2013 International School on Numerical Relativity
and Gravitational Waves (APCTP Pohang, Korea)

Aug 11, 2013

Alignment Sensing and Control for the KAGRA Interferometer

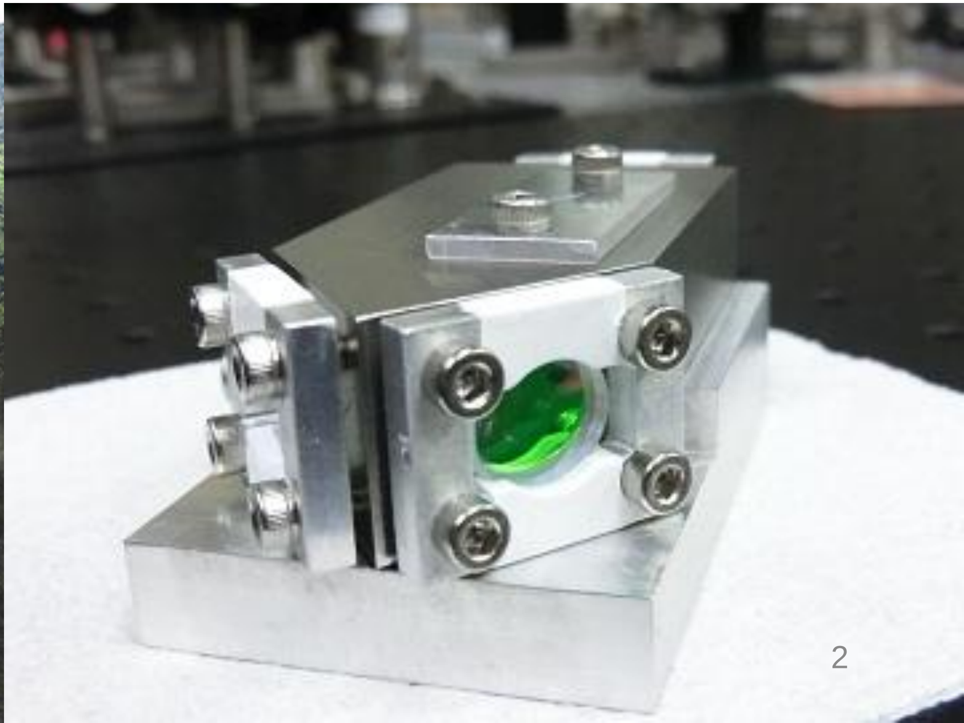
Yuta Michimura

Ando Group

Department of Physics, University of Tokyo

Self introduction

- Yuta Michimura (道村唯太　みちむらゆうた)
- Department of Physics, University of Tokyo
- Relativity-related experiment using some optics
  - designing KAGRA interferometer
  - light speed anisotropy search



Outline

- Introduction to interferometric GW detection
  - KAGRA interferometer
  - basic principle of GW detection
  - importance of length and alignment control
  - signal extraction of mirror motions
- Modeling alignment sensing and control scheme in KAGRA
  - difficulties
  - current status

References

- Educational papers:
  E. D. Black & R. N. Gutenkunst:
    Am. J. Phys. **71**, 365 (2003)
  H. Kogelnik & T. Li:
    Appl. Opt. **5**, 1550 (1996)
- KAGRA specific:
  Y. Aso, Y. Michimura, K. Somiya+:
    arXiv:1306.6747 (PRD accepted)
  K. Somiya, KAGRA Collaboration:
    Classical Quantum Gravity **29**, 124007 (2012)

KAGRA

- cryogenic interferometric GW detector
- operation in full configuration ~2017

Pohang
浦項
포항

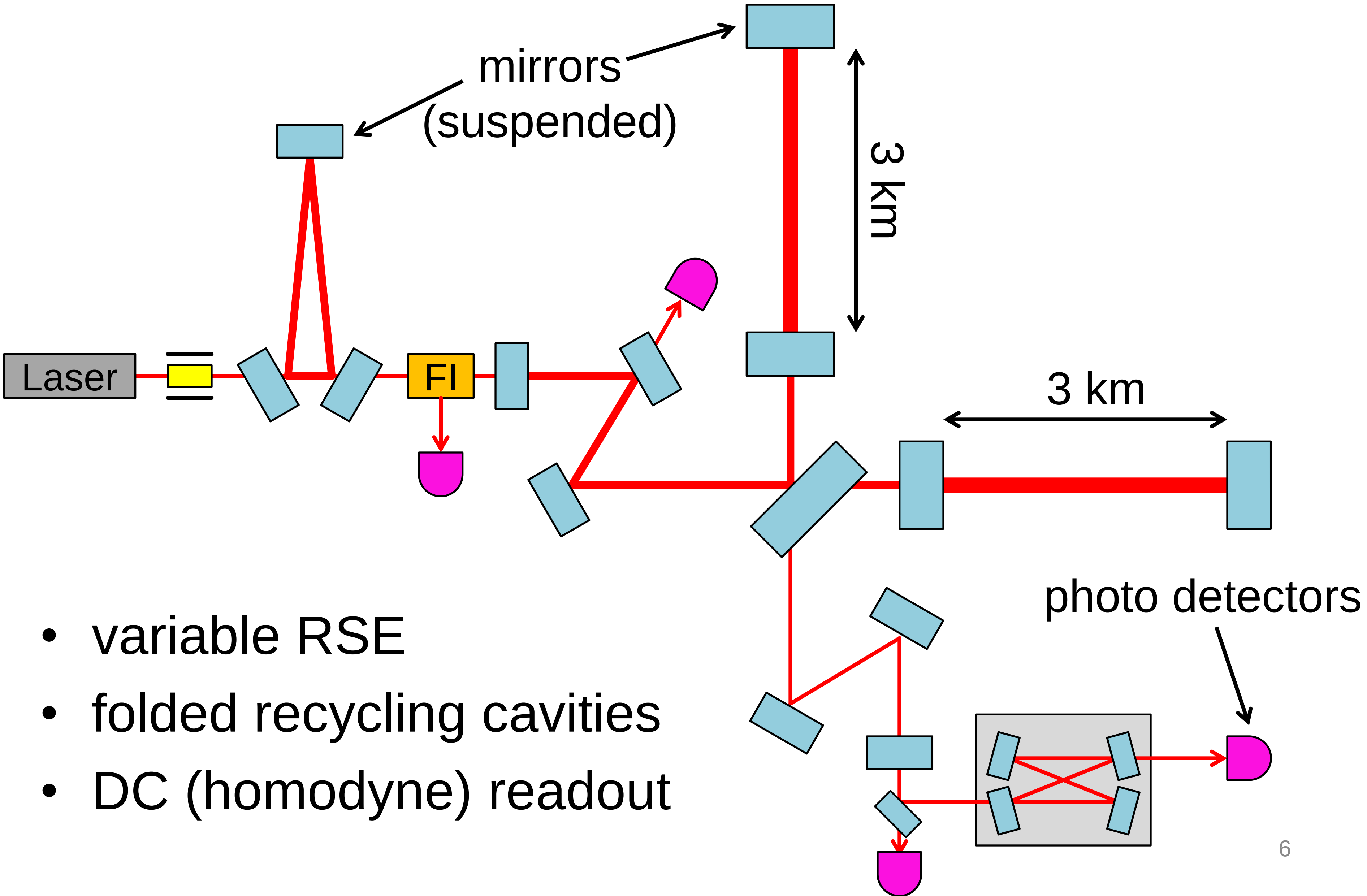
KAGRA
神楽
かぐら

~1 km underground

3 km

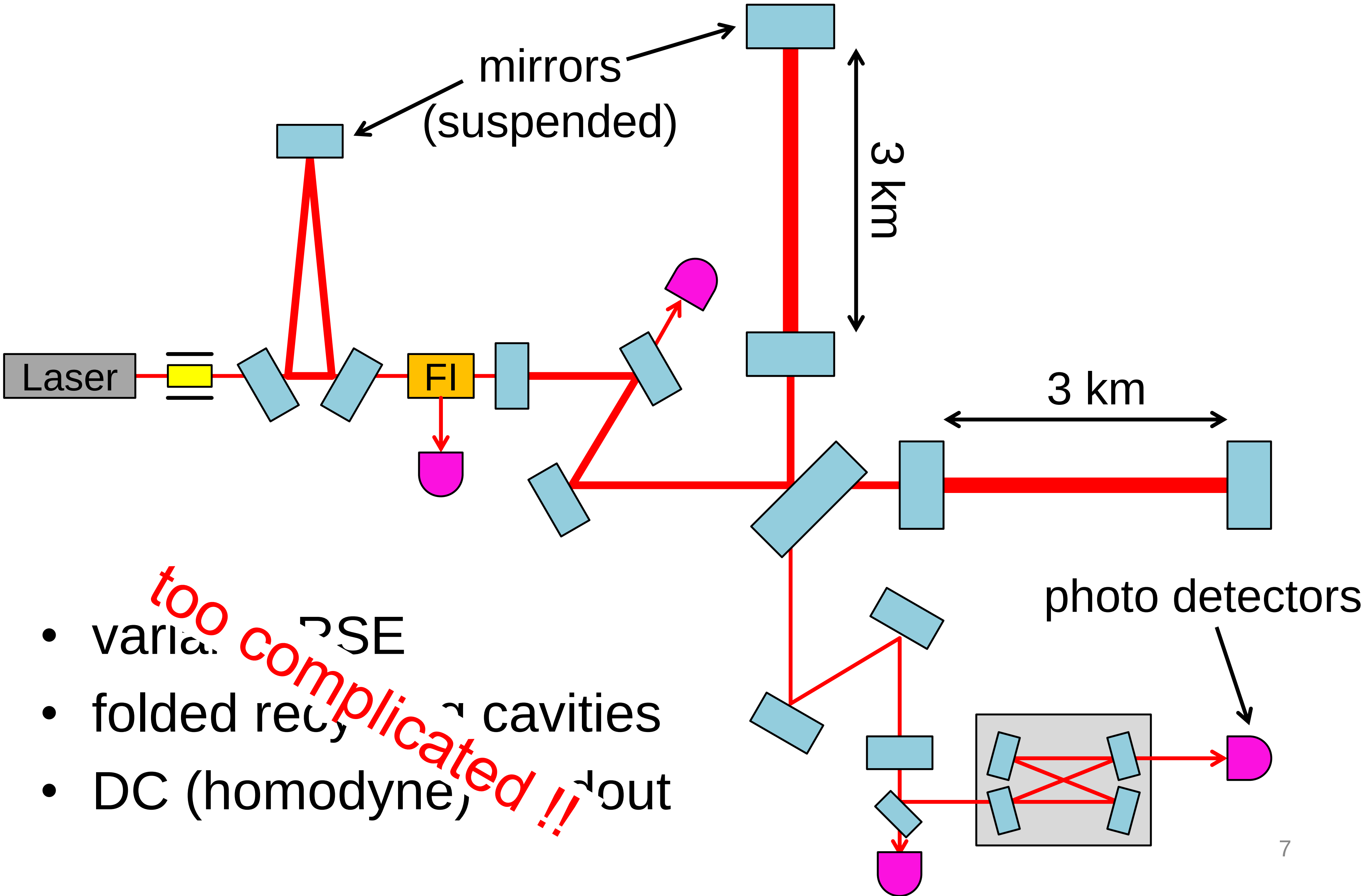
3 km

KAGRA interferometer



- variable RSE
- folded recycling cavities
- DC (homodyne) readout

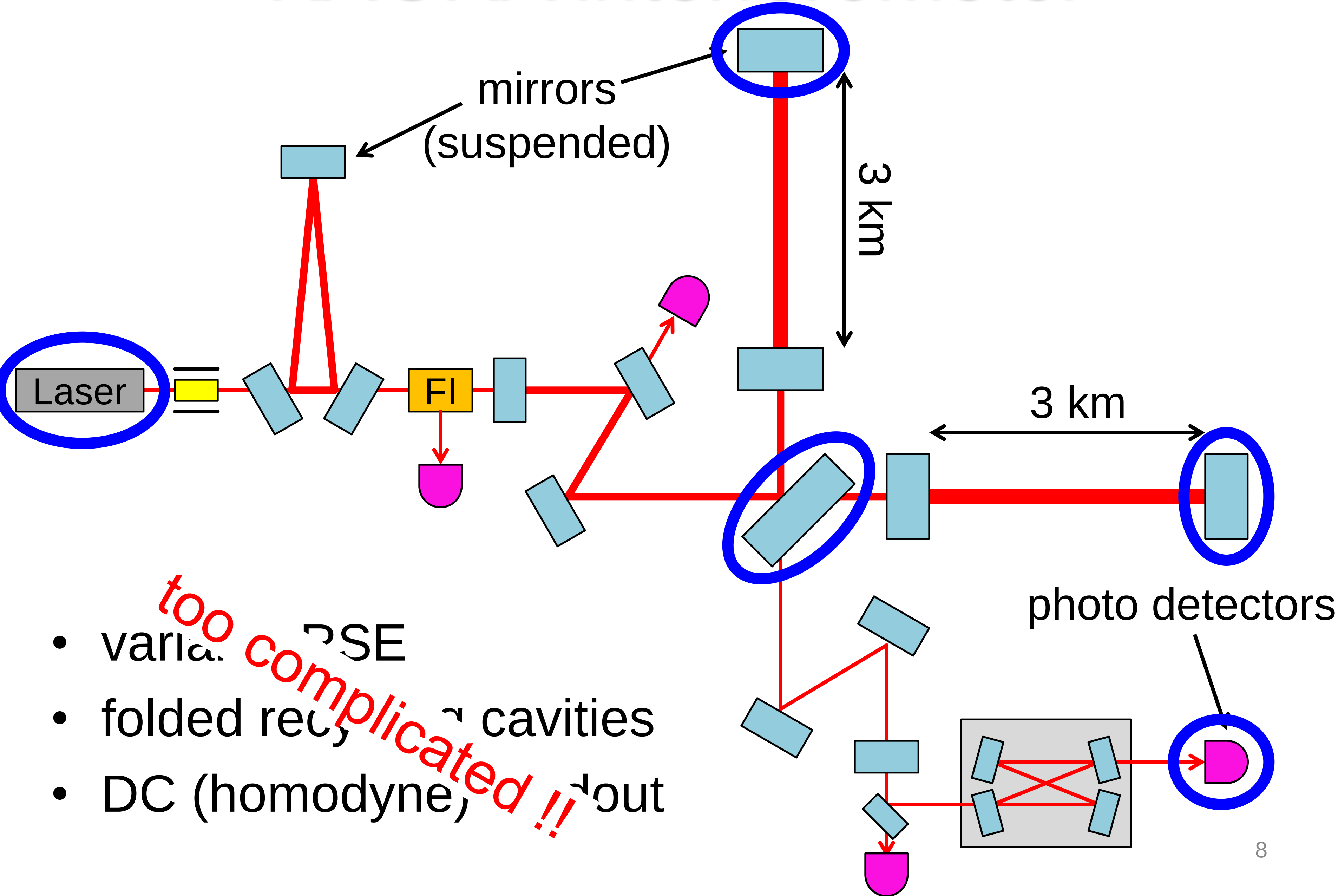
KAGRA interferometer



- varia RSE
- folded recy g cavities
- DC (homodyne) dout

too complicated !!

KAGRA interferometer



- varia RSE
- folded rec cavities
- DC (homodyne) out

too complicated !!

Michelson interferometer

- GW comes
  → lengths change
  → laser interference
  fringe changes at PD
  → GW detection

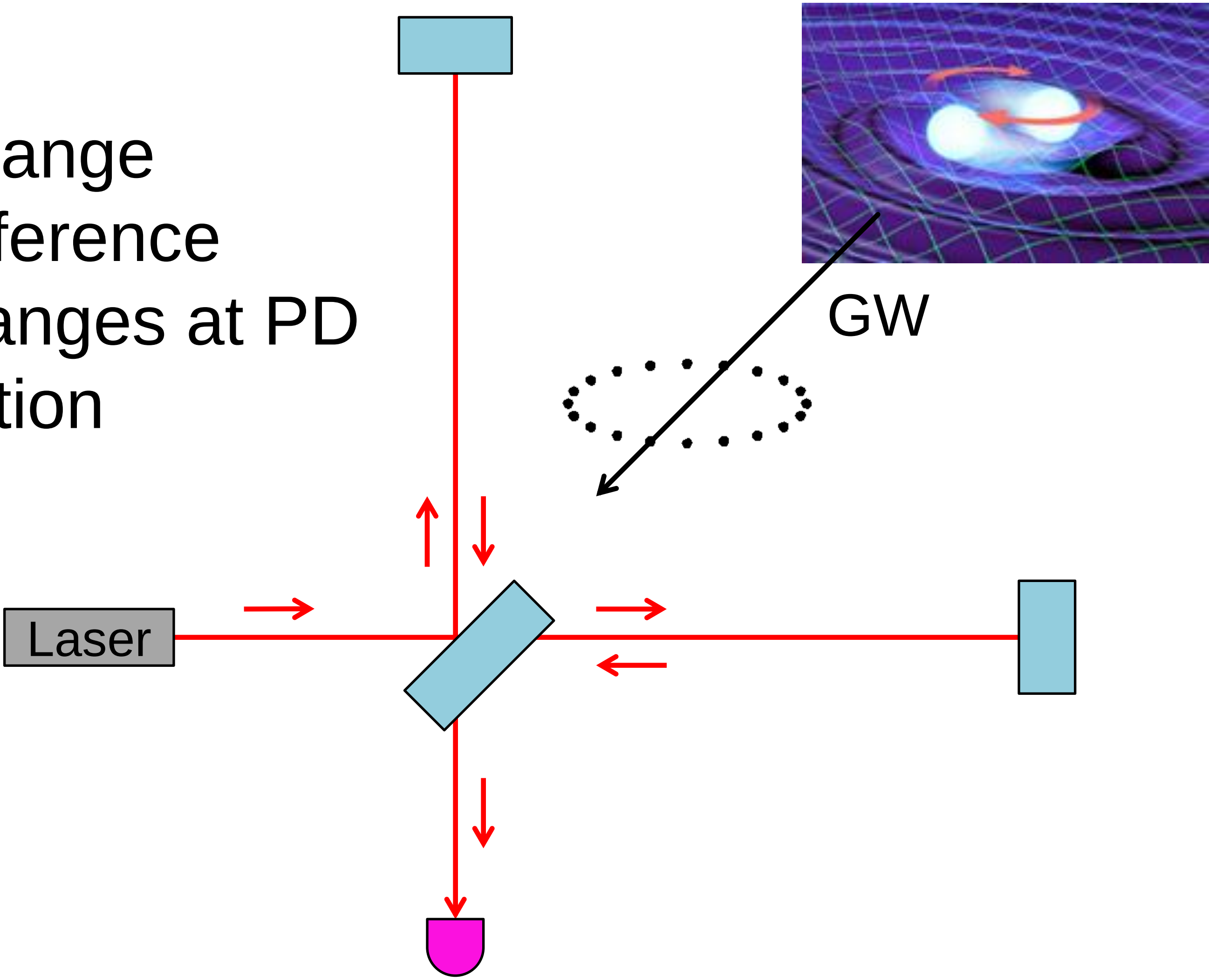
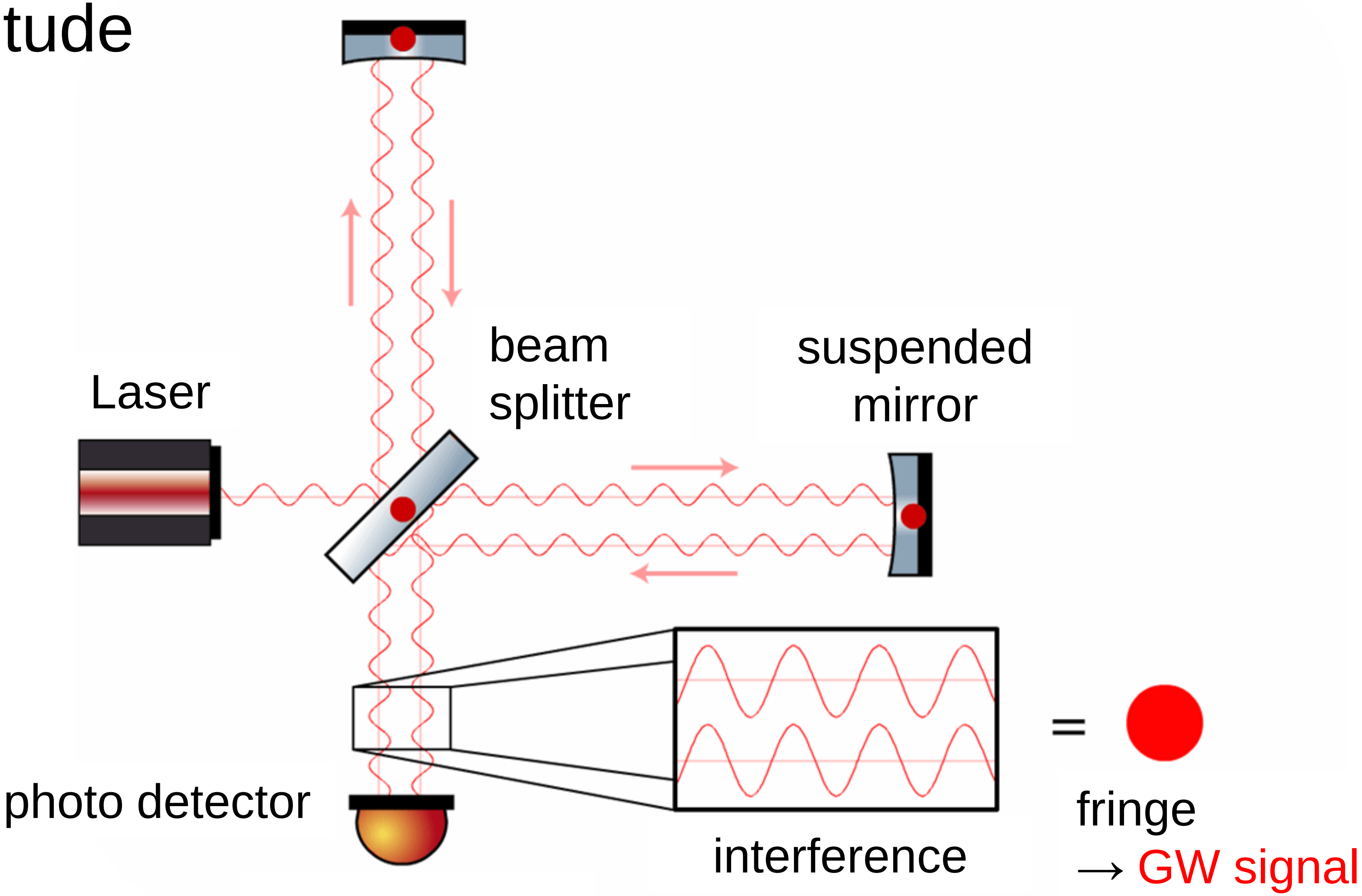


