Future Plans of Ground Based GW projects 地上の将来計画

S.Haino

KAGRA collaboration

CRC town meeting (Dec./21, 2019)

Typical GW strain amplitude

$$h \sim \frac{2G}{c^4 R}\ddot{I} \sim \frac{r_g}{R} = \frac{\text{Schwarzschild radius}}{\text{Distance to the source}}$$

e.g. Solar mass (r_g~3km) NS-NS binary merging at ~speed of light located at 100 Mpc away

$$h \sim \frac{3\ \text{km}}{100\ \text{Mpc}} = 10^{-21}$$

GW signal is very tiny but propagate as 1/R (not 1/R^2)

Quick review in GW science

Based on SH's personal view with help of A.Nishizawa

Topic/Source	Ground (2G)	Ground (3G)	Space	Comment
BNS, NSBH	○	◎	○	Science: Test of GR, NS EoS, Multi messenger, sGRB, Standard siren, …
Stellar-mass BBH	◎	◎	○	Science: Test of GR, Formation scenario, … Space: inspiral phase
Intermediate BBH	△	◎	◎	Science: Formation scenario, Test of GR, …
Pulsar CW	△(?)	○(?)	△(?)	Depends on models Science: NS EOS and internal structure
Massive BBH	×	×	◎	Science: Formation scenario, Test of GR, …
EMRI Harmonics	×	△	◎	Science: Formation scenario, Test of GR, …
WD, GB	×	×	◎	Science: SN astrophysics, Standard siren
Supernovae	?	○(?)	△(?)	Depends on model and luck Science: explosion mechanism
Primordial GW	?	?	◎(?)	Depends on models Science: Direct test of inflation
Cosmology	○	◎	◎	Source: BNS/NSBH, BBH, WD, Primordial
Test of GR	◎	◎	◎	Source: BNS/NSBH, BBH, EMRI

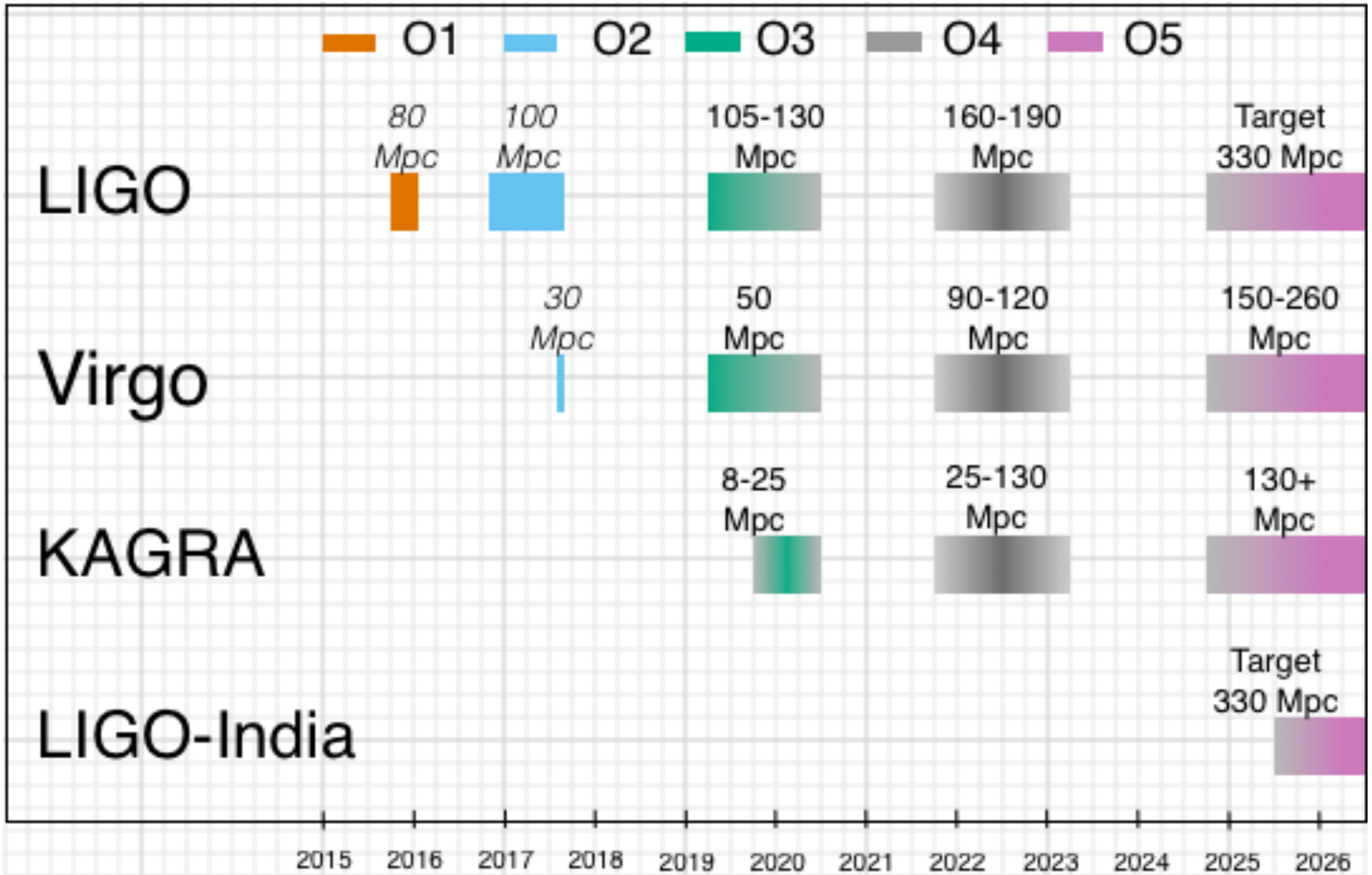
BNS: Binary Neutron Star, NSBH: Neutron Star-Black Hole, BBH: Binary Black Hole,
CW: Continuous Wave, EMRI: Extreme mass ratio inspiral, WD: White Dwarf, GB: Galactic Binary

Future Prospects (ground based)

- Near term (5~10 years) - 2G (2nd Generation)
  - (Almost) funded in U.S. and Europe
  - O4 in 2022~
  - O5 in 2025~
- Far term (10~ years) - 3G (3rd Generation)
  - New facility and big funding needed
  - Cosmic Explorer (US)
  - Einstein Telescope (ET)
  - Japan ? Discussion in this session
  - …

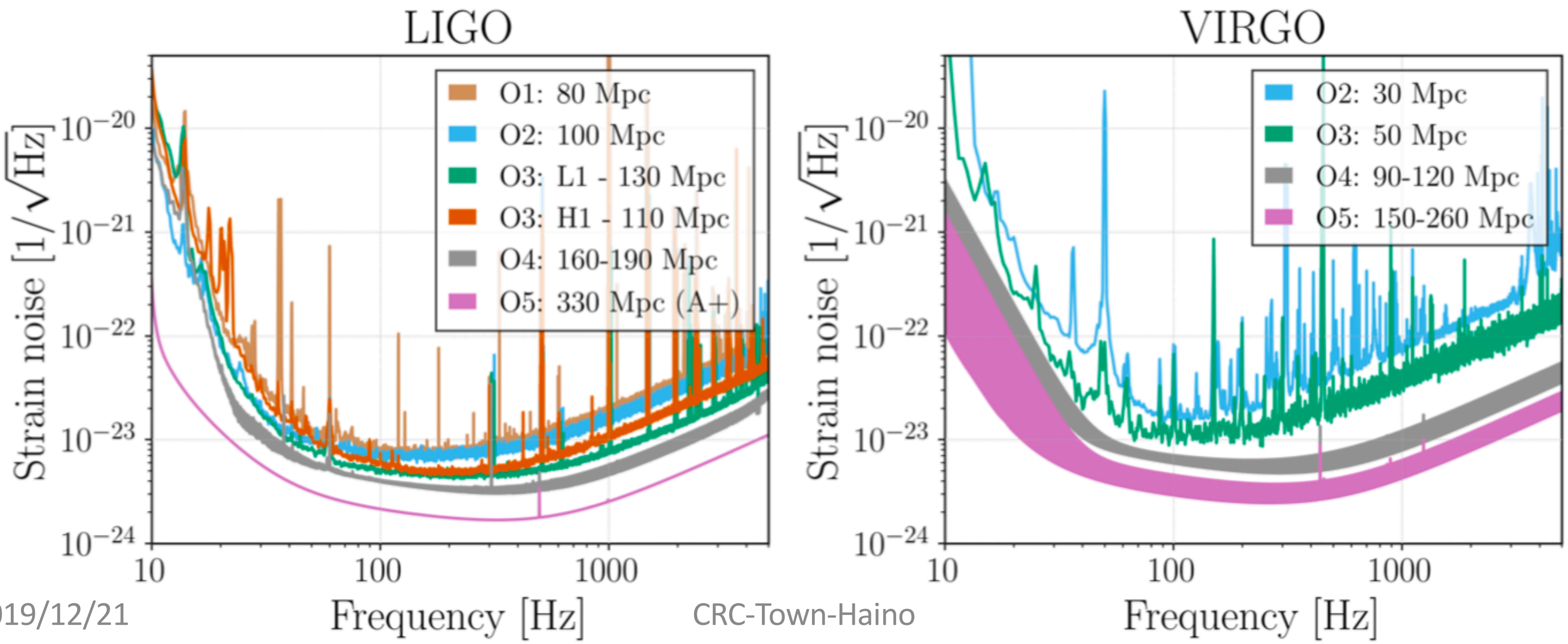
LIGO/Virgo O4, O5 projection

- [LIGO-P1200087][arXiv:1304.0670]



LIGO/Virgo O4, O5 projection

- Updated on July/11/2019 at LIGO-P1200087 also at arXiv:1304.0670
- LIGO O4: 160 – 190 Mpc O5: 330 Mpc
- Virgo O4: 90 – 120 Mpc O5: 150-260 Mpc



(Advanced LIGO+ in U.S.) L. McCuller GWADW 2019

A+ Orientation

- An incremental upgrade to aLIGO that leverages existing technology and infrastructure, with minimal new investment and moderate risk
- Target: factor of 1.7* increase in binary inspiral detection range over aLIGO baseline design
  - ➔About a factor of 4-7 greater CBC event rate
- Bridge to future 3G GW astrophysics, cosmology, and nuclear physics
- Stepping stone to 3G detector technology
- Can be observing within 6 years (late 2024)

*BBH 30/30 $M_\odot$: 1.6x
*BNS 1.4/1.4 $M_\odot$: 1.9x

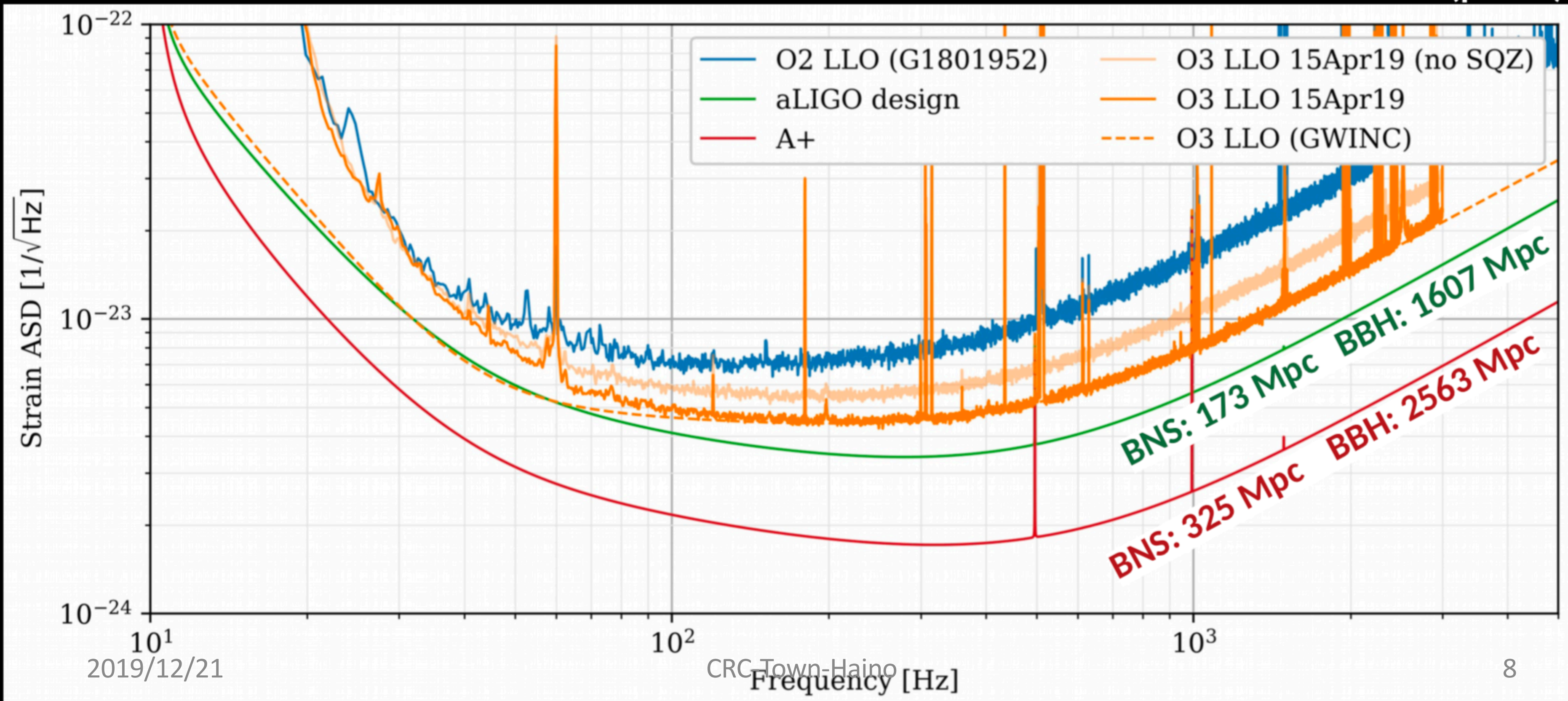
(Advanced LIGO+ in U.S.)

