The Dawn of Gravitational-wave Astronomy

University of Tokyo, Institute for Cosmic Ray Research

Keiko Kokeyama

ICEHAP Seminar @ Chiba University

January 26^{th}, 2017

My Profile

Keiko Kokeyama

- Originally from Kobe, Kansai
- Gravitational Wave Detection
- Working for KAGRA Project
- PhD in Ochanomizu University
- Worked in LIGO Livingston, etc.

Contents

- Gravitational Wave (GW) Detection
- About the Interferometric Detectors
- Japanese Project, KAGRA
- Future Prospects
- (If we have time) Additional Stories

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LIGO Detected Gravitational Waves!

Nobel Prize!?

They already won...

- Special Breakthrough Prize in Fundamental Physics (Drever, Thorne, Weiss and the LIGO discovery team)
- 2016 Kavli Prize in Astrophysics (Drever, Thorne and Weiss)
- Shaw prize in Astronomy (Drever, Thorne and Weiss)
- 2016 Gruber Foundation Cosmology Prize (Drever, T ... d t ... ry t

Thorne

Drever

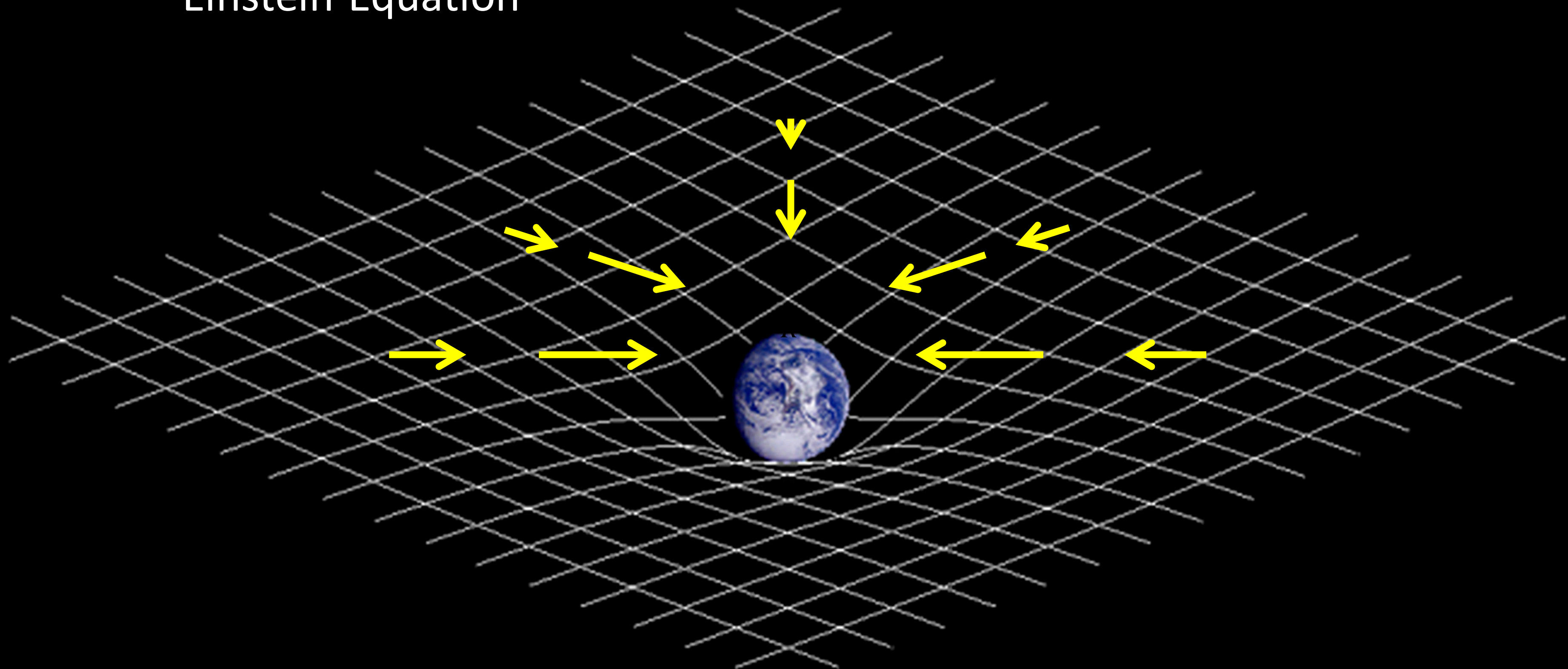
Weiss

Gravity and Gravitational Waves

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi \frac{G}{c^4} T_{\mu\nu}$$

