Review of LIGO Upgrade Plans

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References

- J. Miller +, PRD 91, 062005 (2015)
  Prospects for doubling the range of Advanced LIGO
- B. Shapiro +, Cryogenics 81, 83 (2017)
  Cryogenically cooled ultra low vibration silicon mirrors for gravitational wave observatories
- B P Abbott +, CQG 34, 044001 (2017)
  Exploring the sensitivity of next generation gravitational wave detectors
- LSC, LIGO-T1500290
  Instrument Science White Paper 2015
- LSC, LIGO-T1600119
  The LSC-Virgo White Paper on Instrument Science (2016-2017 edition)

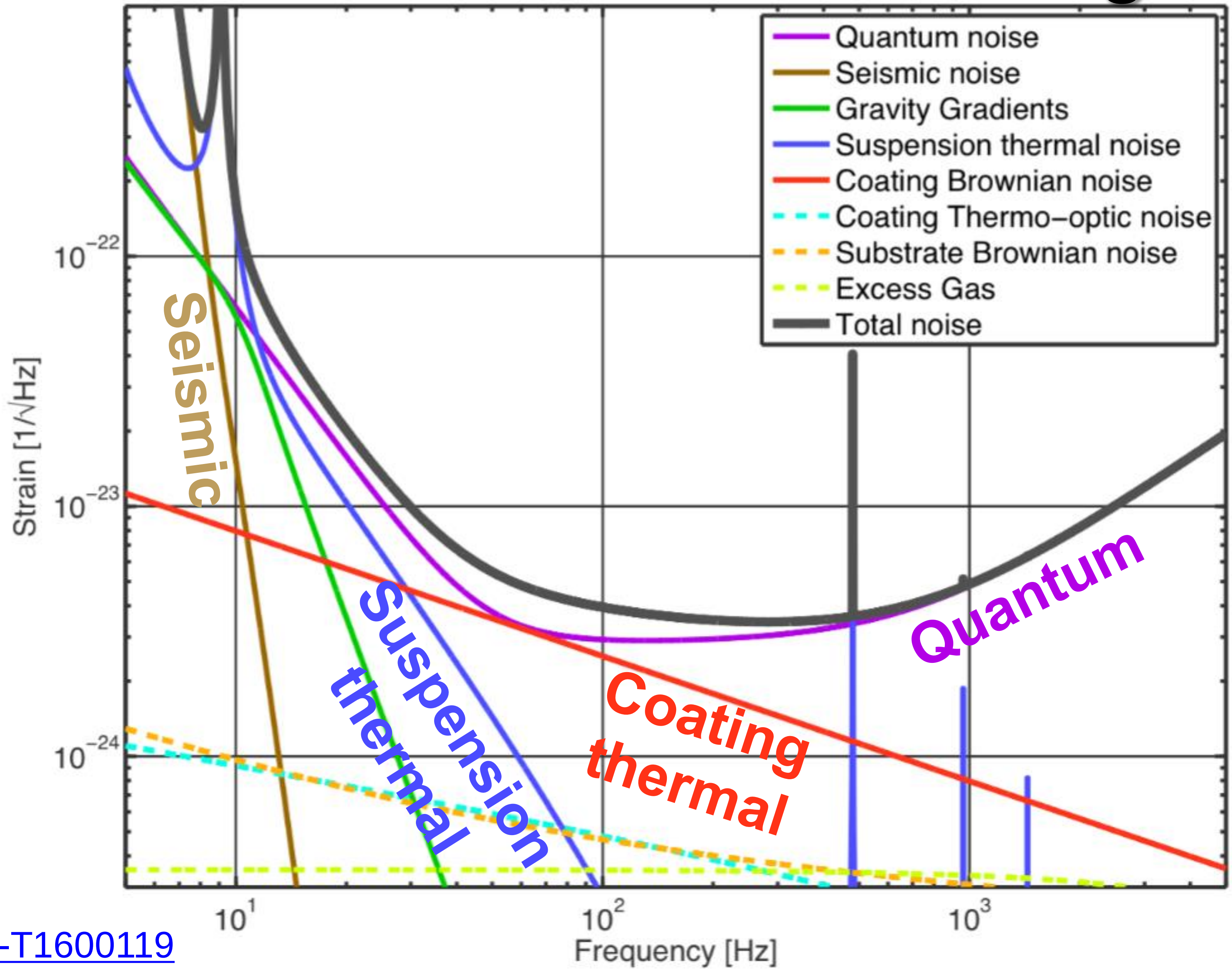
GW Detectors in the World

	USA	Europe	Japan
1G	LIGO (2002-2007) Enhanced LIGO (2009-2010)	GEO (2002-2009) GEO-HF (2009-) Virgo (2007-2011)	TAMA (1999-2004)
2G	Advanced LIGO (2015-) A+ (2017?-)	Advanced Virgo (2017?-)	KAGRA (2020?-) KAGRA+ (2024??-)
3G	Voyager (2025?-) Cosmic Explorer (2035?-)	Einstein Telescope (2030?-)	

GW Detectors in the World

	USA	Europe		Japan
1G	LIGO (2002-2007) Enhanced LIGO (2009-2010)	GEO (2002-2009) GEO-HF (2009-)	Virgo (2007-2011)	TAMA (1999-2004)
2G	Advanced LIGO (2015-) A+ (2017?-)		Advanced Virgo (2017?-)	KAGRA (2020?-) KAGRA+ (2024??-)
3G	Voyager (2025?-) Cosmic Explorer (2035?-)	Einstein Telescope (2030?-)		

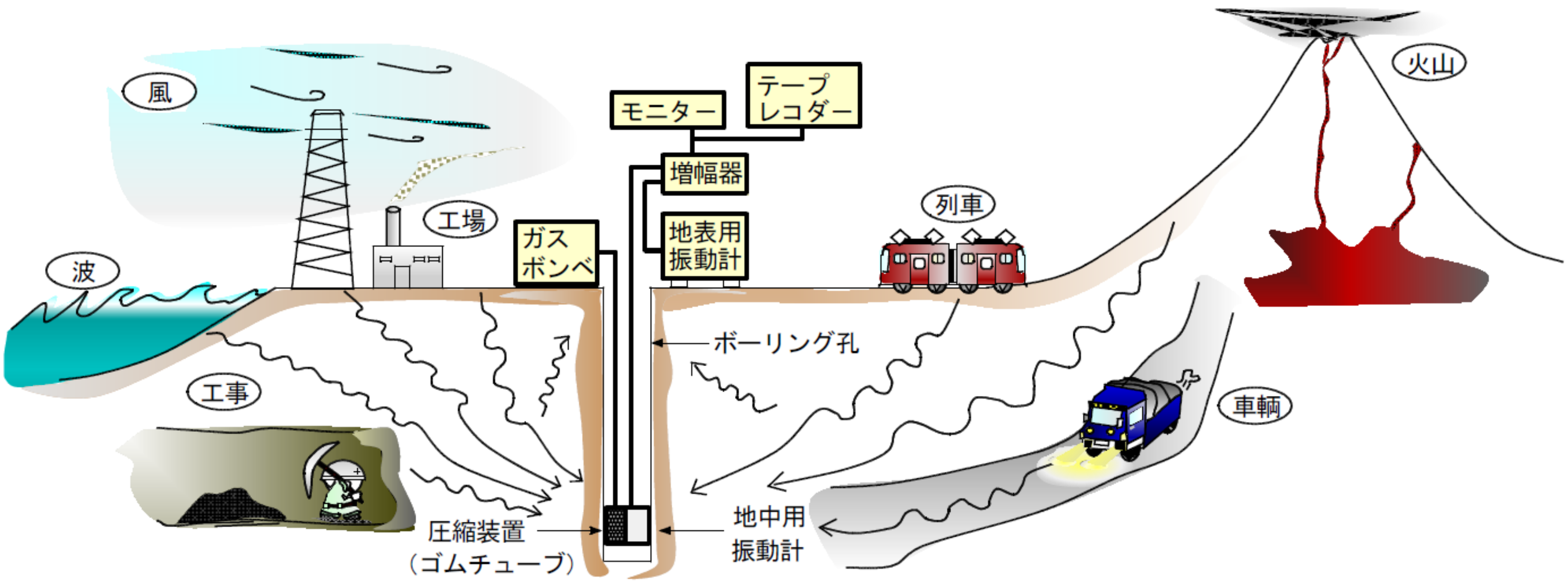
Advanced LIGO Noise Budget



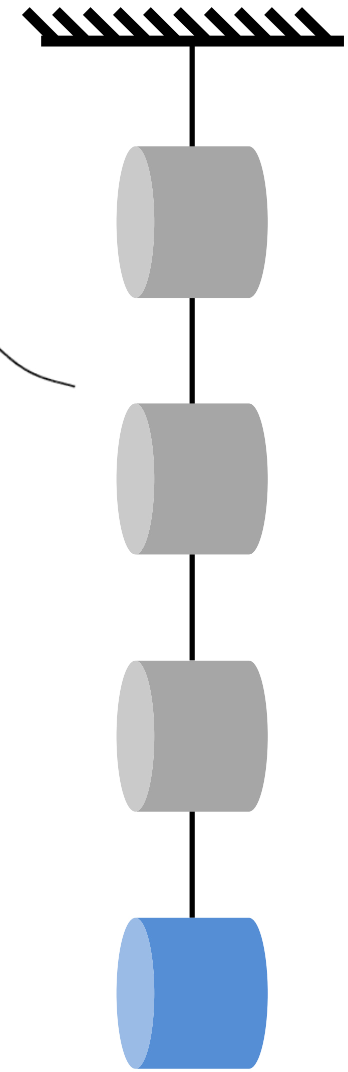
LIGO-T1600119

Seismic Noise

- Ground motion



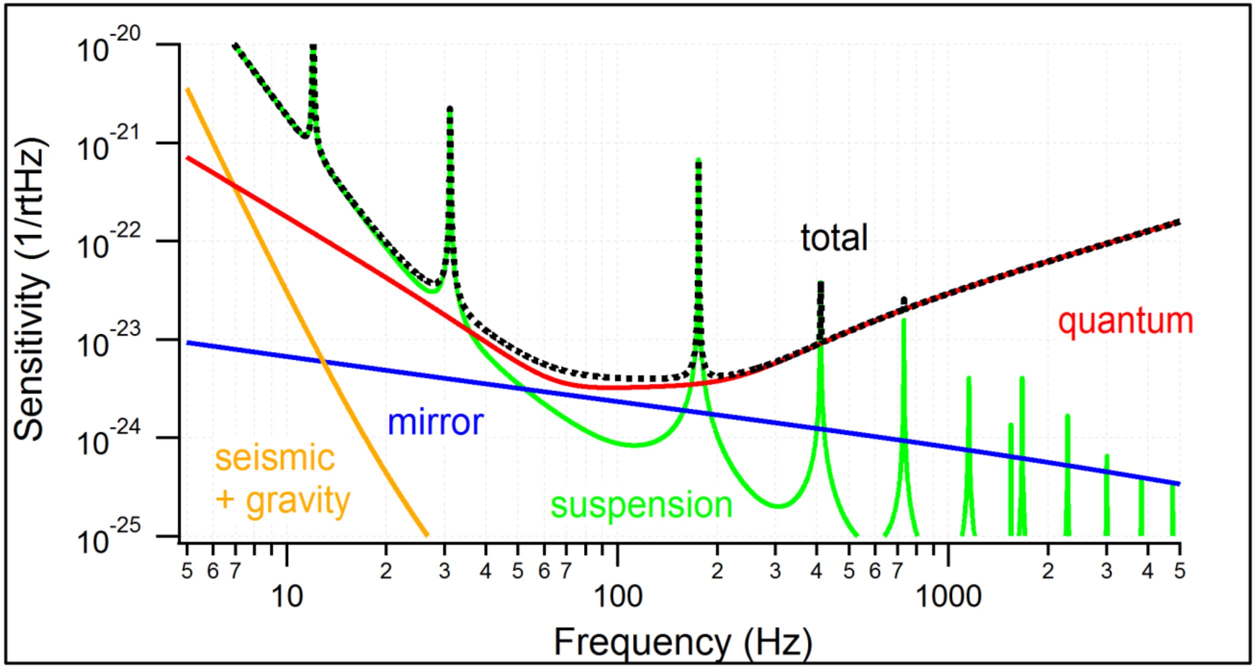
http://www.kinki-geo.co.jp/joujibidou.pdf



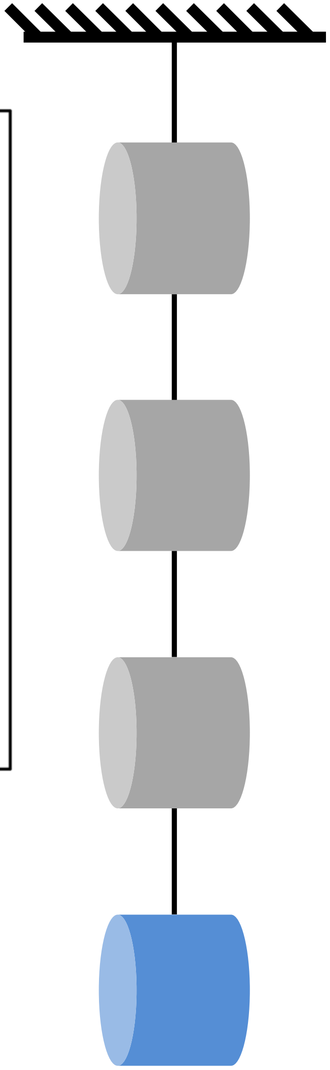
- Reduction method
  - longer arms
  - low frequency suspension
  - multiple stage suspension
  - site selection (underground, less human activities)

