Space Gravitational Wave Antenna DECIGO and B-DECIGO

Illustration: Sora

Seiji Kawamura (Nagoya University)

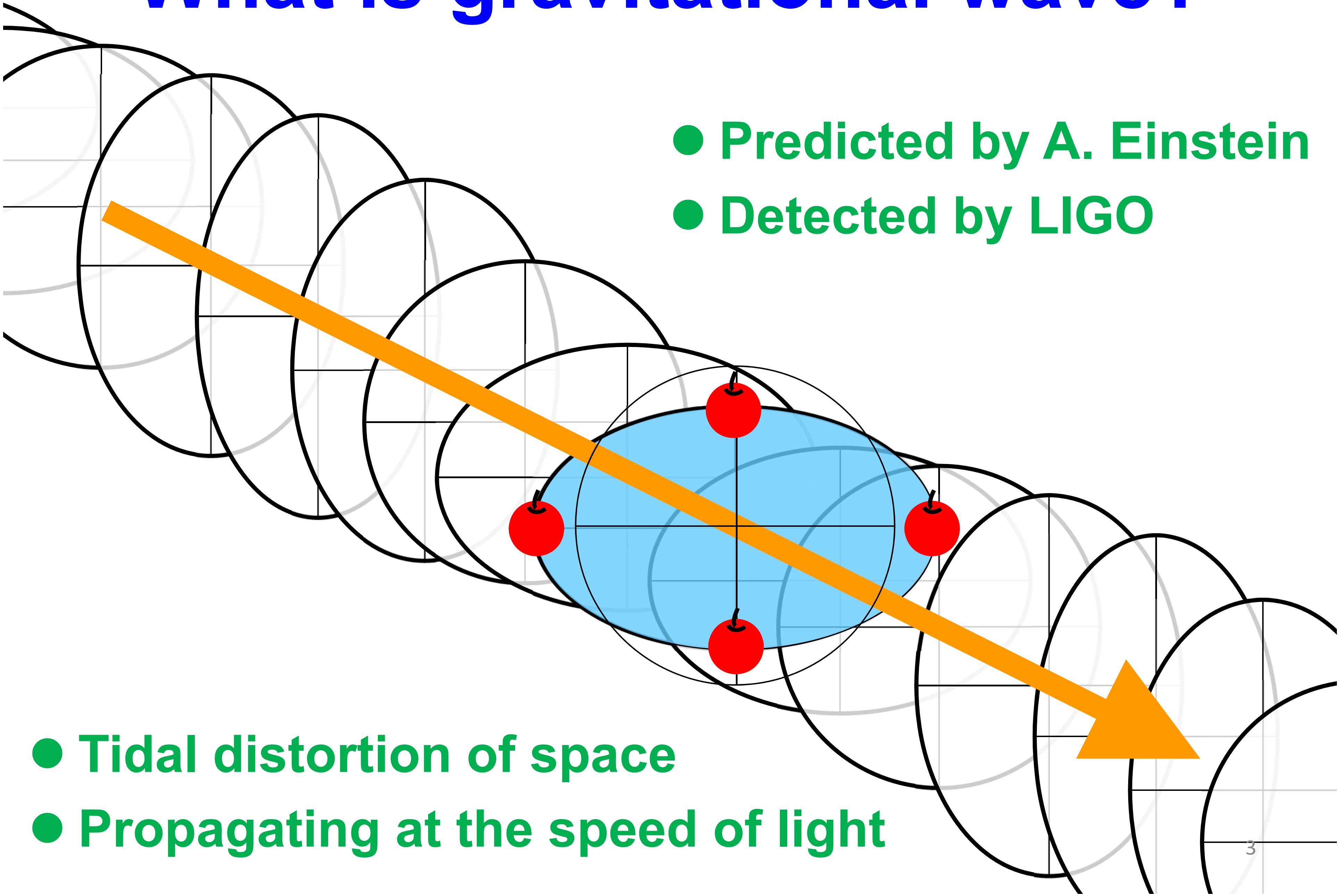
Feb. 18, 2019

The 4th International Workshop on "Higgs as a Probe of New Physics“ @ Osaka University

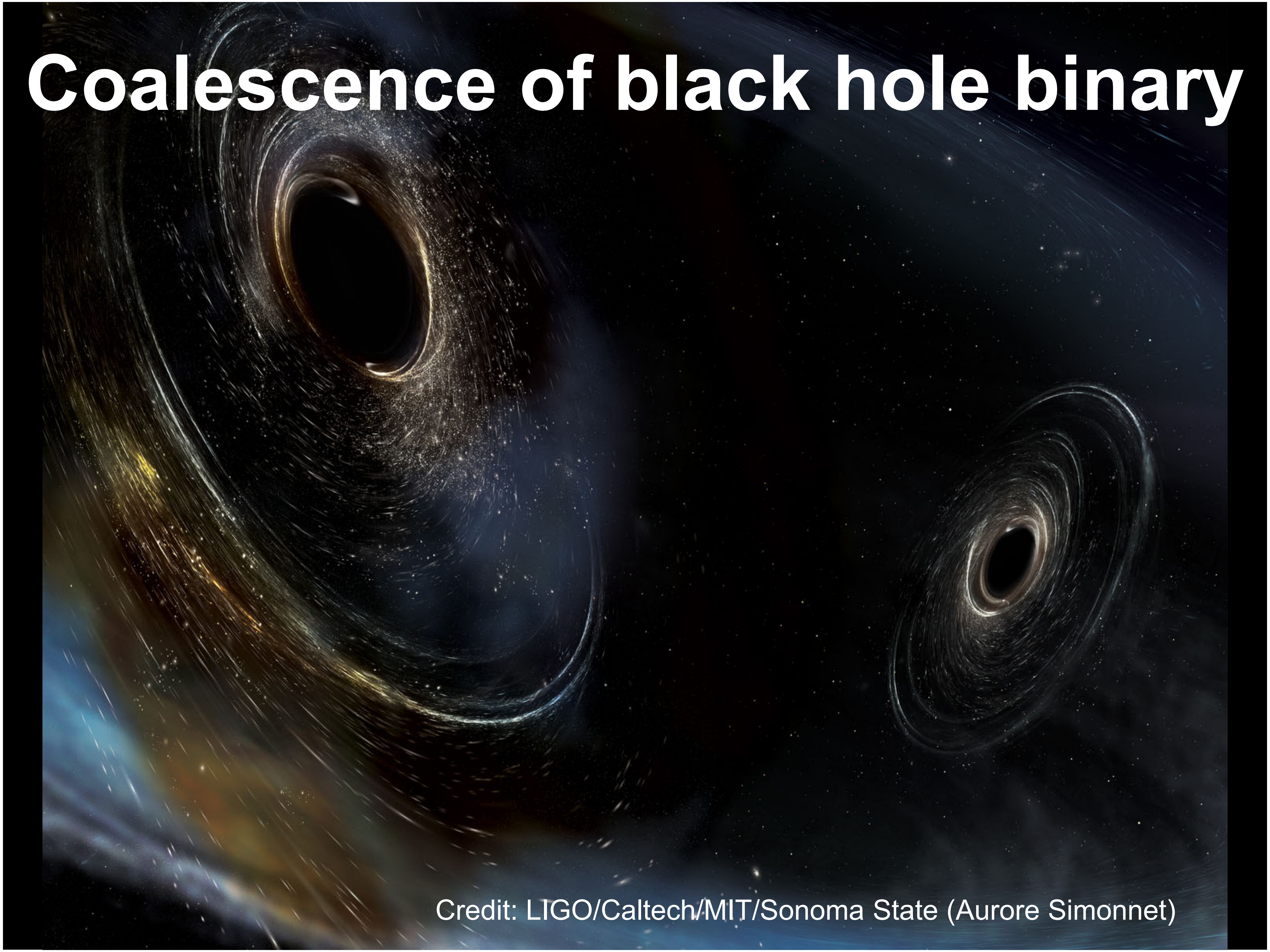
Outline

- Gravitational wave and its detection
- (LISA)
- DECIGO
- B-DECIGO
- Summary

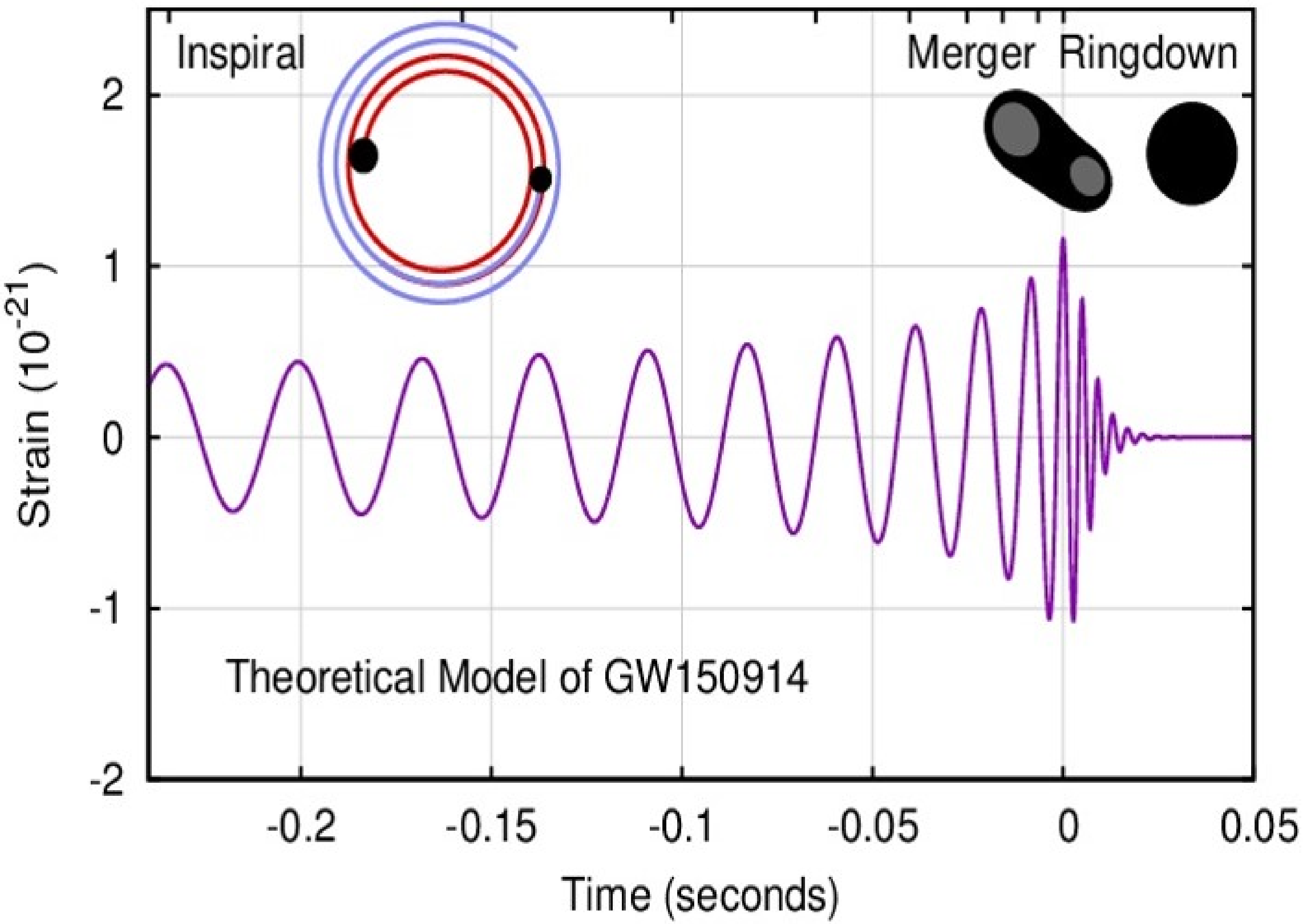
What is gravitational wave?



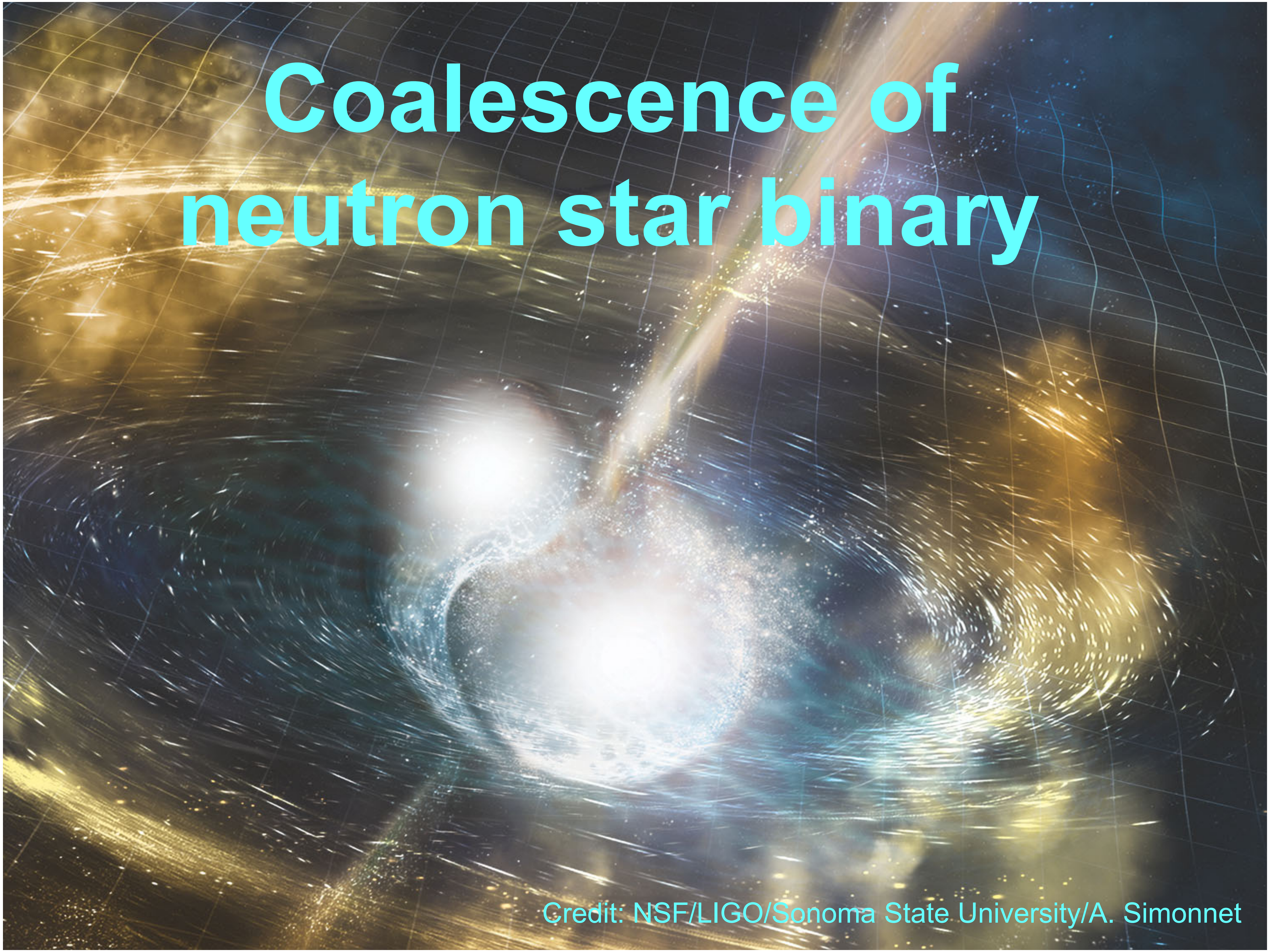
- Predicted by A. Einstein
- Detected by LIGO
- Tidal distortion of space
- Propagating at the speed of light

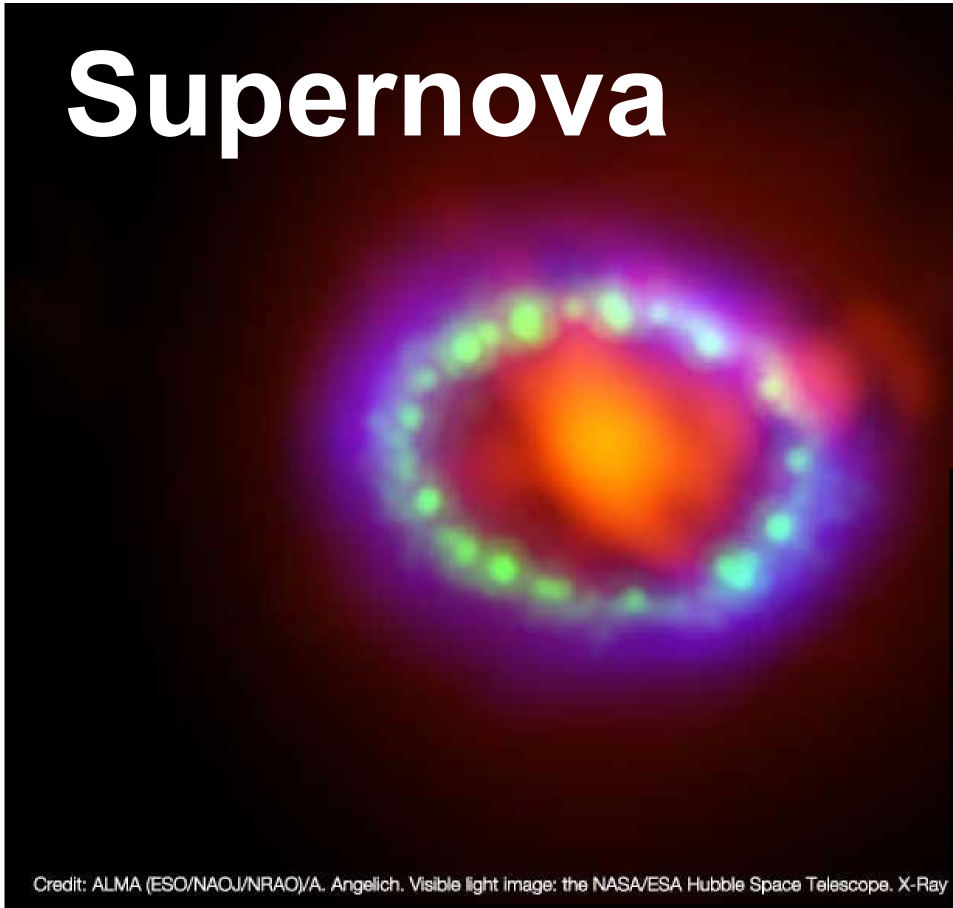

Coalescence of black hole binary
Credit: LIGO/Caltech/MIT/Sonoma State (Aurore Simonnet)

