Prospects for the First Year of Reiwa 令和元年度の抱負

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Contents

- Looking back on the year 2018
- My plans and expectations for the year 2019
- Hot topics
  - DANCE: Dark matter Axion riNg Cavity Experiment
  - Optical levitation of photonic crystal mirror
  - Lorentz invariance test in space
  - C-DECIGO: km scale GW detector in space

My Plans 2018

Almost done

Done

Incorporated squeezing but not much progress on optimization

White paper on going, but not a feasibility study yet as we had imagined

Very fruitful visit

Less visit than anticipation

Enomoto-kun on ALS, Yamakoh-kun on MZM

My Plans 2018

- Finish axion paper.
- Finish bKAGRA Phase-1 paper.
- More investigation on sensitivity optimization for parameter estimation (incorporate detection rate, aLIGO/AdV sensitivity dependence, IM parameters, squeezing, polarization optimization).
- Realistic feasibility study for KAGRA+.
- Virgo visit from June 4 to August 18.
- KAGRA interferometer works from August (or October?).
- Summarize KAGRA lock acquisition scheme, including ALS and MZI modulation.
- In-vac RF PD and RF QPD.

Not yet

Frequently Asked Questions

- What percent of your time is spent to KAGRA?
- How often do you go to Kamioka?

He is a KAGRA member. He must be busy with KAGRA. But what does he do in specific?

He is not coming to Kamioka very often. He must be busy with different things. I'm not sure what he is actually doing in KAGRA.

I'm just curious. He does a lot of interesting things.

Effort Report for 2018

2018

January

Sun	Mon	Tue	Wed	Thu	Fri	Sat
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19J	20J
21J	22K	23K	24K	25K	26	27
28	29T	30J	31K			

February

Sun	Mon	Tue	Wed	Thu	Fri	Sat
				1T	2	3
4	5	6K	7K	8K	9	10
11	12	13K	14K	15K	16	17
18	19	20	21	22	23T	24
25	26T	27T	28T			

March

Sun	Mon	Tue	Wed	Thu	Fri	Sat
				1	2T	3
4	5K	6K	7K	8K	9	10
11	12	13	14	15	16	17
18	19	20	21	22T	23T	24T
25T	26	27	28	29	30	31

April

Sun	Mon	Tue	Wed	Thu	Fri	Sat
1	2	3	4	5	6T	7
8	9K	10K	11	12	13	14
15	16	17	18	19	20	21
22	23K	24K	25K	26	27	28
29	30					

May

Sun	Mon	Tue	Wed	Thu	Fri	Sat
		1	2	3	4	5
6	7	8	9	10	11A	12A
13A	14A	15A	16A	17A	18A	19A
20A	21A	22	23	24J	25J	26J
27	28J	29	30	31		

June

Sun	Mon	Tue	Wed	Thu	Fri	Sat
					1	2
3	4A	5A	6A	7A	8A	9A
10A	11A	12A	13A	14A	15A	16A
17A	18A	19A	20A	21A	22A	23A
24A	25A	26A	27A	28A	29A	30A

July

Sun	Mon	Tue	Wed	Thu	Fri	Sat
1A	2A	3A	4A	5A	6A	7A
8A	9A	10A	11A	12A	13A	14A
15A	16A	17A	18A	19A	20A	21A
22A	23A	24A	25A	26A	27A	28A
29A	30A	31A				

August

Sun	Mon	Tue	Wed	Thu	Fri	Sat
			1A	2A	3A	4A
5A	6A	7A	8A	9A	10A	11A
12A	13A	14A	15A	16A	17A	18A
19	20	21	22	23	24J	25J
26J	27	28	29	30	31	

September

Sun	Mon	Tue	Wed	Thu	Fri	Sat
						1
2	3K	4K	5K	6	7	8
9	10K	11K	12K	13K	14J	15J
16J	17	18	19	20	21	22K
23K	24K	25K	26	27	28	29
30						

October

Sun	Mon	Tue	Wed	Thu	Fri	Sat
	1	2	3	4	5	6
7	8	9K	10K	11K	12K	13
14	15	16T	17	18	19T	20T
21K	22K	23K	24K	25	26	27
28J	29J	30J	31			

November

Sun	Mon	Tue	Wed	Thu	Fri	Sat
				1J	2J	3
4	5T	6	7	8K	9K	10K
11K	12	13T	14	15	16	17
18T	19	20	21T	22T	23	24
25	26	27	28	29	30	

December

Sun	Mon	Tue	Wed	Thu	Fri	Sat
						1
2	3	4T	5T	6T	7	8
9	10	11J	12	13	14	15
16	17T	18	19	20	21	22
23	24	25	26	27	28	29
30	31					

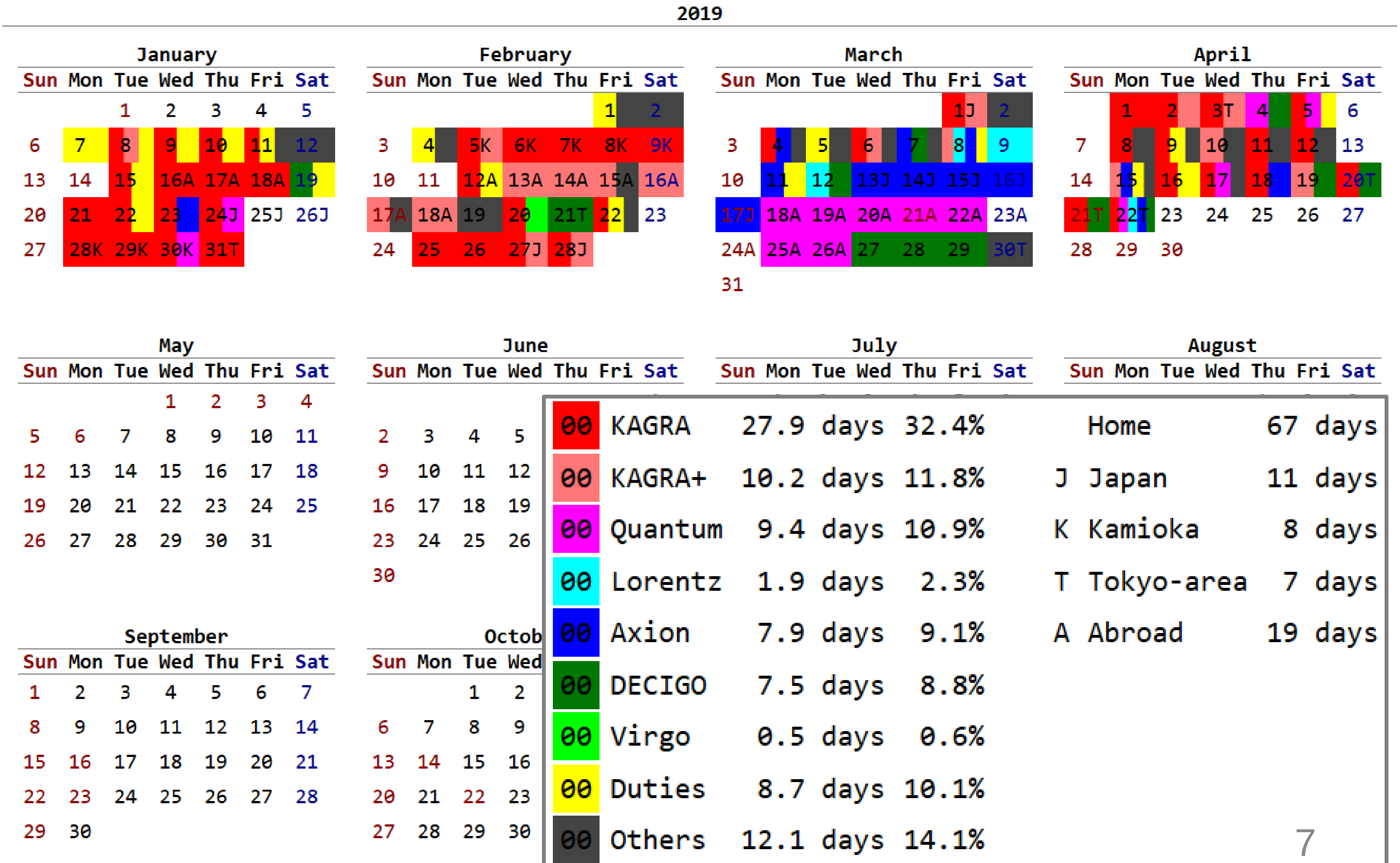
Effort Report for 2018

- 53 % effort on KAGRA (including KAGRA+)
  65 % effort if excluding Virgo
- 43 days / year (3.6 days/month) at Kamioka
  4.8 days/month if excluding Virgo period

00	KAGRA	99.0 days	37.1%		Home	191 days
00	KAGRA+	43.7 days	16.4%	J	Japan	20 days
00	Quantum	10.1 days	3.8%	K	Kamioka	43 days
00	Lorentz	0.0 days	0.0%	T	Tokyo-area	24 days
00	Axion	10.3 days	3.9%	A	Abroad	87 days
00	DECIGO	5.0 days	1.9%			
00	Virgo	46.9 days	17.6%			
00	Duties	34.3 days	12.9%			
00	Others	17.7 days	6.6%			

* Number of days spent was counted for each topic based on my personal record.
If n topics on the same day, 1/n was allocated for each topic.

Effort Report for 2019 (so far)



00	KAGRA	27.9 days	32.4%		Home	67 days
00	KAGRA+	10.2 days	11.8%	J	Japan	11 days
00	Quantum	9.4 days	10.9%	K	Kamioka	8 days
00	Lorentz	1.9 days	2.3%	T	Tokyo-area	7 days
00	Axion	7.9 days	9.1%	A	Abroad	19 days
00	DECIGO	7.5 days	8.8%			
00	Virgo	0.5 days	0.6%			
00	Duties	8.7 days	10.1%			
00	Others	12.1 days	14.1%			

My Expectations JFY2018

Not done (SNR 0.14)

Not enough resolution

Done (3mm dia. 0.5 mm thick, RoC 100 mm)

Not yet

Succeeded in cooling TOBA to 8.5 K

Kind of

My Expectations 2018

- Observe radiation pressure noise with torsion pendulum.
- Horizontal restoring force confirmation for optical levitation.
- Fabricate ~10 mg curved mirror.
- Start observation for Lorentz violation search, summarize the current setup.
- Some experimental result at cryogenic temperatures.
- Start DECIGO experiment.

My Expectations JFY2018

Nothing beyond my expectation……

Not d… 0.14)

Not enough resolution

Done (3mm dia. 0.5 mm thick, RoC 100 mm)

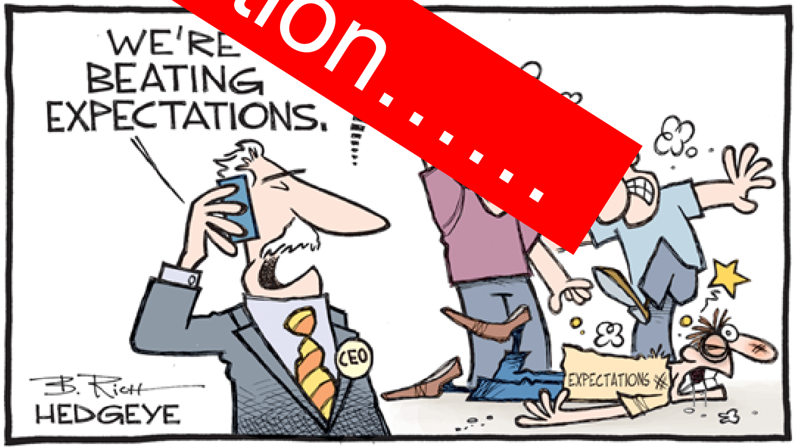
Not yet

Succeeded in cooling TOBA to 8.5 K

Kind of

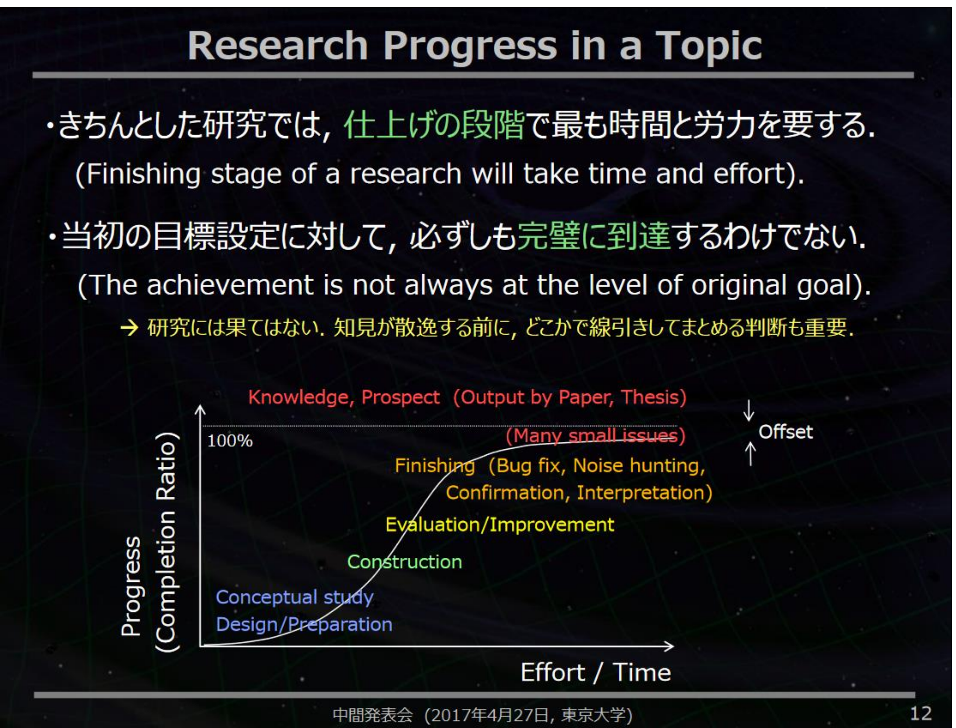
My Expectations 2018

- …diation pressure noise with torsion pendulum.
- Hori… …ring force confirmation for optical levitation.
- Fabricate … …rved mirror.
- Start observati… …tz violation search, summarize the current setup.
- Some experimental resu… …nic temperatures.
- Start DECIGO experiment.



