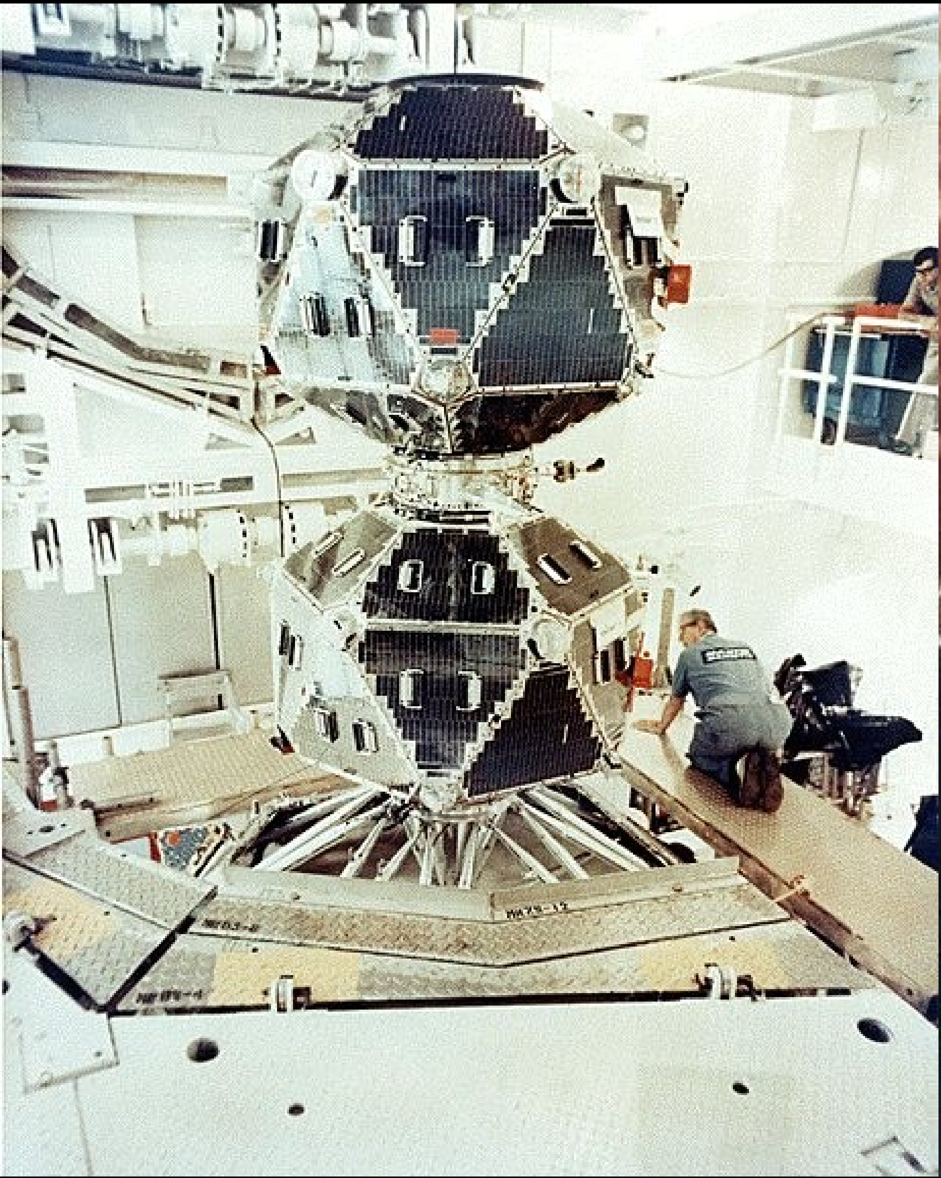
重力波天文学II

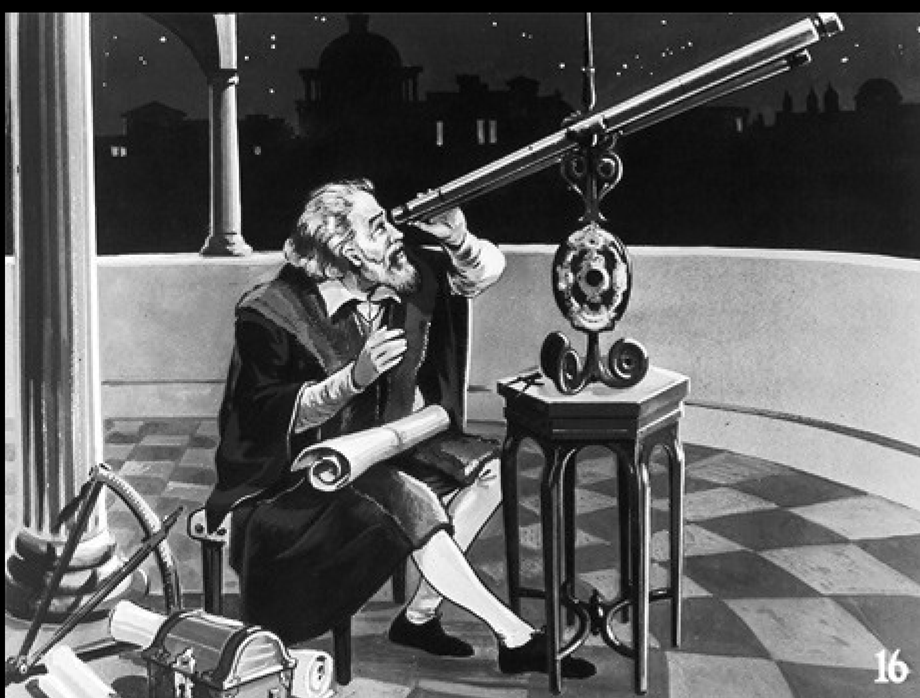
干渉計型重力波検出器KAGRAの仕組み

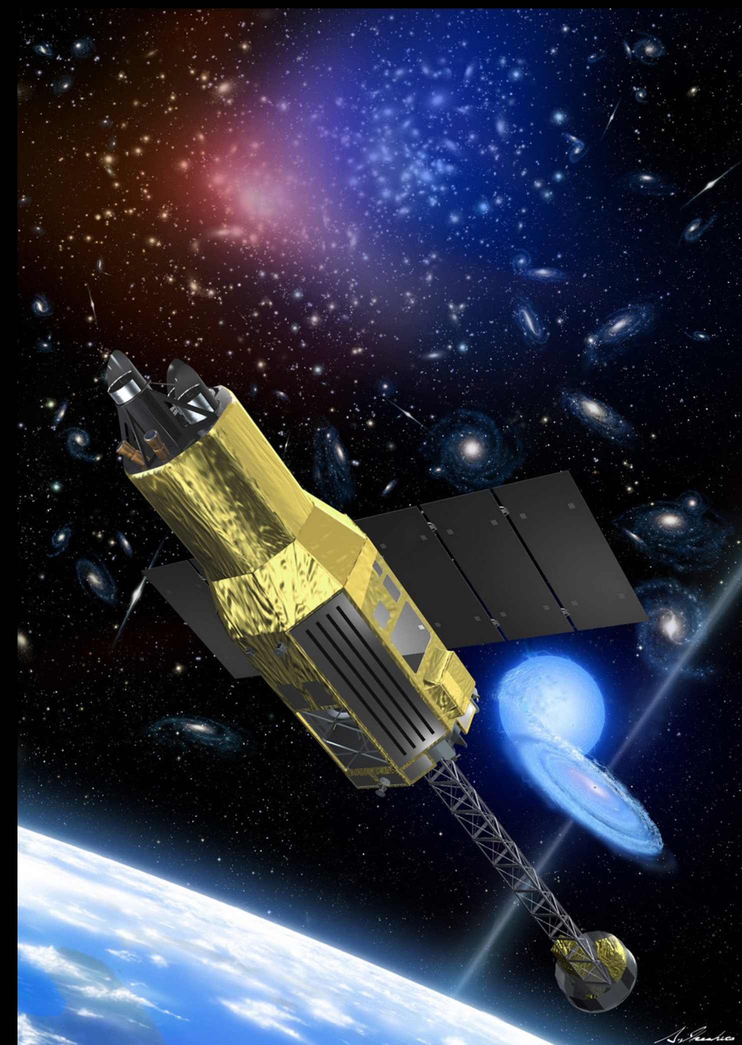
国立天文台･重力波プロジェクト推進室
麻生 洋一

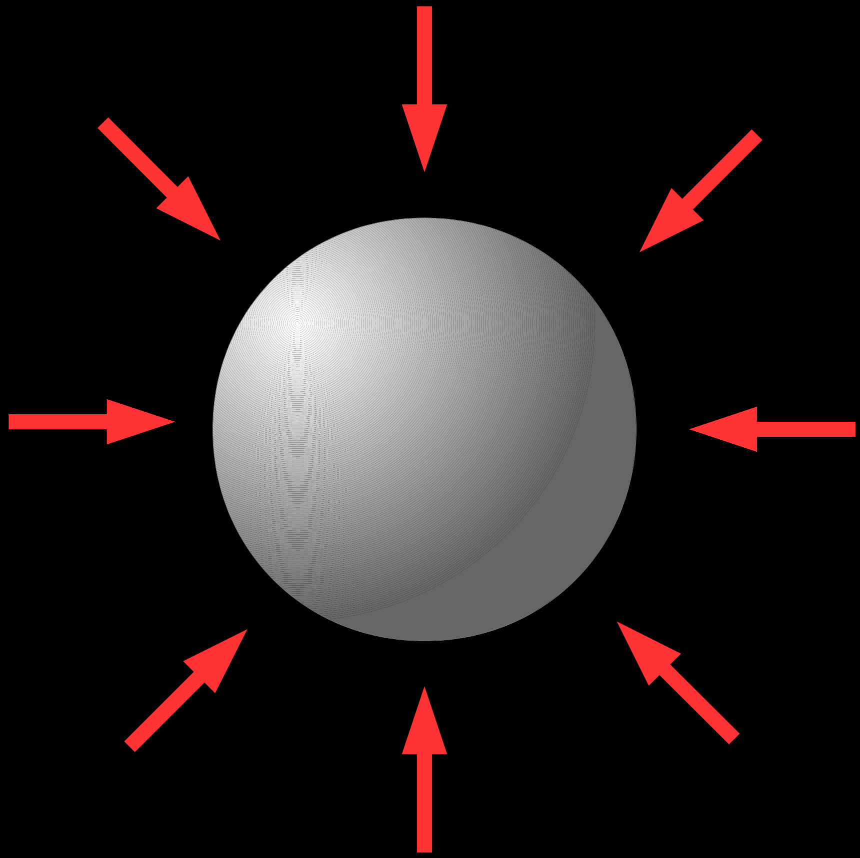
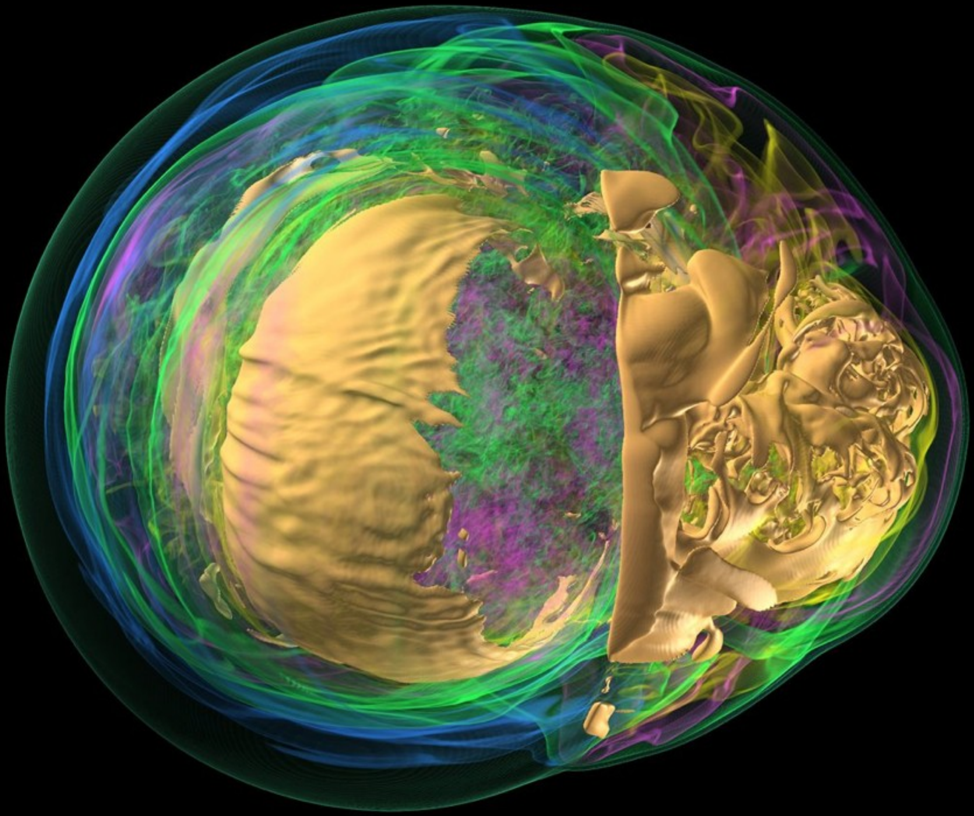


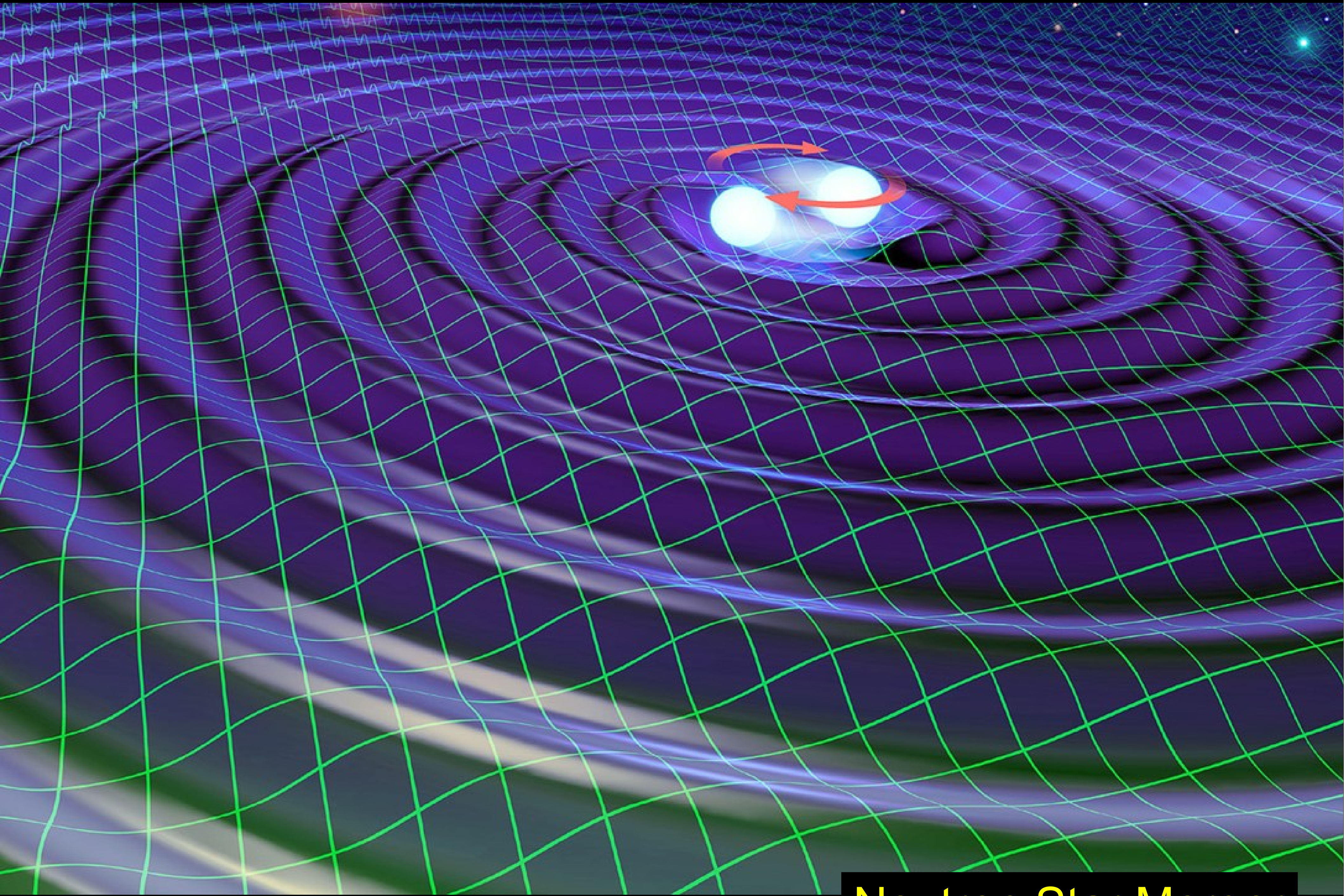

Gamma-ray Burst

Mostly Electric Magnetic Observations

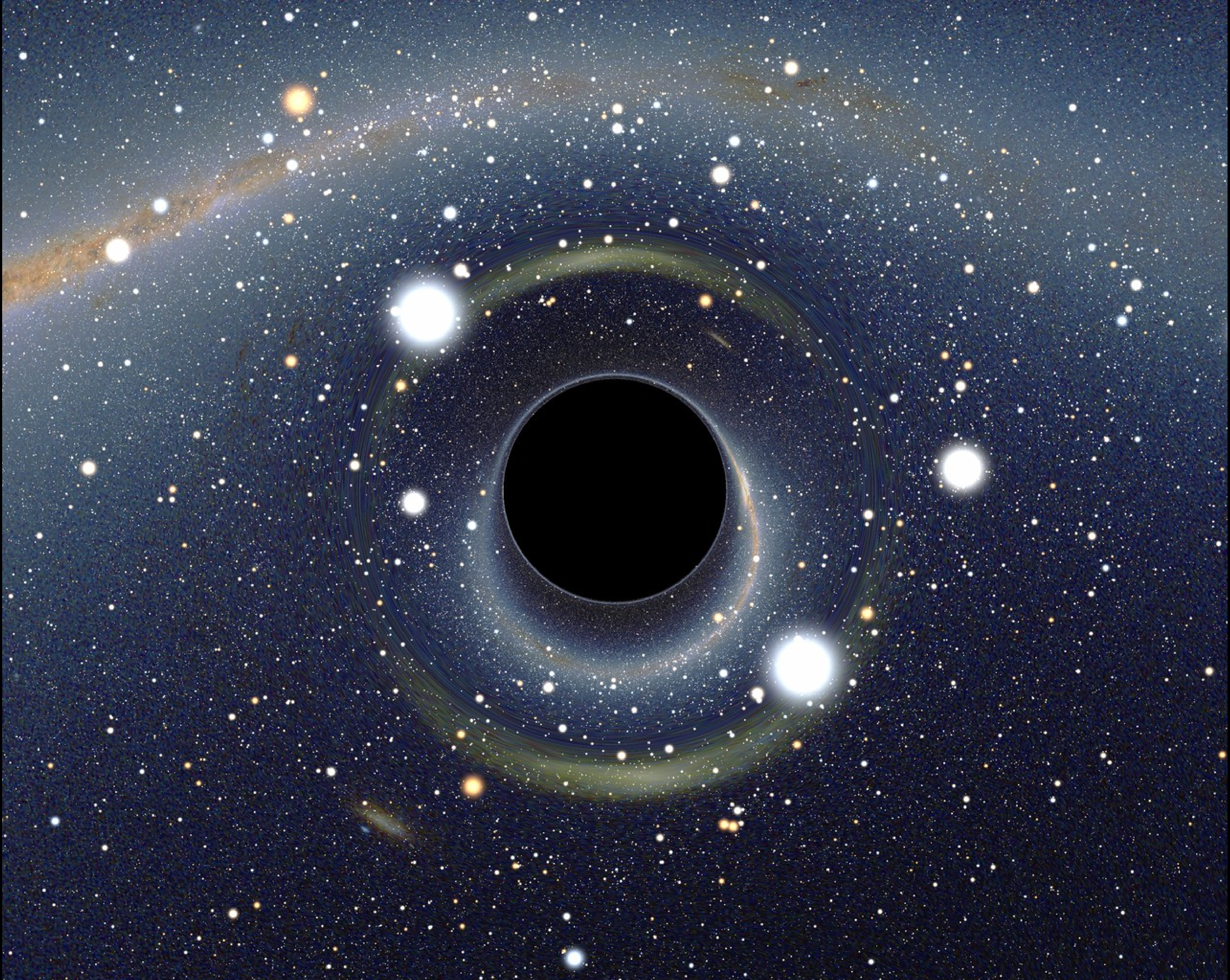


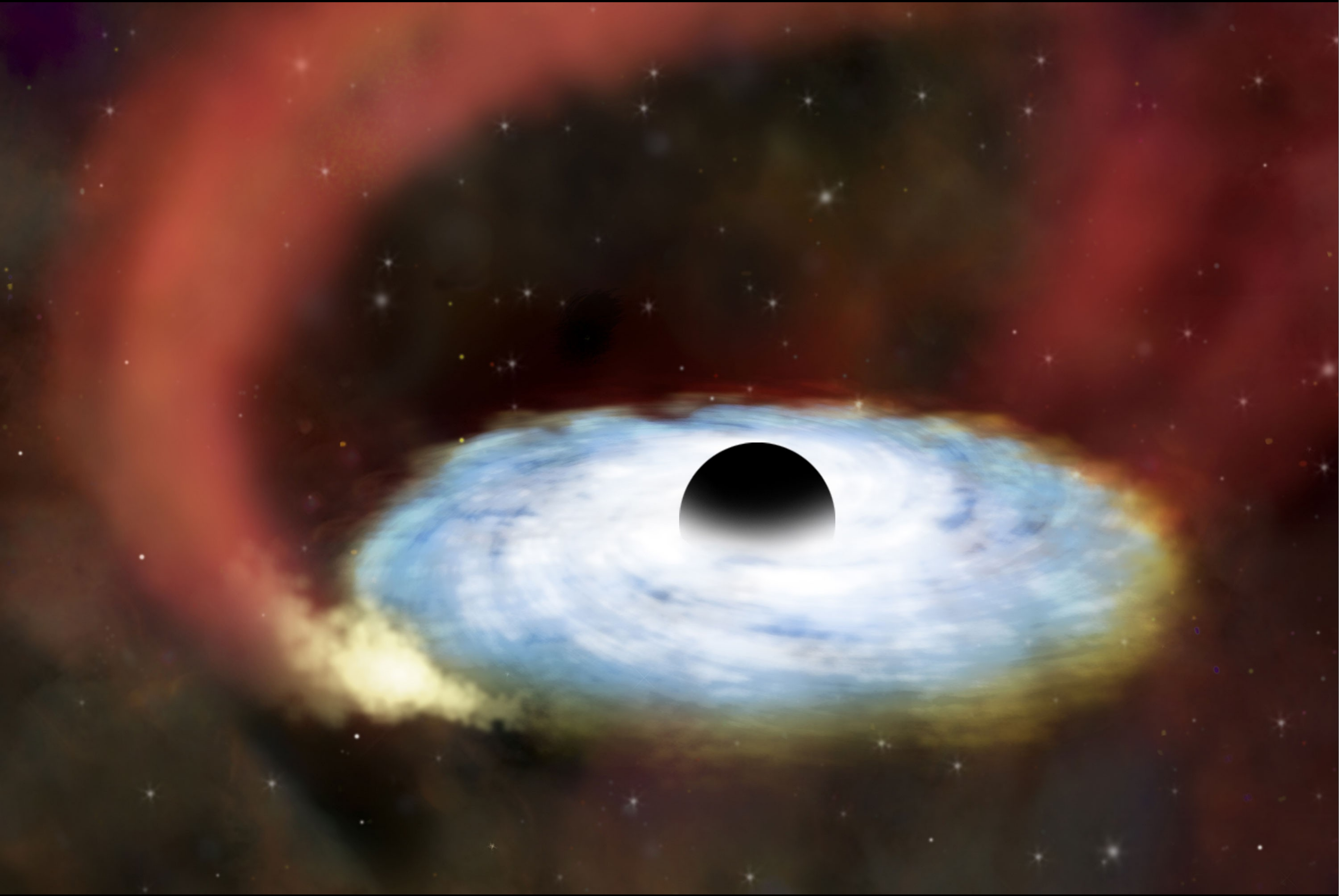


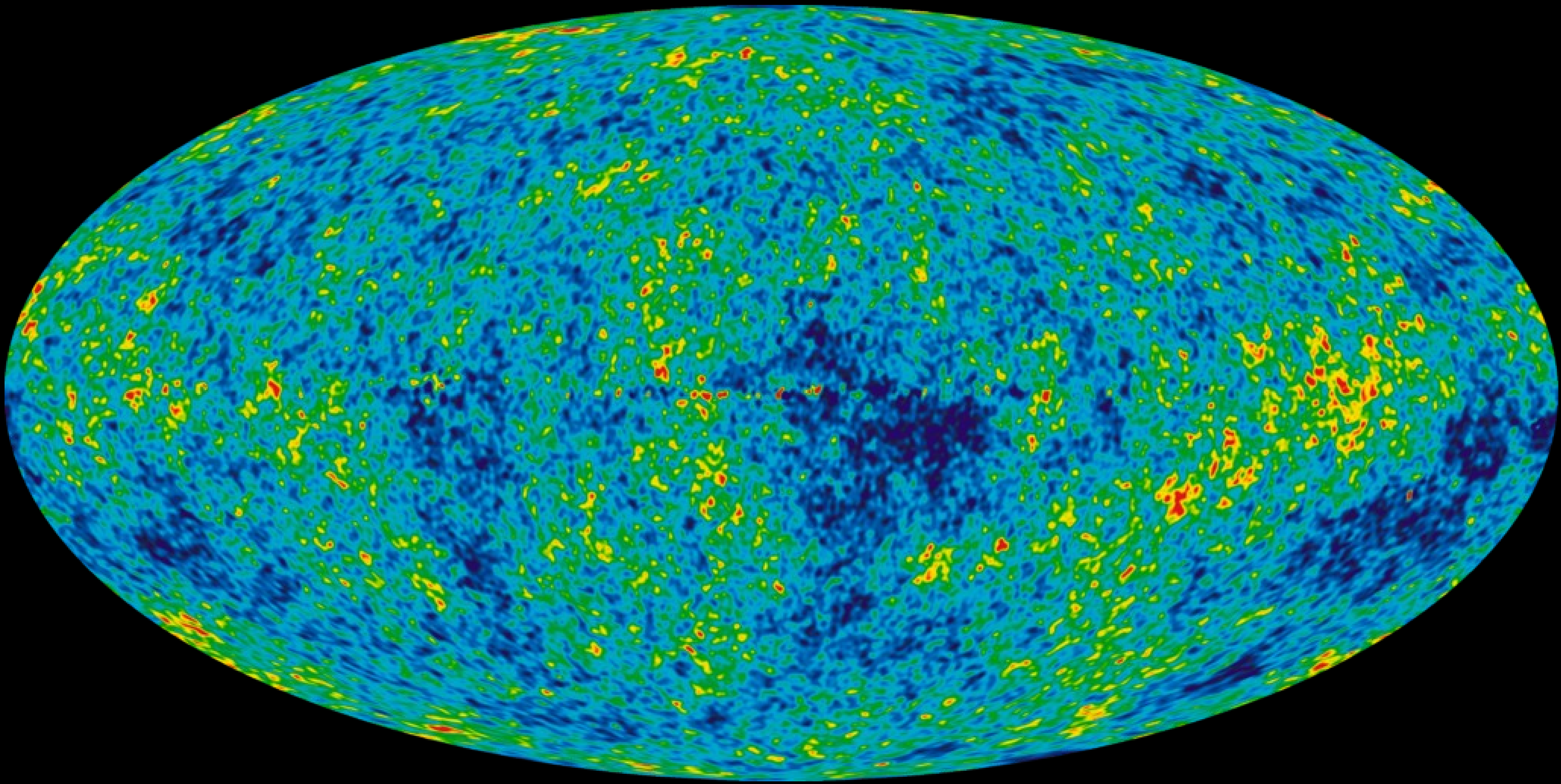





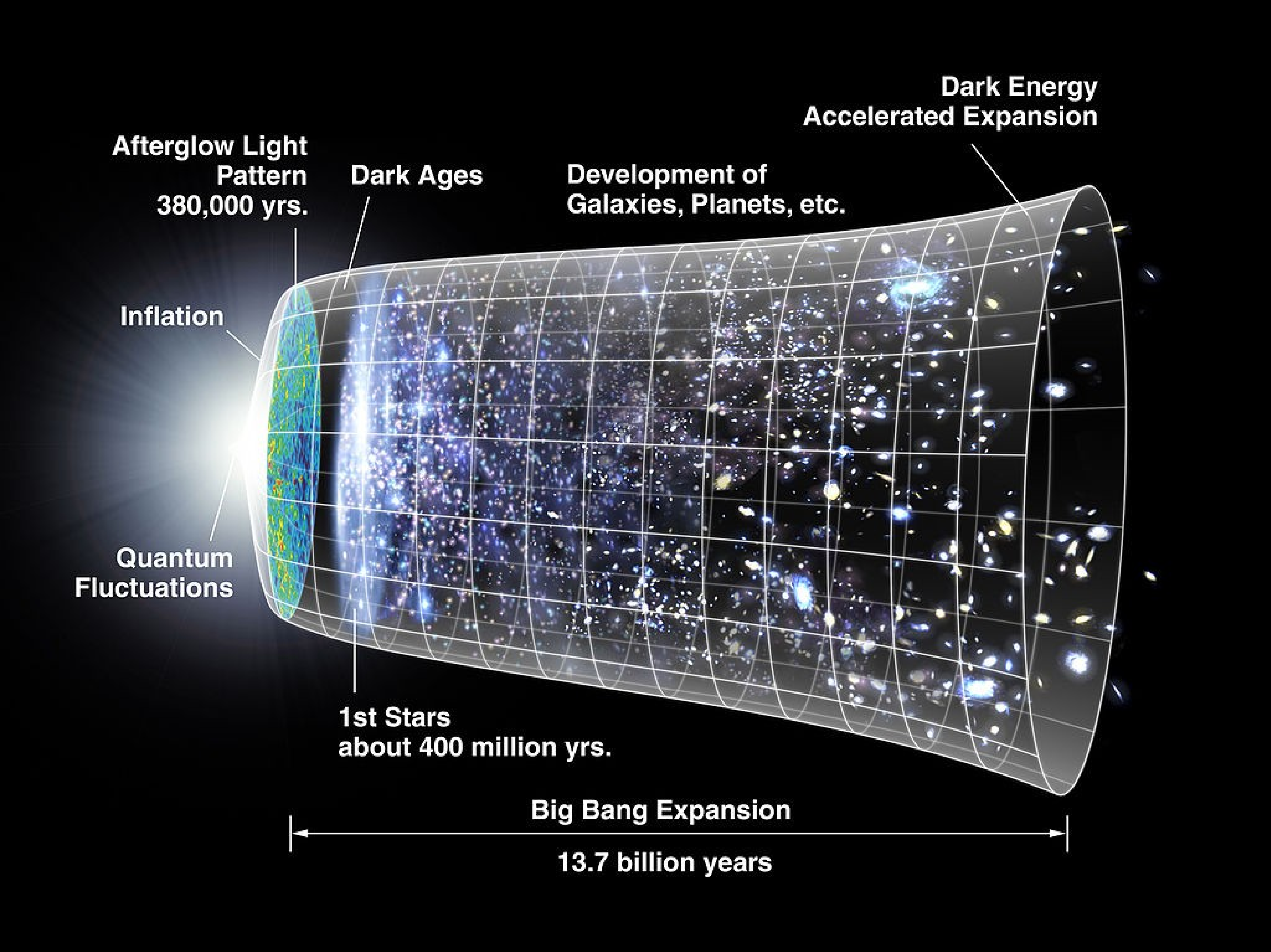
Neutron Star Merger



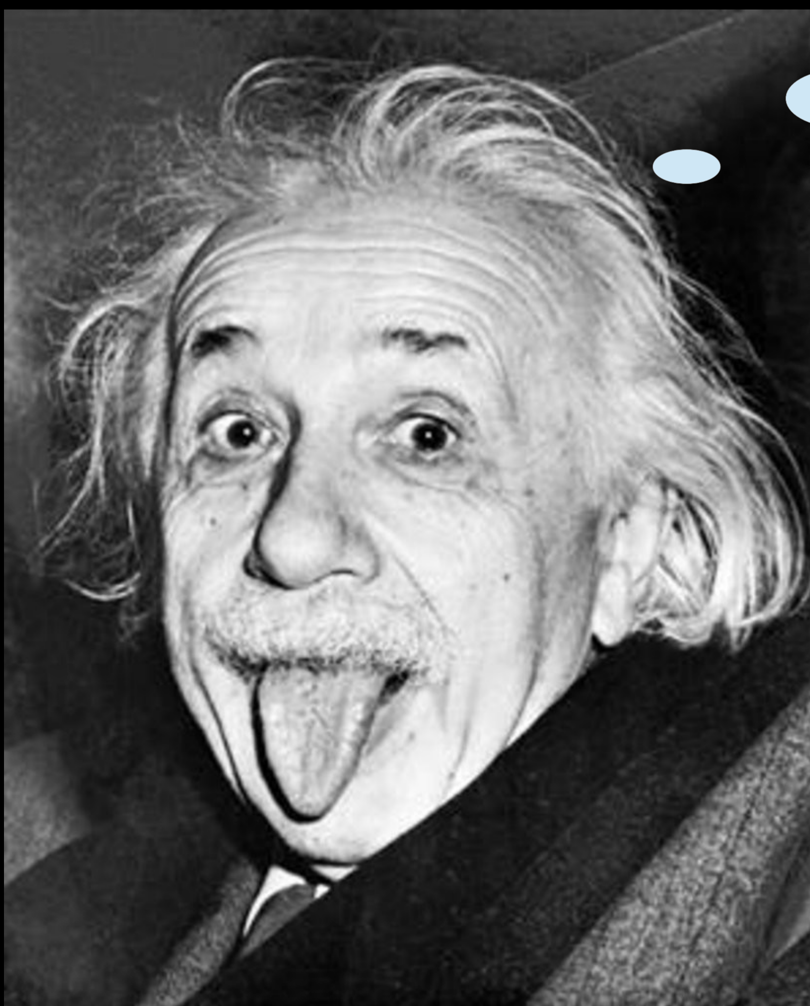


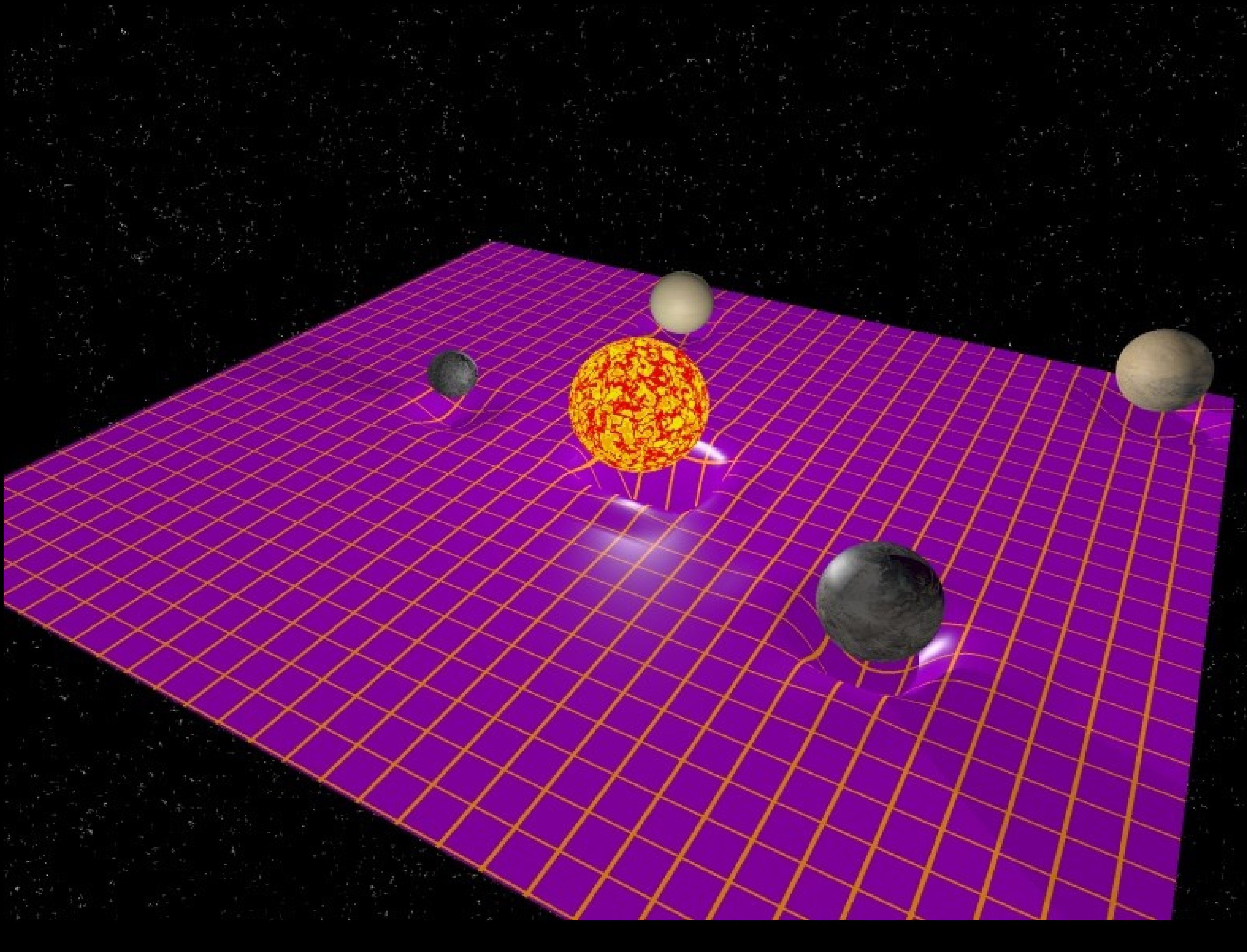


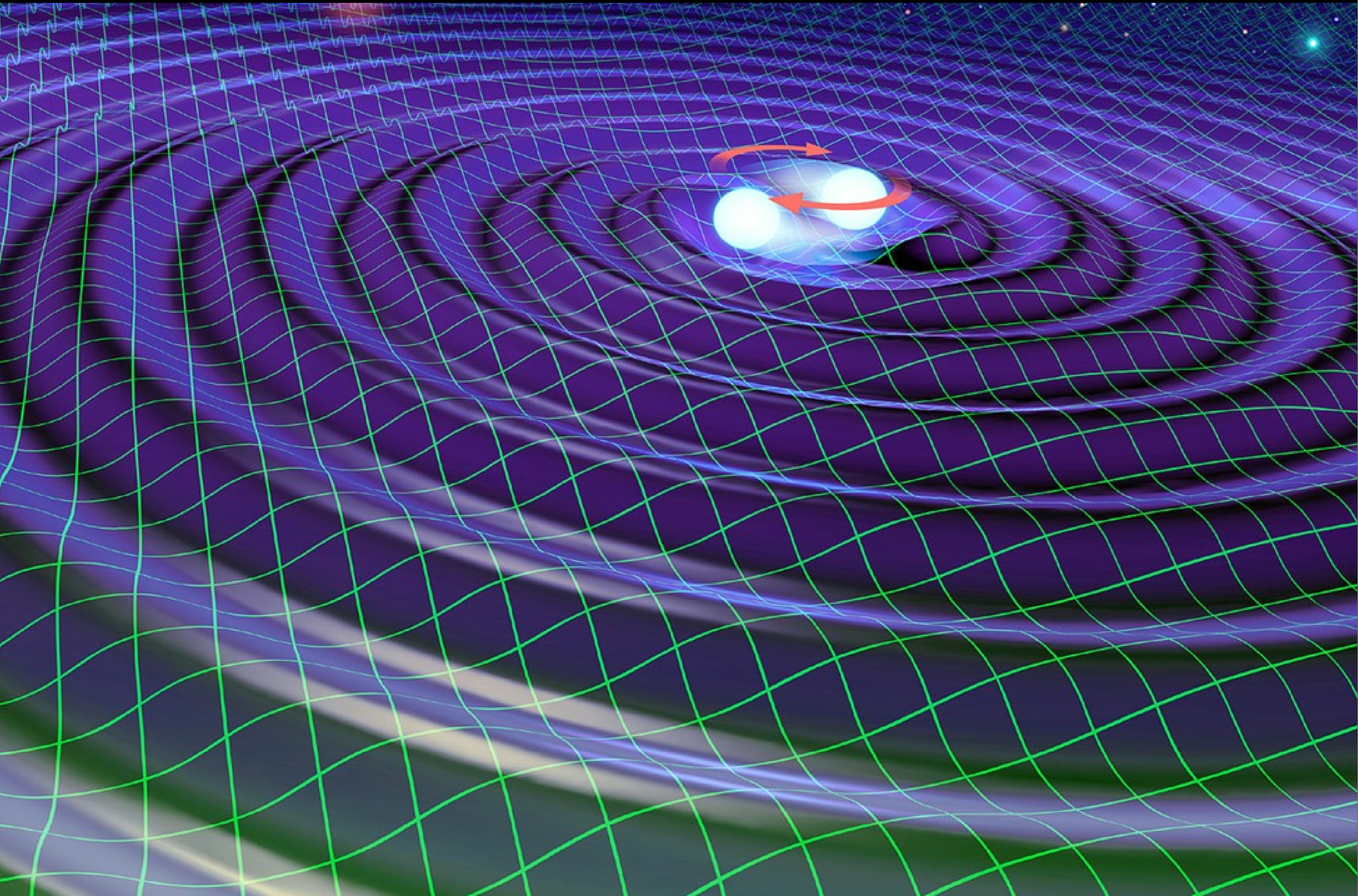
Cosmic Microwave Background


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

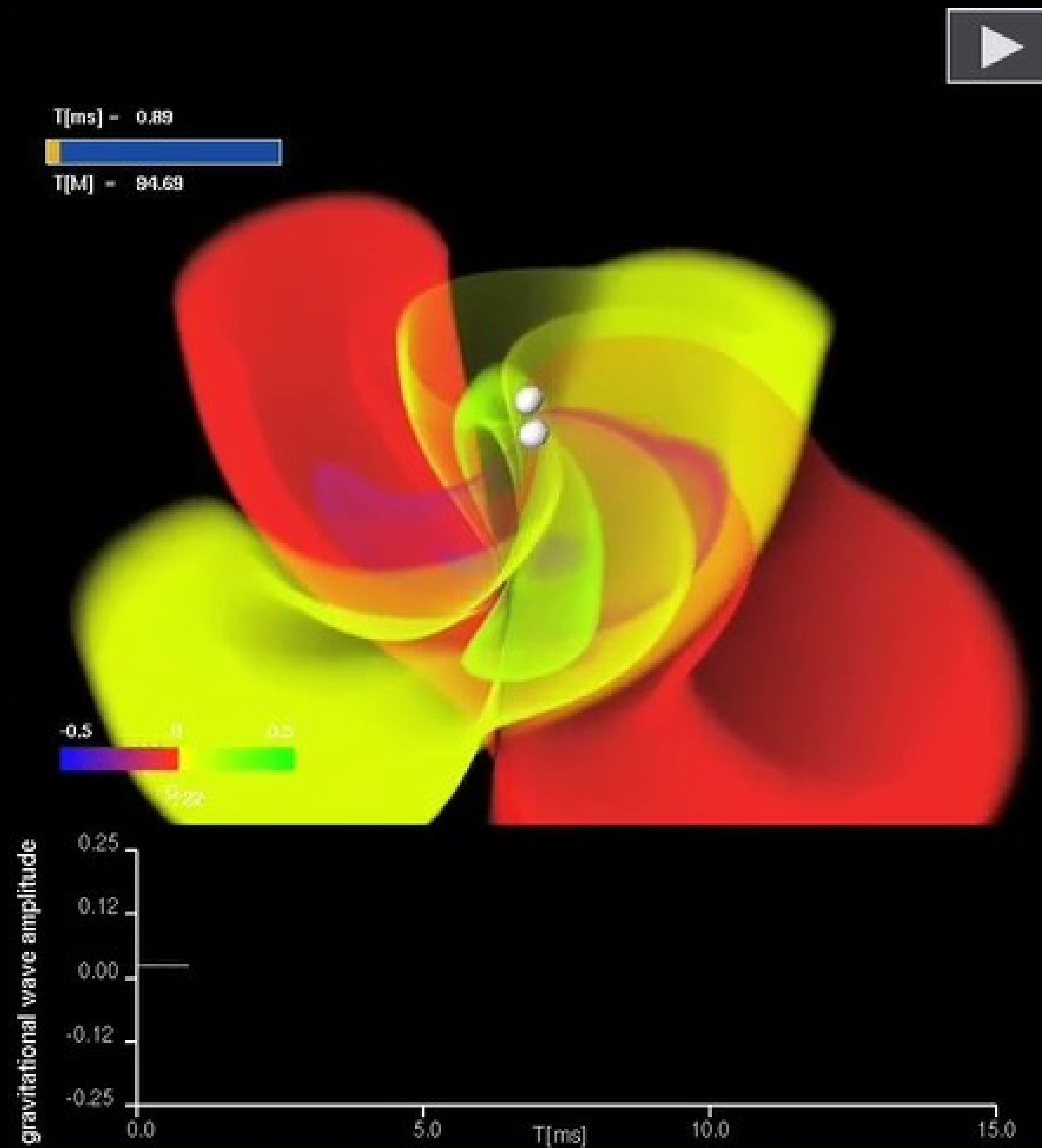




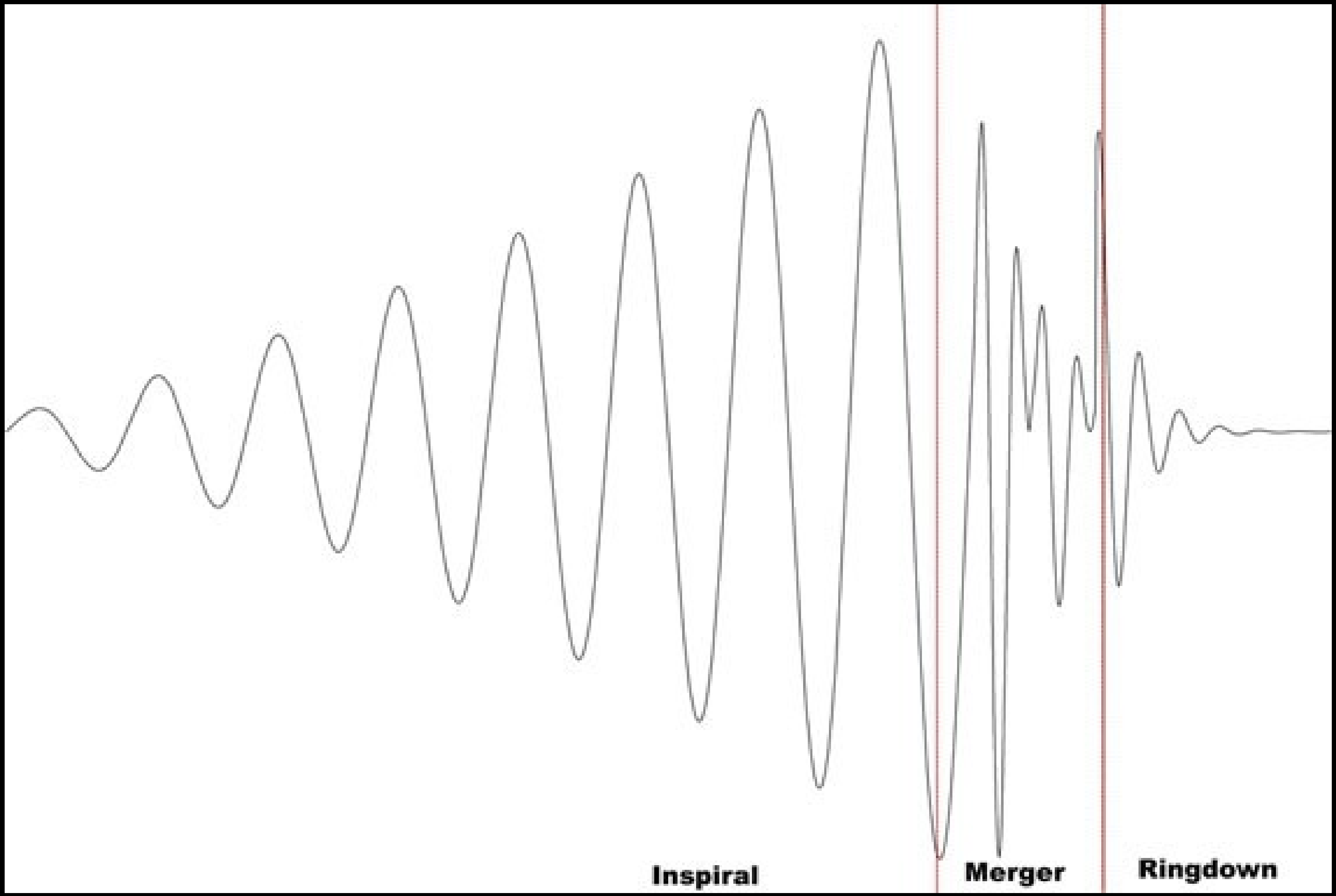


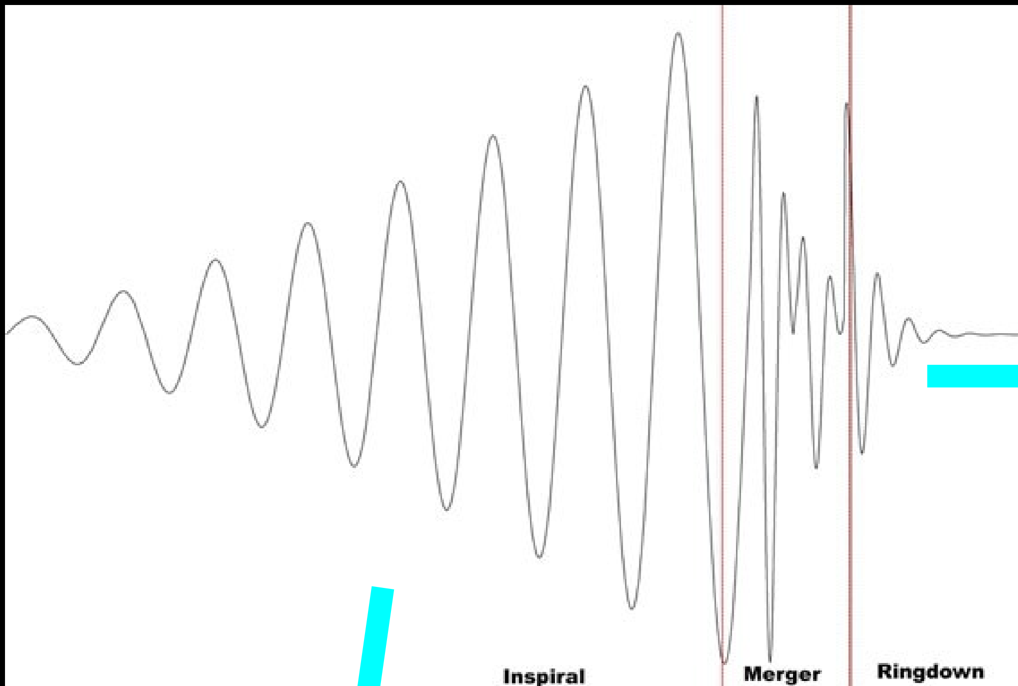
大質量の巨視的な 運動

非常に弱い相互作用



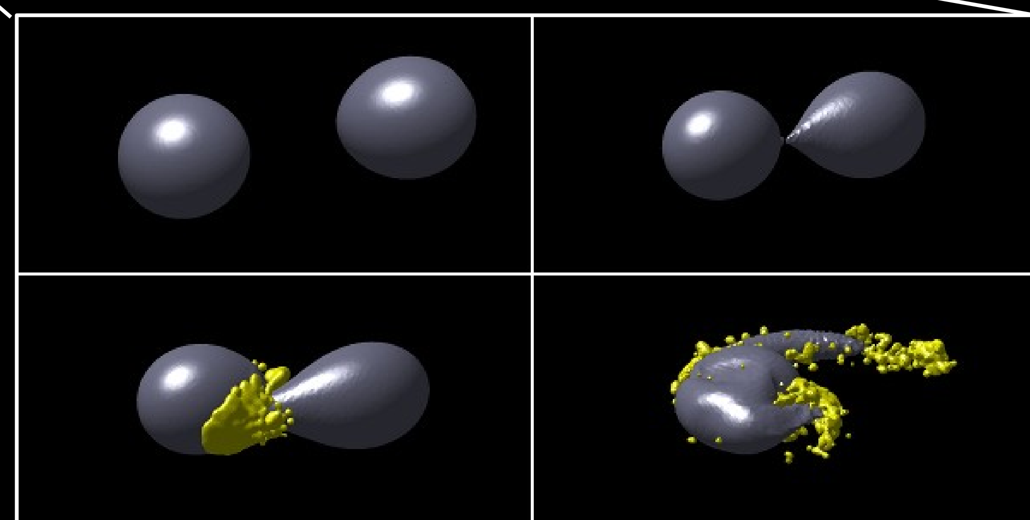
T[ms] = 0.89
T[M] = 94.69
-0.5
0
gravitational wave amplitude
0.25
0.12
0.00
-0.12
-0.25
0.0
5.0
T[ms]
10.0
15.0


