Lab Midterm Seminar

May 16, 2025

Creation 2025

Yuta Michimura

RESCEU, University of Tokyo

Kavli IPMU, WPI, UTIAS, University of Tokyo

Background image from 2023 P5 Report

Contents

- Reflections on 2024
- Plans for 2025
- KAG-Λ
- Breaking news
  - More on cosmic birefringence
  - Evolving dark energy
  - Supernova relic neutrino
  - CP violation in neutrino
  - Levitated mechanics in space

How's RESCEU?

- Paradise

Review of My Plans for 2024

My Plans for 2024

- Achieve 10 Mpc sensitivity with KAGRA — Round up!

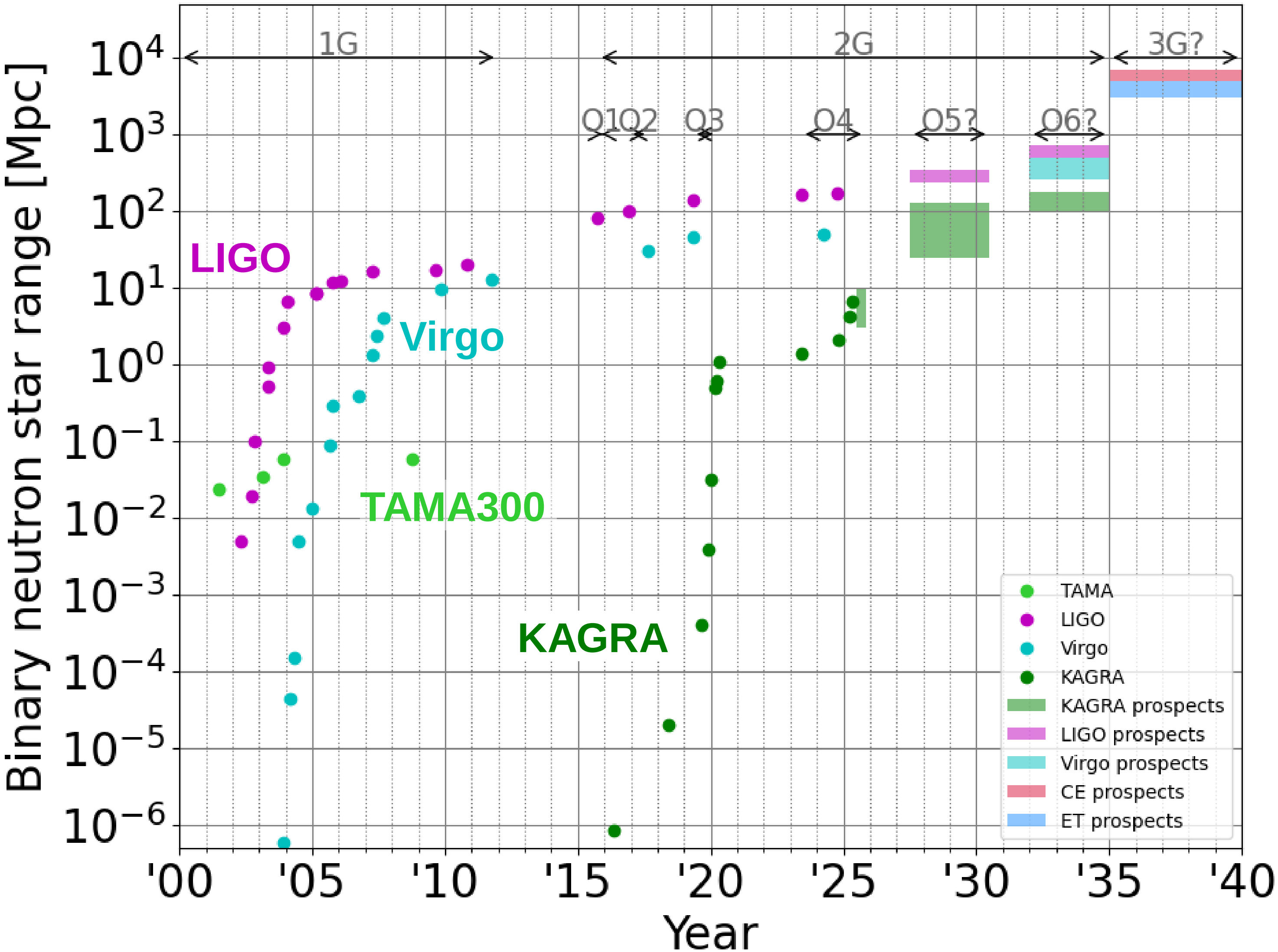
  Let's visit Kamioka together!
- Re-organize KAGRA future discussions — White paper 2024 released
- In-vac PD and QPD for KAGRA — PD ordered, QPD next
- Possibly following or at least think about them
  - Silicon birefringence fluctuation measurements — With Cardiff
  - Characterization of optical levitation mirrors (in collaboration with ANU) — M. Honjo?
  - Quantum nature of gravity experiments — M. Honjo?
  - Search for various signals in LIGO HF data at FSRs — Results presented at LVK
  - Axion optomechanics, long SRC, GW tests of GR … — Still thinking…

Volunteers welcomed!

18

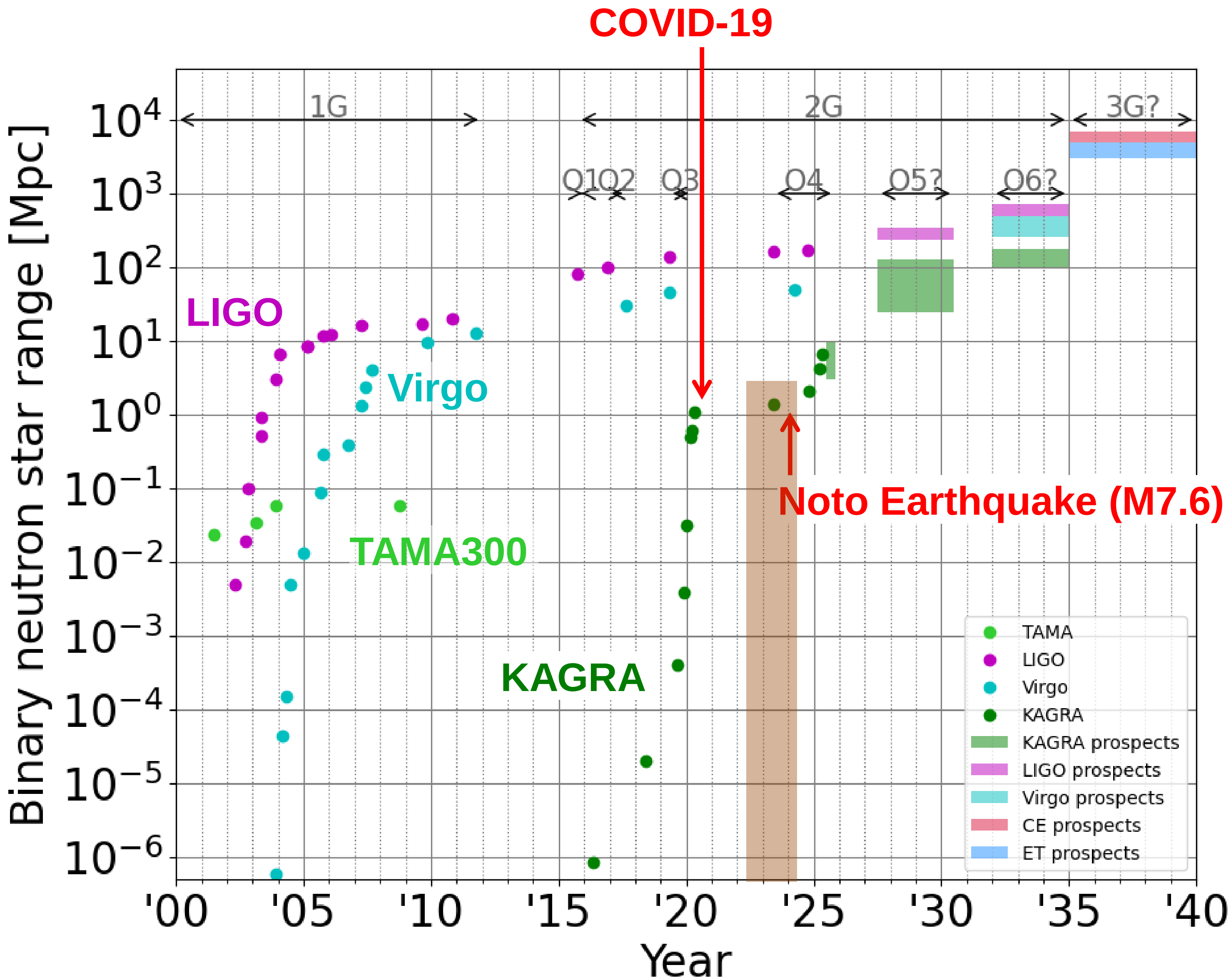
Uncalibrated Unofficial Preliminary Work-in-Progress

Sensitivity History



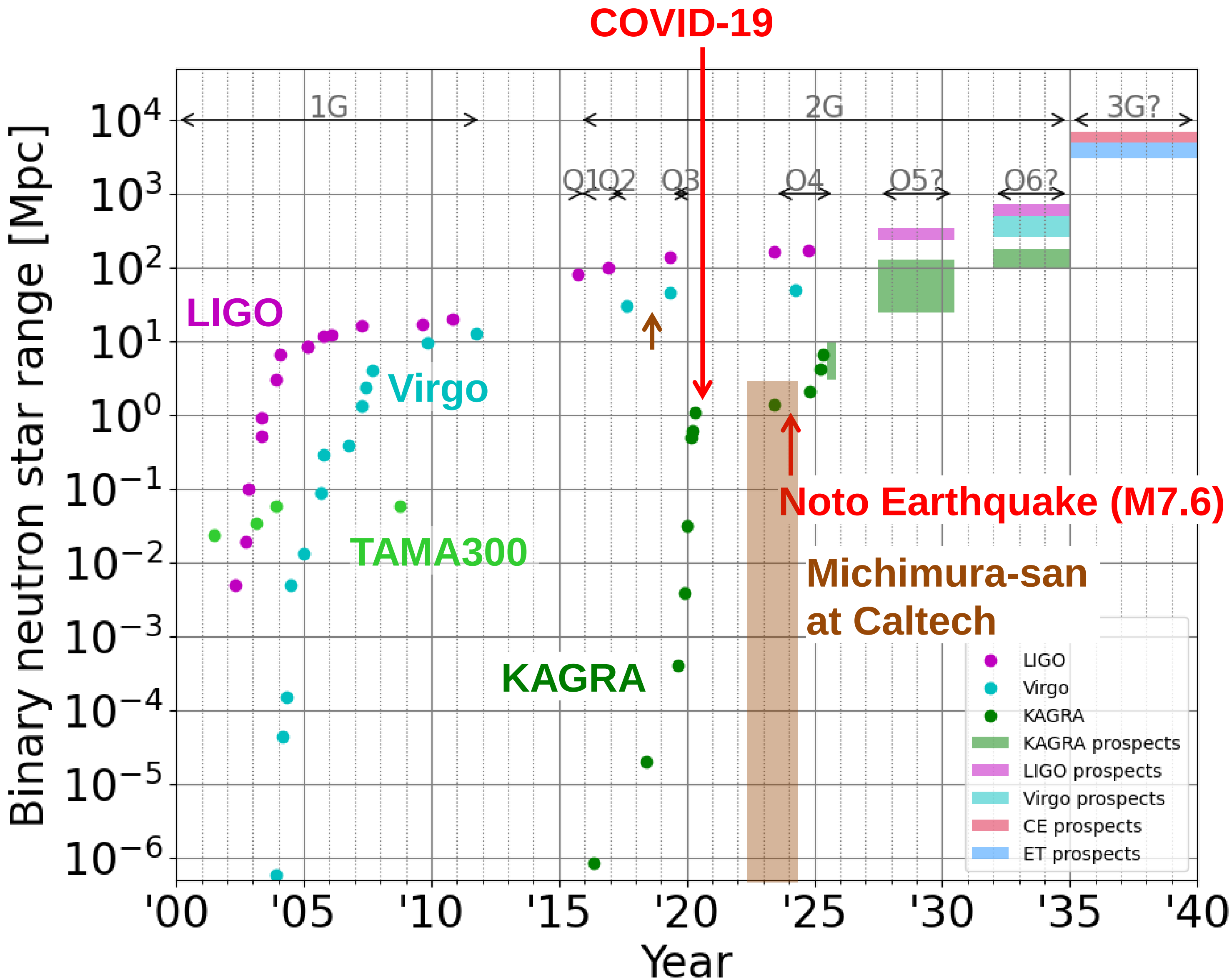
Uncalibrated Unofficial Preliminary Work-in-Progress

Sensitivity History

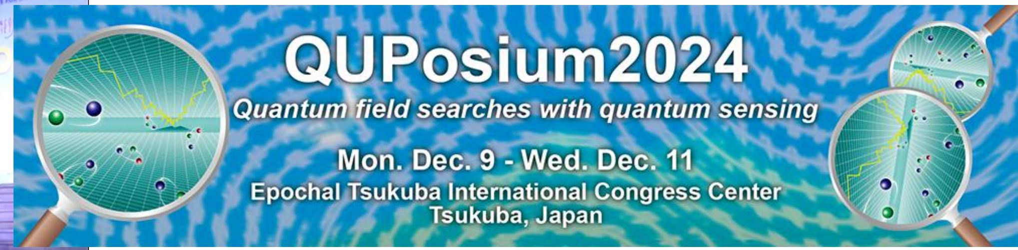


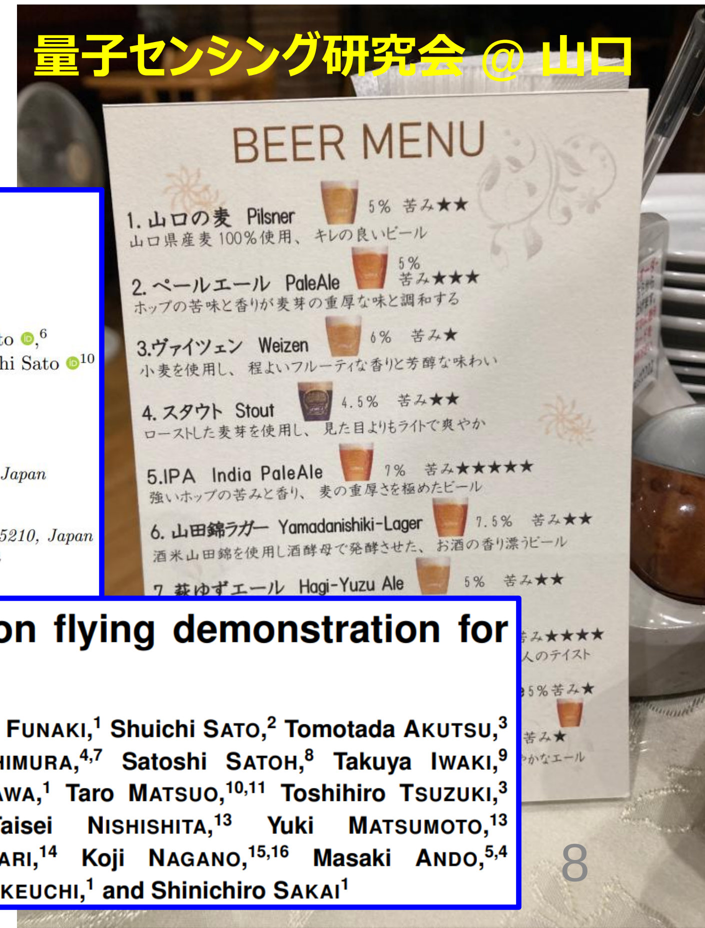
Uncalibrated Unofficial Preliminary Work-in-Progress

Sensitivity History



Other Things in 2024





RESCEU-3/25

Initial acquisition requirements for optical cavities in the space gravitational wave antennae DECIGO and B-DECIGO

Yuta Michimura[1,2,*] Koji Nagano[3,4,†] Kentaro Komori[1,5] Kiwamu Izumi[6] Takahiro Ito[6] Satoshi Ikari[7] Tomotada Akutsu[8] Masaki Ando[5,1] Isao Kawano,[6] Mitsuru Musha[9] and Shuichi Sato[10]

[1] *Research Center for the Early Universe (RESCEU), Graduate School of Science, University of Tokyo, Bunkyo, Tokyo 113-0033, Japan*
[2] *Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU), WPI, UTIAS, University of Tokyo, Kashiwa, Chiba 277-8568, Japan*
[3] *Institute for Multidisciplinary Sciences, Yokohama National University, Yokohama, Kanagawa 240-8501, Japan*
[4] *LQUOM, Inc., Yokohama, Kanagawa 240-8501, Japan*
[5] *Department of Physics, The University of Tokyo, Bunkyo, Tokyo 113-0033, Japan*
...l Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa 252-5210, Japan
...tics and Astronautics, University of Tokyo, Bunkyo, Tokyo 113-8656, Japan
...ronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan

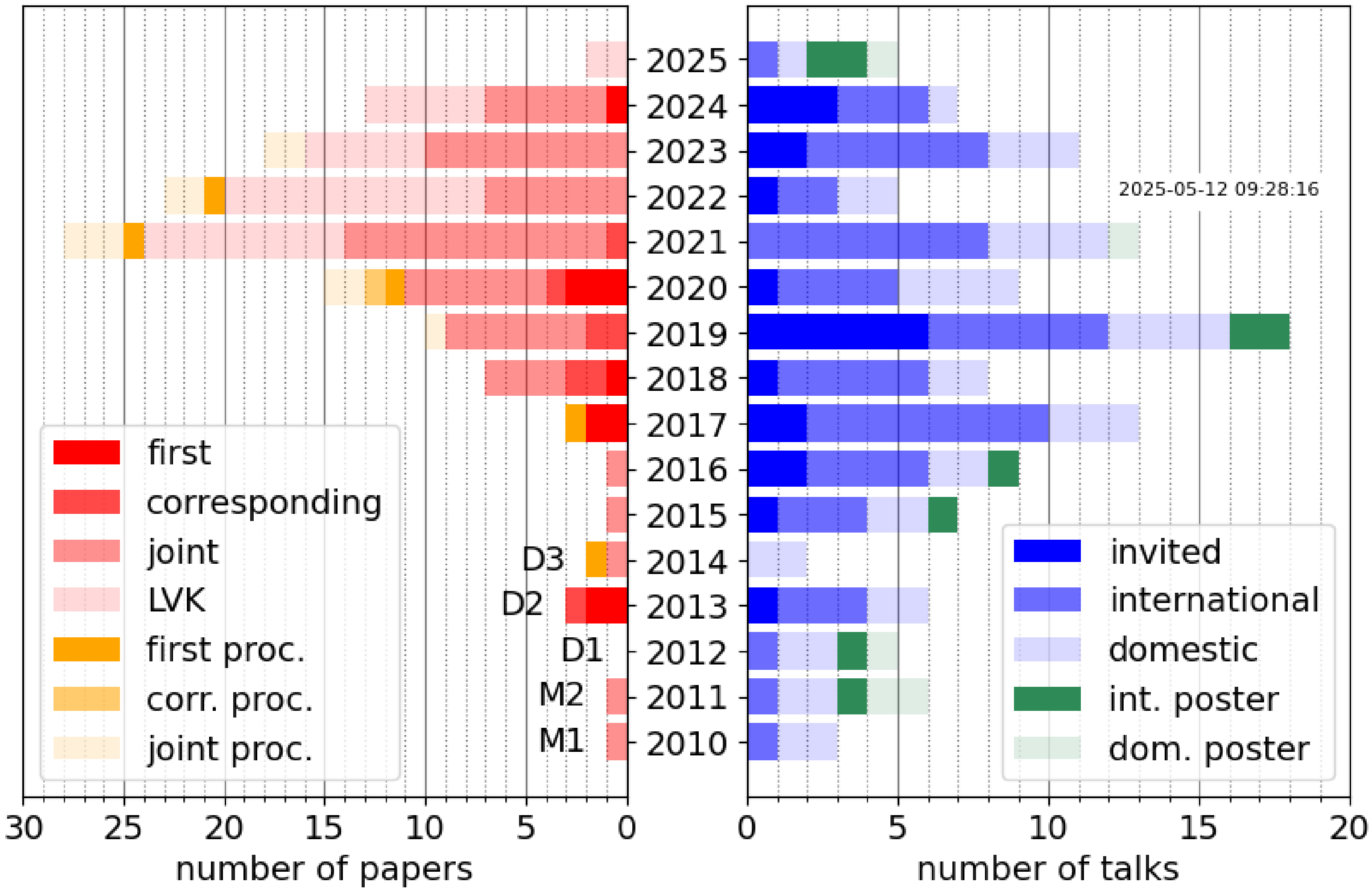
SILVIA: Ultra-precision formation flying demonstration for space-based interferometry

