# Deterministic DRMI Locking Using an AS Carrier

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# Motivation: DRMI and the AS Carrier

- **Goal**: Acquire DRMI in Cosmic Explorer *deterministically*

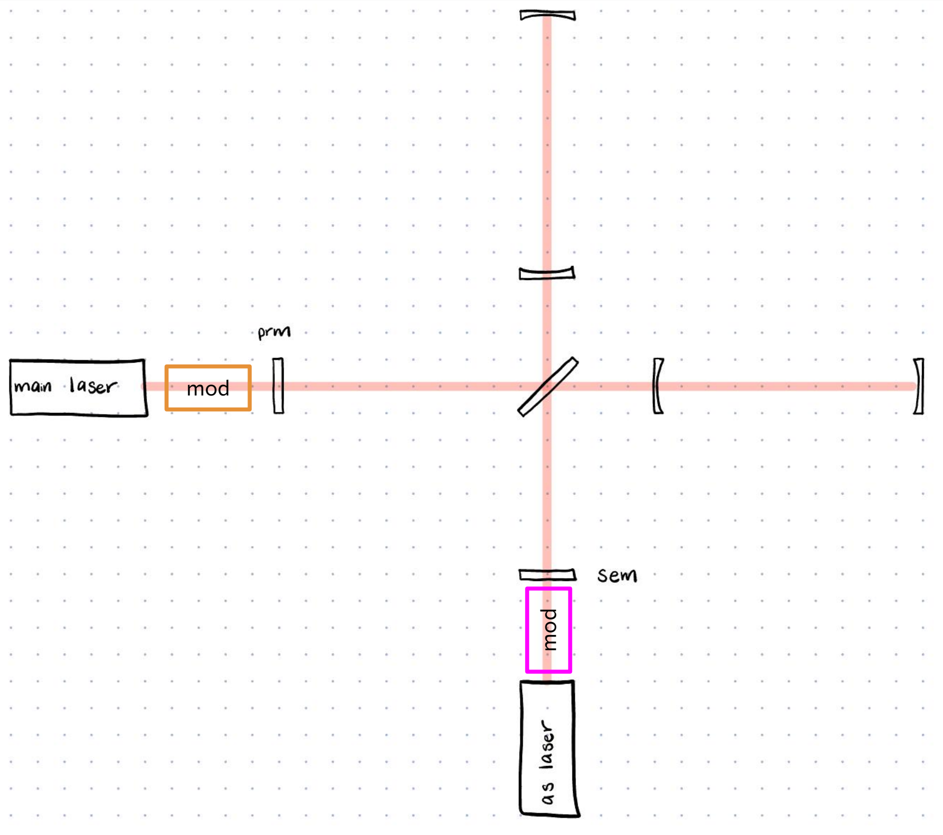
- **Idea**: Use the squeezer beam to help acquire the interferometer.

  The SQZ beam enters the interferometer in a **different quadrature** to the main beam.

  The SQZ beam could be **frequency offset** from the main beam,
  and have it's own set of **RF sidebands**.

- *Is it possible to acquire DRMI in a completely deterministic way?*

- Idea of a subcarrier is not new [1]



# Motivation: Deterministic DRMI

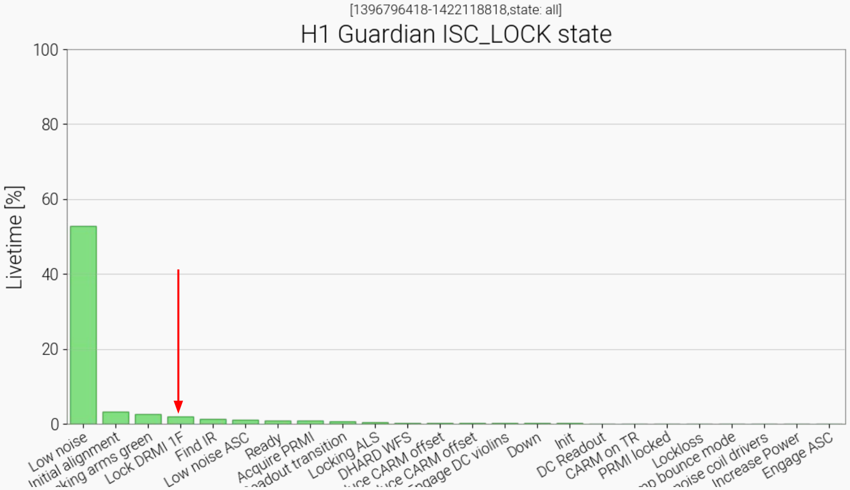
Currently, we must wait for the three main degrees of freedom of DRMI (MICH, PRCL, SECL), to *randomly* swing into the proper resonant condition.
In the current detectors, this process is pretty well-tuned to quickly acquire DRMI on the first couple of "flashes" of resonance. Still, some time is lost here.

**In O4b at LHO (April 10, 2024 - Jan 28, 2025),**

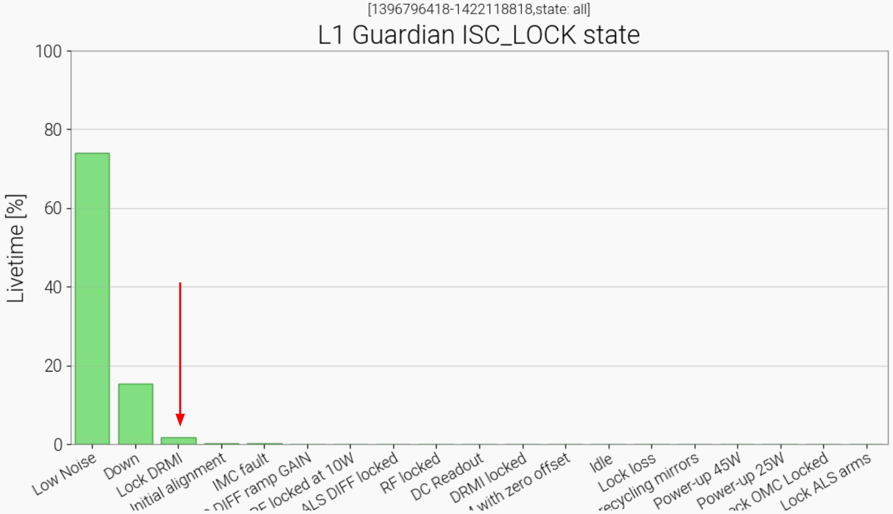
1. We spent 1.94% of detector time in ACQUIRE_DRMI_1F,
2. We entered the state ACQUIRE_DRMI_1F 2868 times
   a. We lost lock here 337 times
   b. We entered ACQUIRE_PRMI 1100 times (after three minutes we give up I think)
   c. We acquired DRMI the rest of the 1431 times (entering state 102, I assume is acquired)

From summary pages:
https://ldas-jobs.ligo.caltech.edu/~detchar/summary/gps/1396796418-1422118818/locking/h1_isc_lock/
**Similarly for LLO, we spent 1.64% of detector time in LOCK_DRMI.**
https://ldas-jobs.ligo.caltech.edu/~detchar/summary/gps/1396796418-1422118818/locking/l1_isc_lock/

# Motivation: Lower Lock Acquisition Times




**Takeaway**: Normal locking conditions is fine for DRMI, leading to around ~minute lock times.
*But acquisition time can be long*, especially in times of bad weather or high microseism.



