Future prospects of the optical levitation experiment (光学浮上実験の今後の展望)

KAGRA observatory,
Institute for cosmic ray research,
University of Tokyo

NAGANO Koji (長野 晃士)

Overture

Q. Who am I?

A. I'm NAGANO Koji, 1st year of Ph.D. course, belonging to KAGRA observatory, ICRR, University of Tokyo.

Q. What did I do in my master course?

A. I studied on the quantum noise reduction technique for KAGRA (ponderomotive squeezing and homodyne detection) in Kashiwa, called QND (quantum non-demolition) exp.. For detail, please see my master thesis on JGW-P1706052.

In addition, I visited Caltech and U. Grasgow. What I did in Caltech will be published as paper someday.

Q. Will I talk about what I did in master course?

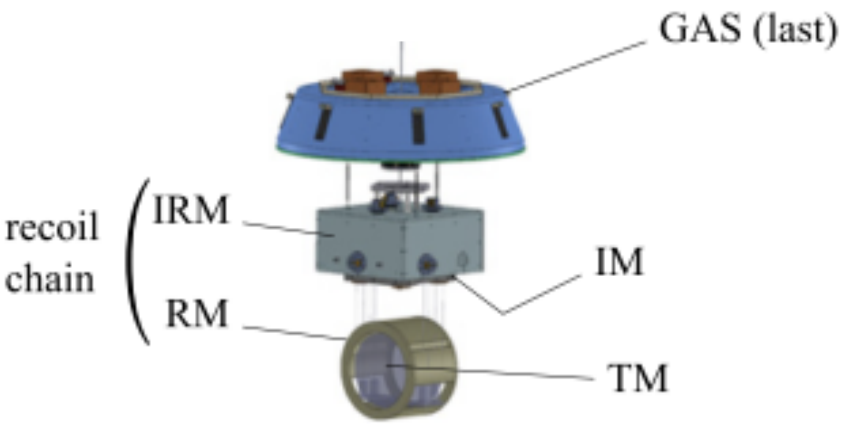
A. No, I will not. I will talk about my future work, "optical levitation experiment," which I will do in my Ph.D. course.

Outline

- Introduction
- Schedule
- Applications of optical levitations
- Experimental setup design proposal
- Problems
- Conclusion
- Summary

Introduction

- For gravitational-wave (GW) detections or studies of the macroscopic quantum mechanics, extremely low noise systems are required.
- About the seismic noise reduction, suspension systems are often used.
- However, the suspension systems induce additional thermal noises.



Suspension system of KAGRA (Cryogenic part)
E. Hirose+, CQG (2014)

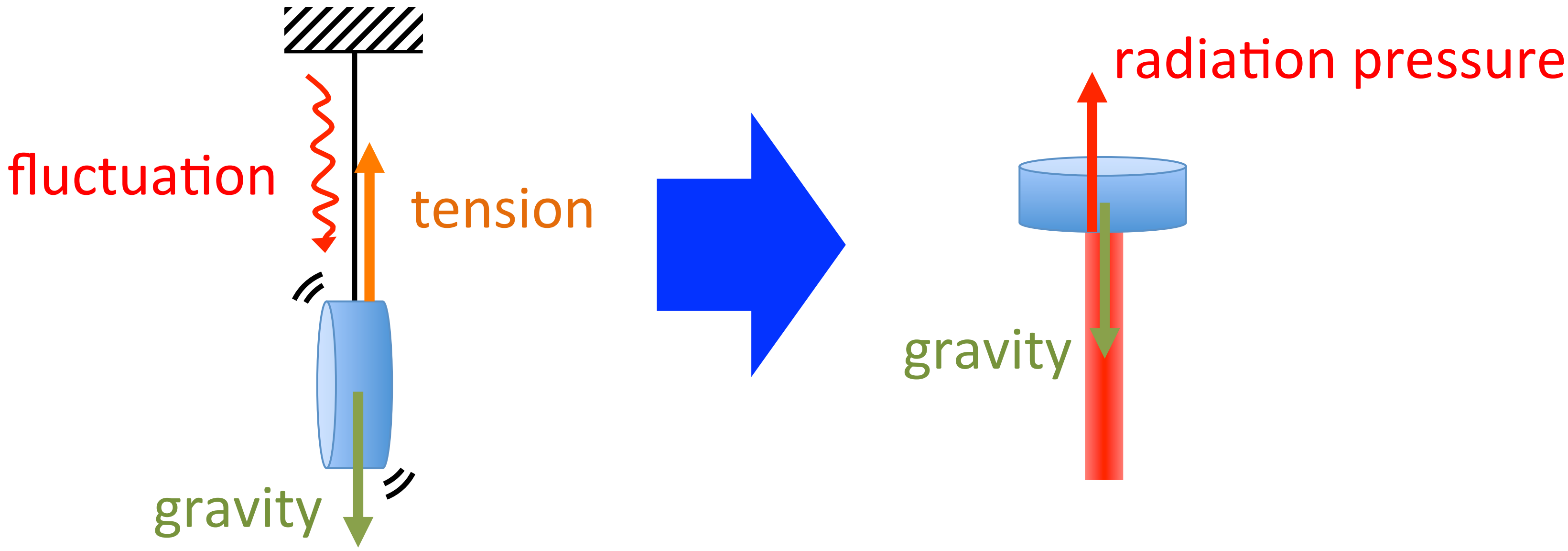
K. Komori, Master thesis, University of Tokyo (2016)

Introduction

- Suspension thermal noise is one of the major noise sources of interferometers which close the sensitivity window reaching the standard quantum limit (SQL).
- Reaching SQL is a kind of milestone of **the test of the macroscopic quantum mechanics**.
- In addition, if we can demonstrate to beat SQL, that is, to reduce the quantum noise, it leads to **improvement of the sensitivity of GW detectors.**

Introduction

- The suspension thermal noise can be extinguished when masses are levitated with optical radiation pressure instead of suspended with mechanical wires.
- This technique is called as an optical levitation (OL).



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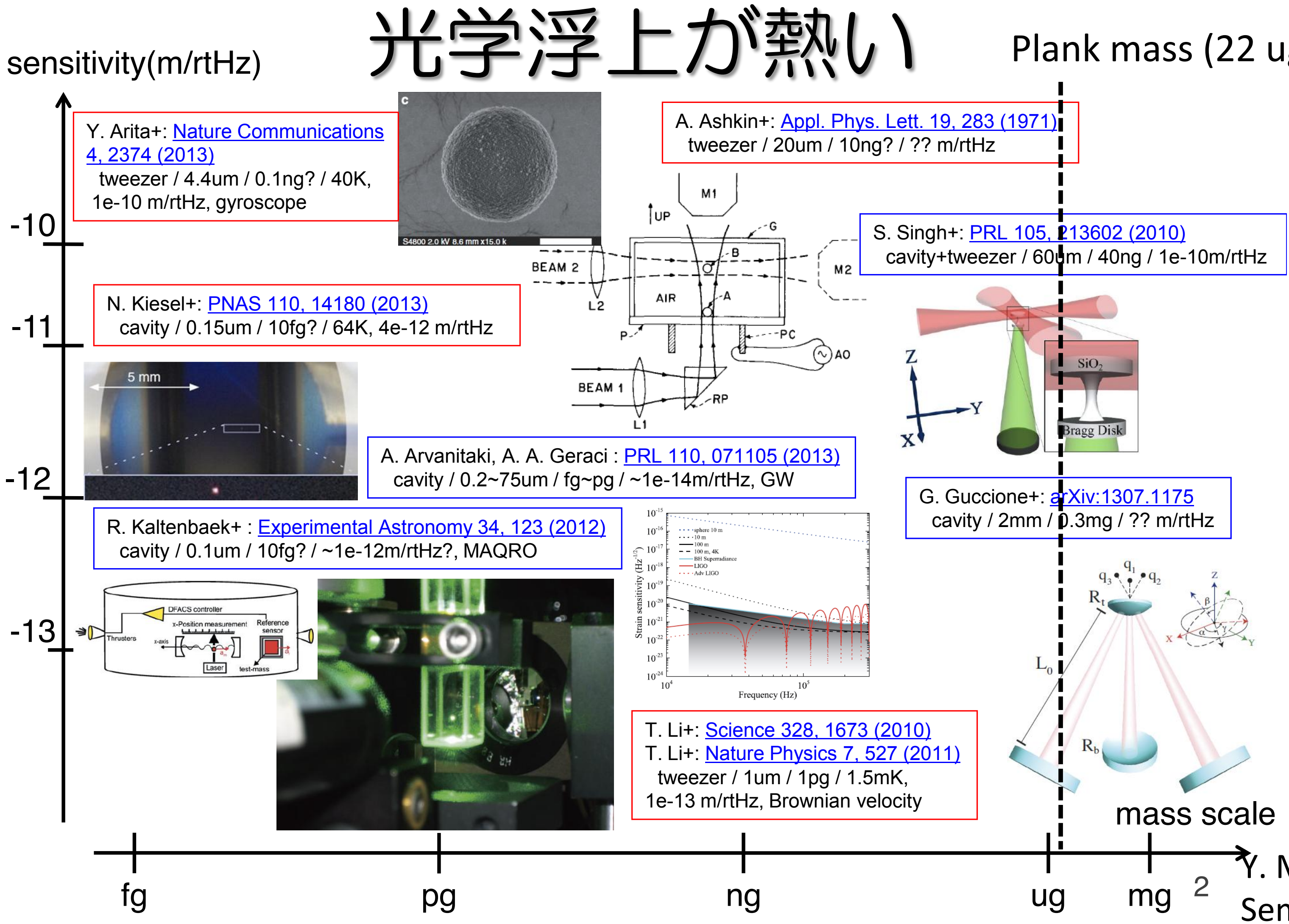

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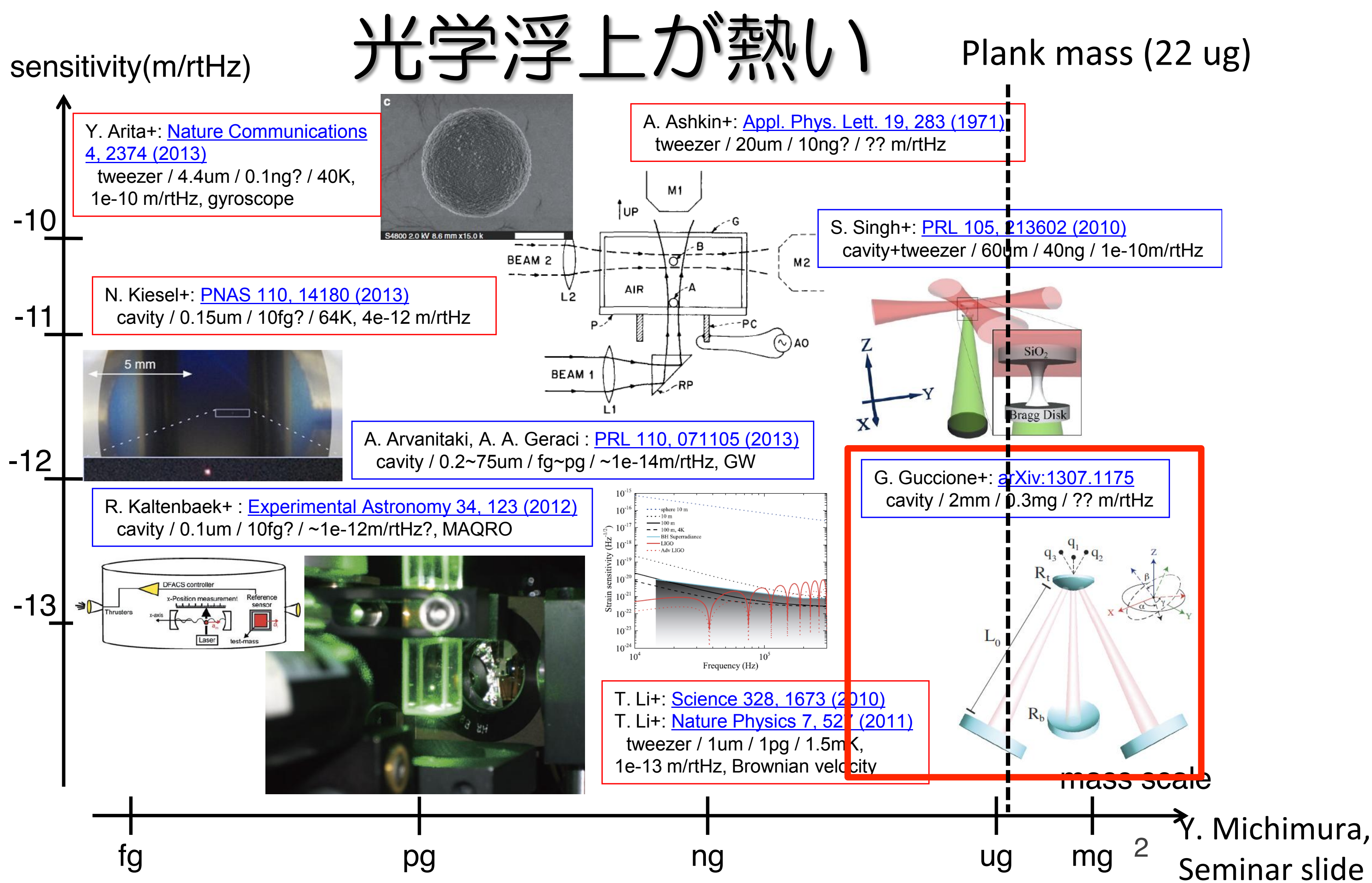
Y. Michimura, Seminar slide

Introduction



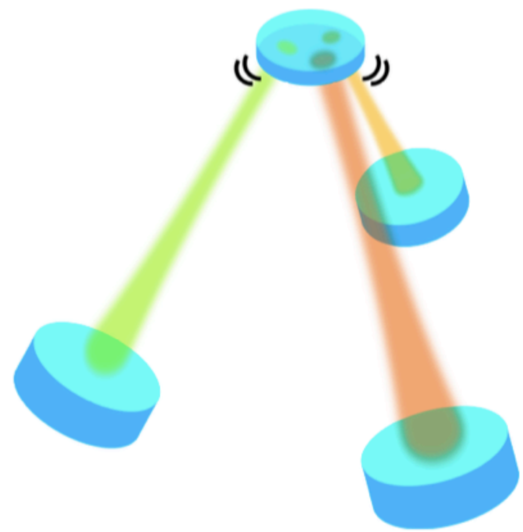
Introduction

- So far, two types (or more?) of OLs for mg-scale mirrors have been proposed.