L. McCuller GWADW 2019

A+ Upgrade: Sensitivity Target

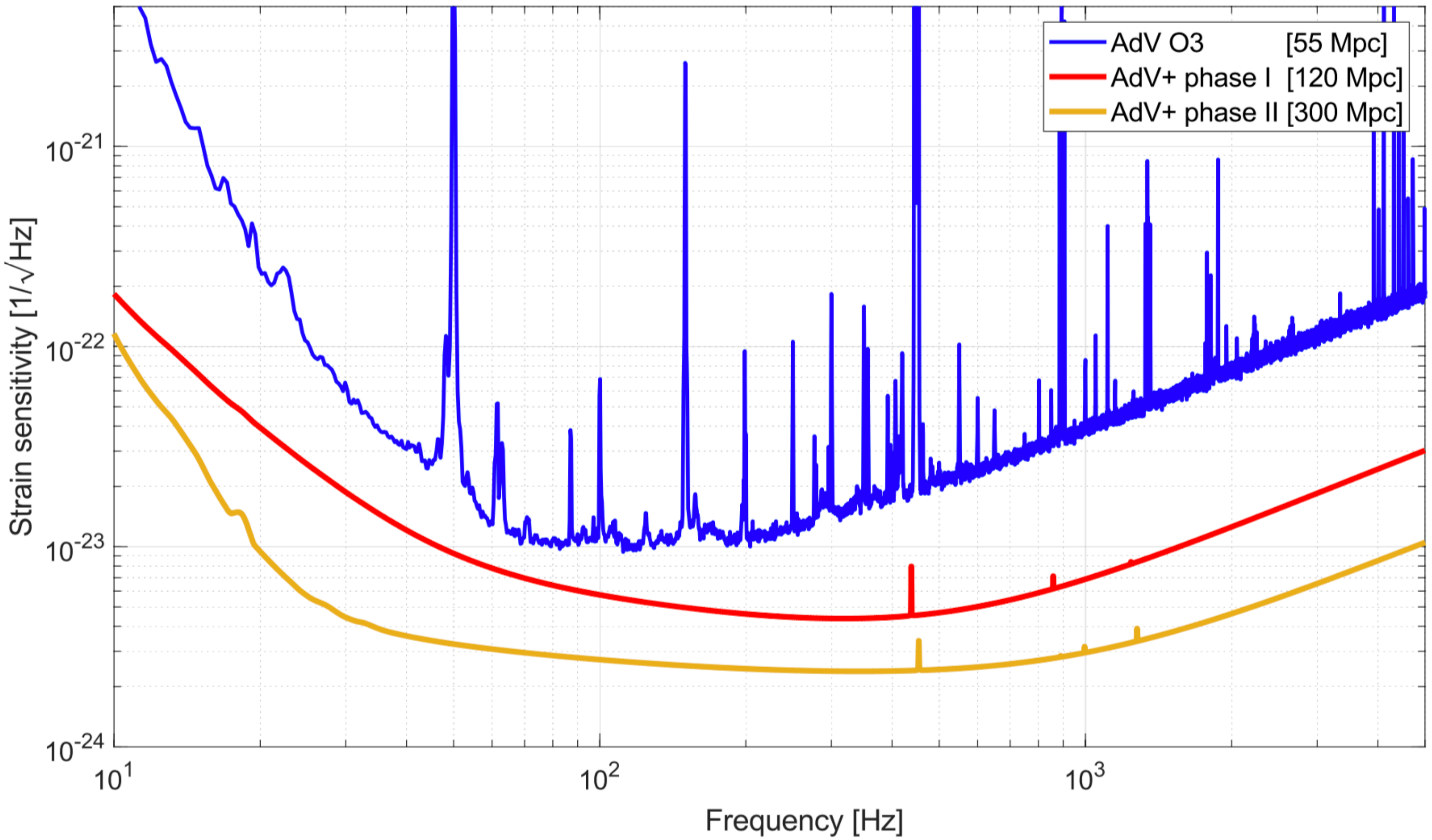
- Reduce quantum noise
  - Improved optical losses
  - Improved readout
  - Frequency-Dependent Squeezing
- Reduce thermal noise
  - Improved mirror coatings

Reference Curves LIGO Document T1800042-v5 (public)



O5: AdV+ (Advanced Virgo+ in Italy)

J. Degallaix GWADW 2019



For phase II that is the absolute best possible with large input and end mirrors and reduction of coating thermal noise

3G: Each region's prospects

Projects being discussed for many years

- U.S – CE1 (2030~) /CE2 (2040~)
- Europe – ET (2030~)

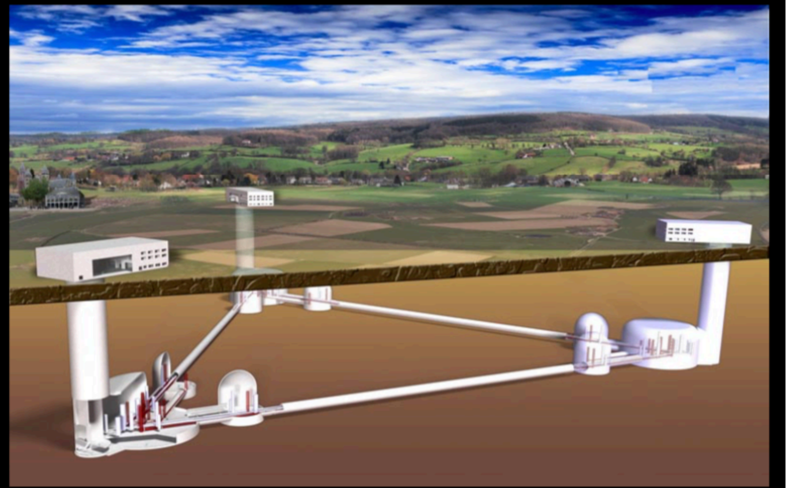
Projects being proposed recently

- Australia – oz-HF (?)
- China – ZAIGA (?)

L. Cadonati 5th KAGRA International Workshop 2019

The 3rd Generation

~10^5 binary coalescences per year (2030s)

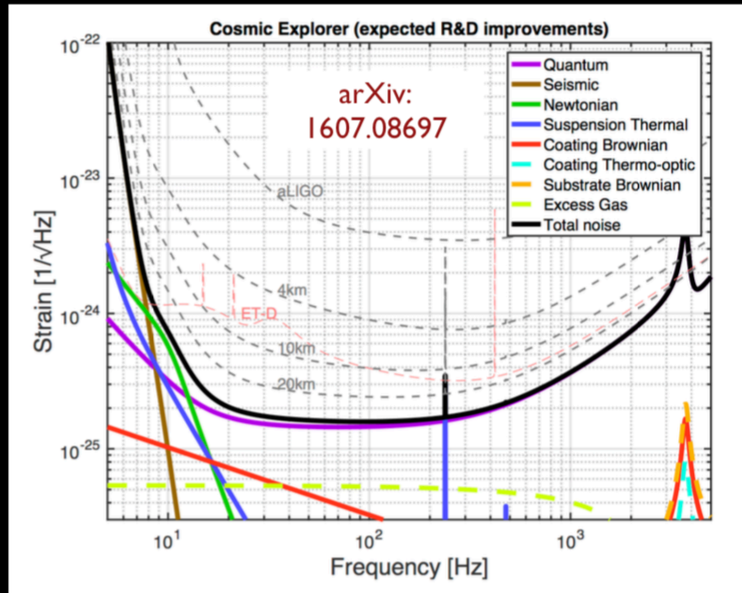


Einstein Telescope

- European conceptual design study
- Multiple instruments in xylophone configuration
- underground to reduce newtonian background
- 10 km arm length, in triangle.
- Assumes 10-15 year technology development.

Cosmic Explorer

- NSF-funded US conceptual design study starting now
- 40km surface Observatory baseline
- Signal grows with length – not most noise sources
- Thermal noise, radiation pressure, seismic, Newtonian unchanged; coating thermal noise improves faster than linearly with length



LIGO-G1900215 The 5th Kagra International Workshop - Perugia, February 14-15, 2019 32

Cosmic Explorer (U.S.)

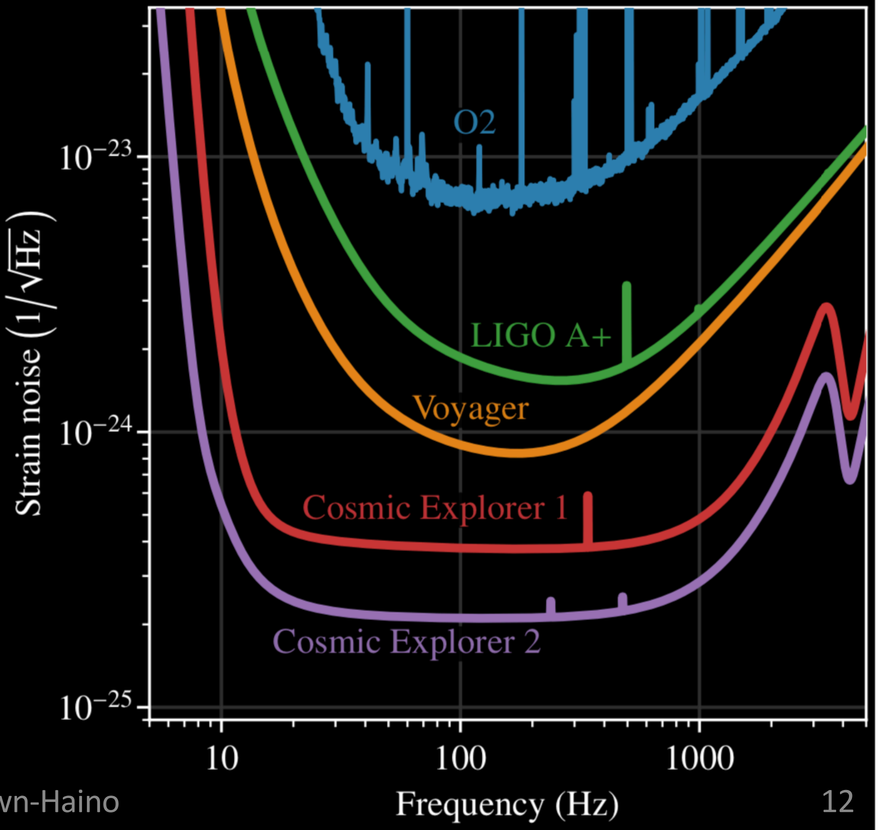
E. Hall DAWN-V (2019)

Cosmic Explorer will proceed in two stages:

2030s: room-temperature glass at 1.0 μm (like aLIGO)
2040s: cryogenic silicon at 1.5 or 2.0 μm (like Voyager)

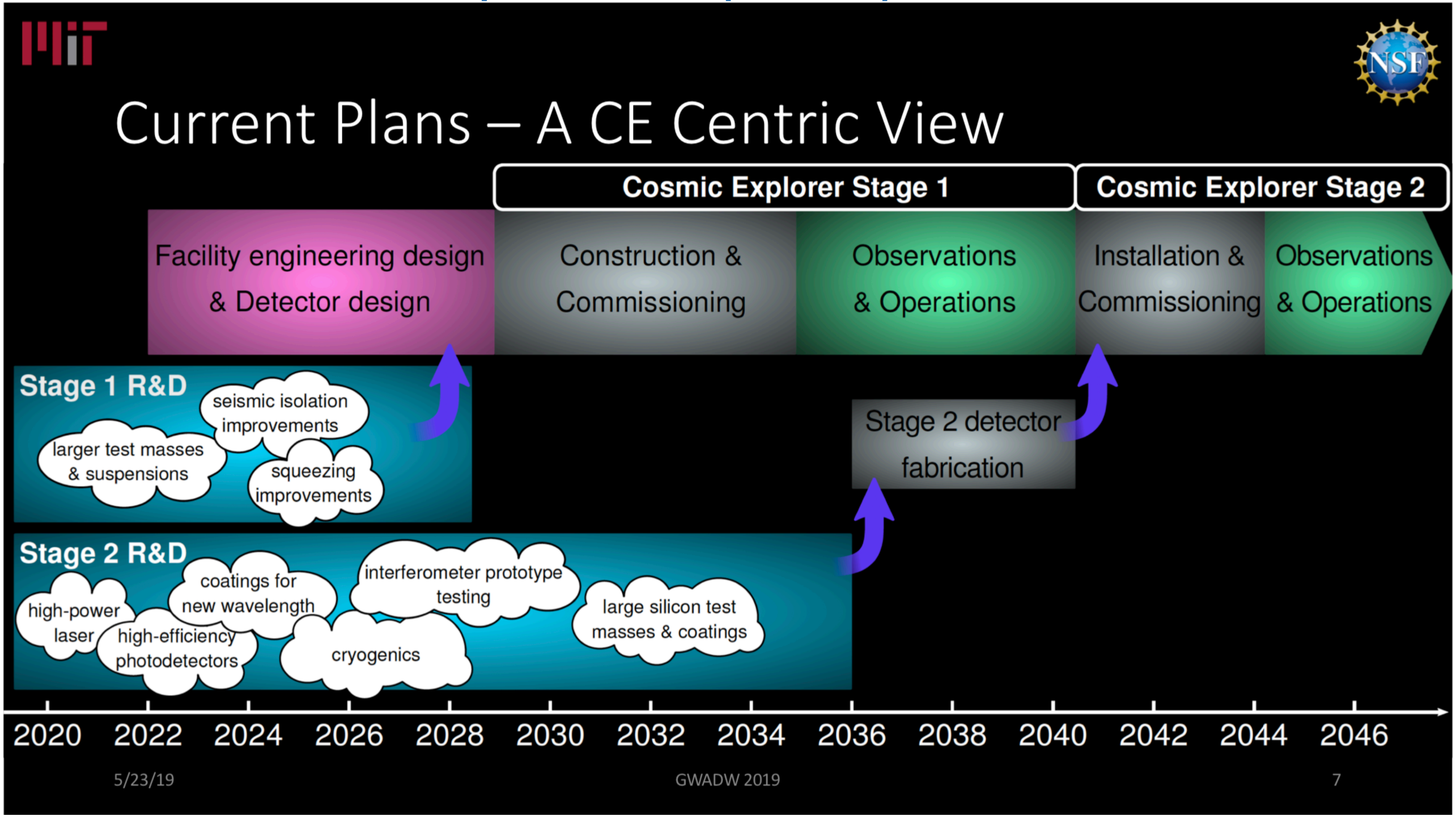
A two-stage approach

	CE1 2030s, à la aLIGO	CE2 2040s, à la Voyager
Wavelength	1.0 μm	1.5 to 2.0 μm
Temp.	293 K	123 K
Material	glass	silicon
Mass	320 kg	
Coating	silica/tantala	silica/aSi
Spot size	12 cm	14 to 16 cm
Suspension	1.2 m fibers	1.2 m ribbons
Arm power	1.4 MW	2.0 to 2.3 MW
Squeezing	6 dB	10 dB

