The Dawn of Gravitational Wave Astronomy

SXS

KMI colloquium
Apr. 26, 2017
Nagoya University, Nagoya, Japan

Seiji Kawamura (ICRR, UTokyo)

Outline:

- Gravitational wave and detector
- Existing detectors
  - LIGO, Virgo, KAGRA
- Future detectors
  - ET, LISA, DECIGO
- Summary

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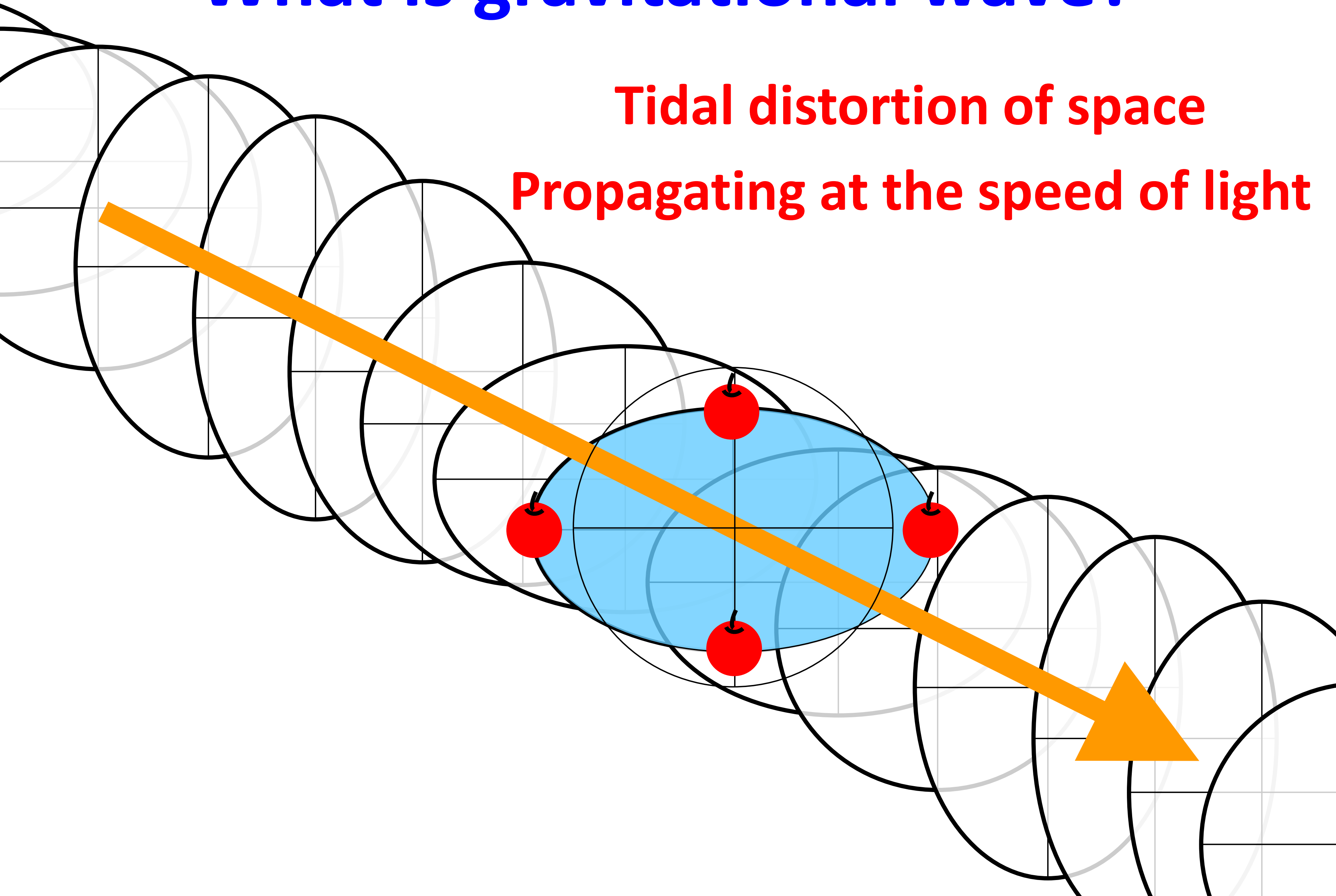
What is gravitational wave?



Profile of gravitational wave

- Derived by A. Einstein in his general relativity

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\kappa T_{\mu\nu}$$

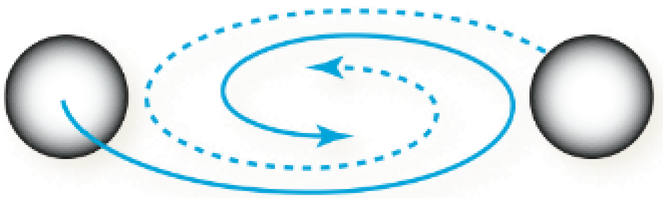
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

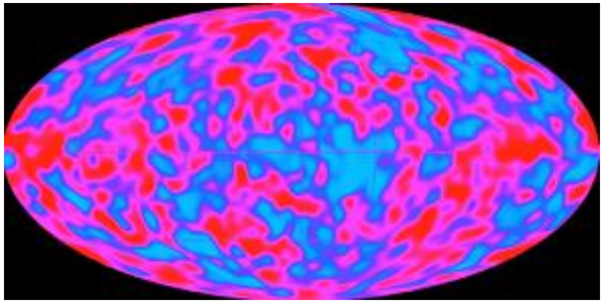
$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) h_{\mu\nu} = 0$$

- Propagates at the speed of light
- Propagates in vacuum
- Penetrates anything
- Detected by LIGO recently

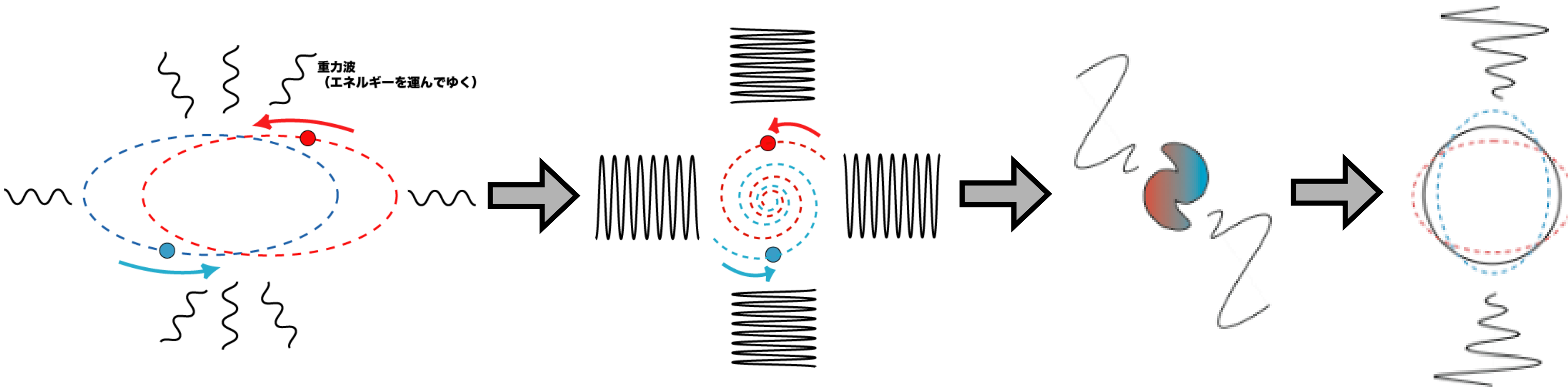
Gravitational wave sources

- **Binary coalescence:**
  - Neutron star
  - Black hole
- **Burst:**
  - Supernovae
- **Black hole ringdown:**
- **Continuous:**
  - Pulsar
  - Binary
- **Stochastic Background**
  - Early universe (i.e. Inflation)
  - Cosmic string
- **Unknown**

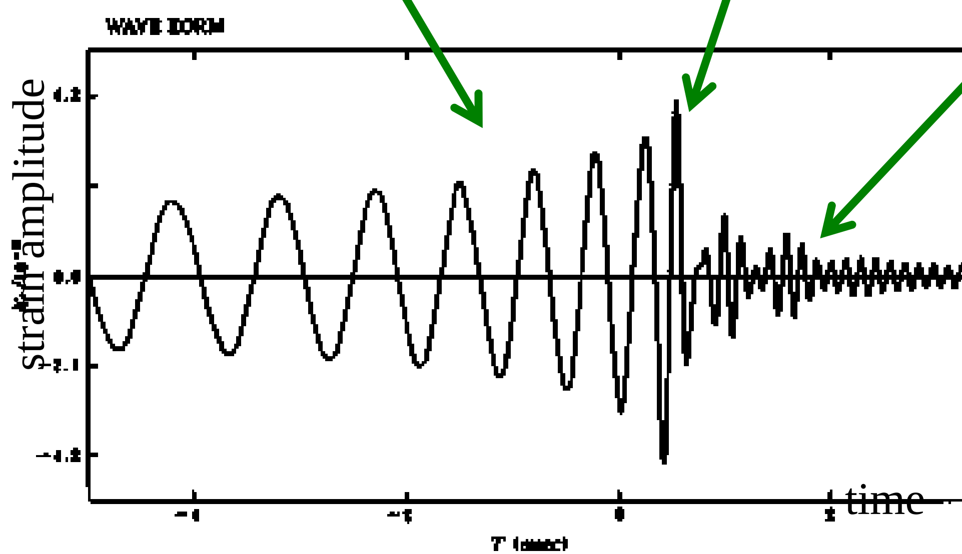




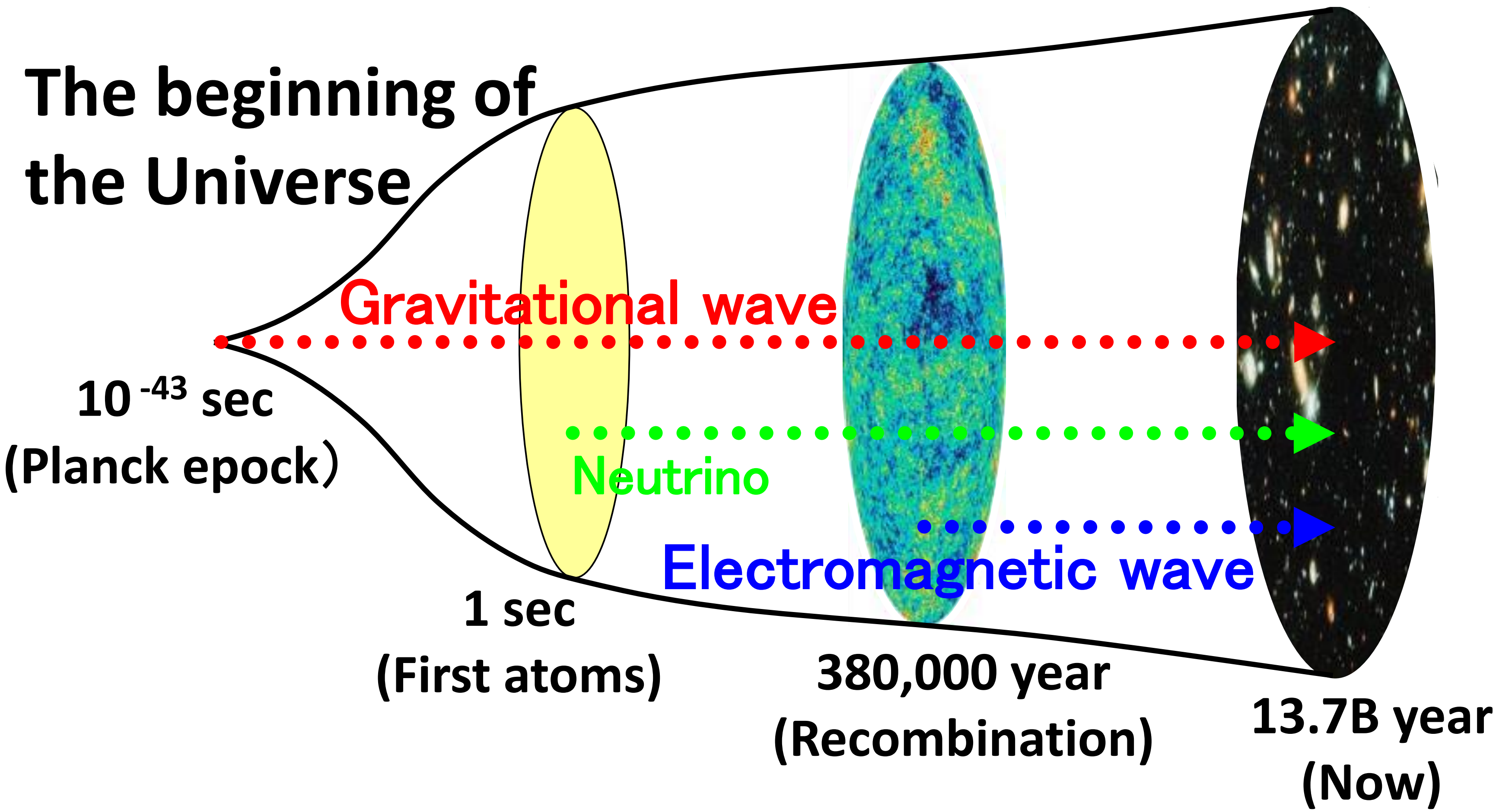
Neutron star binary coalescence



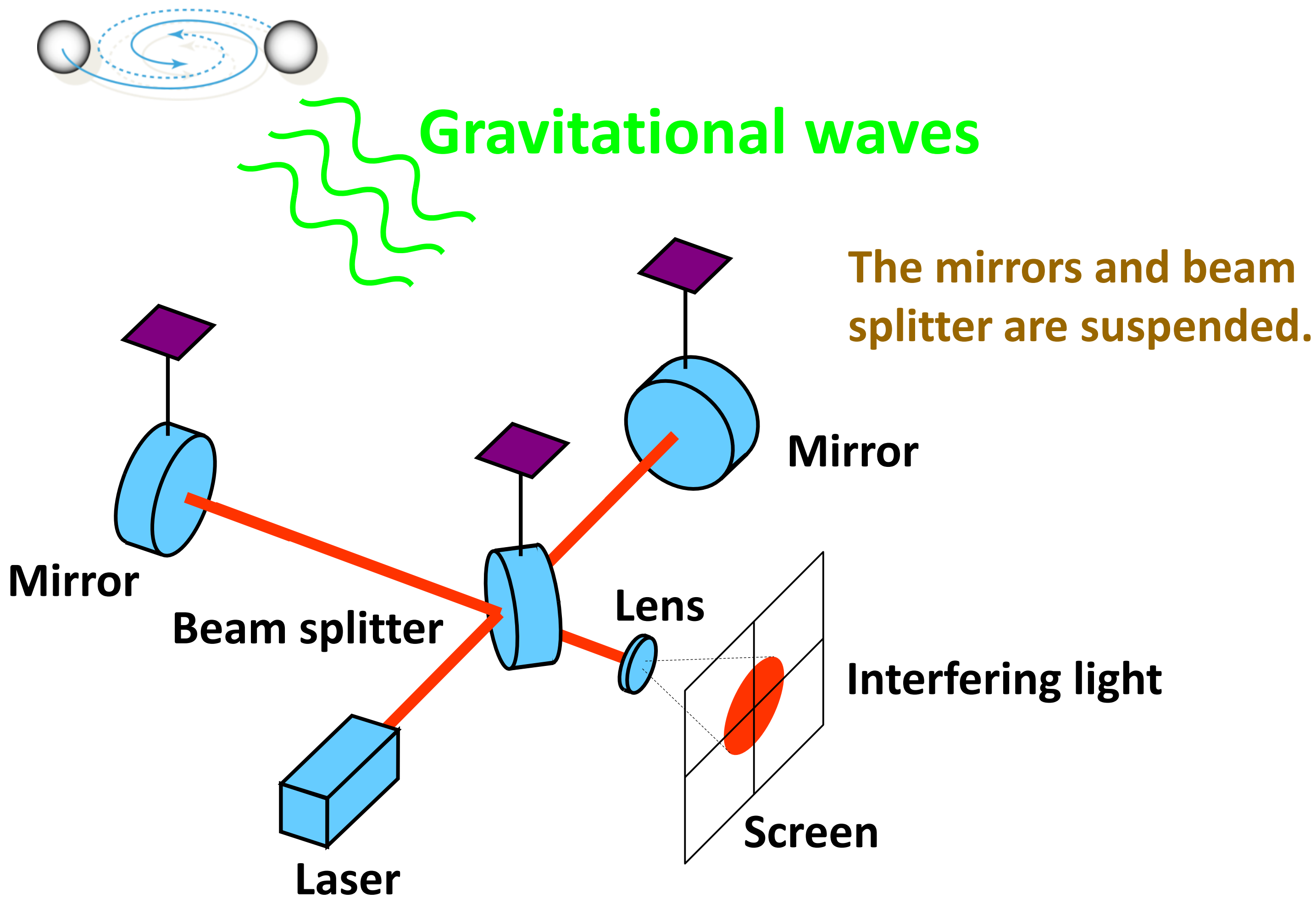
inspiral phase merger Black hole quasi-normal mode



Observation of the beginning of the Universe



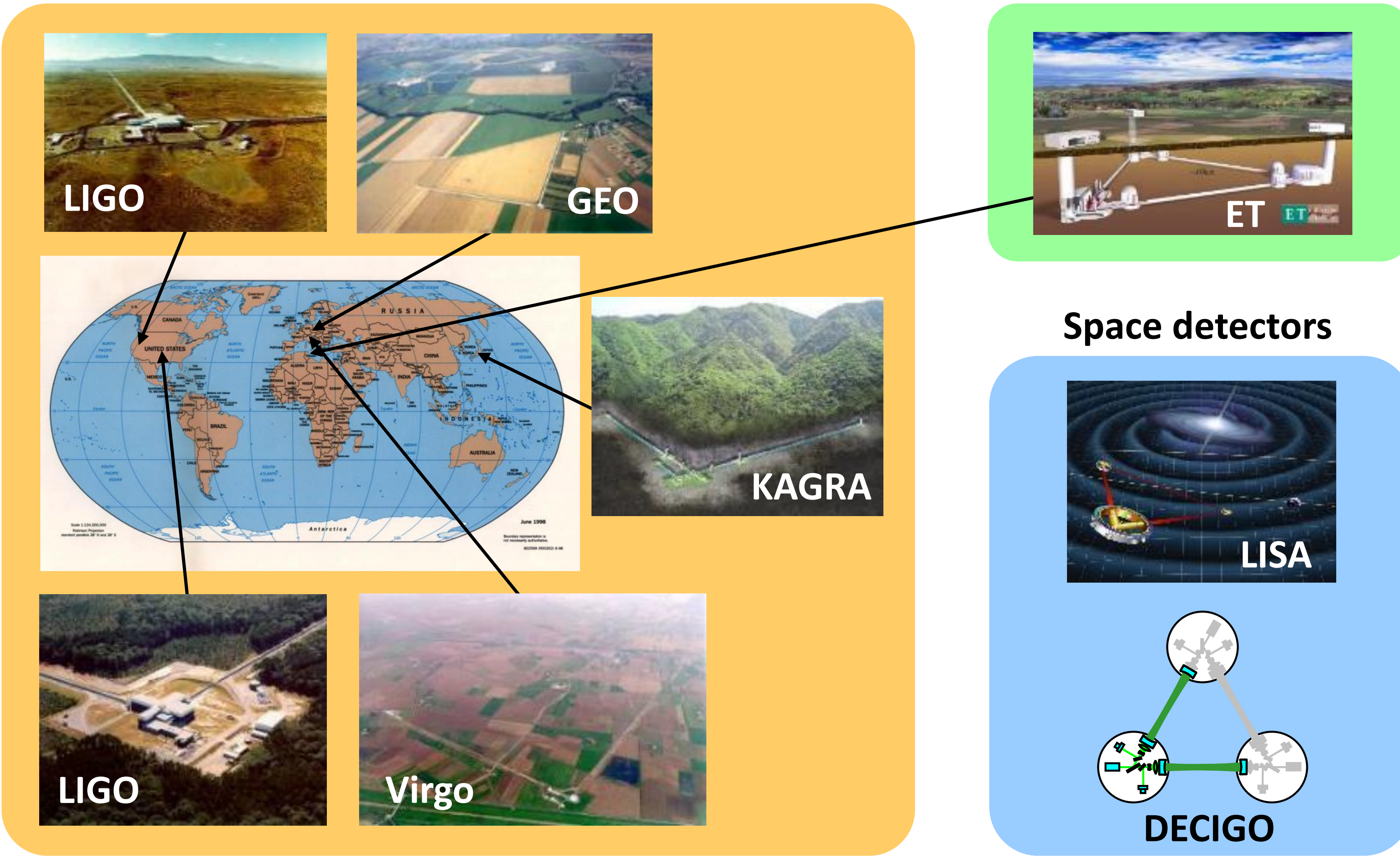
Gravitational wave detector



Detectors in the world

Ground-based 2nd-generation detectors

Ground-based 3rd-generation detectors



Outline:

- Gravitational wave and detector
- **Existing detectors**
  - LIGO, Virgo, KAGRA
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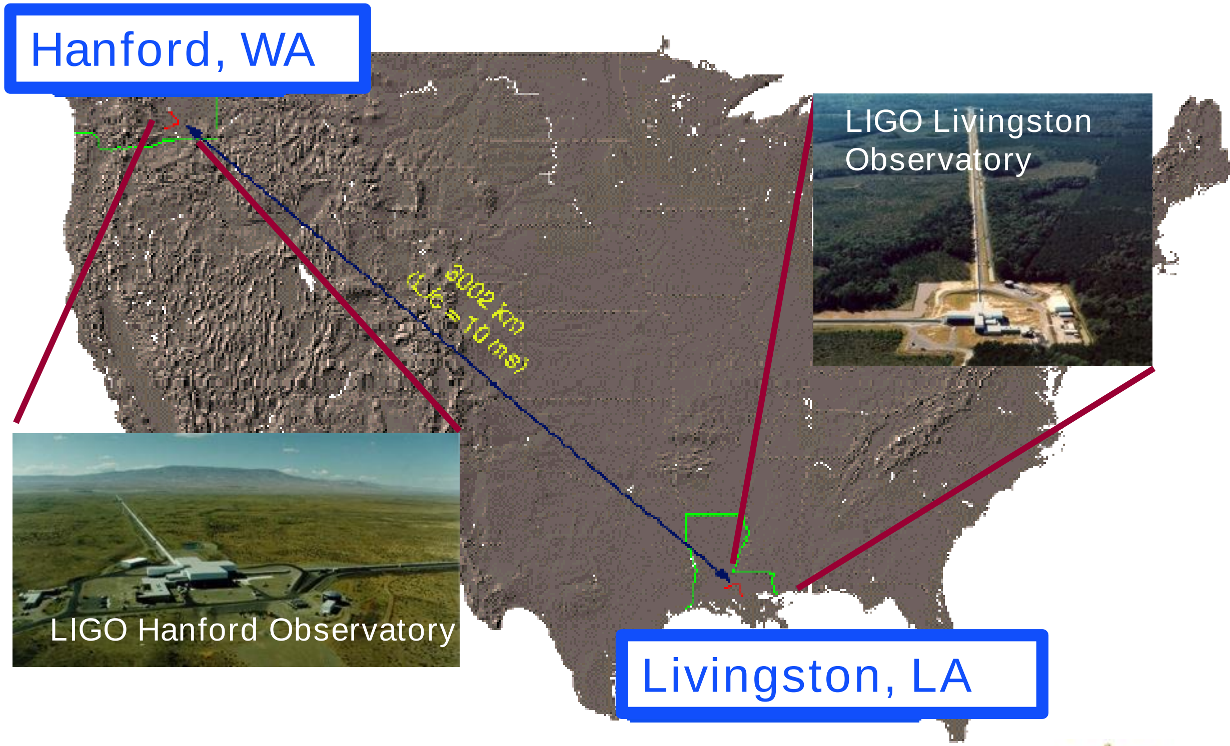
LIGO