Takahiro Ito,[1] Kiwamu Izumi,[1] Isao Kawano,[1] Ikkoh Funaki,[1] Shuichi Sato,[2] Tomotada Akutsu,[3] Kentaro Komori,[4,5] Mitsuru Musha,[6] Yuta Michimura,[4,7] Satoshi Satoh,[8] Takuya Iwaki,[9] Kentaro Yokota,[9] Kenta Goto,[9] Katsumi Furukawa,[1] Taro Matsuo,[10,11] Toshihiro Tsuzuki,[3] Katsuhiko Yamada,[12] Takahiro Sasaki,[13] Taisei Nishishita,[13] Yuki Matsumoto,[13] Chikako Hirose,[13] Wataru Torii,[1] Satoshi Ikari,[14] Koji Nagano,[15,16] Masaki Ando,[5,4] Seiji Kawamura,[11] Hidehiro Kaneda,[11] Shinsuke Takeuchi,[1] and Shinichiro Sakai[1]

Every talk is a job talk

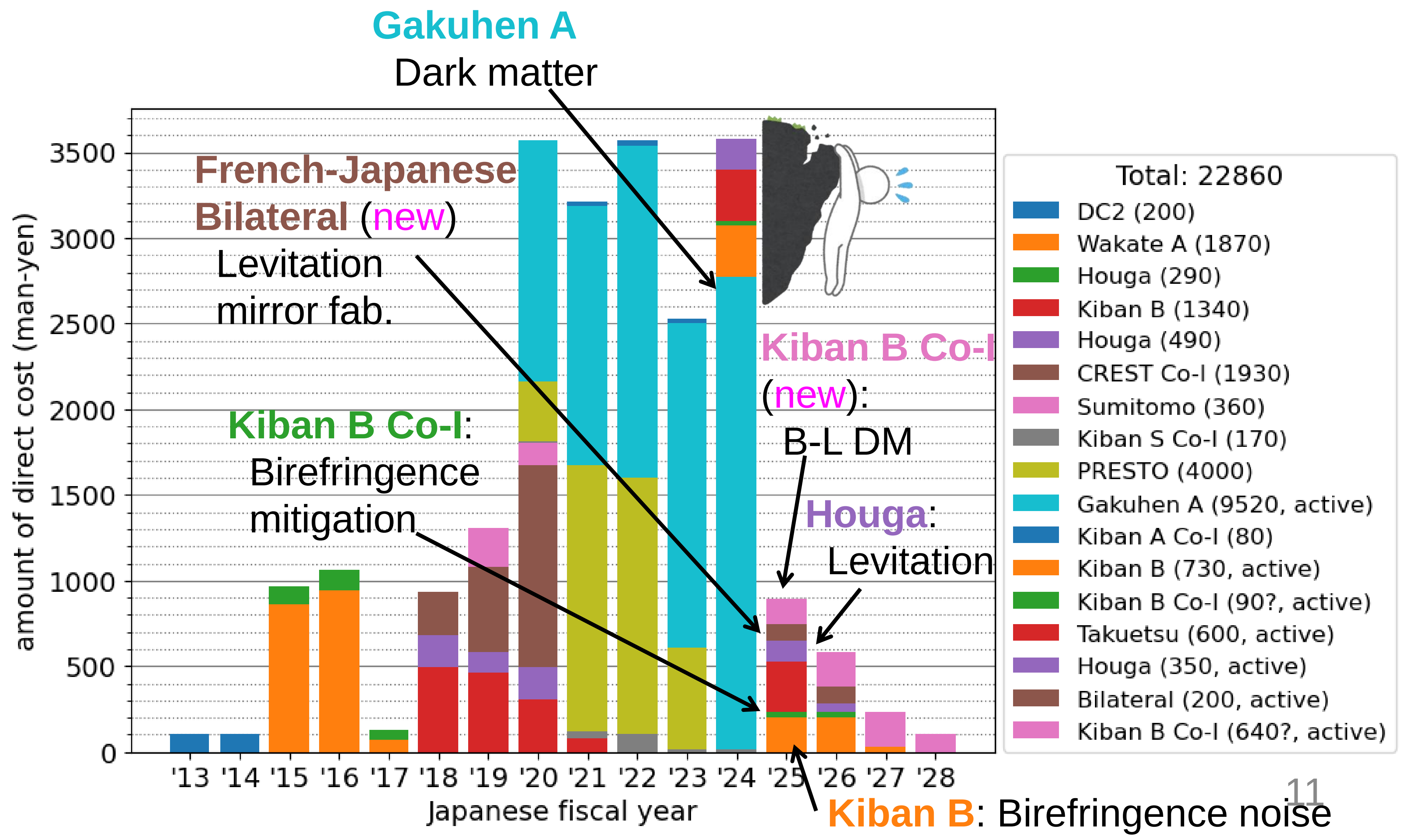
Productivity

- I need to increase the productivity (as always!)



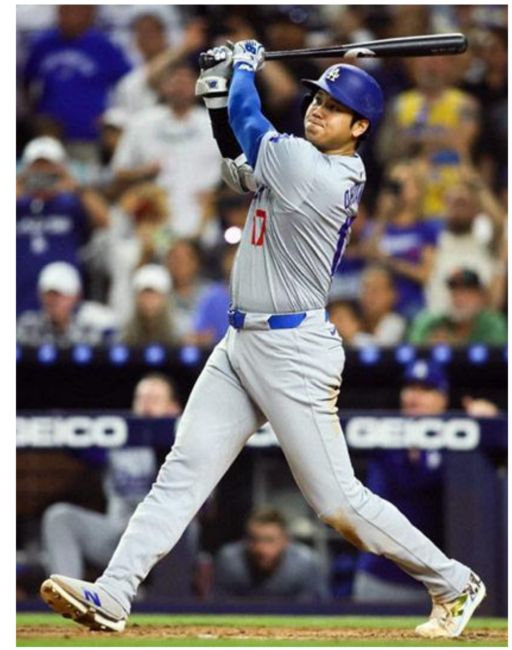
Grants

- Applying for 4 (+1 or more) to prepare for the coming years

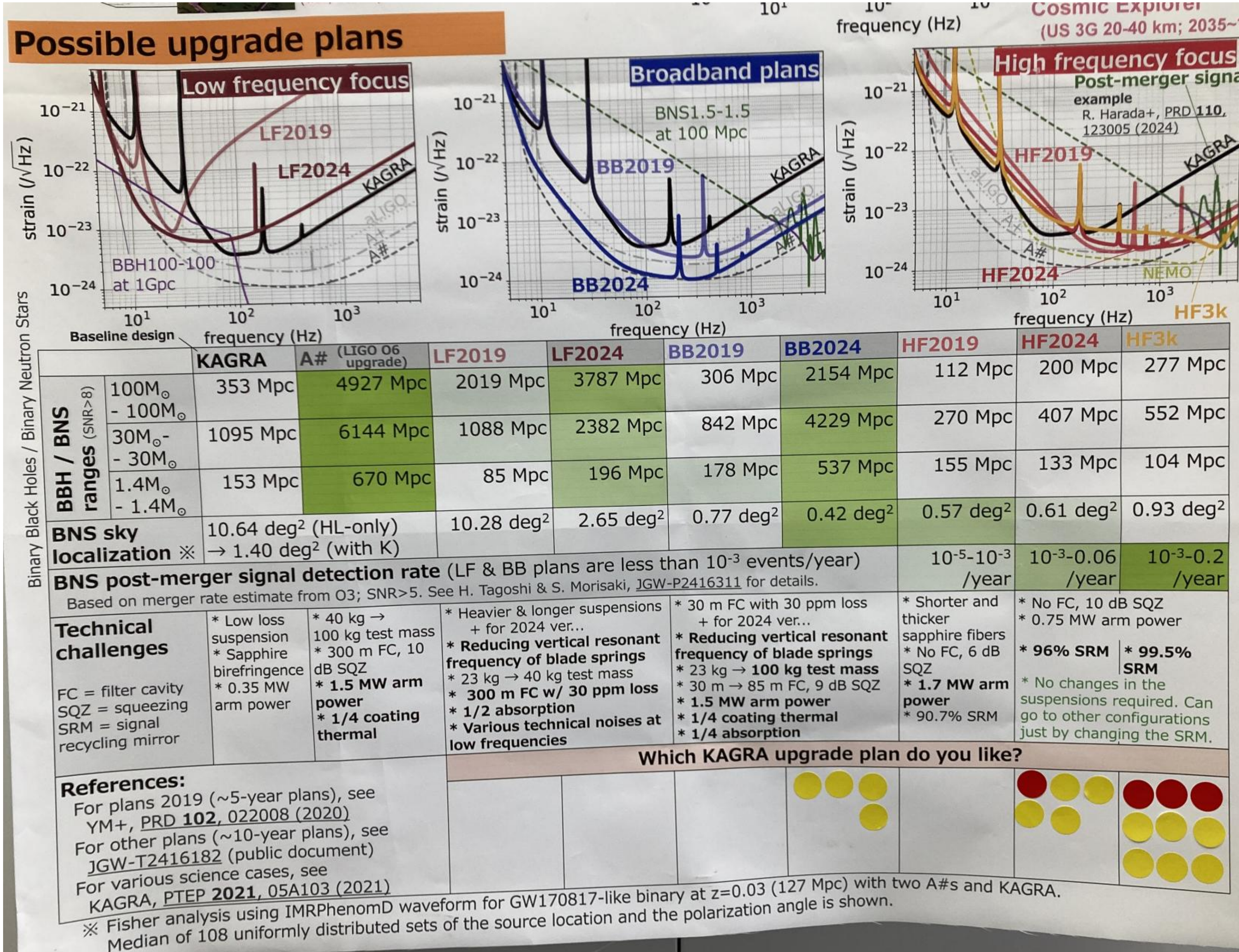


Budget Applications

- Involved in 6 applications in 2024 (+1 still on-going)
- 2 successful, 4 failed
- Statistically as expected but disappointing
- Comments:
  - Tokyo
  - Quantum
- Hard to convince/judge other fields



Popularity Vote



	KAGRA	A# (LIGO O6 upgrade)	LF2019	LF2024	BB2019	BB2024	HF2019	HF2024	HF3k
BBH / BNS ranges (SNR>8): $100M_\odot$ - $100M_\odot$	353 Mpc	4927 Mpc	2019 Mpc	3787 Mpc	306 Mpc	2154 Mpc	112 Mpc	200 Mpc	277 Mpc
$30M_\odot$ - $30M_\odot$	1095 Mpc	6144 Mpc	1088 Mpc	2382 Mpc	842 Mpc	4229 Mpc	270 Mpc	407 Mpc	552 Mpc
$1.4M_\odot$ - $1.4M_\odot$	153 Mpc	670 Mpc	85 Mpc	196 Mpc	178 Mpc	537 Mpc	155 Mpc	133 Mpc	104 Mpc
BNS sky localization ※	10.64 deg^2 (HL-only) → 1.40 deg^2 (with K)		10.28 deg^2	2.65 deg^2	0.77 deg^2	0.42 deg^2	0.57 deg^2	0.61 deg^2	0.93 deg^2
BNS post-merger signal detection rate (LF & BB plans are less than 10^{-3} events/year) Based on merger rate estimate from O3; SNR>5. See H. Tagoshi & S. Morisaki, JGW-P2416311 for details.							10^{-5}-10^{-3} /year	10^{-3}-0.06 /year	10^{-3}-0.2 /year
Technical challenges FC = filter cavity SQZ = squeezing SRM = signal recycling mirror	* Low loss suspension * Sapphire birefringence * 0.35 MW arm power	* 40 kg → 100 kg test mass * 300 m FC, 10 dB SQZ * 1.5 MW arm power * 1/4 coating thermal	* Heavier & longer suspensions + for 2024 ver... * Reducing vertical resonant frequency of blade springs * 23 kg → 40 kg test mass * 300 m FC w/ 30 ppm loss * 1/2 absorption * Various technical noises at low frequencies		* 30 m FC with 30 ppm loss + for 2024 ver... * Reducing vertical resonant frequency of blade springs * 23 kg → 100 kg test mass * 30 m → 85 m FC, 9 dB SQZ * 1.5 MW arm power * 1/4 coating thermal * 1/4 absorption		* Shorter and thicker sapphire fibers * No FC, 6 dB SQZ * 1.7 MW arm power * 90.7% SRM	* No FC, 10 dB SQZ * 0.75 MW arm power * 96% SRM * No changes in the suspensions required. Can go to other configurations just by changing the SRM.	* 99.5% SRM
Which KAGRA upgrade plan do you like?									

References:
For plans 2019 (~5-year plans), see YM+, PRD 102, 022008 (2020)
For other plans (~10-year plans), see JGW-T2416182 (public document)
For various science cases, see KAGRA, PTEP 2021, 05A103 (2021)

※ Fisher analysis using IMRPhenomD waveform for GW170817-like binary at z=0.03 (127 Mpc) with two A#s and KAGRA. Median of 108 uniformly distributed sets of the source location and the polarization angle is shown.

My Plans for 2025

- First (faint) detection of GWs in KAGRA
- First axion dark matter search with KAGRA
- Improved vector dark matter search with KAGRA
- In-vac RF QPDs for KAGRA
- Characterization of optical levitation mirrors
- Better quantum nature of gravity experiments
- Michelson interferometer for outreach

- And expecting…
  - Axion search with wavelength tunable DANCE

Recent Multi-Messenger Events

- Feb 17-19, 2025
  Theories of Astrophysical Big Bangs 2025 @ RIKEN
- Apr 23-24, 2025
  From Quarks to Neutron Stars: Insights from kHz gravitational waves @ Hongo
- Apr 25, 2025
  Paul Lasky RESCEU Colloquium @ Hongo

Atomic physics

Origin of heavy elements
Origin of GRBs etc.

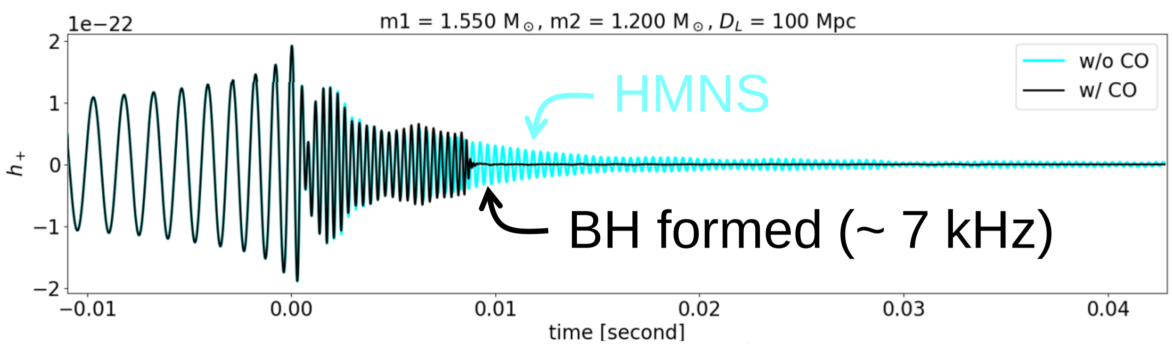
EM: Gamma-ray burst, kilonova

Late-inspiral:
Tidal deformability,
Sky localization


Credit: Carl Knox
N. Sarin, P. D. Lasky, [General Relativity and Gravitation 53, 59 (2021)]

Early-inspiral:
Mass, Distance, Viewing angle
Inclination

R. Harada+, [PRD 110, 123005 (2024)]



GW

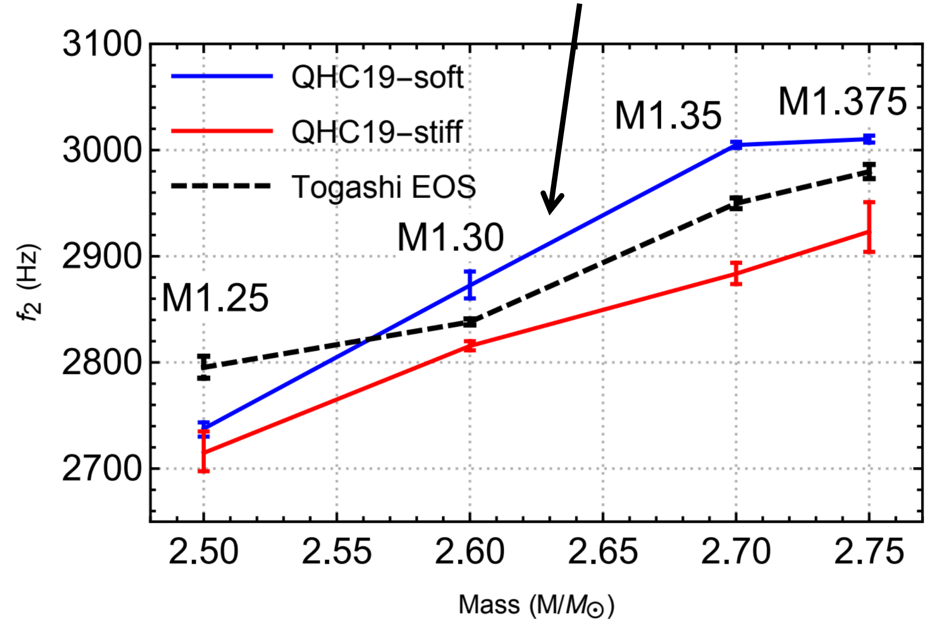
?

Equation of state

Detecting Post-Merger is Hard

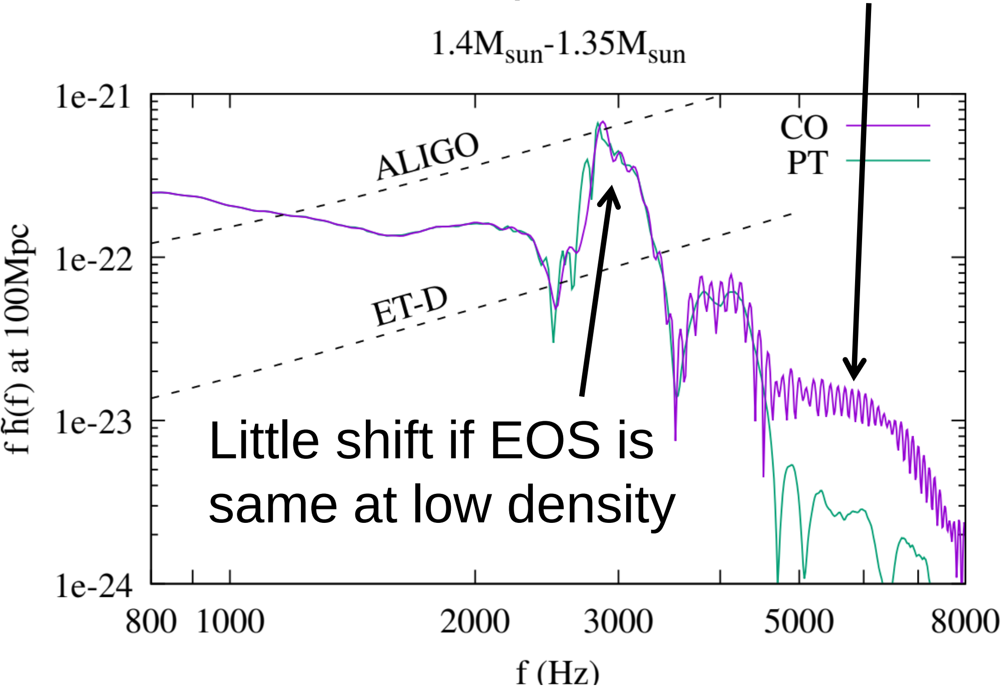
- Low BNS event rate
- Also hard to say something about EOS with a single event?

