Q-EYES 2025 @ KEK

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Laser interferometric searches for gravitational waves and ultralight dark matter

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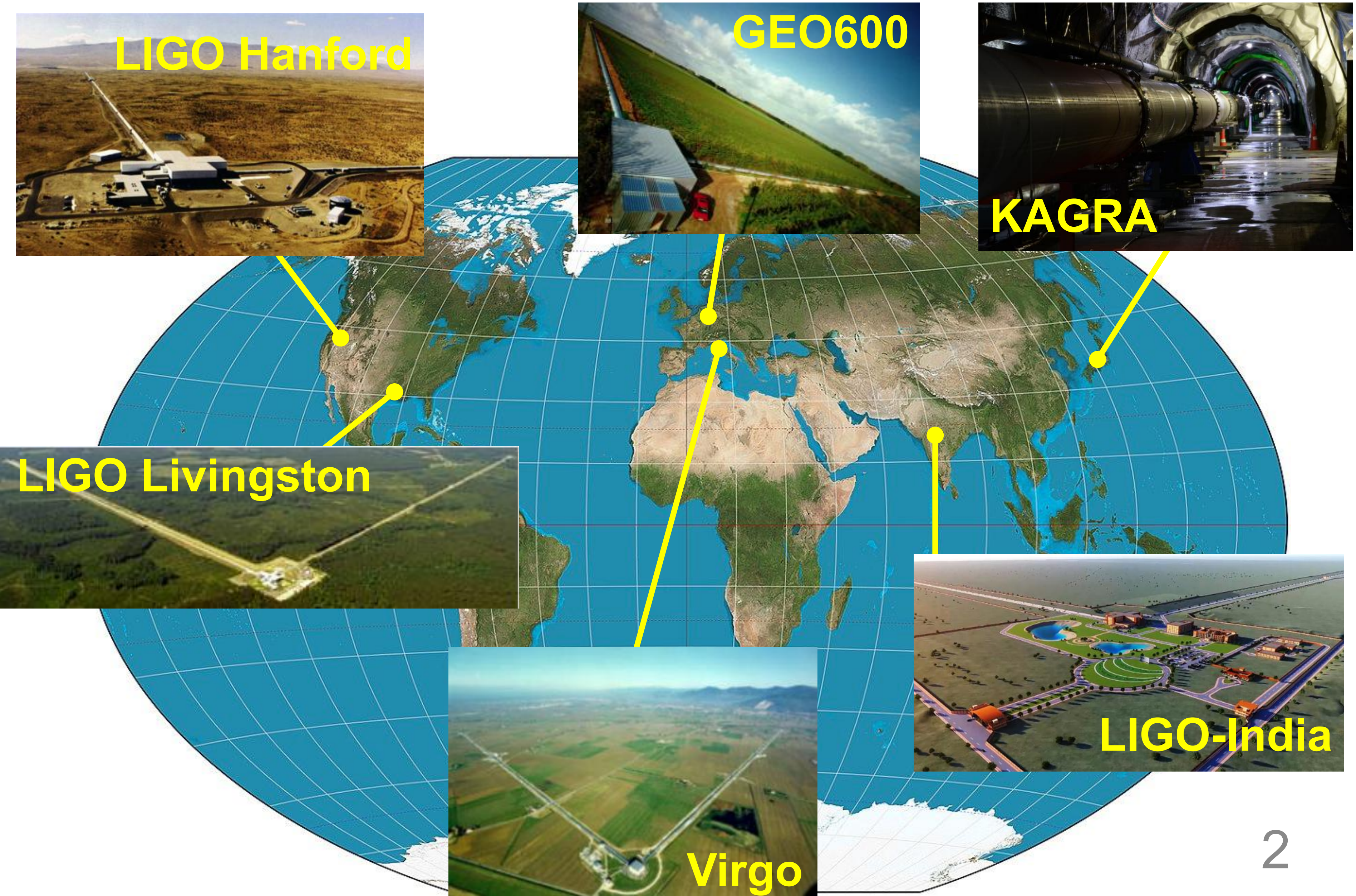
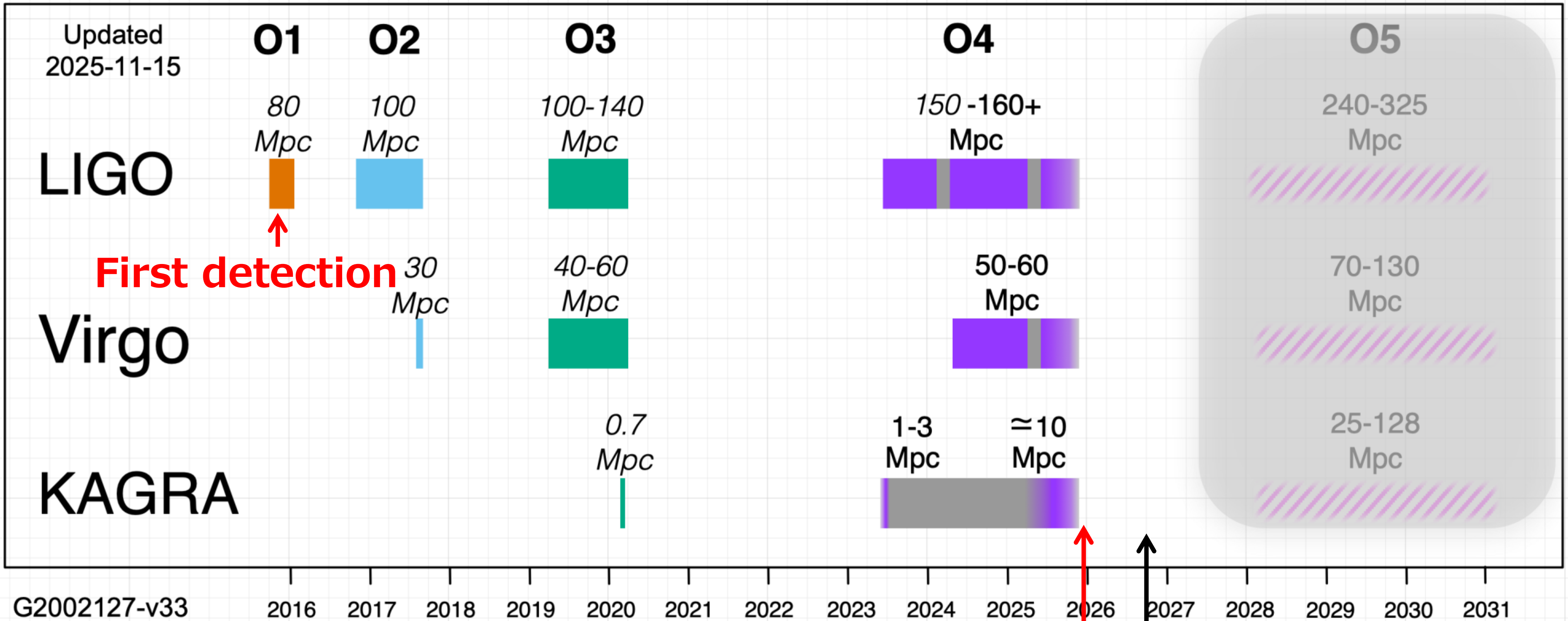
Laser Interferometric GW Detectors



Coordinated Observing Runs

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



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

Further and Clearer

- 300+ events with increased detector sensitivity

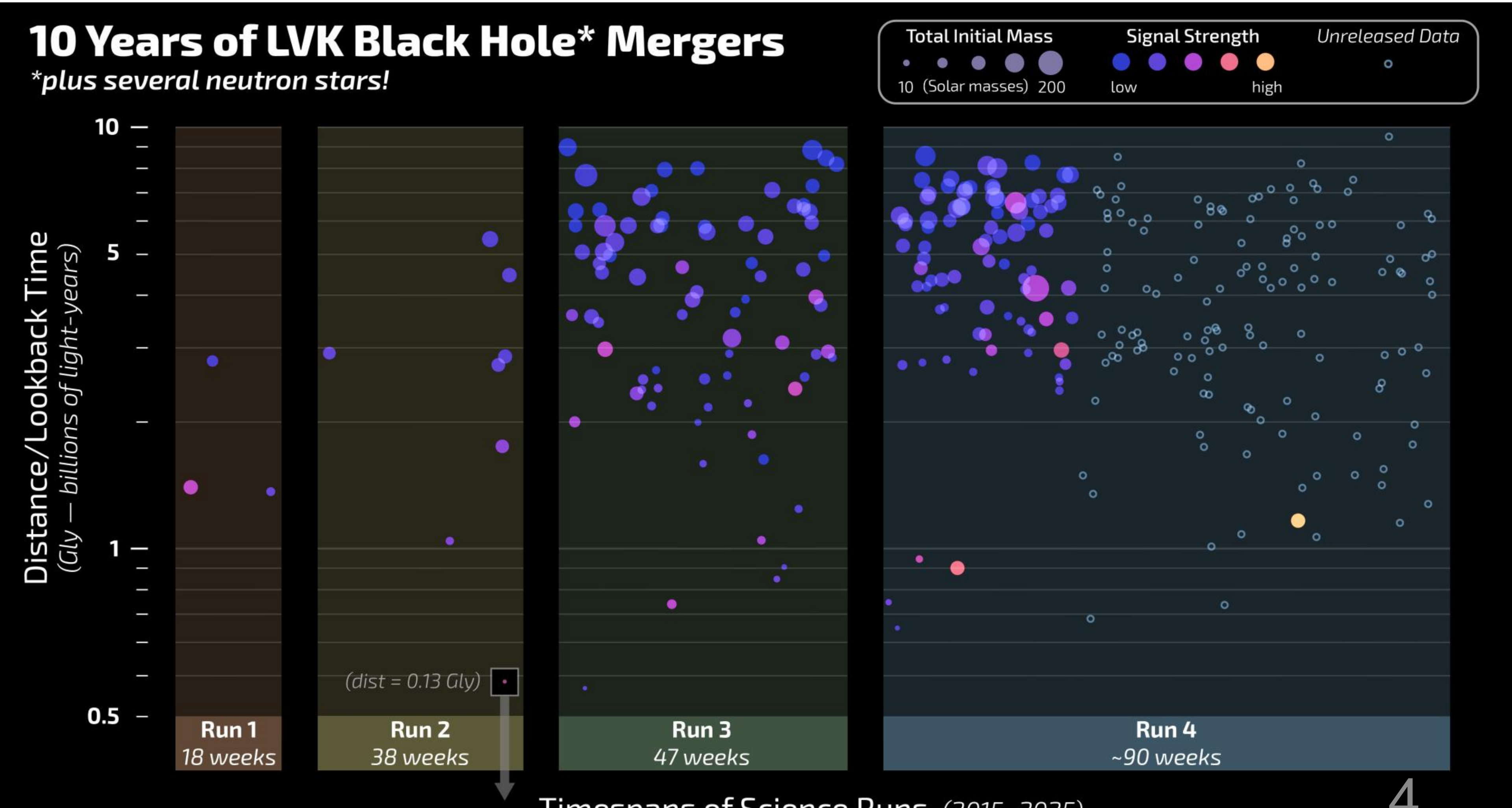
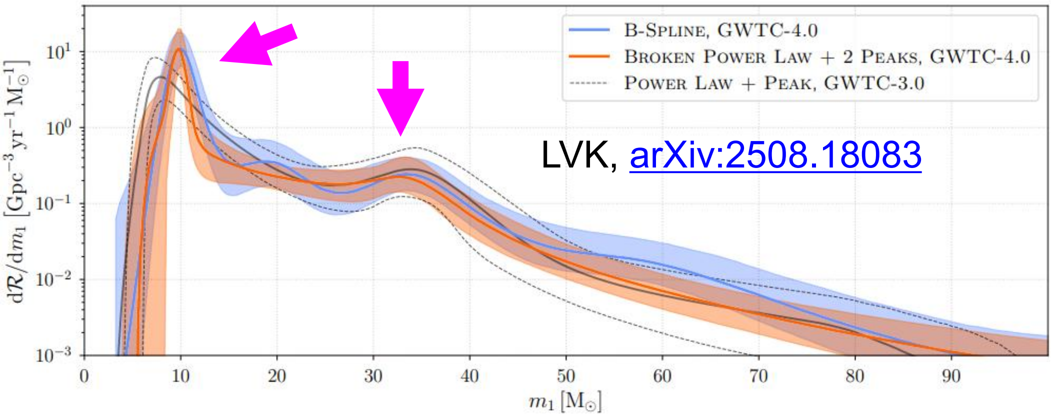


Image credit: LIGO/Caltech/MIT/R. Hurt (IPAC)

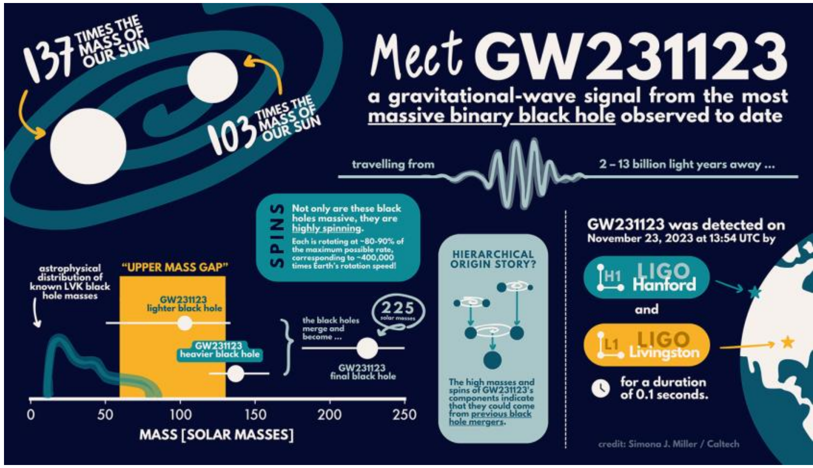
Some of Highlights

Population studies



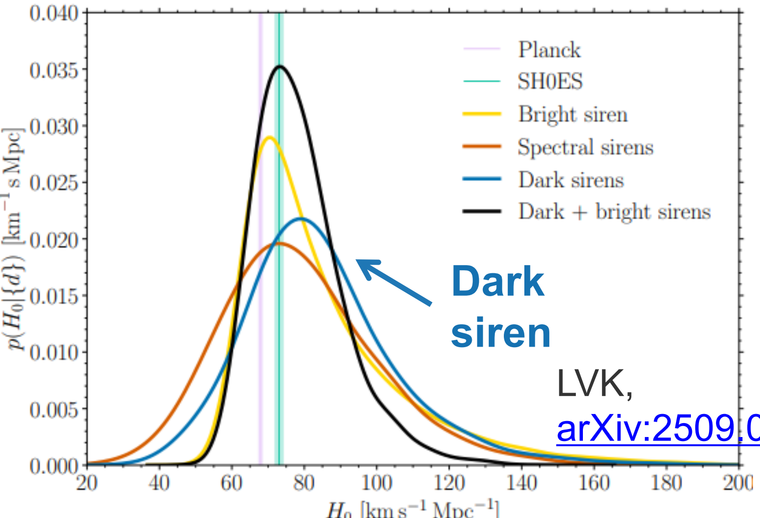
LVK, arXiv:2508.18083

IMBH events



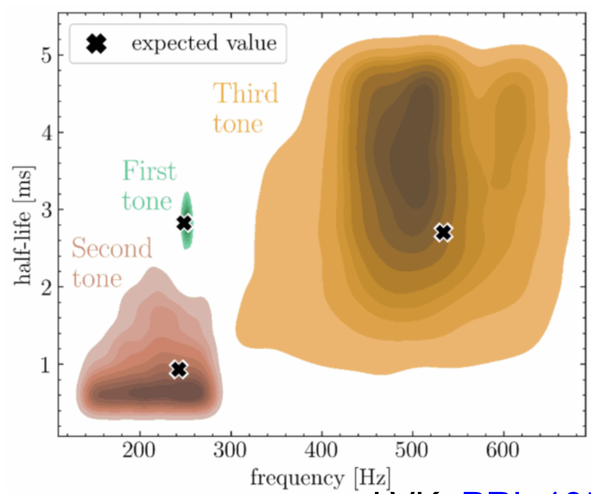
LVK, ApJL 993 L25 (2025)