But we wrote many papers than before

- Great!
- But only one paper on experimental result
- We have to complete our experiments at some point



- Earthquake-induced prompt gravity signals identified in dense array data in Japan
  - Masaya Kimura, Nobuki Kame, Shingo Watada, Makiko Ohtani, Akito Araya, Yuichi Imanishi, Masaki Ando and Takashi Kunugi
  - Earth, Planets and Space 71, 27 (2019)
- Demonstration of Displacement Sensing of a mg-Scale Pendulum for mm- and mg-Scale Gravity Measurements
  - Nobuyuki Matsumoto, Seth B. Cataño-Lopez, Masakazu Sugawara, Seiya Suzuki, Naofumi Abe, Kentaro Komori, Yuta Michimura, Yoichi Aso, and Keiichi Edamatsu
  - Phys. Rev. Lett. 122, 071101 (2019)
  - arXiv:1809.05081
- KAGRA: 2.5 generation interferometric gravitational wave detector
  - KAGRA Collaboration
  - Nature Astronomy 3, 35 (2019)
  - arXiv:1811.08079

2018

- Optical Ring Cavity Search for Axion Dark Matter
  - Ippei Obata, Tomohiro Fujita, Yuta Michimura
  - Phys. Rev. Lett. 121, 161301 (2018)
  - arXiv:1805.11753
- Polarization test of gravitational waves from compact binary coalescences
  - Hiroki Takeda, Atsushi Nishizawa, Yuta Michimura, Koji Nagano, Kentaro Komori, Masaki Ando, Kazuhiro Hayama
  - Phys. Rev. D 98, 022008 (2018)
  - arXiv:1806.02182
- Particle swarm optimization of the sensitivity of a cryogenic gravitational wave detector
  - Yuta Michimura, Kentaro Komori, Atsushi Nishizawa, Hiroki Takeda, Koji Nagano, Yutaro Enomoto, Kazuhiro Hayama, Kentaro Somiya, Masaki Ando
  - Phys. Rev. D 97, 122003 (2018)
  - arXiv:1804.09894
- Space Gravitational Wave Antenna DECIGO and B-DECIGO
  - Seiji Kawamura et al.
  - International Journal of Modern Physics D 27, 1845001 (2018)
- Seismic cross-coupling noise in torsion pendulums
  - Tomofumi Shimoda, Naoki Aritomi, Ayaka Shoda, Yuta Michimura, and Masaki Ando
  - Physical Review D 97, 104003 (2018)
  - arXiv:1802.06542
- Direct approach for the fluctuation-dissipation theorem under nonequilibrium steady-state conditions
  - Kentaro Komori, Yutaro Enomoto, Hiroki Takeda, Yuta Michimura, Kentaro Somiya, Masaki Ando, and Stefan W. Ballmer
  - Physical Review D 97, 102001 (2018)
  - arXiv:1803.00585
- Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA
  - KAGRA Collaboration, LIGO Scientific Collaboration, Virgo Collaboration
  - Living Reviews in Relativity 21, 3 (2018)
  - arXiv:1304.0670

Summary of JFY2018

- Couldn’t go to Kamioka very much than I had anticipated
- Many MIF related things not designed yet
- Done a lot of small tasks, but no highlight?
  - axion papers (good continuation so far)
  - bKAGRA Phase 1 paper & Nature Astronomy article
- Virgo visit was very good
- High school lectures for the first time
- New people related to axion, FF, Q-LEAP and QFilter
- Need to accelerate Lorentz violation, optical levitation and axion experiments
- Need to summarize current experiments
- Too many topics?

My Plans JFY2019

- Achieve 20 Mpc
- Complete remaining things
  - in-vac PDs and QPDs, beam dumps
  - optical table cover and tubes
  - beam shutter, new OMC
  - upgraded MZM
- Finish KAGRA+ paper and FPC White Paper
- Interferometer modeling
  - ASC
  - ITM inhomogeneity
  - parametric instability
- Some space mission proposal
- DANCE Act 1
- New mirror for optical levitation

My Expectations JFY2019

- The best arm length stabilization
- Achieve 10^{-15} /rtHz @ 0.1 Hz (or at least the best sensitivity)
- Demonstrate DECIGO interferometer controls
- Summarize DECIGO system requirements
- Squeezed angle rotation at some frequency
- Start Lorentz violation search with upgraded setup
- Horizontal restoring force confirmation for optical levitation
- Q measurement at cryogenic temperatures

- 3 PhD theses and 2 Master theses !!!!!
- New staff member in our group
  (from slightly different field)

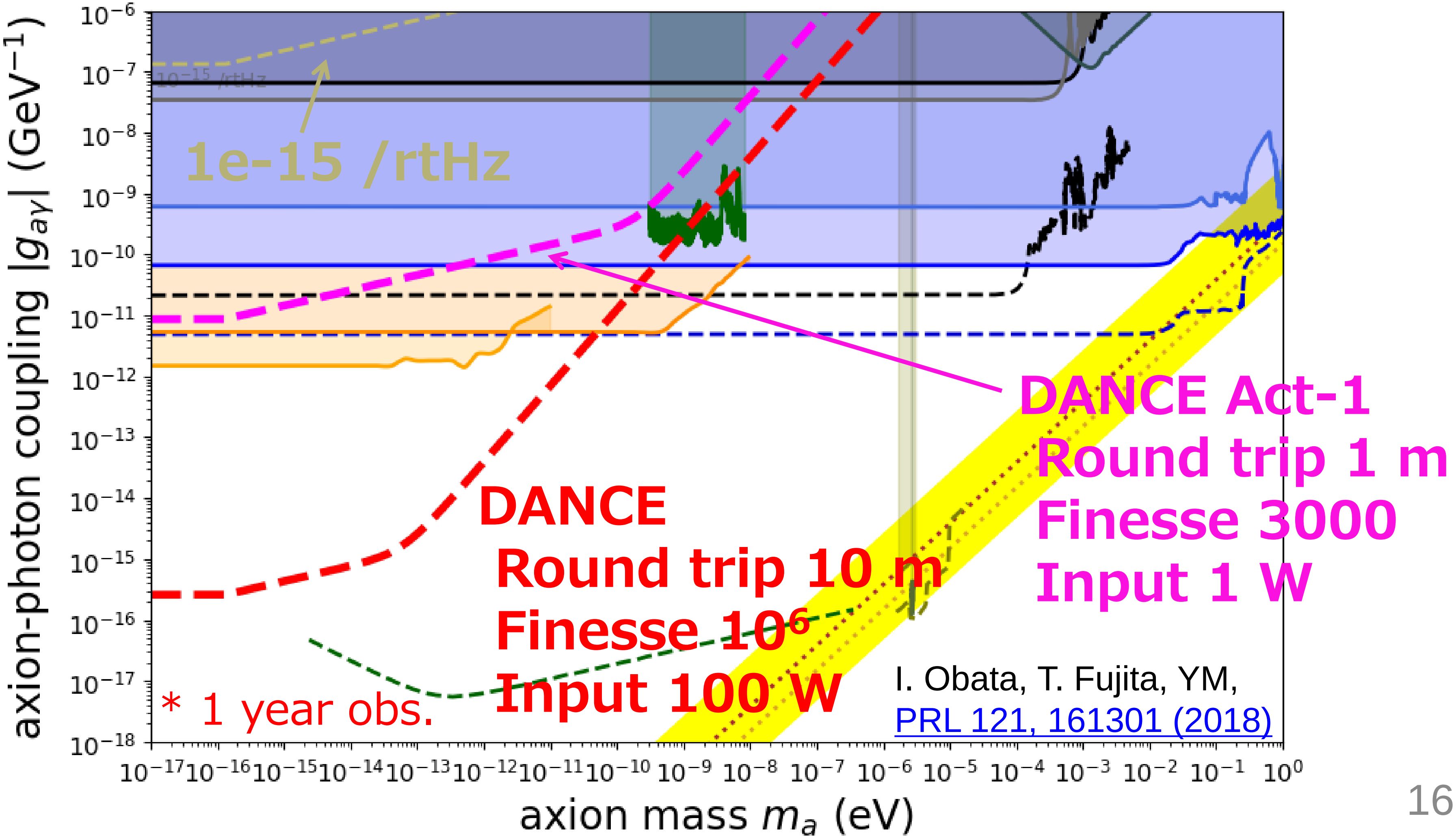
Schedules in JFY2019

- June 18: ICRR Seminar @ Kashiwa
- June: KIW6 @ Wuhan
- July: GR22 and Amaldi13 @ Valencia
- August: KAGRA F2F @ Toyama
- September: LVC @ Warsaw (??)
- September: TAUP2019 @ Toyama (?)
- September: 日本物理学会 @ 山形大学
- October: GWPAW2019 @ RESCEU (?)
- November: 量子エレクトロニクス研究会 @ 山中寮
- December: KAGRA F2F @ RESCEU
- December: 理論懇 @ 国立天文台
- March: 日本物理学会 @ 名古屋大学

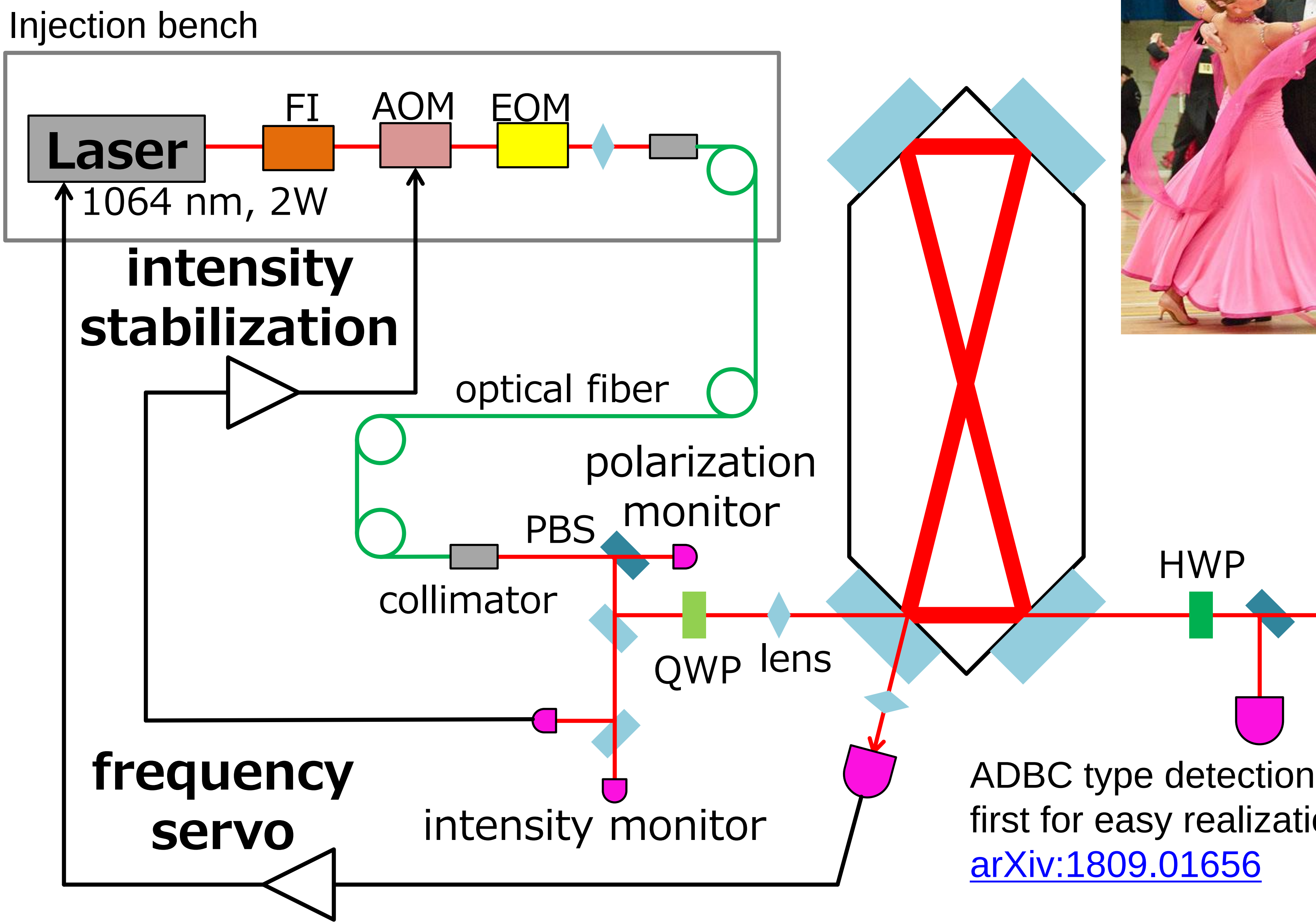
Dark matter Axion search with RiNg Cavity Experiment

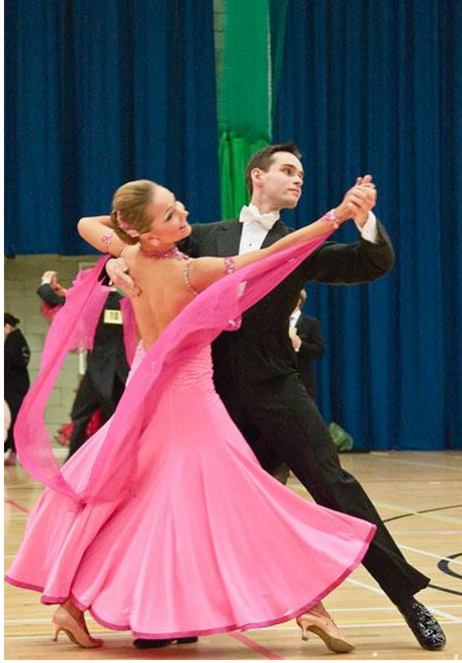
DANCE

- Ring cavity Experiment Is sensitive for Wide range of Axions
- Prototype experiment: DANCE Act-1