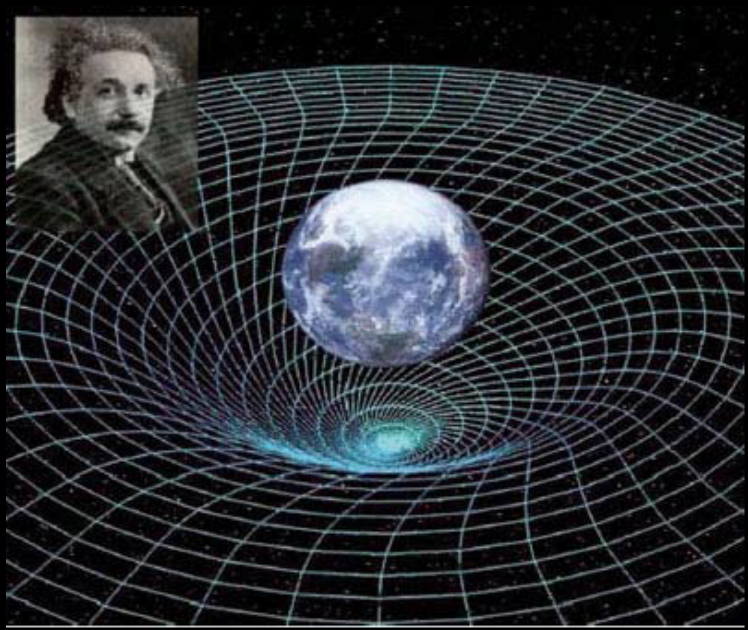
Einstein Equation

The equation to express how mass distributions affect to space-time

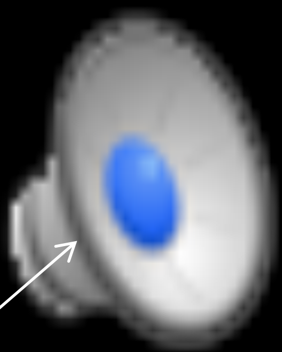


Strain of space-time propagates at the speed of light