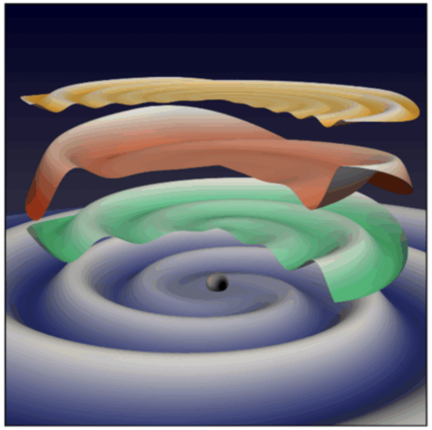
Cosmic expansion measurements



LVK, arXiv:2509.04348

Tests of General Relativity

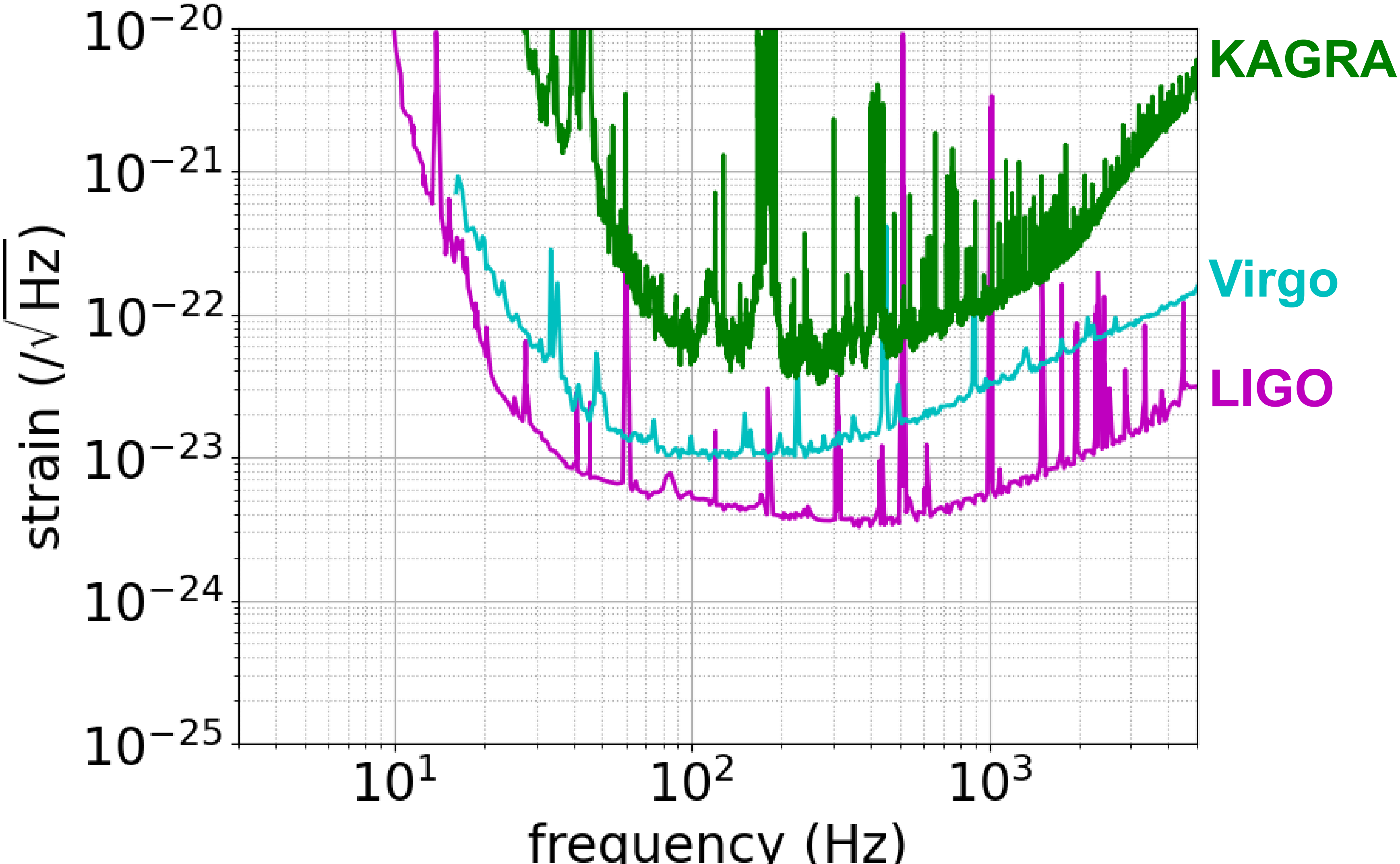




LVK, [PRL 135, 111403 (2025)](PRL 135, 111403 (2025))

