Interferometer control of KAGRA

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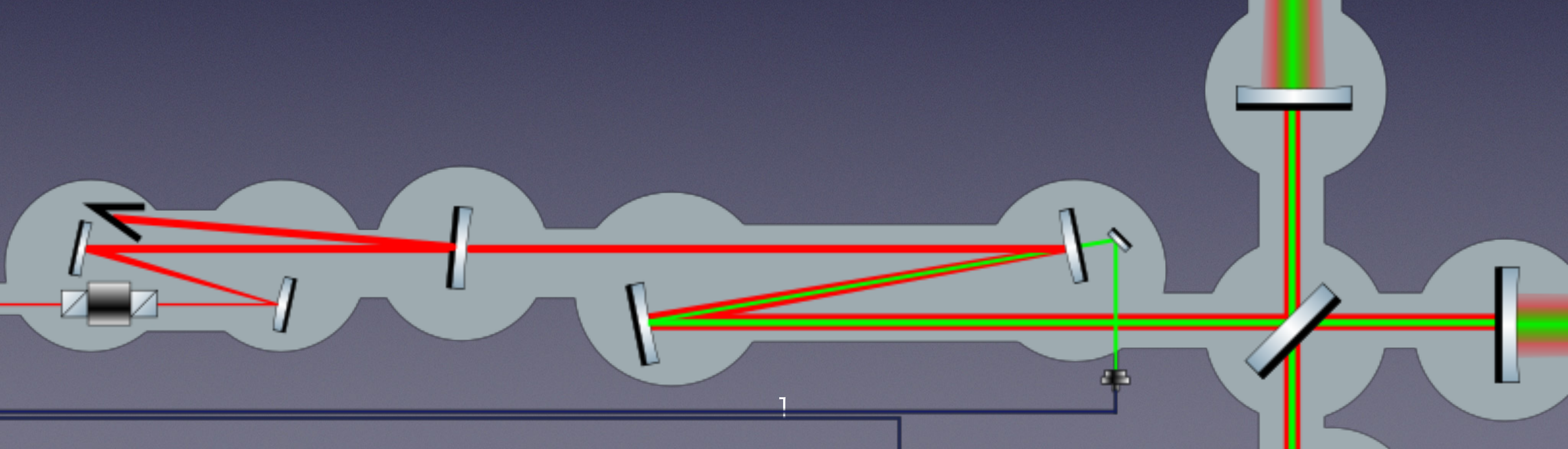

- Gravitational wave detector
- Control of the interferometer
- Experimental result:
  Status of KAGRA interferometer
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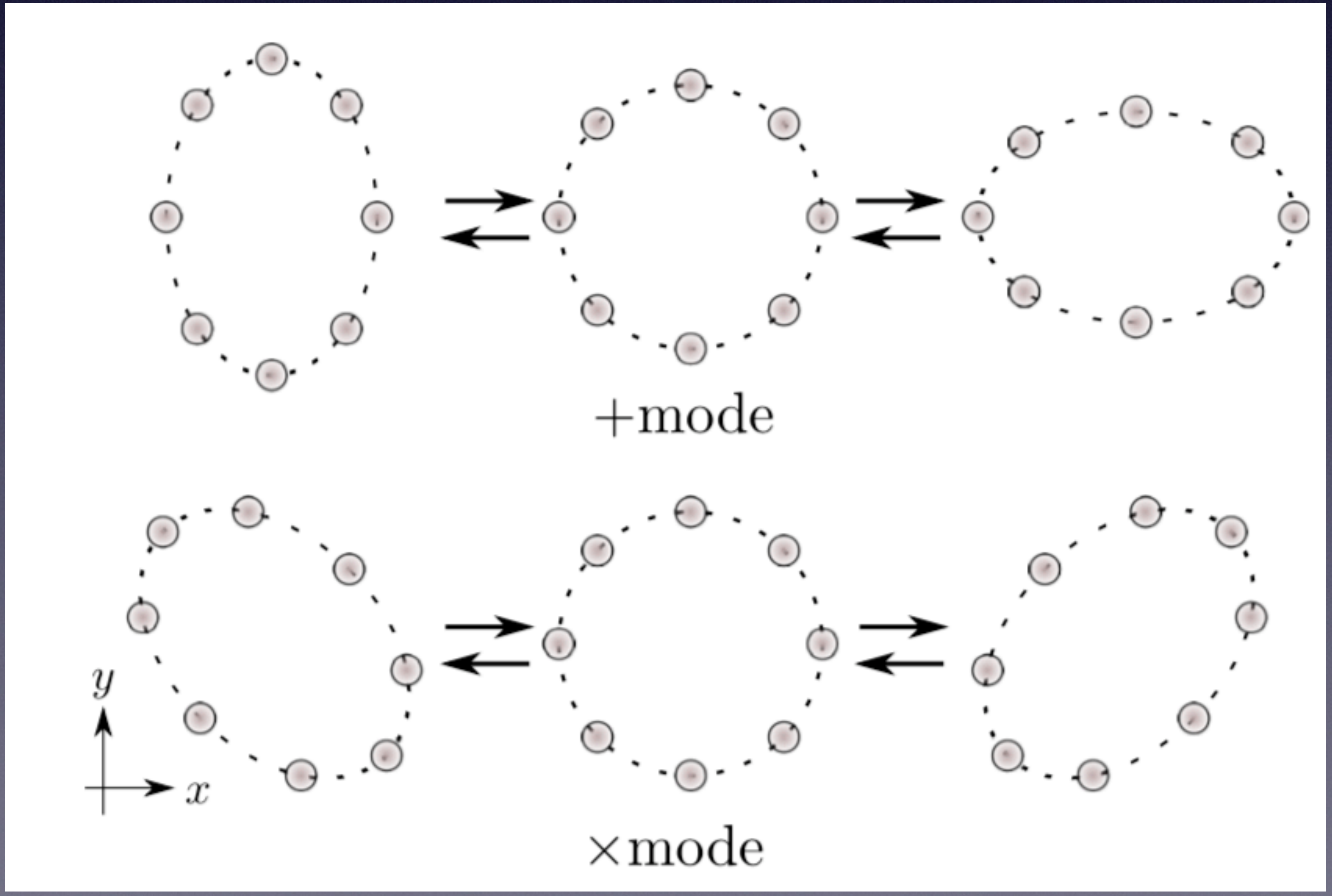
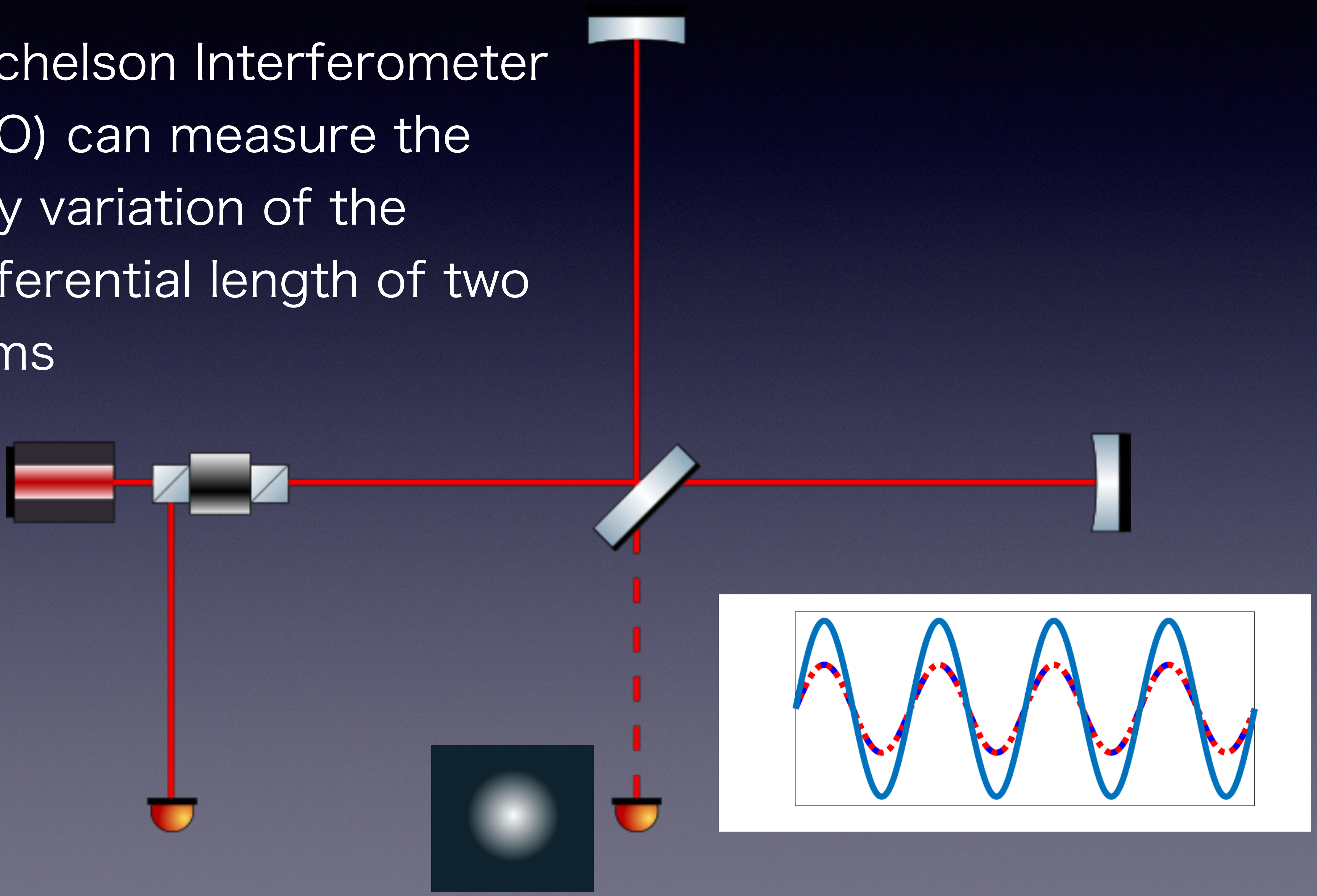
Gravitational Wave

- Gravitational wave:
  Cause variation of the distance between free-falling masses.



Gravitational wave detector

- Michelson Interferometer (IFO) can measure the tiny variation of the differential length of two arms



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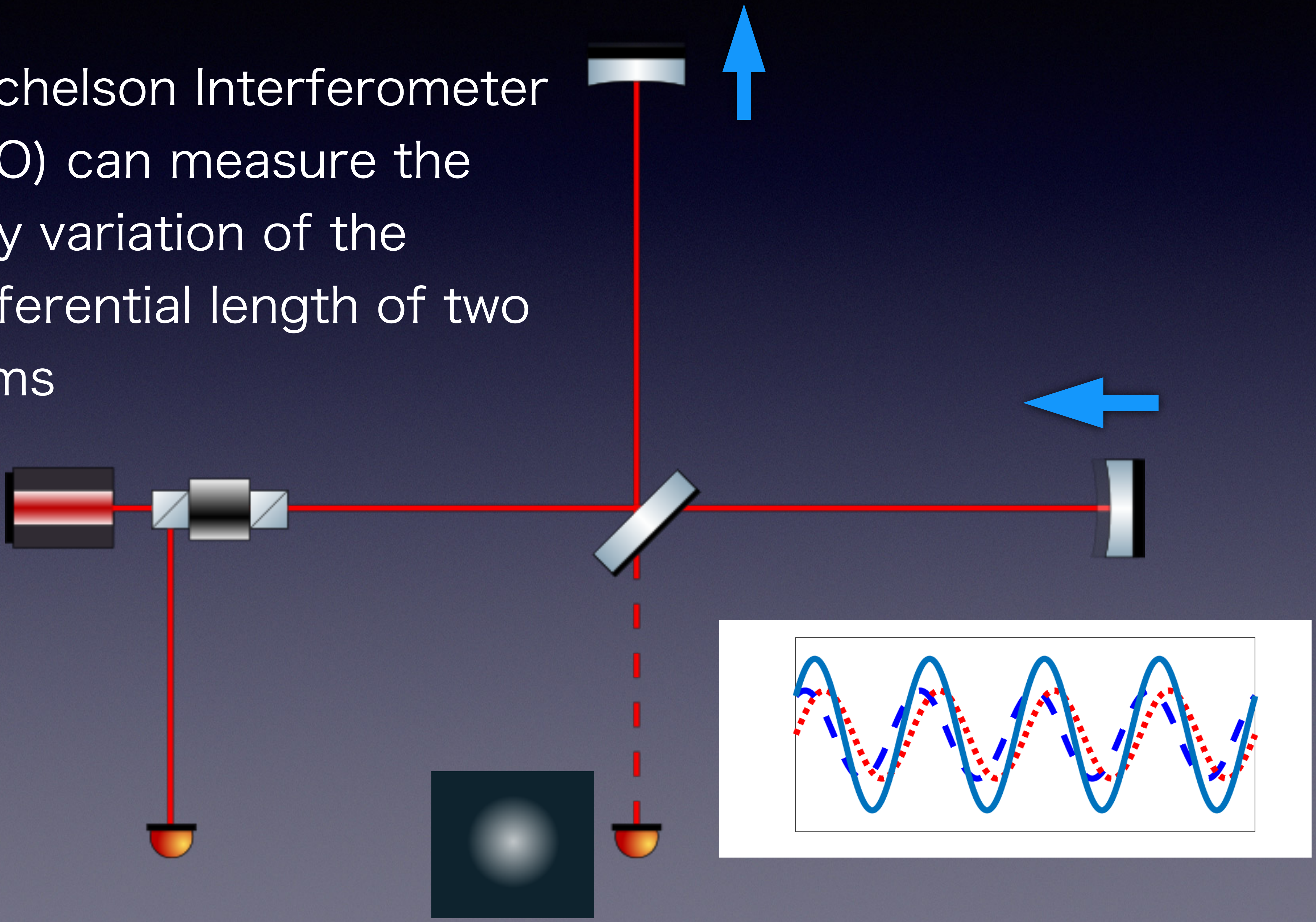