Various peak frequencies



Huang, Baiotti, Kojo, Takami, Sotani, Togashi, Hatsuda, Nagataki, Fan, [PRL **129**, 181101 (2022)]

BH quasi-normal mode



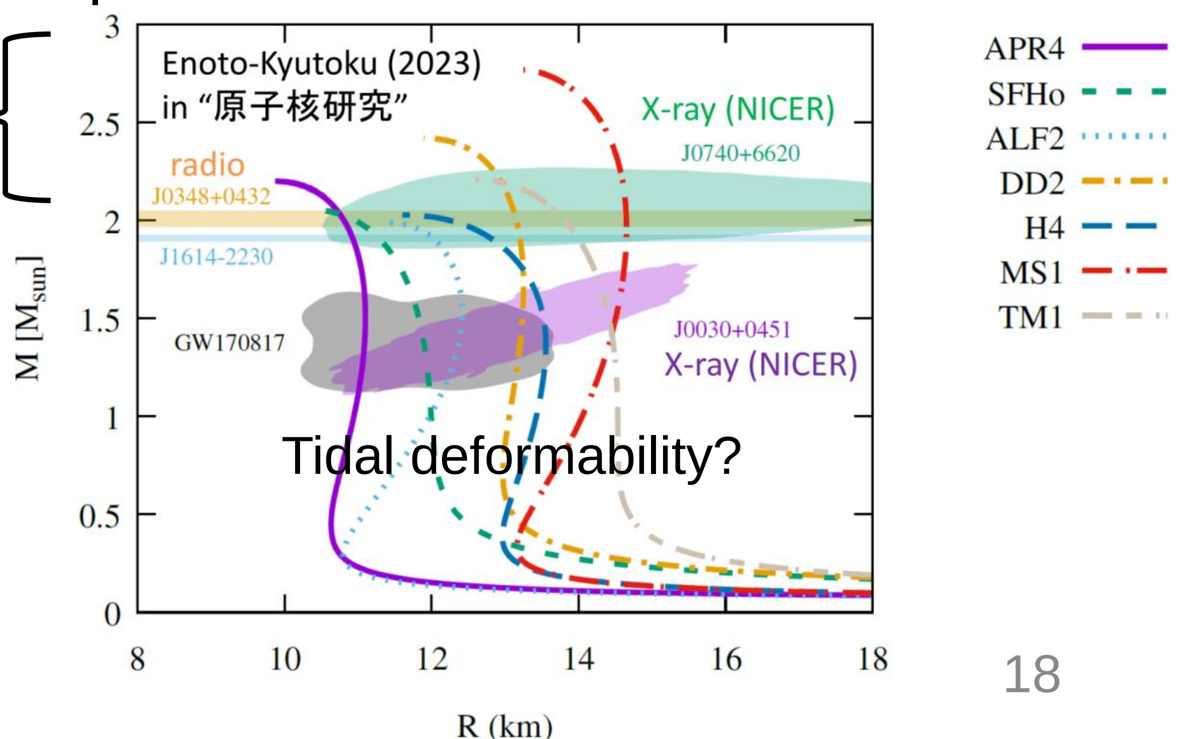
Little shift if EOS is same at low density

Fujimoto, Fukushima, Hotokezaka, Kyutoku, [PRD **111**, 063054 (2025)]

Constraining Equation of State

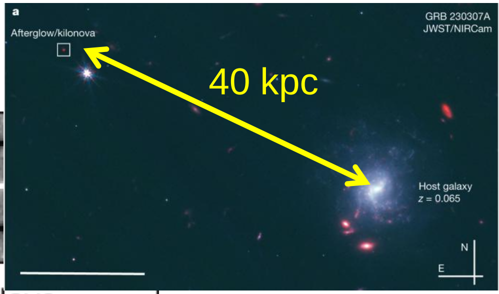
- Best chance is to measure maximum mass of neutron stars and tidal deformability?
- EM counterpart required to say that it had a neutron star
- Sky localization optimized KAGRA is similar to tidal deformability optimized KAGRA
  → Multi-messenger optimized KAGRA

Maximum mass?

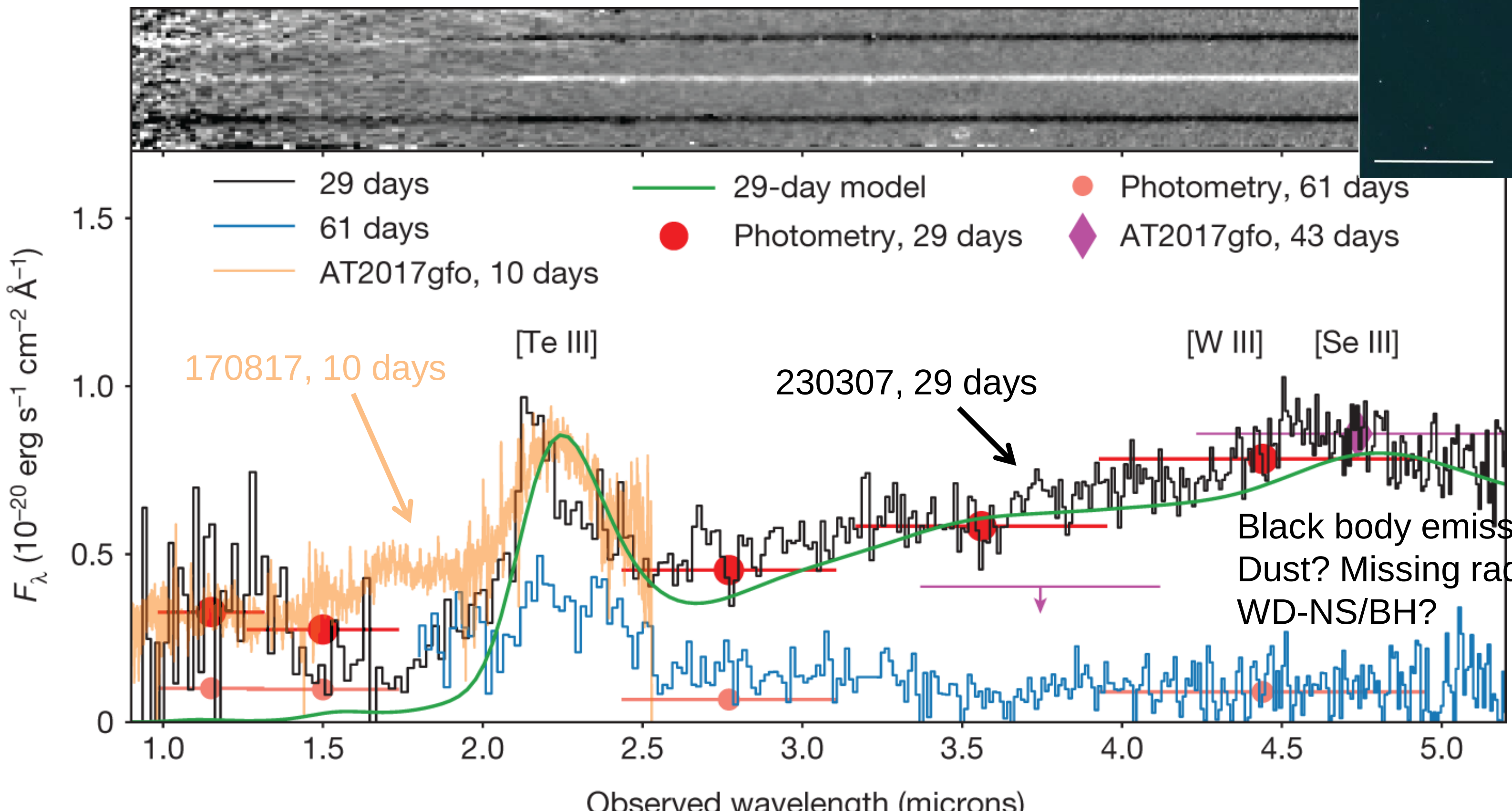


GRB230307A Excess

- Not collapsar due to large offset (~40 kpc) from host galaxy
- Likely BNS merger but long GRB (~ 35 sec)
- Similar kilonova to 170817 but extremely red



A. J. Levan+, [Nature **626**, 737 (2024)]



Black body emission?
Dust? Missing radiation transport?
WD-NS/BH?

With or Without GW

- 170817 (short GRB < 2 sec; GW+EM)

40 Mpc, 31 deg^2 → 28 deg^2
Detected with
LHO @ 47 Mpc
LLO @ 96 Mpc
Virgo @ 26 Mpc

NS-NS from mass and kilonova

MNS lived for O(10~100) msec?
→ short GRB?

Probably BH is formed

- 190425 (GW only)

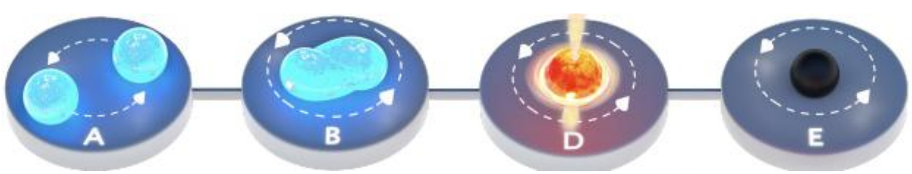
159 Mpc, 10,500 deg^2 → 8284 deg^2
Detected with
LLO @ 135 Mpc
Virgo @ 48 Mpc

Probably NS-NS from mass

Probably prompt collapse to BH from mass

- 230307 (long GRB ~ 35 sec; EM only)

Also GRB211211A (long GRB ~ 50 sec @ 350 Mpc) is similar situation with GRB230307A



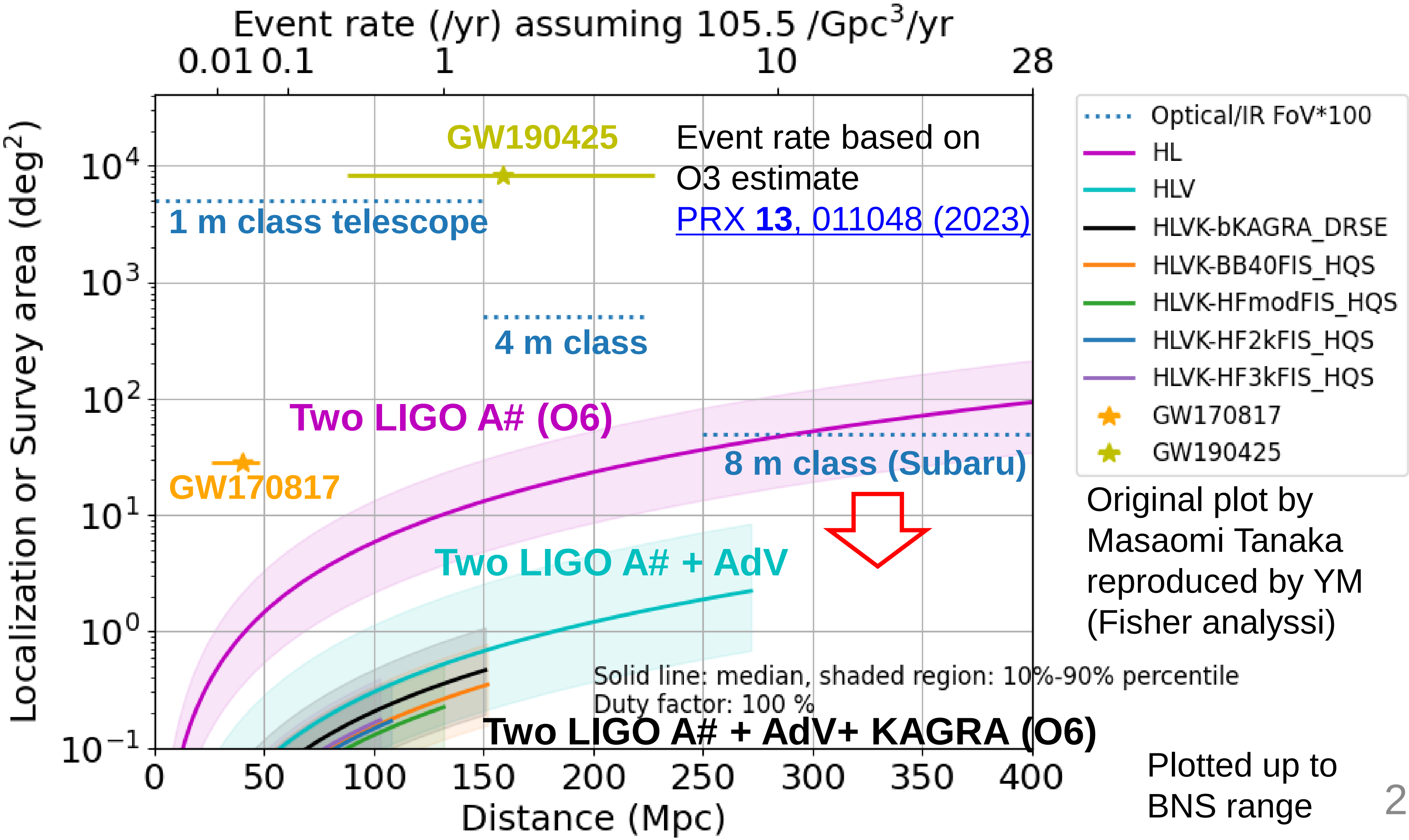
Probably NS-NS from kilonova
Could be WD/NS/BH?

MNS lived for O(100~1000) msec?
→ long GRB?

290 Mpc (from host galaxy)

Sky Localization Requirement

- For optical/IR follow-up, localization at distance may be important… (but also 8 m telescopes have limited availability)

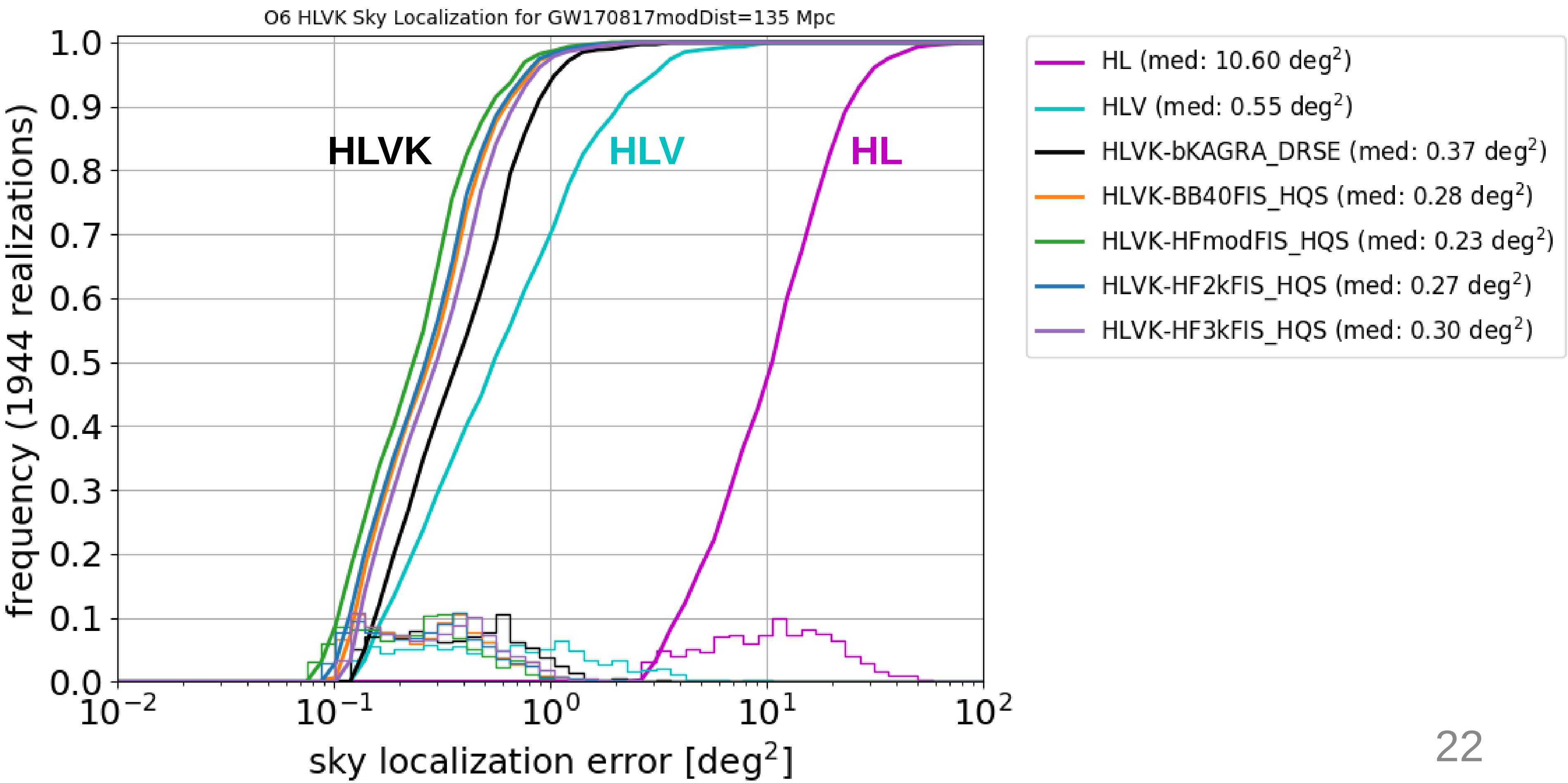


Original plot by Masaomi Tanaka reproduced by YM (Fisher analyssi)

Plotted up to BNS range

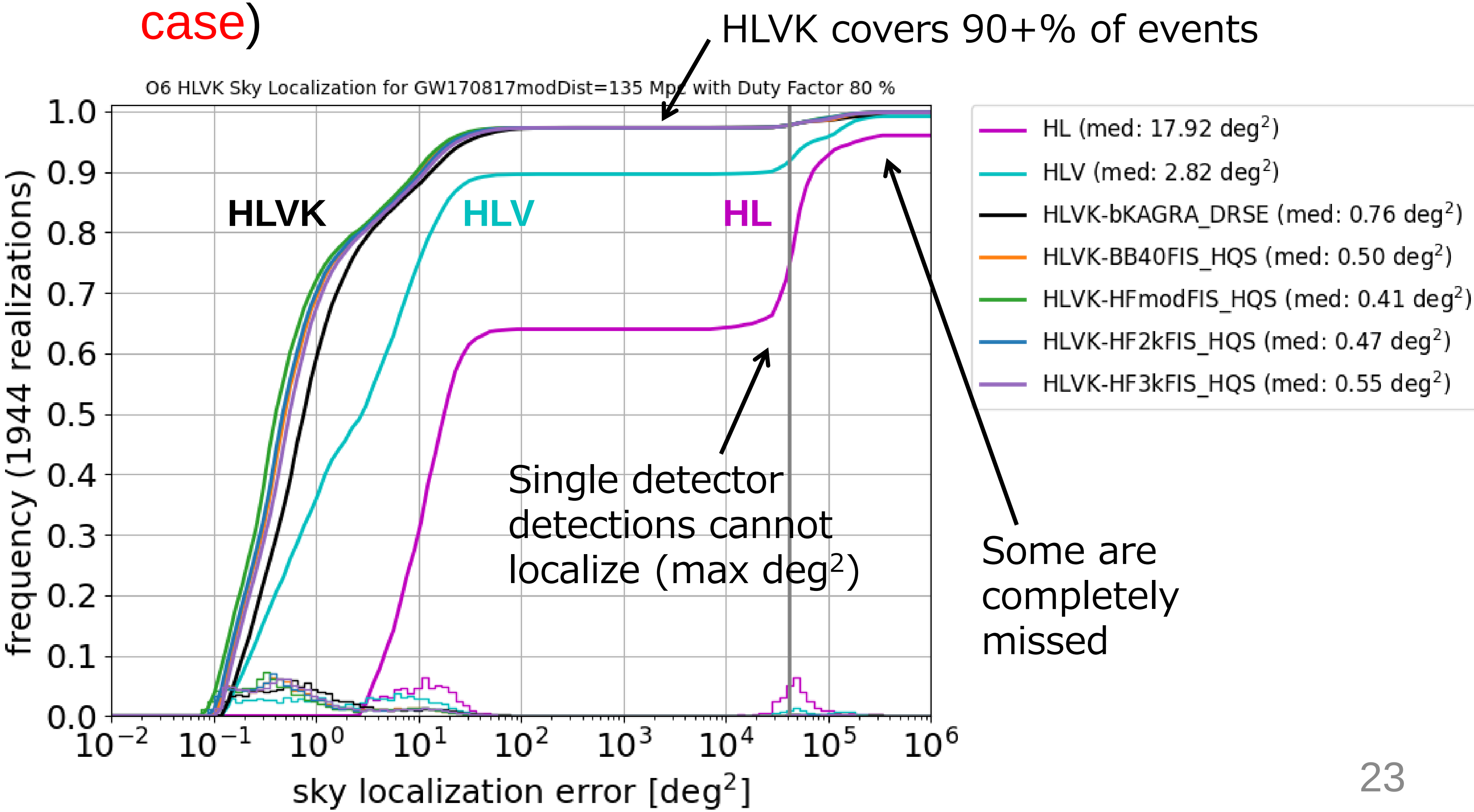
Sky Localization Distribution

- From this plot, it seems like HFmod the best choice
- But this plot implicitly assume 100% duty factor