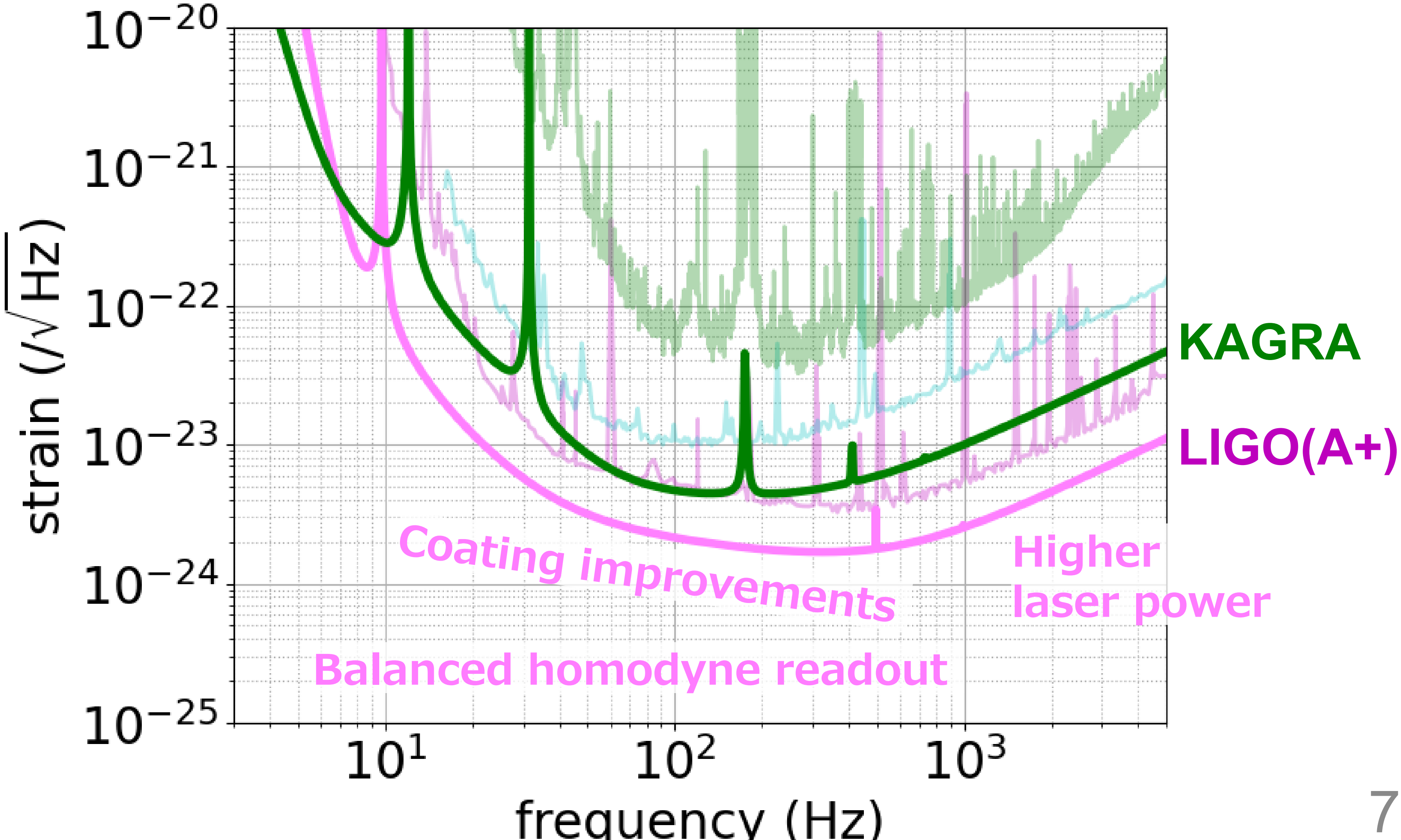
LIGO-Virgo-KAGRA Sensitivity

- Sensitivity during O4



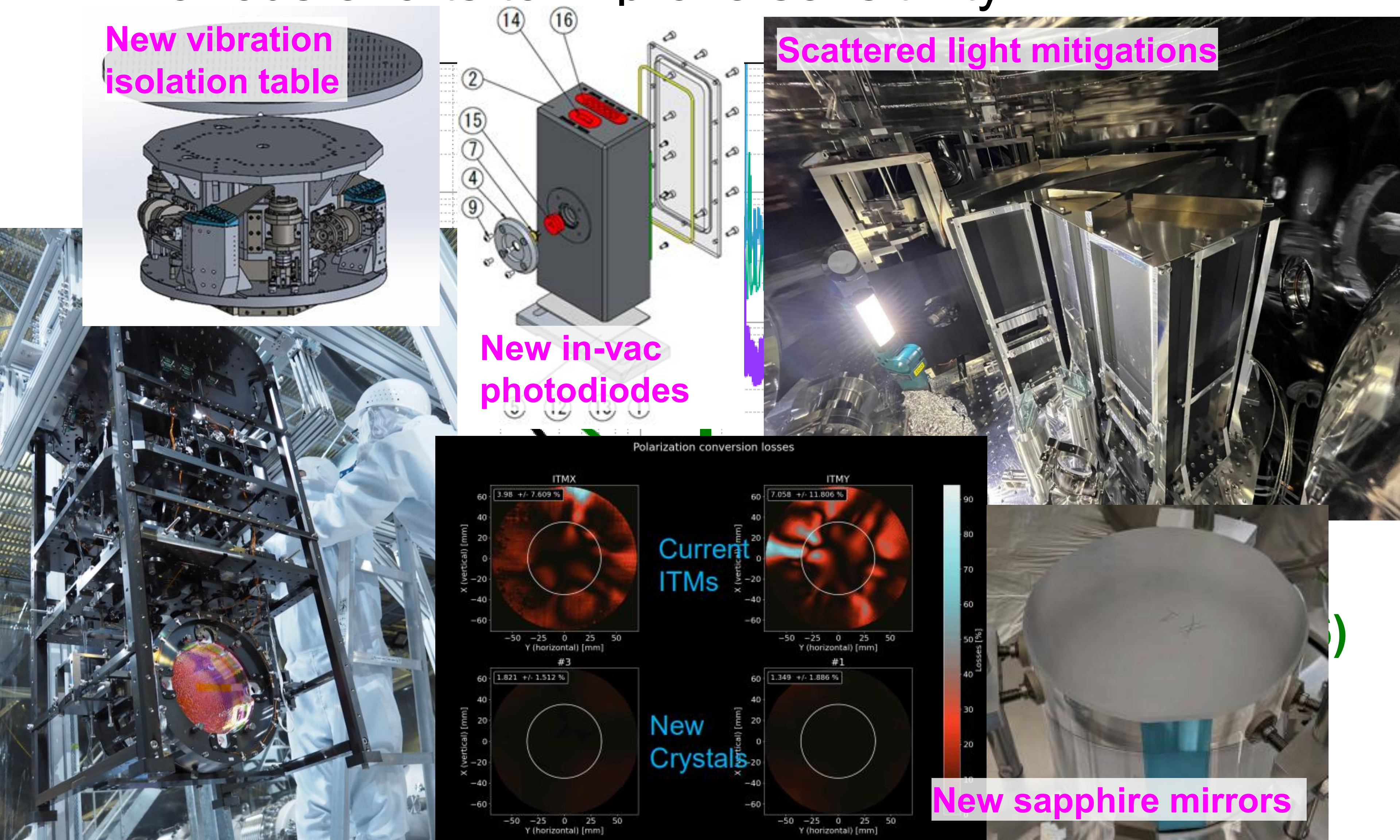
Projected Sensitivity for O5

- O5 planned 2028~



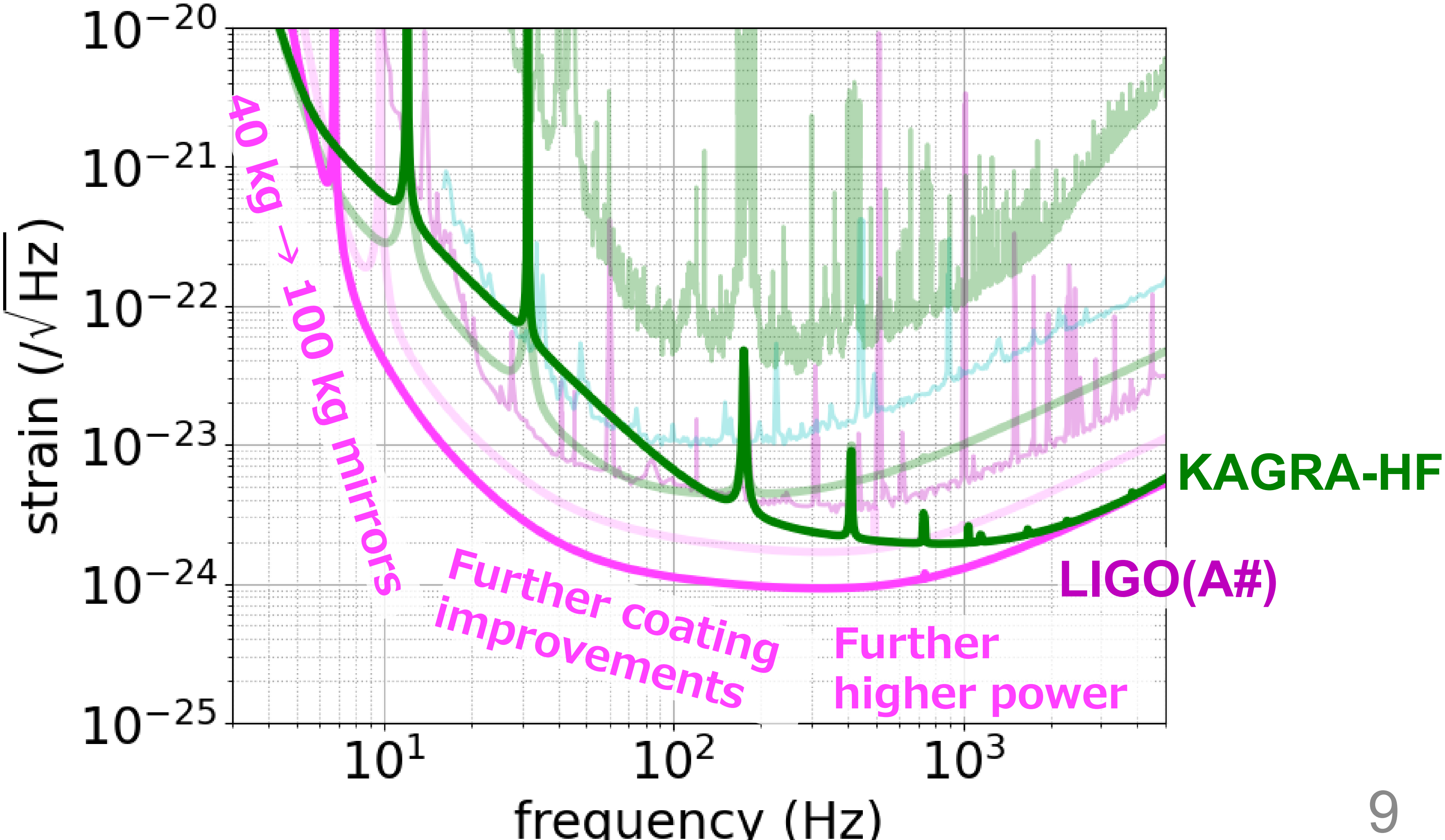
KAGRA Upgrades for O5

- Various efforts to improve sensitivity



Projected Sensitivity for O6

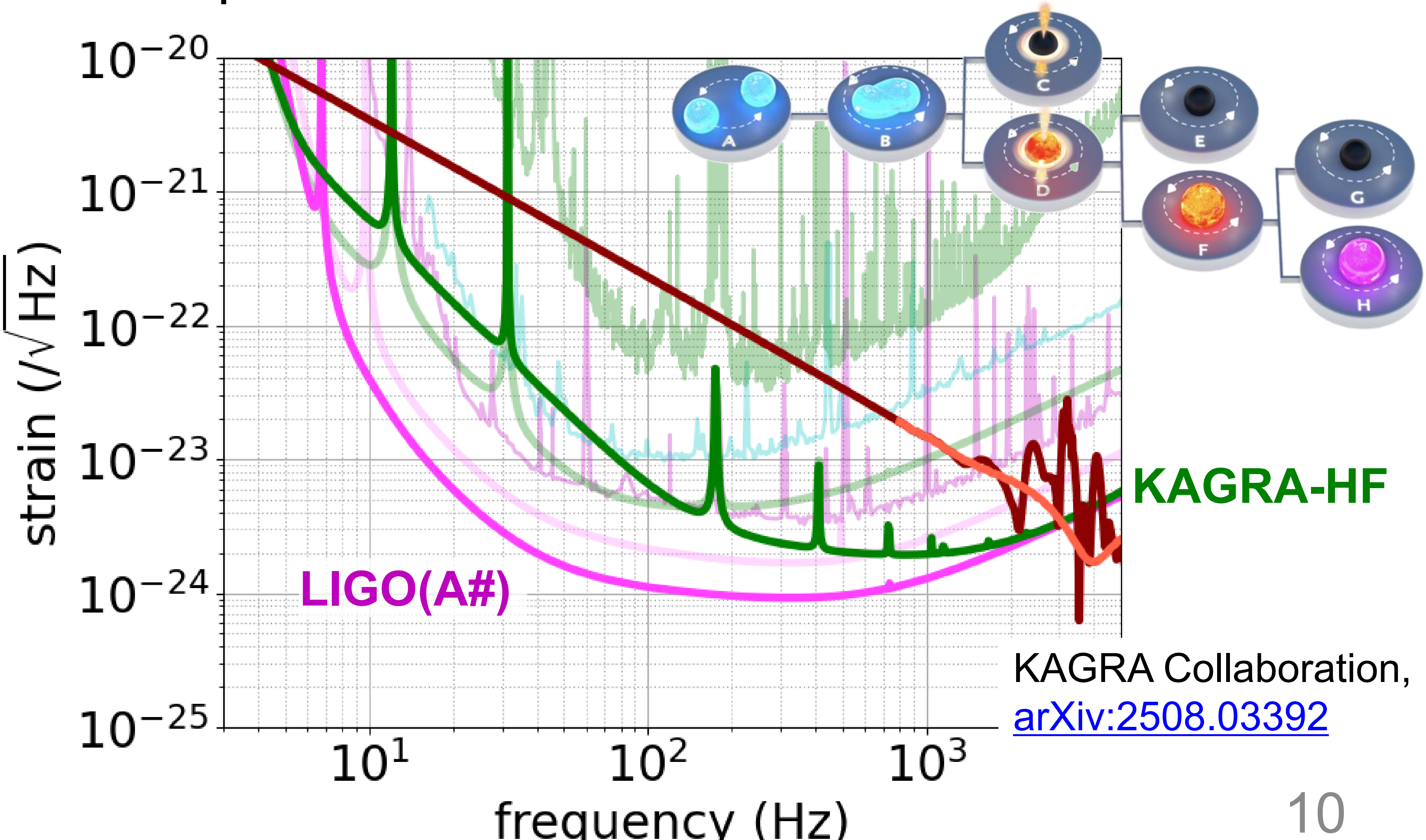
- O6 planned 2030+~



Projected Sensitivity for O6

- O6 planned 2030+~

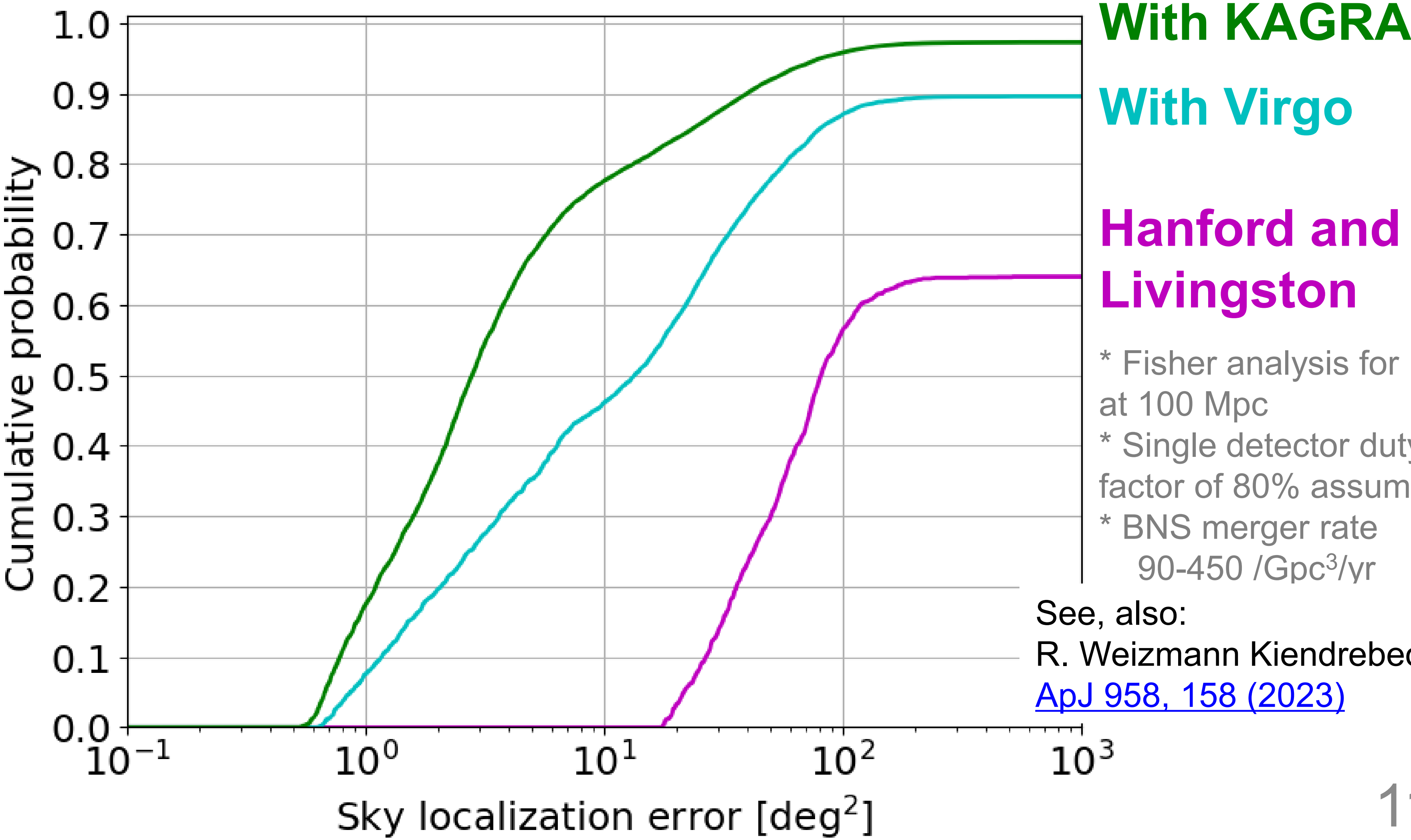
Sarin & Lasky,
[Gen. Relativ. Gravit. 53, 59 (2021)]



KAGRA Collaboration,
[arXiv:2508.03392]

Sky Localization in O5 (2028~)

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



* Fisher analysis for BNS at 100 Mpc

* Single detector duty factor of 80% assumed

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

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

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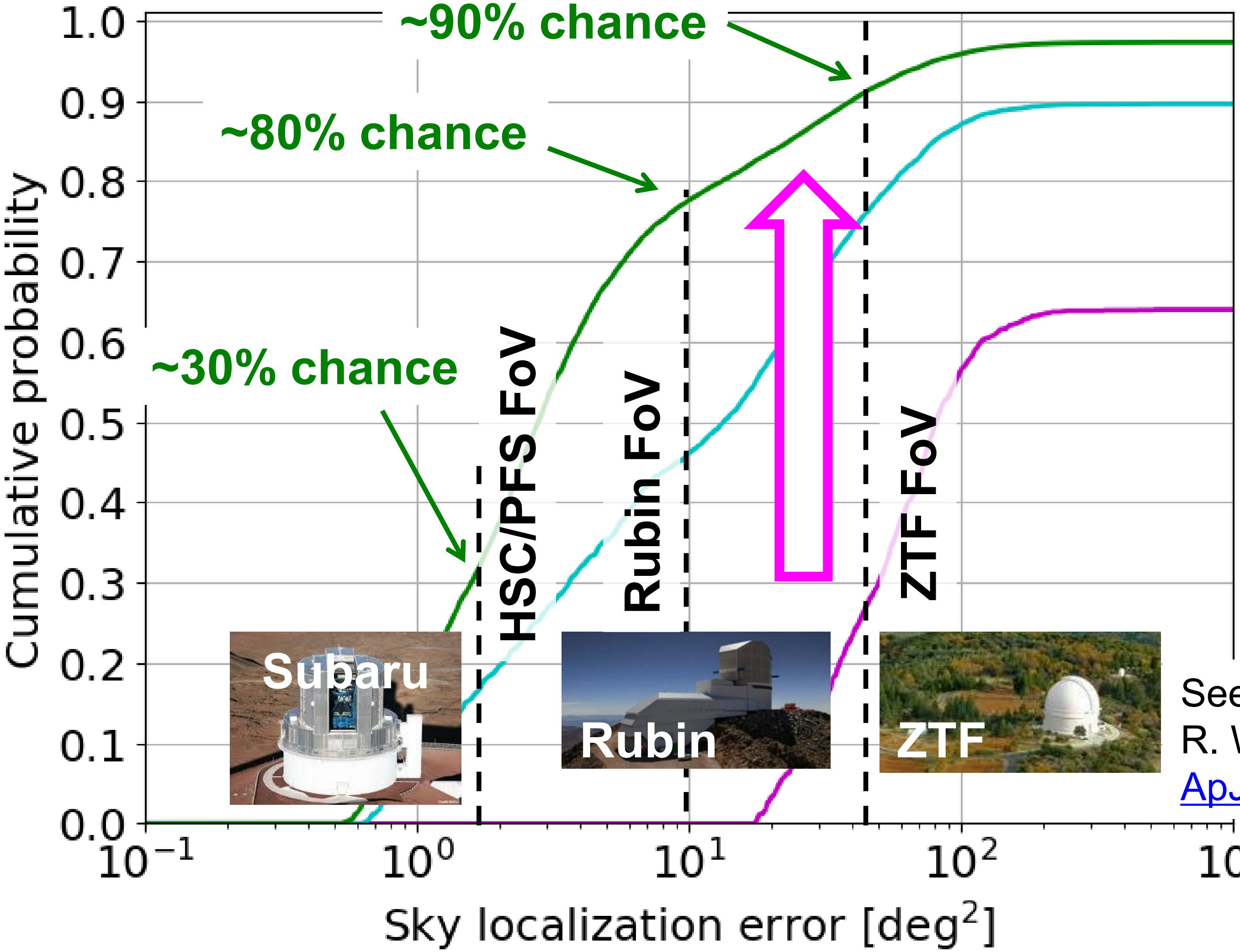


With KAGRA

With Virgo

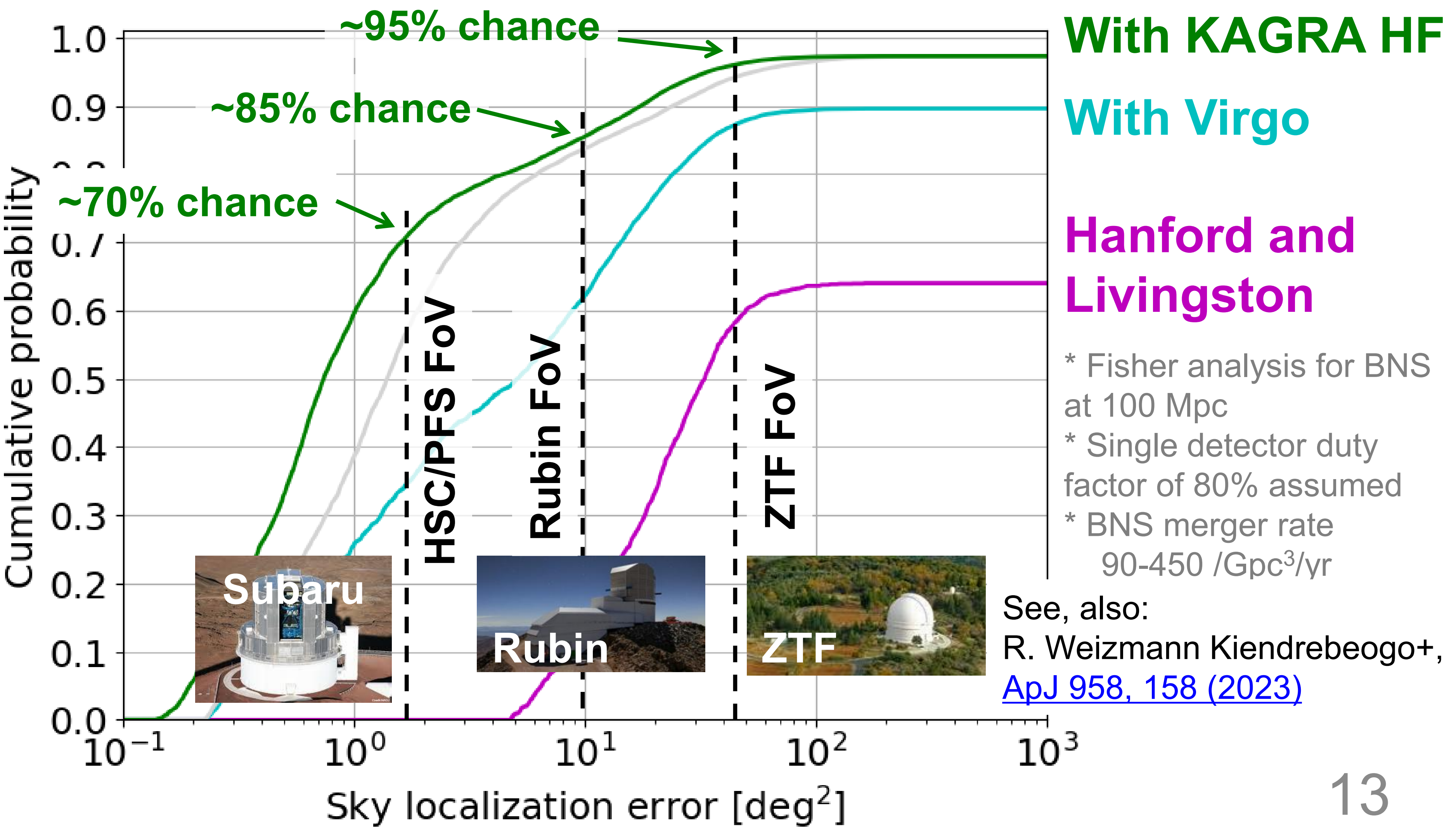
Hanford and Livingston

* Fisher analysis for BNS at 100 Mpc
* 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



* Fisher analysis for BNS at 100 Mpc
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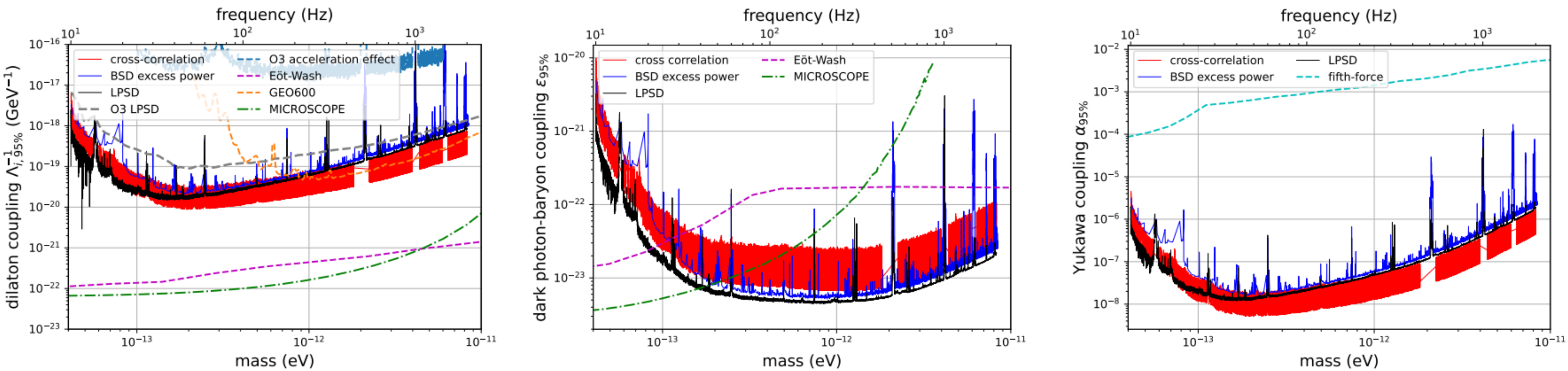
See, also:
R. Weizmann Kiendrebeogo+, [ApJ 958, 158 (2023)]

Searches for New Physics

Personal Picks!