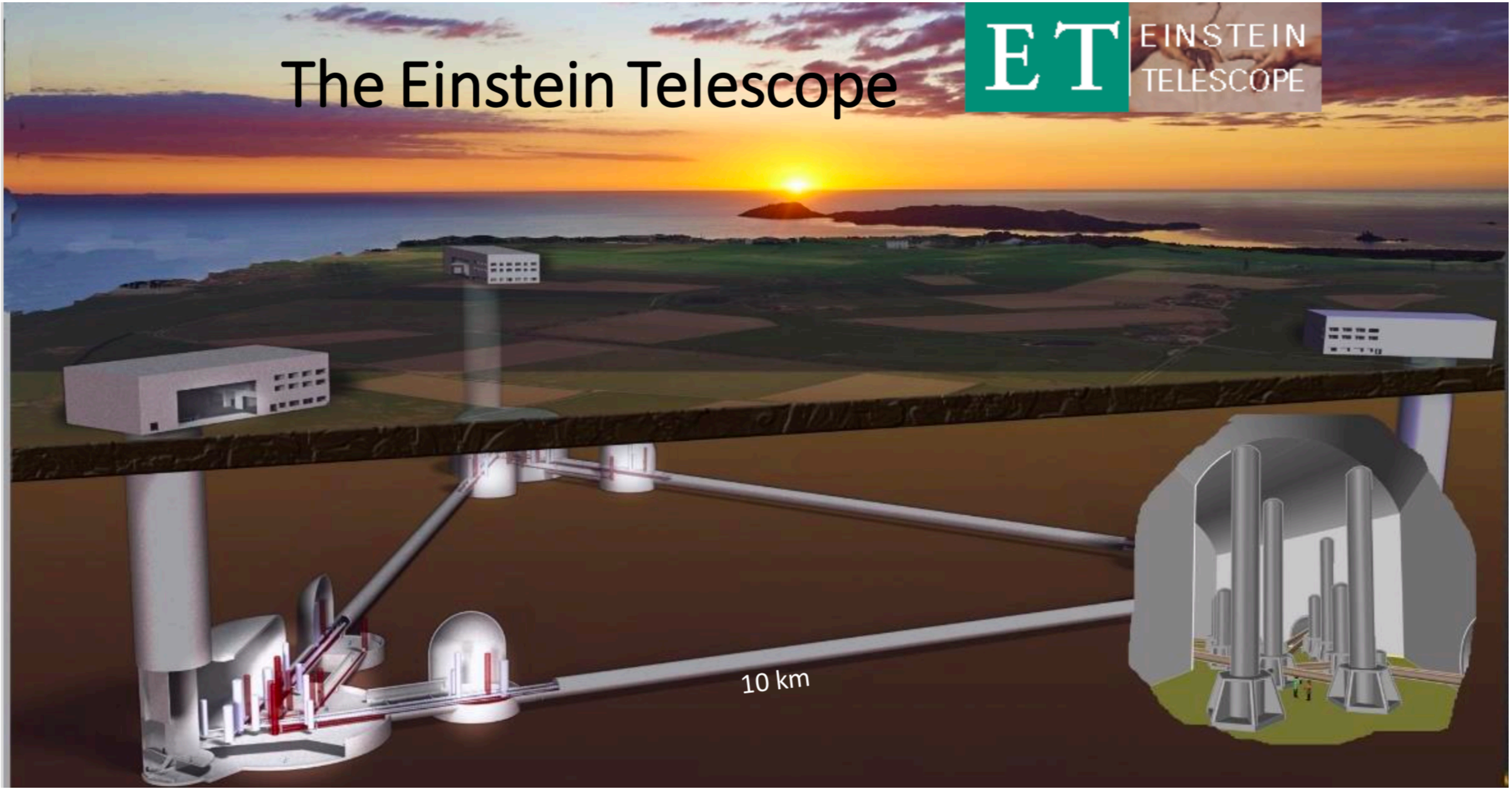


Cosmic Explorer (U.S.)

M. Evans GWADW 2019



M. Punturo KIW5 2019



M. Punturo KIW5 2019

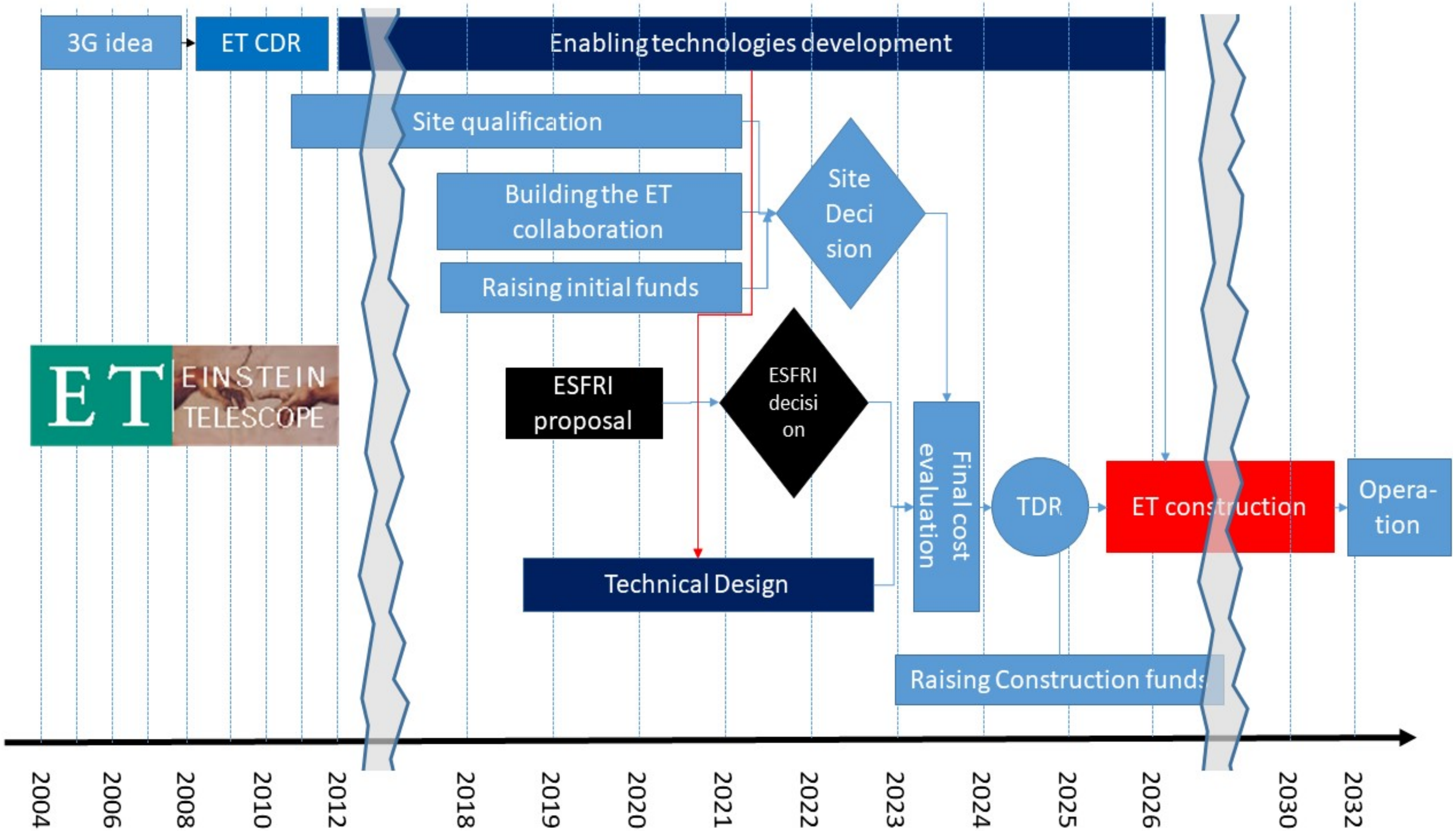
The 3G/ET key points

- ET is THE 3G new GW observatory
  - 3G: Factor 10 better than advanced (2G) detectors
  - New:
    - We need a new infrastructures because
      - Current infrastructures will limit the sensitivity of future upgrades
      - In 2030 current infrastructures will be obsolete
  - Observatory:
    - Wide frequency, with special attention to low frequency (few HZ)
      - See later
    - Capable to work alone (characteristic to be evaluated in the international scenario)
      - (poor) Localization capability
      - Polarisations (triangle)
      - High duty cycle: redundancy
    - 50-years lifetime of the infrastructure
      - Compliant with the upgrades of the hosted detectors

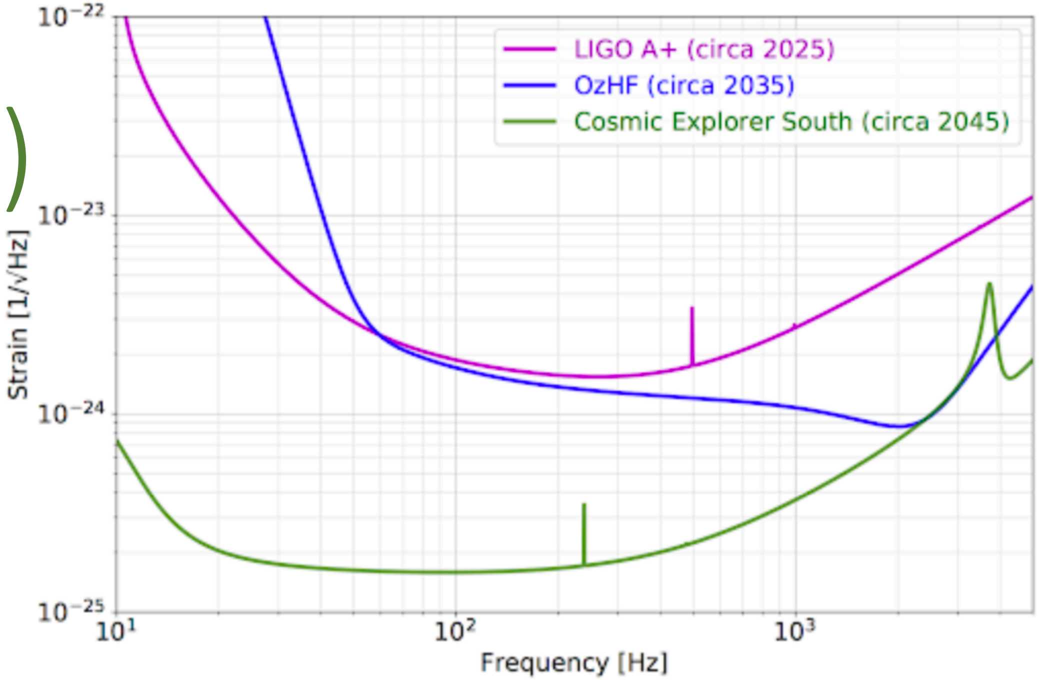
M.Punturo -ET 12

Operation planned from 2032 M. Punturo KIW5 2019

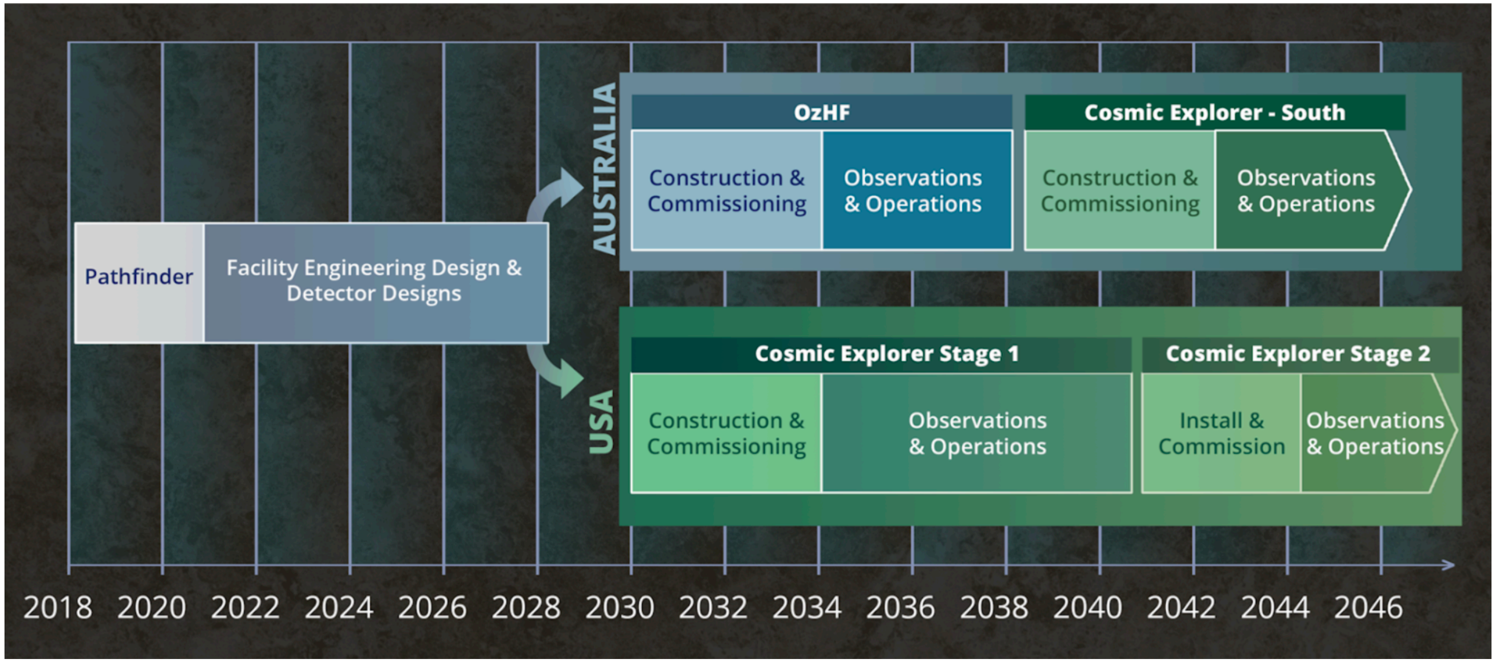
ET roadmap



oz-HF (Australia)