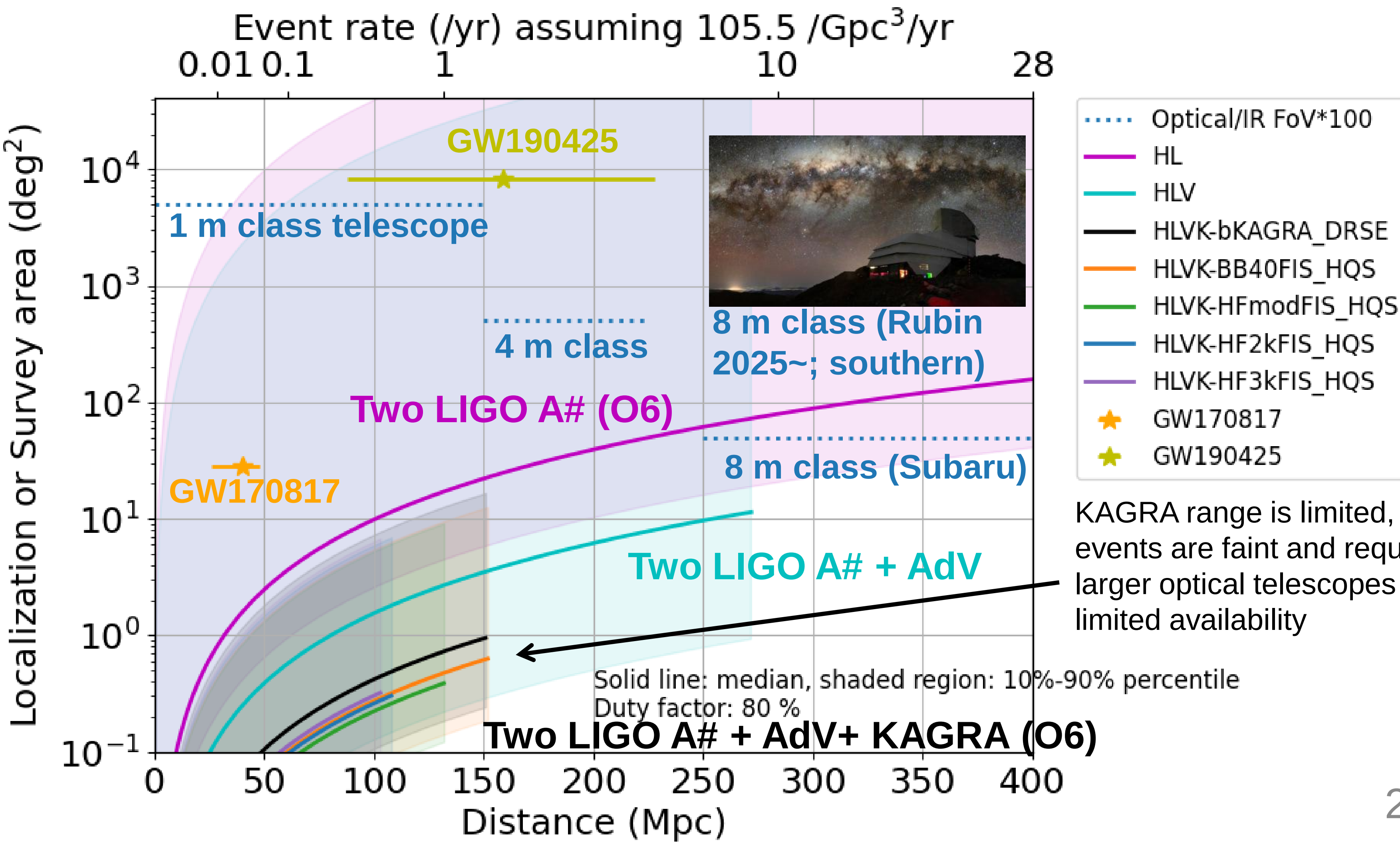
Real Sky Localization Distribution

- In reality, some fraction is not well localized due to limited duty factor (see below for single detector duty factor of 80% case)



Real Sky Localization vs Distance

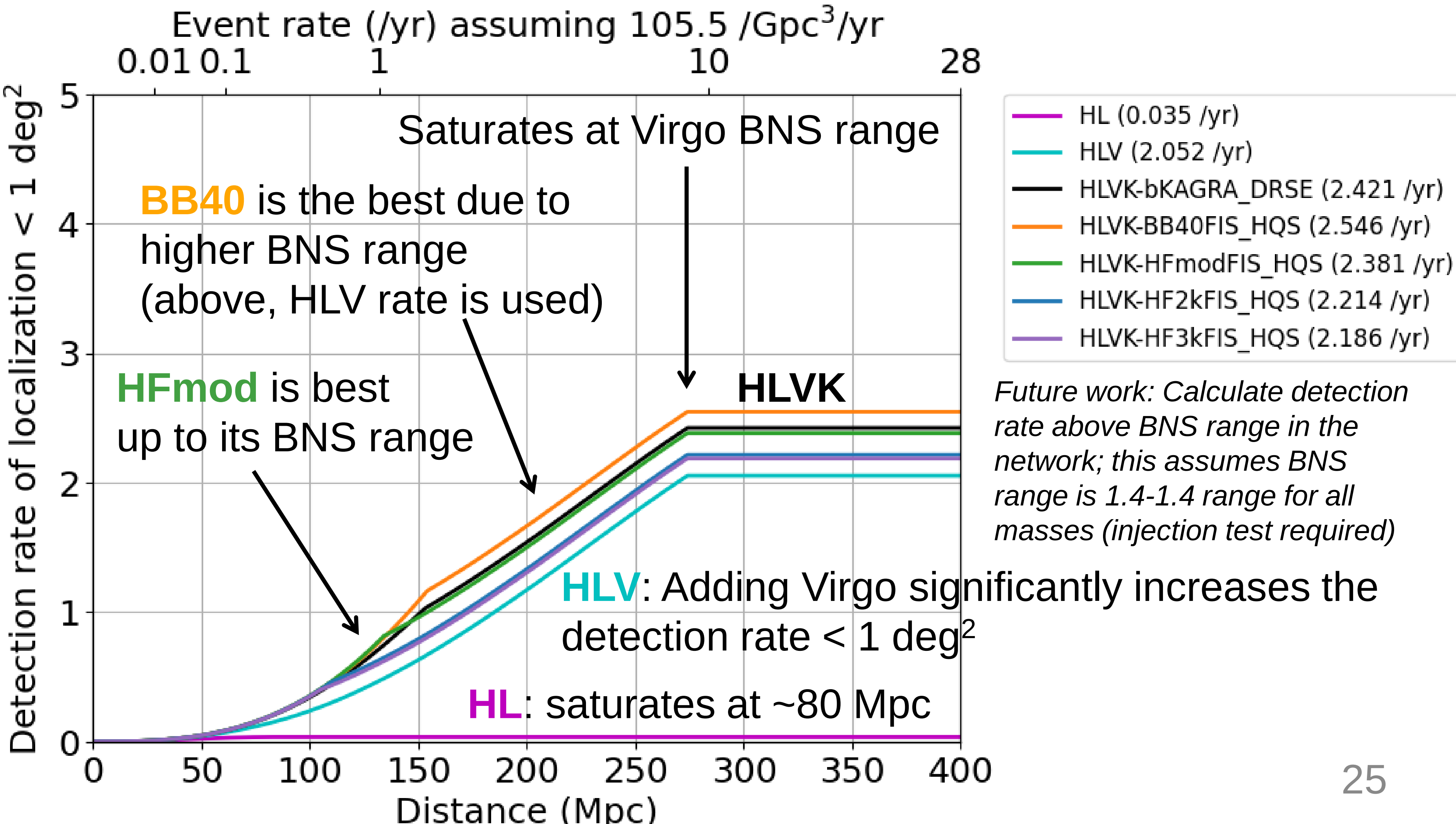
- Many events are not well localized with HLV network, but mostly covered by HLVK network



KAGRA range is limited, but far events are faint and require larger optical telescopes with limited availability

Detection Rate of < 1 deg^2

- By integrating probability(<1 deg^2) over distance, detection rate can be estimated



Future work: Calculate detection rate above BNS range in the network; this assumes BNS range is 1.4-1.4 range for all masses (injection test required)

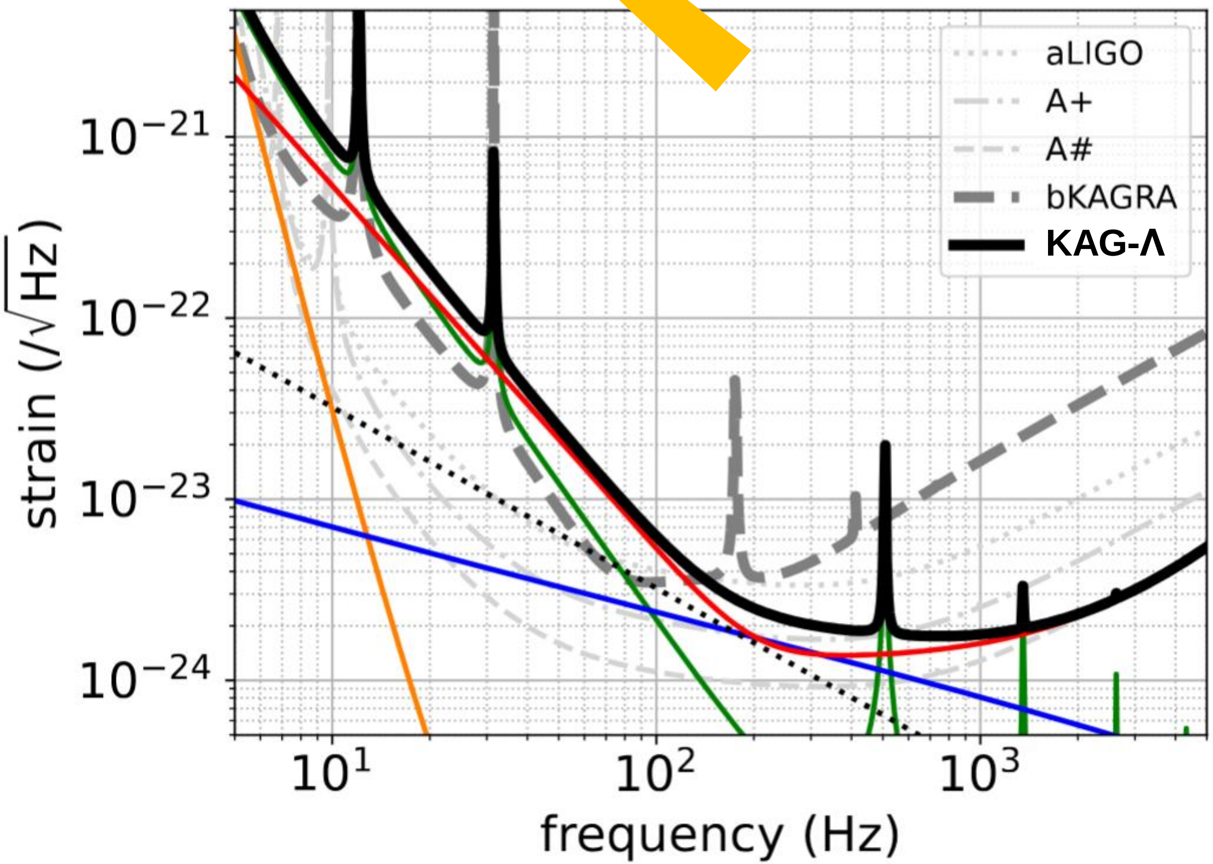
Detection Rate of < 1 deg^2

- By integrating probability(<1 deg^2) over distance, detection rate can be estimated
- 1 deg^2 is a typical field of view of optical~IR telescopes
- In this case, **BB40** performs better (x1.5 than HLV case!)
- **HFmod** is also good (also for tidal deformability)

	HL	HLV	bKAGRA	BB40	HFmod	HF2k	HF3k
BNS range	670 Mpc	273 Mpc	152 Mpc	153 Mpc	133 Mpc	109 Mpc	104 Mpc
Median localization [1]	10.6 deg^2	0.55 deg^2	0.37 deg^2	0.28 deg^2	0.23 deg^2	0.27 deg^2	0.30 deg^2
< 10 deg^2 rate [2]	1.1 /yr	5.3 /yr	5.5 /yr	5.6 /yr	5.5 /yr	5.4 /yr	5.4 /yr
< 1 deg^2 rate [2]	0.04 /yr	2.1 /yr	2.4 /yr	2.5 /yr	2.4 /yr	2.2 /yr	2.1 /yr
Post-merger rate [3]				< 10^{-3} /yr	< 0.06 /yr	< 0.1 /yr	< 0.2 /yr
Tidal deformability improvement compared with HL case [4]				~25%	~55%	~45%	~30%

[1] At 135 Mpc, for 100% duty factor case
[2] Detection rate for 80% duty factor case
[3] Detection rate with SNR>5. Depend on neutron star equation of state and BNS event rate. See H. Tagoshi & S. Morisaki, JGW-P2416311 for details.
[4] Reduction of estimation error due to addition of KAGRA. See S. Morisaki, JGW-G2516593 for details.

Introducing… KAG-Λ

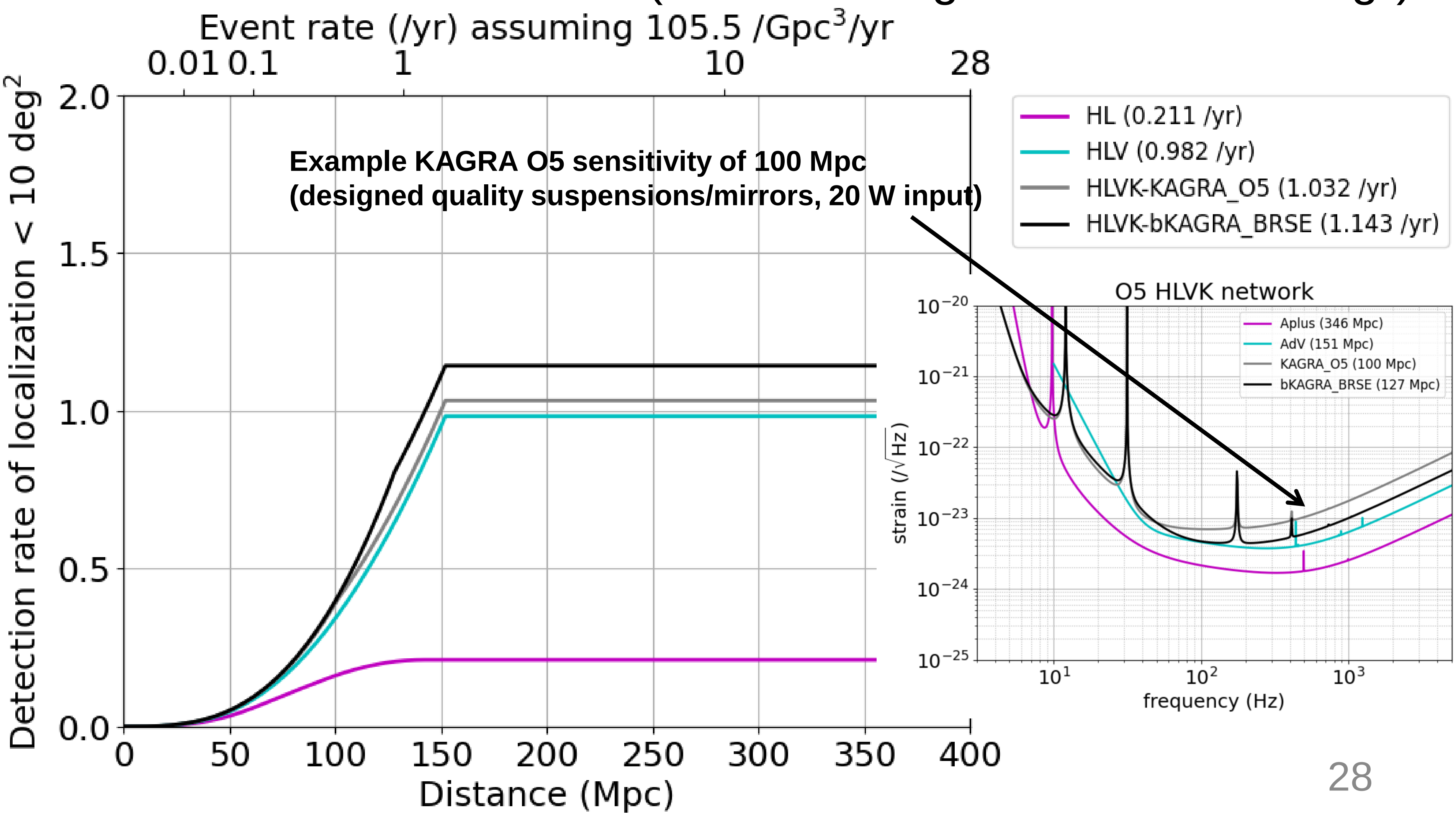


	Symbol	Default	KAG-Λ
SRC detuning angle (deg)	$\phi_{\rm det}$	3.5	0
Homodyne angle (deg)	ξ	135.1	91.3
Mirror temperature (K)	$T_{\rm m}$	22	22.2
Power at BS (W)	I_0	673.6	3140.5
SRM reflectivity (%)	$R_{\rm SRM}$	84.64	95.6
Sapphire fiber length (cm)	l_3	35	20
Sapphire fiber diameter (mm)	d_2	1.6	2.1
Mirror mass (kg)	m	22.8	22.8
Beam radius (mm)	w_2	35.0	35.0
FC length (m)	$L_{\rm fc}$	0	0
Maximum detected squeezing (dB)	$\sigma_{\rm maxSQZ}$	0.0	7.2
ITM transmission (%)	$T_{\rm ITM}$	0.4	0.4
Arm cavity round-trip loss (ppm)	$\Lambda_{\rm rt}$	100	100
SRC loss (ppm)	$\Lambda_{\rm SR}$	2000	500
PD loss (%)	$\Lambda_{\rm out}$	10	5
Injection losses (%)	$\Lambda_{\rm inj}$	5	5
FC round-trip loss (ppm)	$\Lambda_{\rm fc}$	0	0
Readout loss (%)	$\Lambda_{\rm ro}$	0	0
Coating loss angle 1 (1e-4)	$\phi_{\rm c1}$	3	3
Coating loss angle 2 (1e-4)	$\phi_{\rm c2}$	5	5
IM mass (kg)	m_1	20.5	20.5
IM wire length (cm)	l_1	26.1	26.1
IM wire diameter (mm)	d_1	0.6	0.6
Blade spring vertical resonance (Hz)	$f_{\rm mg}$	14.5	14.5
Substrate absorption (ppm/cm)	$\beta_{\rm m}$	50	50
Coating absorption (ppm)	$\beta_{\rm c}$	0.5	0.5
Additional heat (mW)	$P_{\rm amb}$	50	50
$100-100M_\odot$ inspiral range (Mpc)		353	158
$30-30M_\odot$ inspiral range (Mpc)		1095	388
$1.4-1.4M_\odot$ inspiral range (Mpc)		153	156
Sensitivity at dip (1/rtHz)		3.5e-24	1.8e-24