# Why is acquiring DRMI hard?

1. Lack of knowledge of optic positions
2. Strongly coupled resonant conditions

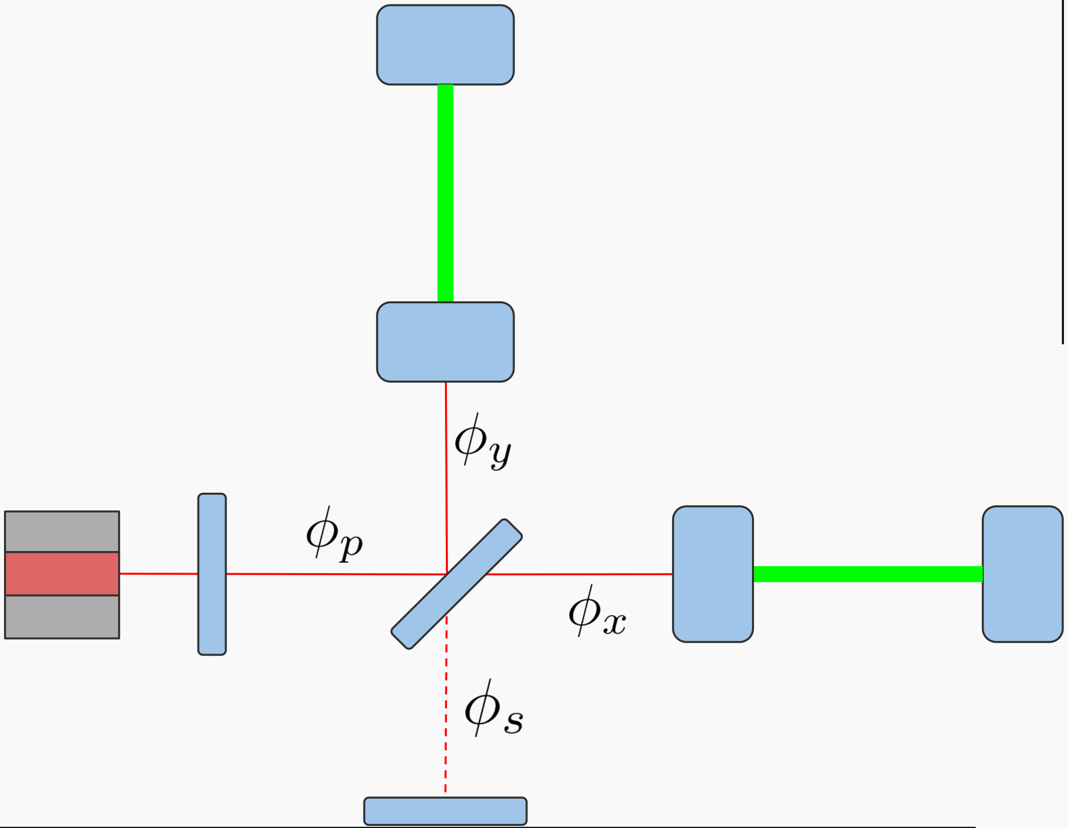
Moving the BS or ITM positions changes all three corner degrees of freedom phases

$$\{\phi_M, \phi_P, \phi_S\}$$

$$\phi_M = \frac{\phi_x - \phi_y}{2}$$

$$\phi_P = \frac{\phi_x + \phi_y}{2} + \phi_p$$

$$\phi_S = \frac{\phi_x + \phi_y}{2} + \phi_s$$



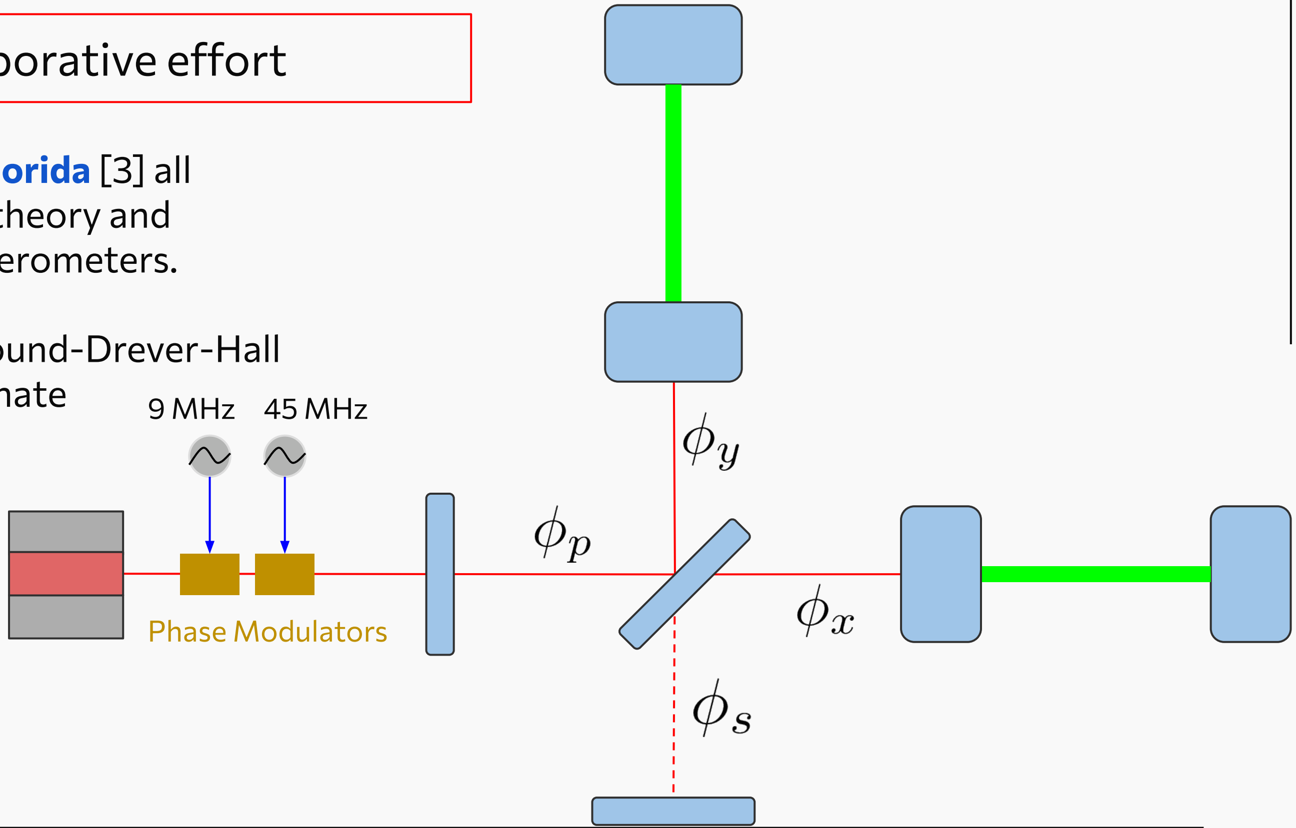
# How can you possibly acquire DRMI?

Great collaborative effort

Caltech [4,6], **MIT** [1,5], and **Florida** [3] all contributed to DRMI locking theory and demonstrated tabletop interferometers.

Advanced LIGO uses clever Pound-Drever-Hall error signals designed to resonate in only certain parts of the interferometer.

This allows us to “pick off” signals that are relevant for detecting our corner degrees of freedom.



