Requirements for B-DECIGO

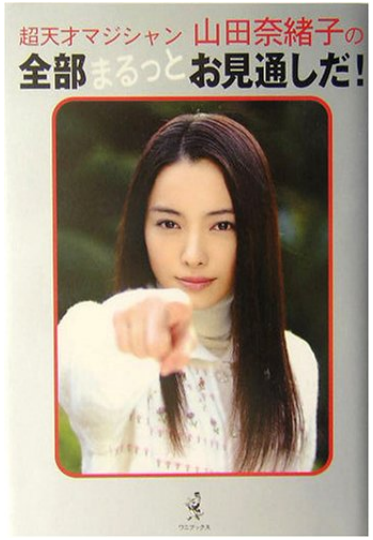
Koji Nagano (長野 晃士)
Institute for Cosmic Ray Research, University of Tokyo

Abstract

- DECIGO is very good detector.
- B-DECIGO is also good detector.
- I considered the feasibility of B-DEICOG and found B-DECIGO requirements seem to be possible if we will do our best.

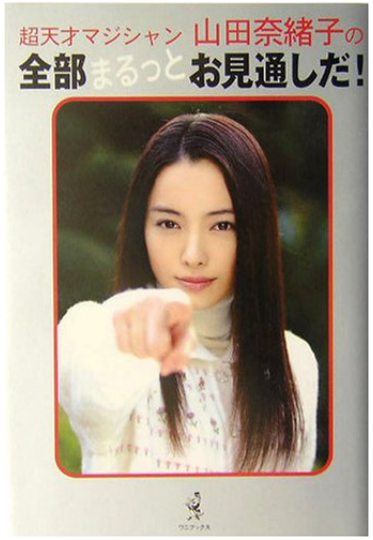
Abstract

- DECIGO is very good detector.
- B-DECIGO is also good detector.
- I considered the feasibility of B-DEICOG and found B-DECIGO requirements seem to be possible if we will do our best.



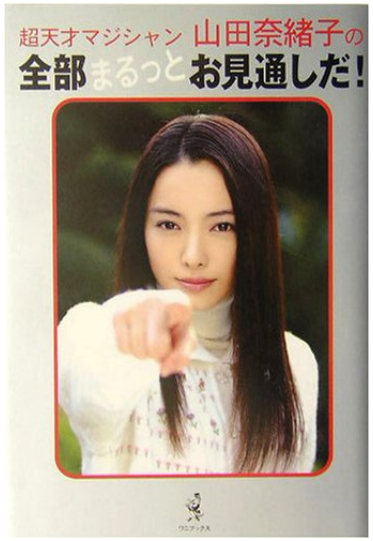
Abstract

- DECIGO is very good detector.
- B-DECIGO is also good detector.
- I considered the feasibility of B-DEICOG and found B-DECIGO requirements seem to be possible if we will do our best.



Abstract

- DECIGO is very good detector.
- B-DECIGO is also good detector.
- I considered the feasibility of B-DEICOG and found B-DECIGO requirements seem to be possible if we will do our best.



Outline

1. Overture
2. Introduction
3. Requirements for B-DECIGO
4. Conclusion

Overture

Why do I study on DECIGO?

Overture

Why do I study on DECIGO?

https://en.wikipedia.org/wiki/Eclipse_(horse)

Outline

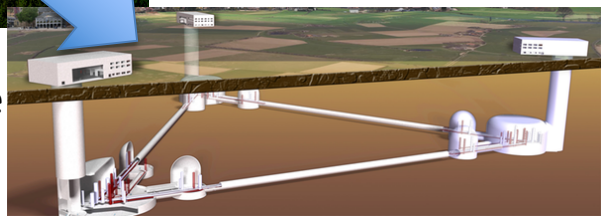
1. Overture
2. Introduction
3. Requirements for B-DECIGO
4. Conclusion

Introduction

- So far, 11 gravitational wave (GW) events have been detected by ground-based detectors.
- For further expansion of the GW physics and astronomy, we have two choices.

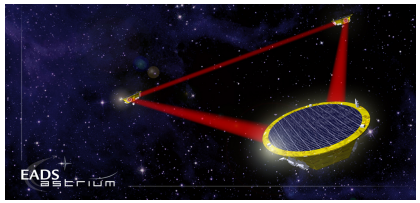
Improve ground-based detectors' sensitivity (10 Hz-1 kHz)

LIGO Livingston (Credit: Caltech/MIT/LIGO Lab)



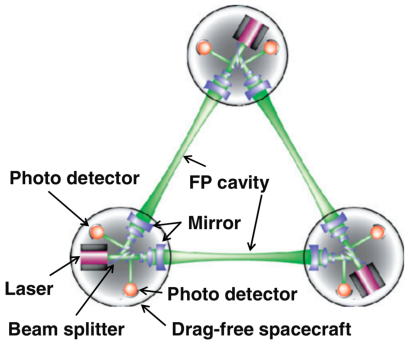
Einstein telescope (http://www.et-gw.eu)

Develop space detectors (0.1 mHz-10 Hz)



LISA (Credit: EADS Astrium)

DECIGO (S. Kawamura+, CQG, 2011)

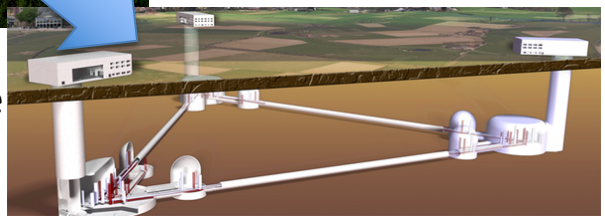


Introduction

- So far, 11 gravitational wave (GW) events have been detected by ground-based detectors.
- For further expansion of the GW physics and astronomy, we have two choices.

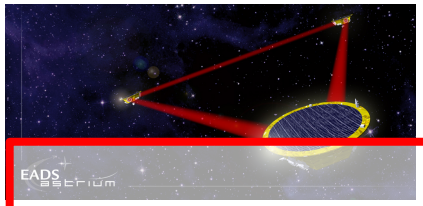
Improve ground-based detectors' sensitivity (10 Hz-1 kHz)

LIGO Livingston (Credit: Caltech/MIT/LIGO Lab)



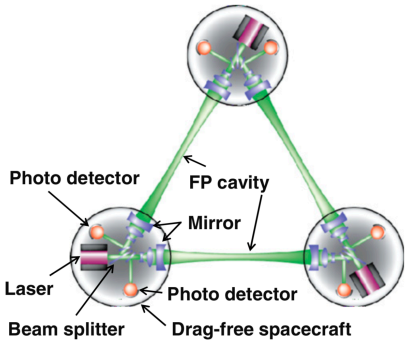
Einstein telescope (http://www.et-gw.eu)

Develop space detectors (0.1 mHz-10 Hz)



LISA (Credit: EADS Astrium)

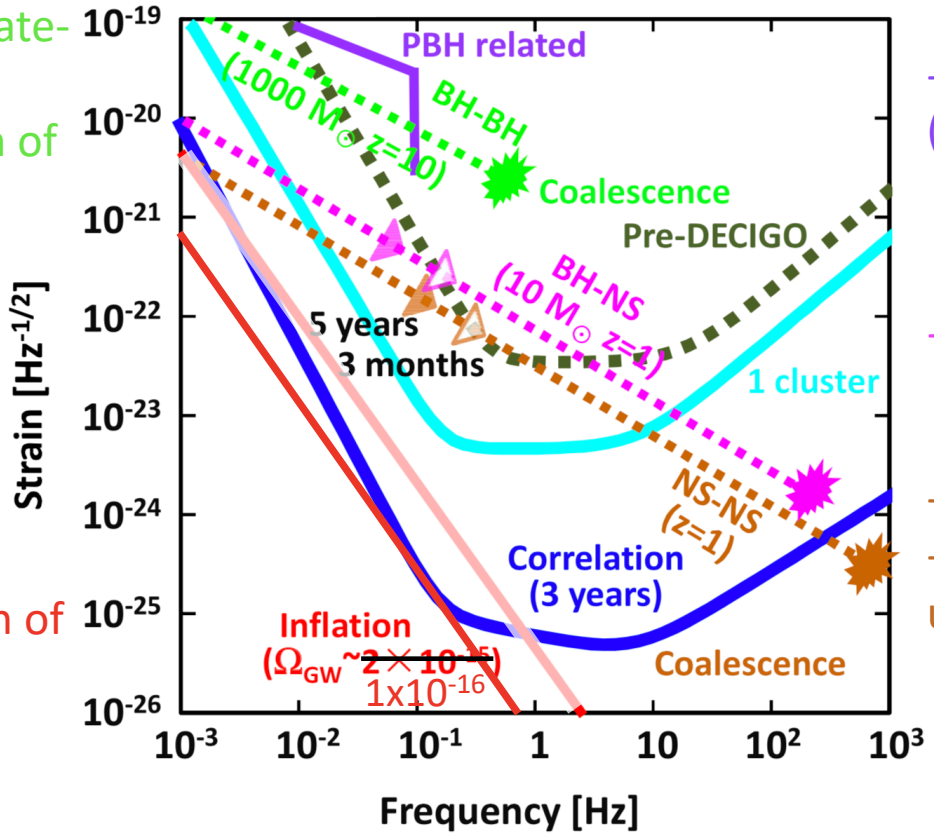
DECIGO (S. Kawamura+, CQG, 2011)



DECIGO

- Observe intermediate-mass black holes
->Reveal mechanism of formulation of supermassive black holes

- Verify inflation
-> Direct observation of the beginning of the universe



DECIGO sensitivity (S. Kawamura+, CQG, 2011)

- Dark-matter (candidate) search

- Test gravity theories

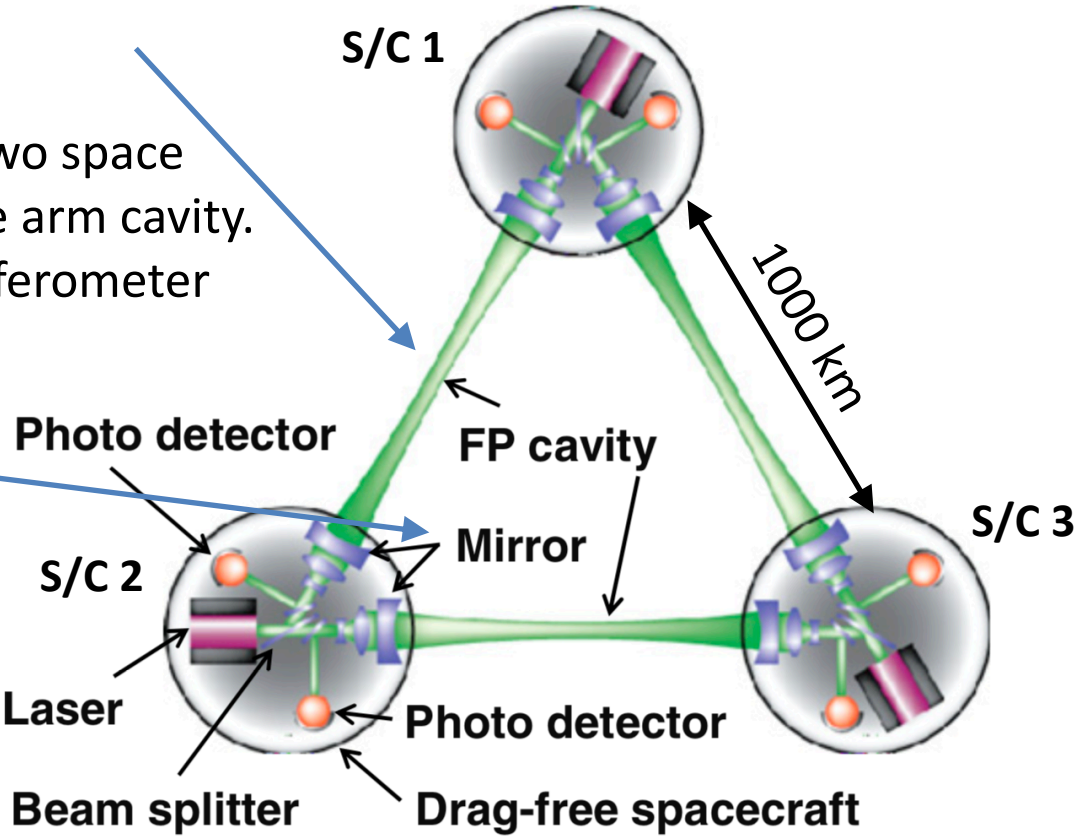
- Study neutron physics
- Measure accelerated universe directly
-> Dark-energy search

DECIGO

Arm (Fabry-Perot (FP) cavity) ←To improve best sensitivity
- Length: 1000 km
- Finesse: 10
- Two beams from two space crafts co-exist in one arm cavity.
= Dual-pass FP interferometer

Mirror
- Mass: 100 kg

Laser
- Wavelength: 515 nm
- Incident power: 10 W
- Freq. fluctuation: <1 Hz/rtHz @1 Hz



Pre-conceptual design of DECIGO
(S. Kawamura+, CQG, 2011)