Y. Kuwahara, Master thesis, University of Tokyo (2016)

sandwich type

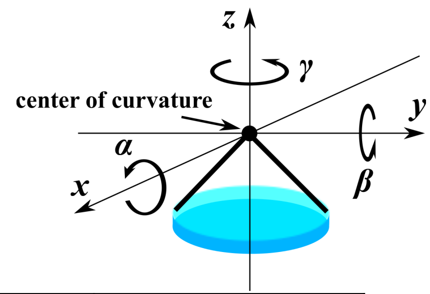
Y. Michimura+, arXiv (2017), Opt. Express (under review)



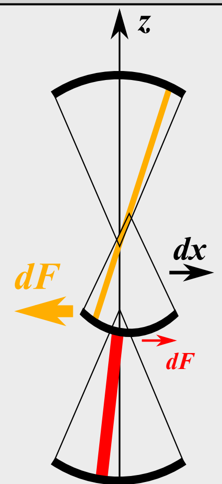
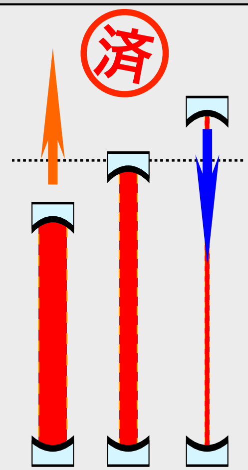
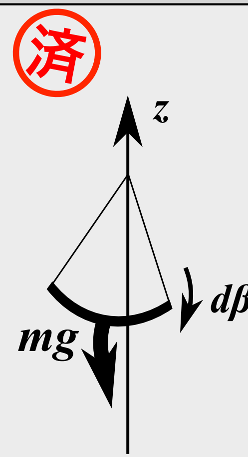
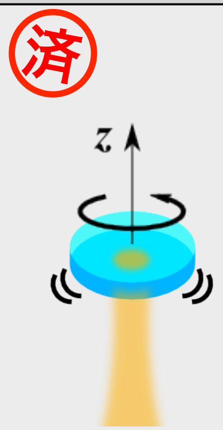
tripod type

G. Guccione+, PRL (2013)

自由度と安定性



➢ 浮上鏡の曲率中心の運動（並進3自由度，回転3自由度）

自由度	水平(x,y)並進	鉛直(z)並進	x, y軸回転	z軸回転
復元力	サンドイッチ構成の復元力	光バネ	重力	なし
模式図				

Y. Kuwahara, Master thesis defense , University of Tokyo (2016)

Introduction

- Advantages and disadvantages of the two type OL:

Y. Kuwahara, Master thesis, University of Tokyo (2016)

表 3.1: 三脚型とサンドイッチ型の比較。

	三脚型	サンドイッチ型
利点	鏡を支えるだけのパワーでよい。	光が 2 本でよい。 z 並進を直接見ることができる。
弱点	3 本の光のバランスをとる機構が必要。 鏡が大きくなる。	鏡を支える以上のパワーが必要。 光軸を重力方向に合わせる機構が必要。

- Since the sandwich type OL has not yet been experimentally demonstrated, we have to do it.
  - According to rumor, the tripod type OL has been demonstrated already in ANU.

Introduction

Purposes of the optical levitation experiment

- Demonstrating the optical levitation with sandwich configuration
- Achievement of the sensitivity reaching SQL.
- Test of the macroscopic quantum mechanics, the development of the technique to improve the sensitivity of GW detectors, such as KAGRA, and other sciences.

(and Education of myself and junior students.)

Schedule

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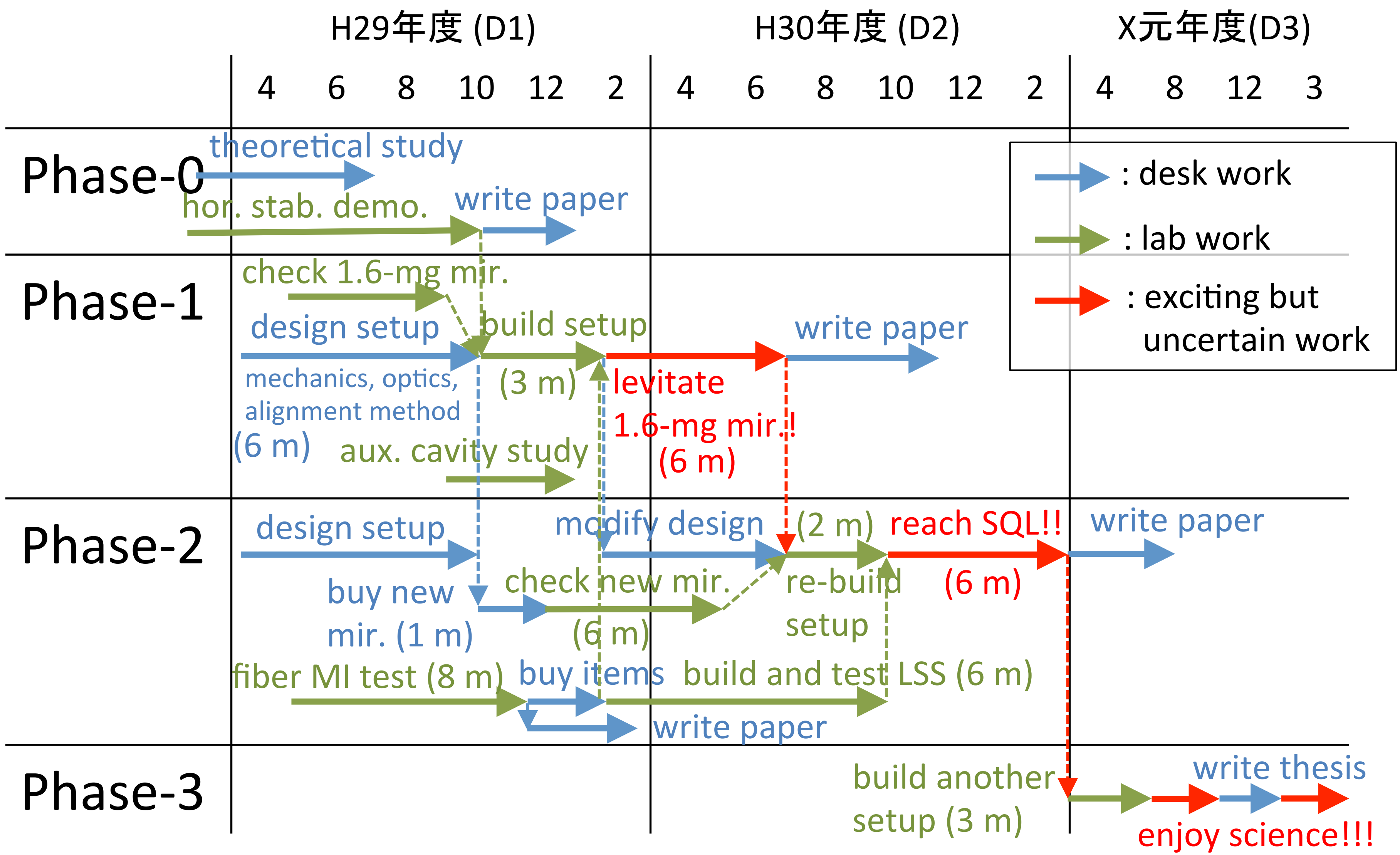
Schedule



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H30年度 (D2)
X元年度(D3)
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theoretical study
hor. stab. demo.
write paper
Phase-1
check 1.6-mg mir.
design setup
mechanics, optics, alignment method
(6 m)
build setup
(3 m)
levitate 1.6-mg mir.!
(6 m)
write paper
aux. cavity study
Phase-2
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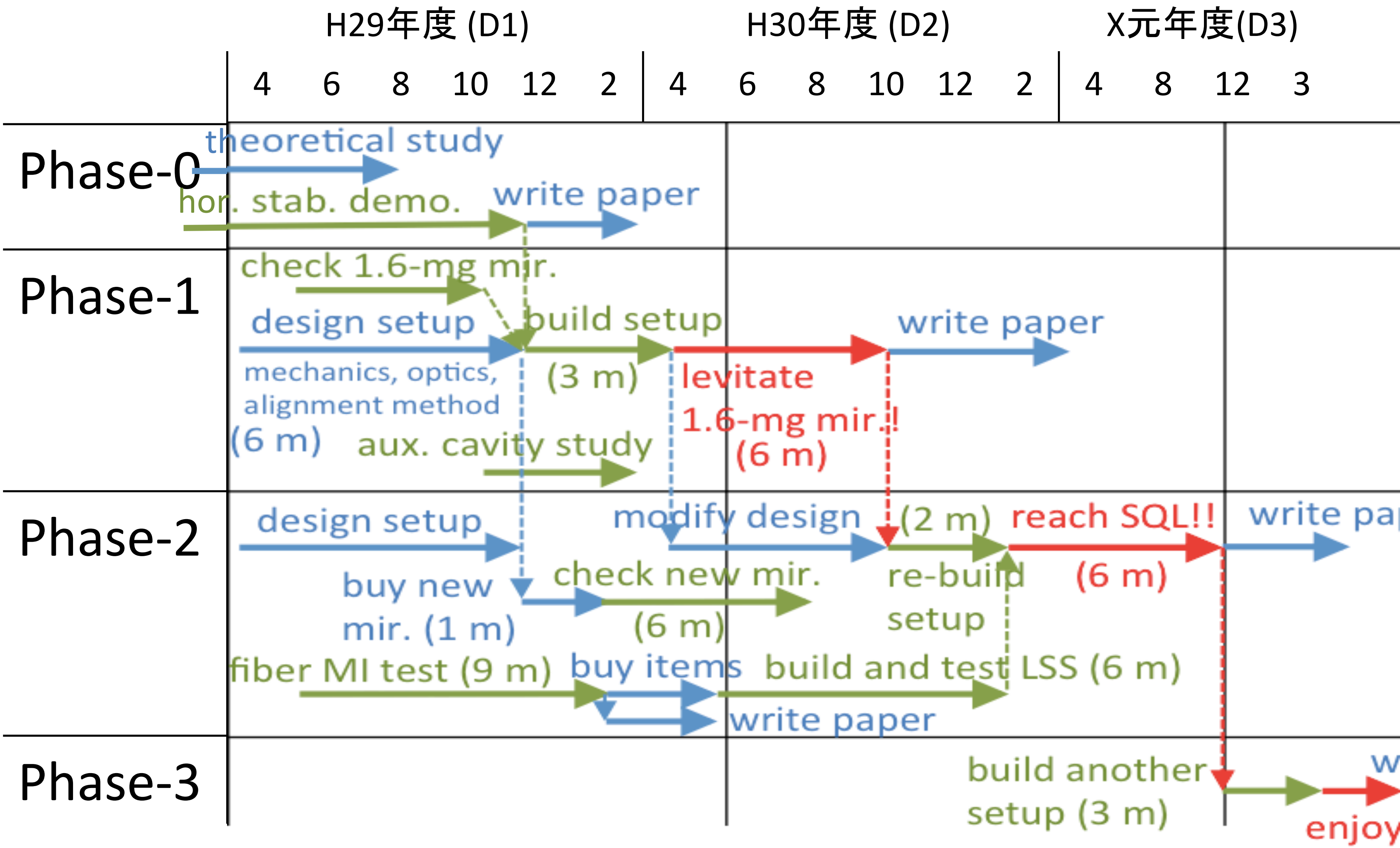
(6 m)
modify design
(2 m)
re-build setup
reach SQL!!
(6 m)
write paper
fiber MI test (8 m)
buy items
build and test LSS (6 m)
write paper
Phase-3
build another setup (3 m)
write thesis
enjoy science!!!
: desk work
: lab work
: exciting but uncertain work

Schedule



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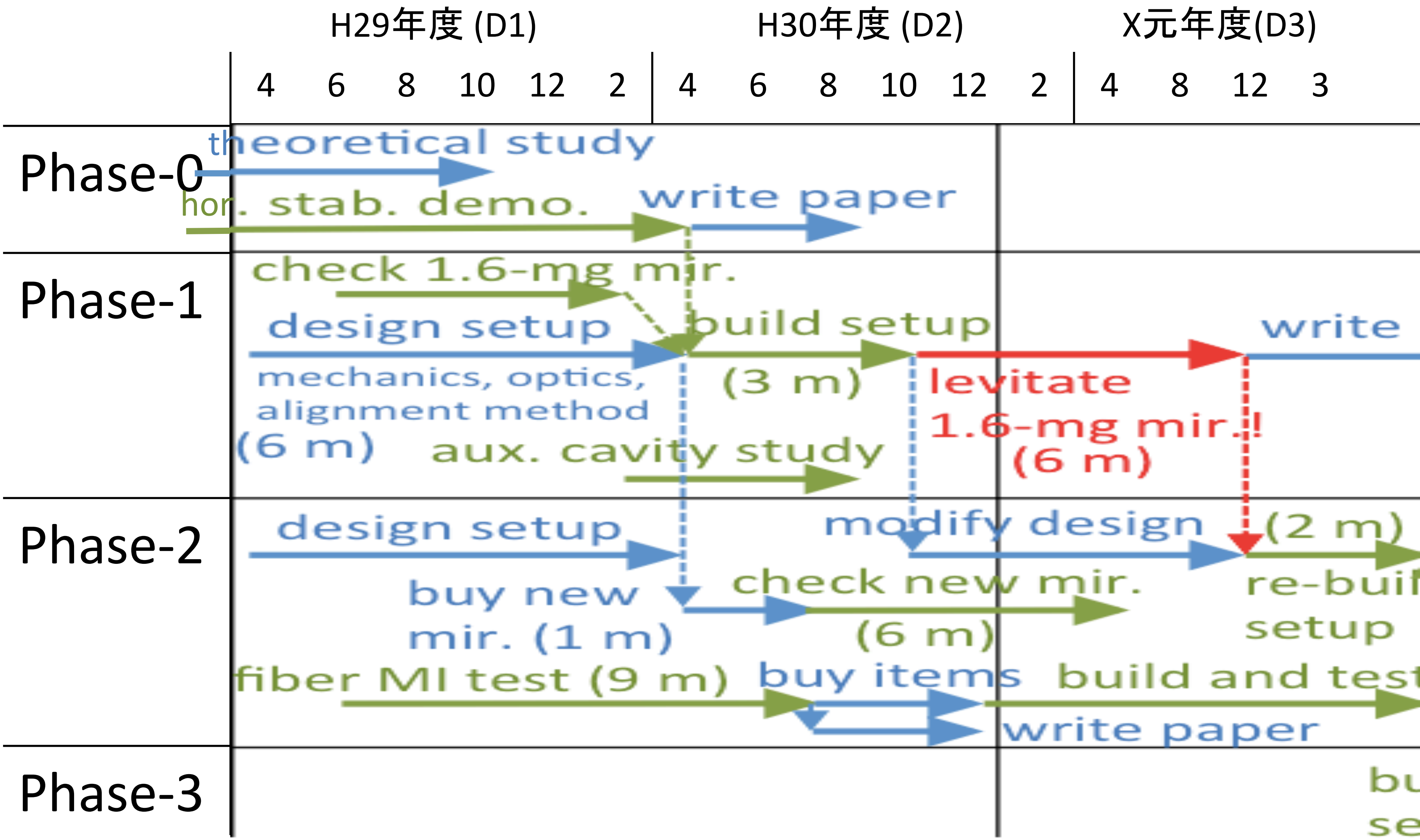