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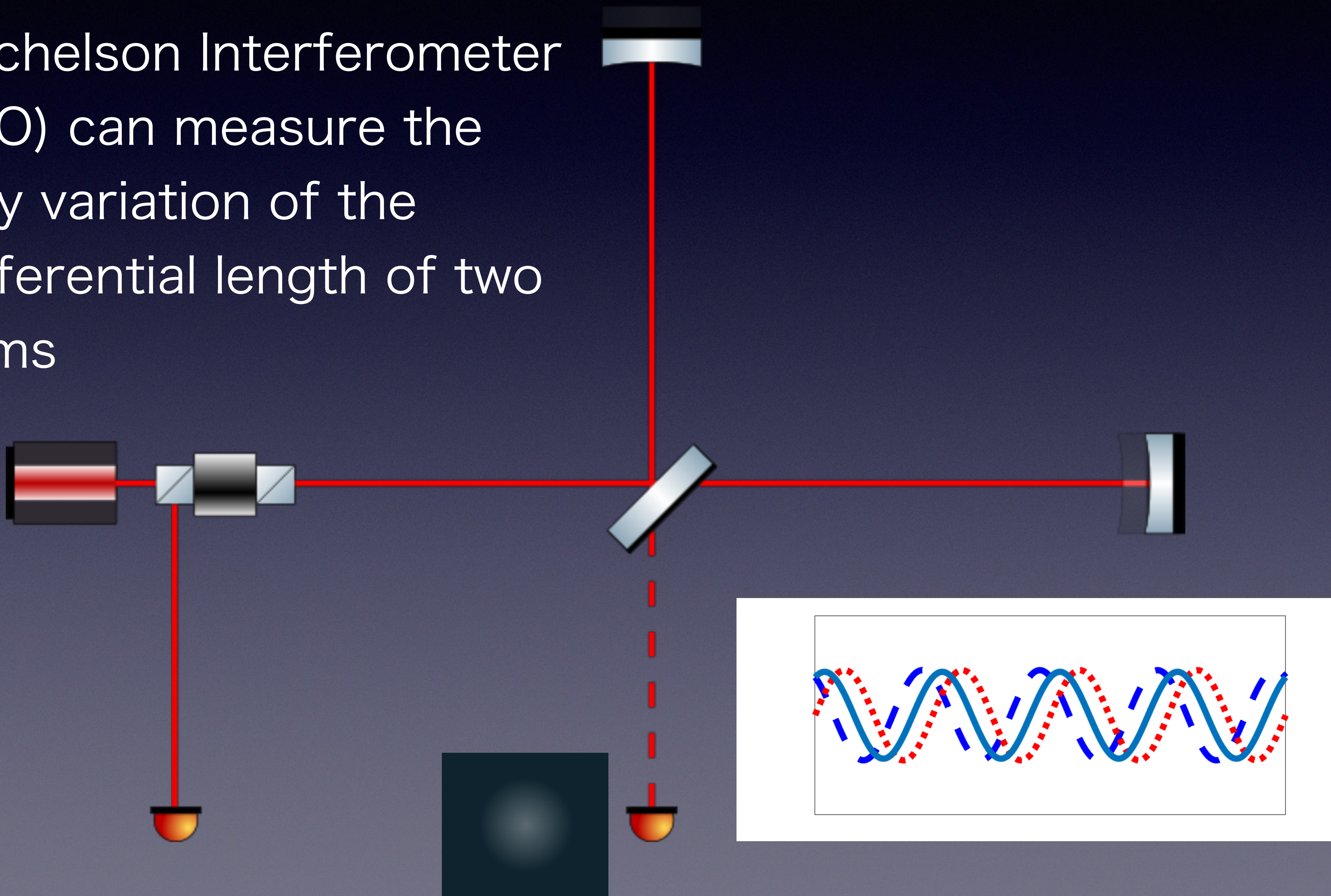

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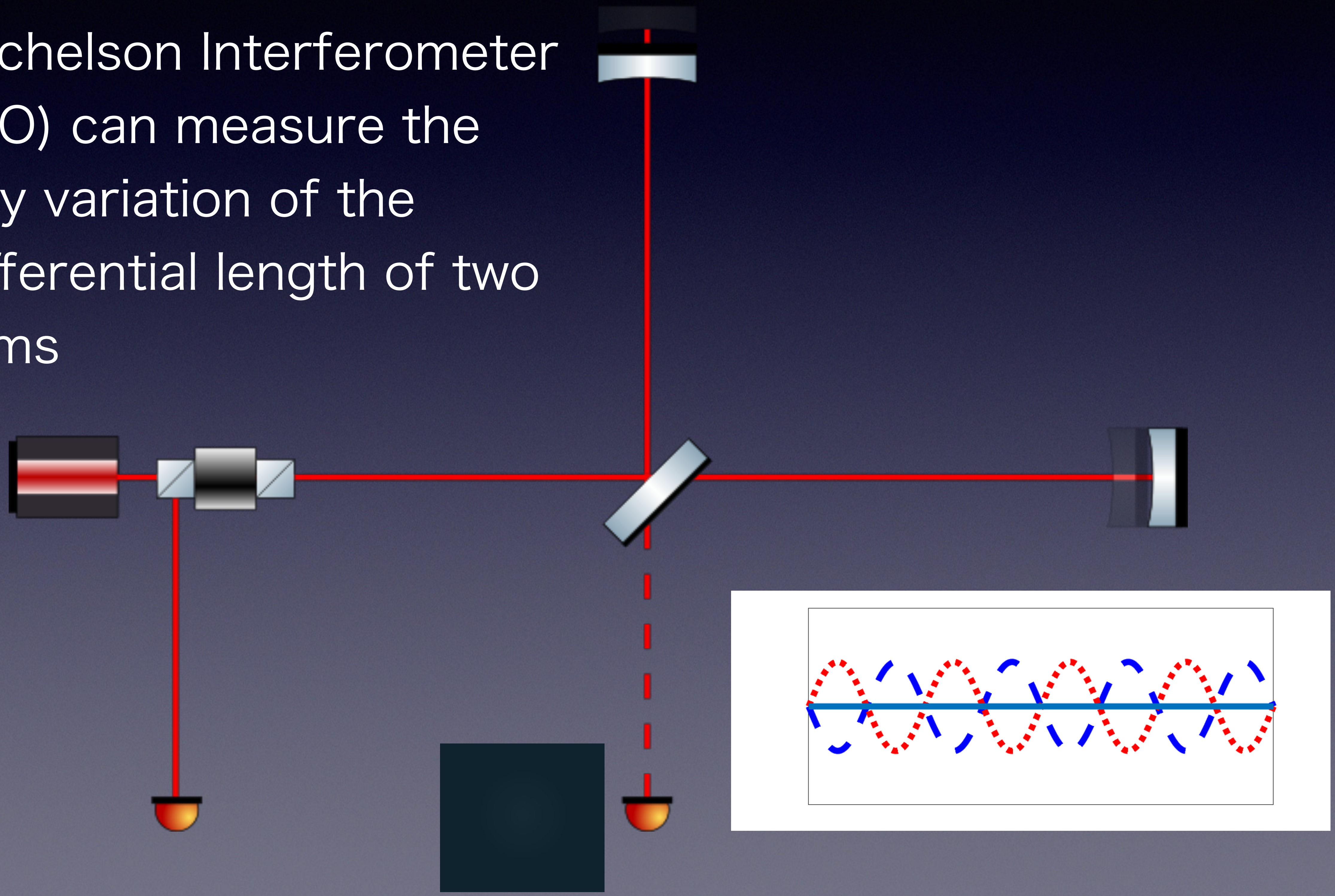
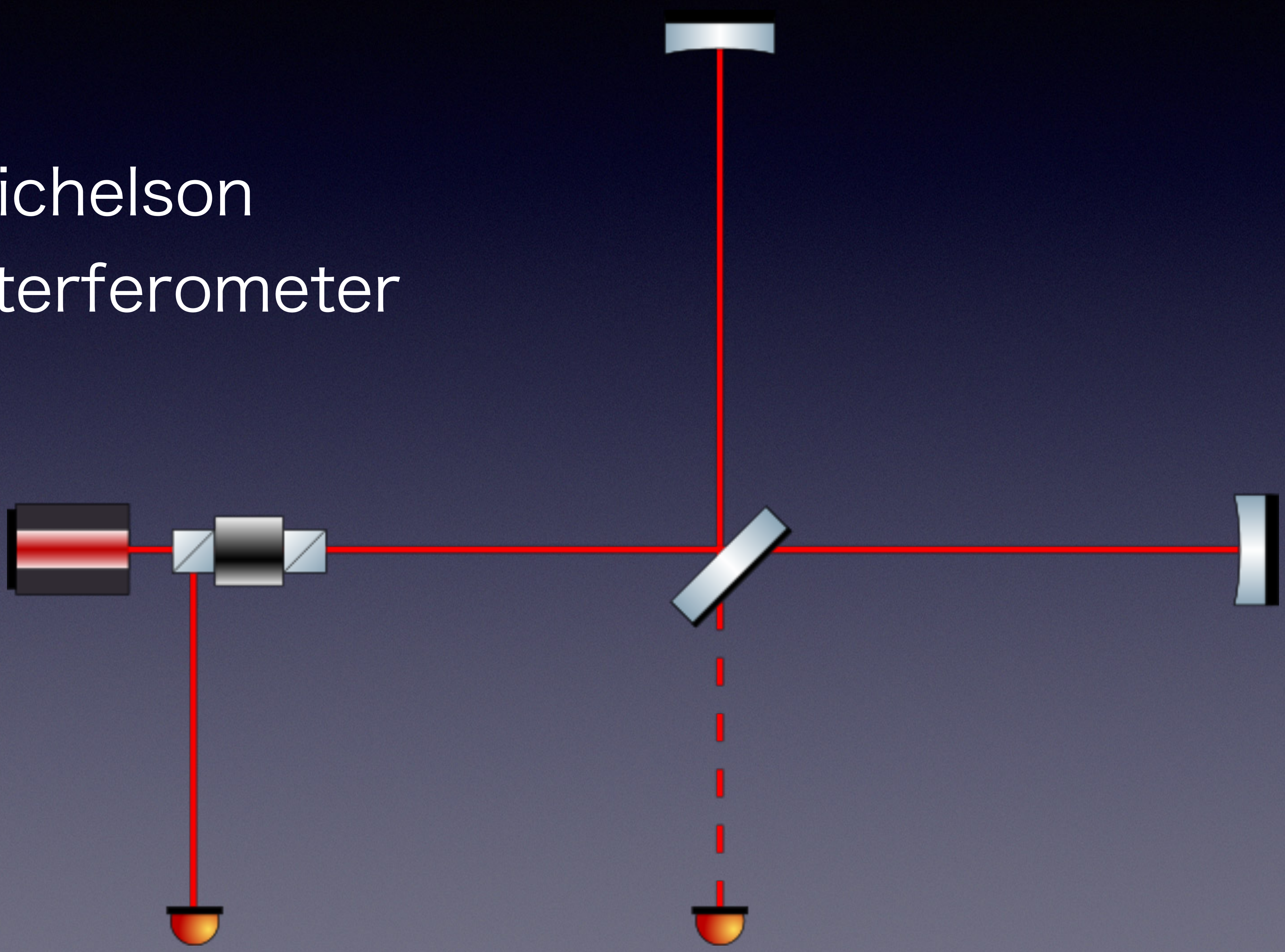