Inspiral
Merger
Ringdown



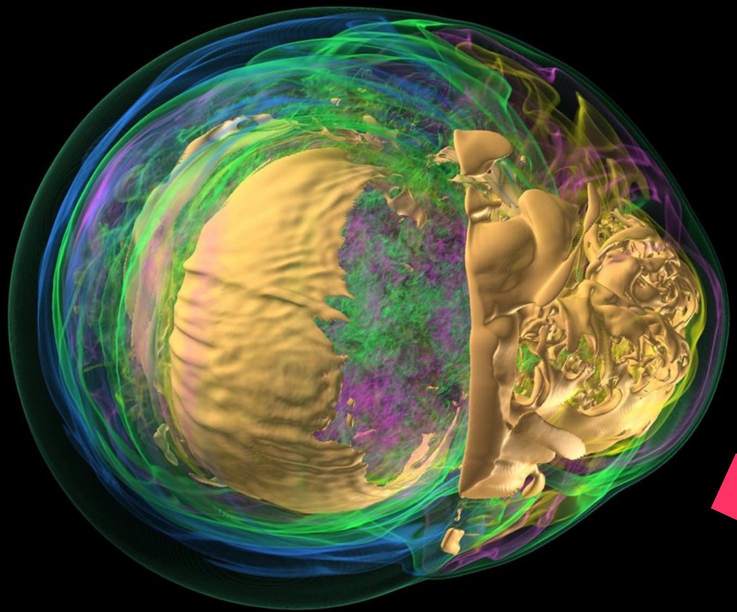
ブラックホール
質量･スピン

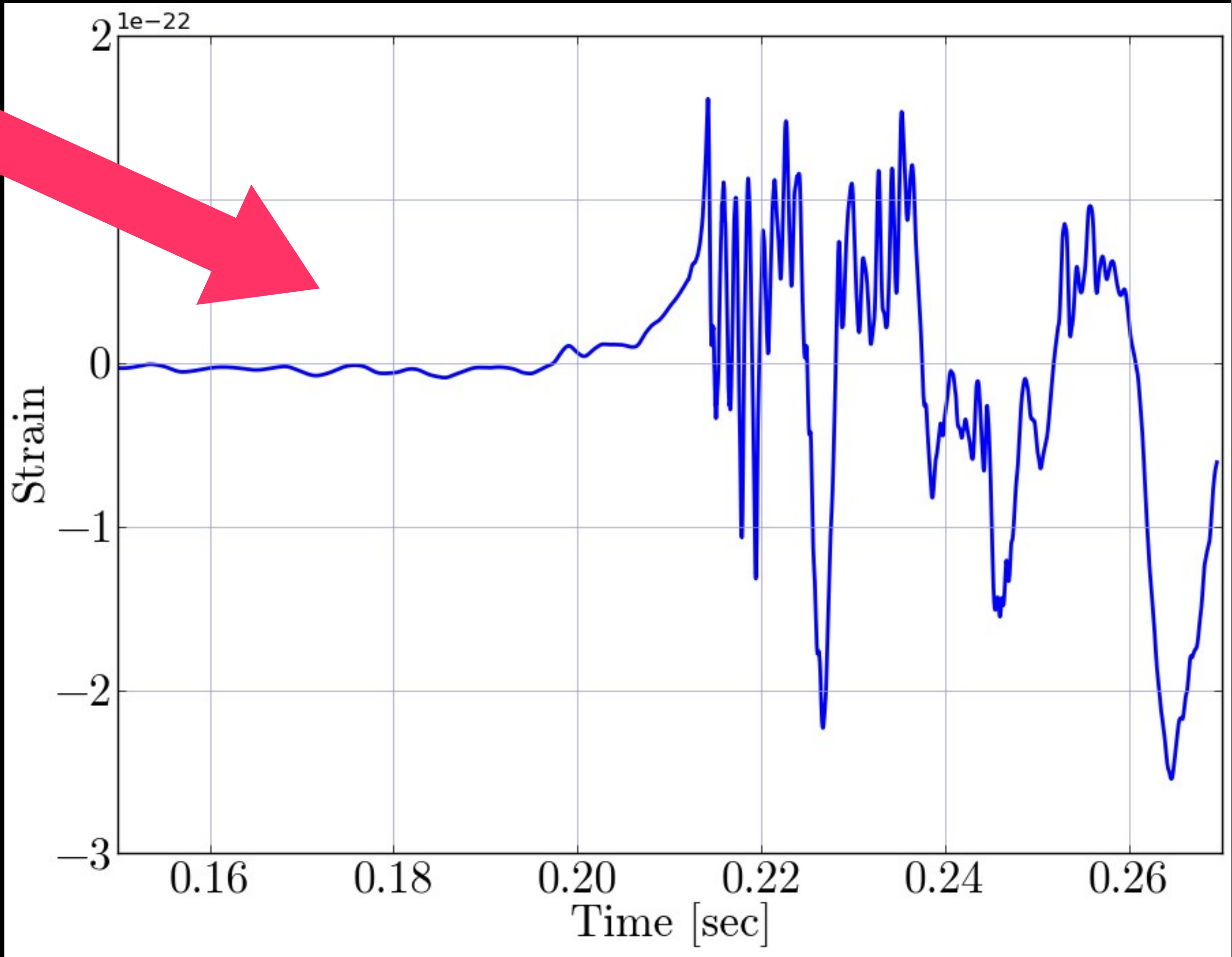
波源までの距離

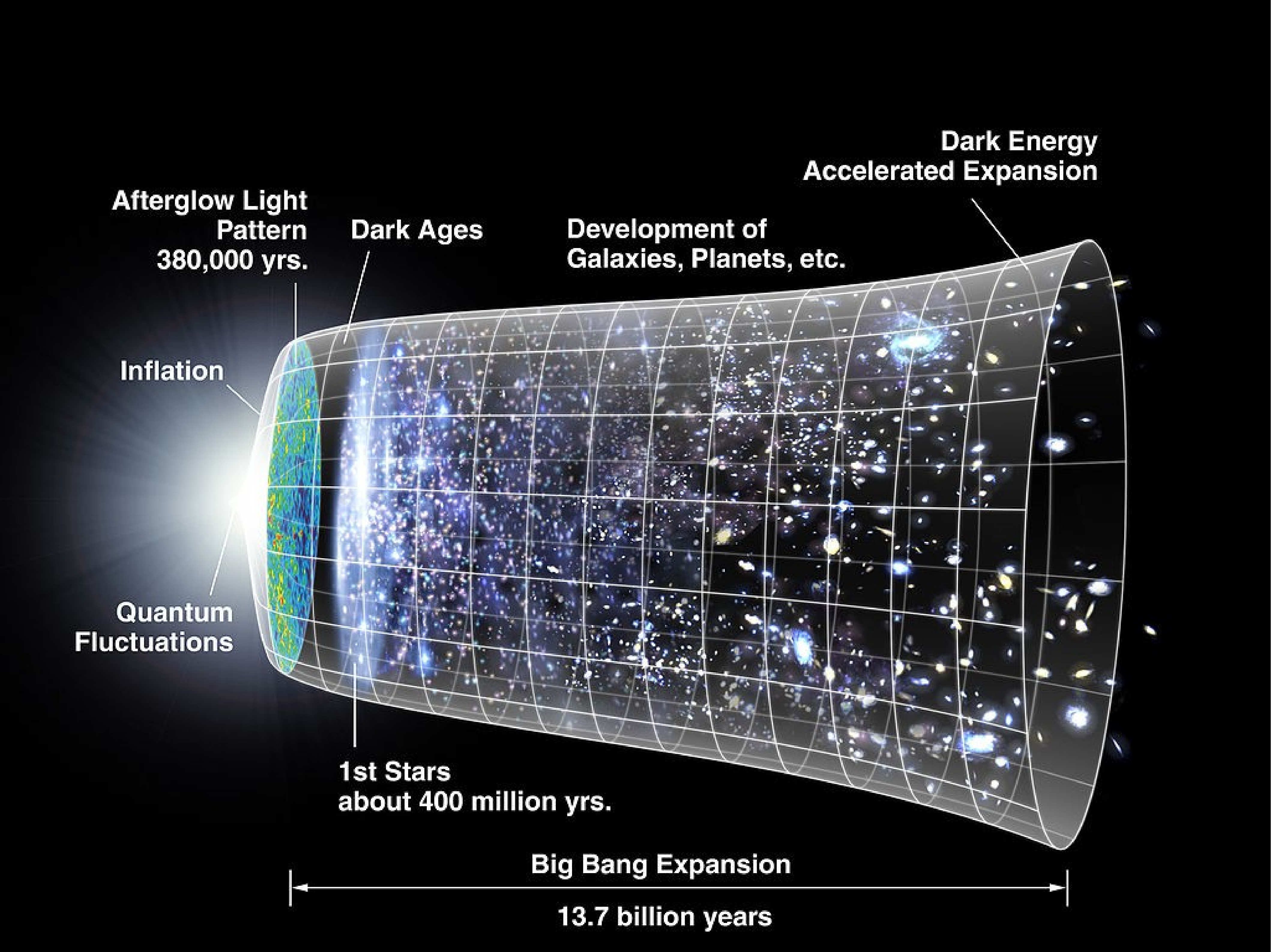


中性子星内部構造

恒星のコア崩壊






Dark Energy
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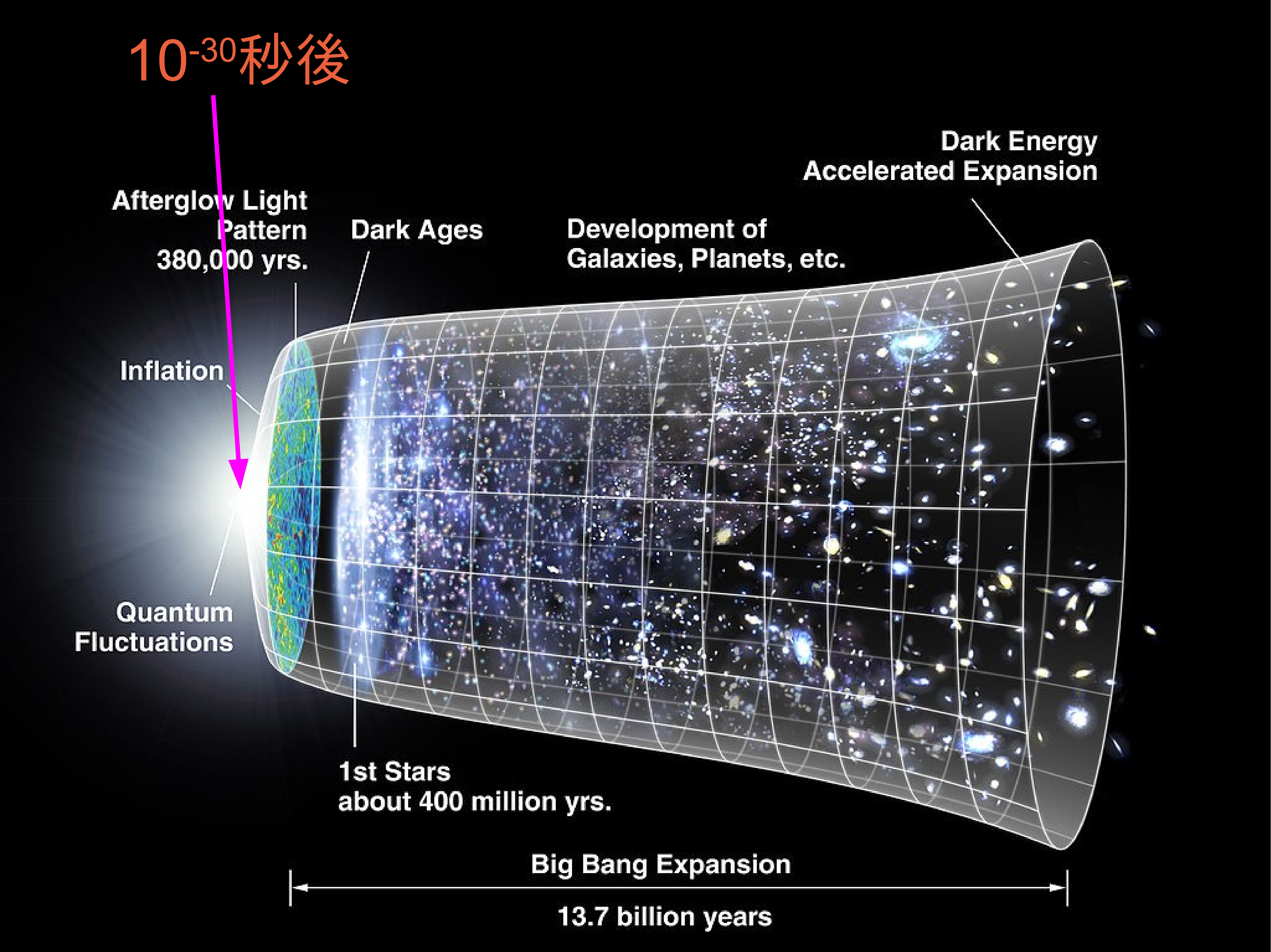
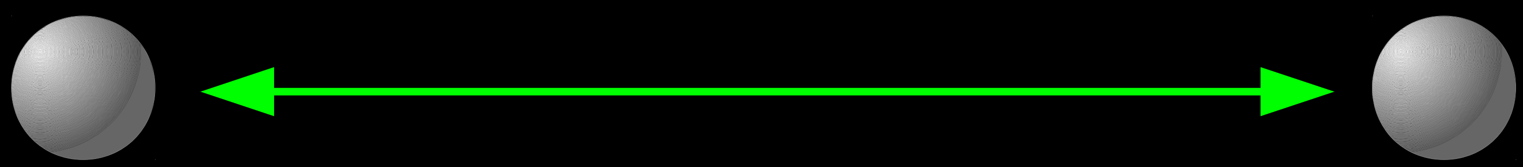
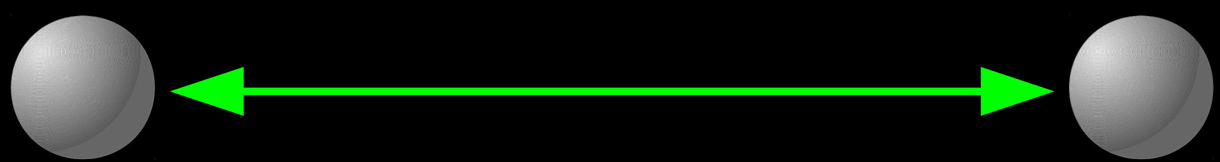
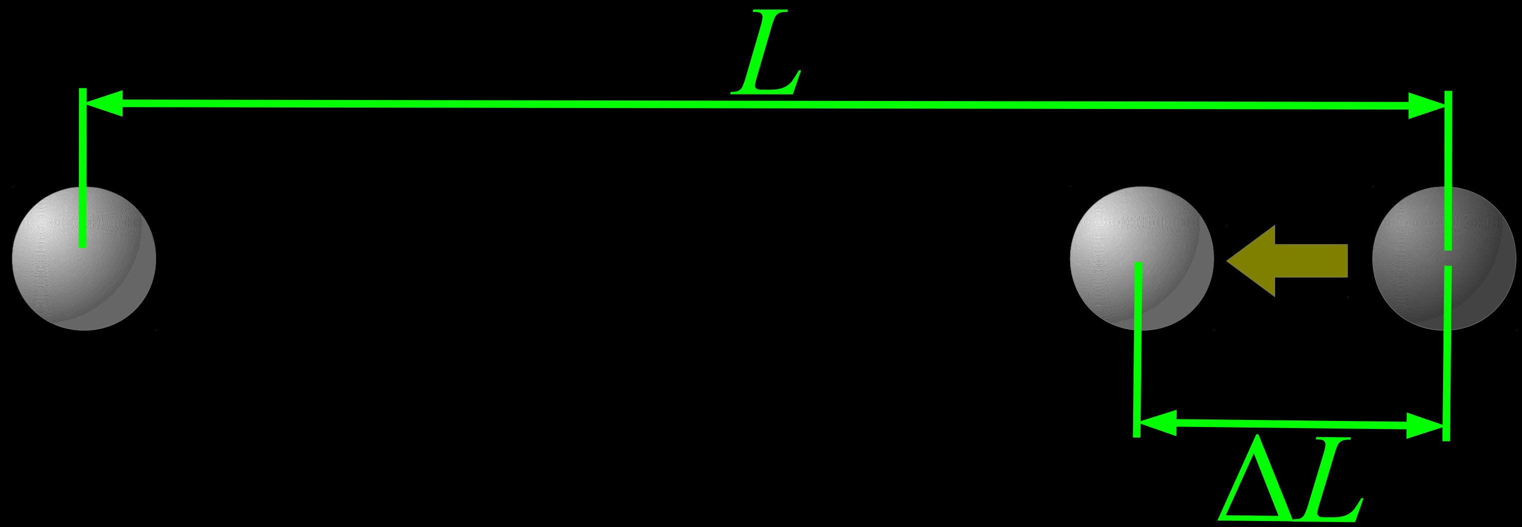


10^-30秒後
Afterglow Light Pattern 380,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Dark Energy Accelerated Expansion
Inflation
Quantum Fluctuations
1st Stars about 400 million yrs.
Big Bang Expansion
13.7 billion years

どうやって重力波を検出するのか?





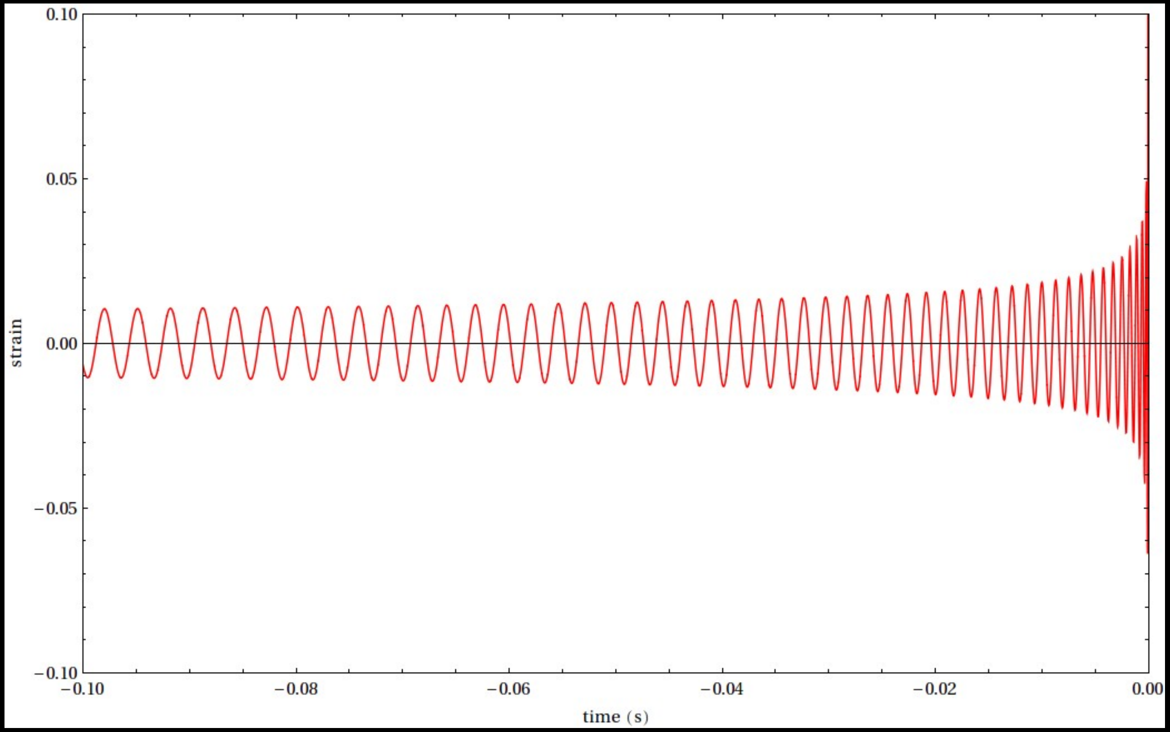


$$h = \frac{\Delta L}{L}$$

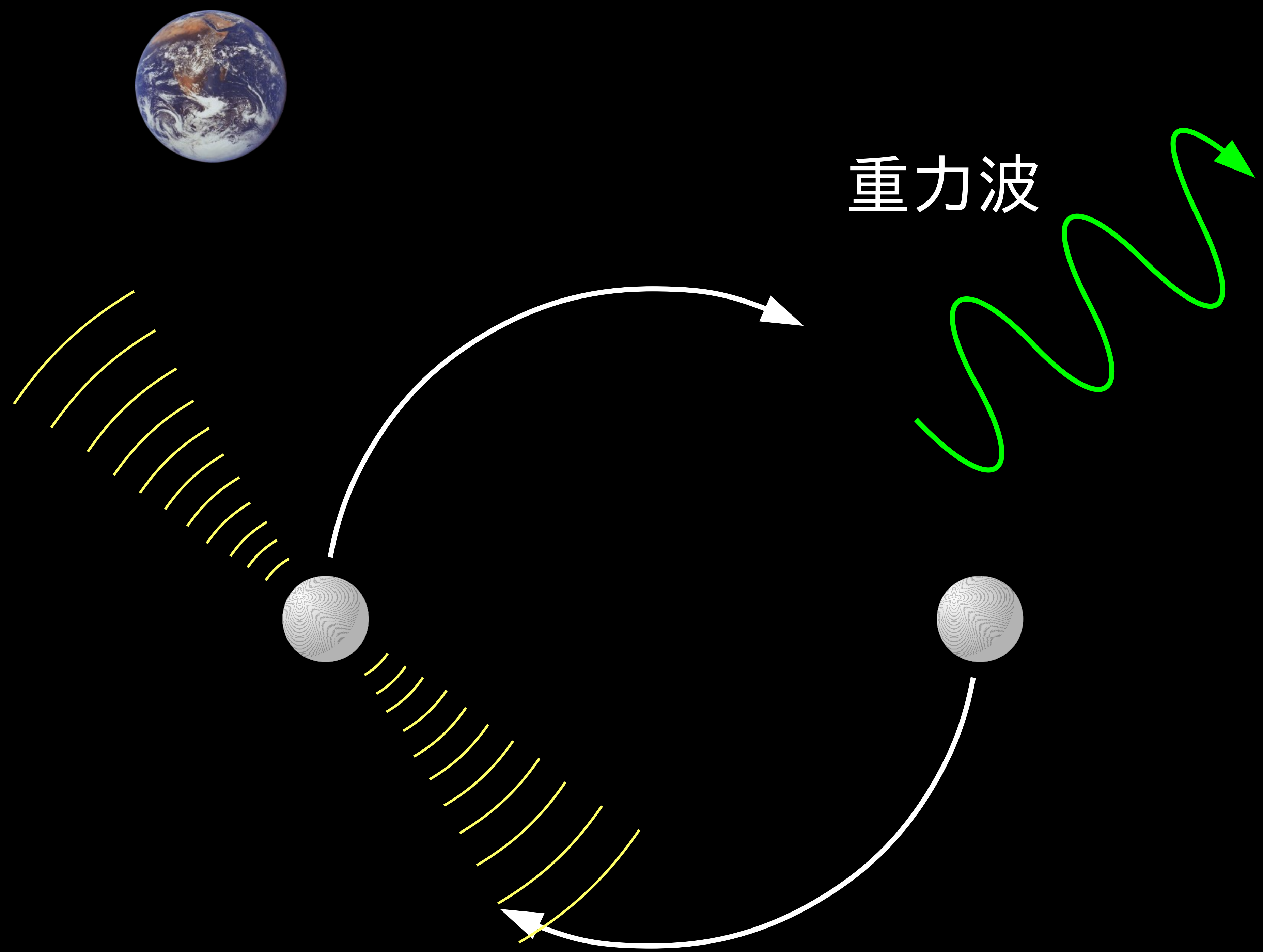
重力波振幅

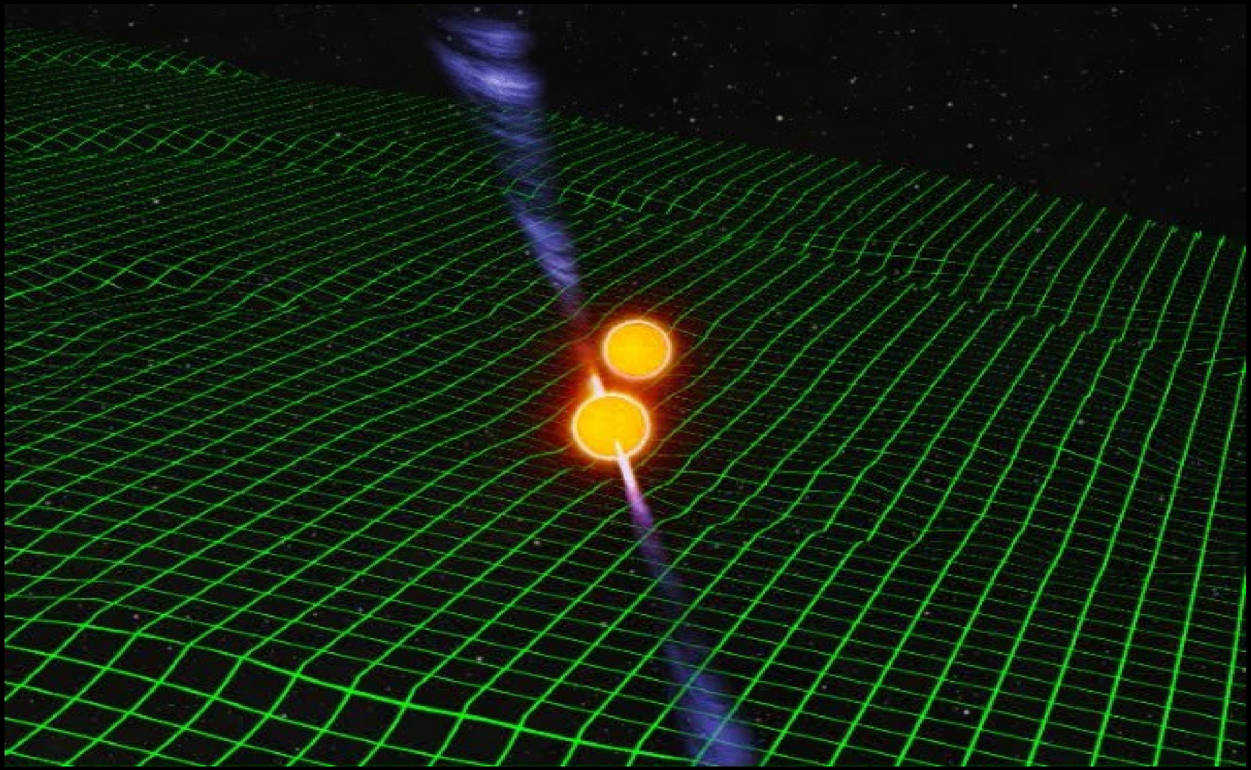
h の値はどのぐらいか?

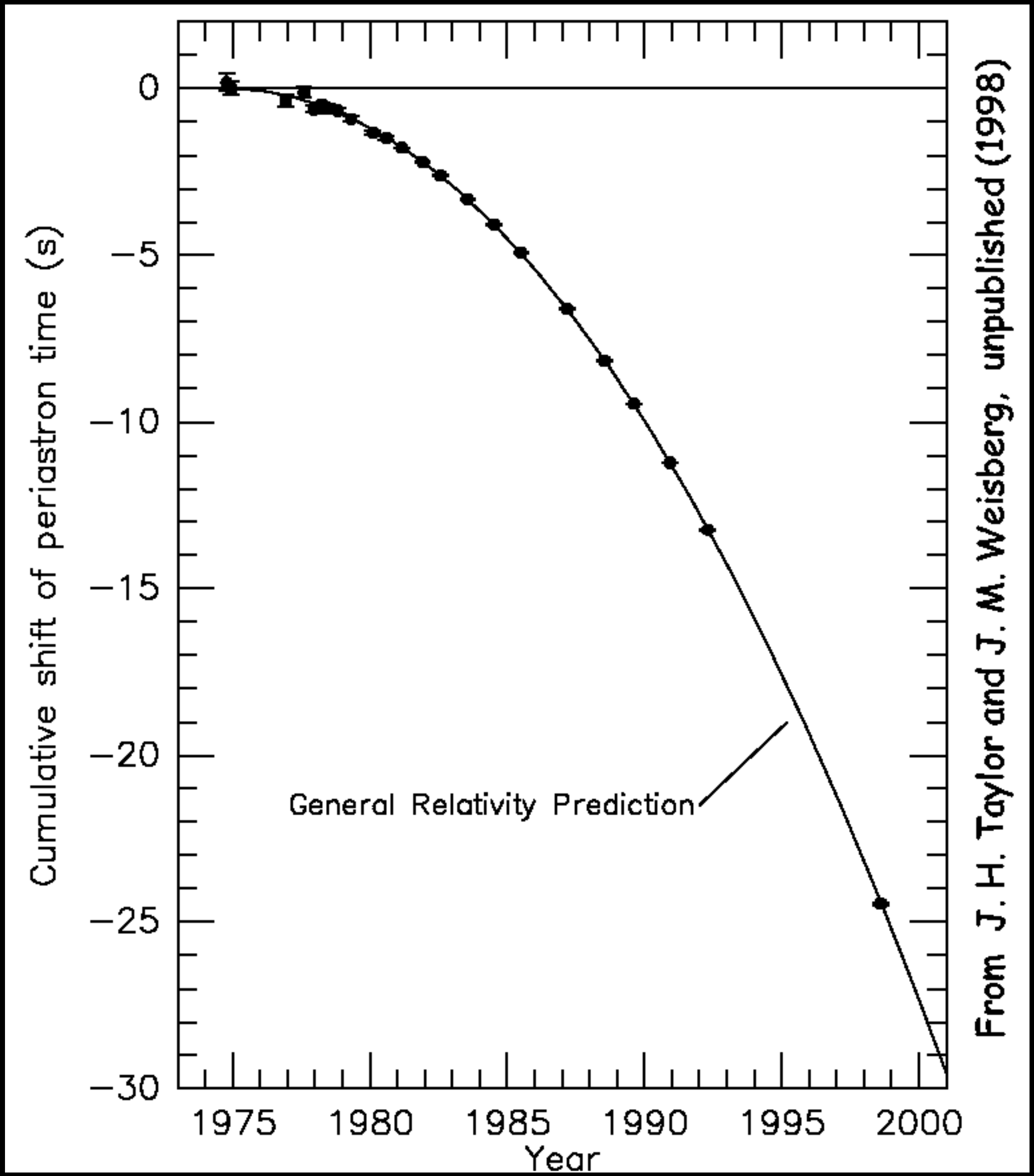
年間1イベント以上



0.10
0.05
0.00
−0.05
−0.10
strain
−0.10
−0.08
−0.06
−0.04
−0.02
0.00
time (s)

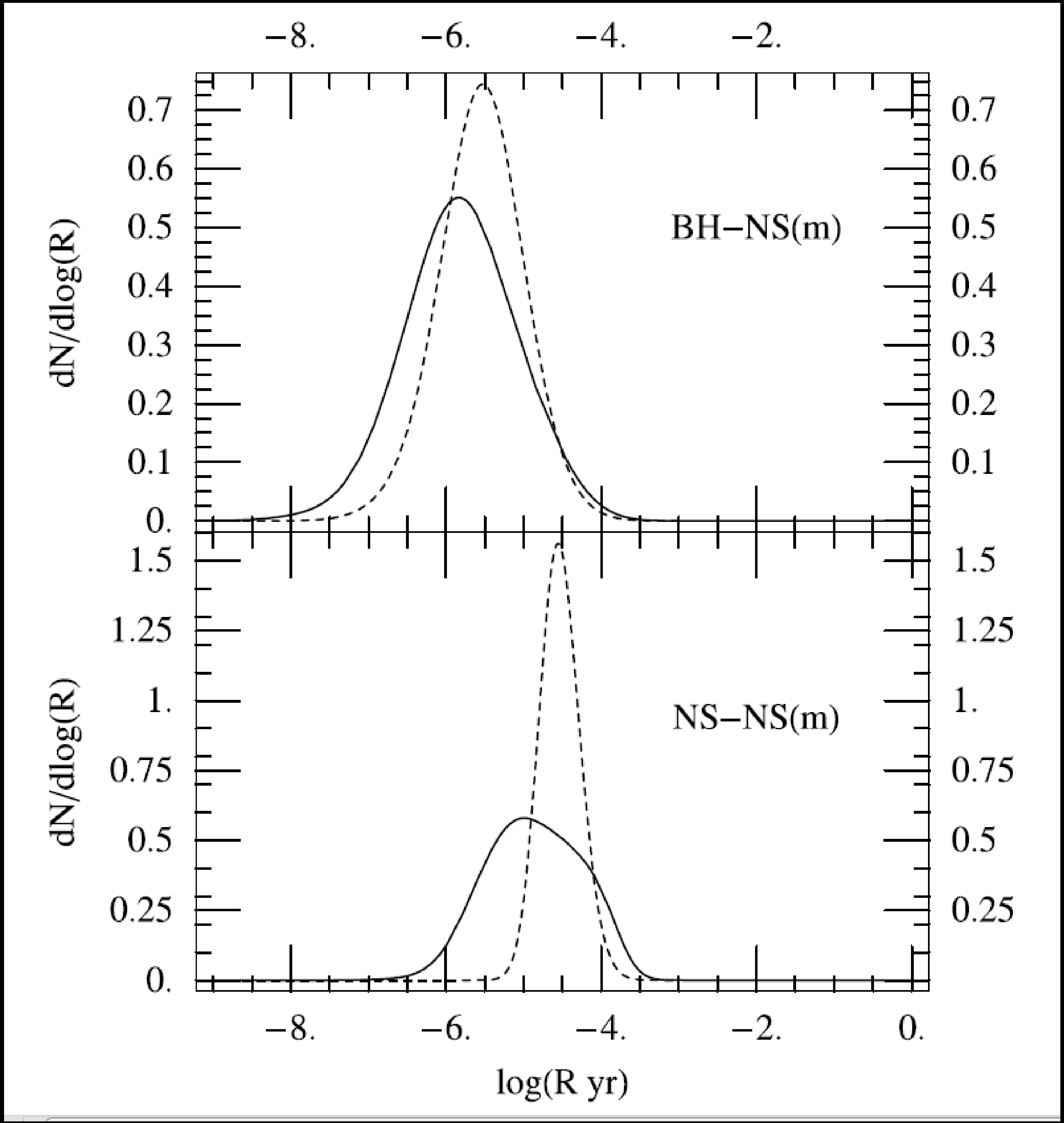

重力波

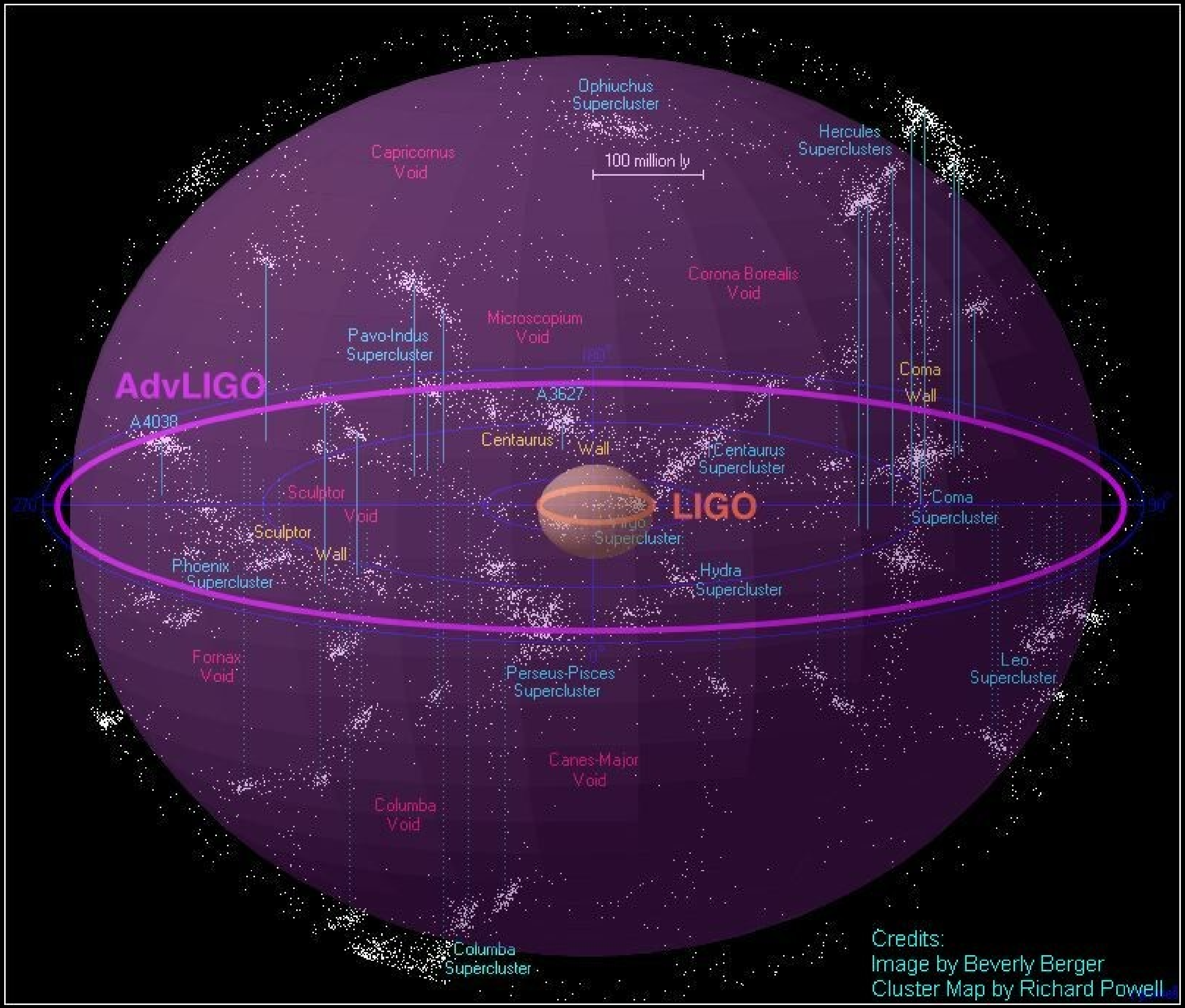



0
−5
−10
−15
−20
−25
−30
1975
1980
1985
1990
1995
2000
Year
Cumulative shift of periastron time (s)
General Relativity Prediction
From J. H. Taylor and J. M. Weisberg, unpublished (1998)


