivation

The low-frequency has upwards of 2 orders of magnitude to improve upon for O5!



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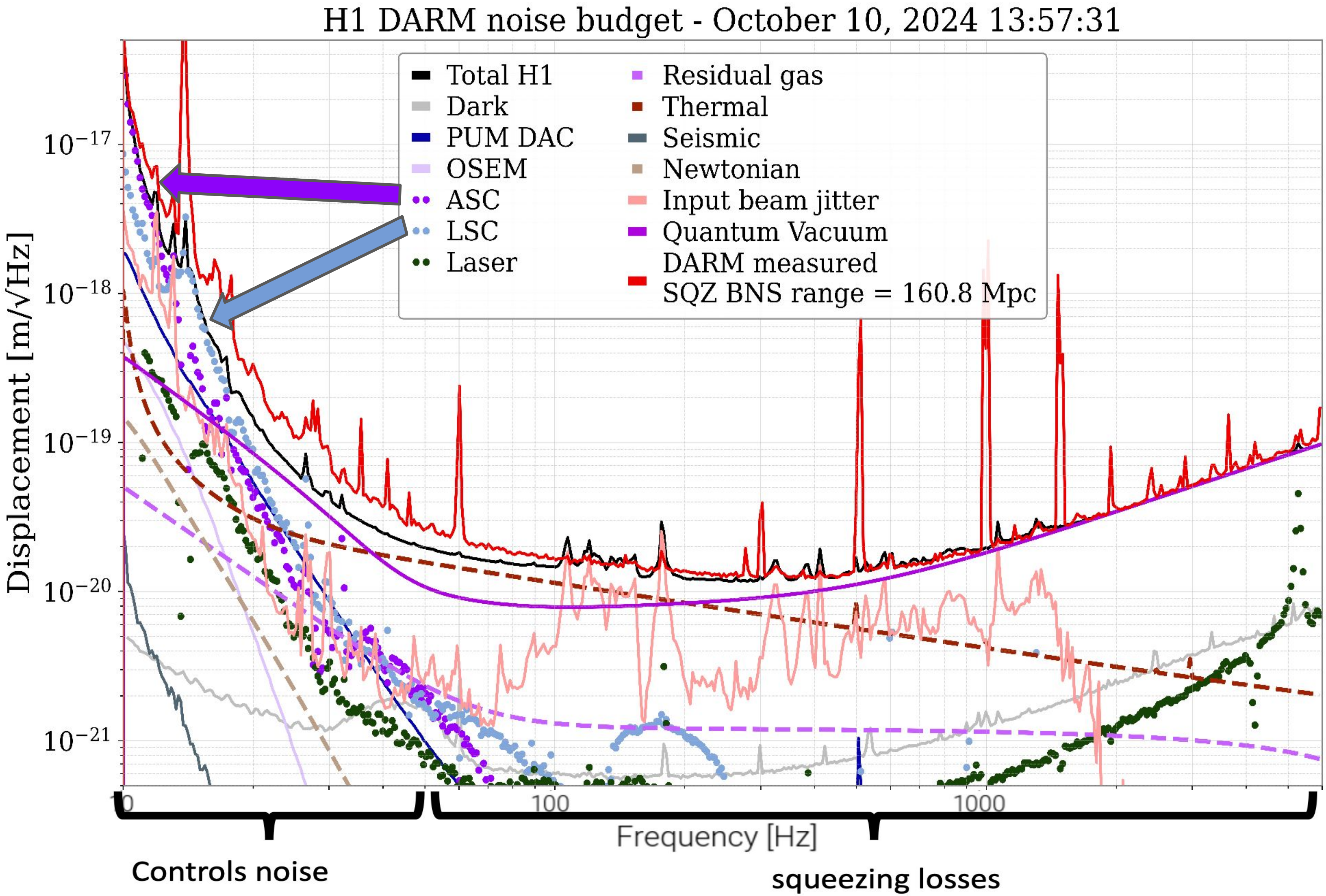
https://dcc.ligo.org/public/0161/P1900218/002/SummaryForObservers.pdf

The Problem?



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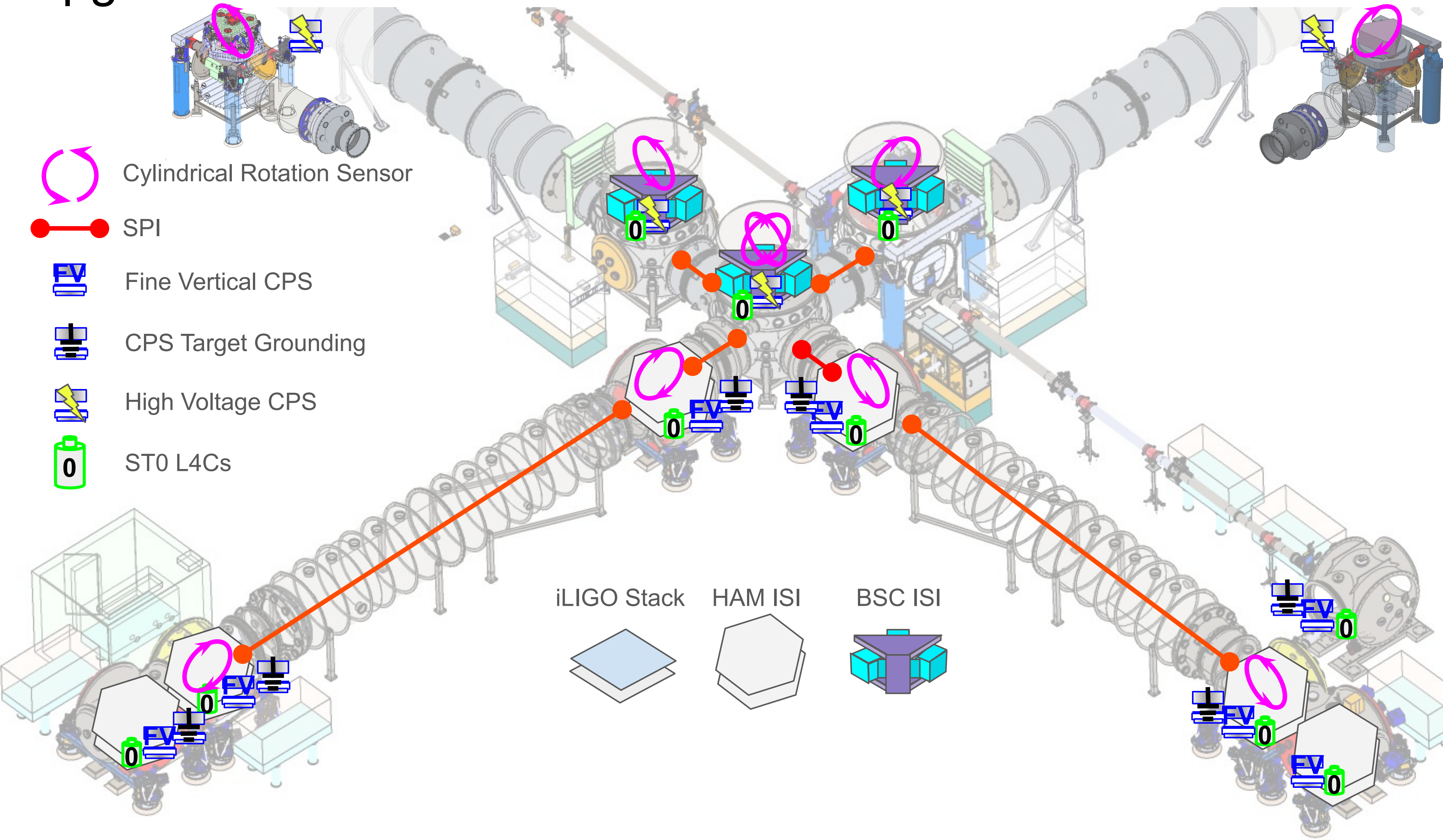
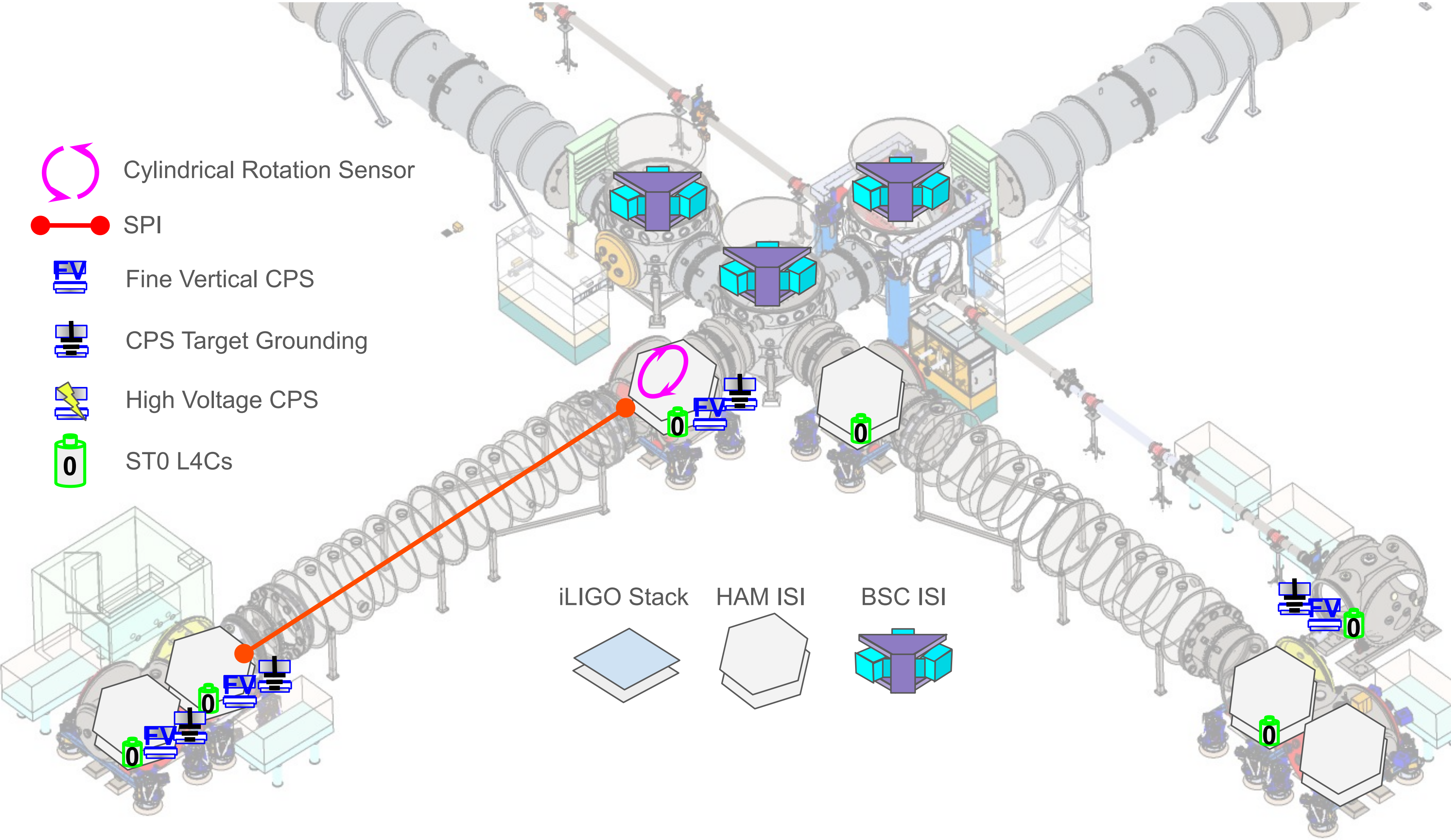
The SWG Dream: Integrated Collection of Sensor Upgrades



The First Step: SPI Pathfinder (Install Target Nov 2025)

We have a final design doc! [T2400145]



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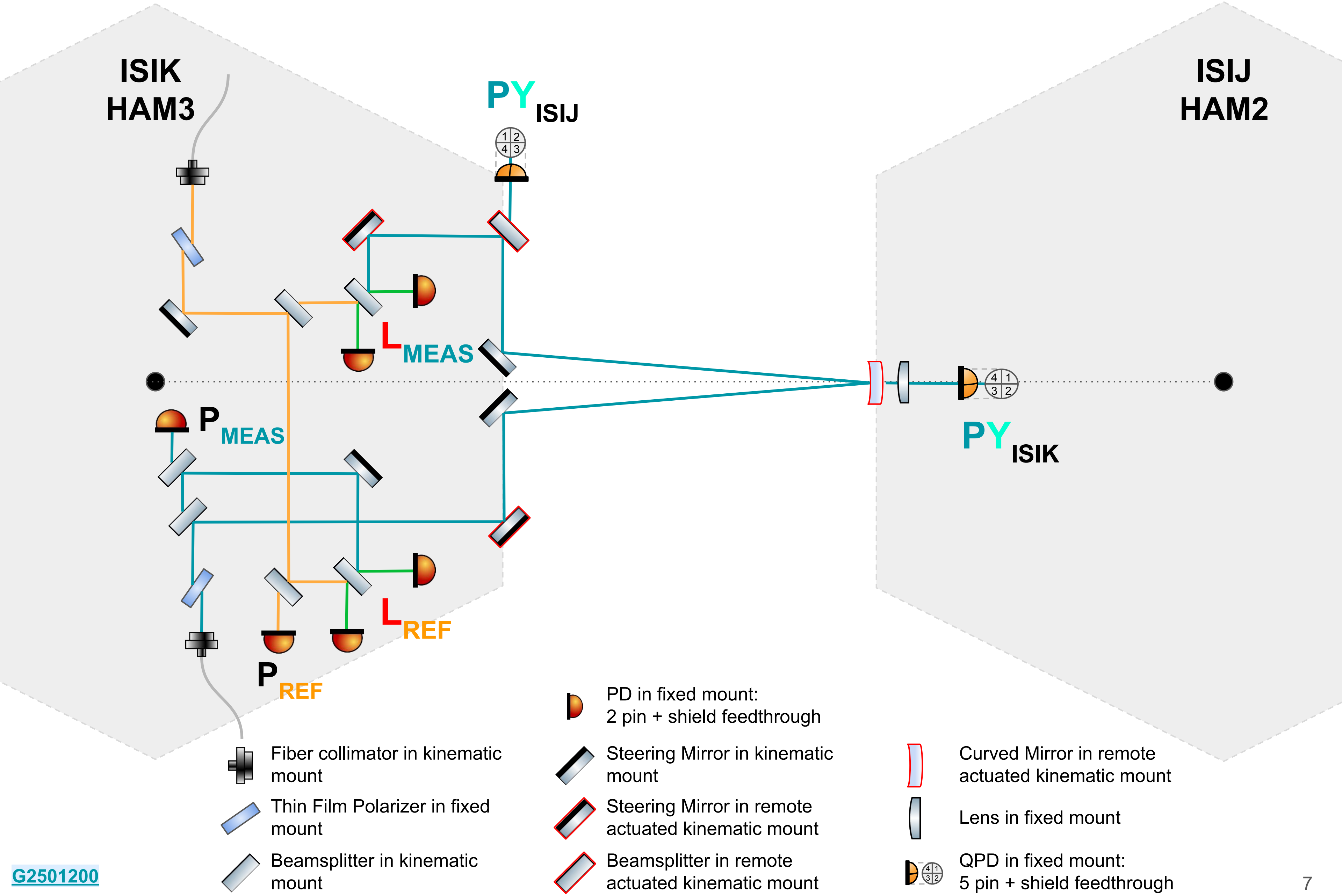
FINAL Optical Layout (Conceptually)