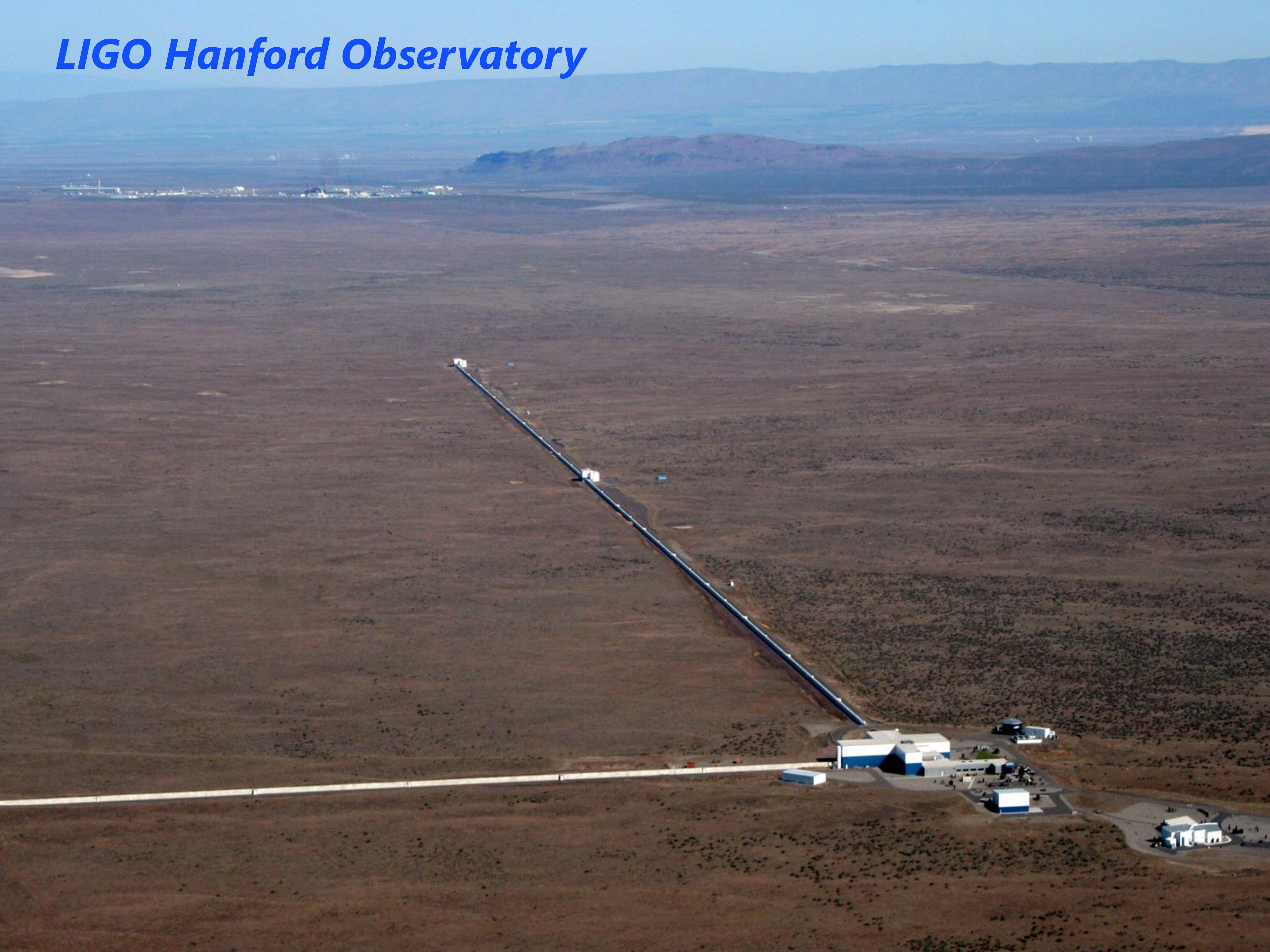
LIGO Laboratory:
180 staff located at Caltech, MIT, Hanford, Livingston

LIGO Scientific Collaboration:
~ 1000 scientists, ~80 institutions, 15 countries

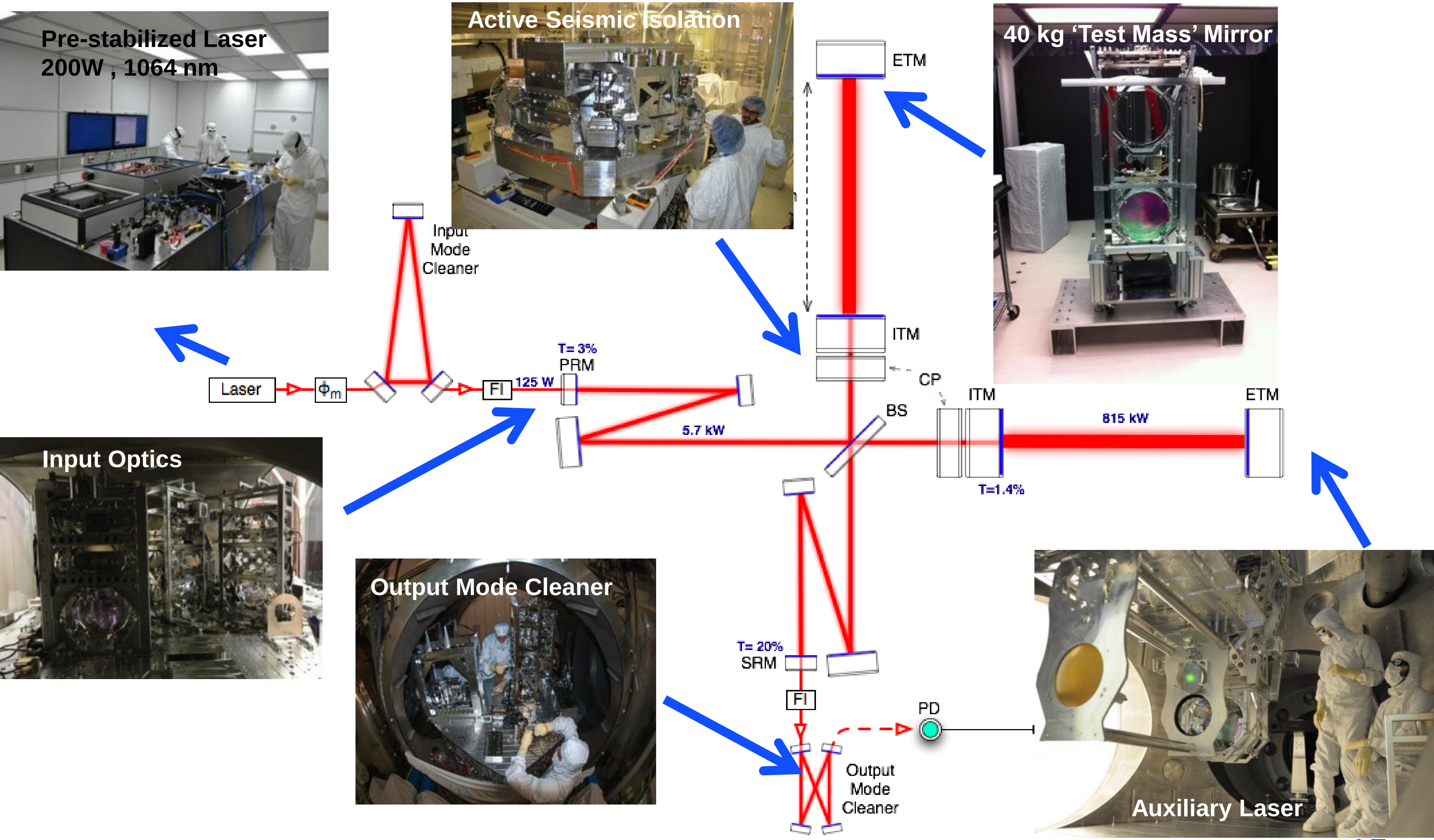



LIGO Livingston Observatory
4 km
4 km

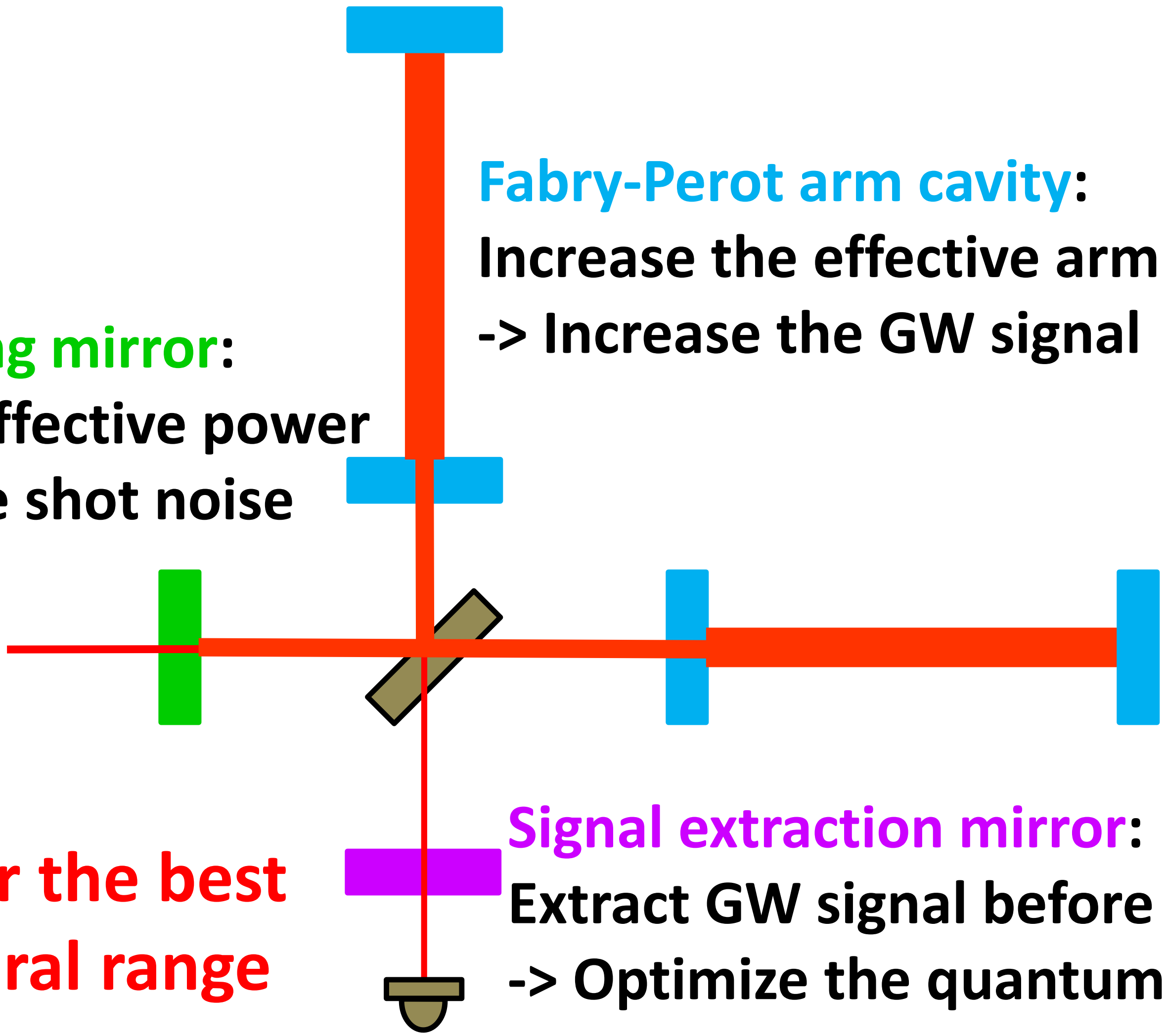
LIGO Hanford Observatory



Advanced LIGO Interferometer



RSE interferometer



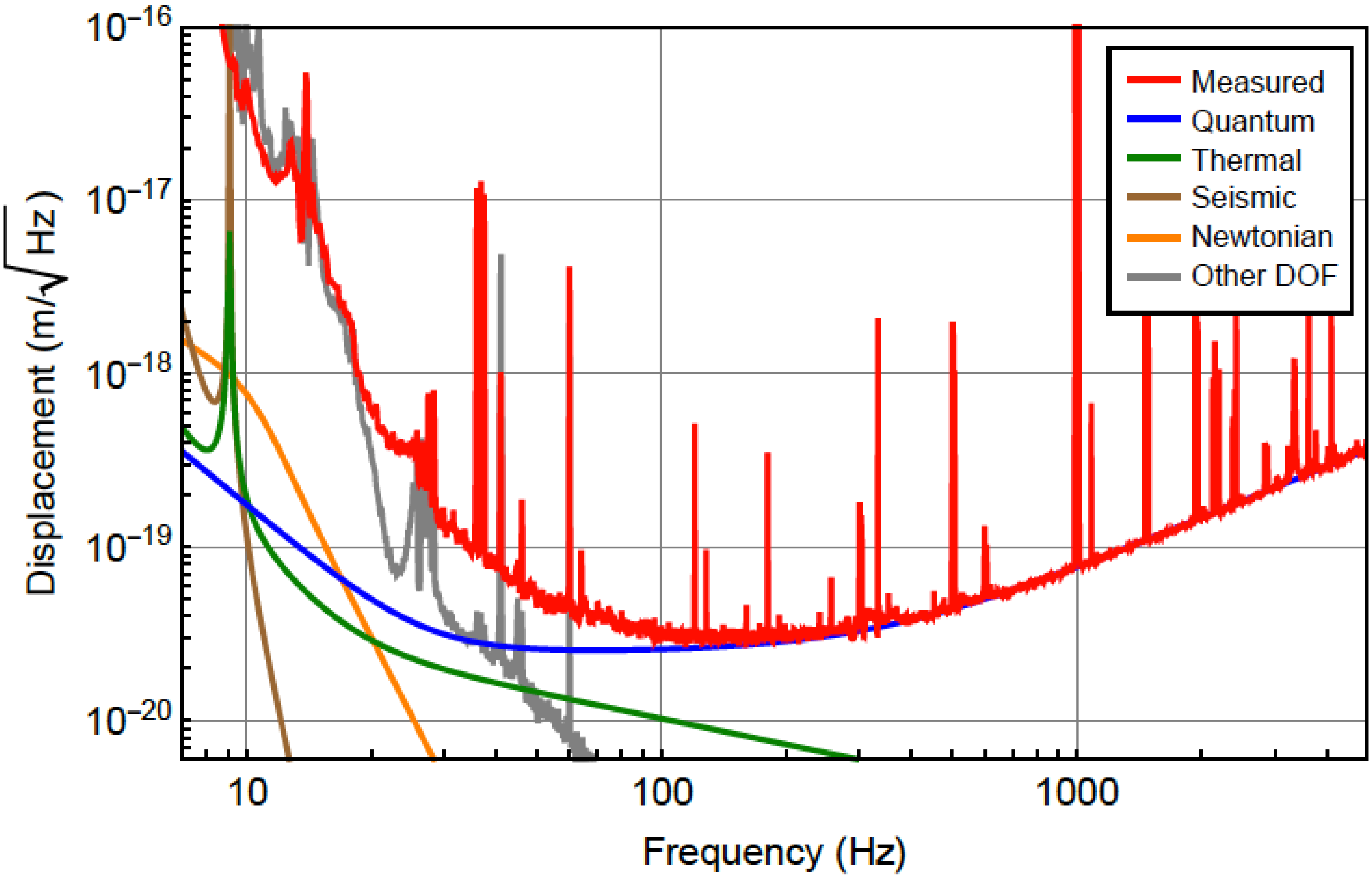
Fabry-Perot arm cavity:
Increase the effective arm length
-> Increase the GW signal

Power recycling mirror:
Increase the effective power
-> Improve the shot noise

Signal extraction mirror:
Extract GW signal before cancellation
-> Optimize the quantum noise

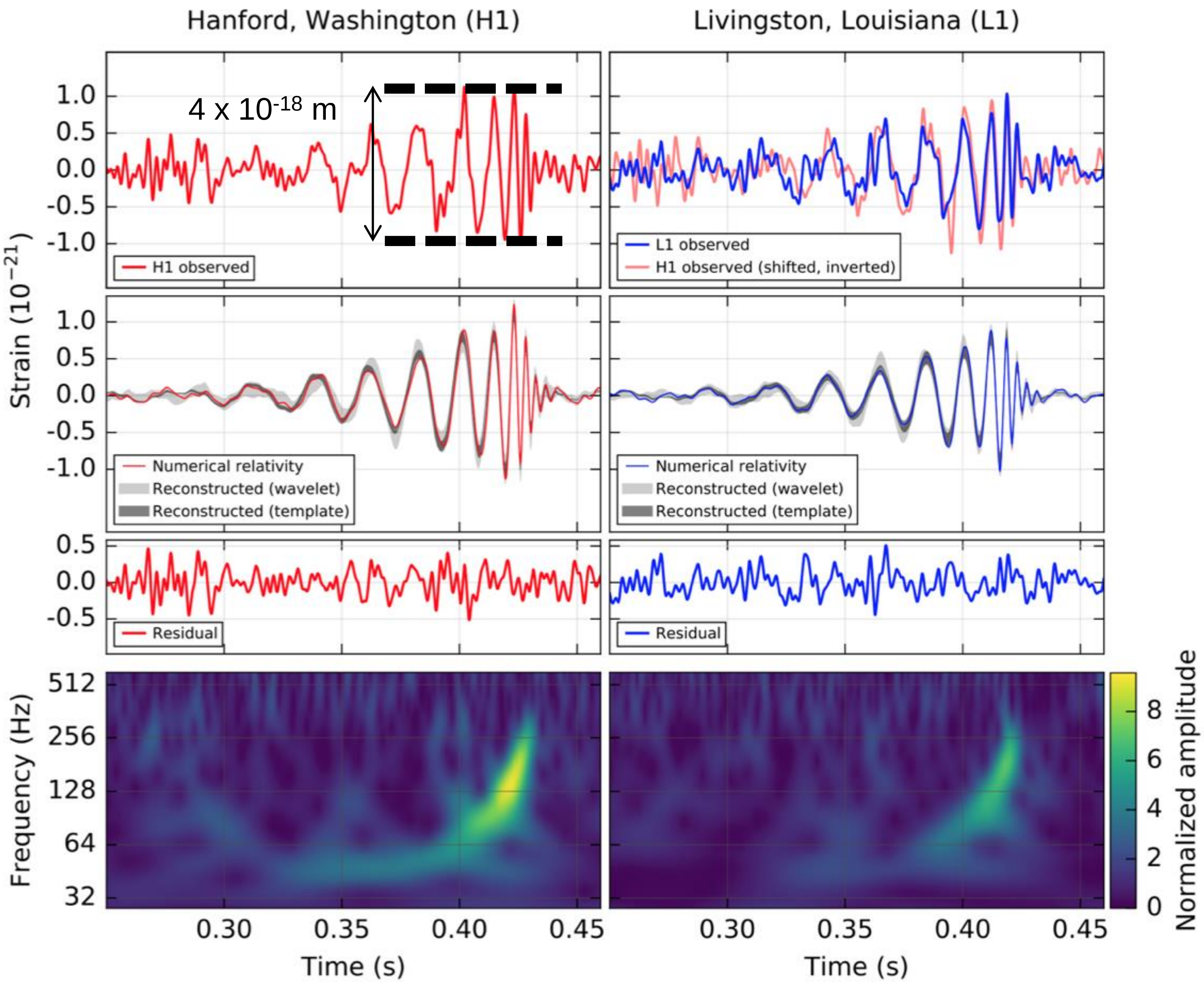
Detuned for the best NS-NS inspiral range

The Advanced LIGO Detector Sensitivity During O1

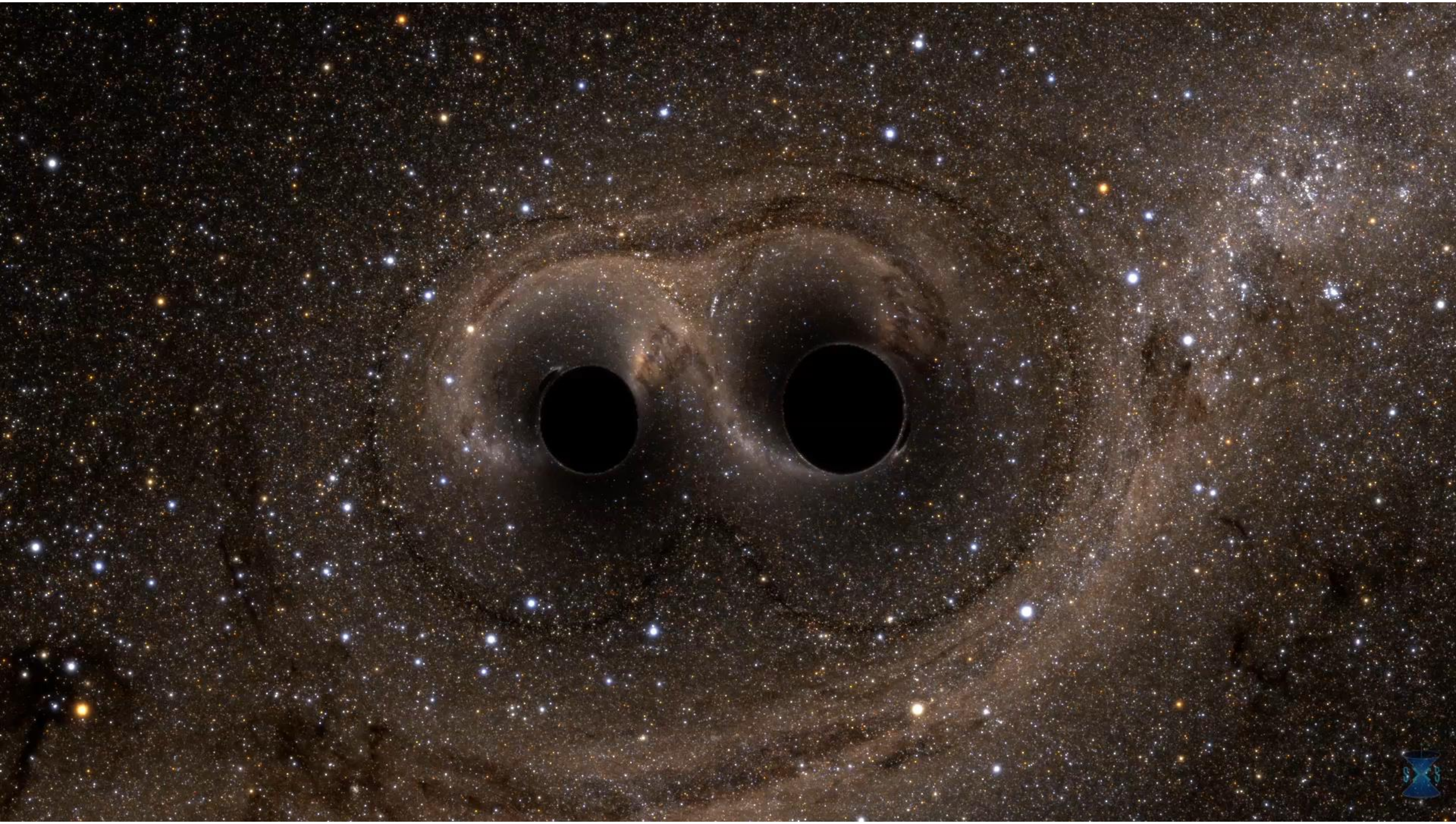


Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, “GW150914: The Advanced LIGO Detectors in the Era of First Discoveries”, Phys. Rev. Lett. **116**, 131103 (2016).