DANCE Act-1

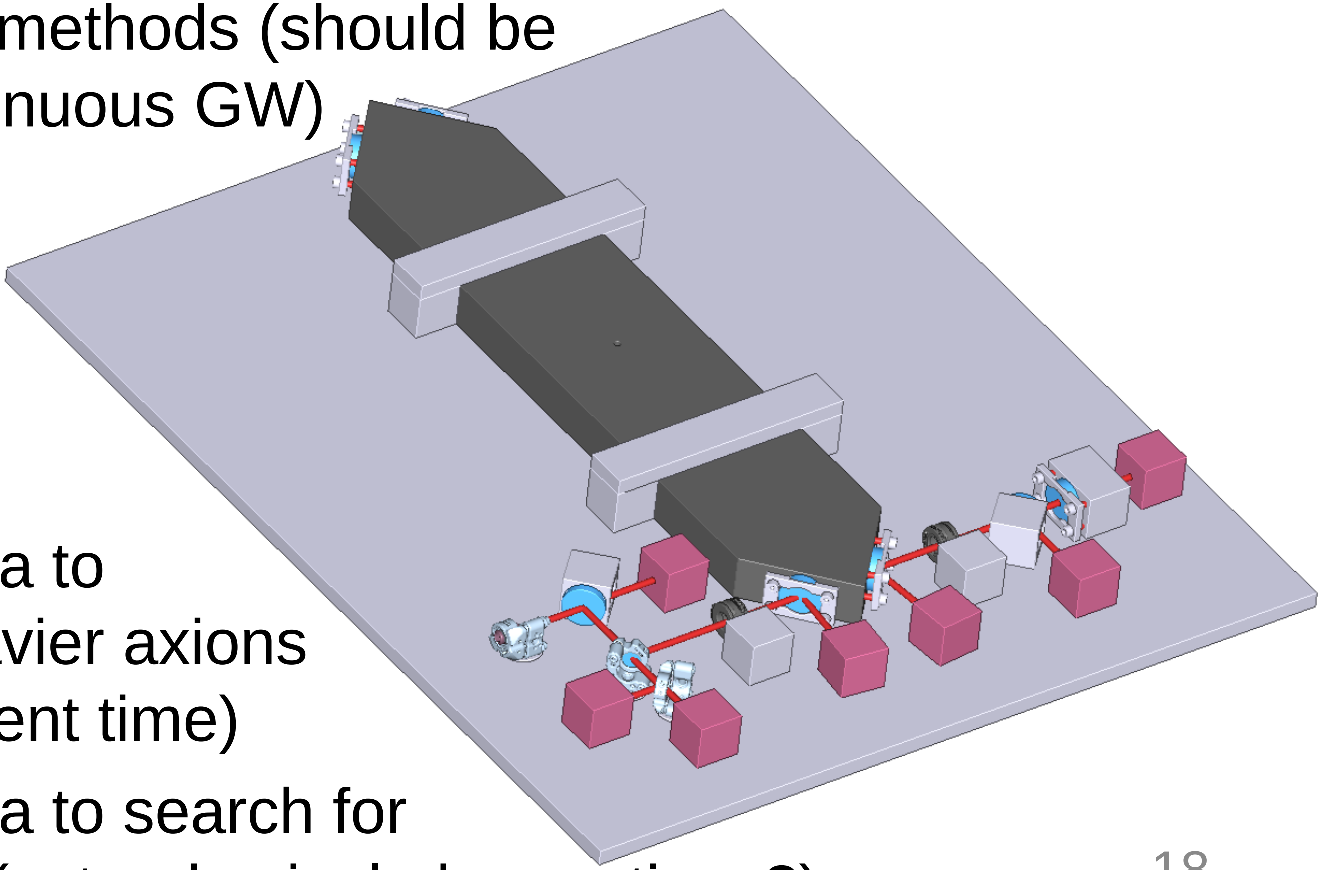




ADBC type detection
first for easy realization
arXiv:1809.01656

Things We Need to Check

- Resonance of circular polarization
- Resonant frequency difference between s-pol and p-pol
- Sensitivity calculations for ADBC type detection
- Data analysis methods (should be similar to continuous GW)

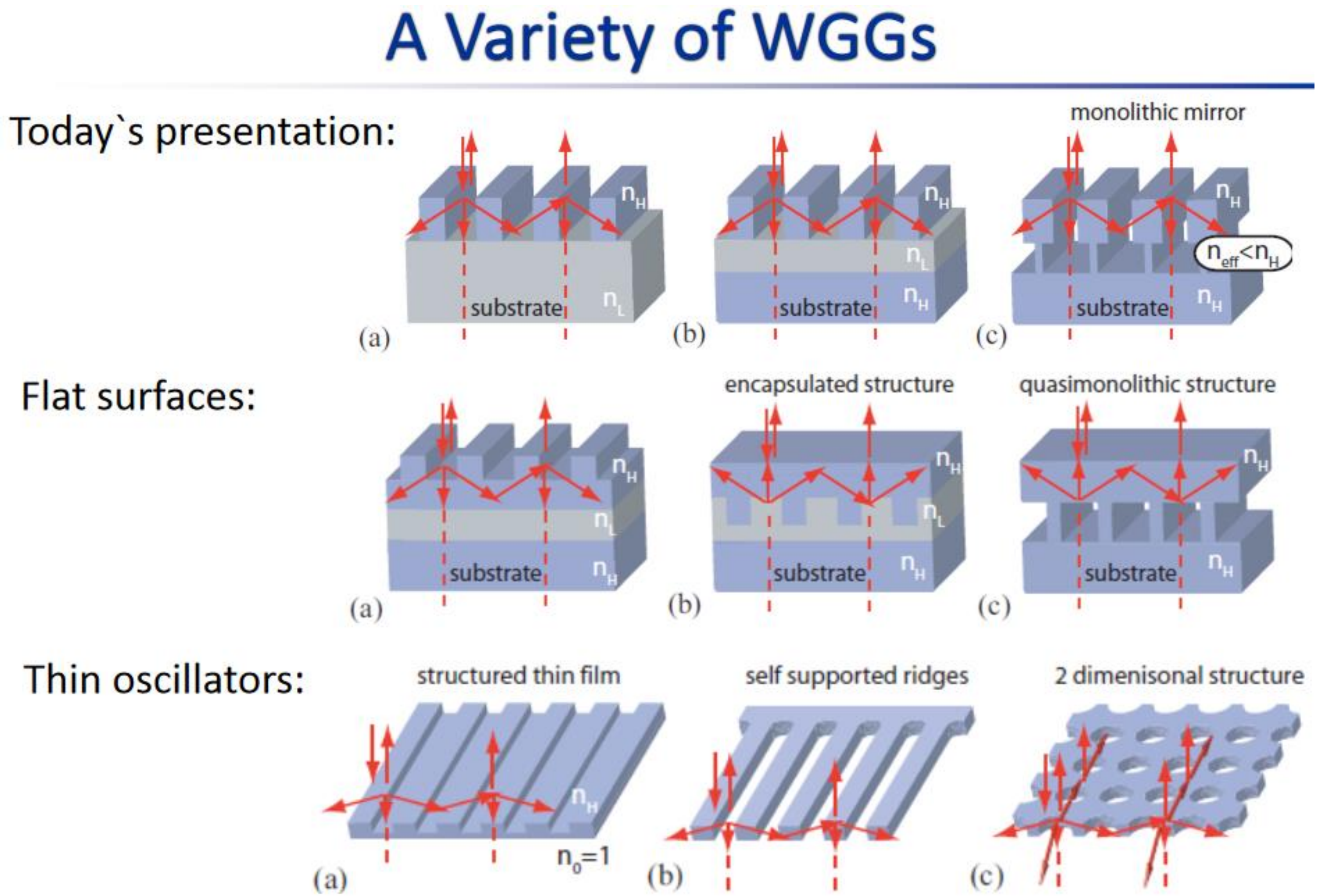


- Some new idea to search for heavier axions (shorter coherent time)
- Some new idea to search for lighter axions (astrophysical observations?)

Optical Levitation of Photonic Crystal Mirror

Photonic Crystals

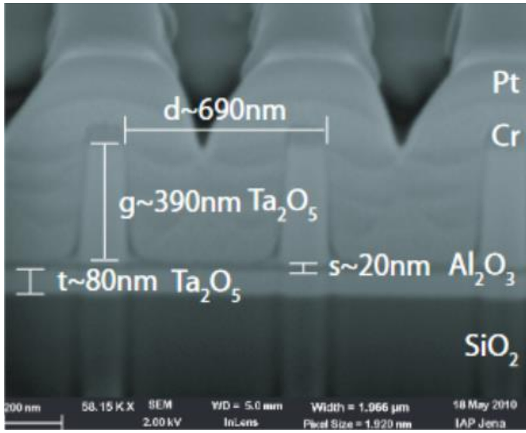
- I'm not sure what they are, but they look interesting
- Variety of ways for realization, variety of applications



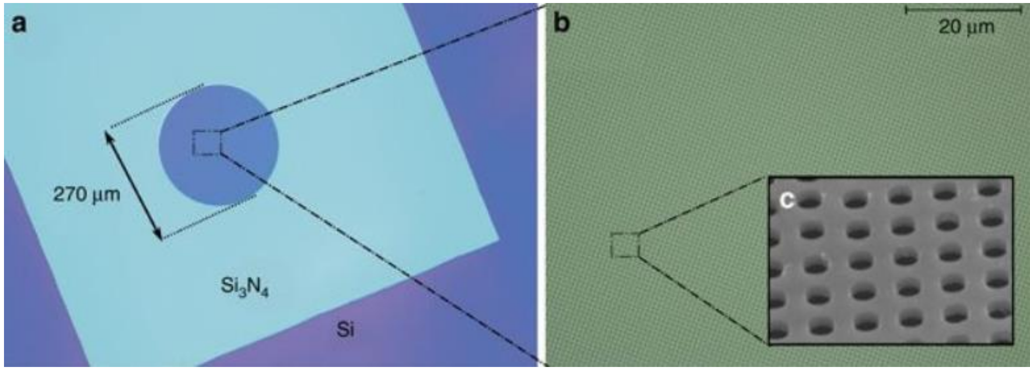
D. Friedrich, JGW-G1200794

High Reflectivity

- Demonstrated R=99.2 % @ 1064 nm
  for future GW detectors
  to reduce coating thermal noise
  Waveguide grating mirror in a fully suspended
  10 meter Fabry-Perot cavity
  D. Friedrich+, Optics Express 19, 14955 (2011)



- Reflectivity of 0 to 99.9470±0.0025% @ 1μm
  - high dependence on
    incident angle
    polarization
    wavelength
  - freedom for design
    ↔ you need careful tuning
  High-finesse Fabry-Perot cavities with bidimensional Si3N4
  photonic-crystal slabs
  X. Chen+, Light: Science & Applications 6, e16190 (2017)



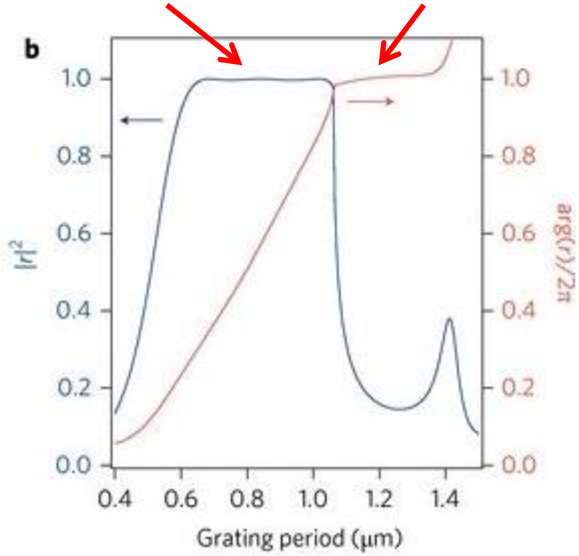
LKB group

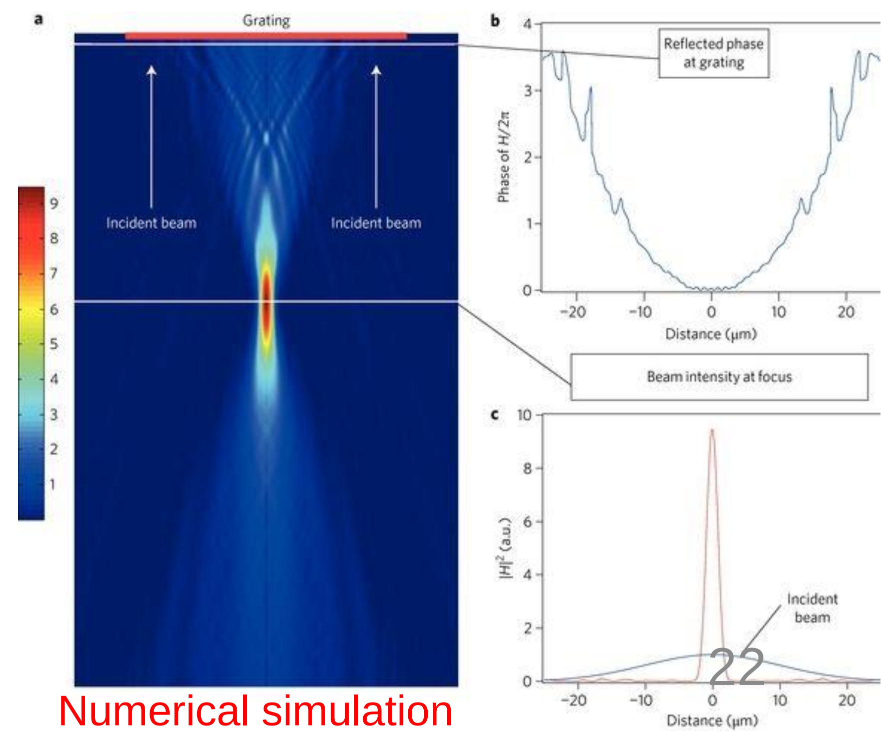
Curved Mirror

- Flat dielectric grating reflectors with focusing abilities
  D. Fattal+, Nature Photonics 4, 466 (2010)
- 450 nm thick Si on a quartz substrate
- Phase of the reflected beam depends on grating period
- Curved mirror can be realized by changing the grating period along the radial direction