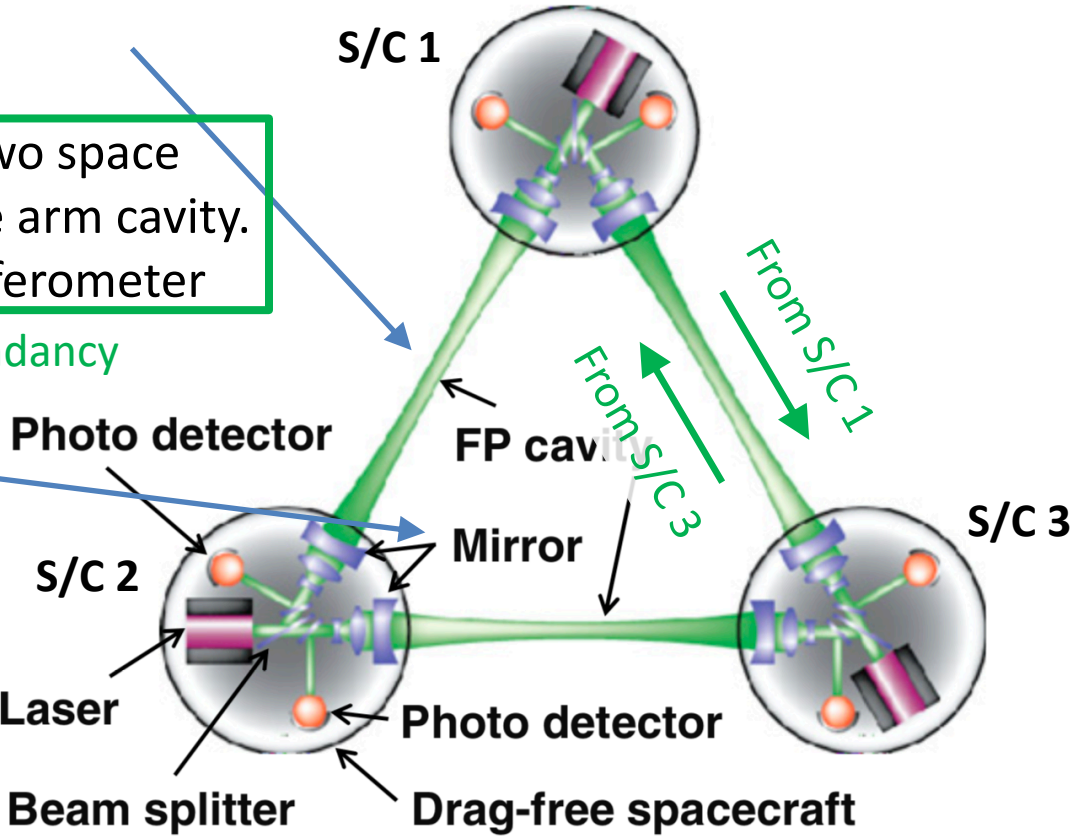
DECIGO

Arm (Fabry-Perot (FP) cavity) ←To improve best sensitivity
- Length: 1000 km
- Finesse: 10
- Two beams from two space crafts co-exist in one arm cavity.
= Dual-pass FP interferometer

To secure the redundancy

Mirror
- Mass: 100 kg

Laser
- Wavelength: 515 nm
- Incident power: 10 W
- Freq. fluctuation: <1 Hz/rtHz @1 Hz



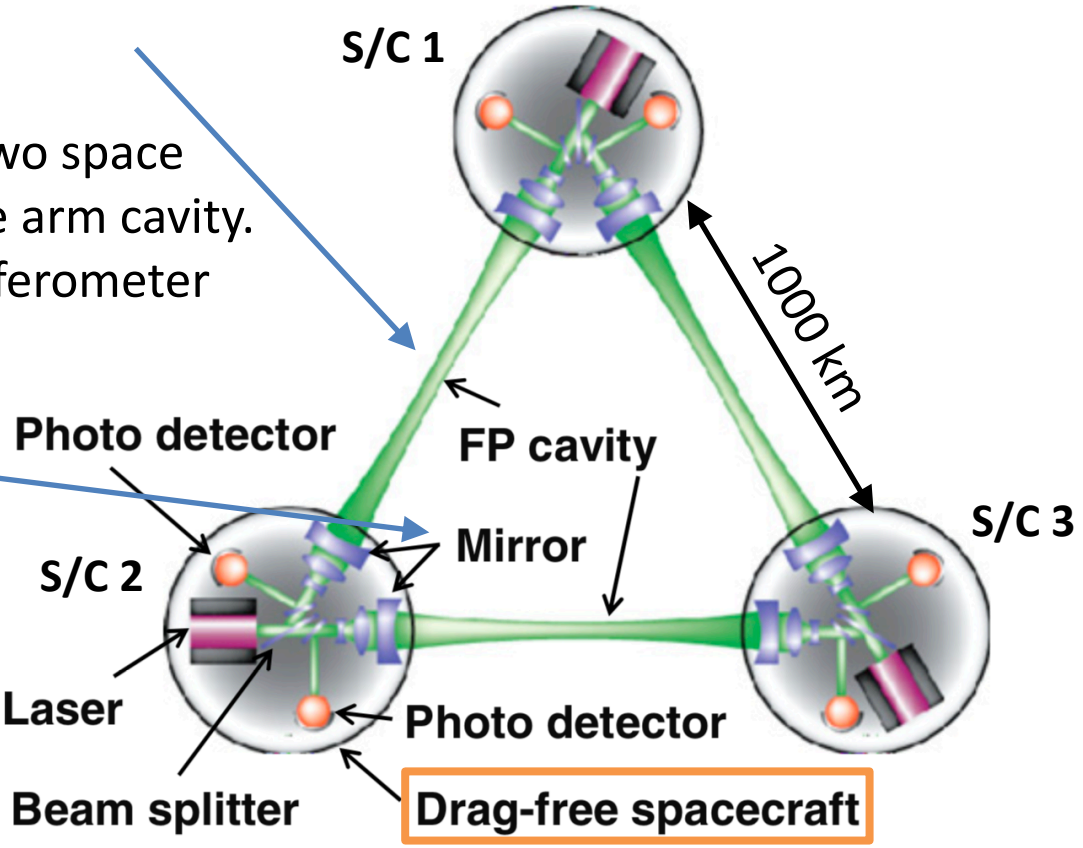
Pre-conceptual design of DECIGO
(S. Kawamura+, CQG, 2011)

DECIGO

Arm (Fabry-Perot (FP) cavity) ←To improve best sensitivity
- Length: 1000 km
- Finesse: 10
- Two beams from two space crafts co-exist in one arm cavity.
= Dual-pass FP interferometer

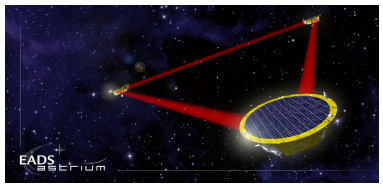
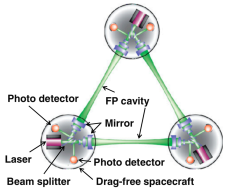
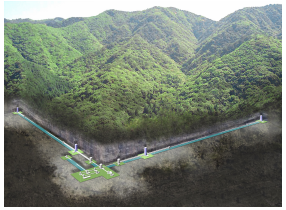
Mirror
- Mass: 100 kg

Laser
- Wavelength: 515 nm
- Incident power: 10 W
- Freq. fluctuation: <1 Hz/rtHz @1 Hz

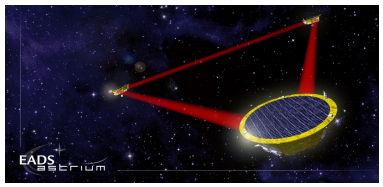
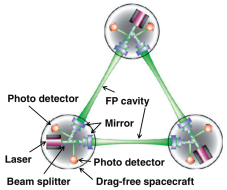
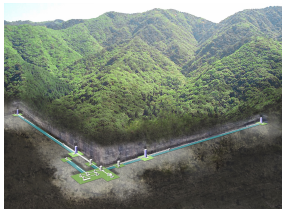


Pre-conceptual design of DECIGO
(S. Kawamura+, CQG, 2011)

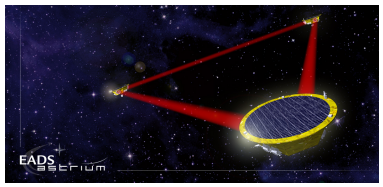
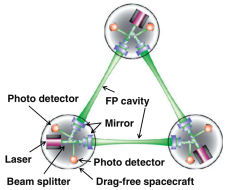
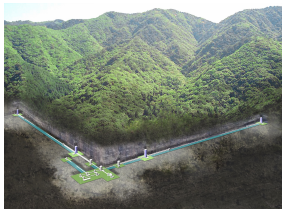
DECIGO, LISA, and KAGRA

	 LISA	 **DECIGO**	 KAGRA
Space/Ground	Space	Space	Ground
Arm length	2.5 Gm	1000 km	3 km
Obs. freq.	10^{-4}-10^{-1} Hz	10^{-1}-10 Hz	10-10^{4} Hz
Optical configuration	Optical transponder (In-direct ITF)	Dual-pass FP interferometer (Direct ITF)	RSE interferometer (Direct ITF)
DF control	Necessary	Necessary	Not necessary

DECIGO, LISA, and KAGRA

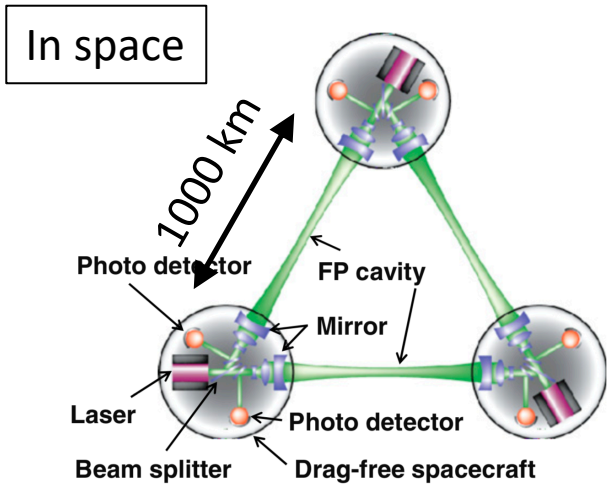
	 LISA	 **DECIGO**	 KAGRA
Space/Ground	Space	Space	Ground
Arm length	2.5 Gm	1000 km	3 km
Obs. freq.	10^{-4}-10^{-1} Hz	10^{-1}-10 Hz	10-10^{4} Hz
Optical configuration	Optical transponder (In-direct ITF)	Dual-pass FP interferometer (Direct ITF)	RSE interferometer (Direct ITF)
DF control	Necessary	Necessary	Not necessary

DECIGO, LISA, and KAGRA

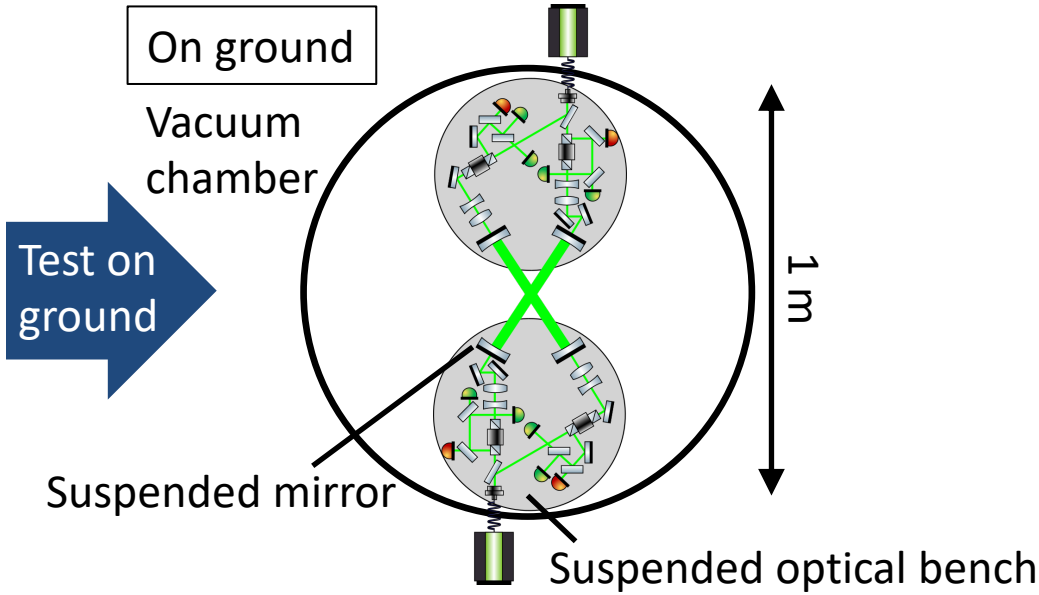
	 LISA	 **DECIGO**	 KAGRA
Space/Ground	Space	Space	Ground
Arm length	2.5 Gm	1000 km	3 km
Obs. freq.	10^{-4}-10^{-1} Hz	10^{-1}-10 Hz	10-10^{4} Hz
Optical configuration	Optical transponder (In-direct ITF)	Dual-pass FP interferometer (Direct ITF)	RSE interferometer (Direct ITF)
DF control	Necessary	Necessary	Not necessary

Test bench for interferometer operation

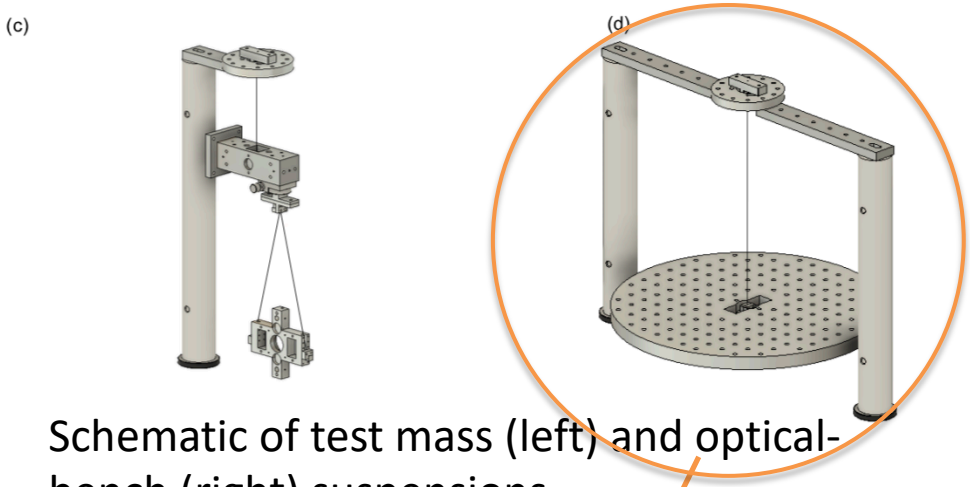
- For demonstration of Fabry-Perot interferometer with drag-free control, a test bench is being constructed.
  - This test bench has optical (interferometer) and mechanical (drag-free) part.