NAT. MDCCC XXXIII OB. MDCCC XCVI.
ALFR. NOBEL

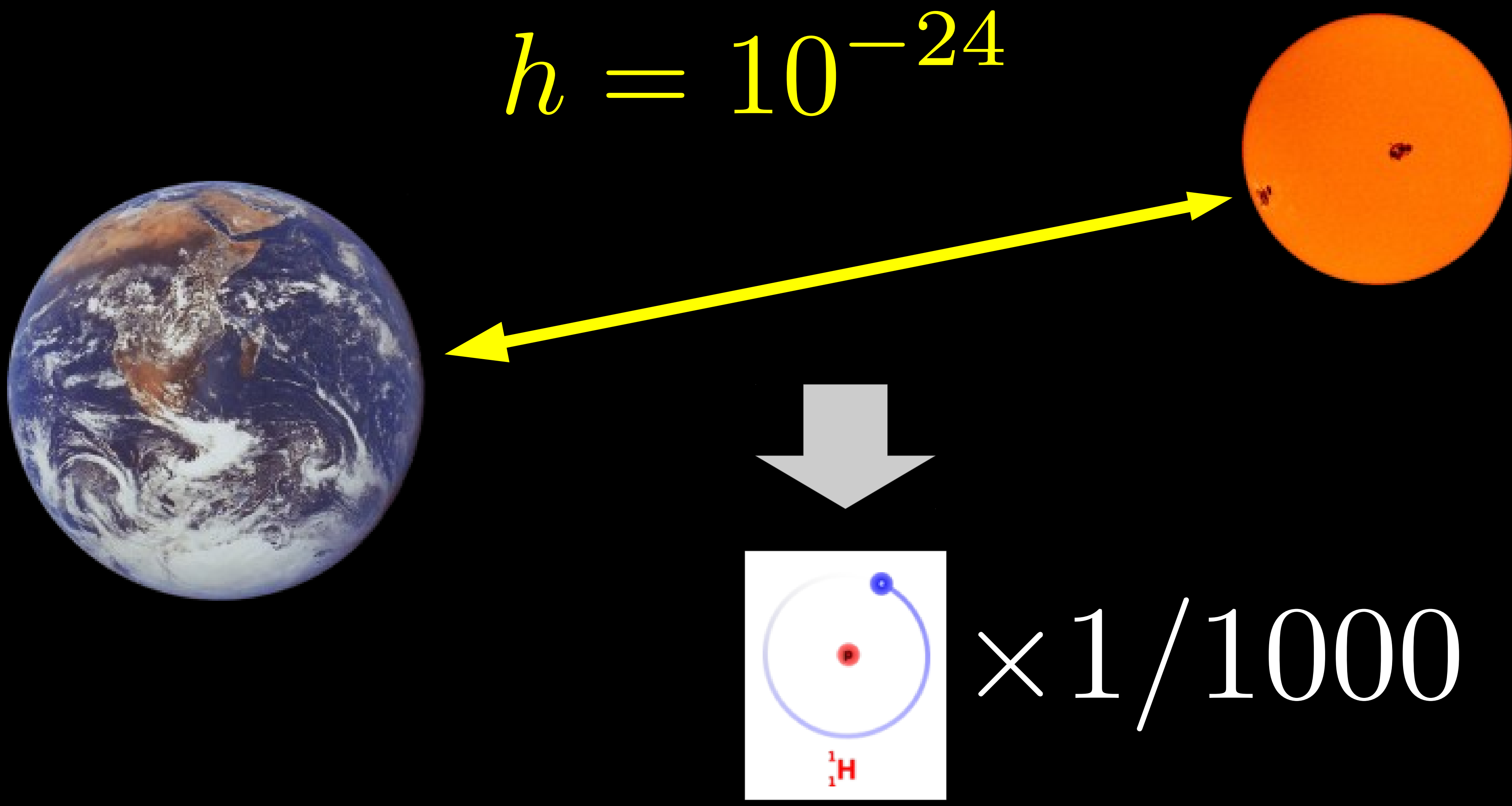
1銀河当たり, 1万 - 10万年に一回



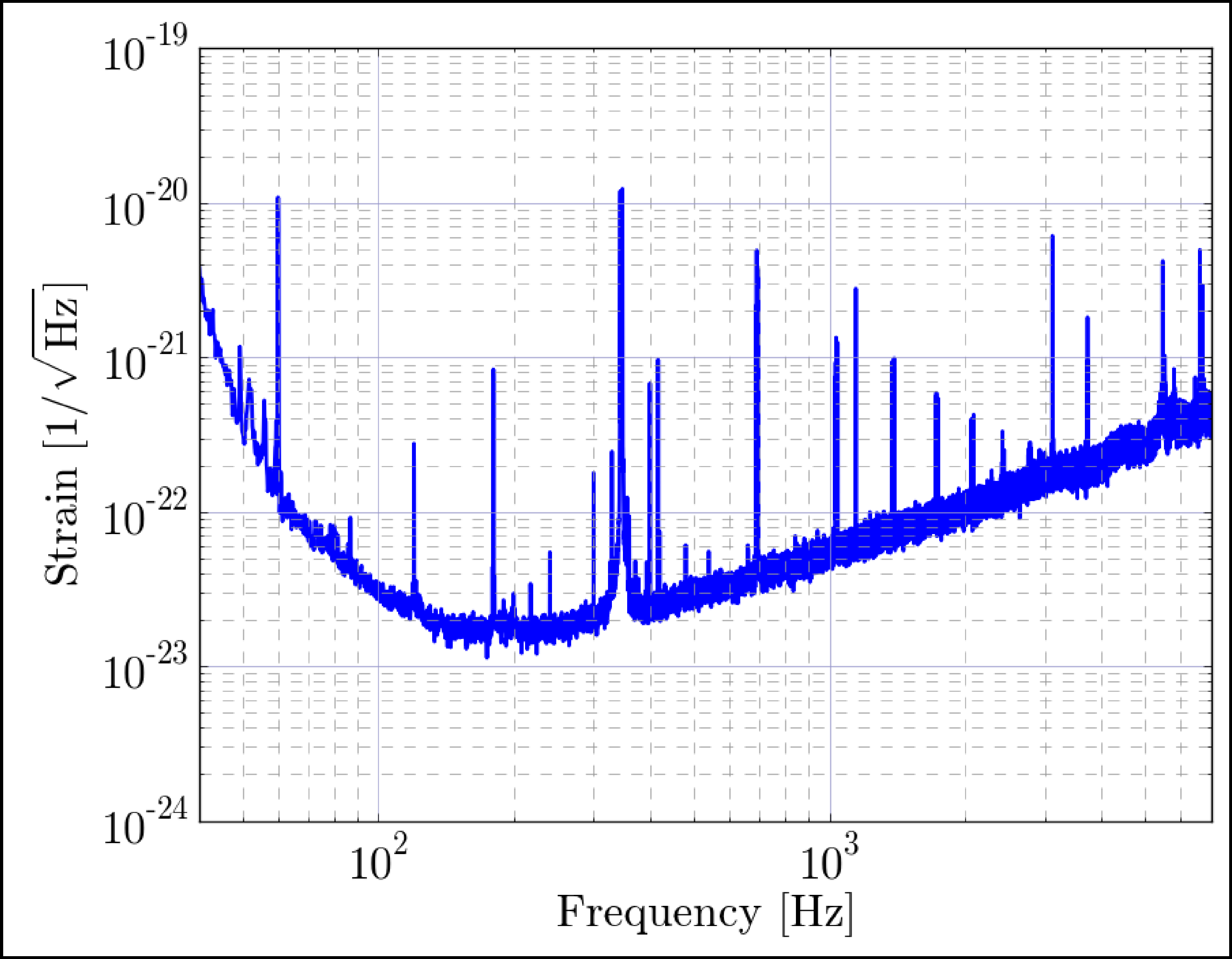


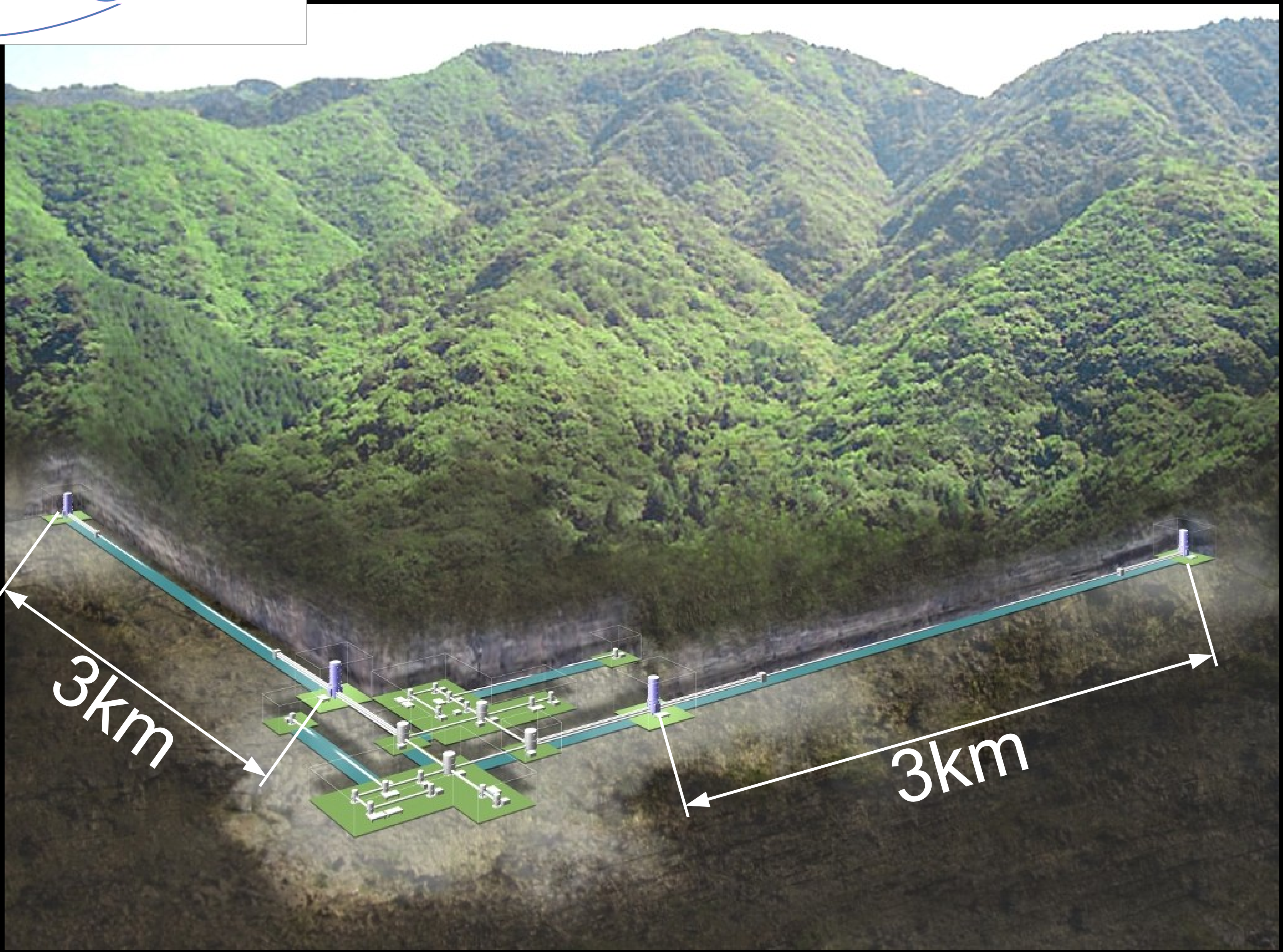
200Mpc = 6億5千万光年

$$h = 10^{-23} \sim 10^{-24}$$

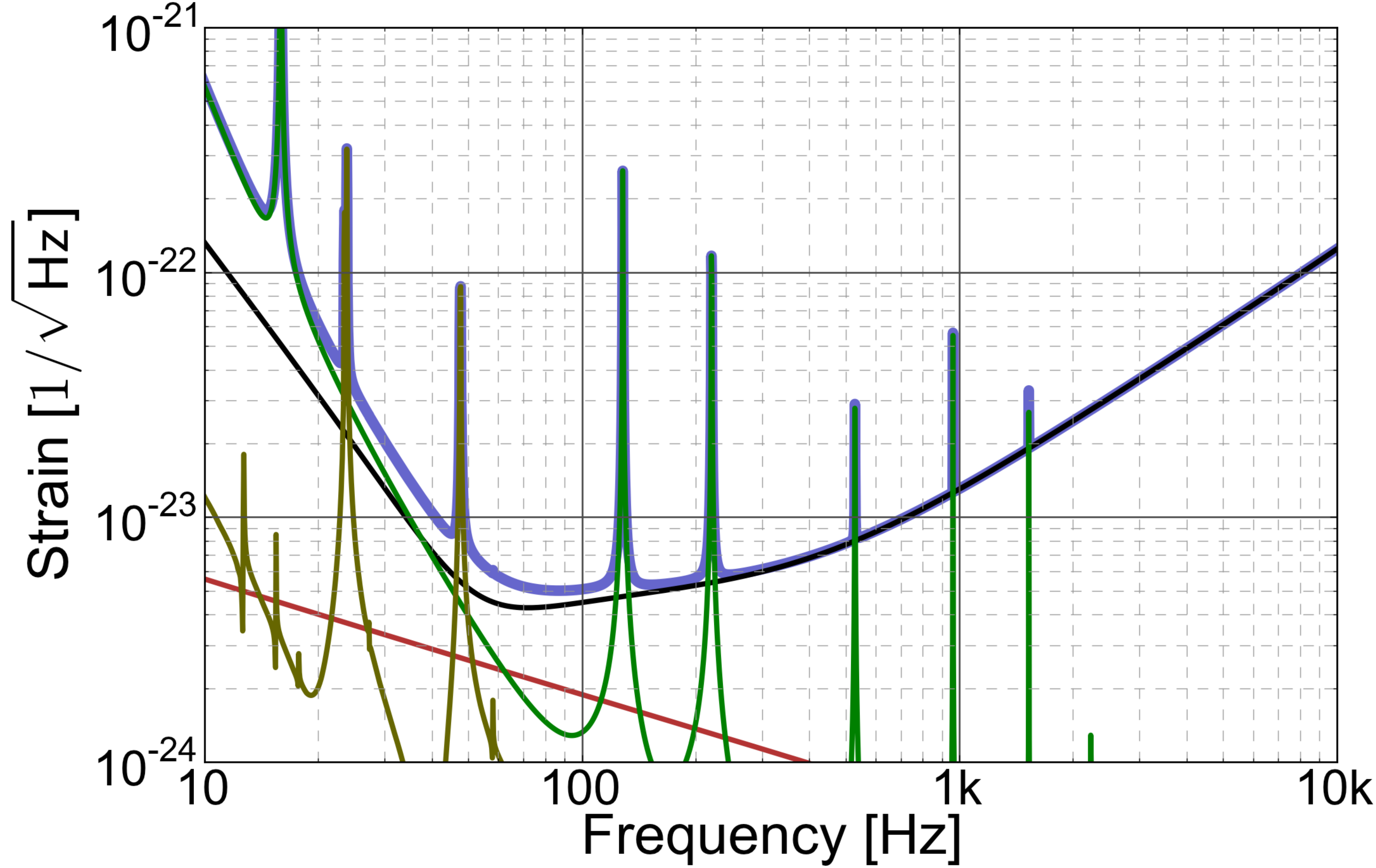

$h = 10^{-24}$
$^{1}_{1}H$
$\times 1/1000$

LIGO S6 Sensitivity

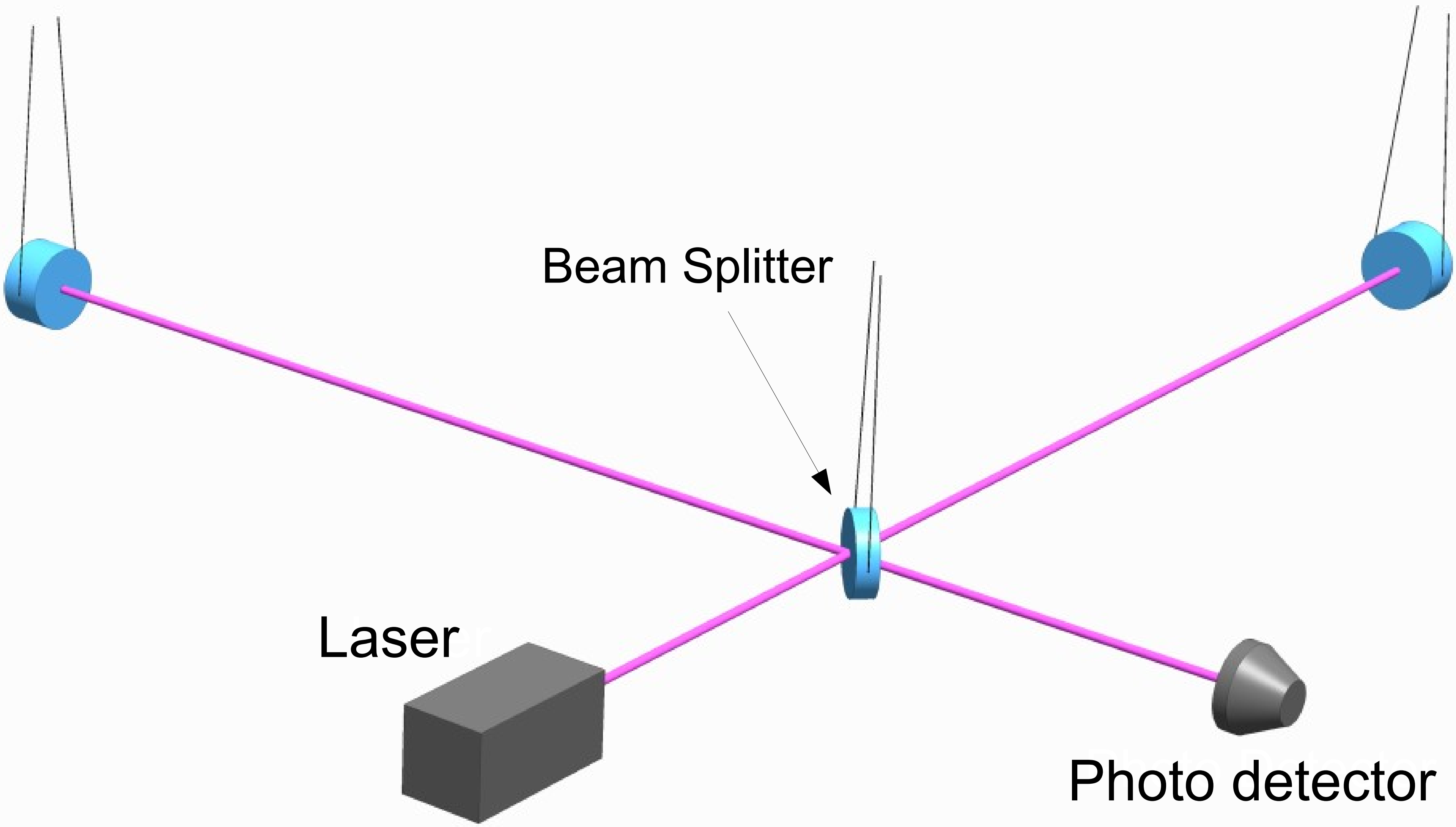


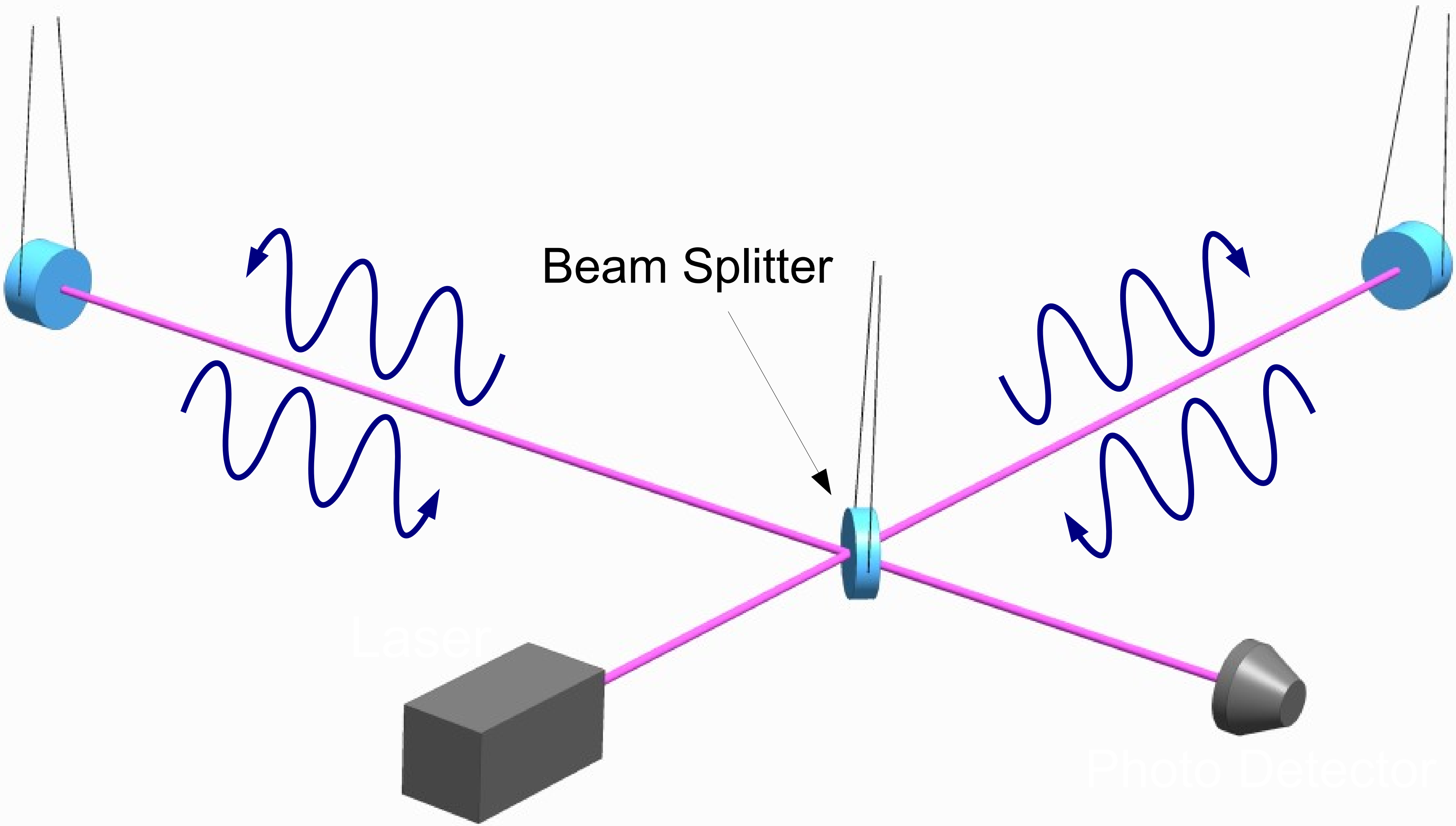

3km
3km

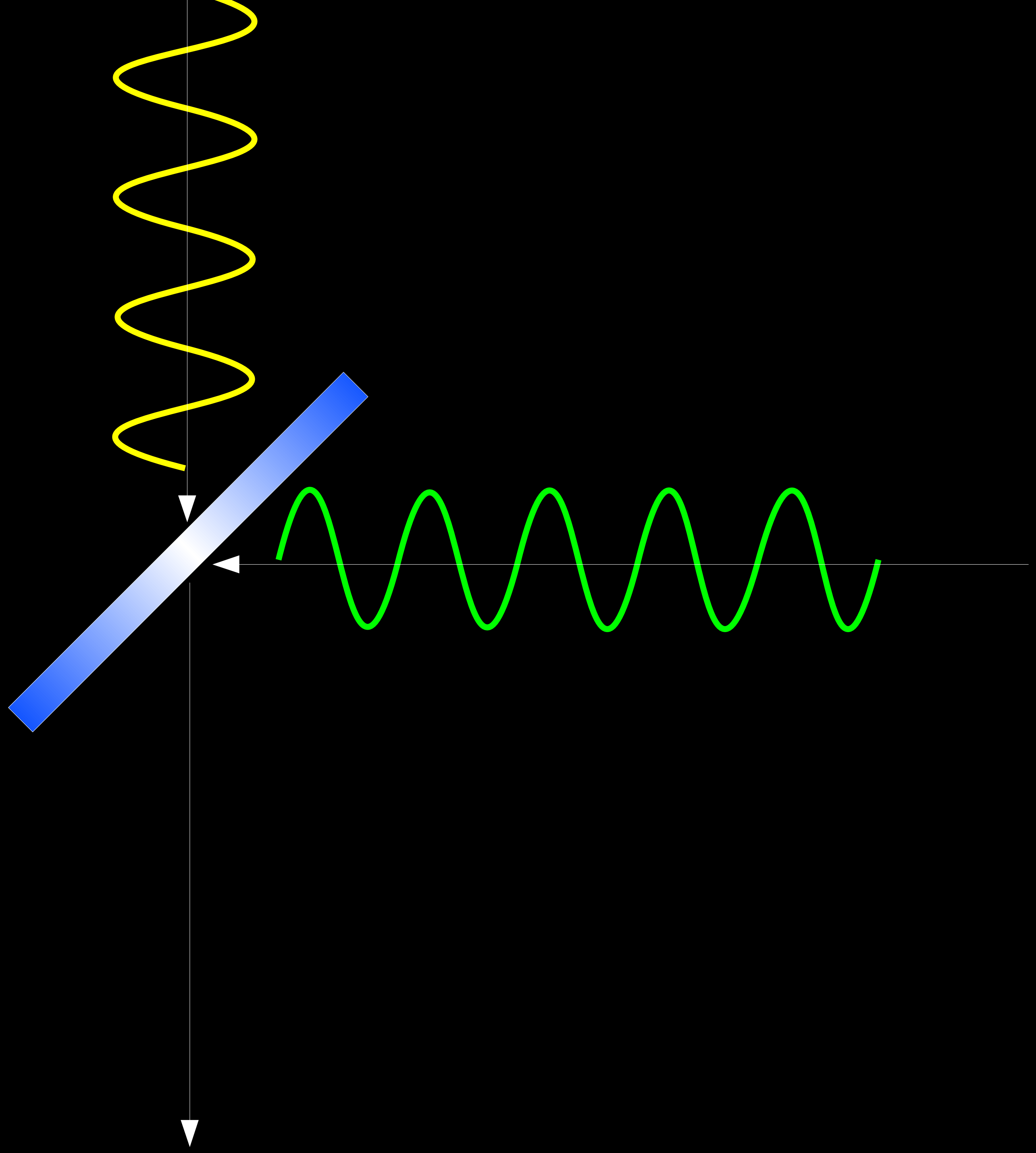
Target Sensitivity of KAGRA

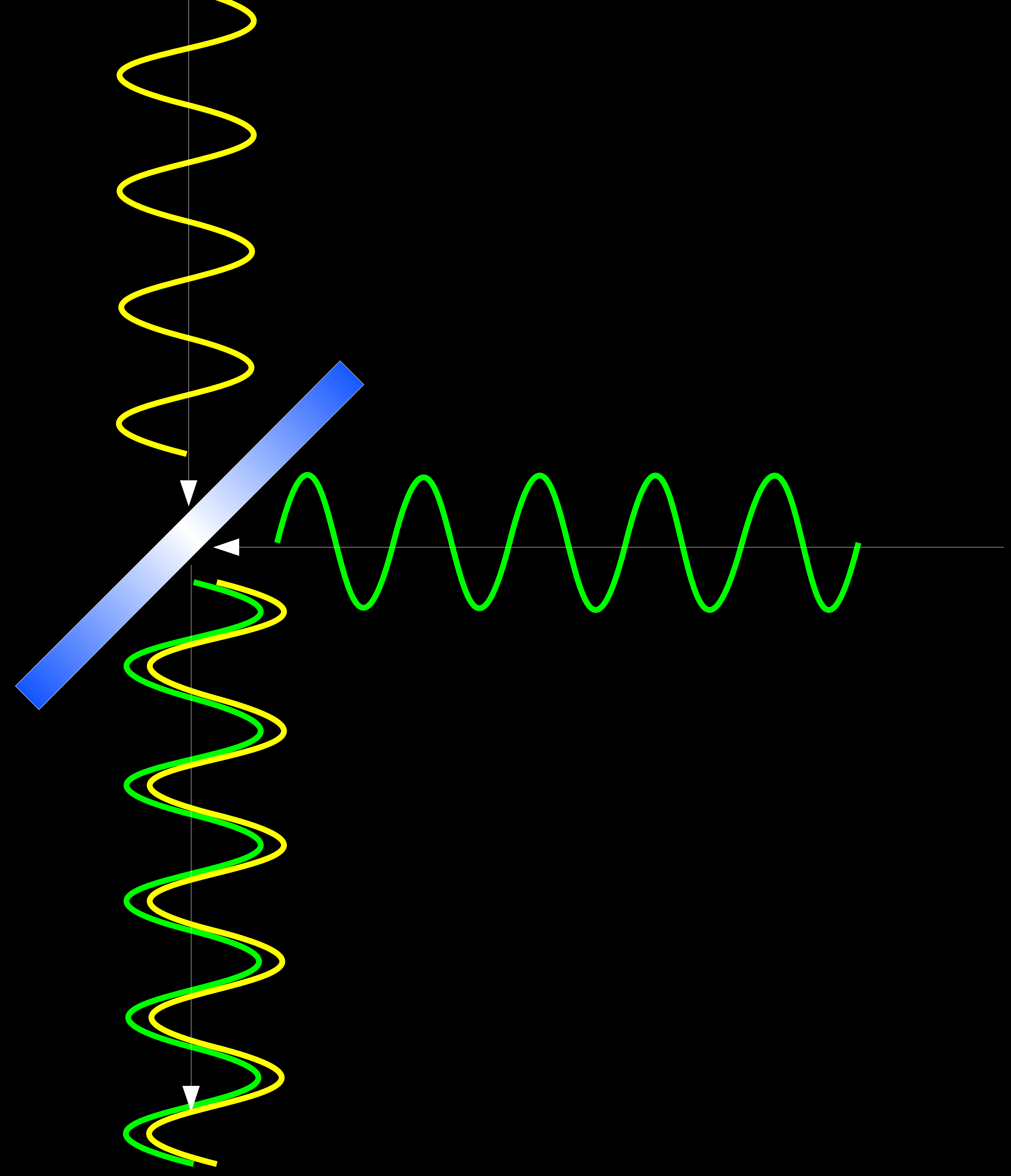


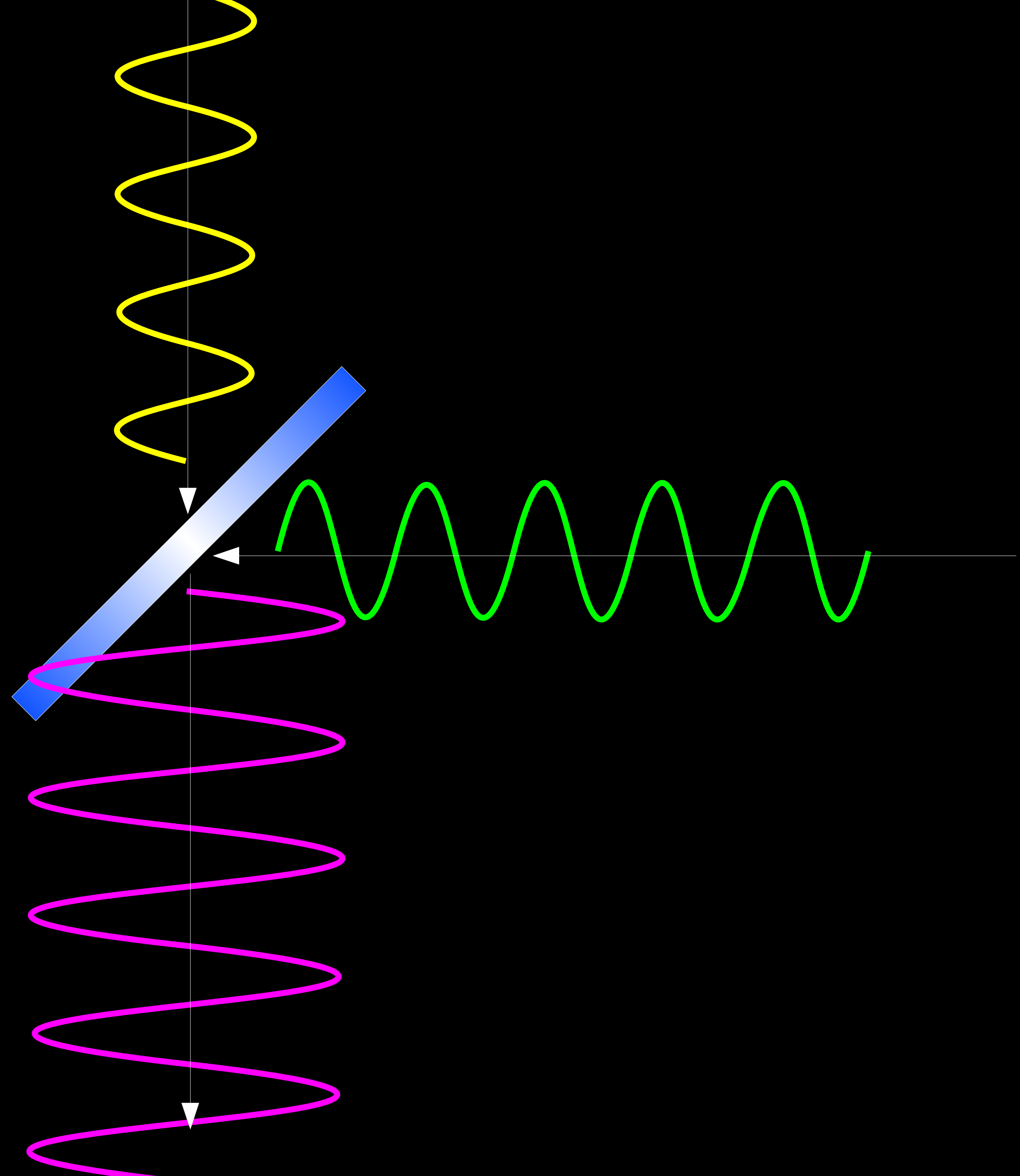
Michelson Interferometer

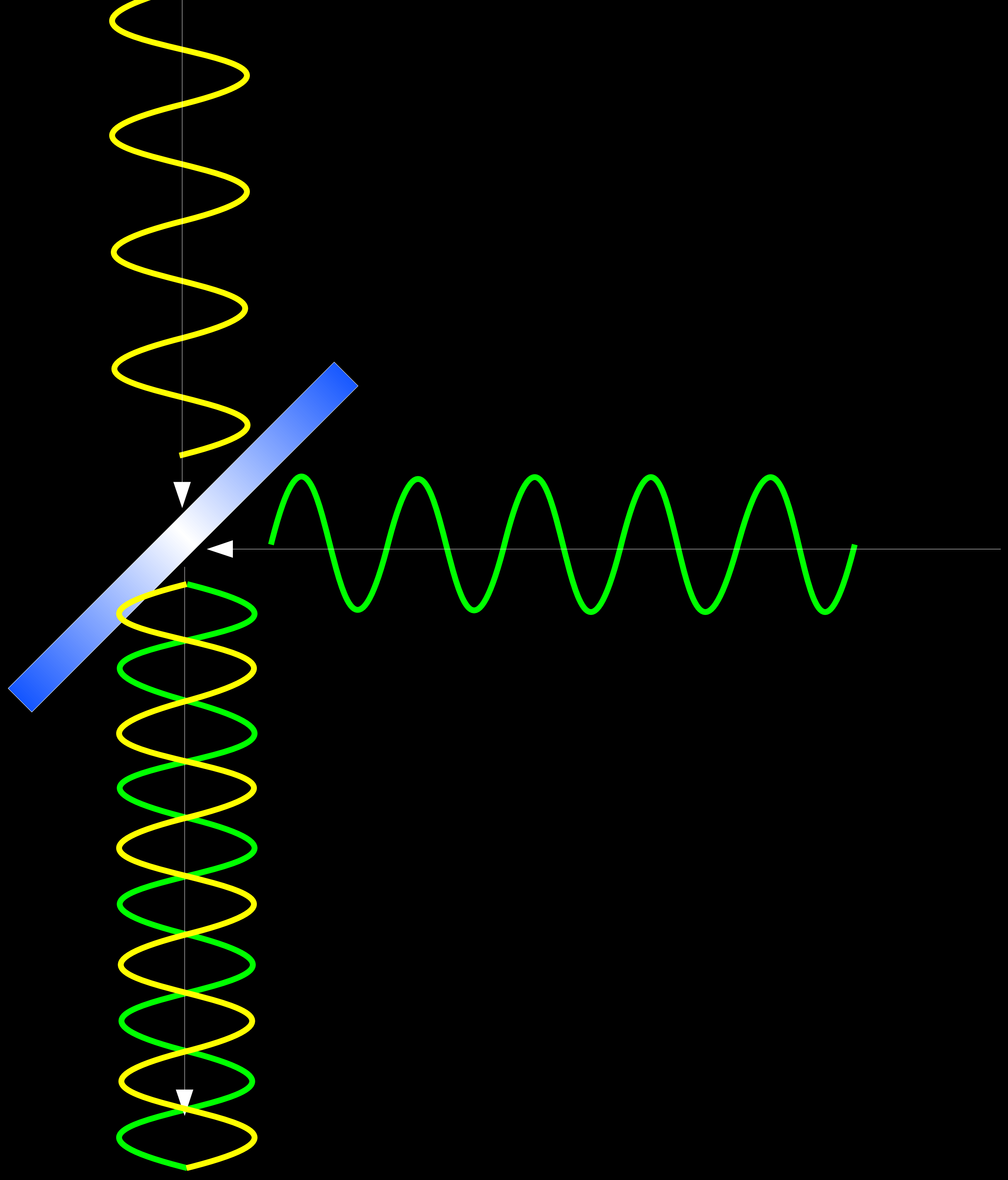


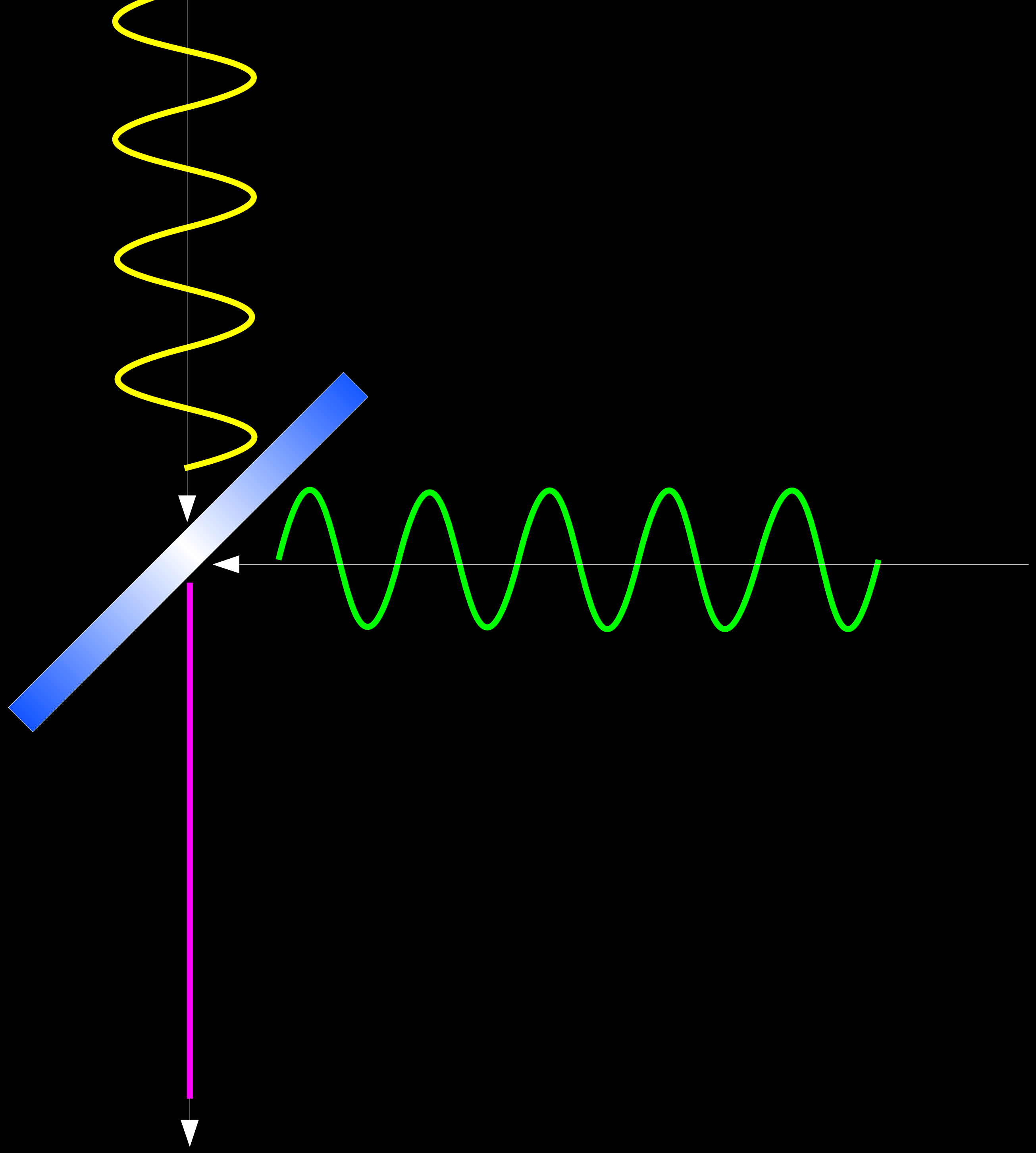

Beam Splitter
Laser
Photo Detector

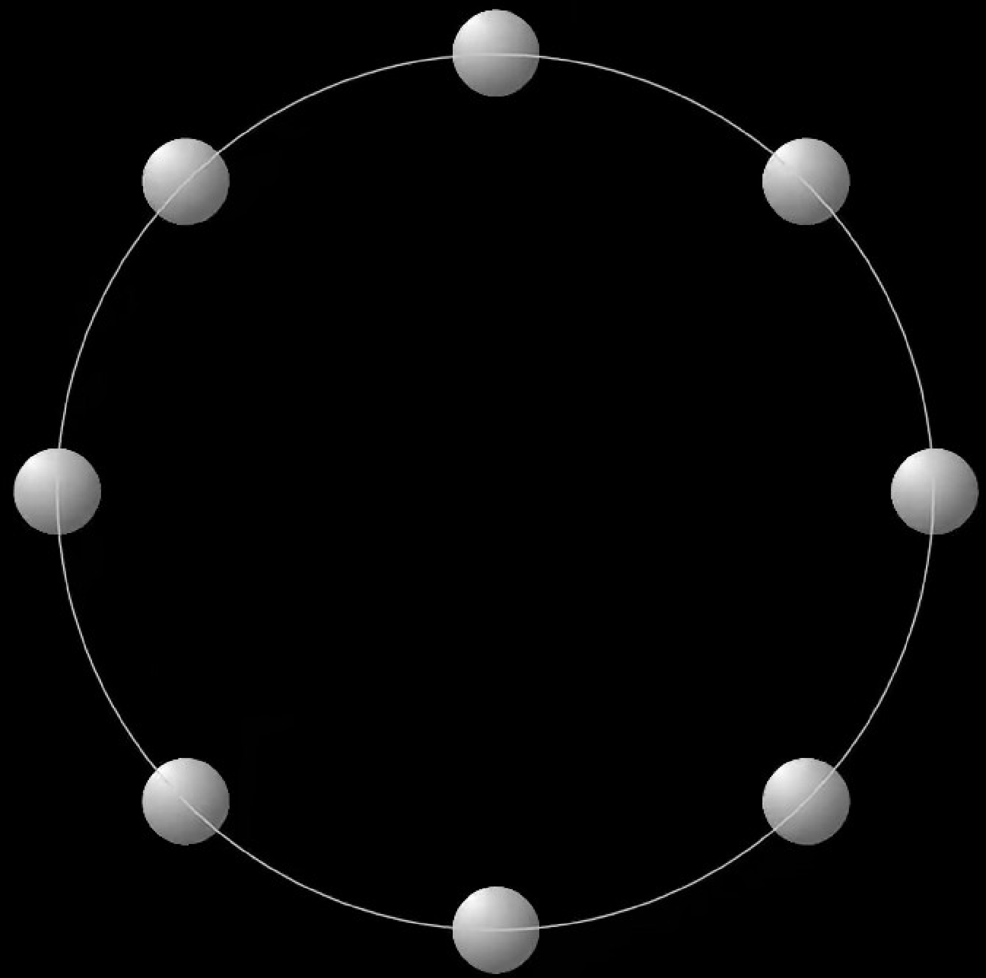


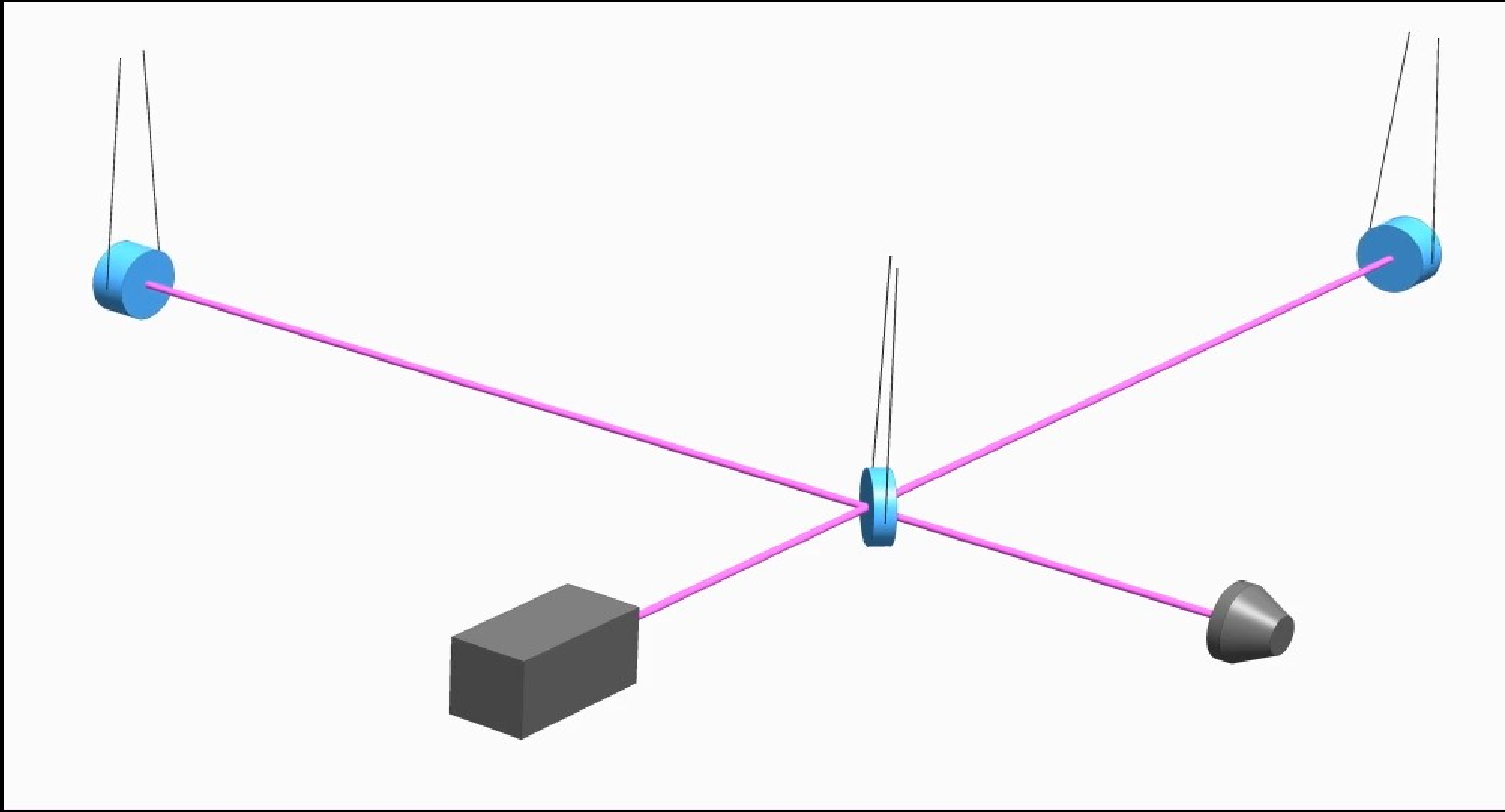


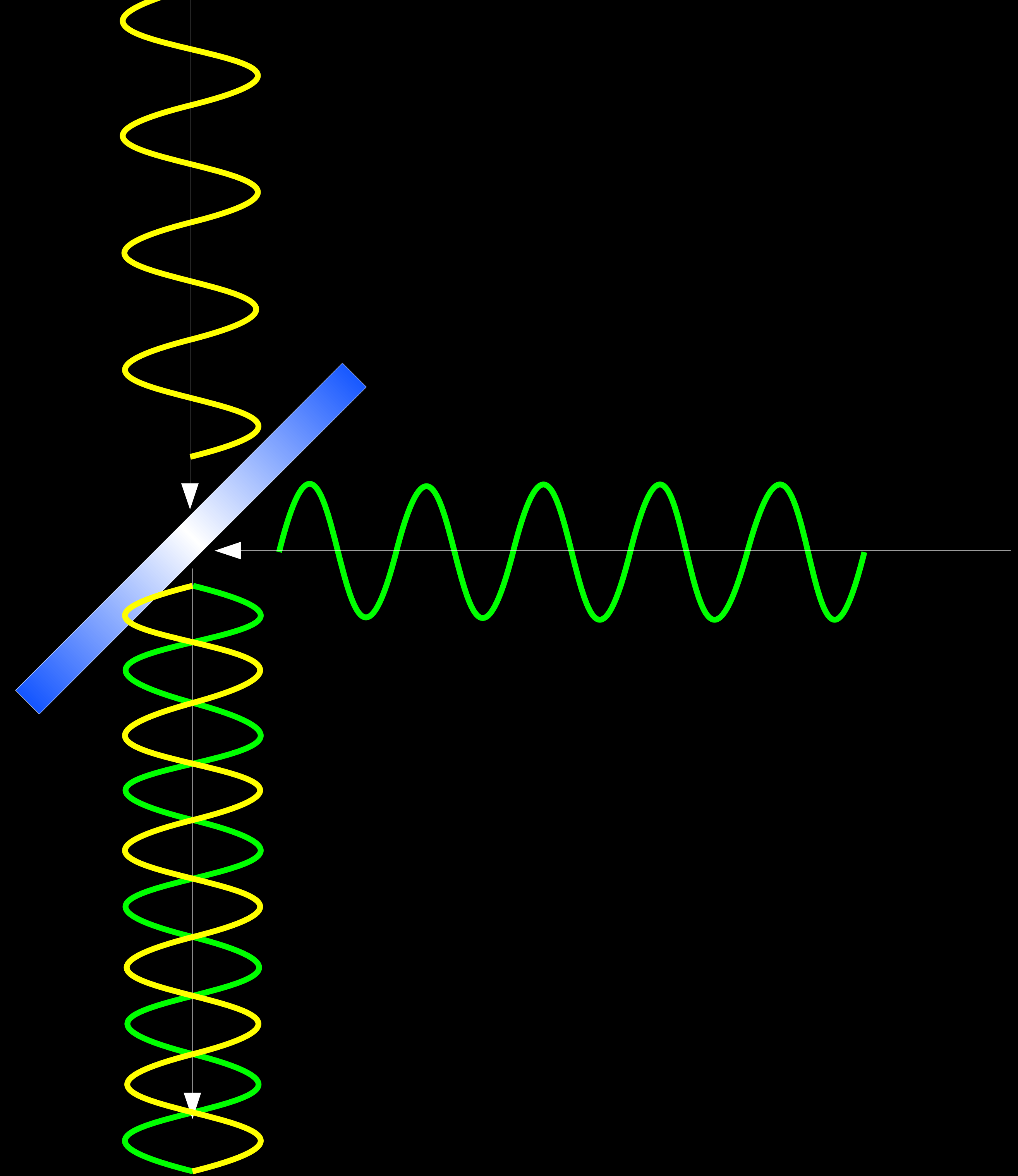


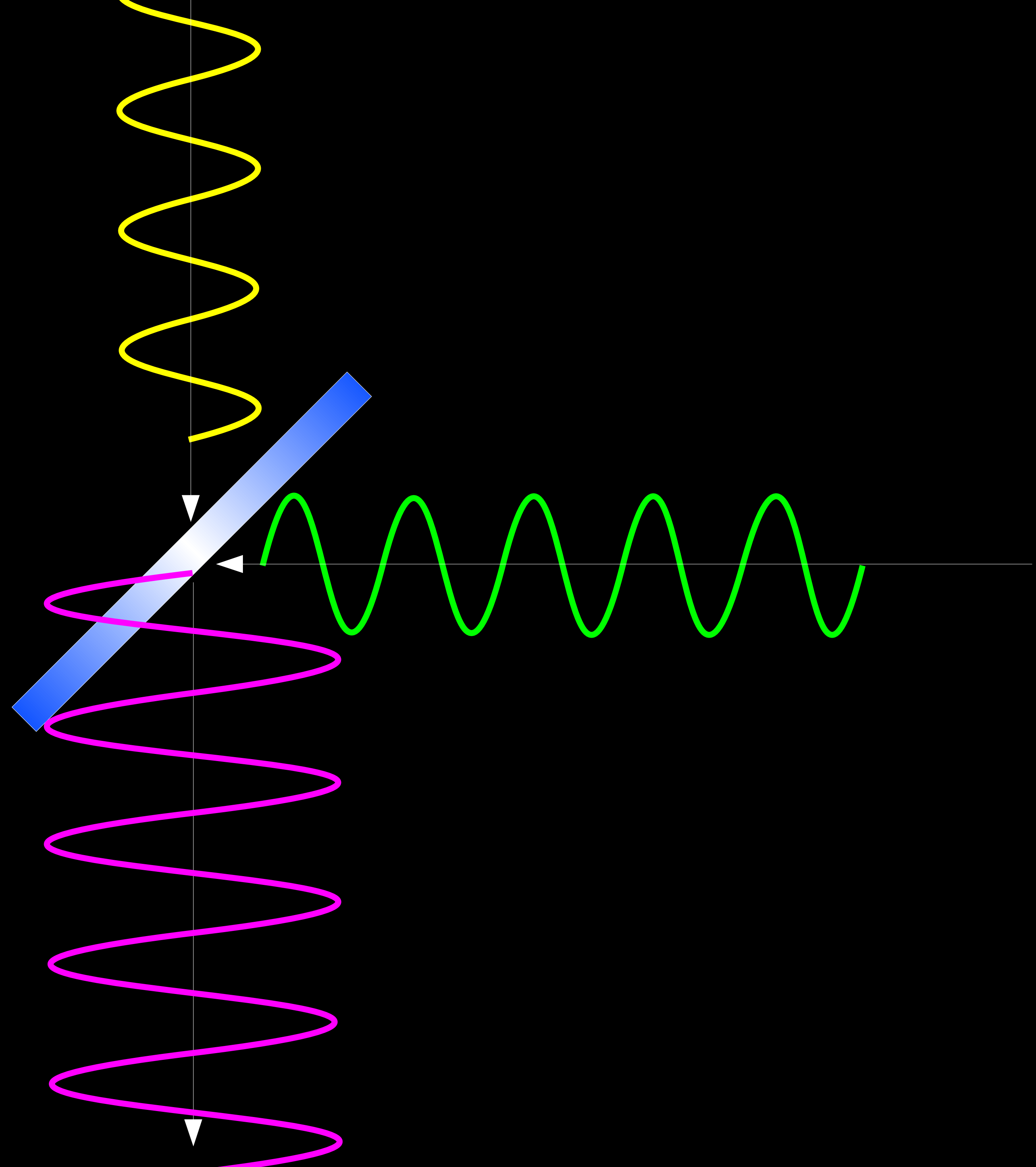




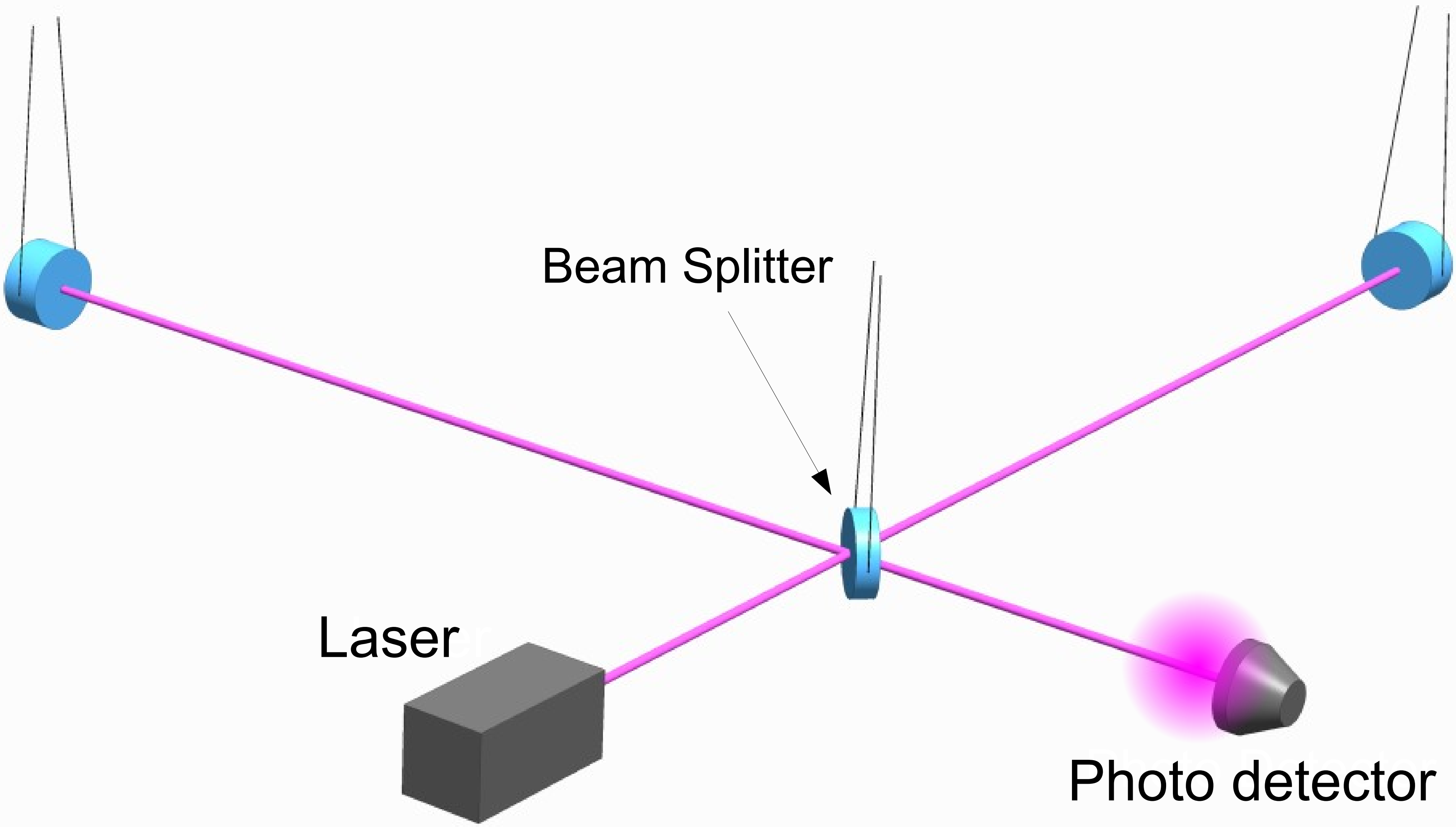








Michelson Interferometer



スカラー場

$$E(t) = E_0 e^{i(\Omega t + \phi)}$$

物理的に意味を持つのは実部

自由空間伝播演算子

$$P_{\mathrm{free}}(x) = e^{-ikx}$$

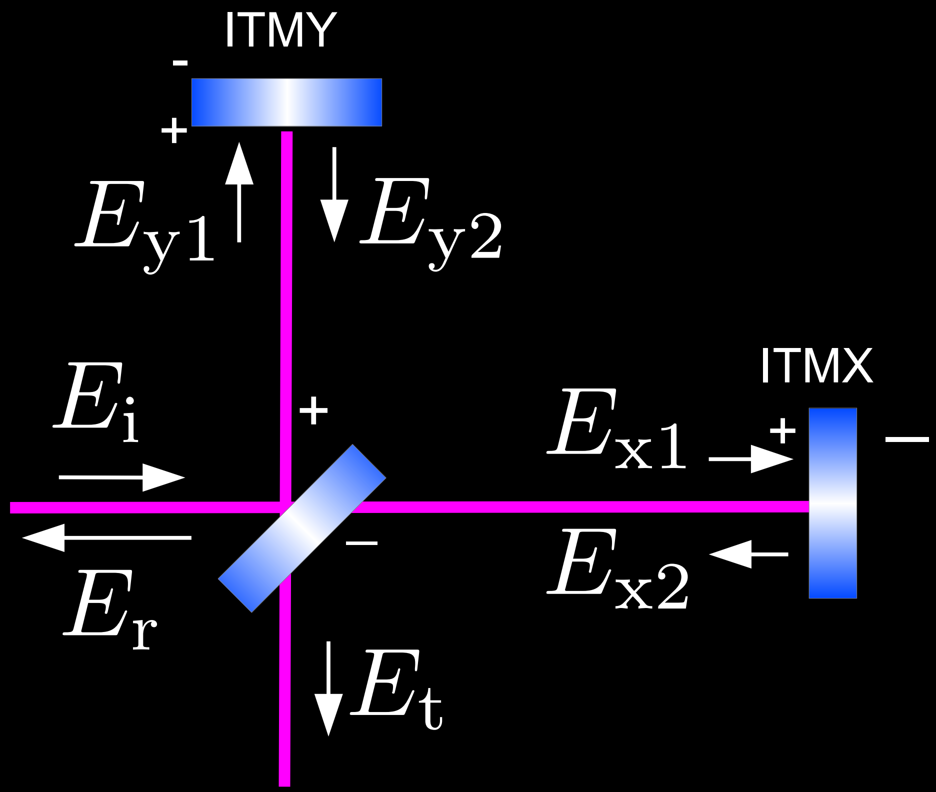
$$P_{\mathrm{free}}(x) \cdot E(t) = E_0 e^{i(\Omega t - kx + \phi)}$$

