December 5, 2025

レーザー干渉計型重力波検出器
Laser interferometric gravitational wave detectors
7. Future

Yuta Michimura
RESCEU, University of Tokyo
michimura@resceu.s.u-tokyo.ac.jp

https://yutamich.gitlab.io/lectures.html#lectures

Assignment for Dec 5

- Describe your overall impressions of the lectures and list up the topics you want to study further.
- You may also answer from the Google Form below https://forms.gle/6AwJ48XcpWQXqMon9

Don't forget to put your name and student#

You may answer in any language

Plan of the Lecture Today

- My Top 5 favorite gravitational wave events
- Next generation detectors
- Space gravitational wave detectors

- **Goal**: Understand that improvements in the detectors are necessary for better future

My Favorite GW Events

1. GW170817
2. GW190521
3. GW231123
4. GW250114
5. GW190814

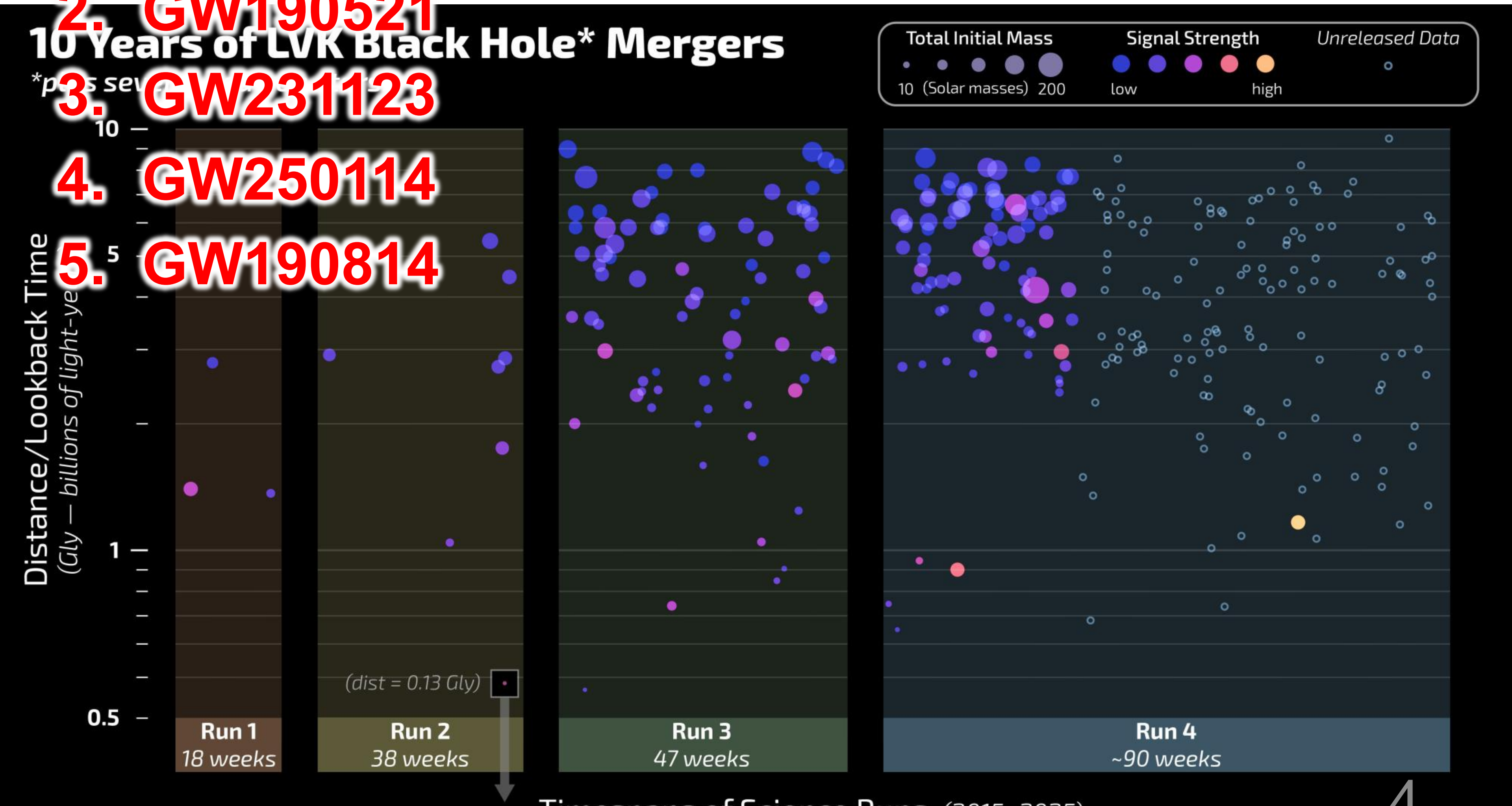
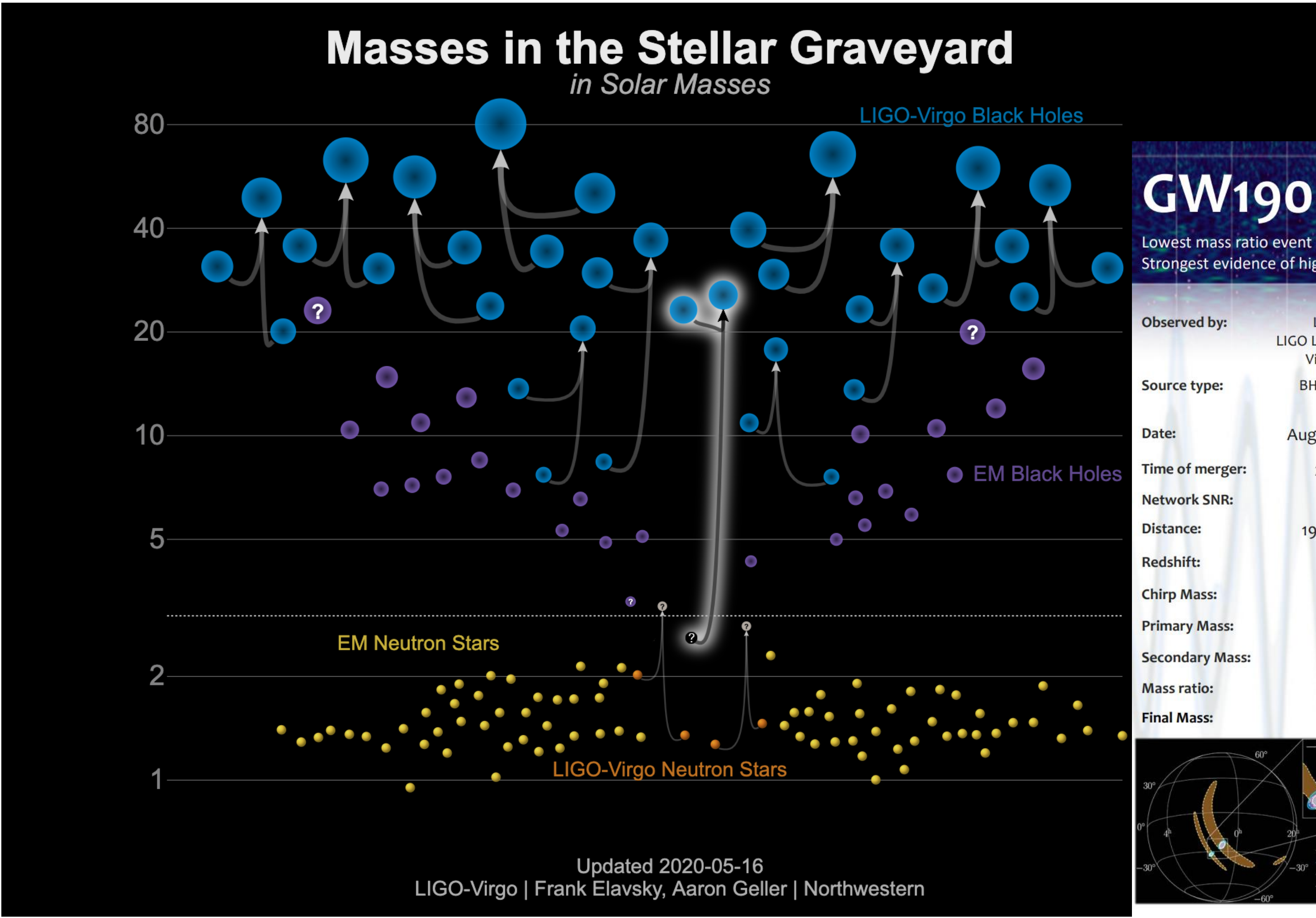


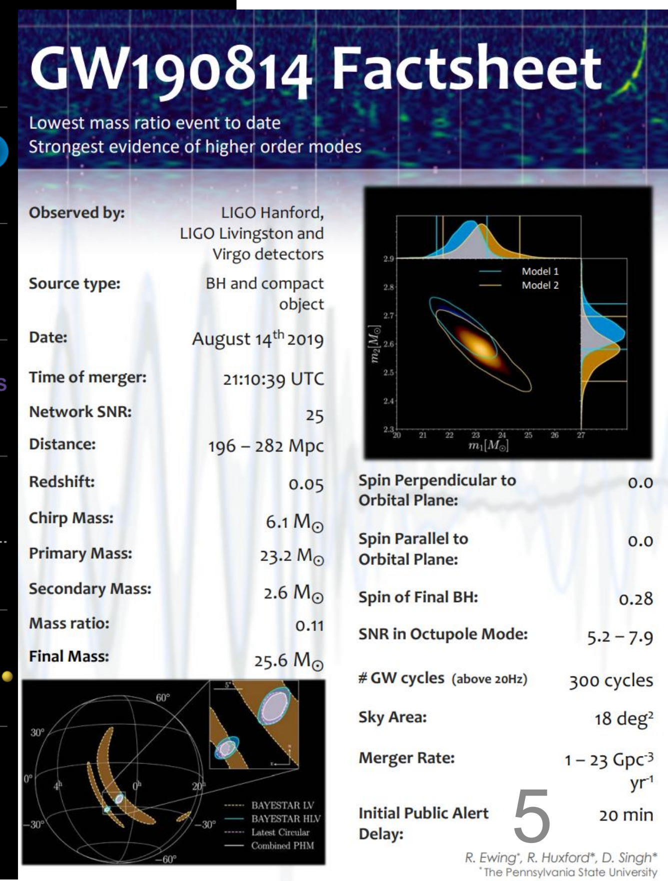
Image credit: LIGO/Caltech/MIT/R. Hurt (IPAC)

No. 5 GW190814: 23$M_\odot$ + 2.6$M_\odot$

- Lowest mass ratio, mystery compact object

[2020 *ApJL* **896** L44]





GW190814 Factsheet

Lowest mass ratio event to date
Strongest evidence of higher order modes

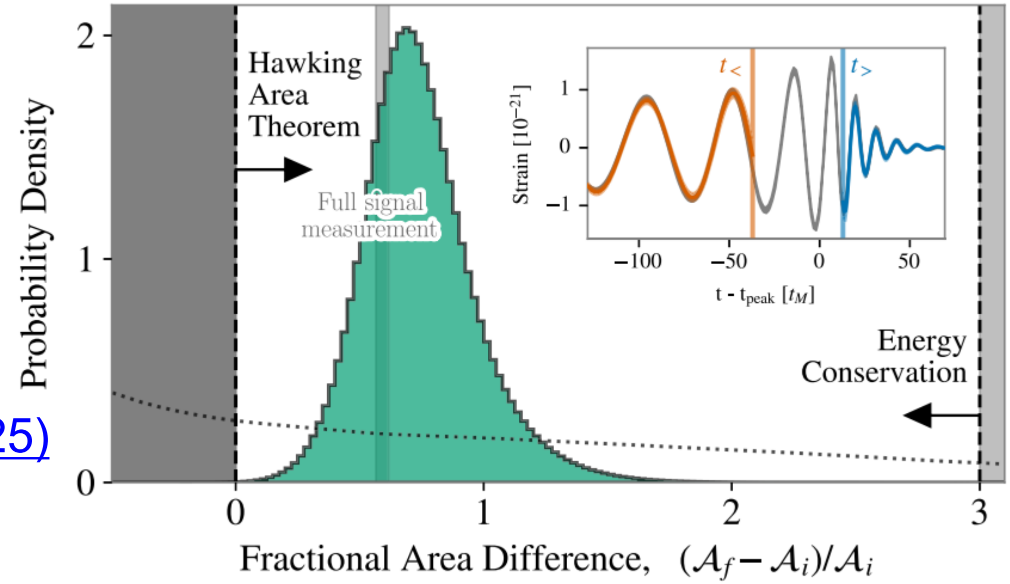
Observed by:	LIGO Hanford, LIGO Livingston and Virgo detectors
Source type:	BH and compact object
Date:	August 14^{th} 2019
Time of merger:	21:10:39 UTC
Network SNR:	25
Distance:	196 – 282 Mpc
Redshift:	0.05
Chirp Mass:	6.1 $M_\odot$
Primary Mass:	23.2 $M_\odot$
Secondary Mass:	2.6 $M_\odot$
Mass ratio:	0.11
Final Mass:	25.6 $M_\odot$
Spin Perpendicular to Orbital Plane:	0.0
Spin Parallel to Orbital Plane:	0.0
Spin of Final BH:	0.28
SNR in Octupole Mode:	5.2 – 7.9
# GW cycles (above 20Hz)	300 cycles
Sky Area:	18 deg^2
Merger Rate:	1 – 23 Gpc^{-3} yr^{-1}
Initial Public Alert Delay:	20 min

R. Ewing*, R. Huxford*, D. Singh*
*The Pennsylvania State University

No.4

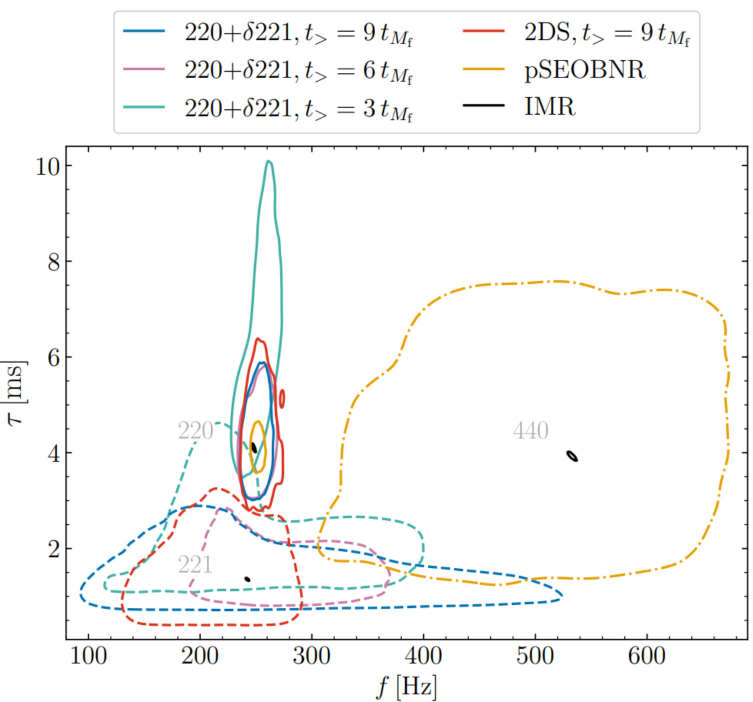
GW250114: Area Law, Overtones

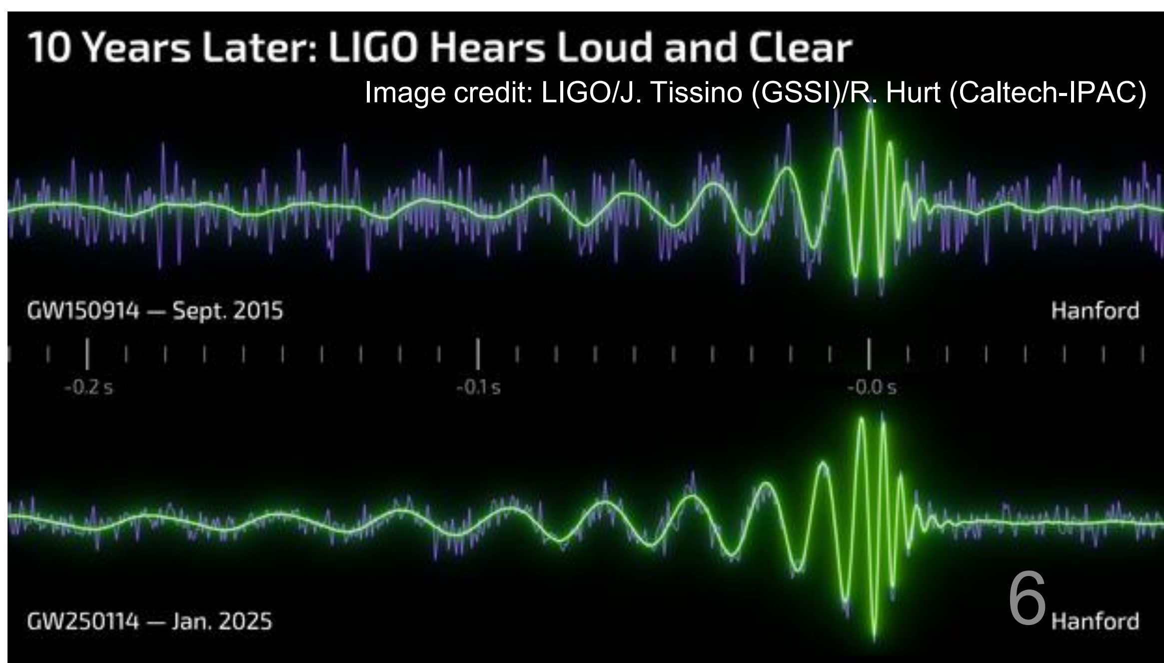
- Largest network SNR of ~80 (L+H) enabling new tests



[PRL **135**, 111403 (2025)]

[arXiv:2509.08099]



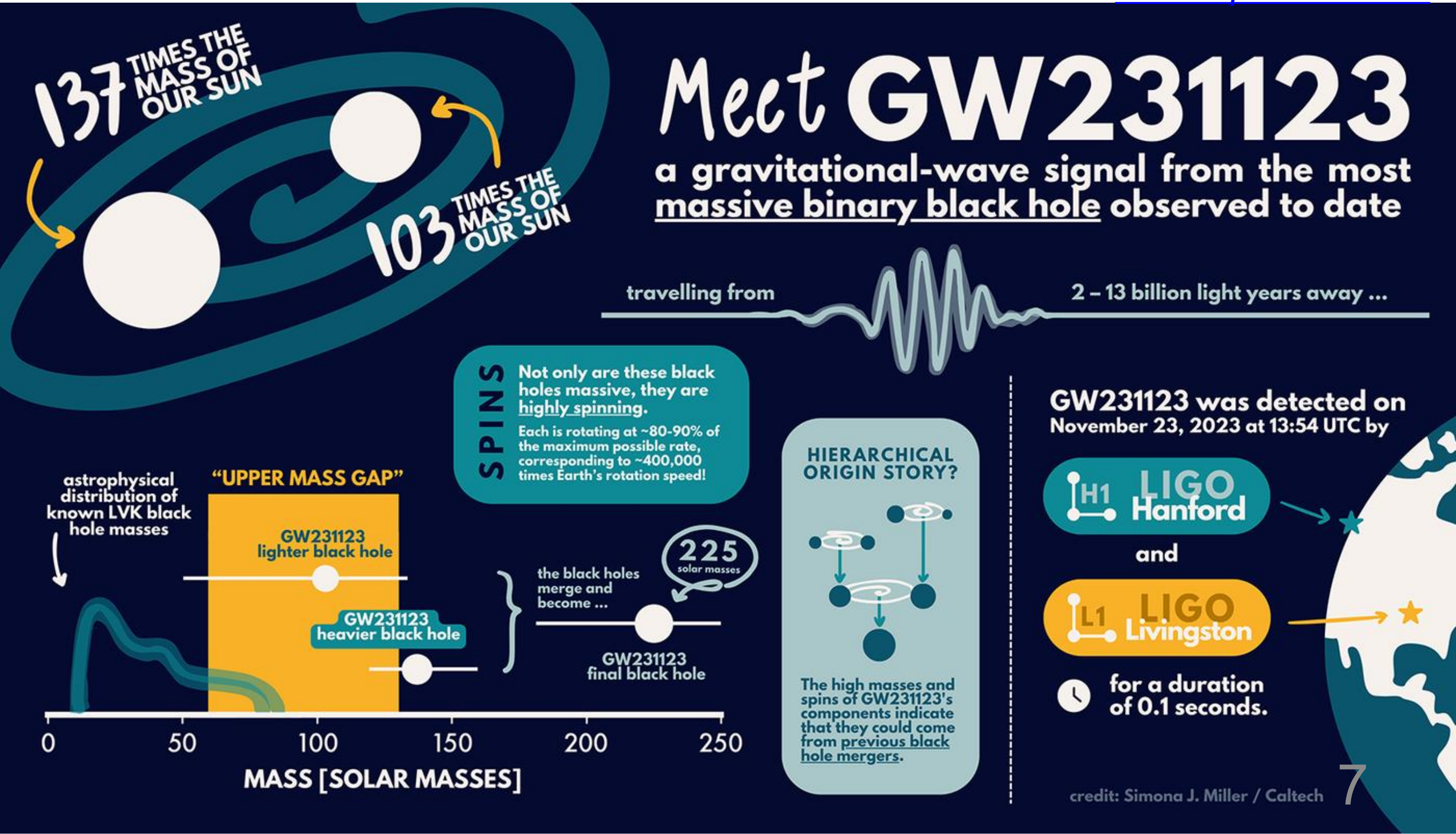


No 3

GW231123: Heaviest Binary BHs

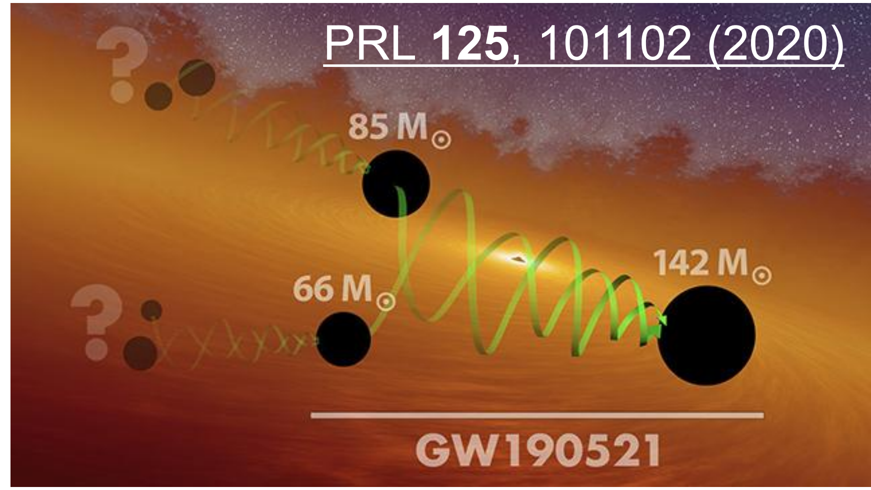
- Hint for the origin of heavy stellar-mass BHs?

2025 *ApJL* **993** L25

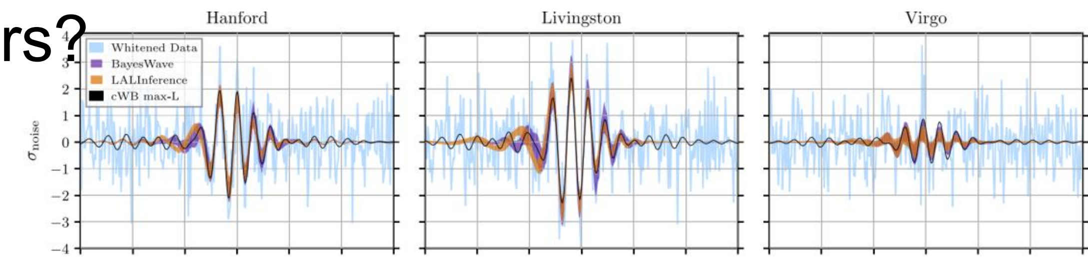


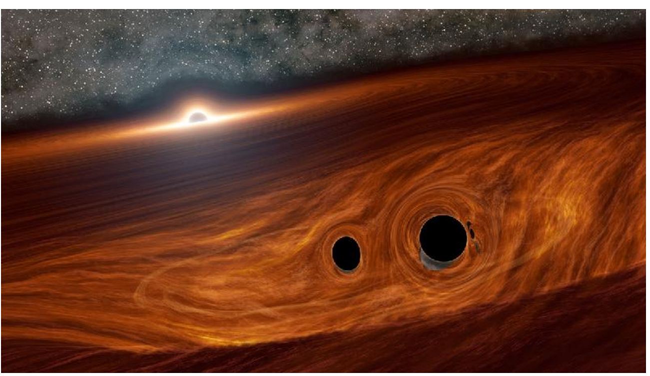
GW190521: First IMBH event

- Zwicky Transient Facility found the electromagnetic flare consistent with expectations for a kicked binary black hole merger in the accretion disk. Repeat flare in 1.6 years?

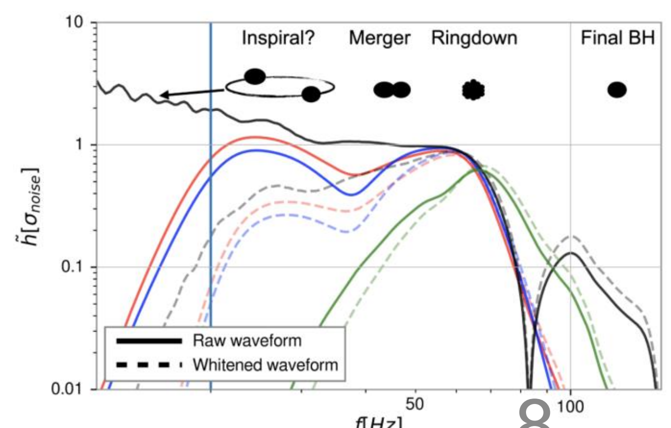


PRL **125**, 101102 (2020)





M. J. Graham+, PRL **124**, 251102 (2020)



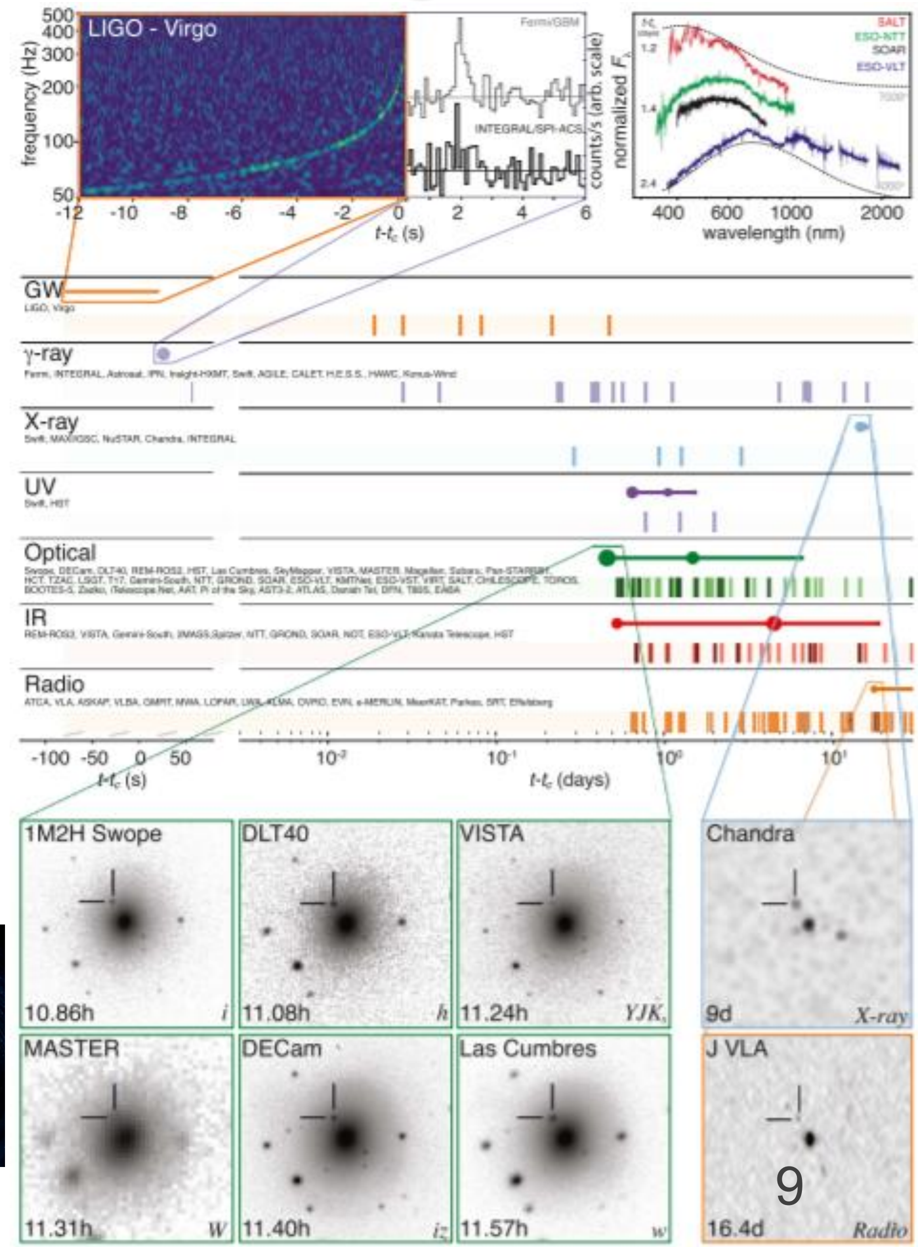
- Could be collision of Proca stars? Vector boson star of 8.7e-13 eV

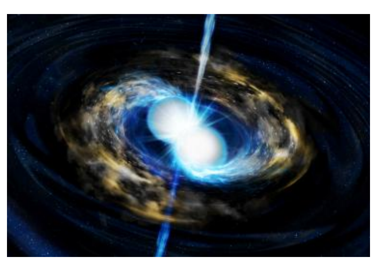
Juan Calderón Bustillo+, PRL **126**, 081101 (2021)

No.1

GW170817: Multi-messenger Event

- Detected by HLV, localized ~30 deg^2
- Short gamma-ray burst, kilonova detected
- Speed of gravity
- Hubble constant
- Studies of neutron star equation of state
- Evidence for production of heavy elements

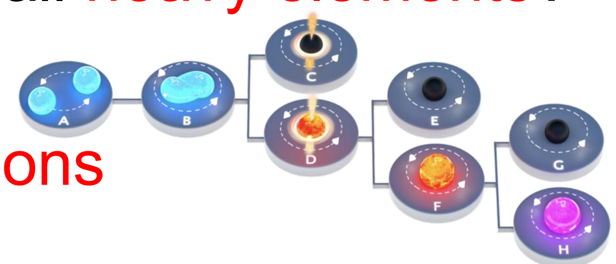




LV and many, [ApJL 848, L12 (2017)]

So, What's Left?

- What is the origin of heavy black holes?
- What are the compact objects in ~3-5 $M_\odot$ range?
- What happened after the BNS merger?
- What are the progenitors of GRBs and kilonovae?
  - Short/long GRBs explained by BNS?
  - Diversity of kilonovae? c.f. GRB211211A, GRB230307A
- Can BNS mergers explain the origin of all heavy elements?
- QCD phase transition?
- Tests of general relativity with polarizations
- Hubble tension, dynamical dark energy …
- Continuous waves, bursts from supernovae …



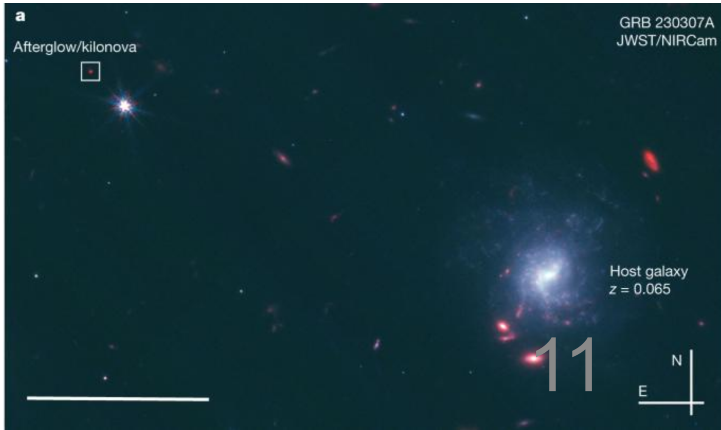
Sarin & Lasky, GRG 53, 59 (2021)

- Clear need for more detectors with better sensitivity
- More multi-messenger detections

Power of Multi-Messenger Obs.

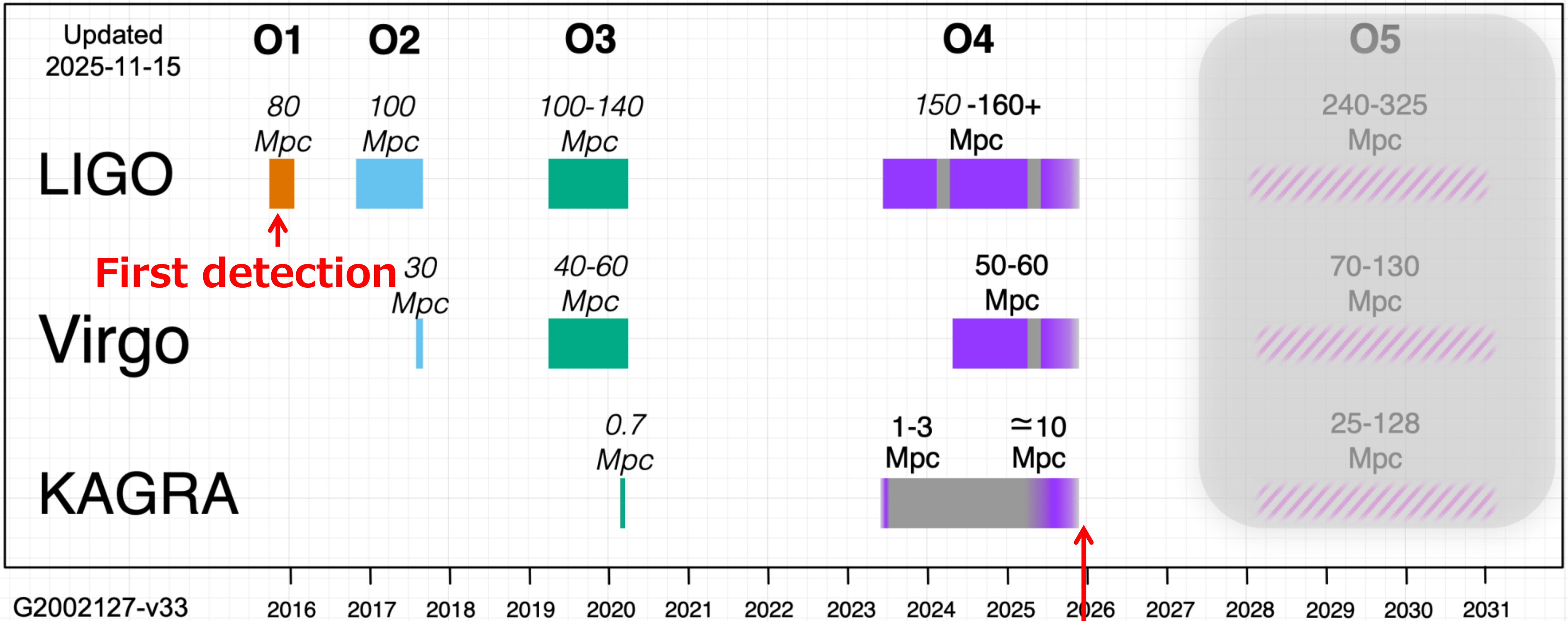
- **GW170817** (**GW** + **EM** event) @ 40 Mpc
  - Localized to 30 deg^2 with Hanford, Livingston, Virgo
  - GW from BNS merger, short GRB, kilonova detected
- **GW190425** (**GW** only event) @ 159 Mpc
  - Localized to ~8000 deg^2 with Livingston, Virgo
  - GW from BNS merger, no EM counterpart
  - Probably prompt collapse to BH??
- **GRB211211A** (**EM** only event) @ ~350 Mpc
- **GRB230307A** (**EM** only event) @ ~300 Mpc
  - GW detectors not operating
  - BNS merger??
  - Long GRB
  - kilonova spectrum different from GW170817 (really BNS??)

