

極限計測技術で拓く新しい天文学

重力波望遠鏡KAGRA

国立天文台 重力波プロジェクト推進室
麻生洋一

2015/12/9 第5回 可視赤外線観測装置技術ワークショップ

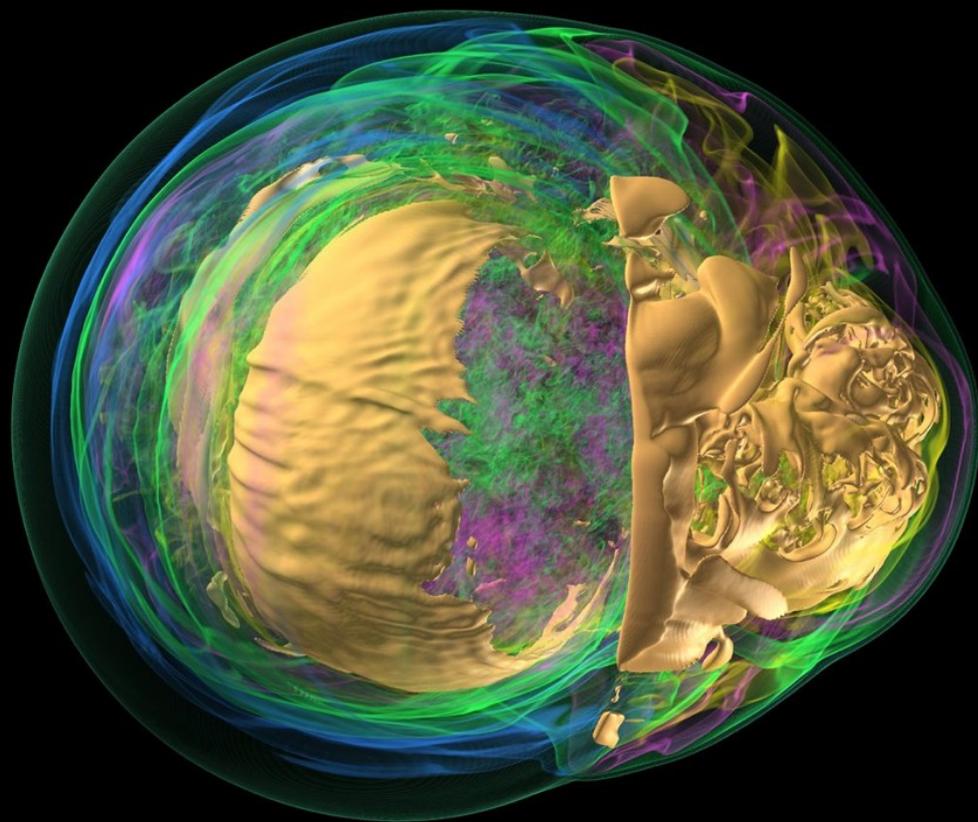
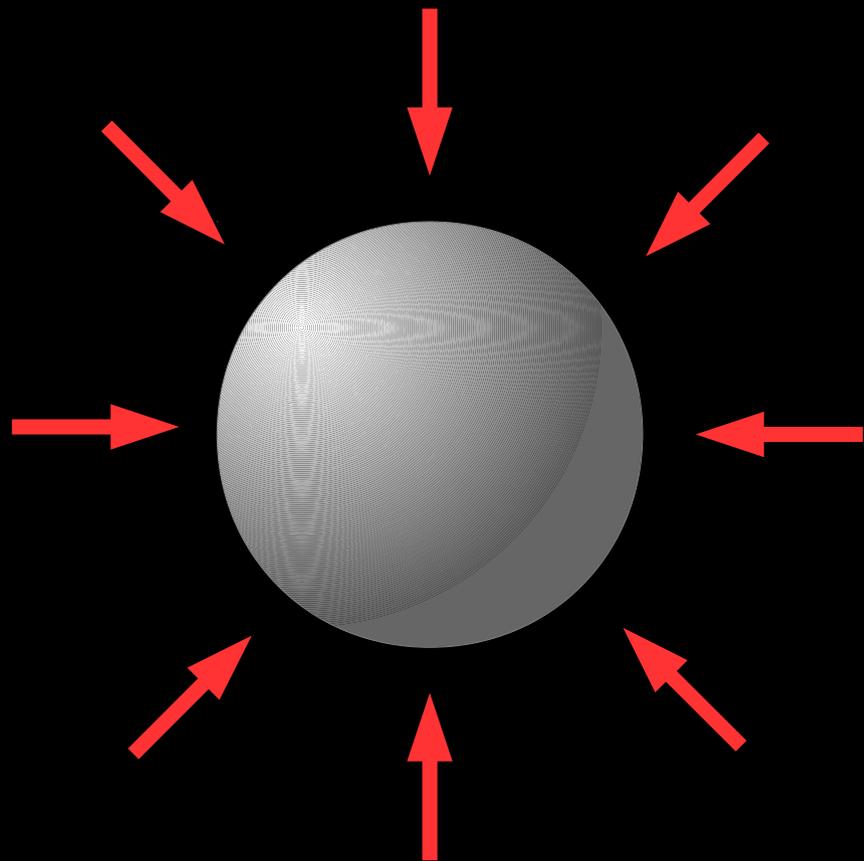
電磁波による観測

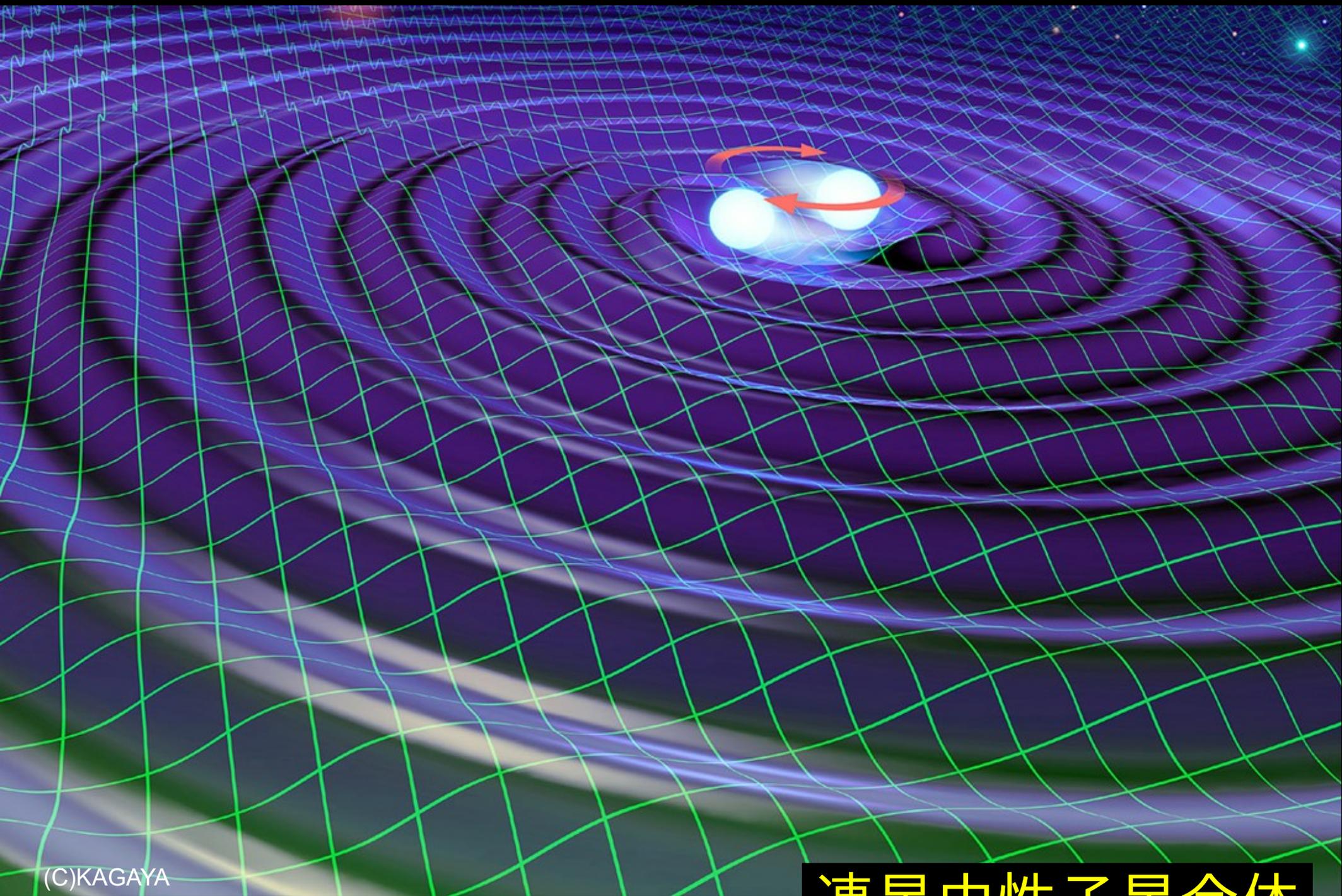




ガンマ線バースト

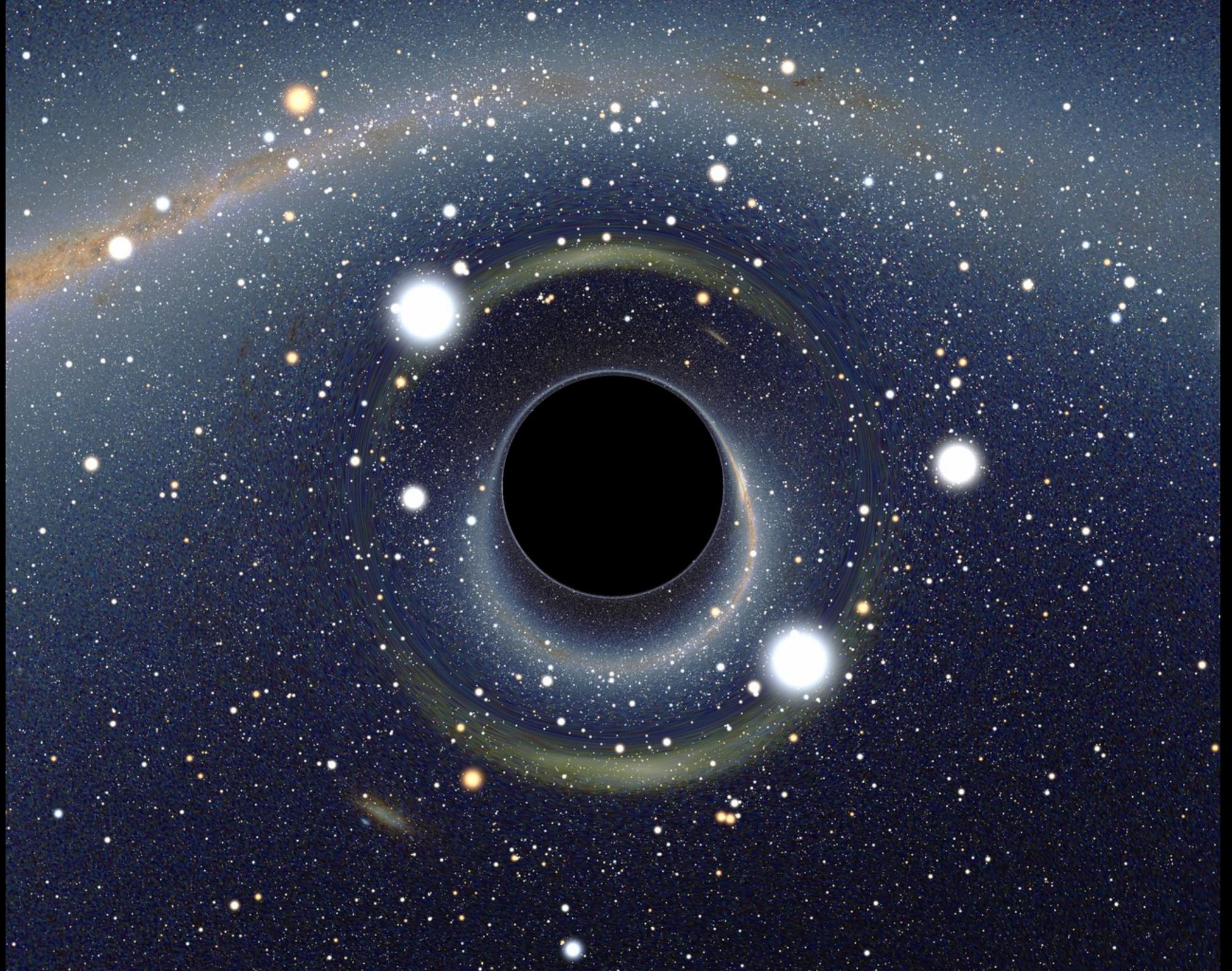
星コアの重力崩壊

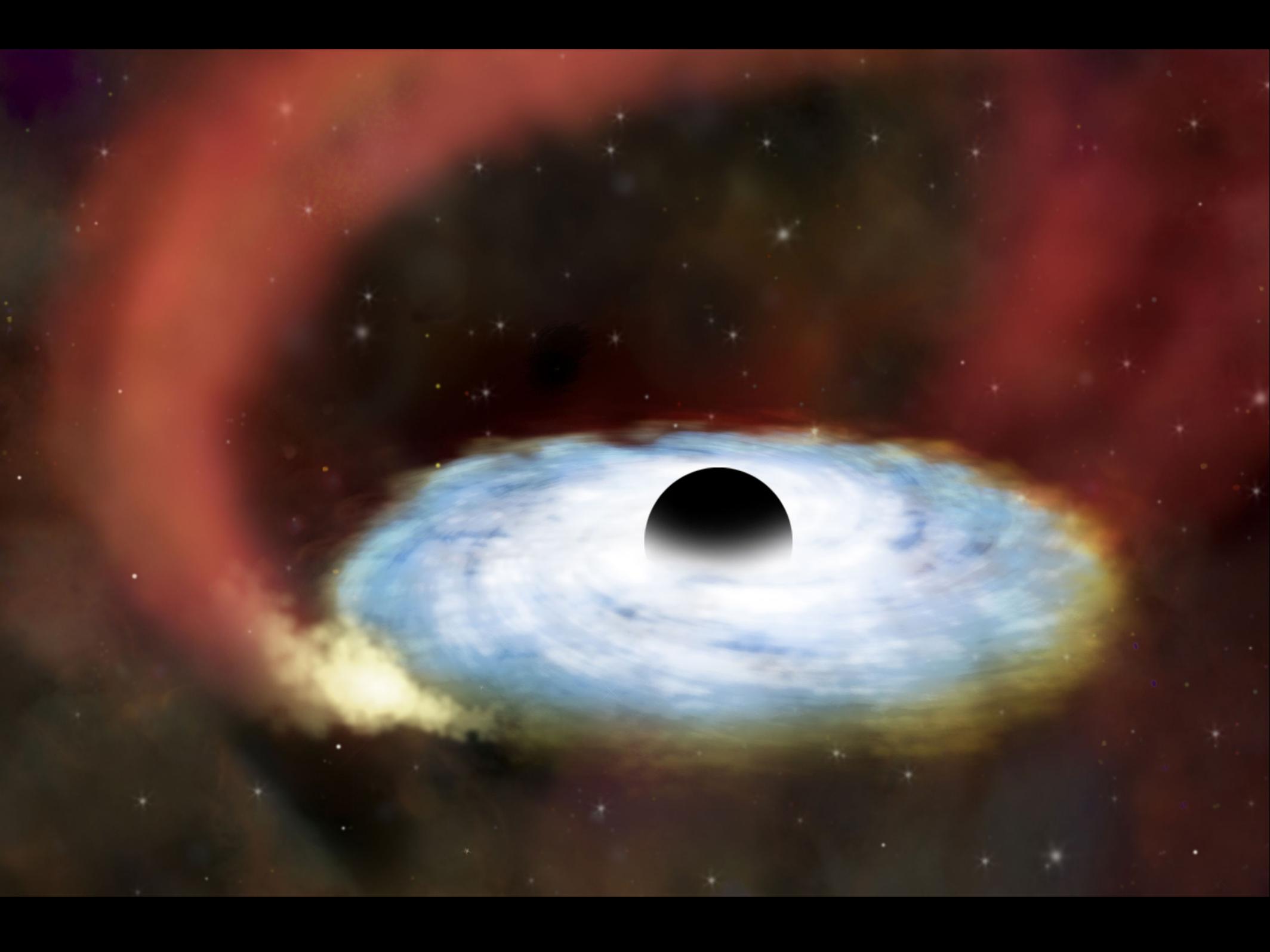


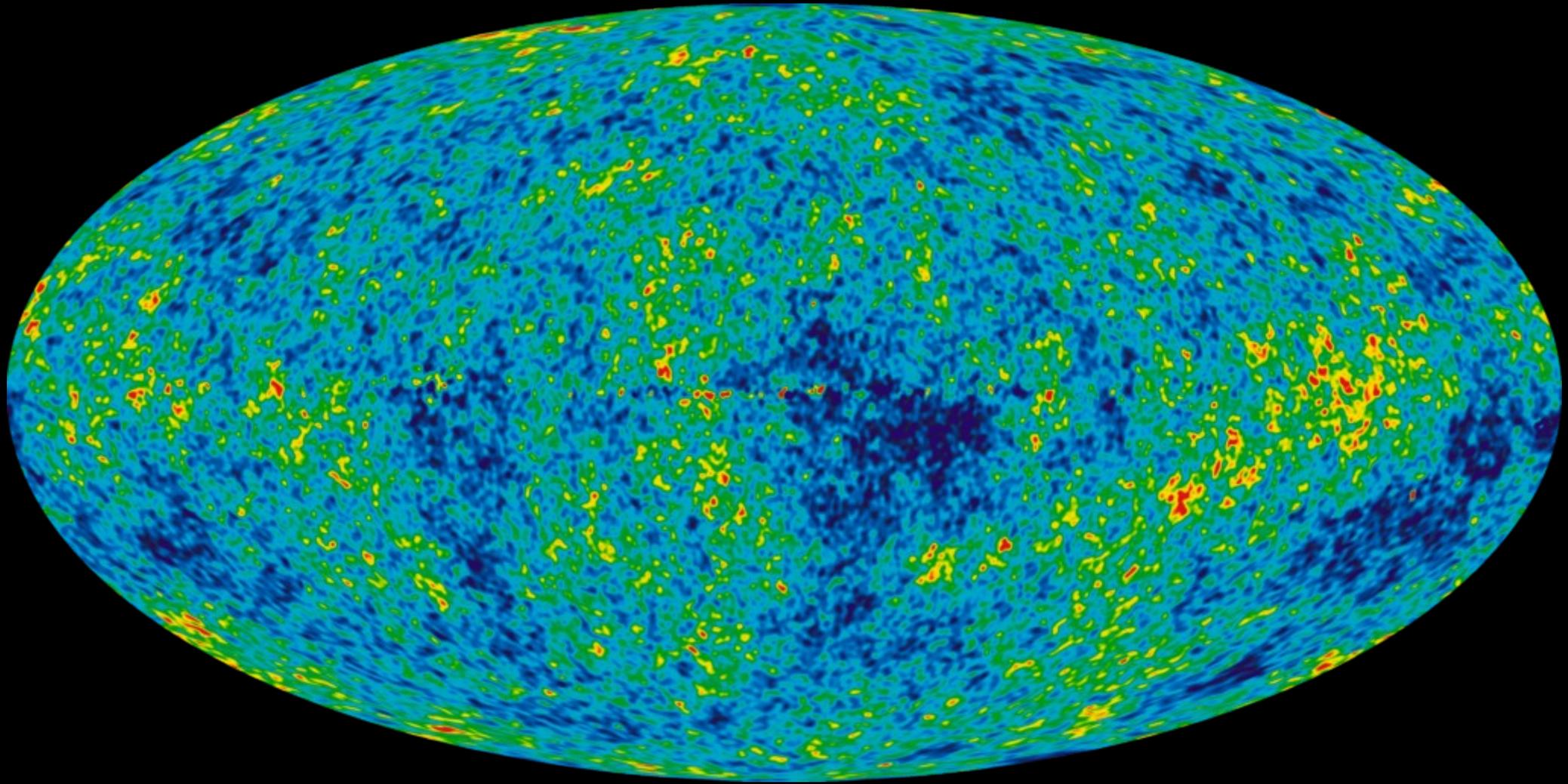


(C)KAGAYA

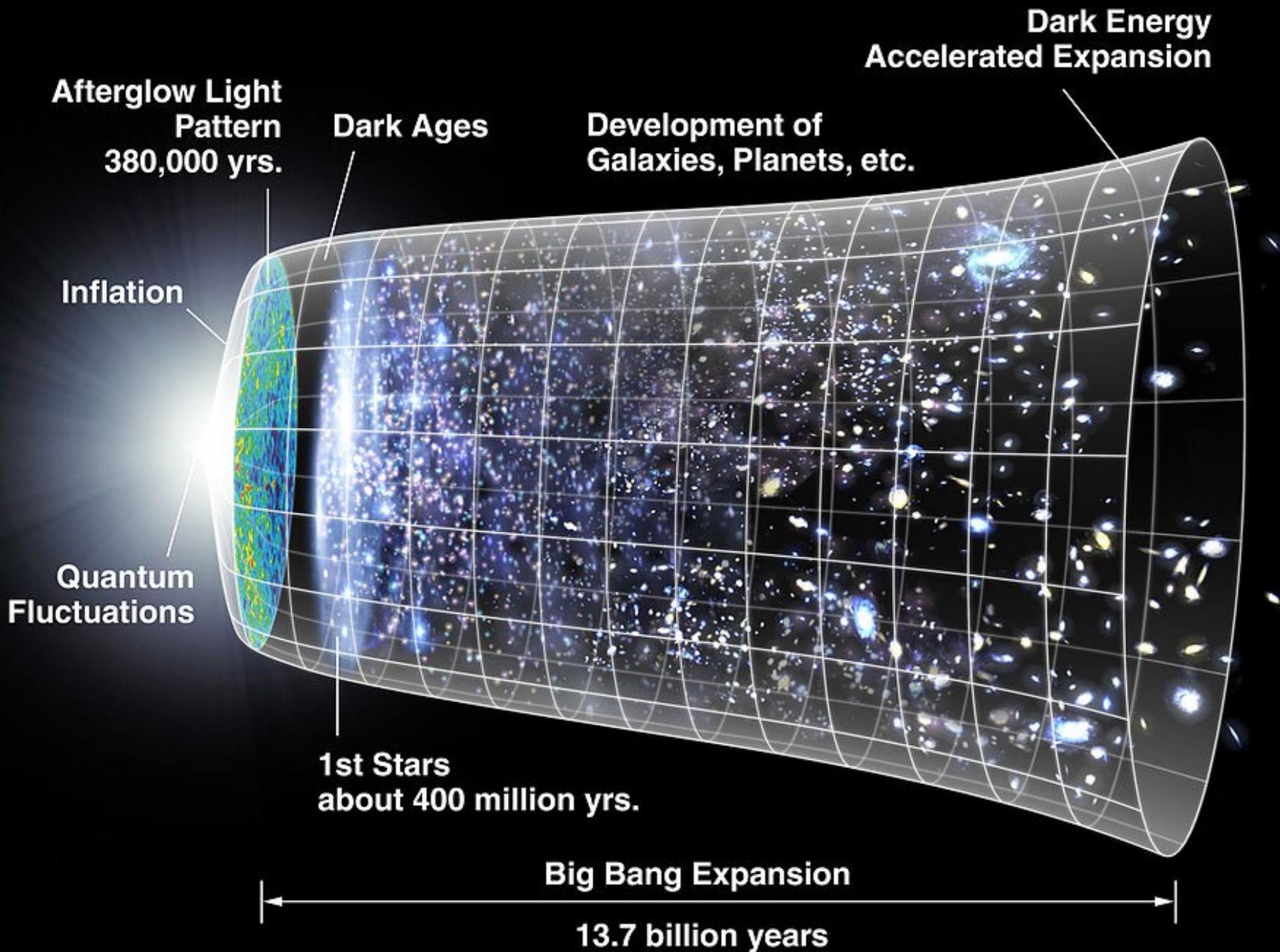
連星中性子星合体



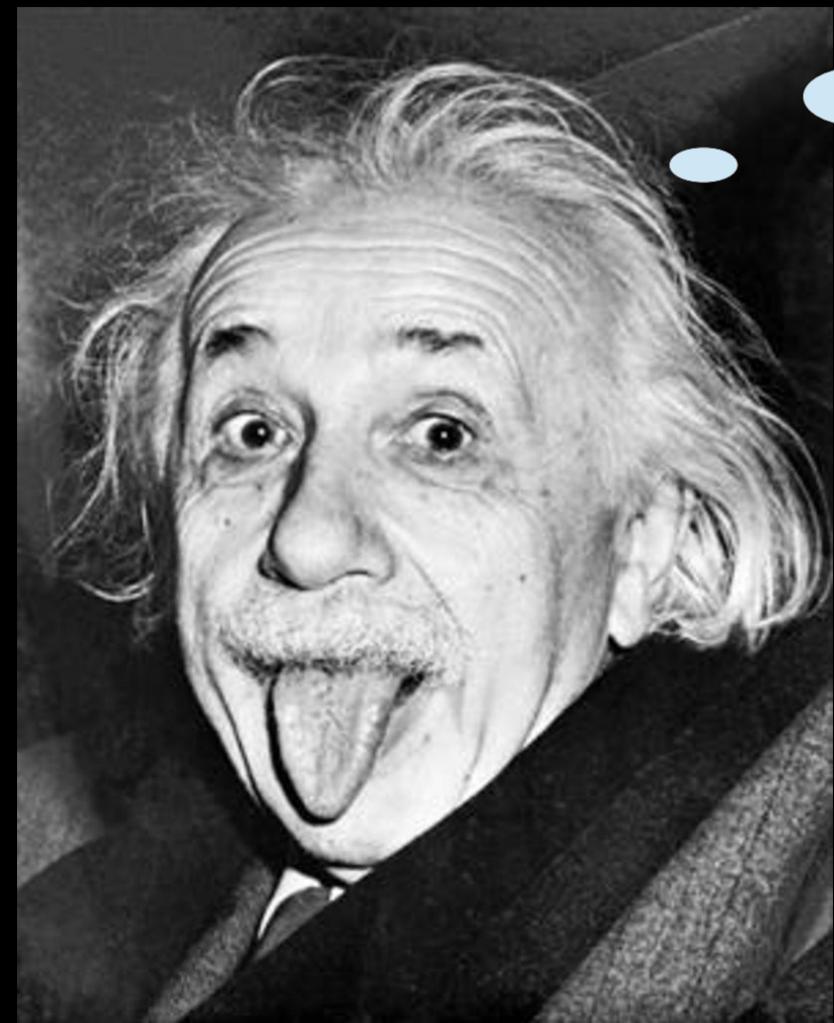


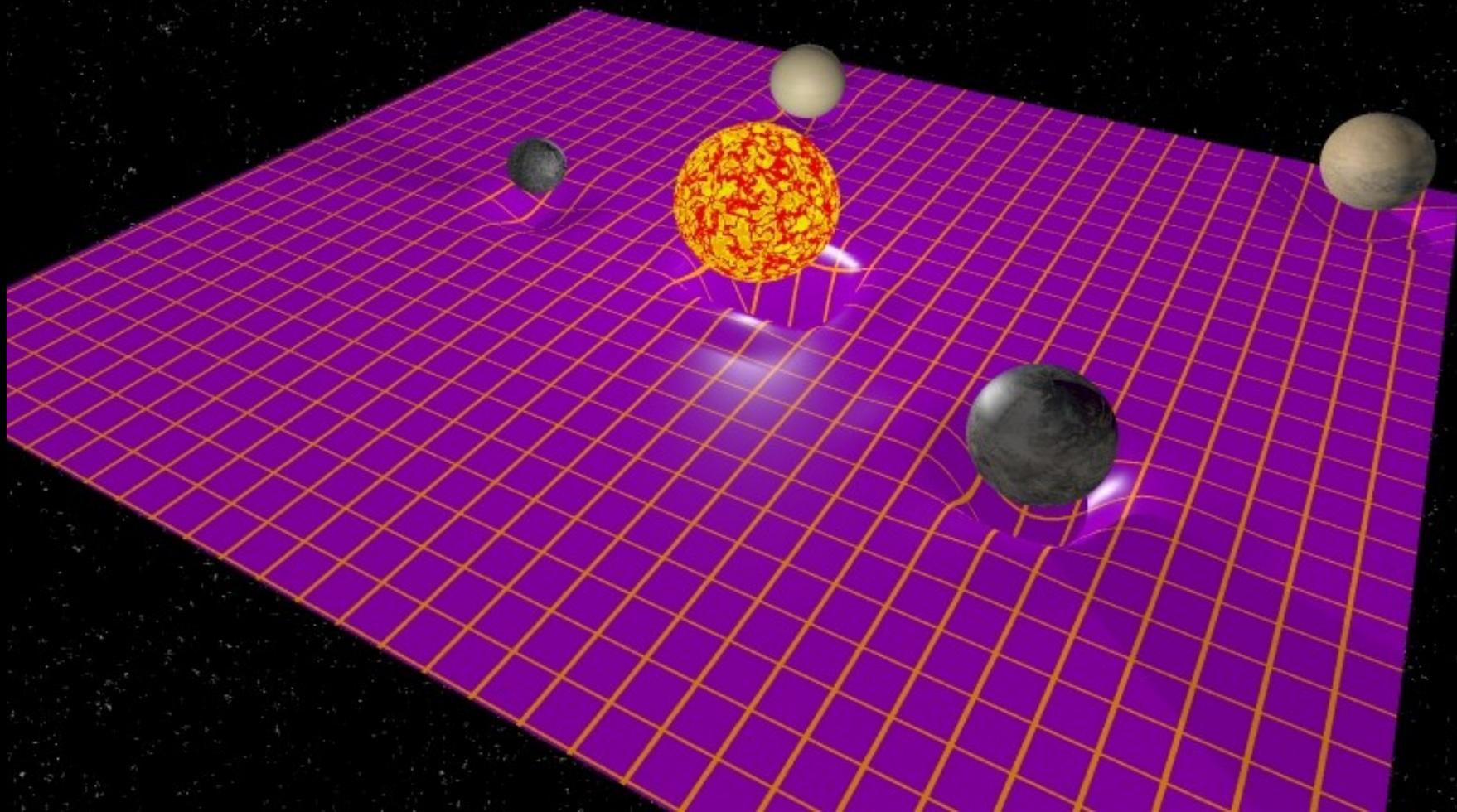


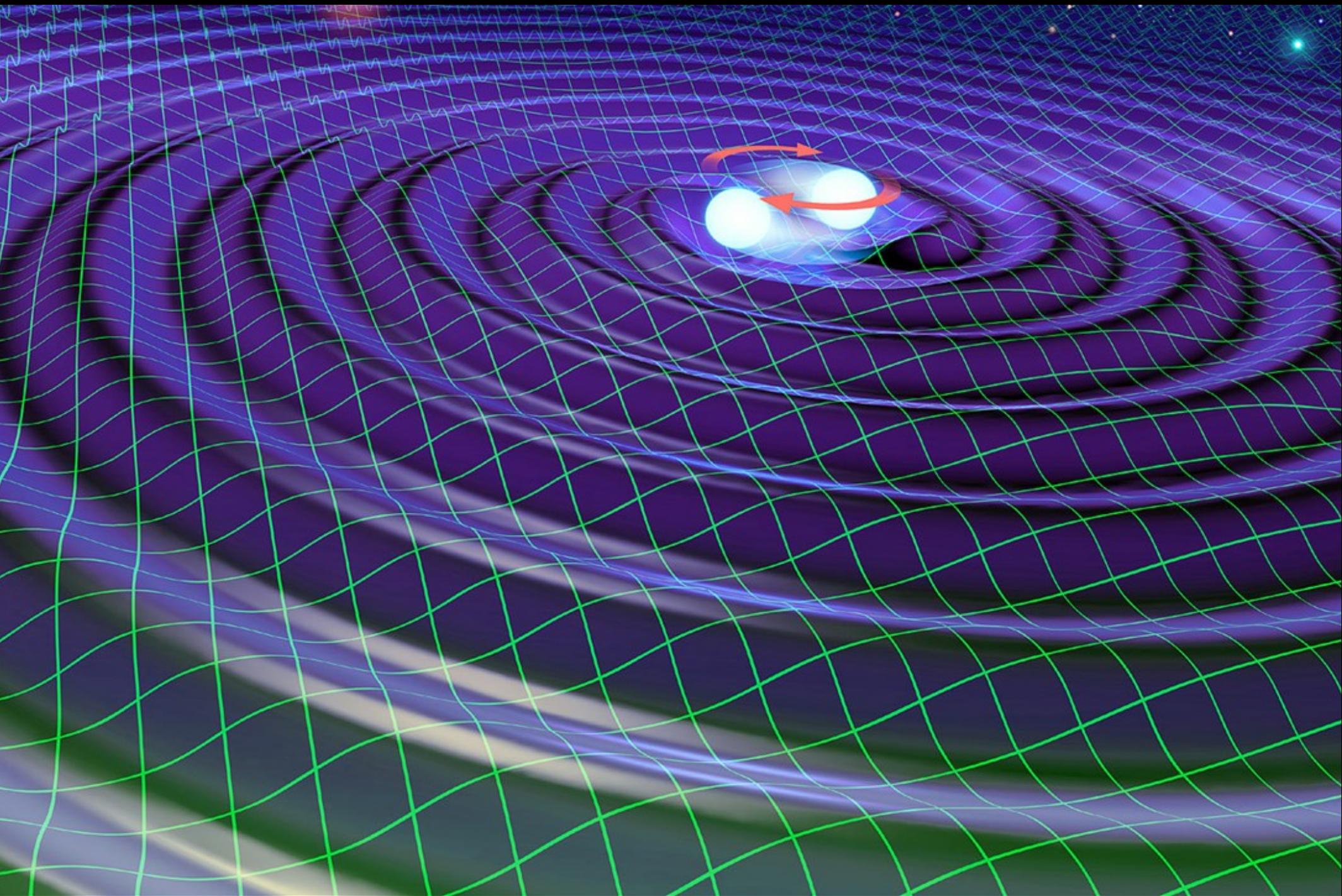
Cosmic Microwave Background



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







重力波

電磁波

生成機構

巨視的な質量
の運動

荷電粒子の運動

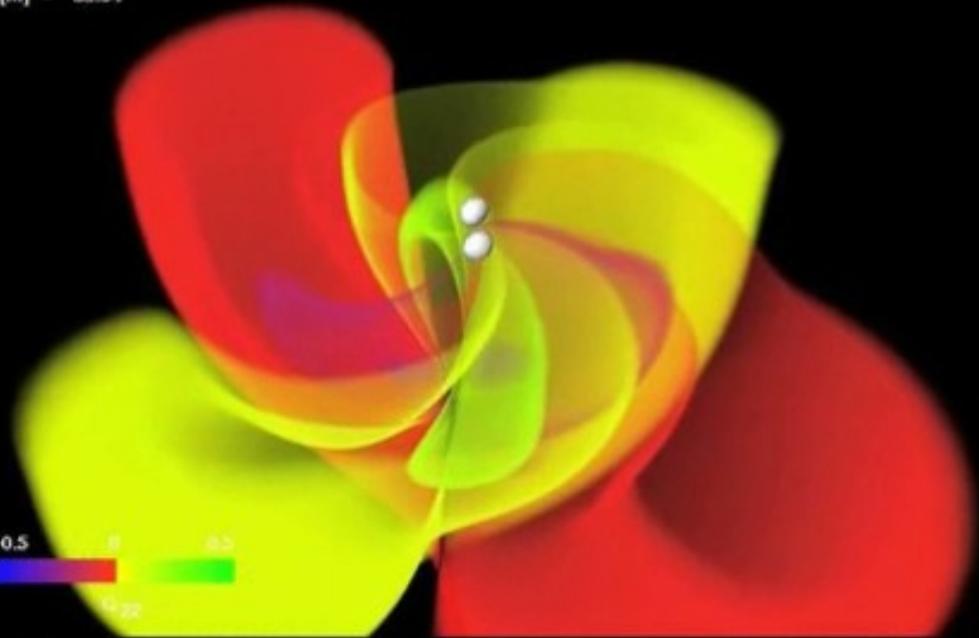
物質との相互作用

極めて弱い

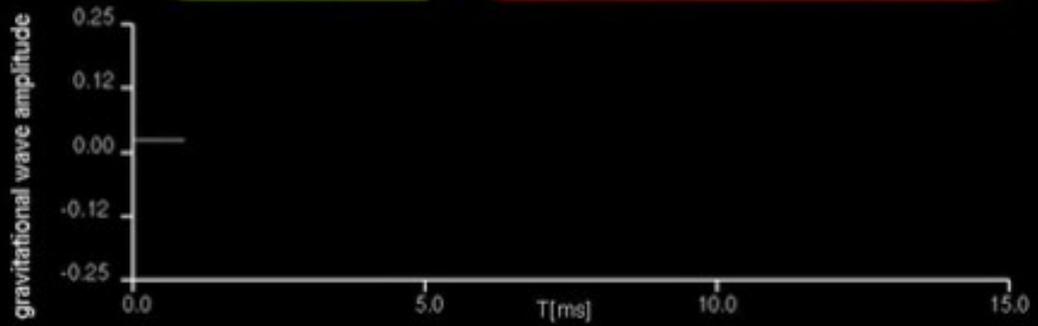
強い



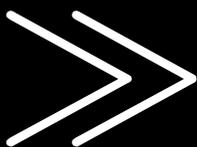
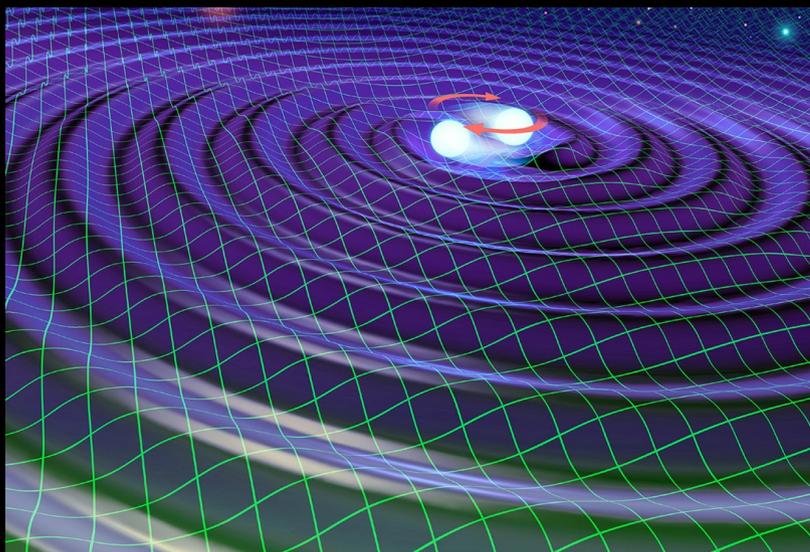
T[ms] - 0.88
T[M] - 83.64



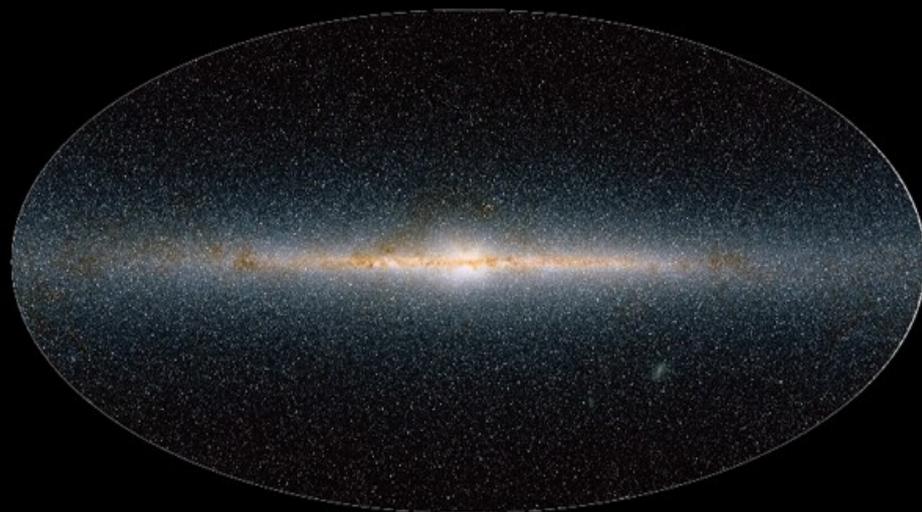
-0.5 0 0.5



重力波の
エネルギー放出率



全宇宙可視光
のエネルギー放出率



重力波のLuminosityスケール

$$L_0 = 3.6 \times 10^{52} \text{ J/s}$$

太陽のLuminosity

$$L_{\text{sun}} = 3.8 \times 10^{26} \text{ J/s}$$

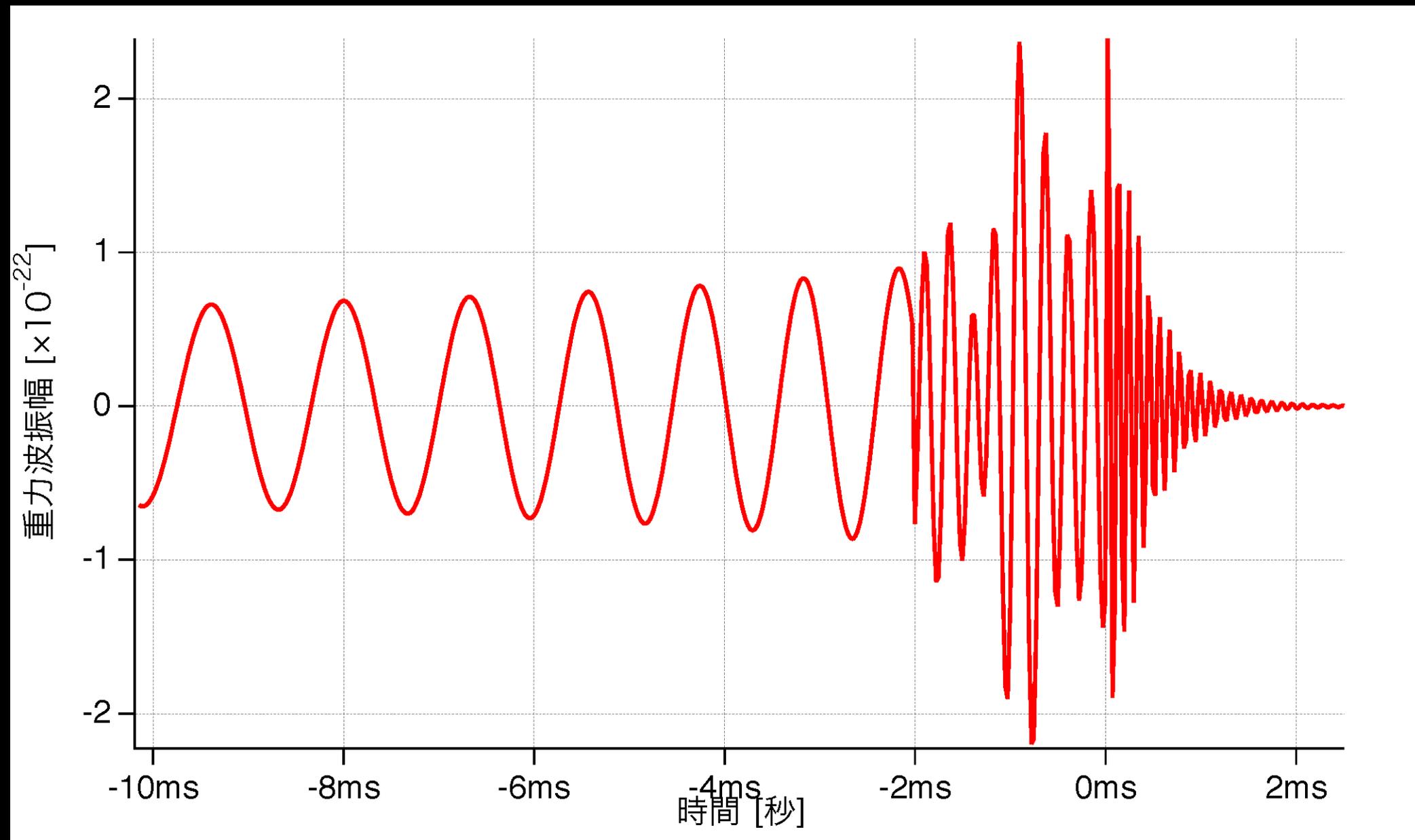
銀河のLuminosity

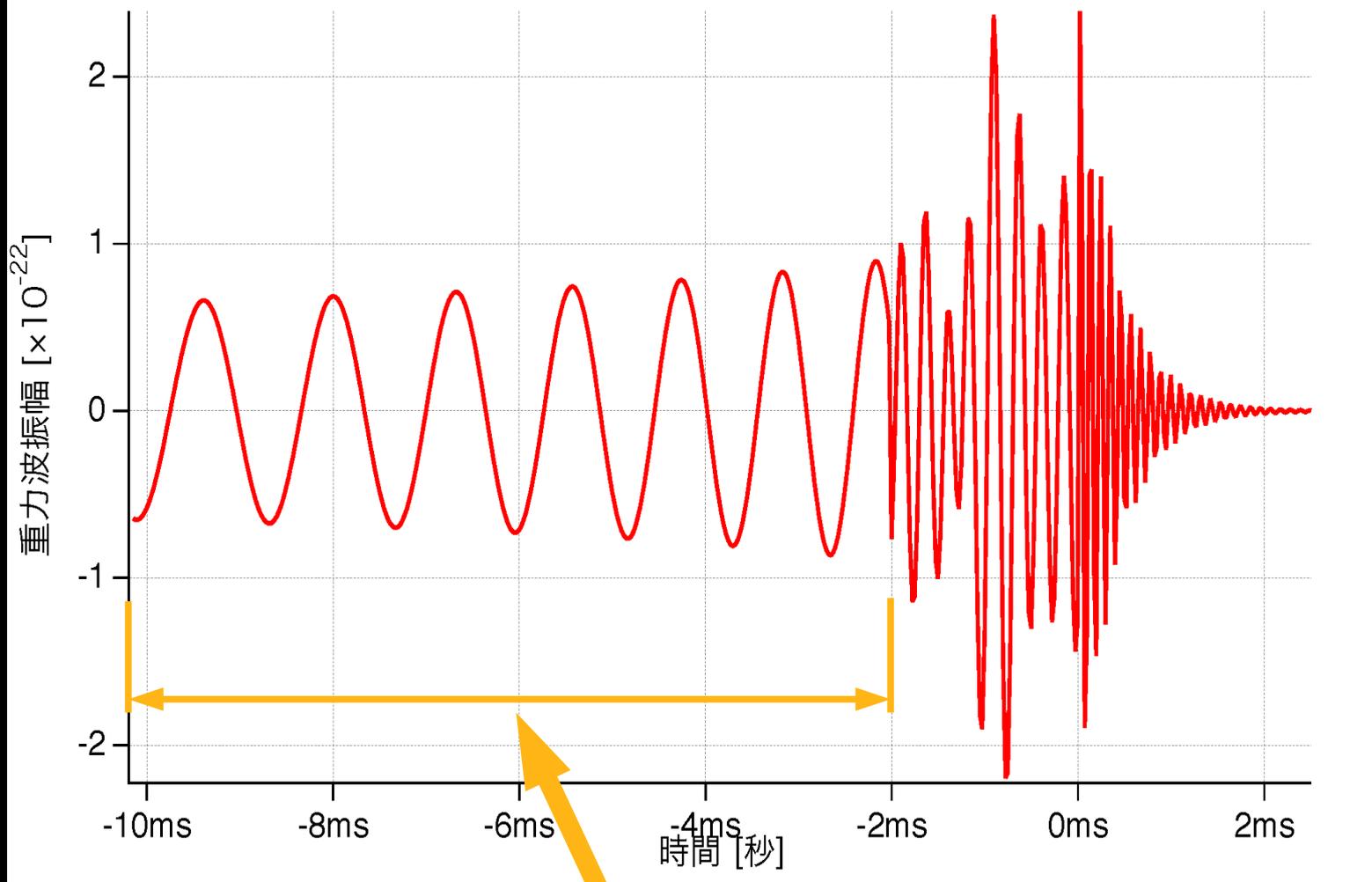
$$L_{\text{galaxy}} = 10^{37} \text{ J/s}$$