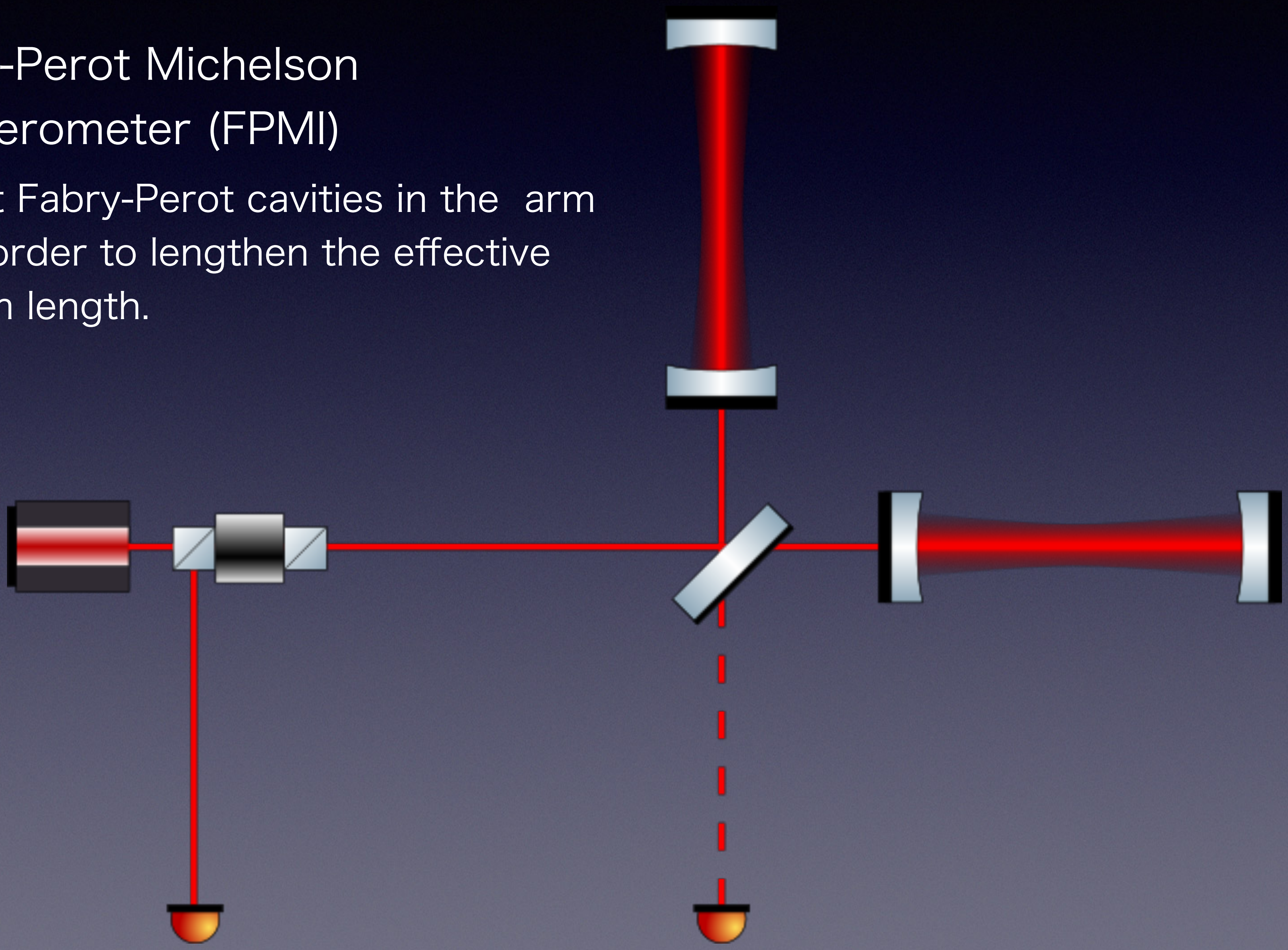
IFO configuration

- Michelson interferometer



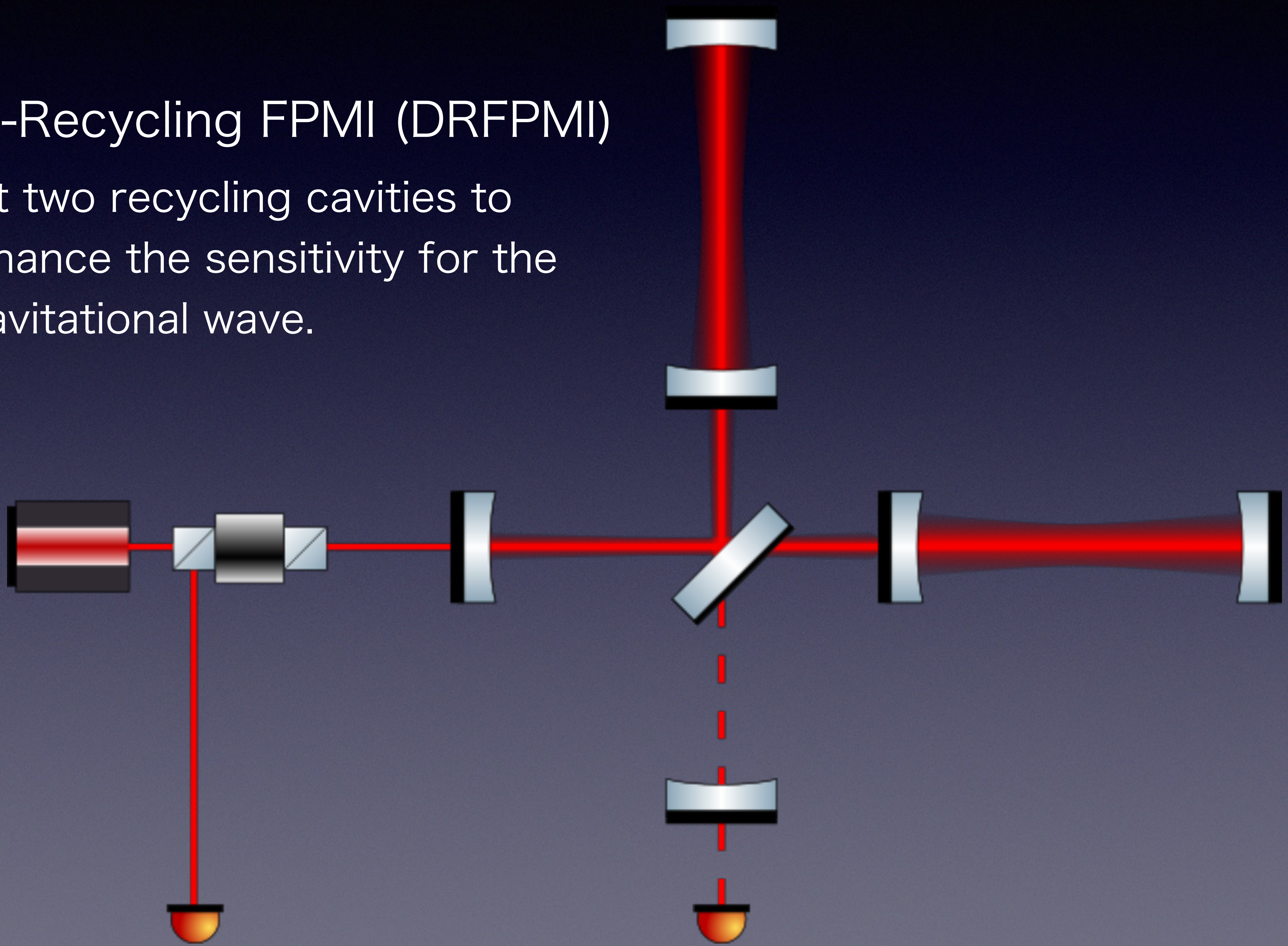
IFO configuration

- Fabry-Perot Michelson Interferometer (FPMI)
  - ➡ Put Fabry-Perot cavities in the arm in order to lengthen the effective arm length.



IFO configuration

- Dural-Recycling FPMI (DRFPMI)
  - ➡ Put two recycling cavities to enhance the sensitivity for the gravitational wave.



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IFO control

- The GW detector is an IFO composed of multiple optical cavities.

➡ All of them needs to be ‘locked’ on the resonance.

➡ The IFO has five degree-of-freedoms (DoFs) in length needed to be controlled.

IFO DoFs

For arm cavities:

Common arm length (DARM): (Lx + Ly)/2

Differential arm length (CARM): (Lx + Ly)/2

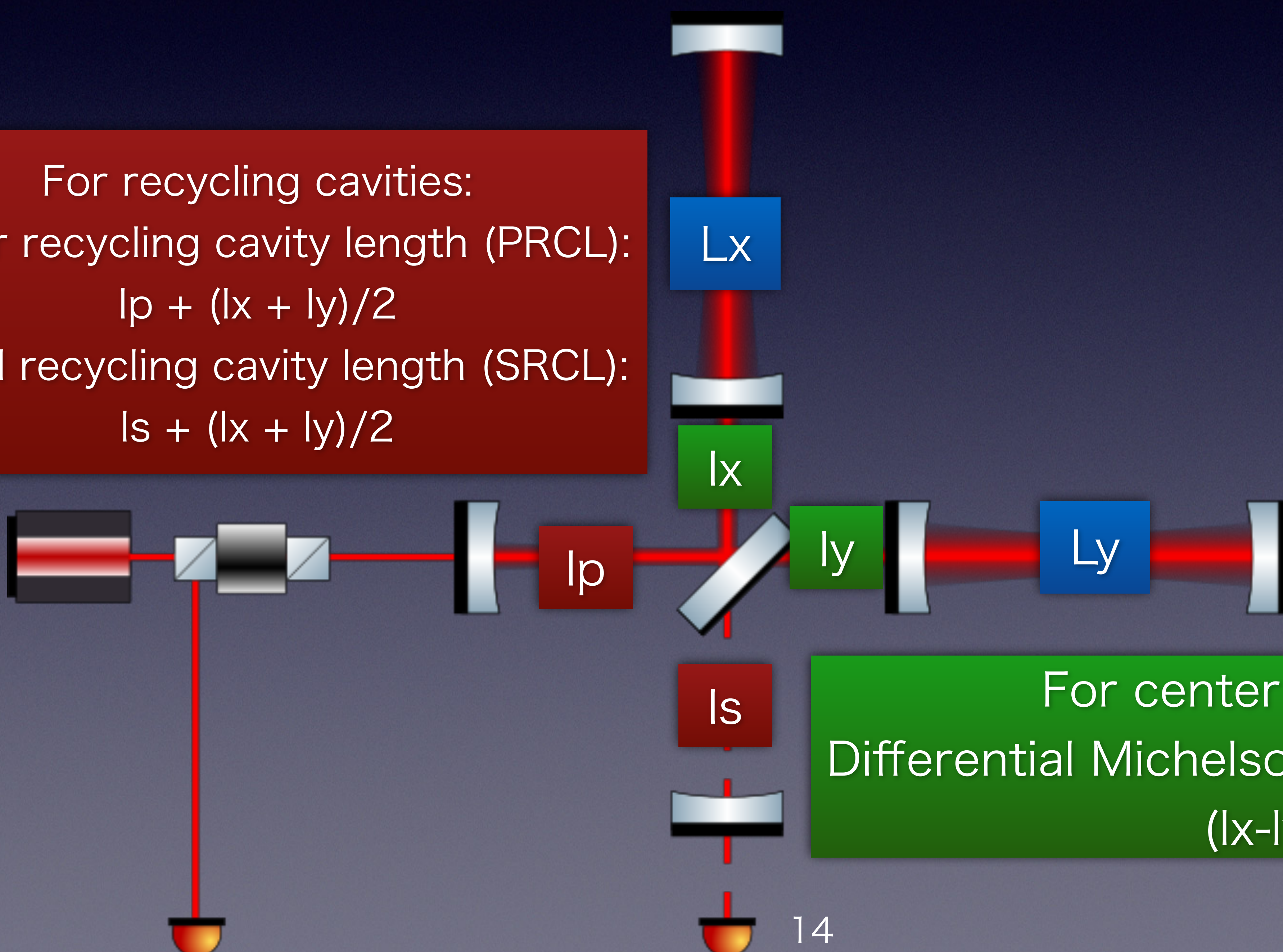
For recycling cavities:

Power recycling cavity length (PRCL):

lp + (lx + ly)/2

Signal recycling cavity length (SRCL):

ls + (lx + ly)/2



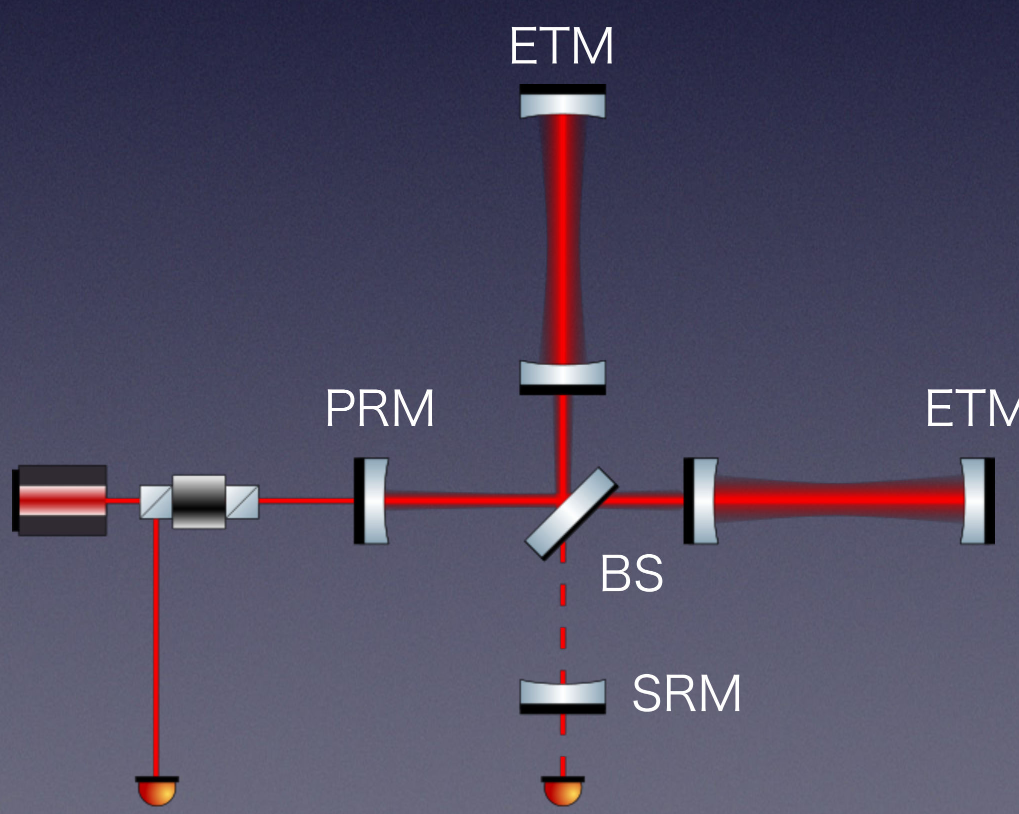
For center Michelson:

Differential Michelson arm length(MICH):

(lx-ly)/2

Actuators

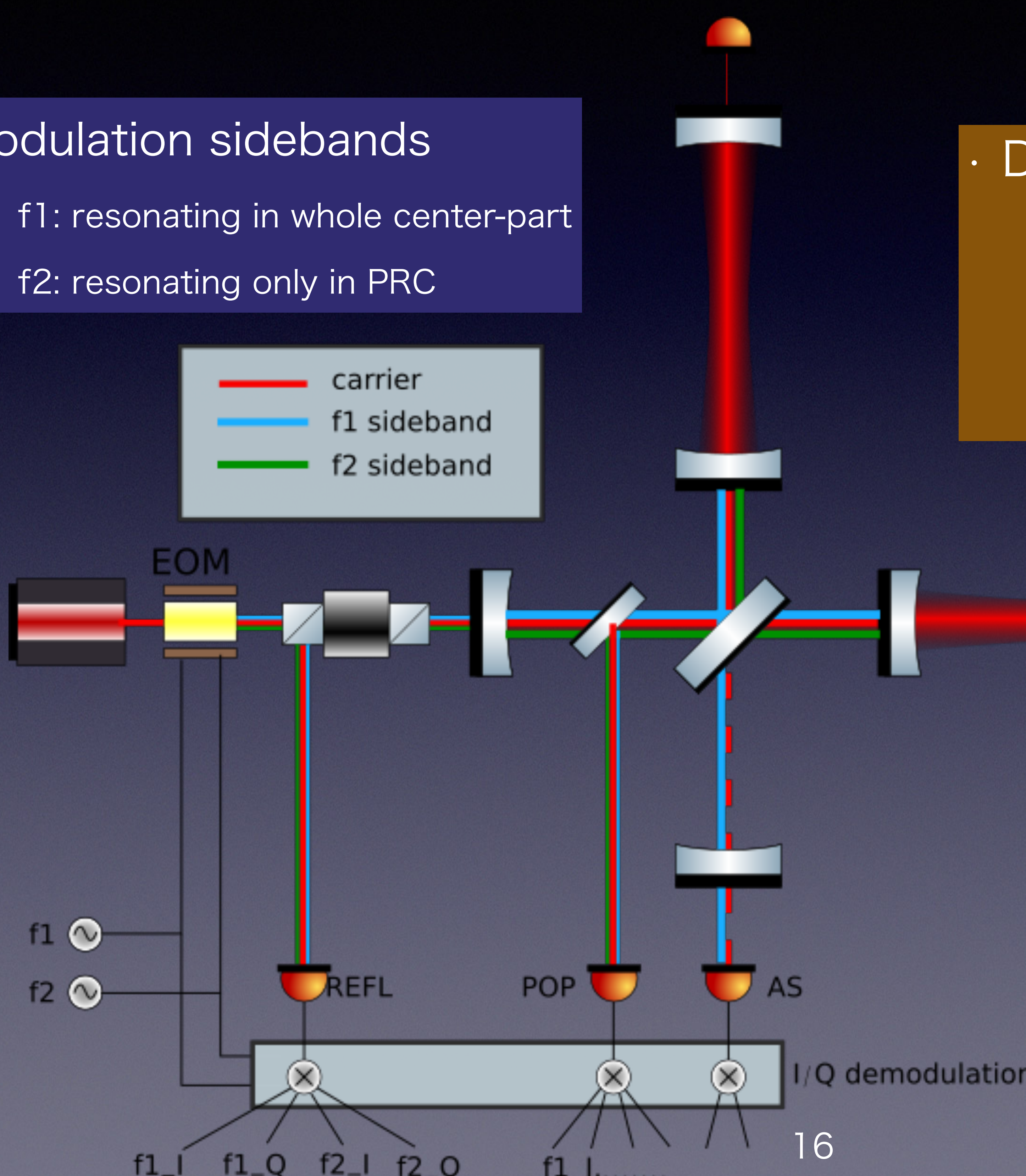
- All mirrors for the IFO are suspend and can be actuated by using coil-magnet actuators.
- The laser frequency can be also actuated.
- Actuators for each DoF:
  - ✓ CARM : the laser frequency
  - ✓ DARM : One of end test mass(ETM)
  - ✓ MICH : The beam splitter
  - ✓ SRCL : The power recycling mirror
  - ✓ PRCL : The signal recycling mirror



Sensors

- Modulation sidebands
  - f1: resonating in whole center-part
  - f2: resonating only in PRC

- DC photo detectors
  - Anti-symmetric port(AS)
  - Transmission monitor in both end stations



- RF photo detectors
  - Reflection port (REFL), pick-off port in PRC (POP), and anti-symmetric port(AS)
  - Each PD signals demodulated with f1 and f2 of orthogonal phases. (only for f1 in AS)

Lock acquisition

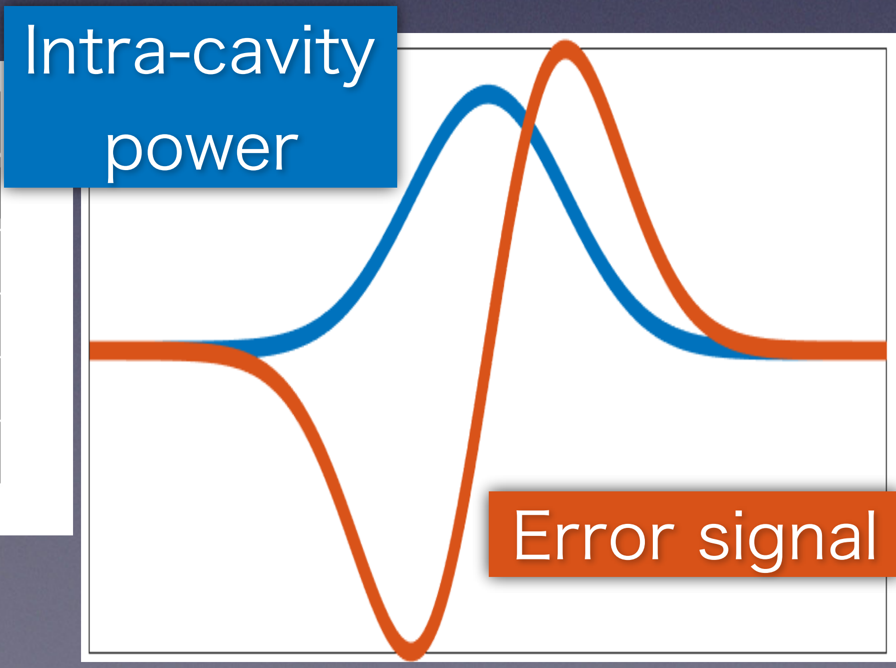
- The signal from the sensors are not well diagonalized.
- Also, their linear range of the error signal is limited around the resonance.
- Therefore, we need to establish the lock acquisition procedure to operate the full interferometer.