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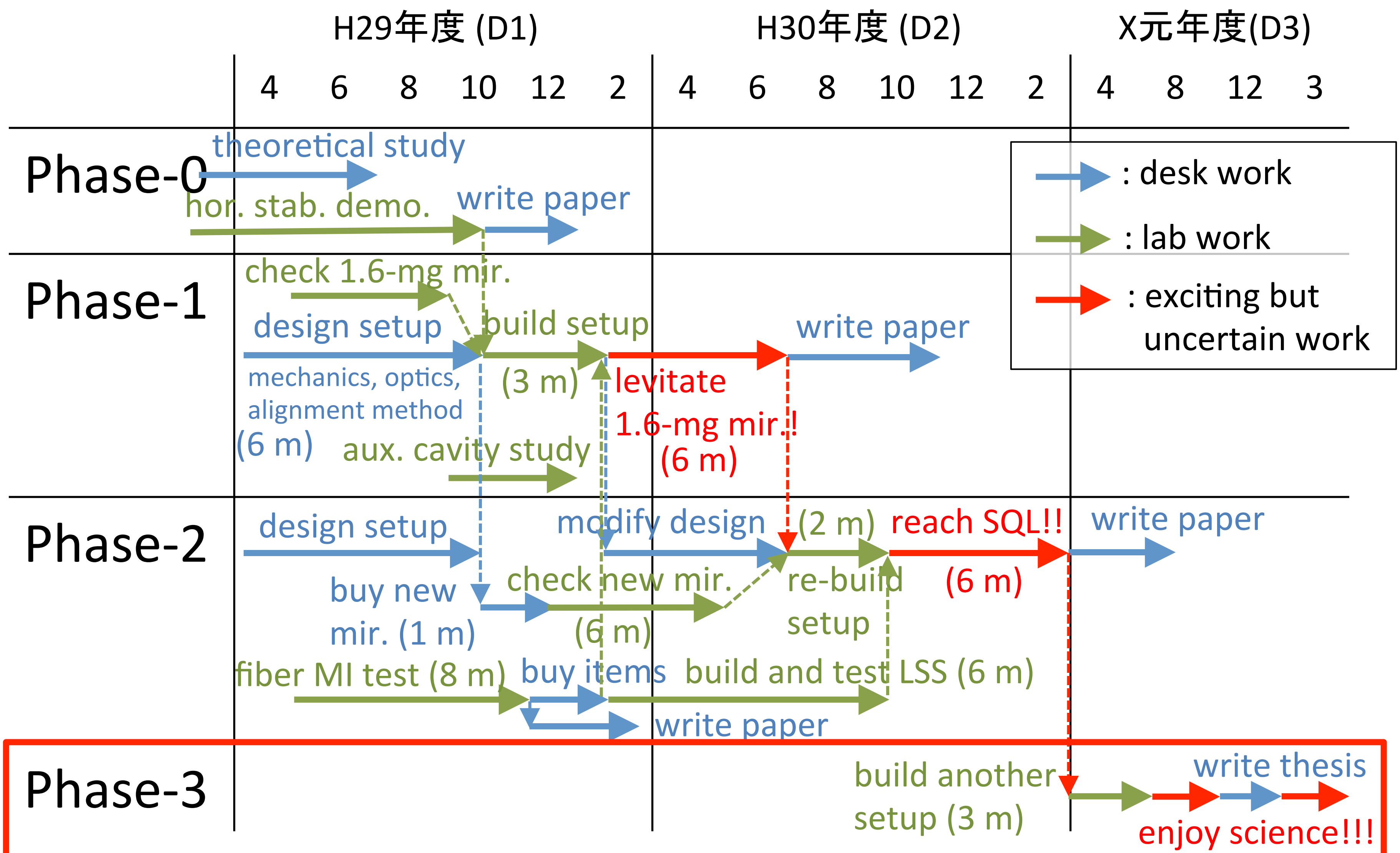

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Applications of optical levitations

光学浮上の応用先

Y. Michimura,
Seminar slide

- 古典力学と量子力学を繋ぐモデルの検証
  R. Penrose: Gen. Rel. Grav. 28, 1572 (1996)
  A. Bassi+: Rev. Mod. Phys. 85, 471 (2013)
- 重力デコヒーレンスの観測
  R. Kaltenbaek+: Experimental Astronomy 34, 123 (2012)
- 巨視的量子現象
  エンタングルメント、Schrödingerの猫 etc.
- 超高精度力センサ(～10^{-20} N/rtHz)
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  A. Arvanitaki, A. A. Geraci: PRL 110, 071105 (2013)
- 量子情報的な応用(回転の自由度を利用)

4

- **重力波検出における量子雑音低減方法の実証**

Applications of optical levitations

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4

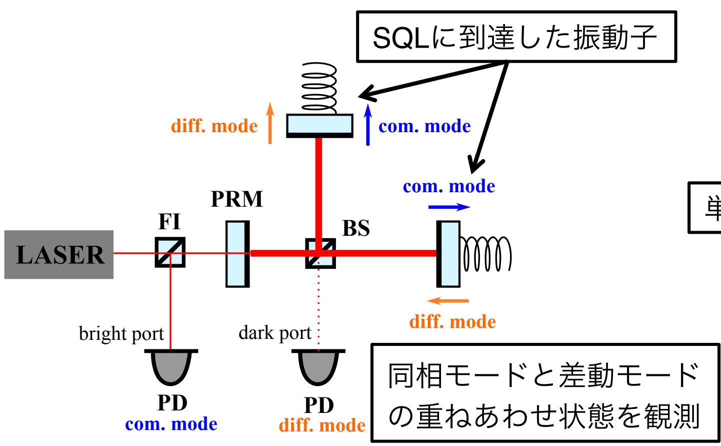
Test of macroscopic quantum mechanics

Applications of optical levitations

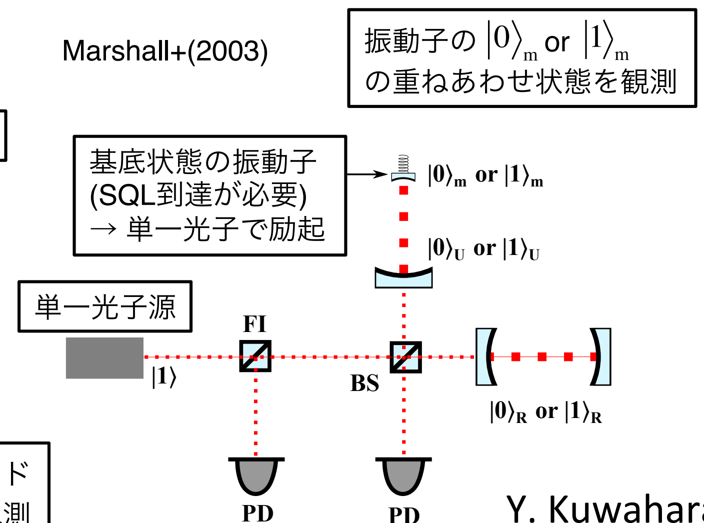
提案されている検証方法

- 巨視的な物体では，直接二重スリット実験をする代わりに
  それに相当する実験をし，重ね合わせが生じるかどうか検証する。
- SQLへの到達が必要条件

Müller-Ebhardt+(2008)



Marshall+(2003)



2016/01/27 修士論文審査会 9

Y. Kuwahara, Master thesis defense, University of Tokyo (2016)

Applications of optical levitations

gravity experiment

Development of the noise reduction technique and GW detection

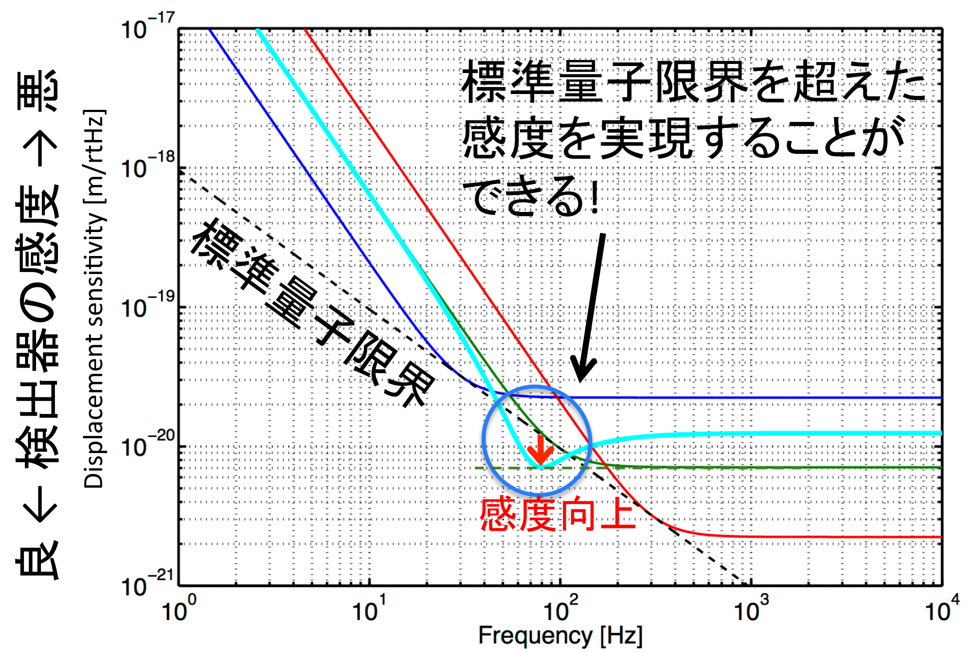
- 重力波検出における量子雑音低減方法の実証

Applications of optical levitations

重力波検出器の量子雑音の低減

- ~~通常の~~重力波検出器の量子雑音

ホモダイン検波をしたときの



K. Nagano, Master thesis defense, University of Tokyo (2017)

修士論文審査会 (東京大学 本郷キャンパス、2017年1月16日) 11

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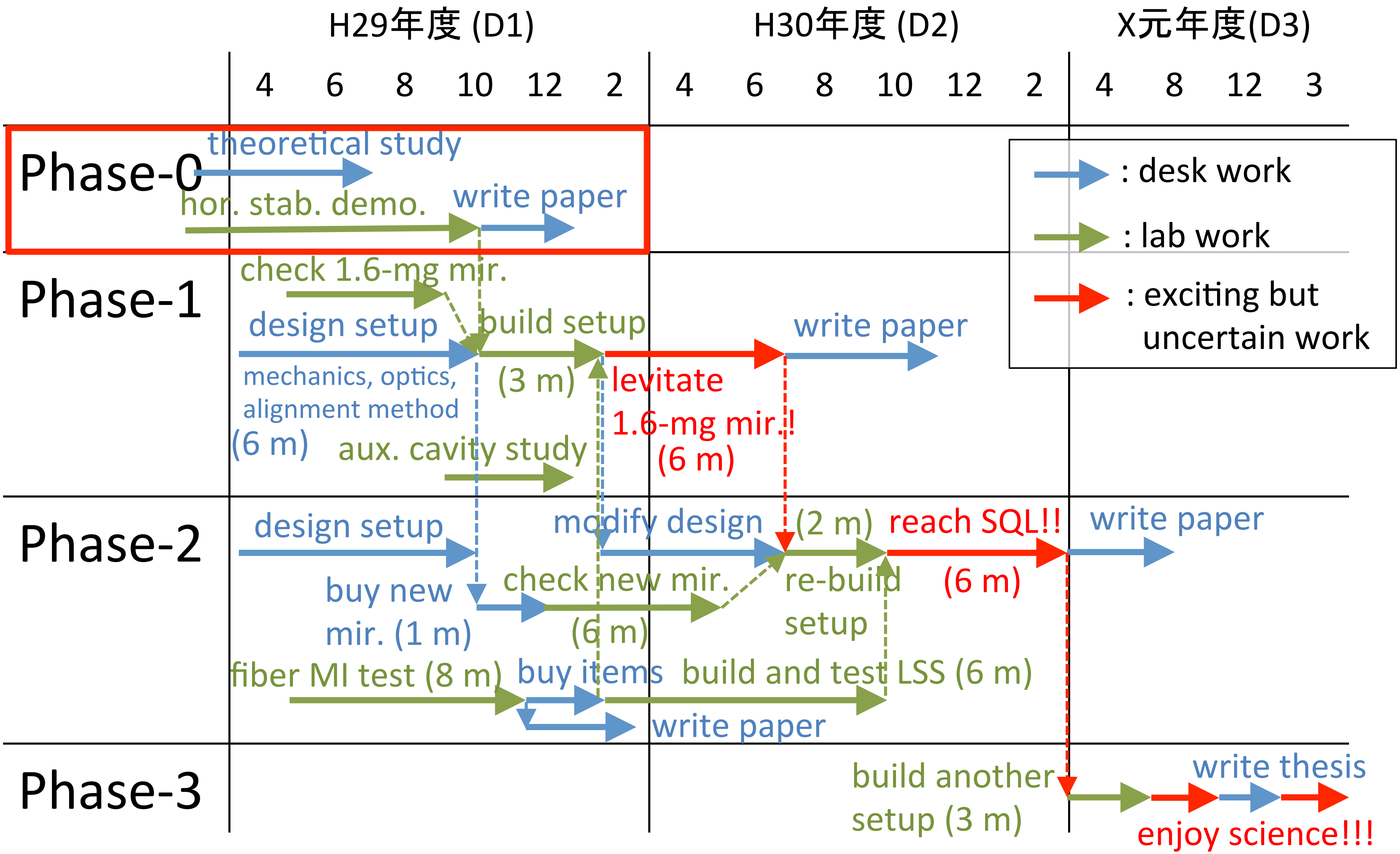

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Horizontal optical spring demonstration