photo detector
→ GW signal

MI as a GW detector

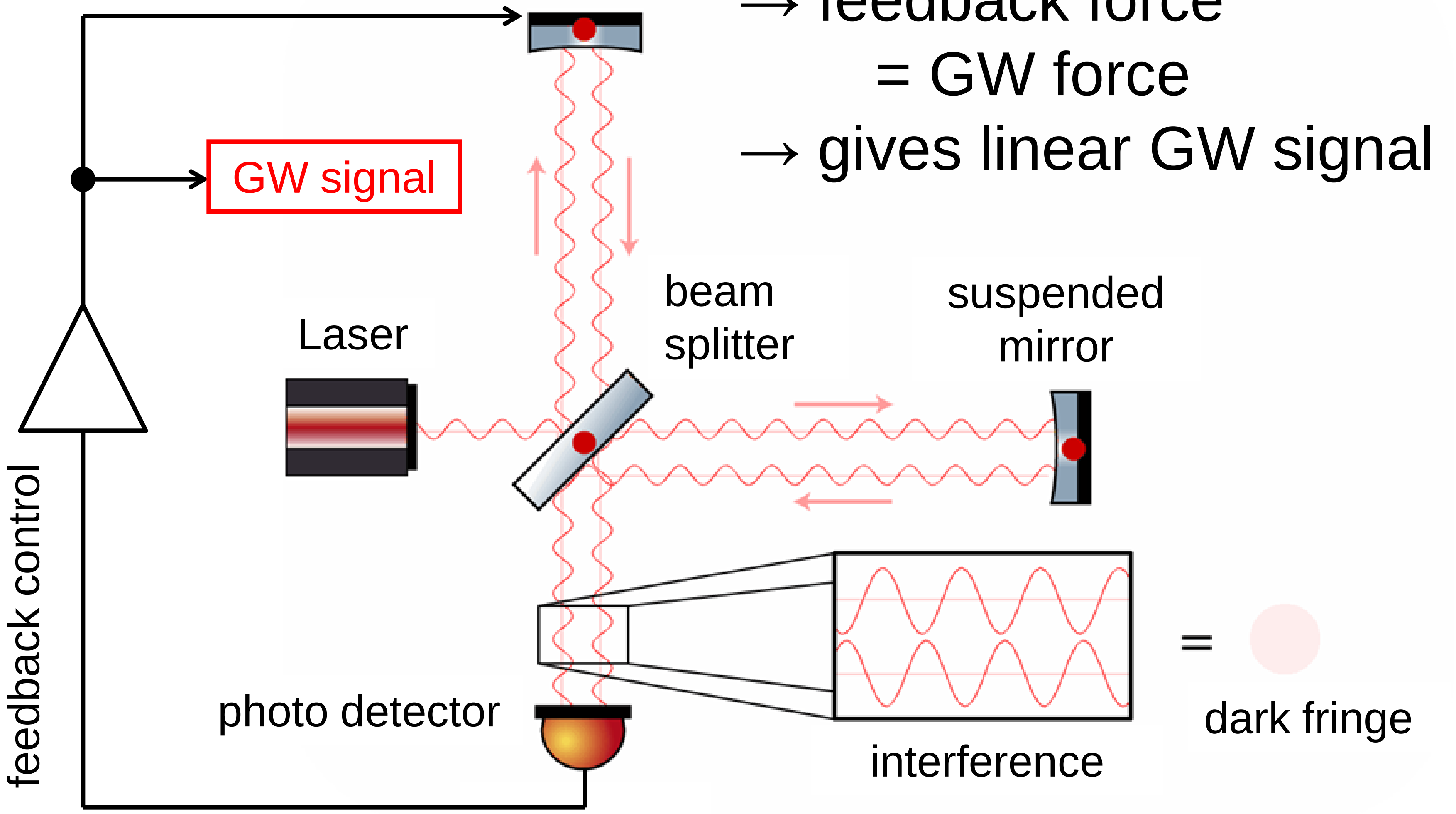
- fringe gives GW signal, but it is not linear to GW amplitude



CG/AEI?

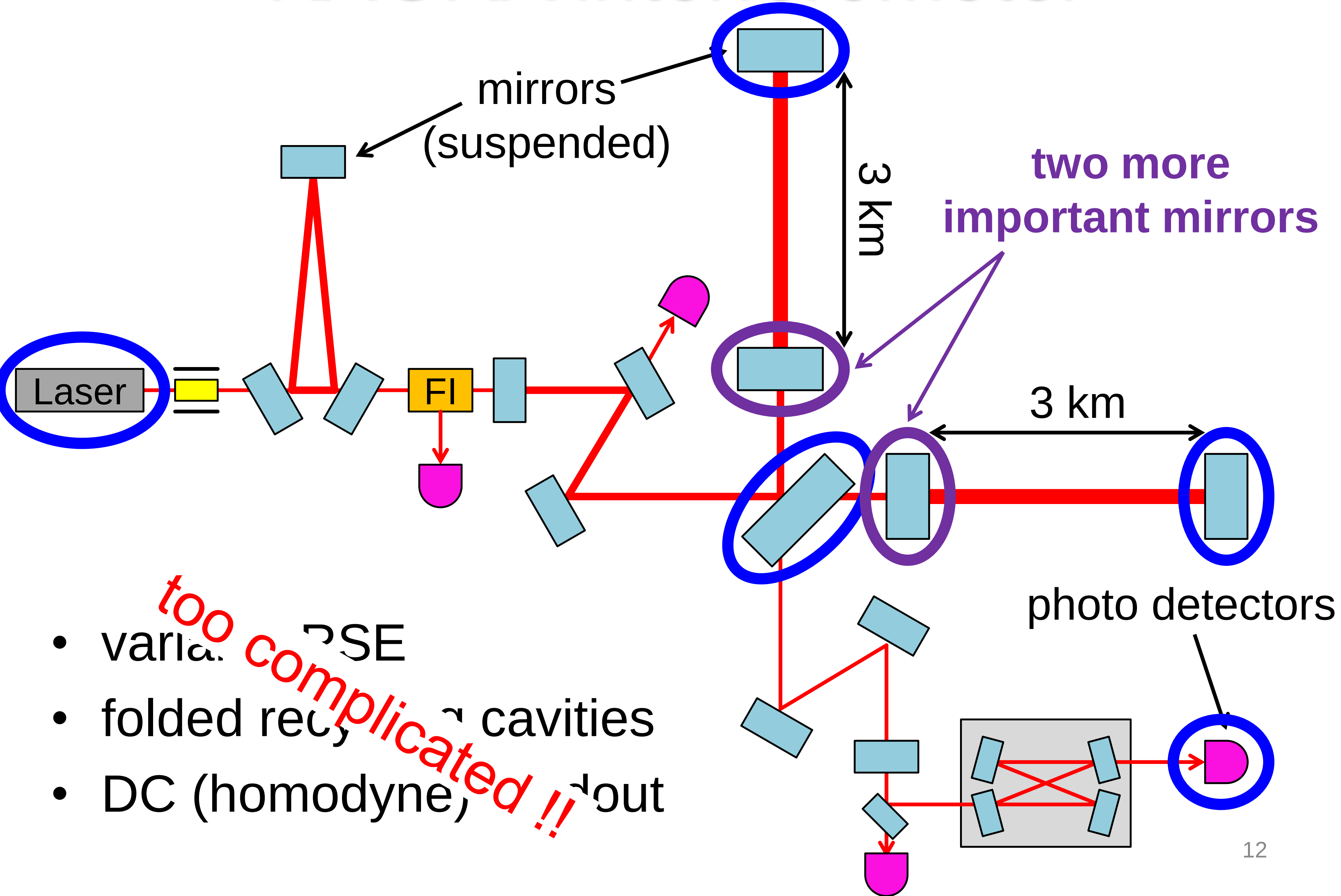
Controlling the interferometer

- control mirror motion so that fringe doesn't change
  → feedback force
  = GW force
  → gives linear GW signal



CG/AEI?

KAGRA interferometer



mirrors
(suspended)

3 km

two more important mirrors

Laser

FI

3 km

photo detectors

too complicated !!

- varia RSE
- folded rec cavities
- DC (homodyne) out

Michelson interferometer

- length change vs phase shift is linear

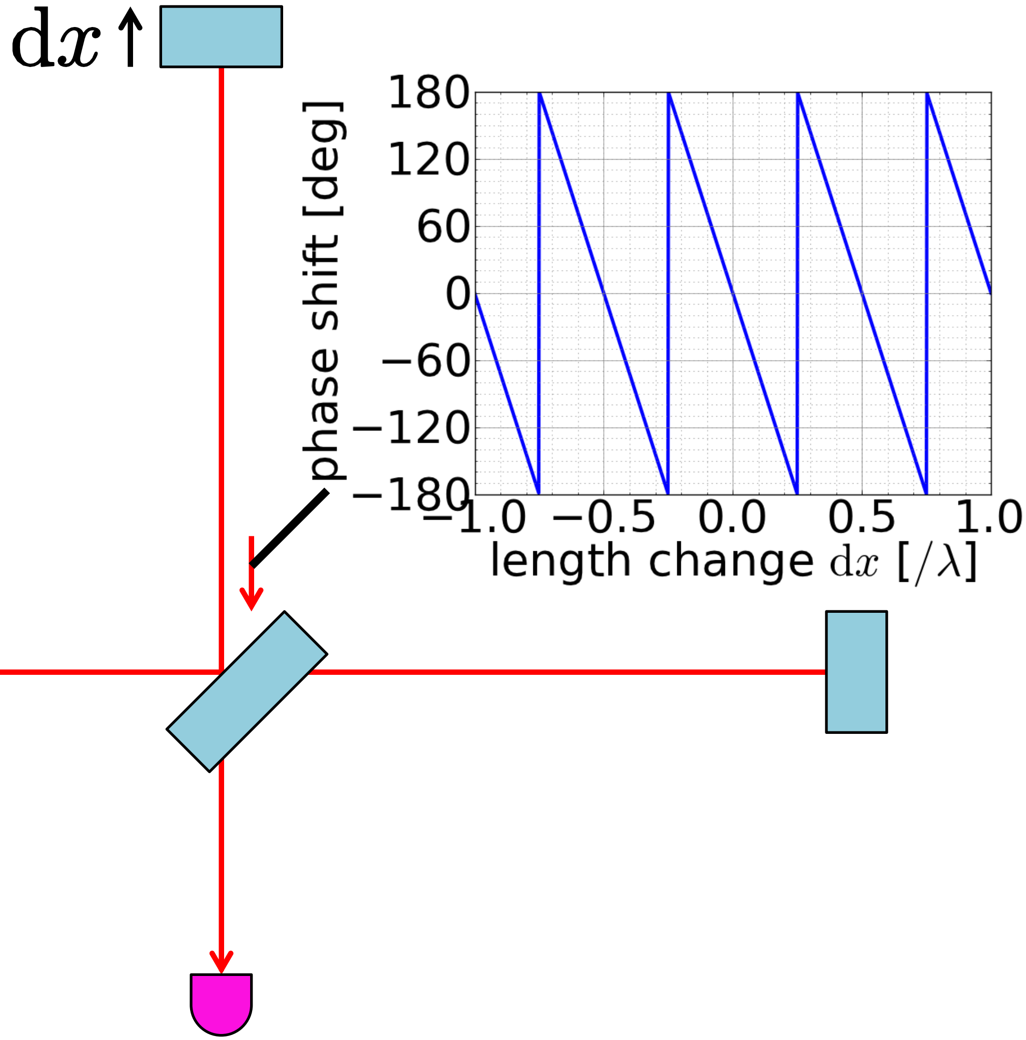


photo detector
→ GW signal

Fabry-Perot MI

- Fabry-Perot cavity gives enlarged phase shift
  → better sensitivity
  to GW
- but only at the resonance

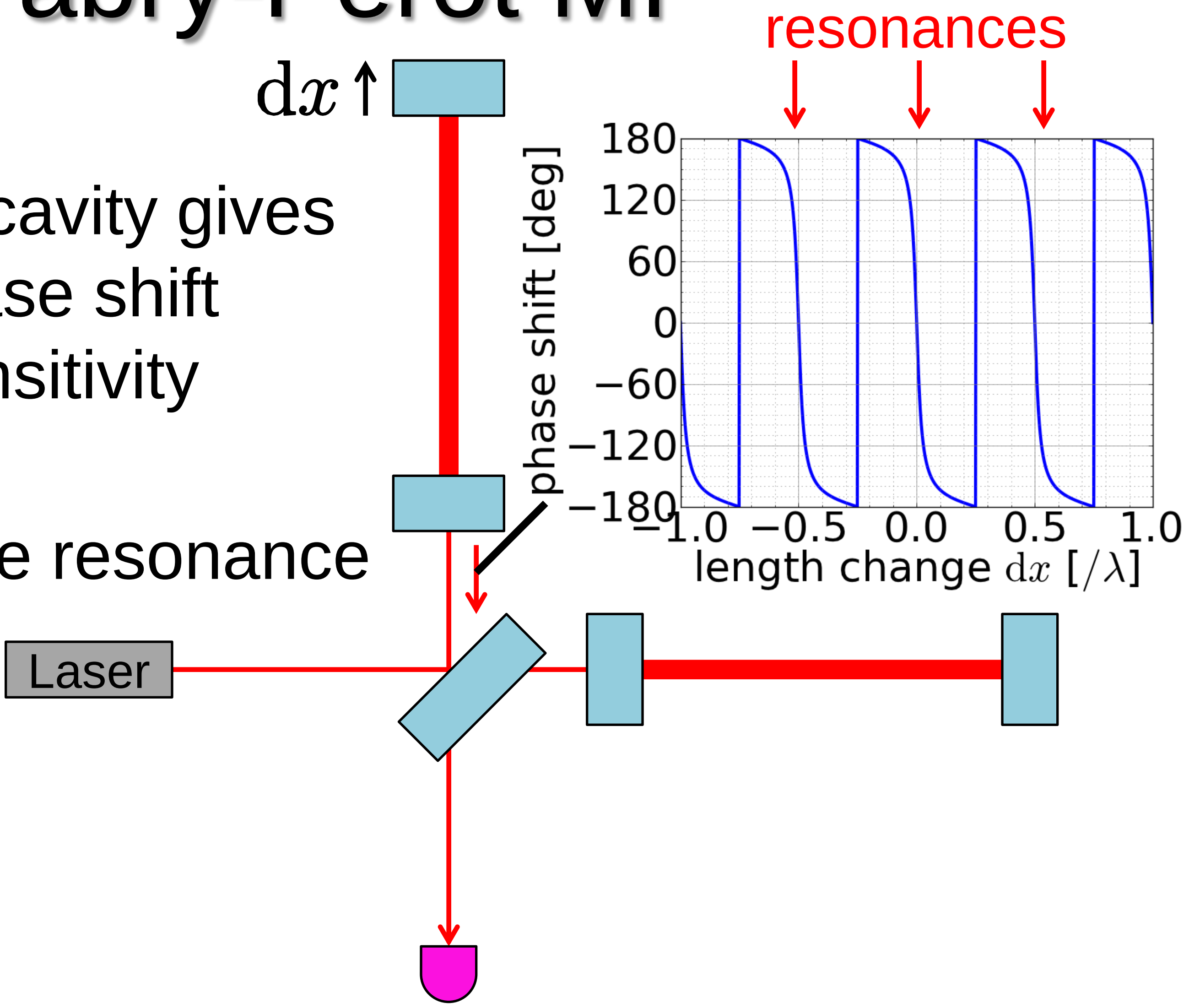


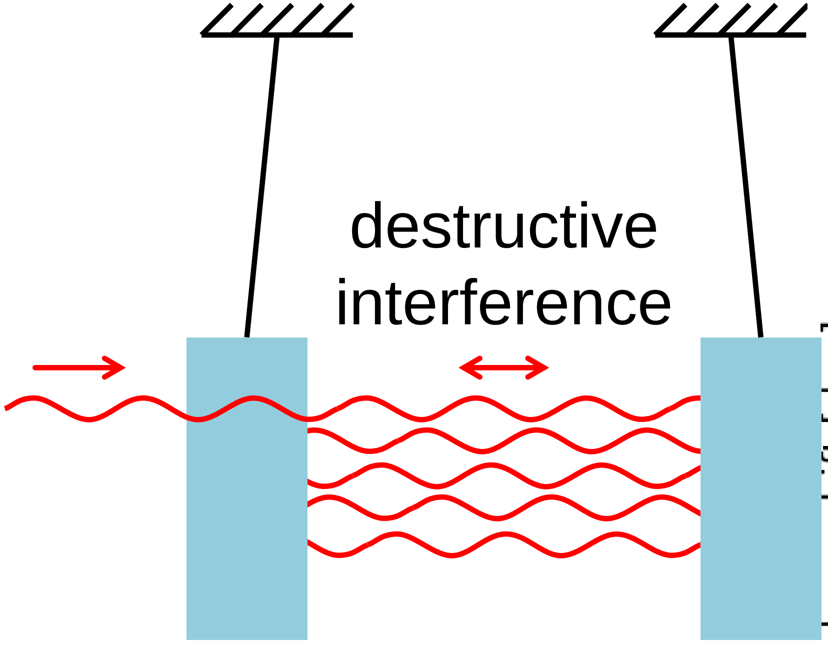
photo detector
→ GW signal

Resonance of FP cavity

- laser beam resonates when

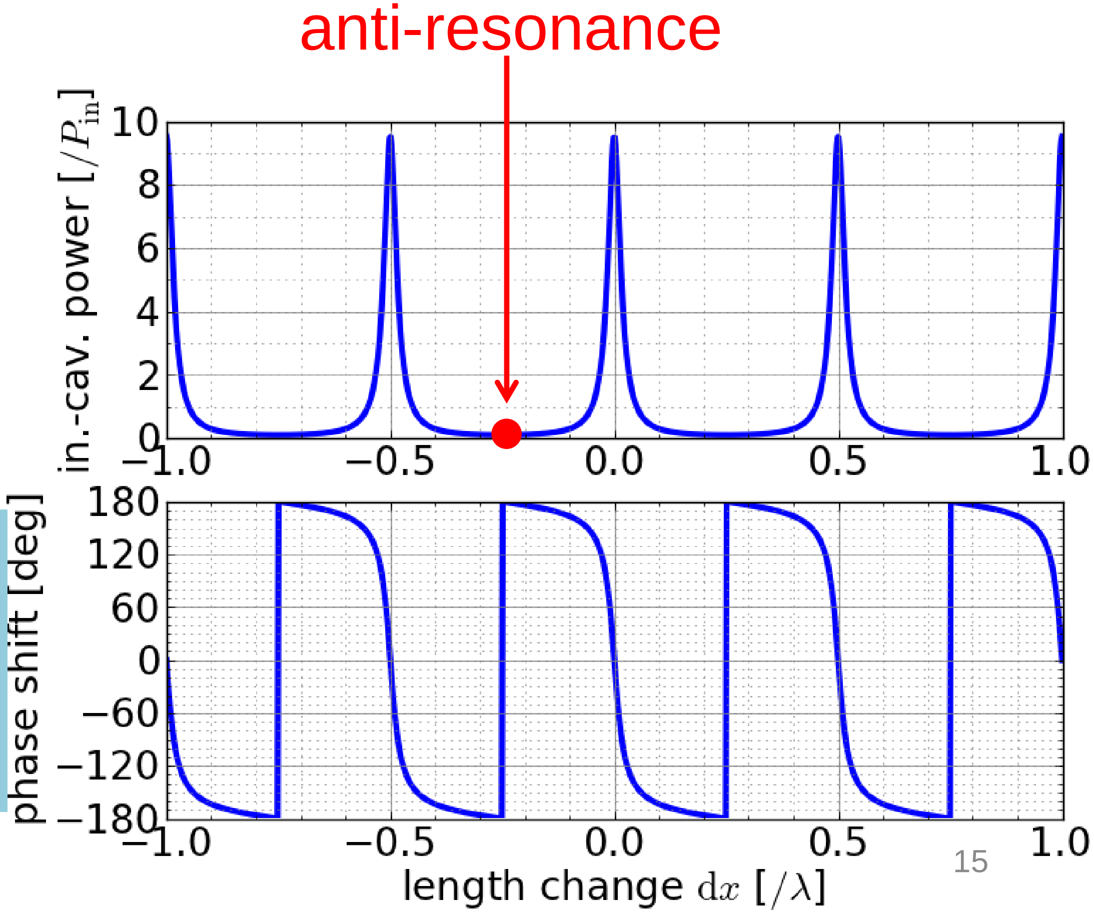
$$2L = m\lambda \qquad (\,m \text{ is an integer})$$