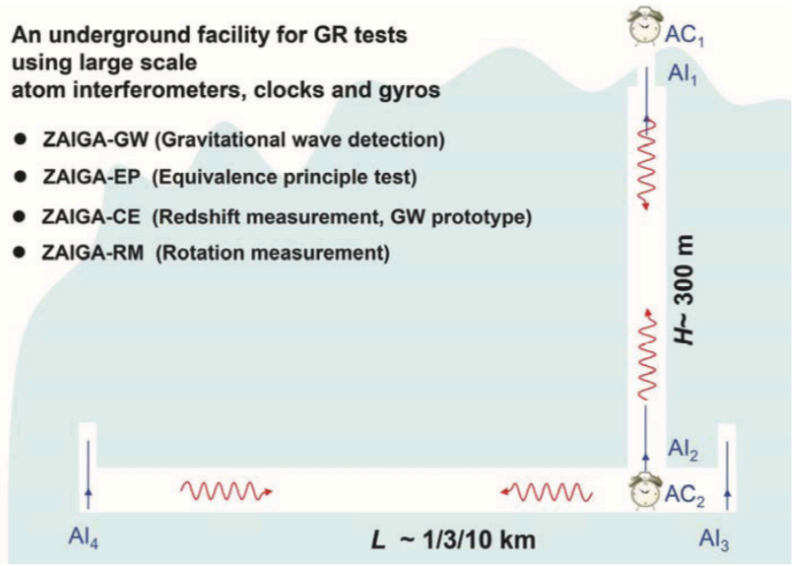


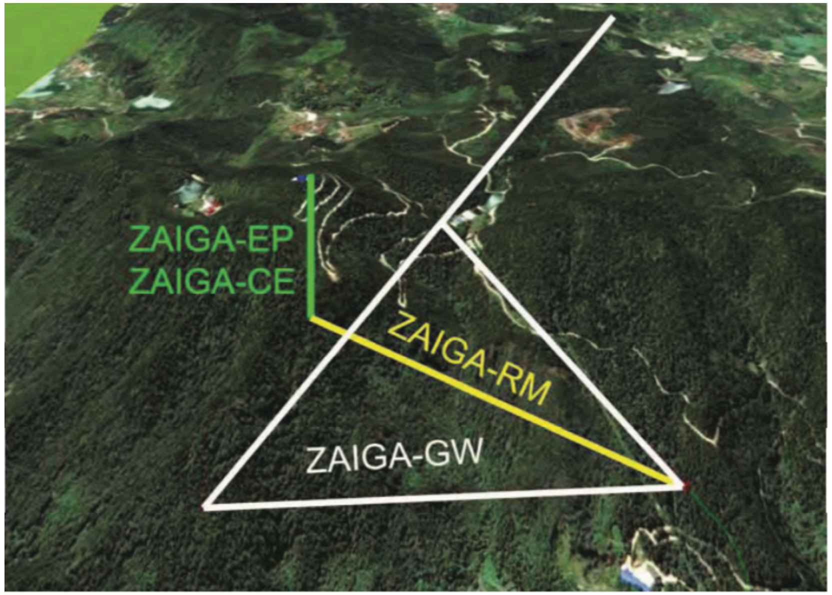
arXiv:1912.06305



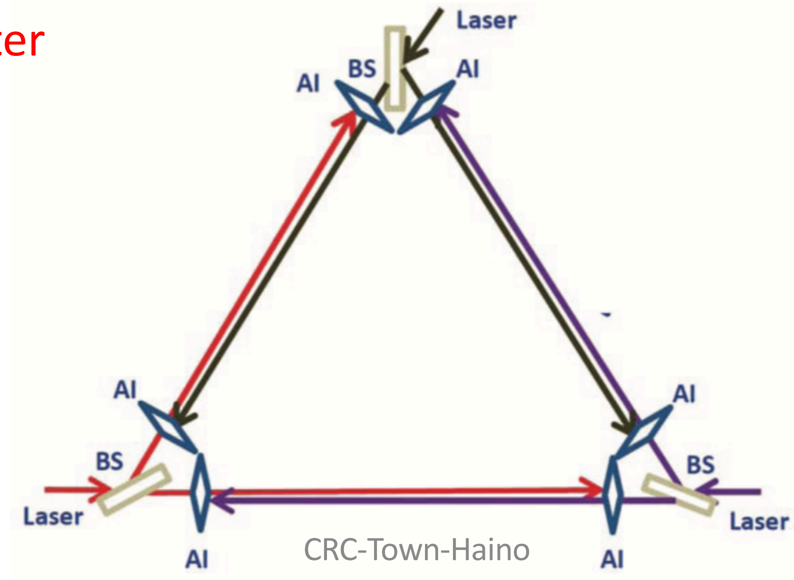
ZAIGA-GW (China)

arXiv:1903.09288

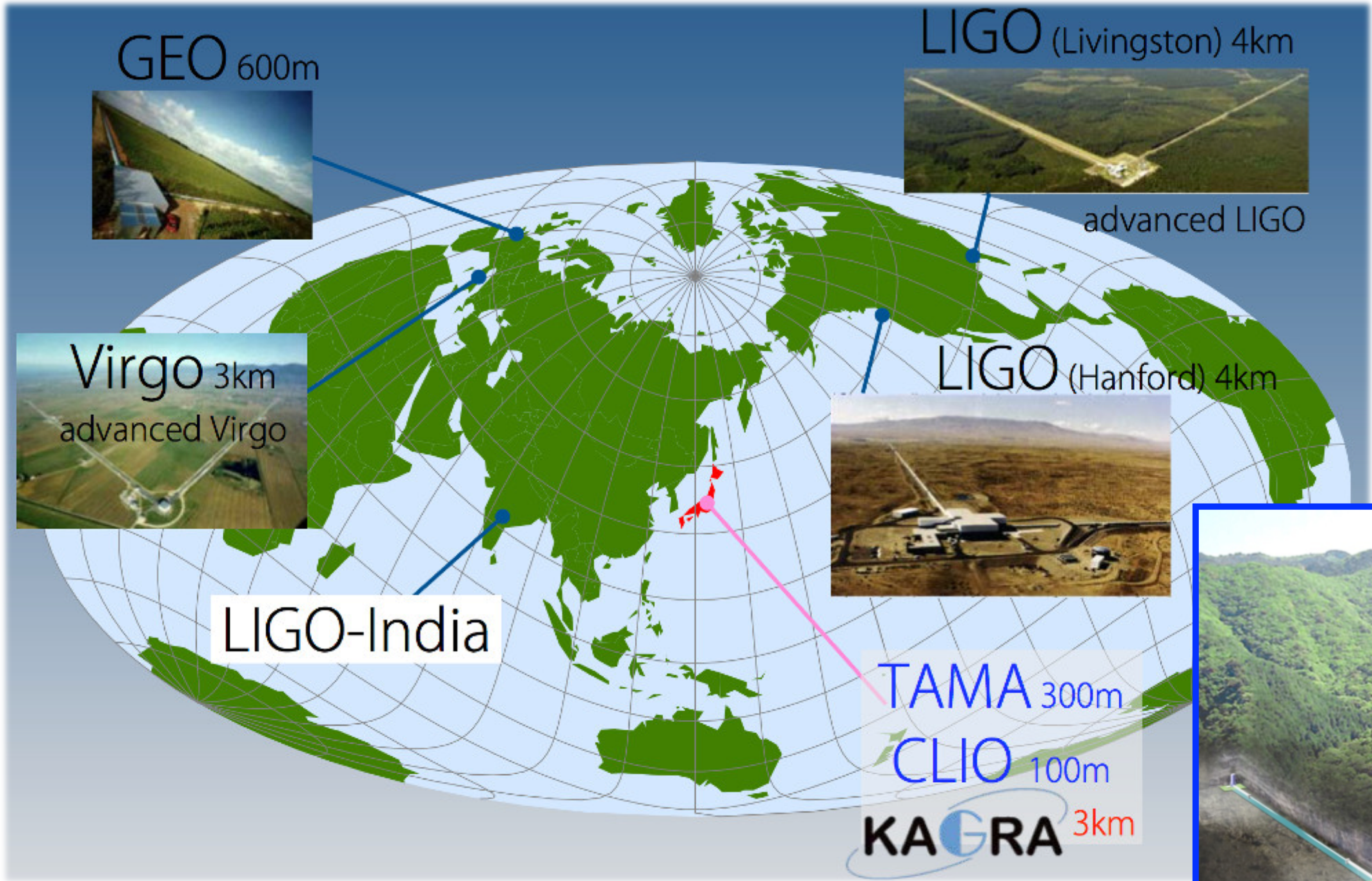


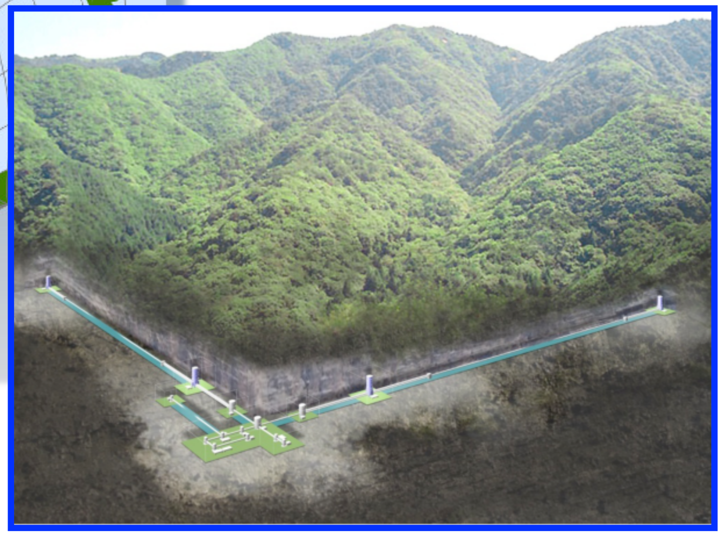


Atomic Interferometer



Then, KAGRA (Japan)



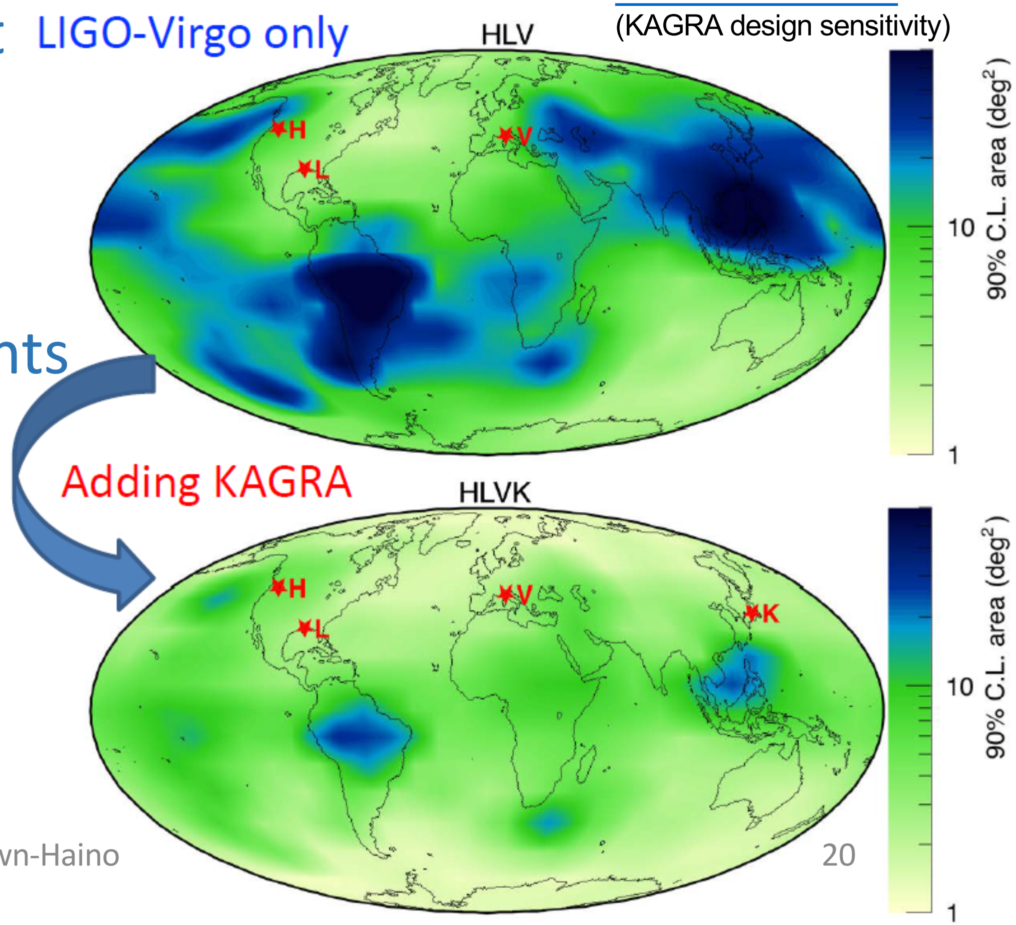


Contributions expected by KAGRA

- Detector network duty factor (N>=3)
  HLV 34% (3/3) → HLVK 65% (3/4) (assuming 70% each)
- Sky localization improvement
  Typically factor of 3
  - EM counterpart
  - Hubble constant
- GW polarization measurements
  - Test of General Relativity
  including polarization modes

