

The future of gravitational wave detectors



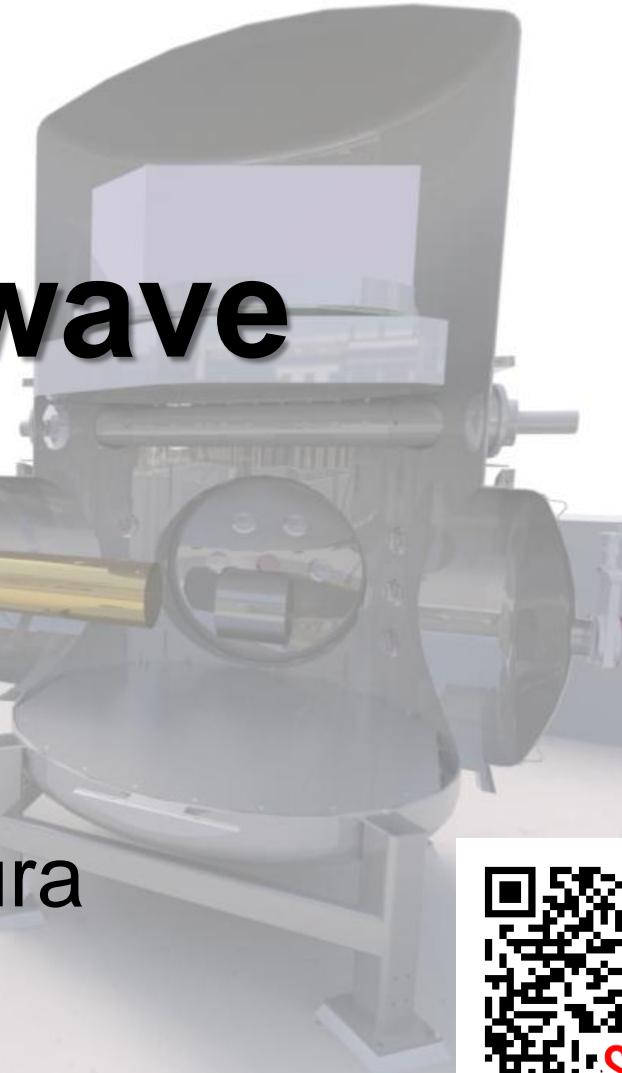
Yuta Michimura

道村 唯太

RESCEU, University of Tokyo

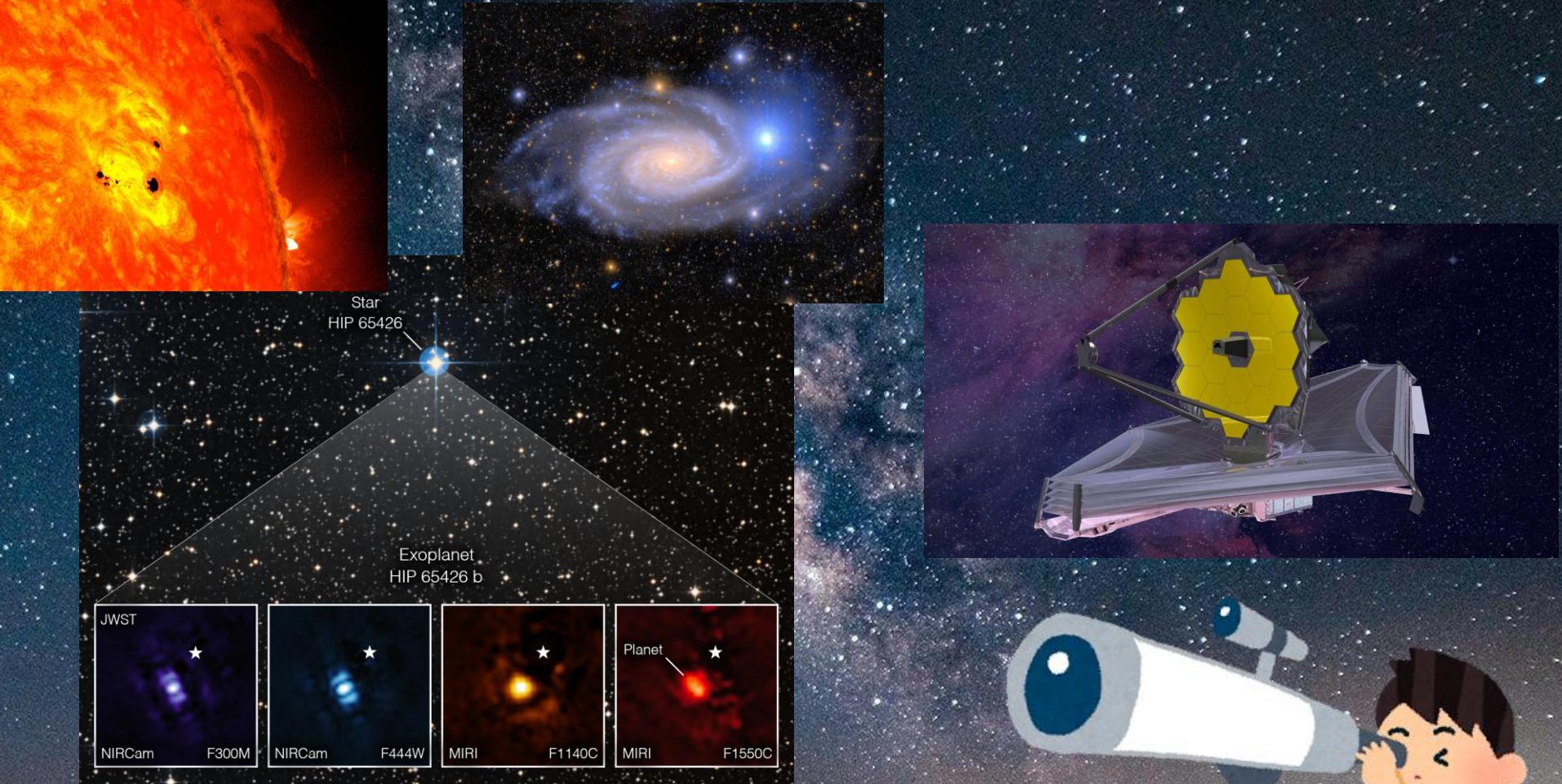
michimura@resceu.s.u-tokyo.ac.jp

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

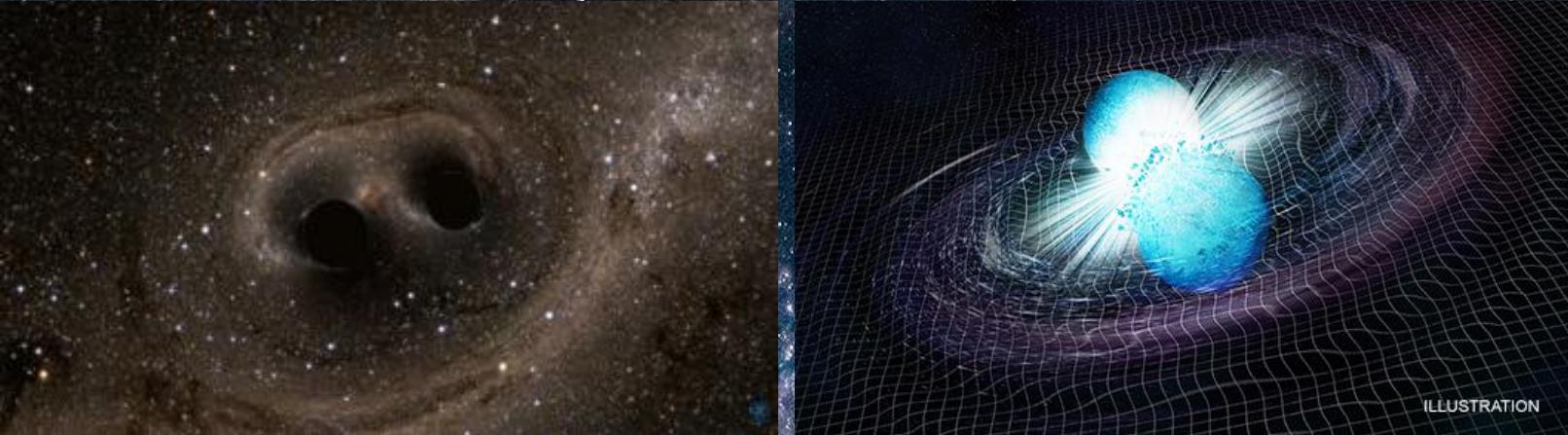




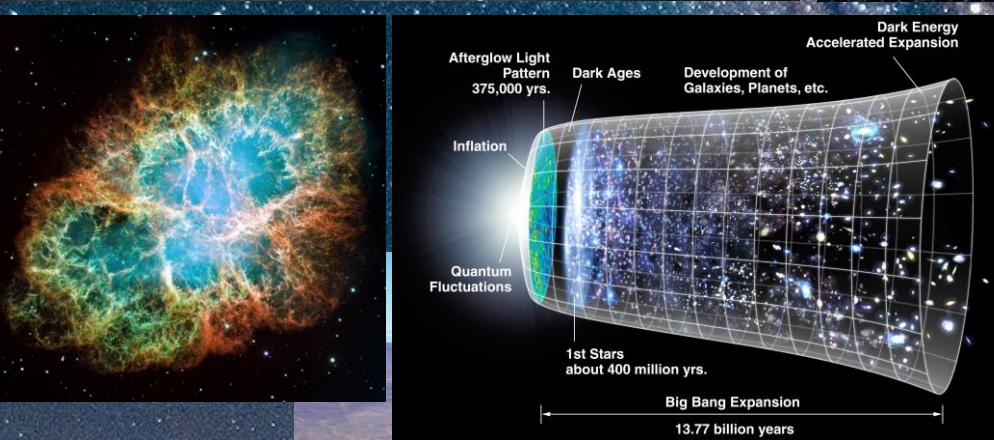






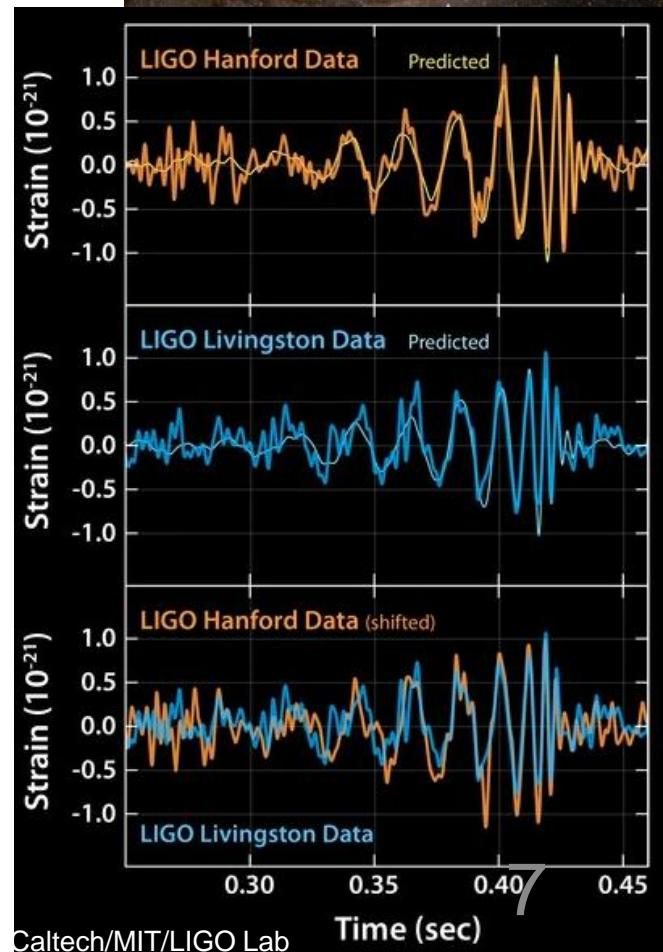
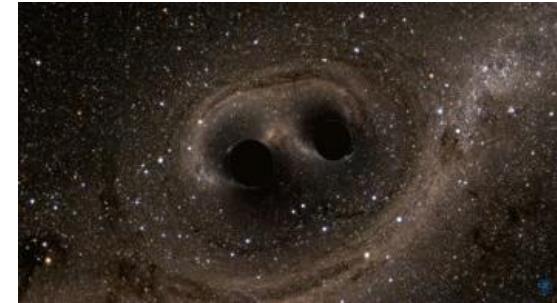
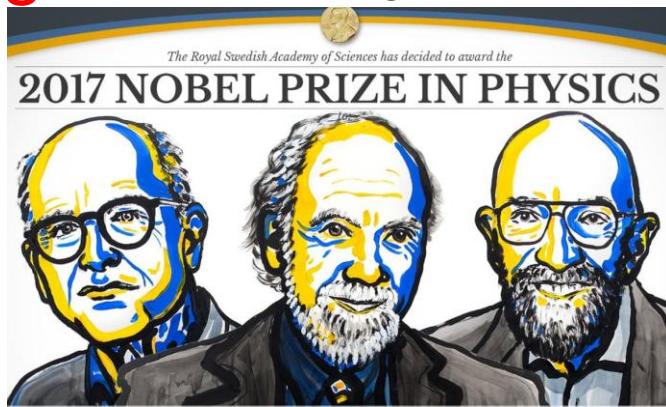
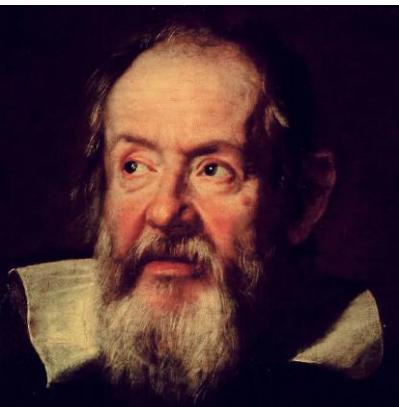


ILLUSTRATION



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

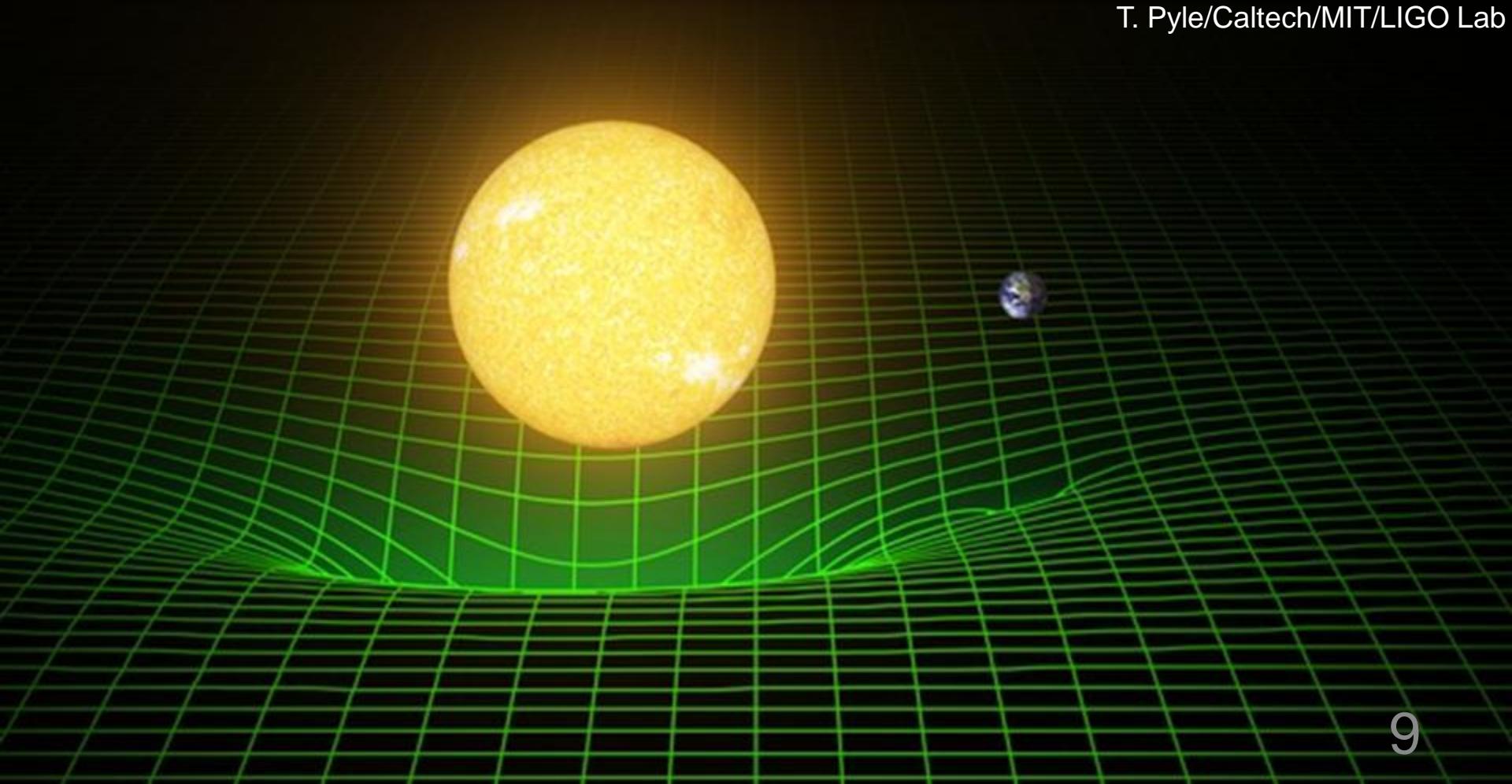
Plan of the Talk

- **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

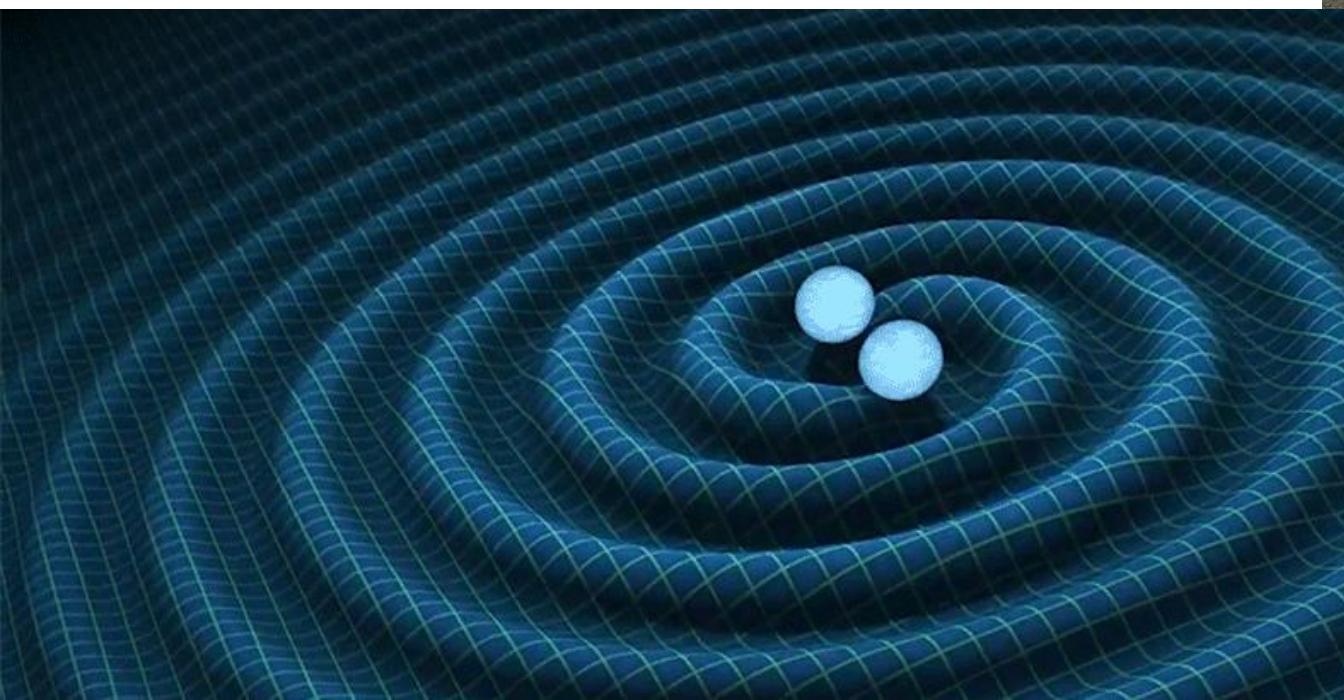
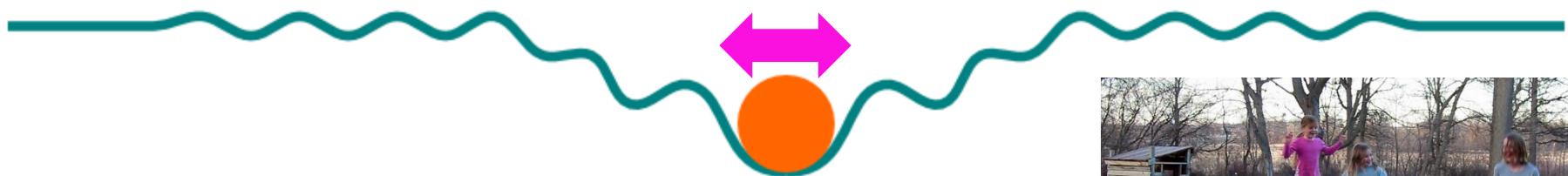
- space-time bends with presence of mass
- bending affects motion of objects → gravity

T. Pyle/Caltech/MIT/LIGO Lab



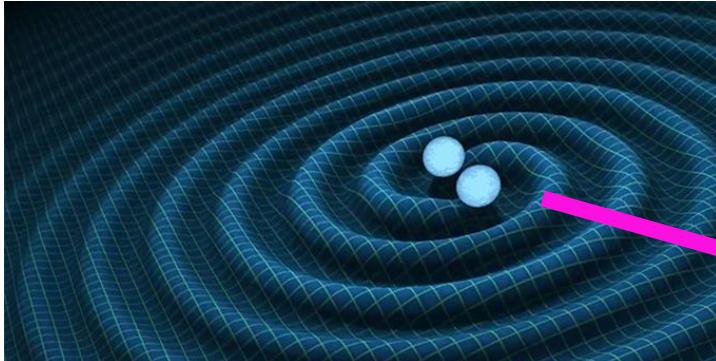
Gravitational Waves

- ripples in space-time created by motion of objects



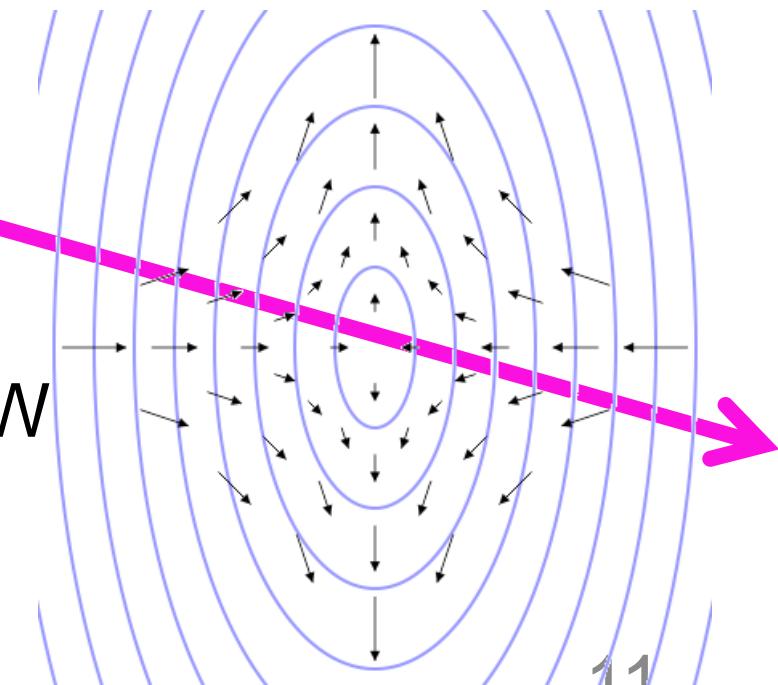
Characteristics of GWs

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



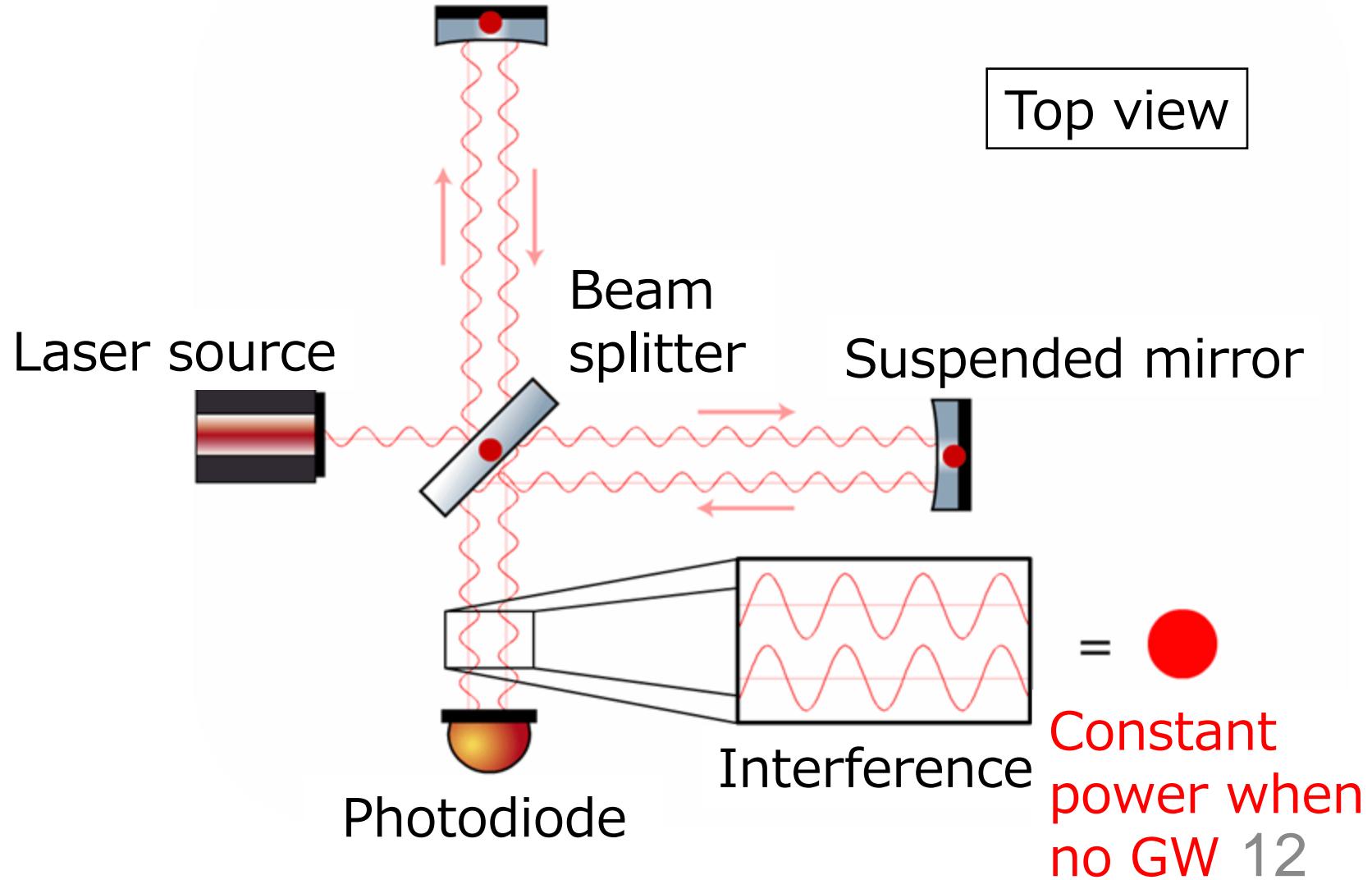
- large mass and large acceleration creates large GW
- GW strain
= **fraction of length change**

