Physics Colloquium @ Cornell University

December 2, 2024

The future of gravitational wave detectors

Yuta Michimura

道村 唯太

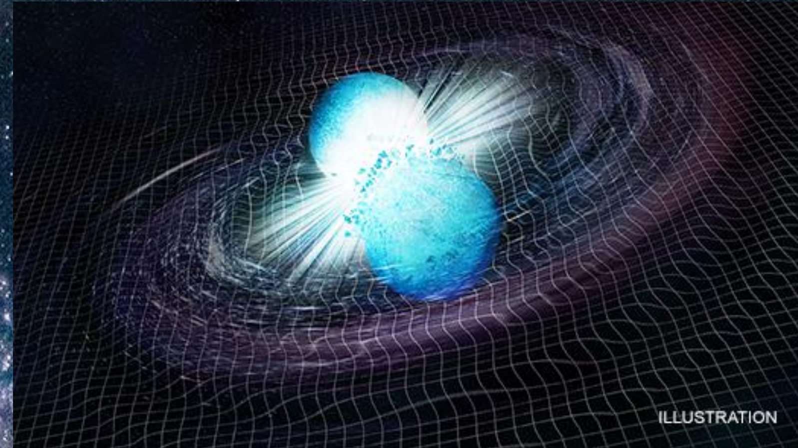
RESCEU, University of Tokyo

michimura@resceu.s.u-tokyo.ac.jp

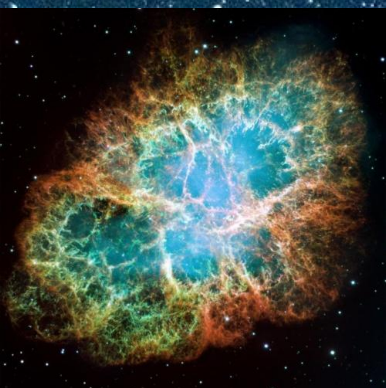
Slides are available at https://tinyurl.com/YM20241202

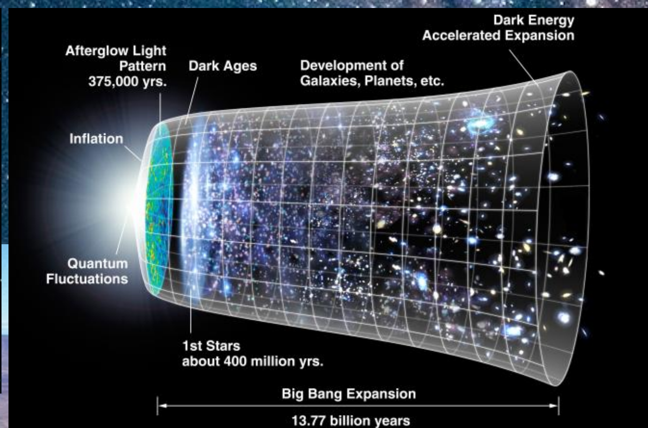
SLIDES

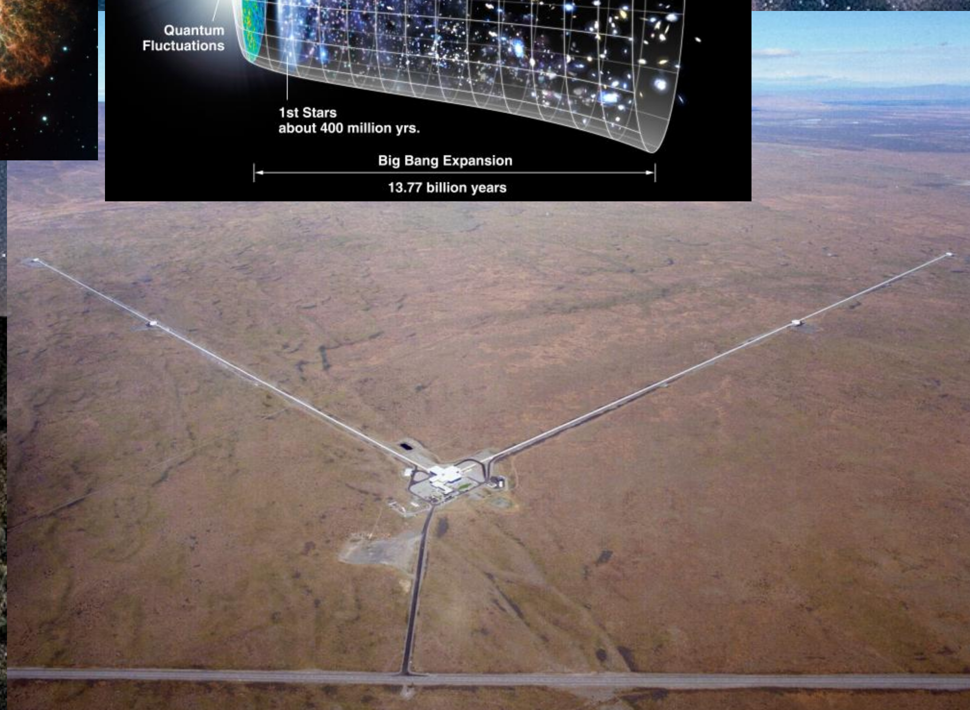

Star
HIP 65426
Exoplanet
HIP 65426 b
JWST
NIRCam
F300M
NIRCam
F444W
MIRI
F1140C
Planet
MIRI
F1550C
Credit:NAOJ



ILLUSTRATION

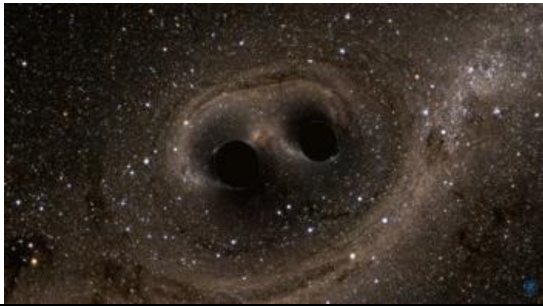


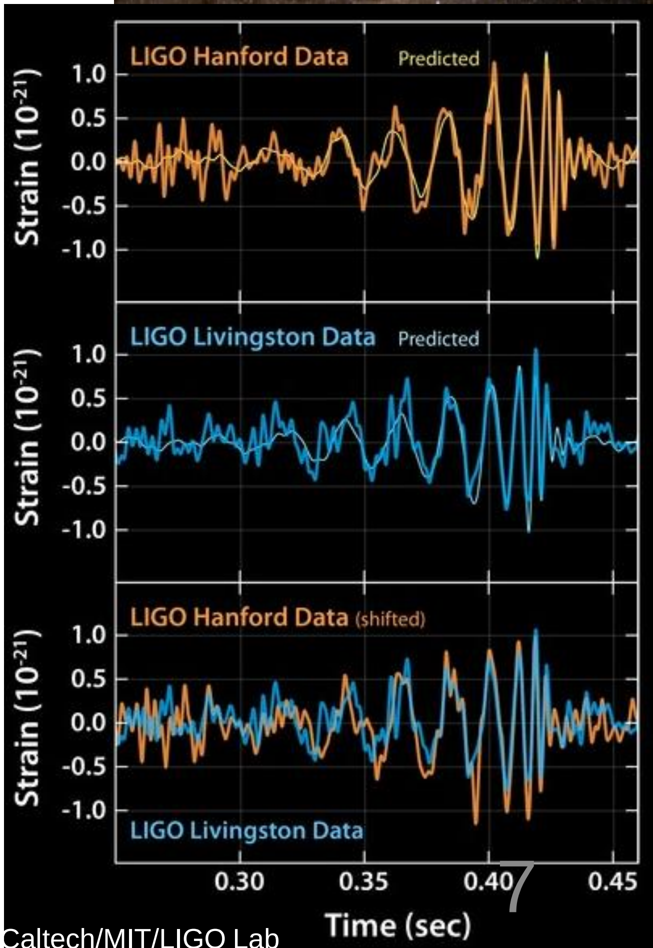

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years



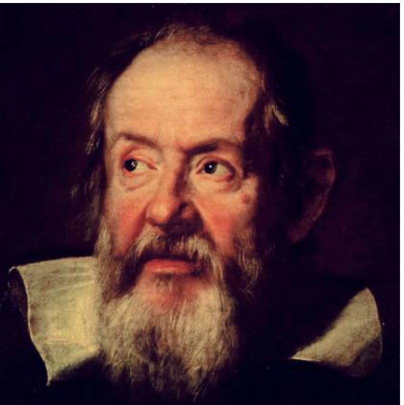
GW150914: First Sound

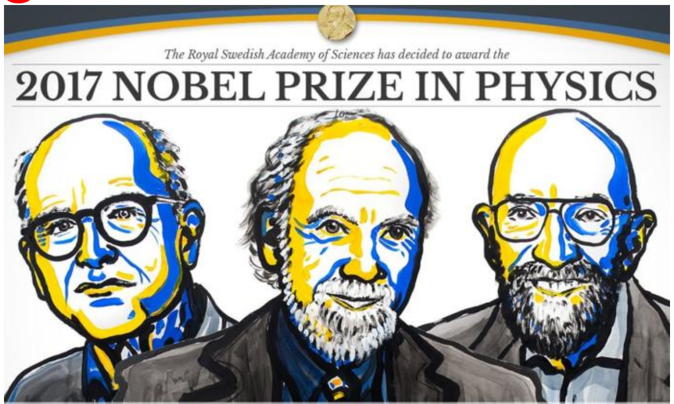
- **September 14, 2015**: Two LIGO detectors in the US detected gravitational waves from merging black holes
  → Beginning of astronomy with "sound"
- **1609**: Galileo made telescopes
  → Beginning of astronomy with "light" (electromagnetic waves)





Caltech/MIT/LIGO Lab



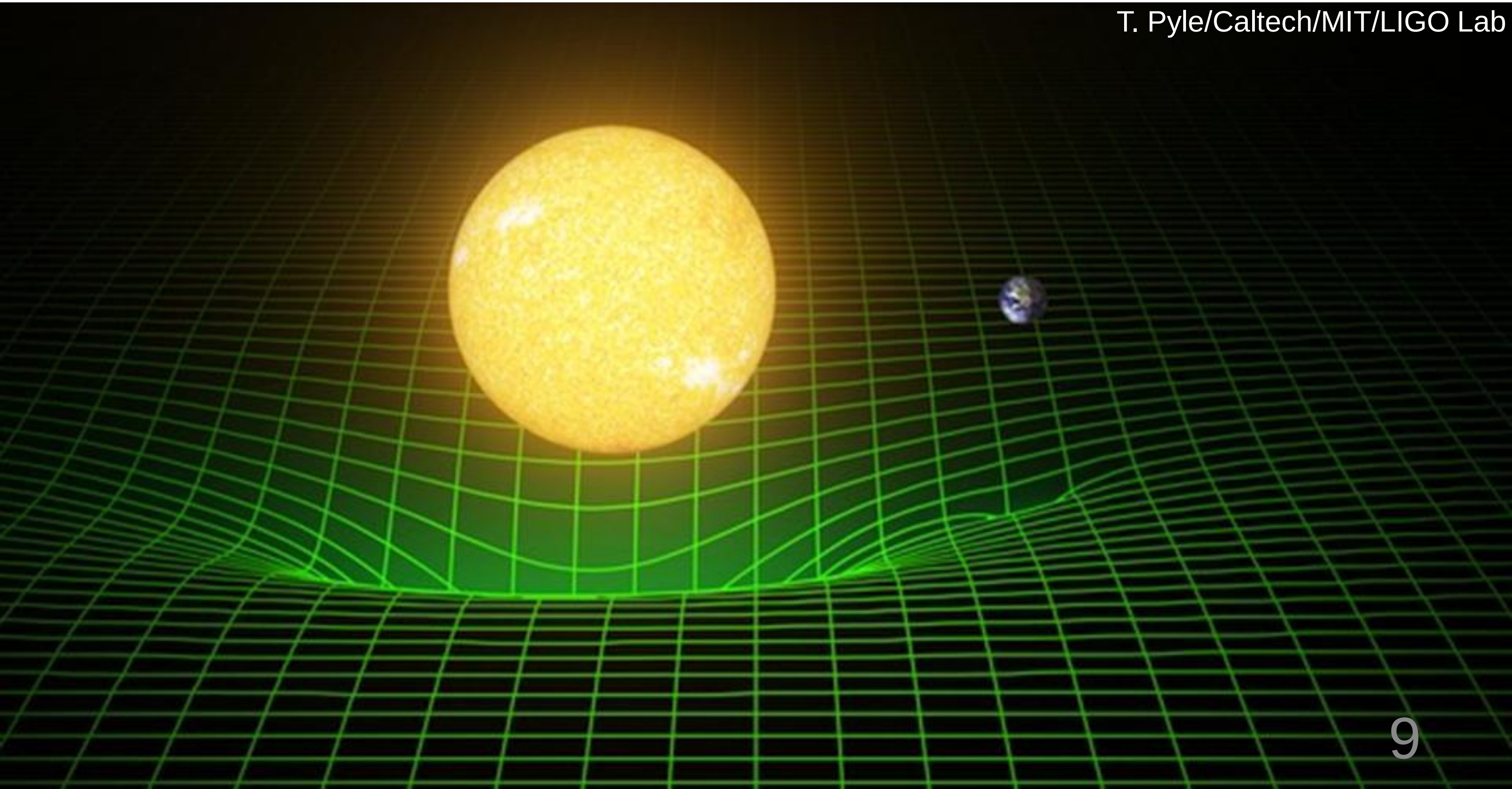


Plan of the Talk

- **What are gravitational waves?**
  - Einstein's general relativity
- **How do we detect them?**
  - Laser interferometer
- **The status of gravitational wave observations**
  - By LIGO-Virgo-KAGRA detectors
- **Next generation detectors**
  - Voyager, Cosmic Explorer, Einstein Telescope
- **Space-based detectors**
  - LISA, DECIGO
- **Particle physics with GW detectors**
  - Ultralight dark matter, quantum gravity

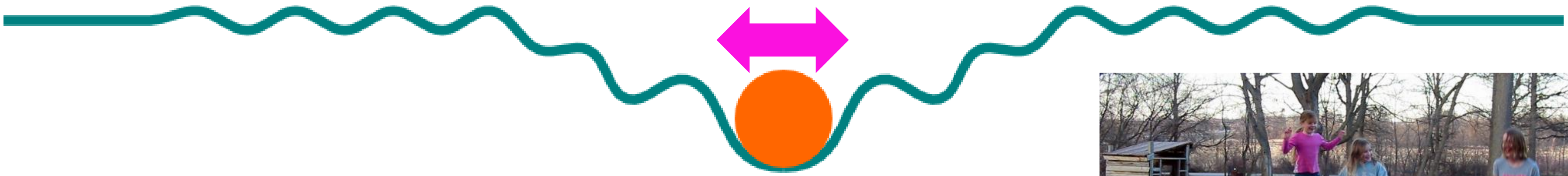
Gravity in General Relativity

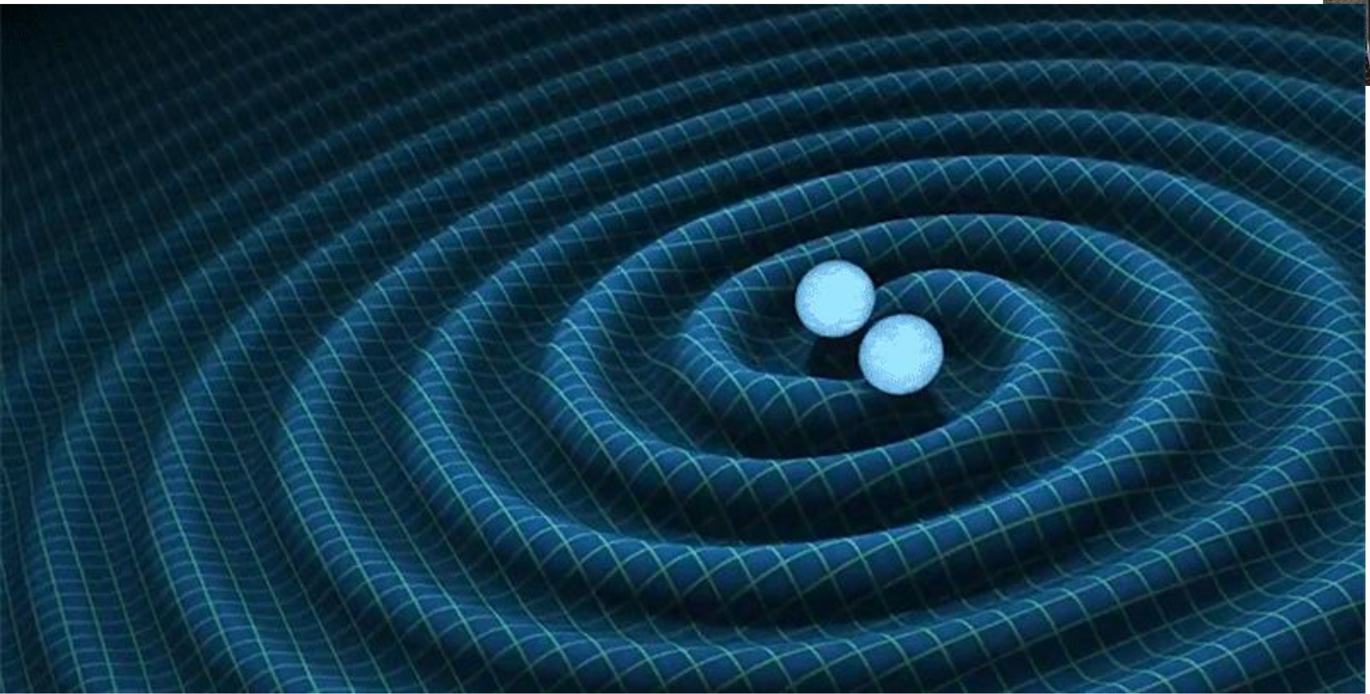
- space-time bends with presence of mass
- bending affects motion of objects → gravity



Gravitational Waves

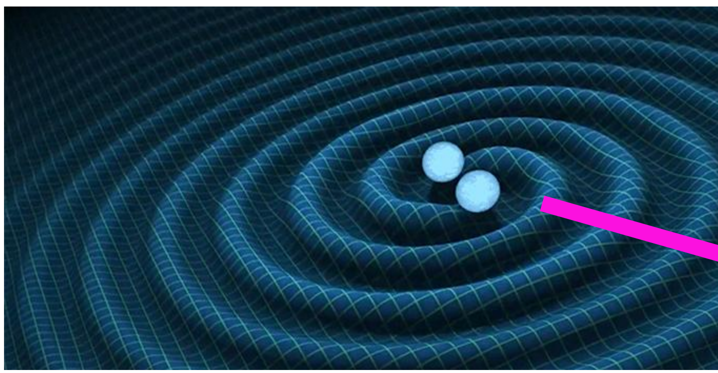
- ripples in space-time created by motion of objects

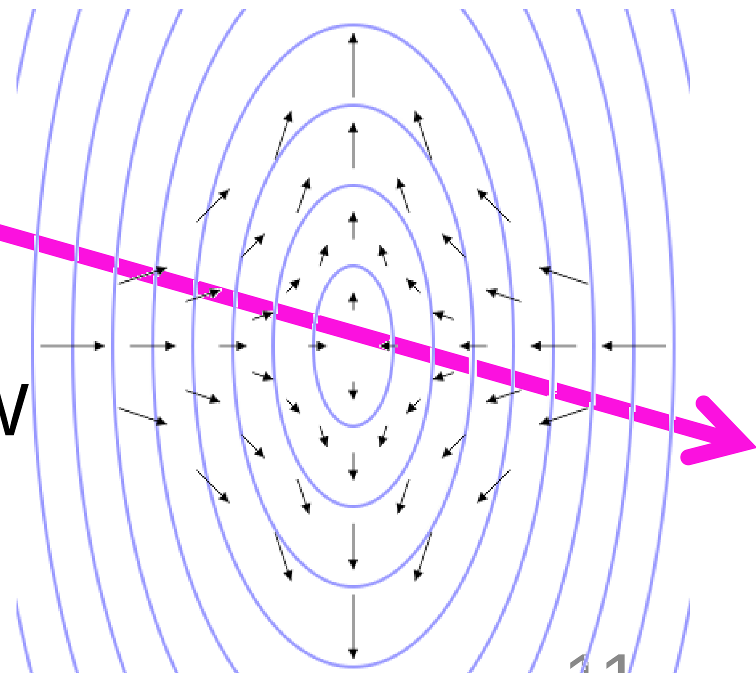




Characteristics of GWs

- propagates at the speed of light
- quadrupole radiation (+ mode and x mode)
- high transmissivity $\leftrightarrow$ very weak interaction



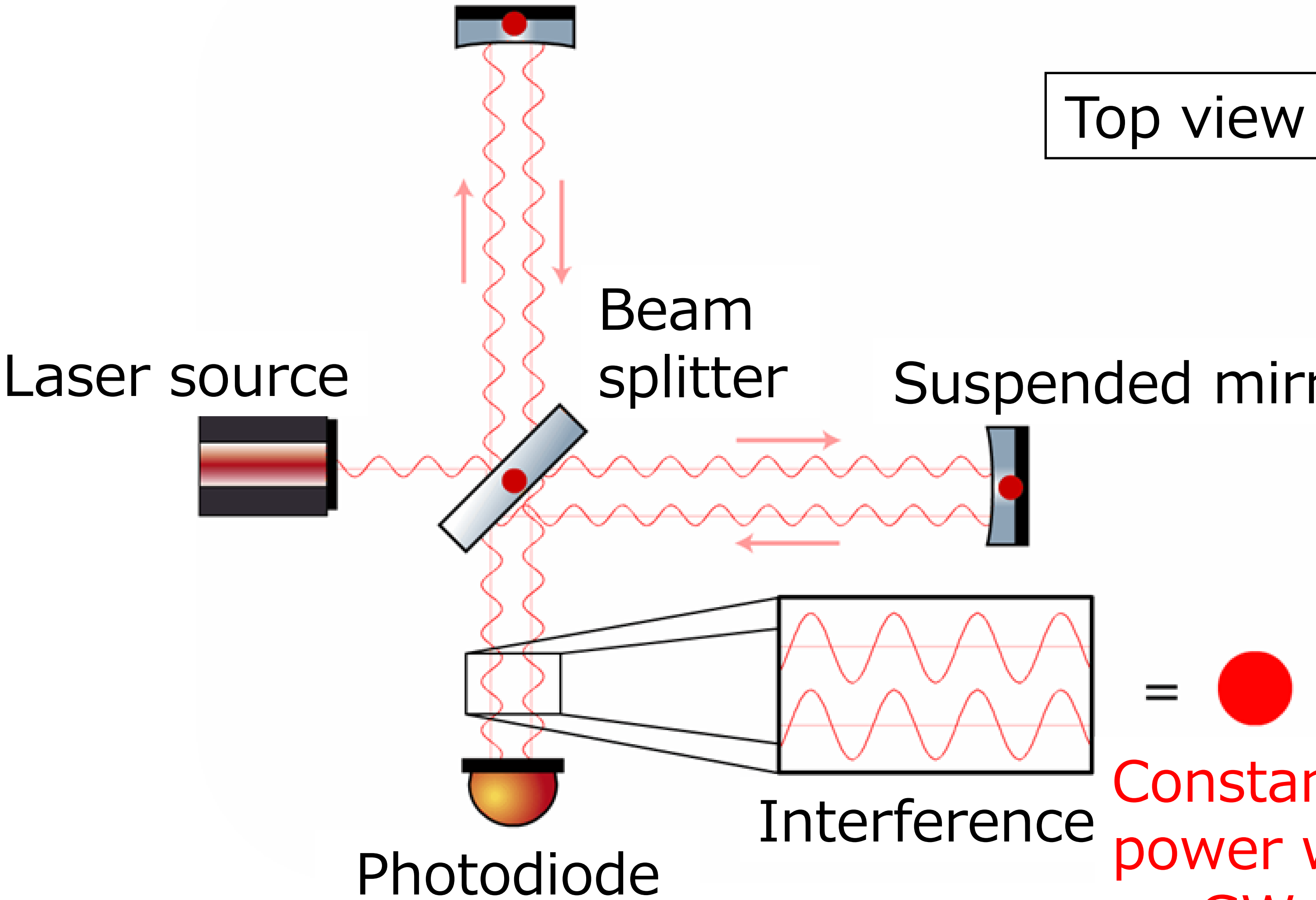


- large mass and large acceleration creates large GW
- GW strain
  = fraction of length change

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

Laser Interferometric GW Detector

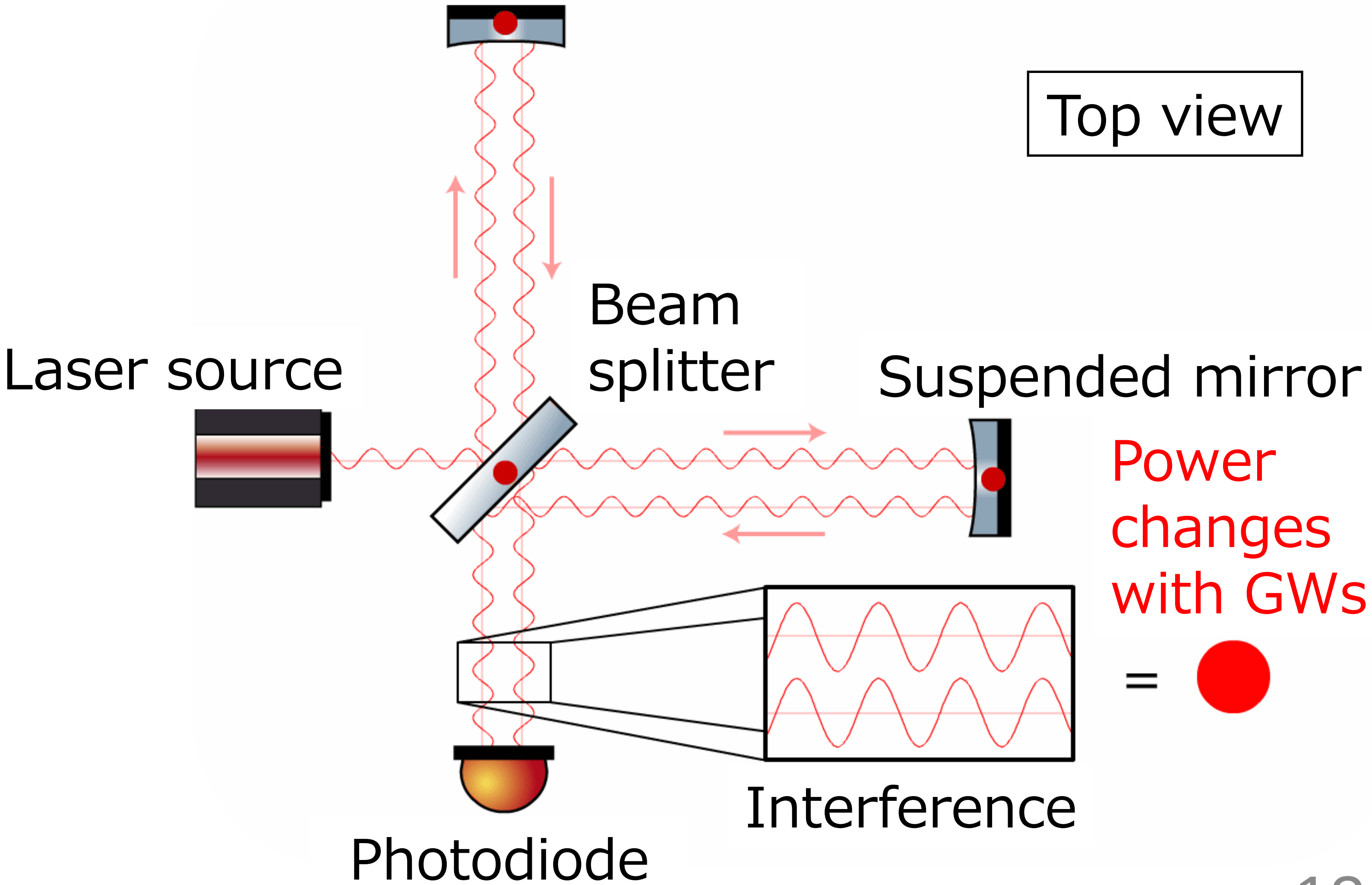
- measure differential arm length change



