第24回DECIGOワークショップ@京都大学

2025年12月6日

DECIGO量子ネットワーク

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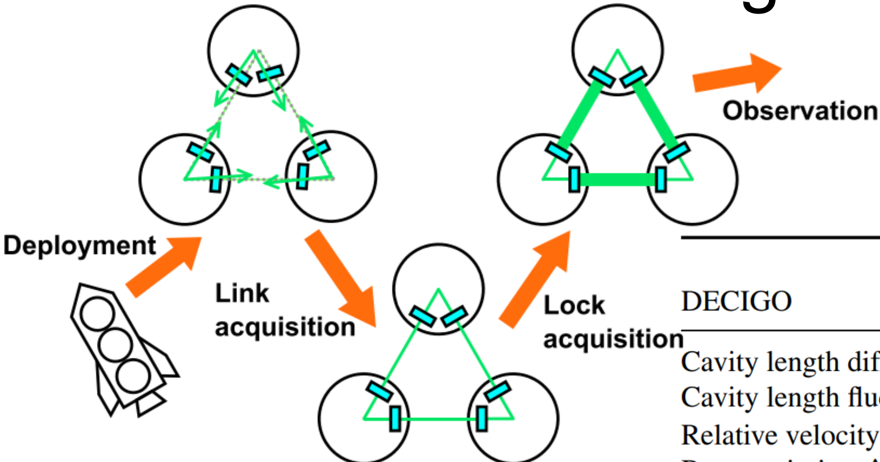
Is DECIGO Feasible?

- Common misunderstanding: "Forming optical cavities between satellites sounds impossible"
  → It is hard, but possible by using multiple sensors & actuators during initial acquisition sequence

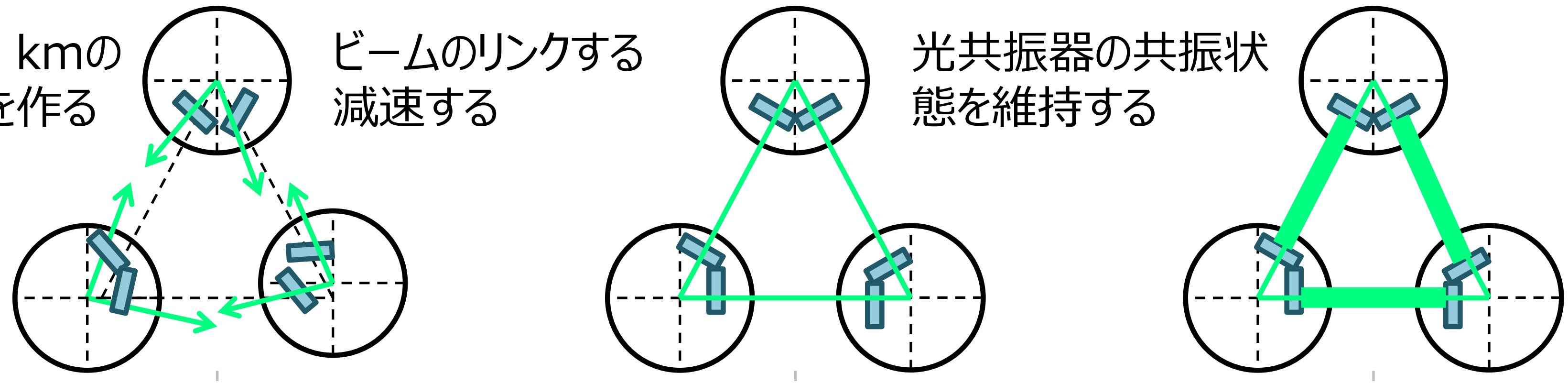


YM+, CQG **42**, 225027 (2025)

DECIGO	Deployment goal	Link acquisition goal	Lock acquisition goal
Cavity length difference ΔL	2 km	same	same
Cavity length fluctuations δL_{rms}	—	34 cm	0.5 nm
Relative velocity between mirrors v	—	$1.2\ \mu\mathrm{m\ s}^{-1}$	$23\ \mathrm{nm\ s}^{-1}$
Beam pointing $\Delta\theta_{\mathrm{beam}}$	3 mrad	$0.46\ \mu$rad	—
Mirror relative alignment $\Delta\theta$	—	$0.23\ \mu$rad	0.035 nrad
B-DECIGO			
Cavity length difference ΔL	40 m	same	same
Cavity length fluctuations δL_{rms}	—	3.4 cm	0.1 nm
Relative velocity between mirrors v	—	$0.12\ \mu\mathrm{m\ s}^{-1}$	$23\ \mathrm{nm\ s}^{-1}$
Beam pointing $\Delta\theta_{\mathrm{beam}}$	3 mrad	$1.5\ \mu$rad	—
Mirror relative alignment $\Delta\theta$	—	$0.73\ \mu$rad	0.35 nrad