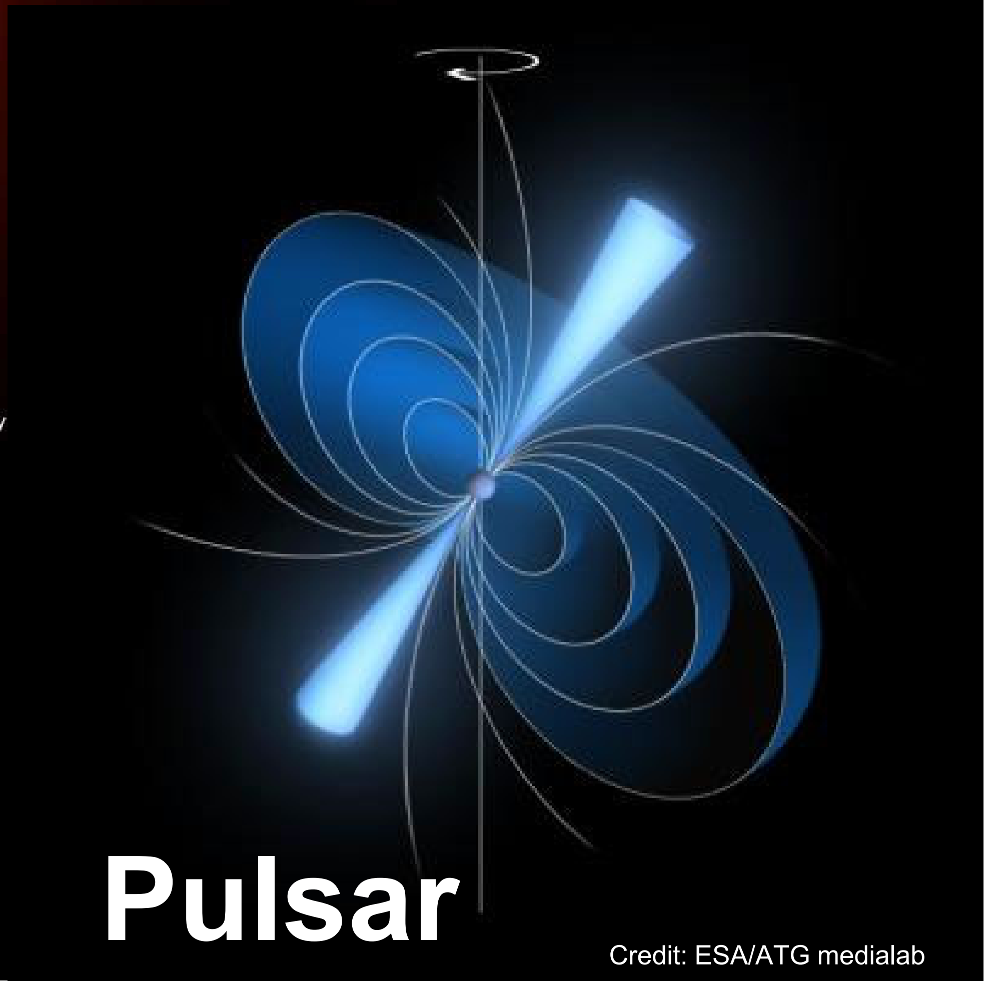
GWs from black hole binary



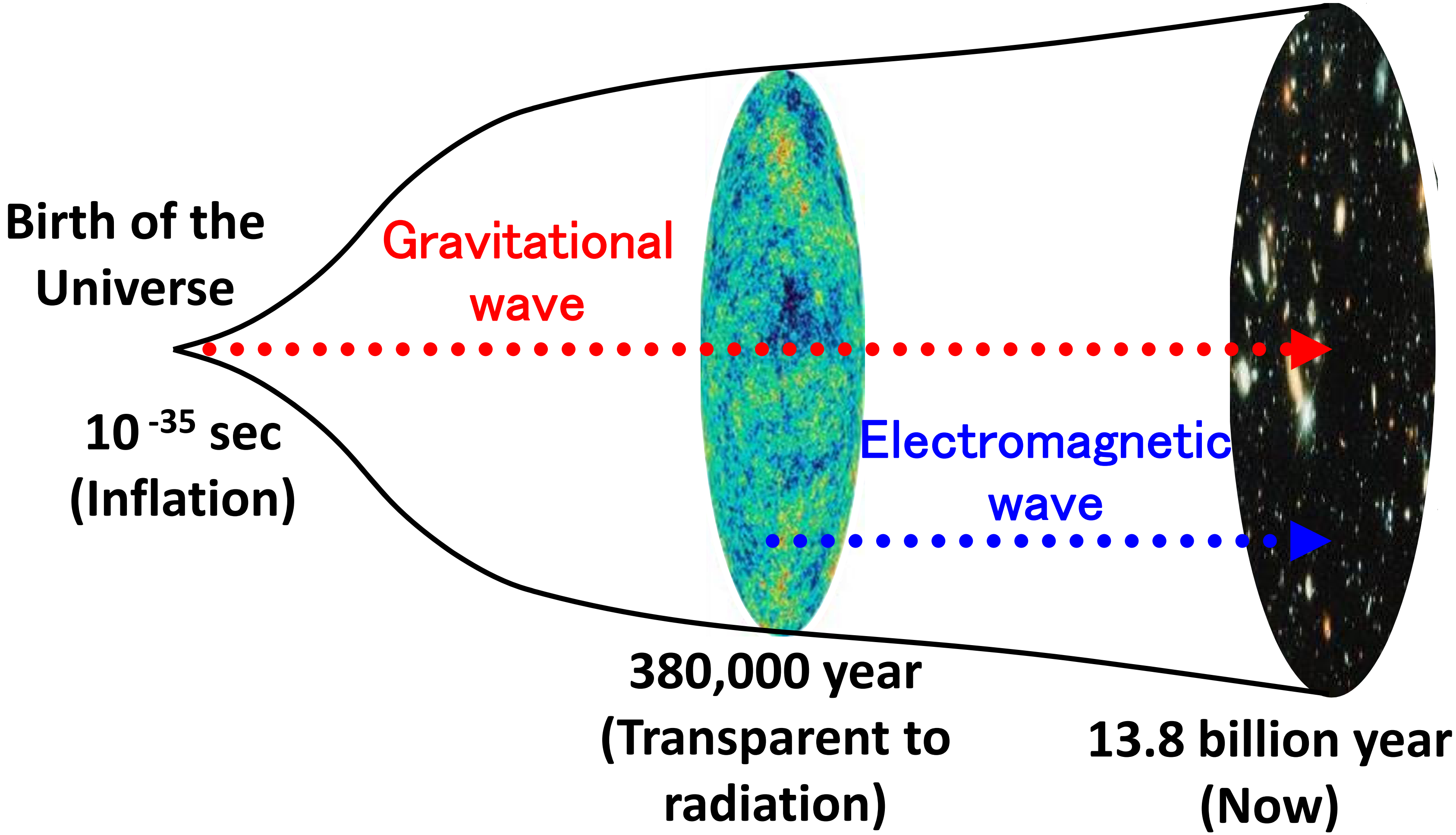
Credit: Carlos O. Lousto and James Healy


Coalescence of neutron star binary
Credit: NSF/LIGO/Sonoma State University/A. Simonnet

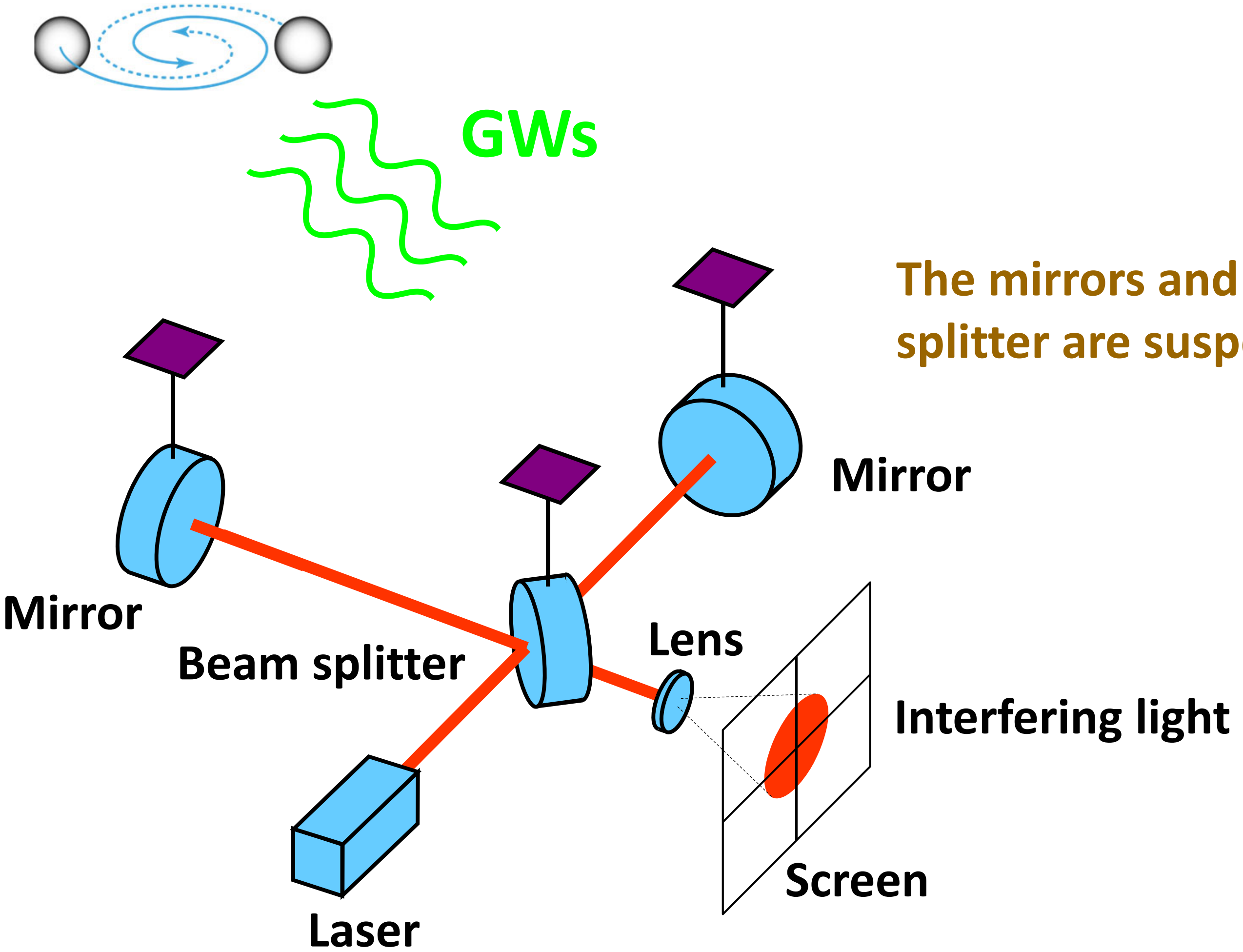

Supernova
Credit: ALMA (ESO/NAOJ/NRAO)/A. Angelich. Visible light image: the NASA/ESA Hubble Space Telescope. X-Ray


Pulsar
Credit: ESA/ATG medialab

Observation of the beginning of the Universe

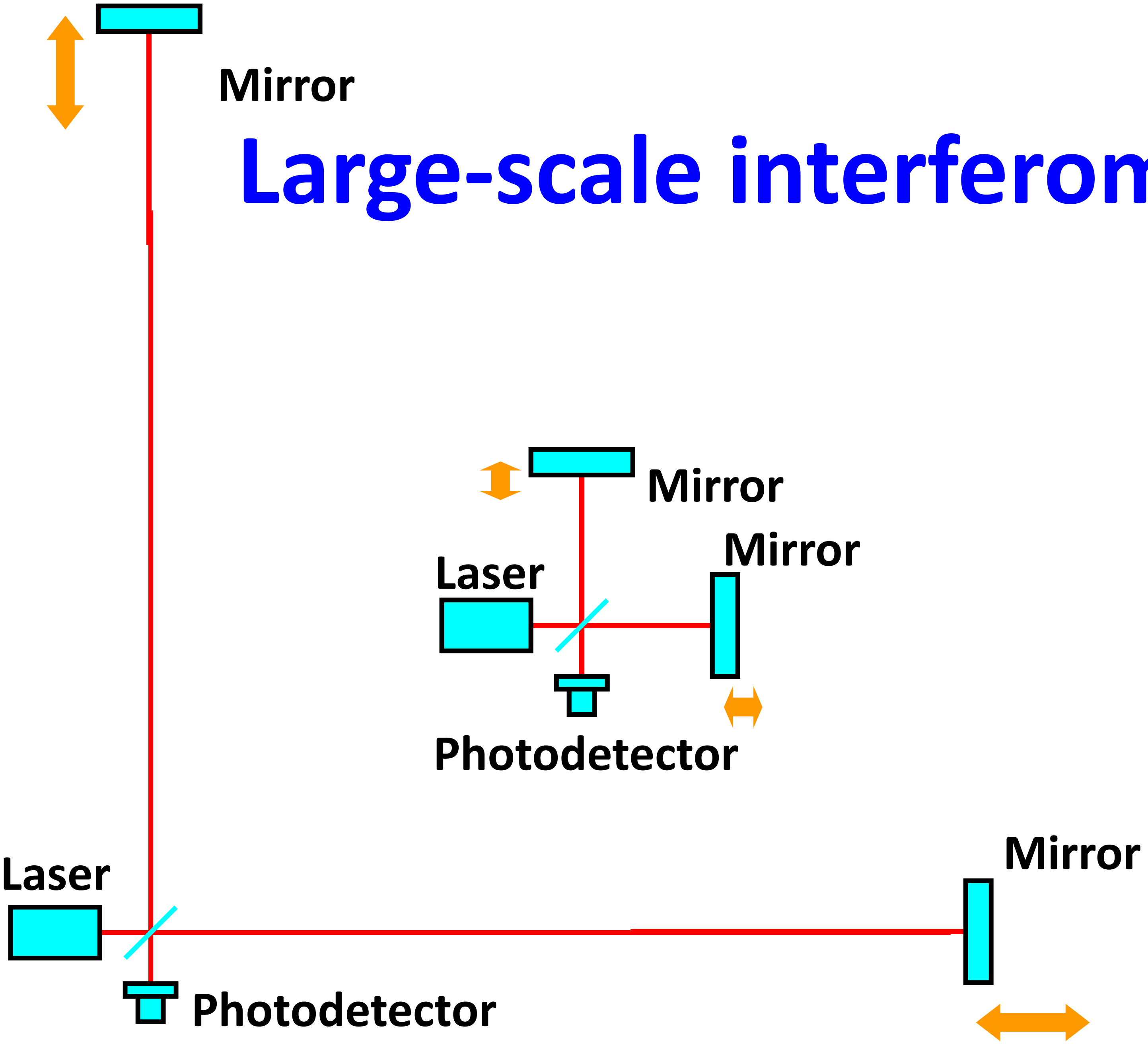


GW detector

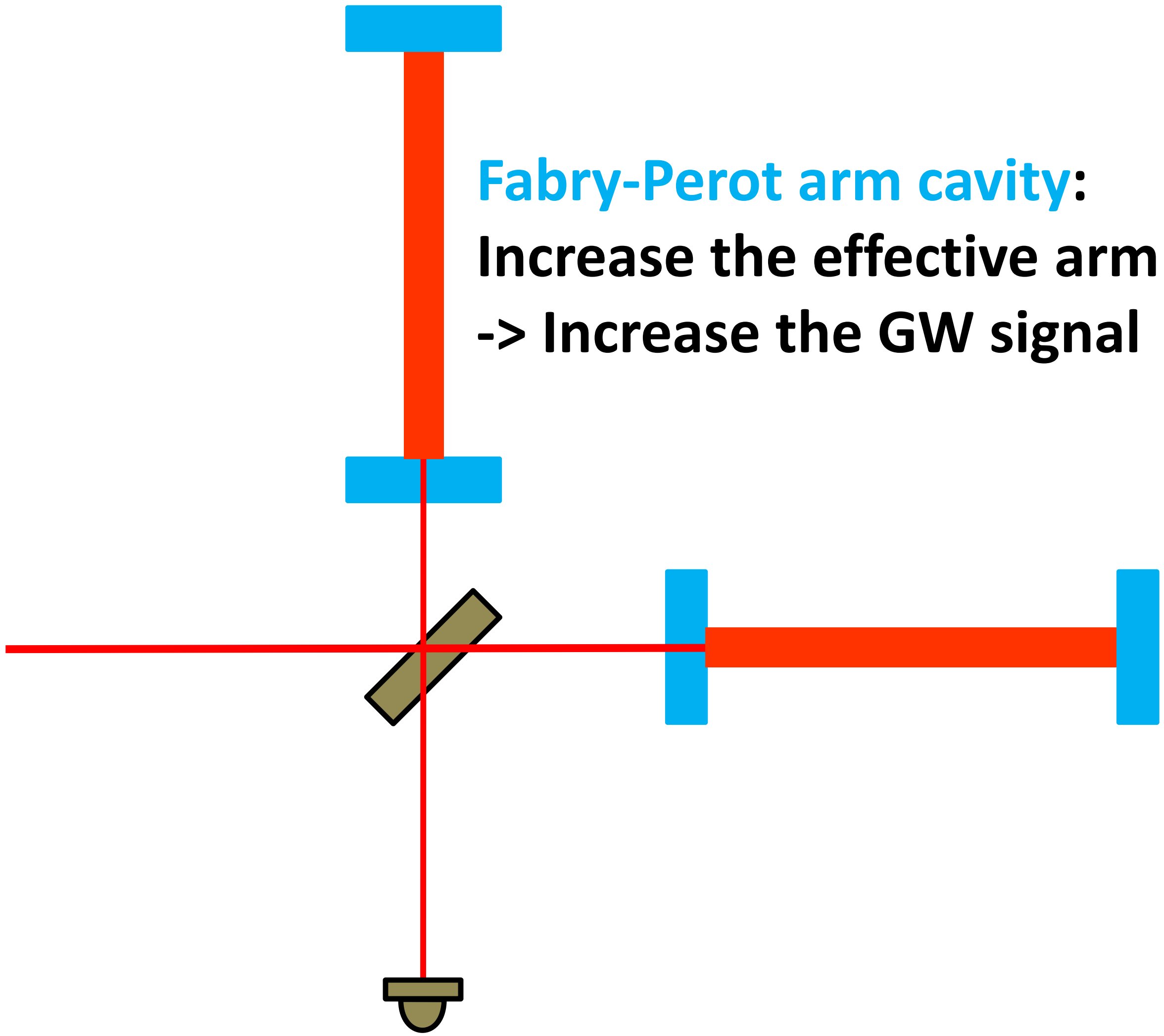


The mirrors and beam splitter are suspended.