Reflectivity is not so dependent

Phase is dependent

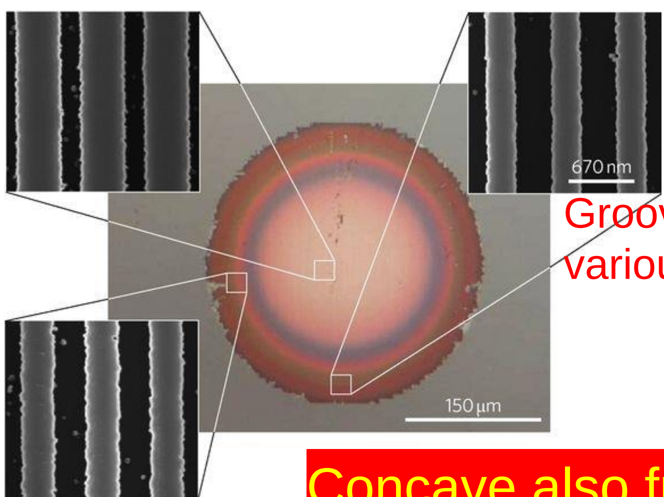




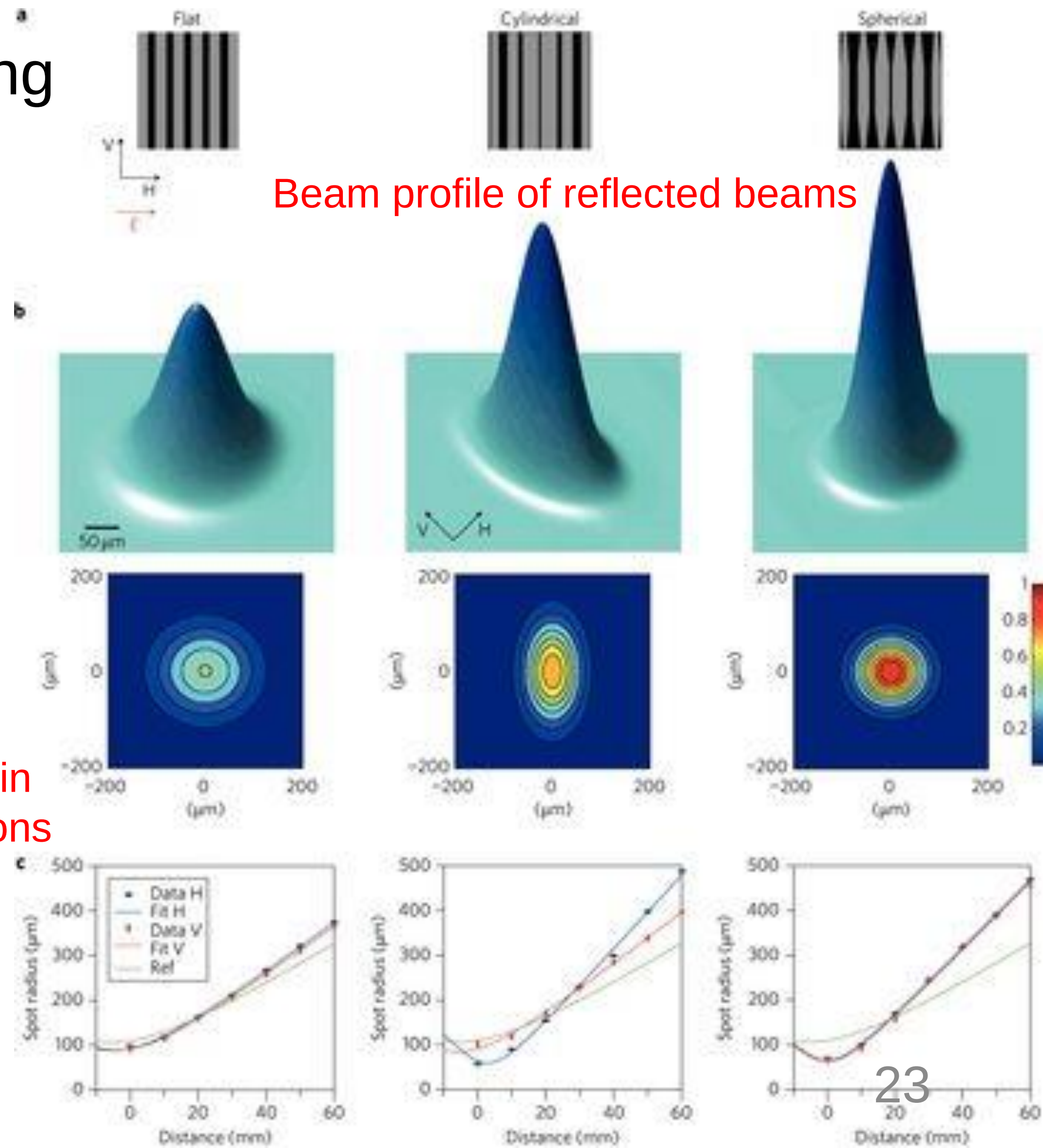
Numerical simulation

Curved Mirror

- Experimentally confirmed beam focusing
  - R = 80-90% (expected 98%)
    Due to proximity effects in the electron-beam lithography step, and surface roughness
  - RoC = 20 ± 3 mm (expected 17.9 mm)



Groove width in various locations

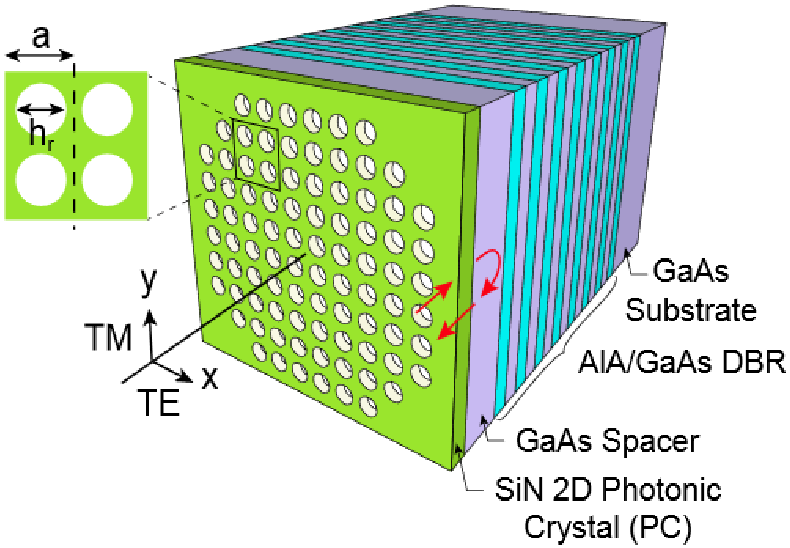


Beam profile of reflected beams

Concave also from the back side???

Curved Mirror with High Reflectivity

- Photonic crystal-based flat lens integrated on a Bragg mirror for high-Q external cavity low noise laser
  M. S. Seghilani+, Optics Express 22, 5962 (2014)
- Phase of reflected beam is dependent on filling factor



Distributed Bragg reflector (DBR) for high reflectivity

Filling factor $f = h_r/a$

Phase is dependent

Reflectivity is not so dependent

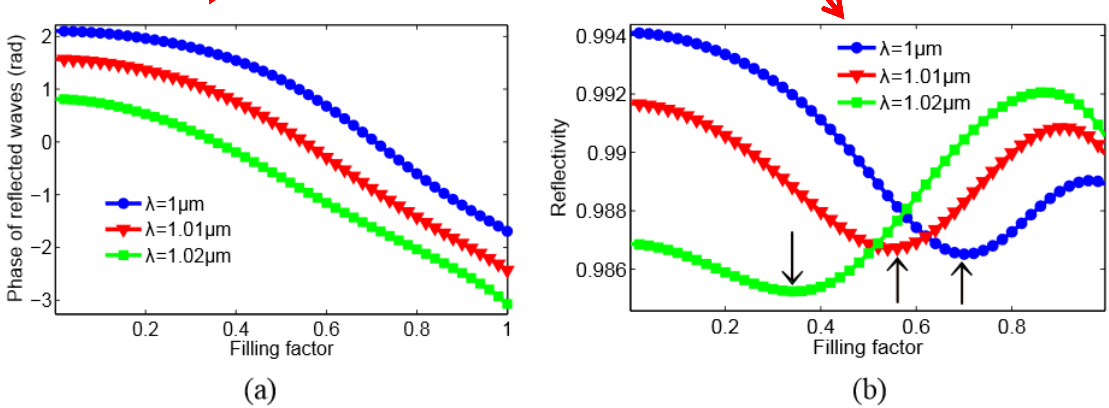
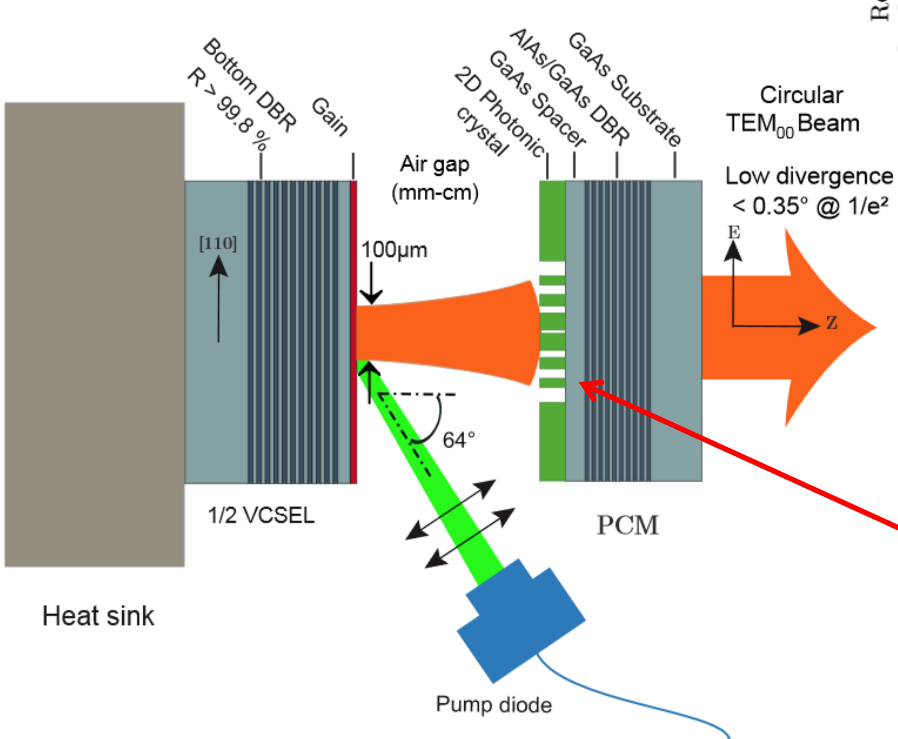
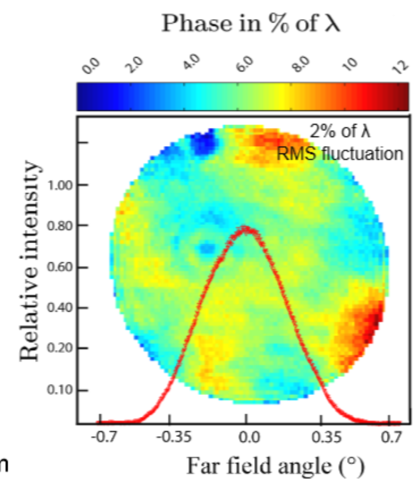


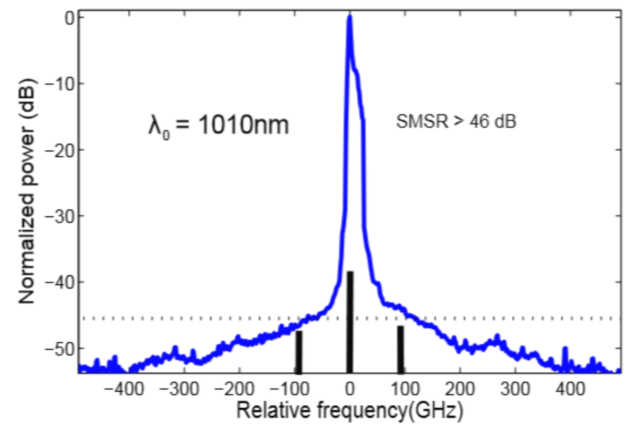
Fig. 3. (a) Phase of the reflected plane waves by PCM as a function of the filling factor at work wavelength $\lambda_0 = 1010nm \pm 10nm$ (PC thickness=280nm, Spacer thickness=142nm, a=280nm). (b) Corresponding PCM reflectivity, black arrows show the optical resonance effect moving when the wavelength changes.

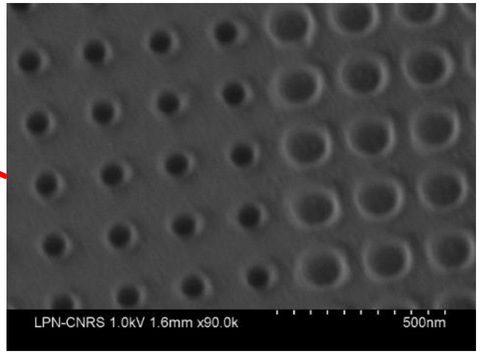
Curved Mirror with High Reflectivity

- Curved mirror can be realized by changing the filling factor along the radial direction
- Demonstrated a laser with this mirror
  R > 99%
  RoC = 20 mm









Optical Levitation

- We had difficulties in fabricating a mirror

	For SQL	Prototype	For suspended experiment
Mass	0.2 mg	~1.6 mg	~ 7 mg
Size (mm)	φ 0.7 mm t 0.23 mm	φ 3 mm t 0.1 mm	φ 3 mm t 0.5 mm
RoC	30 mm convex	30±10 mm convex (measured: 15.9±0.5 mm)	100 mm concave (previously flat ones were used)
Reflectivity	97 % (finesse 100)	>99.95 % (measured: >99.5%)	99.99%
Comment	Optics Express 25, 13799 (2017)	Only one without big cracks	Succeeded

- Can we put photonic crystal to (effectively) make curvature?
- Can we keep high reflectivity?
- Sandwich configuration possible?

Other Approaches?

too dirty for us!

Proposal

- Polarization-independent beam focusing by high-contrast grating reflectors
  W. Su+, [Optics Communications 325, 5 (2014)]
  - curved mirror by grating with parabolic surface
  - ~9 um focal length
  - focusing consistent with diffraction limit

too small for us!

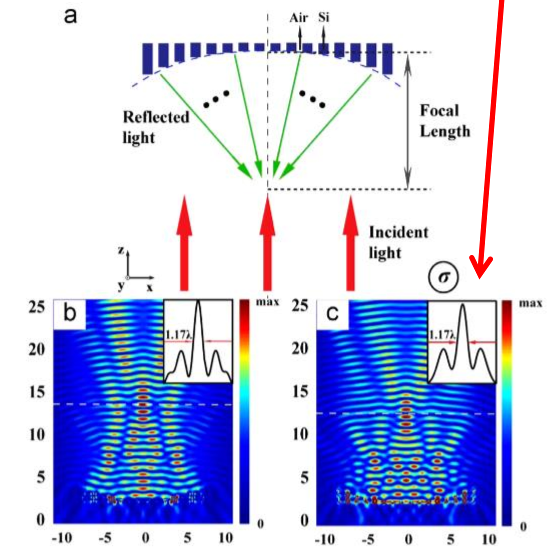
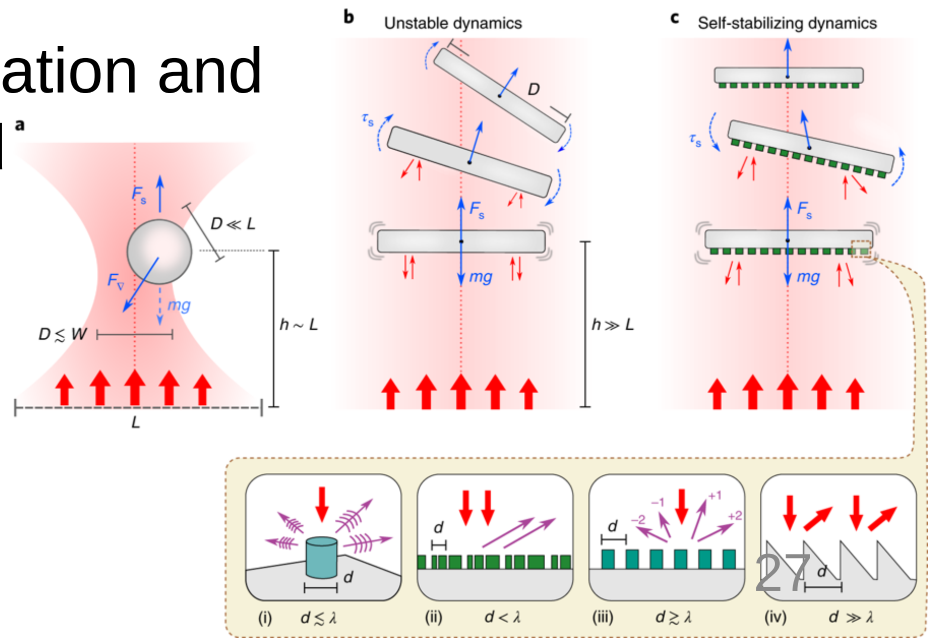


Fig. 2. (a) Schematic of a 2D HCG focusing reflector. The intensity distribution of the focused beam when (b) TE and (c) TM waves illuminate from the bottom side. The wavelength of the incident light is 1.55 μm, and the white line is the position of focal point. FWHMs are both 1.17λ.