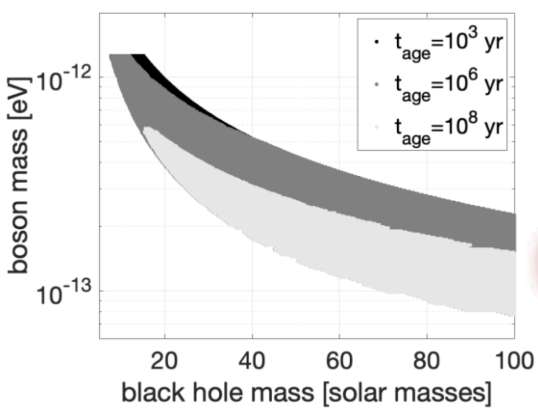
Ultralight dark matter (10^{-13}~10^{-11} eV range)

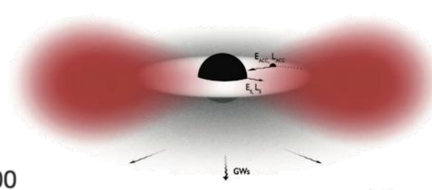


(a) Dilatons (b) Dark photons (c) Tensor bosons

LVK, [arXiv:2510.27022]()

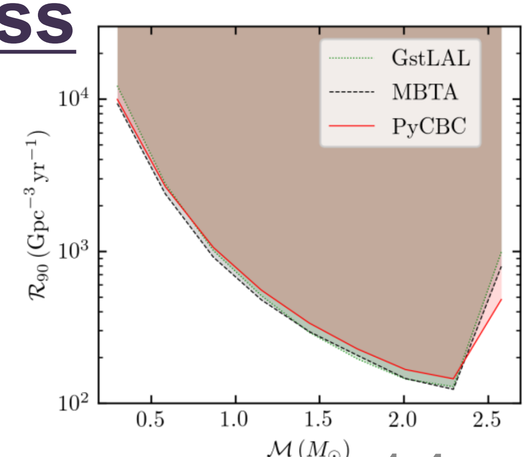
Boson clouds





LVK, [PRD 105, 102001 (2022)]()

Sub-solar-mass primordial black holes



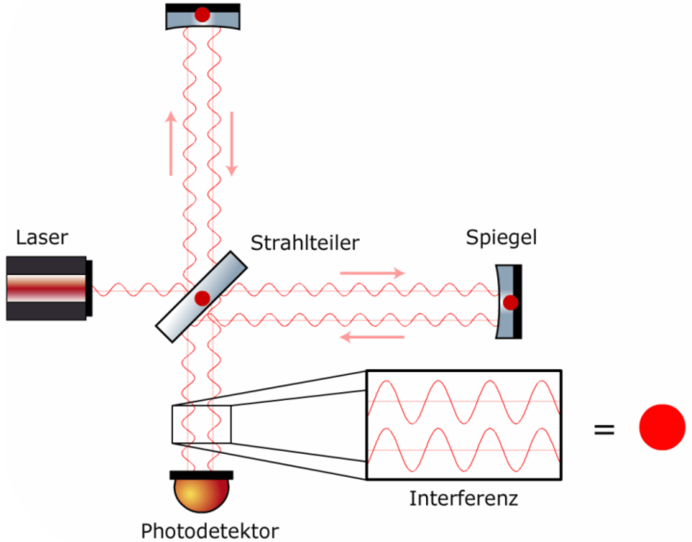
LVK, [MNRAS 524, 5984 (2023)]()

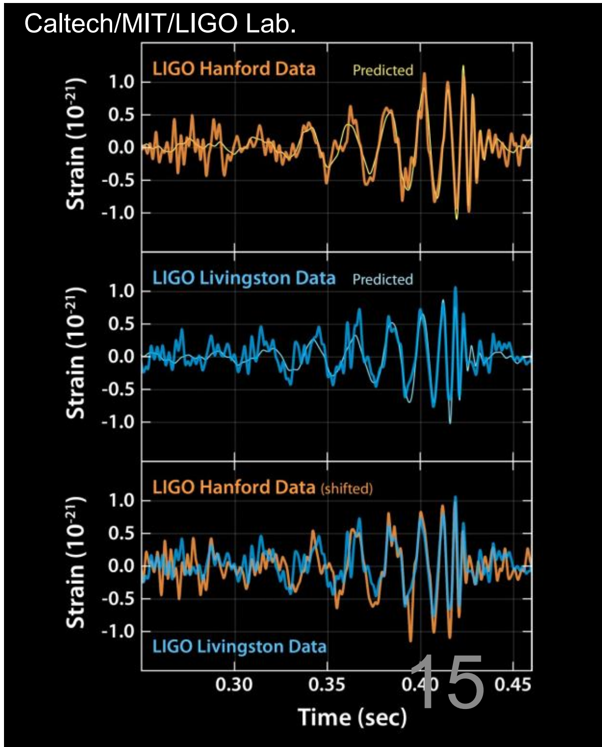
Ultralight Dark Matter

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

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

- Laser interferometers are sensitive to such oscillating changes (rather than "pulse" signals from particles)



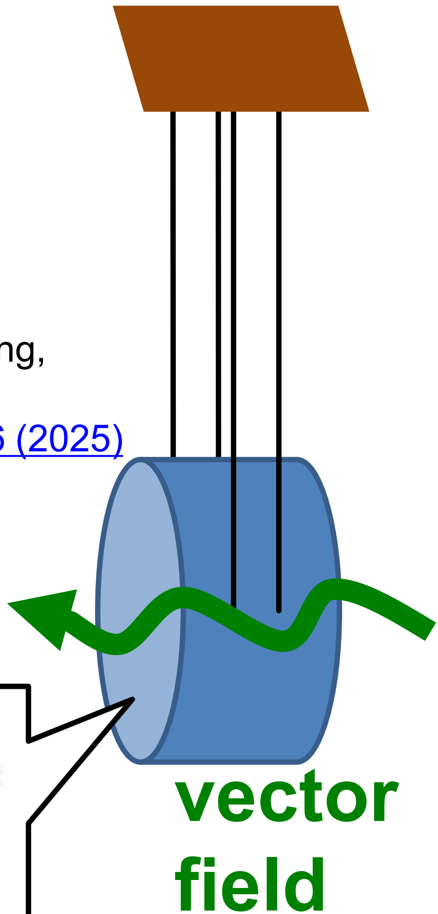


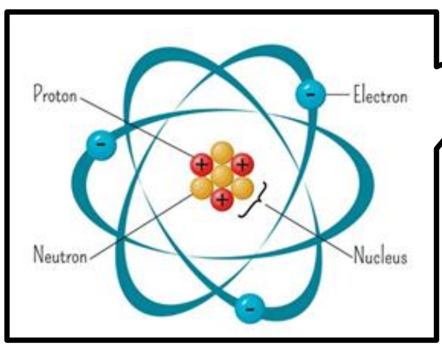
Gauge Boson Dark Matter

- Possible new physics beyond the standard model:
  New gauge symmetry and gauge boson
- New gauge boson can be dark matter
- B-L (baryon minus lepton number)
  - Conserved in the standard model
  - Motivations from neutrino mass, matter-antimatter asymmetry
  - Roughly 0.5 per neutron mass, but slightly different between materials
    Fused silica: 0.501
    Sapphire: 0.510

Y. Cheng, J. Sheng, T. T. Yanagida, [PLB 860, 139156 (2025)]

- Gauge boson DM gives oscillating force





Oscillating Force from Gauge Field

- Acceleration of mirrors

charge

gauge boson mass

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

polarization

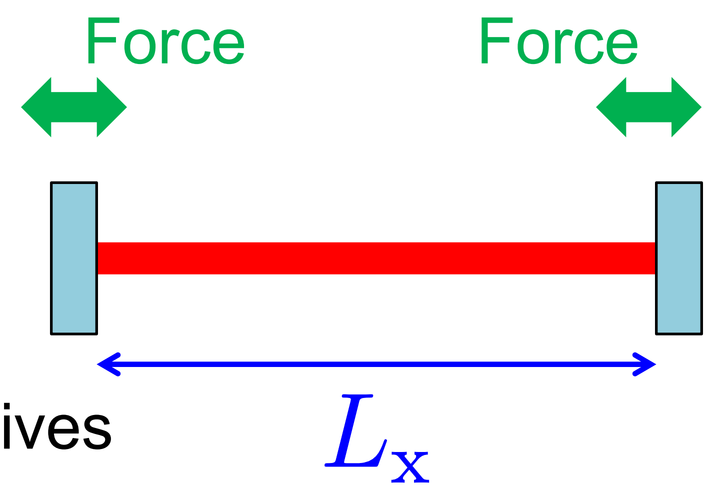
coupling (normalized by e)

mirror mass

DM density

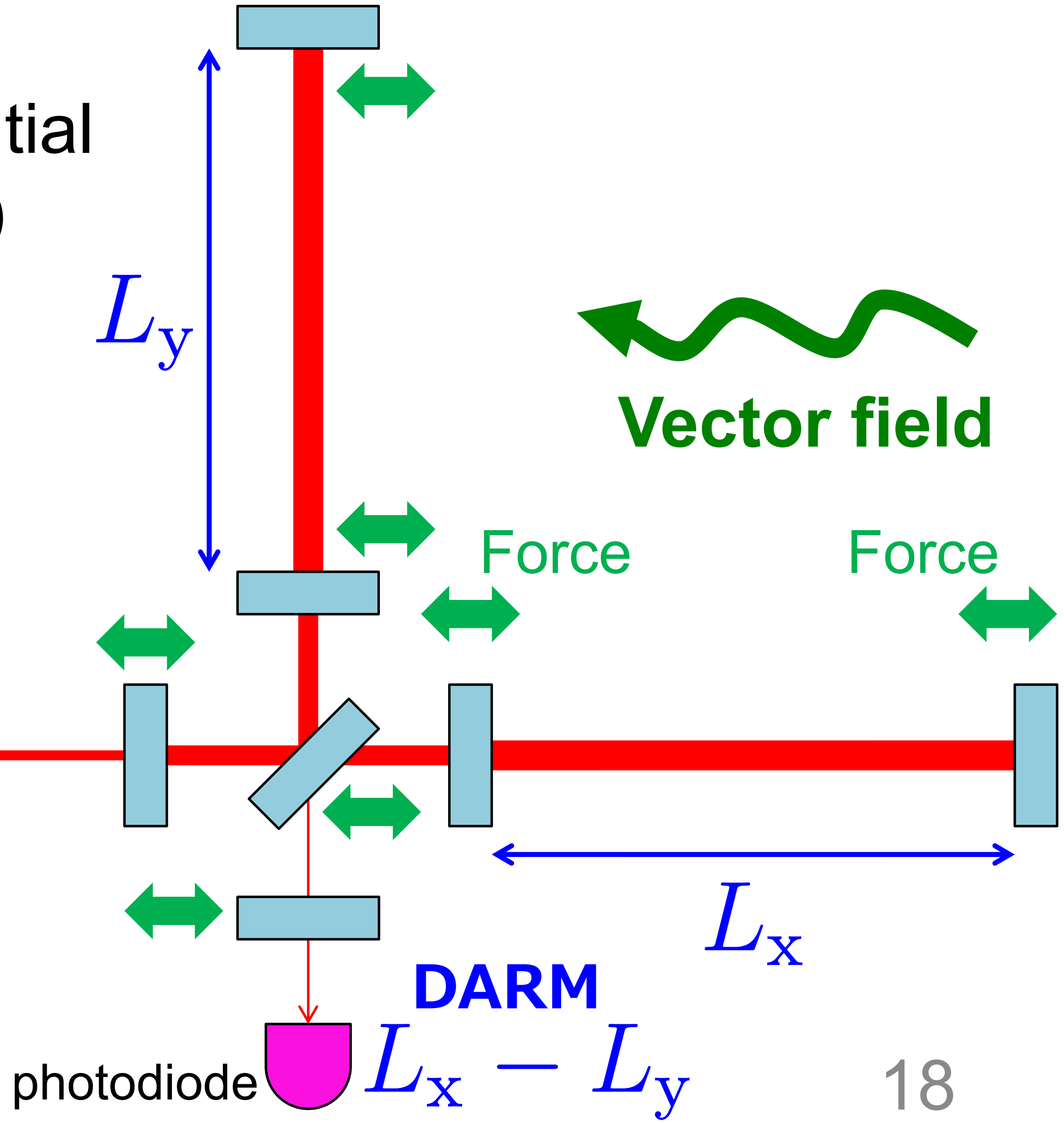
different phase at different position

- Gauge boson mass and coupling can be measured by measuring the oscillating mirror displacement
- Almost no signal for symmetric cavity, but finite light traveling time gives some signal
  (phase difference is 10^{-5} rad @ 100 Hz for km cavity)



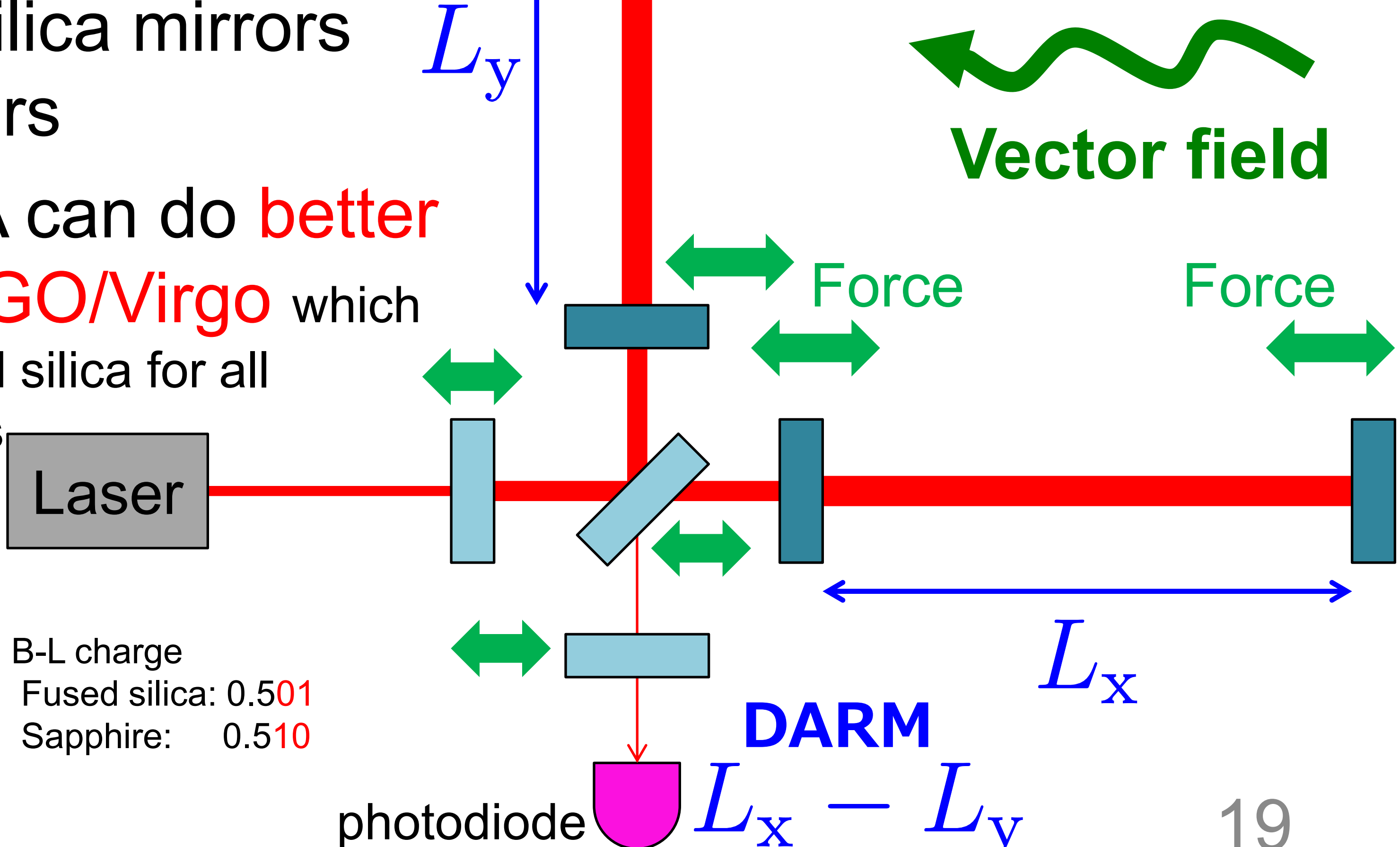
Search with GW Detectors

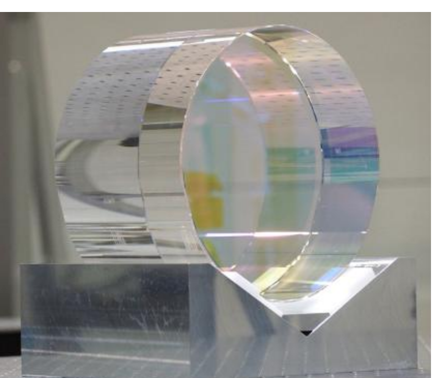
- GW Detectors are sensitive to differential arm length (DARM) change
- Most of the signal is cancelled out (LIGO/Virgo case)