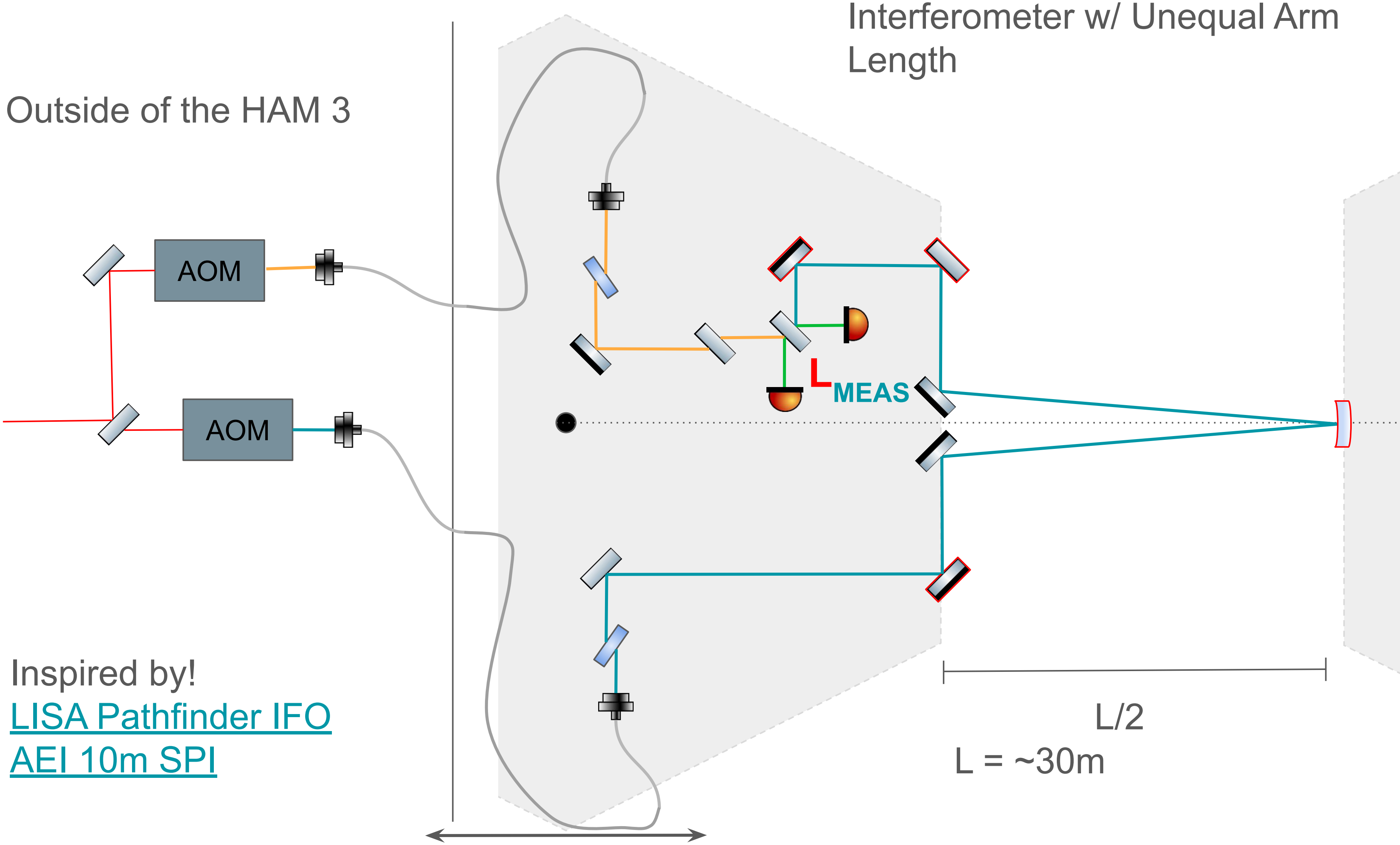
We have a final design doc! T2400145



SPI LONG (Alone)

Heterodyne Mach-Zehnder Interferometer w/ Unequal Arm Length

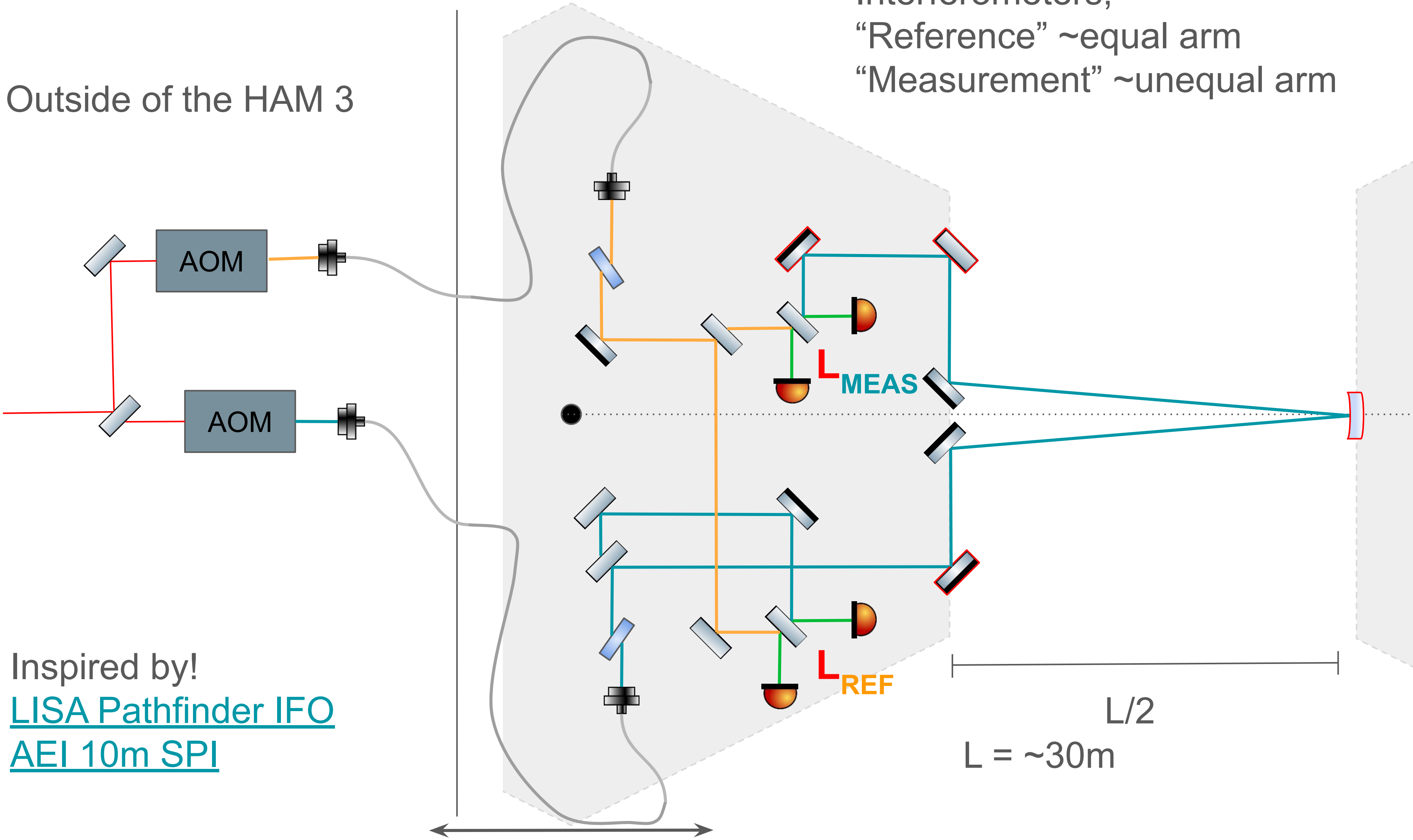
Outside of the HAM 3



Inspired by!
[LISA Pathfinder IFO]
[AEI 10m SPI]

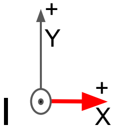
SPI LONG (Alone)

Two Heterodyne Mach-Zehnder Interferometers,
“Reference” ~equal arm
“Measurement” ~unequal arm



Inspired by!
[LISA Pathfinder IFO]
[AEI 10m SPI]

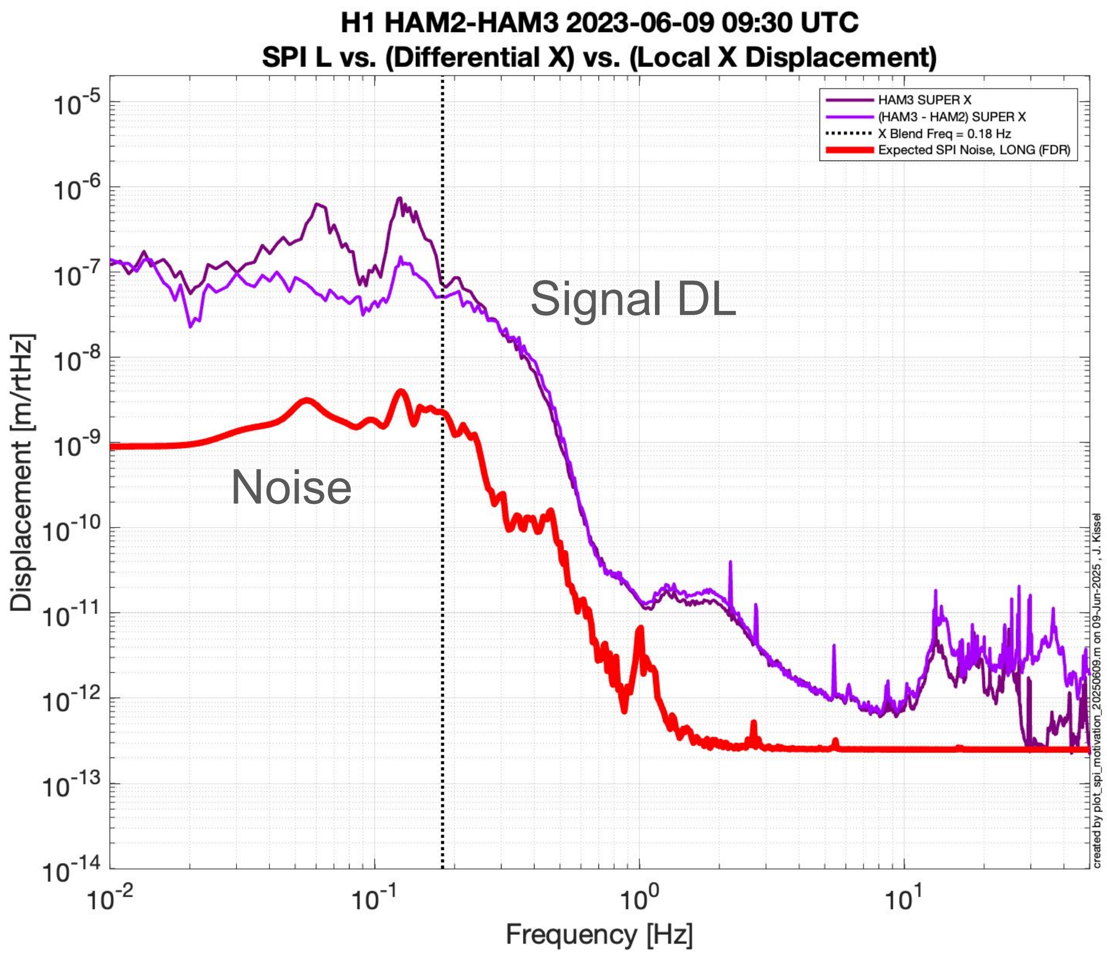
Expected SPI **LONG** Performance



Local X

Differential X

SPI Sensor Noise



Plot from LHO Logbook: 83412

We won't be able to get all the way down to SPI LONG noise we'll still be limited by rolling off GS13 noise, its still MUCH less than current performance.

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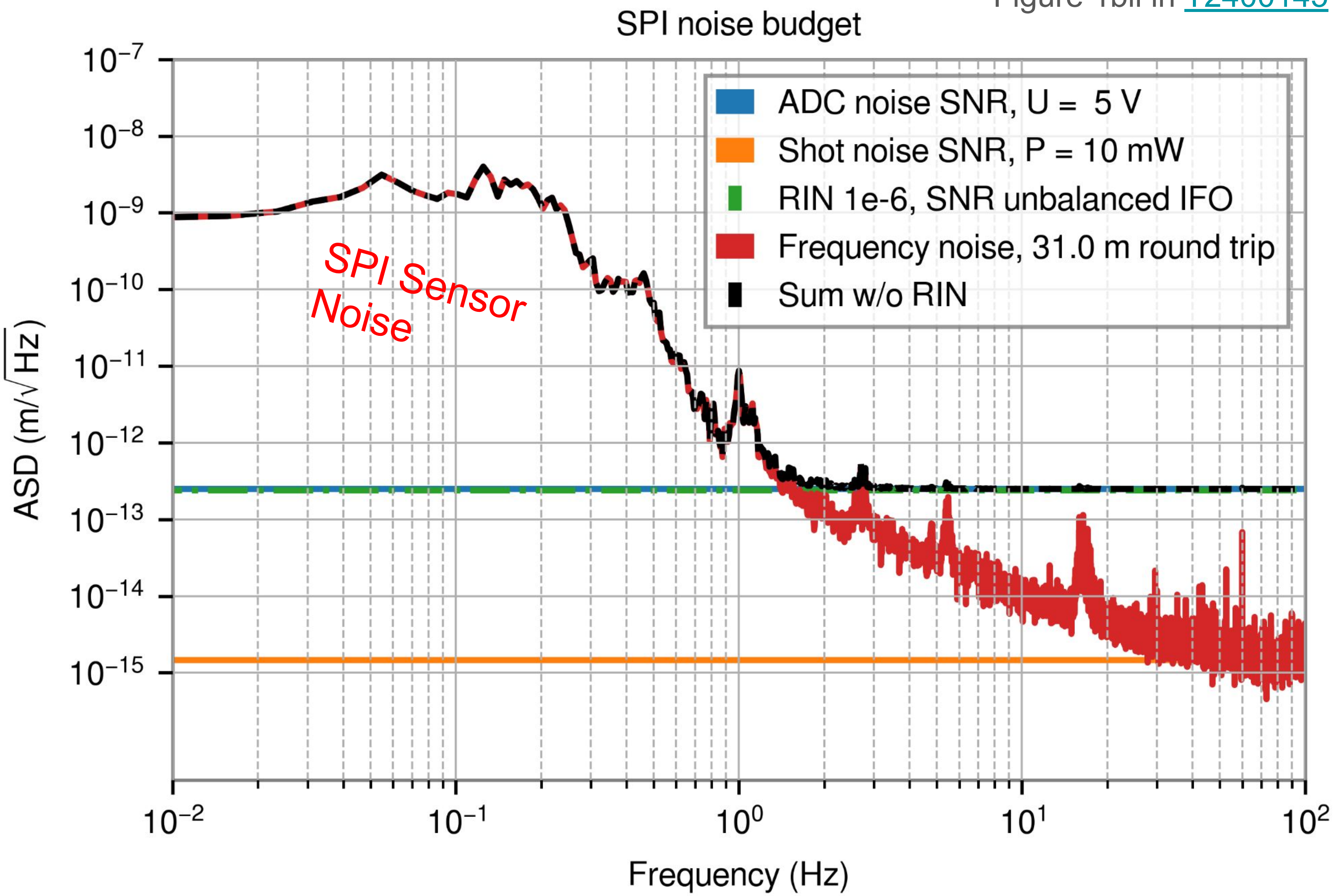
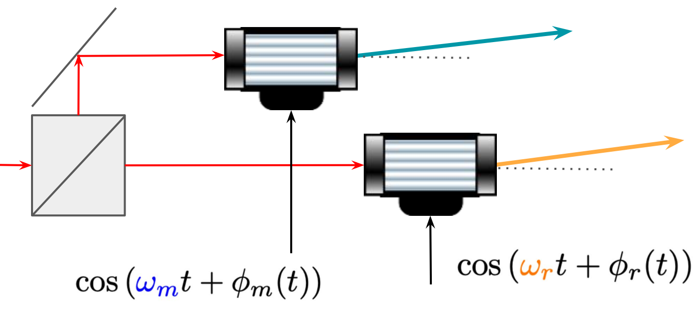
Expected SPI **LONG** Budget

Figure 1bii in T2400145

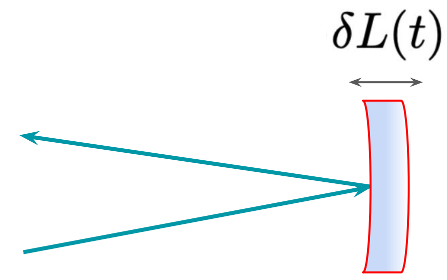


SPI **LONG** is currently limited by Laser Frequency Noise up to ~2Hz then ADC Noise past ~2Hz

Field Equations to Power on Each PD



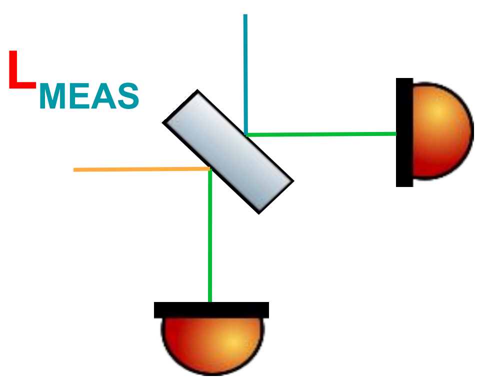
(Fiber) AOMs frequency shift the light at a slight difference in frequency plus noise from the RF sources.