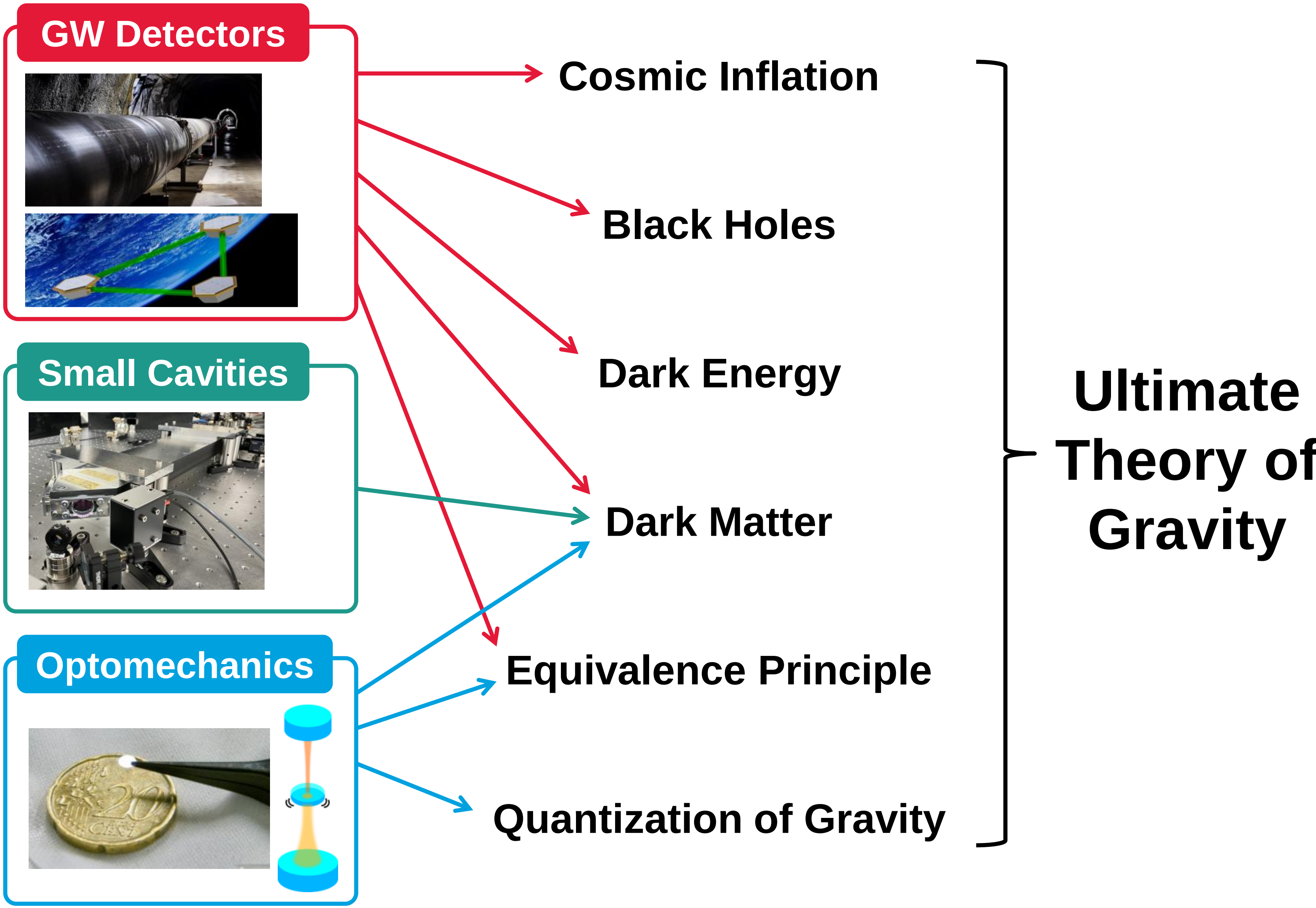
YM+, PRD **102**, 022008 (2020)
KAGRA Instrument Science White Paper
JGW-T2416182 (public document)

How About KAGRA O5?

- Maybe it is more appealing to say median sky localization, as detection rate is low (HLV 1.55 deg^2 -> HLVK 1.01 deg^2)

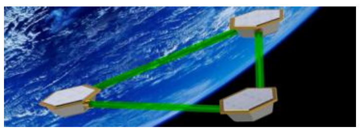


Main Projects

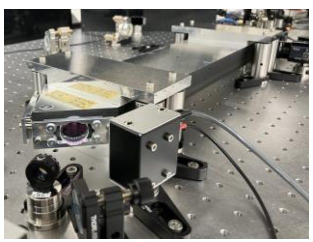


Breaking News

GW Detectors



Small Cavities



Optomechanics

Cosmic Inflation

Black Holes

Dark Energy

Dark Matter

Equivalence Principle

Quantization of Gravity

Cosmic Birefringence

Dynamical Dark Energy

Supernova Relic Neutrino

CP Violation in Neutrino

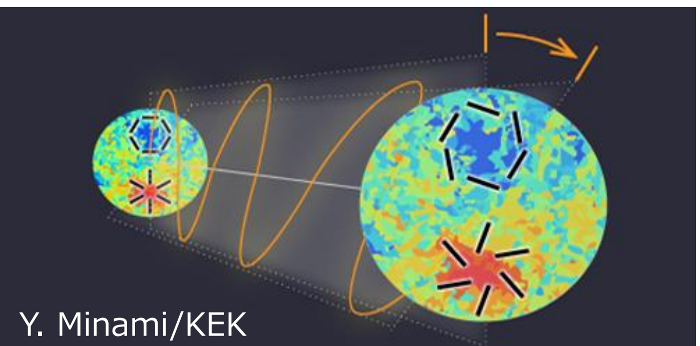
Levitated Mechanics in Space

T. Louis+, [arXiv:2503.14452](https://arxiv.org/abs/2503.14452)

ACT DR6

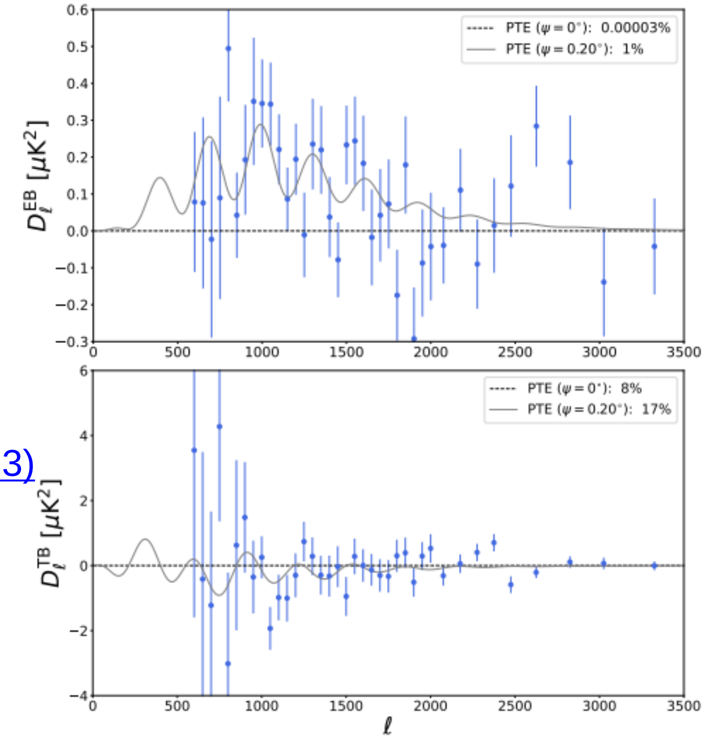
- Atacama Cosmology Telescope Data Release 6
  - 6 m radio telescope in Chile
- Cosmic birefringence angle

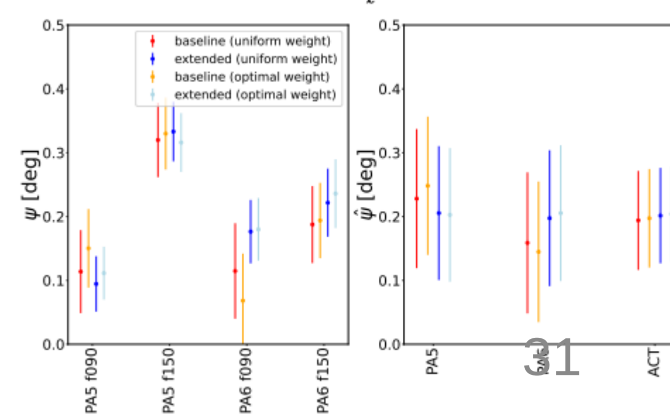
$$\beta = 0.20^\circ \pm 0.08^\circ$$



WMAP9+Planck gives 0.27±0.08
Eskilt+, PRL **131**, 121001 (2023)

Combined ~4σ!?

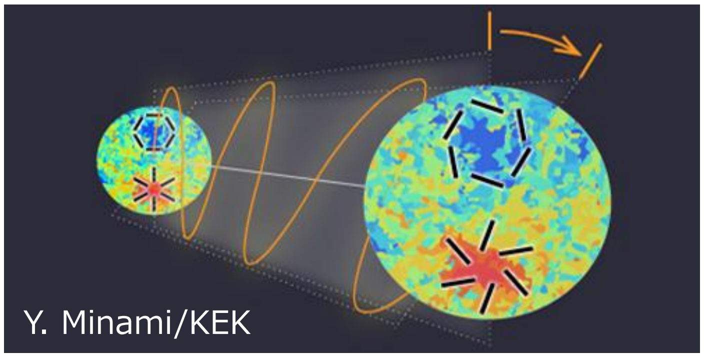




Axions for DE and DM

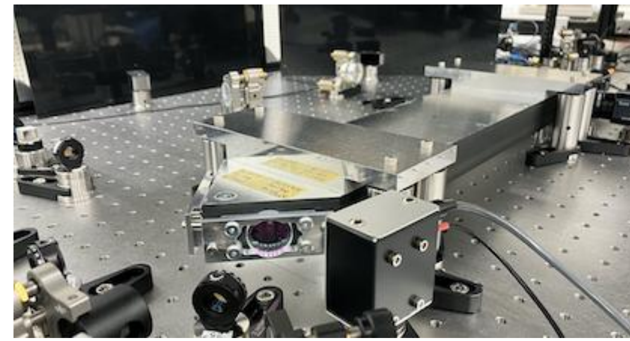
- Cosmic birefringence can be explained by axion-like particles

Dark Energy (low mass)

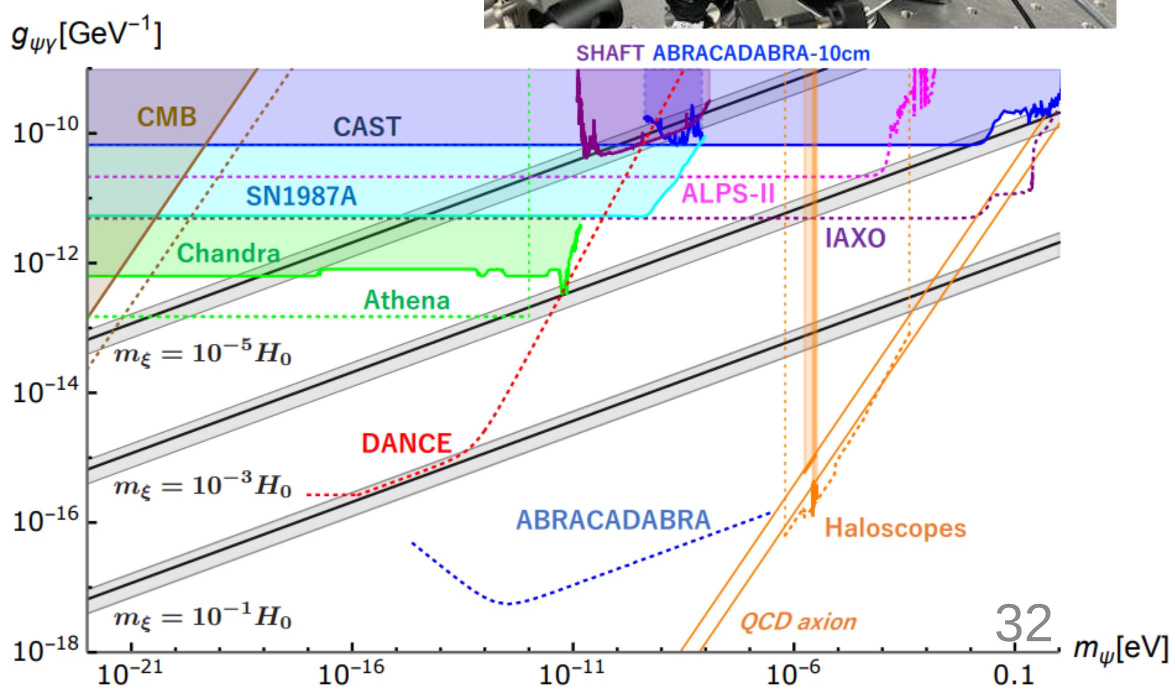


Two axions?

Dark Matter (higher mass)



- If axions exist, there could be multiple axions (String Axiverse)



I. Obata, [JCAP **09**, 062 (2022)]

M. Baryakhtar+, [arXiv:2504.10607](https://arxiv.org/abs/2504.10607)

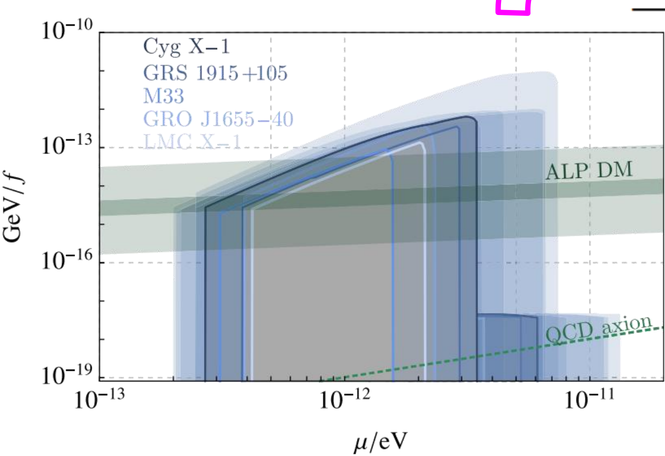
Limit on Axion-Photon Coupling

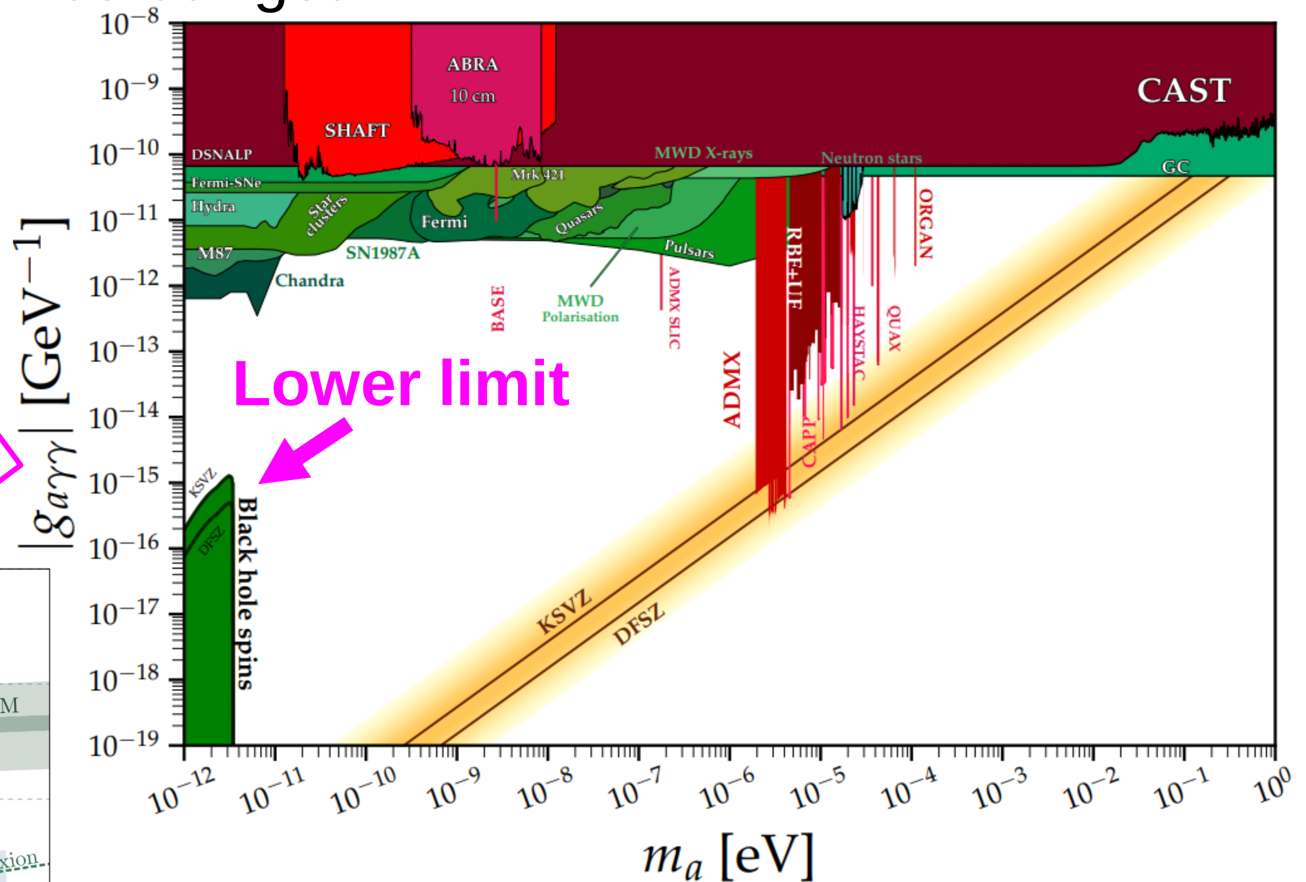
- Recent review by Masha Baryakhtar, Leslie Rosenberg, Gray Rybka
- Loewer limit can be our goal

[PPNP **102**, 89 (2018)]()

$$g_{A\gamma} \equiv \frac{\alpha}{2\pi}\frac{C_{A\gamma}}{f_A} = 2.0 \times 10^{-16} C_{A\gamma}\frac{m_A}{\mu\mathrm{eV}}\ \mathrm{GeV}^{-1}$$