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



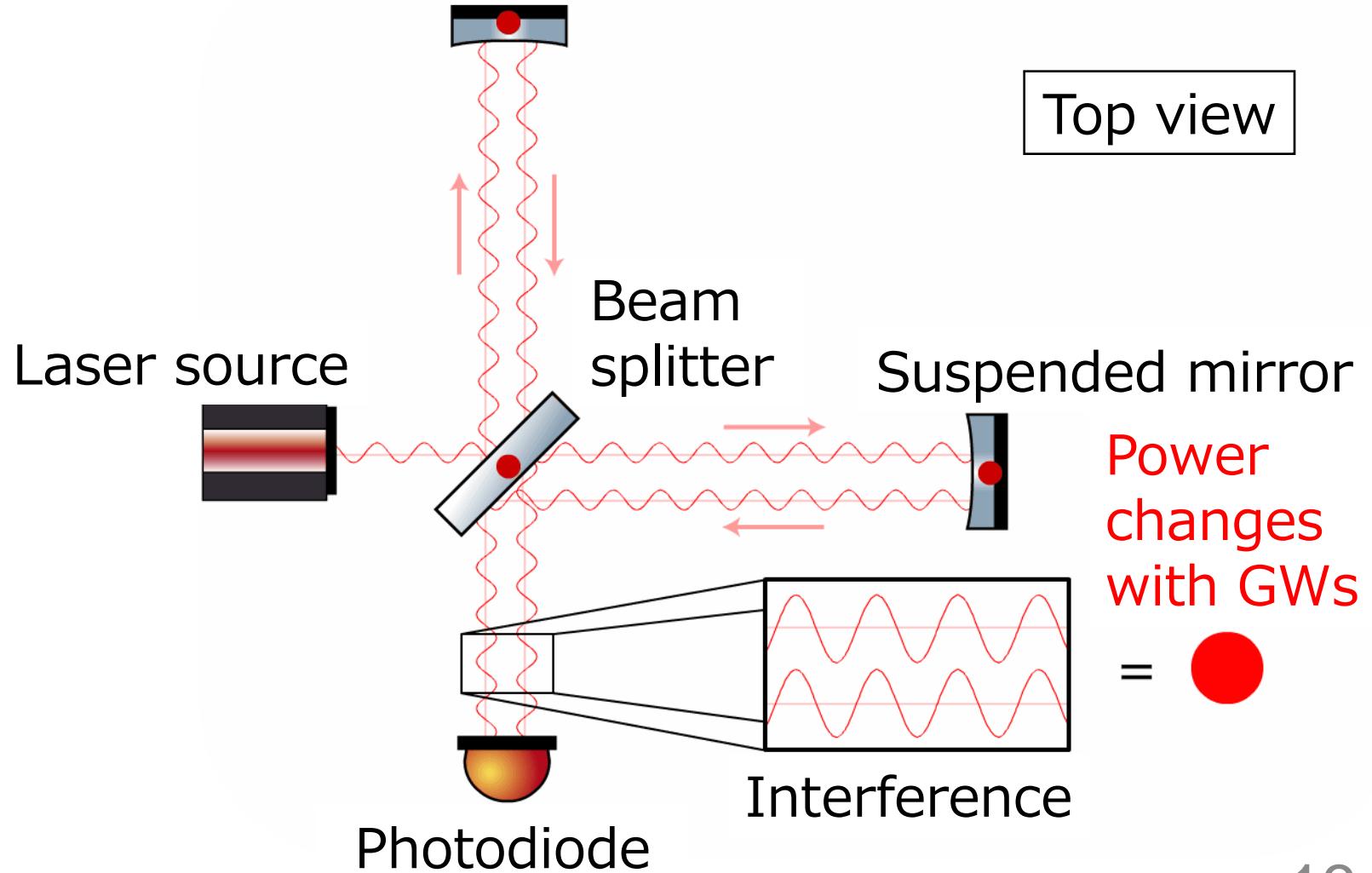
Laser Interferometric GW Detector

- measure **differential** arm length change



Laser Interferometric GW Detector

- measure **differential** arm length change

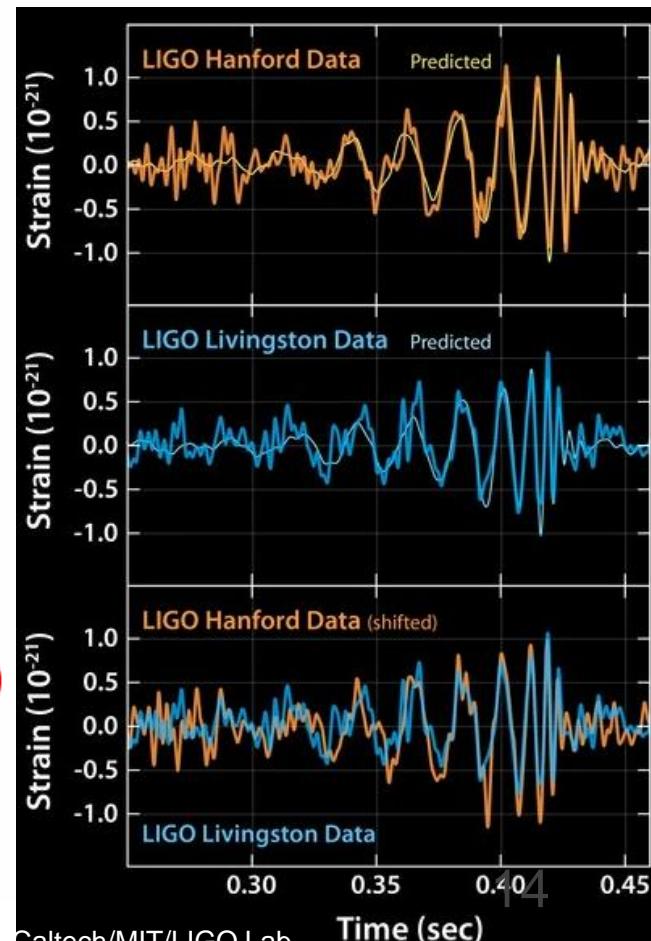
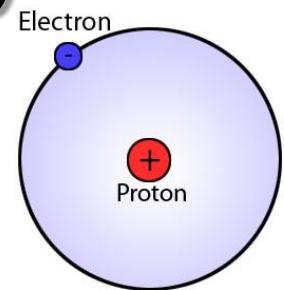
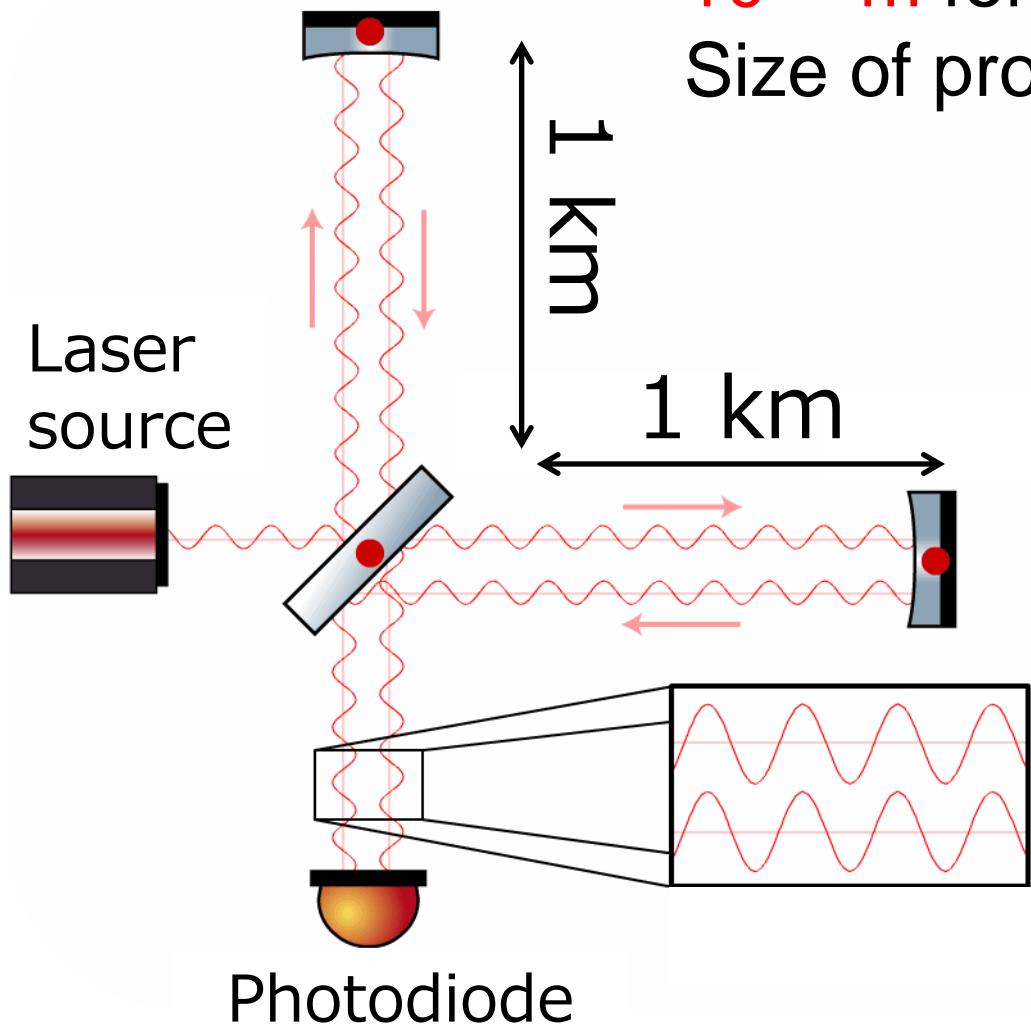


Amplitude of GW is Tiny

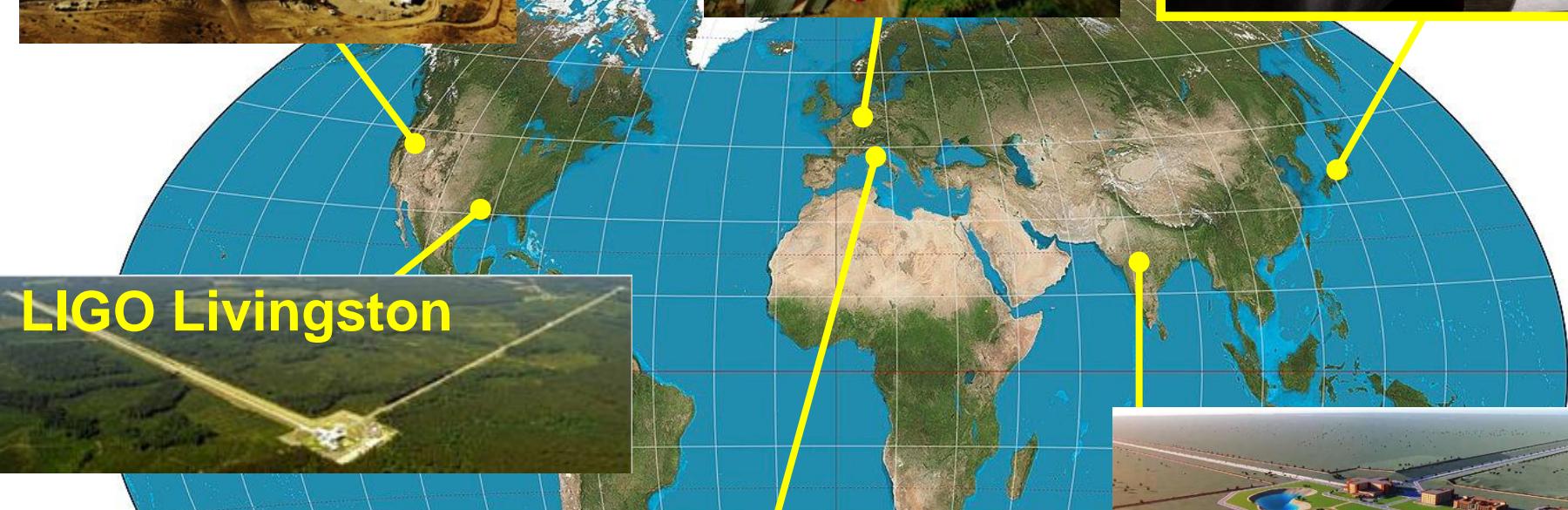
- for example, $h \sim 10^{-21}$

10^{-18} m for 1 km arm

Size of proton: 10^{-15} m

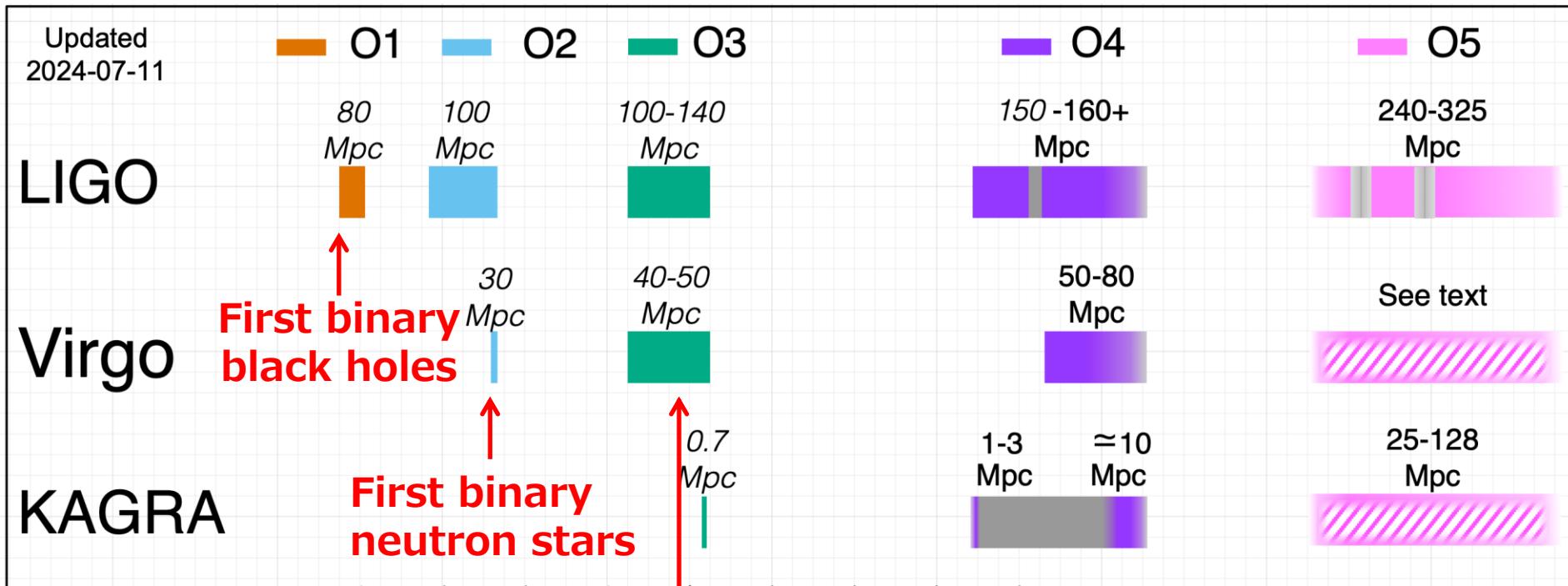


Global Network of GW Detectors



LIGO-Virgo-KAGRA Observation

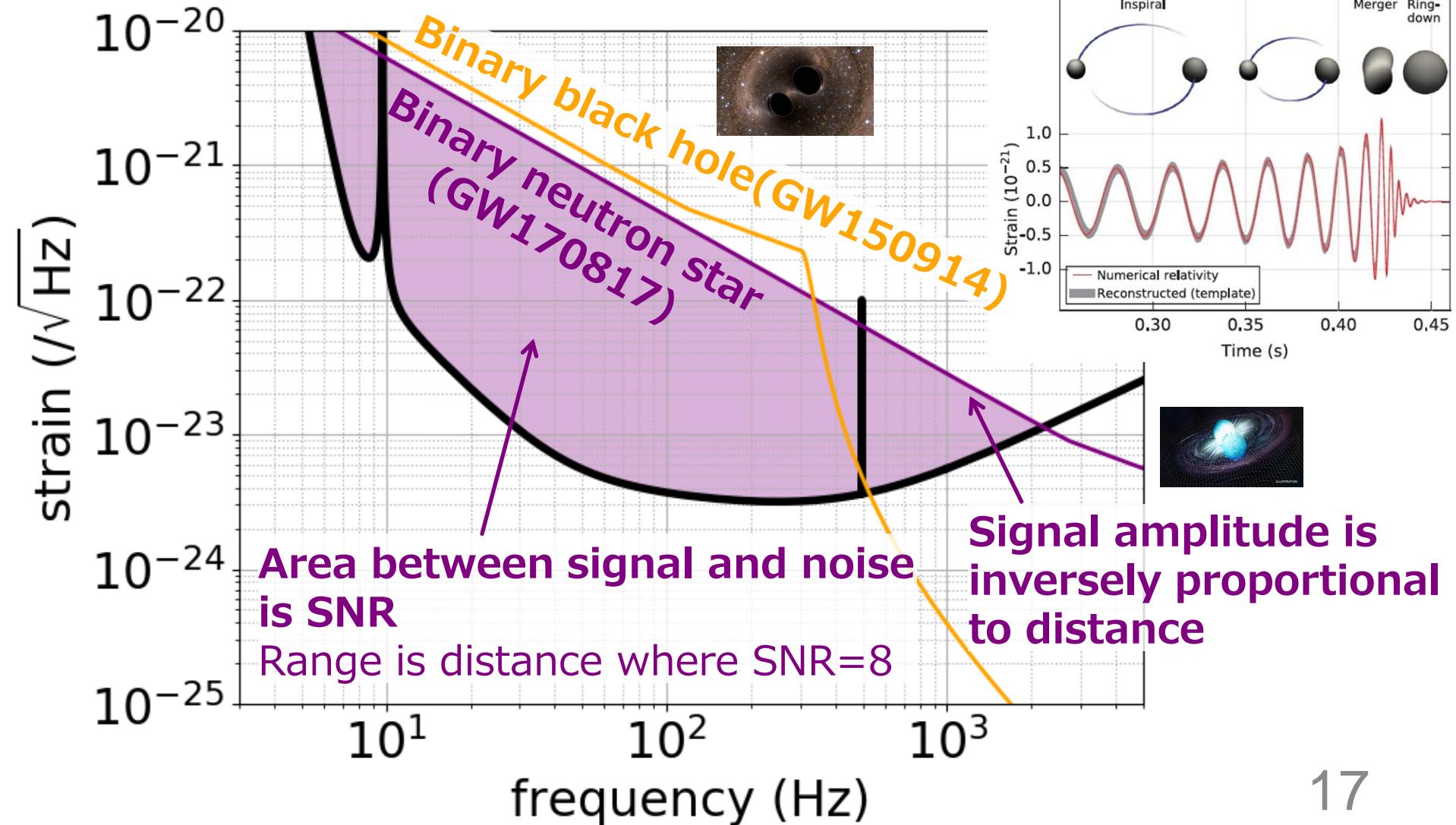
- Coordinated runs to detect GW signals by multiple detectors



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

Inspiral Range

- x2 the sensitivity, x8 the detection rate

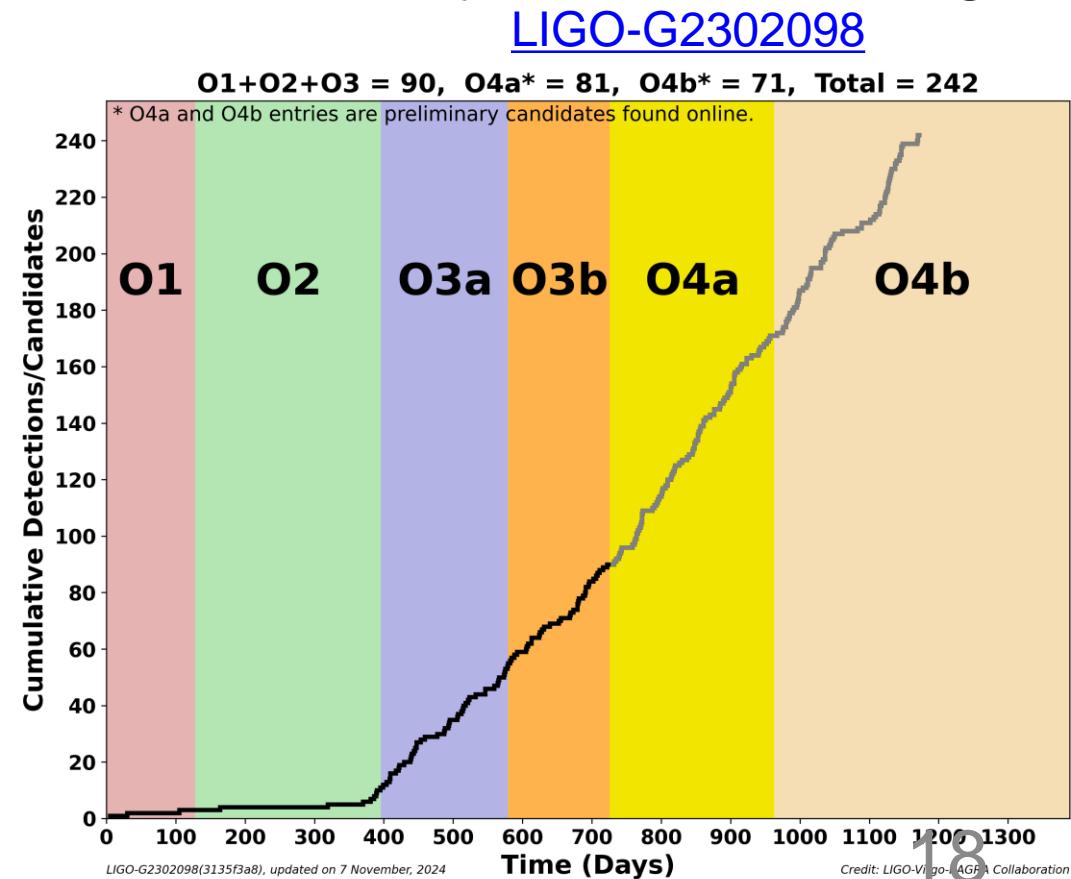


O4 Observing Run

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



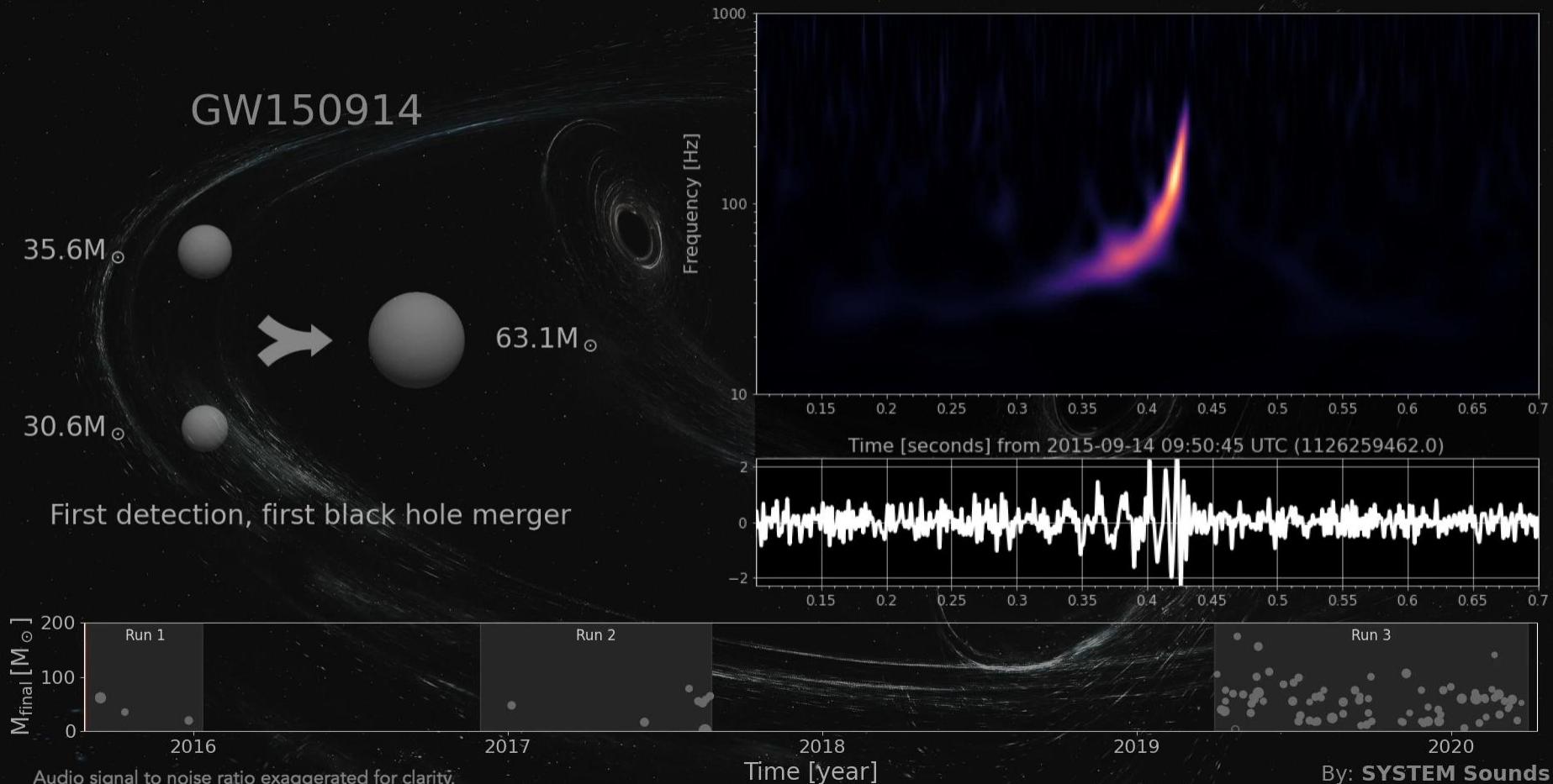
<https://apps.apple.com/jp/app/gravitational-wave-events/id1441897107>



Sound from Binary Coalescences

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

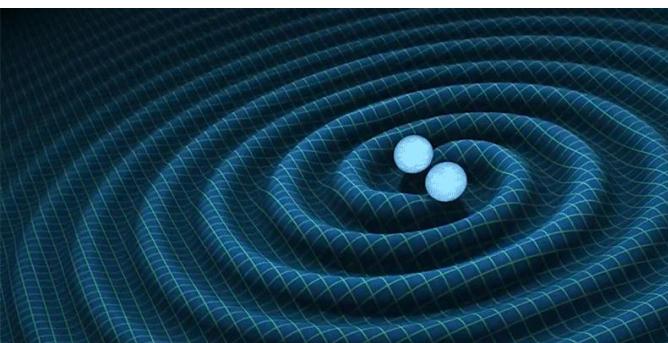
SOUND OF GRAVITATIONAL WAVES



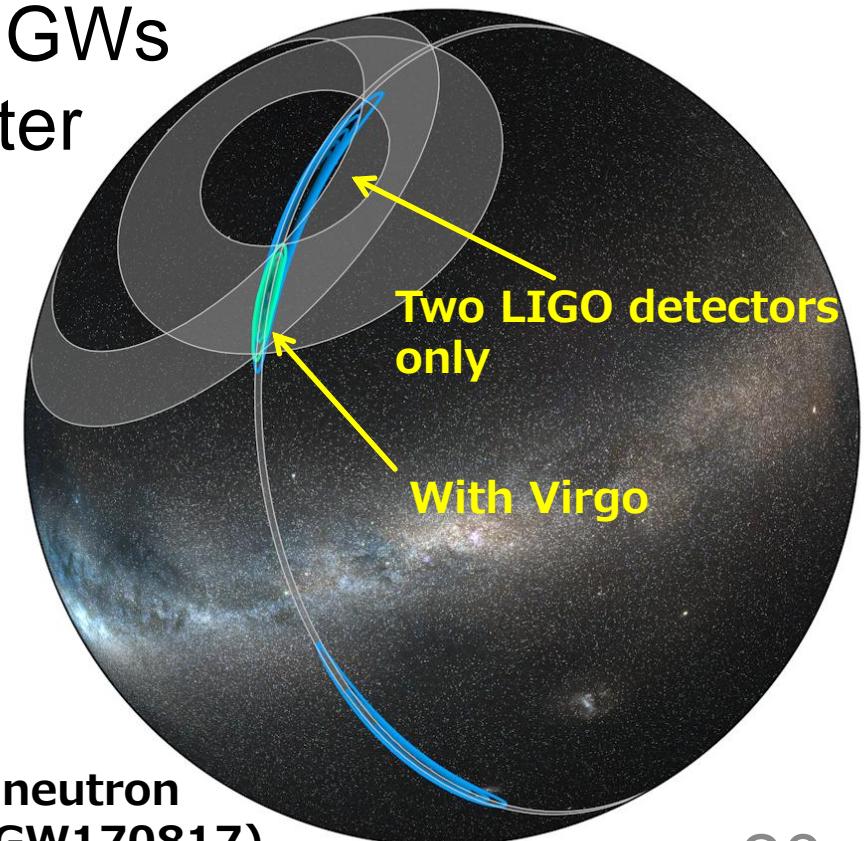
By: SYSTEM Sounds

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**



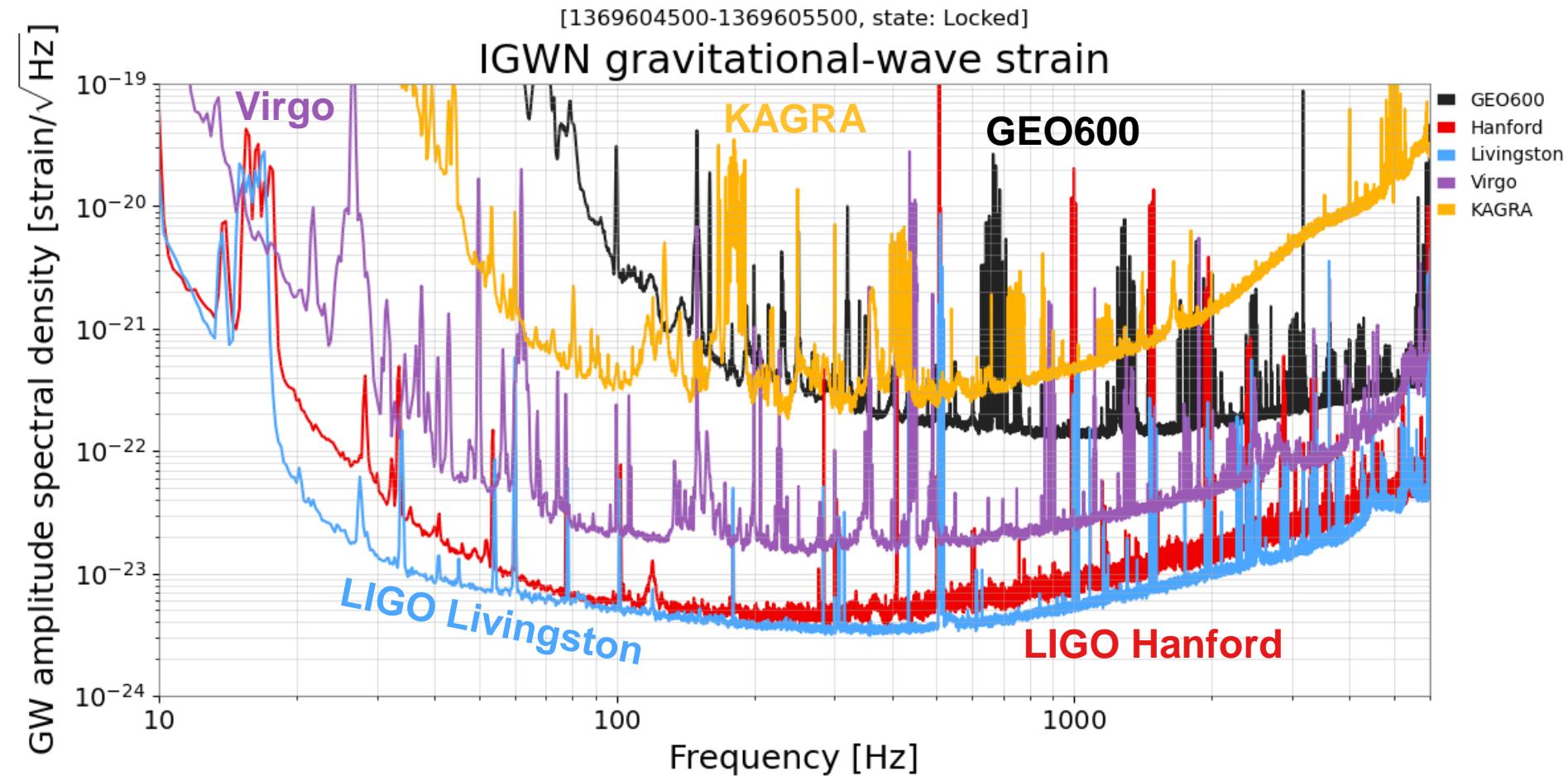
First binary neutron star event (GW170817)