- intra-cavity power builds up at resonance



destructive interference

anti-resonance

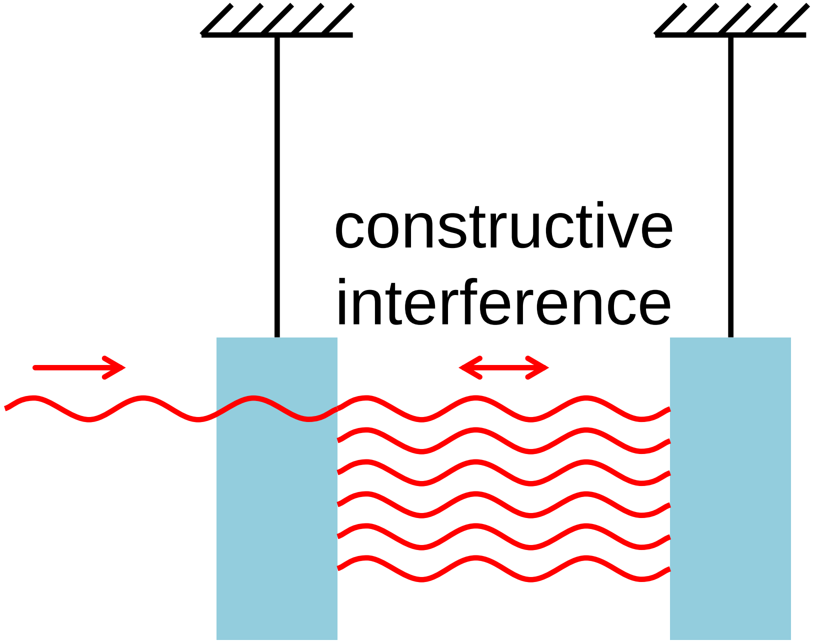


Resonance of FP cavity

- laser beam resonates when

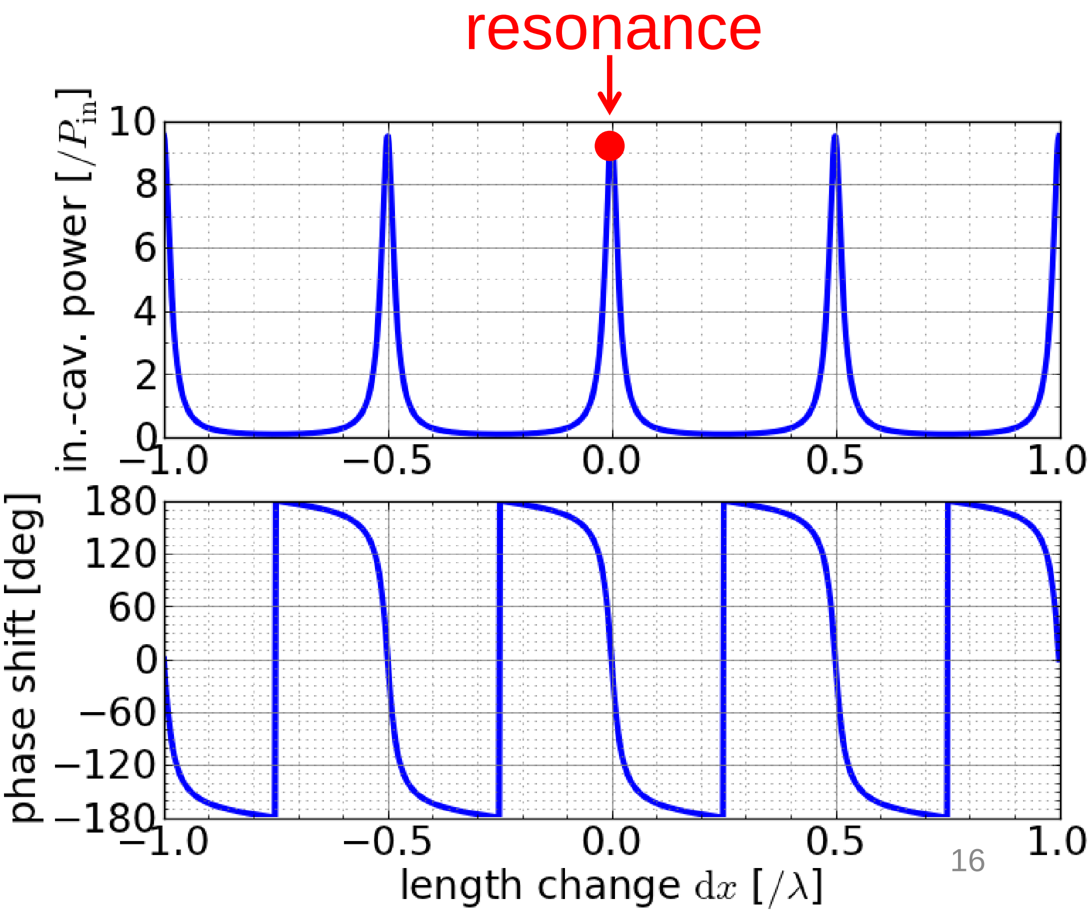
$$2L = m\lambda \qquad (\, m \text{ is an integer})$$

- intra-cavity power builds up at resonance



constructive interference

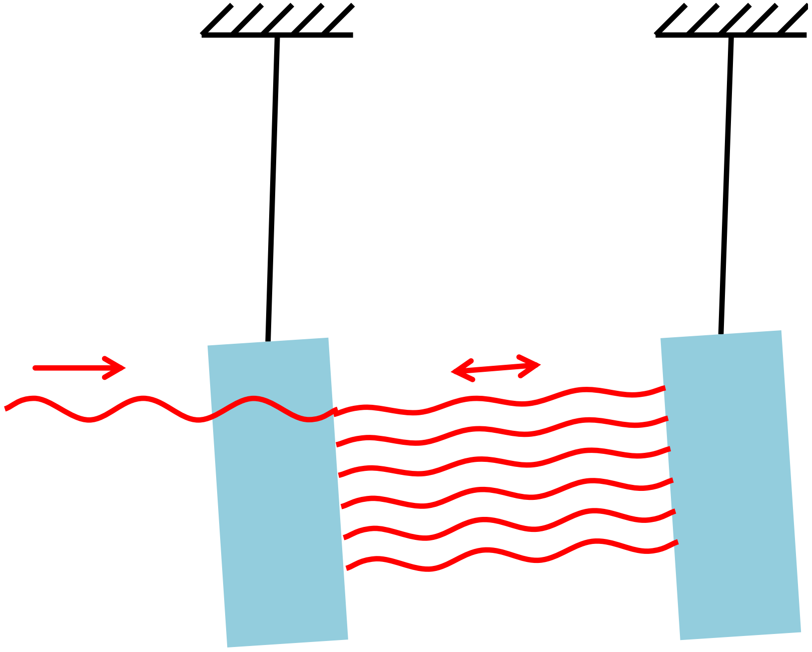
resonance



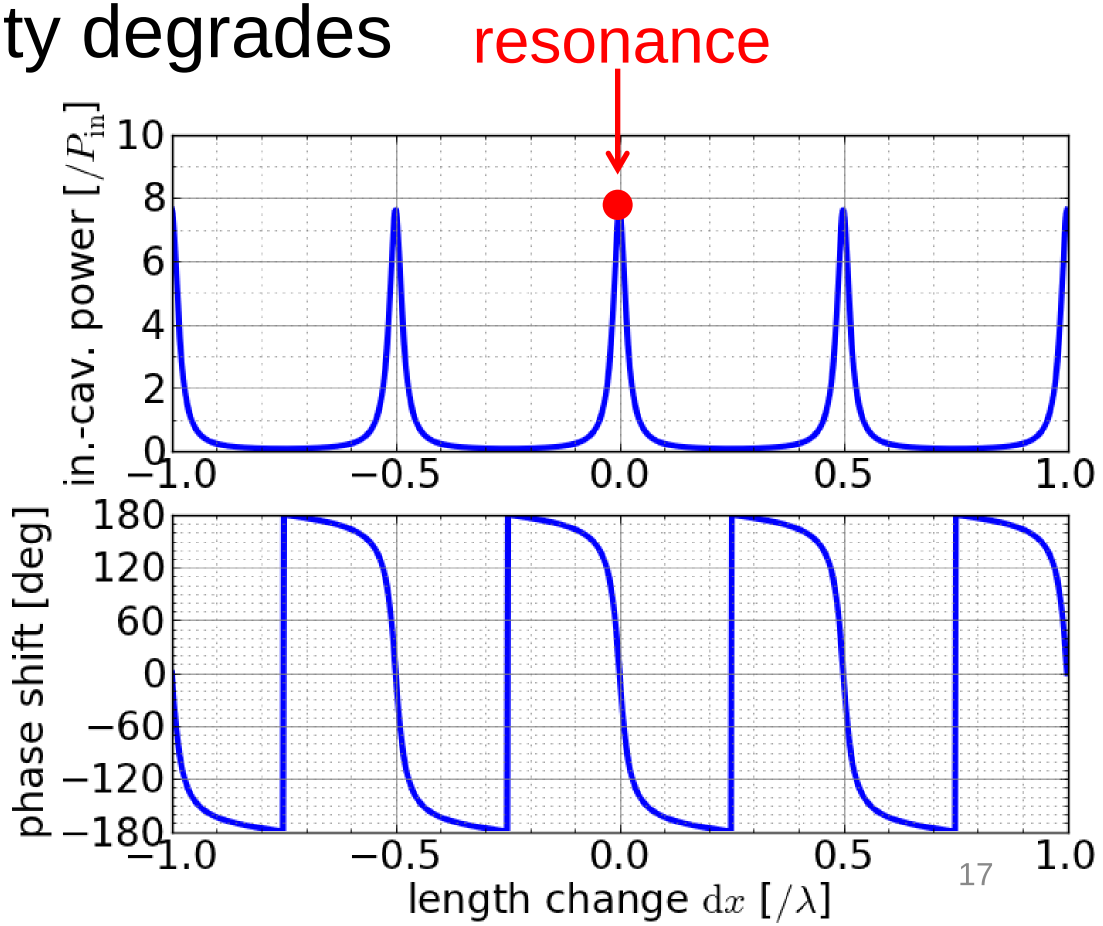
resonance

Alignment of FP cavity

- mis-alignment degrades coupling of incident beam and FP cavity
  → intra-cavity power degrades
  → phase sensitivity degrades



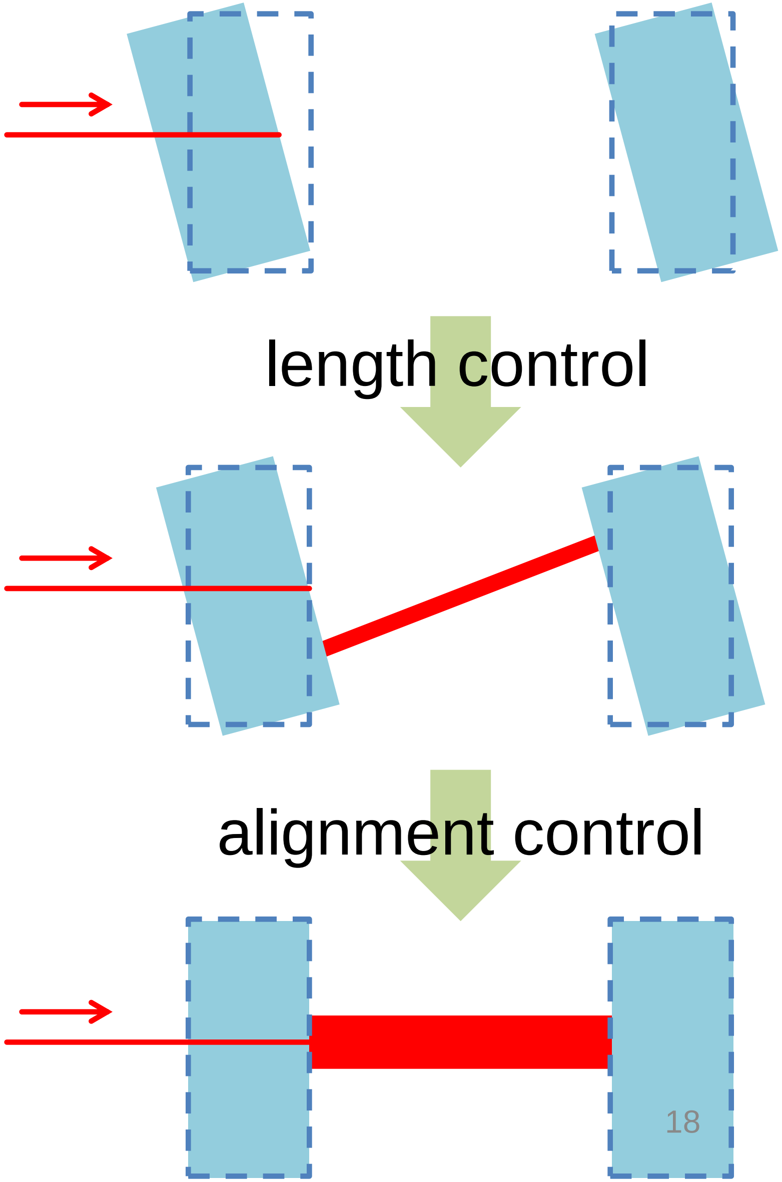
mis-aligned



resonance

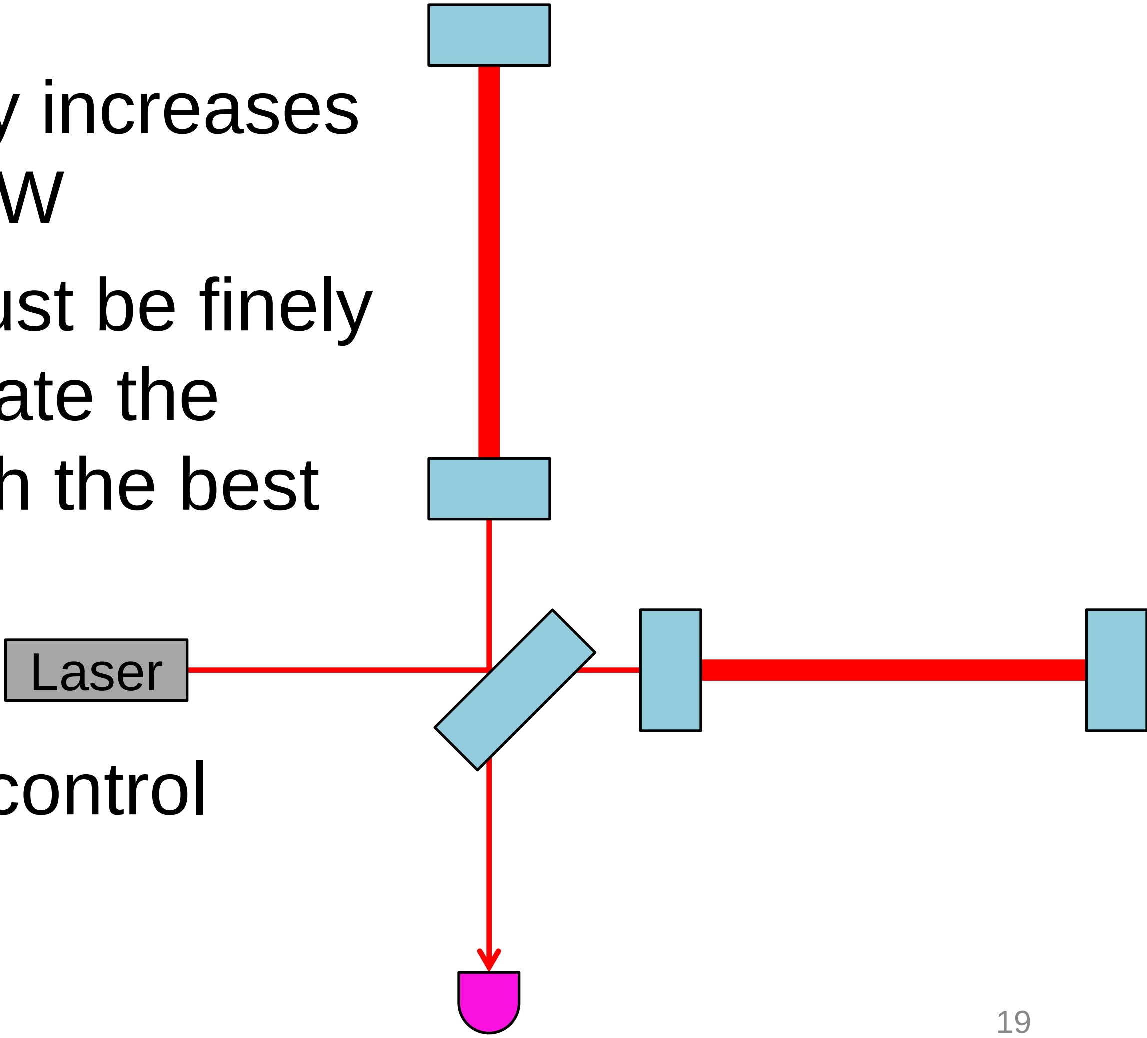
Operating point of FP cavity

- length control (LSC)
  → keeps FP at resonance
  (~ 1 um → < 0.1 nm)
- alignment control (ASC)
  → keeps coupling of FP
  and incident beam
  at maximum
  (~ 1 urad → < 10 nrad)
- length control and alignment control is essential for GW detection



Summary 1/3

- Interferometric GW detector is basically Michelson interferometer
- Fabry-Perot cavity increases its sensitivity to GW
- Mirror motions must be finely controlled to operate the interferometer with the best sensitivity



- Then how do we control them?

Well, it’s pretty complicated

- I’m not sure if you want to know how

Well, it’s pretty complicated

- I’m not sure if you want to know how

- But I will try to explain how anyway
- You will learn about
  - homodyne phase detection and heterodyne phase detection
  - phase modulation of laser beam
  - Gaussian beam

GW detection is phase detection

- GW changes length
  → phase of laser beam (EM wave) changes
- but photo detector is not sensitive to the phase of the laser beam
- Photo detector is sensitive to amplitude

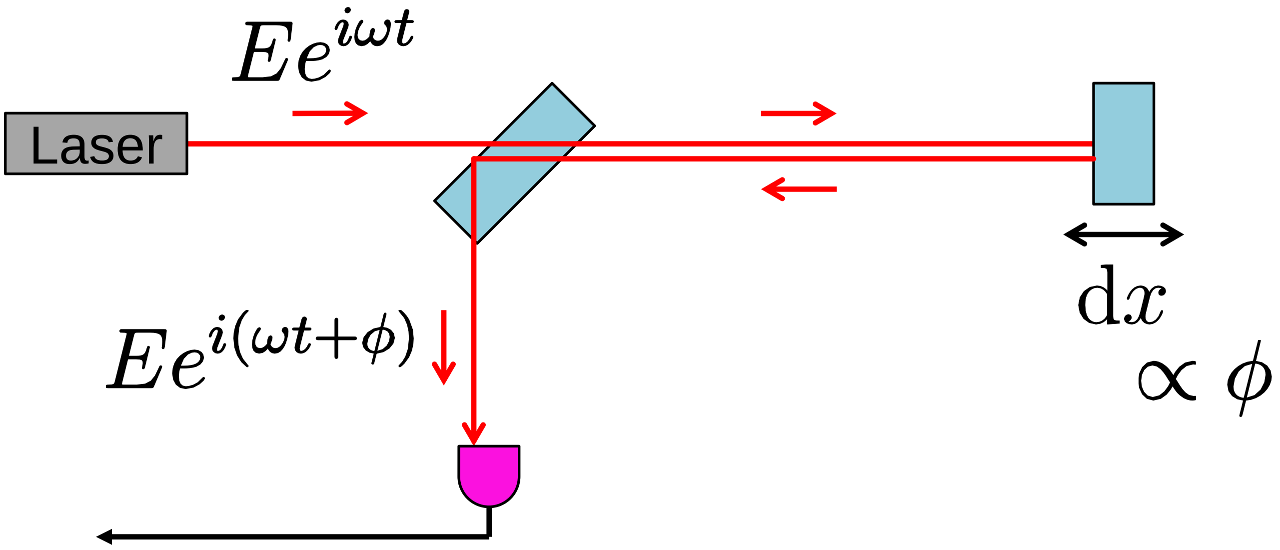


photo current

$$I \propto \left|Ee^{i(\omega t+\phi)}\right|^2$$
$$= E^2$$

Reference beam is needed

- if there's a reference beam, you can convert phase change to amplitude change
- that's why we need interferometry