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

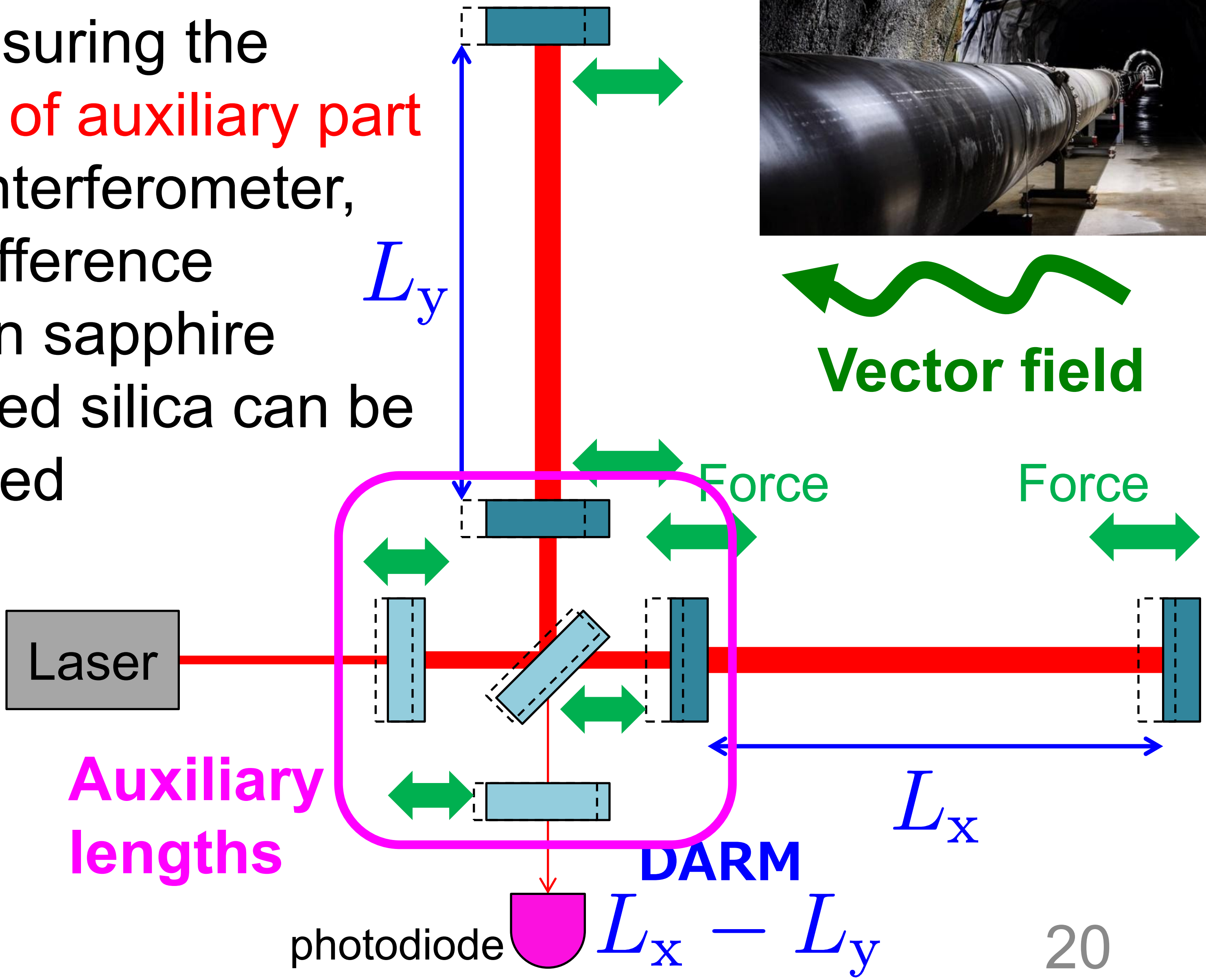


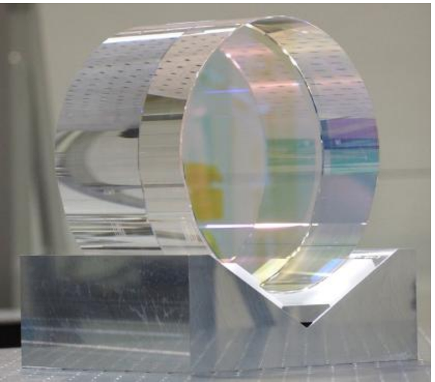


B-L charge
Fused silica: 0.501
Sapphire: 0.510

Search with KAGRA

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

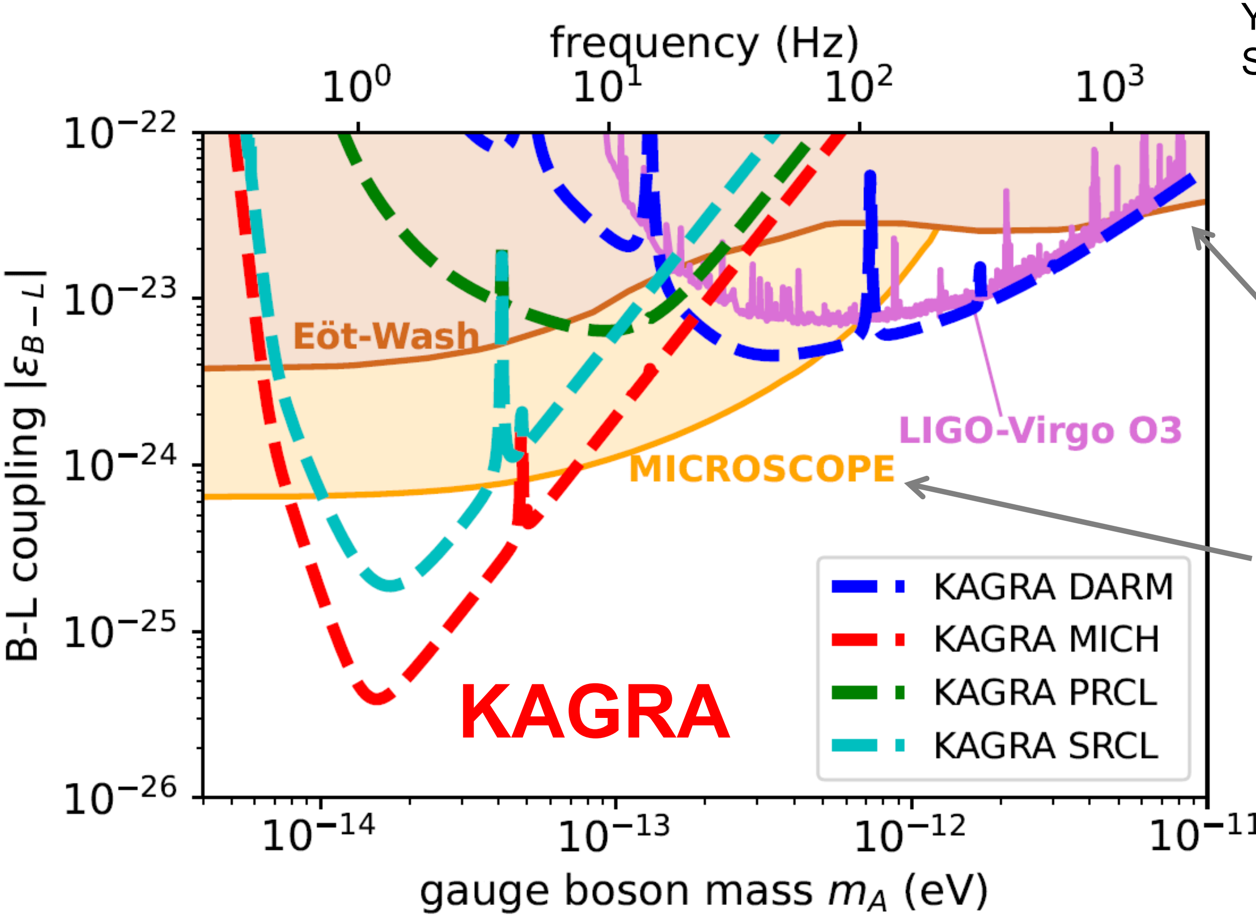




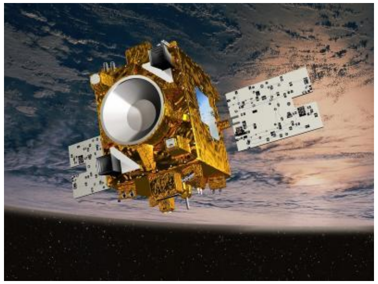
Sensitivity to Gauge Boson DM

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

YM+, [PRD **102**, 102001 (2020)]
S. Morisaki+, [PRD **103**, L051702 (2021)]

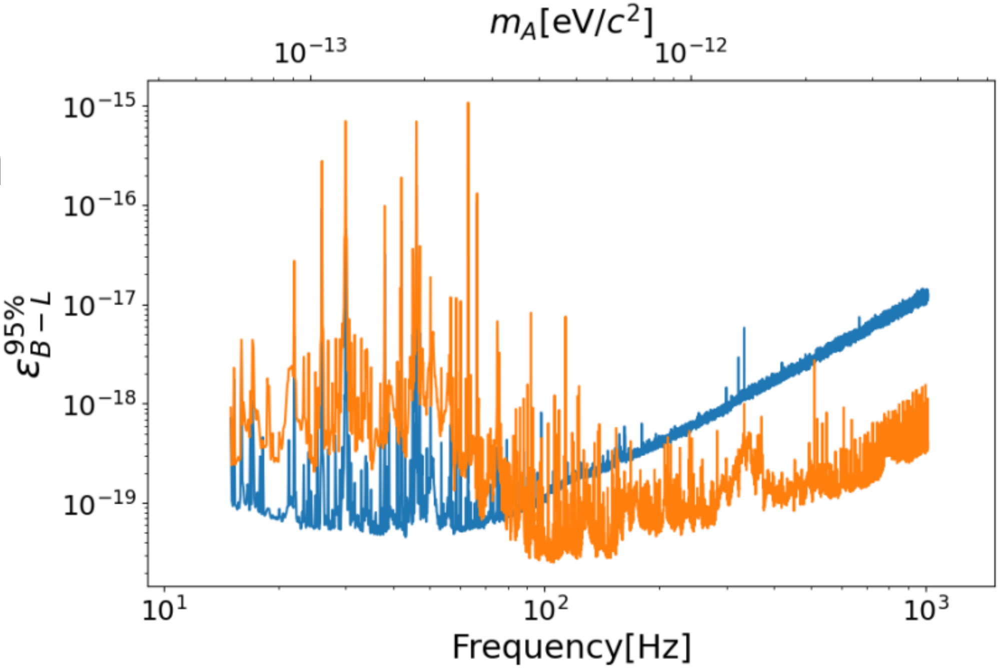


Eöt-Wash
torsion pendulum



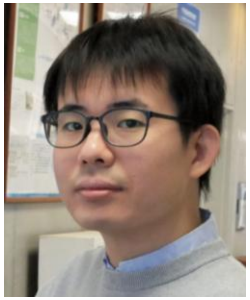
First Results from KAGRA

- Using data from KAGRA O3GK run in 2020
- Still ~5 orders of magnitude worse than equivalence principle tests



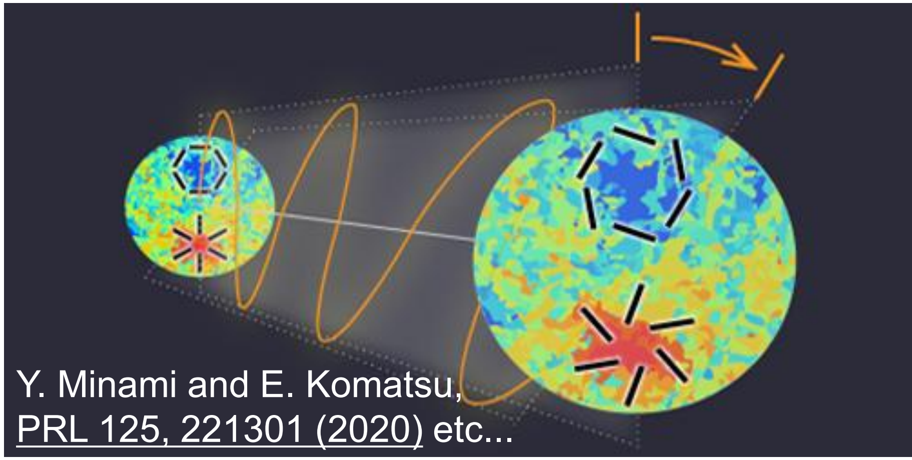
- Demonstrated the feasibility of using auxiliary channels for astrophysics
- Search with latest observing run (O4c) on going

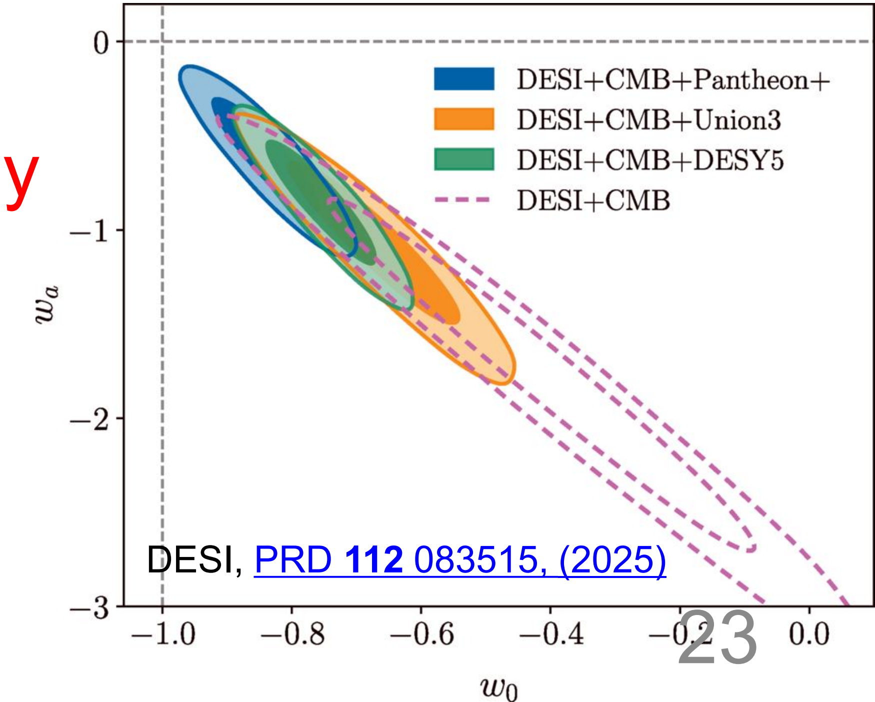
LIGO-Virgo-KAGRA, PRD **110**, 042001 (2024)
(Paper written by J. Kume with 1800 authors!)