# DRMI Locking Resonance Conditions

**Carrier**

These get flipped once the arms are brought on resonance

1. Michelson dark fringe
2. Power recycling cavity length is ANTIRESONANT for carrier
3. Signal extraction cavity length is RESONANT for carrier

$$\phi_M = 0^\circ$$
$$\phi_P = 90^\circ$$
$$\phi_S = 0^\circ$$

**9 MHz sidebands**

4. Michelson small offset via Schnupp Asymmetry
5. Power recycling cavity length is RESONANT for 9 MHz
6. Signal extraction cavity length is ANTIRESONANT for 9 MHz

$$\phi_{MRF1} = \frac{2\Omega_1 \ell_M}{c}$$
$$\phi_P \pm \phi_{PRF1} = 0^\circ$$
$$\phi_S \pm \phi_{SRF1} = 90^\circ$$

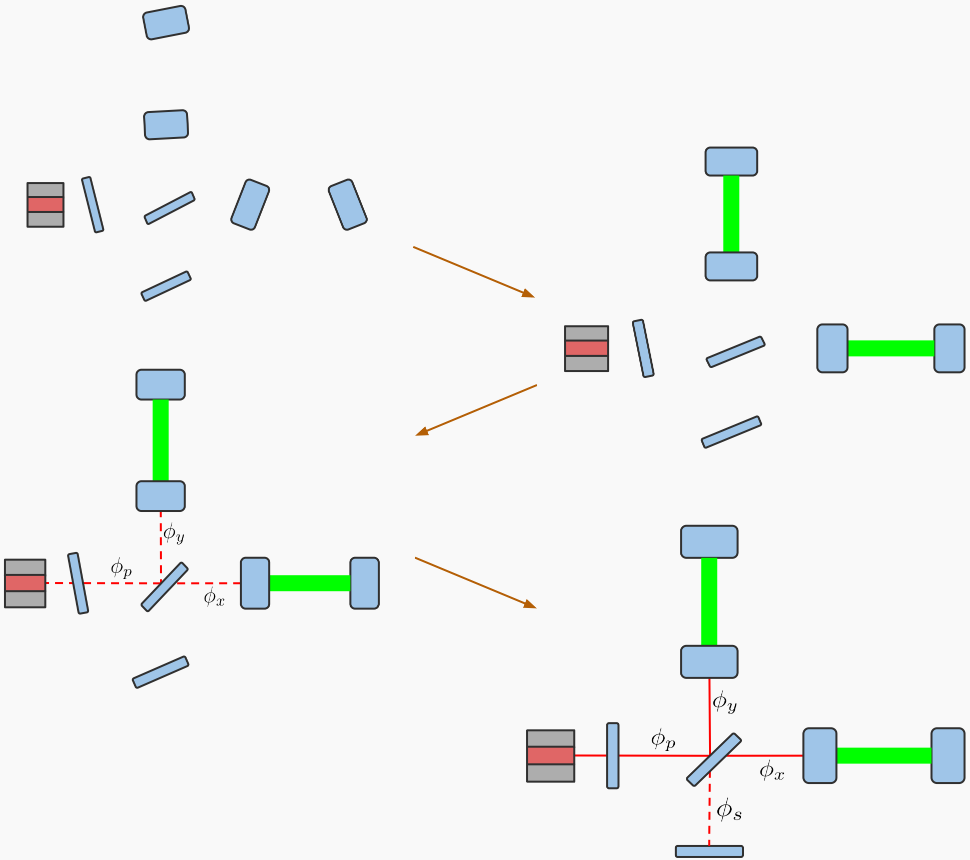
**45 MHz sidebands**

7. Michelson small offset via Schnupp Asymmetry
8. Power recycling cavity length is RESONANT for 45 MHz
9. Signal extraction cavity length is RESONANT for 45 MHz

$$\phi_{MRF2} = \frac{2\Omega_2 \ell_M}{c}$$
$$\phi_P \pm \phi_{PRF2} = 0^\circ$$
$$\phi_S \pm \phi_{SRF2} = 0^\circ$$

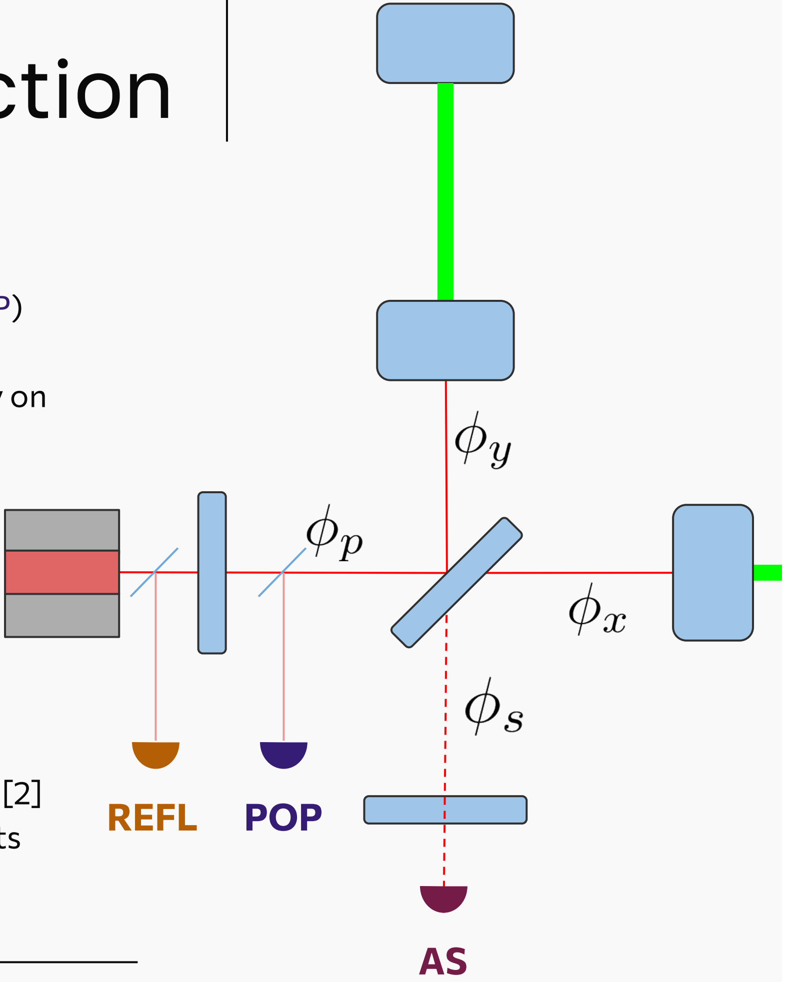
# Current aLIGO Locking Sequence

1. Initial alignment
2. **PRM, SEM** misaligned
3. Arms locked via **green ALS beams**
4. Arms held **off-resonance** for main IR laser frequency
5. **DRMI lock acquisition**:
   **PRM, SEM,** and **BS** aligned and allowed to swing freely. When the correct resonance conditions are triggered, controls are engaged to catch DRMI.