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

Sensitivity Curves

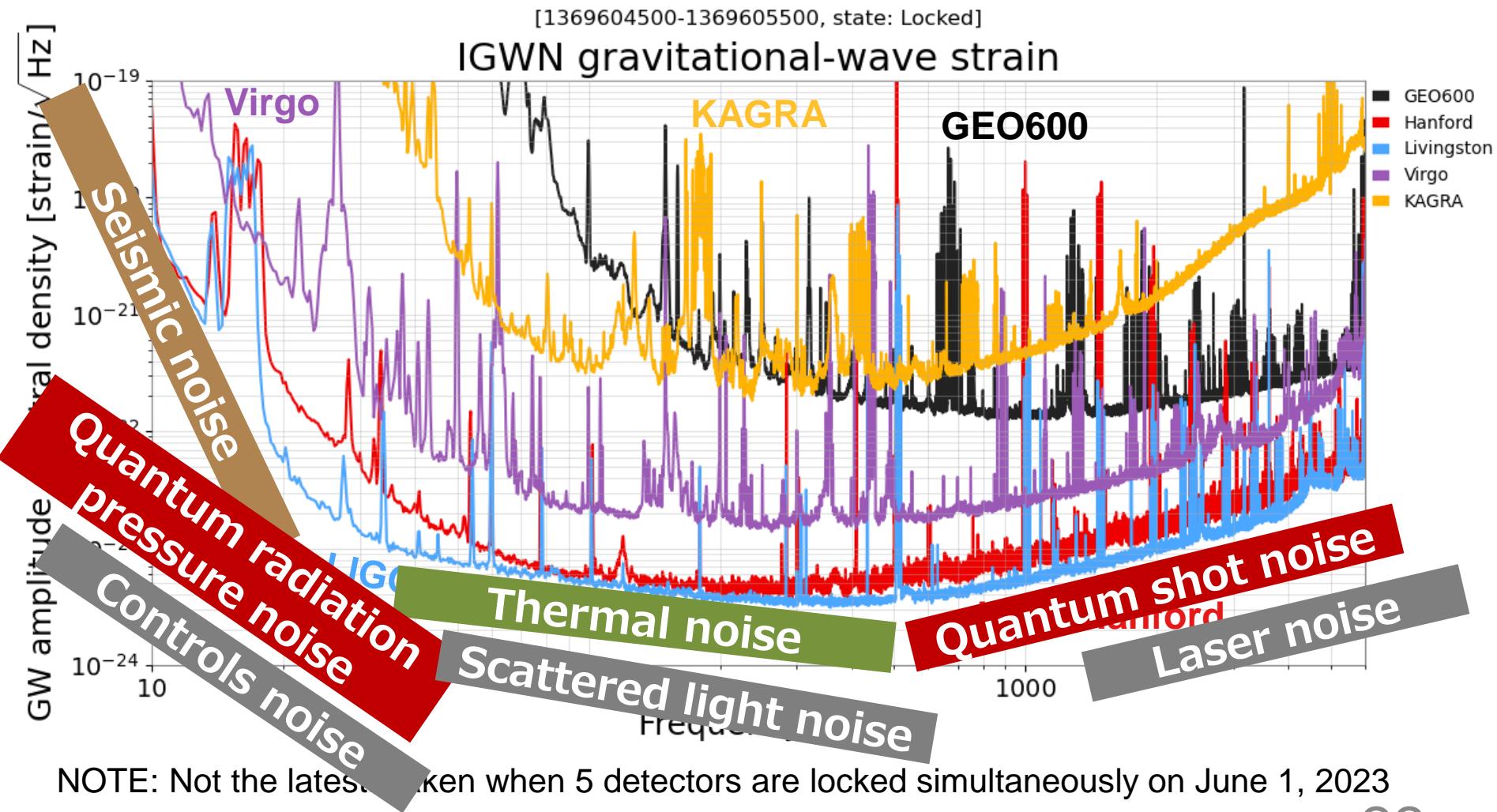
- Smaller the better in y-axis



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

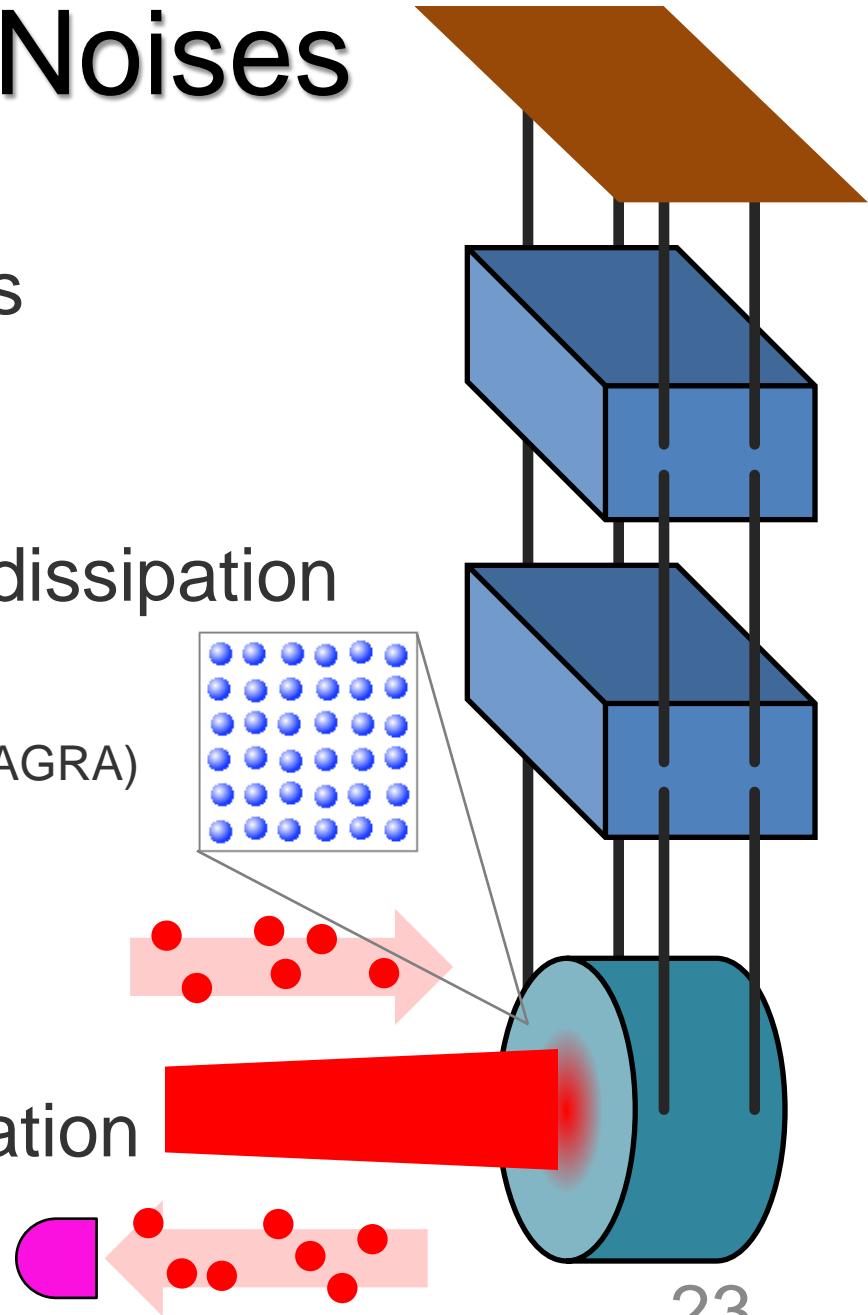
Noise Sources

- Various noises limit the sensitivity

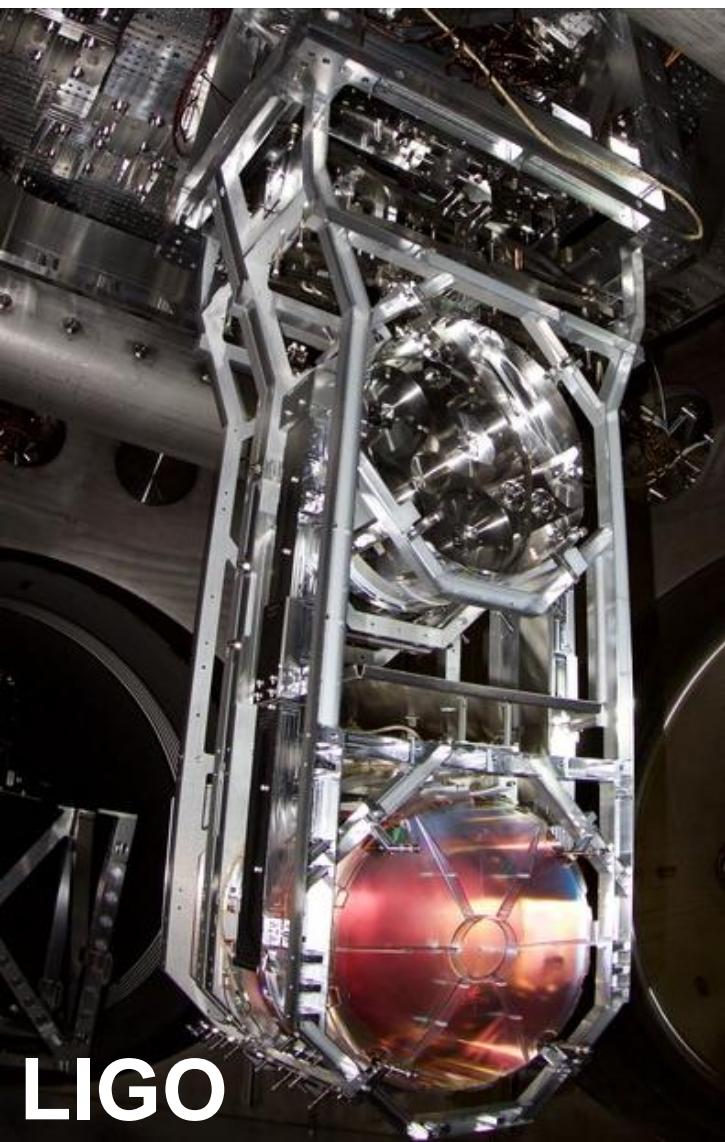


Reducing Noises

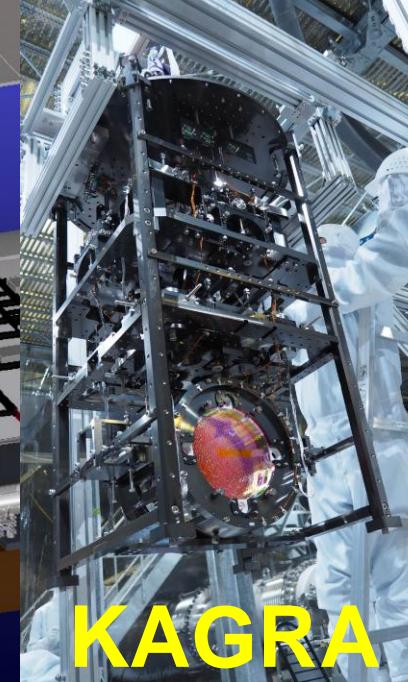
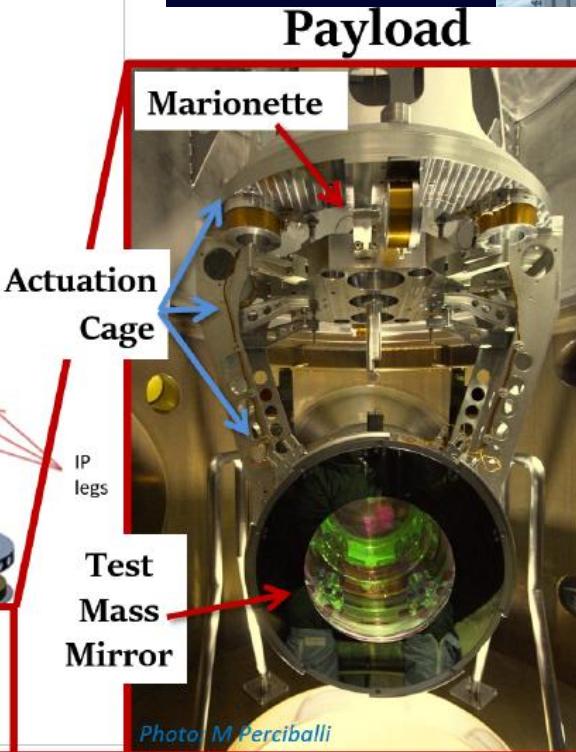
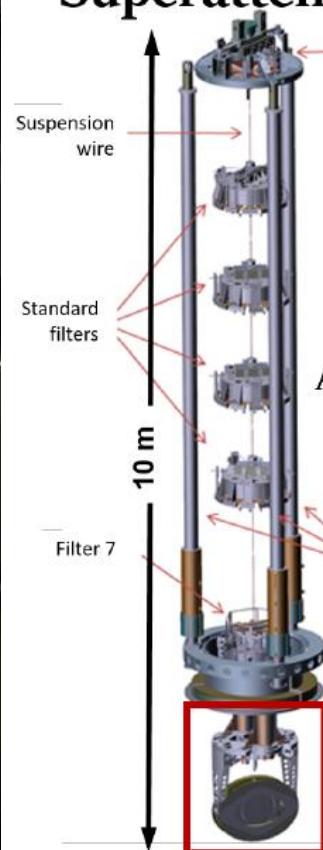
- Seismic noise
 - Multi-stage suspensions
 - Underground (only KAGRA)
- Thermal noise
 - Use materials with low dissipation
 - Larger beam size
 - Cryogenic cooling (only KAGRA)
- Quantum noise
 - Squeezing
 - Heavier mirrors
 - Interferometer configuration
- Larger is better $h = \frac{\delta L}{L}$



Vibration Isolation Systems

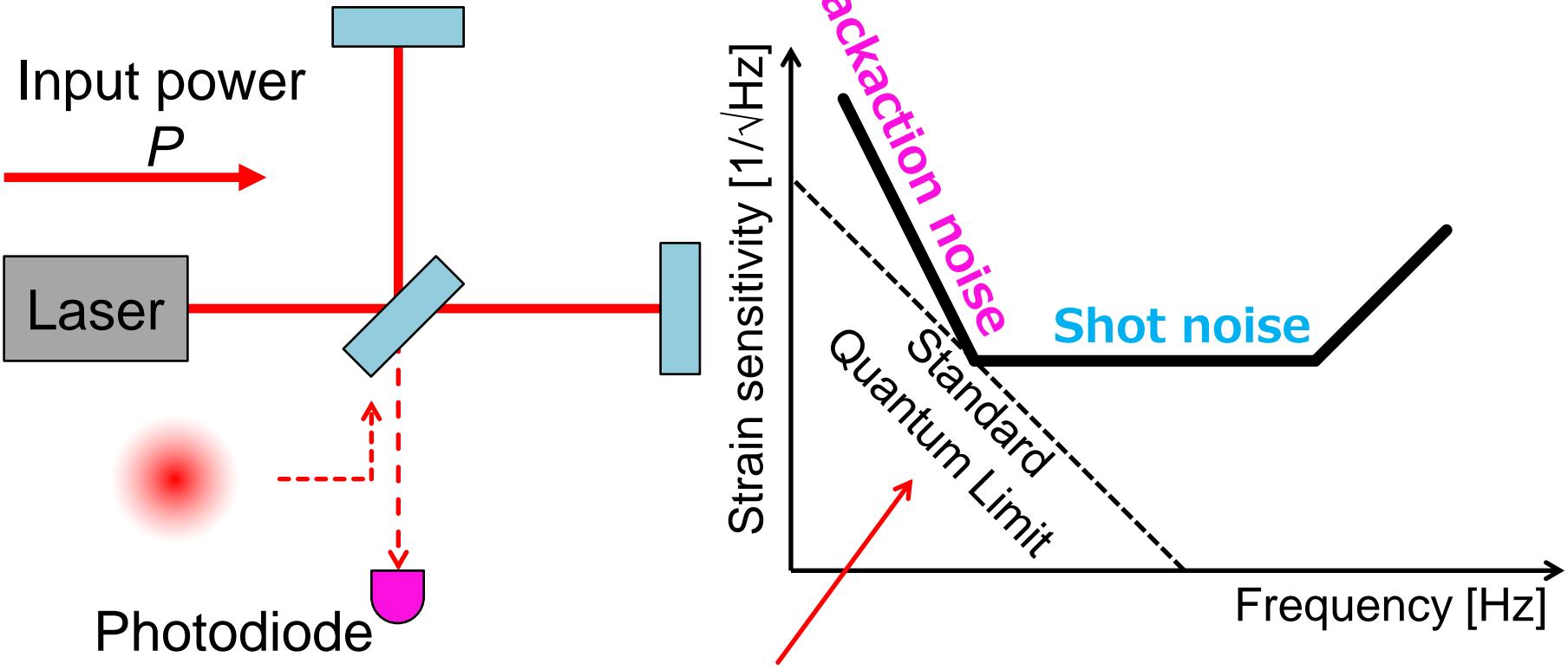


Virgo
Superattenuator



Quantum Noise

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

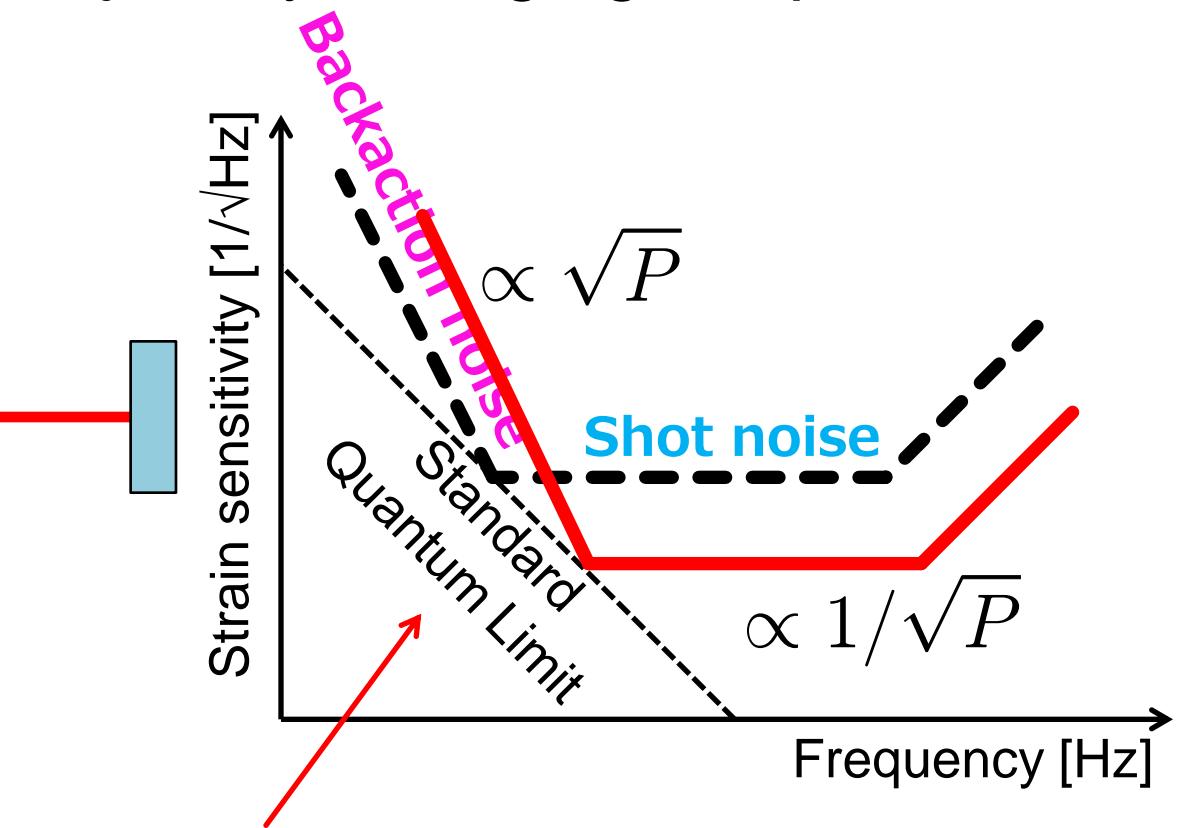
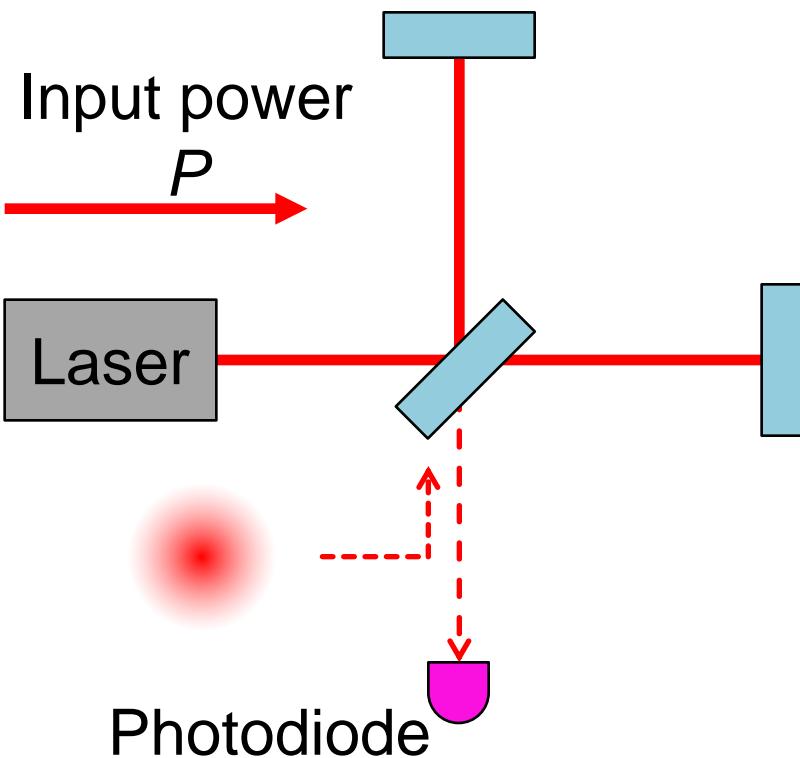


From Heisenberg's uncertainty principle

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

Quantum Noise

- Cannot beat SQL just by changing the power

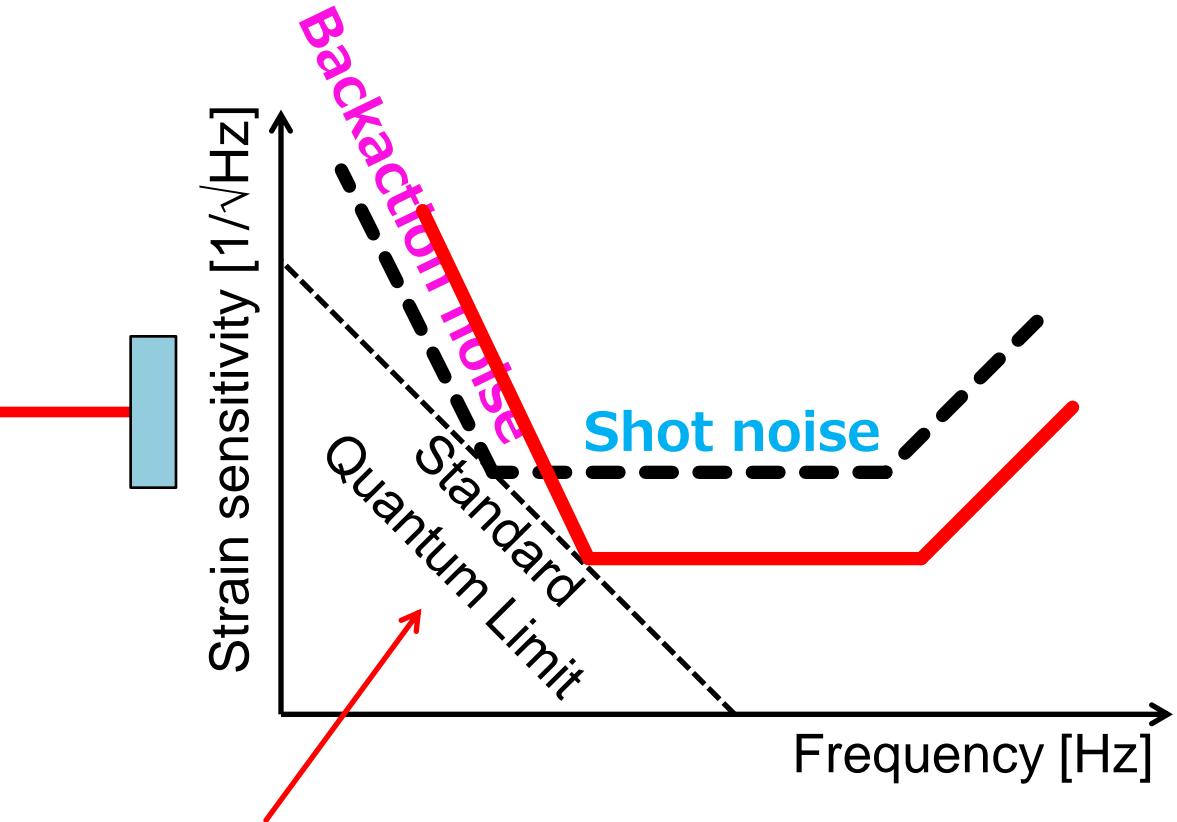
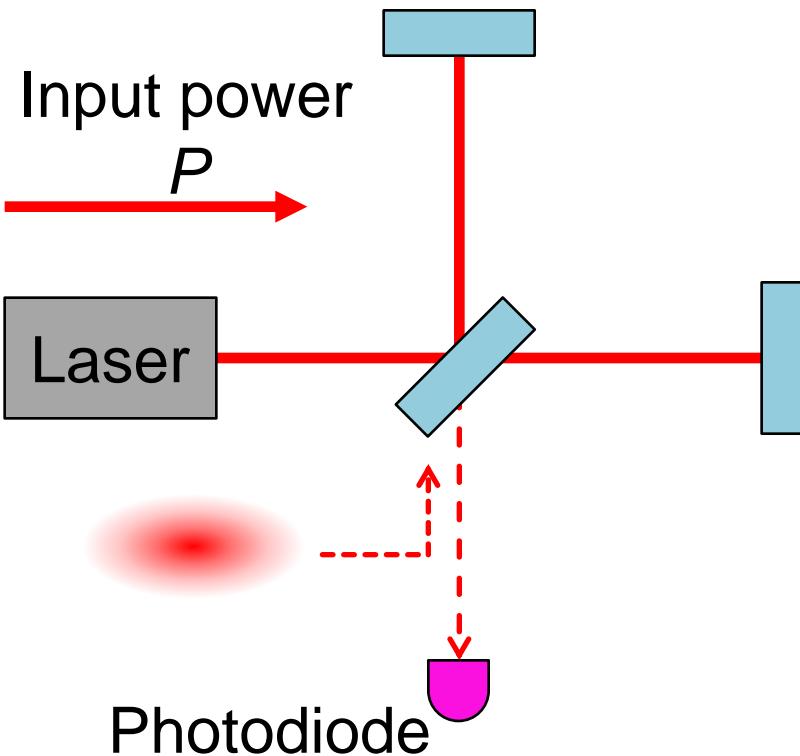