B-DECIGO 初期捕捉の流れ

展開	リンクアクイジション	ロックアクイジション	観測
ざっくり100 kmの正三角形を作る	ビームのリンクする減速する	光共振器の共振状態を維持する	



正三角形の精度 40 m以下

GPS(的なもの)
衛星スラスタ

鏡間の相対距離変動 3 cm以下 0.1 nm以下

SILVIA で実証

なんらかのセンサ
テストマス、衛星スラスタ

PDH
テストマス

鏡間の相対速度 1 cm/sec以下 80 um/sec以下 23 nm/sec 以下

GPS(的なもの)
衛星スラスタ

0.12 um/sec以下

PDH
レーザー周波数

PDH
テストマス

相対角度精度 3 mrad以下 1.5 urad以下 0.4 nrad以下

スタートラッカ
衛星スラスタ

AOD
ステアリングミラー、テストマス

QPD？

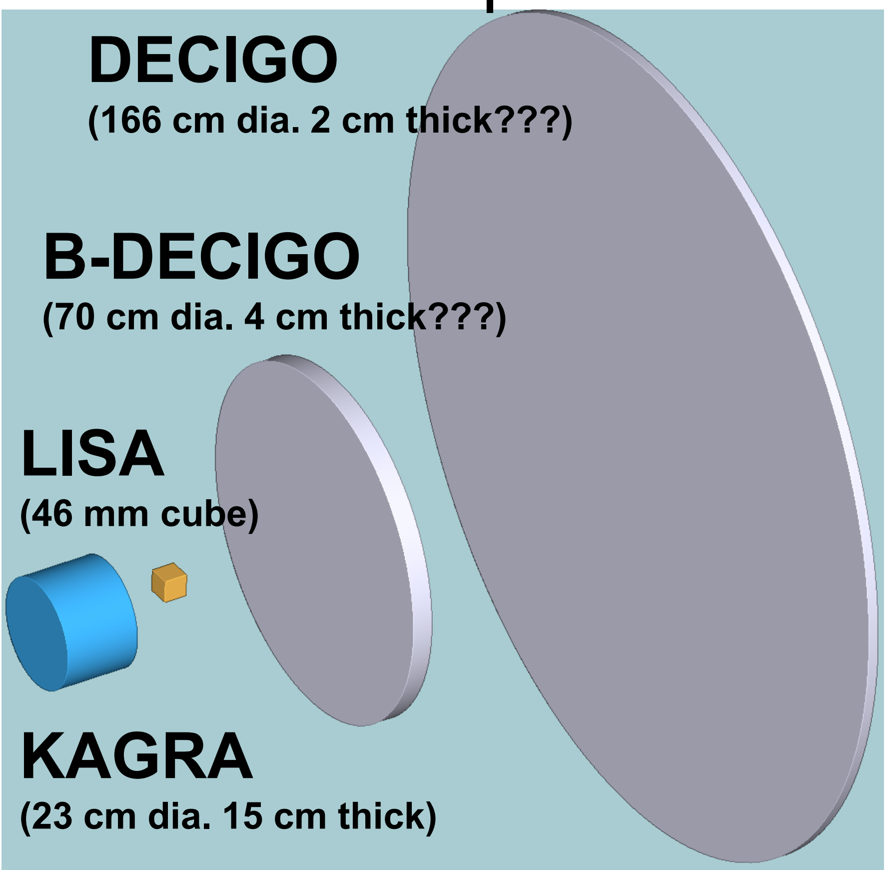
WFS
テストマス

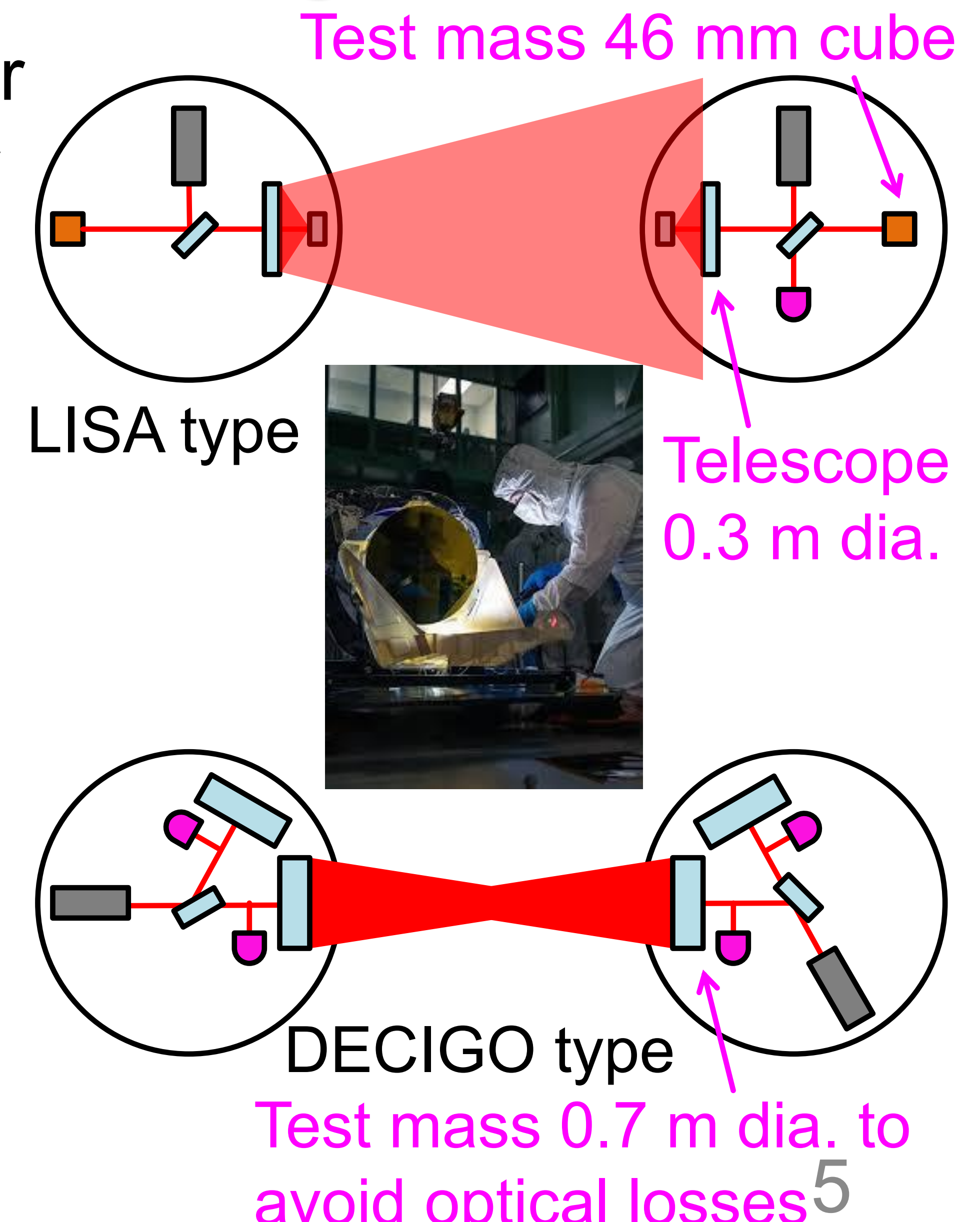
Design Comparison

	LISA	TianQin	B-DECIGO
Arm length	2.5e6 km	1.7e5 km	100 km
Interferometry	Optical transponder	Optical transponder	Fabry-Pérot cavity (F=100)
Laser frequency stabilization	Reference cavity, 1064 nm (~3 W)	Reference cavity, 1064 nm	Iodine, 515 nm (~1 W)
Orbit	Heliocentric	Geocentric, facing J0806.3+1527	Geocentric (TBD)
Flight configuration	Constellation flight	Constellation flight	Formation flight
Test mass	1.96 kg (46 mm cube of Au-Pt alloy)	2.45 kg (50 mm cube of Au-Pt alloy)	30 kg (70 cm dia, 4 cm thick Fused Silica???)
Force noise req.	8e-15 N/rtHz Achieved PRL 120, 061101 (2018)	7e-15 N/rtHz CQG 33, 035010 (2016)	1e-16 N/rtHz

Tough Part is the Large Mirrors

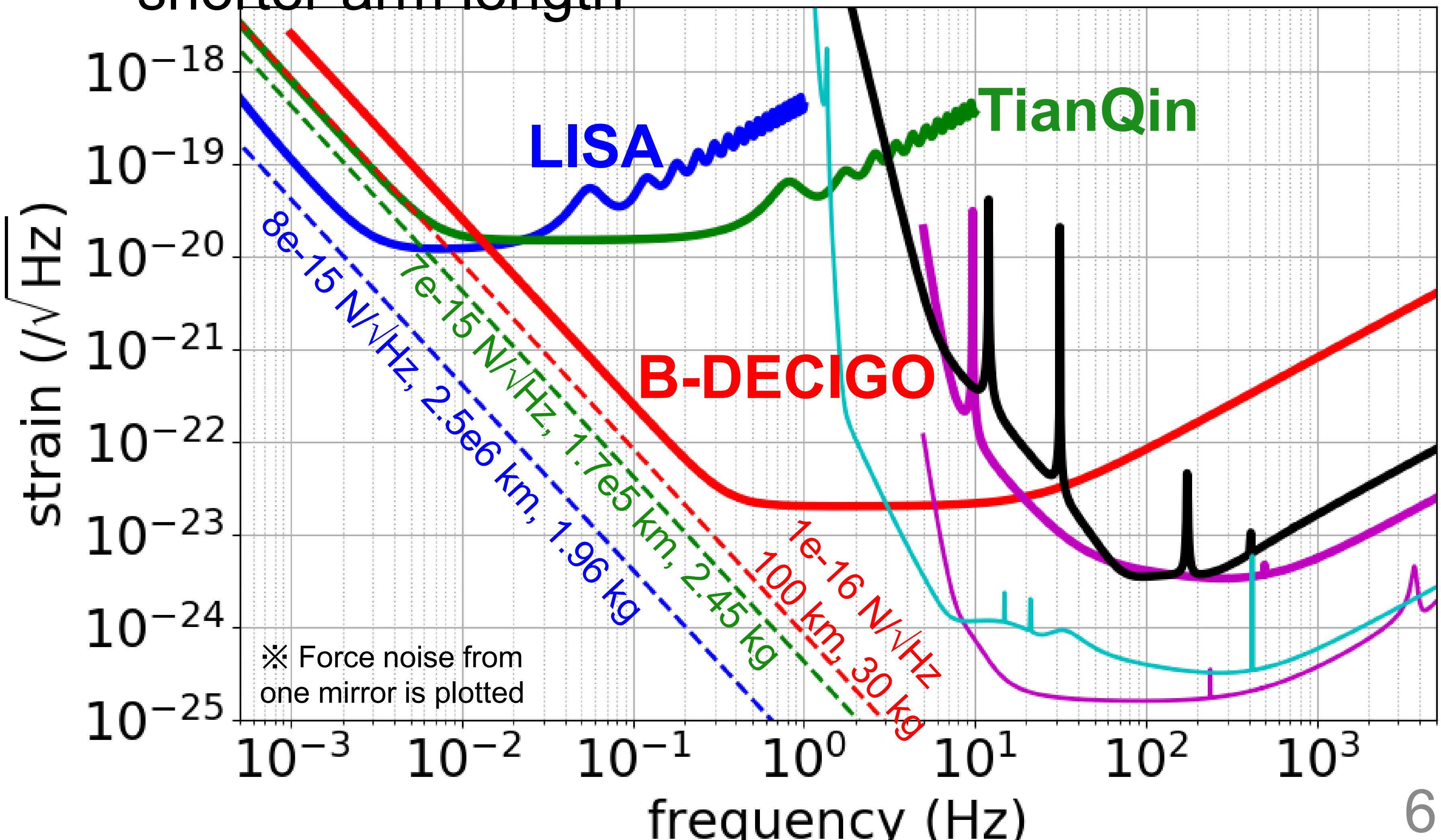
- Shorter arms and larger mirrors are required for reflecting all the light to form optical cavities