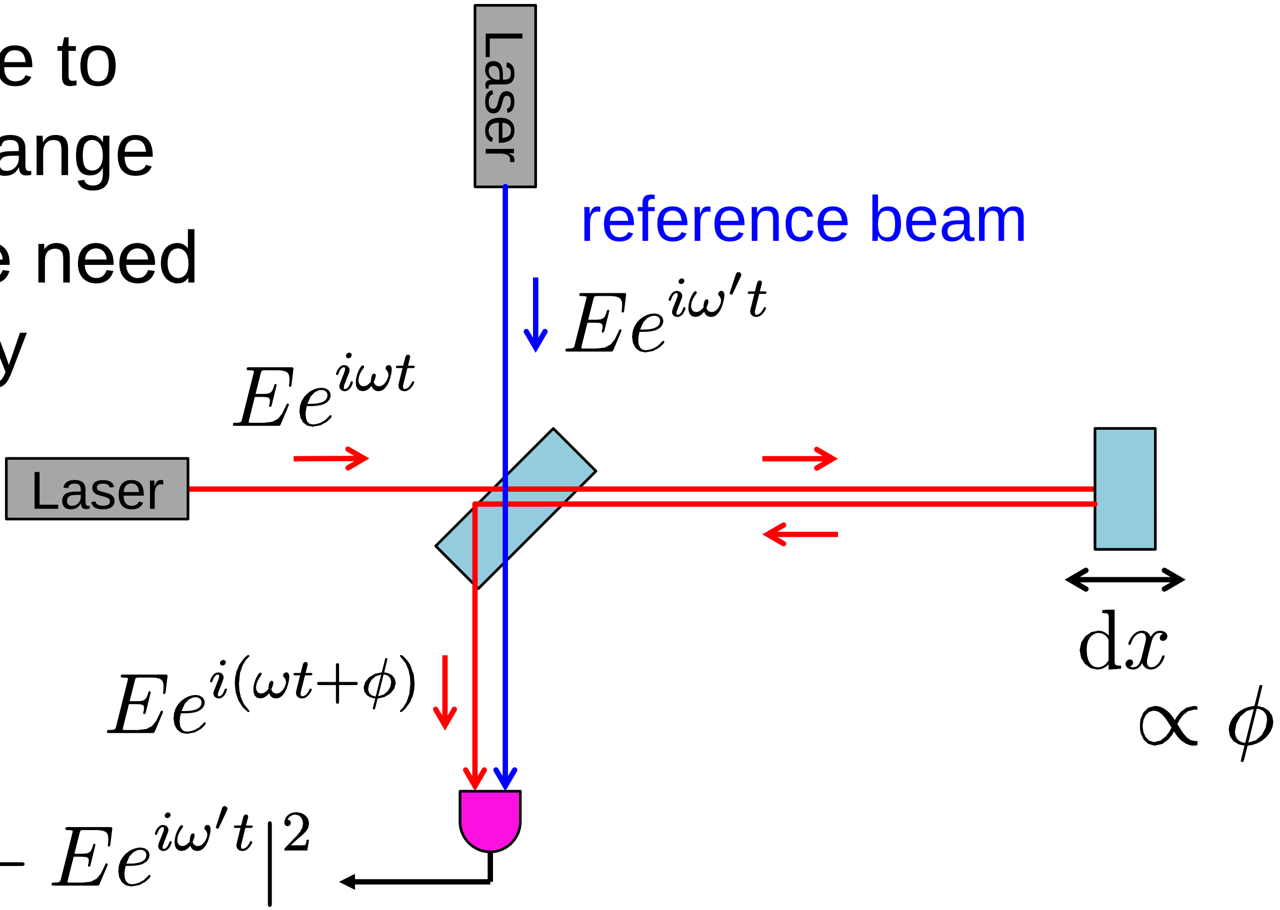


photo current

$$I \propto |Ee^{i(\omega t+\phi)} + Ee^{i\omega' t}|^2$$

$$= 2E^2[1 + \cos((\omega - \omega')t + \phi)]$$

Homodyne and heterodyne

- if $\omega - \omega' = 0$

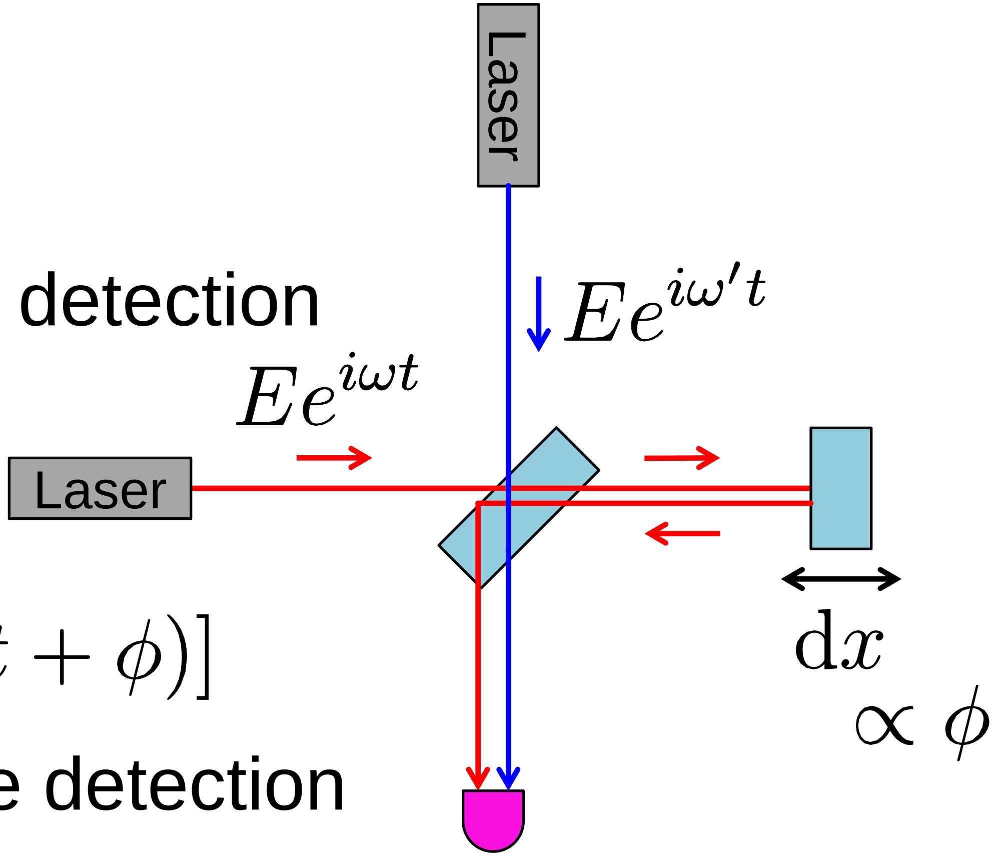
  $$I \propto 2E^2[1 + \cos\phi]$$

  → homodyne phase detection

- if $\omega - \omega' = \Omega$

  $$I \propto 2E^2[1 + \cos(\Omega t + \phi)]$$

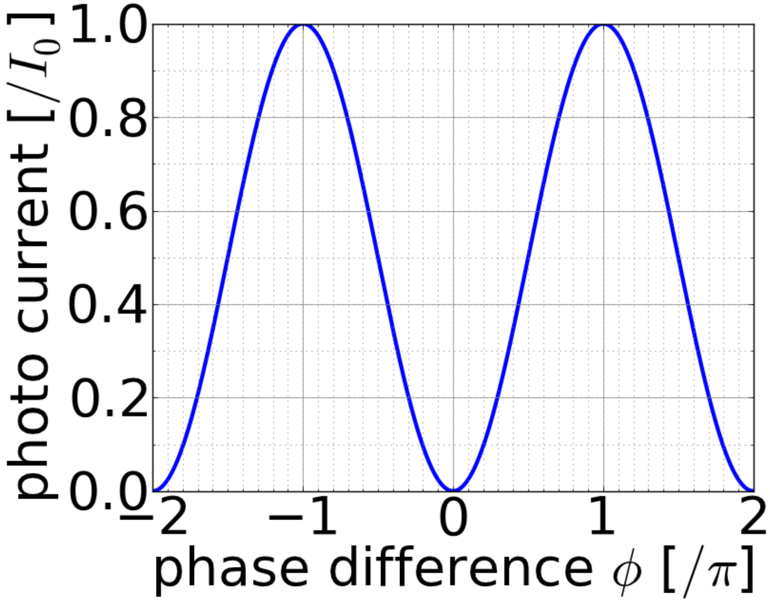
  → heterodyne phase detection

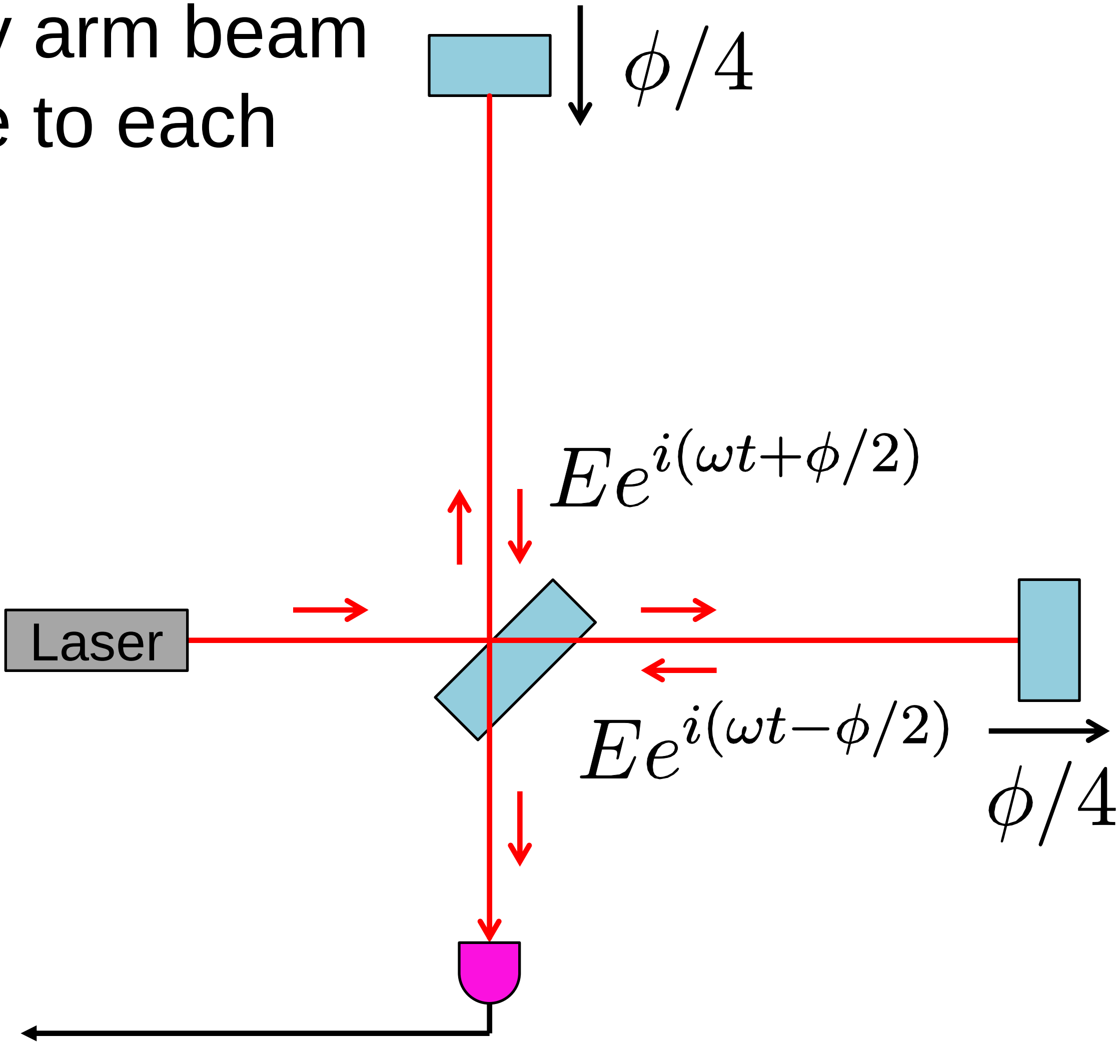


Michelson is homodyne

- x arm beam and y arm beam act as a reference to each other

$$I \propto \frac{1}{2}E^2(1-\cos\phi)$$

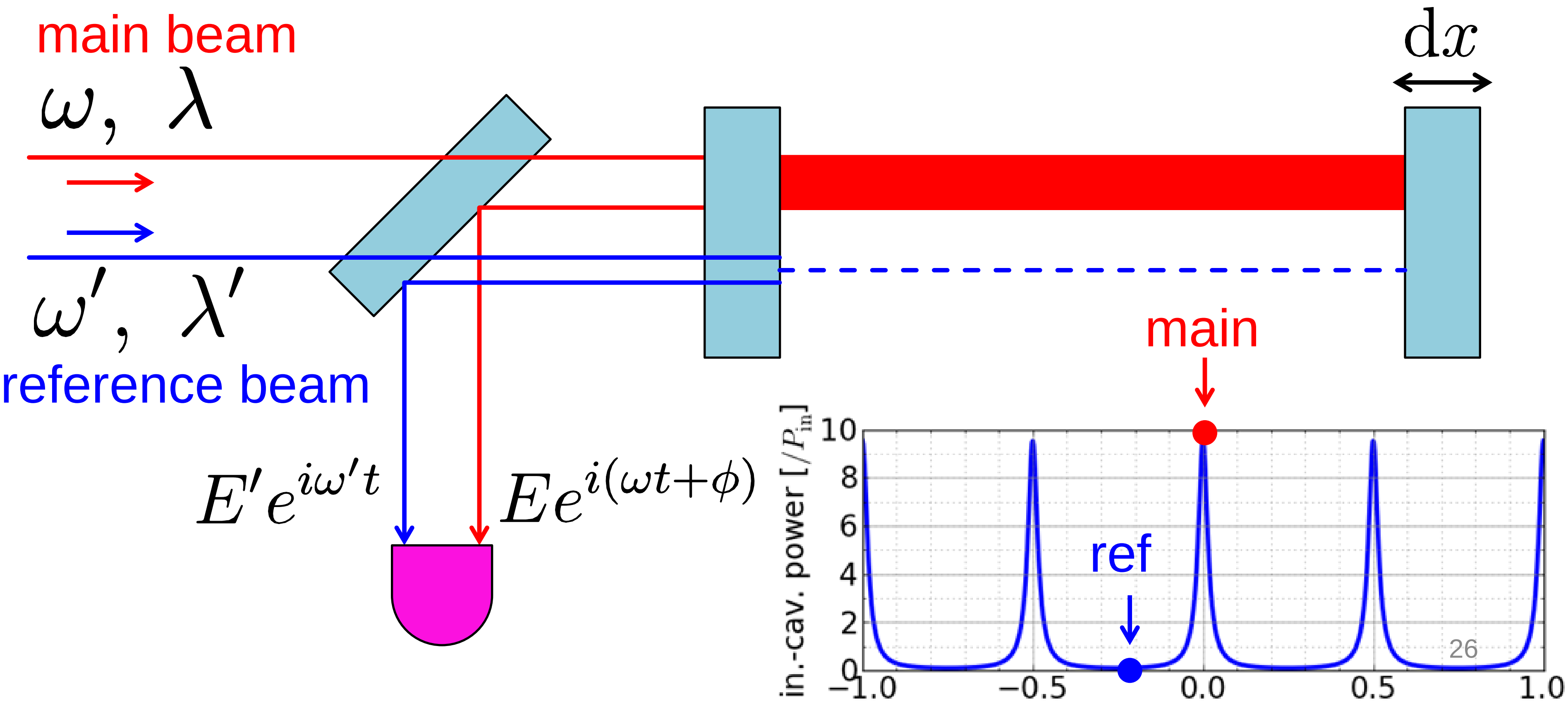




Heterodyne for Fabry-Perot cavity

- put 2 beams with different frequencies
- main beam resonates, but reference beam doesn't

$$2L = m\lambda \qquad\qquad 2L \neq m\lambda'$$



Phase modulation

- electric field of a laser beam (plane wave)

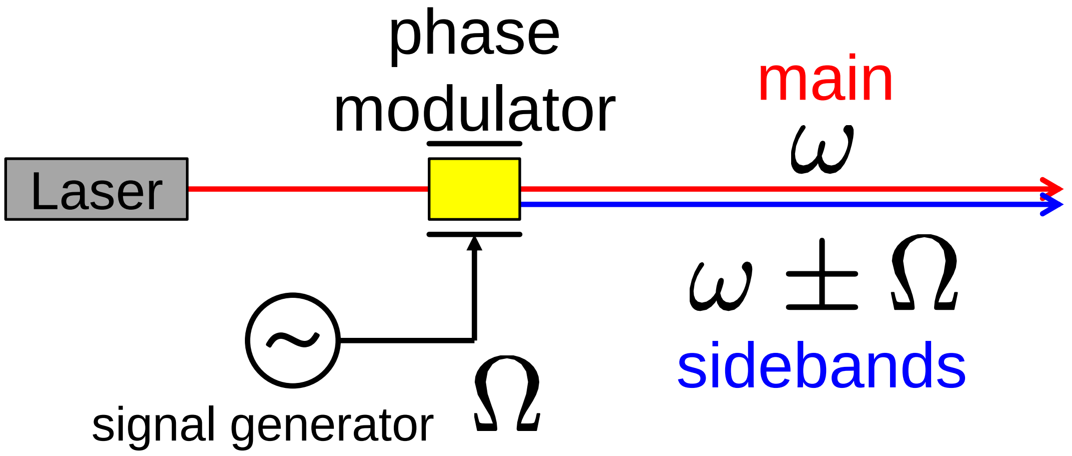
$$E = E_0 e^{i\omega t}$$

- phase modulation creates sidebands

$$E = E_0 e^{i(\omega t + \beta \sin \Omega t)}$$

$$\simeq E_0 [J_0(\beta) e^{i\omega t} + J_1(\beta) e^{i(\omega+\Omega)t} - J_1(\beta) e^{i(\omega-\Omega)t}]$$

main upper sideband lower sideband

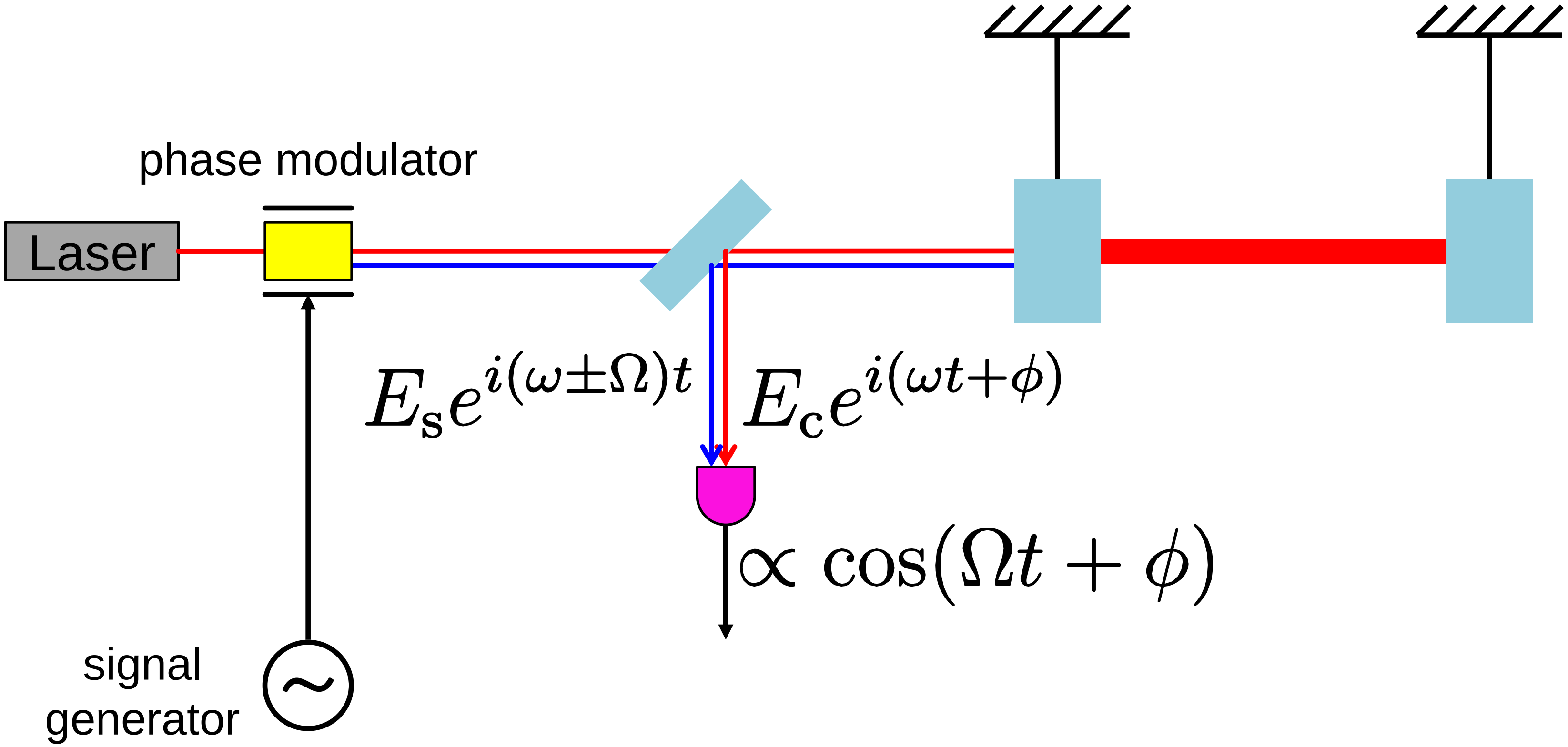


electro-optic phase modulator

- sidebands work as reference beam

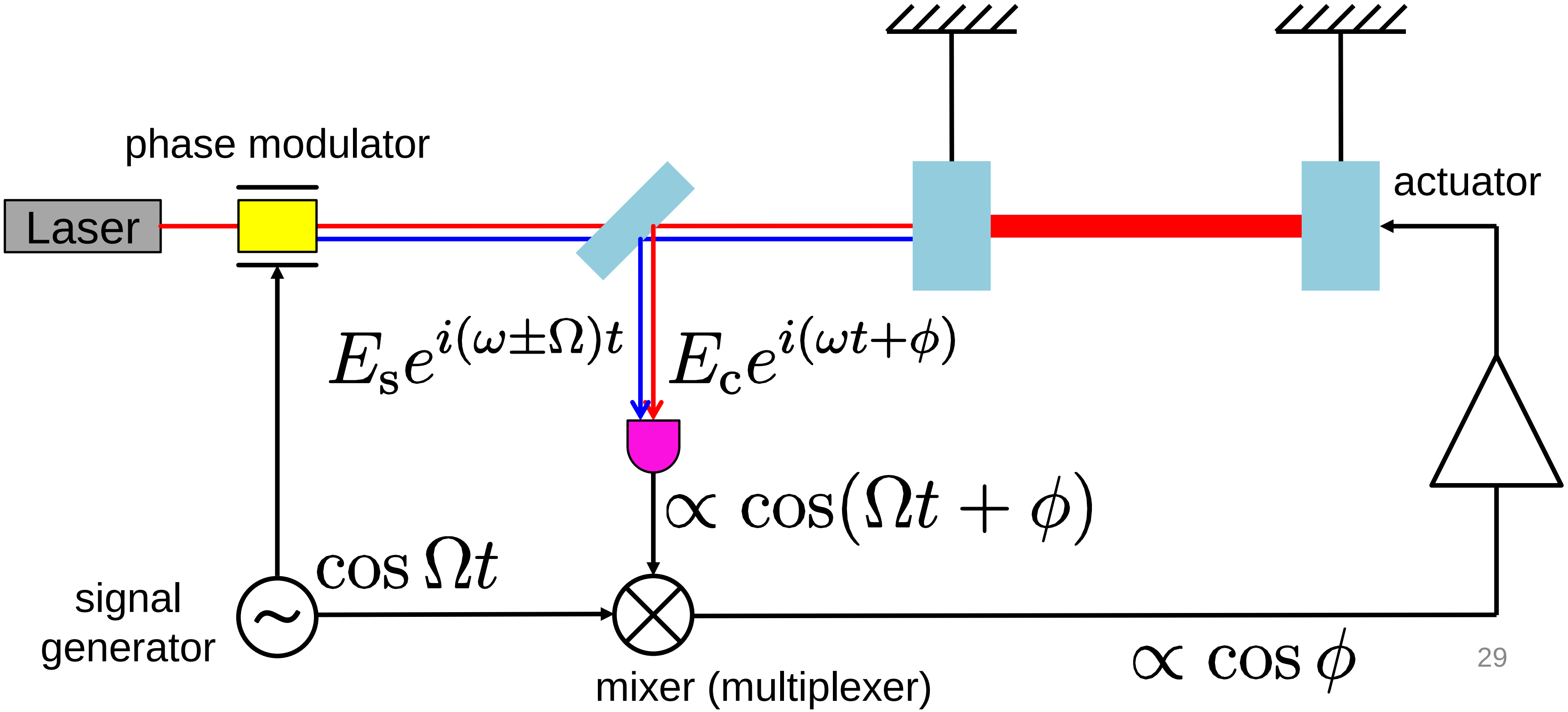
Length sensing of FP cavity

- interference between
  - sidebands (reference)
  - main beam (carries cavity length info.)
- called Pound-Drever-Hall method