From Heisenberg's uncertainty principle

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

Injection of Squeezed Vacuum

- Still cannot beat SQL

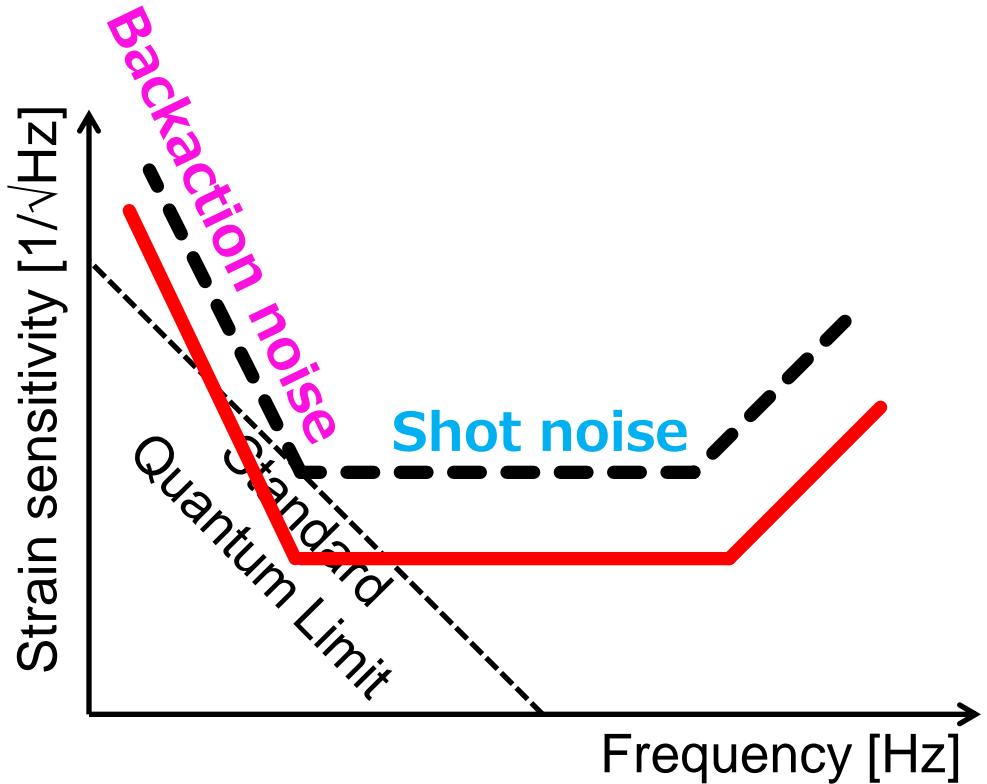
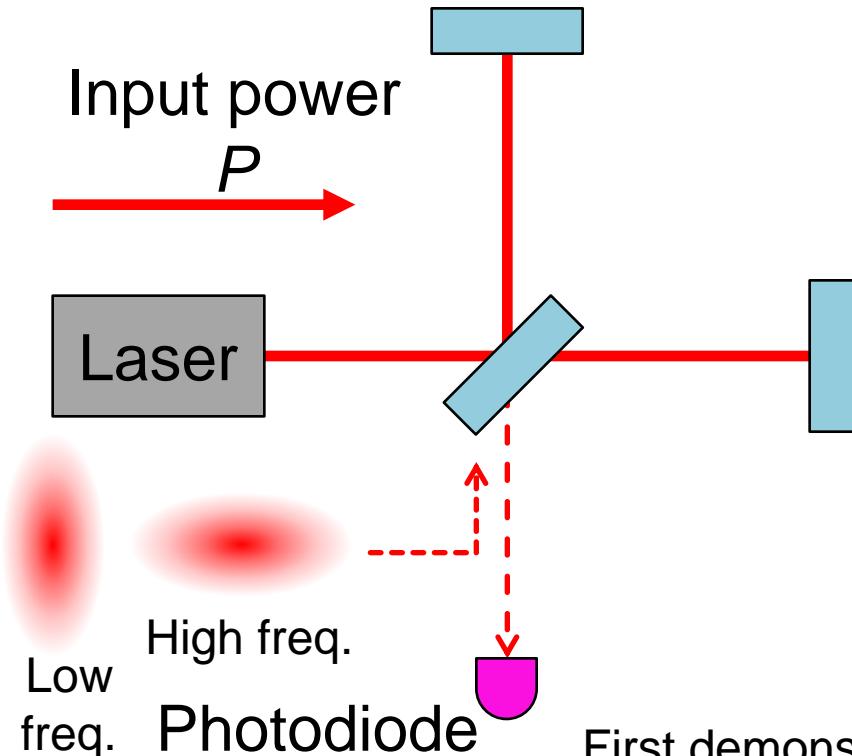


From Heisenberg's uncertainty principle

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Frequency Dependent Squeezing

- Can beat SQL



First demonstration by NAOJ and MIT

Y. Zhao+, [PRL 124, 171101 \(2020\)](#)

L. McCuller+, [PRL 124, 171102 \(2020\)](#)

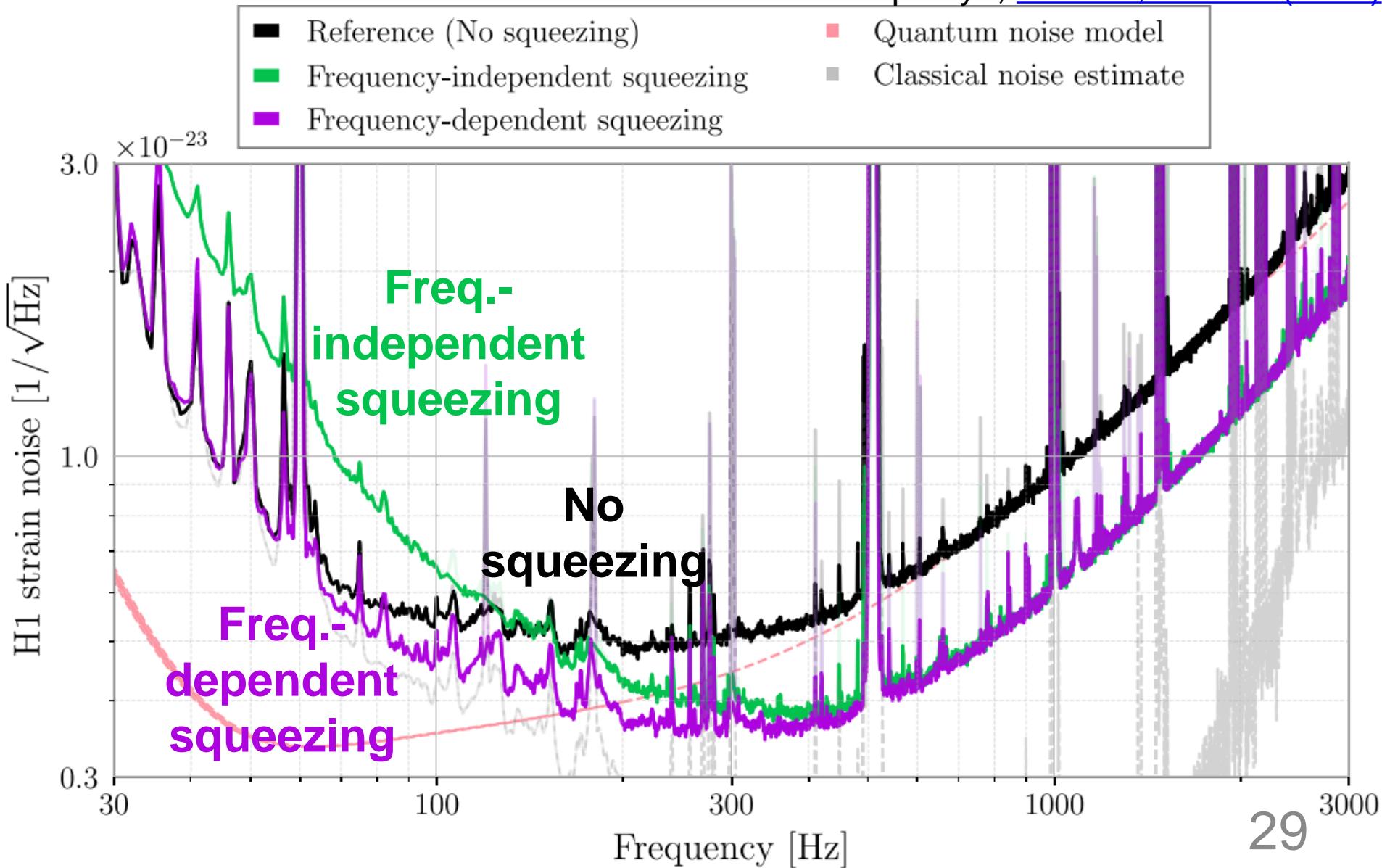
Already installed in LIGO and Virgo

D. Ganapathy+, [PRX 13, 041021 \(2023\)](#)

Virgo, [PRL 131, 041403 \(2023\)](#)

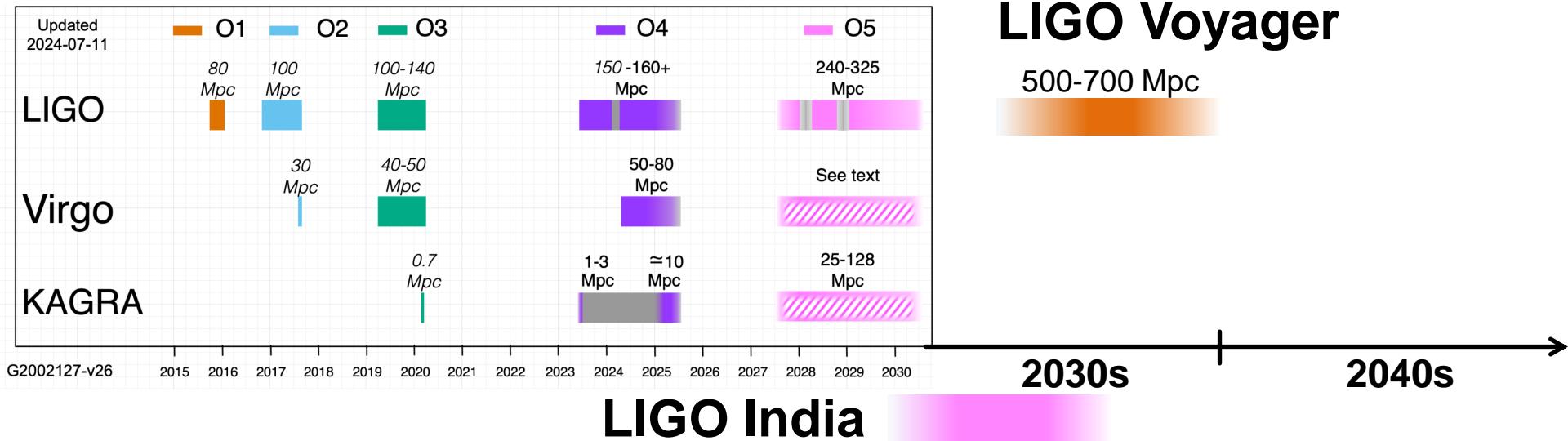
Frequency Dependent Squeezing

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



Next Generation Detectors

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



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

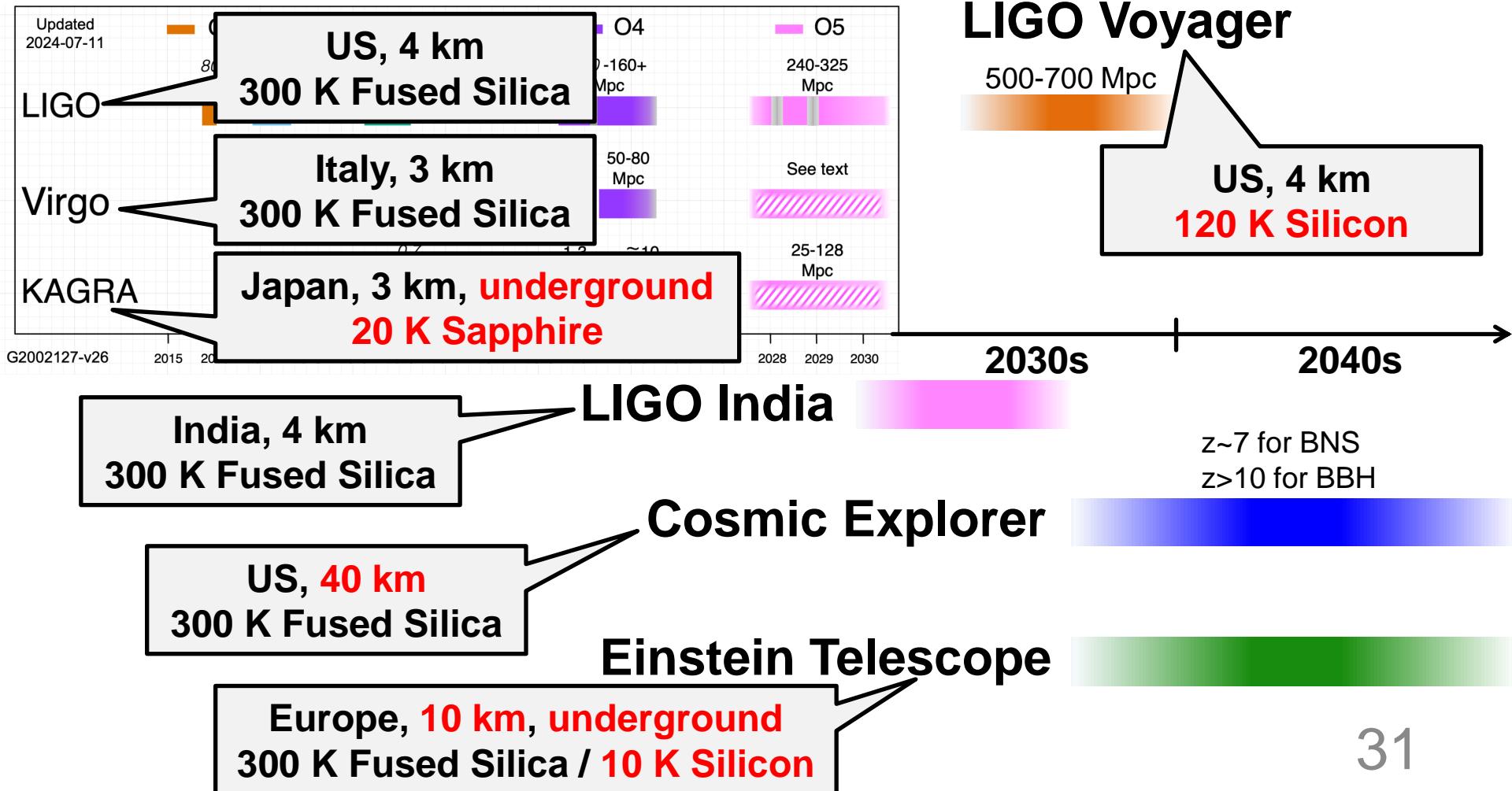
Cosmic Explorer

$z \sim 7$ for BNS
 $z > 10$ for BBH

Einstein Telescope

Next Generation Detectors

- Cryogenic upgrade plan: LIGO Voyager
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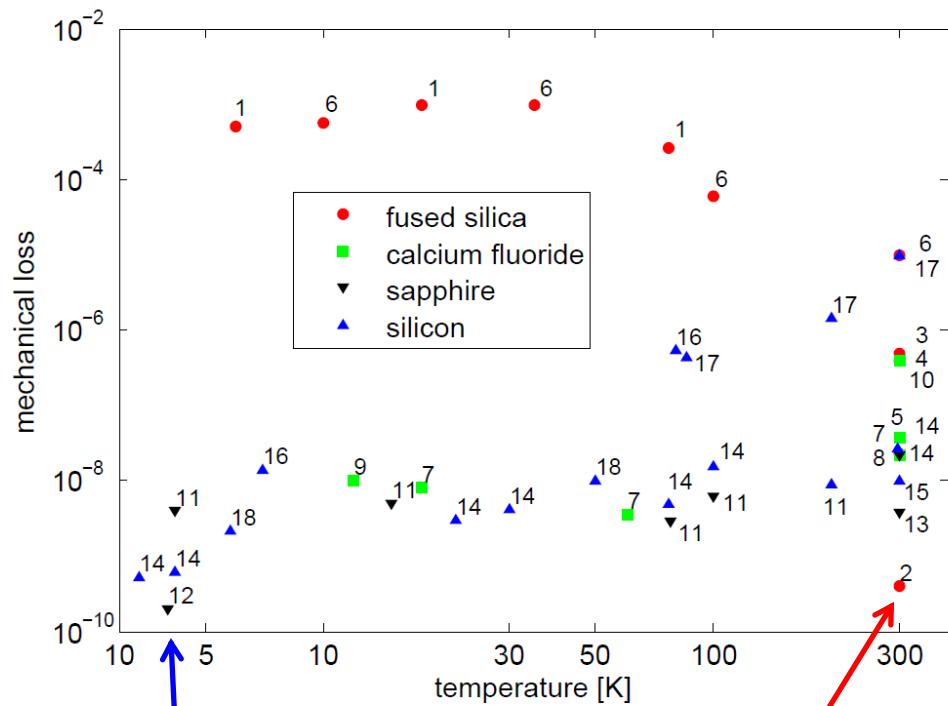


Why Different Mirror Materials?

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

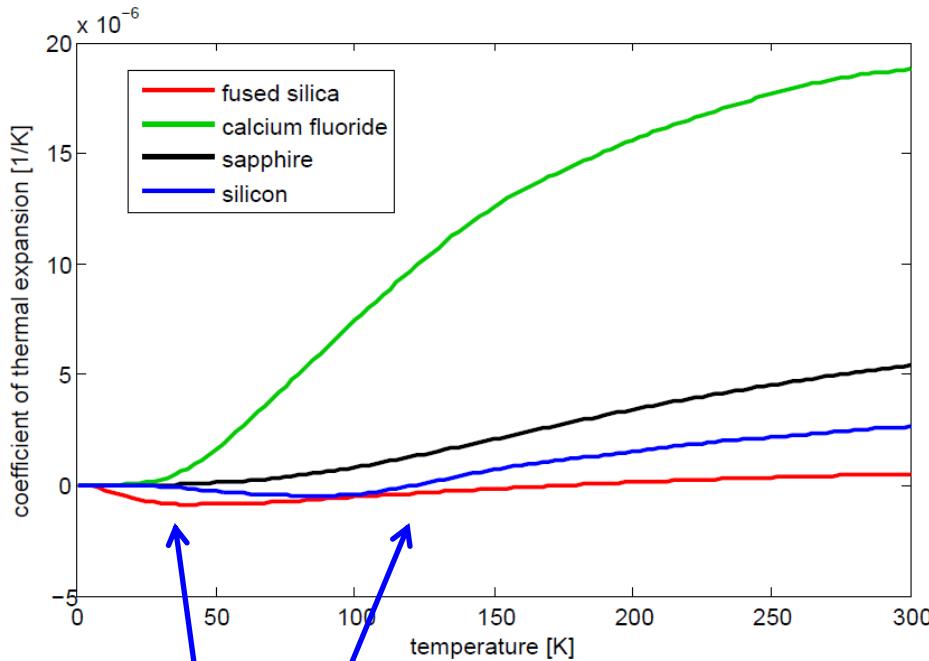
Temperature \rightarrow Mechanical loss angle
(temperature dependent)

ET-027-09



Sapphire / silicon
is good at
cryogenic temp.

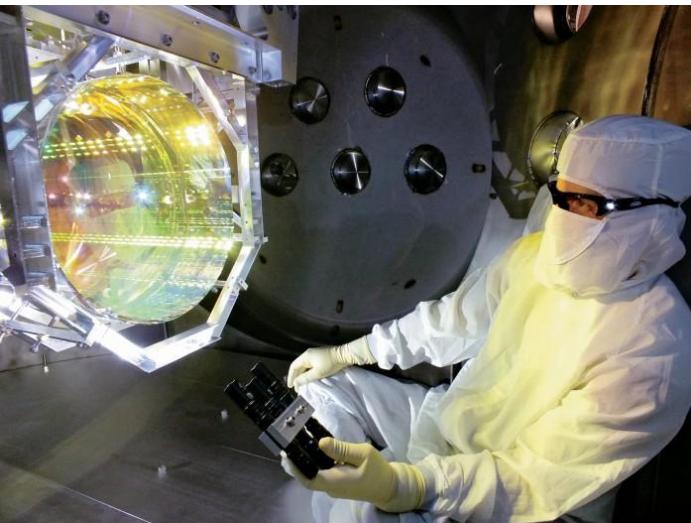
Fused silica
is good at
room temp.



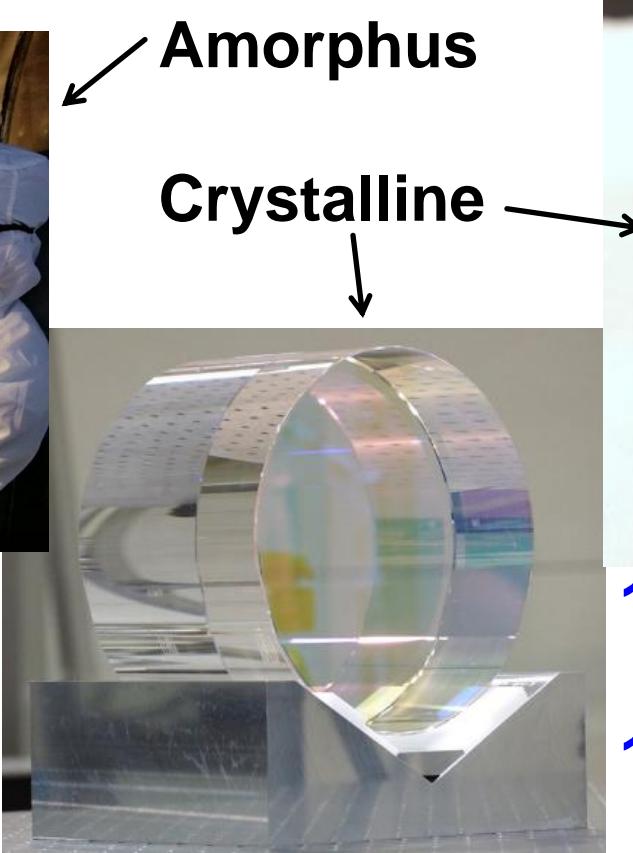
Silicon has zero
thermal expansion
at 18 K and 123 K

Different Wavelengths

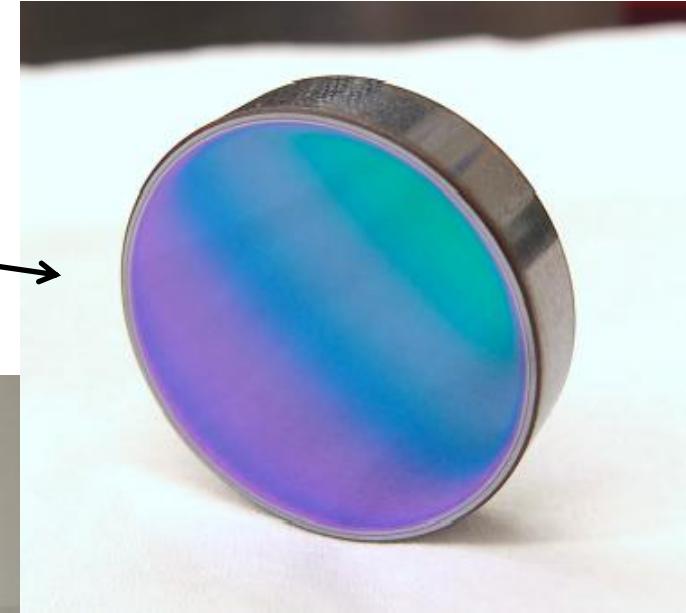
- Different mirror materials require different laser wavelengths



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



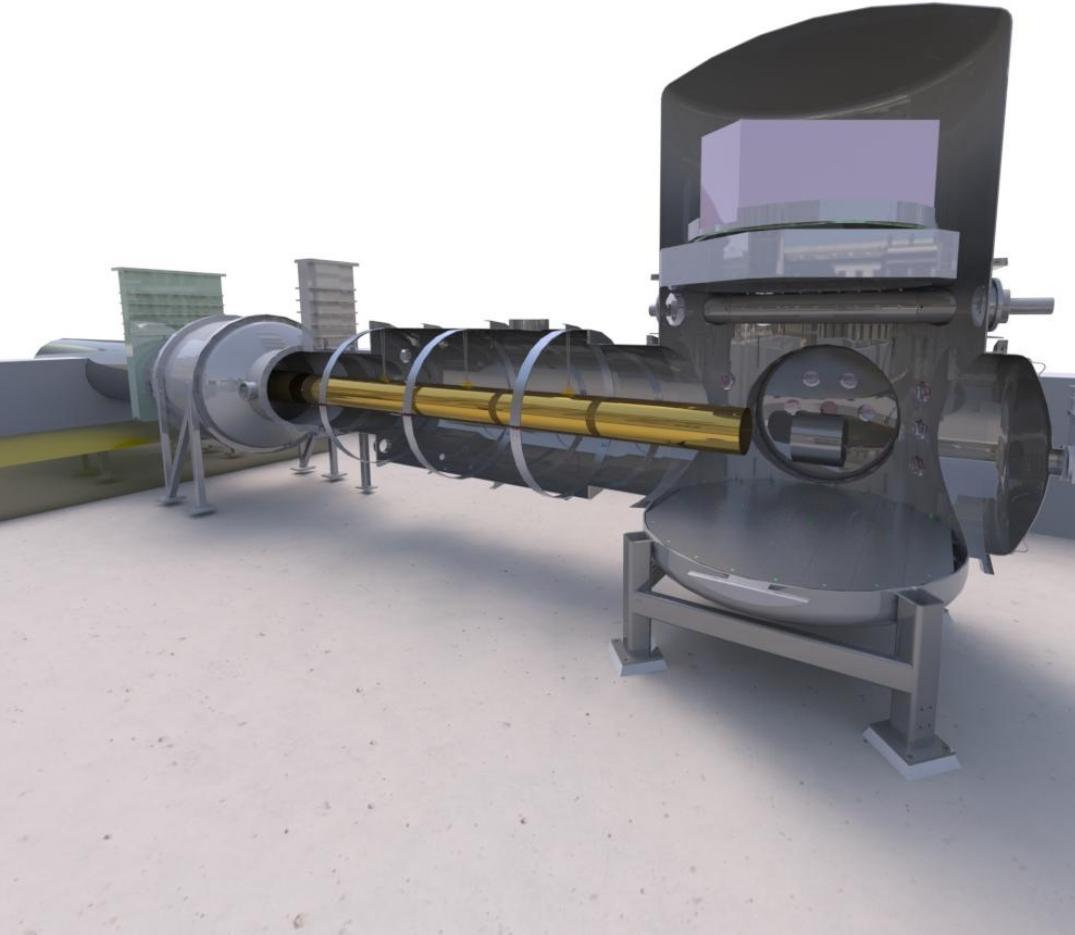
**20 K Sapphire
KAGRA @ 1064 nm**



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

LIGO Voyager

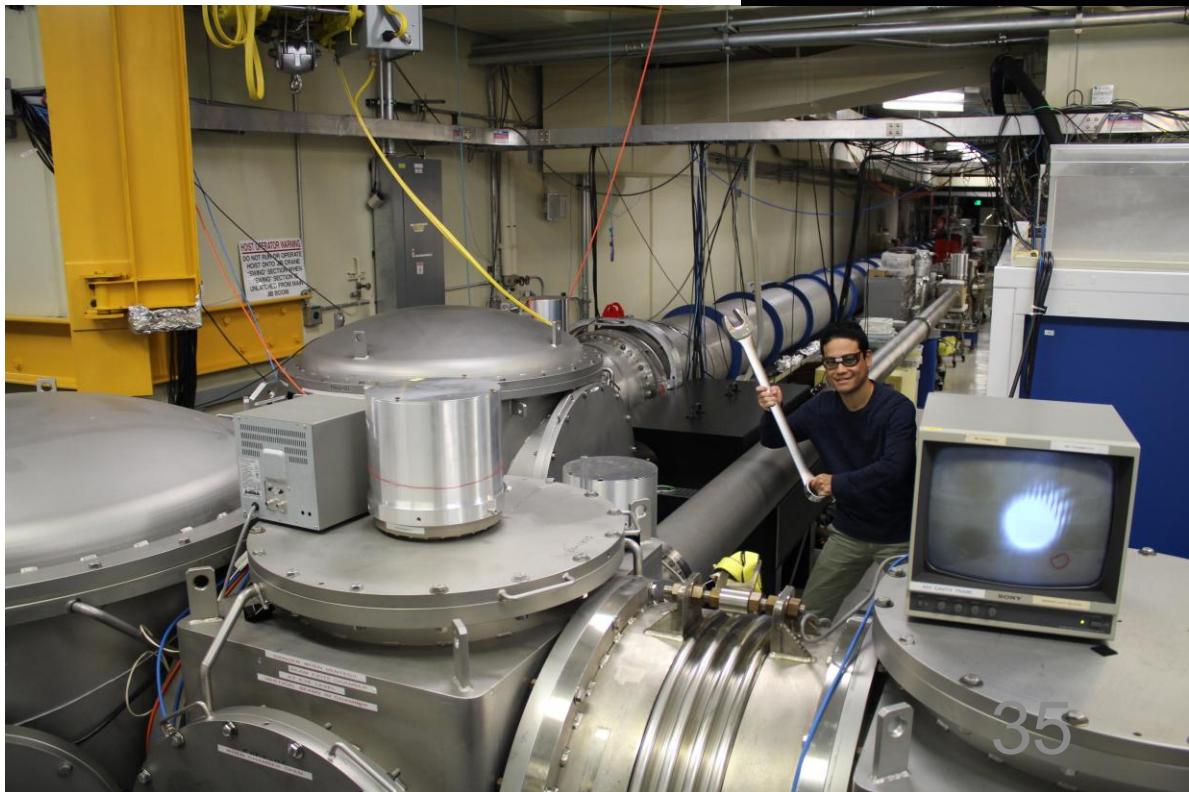
- Cryogenic upgrade to existing 4 km LIGO
- Intermediate step towards 10-40 km detectors