Levan+, [Nature 626, 737 (2024)]()



LIGO-Virgo-KAGRA Observations

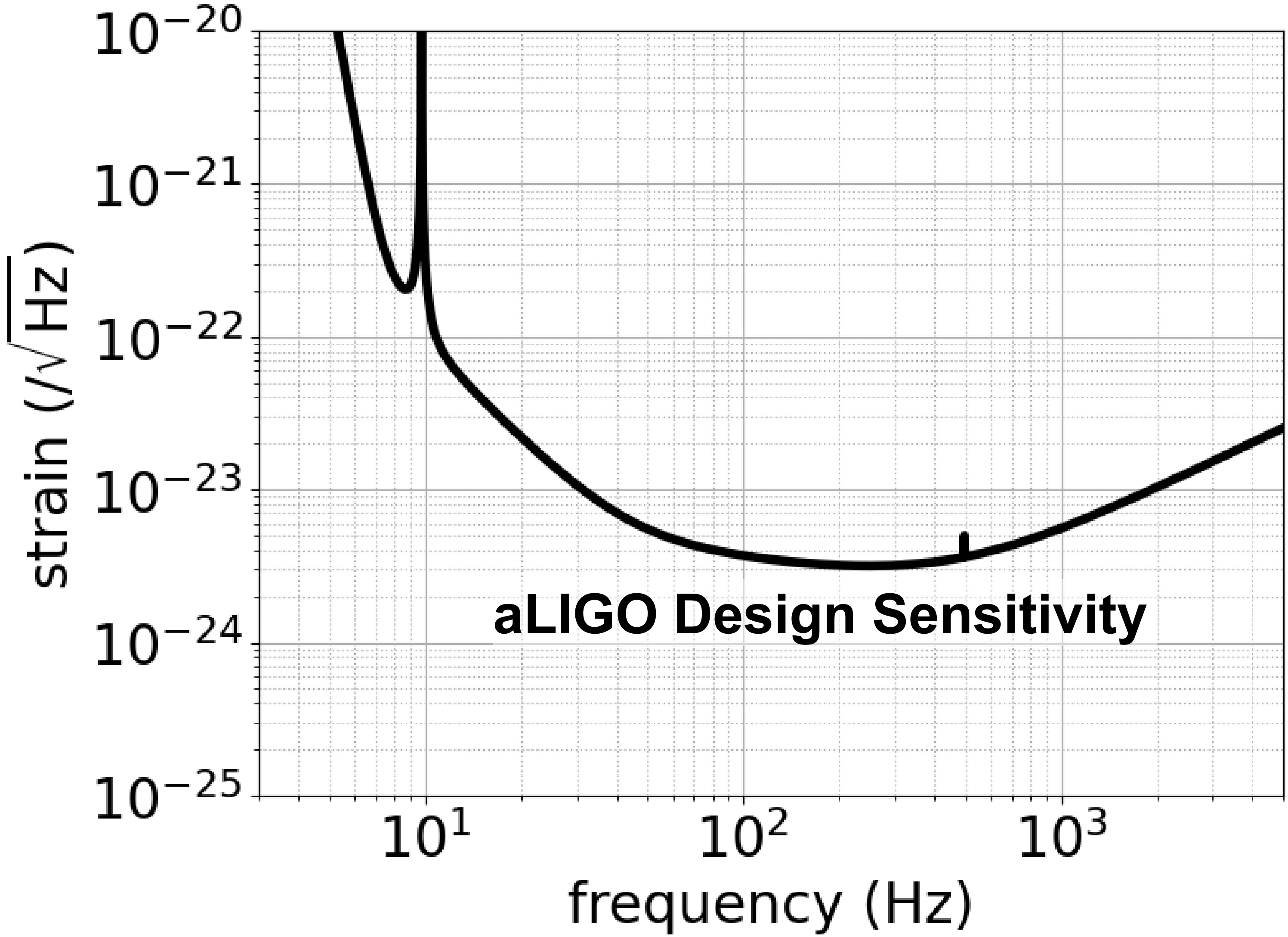
- Coordinated runs to detect GW signals by multiple detectors for better sky localization etc.



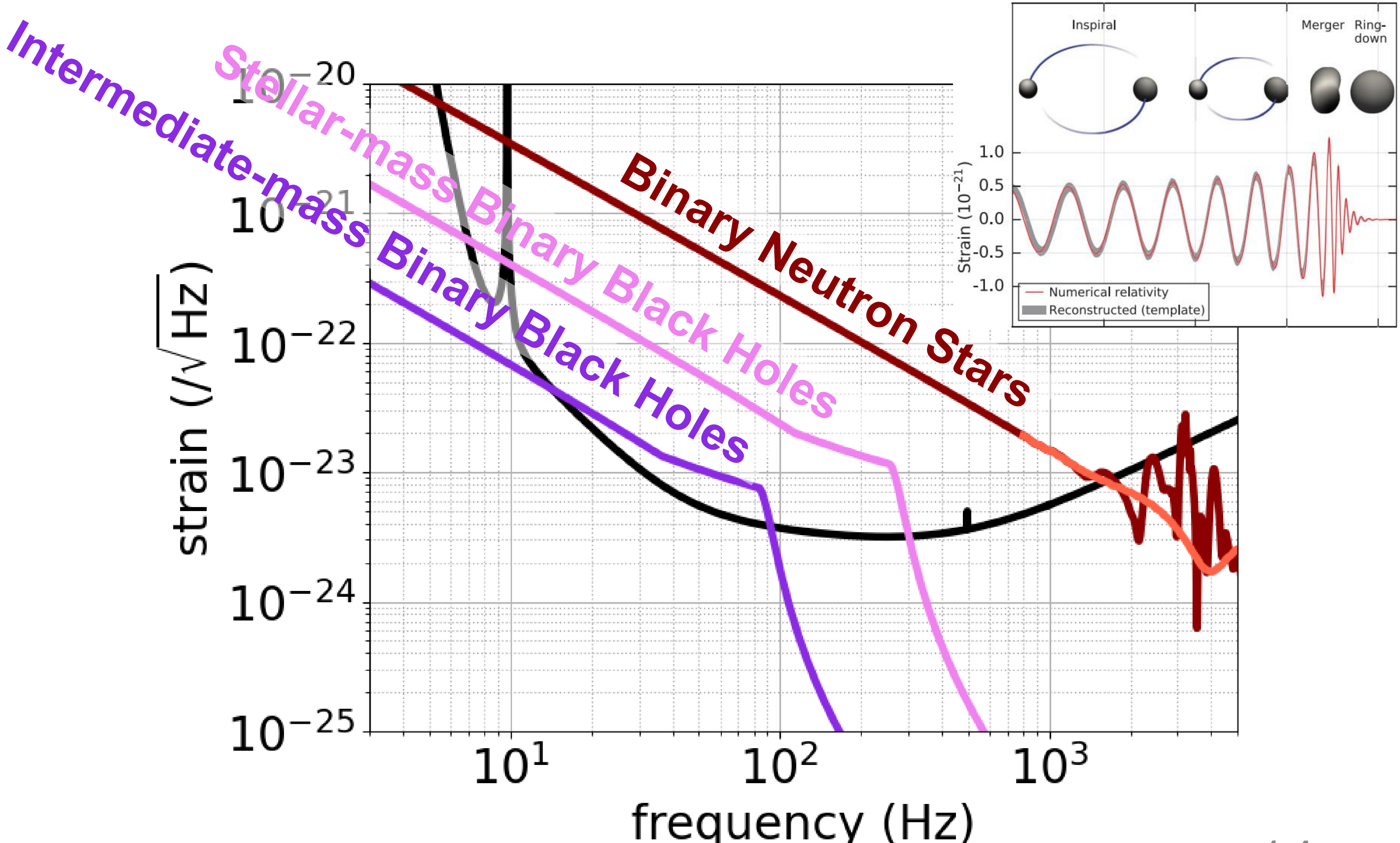
https://observing.docs.ligo.org/plan/

Today: post-O4 characterizations

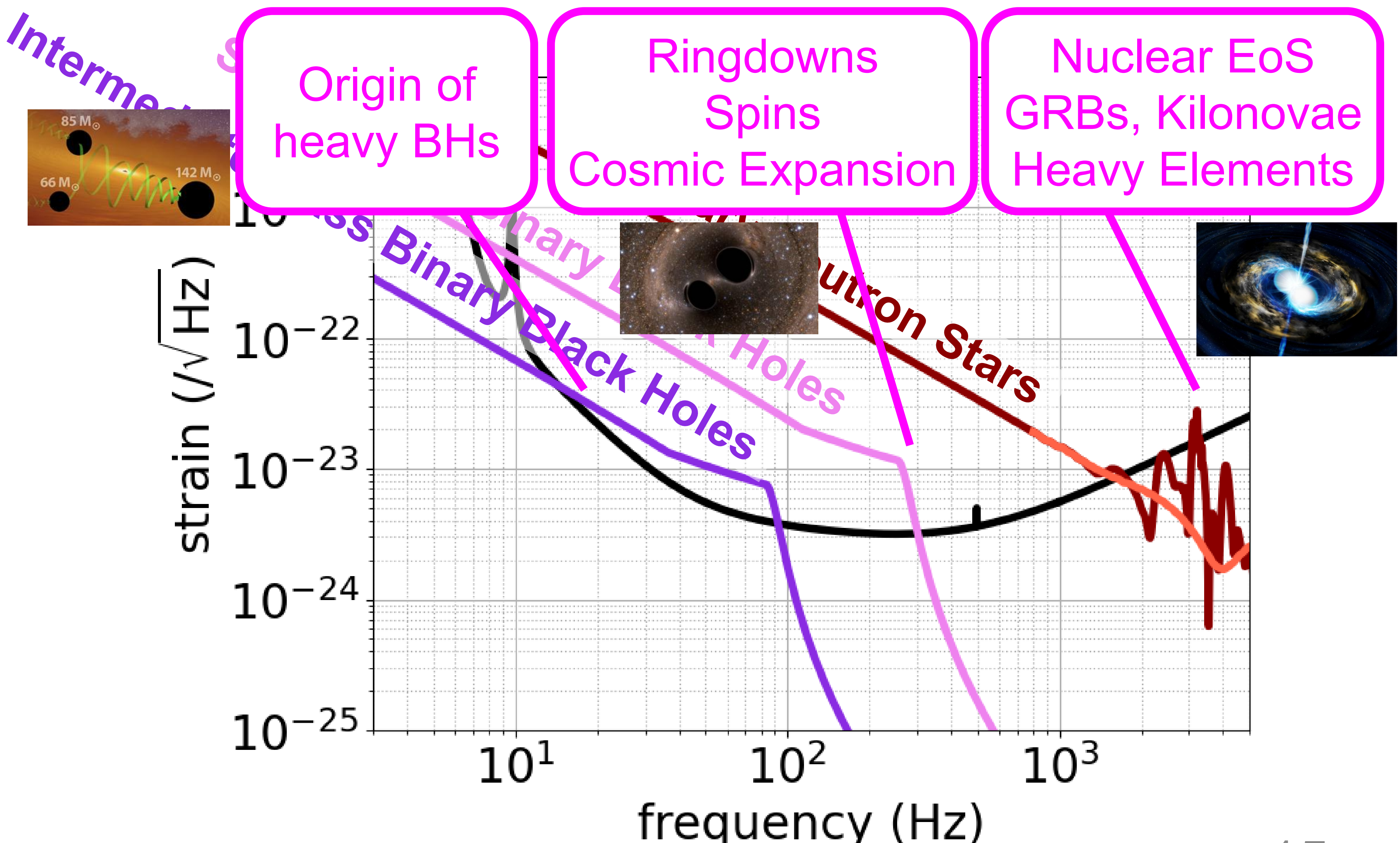
Sensitivity Band



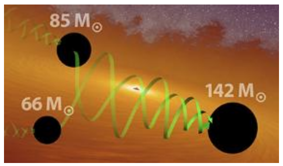
Sensitivity Band and Science



Sensitivity Band and Science



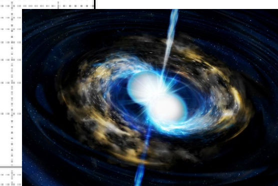
Limiting Noises

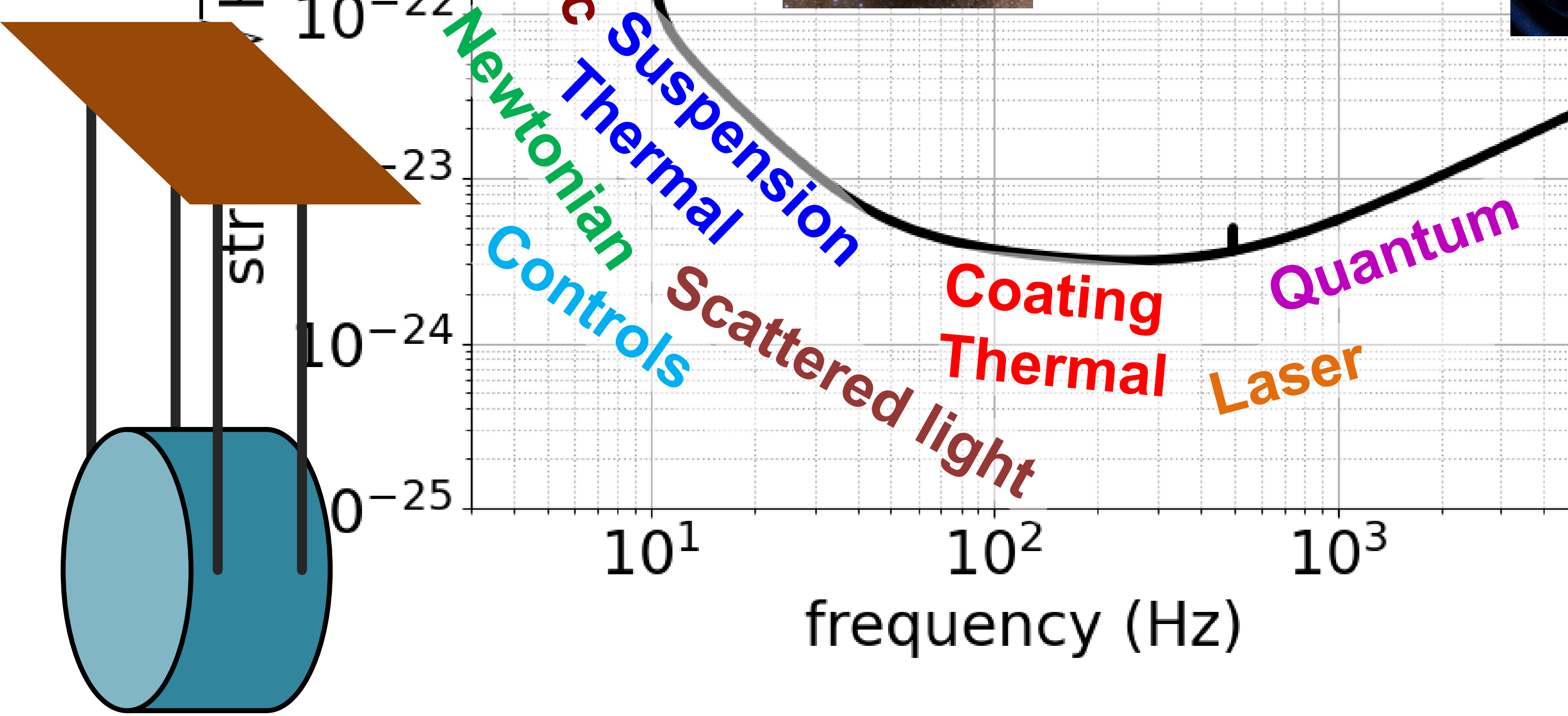


Origin of heavy BHs

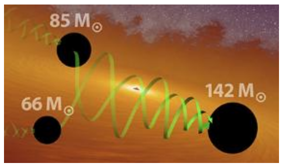
Ringdowns
Spins
Cosmic Expansion

Nuclear EoS
GRBs, Kilonovae
Heavy Elements





Noise Reducing Techniques



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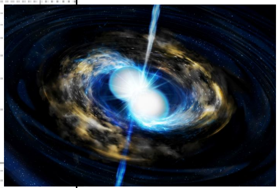
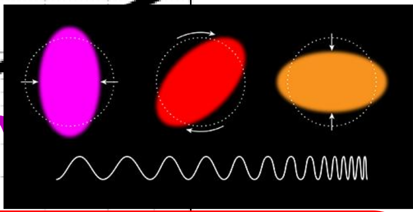


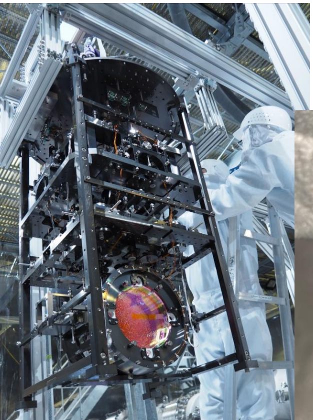
Seismic
Suspension
10^{-22}
frequency (Hz)

Heavier Mirrors
Suspensions
Noise Cancellation
Machine Learning

Larger Mirrors
Coating Improvements
Cryogenics



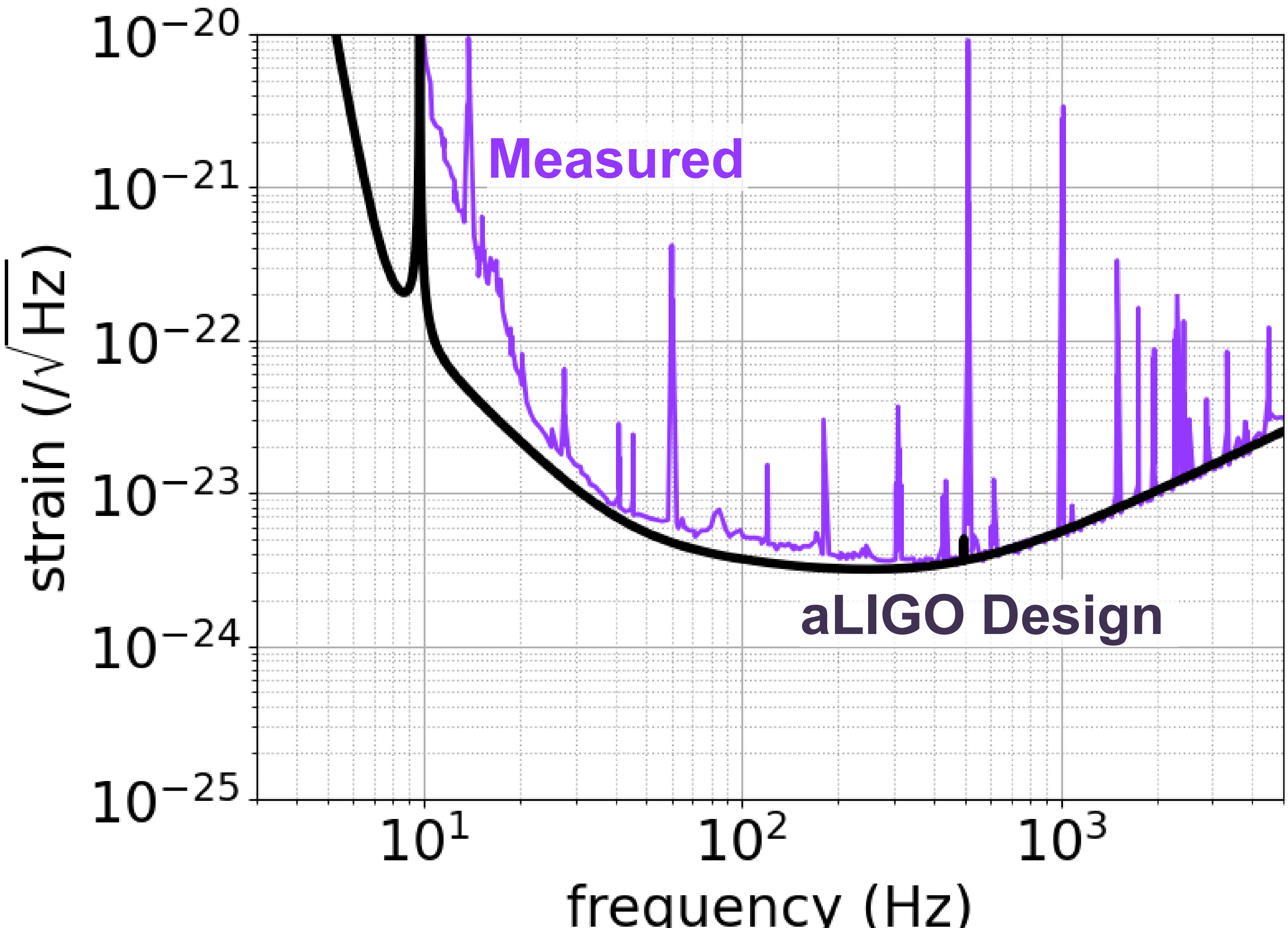
Higher Power
Squeezing
(frequency dependent)



LIGO-G2200805

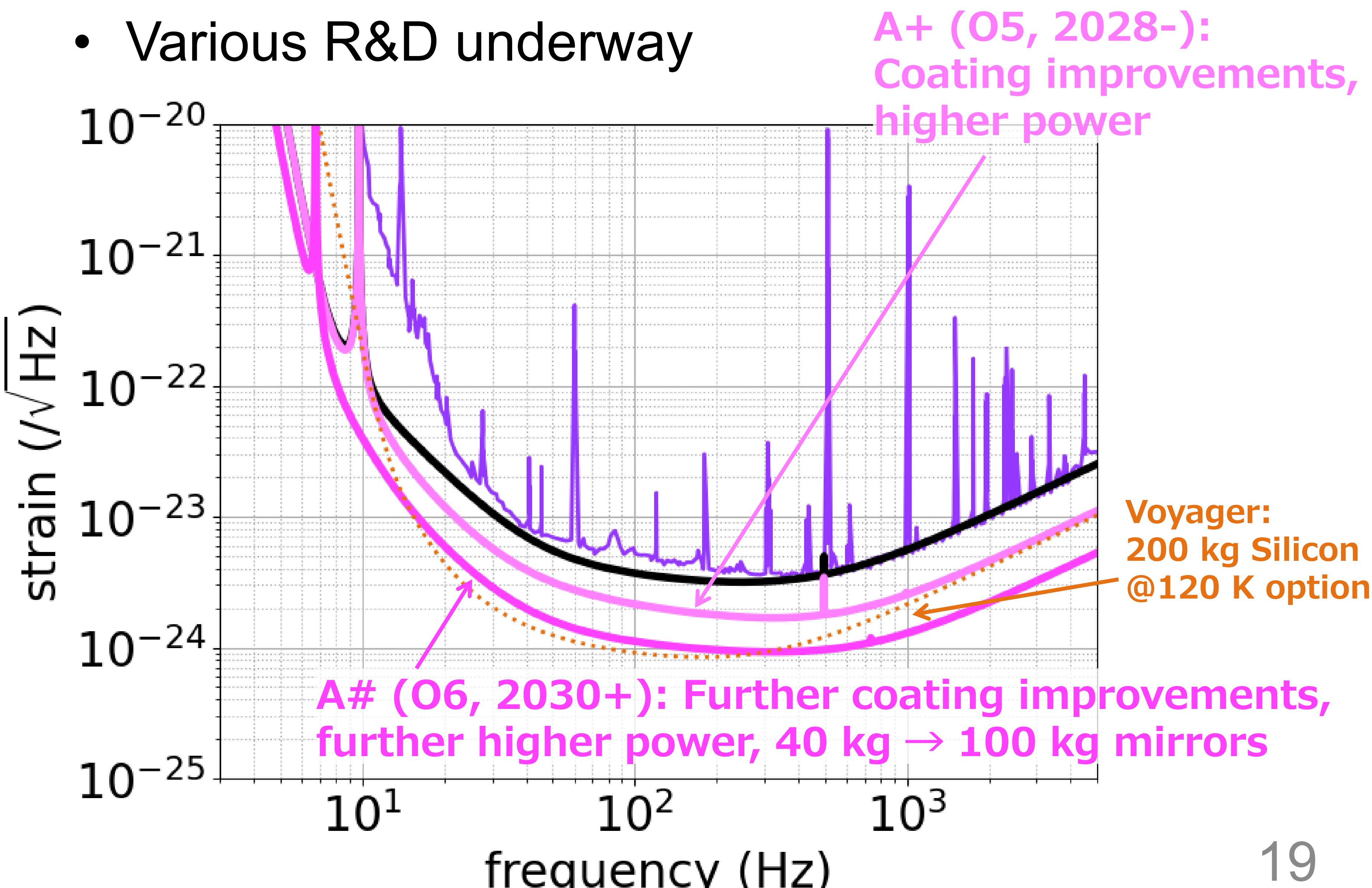
LIGO (US, 4 km, Room Temp.)

- Hanford & Livingston operating at ~150 Mpc



LIGO (US, 4 km, Room Temp.)

- Various R&D underway



LIGO (US, 4 km, Room Temp.)

- Various R&D underway

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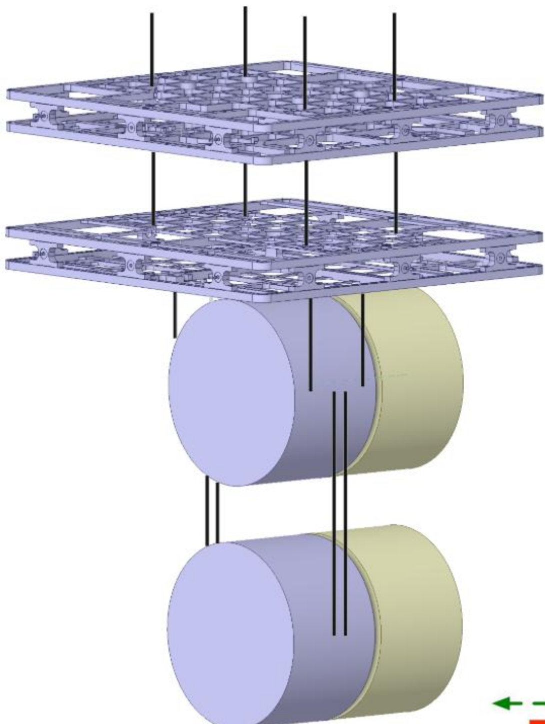
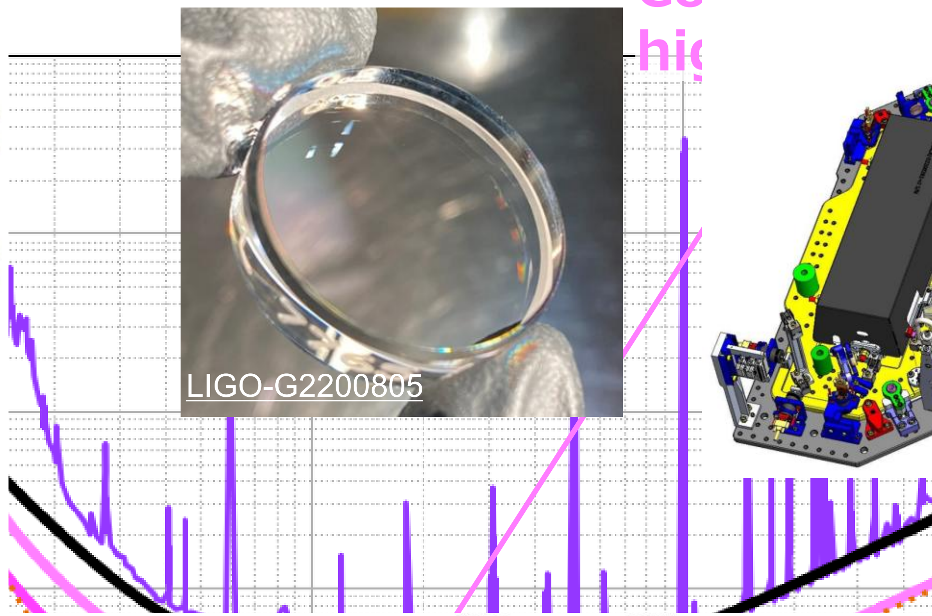
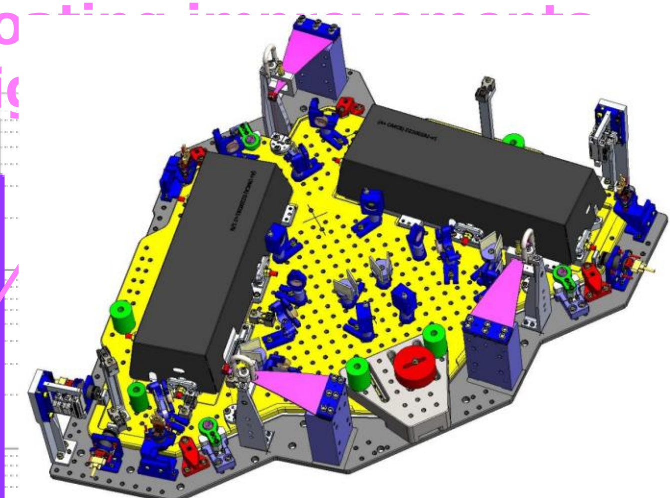


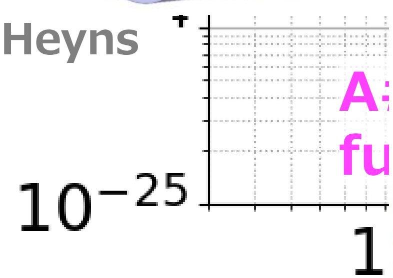




LIGO-T2100318

Voyager:
kg Silicon
0 K option

JD Heyns



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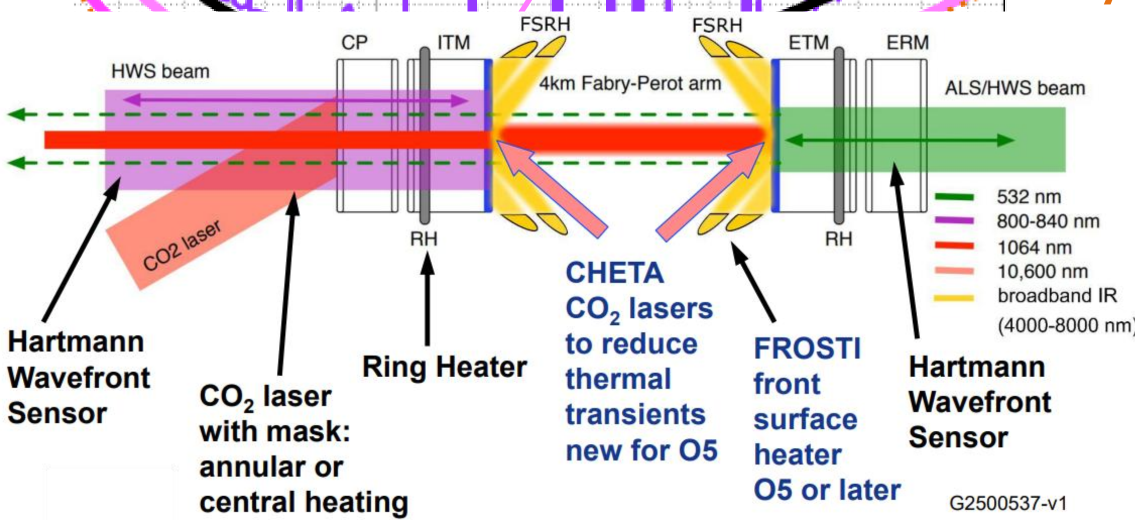
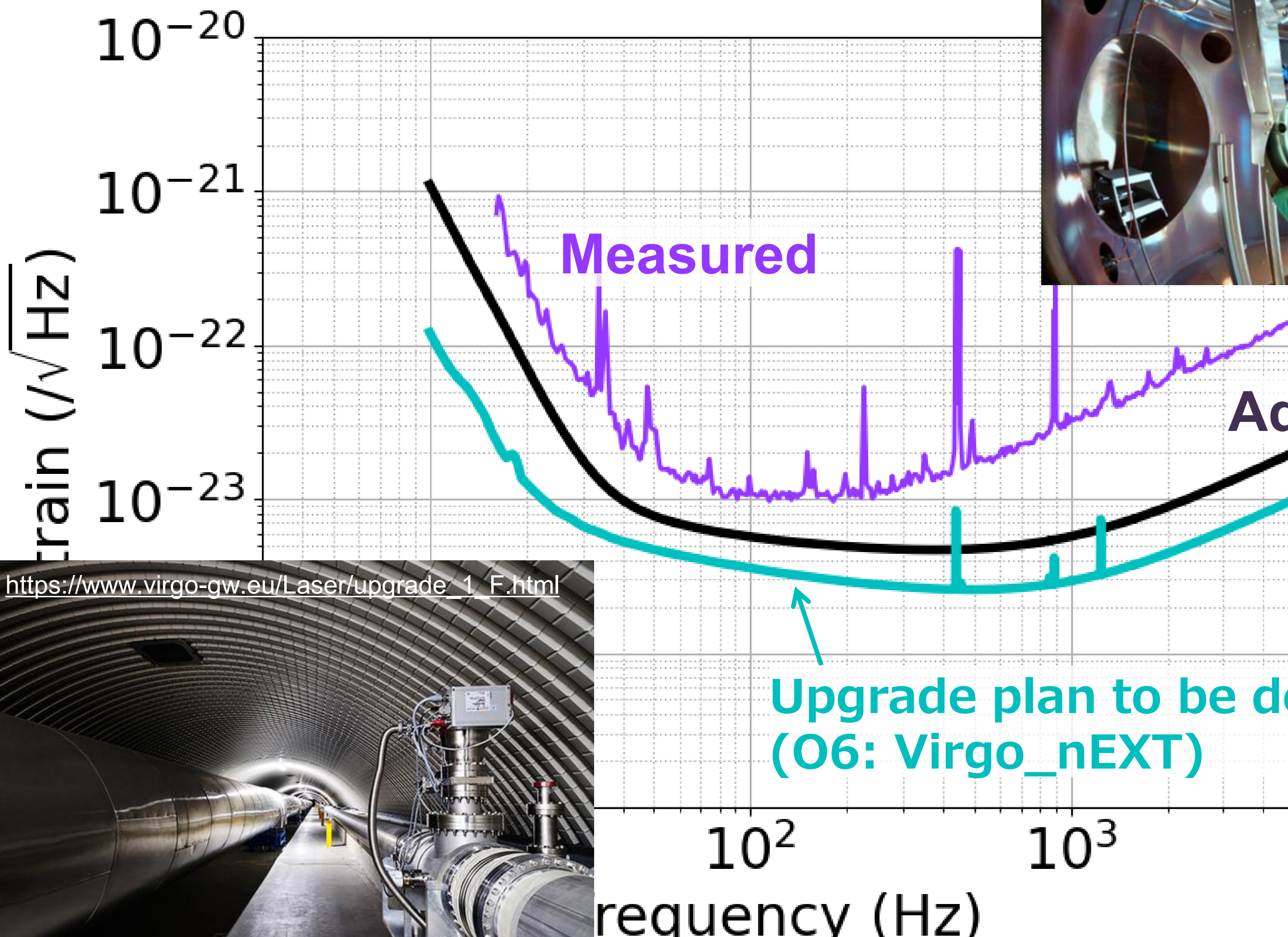
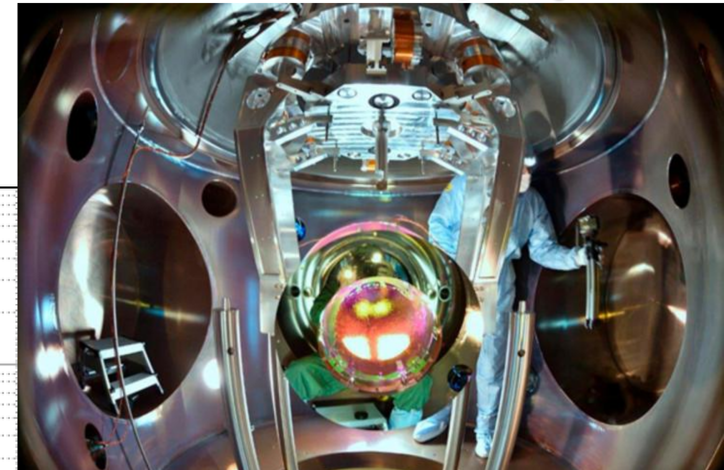


Virgo (Italy, 3 km, Room Temp.)