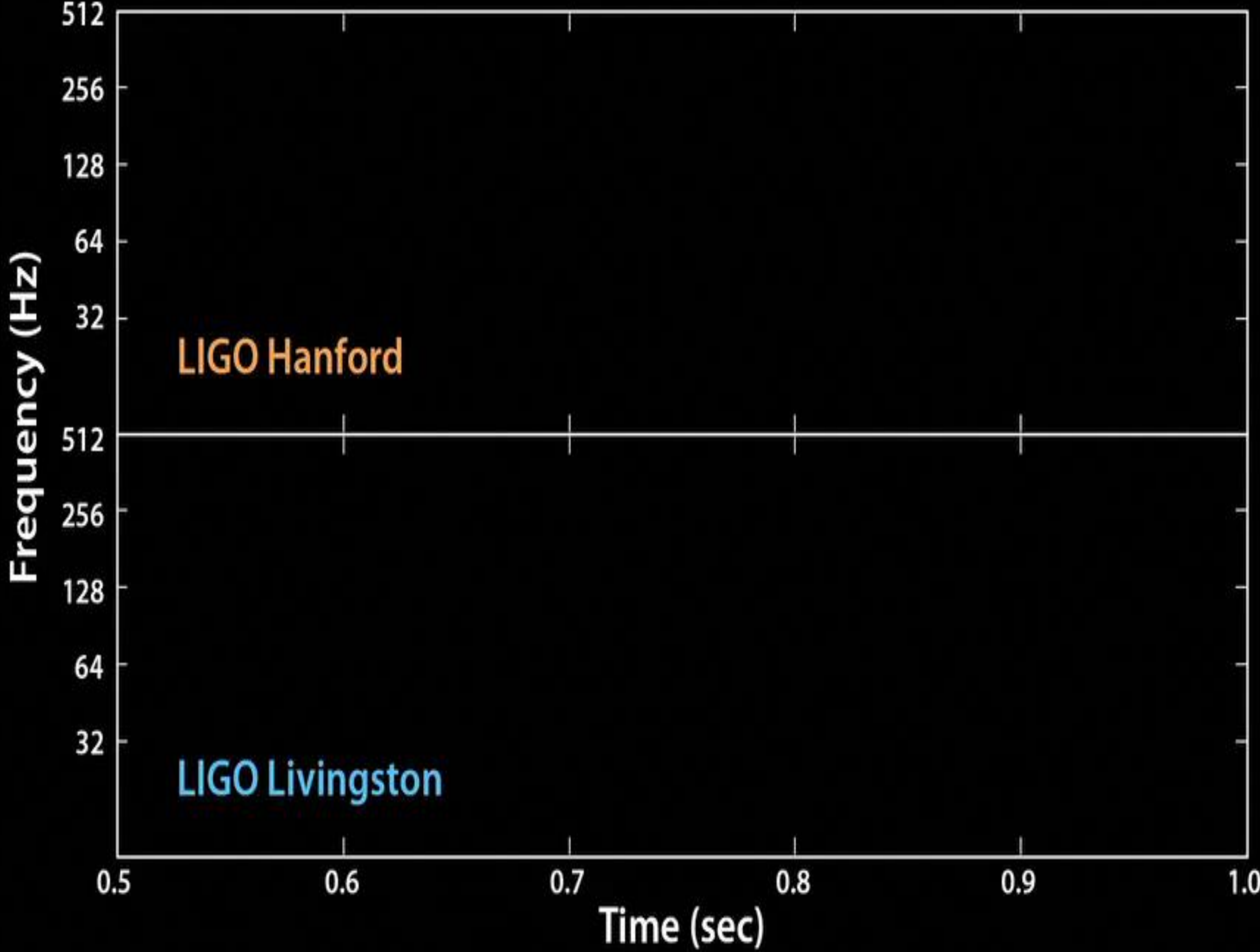
Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, "Observation of Gravitational Waves from a Binary Black Hole Merger" **Phys. Rev. Lett. 116, 061102 (2016)**

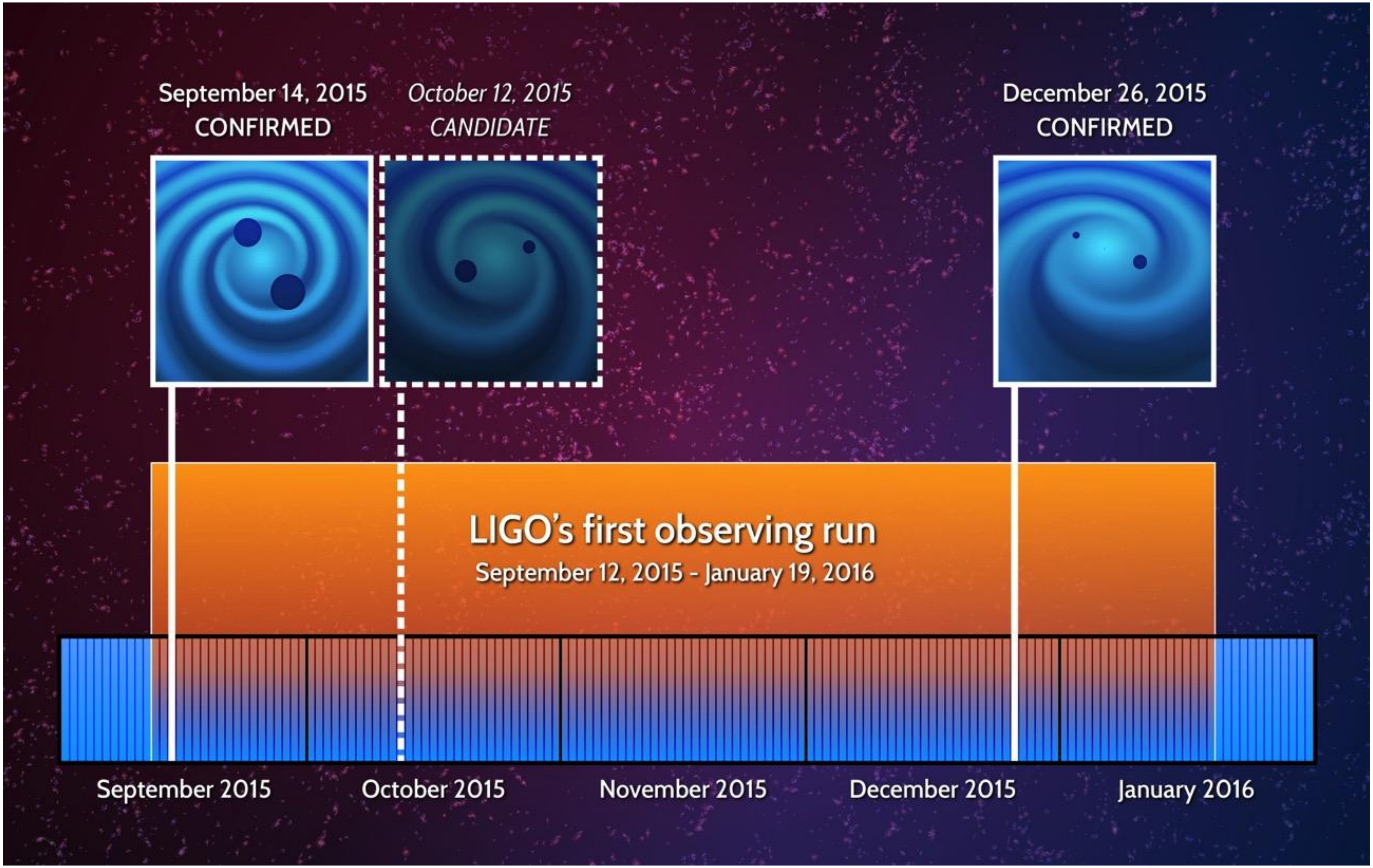


Source of detected gravitational wave



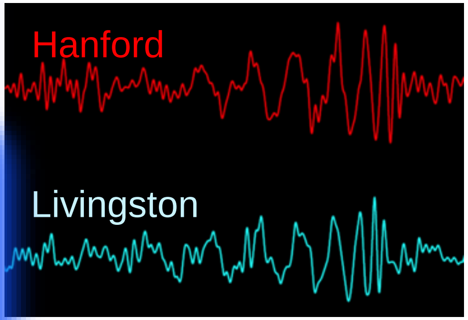
SXS


512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)


September 14, 2015
CONFIRMED
October 12, 2015
CANDIDATE
December 26, 2015
CONFIRMED
LIGO's first observing run
September 12, 2015 - January 19, 2016
September 2015
October 2015
November 2015
December 2015
January 2016

Extracting Astrophysical Parameters from Detections

	GW150914	GW151226	LVT151012
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}$	$14.2^{+8.3}$	23^{+18}
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600
Final spin a_{f}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$

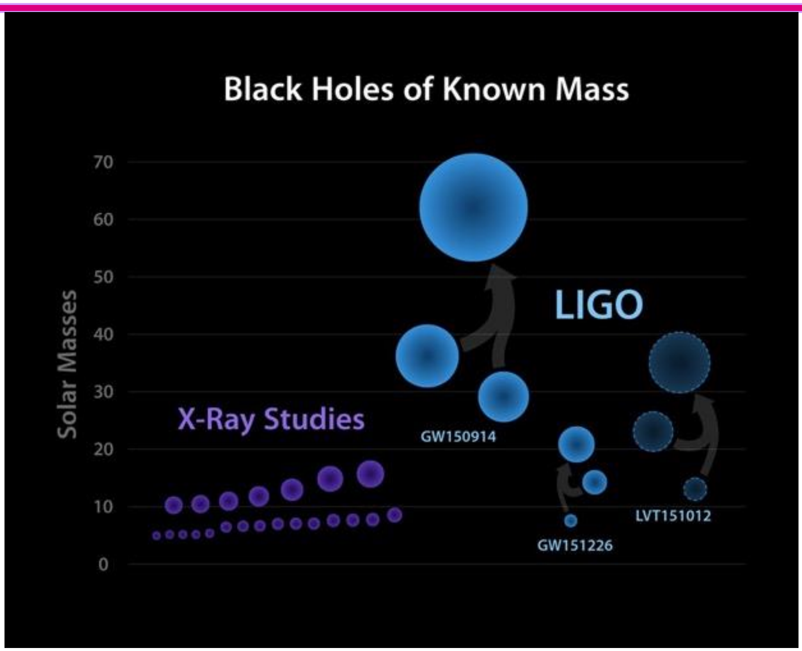


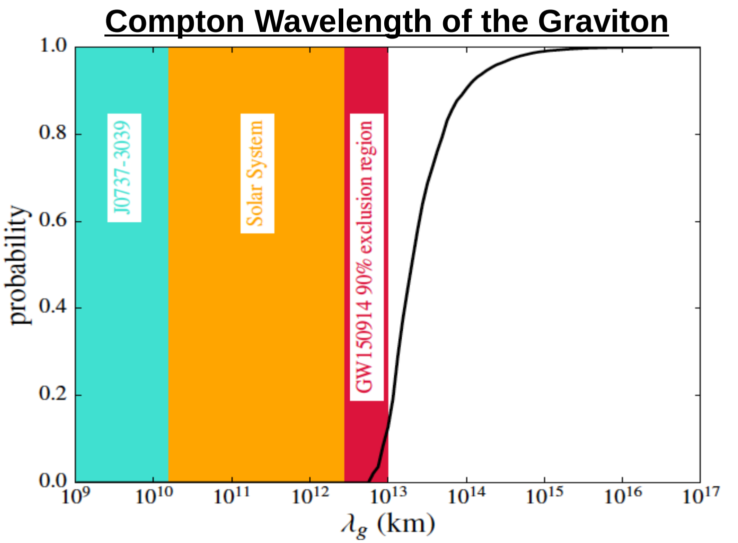
Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, “Binary Black Hole Mergers in the first Advanced LIGO Observing Run”, https://arxiv.org/abs/1606.04856, accepted in Phys. Rev. X

Implications for Astrophysics and General Relativity

- First direct observation of a binary black hole merger!
  - BBH systems can merge in a Hubble time
  - GWs may be the only way to detect BBH mergers
- First direct experimental evidence for ‘heavy’ stellar mass black holes
  - Implication: assuming direct formation from core collapse of heavy star, favors low metallicity environment (z < ½)
  - Implication: ‘kicks’ from core collapse supernova can’t be very large
- Binary black hole merger rates are in the range 10 – 240 per Gpc^3 per year
- BBH mergers are Kerr black holes, consistent with general relativity
- First test of general relativity in the dynamical strong field limit:
  - Inspiral waveforms consistent with Post-Newtonian expansion
  - Limit on graviton mass

$$m_g \leq 1.2 \times 10^{-22}\ \mathrm{eV}/c^2$$

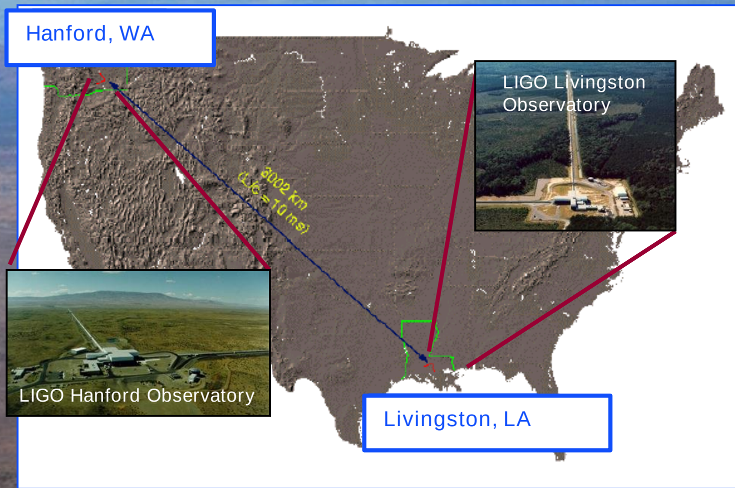


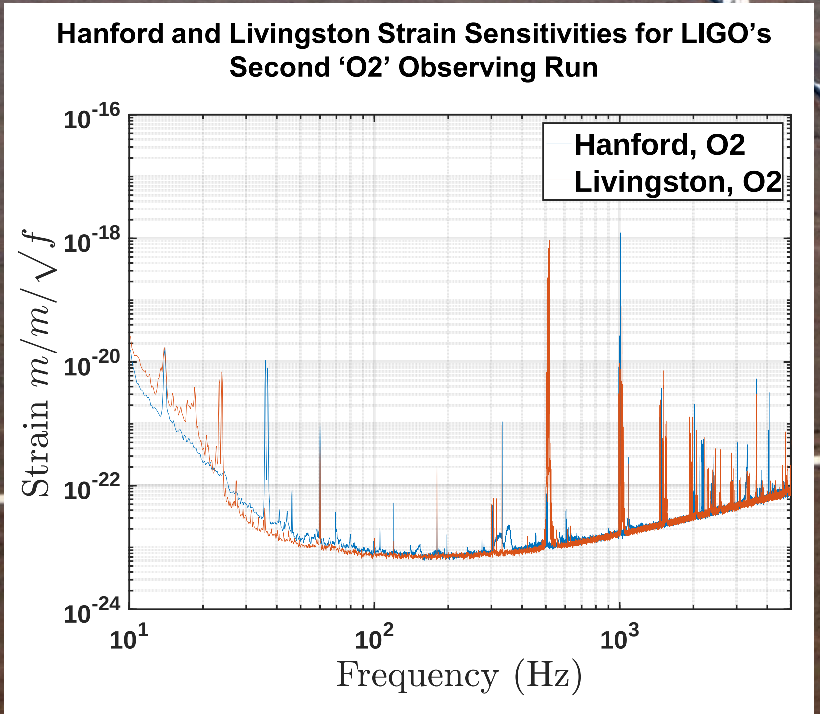


Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, “Astrophysical Implications of the Binary Black Hole Merger GW150914”, Ap. J. Lett. **818**, L22 (2016).
Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, “Tests of General Relativity with GW150914” **Phys. Rev. Lett. 116, 061102 (2016)**

LIGO

- LIGO's first 'O1' observing run (Sept 12, 2015 – Jan 19, 2016)
  - *Produced first direct gravitational wave detections!*
- LIGO began O2 run on November 30, 2016; 6 month scheduled duration
  - LIGO Livingston interferometer operating at nearly 1/2 design sensitivity
  - LIGO Hanford interferometer operating at approximately 1/3 design sensitivity
  - Joint running with Advanced Virgo planned for the 2nd half of O2





LSC LIGO Scientific Collaboration

NEWS

APRIL 2017 UPDATE ON LIGO'S SECOND OBSERVING RUN

6 April 2017 -- The second Advanced LIGO run began on November 30, 2016 and is currently in progress. As of March 23 approximately 48 days of Hanford-Livingston coincident science data have been collected, with a scheduled break between December 22, 2016 and January 4, 2017. The average reach of the LIGO network for binary merger events has been around 70 Mpc for 1.4+1.4 Msun, 300 Mpc for 10+10 Msun and 700 Mpc for 30+30 Msun mergers, with relative variations in time of the order of 10%.

As of March 23, 6 triggers, identified by online analysis using a loose false-alarm-rate threshold of one per month, have been identified and shared with astronomers who have signed memoranda of understanding with LIGO and Virgo for electromagnetic followup. A thorough investigation of the data and offline analysis are in progress; results will be shared when available.

LIGO's Plans for the Future

- After O2 run completes, Advanced LIGO detectors will undergo a period of commissioning and detector improvements
  - Goal is to achieve design sensitivity by the end of the decade → 200 Mpc average binary neutron star (BNS) detection range, 1.3 Gpc average binary black hole (BBH) detection range
- Longer duration O3 and O4 runs are planned in the next 5 year period
- Early next decade, a set of upgrades to Advanced LIGO is anticipated
  - Broadband squeezed light injection to reduce quantum noise (shot noise and radiation pressure)
  - Improved test mass mirror coatings to reduce thermal noise in the critical mid-frequency band region
  - Preliminary design sensitivity increase to 350/2200 Mpc BNS/BBH detection range
- LIGO-India has been approved and is underway; expected to begin operations in 2024
  - An international collaboration between the USA and India to construct an identical Advanced LIGO interferometer in India
- Longer term: plans for a new network of ground-based observatories with sensitivities capable of 'seeing' back to the formation of the first stars

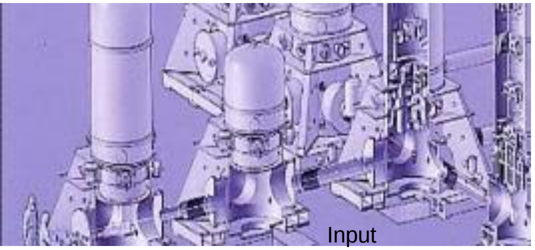
Advanced Virgo

- Participated by scientists from Italy and France (former founders of Virgo), The Netherlands, Poland, Hungary, and Spain

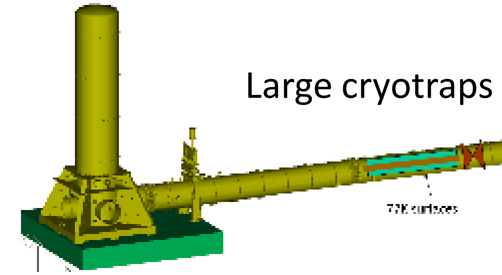
Tot.~300 scientists

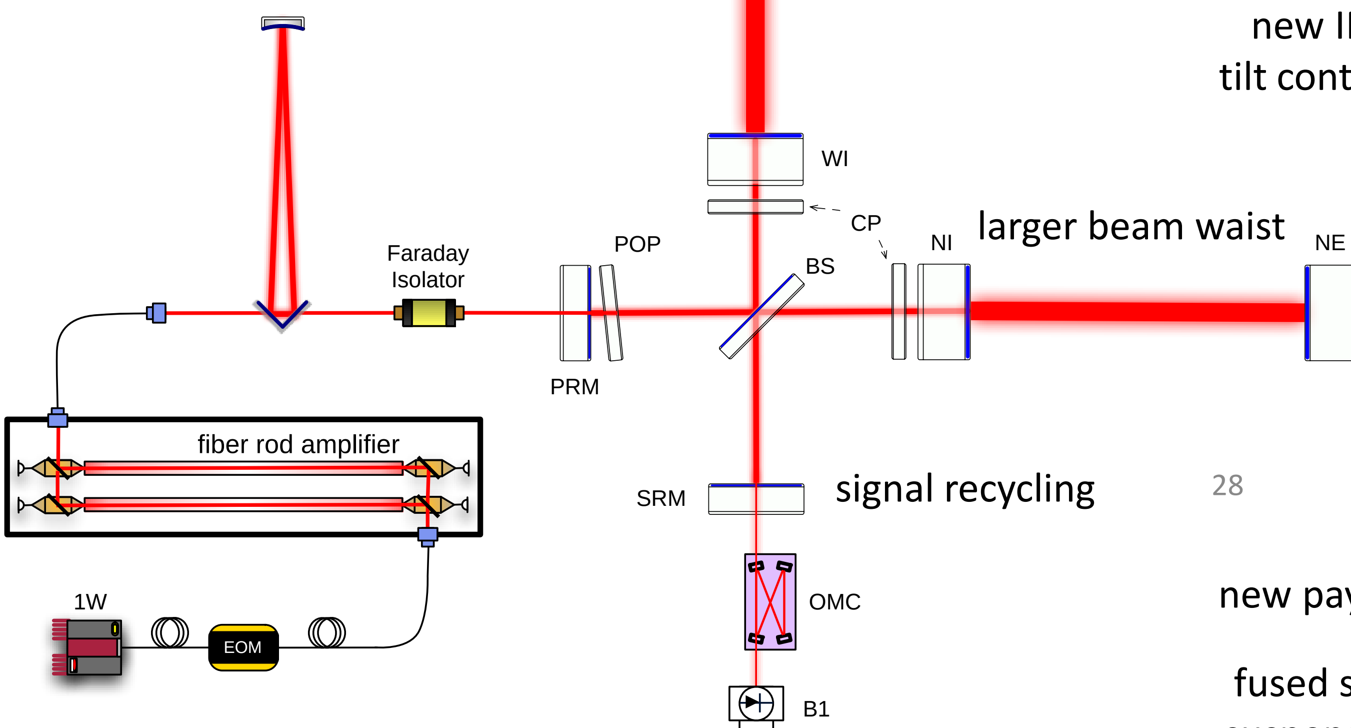
Ad Virgo in a nutshell

Larger central vacuum links



Large cryotraps





heavier mirrors
(42 kg)