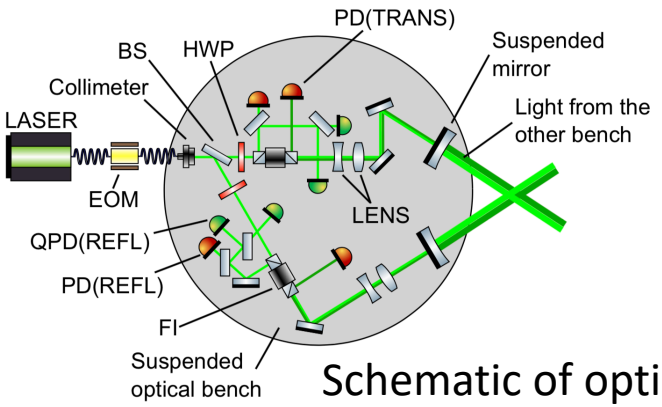
Schematic of DECIGO
(S. Kawamura+, CQG, 2011)



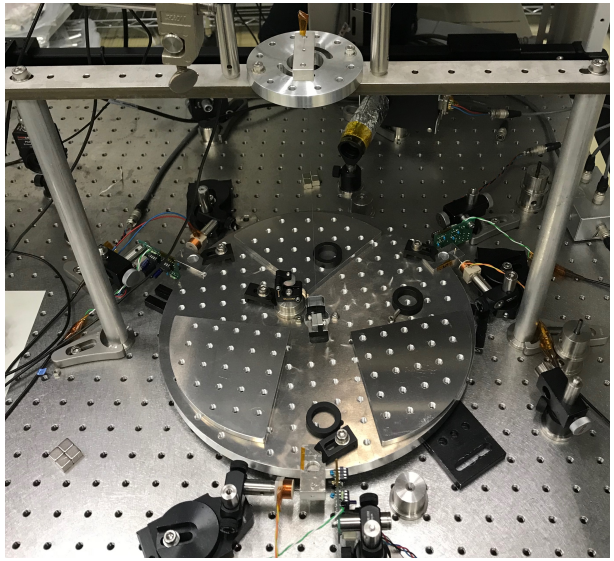
Schematic of the test bench



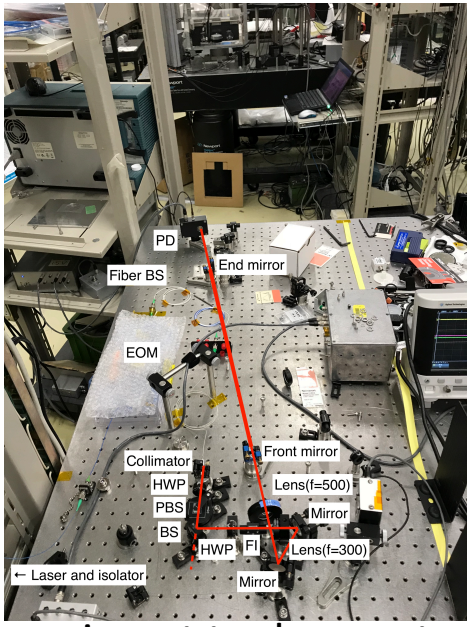
Schematic of test mass (left) and optical-bench (right) suspensions.



Schematic of optics.



Picture of suspended optical bench.



Experiment to demonstrate Dual-Pass FP interferometer.

Outline

1. Overture
2. Introduction
3. Requirements for B-DECIGO
4. Conclusion

B-DECIGO

Arm (Fabry-Perot (FP) cavity) ←To improve best sensitivity

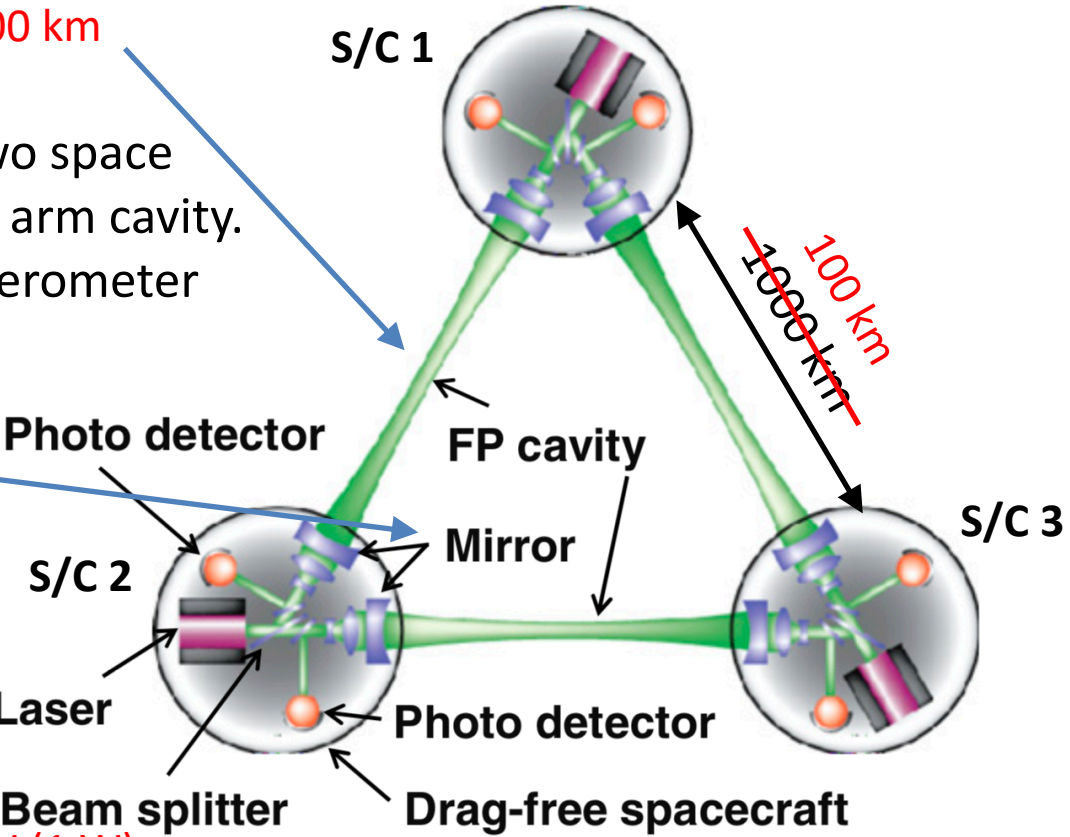
- Length: ~~1000 km~~ 100 km
- Finesse: ~~10~~ 100
- Two beams from two space crafts co-exist in one arm cavity.
= Dual-pass FP interferometer

Mirror

- Mass: ~~100 kg~~ 30 kg

Laser

- Wavelength: 515 nm
- Incident power: ~~10 W~~ 33 mW (1 W)
- Freq. fluctuation: <1 Hz/rtHz @1 Hz

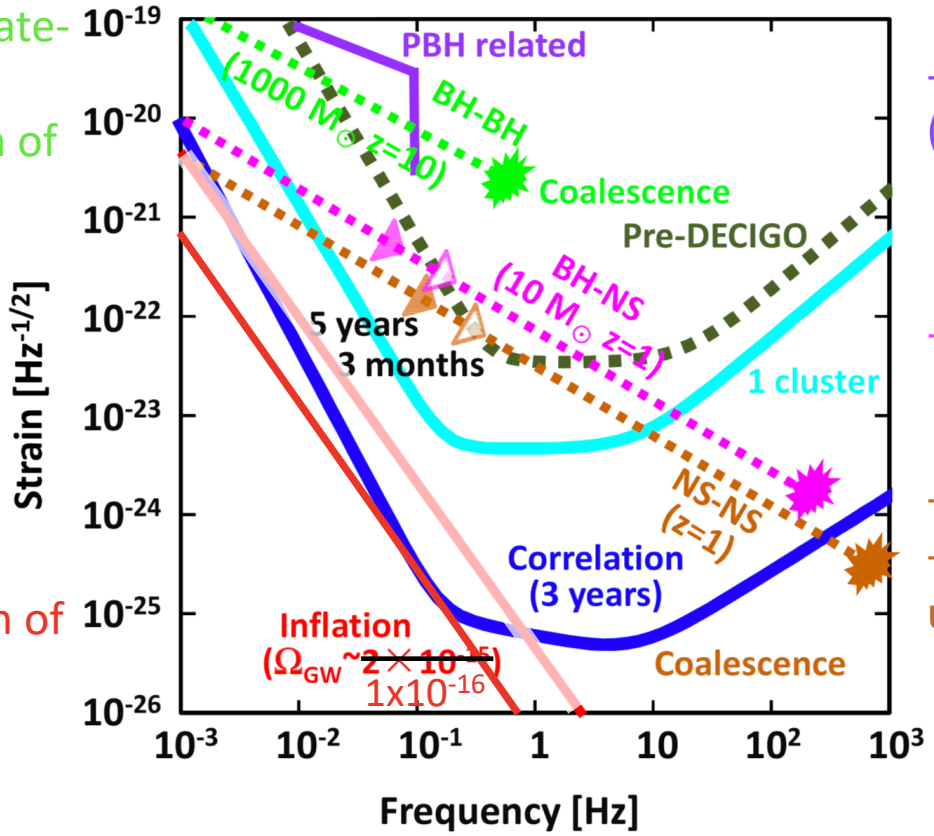


Pre-conceptual design of DECIGO
(S. Kawamura+, CQG, 2011)

B-DECIGO

- Observe intermediate-mass black holes
->Reveal mechanism of formulation of supermassive black holes ○

- Verify inflation
-> Direct observation of the beginning of the universe ×



DECIGO sensitivity (S. Kawamura+, CQG, 2011)

- Dark-matter (candidate) search ○

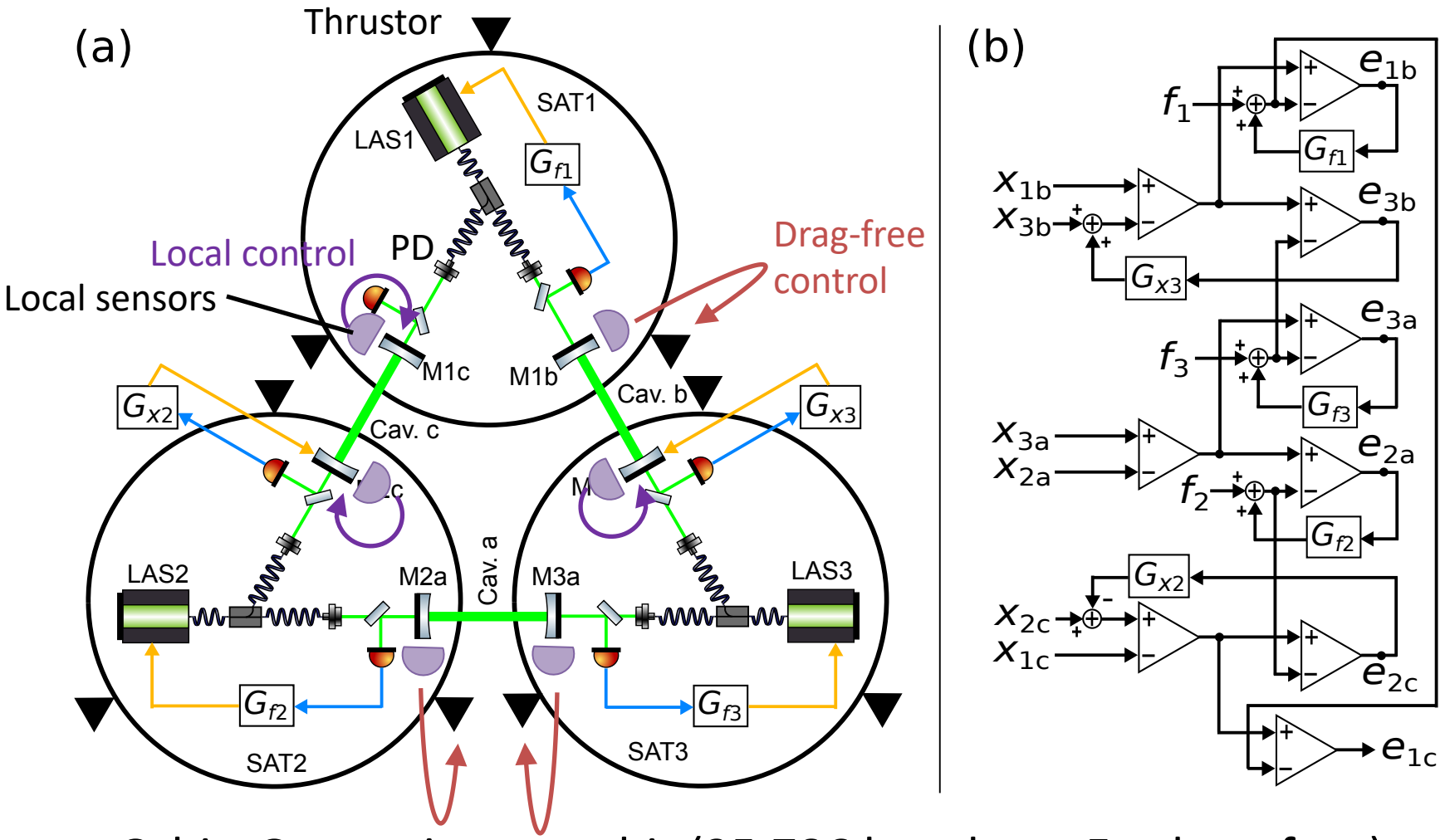
- Test gravity theories ○

- Study neutron physics
- Measure accelerated universe directly
-> Dark-energy search △

Requirement for B-DECIGO

- So far, there is not a base-line design and requirement for B-DECIGO.
  - This is for encouraging for people to consider their original ideas widely.
- Recently, I considered something about B-DECIGO design and requirement.
  - Sensitivity
  - Stability
- This time, I want share them and hear your opinions.