Mirror motion on HAM 2 adds phase to one of the beams

$$\phi_{\delta L}(t) = \frac{2\pi}{\lambda}\delta L(t)$$

The beams recombine on the measured output producing a beat note, $\omega_m - \omega_r = \omega_h$ plus phase noise and our signal



$$A_{meas}\cos(\omega_h t + \phi_{meas}(t)) + \text{DC Terms}$$

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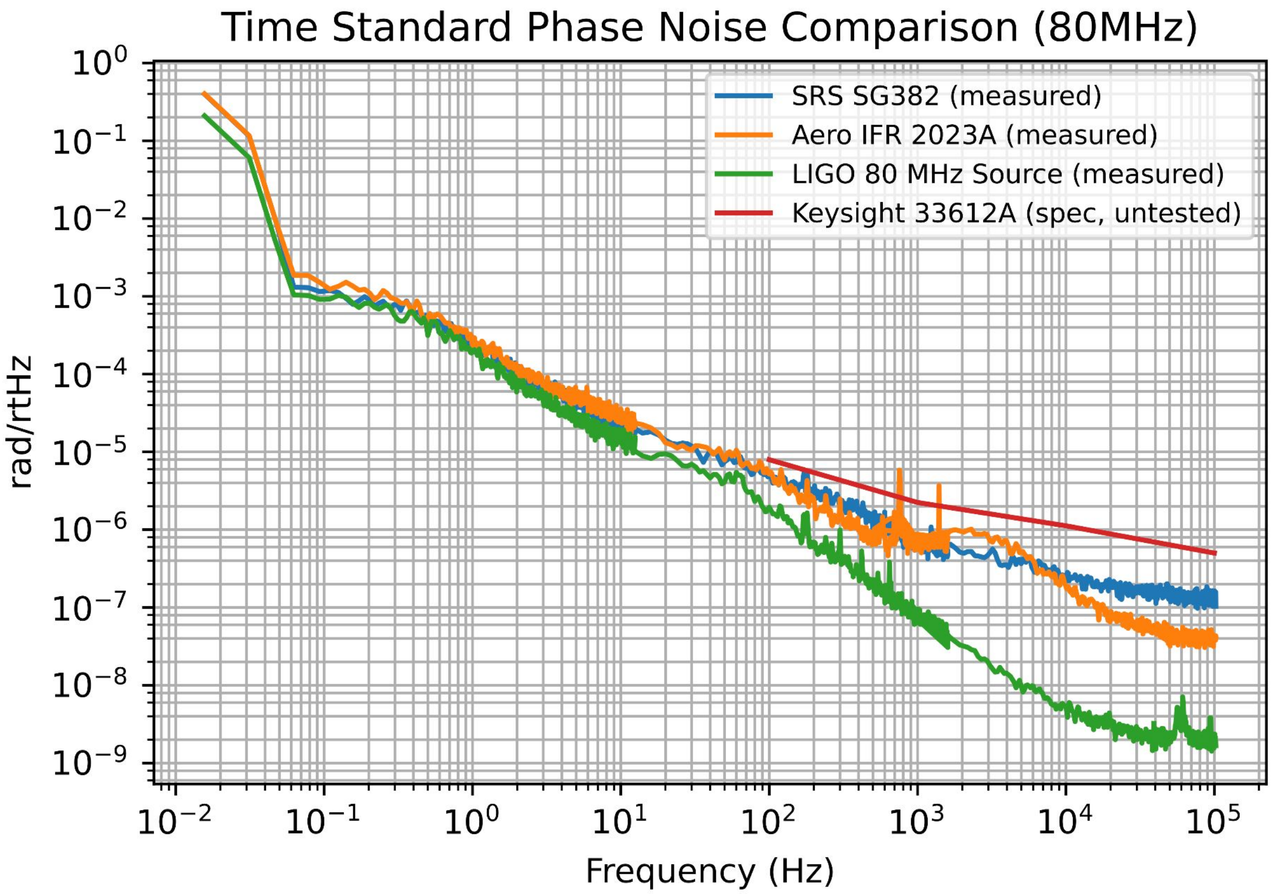
The Oscillator Down-Select



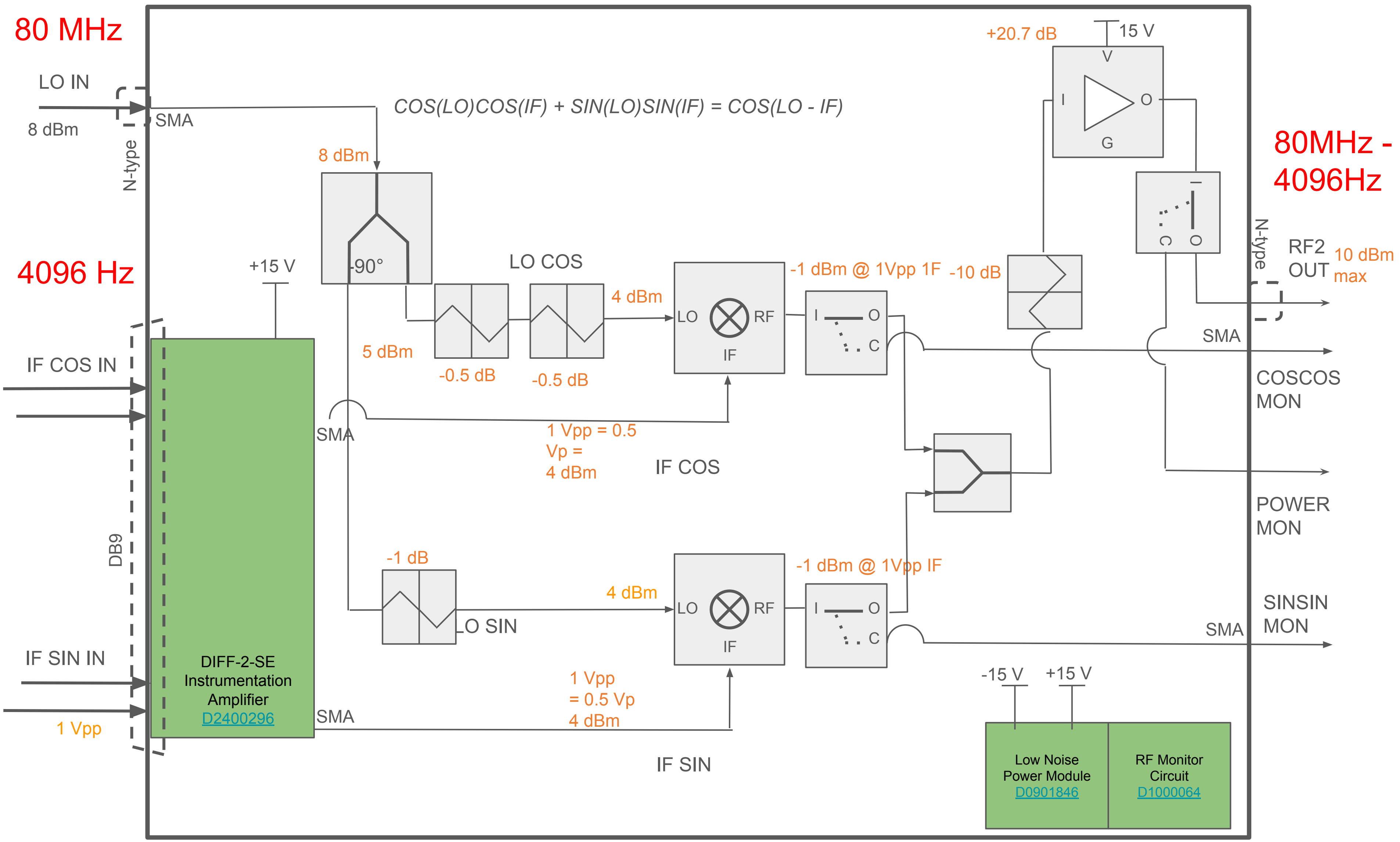
AOMs operate as a frequency shifter around 80 MHz

Commercial Sources are available.

LIGO doesn't like commercial sources in the LVEA because they're powered with AC power

We are using pre-existing 80 MHz from the site to create a frequency shifter

Prototype Design
D2400315-v2



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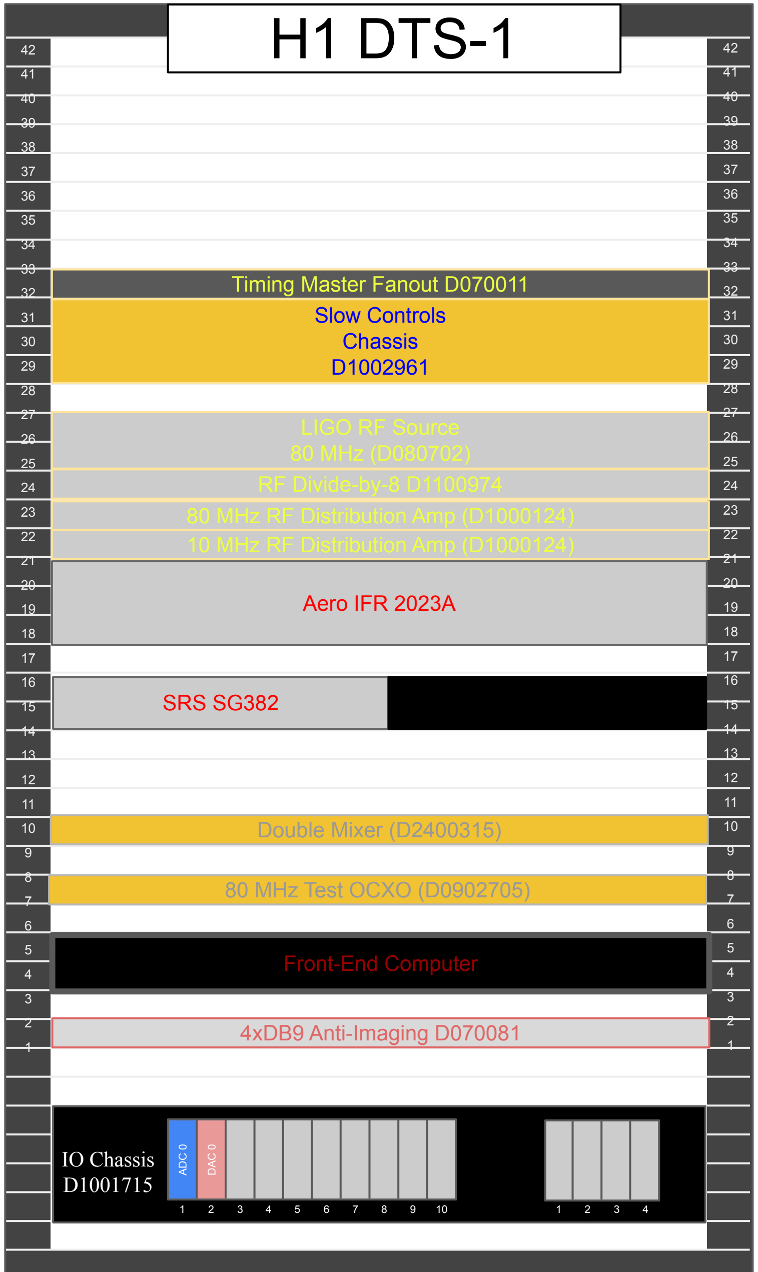
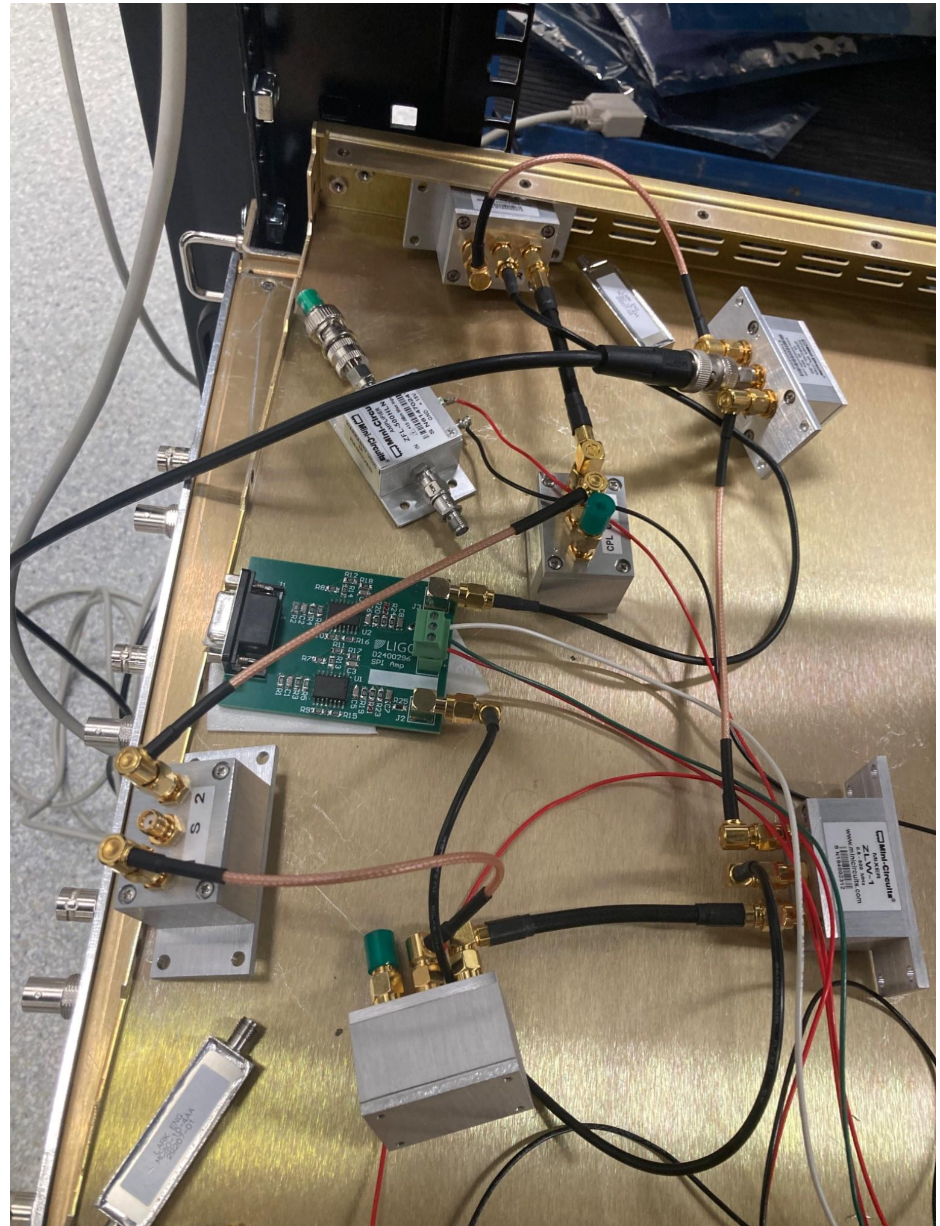
See Slide 31 of G2400903 for how this fits in the greater context of the SPI RF system