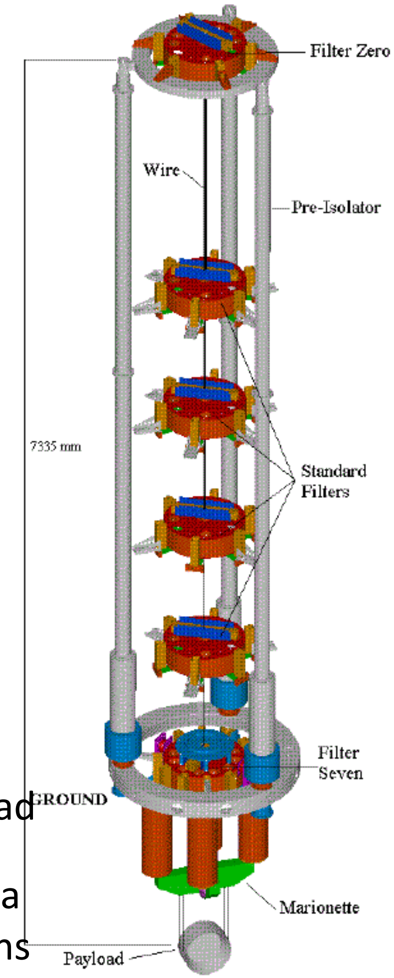
new IP
tilt control

larger beam waist

signal recycling

high power SSL

DC detection

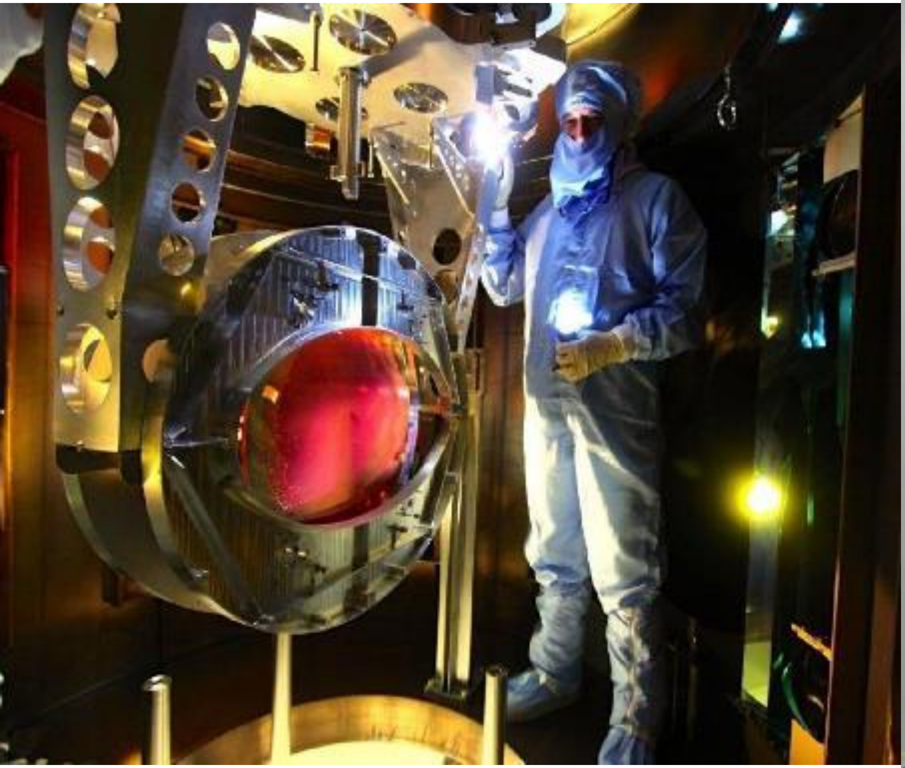


new payload

fused silica
suspensions

Payloads

Beam Splitter integrated hooked to the super attenuator (now in vacuum)

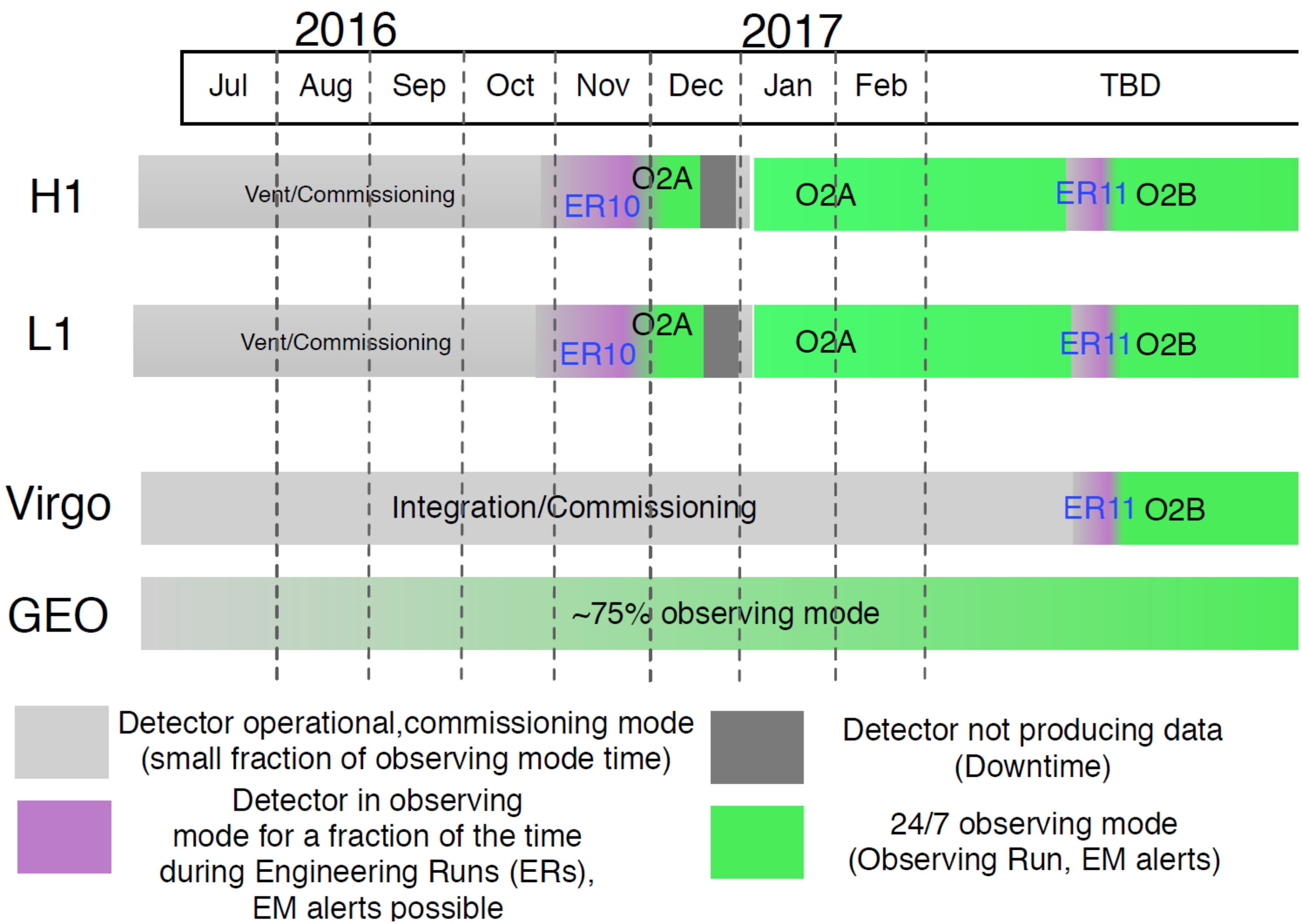


Input mirror payloads of the FP cavities assembled and integrated in the super attenuator vacuum chamber

MILESTONES

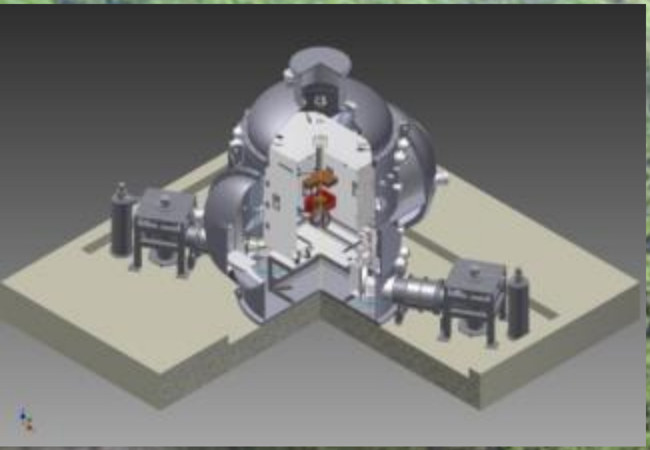
1	LOCK AT HALF FRINGE		ACHIEVED DEC 30TH
2	LOCK AT DARK FRINGE		First lock achieved
3	LOW NOISE STABLE CONFIGURATION	Final alignment, OMC lock, lock on B1, low noise actuation. 1st noise budget	
4	SCIENCE MODE	Full automation, final calibration, more DET benches in vacuum (TBC) - Sensitivity target	

O2 TIMELINE


2016
2017
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
TBD
H1
Vent/Commissioning
ER10
O2A
O2A
ER11
O2B
L1
Vent/Commissioning
ER10
O2A
O2A
ER11
O2B
Virgo
Integration/Commissioning
ER11
O2B
GEO
~75% observing mode
Detector operational,commissioning mode
(small fraction of observing mode time)
Detector not producing data
(Downtime)
Detector in observing
mode for a fraction of the time
during Engineering Runs (ERs),
EM alerts possible
24/7 observing mode
(Observing Run, EM alerts)

KAGRA

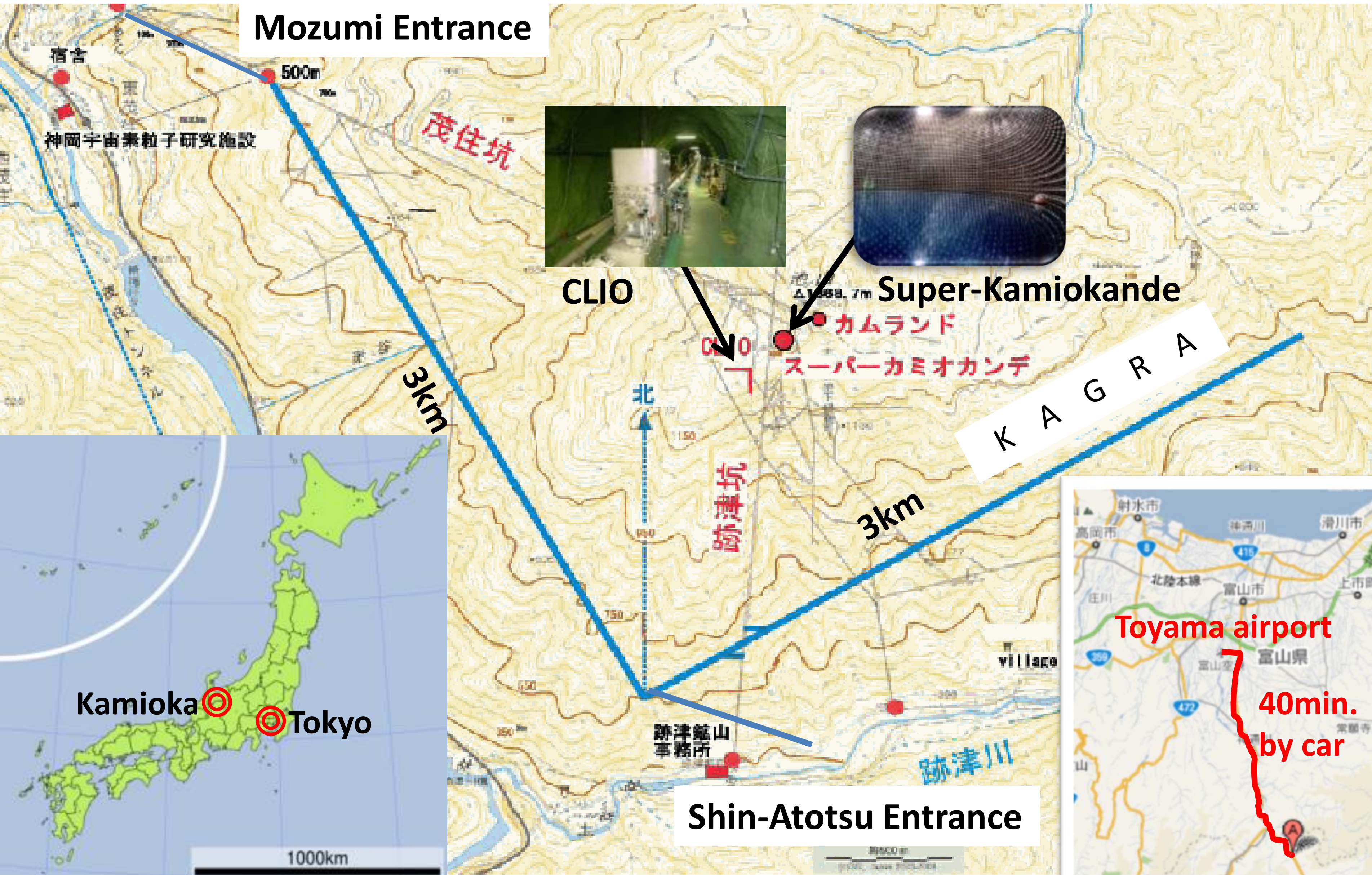
Cryogenic Mirror



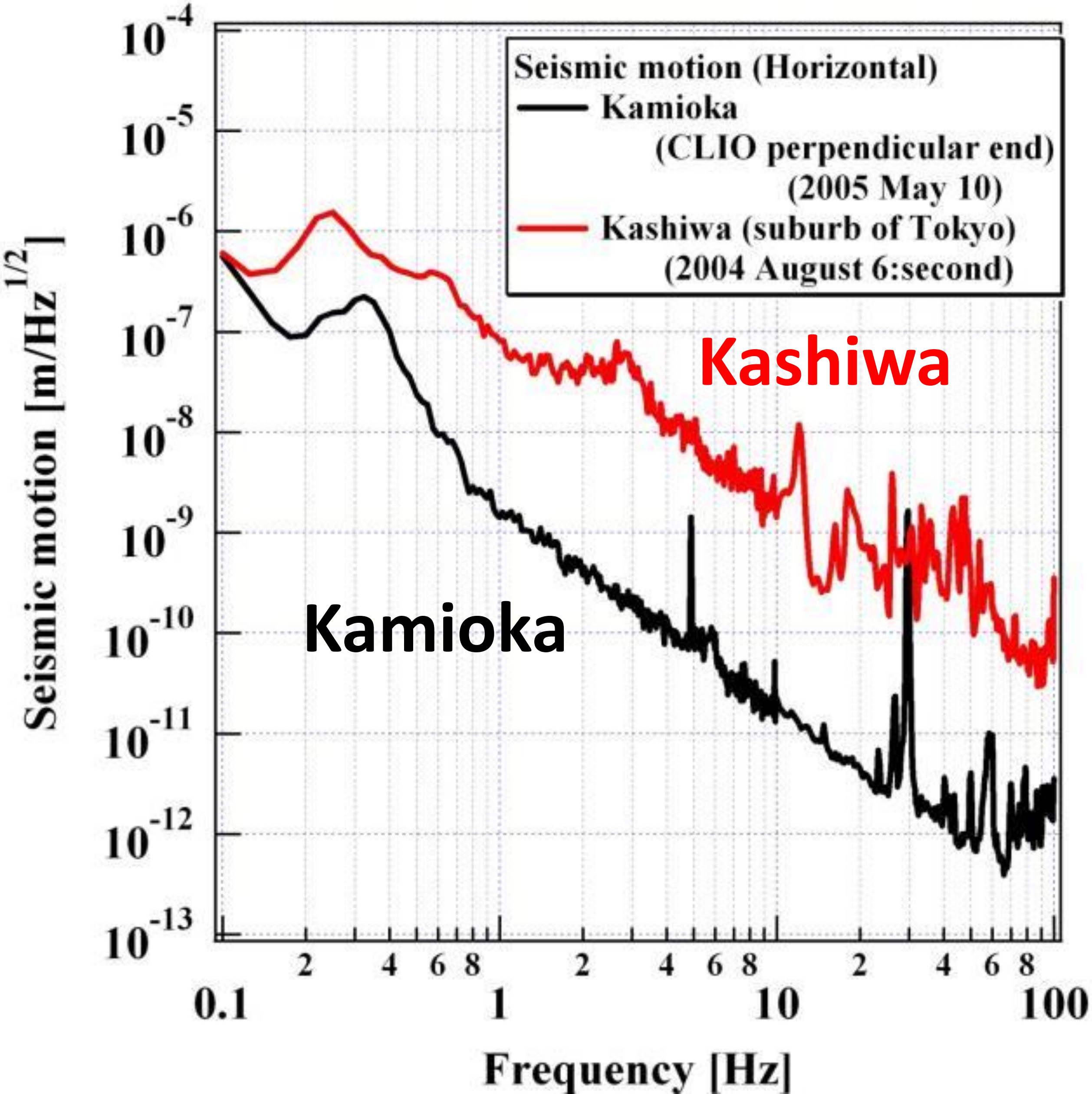
Underground

Technologies crucial for the 3rd-generation detectors; KAGRA can be regarded as a 2.5-generation detector.

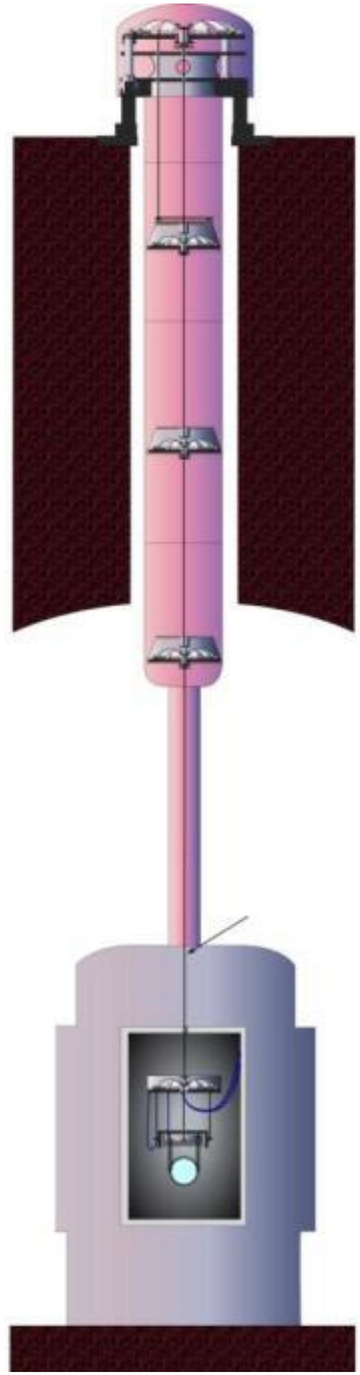
Location (Kamioka)



Ground motion in Kamioka mine



Vibration isolation system



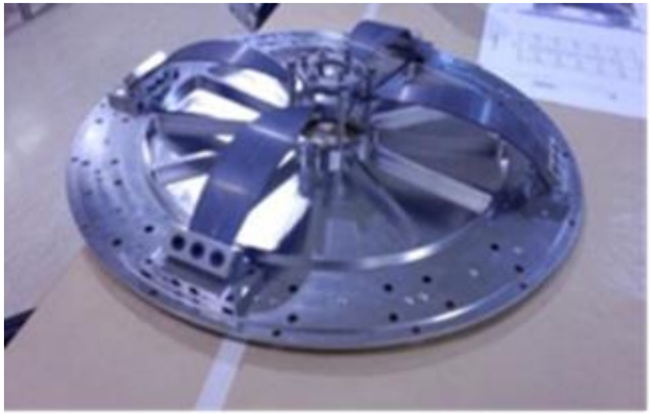
2nd floor

Inverted pendulum
Geometrical antispring (GAS) filter

Multi-stage pendulum (with GAS filter)

1st floor

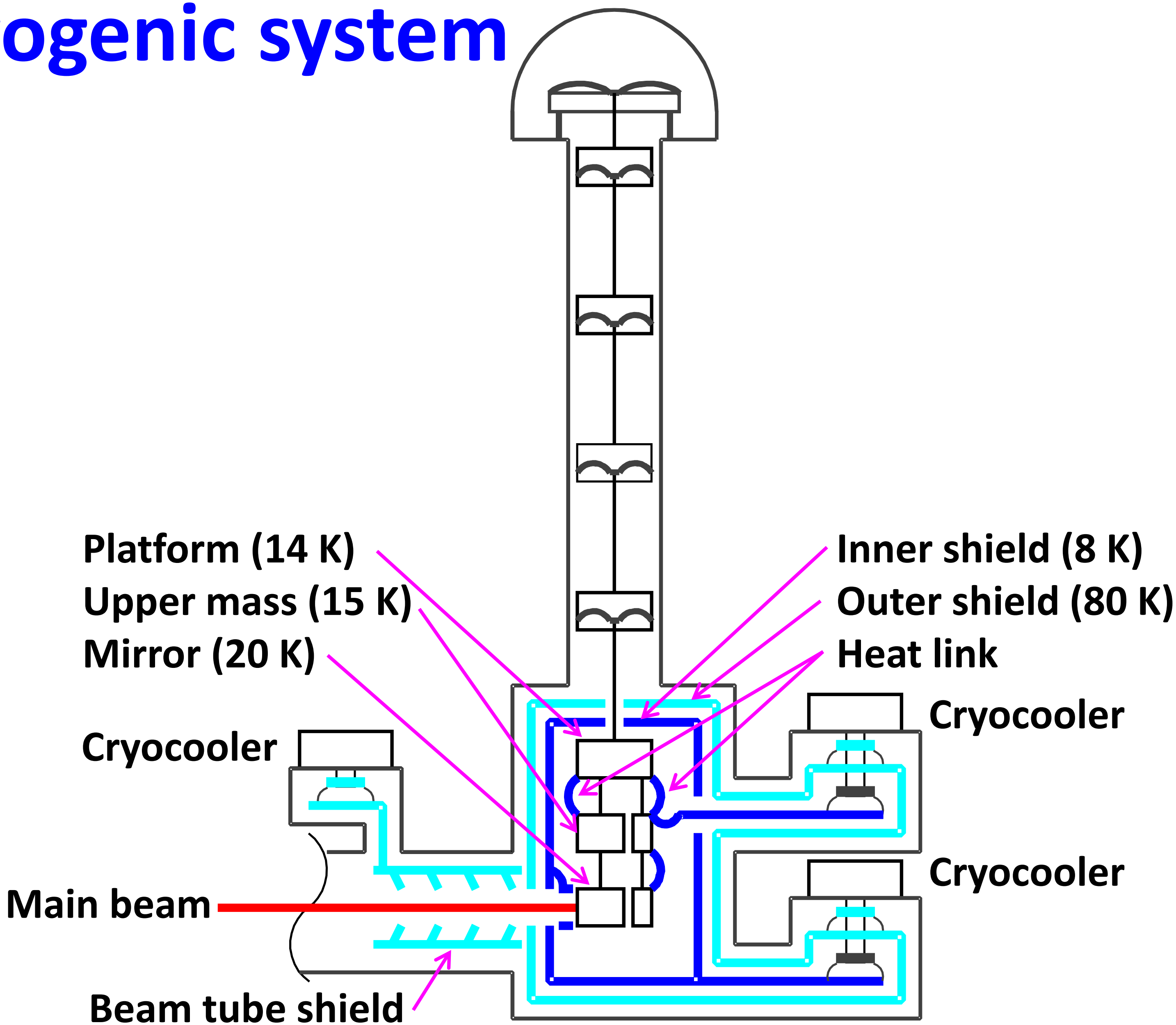
Another pendulum (with GAS filter)
Mirror suspension



GAS filter

Two-layer structure to avoid the resonances of the tall structure.