Large-scale interferometer

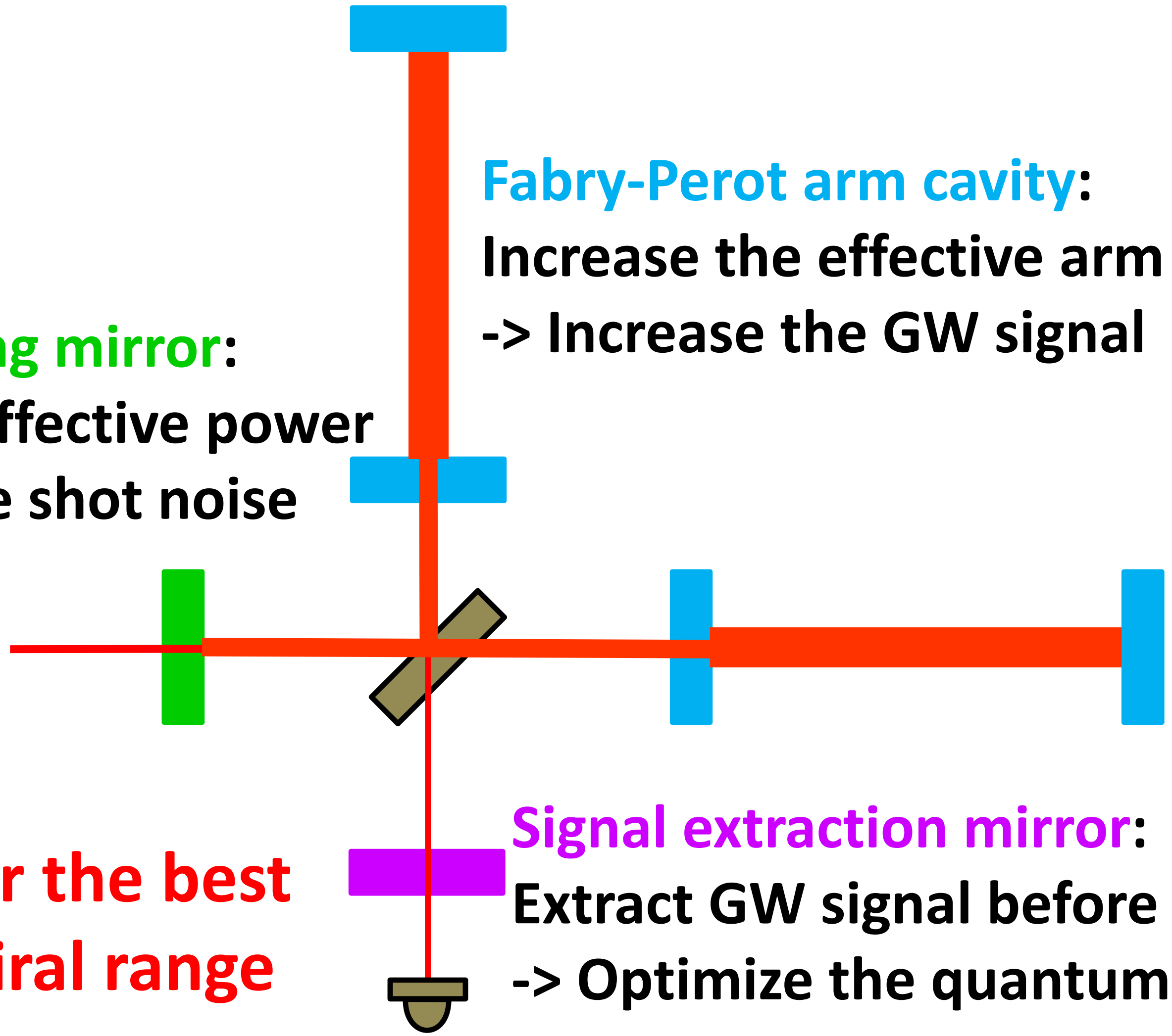


Fabry-Perot Michelson interferometer



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

Resonant Sideband Extraction interferometer



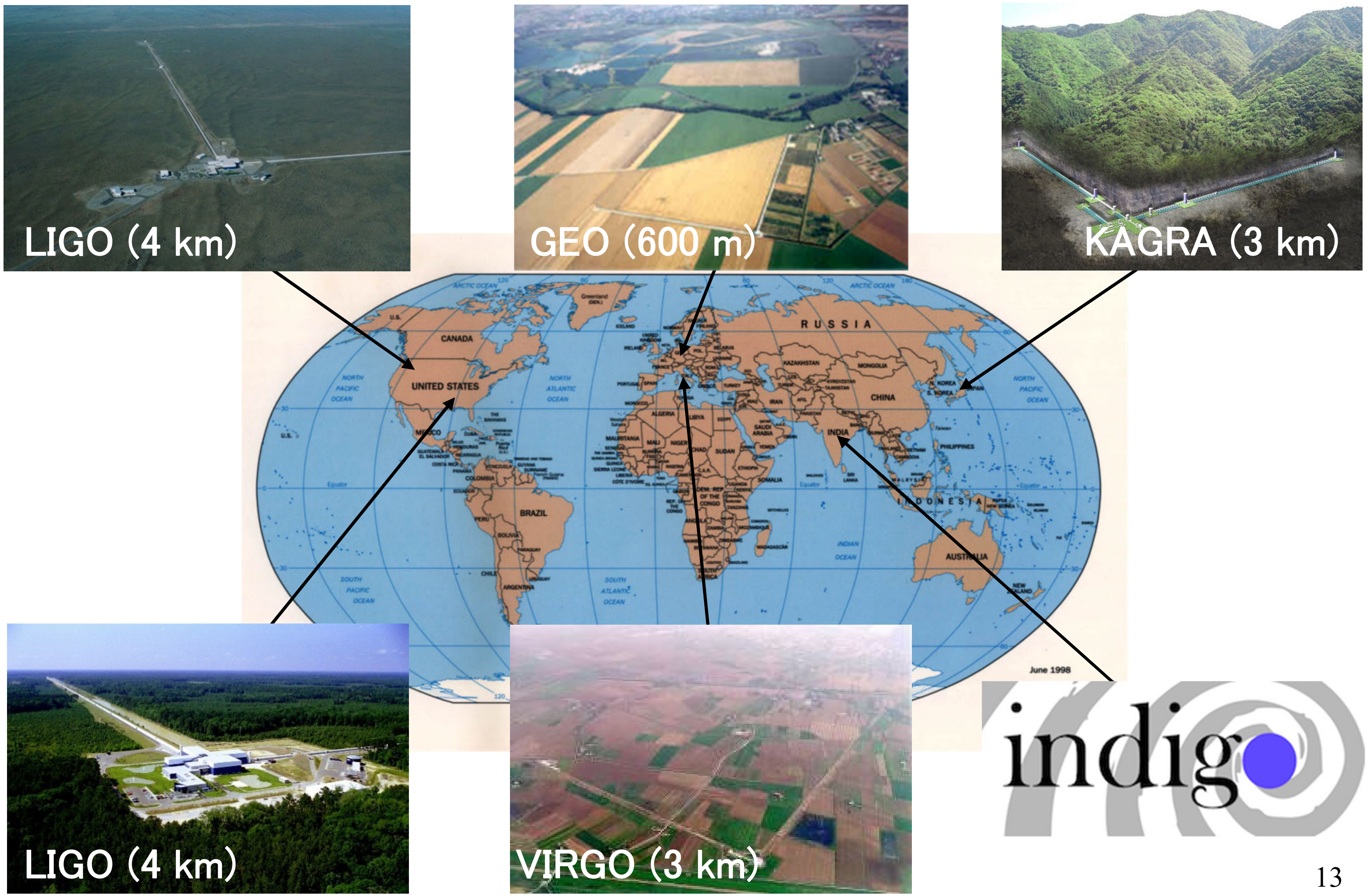
Fabry-Perot arm cavity:
Increase the effective arm length
-> Increase the GW signal

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

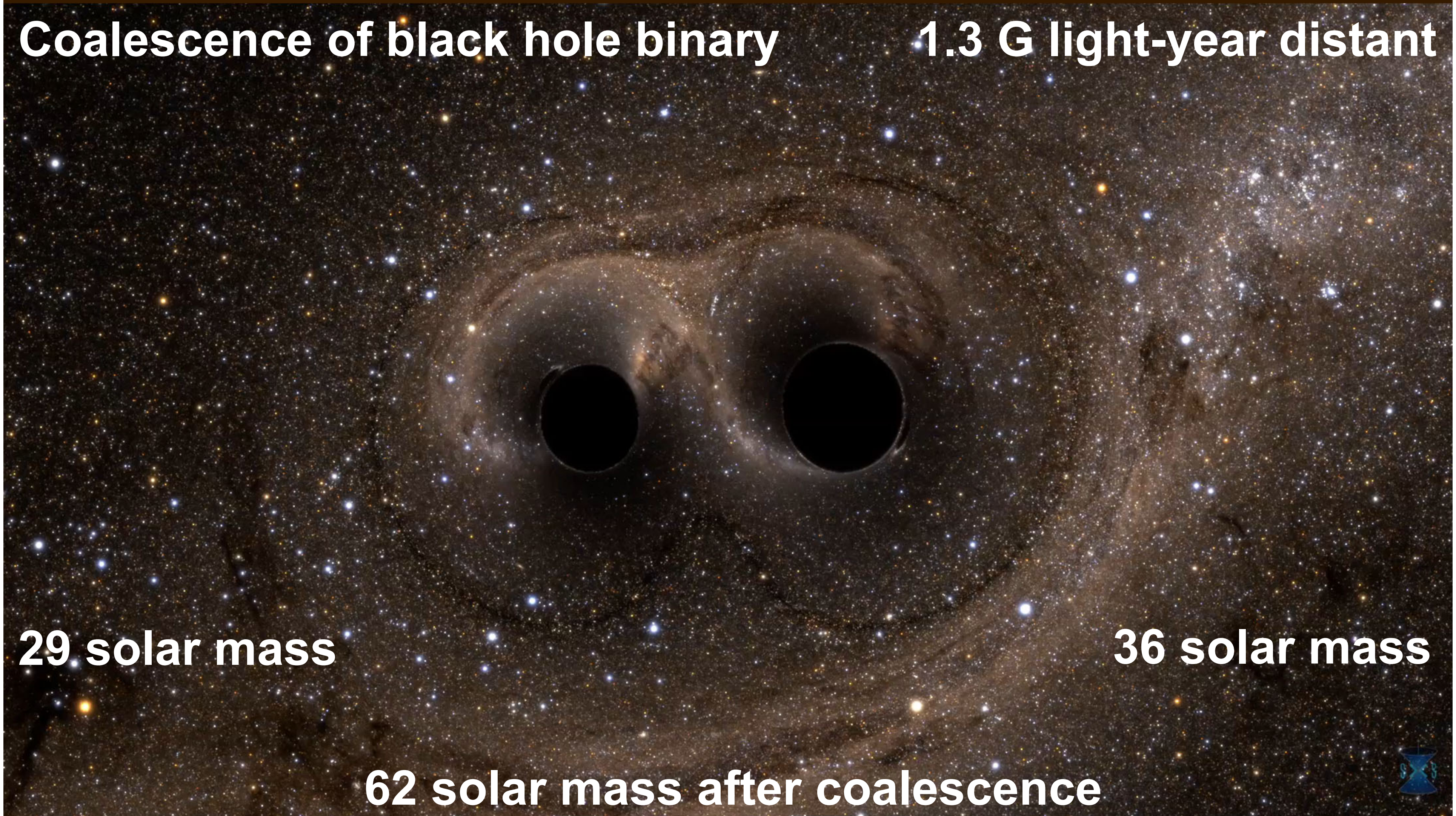
Signal extraction mirror:
Extract GW signal before cancellation
-> Optimize the quantum noise

Detuned for the best NS-NS inspiral range

Large interferometers in the world



First detection: GW150914



Coalescence of black hole binary

1.3 G light-year distant

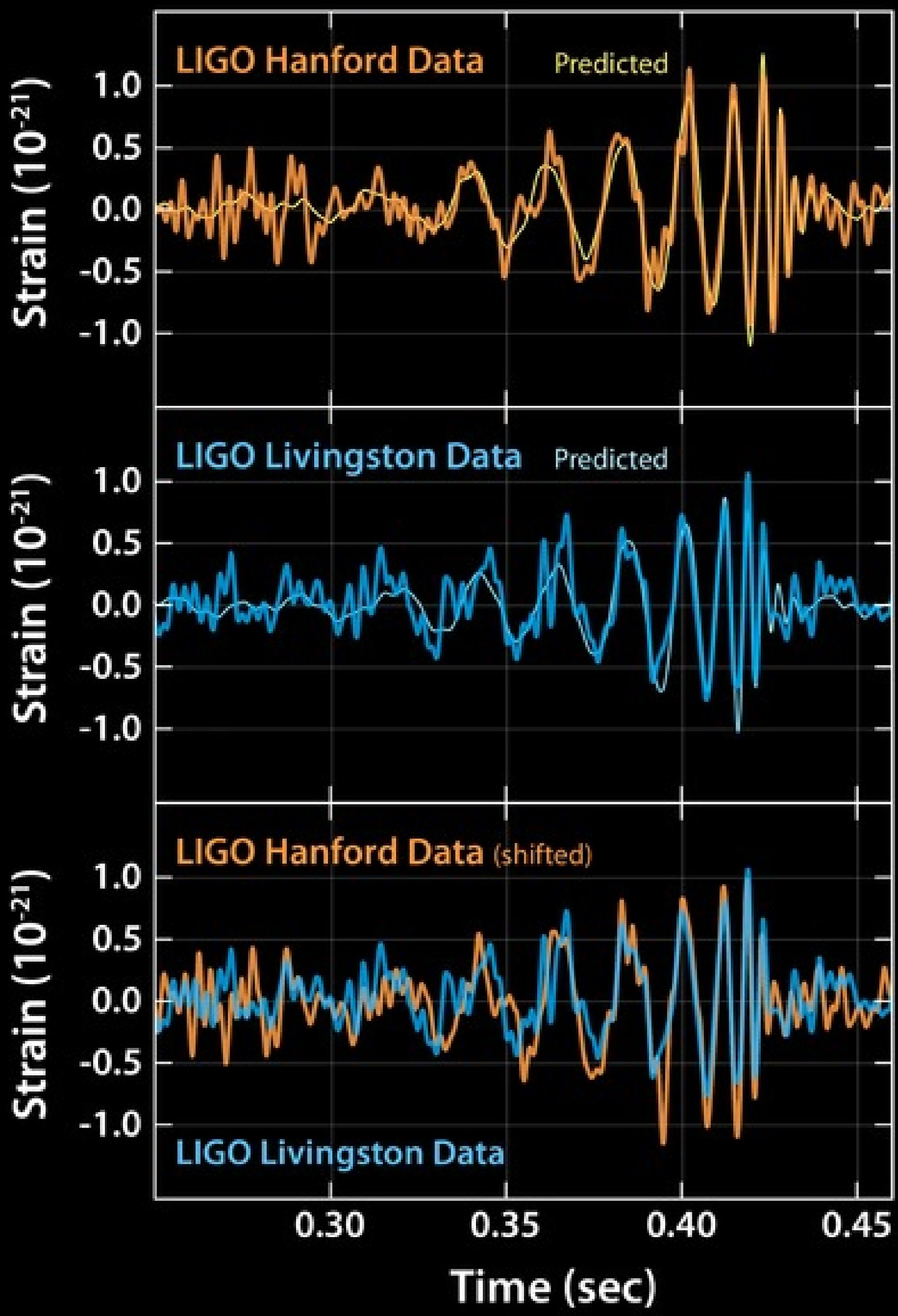
29 solar mass

36 solar mass

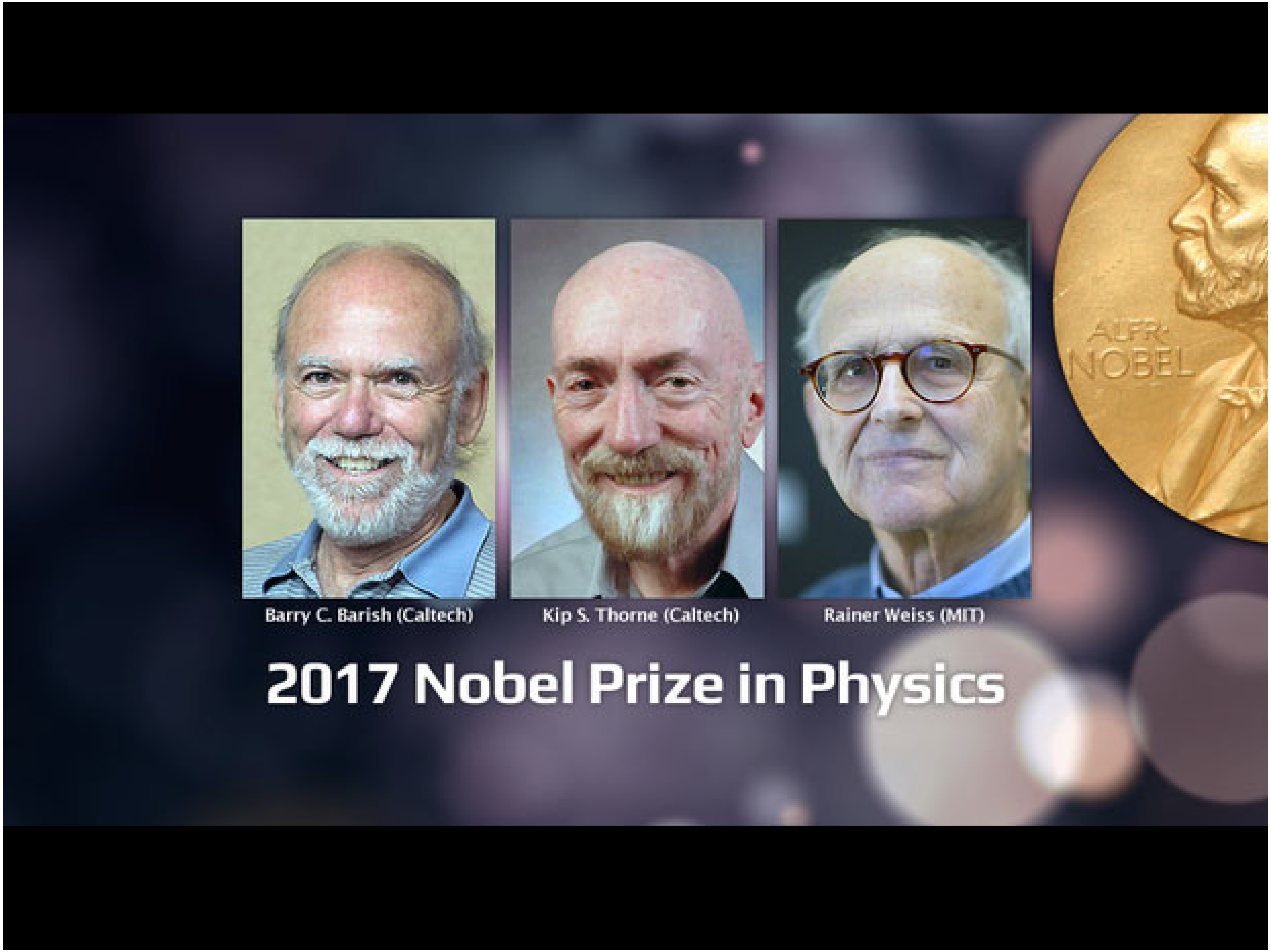
62 solar mass after coalescence

⇒Energy of 3 solar mass emitted as GW

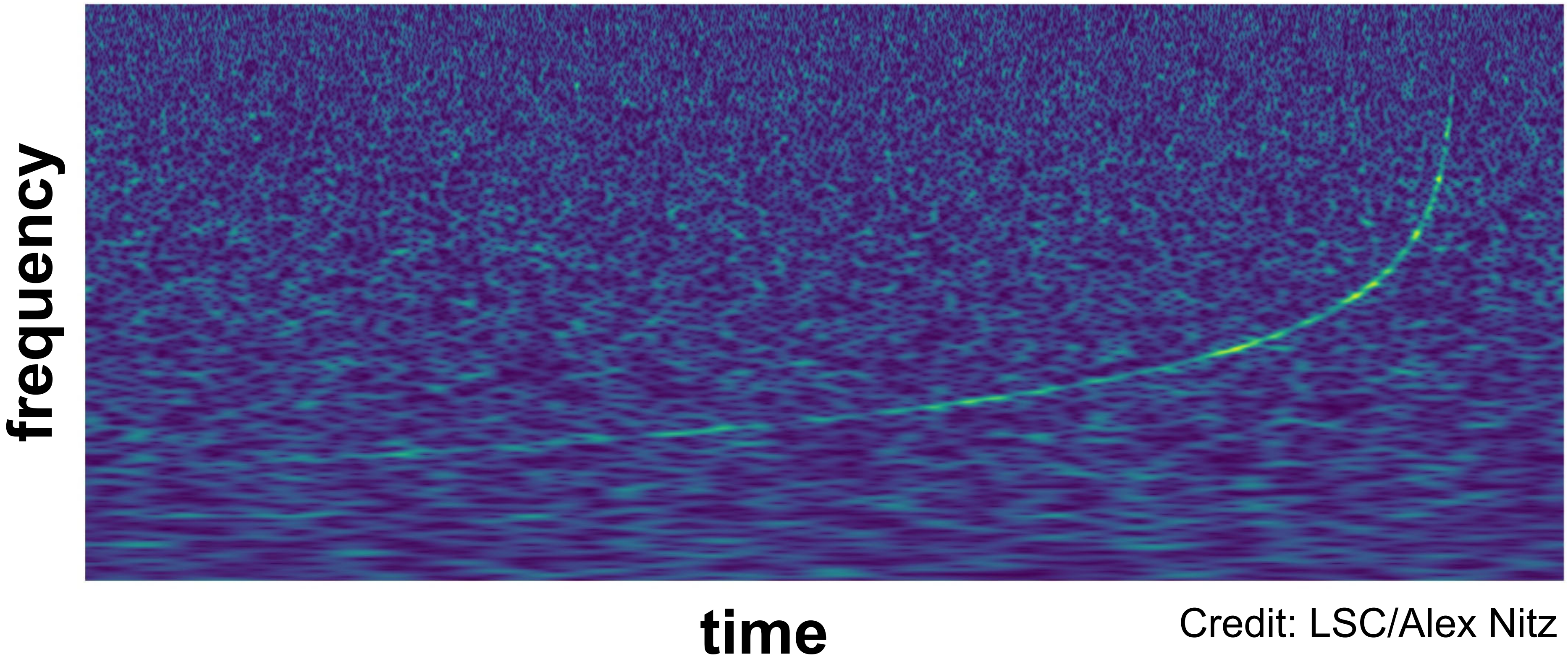
SXS


LIGO Hanford Data
Predicted
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
LIGO Livingston Data
Predicted
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
LIGO Hanford Data (shifted)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
LIGO Livingston Data
0.30
0.35
0.40
0.45
Time (sec)

LIGO


Barry C. Barish (Caltech)
Kip S. Thorne (Caltech)
Rainer Weiss (MIT)
2017 Nobel Prize in Physics