Constant power when no GW

Laser Interferometric GW Detector

- measure differential arm length change

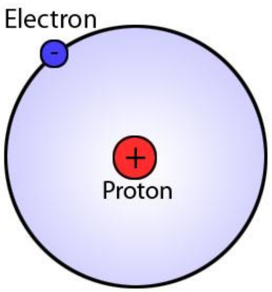


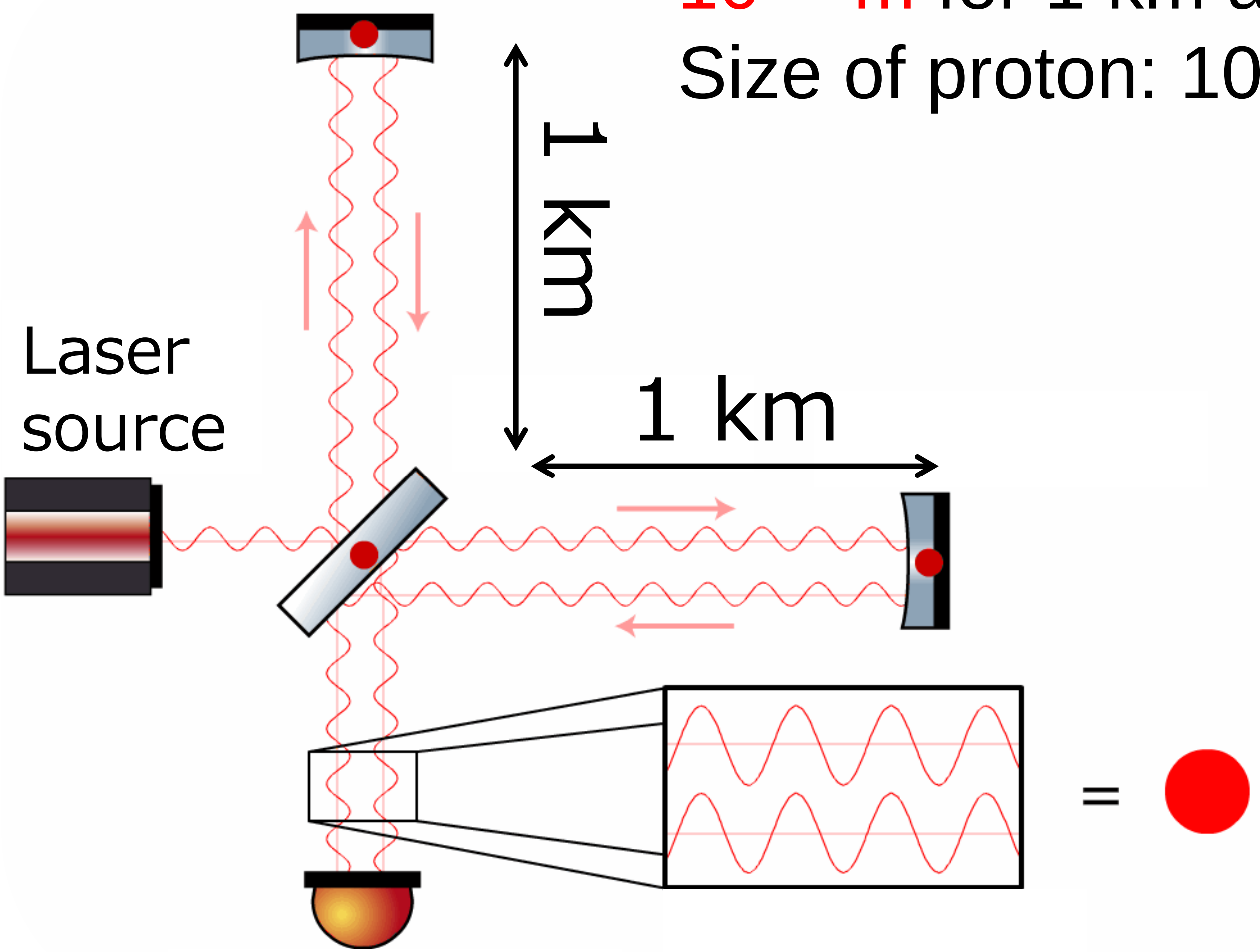
Amplitude of GW is Tiny

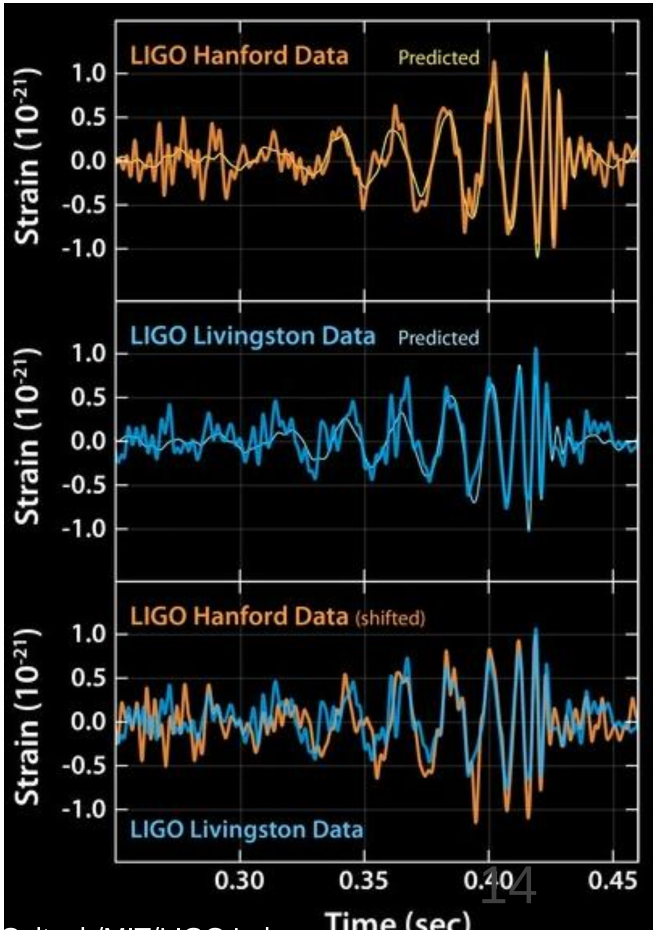
- for example, $h \sim 10^{-21}$

10^{-18} m for 1 km arm

Size of proton: 10^{-15} m

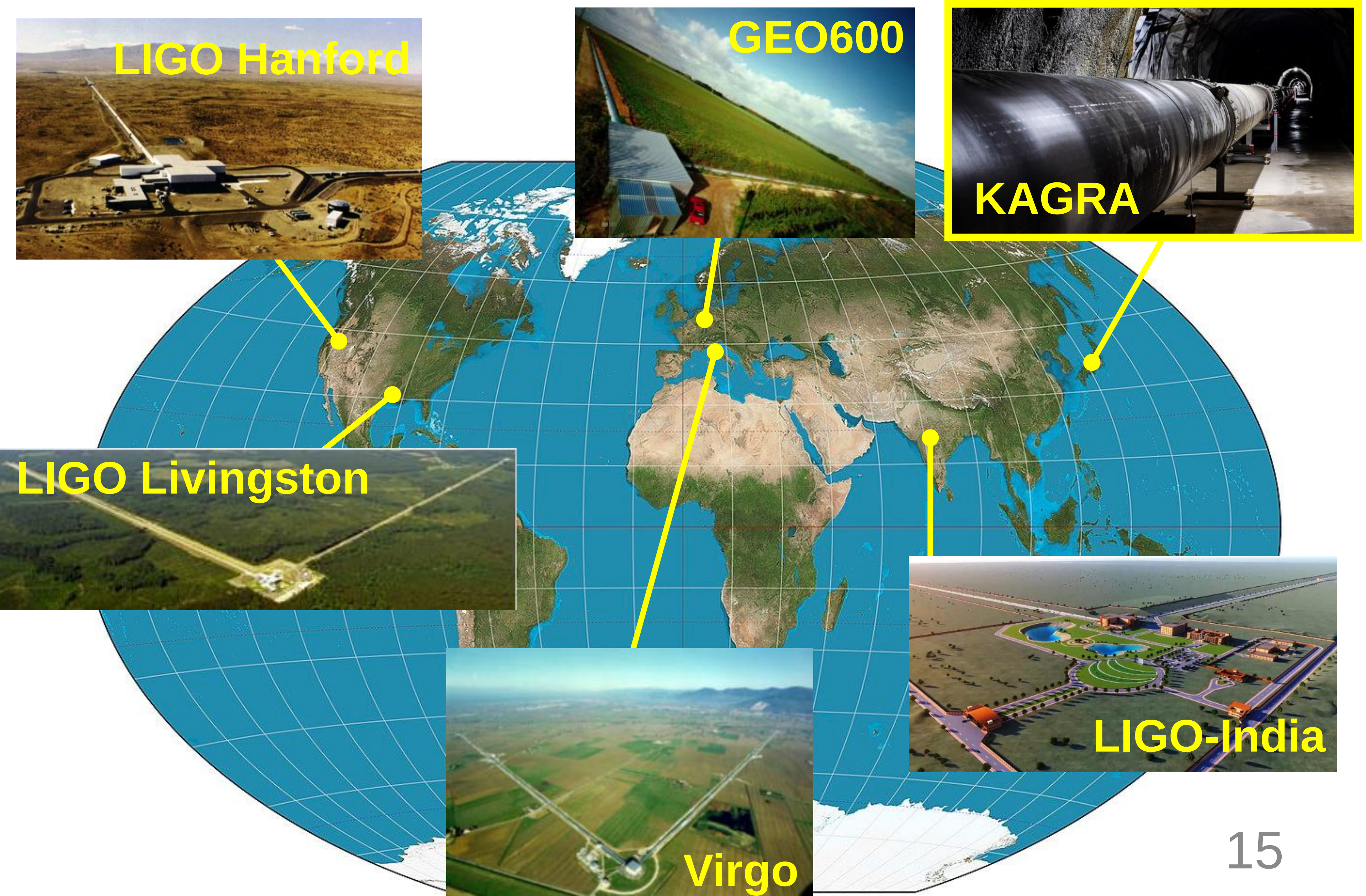






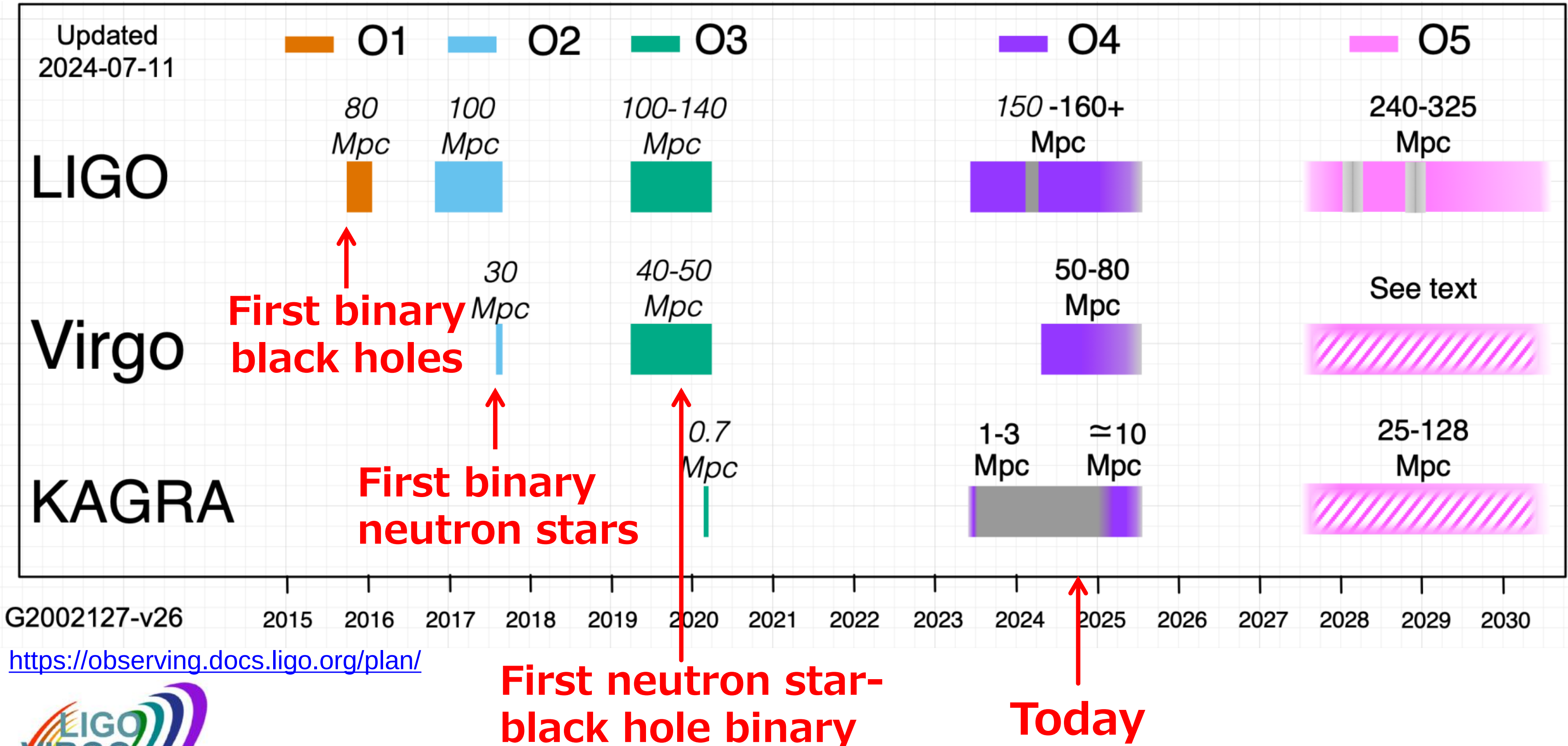
Caltech/MIT/LIGO Lab

Global Network of GW Detectors



LIGO-Virgo-KAGRA Observation

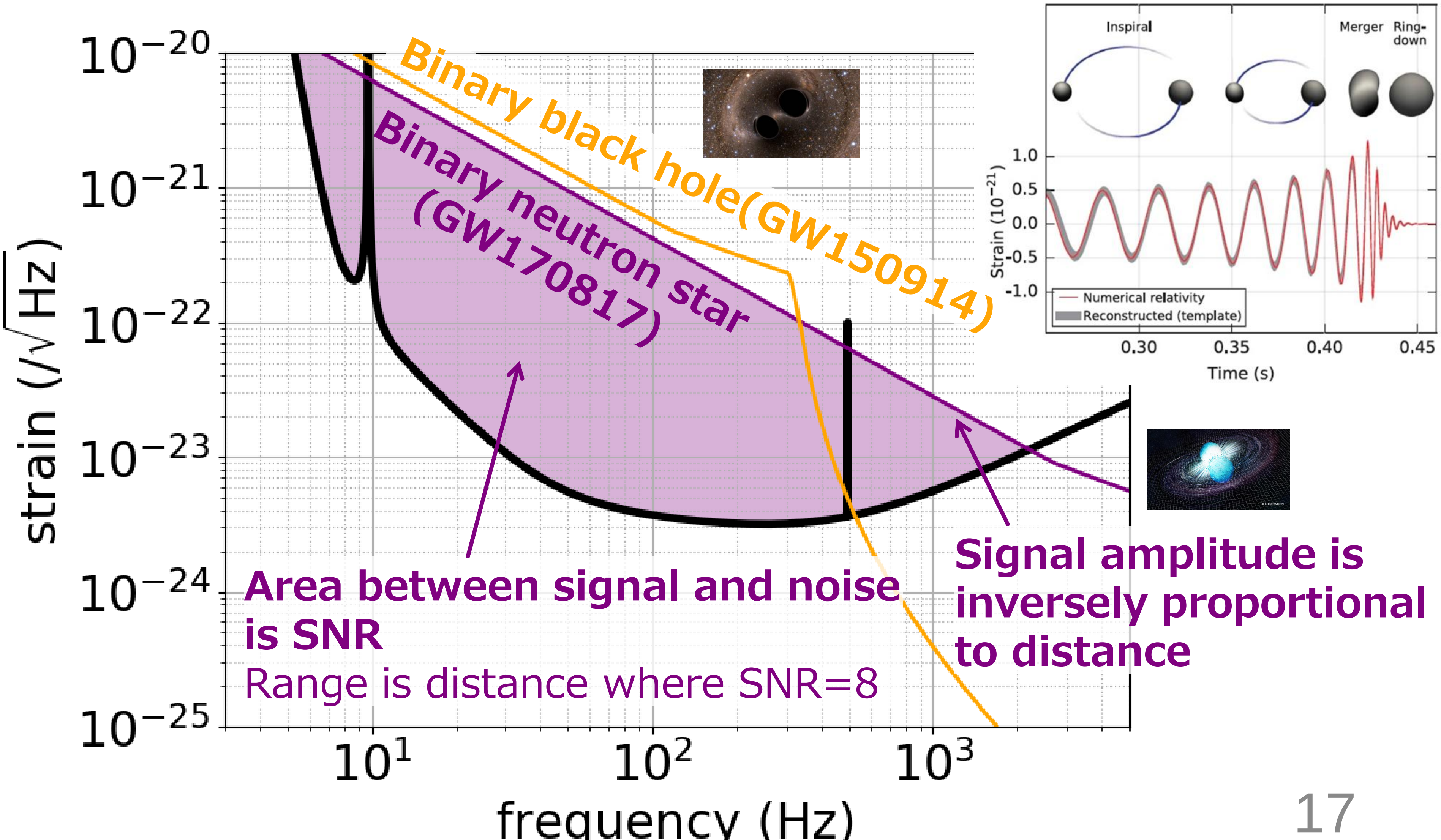
- Coordinated runs to detect GW signals by multiple detectors



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

Inspiral Range

- x2 the sensitivity, x8 the detection rate

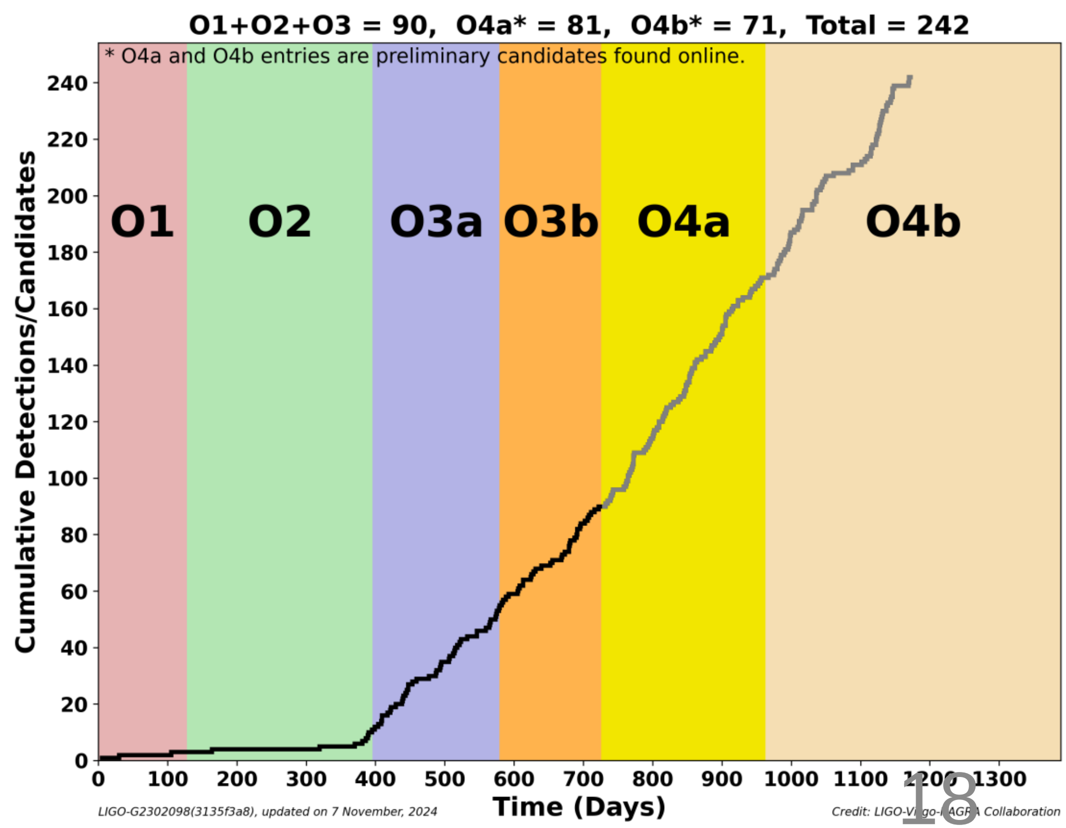


O4 Observing Run

- Started on May 24, 2024
- End on June 9, 2025 (planned)
- More than 150 events reported by LIGO and Virgo

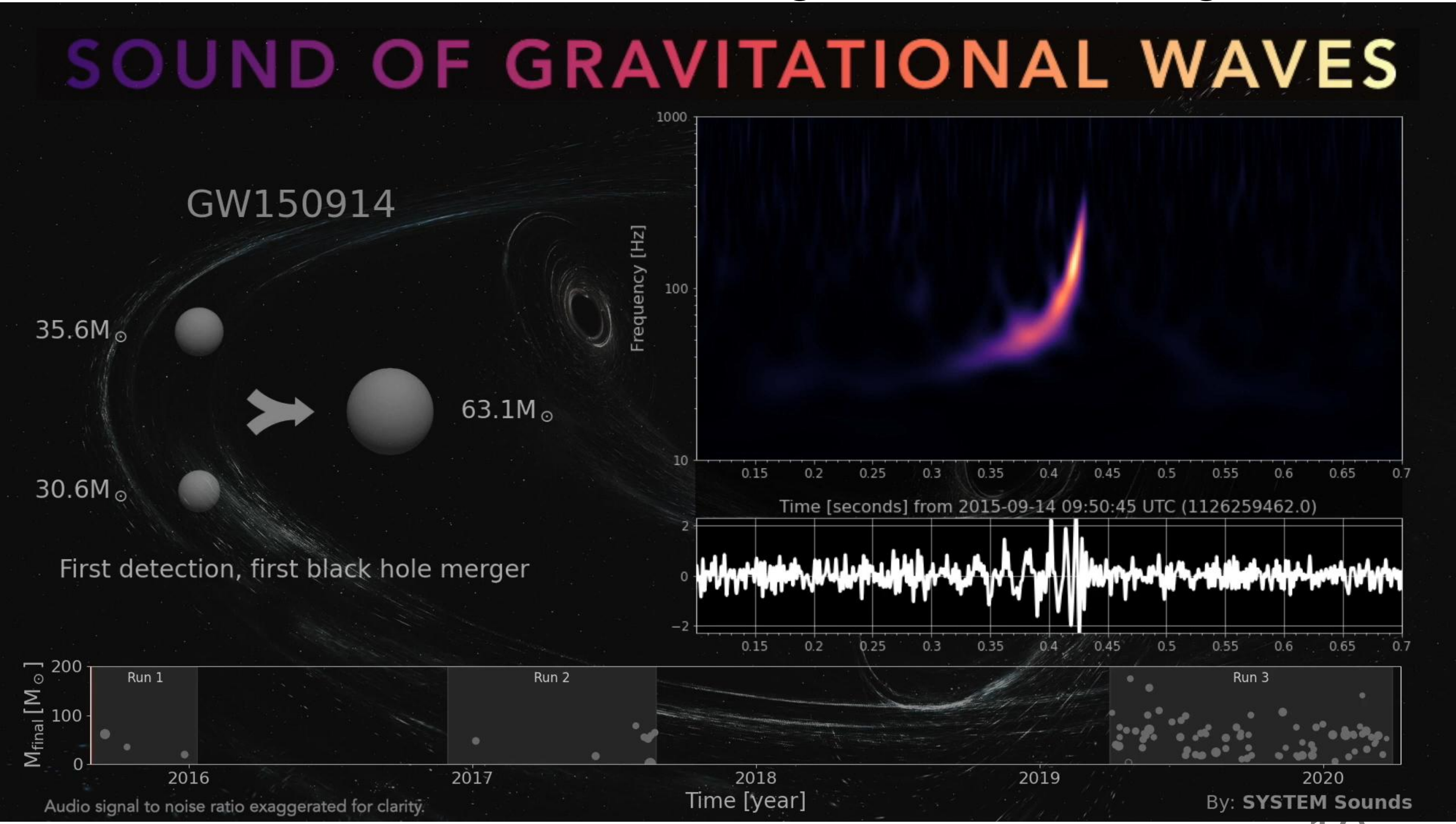
https://apps.apple.com/jp/app/gravitational-wave-events/id1441897107

LIGO-G2302098



Sound from Binary Coalescences

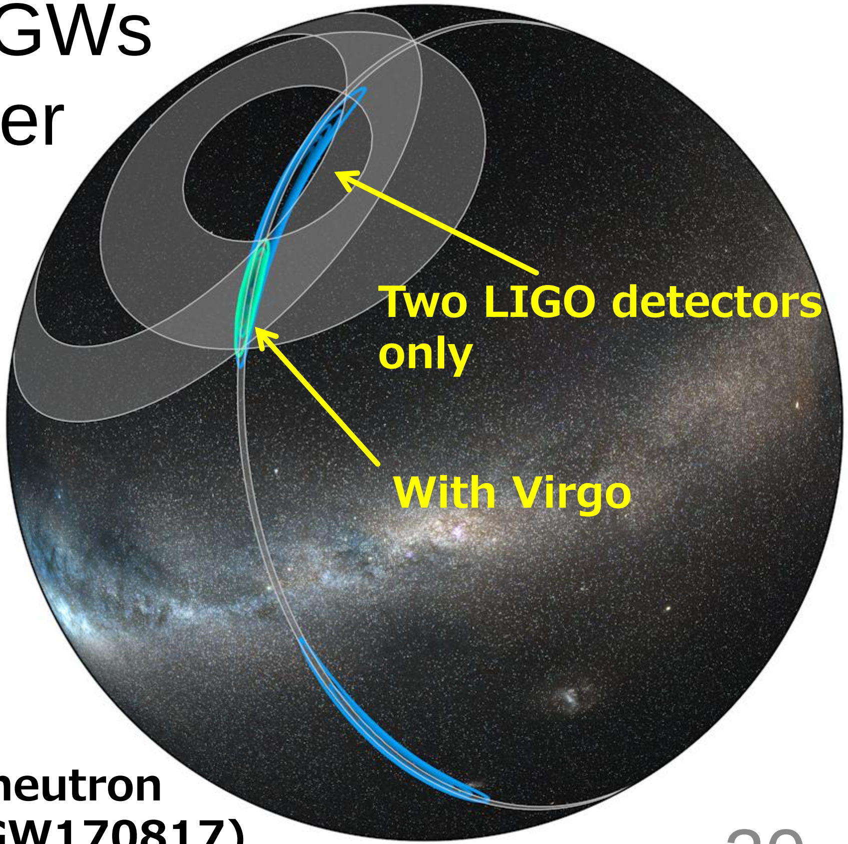
- Louder if closer, tone is higher if mass is lighter

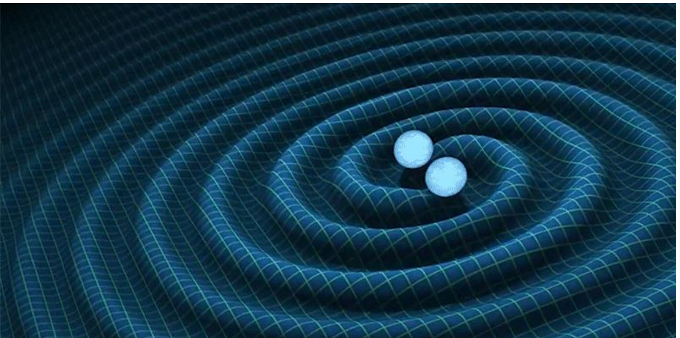


https://youtu.be/gT1VwCTe_90

Why Multiple Detectors?

- Triangulation for sky localization
  → allows to look for electro-magnetic counterparts (hear and see the event)
- Measure polarization of GWs to estimate distance better
  → Hubble constant
- Look for non-standard GW polarizations to test general relativity



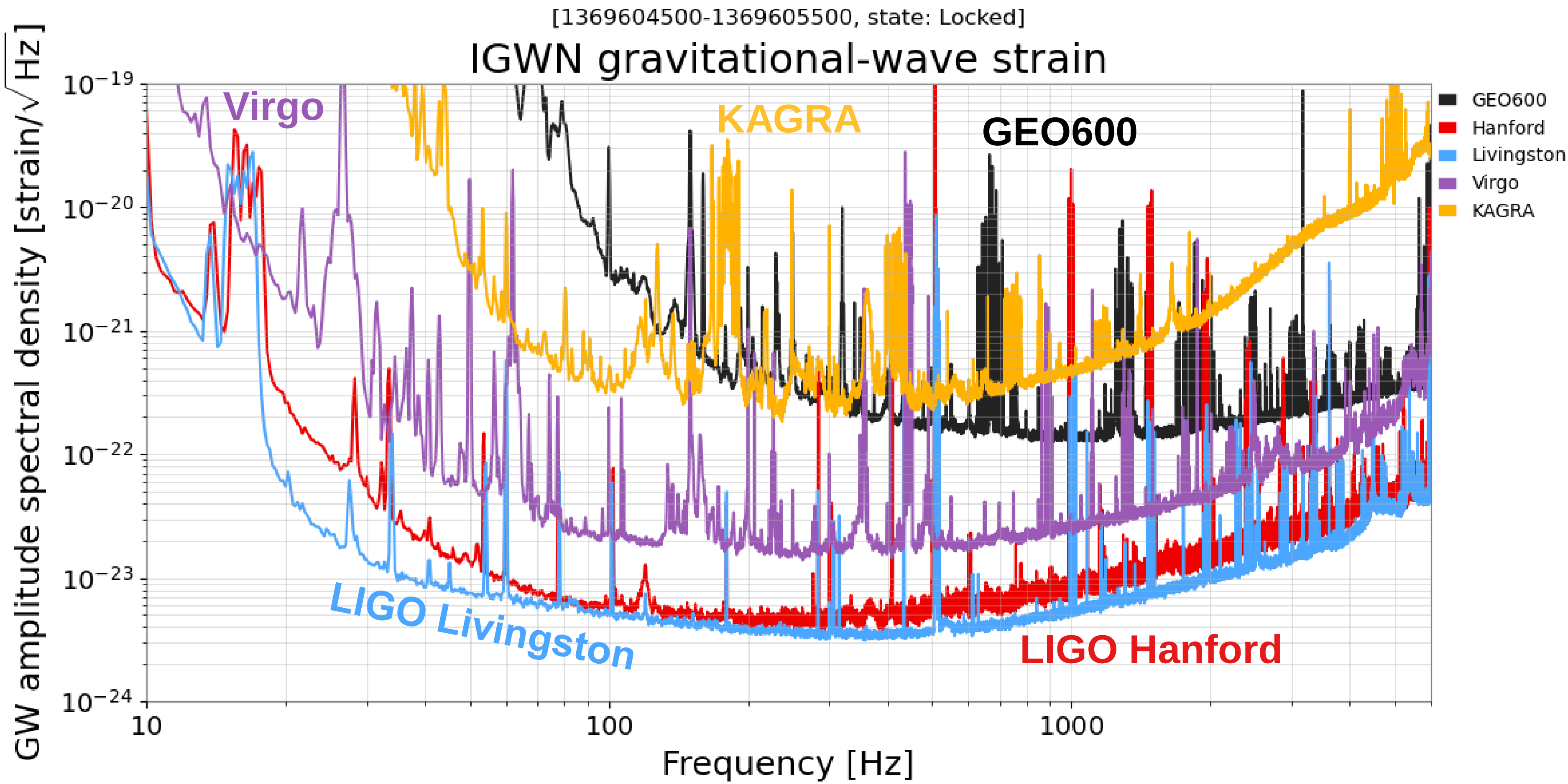


First binary neutron star event (GW170817)

Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)

Sensitivity Curves

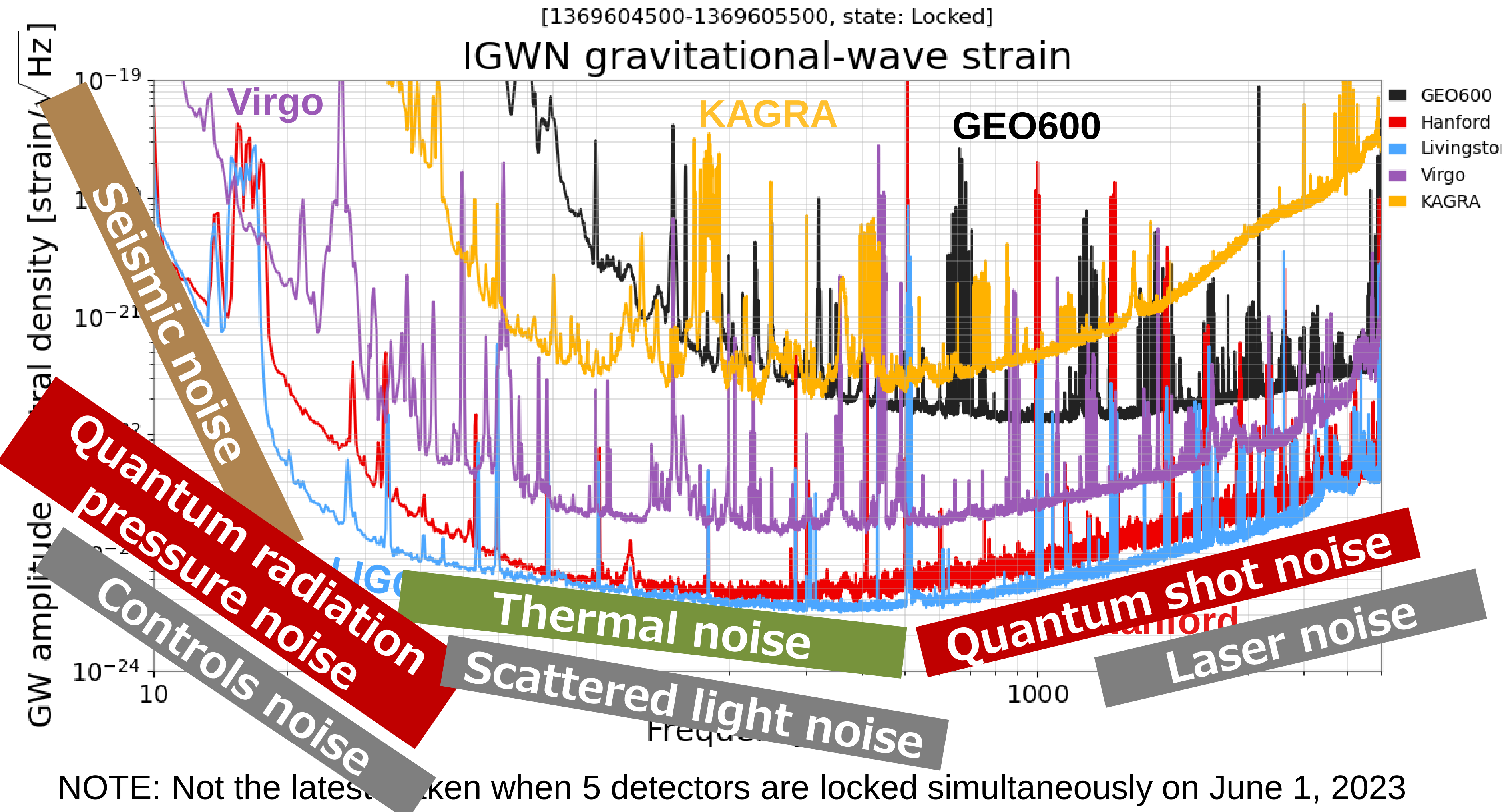
- Smaller the better in y-axis



NOTE: Not the latest. Taken when 5 detectors are locked simultaneously on June 1, 2023