全宇宙の可視光Luminosity

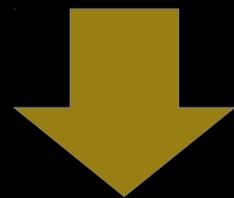
$$L_{\text{univ.}} = 10^{49} \text{ J/s}$$

連星中性子星合体: 重力波の波形



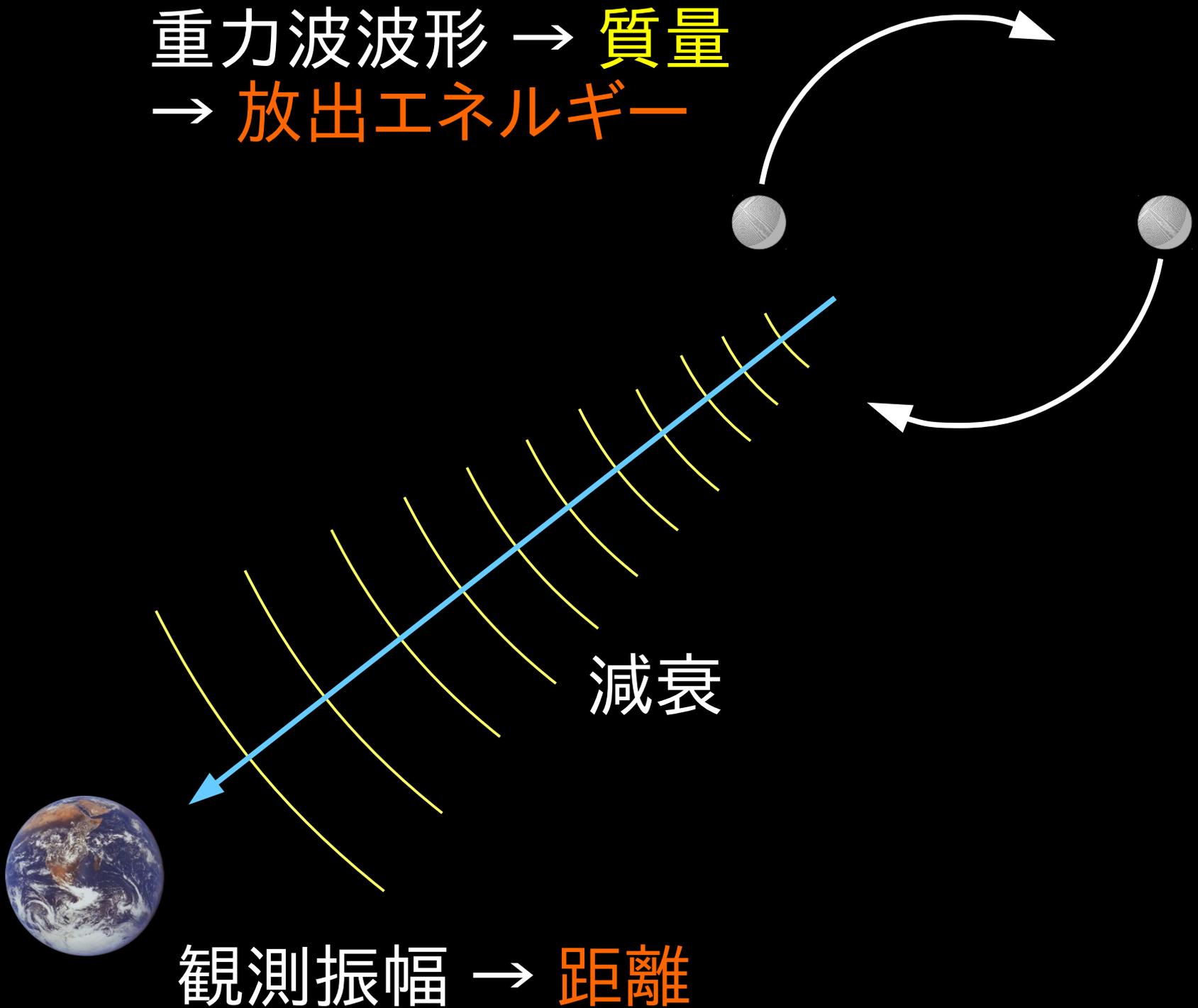


振幅・周波数・周波数変化・位相発展



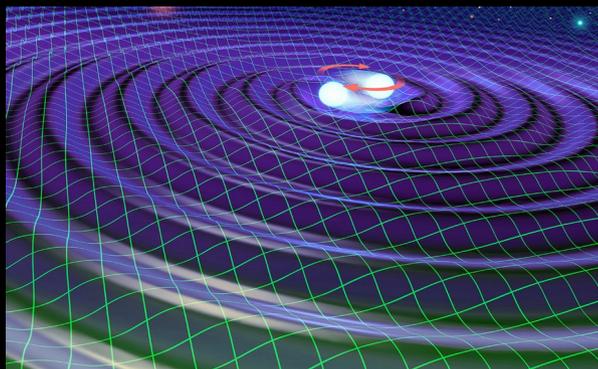
連星系の質量情報

重力波波形 → 質量
→ 放出エネルギー

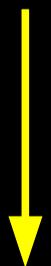


減衰

観測振幅 → 距離



重力波観測



- 距離
- 大まかな位置



ガンマ線バースト
残光観測



- 母銀河特定

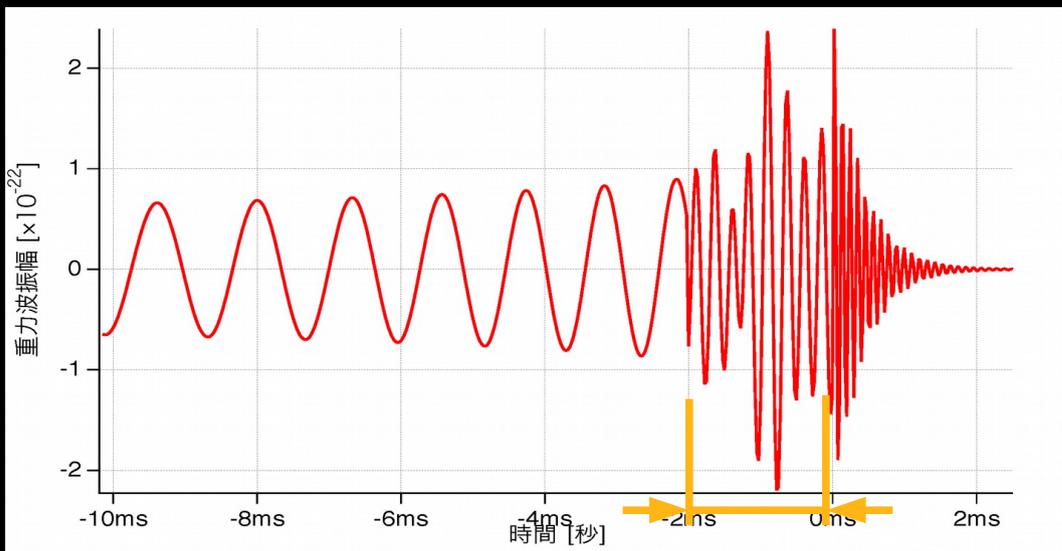


分光観測

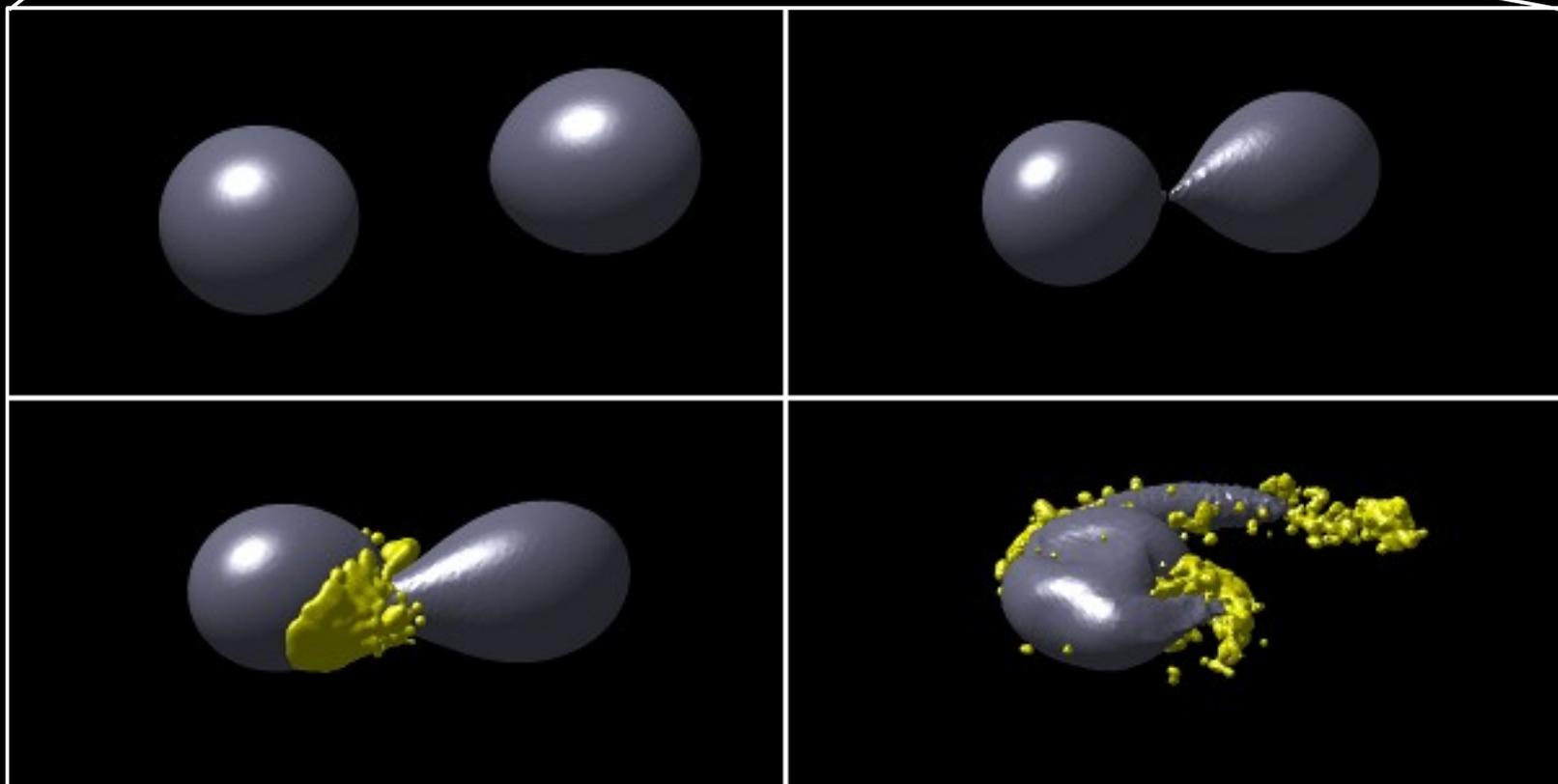


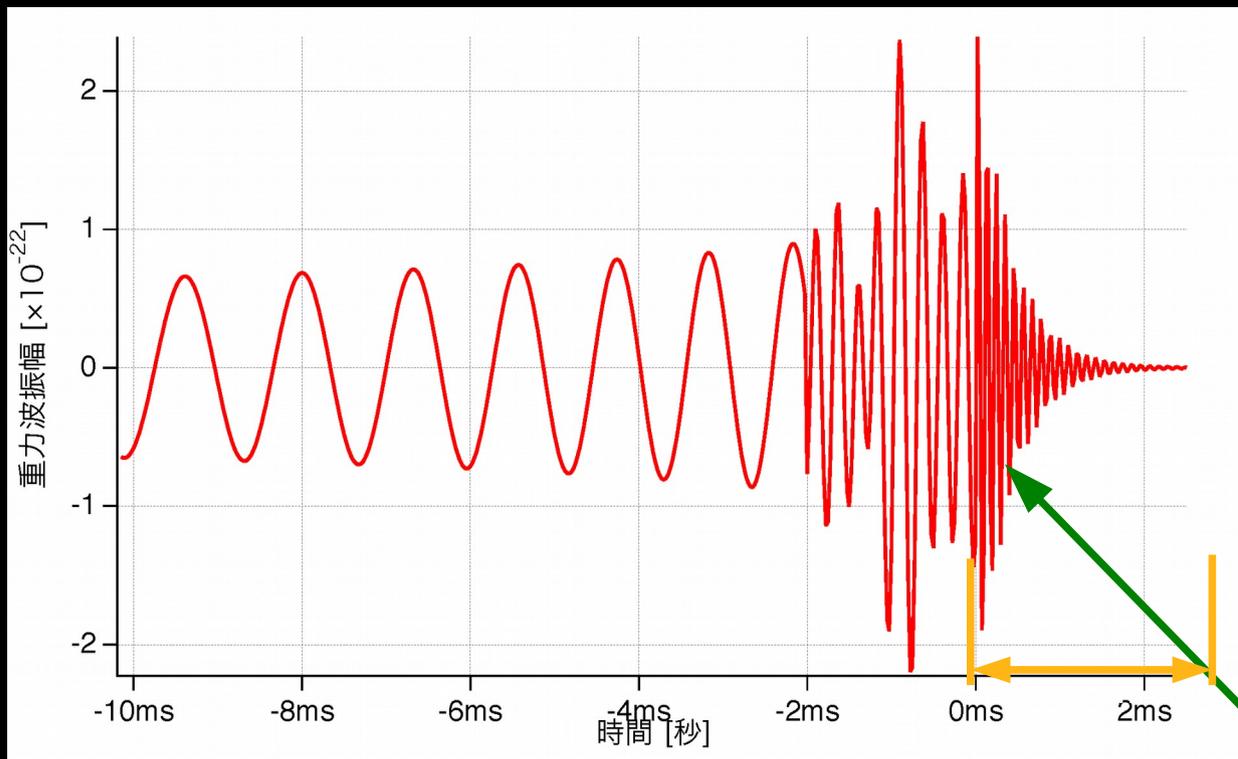
- 赤方偏移

宇宙膨張率の(独立な)測定



中性子星の 状態方程式

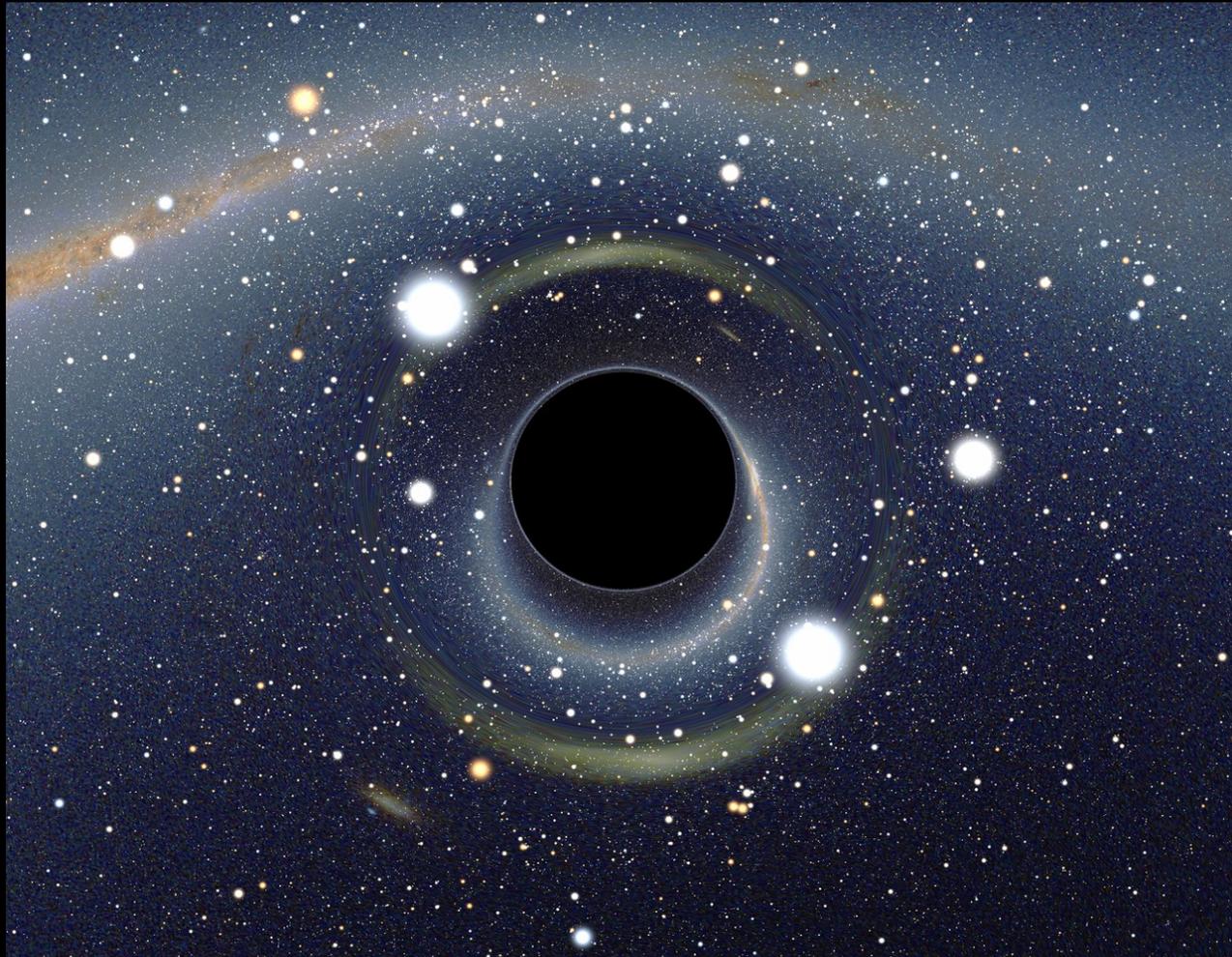




周波数・減衰率

ブラックホールの質量・スピン

ブラックホールの無毛定理

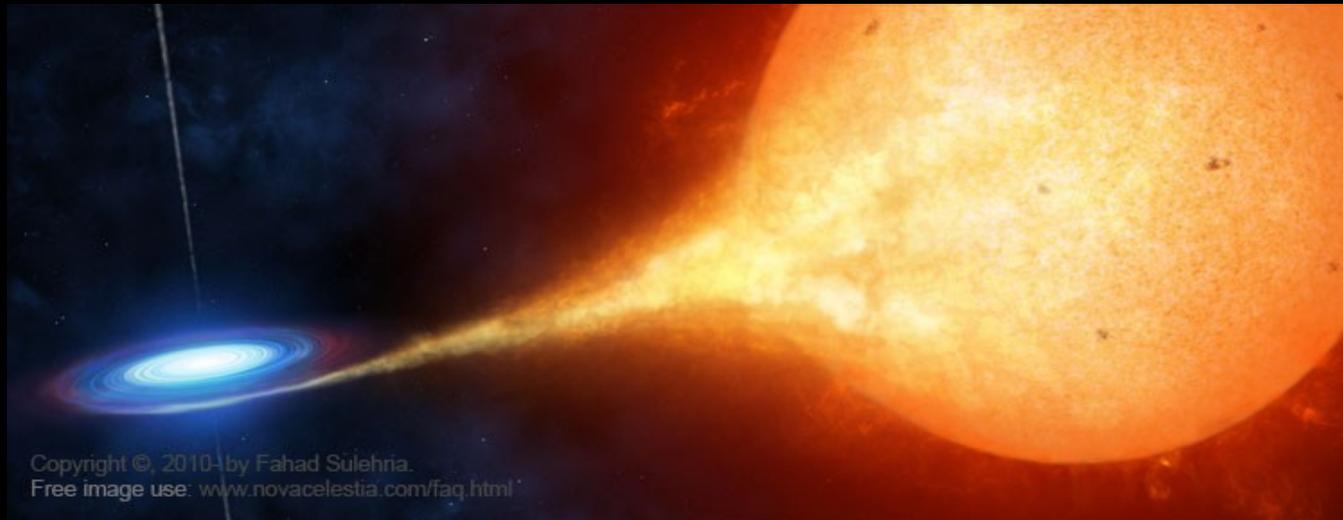
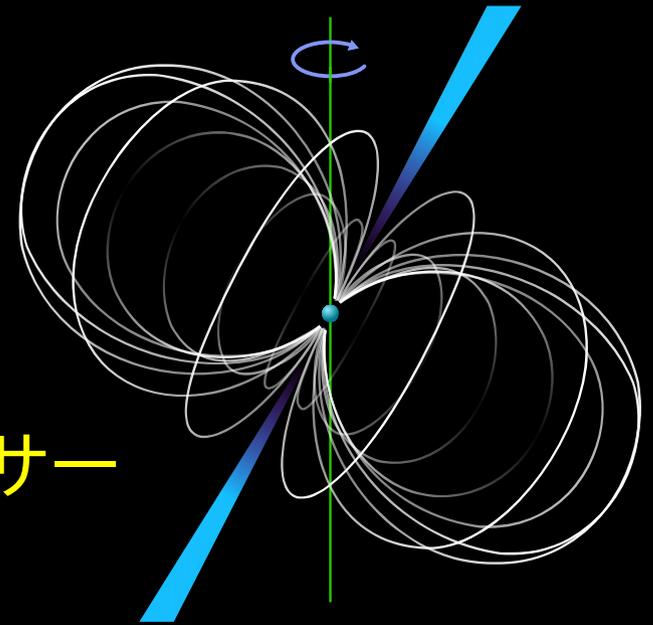


質量・スピン・電荷

超新星爆発

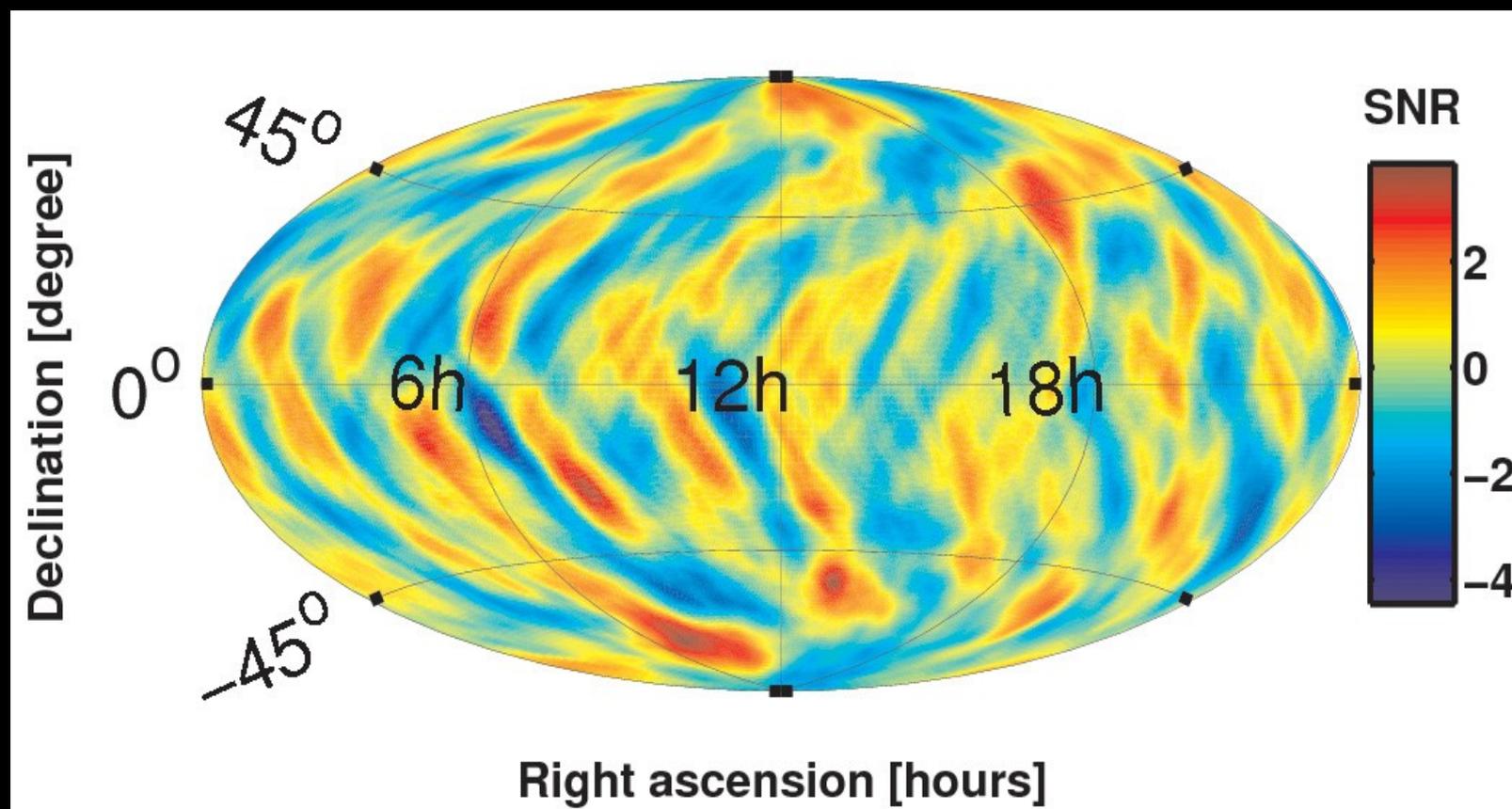


パルサー



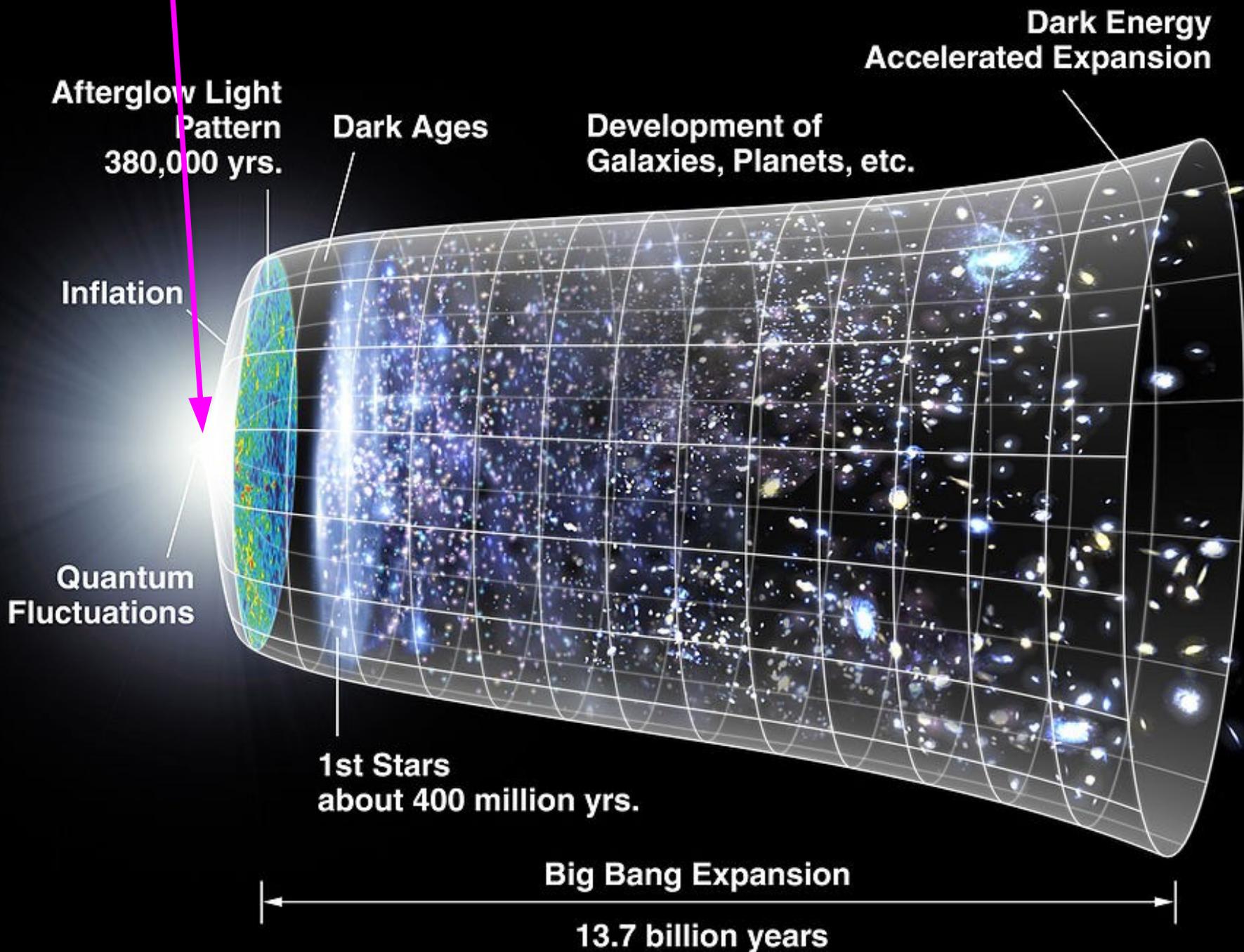
低質量X線連星(LMXB)

宇宙背景重力波

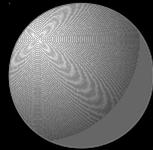
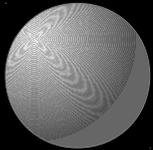


S. Ballmer, CQG (2006)

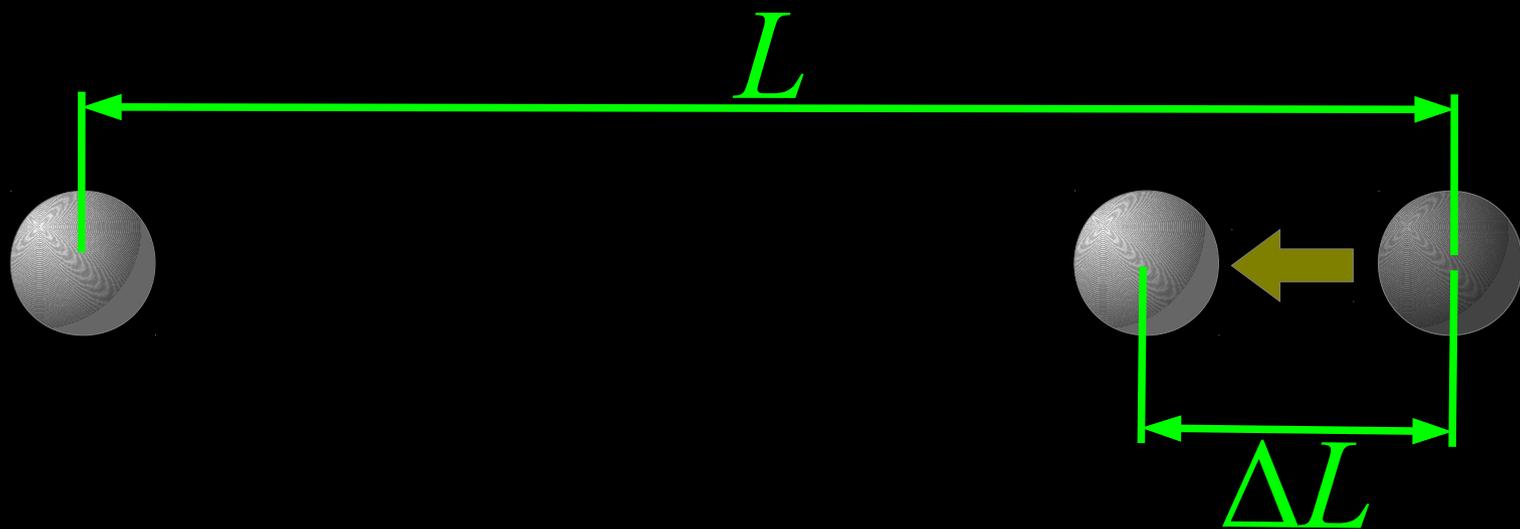
10⁻³⁰秒後



ではどうやって検出するか？







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

重力波振幅

重力波検出器の歴史

最初の実験

Joseph Weber in 1960's
at University of Maryland

共振型重力波検出器 Weber Event

以後, 8カ国, 19の検出器が検出された

レーザー干渉計へのシフト

Robert L. Forward:

1970年代に最初のレーザー干渉計型
重力波検出器を開発

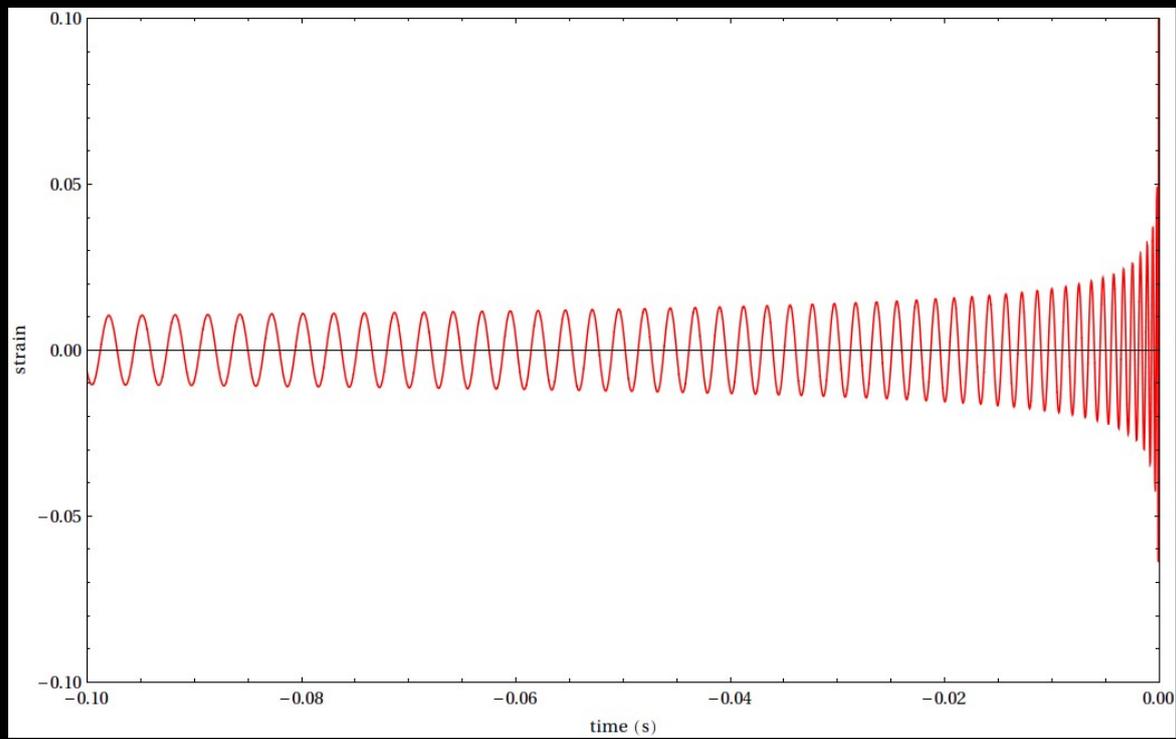
世界中でプロトタイプ干渉計が作られる

Garching, Glasgow, Caltech, Tokyo ...