Static Gravity

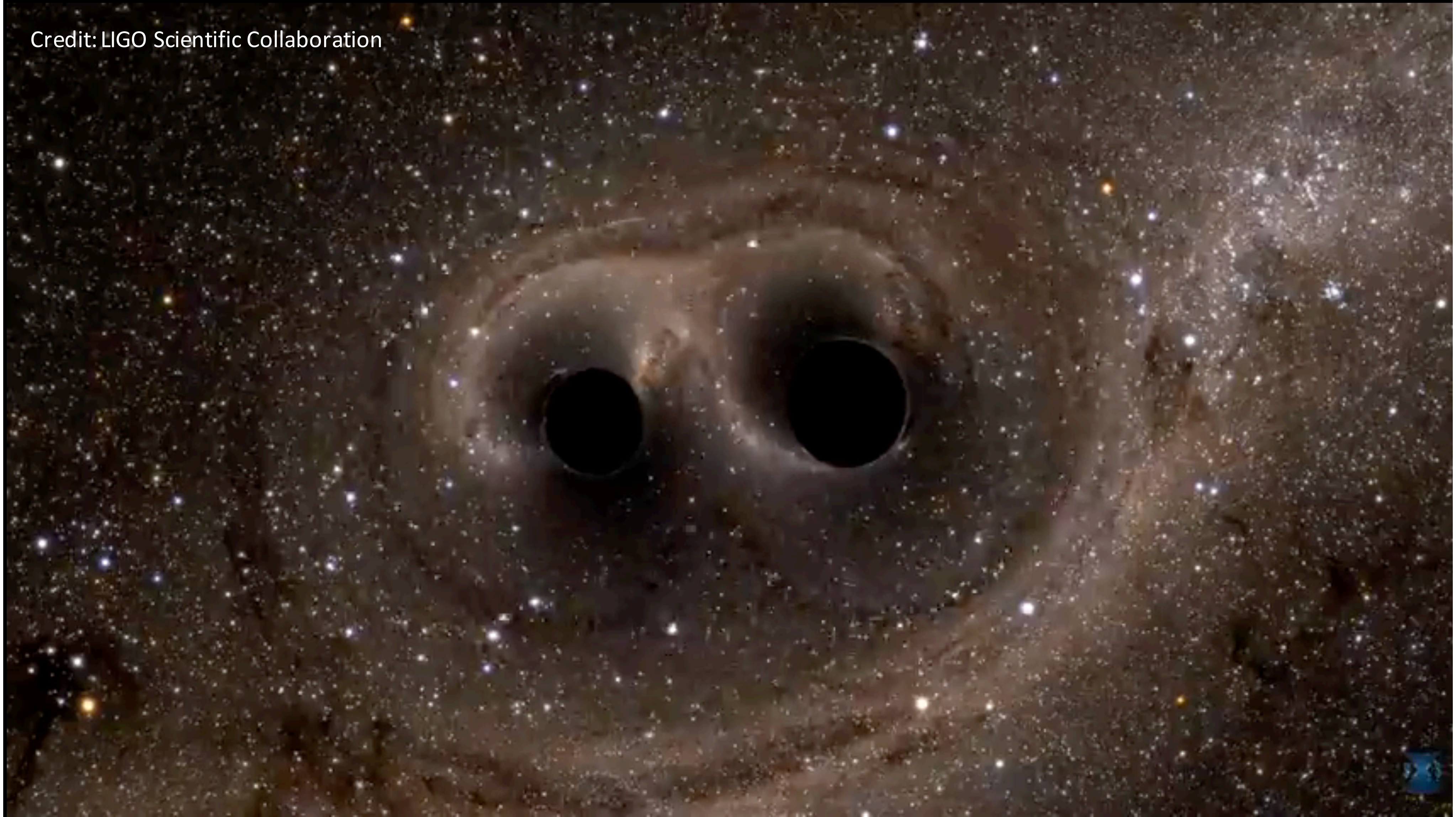


Gravitational Waves



Very heavy masses
non-axial symmetrical moving

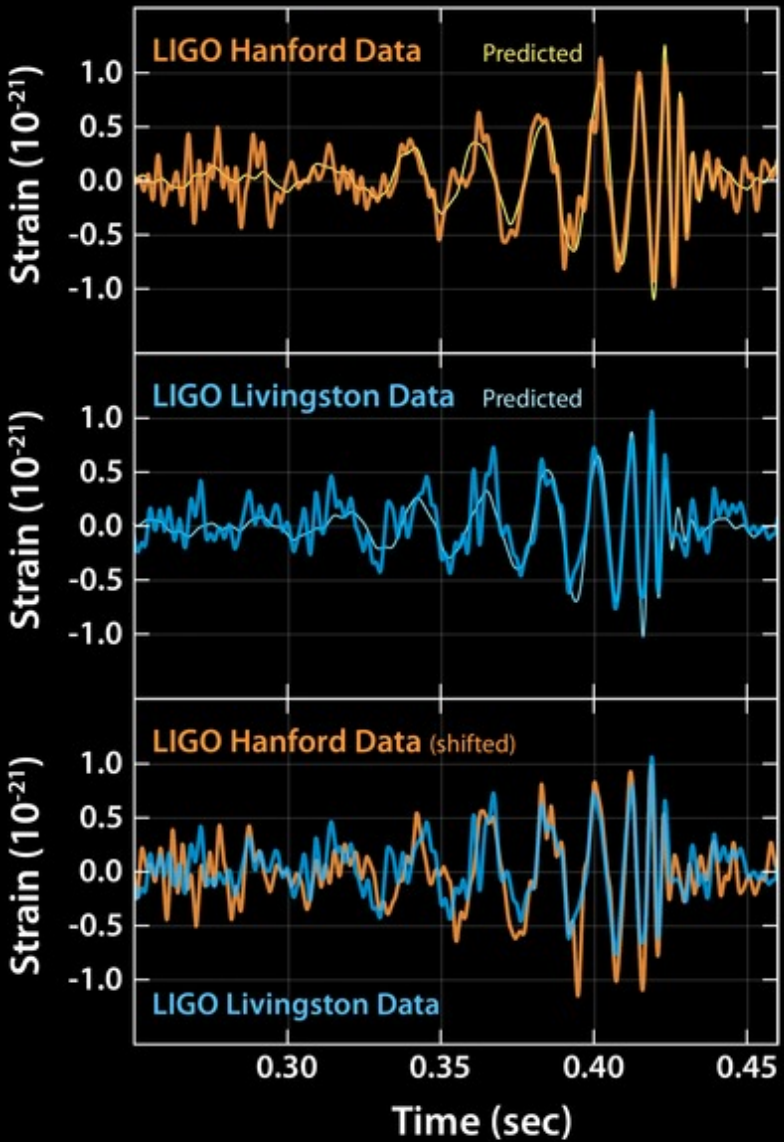
LIGO Caught Signals from Binary Black Holes!