  H. Takeda+, PRD 98, 022008 (2018)

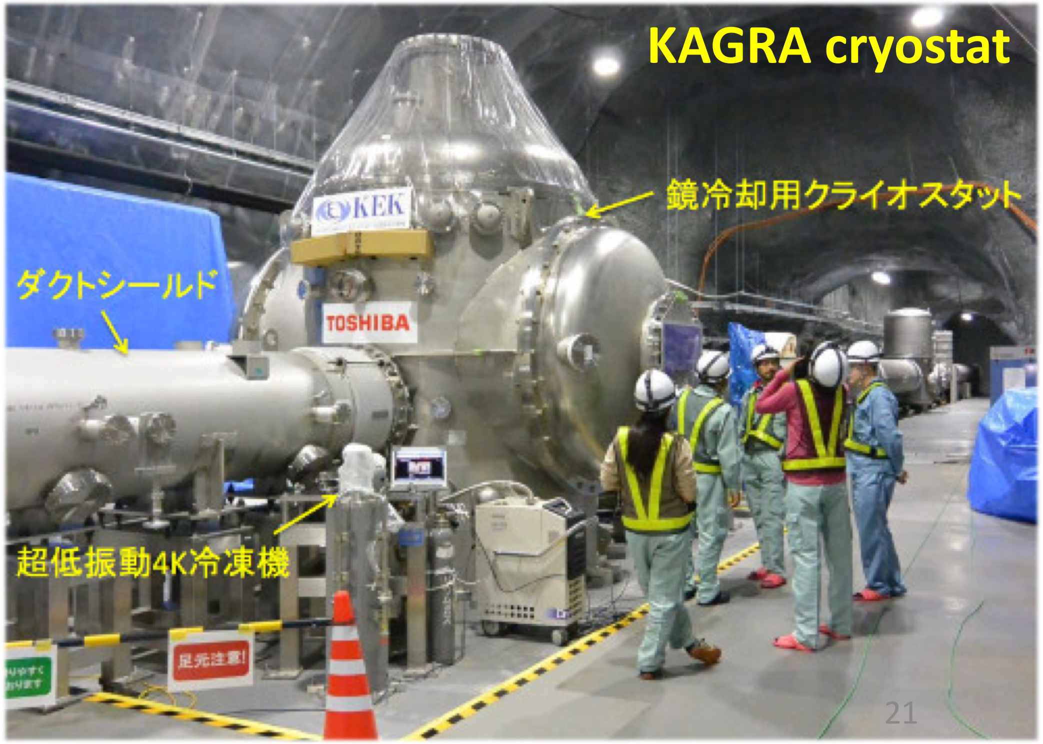
JGW-G1808212
(KAGRA design sensitivity)



Application of Accelerator technologies to KAGRA

**J-PARC neutrino
super-conducting beam line**

KEK cryogenic center is leading the development of KAGRA cryogenic system



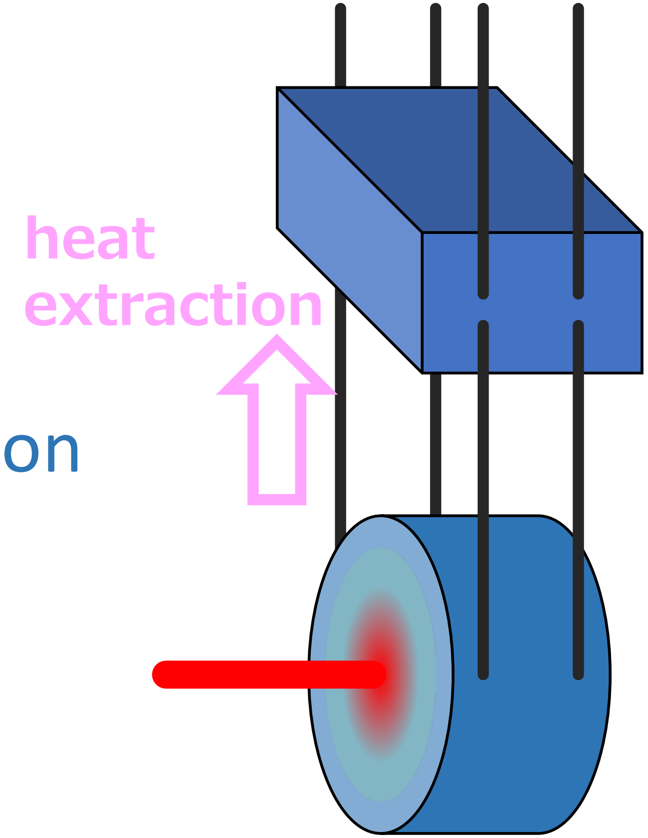
Specific issues for cryogenic

- Not trivial to do both
  - high power (400 kW on mirror)
  - low temperature (20 K)

thinner and longer fibers preferred
for suspension thermal noise reduction

Dilemma

thicker and shorter preferred
for efficient heat extraction



KAGRA Future Planning

- KAGRA has been focusing to finish the installation of current configuration ; discussion on the future upgrade was not so active until 2018

- Finally, KAGRA installation was almost completed and Future Planning Committee (FPC) has been established in Dec./2018 and started discussions on the future upgrade

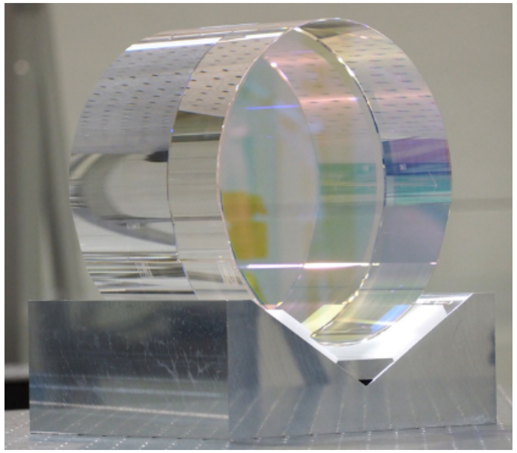
KAGRA now and future

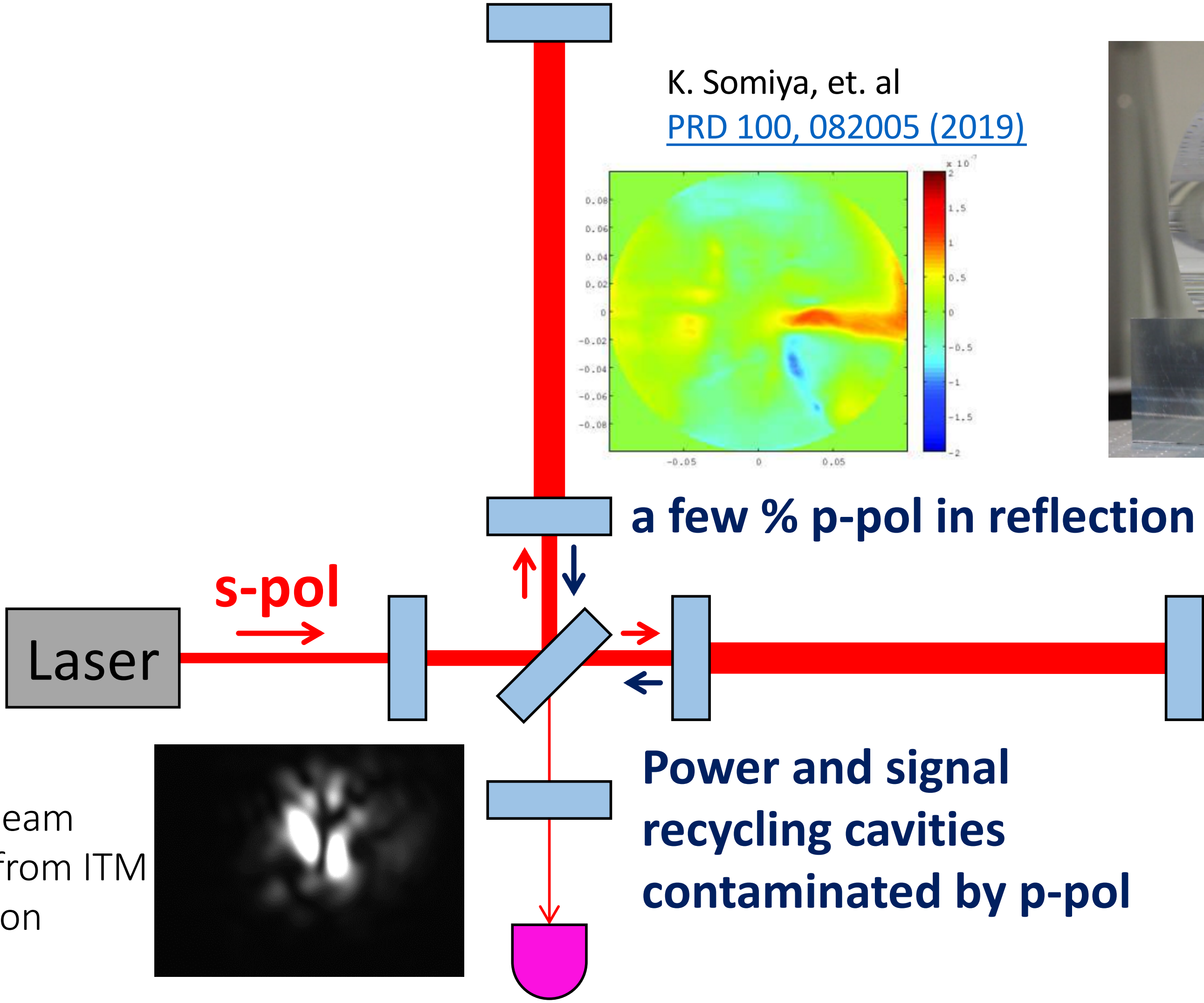
- Even though installation of components is done, we still have many issues [T. Tomaru's talk]

- Birefringence of sapphire bulk is one of the serious issue which prevents us from achieving the design sensitivity even in O4 (2022~)

Sapphire birefringence issue

K. Somiya, et. al
PRD 100, 082005 (2019)





a few % p-pol in reflection

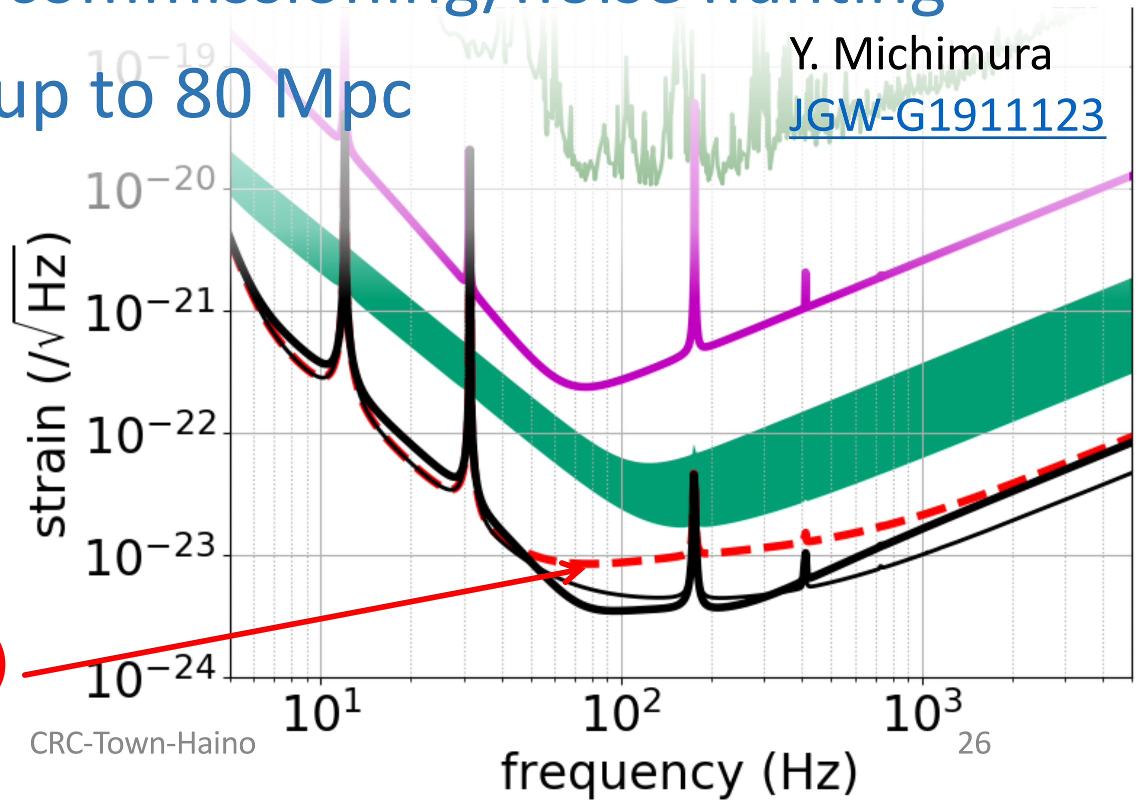
Power and signal recycling cavities contaminated by p-pol

p-pol beam shape from ITM reflection

KAGRA near future prospects

Towards O4 (2022~)

- Manage with the current (birefringent) sapphire
- Most of the time for commissioning/noise hunting
- Expected sensitivity up to 80 Mpc