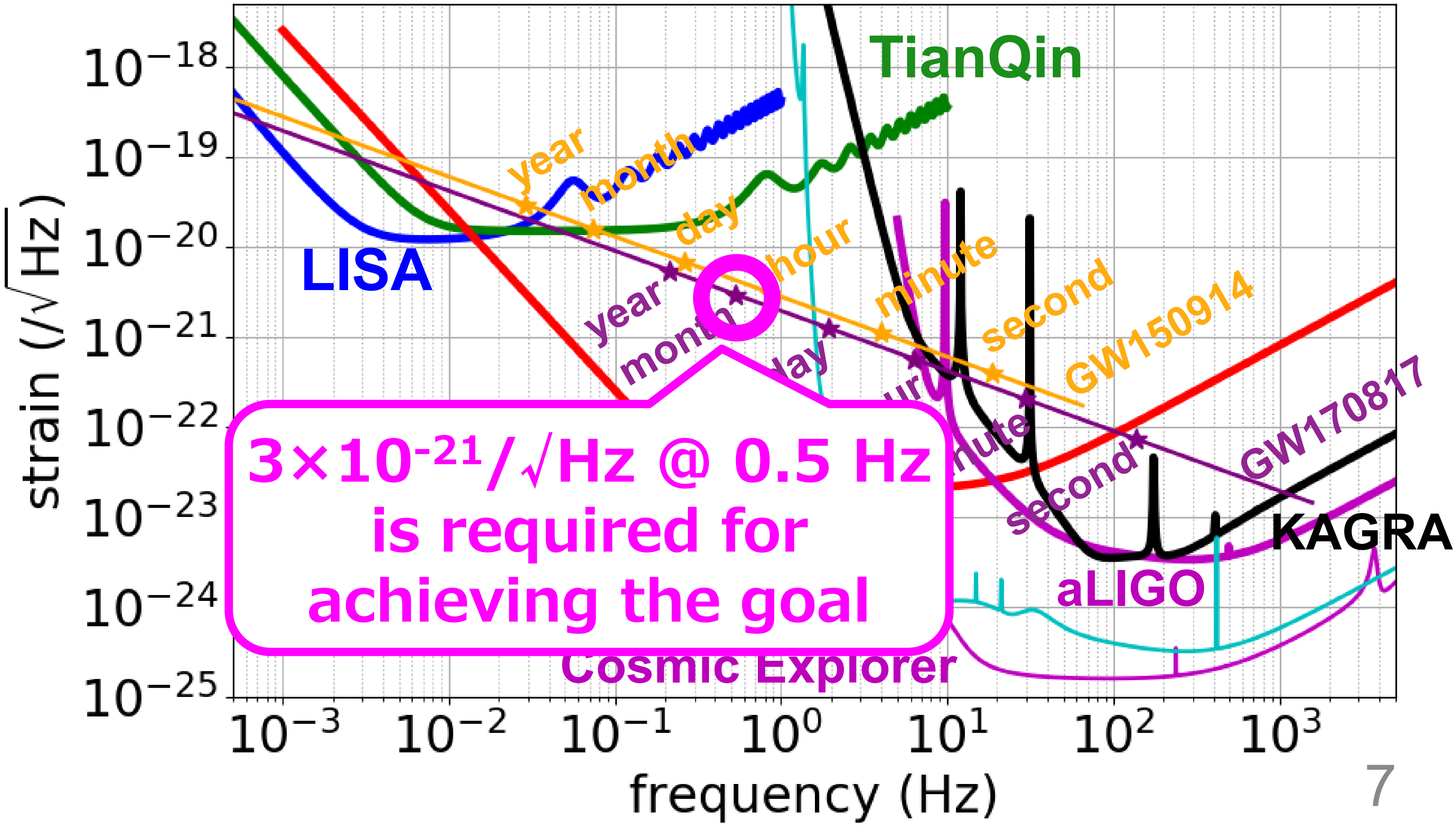
Stringent Force Noise Requirement

- B-DECIGO requirement is most stringent due to shorter arm length



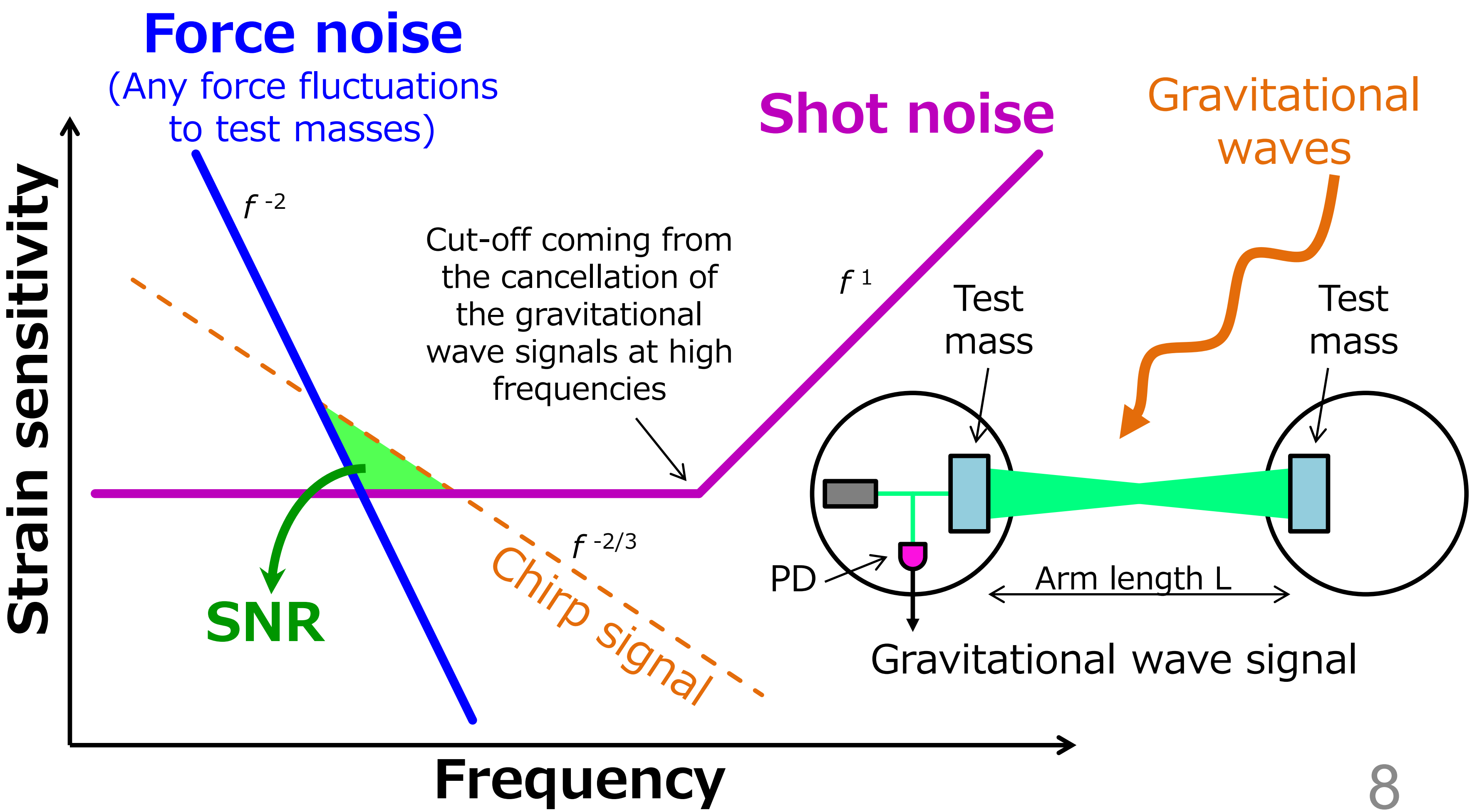
Let’s Start from the Minimum Goal

- **Minimum goal**: Observe GW170817-like binary a month before the merger (or GW150914-like binary an hour before the merger)



Sensitivity of Space Detectors

- Can be modeled with force noise and shot noise



Equations for the Noises

- **Force noise**

Force noise spectrum

※LISA Pathfinder achieved 4×10^{-15} N/√Hz @ 1 mHz

$$h_\mathrm{f} = \frac{n_f}{m\omega^2 L}$$

Mass of test mass

GW frequency

Arm length

→ From n_f , requirement on mL is derived

- **Shot noise**

Laser wavelength

$$h_\mathrm{shot} = \frac{1}{2\pi L}\sqrt{\frac{hc\lambda}{2P}\frac{\pi}{2\mathcal{F}}}$$

Finesse

※F=2/π for Michelson

Arm length

Input power

→ From laser wavelength and power,
requirement on $L\mathcal{F}$ is derived

Requirement on Basic Parameters

- To Achieve 3×10^-21^/√Hz @ 0.5 Hz goal
- If the force noise is 4×10^-15^ N/√Hz

$$h_\mathrm{f} = \frac{n_f}{m\omega^2 L}$$

$$\boxed{mL > 120\,\mathrm{kg}\cdot\mathrm{km}}$$

- If the laser is 515 nm and 10 mW, shot noise gives

$$h_\mathrm{shot} = \frac{1}{2\pi L}\sqrt{\frac{hc\lambda}{2P}\frac{\pi}{2\mathcal{F}}}$$

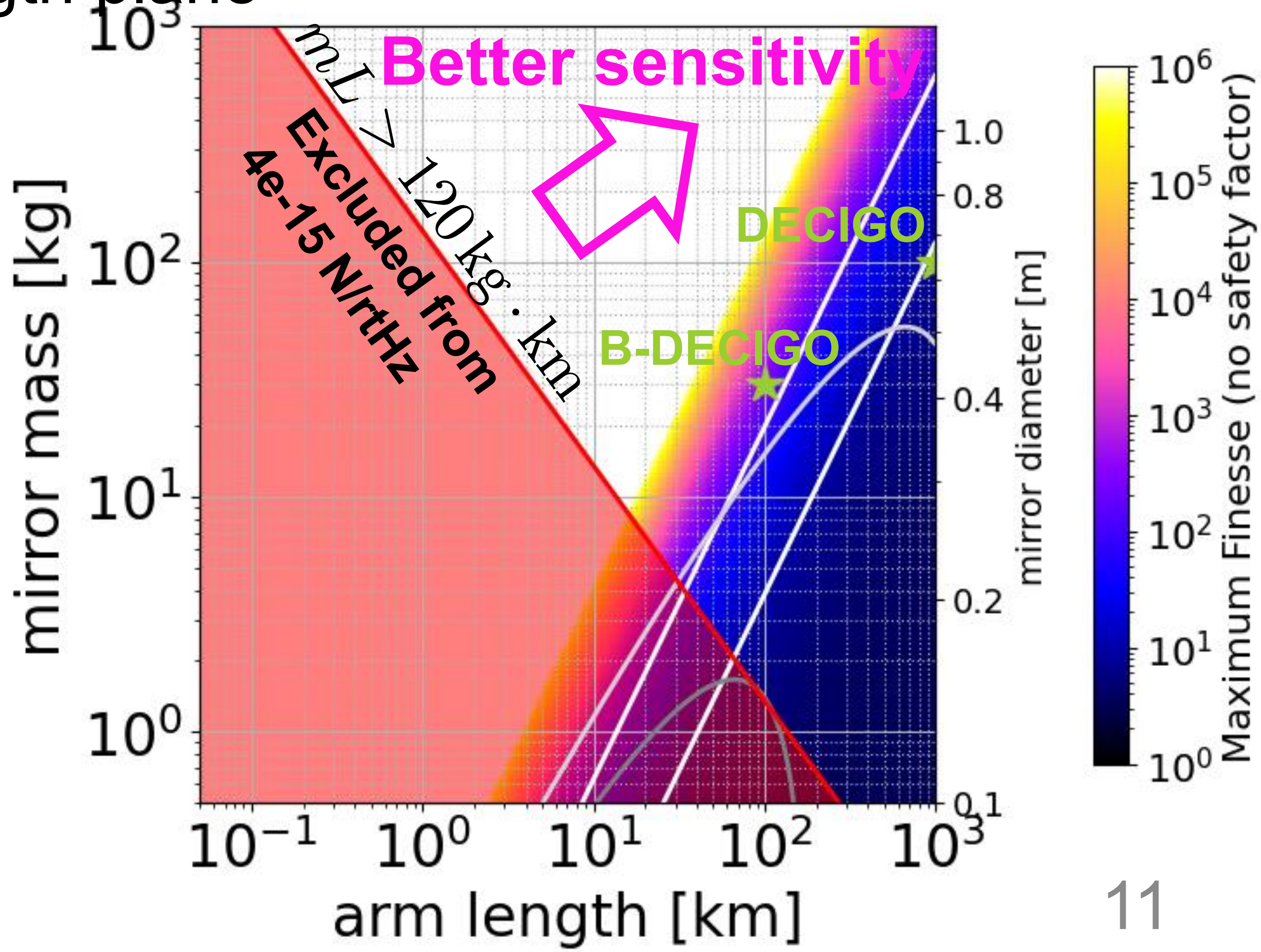
$$\boxed{L\mathcal{F} > 180\,\mathrm{km}}$$