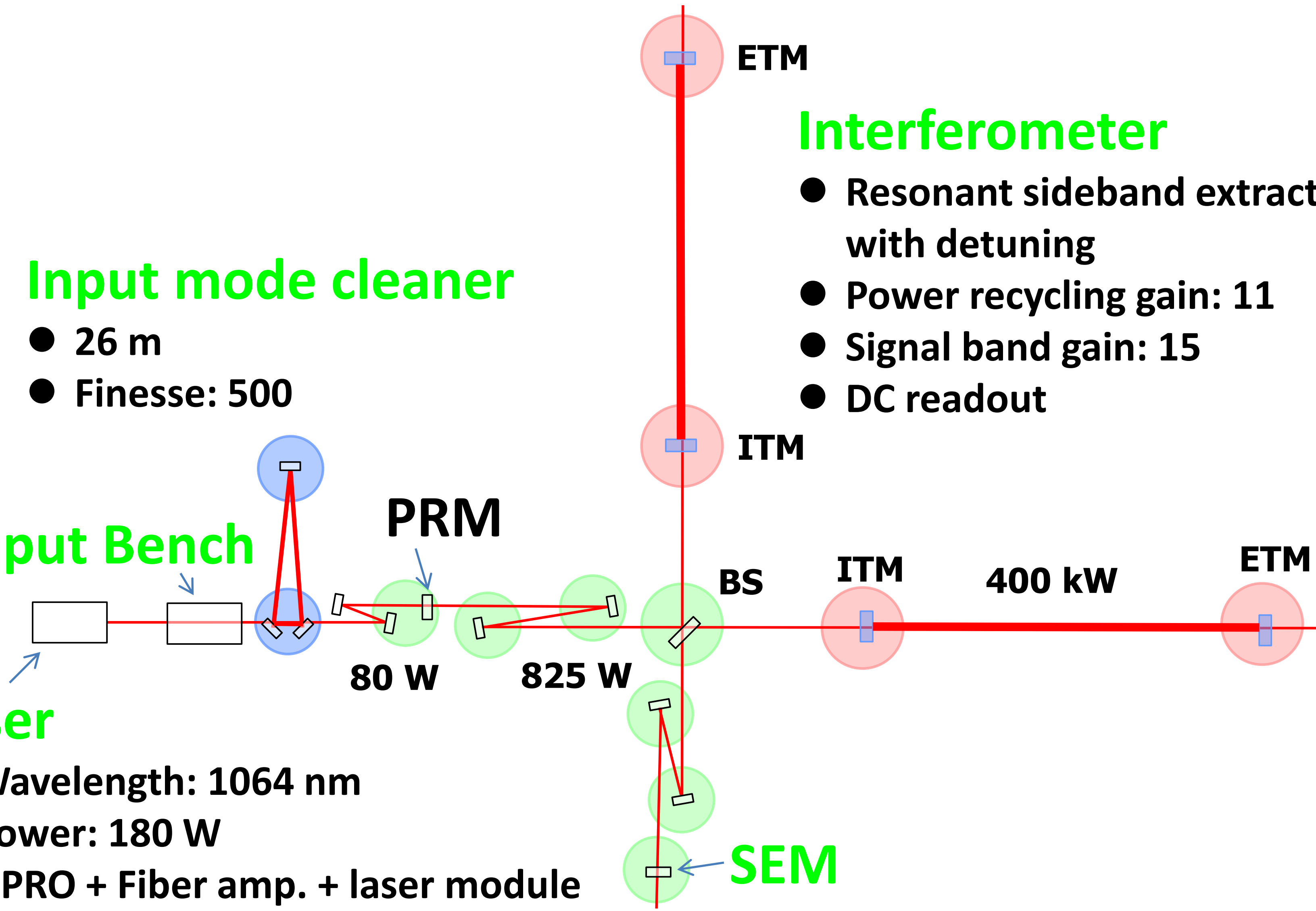
Cryogenic system



Optical configuration

Input mode cleaner
- 26 m
- Finesse: 500

Interferometer
- Resonant sideband extraction with detuning
- Power recycling gain: 11
- Signal band gain: 15
- DC readout

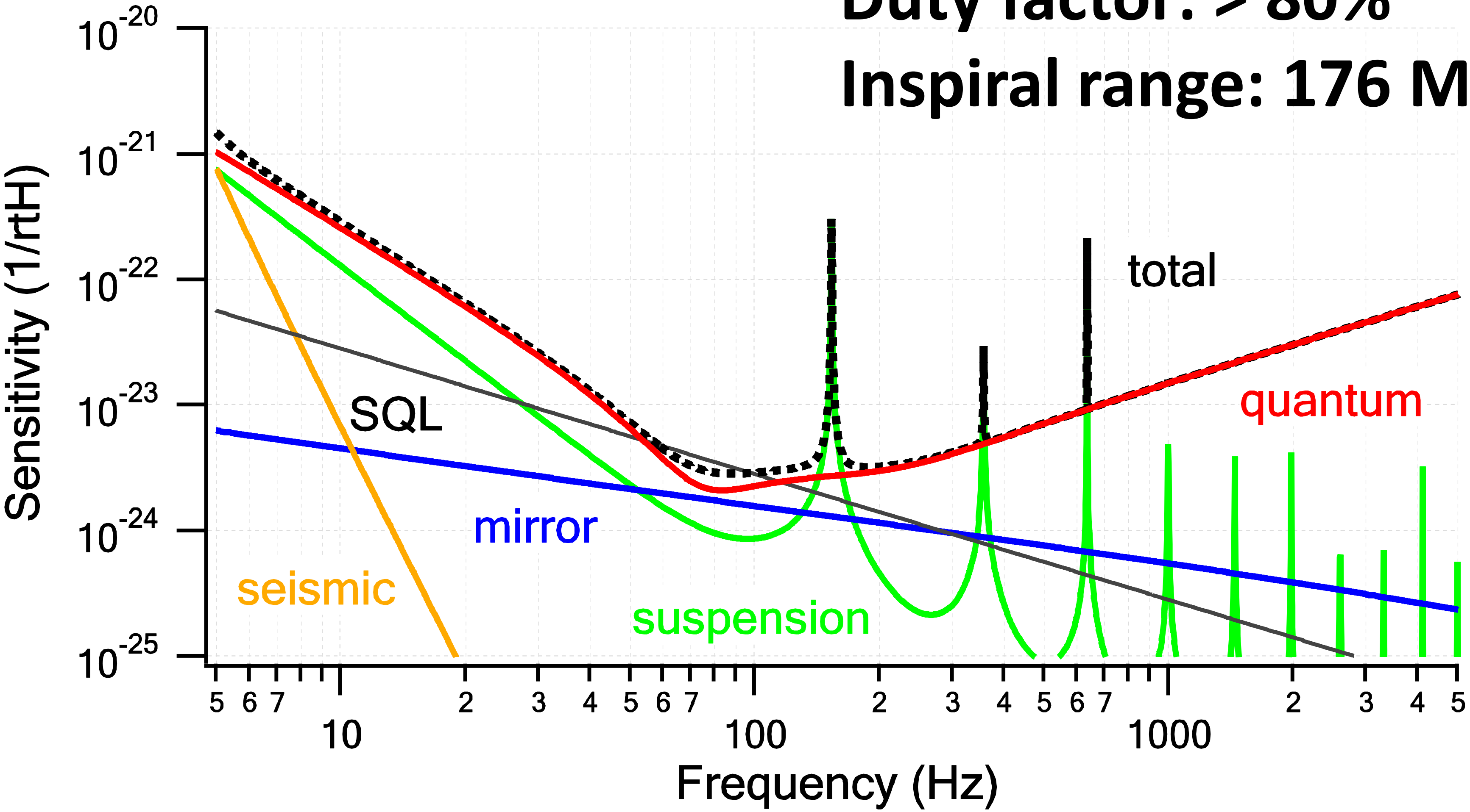


Laser
- Wavelength: 1064 nm
- Power: 180 W
- NPRO + Fiber amp. + laser module

Ultimate sensitivity limit of KAGRA

Duty factor: > 80%

Inspiral range: 176 Mpc



Expected event rate for NS-NS coalescence

Inspiral range: 176 Mpc
(the same definition as LIGO/Virgo)

Assuming Inspiral rate per galaxy: ~100 Myr^{-1}

⇓

Expected event rate: ~10 yr^{-1}

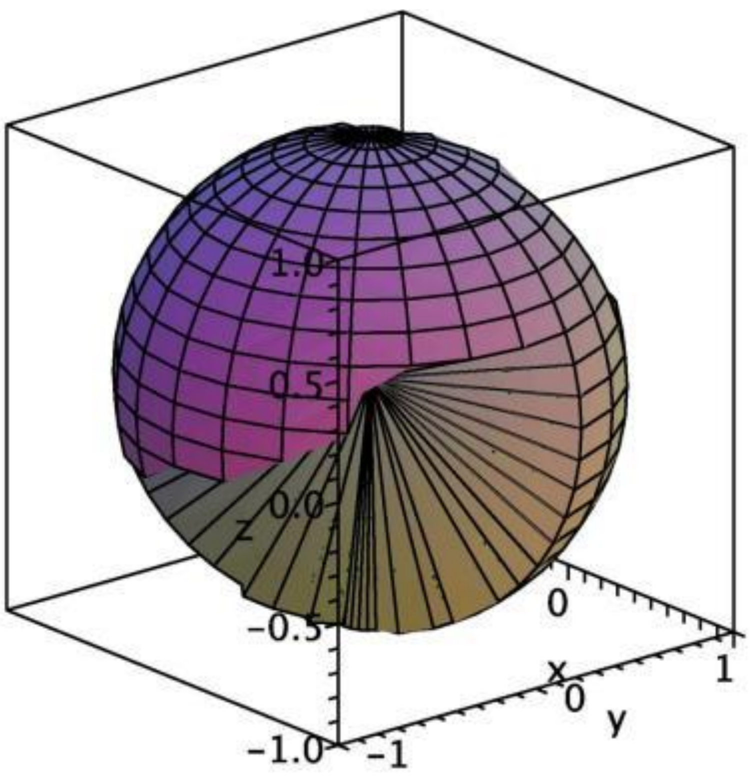
Other GW sources

- **BH-BH coalescence**: e.g. 20 $M_{\odot}$ at 2 Gpc (Binary black hole merger rates are in the range 10 – 240 per Gpc^3 per year.)
- **Quasi-normal mode of BH**: e.g. 100~300 $M_{\odot}$ at 3 Gpc
- **Supernova**: Hopefully ~1 Mpc, ~1 event per 30 years
- **Pulsar**: Crab and Vela, possibly other invisible pulsars
- **Beginning of the Universe**: non-standard model
- **Unknown**: Nature likes to surprise us.

KAGRA in network

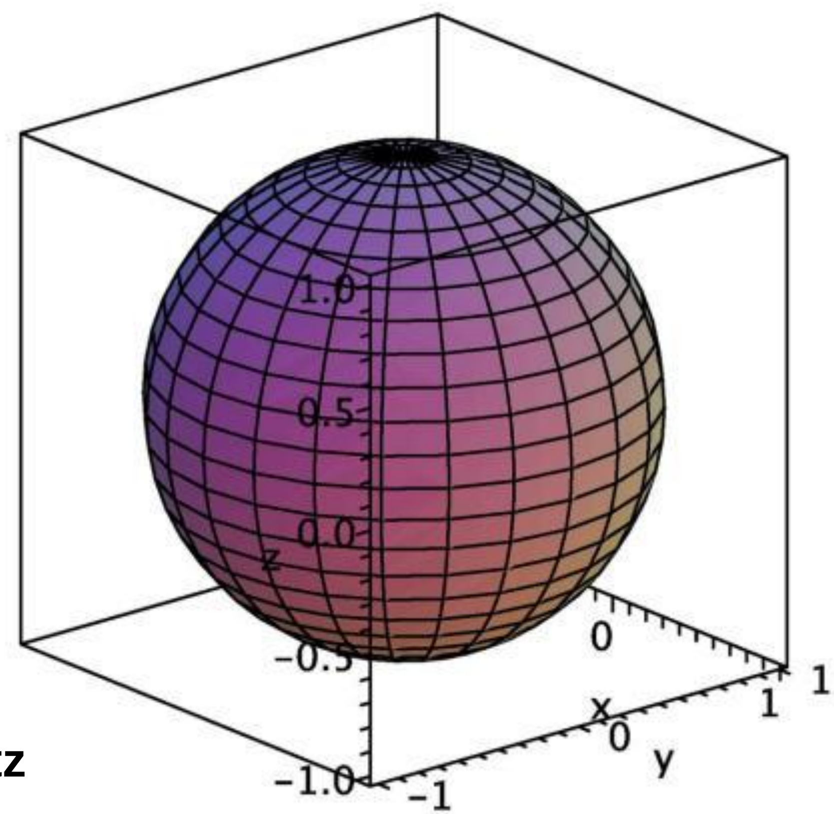
LIGO(H)+LIGO(L)+Virgo

- Coverage at 0.5 M.S.: 72%
- 3 detector duty factor: 51%



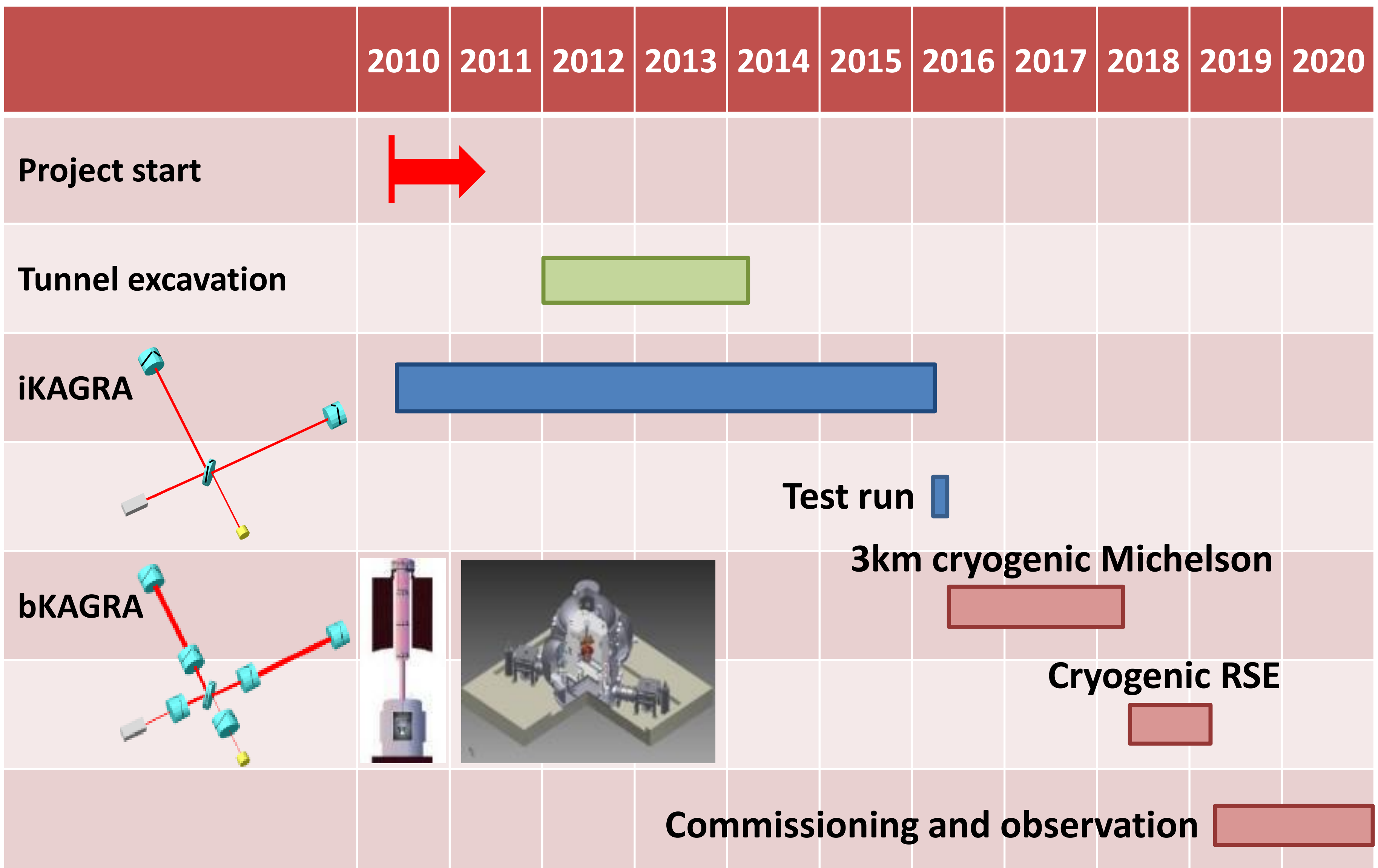
LIGO(H)+LIGO(L)+Virgo+KAGRA

- Max sensitivity (M.S.): +13%
- Coverage at 0.5 M.S.: 100%
- 3 detector duty factor: 82%