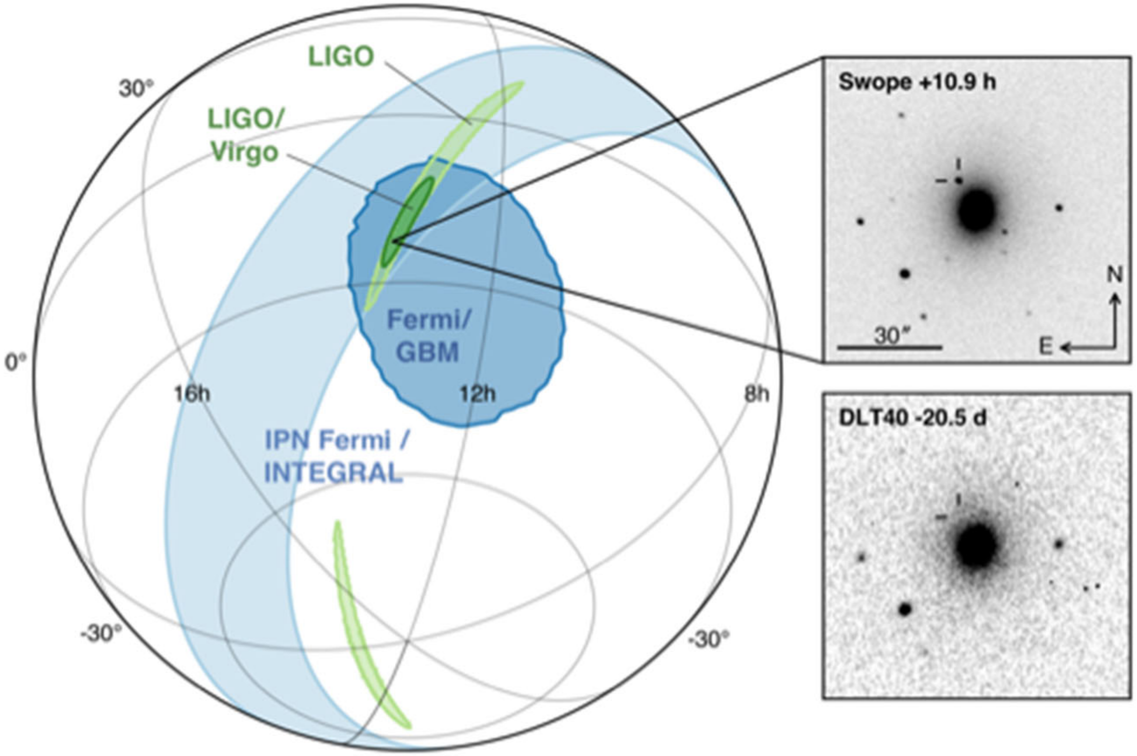
GW from NS-NS: GW170817



Credit: LSC/Alex Nitz

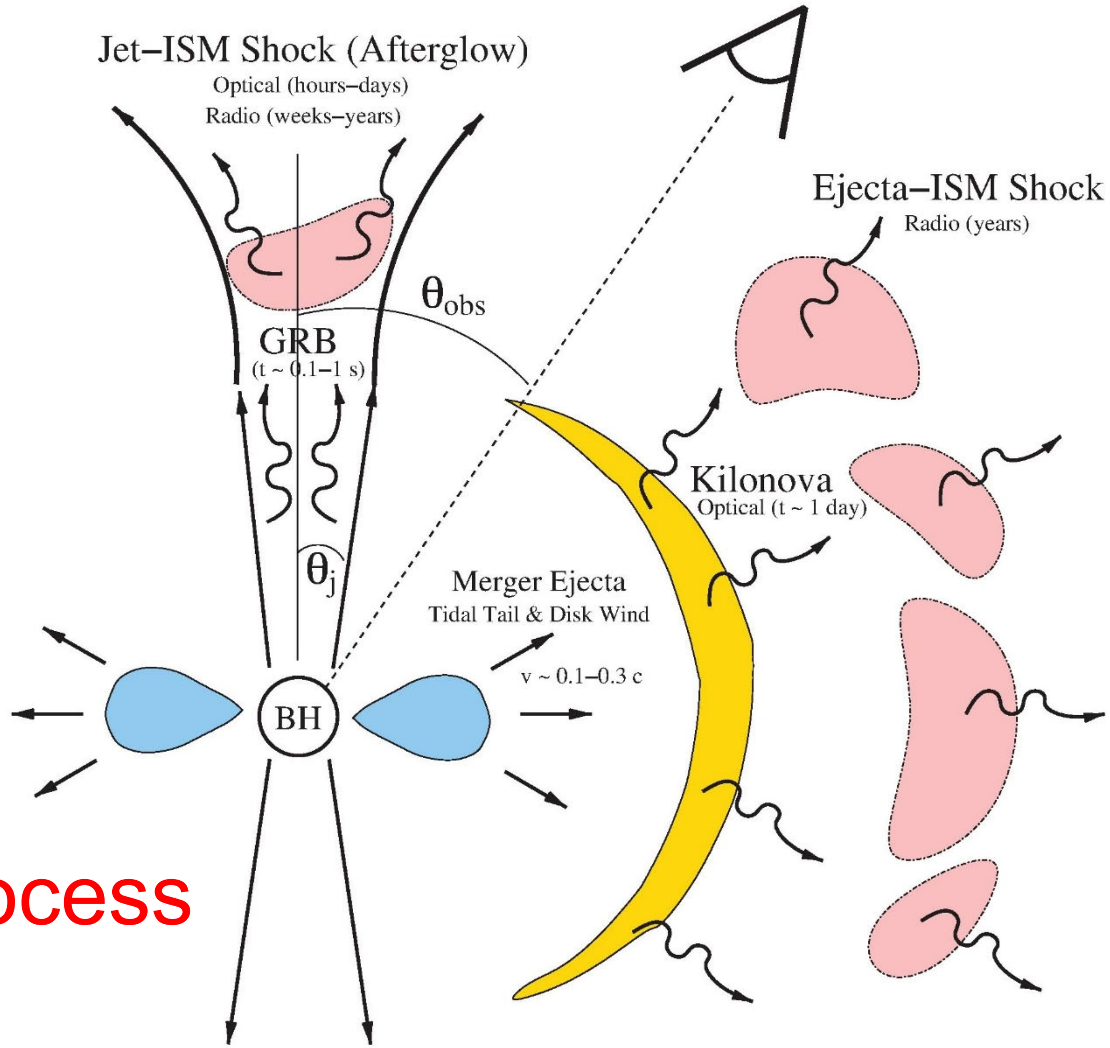
Chirp spectrogram

Multi-messenger observation



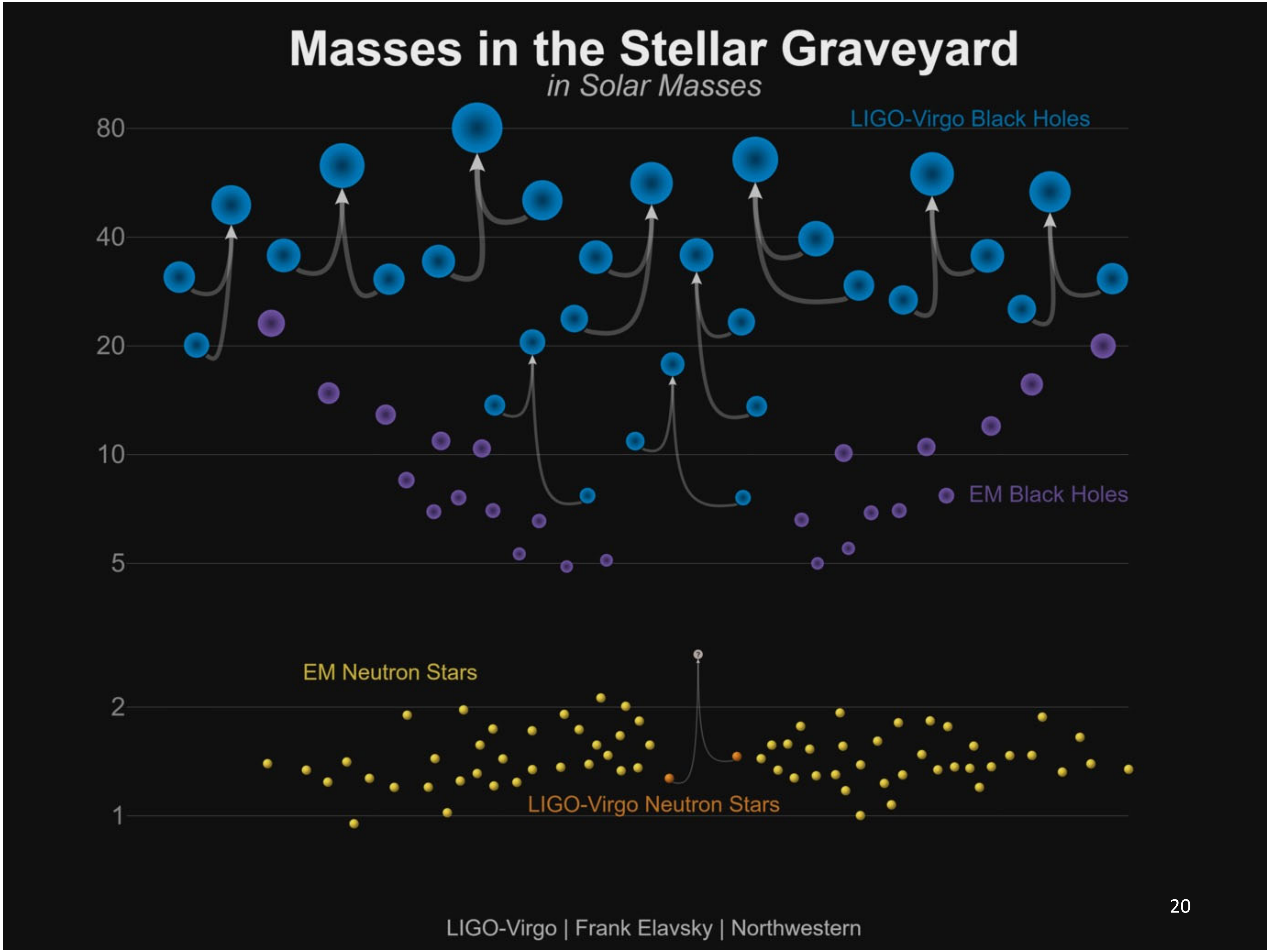
- 1.7 sec.: detection of GRB
- 6 min.: Detection by LIGO
- 41 min.: relationship between GW170817 and GRB170817A reported
- 4 hr.: skymap provided
- 10 hr.: identified by Chilli
- Later: follow-up observation by 70 telescopes

Electromagnetic waves from NS-NS coalescence



R-process

Metzger & Berger 2012



Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
?
LIGO-Virgo | Frank Elavsky | Northwestern

GW detector in space

Arm length can be much longer

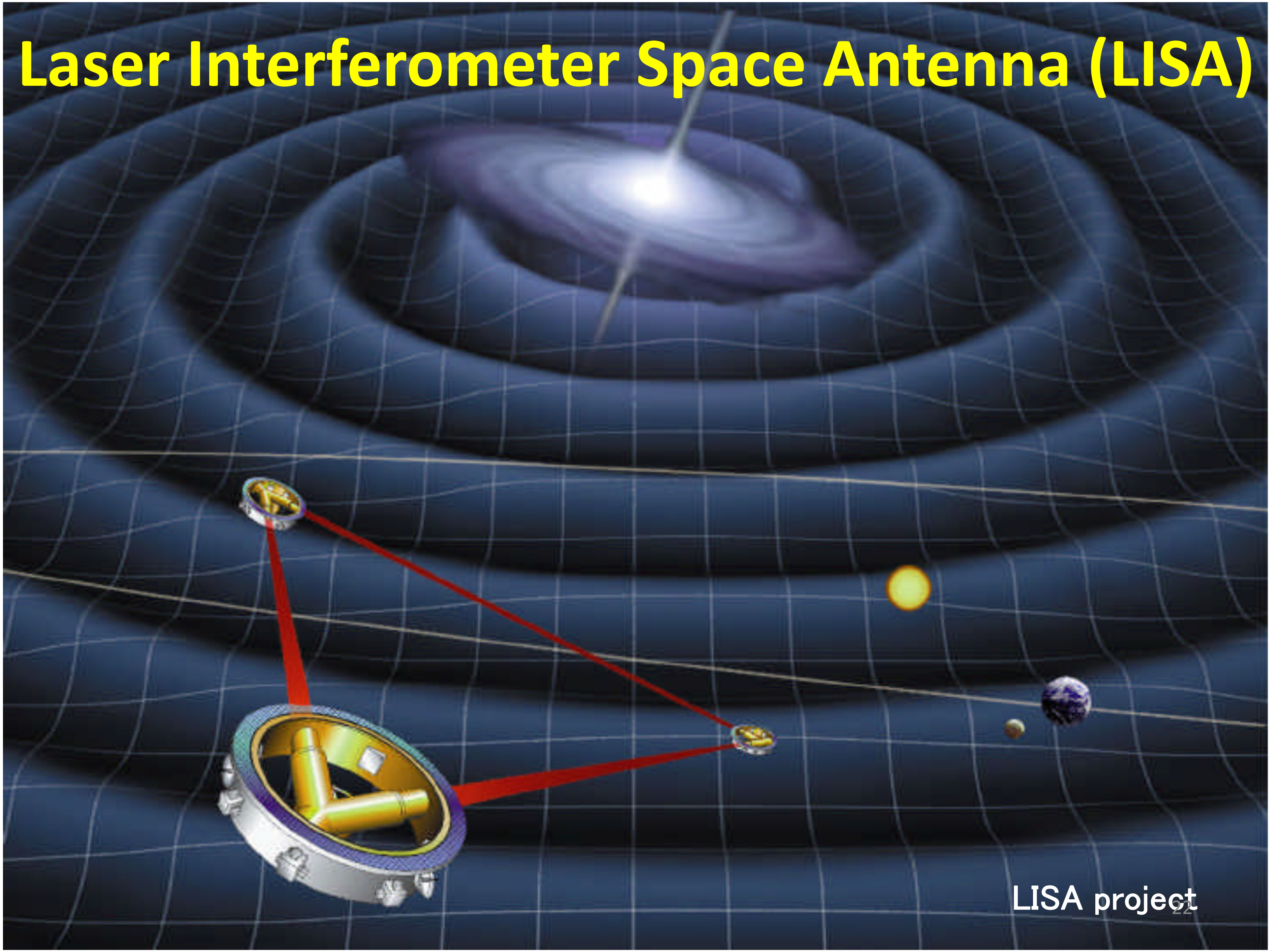
- Signal increases at low frequencies
  - ー Longer interaction between GW and light
- Noise decreases at low frequencies
  - ー No seismic noise and less Newtonian noise

⬇

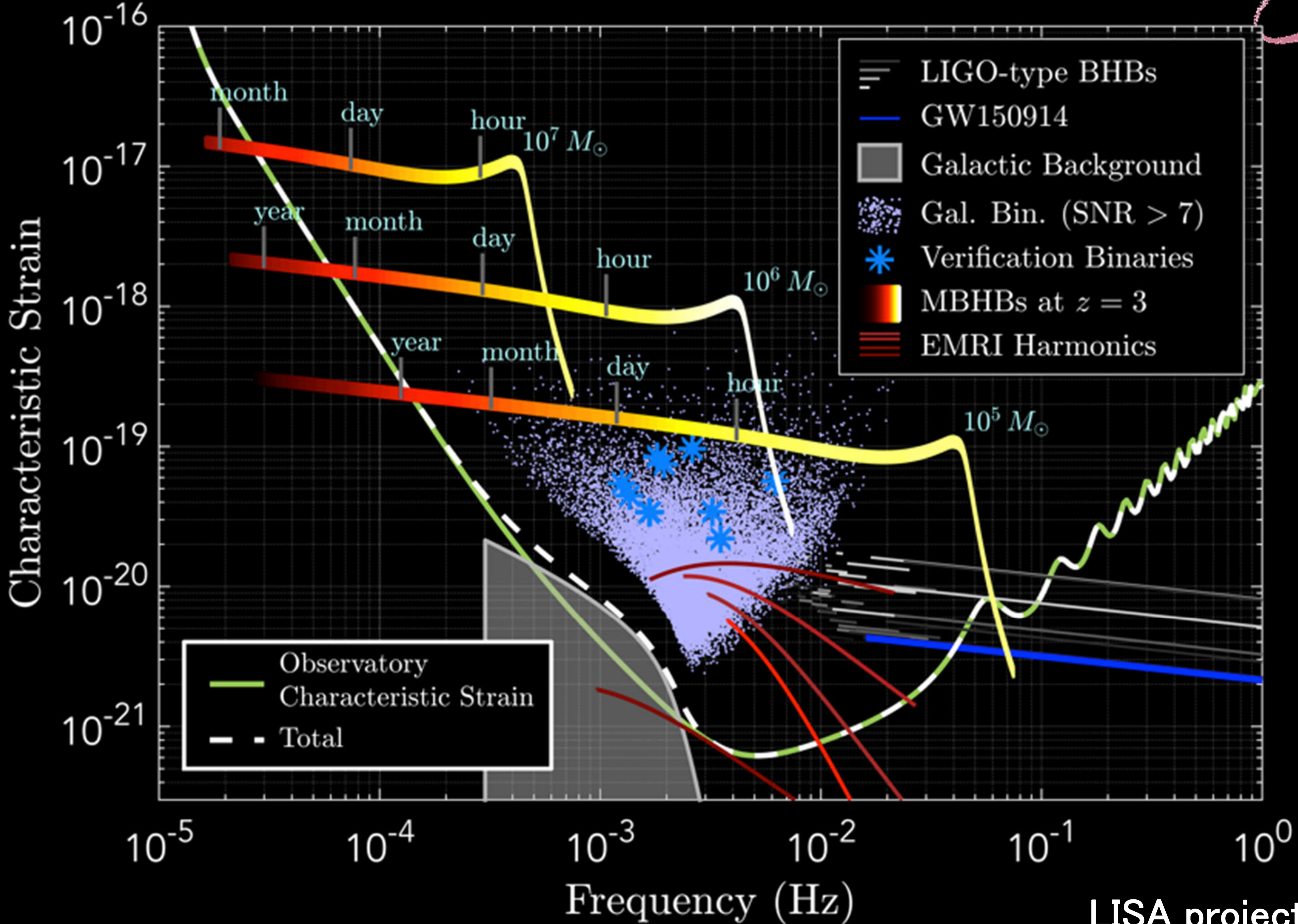
Sensitivity improved at low frequencies

Furthermore, expected GW signals larger

Laser Interferometer Space Antenna (LISA)