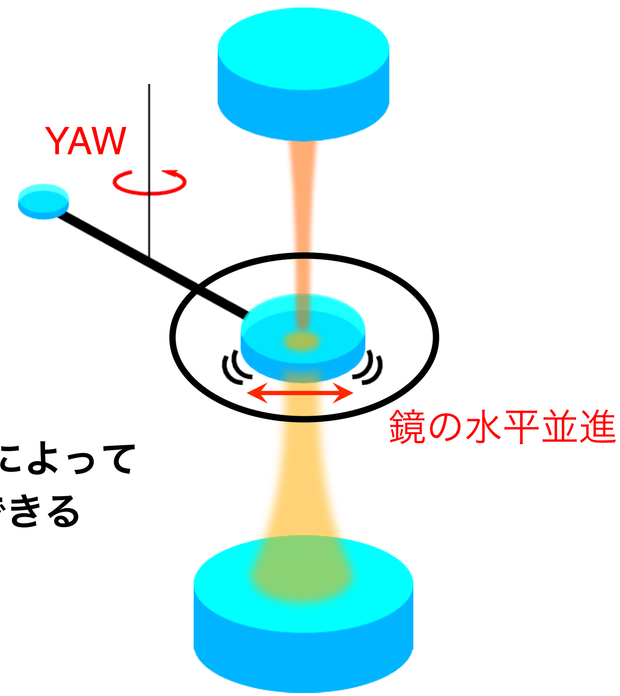
ねじれ振り子の利用

完全な自由質点のmg鏡の代わりに
ねじれ振り子を使用
↓
- やわらかい(共振周波数 ~10 mHz)
- サンドイッチ構成の微小な復元力を感じうる

⇩

✓ **ねじれ振り子の運動(YAW)の変化によってサンドイッチ構成の安定性を検証できる**
  - もとの共振周波数からの上昇を観測

✓ **g程度の鏡を使用できる**
  - 0.5inch, 1inch, etc…



Y. Kuwahara, Master thesis defense , University of Tokyo (2016)

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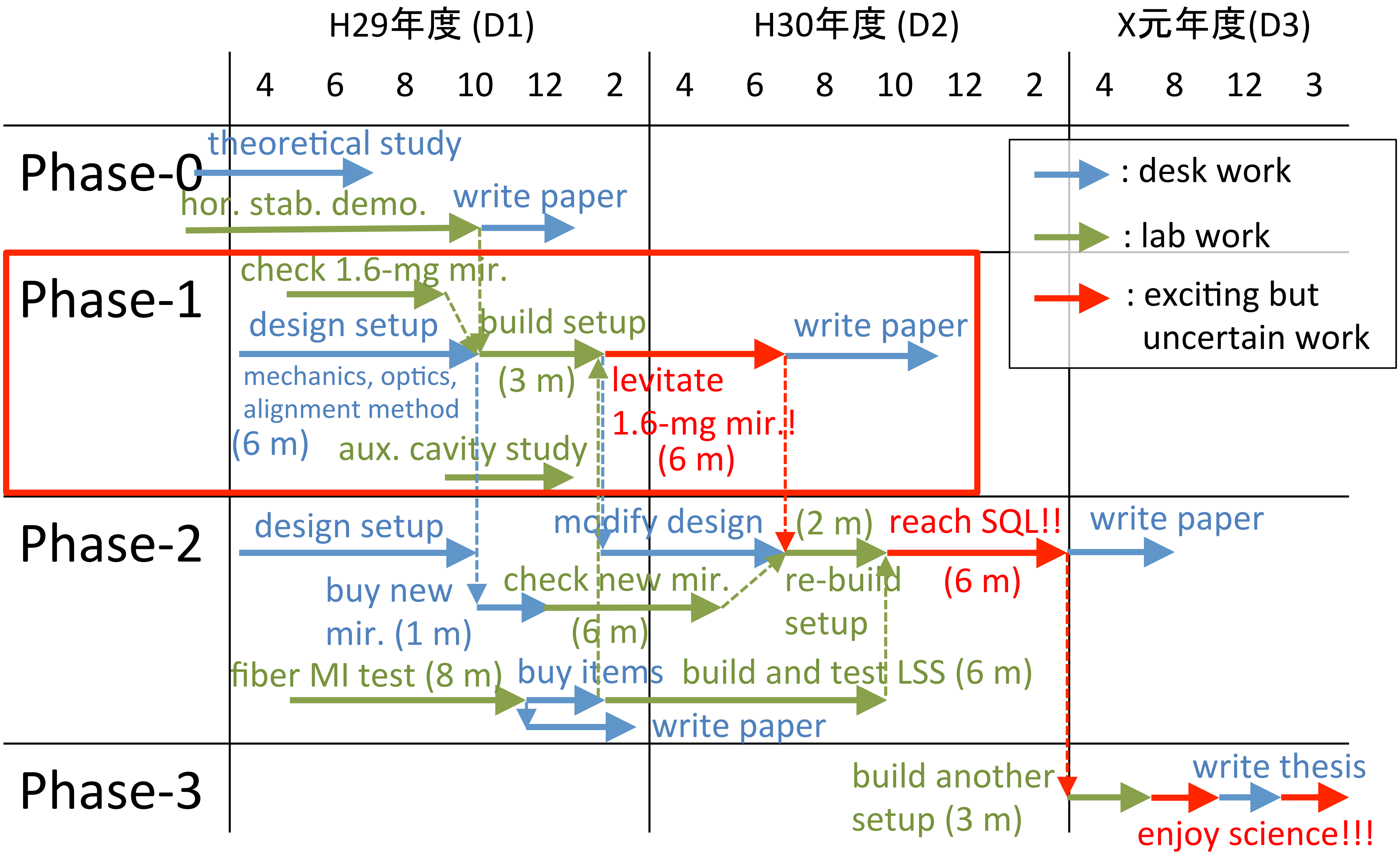

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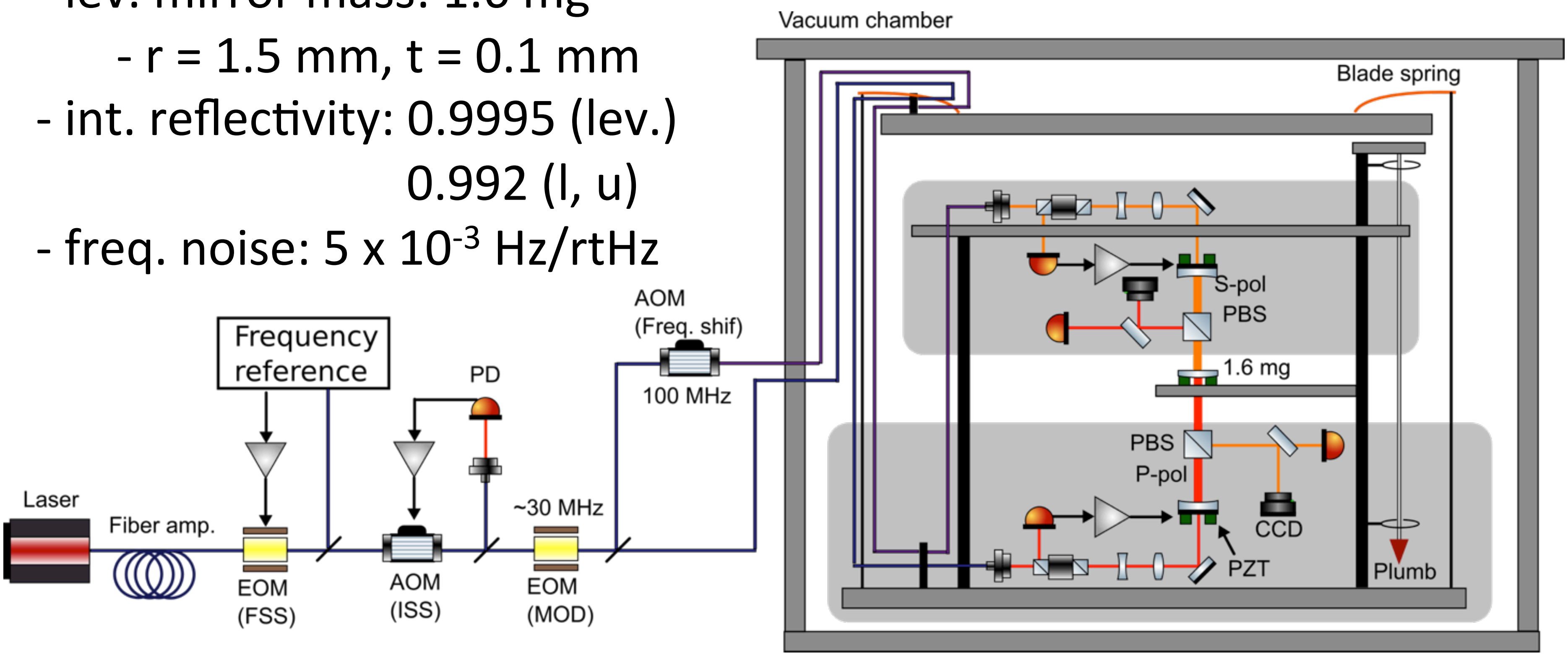
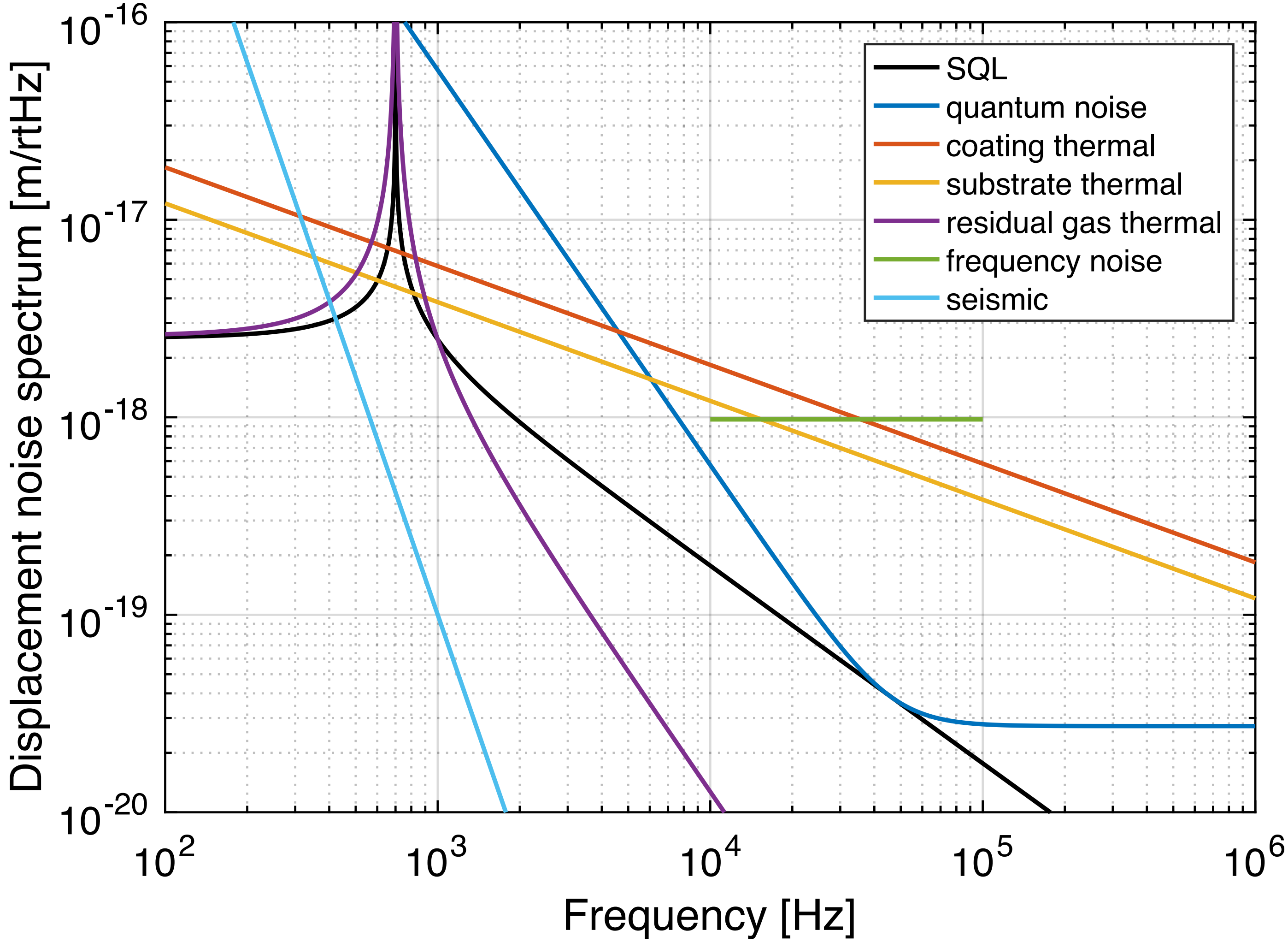
Experimental configuration in Phase-1

- wave length: 1064 nm
- finesse: 700 (lower, upper)
- input power: 8.5 W (lower)
  2.6 W (upper)
- lev. mirror mass: 1.6 mg
  - r = 1.5 mm, t = 0.1 mm
- int. reflectivity: 0.9995 (lev.)
  0.992 (l, u)
- freq. noise: 5×10^{-3} Hz/rtHz

- suspension reso. freq.: ~1 Hz
- main cavity servo UGF: ~ 20 Hz(?)
- optical zenith angle < 0.2 deg
- pressure: 10^{-4} Pa



Sensitivity in Phase-1



Points in Phase-1

- Use the 1.6-mg mirror, which we have already.
- Use relatively high-finesse (~700) cavity.
- Use relatively simple laser stabilization system (LSS).
- Light is introduced to the vacuum chamber thought optical fibers.
- Transmitted lights in the main cavities are extracted by polarizing beam splitter (PBS) in the other cavities to decouple the cavities.
- To keep the optical spring effect, main cavities are suspended for vibration isolation to decrease the unity gain frequency (UGF) of their servo (~ a few 10 Hz).
- (If possible) use new digital control system.

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Introducing **Moku:Lab**,

a new all-in-one device for professional test and measurement.

Moku:Lab couples the signal processing power of an FPGA with high-speed analog inputs and outputs to bring you a new level of flexibility in the lab. Brought to you by Liquid Instruments.

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Moku:Lab

2 CHANNEL ANALOG INPUTS

- 500 MS/s, 12-bit ADCs
- 200 MHz bandwidth (-3 dB)
- 50 Ω / 1 MΩ impedance
- AC/DC coupling

2 CHANNEL ANALOG OUTPUTS

- 1 GS/s, 16-bit DACs
- 200 MHz maximum frequency (300 MHz analog bandwidth)
- 50 Ω impedance
- DC coupled

CONNECTIVITY AND STORAGE

- Wi-Fi
- Ethernet
- 8 GB SD Card

CLOCKS

- Ultra-stable oscillator (accuracy better than 1 ppm)
- 10 MHz reference input
- 10 MHz reference output

NOTE: If we use Moku:Lab in control servo, the frequency range is about 1 MHz because of time delay although sampling frequency is mush higher.

http://www.liquidinstruments.com

Problems(?) in Phase-1

- How to align the optical zenith angle?
- Can we achieve the vertical double optical spring where the cavities don't share the optical path?
- How to decouple the two main cavities from the other?
- How to support the levitating mirror before levitation?
- How to know the mirror is levitated?
- How to suspend the optical bench on which the main cavities are?

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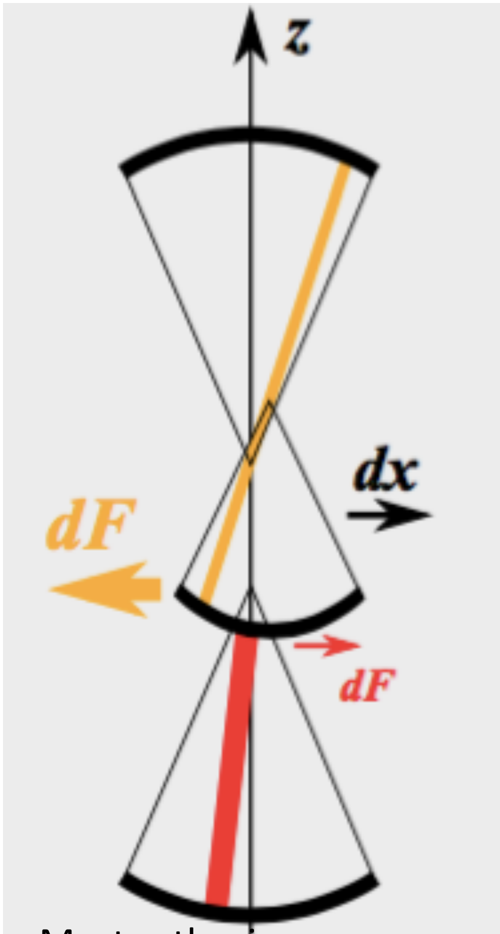
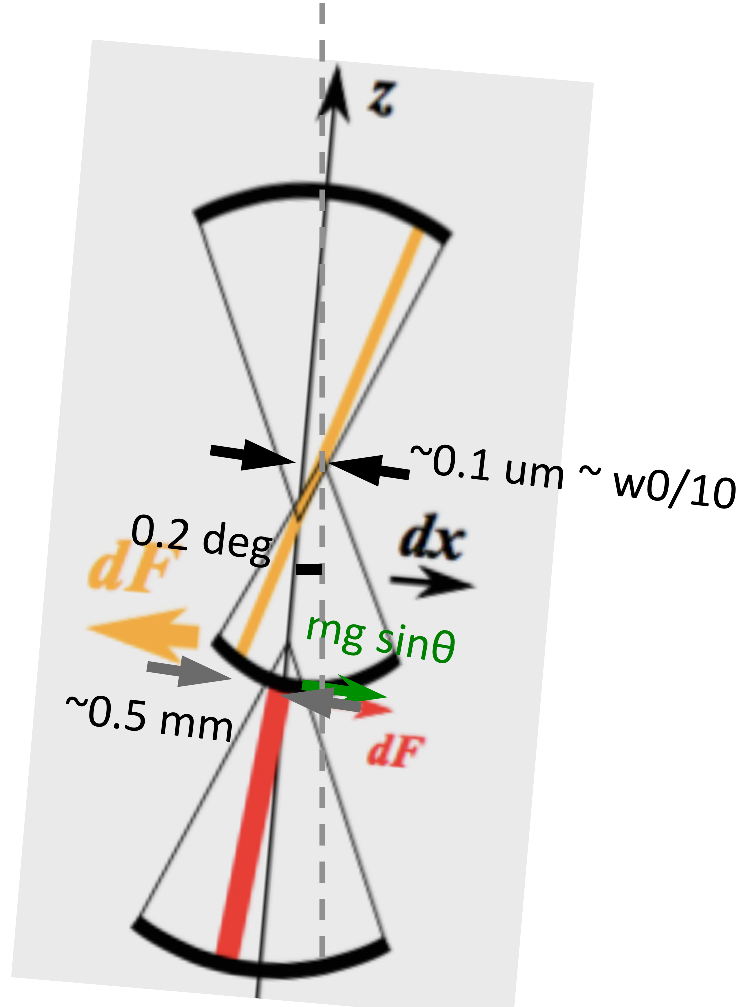
Zenith angle misalignment effect