➡ We use several auxiliary signals during the lock acquisition. (ex. Transmission PD signal, normalized RF PD signal, demodulated by triple of modulation frequency, and so on)

➡ In future, we will generate the third modulation sideband which does not enter any cavity.

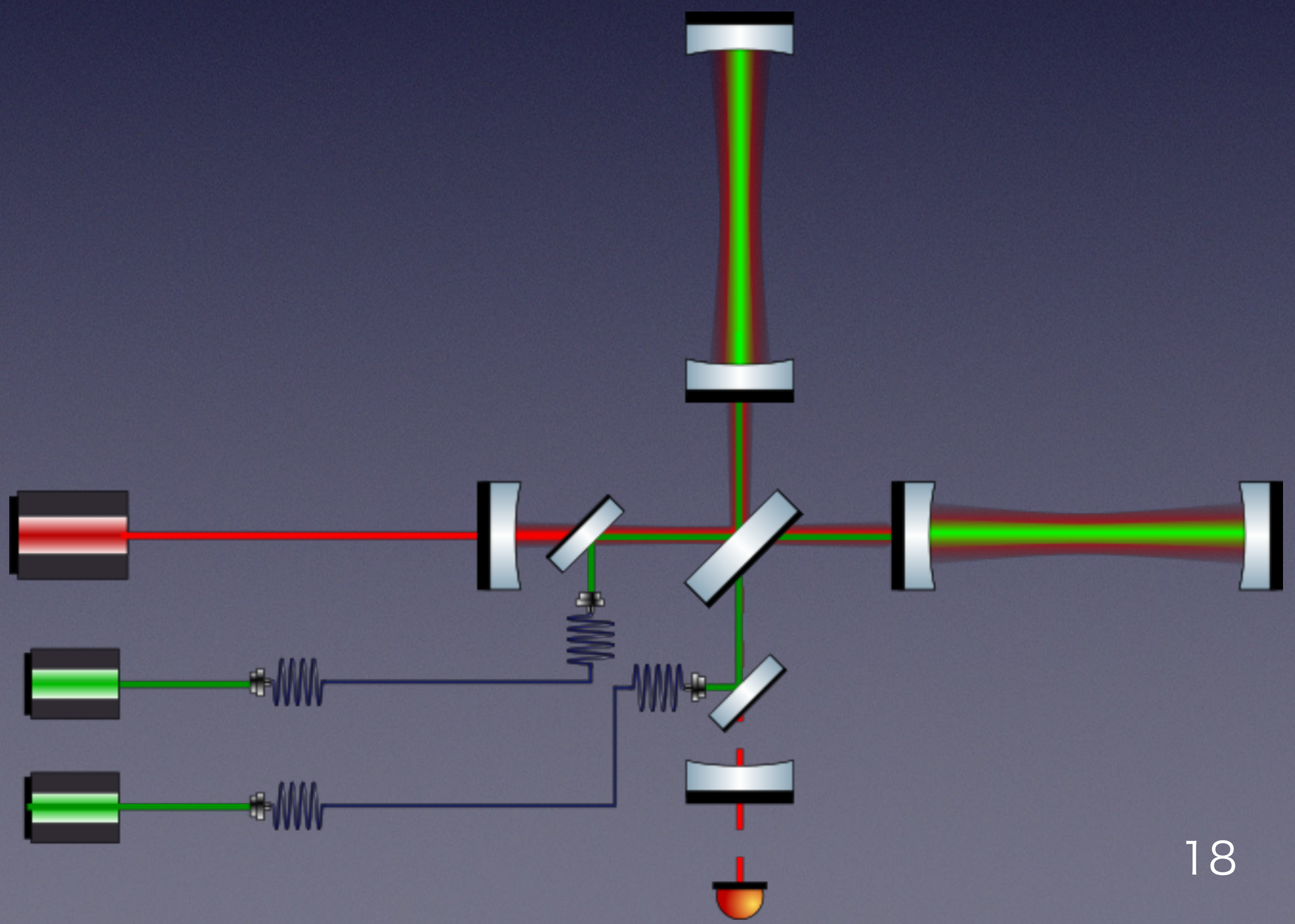
	DARM	**CARM**	**MICH**	**PRCL**	**SRCL**
AS_DC	1.0	3.3×10^{-6}	7.2×10^{-4}	1.8×10^{-7}	5.0×10^{-5}
REFL_1I	9.6×10^{-3}	1.0	5.0×10^{-3}	6.2×10^{-2}	3.0×10^{-2}
REFL_1Q	7.1×10^{-3}	2.6×10^{-4}	1.0	8.5×10^{-2}	2.5×10^{-2}
POP_2I	5.4×10^{-2}	5.7	1.8×10^{-2}	1.0	2.7×10^{-4}
POP_1I	1.8×10^{-1}	19.0	1.1×10^{-1}	2.1	1.0

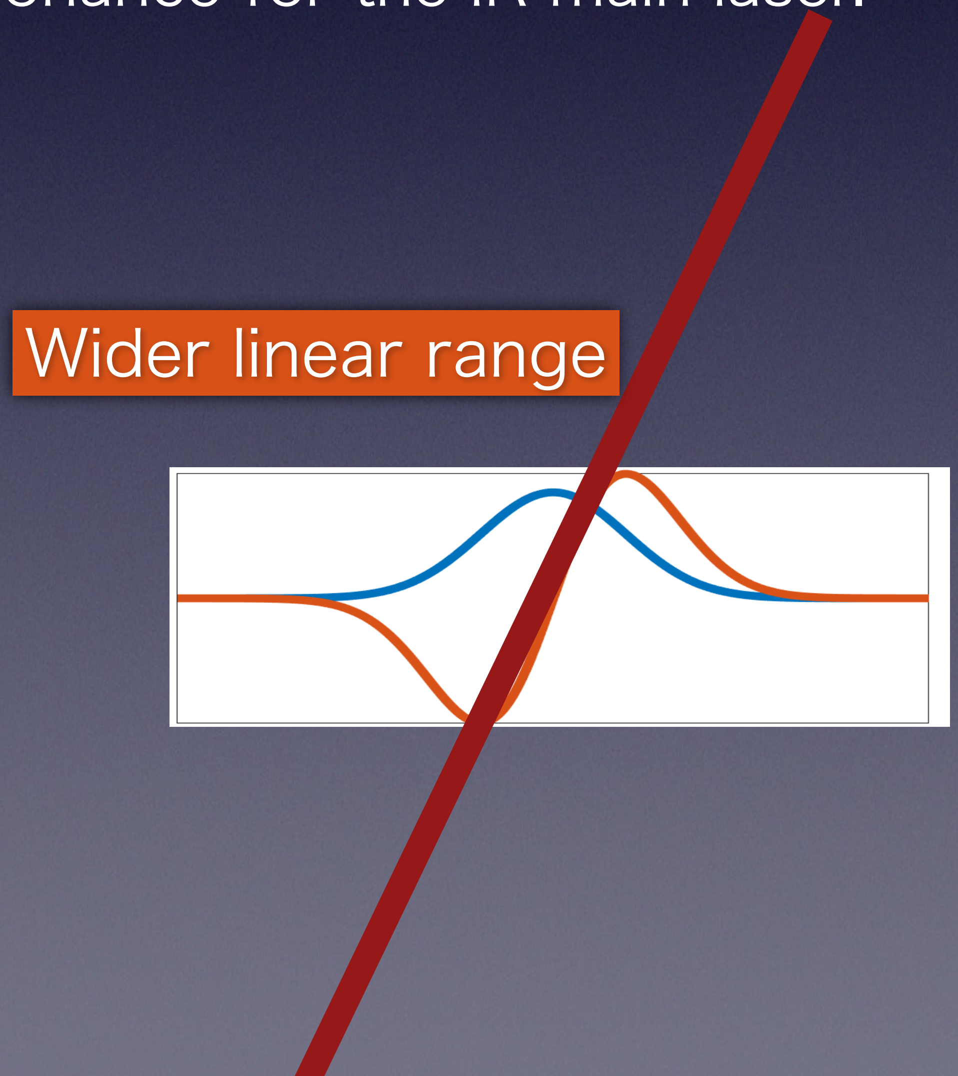
Sensing matrix for each DoF [1]



Arm length stabilization

- We are using the auxiliary laser to utilize the wider linear range length sensor.
  - ➡ Main and aux. Laser are phase locked each other, and the aux. laser lock to the cavity resonance.
  - ➡ Then we can obtain the relative fluctuation between the main laser frequency and the cavity resonance.
- We can control the arm cavity length independently from other DoFs, and even hold the arm cavities on the off-resonance for the IR main laser.





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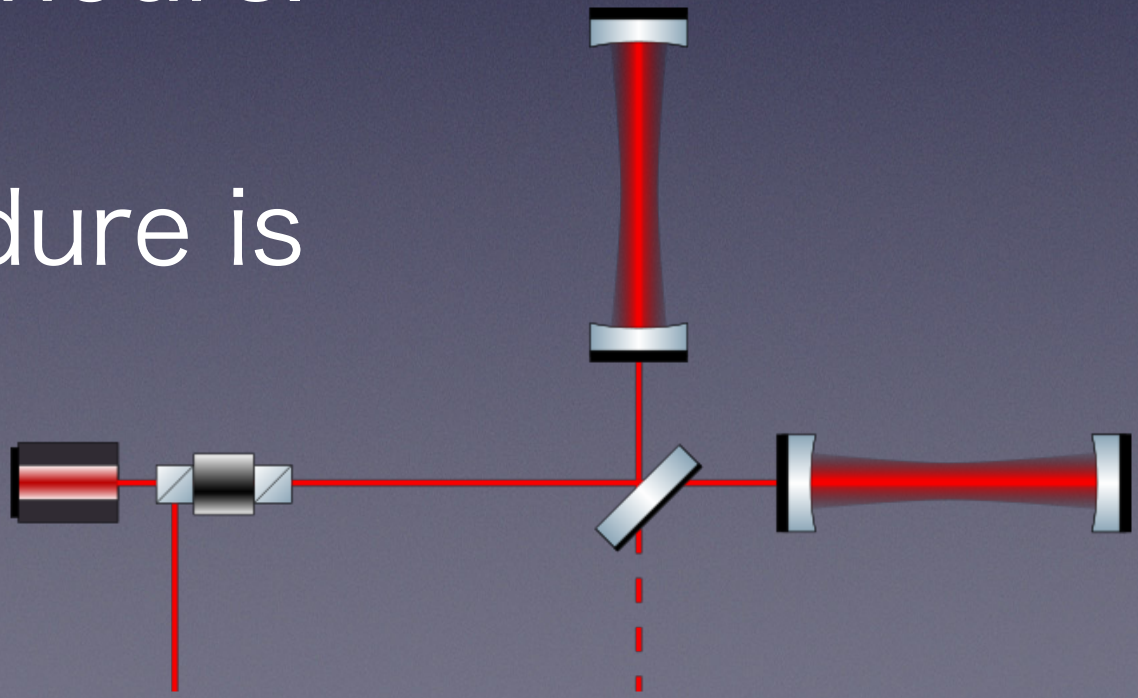
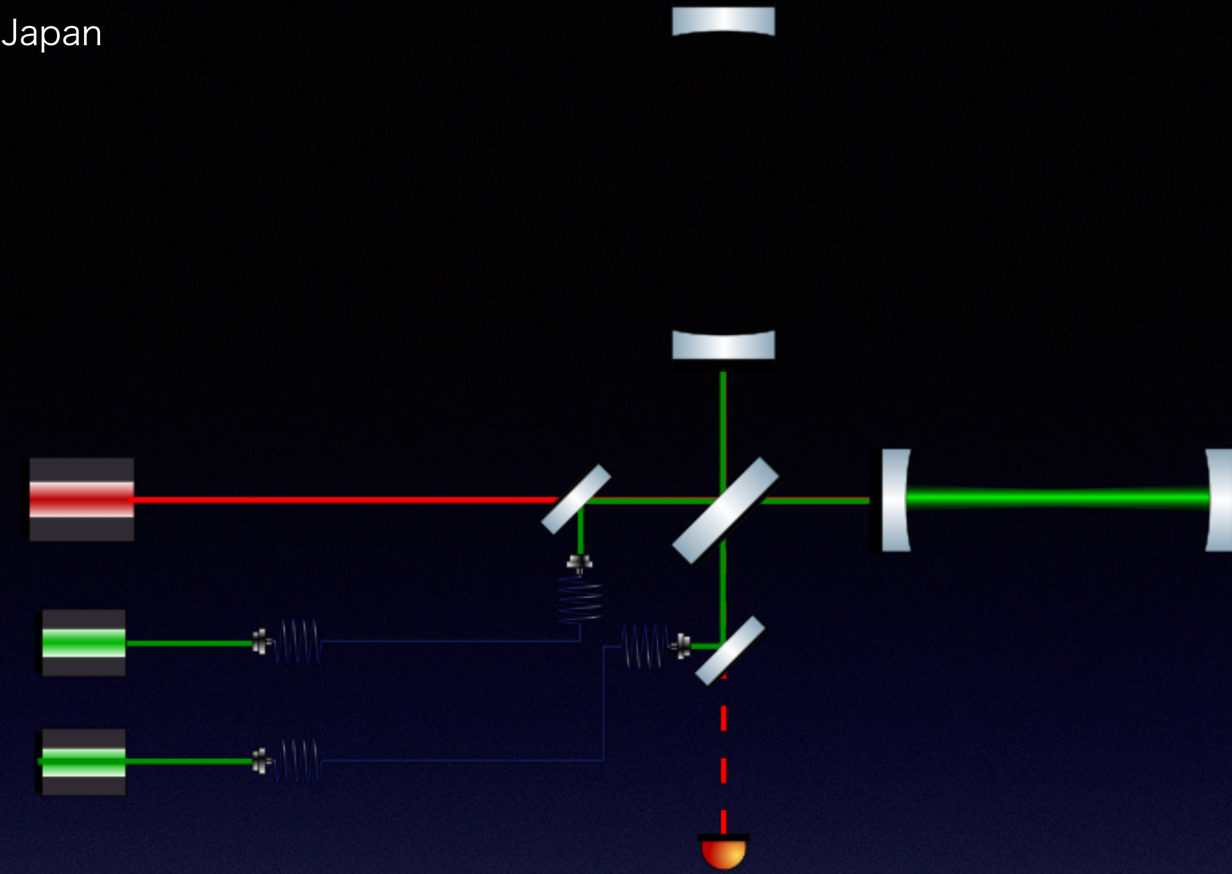
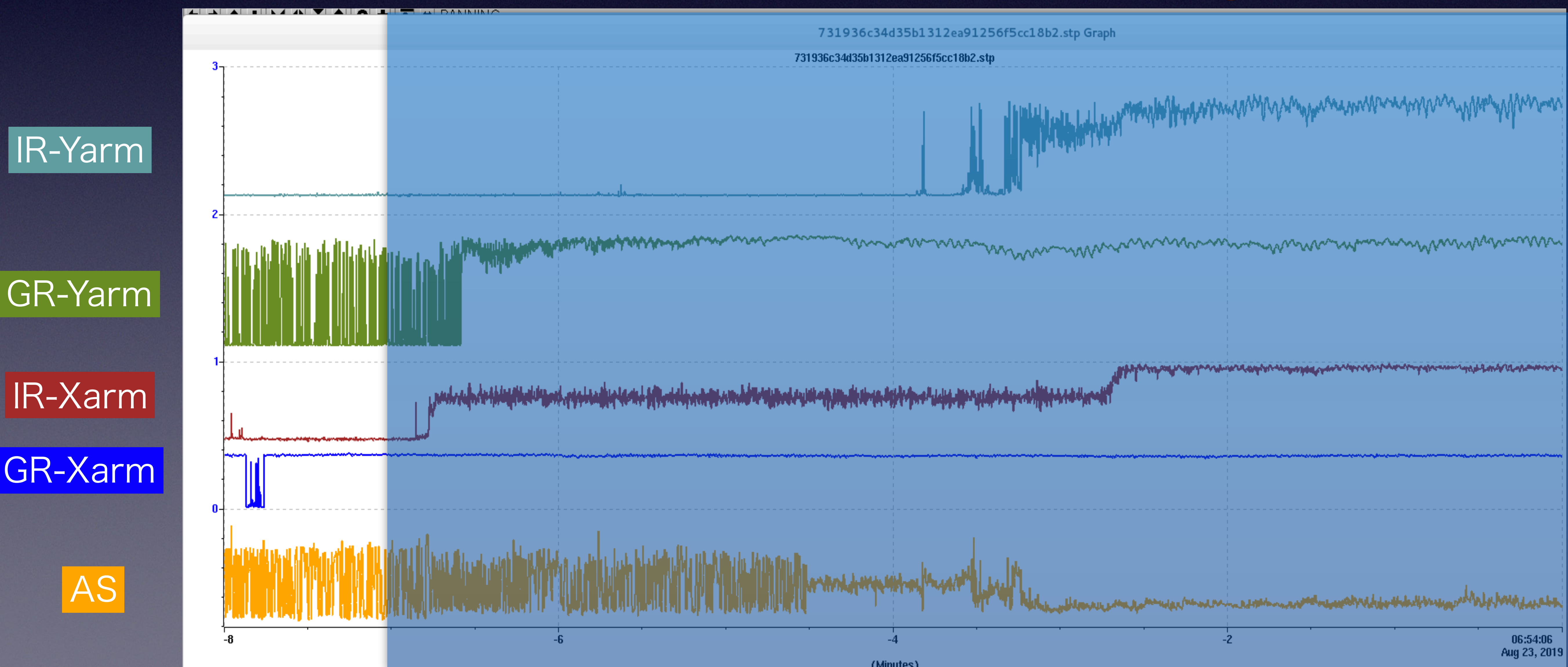
Status of the IFO control in KAGRA