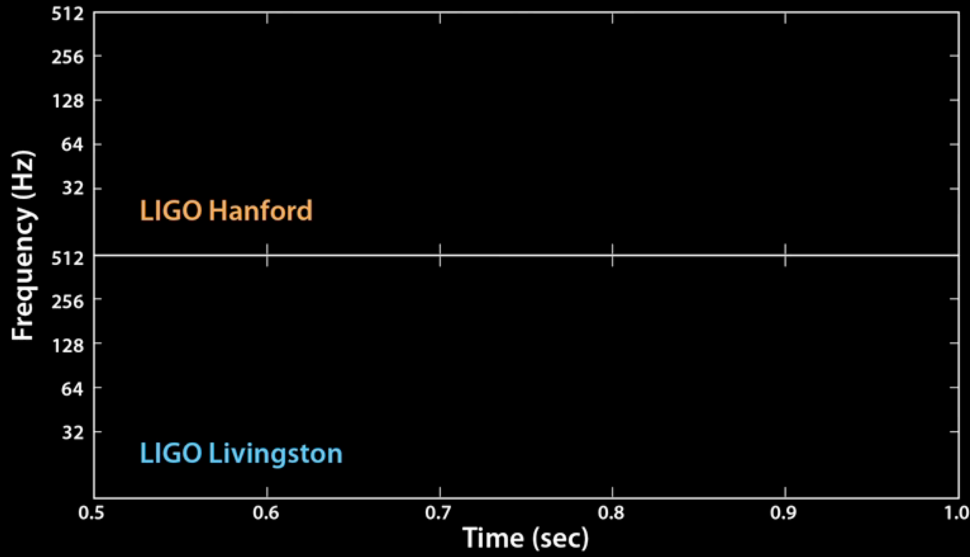


Advanced LIGO: Laser Interferometric GW detectors