Converted $1/f_a$ to $g_{a\gamma\gamma}$ assuming QCD axion





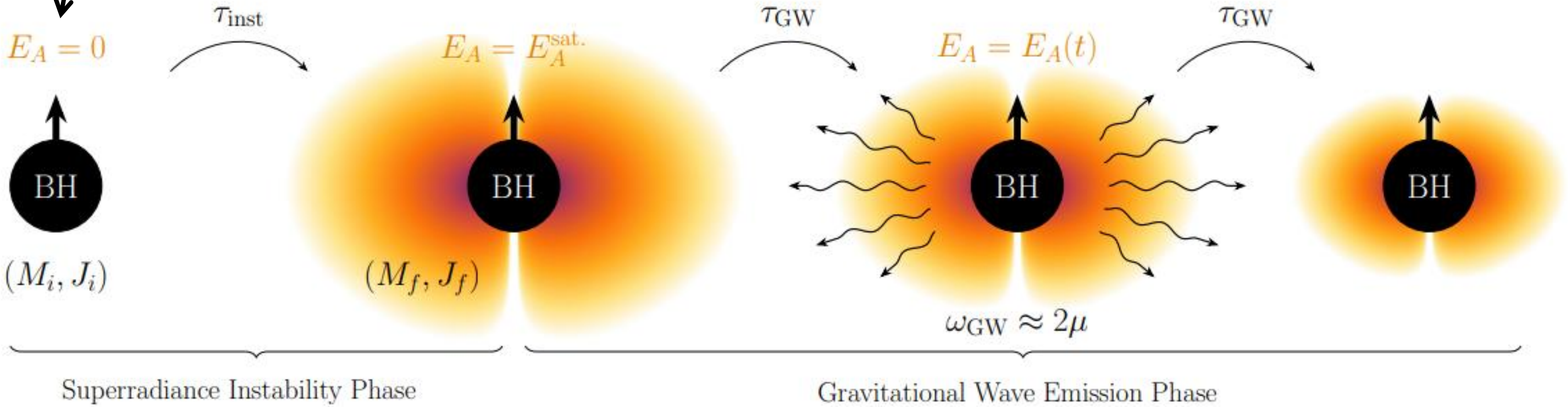
M. Baryakhtar+, [PRD **103**, 095019 (2021)]()

Black Hole Superradiance

- Boson cloud grow by extracting rotational energy of BH
- Lower limit to boson interactions could be obtained from black hole spin measurements and/or gravitational wave measurements

Hard to estimate initial spin (unless we see/hear when BH is born)

BH spin reduced as boson cloud grow
Reduced boson cloud if there are interactions
(reduced GW emission, higher BH spin)



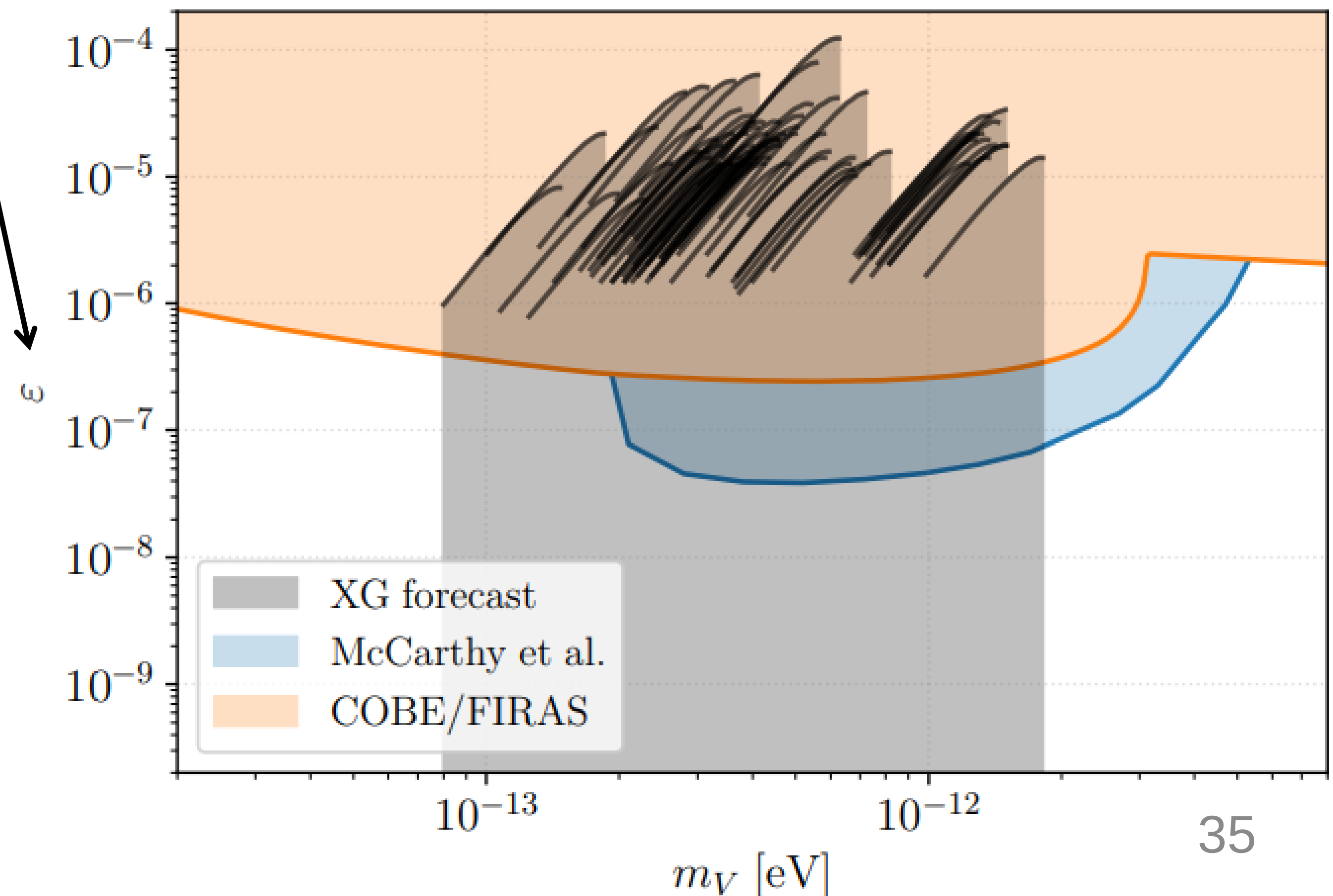
L. Tsukada+, PRD **103**, 083005 (2021)

D. Jones+, arXiv:2412.00320

Prospects for Dark Photon

- Can rule-out some dark photon mass region with 3G detectors
- Should be able to do this also for axions

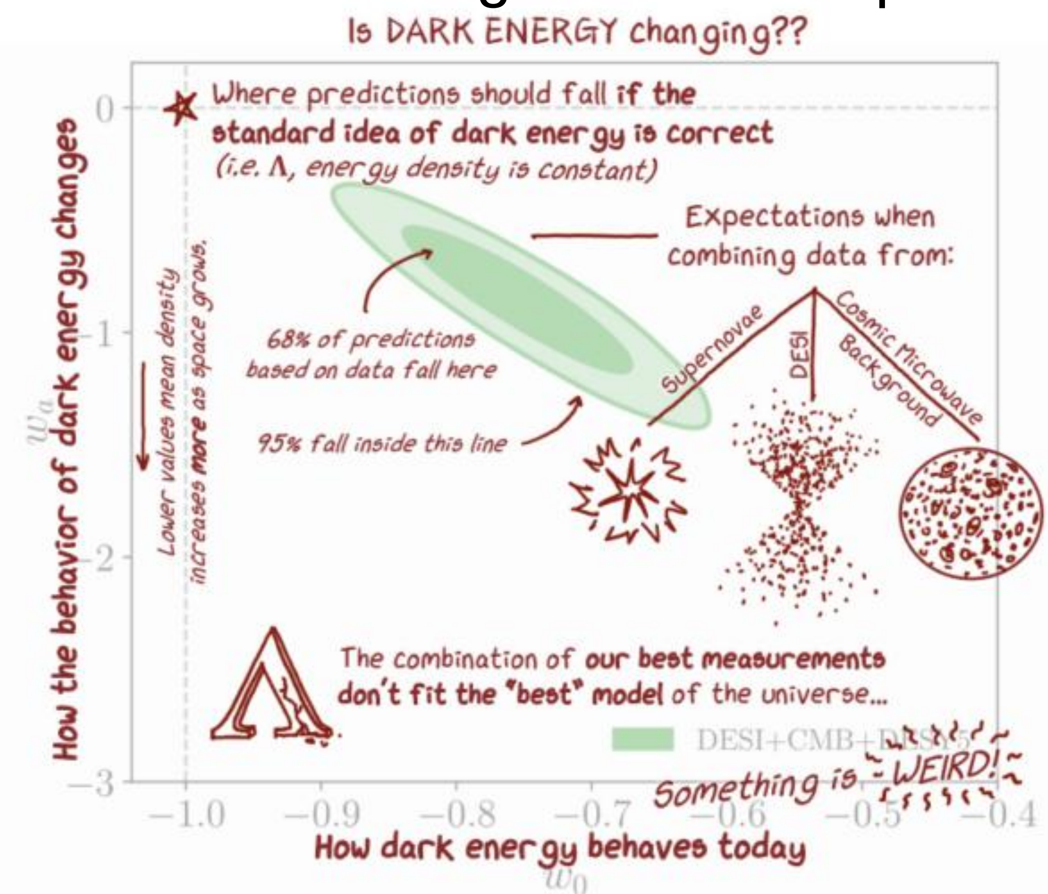
Kinetic mixing (mixing between standard photon and dark photon)

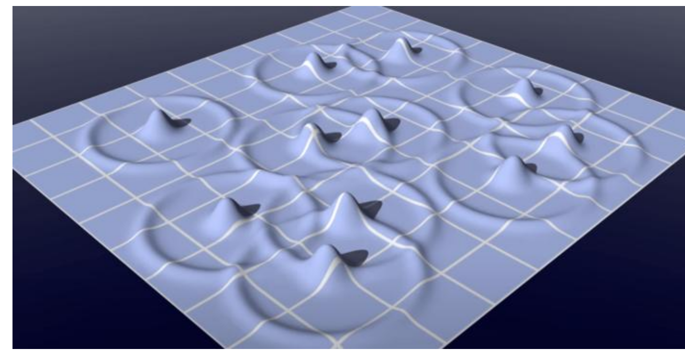


DESI, arXiv:2503.14738

DESI DR2 BAO

- Dark Energy Spectroscopic Instrument Data Release 2
  - 4 m optical telescope in Arizona
- Baryon acoustic oscillation measurements from more than 14 million galaxies and quasars





$$w(z) = w_0 + w_a \frac{z}{1+z}$$

w_0: -1, w_a: 0 is ΛDCM

2.8-4.2σ tension

Axion dark energy can both explain cosmic birefringence

W. Lin+, arXiv:2504.17638

F. B. M. dos Santos+, arXiv:2504.04646

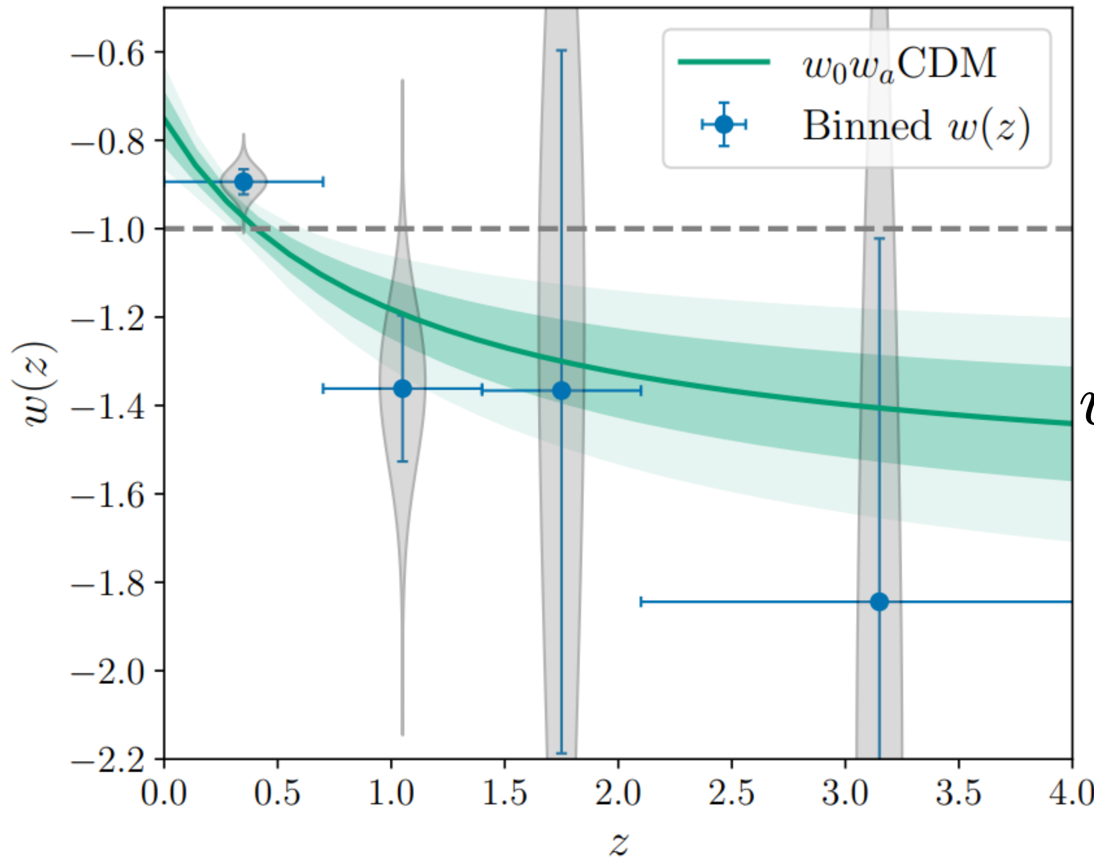
$w_0 w_a$CDM

- DESI result is from low-z measurements
- Can be tested with GW standard siren even with 2G

CMB
z~1100

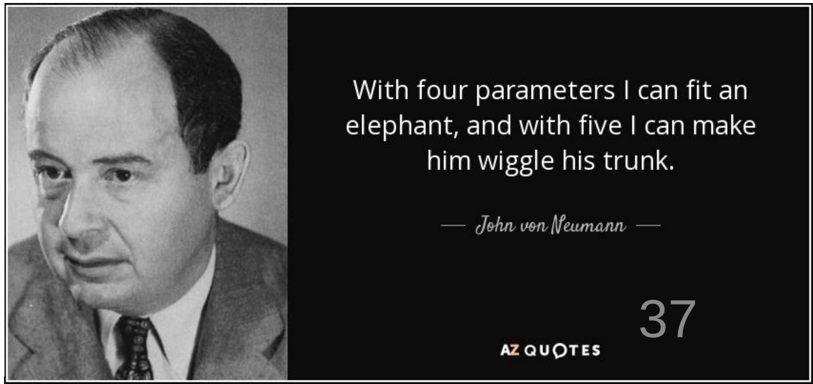
z~10 reachable
with 3G

z~1 reachable with 2G



-1 is ΛDCM

$$w(z) = w_0 + w_a \frac{z}{1+z}$$



F. B. M. dos Santos+, arXiv:2504.04646

With GW Standard Siren

- With GW standard siren, H(z) can be measured
- Independent probe for dynamical dark energy
- This paper assumes redshift can be somehow measured
  - Hard for kilonova with high-z
  - Using galaxy map would be possible

T. Namikawa, A. Nishizawa, A. Taruya, PRL **116**, 121302 (2016)

A New Window on Dynamical Dark Energy: Combining DESI-DR2 BAO with future Gravitational Wave Observations

Felipe Bruno Medeiros dos Santos,[a] **Jonathan Morais,**[a] **Supriya Pan,**[b,c] **Weiqiang Yang,**[d] **Eleonora Di Valentino**[e]

[a]Observatório Nacional, Rua General José Cristino, 20921-400, Rio de Janeiro-RJ, Brazil
[b]Department of Mathematics, Presidency University, 86/1 College Street, Kolkata 700073, India
[c]Institute of Systems Science, Durban University of Technology, PO Box 1334, Durban 4000, Republic of South Africa
[d]Department of Physics, Liaoning Normal University, Dalian, 116029, People's Republic of China
[e]School of Mathematical and Physical Sciences, University of Sheffield, Hounsfield Road, Sheffield S3 7RH, United Kingdom

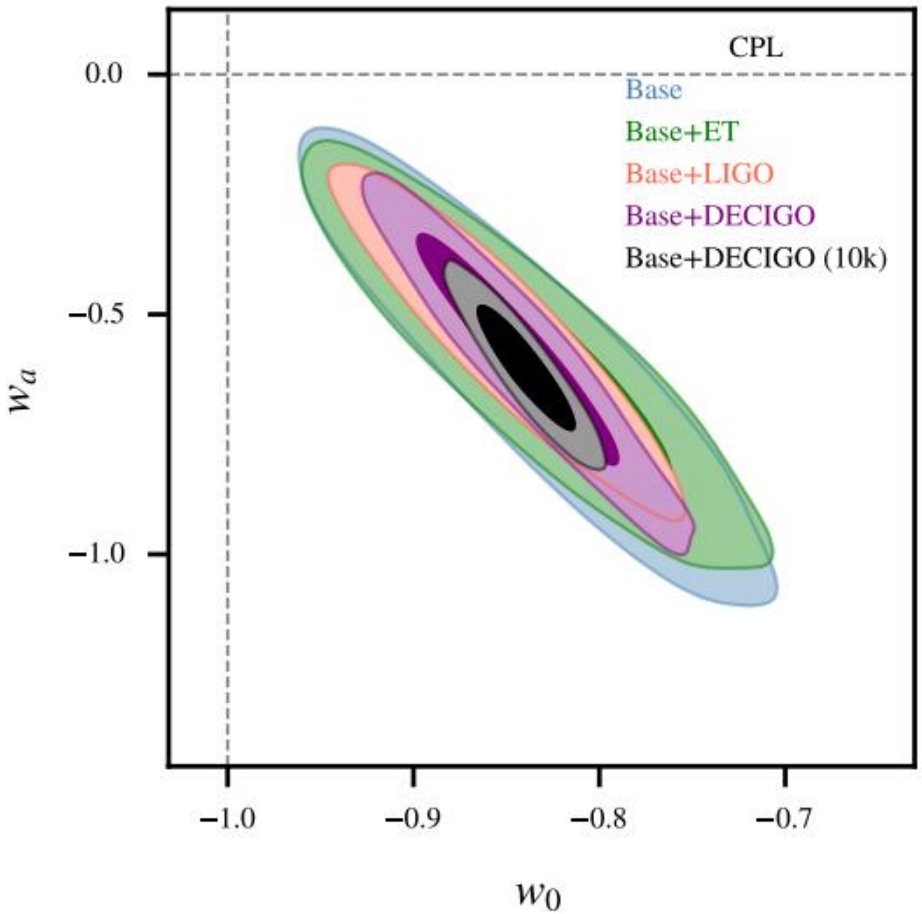
E-mail: fbmsantos@on.br, jonathan.morais0018@gmail.com, supriya.maths@presiuniv.ac.in, d11102004@163.com, e.divalentino@sheffield.ac.uk

Abstract. Baryon acoustic oscillation (BAO) data from the Dark Energy Spectroscopic Instrument (DESI) appear to indicate the first evidence for dynamical dark energy (DDE), with a present-day behavior resembling quintessence. This evidence emerges when the Chevallier-Polarski-Linder (CPL) parametrization of the dark energy equation of state, $w_{\rm de} = w_0 + w_a(1-a)$, is considered, and persists across other functional forms of $w_{\rm de}$. In this work, we investigate how the inclusion of future gravitational wave (GW) standard siren data impacts the uncertainties in cosmological parameters when combined with DESI measurements. Specifically, we analyze the expected contributions from three upcoming GW observatories: the Einstein Telescope (ET), the Deci-hertz Interferometer Gravitational-wave Observatory (DECIGO), and the Laser Interferometer Gravitational-Wave Observatory (LIGO). We find that the addition of GW data, particularly from LIGO and DECIGO, significantly reduces the uncertainties in cosmological parameters, with the extent of the improvement depending on the specific form of $w_{\rm de}$. Our results highlight both the constraining power of future GW observations and the importance of considering a range of cosmological models in data analysis.