Suspension Thermal Noise

- Brownian motion of fibers



http://gwwiki.icrr.u-tokyo.ac.jp/JGWwiki/KAGRA

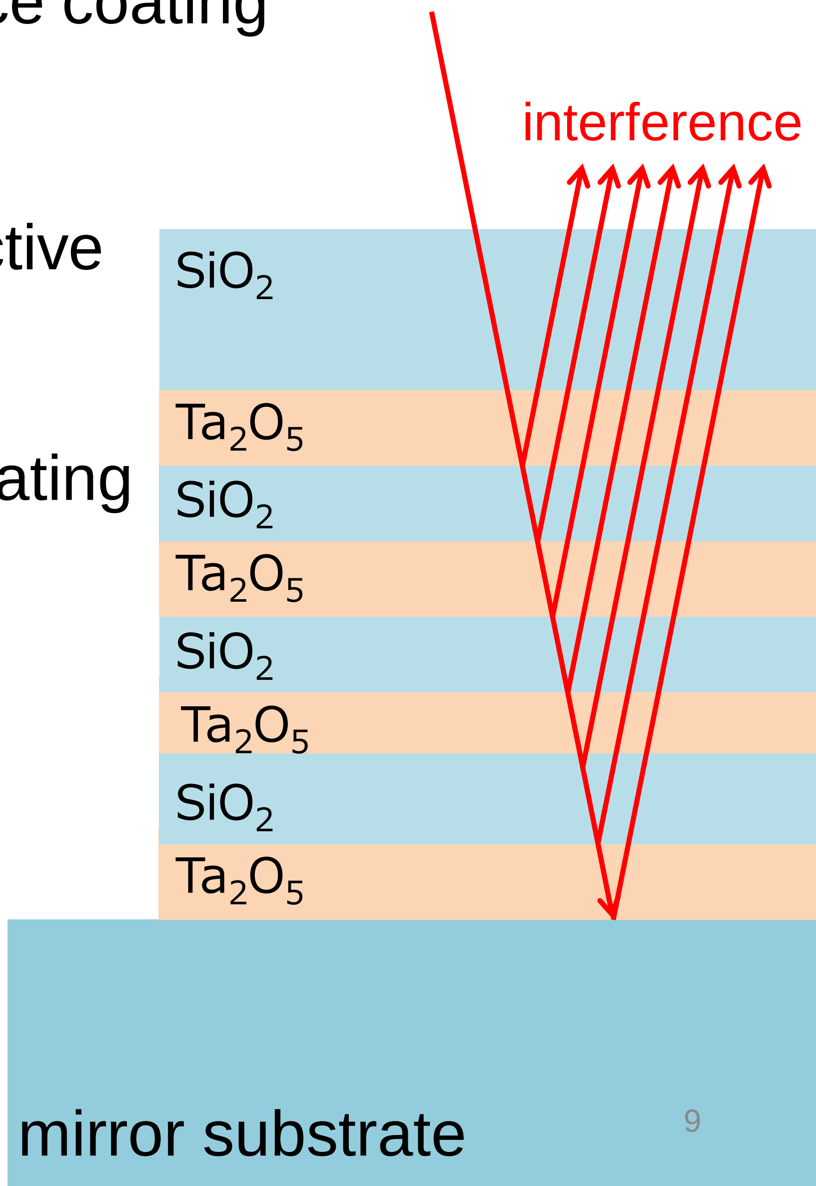


- Reduction method
  - longer arms
  - high Q material
  - longer and thinner fiber
  - cryogenic temperature

Coating Thermal Noise

- Brownian motion of mirror surface coating
- Thermo-optic noise
  - Thermo-refractive noise
    thermal change in the refractive index of the coating
  - Thermo-elastic noise
    thermal expansion of the coating

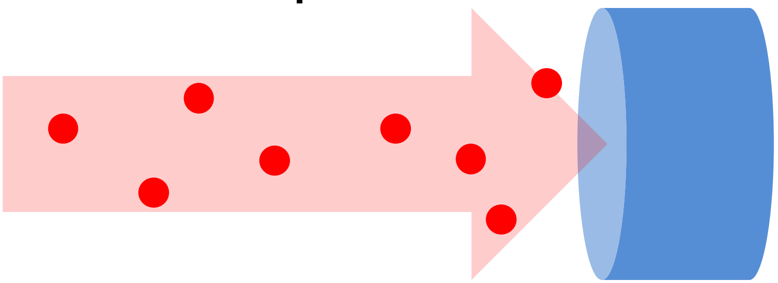
- Reduction method
  - longer arms
  - high Q material
  - cryogenic temperature
  - larger beam size



Quantum Noise

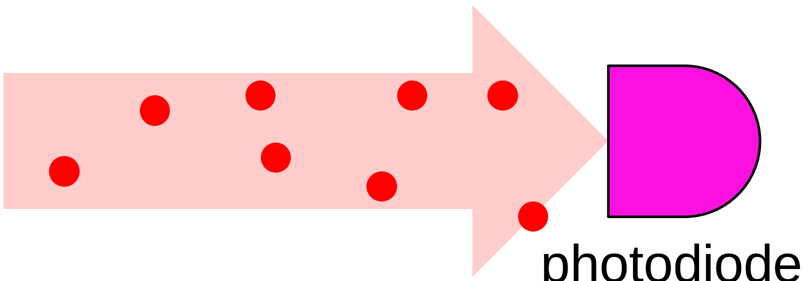
- Quantum fluctuation of light

Radiation pressure noise



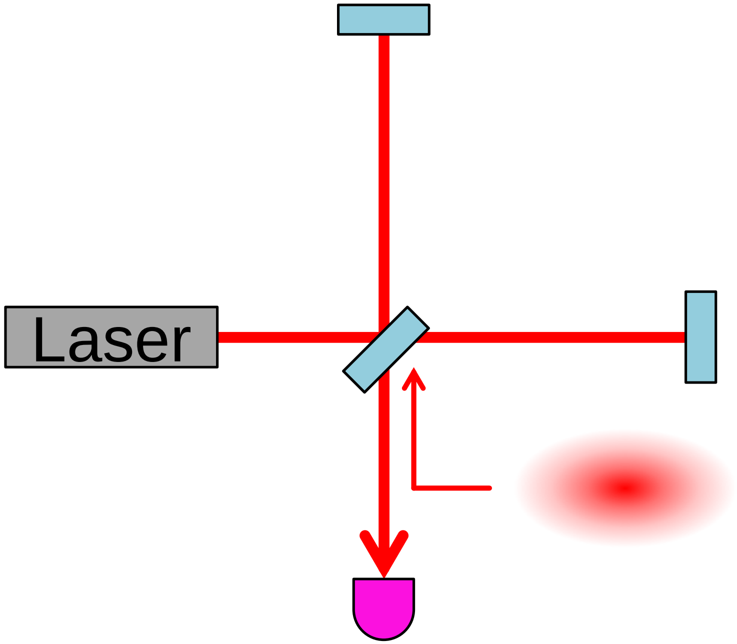
mirror

Shot noise



photodiode

- Reduction method
  - longer arms
  - interferometer configuration
    (higher finesse, RSE, etc.)
  - heavier mirrors
  - squeezing

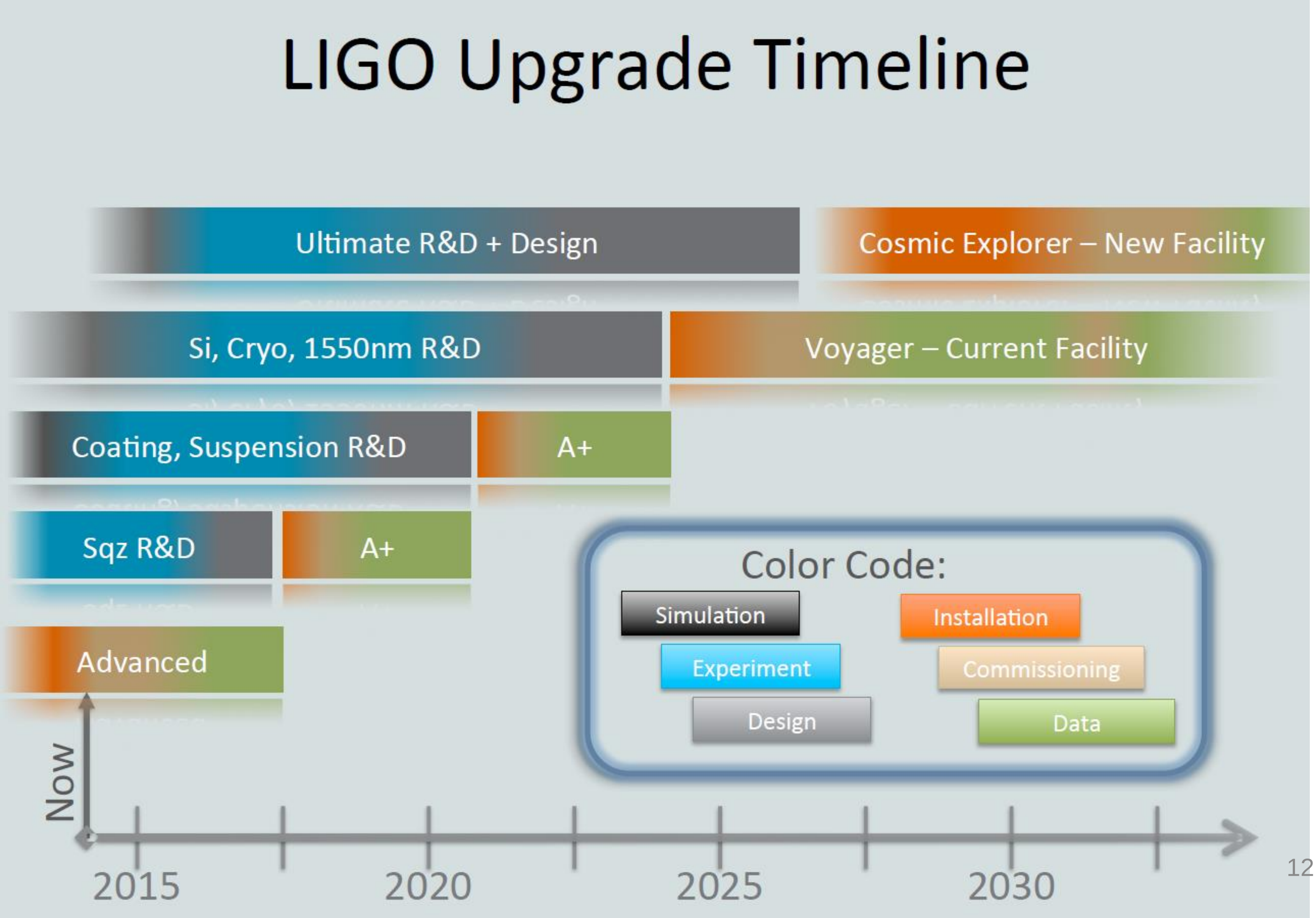


Summary of Noise Reduction

- Longer arms
  Seismic, Suspension thermal, Coating thermal, Quantum
- Better suspension
  Seismic
- Underground
  Seismic
- Lager mirror (allows larger beam size)
  Suspension thermal, Coating thermal, Quantum
- High Q material
  Suspension thermal, Coating thermal
- Cryogenic temperature
  Suspension thermal, Coating thermal
- Squeezing
  Quantum

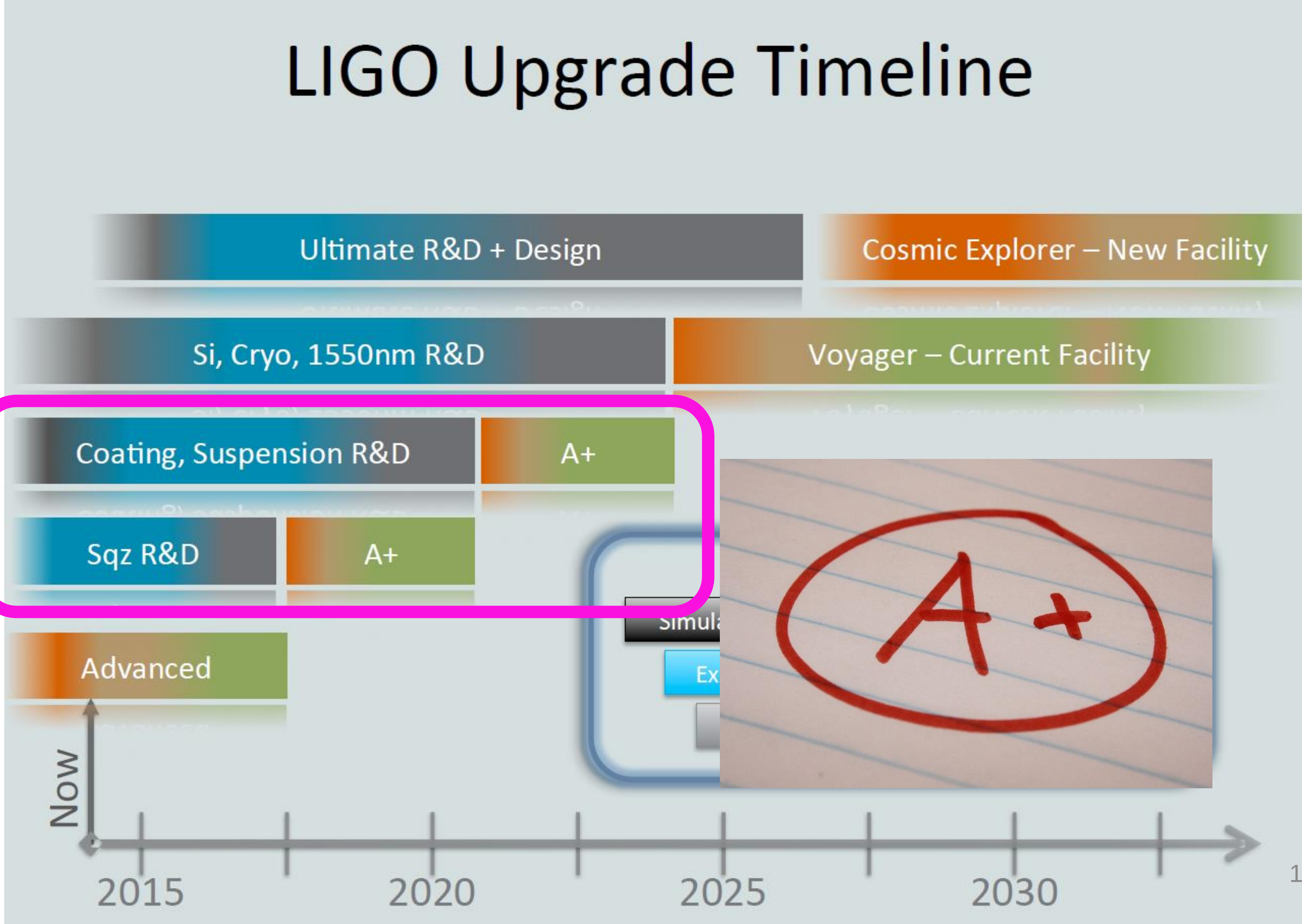
Estimated LIGO Timeline

LIGO-T1600119



Estimated LIGO Timeline

LIGO-T1600119



Advanced LIGO+ (A+)