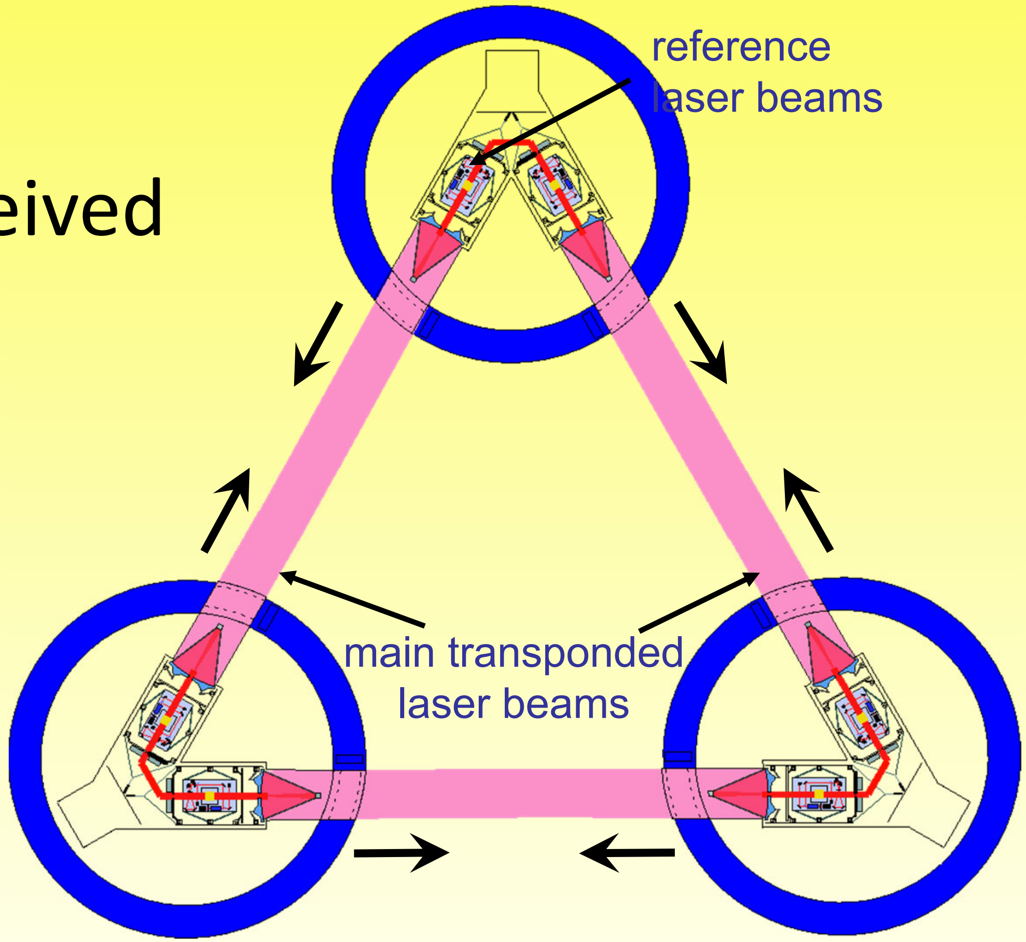
LISA Sources



LISA project

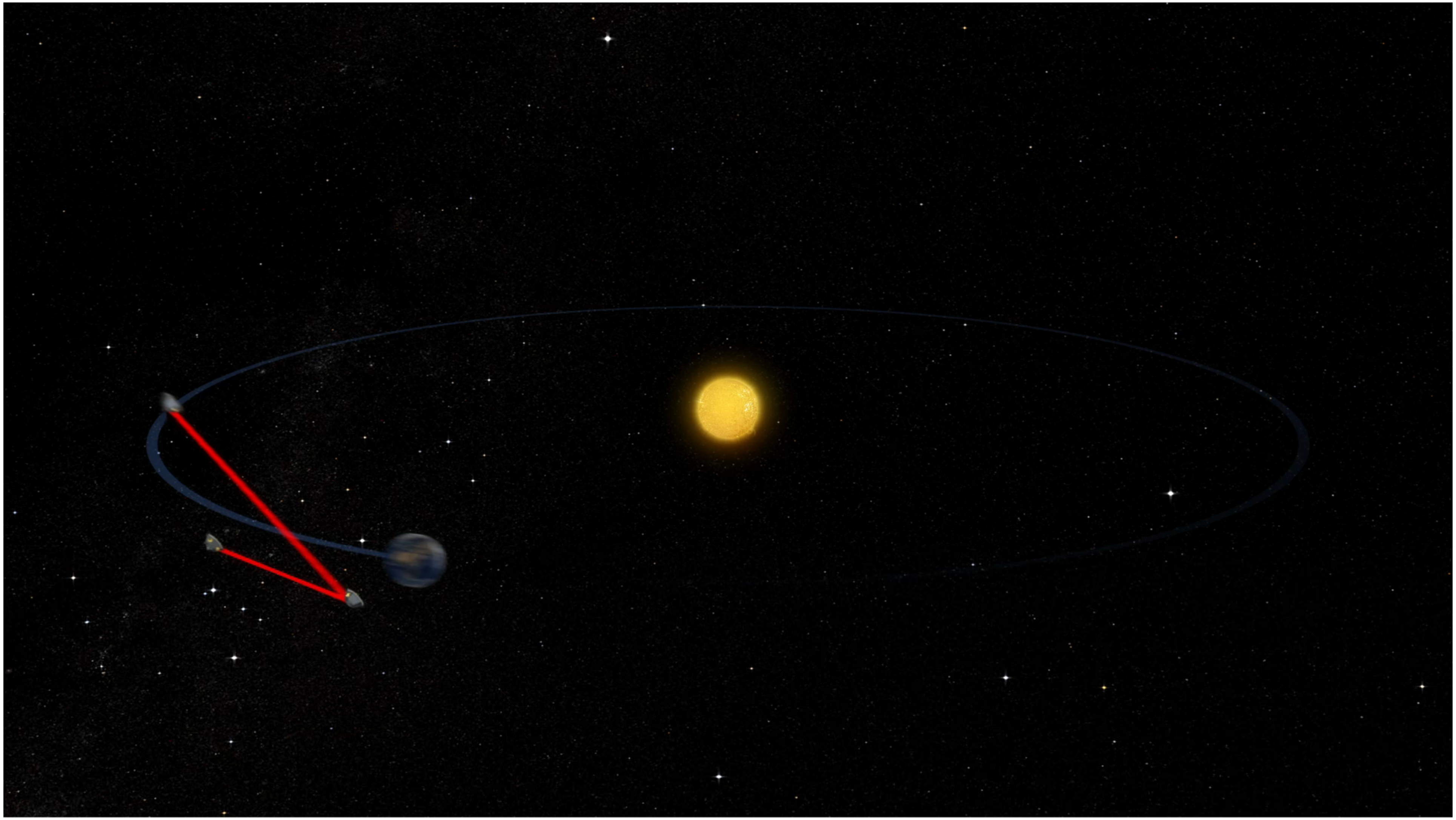
LISA Layout

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



LISA project

LISA Orbit

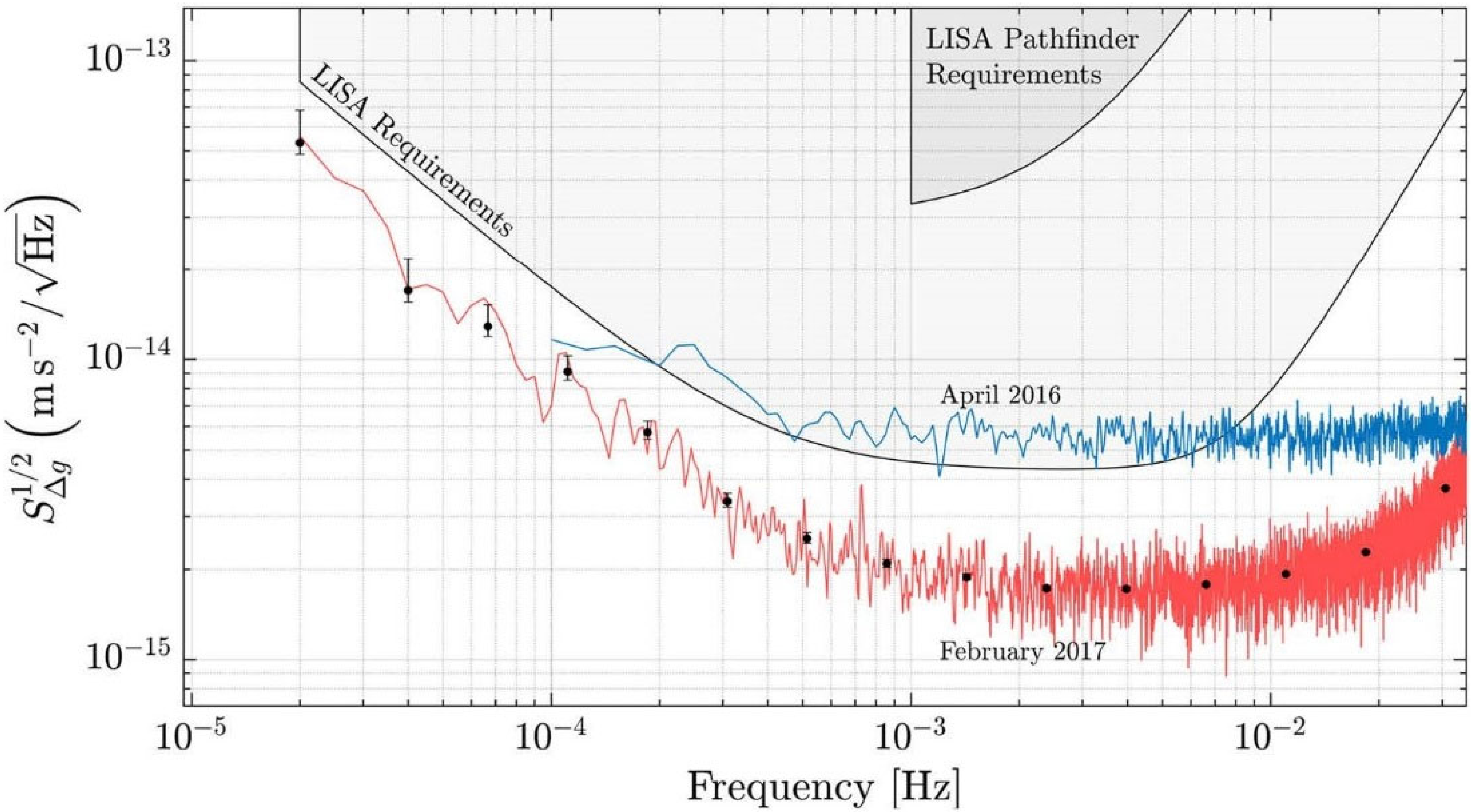


LISA Pathfinder

Launched on Dec. 2, 2015

AEI Hannover

Noise performance of the LISA Pathfinder

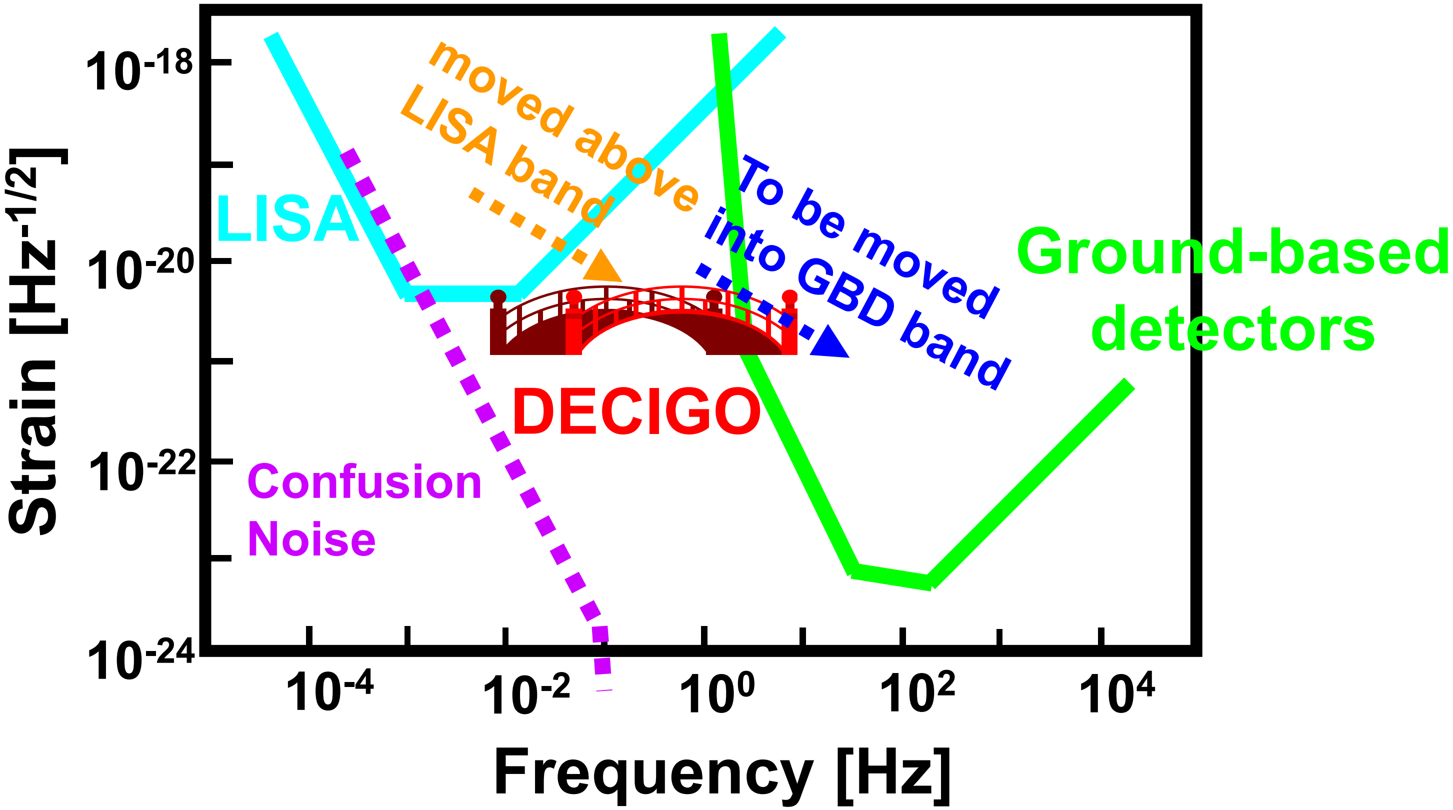


M. Armano et al., PRL **120** (2018) 061101

DECIGO

Deci-hertz Interferometer Gravitational Wave Observatory

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



Possibility of Direct Measurement of the Acceleration of the Universe Using 0.1 Hz Band Laser Interferometer Gravitational Wave Antenna in Space

Naoki Seto,[1] Seiji Kawamura,[2] and Takashi Nakamura[3]
[1]*Department of Earth and Space Science, Osaka University, Toyonaka 560-0043, Japan*
[2]*National Astronomical Observatory, Mitaka 181-8588, Japan*
[3]*Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*
(Received 4 June 2001; published)

It may be possible to construct a laser interferometer gravitational wave antenna in space with $h_{\rm rms} \sim 10^{-27}$ at $f \sim 0.1$ Hz in this century. Using this antenna, (1) typically 10^5 chirp signals of coalescing binary neutron stars per year may be detected with S/N $\sim 10^4$; (2) we can directly measure the acceleration of the universe by a 10 yr observation of binary neutron stars; and (3) the stochastic gravitational waves of $\Omega_{\rm GW} \gtrsim 10^{-20}$ predicted by the inflation may be detected by correlation analysis. Our formula for phase shift due to accelerating motion might be applied for binary sources of LISA.

DOI: PACS numbers: 95.55.Ym, 04.80.Nn, 98.80.Es

I. Introduction.—There are at least four methods to detect gravitational waves: (1) resonant type antenna covering ~kHz band; (2a) laser interferometers on the ground covering 10 Hz–kHz band; (2b) laser interferometers in space like LISA [1] covering 10^{-4}–10^{-2} Hz band; (3) residuals of pulsar timing covering $\sim 10^{-8}$ Hz band; (4) Doppler tracking of the spacecraft covering 10^{-4}–10^{-2} Hz band. It is quite interesting to note that little has been discussed on possible detectors in 10^{-2}–10 Hz band. In this Letter we consider the possible specification of such a detector, which we call DECIGO (Decihertz Interferometer Gravitational Wave Observatory). We argue that the direct measurement of the acceleration of the universe is possible using DECIGO.

II. Specification of DECIGO.—The sensitivity of a space antenna with an arm length of 1/10 of LISA and yet the same assumption of the technology level, such

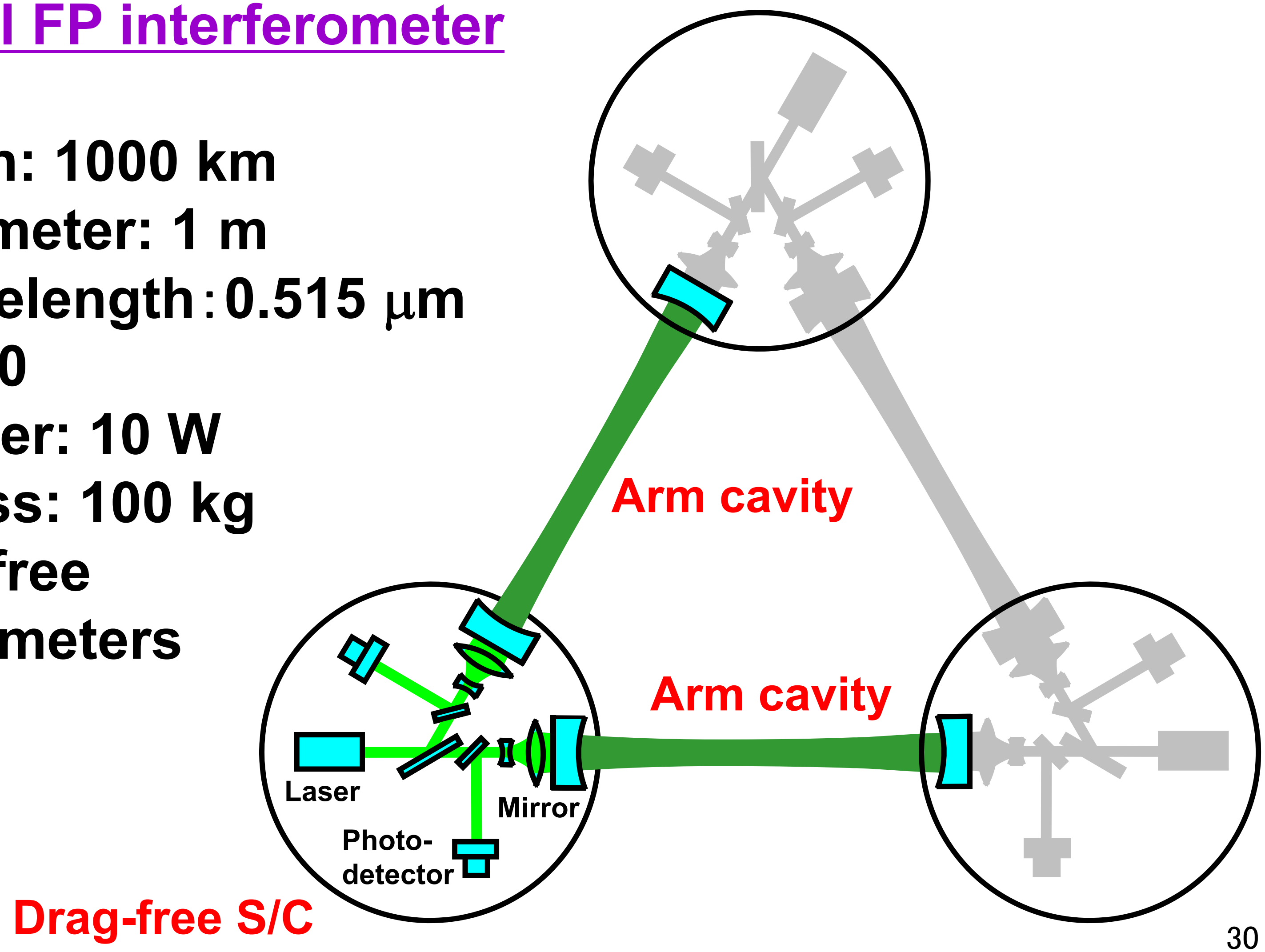
sooner. Note here that when the pioneering efforts to detect the gravitational waves started in the last century using resonant-type detectors as well as laser interferometers, few people expected the present achievement in resonant-type detectors such as IGEC (bar) [3] and in laser inteferometers such as TAMA300 [4], LIGO, GEO600, and VIRGO (for these detectors see [5]). Therefore all the experimentalists and the theorists on gravitational waves should not be restricted to the present levels of the detectors. Our point of view in this Letter is believing the proverb "Necessity is the mother of the invention" so that we argue why a detector like DECIGO is necessary to measure some important parameters in cosmology.