- kg-class test masses and km-class arm length are required
- Forming an optical cavity is not required if

$$L > 180\,\mathrm{km}/(\pi/2) = 114\,\mathrm{km}$$

Mirror Size and Arm Length

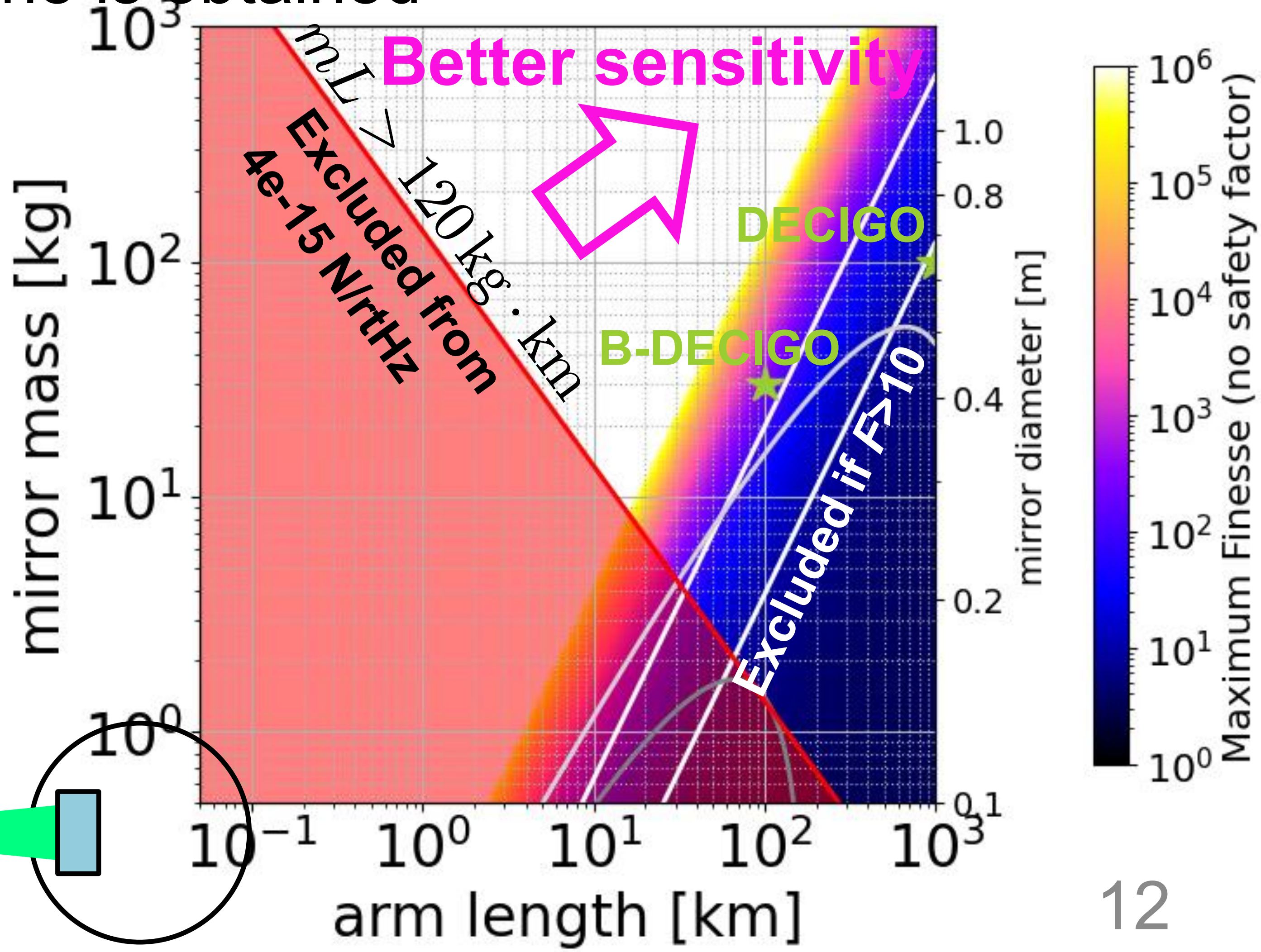
- Force noise requirement gives allowed region in mass-length plane

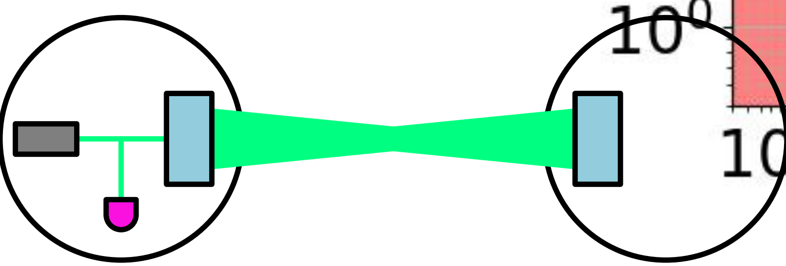


Mirror Size and Arm Length

- From diffraction losses, allowed region in mass-length plane is obtained

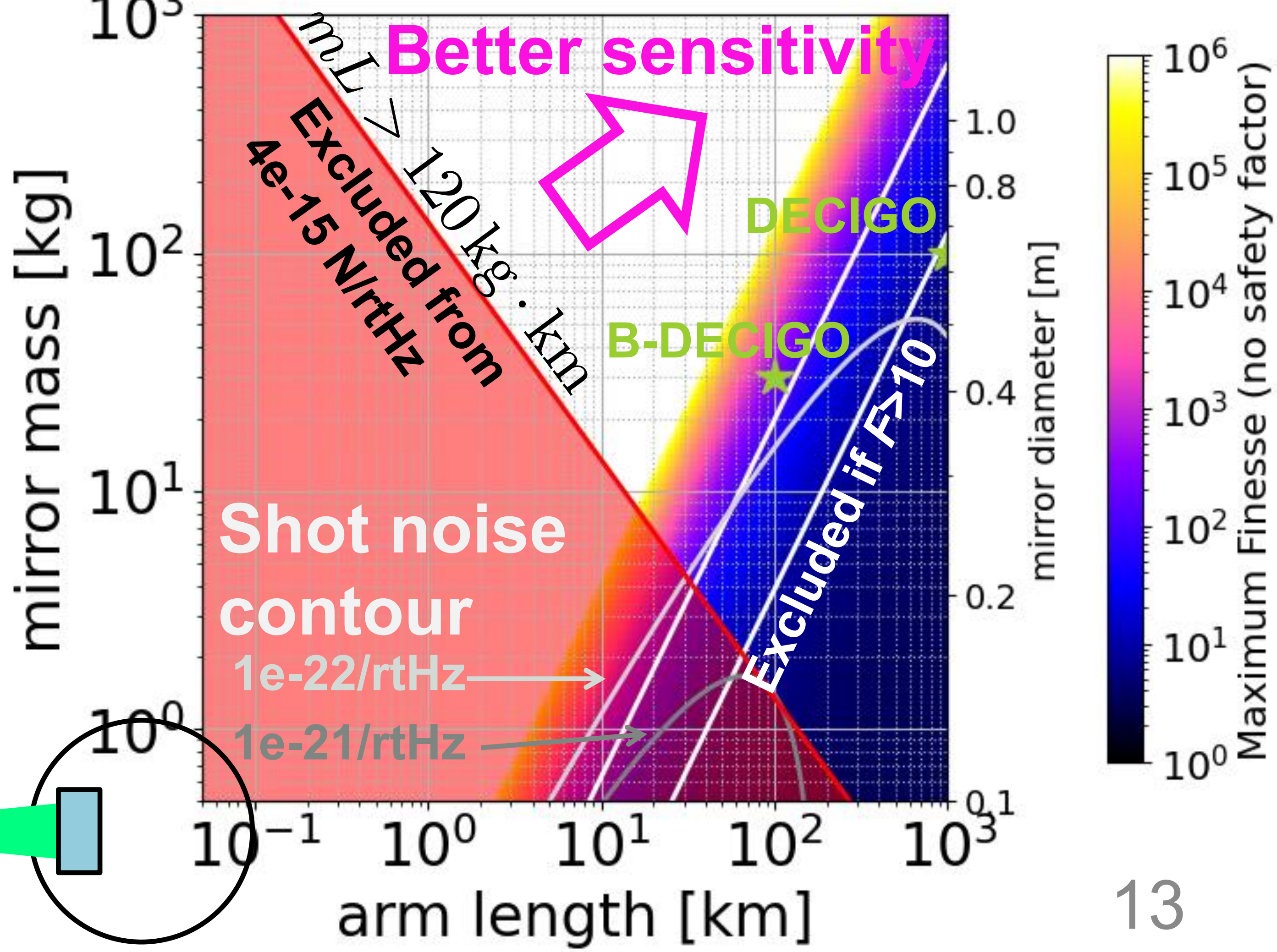
Assuming
- fused silica density,
- aspect ratio 2r/t=3
- g-factor g=-0.65