- Modest cost upgrade of aLIGO (< $10M-20M)
- Factor of 2 improvement in sensitivity
  quantum noise
  coating thermal noise
- Two stages
  - frequency dependent squeezing
    (after O2, 2017)
  - better coating, possibly low-risk changes to suspensions
    (after O3, 2018-2019)

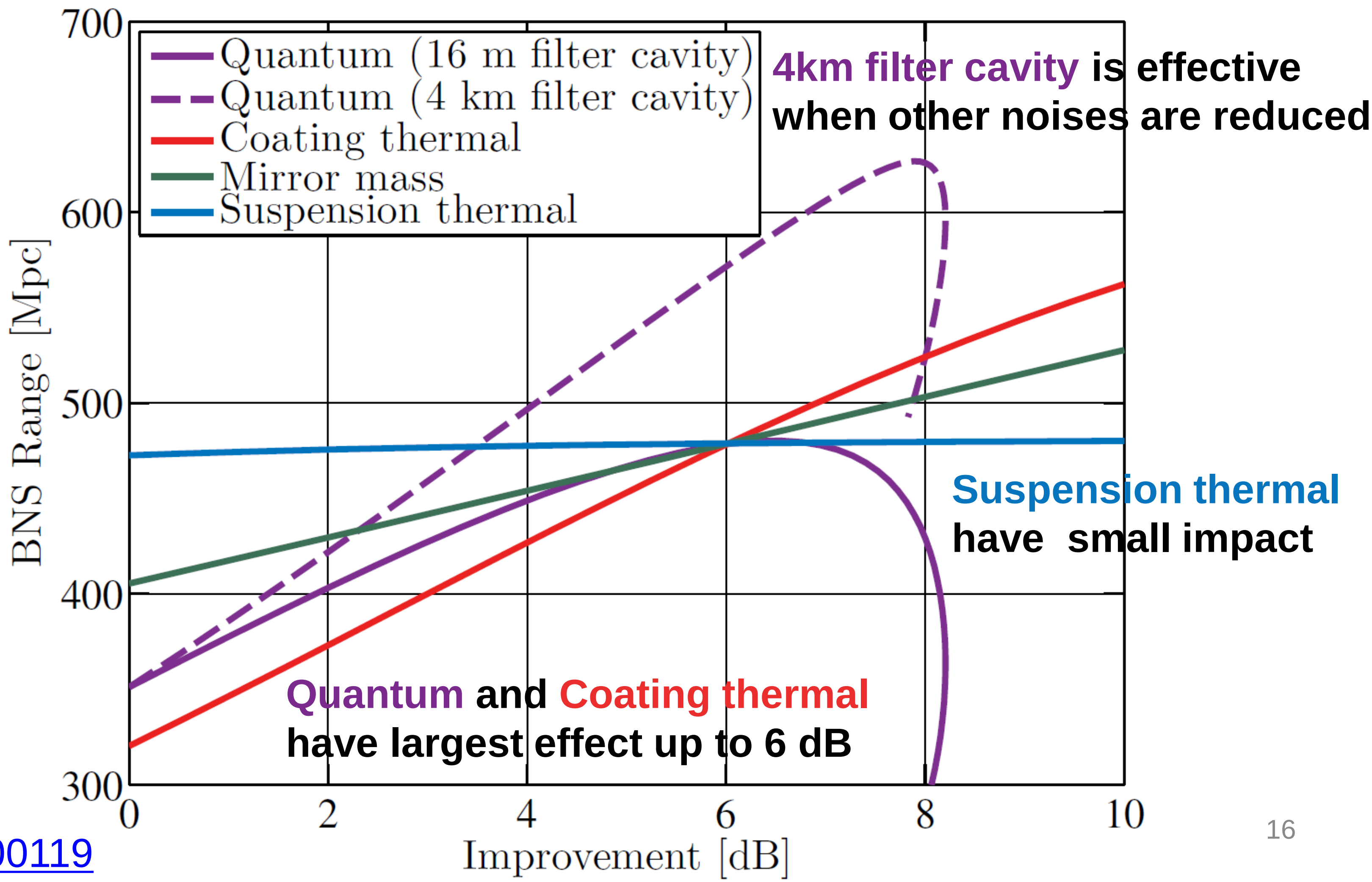
  reduce gas damping,
  improve bounce and roll damping,
  mitigate parametric instabilities, etc.
- Also as risk reduction for aLIGO
  - squeezing in case high power is difficult
  - improved coating in case coating thermal noise is underestimated
- Heavier mass, improved suspension for lower thermal noise
  -> little impact on the astrophysical output

A+ Details

- Frequency dependent squeezing with 16m long filter cavity (4km filter cavity is not required if no change in other noises)
- Coating thermal noise
  AlGaAs crystalline coating not demonstrated with
  40cm-scale mirror
- Heavier mass not feasible
  400kg and 1m diameter fused silica possible
  Polishing with Ion Beam Figuring up to 50cm possible
  Coating up to 40cm possible (CSIRO),
  LMA planning to scale-up
- Suspension thermal noise -> little impact
  longer fiber, higher stress
  heat treatment of fibers to reduce surface losses
  modify geometry

Relative importance of upgrades

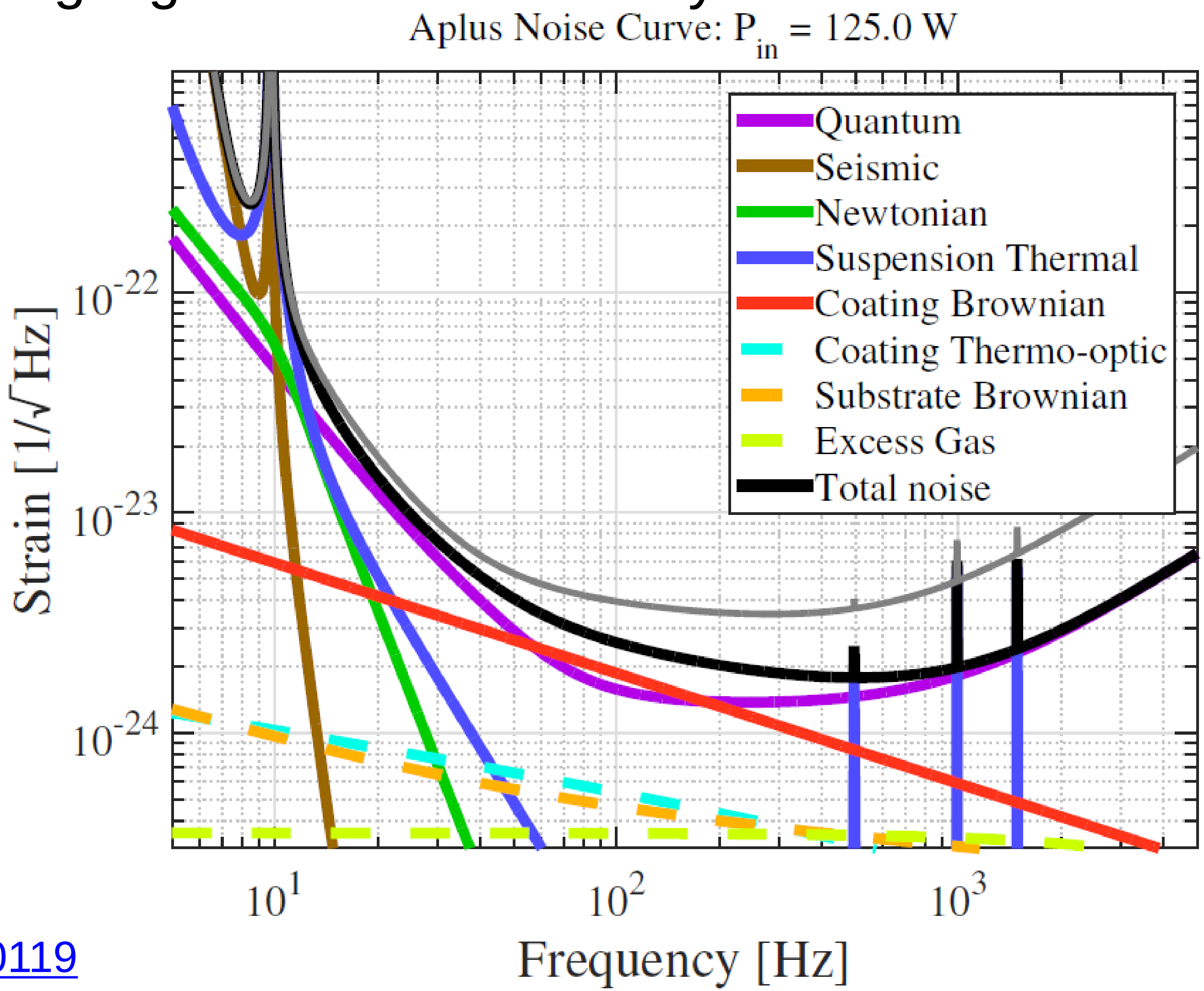
- Benefit of each improvement assuming all other improvements (6 dB) have already been made



LIGO-T1600119

A+ Nominal Noise Budget

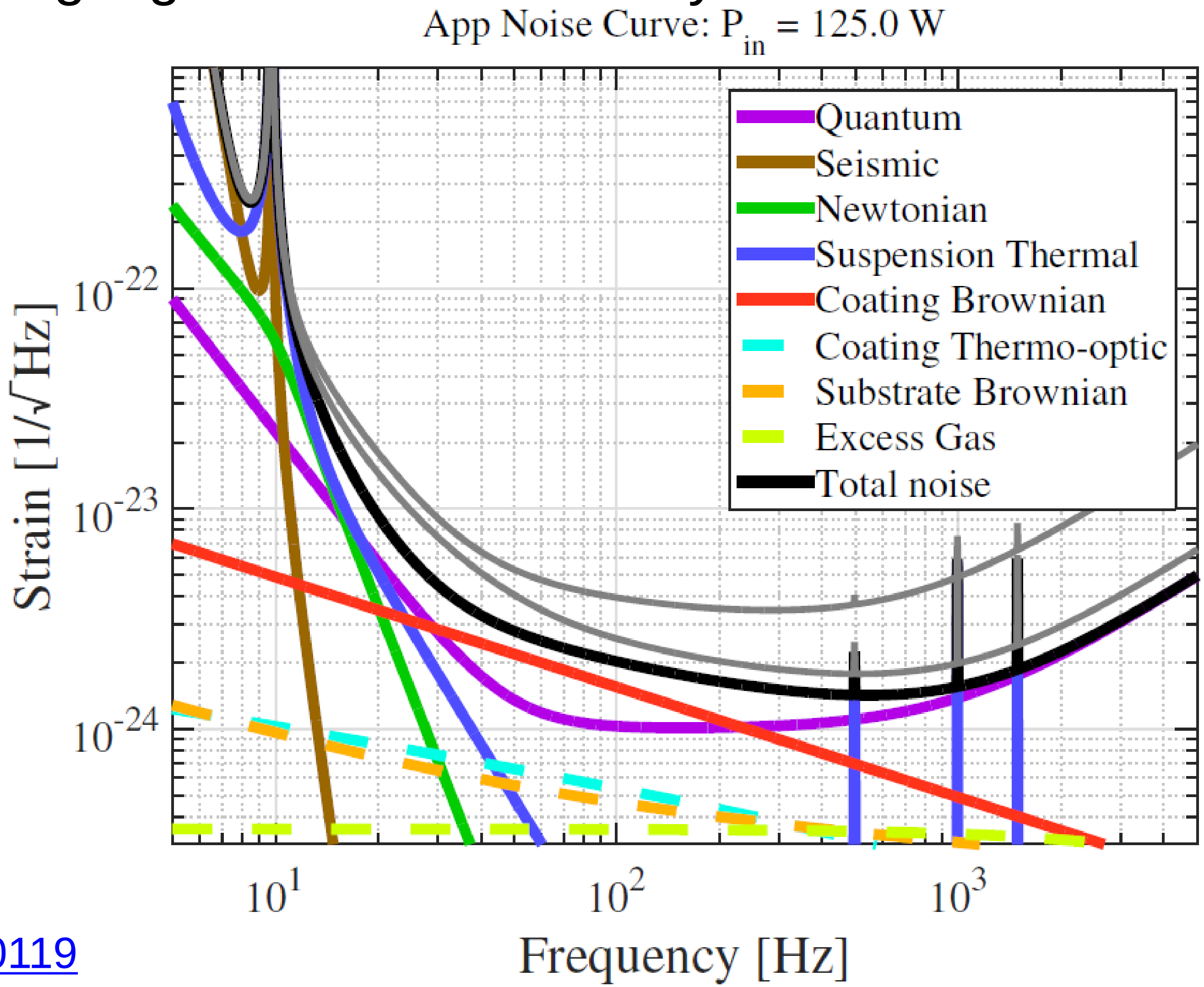
- 16 m filter cavity, 6 dB measured squeezing, 1/2 loss in coating high refractive index layer



LIGO-T1600119

A+ Optimistic Noise Budget

- 4 km filter cavity, 8 dB measured squeezing, 1/4 loss in coating high refractive index layer