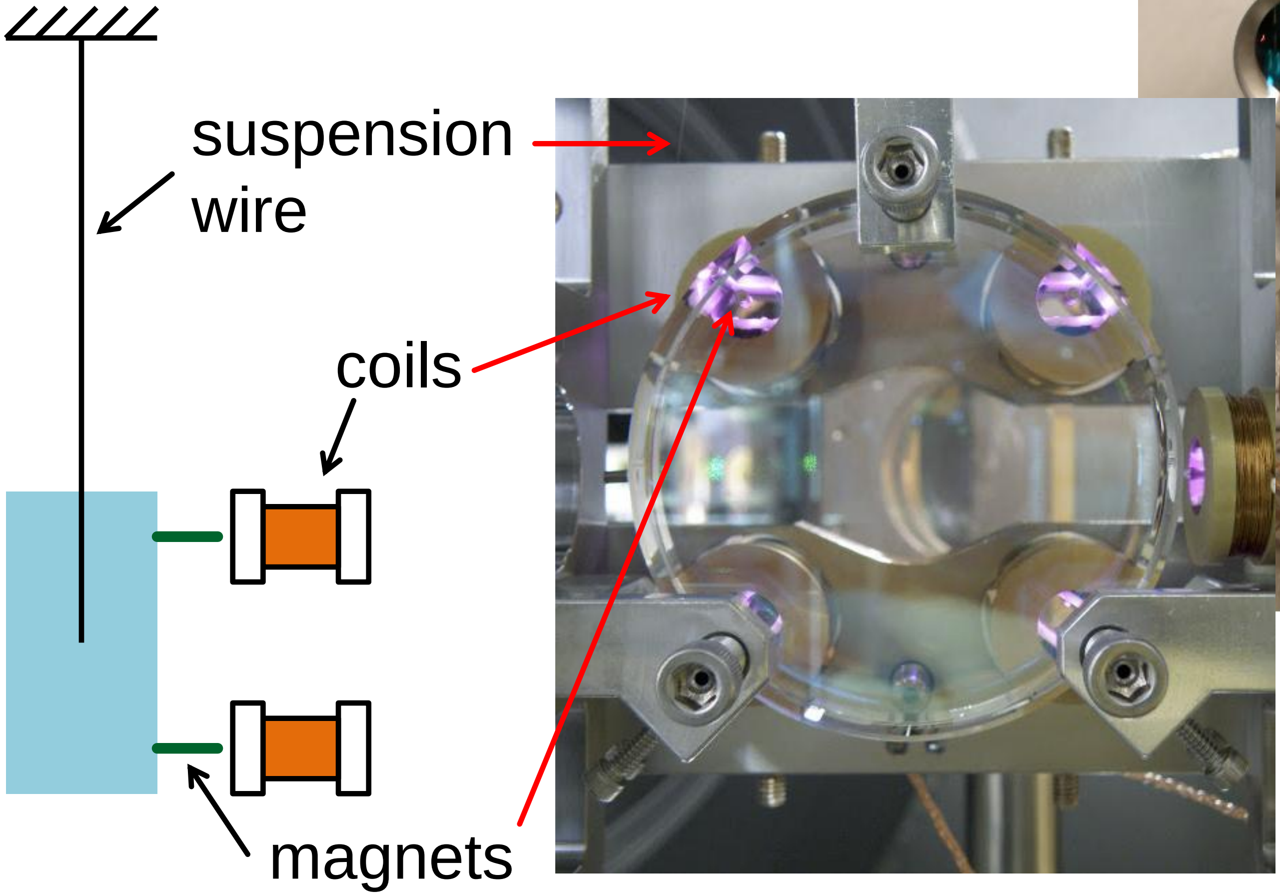
Length control of FP cavity

- demodulate photo detector output
- feedback to actuators attached on mirrors

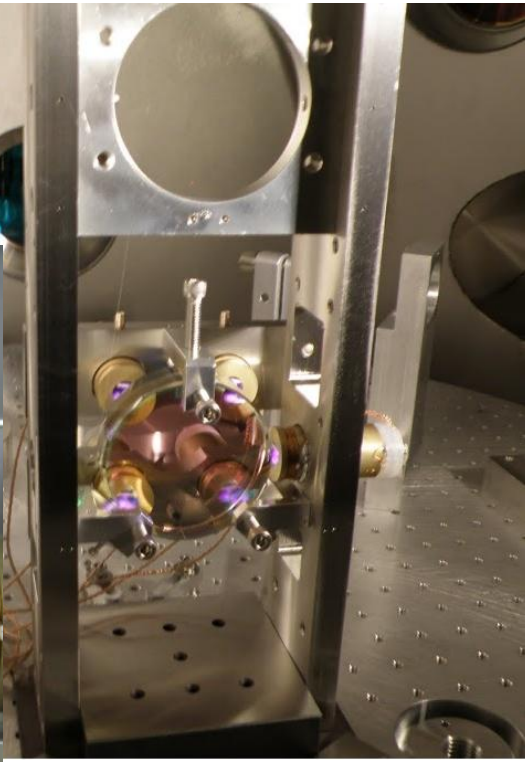


Coil-magnet actuator

- current in coils → creates magnetic field → magnetic force acts on a mirror



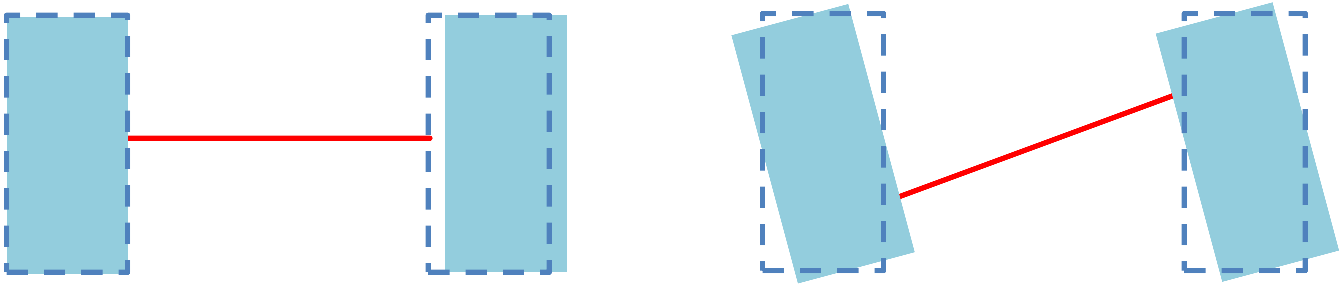
Caltech 40m SRM



Caltech 40m ETMY

Alignment control?

- So far, we have only considered about the length control



- Length control can be understood by plane wave approximation

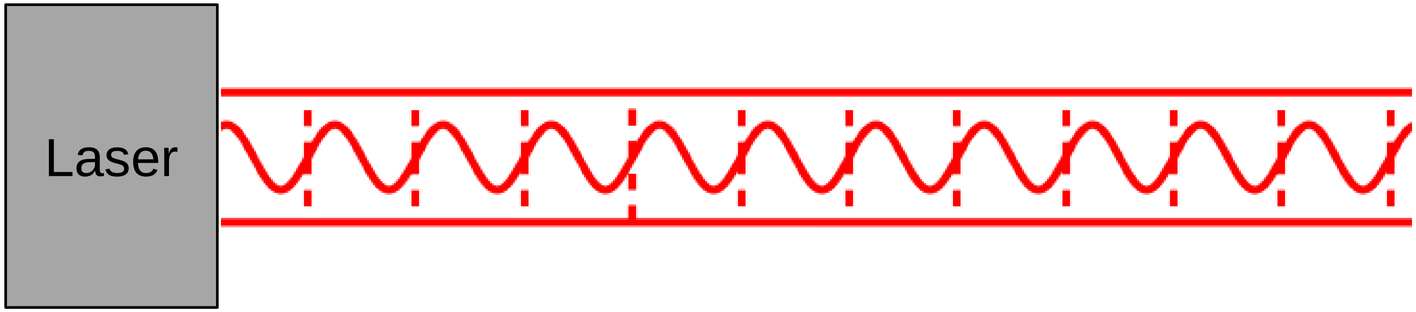
$$E = E_0 e^{i\omega t}$$

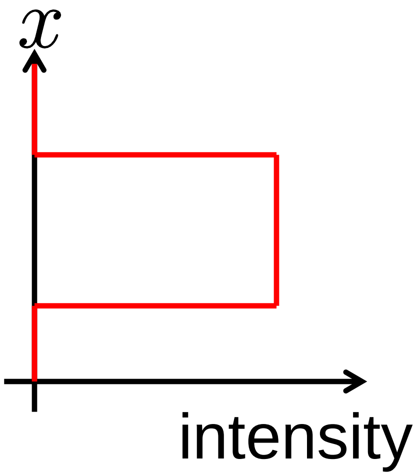
- But laser beams are not plane wave, actually
- They are Gaussian beam
- You need to know about Gaussian beam for understanding alignment control

Gaussian beam

- ”ideal” plane wave

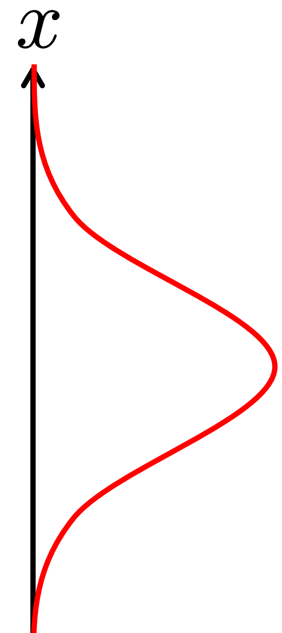
$$E = E_0 R(x, y) e^{i(\omega t - kz)}$$

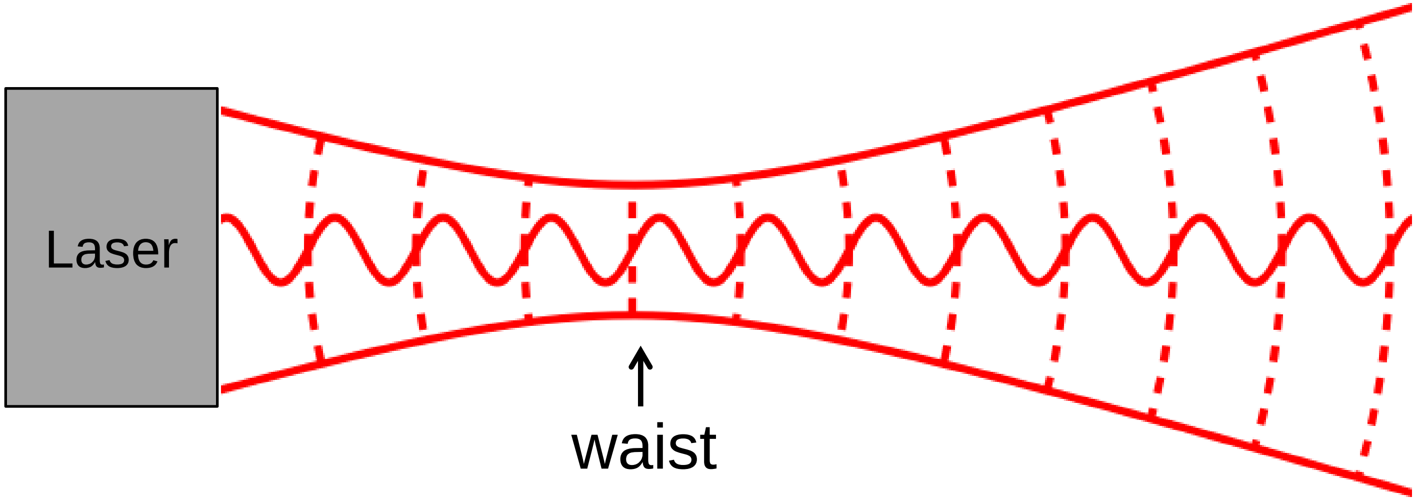




- Gaussian beam

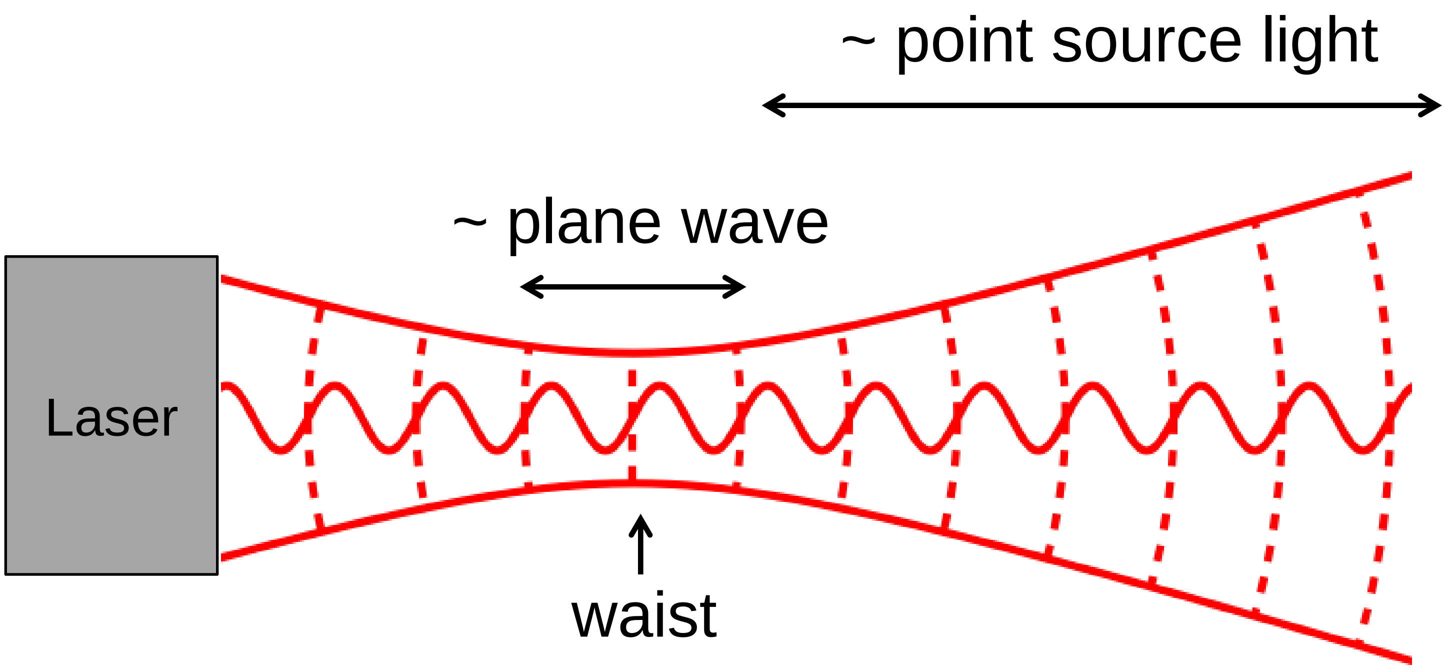
$$E = E_0 U_{00}(x, y, z) e^{i(\omega t - kz + \eta(z))}$$





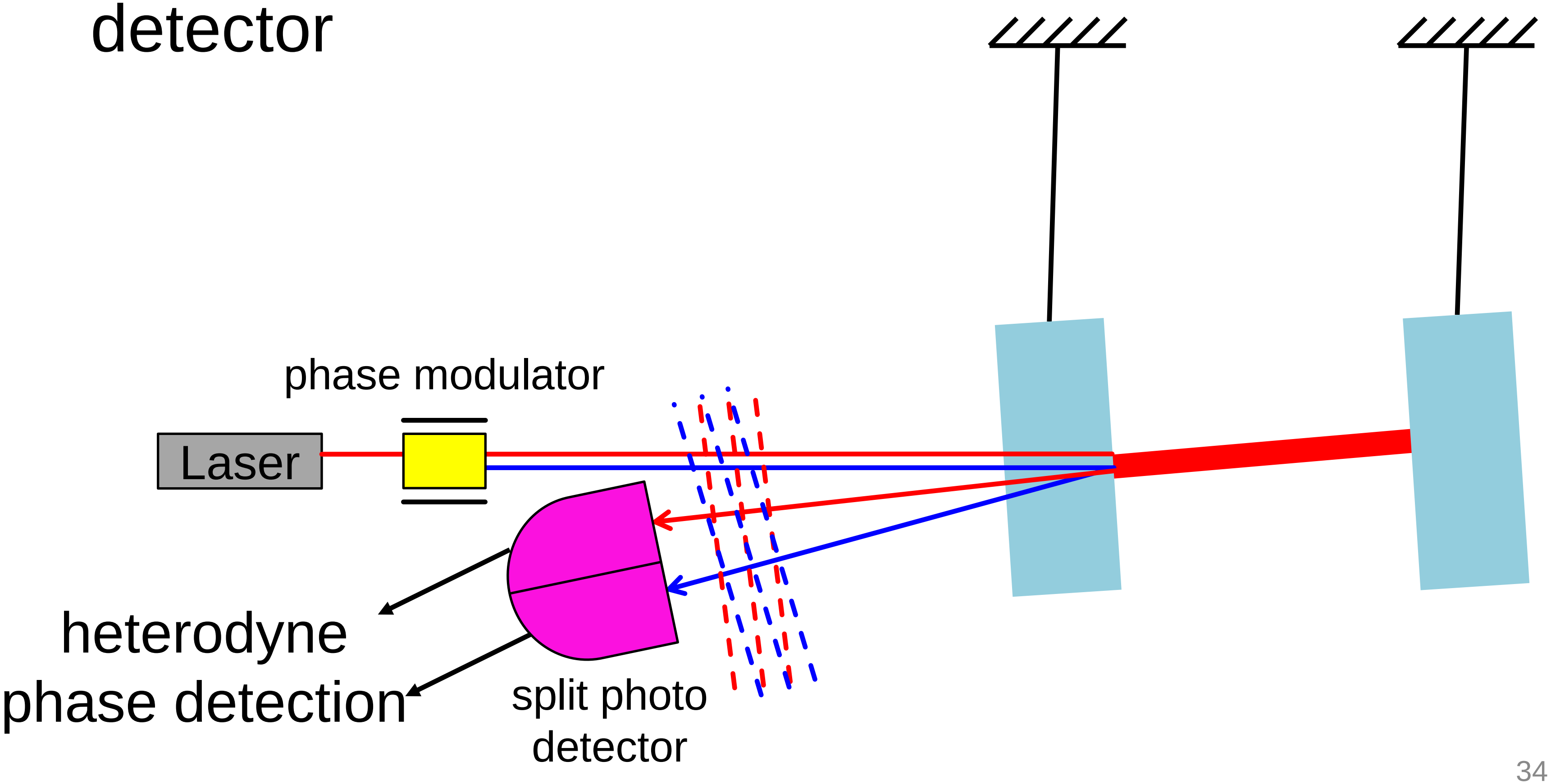
Near field and far field

- Gaussian beam is like
  - plane wave light near the waist
  - point source light far from the waist



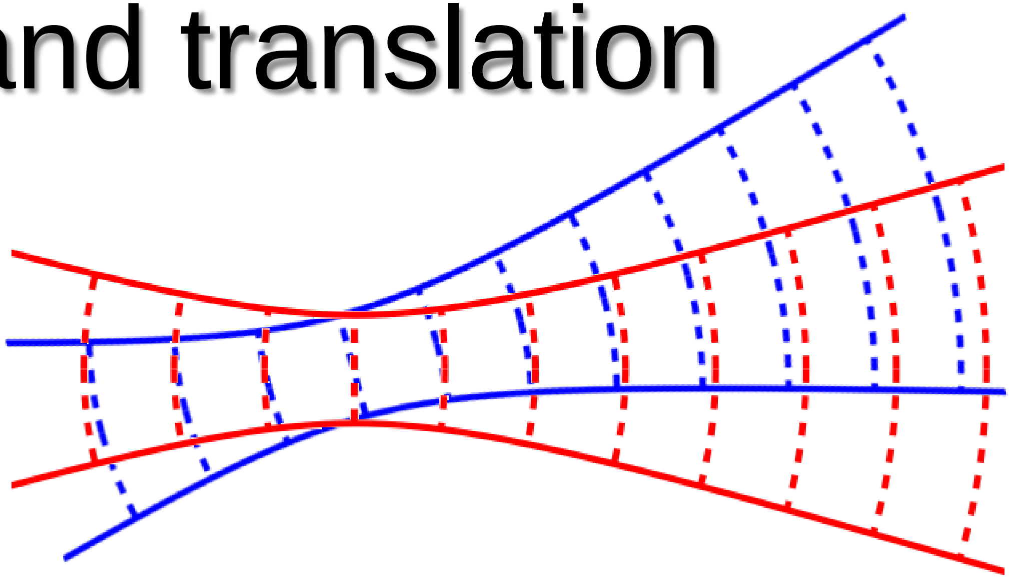
Wavefront sensing

- wavefront of resonating main beam and cavity reflected sidebands are different
- this difference can be detected by split photo detector