鏡による反射

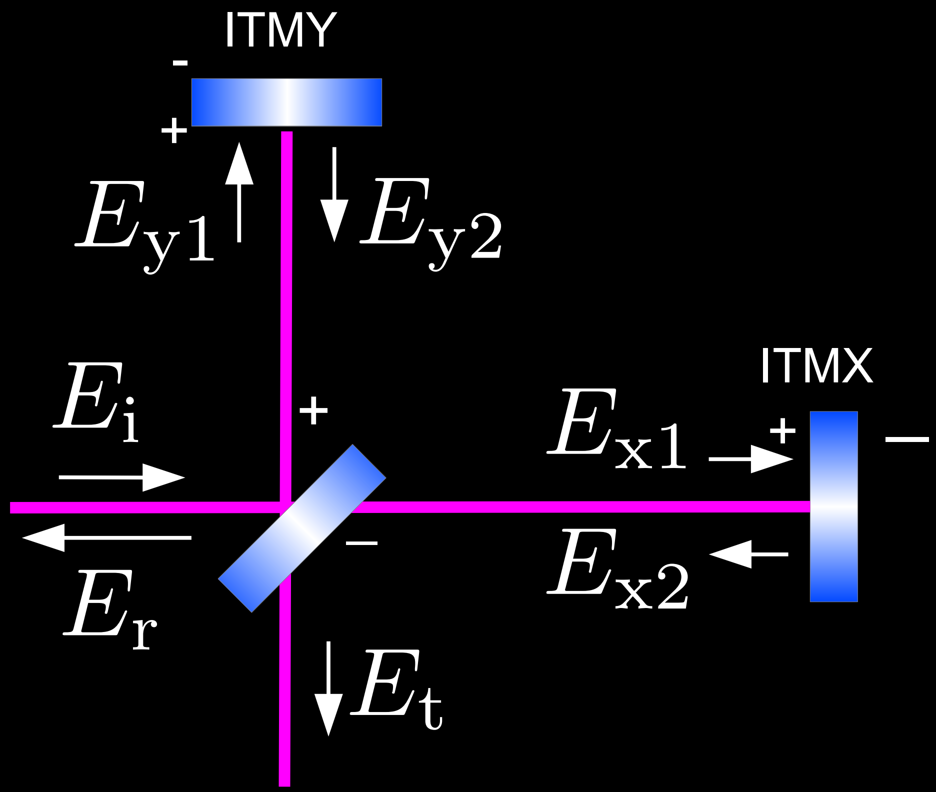
$$R_{\mathrm{mirror}} = r$$

$$R_{\mathrm{mirror}} \cdot E(t) = rE_0 e^{i(\Omega+\phi)}$$

Michelson干渉計

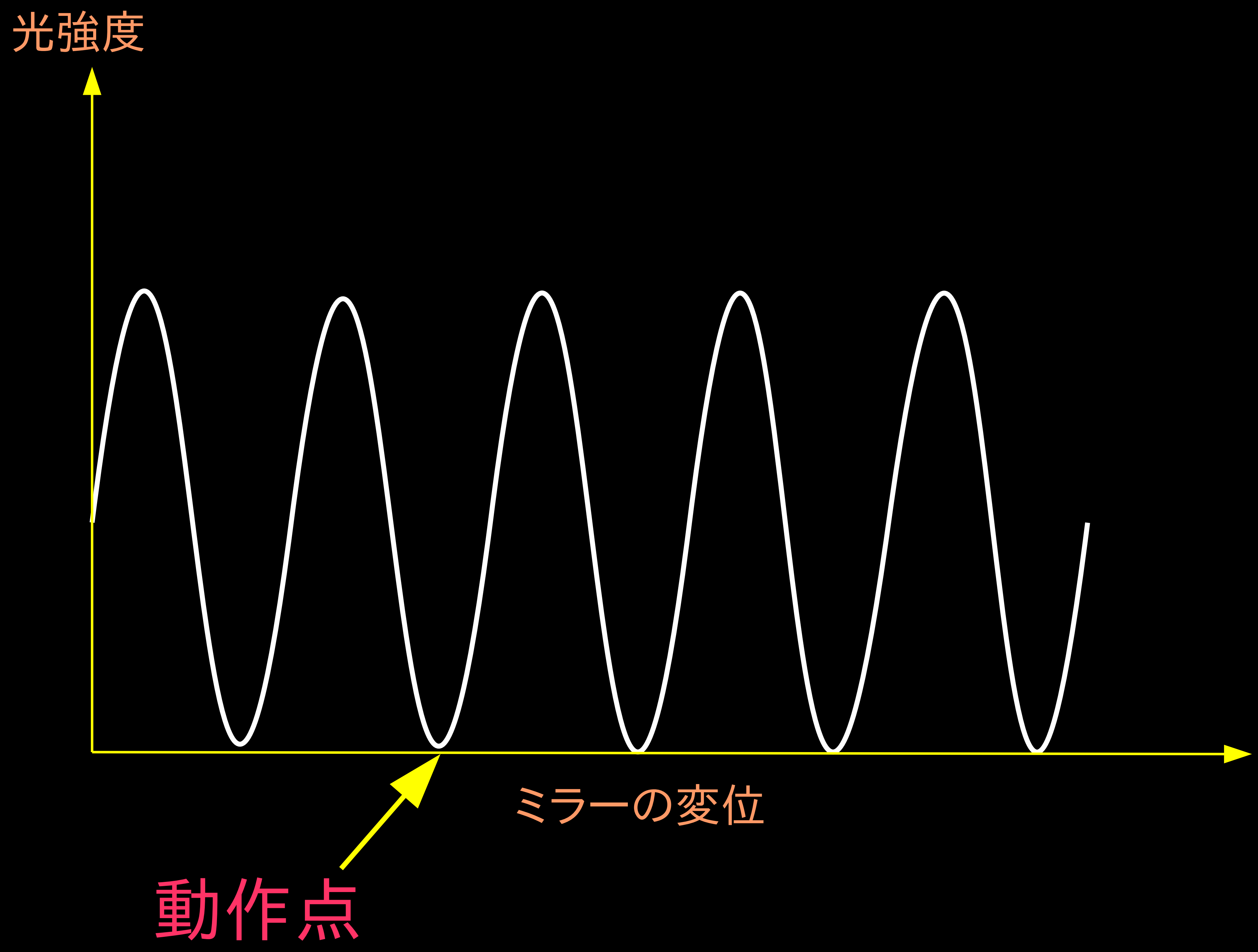


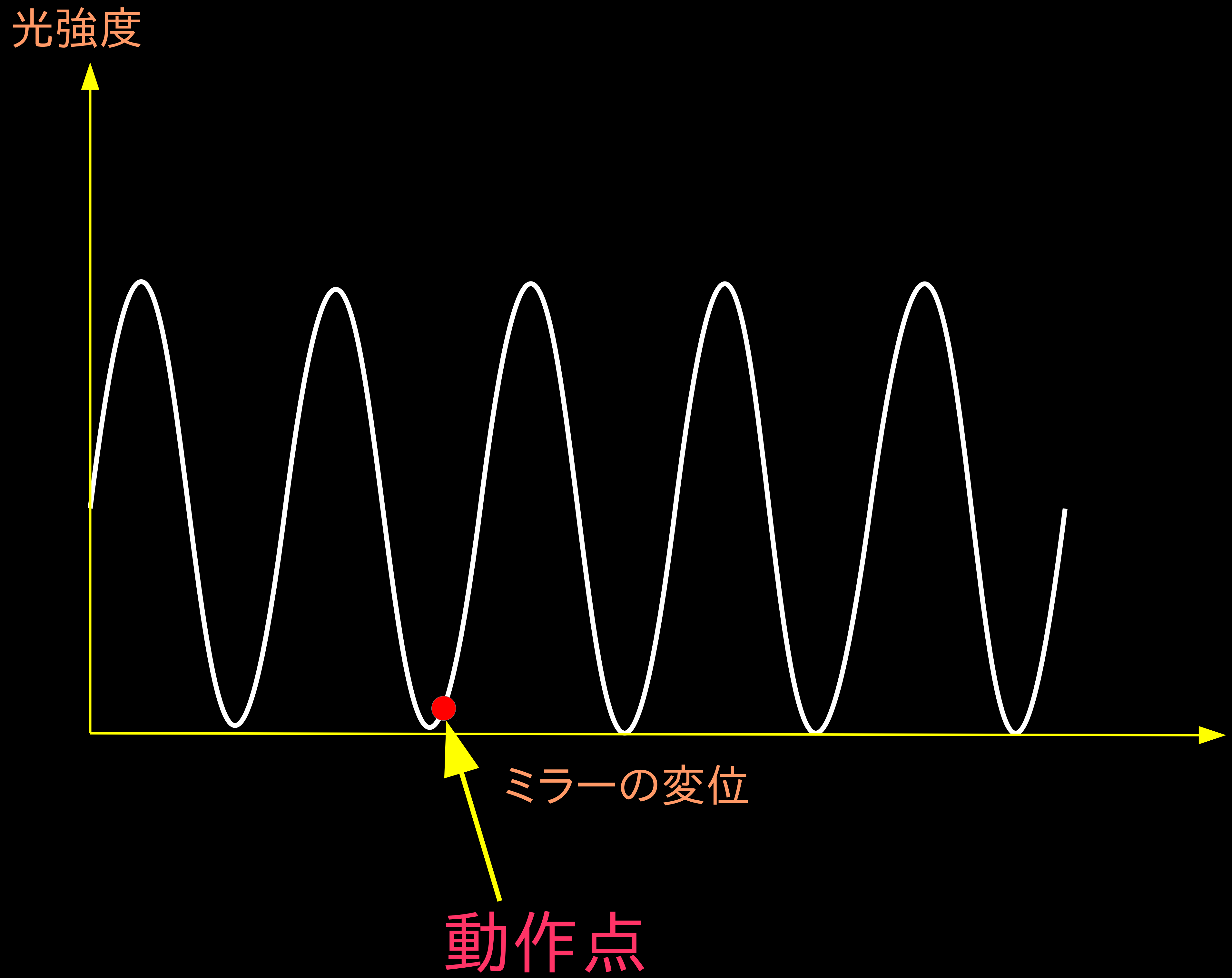
Michelson干渉計

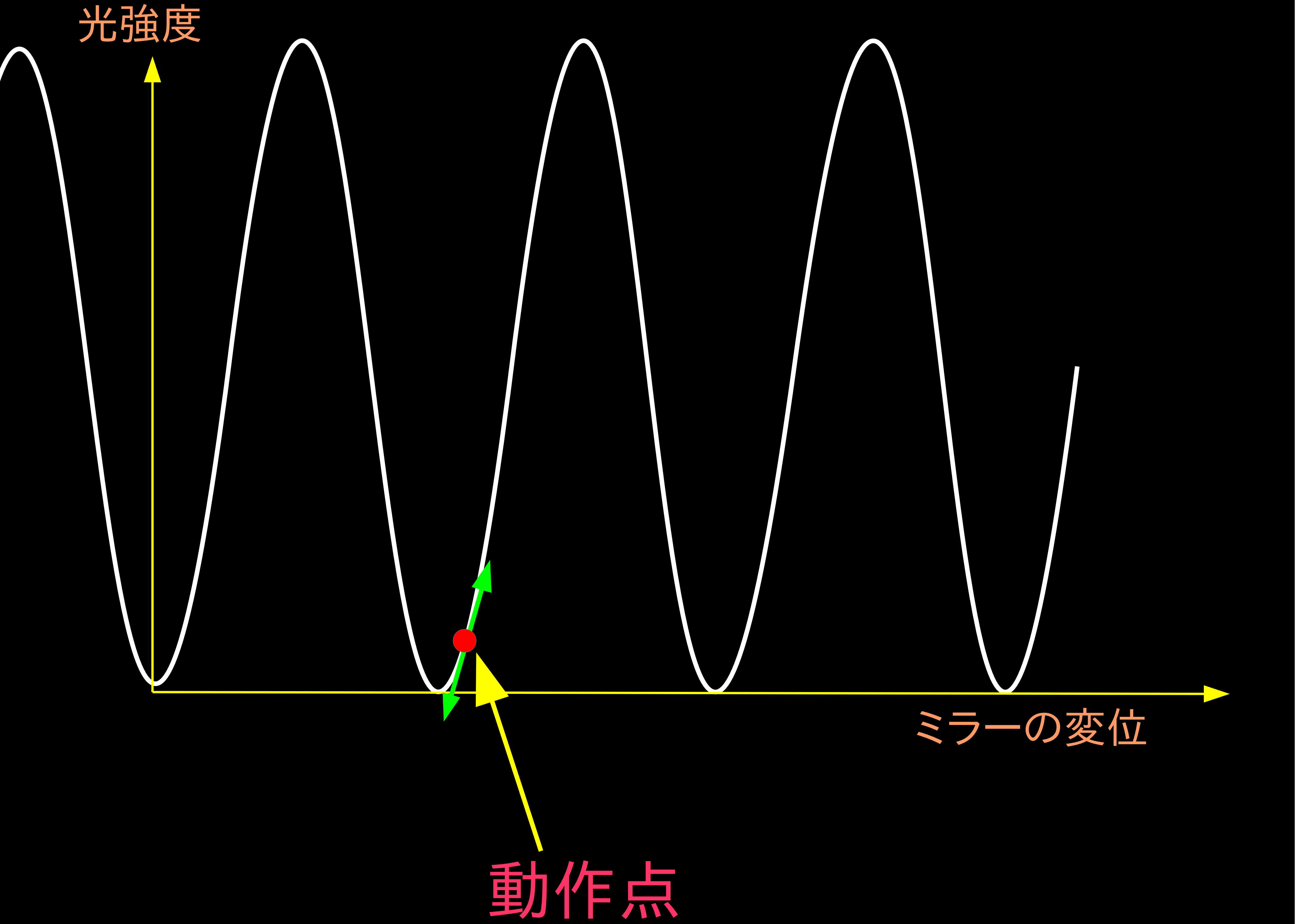


$$E_{\mathrm{x1}} = e^{-ikl_{\mathrm{x}}} E_{\mathrm{i}}/\sqrt{2}$$

$$E_{\mathrm{t}} = e^{-ikl_{\mathrm{y}}} E_{\mathrm{y2}}/\sqrt{2} - e^{-ikl_{\mathrm{x}}} E_{\mathrm{x2}}/\sqrt{2}$$


光強度
ミラーの変位
動作点


光強度
ミラーの変位
動作点



光強度
ミラーの変位
動作点

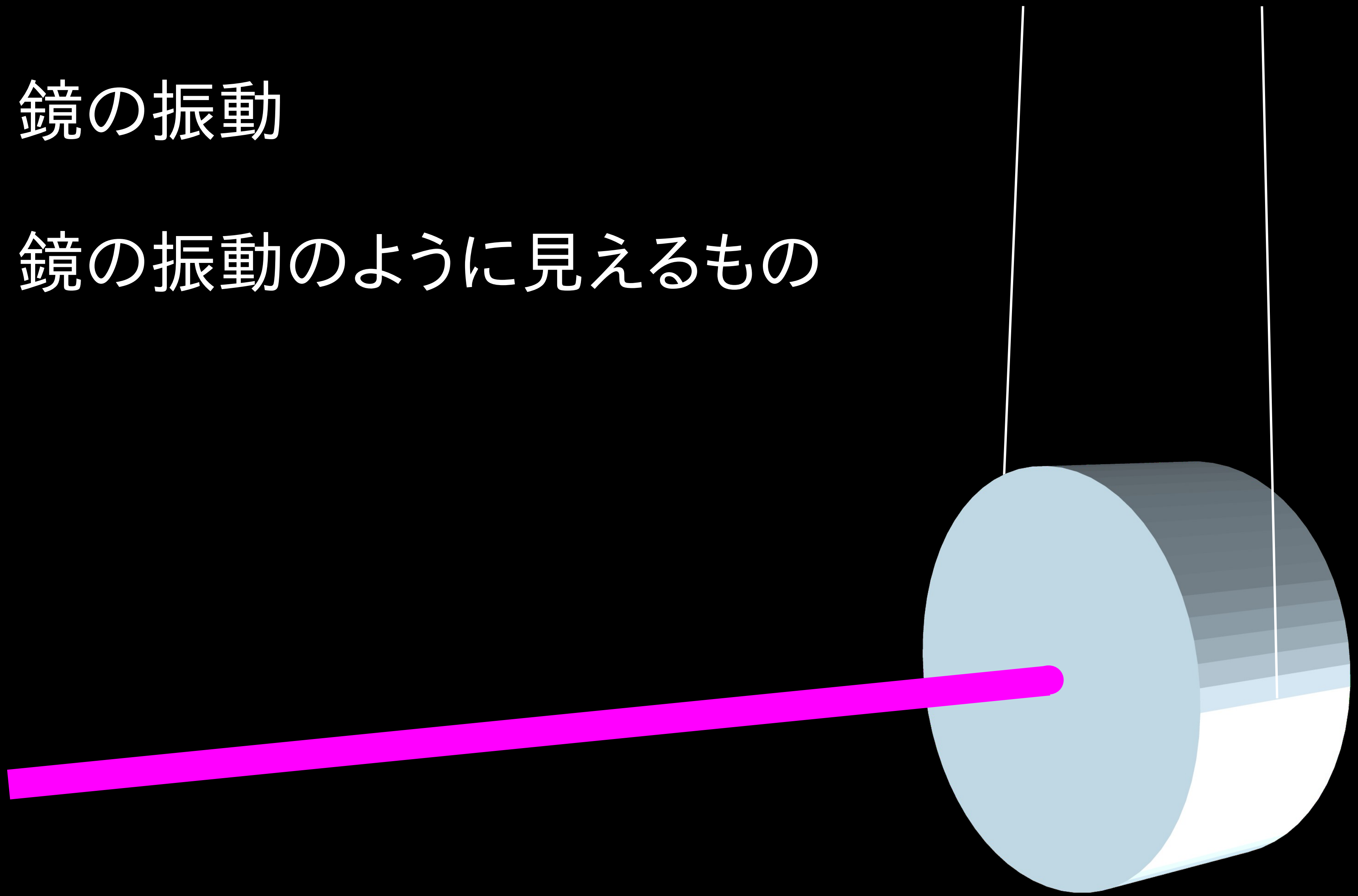
この検出器でどこまで遠くが観測できるのか?

信号 > 雑音

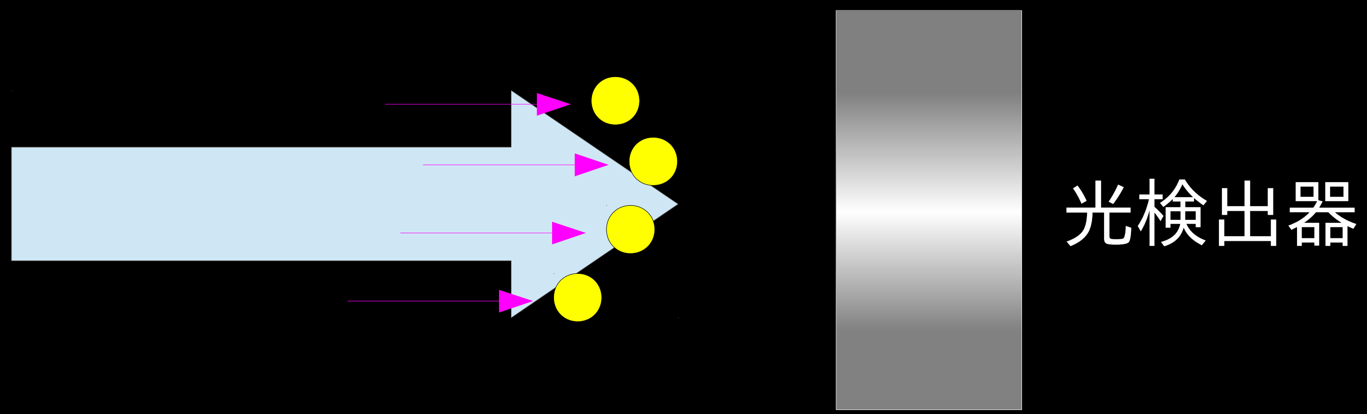
雑音とは何か?

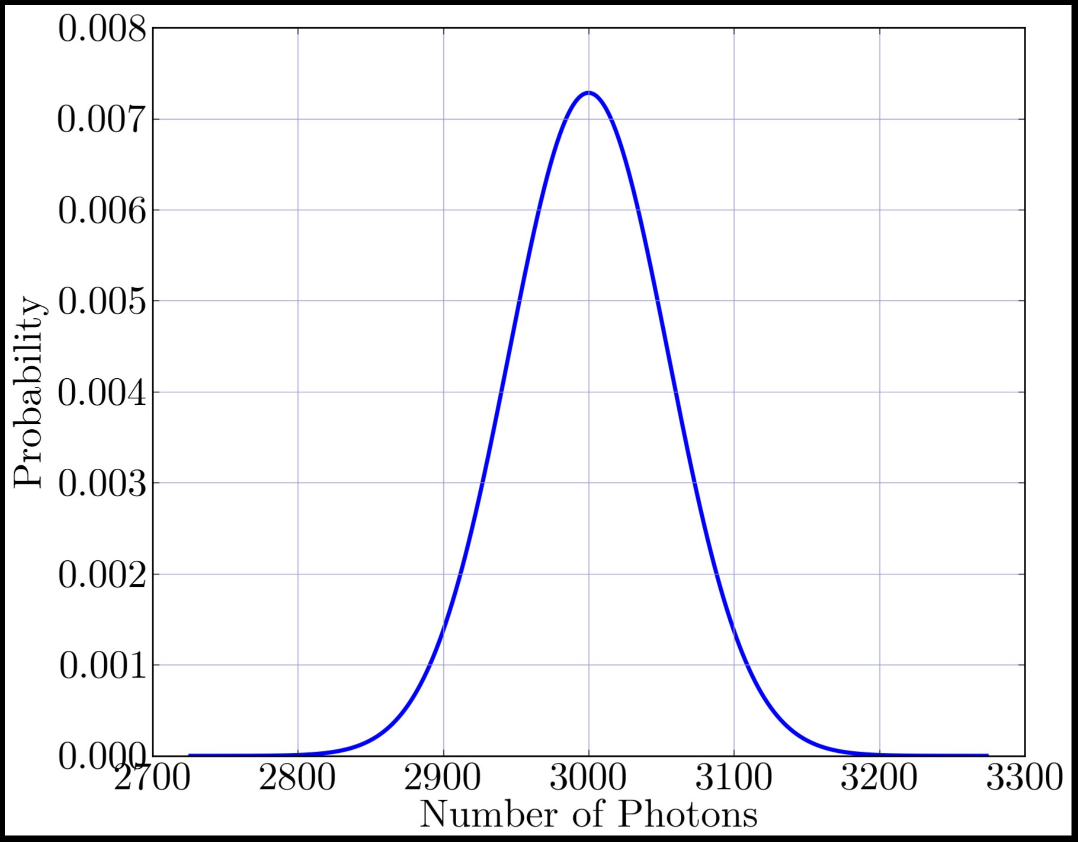
(1) 鏡の振動

(2) 鏡の振動のように見えるもの



ショットノイズ


光検出器

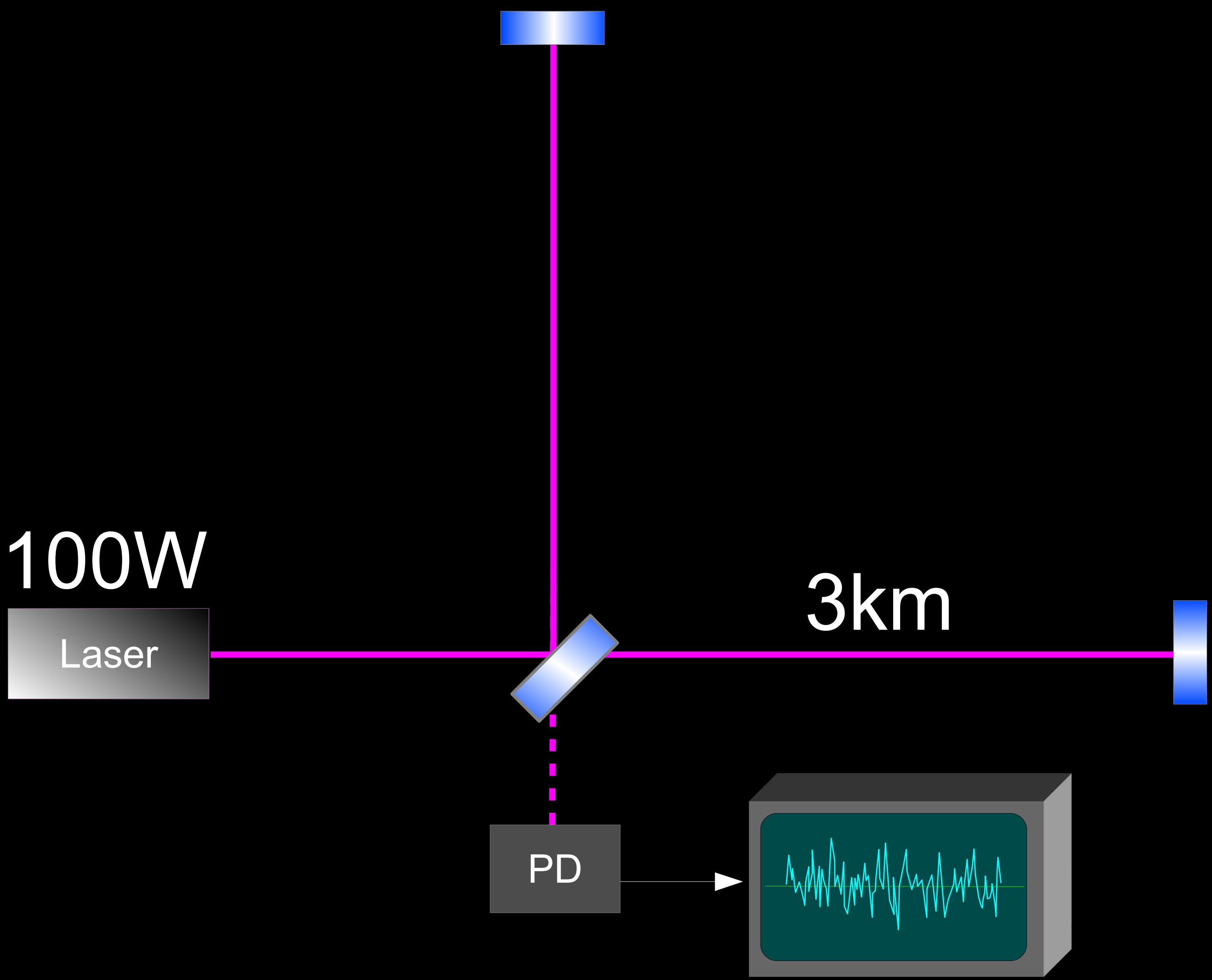

Probability
Number of Photons
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
2700
2800
2900
3000
3100
3200
3300

$$\text{信号} \propto P$$

$$\text{雑音} \propto \sqrt{P}$$

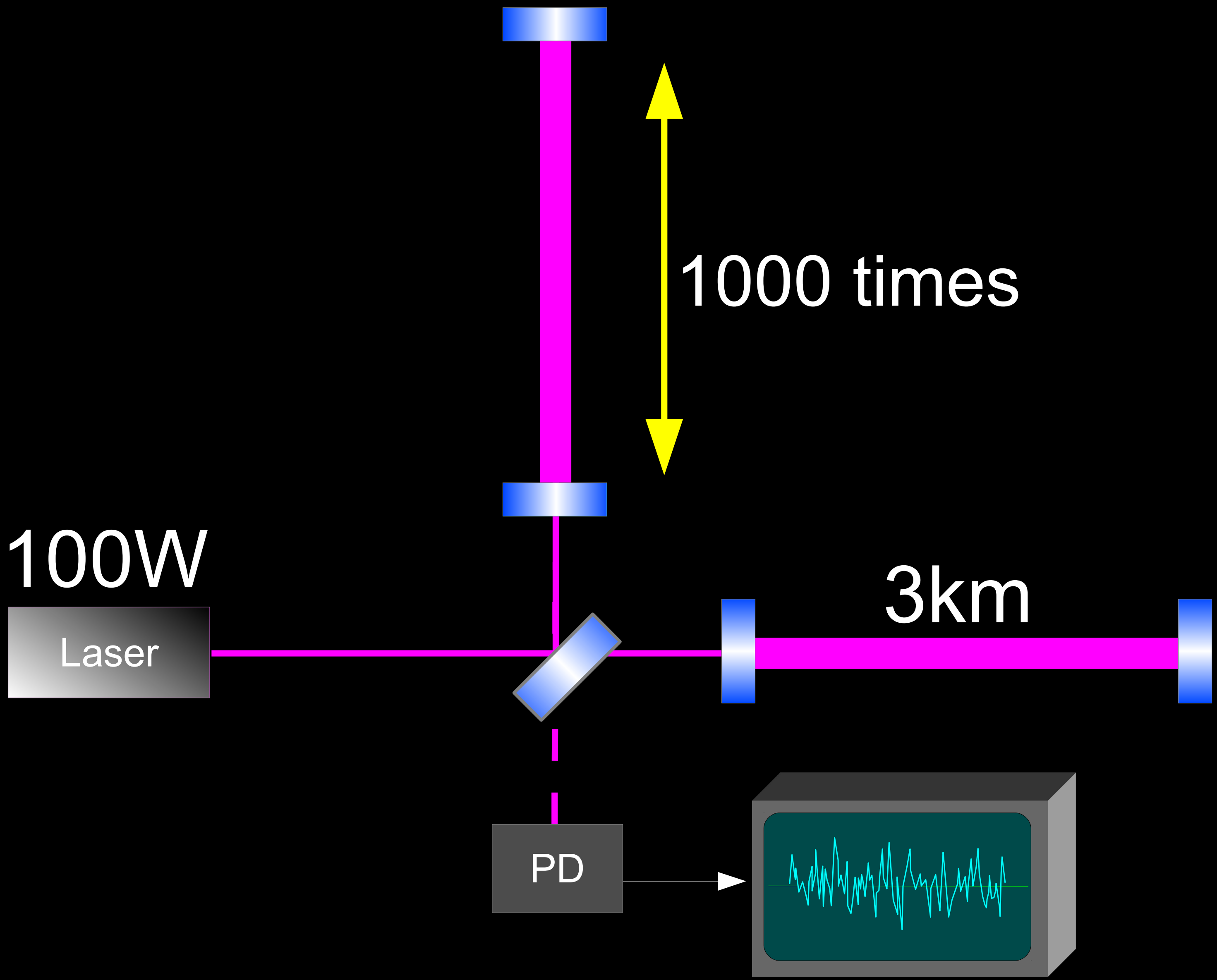
$$\frac{\text{信号}}{\text{雑音}} \propto \sqrt{P}$$