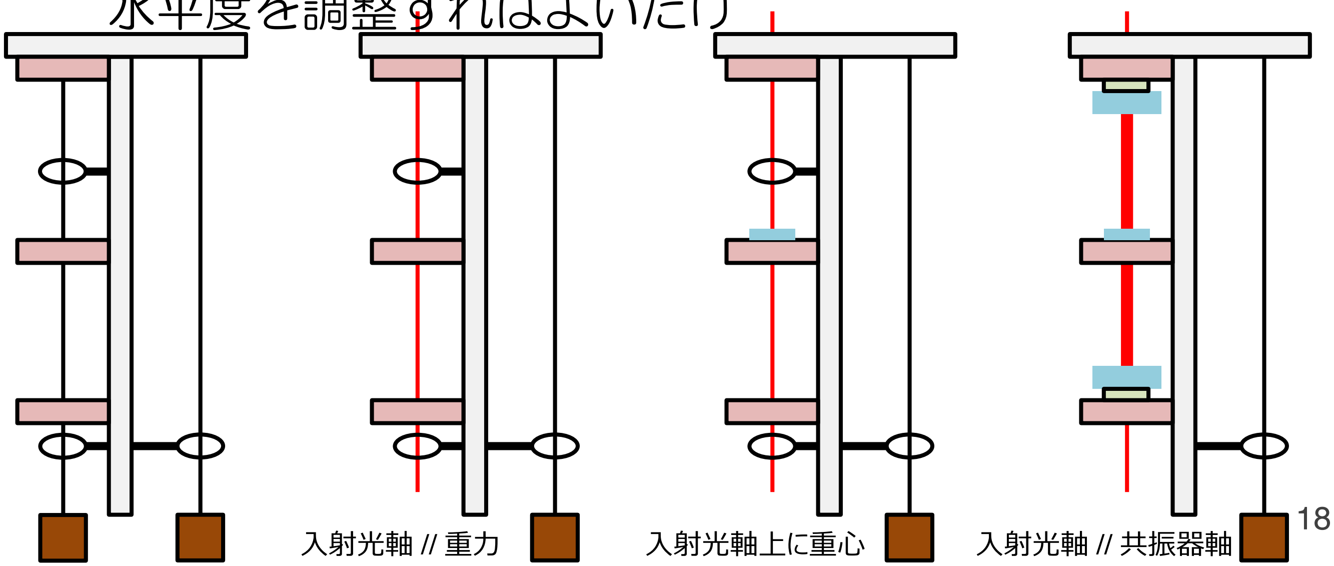
Y. Kuwahara, Master thesis defense , University of Tokyo (2016)

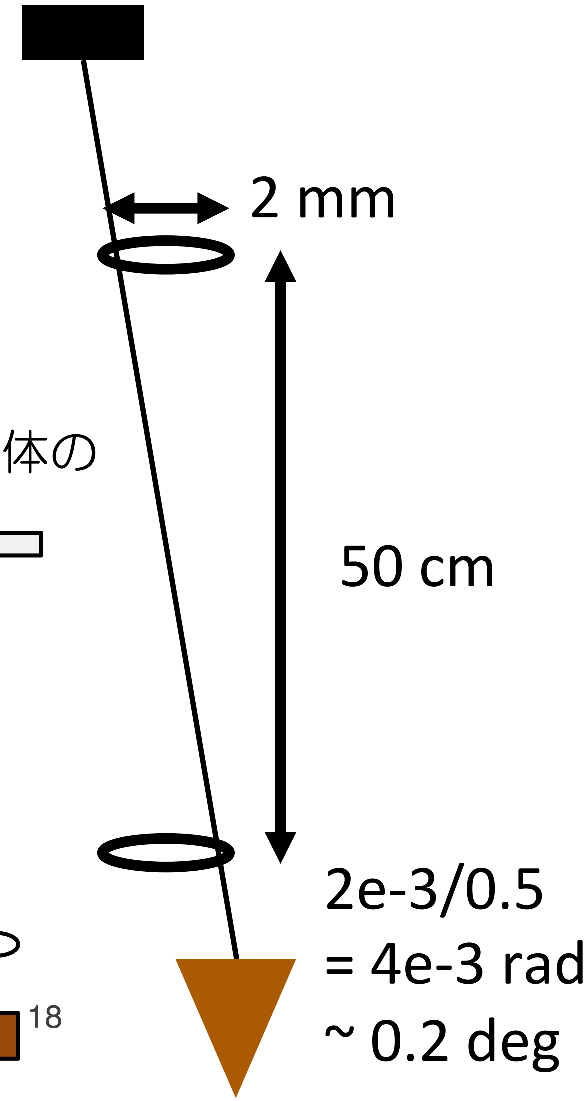
Zenith angle alignment

Y. Michimura, Seminar slide

アラインメント手順案

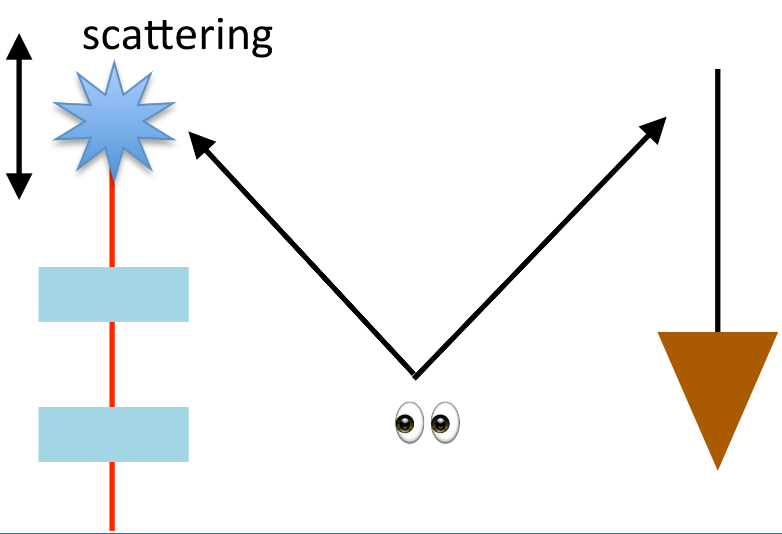
- 2つの錘を吊るした紐がアイリスを通るようにする
- アイリスに通るように上下の入射光軸をアライン
- 入射光が浮上鏡の中心(~重心)に当たるよう配置
- 上下共振器の共振が取れるように各鏡をアライン
- 移動させても、再び紐がアイリスを通るよう光学系全体の水平度を調整すればよいだけ





Other choices to align optical zenith angle

- Use accelerometer and gyro sensor.
  - Accelerometer can detect the gravity direction.
  - Gyro sensor can detect the angle displacement.
- Compare the optical cavity axis with the string of plumb.
  - See the transmitted light axis with IR camera and scattering something.

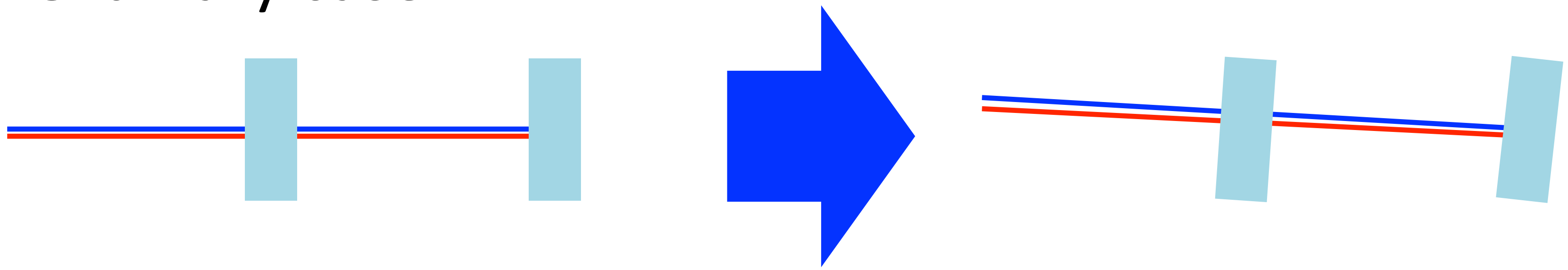


Problems(?) in Phase-1

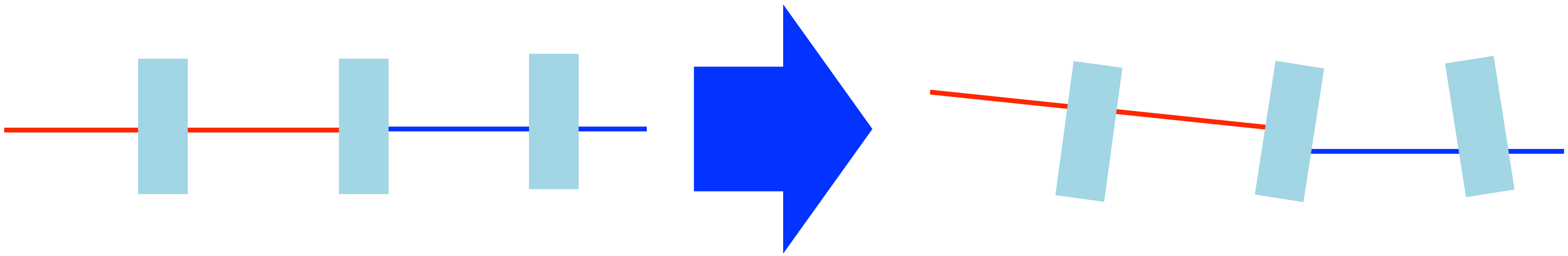
- How to align the optical zenith angle?
- Can we achieve the vertical double optical spring where the cavities don't share the optical path?
- How to decouple the two main cavities from the other?
- How to support the levitating mirror before levitation?
- How to know the mirror is levitated?
- How to suspend the optical bench on which the main cavities are?

Double optical spring

- Ordinary case

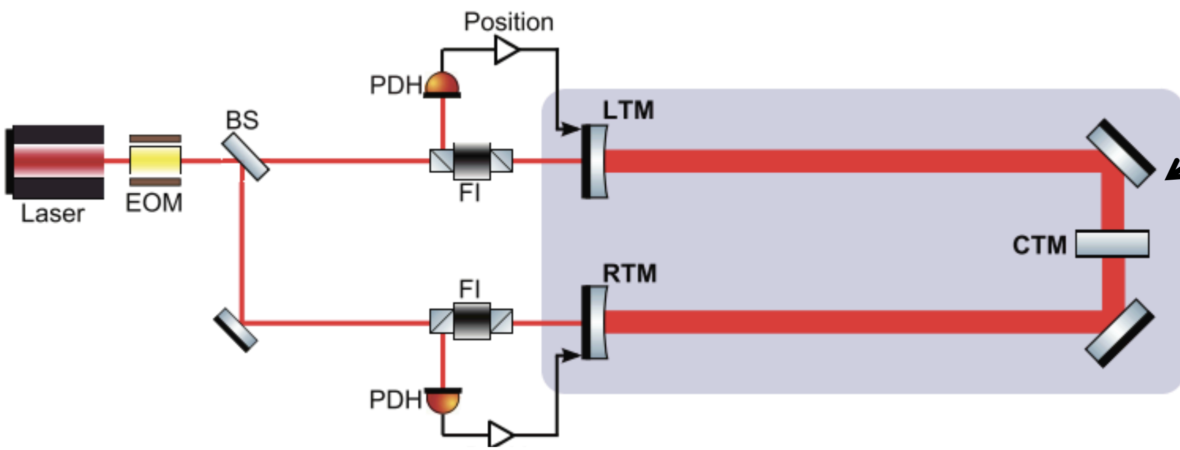


- Sandwich case

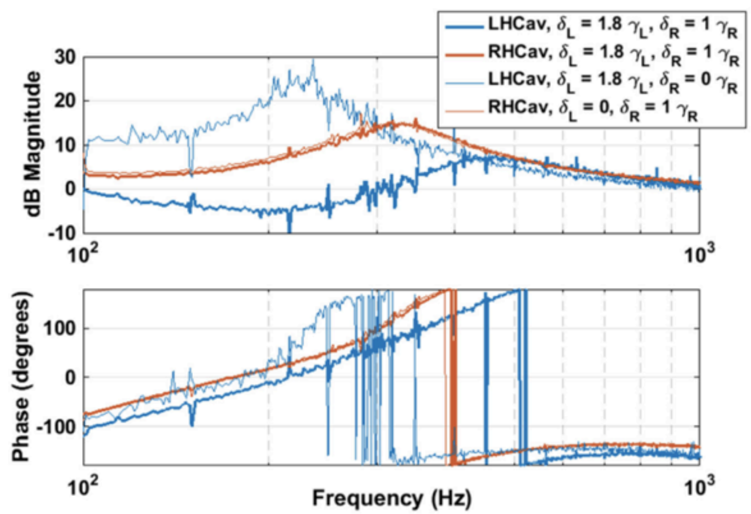


Double optical spring

- Coupled case was demonstrated.



10 m prototype in Glasgow

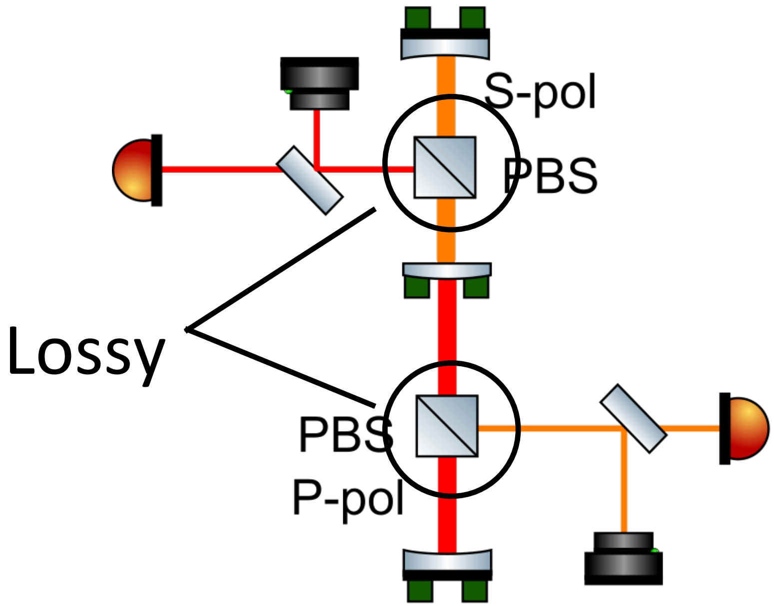


N. Gordon+, "Experimental demonstration of coupled optical springs," CQG (2017)

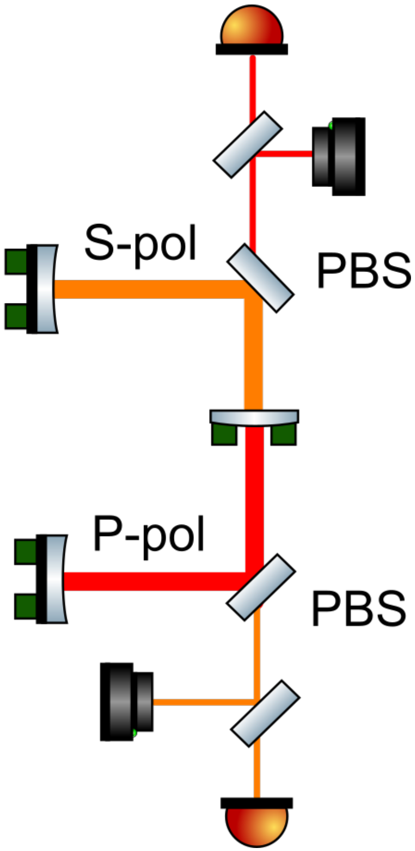
Problems(?) in Phase-1

- How to align the optical zenith angle?
- Can we achieve the vertical double optical spring where the cavities don't share the optical path?
- How to decouple the two main cavities from the other?
- How to support the levitating mirror before levitation?
- How to know the mirror is levitated?
- How to suspend the optical bench on which the main cavities are?