Axion (ALP) Dark Matter

- Various axion-like particles predicted by string theory and supergravity
- Possible explanation to recent measurements of cosmic birefringence and dynamical dark energy
- Many experiments to search for ALPs through axion-photon coupling, using magnetic fields


Y. Minami and E. Komatsu, PRL 125, 221301 (2020) etc...



DESI, PRD **112** 083515, (2025)

Polarization Modulation from Axions

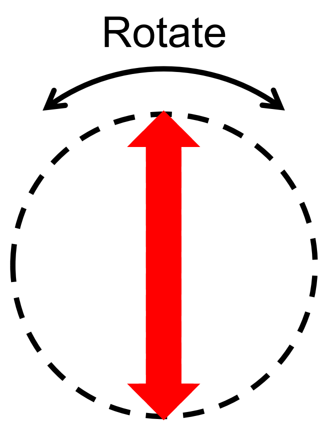
- Axion-photon coupling ($\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$) gives different phase velocity between left-handed and right-handed circular polarizations

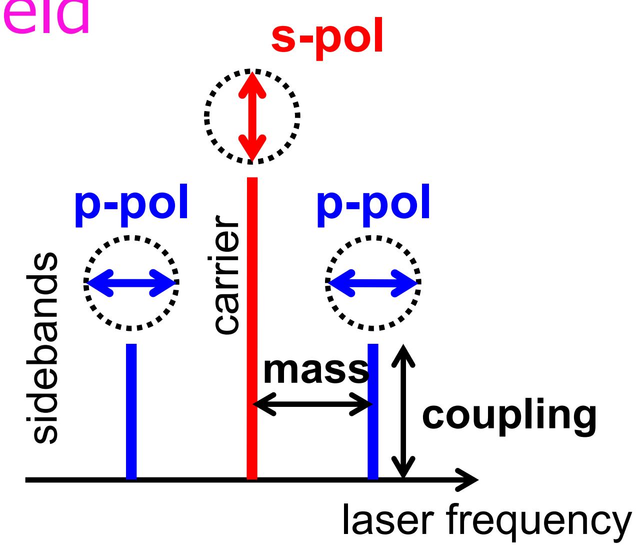
$$c_{\mathrm{L/R}} = \sqrt{1 \pm \frac{g_{a\gamma} a_0 m_a}{k} \sin(m_a t + \delta_\tau)}$$

axion mass

coupling constant axion field

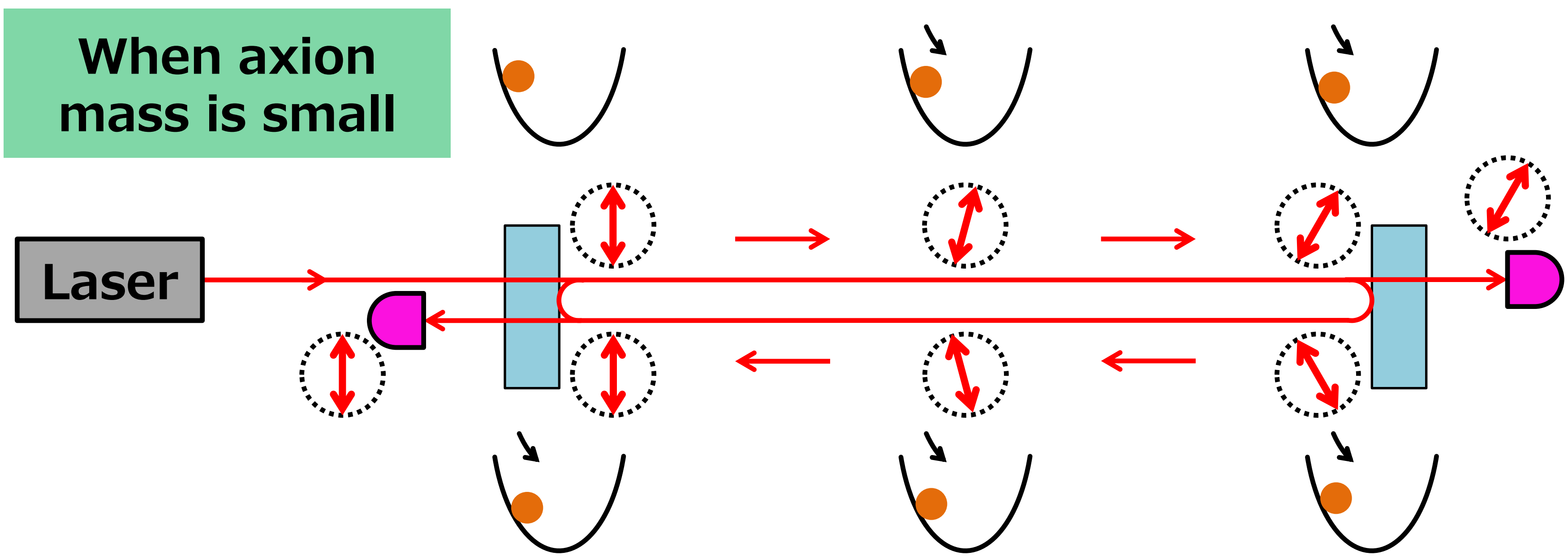
- Linear polarization will be modulated
  - p-pol sidebands will be generated from s-pol
- Search can be done without magnetic field





Linear Cavities for Axion Search

- Polarization flip at mirror reflection can be used to enhance the signal when the round-trip time equals odd-multiples of axion oscillation period
- Long baseline linear cavities in gravitational wave detectors are suitable



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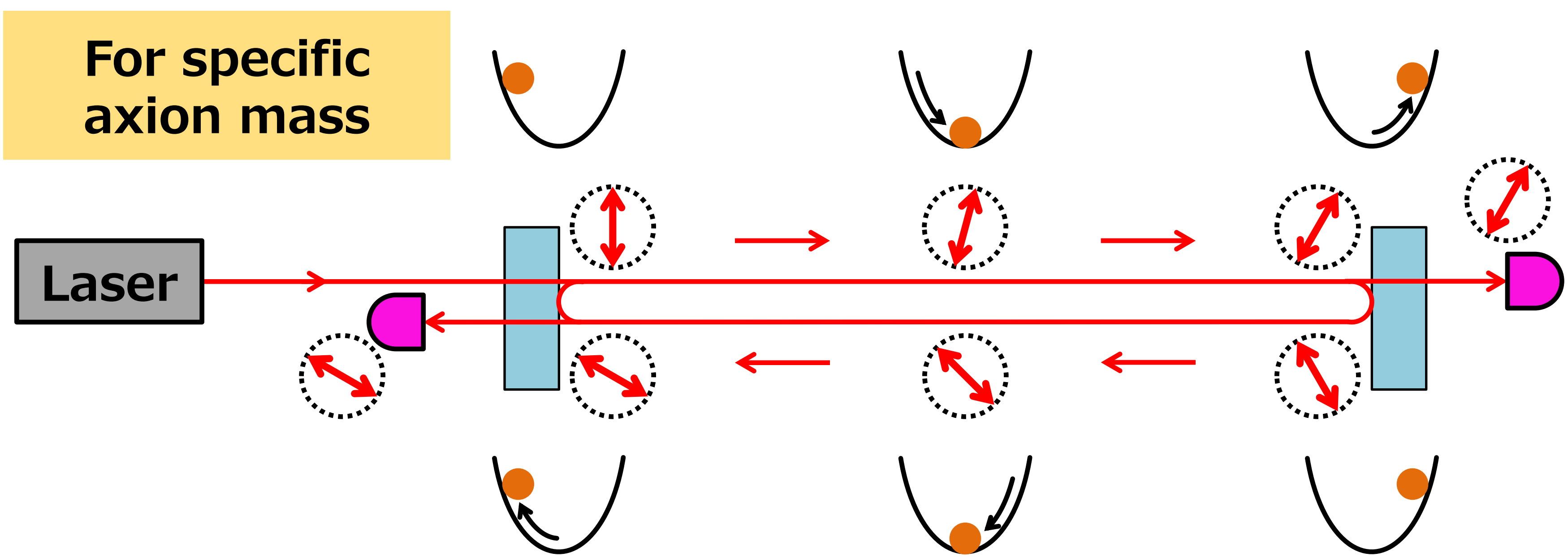
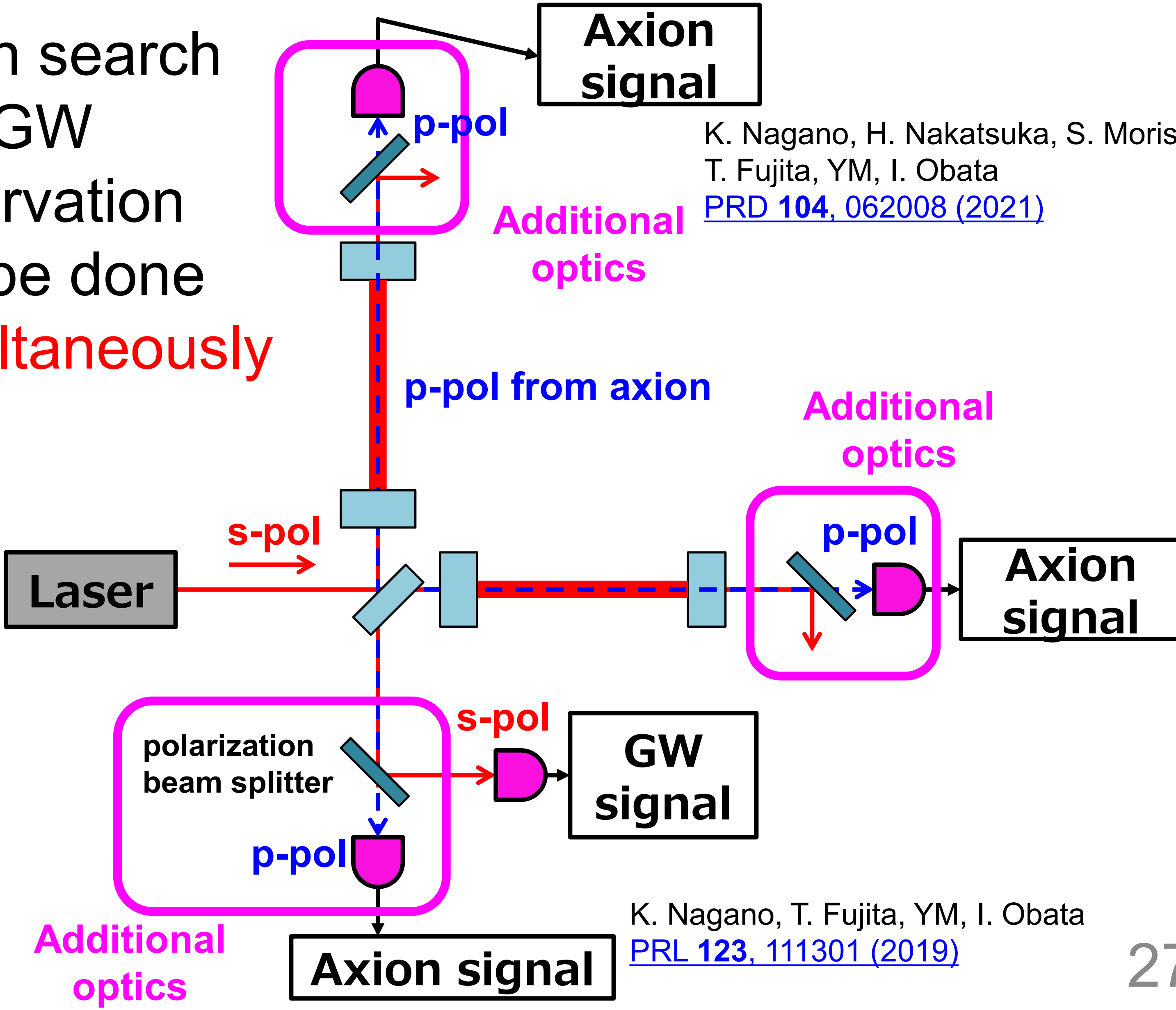


Axion Search with GW Detectors

- Axion search and GW observation can be done simultaneously

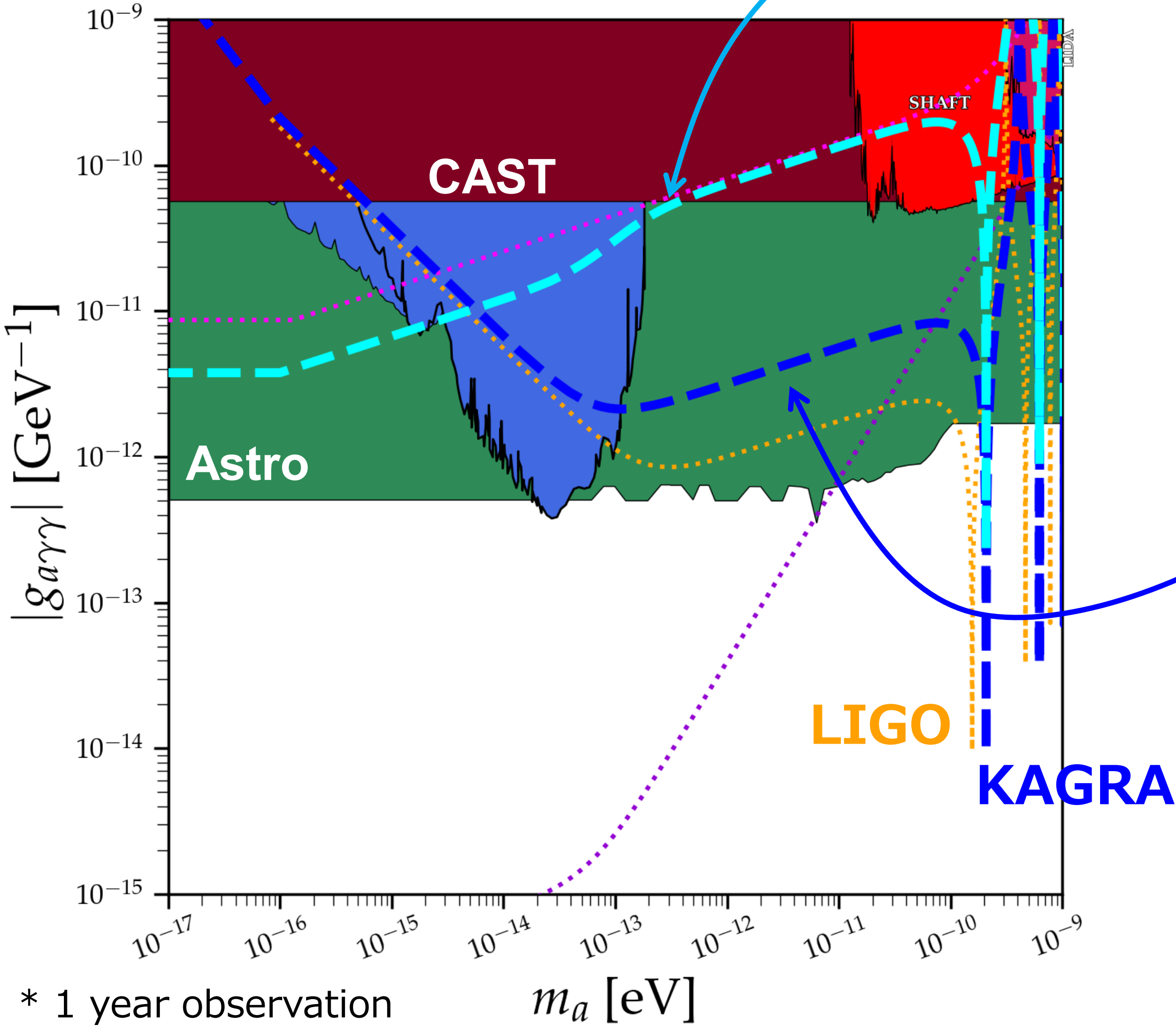


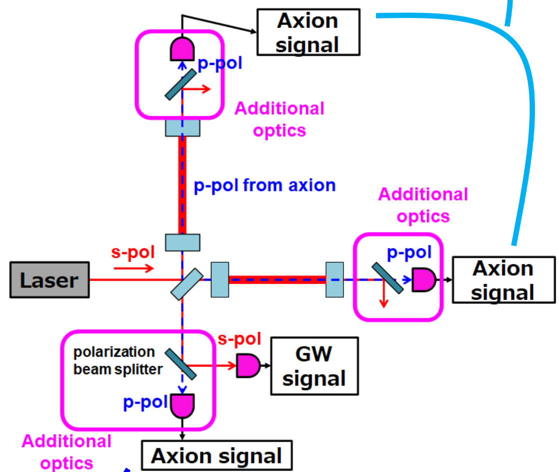
K. Nagano, H. Nakatsuka, S. Morisaki, T. Fujita, YM, I. Obata
PRD **104**, 062008 (2021)