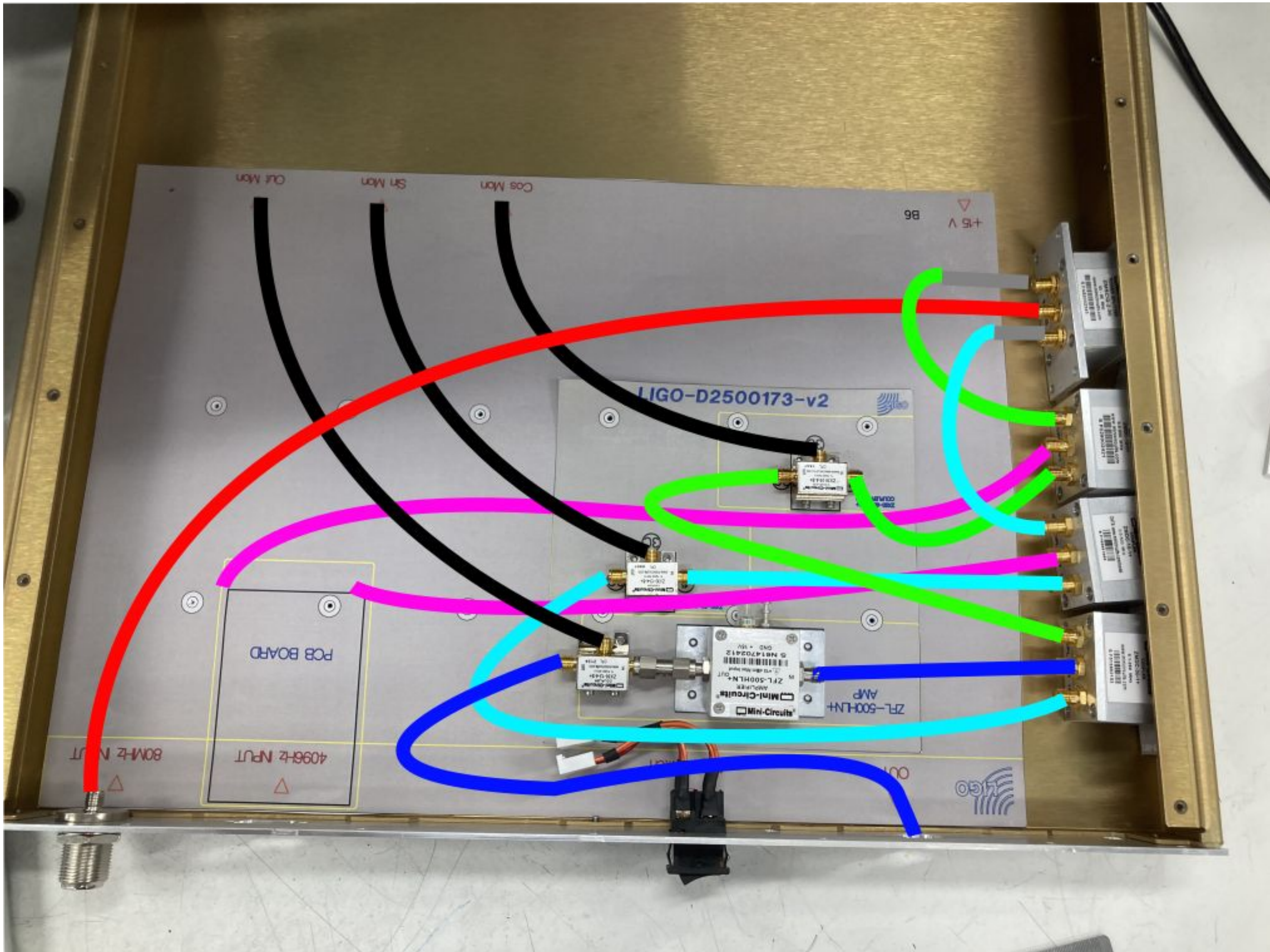
SPI Phase Noise Trade Study LHO DAQ Test Stand Rack Layout D2400283



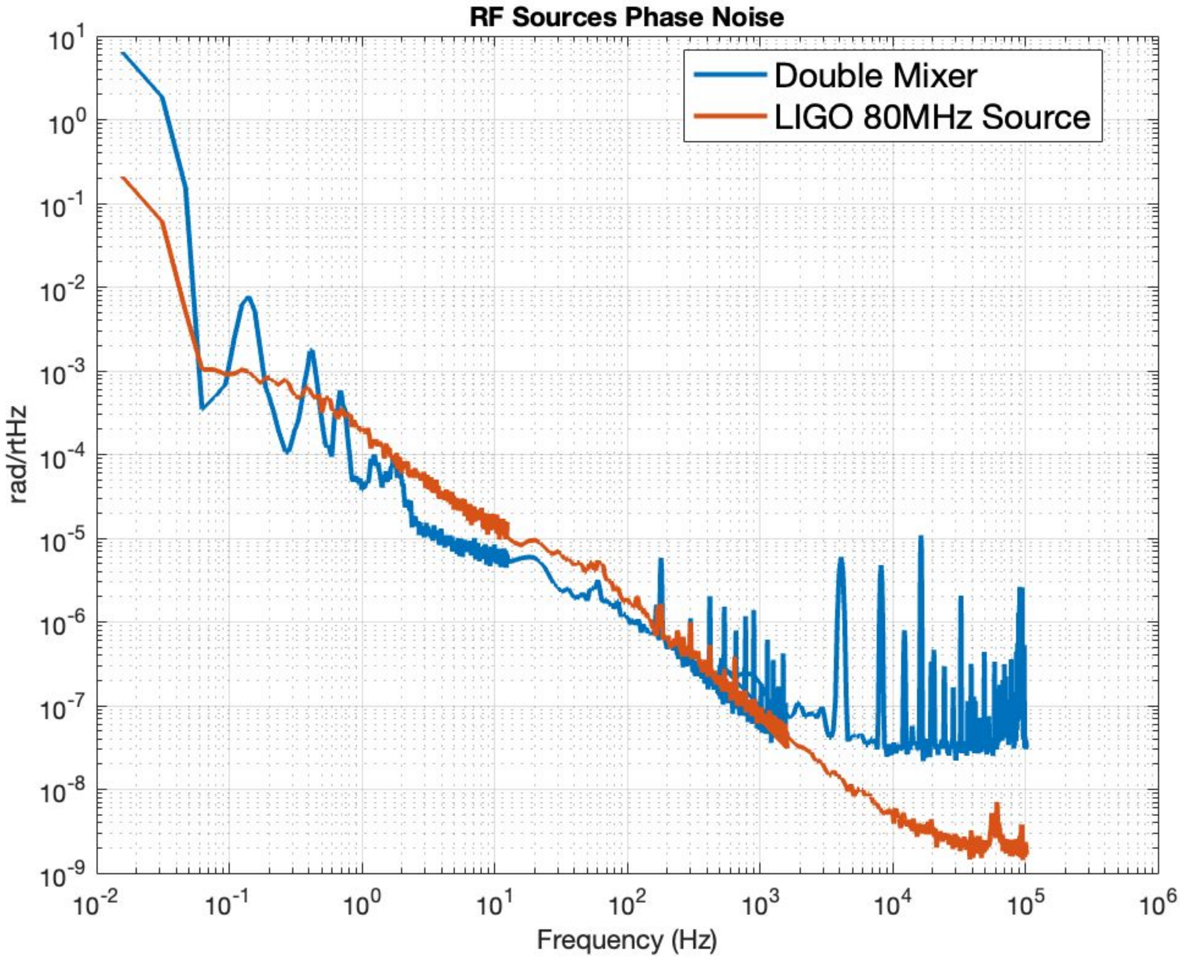
Picture of the Double Mixer Prototype



Picture of the Wire Diagram for the Final Double Mixer Design



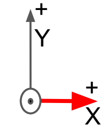
Double Mixer Performance

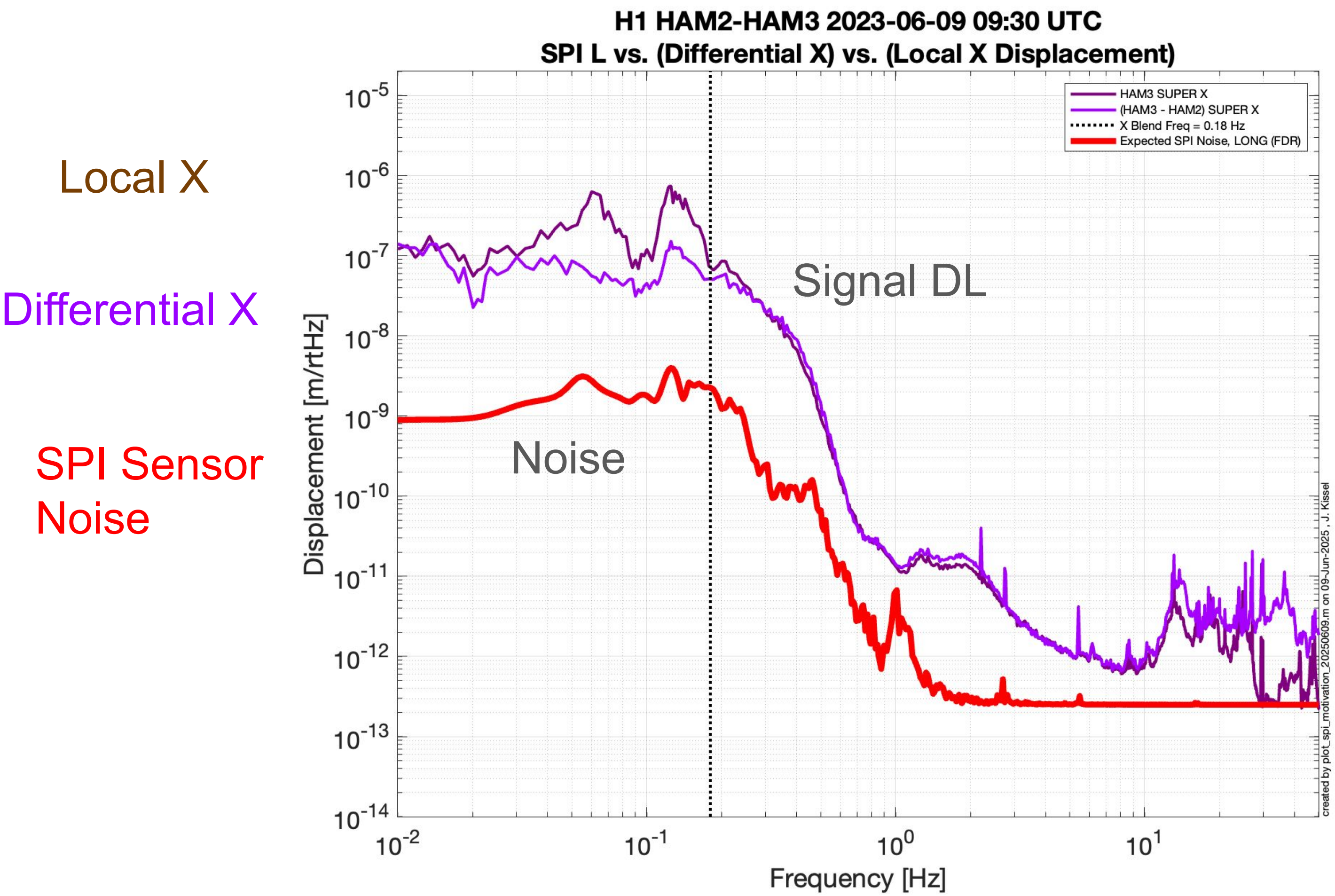


Double Mixer peaks are caused by "Spurs" of our Mixers

The Double Mixer shows comparable performance to the LIGO 80MHz in the frequency region in which SPI operates (<100Hz)

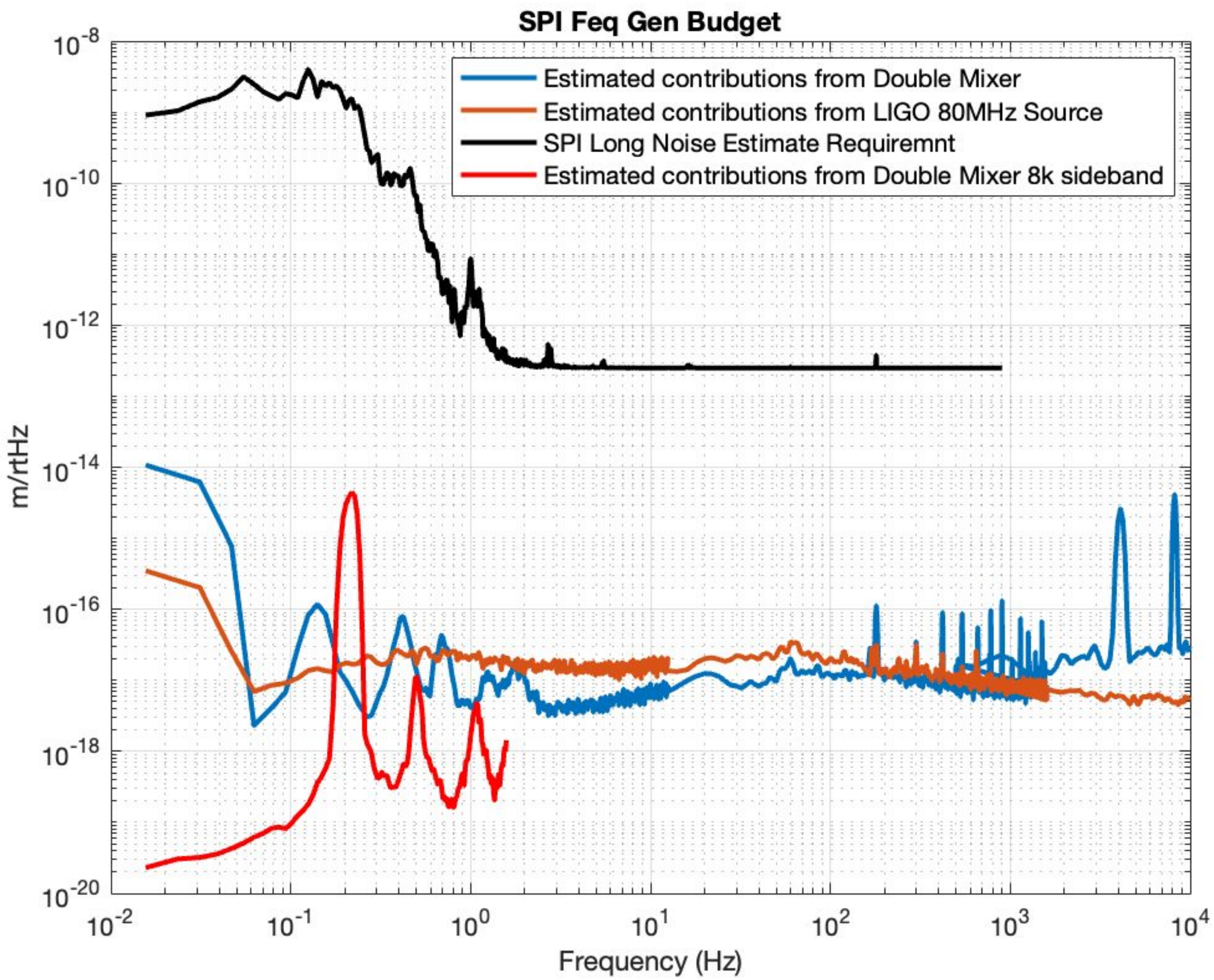
As a reminder Expected SPI **LONG** Performance





Plot from LHO Logbook: [83412]

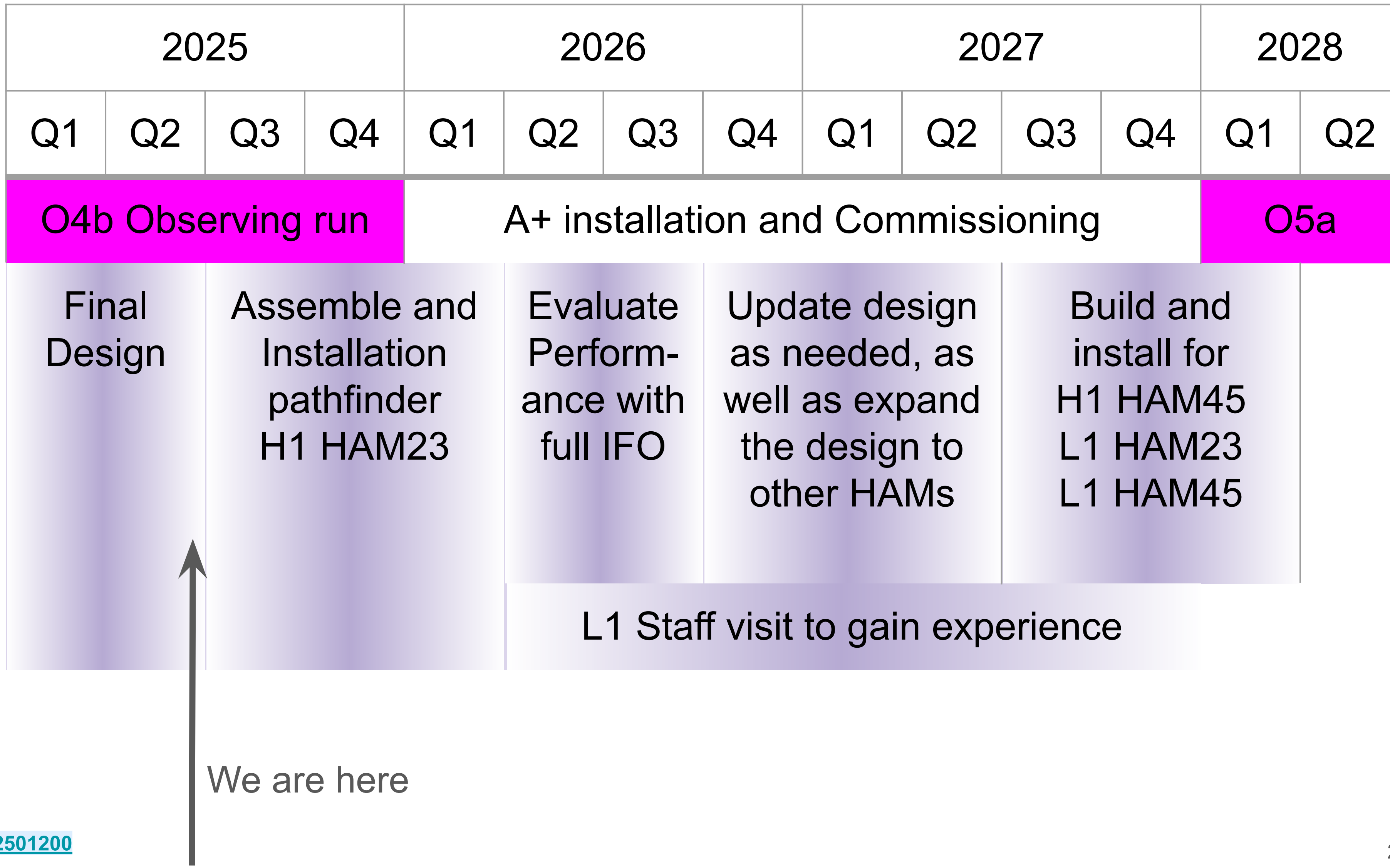
We won't be able to get all the way down to SPI LONG noise we'll still be limited by rolling off GS13 noise, its still MUCH less than current performance.