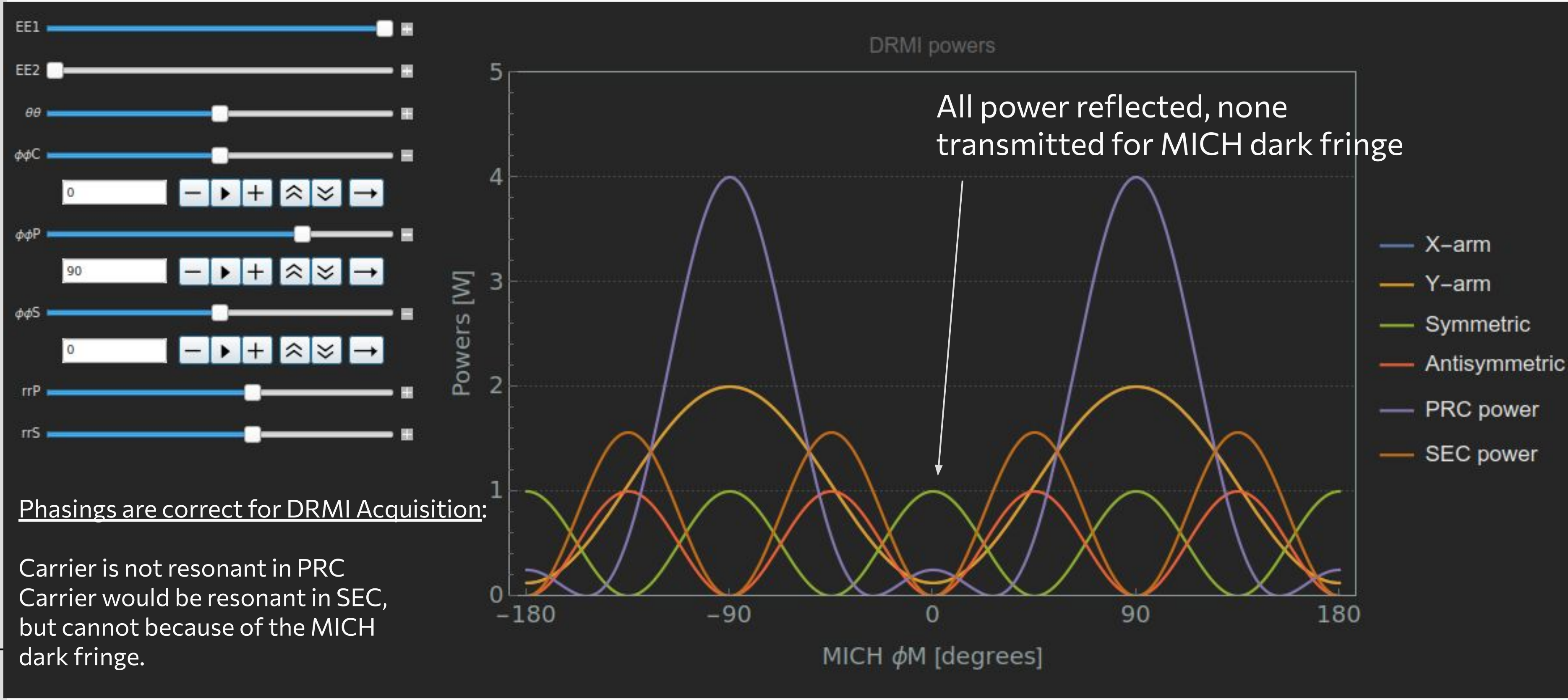
# DRMI Detection

- Main detection ports in aLIGO
  - Reflection port (REFL)
  - Antisymmetric port (AS)
  - Power recycling pick off (POP)
- DRMI acquisition is done on entirely on POP 1f
  - MICH uses POP 45 Q
  - PRCL uses POP 9 I
  - SRCL uses POP 45 I
- Controls are triggered on the **RF Sideband Power Buildups (POP 2f signals)**
  - See Kiwamu's talk from 2014 [2]
  - If **POP18** and **POP90** readouts are high, then sidebands are correctly resonating




| Parameter | Symbol | Value | Units |
|---|---|---|---|
| Main Input Power | $P_{\text{in}}$ | 1 or 0 | W |
| AS Input Power | $P_{\text{as}}$ | 0 or 1 | W |
| Mod Depths | $\Gamma$ | 0.2 | rad |
| PRM Transmission | $T_{\text{prm}}$ | 3.1 | % |
| SEM Transmission | $T_{\text{sem}}$ | 32.3 | % |
| PRC Length | $L_{\text{prm}}$ | 57.659 | m |
| SEC Length | $L_{\text{prm}}$ | 56.009 | m |
| Schnupp Asymmetry | $\ell_{\text{sch}}$ | 4 | cm |
| Mod Freq 1 | $\Omega_1/2\pi$ | 9.1 | MHz |
| Mod Freq 2 | $\Omega_2/2\pi$ | 45.5 | MHz |
| Mod Freq 3 (AS) | $\Omega_3/2\pi$ | 3.12 | MHz |
| MICH Carrier Phase | $\phi_{\text{MICH}}$ | 0 | deg |
| PRCL Carrier Phase | $\phi_{\text{PRCL}}$ | 90 | deg |
| SECL Carrier Phase | $\phi_{\text{SECL}}$ | 0 | deg |
| MICH f1 Phase | $\phi_{\text{MICH,f1}}$ | 0.44 | deg |
| PRCL f1 Phase | $\phi_{\text{PRCL,f1}}$ | 90 | deg |
| SECL f1 Phase | $\phi_{\text{SECL,f1}}$ | 72 | deg |
| MICH f2 Phase | $\phi_{\text{MICH,f2}}$ | 2.19 | deg |
| PRCL f2 Phase | $\phi_{\text{PRCL,f2}}$ | 90 | deg |
| SECL f2 Phase | $\phi_{\text{SECL,f2}}$ | 0 | deg |
| MICH f3 Phase | $\phi_{\text{MICH,f3}}$ | 0.15 | deg |
| PRCL f3 Phase | $\phi_{\text{PRCL,f3}}$ | 36 | deg |
| SECL f3 Phase | $\phi_{\text{SECL,f3}}$ | 30 | deg |