K. Nagano, T. Fujita, YM, I. Obata
PRL **123**, 111301 (2019)

Axion Sensitivity

Arm cavity transmission ports





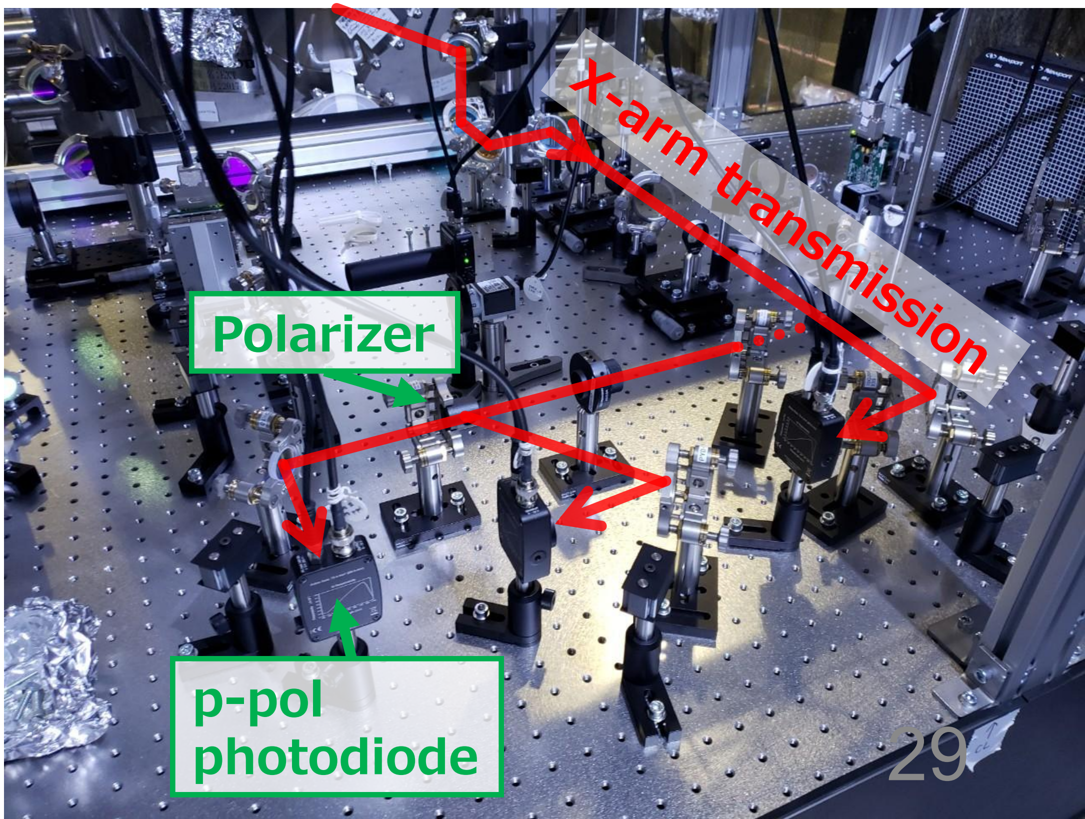
GW detection port

Complemental search using different ports

* 1 year observation

Axion Search with KAGRA Started

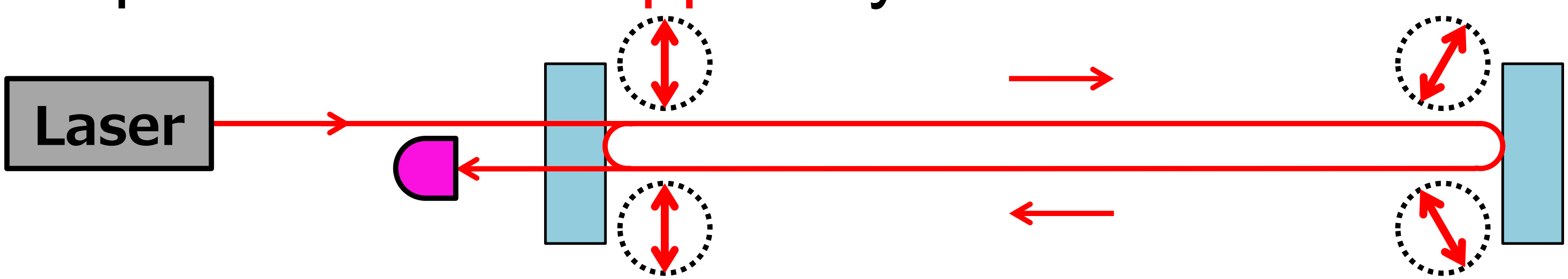
- Polarization optics were installed at transmission ports of KAGRA in 2021
- First simultaneous observation of gravitational waves and axions during O4 (June-August 2025)
- Results released next year
- KAGRA is now the only detector which can also search for axions



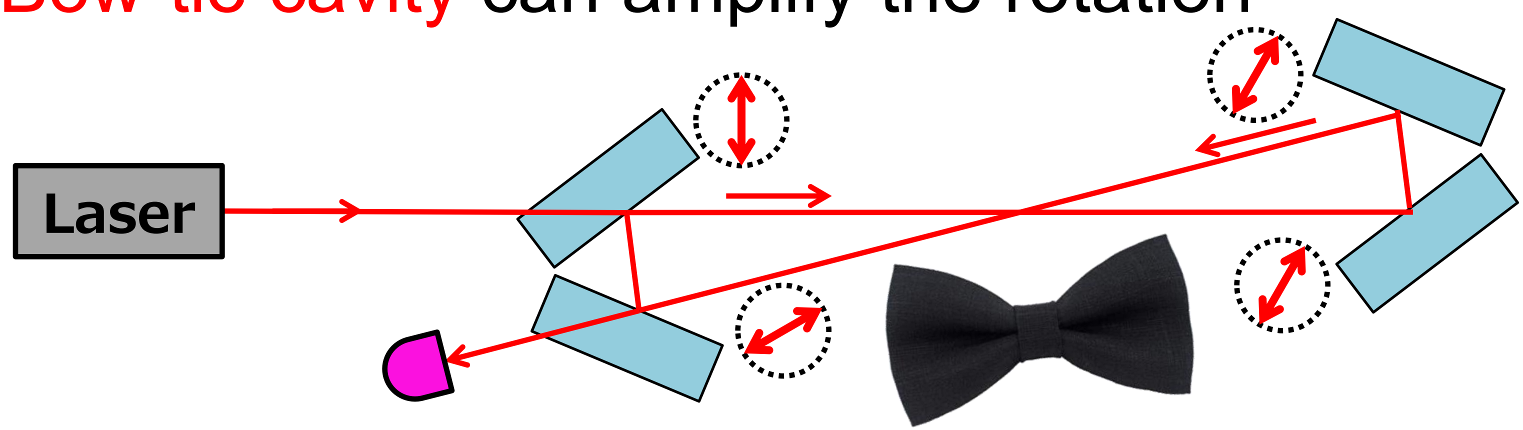
Bow-tie Cavity for Broadband

- Polarization rotation is small for short optical path

- Optical cavities can increase the optical path, but the polarization is flipped by mirror reflections



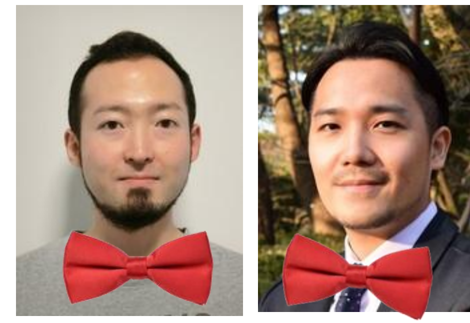
- Bow-tie cavity can amplify the rotation



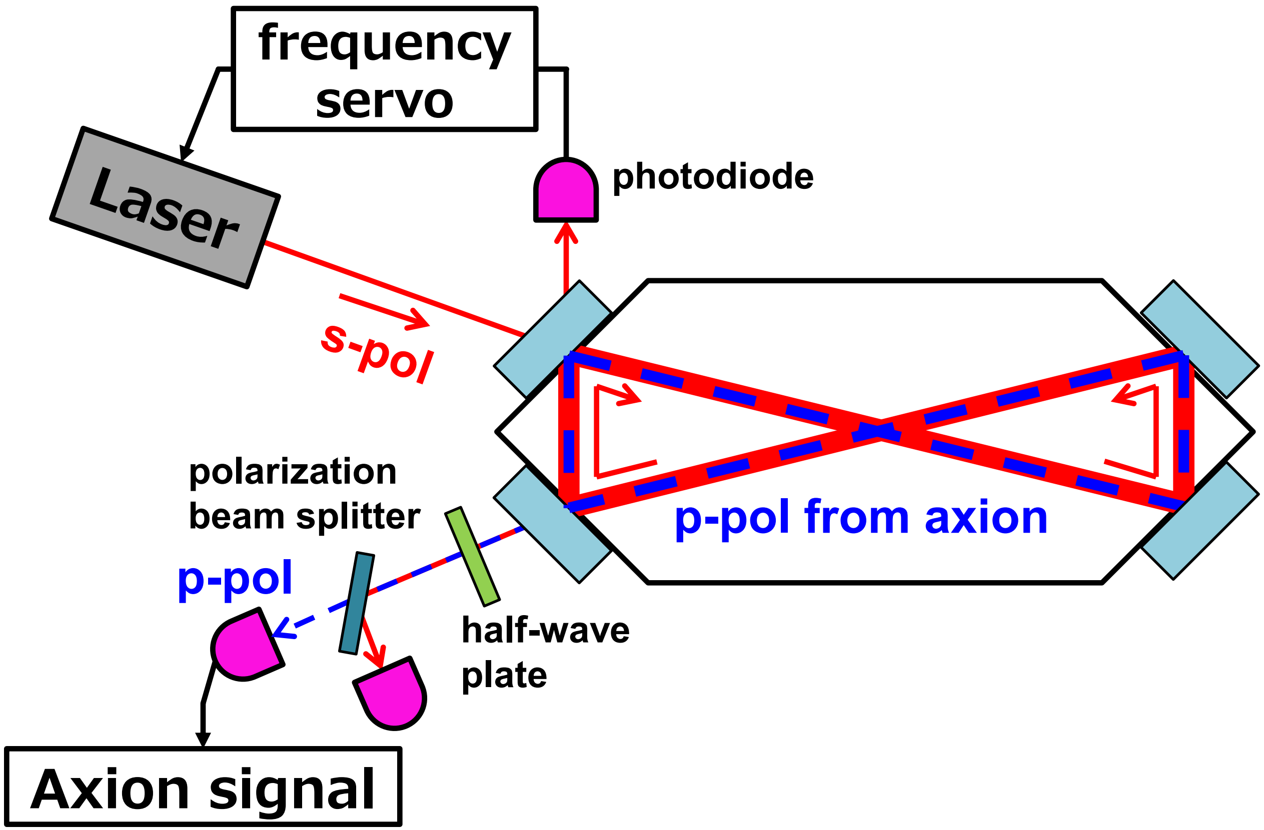
DANCE Setup

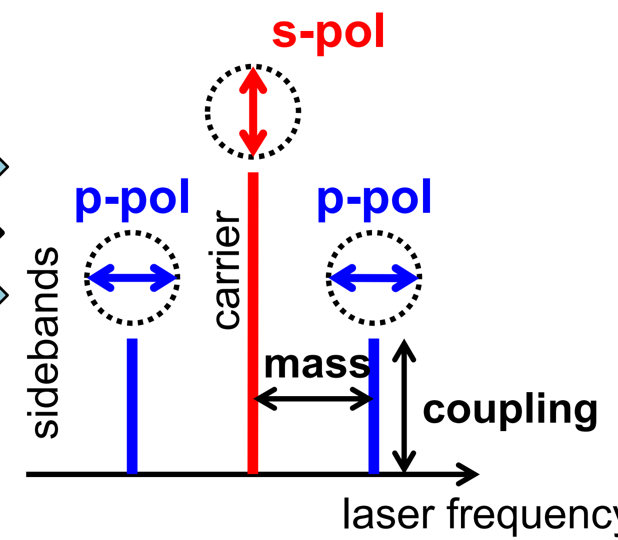
Dark matter Axion search with riNg Cavity Experiment

- Look for amount of modulated p-pol generation in each frequency



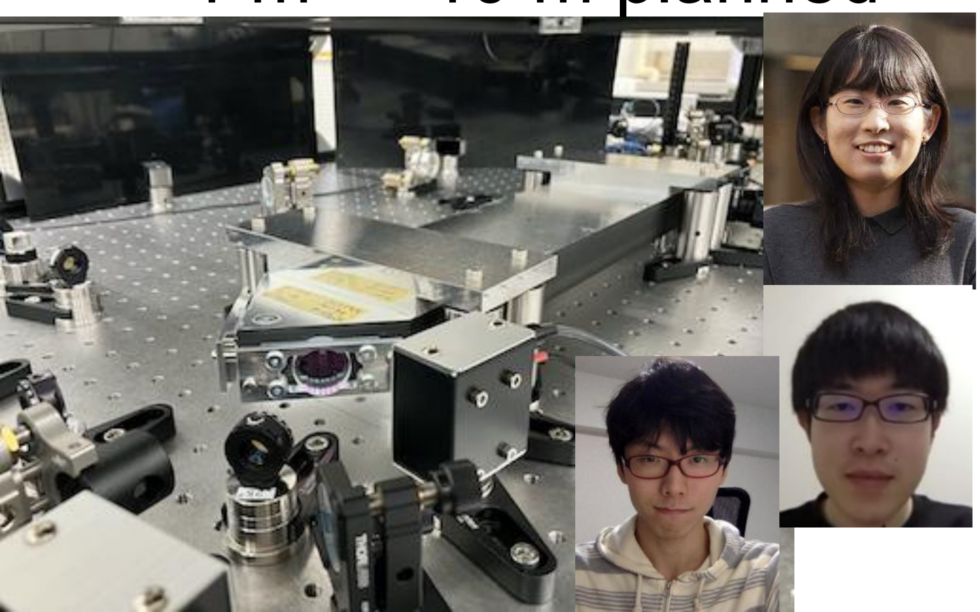
I. Obata, T. Fujita, YM,
[PRL **121**, 161301 (2018)]