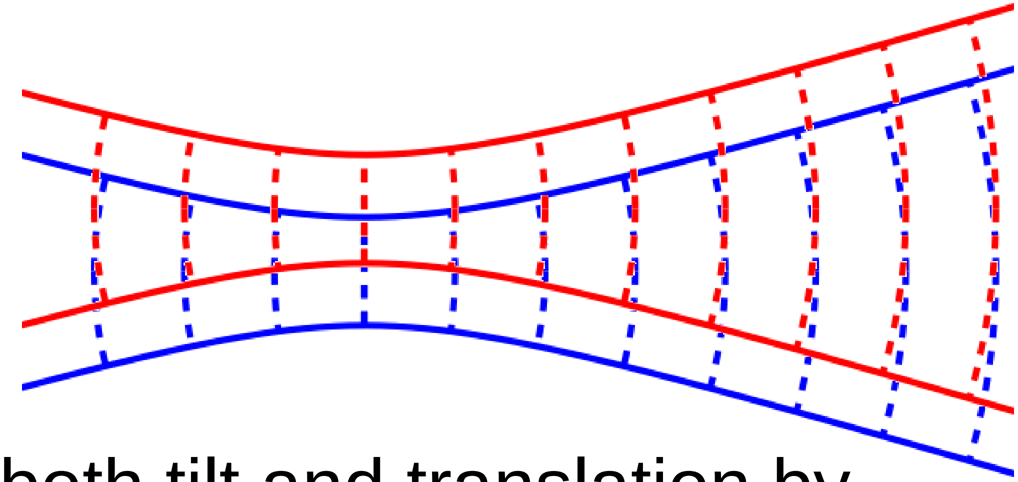


Beam tilt and translation

- sensitivity to beam tilt is high at near field



- sensitivity to beam translation is high at far field



- thus, we can sense both tilt and translation by placing split photo detector at different places → we can align mirrors

Summary 2/3

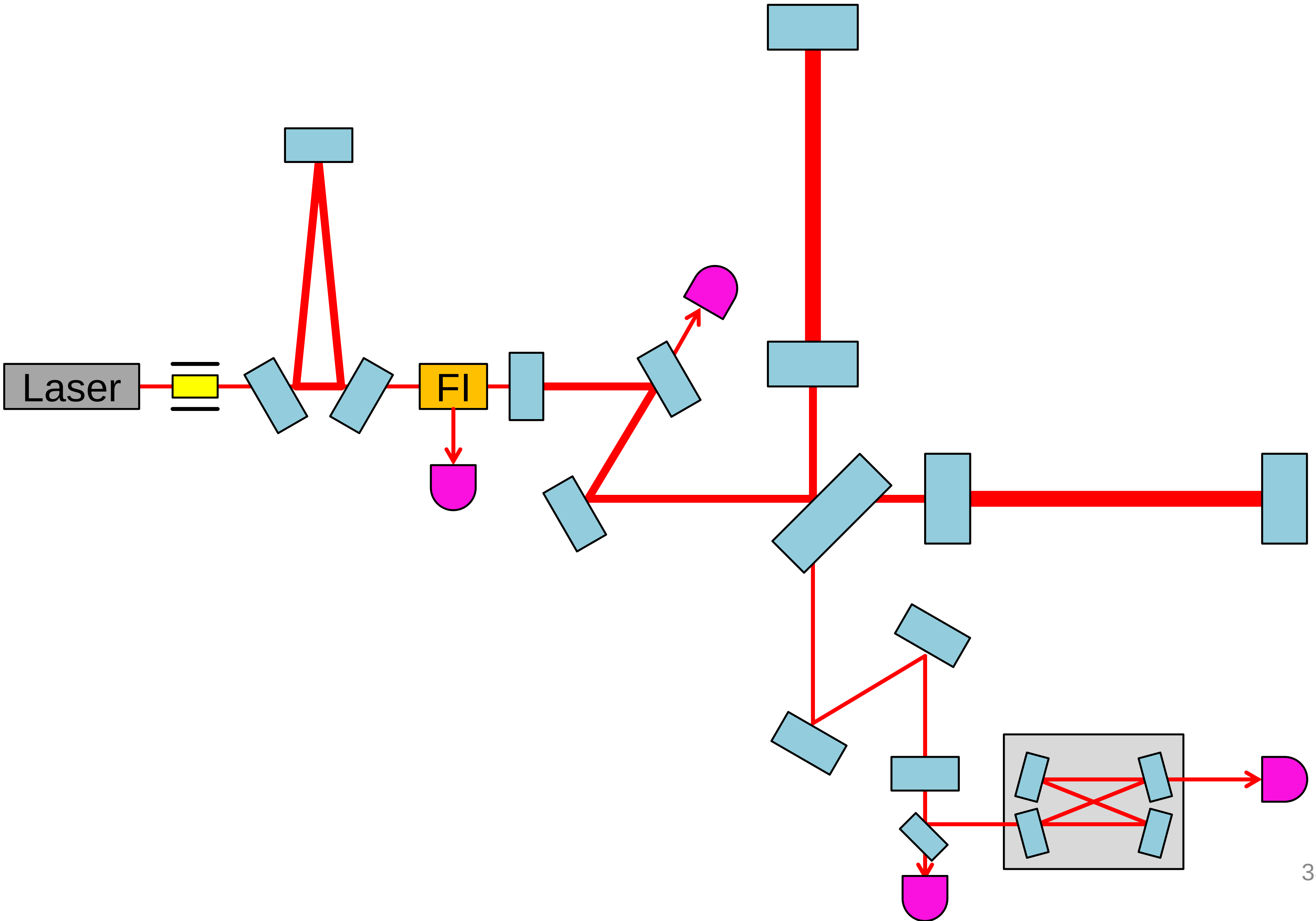
- Phase detection is key for GW detectors
- For phase detection, you always need reference beam
- Phase modulation of beam creates sidebands, which work as reference beam
- Interference of main beam and sidebands gives length signal and alignment signal
- For alignment sensing, wavefront sensing technique is used

- Then what’s the situation in KAGRA?

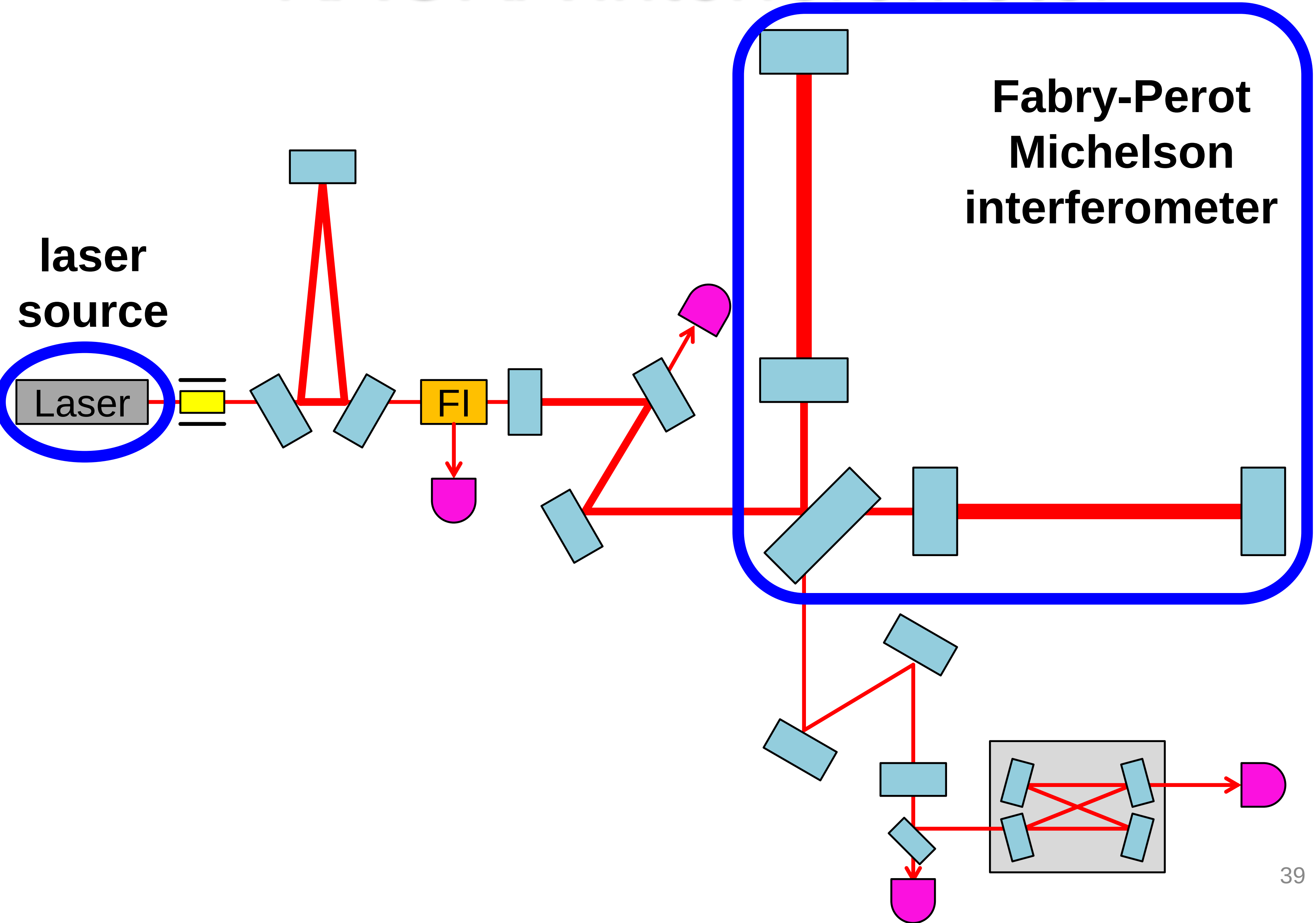
Headache……

- I will briefly explain
  - further technologies used in KAGRA interferometer (and aLIGO, AdVirgo)
  - what I do for KAGRA

KAGRA interferometer



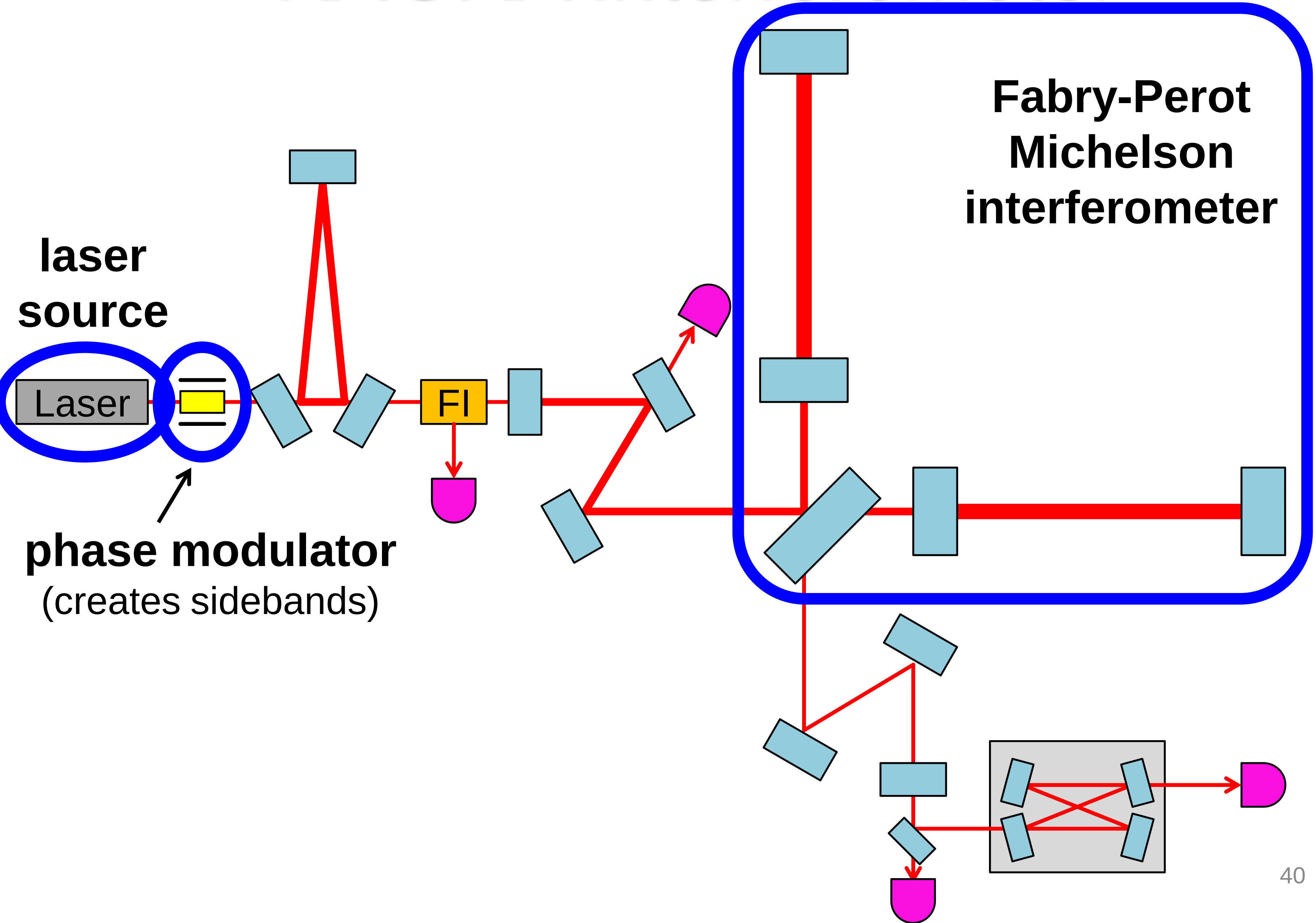
KAGRA interferometer



Fabry-Perot Michelson interferometer

laser source

KAGRA interferometer

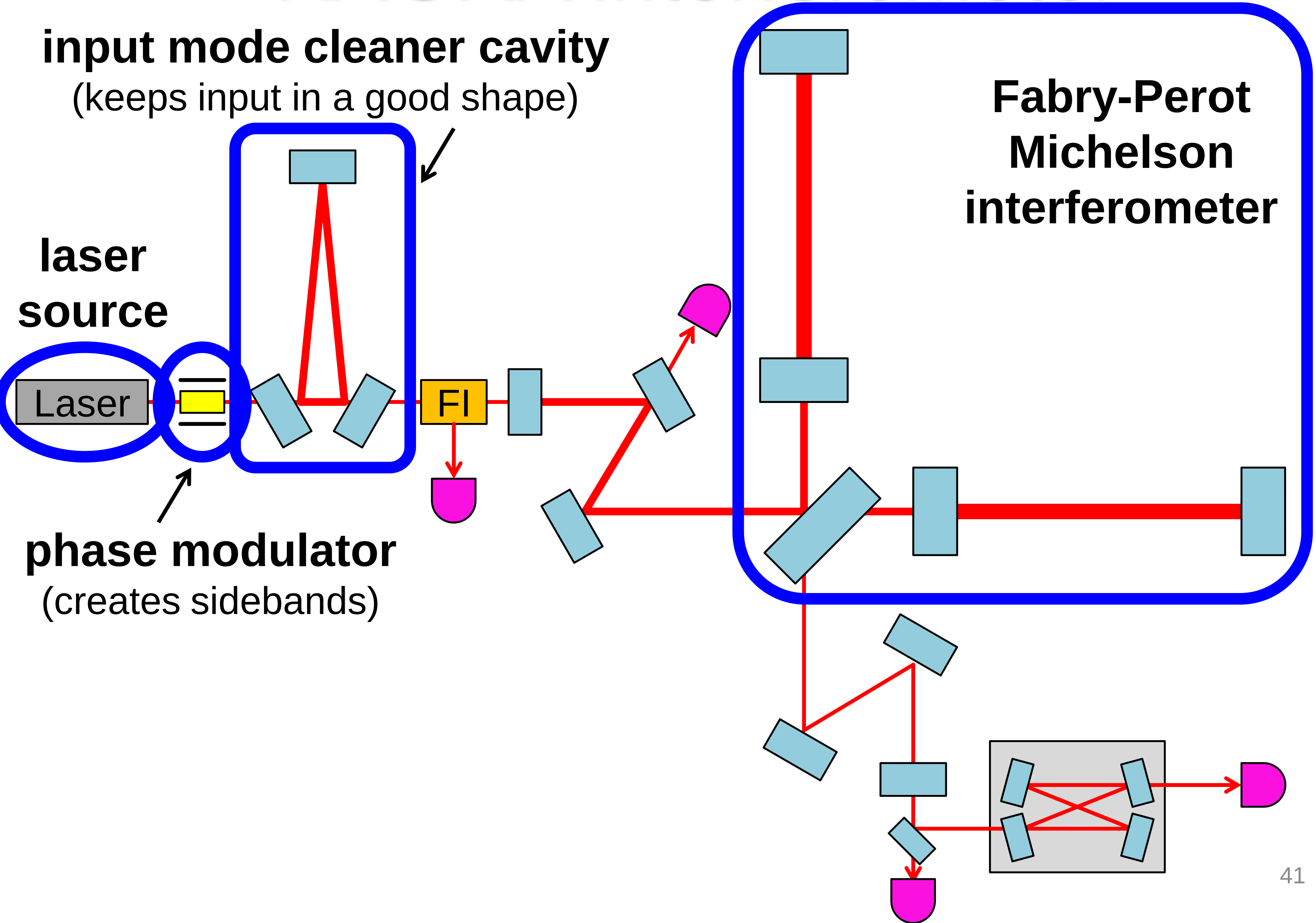


Fabry-Perot Michelson interferometer

laser source

phase modulator
(creates sidebands)

KAGRA interferometer



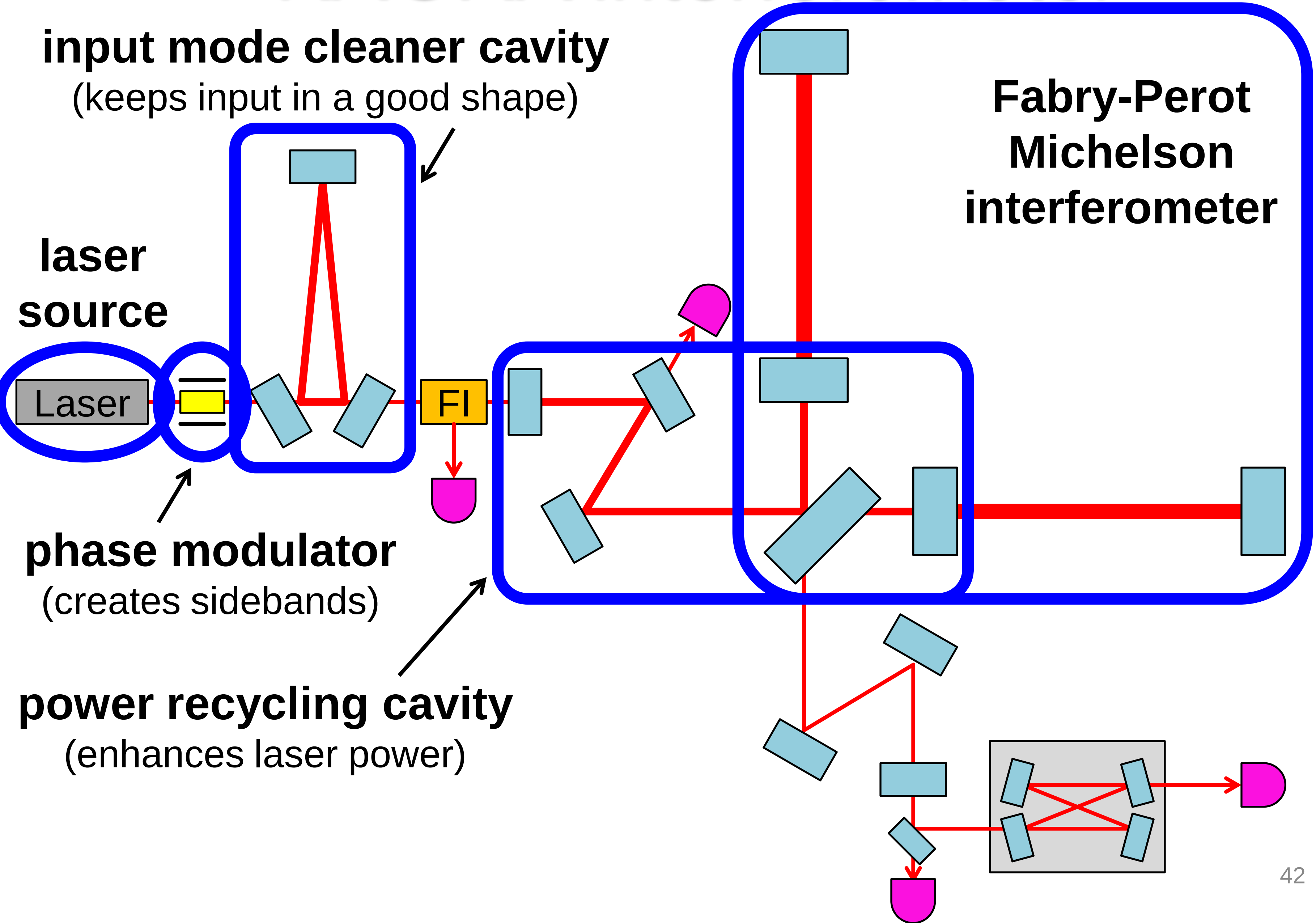
input mode cleaner cavity
(keeps input in a good shape)

laser source

phase modulator
(creates sidebands)