Mariner: 40m Voyager Prototype

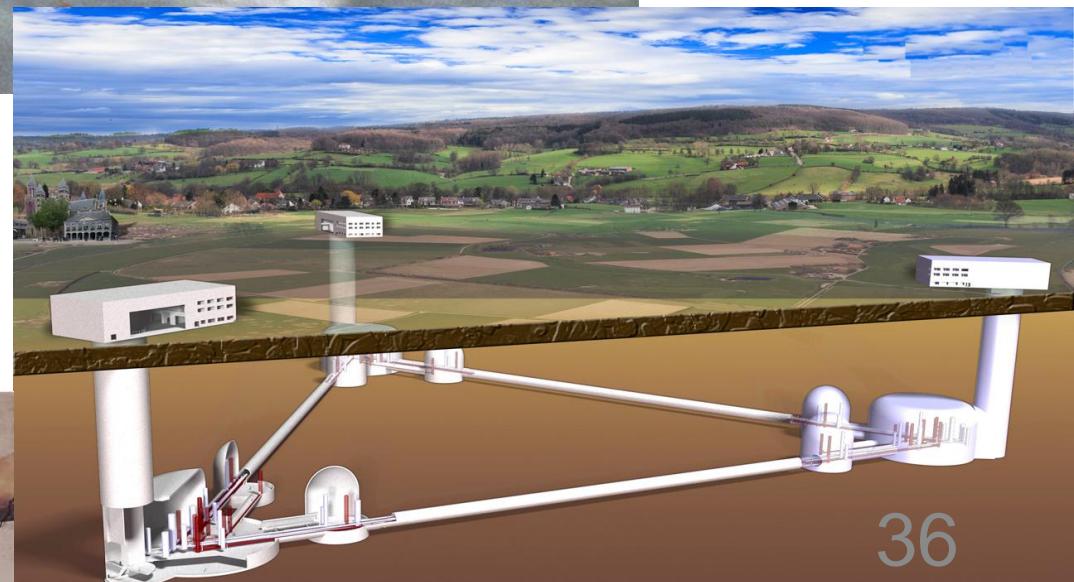
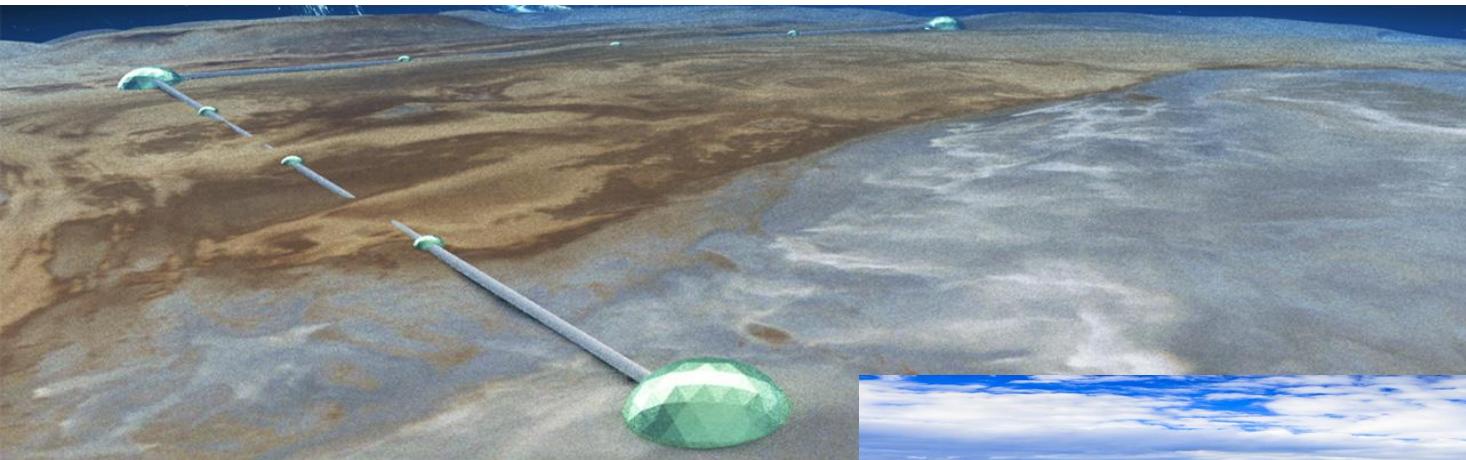
- Prototyping key technologies:
 - Silicon test masses
 - Radiative cooling
 - 123 K operation
 - 2050 nm laser
- To be installed
2025

Caltech



Cosmic Explorer / Einstein Telescope

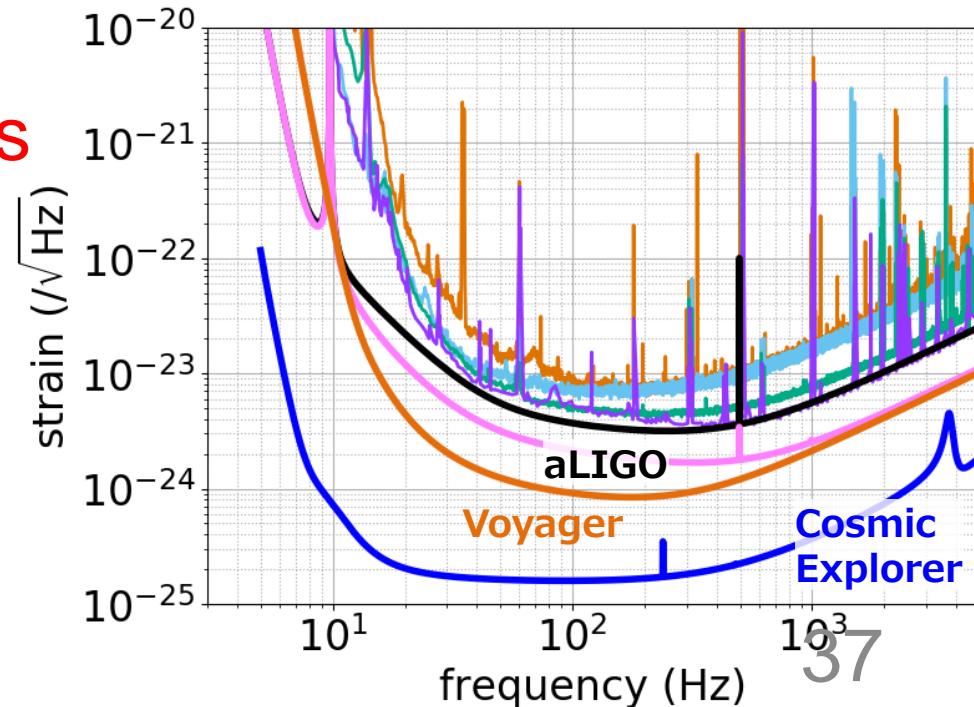
- CE: 40 km, 300 K fused silica
- ET: 10 km, 300 K fused silica & 10 K silicon



Exciting R&Ds for Next Generations

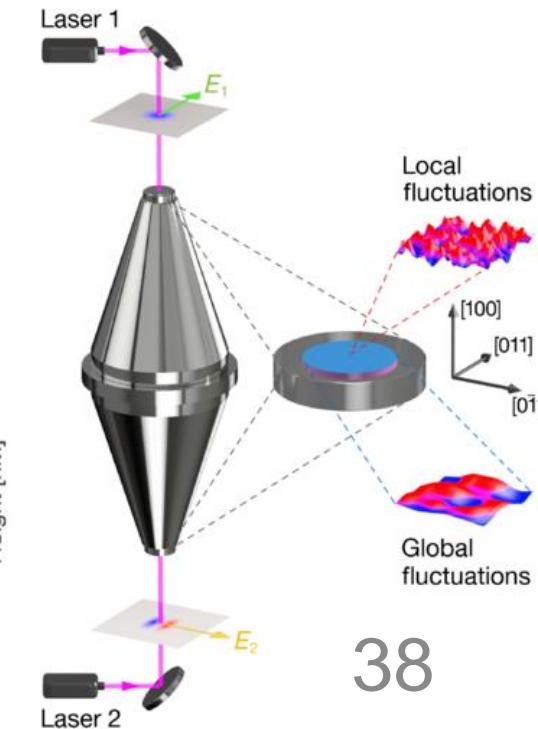
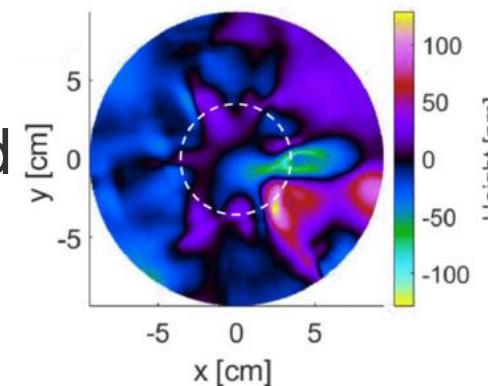
- Stable, high-power laser at **1.5-2 um**
- High quantum efficiency photodiodes for 2 um
- **Large silicon mirror** (φ 45 cm, 200 kg)
 - Low **birefringence**
 - Low absorption
- Low thermal noise
high-reflective coatings
- **Suspensions** for large mirrors
- **High power** handling

... and more



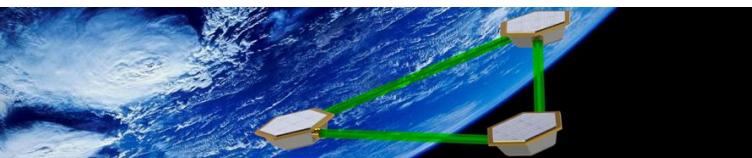
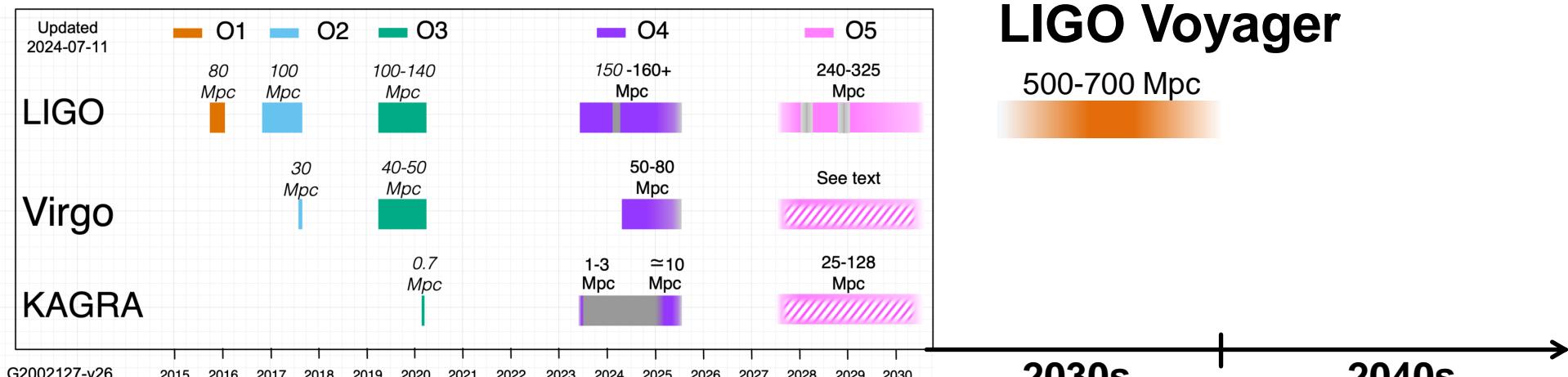
Birefringence and Its Fluctuations

- 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)



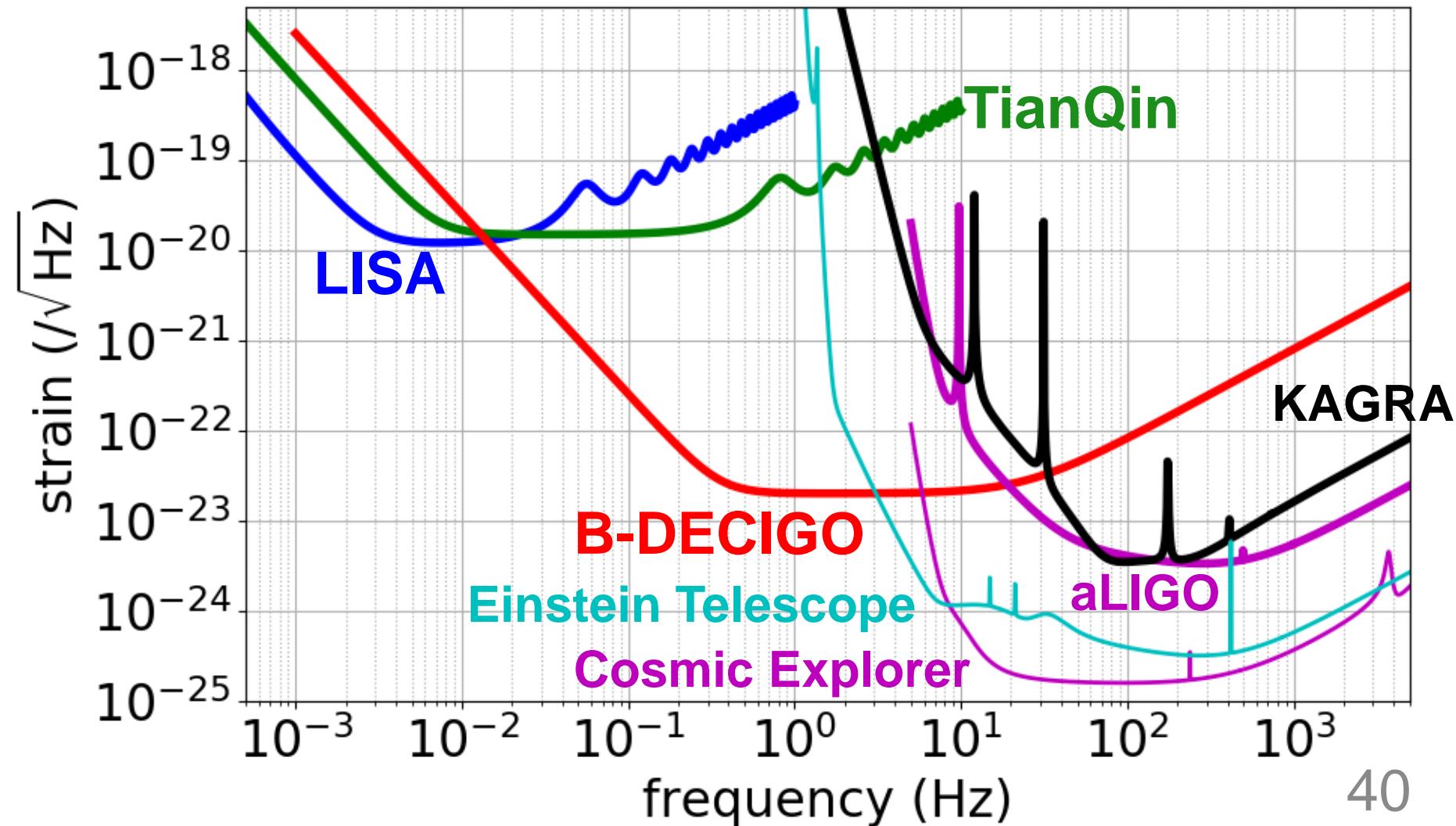
Cosmic Explorer
Einstein Telescope

B-DECIGO

LISA

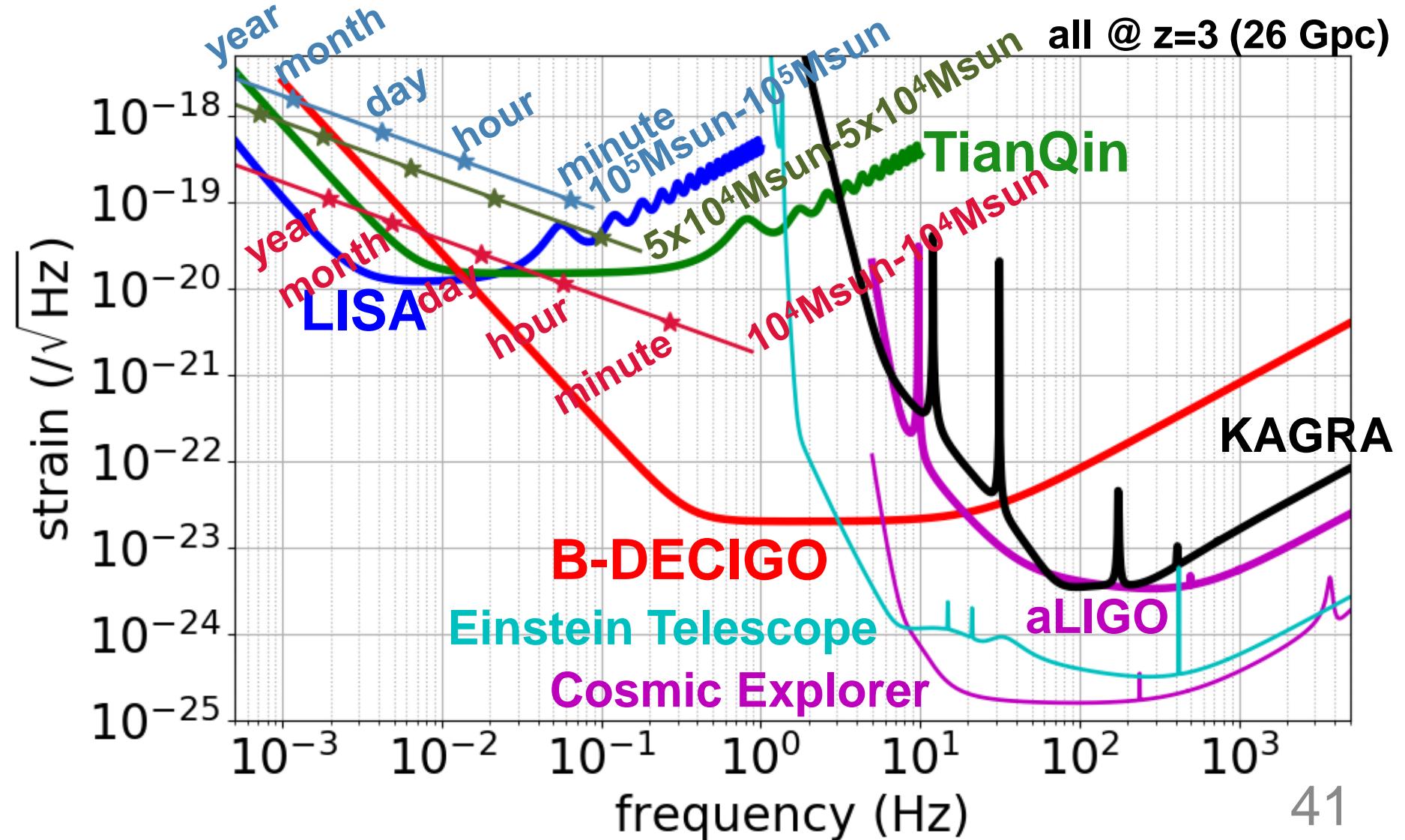
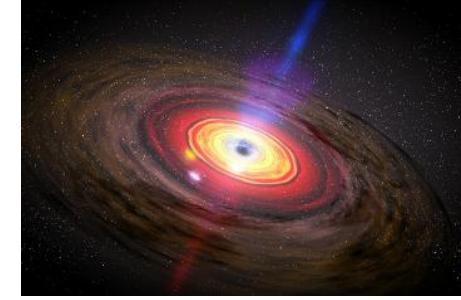
Space-Based Detectors: Sensitivity

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



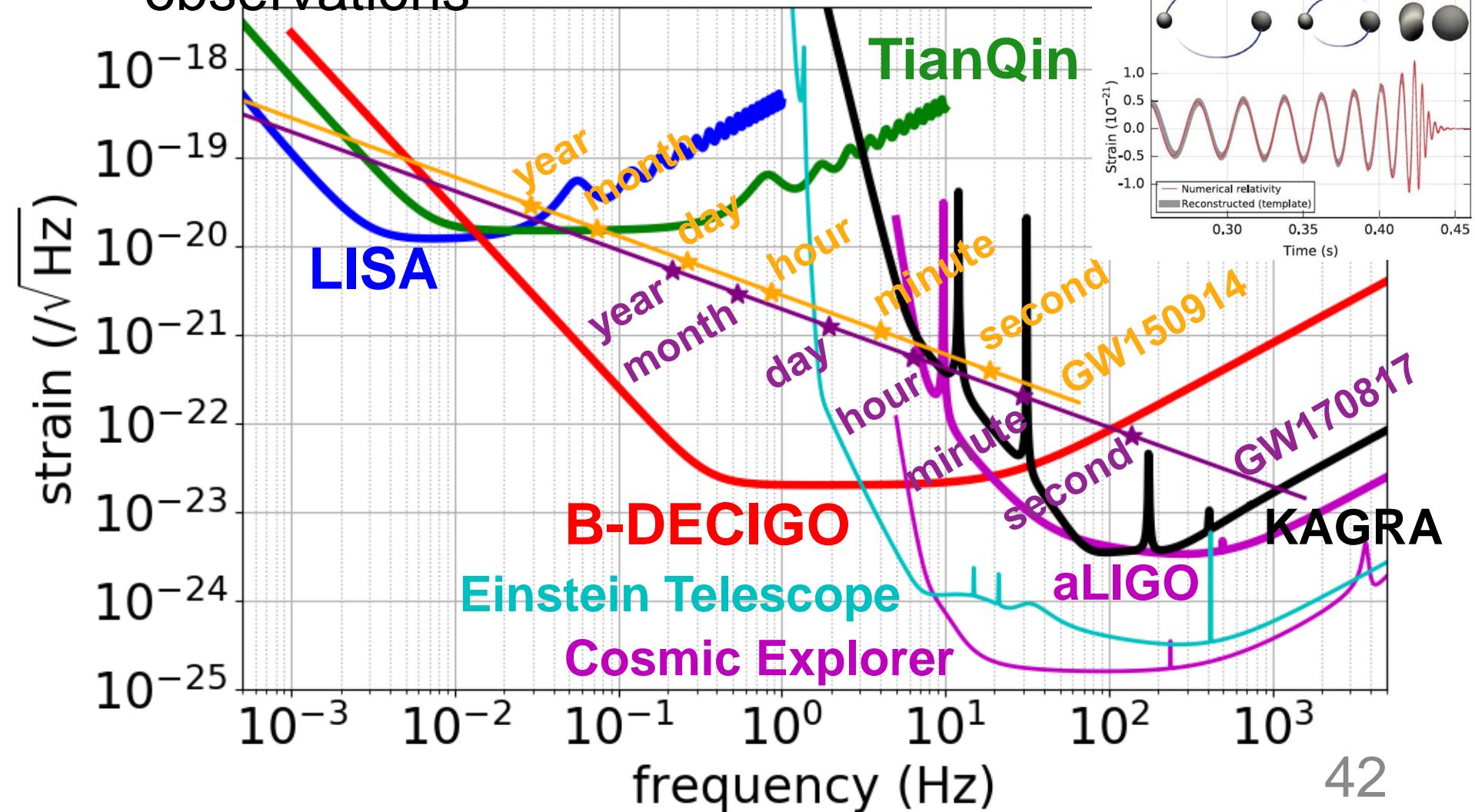
Super Massive Blackholes

- LISA observes SMBH binaries



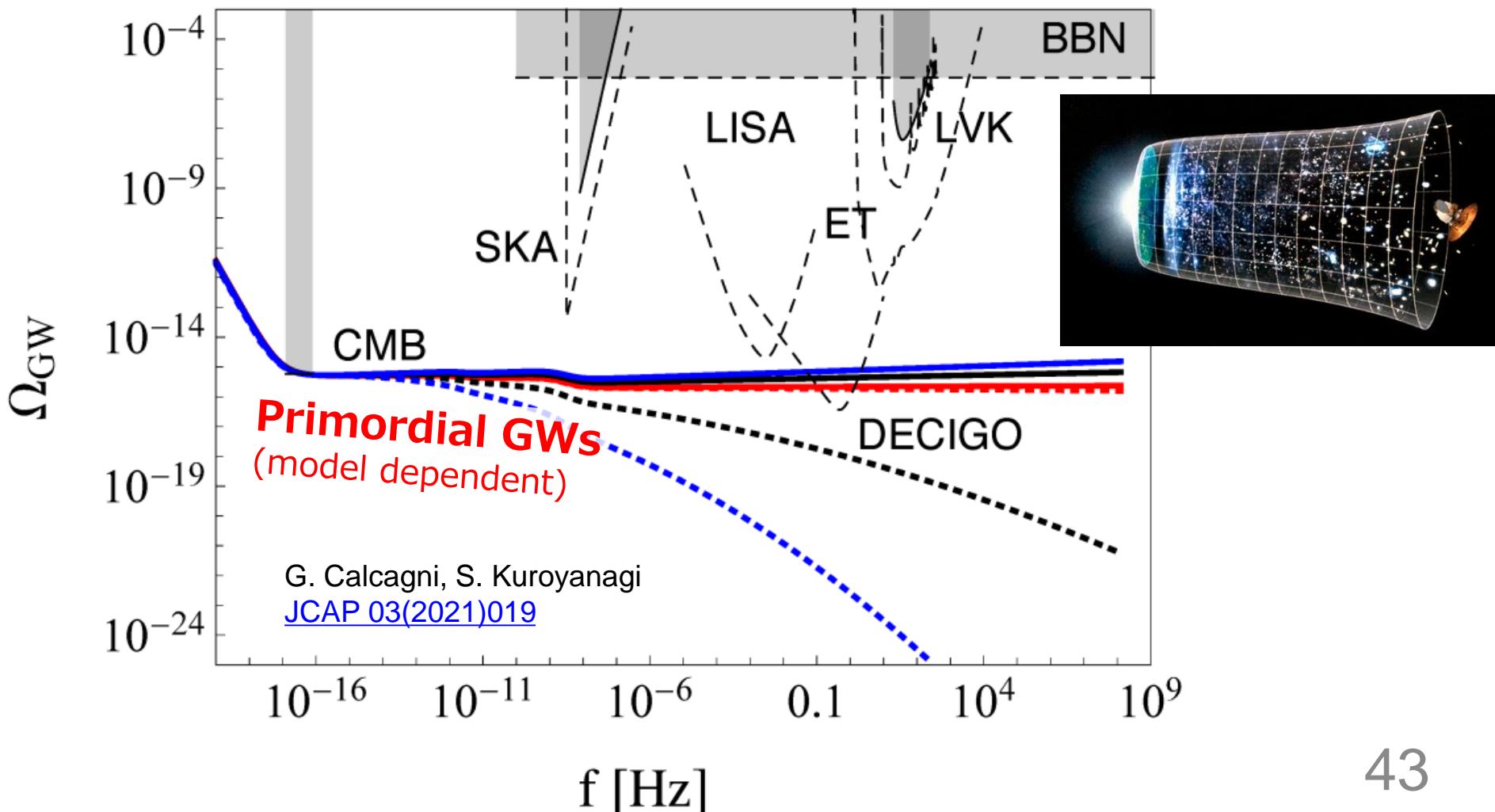
Multi-band Observations

- DECIGO can predict merger time for follow up observations



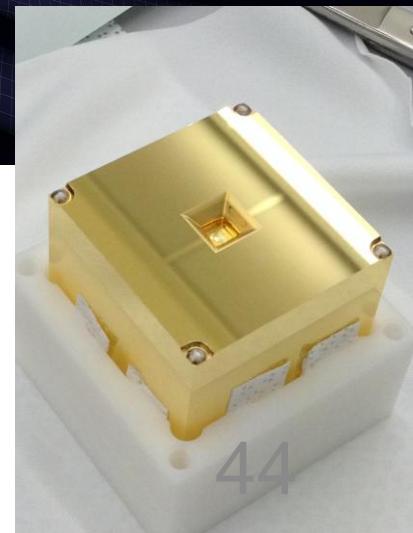
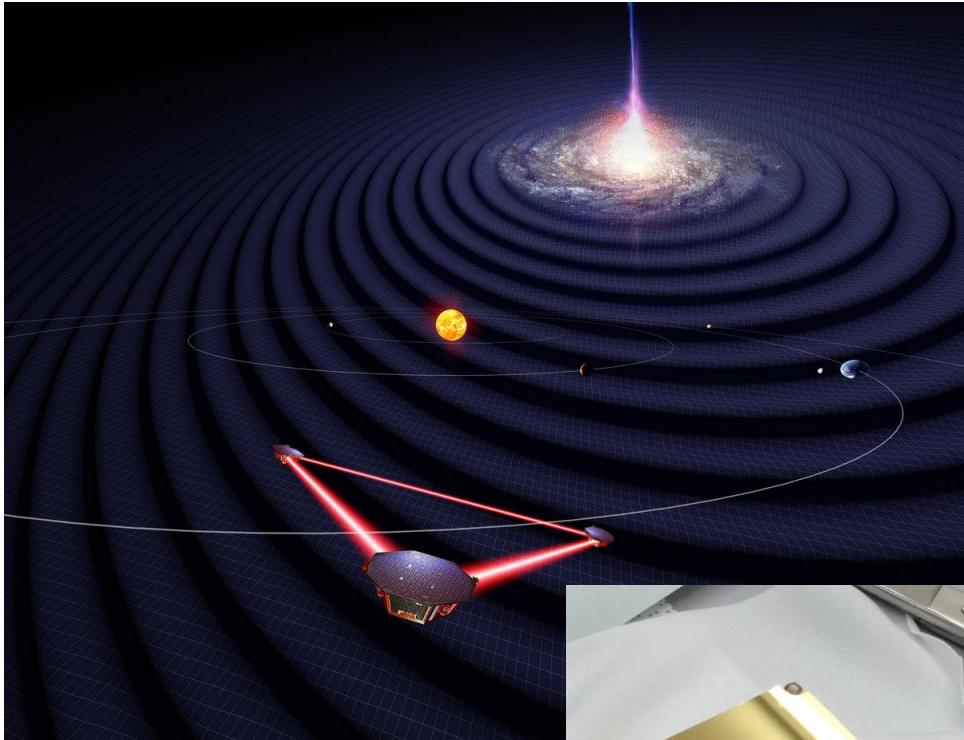
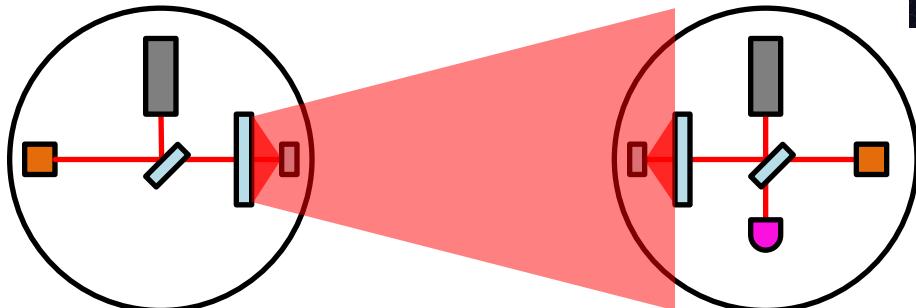
Primordial GWs from Inflation