Michelson Interferometer



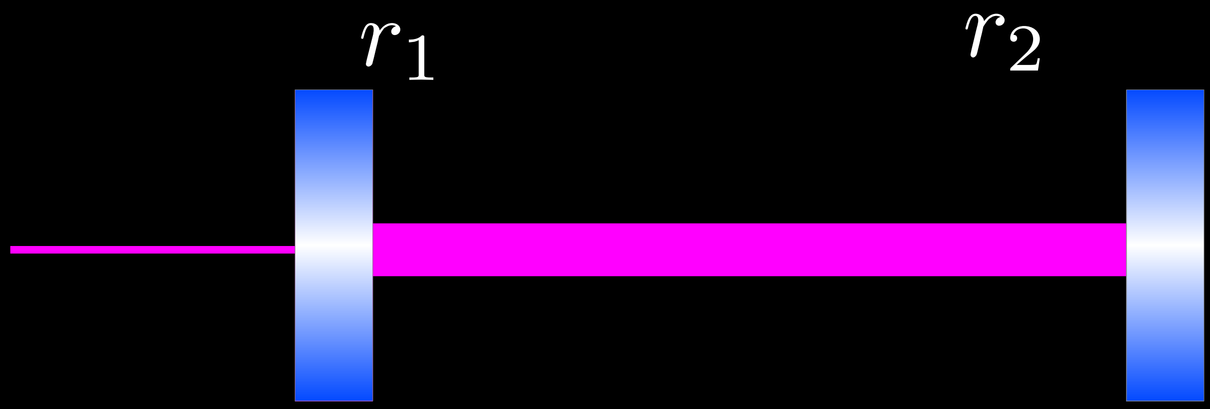
$$h = 2 \times 10^{-21}$$

Fabry-Perot Michelson

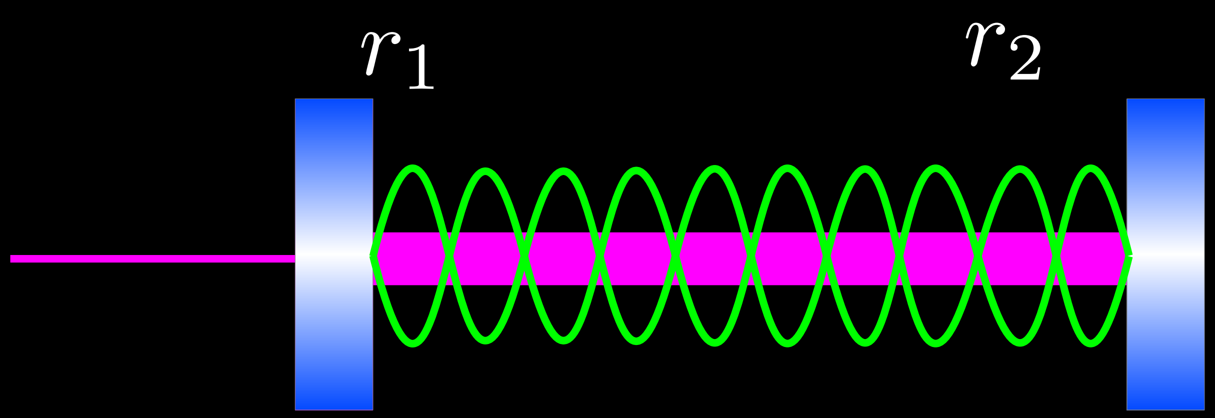


$$h = 2 \times 10^{-24}$$

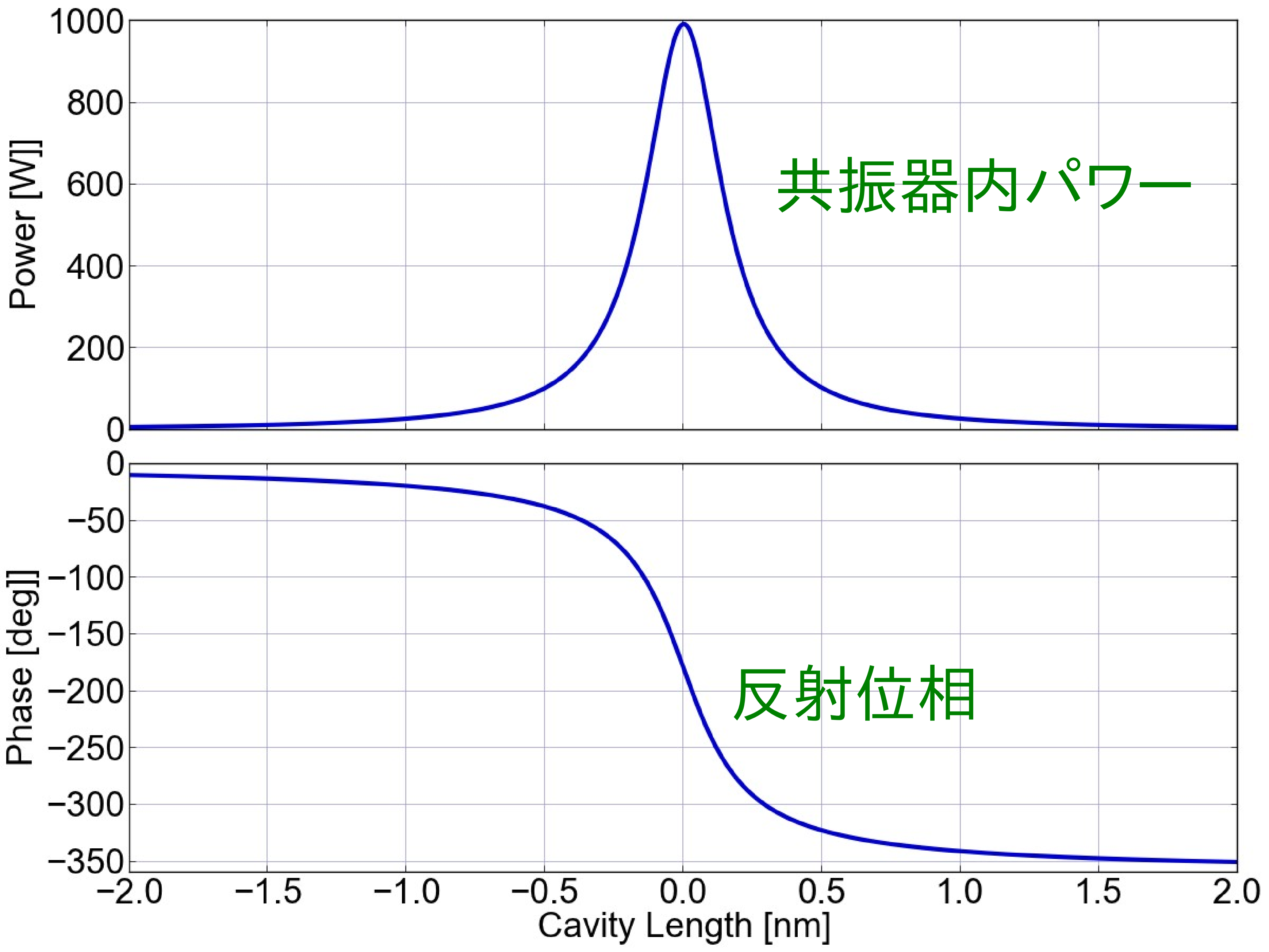
Fabry-Perot Cavity



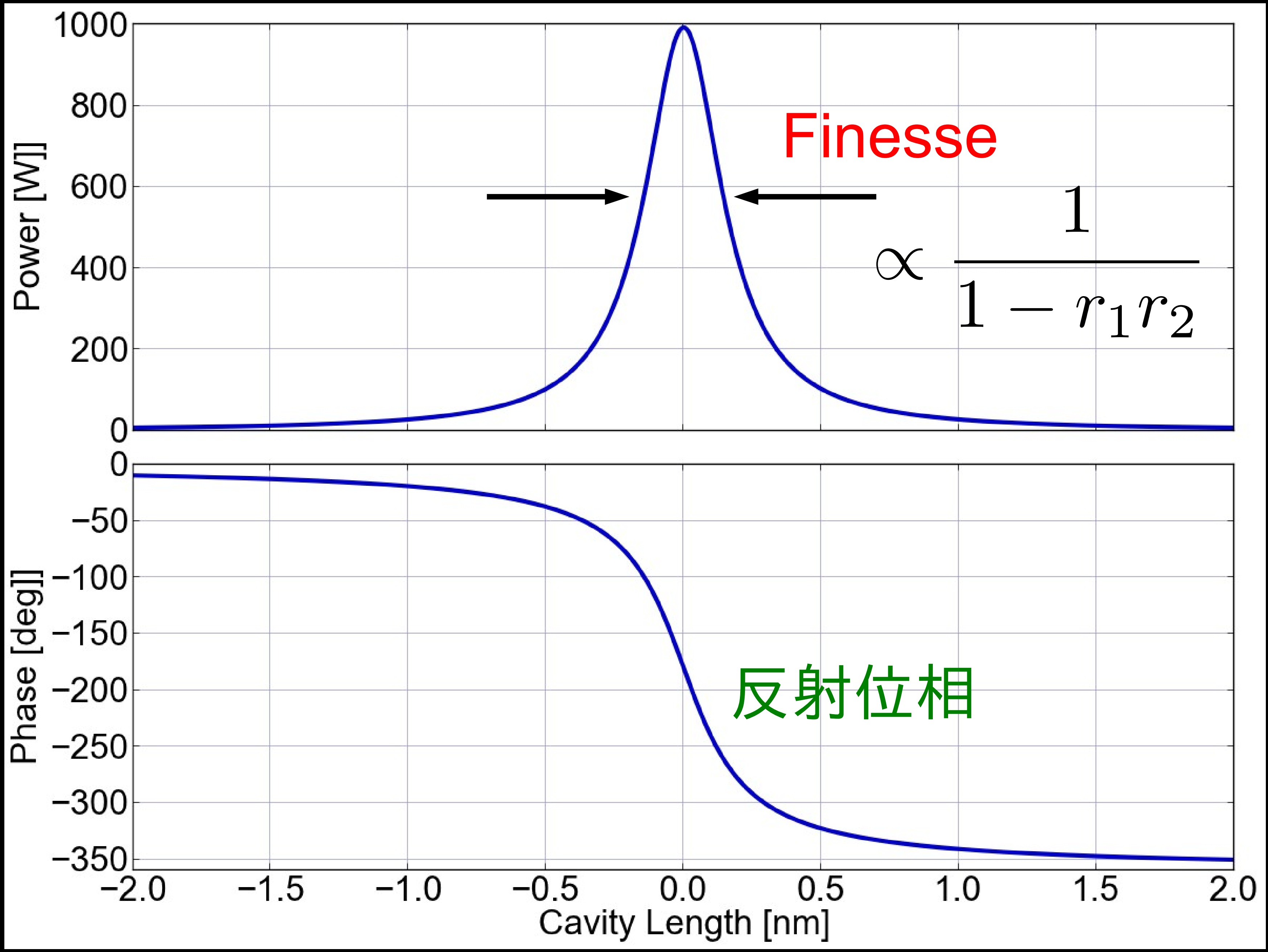
Fabry-Perot Cavity



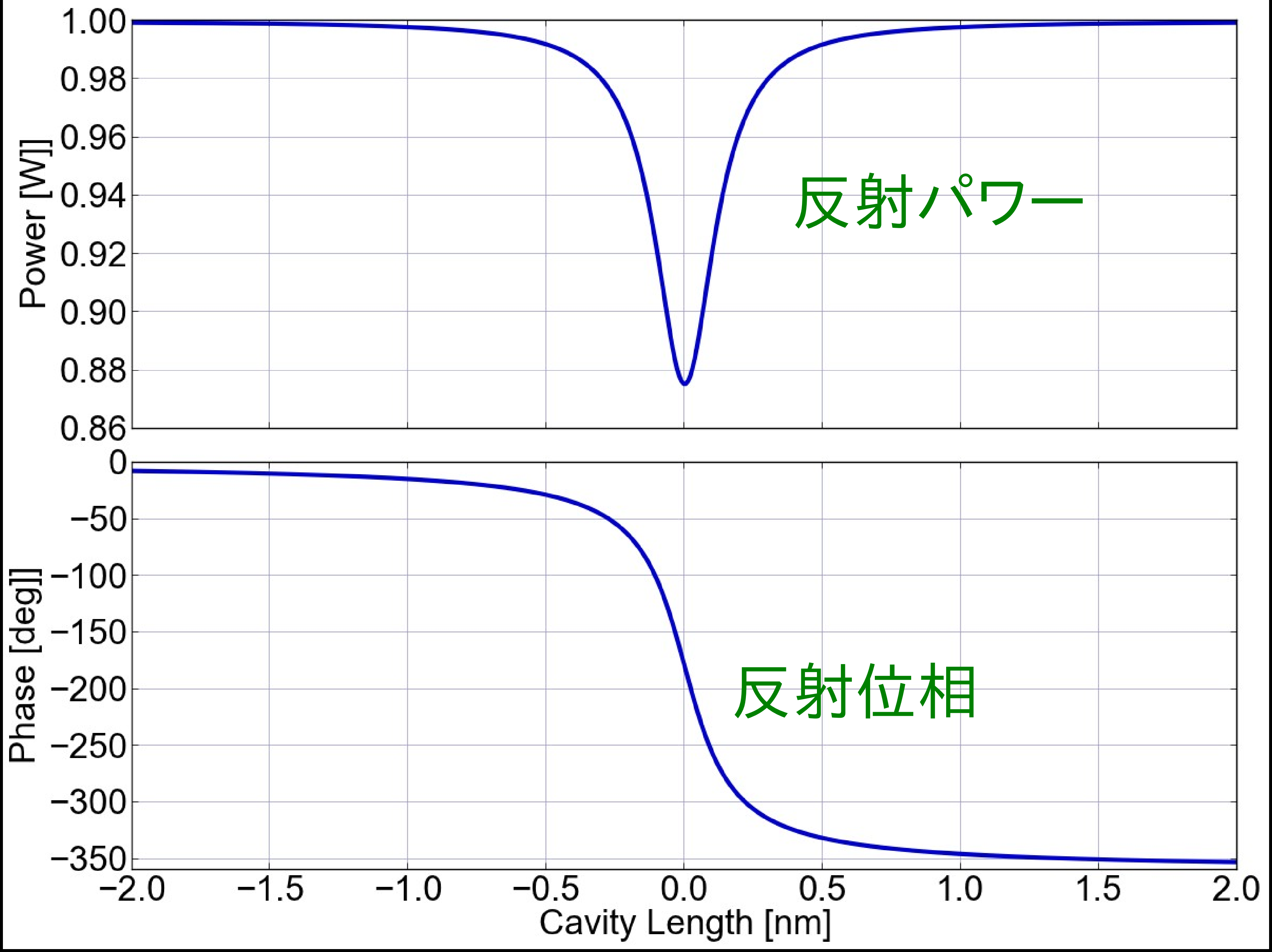
$r_1 < r_2$ Over Coupled



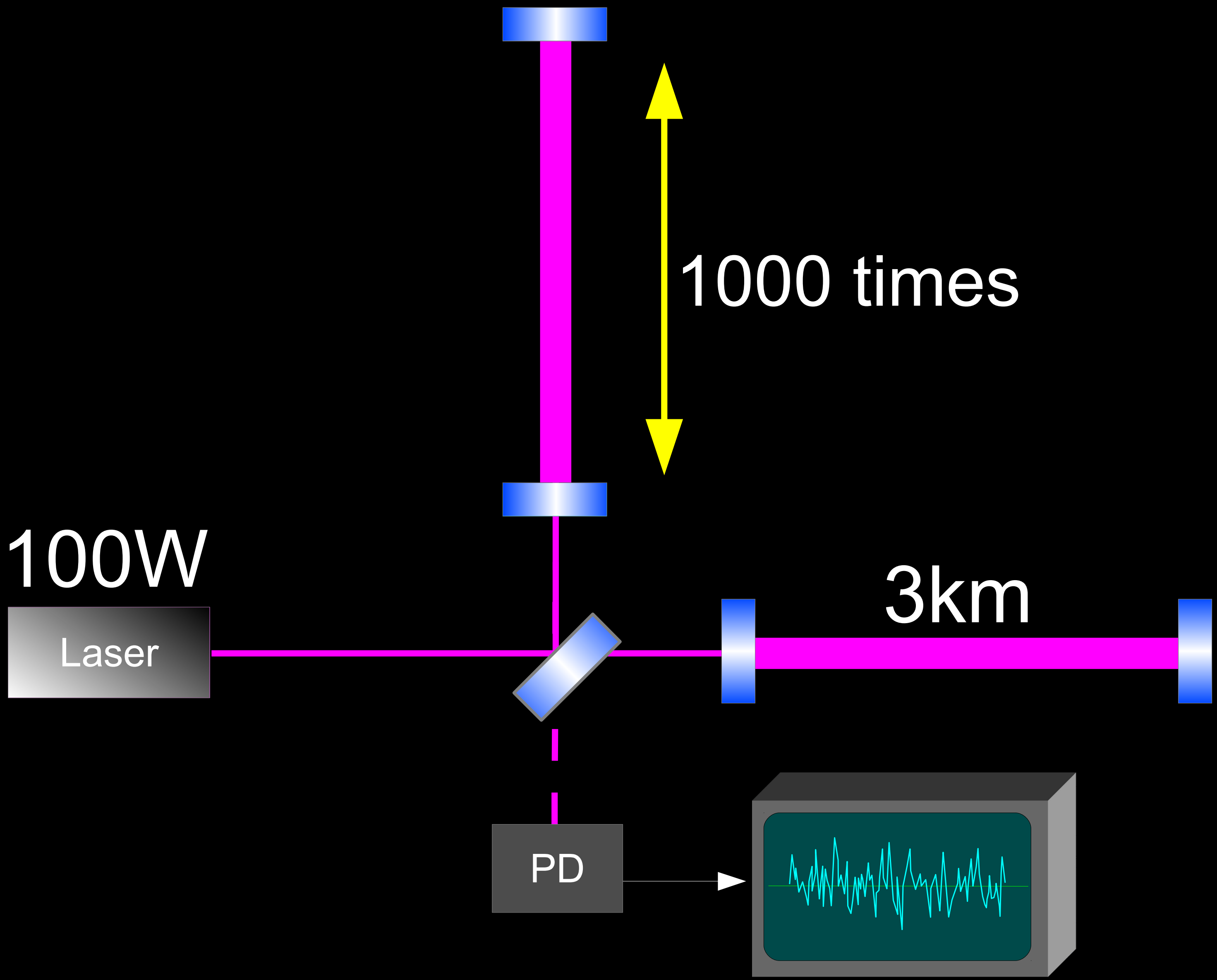
$r_1 < r_2$ Over Coupled



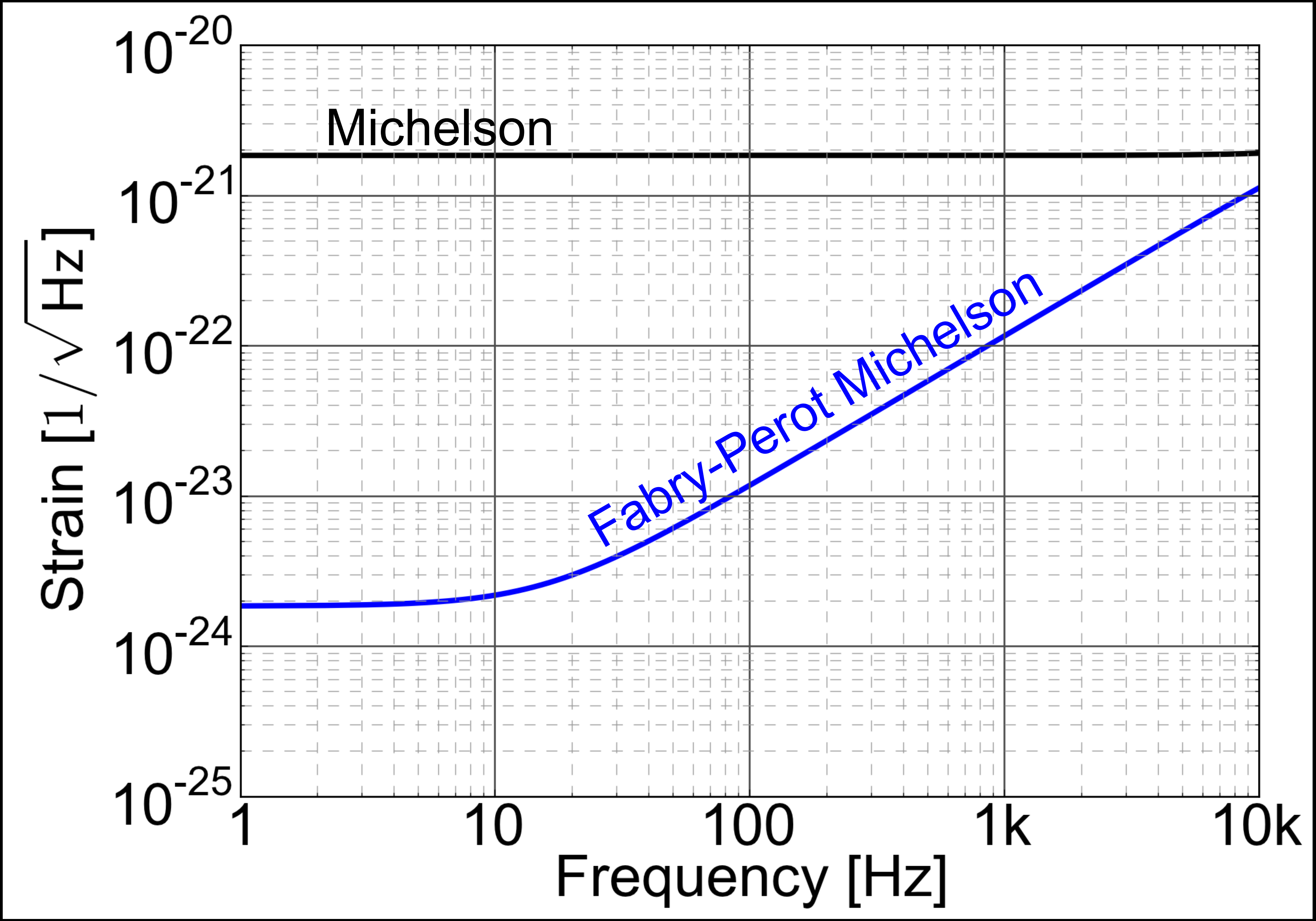
$r_1 < r_2$ Over Coupled

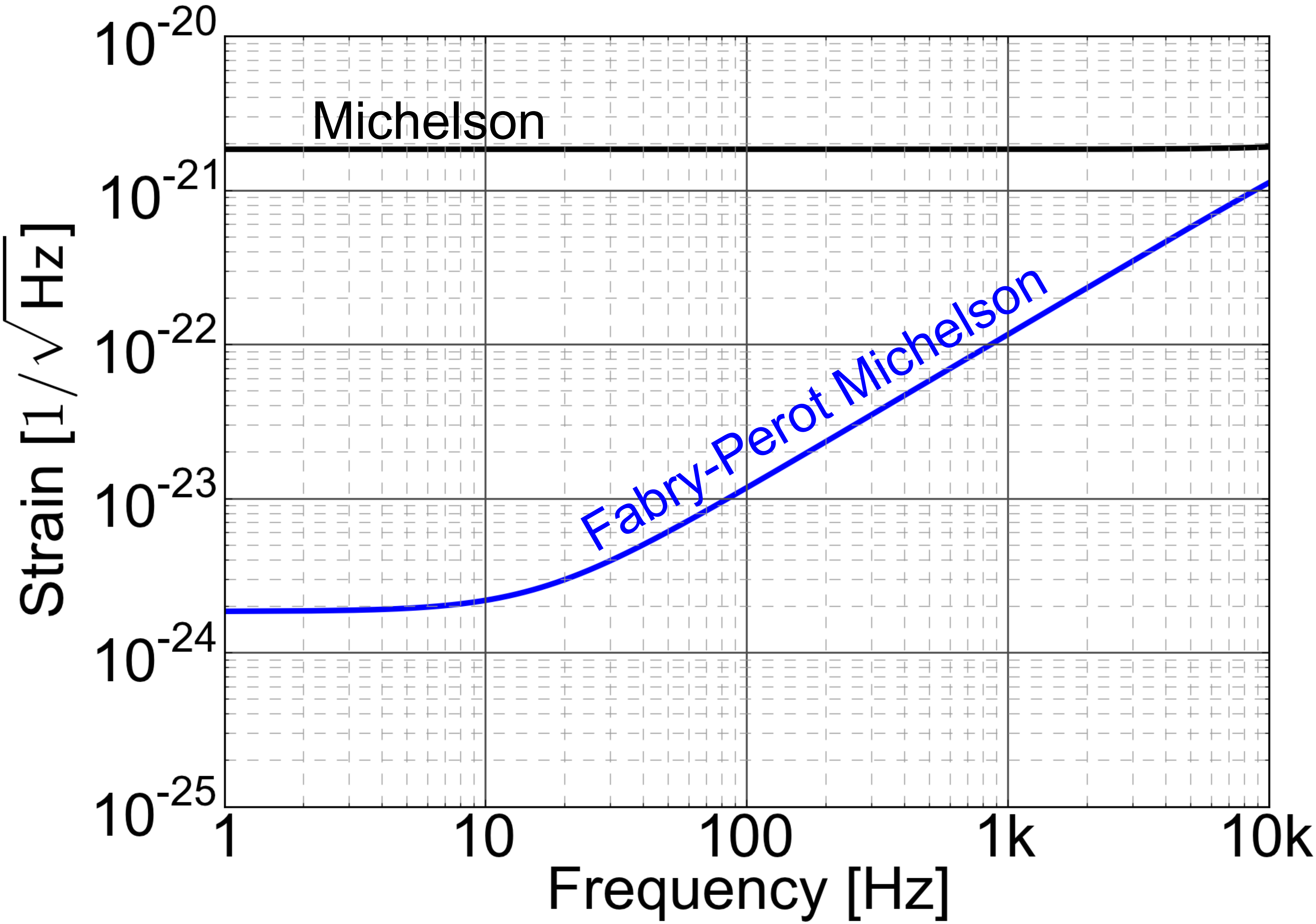


Fabry-Perot Michelson



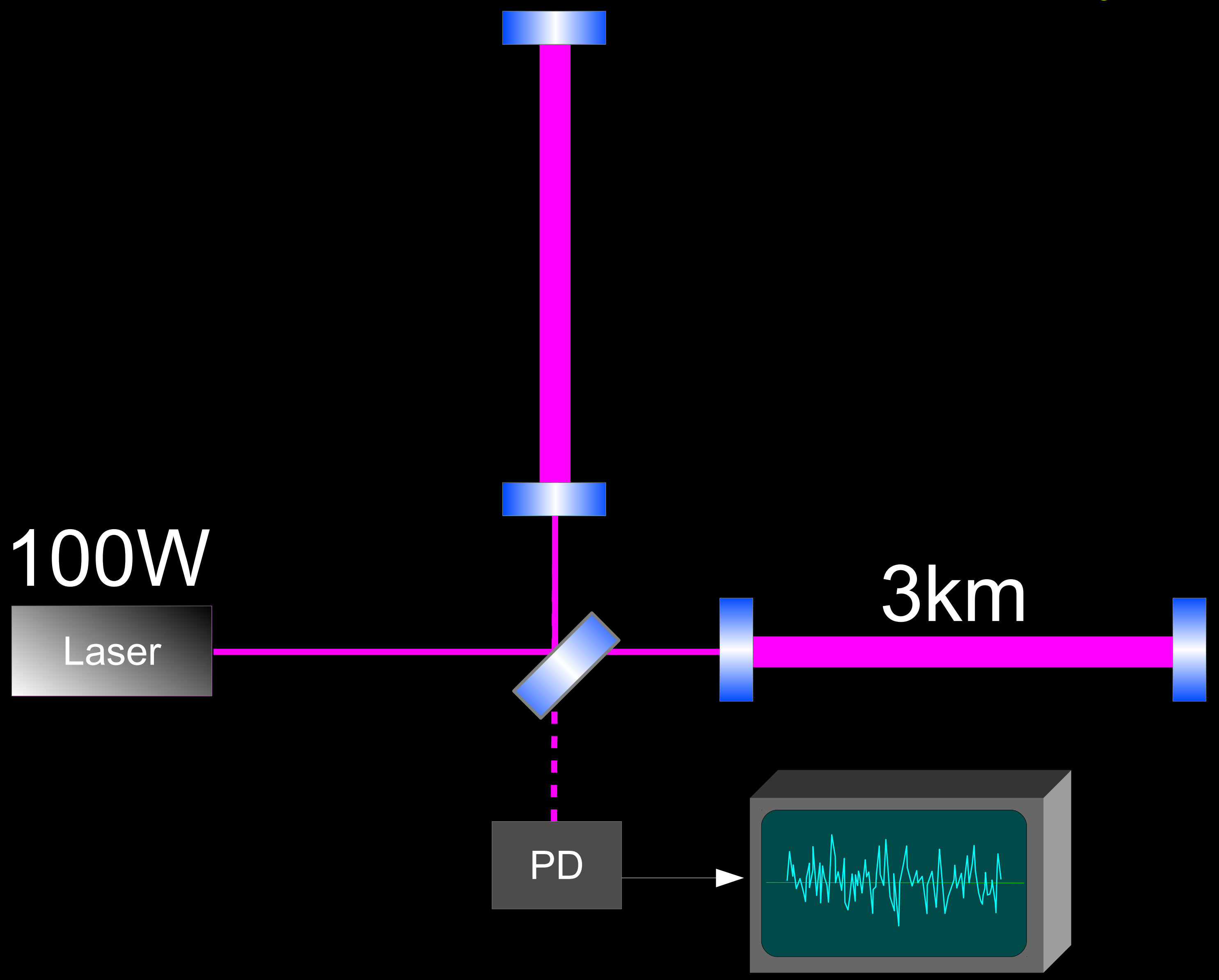
$$h = 2 \times 10^{-24}$$


Michelson
Fabry-Perot Michelson
Strain [1/√Hz]
10^-20
10^-21
10^-22
10^-23
10^-24
10^-25
1
10
100
1k
10k
Frequency [Hz]

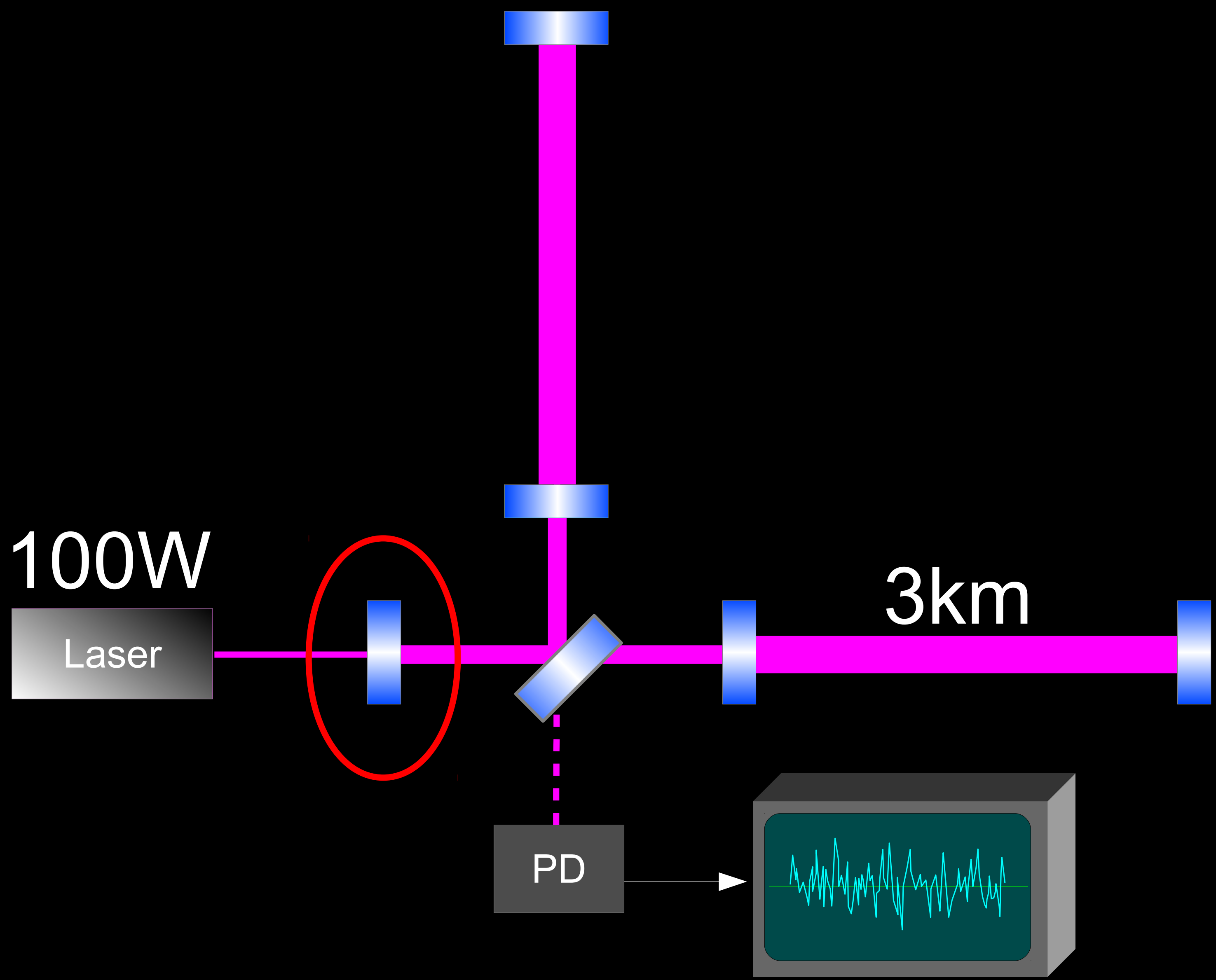


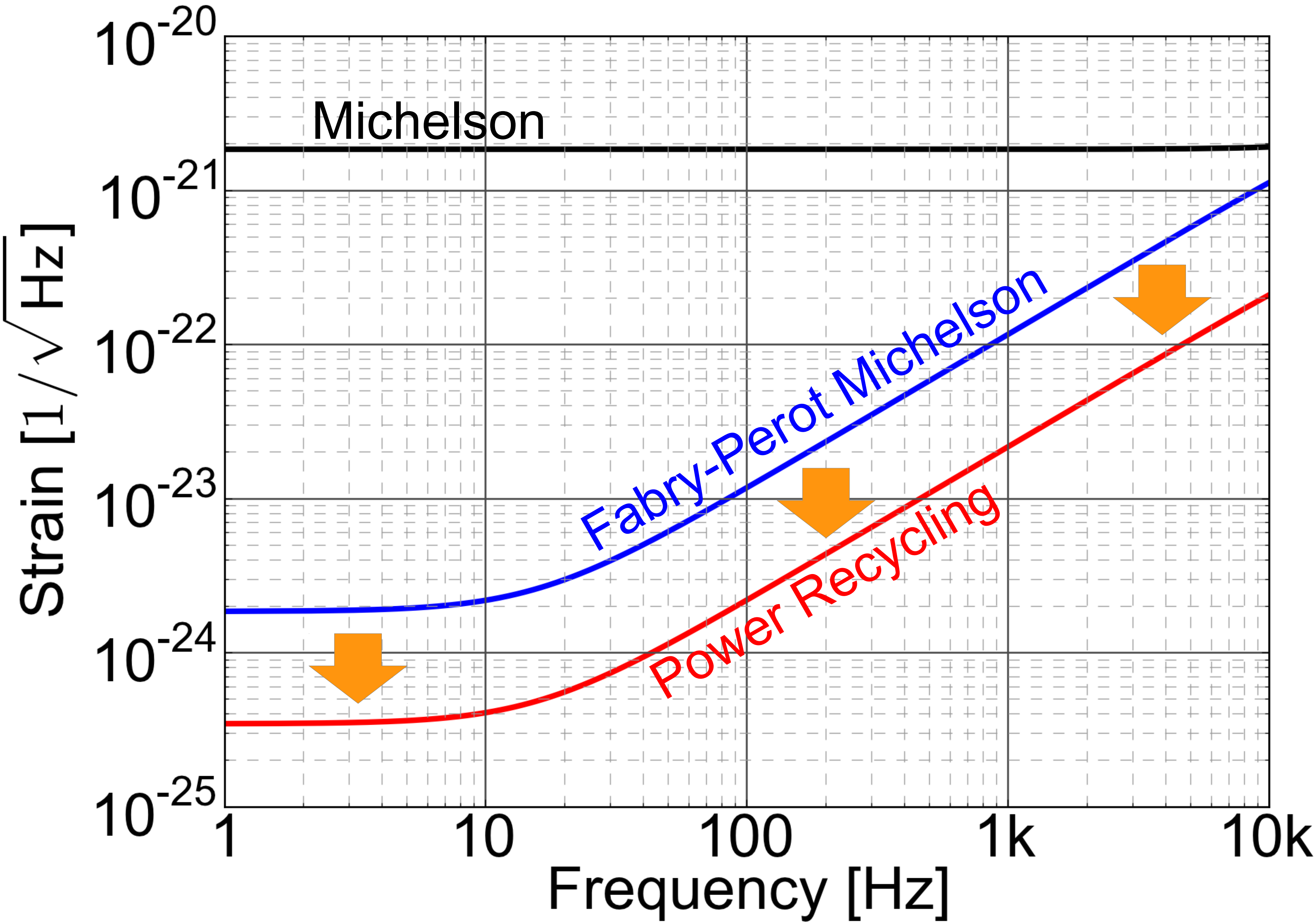
Michelson
Fabry-Perot Michelson
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
1
10
100
1k
10k
Frequency [Hz]
Strain [$1/\sqrt{\mathrm{Hz}}$]

Fabry-Perot Michelson



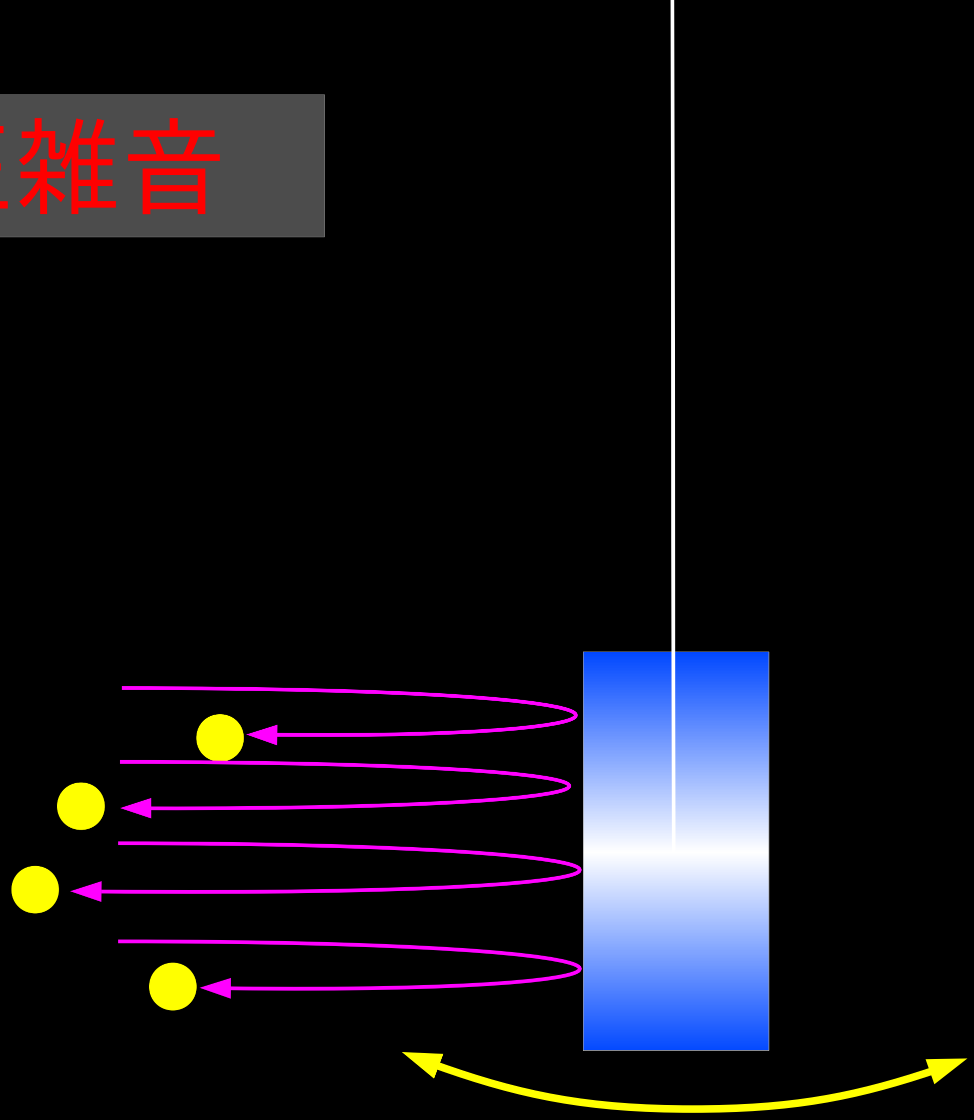
Power Recycling





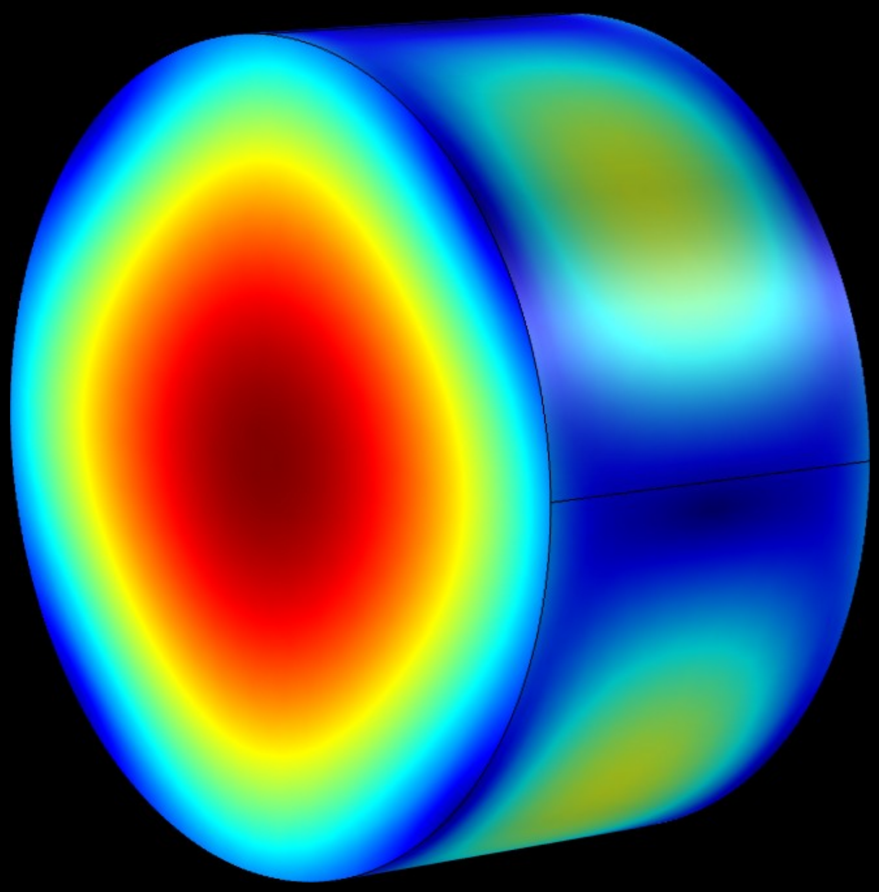
Michelson
Fabry-Perot Michelson
Power Recycling
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
Strain [$1/\sqrt{\mathrm{Hz}}$]
1
10
100
1k
10k
Frequency [Hz]

量子輻射圧雑音

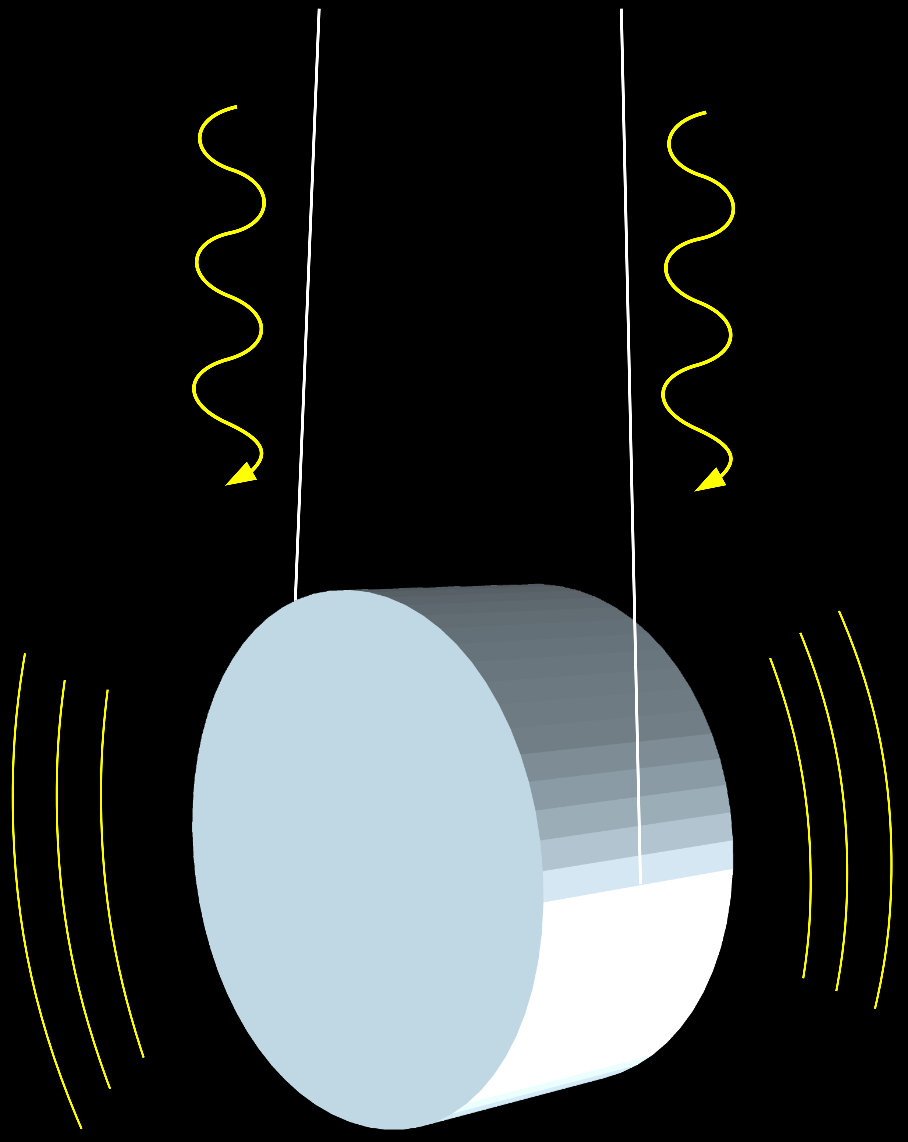


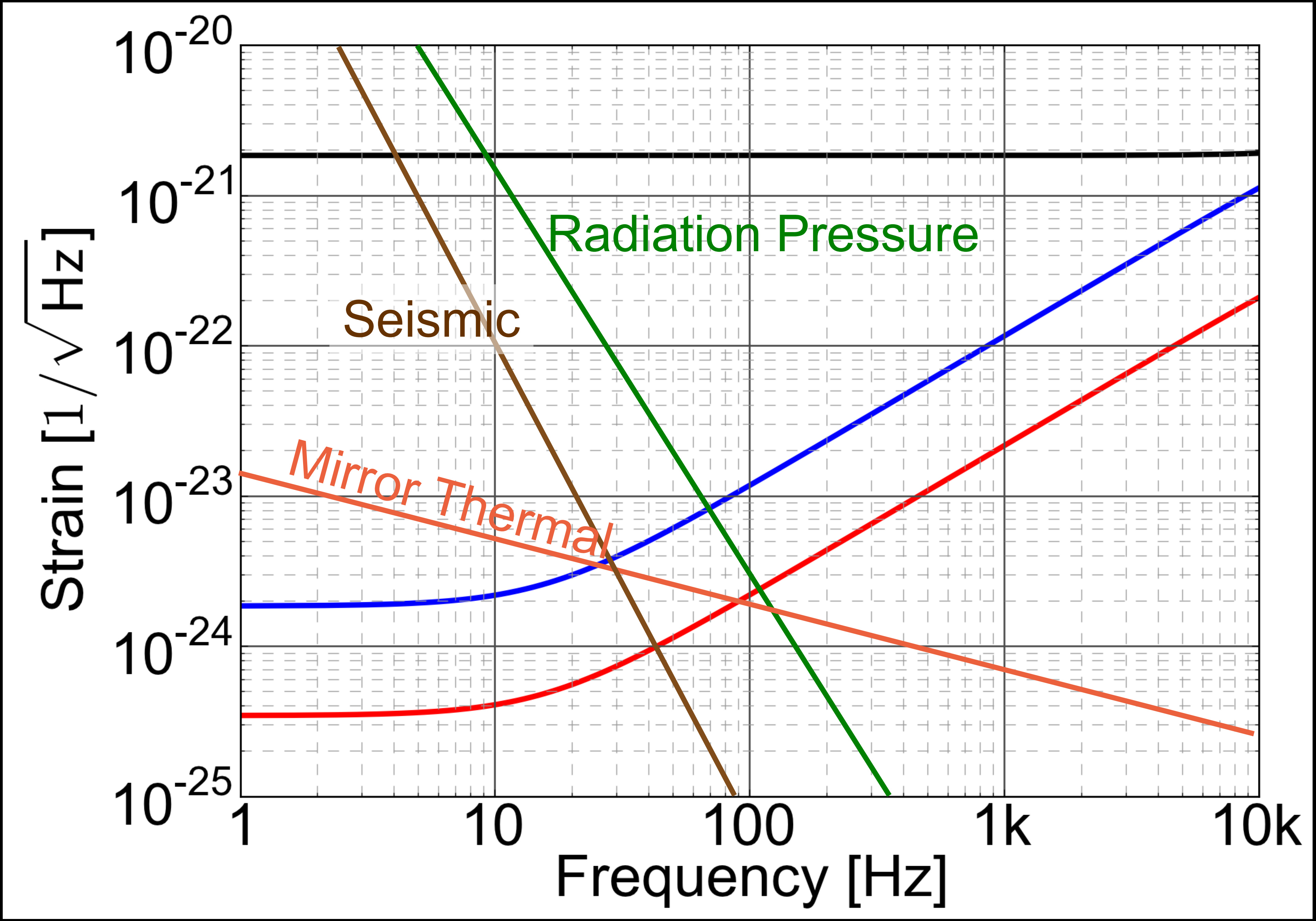
$$\propto \sqrt{P}$$

熱雑音

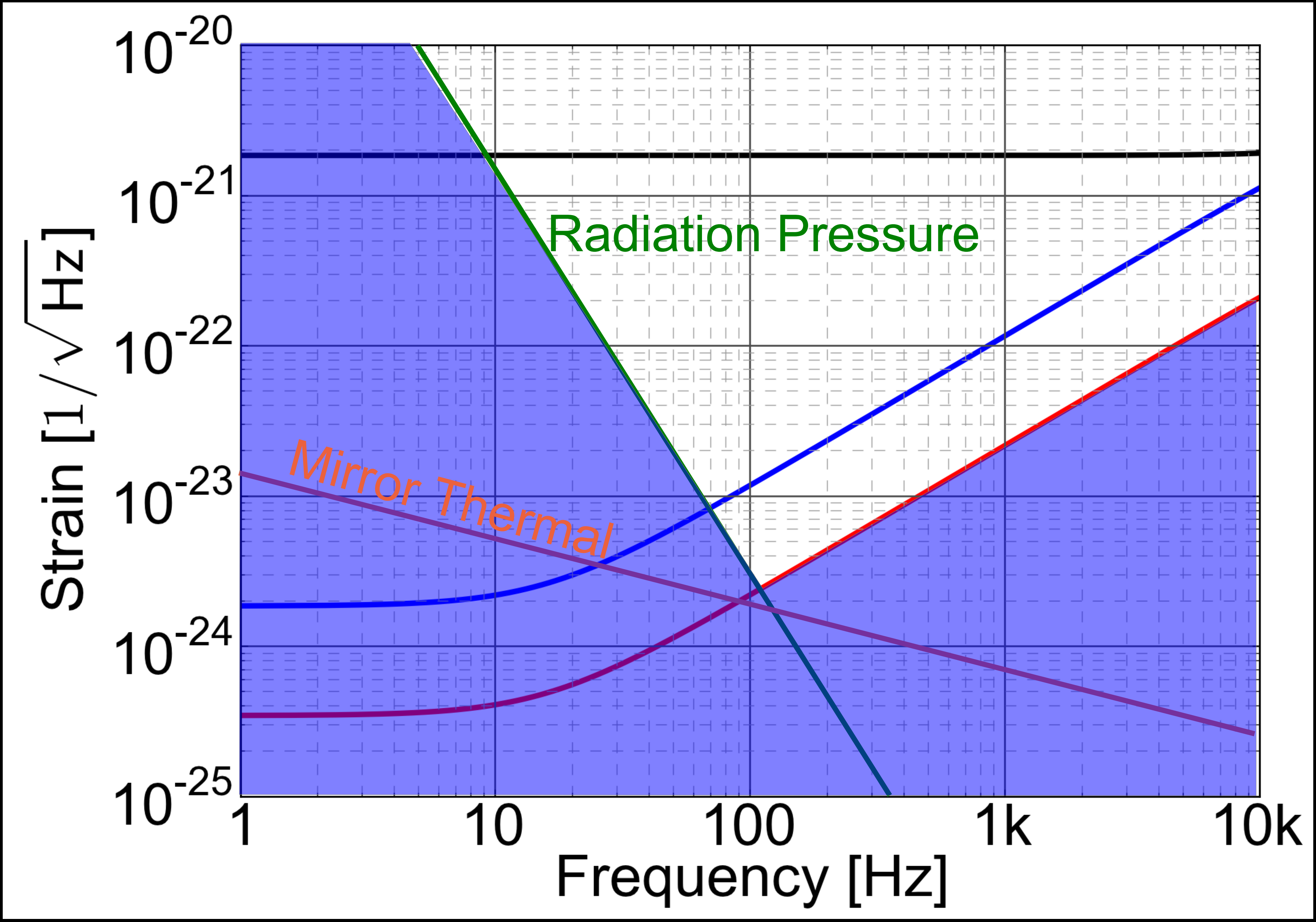


地面振動

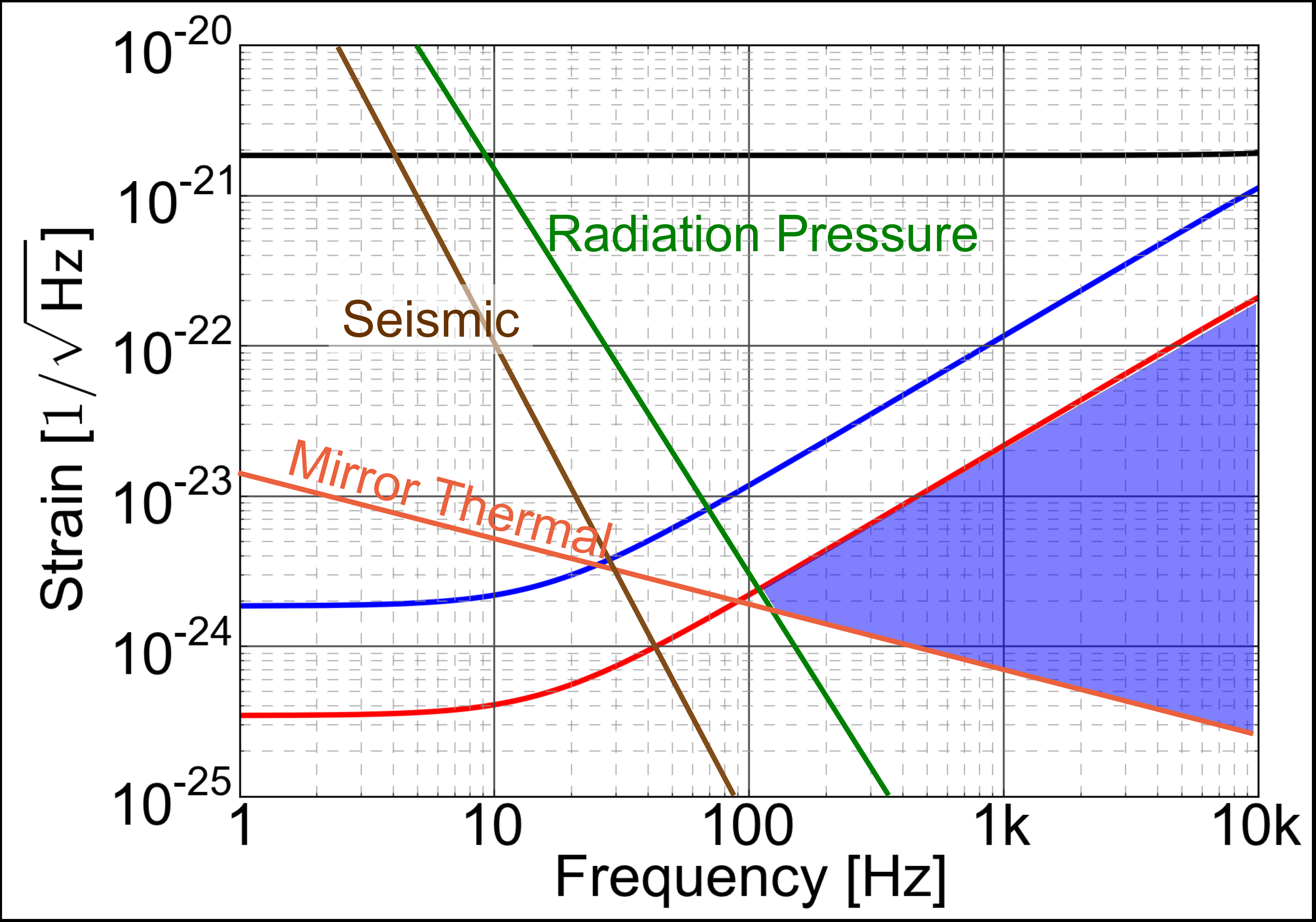




Radiation Pressure
Seismic
Mirror Thermal
Strain [1/√Hz]
Frequency [Hz]
10^-20
10^-21
10^-22
10^-23
10^-24
10^-25
1
10
100
1k
10k

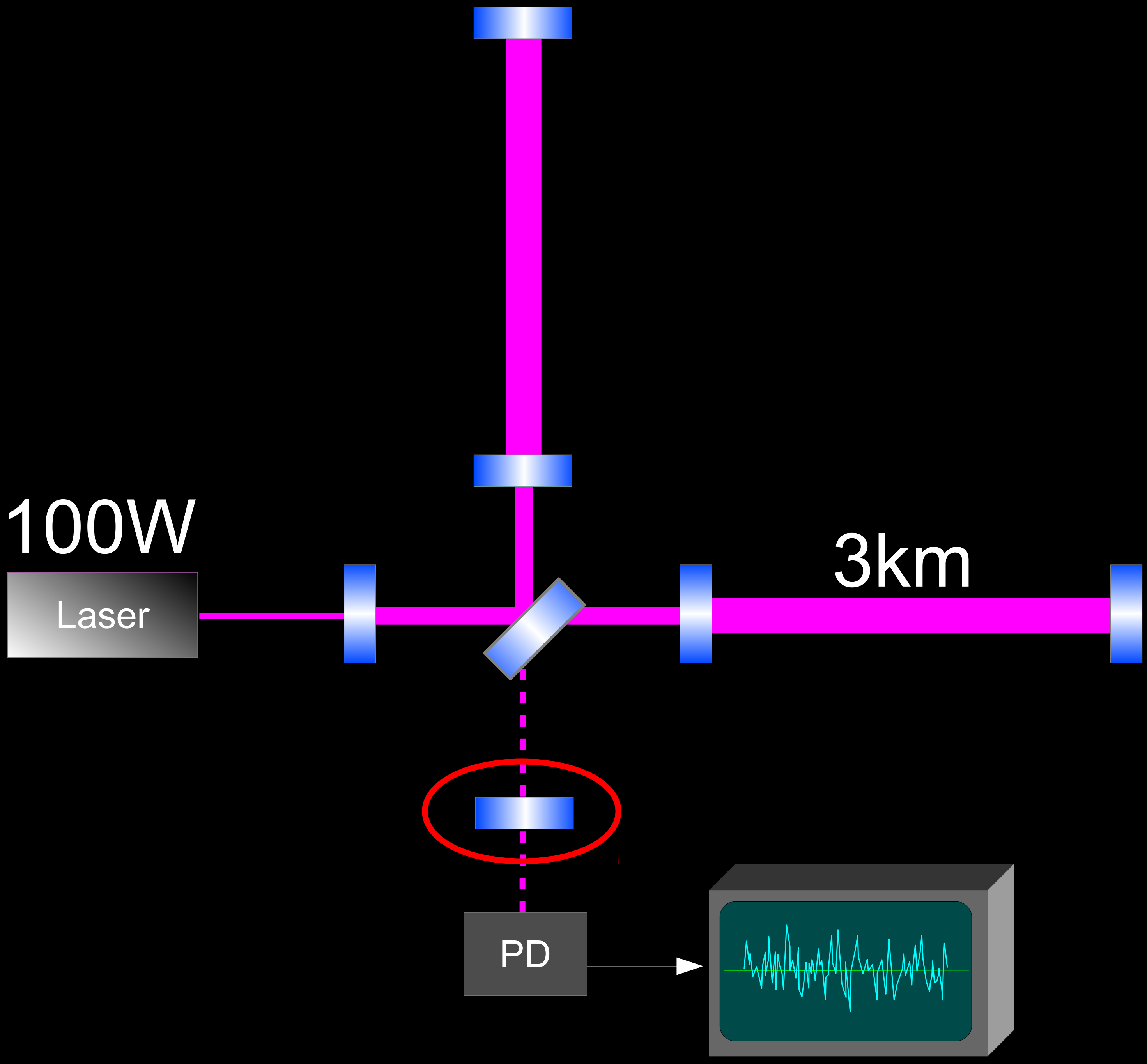


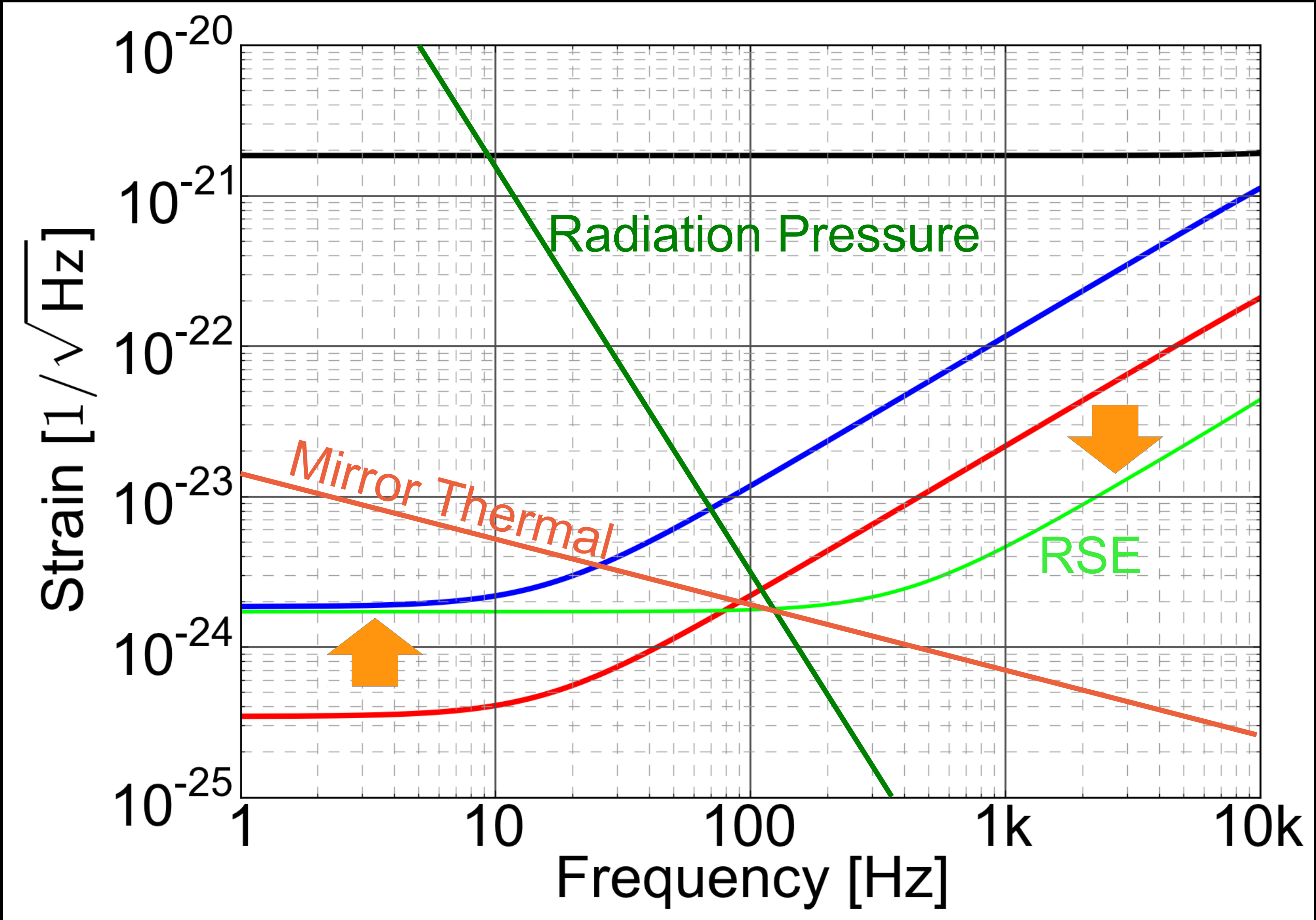
Radiation Pressure
Mirror Thermal
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
Strain $[1/\sqrt{\mathrm{Hz}}]$
1
10
100
1k
10k
Frequency [Hz]