The sensitivity of DECIGO, which is optimized at 0.1 Hz, is assumed to be limited only by radiation pressure noise below 0.1 Hz and shot noise above 0.1 Hz. The contributions of the two noise sources are equal to

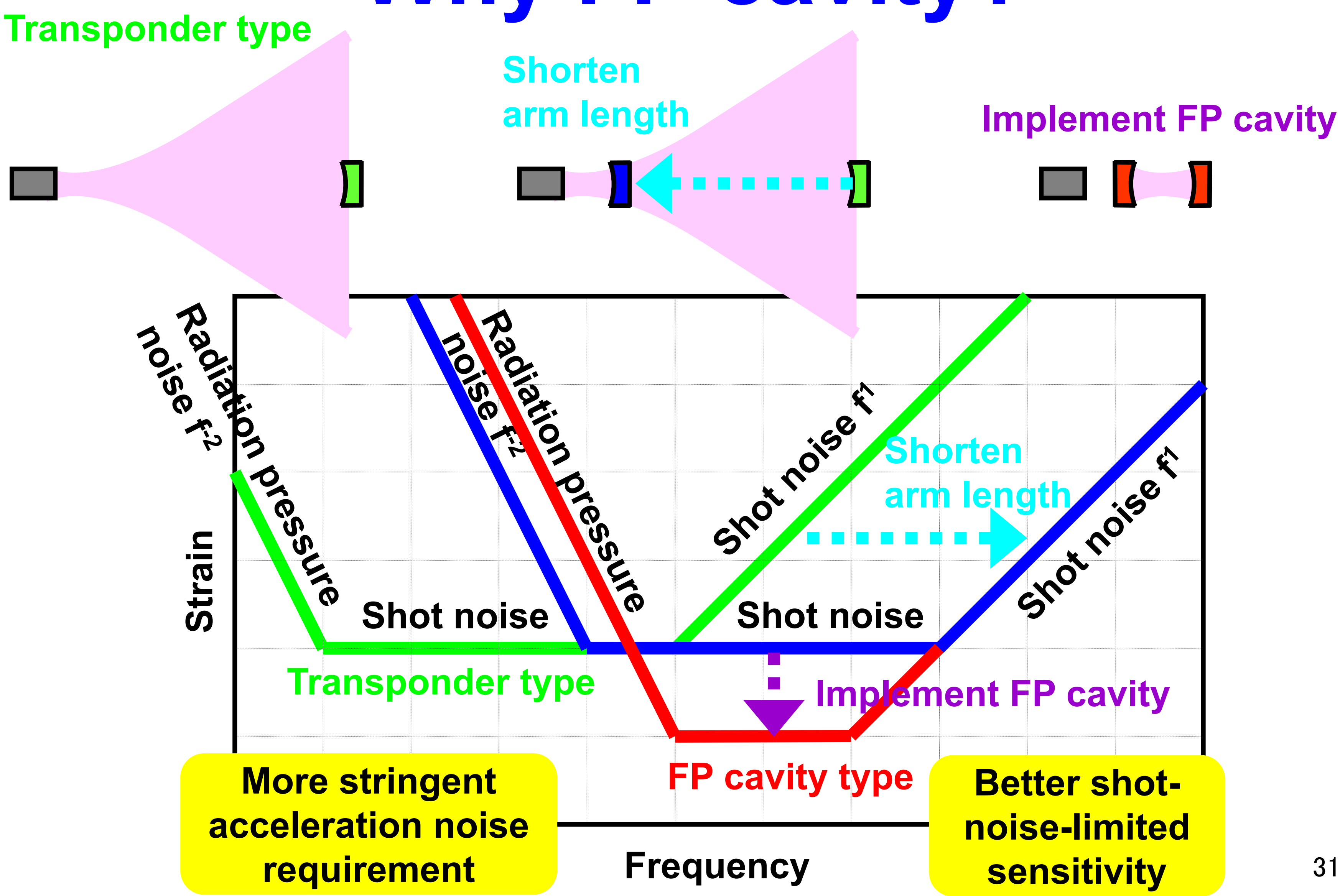
Pre-conceptual design

Differential FP interferometer

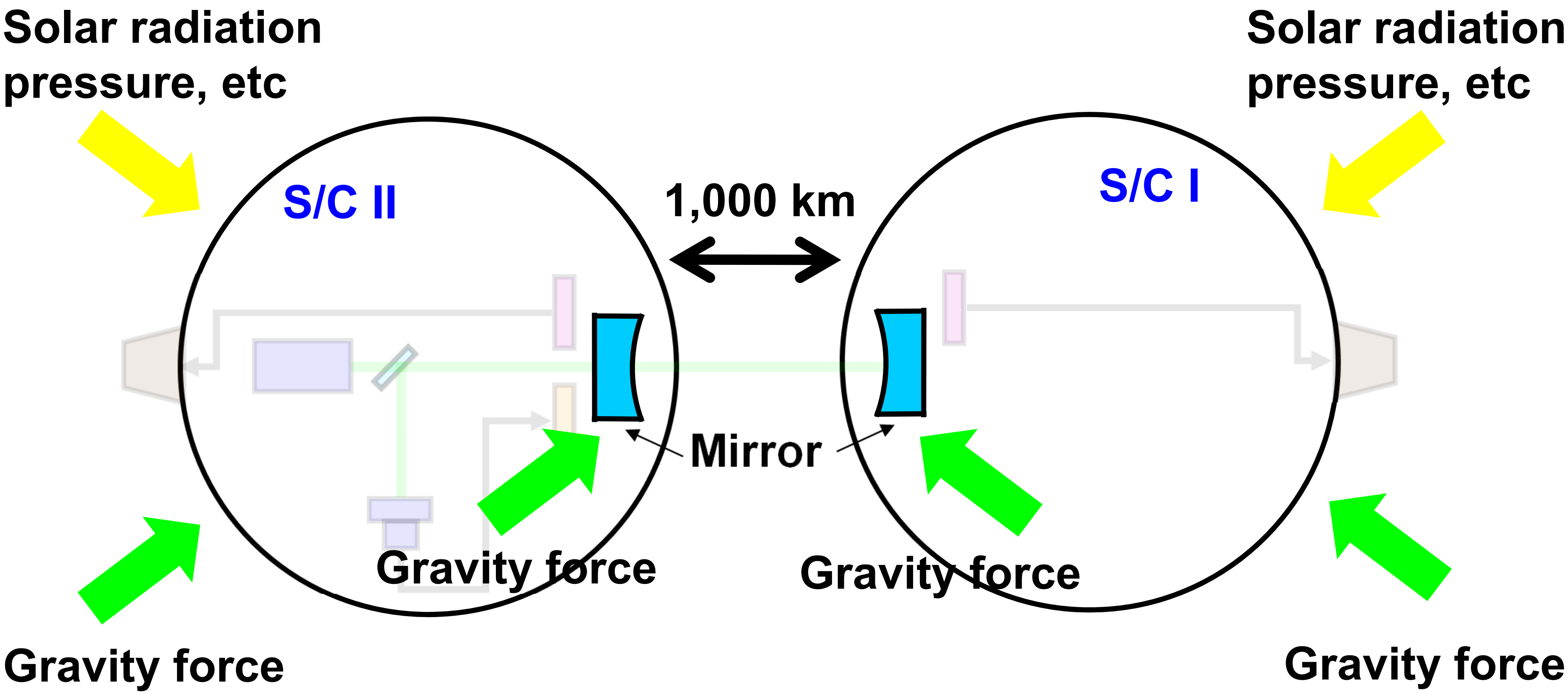
Arm length: 1000 km
Mirror diameter: 1 m
Laser wavelength：0.515 μm
Finesse: 10
Laser power: 10 W
Mirror mass: 100 kg
S/C: drag free
3 interferometers



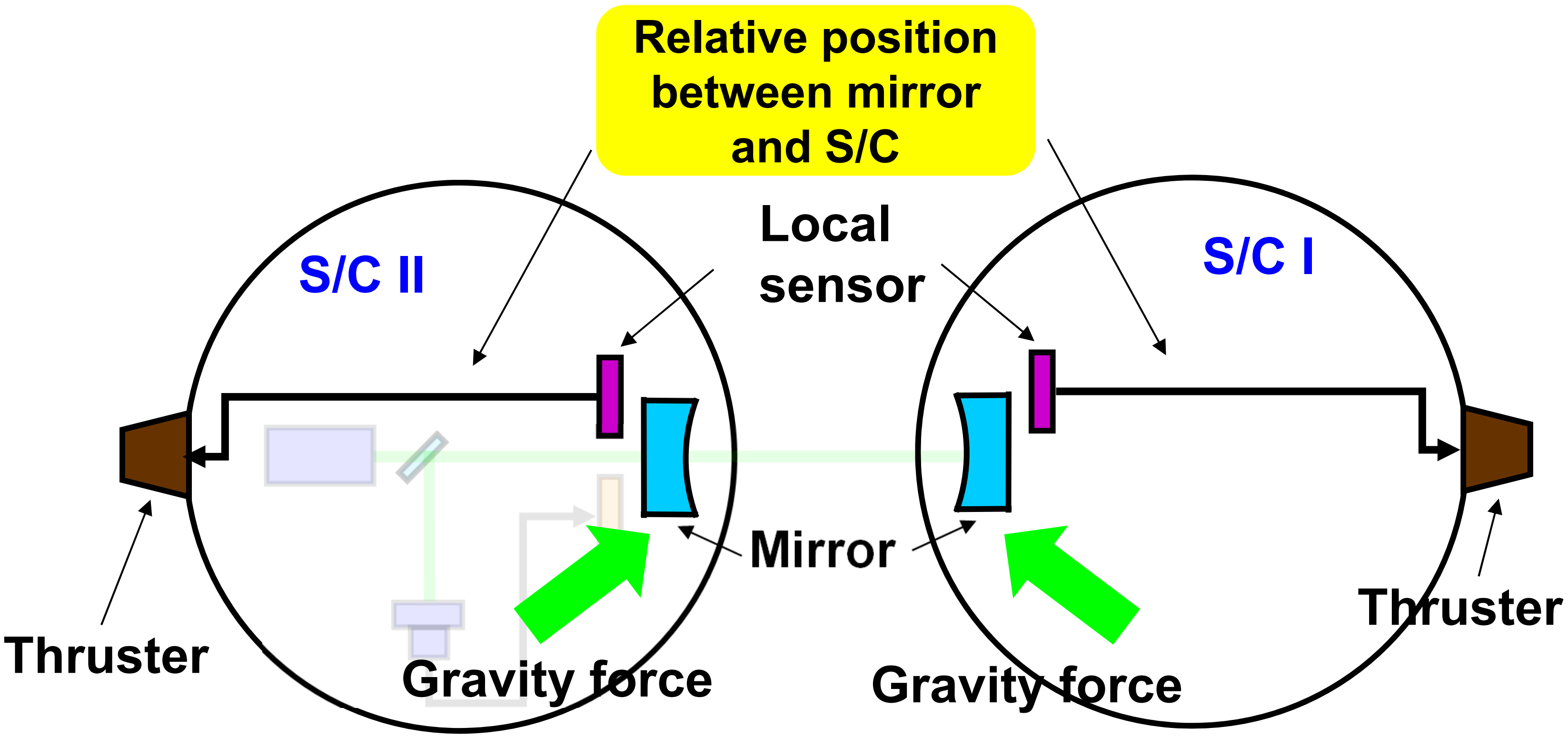
Why FP cavity?



Drag free and FP cavity: compatible?



FP cavity and drag free : compatible?



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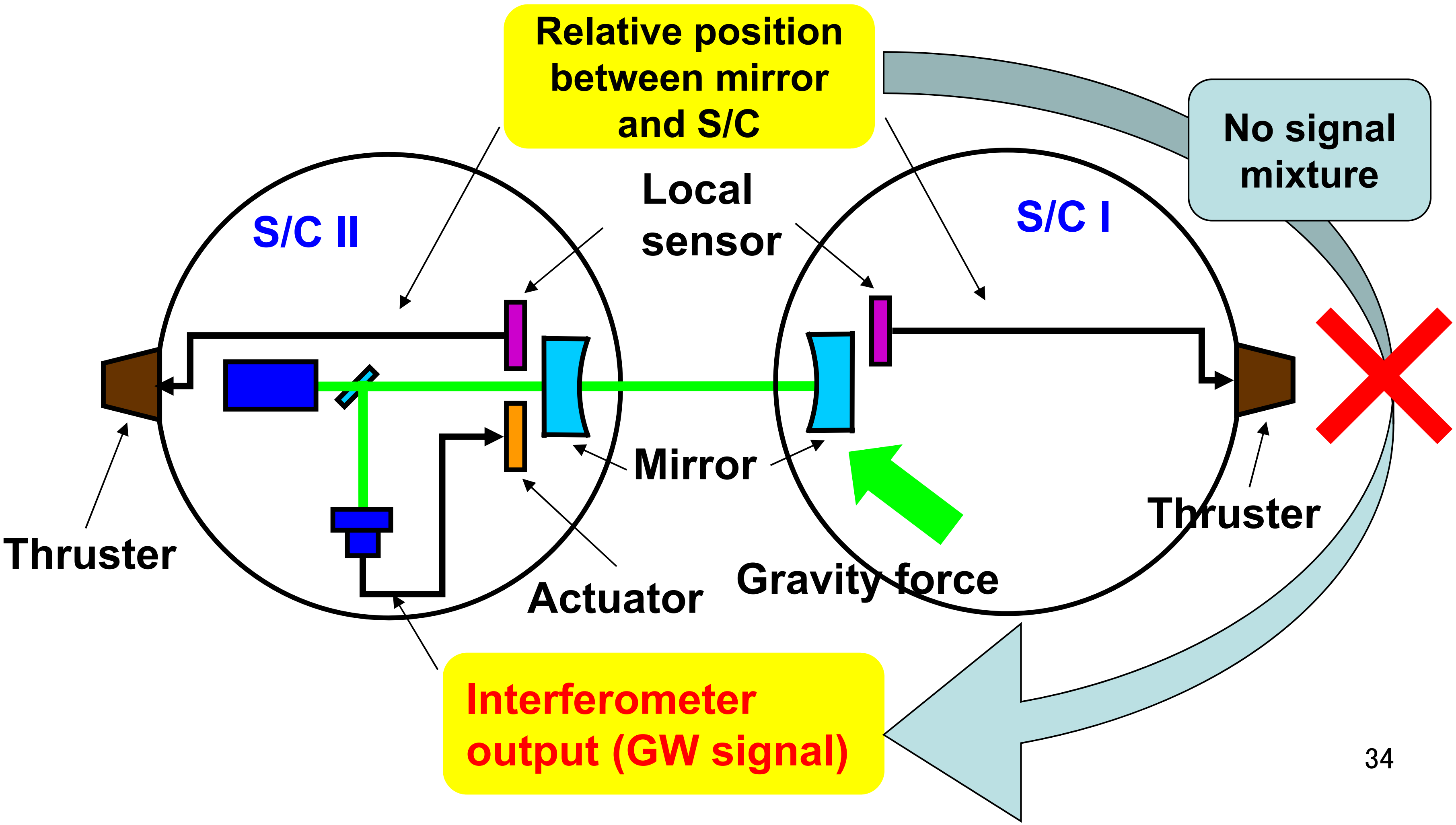
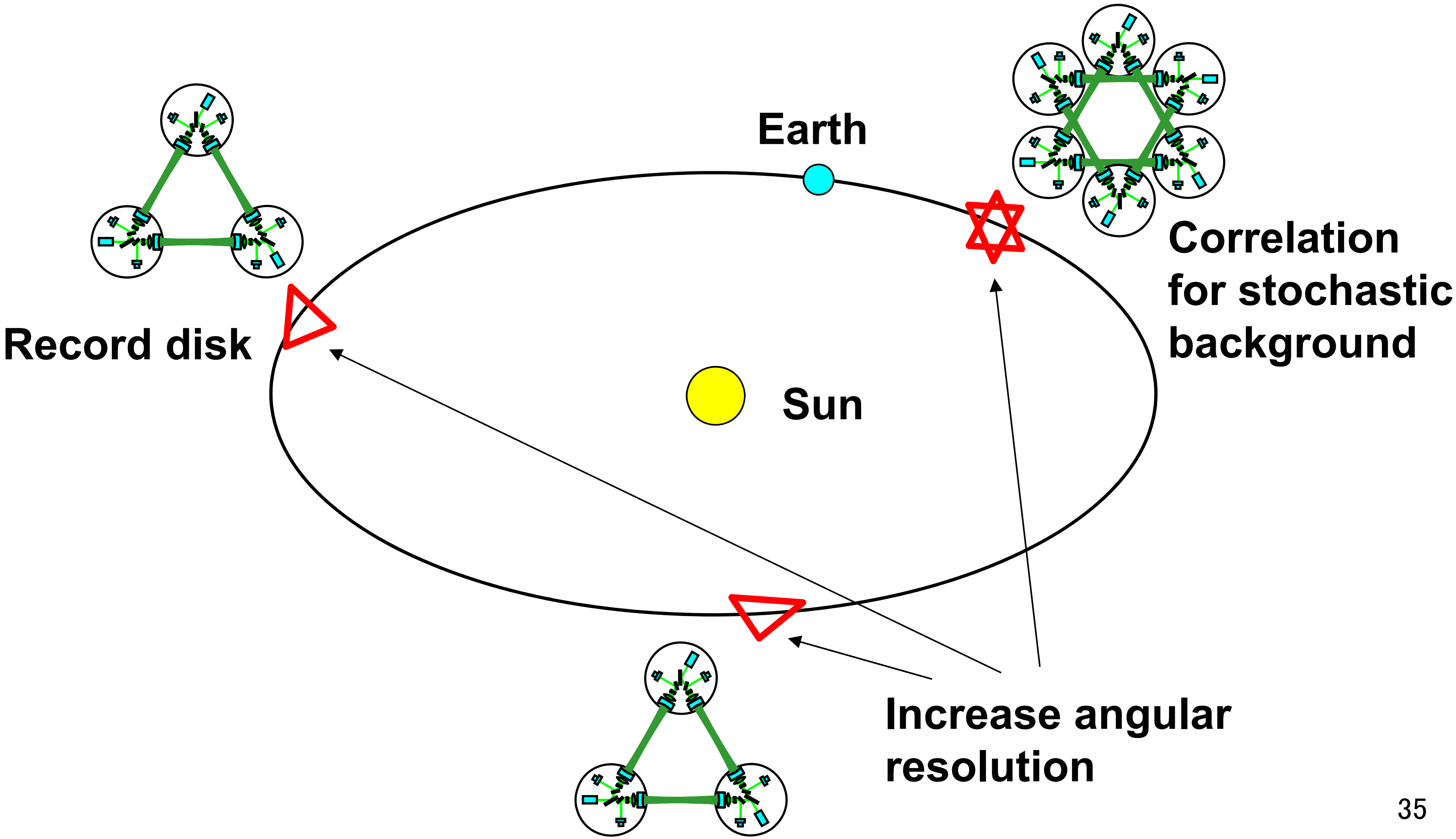


Orbit and constellation (preliminary)