- DECIGO band is suitable for observing **primordial gravitational waves**



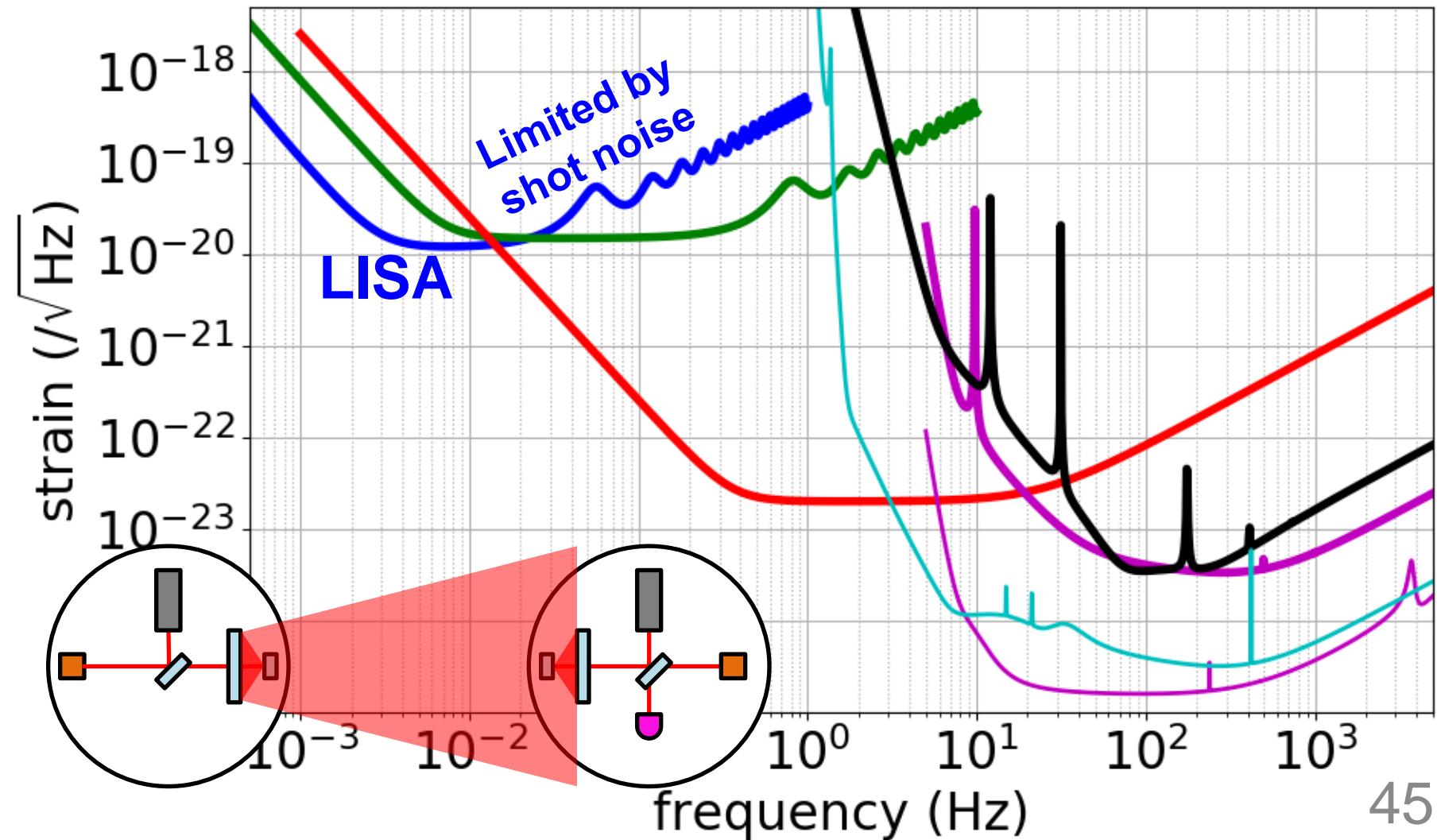
LISA to be Launched Mid-2030s

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



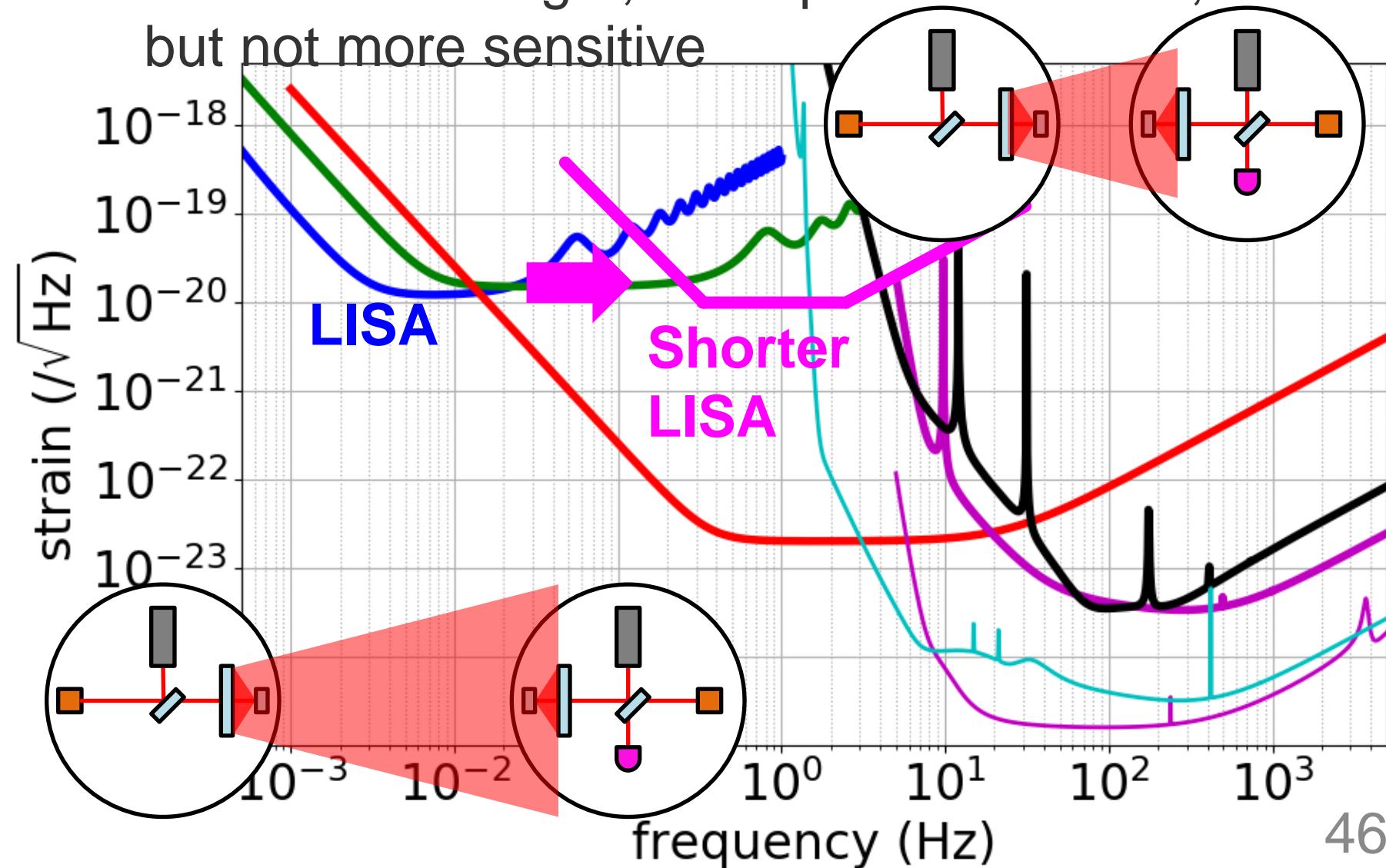
LISA Sensitivity Curve

- 1 W emitted, ~ 100 pW received



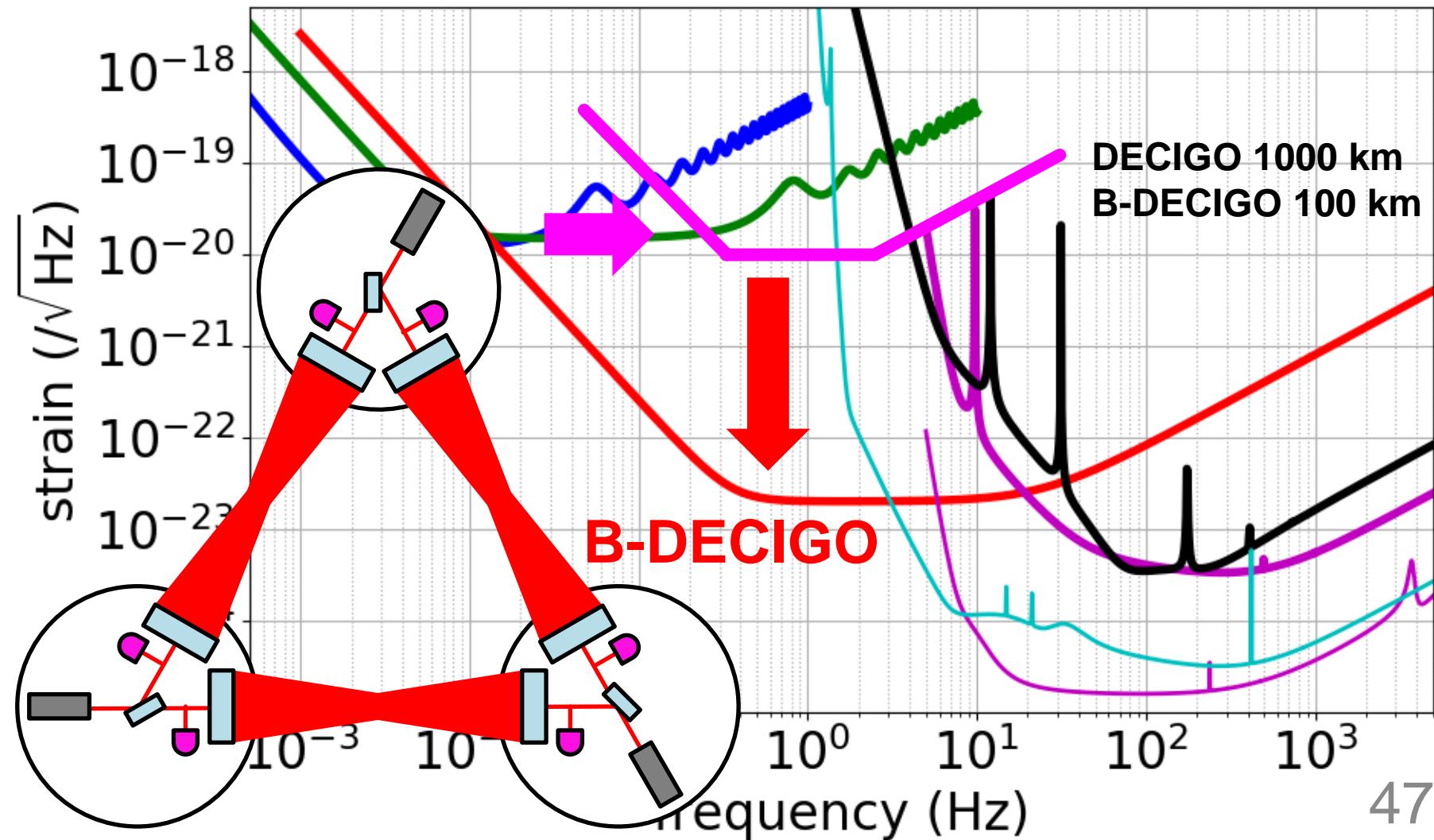
Shorter LISA will not be DECIGO

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



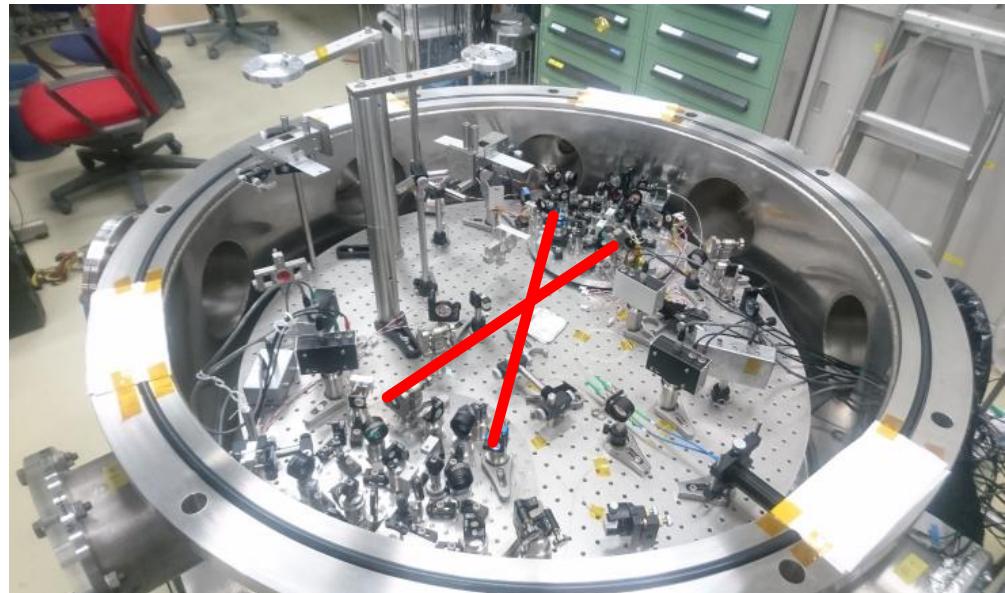
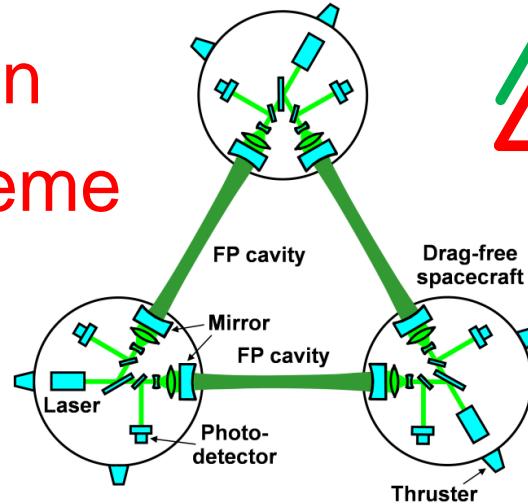
Shorter LISA will not be DECIGO

- Form an optical cavity to enhance the sensitivity



Exciting R&Ds for DECIGO

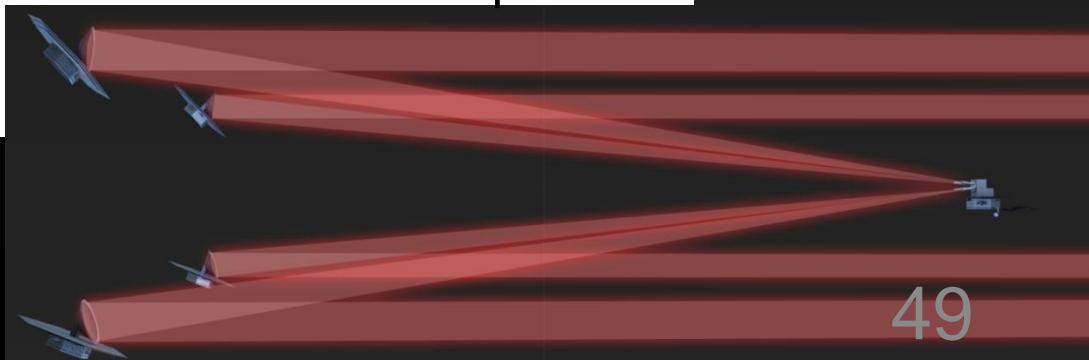
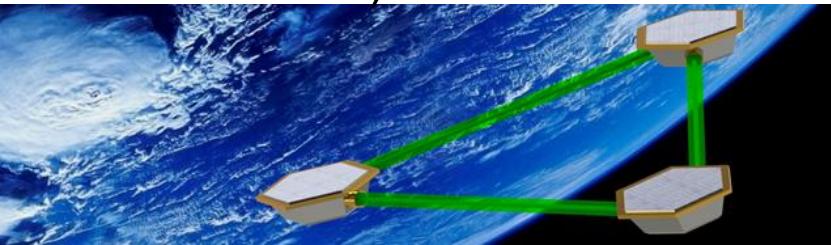
- Interferometer **configuration**
- Interferometer **control scheme**
Demonstration experiments
at UTokyo
- Stable laser source
- Initial **link acquisition**
- Low noise thrusters
- Drag-free controls
- Orbit and satellite
controls
- ... and more!



SILVIA Project

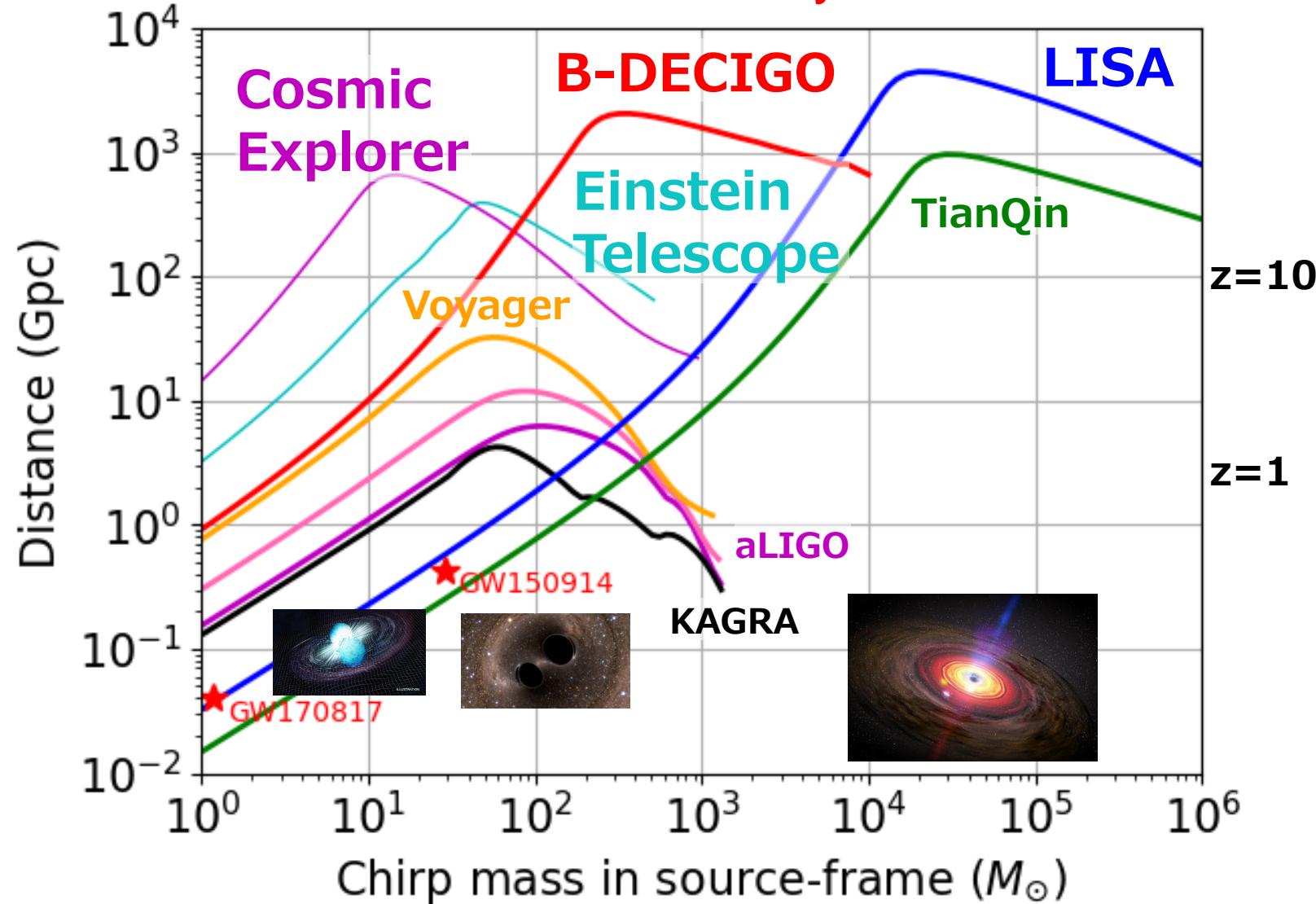


- Space Interferometer Laboratory Voyaging towards Innovative Applications
- Demonstration of **ultra-precision formation flying** with laser interferometer between satellites
- For DECIGO, LIFE etc.
- Proposal submitted to JAXA in Feb 2020 (currently at mission definition phase of JAXA's small satellite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

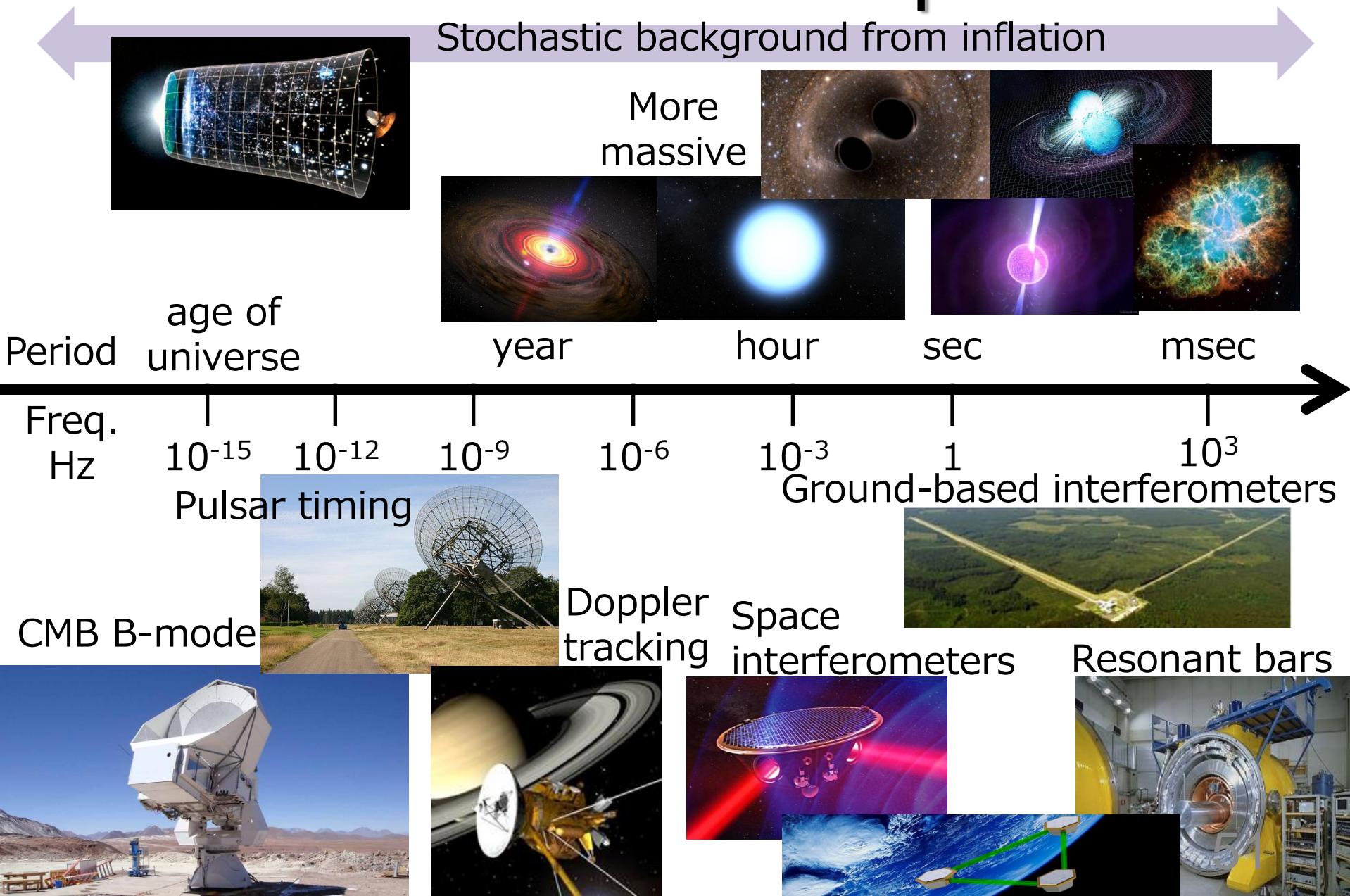


Astrophysical Reach to Binaries

- Covers entire universe by 2030s



Gravitational Wave Spectrum



Gravitational Wave Spectrum

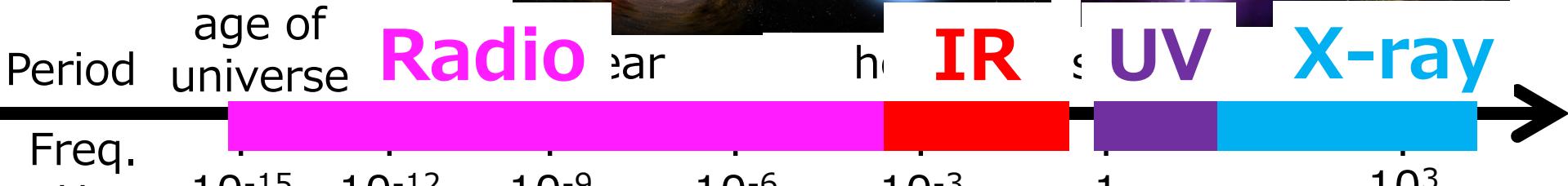


Stochastic background from inflation

More massive



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



Pulsar timing



CMB B-mode



Doppler tracking



Space interferometers



Resonant bars



52

Gravitational Wave Spectrum



Stochastic background from inflation

More massive



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



10^{-15}
 10^{-12}
 10^{-9}

Pulsar timing



10^{-6}

Doppler tracking

10^{-3}

Space interferometers

10^3

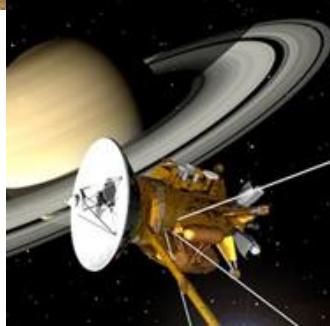
Resonant bars

LISA



LIGO

CMB B-mode



DECIGO



Particle Physics with GW Detectors

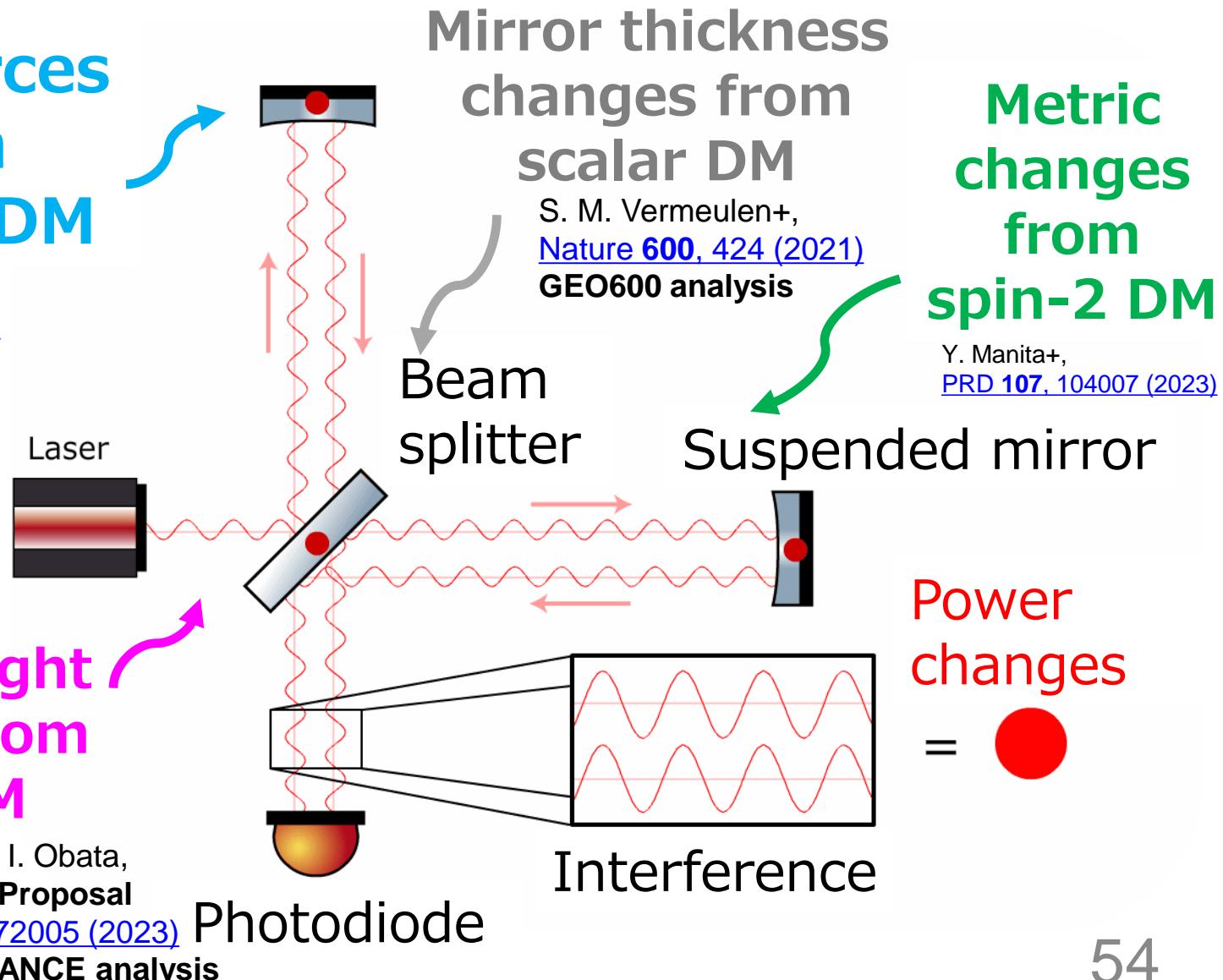
Tiny forces
from
vector DM

LIGO-Virgo-KAGRA,
[PRD 105, 063030 \(2022\)](#)