# DRMI Recreated: Power plots

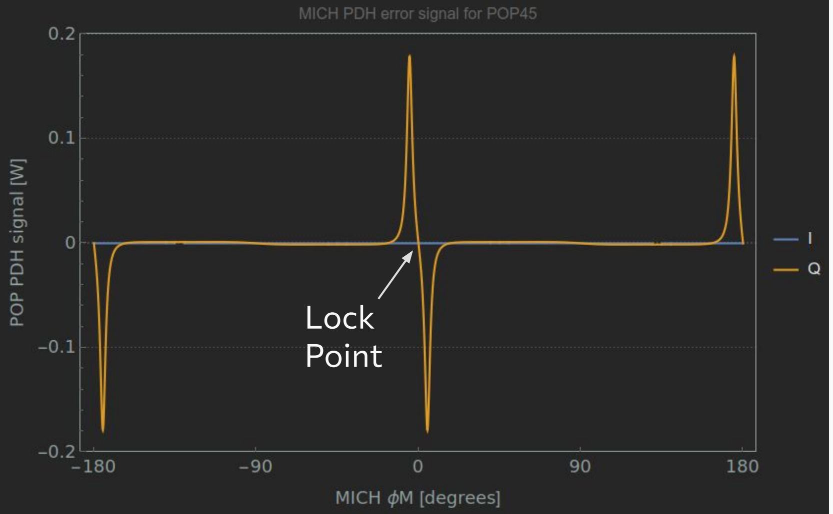


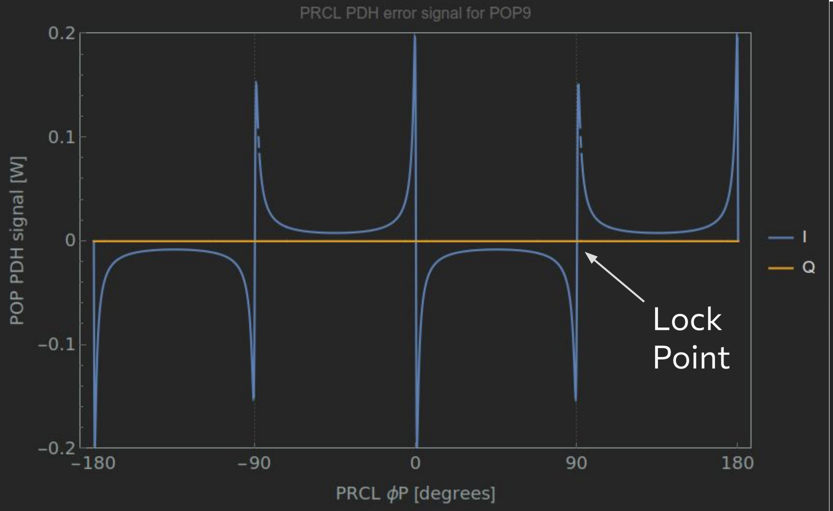

<u>Phasings are correct for DRMI Acquisition</u>:

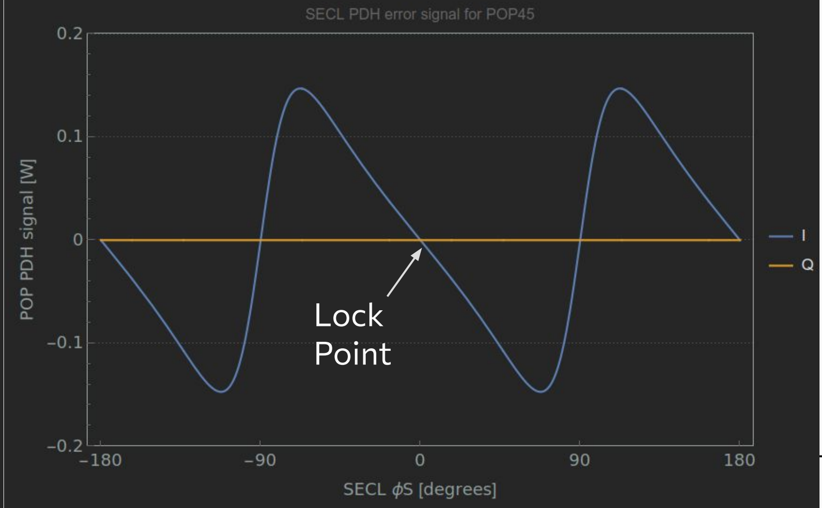
Carrier is not resonant in PRC
Carrier would be resonant in SEC, but cannot because of the MICH dark fringe.

# DRMI Recreated: PDH plots

MICH locked on POP 45 Q at $\phi$M = 0°.
PRCL locked on POP 9 I at $\phi$P = 90°.
SECL locked on POP 45 I at $\phi$S = 0°