Noise Sources

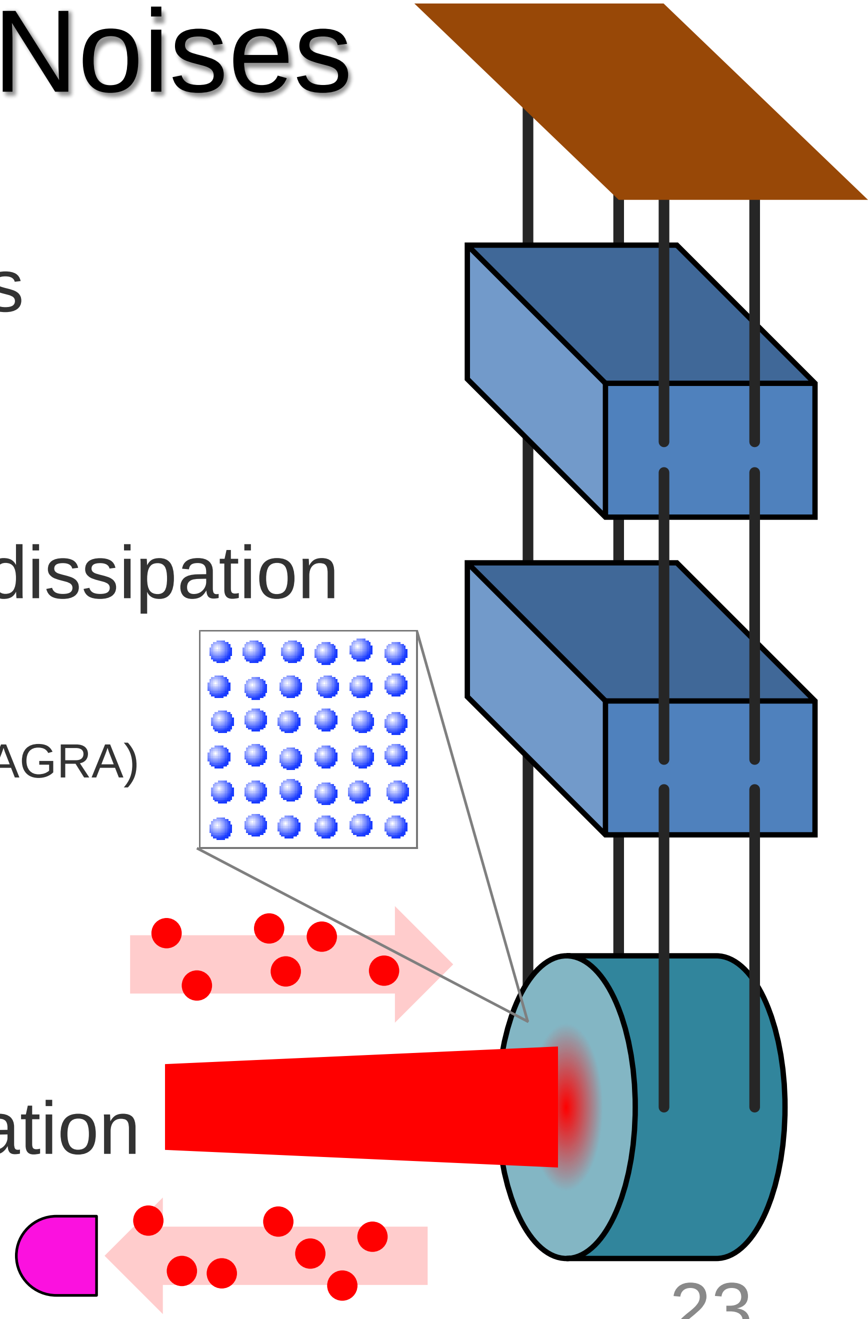
- Various noises limit the sensitivity



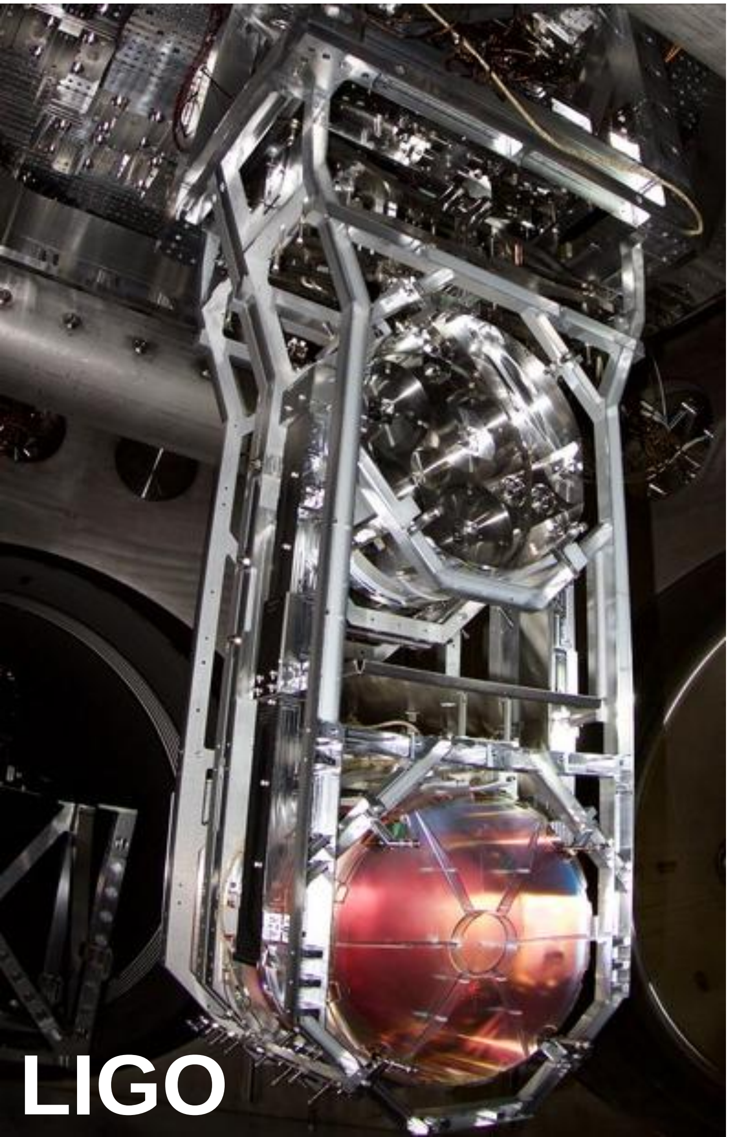
NOTE: Not the latest ... taken when 5 detectors are locked simultaneously on June 1, 2023

Reducing Noises

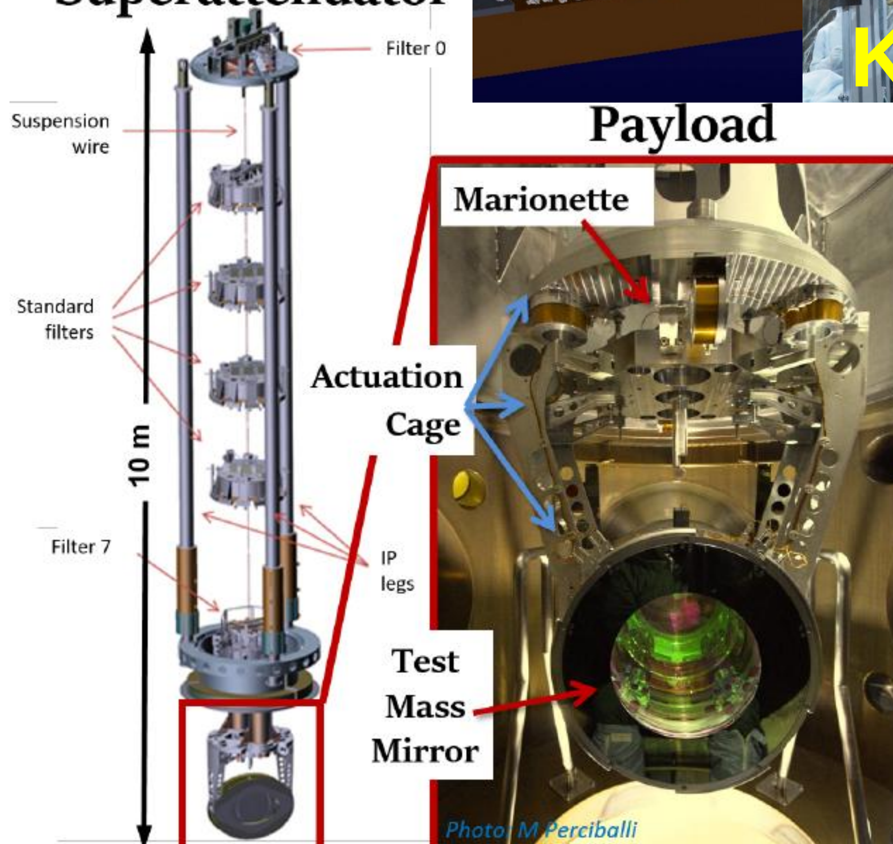
- Seismic noise
  - Multi-stage suspensions
  - Underground (only KAGRA)
- Thermal noise
  - Use materials with low dissipation
  - Larger beam size
  - Cryogenic cooling (only KAGRA)
- Quantum noise
  - Squeezing
  - Heavier mirrors
  - Interferometer configuration
- Larger is better $h = \frac{\delta L}{L}$

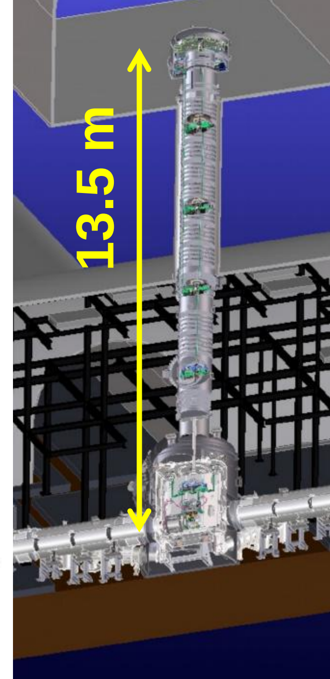


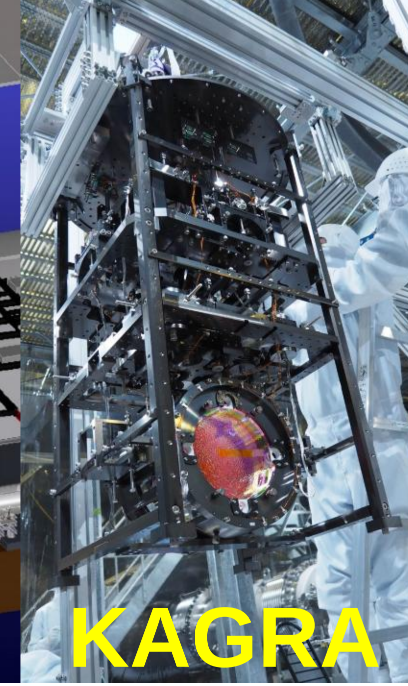
Vibration Isolation Systems



Virgo Superattenuator

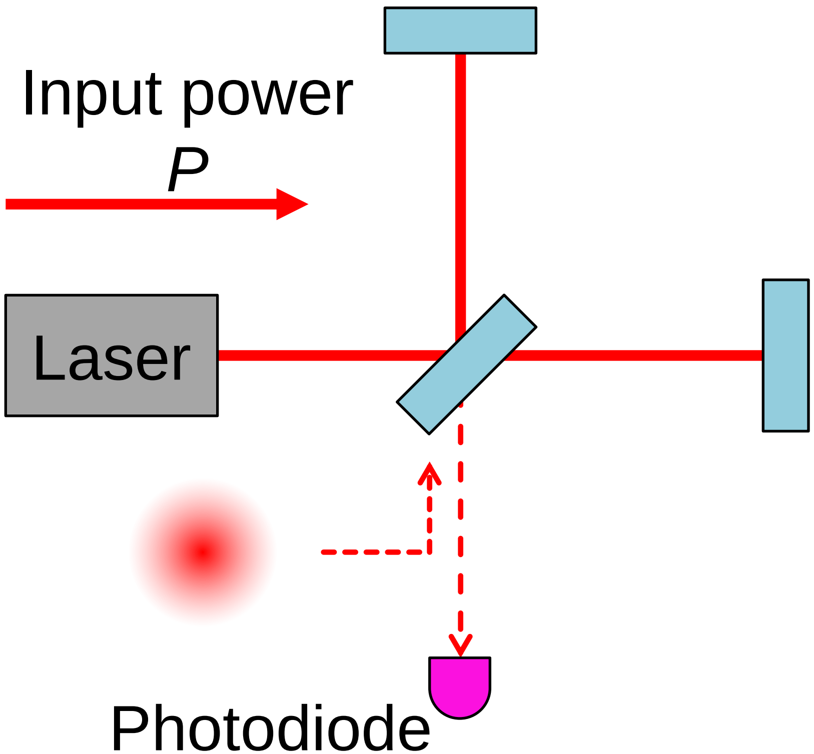


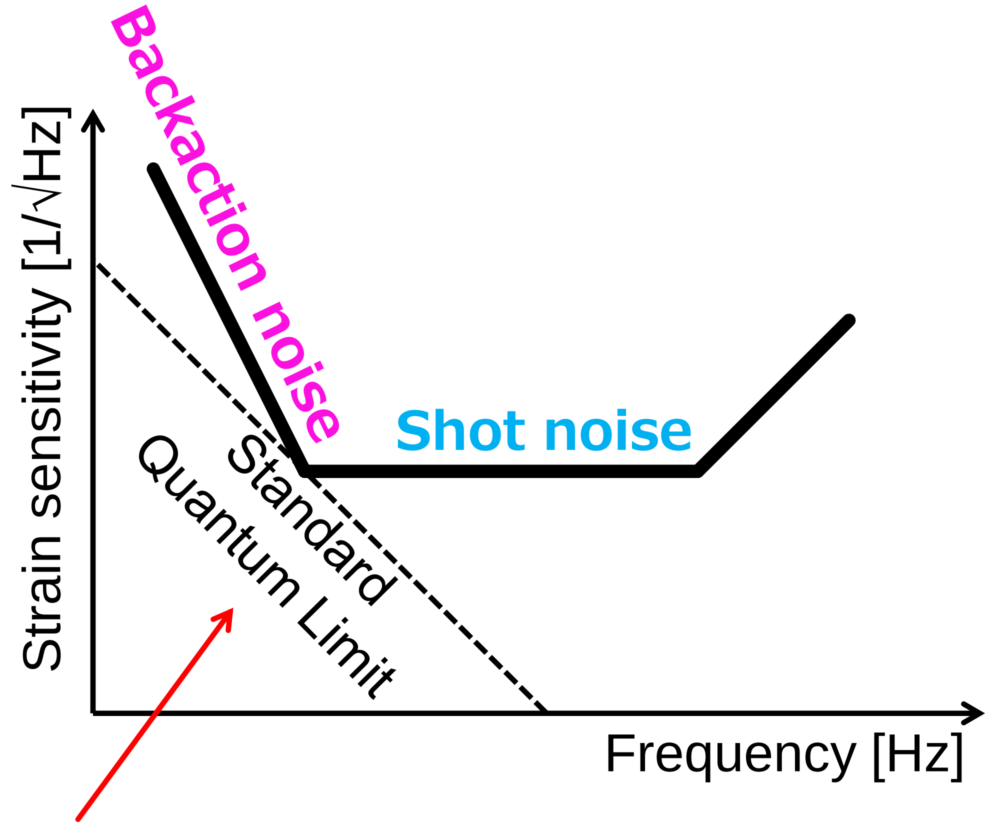




Quantum Noise

- Shot noise $\propto 1/\sqrt{P}$, Backaction $\propto \sqrt{P}$



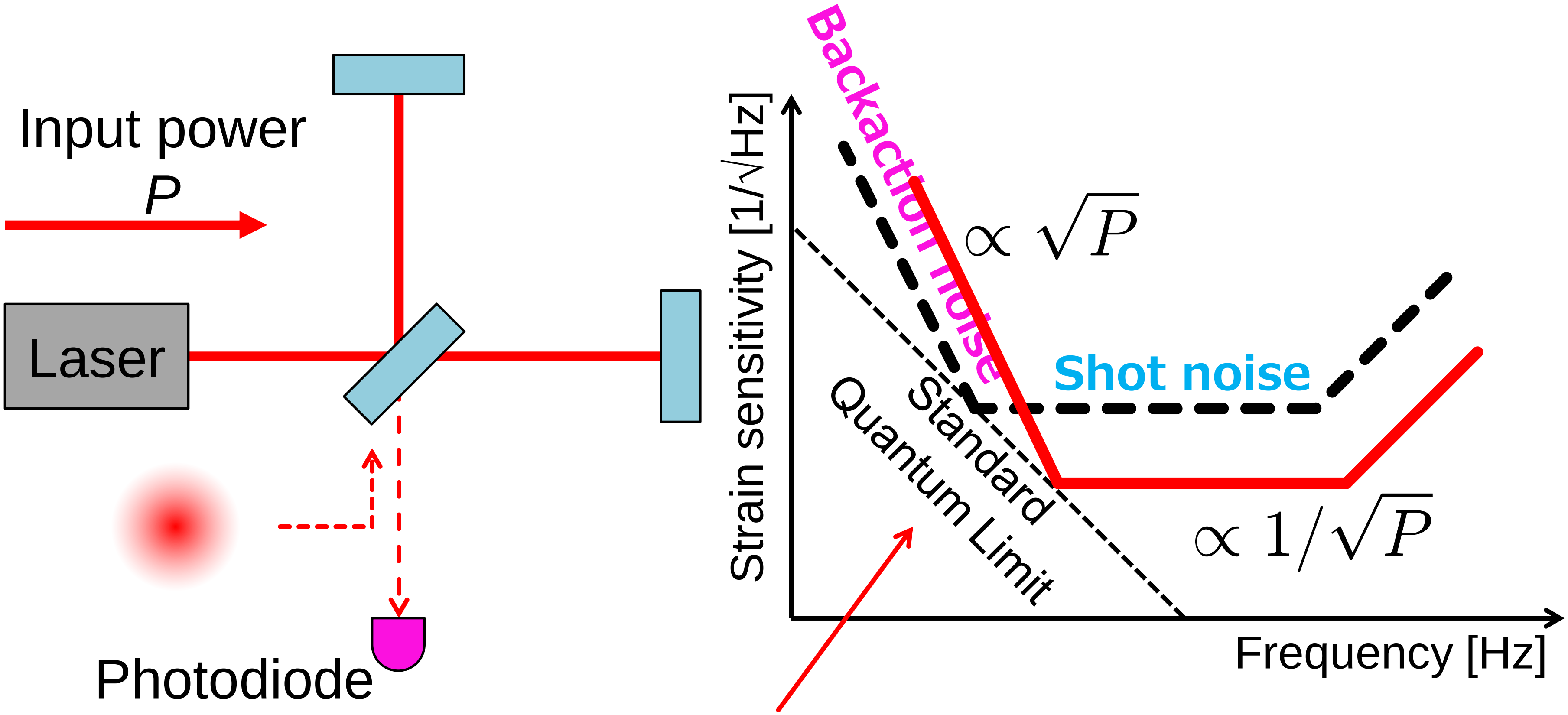


From Heisenberg's uncertainty principle

$$h_{\mathrm{SQL}} = \sqrt{2 h_{\mathrm{shot}} h_{\mathrm{rad}}} = \sqrt{\frac{4\hbar}{m\omega^2 L^2}}$$

Quantum Noise

- Cannot beat SQL just by changing the power

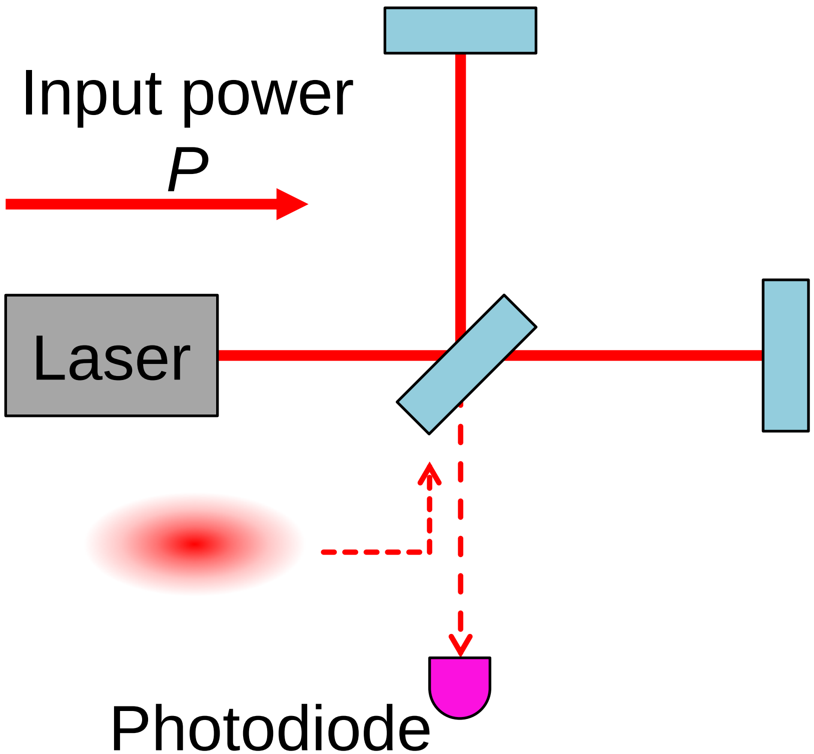


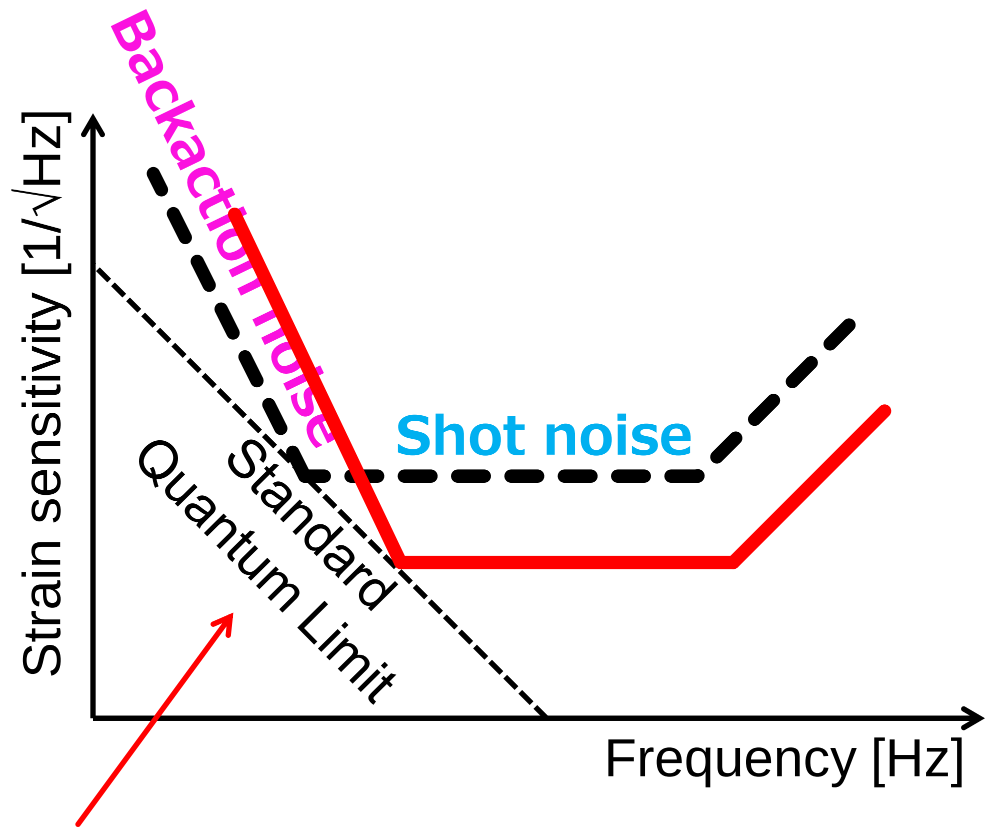
From Heisenberg's uncertainty principle

$$h_{\mathrm{SQL}} = \sqrt{2 h_{\mathrm{shot}} h_{\mathrm{rad}}} = \sqrt{\frac{4\hbar}{m\omega^2 L^2}}$$

Injection of Squeezed Vacuum

- Still cannot beat SQL



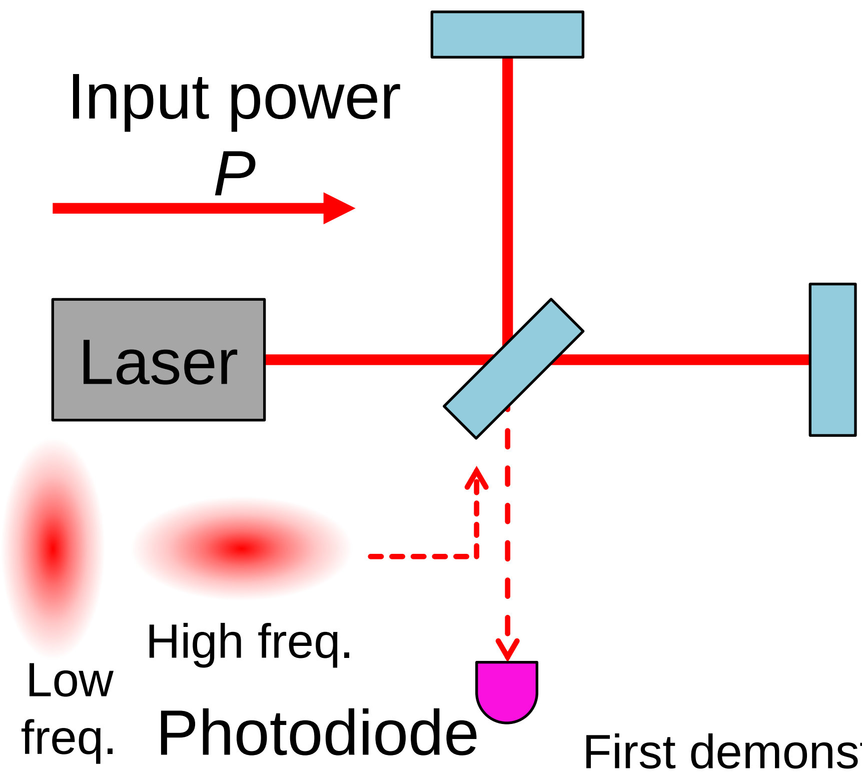


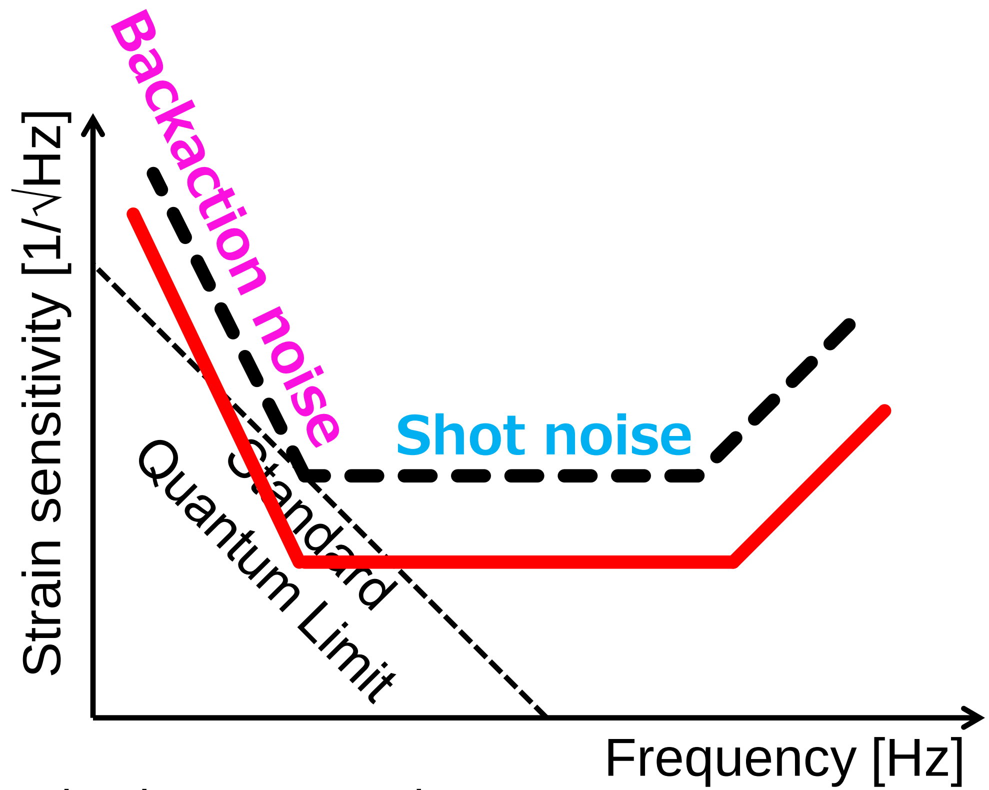
From Heisenberg's uncertainty principle

$$h_{\mathrm{SQL}} = \sqrt{2 h_{\mathrm{shot}} h_{\mathrm{rad}}} = \sqrt{\frac{4\hbar}{m\omega^2 L^2}}$$