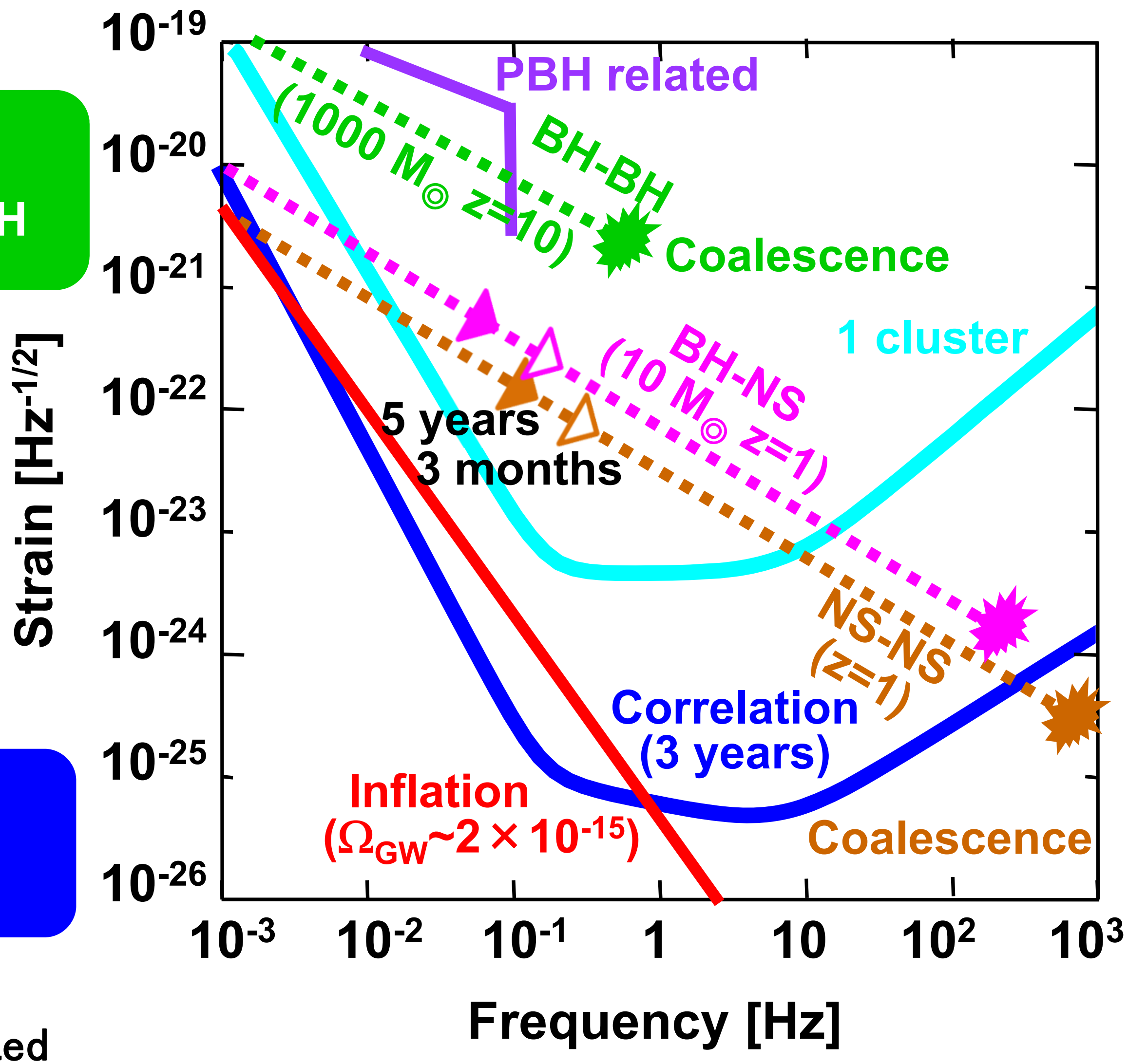


Target sensitivity and science

Super-massive BH

Inflation

To be updated



Dark Matter

Saito, Yokoyama 2009

General relativity

Yagi, Tanaka 2009

Acceleration of expansion of Universe

Seto, Kawamura, Nakamura 2004

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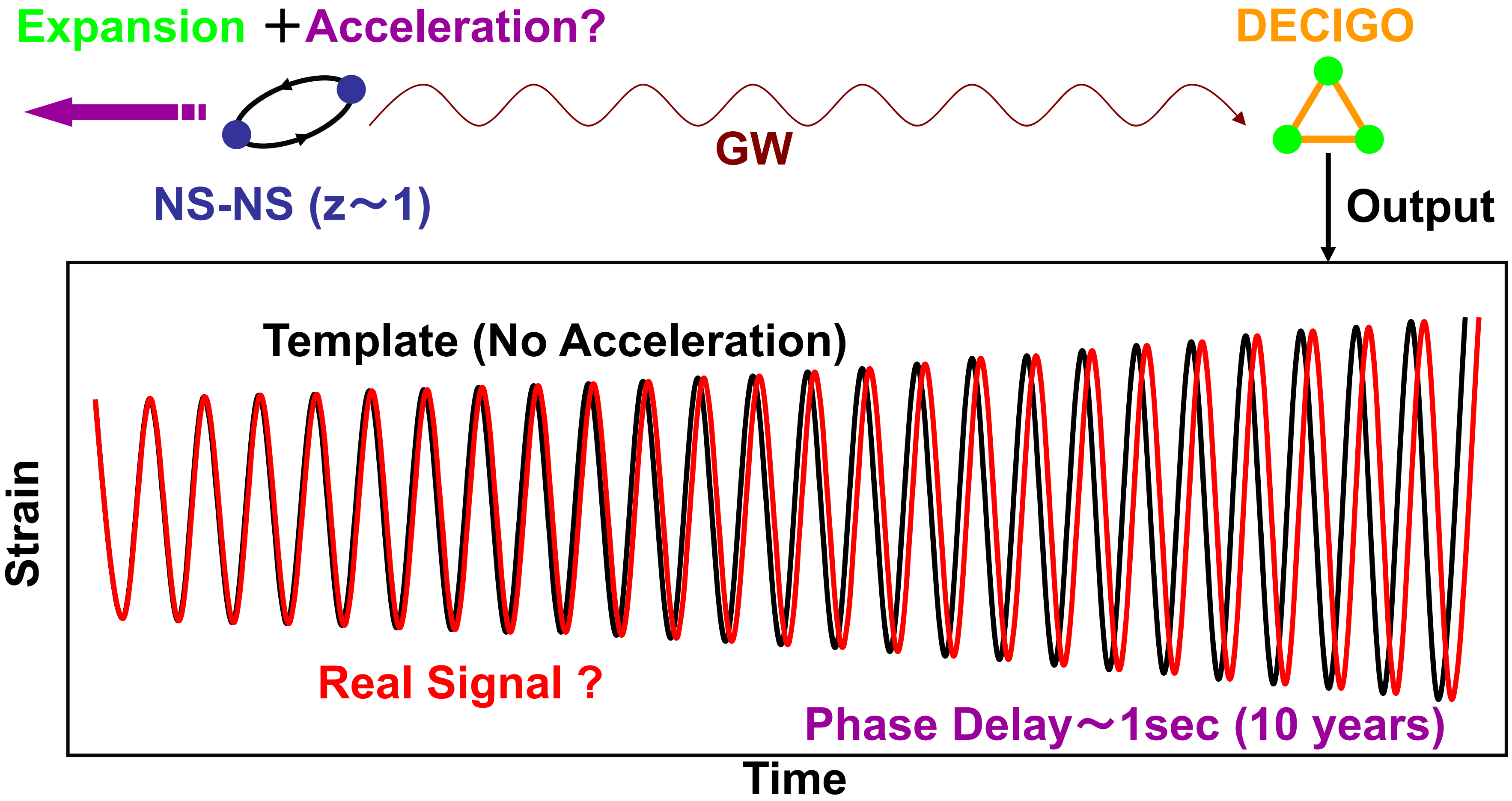
Acceleration of Expansion of the Universe

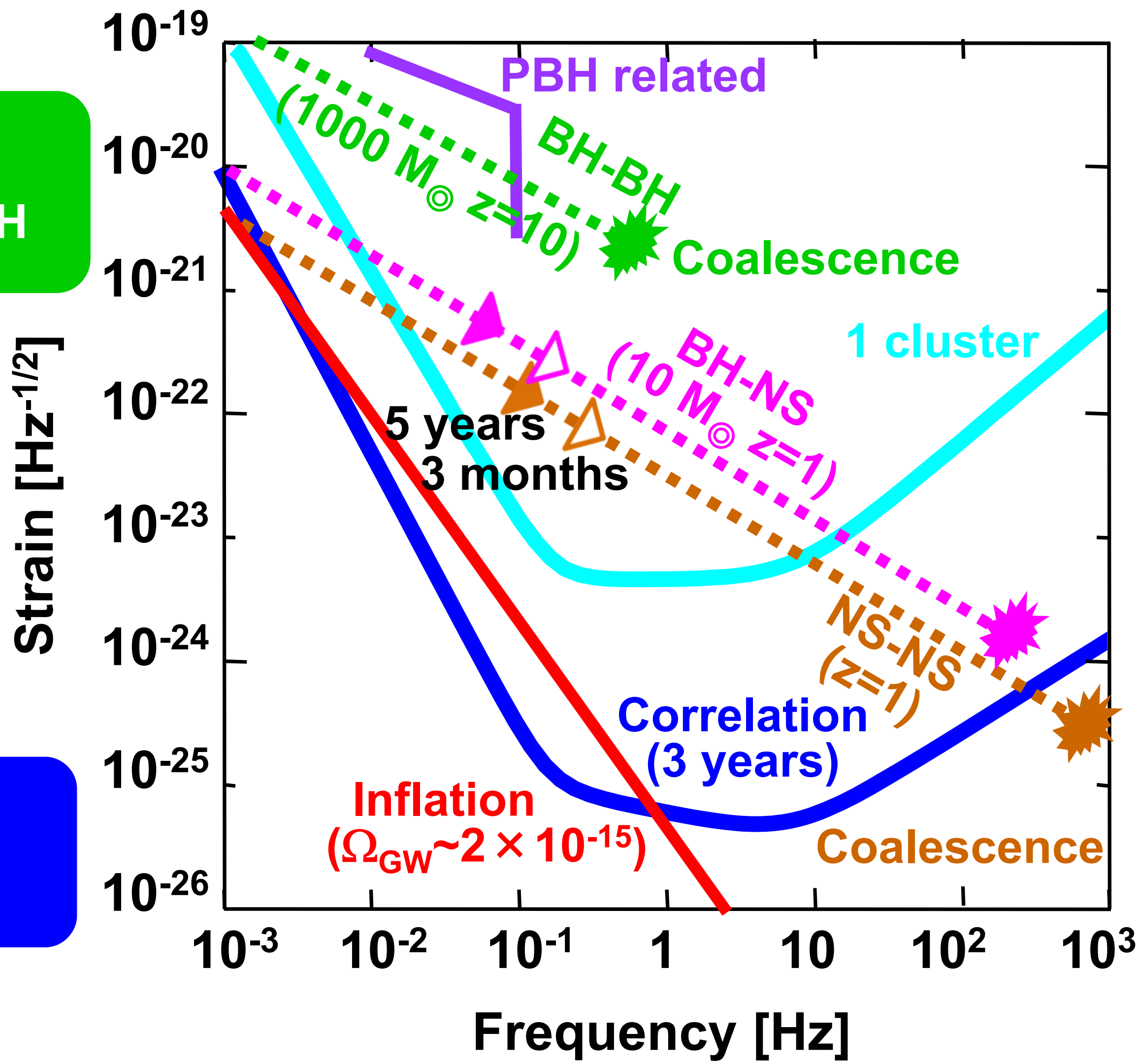


Seto, Kawamura, Nakamura, PRL 87, 221103 (2001)

Target sensitivity and science

Super-massive BH

Inflation



Dark Matter

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General relativity

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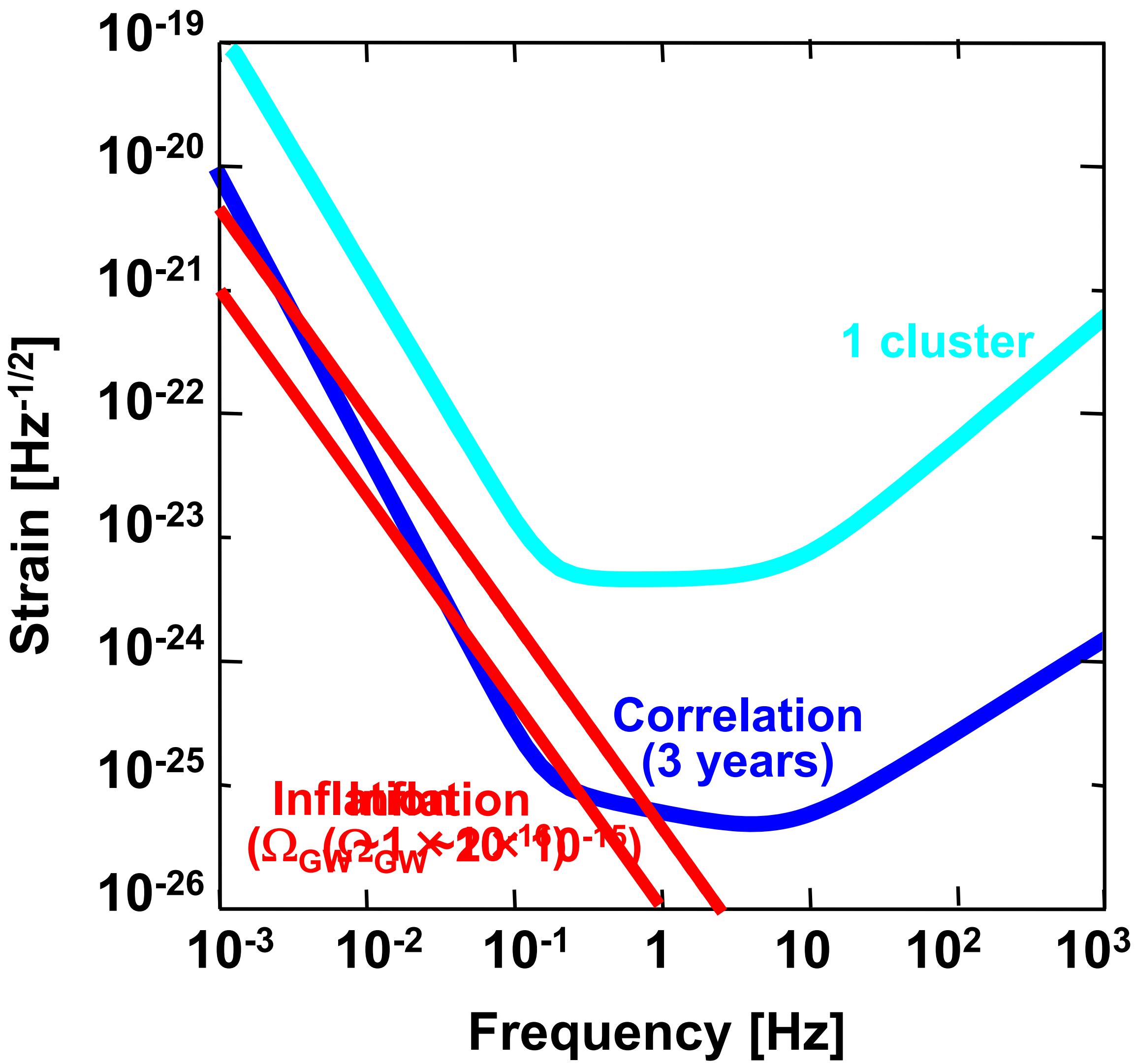
Acceleration of expansion of Universe

Seto, Kawamura, Nakamura 2004

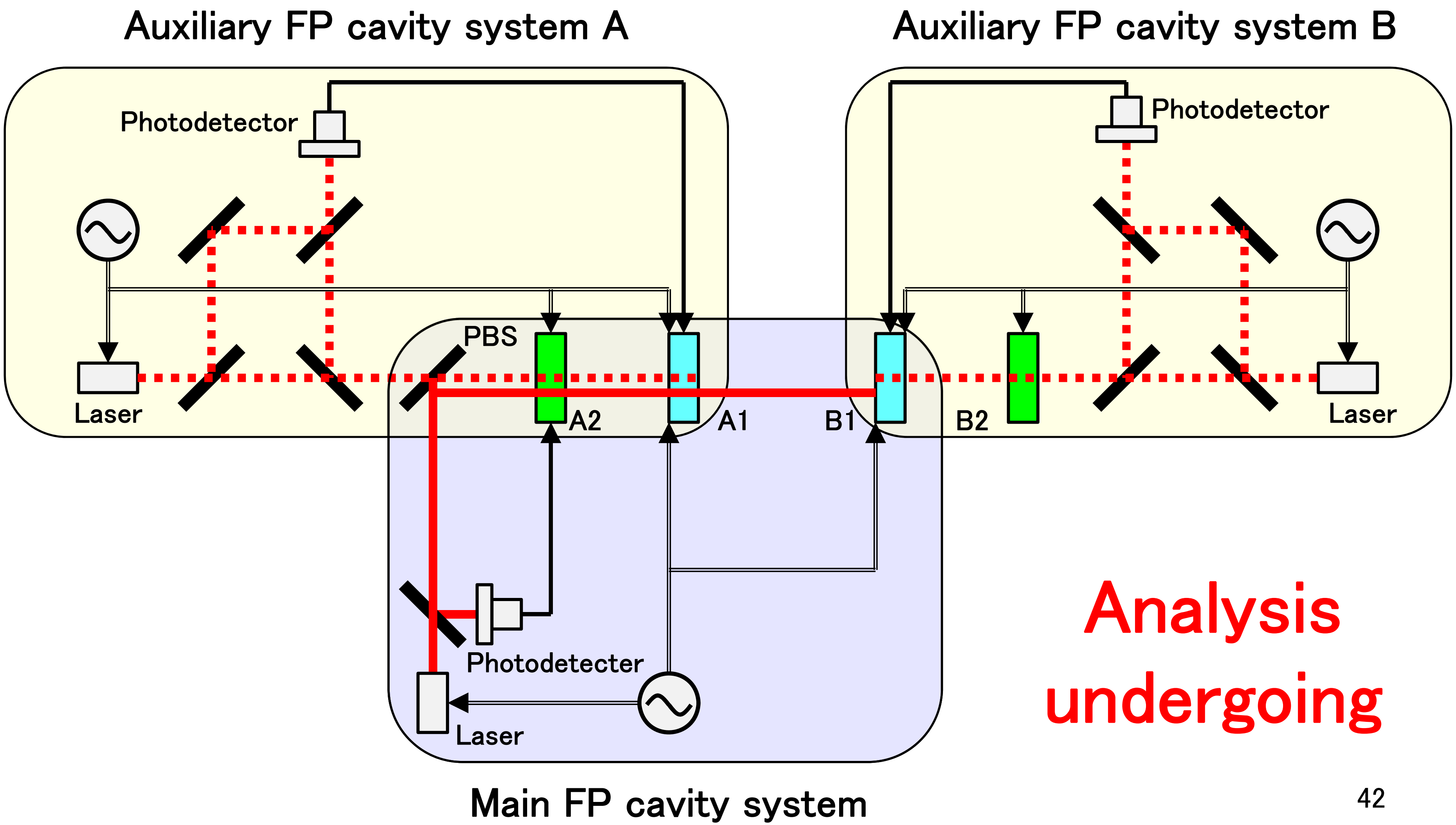
Primordial GW

- Direct observation of primordial GWs from inflation
  - Whether Inflation really happened?
  - Which inflation model is correct?
  - Parity violation?（Clockwise and counterclockwise GW）
    - Seto 2007
  - Separation of Tensor, Vector, scalar mode
    - Nishizawa, Taruya, Kawamura 2010

Upper limit of primordial GW



Implementing broadband quantum locking

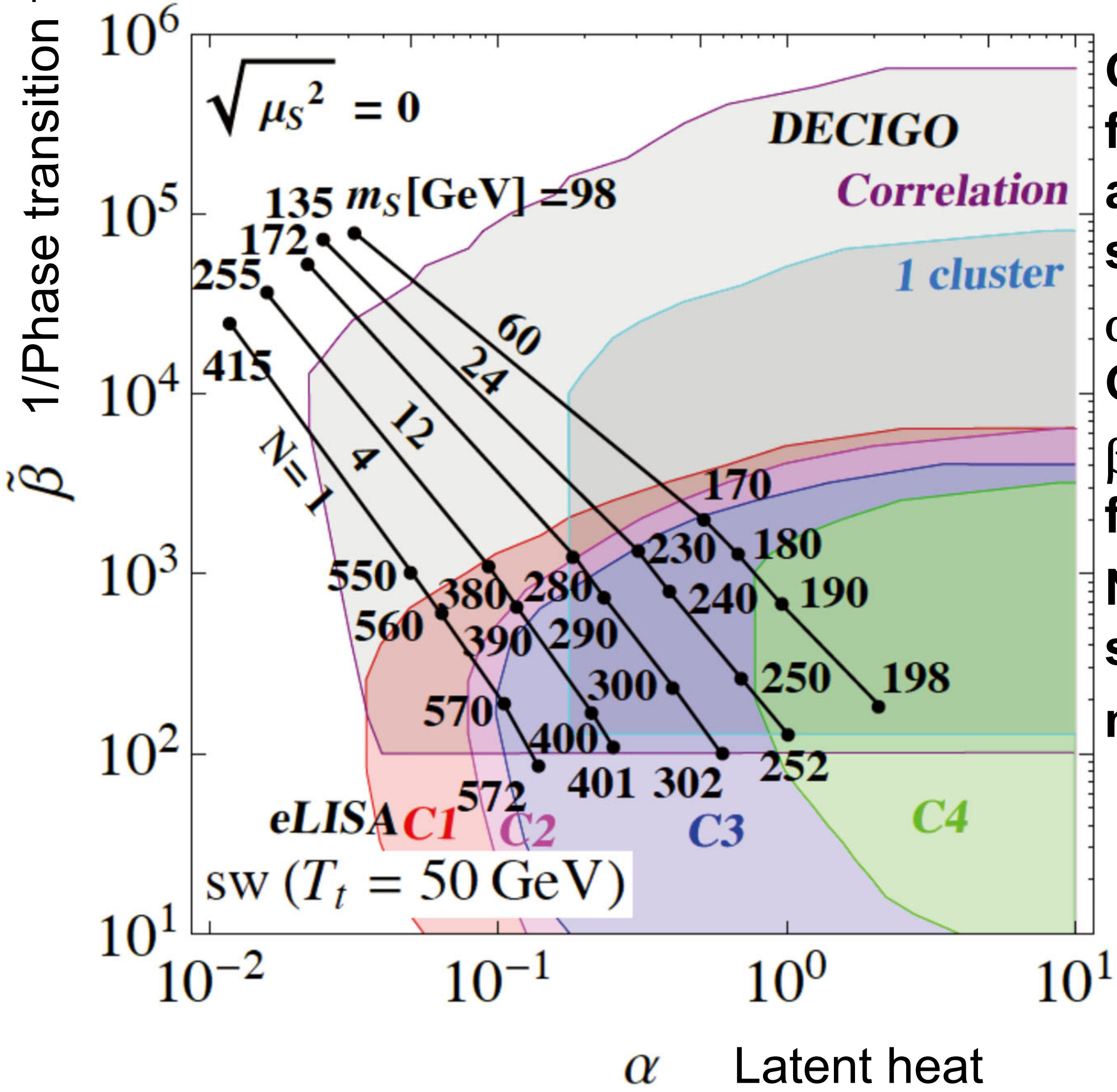


Analysis undergoing

DECIGO and gamma ray burst

- Prediction of NS-NS coalescence
  - z<5; 5 years before coalescence
  - Expected event rate: 10,000 /year (30 /day)
  - Angular accuracy : several milli arcsec
- Assuming short GRB comes from NS-NS coalescence
  - Assuming 1/30 of short GRB can be detected (beaming effect)
  - Expected event rate: 1 /day
- Observation of GRB by EMs