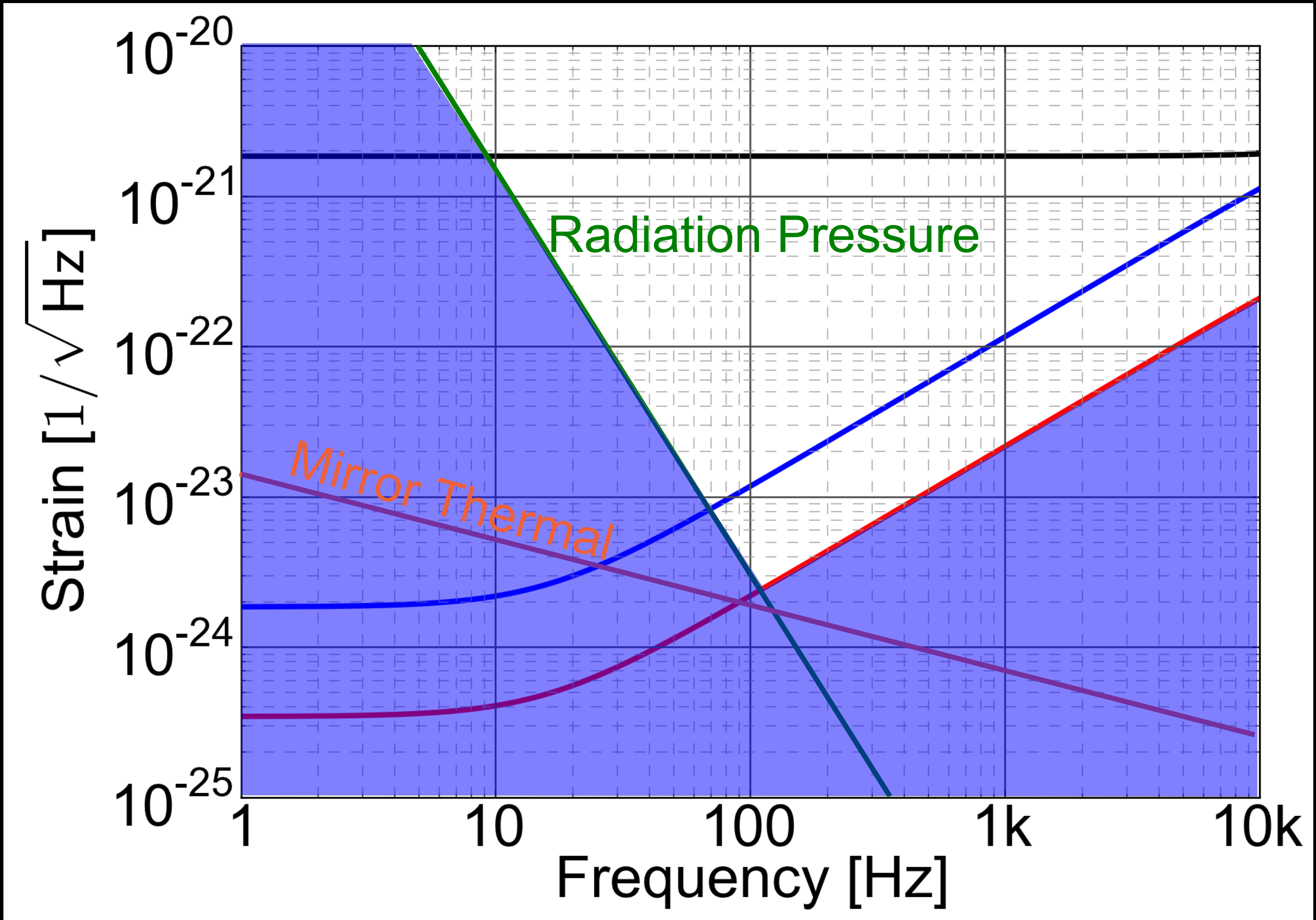
Radiation Pressure
Seismic
Mirror Thermal
Strain [1/√Hz]
Frequency [Hz]
10^-20
10^-21
10^-22
10^-23
10^-24
10^-25
1
10
100
1k
10k

Resonant Sideband Extraction (RSE)

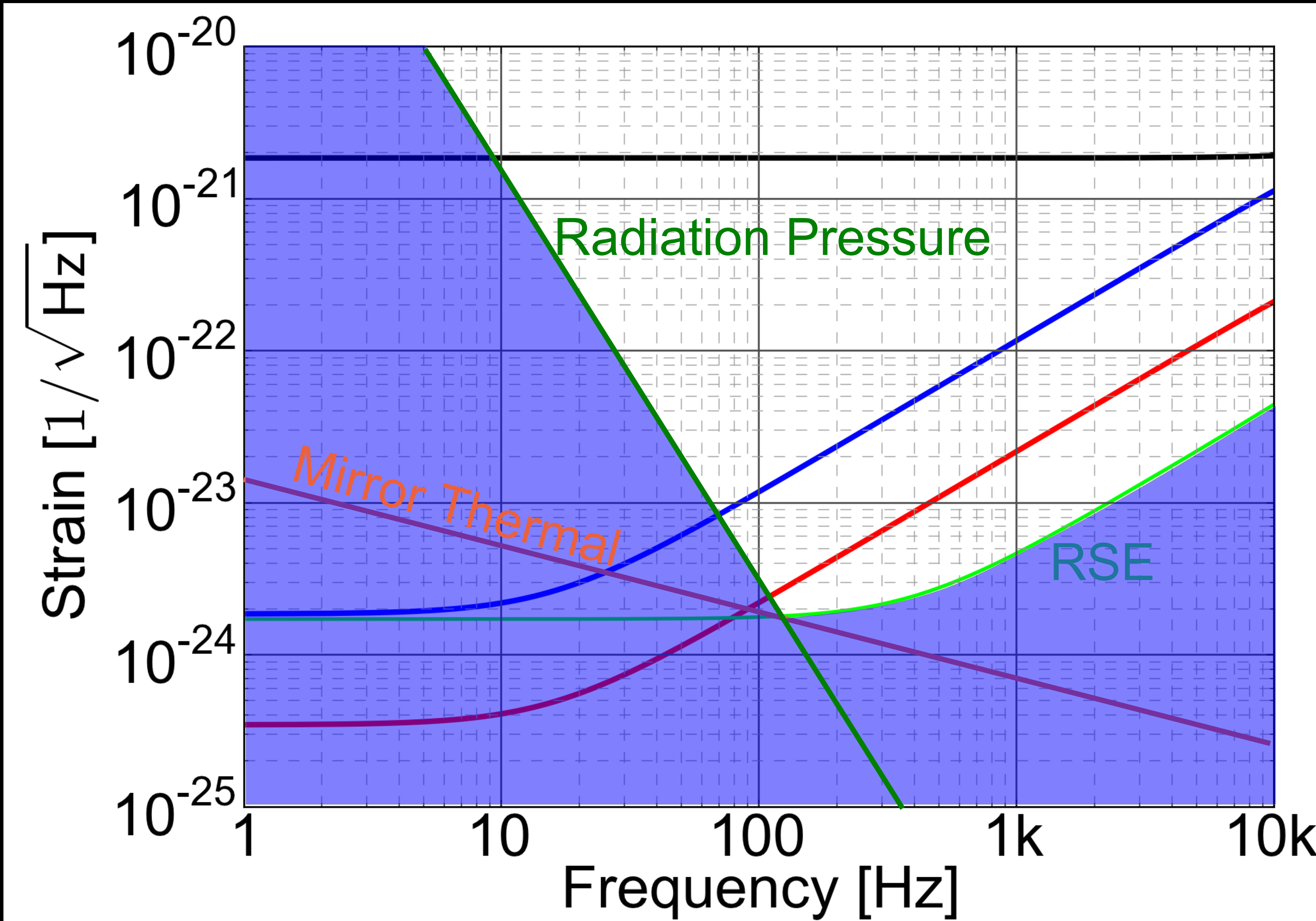




Radiation Pressure
Mirror Thermal
RSE
Strain [1/√Hz]
Frequency [Hz]
10^-20
10^-21
10^-22
10^-23
10^-24
10^-25
1
10
100
1k
10k

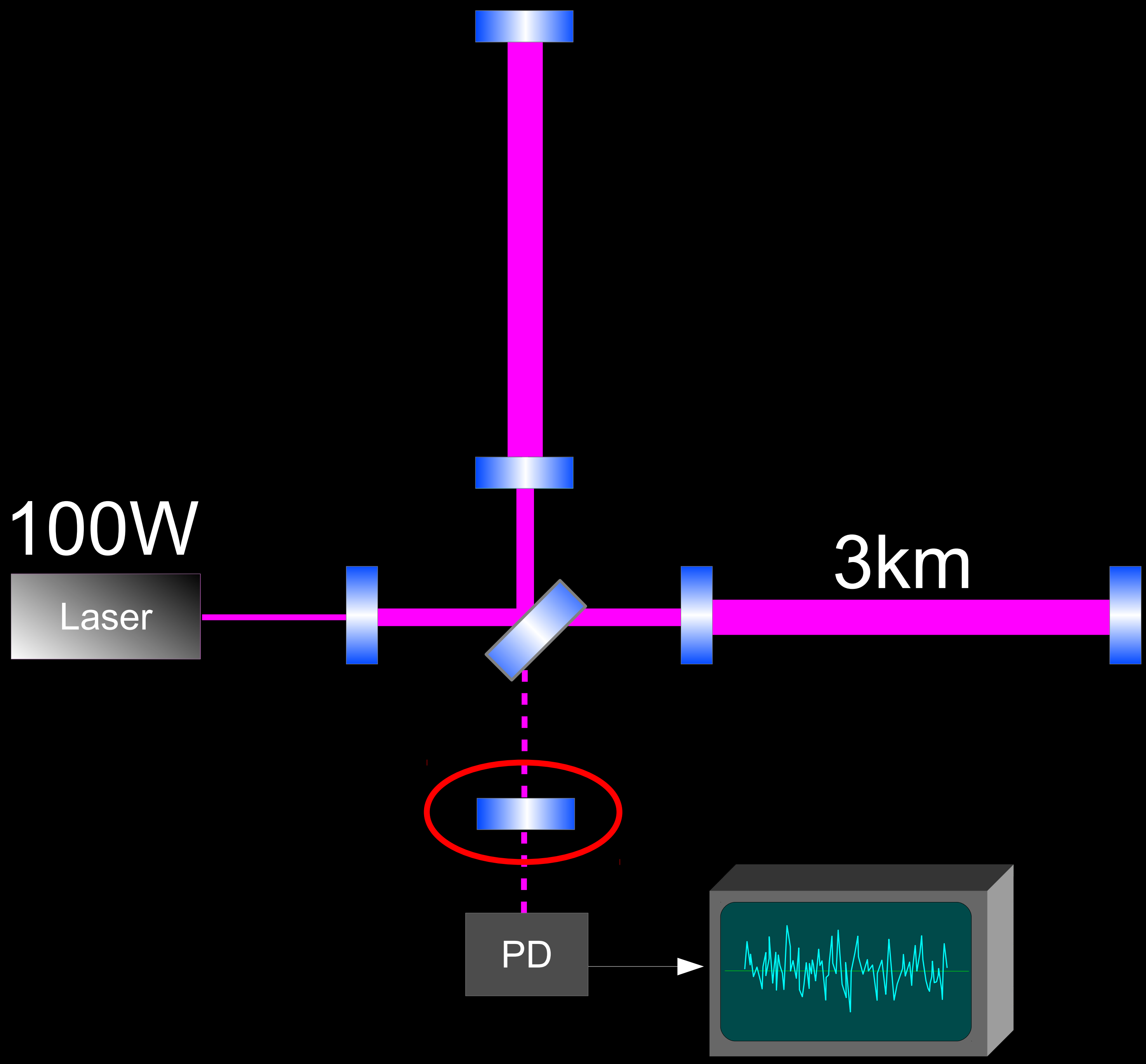


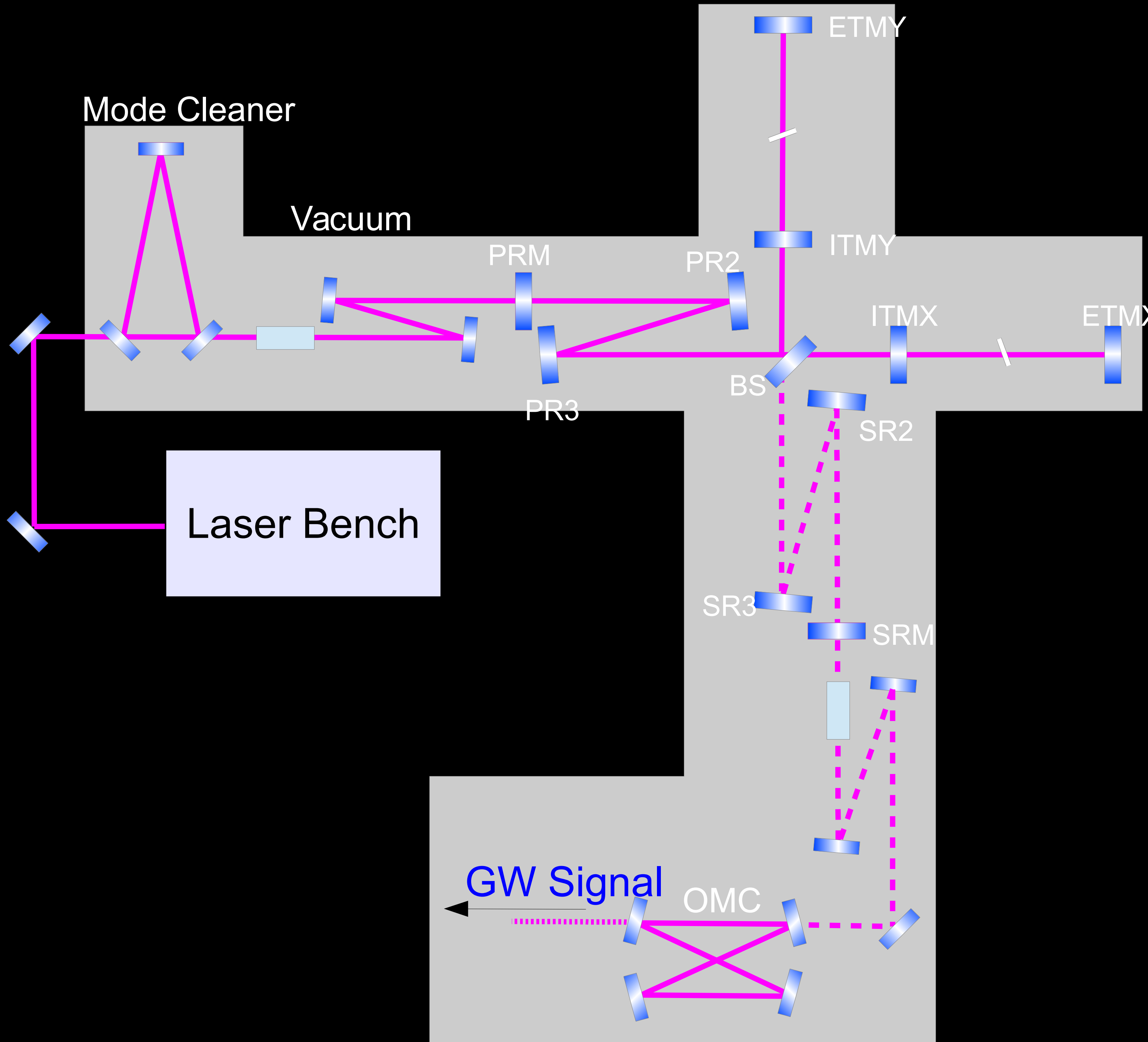
Radiation Pressure
Mirror Thermal
Strain [1 / √Hz]
Frequency [Hz]
10^-20
10^-21
10^-22
10^-23
10^-24
10^-25
1
10
100
1k
10k



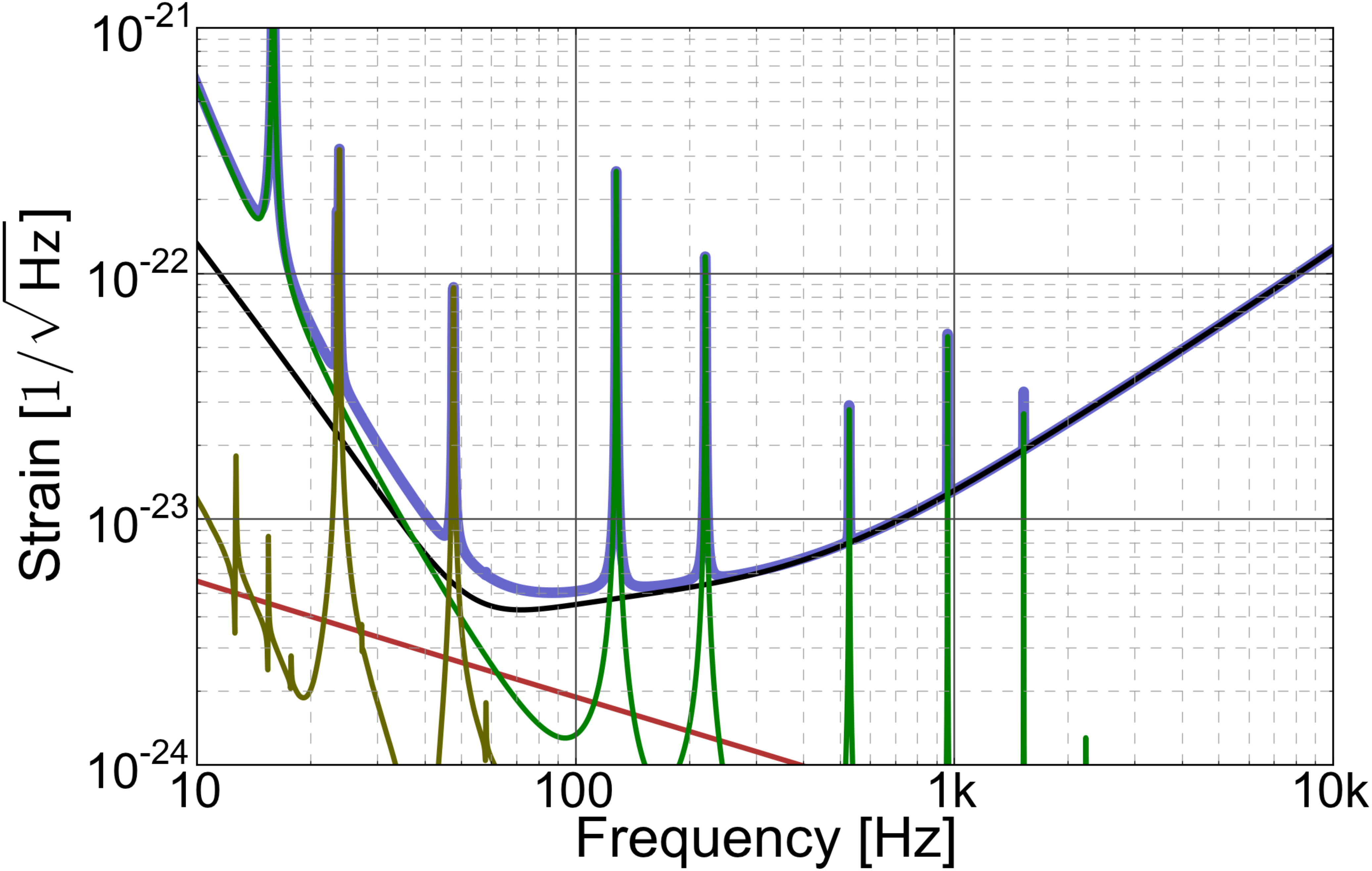
10-20
10-21
10-22
10-23
10-24
10-25
Strain [1/√Hz]
Radiation Pressure
Mirror Thermal
RSE
1
10
100
1k
10k
Frequency [Hz]

Resonant Sideband Extraction (RSE)

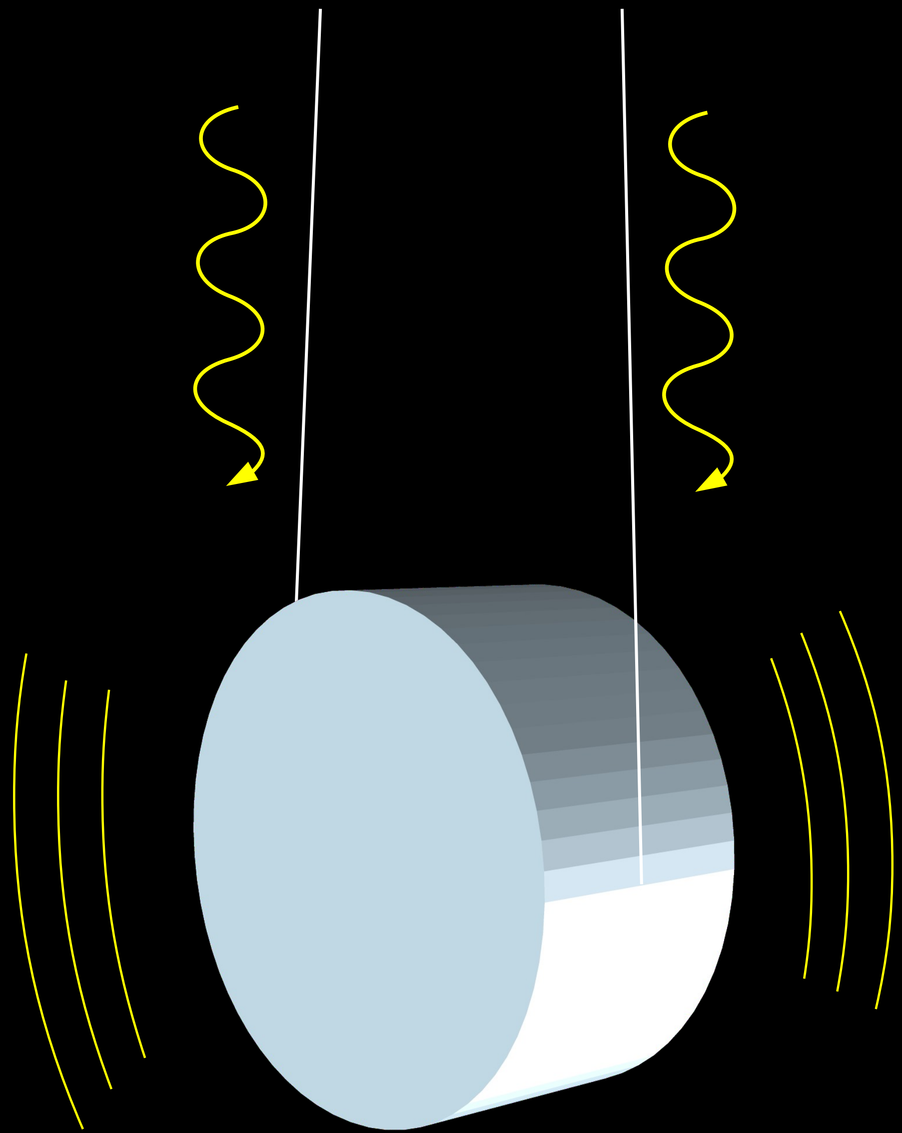



ETMY
Mode Cleaner
Vacuum
PRM
PR2
ITMY
ITMX
ETMX
BS
PR3
SR2
Laser Bench
SR3
SRM
GW Signal
OMC

Target Sensitivity of KAGRA

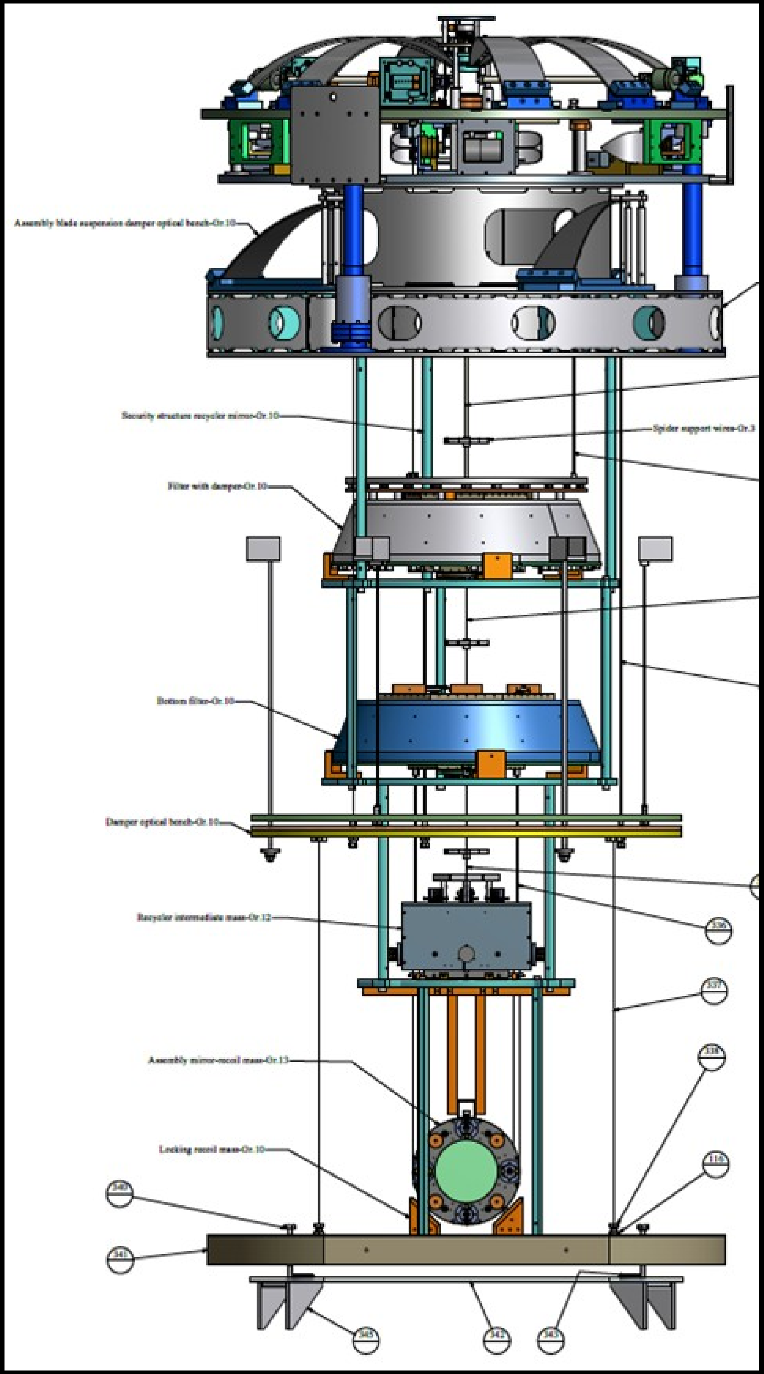


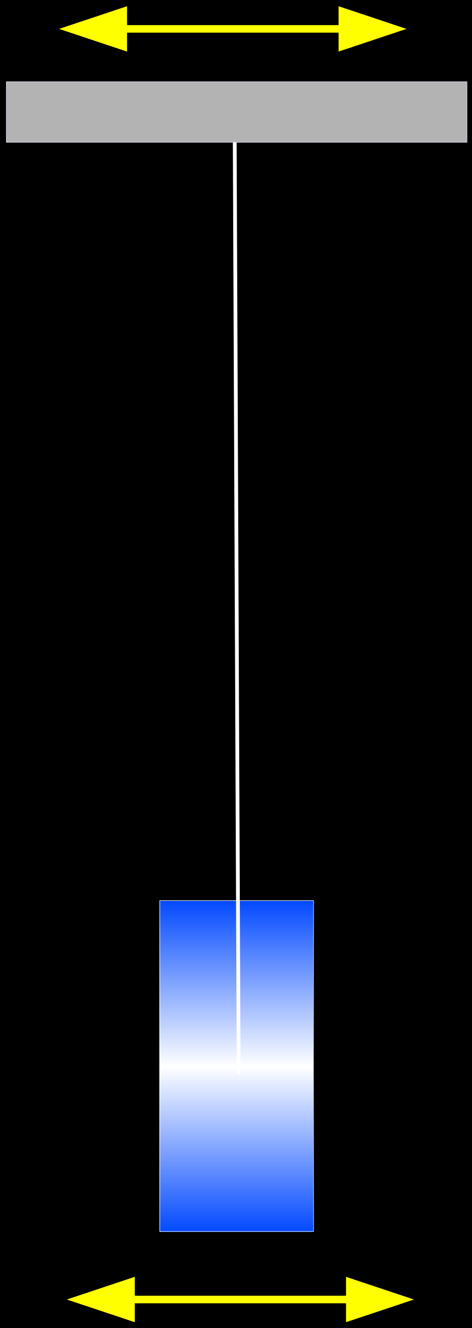
地面振動

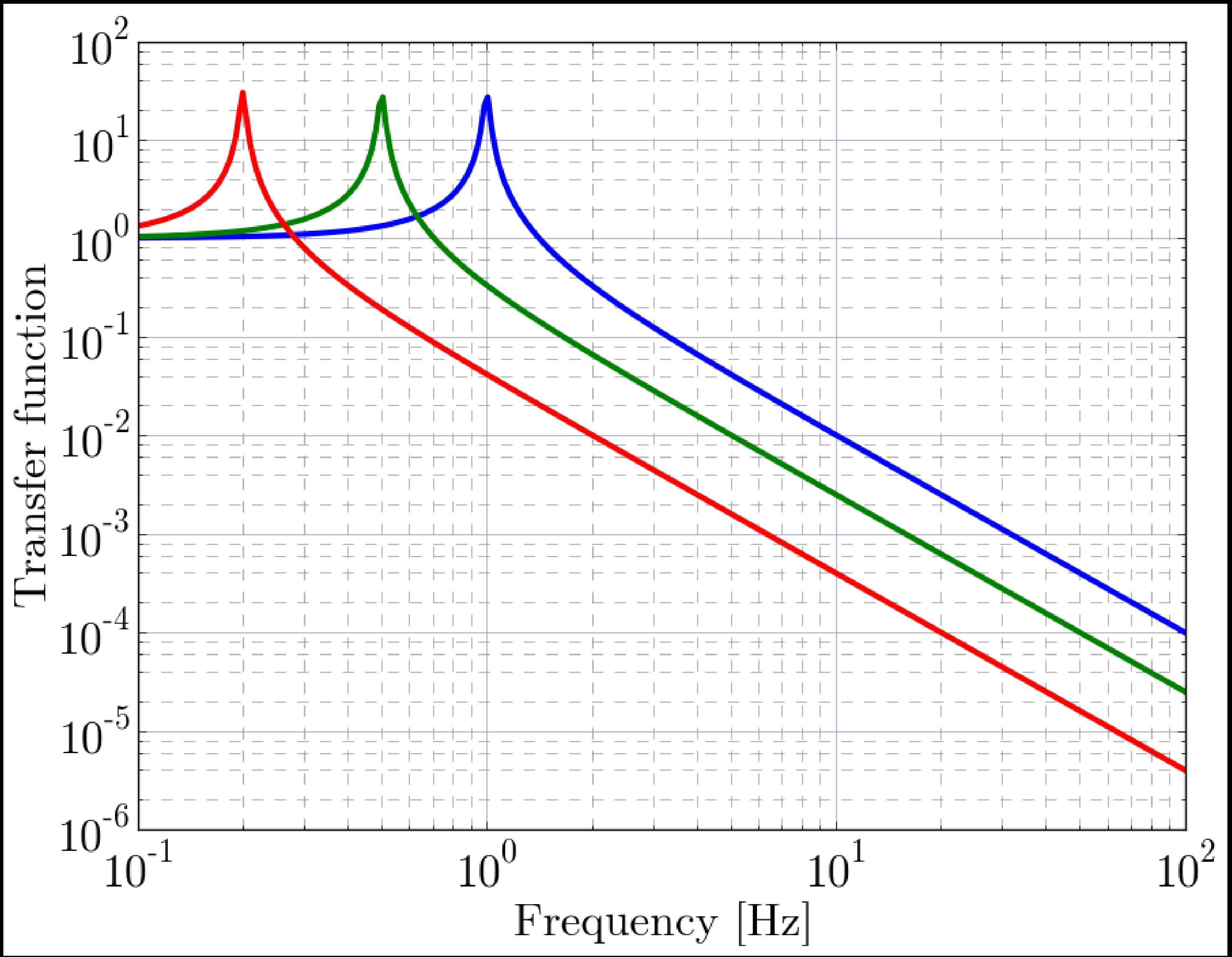


Multi-Stage Vibration Isolation System

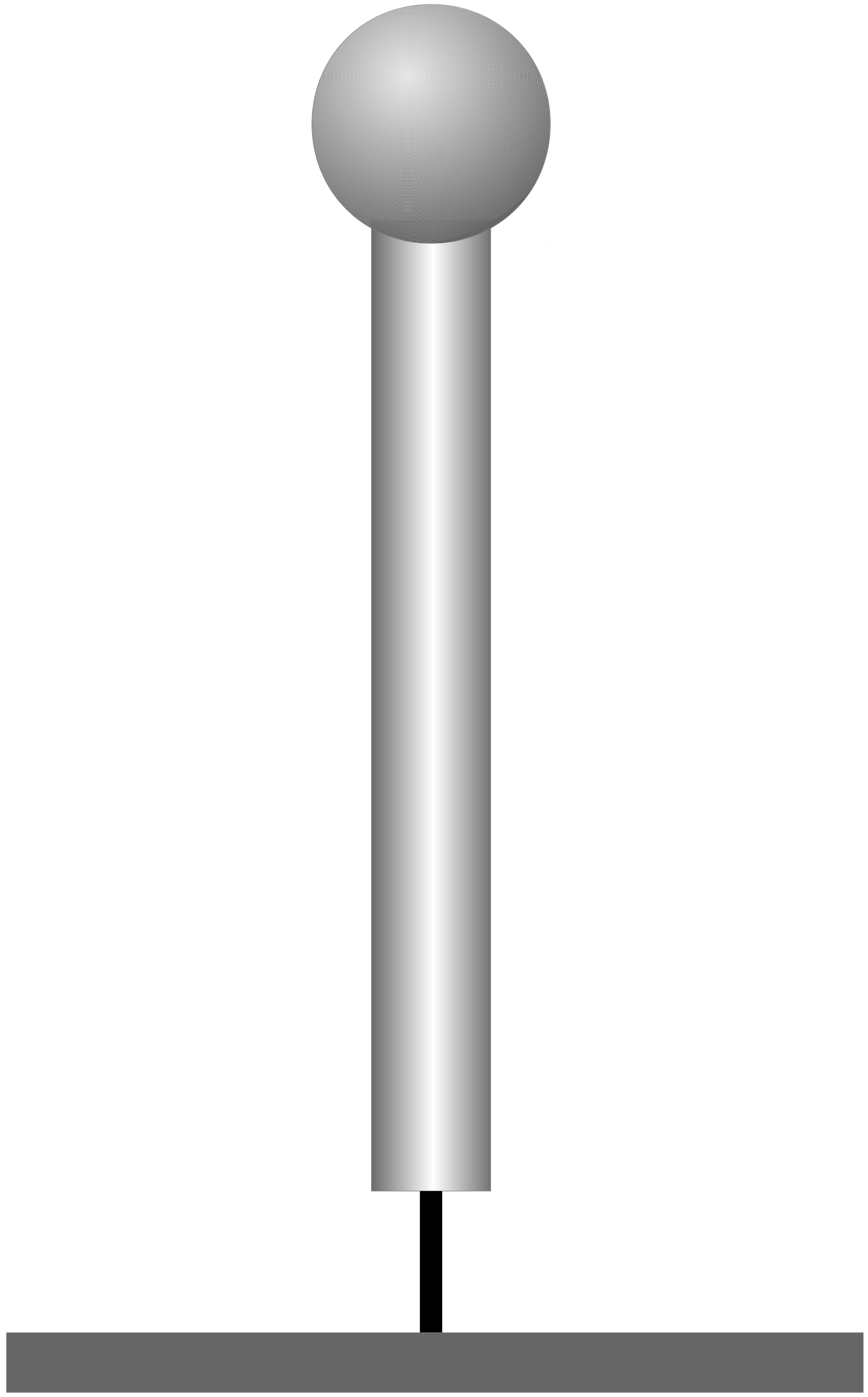
$$\frac{1}{1000000000000}$$

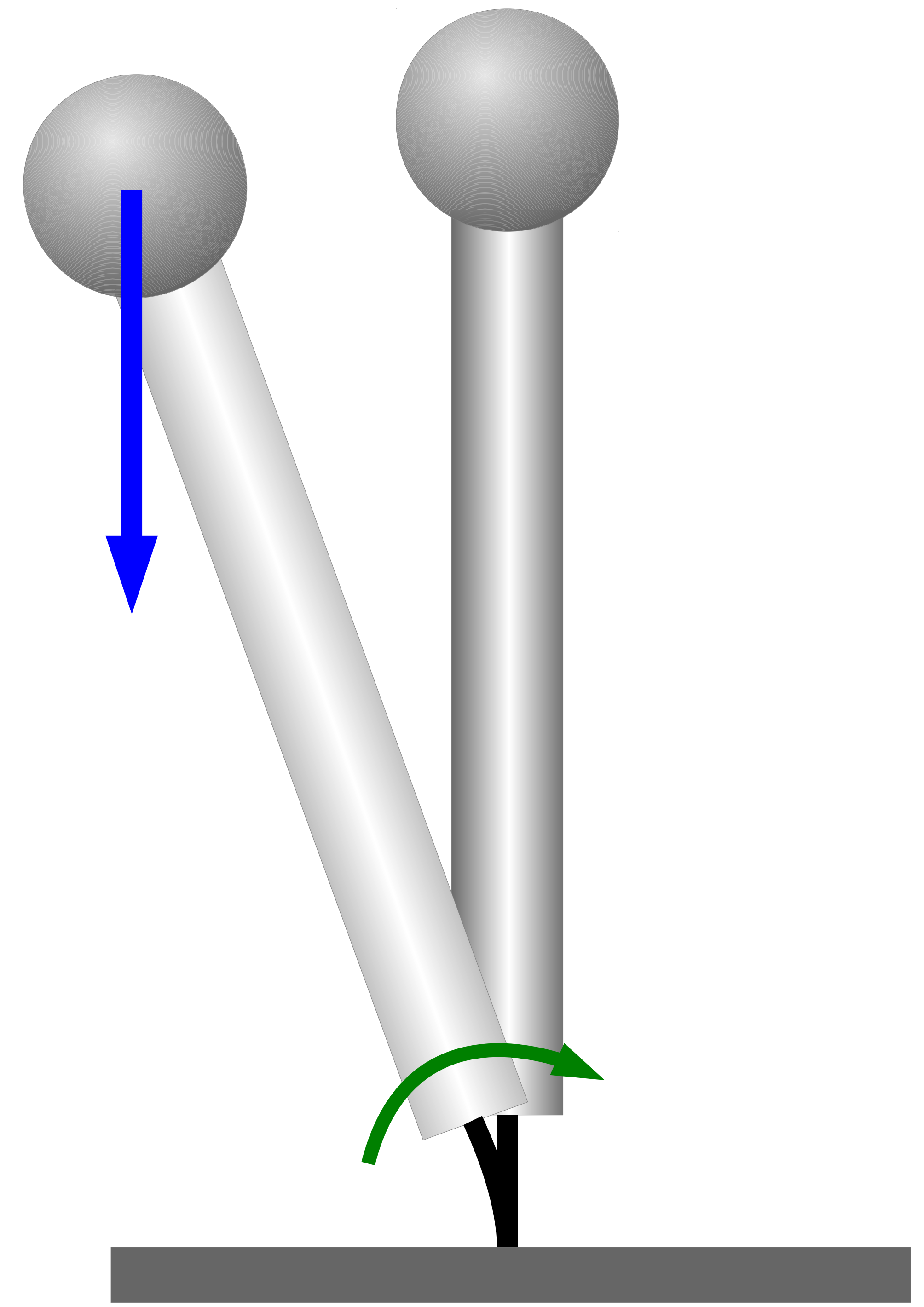


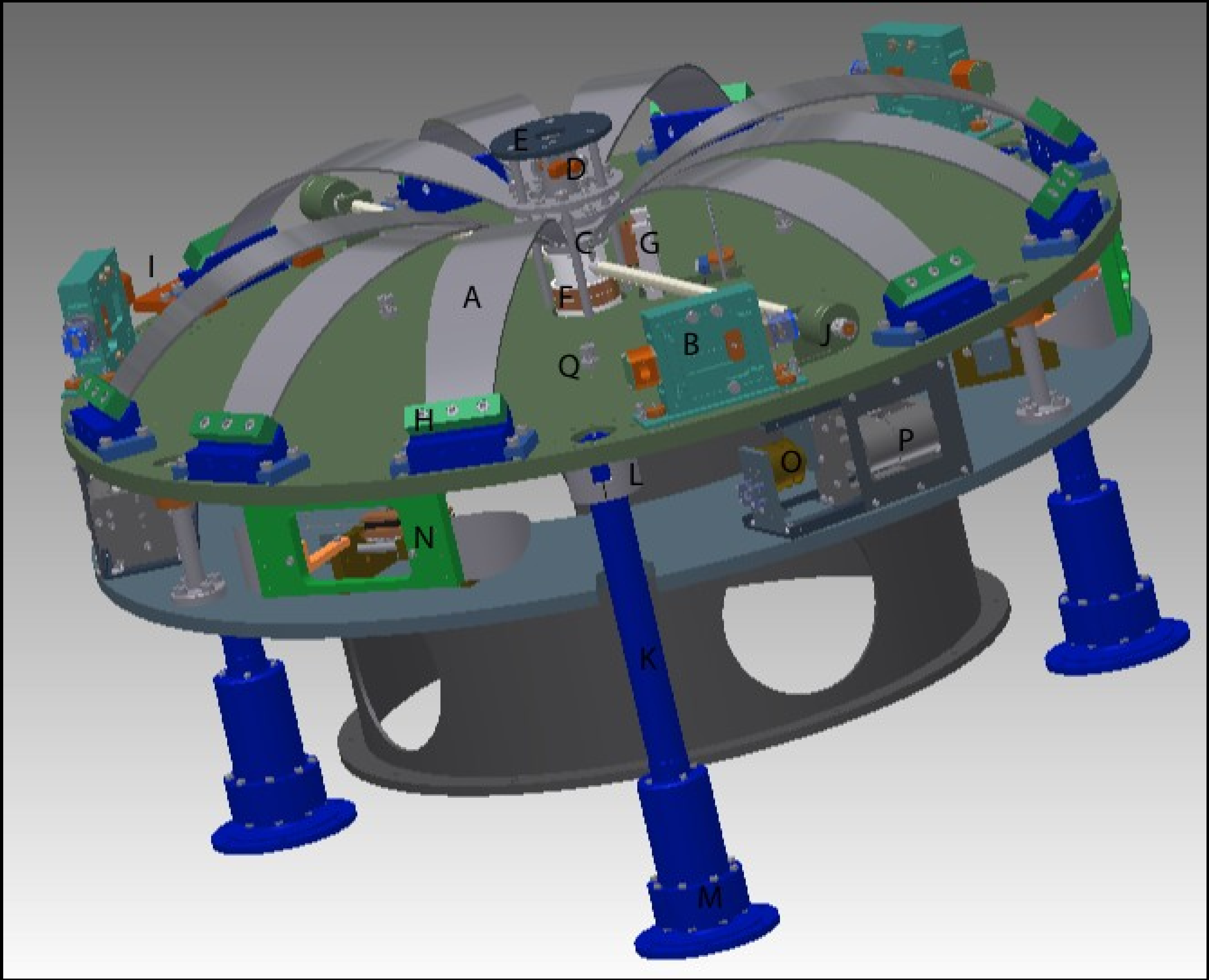


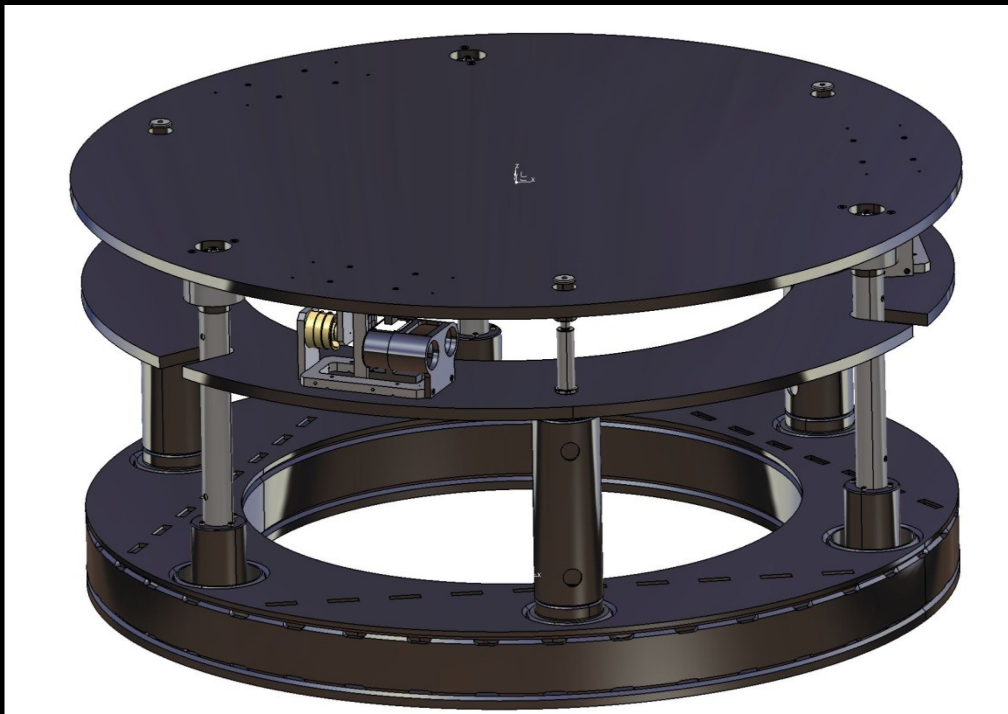


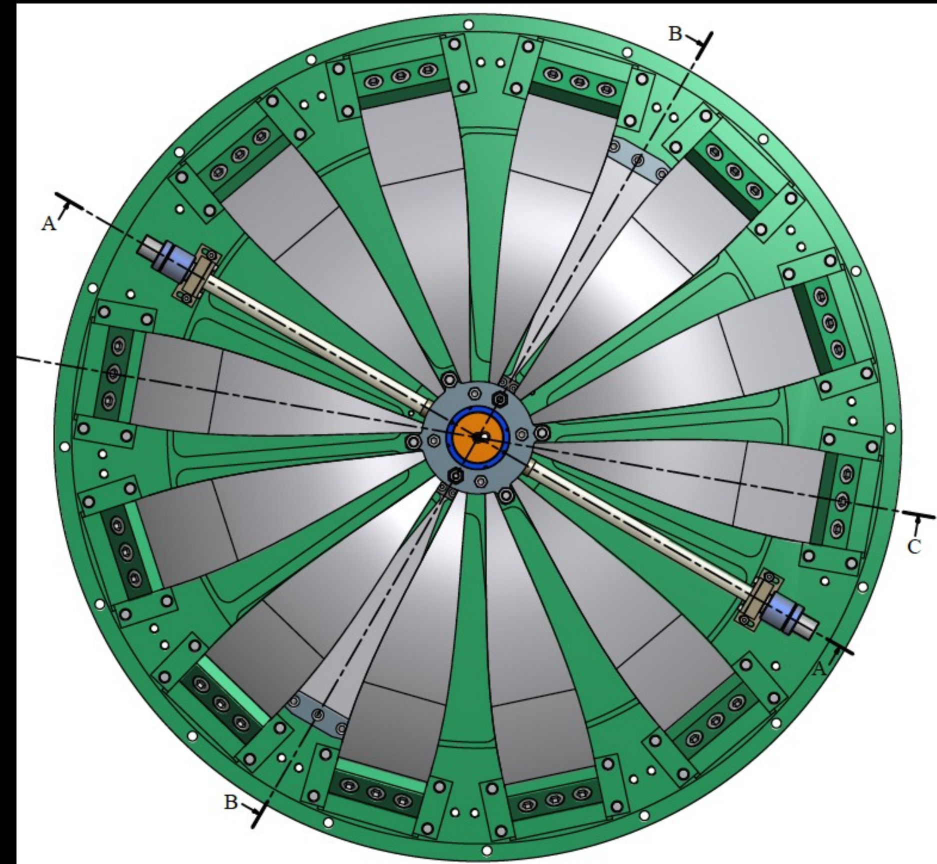
Transfer function
Frequency [Hz]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-1}
10^{0}
10^{1}
10^{2}