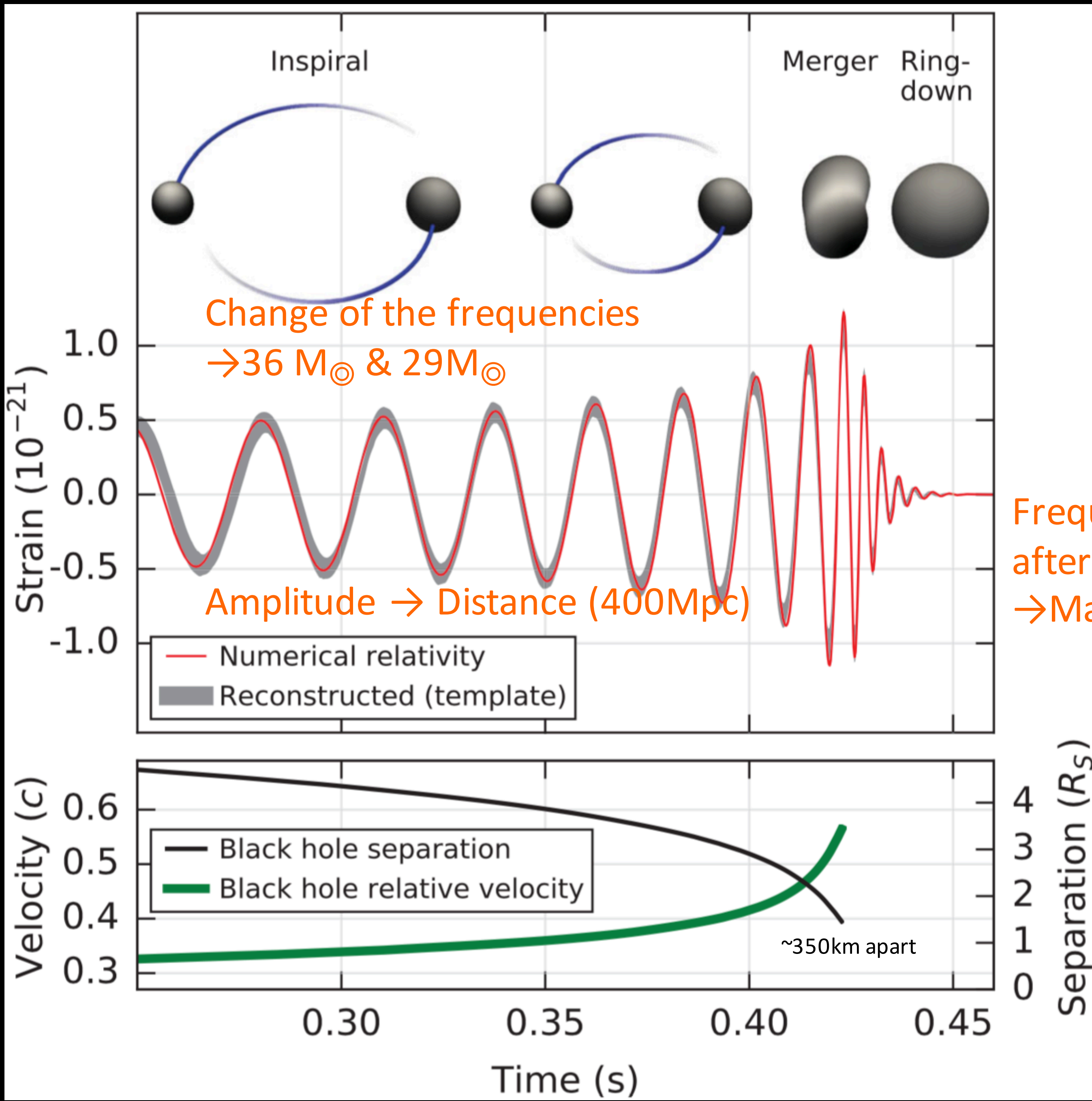
Livingston Observatory (LLO) Hanford Observatory (LHO)

What are the Signals Like?