Initial results show that the added noise cause by RF noise source does not currently seem to be a limiting factor for our noise budget

Noise curves plotted using: $$\frac{L\omega_{noise}}{2(\omega_0 + \omega_m)}\phi_m$$

Timeline



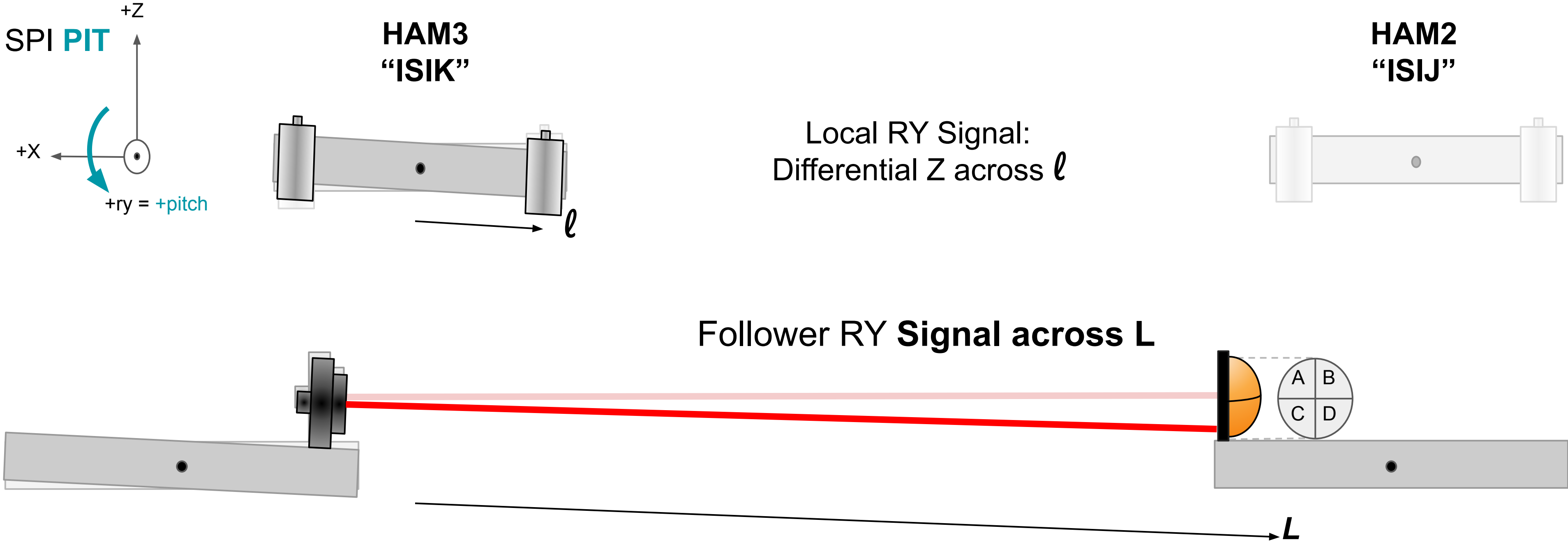
2025
2026
2027
2028
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
O4b Observing run
A+ installation and Commissioning
O5a
Final Design
Assemble and Installation pathfinder H1 HAM23
Evaluate Perform-ance with full IFO
Update design as needed, as well as expand the design to other HAMs
Build and install for H1 HAM45 L1 HAM23 L1 HAM45
L1 Staff visit to gain experience
We are here

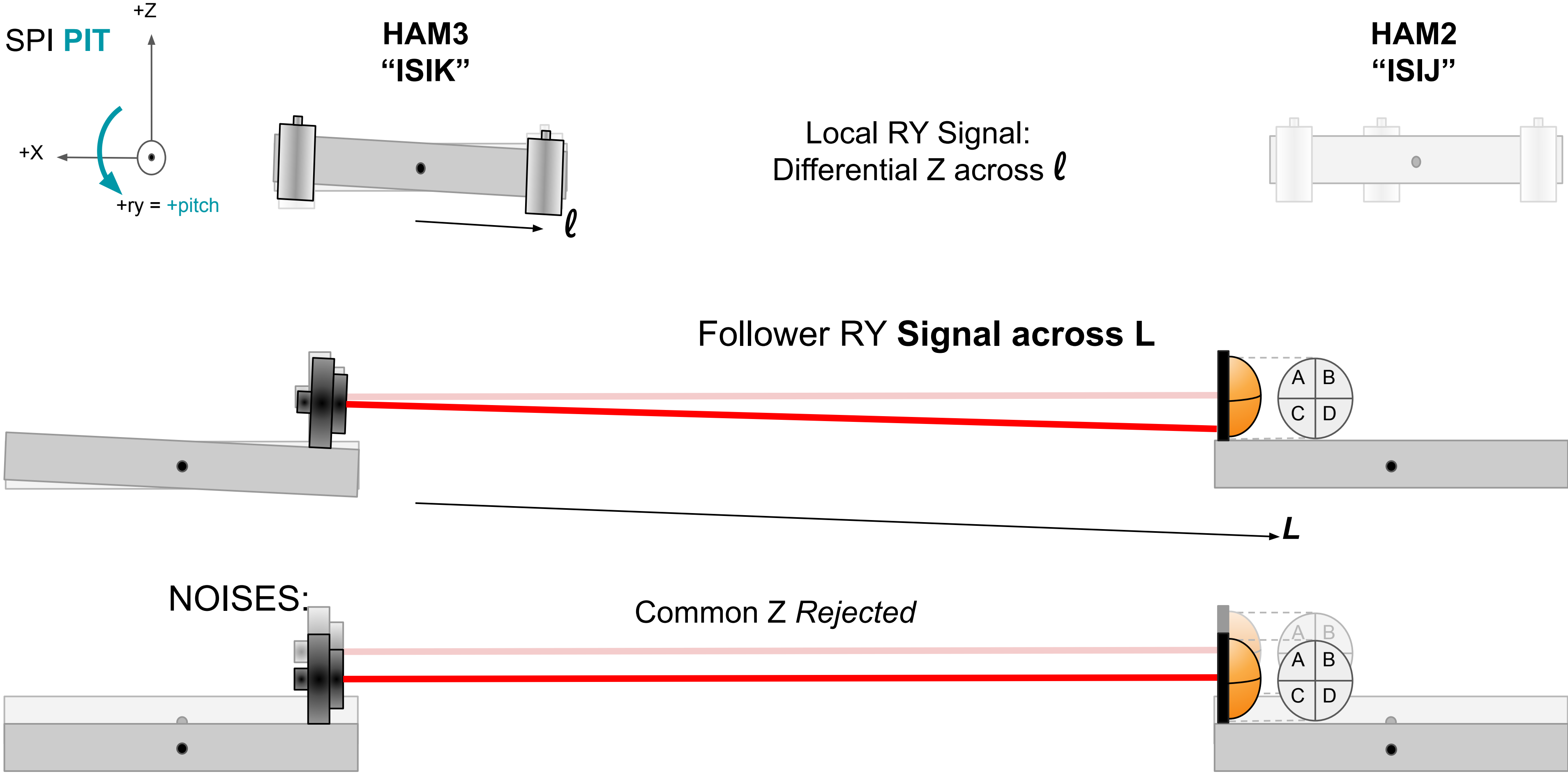
Recap

- SPI Pathfinder will be installed Nov 2025
- SPI Pathfinder dual Mach-Zehnder heterodyne IFO needs two oscillator sources
- We have already built up a second oscillator source that frequency shifts the first oscillator source and tested it
- This is a low-cost, passive oscillator solution that won't contribute AC power noise to the IFO
- We have a final design doc! T2400145

Thank you!

Extra Slides (If time permits)


SPI PIT
+Z
+X
+ry = +pitch
HAM3
"ISIK"
ℓ
Local RY Signal:
Differential Z across ℓ
HAM2
"ISIJ"
Follower RY Signal across L
A
B
C
D
L


SPI PIT
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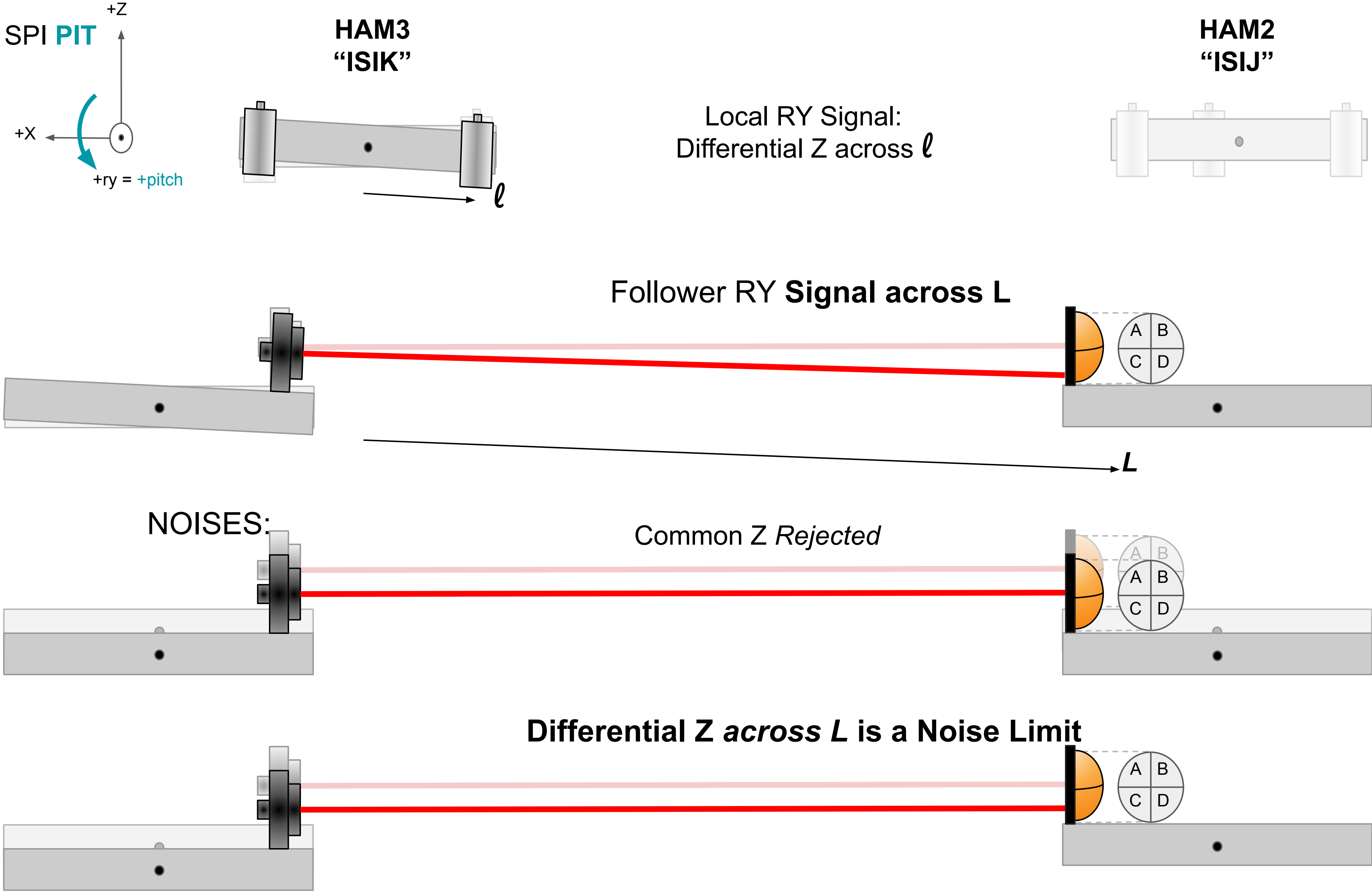
Local RY Signal:
Differential Z across ℓ
ℓ
Follower RY Signal across L
A B
C D
L
NOISES:
Common Z Rejected
A B
C D


SPI PIT
+Z
+X
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HAM2
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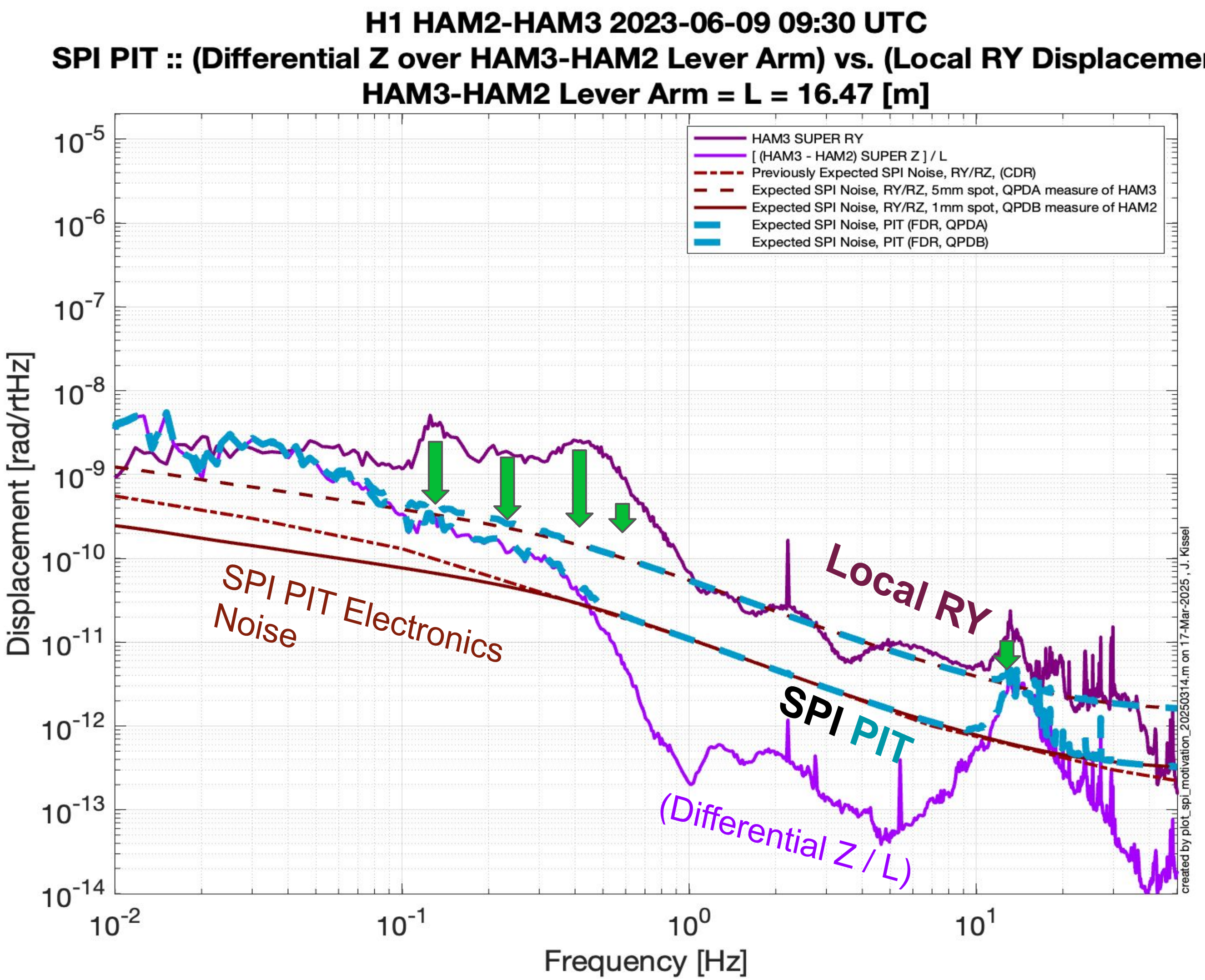
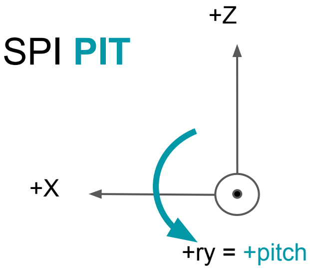
Local RY Signal:
Differential Z across ℓ
ℓ
Follower RY Signal across L
A B
C D
L
NOISES:
Common Z Rejected
A B
C D
Differential Z across L is a Noise Limit
A B
C D