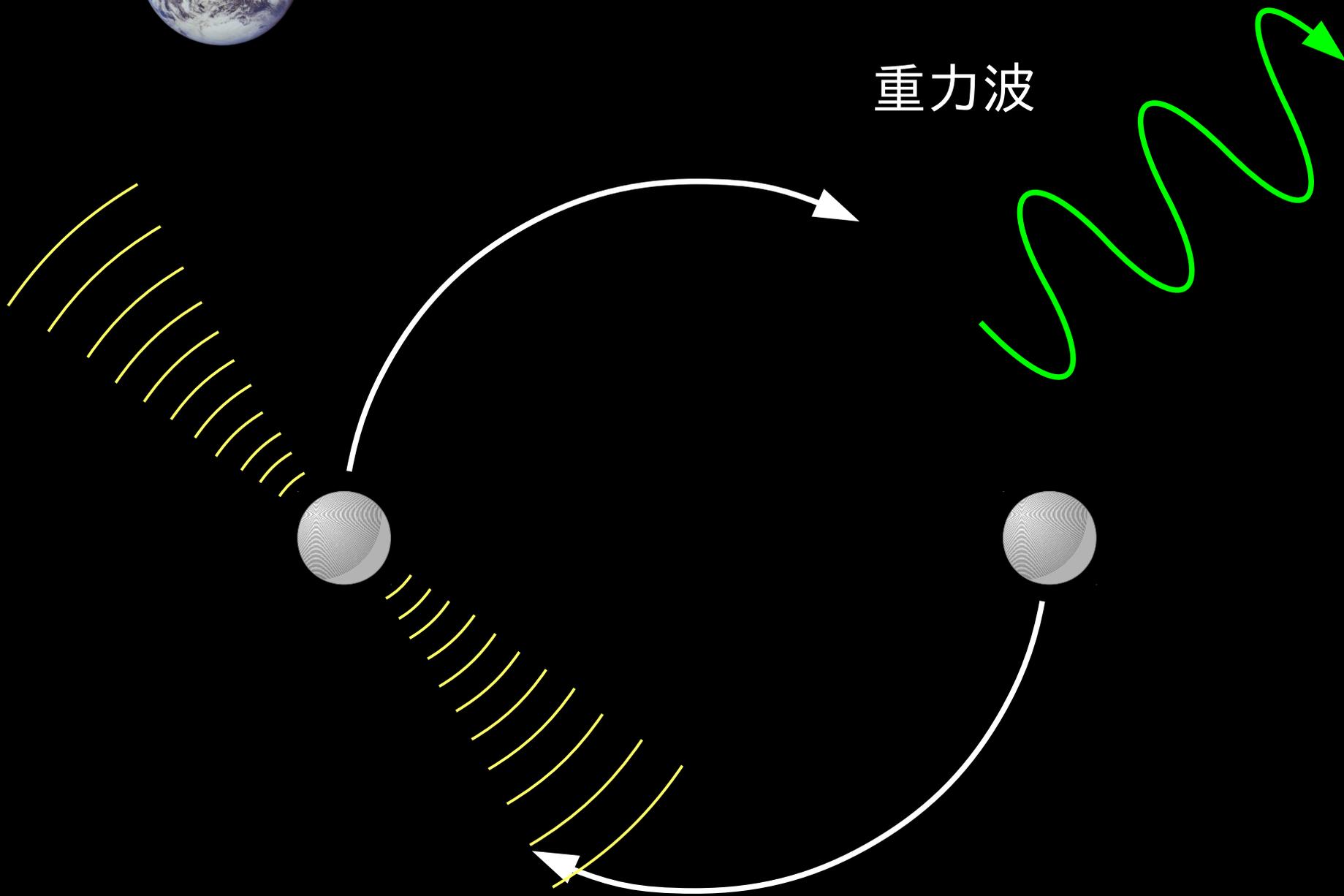
検出すべき h の大きさは？

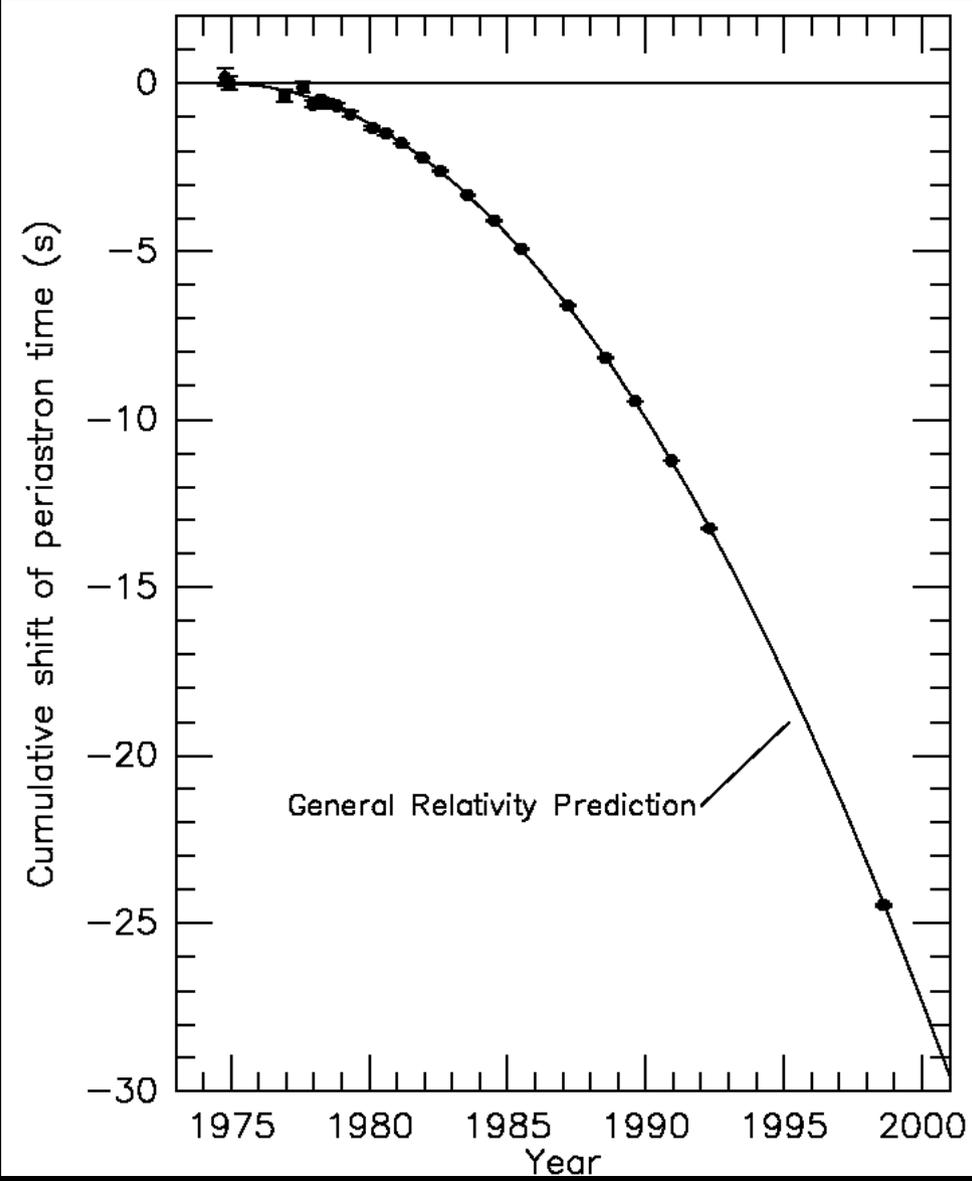
1年に1回以上観測したい



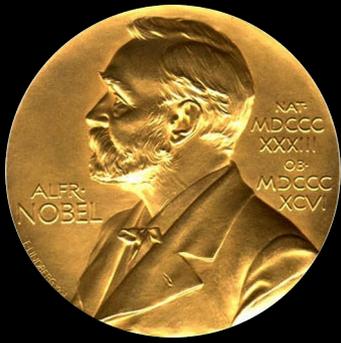


重力波

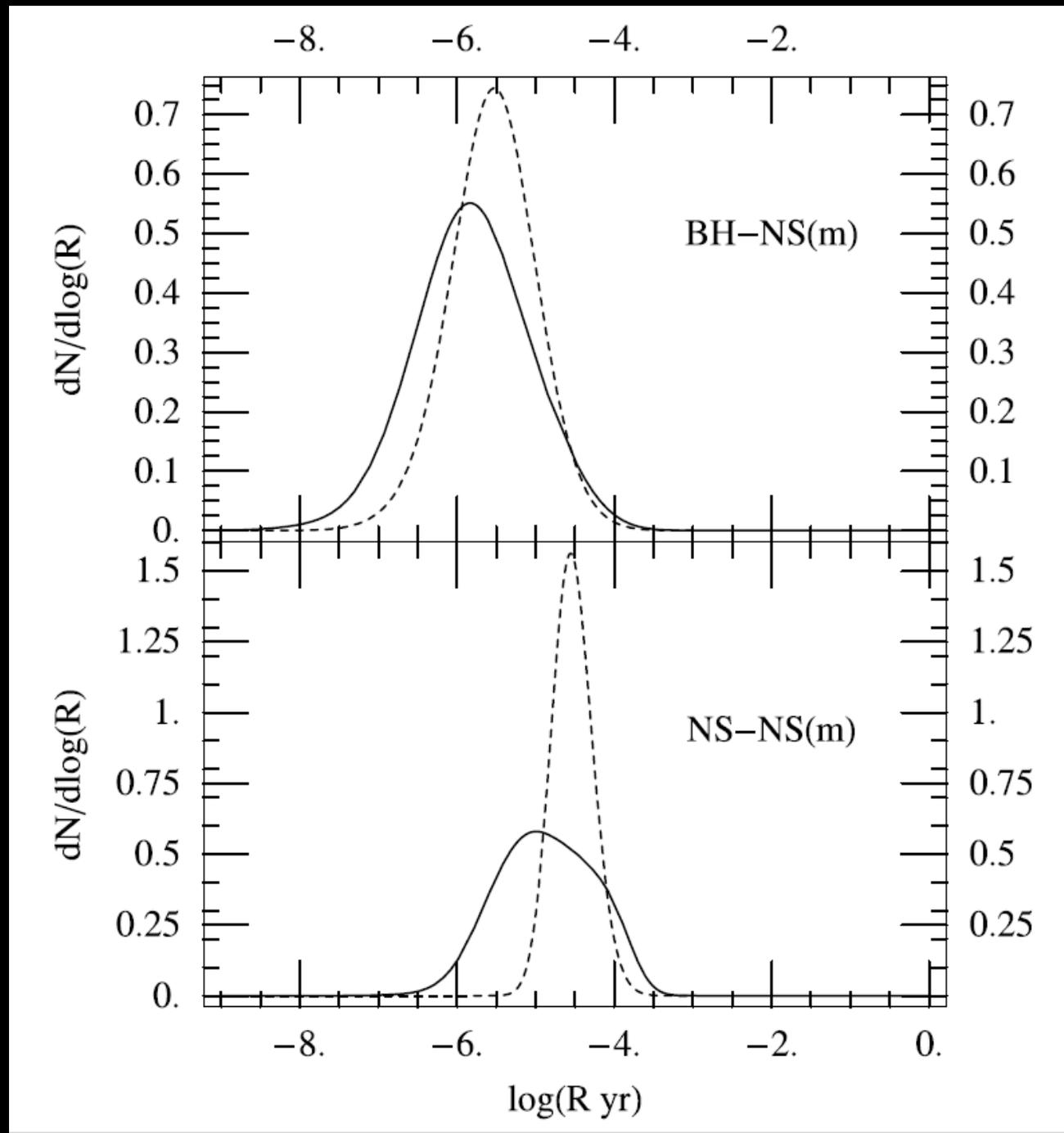


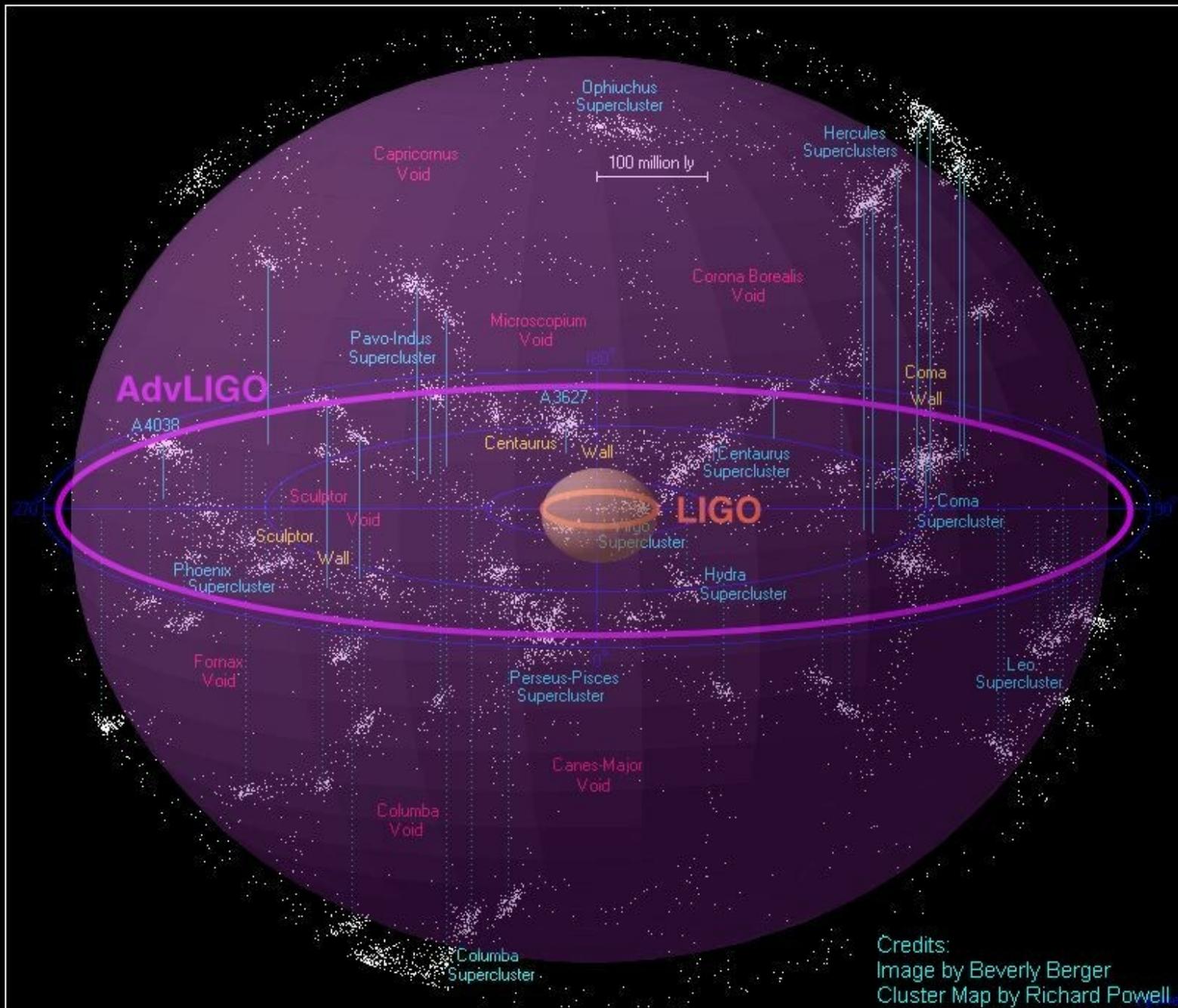


From J. H. Taylor and J. M. Weisberg, unpublished (1998)



銀河系内: 1万から10万年に一回

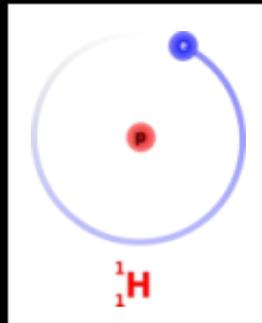
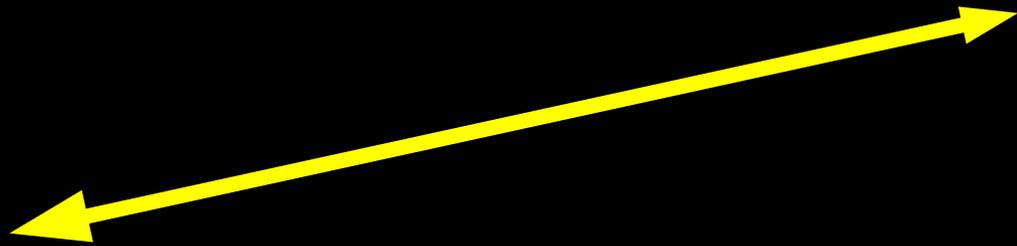
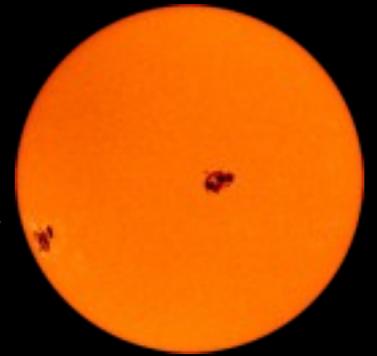