- Operating at ~50 Mpc

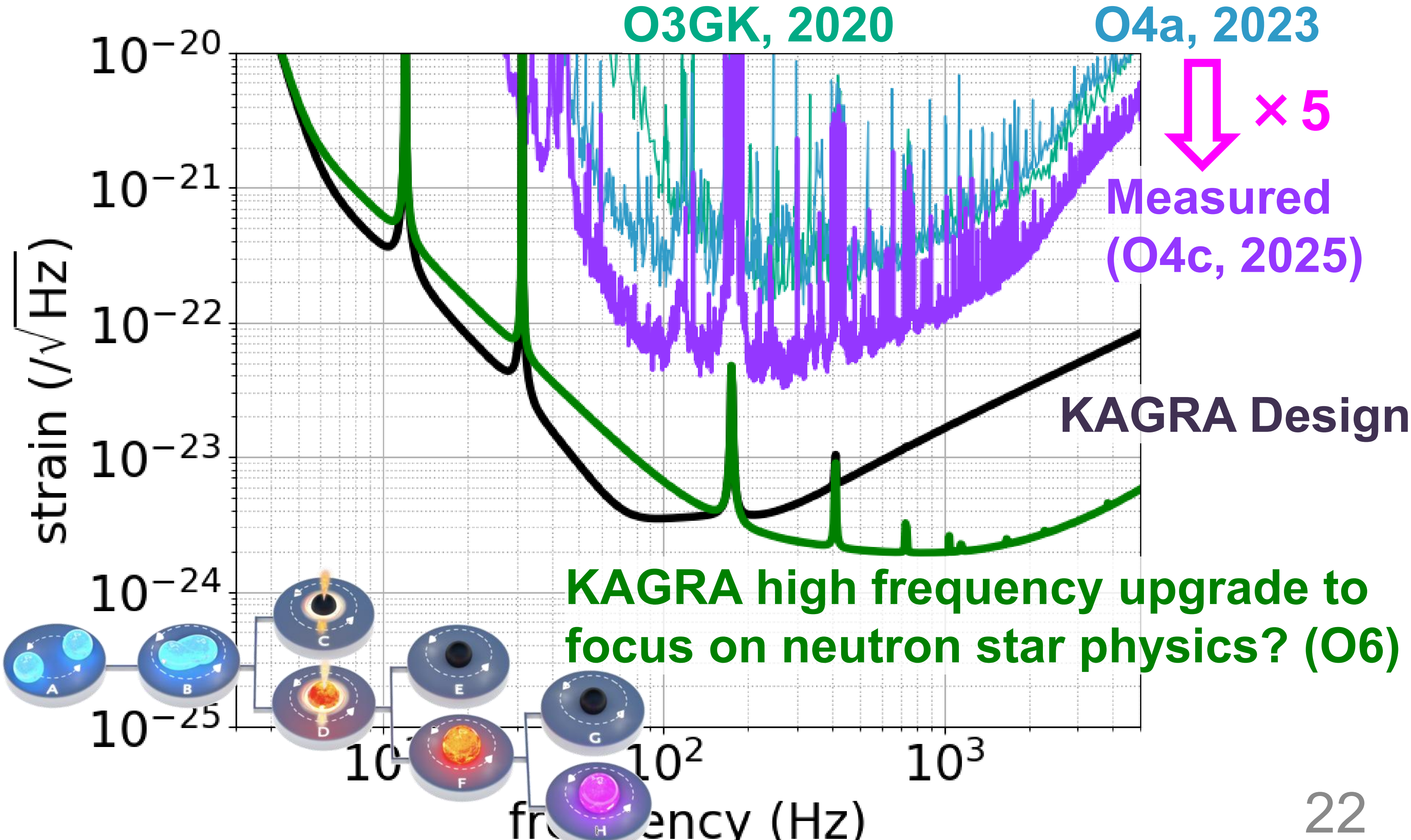




https://www.virgo-gw.eu/Laser/upgrade_1_F.html

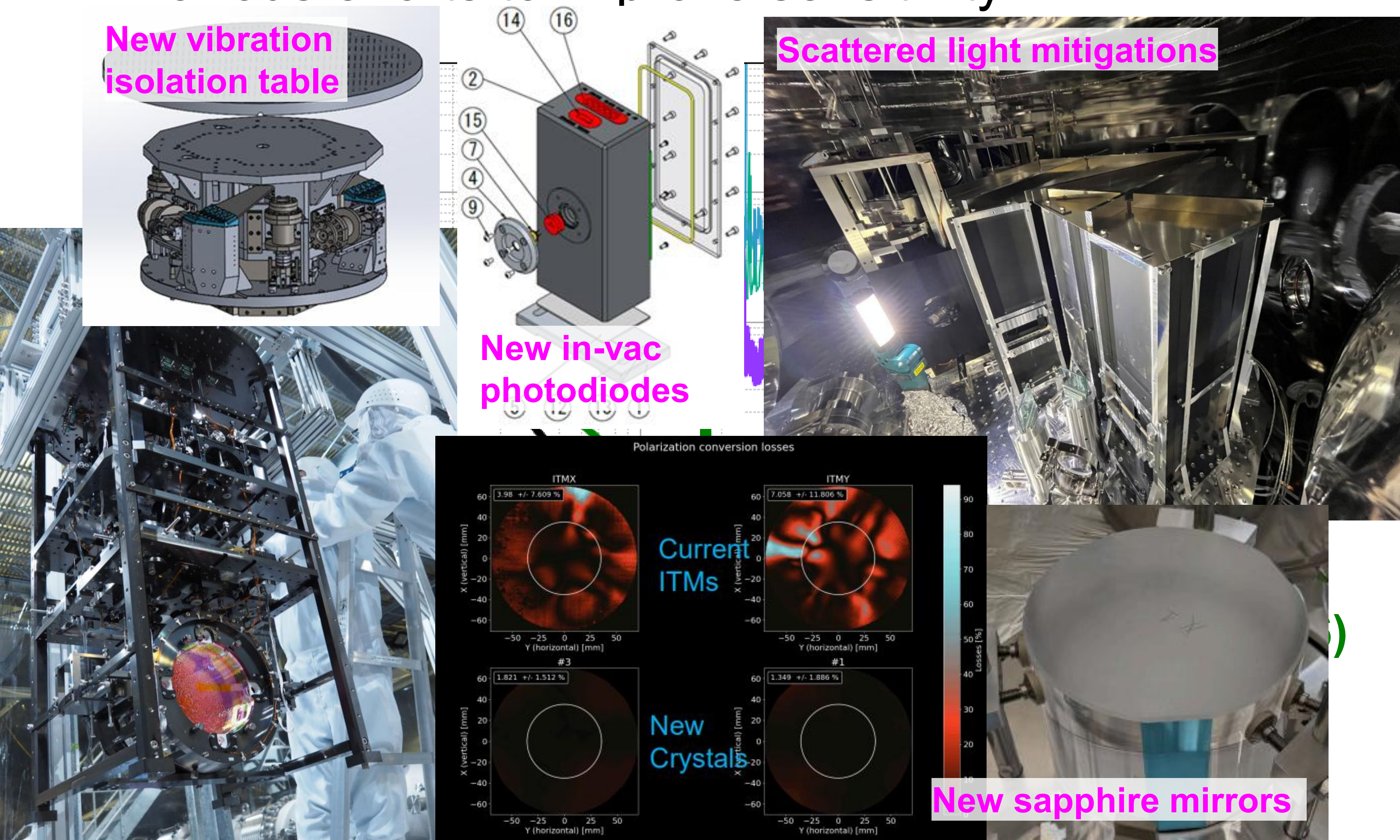
KAGRA (Japan, 3 km, 22 K)

- Operating at ~7 Mpc at ~50 K (IX ~90 K)



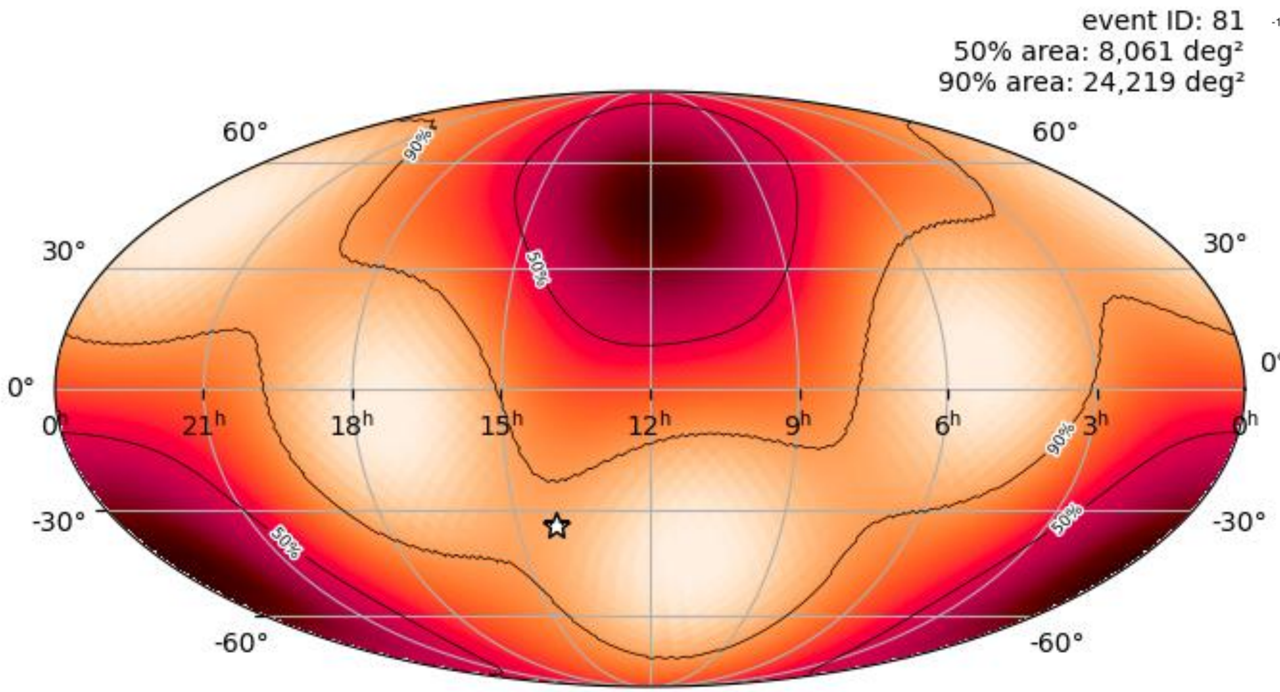
KAGRA (Japan, 3 km, 22 K)

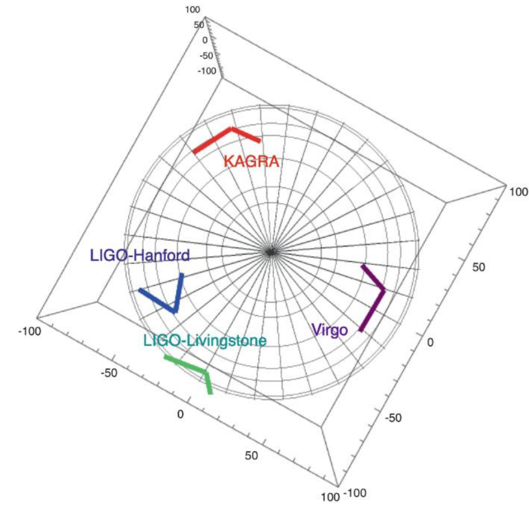
- Various efforts to improve sensitivity



Sky Localization Simulation

- O4 H only

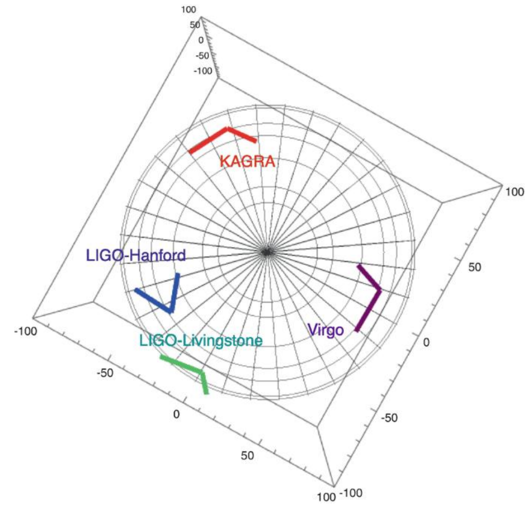


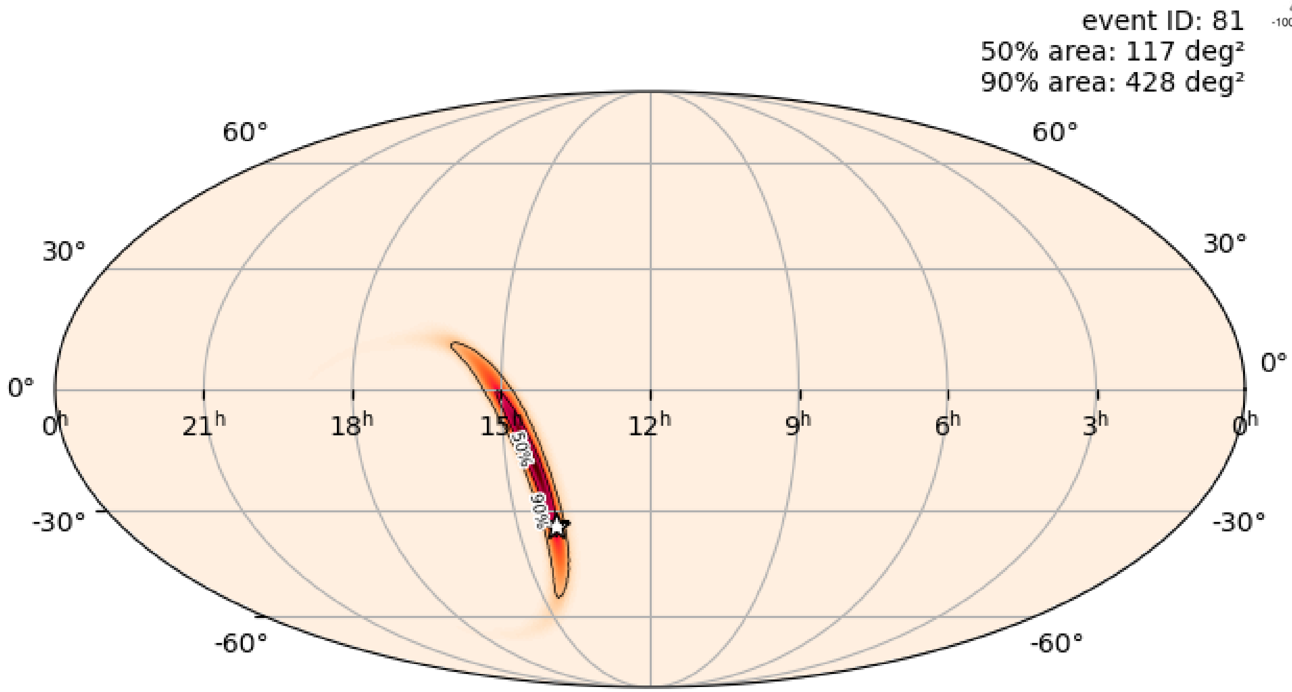


For 1.4-1.4 BNS at 80 Mpc, calculation by Peony Lai and Alvin Li

Sky Localization Simulation

- O4 H + L

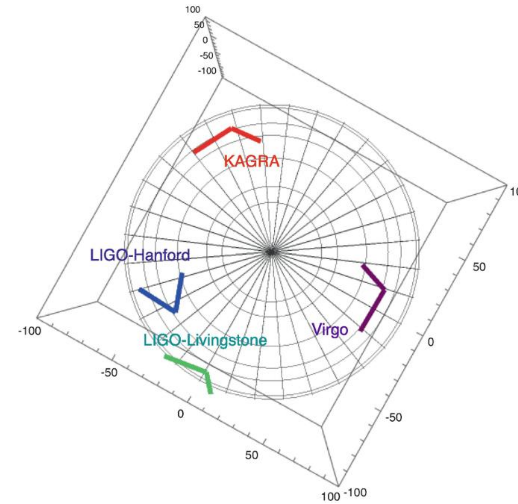


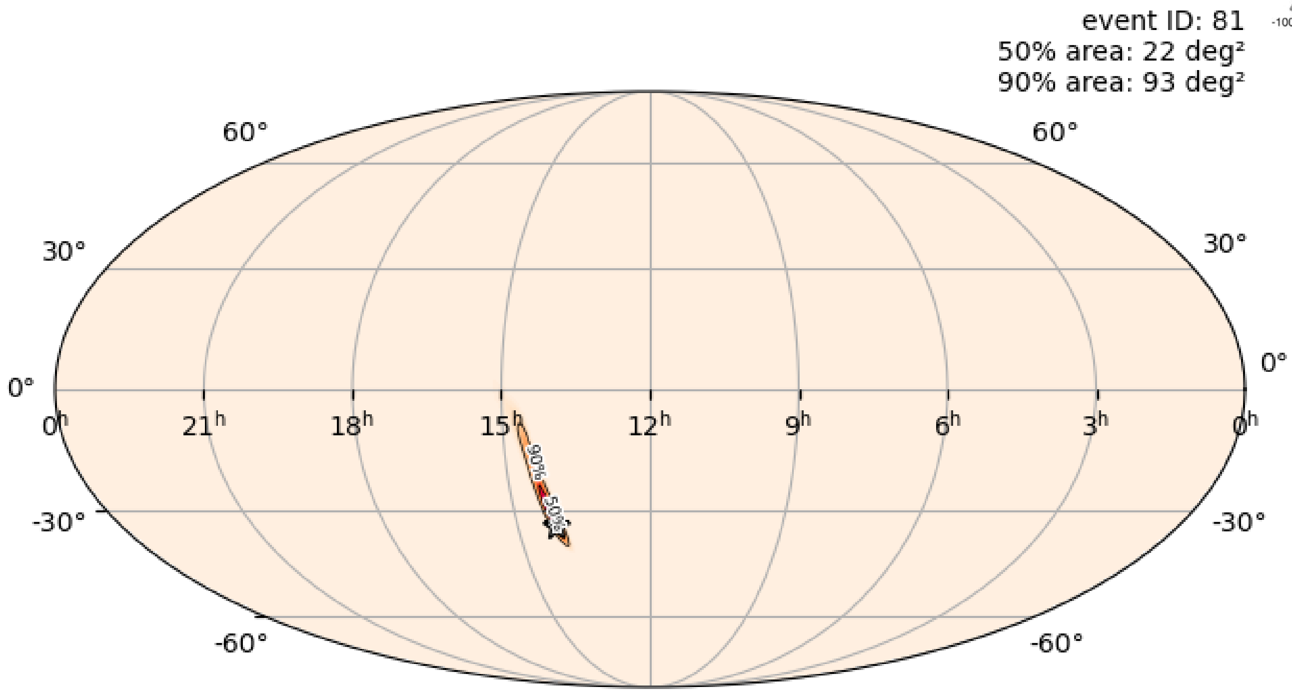


For 1.4-1.4 BNS at 80 Mpc, calculation by Peony Lai and Alvin Li

Sky Localization Simulation

- O4 H + L + V

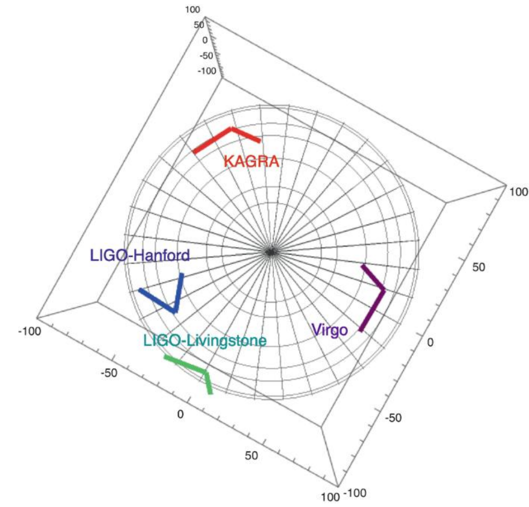


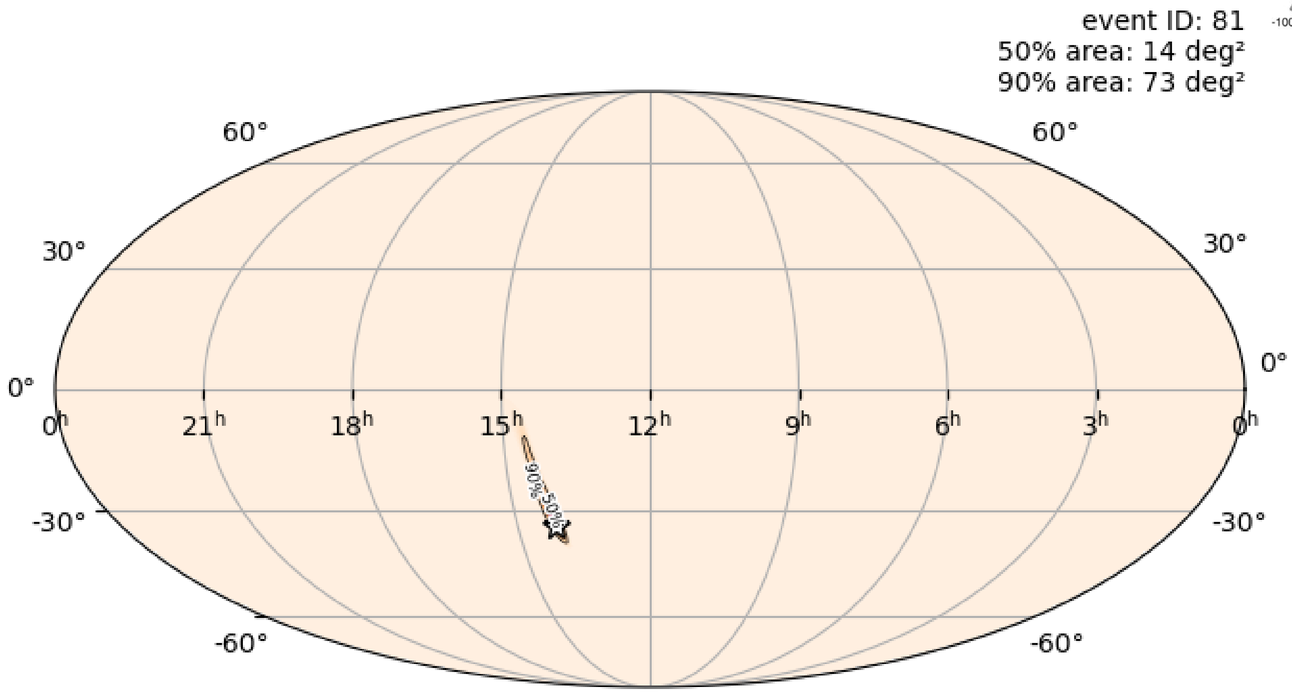


For 1.4-1.4 BNS at 80 Mpc, calculation by Peony Lai and Alvin Li

Sky Localization Simulation

- O4 H + L + V + K(10 Mpc)

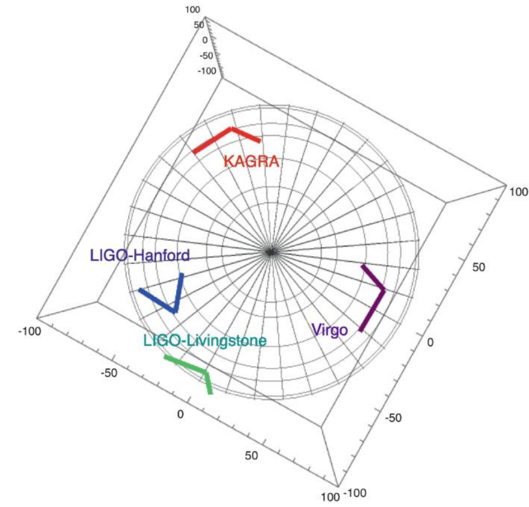


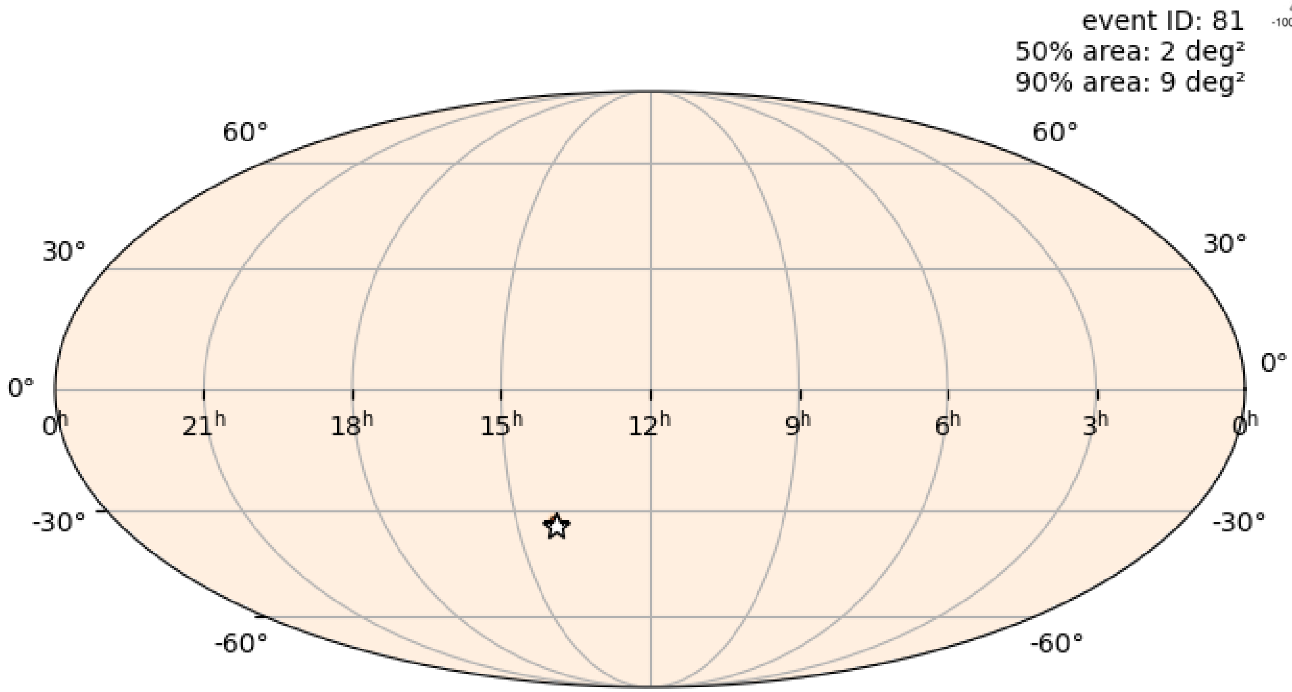


For 1.4-1.4 BNS at 80 Mpc, calculation by Peony Lai and Alvin Li

Sky Localization Simulation

- O4 H + L + V + K(25 Mpc)

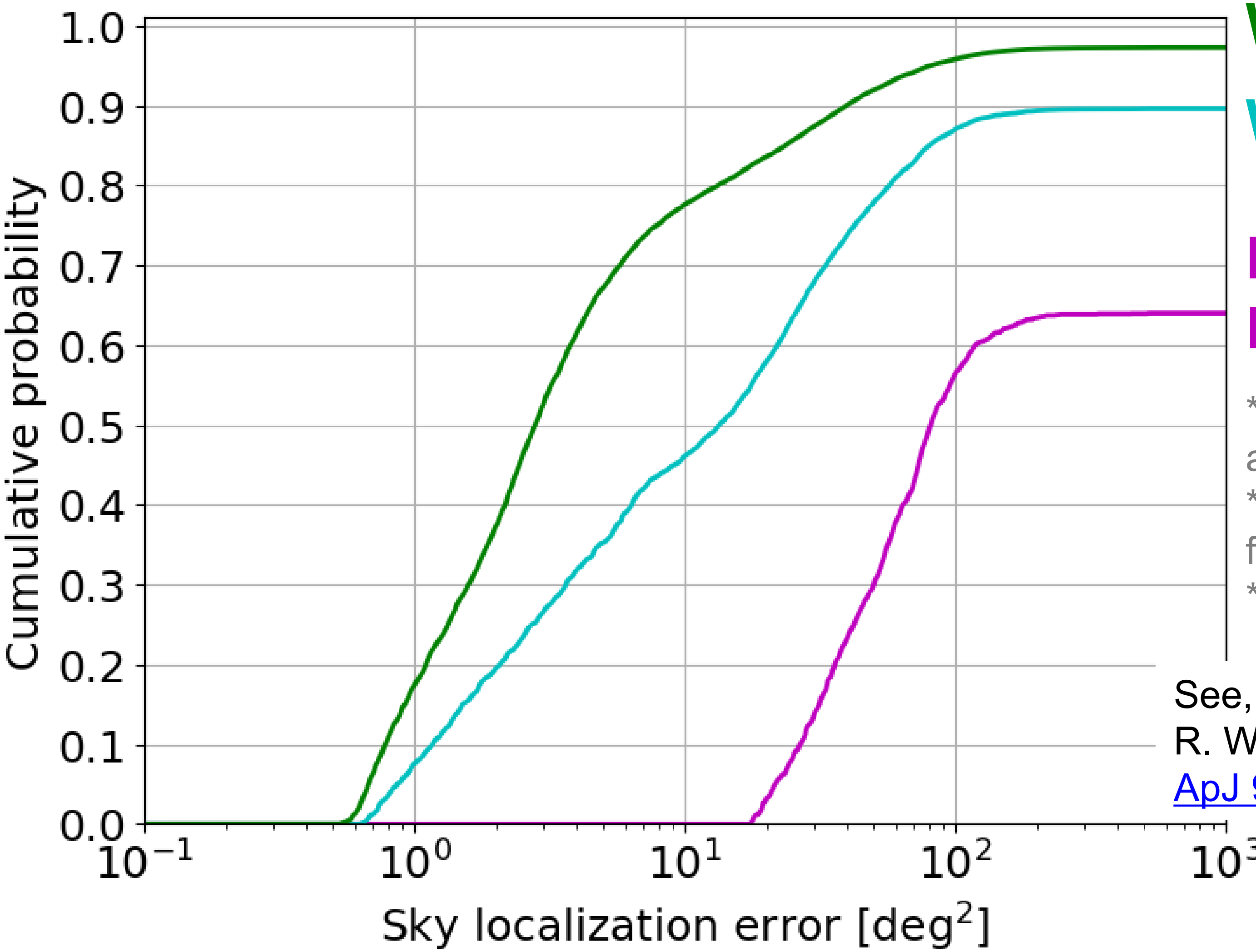




For 1.4-1.4 BNS at 80 Mpc, calculation by Peony Lai and Alvin Li

Sky Localization in O5 (2028~)

- 1~5 BNS detections per year localized < 10 deg²

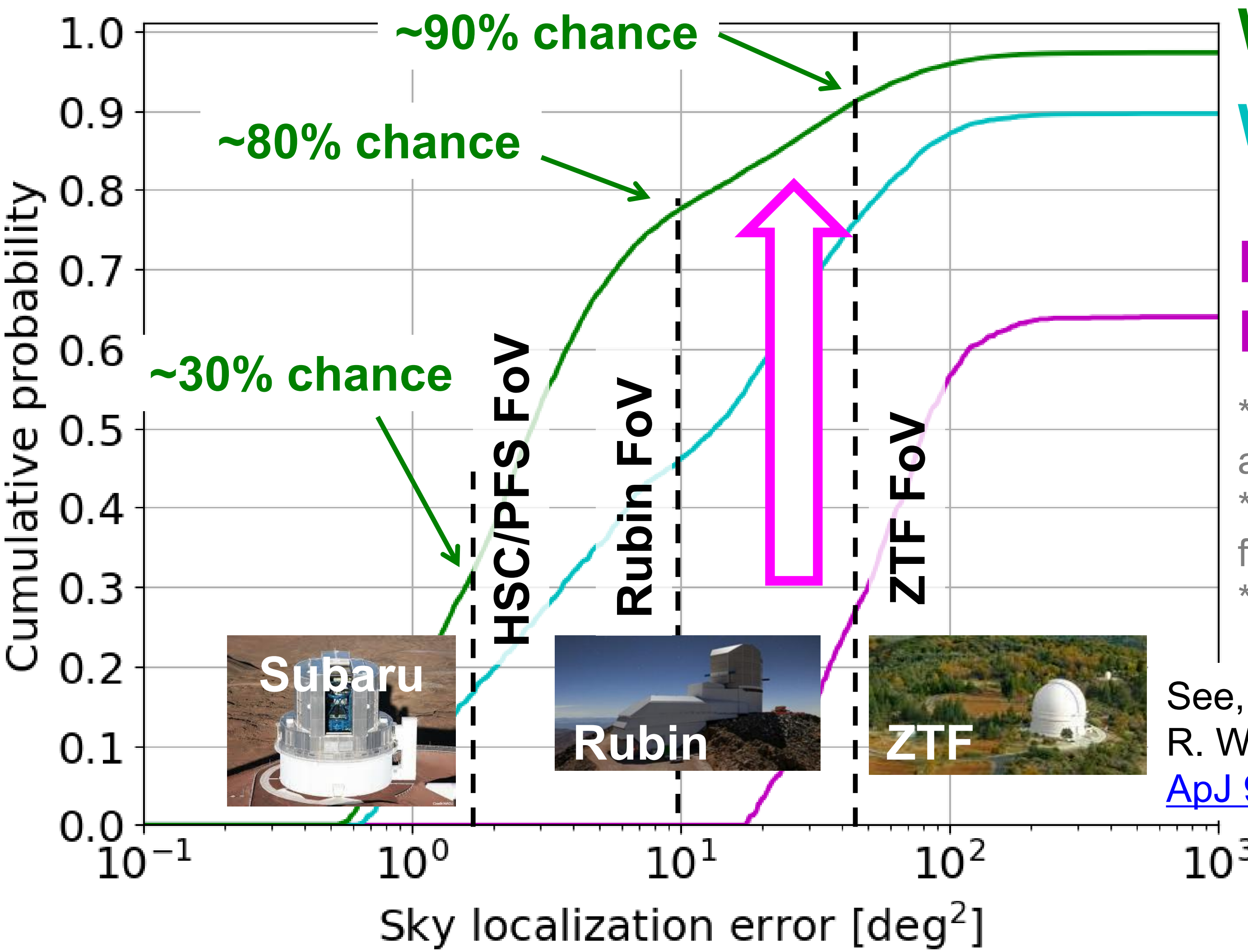


* Fisher analysis for BNS at 100 Mpc
* Single detector duty factor of 80% assumed
* BNS merger rate 90-450 /Gpc³/yr

See, also:
R. Weizmann Kiendrebeogo+, [ApJ 958, 158 (2023)]

Sky Localization in O5 (2028~)

- 1~5 BNS detections per year localized < 10 deg^2



With KAGRA

With Virgo

Hanford and Livingston

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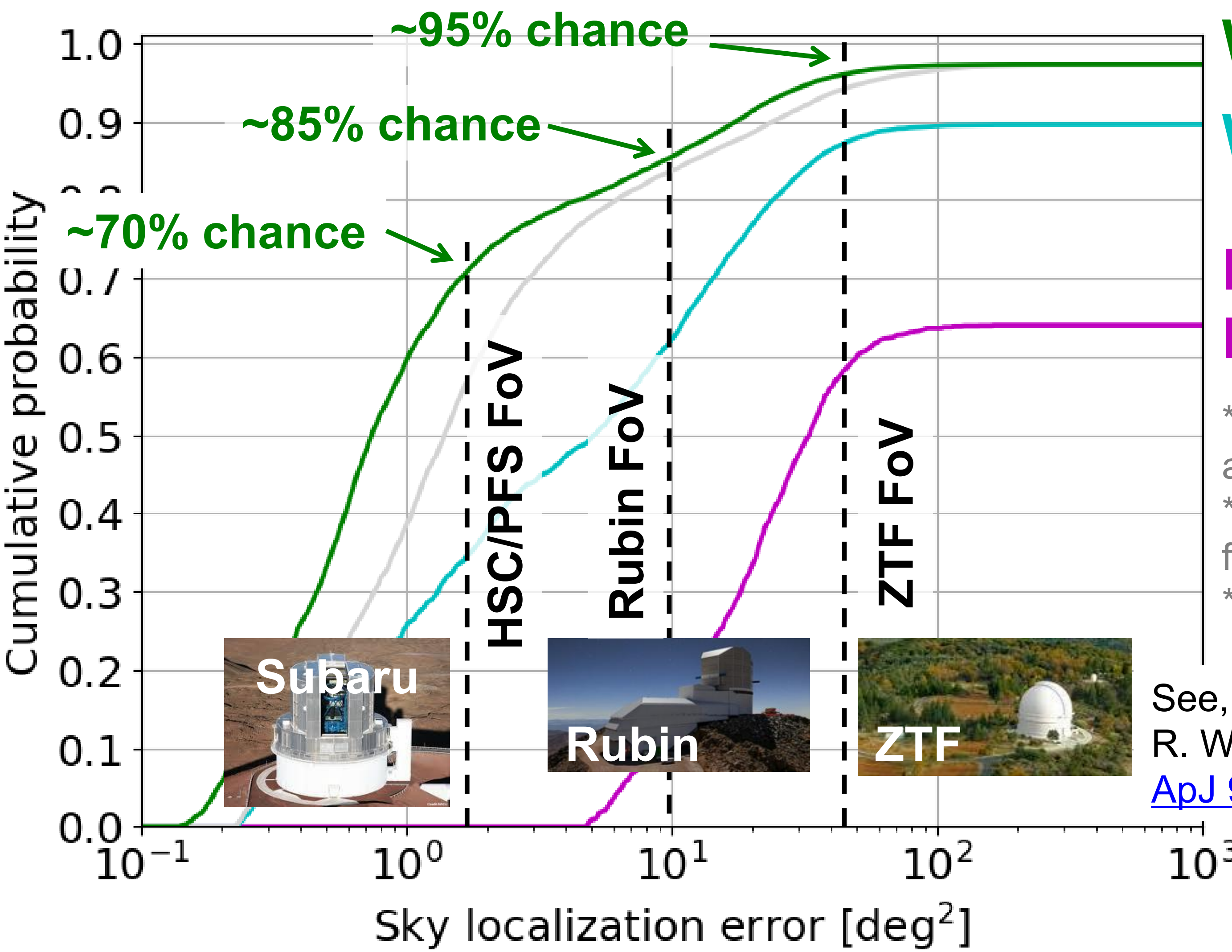
* Single detector duty factor of 80% assumed

* BNS merger rate 90-450 /Gpc^3/yr

See, also:
R. Weizmann Kiendrebeogo+, [ApJ 958, 158 (2023)]

Sky Localization in O6 (2030+)

- 5~23 BNS detections per year localized < 10 deg^2



With KAGRA HF

With Virgo

Hanford and Livingston

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* Single detector duty factor of 80% assumed
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See, also:
R. Weizmann Kiendrebeogo+, [ApJ 958, 158 (2023)]

LIGO-India (4 km, Room Temp.)