B. F. Schutz

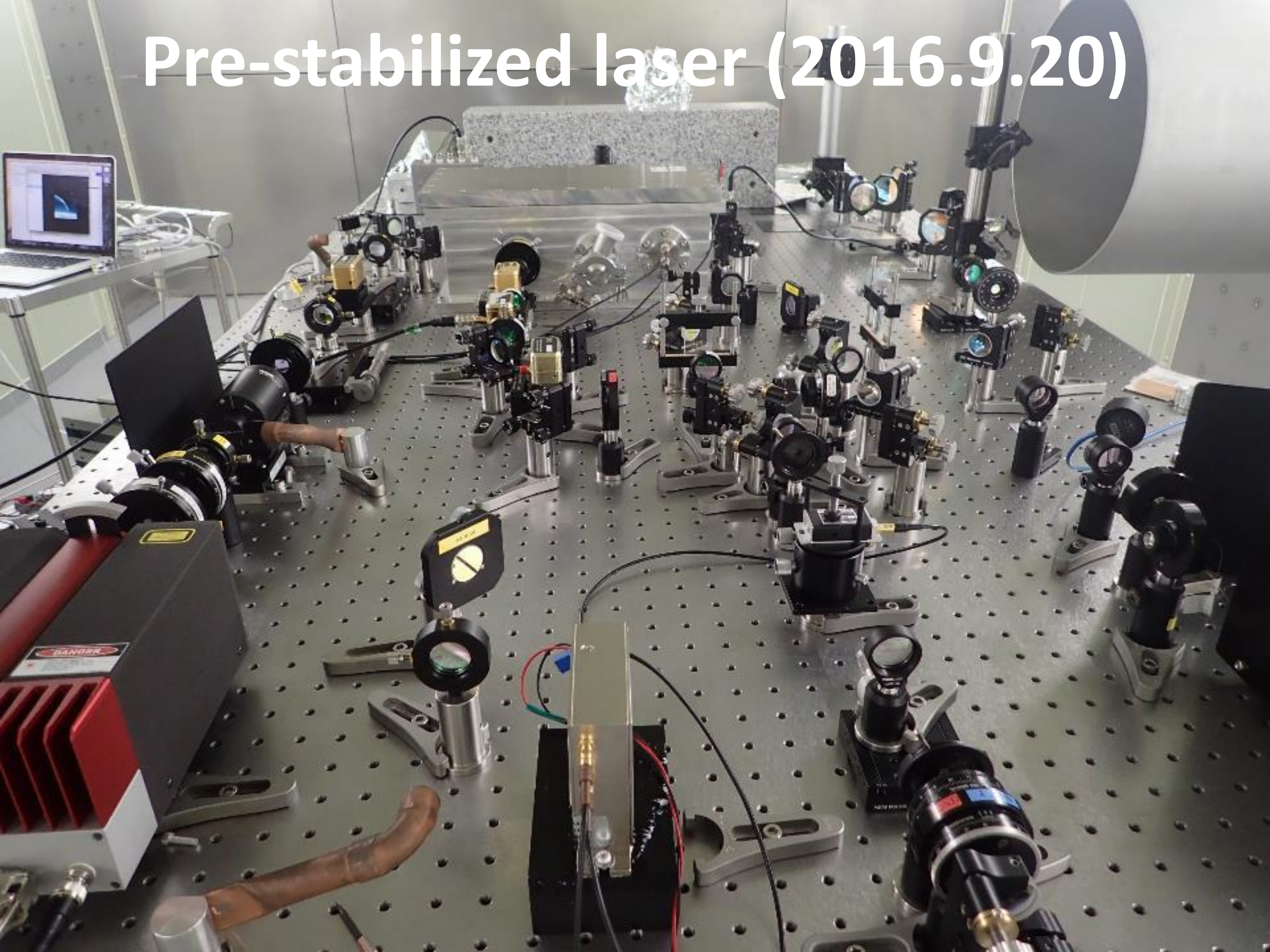
Schedule of KAGRA



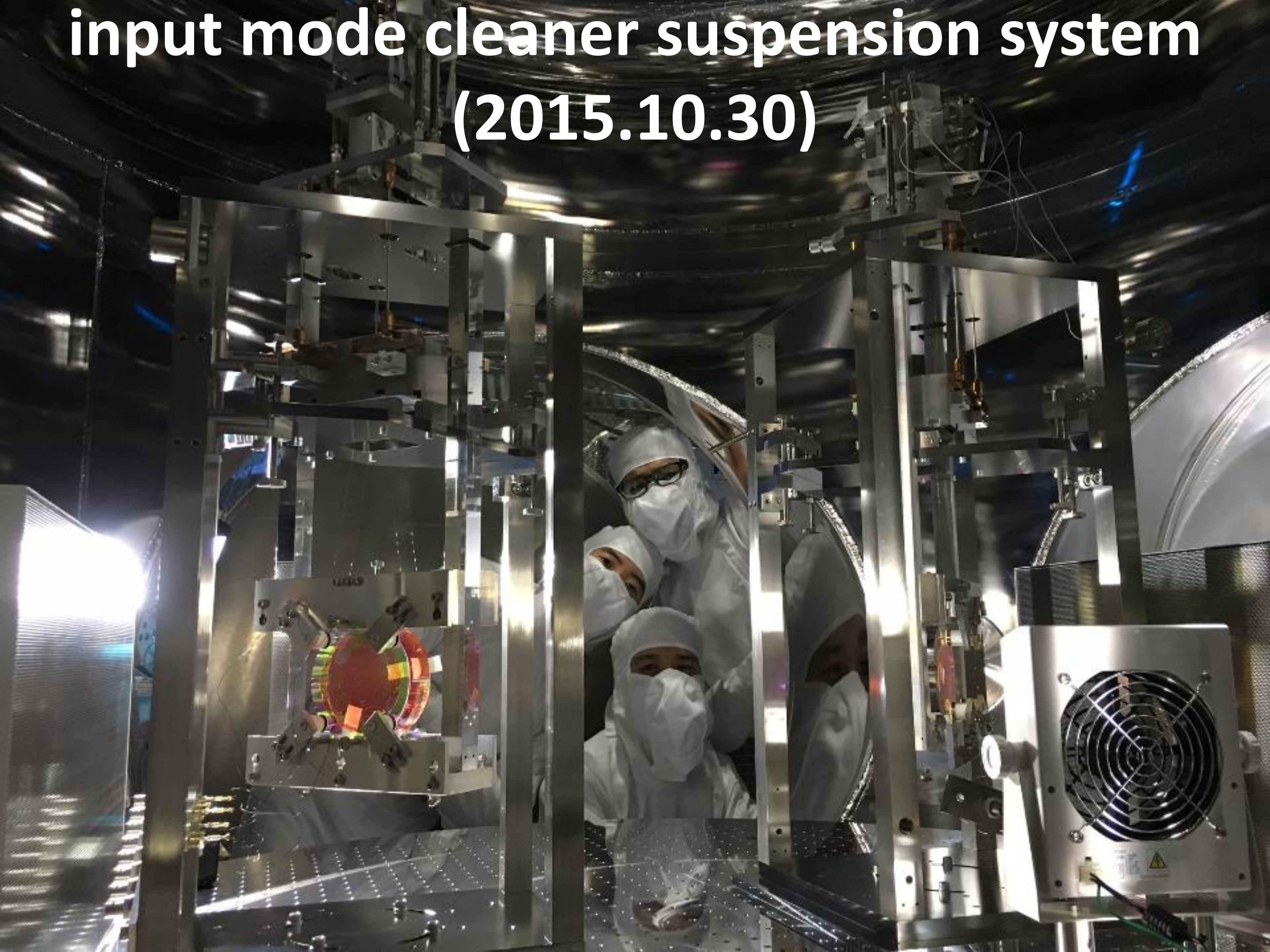
Shin-Atotsu entrance
(2017.1.7)


Central area (2017.1.7)

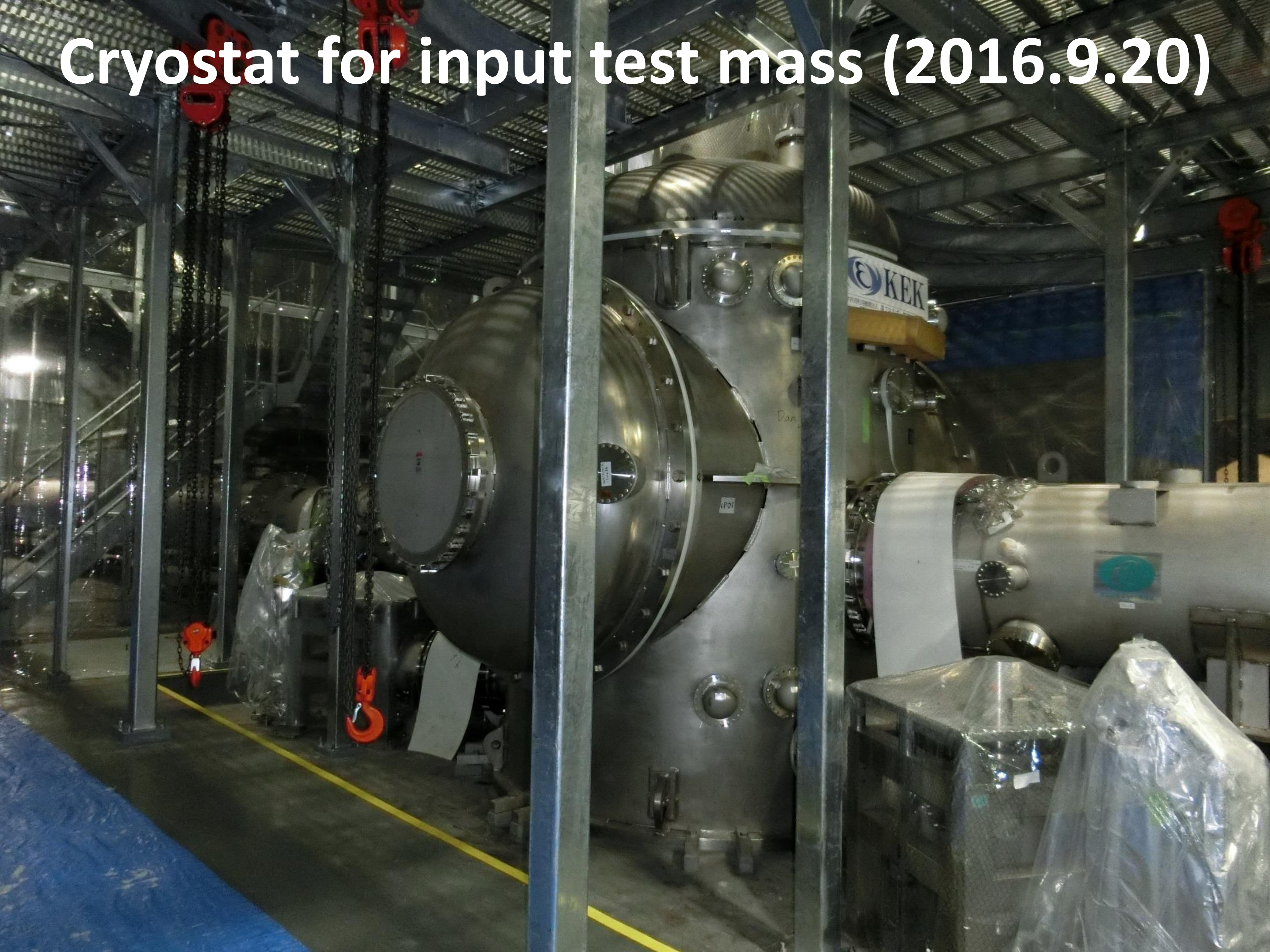
Pre-stabilized laser (2016.9.20)



input mode cleaner suspension system
(2015.10.30)



Cryostat for input test mass (2016.9.20)



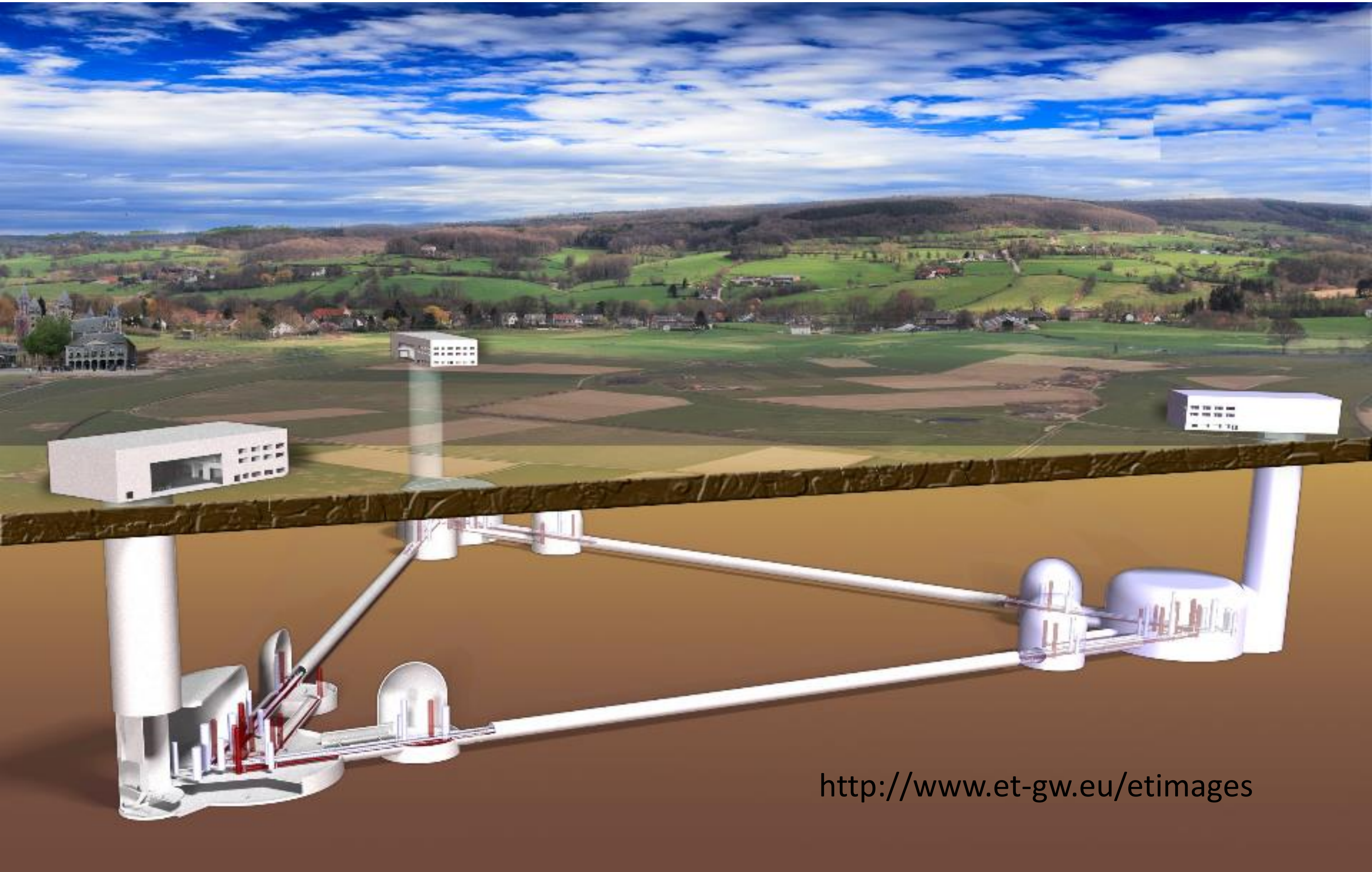
3km arm (2016.2.8)

Control room (2016.2.9)

Outline:

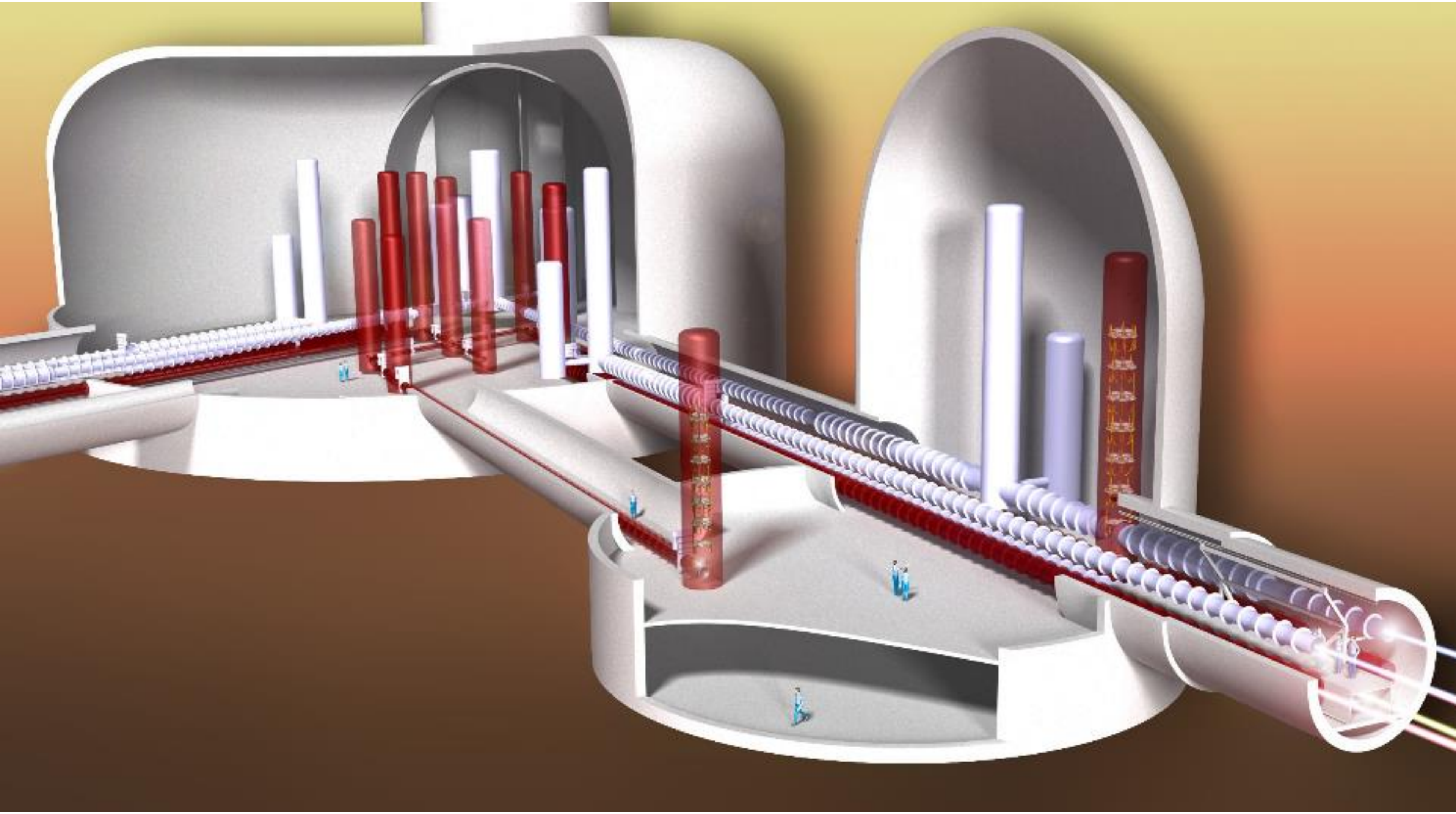
- Gravitational wave and detector
- Existing detectors
  - LIGO, Virgo, KAGRA
- **Future detectors**
  - **ET, LISA, DECIGO**
- Summary

Einstein Telescope (ET)



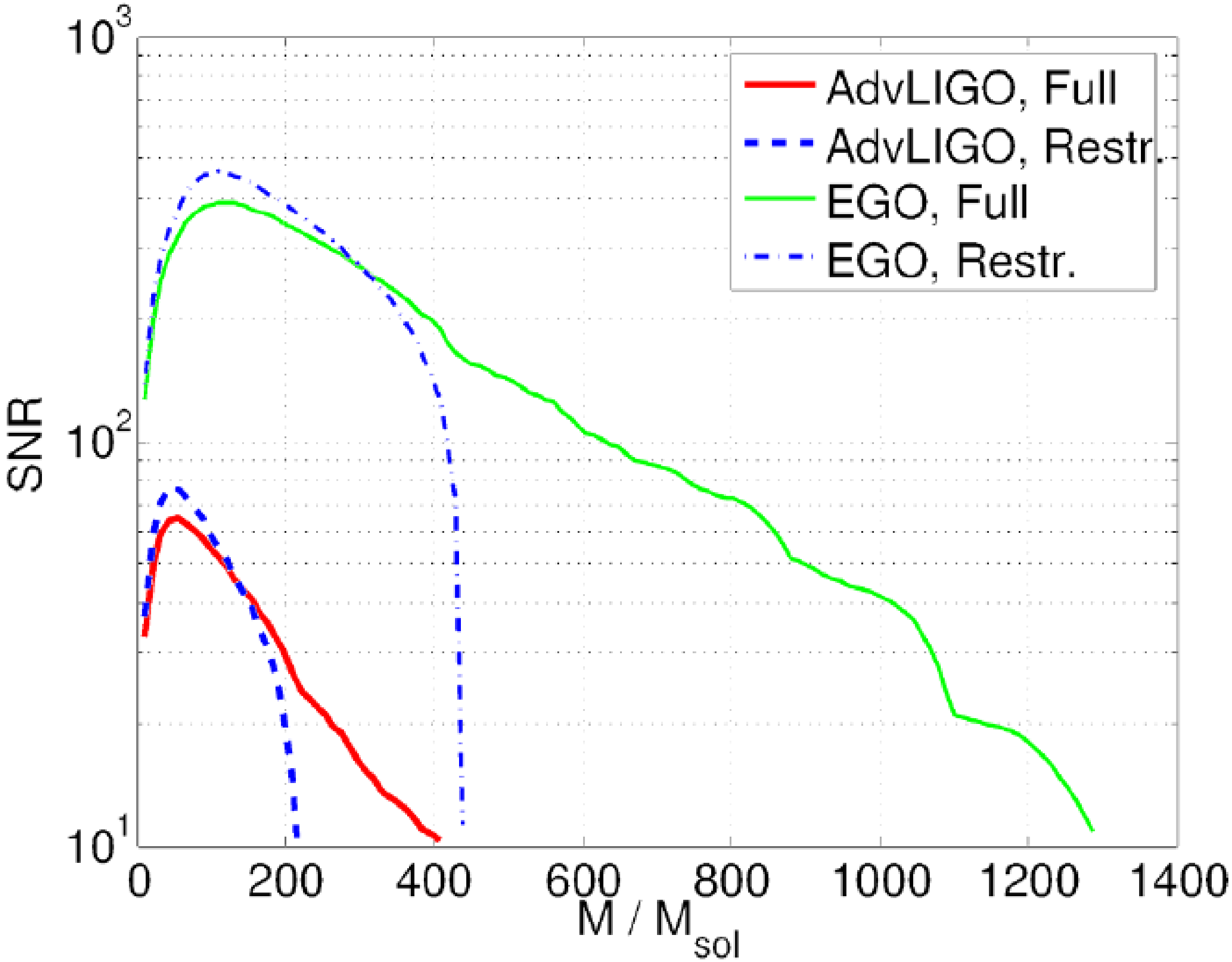
http://www.et-gw.eu/etimages

Central area



http://www.et-gw.eu/etimages

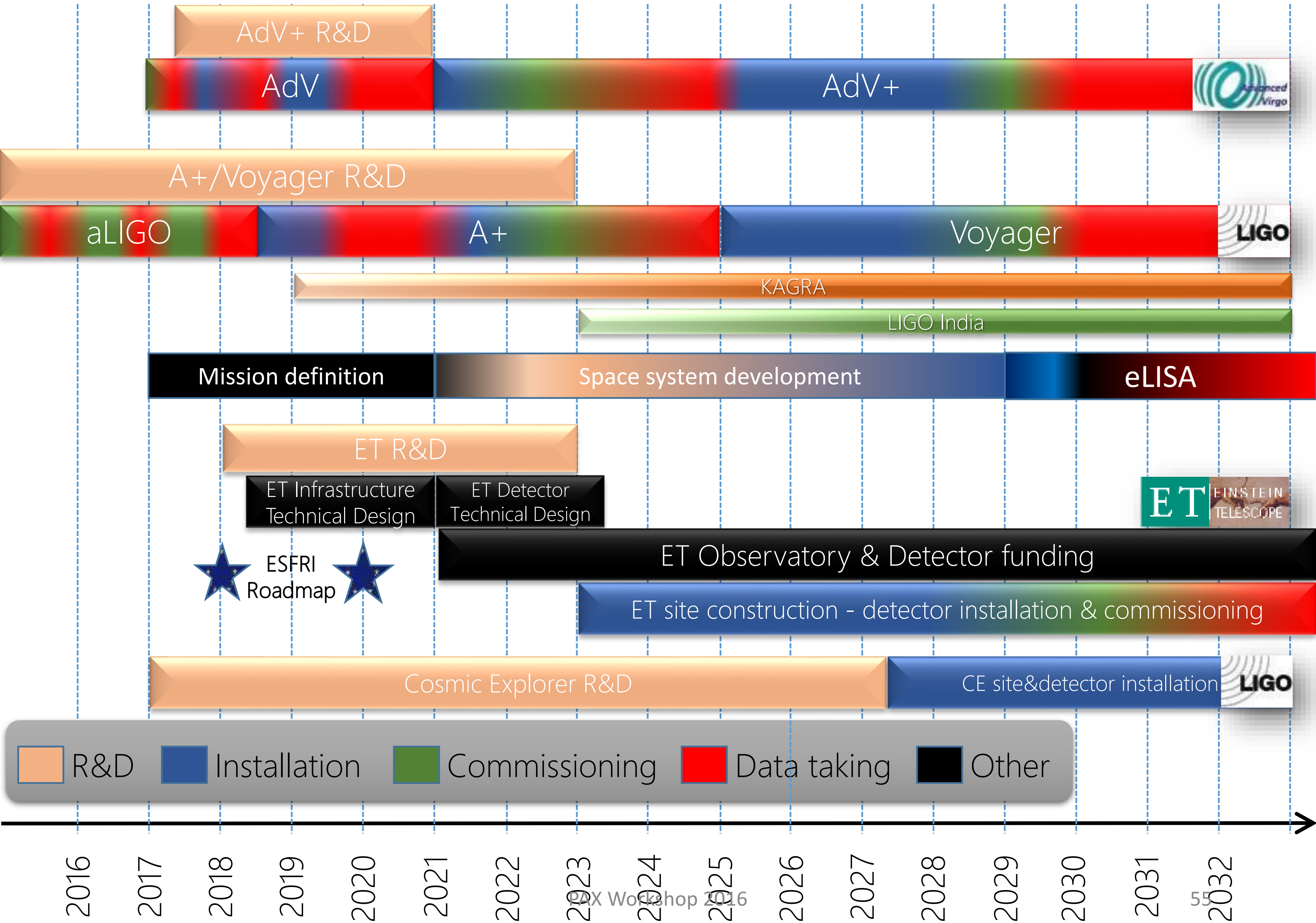
Sensitivity comparison（100 Mpc）



Van Den Broeck and Sengupta (2007)