200Mpc = 6億5千万光年

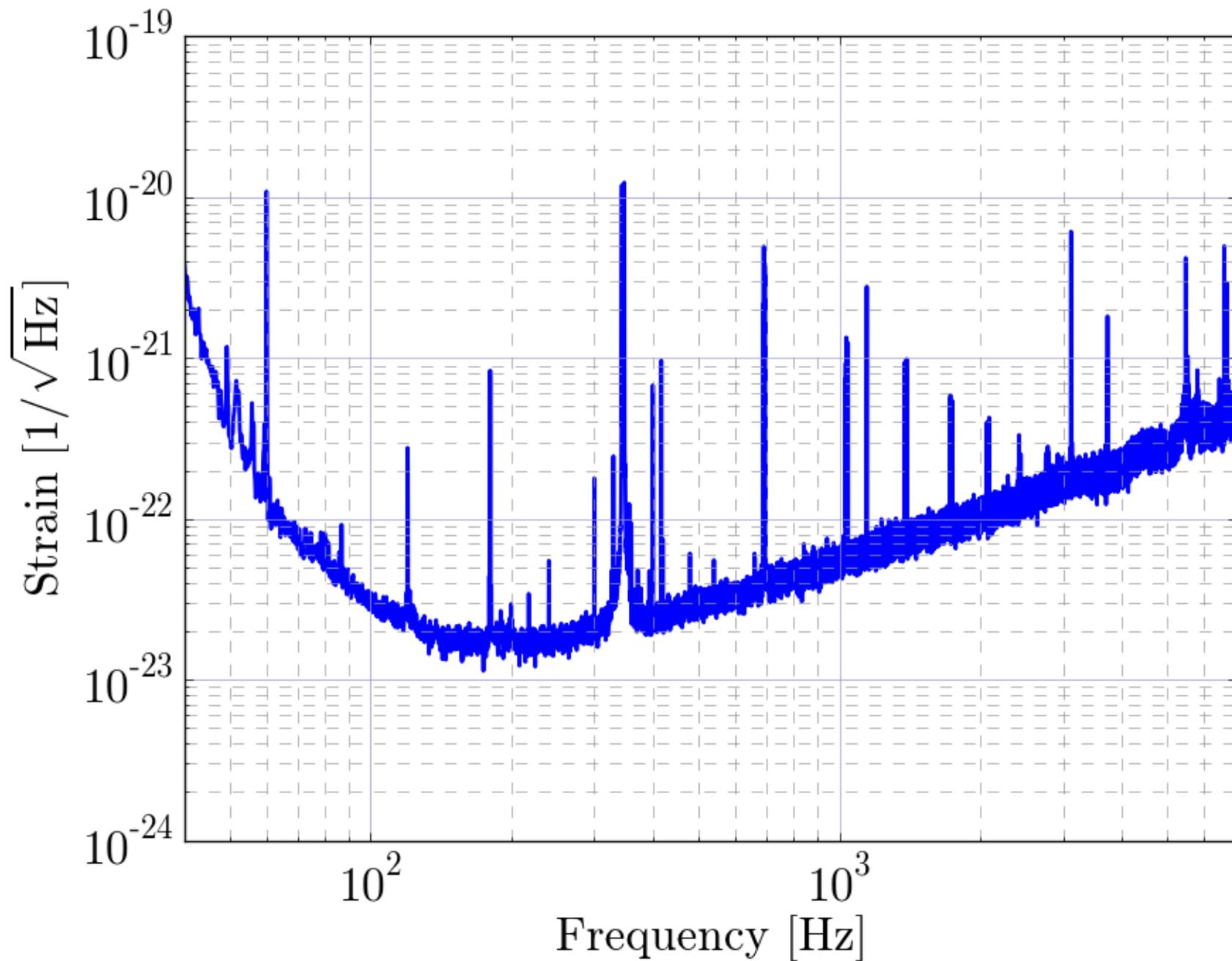
$$h = 10^{-23} \sim 10^{-24}$$

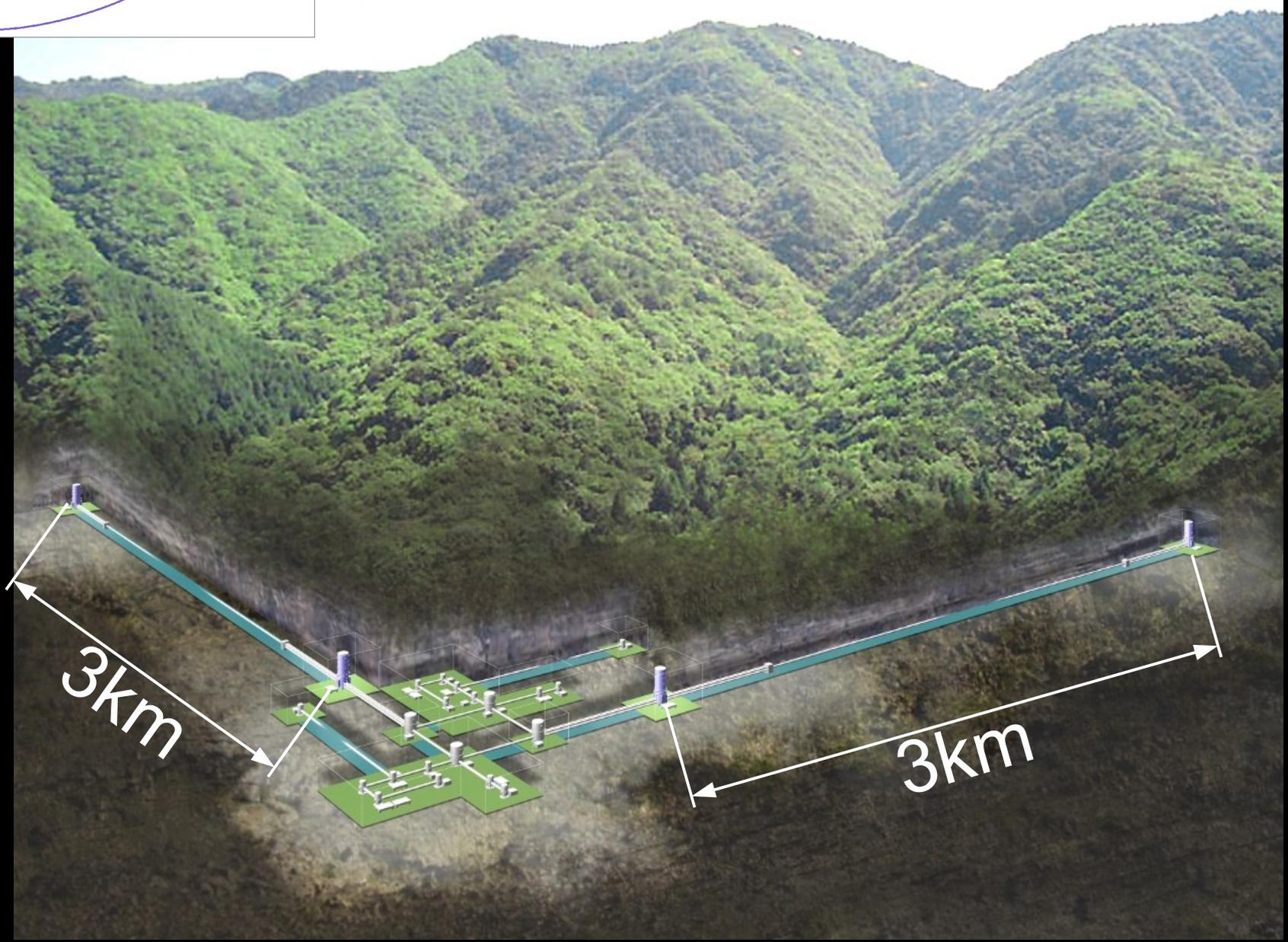
$$h = 10^{-24}$$



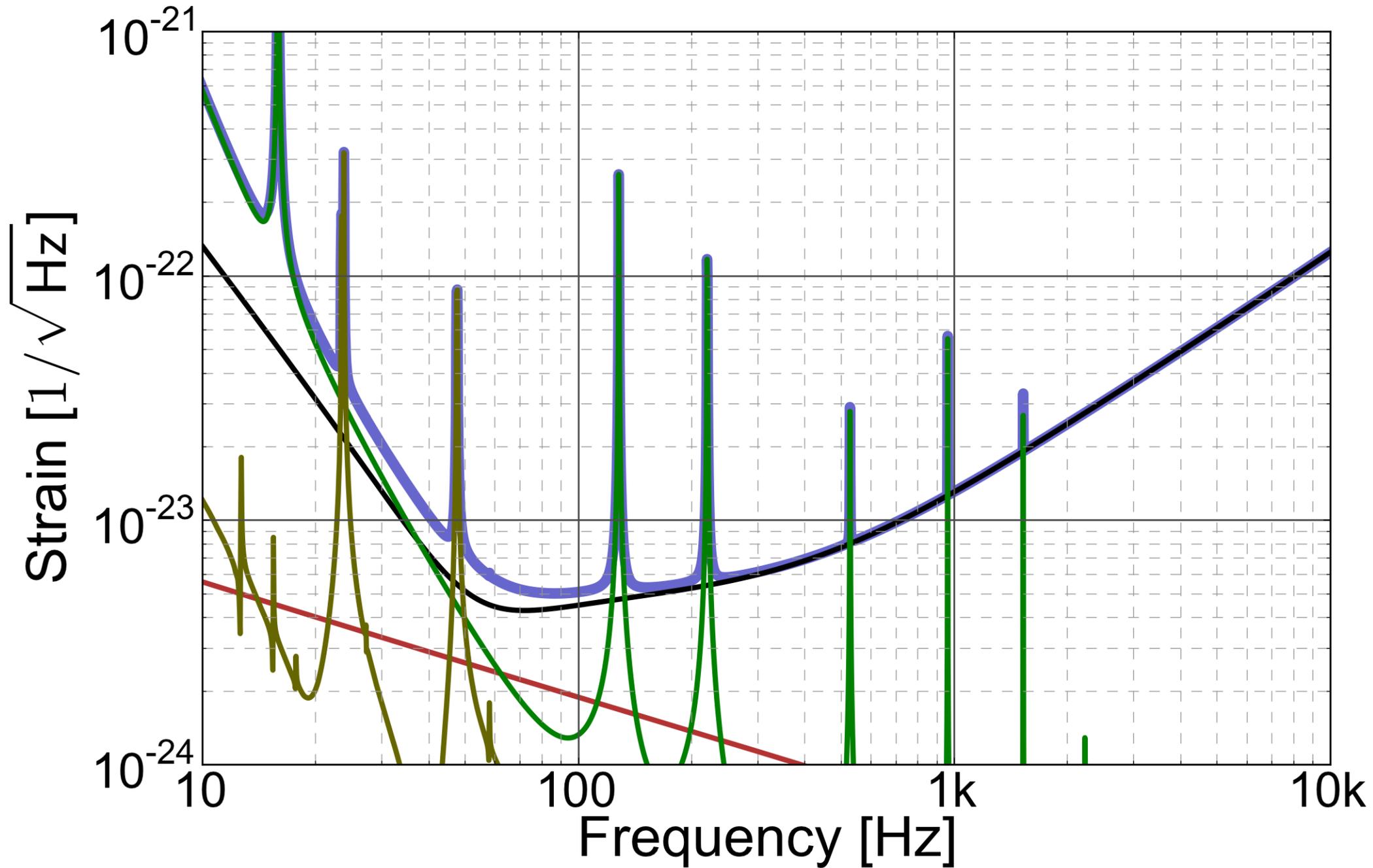
$$\times 1/1000$$

LIGO S6 Sensitivity

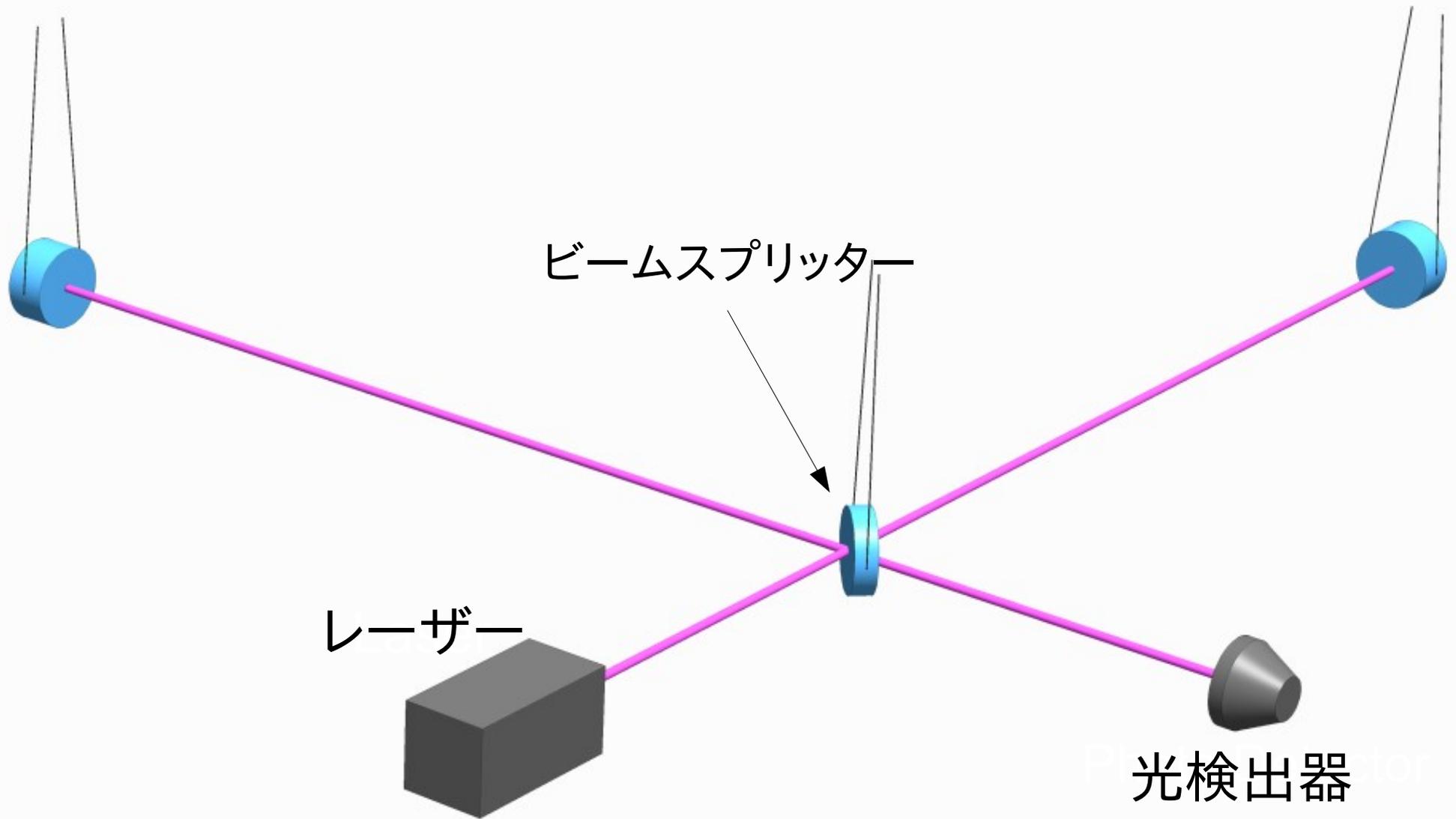


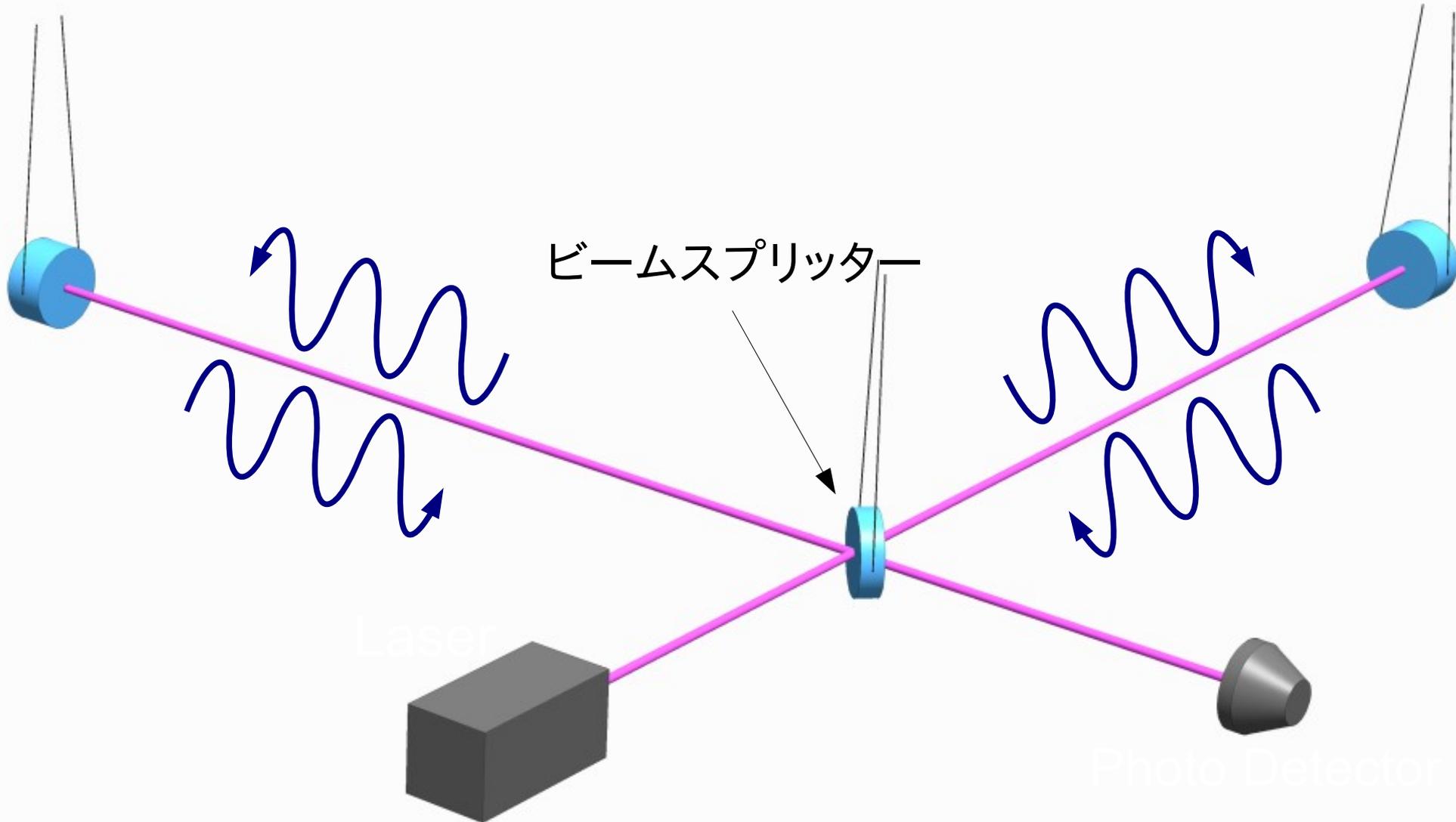


KAGRAの目標感度



マイケルソン干渉計

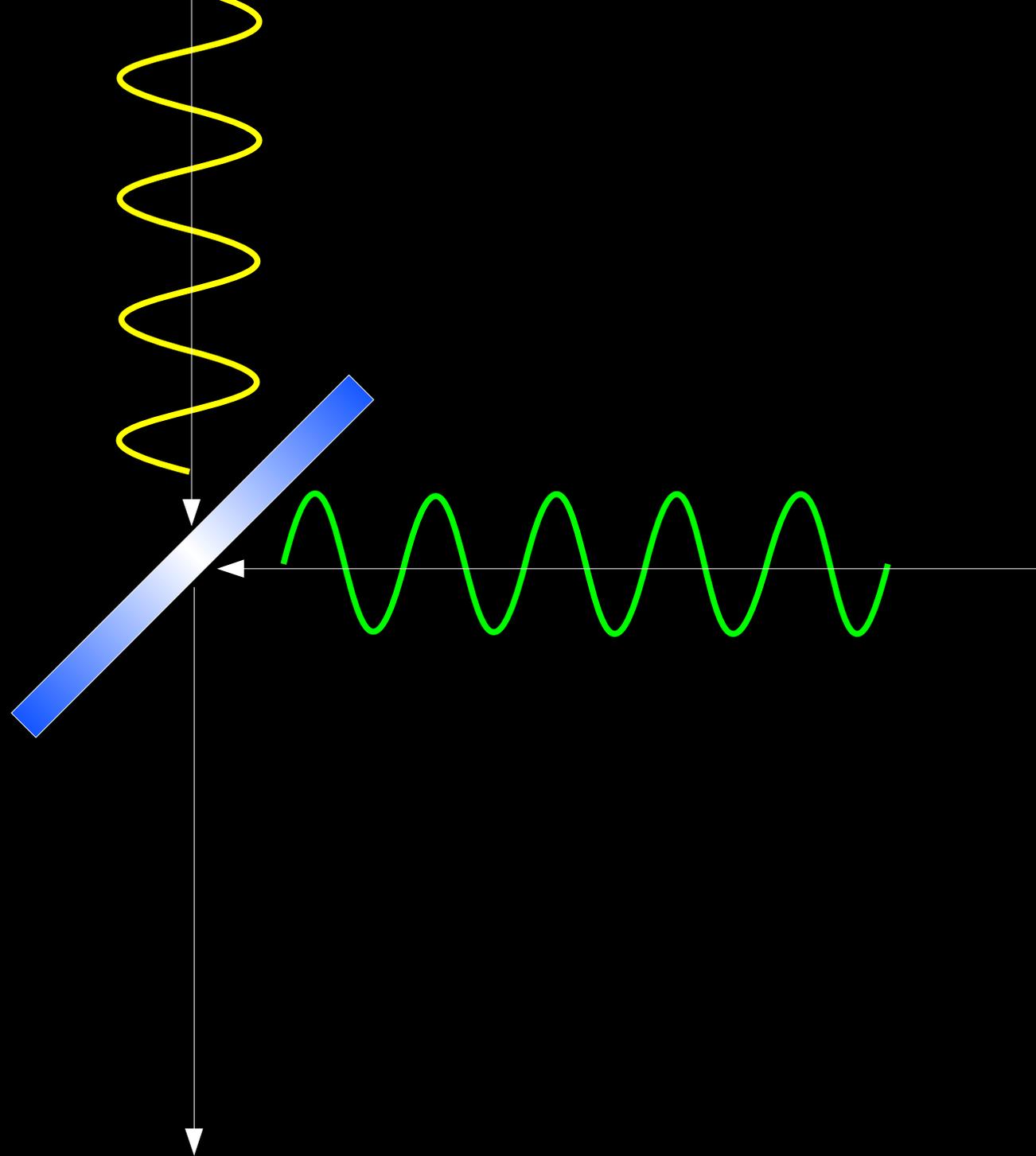


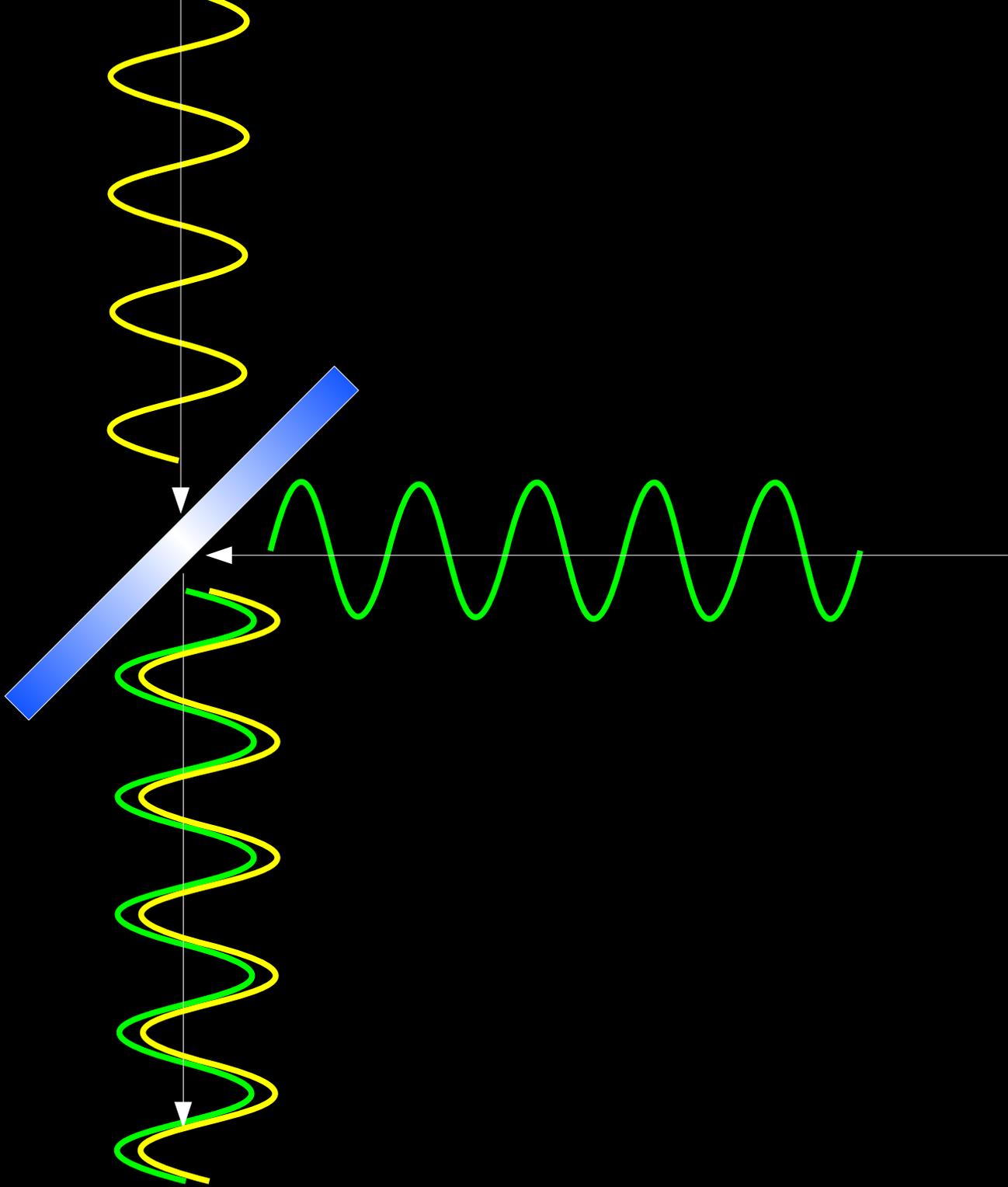


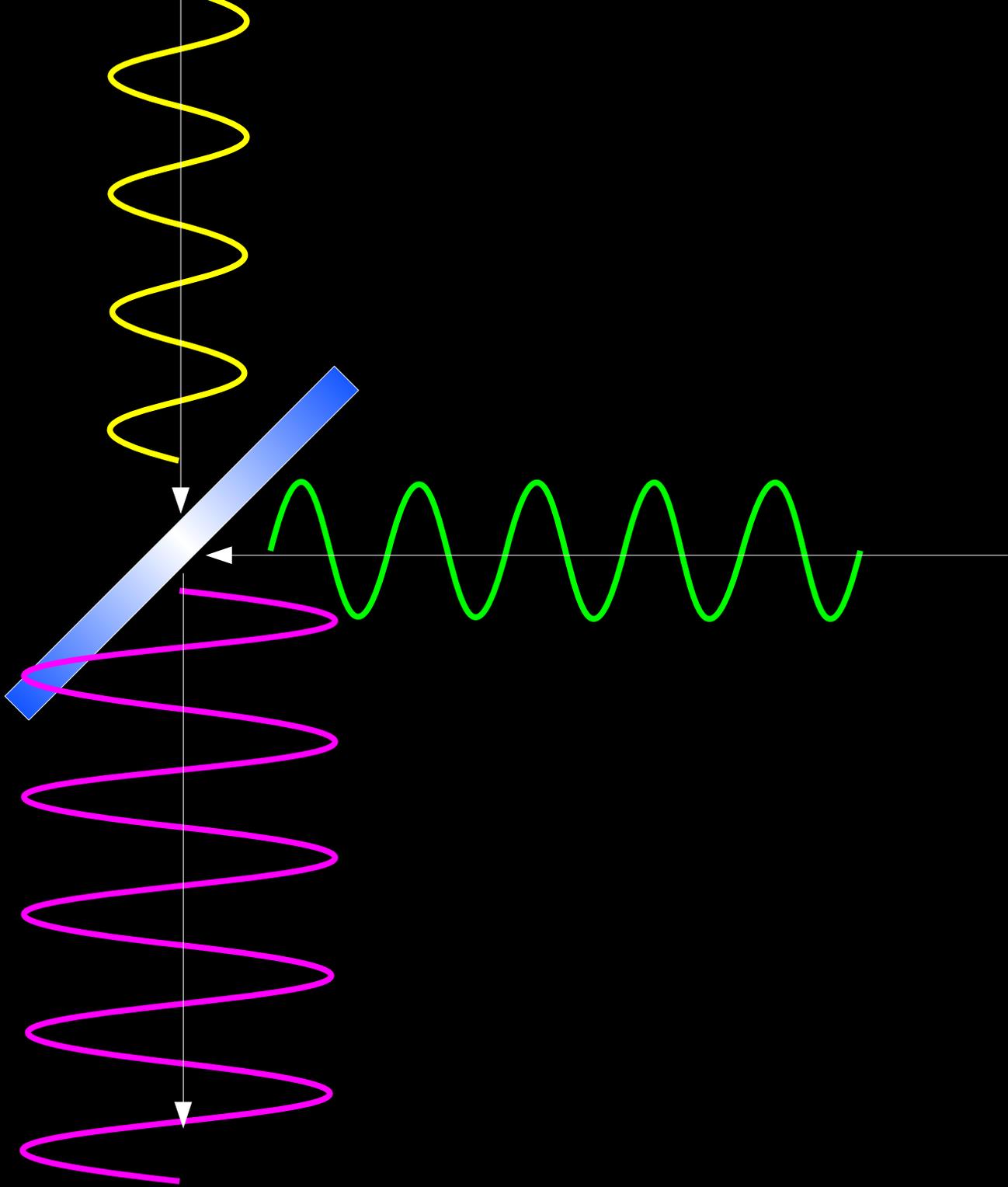
ビームスプリッター

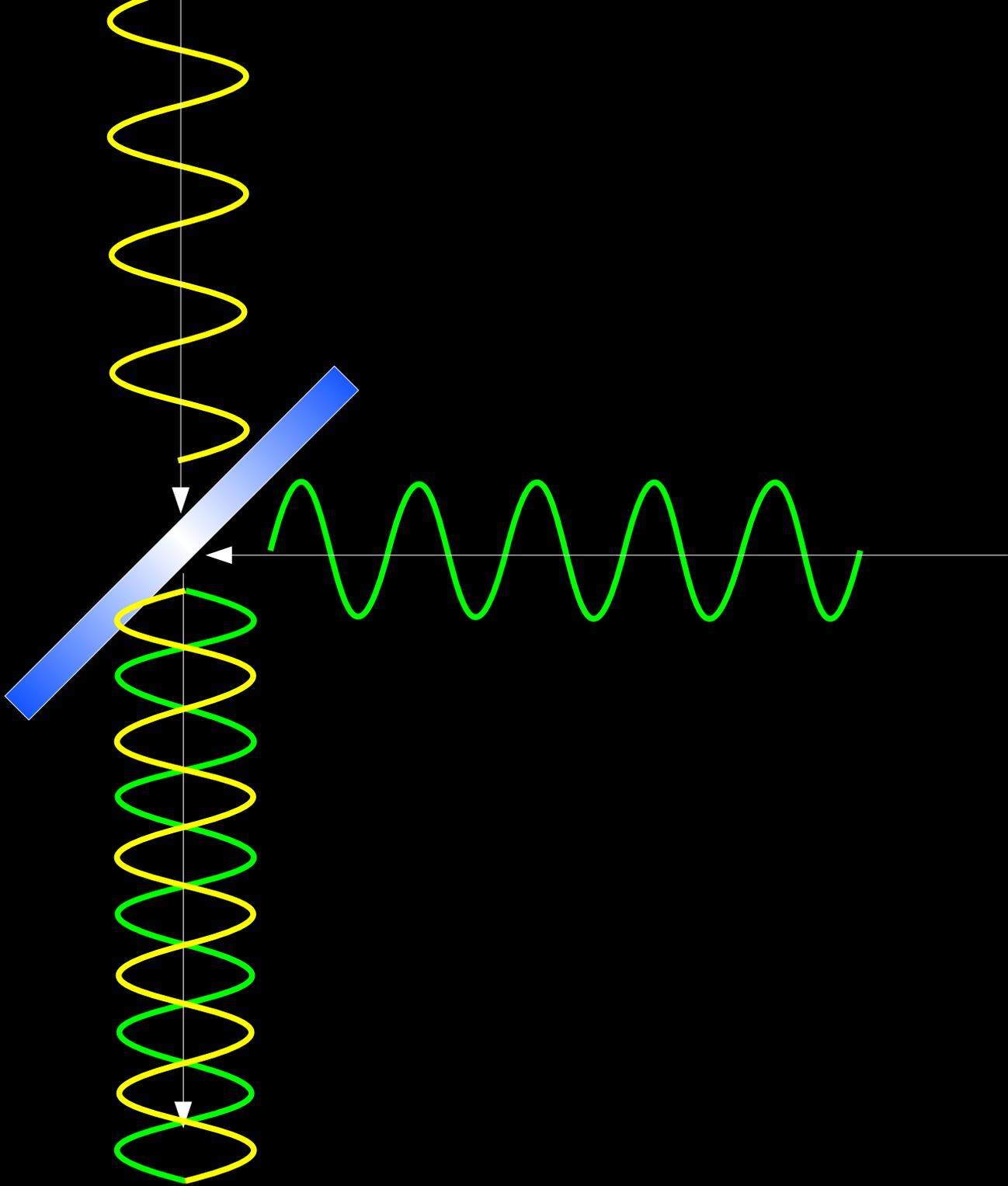
Laser

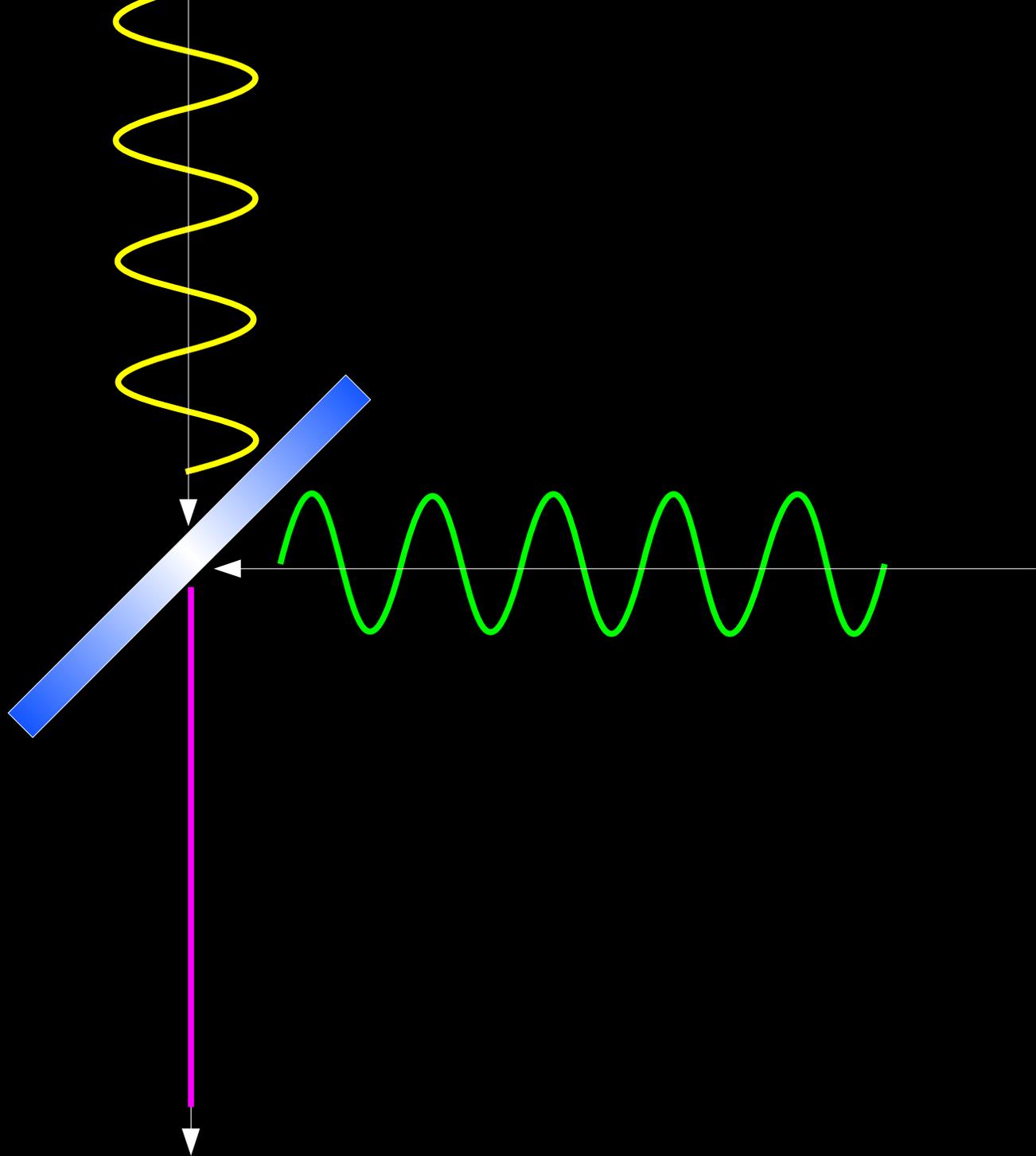
Photo Detector

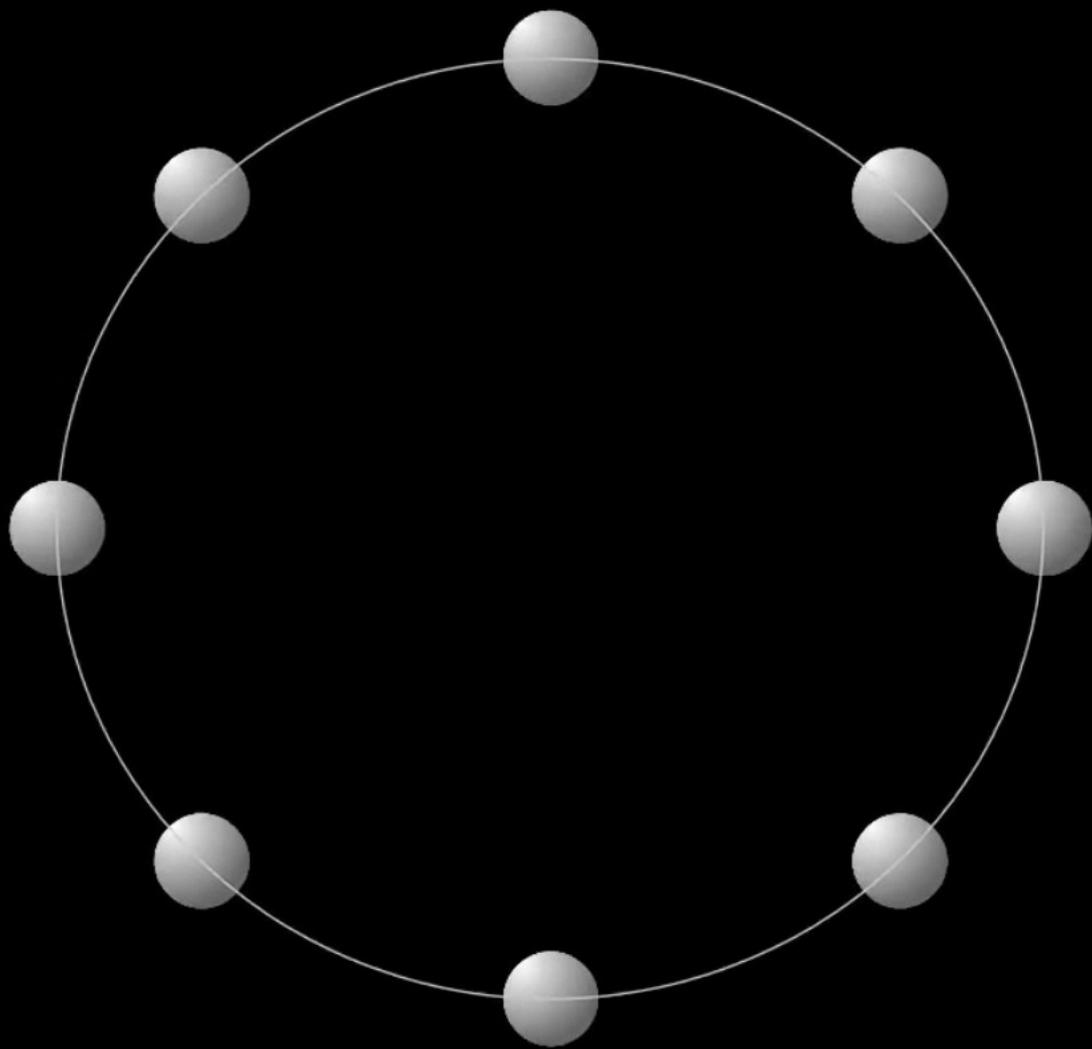


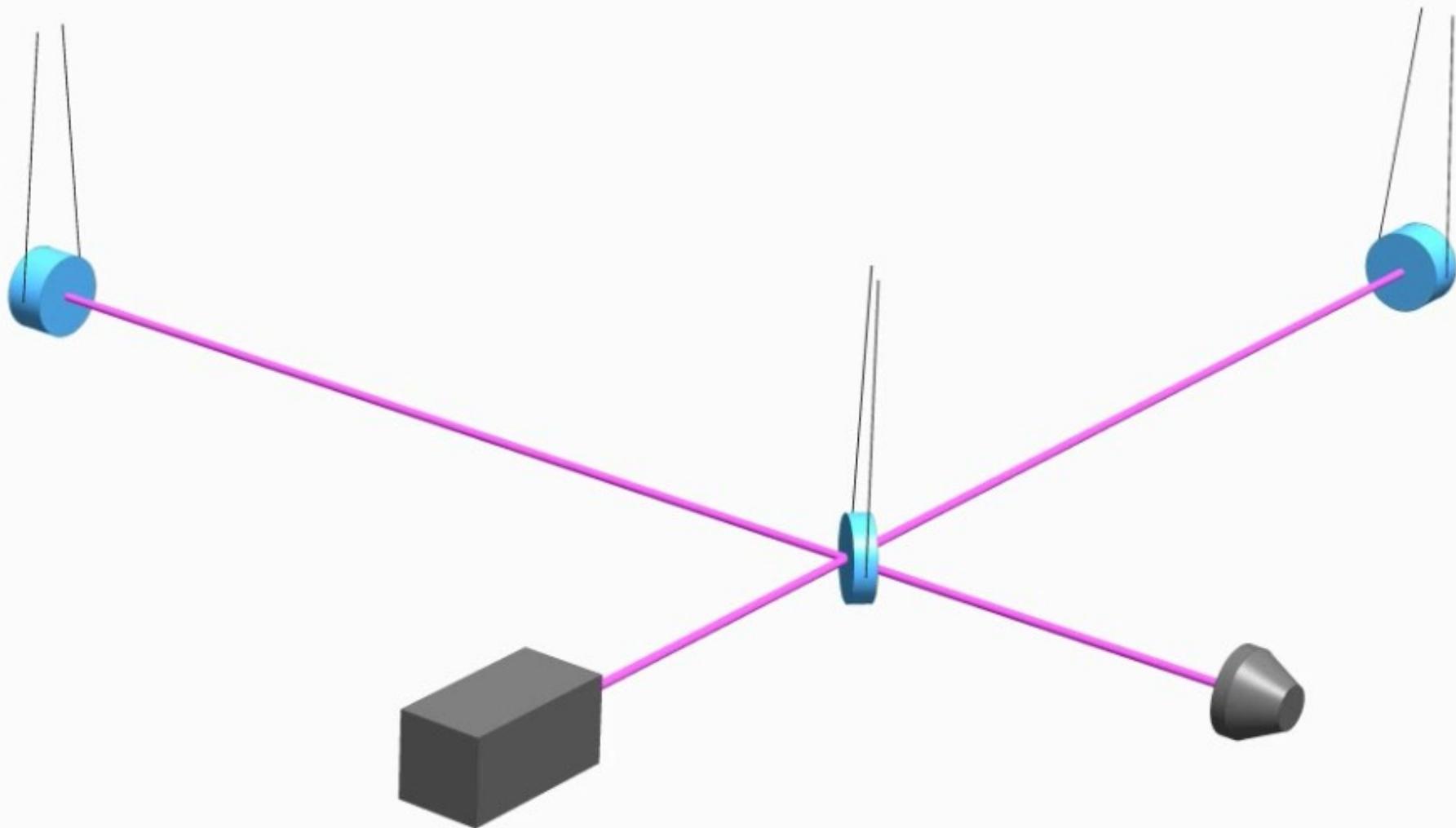


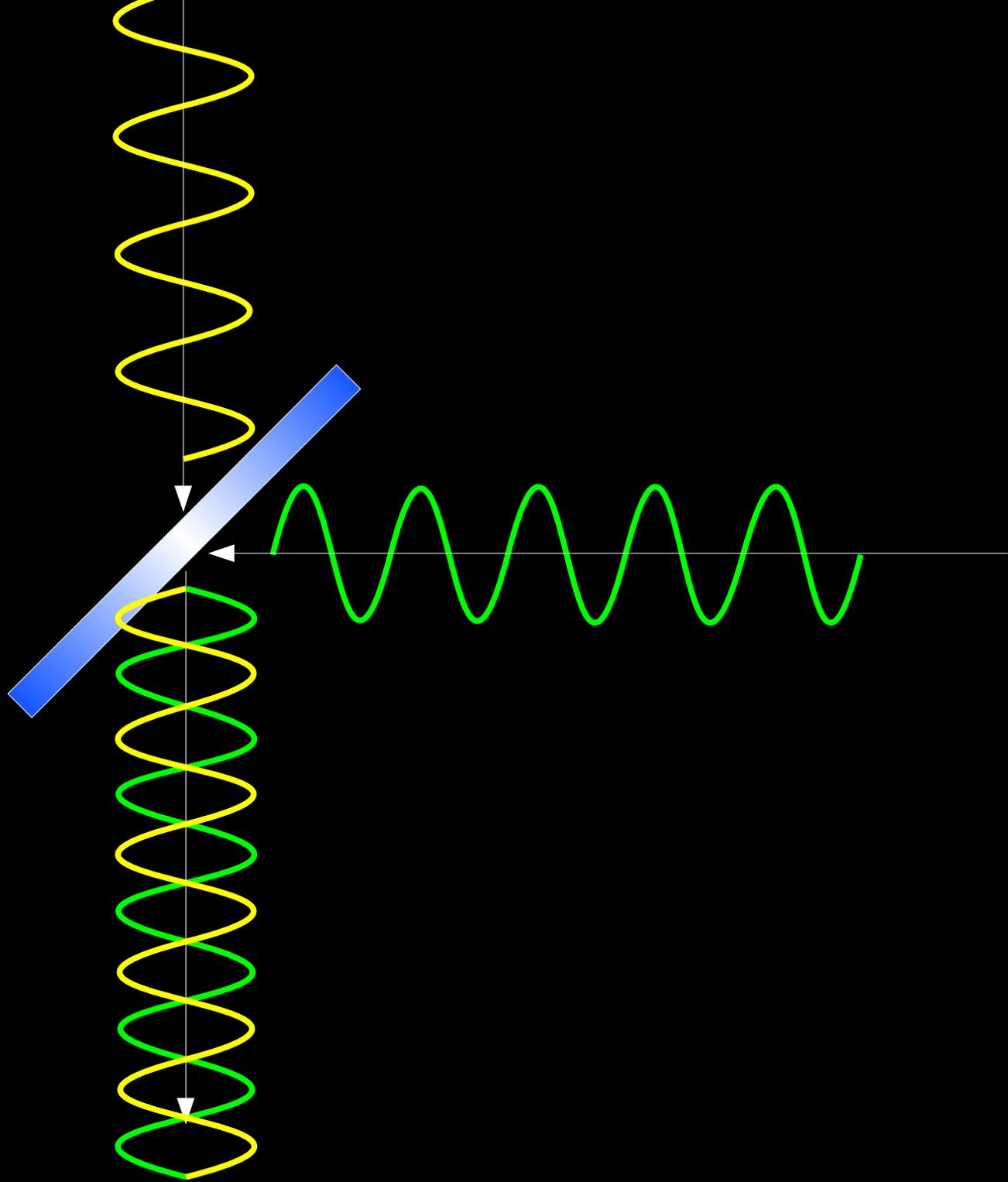


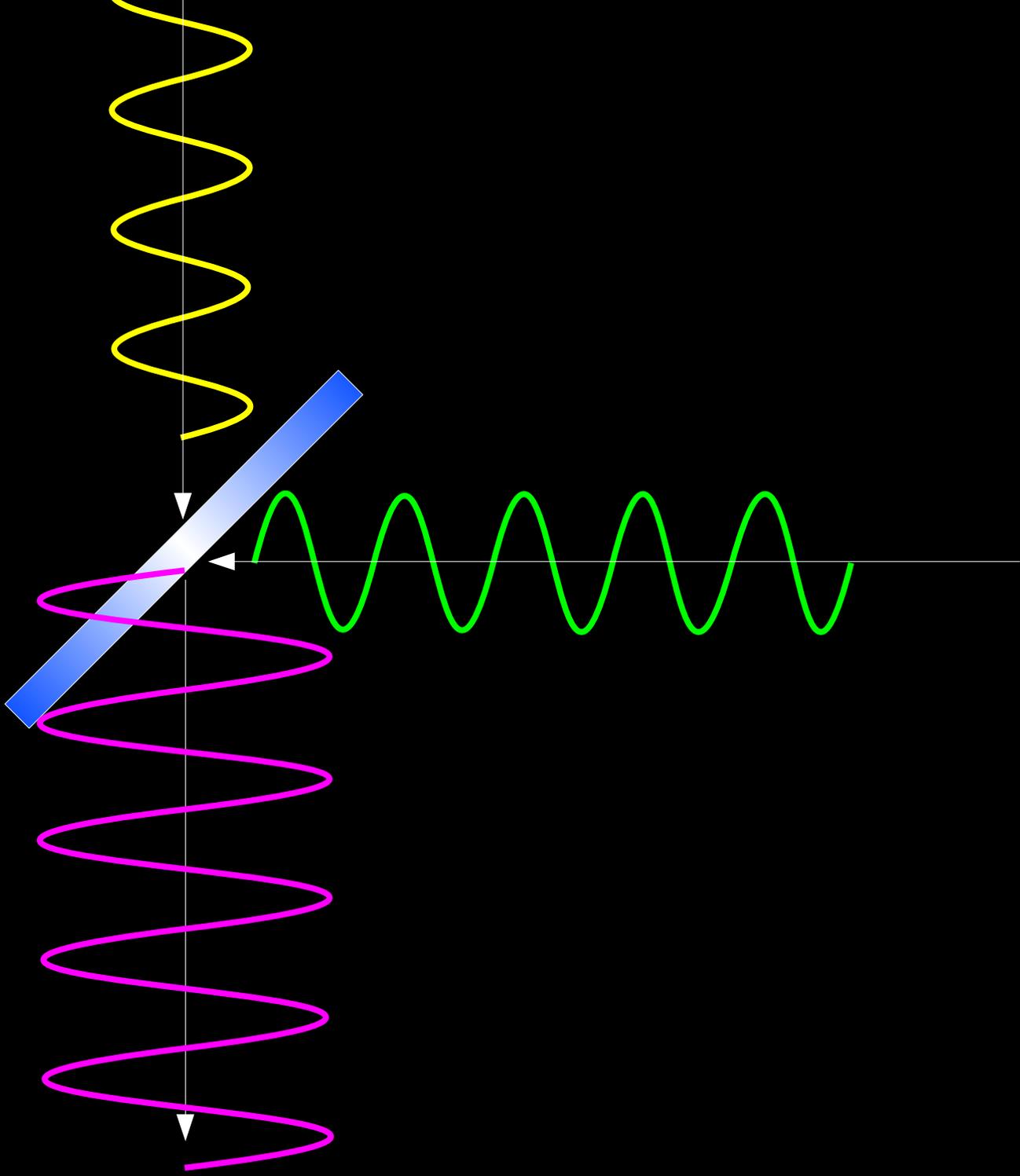




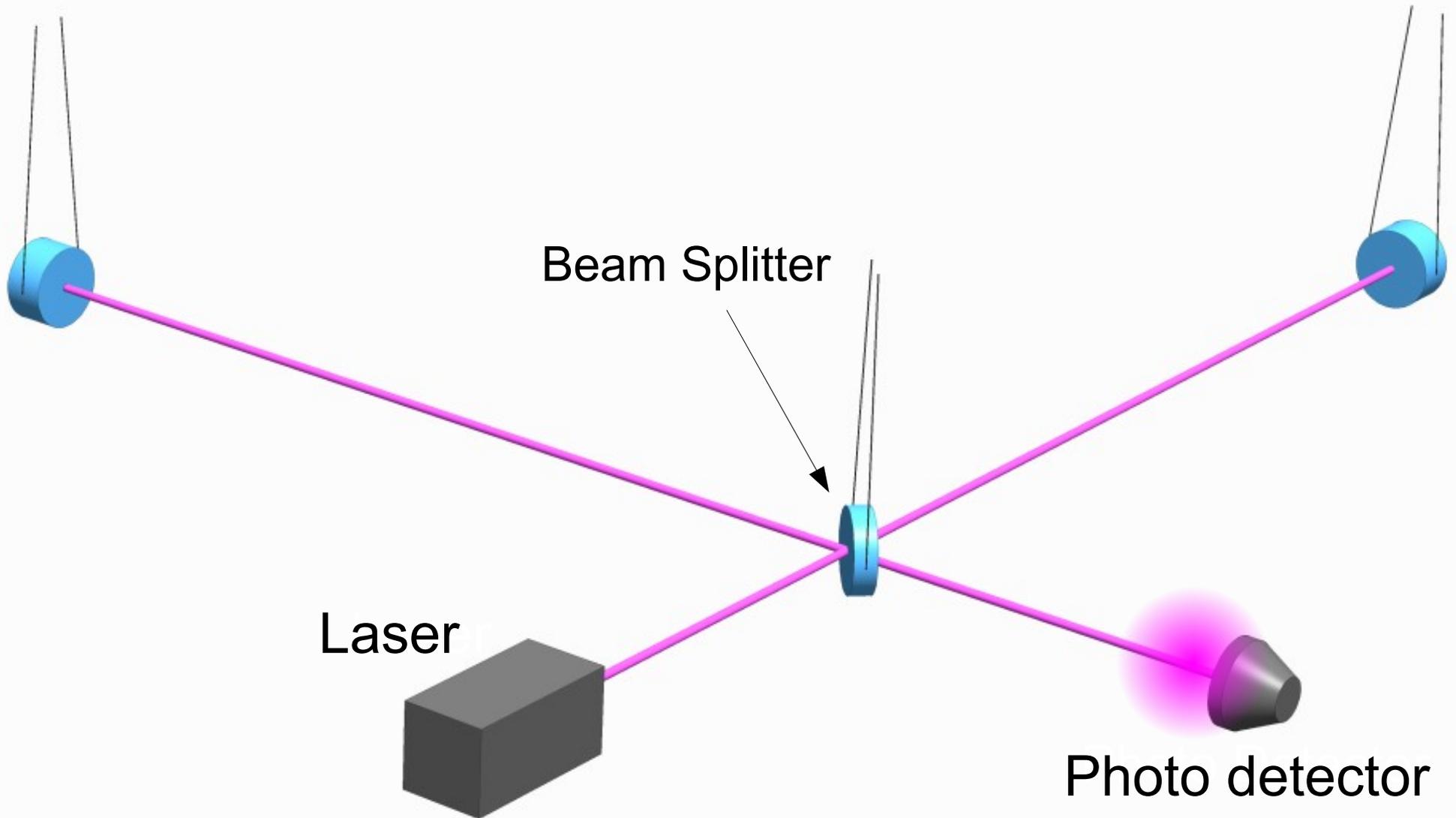








Michelson Interferometer



どこまで見えるのか？

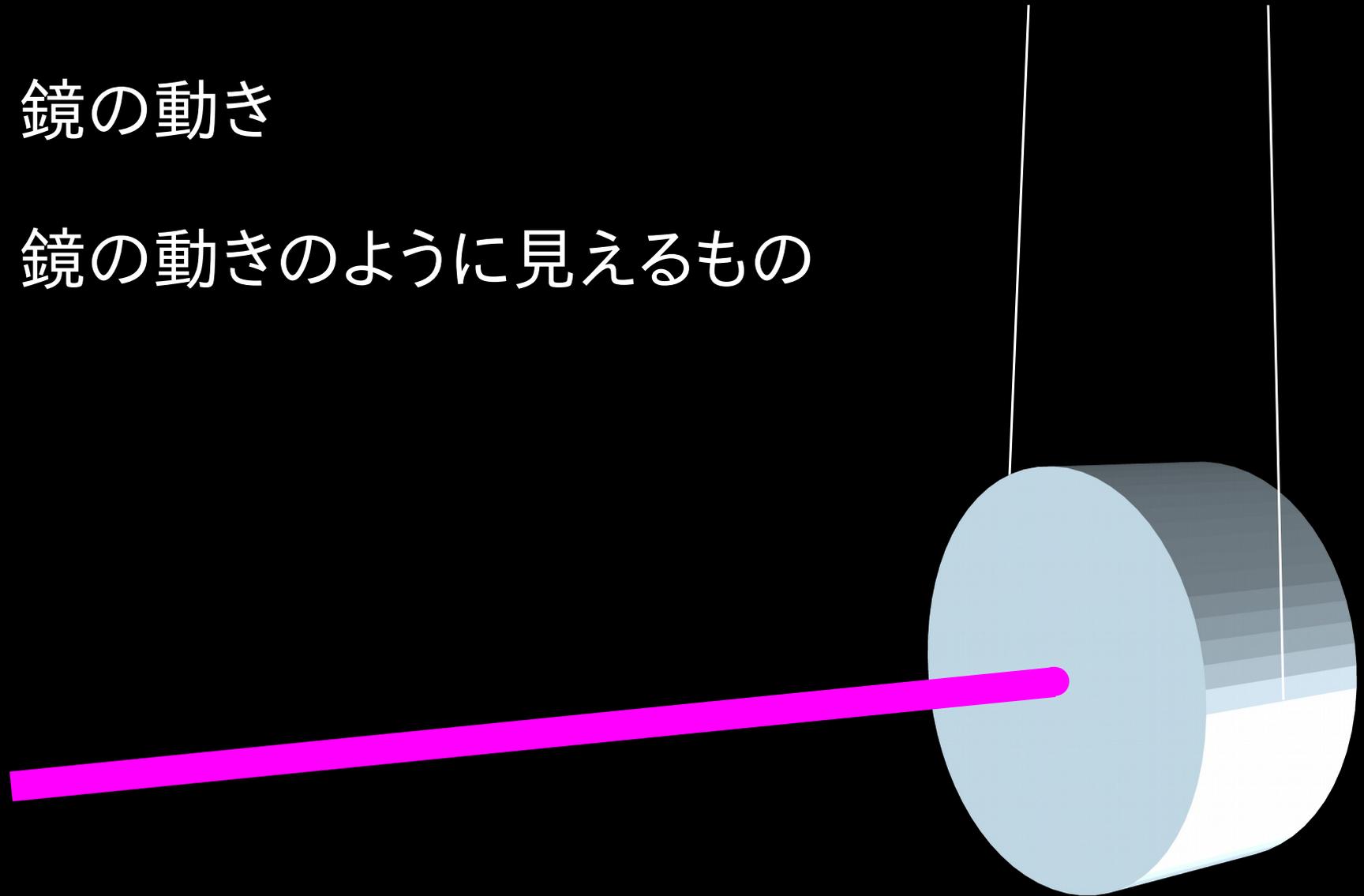


信号 > 雜音

雑音とは？

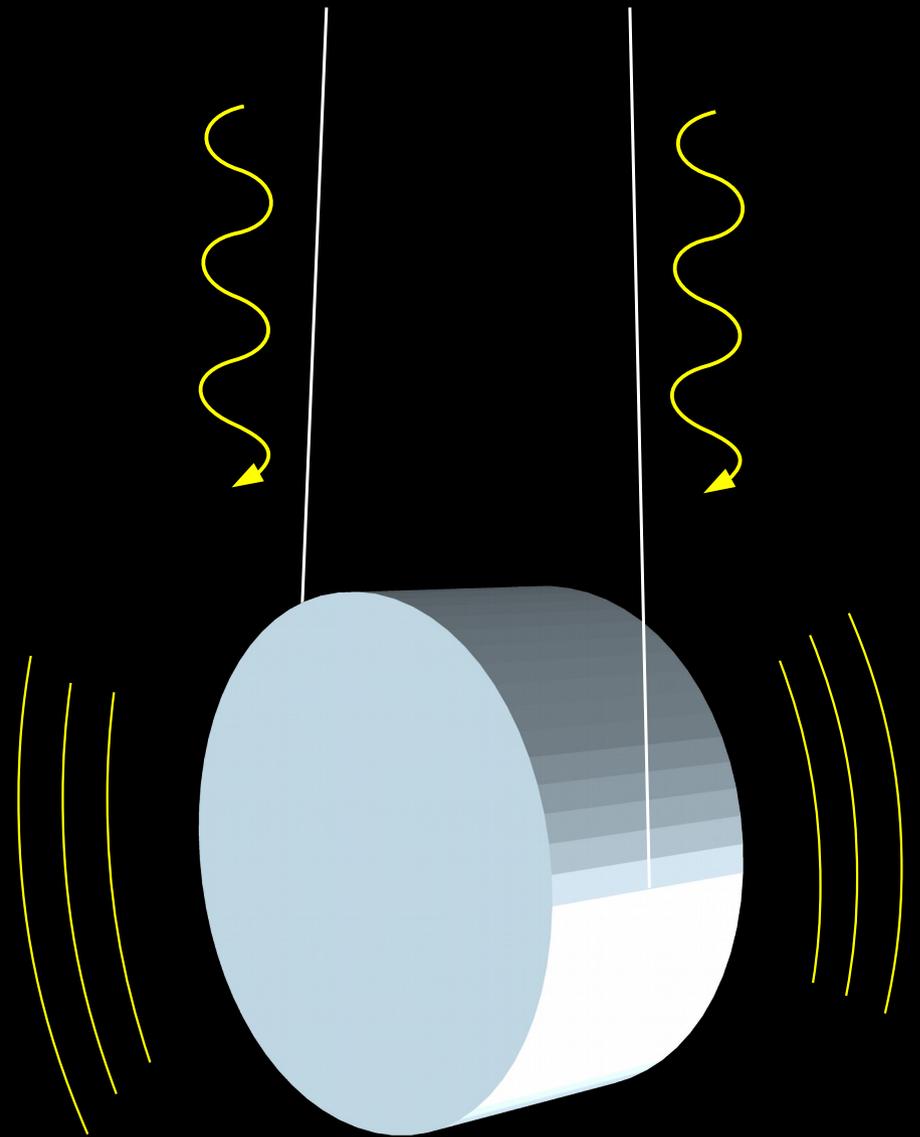
(1) 鏡の動き

(2) 鏡の動きのように見えるもの





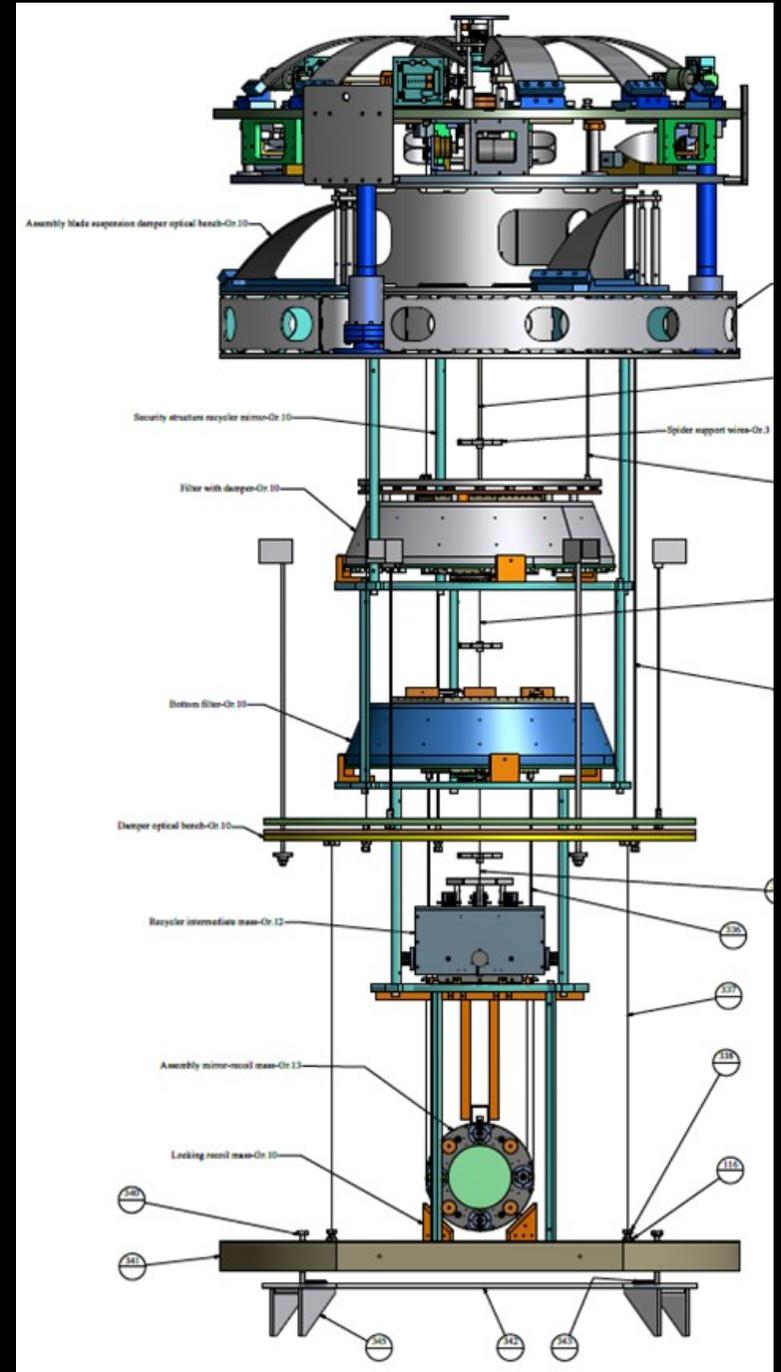
地面振動

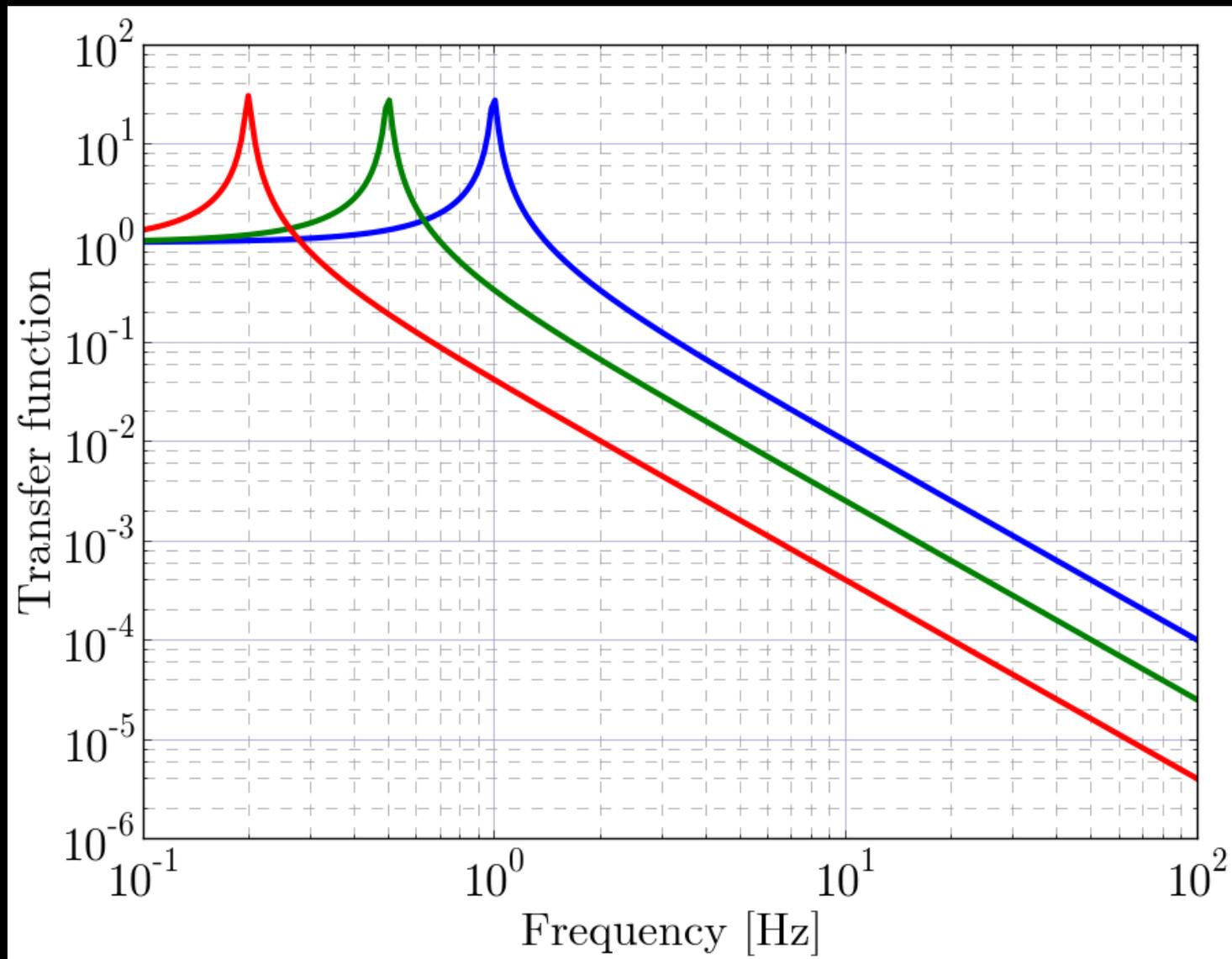
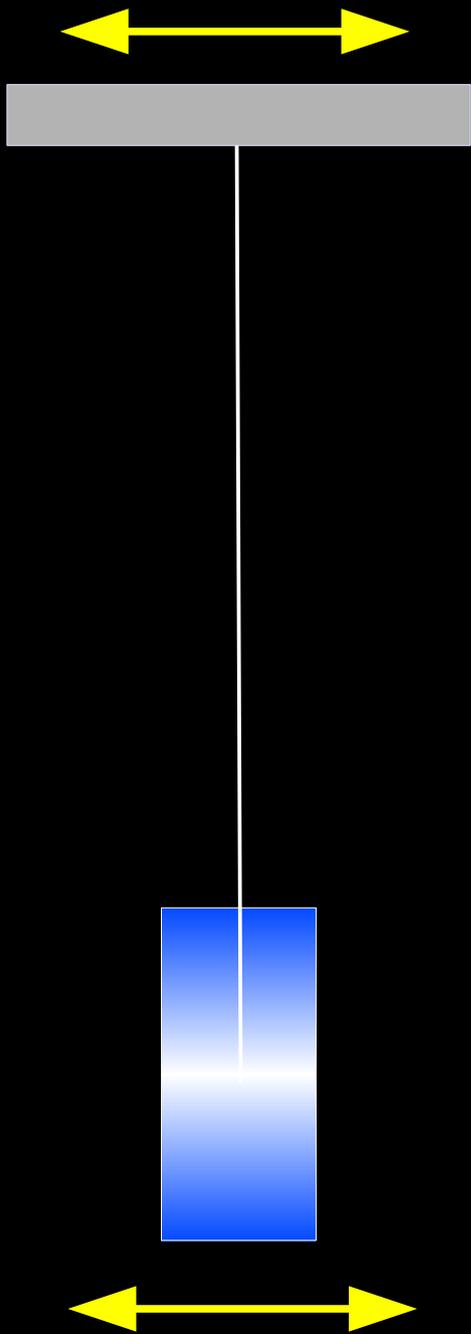