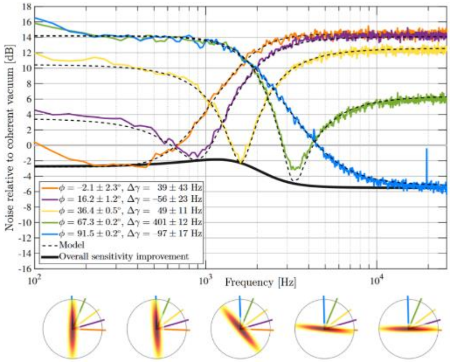
LIGO-T1600119

Other R&Ds

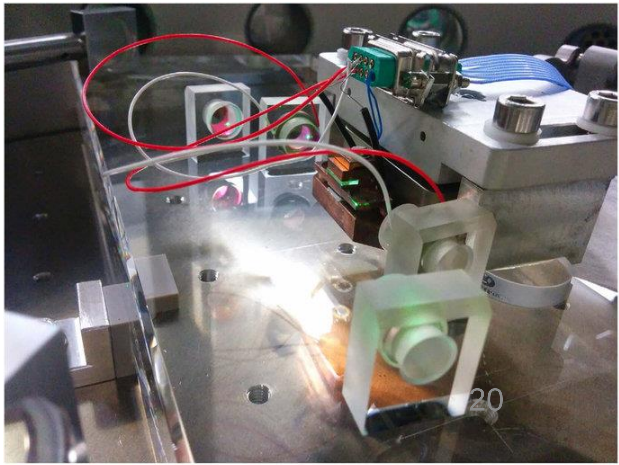
- Mode matching, alignment control (OMC, filter cavity, squeezed light source)
- Newtonian noise subtraction
- Better ISI (Internal Seismic Isolation)
  improved vertical inertial sensor, improved position sensors
  to reduce RMS motion of ISI
- Stray light control
- Arm length stabilization system
  reduce complexity (possibly inject green from vertex)
- Optical coating quality
  to reduce scattering
- Charge mitigation
- PSL design to minimize noise couplings
- Larger BS

Experimental Demonstrations

- K. Goda+, Nature Physics 4, 472 (2008)
  Squeezing with prototype SRMI
- LSC, Nature Physics 7, 962 (2011)
  Squeezing with GEO600
- J. Aasi+, Nature Photonics 7, 613 (2013)
  Squeezing with LHO
- E. Oelker+, PRL 116, 041102 (2016)
  2 m filter cavity at 1.2 kHz

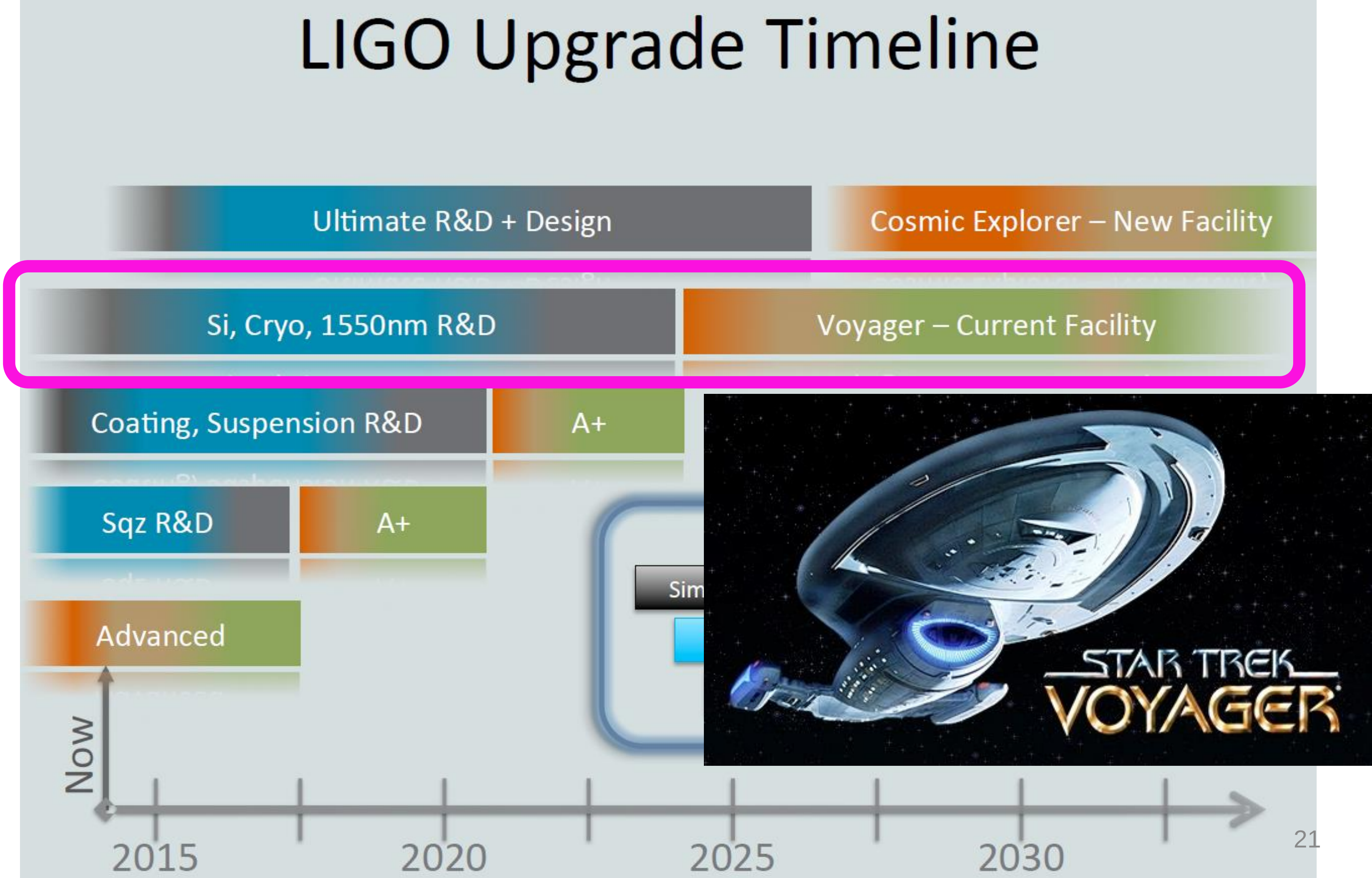


- A. R. Wade+, Scientific Reports 5, 18052 (2015)
- E. Oelker+, Optica 7, 682 (2017)
  ~1mrad phase noise with OPO under high vacuum
- 16 m filter cavity prototype at MIT on going

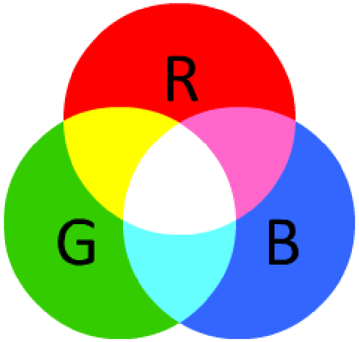


Estimated LIGO Timeline

LIGO-T1600119



Voyager



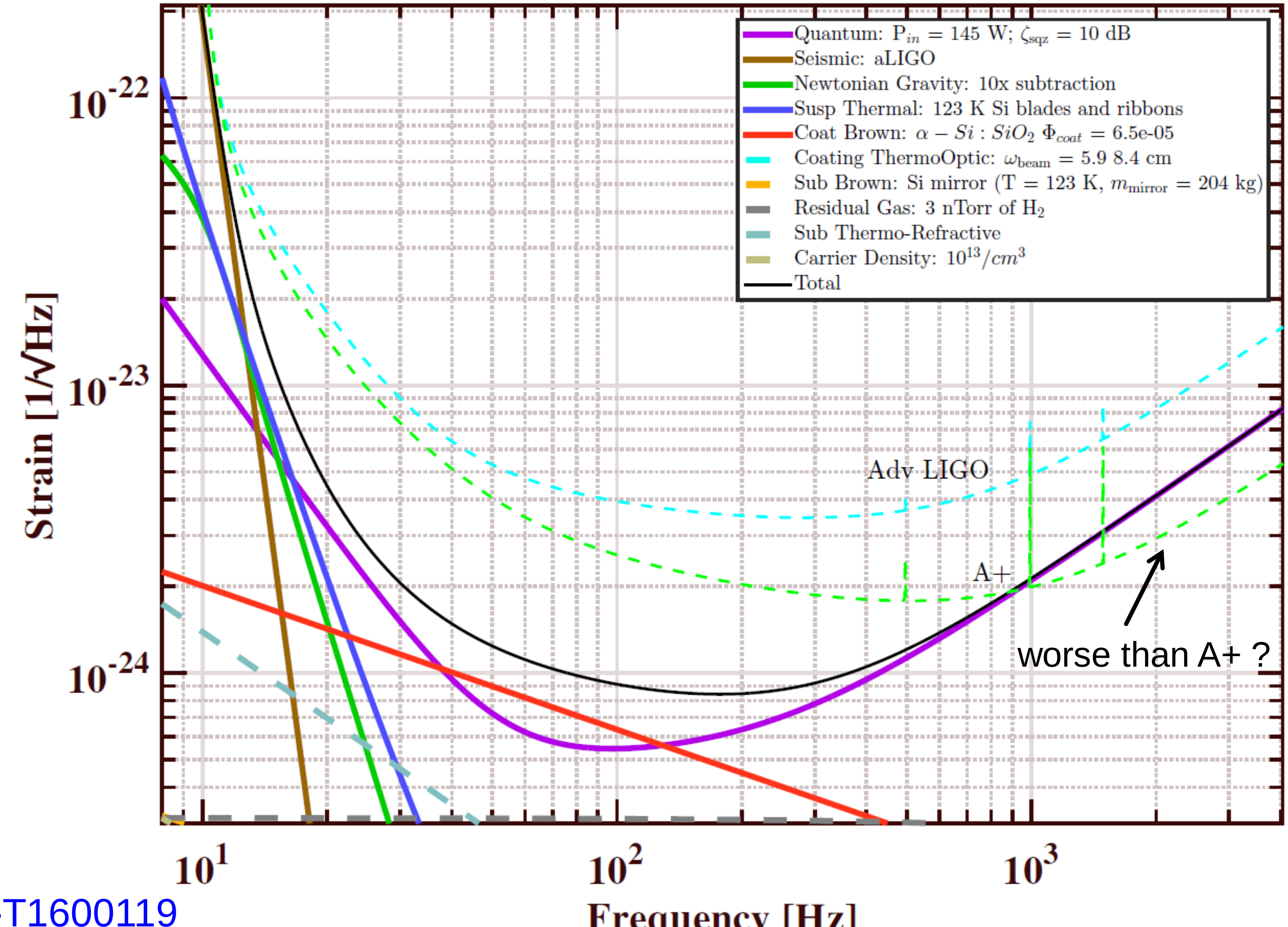
- Major upgrade within existing facility
- Factor of 3 increase in BNS range (~1100Mpc)
- 200 kg Silicon, 123 K
- 200 W laser at 2 um
  wavelength could be 1.55-2.1 um
  - silicon absorption
  - stable high power laser
  - quantum efficiency of PDs for squeezing
    (high for 1064 and 1550 nm)
  - wide angle scatter loss $1/\lambda^2$
- Shin-Etsu will make 45 cm dia. mCZ (magnetic field applied Czochralski)
- amorphous Si/SiO2 coating
- see LIGO-T1400226