“Physics of extreme”

- Extreme matter:
  - Neutron Stars (NS) are a natural laboratory of nuclear physics at densities unreachable in human laboratory
    - We don’t know the state of matter in NS, but the observation of several NS-NS coalescences at high SNR will allow the determination of the NS EOS
- Extreme gravity:
  - GW are the only tool to observe the coalesce of BHs; but is the Kerr solution the right description of a BH?
    - Measuring more than one quasi normal mode in the ringdown of a Bh-BH coalescence it will be possible to test the no-hair theorem
  - Is GR the right gravity theory?
- Extreme Universe:
  - What are the GRB progenitors? Long GRB are produced by BNS coalescence?
  - Is the current cosmological model of the Universe the right one?
    - Measuring simultaneously the GW signal and the GRB flash it will be possible to test the cosmological model



AdV+ R&D
AdV
AdV+
A+/Voyager R&D
aLIGO
A+
Voyager
LIGO
KAGRA
LIGO India
Mission definition
Space system development
eLISA
ET R&D
ET Infrastructure Technical Design
ET Detector Technical Design
EINSTEIN TELESCOPE
ESFRI Roadmap
ET Observatory & Detector funding
ET site construction - detector installation & commissioning
Cosmic Explorer R&D
CE site&detector installation
LIGO
R&D
Installation
Commissioning
Data taking
Other
2016
2017
2018
2019
2020
2021
2022
2023
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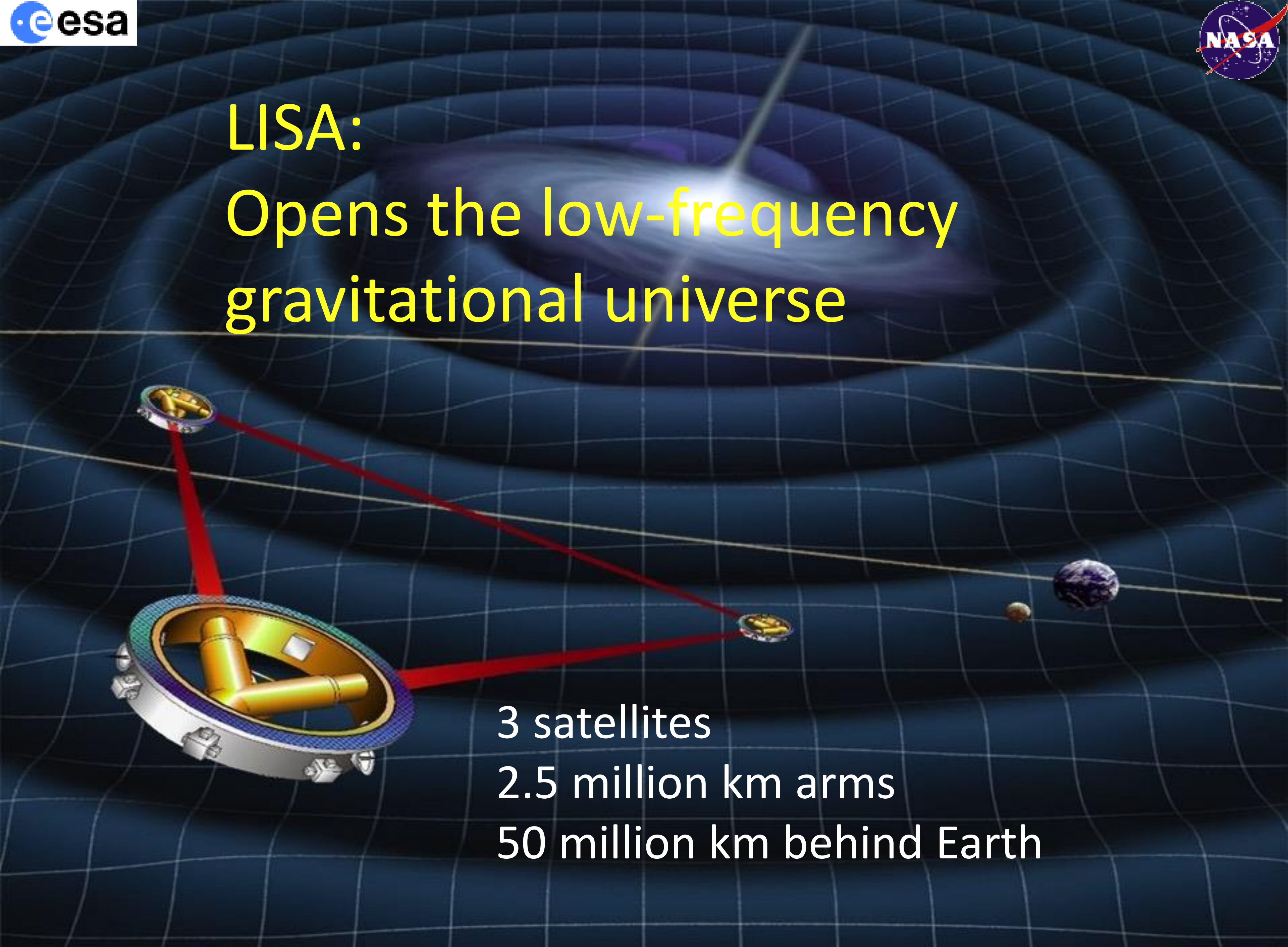
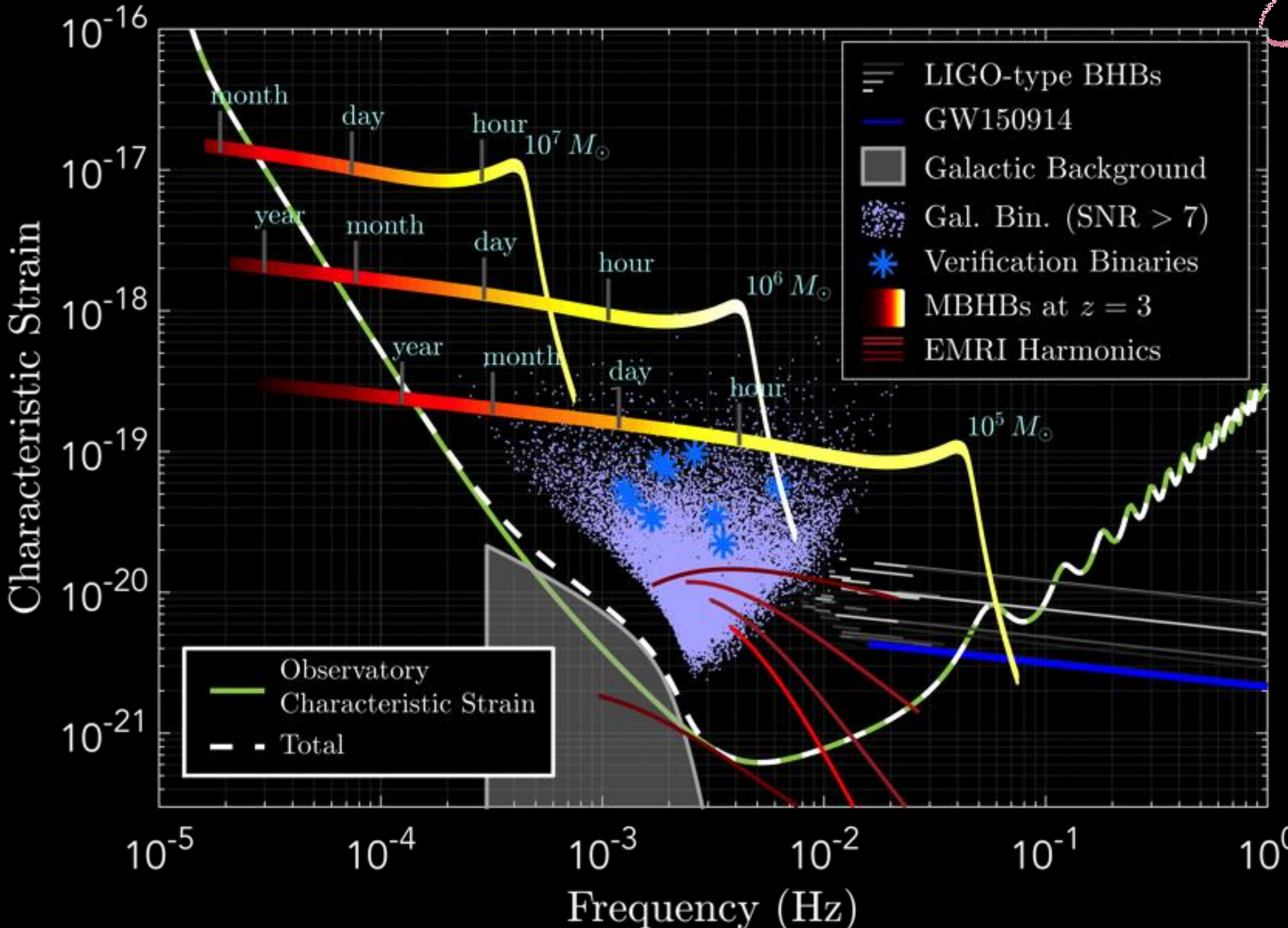
2032

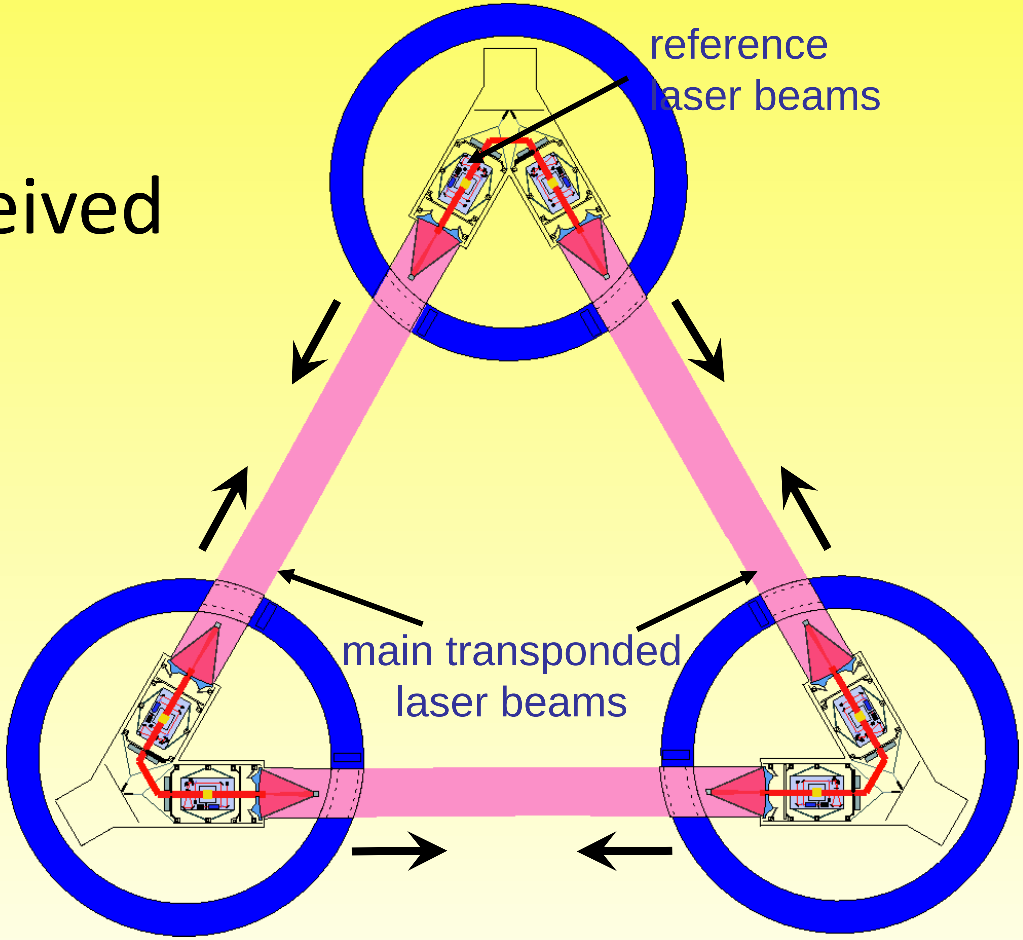

esa
NASA
LISA:
Opens the low-frequency
gravitational universe
3 satellites
2.5 million km arms
50 million km behind Earth

LISA Sources



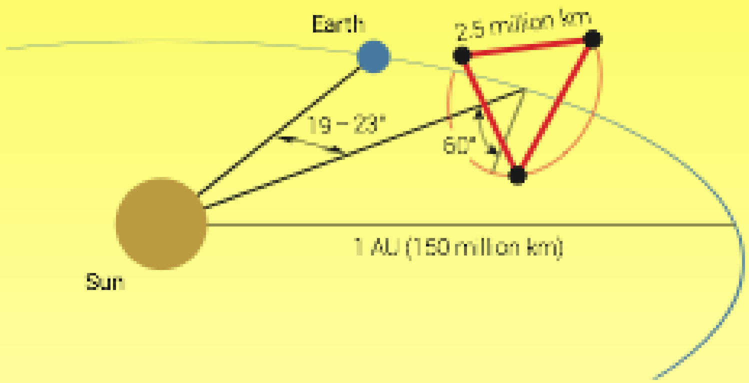
LISA Layout

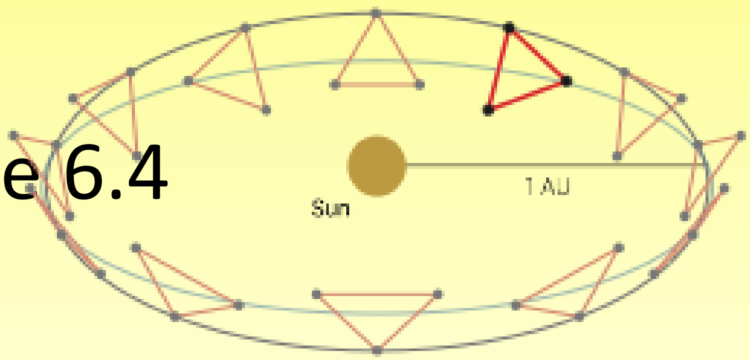
- Laser transponder with 6 Links
- 2.5 Million km arms
- Watt sent – pW received
- Michelson with third arm and Sagnac mode



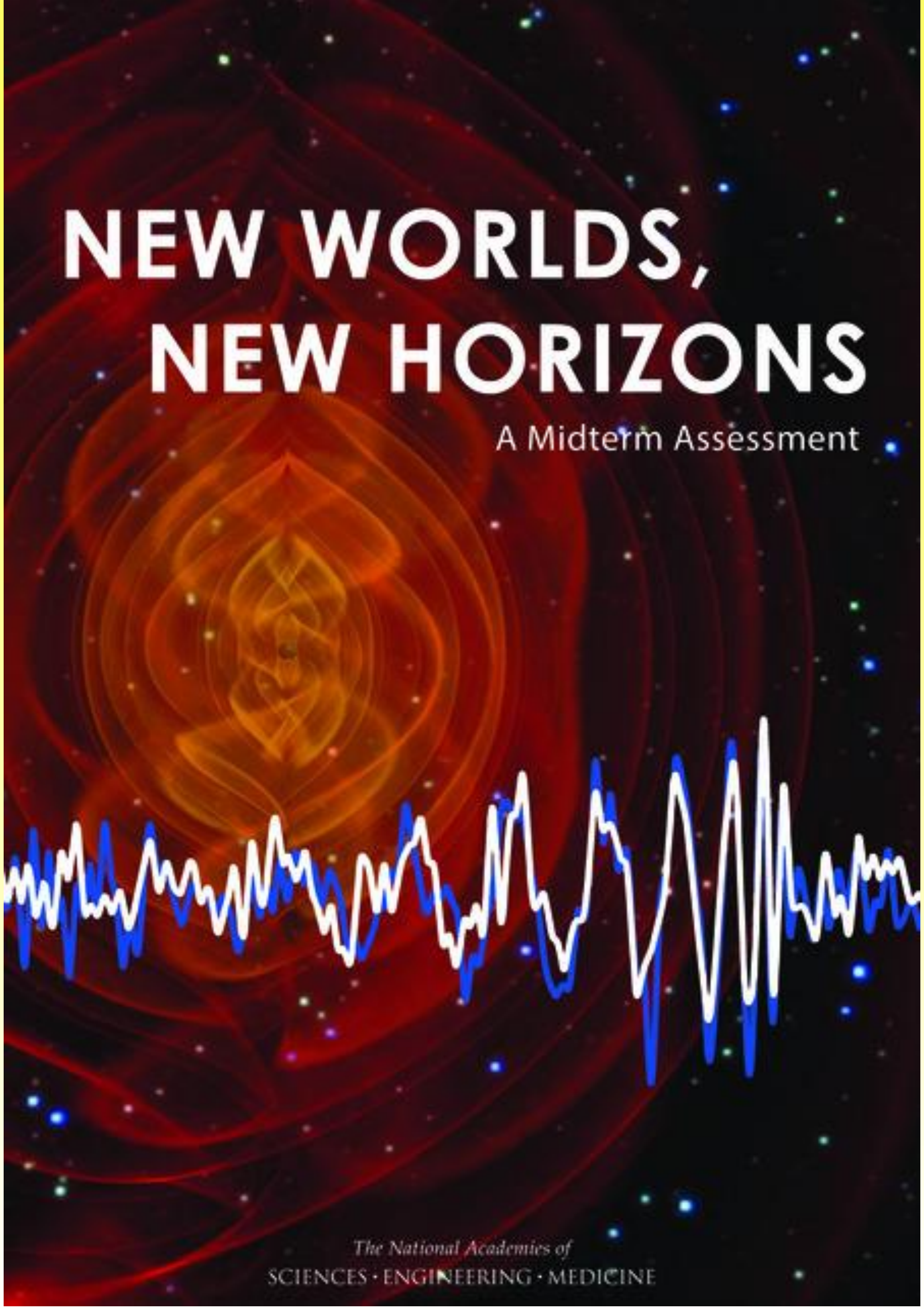
Mission Profile and Orbit

- Three arms of 2.5 Million km
- 2W lasers
- 30 cm telescopes
- Breathing angles ± 1 deg
- Doppler shifts ± 5 MHz
- Launch on dedicated Ariane 6.4
  - Transfer time ~400 days
  - Direct escape V_∞ = 260 m/s
  - Propulsion module and S/C composite





NASA is back in LISA!



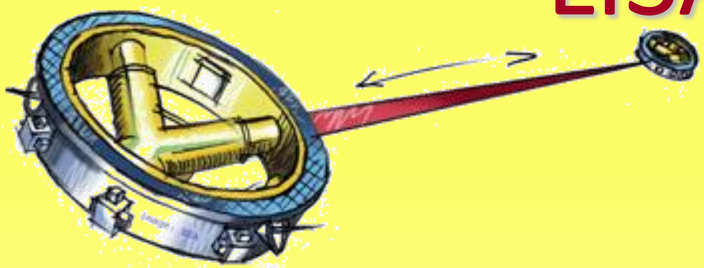
ESA L2 and L3 Missions

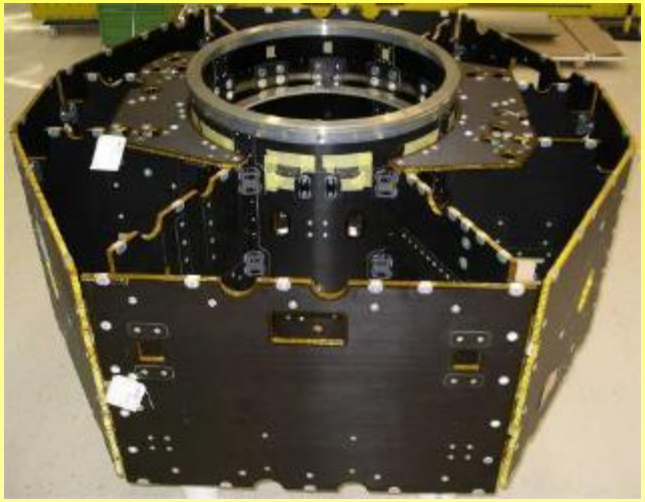
- Call for Mission Concepts fall 2016
- Decision on Implementation 2020
- Launch of L2 in 2028
- Launch of L3 in 2034
- LISA is ready for an early launch!

LISA Pathfinder

- Testing LISA technology in space!