Fabry-Perot Michelson interferometer

KAGRA interferometer



input mode cleaner cavity
(keeps input in a good shape)

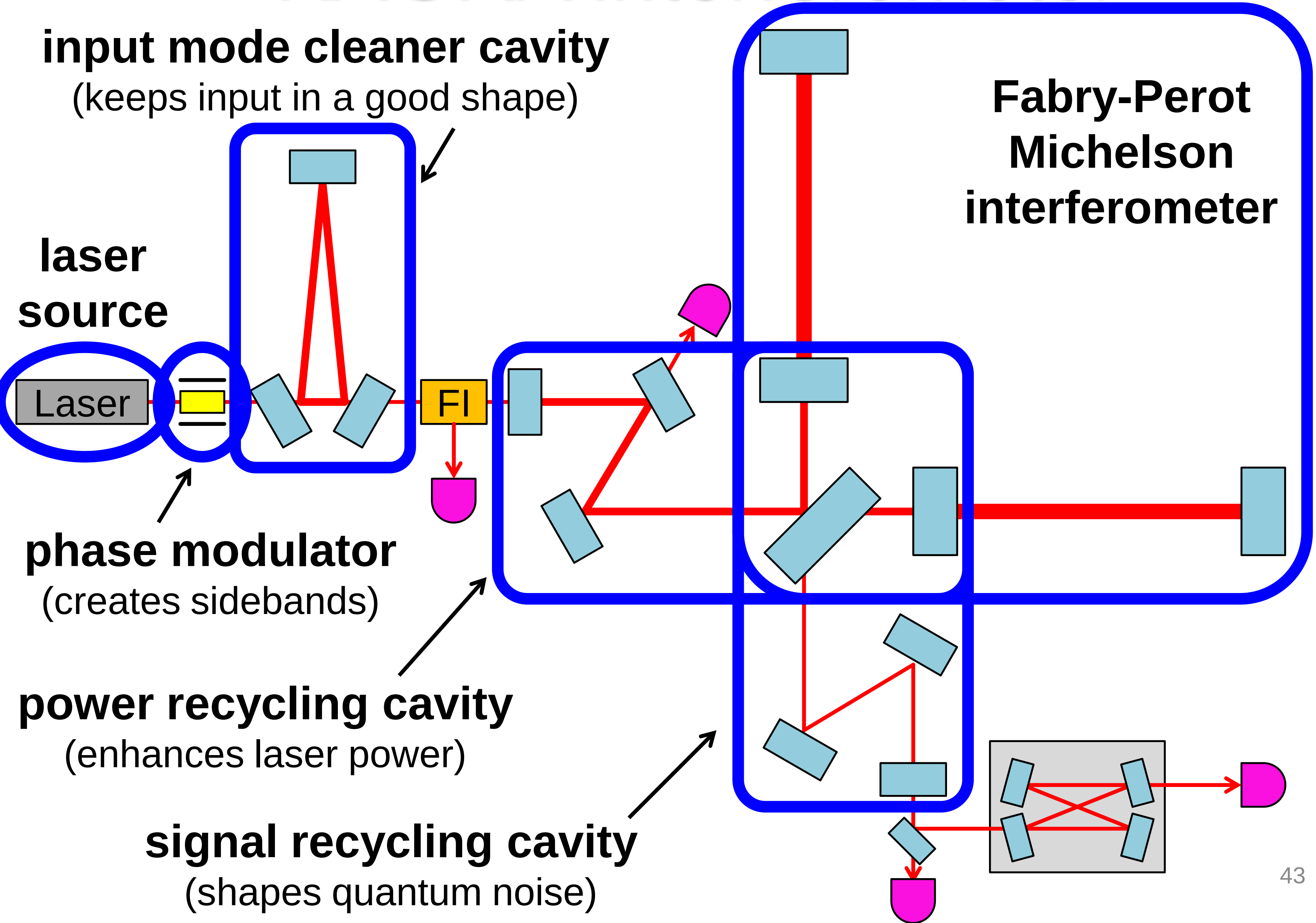
laser source

Fabry-Perot Michelson interferometer

phase modulator
(creates sidebands)

power recycling cavity
(enhances laser power)

KAGRA interferometer



input mode cleaner cavity
(keeps input in a good shape)

laser source

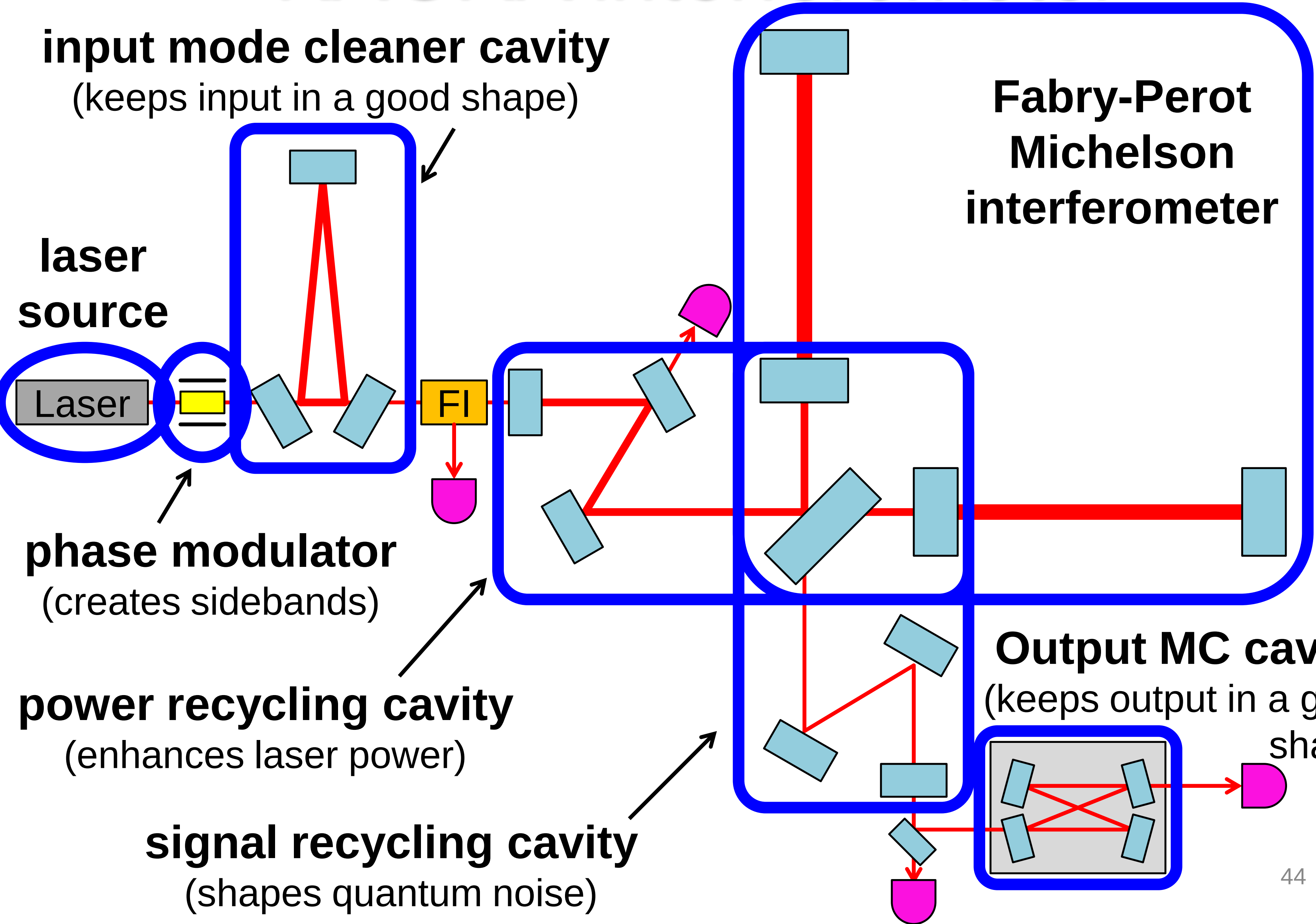
Fabry-Perot Michelson interferometer

phase modulator
(creates sidebands)

power recycling cavity
(enhances laser power)

signal recycling cavity
(shapes quantum noise)

KAGRA interferometer



input mode cleaner cavity
(keeps input in a good shape)

laser source

phase modulator
(creates sidebands)

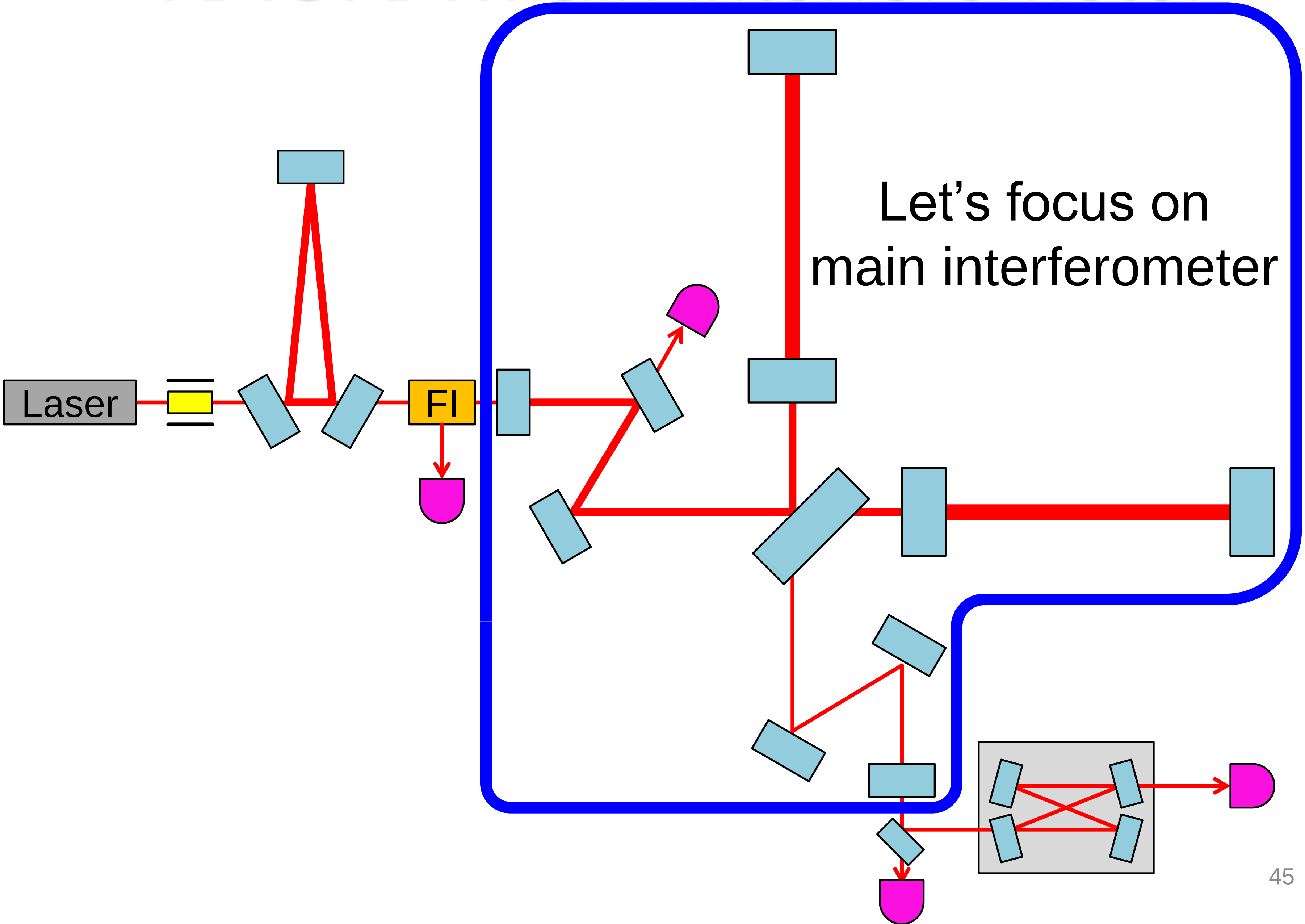
power recycling cavity
(enhances laser power)

signal recycling cavity
(shapes quantum noise)

Fabry-Perot Michelson interferometer

Output MC cavity
(keeps output in a good shape)

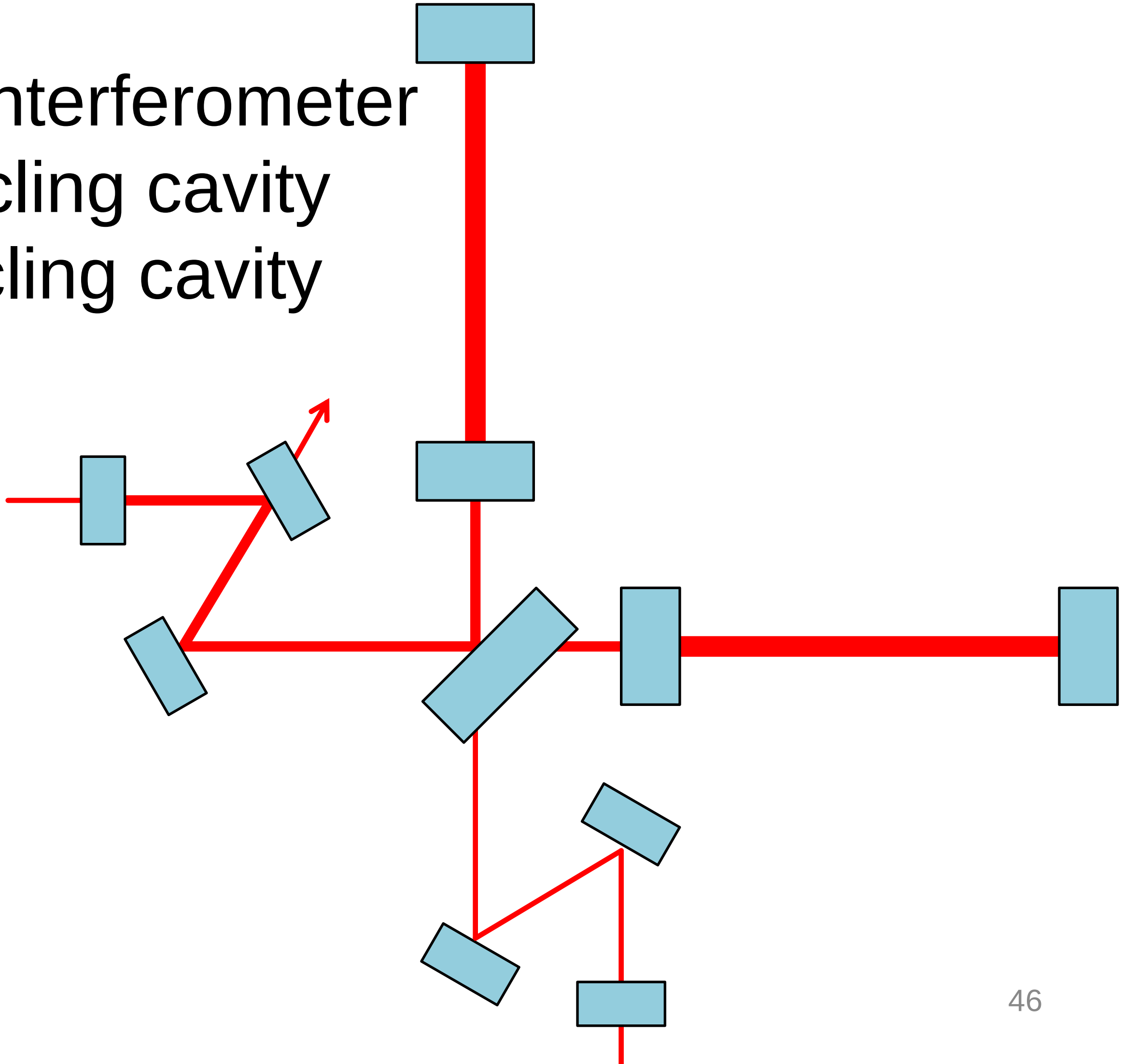
KAGRA main interferometer



Let’s focus on
main interferometer

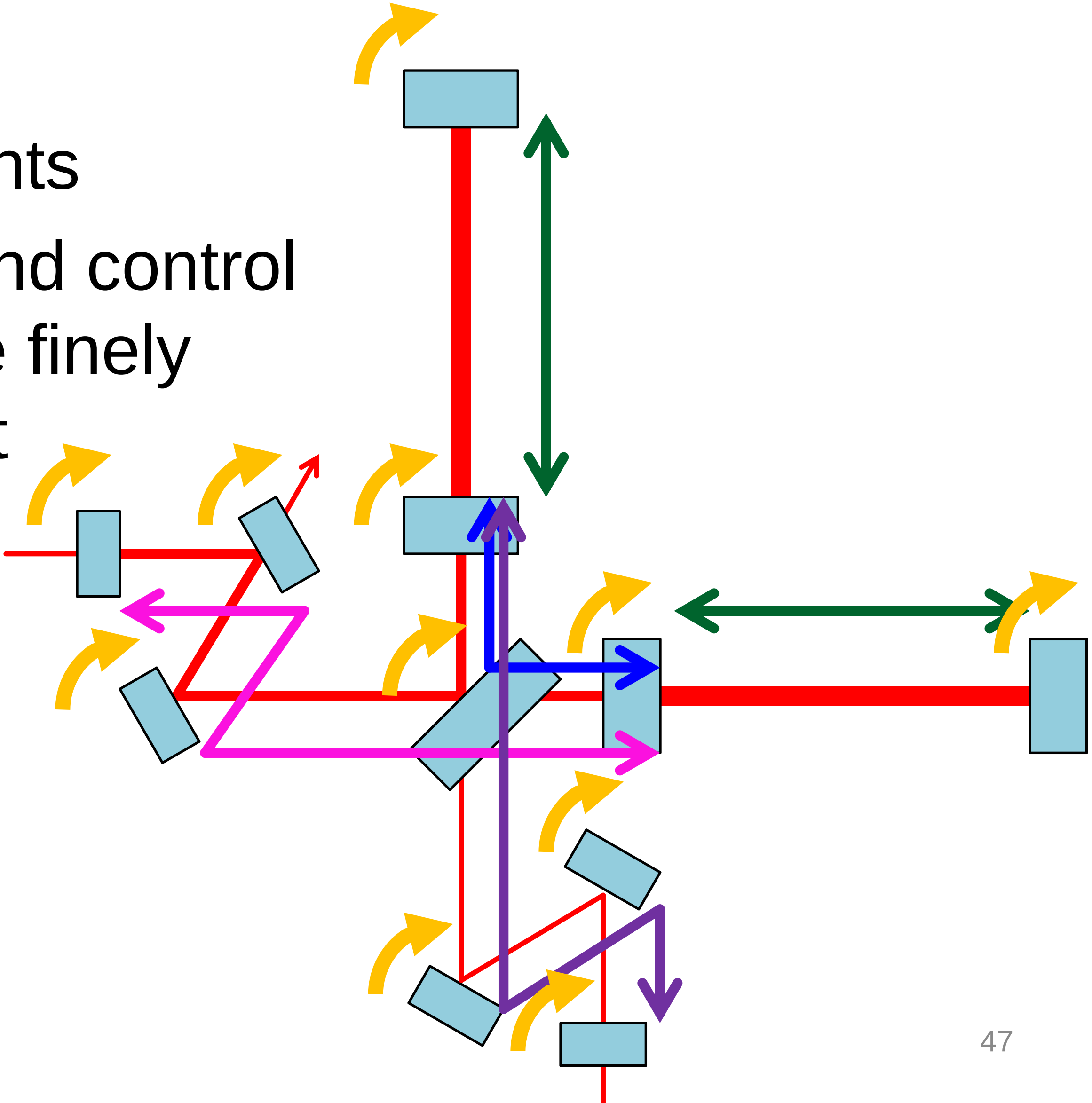
KAGRA main interferometer

- contains
  - 2 FP cavities
  - 1 Michelson interferometer
  - 1 power recycling cavity
  - 1 signal recycling cavity
- in total
  - 11 mirrors
  - 4 FP cavities
  - 1 Michelson