Proposal

- Self-stabilizing photonic levitation and propulsion of nanostructured macroscopic objects
  O. Ilic & H. A. Atwater, [Nature Photonics 13, 289 (2019)]
  - levitation by tailoring asymmetric scattering of light



Lorentz Invariance Test in Space

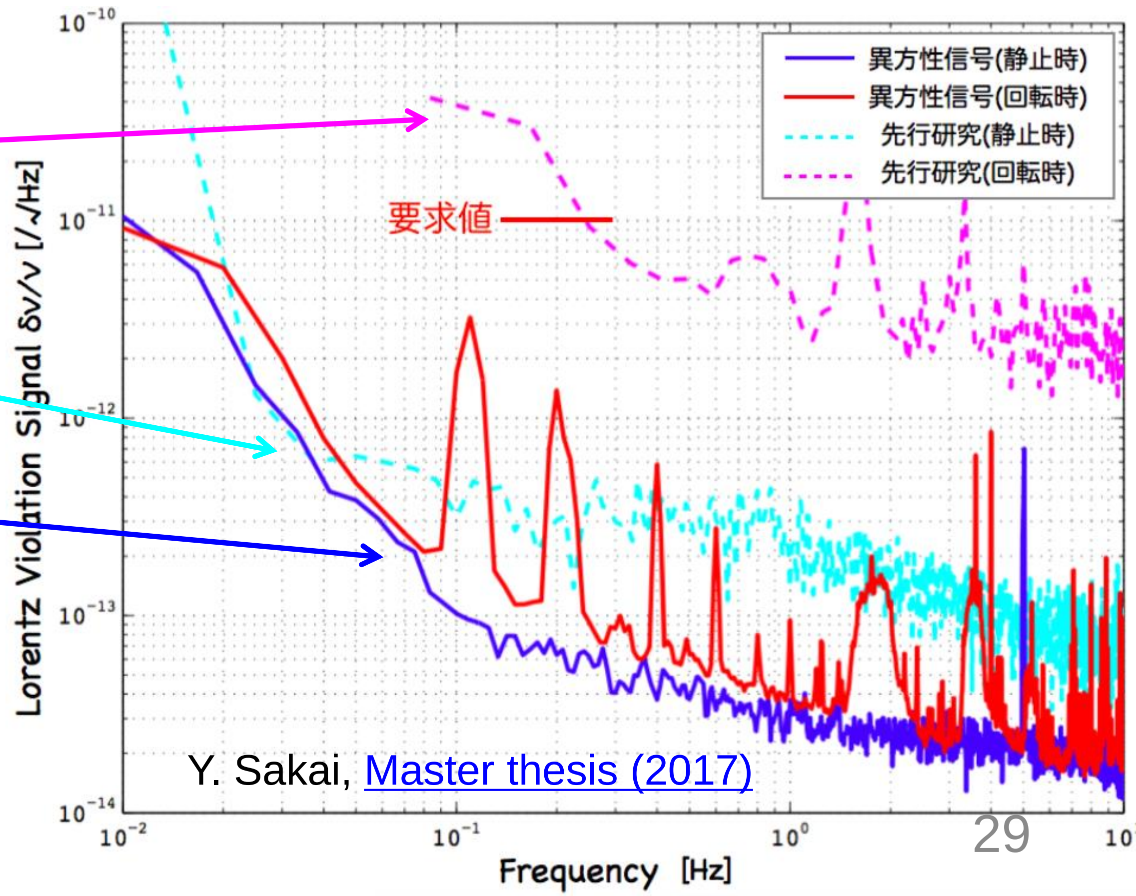
Lorentz Invariance Test

- We can reach $\frac{\delta c}{c} \sim 10^{-17}$ level if noise increase from rotation is negligible (with 1 year observation).
- Maybe we can realize quiet rotation in space!

Rotated (2013)
4e-11 /rtHz @ 0.1 Hz

Stationary (2011)

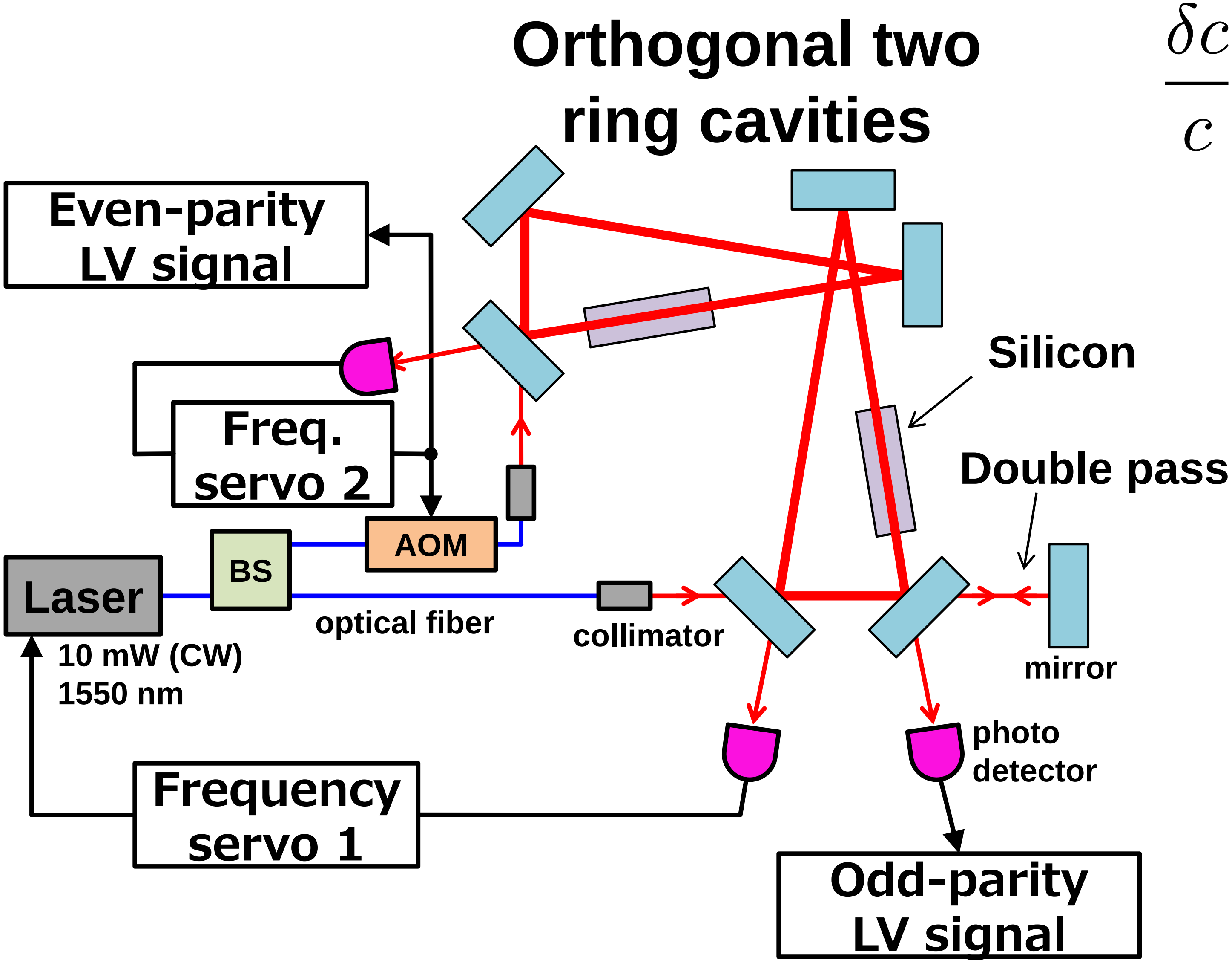
Stationary (2017)
1e-13 /rtHz @ 0.1 Hz



Y. Sakai, Master thesis (2017)

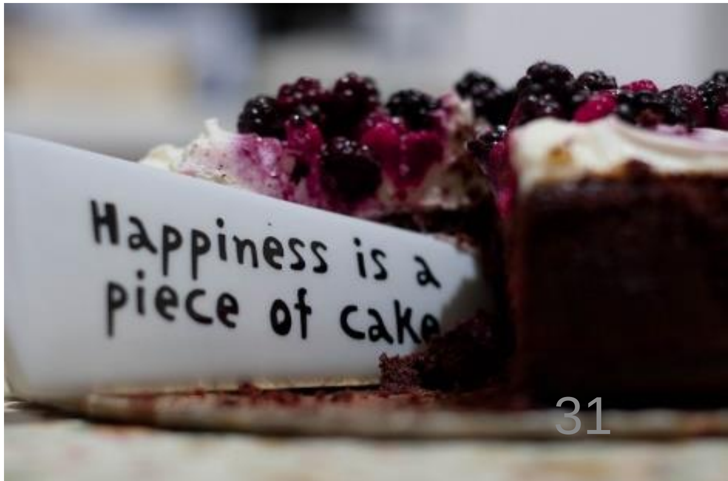
Proposed Setup

- Aim to search for both even-parity and odd-parity LV to $\frac{\delta c}{c} \sim 10^{-17}$



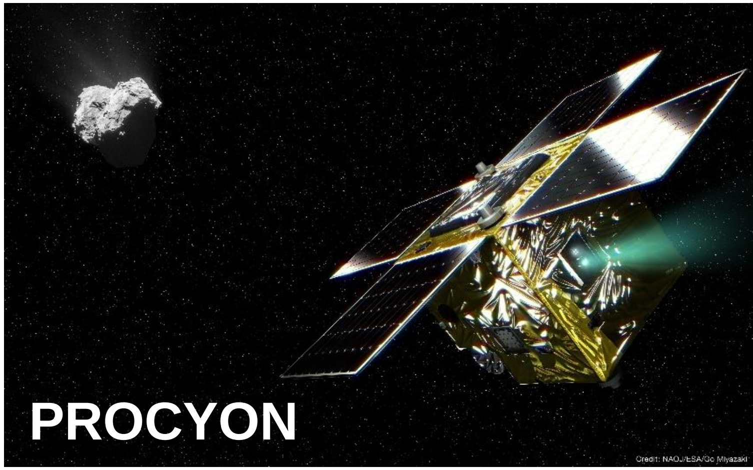
System Requirements

- Frequency noise: 1e-13 /rtHz
  - ground demonstration done for odd, stationary
- Laser: 10 mW, 1550 nm
  - DPF: 50x40x20 cm, 15 kg (~25 W, ~30 V)
  - LPF: 25x25x15 cm, 5 kg
  - No need for DPF, LPF level lasers. Frequency stabilization not necessary
- Temperature stability: 400 nK/rtHz (CMRR 1/100, silicon dn/dT)
  - <400 nK/rtHz at lab for odd confirmed by Takeda
  - ~100 μK/rtHz @ 0.1 mHz for LISA RSI 89, 045004 (2018)
- Attitude control: <~ 1deg,
  - needs satellite spin (@ ~0.1Hz?)
- Observation period: 1 year
  - continuous observation not necessary
  - ~0.01 MB/sec data rate



Possible Satellites

- Micro-satellite (数億円)
  50 cm cubic, ~50 kg
- CubeSat
  1U = 10 cm cubic, 1kg



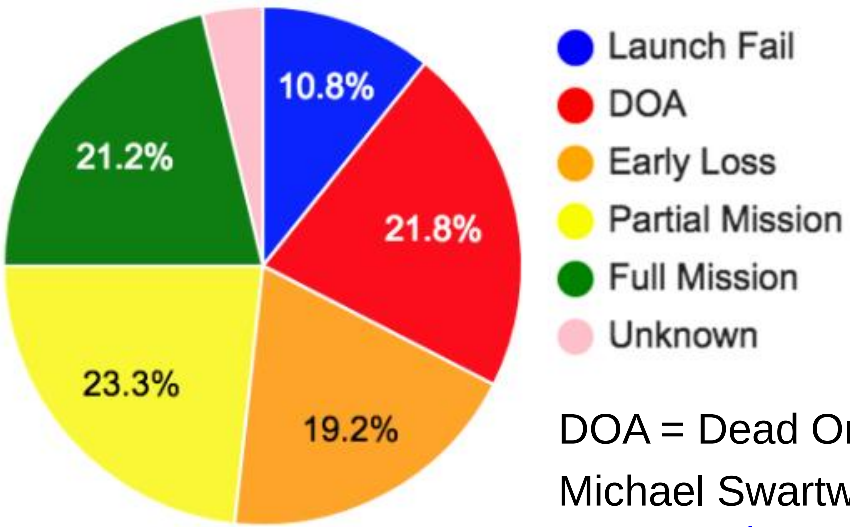


Figure 13. Mission Status for All University-Class Missions (1994-2017)

DOA = Dead On Arrival

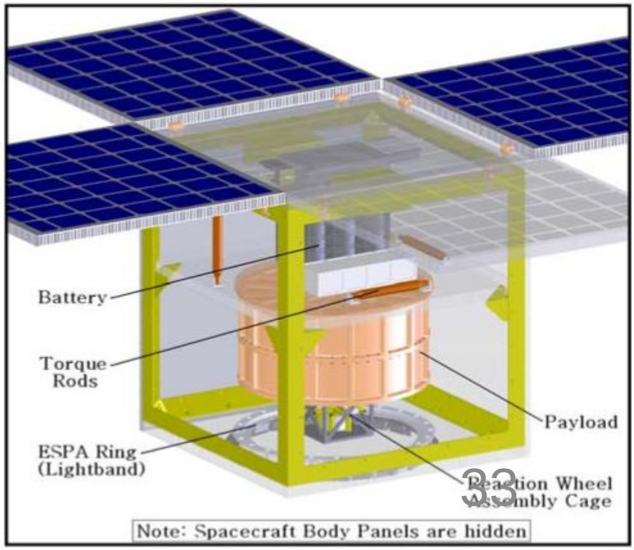
Michael Swartwout, “Reliving 24 Years in the next 12 Minutes: A Statistical and Personal History of University-Class Satellites”