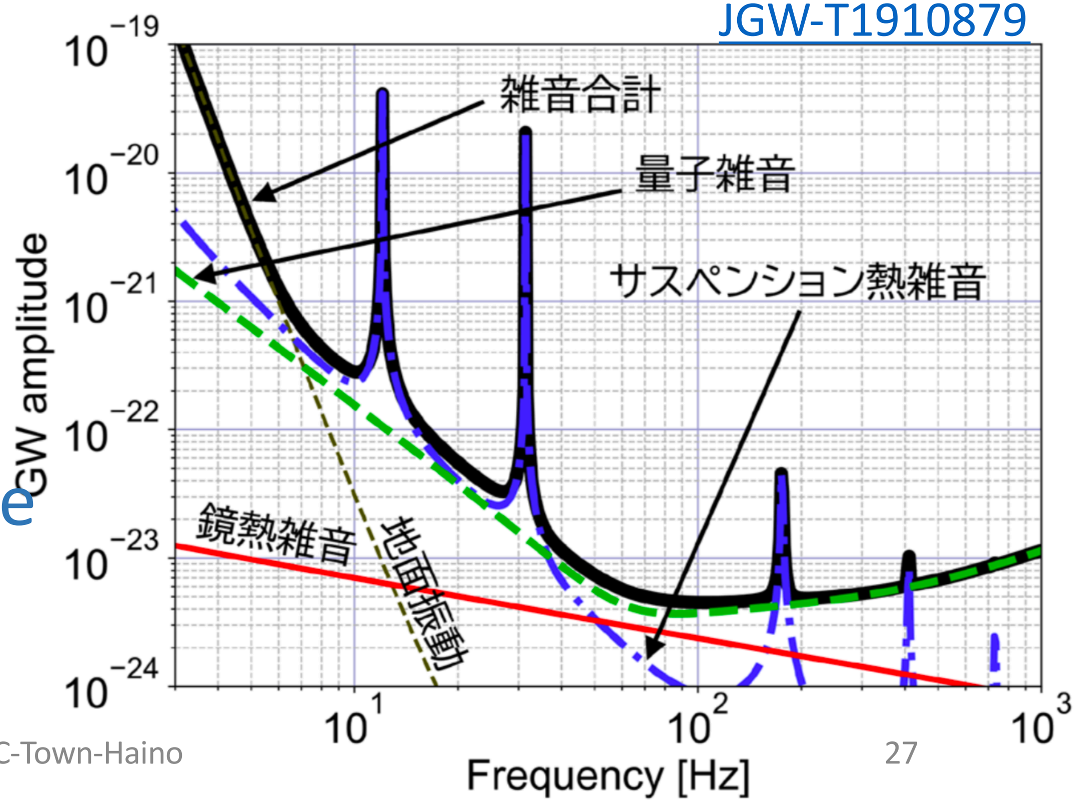


O4 limit (~80 Mpc)

KAGRA near future upgrade

- Highest priority task is to develop high spec. sapphire mirrors with negligible birefringence
- Then, KAGRA design sensitivity is mostly limited by quantum noise
- Frequency dependent squeezing technique is expected to reduce quantum noise in wide frequency range

JGW-T1910879



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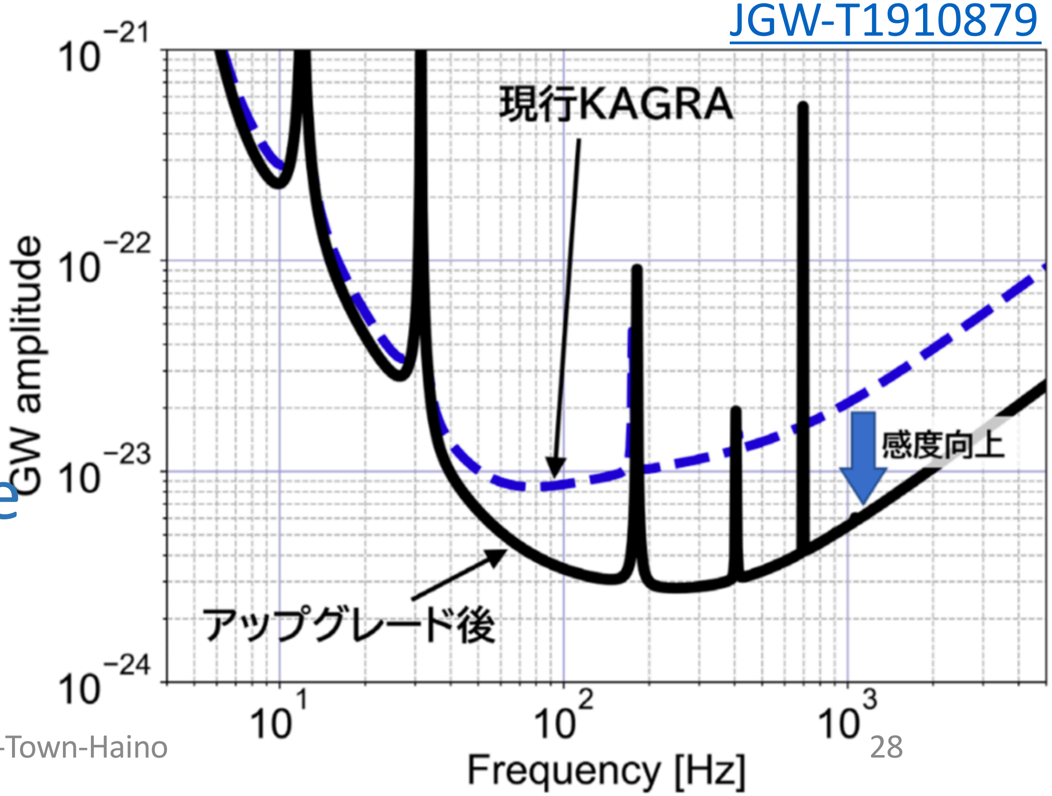


High spec. sapphire mirror

- We have been collaborating with crystal makers in Japan and a research institute in Lyon, France (iLM).
- Recently iLM got a new funding focused on the development of high quality and bigger sapphire substrate

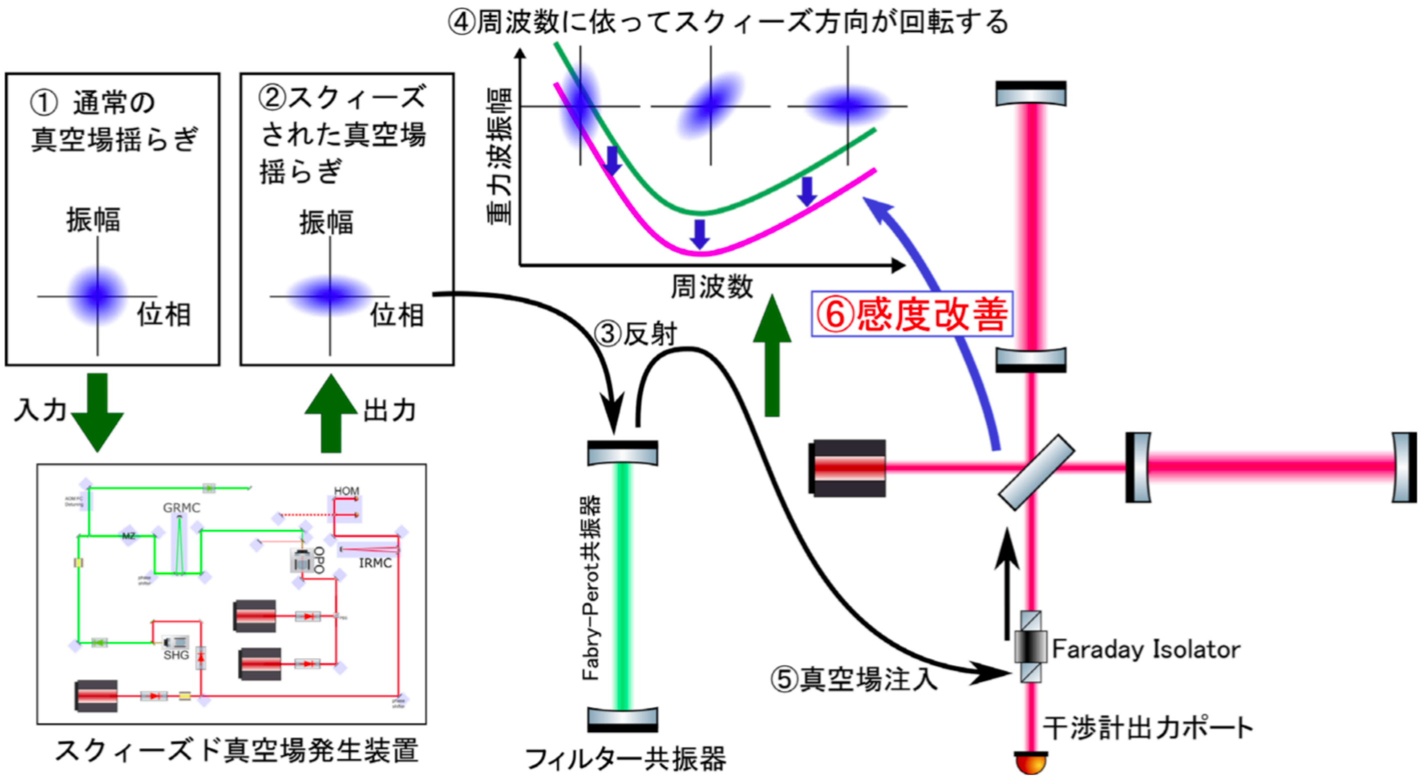
Gravitational Astronomy
Sapphire Optics (OSAG)

KAGRA ↔ iLM INSTITUT LUMIÈRE MATIÈRE

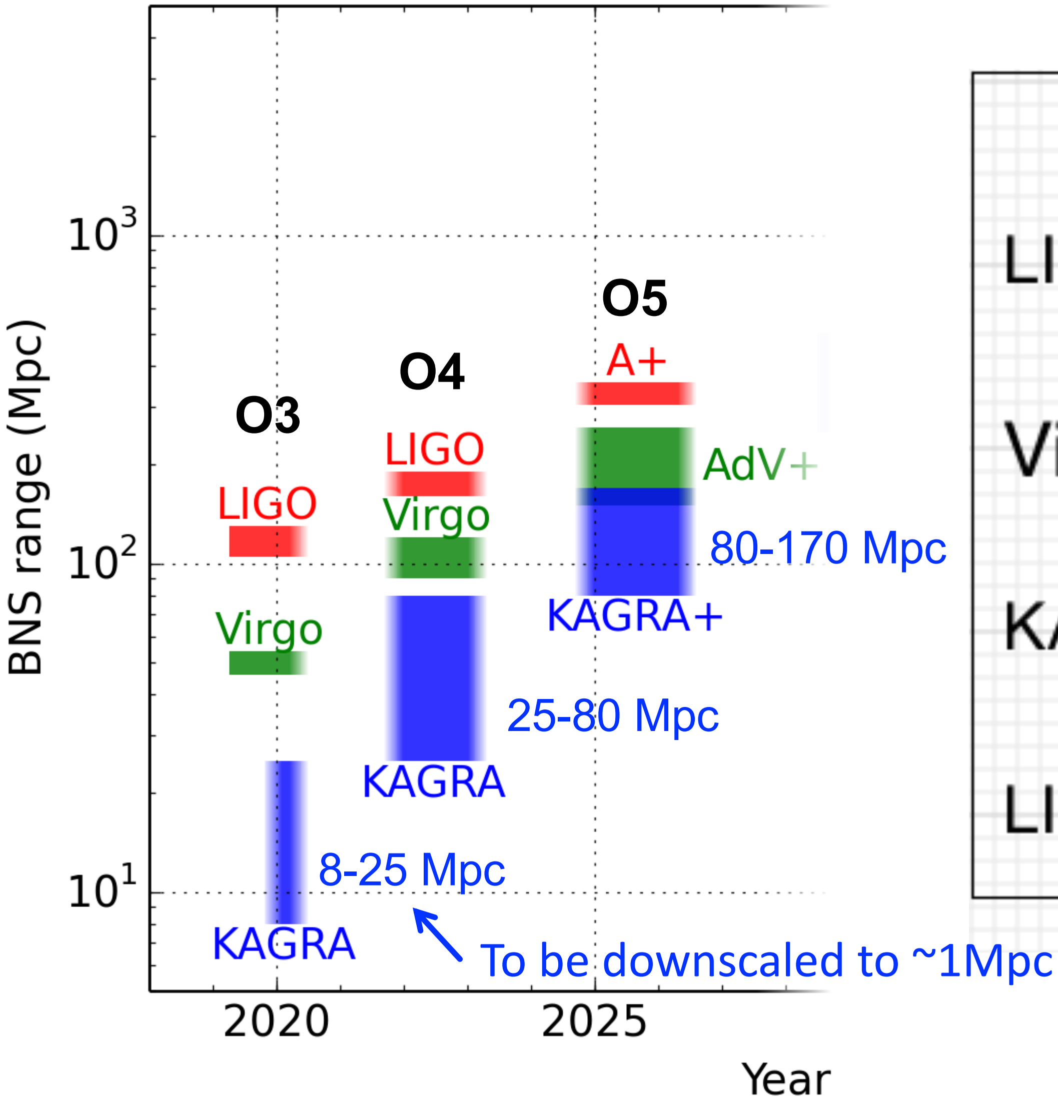
Collaboration

Freq. dependent squeezing

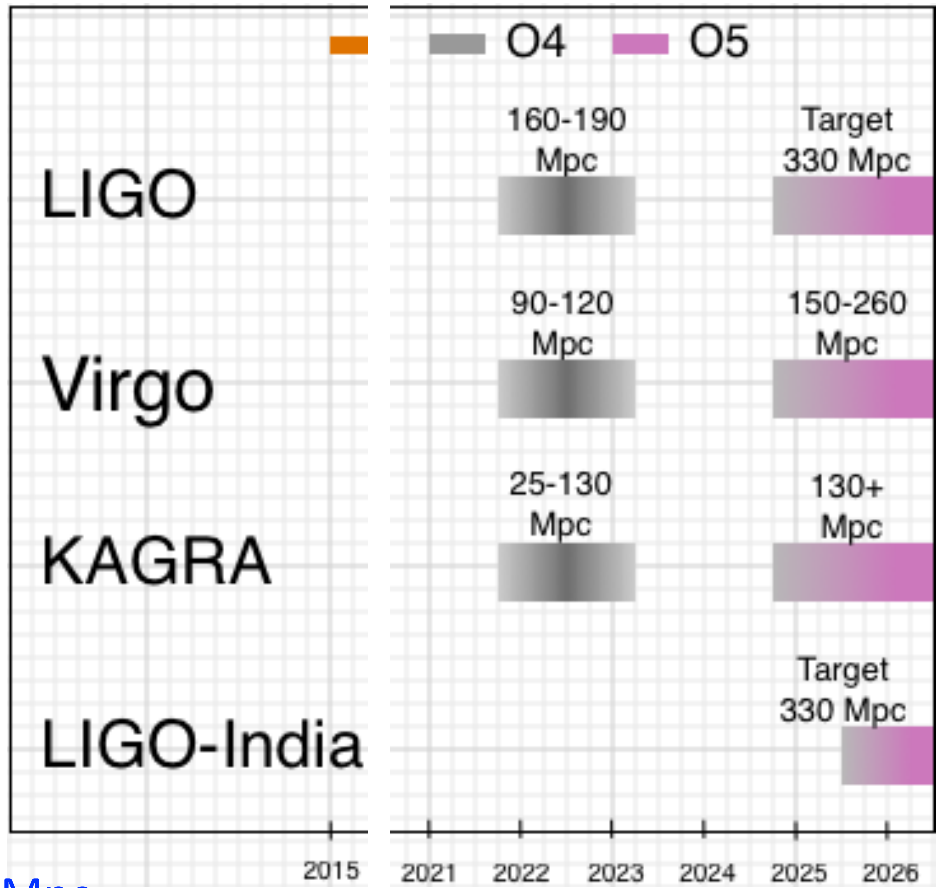
- Active developments in NAOJ and oversea KAGRA institutes (e.g. Taiwan, Korea)