Frequency Dependent Squeezing

- Can beat SQL

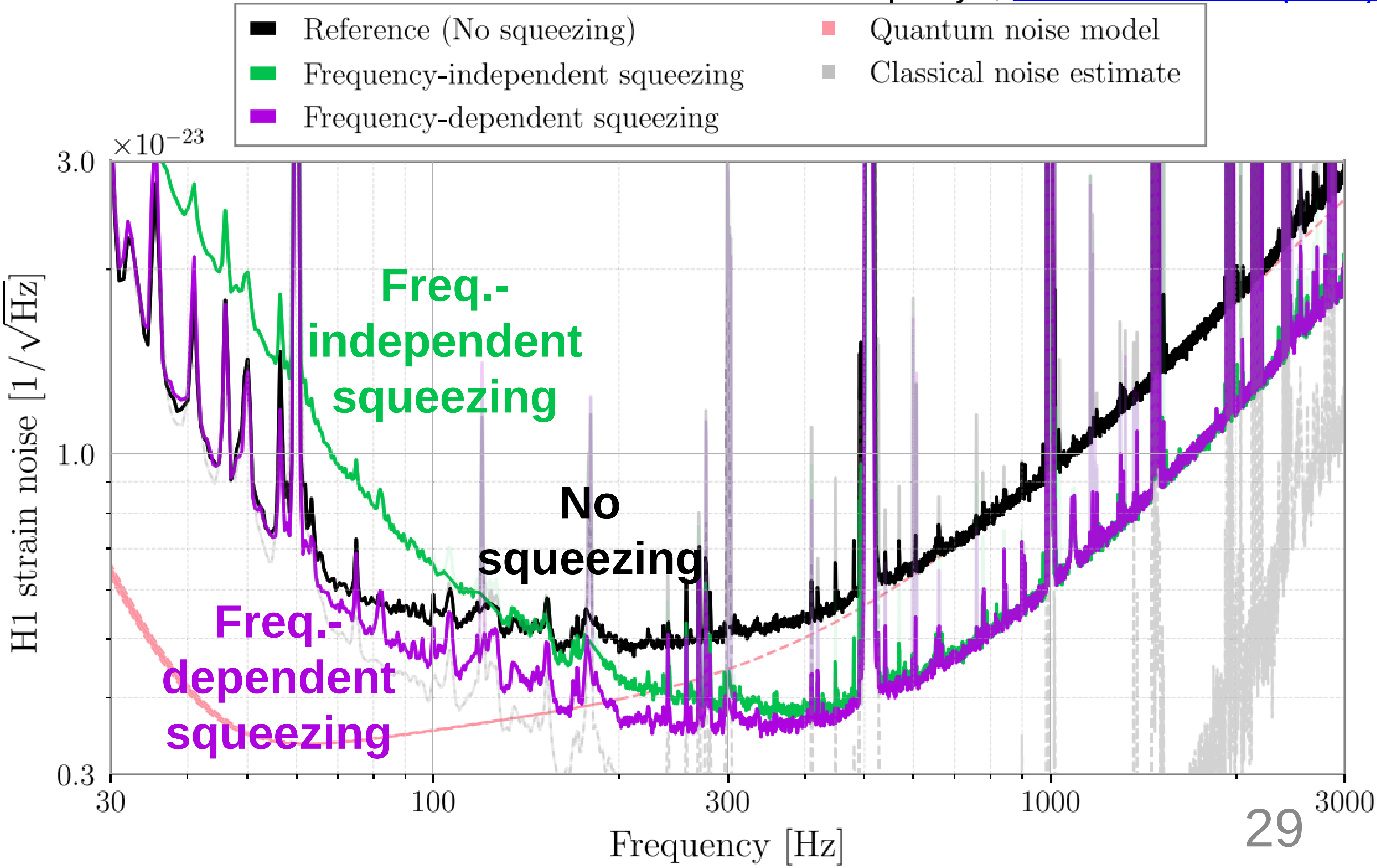




First demonstration by NAOJ and MIT
  Y. Zhao+, PRL **124**, 171101 (2020)
  L. McCuller+, PRL **124**, 171102 (2020)
Already installed in LIGO and Virgo
  D. Ganapathy+, PRX 13, 041021 (2023)
  Virgo, PRL 131, 041403 (2023)

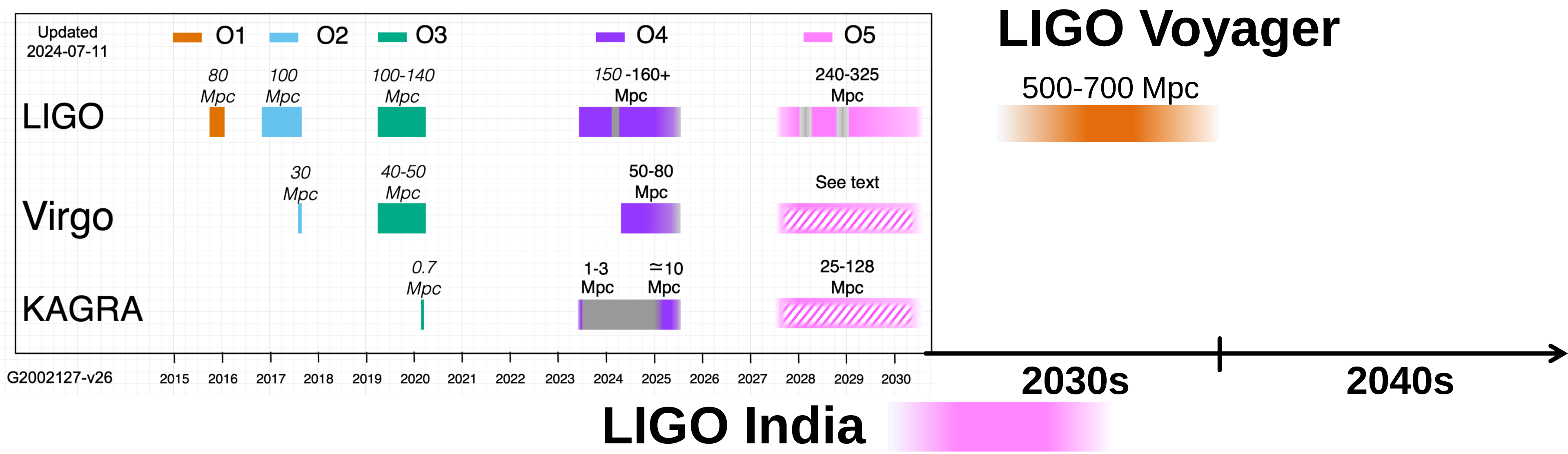
Frequency Dependent Squeezing

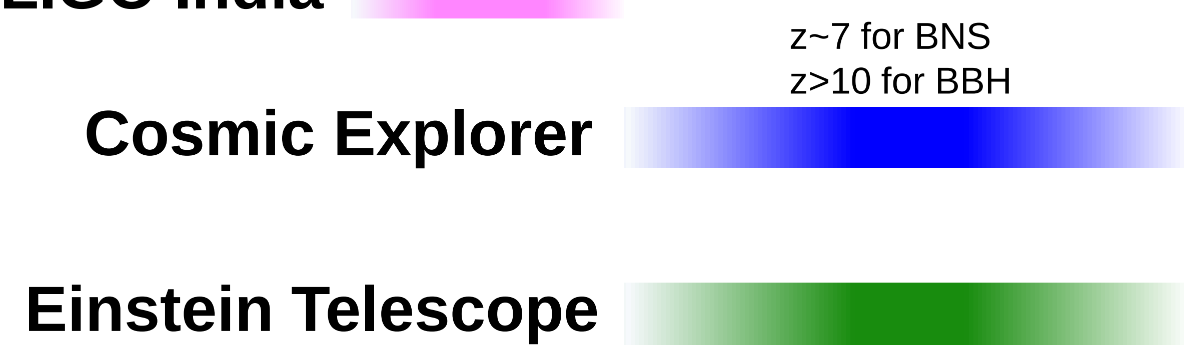
D. Ganapathy+, PRX 13, 041021 (2023)



Next Generation Detectors

- Cryogenic upgrade plan: LIGO Voyager
- 10-40 km plans in the US and Europe

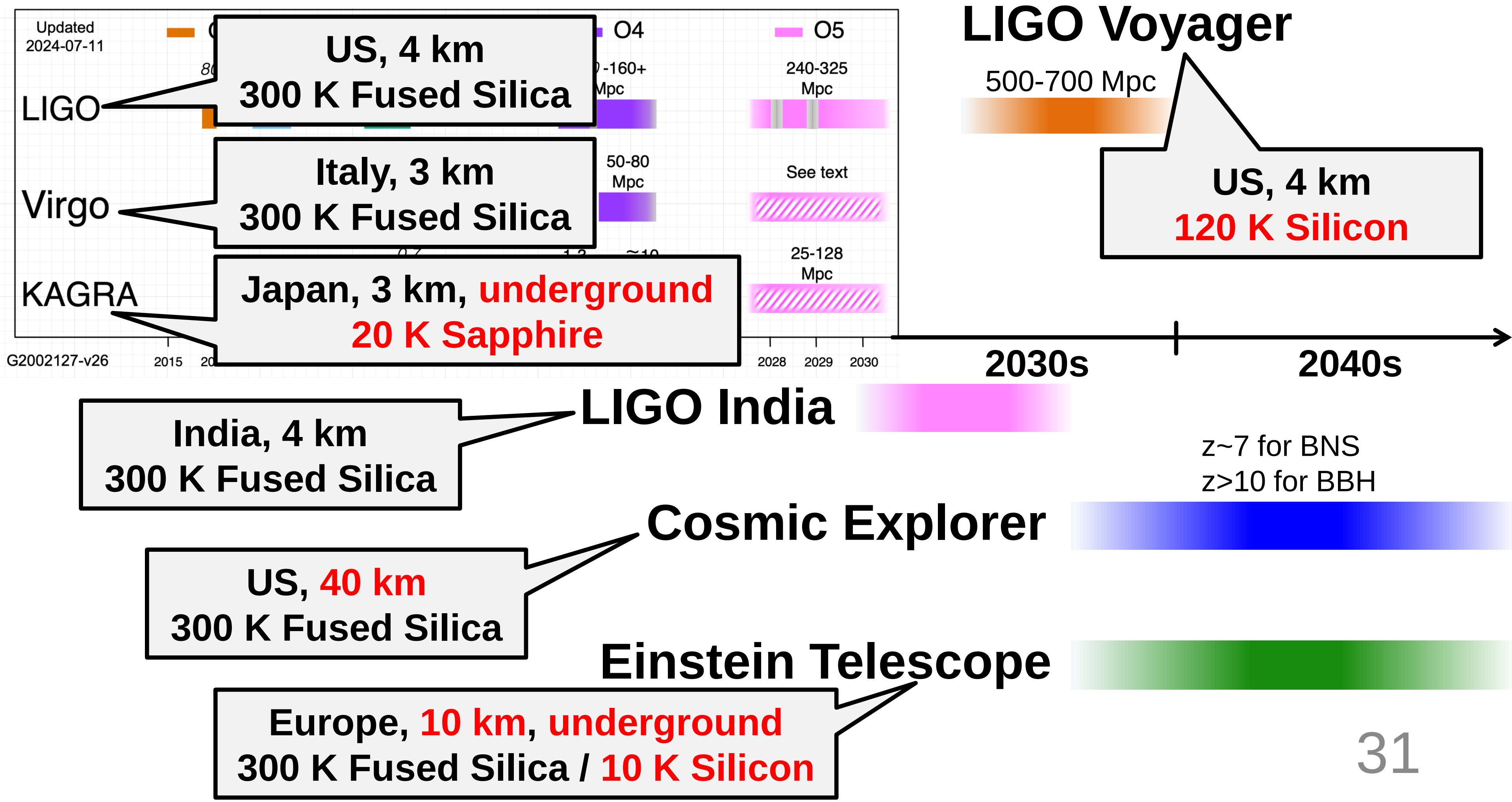




$$h_{\mathrm{SQL}} = \sqrt{\frac{4\hbar}{m\omega^2 L^2}}$$

Next Generation Detectors

- Cryogenic upgrade plan: LIGO Voyager
- 10-40 km plans in the US and Europe



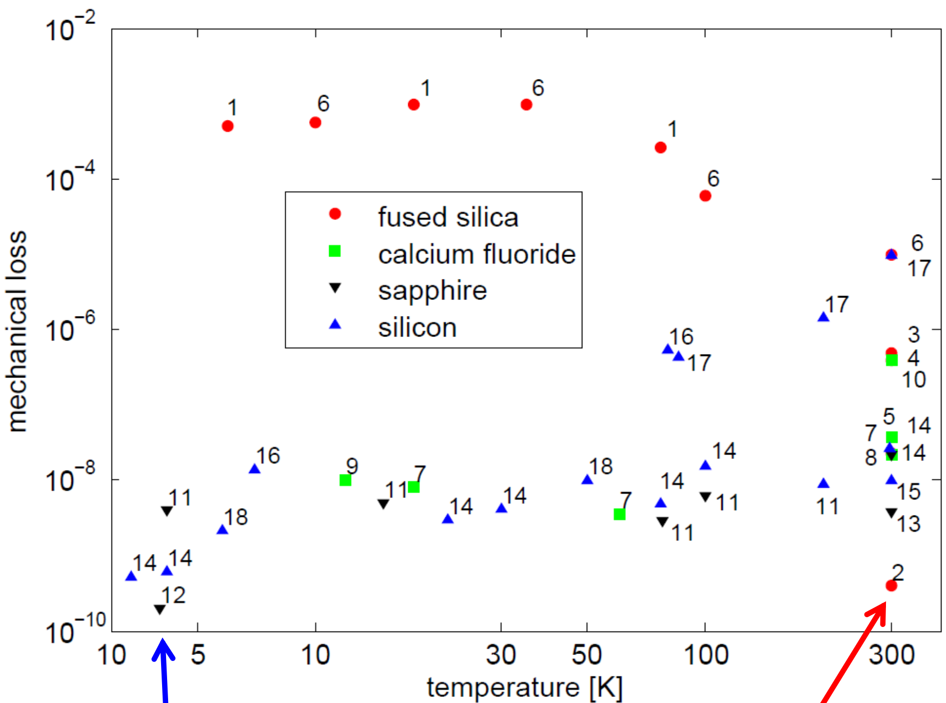
Why Different Mirror Materials?

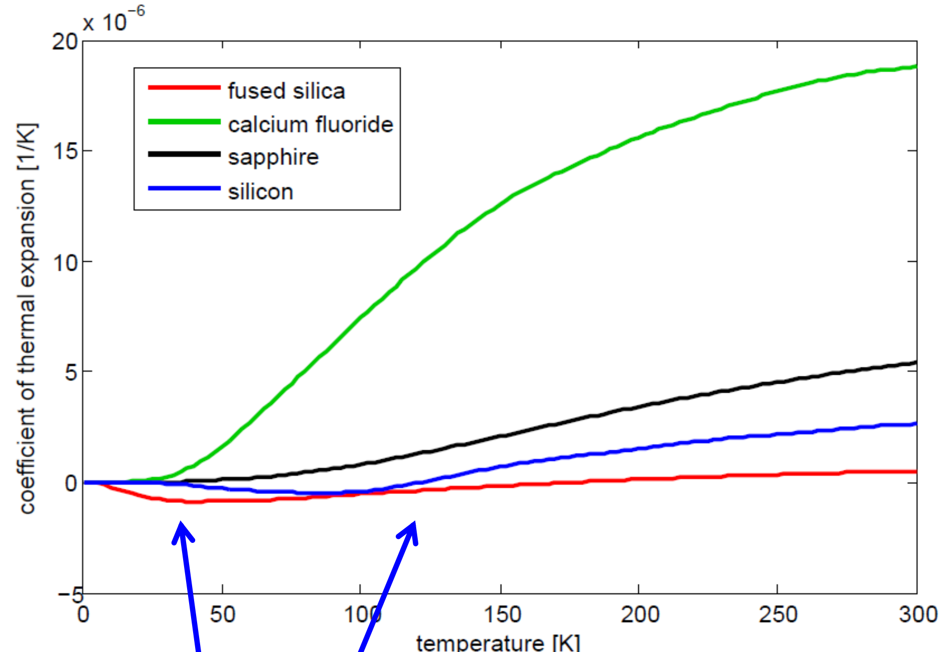
- Thermal noise $\propto \sqrt{T\phi}$

Temperature

Mechanical loss angle (temperature dependent)

[ET-027-09]





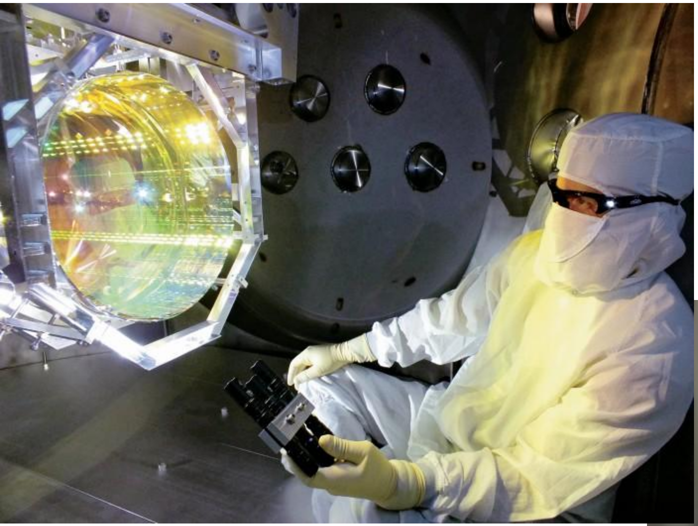
Sapphire / silicon is good at cryogenic temp.

Fused silica is good at room temp.

Silicon has zero thermal expansion at 18 K and 123 K

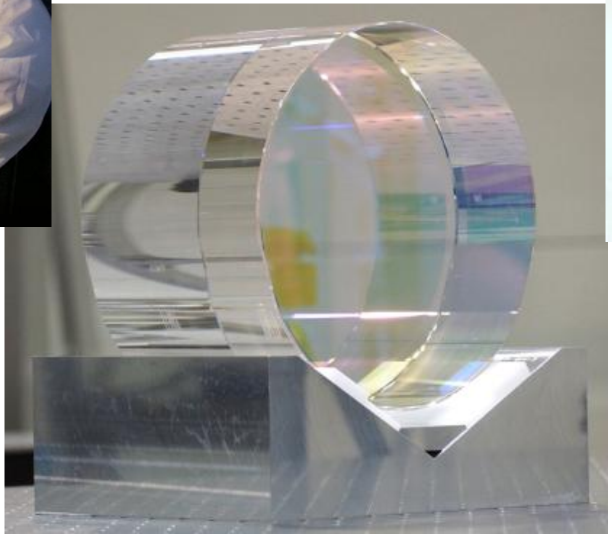
Different Wavelengths

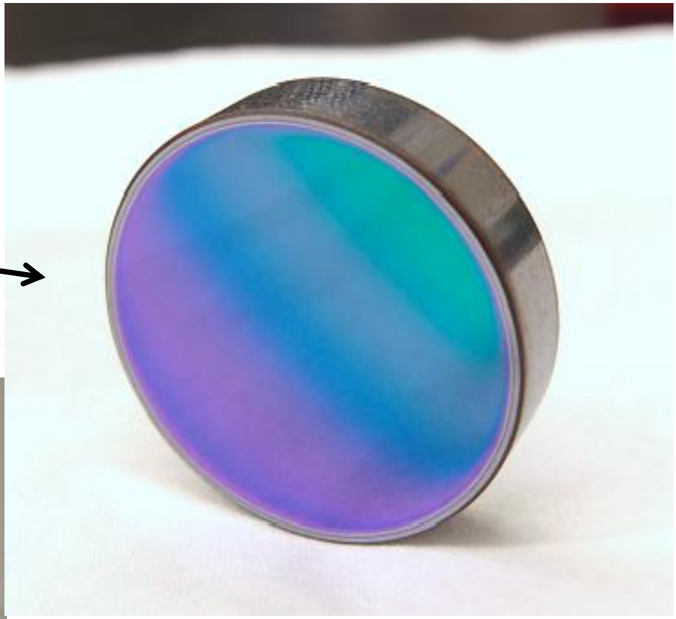
- Different mirror materials require different laser wavelengths



Amorphus

Crystalline





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

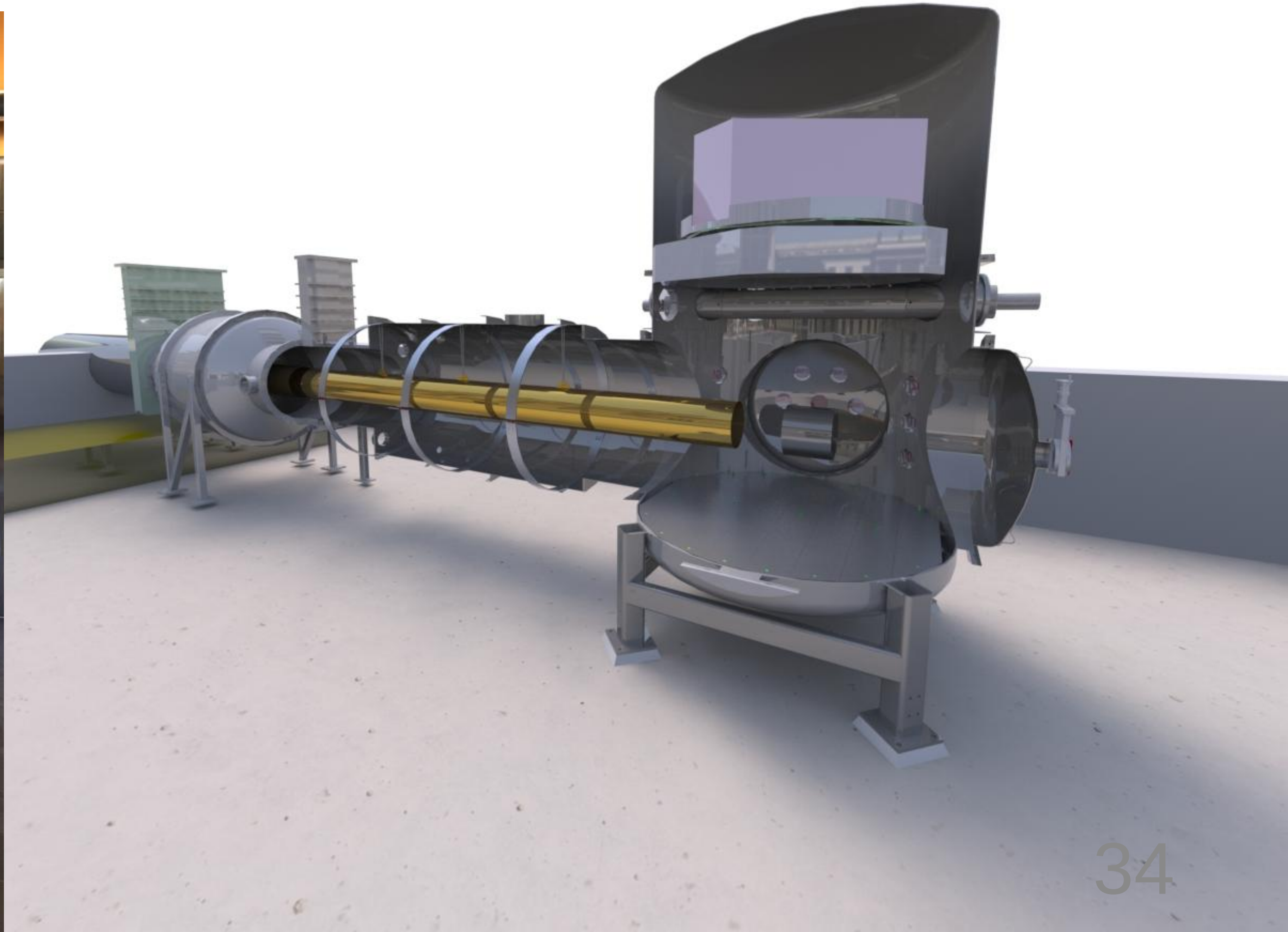
20 K Sapphire
KAGRA @ 1064 nm

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

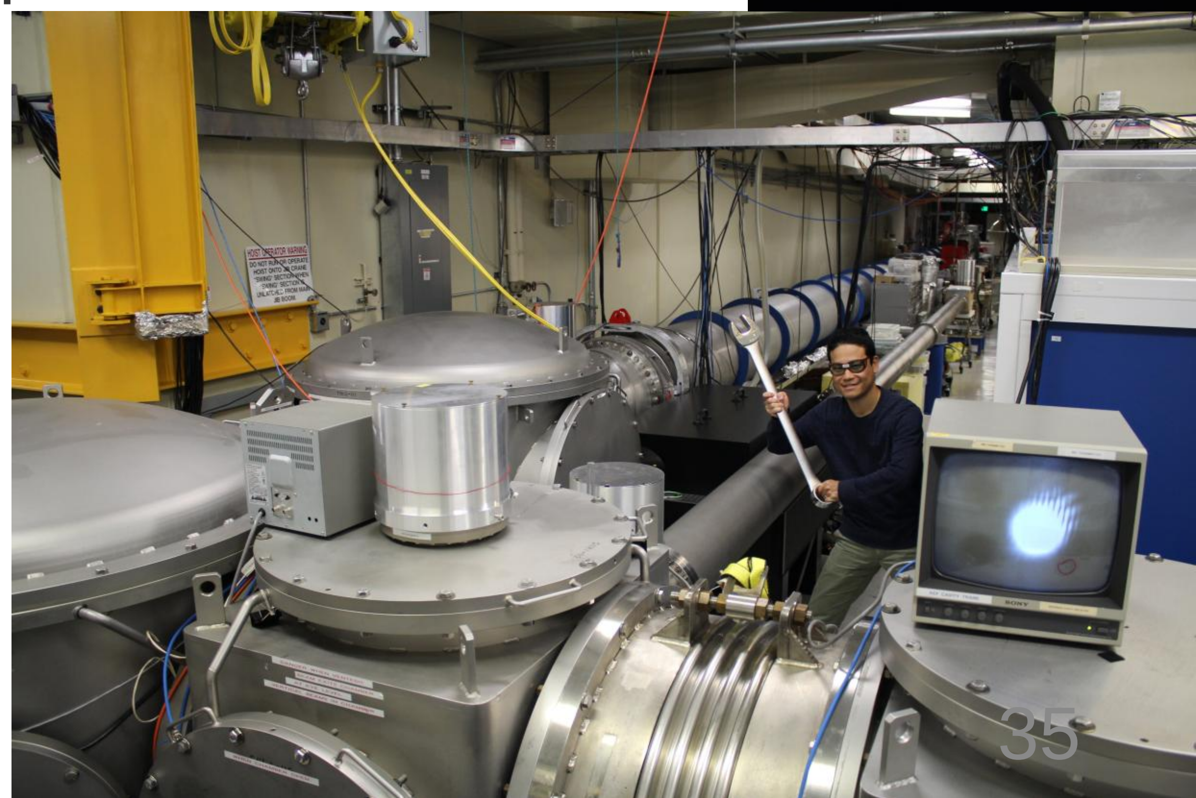
Magnetic CZ silicon (commercially grown up to 45 cm diameter)



Mariner: 40m Voyager Prototype

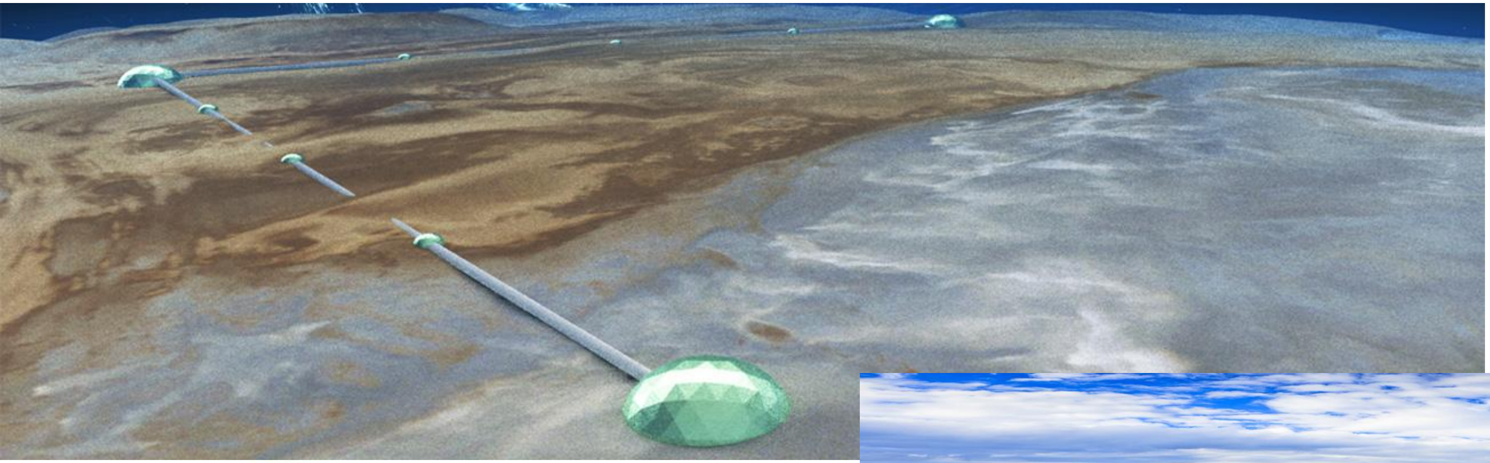
- Prototyping key technologies:
  - Silicon test masses
  - Radiative cooling
  - 123 K operation
  - 2050 nm laser