LIGO Scientific Collaboration, PRL 106, 061102 (2016)



62-(36+29)
= 3 $M_\odot$ energy emit

Impact of the Discovery

- The first observation of space-time strain due to GWs
- The signals do not contradict against GR
- The first observation of binary black holes
- The first observation of the binary black hole merger
- The first observation of $30M_{\odot}$ black holes

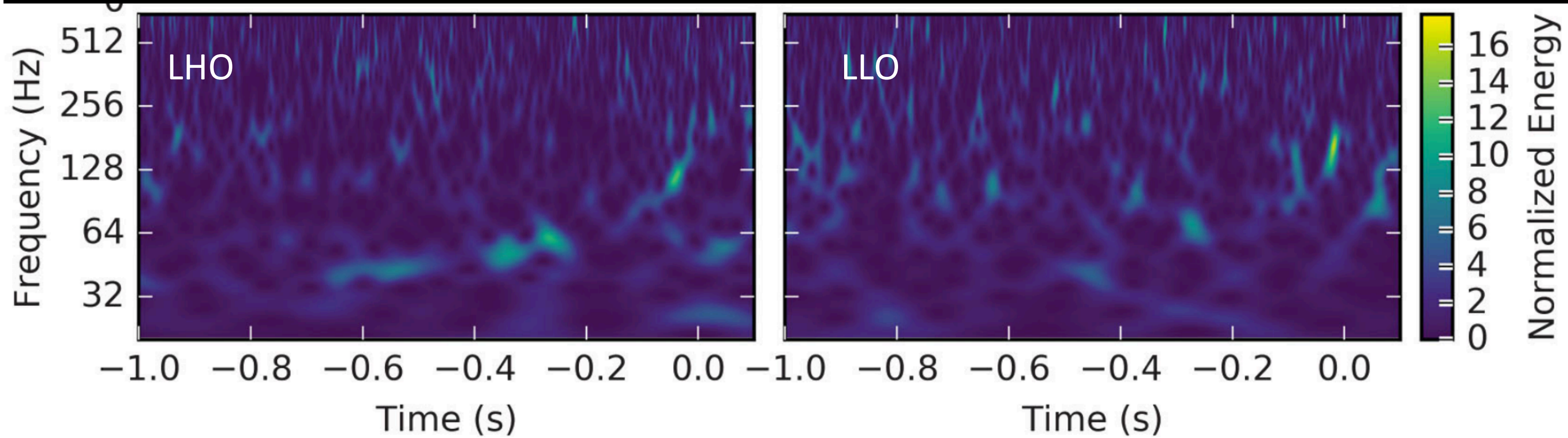
Surprise!

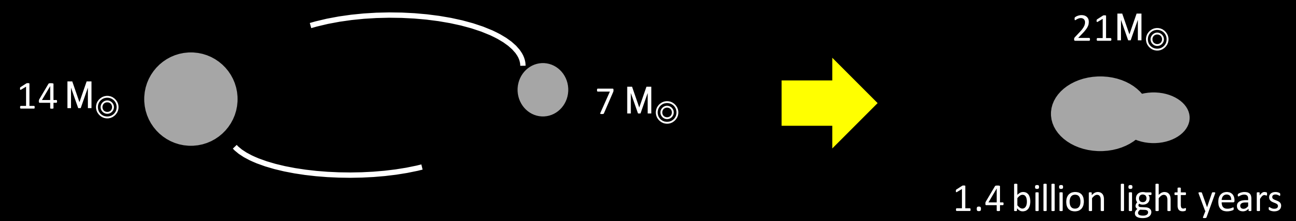
1. The signals came just before the official start of the first observation run
2. People anticipated the first signals would be from binary neutron starts
3. Observed BHs had ~30 solar-mass

The Second Event, GW151226

Another BBH merger!