KAGRA near future projection



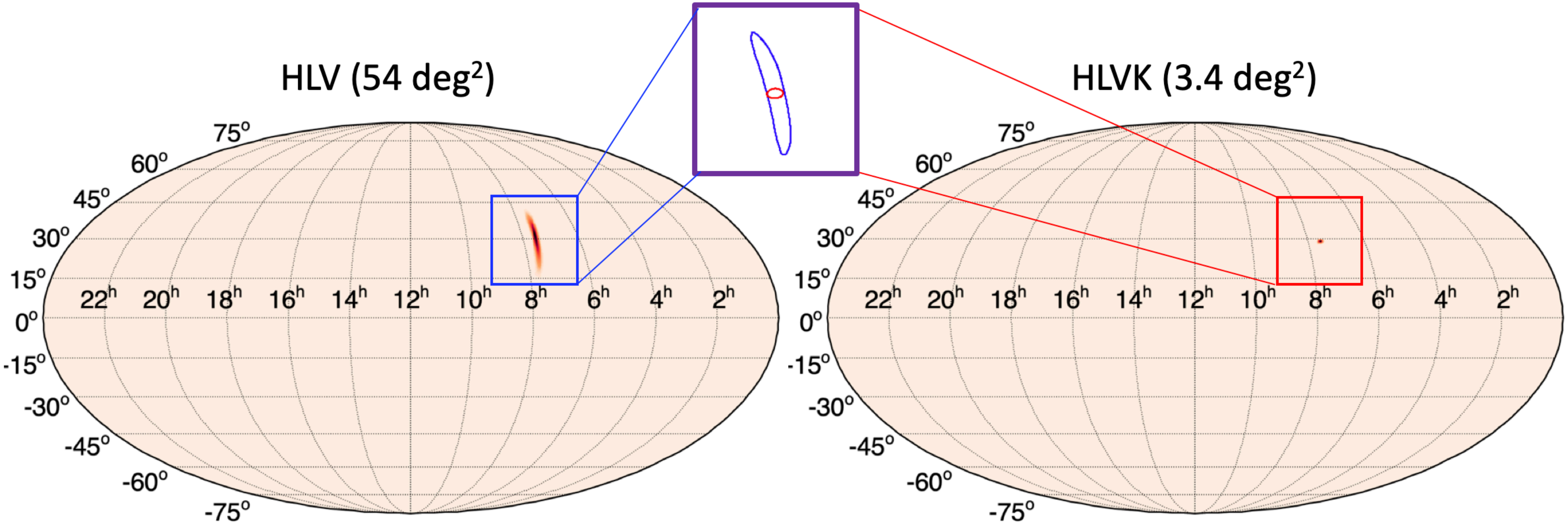
arXiv:1304.0670



KAGRA's contribution in O4~O5

- Sky localization of BNS to be significantly improved

An example of BNS event for which KAGRA can improve the sky localization accuracy



KAGRA far future upgrade idea

- Even though KAGRA is facing a difficult time, once we find the solution of current issues, it is not a dream to consider the far future with ultimate potential of cryogenic sapphire

Ultimate goal of KAGRA

- Assuming 200kg, 10ppm/cm sapphire, 500 W laser and 10dB FD squeezing are available (in 10 years)

- Estimated sensitivity as ~500 Mpc [JGW-G1910533]
- It will be the most sensitive detector with the conventional (1064nm and existing facility) technology

- We need a name; ultimate KAGRA (uKAGRA) ?

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Technological challenges

- Big sapphire mirror with low absorption
  - Collaboration with iLM
  - Proposal accepted for 200kg sapphire facility
- High power laser
  - 500W is not a dream in 5~10 years
- Suspension and heat extraction
- High power tolerance of room temp. optics
- …

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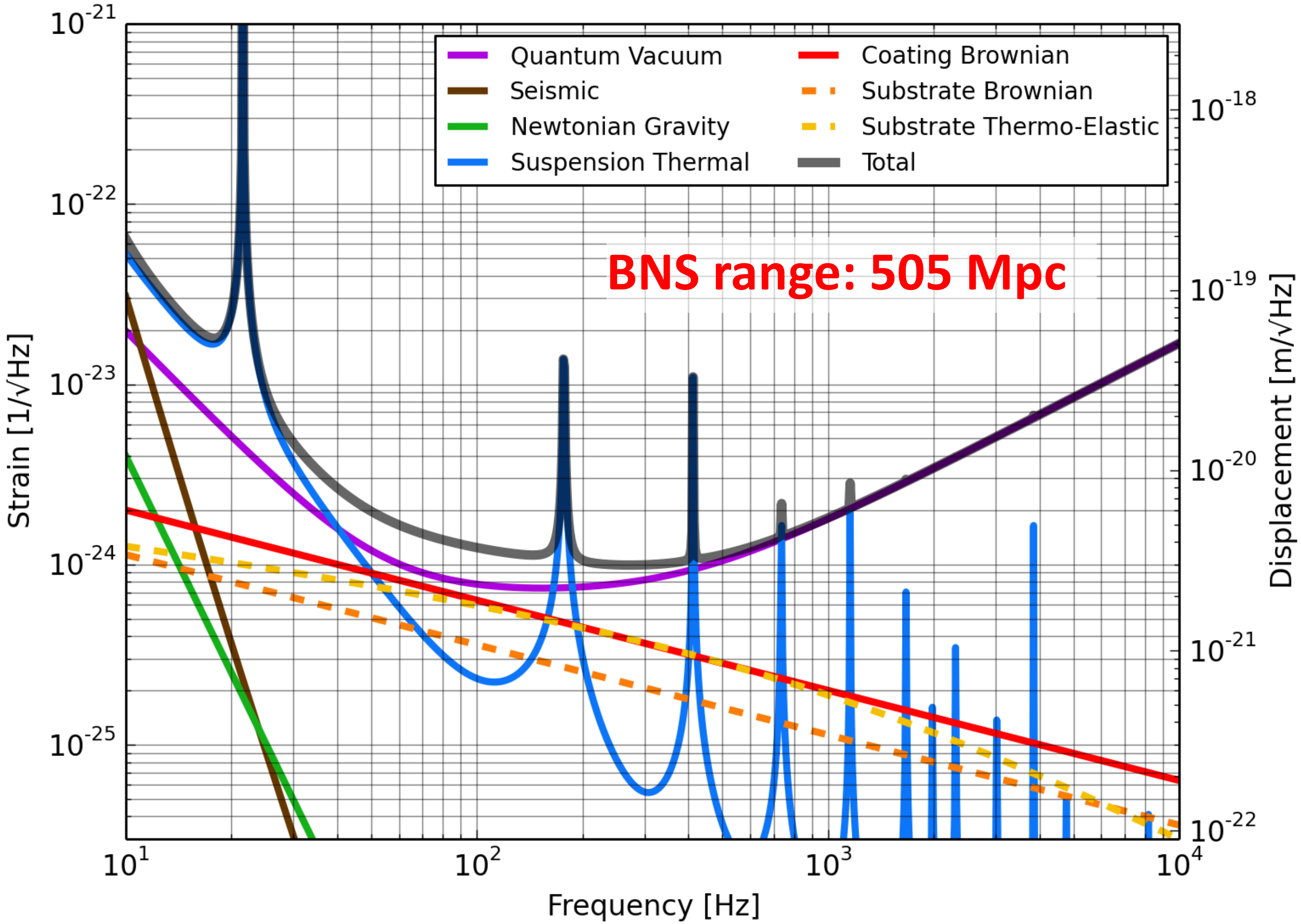
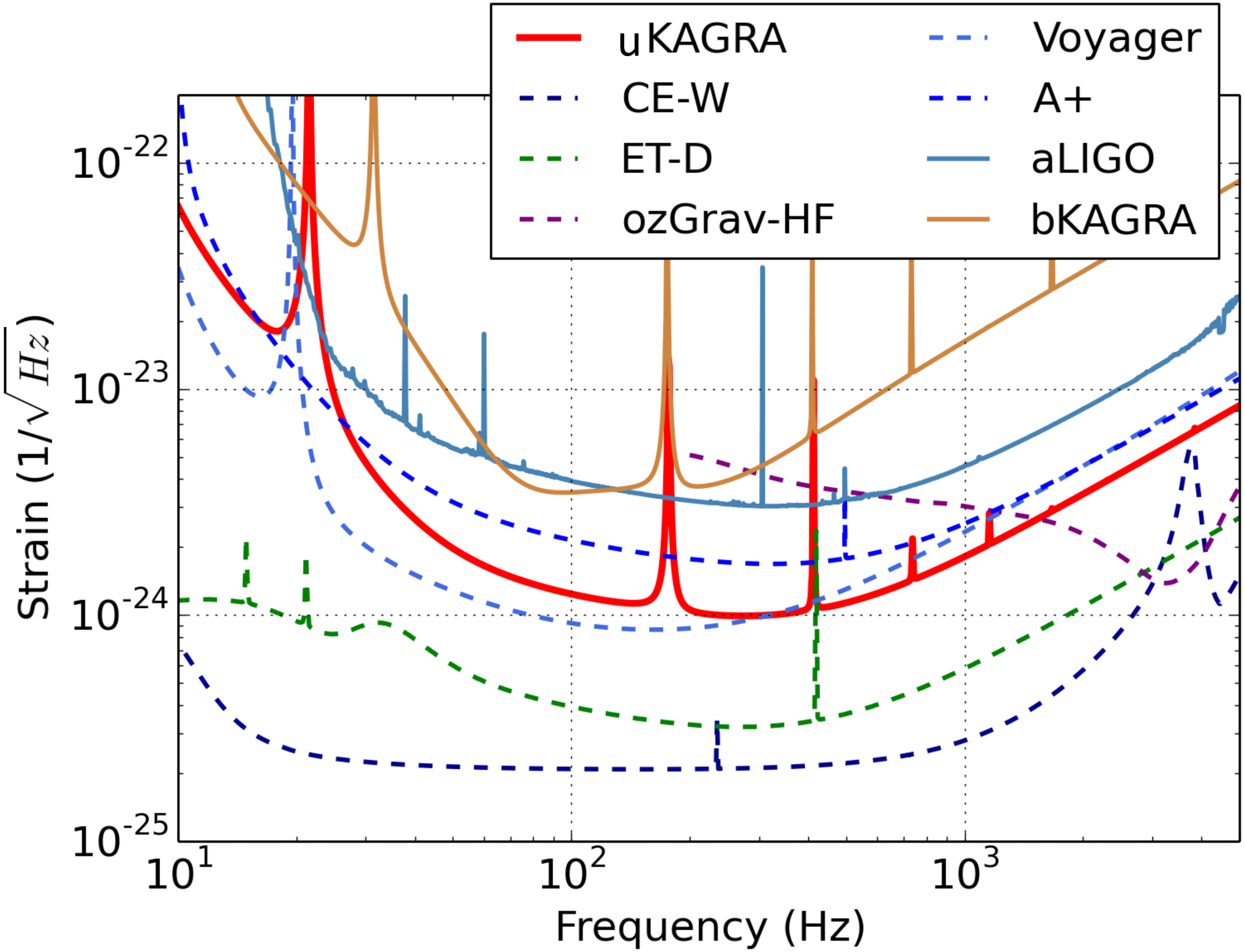
uKAGRA example sensitivity curve