F. B. M. dos Santos+, arXiv:2504.04646

With GW Standard Siren

- With ET, LIGO, DECIGO with 1000 events, DECIGO with 10k events

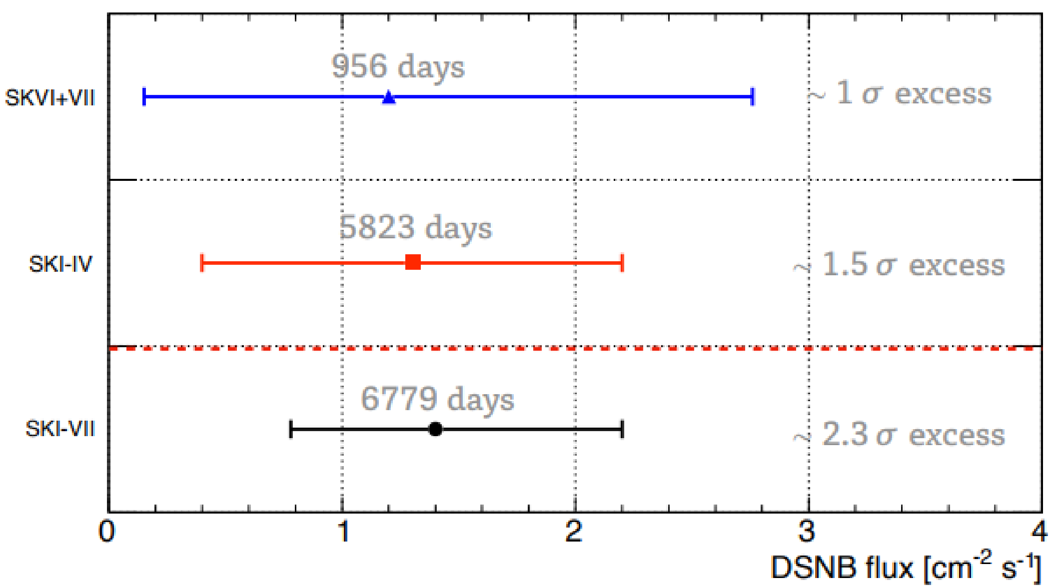


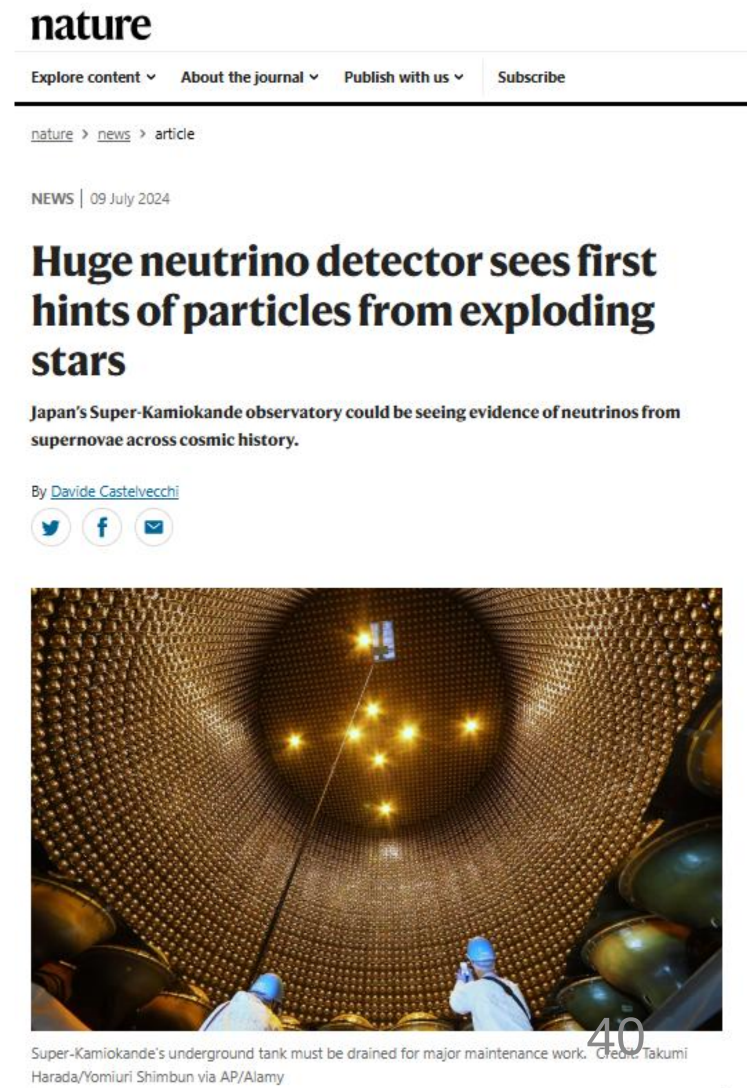
I'm not sure why LIGO performs better than ET.
Not well explained in the paper (ET and LIGO swapped?),

[Nature News 09 July 2024](#)

Supernova Relic Neutrinos

- “At last month’s [Neutrino 2024](#) conference in Milan, Italy, Masayuki Harada, a physicist at the University of Tokyo, [revealed](#) that the first hints of supernova neutrinos…”
- SK (5823 days) + Gd 0.01% (552 days) + Gd 0.03%(404 days)





nature

Explore content · About the journal · Publish with us · Subscribe

nature > news > article

NEWS | 09 July 2024

Huge neutrino detector sees first hints of particles from exploding stars

Japan’s Super-Kamiokande observatory could be seeing evidence of neutrinos from supernovae across cosmic history.

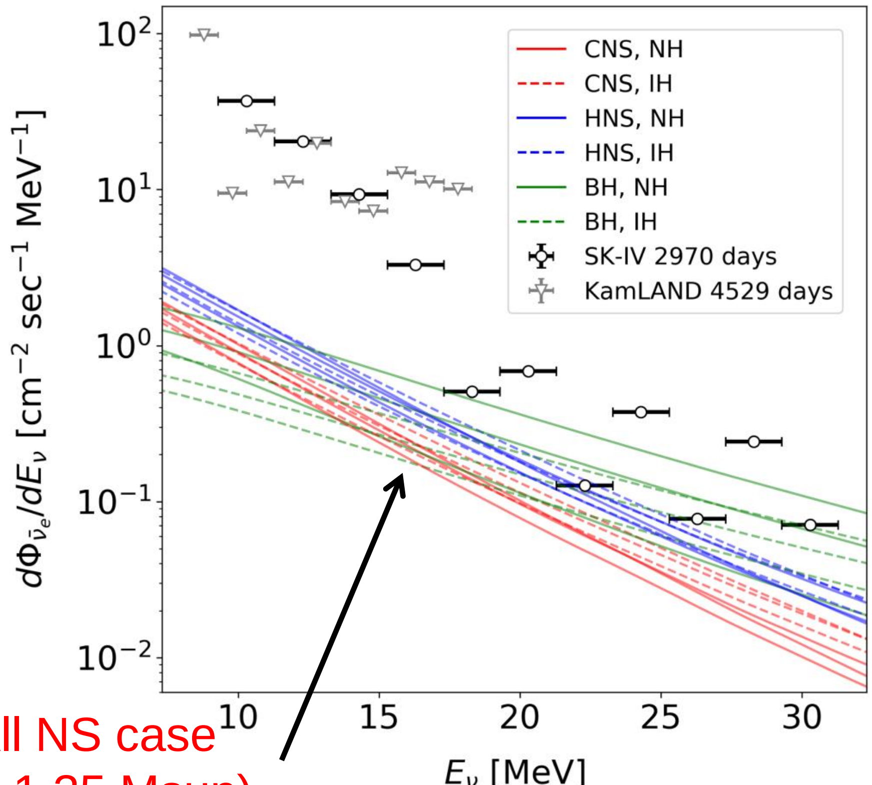
By Davide Castelvecchi

Super-Kamiokande’s underground tank must be drained for major maintenance work. Credit: Takumi Harada/Yomiuri Shimbun via AP/Alamy

Y. Ashida & K. Nakazato, ApJ 937, 30 (2022)

Relationship to NS EoS

- Total energy of neutrinos from core-collapse supernova depend on the remnant mass of neutron stars and equation of state (rate of failed supernova; black hole formation)

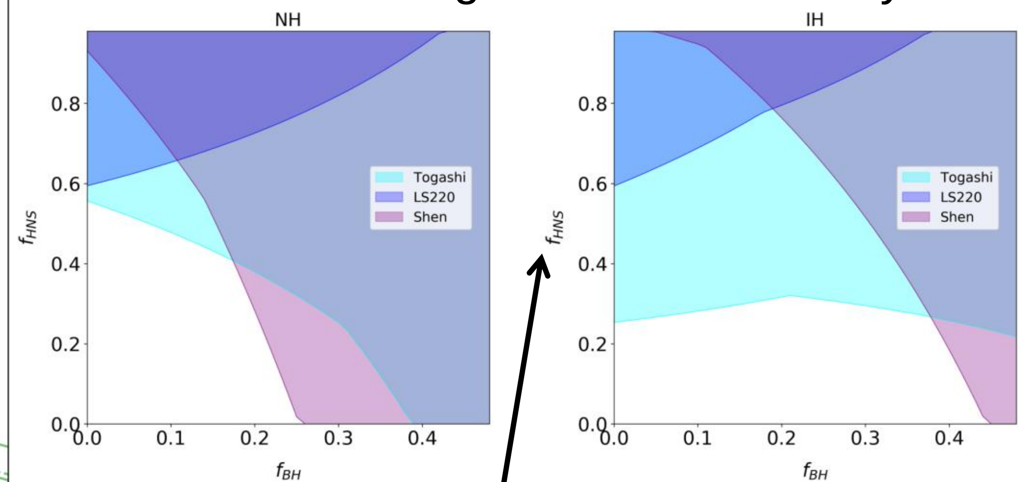


All NS case (~1.35 Msun)

All high mass NS case (>~1.6 Msun)

All BH case

Detectable region with SK-Gd 10 yr



Ratio of high mass NS

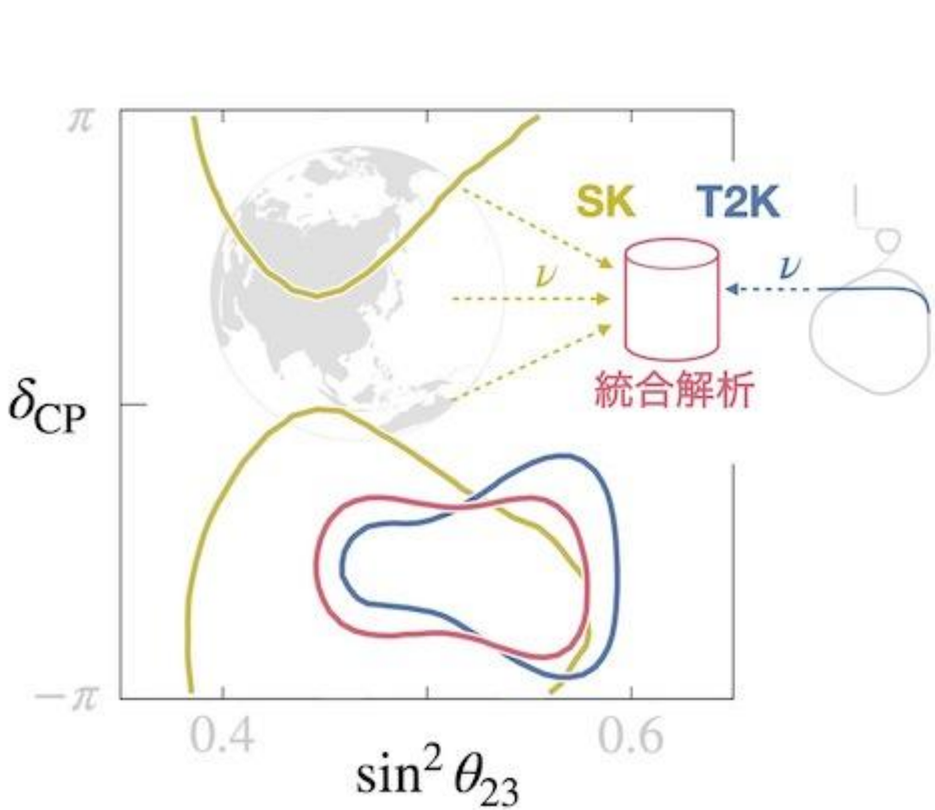
Ratio of BH

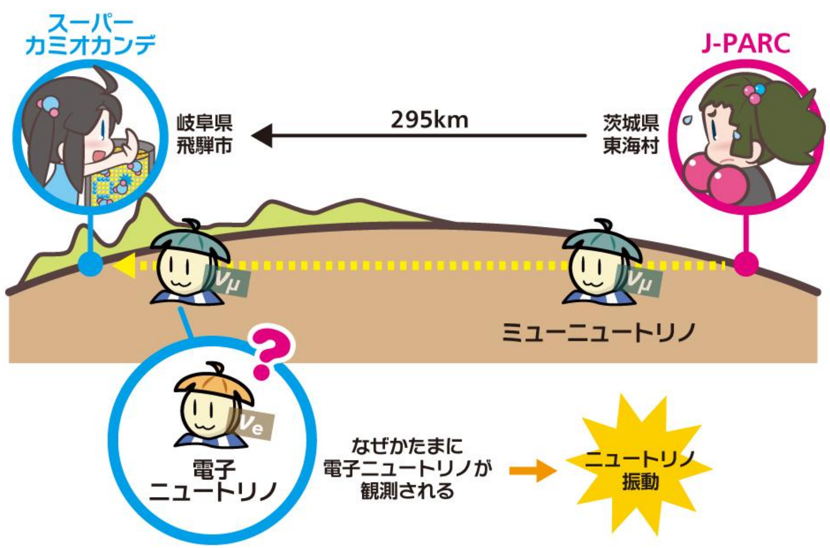
Should be able to combine with GW observations

SK & T2K, PRL **134**, 011801 (2025)

CP Violation in Neutrinos

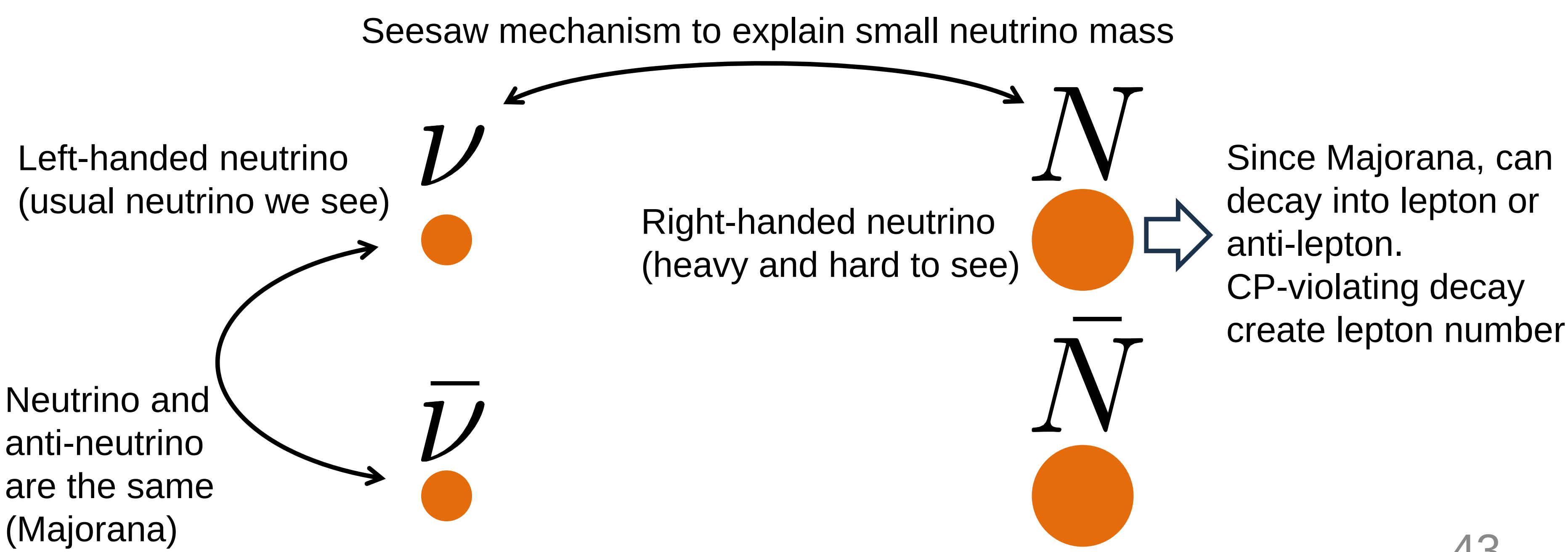
- First joint measurement of neutrino oscillation parameters with SK and T2K
- 1.9 σ exclusion of CP conservation





Leptogenesis

- CP violation in quarks is not enough to create matter-antimatter asymmetry
- Baryon number minus lepton number (B-L) is conserved in standard model
- Lepton number violation can create leptons, and then from B-L conservation, baryons can be created



$U(1)_{B\text{-}L}$ Extension

- $U(1)_{B\text{-}L}$ can be gauged by introducing right-handed neutrinos to cancel gauge anomaly
- New $U(1)_{B\text{-}L}$ symmetry predict B-L gauge boson (Féeton)
- If B-L coupling is small, this can be dark matter

W. Lin, L. Visinelli, D. Xu, T. T. Yanagida, [PRD **106**, 075011 (2022)]
Here, we name this the “féeton mechanism.” The name “féeton” comes from the French word fée for fairy.

J. Homans+, arXiv:2502.17108

Levitation in Space

- "Through a successful application into the 'ESA Payload Masters' competition, a position has been secured with The Exploration Company (TEC) for our experiment to be launched into low Earth orbit in June 2025 for a 3-hour flight to experience approximately 30 minutes of micro-g conditions as part of their 'Mission Possible' Nyx flight."

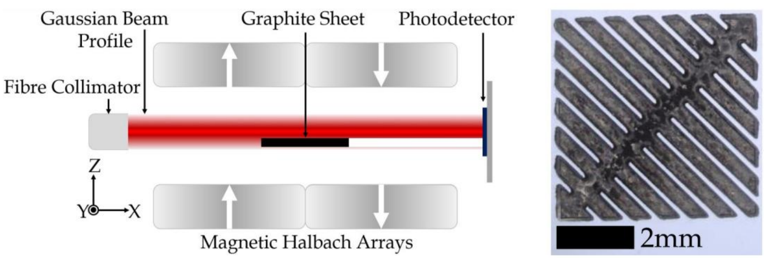


Figure 1. Magnetic trap layout with optical detection. Left: An illustration of the dual Halbach array passive magnetic trap with the laser beam offset from the trap's centre. Graphite levitation position is indicated by the black rectangle in the centre. Laser light is blocked by the graphite and detected in transmission on a photodetector. **Right:** A photograph of pyrolytic graphite sheet laser cut into a fish-bone configuration.