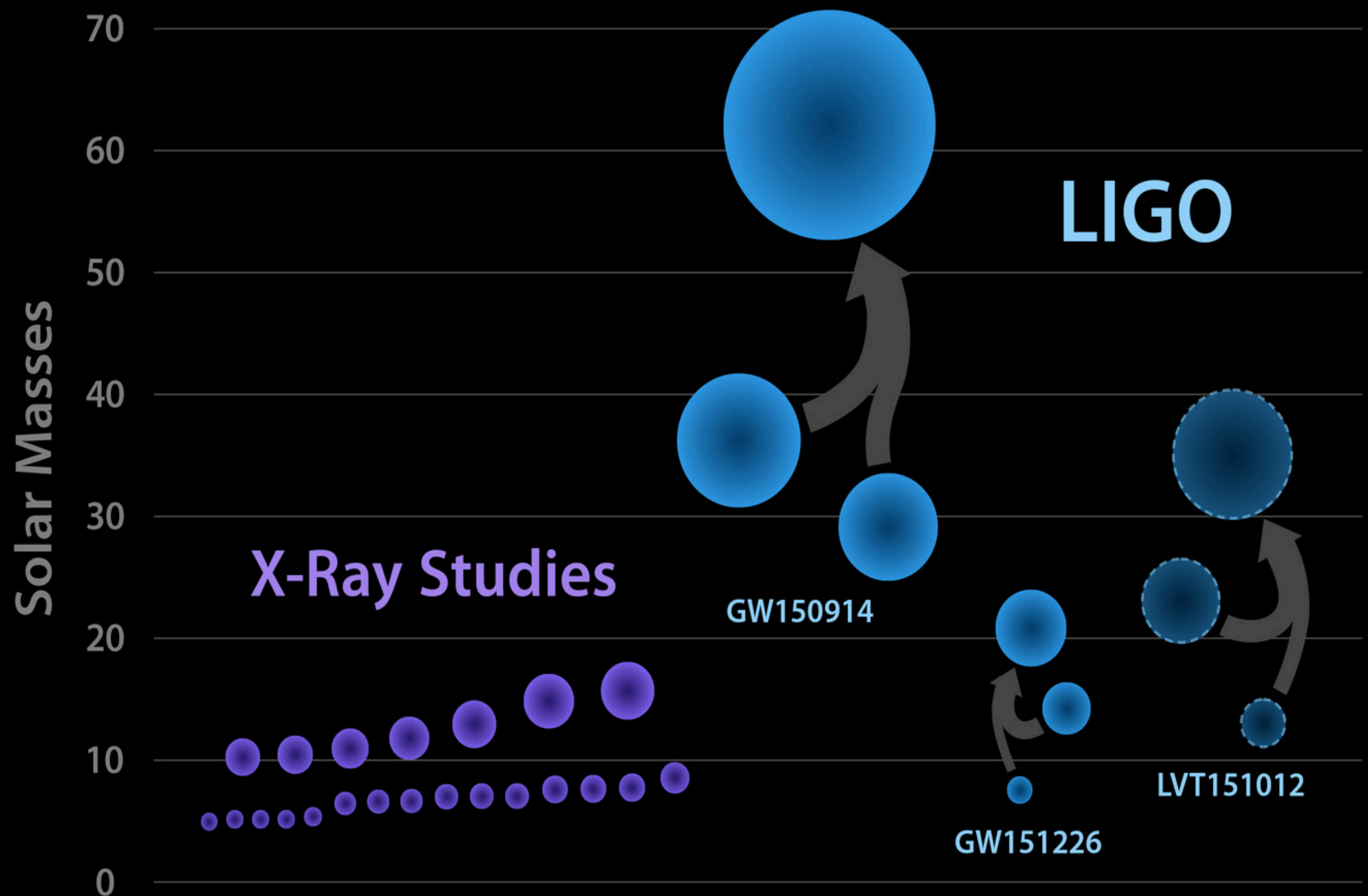
Phys. Rev. Lett. 116, 241103 (2016)





Black hole mergers exist more than we assumed?

30 Solar-mass Black Holes



LIGO; https://www.ligo.caltech.edu/image/ligo20160615e

There are supermassive (>$10^6 M_{\odot}$) BHs

30 Solar-mass Black Holes

How 30$M_{\odot}$ black holes were formed?