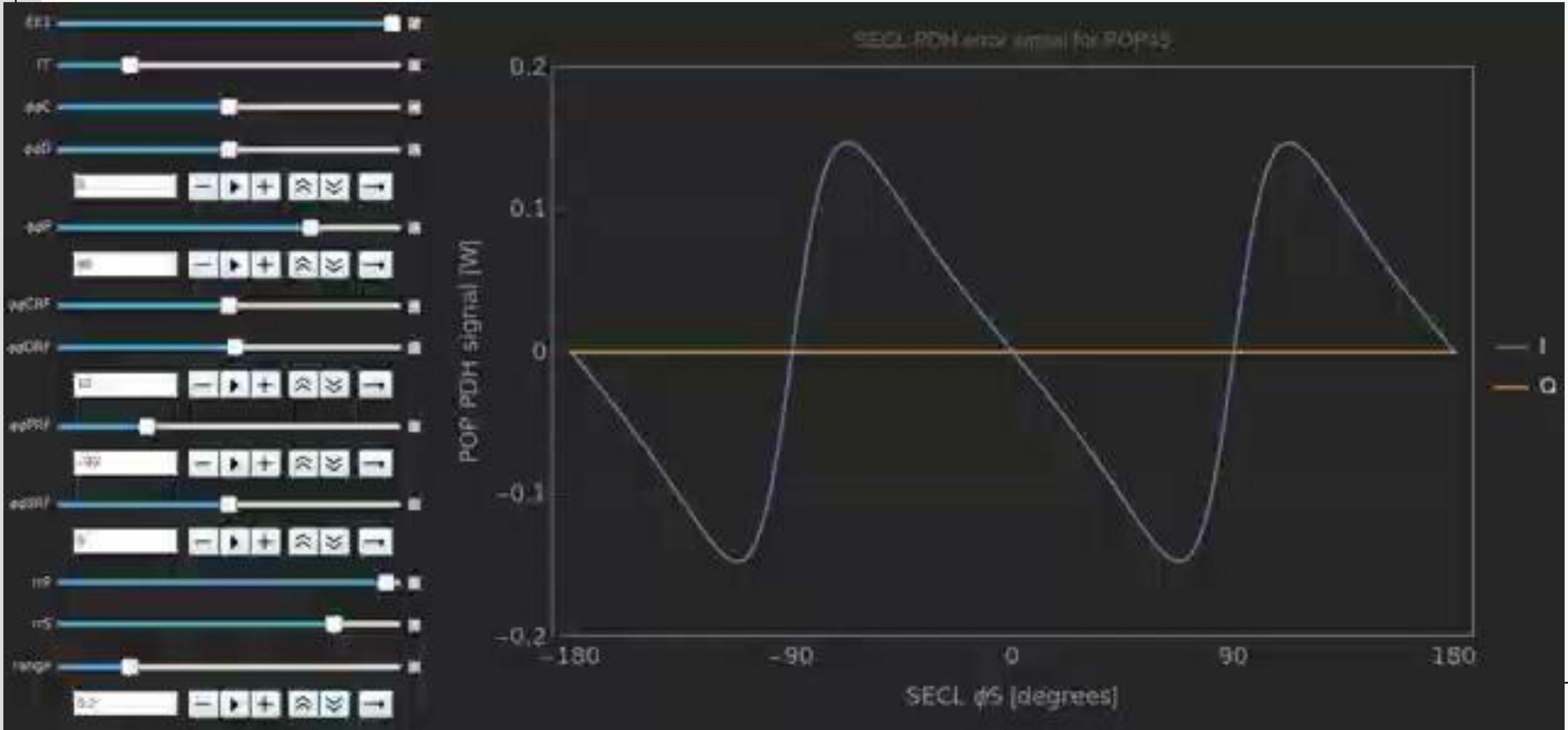


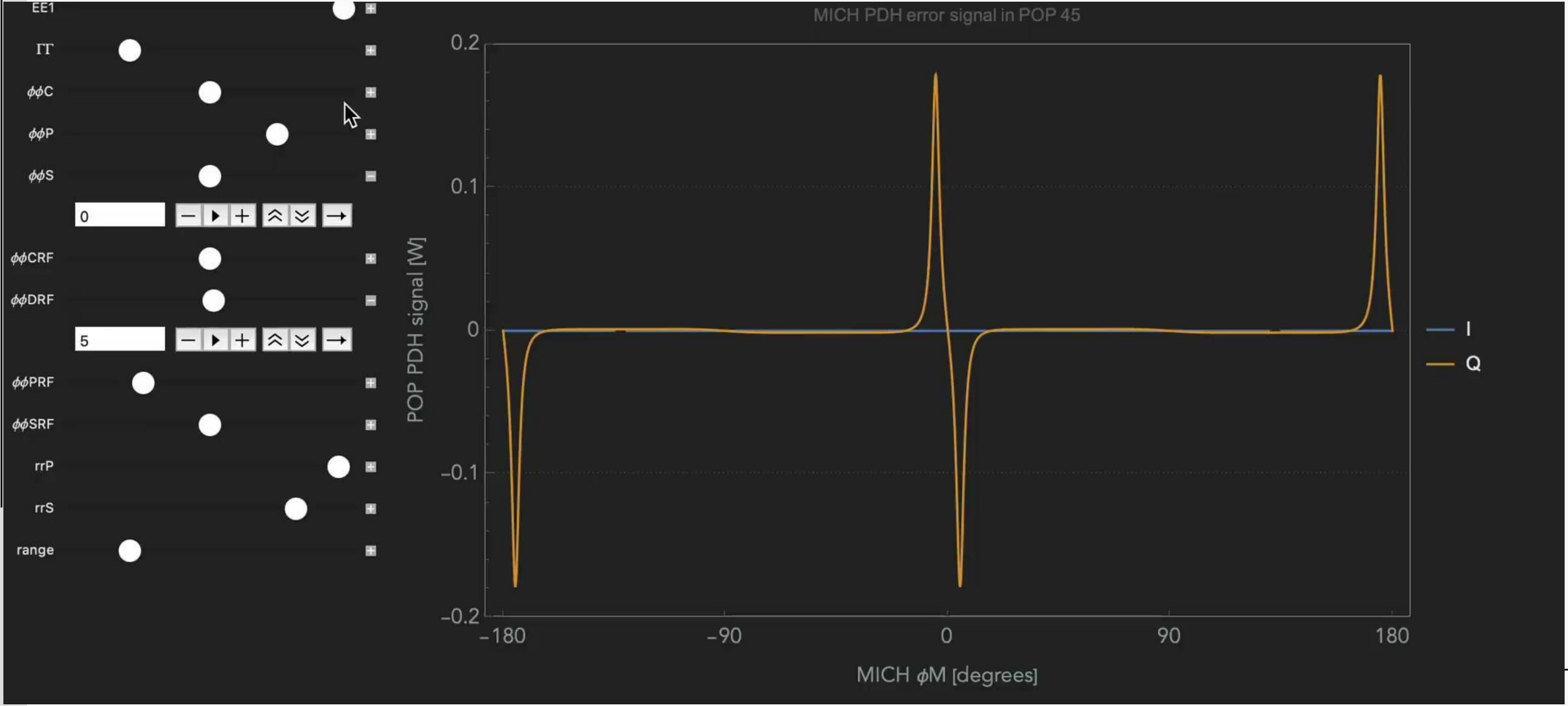
# Problem: PDH error signals sensitive to tuning

Below we examine the SECL error signal while sweeping MICH.  The error signal is unstable.

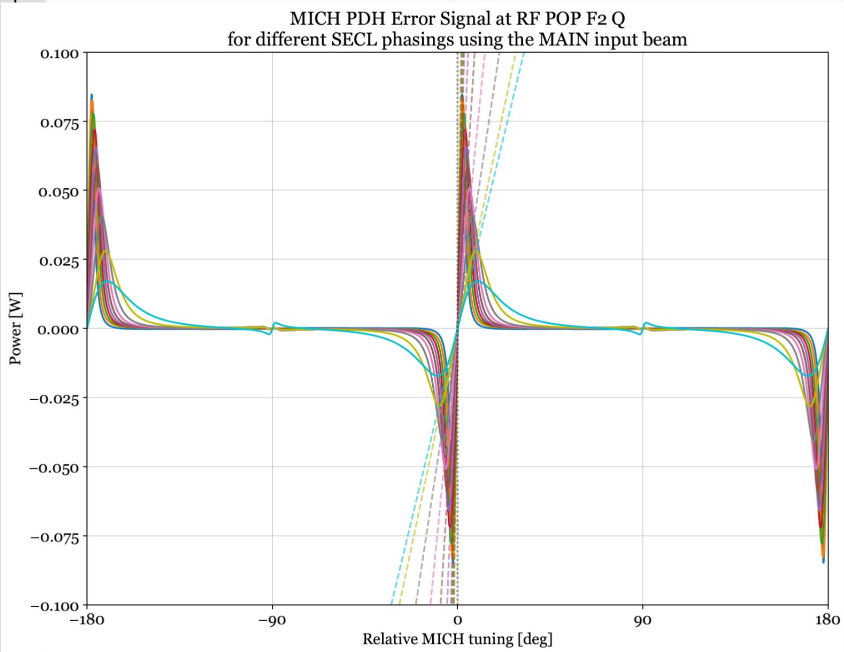


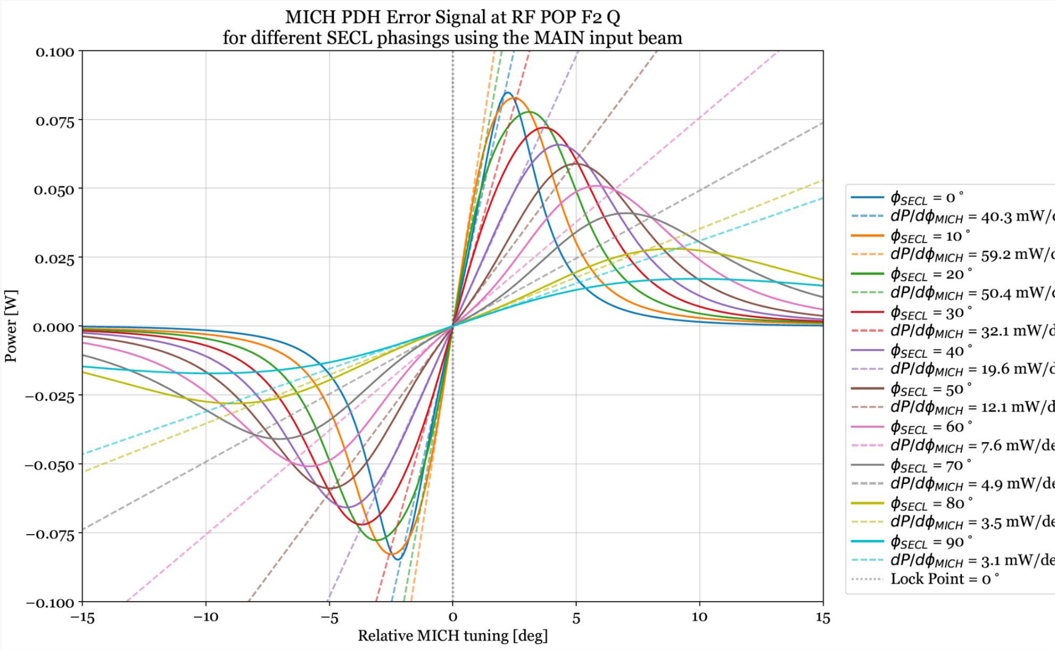
# Solution: Find signals robust to sweeps