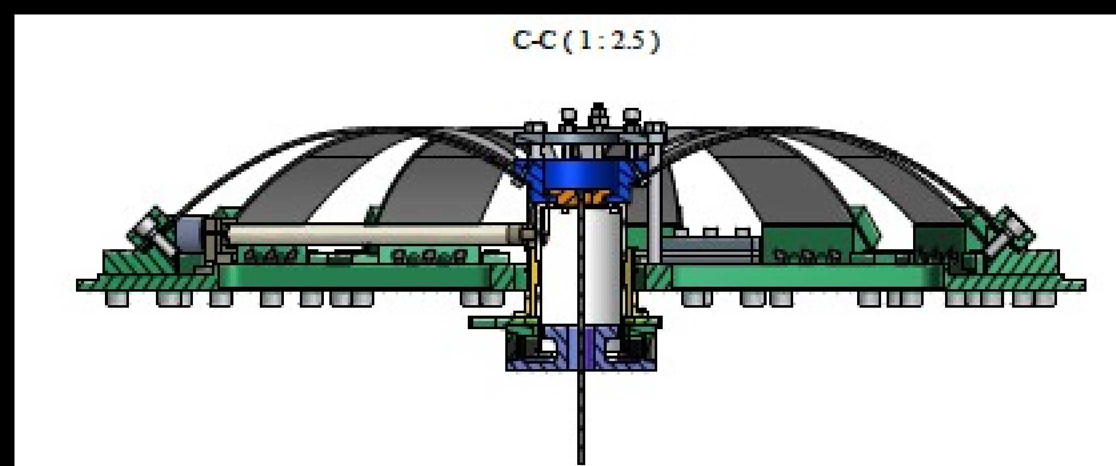



E
D
C
G
I
A
F
B
J
Q
H
P
O
L
N
K
M

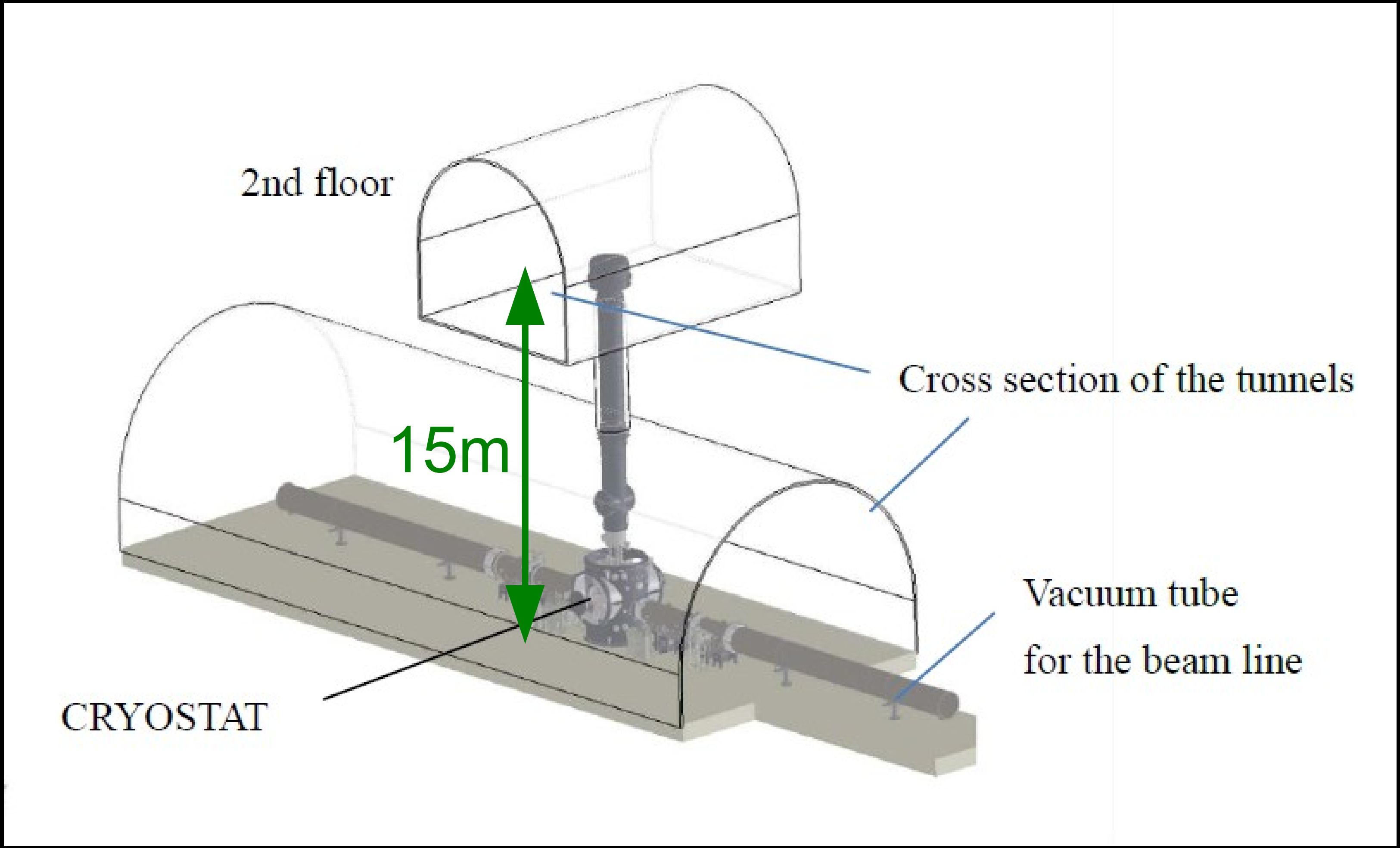


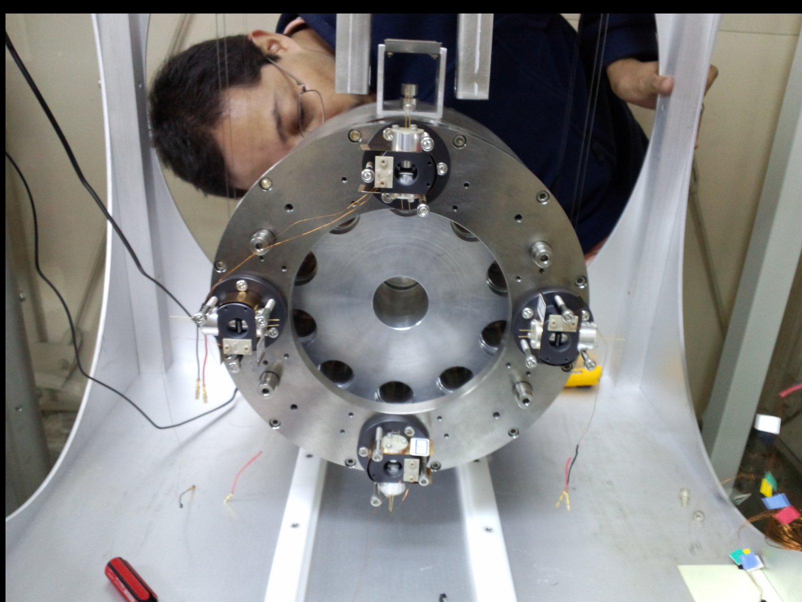


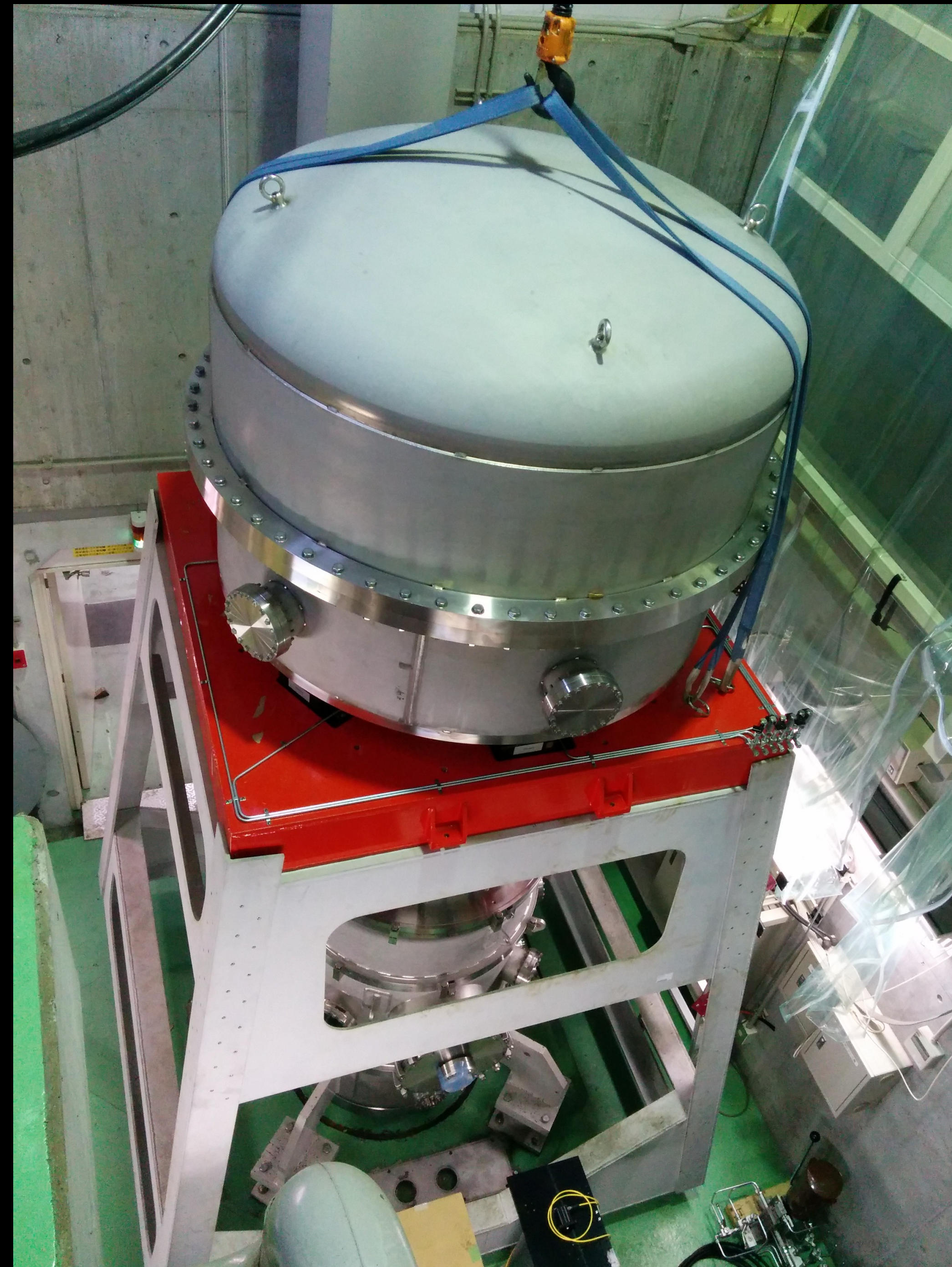
A
B
C
A
B



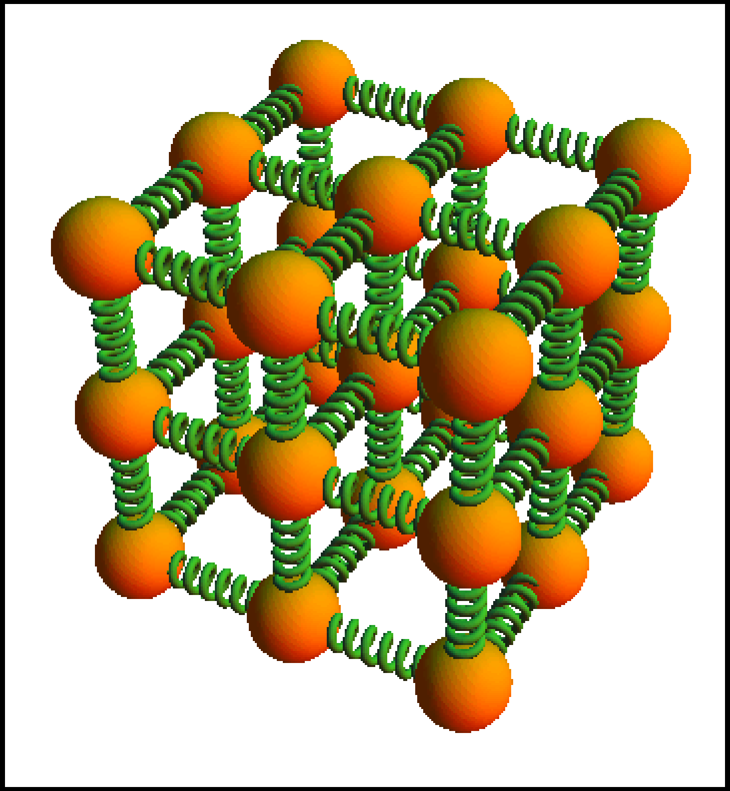
C-C (1 : 2.5)

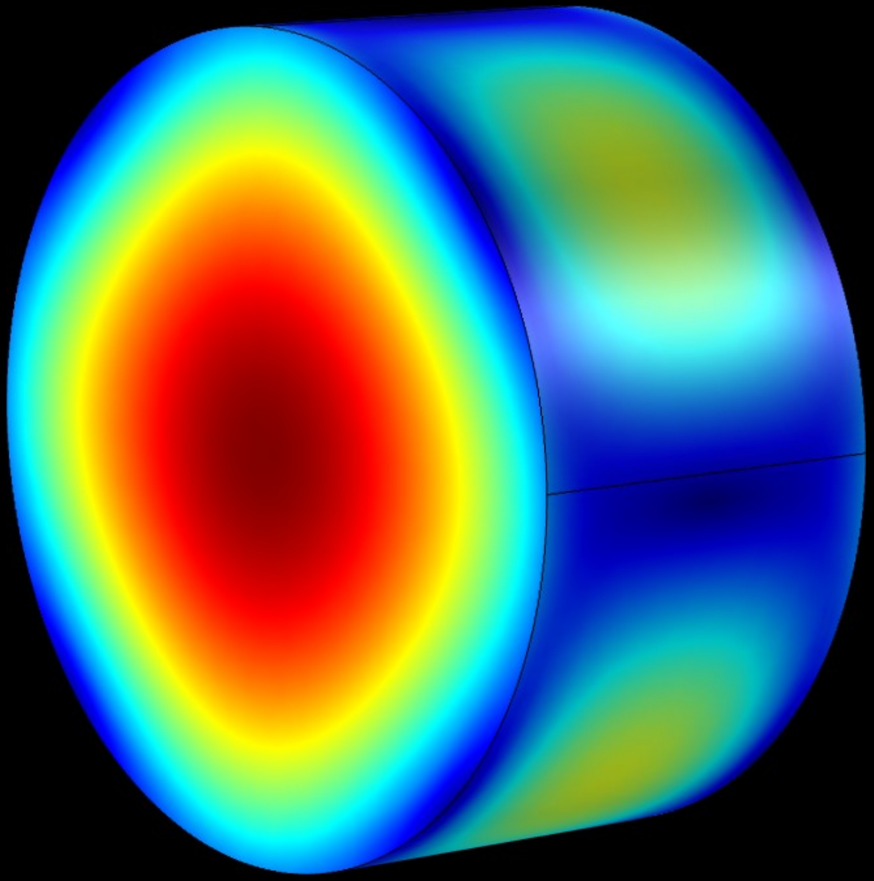

2nd floor
15m
Cross section of the tunnels
Vacuum tube
for the beam line
CRYOSTAT





熱雑音

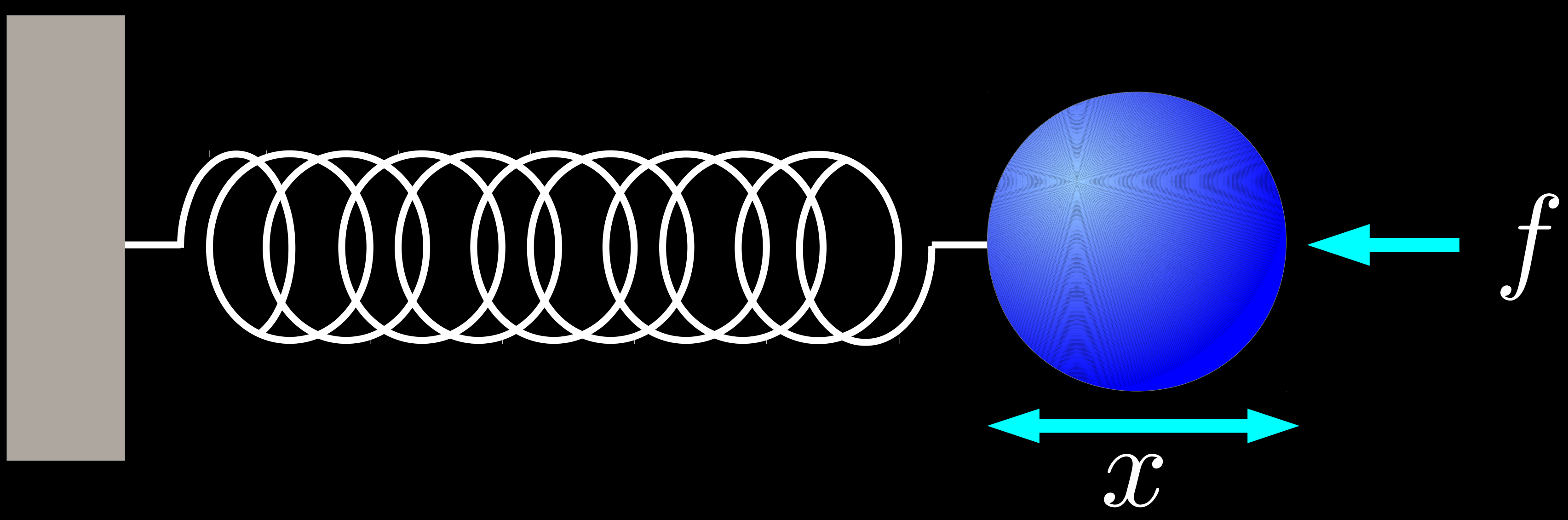




揺動散逸定理

$$G_f(\omega) = 4k_{\mathrm{B}}TR(\omega)$$

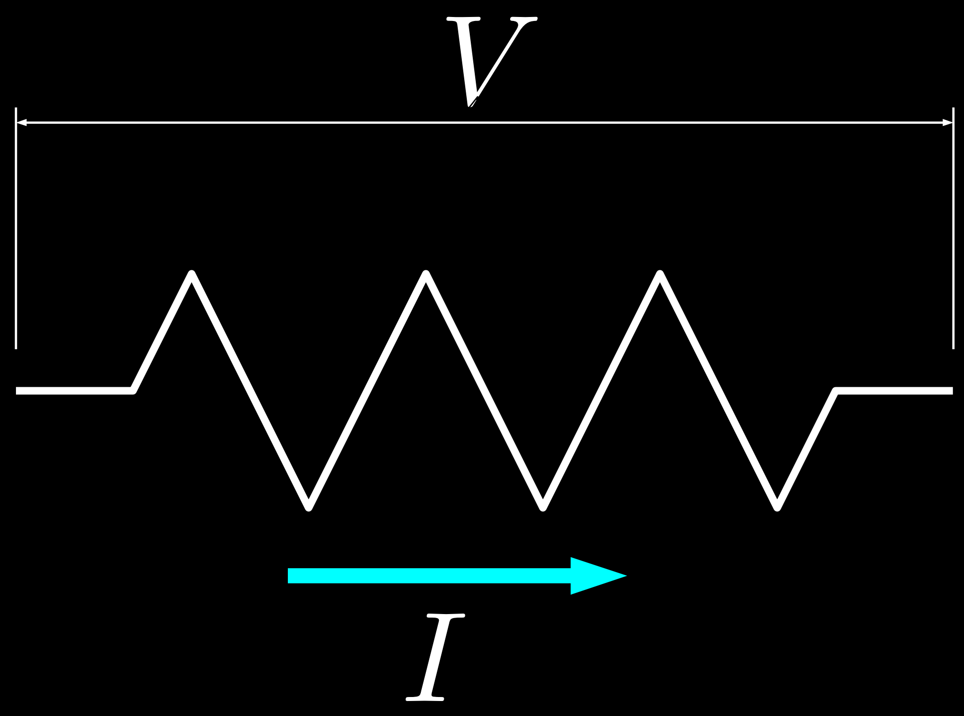
$$R(\omega) = \mathrm{Re}[\tilde{f}(\omega)/\tilde{\dot{x}}(\omega)]$$



抵抗の熱雑音

$$G_V(\omega) = 4k_{\mathrm{B}}TR(\omega)$$

$$R(\omega) = \mathrm{Re}[\tilde{V}(\omega)/\tilde{I}(\omega)]$$

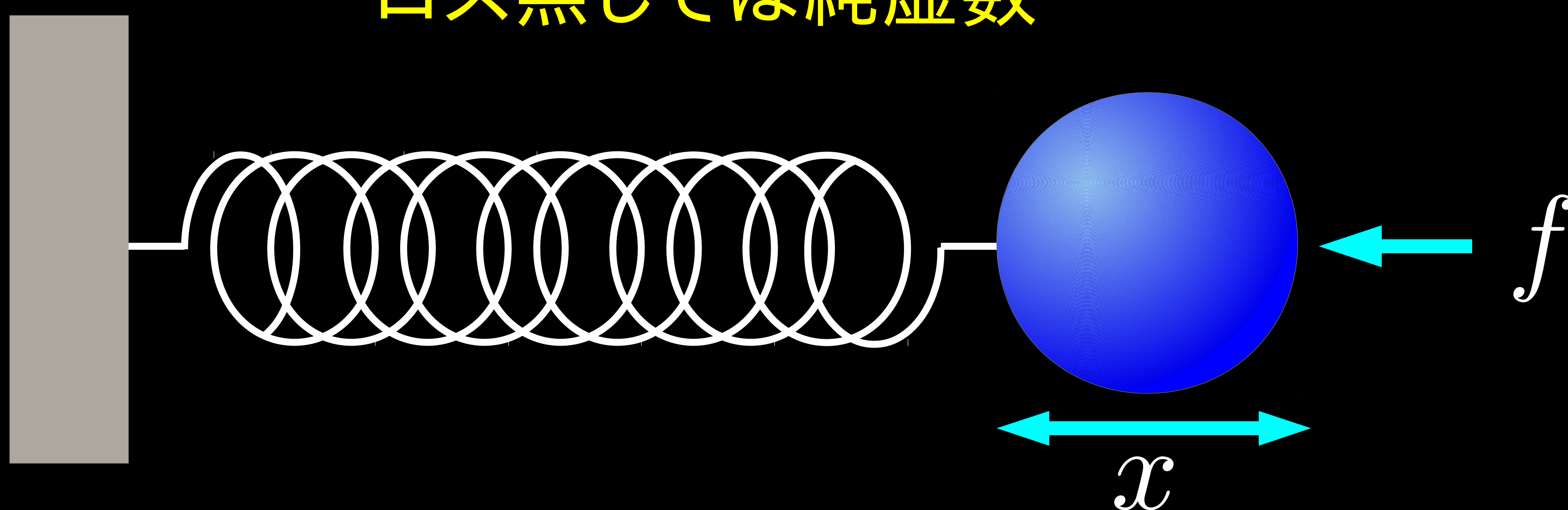


揺動散逸定理

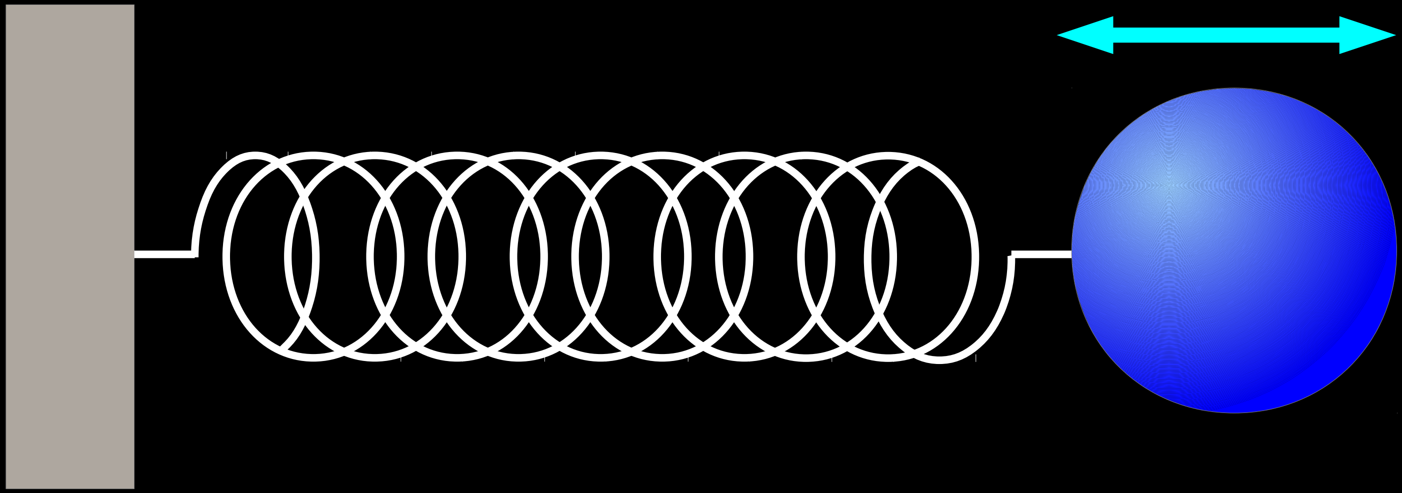
$$G_f(\omega) = 4k_{\mathrm{B}}TR(\omega)$$

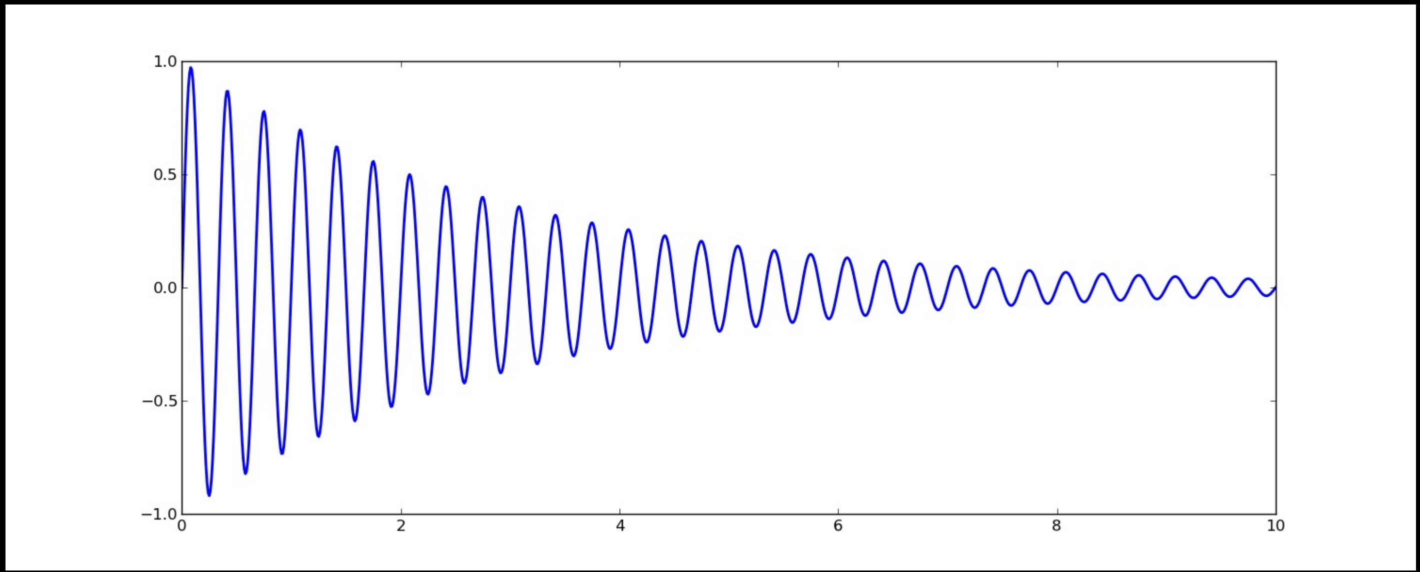
$$R(\omega) = \mathrm{Re}\left|\underline{\tilde{f}(\omega)/\tilde{\dot{x}}(\omega)}\right|$$