- Aundha site acquired in May 2023
- Being built as the Advanced LIGO configuration
- Aim to be operational in the early 2030s

LIGO-G2401602

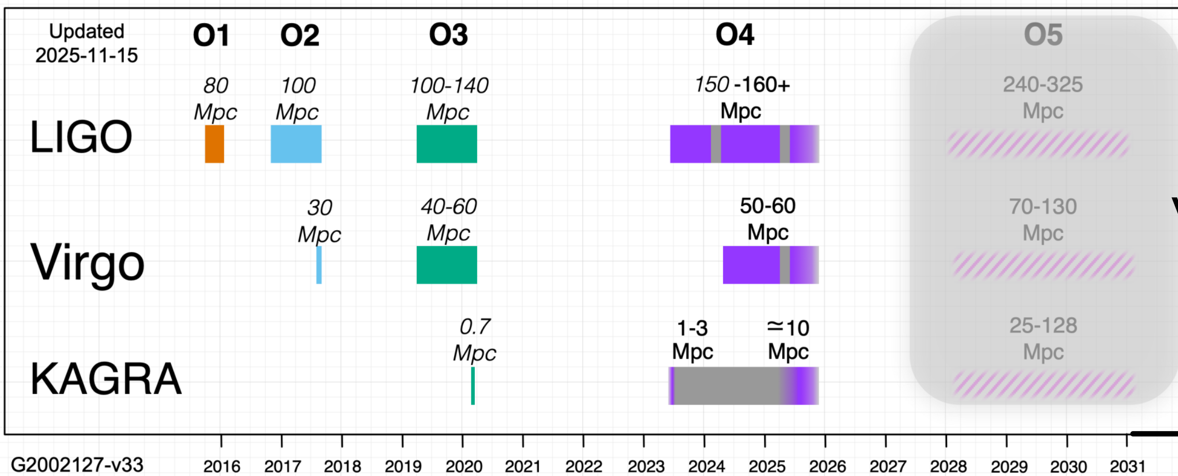
1:1 scale vacuum testing

LIGO-G2500785

10 m prototype at RRCAT being built for testing and training

Next Generation Detectors

- Next generation detectors coming in late 2030s, with space-based detectors (multi-band!)



O6

LIGO A#

Virgo_nEXT

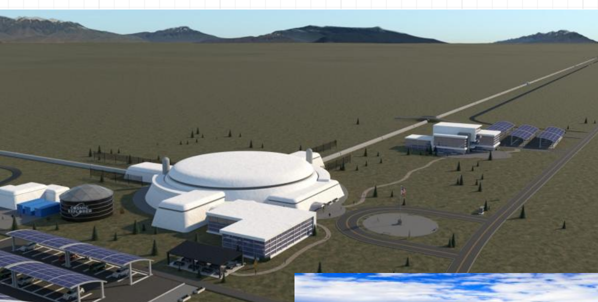
KAGRA HF ?

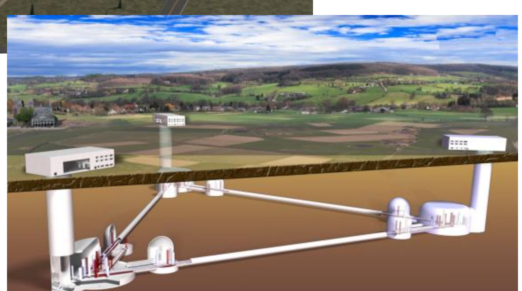
2030s **2040s**

LIGO India

Cosmic Explorer

Einstein Telescope

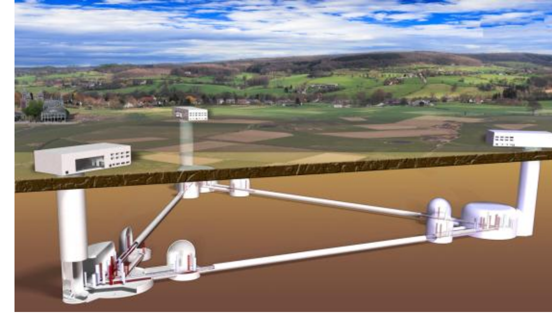




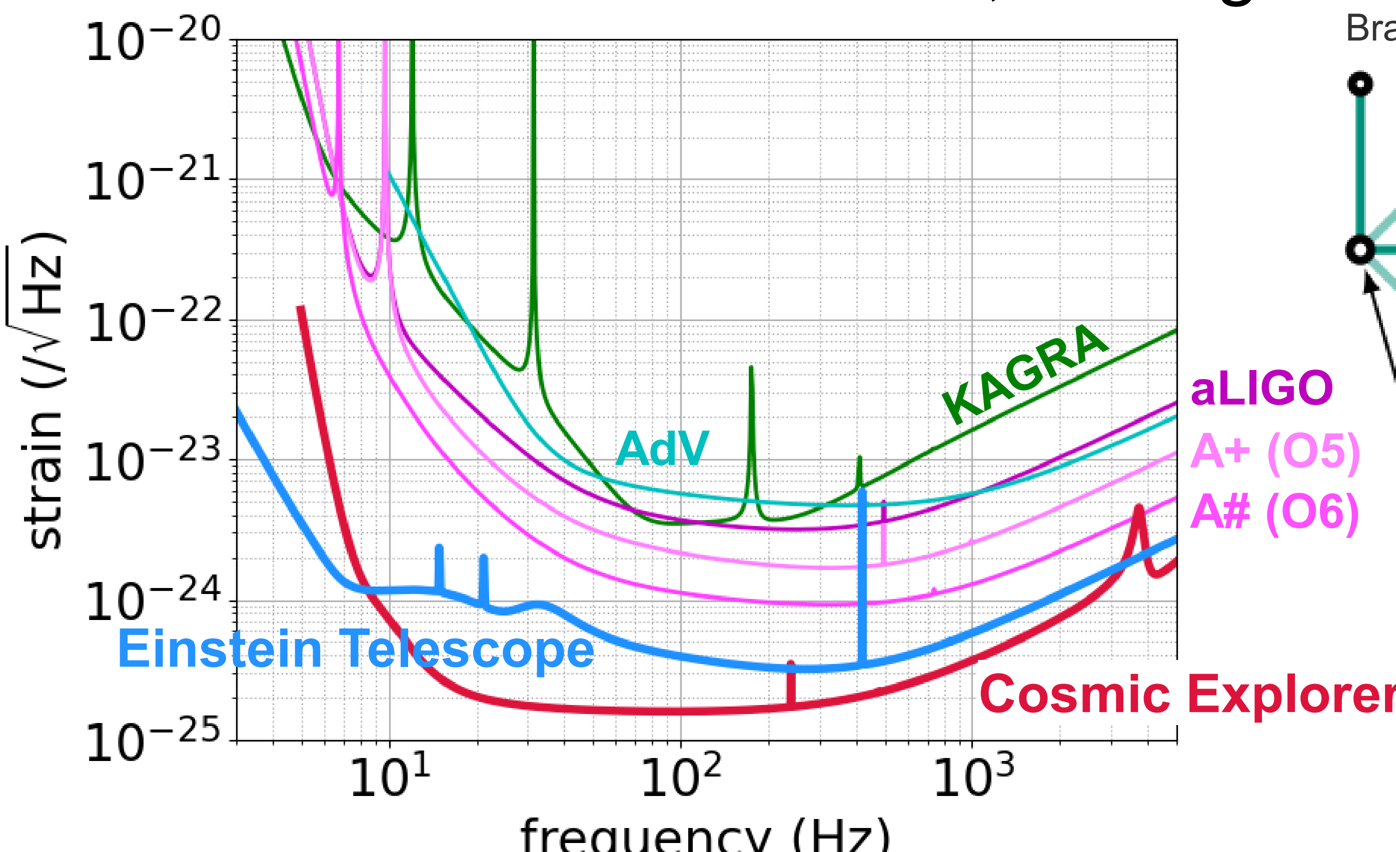
B-DECIGO

LISA

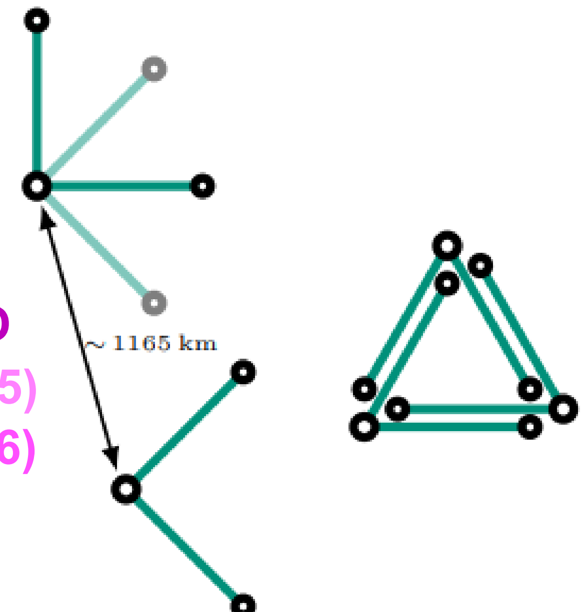
Einstein Telescope

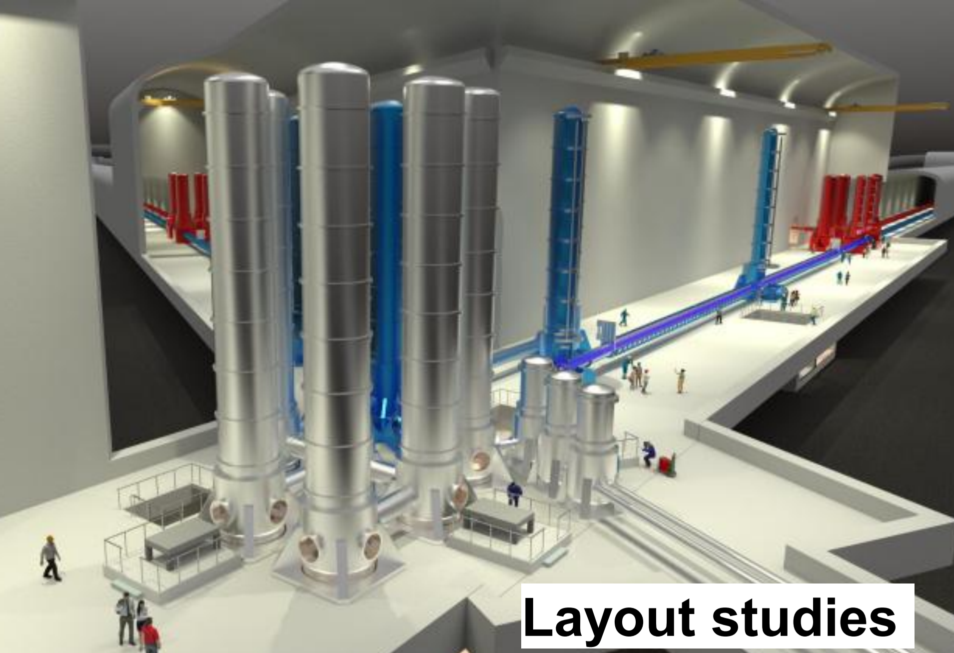


- Xylophone configuration
  - 10 K silicon interferometer for low frequency
  - Room temp. fused silica interferometer for high frequency
- 10 km △ or two 15 km L, underground



Branchesi+, JCAP 07, 068 (2023)

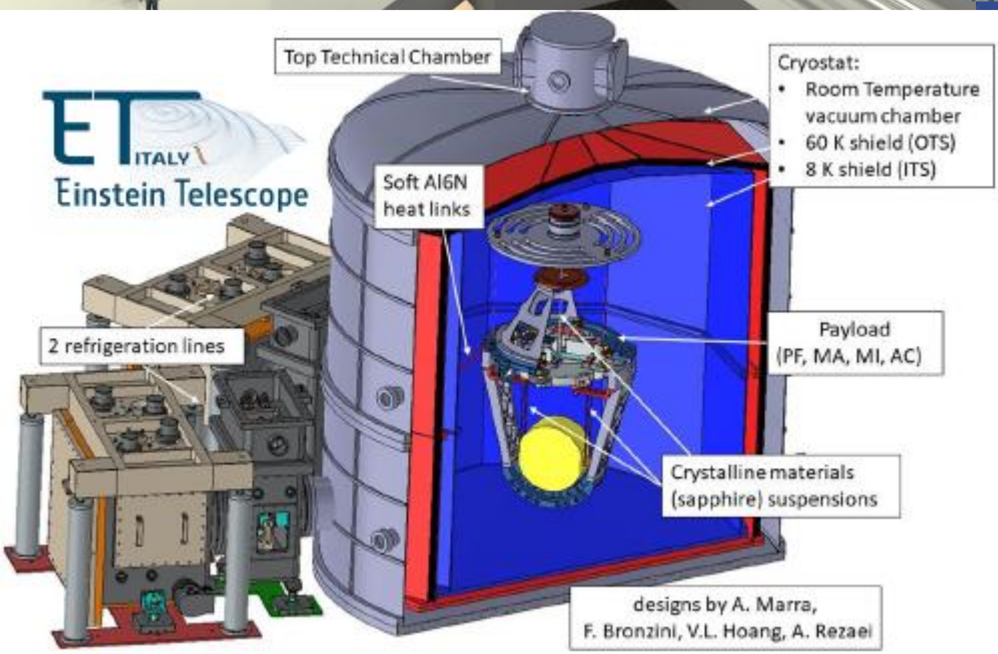




Layout studies

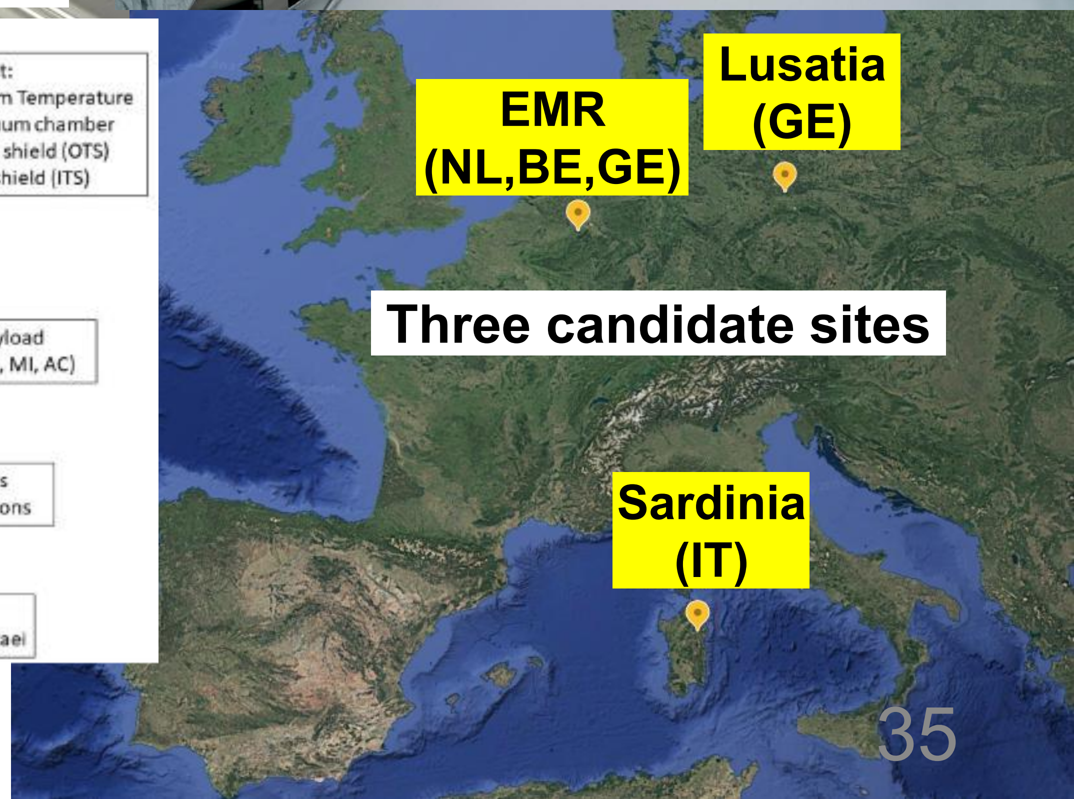
ETpathfinder in Maastricht

https://www.etpathfinder.eu/gallery/



Cryogenic payload in Rome

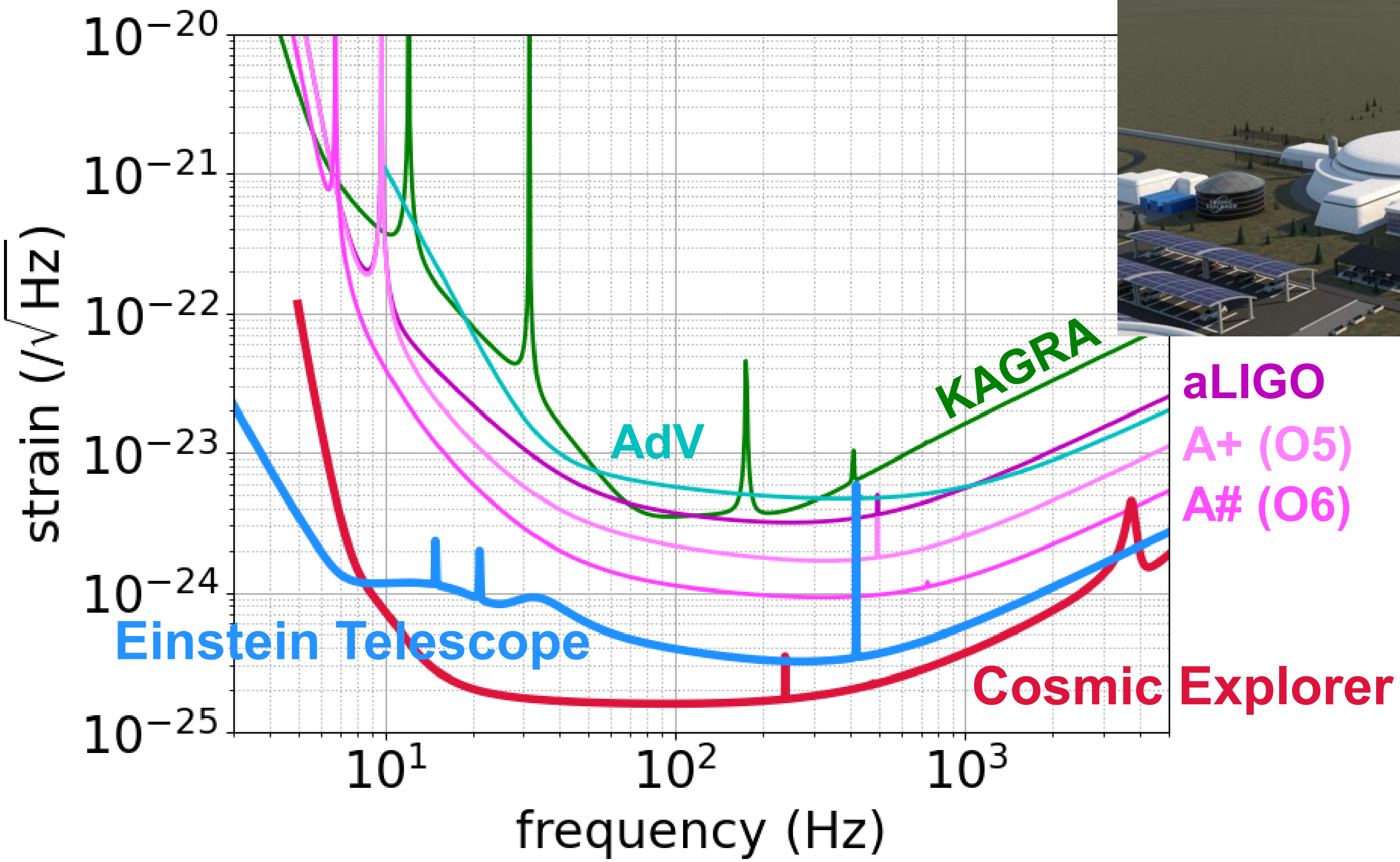
From L. Naticchioni (GWADW2025)

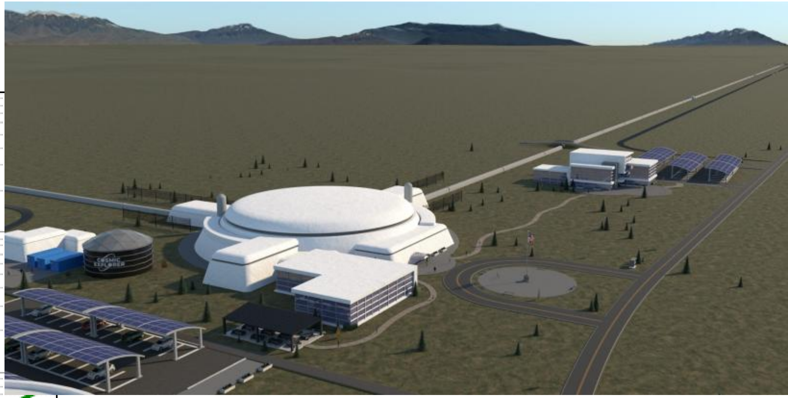


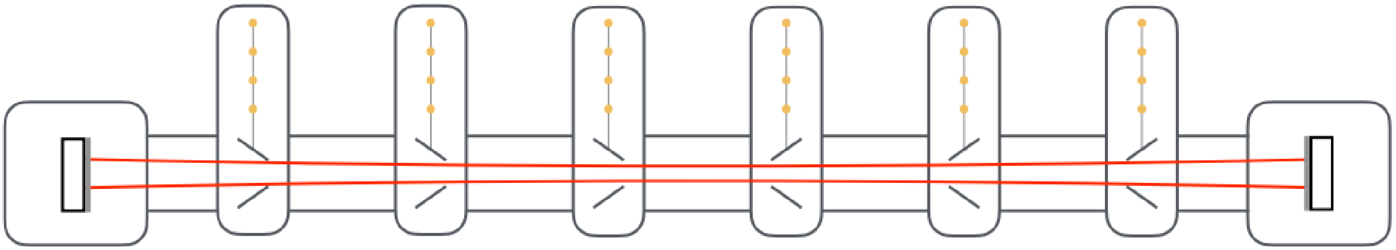
Three candidate sites

Cosmic Explorer

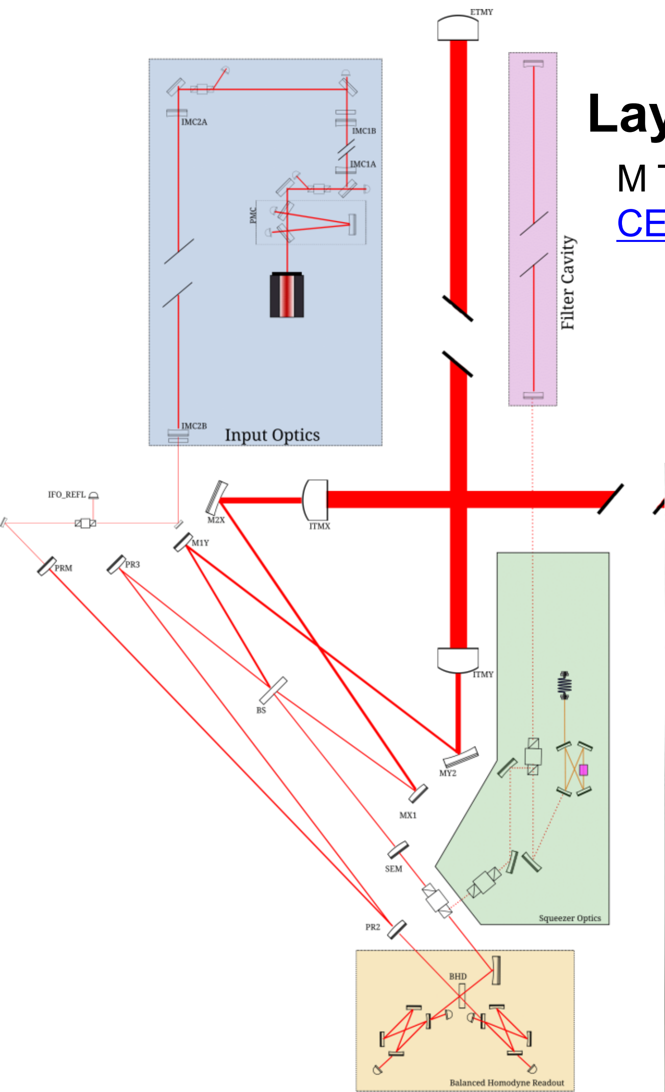
- 40 km and 20 km L-shaped
  - 40 km only if ET in Europe
- Room temp. fused silica (technical overlap with A#)







Stray light mitigation

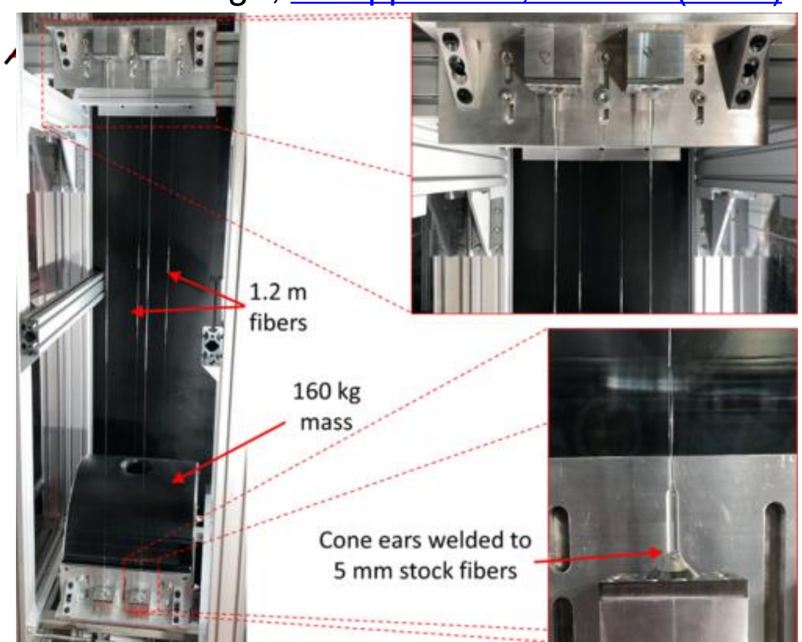


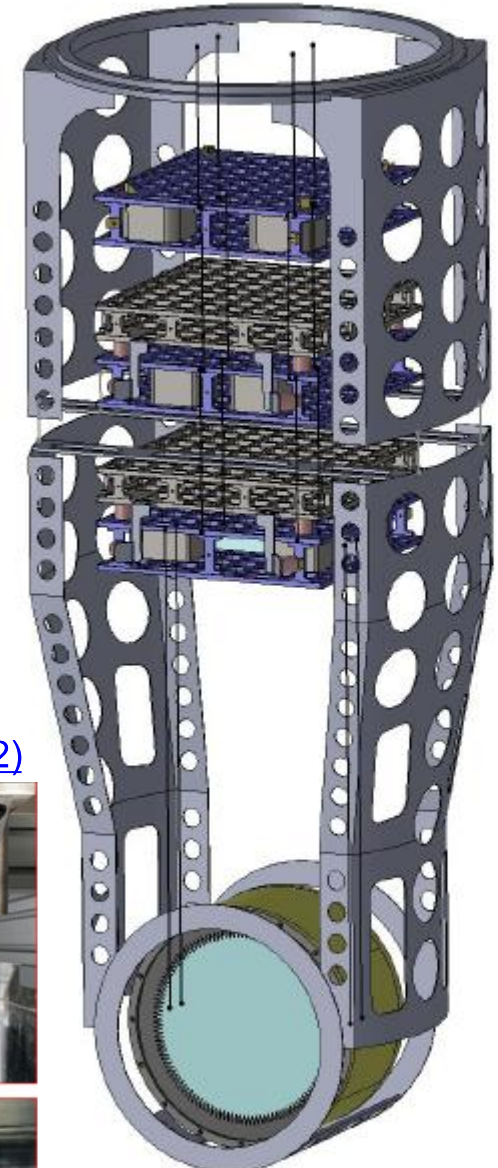
Layout studies

M Todd,
[CE-G2500002]

Heavy suspension tests

Cumming+, [PRApplied 17, 024044 (2022)]

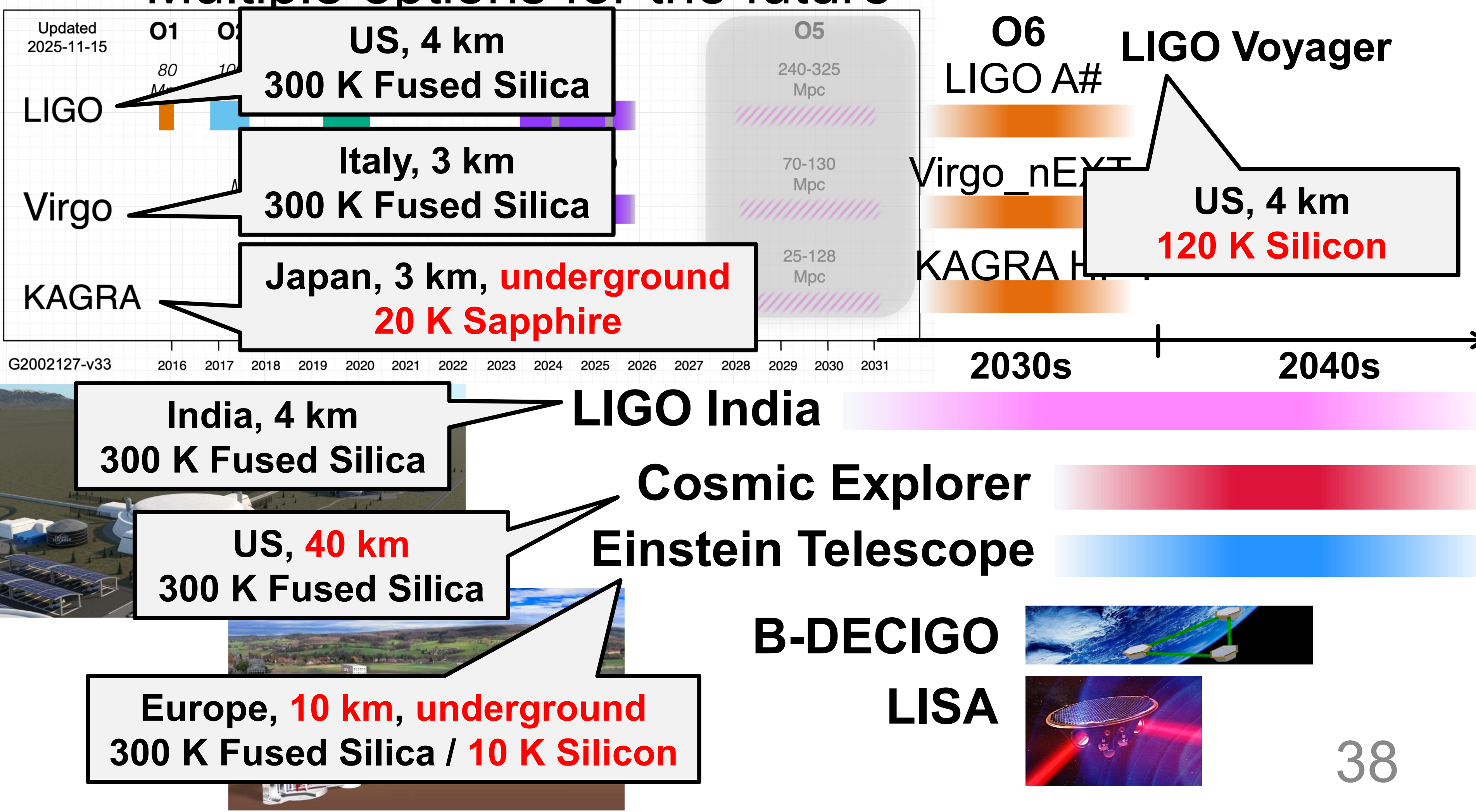




From M. Evans
(GWADW2025)

Different Strategies

- Different strategies for different detectors
- Multiple options for the future



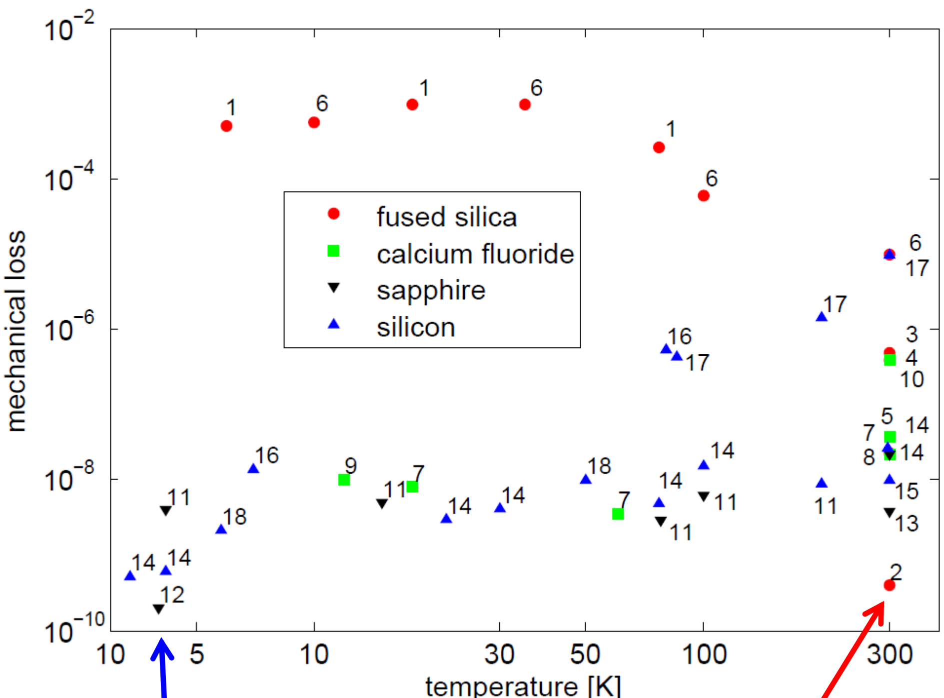
Why Different Mirror Materials?