Sweeping SECL while looking at the MICH error signal (Advanced LIGO params)

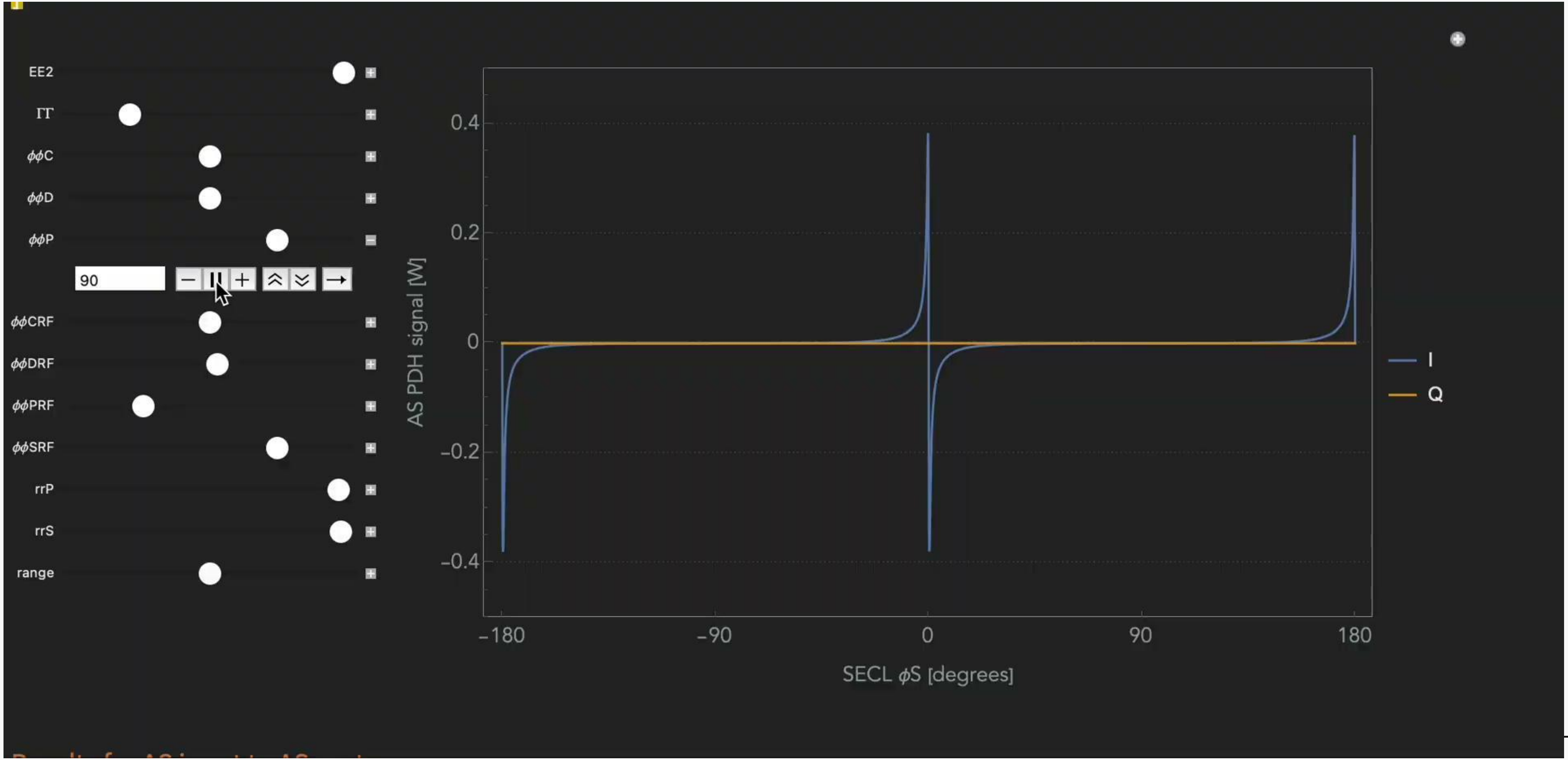


# Gain Scaling



# Using the AS beam in the AS port



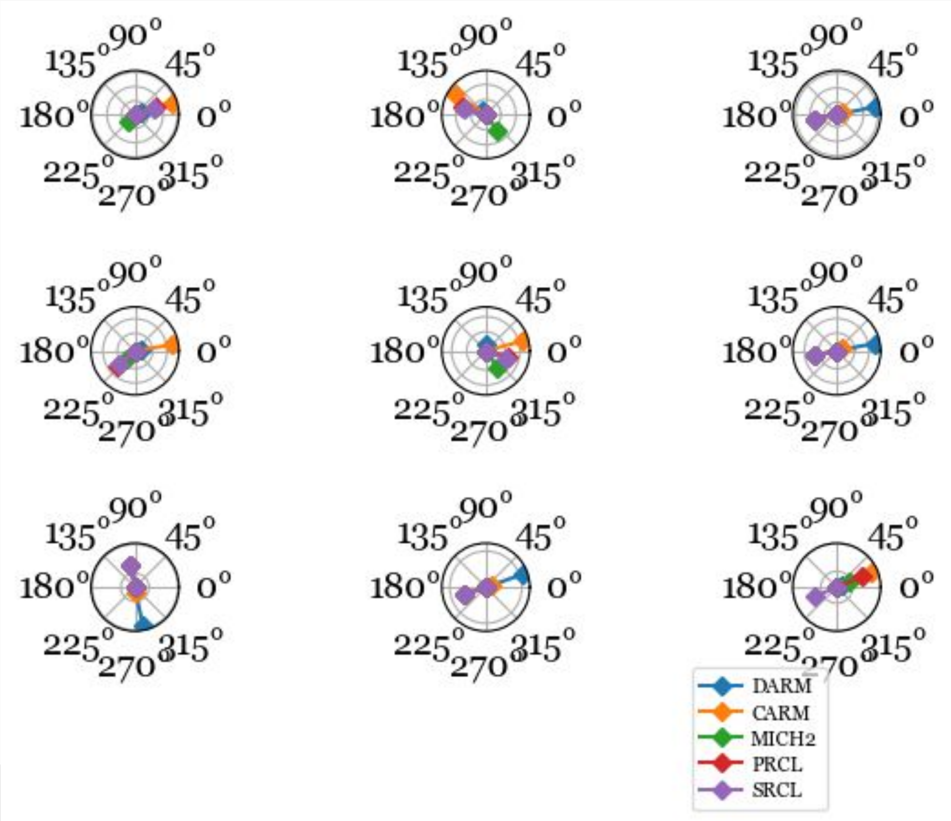
# Sideband Phasors

9 | 45 | 3

REFL

POP

AS



# Future Work

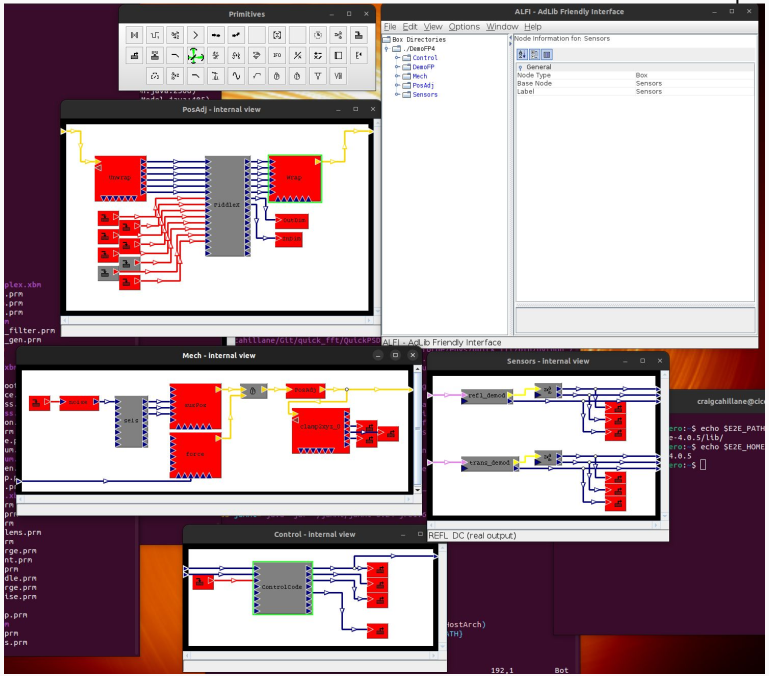
Come up with a complete scheme to lock MICH -> PRMI -> DRMI,
or MICH -> SEMI -> DRMI
without changing PDH optical gains too much.

Homodyne detection?

- Working on a finesse simulation of a simple homodyne detector

Frequency offsets on AS input?

Time Domain simulation?
E2E? Something else?




E2E examples running... but more experience required

# Bibliography


[1] Sigg et. al *Signal extraction in a power-recycled Michelson interferometer with Fabry–Perot arm cavities by use of a multiple-carrier frontal modulation scheme* https://opg.optica.org/ao/fulltext.cfm?uri=ao-37-24-5687&id=60592

[2] Izumi on behalf of LLO O1 commissioning *Notes on DRMI locking at LLO* https://dcc.ligo.org/public/0114/G1400785/001/G1400785_v1_DRMIatLLO.pdf