LIGO/Virgo O3 analysis

LIGO-Virgo-KAGRA,
[PRD 110, 042001 \(2024\)](#)

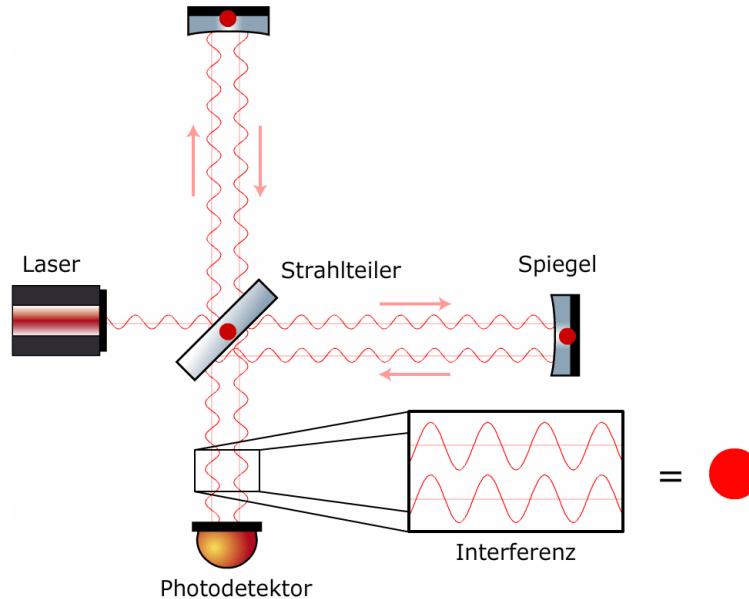
KAGRA O3GK analysis



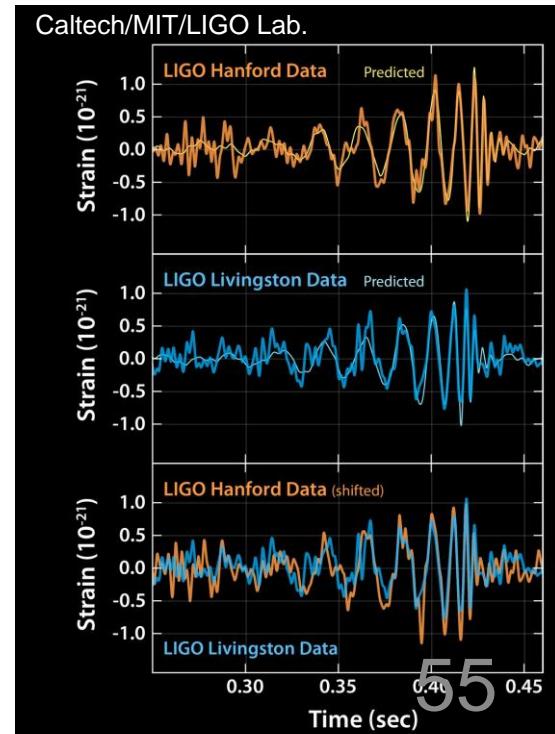
K. Nagano, T. Fujita, YM, I. Obata,
[PRL 123, 111301 \(2019\)](#) Proposal
Y. Oshima+, [PRD 108, 072005 \(2023\)](#)
Table-top experiment DANCE analysis

Ultralight DM with Interferometers

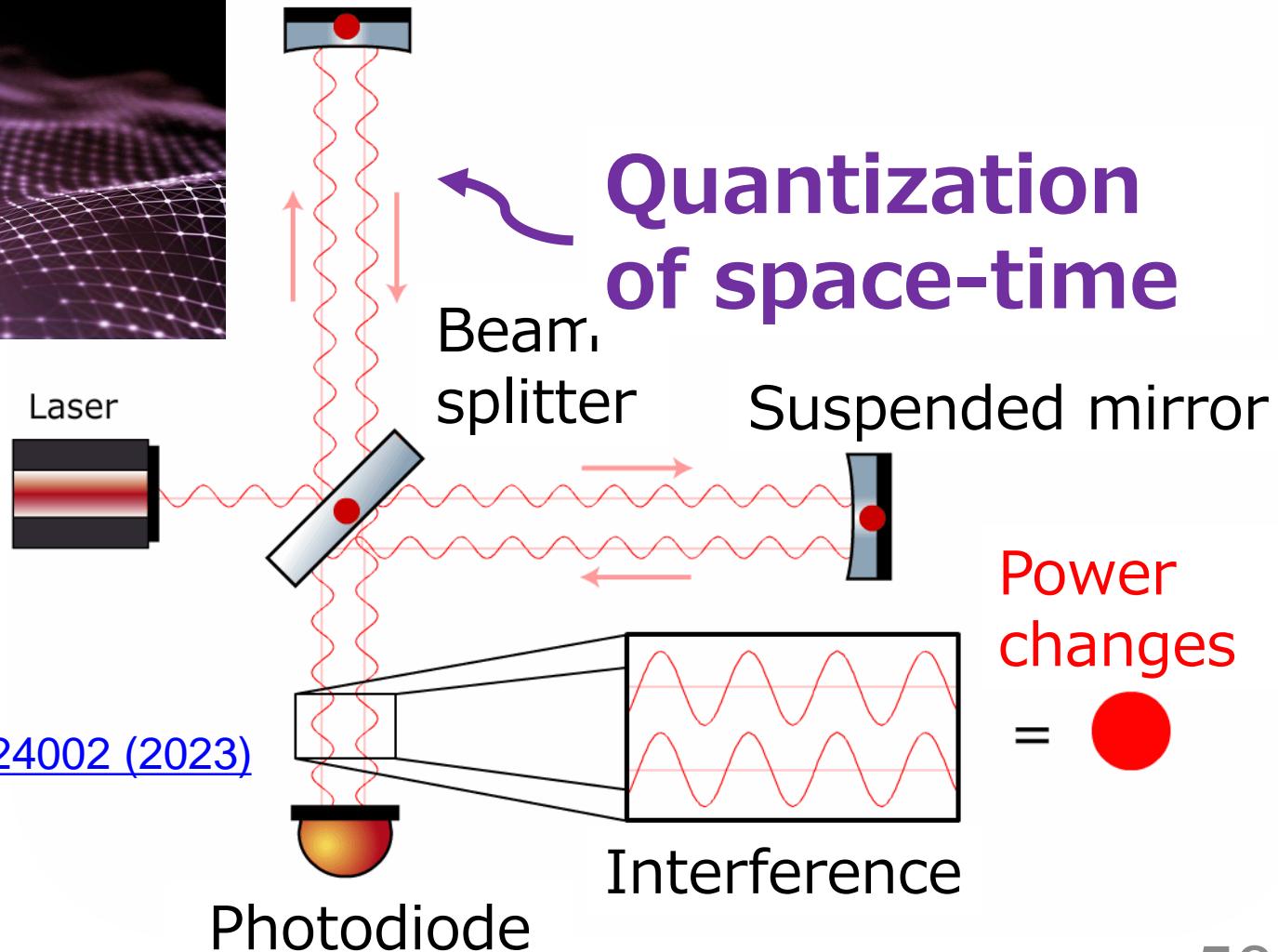
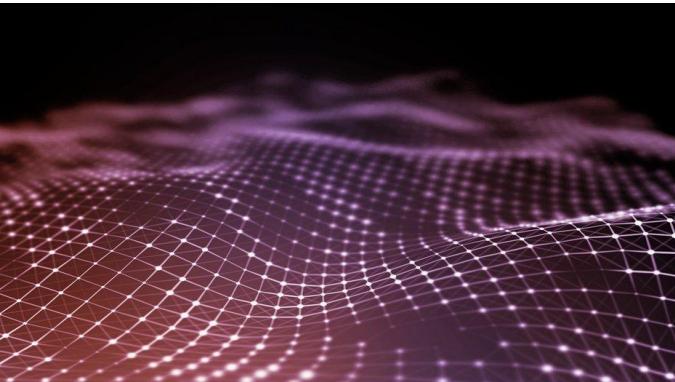
- Bosonic ultralight field (~ 1 eV) are well-motivated from cosmology
- Behaves as **classical waves**
- **Laser interferometers** are sensitive to such oscillating changes



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



Particle Physics with GW Detectors



K. M. Zurek,
[arXiv:2205.01799](https://arxiv.org/abs/2205.01799)

D. Li+, [PRD 107, 024002 \(2023\)](https://doi.org/10.1103/PRD.107.024002)

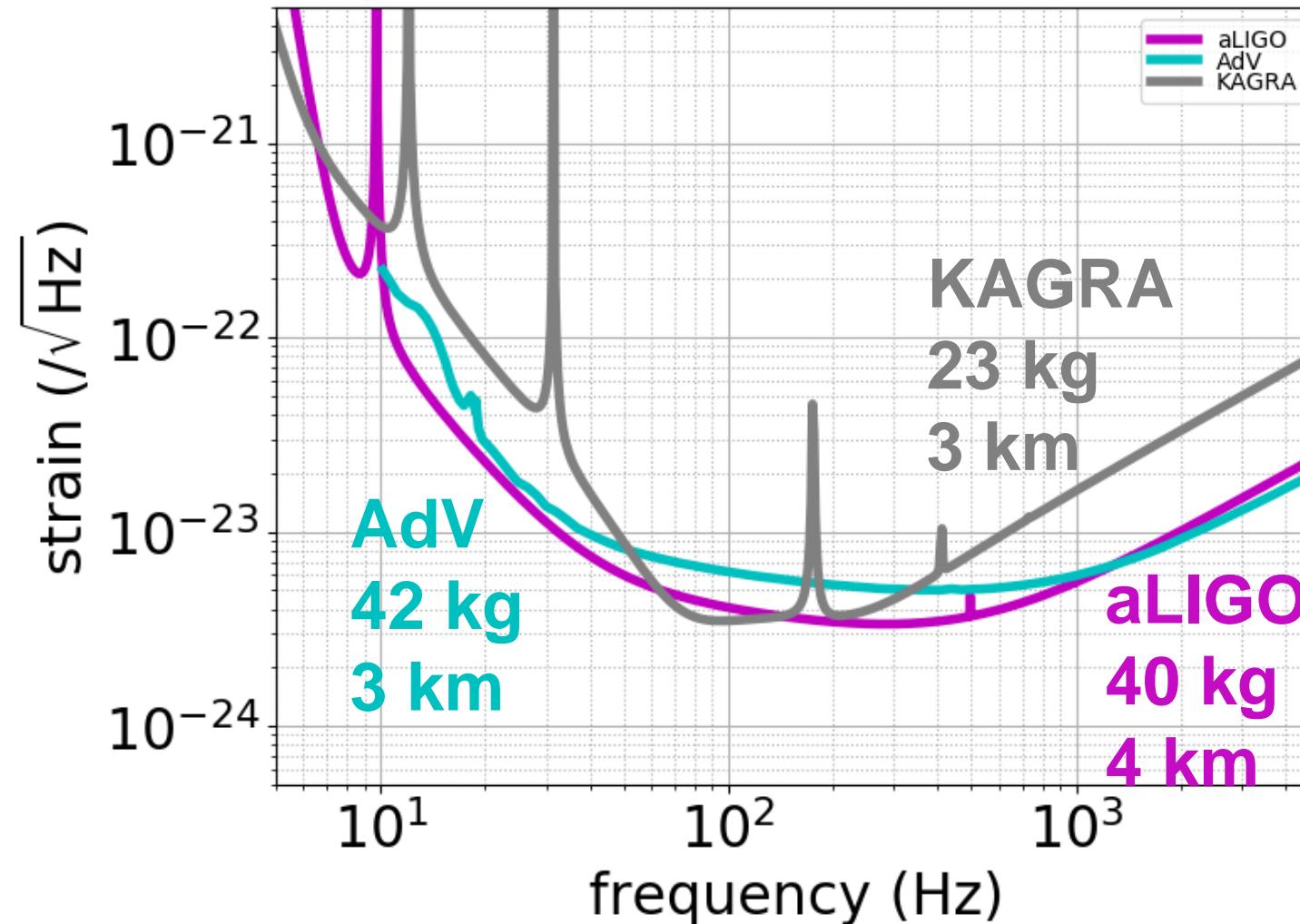
Summary

- 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!*

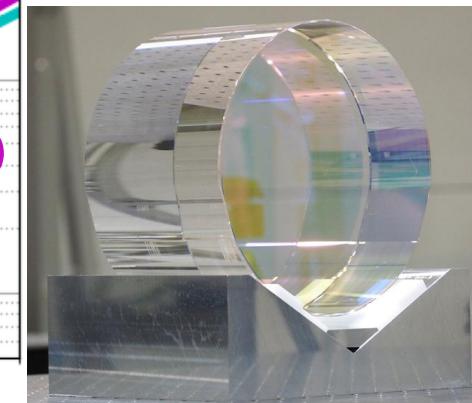
Additional Slides

KAGRA Design Sensitivity

- Not good at low freq. because of **thick and short** fiber (35 cm, $\varphi 1.6$ mm) to extract heat, and **lower mass**

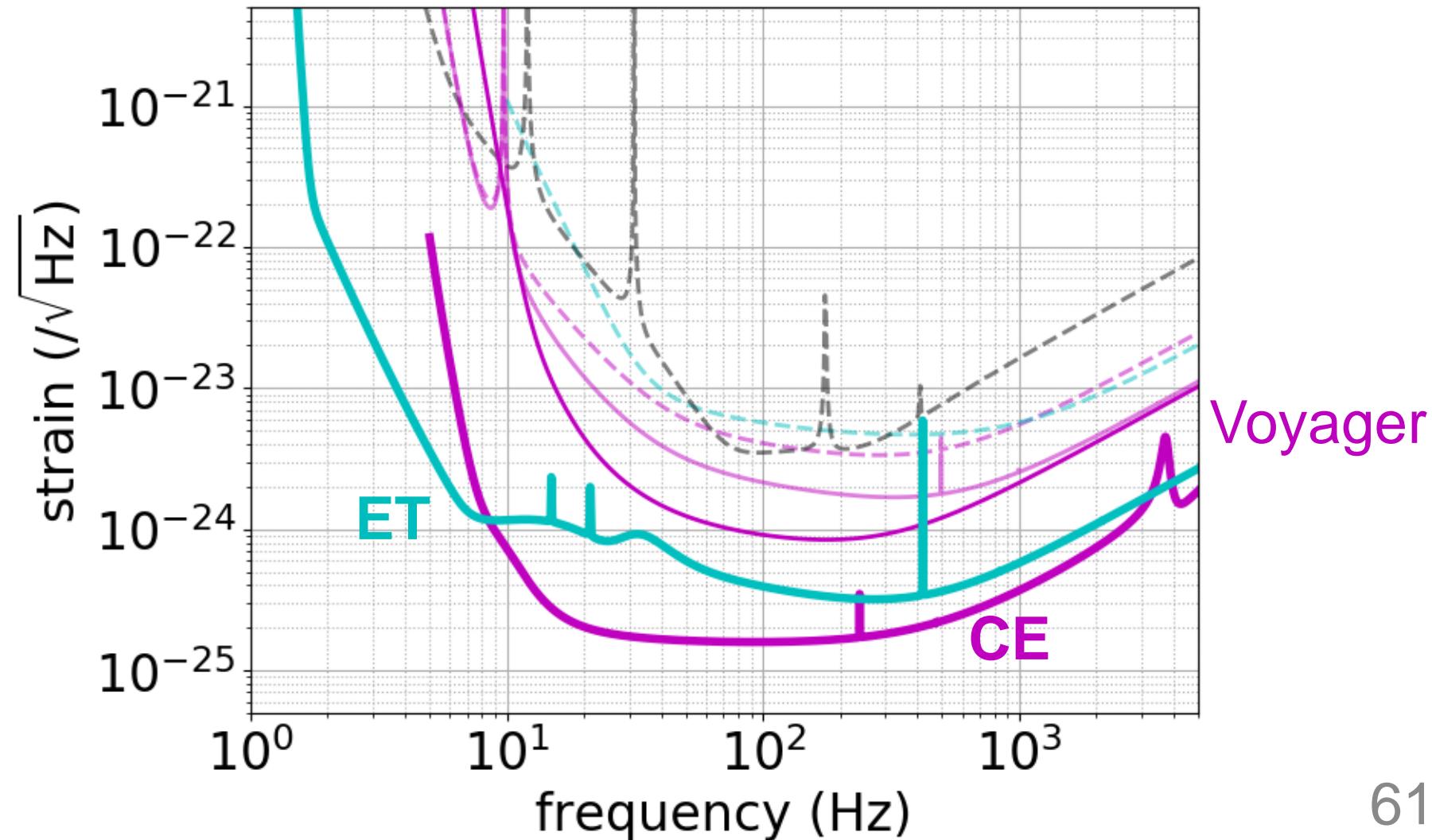


23 kg was the largest available sapphire mirror



Sensitivity of Next Generations

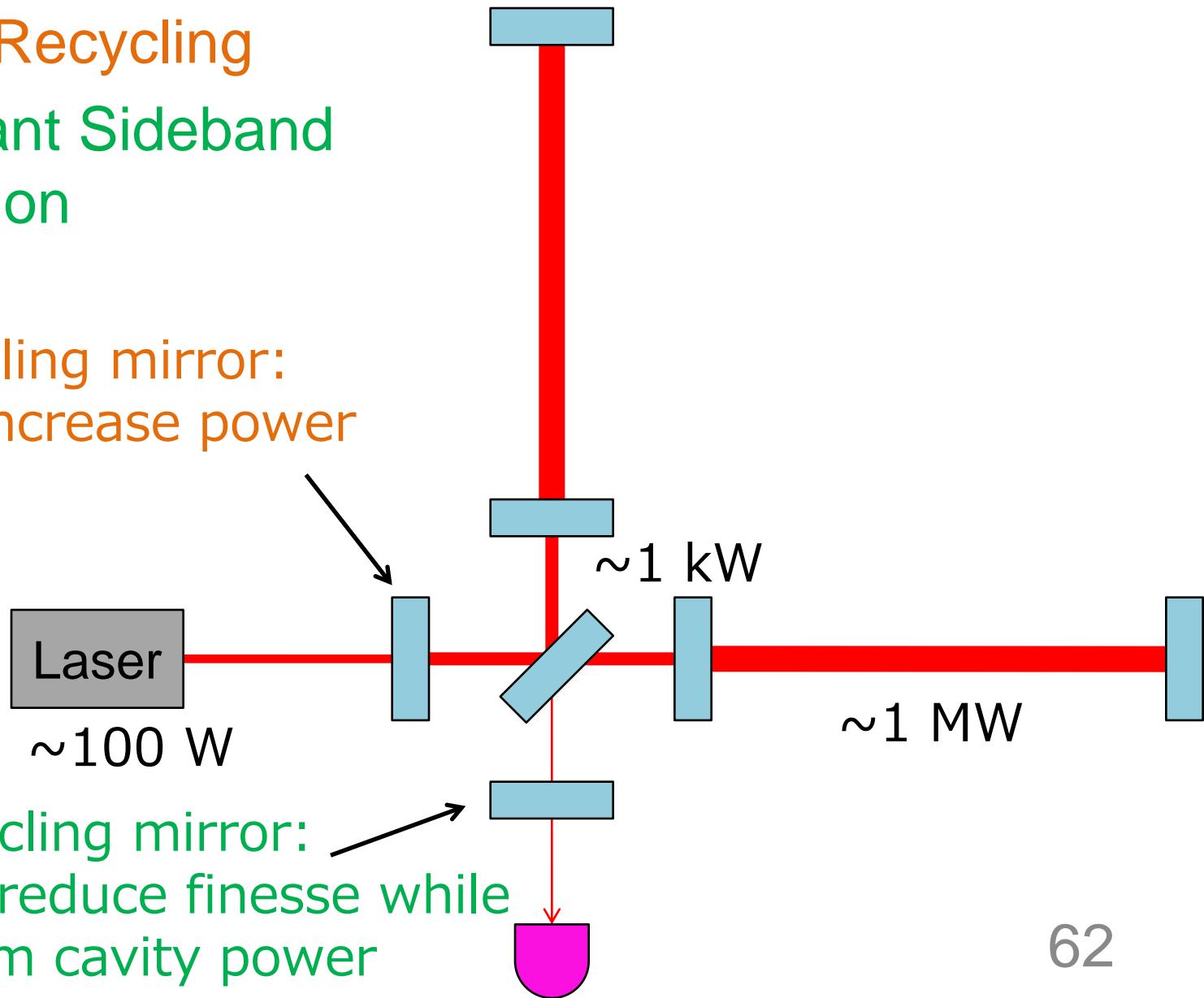
- An order of magnitude improvement



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

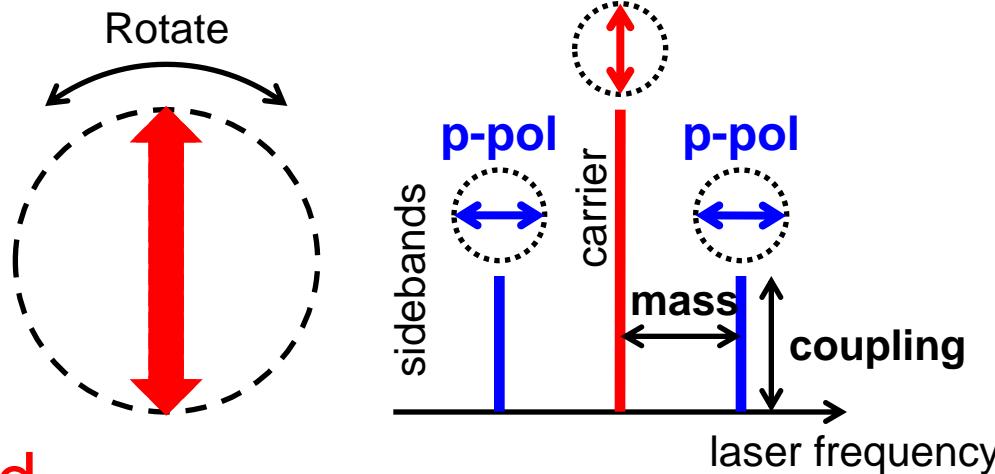
Polarization Modulation from Axions

- 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

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

coupling constant axion field axion mass
s-pol

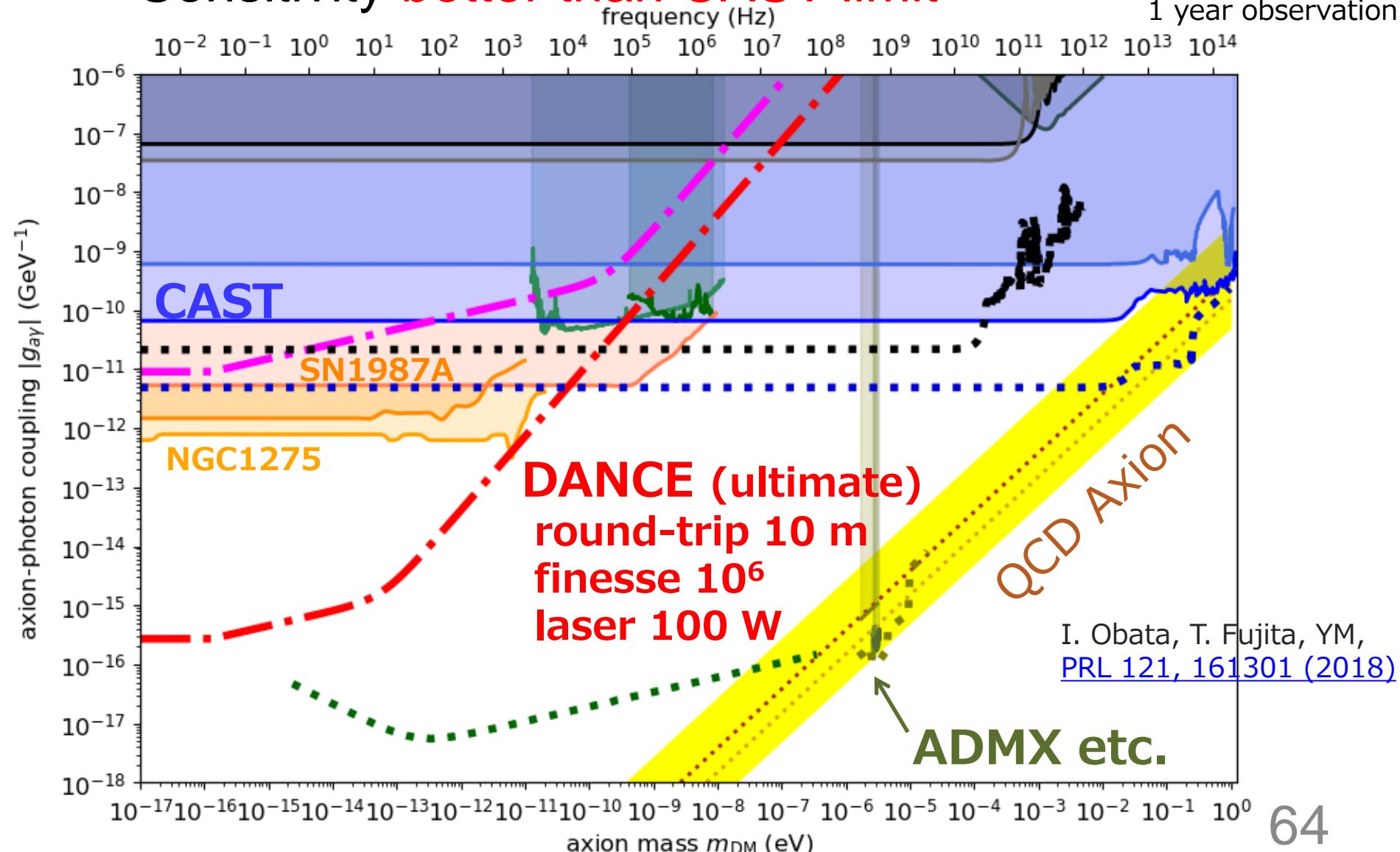
- Linear polarization will be modulated p-pol sidebands will be generated from s-pol
 - Search can be done without magnetic field