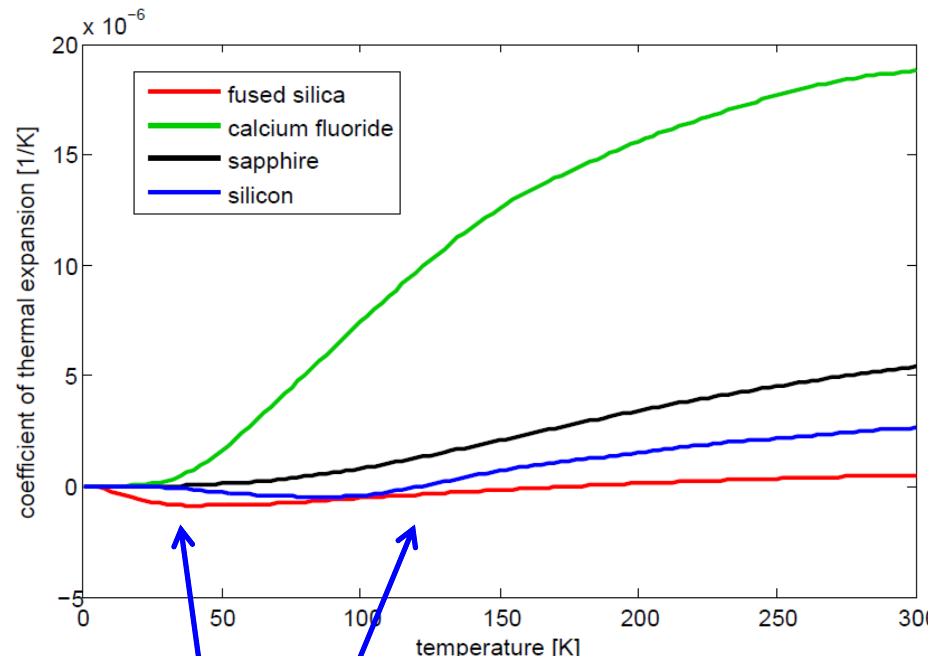
- Thermal noise $\propto \sqrt{T\phi}$

Temperature

Mechanical loss angle (temperature dependent)

ET-027-09





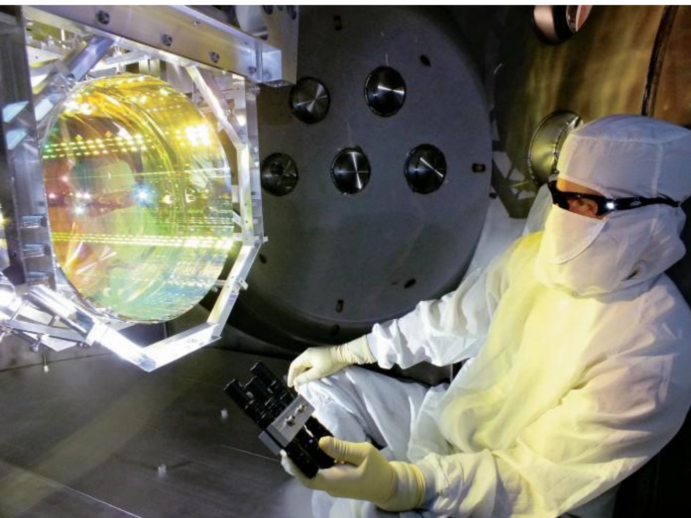
Sapphire / silicon is good at cryogenic temp.

Fused silica is good at room temp.

Silicon has zero thermal expansion at 18 K and 123 K

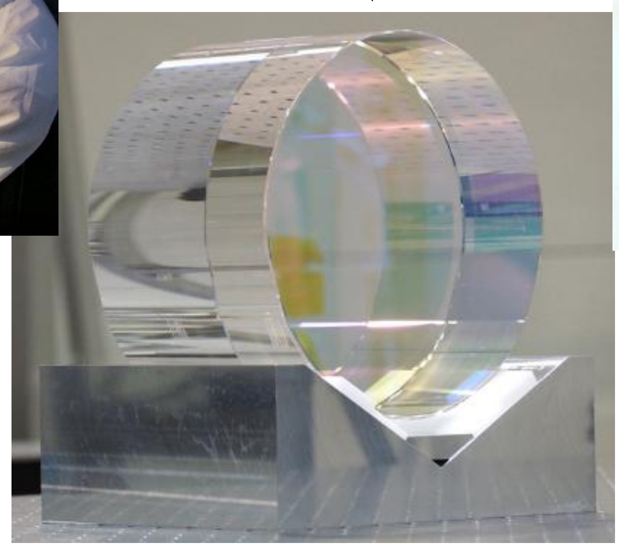
Different Wavelengths

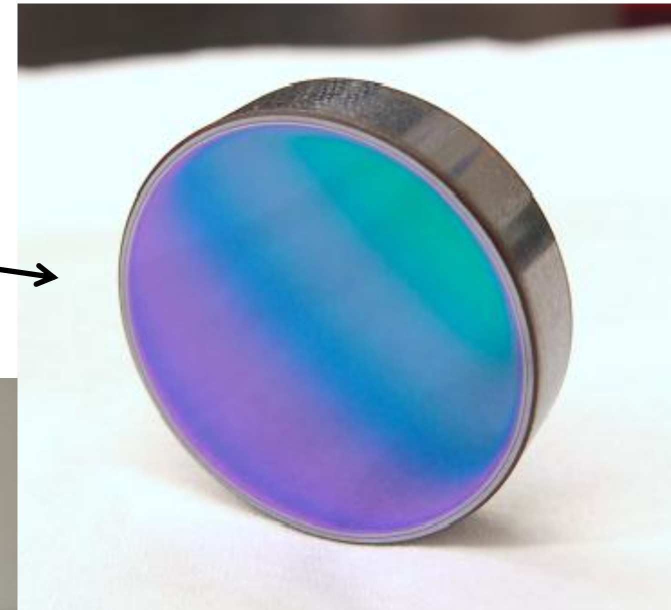
- Different mirror materials require different laser wavelengths



Amorphus

Crystalline





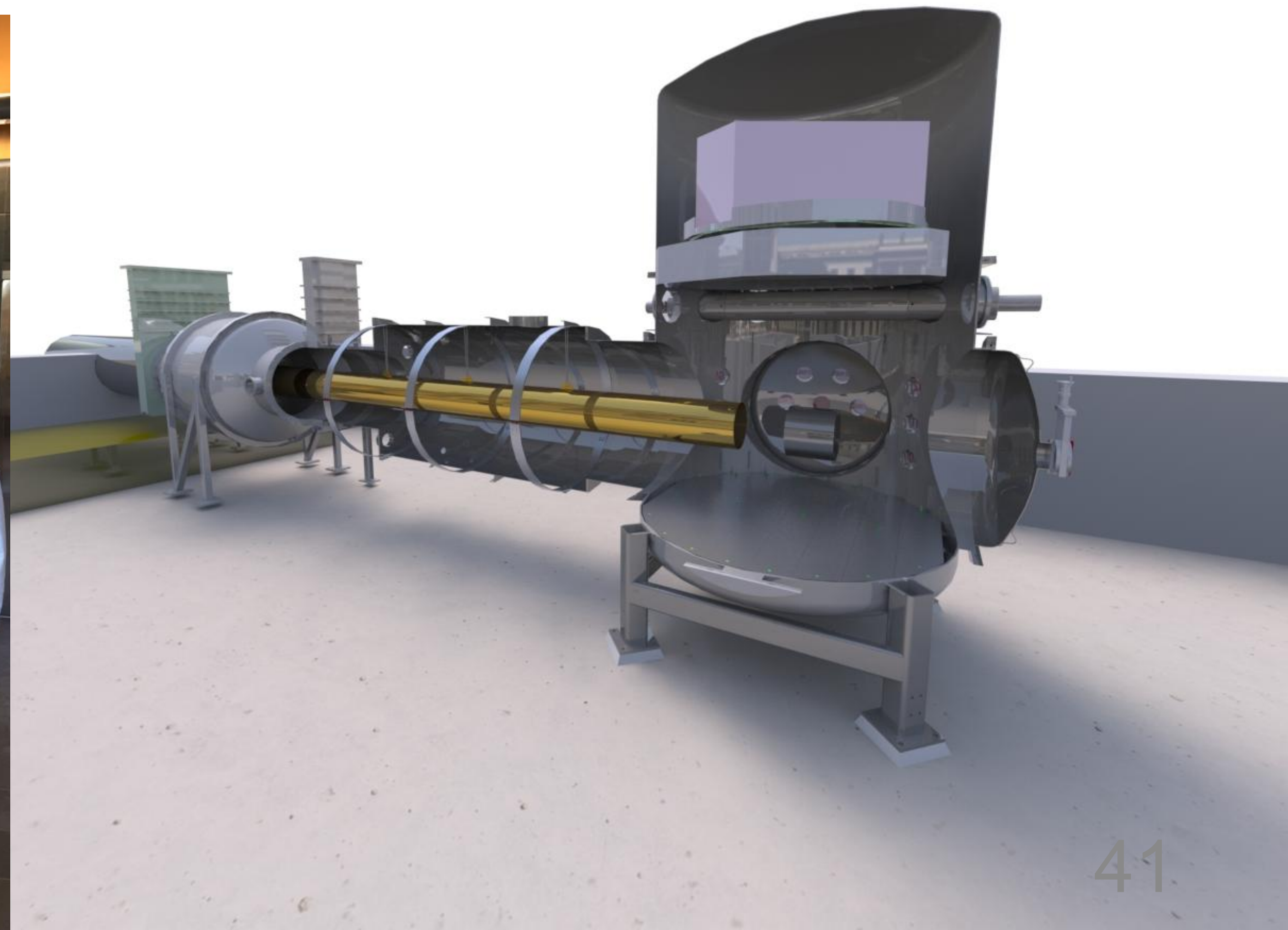
300 K Fused Silica
LIGO, Virgo,
Cosmic Explorer
@ 1064 nm

20 K Sapphire
KAGRA @ 1064 nm

120 K Silicon
Voyager @ 2050 nm
10 K Silicon
Einstein Telescope
@ 1550 nm

LIGO Voyager

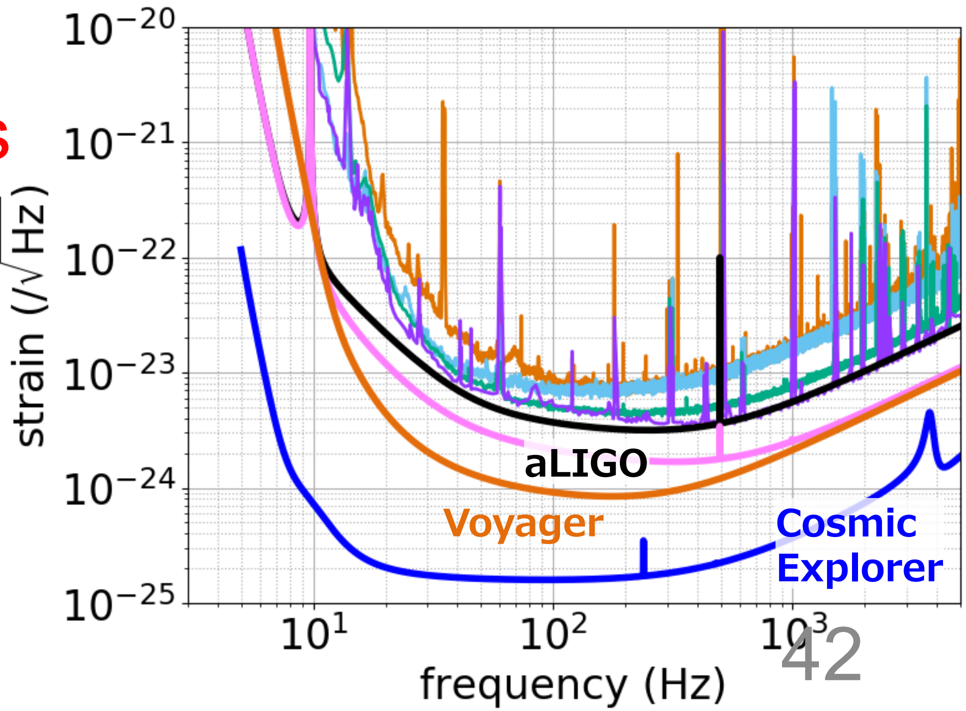
- Cryogenic upgrade to existing 4 km LIGO
- Intermediate step towards 10-40 km detectors



Exciting R&Ds for Next Generations

- Stable, high-power laser at 1.5-2 um
- High quantum efficiency photodiodes for 2 um
- Large silicon or sapphire mirrors (φ 45 cm, 200 kg)
  - Low birefringence
  - Low absorption
- Low thermal noise high-reflective coatings
- Suspensions for large mirrors
- High power handling

… and more



Birefringence and Its Fluctuations

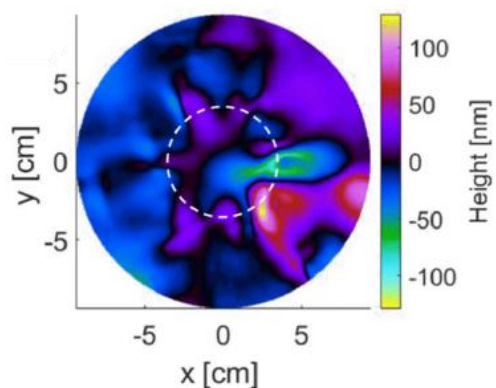
- Birefringence ($\Delta n \sim 10^{-7}$ for silicon) needs to be small for reducing optical losses
- Birefringence fluctuations will also be additional phase noise ($\delta(\Delta n) < 10^{-15}$ /$\sqrt{\mathrm{Hz}}$) YM+, [PRD **109**, 022009 (2024)]
- Excess birefringence noise reported by PTB/JILA

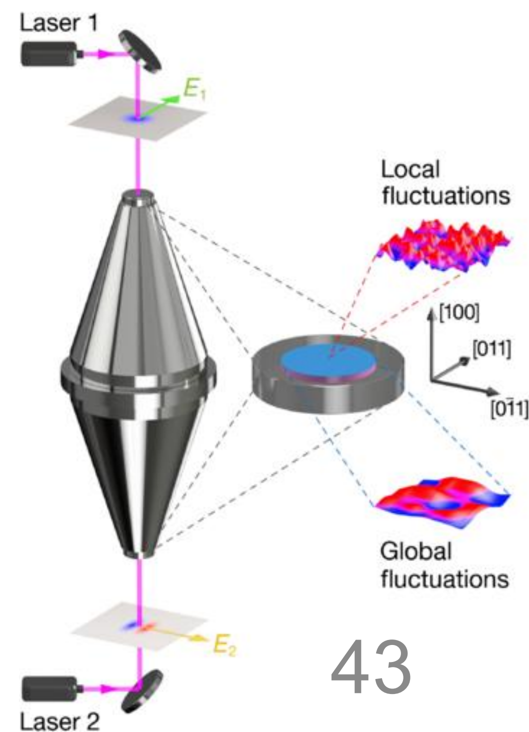
  J. Yu+, [PRX **13**, 041002 (2023)]

- Inhomogeneous birefringence experiences from KAGRA sapphire

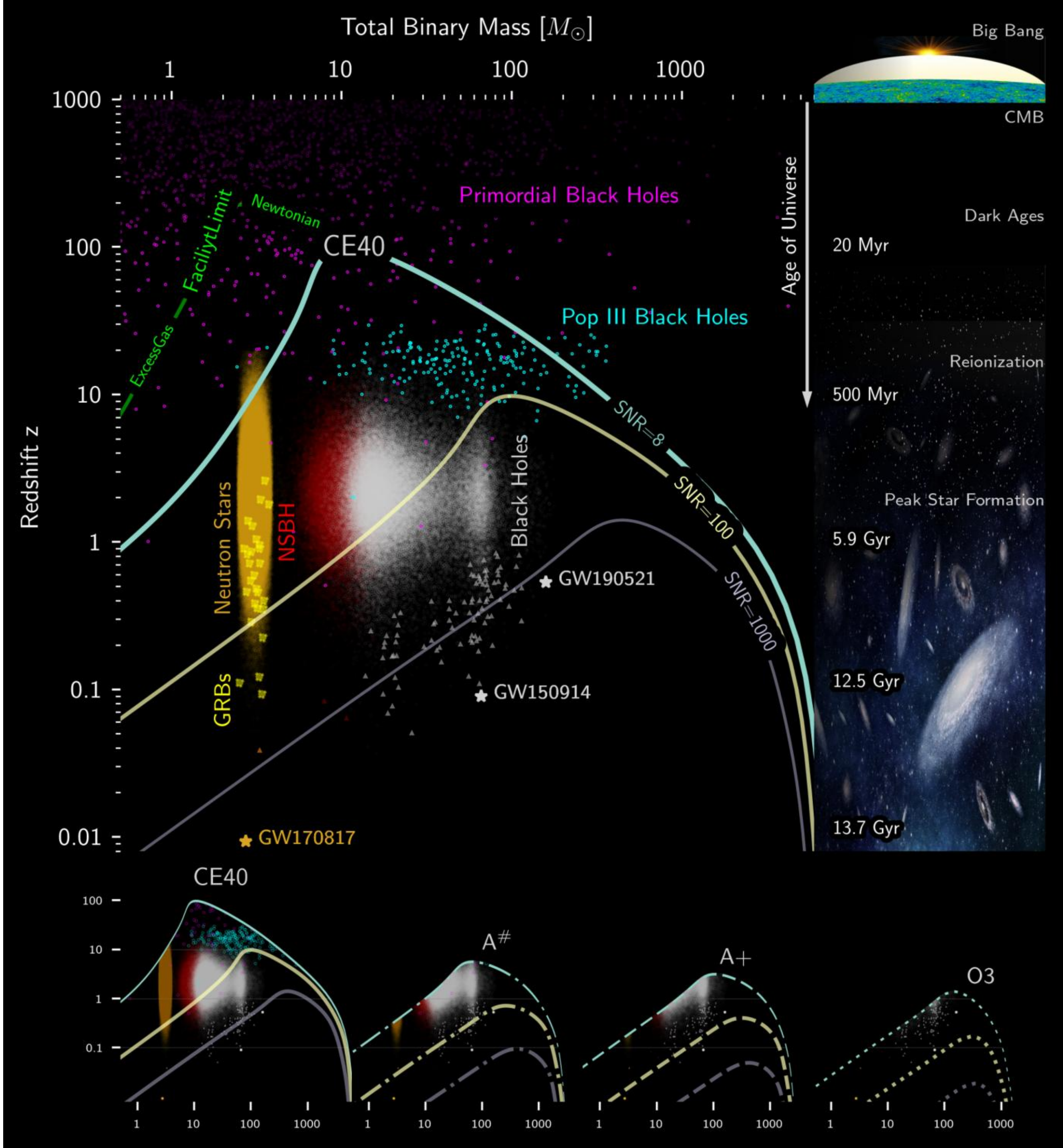
  H. Wang, … , YM, [PRD **110**, 082007 (2024)]

- Active research ongoing to study their effects and mitigation schemes



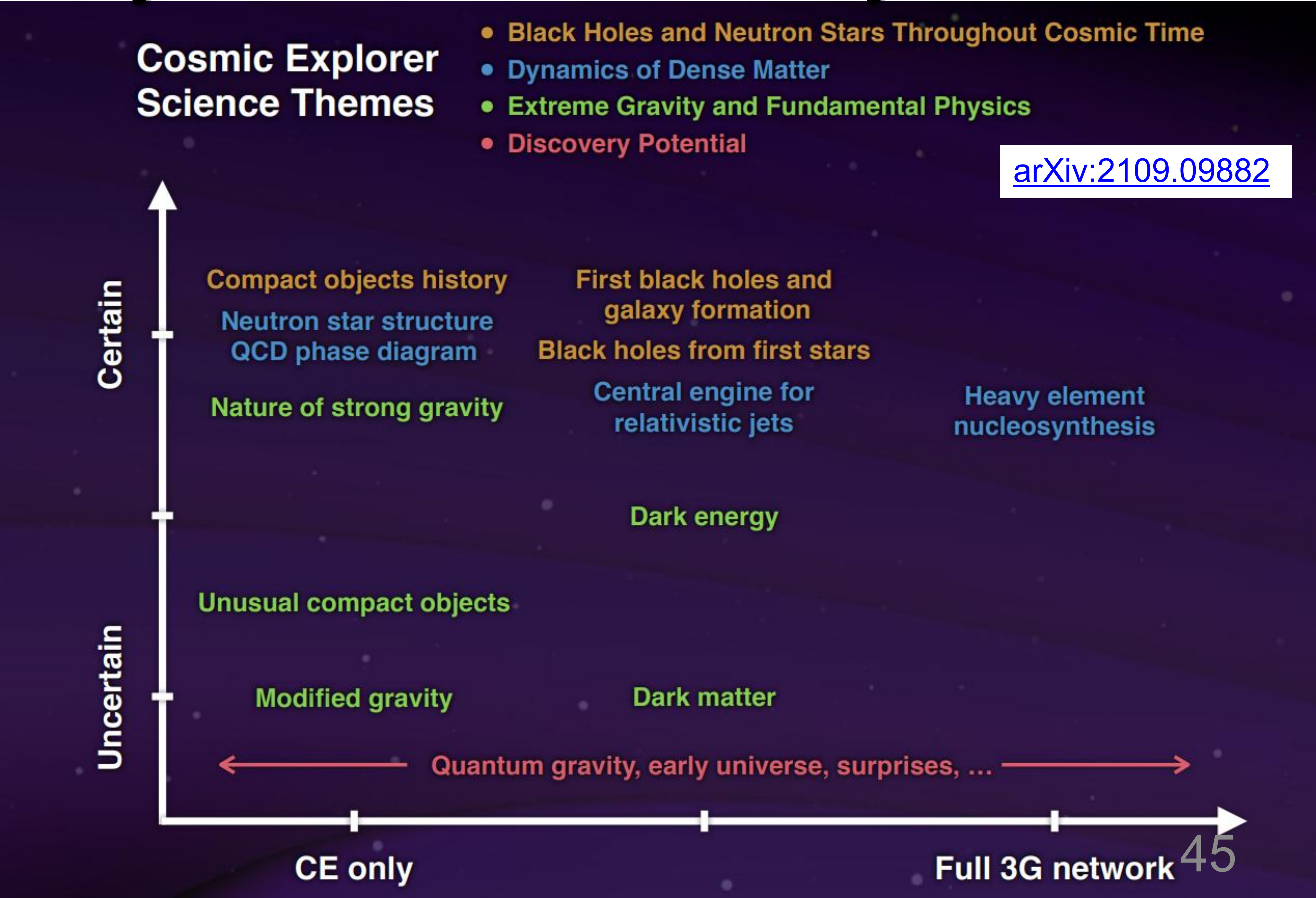


Next Gen. detectors can observe compact binaries throughout cosmic history



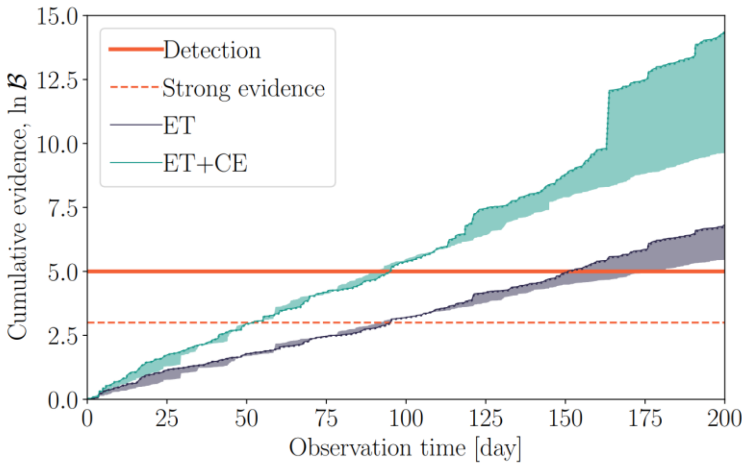
https://gravitationalwaves.syracuse.edu/about/

Key Science Enabled by Next Gen.



Next Gen. Science Personal Picks

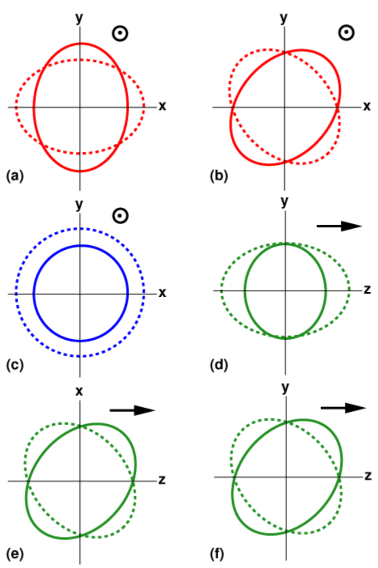
Displacement and Spin Memory



Permanent shift in the displacement and twist of the spacetime could be detected by ET and CE

Goncharov, Donnay, Harms, [PRL 132, 241401 (2024)]

Polarization and Sky Localization

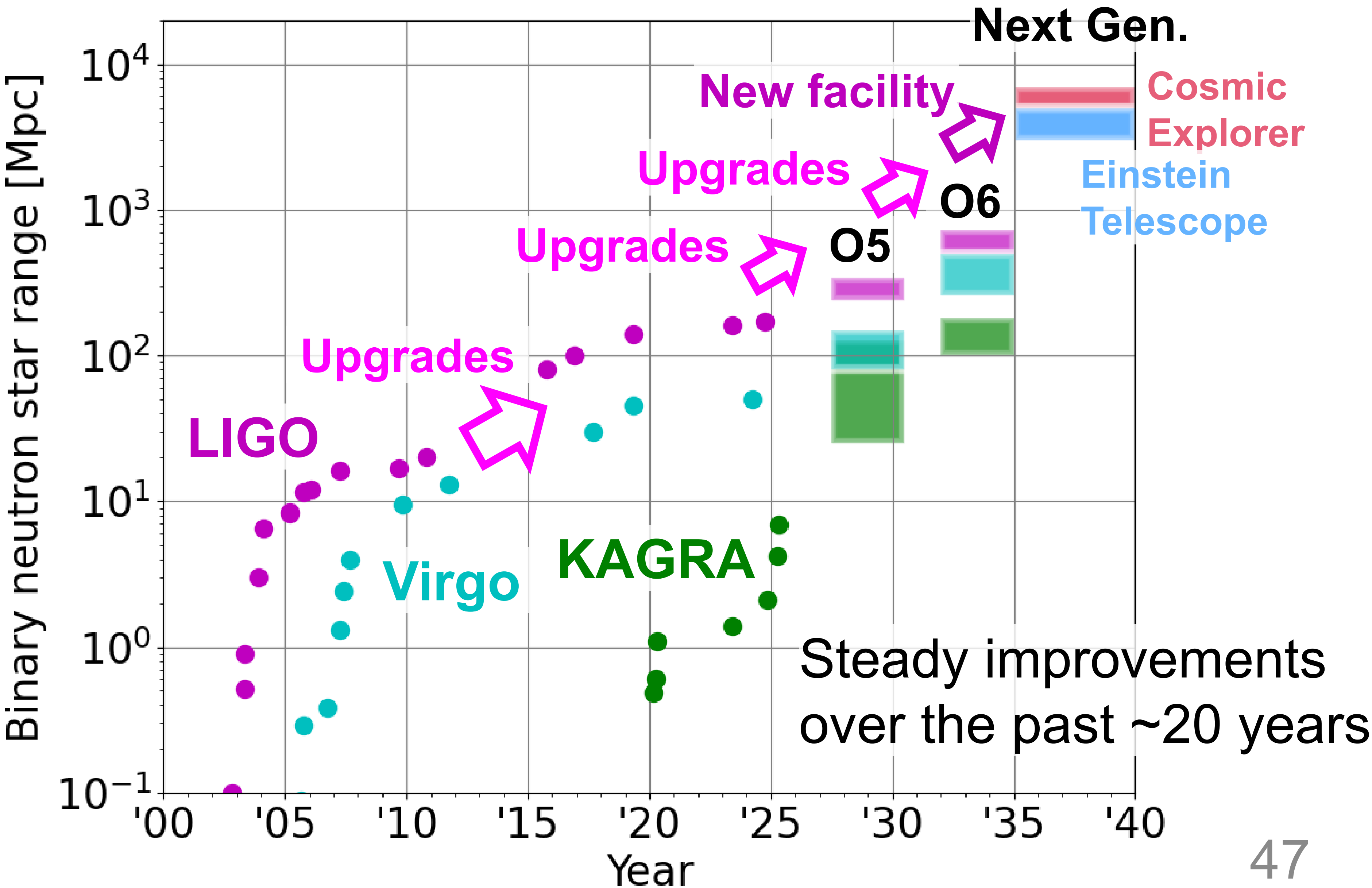


	Parameter	BNS (ET-D—ET-D)	BNS (ET-D—CE)	BNS (CE-CE)
	SNR	75.2	120	151
Model TS1	$\Delta \ln d_L$	0.0520	0.124	0.569
	$\Delta\Omega_s[\mathrm{deg}^2]$	0.346	0.643	3.51
	ΔA_{S1}	0.0797	0.178	0.913

Takeda+, [PRD 100, 042001 (2019)]

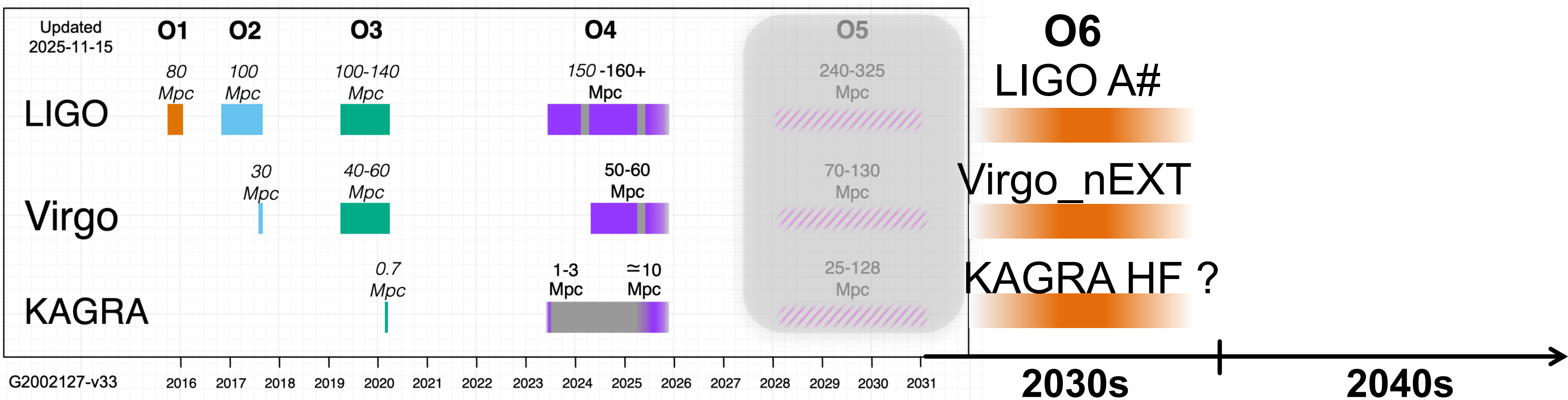
More polarization can be resolved & better sky localization with ET and CE due to low frequency sensitivity and Earth rotation

Sensitivity Evolution



Space-Based Detectors in 2030s

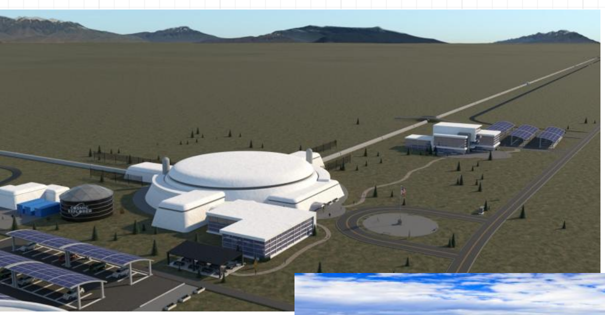
- Aiming below 10 Hz which is inaccessible with ground-based detectors (no seismic noise)