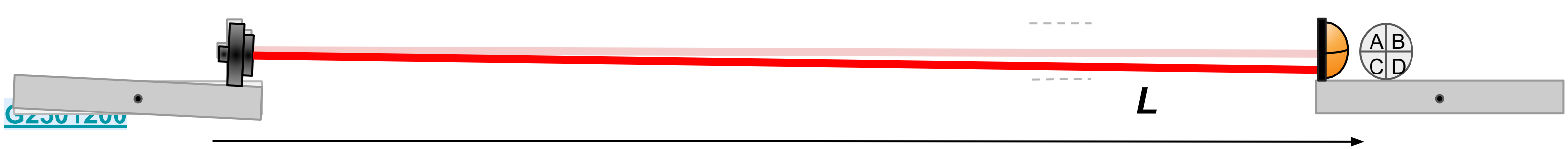
Expected SPI PIT Performance



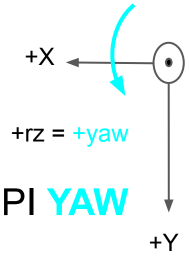
SPI **PIT**

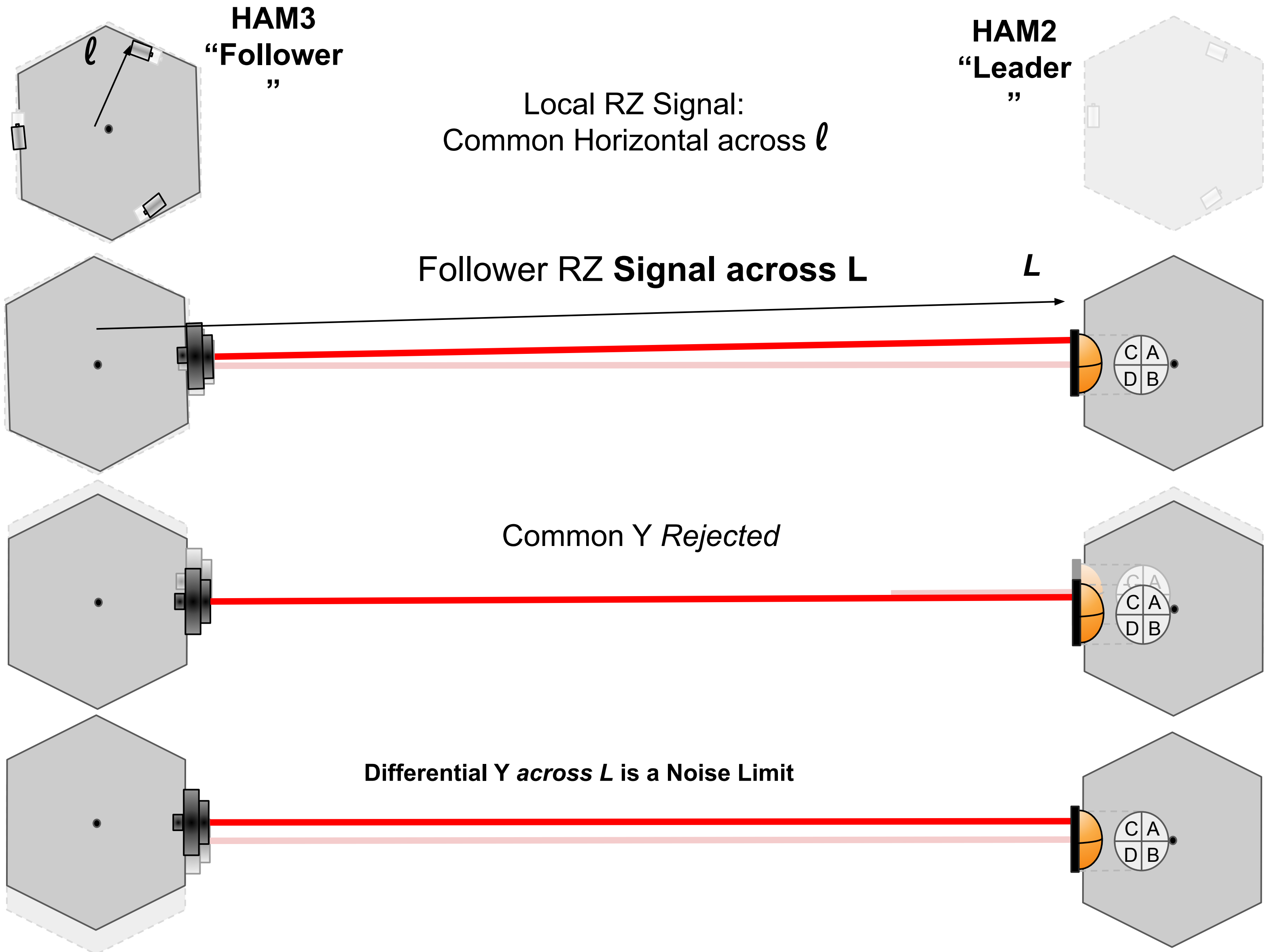


We expect improve platform RY performance by as much as 10-50x between 0.08 - 10 Hz with SPI PIT.



Measuring YAW w/ ONE-WAY Optical Lever





Since we are using QPDs we also get the **YAW** “for free”

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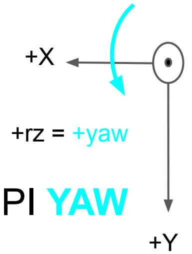
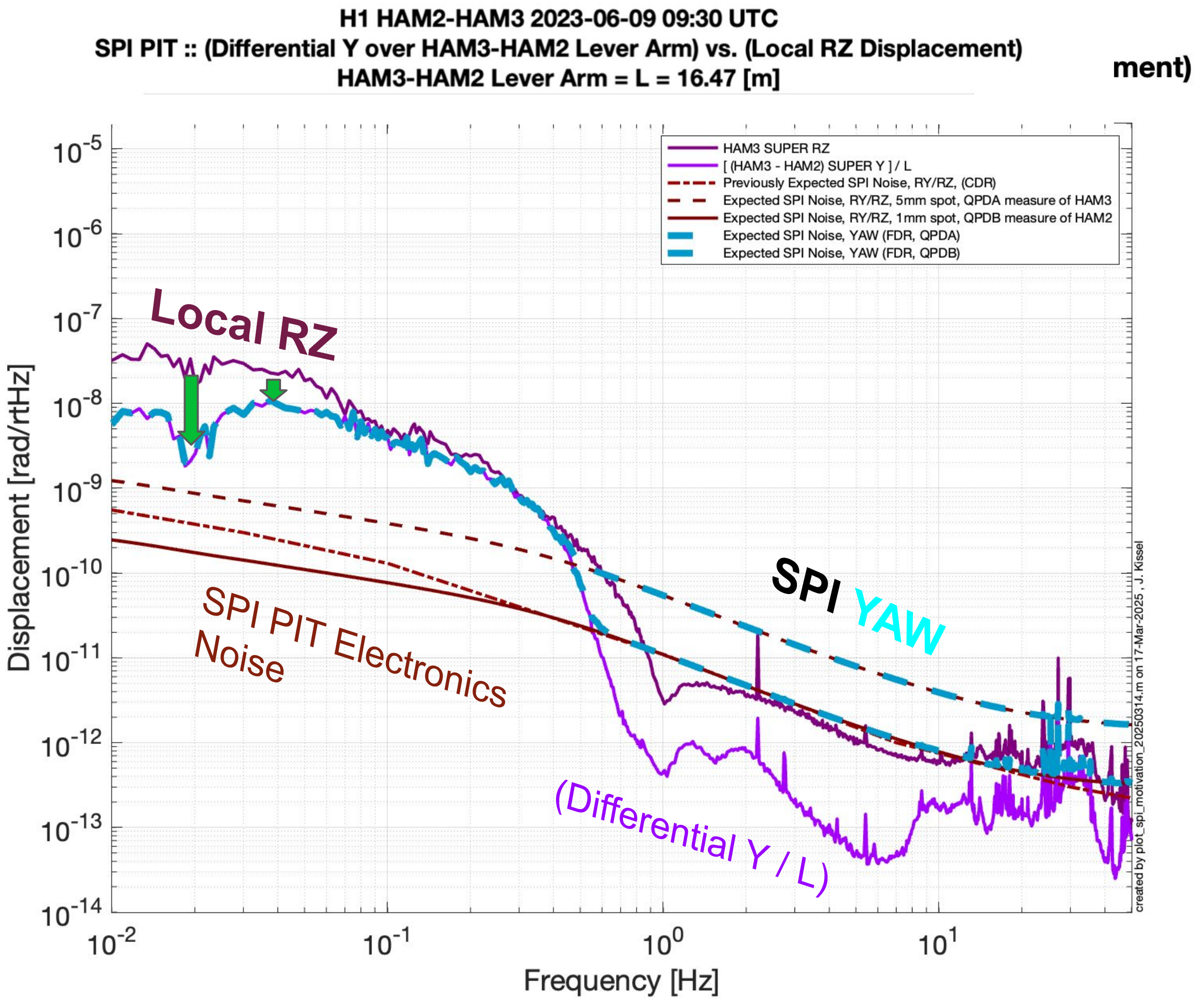
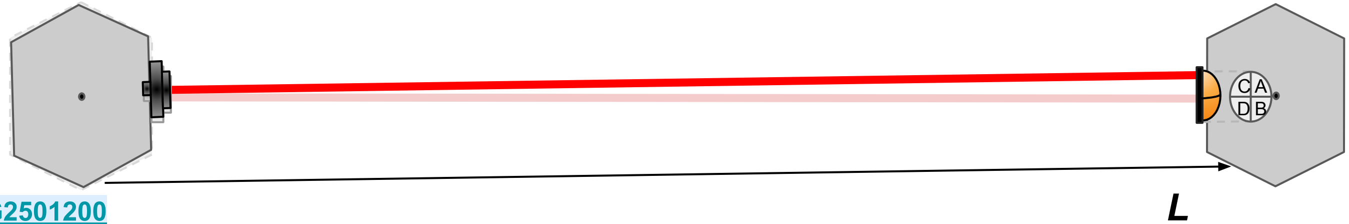
Expected SPI YAW Performance





It is unclear if the Differential Y / L noise limit for **SPI YAW** is better than **Local RZ**

But that is what the pathfinder is for!!



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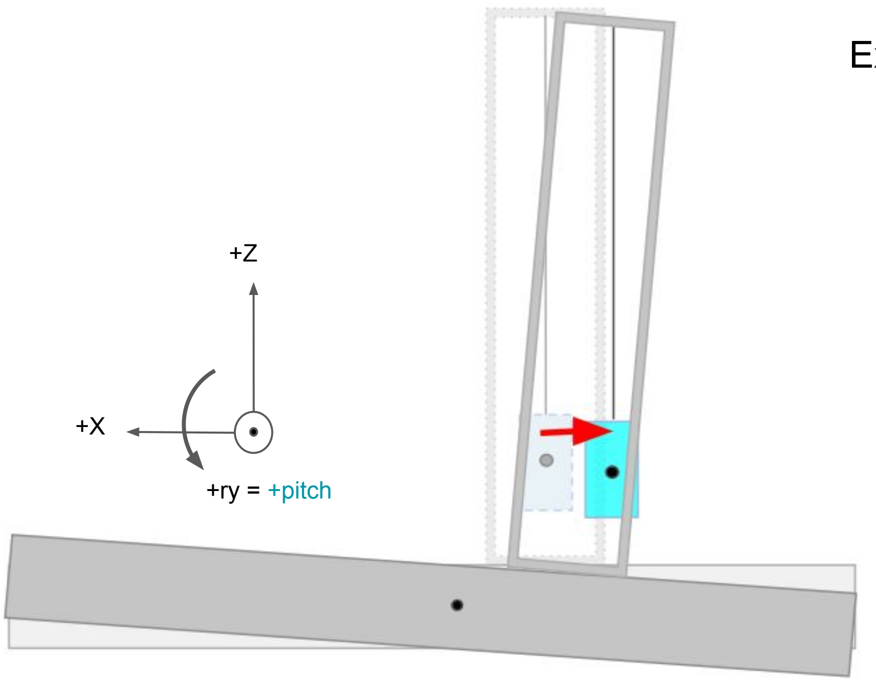
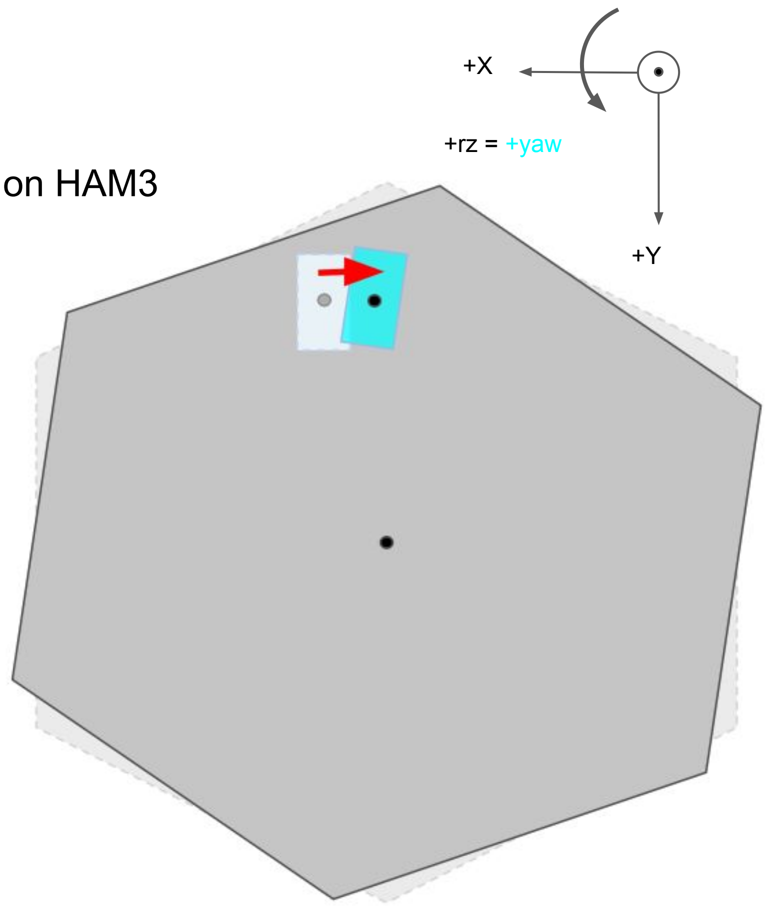
Tilt-to-Length Coupling