- To be installed 2025



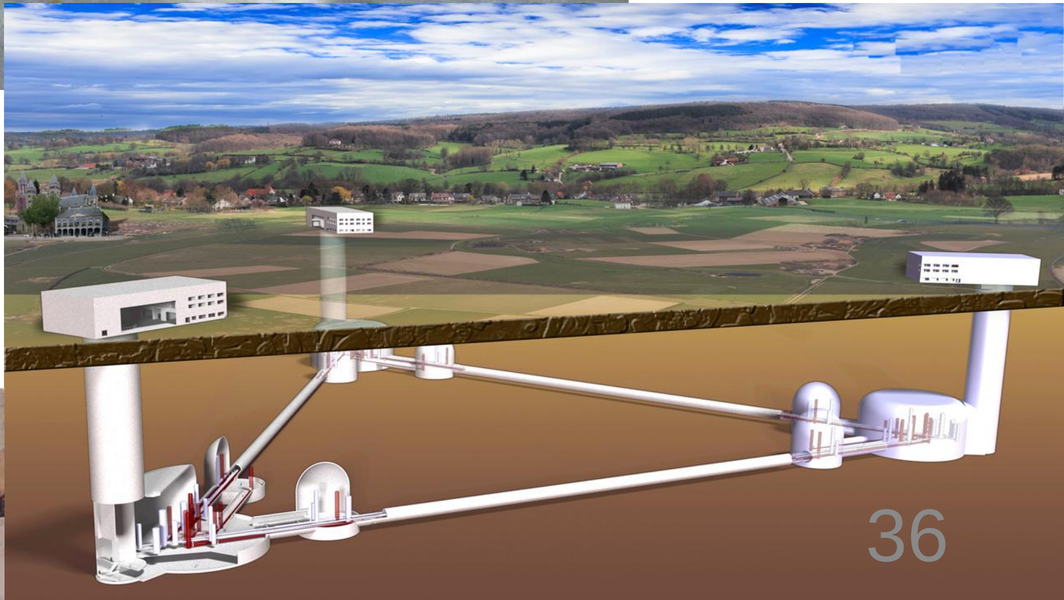
Cosmic Explorer / Einstein Telescope

- CE: 40 km, 300 K fused silica
- ET: 10 km, 300 K fused silica & 10 K silicon



COSMIC EXPLORER

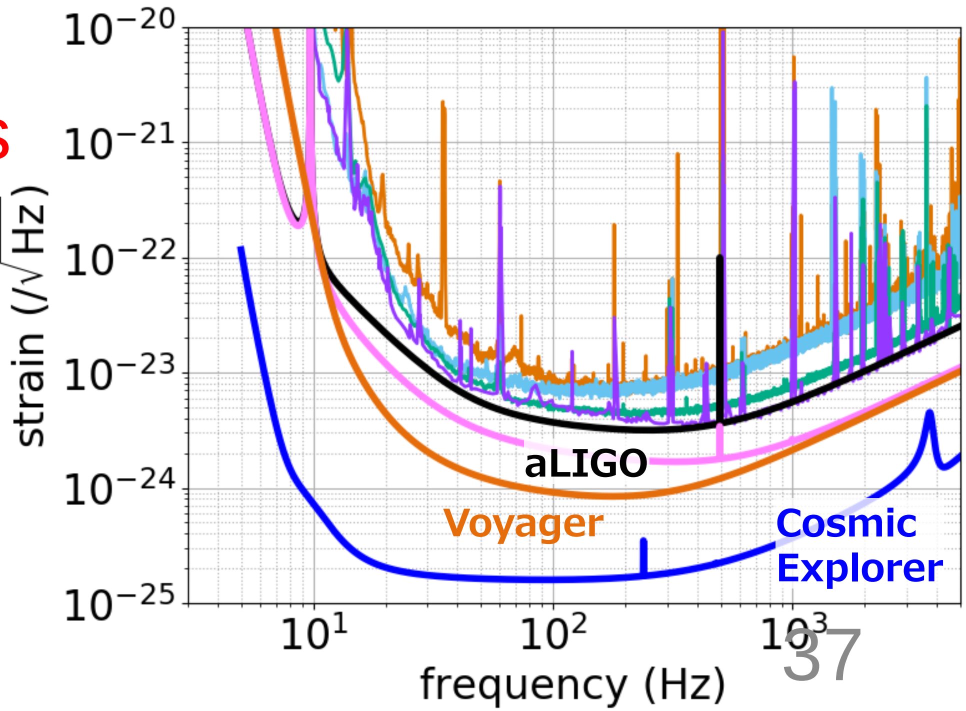
ET EINSTEIN TELESCOPE



Exciting R&Ds for Next Generations

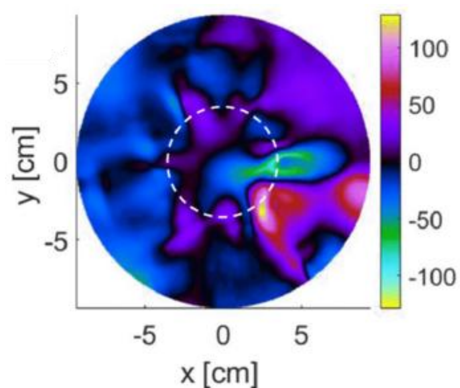
- Stable, high-power laser at 1.5-2 um
- High quantum efficiency photodiodes for 2 um
- Large silicon mirror (φ 45 cm, 200 kg)
  - Low birefringence
  - Low absorption
- Low thermal noise high-reflective coatings
- Suspensions for large mirrors
- High power handling

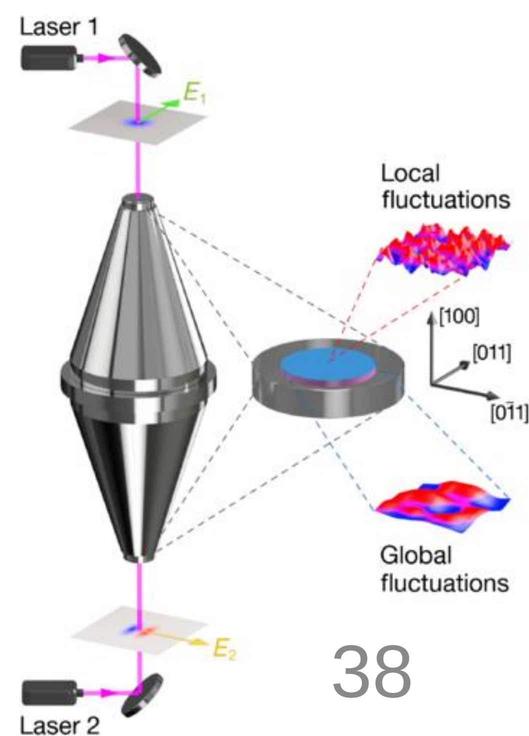
… and more



Birefringence and Its Fluctuations

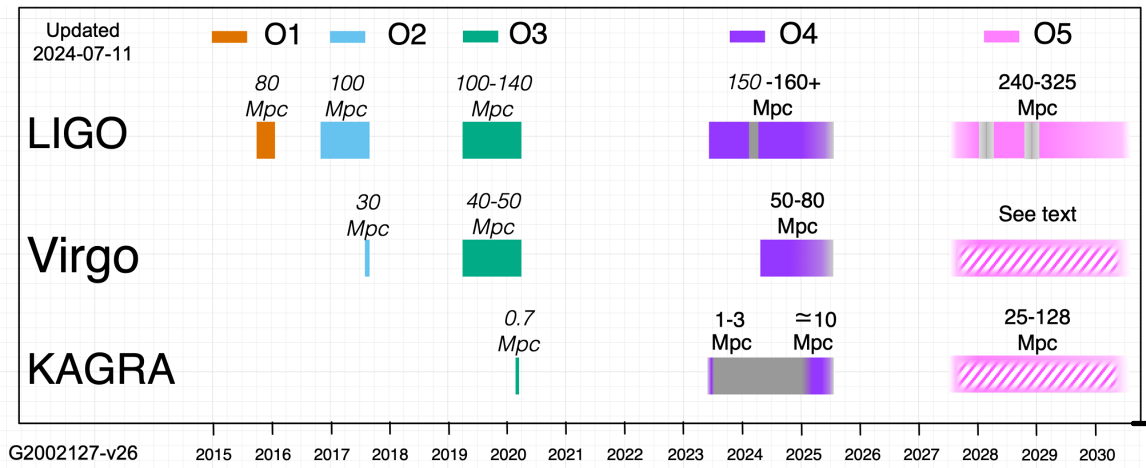
- Birefringence ($\Delta n \sim 10^{-7}$ for silicon) needs to be small for reducing optical losses
- Birefringence fluctuations will also be additional phase noise ($\delta(\Delta n) < 10^{-15}$ /$\sqrt{\text{Hz}}$) YM+, PRD **109**, 022009 (2024)
- Excess birefringence noise reported by PTB/JILA
 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





Space-Based Detectors in 2030s

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



LIGO Voyager

500-700 Mpc

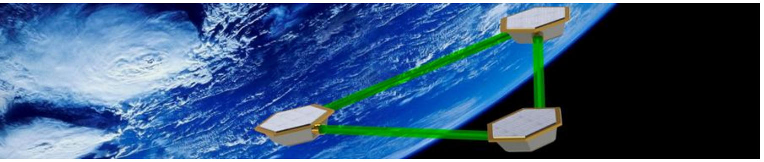
2030s **2040s**

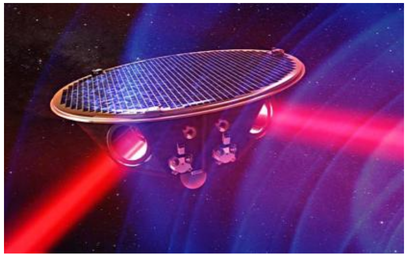
LIGO India

z~7 for BNS
z>10 for BBH

Cosmic Explorer

Einstein Telescope



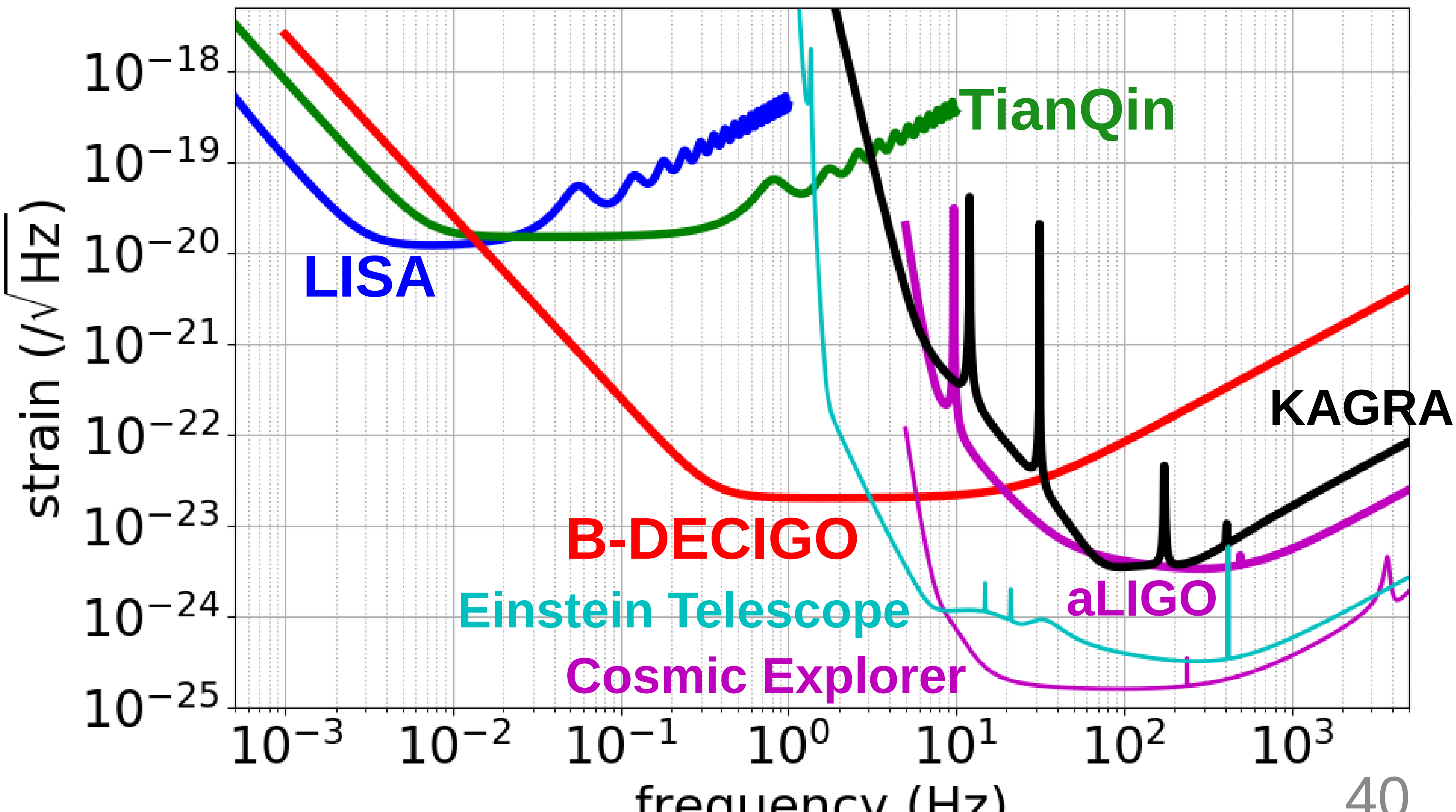


B-DECIGO

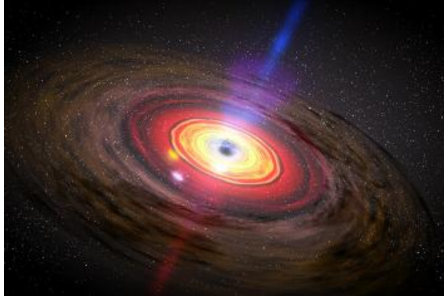
LISA

Space-Based Detectors: Sensitivity

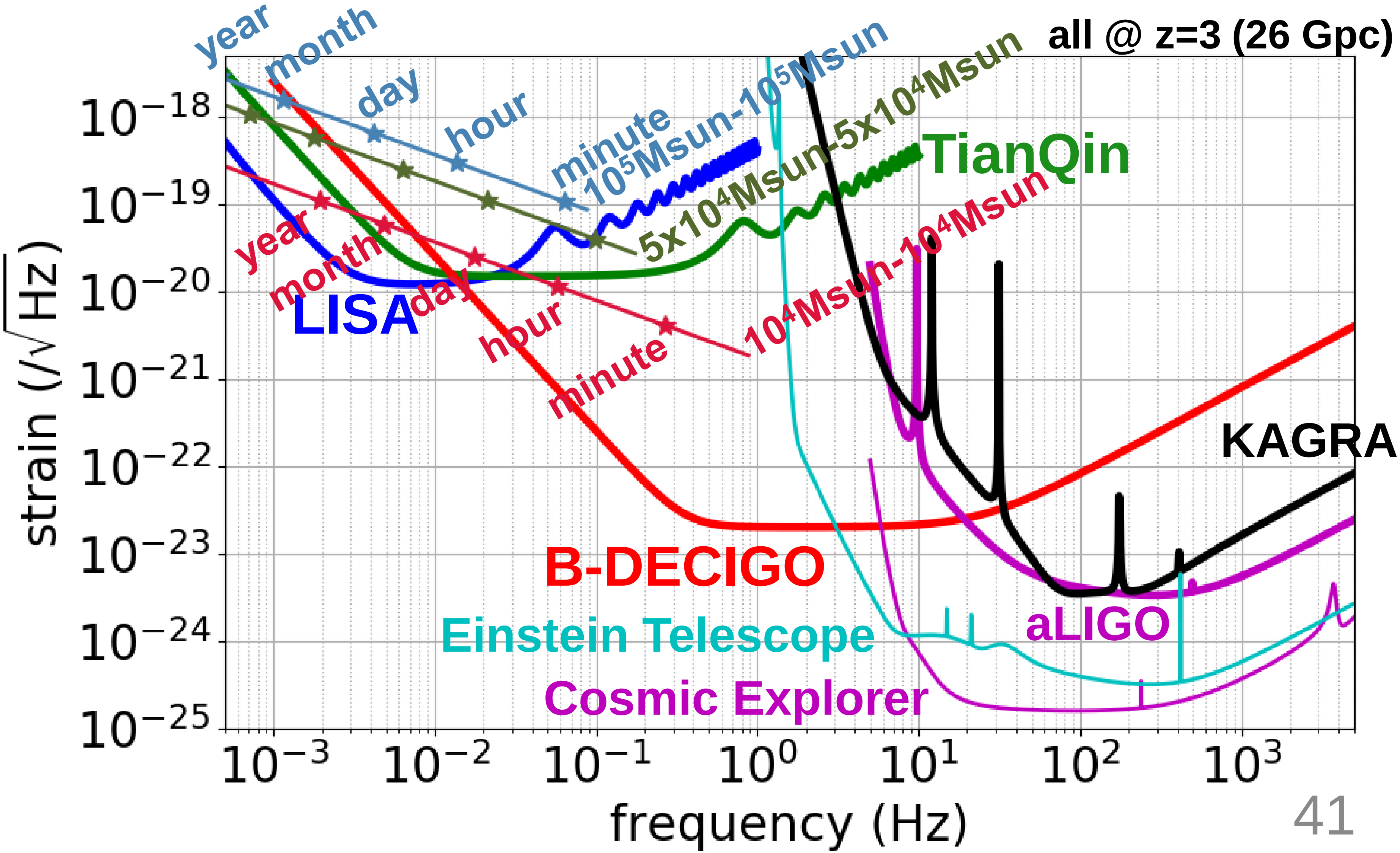
- LISA at 1-10 mHz, DECIGO at 0.1-1 Hz



Super Massive Blackholes

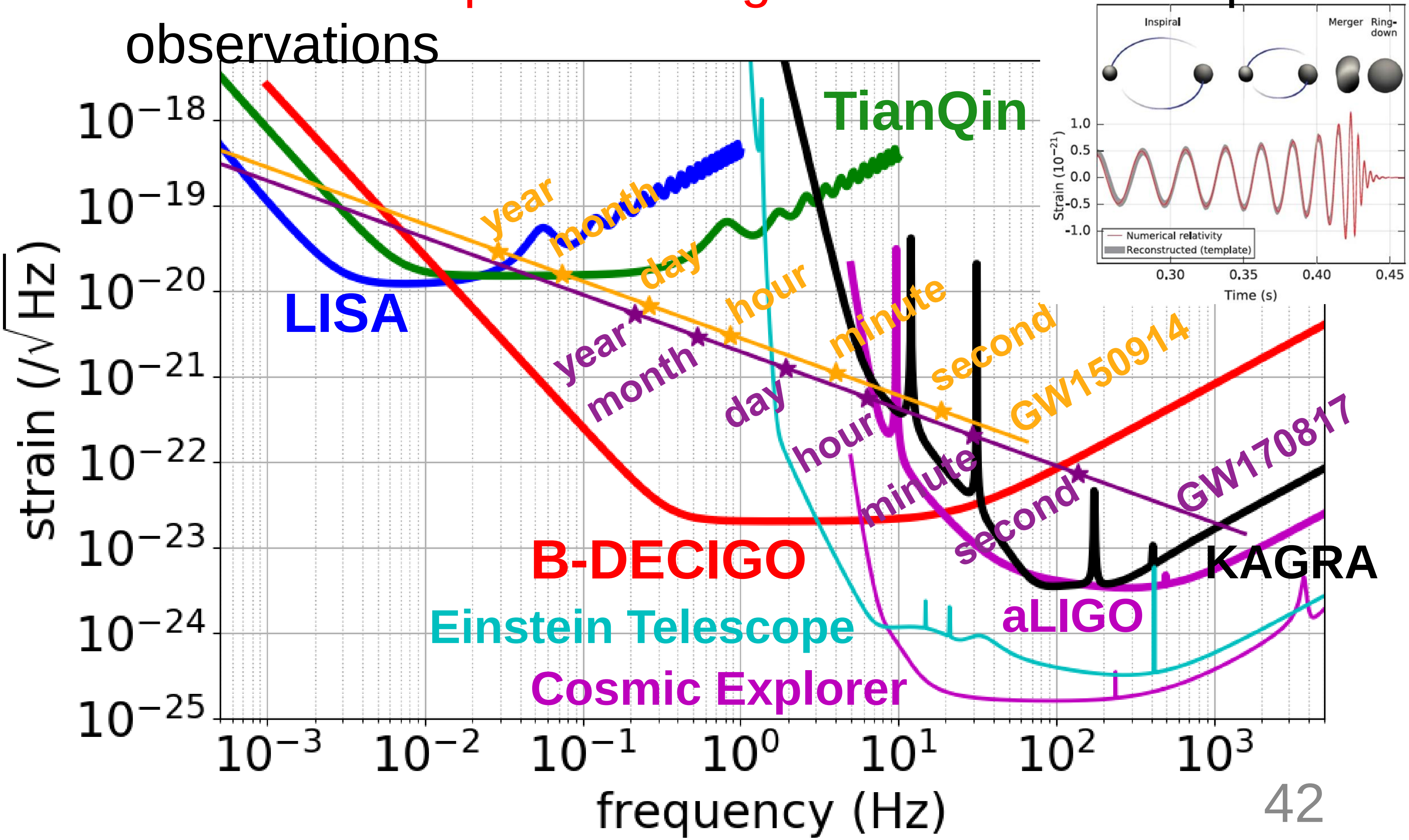


- LISA observes SMBH binaries



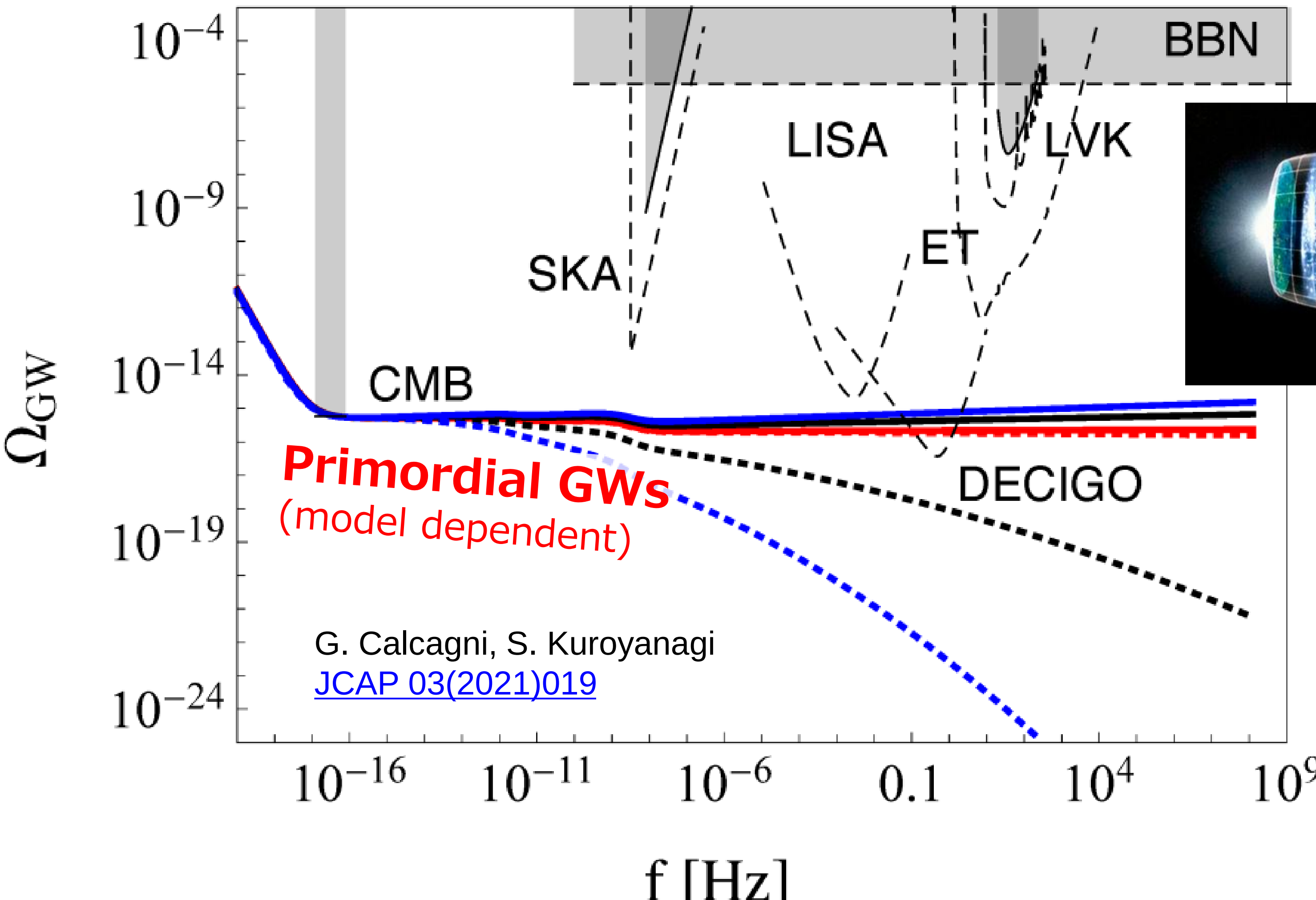
Multi-band Observations

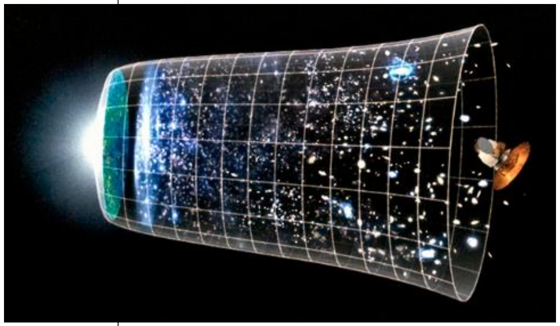
- DECIGO can predict merger time for follow up observations



Primordial GWs from Inflation

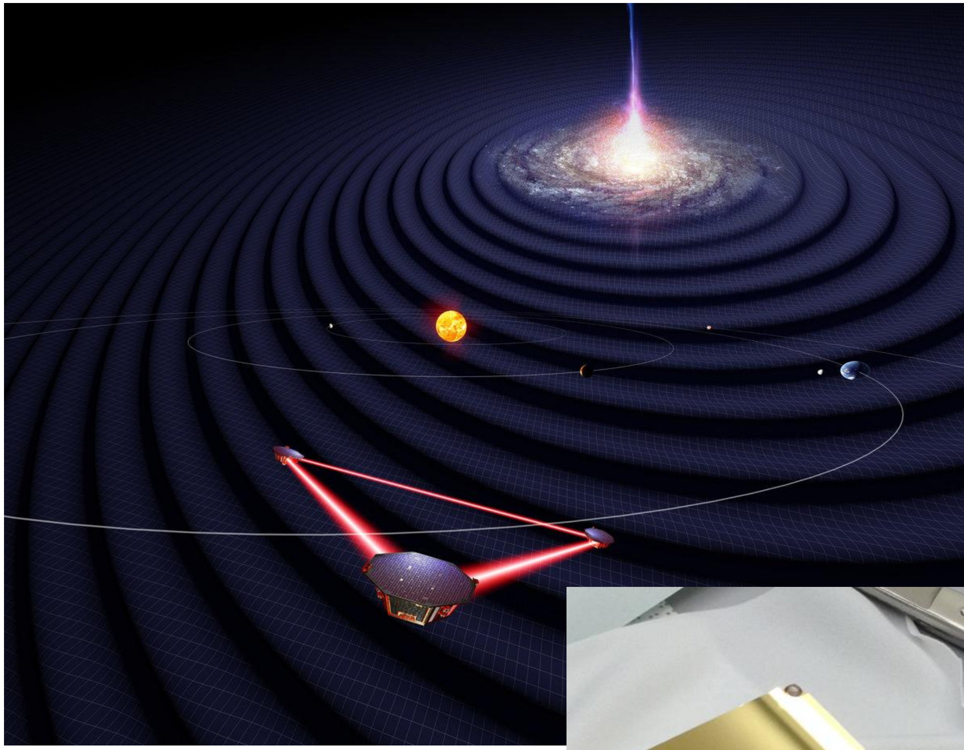
- DECIGO band is suitable for observing primordial gravitational waves