ロス無しでは純虚数

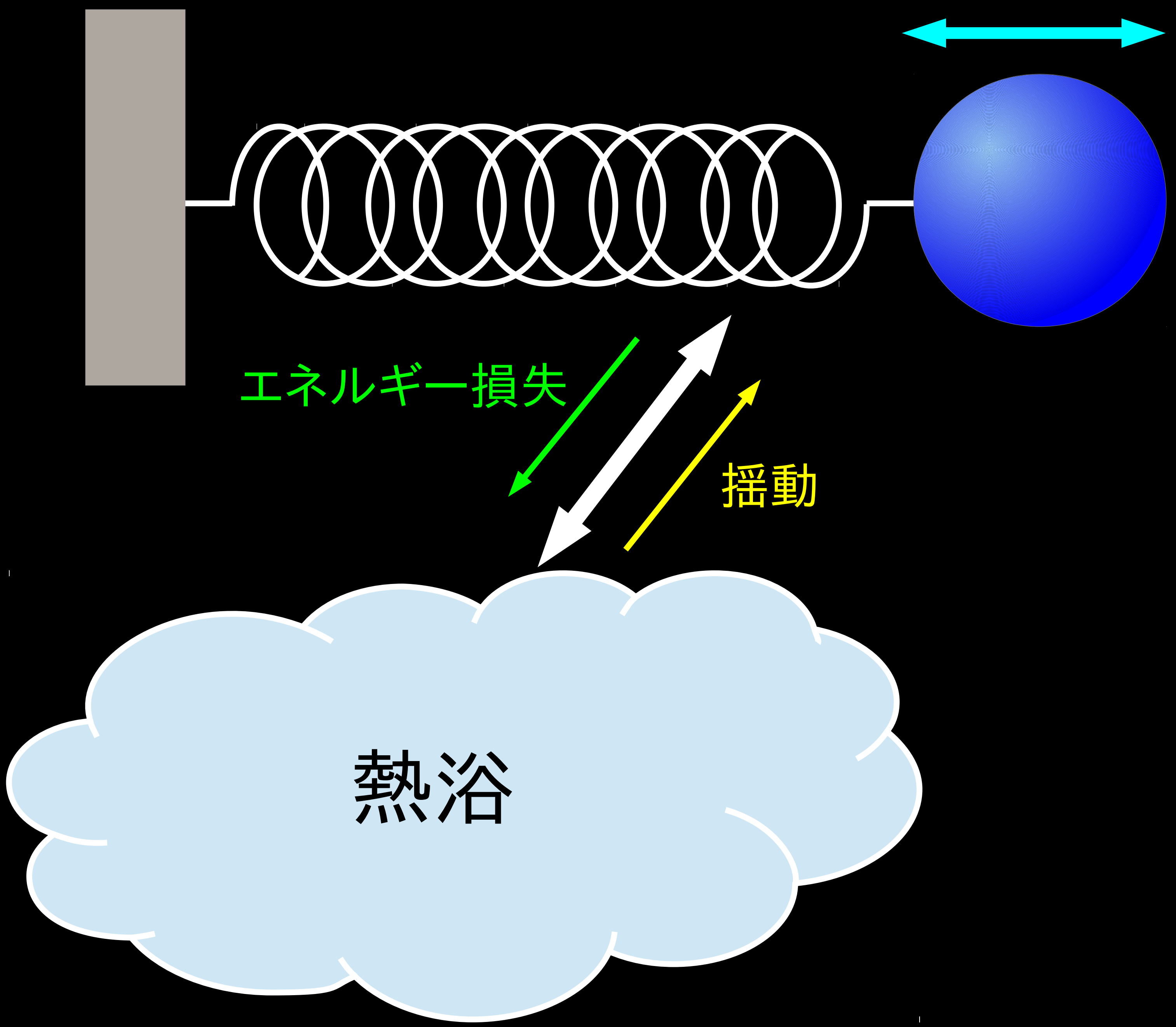


機械損失とQ値



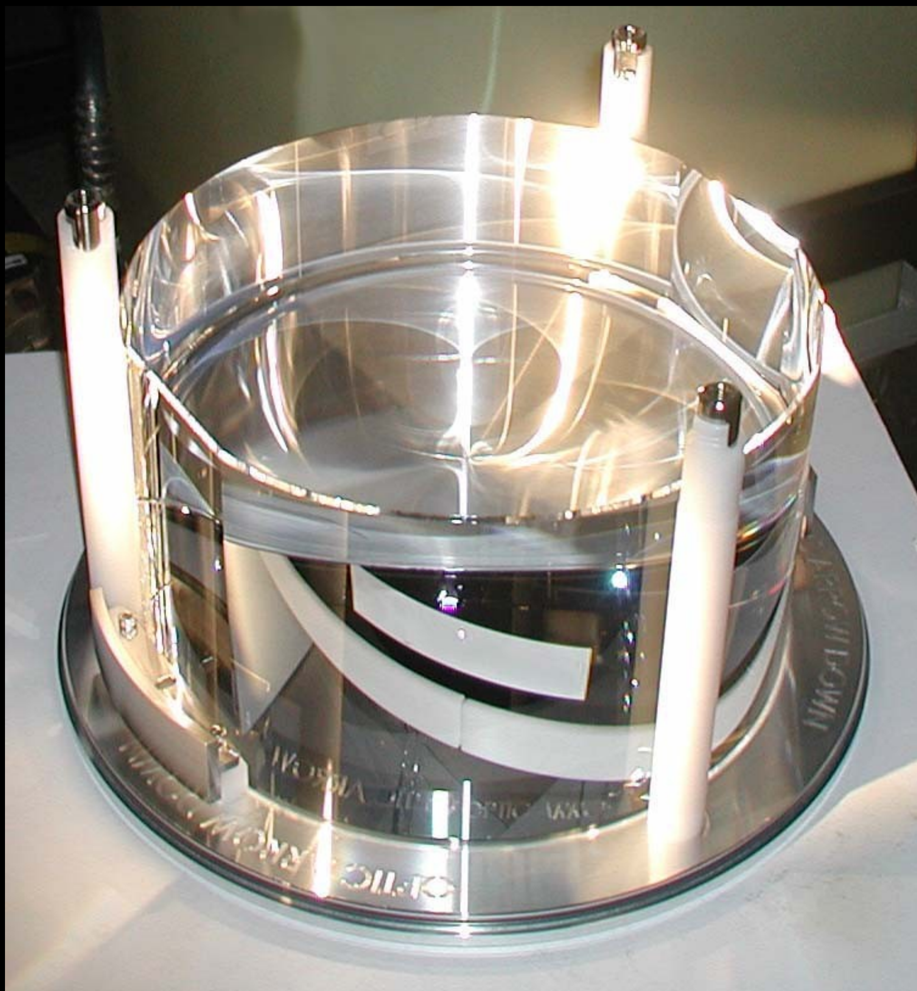


機械損失∝1/Q

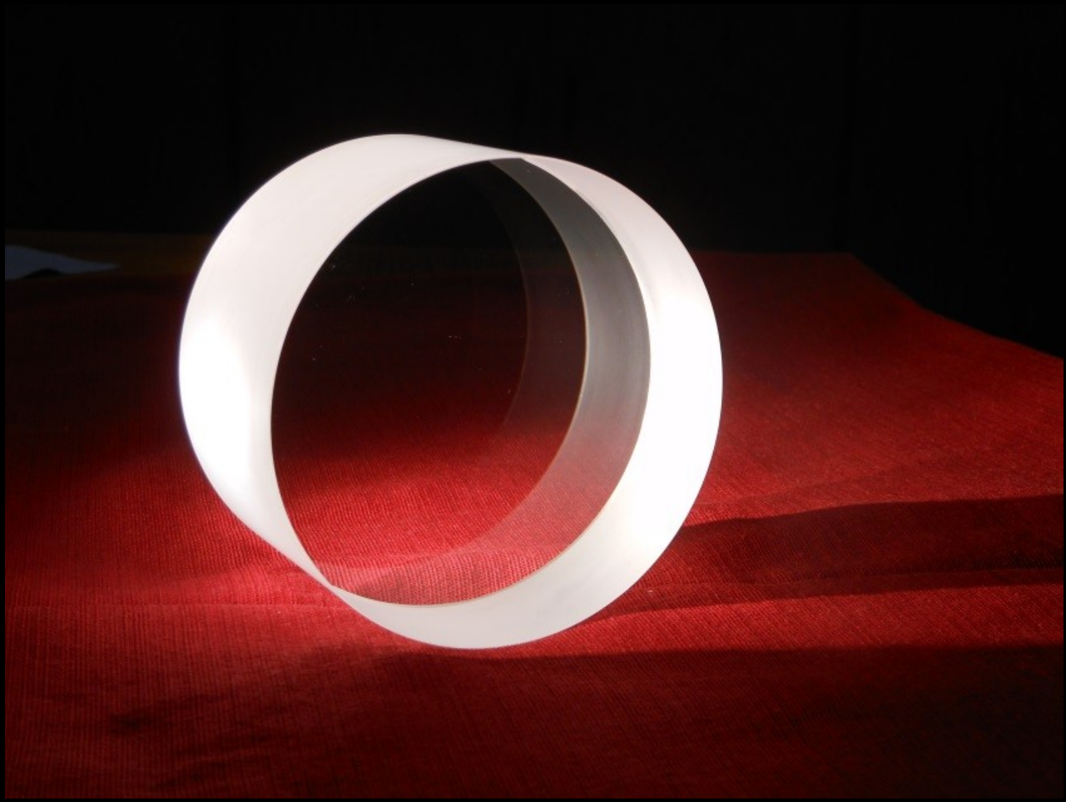


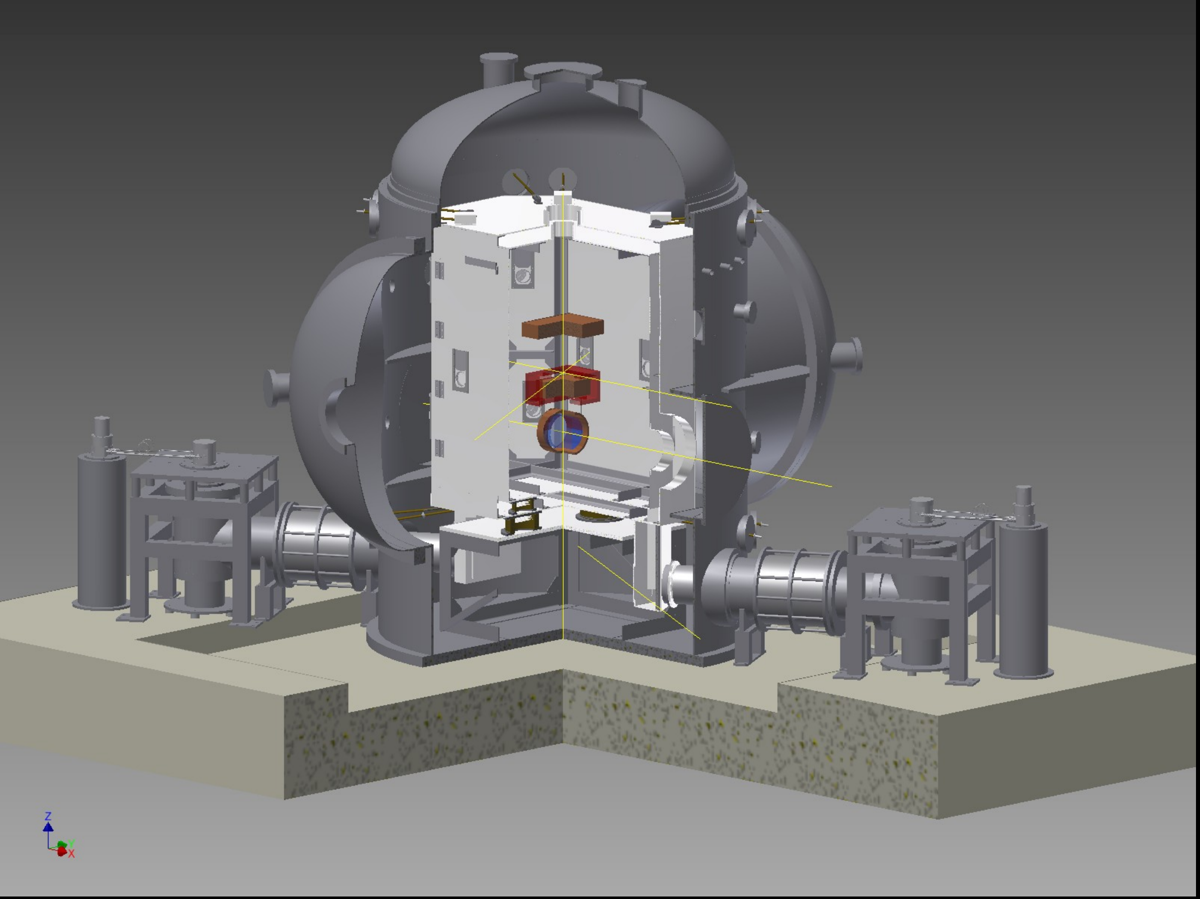
エネルギー損失
揺動
熱浴

Fused Silica



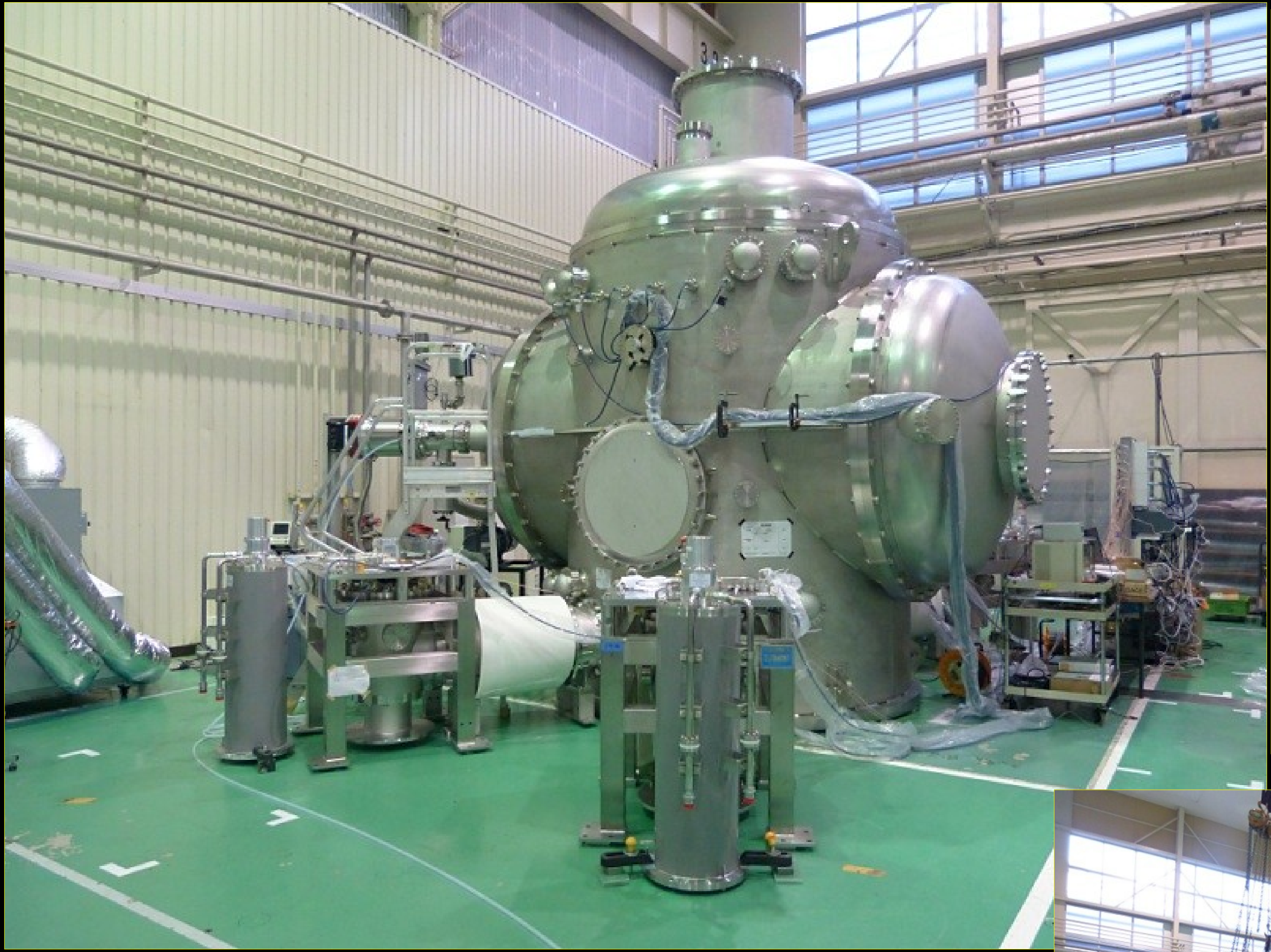
Sapphire





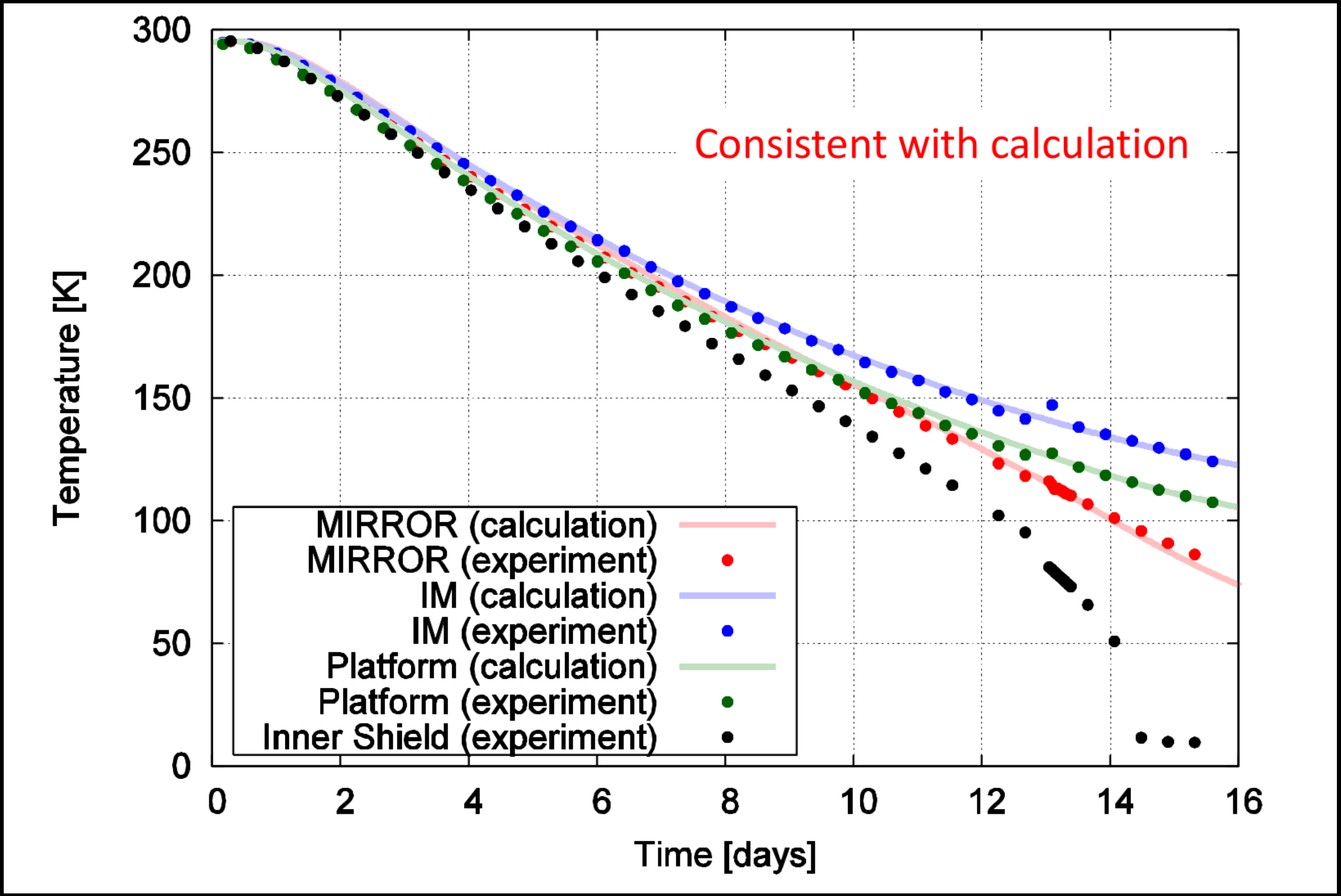
Cryogenic
Sapphire Mirrors

Cooled down to 20K

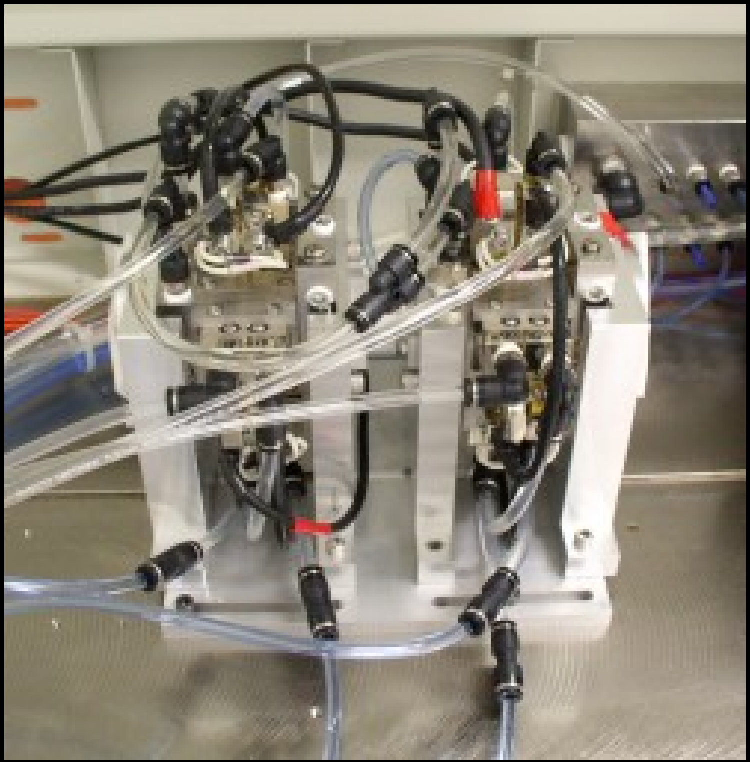


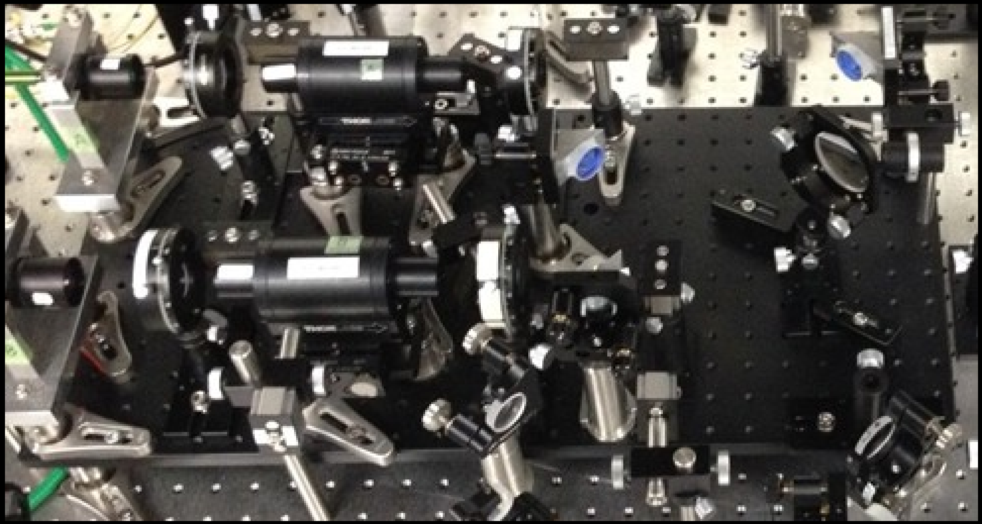
Cryostat test @ TOSHIBA

Cooling curve of the cryostat and a dummy suspension

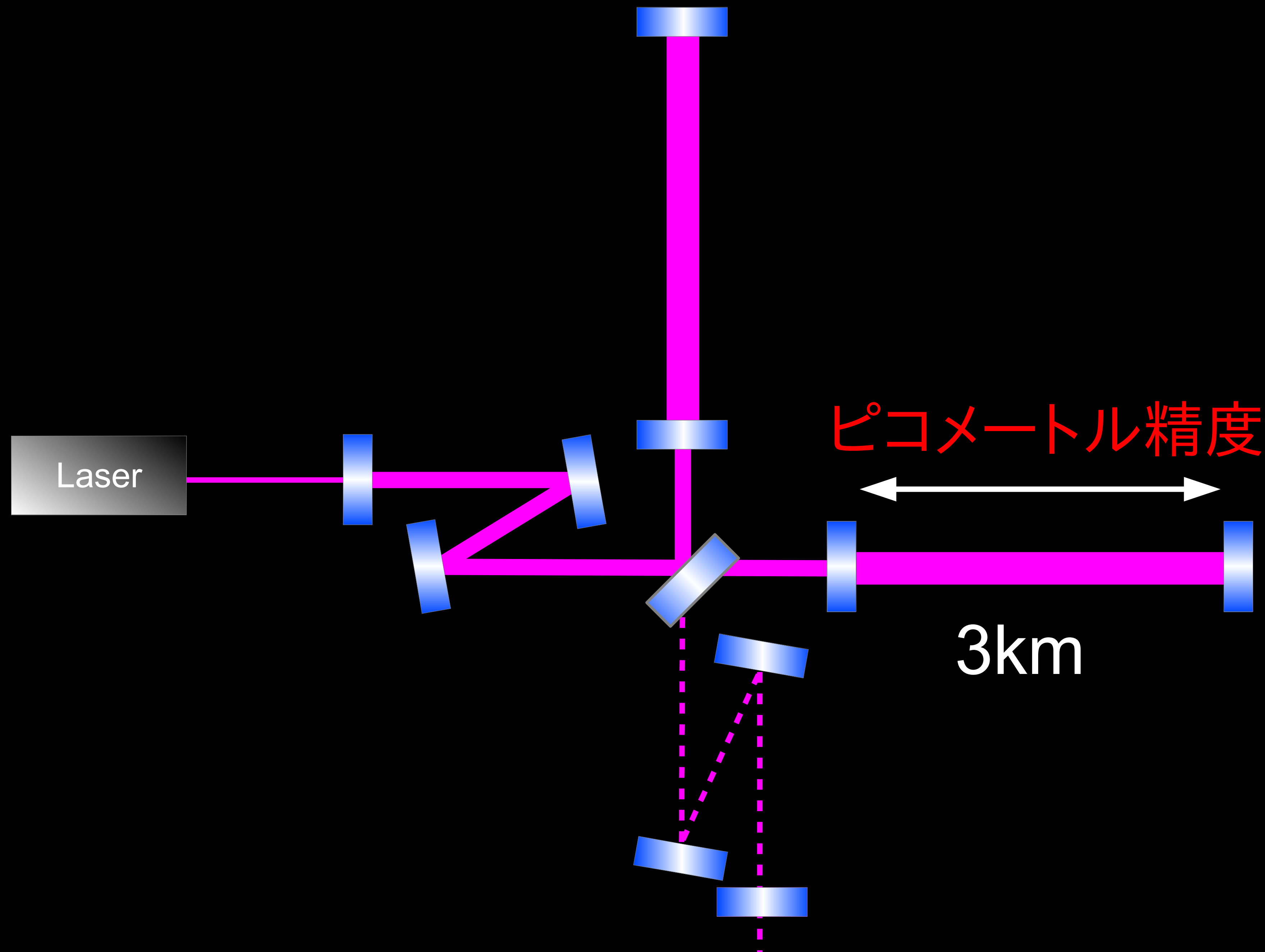


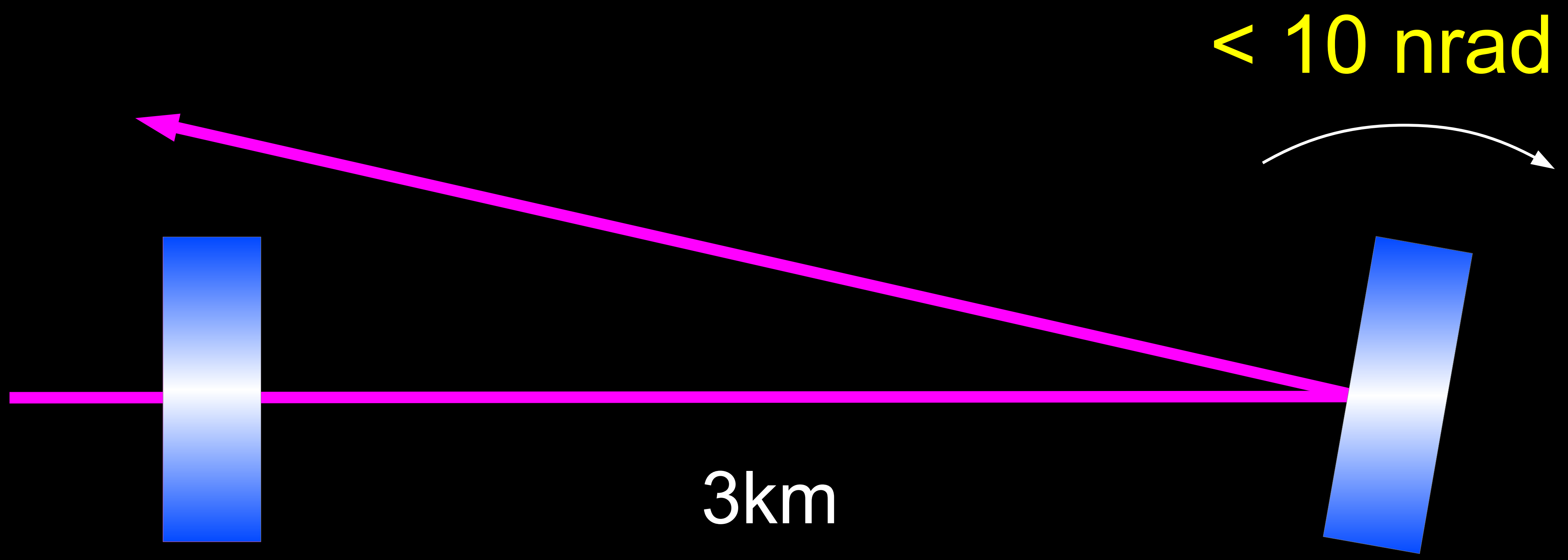
180W Ultra Stable Laser

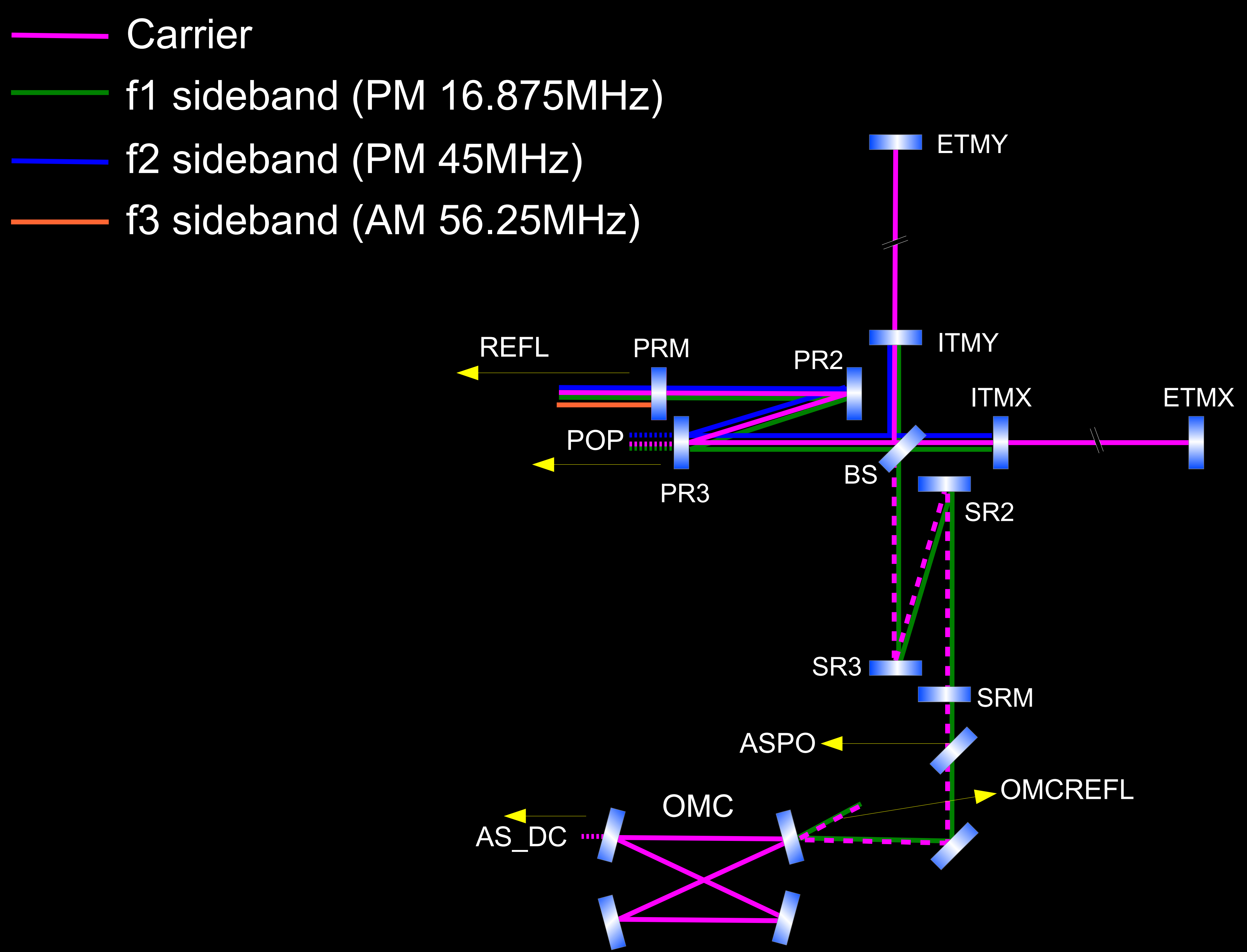




干渉計を最適動作点に保つ

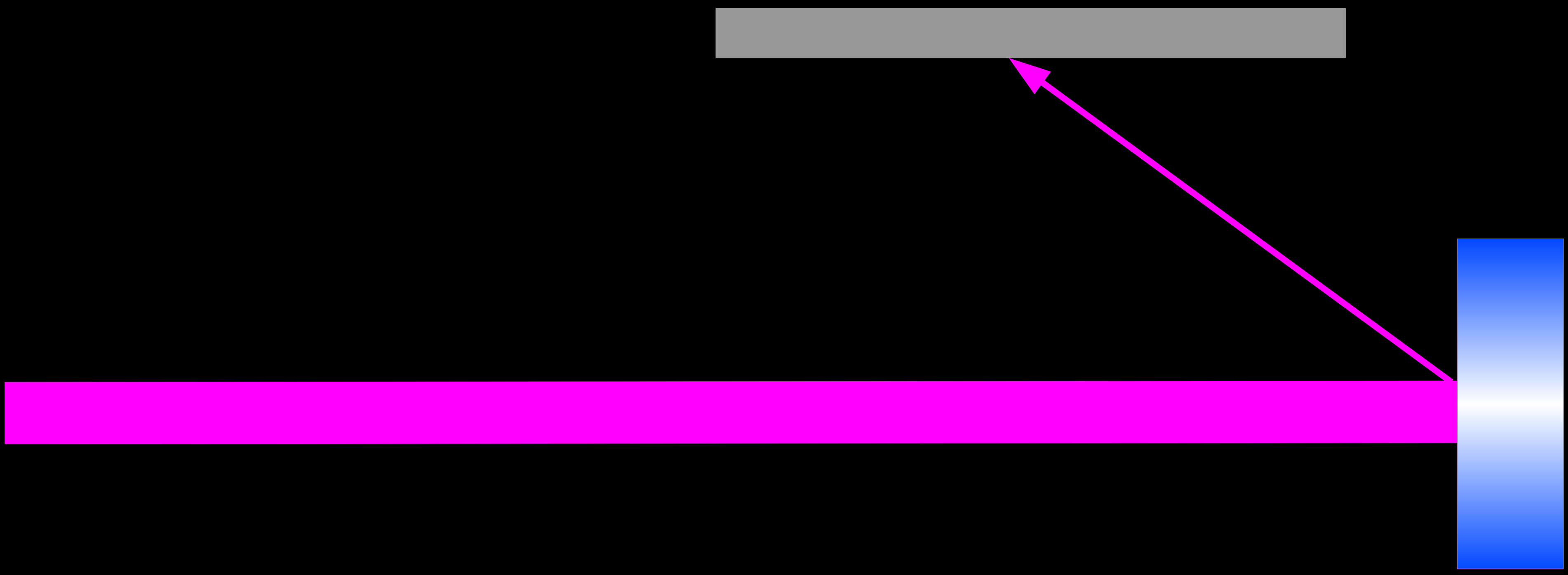



< 10 nrad
3km

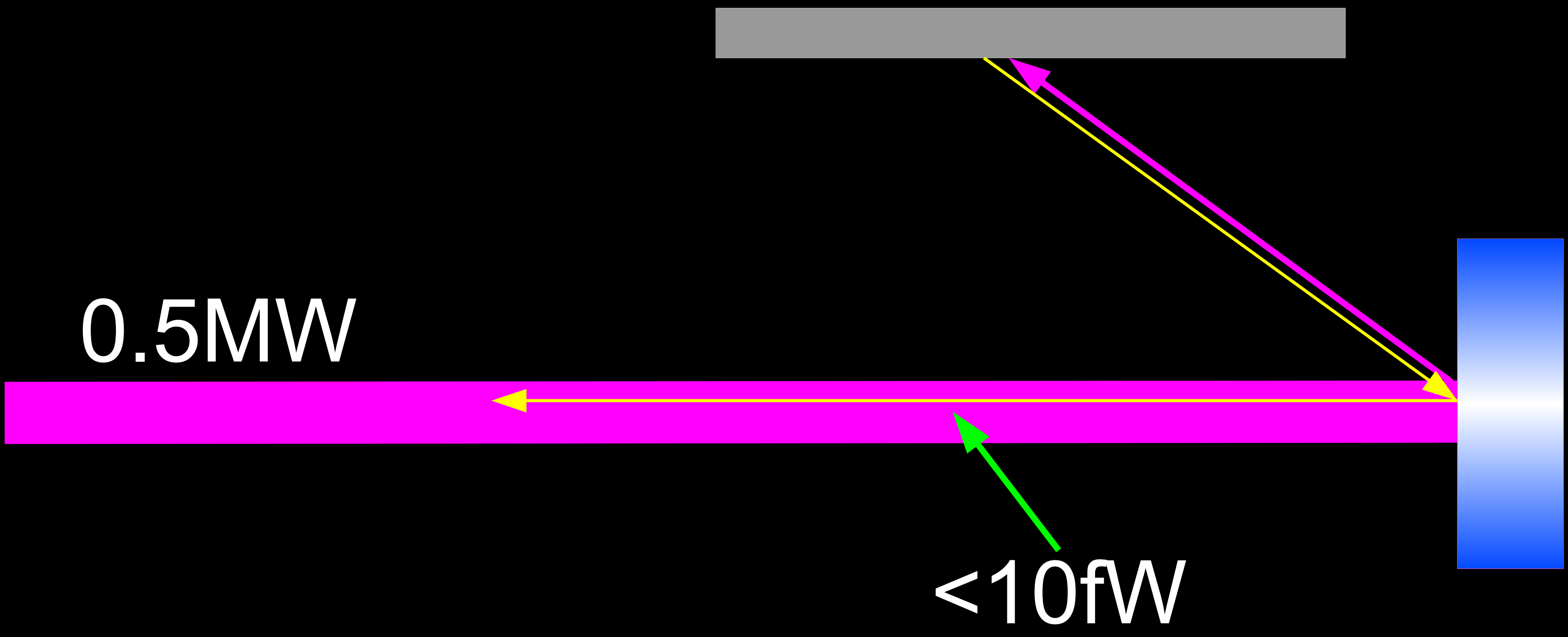

Carrier
f1 sideband (PM 16.875MHz)
f2 sideband (PM 45MHz)
f3 sideband (AM 56.25MHz)
ETMY
ITMY
REFL
PRM
PR2
ITMX
ETMX
POP
BS
PR3
SR2
SR3
SRM
ASPO
OMCREFL
OMC
AS_DC

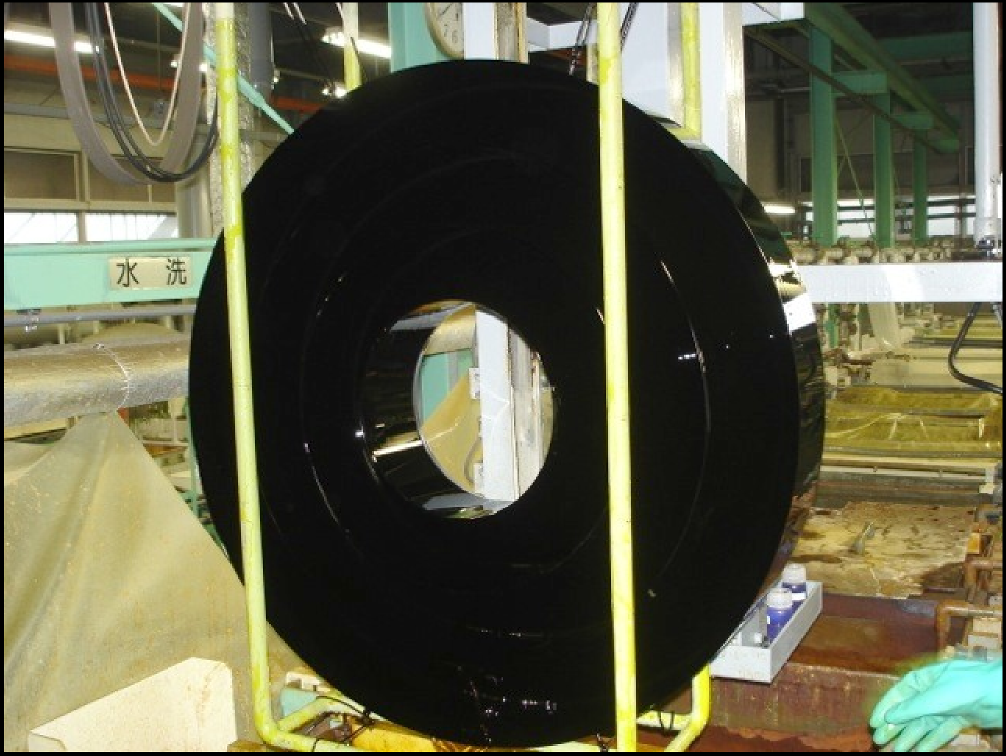
散乱光雑音

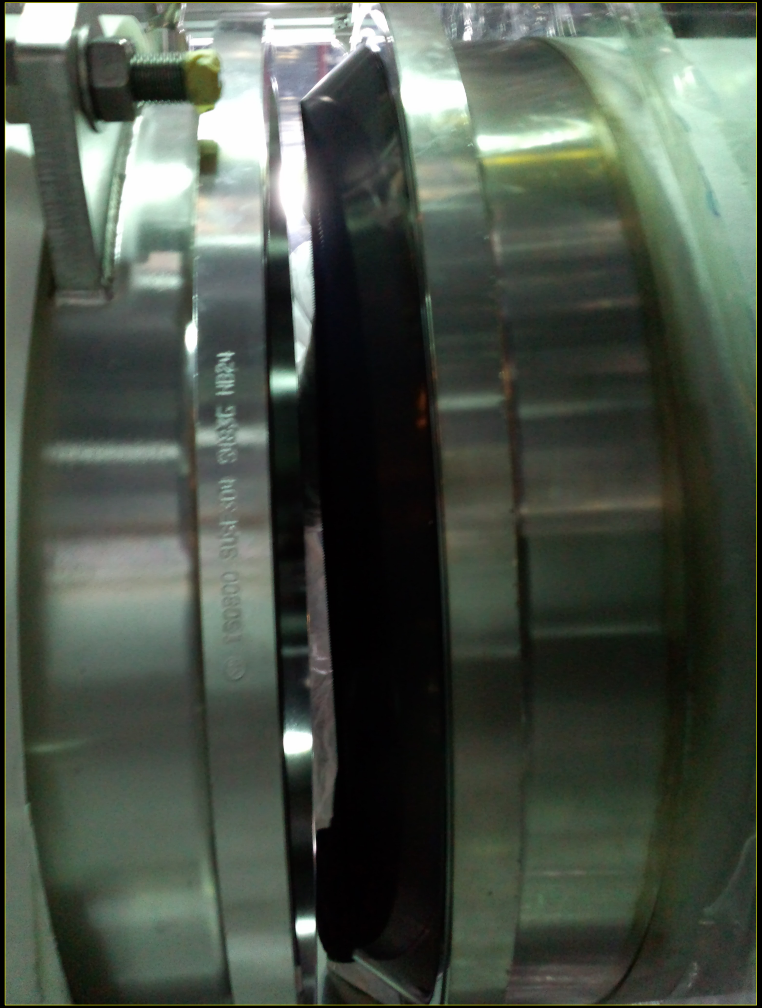
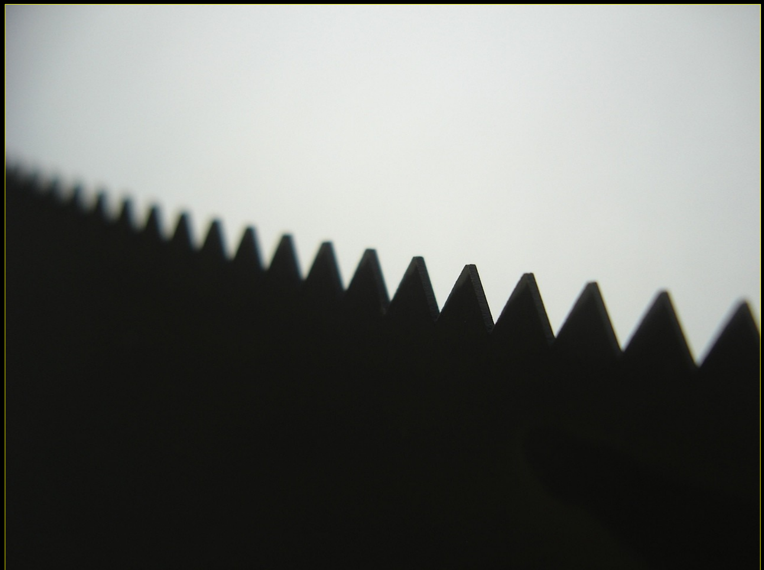
散乱光雑音



散乱光雑音




水 洗

KAGRA プロジェクト

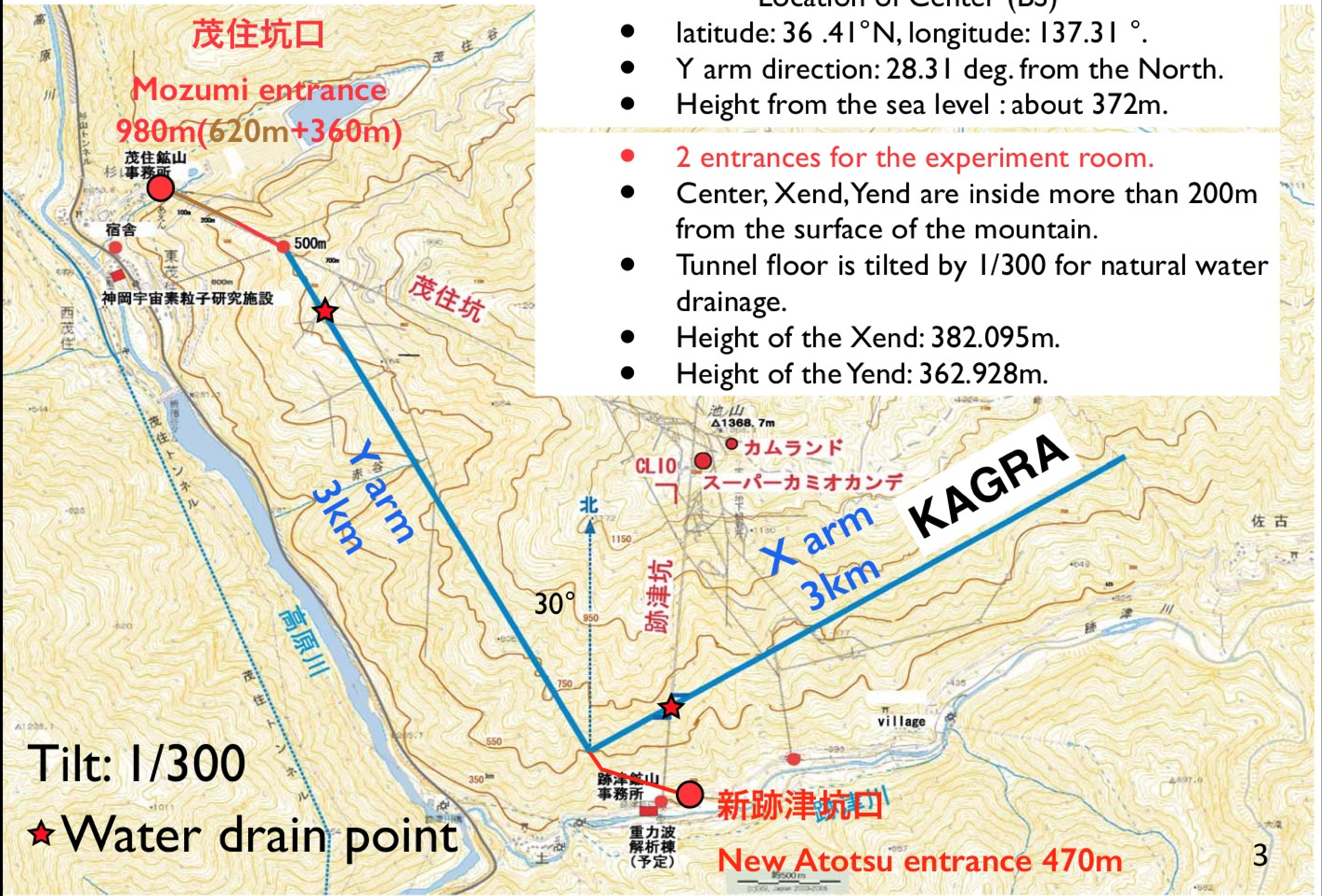
- ホスト機関: 東大宇宙線研, 国立天文台, KEK

  KAGRA Collaboration

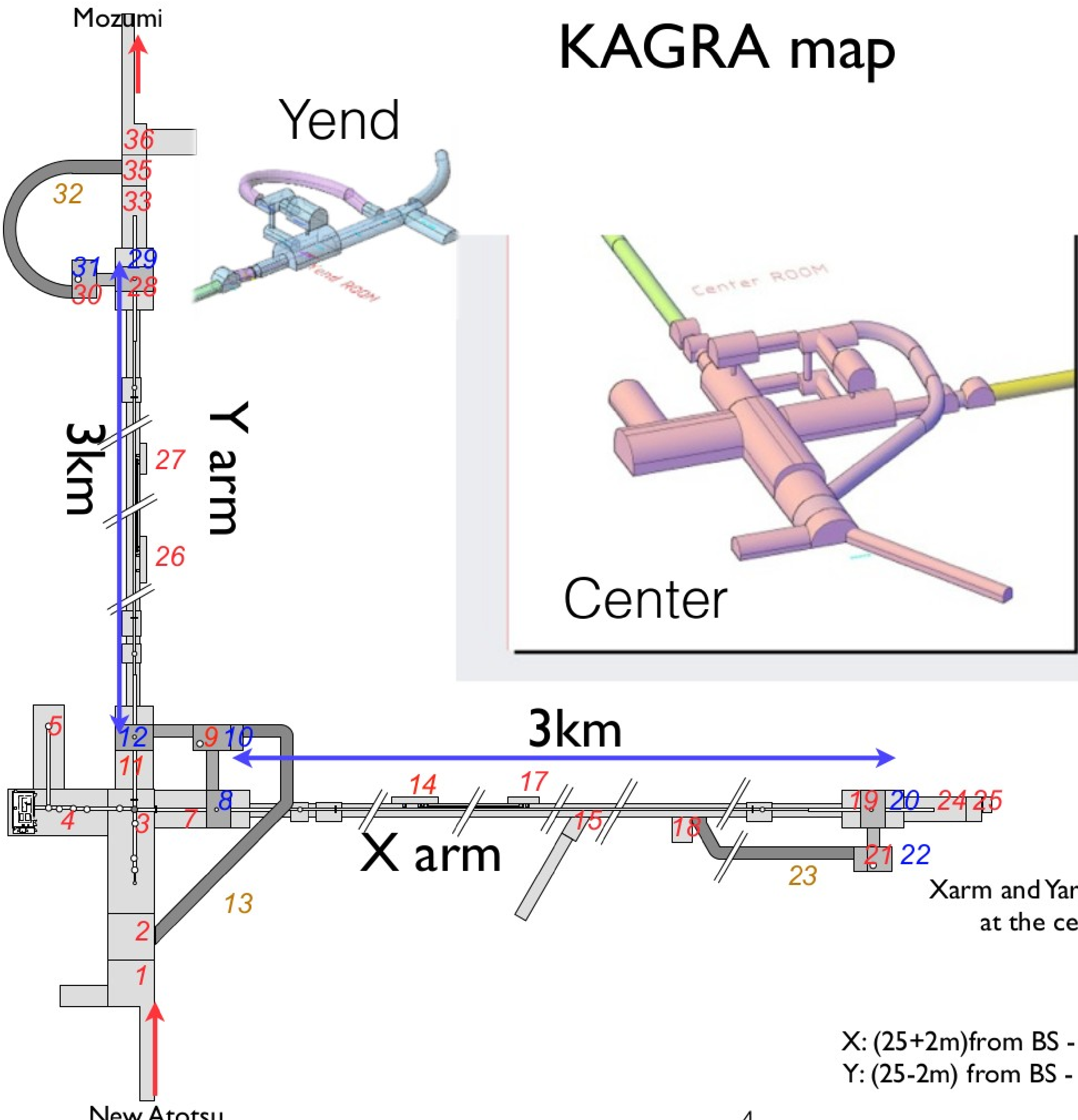
- 国内28機関, 海外36機関
- 共同研究者: 国内155人, 海外76人

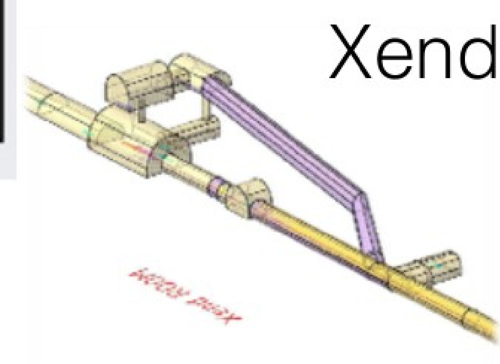
Location of Center (BS)

- latitude: 36 .41°N, longitude: 137.31 °.
- Y arm direction: 28.31 deg. from the North.
- Height from the sea level : about 372m.
- 2 entrances for the experiment room.
- Center, Xend, Yend are inside more than 200m from the surface of the mountain.
- Tunnel floor is tilted by 1/300 for natural water drainage.
- Height of the Xend: 382.095m.
- Height of the Yend: 362.928m.



KAGRA map





Xarm and Yarm cross perpendicularly at the center of BS chamber.

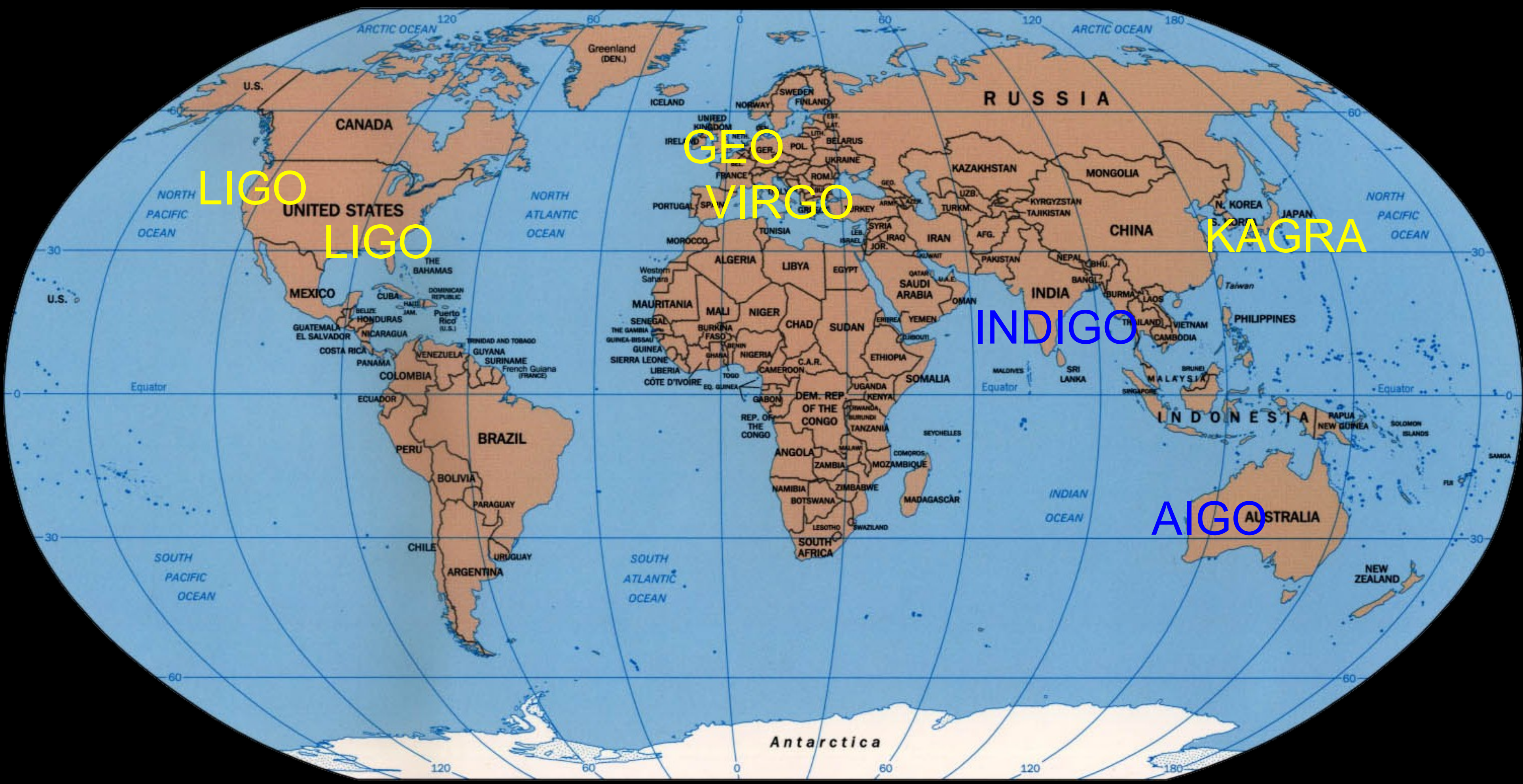
3km:

X: (25+2m)from BS - Center of X end cryostat room

Y: (25-2m) from BS - Center of Y end cryostat room

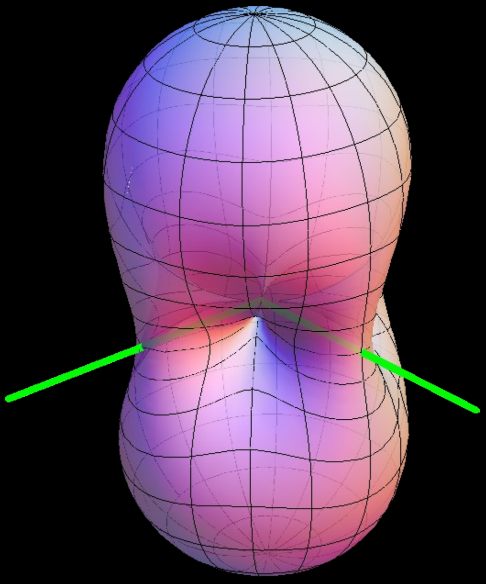

VAT

World Wide Network of GW Detectors



Start observations: ~ 2017

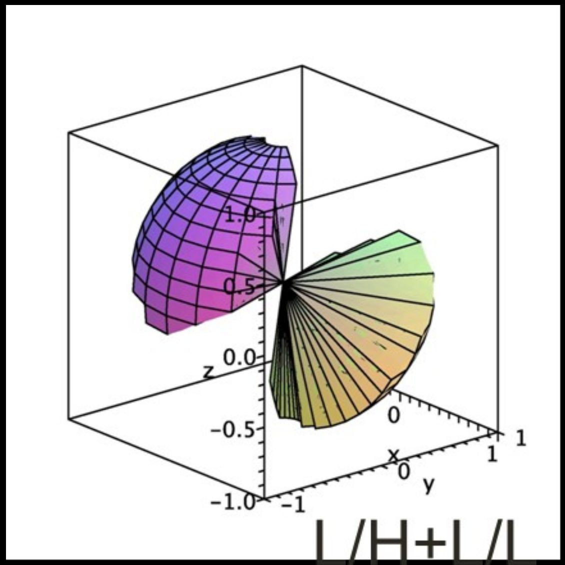
天球カバー率

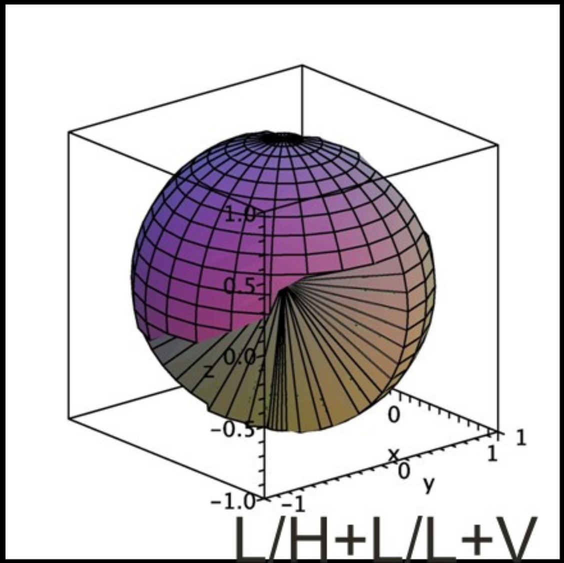


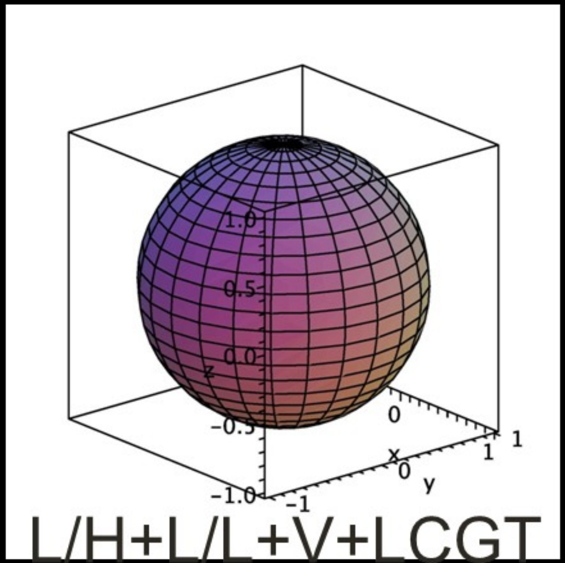
LIGO Only

LIGO+VIRGO

LIGO+VIRGO+KAGRA





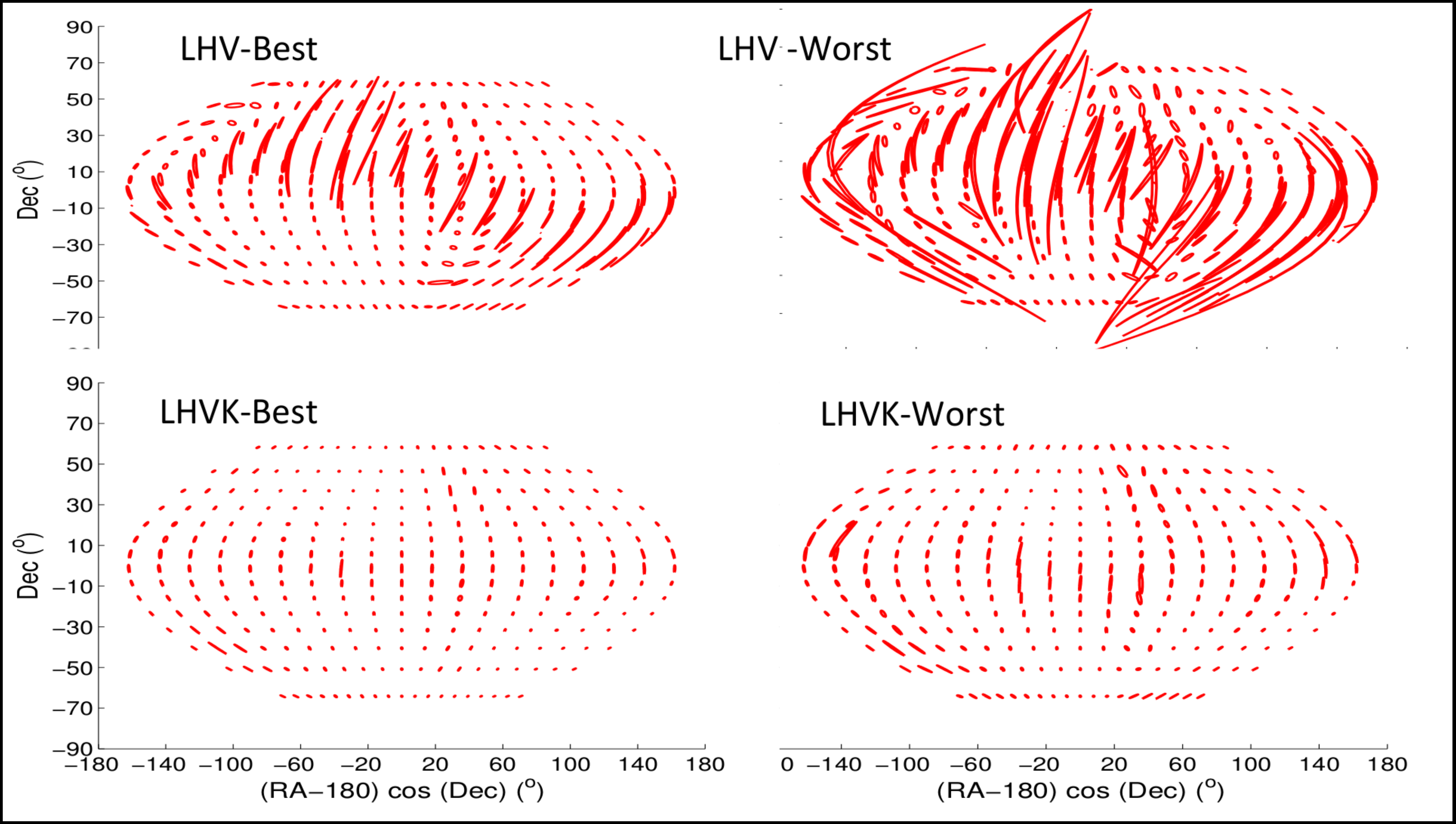


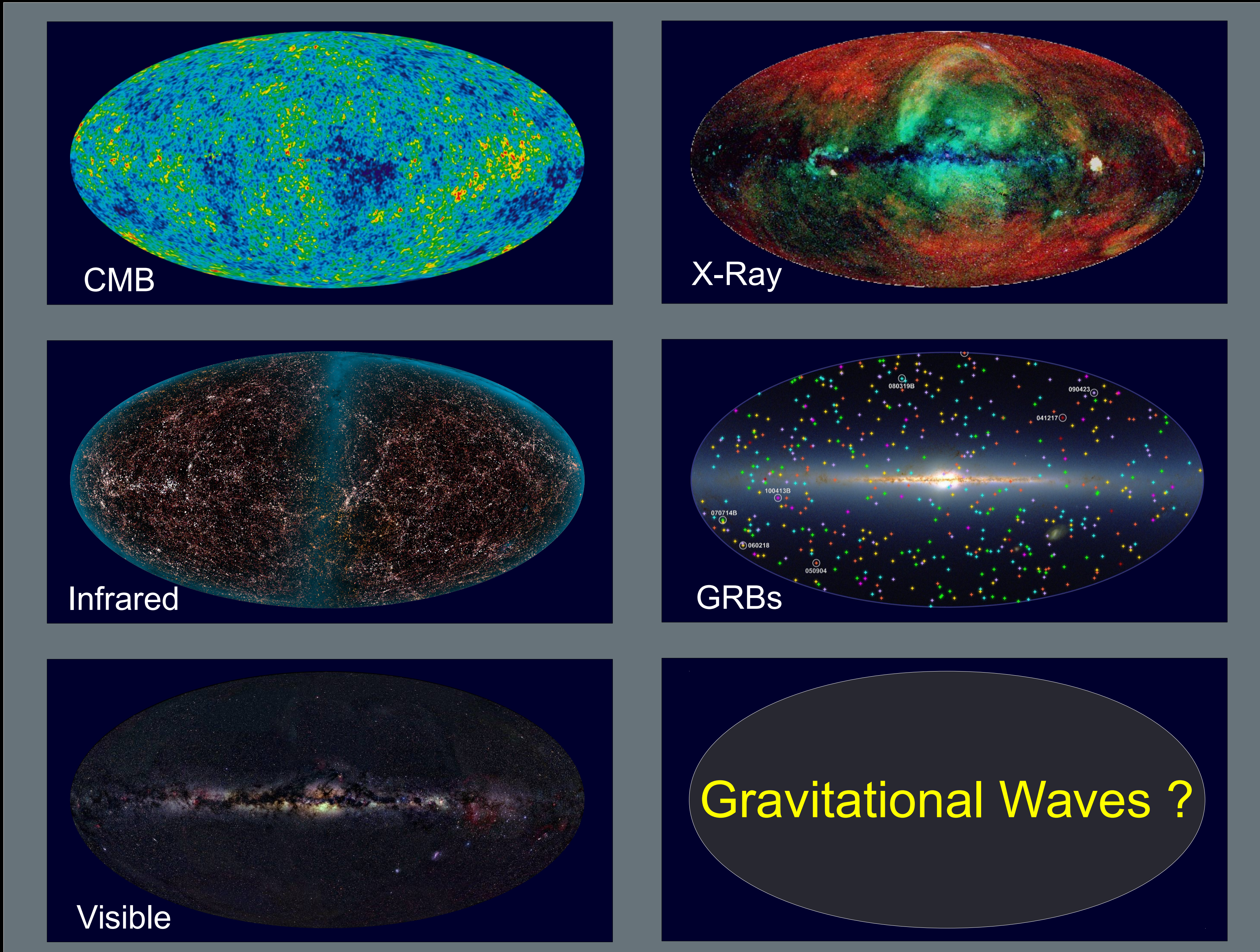
33%

72%

100%

重力波源の位置決定精度




CMB
X-Ray
Infrared
080319B
090423
041217
100413B
070714B
060218
050904
GRBs
Visible
Gravitational Waves ?