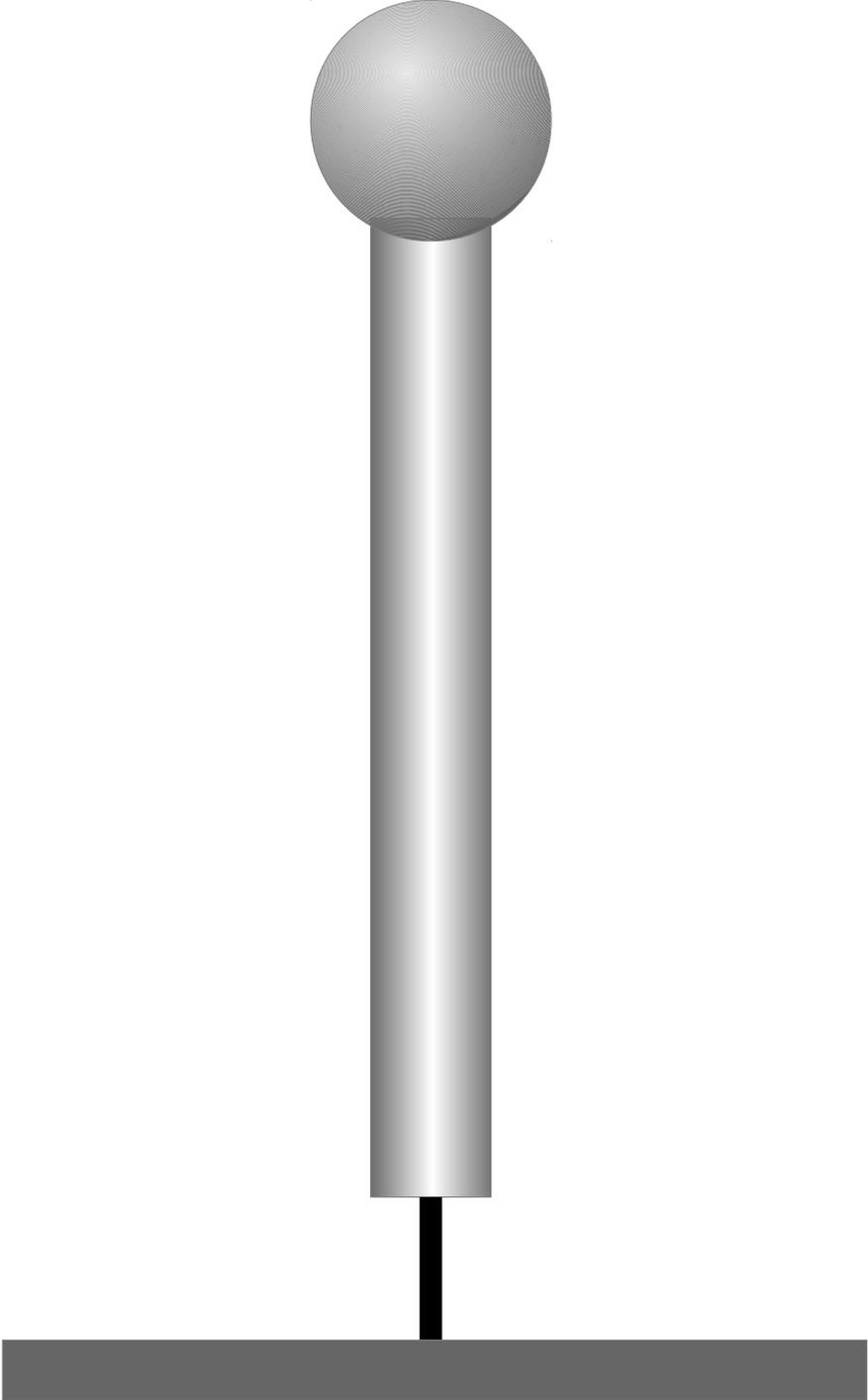
多段防振システム

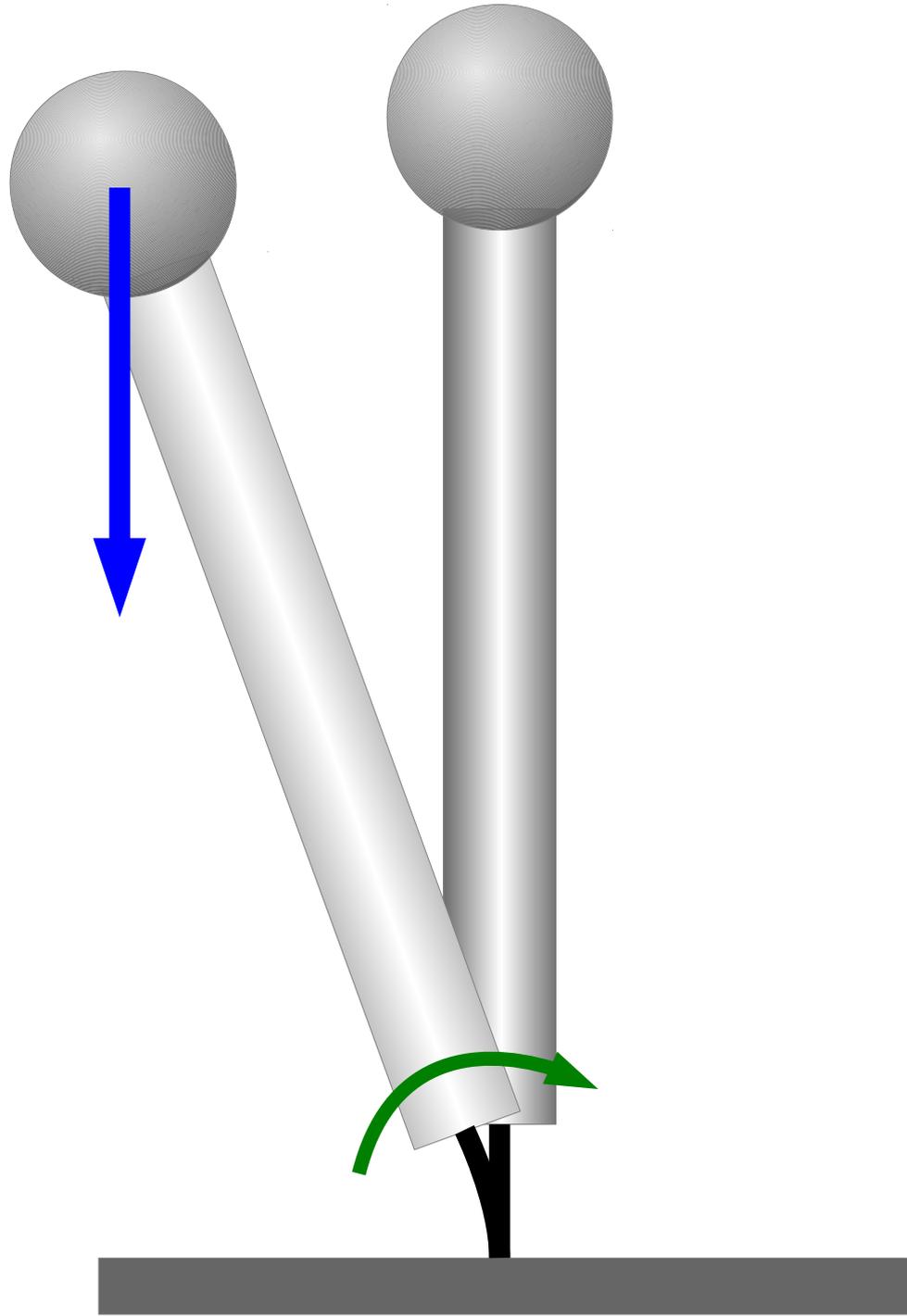
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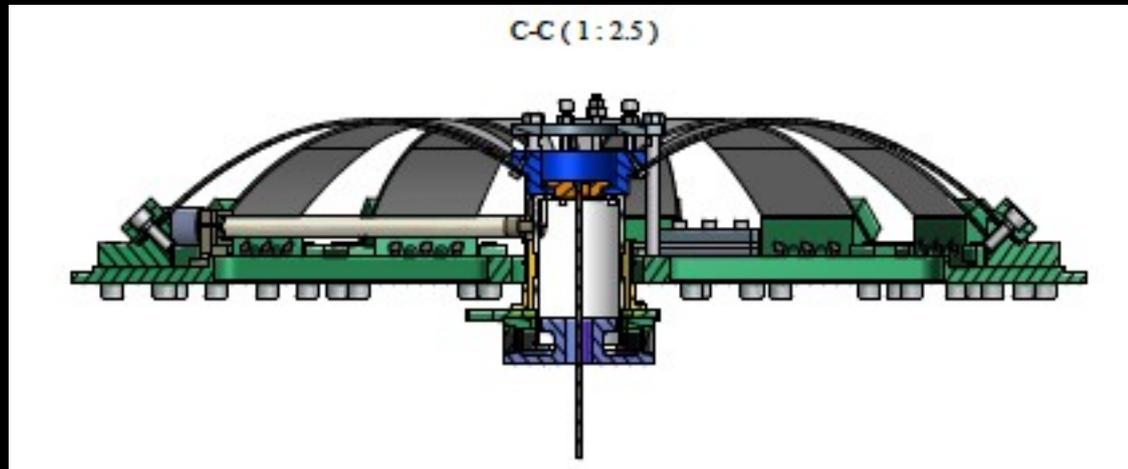
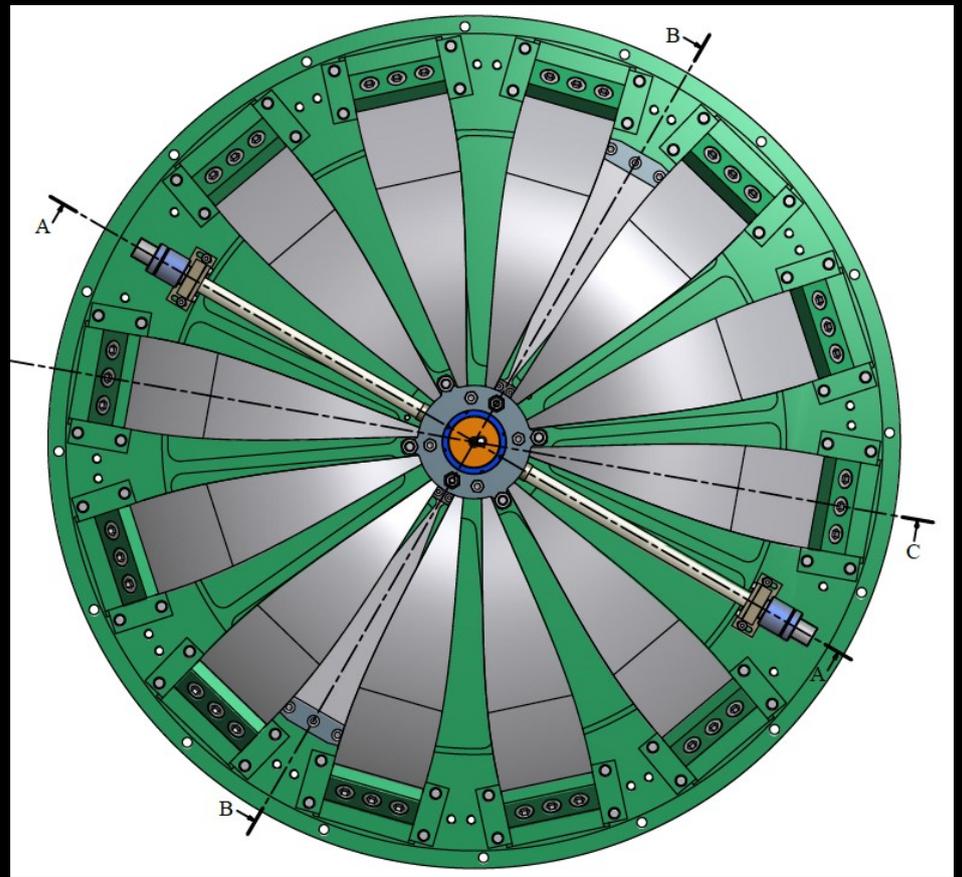
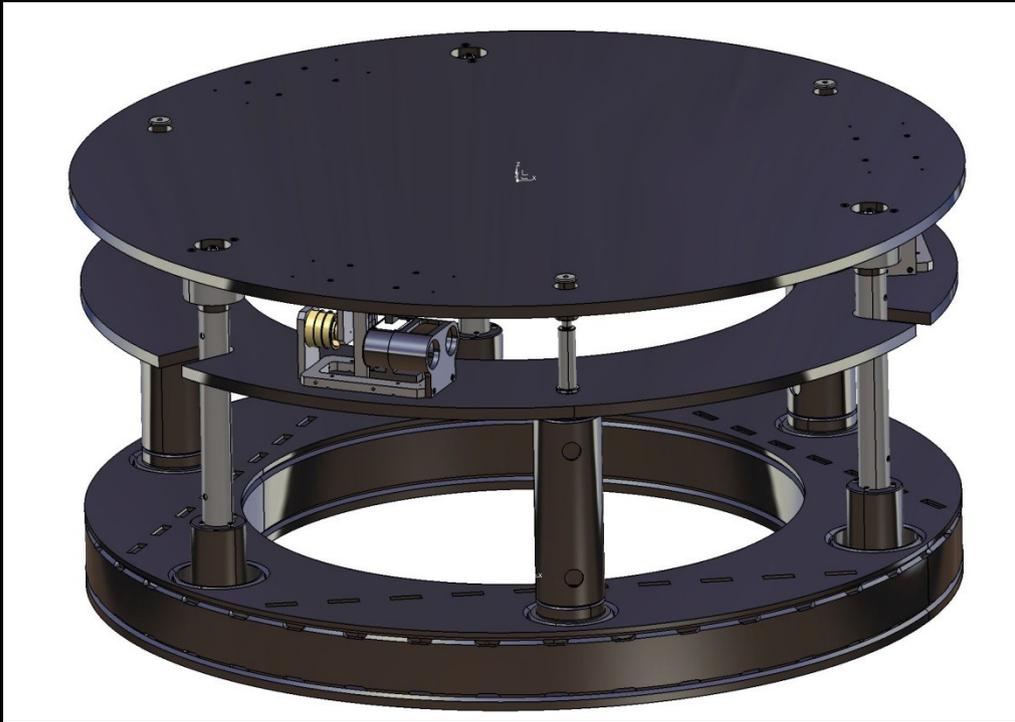
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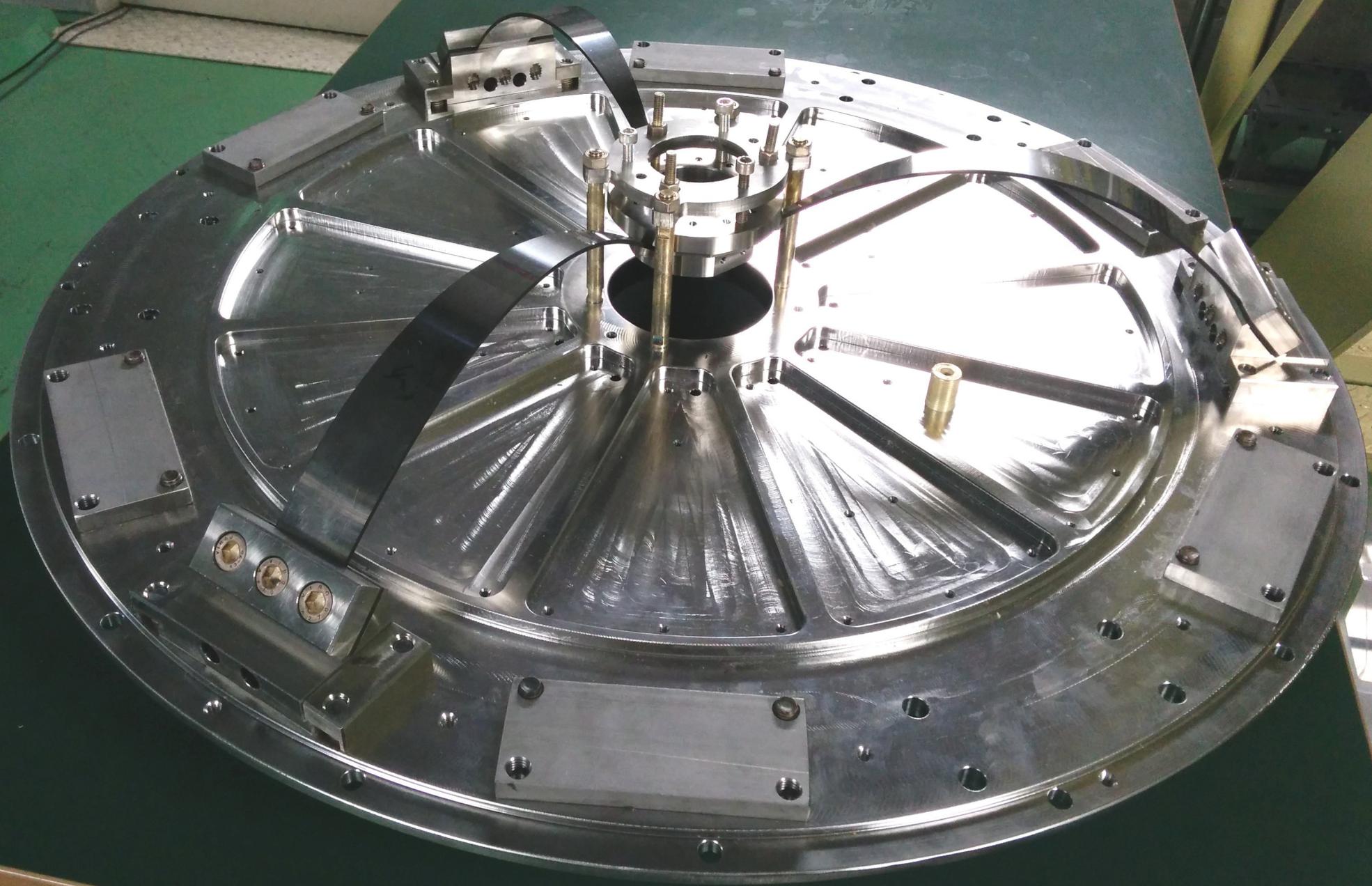


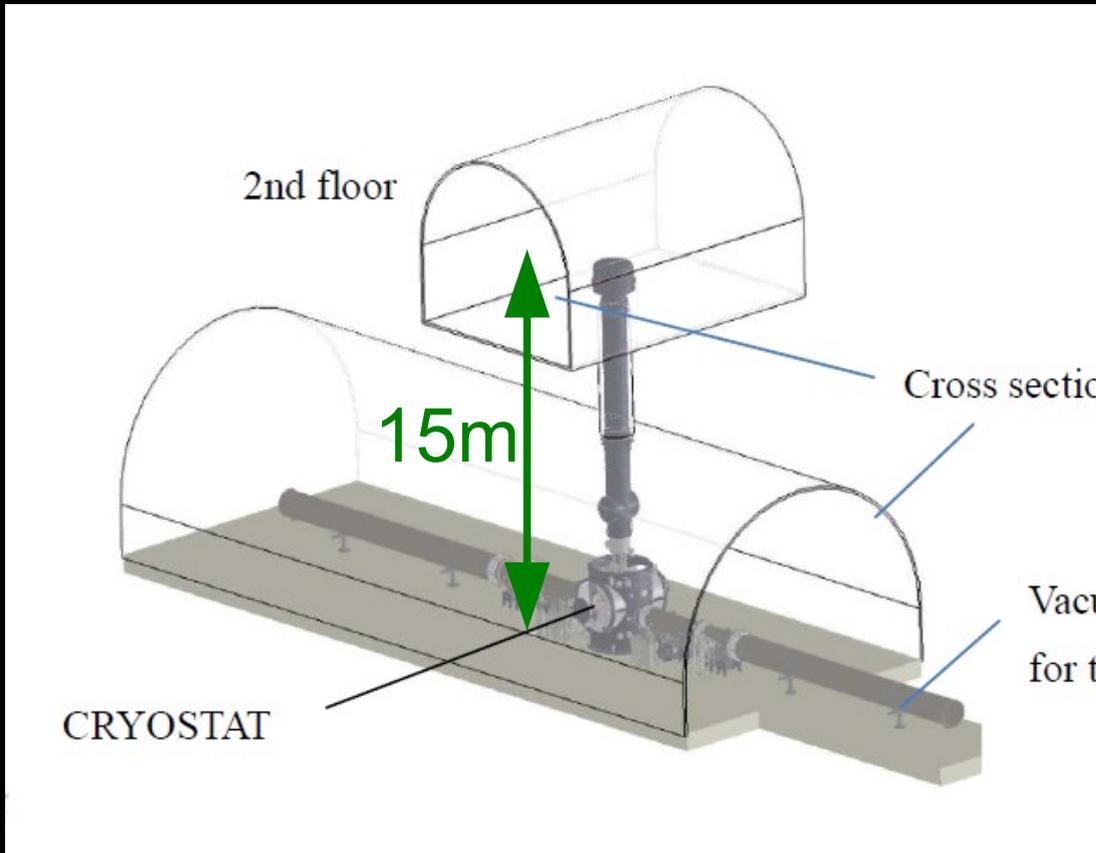
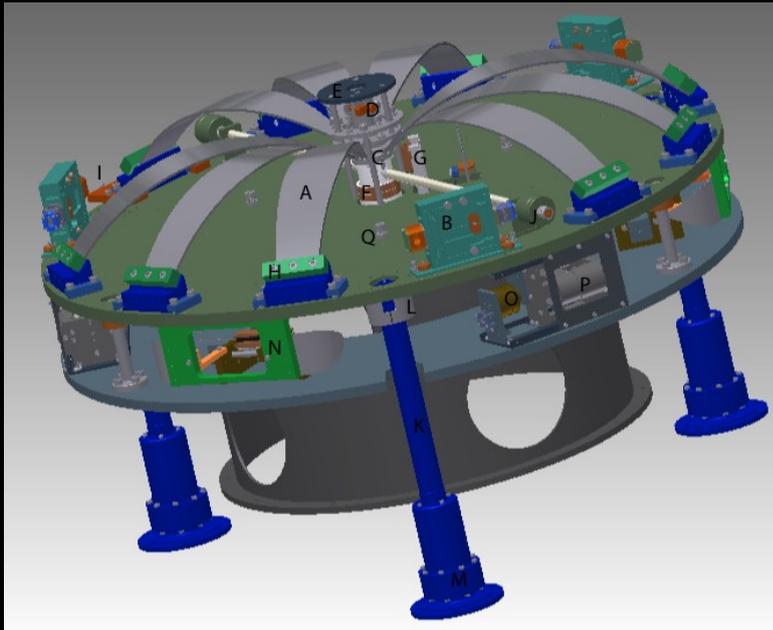




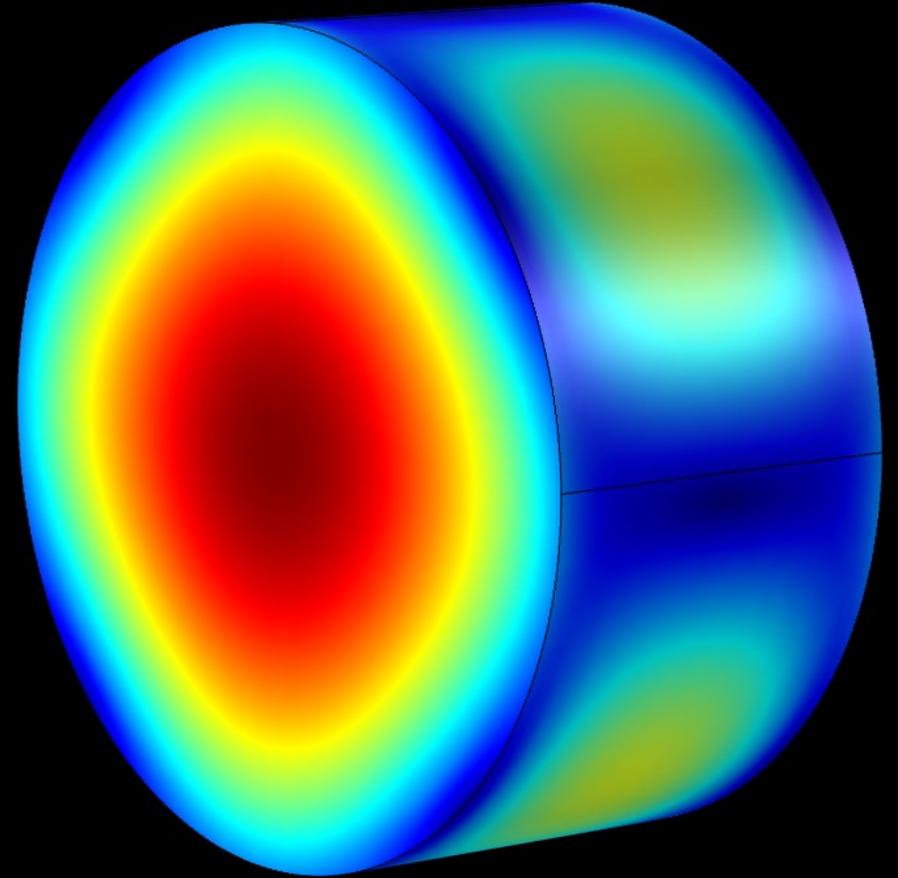
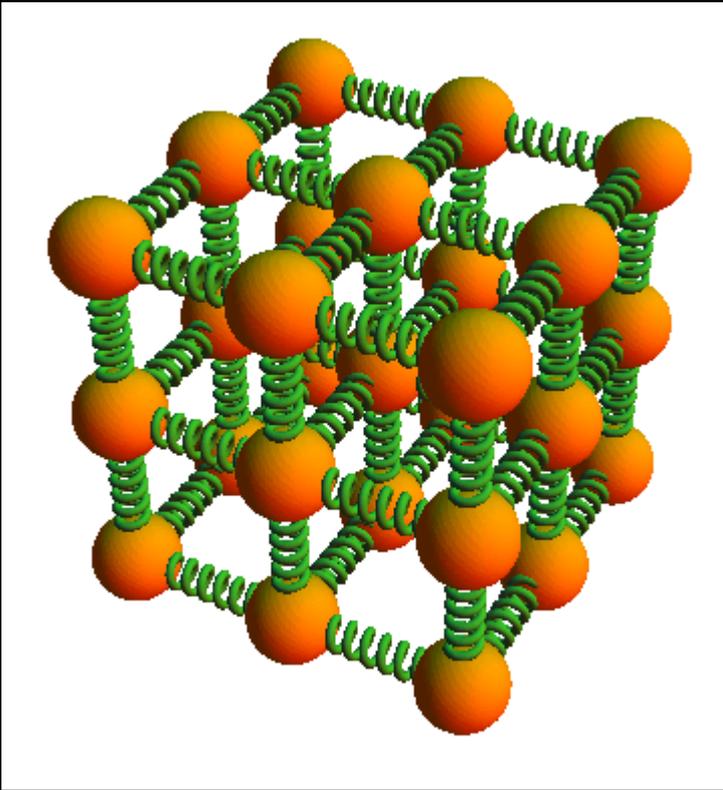




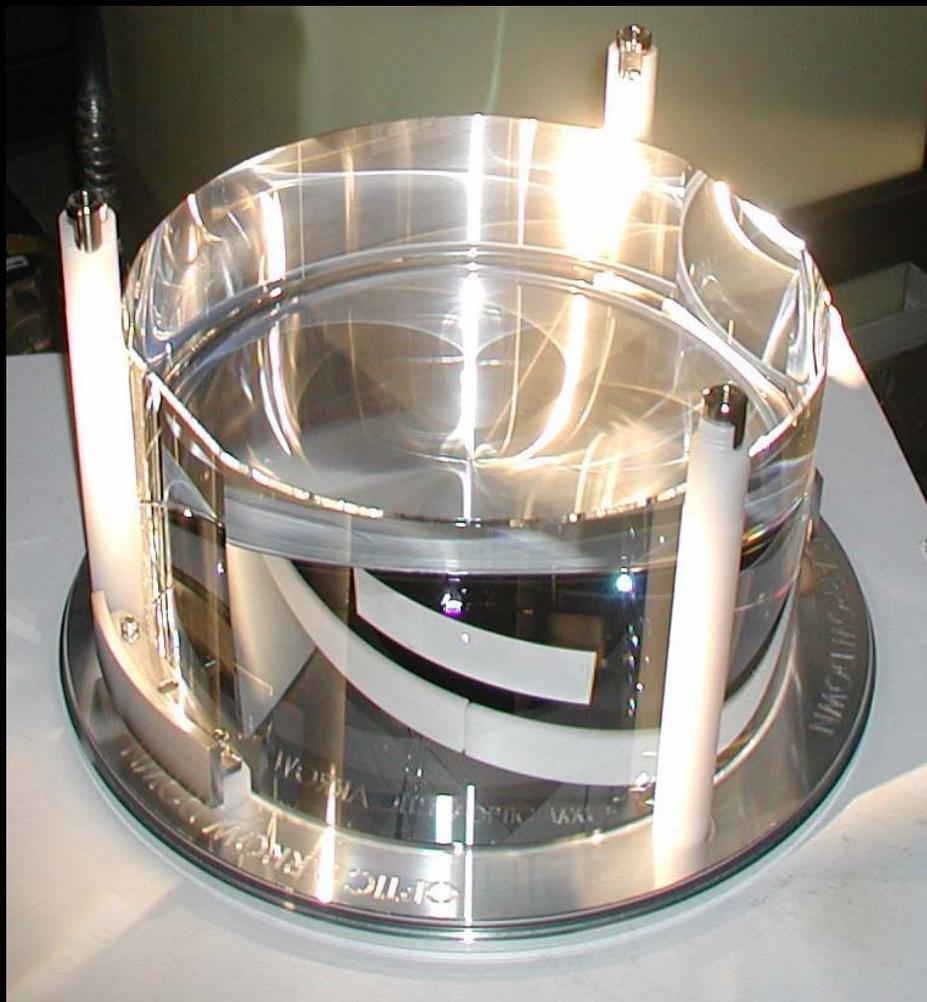




熱雑音

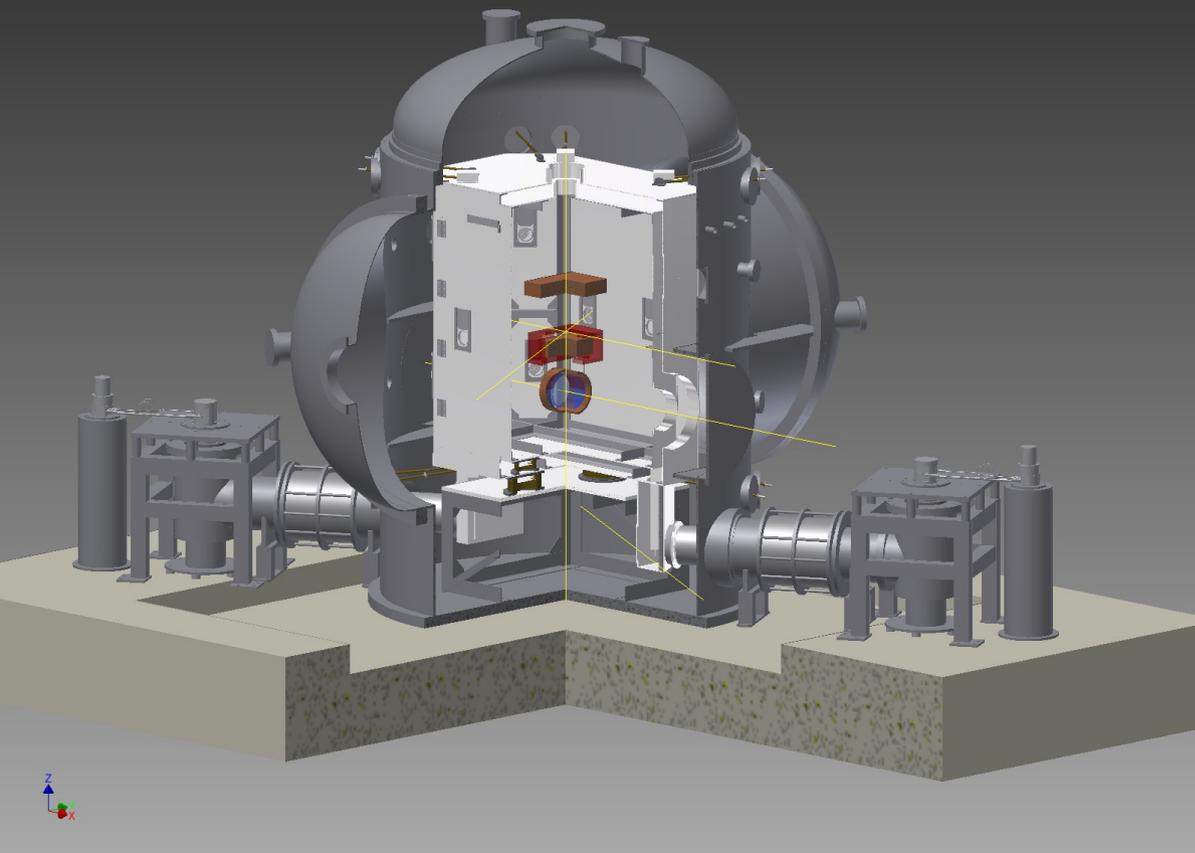


Fused Silica



Sapphire





低温サファイア鏡

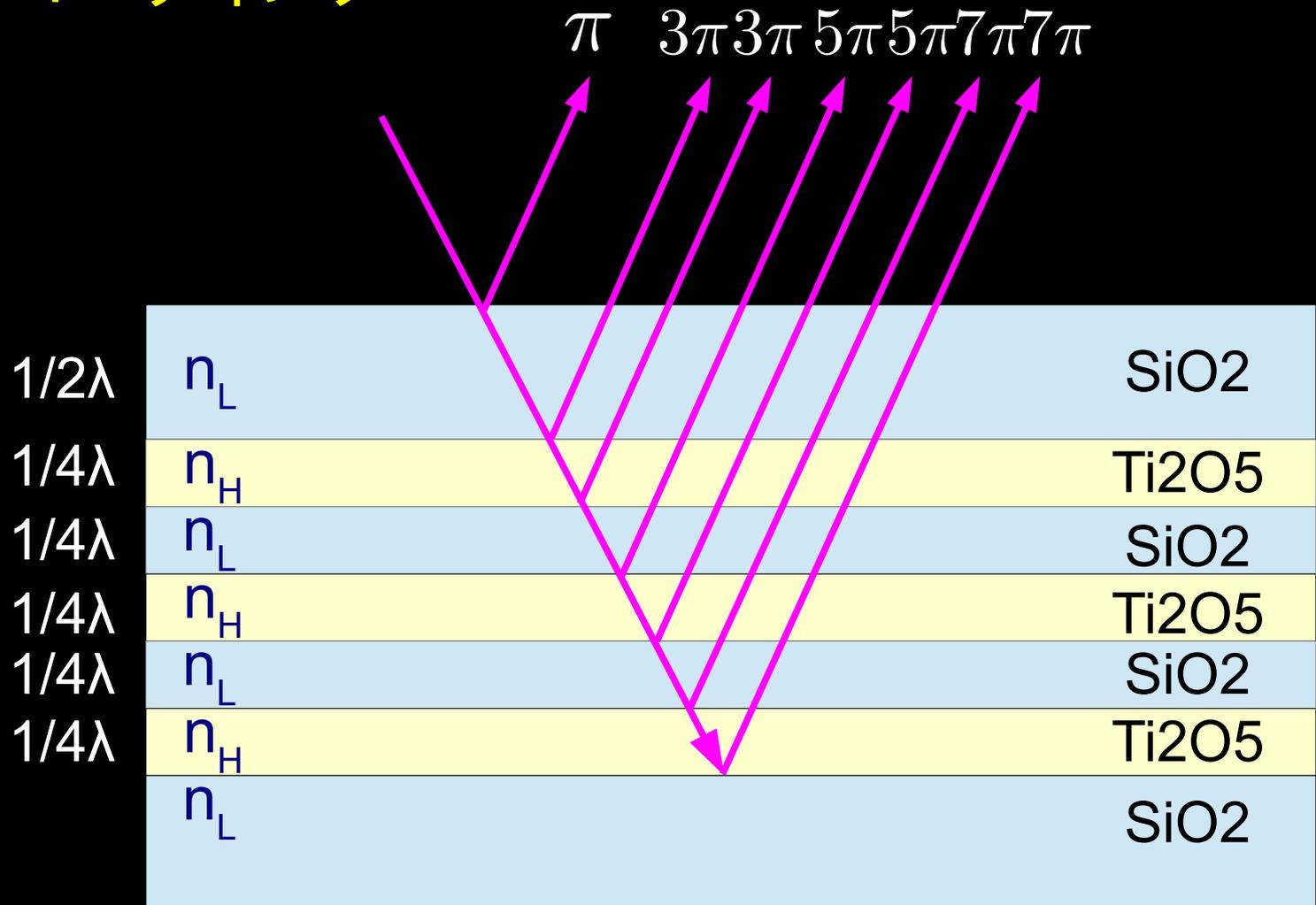
20Kまで冷却



高反射率コーティング

1/4λ スタック

$$n_L < n_H$$



コーティング材質: 機械的Q値が悪い, 光が直接当たる場所

→ 熱雑音レベルを決めている

大型超低損失ミラー

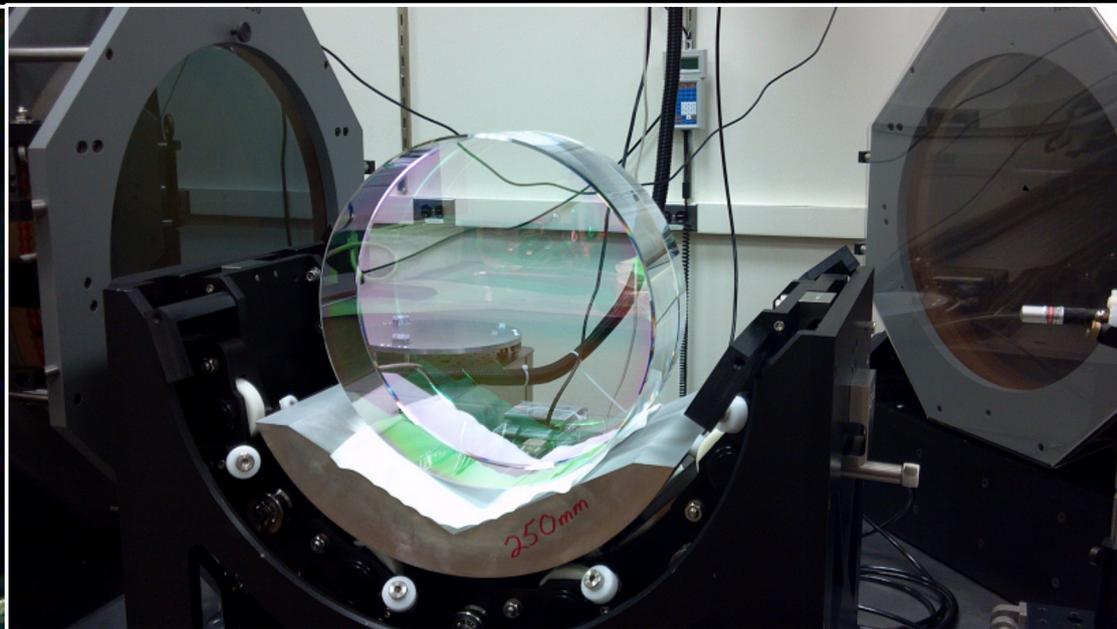
光学損失: 50ppm未満

面精度: $\lambda/100$

面粗さ: 10Å未満

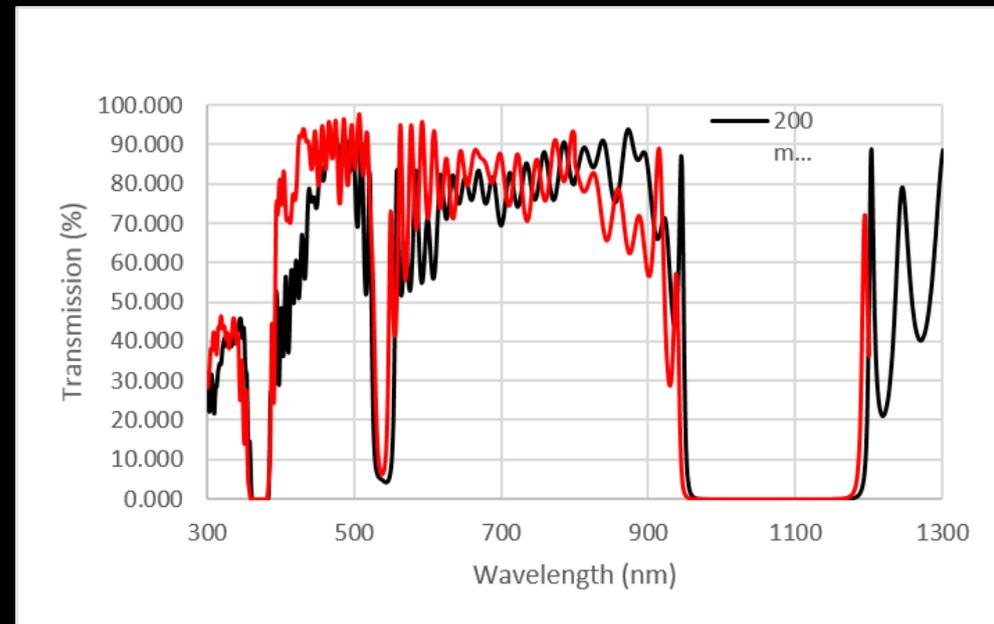
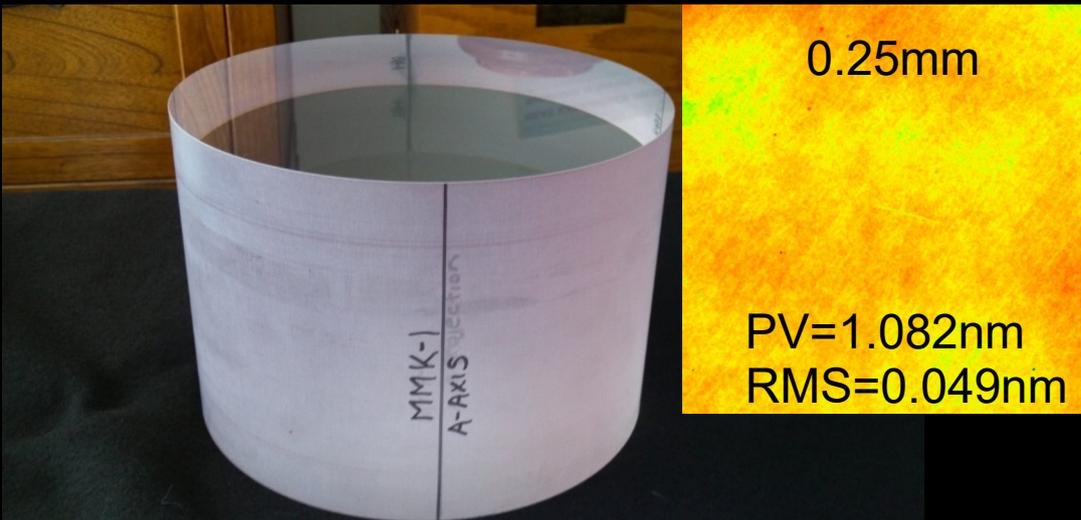
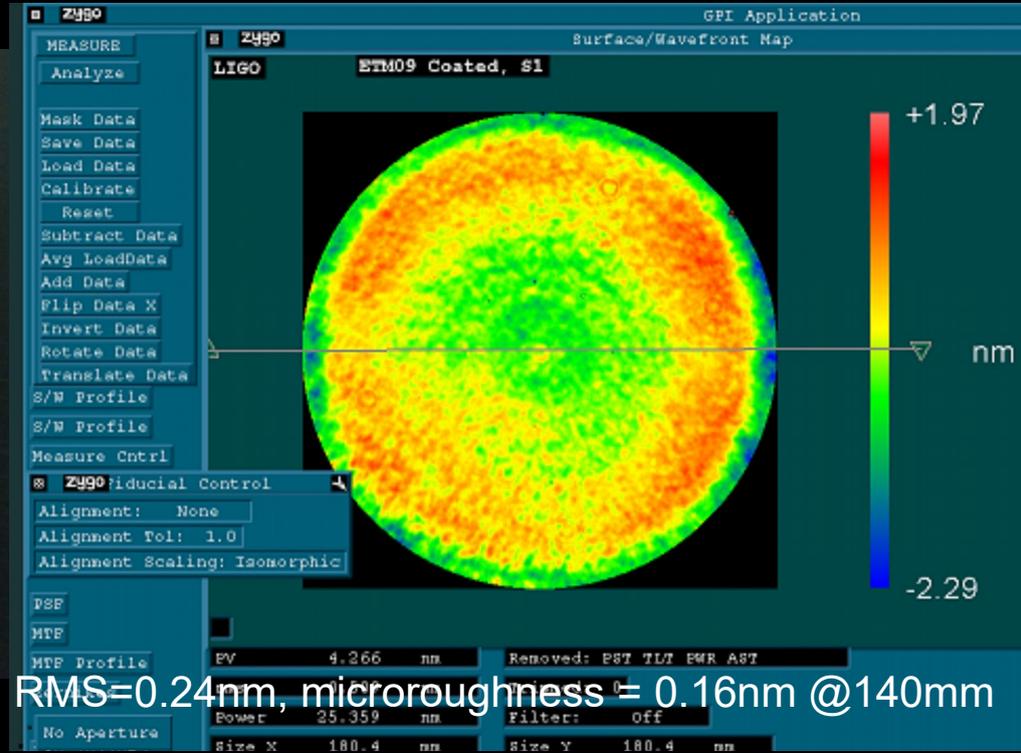
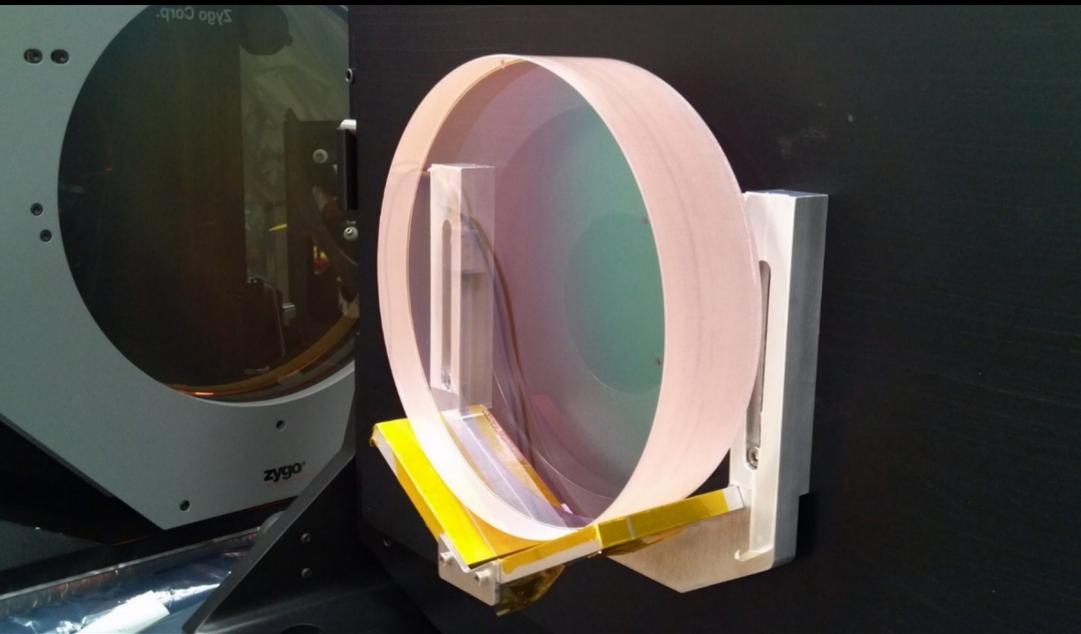


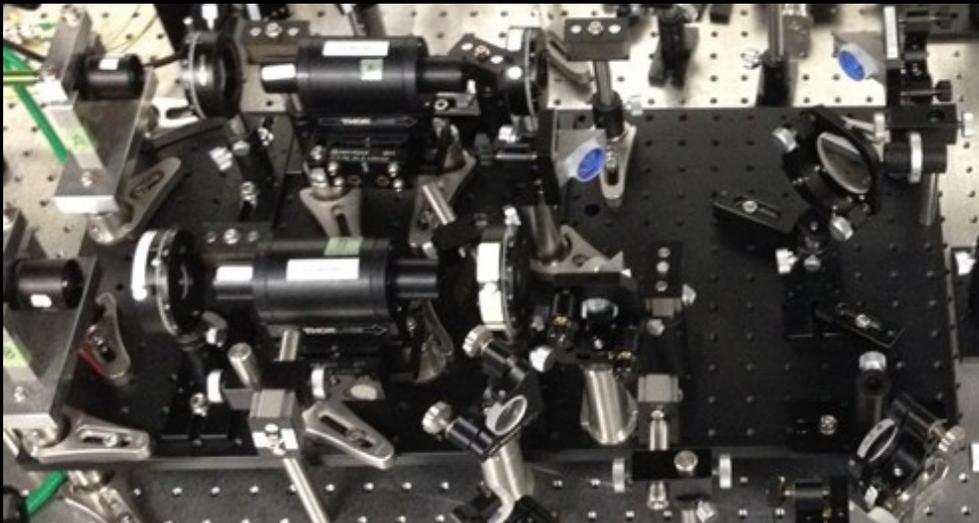
Beamsplitter(370mm dia) during coating characterization



iKAGRA TM (250mm dia) during figure measurement

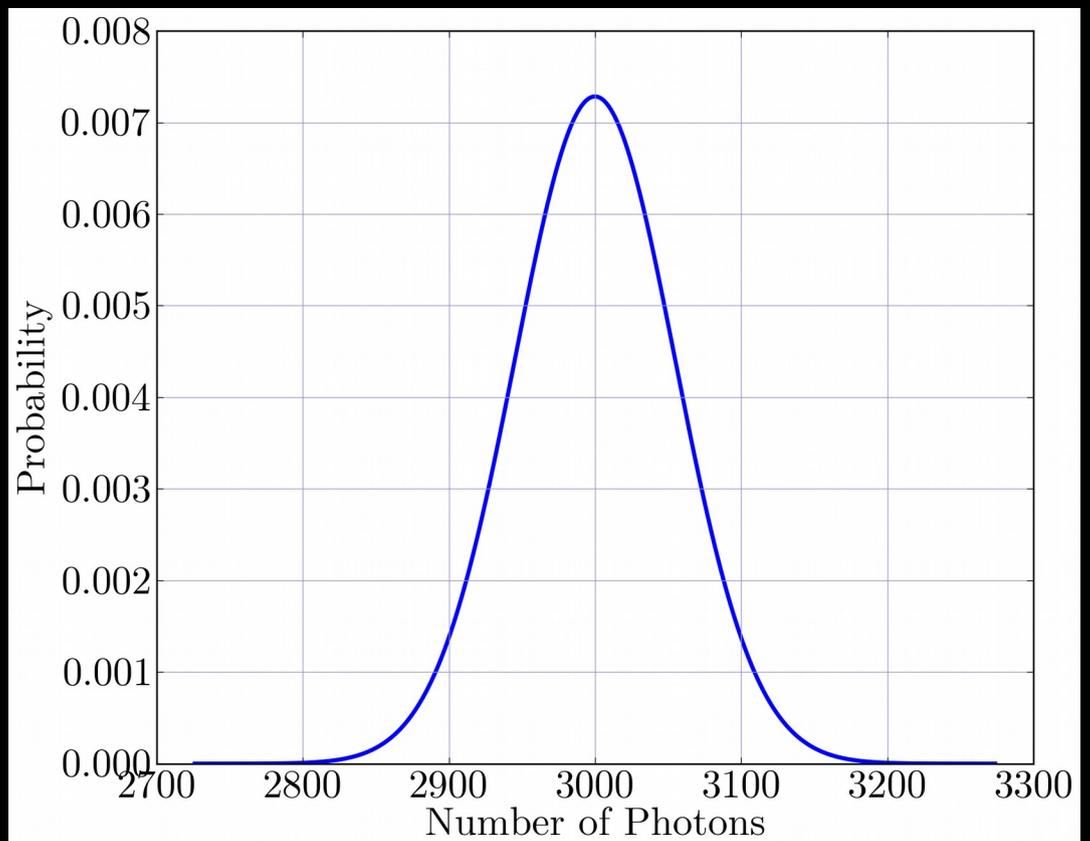
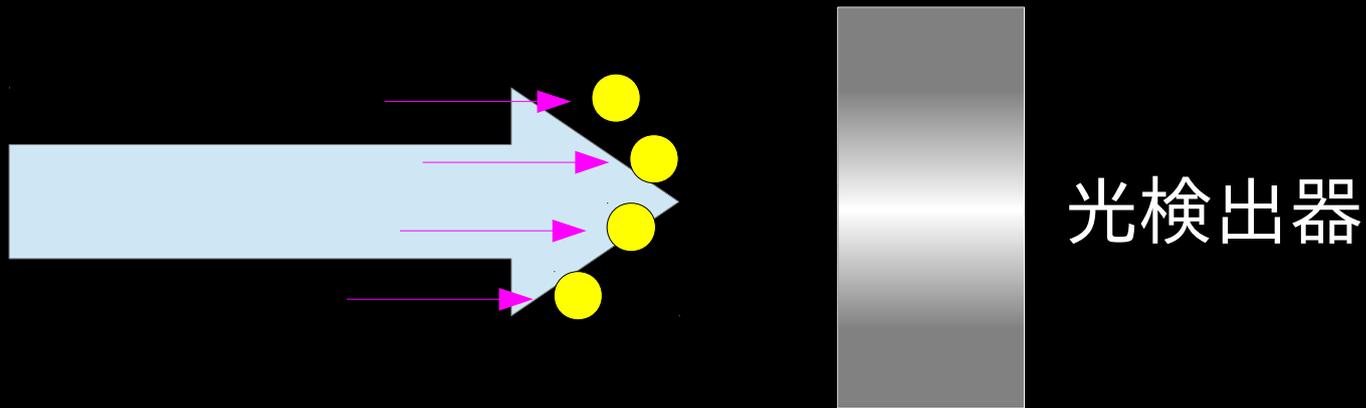
Sapphire Mirror Polishing