ShinEtsu

R. X. Adhikari, GWADW2017

Voyager Noise Budget

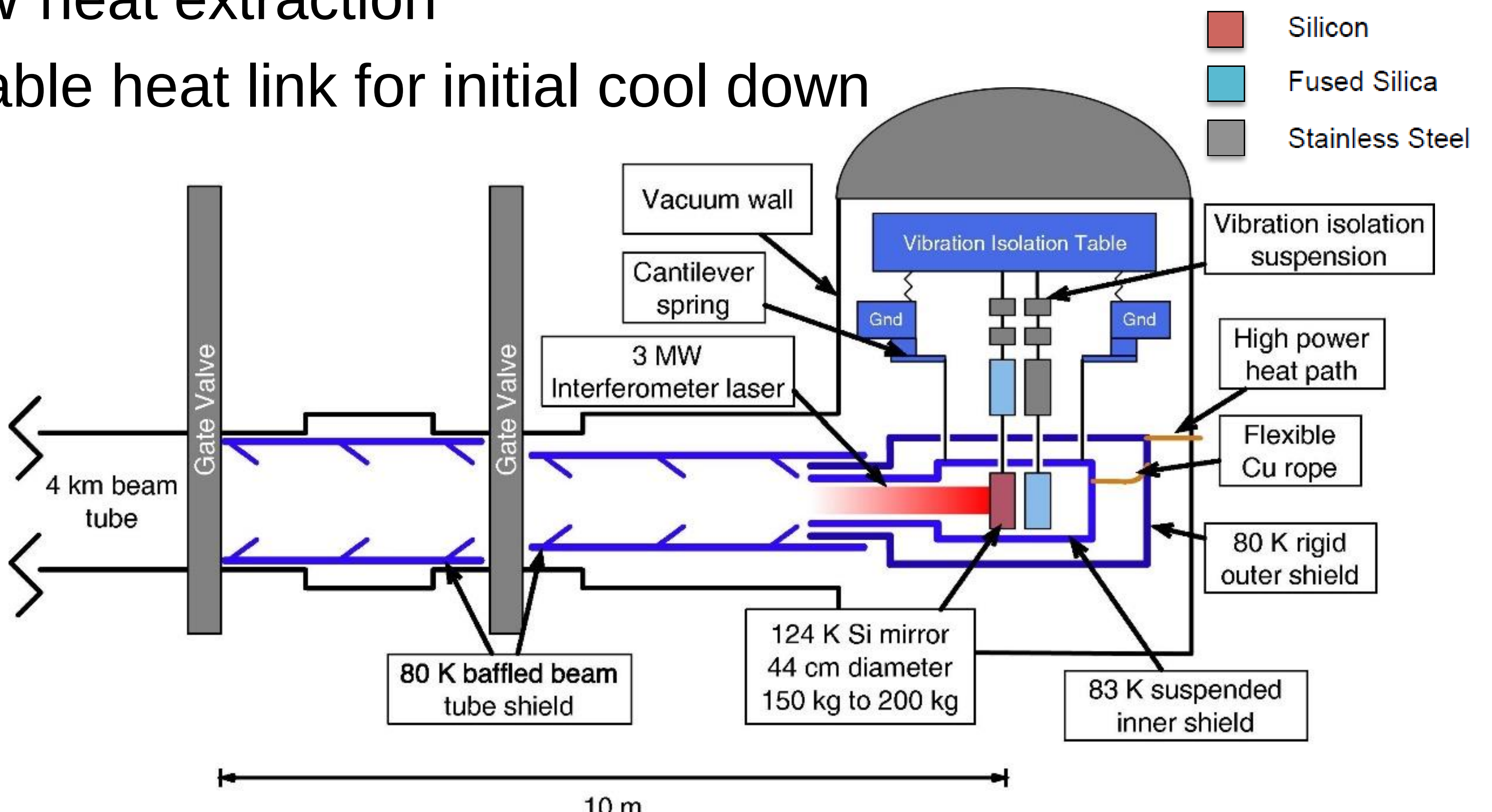
- 300m filter cavity, 10 dB squeezing



LIGO-T1600119

Cryogenic Layout

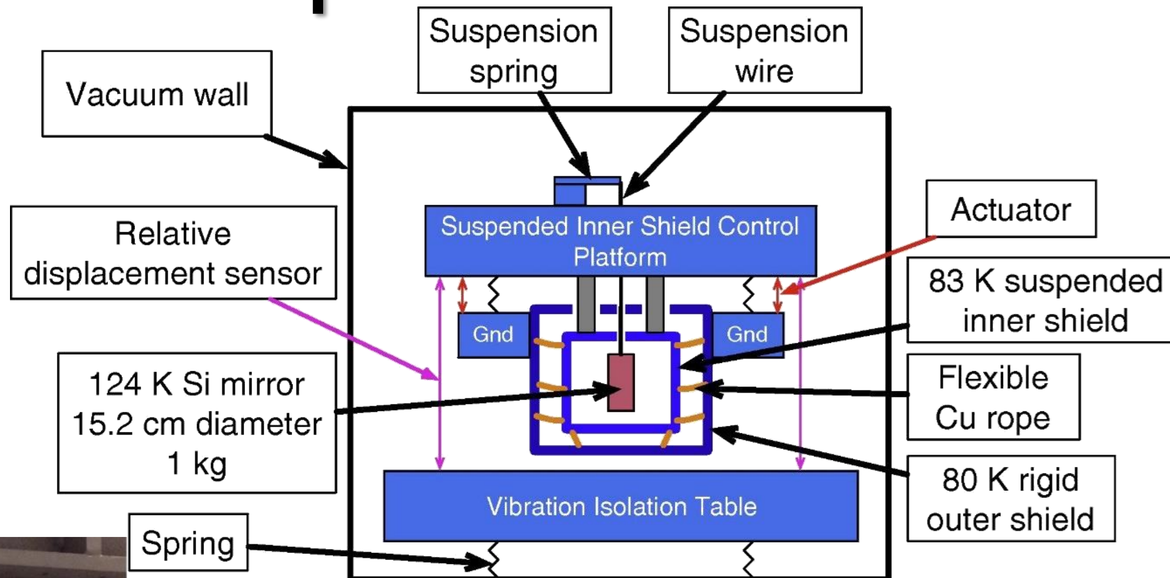
- 123 K for zero thermal expansion
  thermoelastic noise, minimize RoC change
- Radiative cooling (no conductive heat path needed)
  5 W heat extraction
- Movable heat link for initial cool down

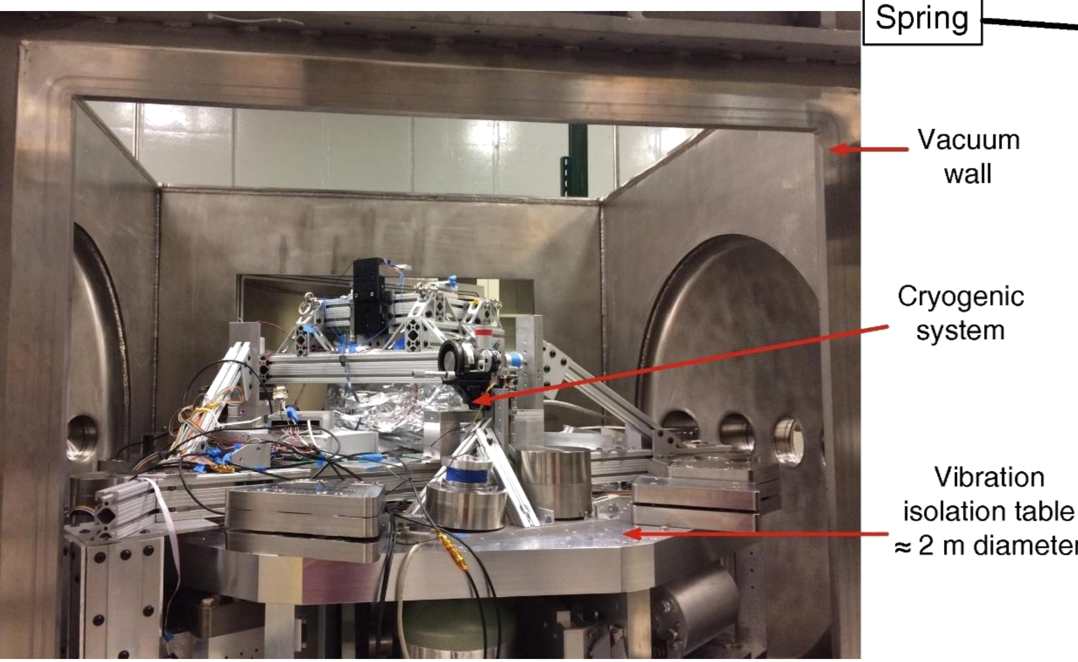


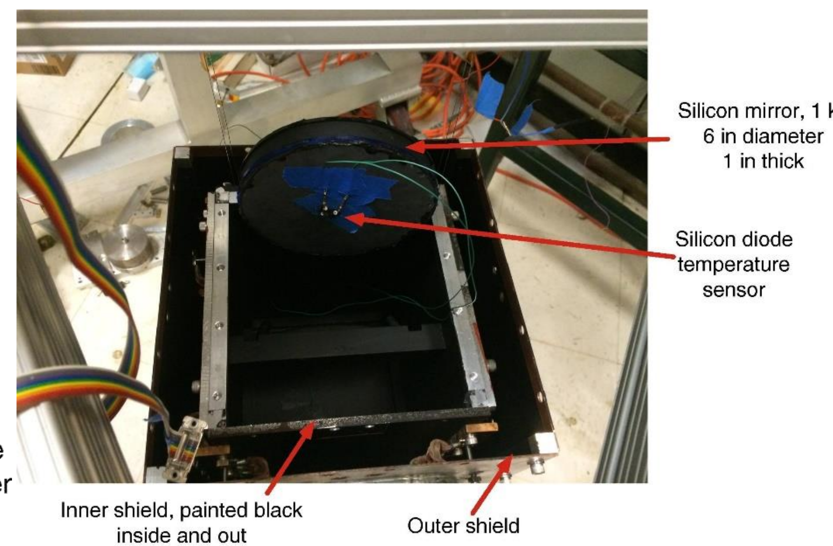
B. Shapiro +, [Cryogenics 81, 83 (2017)] & [LIGO-T1400226]