- We succeeded to lock the IFO with FPMI configuration.
- Once the FPMI got locked, it continues to be locked for more than 6 hours.
- The lock acquisition procedure is automated.

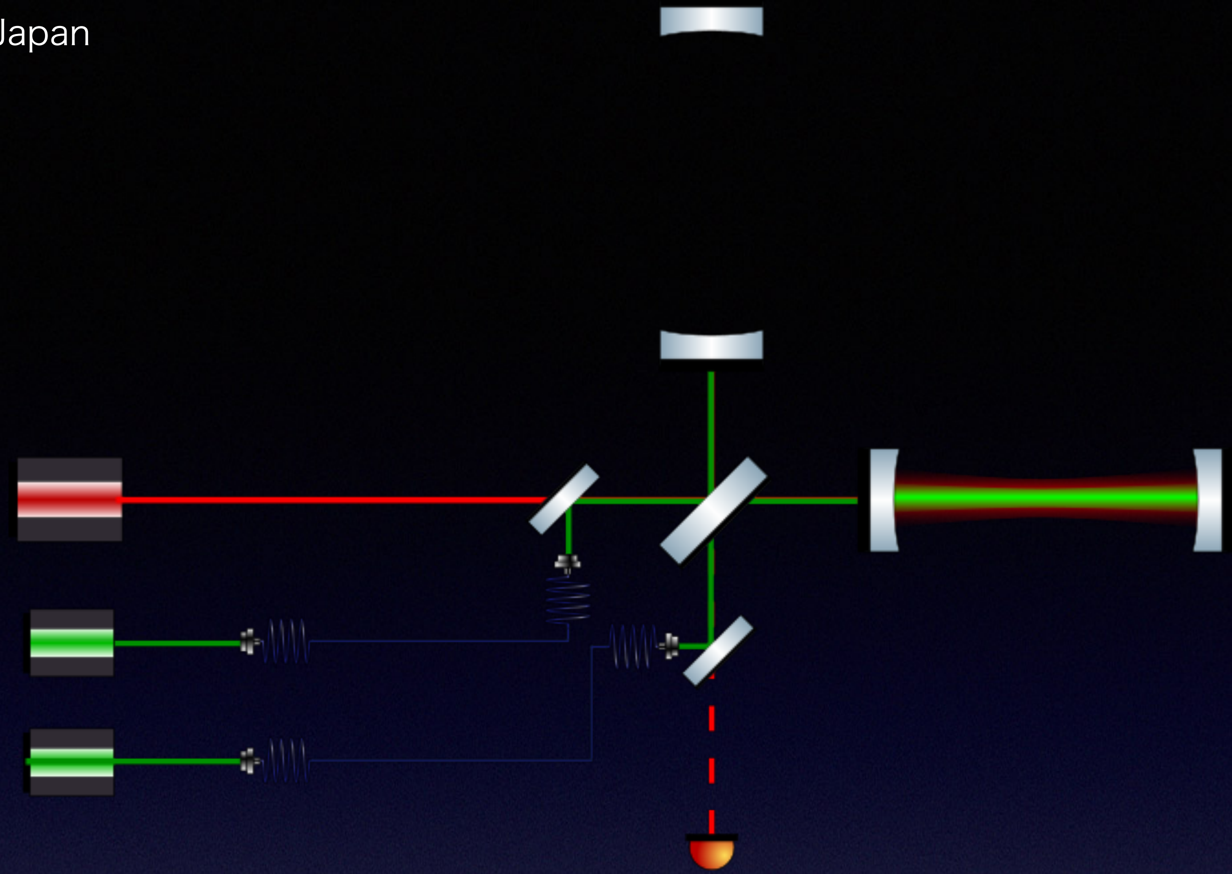


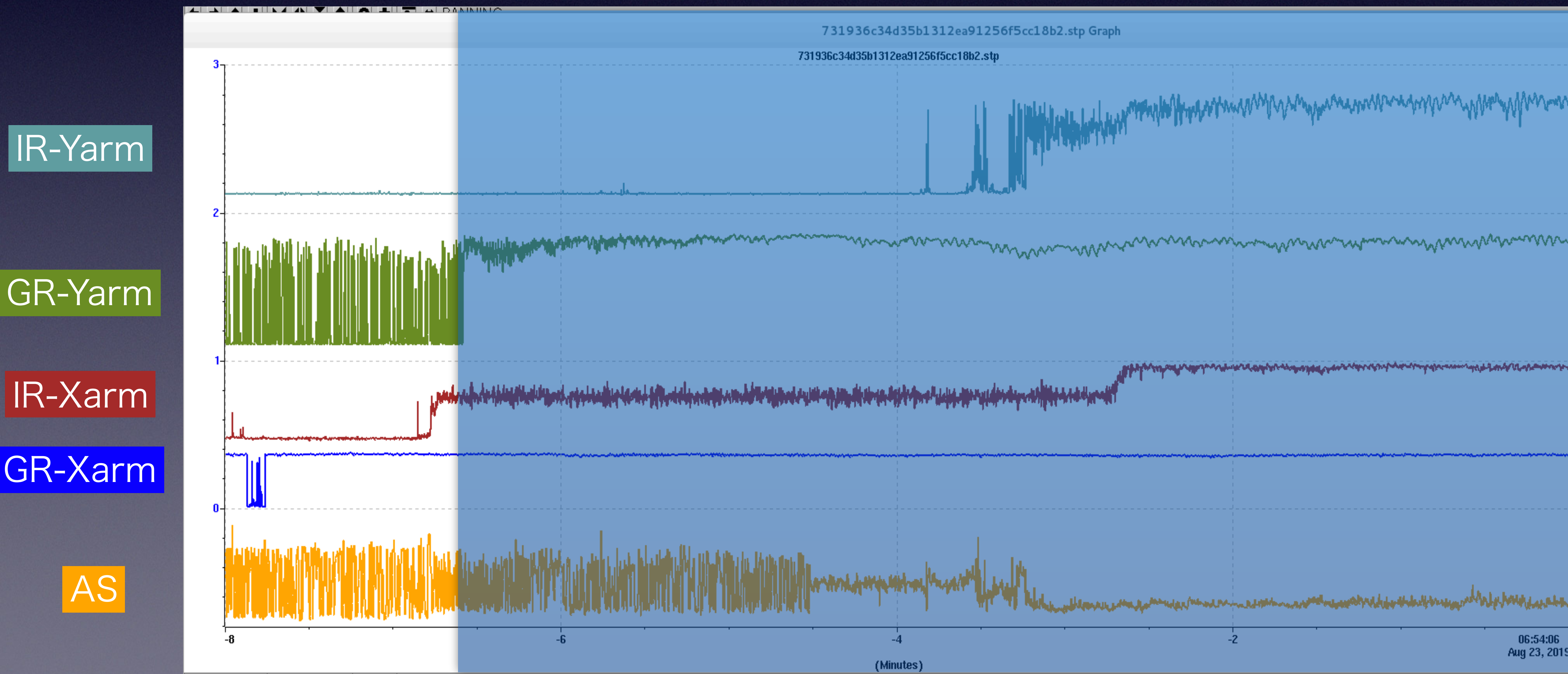
- Phase 1.
  - ➡ Lock the aux. laser to the Xarm cavity.
  - ➡ Hold the laser frequency at off-resonance of the arm cavity.



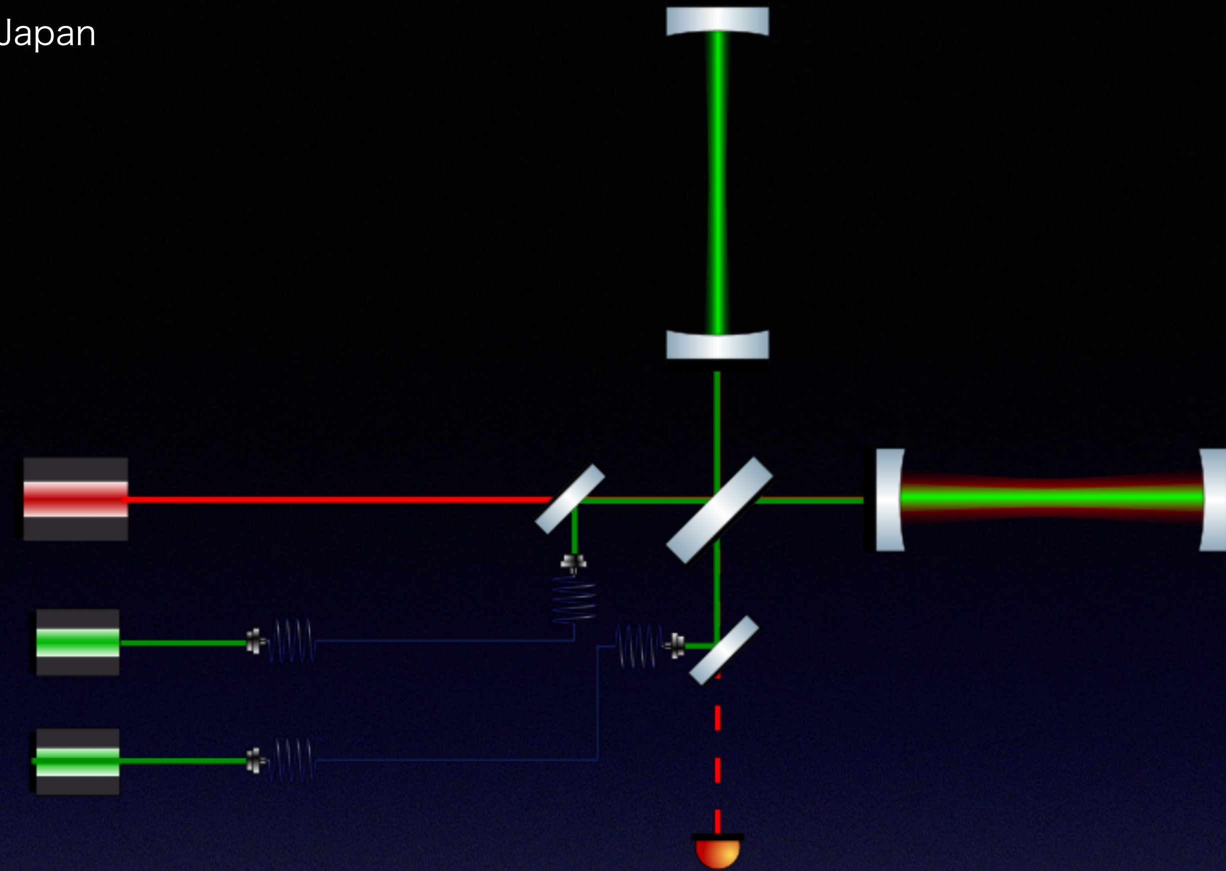


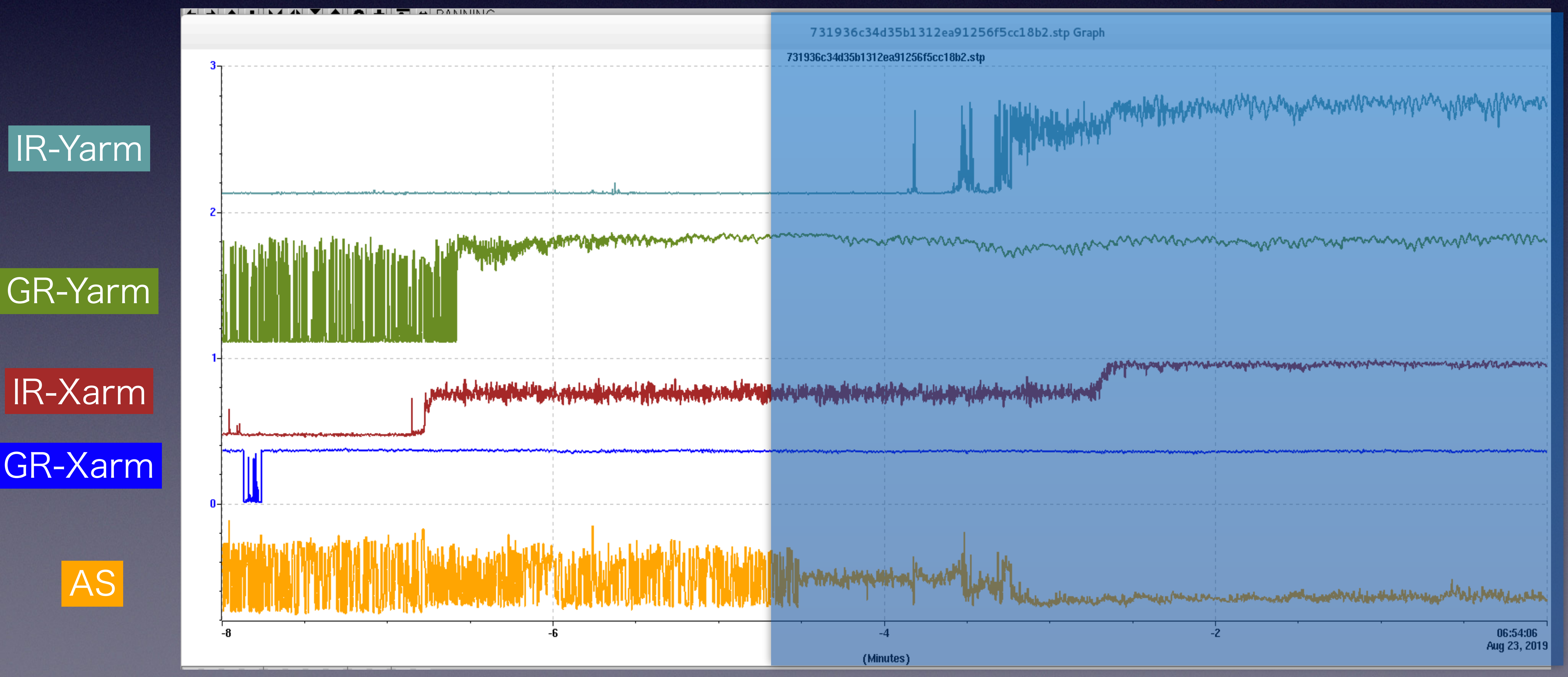
- Phase 2.
  - Bring the Xarm close to the resonance by the aux. laser
  - Hand-off the control from aux. laser signal to the transmitted signal.