量子力学的不确定性原理

ショットノイズ



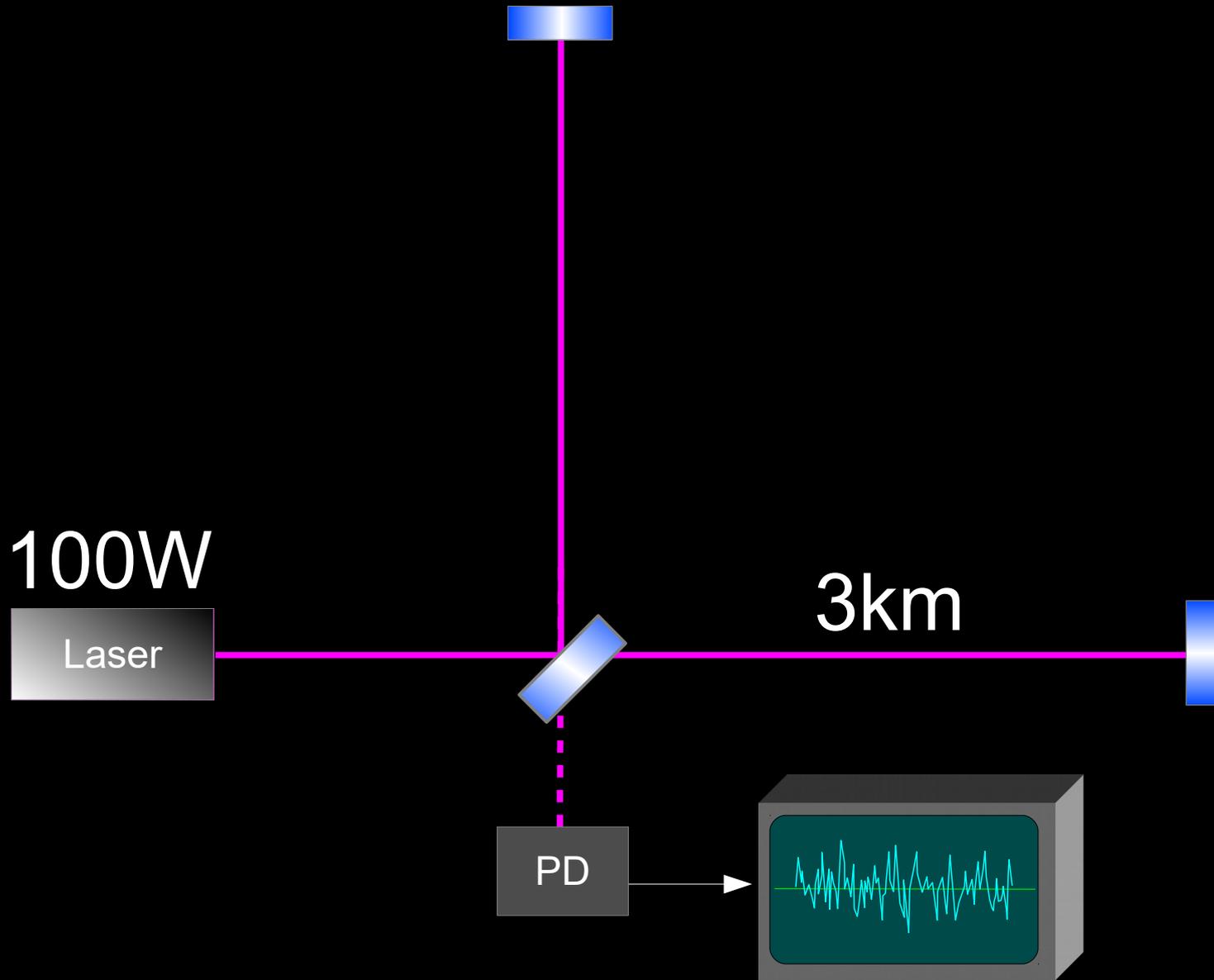
信号 $\propto P$

雜音 $\propto \sqrt{P}$



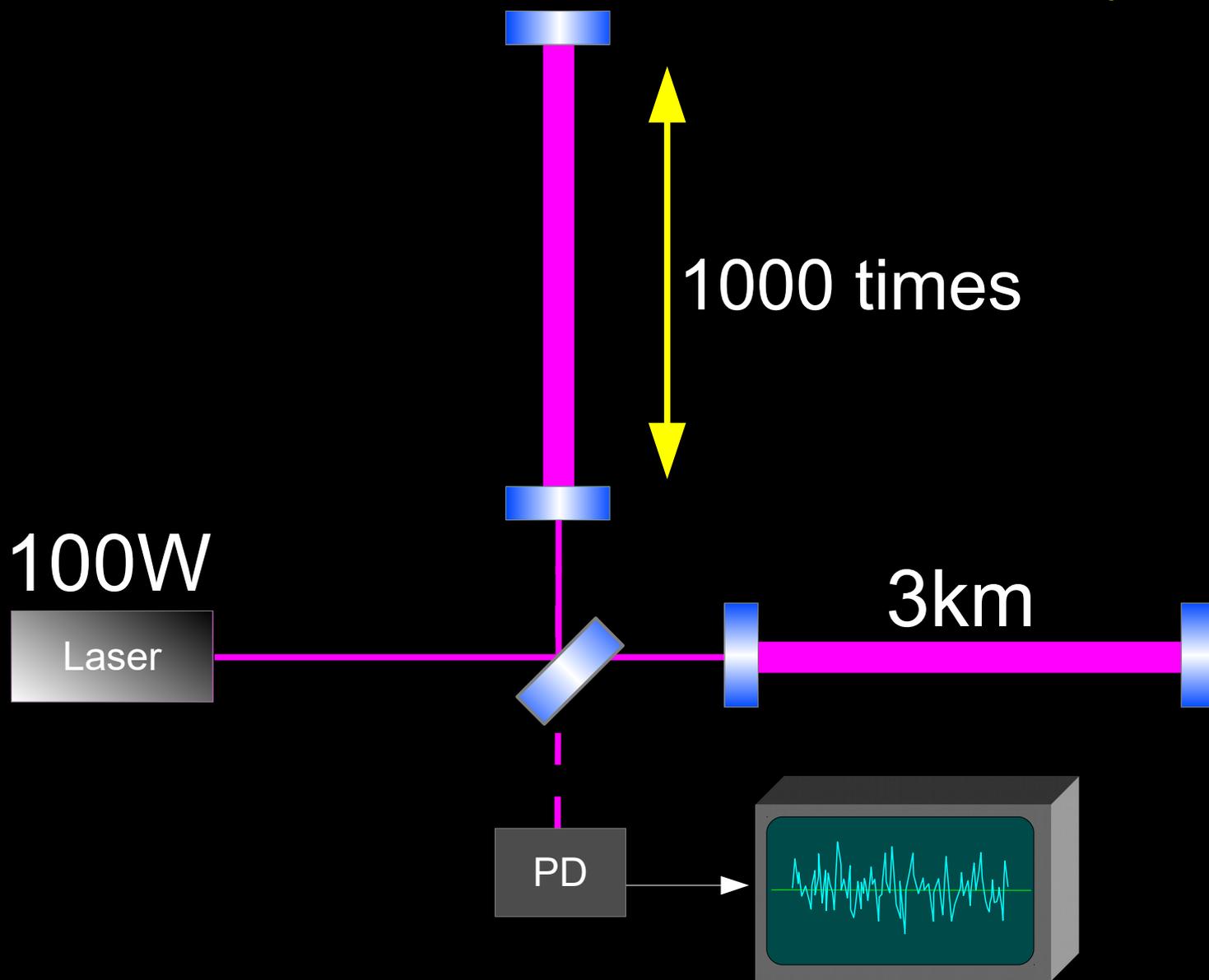
$$\frac{\text{信号}}{\text{雜音}} \propto \sqrt{P}$$

マイケルソン干渉計



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

Fabry-Perot Michelson

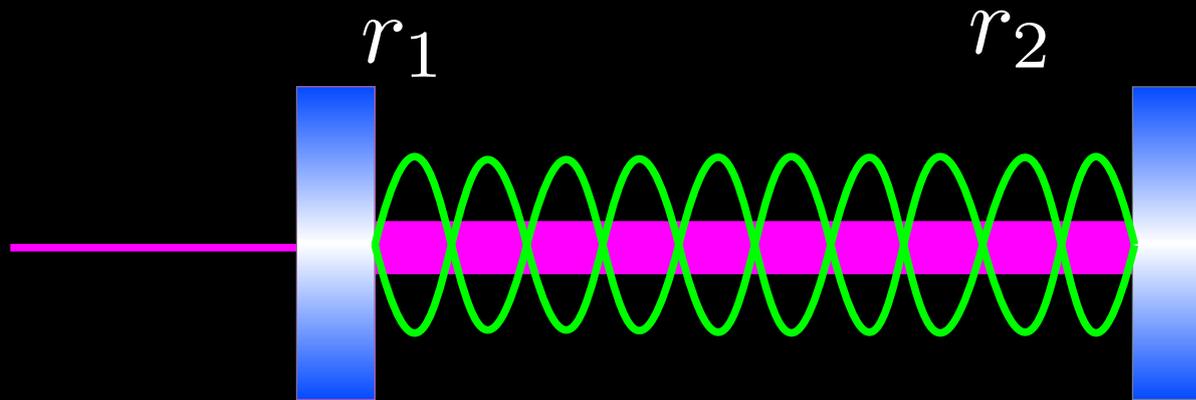


$$h = 2 \times 10^{-24}$$

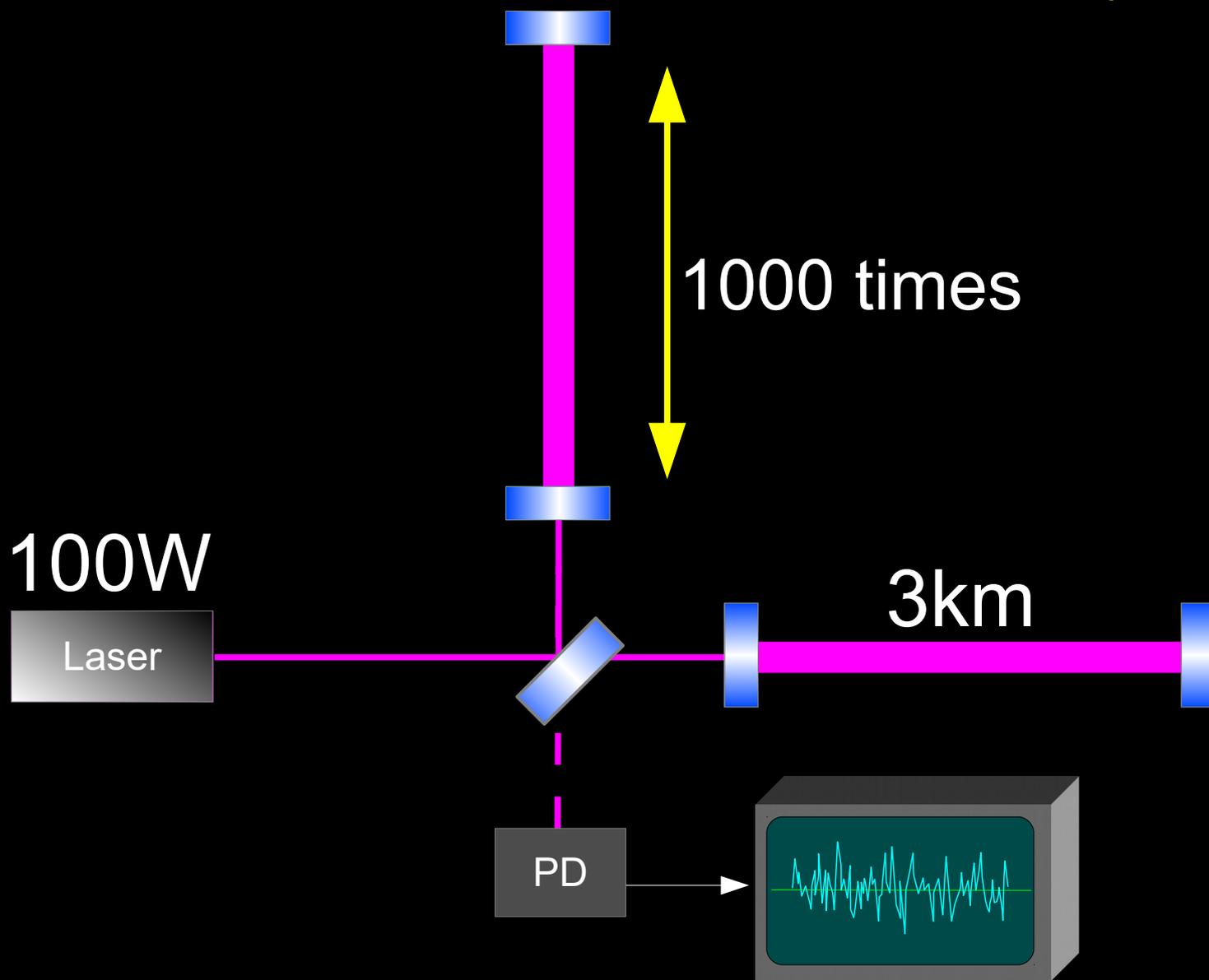
Fabry-Perot Cavity



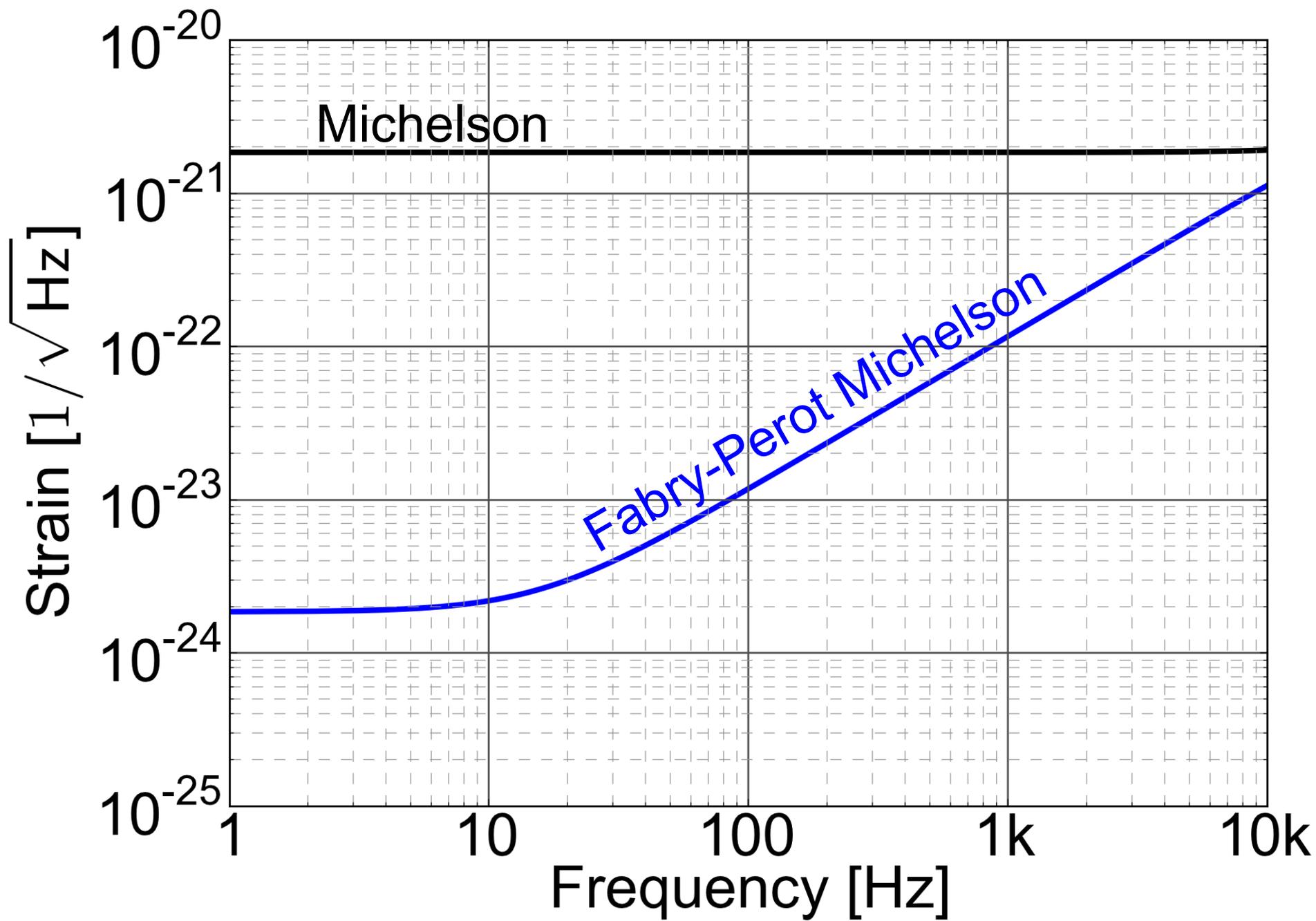
Fabry-Perot Cavity



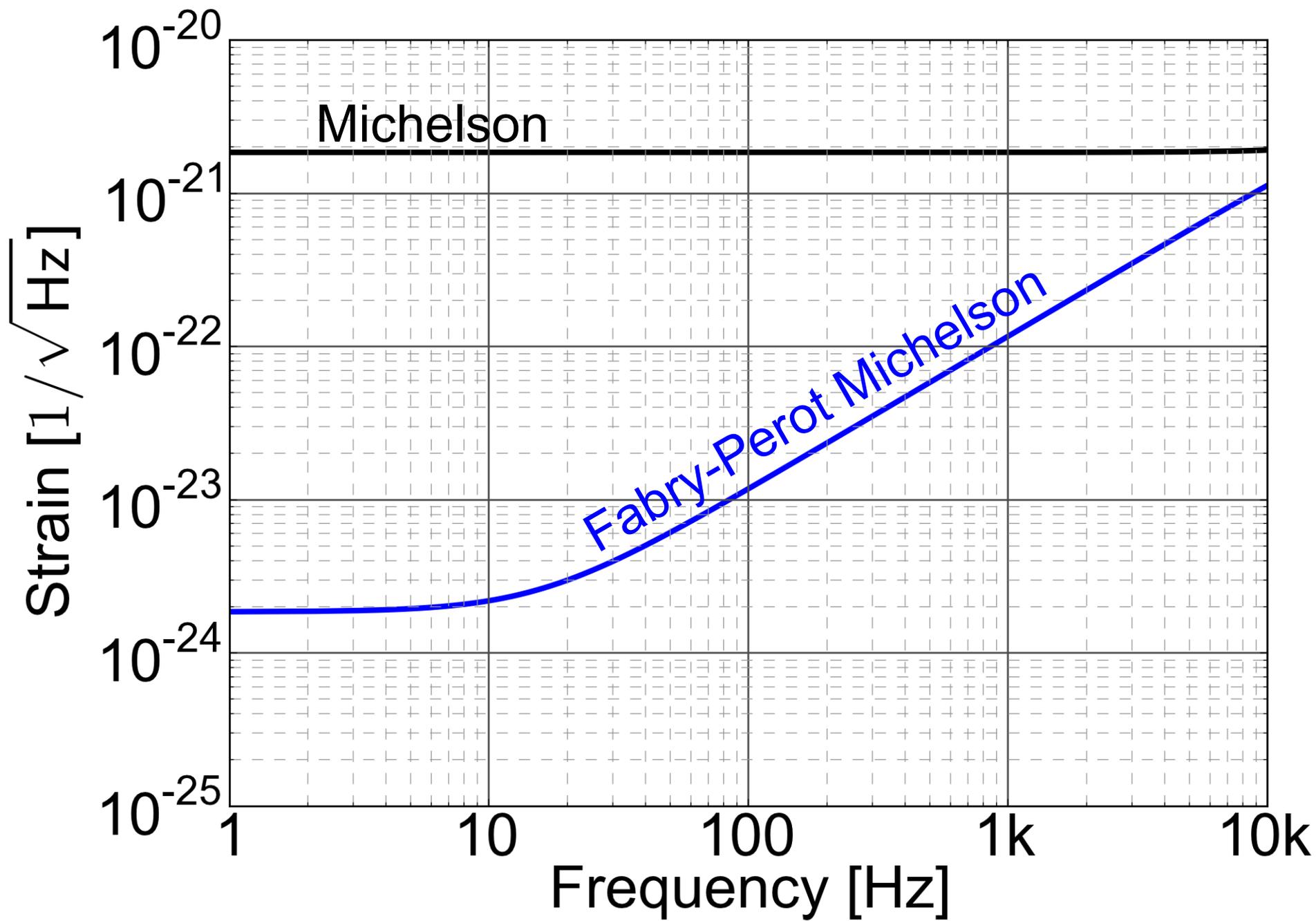
Fabry-Perot Michelson



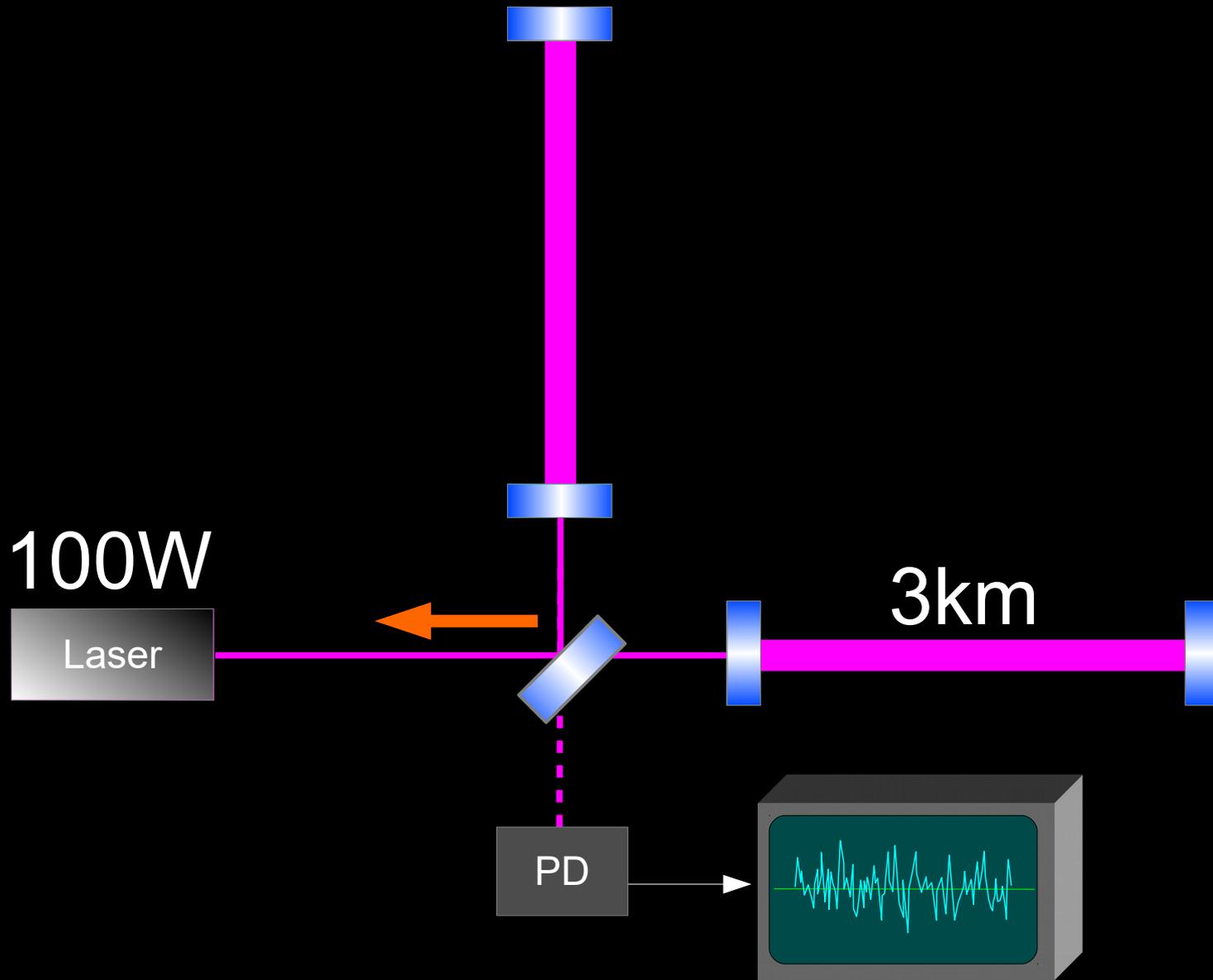
$$h = 2 \times 10^{-24}$$



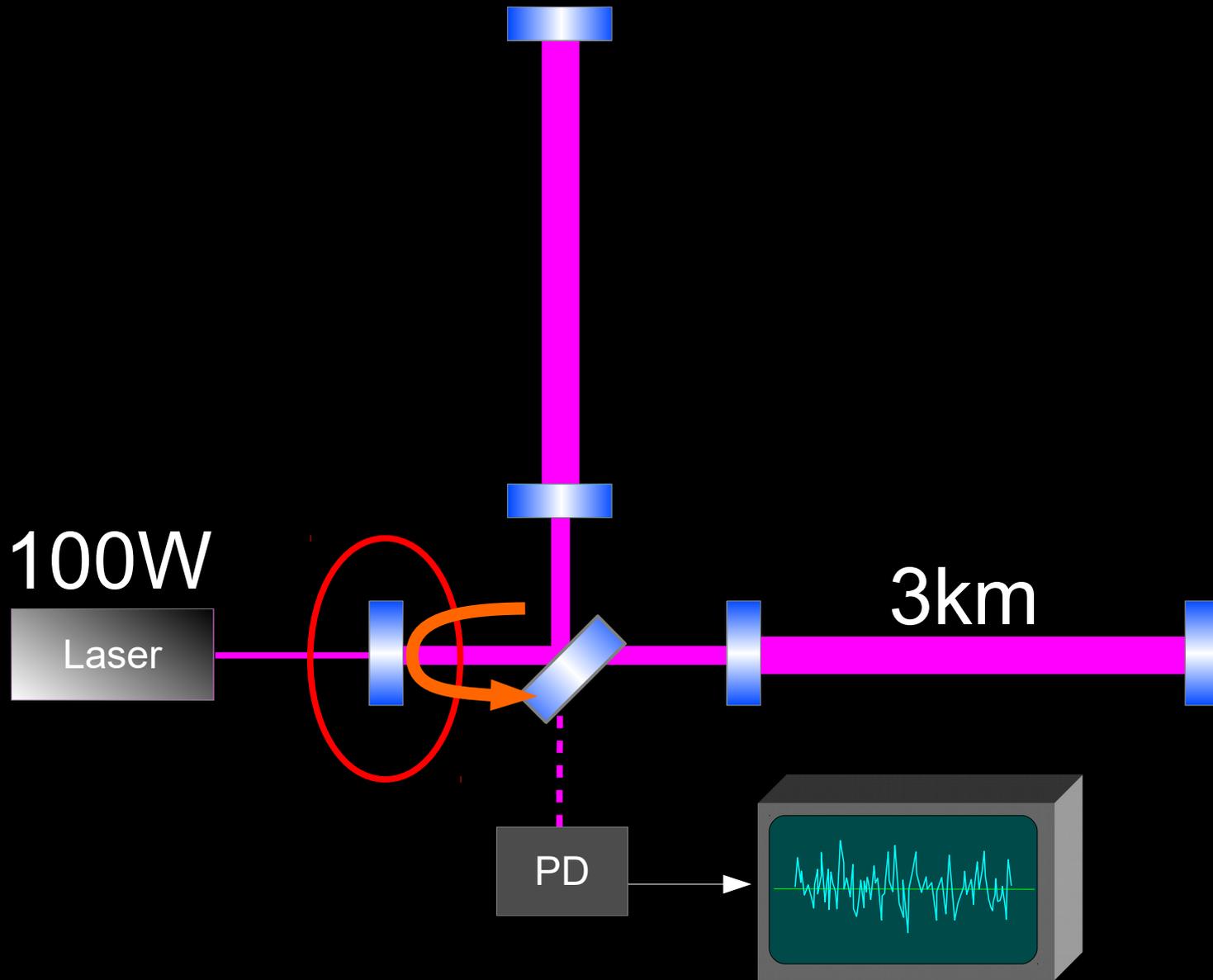


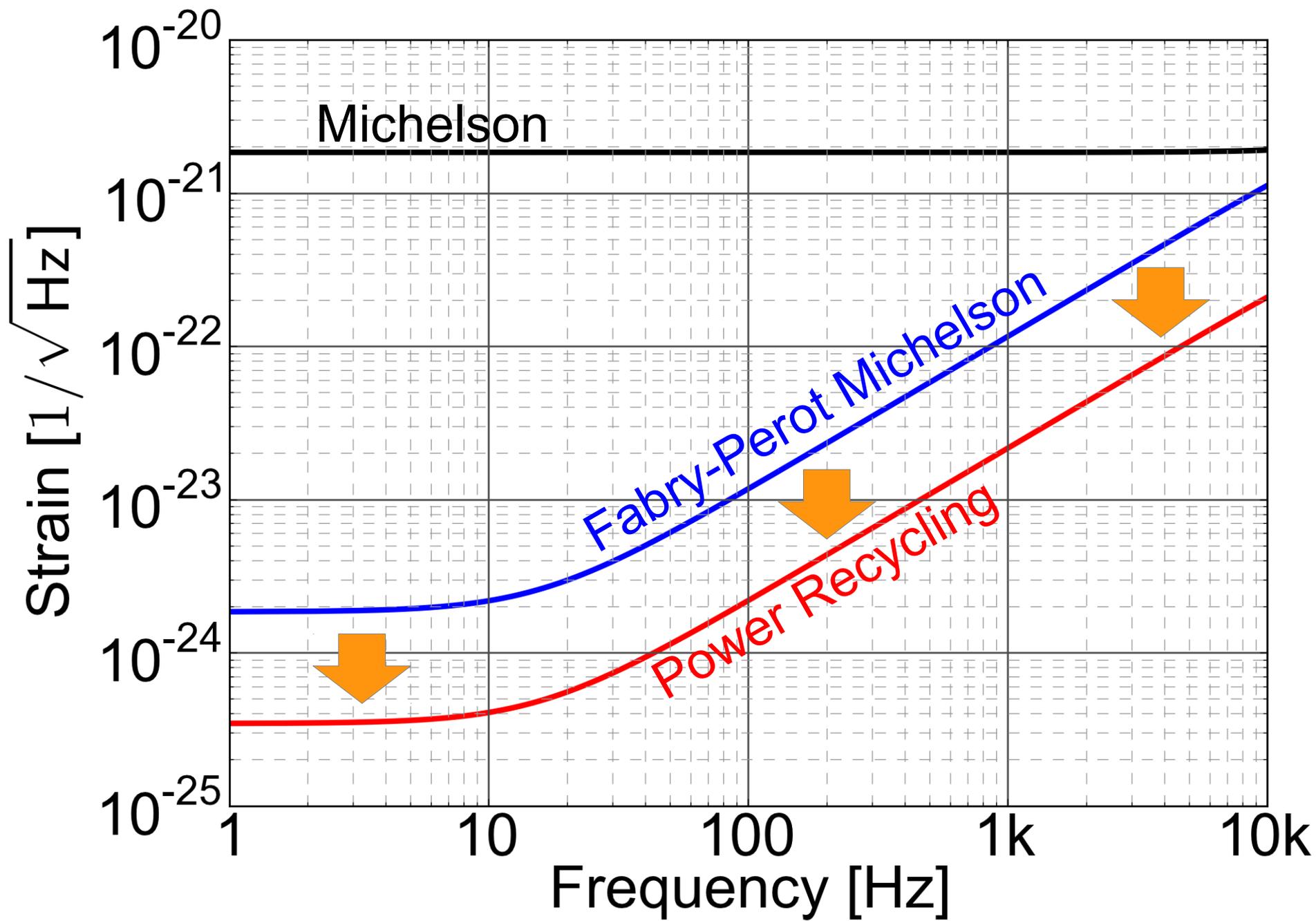


Fabry-Perot Michelson

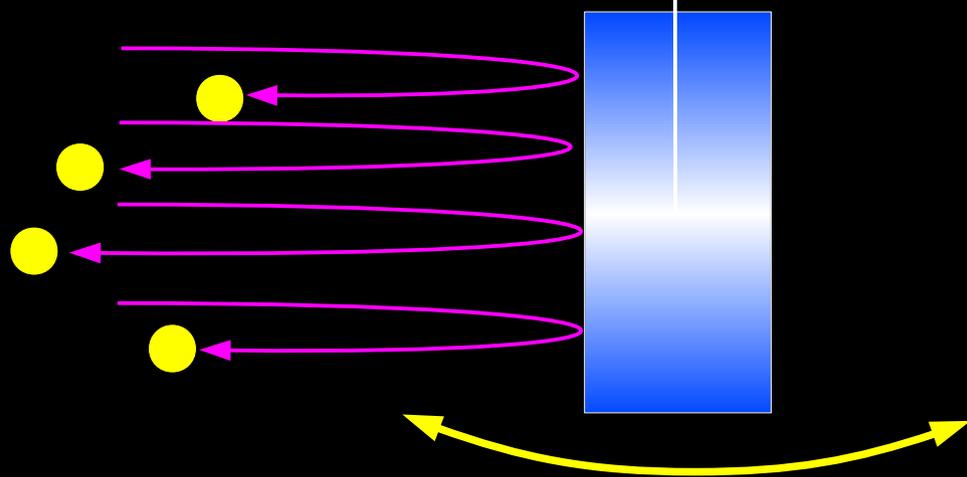


Power Recycling



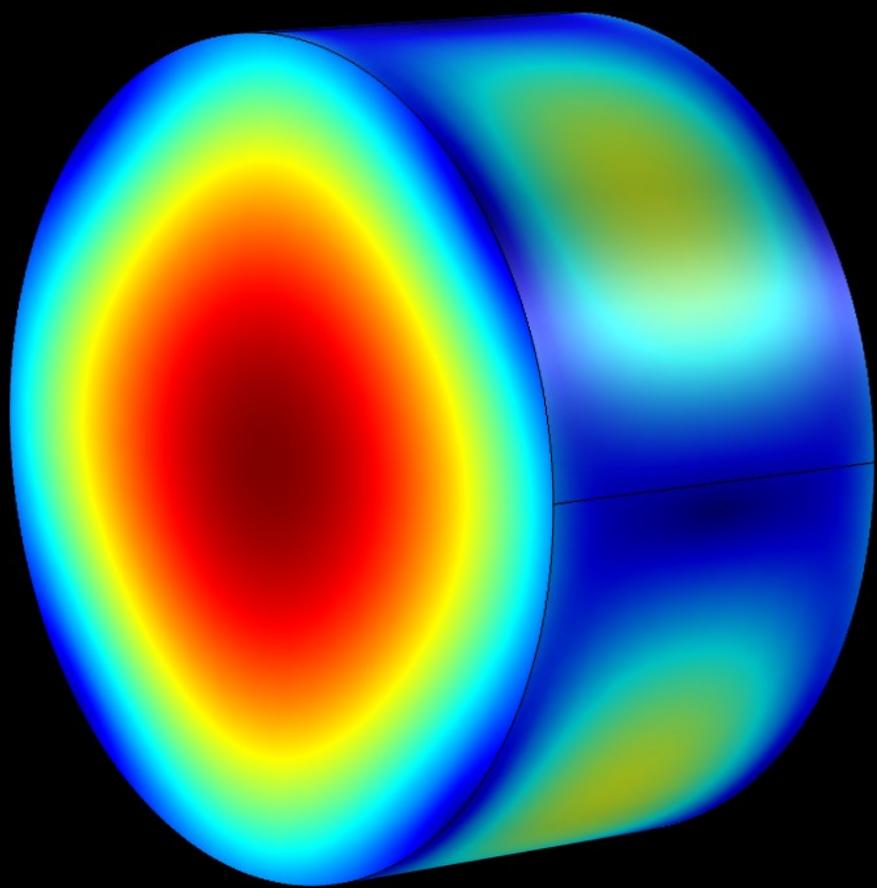


量子輻射压雜音

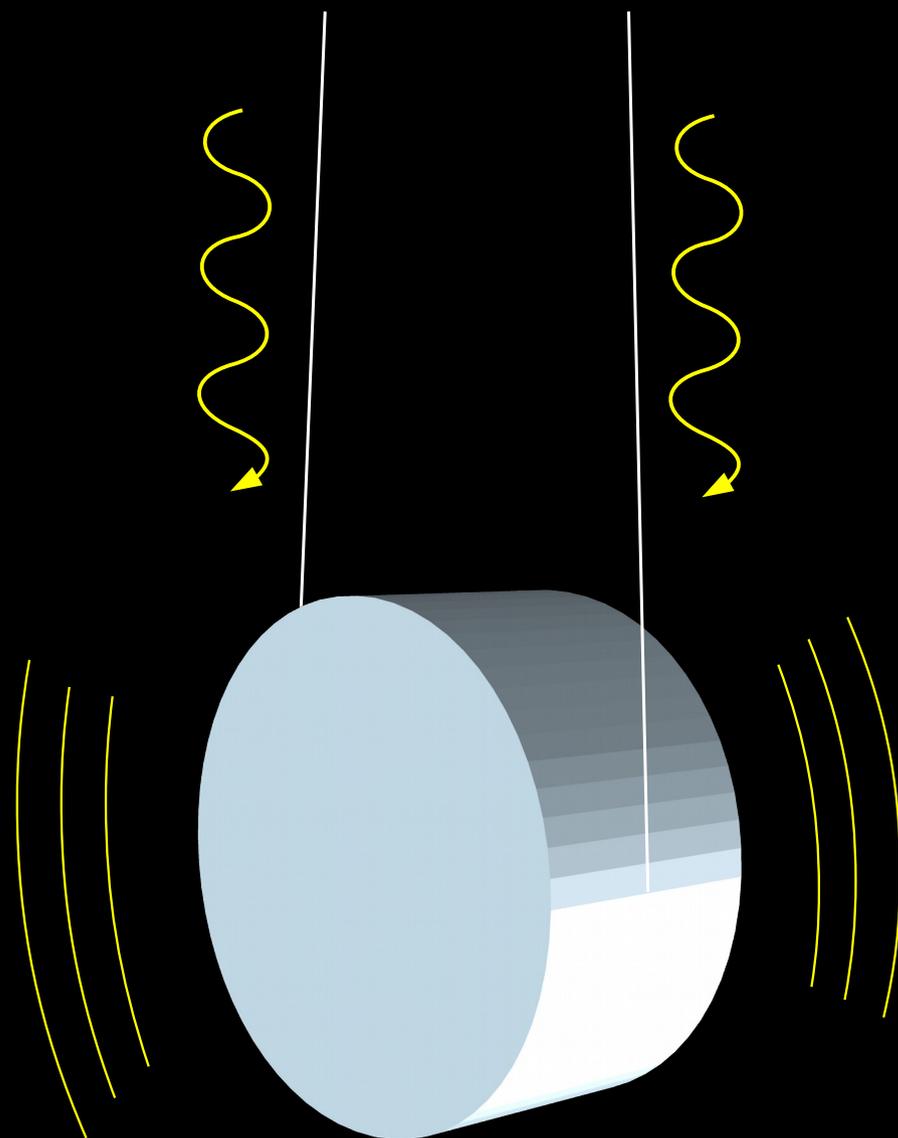


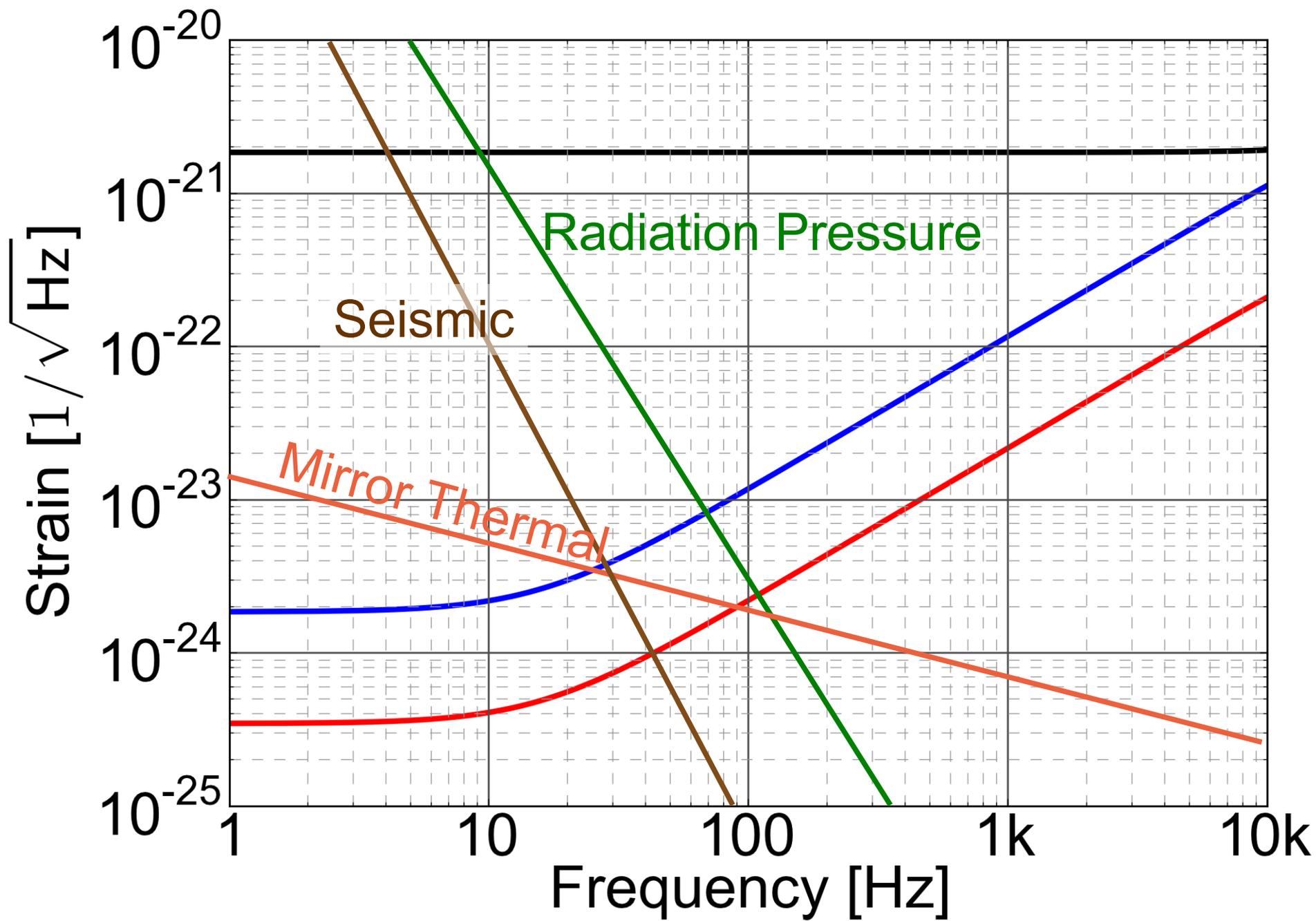
$$\frac{\text{信号}}{\text{雜音}} \propto 1/\sqrt{P}$$