Example PR2 on HAM3



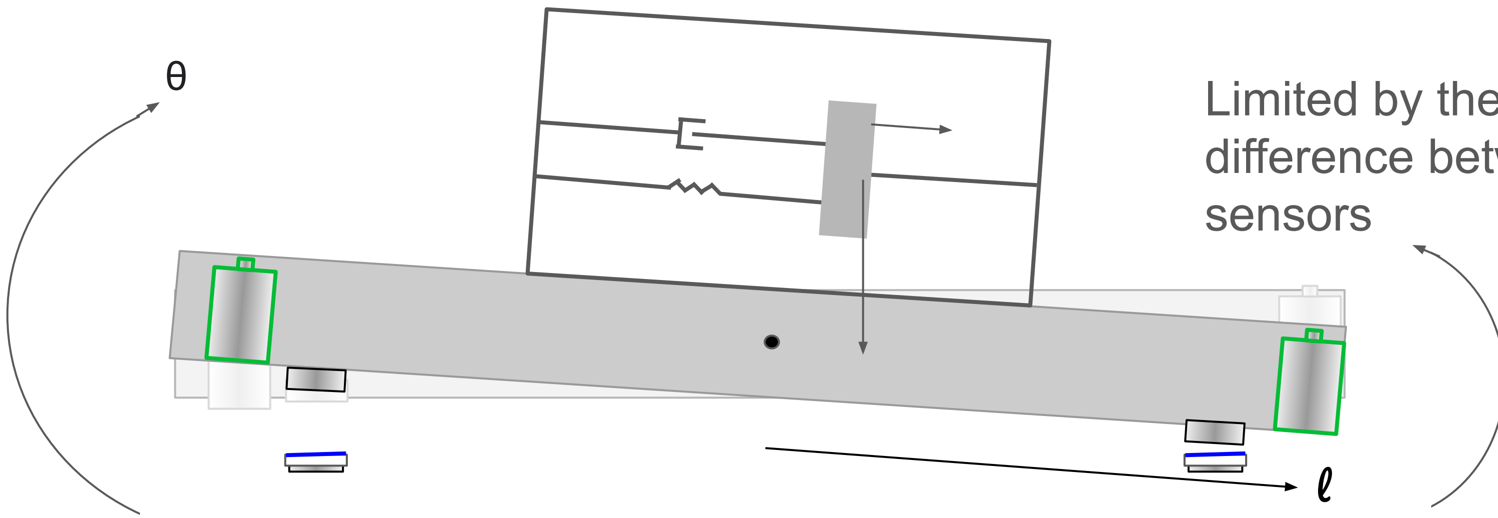
https://dcc.ligo.org/LIGO-G2400623

HAM: Horizontal Access Module (Vacuum Chamber)

Tilt-to-Horizontal Coupling

Tilt is interpreted as Horizontal Motion in seismometers

F = -mgθ



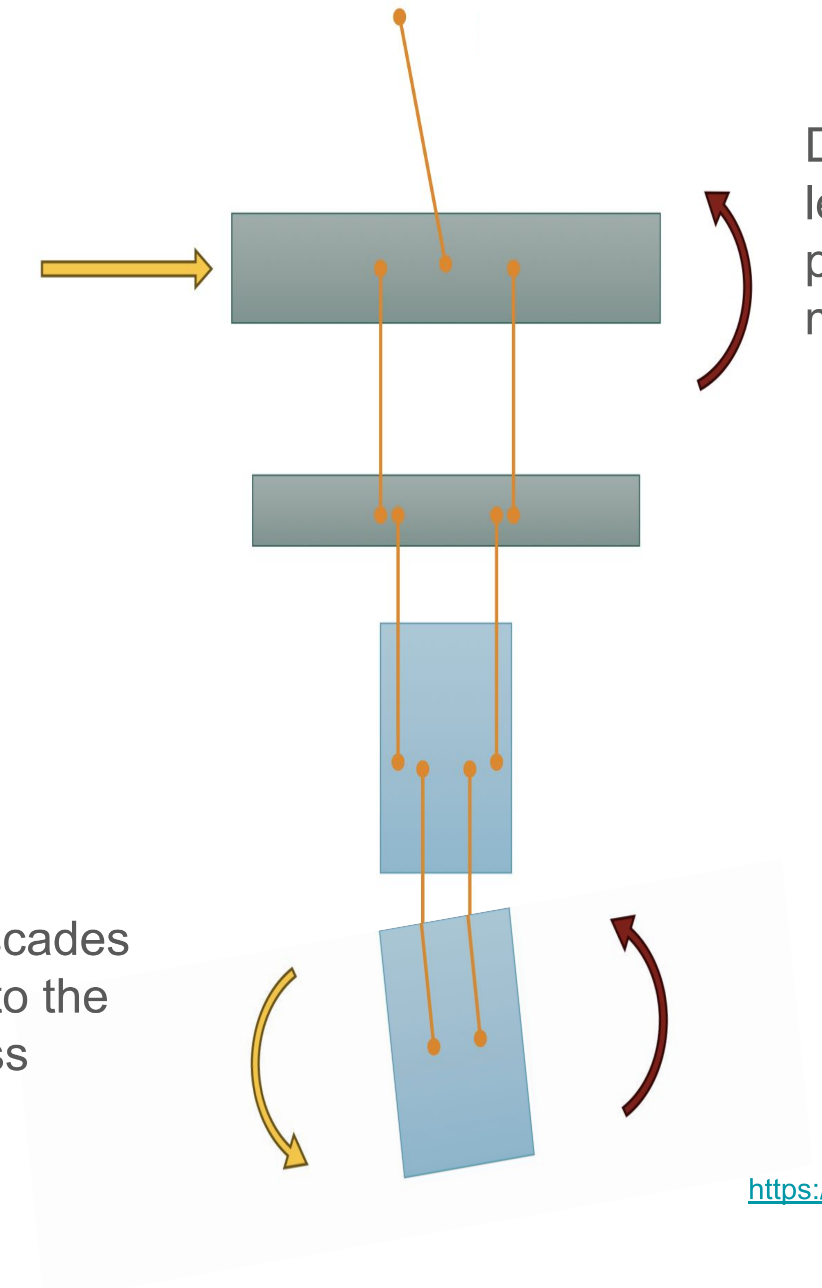
Limited by the gain difference between sensors

GS13s – Inertial Sensors

CPS – Displacement Sensors

Sensor Noise because lever is very short $\ell \approx 1$m

Length-to-Tilt Coupling

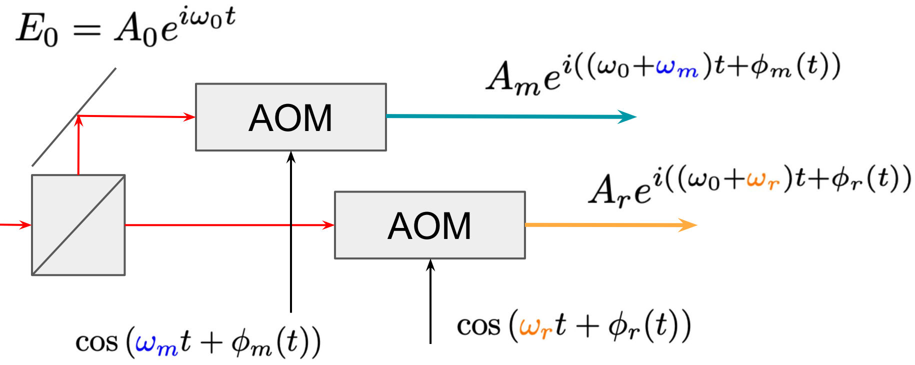


Driving in length causes pitch in top mass

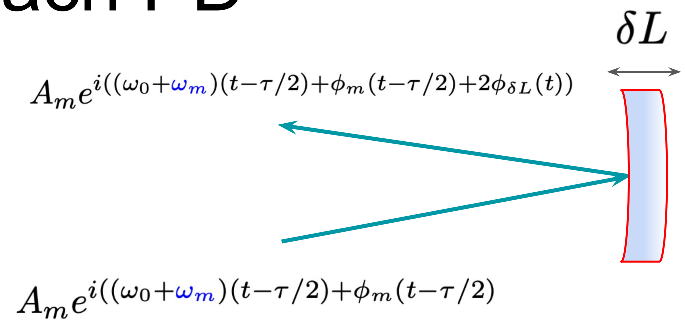
This cascades down into the test mass

https://dcc.ligo.org/LIGO-G2400623

Field Equations to Power on Each PD



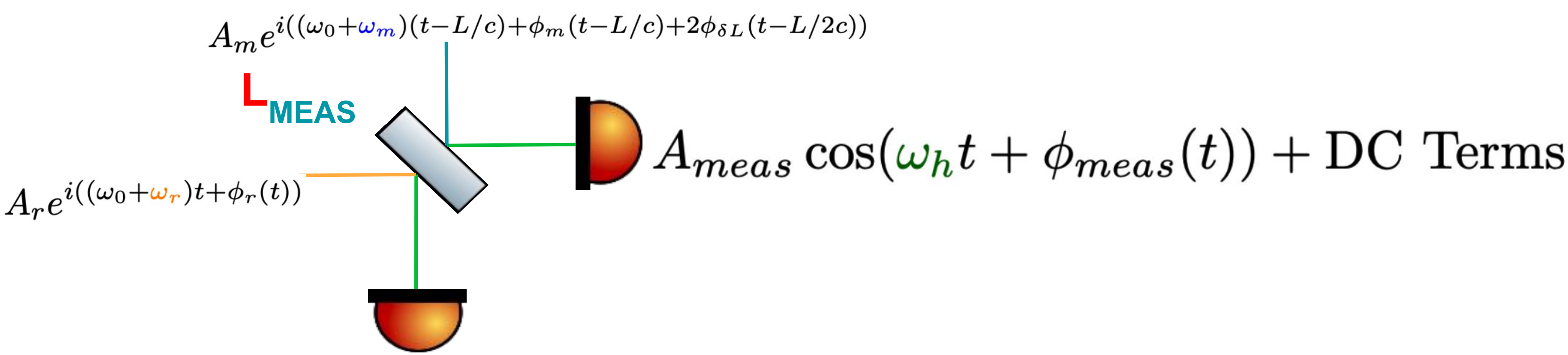
AOMs Frequency shift the light at a slight difference in frequency plus noise from the RF sources.



Mirror motion on HAM 2 adds phase to one of the beams

$$\phi_{\delta L}(t) = \frac{2\pi}{\lambda}\delta L(t) \qquad \tau = \frac{L}{c}$$

The beams recombine on the measured output producing a beat note, $\omega_m - \omega_r = \omega_h$ plus phase noise and our signal



$$\phi_{meas}(t) = \phi_m(t - L/c) + \phi_r(t) + 2\phi_{\delta L}(t - L/2c)$$

How to define Phase Noise

Phase noise denotes the noise that phase modulates into a system.[1][2]

$$A_0 e^{i(\omega_0 t + \phi_n)} \rightarrow A_0 e^{i(\omega_0 t + m_n \cos(\omega_n t))}$$

Where mn*cos(ωn t) is the phase modulation that represents the phase noise [rad/rtHz].

[1] J. Rutman, "Characterization of phase and frequency instabilities in precision frequency sources: Fifteen years of progress," in *Proceedings of the IEEE*, vol. 66, no. 9, pp. 1048-1075, Sept. 1978, doi: 10.1109/PROC.1978.11080.

Support that this is the correct result

Taking just the noise term:

$$\delta x = \frac{L\,\omega n}{(\omega 0 + \omega m)}\,\phi ns$$

Convert angular frequency to frequency ***v***

$$\frac{\delta x}{L} = \frac{\nu n\,\phi ns}{(\nu 0 + \nu m)}$$

Convert Phase noise to frequency noise ***δv*** [1]

$$\delta \nu = \frac{1}{2\pi}\,\frac{d\phi ns}{dt}$$

$$\frac{\delta L}{L} = \frac{\delta f}{f}$$

$$\frac{\delta x}{L} = \frac{\delta \nu}{(\nu 0 + \nu m)}$$

This is a well known equation when talking about how frequency noise affects the strain in interferometers

[1] J. Rutman, "Characterization of phase and frequency instabilities in precision frequency sources: Fifteen years of progress," in *Proceedings of the IEEE*, vol. 66, no. 9, pp. 1048-1075, Sept. 1978, doi: 10.1109/PROC.1978.11080.

This includes the Reference Laser

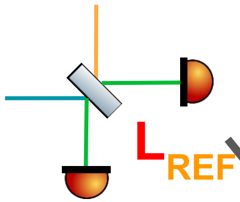
Following the same steps as with the measured laser we get

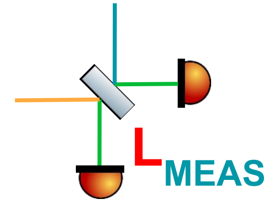
$$-\frac{(\omega 0 + \omega m)}{c}\left(\delta L + \frac{L\ \omega n}{\omega 0 + \omega m}\phi ms - \frac{q\ \omega n}{\omega 0 + \omega m}\phi rs\right)$$

This result shows that phase noise couples into our output proportionally to the path length difference between the reference interferometer and measurement interferometer on both lasers. This means the more noisy signal should go into the reference interferometer as the path length difference is much smaller. One can understand this result as, even if the reference is messy, the two paths on the measurement beam still compares with the same reference.

Heterodyne I/Q Demodulation

$A_{ref}\cos(\omega_h t + \phi_{ref}(t))$



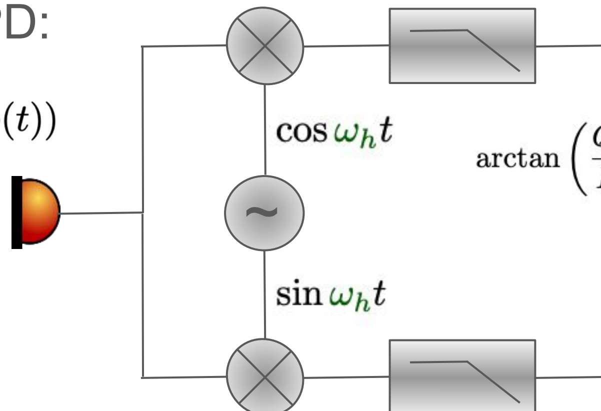


Demodulate (Extract Phase)

$A_{meas}\cos(\omega_h t + \phi_{meas}(t))$

For each PD:

$A_h\cos(\omega_h t + \phi(t))$



$$I = A_h LPF(\cos(\phi) - \cos(2\omega_h t + \phi))$$

$$\arctan\left(\frac{Q}{I}\right) = \arctan\left(\frac{A_h LPF[\sin(\hat{\phi}(f)) - \sin(\hat{\phi}(f - 2\omega_h))]}{A_h LPF[\cos(\hat{\phi}(f)) - \cos(\hat{\phi}(f - 2\omega_h))]}\right) \approx Lp(\hat{\phi}(f) + \hat{\phi}(f - 2\omega_h))$$

We also care about phase noise at double the beat frequency

$$Q = A_h LPF(\sin(\phi) - \sin(2\omega_h t + \phi))$$

Subtract the from the reference interferometer

$$\phi_{meas}(t) - \phi_{ref}(t) = 2\phi_{\delta L}(t - L/2c) + \phi_m(t - L/c) - \phi_m(t)$$