My design of B-DECIGO



Orbit: Geostationary orbit (35,786 km above Earth surface)

My design of B-DECIGO

Some notes

- In this design, all arms must have the same arm length in the sub-wavelength level (~0.1 um) if the lasers have different wavelength.
- AOM cannot be inserted into the one arm.
- Drag-free controls have large (>1) gain in all frequency.
- Local controls have large gain below observation frequency.
- Along the longitudinal DoF, there is no local control.
- For frequency loop, laser source port is not available. A kind of double pass AOM technique should be used and only the AOM can be actuated.

My design of B-DECIGO

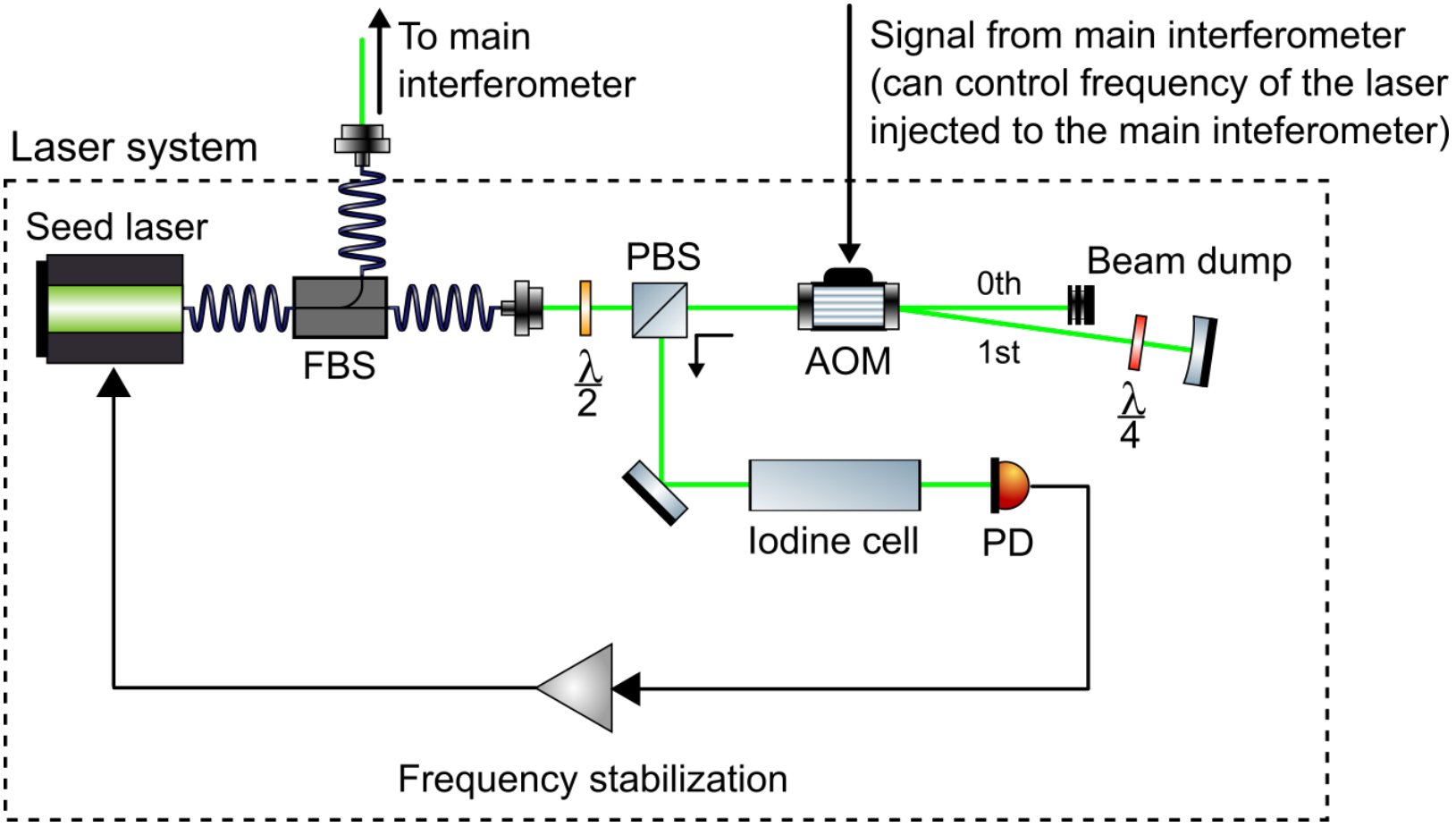


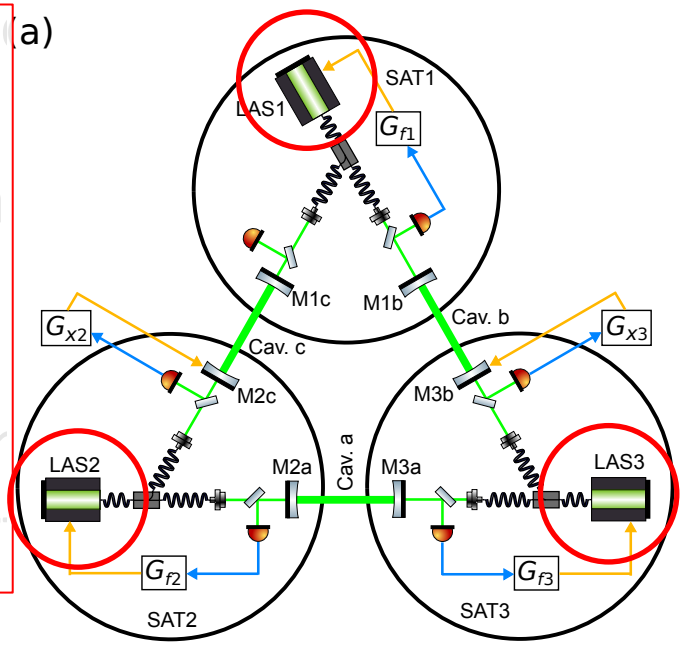
Fig.: Schematic of frequency stabilizing system with double pass AOM.

My design of B-DECIGO

Some notes

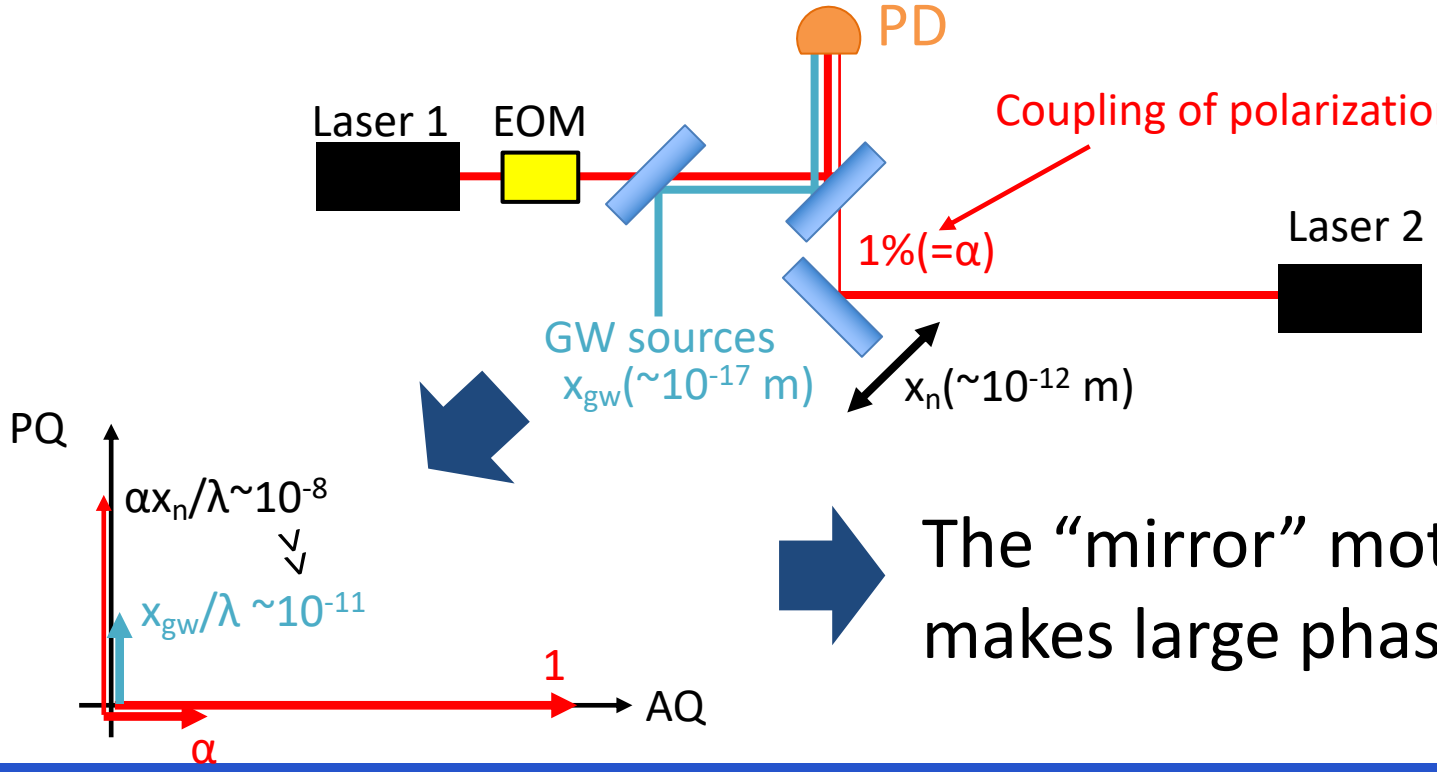
- In this design, all arms must have the same arm length in the sub-wavelength level (~0.1 um) if the lasers have different wavelength.

↑This comes from the frequency shift of the laser sources.
Is this necessary?



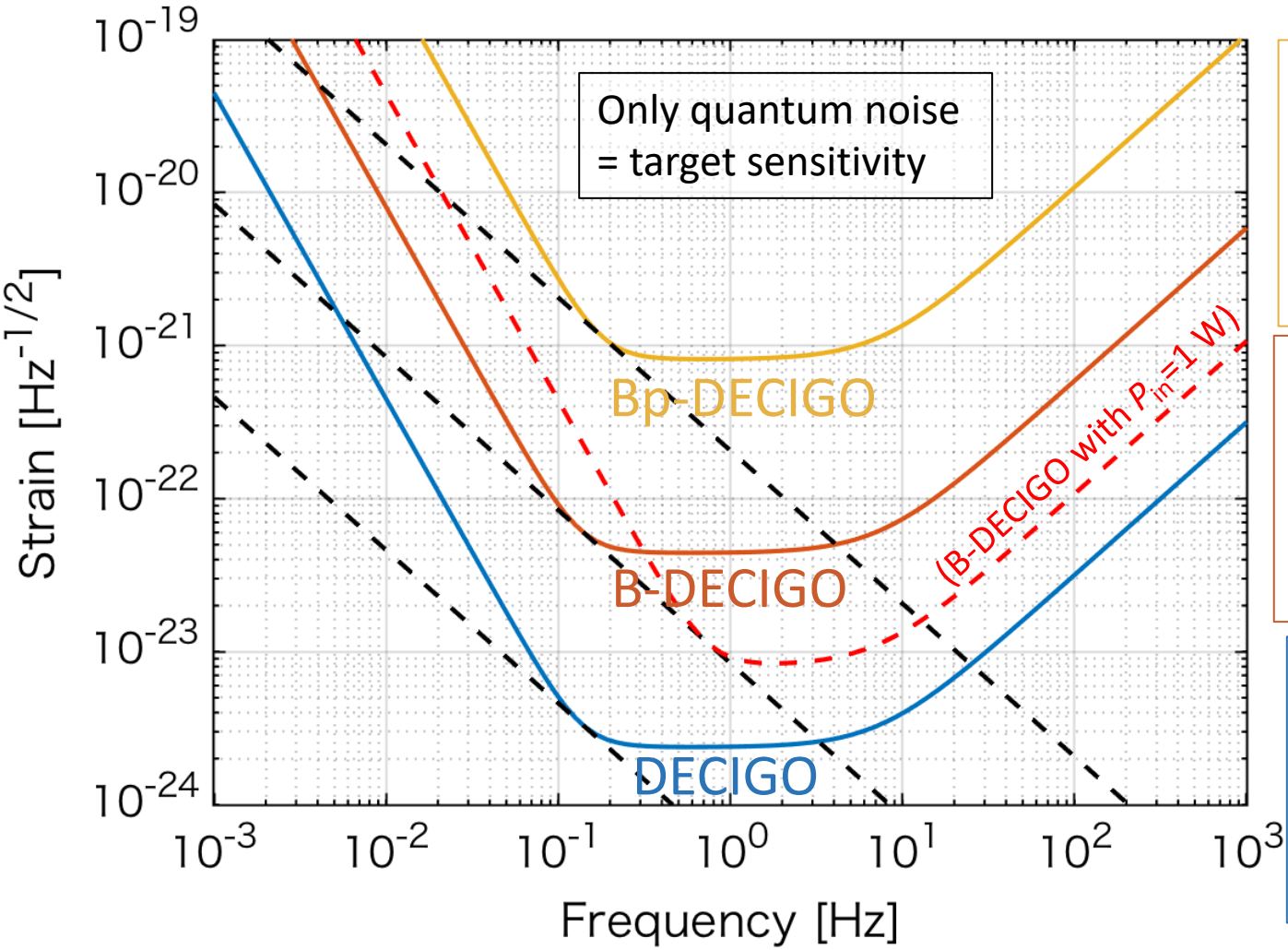
Frequency shift of laser sources

- Answer: *This may be necessary.*
- If the frequency is same, the situation can be written in the following schematic