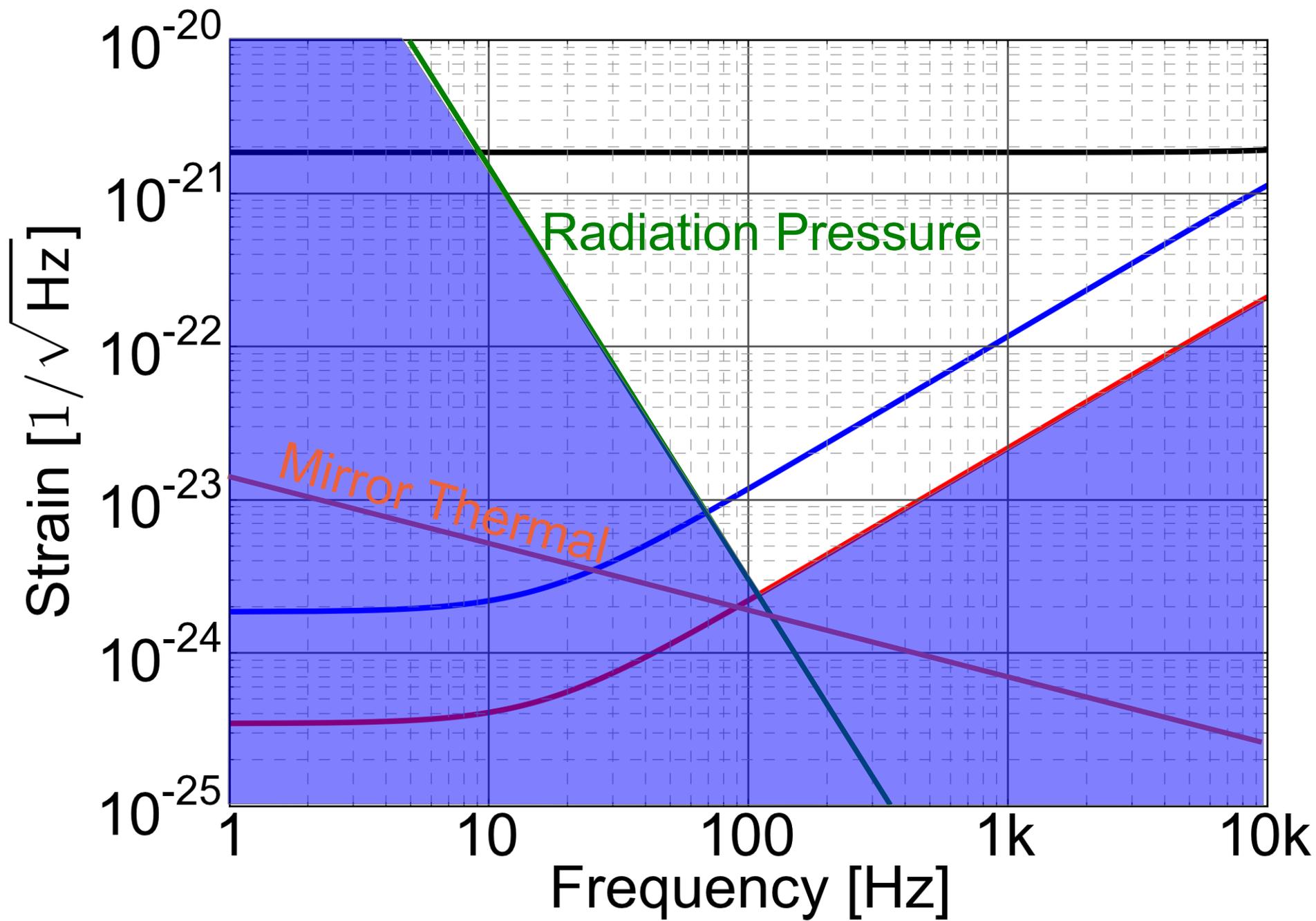
熱雜音

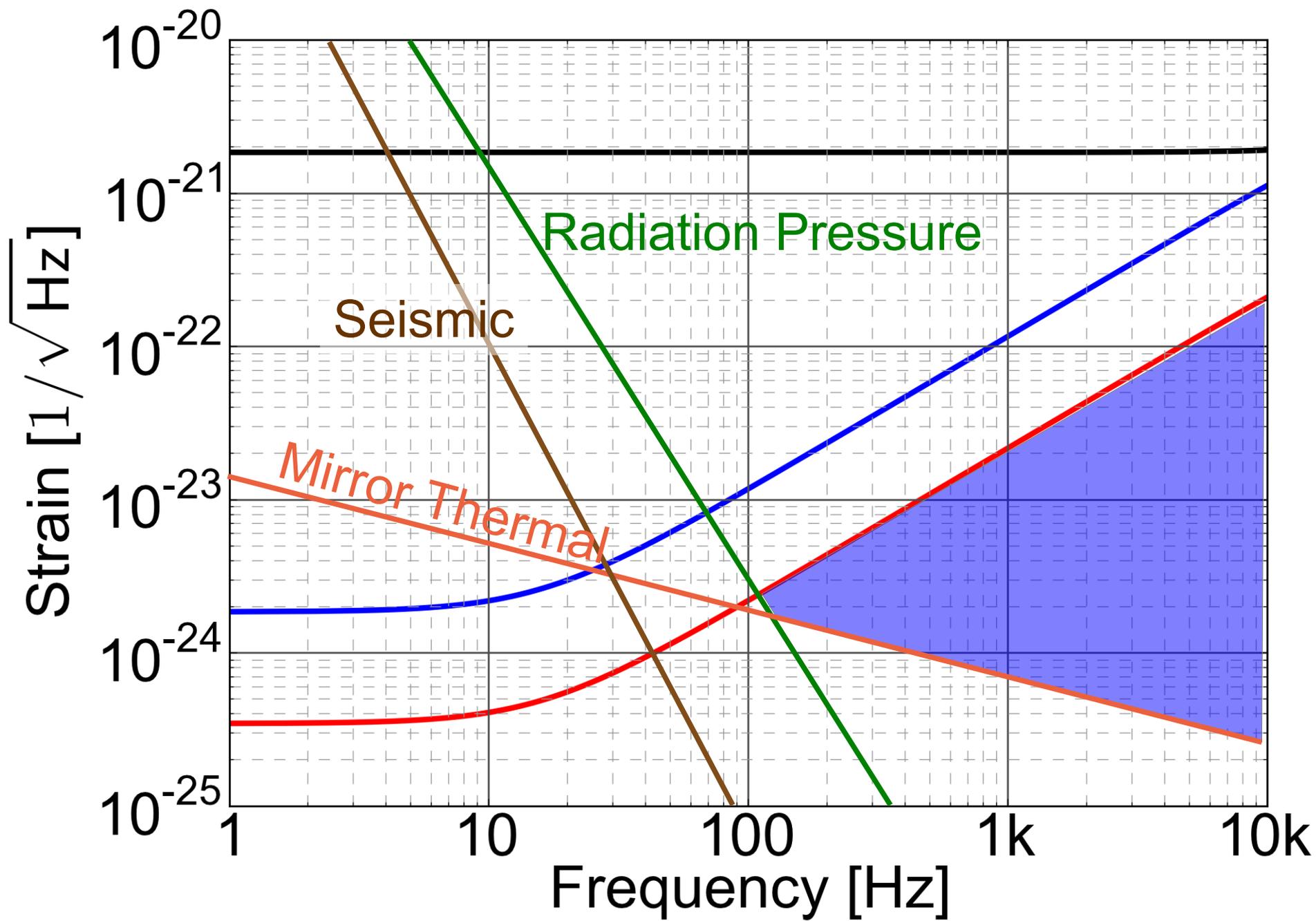


地面振動

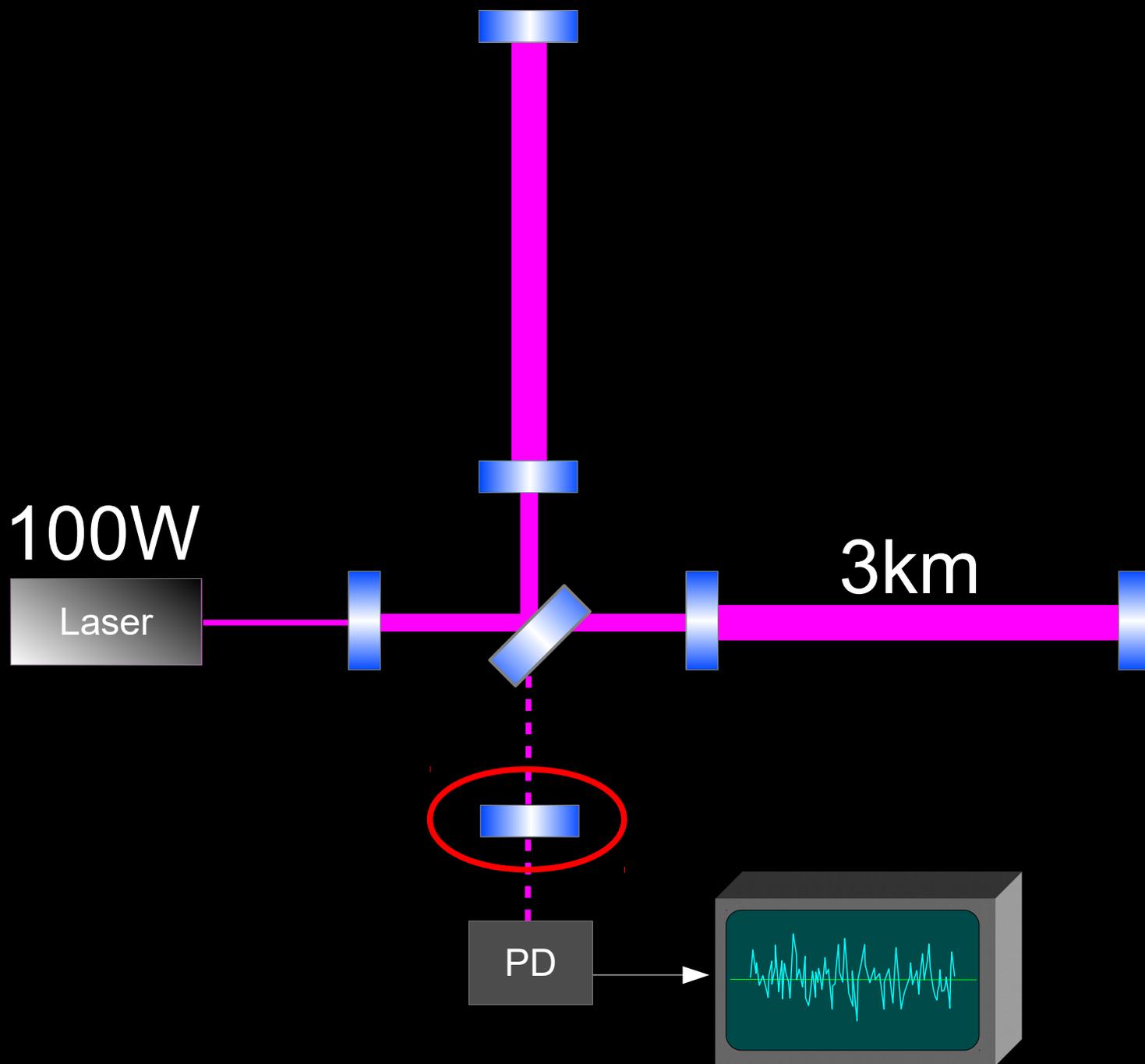


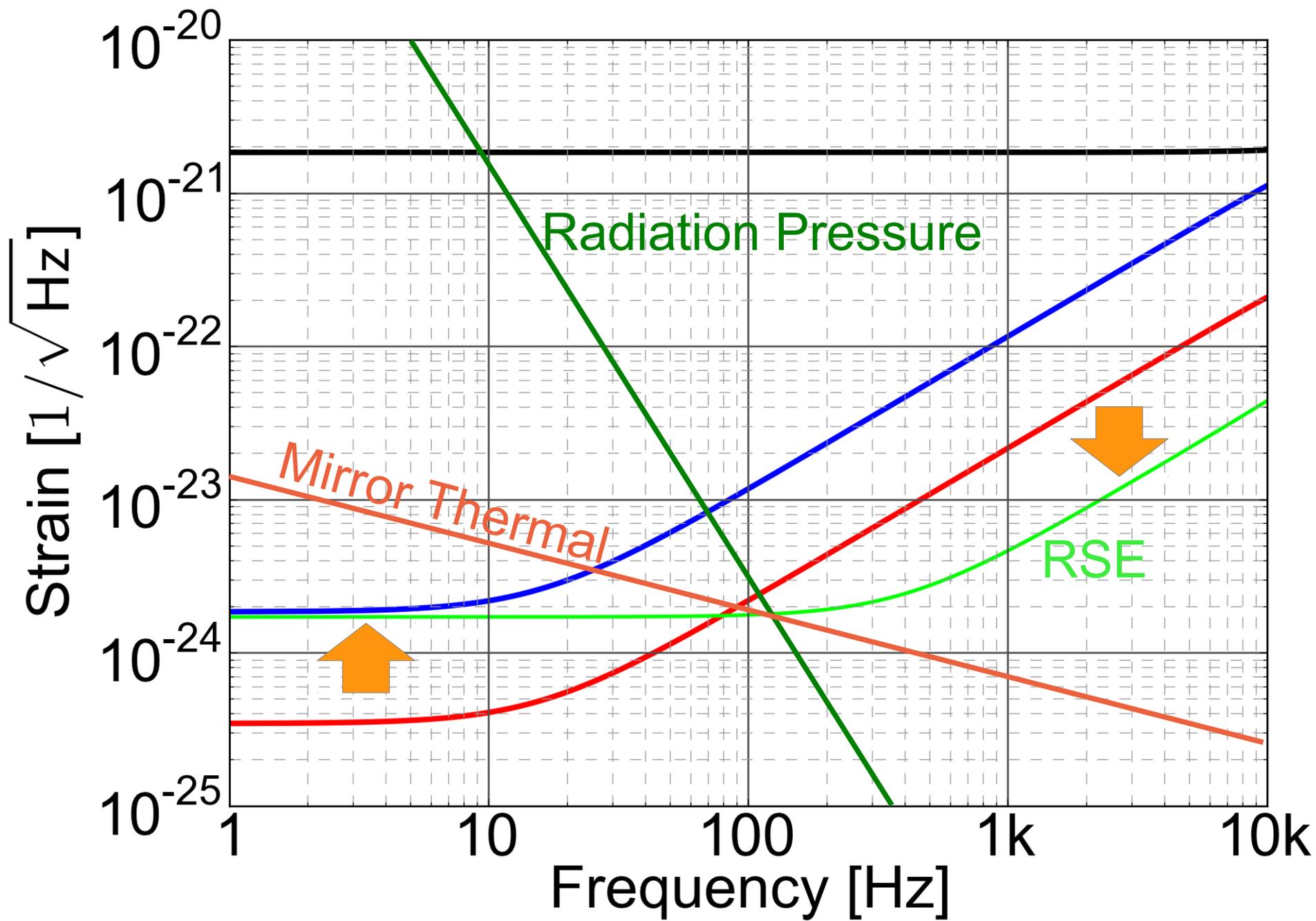


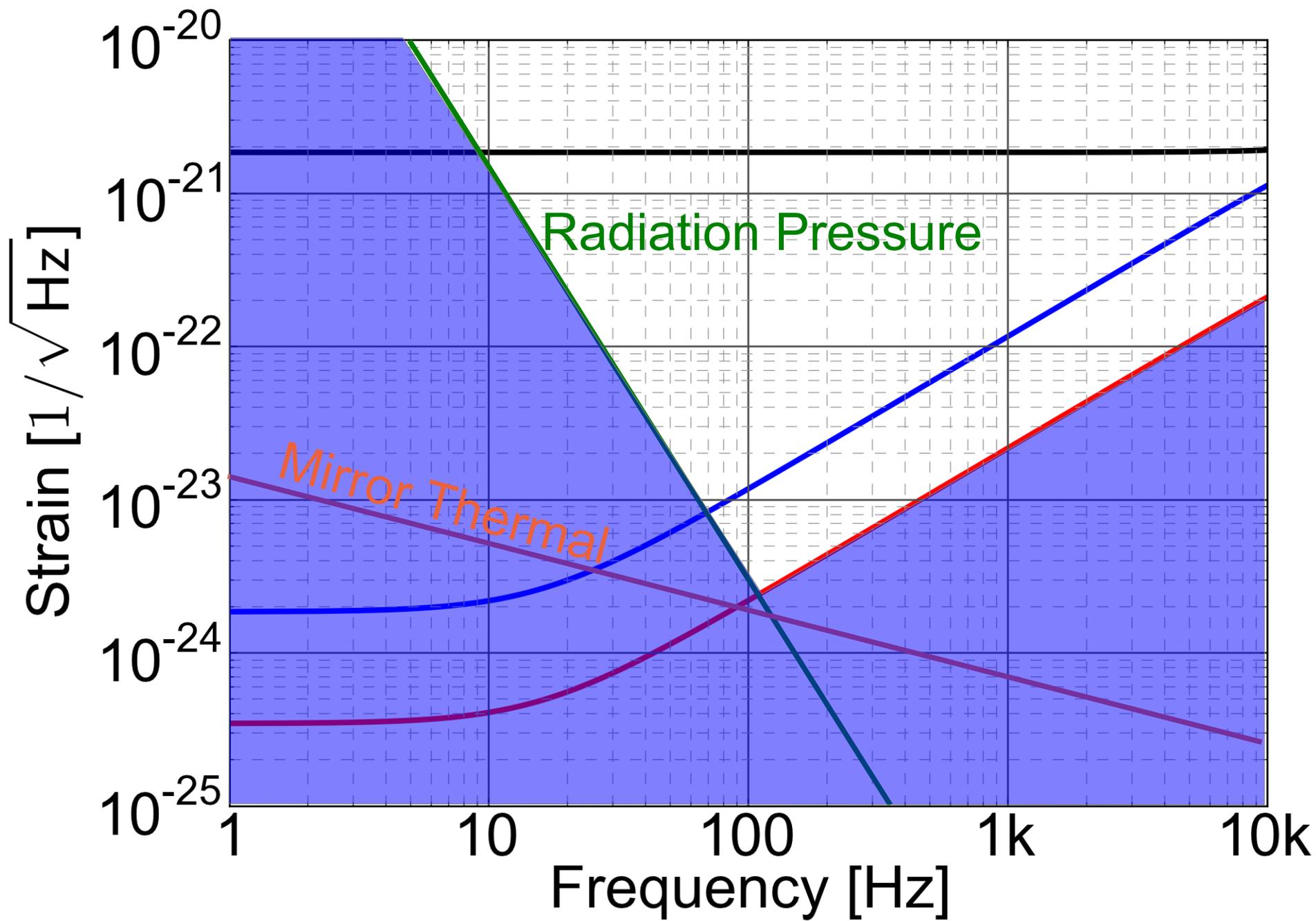


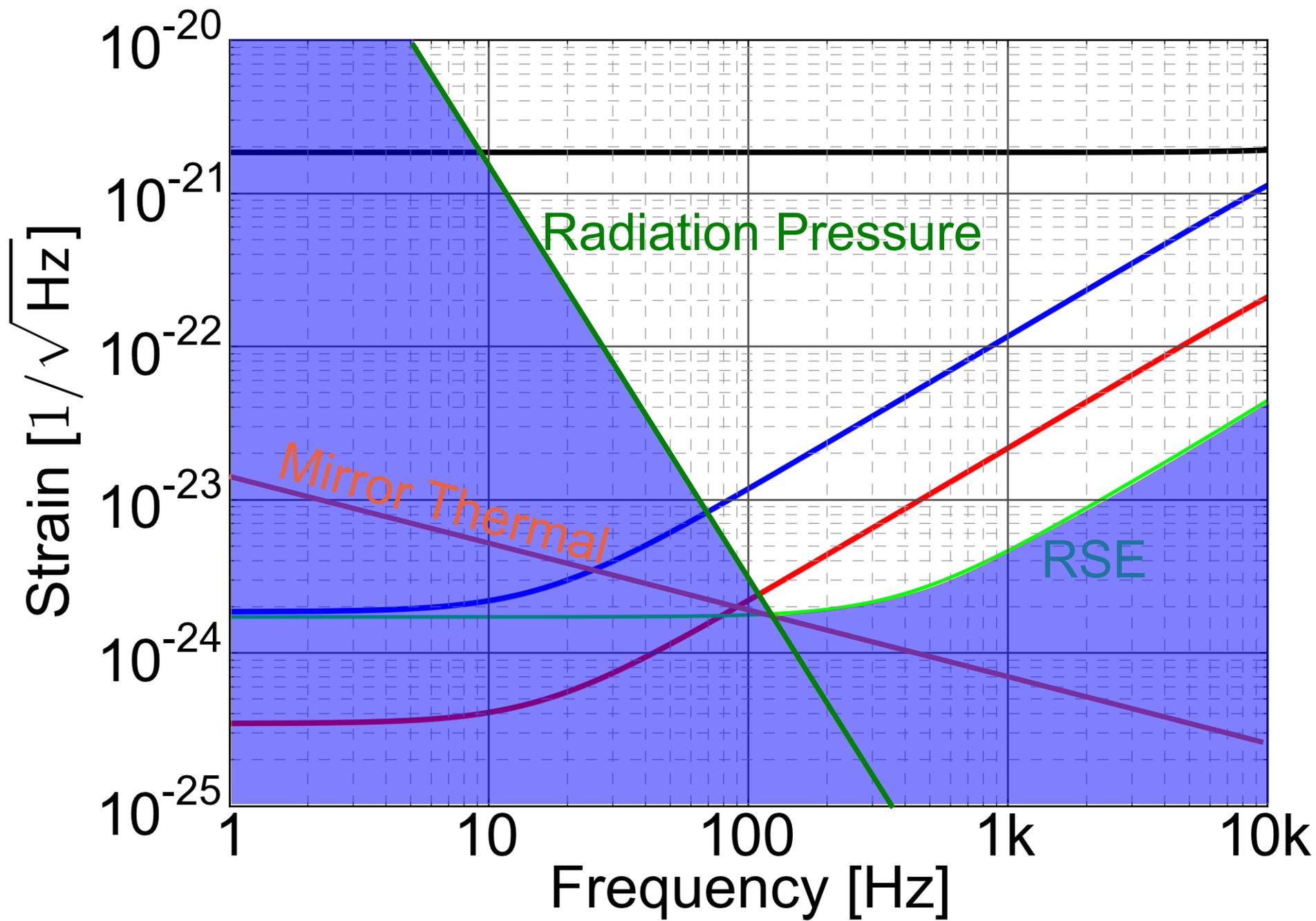


Resonant Sideband Extraction (RSE)

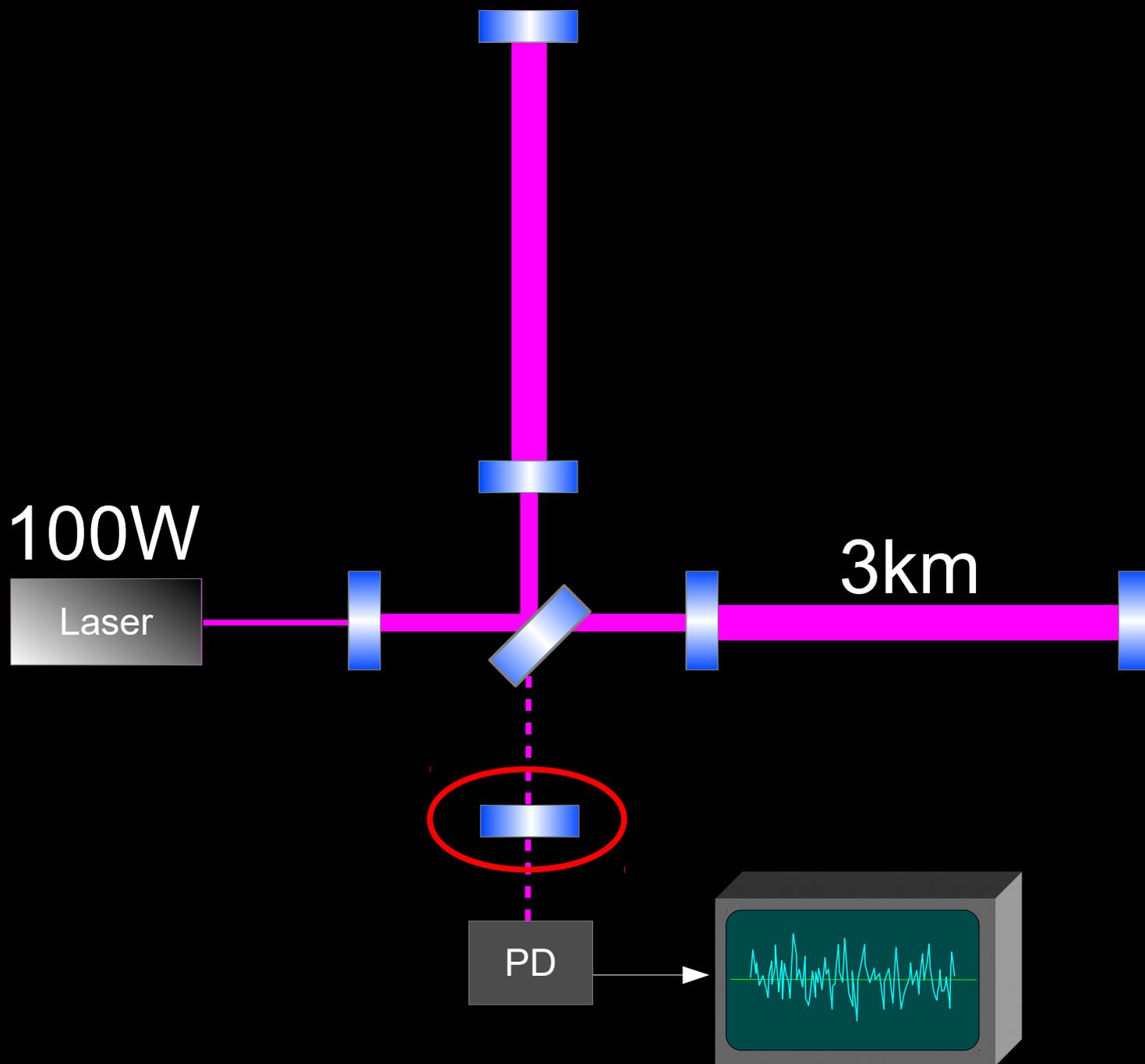


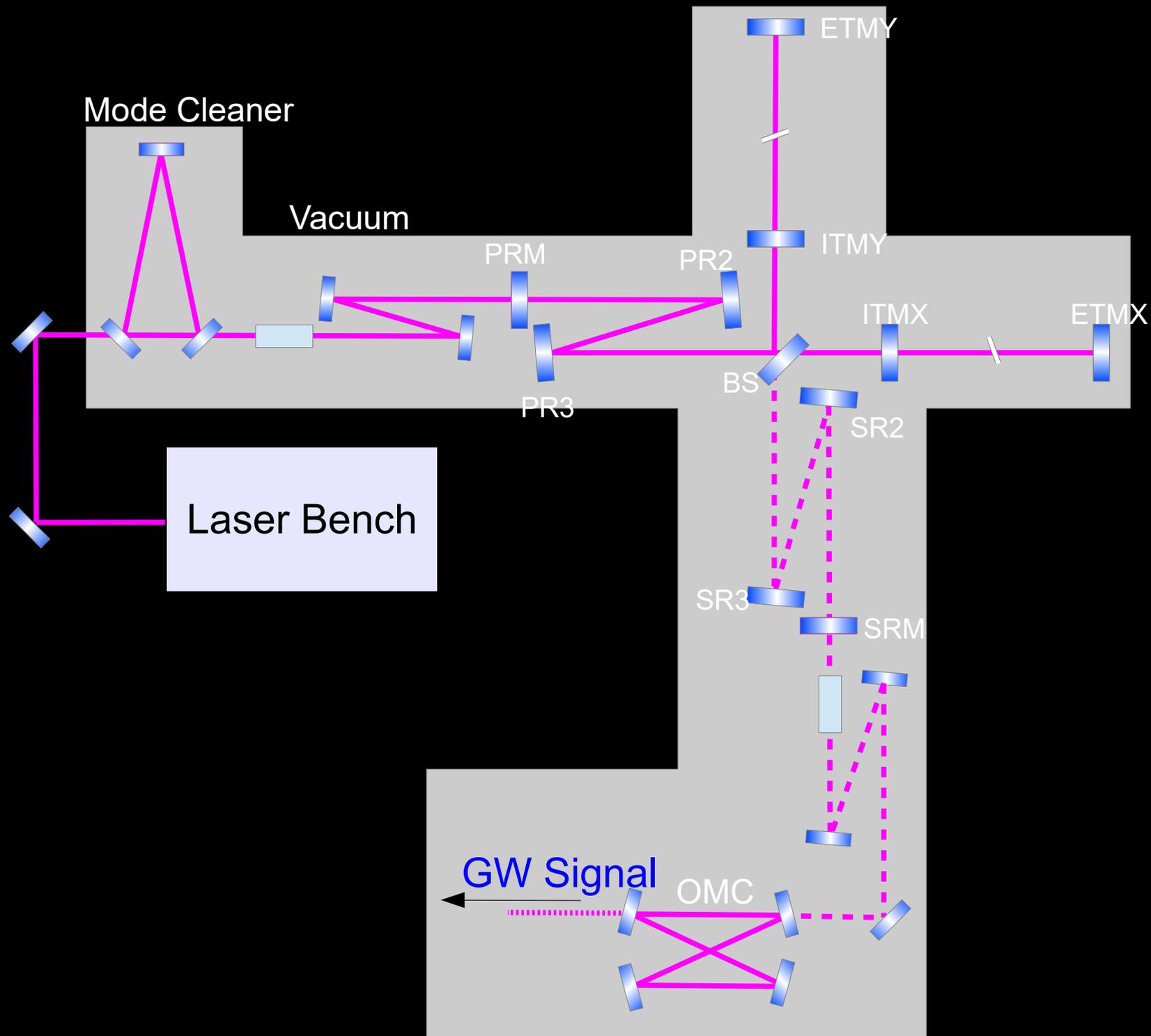




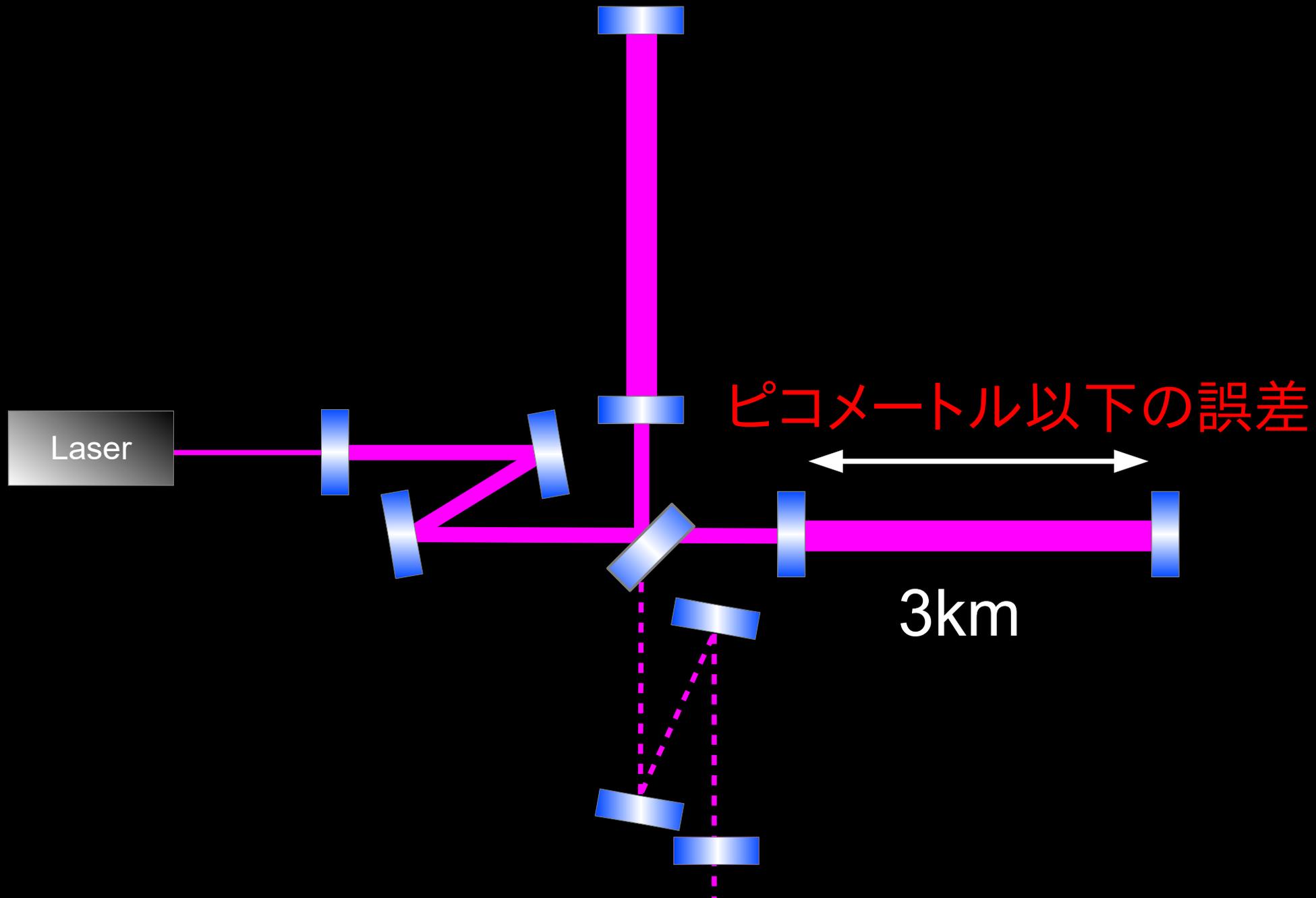


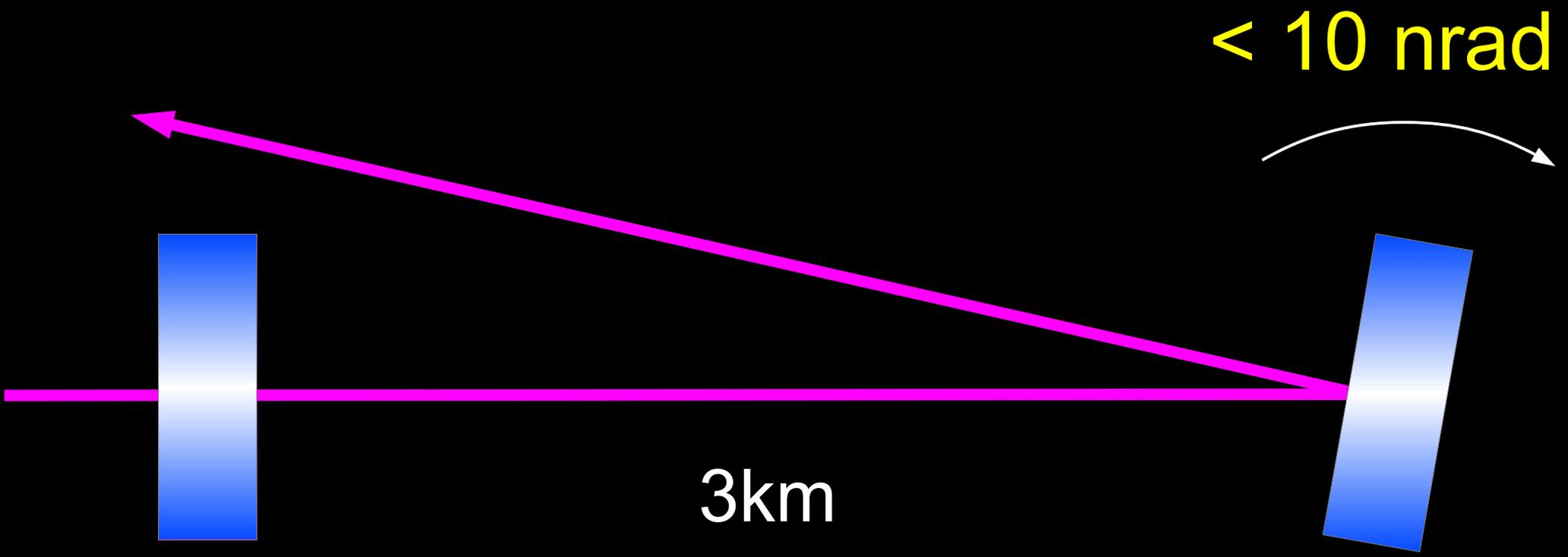
Resonant Sideband Extraction (RSE)



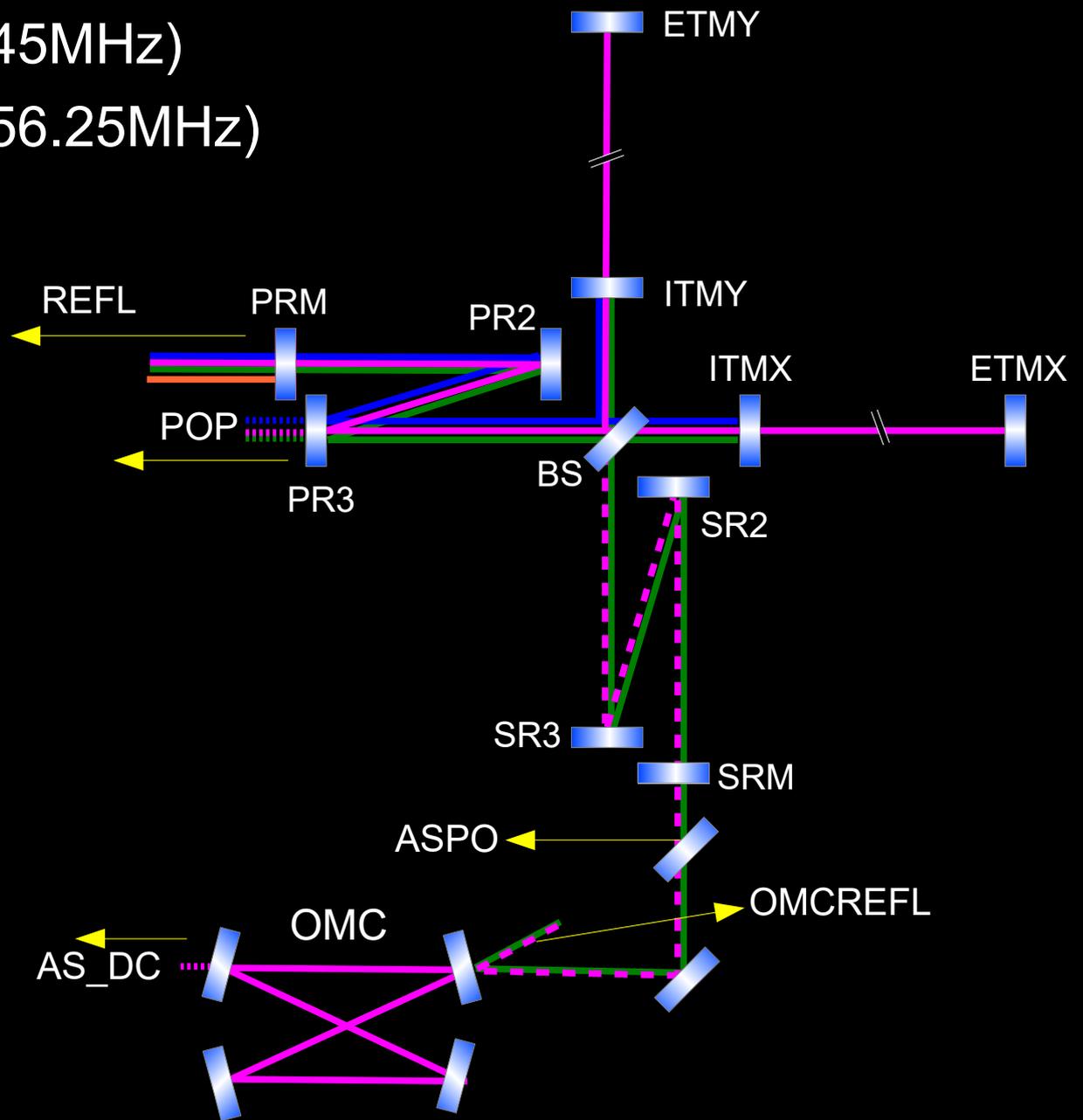


干渉計を最適動作点に保持する



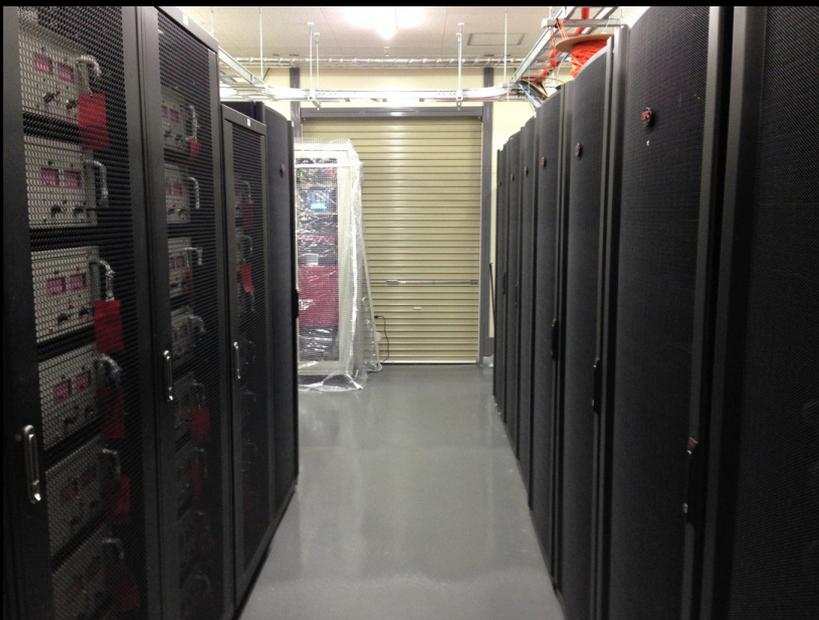


- Carrier
- f1 sideband (PM 16.875MHz)
- f2 sideband (PM 45MHz)
- f3 sideband (AM 56.25MHz)



Remote control

Server Room



Control Room



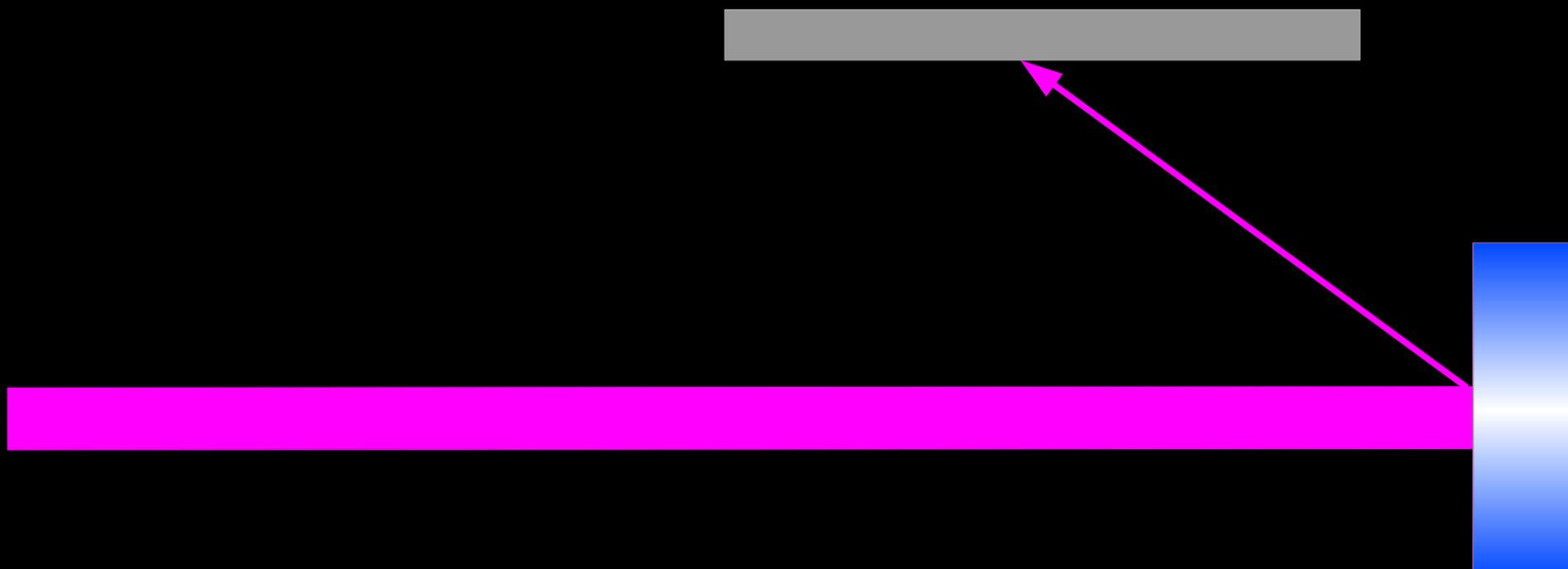
I/O Racks



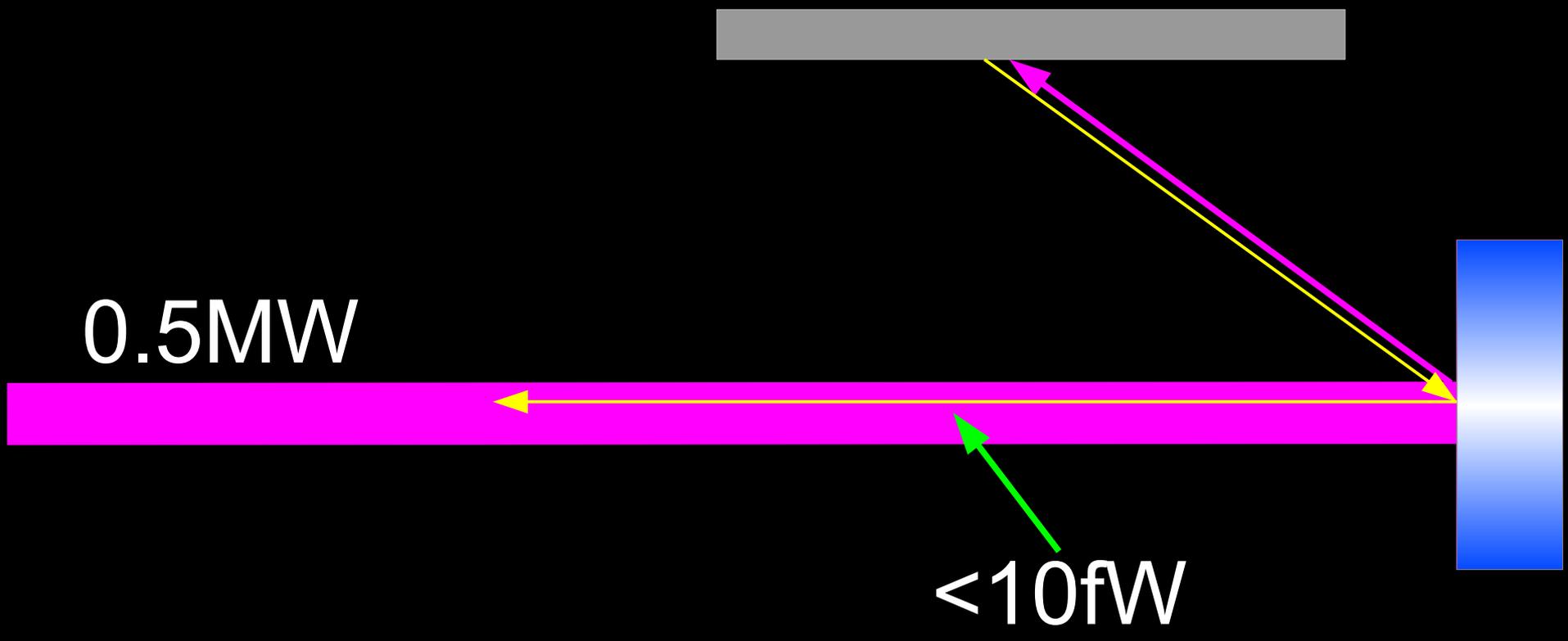
散乱光雜音



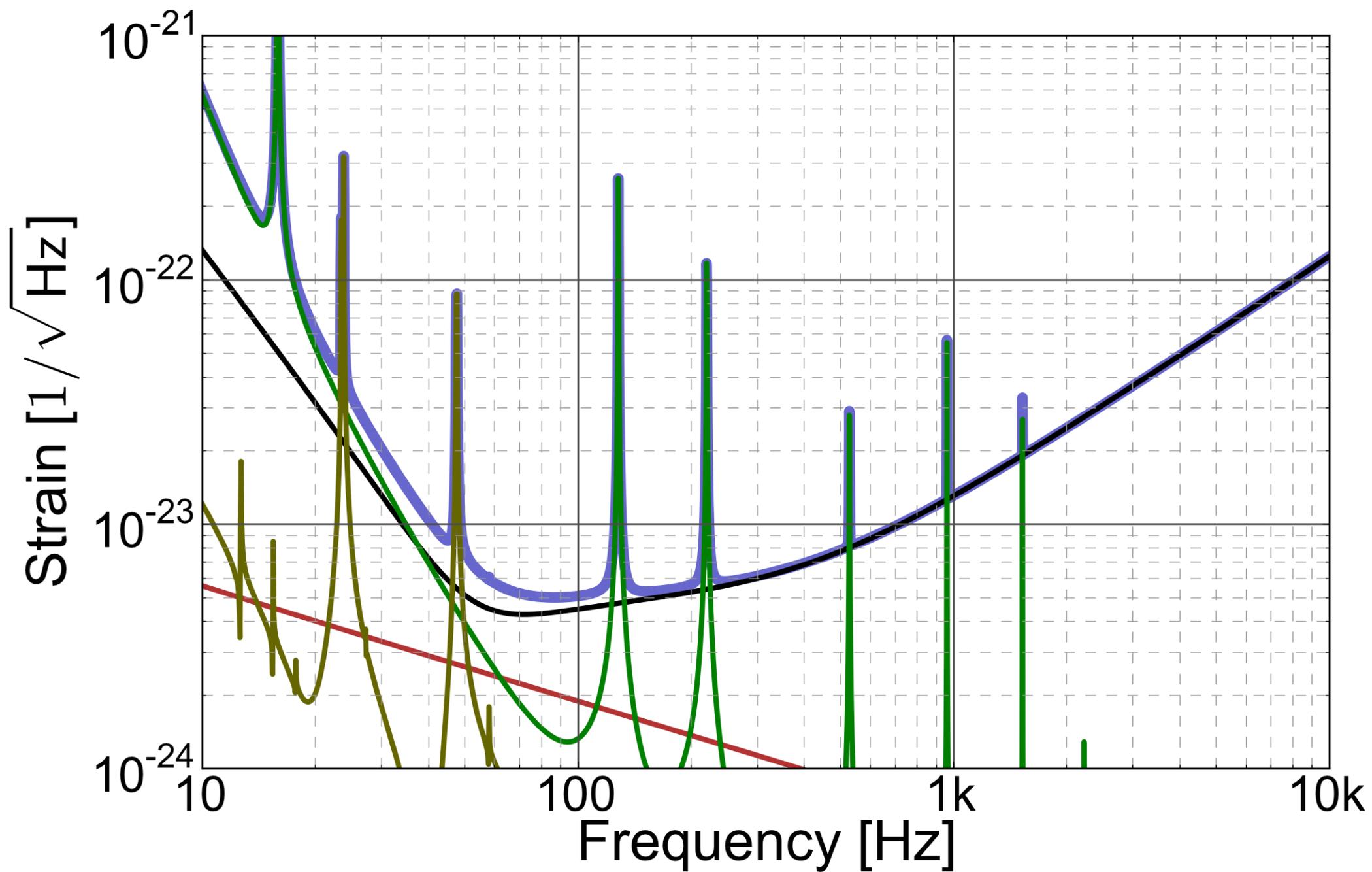
散乱光雜音



散乱光雑音



KAGRAの目標感度



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172人, 海外69人



国立天文台の役割

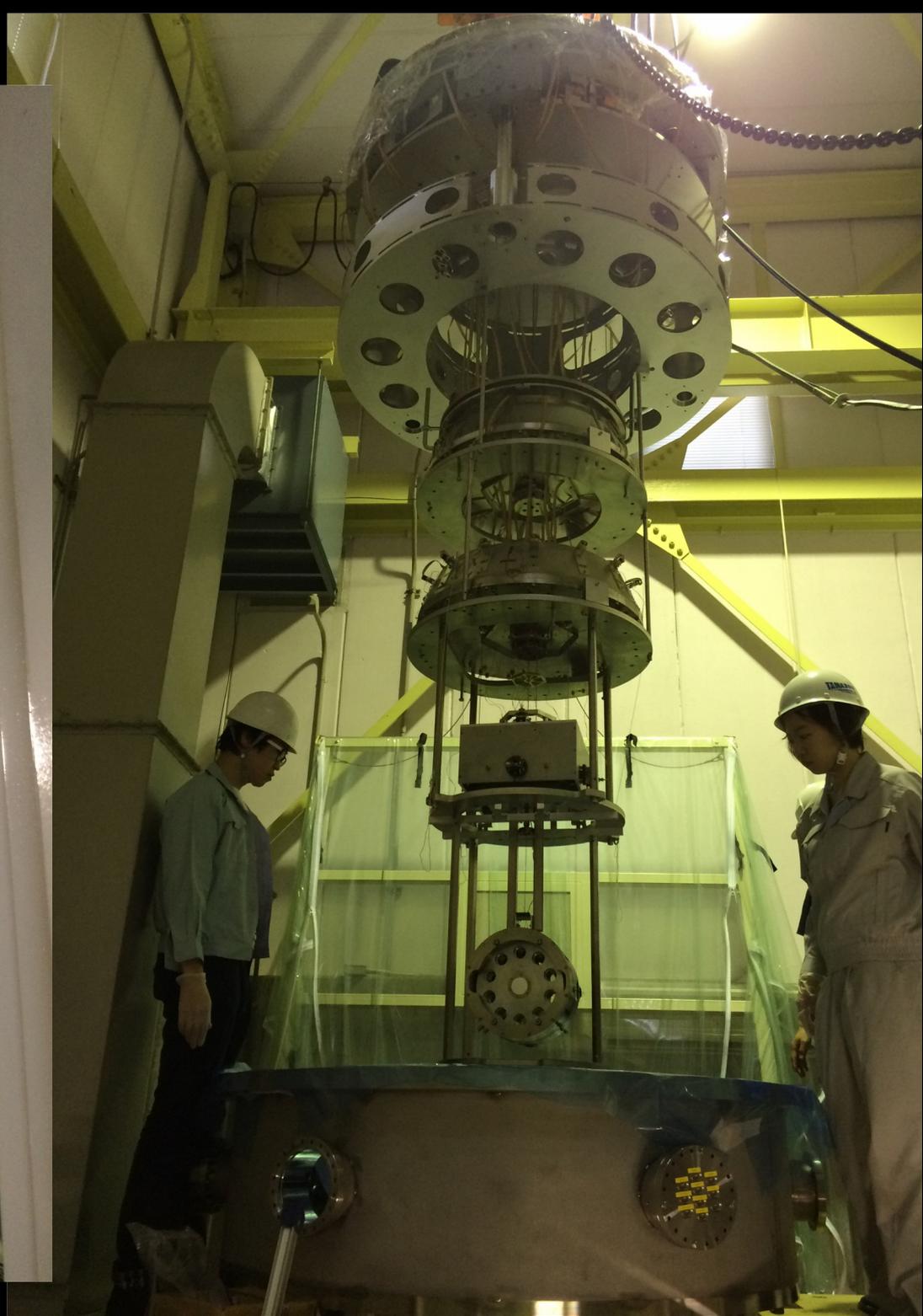
防振装置開発

補助光学系

(迷光対策, 光てこ装置, ビーム縮小望遠鏡など)

ミラー性能評価

主干涉計 設計・制御





Newport
RS 4000™
Stabilized High Table, Exp. with Z-axis Dampers
1/2" Bore Opt. Table, 1000mm x 1000mm, 100kg

Holder

Lens Holder

st Holder

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.