Further Investigation Necessary

- Rotation
  - satellite rotation or rotation inside the satellite
  - rotation speed
  - rotation stability, vibrations
  - effect of gravity gradient to even parity experiment
- Laser source
  - smaller laser source
- Cavity
  - even parity setup
  - more compact

STAR

Space-Time Asymmetry Research

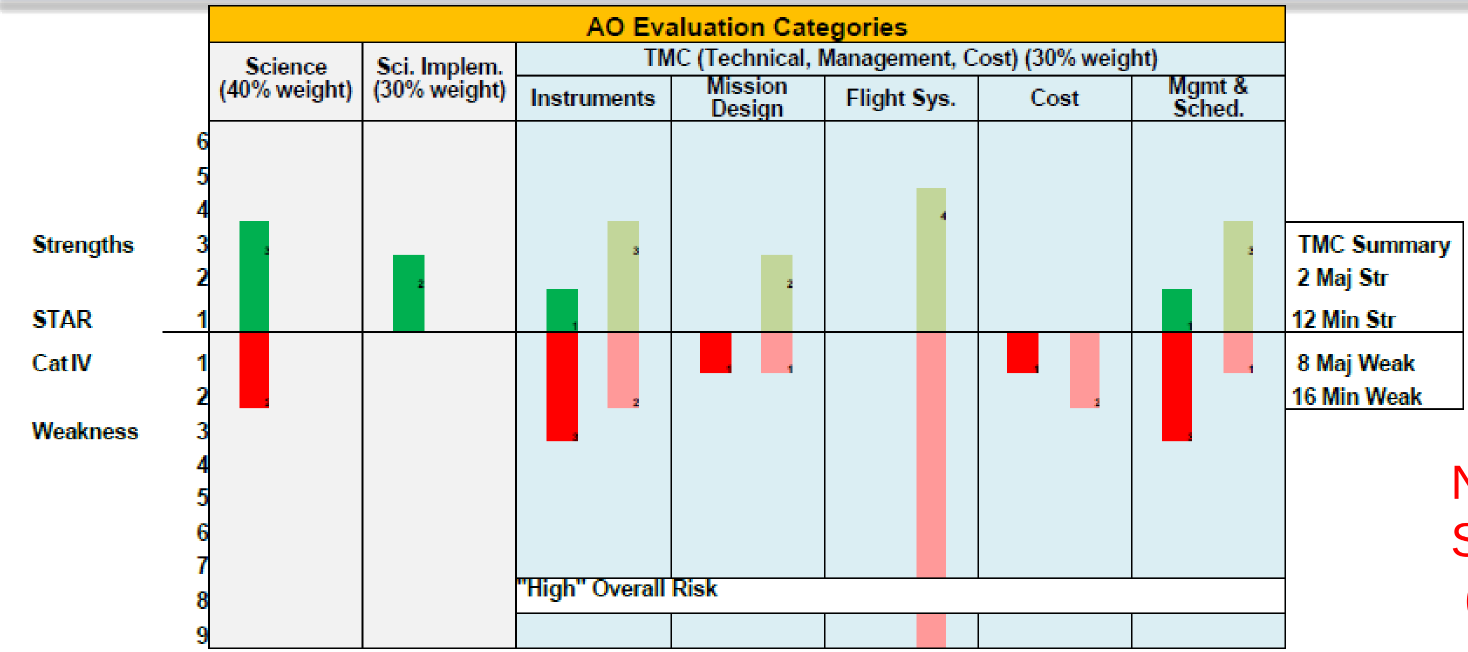


https://web.stanford.edu/~sbuchman/publications-PDF/Technology%20Development%20for%20Space%20Time%20Asymmetry%20Research%20(STAR)%20Mission.pdf

STAR was not Selected in 2008

http://www.stanford.edu/group/lisasymposium/LISA8_Byer.pdf

STAR Review Summary (MOO 2008)



NASA
Small Explorers
(SMEX) mission

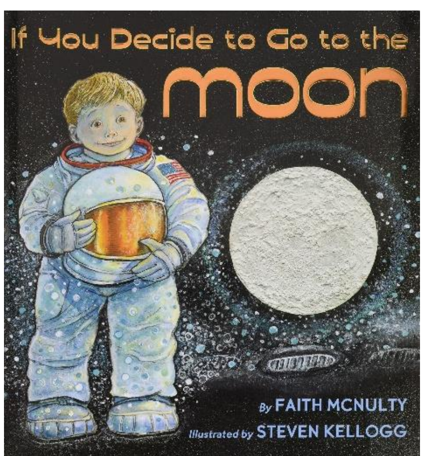
Science Major Strengths (5): Free flying observatory; Possibility of measuring violations in Lorentz invariance; Improved limits on violations of Lorentz invariance; Expert team; Instrument has rich heritage
Science Major Weaknesses (2): Not clear STAR measurements will be ahead of ground observations; no discussion of stretching of cavities by Earth's gravitational gradient
TMC Major Strength (2): Redundant science payload; excellent science team
TMC Major Weaknesses (8): Inadequate instrument tech development plans (three examples given); Orbit of 850 km won't decay in 25 years; Cost and workforce information inconsistent with schedule and required work; No dedicated PM; Inexperienced spacecraft team; Inadequate schedule detail

km-scale
Space Gravitational Wave Detector

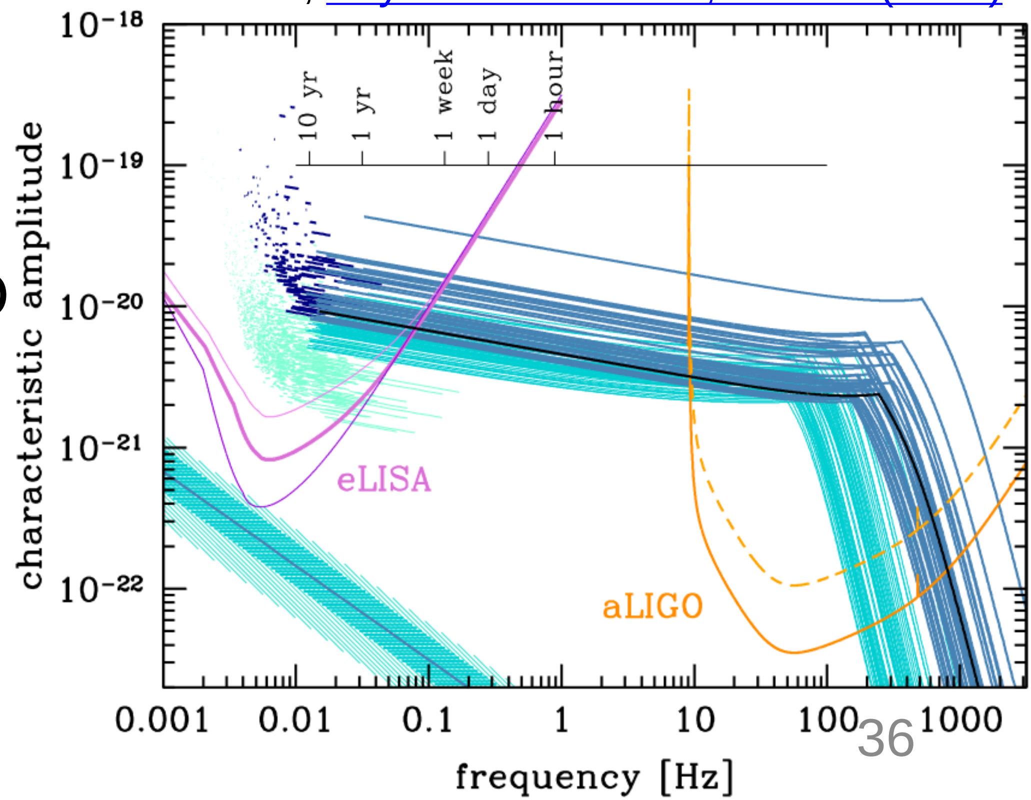
Motivations

- Demonstration of multiband gravitational wave detection
  - Detect BBHs and BNSs a few days before the merger
- IMBH search with unprecedented sensitivity

- km-scale space mission
- Demonstration of interferometry and formation flight for B-DECIGO and DECIGO



A. Sesana, Phys. Rev. Lett. 116, 231102 (2016)



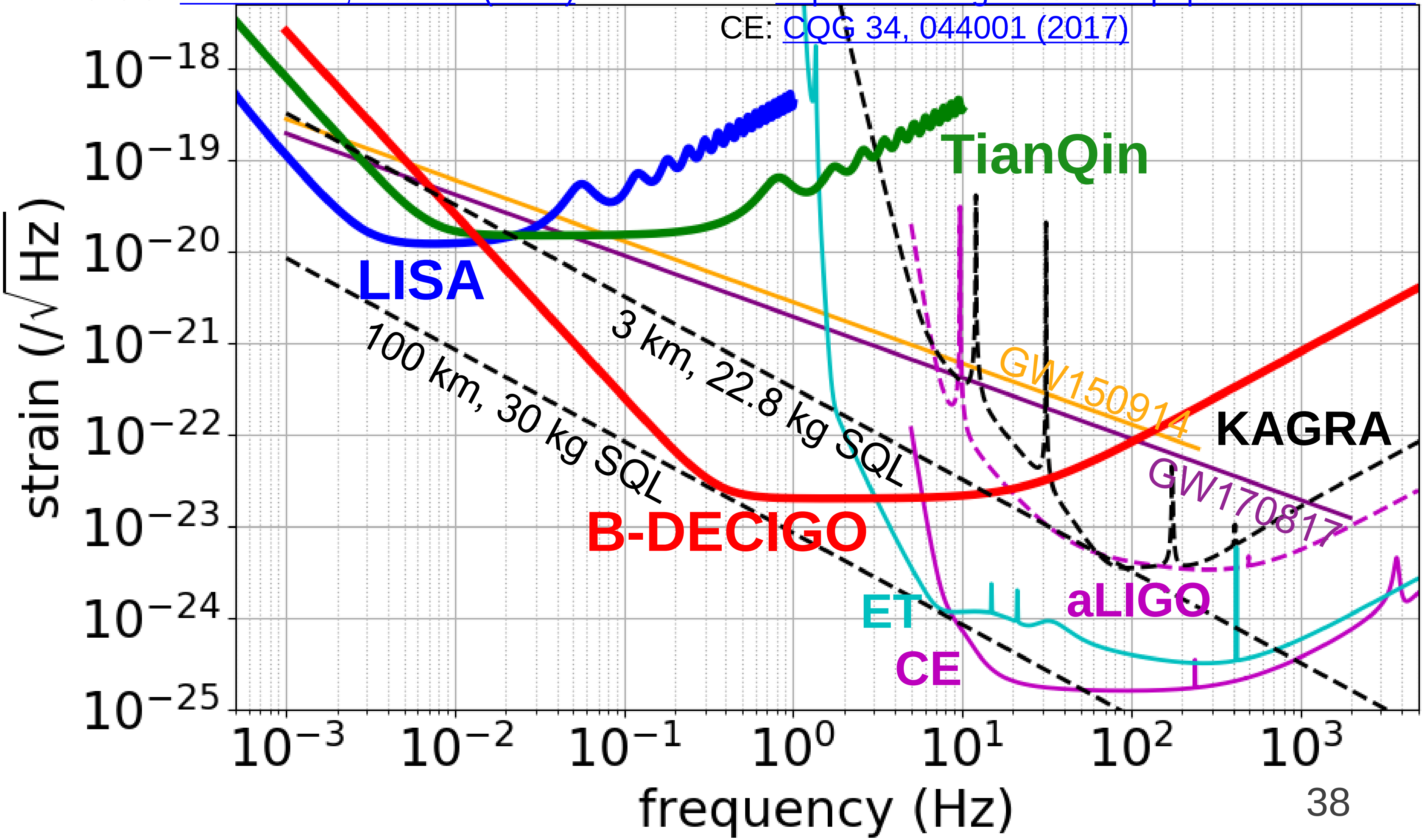
Existing Space GW Projects

	LISA	TianQin	B-DECIGO
Arm length	2.5e6 km	1.7e5 km	100 km
Interferometry	Optical transponder	Optical transponder	Fabry-Pérot cavity
Laser frequency stabilization	Reference cavity, 1064 nm	Reference cavity, 1064 nm	Iodine, 515 nm
Orbit	Heliocentric	Geocentric, facing J0806.3+1527	Geocentric (TBD)
Flight configuration	Constellation flight	Constellation flight	Formation flight
Test mass	1.96 kg	2.45 kg	30 kg
Force noise req.	8e-15 N/rtHz Achieved PRL 120, 061101 (2018)	7e-15 N/rtHz CQG 33, 035010 (2016)	1e-16 N/rtHz