Gravitational waves as a probe of extended scalar sectors



GW expected from strongly first order phase transition at the electroweak symmetry breaking

α: related to amplitude of GW

β: related to peak frequency

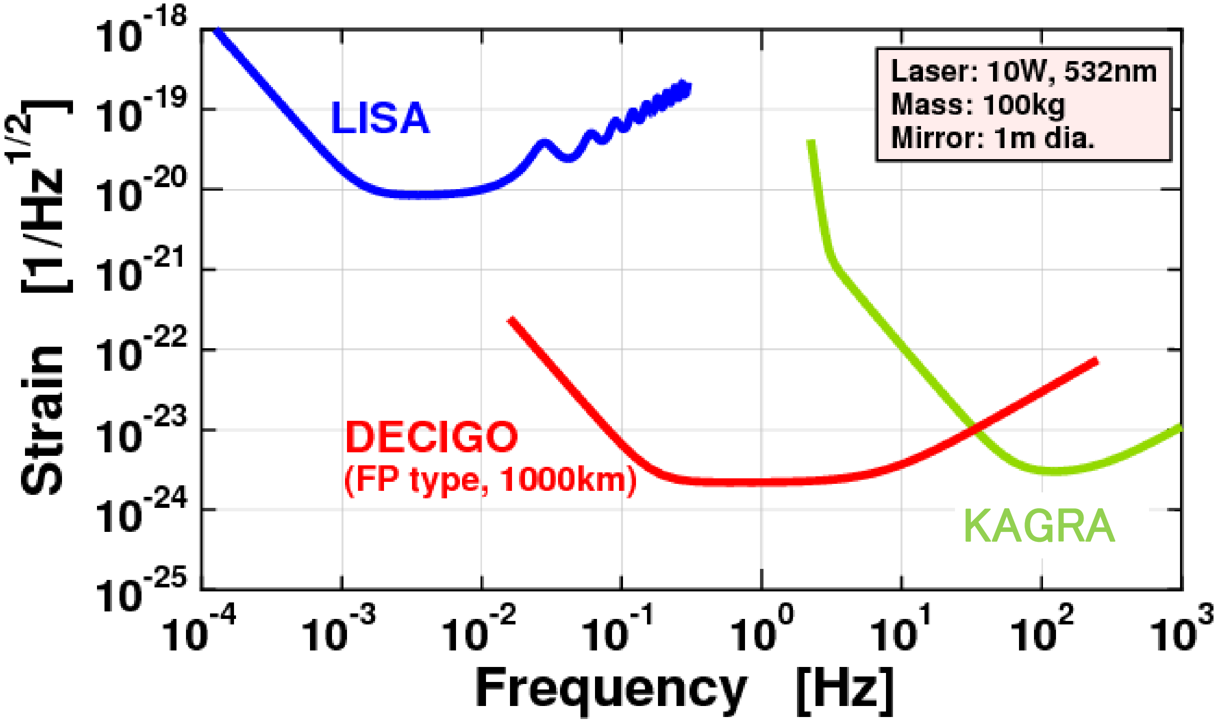
N: Number of additional scalar fields

m_s: Mass of scalar field

Kakizaki, Kanemura, Matsui, PRD **92** (2015) 115007; modified by Kanemura

Requirements

- Force noise: 25 times more stringent than LISA
  - Comparable in terms of strain; distance: 1/2500, mirror mass: 100
- Sensor noise: 30 times looser than KAGRA
  - Comparable in terms of strain; storage time 30)



Roadmap several year ago

	2009	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29

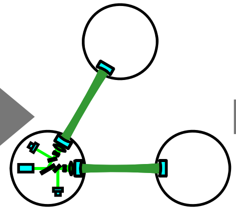
Mission

R&D
Fabrication

SWIM

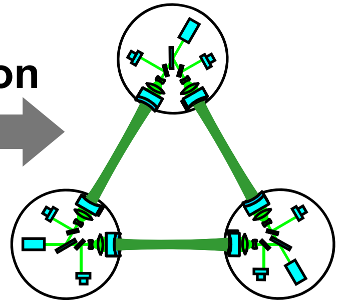
DICIGO Pathfinder

R&D
Fabrication



Pre-DECIGO

R&D
Fabrication

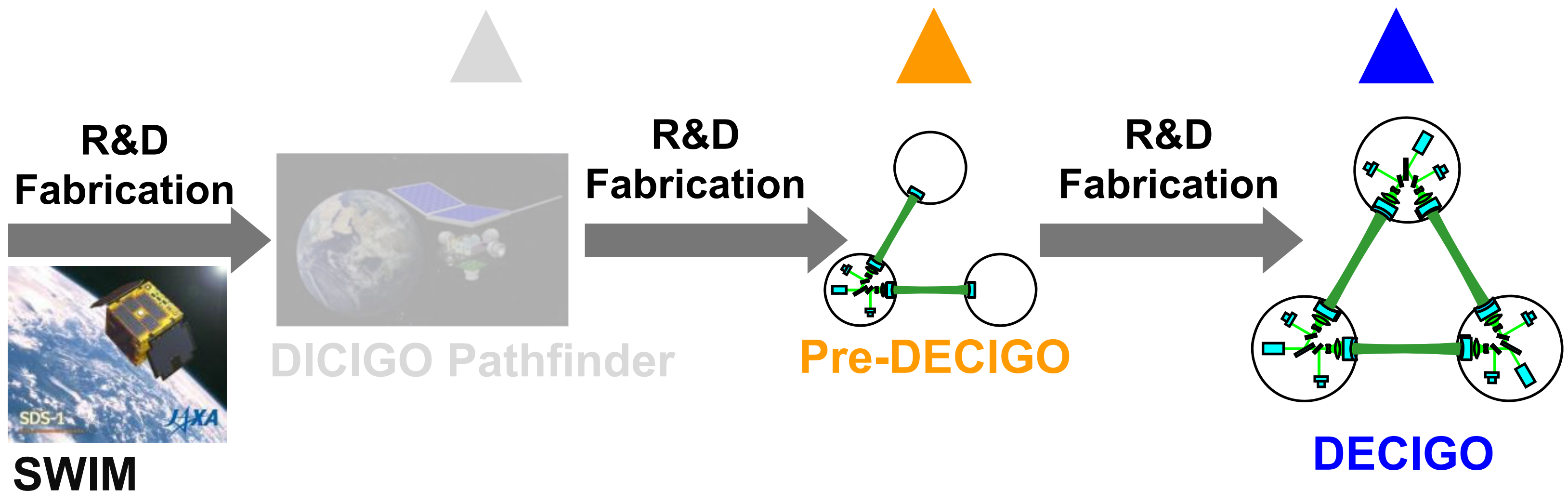


DECIGO

Objectives	Test of key technologies	Detection of GW w/ minimum spec. Test FP cavity between S/C	Full GW astronomy
Scope	1 S/C 1 arm	3 S/C 1 interferometer	3 S/C, 3 interferometers 4 clusters

Roadmap updated

Mission



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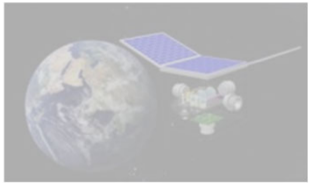
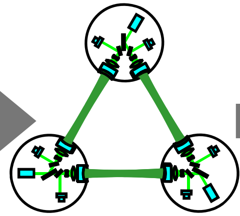
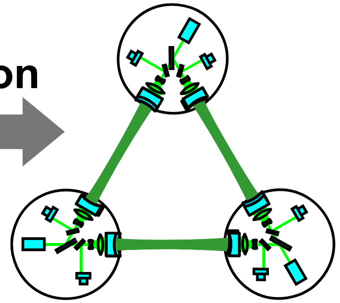
Scope	1 S/C 1 arm	3 S/C 1 interferometer	3 S/C, 3 interferometers 4 clusters

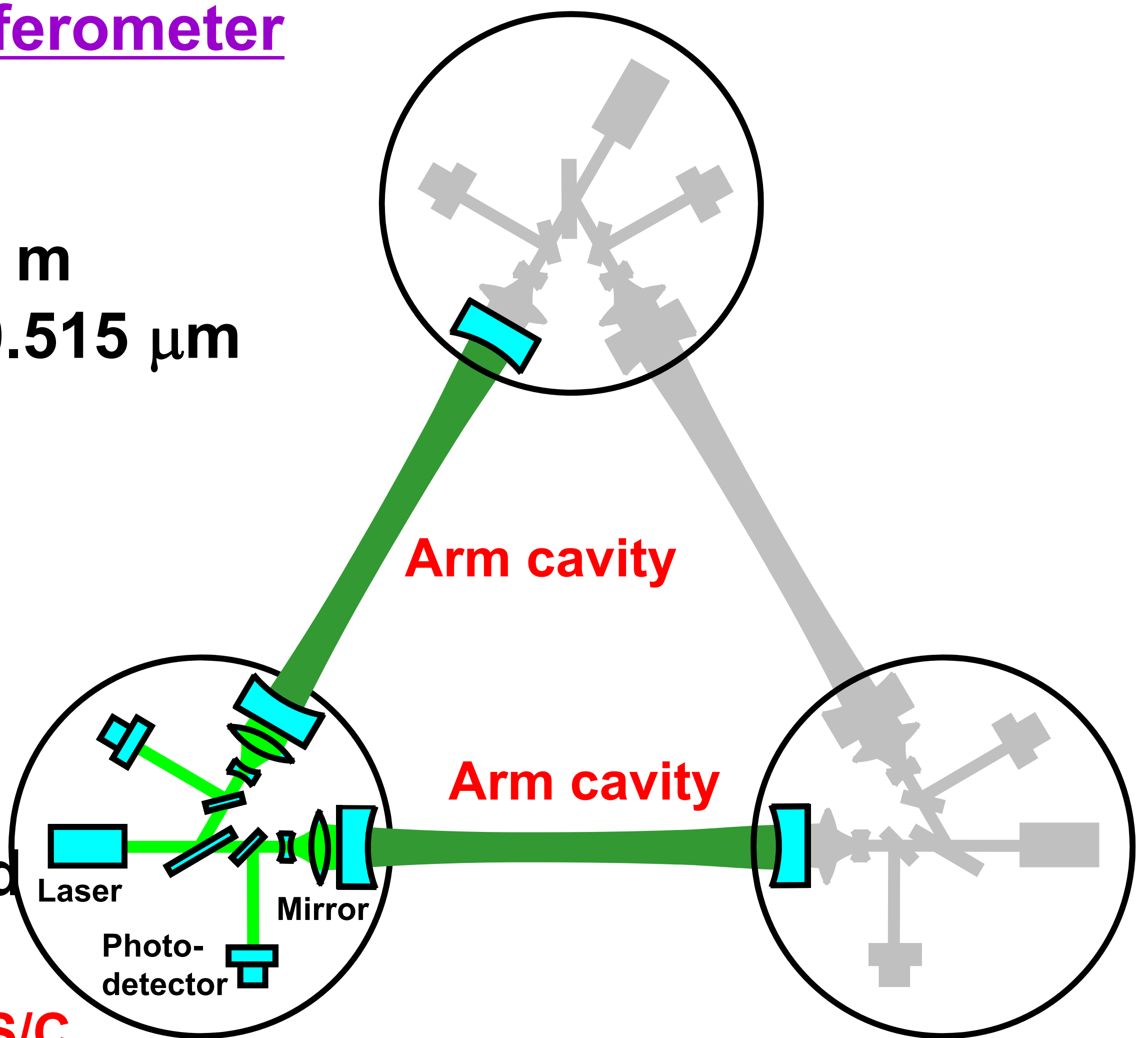
Roadmap updated

Mission	R&D Fabrication  SWIM  DICIGO Pathfinder	R&D Fabrication  B-DECIGO	R&D Fabrication  DECIGO
Objectives	Test of key technologies	Detection of GW w/ minimum spec. Test FP cavity between S/C	Full GW astronomy
Scope	1 S/C 1 arm	3 S/C 3 interferometer	3 S/C, 3 interferometers 4 clusters

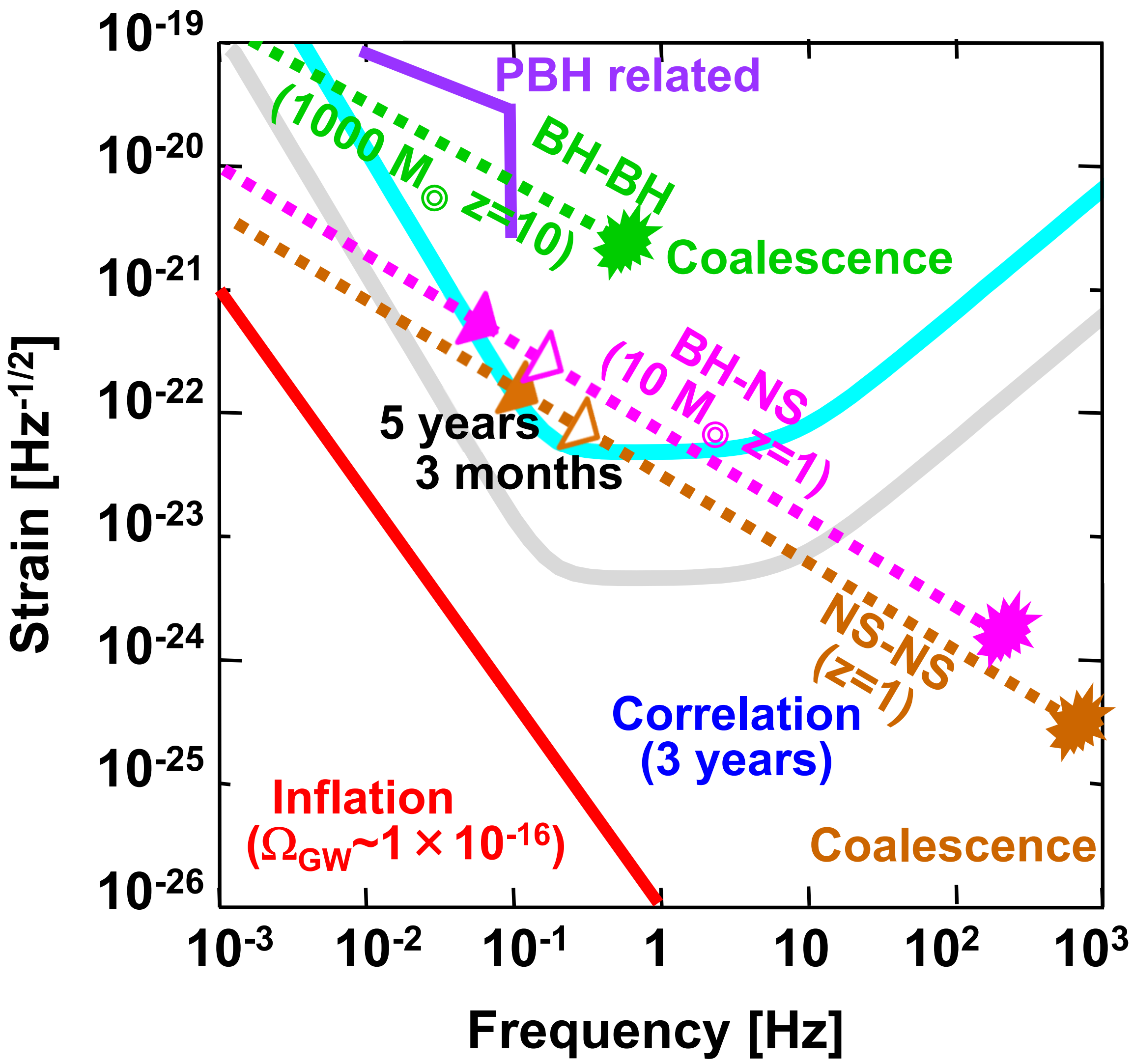
B-DECIGO

Differential FP interferometer

Arm length: 100 km
Mirror diameter: 0.3 m
Laser wavelength：0.515 μm
Finesse: 100
Laser power: 1 W
Mirror mass: 30 kg
S/C: drag free
3 interferometers
Orbit: TBD
(Record disk around the Earth?)



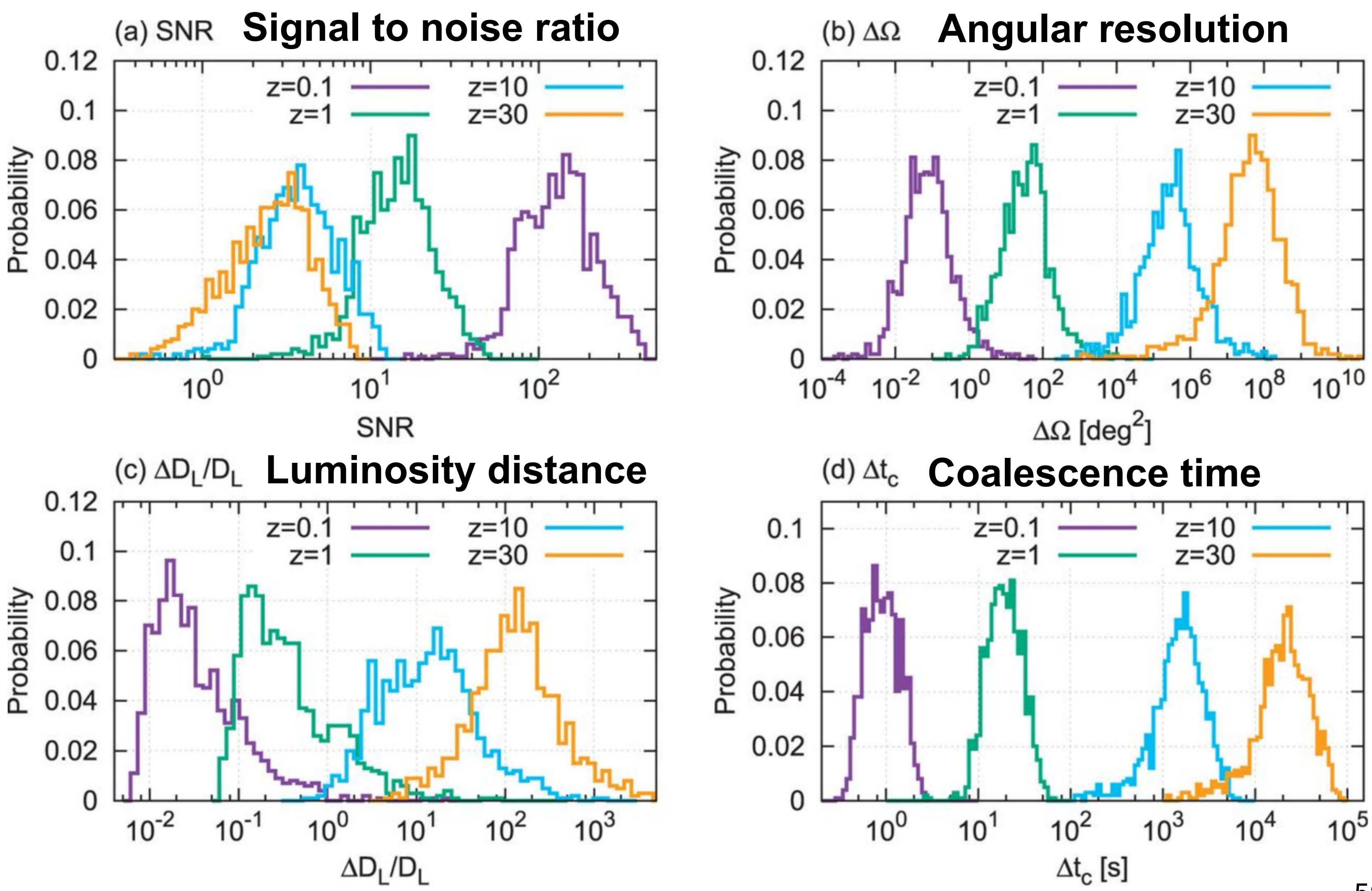
Target sensitivity



Objectives

- Observation of NS-NS (BH) binary
  - Prediction of timing of NS-NS (BH) coalescence
  - 100 /year
- Observation of intermediate-mass BH-BH
- Removal of foreground for DECIGO
- Verification of technology for DECIGO

Parameter estimation



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Summary

- DECIGO will accomplish a variety of amazing science including direct observation of the birth of the Universe and Higgs-related science.
- I would like to strongly encourage researchers of Higgs to think of new ideas to obtain clue of Higgs from detection of GW by DECIGO.