[3] Muller et. al *Dual-recycled cavity-enhanced Michelson interferometer for gravitational-wave detection* https://opg.optica.org/ao/fulltext.cfm?uri=ao-42-7-1257&id=71366

[4] Strain et. al *Sensing and control in dual-recycling laser interferometer gravitational-wave detectors* https://opg.optica.org/ao/fulltext.cfm?uri=ao-42-7-1244&id=71365

[5] Evans et. al *Lock acquisition of a gravitational-wave interferometer* https://opg.optica.org/ol/fulltext.cfm?uri=ol-27-8-598&id=68542

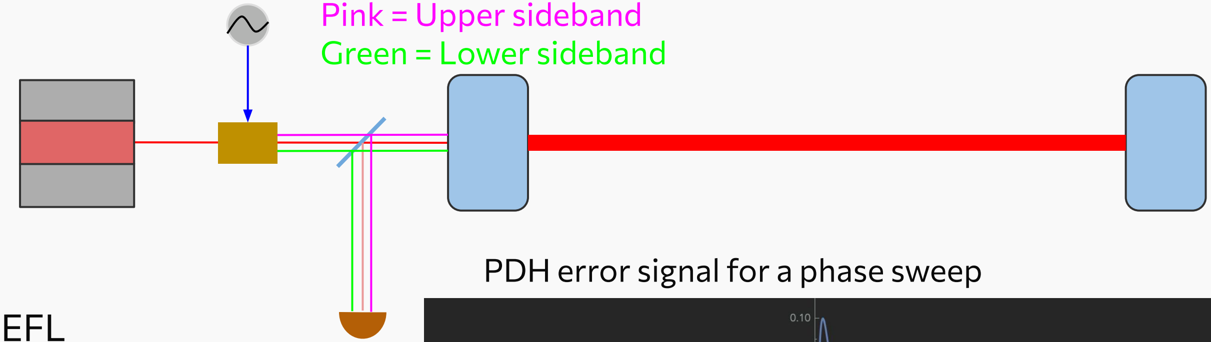
[6] Regehr et. al *Demonstration of a power-recycled Michelson interferometer with Fabry–Perot arms by frontal modulation* https://opg.optica.org/ol/fulltext.cfm?uri=ol-20-13-1507&id=34501

# Extra Slides

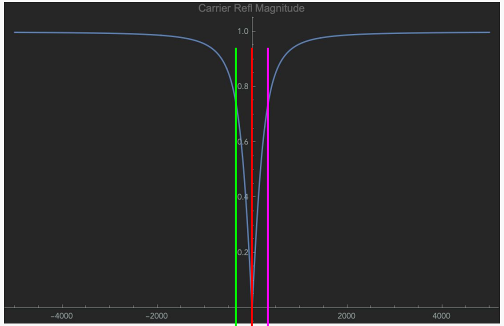
# Fabry-Perot PDH frequency locking

Create phase-modulated RF sidebands on the input.
Use RF sidebands as a stable, independent reference

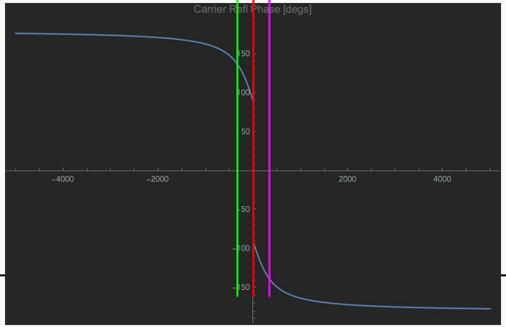
Red = Carrier laser beam
Pink = Upper sideband
Green = Lower sideband



REFL



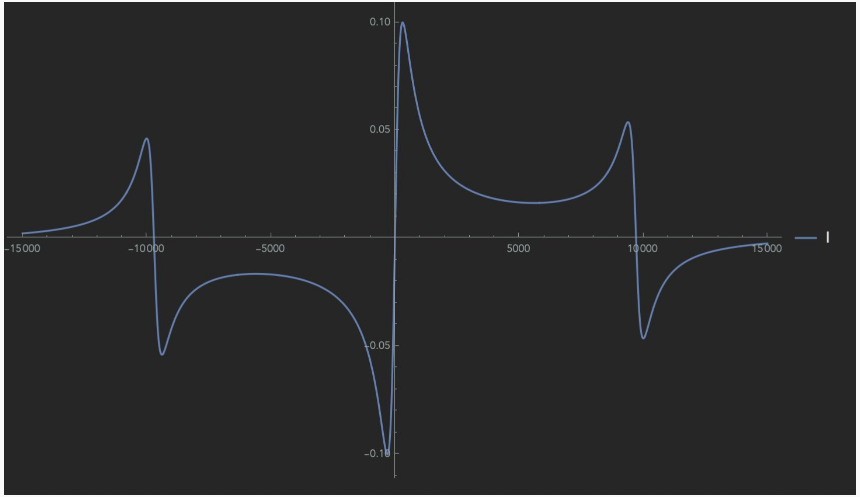

REFL
Magnitude




REFL
Phase

PDH error signal for a phase sweep

Power [W]




Laser frequency sweep [Hz]