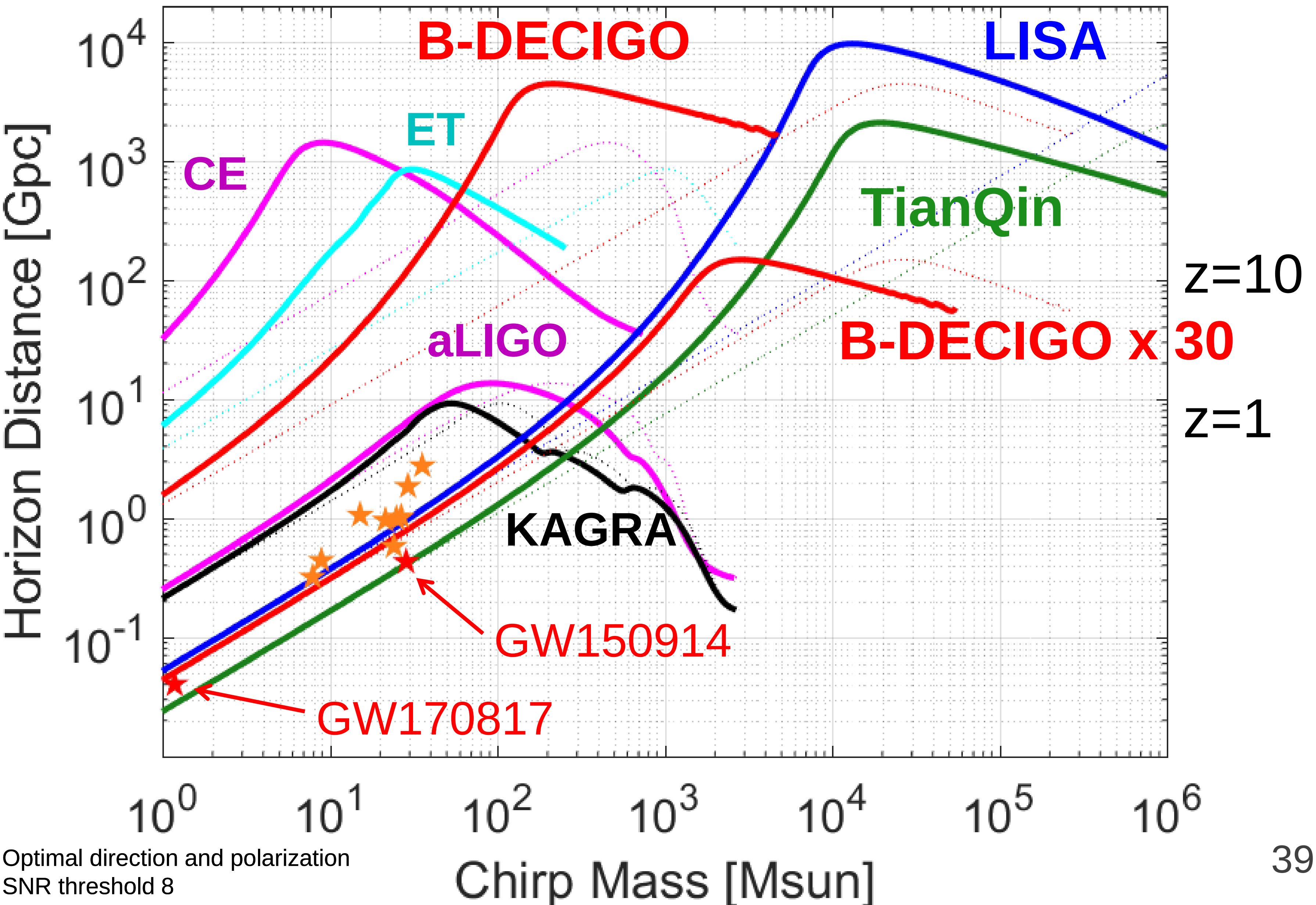
Sensitivity Comparison

LISA: https://perf-lisa.in2p3.fr/
TianQin: arXiv:1902.04423 (from Yi-Ming Hu)
B-DECIGO: PTEP 2016, 093E01 (2016)

KAGRA: PRD 97, 122003 (2018)
aLIGO: LIGO-T1800044
ET: http://www.et-gw.eu/index.php/etdsdocument
CE: CQG 34, 044001 (2017)

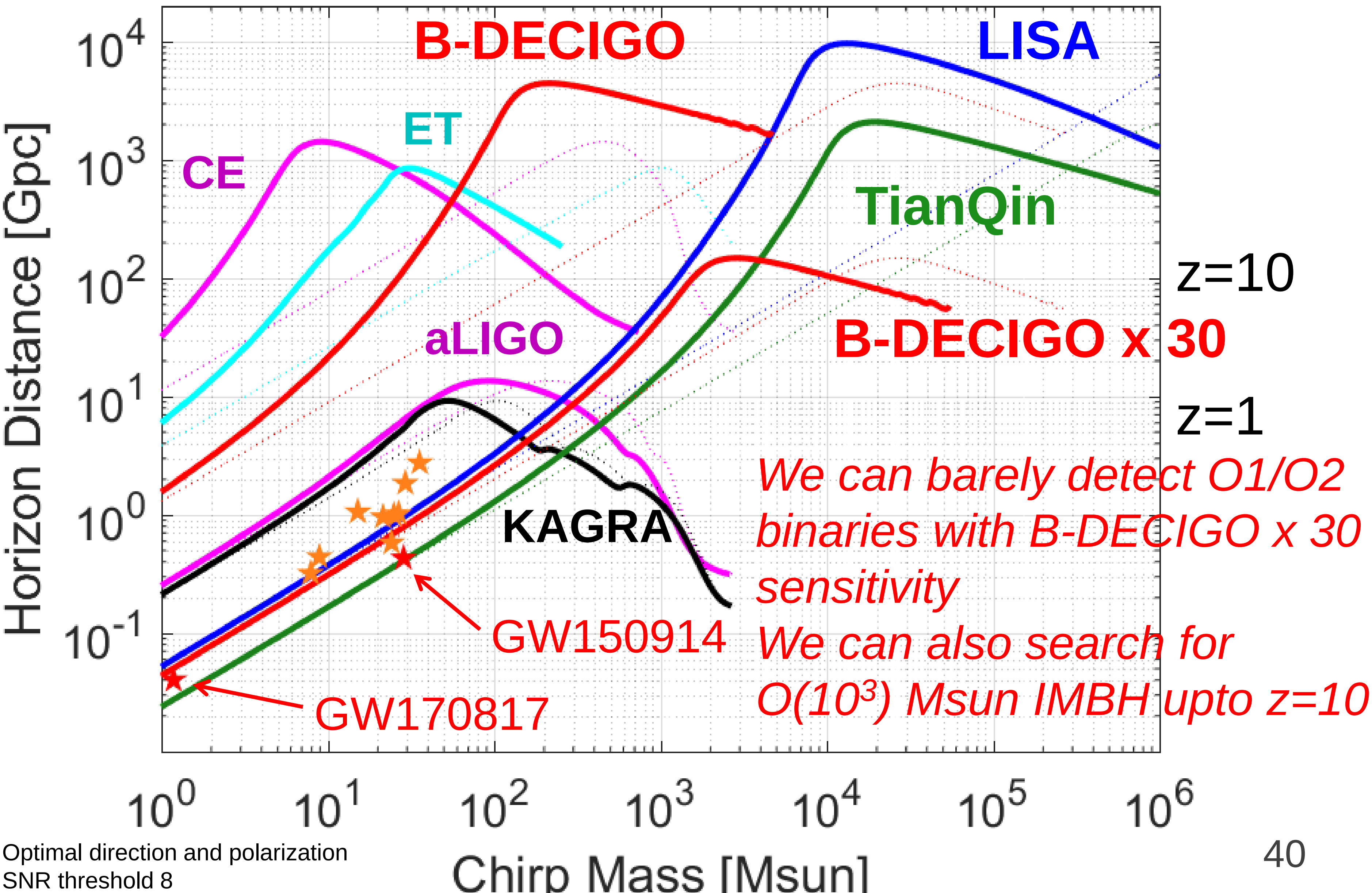


Horizon Distance



Optimal direction and polarization
SNR threshold 8

Horizon Distance



Optimal direction and polarization
SNR threshold 8

C-DECIGO

- Target sensitivity
  C-DECIGO
  = B-DECIGO x 30
  = DECIGO x 300

- For GW150914 and GW170817 like binaries, C-DECIGO can measure coalescence time to < ~150 sec a few days before the merger

Multiband gravitational-wave astronomy: Observing binary inspirals with a decihertz detector, B-DECIGO

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[2] *Faculty of Law, Ryukoku University, Kyoto 612-8577, Japan*
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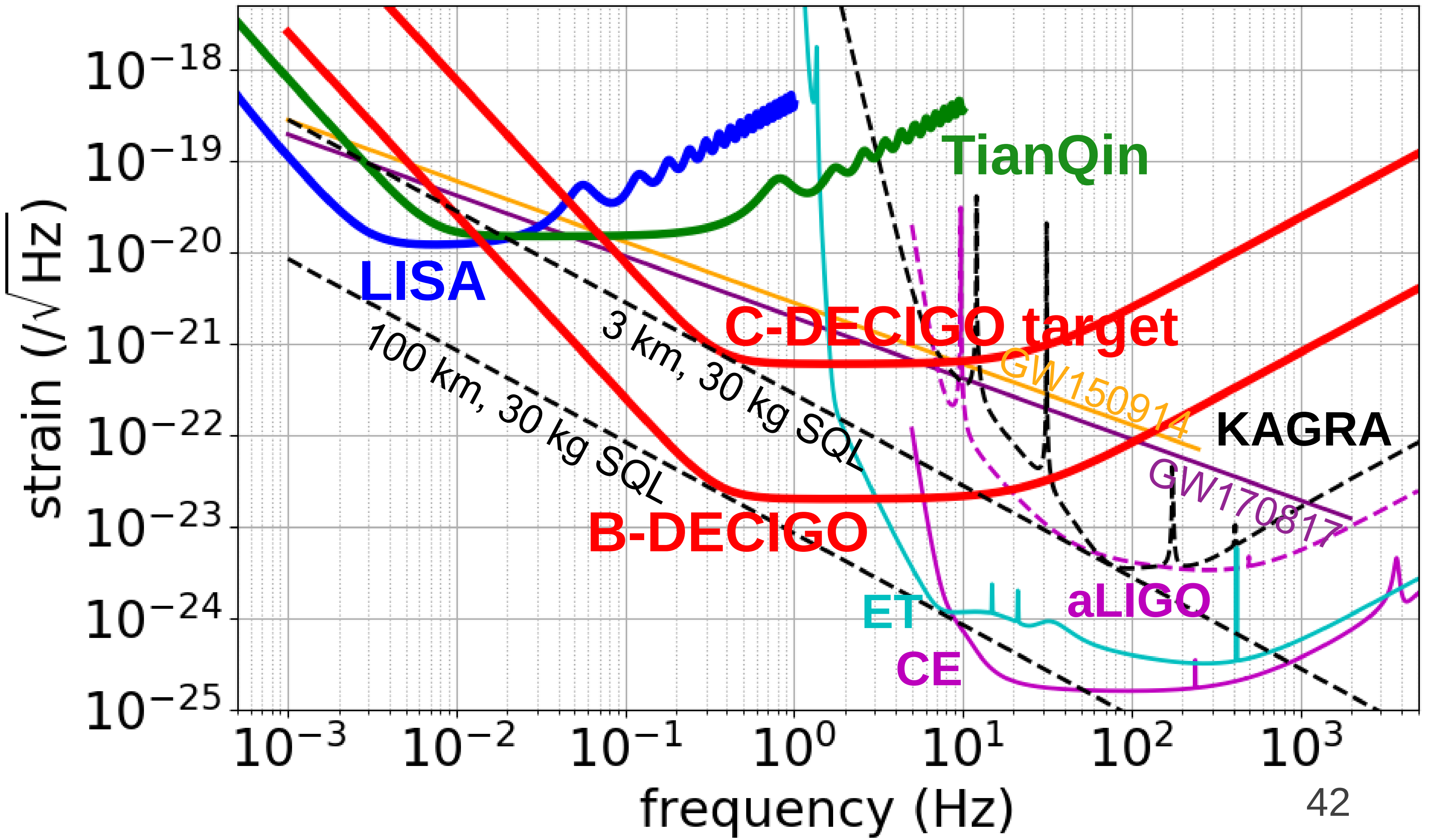
An evolving Japanese gravitational-wave (GW) mission in the decihertz band, B-DECIGO (DECihertz laser Interferometer Gravitational wave Observatory), will enable us to detect GW150914-like binary black holes, GW170817-like binary neutron stars, and intermediate-mass binary black holes out to cosmological distances. The B-DECIGO band slots in between the aLIGO–Virgo–KAGRA–IndIGO (hectohertz) and LISA (millihertz) bands for broader bandwidth; the sources described emit GWs for weeks to years across the multiple bands to accumulate high signal-to-noise ratios. This suggests the possibility that joint detection would greatly improve the parameter estimation of the binaries. We examine B-DECIGO's ability to measure binary parameters and assess to what extent multiband analysis could improve such measurement. Using non-precessing post-Newtonian waveforms with the Fisher matrix approach, we find for systems like GW150914 and GW170817 that B-DECIGO can measure the mass ratio to within $< 0.1\%$, the individual black-hole spins to within $< 10\%$, and the coalescence time to within < 5 s about a week before alerting aLIGO and electromagnetic facilities. Prior information from B-DECIGO for aLIGO can further reduce the uncertainty in the measurement of, e.g., certain neutron star tidally induced deformations by a factor of ~6, and potentially determine the spin-induced neutron star quadrupole moment. Joint LISA and B-DECIGO measurement will also be able to recover the masses and spins of intermediate-mass binary black holes at percent-level precision. However, there will be a large systematic bias in these results due to post-Newtonian approximation of exact GW signals.

S. Isoyama+, [PTEP 2018, 073E01 (2018)]

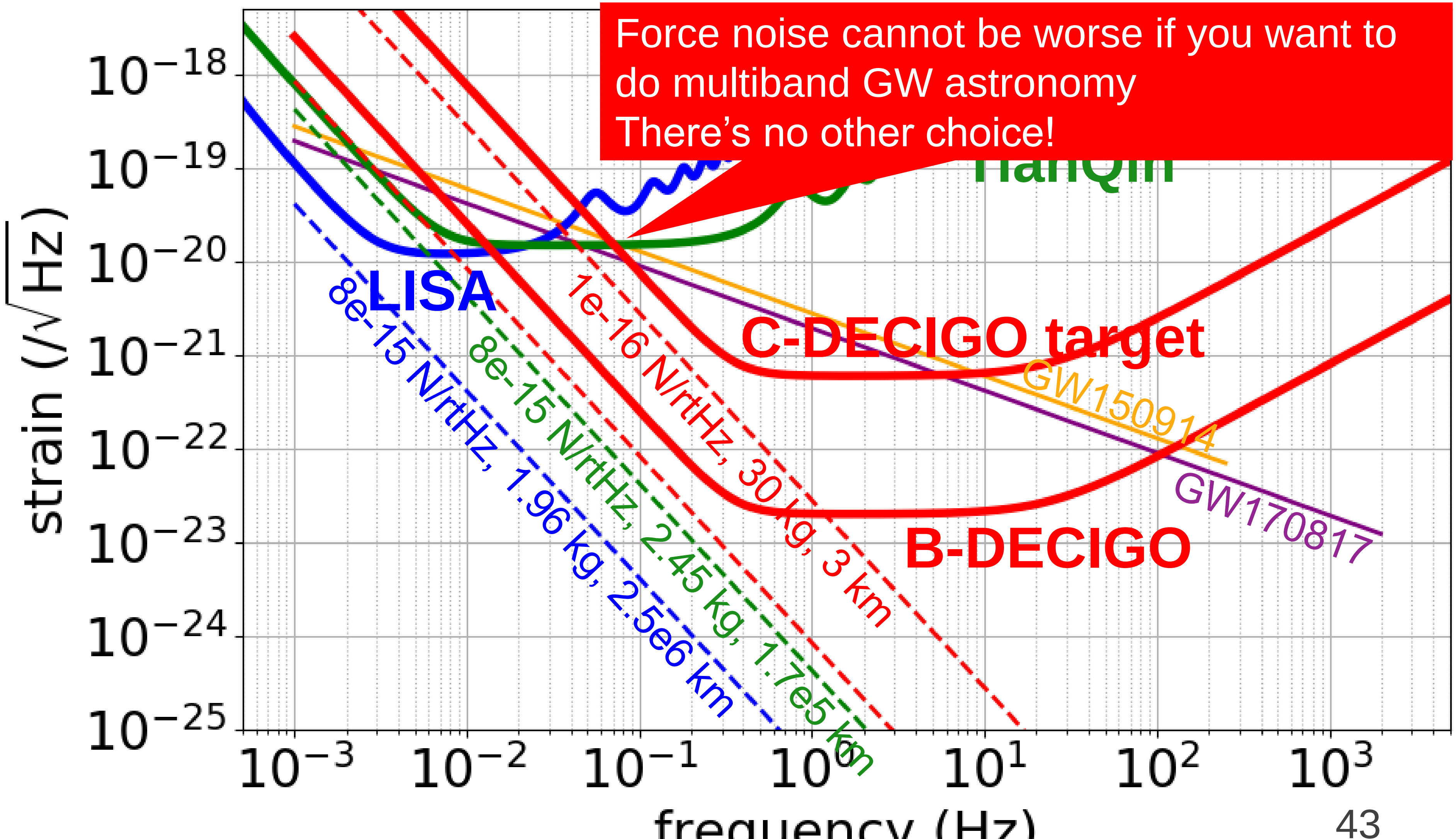
Sensitivity Target

- Requires $\sqrt{mL} > 3\sqrt{30}\ \sqrt{\mathrm{kg}\cdot\mathrm{km}}$ detector from SQL