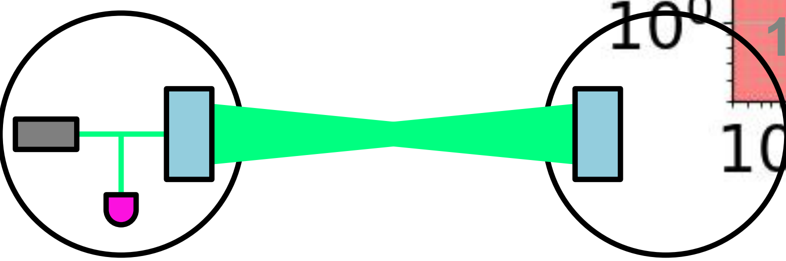




Mirror Size and Arm Length

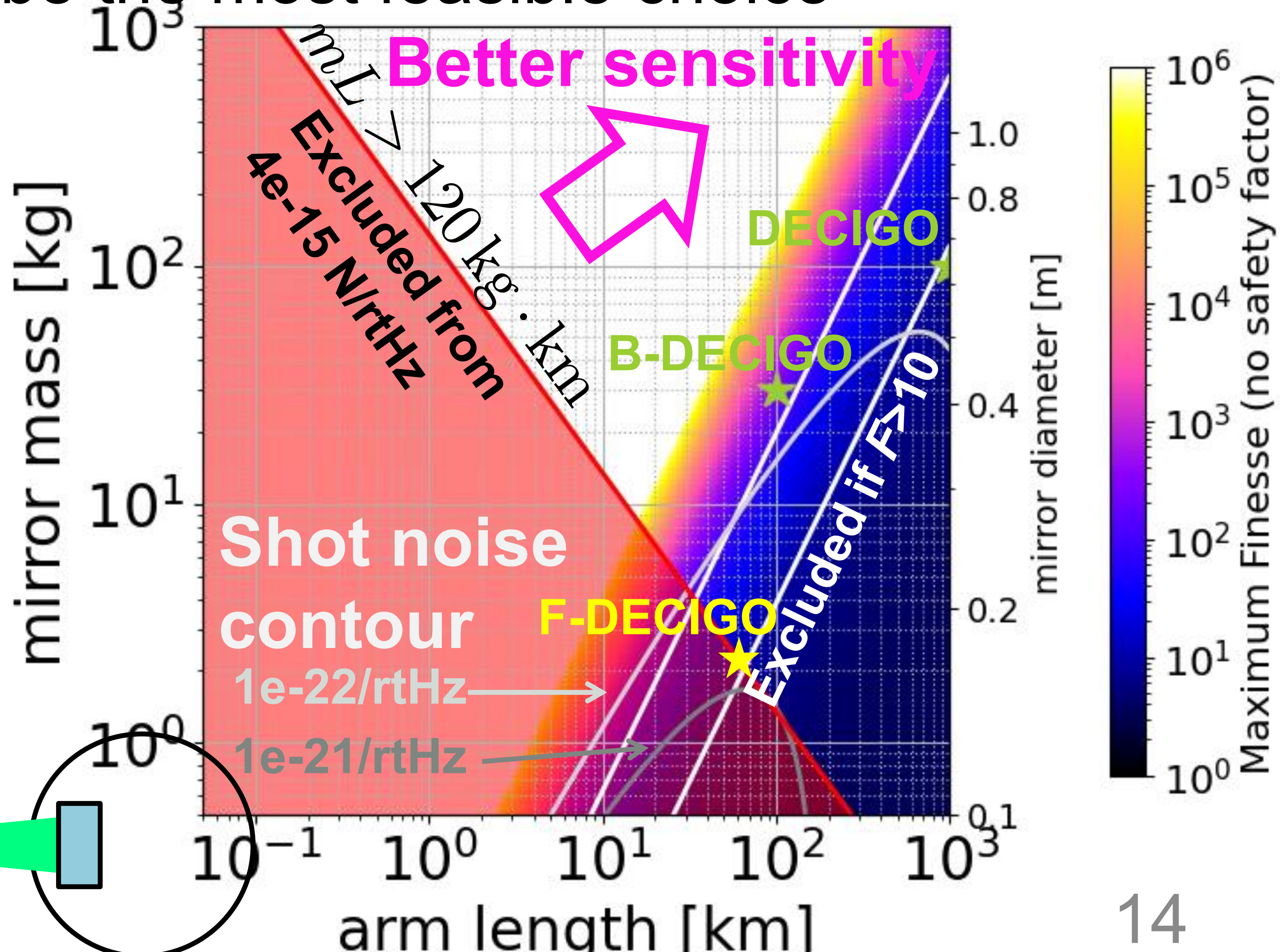
- Shot noise can also be calculated from the arm length and finesse

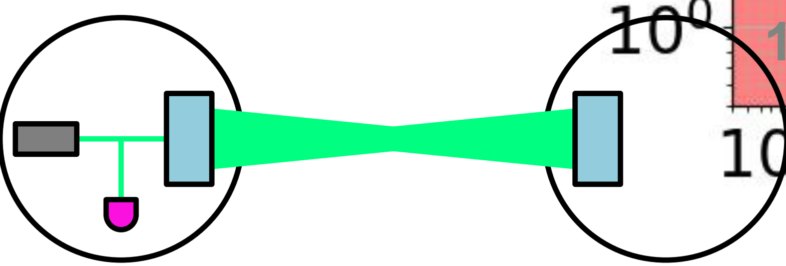




Mirror Size and Arm Length

- Arm length of 60 km, mass of 2 kg, Finesse of 10 seems to be the most feasible choice