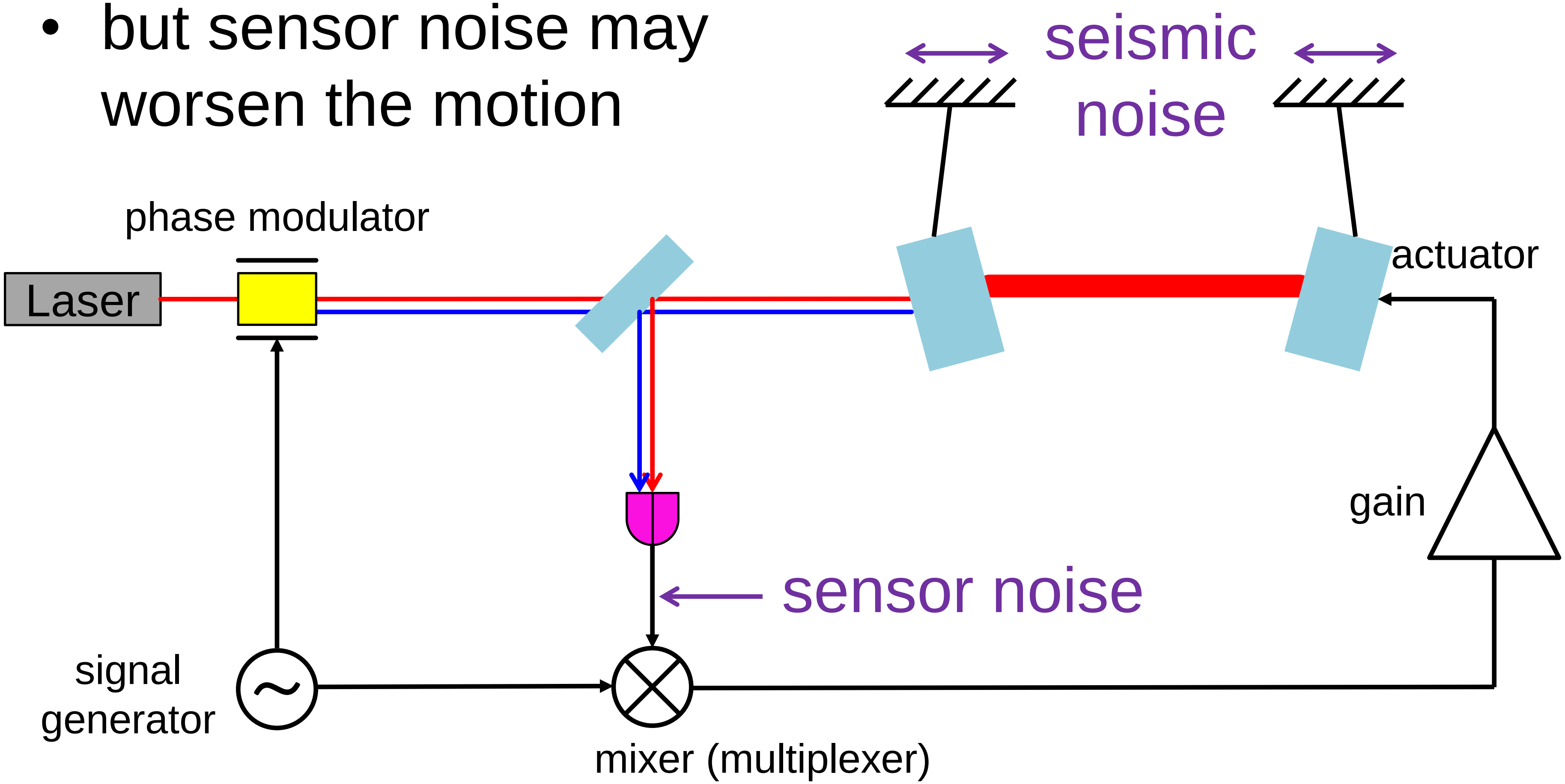
Degrees of freedom to control

- in total
  - 5 lengths
  - 11x2 alignments
- interferometer and control scheme must be finely designed so that KAGRA meets target sensitivity



Alignment sensing and control

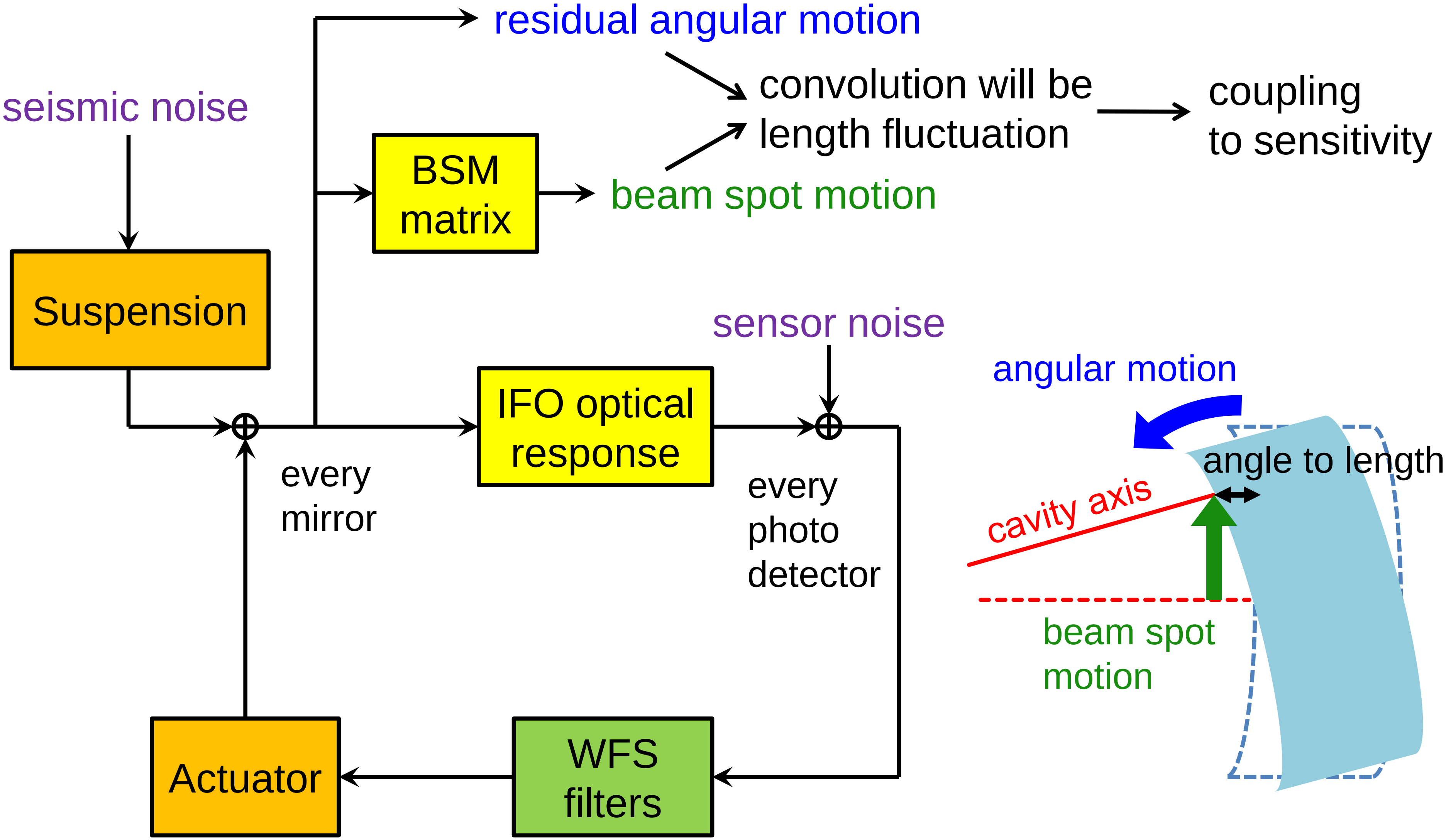
- mirror angular motion creates noise
- so we want to control them with high gain
- but sensor noise may worsen the motion



seismic noise

sensor noise

Modeling ASC



residual angular motion

convolution will be
length fluctuation

coupling
to sensitivity

seismic noise

BSM
matrix

beam spot motion

Suspension

sensor noise

IFO optical
response

every
mirror

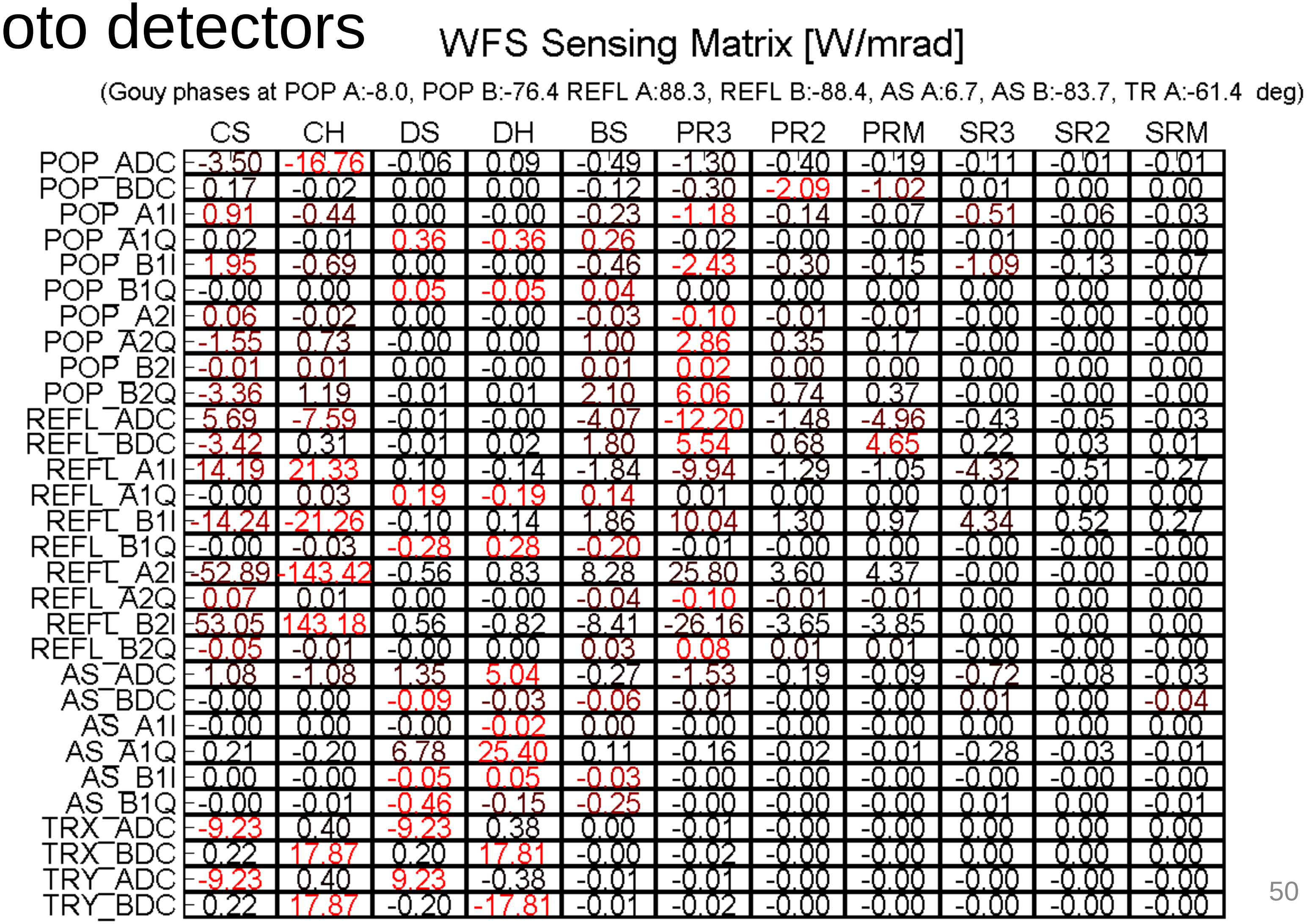
every
photo
detector

Actuator

WFS
filters

Angular sensing matrix

- angular mirror motions are sensed at different photo detectors



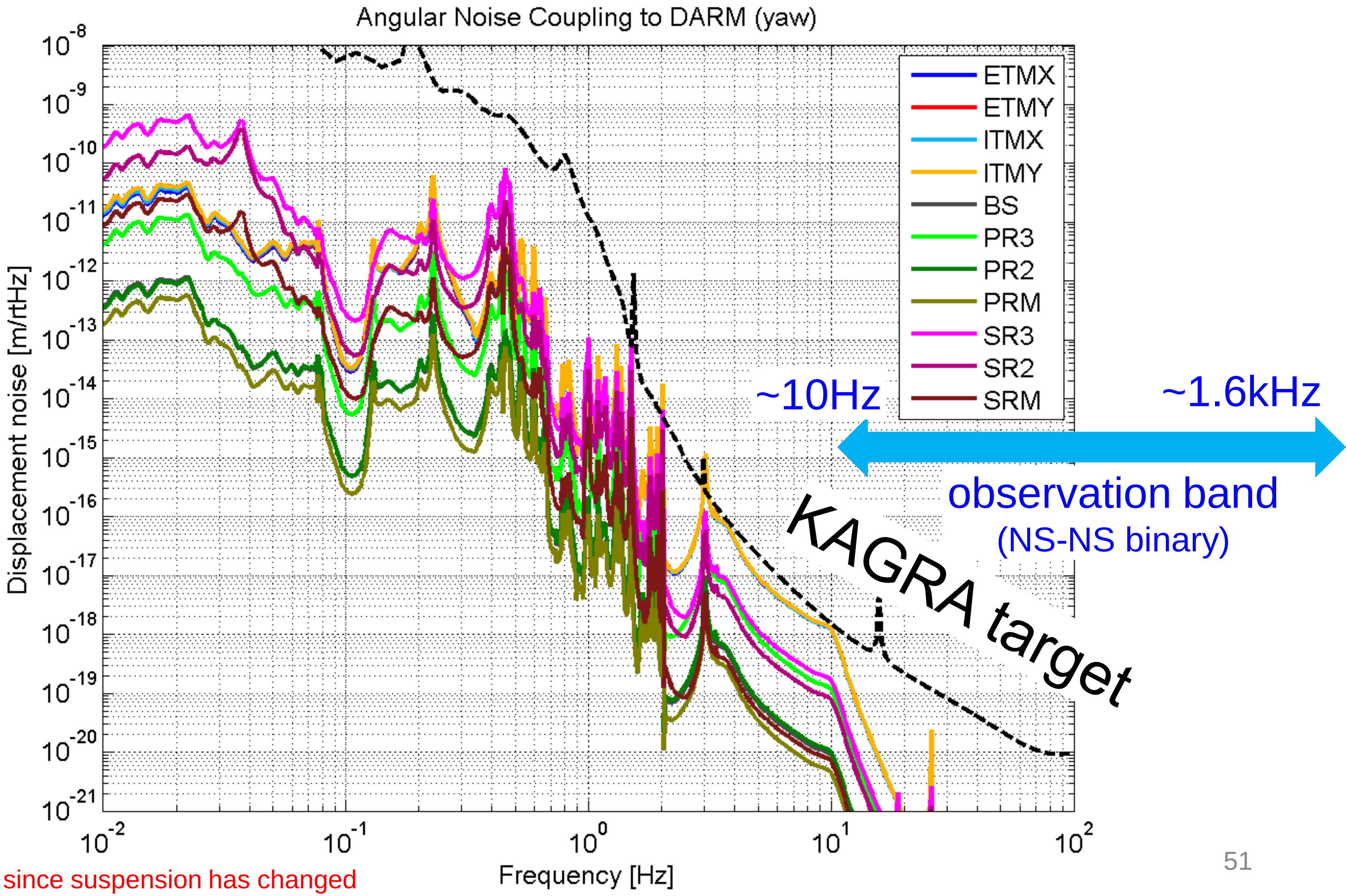
WFS Sensing Matrix [W/mrad]

(Gouy phases at POP A:-8.0, POP B:-76.4 REFL A:88.3, REFL B:-88.4, AS A:6.7, AS B:-83.7, TR A:-61.4 deg)

	CS	CH	DS	DH	BS	PR3	PR2	PRM	SR3	SR2	SRM
POP_ADC	-3.50	-16.76	-0.06	0.09	-0.49	-1.30	-0.40	-0.19	-0.11	-0.01	-0.01
POP_BDC	0.17	-0.02	0.00	0.00	-0.12	-0.30	-2.09	-1.02	0.01	0.00	0.00
POP_A1I	0.91	-0.44	0.00	-0.00	-0.23	-1.18	-0.14	-0.07	-0.51	-0.06	-0.03
POP_A1Q	0.02	-0.01	0.36	-0.36	0.26	-0.02	-0.00	-0.00	-0.01	-0.00	-0.00
POP_B1I	1.95	-0.69	0.00	-0.00	-0.46	-2.43	-0.30	-0.15	-1.09	-0.13	-0.07
POP_B1Q	-0.00	0.00	0.05	-0.05	0.04	0.00	0.00	0.00	0.00	0.00	0.00
POP_A2I	0.06	-0.02	0.00	-0.00	-0.03	-0.10	-0.01	-0.01	-0.00	-0.00	-0.00
POP_A2Q	-1.55	0.73	-0.00	0.00	1.00	2.86	0.35	0.17	-0.00	-0.00	-0.00
POP_B2I	-0.01	0.01	0.00	-0.00	0.01	0.02	0.00	0.00	0.00	0.00	0.00
POP_B2Q	-3.36	1.19	-0.01	0.01	2.10	6.06	0.74	0.37	-0.00	-0.00	-0.00
REFL_ADC	5.69	-7.59	-0.01	-0.00	-4.07	-12.20	-1.48	-4.96	-0.43	-0.05	-0.03
REFL_BDC	-3.42	0.31	-0.01	0.02	1.80	5.54	0.68	4.65	0.22	0.03	0.01
REFL_A1I	14.19	21.33	0.10	-0.14	-1.84	-9.94	-1.29	-1.05	-4.32	-0.51	-0.27
REFL_A1Q	-0.00	0.03	0.19	-0.19	0.14	0.01	0.00	0.00	0.01	0.00	0.00
REFL_B1I	-14.24	-21.26	-0.10	0.14	1.86	10.04	1.30	0.97	4.34	0.52	0.27
REFL_B1Q	-0.00	-0.03	-0.28	0.28	-0.20	-0.01	-0.00	0.00	-0.00	-0.00	-0.00
REFL_A2I	-52.89	-143.42	-0.56	0.83	8.28	25.80	3.60	4.37	-0.00	-0.00	-0.00
REFL_A2Q	0.07	0.01	0.00	-0.00	-0.04	-0.10	-0.01	-0.01	0.00	0.00	0.00
REFL_B2I	53.05	143.18	0.56	-0.82	-8.41	-26.16	-3.65	-3.85	0.00	0.00	0.00
REFL_B2Q	-0.05	-0.01	-0.00	0.00	0.03	0.08	0.01	0.01	-0.00	-0.00	-0.00
AS_ADC	1.08	-1.08	1.35	5.04	-0.27	-1.53	-0.19	-0.09	-0.72	-0.08	-0.03
AS_BDC	-0.00	0.00	-0.09	-0.03	-0.06	-0.01	-0.00	-0.00	0.01	0.00	-0.04
AS_A1I	-0.00	0.00	-0.00	-0.02	0.00	-0.00	-0.00	-0.00	0.00	0.00	0.00
AS_A1Q	0.21	-0.20	6.78	25.40	0.11	-0.16	-0.02	-0.01	-0.28	-0.03	-0.01
AS_B1I	0.00	-0.00	-0.05	0.05	-0.03	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00
AS_B1Q	-0.00	-0.01	-0.46	-0.15	-0.25	-0.00	-0.00	-0.00	0.01	0.00	-0.01
TRX_ADC	-9.23	0.40	-9.23	0.38	0.00	-0.01	-0.00	-0.00	0.00	0.00	0.00
TRX_BDC	0.22	17.87	0.20	17.81	-0.00	-0.02	-0.00	-0.00	0.00	0.00	0.00
TRY_ADC	-9.23	0.40	9.23	-0.38	-0.01	-0.01	-0.00	-0.00	-0.00	-0.00	-0.00
TRY_BDC	0.22	17.87	-0.20	-17.81	-0.01	-0.02	-0.00	-0.00	-0.00	-0.00	-0.00

ASC noise coupling to sensitivity

- close, but meets requirement



~10Hz

~1.6kHz

observation band

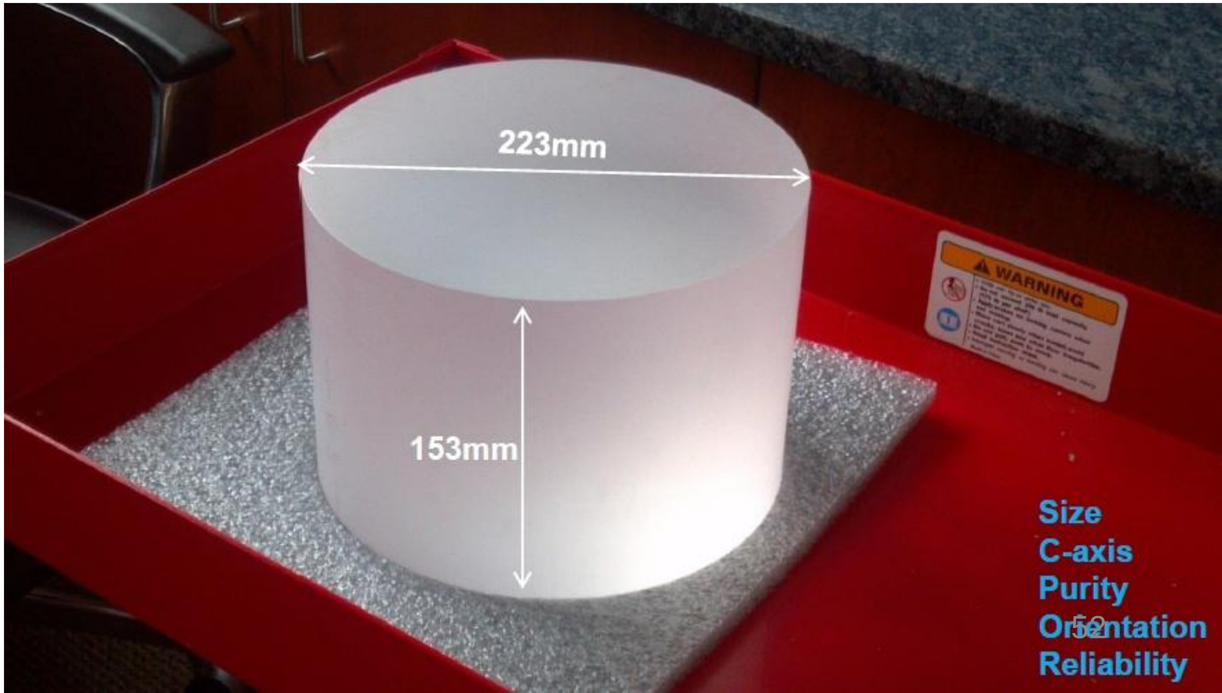
(NS-NS binary)

KAGRA target

OBSOLETE since suspension has changed

Current status

- finalized KAGRA interferometer design
- confirmed they are reasonable from ASC and many other considerations
- mirrors being fabricated
- ASC barely meets requirement, detailed simulation on-going



E. Hirose: JGW-G101786

Summary 3/3

- There are many degrees of freedom to control KAGRA interferometer
- Modeling interferometer control scheme is essential for designing interferometer
- I developed a model for simulating alignment sensing and control scheme for KAGRA
- We finalized KAGRA interferometer design
- More detailed, practical designing on going

Thank you
감사합니다
ありがとう