Force Noise

- Requires 1e-16 N/rtHz for $mL = 90\,\mathrm{kg}\cdot\mathrm{km}$



Quantum Noise and Topology

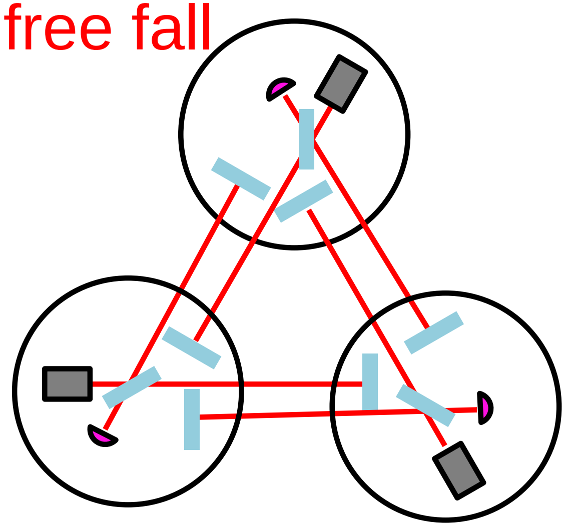
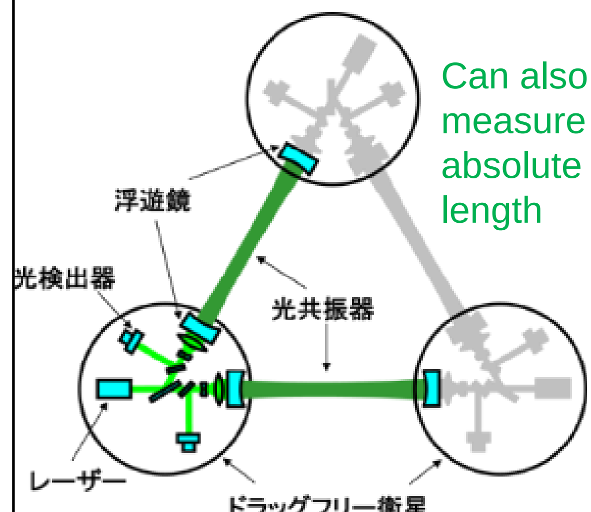
- Optical transponder (LISA/TianQin-style)
  Cannot dig the bucket unless you increase
  the size of the test mass
- Michelson interferometer
  - arm length: 30 km
  - mirror mass: 3 kg (diffraction loss is small enough)
  - input power: 3 W (arm should be long to reduce power)

  gives you C-DECIGO target
- Fabry-Perot interferometer (DECIGO-style)
  - arm length: 3 km
  - mirror mass: 30 kg
  - finesse: 300
  - input power: 0.01 W

  gives you C-DECIGO target (one example)

Michelson or Fabry-Perot

- Fabry-Perot seems reasonable choice

	Michelson	Fabry-Perot
Initial alignment	Same accuracy required	
Difficulties	Recombination	Cavity
3 satellites	BS have to be in free fall 	BS can be fixed  Can also measure absolute length
Arm length change	Possible (if mode mismatch is accepted)	Possible (if mode mismatch is accepted)

Mirror Mass and Arm Length

- Force noise requirement

$$h_{\rm f} = \frac{f}{m\omega^2 L} = \frac{1\times 10^{-16}\,{\rm N}/\sqrt{\rm Hz}}{90\,{\rm kg}\cdot{\rm km}\,\omega^2}$$

- Radiation pressure noise

$$h_{\rm rp} = \frac{1}{m\omega^2 L}\frac{4\mathcal{F}}{\pi}\sqrt{\frac{16\pi\hbar P}{c\lambda}} = k_{\rm safe} h_{\rm f}$$

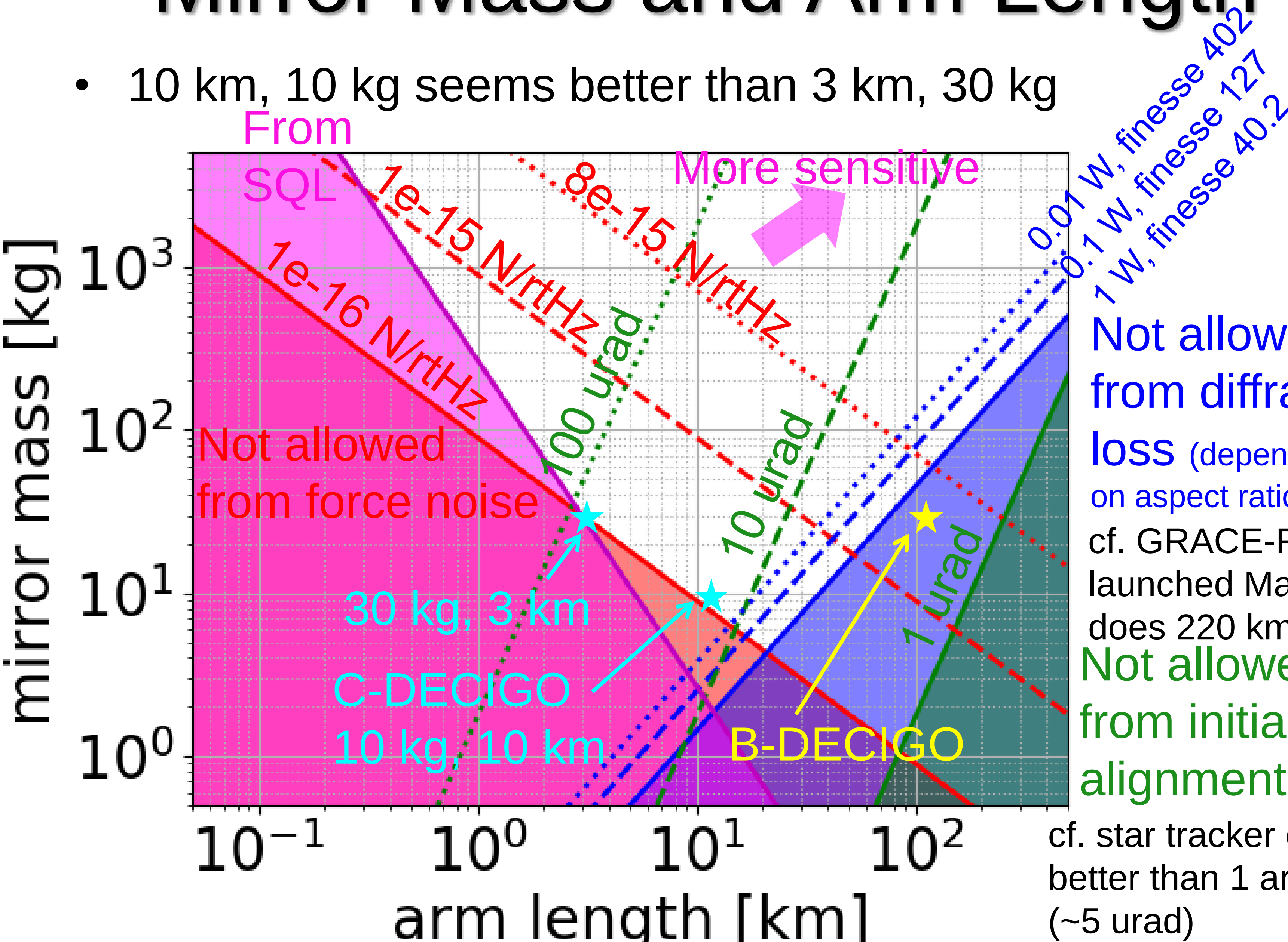
Say, this is 3

There's no point in reducing the finesse and input power if force noise is larger, in terms of sensitivity.

- If you fix requirement for f, requirement for mL is set
- If you fix P, finesse $\mathcal{F}$ is set
- Assuming g-factor g=0.3 and L, beam size is calculated
- This gives you the minimum mirror mass from diffraction loss (assume fused silica, aspect ratio t/d = 1)
- Also, if you fix initial alignment accuracy, minimum mirror diameter d is determined from d/L

Mirror Mass and Arm Length

- 10 km, 10 kg seems better than 3 km, 30 kg



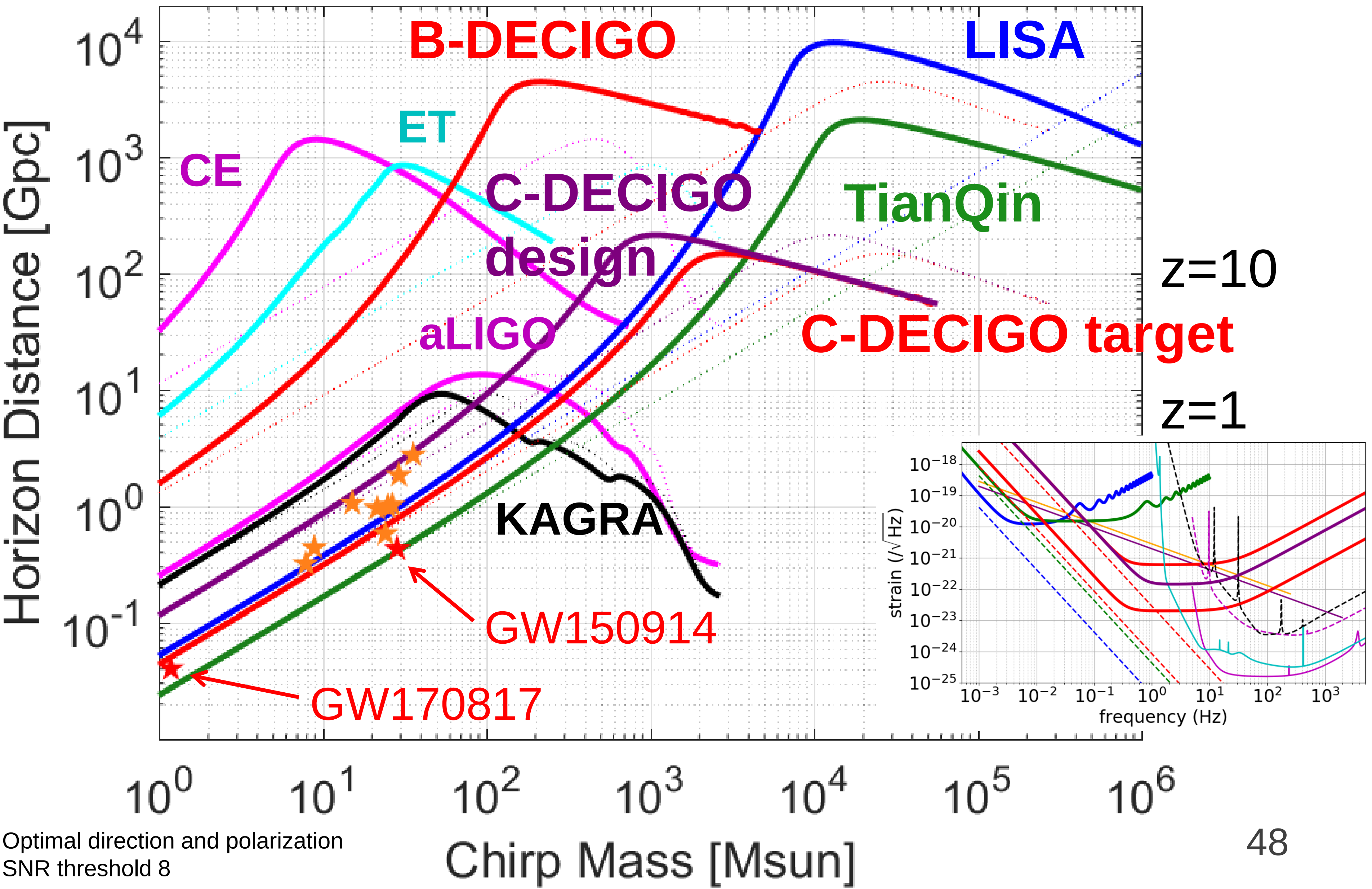
Not allowed from diffraction loss (depends much on aspect ratio)

cf. GRACE-FO launched May 2018 does 220 km FF

Not allowed from initial alignment

cf. star tracker can do better than 1 arcsec (~5 urad)

C-DECIGO Design



Optimal direction and polarization
SNR threshold 8

C-DECIGO Summary

- Multiband gravitational wave astronomy
  - Measure coalescence time of O1/O2 binaries within a few minutes, a few days before the merger
- IMBH search
  - O(10^3) Msun IMBH within the whole universe
  - Better than ET/CE and LISA
- C-DECIGO design parameters
  - Arm length: 10 km
    (Does this reduce the cost? Or increase the feasibility?)
  - Mirror mass: 10 kg
  - Force noise: <1e-16 N/rtHz (same as B-DECIGO)
  - finesse: 400
  - input power: 0.01 W (no high power amp necessary?)
- Better to do B-DECIGO if the cost is similar

Findings

- To do original science in 3G-LISA era,
  - Force noise < ~1e-16 N/rtHz
  - $mL > 90\,\mathrm{kg}\cdot\mathrm{km}$
  - $\sqrt{m}L > 3\sqrt{30}\,\sqrt{\mathrm{kg}}\cdot\mathrm{km}$

  are required
- Fabry-Perot seems more feasible
- Although beam size will be smaller for shorter arm length, it requires heavier mass to keep force noise requirement the same (~ a few kg is the minimum for the test mass)
- Longer arm length is better due to SQL but
  - initial alignment accuracy will be tougher
  - higher power laser will be necessary due to lower finesse (diffraction loss)

Summary

- Reviewed
  Experiments all look
  Interesting and
  We should take
  Action !