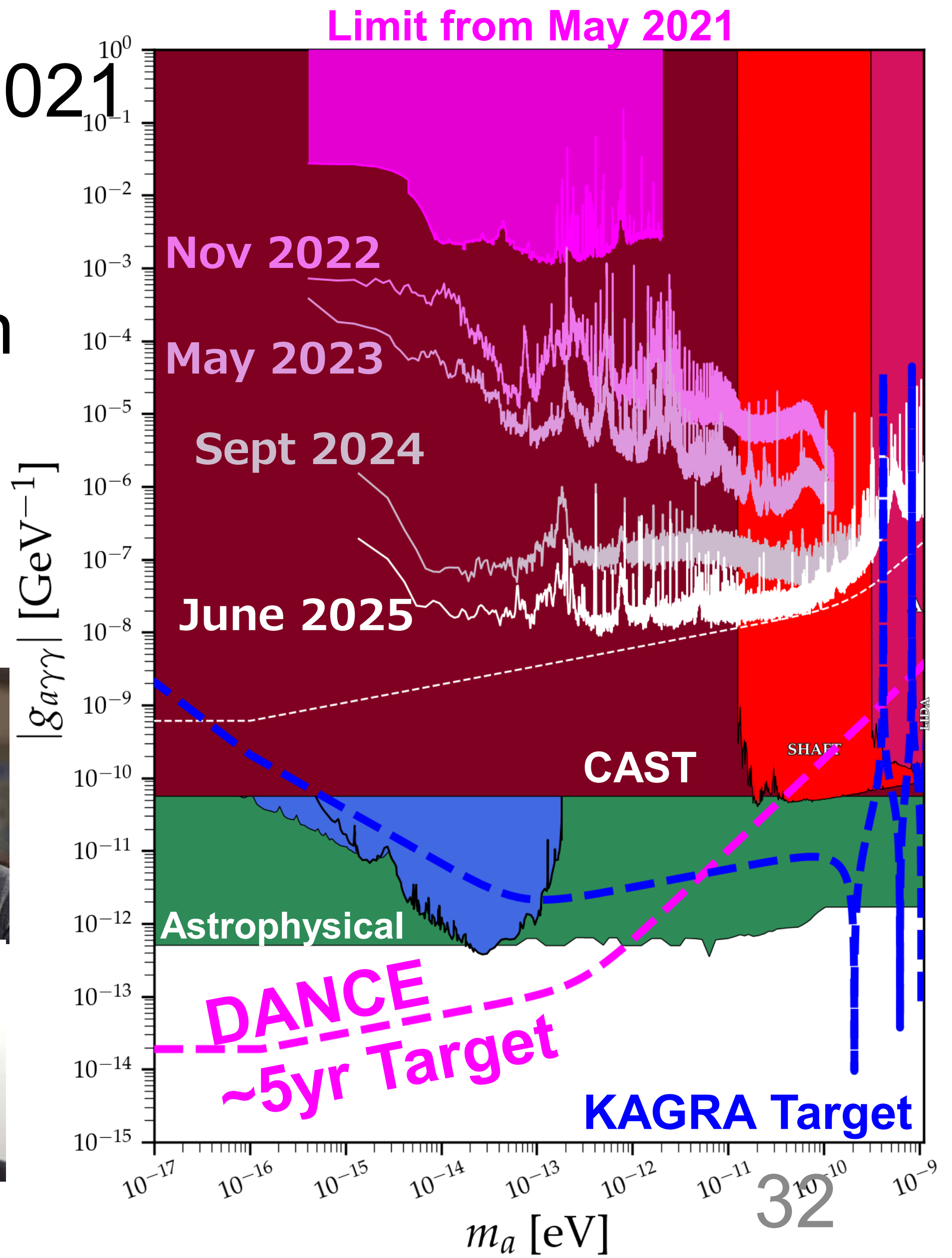




DANCE

- First demonstration in 2021
  Y. Oshima+, PRD **108**, 072005 (2023)
- ~5 orders of magnitude improvement since then
  H. Takidera+, PRD **112**, 063048 (2025)
  H. Fujimoto, PhD thesis (UTokyo 2025)
- 6 mW → 1 W,
  1 m → 10 m planned

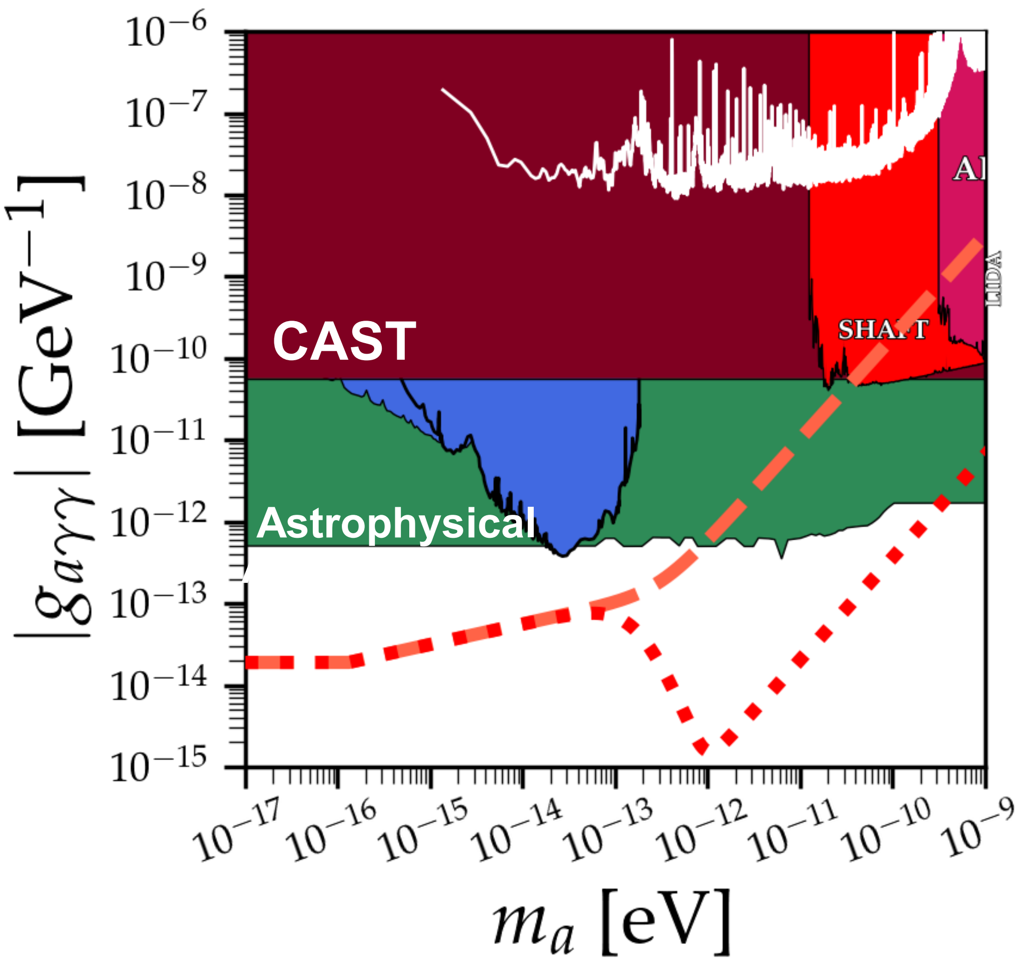




Photon Counting for DANCE

- Sensitivity ultimately limited by quantum shot noise
- This can be avoided with single photon detection

H. Ysu+, PRD **109**, 095042 (2024)



Example sensitivity improvement

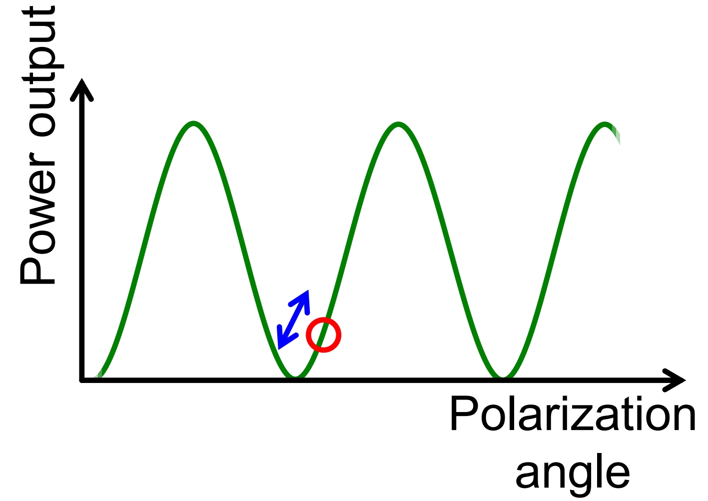
Dark count rate: 10^{-6} Hz

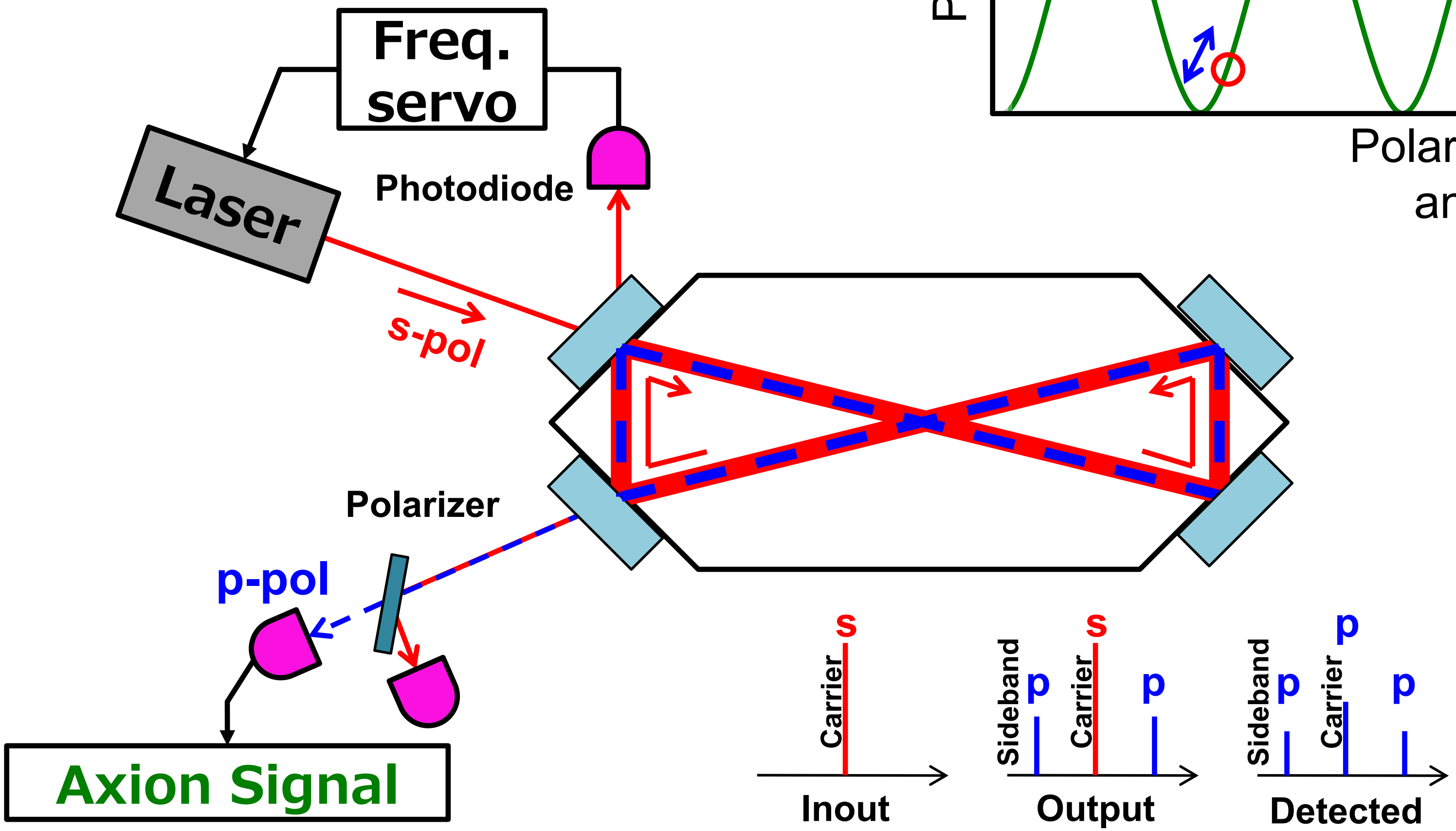
Bandwidth: 1 Hz

Caveat: Envelope of narrowband search is shown

DANCE Setup Now

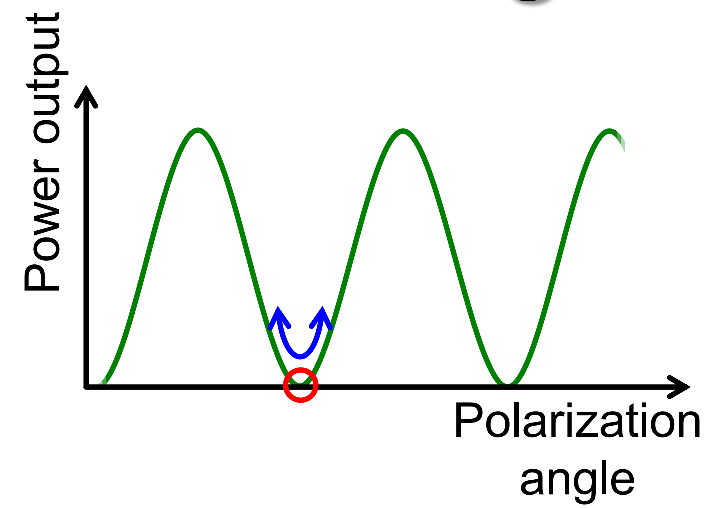
- P-pol power change monitored with a photodiode

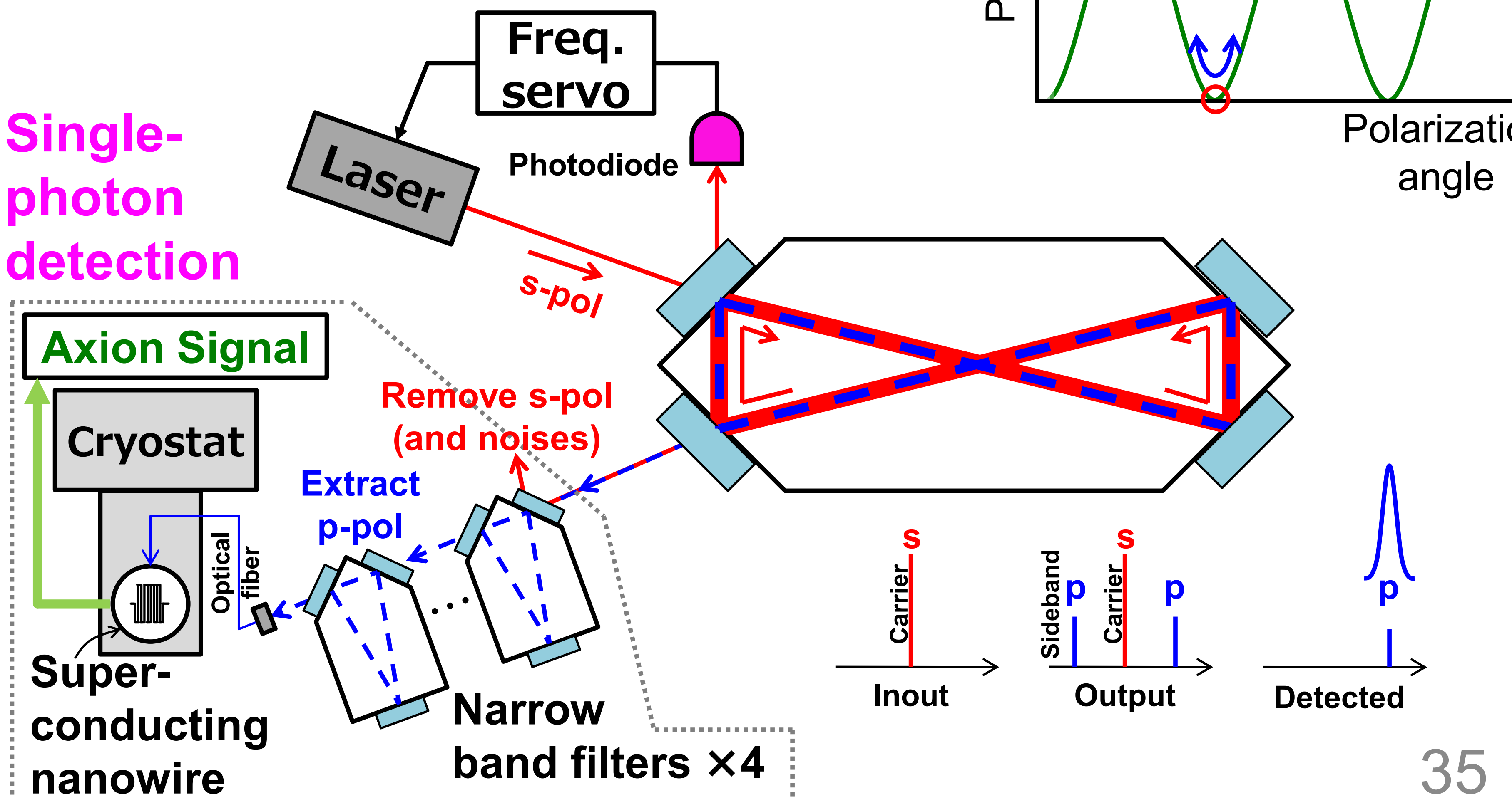




DANCE with Photon Counting

- Signal photon detected with a single-photon detector





Summary

- O4 finished with significant results (… and more to come!)
- LIGO, Virgo, KAGRA planning further upgrades to aid multi-messenger astronomy
- KAGRA can also do unique beyond standard model particle searches (axions, gauge bosons)
- First simultaneous observation of GWs and axions done with KAGRA this year
- Broadband axion search with DANCE ongoing
- Quantum sensing techniques can be applied to DANCE (photon counting)

ダークマターの正体は何か？
広大なディスカバリースペースの網羅的研究
文部科学省 科学研究費助成事業 学術変革領域研究 (2020–2024)
What is dark matter? - Comprehensive study of the huge discovery space in dark matter

公益財団法人 三菱財団
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