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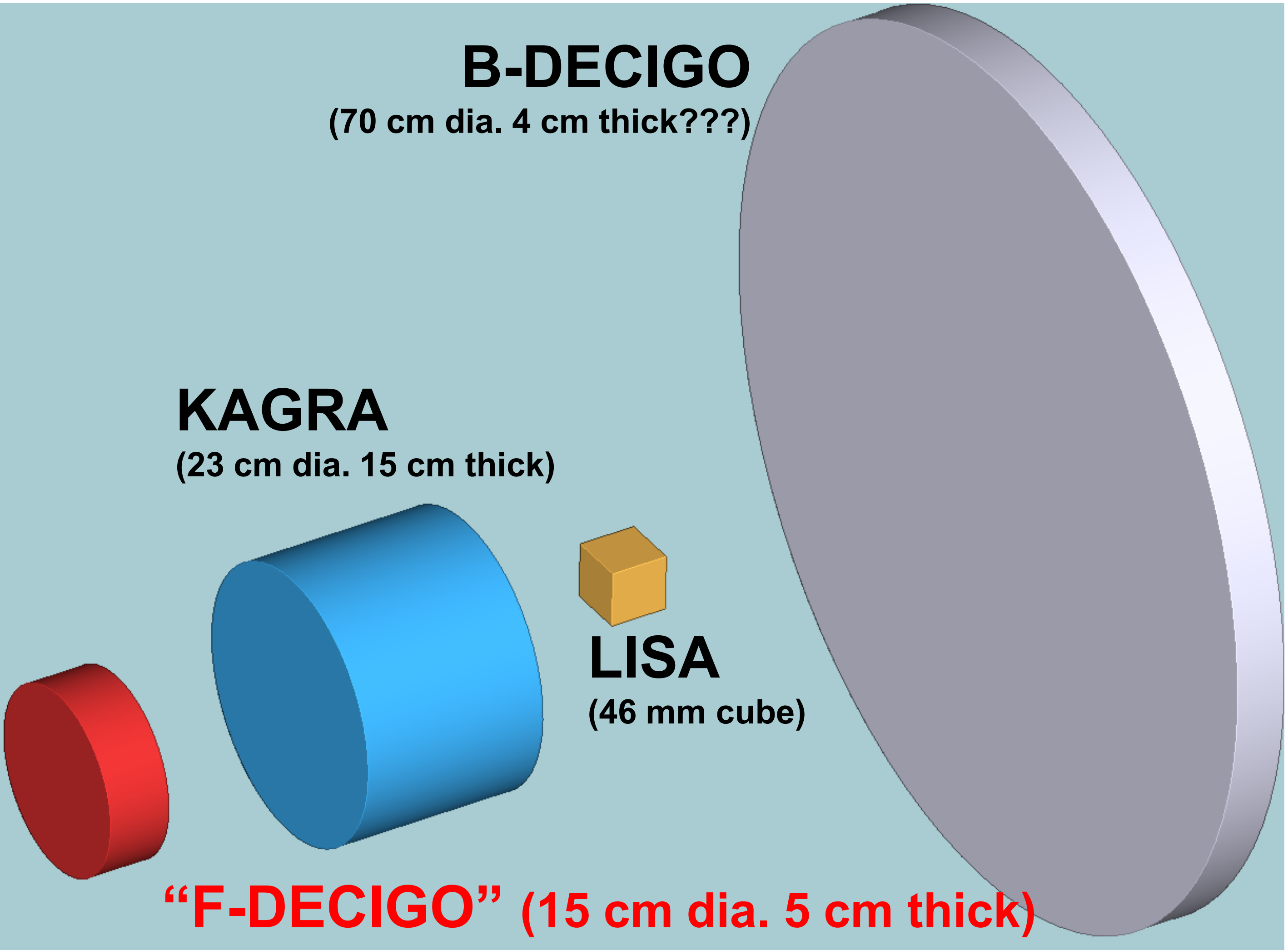
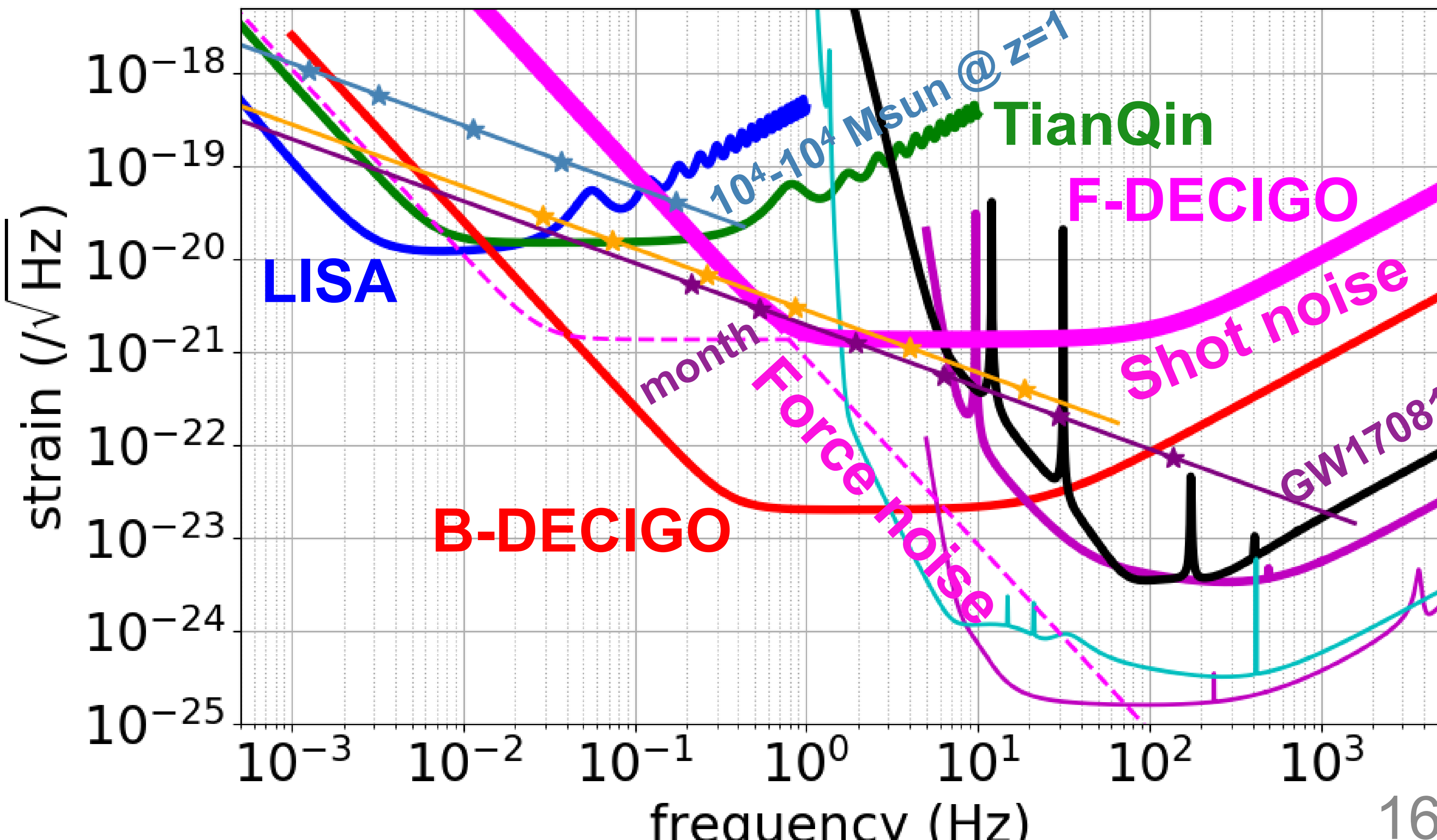


60 km & 2 kg “F-DECIGO” Concept

- Barely meets the goal

Proposed in 2019
日本物理学会2019年秋季大会 @山形大学
第18回DECIGO Workshop @京都大学
Later FF-DECIGO → SILVIA



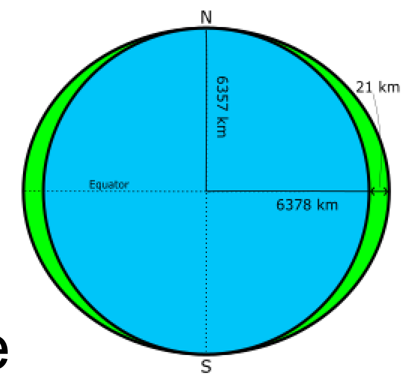
F-DECIGO Orbit

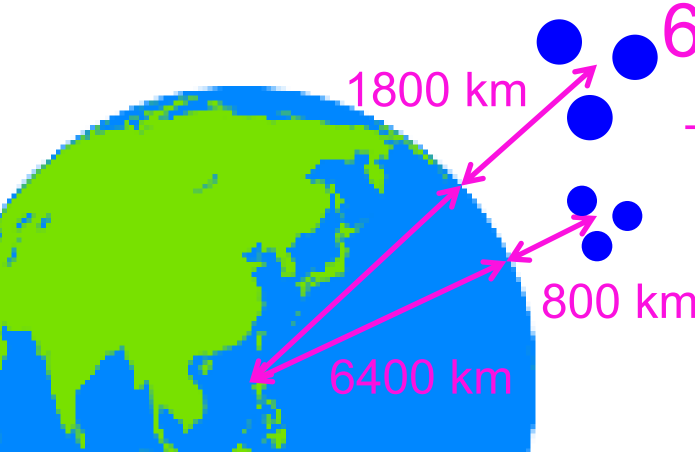
- If geocentric orbit, relative force from Earth J2 term is proportional to mL

J2 coefficient, Earth mass, Mirror mass, Arm length

$$f_{J_2} = m a_{J_2} \sim \frac{3 J_2 G M_\mathrm{E} R_\mathrm{E}^2}{2(R_\mathrm{E} + H)^5} m L$$

Earth radius, Orbital altitude





60 km * 2 kg detector at 1800 km
→ 2e-4 N from J2

100 m * 100 g detector at 800 km
→ 4e-8 N from J2

Calculation done with T. Ito’s code

J2 Term and Sensitivity

- If orbital altitude and actuator dynamic range is given, achievable strain sensitivity can be calculated

dynamic range

$$h = \frac{\delta f}{m\omega^2 L} = \frac{f_{J_2}/D_R}{m\omega^2 L} \sim \frac{3J_2 G M_\mathrm{E} R_\mathrm{E}^2/D_R}{2\omega^2(R_\mathrm{E}+H)^5}$$

$$< 3\times 10^{-21}/\sqrt{\mathrm{Hz}} \,@\, 0.5\,\mathrm{Hz}$$

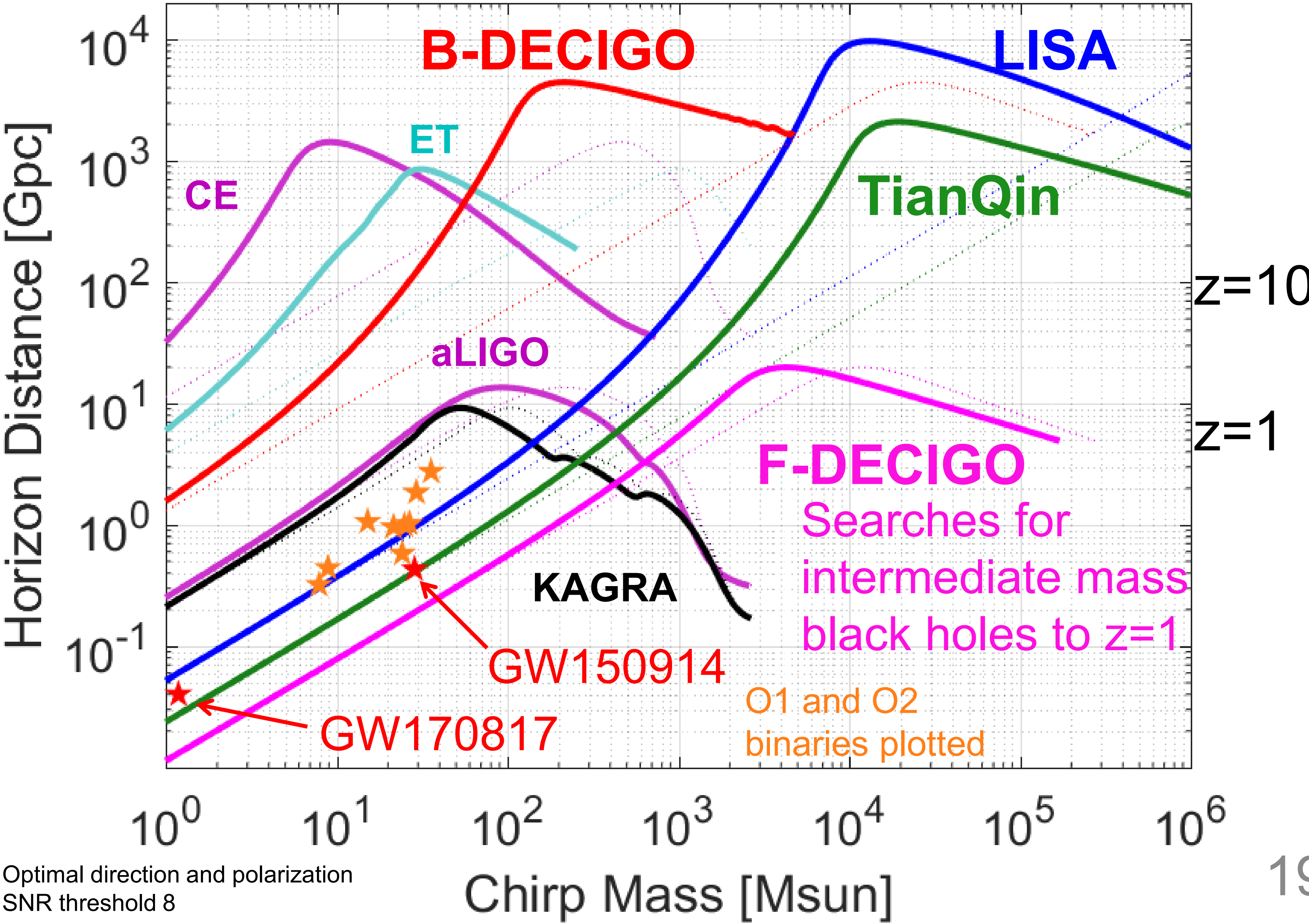
This requires altitude higher than 3.3e7 m with dynamic range 10^7 rtHz