Convert phase to length

$$\delta L + \frac{L\omega_{noise}}{2(\omega_0 + \omega_m)}\phi_m$$

Noise

Signal

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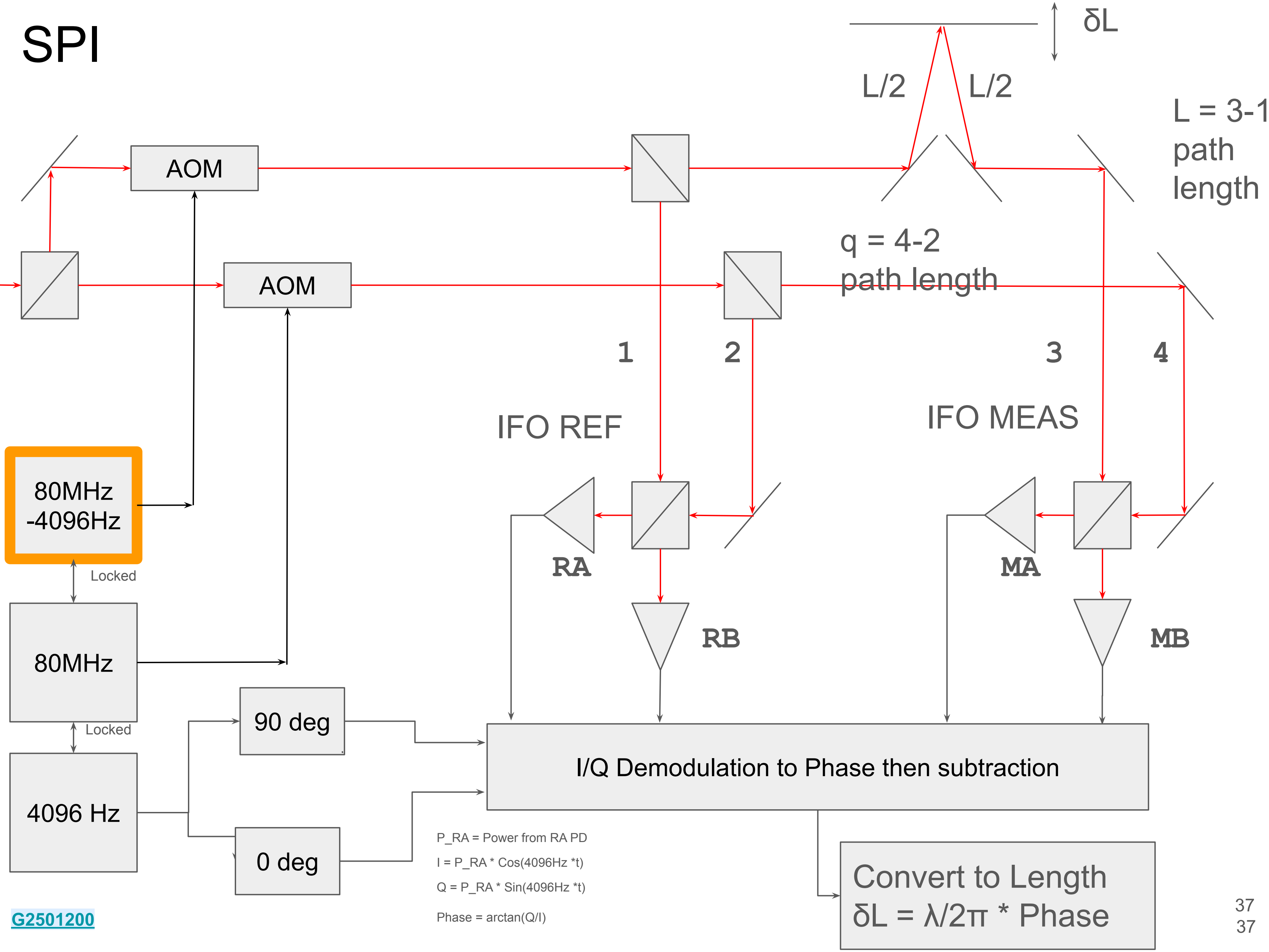
SPI



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Context

We have a description on how a RF signal will propagate through our system, we have the Phase noise of our RF signal, and we have out expected total noise budget. What we do not have is a convincing formalism on how phase noise affects our signal. We currently have three different formalisms on how noise interacts with our signal:

1. Phase noise is an added phase component of our RF signal.

   $E = A\exp(wt) \rightarrow A\exp(wt + \phi)$

   Where ϕ is the representation of phase noise. Results show that SPI is insensitive to this formalism of noise as all terms are canceled out.

2. Phase noise is a summation of smaller signals around the carrier and the important side band and its harmonics(4096 Hz in our case). Results show this only has an effect if the 2 harmonic and/or beyond is included

   $E = A\exp(wt) \rightarrow A\exp(wt + \phi) + A1 \exp(2\pi(f \pm 4096)\, t + \Psi)+...$

3. Phase noise is a summation of all power at all frequencies. Initial results show there is an effect.

   $E = A\exp(wt) \rightarrow A\exp(w1{*}t) + A1 \exp(w2{*}t) + \ldots$

4. Phase noise is a added component of the RF signal but with the caveat that it phase modulates the signal with a range of frequencies

   $E = A\exp(wt) \rightarrow A\exp(wt + \Gamma\cos(wn\, t))$ (This is the one we use)

Fourth Formalism (cont.)

The fourth Formalism is mathematically similar to the first formalism and have all the noise cancel in the interferometer except in the case of an arrival time difference between the paths (t -> t - **τ** = t - L/c)

$$ER1 = A1\left(1+\frac{\alpha 1}{A1}\right) e^{i\,((\omega 0+\omega m)*t\ +\Gamma \operatorname{Cos}[\omega n*t])}$$

$$ER2 = A2\left(1+\frac{\alpha 2}{A2}\right) e^{i\,((\omega 0+\omega r)*t\ +\psi)}$$

(* MEAS IFO *)

$$EM3 = A3\left(1+\frac{\alpha 3}{A3}\right) e^{i\,((\omega 0+\omega m)*t-(\omega 0+\omega m)*L/c\ +\Gamma \operatorname{Cos}[\omega n*t-\omega n*L/c]+(\omega 0+\omega m)*\delta L/c)}$$

$$EM4 = A4\left(1+\frac{\alpha 4}{A4}\right) e^{i\,((\omega 0+\omega r)*t\ +\psi)}$$

Where:
ω0 = original laser frequency[THz]
ωm = 80-[MHz]
ωr = 80[MHz]
δL = mirror position
L = path length difference between path 1 and 3
c = speed of light
ψ = phase noise of 80 oscillator

Phase Noise on the Reference Laser

An interesting result is if phase noise is also put on the reference laser. We also define the reference laser to have a small path length difference, q << L.

$$ER1 = A1\left(1+\frac{\alpha 1}{A1}\right) e^{i((\omega 0+\omega m)*t+\Gamma m\, Cos[\omega n*t])}$$

$$ER2 = A2\left(1+\frac{\alpha 2}{A2}\right) e^{i((\omega 0+\omega r)*t+\Gamma r\, Cos[\omega n*t])}$$

(* MEAS IFO *)

$$EM3 = A3\left(1+\frac{\alpha 3}{A3}\right) e^{i((\omega 0+\omega m)*t-(\omega 0+\omega m)*L/c+(\omega 0+\omega m)*\delta L/c+\Gamma m\, Cos[\omega n*t-L*\omega n/c])}$$

$$EM4 = A4\left(1+\frac{\alpha 4}{A4}\right) e^{i((\omega 0+\omega r)*t-(\omega 0+\omega m)*q/c+\Gamma r\, Cos[\omega n*t-q*\omega n/c])}$$

Where:

$\omega 0$ = original laser frequency[THz]

ωm = 80-[MHz]

ωr = 80[MHz]

δL = mirror position

L = path length difference between path 1 and 3

q = path length difference between path 2 and 4

c = speed of light

$\Gamma m \cos(\omega m\, t)$ represents the phase noise of the measure laser

$\Gamma r \cos(\omega r\, t)$ represents the phase noise of the reference laser

Bad Sidebands coupling into phase readout

In I/Q demod sidebands all noise far from carrier is suppressed due to the low pass filter. For example, in this signal just before the low pass filter

$$-A1\,A2\,R1\,T1\,\mathrm{Cos}[\phi n] + A1\,A2\,R1\,T1\,\mathrm{Cos}[\phi n + 2\,t\,\omega m - 2\,t\,\omega r] - A1^2\,R1^2\,\mathrm{Sin}[t\,\omega m - t\,\omega r] - A2^2\,T1^2\,\mathrm{Sin}[t\,\omega m - t\,\omega r]$$

All $\omega m - \omega r$ terms are suppressed due to the low pass filter. As such, an the low pass would just pull out the Cos[ϕn] term. However, if ϕn is large around 2($\omega m - \omega r$), then the Cos[ϕn + 2t($\omega m - \omega r$)] would also have a low frequency component. If (- ϕn) ~~ 2t($\omega m - \omega r$), then there's a DC component.

Bad Sidebands quick calculation (results)

$$\frac{(\omega 0+\omega m)}{c}\,\frac{\left(\Gamma 8k^2-2\left(2+\Gamma DC^2\right)-2\,\Gamma DC^2\,\mathrm{Cos}[2\,t\,\omega DC]\right)}{(2+\Gamma 8k\,\mathrm{Sin}[t\,(\omega 8K-2\,\omega h)])}\,\frac{1}{2-2\,x\,\Gamma DC\,\mathrm{Cos}[t\,\omega DC]+x\,\Gamma 8k\,\mathrm{Cos}[t\,(\omega 8K-2\,\omega h)]+\Gamma 8k\,\mathrm{Sin}[t\,(\omega 8K-2\,\omega h)]}\,\delta L$$

To a first order approximation

$$-\frac{(\omega 0+\omega m)}{c}\left(\frac{\delta L}{1+\Gamma 8k\,\mathrm{Sin}[t\,(\omega 8K-2\,\omega h)]}\right) \quad \text{or} \quad -\frac{(\omega 0+\omega m)}{c}\,(\delta L-\Gamma 8k\,\delta L\,\mathrm{Sin}[t\,(\omega 8K-2\,\omega h)])$$

This result shows that sidebands couple proportionally to the mirror motion

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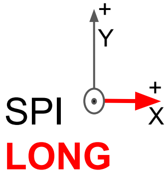
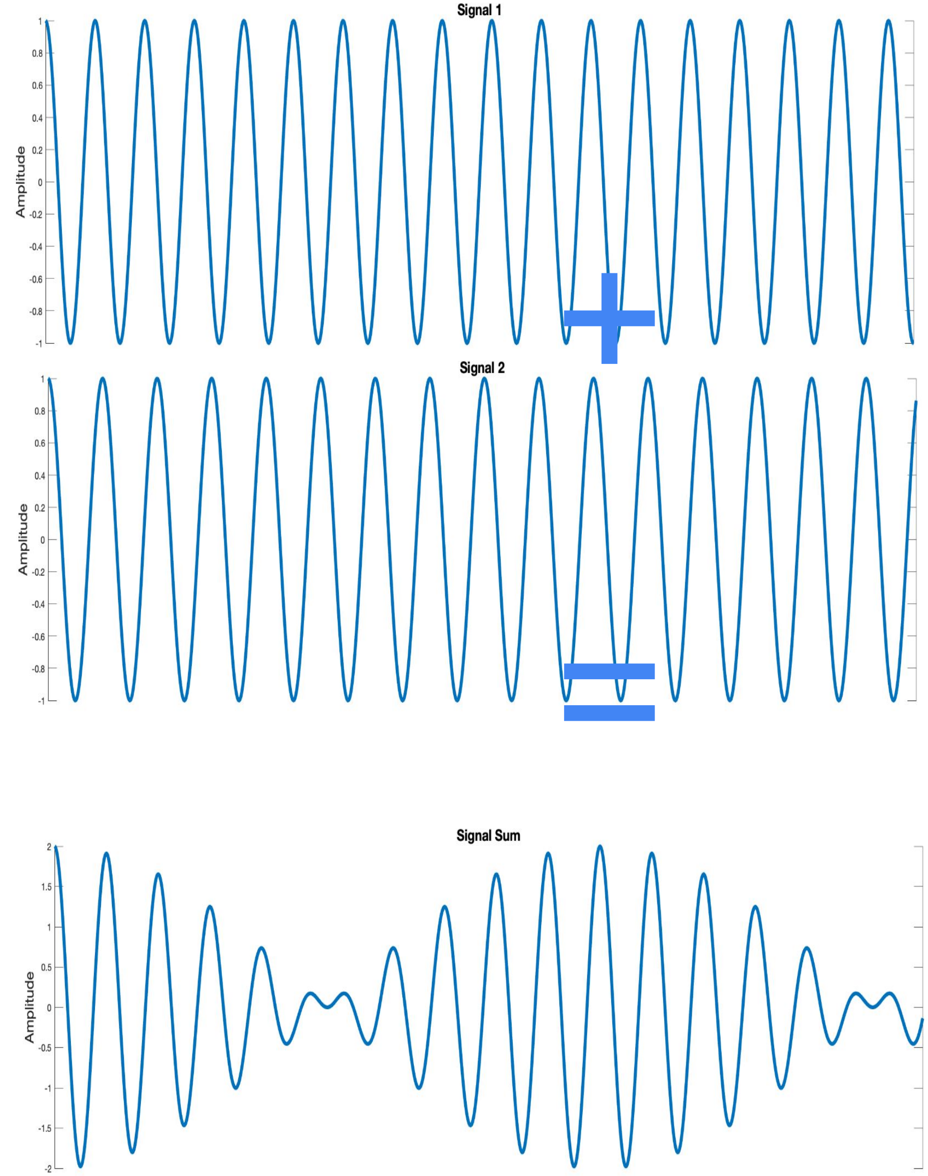
Heterodyne Sensing Intro



Superposition (sum) with slightly different frequencies

$$\cos\omega_1 + \cos\omega_2 = 2\cos\frac{\omega_1 - \omega_2}{2}\cos\frac{\omega_1 + \omega_2}{2}$$



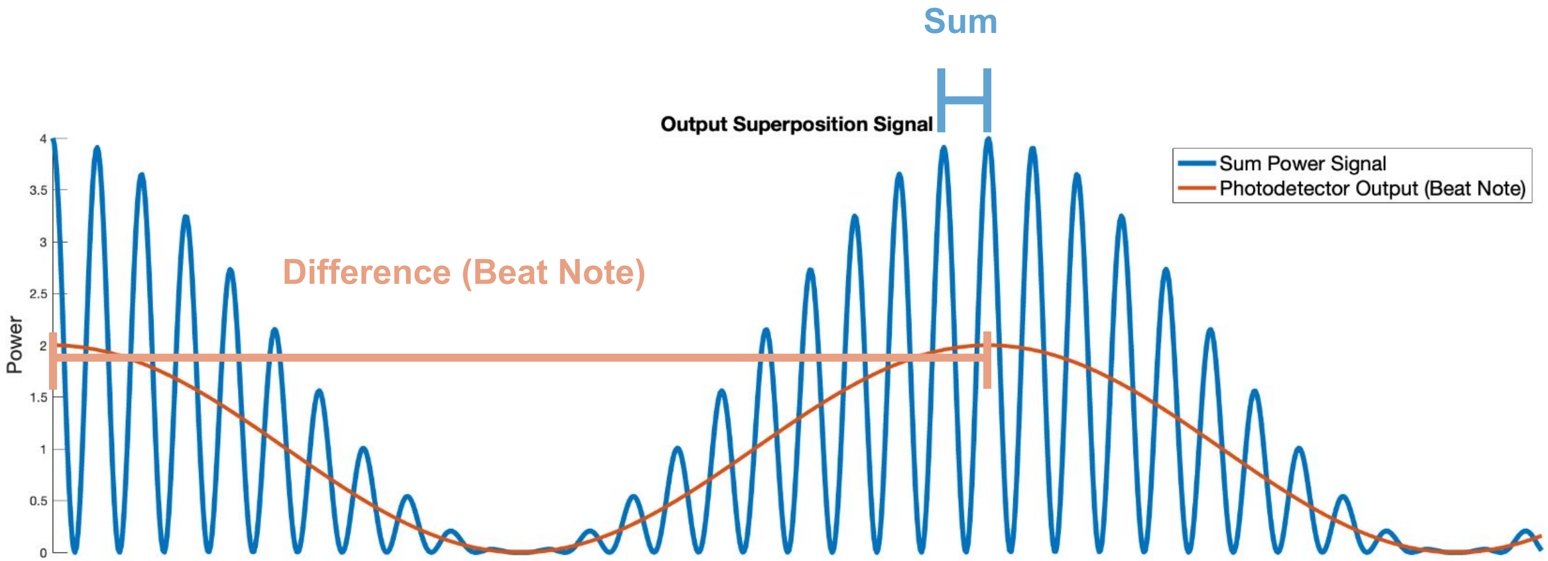
Made up of 2 components, sum and difference, of the frequencies of the original signals

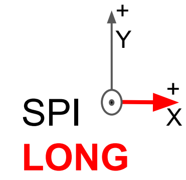
Photodiode Output sees power which is the square of this signal

SPI LONG

Power Output on Photodiode (not to scale)

The true signal is the Sum Power Signal, however, the frequency is so high (about 3 x10^{14} Hz in pathfinder case) that the photodiode will only detect the average power of the signal Beat Note (4096 Hz in pathfinder case)





Doppler Shift

The Output will be fluctuating at the beat note frequency

Any longitudinal shifts between the tables will doppler shift the frequency of the beam

This will cause a shift in the frequency of the beat output signal which produces our error signal