LISA Pathfinder

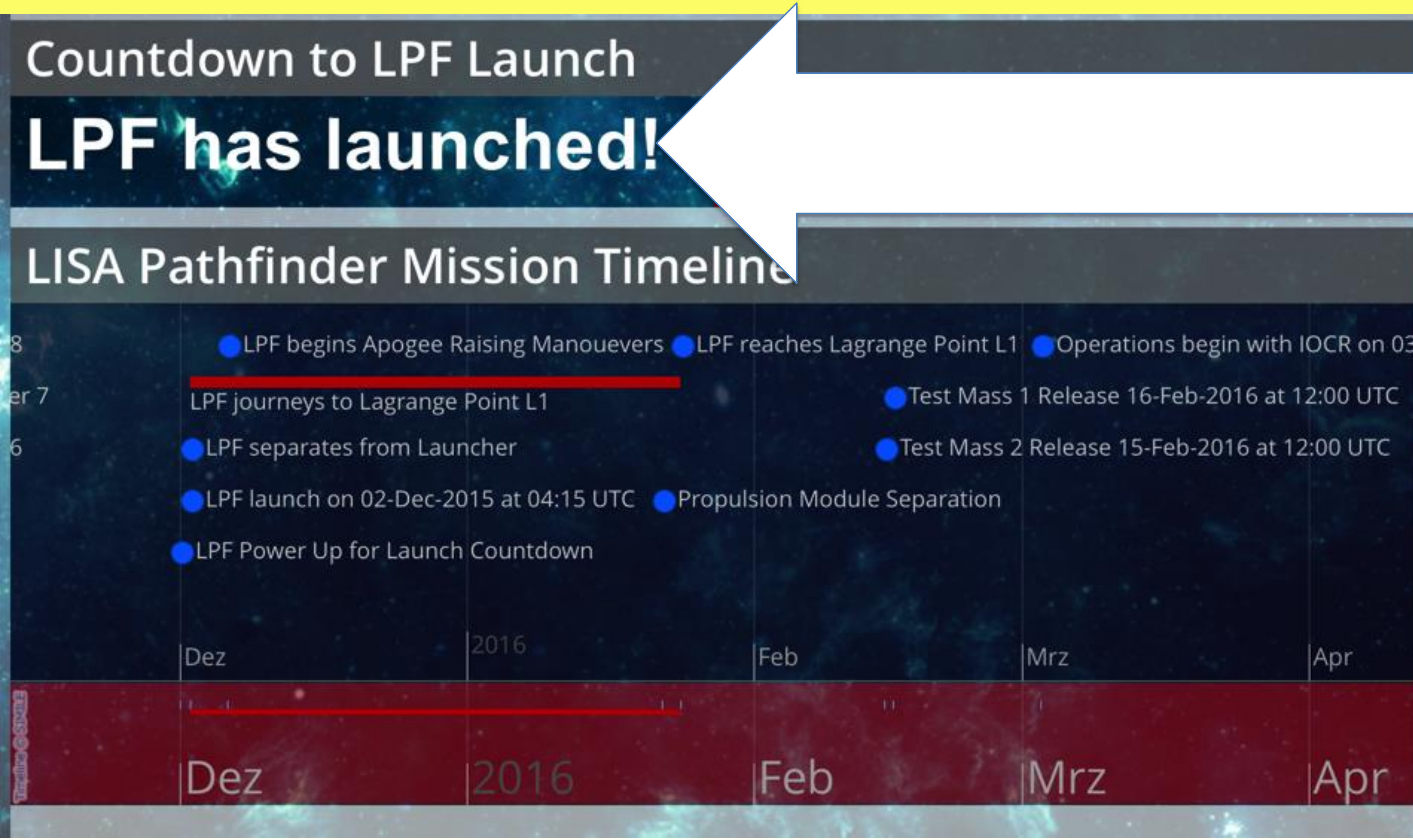




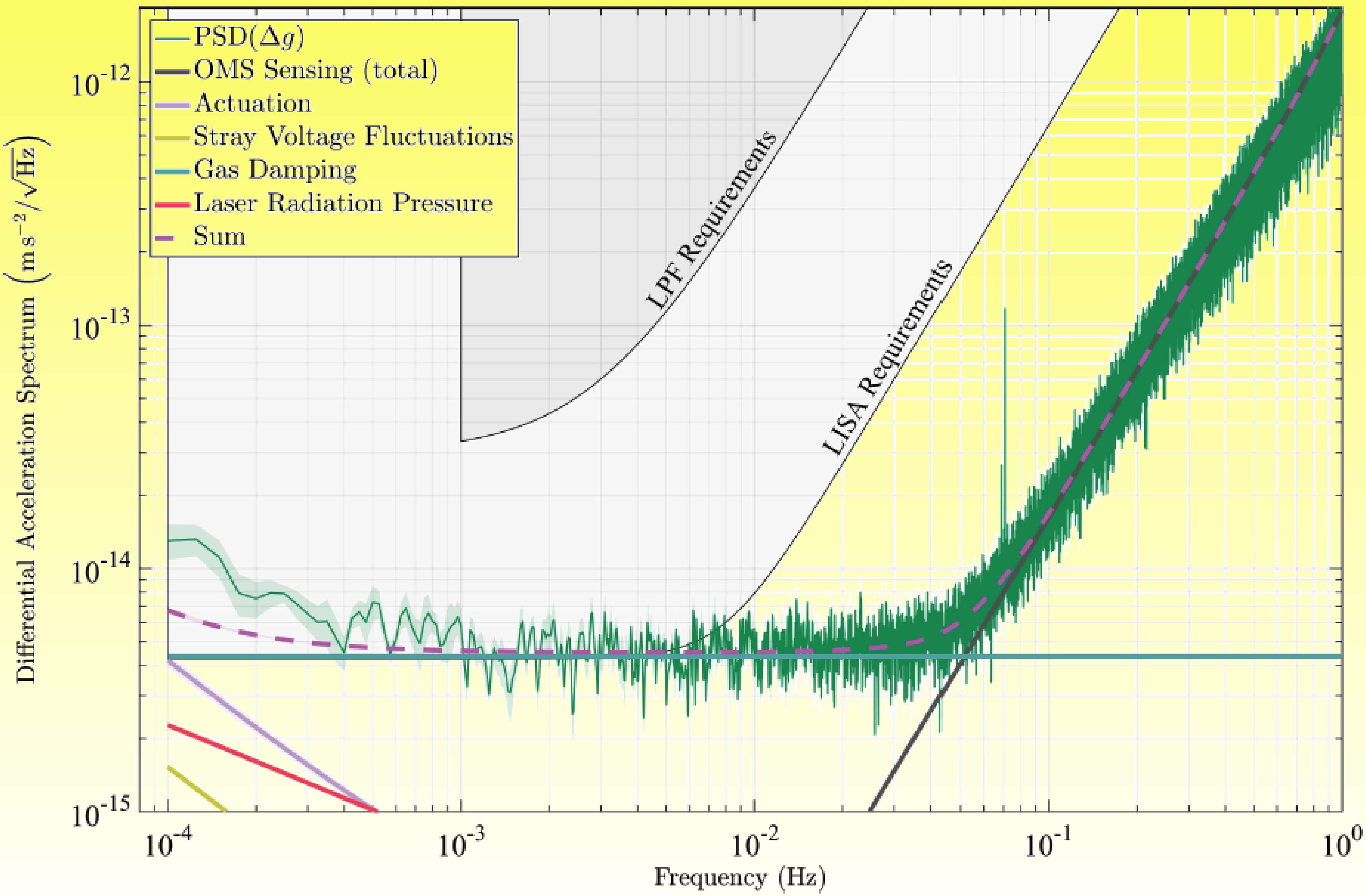
- Take one LISA arm
- Squeeze it into ONE satellite

Courtesy: Stefano Vitale

100 Years since GR Publication: Dec. 2, 2015



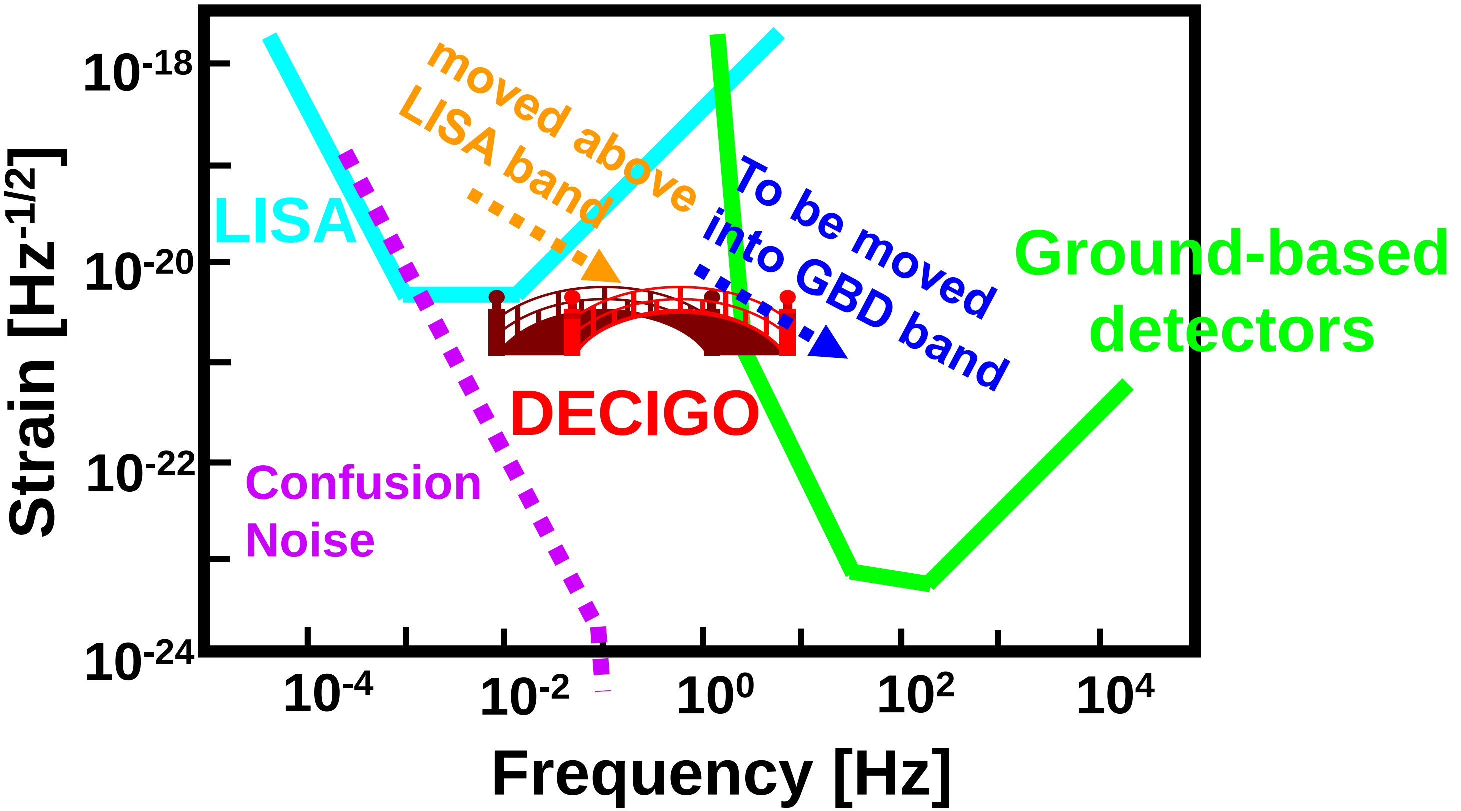
What do we know?



DECIGO

Deci-hertz Interferometer Gravitational Wave Observatory

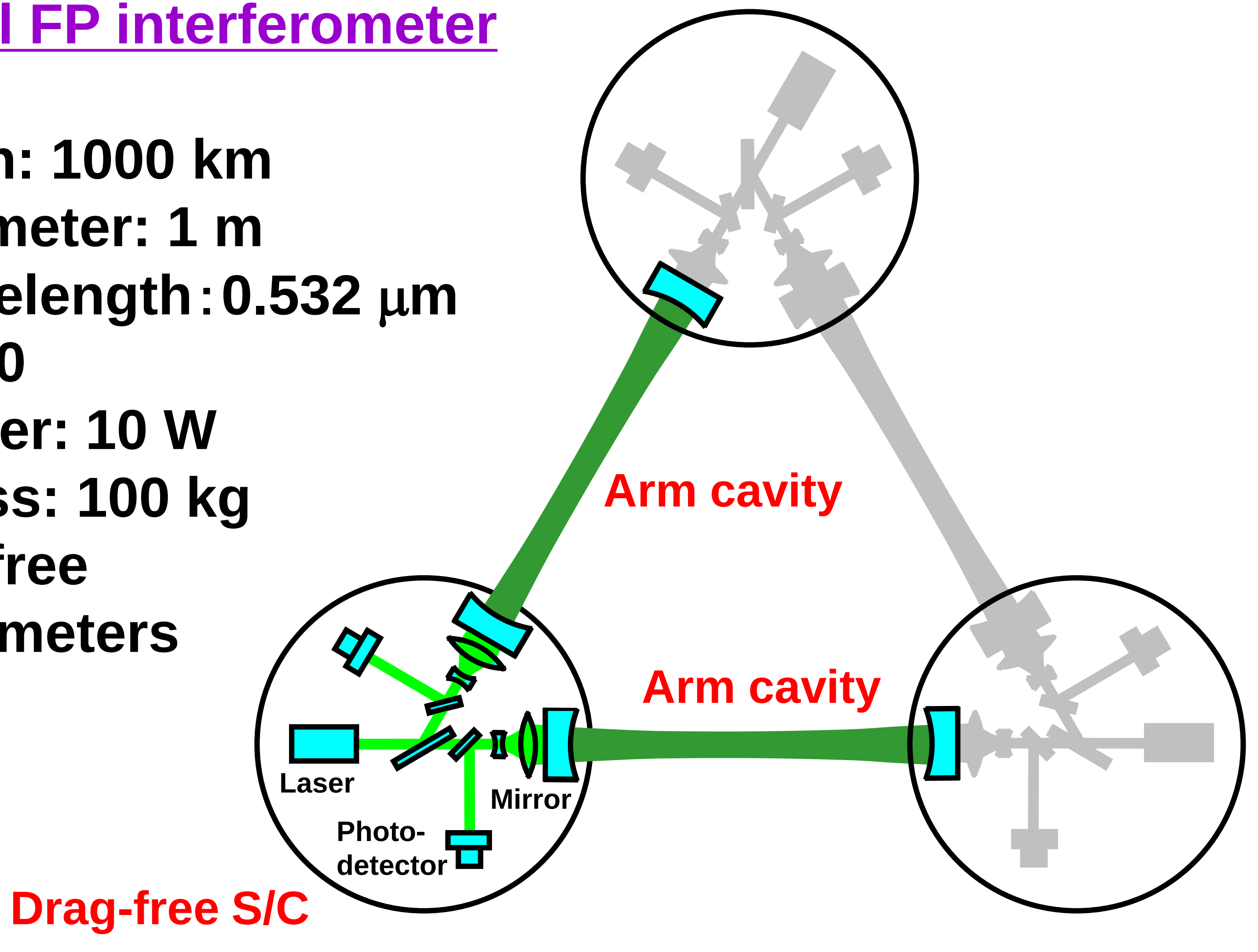
- **Bridges the gap between LISA and ground-based detectors**
- **Low confusion noise -> Extremely high sensitivity**



Pre-conceptual design

<u>Differential FP interferometer</u>

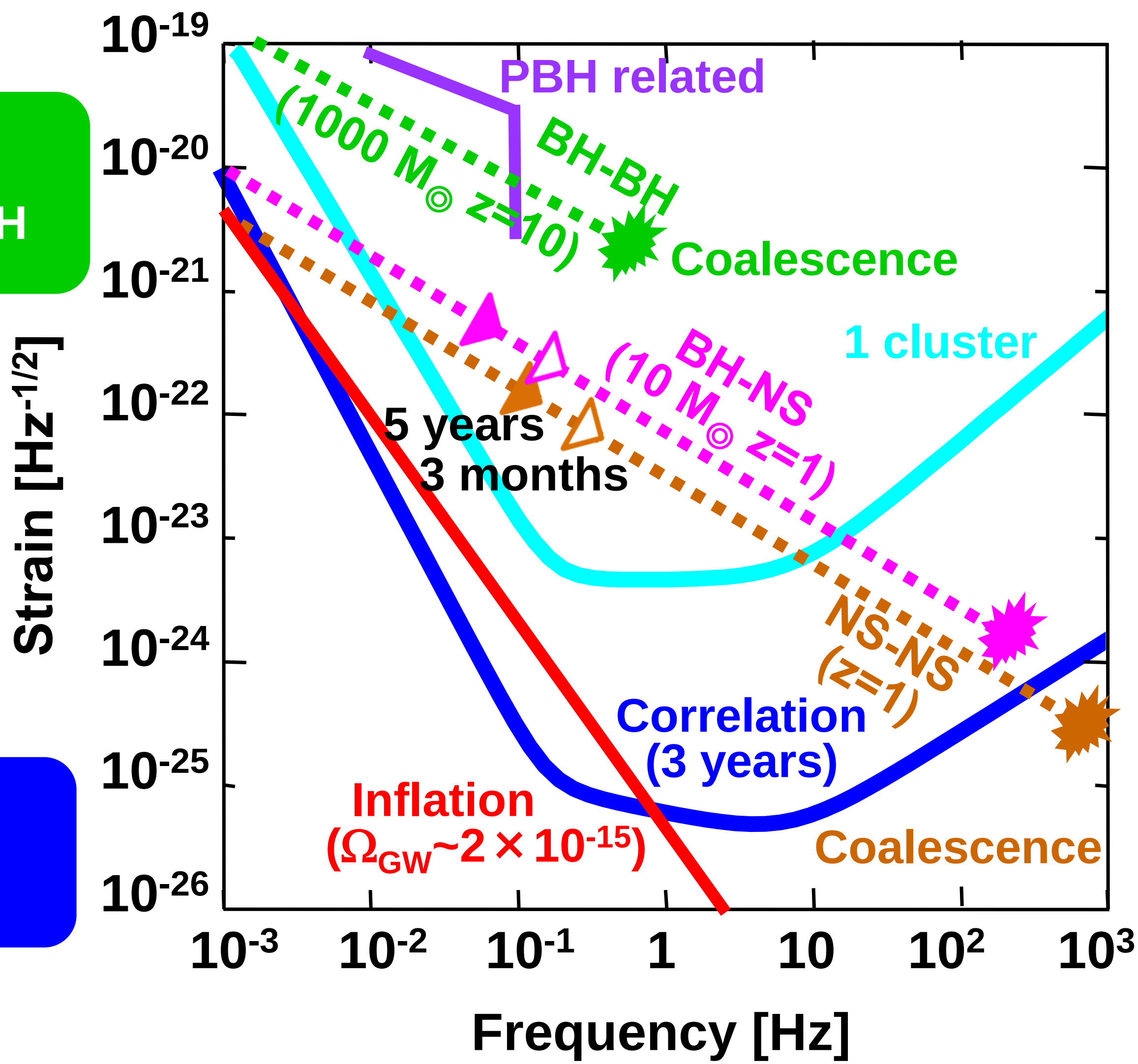
Arm length: 1000 km
Mirror diameter: 1 m
Laser wavelength：0.532 μm
Finesse: 10
Laser power: 10 W
Mirror mass: 100 kg
S/C: drag free
3 interferometers



Target sensitivity and science

Super-massive BH

Inflation



Dark Matter

Saito, Yokoyama 2009

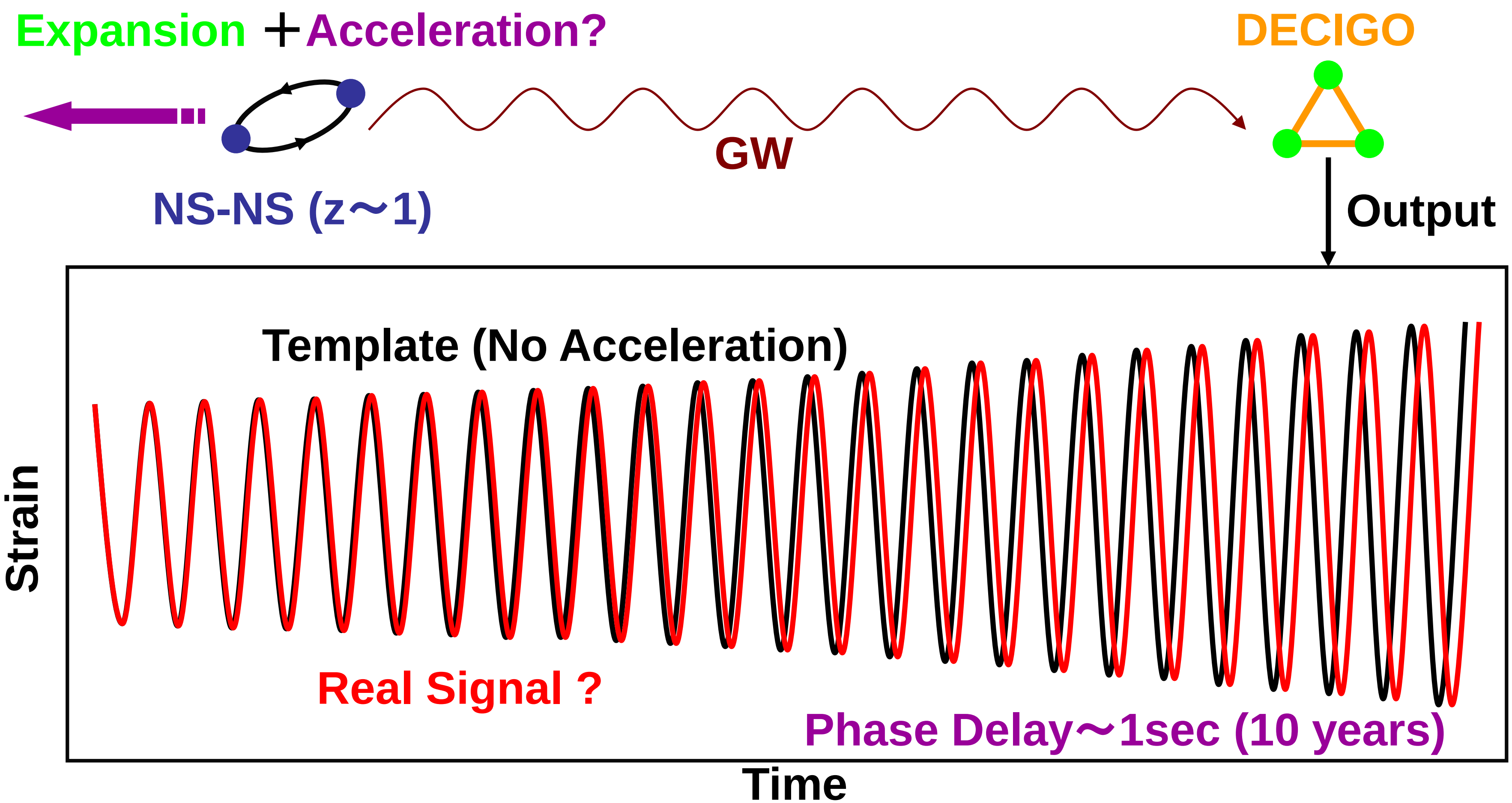
General relativity

Yagi, Tanaka 2009

Acceleration of expansion of Universe

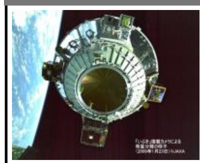
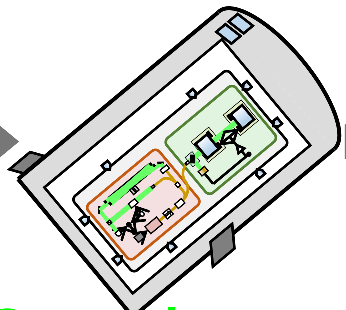
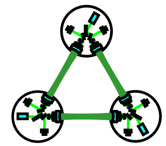
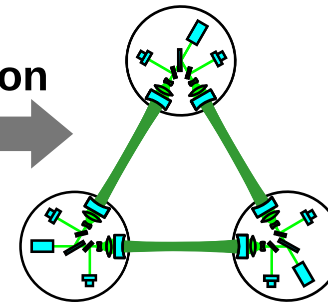
Seto, Kawamura, Nakamura 2004

Acceleration of Expansion of the Universe



Seto, Kawamura, Nakamura, PRL 87, 221103 (2001)

Roadmap

	2014	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
Mission	R&D Fabrication  SWIM				 Ground test + piggyback				R&D Fabrication			 B-DECIGO			R&D Fabrication			 DECIGO		
Objectives	Test of key technologies								Detection of GW Test FP cavity between S/C						Direct observation of the inflation					
Scope	1 S/C 1 arm								3 S/C 3 interferometer						3 S/C, 3 interferometer 3 or 4 units					

Outline:

- Gravitational wave and detector
- Existing detectors
  - LIGO, Virgo, KAGRA
- Future detectors
  - ET, LISA, DECIGO
- **Summary**

Summary

- **Gravitational waves have been detected for the first time.**
- **Gravitational wave astronomy has been established.**
- **Gravitational wave astronomy will be developed with the addition of Virgo and KAGRA.**
- **ET, LISA, and DECIGO will produce amazing science in the future.**