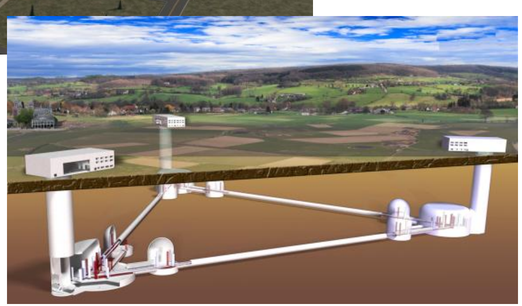


LIGO India

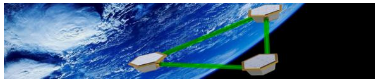
Cosmic Explorer

Einstein Telescope

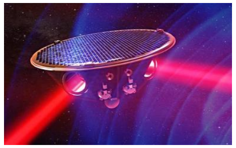




B-DECIGO

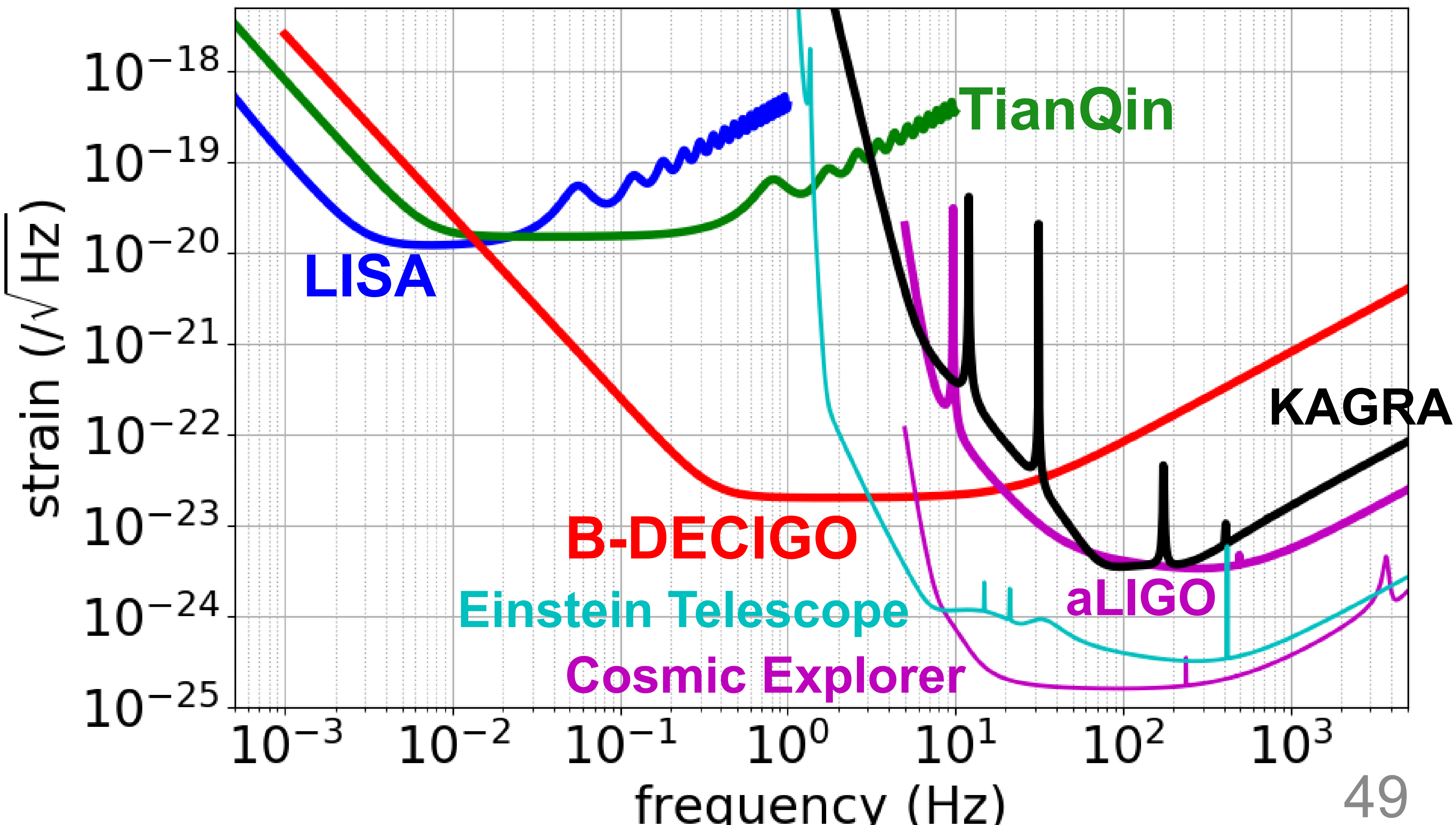


LISA

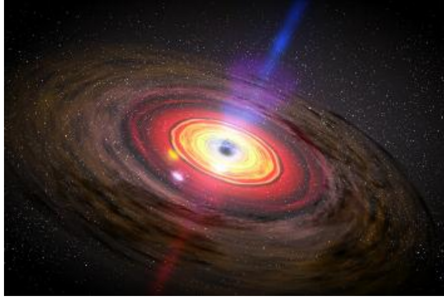


Space-Based Detectors: Sensitivity

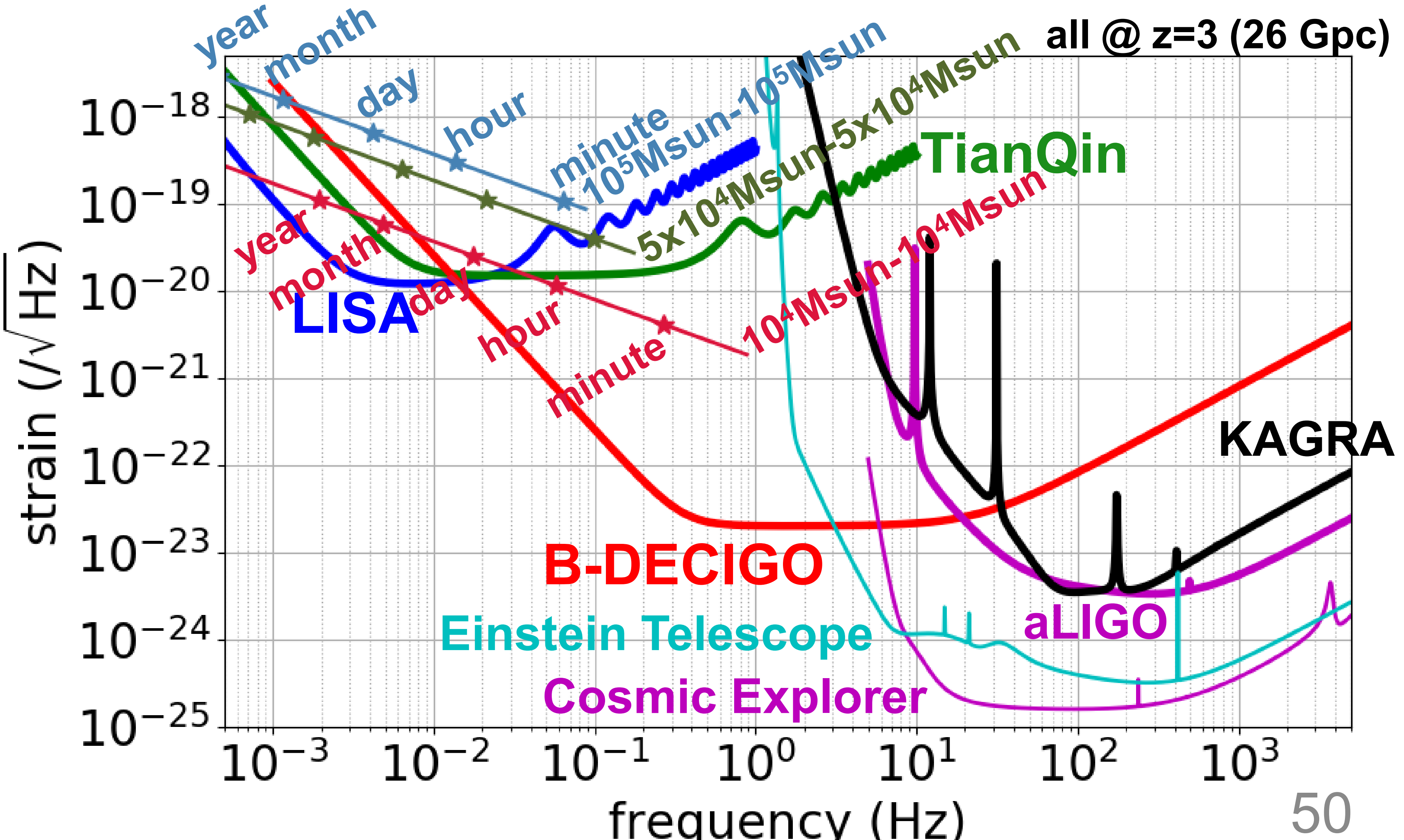
- LISA at 1-10 mHz, DECIGO at 0.1-1 Hz



Super Massive Blackholes

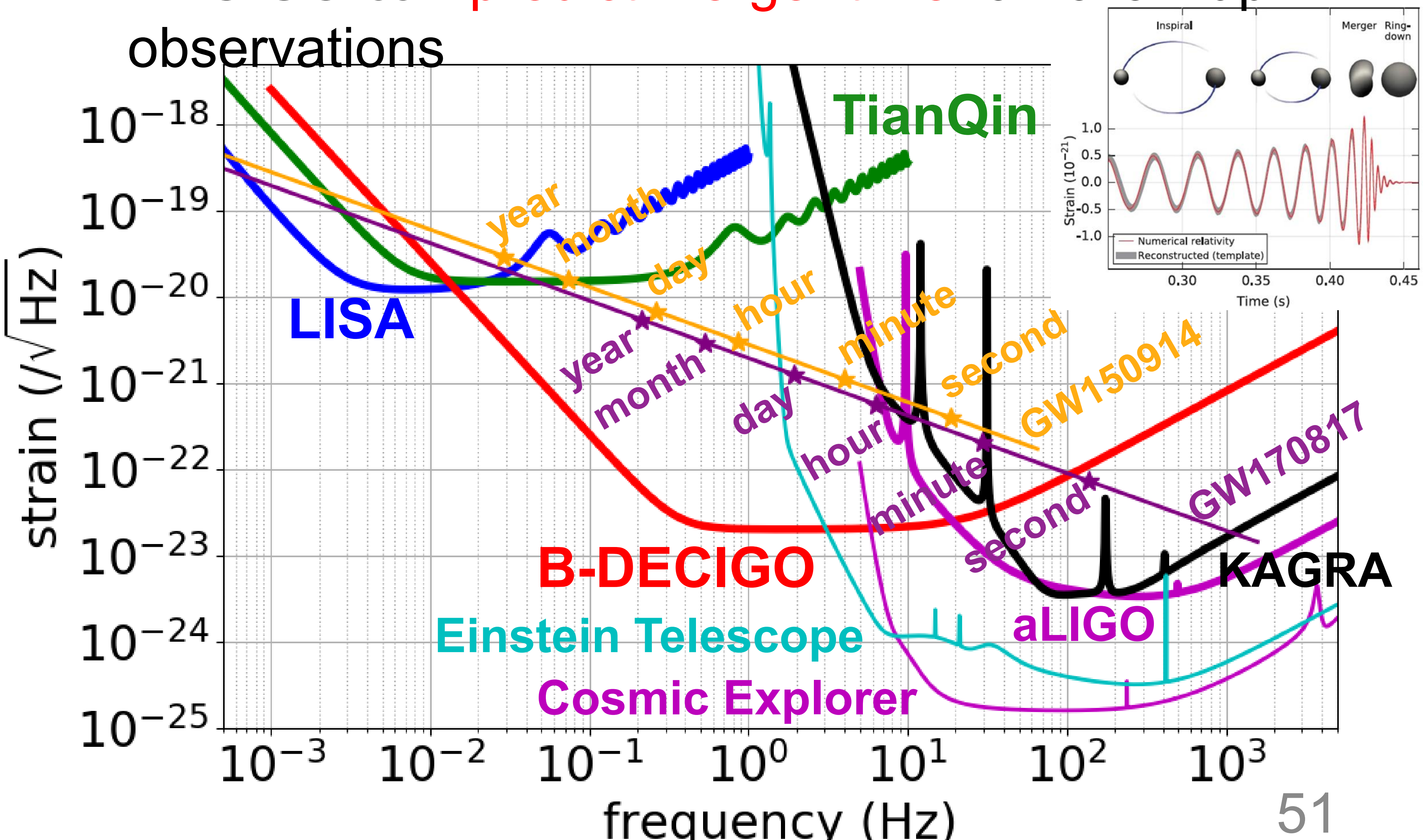


- LISA observes SMBH binaries



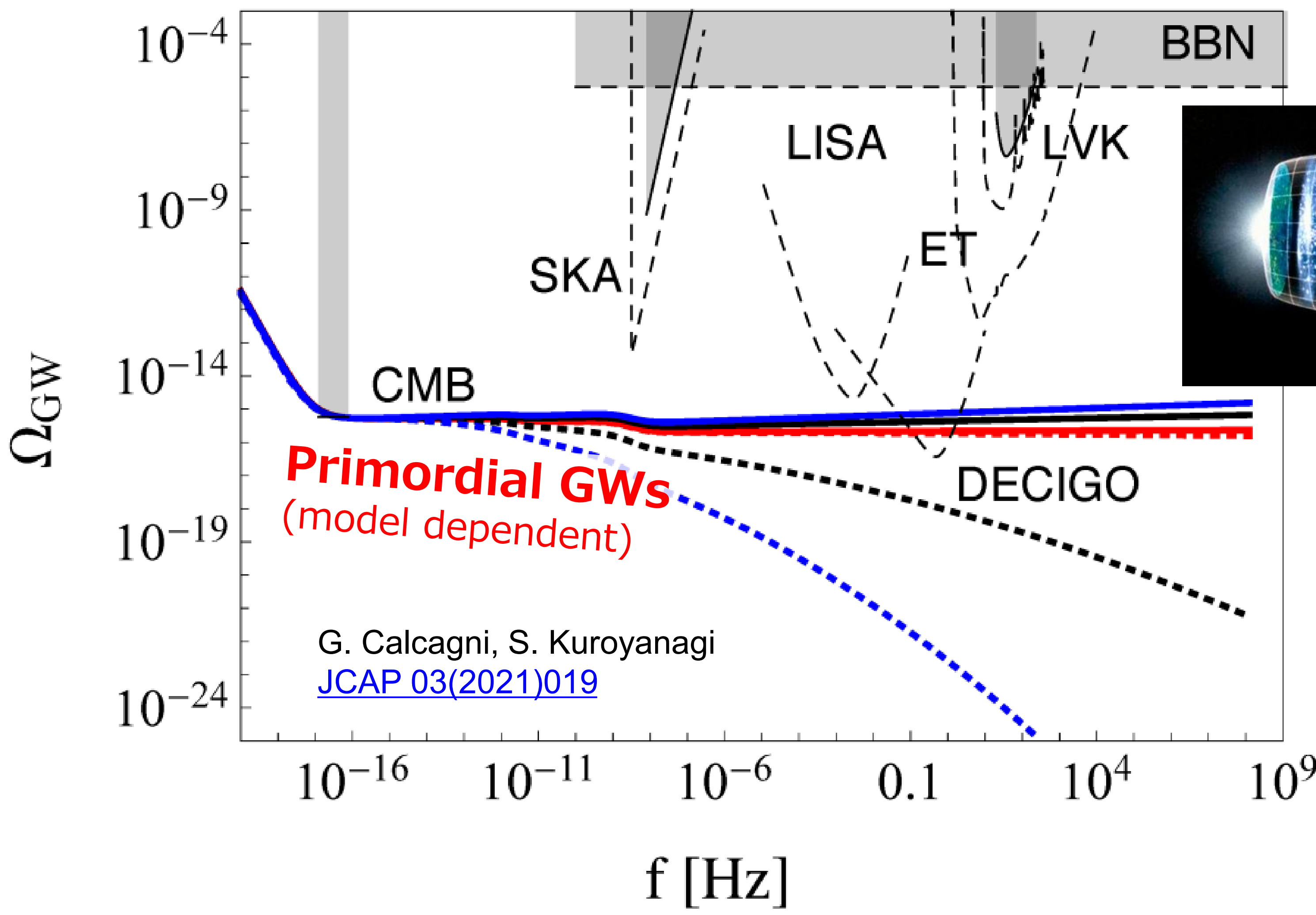
Multi-band Observations

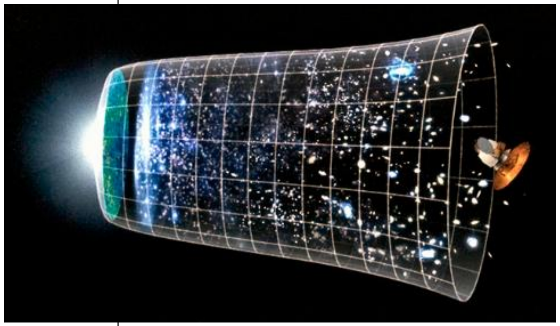
- DECIGO can predict merger time for follow up observations



Primordial GWs from Inflation

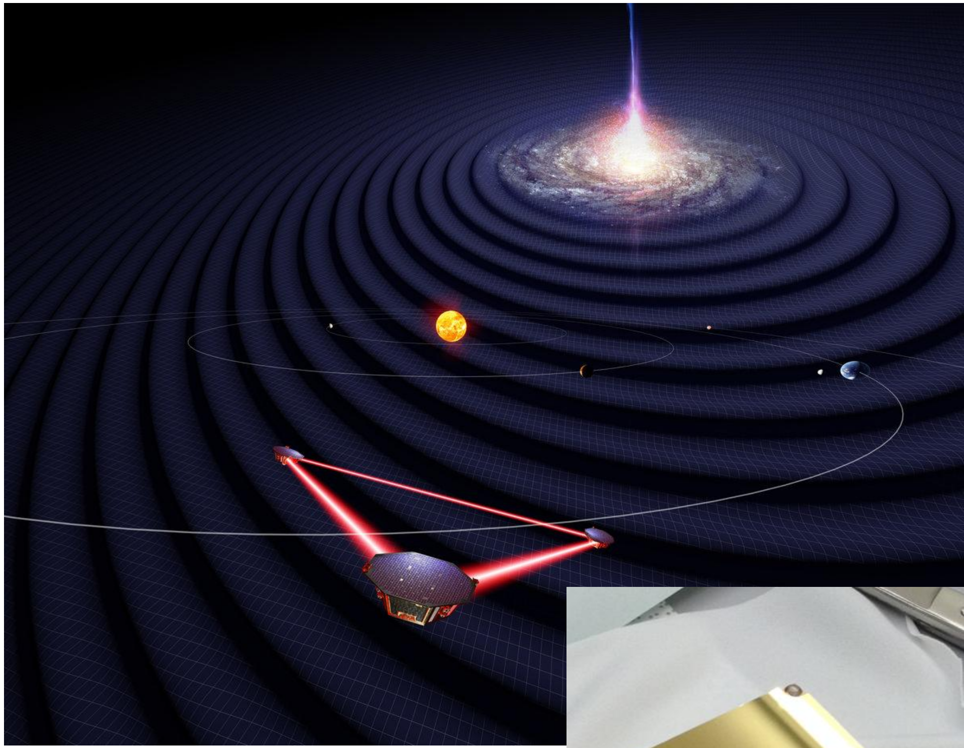
- DECIGO band is suitable for observing primordial gravitational waves

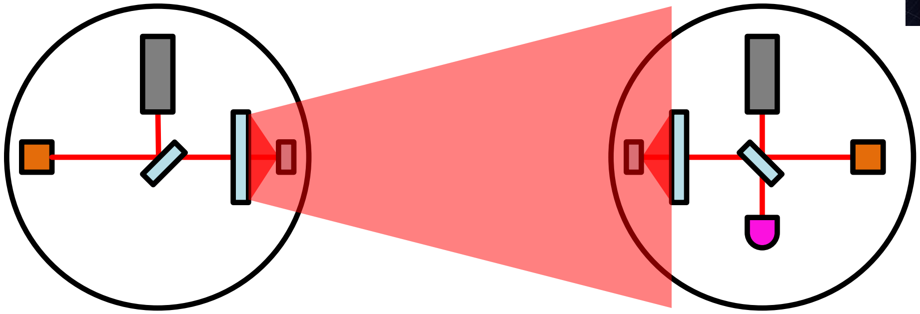


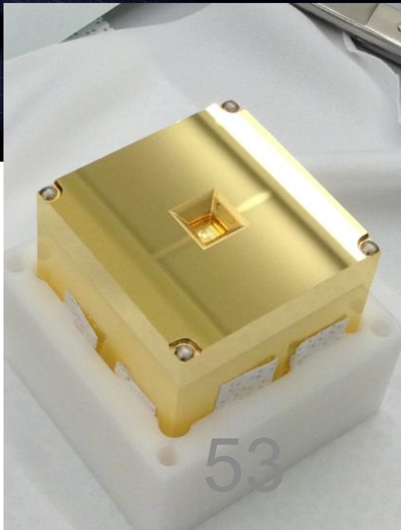


LISA to be Launched Mid-2030s

- Three satellites, 2.5×10^6 km arms
- Free-fall demonstrated with LISA Pathfinder in 2016
- Optical transponder:
  Measures phase of laser beam

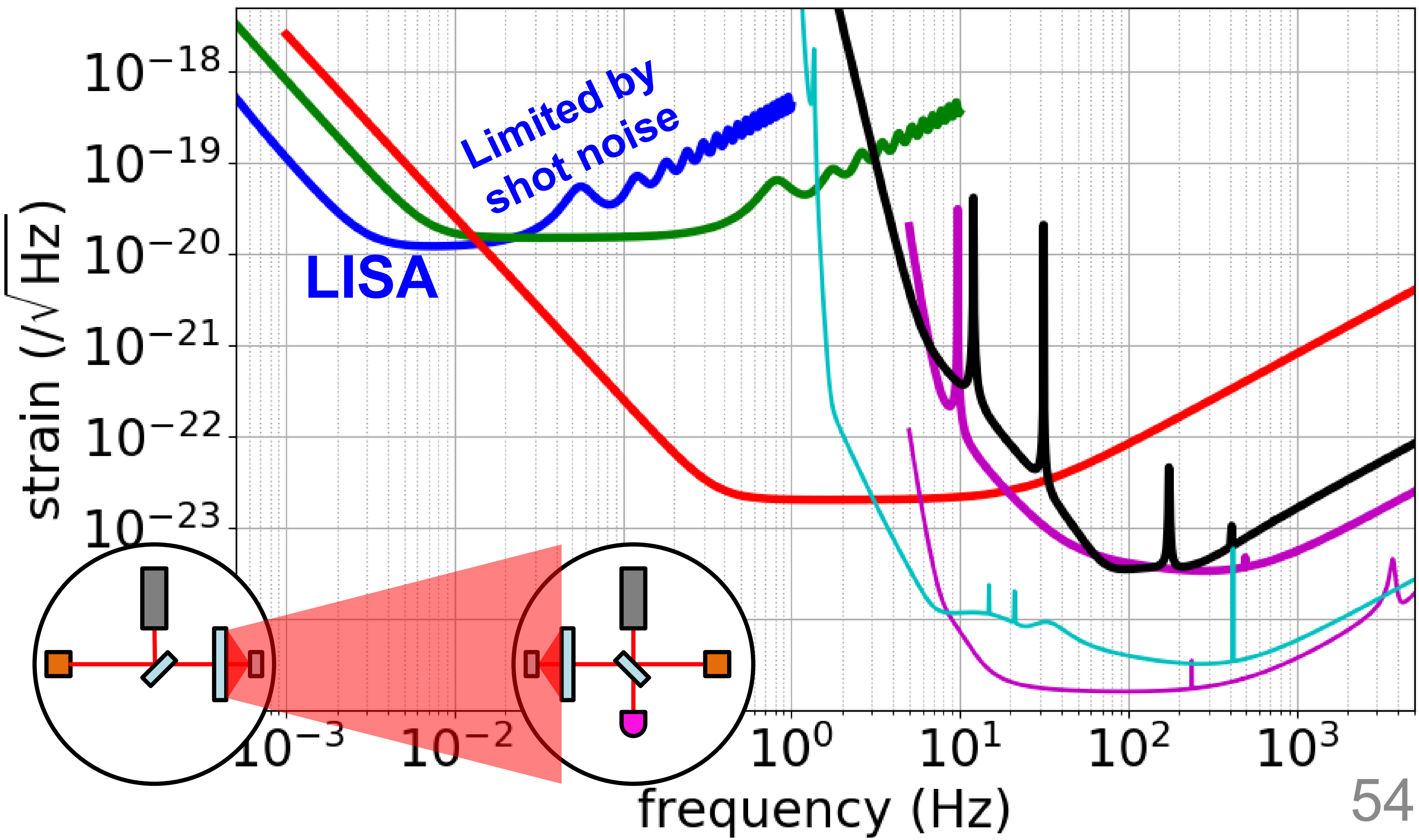






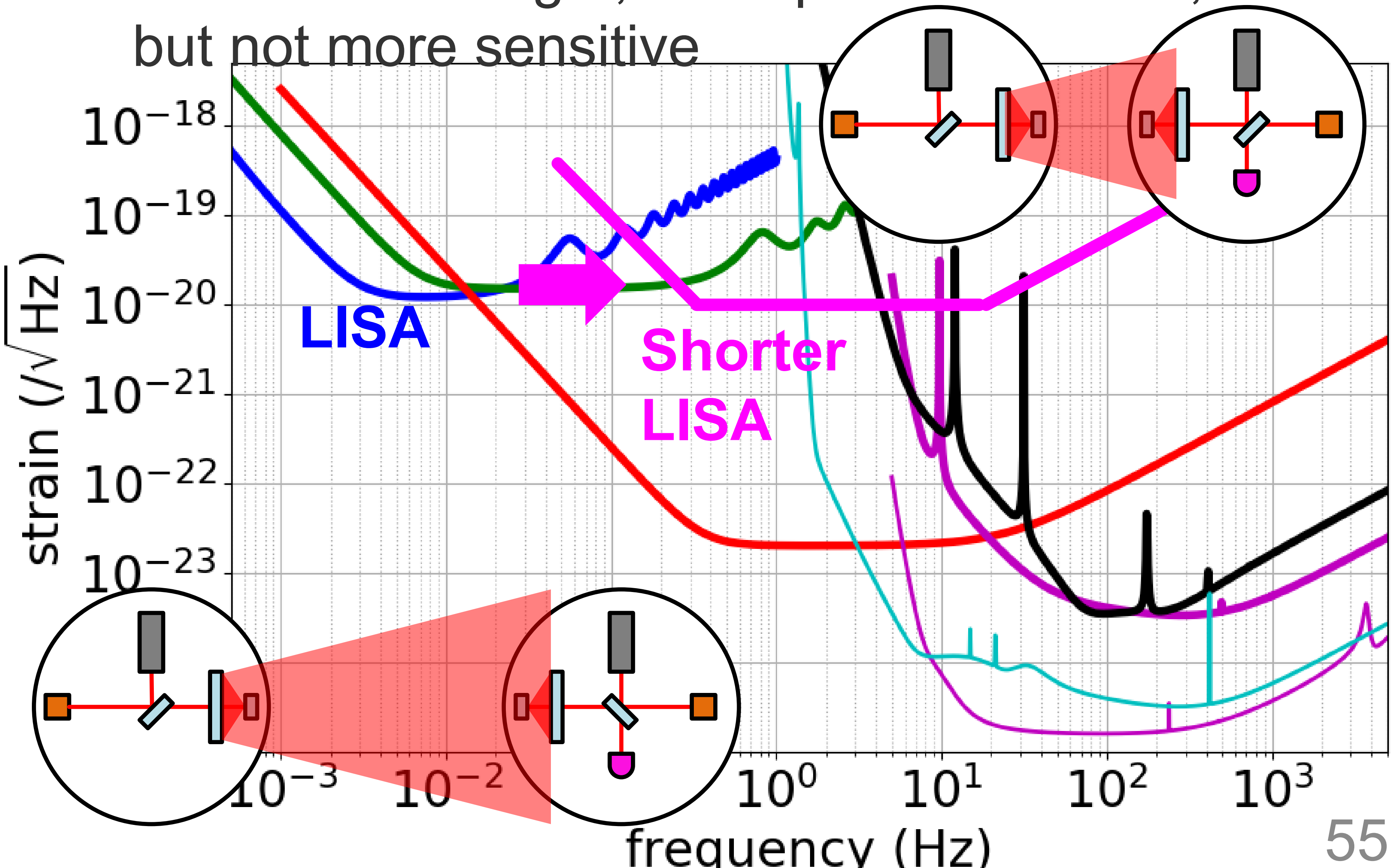
LISA Sensitivity Curve

- 1 W emitted, ~100 pW received



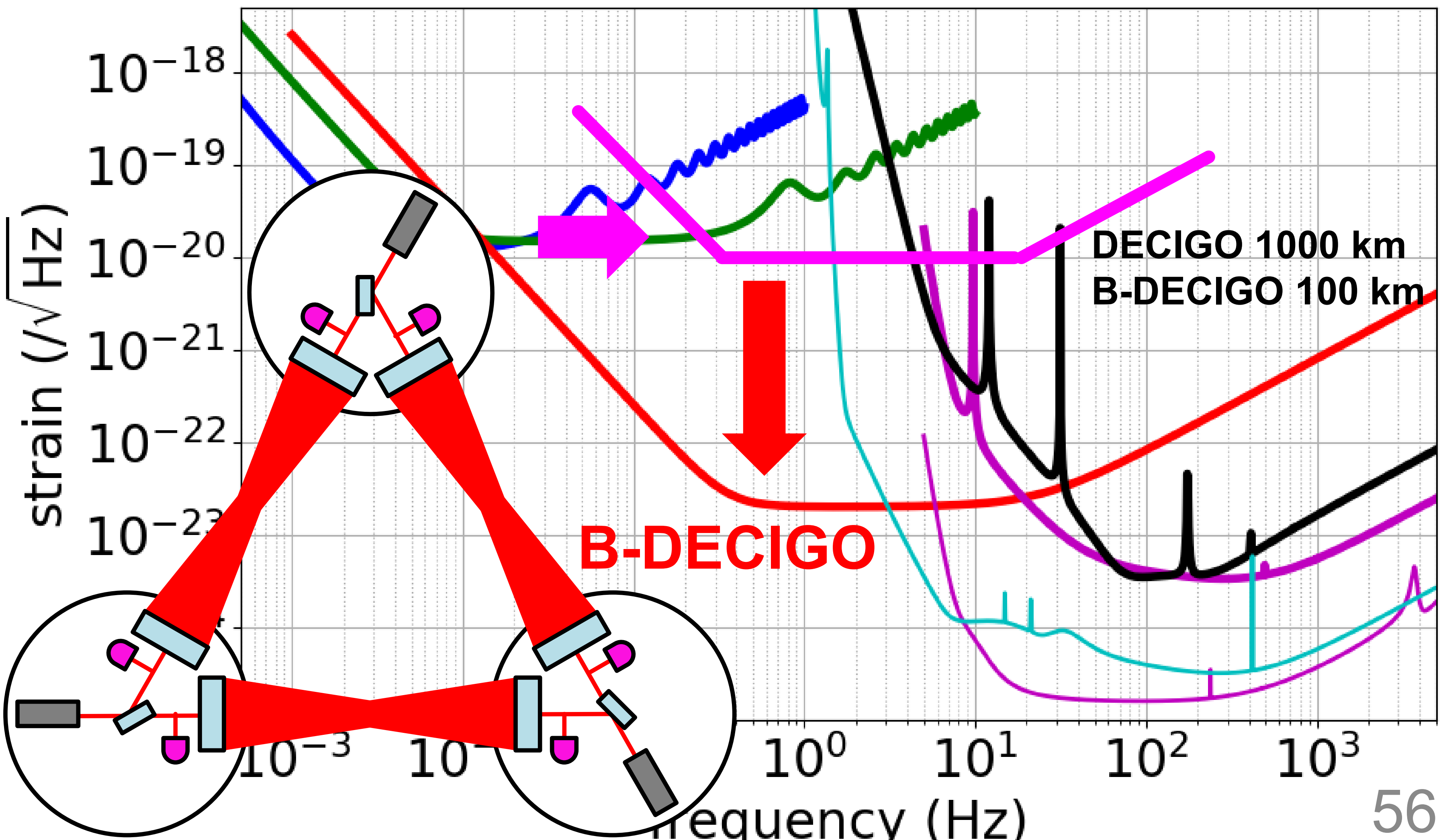
Shorter LISA will not be DECIGO

- Shorter arm length, more power received, but not more sensitive



Shorter LISA will not be DECIGO

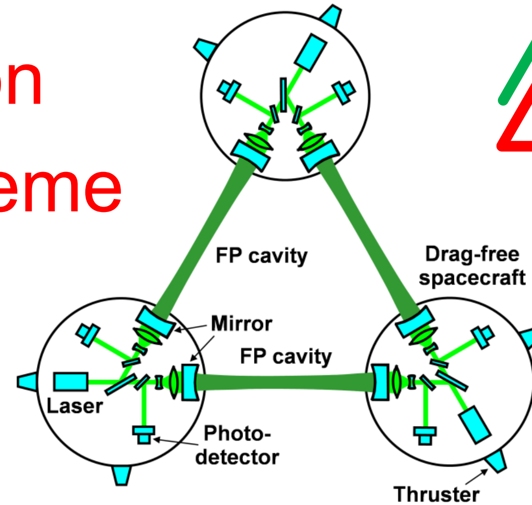
- Form an optical cavity to enhance the sensitivity

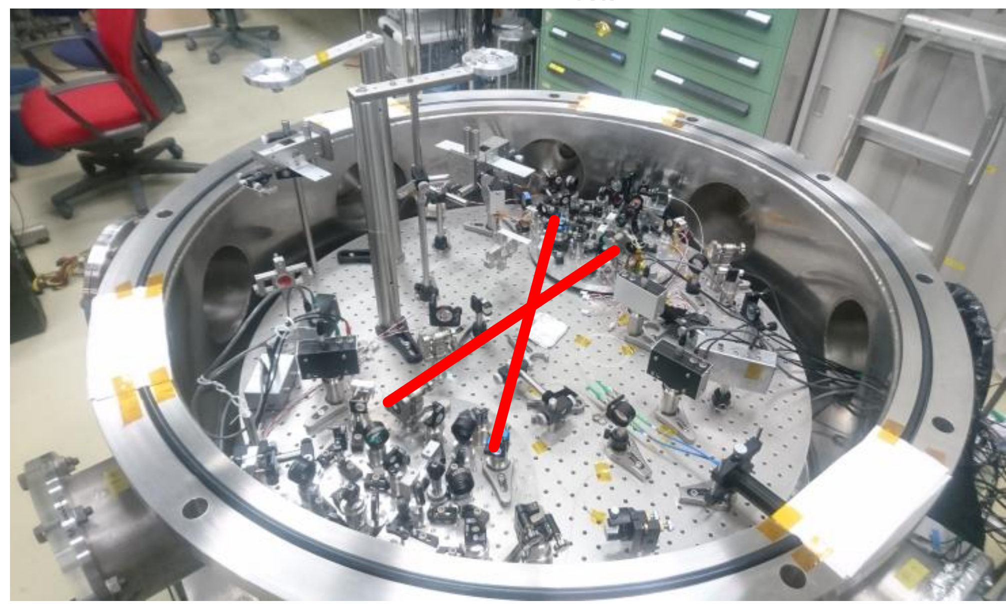


Exciting R&Ds for DECIGO

- Interferometer configuration
- Interferometer control scheme
  Demonstration experiments at UTokyo
- Stable laser source
- Initial link acquisition
- Low noise thrusters
- Drag-free controls
- Orbit and satellite controls

… and more!