Stanford Experiment

- Demonstrated
  low temperature
  and
  low vibration
  can be realized



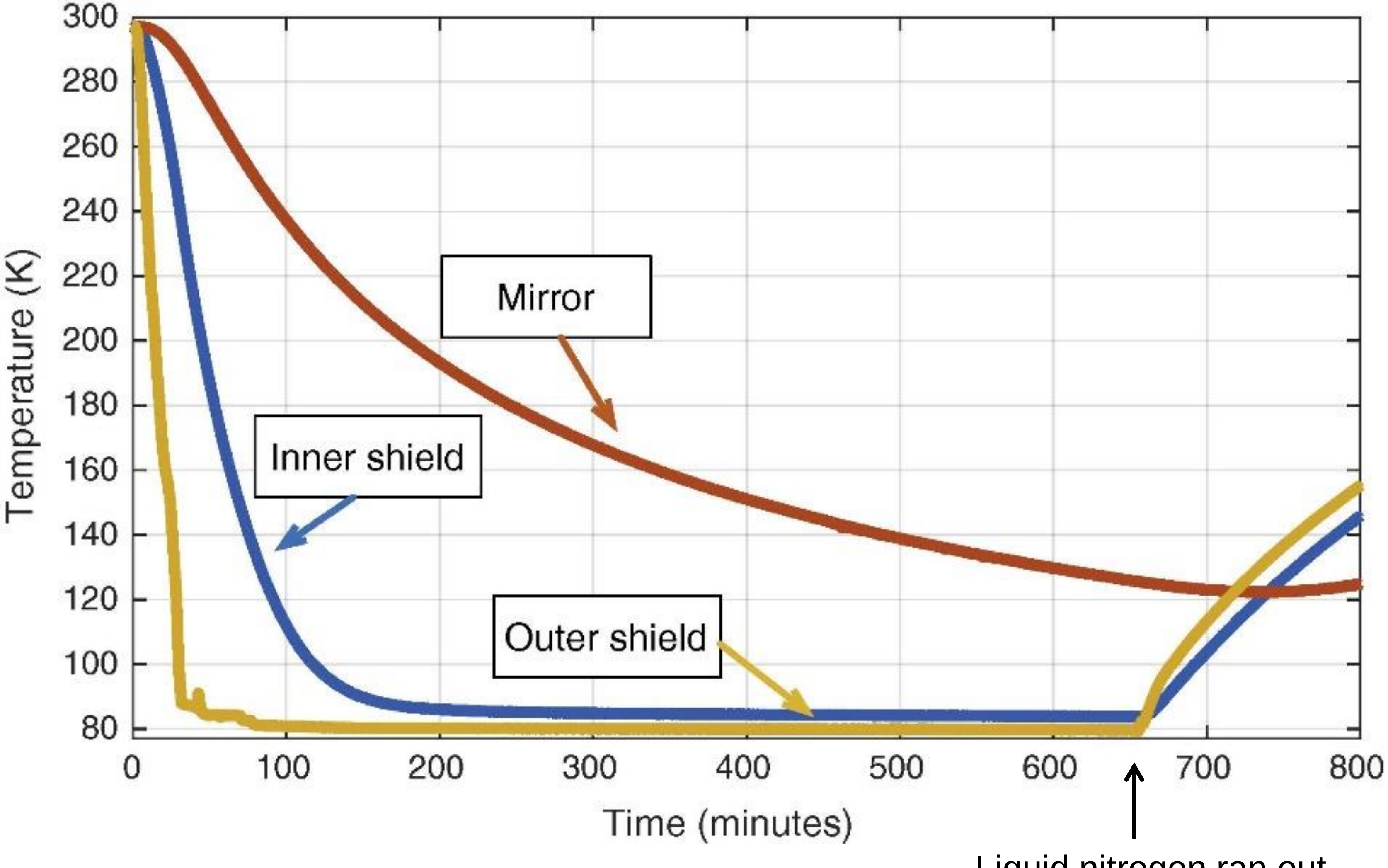




B. Shapiro +, [Cryogenics 81, 83 (2017)]

Stanford Experiment

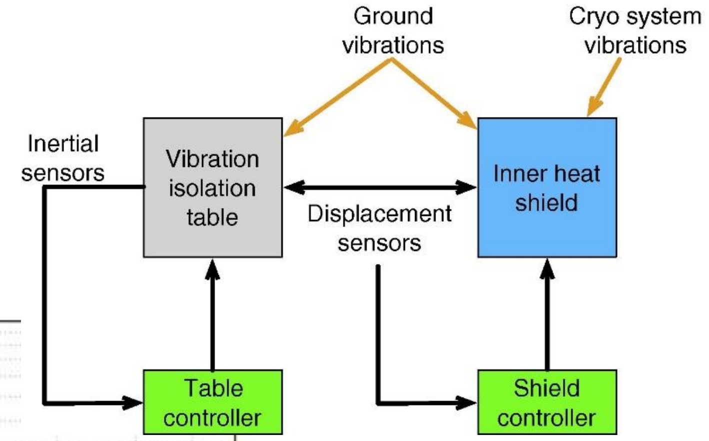
- Mirror reached 121 K

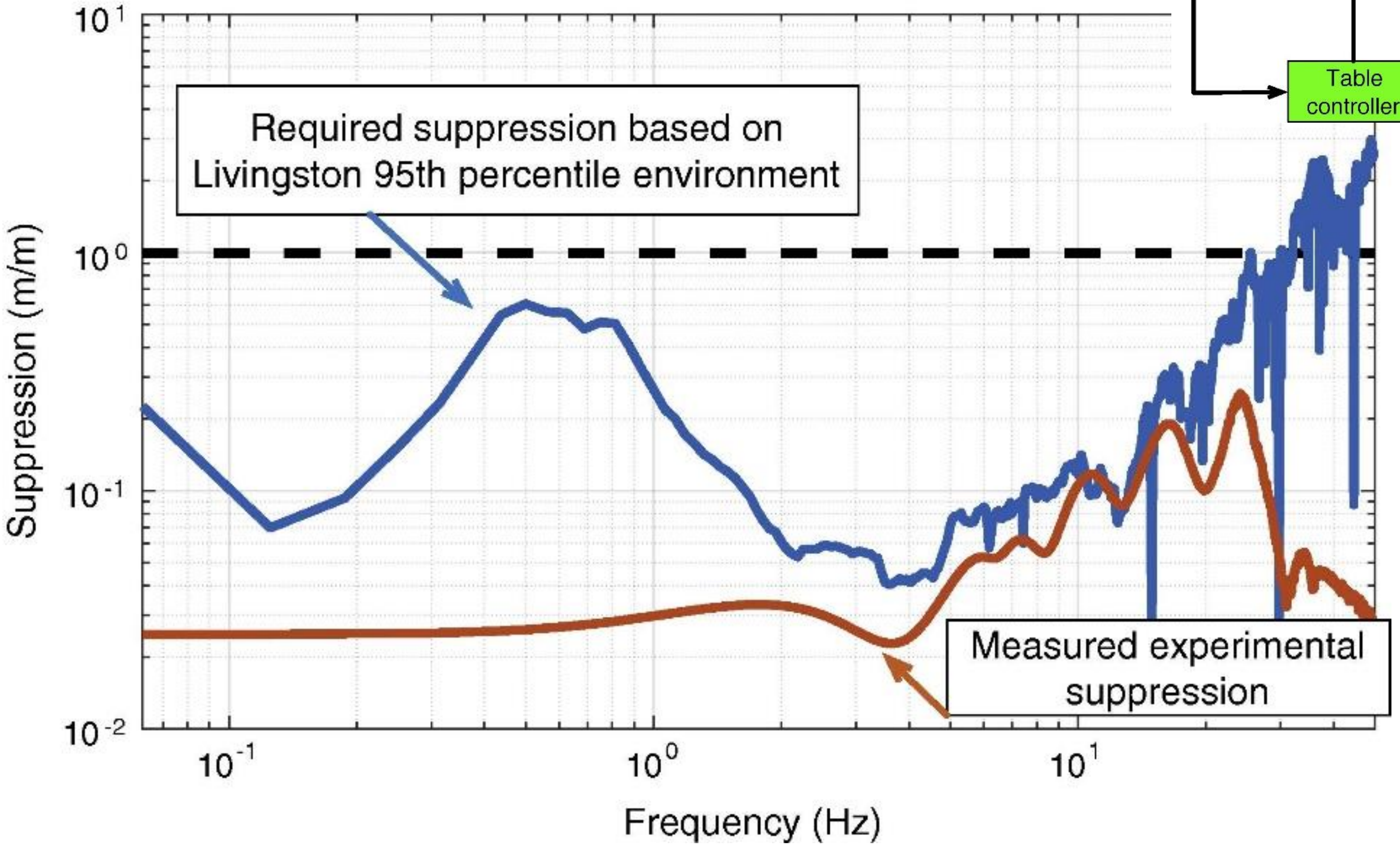


B. Shapiro +, [Cryogenics 81, 83 (2017)]

Stanford Experiment

- Inner shield displacement meets the requirement (from scattering)

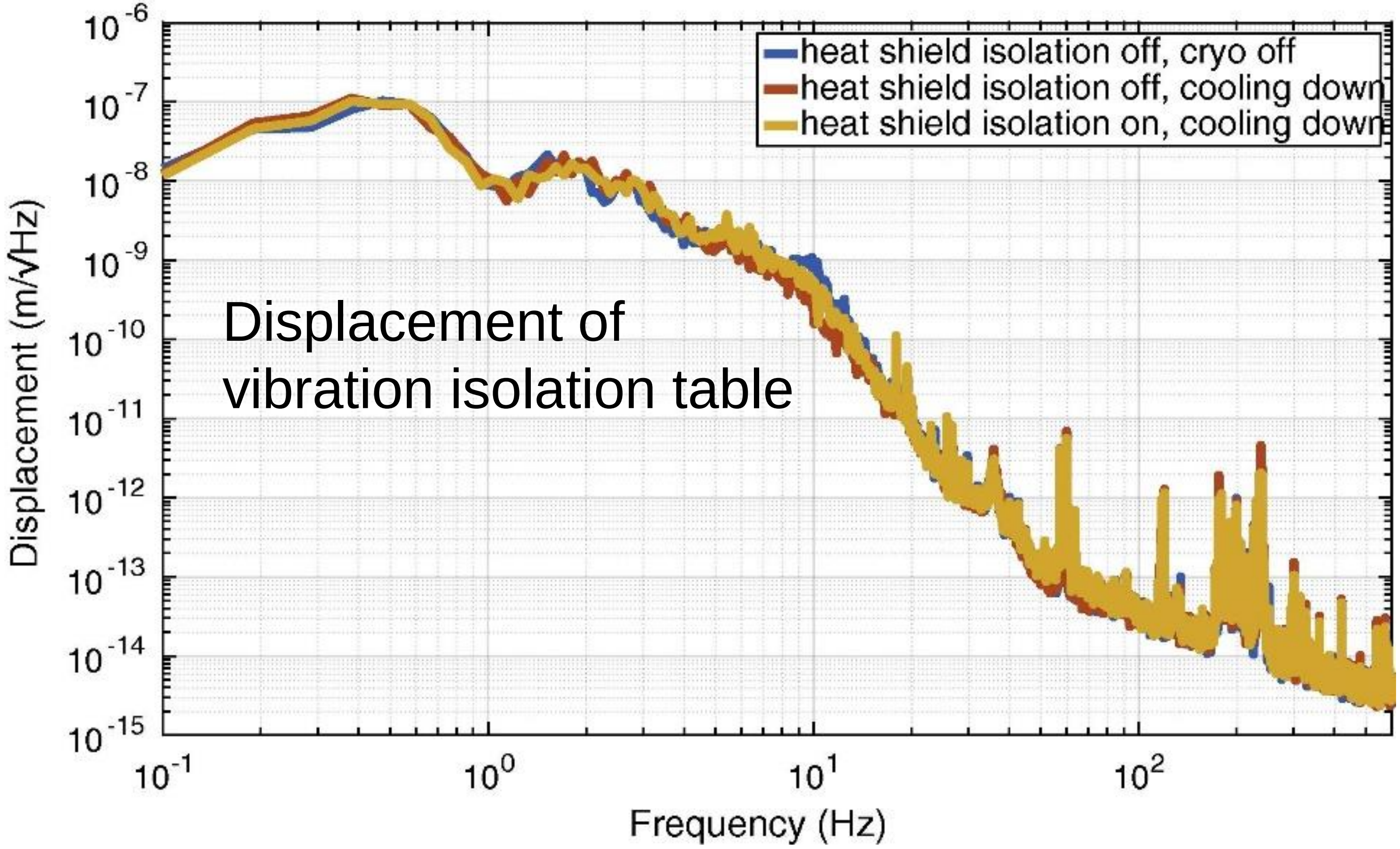




B. Shapiro +, [Cryogenics 81, 83 (2017)]

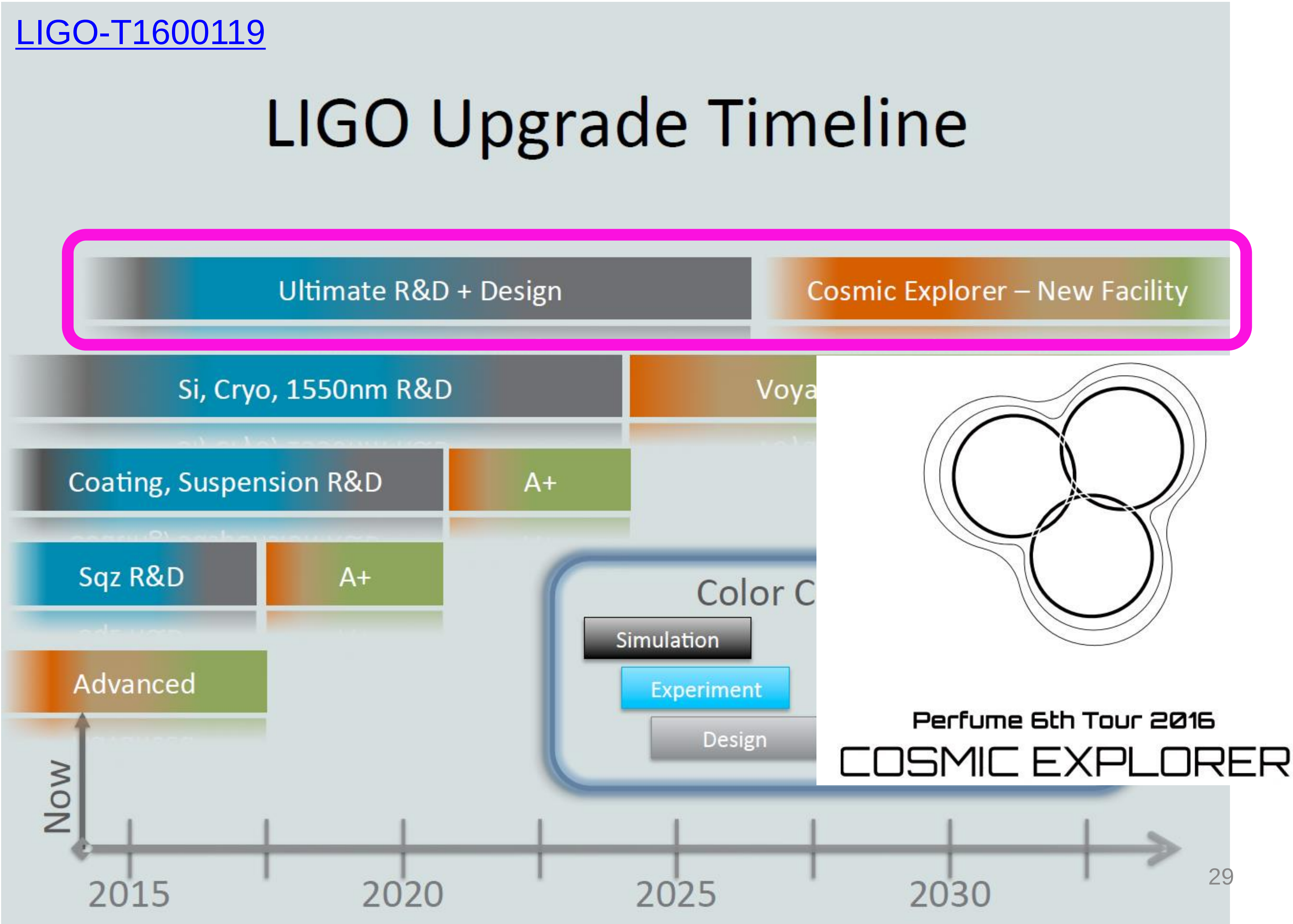
Stanford Experiment

- Cryogenic system is not impacting the vibration isolation of the mirror



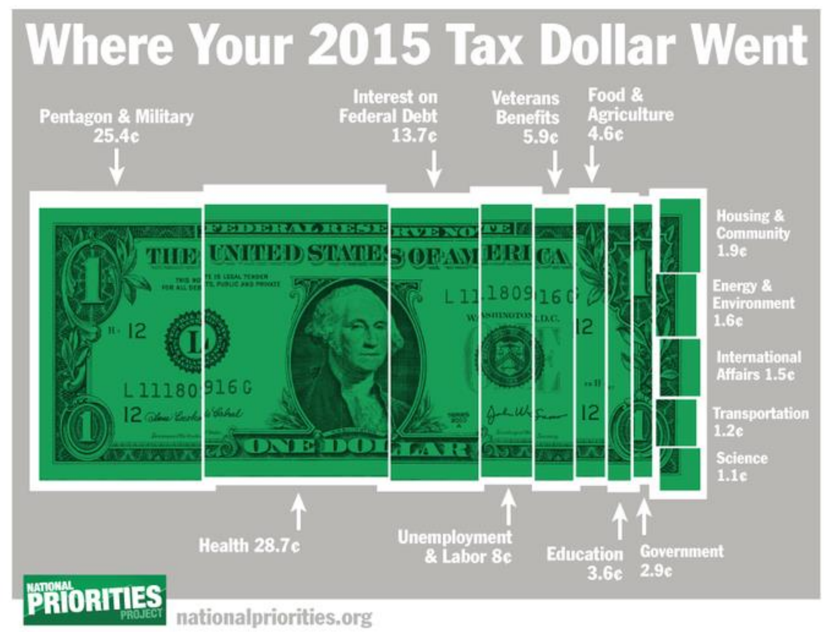
B. Shapiro +, [Cryogenics 81, 83 (2017)]

Estimated LIGO Timeline



Cosmic Explorer

- New facility
- BNS range beyond z=1 (~4 Gpc)
- Adapt A+ and Voyager technology to much longer arms
- Or, shorter baseline designs with breakthroughs in
  - Newtonian noise cancellation
  - coating and mechanical system engineering
  - quantum non demolition interferometry
- Long life time (~50 years)
- On the surface or underground
  1-10 Hz sensitivity in terms of science/dollar
- L-shape or triangular shape
  polarizations



Longer Arms

- Quantum noise (*fixed cavity pole*)

$$\frac{h_{\mathrm{shot}}}{h_{0\,\mathrm{shot}}} = \sqrt{\frac{2\ \mathrm{MW}}{P_{\mathrm{arm}}}}\sqrt{\frac{\lambda}{1.5\ \mu\mathrm{m}}}\left(\frac{3}{r_{\mathrm{sqz}}}\right)\sqrt{\frac{40\ \mathrm{km}}{L_{\mathrm{arm}}}}$$

$$\frac{h_{\mathrm{RPN}}}{h_{0\,\mathrm{RPN}}} = \sqrt{\frac{P_{\mathrm{arm}}}{2\ \mathrm{MW}}}\sqrt{\frac{1.5\ \mu\mathrm{m}}{\lambda}}\left(\frac{3}{r_{\mathrm{sqz}}}\right)\left(\frac{320\ \mathrm{kg}}{m_{\mathrm{TM}}}\right)\left(\frac{40\ \mathrm{km}}{L_{\mathrm{arm}}}\right)^{3/2}$$

Hidden dependence: longer arms require larger mass because of larger beam

- Coating thermal noise (*fixed cavity geometry; w∝L*)

$$\frac{h_{\mathrm{CTN}}}{h_{0\,\mathrm{CTN}}} = \sqrt{\frac{T}{123\ \mathrm{K}}}\sqrt{\frac{\phi_{\mathrm{eff}}(T)}{5\times 10^{-5}}}\left(\frac{40\ \mathrm{km}}{L_{\mathrm{arm}}}\right)^{3/2}$$

Coating thickness and beam size grow with wavelength but the effects cancel

- Suspension thermal noise and seismic noise
  vertical noise coupling linearly increases with length
  (due to the curvature of the Earth)