The “mirror” motion makes large phase noise

Sensitivity of B-DECIGO

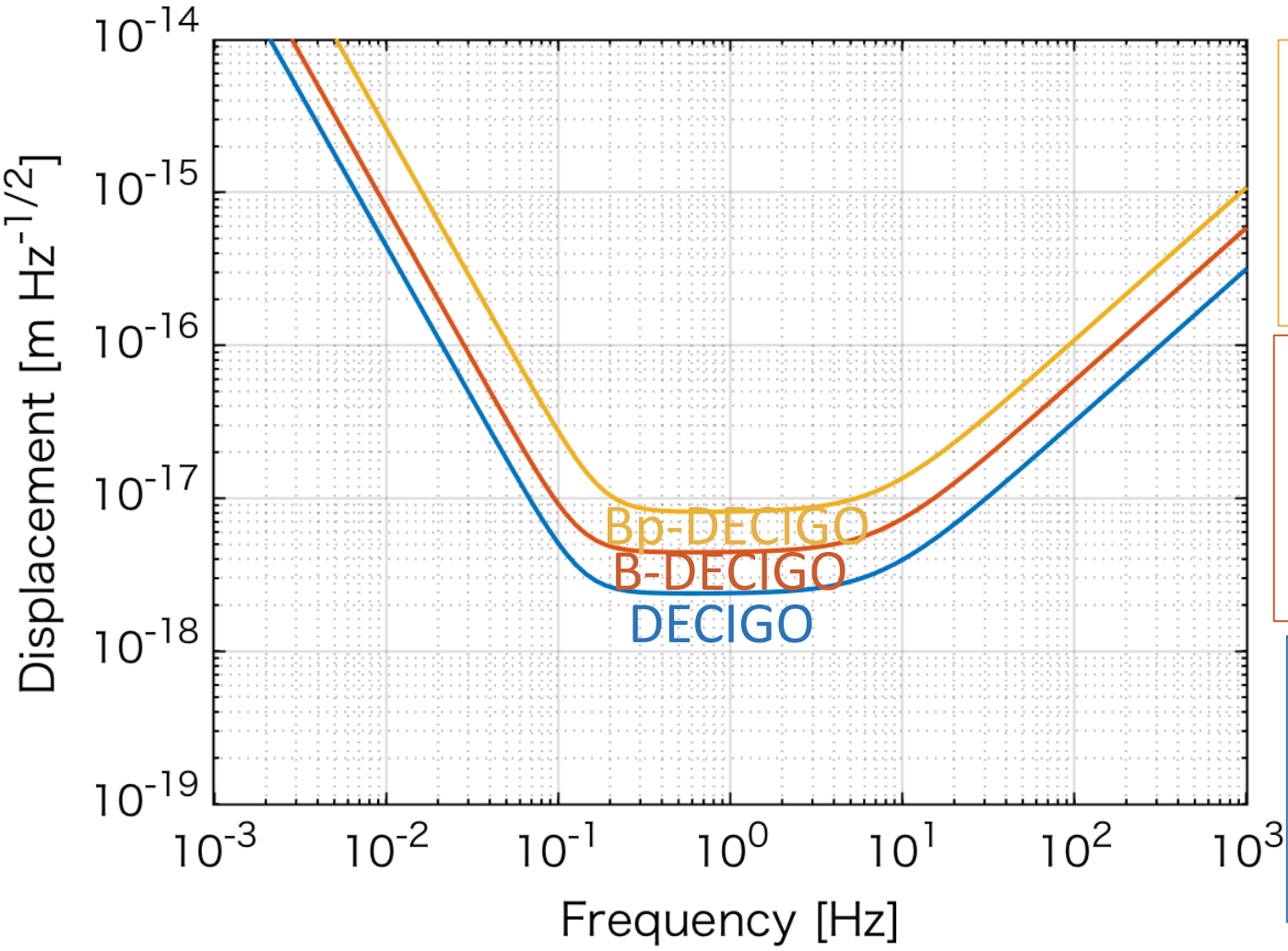


Bp-DECIGO
L = 10 km
F = 1000
m = 5 kg
P_{in} = 10^{-4} W

B-DECIGO
L = 100 km
F = 100
m = 30 kg
P_{in} = 33 mW

DECIGO
L = 1000 km
F = 10
m = 100 kg
P_{in} = 10 W

Sensitivity of B-DECIGO

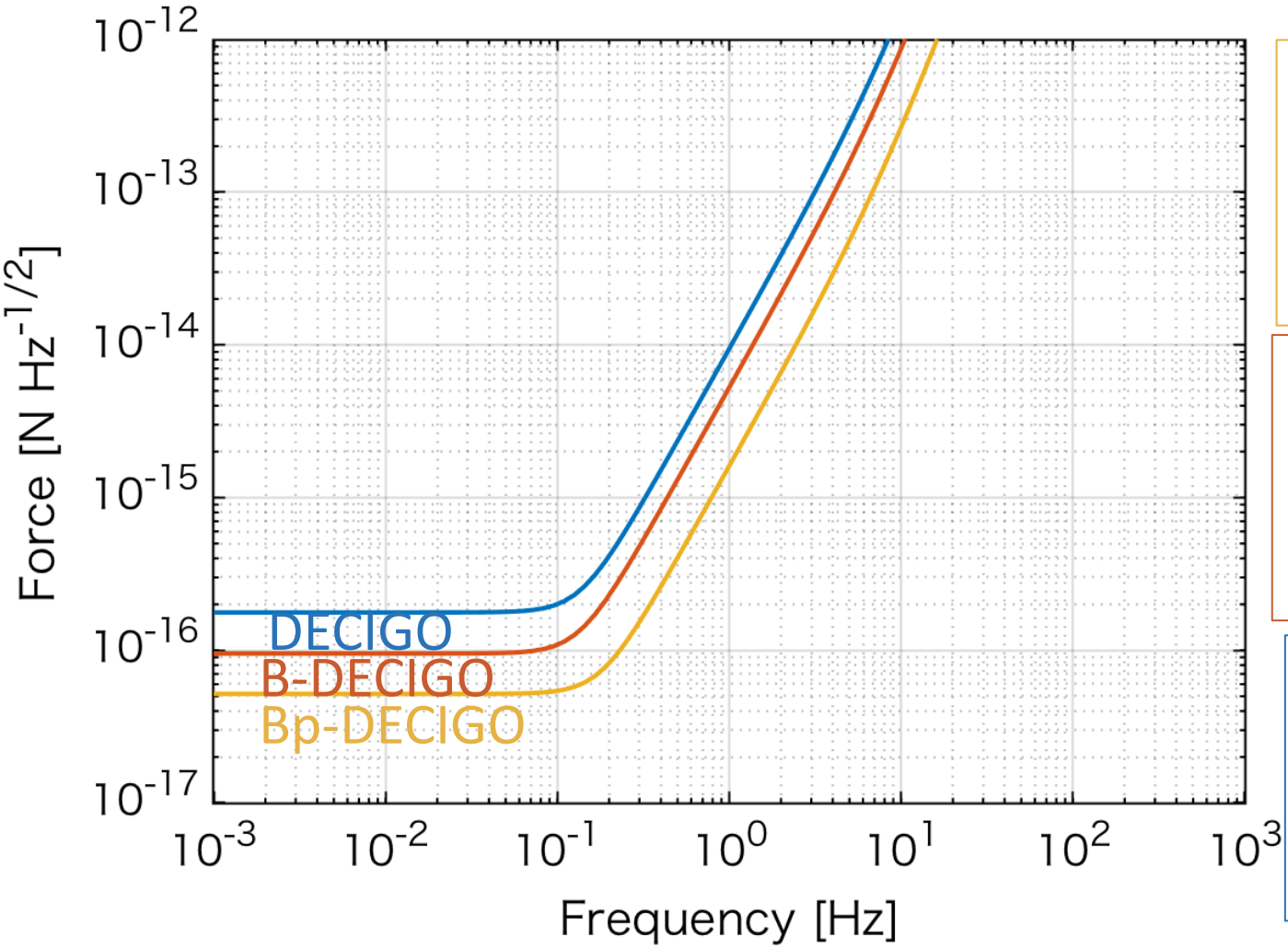


Bp-DECIGO
L = 10 km
F = 1000
m = 5 kg
P_{in} = 10^{-4} W

B-DECIGO
L = 100 km
F = 100
m = 30 kg
P_{in} = 33 mW

DECIGO
L = 1000 km
F = 10
m = 100 kg
P_{in} = 10 W

Sensitivity of B-DECIGO



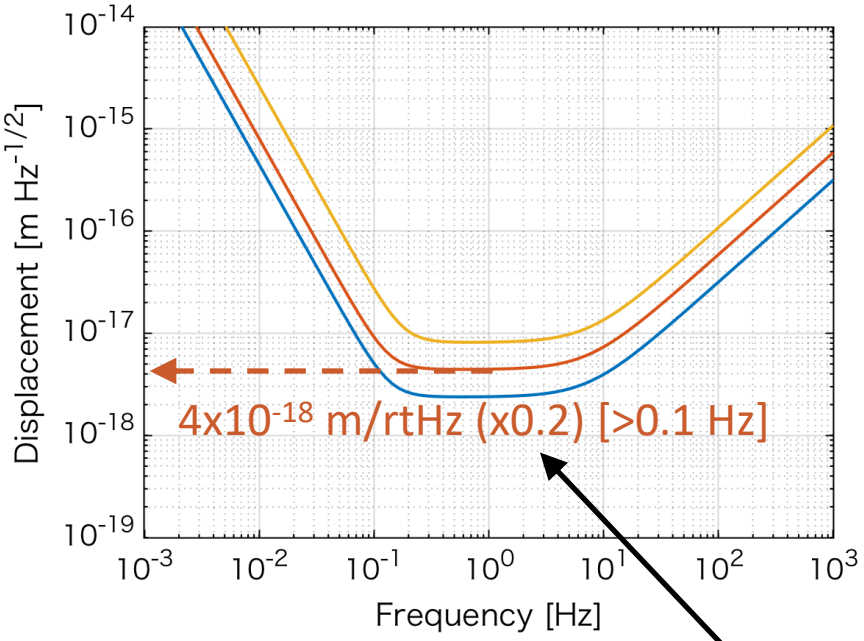
Bp-DECIGO
L = 10 km
F = 1000
m = 5 kg
P_{in} = 10^{-4} W

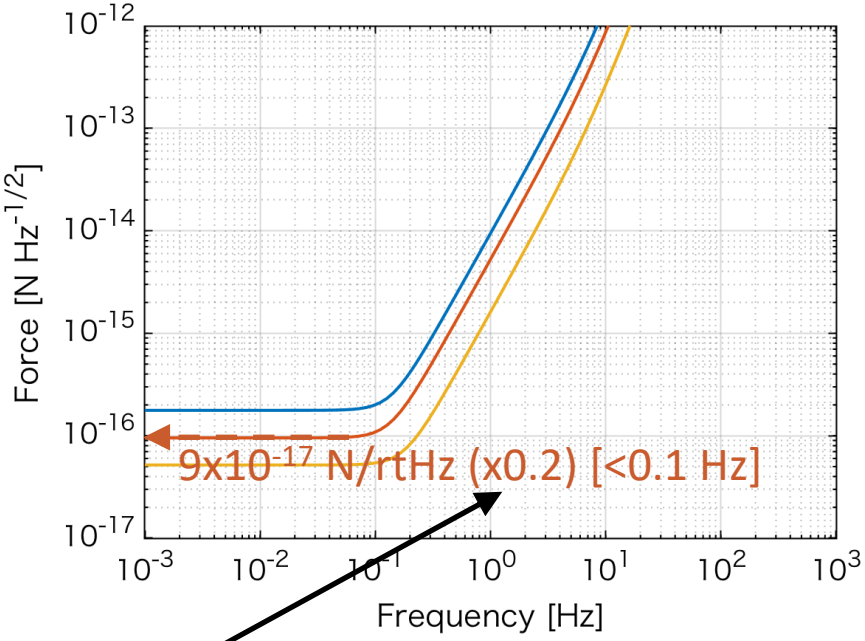
B-DECIGO
L = 100 km
F = 100
m = 30 kg
P_{in} = 33 mW