Decoupling two main cavities



or



eg) Thorlabs: high-power cube PBS (PBS12-1064-HP), T = 0.988

- Can we use prism instead of PBS?

eg1) Thorlabs: plate PBS (PBSW-1064), Tp = 0.993, Ts = 0.0055 (1-Ts = 0.9945)

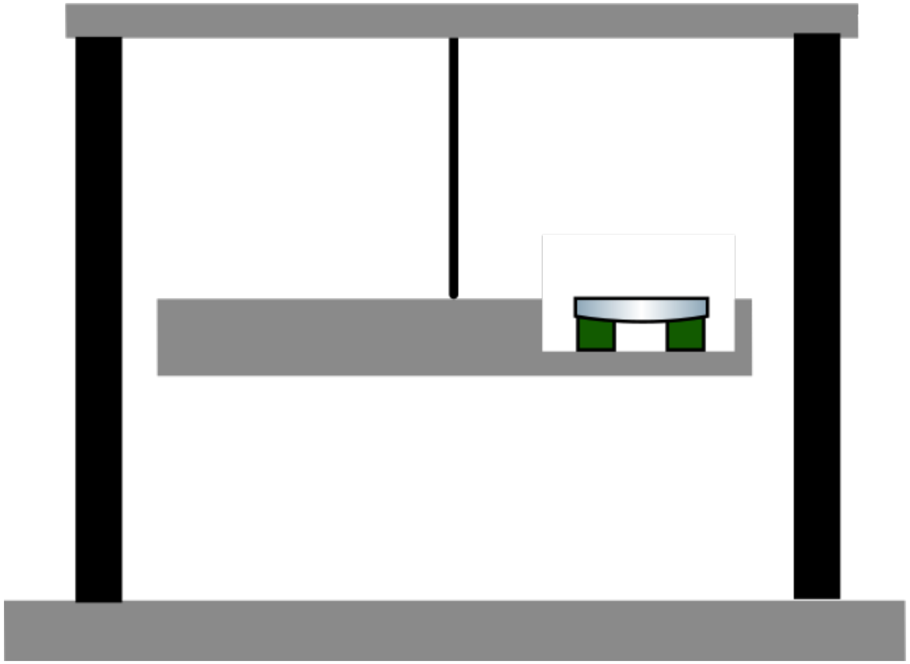
eg2) Thorlabs: plate FPB (FPB1059-43), Tp = 0.992, Ts = 6e-5 (1-Ts = 0.99994)

Problems(?) in Phase-1

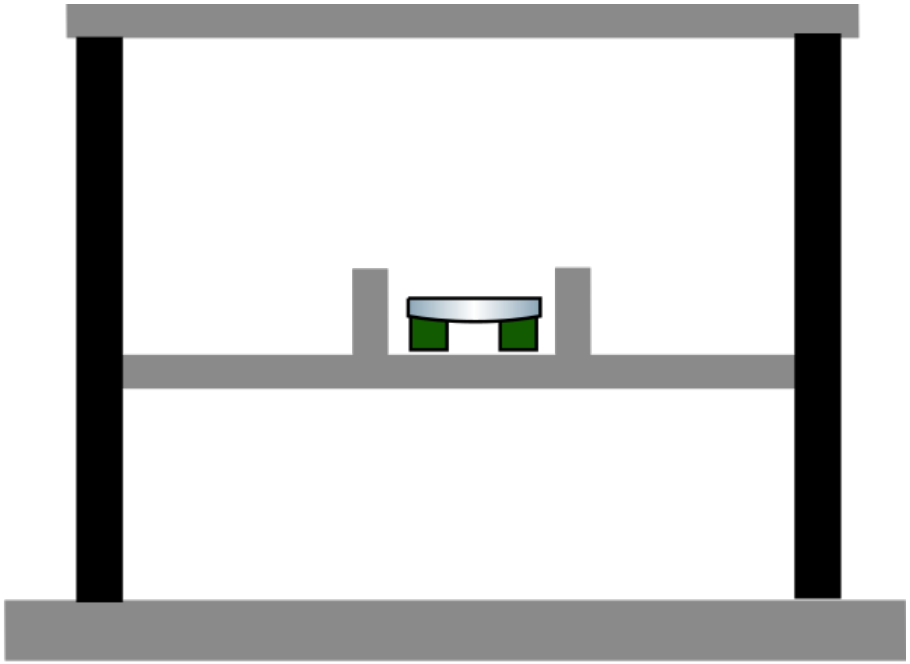
- How to align the optical zenith angle?
- Can we achieve the vertical double optical spring where the cavities don't share the optical path?
- How to decouple the two main cavities from the other?
- How to support the levitating mirror before levitation?
- How to know the mirror is levitated?
- How to suspend the optical bench on which the main cavities are?

Levitating mirror support

- On torsion pendulum



- On fixed stage

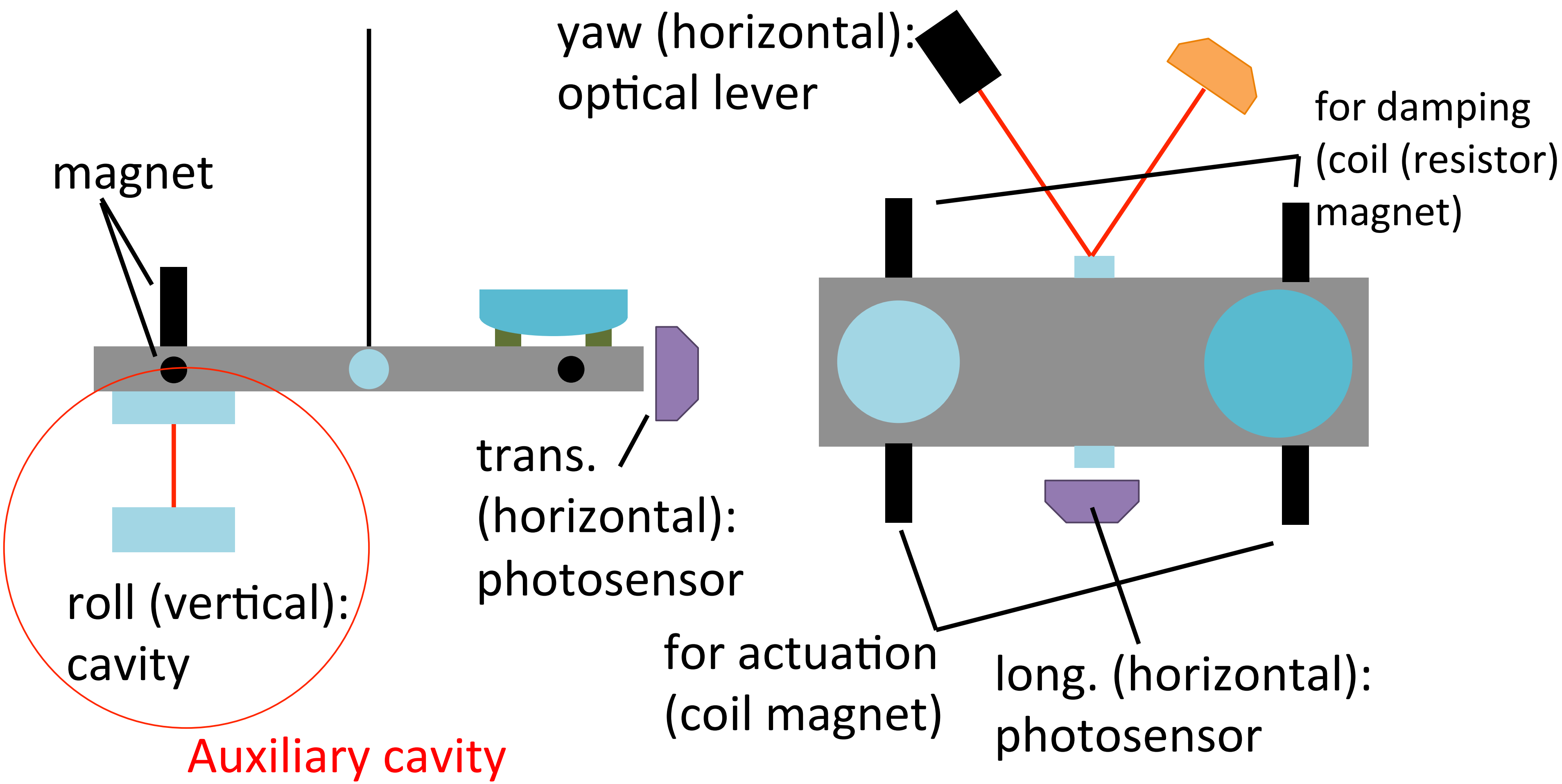


Levitating mirror support

- Advantage of torsion pendulum
  - mirror position can be adjusted.
  - vertical and horizontal optical spring effect can be measured.
- Disadvantage of torsion pendulum
  - mirror position is not stable without control.
  - requirement for mirror displacement RMS
    - vertical: << 50 pm (free run: 50 um)
    - horizontal: << 0.6 um (free run: 1 mm)
  - very strong servo control and damping is required.
  - low noise sensing for roll is also required.

Auxiliary cavity

- Sensing method of torsion pendulum



Problems(?) in Phase-1

- How to align the optical zenith angle?
- Can we achieve the vertical double optical spring where the cavities don’t share the optical path?
- How to decouple the two main cavities from the other?
- How to support the levitating mirror before levitation?
- How to know the mirror is levitated?
- How to suspend the optical bench on which the main cavities are?

How to detect the mirror levitation

- When the mirror levitate, the mirror's mechanical response should change dramatically. Thus, we can know the mirror levitation by measuring the open loop transfer function.
- Moreover, if we add the line signal into the PZT on which the mirror is (or the aux. cavity incident light power) and shake the mirror,
  - when the mirror is not levitated, the signal can be detected with the main cavity
  - when the mirror is levitated, the signal can NOT be detected with the main cavity

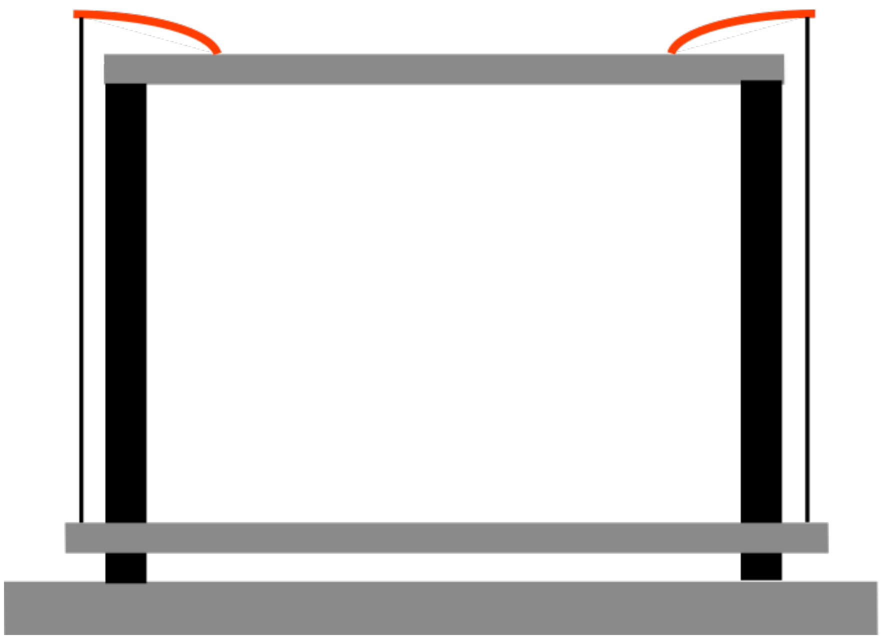
Problems(?) in Phase-1

- How to align the optical zenith angle?
- Can we achieve the vertical double optical spring where the cavities don't share the optical path?
- How to decouple the two main cavities from the other?
- How to support the levitating mirror before levitation?
- How to know the mirror is levitated?
- How to suspend the optical bench on which the main cavities are?

Blade spring or spring?

- Target resonant frequency is 1 Hz for horizontal and vertical.