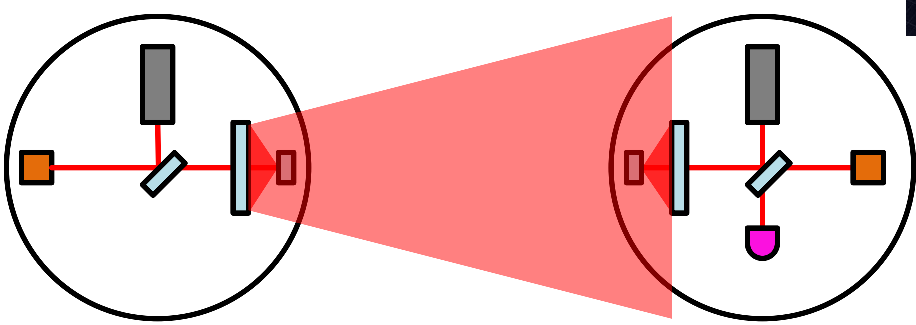


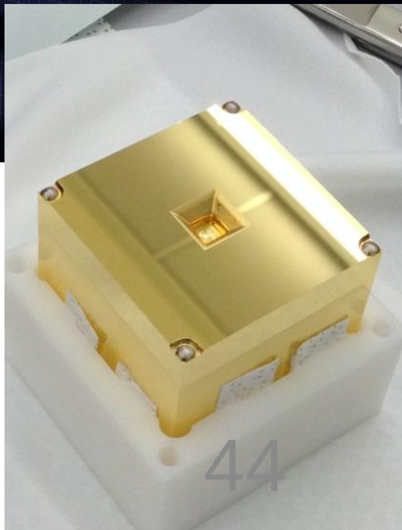


LISA to be Launched Mid-2030s

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

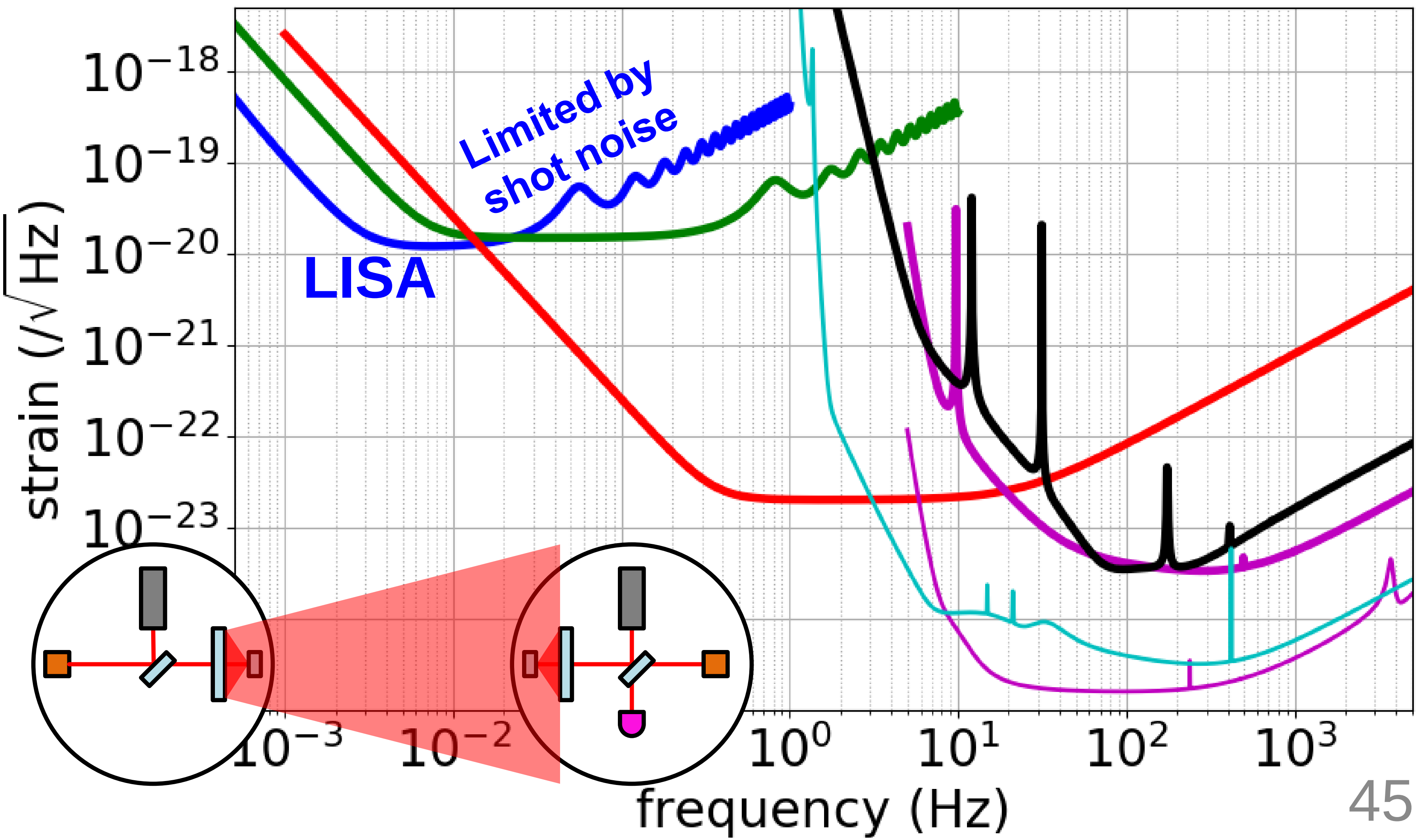






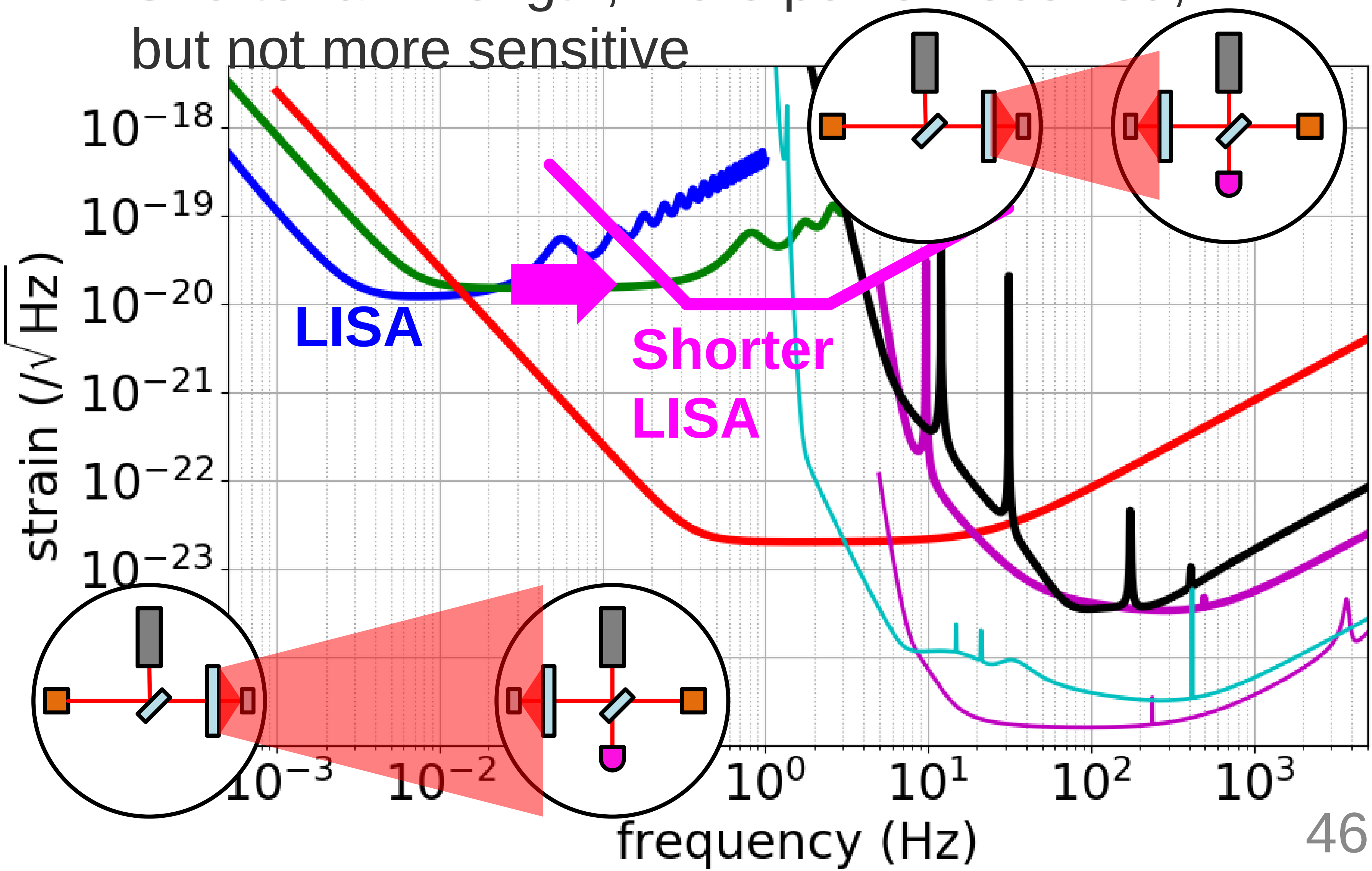
LISA Sensitivity Curve

- 1 W emitted, ~100 pW received



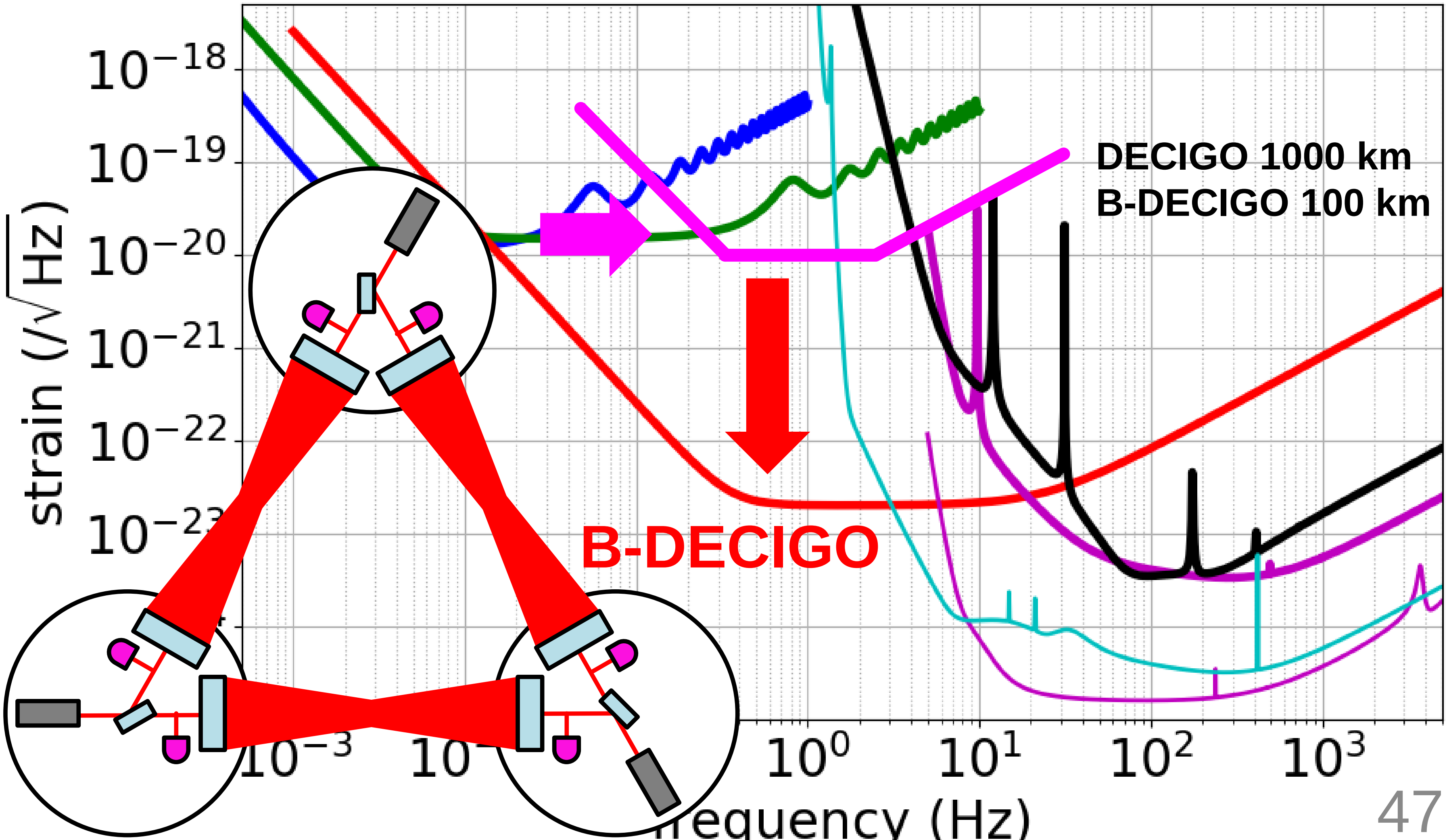
Shorter LISA will not be DECIGO

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

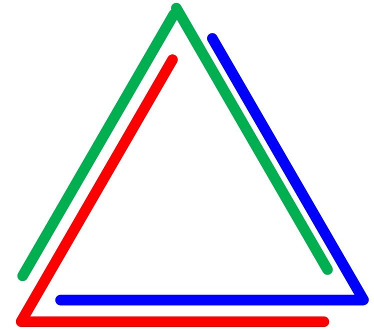


Shorter LISA will not be DECIGO

- Form an optical cavity to enhance the sensitivity

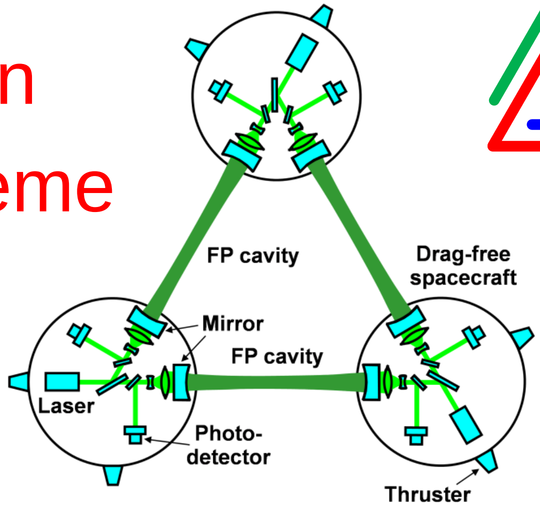


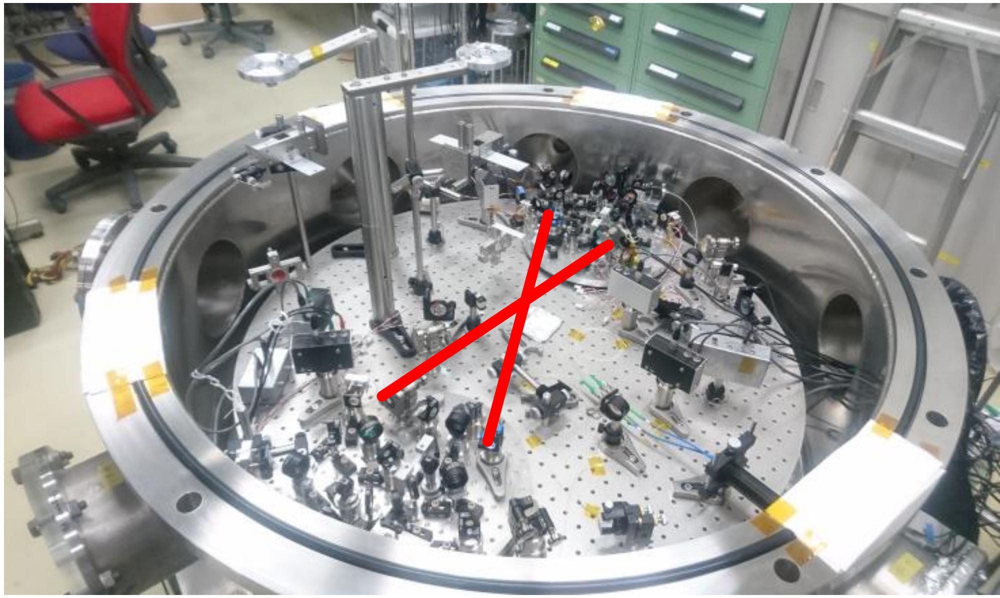
Exciting R&Ds for DECIGO



- 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!





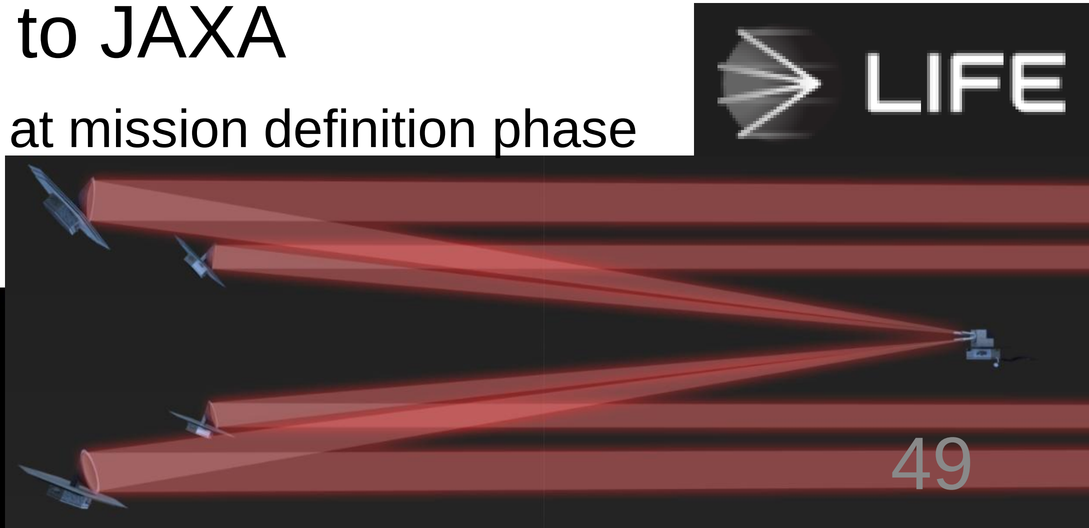
東京大学 THE UNIVERSITY OF TOKYO

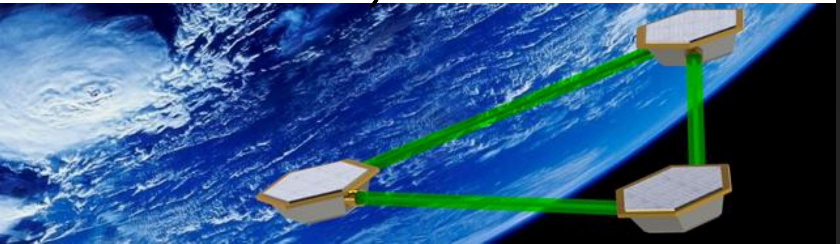
K. Nagano, H. Takeda, YM+
CQG **38**, 085018 (2021)

SILVIA Project

- Space Interferometer Laboratory Voyaging towards Innovative Applications

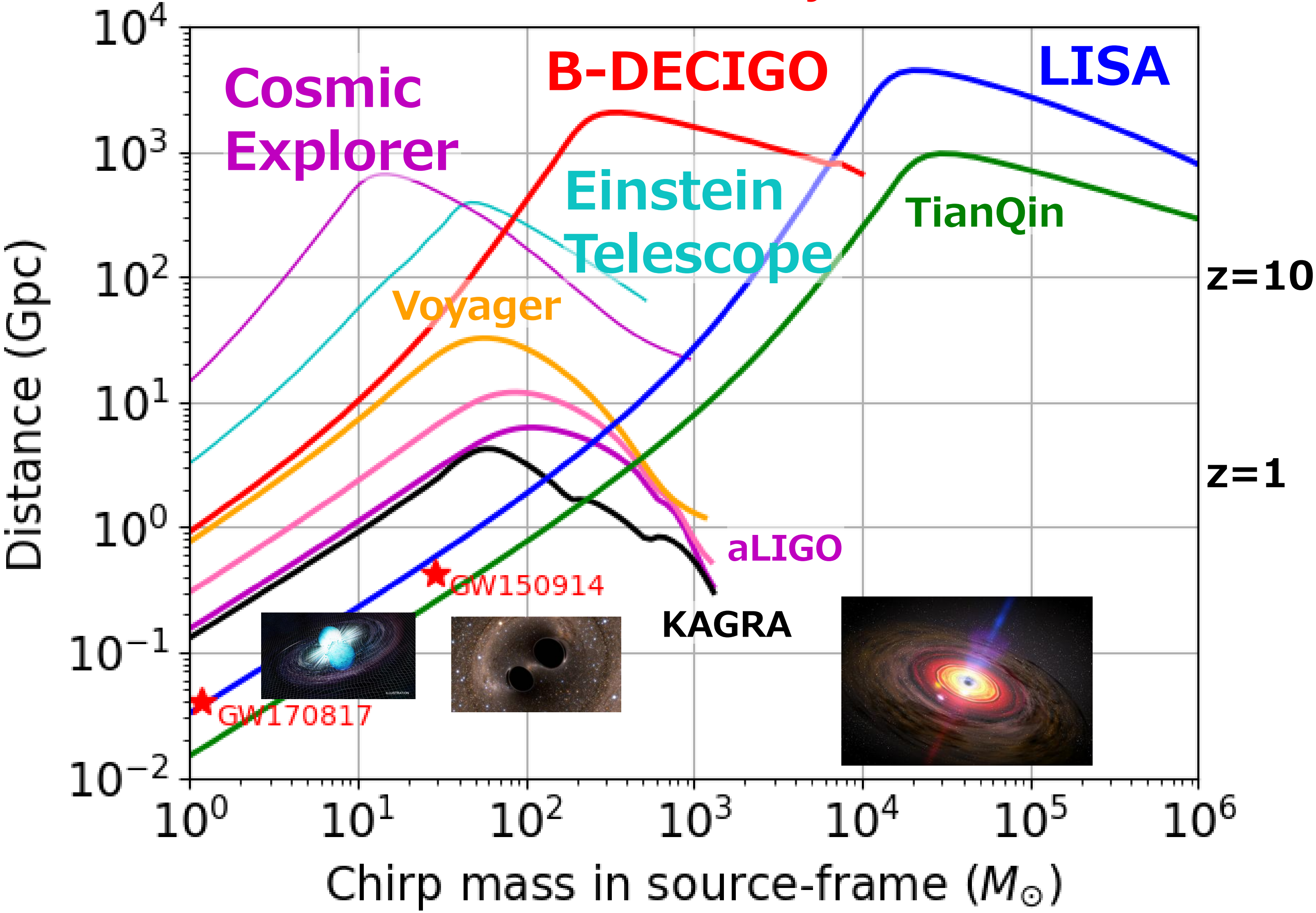
- Demonstration of ultra-precision formation flying with laser interferometer between satellites
- For DECIGO, LIFE etc.
- Proposal submitted to JAXA in Feb 2020 (currently at mission definition phase of JAXA's small satellite mission)



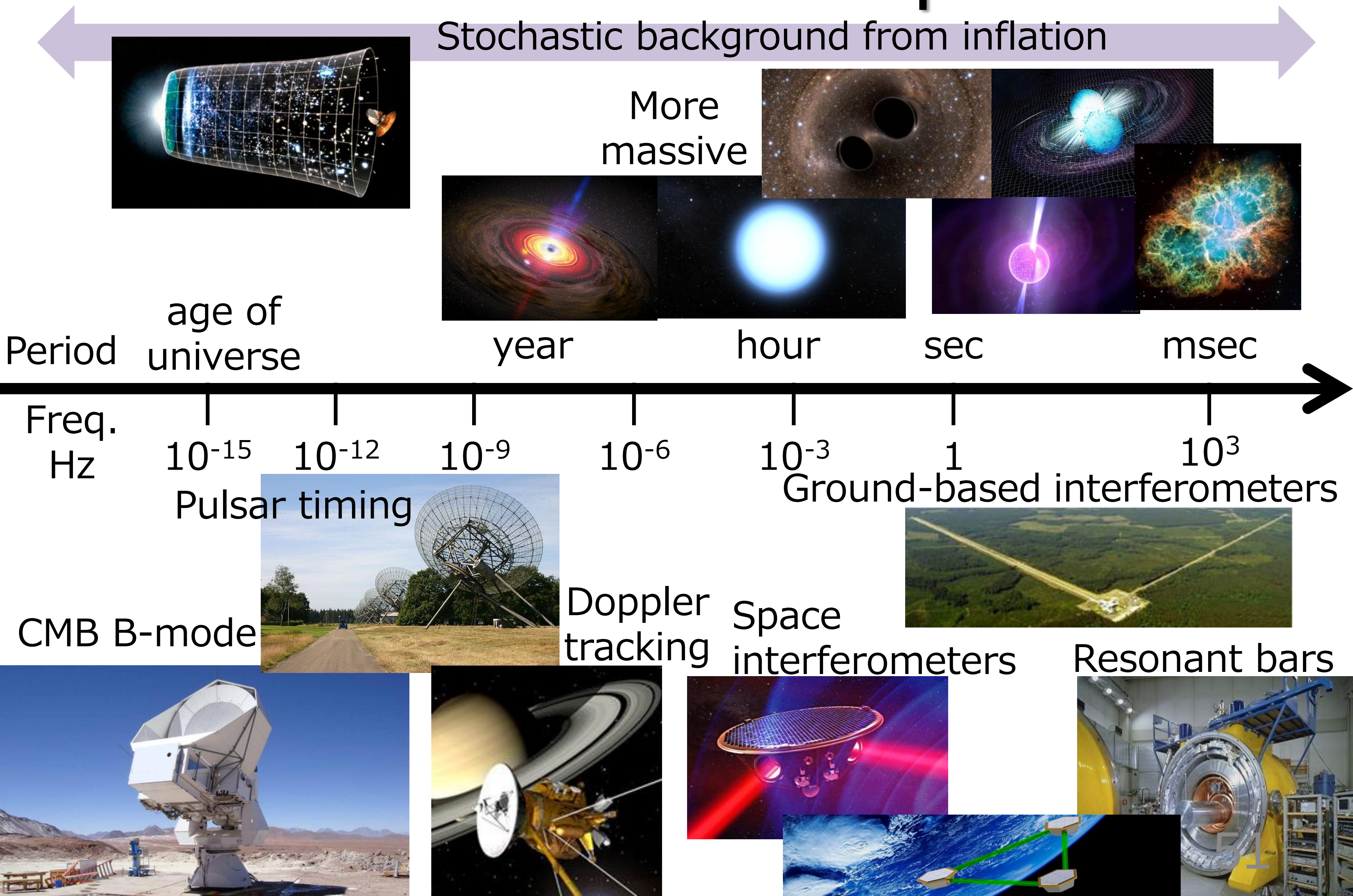


Astrophysical Reach to Binaries

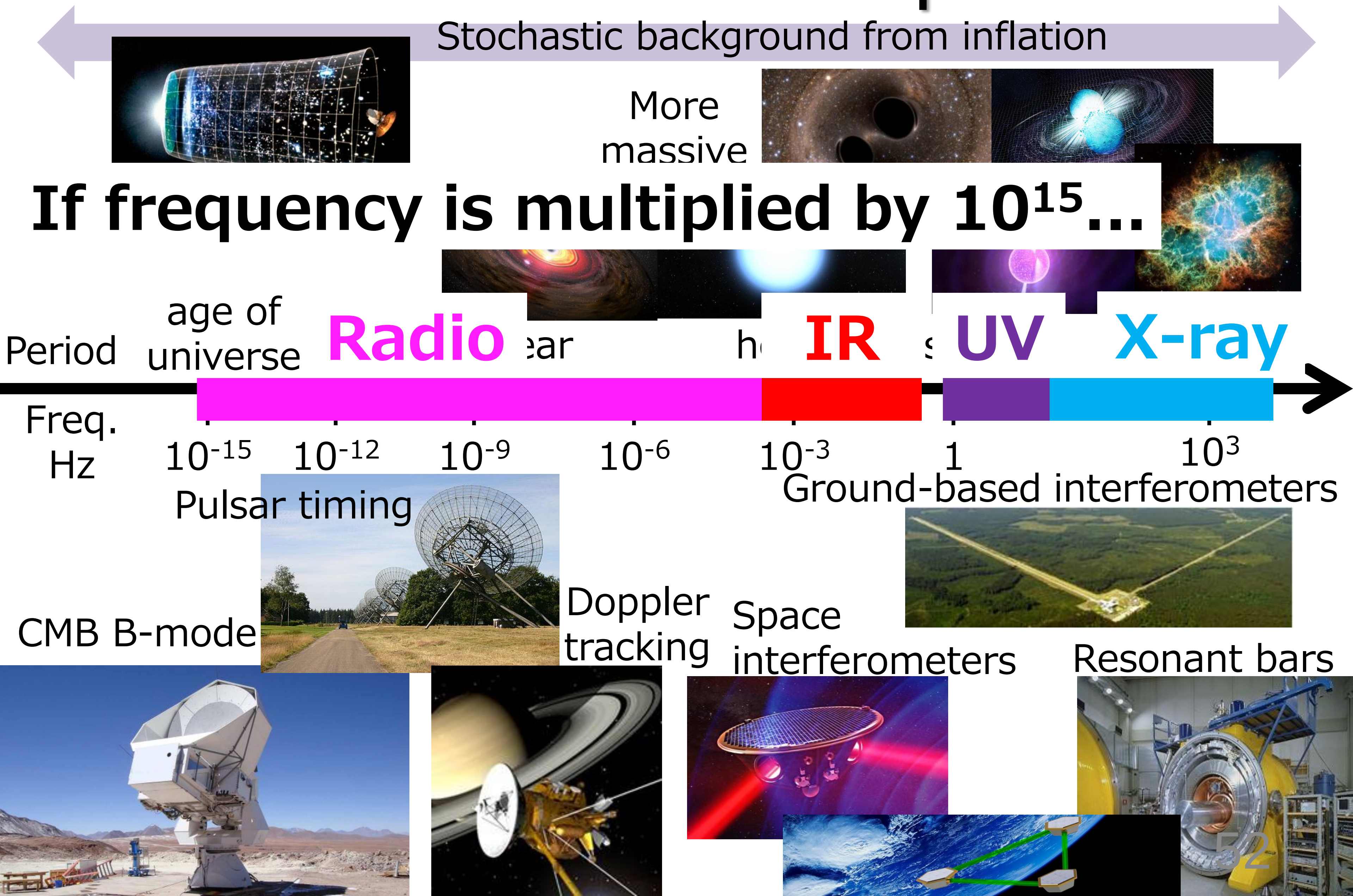
- Covers entire universe by 2030s



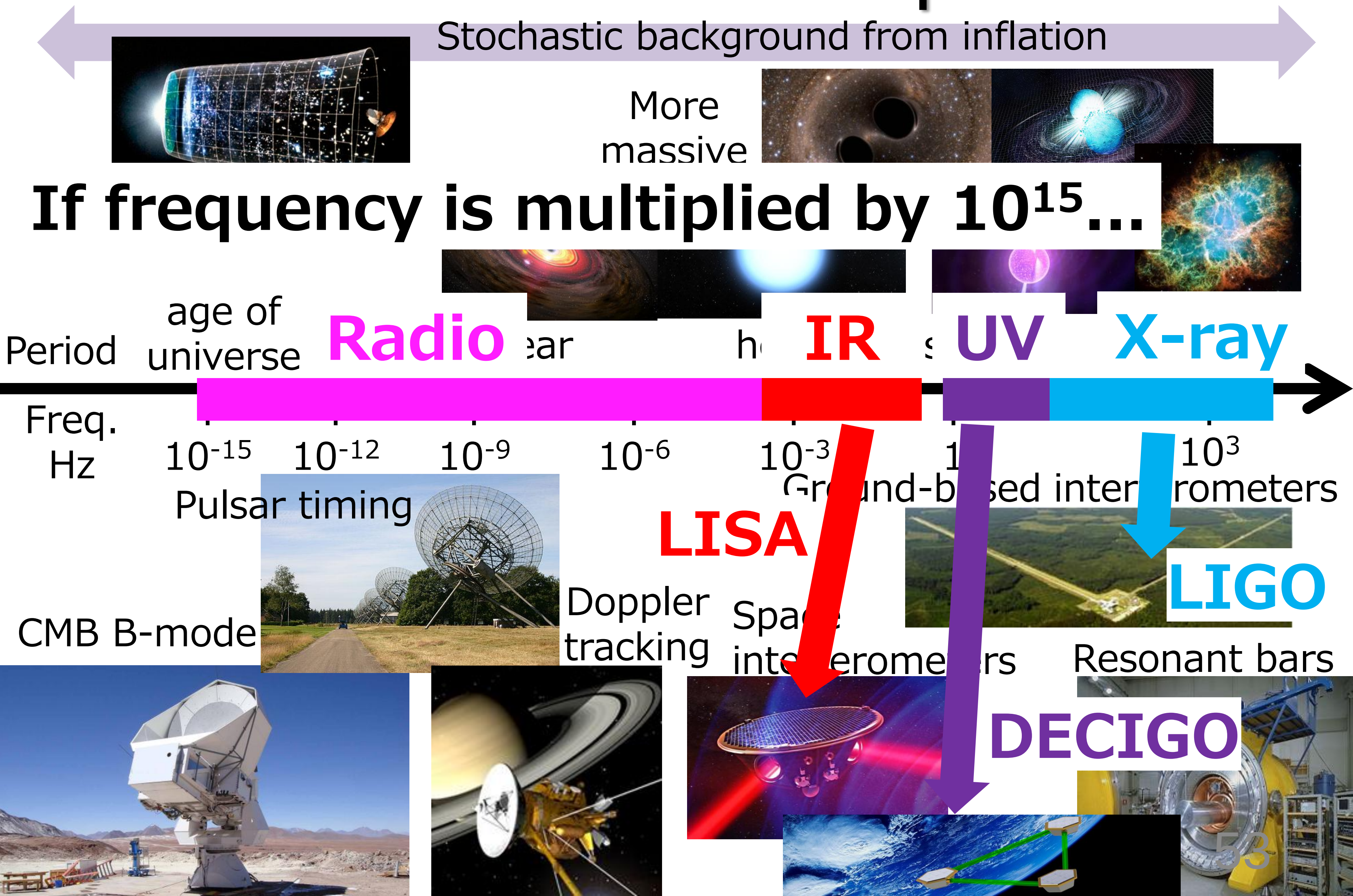
Gravitational Wave Spectrum



Gravitational Wave Spectrum



Gravitational Wave Spectrum



Particle Physics with GW Detectors

Tiny forces from vector DM

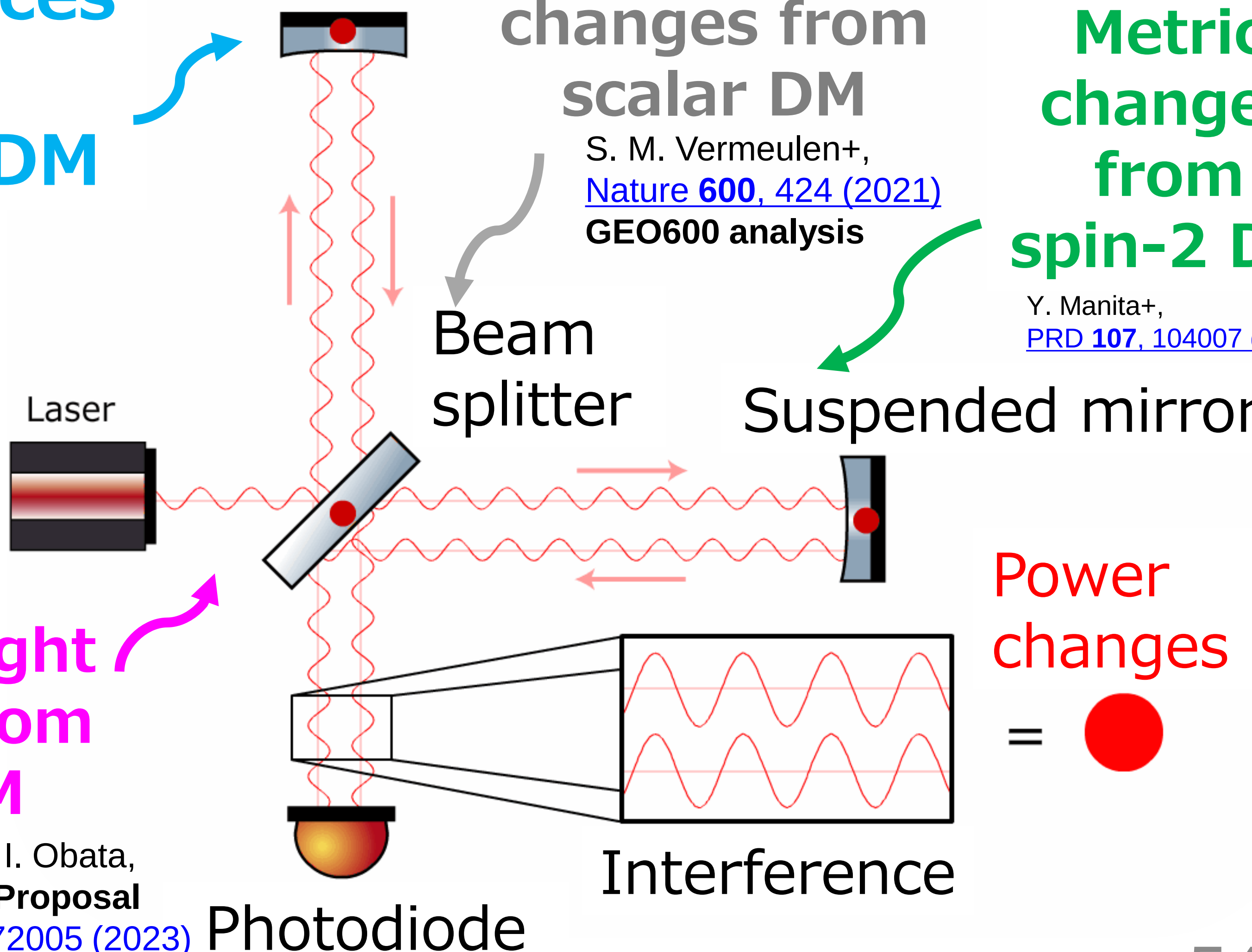
LIGO-Virgo-KAGRA, PRD **105**, 063030 (2022)
LIGO/Virgo O3 analysis
LIGO-Virgo-KAGRA, PRD 110, 042001 (2024)
KAGRA O3GK analysis