DECIGO
L = 1000 km
F = 10
m = 100 kg
P_{in} = 10 W

Sensitivity requirement for B-DECIGO

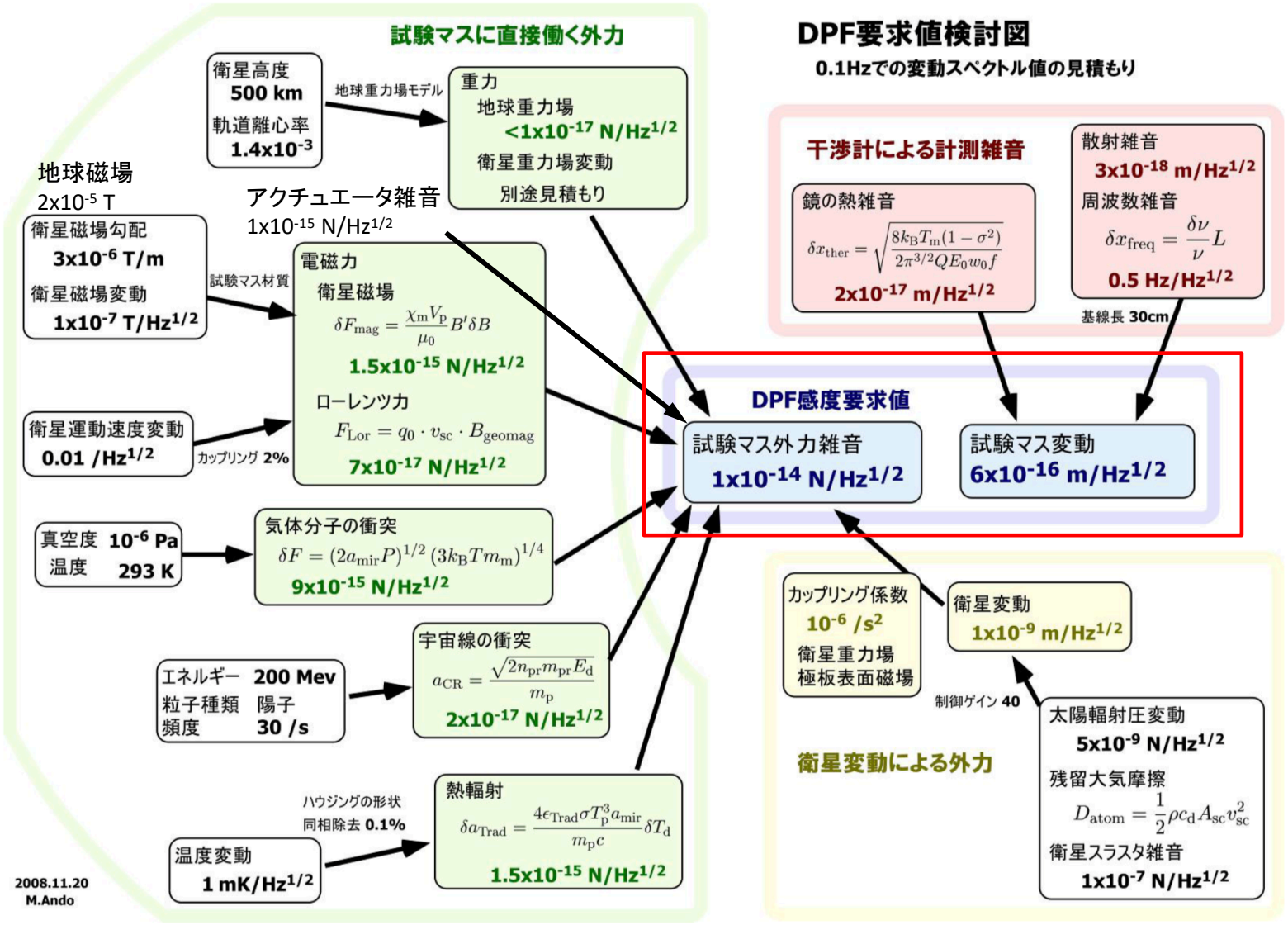
- Displacement noise
- Force noise



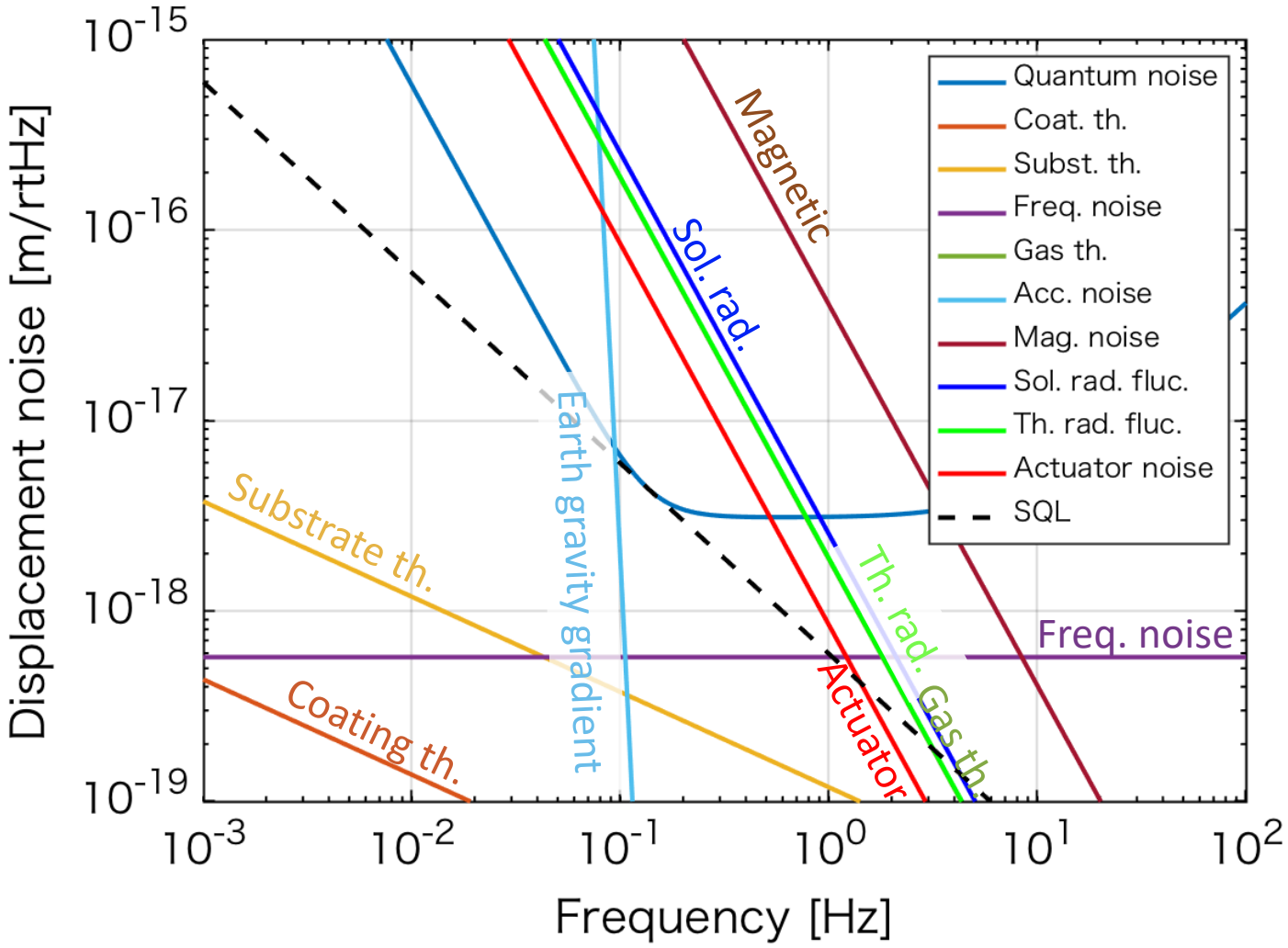


If safety factor = 5

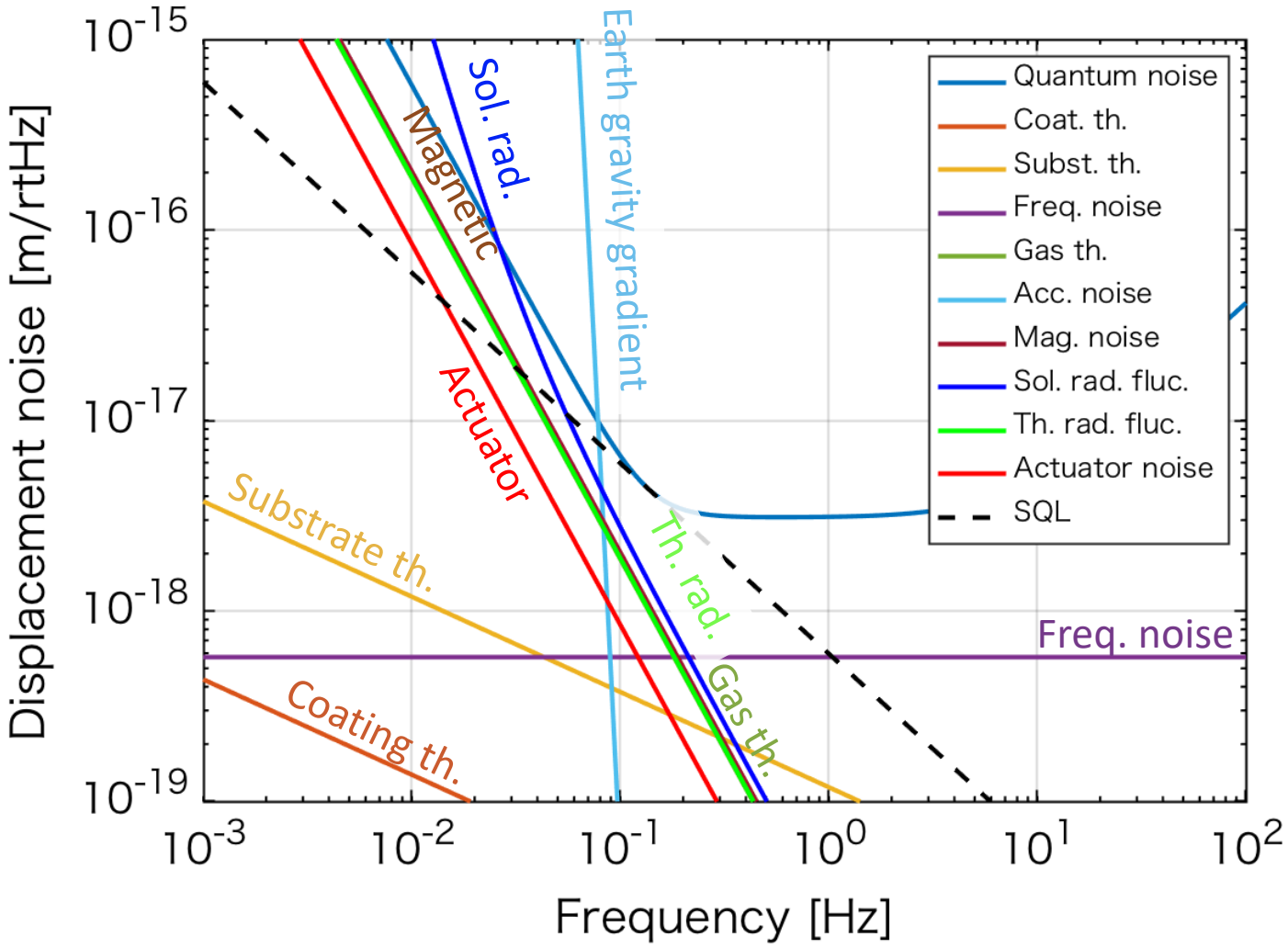
List of expected noises



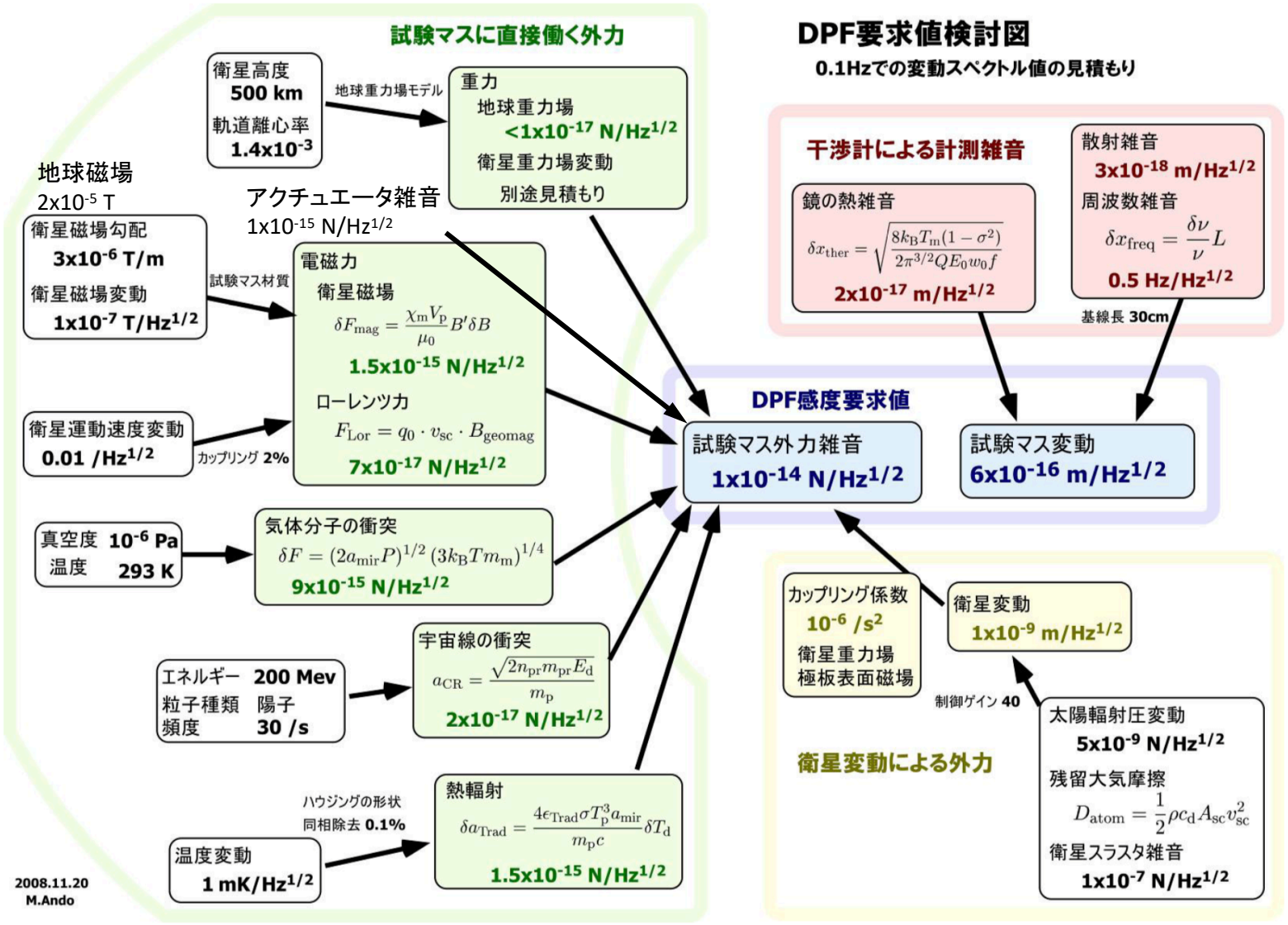
B-DECIGO sensitivity with DPF parameters



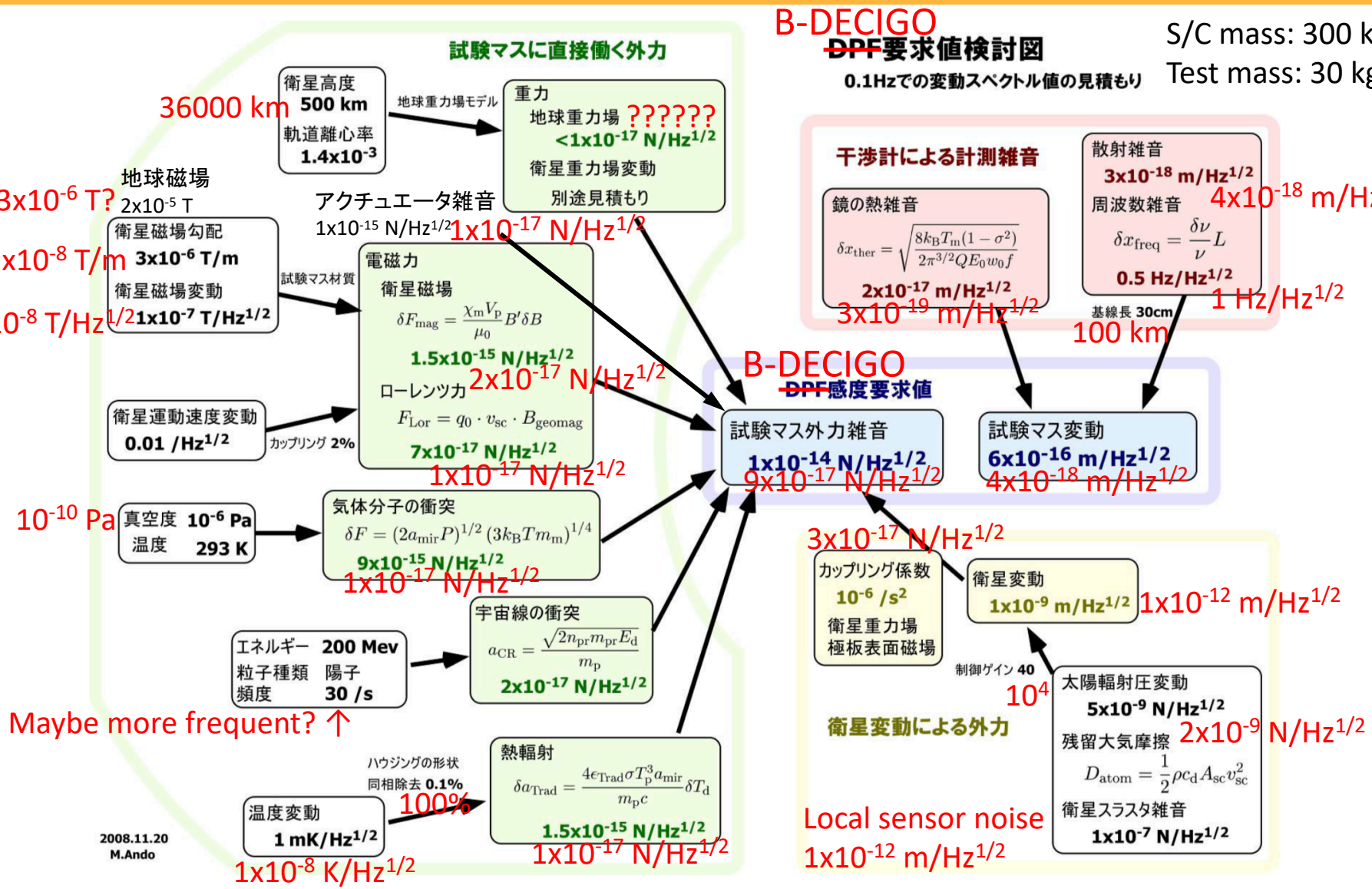
B-DECIGO sensitivity with new parameters



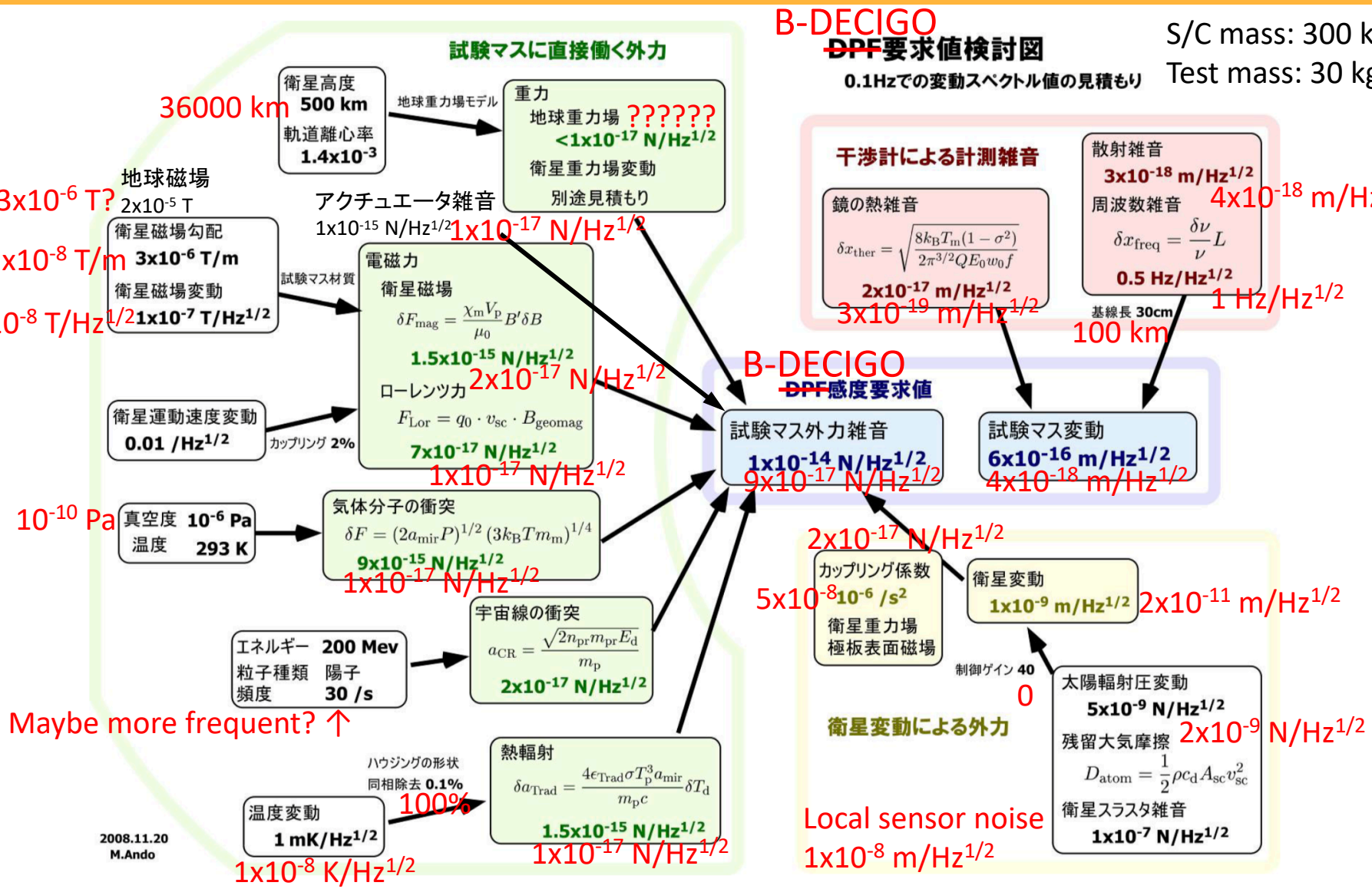
Requirements diagram for DPF



Requirements diagram for B-DECIGO



Requirements diagram for B-DECIGO (2)



Stability requirement for B-DECIGO

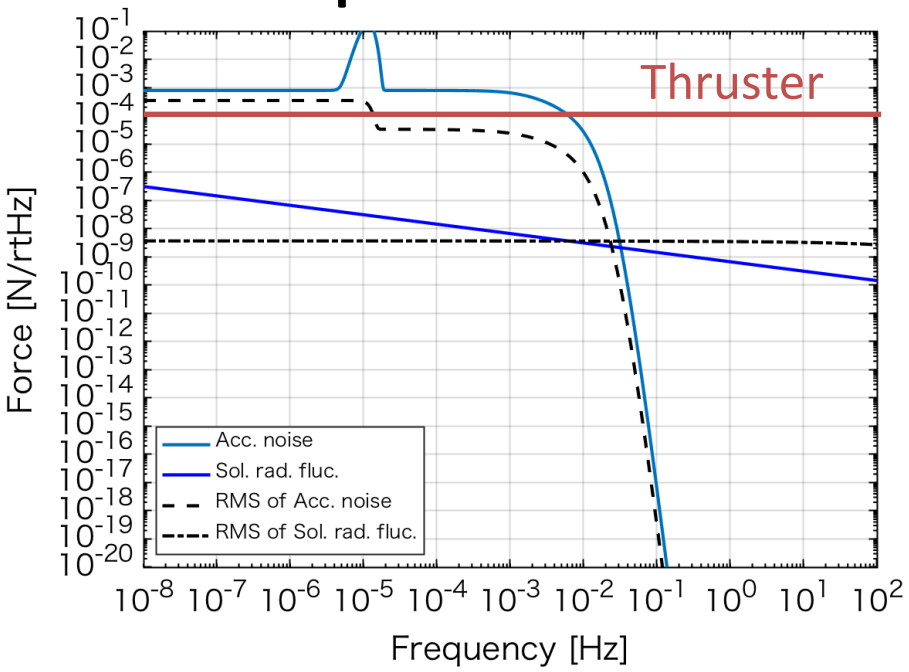