- Blade spring



or

- Spring

Other things in Phase-1

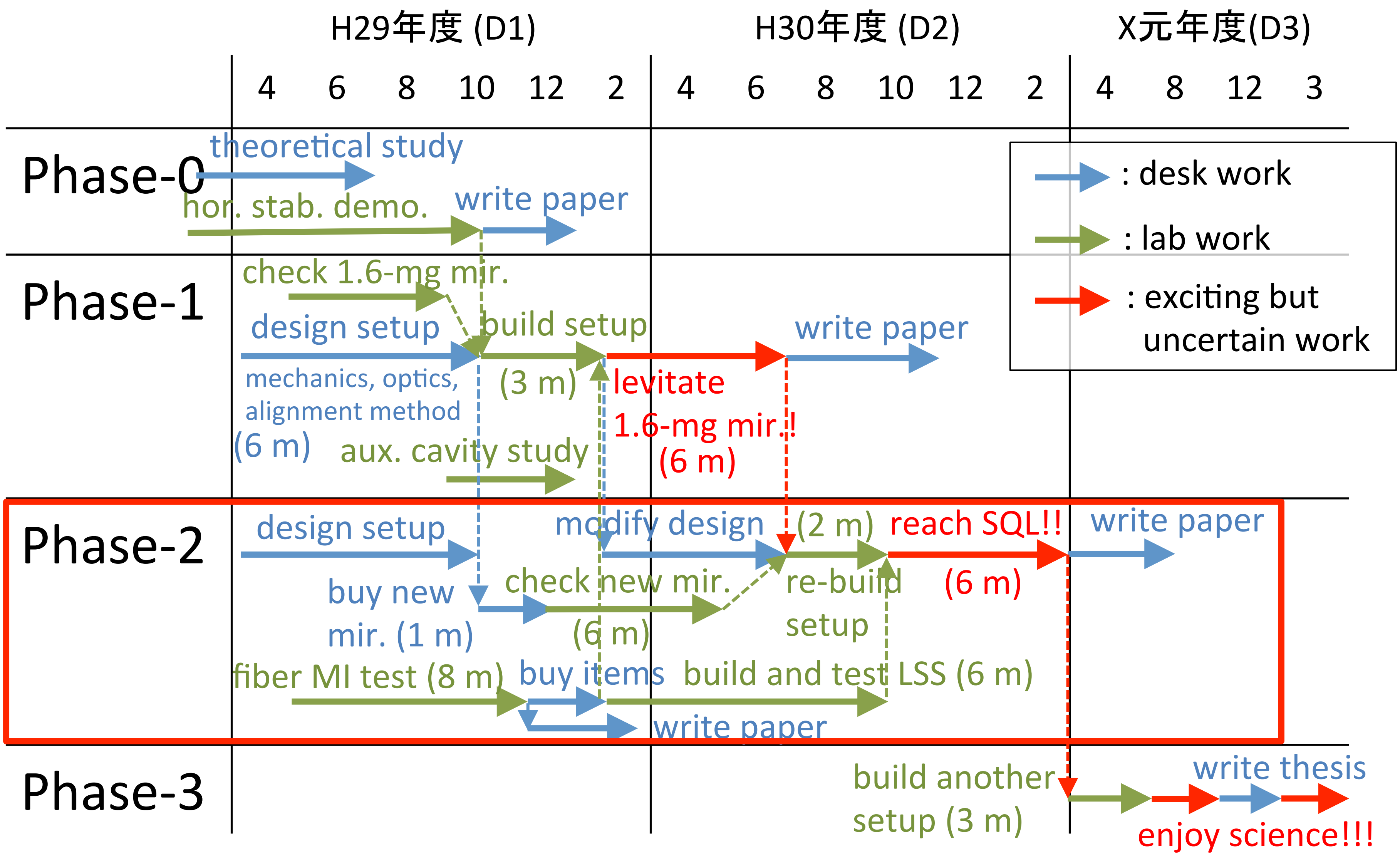
- Not considered problems
  - How to make a stable detuning.
  - Vacuum system.
- To do
  - Build laser power amplitude system.
  - Make freq. reference for freq. stabilization.
  - Design LSS, suspension, optics arrangement.
  - (Build new digital system.)
- To buy
  - Fiber optics compatible with 1064-nm laser.
    - fiber (covered and bare), EOM x2, AOM x2, fiber optics (BS, collimator, FI, and so on), fiber feed through, fiber amp., (laser source?), and so on.
  - Cavity mirror (for main and aux.)
  - Suspension system and optical bench.

Schedule

At first, let me divide our OL experiment into four phases.

- Phase-0 (we are here)
  - Confirmation of the possibility of the sandwich type OL. (theoretical study and R&D)
- Phase-1
  - Demonstration of the OL with sandwich configuration.
  - No sensitivity requirement.
- Phase-2
  - Achievement of the sensitivity reaching SQL.
- Phase-3
  - Test of the macroscopic quantum mechanics and the development of the technique to improve the sensitivity of GW detectors.

Schedule

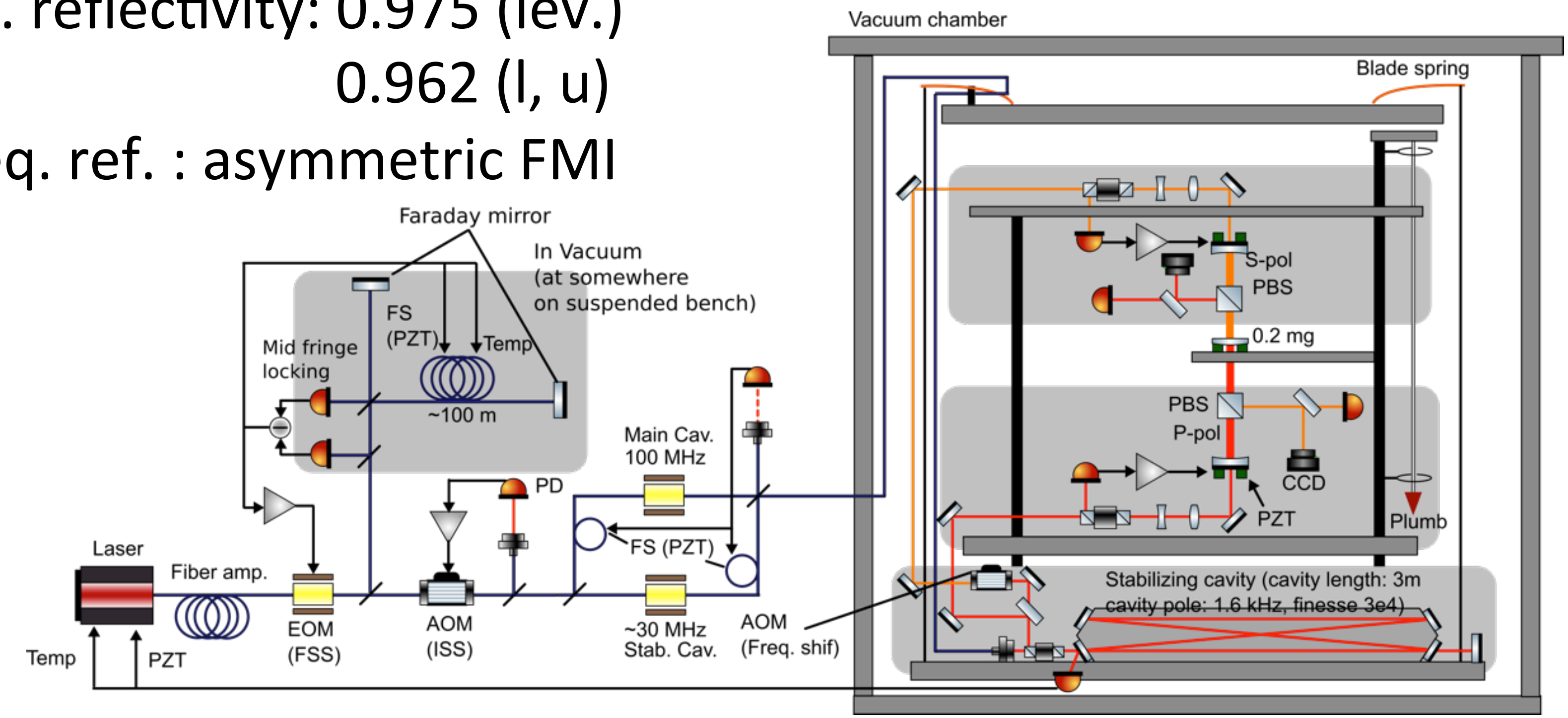


H29年度 (D1)
H30年度 (D2)
X元年度(D3)
4 6 8 10 12 2 4 6 8 10 12 2 4 8 12 3
Phase-0
theoretical study
hor. stab. demo.
write paper
Phase-1
check 1.6-mg mir.
design setup
build setup
mechanics, optics, alignment method
(6 m)
(3 m)
levitate 1.6-mg mir.!
(6 m)
write paper
aux. cavity study
Phase-2
design setup
modify design
(2 m)
reach SQL!!
write paper
buy new mir. (1 m)
check new mir.
(6 m)
re-build setup
(6 m)
fiber MI test (8 m)
buy items
build and test LSS (6 m)
write paper
Phase-3
build another setup (3 m)
write thesis
enjoy science!!!
: desk work
: lab work
: exciting but uncertain work

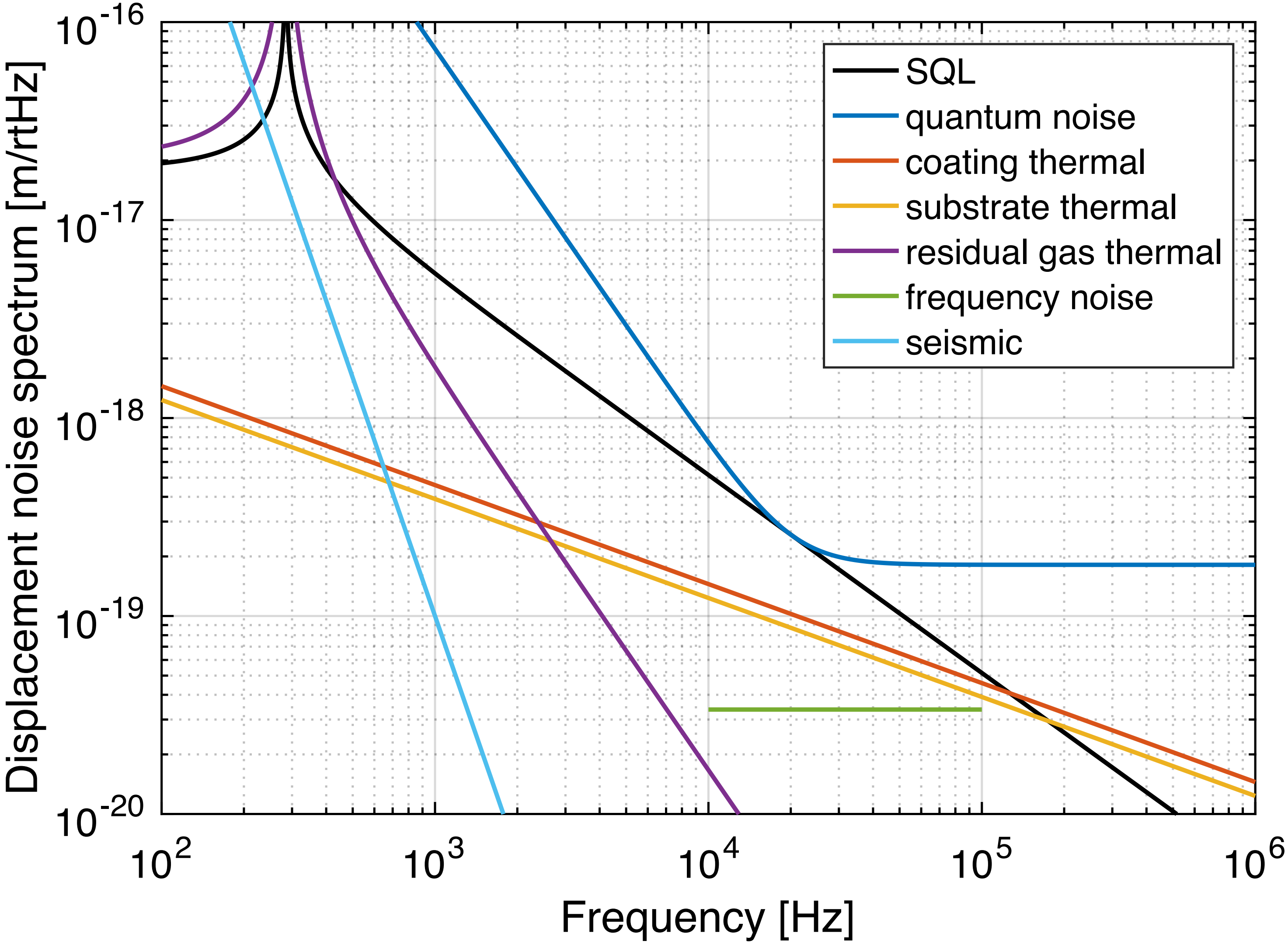
Experimental configuration in Phase-2

- wave length: 1064 nm
- finesse: 100 (lower, upper)
- input power: 10 W (lower)
  2.1 W (upper)
- lev. mirror mass: 0.2 mg
- int. reflectivity: 0.975 (lev.)
  0.962 (l, u)
- freq. ref. : asymmetric FMI

- Passive stabilizing cavity (double pass)
-- length: 3 m (FSR: 100 MHz)
-- finesse: 3 x 10^4
-- cavity pole: 1.6 kHz
-- Intracavity power: ~ 300 kW!!



Sensitivity in Phase-2



Points in Phase-2

- Use new 0.2-mg mirror.
- Use 100-m asymmetric fiber Michelson interferometer (AFMI) for frequency stabilization around 10 kHz.
- Use passive laser stabilizing cavity (PSC), that is the cavity with low cavity pole (~ 1 kHz).
- To get effective (2nd order) passive laser stabilization, the transmitted light is reflected back to the PSC. (Double-pass configuration)

Problems in Phase-2

- Such (0.2-mg) small mirror can be made?
- Is the frequency stabilization using AFMI at 10 kHz possible?
- Circulating power in the PSC is more than 100 kW which could burn its mirrors.
- Effect of the displacement of PSC on the effect of the passive stabilizing should be considered.
- Since cavity pole of main cavities is very high (~8 MHz), RF side band can enter the cavities to some extent.
- Is there any science which can be done using only one cavity reaching SQL?

Problems in Phase-2

- Such (0.2-mg) small mirror can be made?
- Is the frequency stabilization using AFMI at 10 kHz possible?
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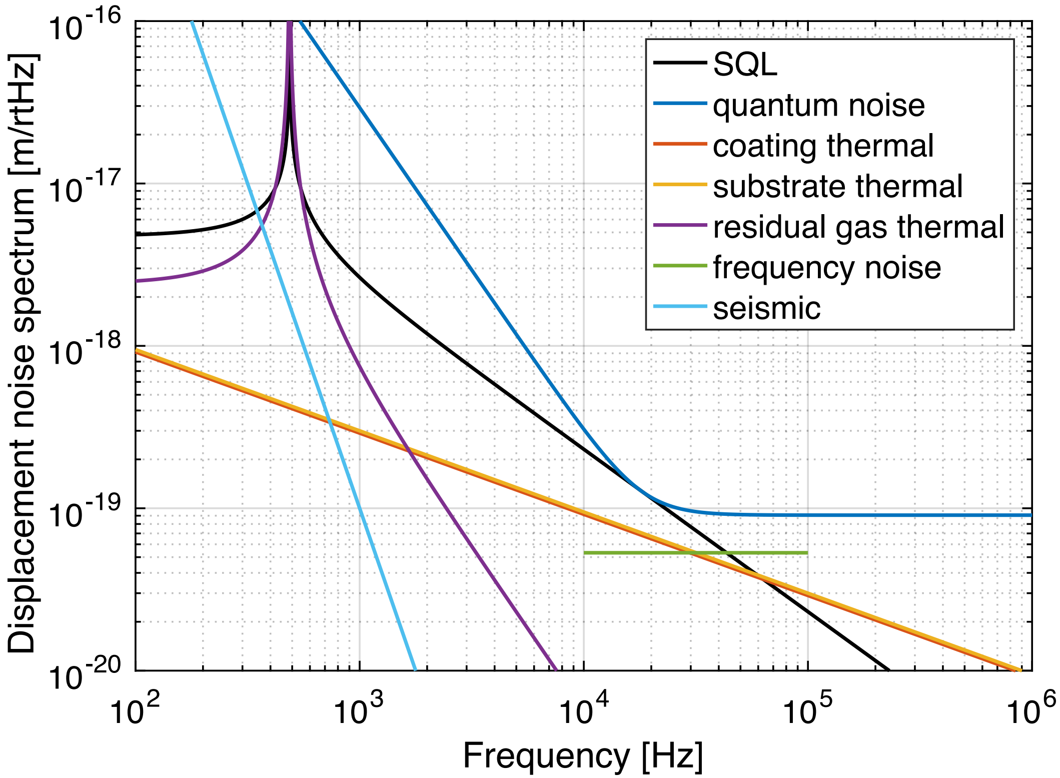
- Since cavity pole of main cavities is very high (~8 MHz), RF side band can enter the cavities to some extent.
- Is there any science which can be done using only one cavity reaching SQL?

Mass of levitated mirror

- As small as possible mirror is better.
- About 1-mg mirror may be upper limit, considering feasible incident power (lower: 40 W, upper: 12 W, finesse 100).