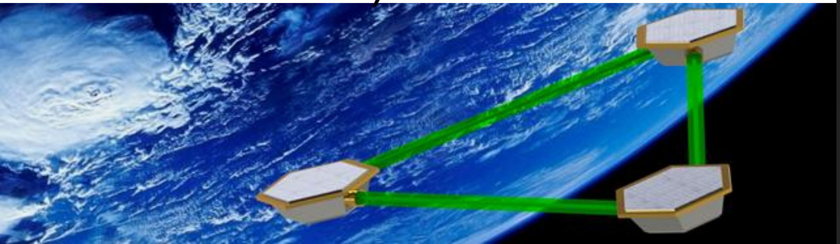


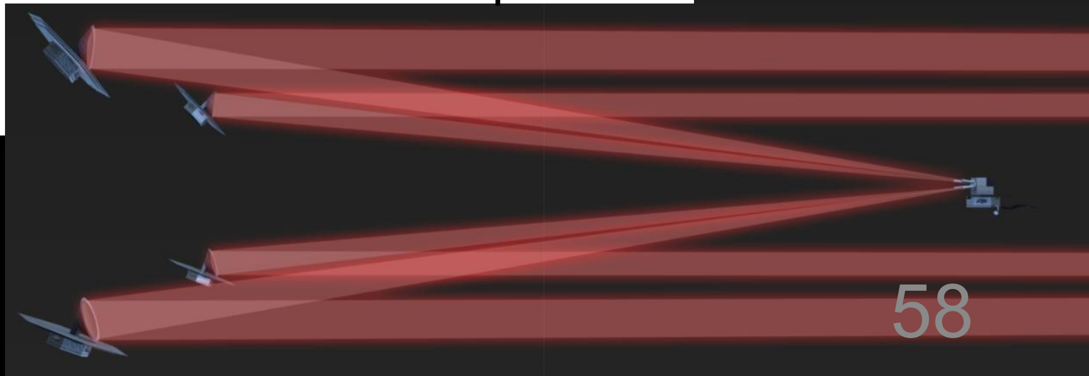
K. Nagano, H. Takeda, YM+
[CQG **38**, 085018 (2021)]

SILVIA Project

- Space Interferometer Laboratory Voyaging towards Innovative Applications
- Demonstration of ultra-precision formation flying with laser interferometer between satellites
- For DECIGO, LIFE etc.
- Proposal submitted to JAXA in Feb 2020 (currently at mission definition phase of JAXA's small satellite mission)

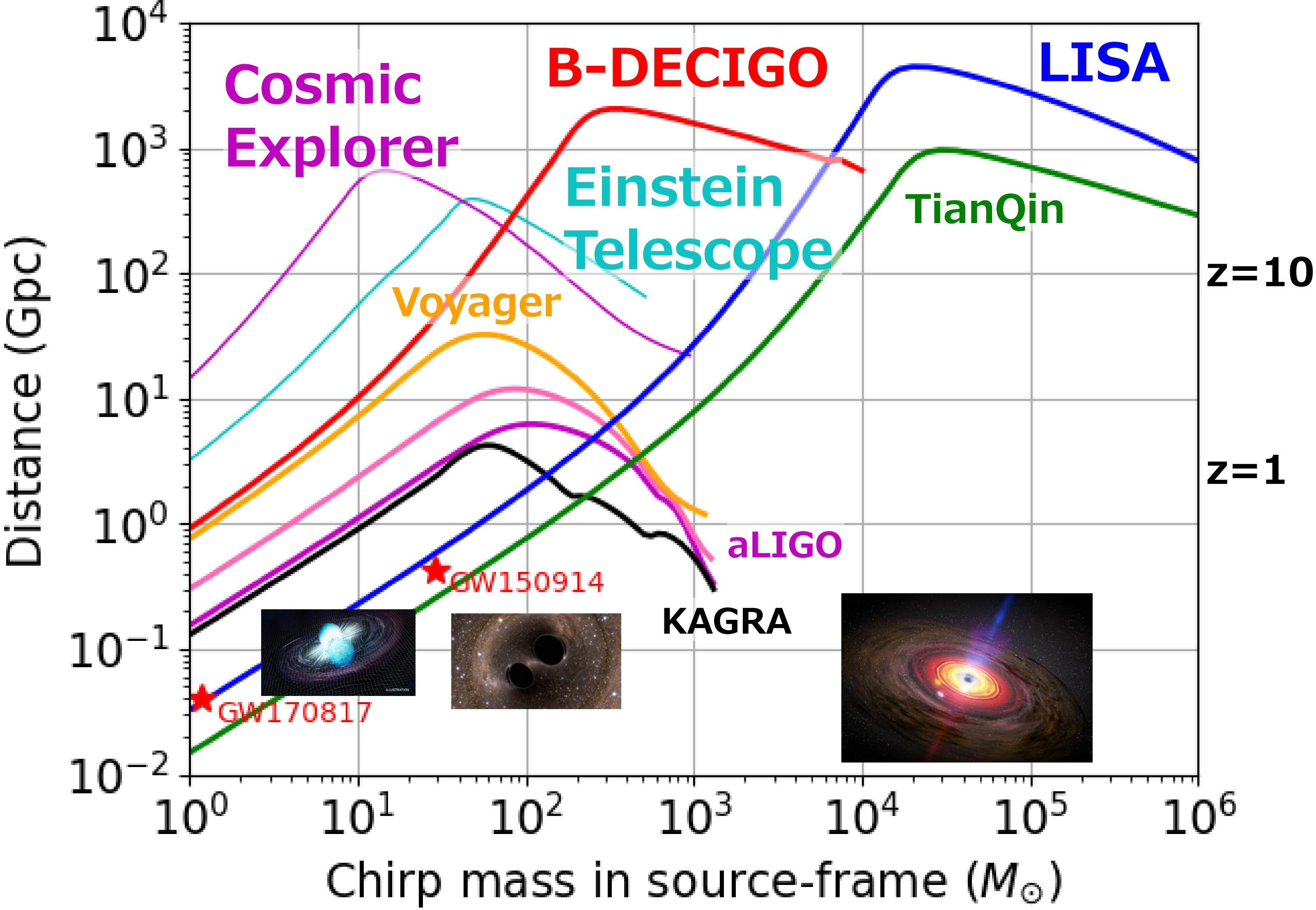
T. Ito+, [PASJ **77**, 1080 (2025)]



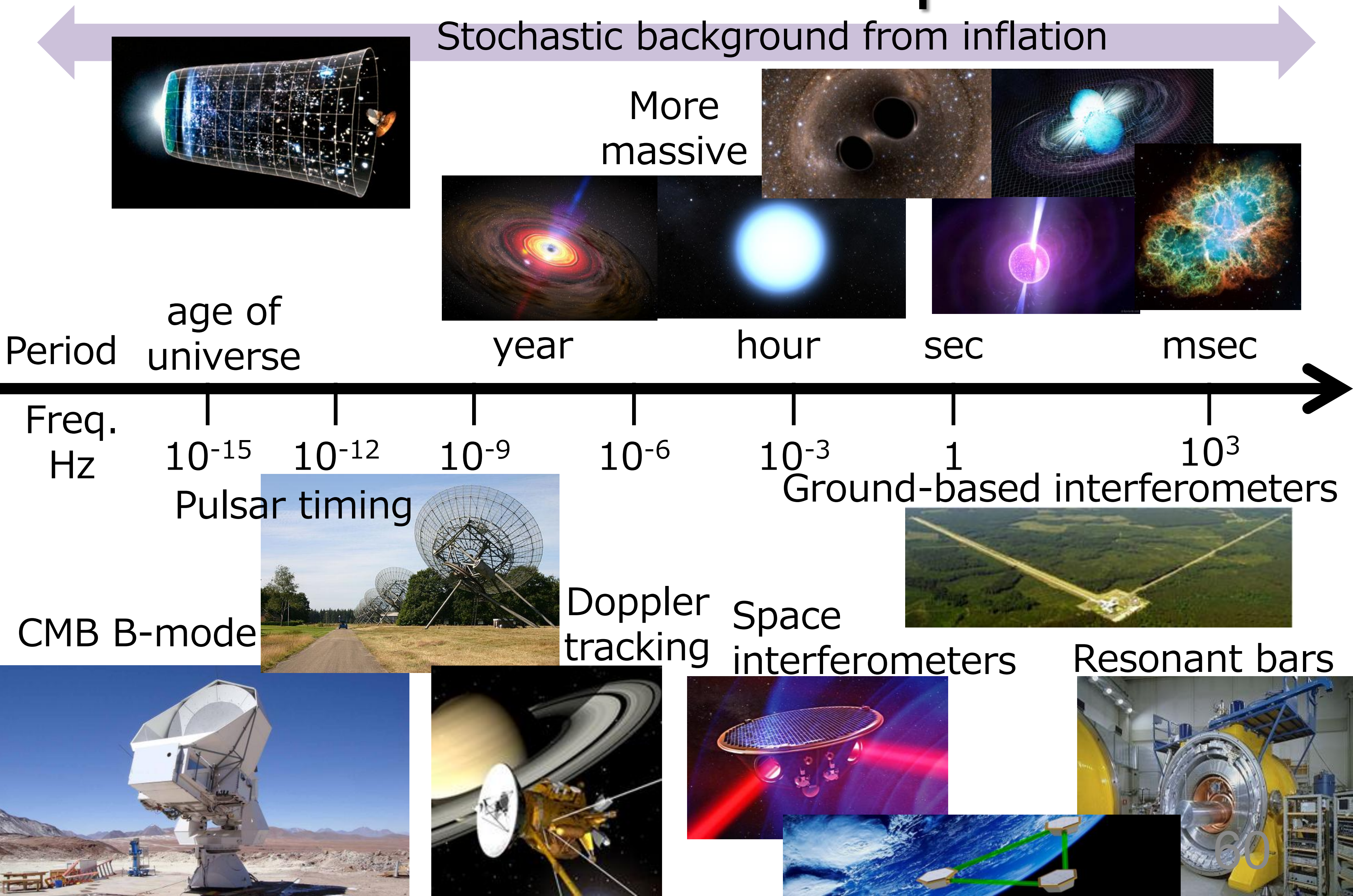


Astrophysical Reach to Binaries

- Covers entire universe by 2030s



Gravitational Wave Spectrum



Gravitational Wave Spectrum

Stochastic background from inflation

More massive

If frequency is multiplied by 10^{15}...

Period	age of universe	Radio	ear	h	IR	s	UV	X-ray

Freq. Hz: 10^{-15}, 10^{-12}, 10^{-9}, 10^{-6}, 10^{-3}, 1, 10^{3}

Pulsar timing

Ground-based interferometers

CMB B-mode

Doppler tracking

Space interferometers

Resonant bars

Gravitational Wave Spectrum

Stochastic background from inflation

More massive

If frequency is multiplied by 10^{15}...

Period | age of universe | Radio | ear | h | IR | s | UV | X-ray

Freq. Hz | 10^{-15} | 10^{-12} | 10^{-9} | 10^{-6} | 10^{-3} | 1 | 10^{3}

Pulsar timing

Ground-based interferometers

LISA

LIGO

CMB B-mode

Doppler tracking

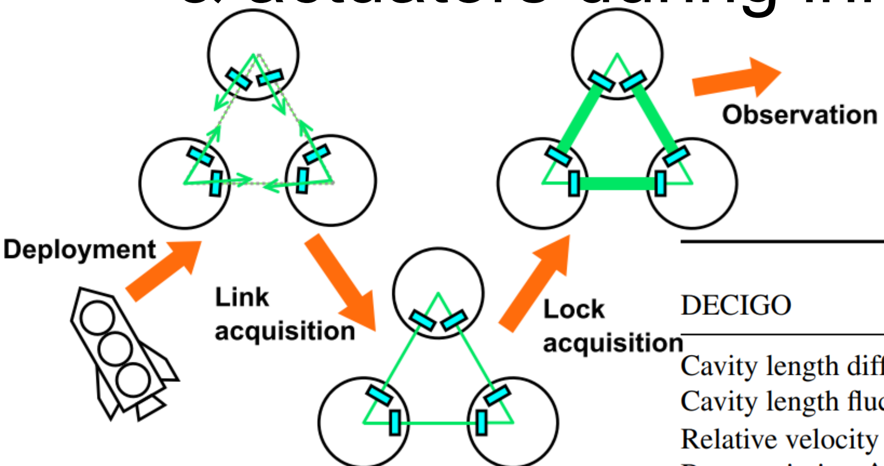
Space interferometers

Resonant bars

DECIGO

But wait… Is DECIGO Feasible?

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



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

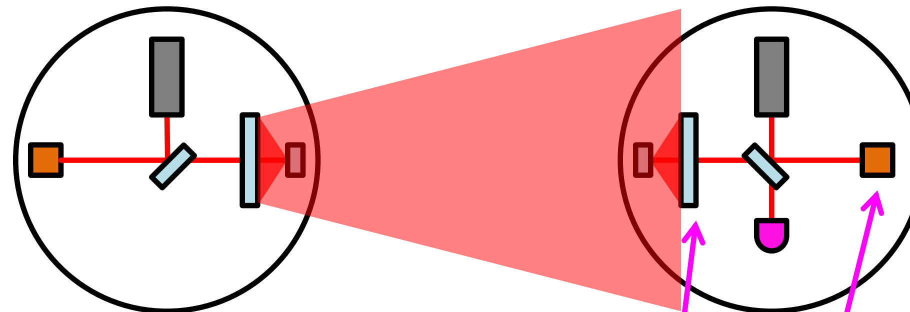
DECIGO	Deployment goal	Link acquisition goal	Lock acquisition goal
Cavity length difference ΔL	2 km	same	same
Cavity length fluctuations δL_{rms}	—	34 cm	0.5 nm
Relative velocity between mirrors v	—	1.2 μm s^{-1}	23 nm s^{-1}
Beam pointing $\Delta\theta_{\mathrm{beam}}$	3 mrad	0.46 μrad	—
Mirror relative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

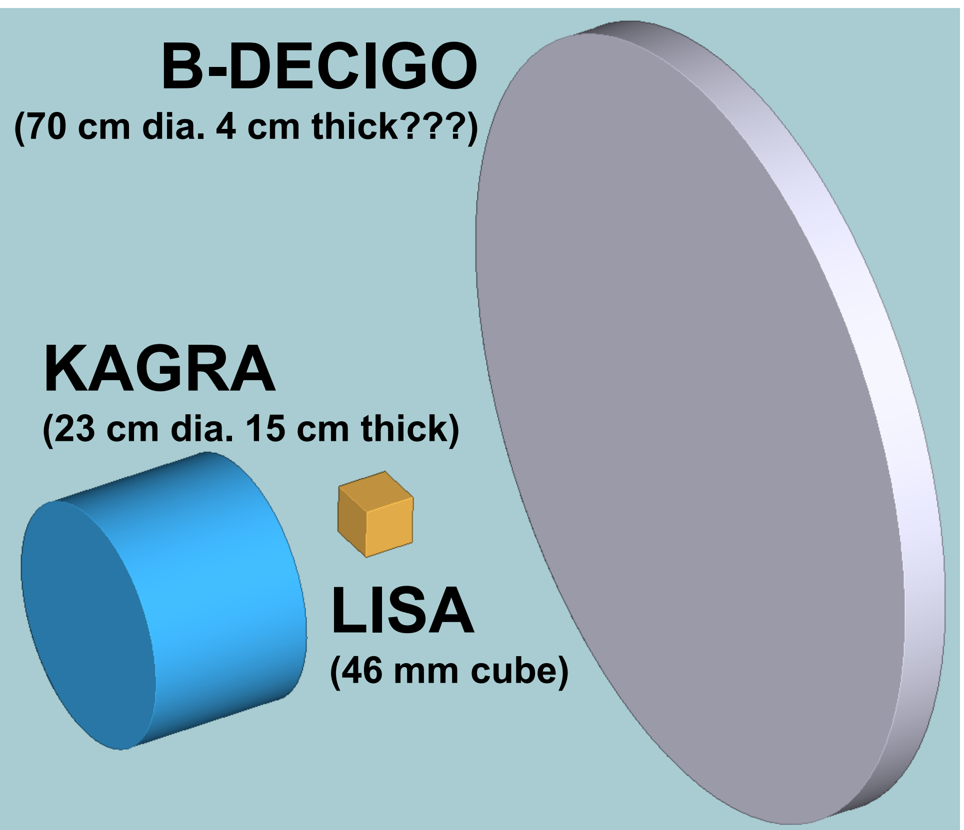
Design Comparison

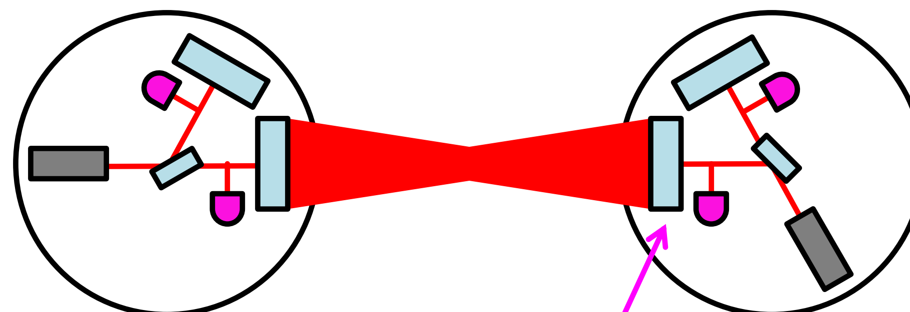
	LISA	TianQin	B-DECIGO
Arm length	2.5e6 km	1.7e5 km	100 km
Interferometry	Optical transponder	Optical transponder	Fabry-Pérot cavity (F=100)
Laser frequency stabilization	Reference cavity, 1064 nm (~3 W)	Reference cavity, 1064 nm	Iodine, 515 nm (~1 W)
Orbit	Heliocentric	Geocentric, facing J0806.3+1527	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

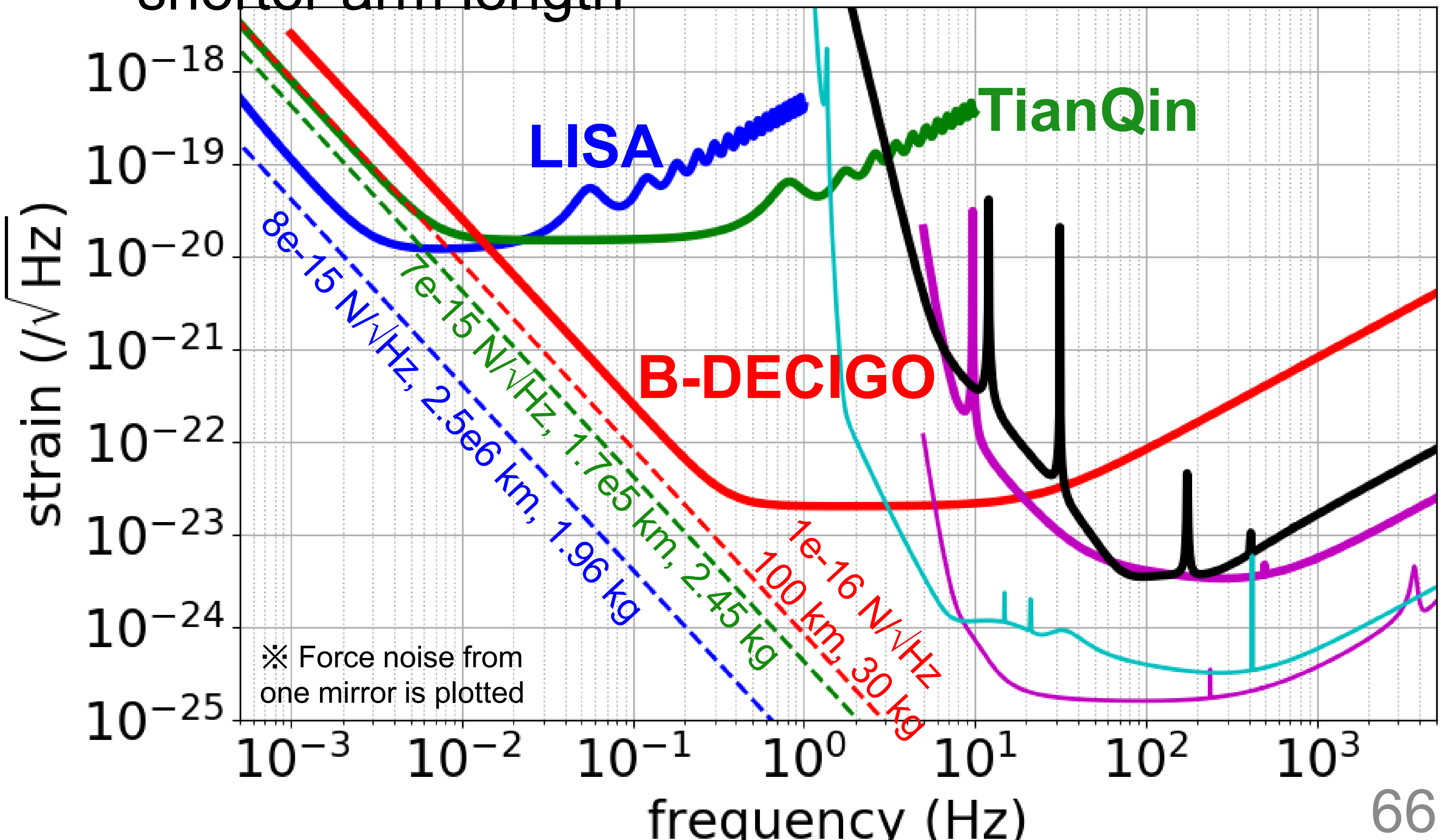






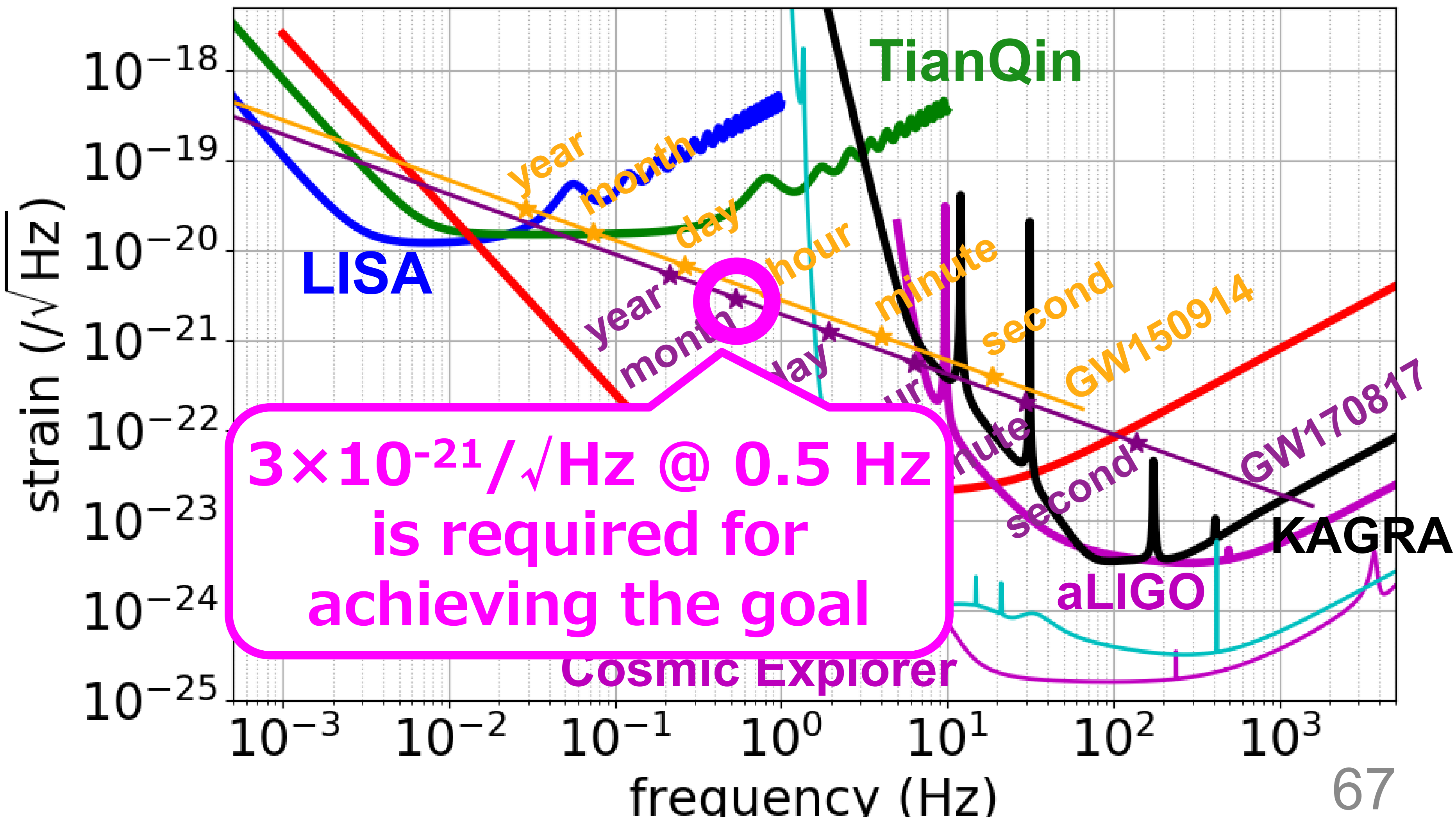
Stringent Force Noise Requirement

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



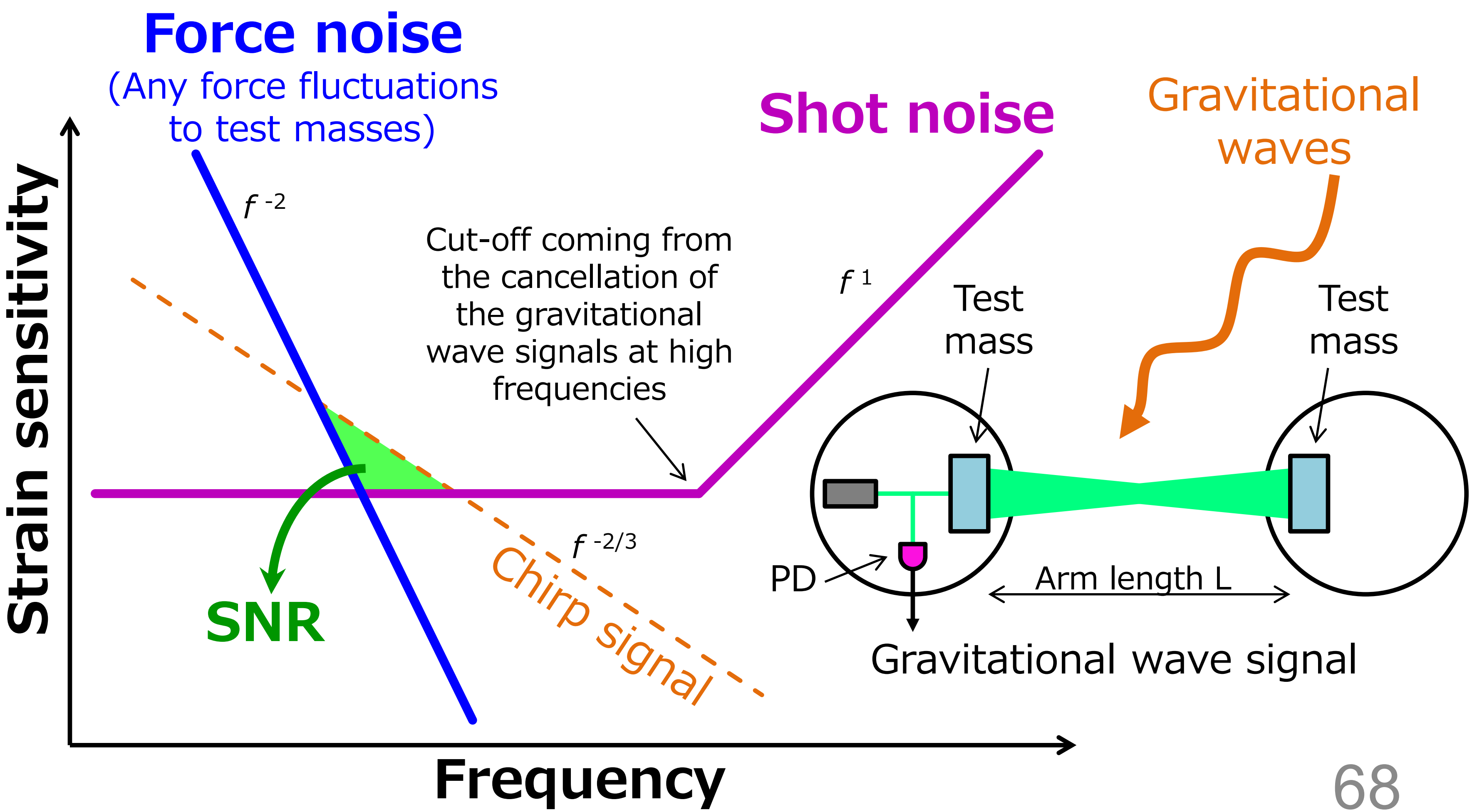
Let's Start from the Minimum Goal

- **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 $3\times10^{-21}/\sqrt{\text{Hz}}$ @ 0.5 Hz goal
- If the force noise is 4×10^{-15} N/$\sqrt{\text{Hz}}$

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

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

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

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

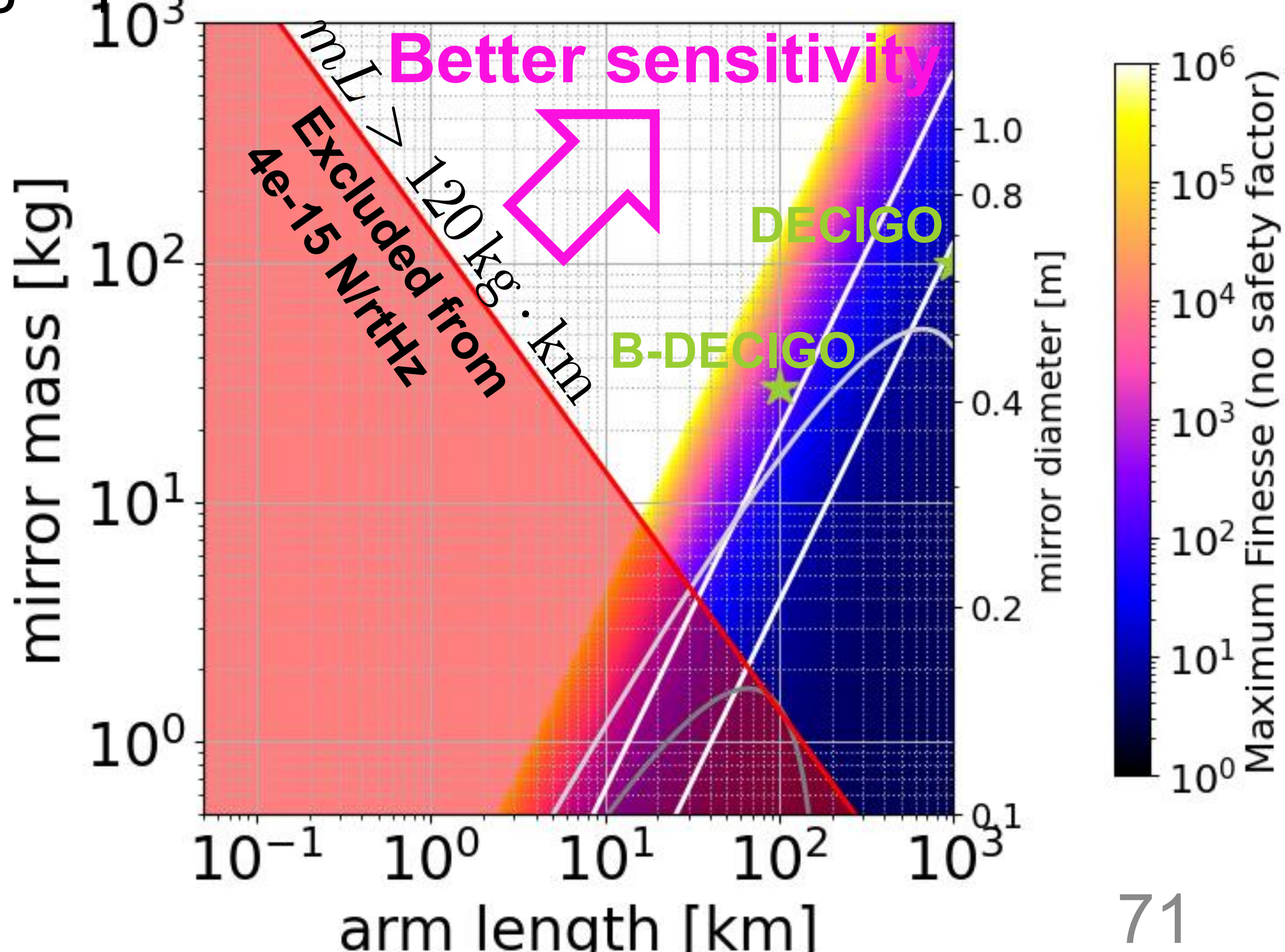
$$h_{\mathrm{shot}} = \frac{1}{2\pi L}\sqrt{\frac{hc\lambda}{2P}\frac{\pi}{2\mathcal{F}}}$$

- 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

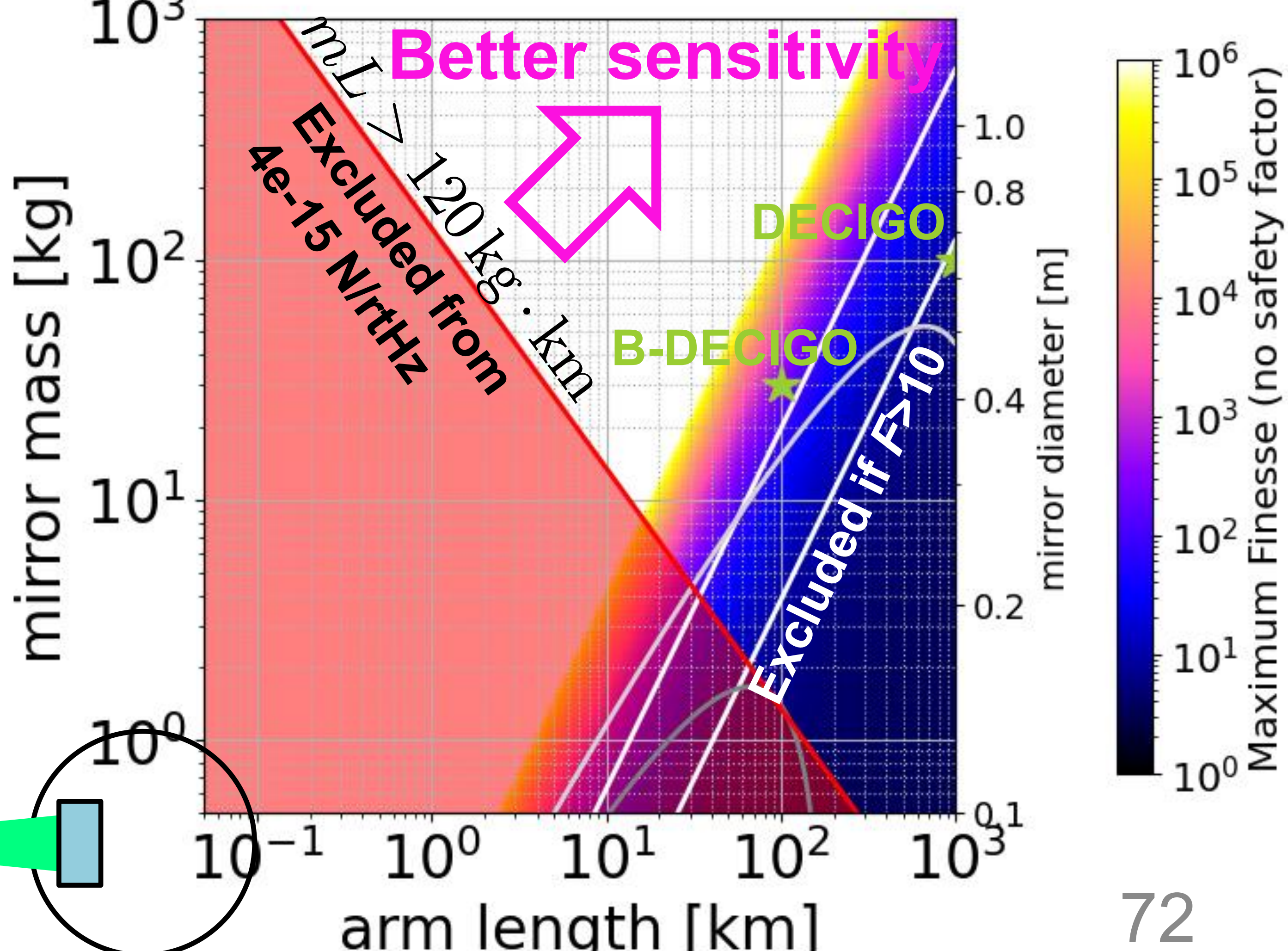
- Force noise requirement gives allowed region in mass-length plane

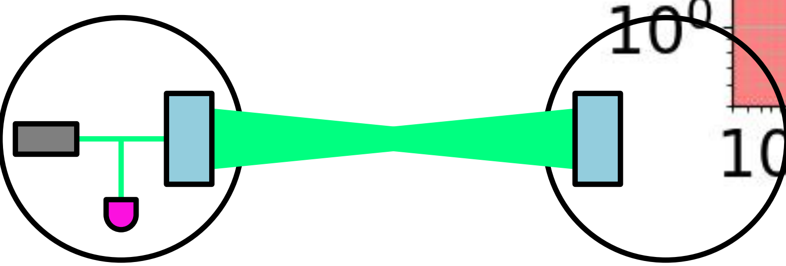


Mirror Size and Arm Length

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

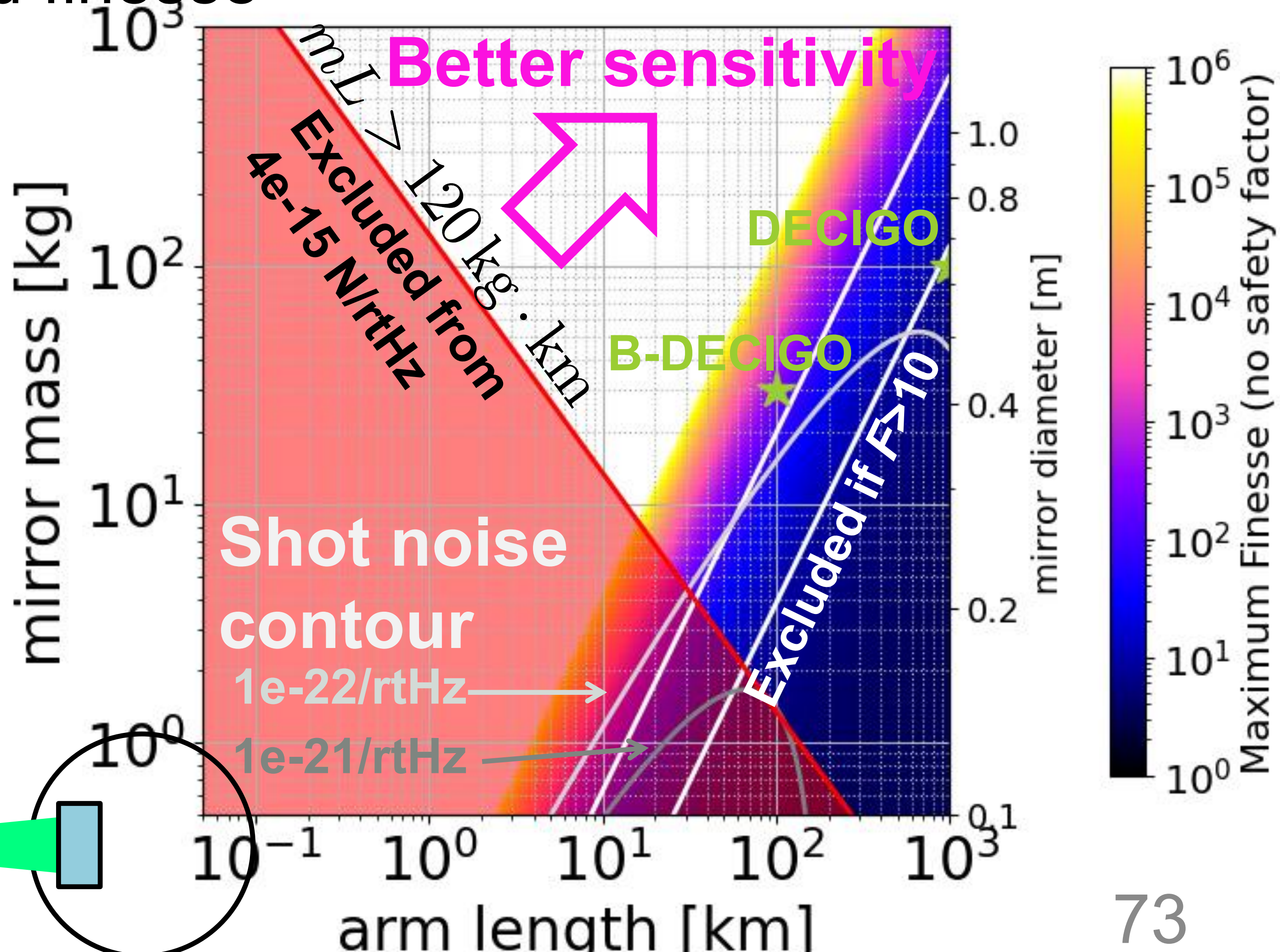
Assuming
- fused silica density,
- aspect ratio 2r/t=3
- g-factor g=-0.65