- Usually, it is considered as the fluctuation of the arm length should be within 1% (=+/- 0.5%)
  - In B-DECIGO case, +/- 500 m (= 10^5 [m]x0.005).
- This value comes from range of actuation range of laser sources, 0.1%(?). (←Koheras, AdjustiK Y10)
- However, we should consider the range of AOM, e.g. 1 GHz.
- Range of 1 GHz corresponds to the fluctuation of arm length of 3 ppm (= +/- 0.15 m).
- **We should consider how to deal with this problem!!**

Stability requirement for B-DECIGO

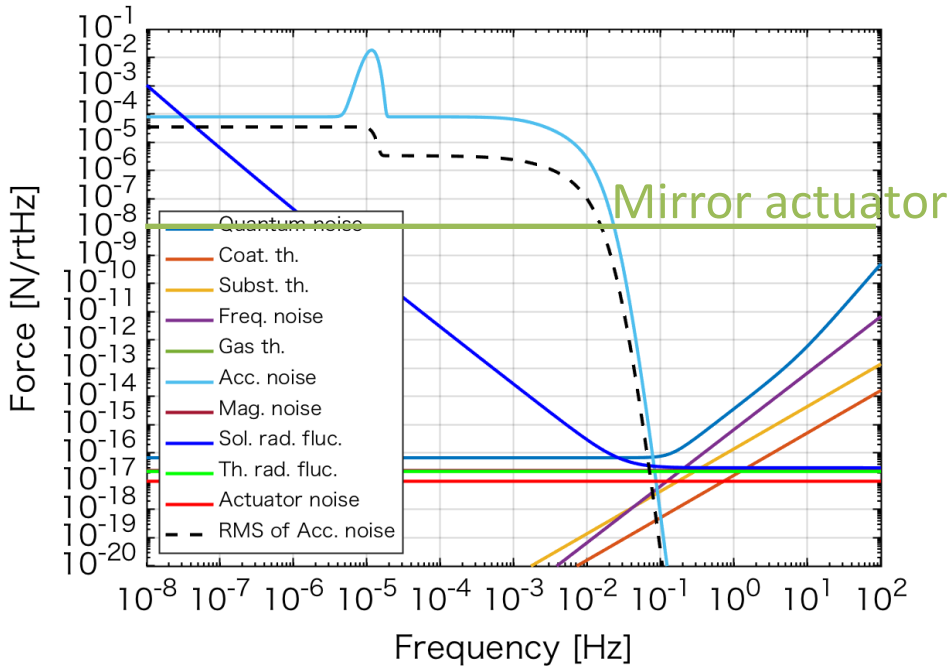
- Let's assume the actuation range problem will be solved in near future.
- Then we should consider the actuation range of,
  - Mirror actuators ($<10^{-8}$ N)
  - Thrusters (~<100 uN, 3 year operation?)