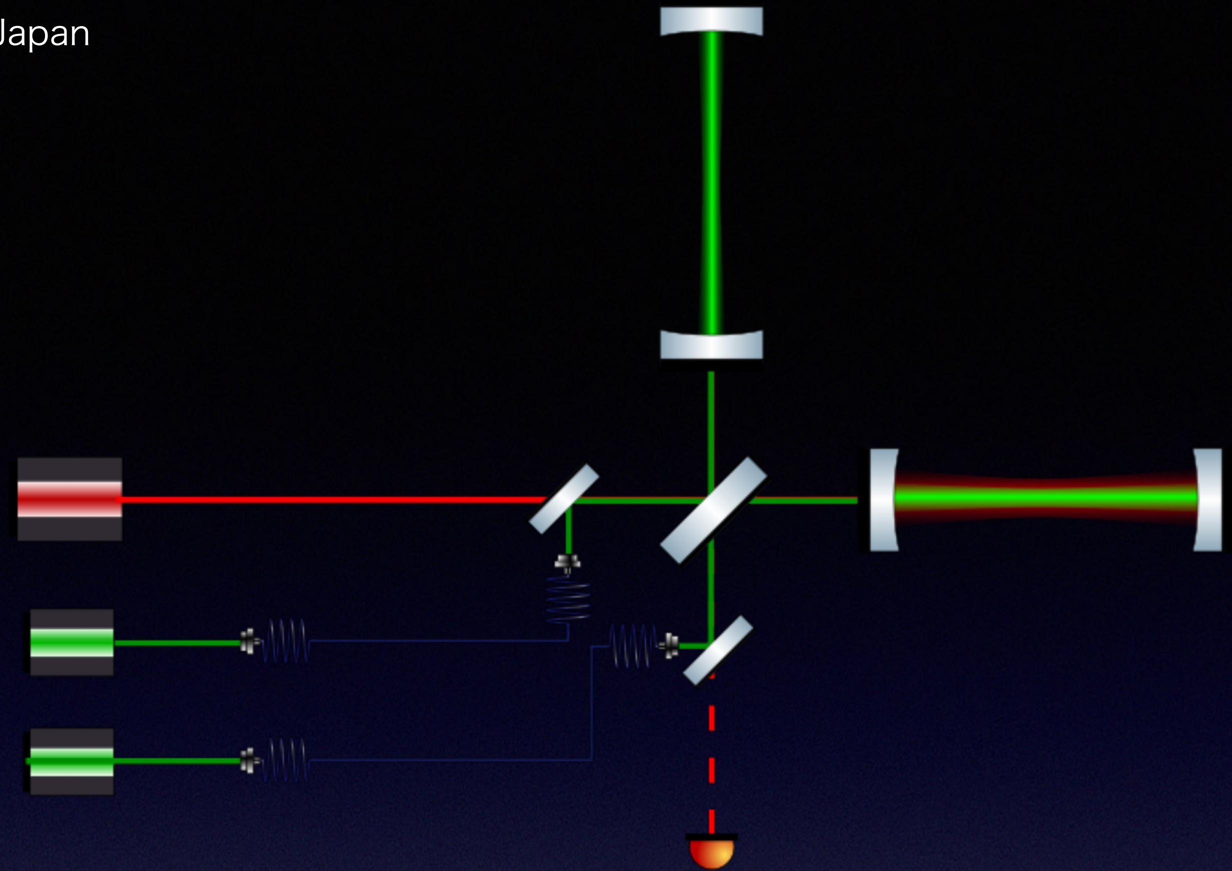
- Phase 3.
  - ➡ Lock the aux. laser to the Yarm cavity.
  - ➡ Hold the laser frequency at off-resonance of the arm cavity.
  - ➡ The control signal is fed back to the suspension.

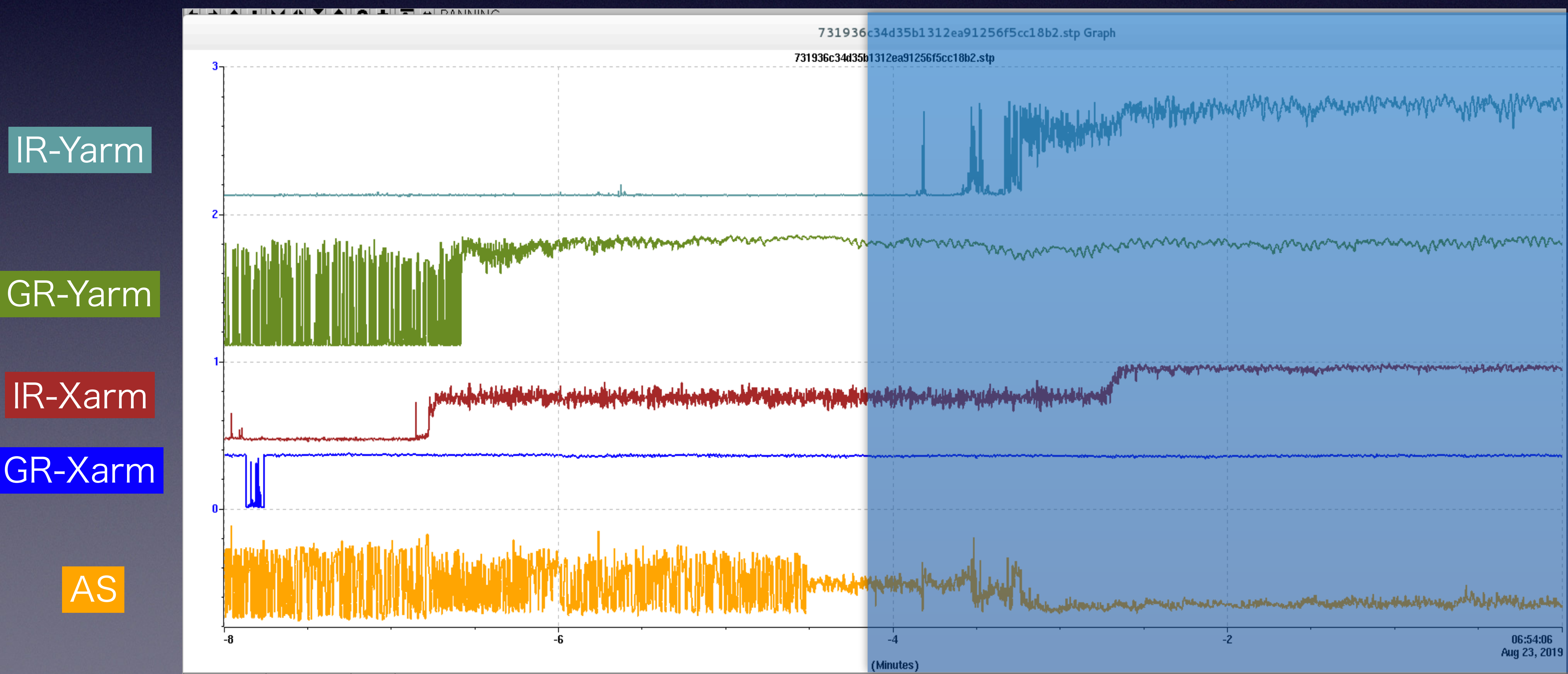




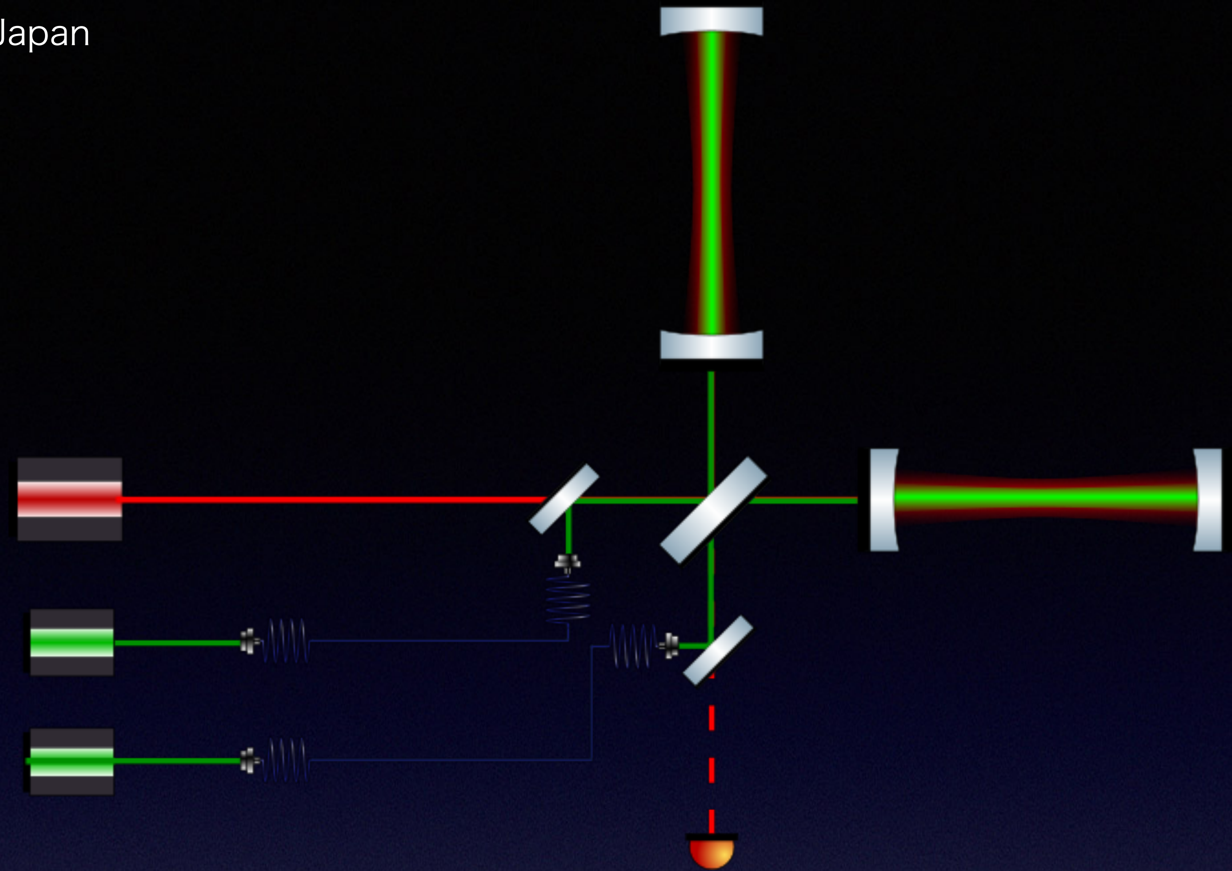
- Phase 4.

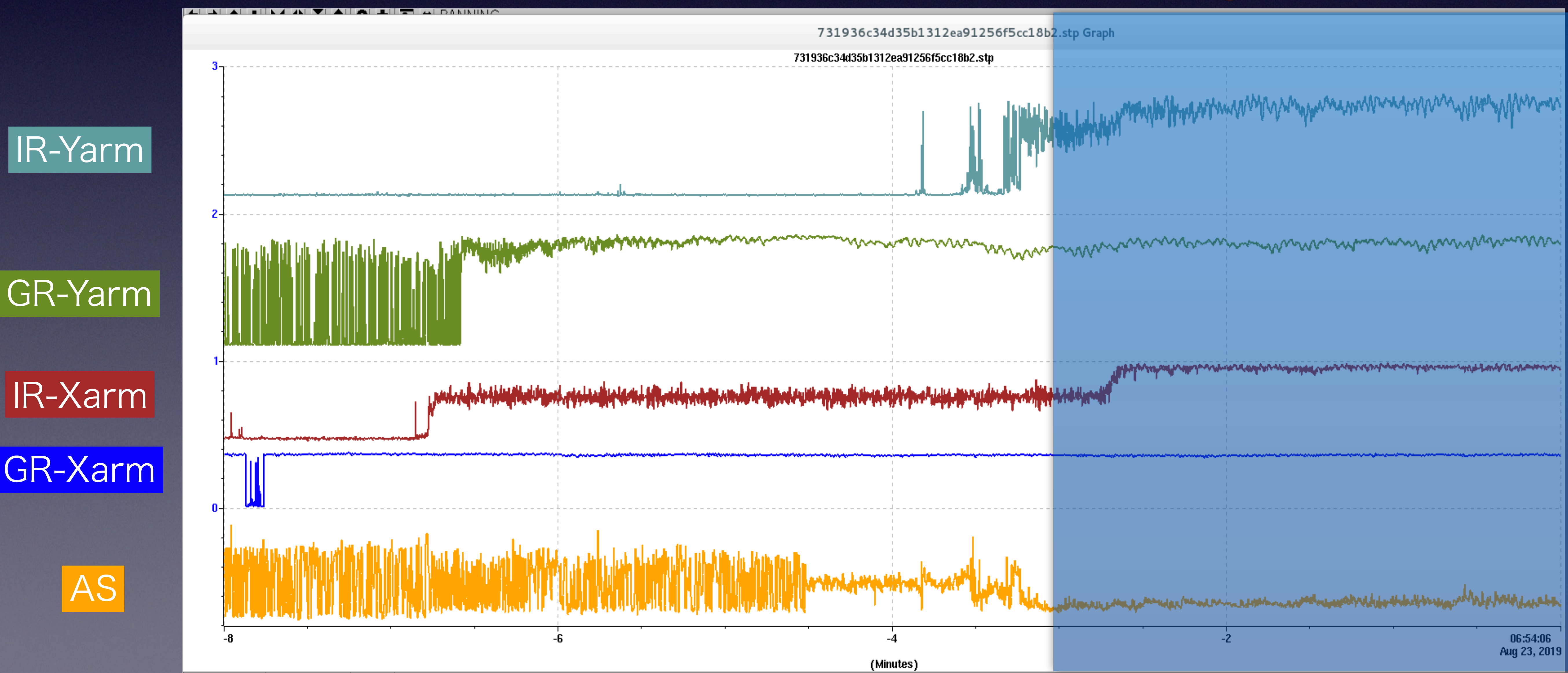
  ➡ Lock the center Michelson.