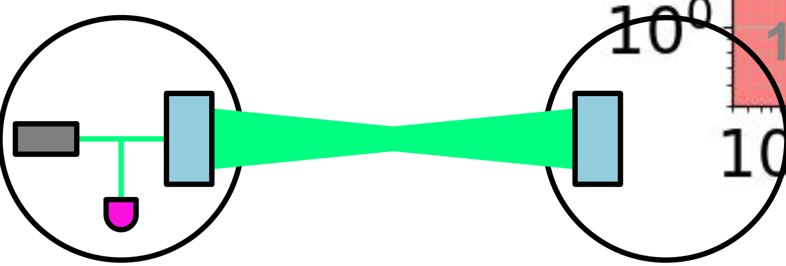




Mirror Size and Arm Length

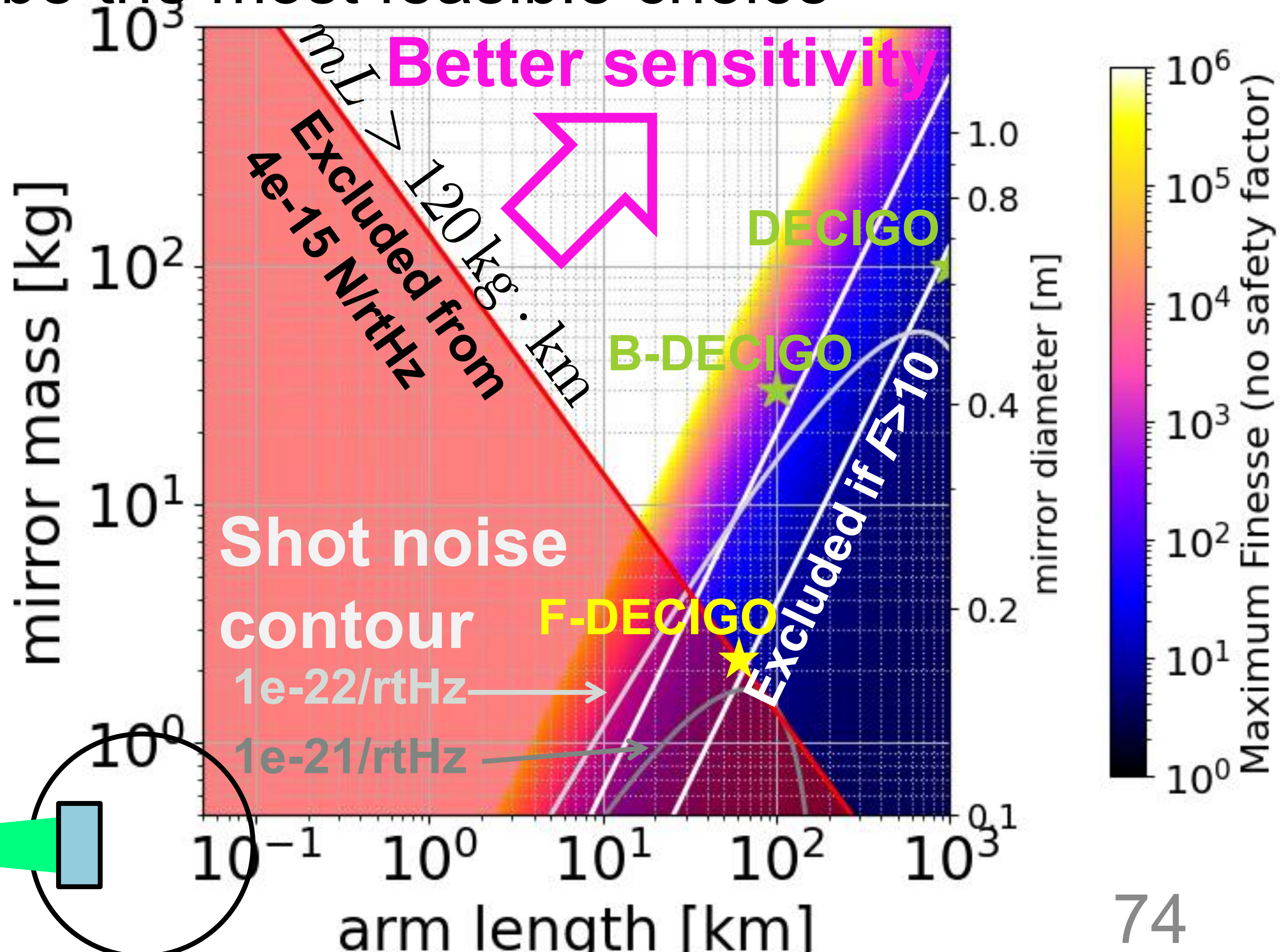
- Shot noise can also be calculated from the arm length and finesse

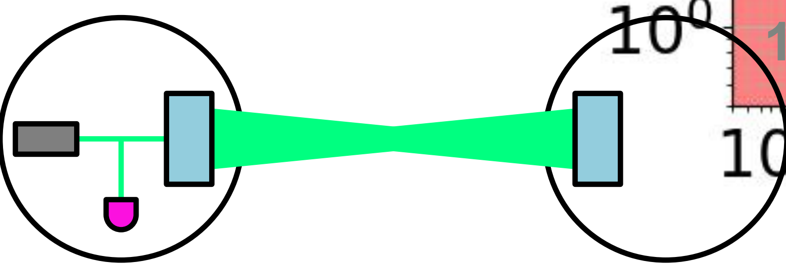




Mirror Size and Arm Length

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





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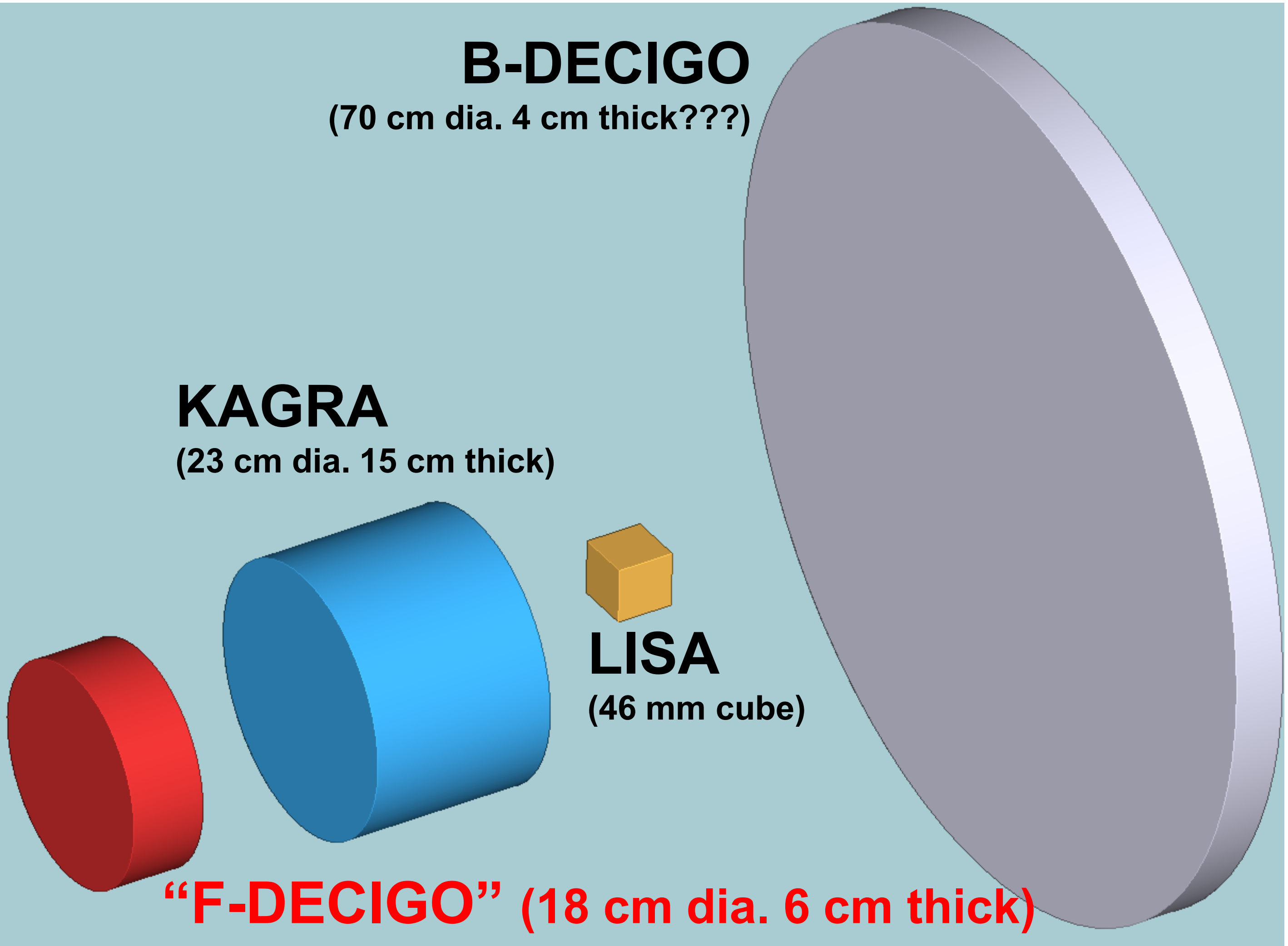
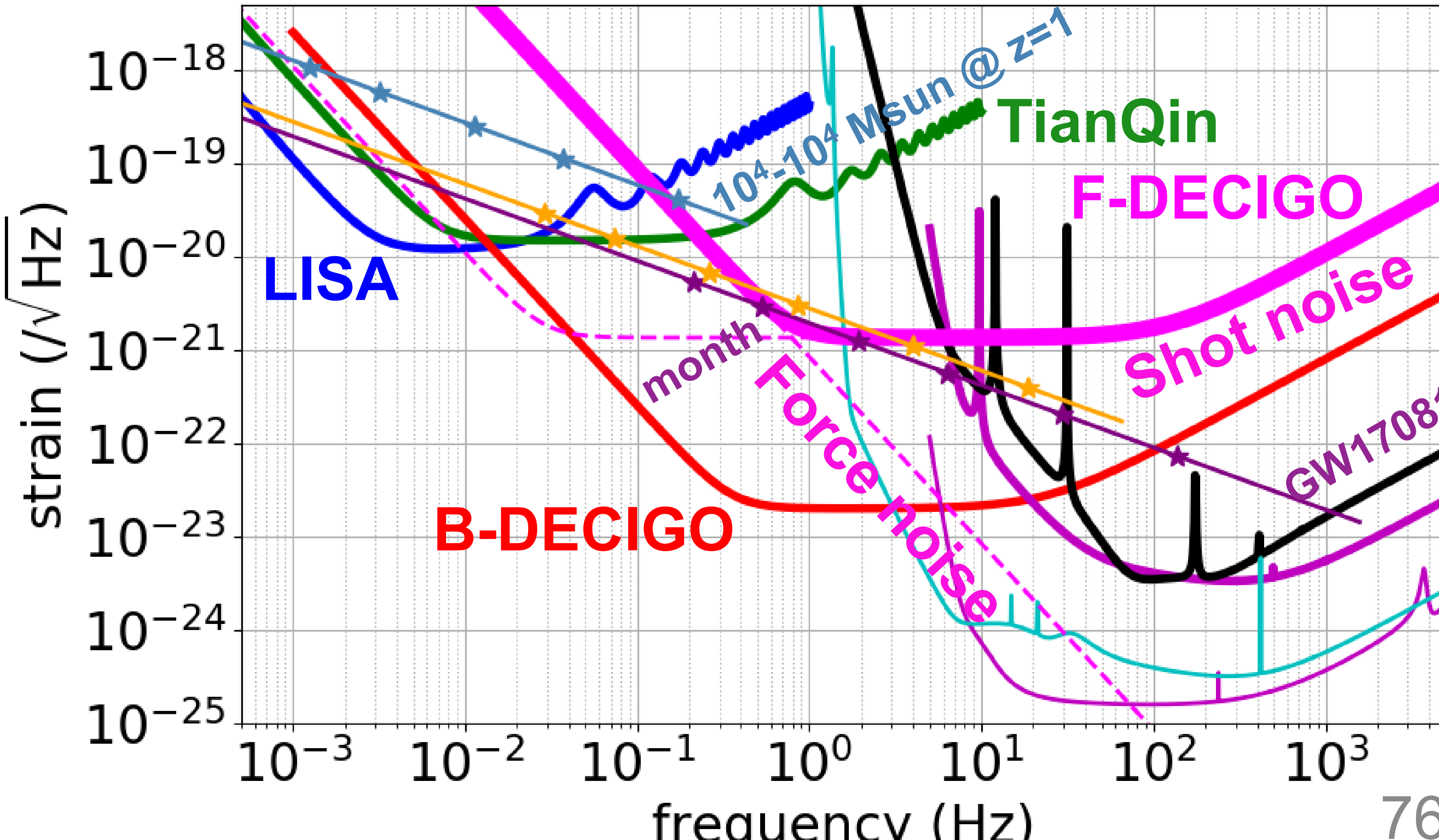


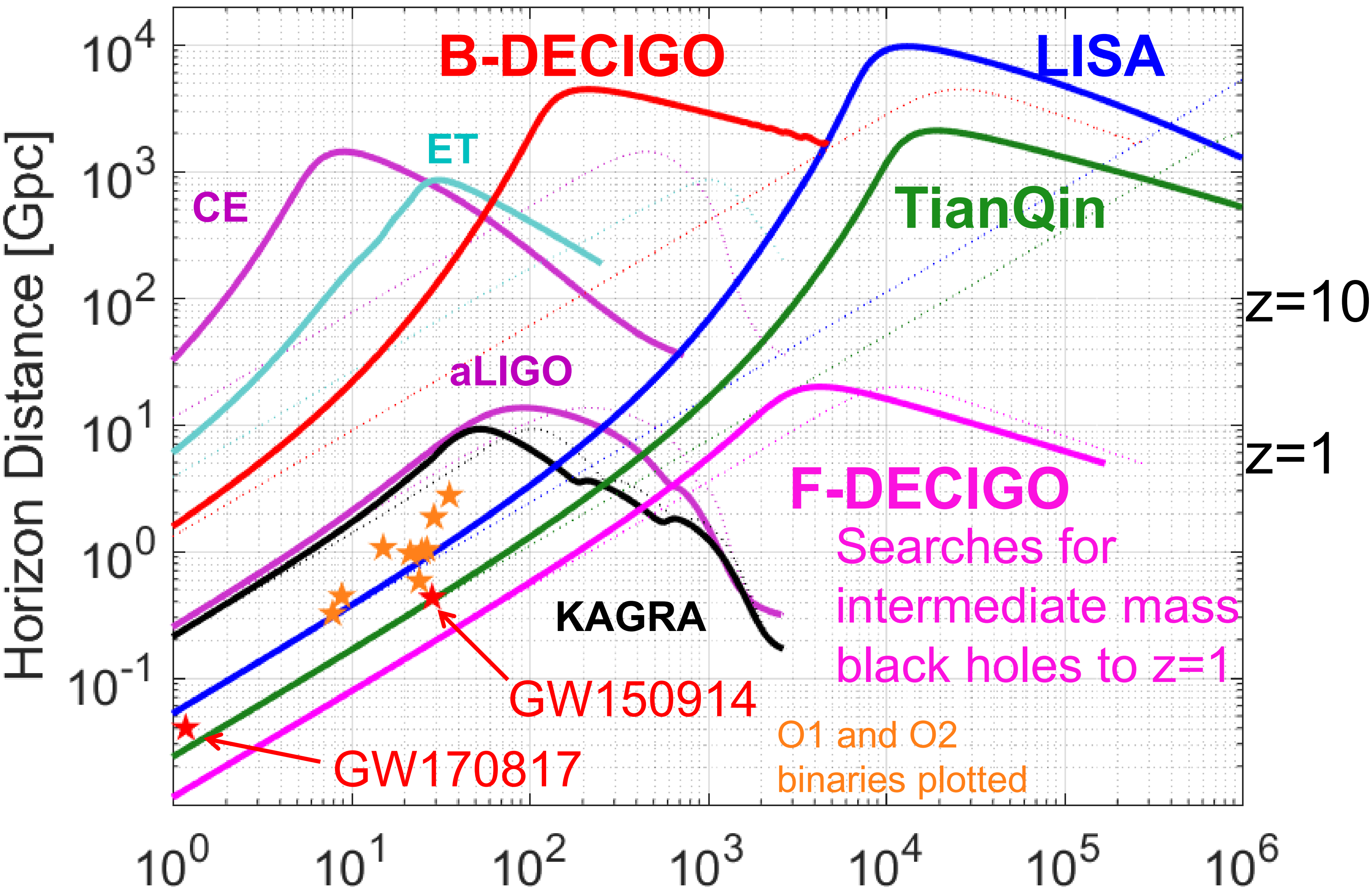
60 km & 2 kg “F-DECIGO” Concept

- 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



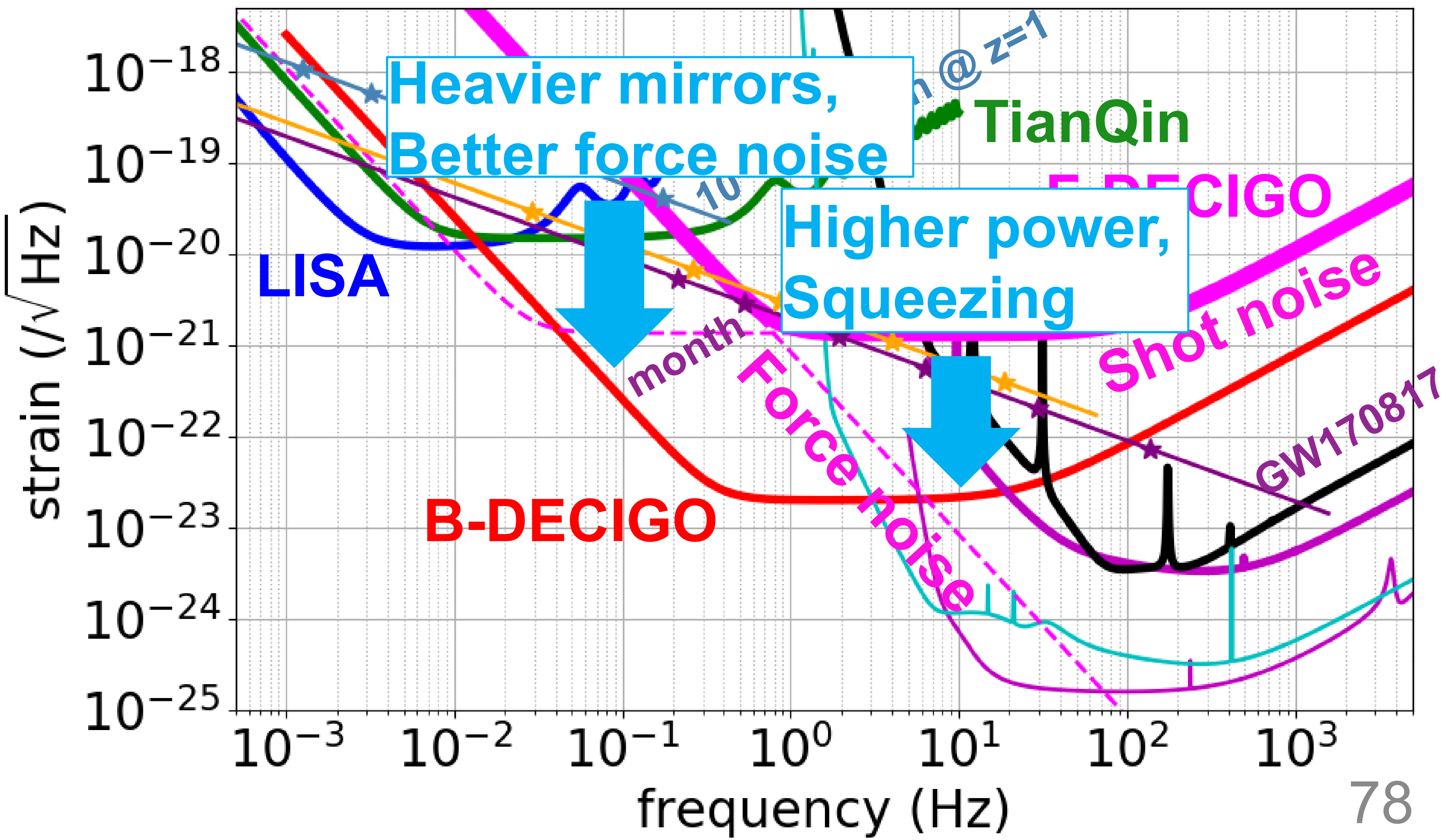
Horizon Distance



Optimal direction and polarization
SNR threshold 8

Beyond F-DECIGO Concept

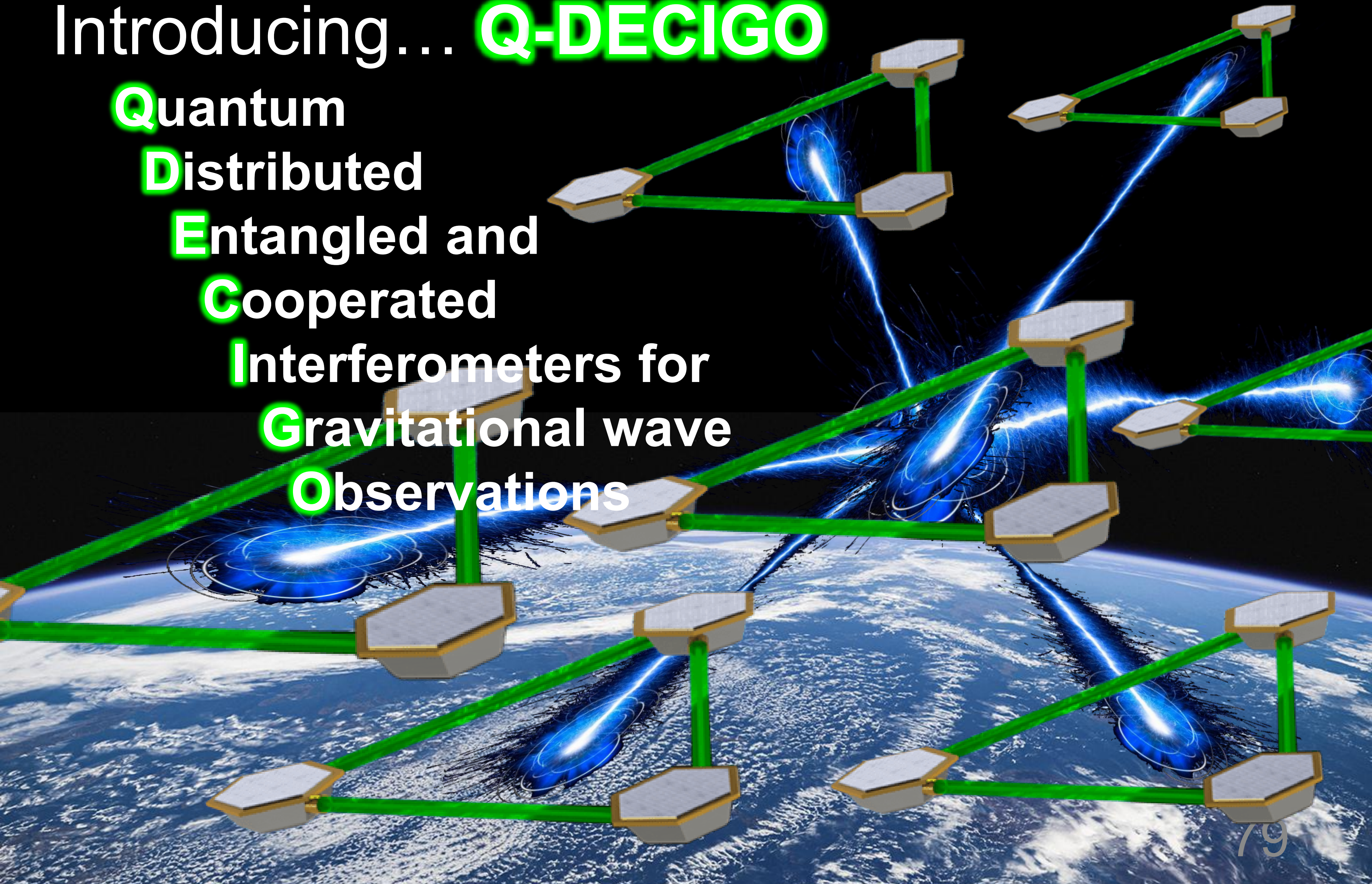
- Heavier mirrors are required for better range



Not Satisfied?

Introducing… Q-DECIGO

Quantum
Distributed
Entangled and
Cooperated
Interferometers for
Gravitational wave
Observations

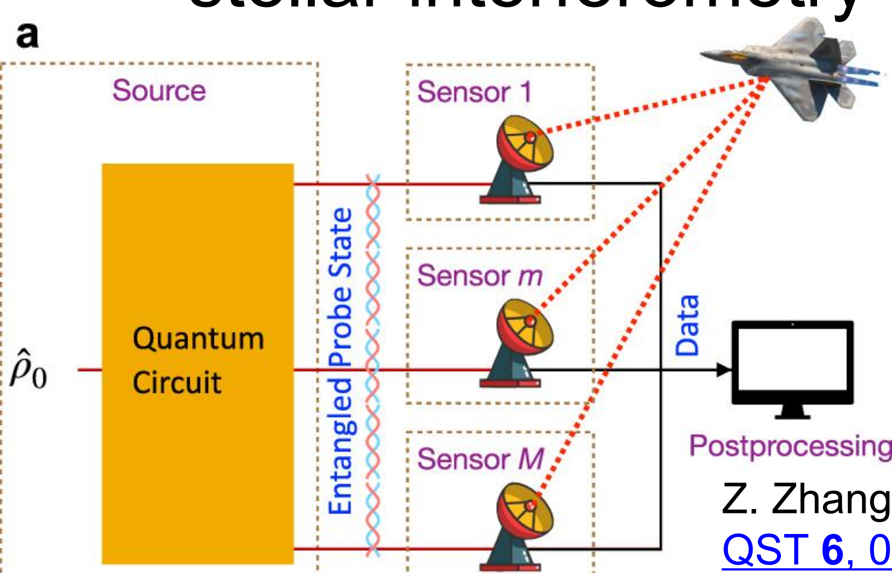


Distributed Quantum Sensing

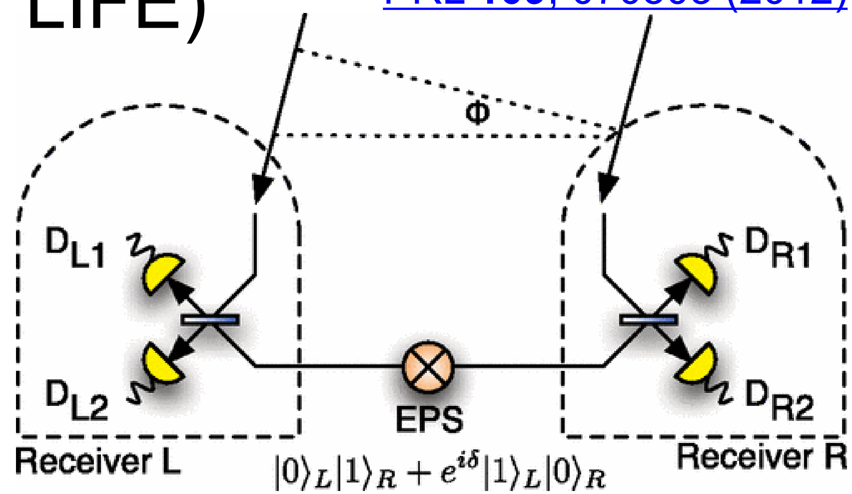
- By entangling sensing nodes, Heisenberg scaling is possible (∝ N instead of standard quantum limit scaling ∝ √N)
- ~100 of feasible F-DECIGO would make B-DECIGO sensitivity
- Can also be applied to long baseline stellar interferometry (e.g. LIFE)

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

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



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



Entangled Photon Source

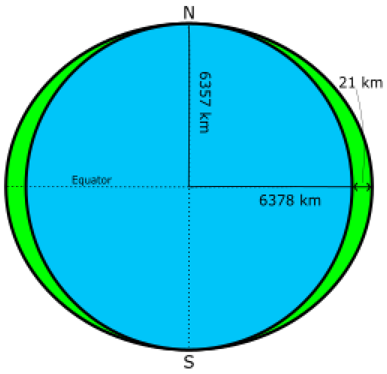
Q-DECIGO Orbit

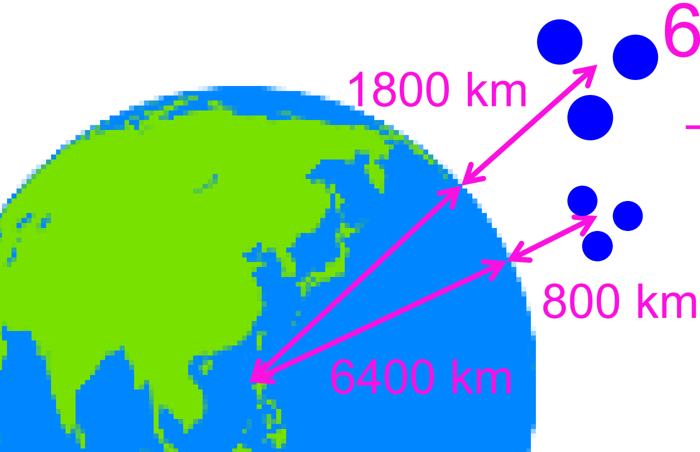
- If geocentric orbit, relative force from Earth J2 term is proportional to mL

J2 coefficient, Earth mass, Mirror mass, Arm length

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

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

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

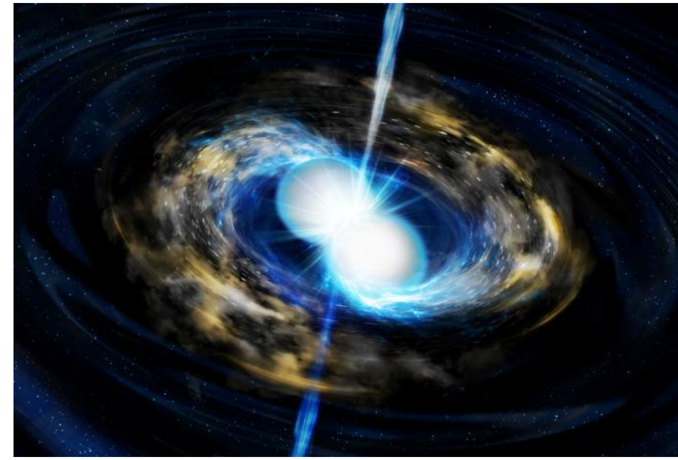
$$< 3 \times 10^{-21}/\sqrt{\mathrm{Hz}} \,@\, 0.5\,\mathrm{Hz}$$

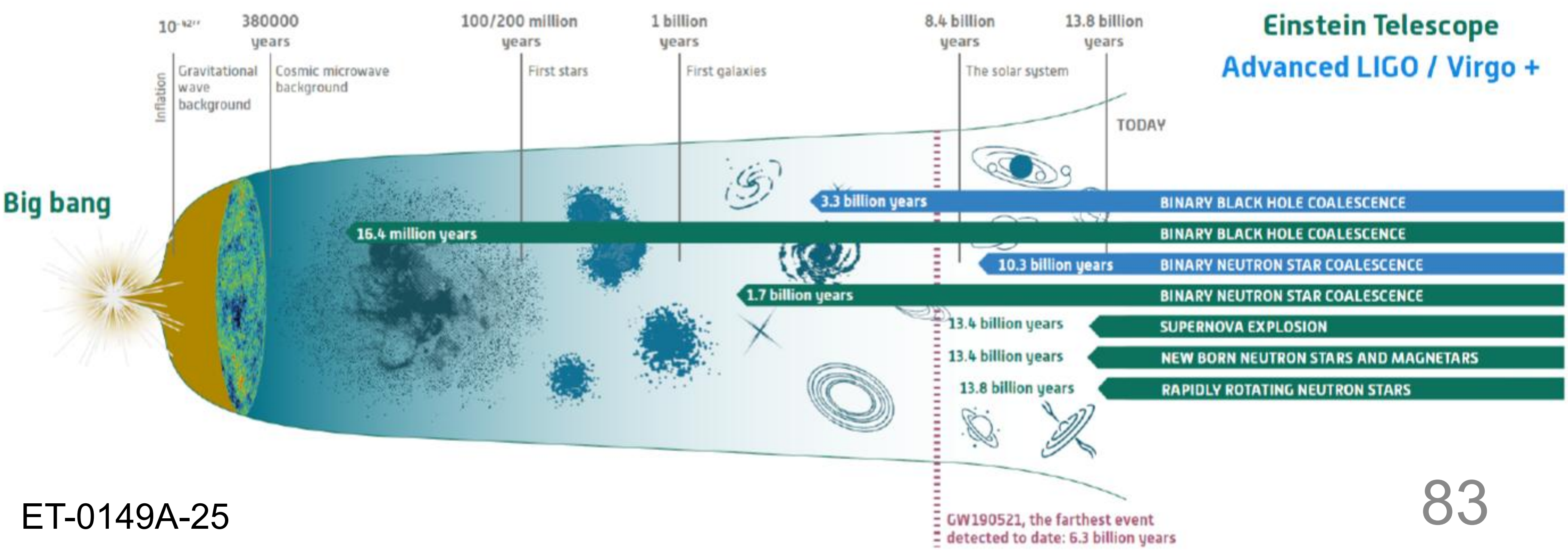
This requires altitude higher than 3.3e7 m with dynamic range 10^7 rtHz
(Geosynchronous orbit 3.6e7 m will do)

- This cannot be avoided by increasing mL
  $\rightarrow$ Low Earth orbit won't work. Back-linked?

Summary

- The future is bright and loud!
- The future is yours to shape!





Assignment for Dec 5

- Describe your overall impressions of the lectures and list up the topics you want to study further.
- You may also answer from the Google Form below https://forms.gle/6AwJ48XcpWQXqMon9

Don’t forget to put your name and student#

You may answer in any language