Mirror thickness changes from scalar DM

S. M. Vermeulen+, Nature **600**, 424 (2021)
GEO600 analysis

Metric changes from spin-2 DM

Y. Manita+, PRD **107**, 104007 (2023)



Speed of light changes from axion DM

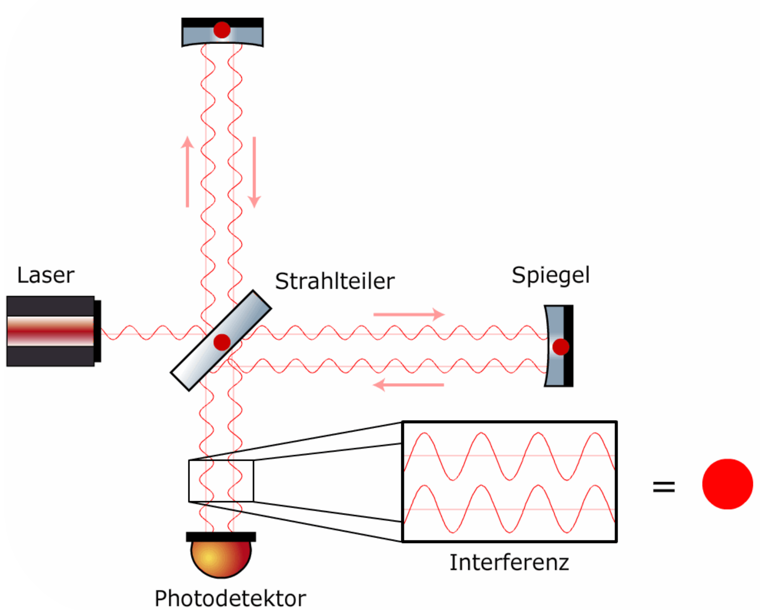
K. Nagano, T. Fujita, YM, I. Obata, PRL **123**, 111301 (2019) **Proposal**
Y. Oshima+, PRD **108**, 072005 (2023)
Table-top experiment DANCE analysis

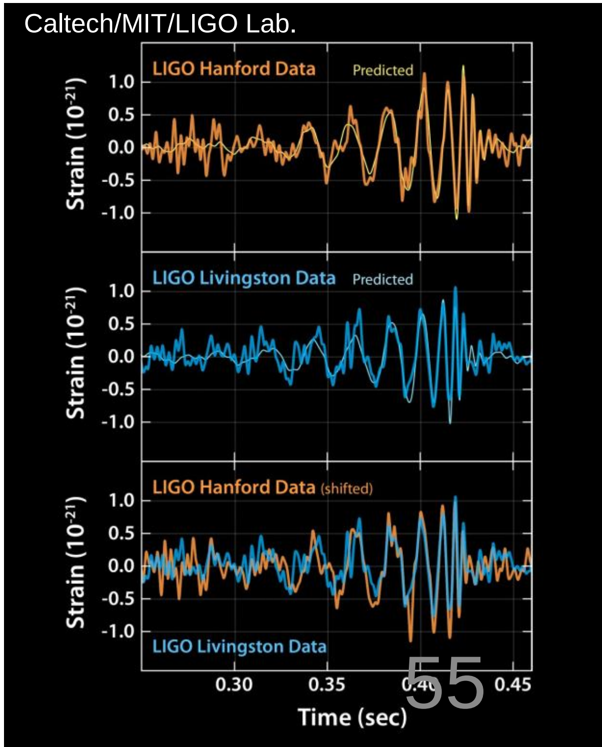
Ultralight DM with Interferometers

- Bosonic ultralight field (<~1 eV) are well-motivated from cosmology
- Behaves as classical waves

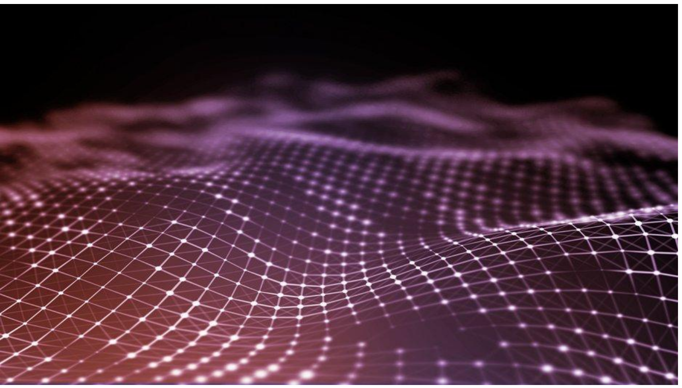
$$f = 242 \text{ Hz} \left(\frac{m_{\rm DM}}{10^{-12} \text{ eV}} \right)$$

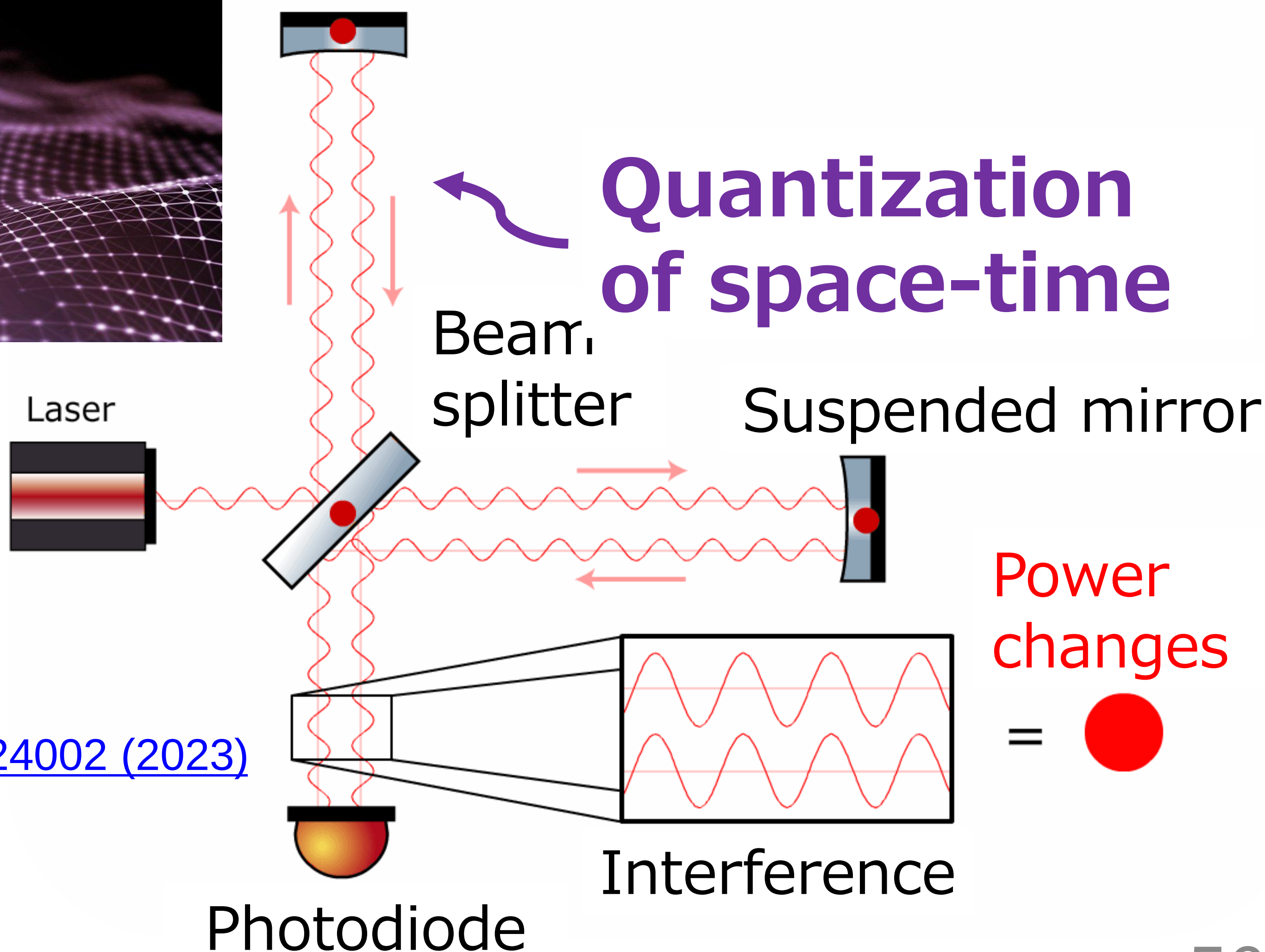
- Laser interferometers are sensitive to such oscillating changes





Particle Physics with GW Detectors





K. M. Zurek,
arXiv:2205.01799
D. Li+, PRD 107, 024002 (2023)

Summary

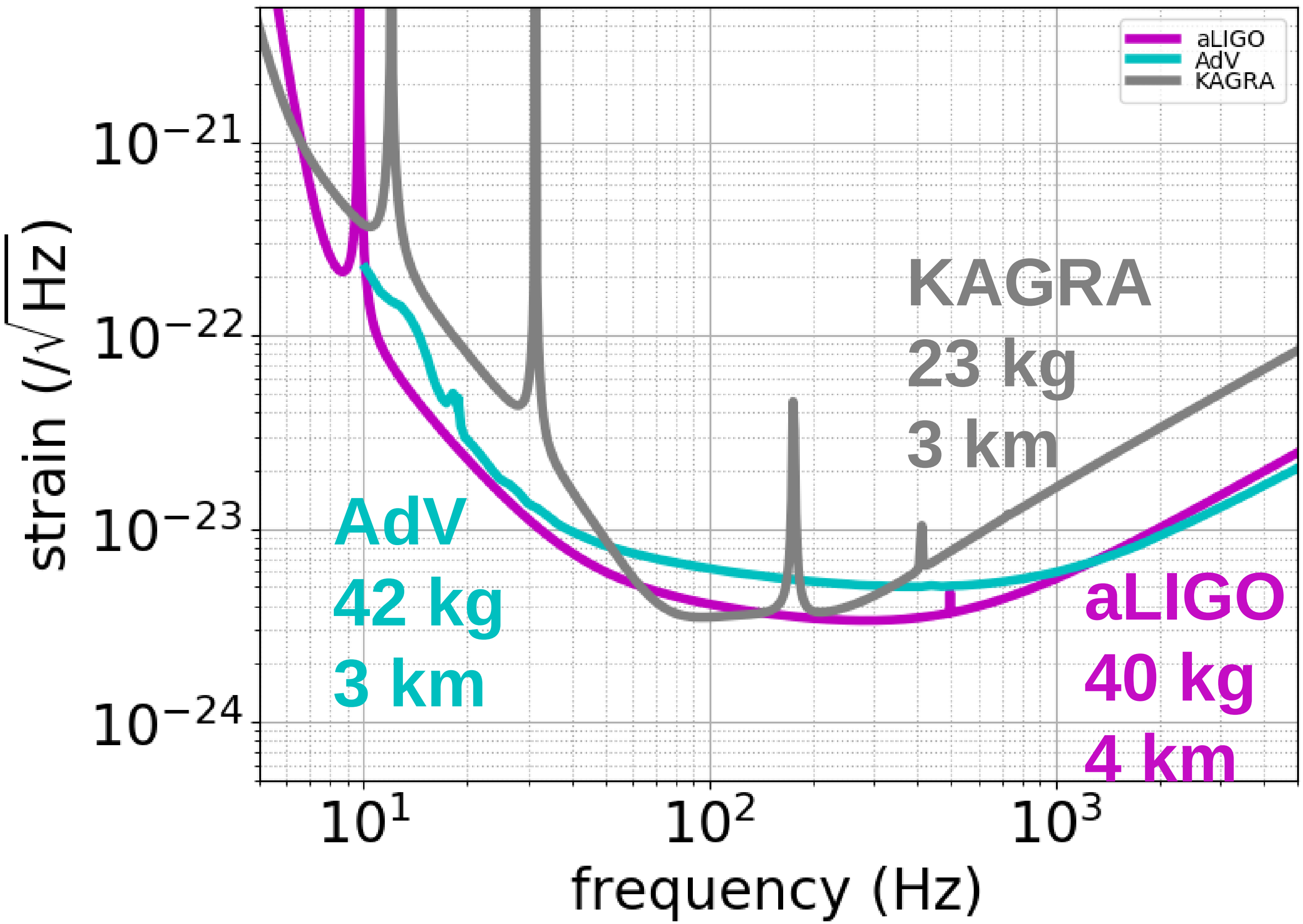
- Gravitational wave astronomy and physics have just begun
- Detector developments will directly enhance observational science
- Next generation detectors enable observations of binary coalescences from entire universe
- Space based detectors enable multi-band observations and observation of gravitational wave background from inflation

- *Future is bright and yours to shape!*

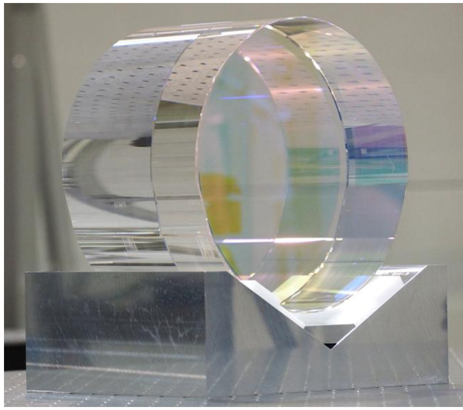
Additional Slides

KAGRA Design Sensitivity

- Not good at low freq. because of thick and short fiber (35 cm, φ1.6 mm) to extract heat, and lower mass

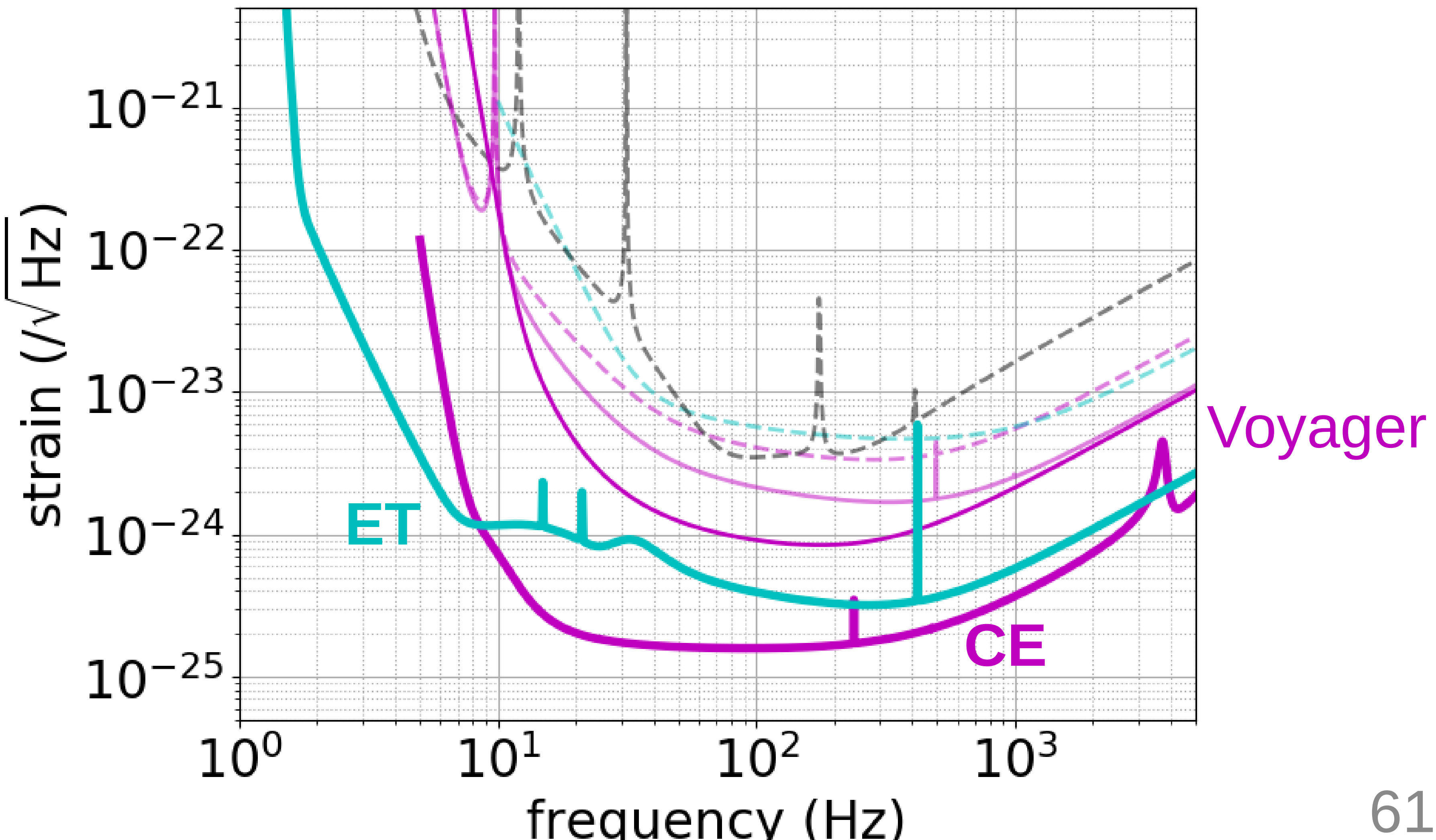


23 kg was the largest available sapphire mirror



Sensitivity of Next Generations

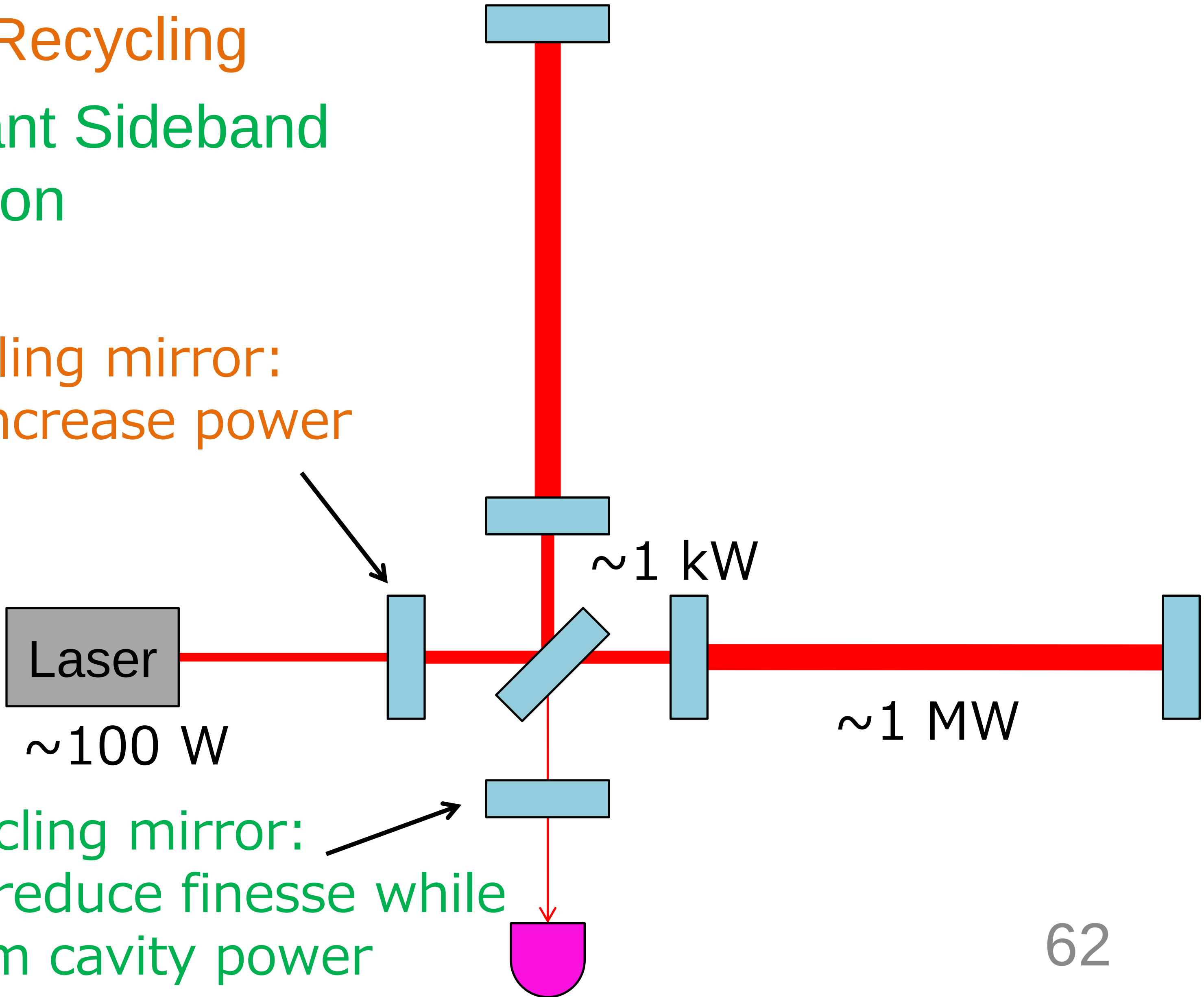
- An order of magnitude improvement



Resonant Sideband Extraction

- Power Recycling
- Resonant Sideband Extraction

Power recycling mirror:
Effectively increase power



Signal recycling mirror:
Effectively reduce finesse while keeping arm cavity power

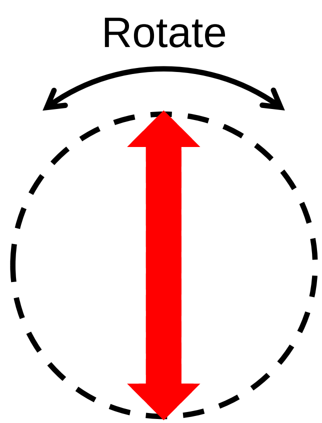
Polarization Modulation from Axions

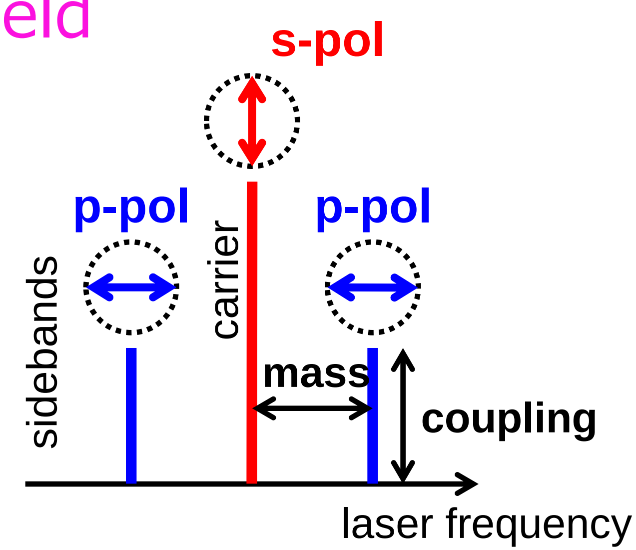
- Axion-photon coupling ($\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$) gives different phase velocity between left-handed and right-handed circular polarizations

$$c_{\mathrm{L/R}} = \sqrt{1 \pm \frac{g_{a\gamma} a_0 m_a}{k} \sin(m_a t + \delta_\tau)}$$

coupling constant　axion field　axion mass

- Linear polarization will be modulated
  - p-pol sidebands will be generated from s-pol
- Search can be done without magnetic field

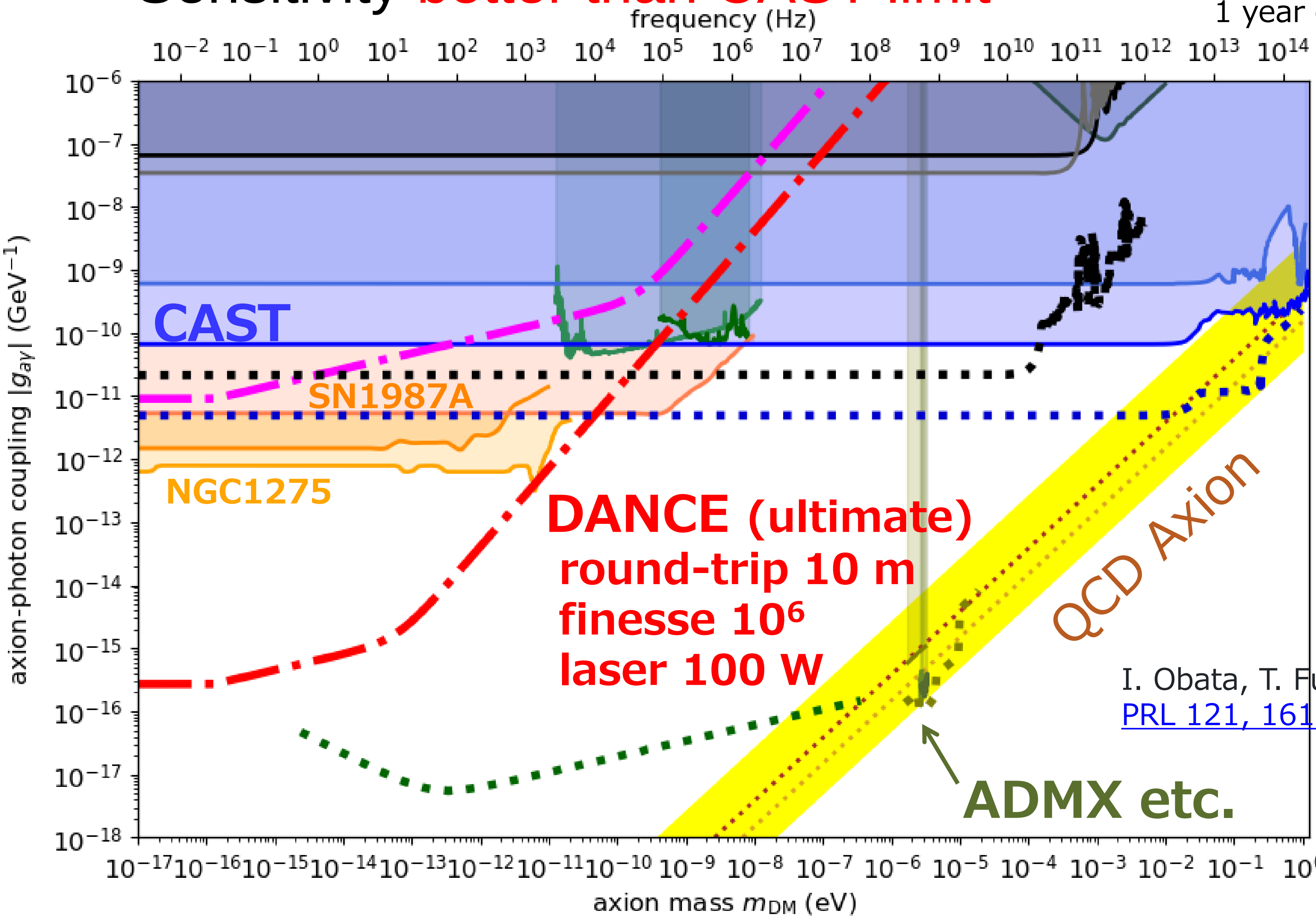




Sensitivity of DANCE

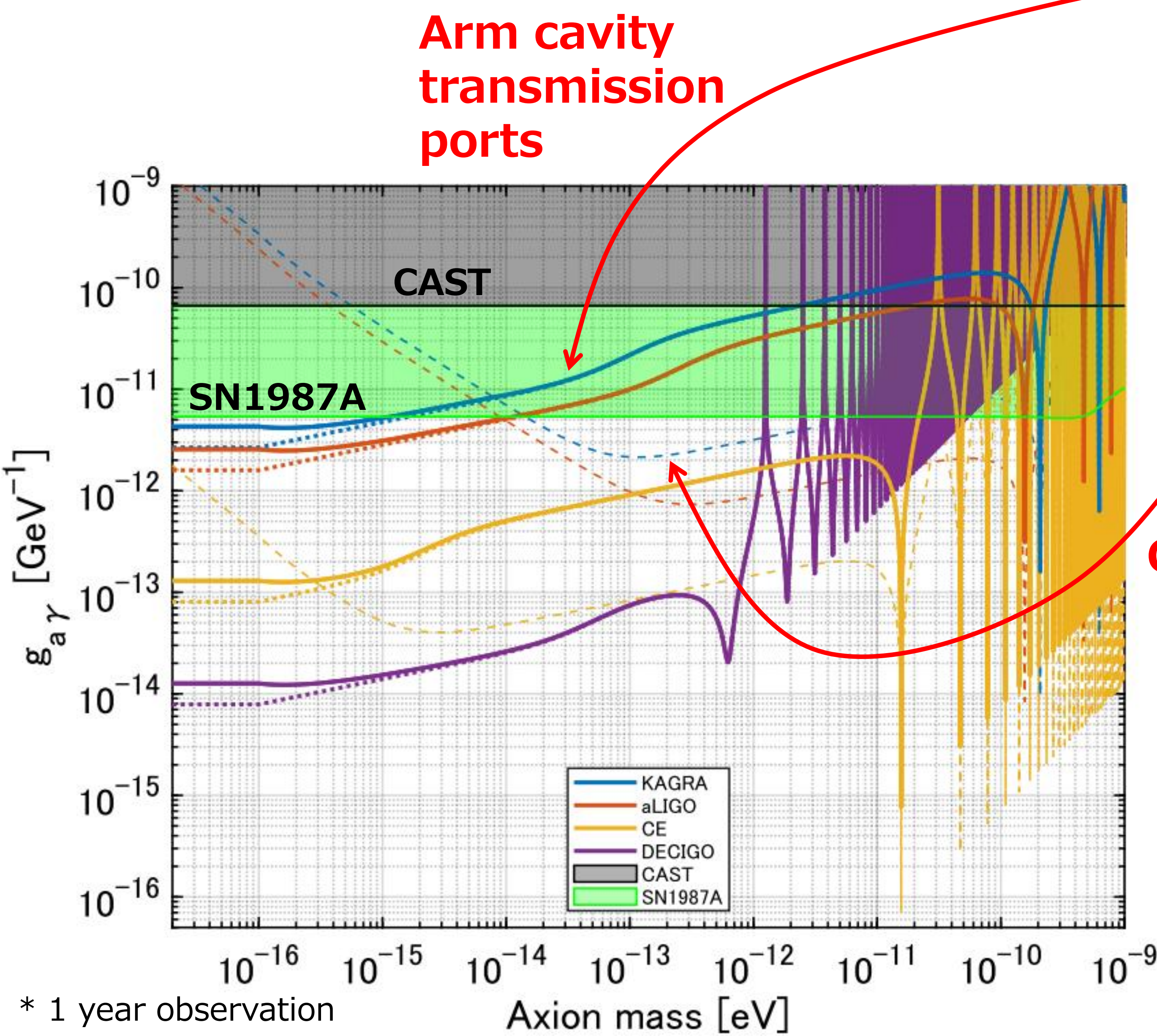
- Sensitivity better than CAST limit

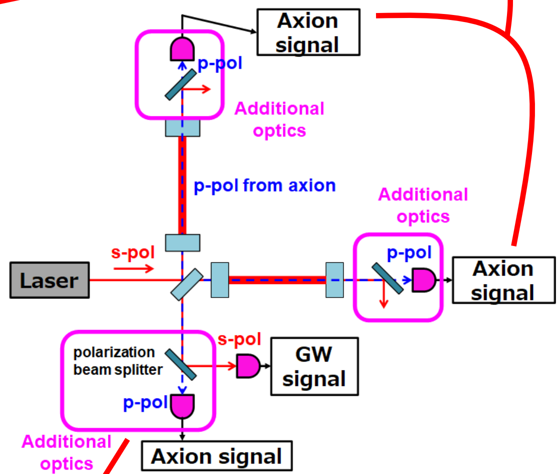
* Shot noise limited
1 year observation



I. Obata, T. Fujita, YM,
PRL 121, 161301 (2018)

Axion Sensitivity





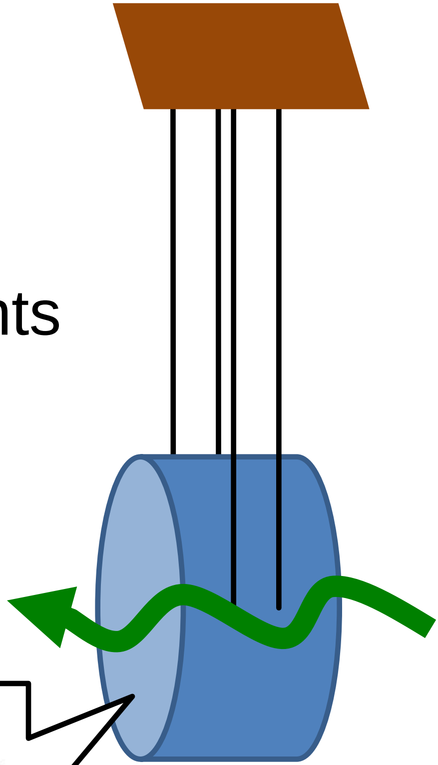
Complemental search using different ports