Parameter	Specification
Volume	$20 \times 20 \times 15$ cm
Mass	≤ 10 kg
Power	$1\ W_{av}/kg \leq 10\ W_{av}$, $84\ W_{peak}$, 28 V
Data	1 GB main storage, 100 MB backup
Thermal conditions	$0 \to 50°C$

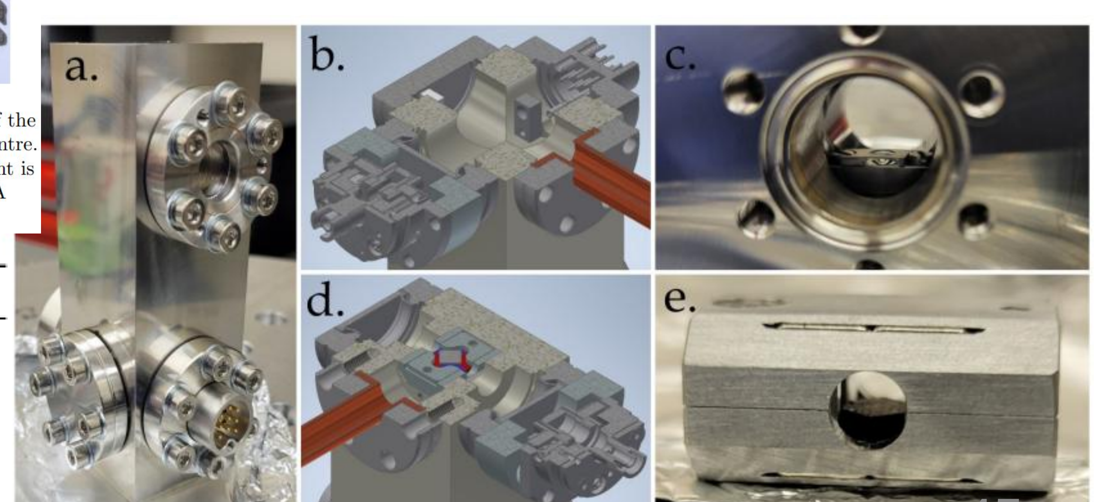
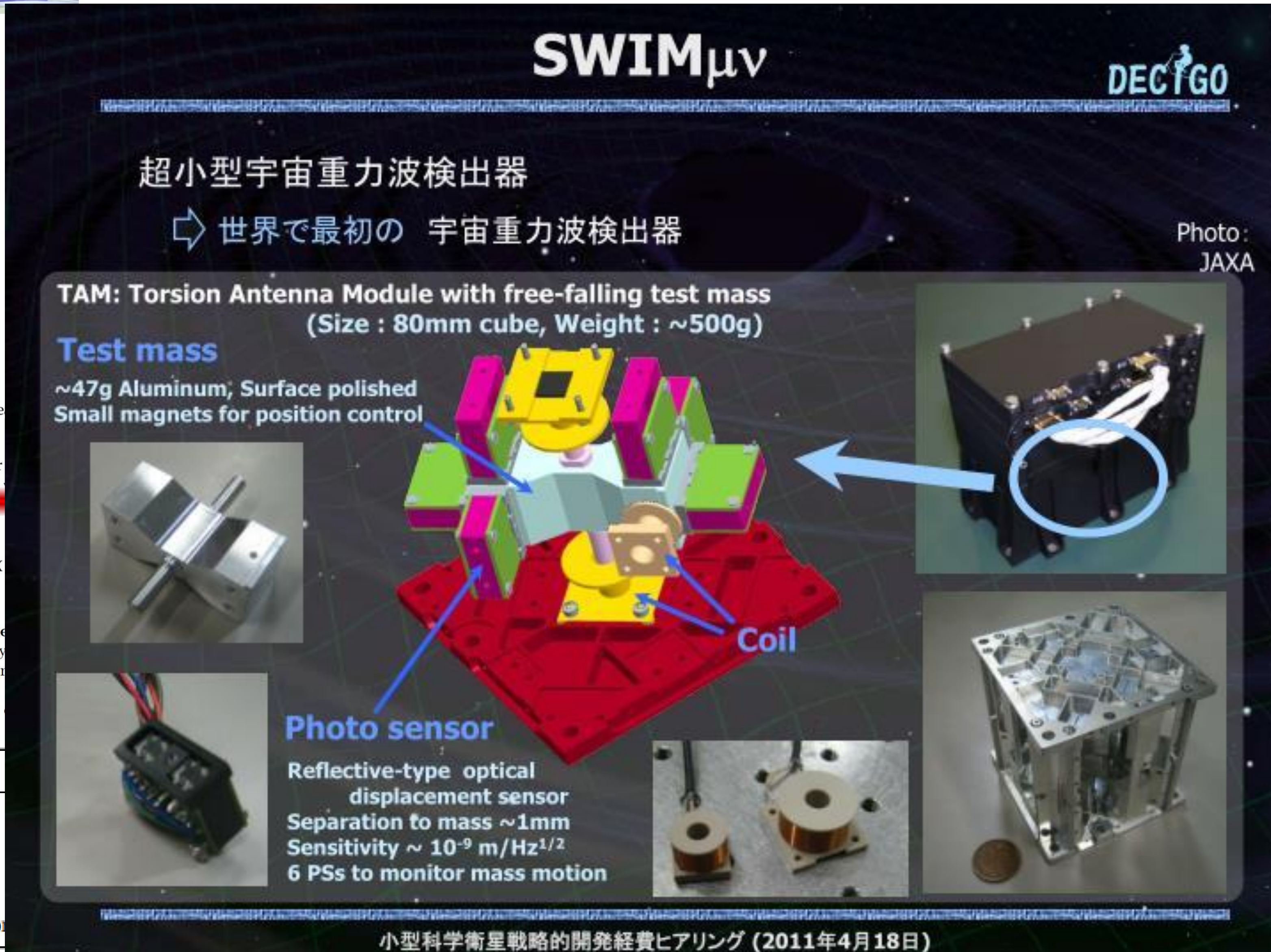


Figure 2. Details of vacuum chamber with optical and magnetic traps. a. The

J. Homans+, arXiv:2502.17108

Levitation in Space

- d
  The
  flight



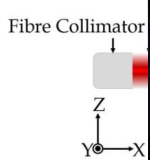


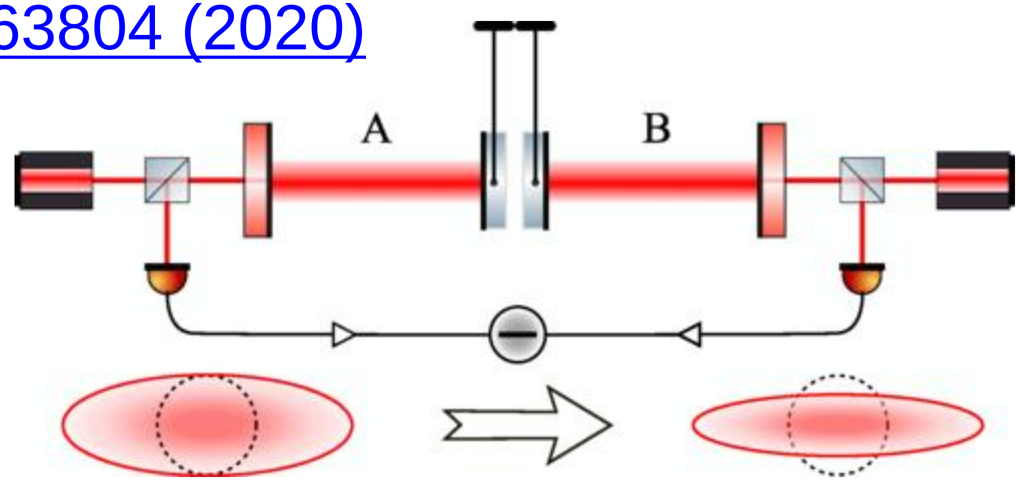
Figure 1. Magne
dual Halbach array
Graphite levitation
blocked by the
photograph

Parameter
Volume
Mass
Power
Data
Thermal co

Figure 2. Details of vacuum chamber with optical and magnetic traps. a. The

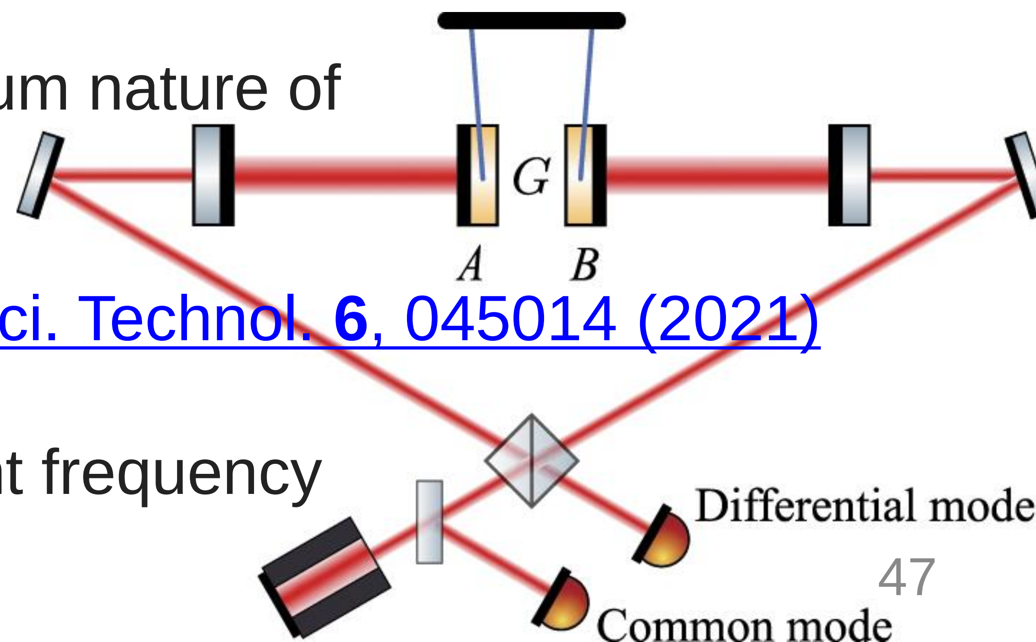
Gravitational Entanglement

- Quantum correlations of light mediated by gravity
  H. Miao+, PRA **101**, 063804 (2020)



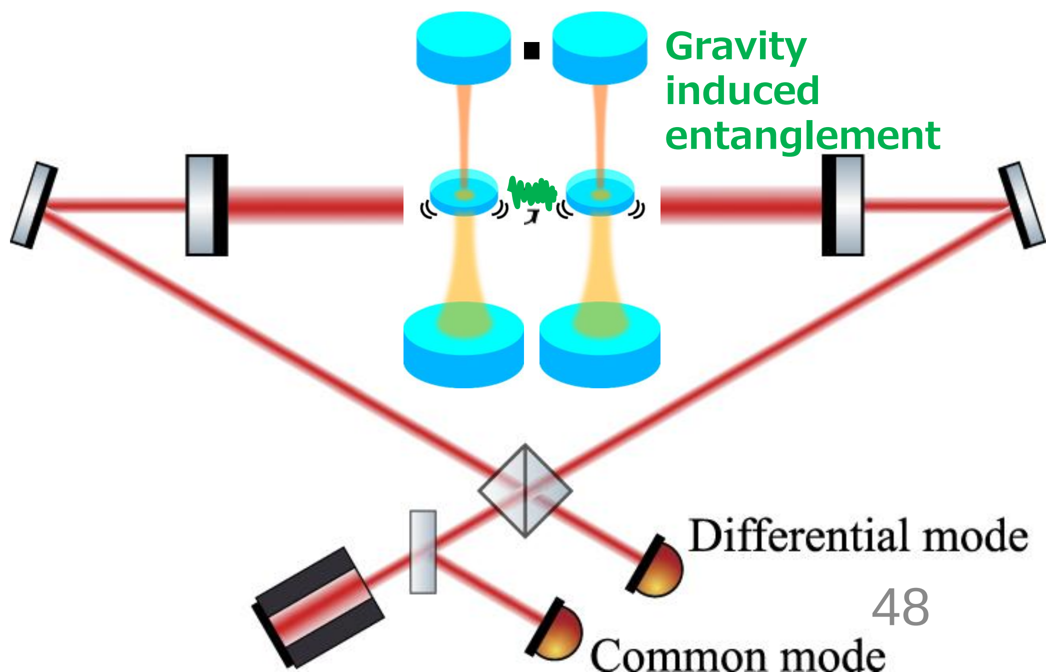
- Signatures of the quantum nature of gravity in the differential motion of two masses
  A. Datta+, Quantum Sci. Technol. **6**, 045014 (2021)

  OK, but small resonant frequency shift



With Optical Levitation

- Inverted Oscillators for Testing Gravity-induced Quantum Entanglement
  T. Fujita, Y. Kaku, A. Matsumuta, YM, arXiv:2308.14552
- We proposed to use inverted oscillators to make time it takes to generate entanglement fast
- We did not discuss how to measure the entanglement



Entanglement via Classical Gravity

PHYSICAL REVIEW D **107,** 024004 (2023)

Y. Liu+,
[PRD **107**, 024004 (2023)]

Semiclassical gravity phenomenology under the causal-conditional quantum measurement prescription

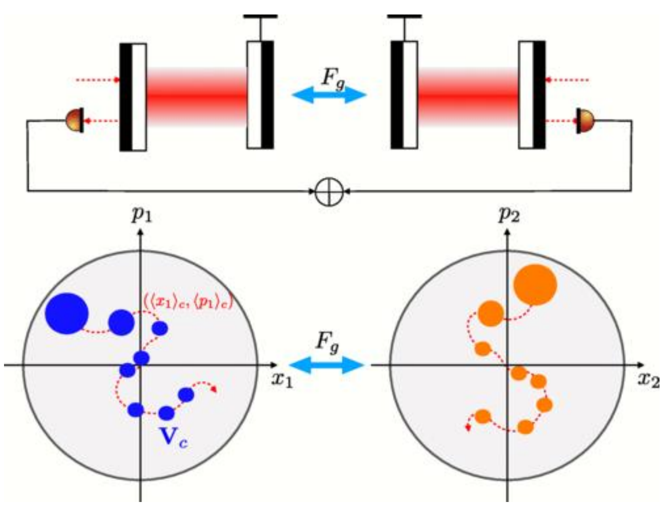
Yubao Liu,[1] Haixing Miao,[2] Yanbei Chen,[3,*] and Yiqiu Ma[1,4,†]

[1]*Center for Gravitational Experiment, Hubei Key Laboratory of Gravitation and Quantum Physics, School of Physics, Huazhong University of Science and Technology, Wuhan 430074, China*
[2]*State Key Laboratory of Low Dimensional Quantum Physics, Department of Physics, Tsinghua University, Beijing 100084, China*
[3]*Burke Institute of Theoretical Physics, California Institute of Technology, Pasadena, California 91125, USA*
[4]*Department of Astronomy, School of Physics, Huazhong University of Science and Technology, Wuhan 430074, China*

(Received 26 July 2022; accepted 14 December 2022; published 5 January 2023)

The semiclassical gravity sourced by the quantum expectation value of the matter's energy-momentum tensor will change the evolution of the quantum state of matter, which can be described by the Schrödinger-Newton (SN) equation. Understanding the phenomenology of the SN equation is important for experimentally testing the quantumness of gravity. In the SN theory, semiclassical gravity contributes a gravitational potential term depending on the matter's quantum state. This state-dependent potential introduces the complexity of the quantum state evolution and measurement in SN theory, which is different for different quantum measurement prescriptions. Previous theoretical investigations on the SN-theory phenomenology in the optomechanical experimental platform were carried out under the so-called post/preselection prescription. This work will focus on the phenomenology of SN theory under the causal-conditional prescription, which fits the *standard intuition* of the continuous quantum measurement process. We found that under the causal-conditional prescription, the quantum state of the test mass mirrors is conditionally prepared by the continuous projection of the outgoing light field in an optomechanical system. Hence a *quantum-trajectory-dependent gravitational potential* is created, which *significantly changes* the system evolution. This work provides an extensive analysis of this new picture of system evolution, and shows that various experimentally measurable signatures predicted by SN theory under causal-conditional prescription *cannot be distinguished* from that predicted by quantum gravity unless a very extreme experimental parameter region is assumed. Therefore, our new understanding of SN phenomenology provides an important caution toward the experimental verification of quantum gravity.

DOI: 10.1103/PhysRevD.107.024004



Role of Quantum Measurement

- D. Miki, Y. Kaku, Y. Liu, Y. Ma, Y. Chen, arXiv:2503.11882

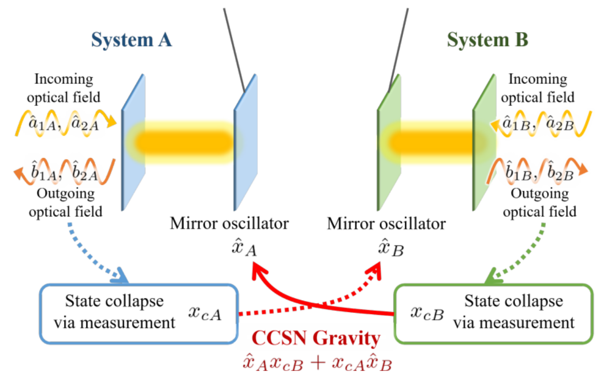
The Role of Quantum Measurements when Testing the Quantum Nature of Gravity

Daisuke Miki,[1,*] Youka Kaku,[2,†] Yubao Liu,[3,‡] Yiqiu Ma,[3,§] and Yanbei Chen[4,¶]

[1]*Department of Physics, Kyushu University, 744 Motooka, Nishi-Ku, Fukuoka 819-0395, Japan*
[2]*Department of Physics, Graduate School of Science, Nagoya University, Chikusa, Nagoya 464-8602, Japan*
[3]*National Gravitation Laboratory, Hubei Key Laboratory of Gravitation and Quantum Physics, School of Physics, Huazhong University of Science and Technology, Wuhan, 430074, China*
[4]*Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, California 91125, USA*

(Dated: March 18, 2025)

In order to test the quantum nature of gravity, it is essential to explore the construction of classical gravity theories that are as consistent with experiments as possible. In particular, the classical gravity field must receive input regarding matter distribution. Previously, such input has been constructed by taking expectation values of the matter density operator on the quantum state, or by using the outcomes of all measurements being performed on the quantum system — or by using information obtained by auxiliary observers (like those that lead to the CSL and Diosi-Penrose collapses) that continuously monitor the quantum dynamics. We propose a framework that unifies these models, and argue that the Causal Conditional Formulation of Schrödinger-Newton (CCSN) theory, which takes classical inputs only from experimental and environmental channels — without auxiliary observers — is a minimum model within this framework. Since CCSN can be viewed as a quantum feedback control scheme, it can be made explicitly causal and free from pathologies that previously plagued Schrödinger-Newton (SN) theories. Since classical information from measurement results are used to generate classical gravity, CCSN can mimic quantum gravity better than one would naively expect for a classical theory — making it more subtle to perform tests of the quantum nature of gravity. We predict experimental signatures of CCSN in two concrete scenarios: (i) a single test mass continuously monitored by light, and (ii) two objects interacting via mutual gravity, each monitored separately. In case (i), we show that the mass-concentration effect of self classical gravity still makes CCSN much easier to test than testing the establishment of mutual entanglement, yet the signatures are more subtle than previously thought for classical gravity theories. Using time-delayed measurements and non-stationary measurements, which delay or suspend the flow of classical information into classical gravity, one can make CCSN more detectable. In case (ii), we show that mutual gravity generated by CCSN can lead to correlations that largely mimic signatures of quantum entanglement in steady-state measurements. Rigorous protocols that rule out LOCC channels, which are experimentally more challenging than simply testing steady-state entanglement, must be applied in order to completely rule out CCSN.



Classical Gravity Models

- D. Miki, Y. Kaku, Y. Liu, Y. Ma, Y. Chen, [arXiv:2503.11882]

Class	Model	Auxiliary Observers Introduced?	Auxiliary Outcomes used to Generate ϕ?	Experimental Measurement Outcomes used to Generate ϕ?	Features
Collapse Models	Diosi-Penrose [19, 20]	Measure **g** everywhere	No	No	Gravity not implemented
	CSL [21, 22]	Measure Smeared Matter Distribution	No	No	
Schrödinger-Newton	Pre-Selection [3, 6] S-N	No	No	No	Violates Page-Geilker
	Post-Selection S-N [6]	No	No	Yes	Future measurement choices influence past.
	Causal-Conditional S-N [7, 8, 10, 11]	No	No	Obtain conditional expectation of positions then generate gravity via classical feedback	Preserves causality
Classical Gravity with Auxiliary Observers	N-H extension of S-N [23]	Measure **g** everywhere	Yes	No	Classical gravity via Diosi-Penrose measurements
	KTM Model [13, 14]	Measure position of each mass	Uses instant outputs of position channels	No	Instant outputs are very noisy
	Oppenheim's Model [24]	Yes	Yes	No	More general and includes NH and KTM
	Unified model	Measure position of each mass	Yes	Yes	Can incorporate all above models

For some reason collapses

Gravity generated at expectation value

Auxiliary observers measure wave function and generate gravity

Summary

- Many exciting advances in related fields provide further motivation for our experiments!