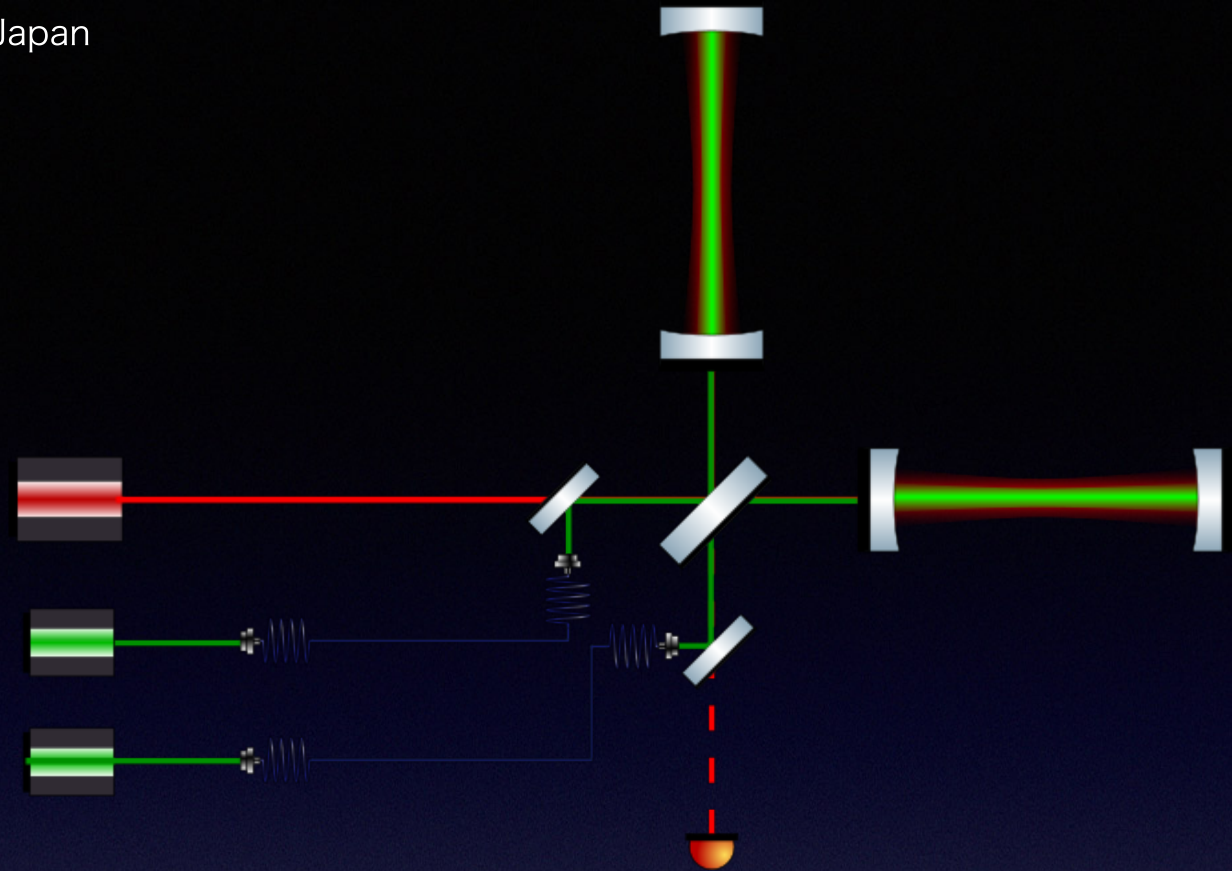




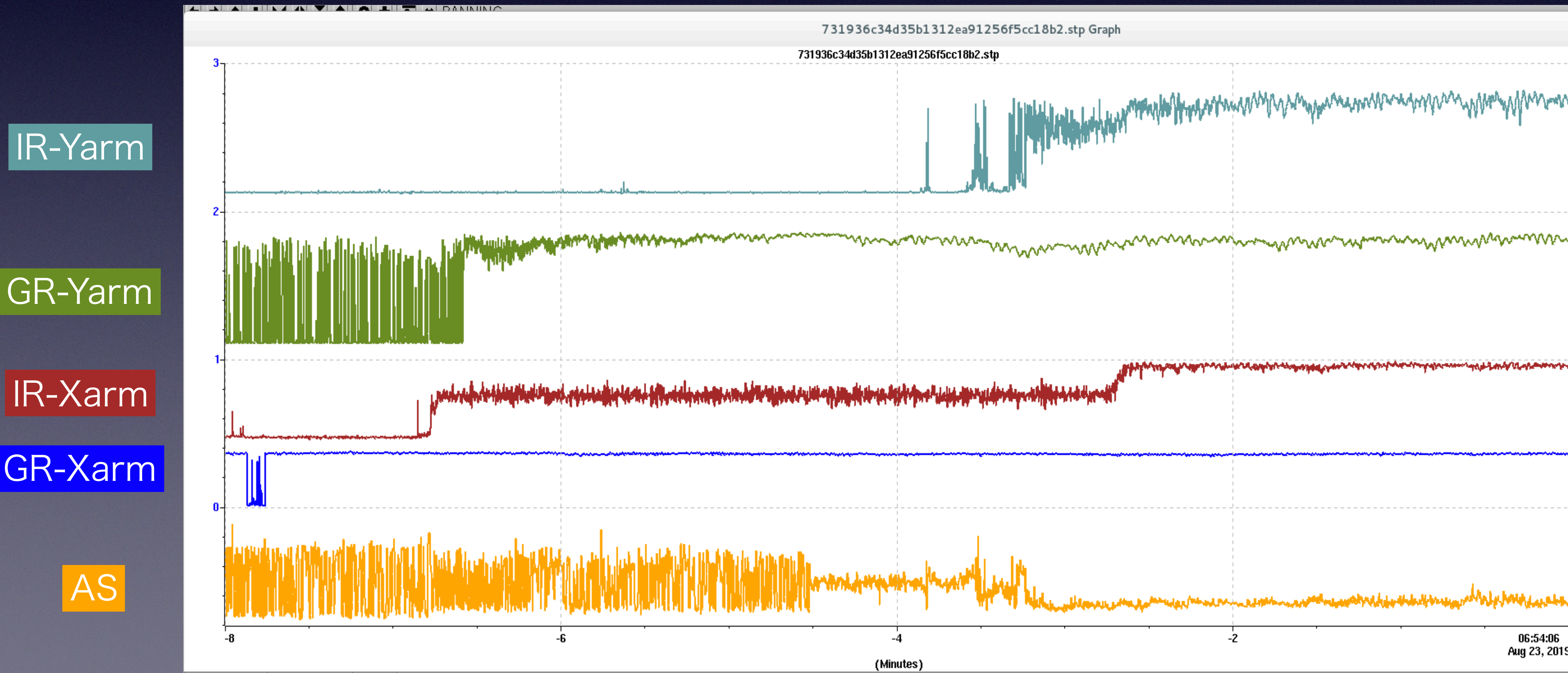
- Phase 5.
  ➡ Bring the other arm on the resonance.



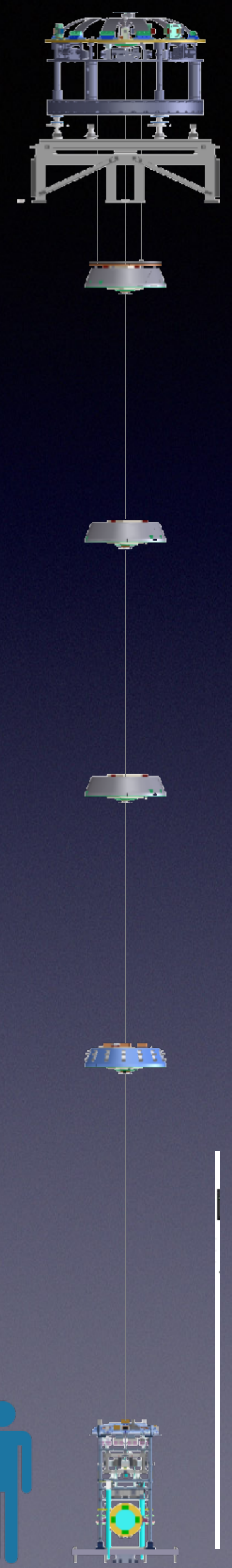




- Phase 6.
  - ➡ Hand-off the control from aux. signals to the RF PD signals.



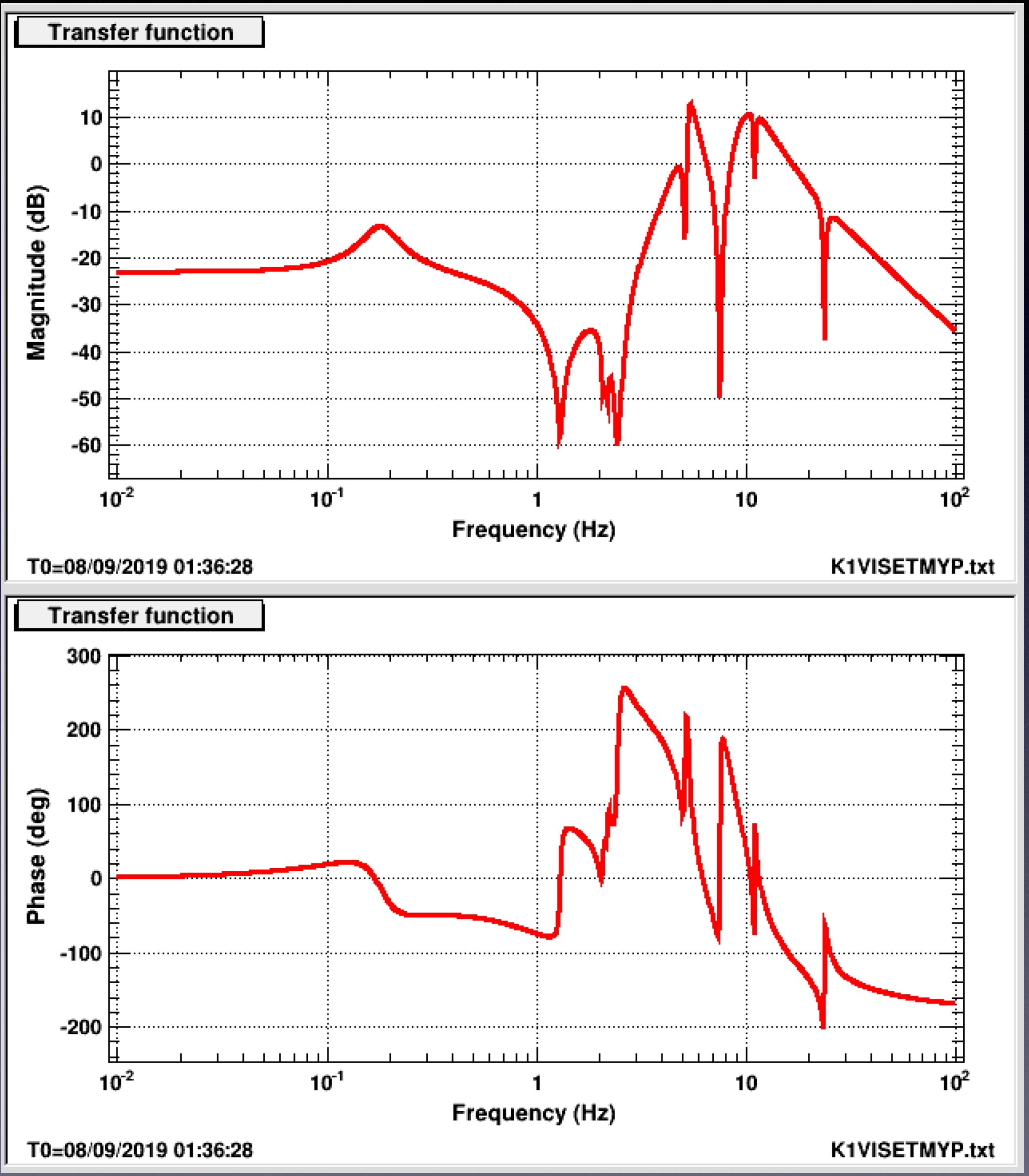
Actuation of the suspension



- One difficulty of the IFO control is the suspension actuation.
- Especially, the suspension for the arm cavity mirrors are huge and complicated.
  - ➡ 13 meter height
  - ➡ 8-stage pendulum
- For the stable operation of the IFO, the actuators need to be well tuned.
  - ➡ Diagonalization of the longitudinal motion and the angular motion.
  - ➡ Design of the control filter for the hierarchical control

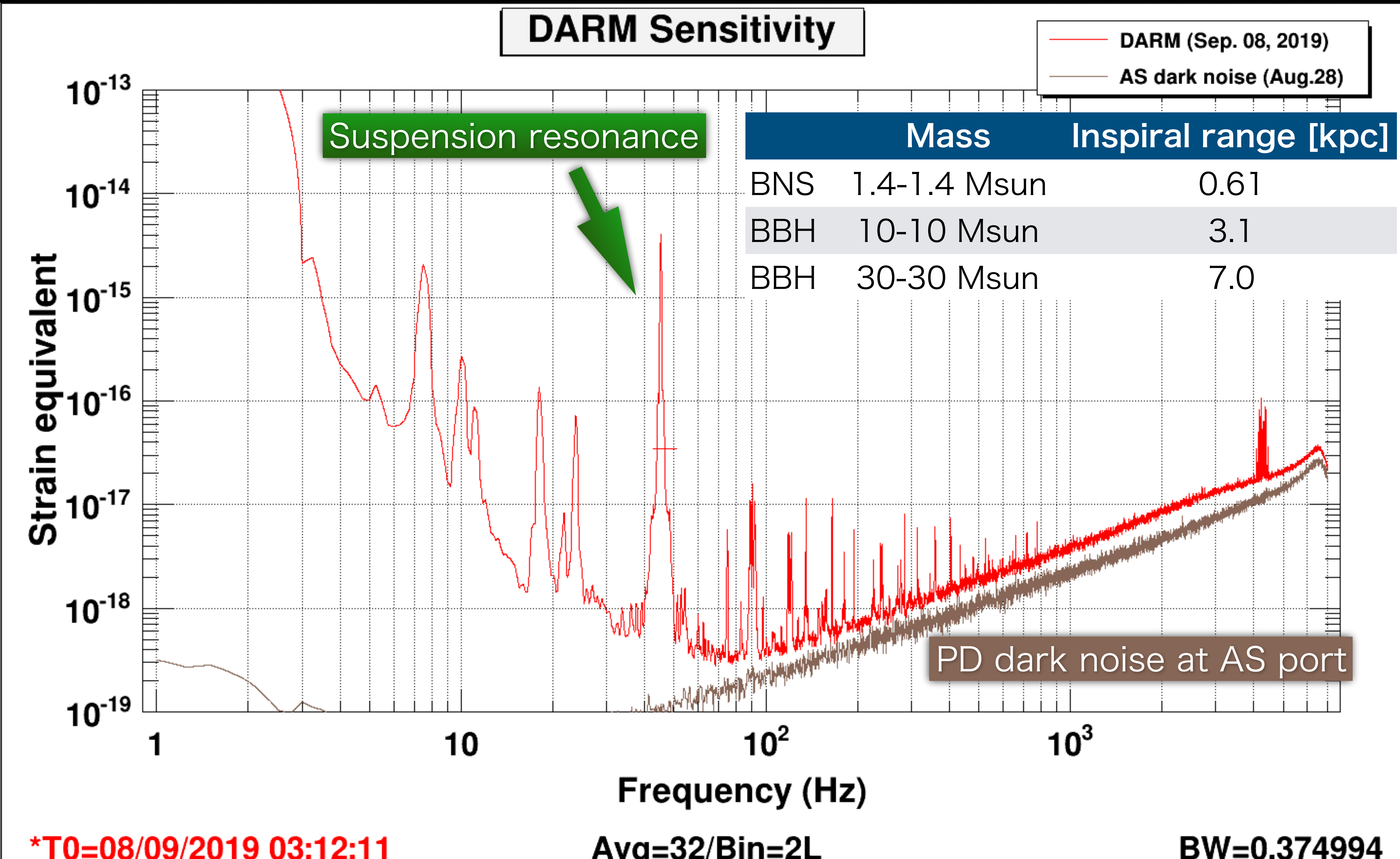
Suspension control

- To satisfy the control band width and the actuator range, two or more stages of the suspension are actuated in 'hierarchical' way.
- To realize the stable control, the control filter needs to be finely tuned.
- The control filter for one of the ETM has been implemented, and stably actuated.