(Geosynchronous orbit 3.6e7 m will do)

- This cannot be avoided by increasing mL

$\rightarrow$ Low Earth orbit won't work. Back-linked?

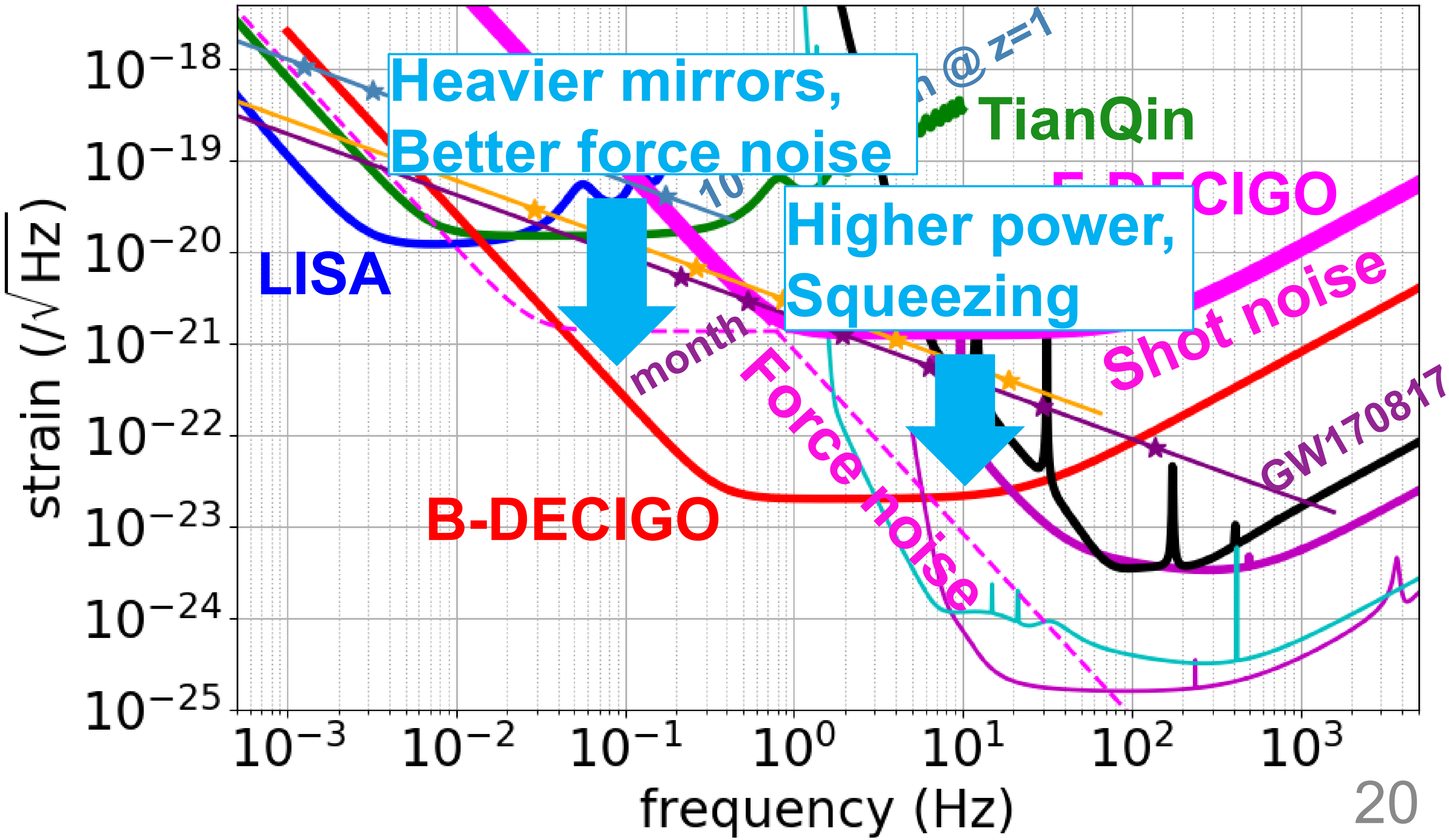
Horizon Distance



Optimal direction and polarization
SNR threshold 8

Beyond F-DECIGO Concept

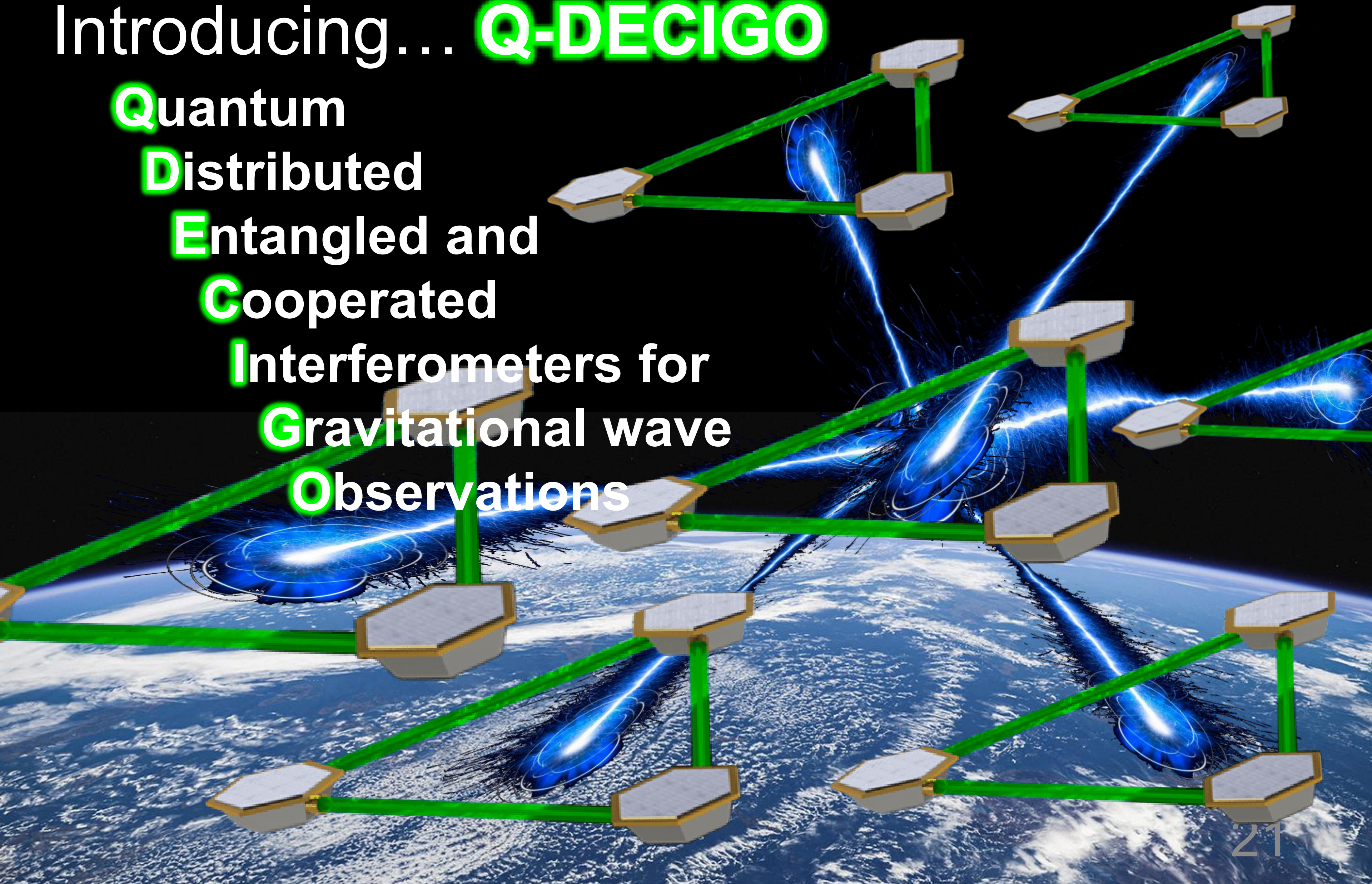
- Heavier mirrors are required for better range



Not Satisfied?