Problems in Phase-2

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AFMI vs Reference cavity

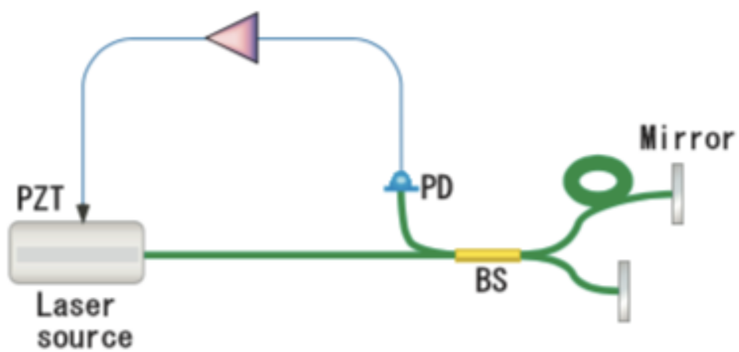
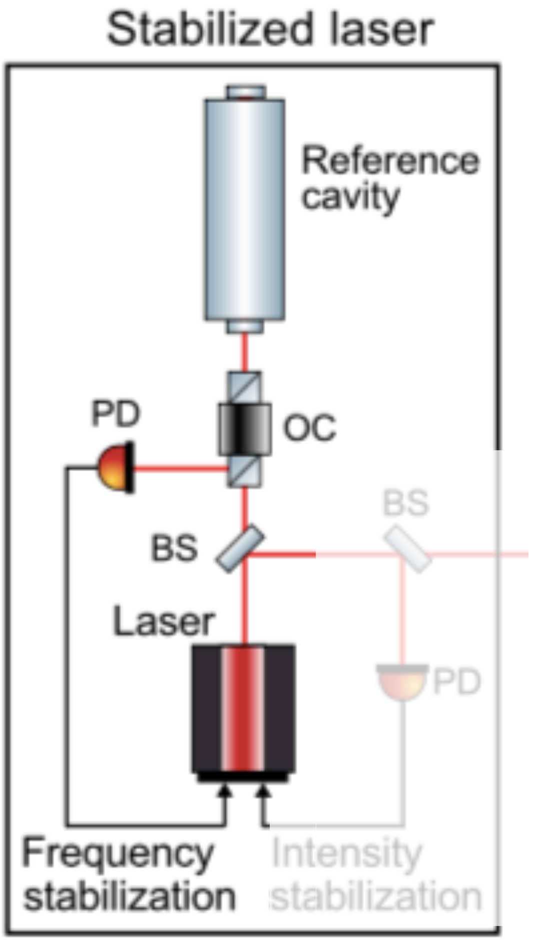


図 5.12: 周波数安定化光学系の基本構造

S(?). Takahashi, Master thesis, University of Tokyo (2008)

or



K. Nagano, Master thesis, University of Tokyo (2017)

AFMI vs Reference cavity

- Requirement of the frequency noise is 1×10^{-4} Hz/rtHz at 10 kHz.
- For the active stabilization, it is relaxed to be ~5×10^{-3} Hz/rtHz at 10 kHz thanks to the PSC.
- Displacement sensitivity requirement.
  - For AFMI (with 100-m asymmetry)
    - $x_{AFMI} = 1.7 \times 10^{-15}$ m/rtHz
  - For reference cavity (cavity length 20 cm)
    - $x_{RC} = 3.3 \times 10^{-18}$ m/rtHz
  - Suspended mirror cavity (like KAGRA's input mode cleaner) can be used?

Asymmetric fiber MI sensitivity

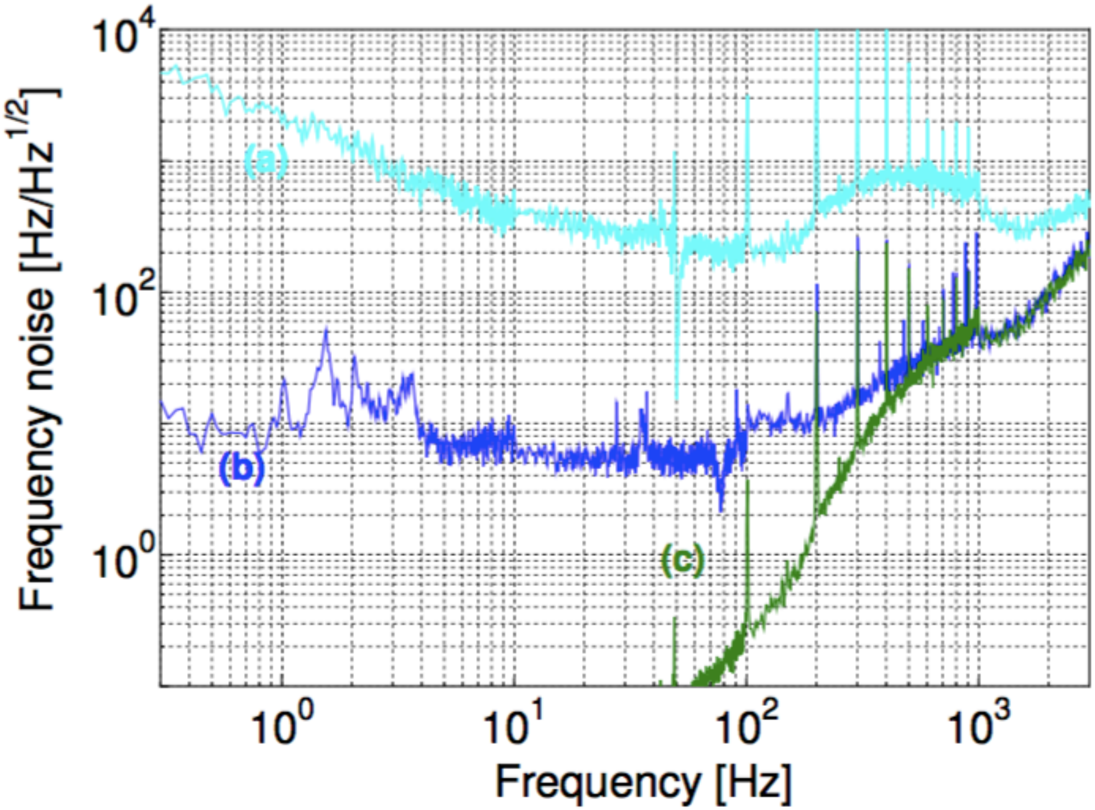


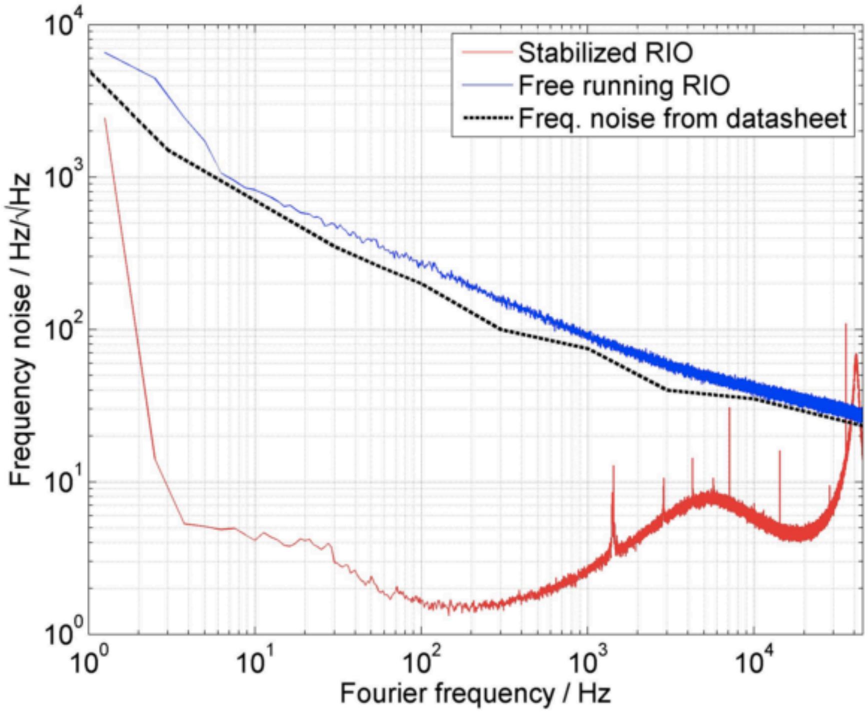
図 5.22: 周波数安定化の結果。(a): Free run でのノイズ。(b):制御後の Monito signal。(c): Free run ノイズと伝達関数から計算した、本実験での制御の設計値。低周波帯域ではグラフの表示範囲より小さい値になっている。

S(?). Takahashi, Master thesis, University of Tokyo (2008)

NOTE: In this measurement, laser source was 1550-nm DFB fiber laser, which may be more noisy than 1064-nm NPRO laser.

NOTE2: Asymmetry was 100 m.

Asymmetric fiber MI sensitivity



NOTE: In this measurement, laser source was 1540-nm RIO fiber laser, which is more noisy than 1064-nm NPRO laser.

NOTE2: Asymmetry was 2.09 km.

Figure 2. Single sideband frequency noise analysis of the ORION laser module. Comparison of the free-running, stabilized laser and the noise data from the manufacturer's datasheet [14].

R. Šmíd+, "Frequency Noise Suppression of a Single Mode Laser with an Unbalanced Fiber Interferometer for Subnanometer Interferometry," Sensors (2015)

Problems in Phase-2

- Such (0.2-mg) small mirror can be made?
- Is the frequency stabilization using AFMI at 10 kHz possible?
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- Is there any science which can be done using only one cavity reaching SQL?

Circulating power in PSC

- Circulating power in PSC will be very large, more than 100 kW.
  - For example, circulating power in KAGRA's PMC with high power (~100 W) laser is less than 10 kW.
  - With pulse laser (10 ps and 250 MHz repetition rate), 670 kW of average power was demonstrated. H. Carstens+, Opt. Lett. (2014)
- Is it OK? Or can we resolve it?
  - Make beam size large? (smaller intensity)
  - Make longer cavity? (smaller finesse)
  - Cool the cavity with liquid nitrogen?
- Anyway, very careful treatment is required to avoid contamination, for example dust.

Problems in Phase-2

- Such (0.2-mg) small mirror can be made?
- Is the frequency stabilization using AFMI at 10 kHz possible?
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Science of optical levitation experiment

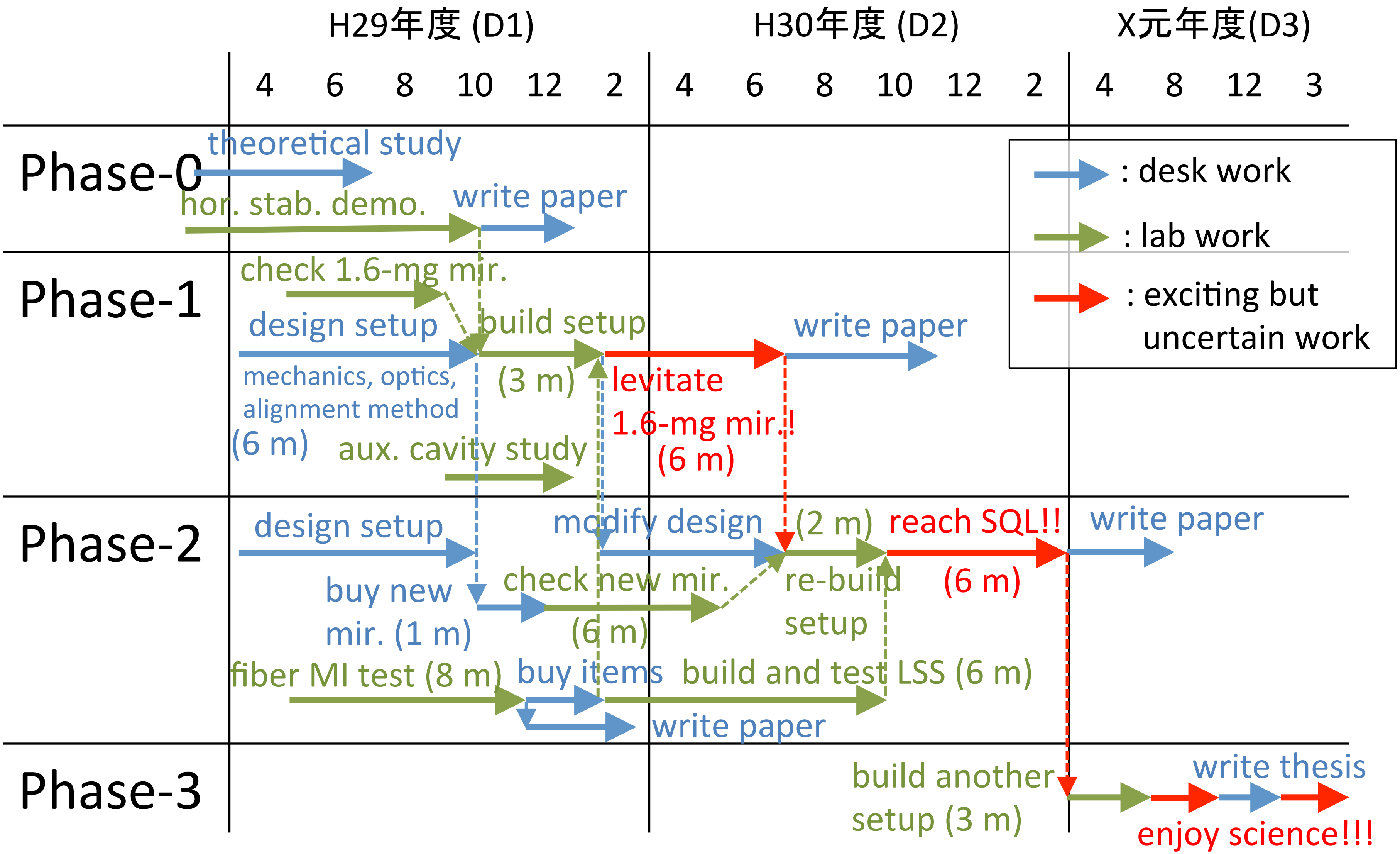
- All science ideas using optical levitation which I have so far require two cavities reaching SQL.
- However, it takes a lot of time and effort to build another cavity.
- Thus I'd like to do some scientific works with only one cavity reaching SQL.
- I believe interesting science must exist.
- If you have any idea, please share it with me.

Other things in Phase-2

- Not considered problems
  - The effect of the upper cavity's radiation pressure noise.
- To do
  - Design suspension, optics arrangement.
  - Discuss the possibility of the small mirror with manufacturing company (Sigma, LMS, ...).
- To buy
  - New small mirror, cavity mirrors.

Conclusion

Summary


H29年度 (D1)
H30年度 (D2)
X元年度(D3)
4 6 8 10 12 2 4 6 8 10 12 2 4 8 12 3
Phase-0
theoretical study
hor. stab. demo.
write paper
Phase-1
check 1.6-mg mir.
design setup
build setup
mechanics, optics, alignment method
(6 m)
(3 m)
aux. cavity study
levitate 1.6-mg mir.!
(6 m)
write paper
Phase-2
design setup
buy new mir. (1 m)
modify design
check new mir.
(6 m)
(2 m)
re-build setup
reach SQL!!
(6 m)
write paper
fiber MI test (8 m)
buy items
build and test LSS (6 m)
write paper
Phase-3
build another setup (3 m)
write thesis
enjoy science!!!
: desk work
: lab work
: exciting but uncertain work

End