One of the control filter for hierarchical control

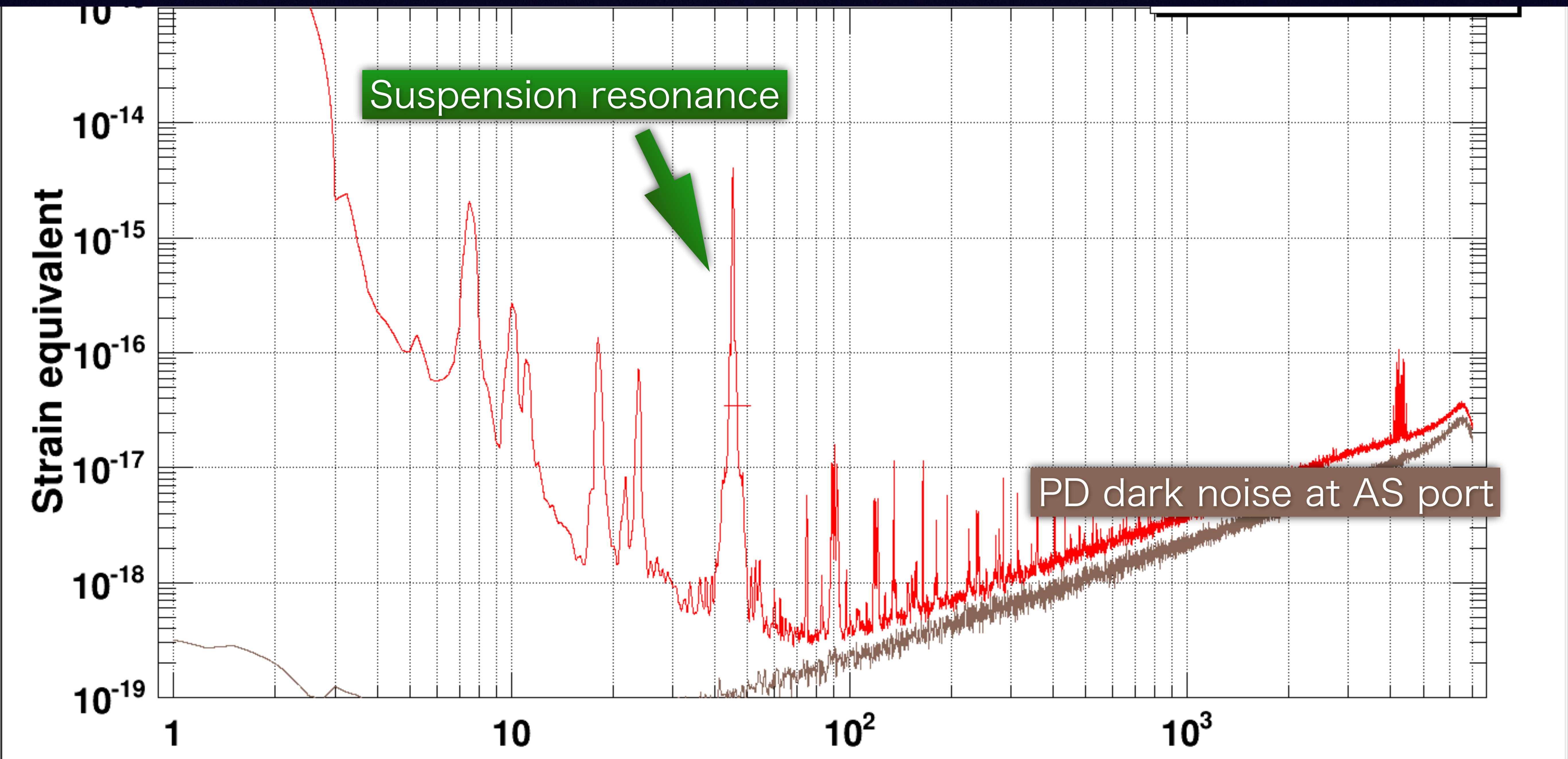
Latest sensitivity



	Mass	Inspiral range [kpc]
BNS	1.4-1.4 Msun	0.61
BBH	10-10 Msun	3.1
BBH	30-30 Msun	7.0

Latest sensitivity

- Noise hunting is on going in parallel.
  - Many physical environment monitor system. (ex. Seismometer, microphone, magnetometer, and so on.)
  -



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For the next

- Lock acquisition of Dual-Recycling FPMI.
- Noise hunting
  - ➡45 Hz resonant peak.
  - ➡PD dark noise.
  - ➡Frequency noise.
  - ➡…
- Alignment sensing and control
  - ➡Actuator diagonalization
  - ➡Sensing matrix measurement
  - ➡Noise hunting for ASC
-

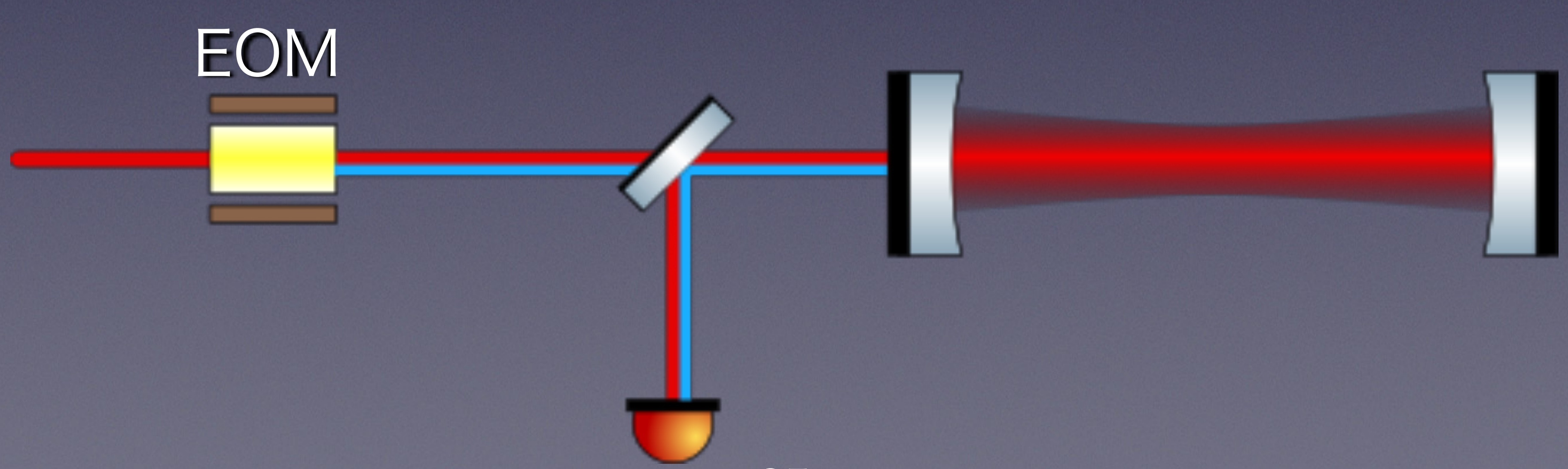
Summary

- We succeeded to lock the FPMI.
- FPMI control is stable and lock acquisition process is automated.
- Still, we have two DoFs not to be succeeded to control. Move on it.
- Noise hunting is on going in parallel.

Appendix

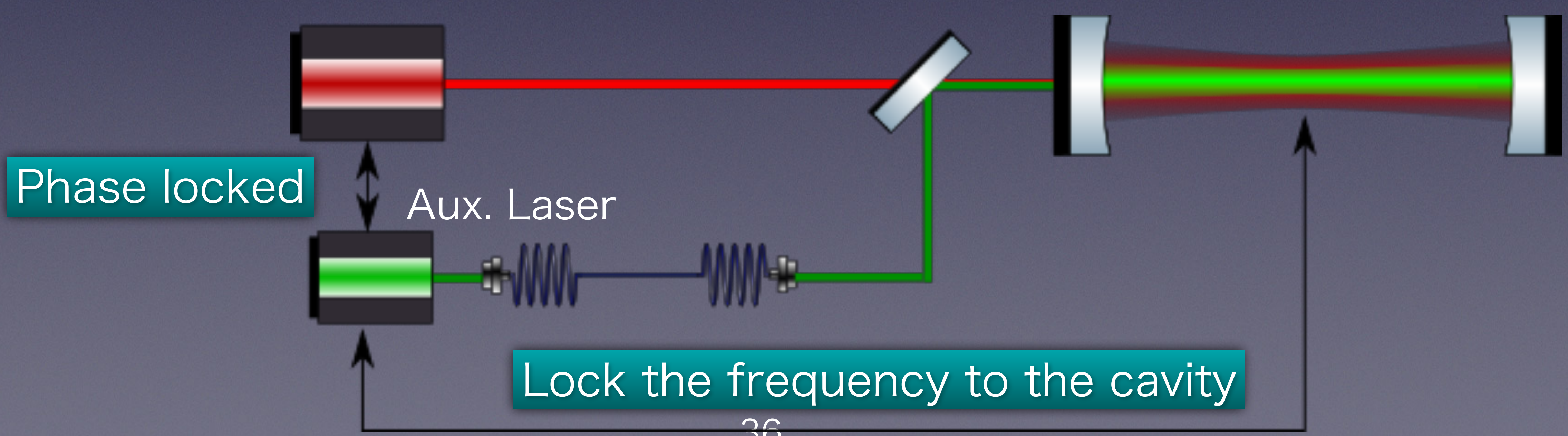
Signal acquisition

- To extract the error signal for the cavity length control, frontal modulation method is used.
  - ➡ Generate the phase modulation sideband in a radio frequency.
  - ➡ Only the carrier resonates in the cavity and the sideband are reflected from the input mirror.
  - ➡ By using the sideband as the local oscillator, we can extract the cavity length information.



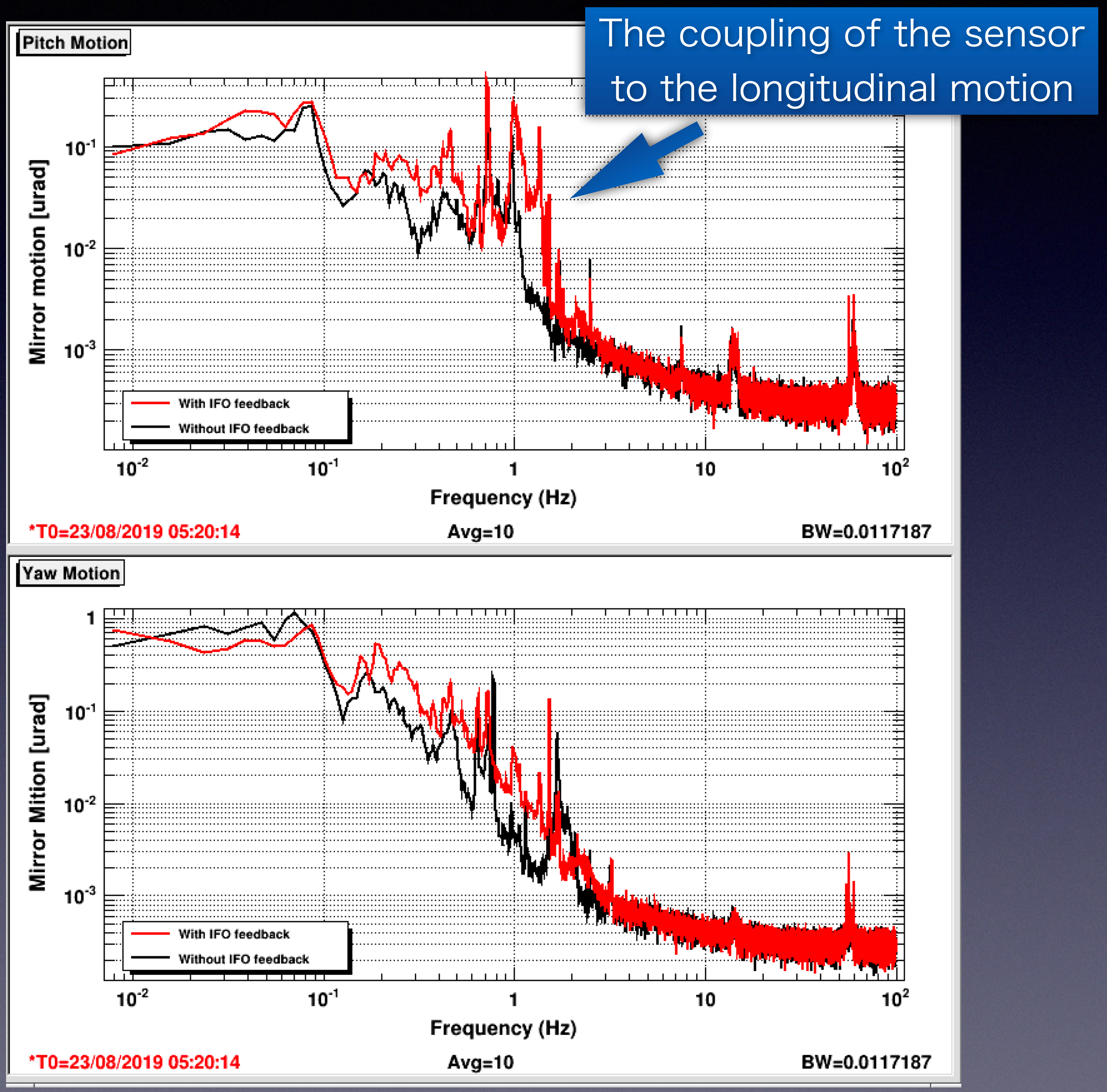
Arm length stabilization

- The main laser and the aux. laser is locked in those phase each other.
- By locking the aux. laser to the arm cavity, we can know the relative fluctuation of the main laser frequency and the arm cavity resonance.



Diagonalization of the suspension

- Angular motion of the suspension is small enough to maintain the lock for several hours.



Angular motion with/without the feedback.

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