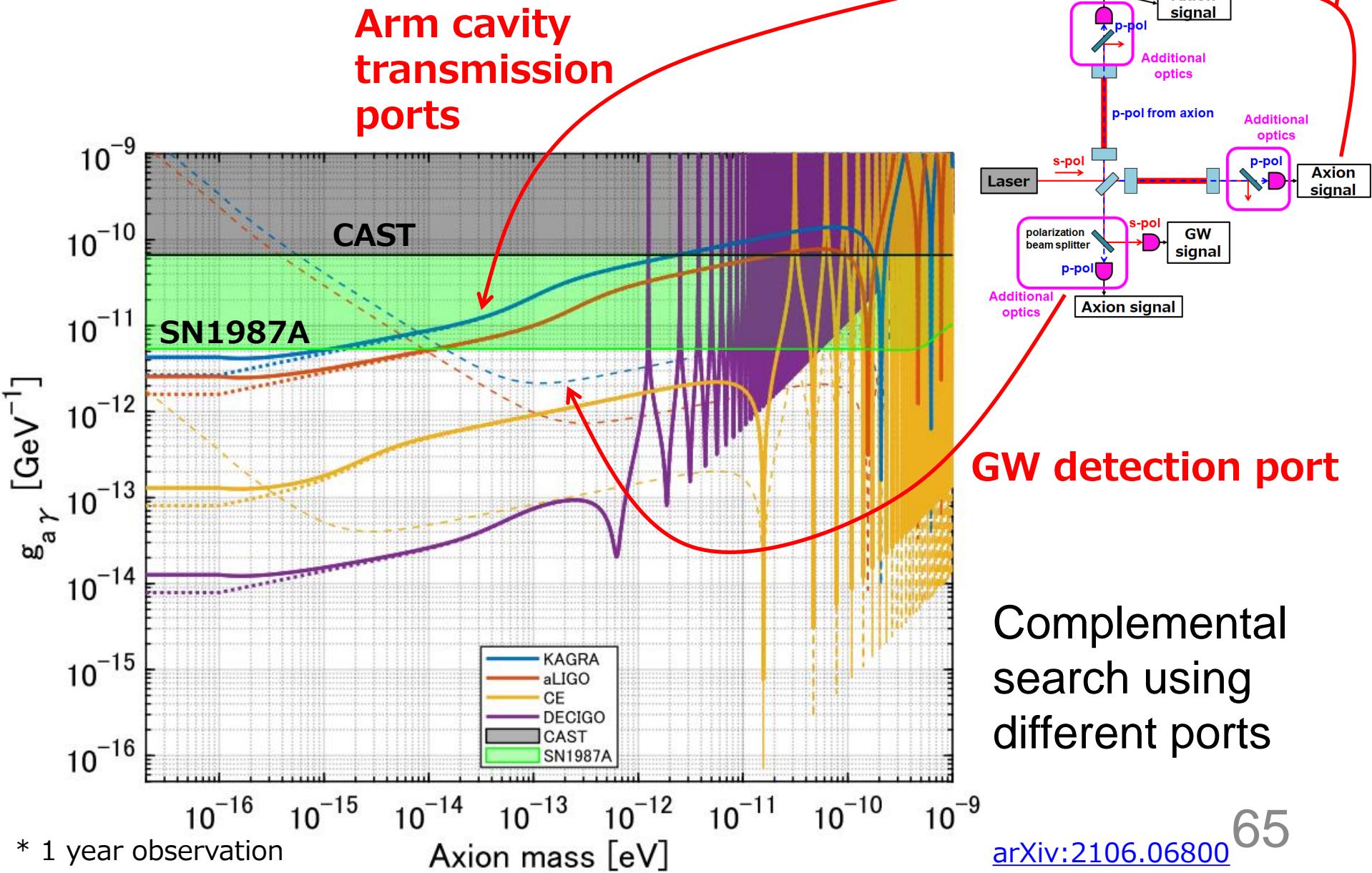
Sensitivity of DANCE

- Sensitivity **better than CAST limit**

* Shot noise limited
1 year observation

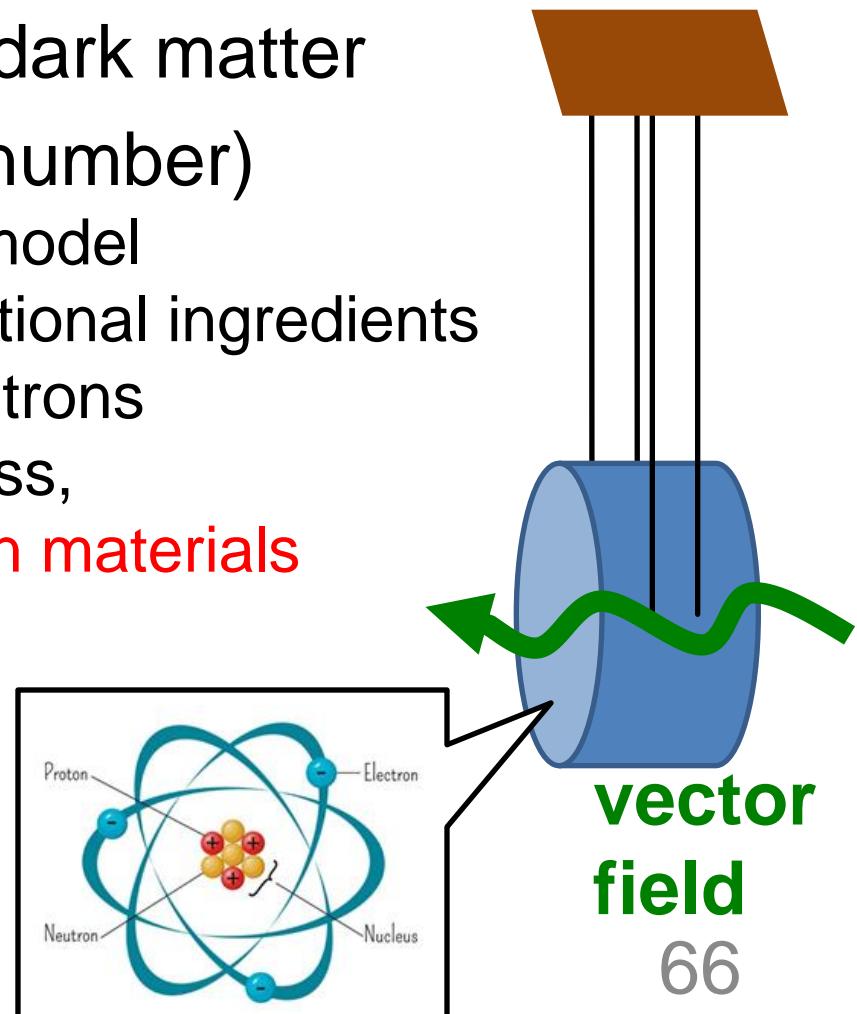


Axion Sensitivity



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**



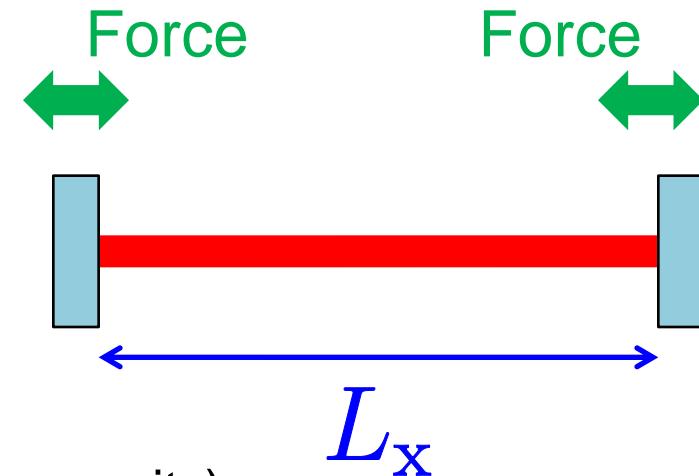
Oscillating Force from Vector Field

- Acceleration of mirrors

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

charge
coupling (normalized by e)
mirror mass
vector boson mass
polarization
different phase at different position
DM density

- 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**?



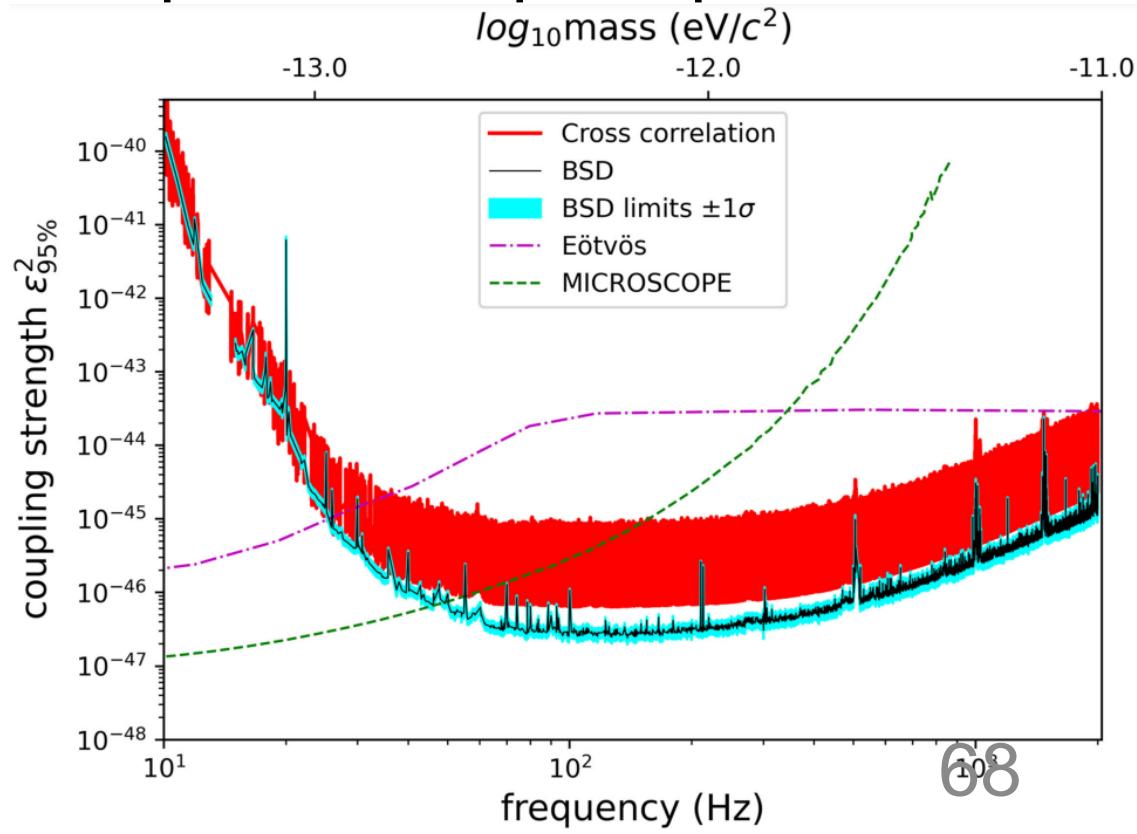
Previous Searches with LIGO/Virgo

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

H-K Guo+, [Communications Physics 2, 155 \(2019\)](#)

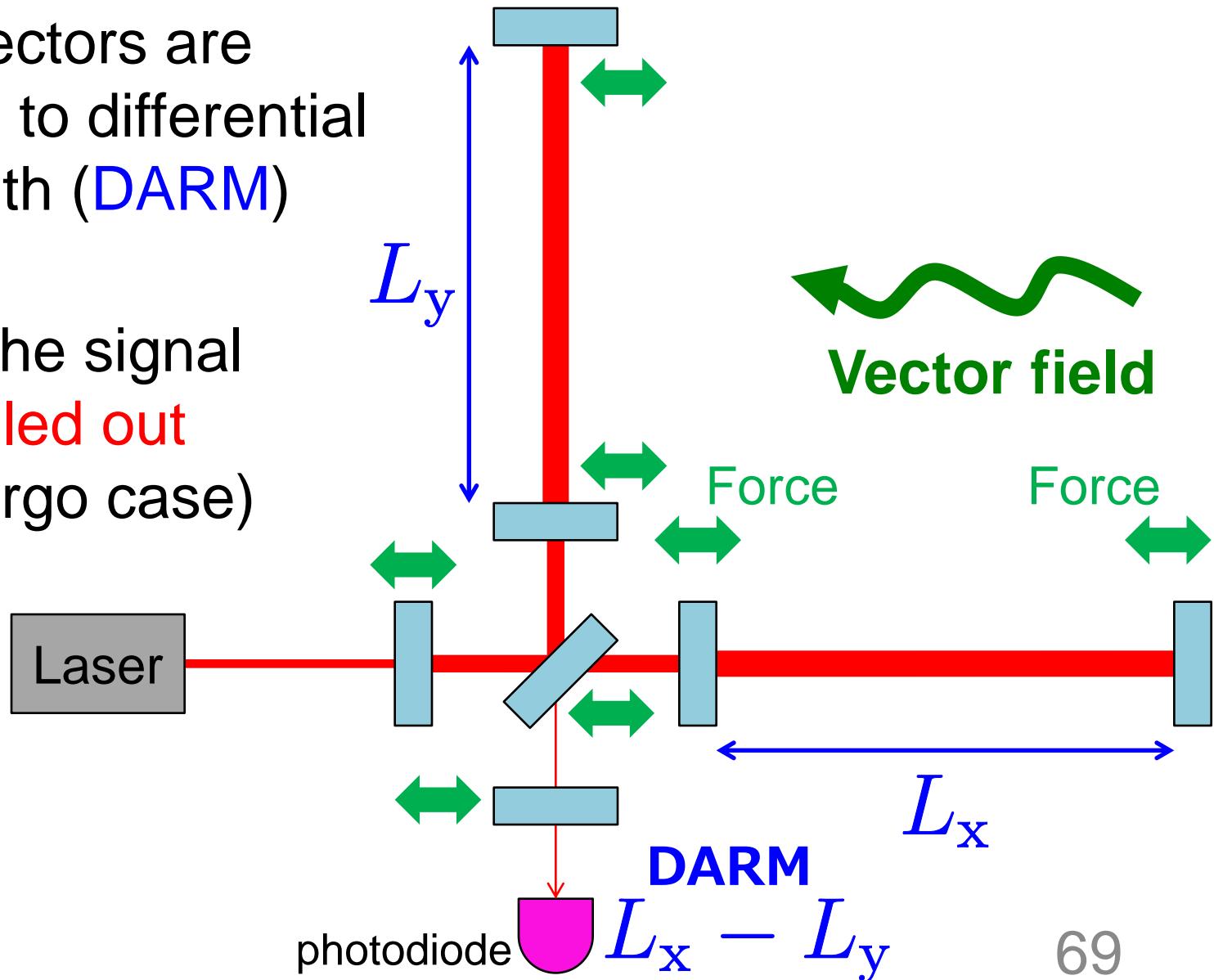
LIGO-Virgo-KAGRA Collaboration, [PRD 105, 063030 \(2022\)](#)

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

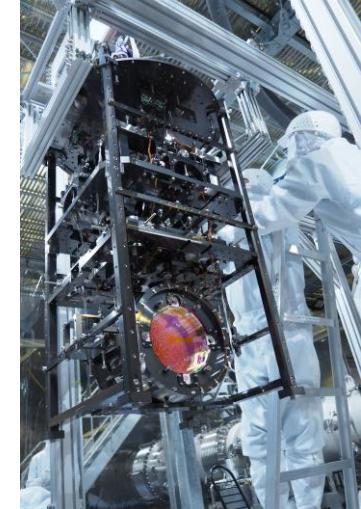


Search with GW Detectors

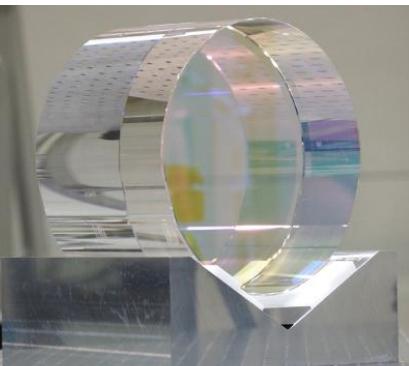
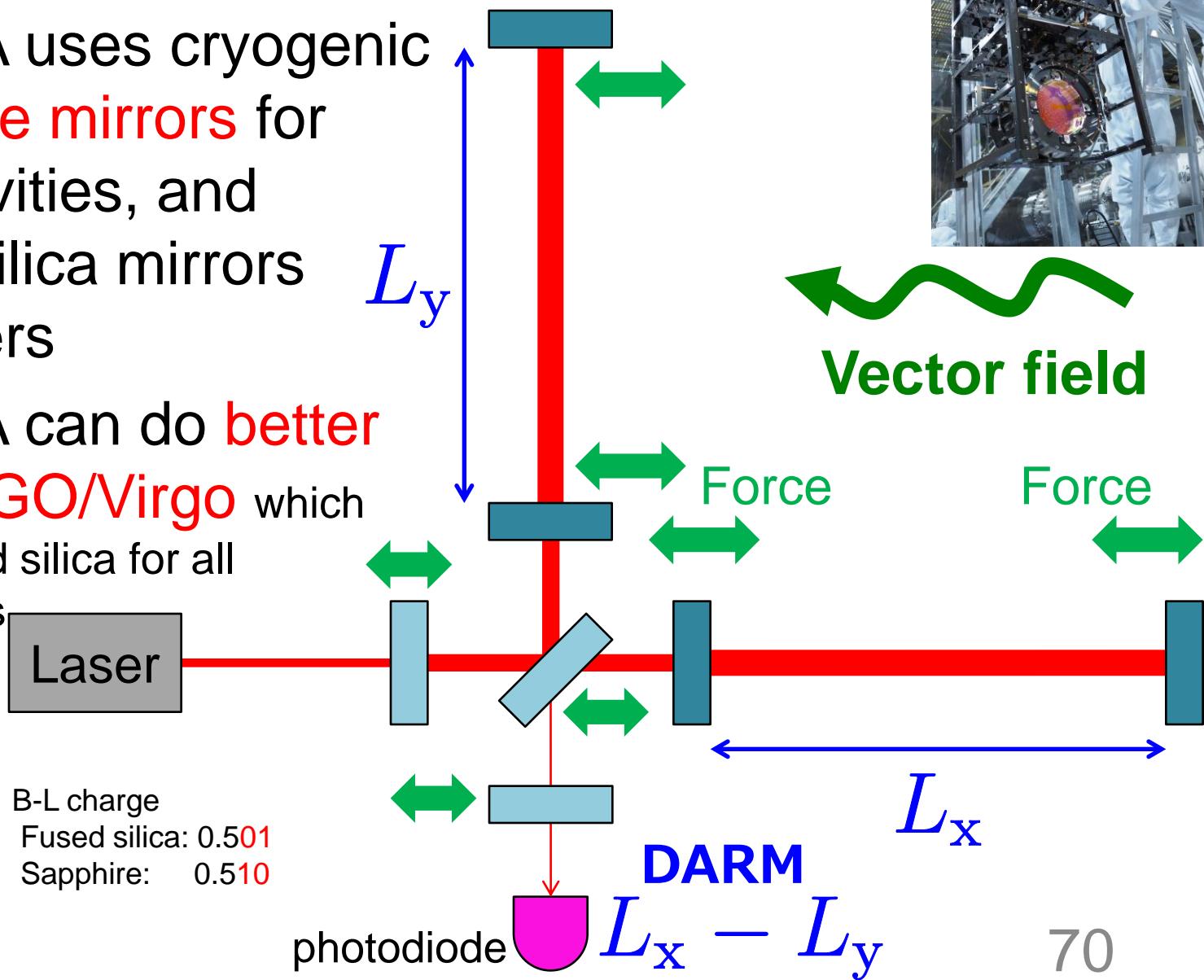
- GW Detectors are sensitive to differential arm length (**DARM**) change
- Most of the signal is **cancelled out** (LIGO/Virgo case)



Search with KAGRA

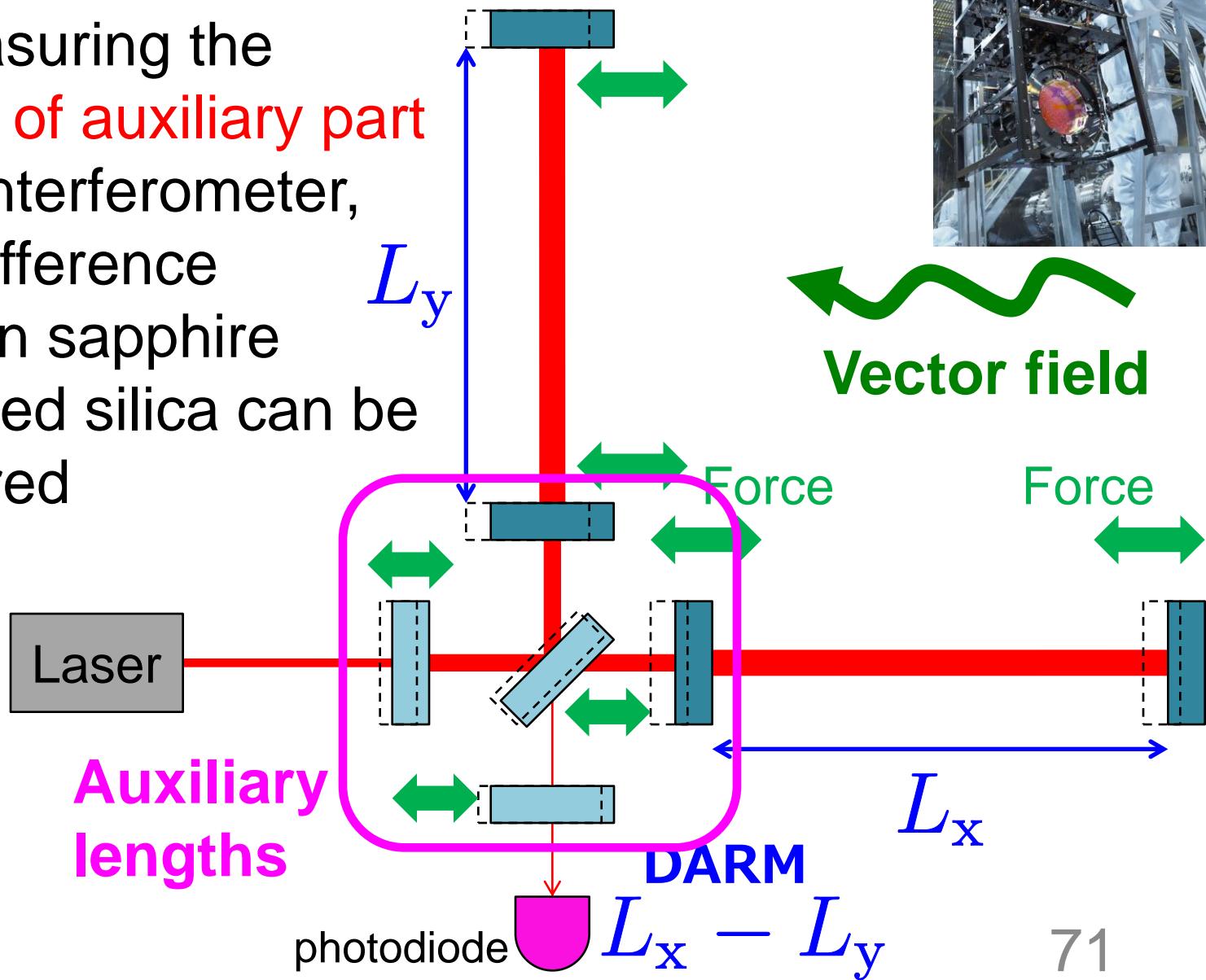


- KAGRA uses cryogenic sapphire mirrors for arm cavities, and fused silica mirrors for others L



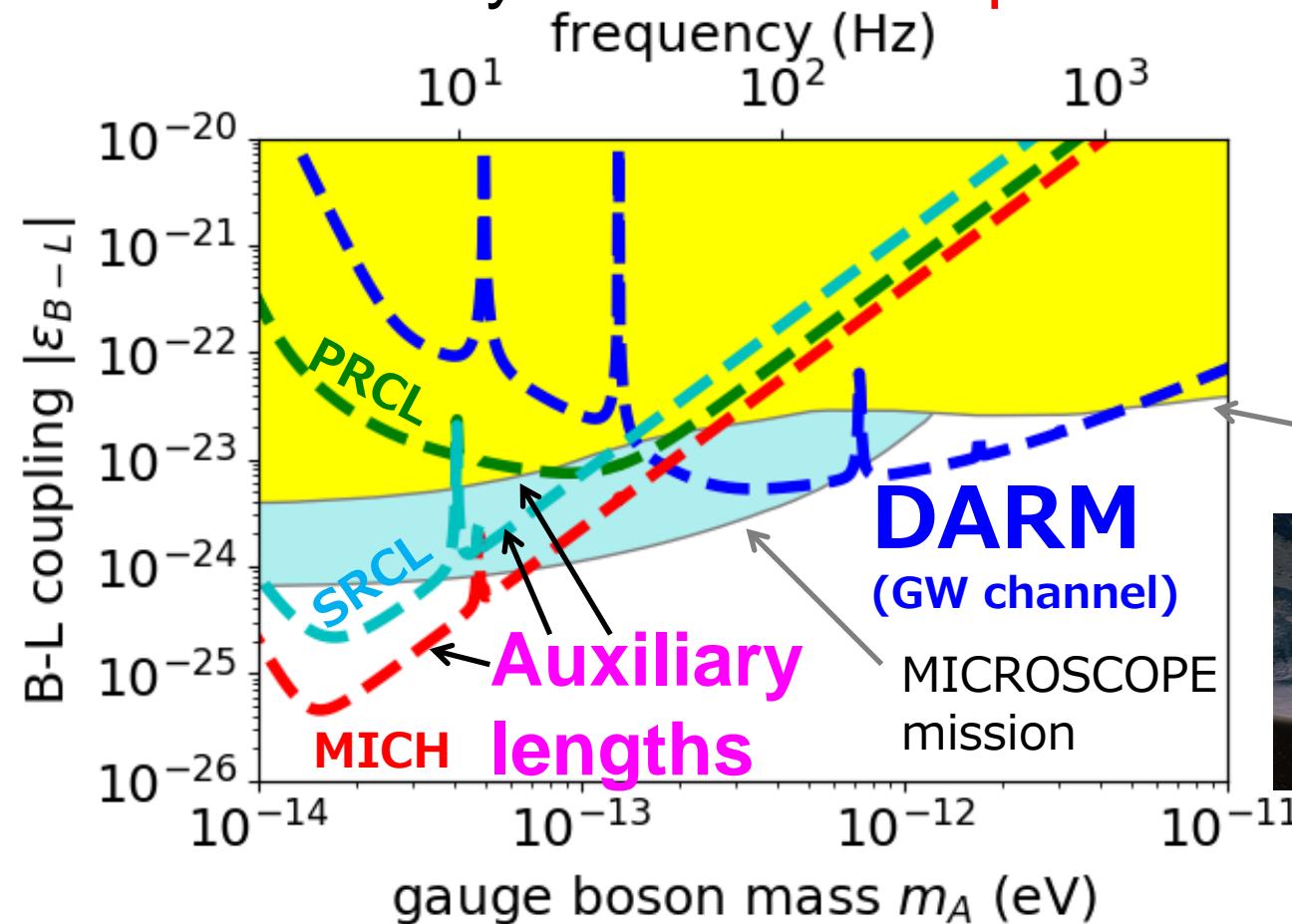
Search with KAGRA

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



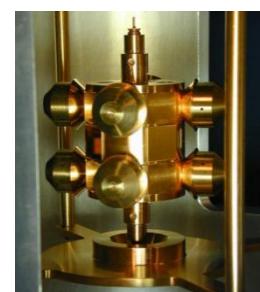
KAGRA Vector Boson Sensitivity

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



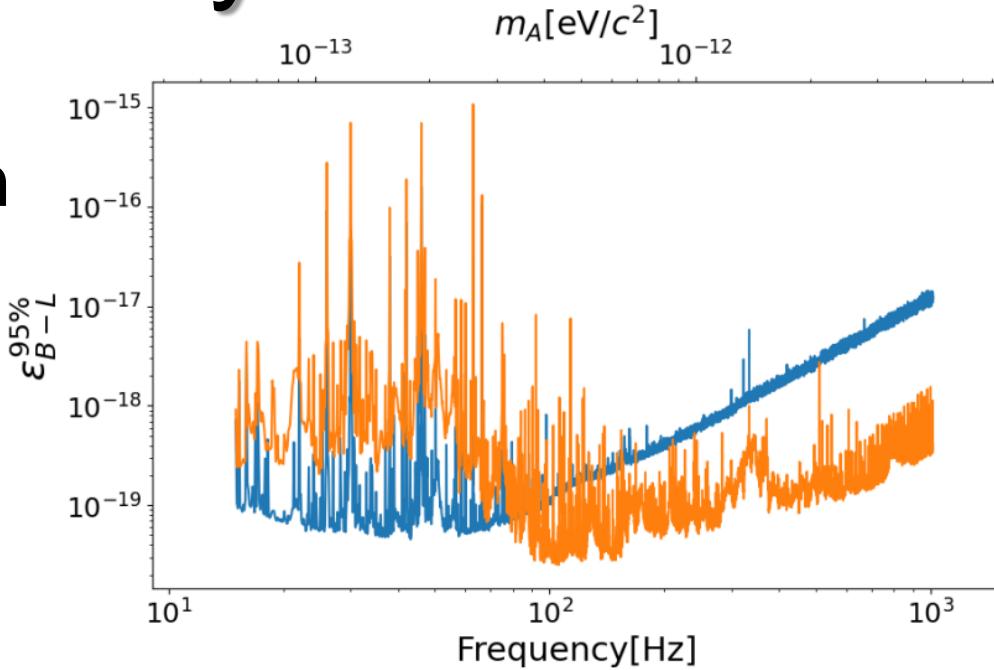
YM, T. Fujita, S. Morisaki,
H. Nakatsuka, I. Obata,
[PRD 102, 102001 \(2020\)](#)

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	
A. G. Alton	¹
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A. Adelberger	⁹
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D. Agarwal	¹³
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S. Ansoldi	^{32,33}
M. Antelli	³⁴
M. Antelli	³⁵
S. Antelli	³⁶
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M. Antelli	³⁸
S. Antelli	³⁹
M. Antelli	⁴⁰
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M. Arun	⁴⁵
G. Asztalos	⁴⁶
Y. Aszkenasy	⁴⁷
S. Avendaño	⁴⁸
S. Ayala	⁴⁹
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