Tilt: $1/300$

★ Water drain point



2012年末



掘削完了直後



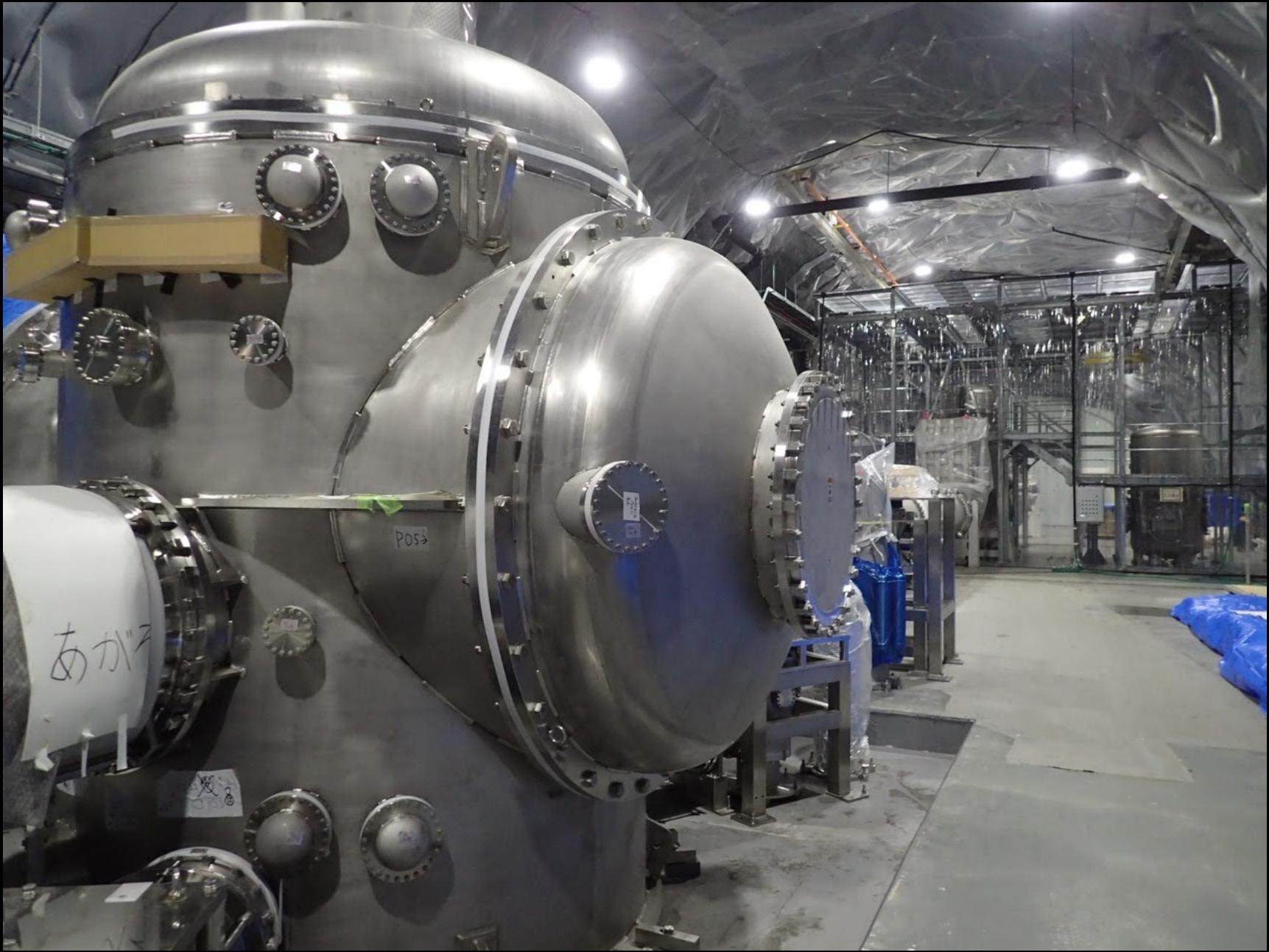


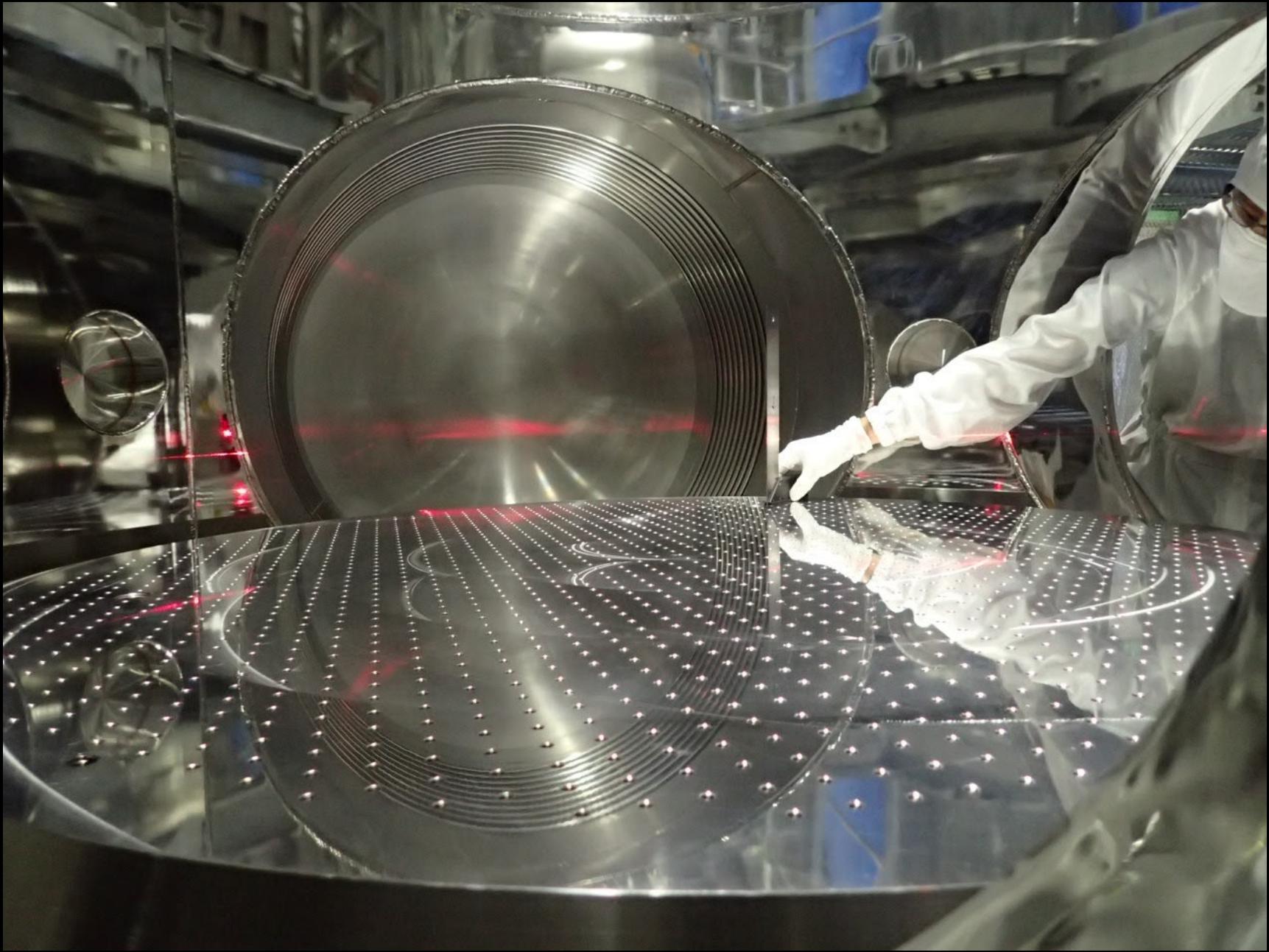
2015年4月



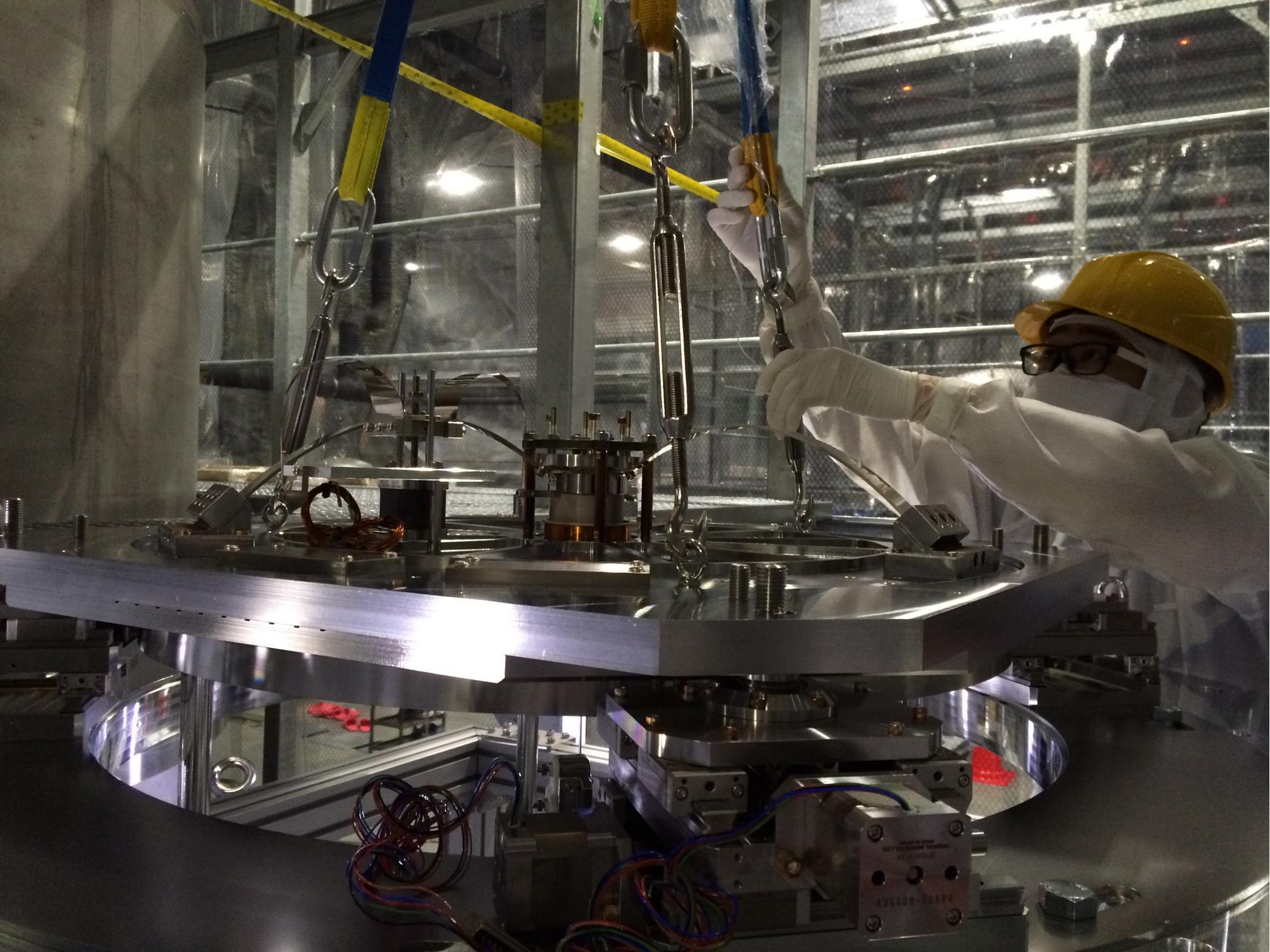
2015年8月

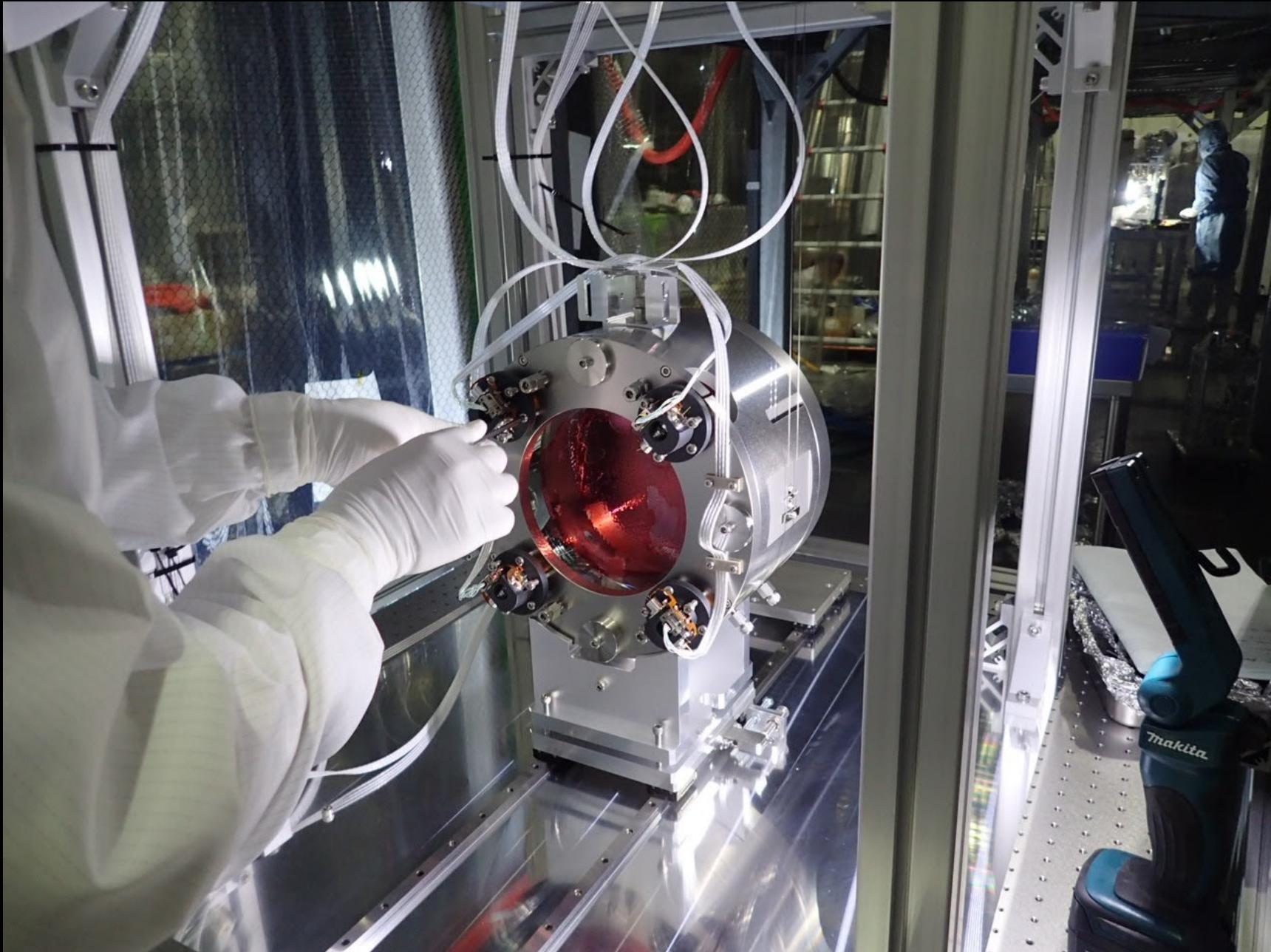


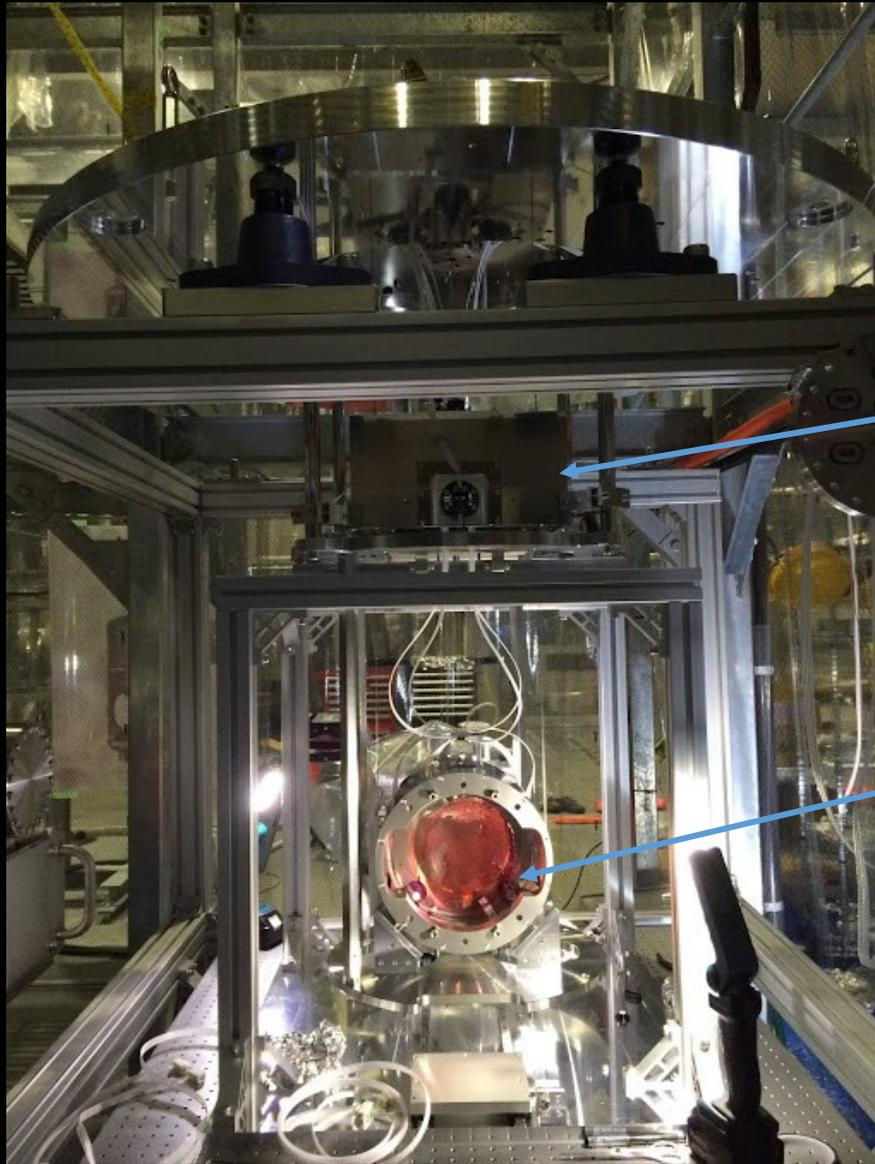










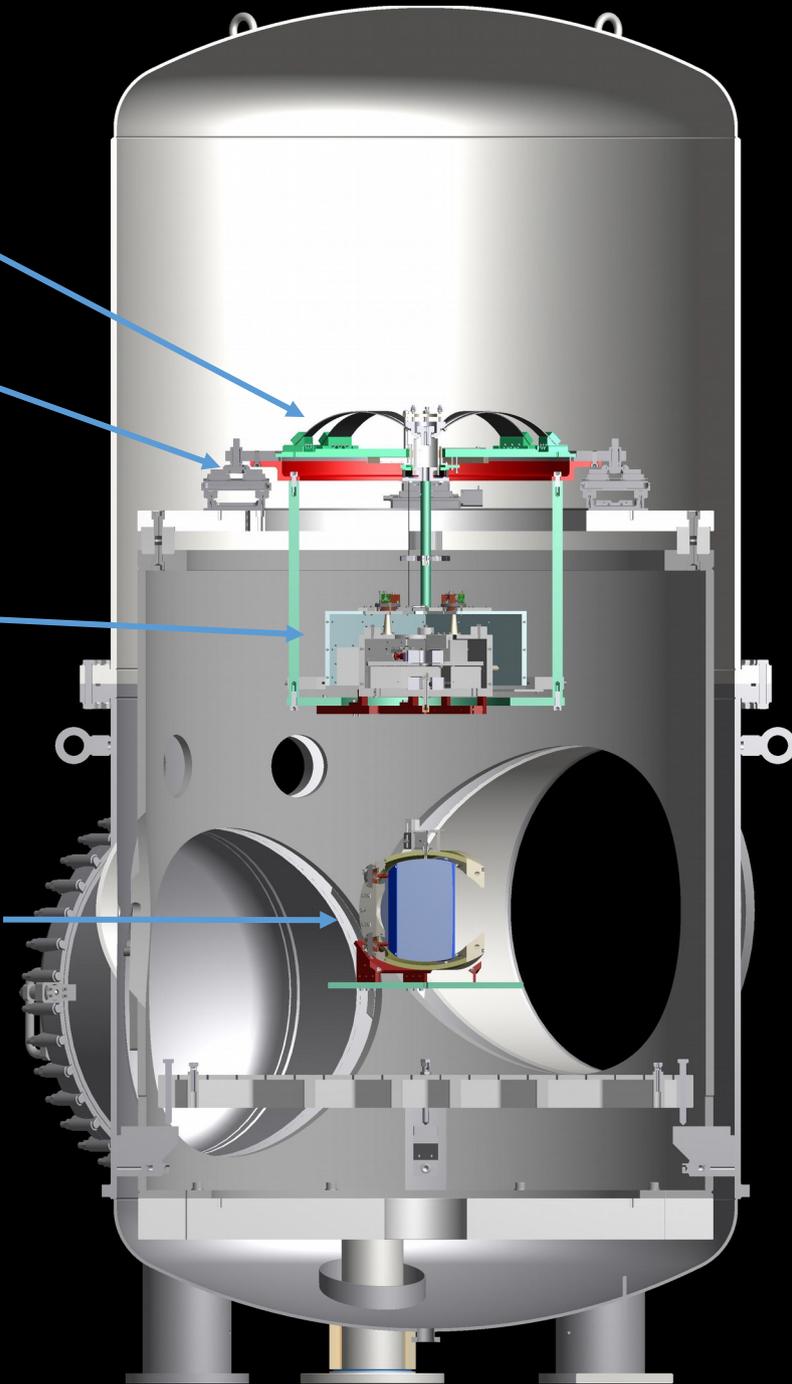


Bottom filter

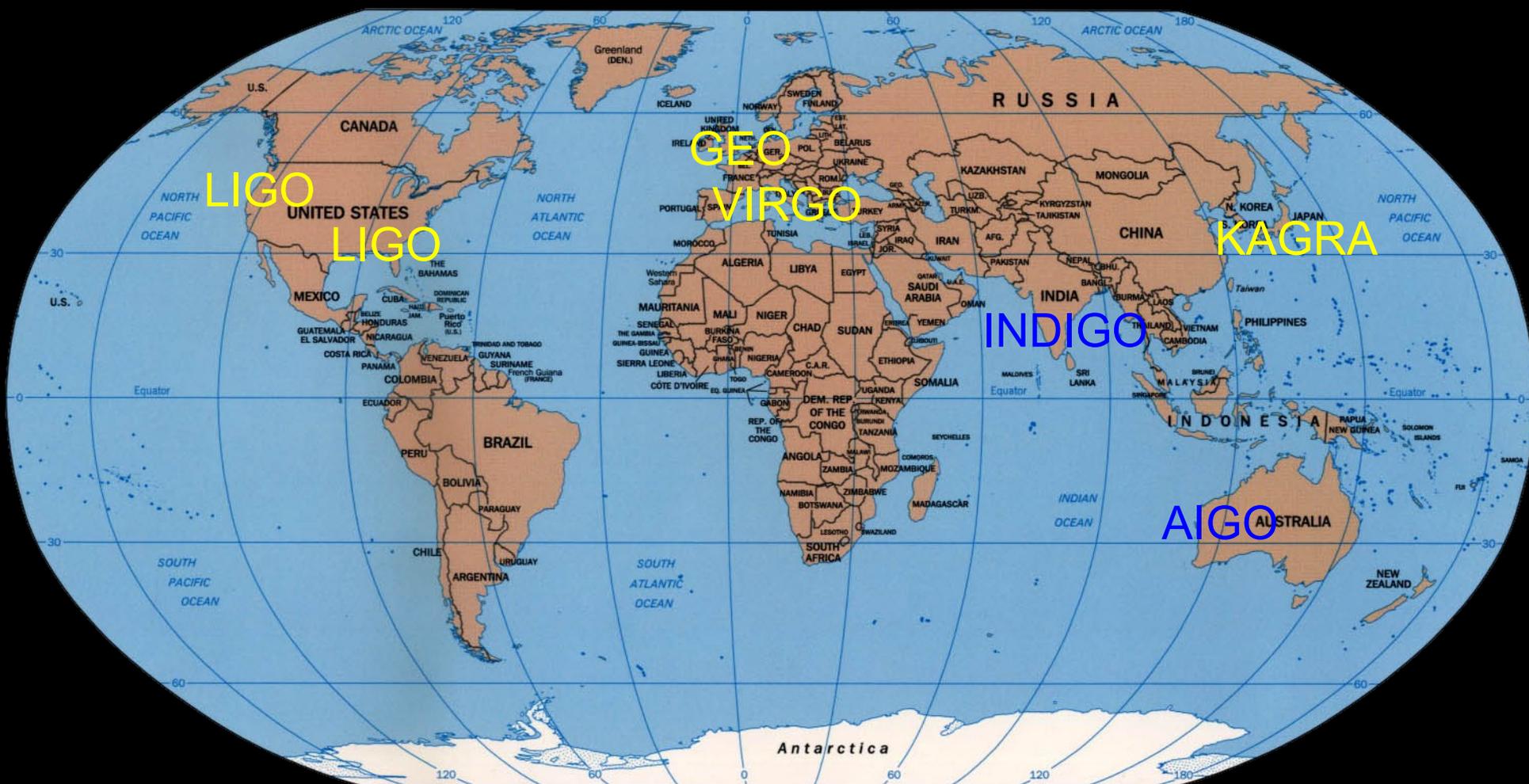
Traverser

Intermediate
Mass &
Intermediate
Recoil Mass

Test Mass &
Recoil Mass

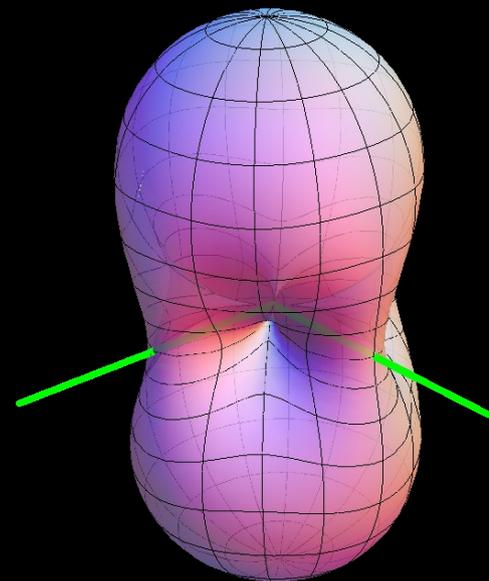


世界の重力波検出器ネットワーク



観測開始: ~ 2017-2018

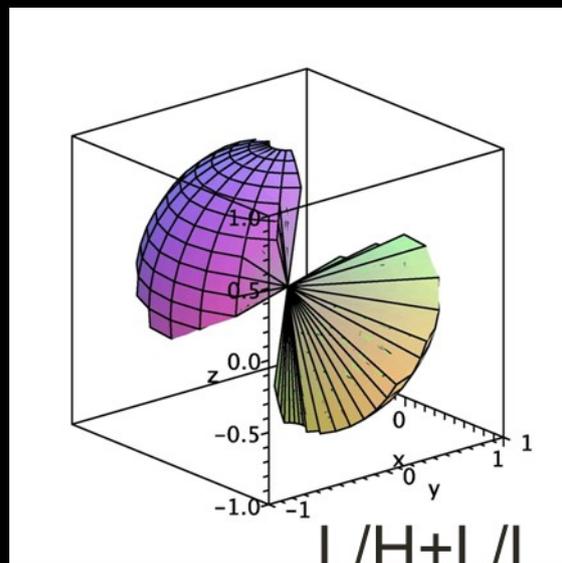
天球カバー率



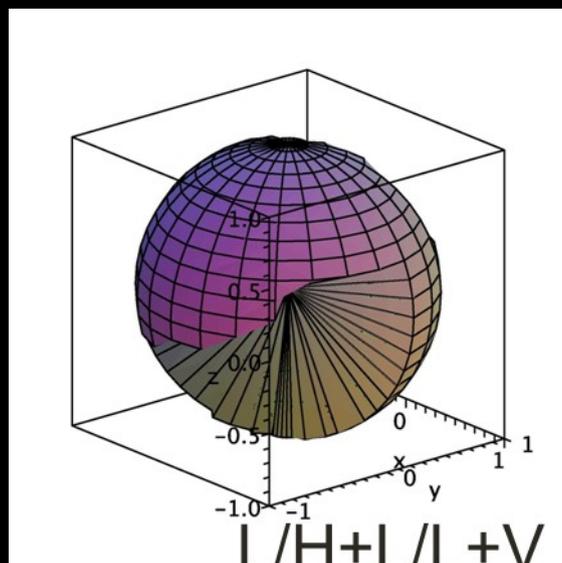
LIGO Only

LIGO+VIRGO

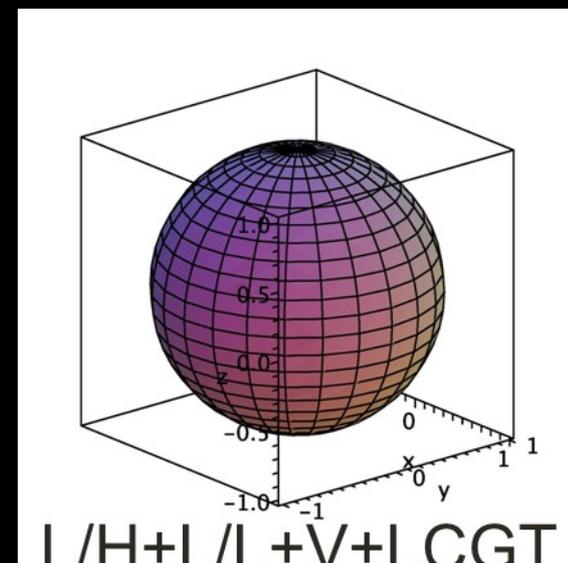
LIGO+VIRGO+KAGRA



33%

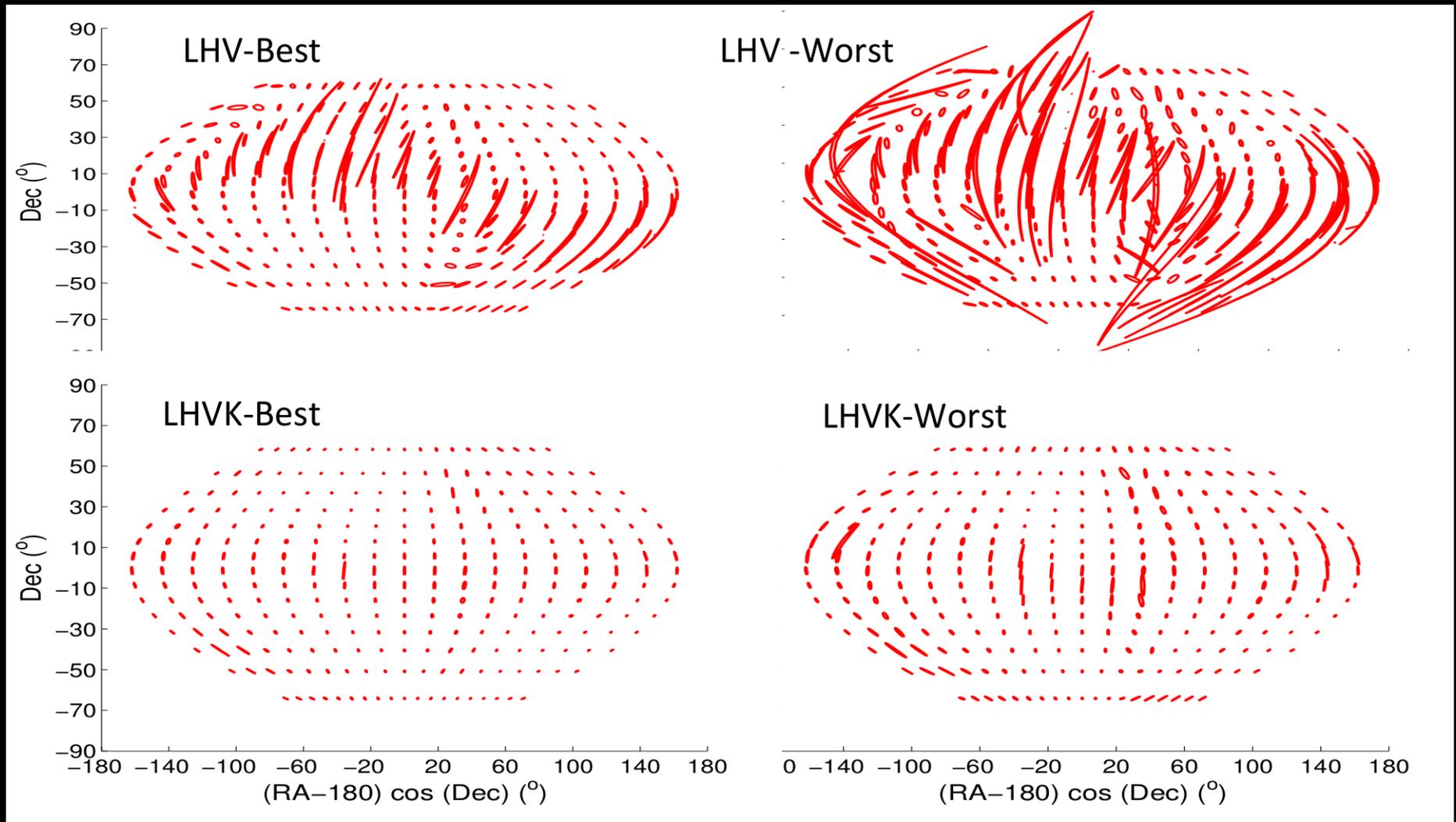


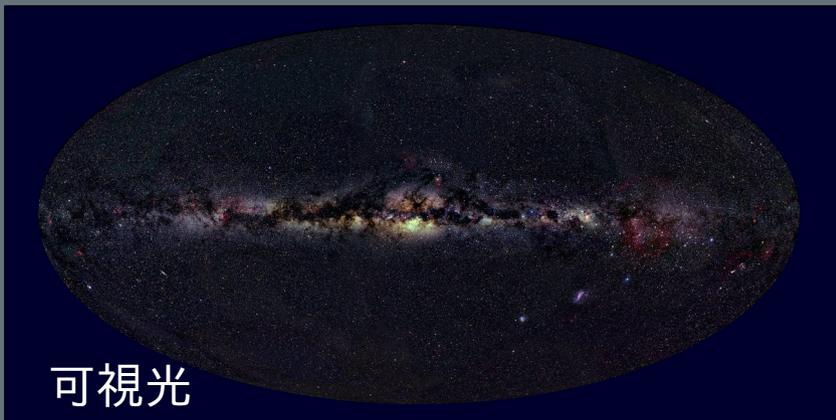
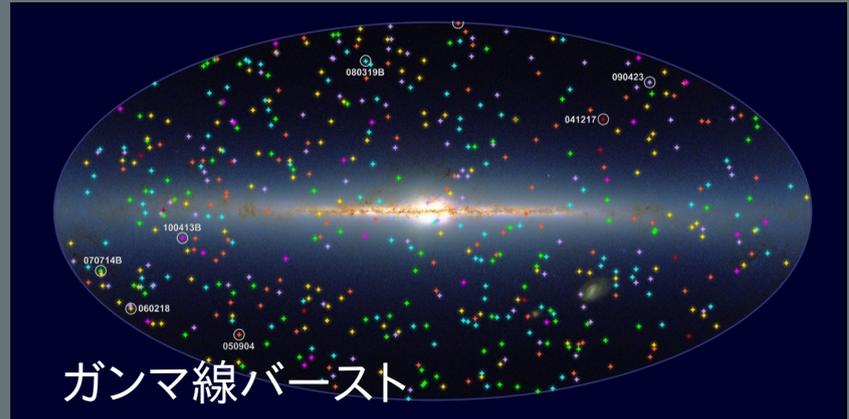
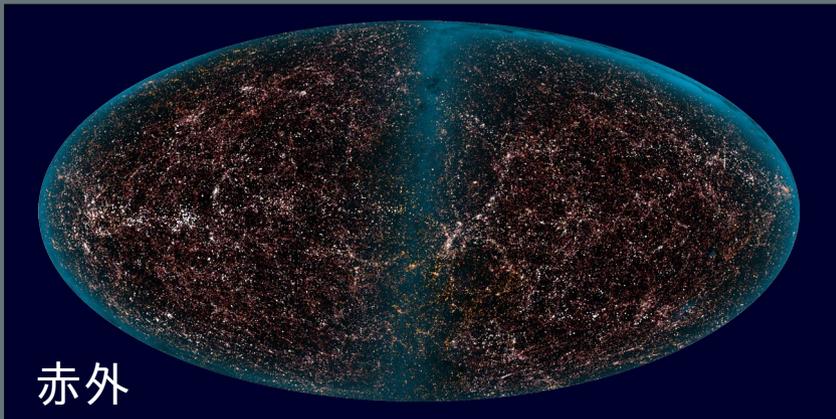
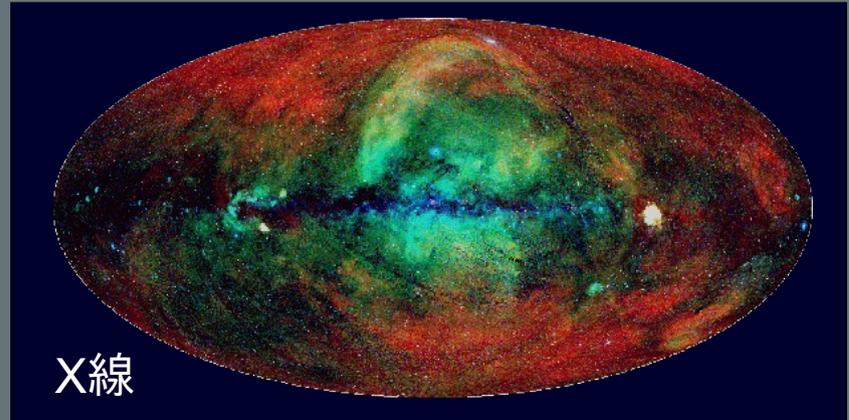
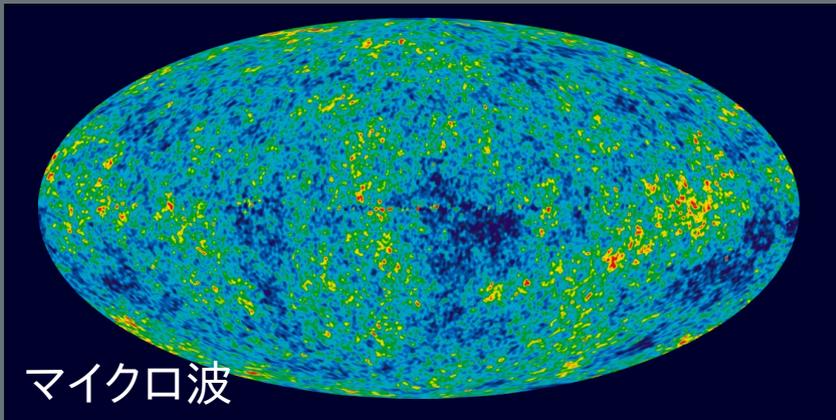
72%



100%

重力波源の位置決定精度





重力波?