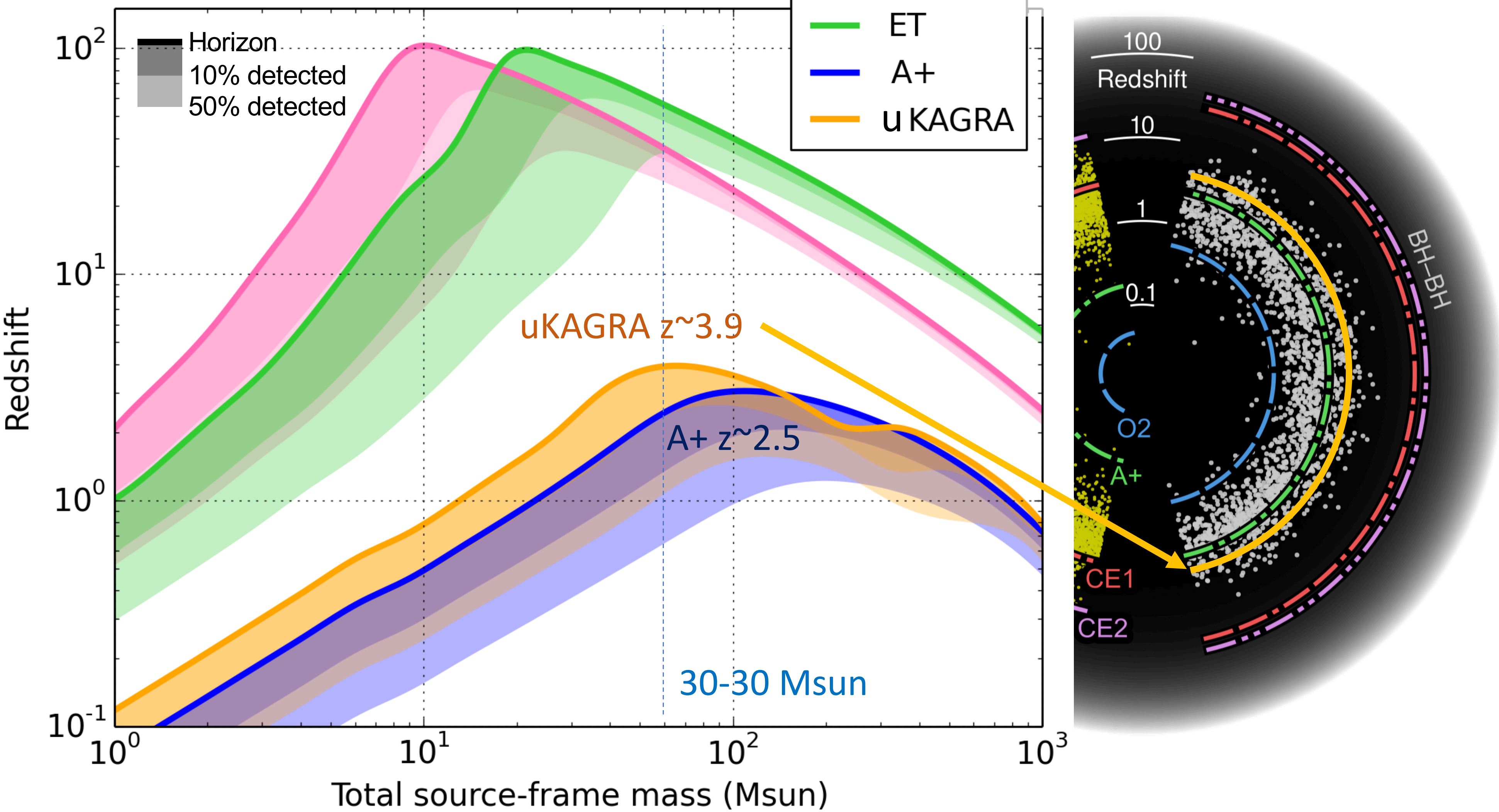


Comparison with other detectors

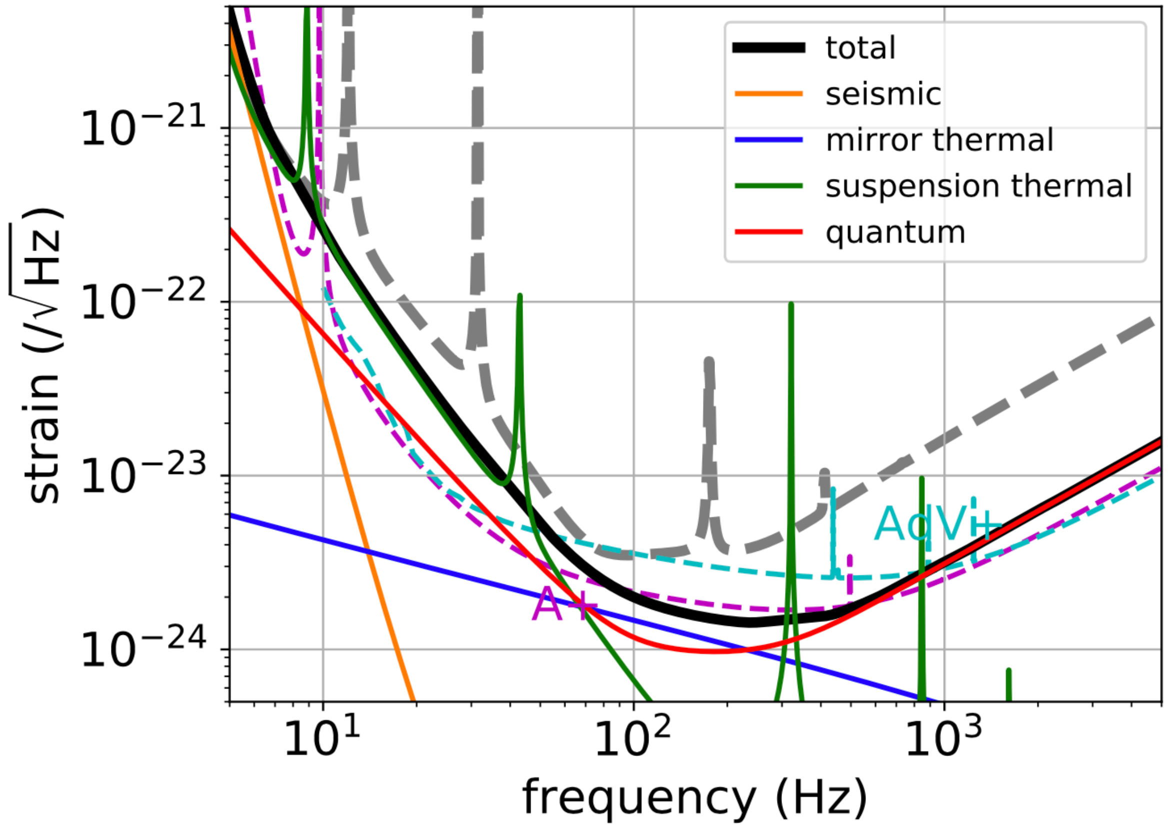


Redshift reach VS total mass

uKAGRA would be able to reach most of the BBH sources



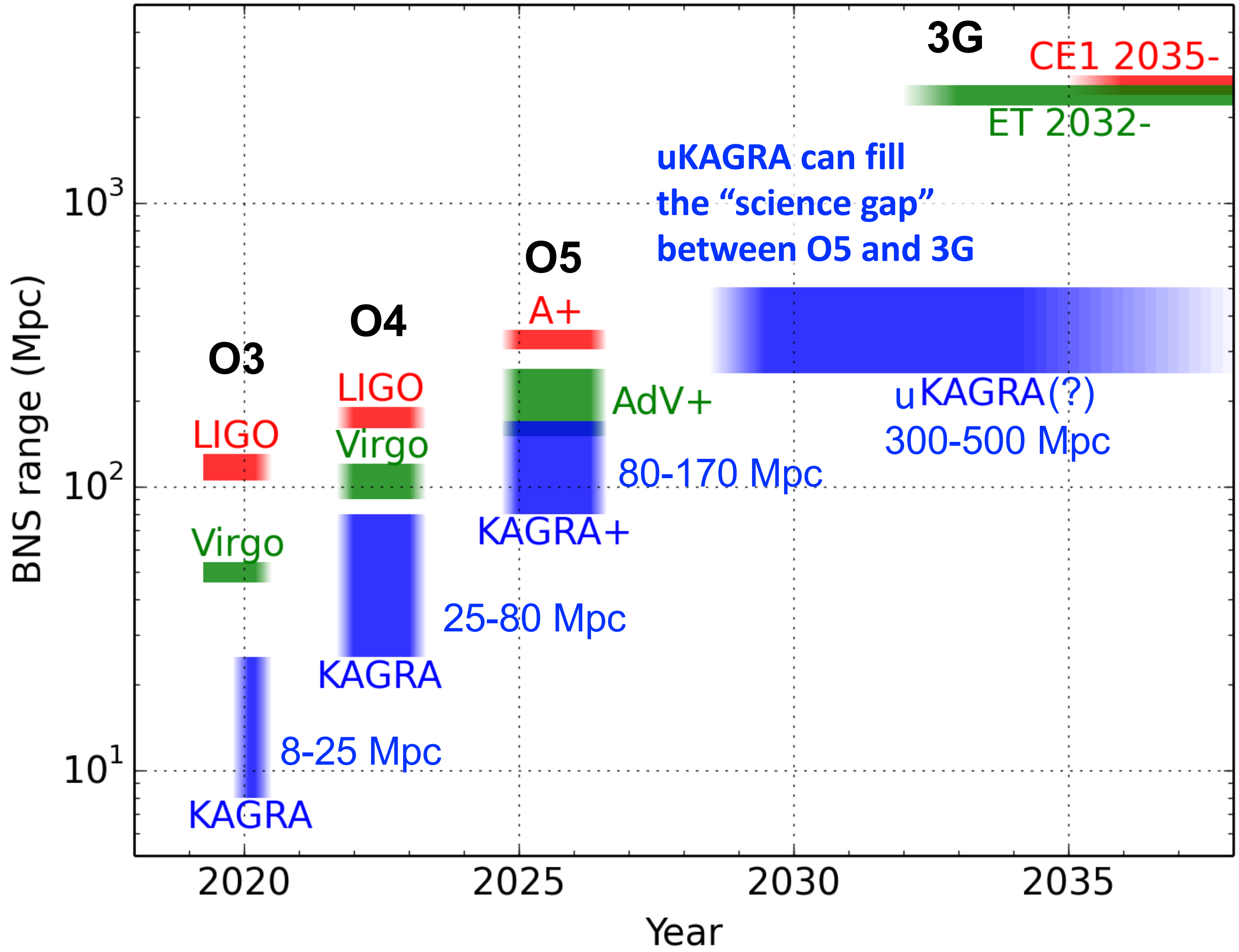
In case of 100kg/350W



JGW-T1809537

		Combined
detuning angle (deg)	$\phi_{\rm det}$	0.3
homodyne angle (deg)	ζ	93.0
mirror temperature (K)	$T_{\rm m}$	20.0
SRM reflectivity (%)	$R_{\rm SRM}$	80.9
fiber length (cm)	$l_{\rm f}$	33.1
fiber diameter (mm)	$d_{\rm f}$	3.6
mirror mass (kg)	m	100
input power at BS (W)	I_0	3470
maximum detected squeezing (dB)		5.1 (FC)
$100M_\odot$-$100M_\odot$ inspiral range (Mpc)		702
$30M_\odot$-$30M_\odot$ inspiral range (Mpc)		1762
$1.4M_\odot$-$1.4M_\odot$ inspiral range (Mpc)		**307**
median sky localization error (deg^2)		0.099

KAGRA future projection



Prospects of GW science

- Continuous sensitivity improvements offer us increasing events (3rd power) and science cases
  - Neutron Star Equation of State (EoS)
  - Test of General Relativity at extreme conditions
- New generation of Multi-messenger science
  - Short GRB
  - Precision and independent determination of cosmological constants
- Possible detection of new sources
  - Supernovae (with EM, GW and neutrino)
  - Massive BBH, …

Advantage of KAGRA in 3G era

- Existing facility
  - KAGRA observatory should work for >15 years
  - New and huge facilities needed for 3G (CE, ET)
    → difficulty and unknown about the fundings

- Long experience of cryogenic sapphire
  - New technology (e.g. cryogenic silicon mirror)
    is very challenging and uncertain for 3G (CE, ET)
    → they don't even know what are the issues

Concerns on a big facility - ILC

Science Council of Japan, Dec./ 2018

国際リニアコライダー計画の見直し案
に関する所見

総合所見

(中略)

一方では、人類が持つ有限のリソースに鑑みれば、高エネルギー物理学に限らず、実験施設の巨大化を前提とする研究スタイルは、いずれは持続性の限界に達するものと考えられる。ビッグサイエンスの将来の在り方は、学術界全体で考えなければならない課題である。

Summary

- Even though it is a difficult time for KAGRA, the future is still bright
  - At least we know what are the issues
  - KAGRA can maximize the advantage of existing underground facility

- KAGRA should catch up to LV in ~5 years (~80 Mpc), reach the same sensitivity in ~10 years (~160 Mpc) and aim at the ultimate configuration (~500 Mpc)

Parameters assumed (dimensions)

As an example; further optimization may be needed

Parameter name	bKAGRA	uKAGRA
Mirror size (and mass)	ϕ22cm ×15 cm (22.8 kg)	ϕ45cm ×31.5 cm (200 kg)
Sapphire suspension	ϕ1.6mm ×35cm	ϕ2.7mm ×50cm
Wire safety factor	12.58	5.0
Intermediate mass	20.5 kg	180 kg
Beam size	3.5 cm	7.0 cm
Clear aperture (4σ)	14 cm	28 cm
Coating improvement	None	x2
Squeezer	None	Freq. dependent (10 dB)
Filter cavity	None	300 m

Parameters assumed (power-related)

As an example; further optimization may be needed

Parameter name	bKAGRA	uKAGRA
Laser power (before PRM)	70.1 W	500 W
Power at BS	674 W	4.8 kW
Arm power	0.32 MW	2.3 MW
Mirror temperature	22 K	18.4 K
Heat to be extracted (ITM)	0.72 W	2.76 W
Heat absorption	50 ppm/cm	10 ppm/cm
Thermal conductivity coefficient (α_0)*1	7.98 W/K/m	16 W/K/m
Thermal conductivity (κ)*1	7.2 kW/K/m	19.8 kW/K/m

*1 $\kappa = \alpha_0\, d/d_0\, T^\beta$, where d_0 is diameter of bKAGRA suspension (1.6mm)