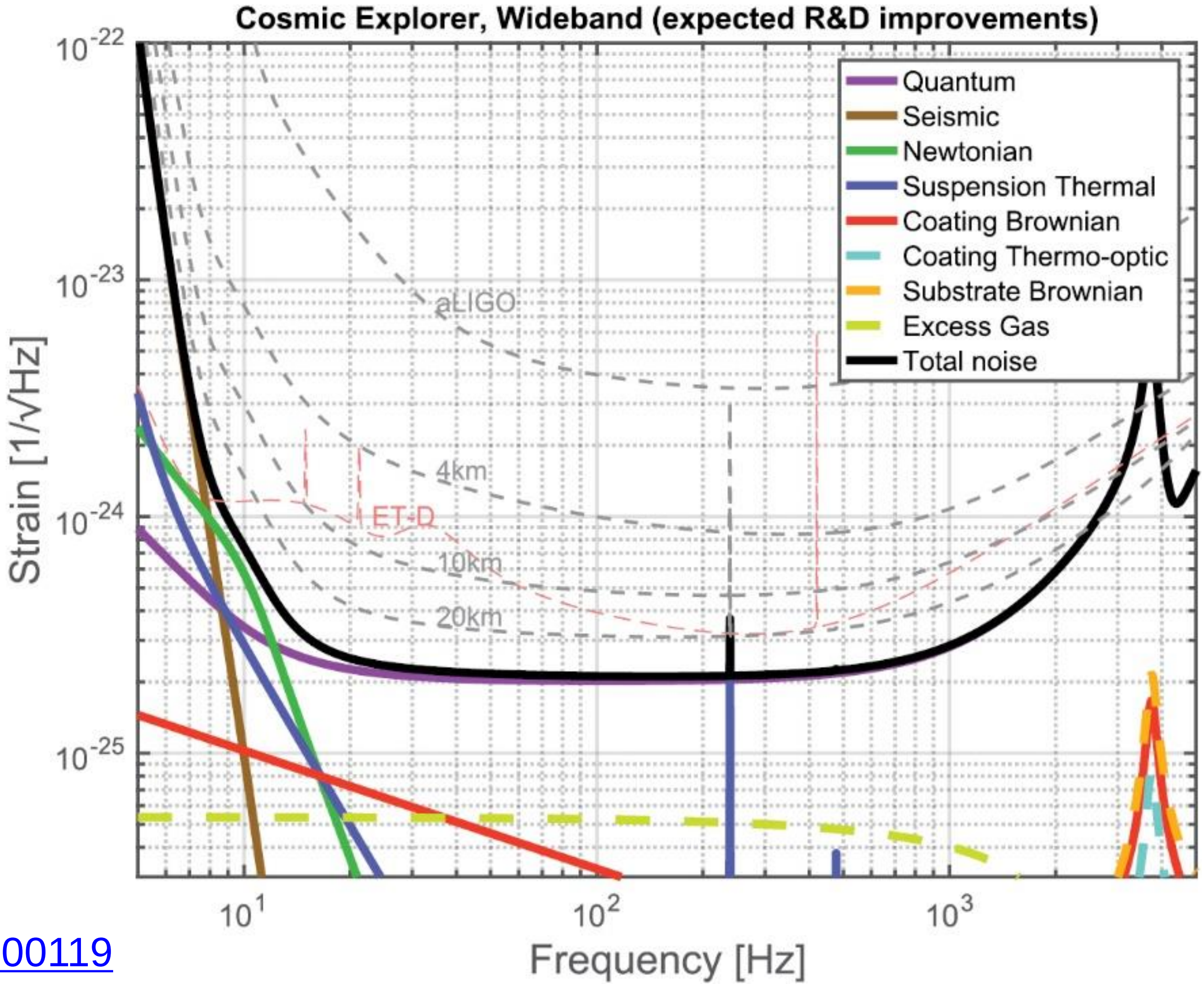
B P Abbott +, [CQG 34, 044001 (2017)]

40 km

- From Hongo Campus to Hachioji

CE Optimistic Noise Budget

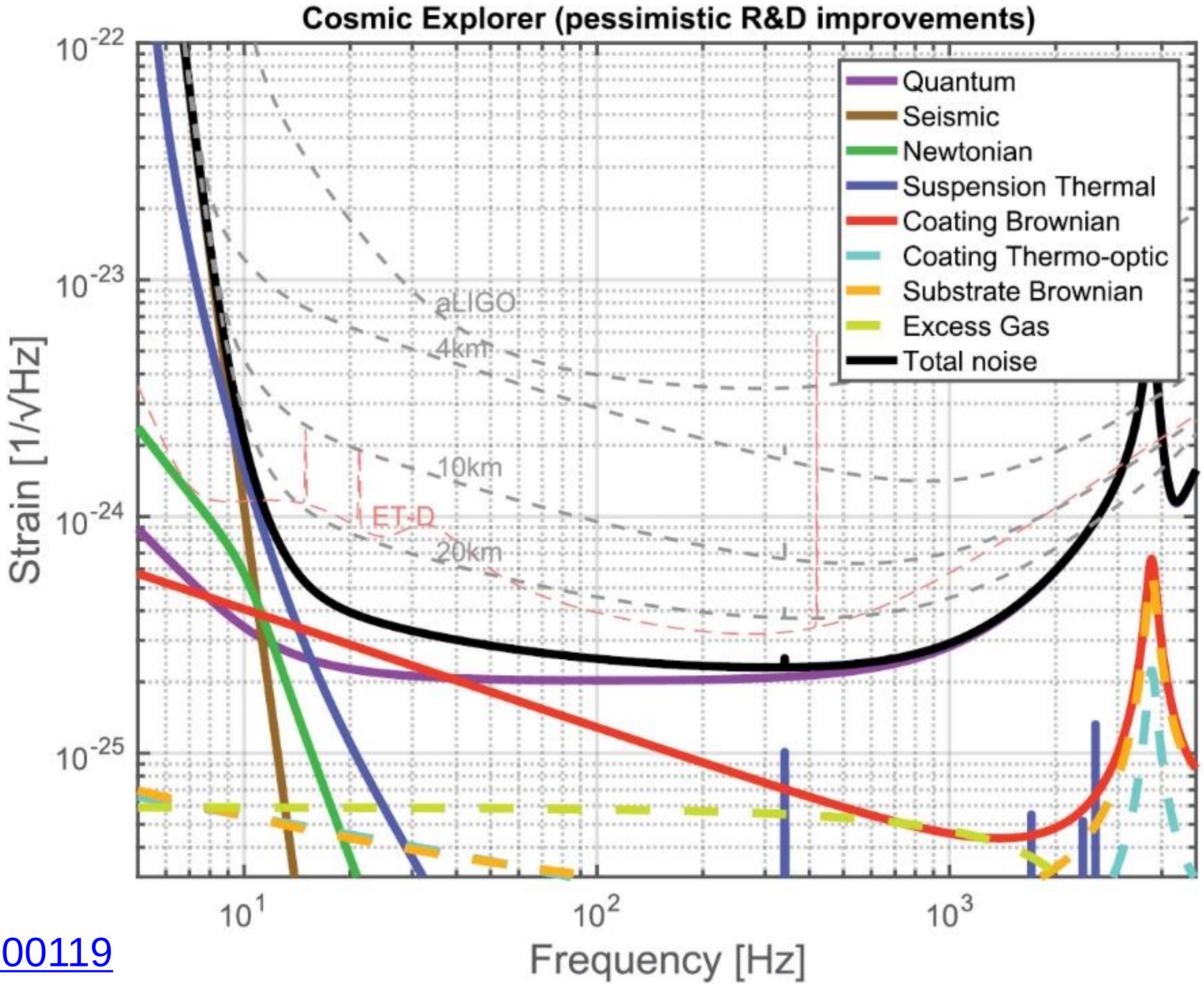
- Based on Voyager technology (Silicon, 123 K, 1550 um)



LIGO-T1600119

CE Pessimistic Noise Budget

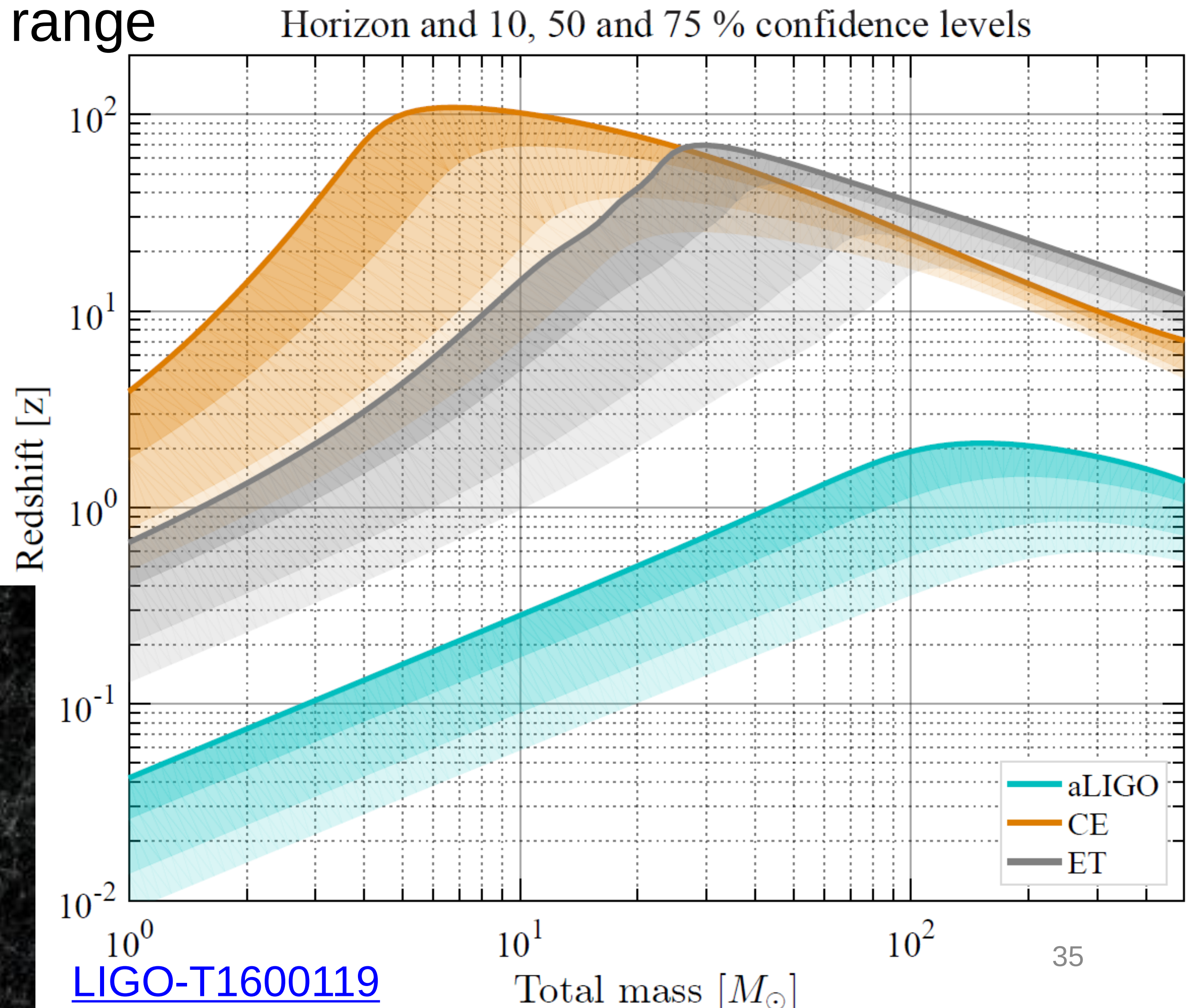
- Based on A+ technology, conservative coating improvement



LIGO-T1600119

Astrophysical Reach

- Essentially all compact binary coalescence in the universe for z>20 mass range



LIGO-T1600119

Other Issues (= Chances) on ISC 1

LIGO-T1600119

- Vibration noise from heat links
  suspension point interferometer ?
- Improve robustness of the arm length stabilization system
  inject green from vertex ?
- High power photo-detection
- Mode matching of output mode-cleaner (OMC)
  interferometer thermal state
- Balanced homodyne detection for DARM
  to allow for tunable homodyne readout angle
  to avoid technical noises
- Sidles-Sigg instability
  potential threat for Voyager/CE since higher power
  angular control noise reduction ?
  optical trapping of alignment ?