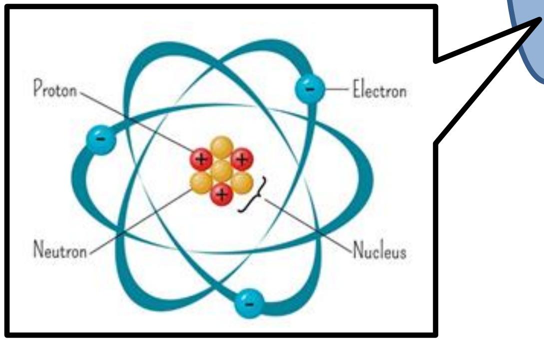
* 1 year observation

arXiv:2106.06800

Vector Boson

- Possible new physics beyond the standard model:
  New gauge symmetry and vector boson
- New vector boson can be dark matter
- B-L (baryon minus lepton number)
  - Conserved in the standard model
  - Can be gauged without additional ingredients
  - Equals to the number of neutrons
  - Roughly 0.5 per neutron mass,
    but slightly different between materials
    Fused silica: 0.501
    Sapphire: 0.510
- Vector boson DM
  gives oscillating force





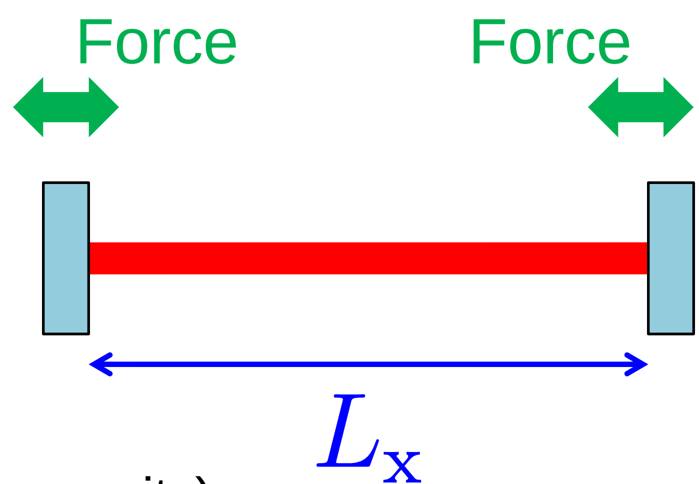
Oscillating Force from Vector Field

- Acceleration of mirrors

$$\vec{a}(t,\vec{x}) = \epsilon_D e \frac{q_D}{M} \sqrt{2\rho_{DM}} \vec{e}_A \sin\left(m_A t - \vec{k}\cdot\vec{x}\right)$$

charge (q_D); vector boson mass (m_A); coupling (normalized by e) (ϵ_D); mirror mass (M); DM density (ρ_{DM}); polarization ($\vec{e}_A$); different phase at different position ($\vec{k}\cdot\vec{x}$)

- Vector boson mass and coupling can be measured by measuring the oscillating mirror displacement



- Almost no signal for symmetric cavity if cavity length is short (phase difference is 10^{-5} rad @ 100 Hz for km cavity)
- How about using interferometric GW detectors?

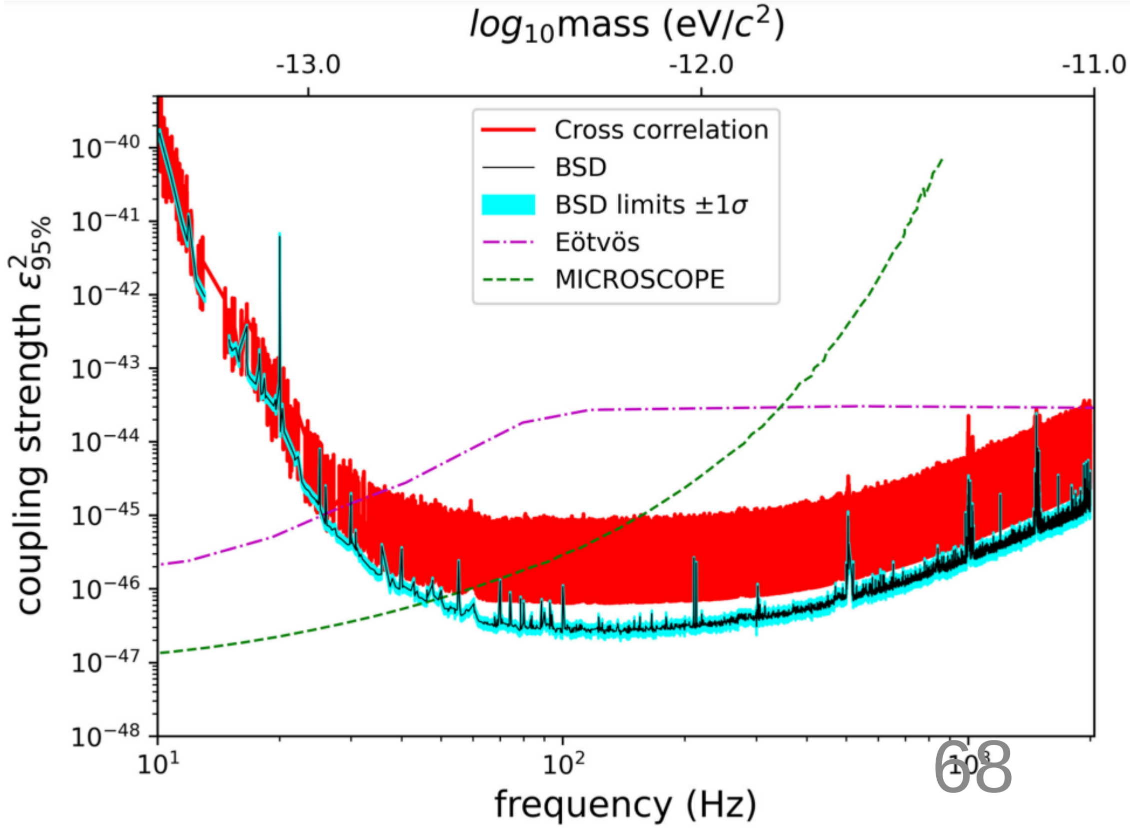
A. Pierce+, PRL **121**, 061102 (2018)

Previous Searches with LIGO/Virgo

- Vector boson dark matter search with LIGO O1 data and LIGO/Virgo O3 data have been done

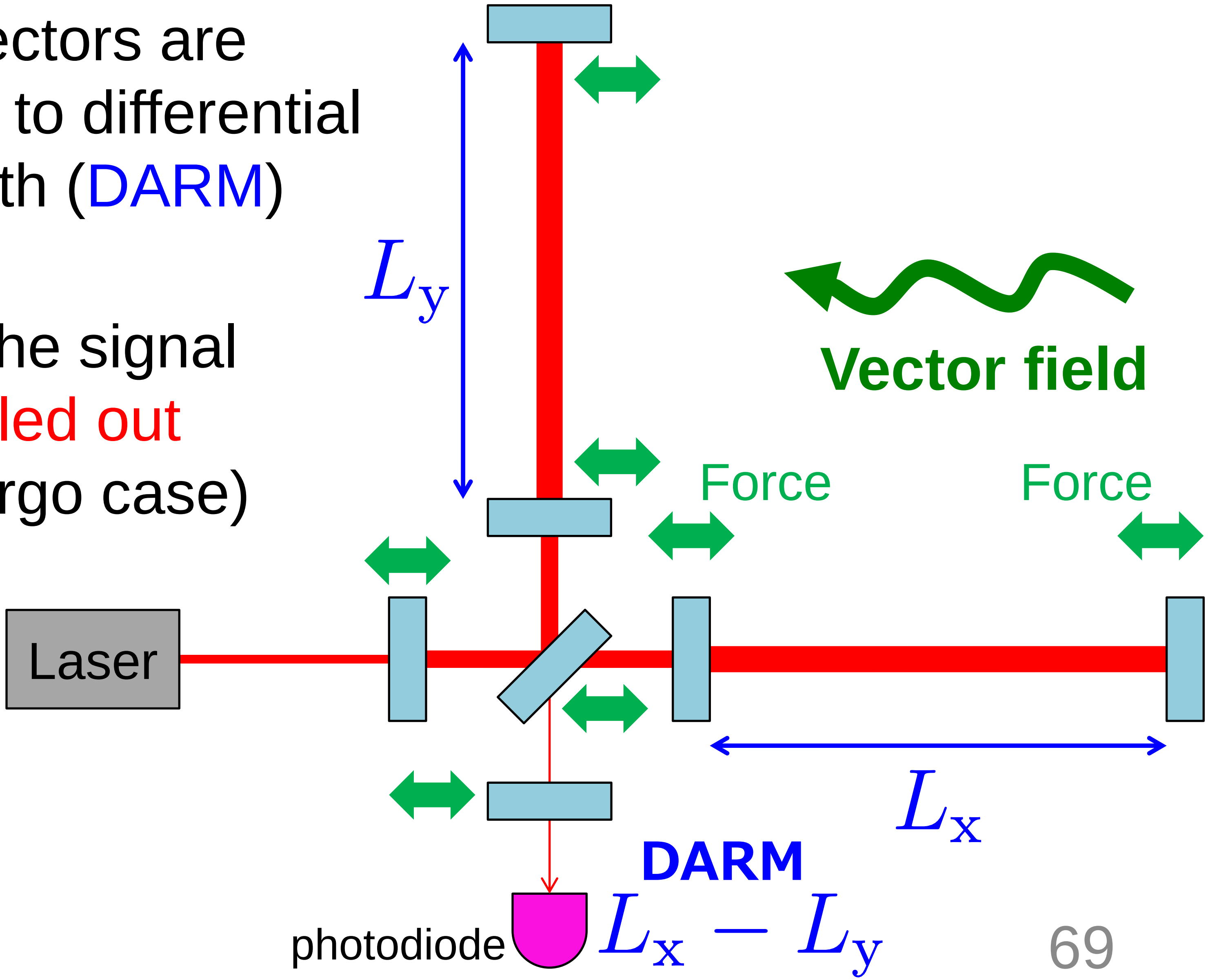
  H-K Guo+, [Communications Physics **2**, 155 (2019)]
  LIGO-Virgo-KAGRA Collaboration, [PRD **105**, 063030 (2022)]

- Better constraint than equivalence principle tests
- Even better constraint could be obtained from KAGRA

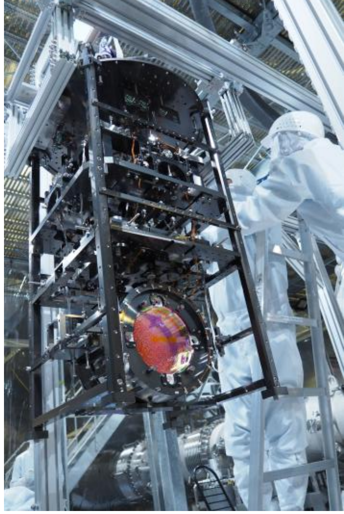


Search with GW Detectors

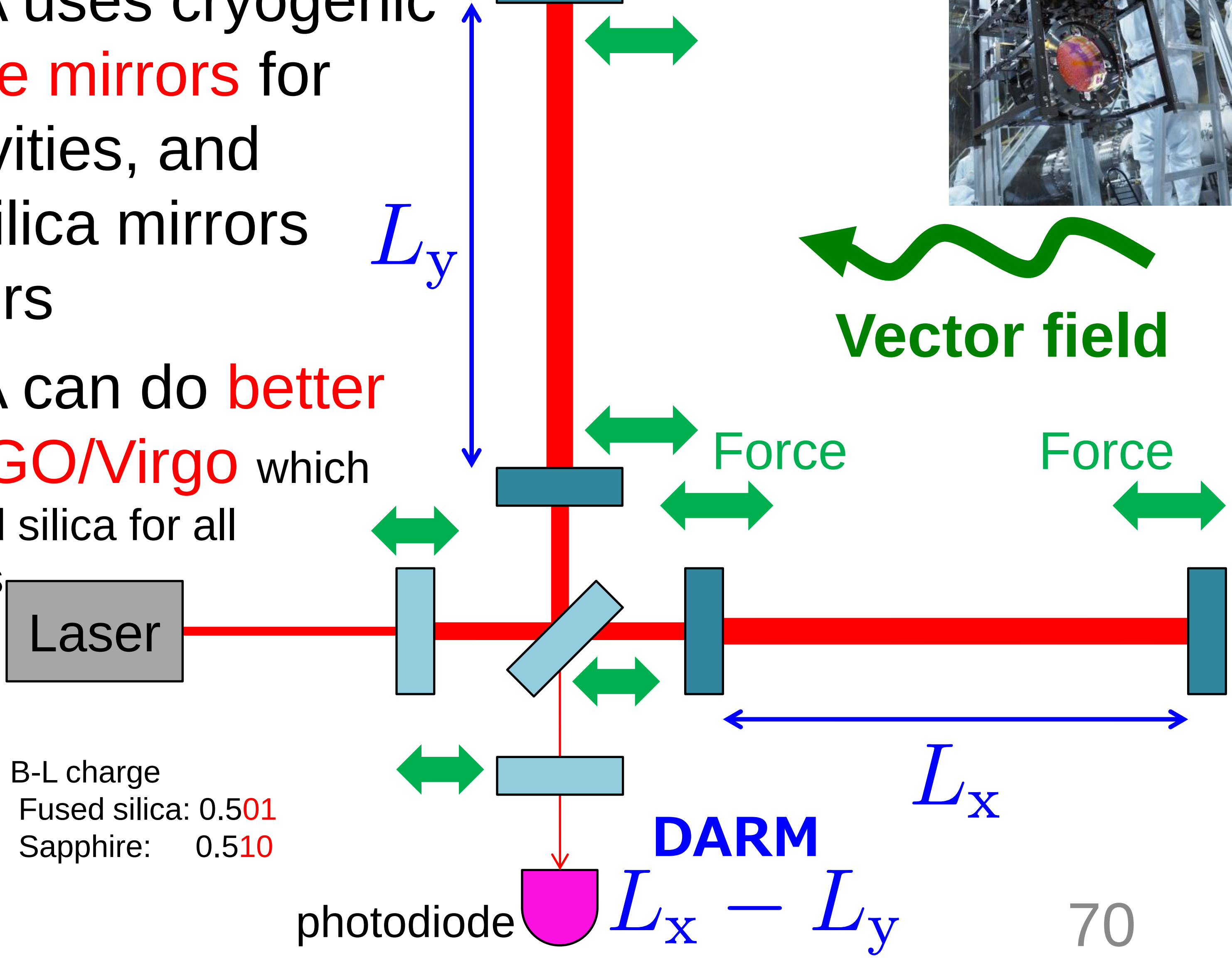
- GW Detectors are sensitive to differential arm length (DARM) change
- Most of the signal is cancelled out (LIGO/Virgo case)

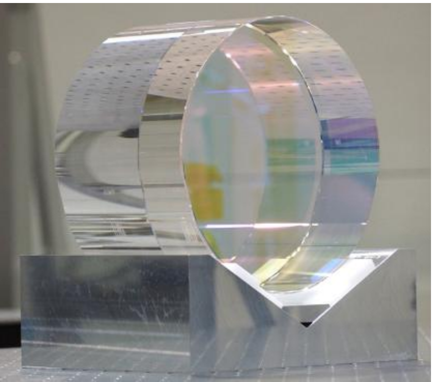


Search with KAGRA



- KAGRA uses cryogenic sapphire mirrors for arm cavities, and fused silica mirrors for others
- KAGRA can do better than LIGO/Virgo which uses fused silica for all the mirrors

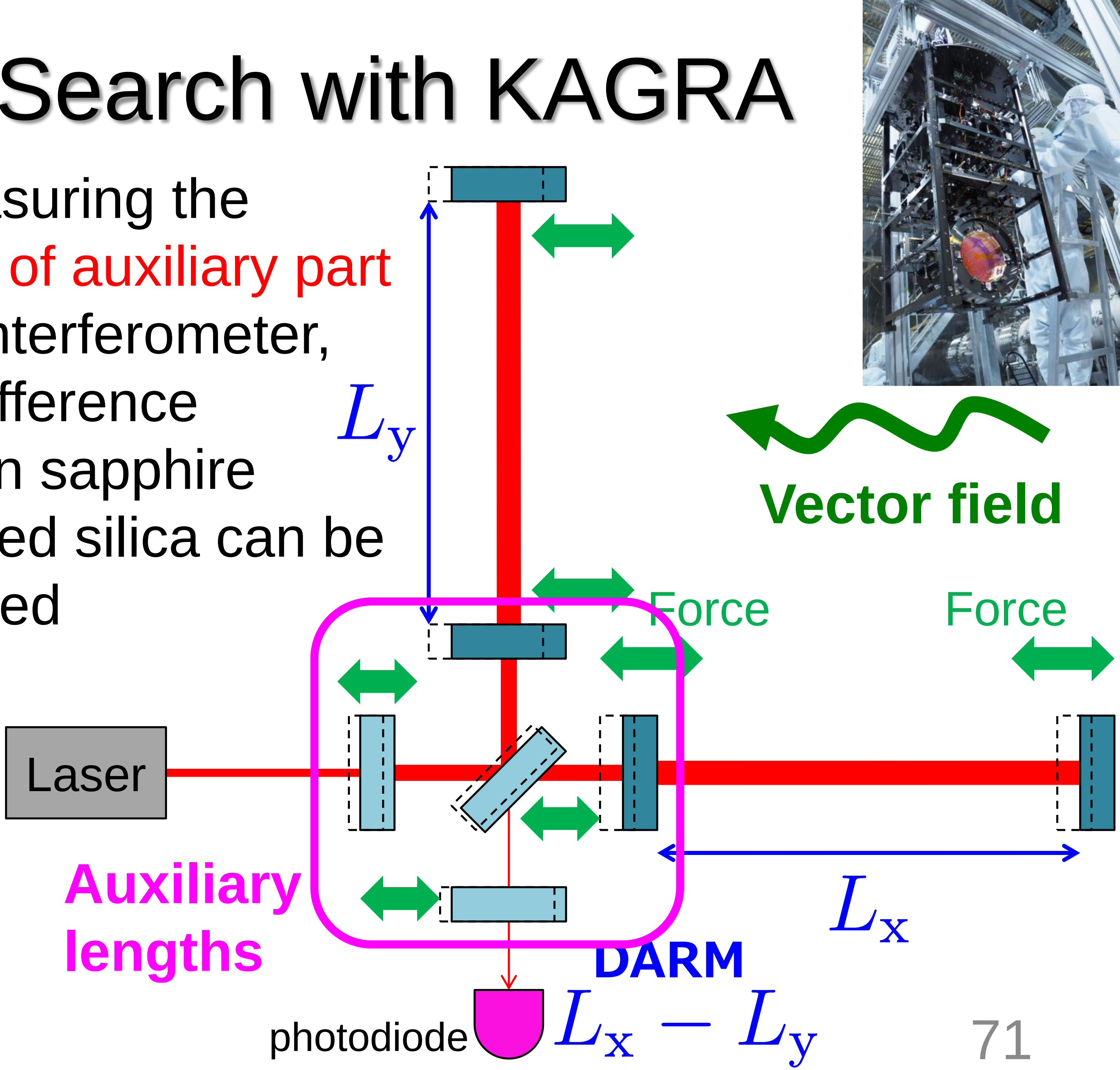




B-L charge
Fused silica: 0.501
Sapphire: 0.510

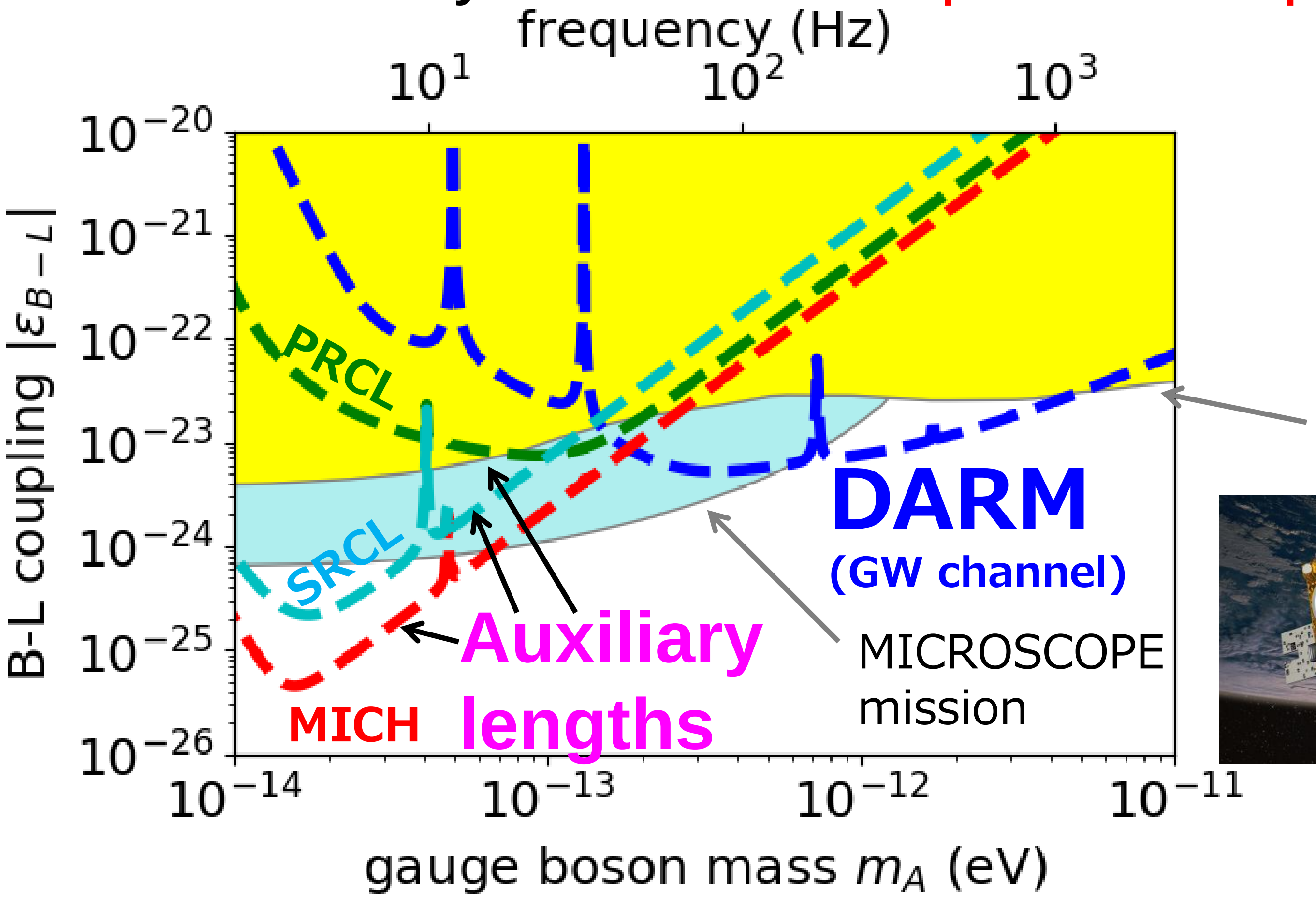
Search with KAGRA

- By measuring the lengths of auxiliary part of the interferometer, force difference between sapphire and fused silica can be measured



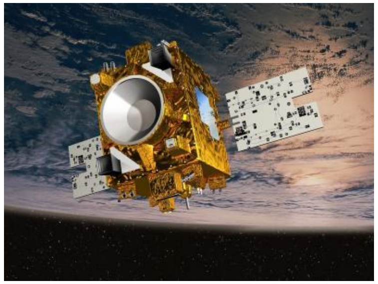
KAGRA Vector Boson Sensitivity

- Auxiliary length channels have better design sensitivity than DARM (GW channel) at low mass range
- Sensitivity better than equivalence principle tests



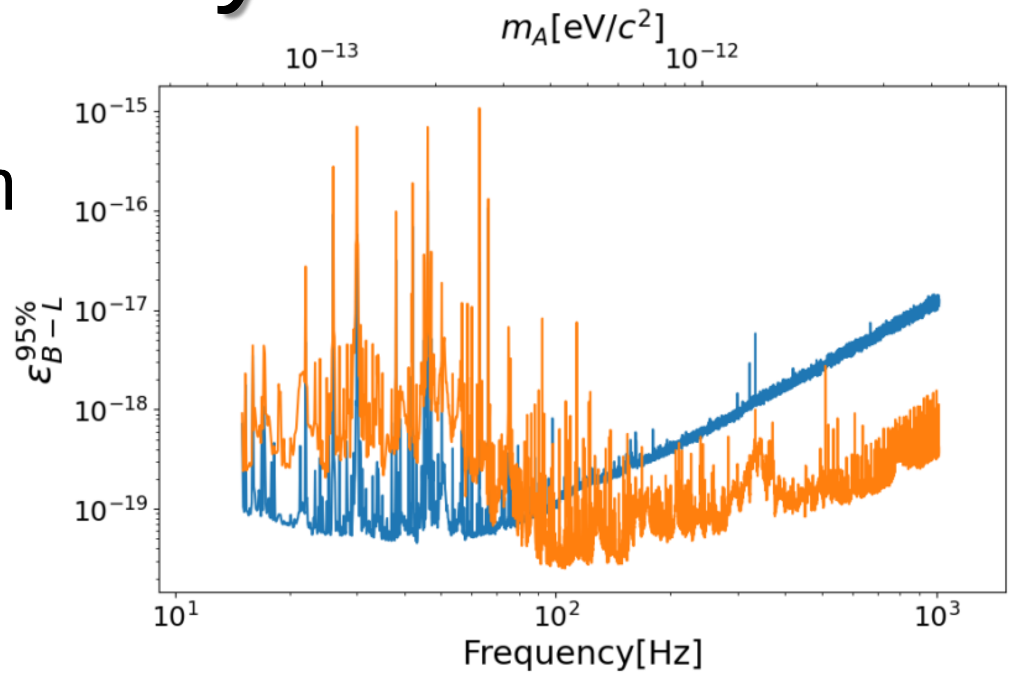
YM, T. Fujita, S. Morisaki, H. Nakatsuka, I. Obata, [PRD 102, 102001 (2020)]

S. Morisaki, T. Fujita, YM, H. Nakatsuka, I. Obata, [PRD 103, L051702 (2021)]



KAGRA Data Analysis Results

- Still ~5 orders of magnitude worse than equivalence principle tests
- Demonstrated the feasibility of using auxiliary channels for astrophysics
- New data will be available from O4b and beyond




Ultralight vector dark matter search using data from the KAGRA O3GK run

arXiv:2403.03004v1 [astro-ph.CO] 5 Mar 2024

LIGO-Virgo-KAGRA, [arXiv:2403.03004](https://arxiv.org/abs/2403.03004)
(Paper written by J. Kume with 1800+ authors!)