Introducing… **Q-DECIGO**

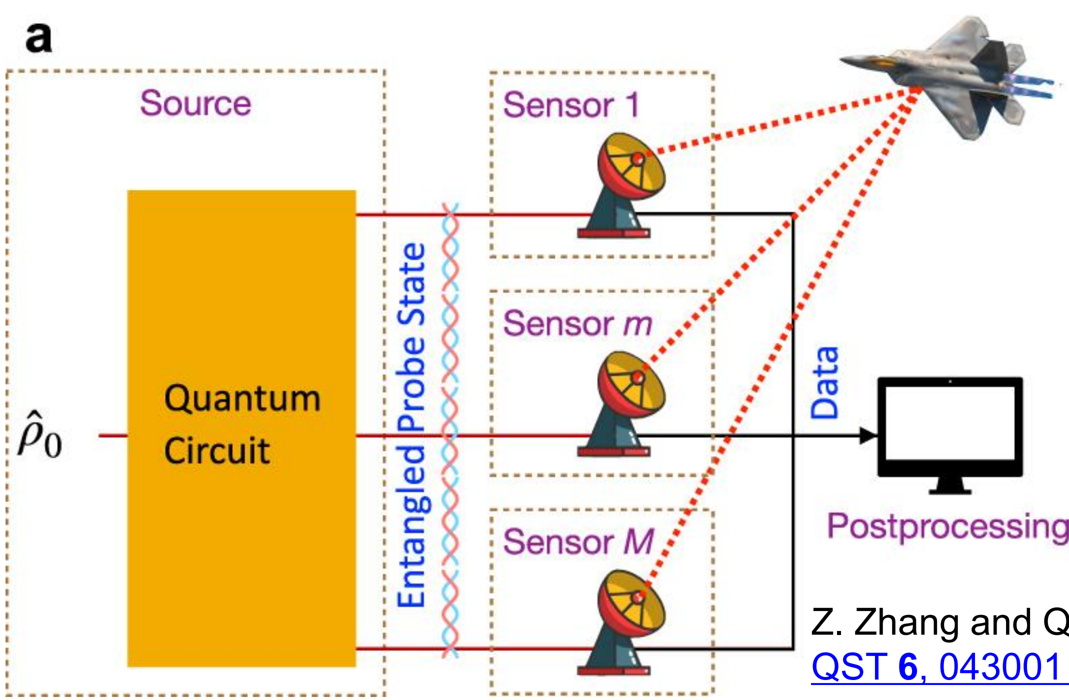
Quantum
Distributed
Entangled and
Cooperated
Interferometers for
Gravitational wave
Observations



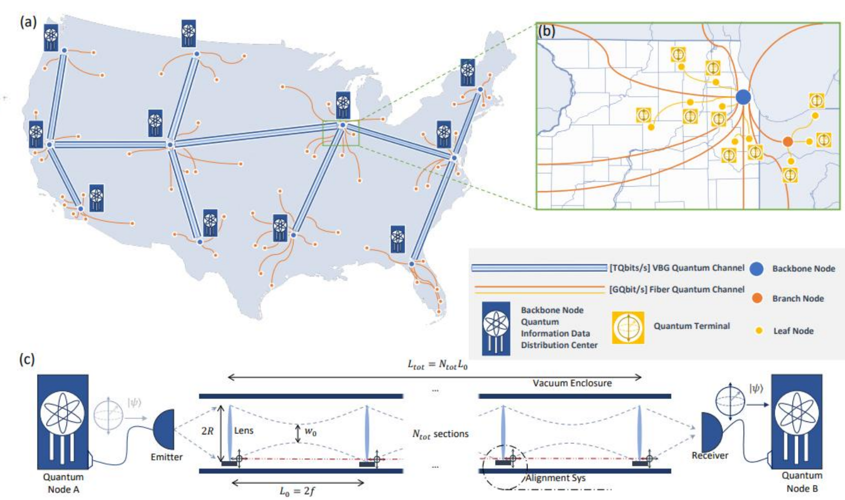
Distributed Quantum Sensing

- By entangling sensing nodes, Heisenberg scaling is possible (∝ N instead of standard quantum limit scaling ∝ √N)
- ~100 of feasible F-DECIGO would make B-DECIGO sensitivity

Caveat: Will not work on classical force noise. Have heavier reference proof mass?



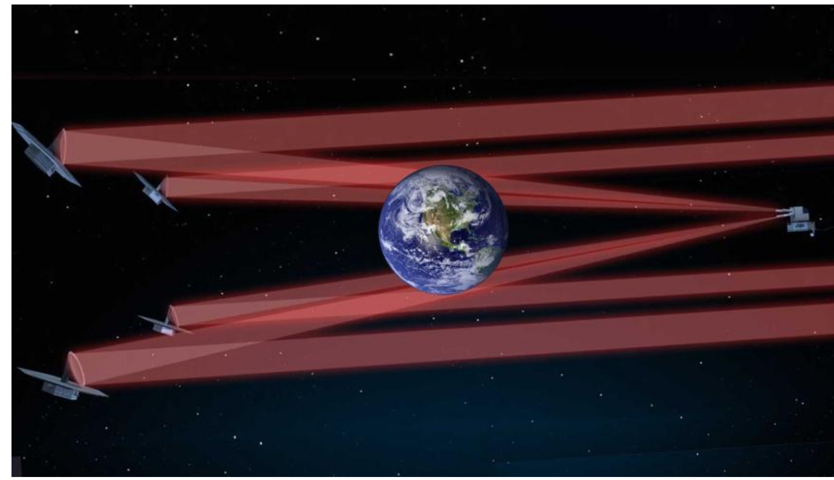
Z. Zhang and Q. Zhuang, [QST **6**, 043001 (2021)]

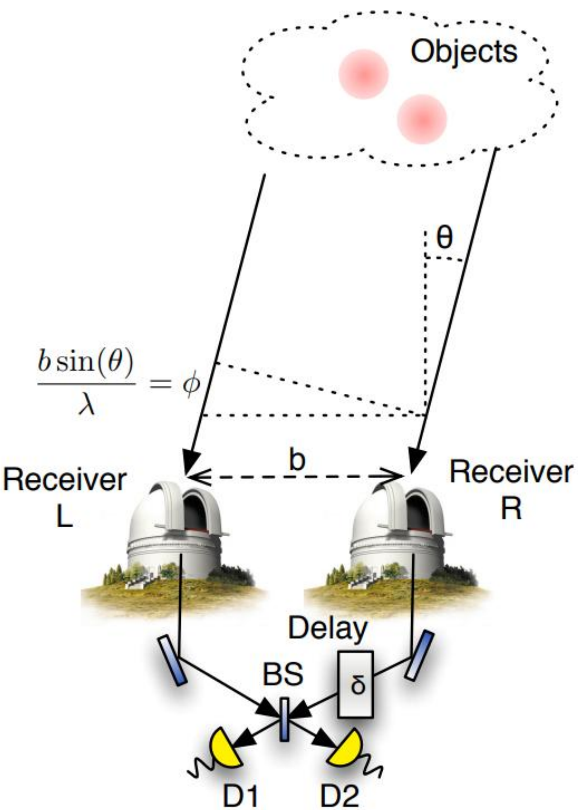


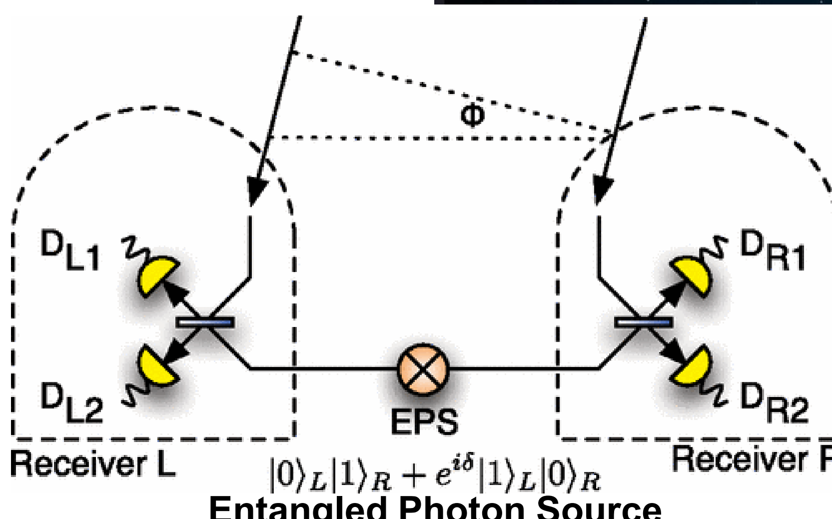
Y. Huang+, [PRL **133**, 020801 (2024)]

Synergy with Stellar Interferometry

- Long baseline stellar interferometry (e.g. LIFE) can also be done with entangled telescopes







D. Gottesman+, [PRL **109**, 070503 (2012)]

まとめ

- 衛星間で光共振器を作るのはなんとかなる
- 共振器長と鏡の大きさの課題
  - 感度のためには共振器長を長くしたい
  - 長くすると鏡を大きくしないといけない
  - 力の雑音への要求も厳しい
- 60 km、2 kgプランの提案
- 量子エンタングルメントを利用することで、多数の小型が1台の大型に勝てる可能性
- まずは1台ができるスケーラビリティ