Actuation range

Space craft



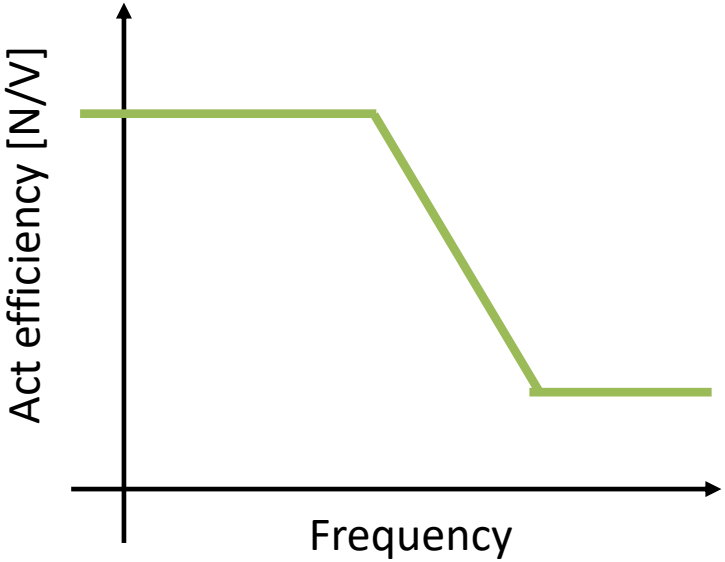
Test mass

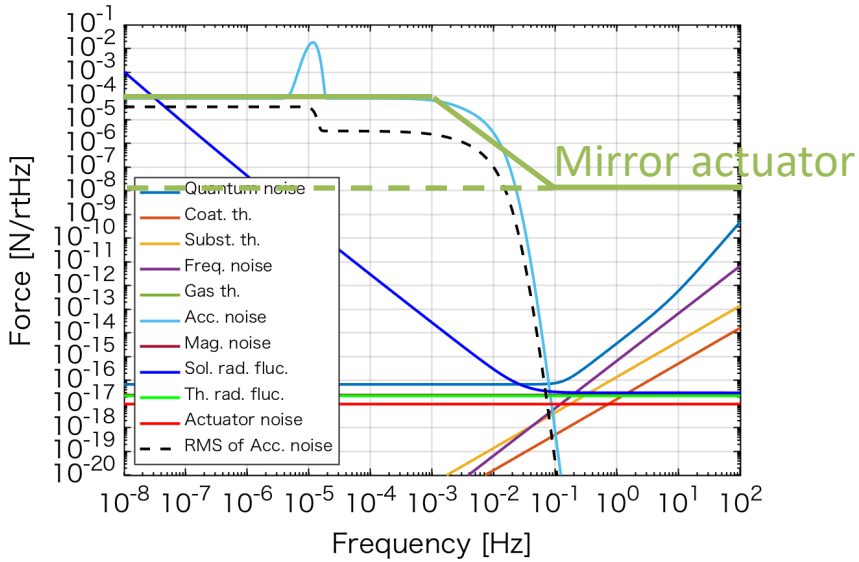


Note: Acceleration noise (Earth's gravity gradient) is not so well estimated that it could be changed especially above 10^{-3} Hz.

Mirror actuator

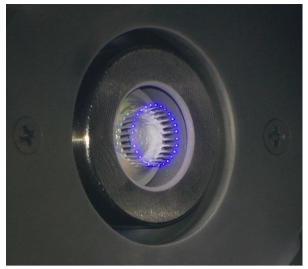
- Maximum force of 10^{-8} N is NOT enough.
- We should consider something.
- For example, frequency dependent actuator range (= frequency dependent impedance).





Thruster

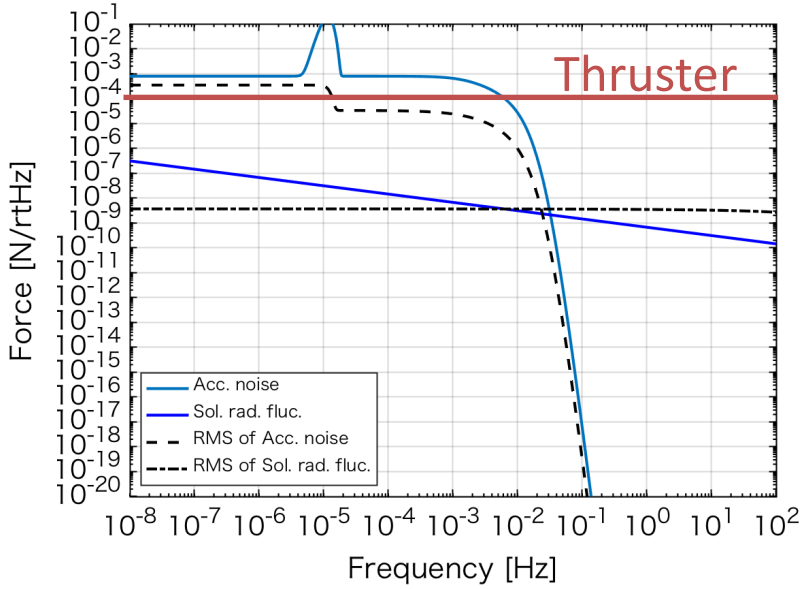
- Maximum force of 100 uN is slightly smaller than requirement. However, If we use several, it meets requirement.
- Operation time is also OK if we use FEEP.
  - ~ 4 years = 6000 [s] x (9.8/1e-4) x 0.23



FEEP (€ 30,000~)

PARAMETER	VALUE
Dynamic thrust range	10 µN to 0.4 mN
Nominal thrust	350 µN
Specific impulse	2,000 to 6000 s
Propellant mass	230 g
Total impulse	more than 5,000 Ns
Power at nominal thrust	40 W incl. neutralizer
Outside dimensions	100.0 x 100.0 x 82.5 mm
Mass (dry / wet)	670 / 900 g
Total system power	8 – 40 W
Hot standby power	3.5 W
Command interface	RS422/RS485
Temperature envelope (non-operational)	-40 to 105°
Temperature envelope (operational)	-20 to 40 °C
Supply voltage	12V, 28 V, other voltages upon request

https://www.enpulsion.com



Outline

1. Overture
2. Introduction
3. Requirements for B-DECIGO
4. Conclusion

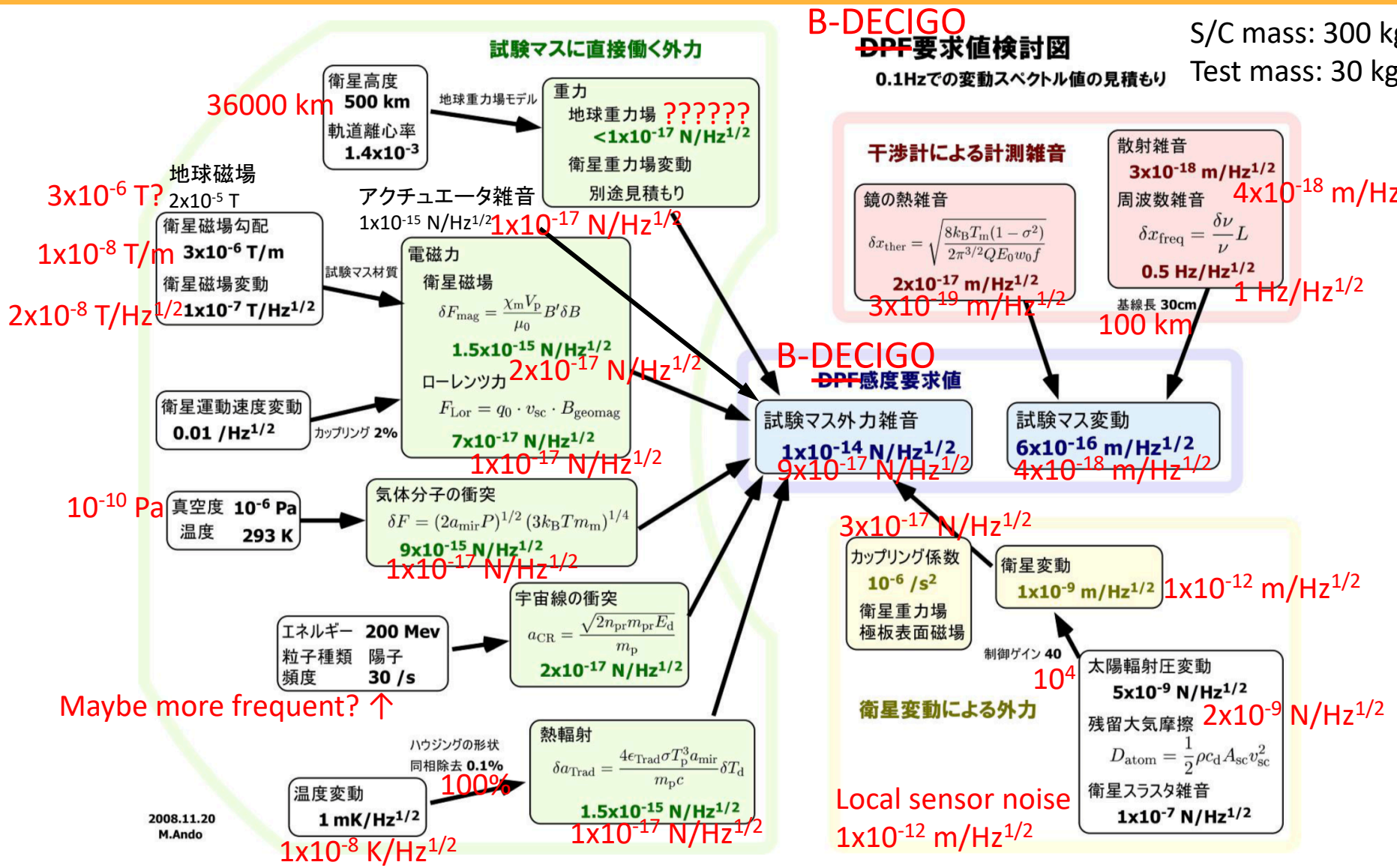
Conclusion

- B-DECIGO seems to be possible if we do our best.
- To do
  - Estimate Earth's gravity gradient effect
  - Estimate cosmic ray research
  - (Demonstration)
- Challenges
  - Vacuum pressure (10^{-10} Pa)
  - Magnetic noise (B' and δB)
  - Sensitive local sensors (10^{-12} m/$Hz^{1/2}$)
  - Large range AOM (or other frequency actuator)

Conclusion

- However, I showed just my idea.
- Please consider your B-DECIGO freely!

Requirements diagram for B-DECIGO



Cheat sheet

	DPF	B-DECIGO	Misc
Magnetic noise			
Magnetic fluctuation, δ B [T/rtHz]	1e-7	2e-8	Christian Trenkel et al 2017 J. Phys.: Conf. Ser. **840** 012006
Magnetic gradient, B' [T/m]	3e-6	1e-8	
Residual gas thermal			
Pressure [Pa]	1e-6	1e-9	
Solar radiation pressure noise			
Solar radiation fluctuation [N/rtHz]	4e-10	4e-10	at 0.1 Hz
Local sensor sensitivity [m/rtHz]	1e-10	1e-13	
Thruster noise, Fth [N/rtHz]	1e-7	1e-7	
Coupling, α [1/s^2]	1e-6	1e-6	
Actuator noise			
Actuator noise, Fact [N/rtHz]	1e-15	1e-17	in KAGRA 1e-14 (Yuta Michimura et al 2017 Class. Quantum Grav. **34** 225001)
Thermal radiation fluctuation			
Temperature fluctuation, δ T [K/rtHz]	1e-3	1e-6	
Common mode rejection	1e-3	1	
Shield	1	1e-2	
Frequency noise			
Frequency noise [Hz/rtHz]	0.5	1	
Control gain	?	3e8	
Thermal noise			
Substrate loss angle		1e-7	
Costing loss angle (SiO_2, Ta_2O_5)		0.5e-4, 2e-4	In Ta_2O_5, Ti is doped.
Beam radius [cm]		14	