Other Issues (= Chances) on ISC 2

LIGO-T1600119

- Alignment sensing and control
  OMC, squeezed light source, filter cavities ……
  higher power, more higher order modes
  band of GW detection moves down, but bandwidth
  of alignment control increases (Sidles-Sigg)
- Thermal aberration sensing and control
  modeling, wavefront sensors
- Fast data acquisition (increase sampling frequency)
- Adaptive noise cancellation, automatic optimization, modern control
- Virtual interferometer (Simulated Plant)
- Mechanical simulation tool for vibration isolation system
  automatically compute thermal noise
- Modelling thermal distortions and radiation pressure

Summary

- Integrated realistic studies, R&D experiments are ongoing for LIGO upgrades (may be not scientifically exciting itself, but necessary for big science)

LIGO-T1600119

IFO Cases	aLIGO	A+	Voyager	CE (pess)	CE
Arm Length [km]	4	4	4	40	40
Mirror Mass [kg]	40	80	200	320	320
Mirror Material	Silica	Silica	Silicon	Silica	Silicon
Mirror Temp [K]	295	295	123	295	123
Sus Temp [K]	295	295	123	295	123
Sus Fiber	60cm SiO2	60cm SiO2	60 cm Si	1.2m SiO2	1.2m Si
Fiber Type	Fiber	Fiber	Ribbon	Fiber	Ribbon
Input Power [W]	125	125	140	150	220
Arm Power [kW]	710	1150	3000	1400	2000
Wavelength [nm]	1064	1064	2000	1064	1550
NN Suppression	1	1	10	10	10
Beam Size [cm]	5.5 / 6.2	5.5 / 6.2	5.8 / 8.4	12 / 12	14 / 14
SQZ Factor [dB]	0	6	8	10	10
F. C. Length [m]	none	16	300	4000	4000

Summary

- Integrated realistic studies, R&D experiments are ongoing for LIGO upgrades (may be not scientifically exciting itself, but necessary for big science)

LIGO-T1600119

IFO Cases	KAGRA	A+	Voyager	CE (pess)	CE
Arm Length [km]	**3**	4	4	40	40
Mirror Mass [kg]	**23**	80	200	320	320
Mirror Material	**Sapphire**	Silica	Silicon	Silica	Silicon
Mirror Temp [K]	**23 K**	295	123	295	123
Sus Temp [K]	**23 K**	295	123	295	123
Sus Fiber	**35 cm Sap.**	60cm SiO2	60 cm Si	1.2m SiO2	1.2m Si
Fiber Type	**Fiber**	Fiber	Ribbon	Fiber	Ribbon
Input Power [W]	**55**	125	140	150	220
Arm Power [kW]	**290**	1150	3000	1400	2000
Wavelength [nm]	**1064**	1064	2000	1064	1550
NN Suppression	**1**	1	10	10	10
Beam Size [cm]	**3.5 / 3.5**	5.5 / 6.2	5.8 / 8.4	12 / 12	14 / 14
SQZ Factor [dB]	**0**	6	8	10	10
F. C. Length [m]	**none**	16	300	4000	4000

Summary

- Integrated realistic studies, R&D experiments are ongoing for LIGO upgrades (may be not scientifically exciting itself, but necessary for big science)

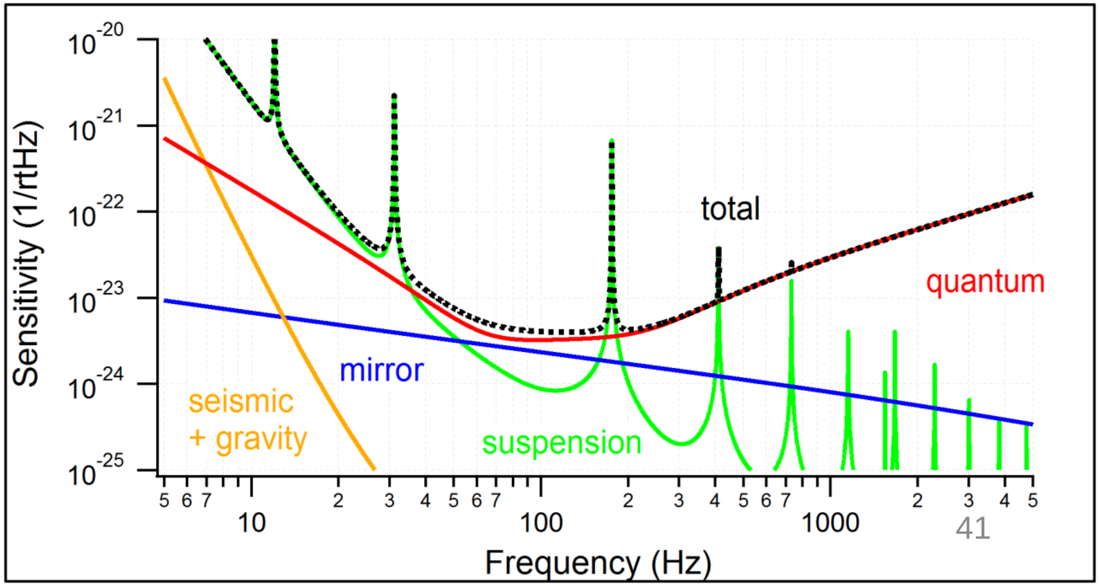
LIGO-T1600119

IFO Cases	KAGRA	A+	Voyager	CE (pess)	CE
Arm Length [km]	**3**	4	4	40	40
Mirror Mass [kg]	**23**				
Mirror Material	**Sapphire**				
Mirror Temp [K]	**23 K**				
Sus Temp [K]	**23 K**				
Sus Fiber	**35 cm Sap.**				
Fiber Type	**Fiber**				
Input Power [W]	**55**				
Arm Power [kW]	**290**				
Wavelength [nm]	**1064**				
NN Suppression	**1**				
Beam Size [cm]	**3.5 / 3.5**				
SQZ Factor [dB]	**0**	6	8	10	10
F. C. Length [m]	**none**	16	300	4000	4000

KAGRA+?

- We should plan ahead (~10 years)
- Some R&D ongoing, but needs integrated study
  - 300 m filter cavity experiment at NAOJ
  - coating thermal noise experiment at NAOJ
  - mirror absorption measurement at NAOJ
- Heat extraction vs suspension thermal noise
  - thick short suspension is better for heat extraction
  - thin long suspension is better for thermal noise

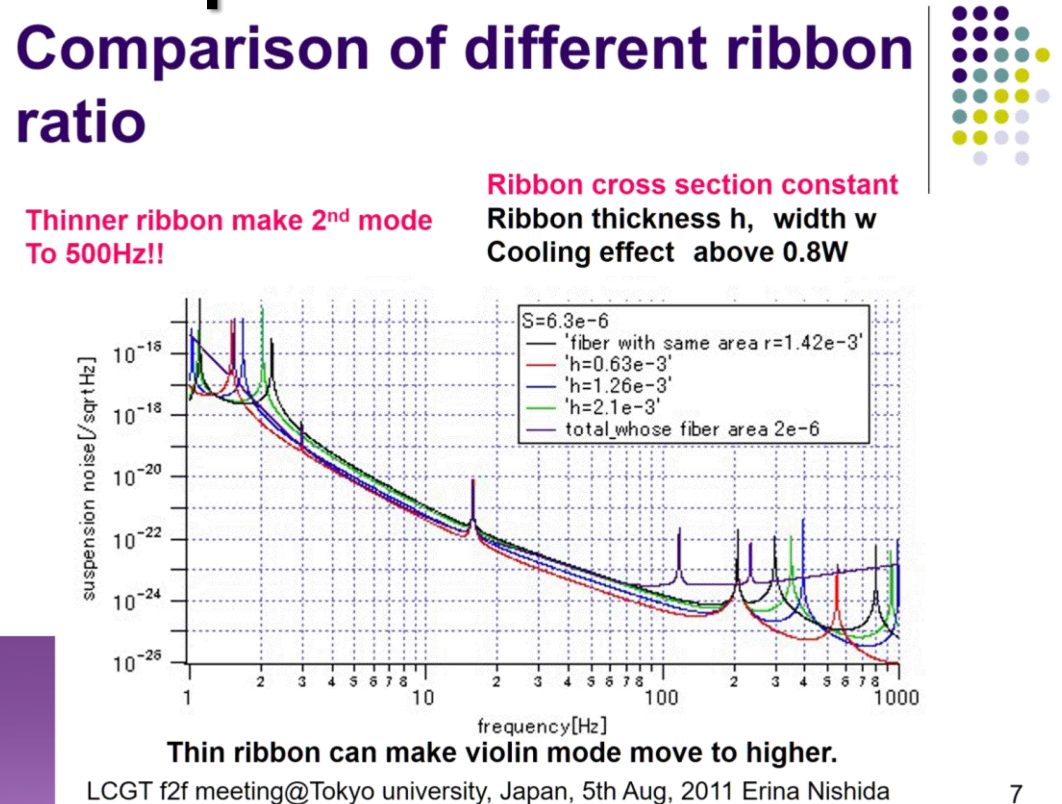
  - lower the power ?
  - less absorption ?
  - half cryogenic ?
  - 123 K ?
  - ribbon ?



http://gwwiki.icrr.u-tokyo.ac.jp/JGWwiki/KAGRA

Ribbon Suspension

- Keep cross section to keep heat extraction, but move violin modes to higher frequency

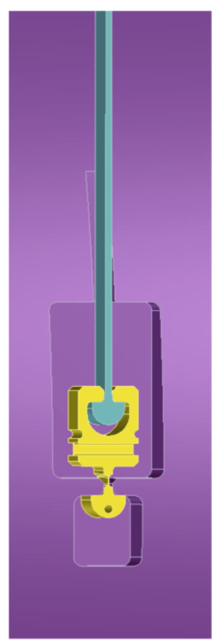


R. DeSalvo, [JGW-G1201101] (2012)

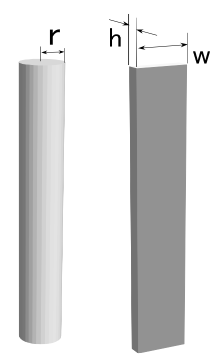
Mirror attachment

Key features:

- Mini-alcoves (low volume machining)
- Machining before coating deposition
- Minimize substrate induced stress
- Recessed attachment, Low vulnerability
- No bonding shear noise
- No flats, 100% of mirror surfaceavailable



E. Nishida, [JGW-G1100558] (2011)



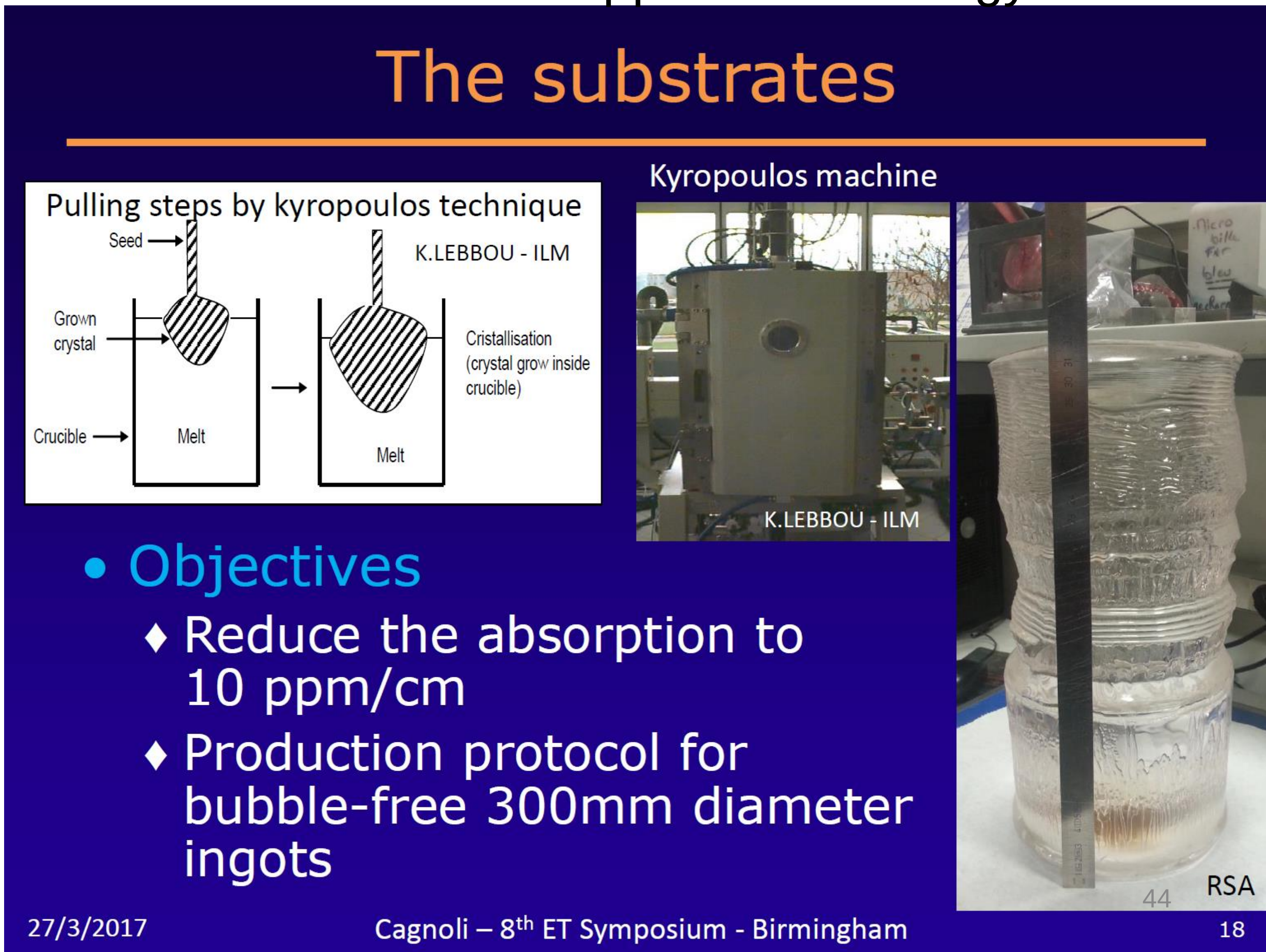
Sapphire vs Silicon

Yoichi Aso, JGW-G1000113 (slide from LCGT f2f meeting 2010)

	サファイア	シリコン
大きな結晶	C軸成長は難しい C軸切り出し?	半導体グレードのものは既に存在する
複屈折	大(現状、要求値を満たさない)	小 (問題にならない)
光学吸収	大 (20ppm/cm以上)	小 (0.01ppm/cm)
シリケートボンディング	強度1MPa程度	強度10MPa弱
屈折率	1.7	3.5 (Monolithic Coatingが可能)
加工性	硬い	サファイアよりは若干柔らかい
波長	1064nmの技術が使える	1550nmへ乗り換える必要
開発の見通し	大きなC軸サファイアの需要がない	半導体業界からの大型化への需要 ETによる活発なR&D
一般受け	かっこいい	シリコーンと誤解されると悲惨

GAST Proposal by LMA et al

- Gravitational-wave Advanced Sapphire Technology



G. Cagnoli, 8th ET Symposium (2017)

Random Thoughts

- Underground facility and serious cryogenic system (20 K) are futuristic attractive infrastructure
- Filter cavity seems feasible, but adds more complexity (alignment, mode matching, etc.)
- Heavier mass + frequency independent squeezing + low power + cryogenic + underground sounds simple for me
- Could be sapphire, could be silicon
- R&D facility for heavier mass cryogenic suspension, mirror polish, coating ?
- Silicon prototype interferometer ?