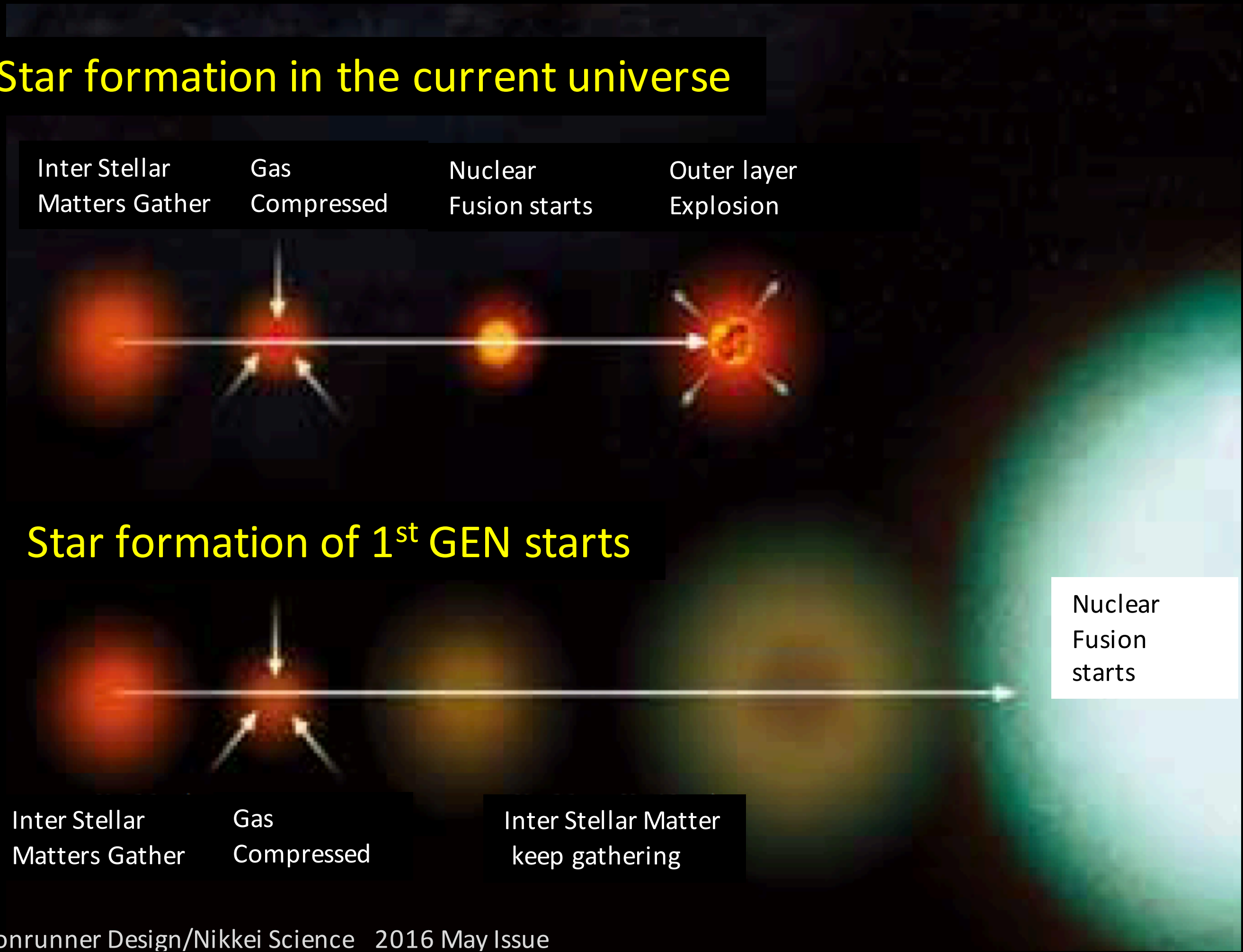


Figure: Moonrunner Design/Nikkei Science 2016 May Issue

The observed black holes might be from the early universe?

Kinugawa et al, MNRAS 442, 2963–2992 (2014)

Conventional observations with electro-magnetic waves

Observations with Gravitational waves

Illustration: Sora Kawamura

Photo album for
13 billion years of the universe

Sound track of the universe

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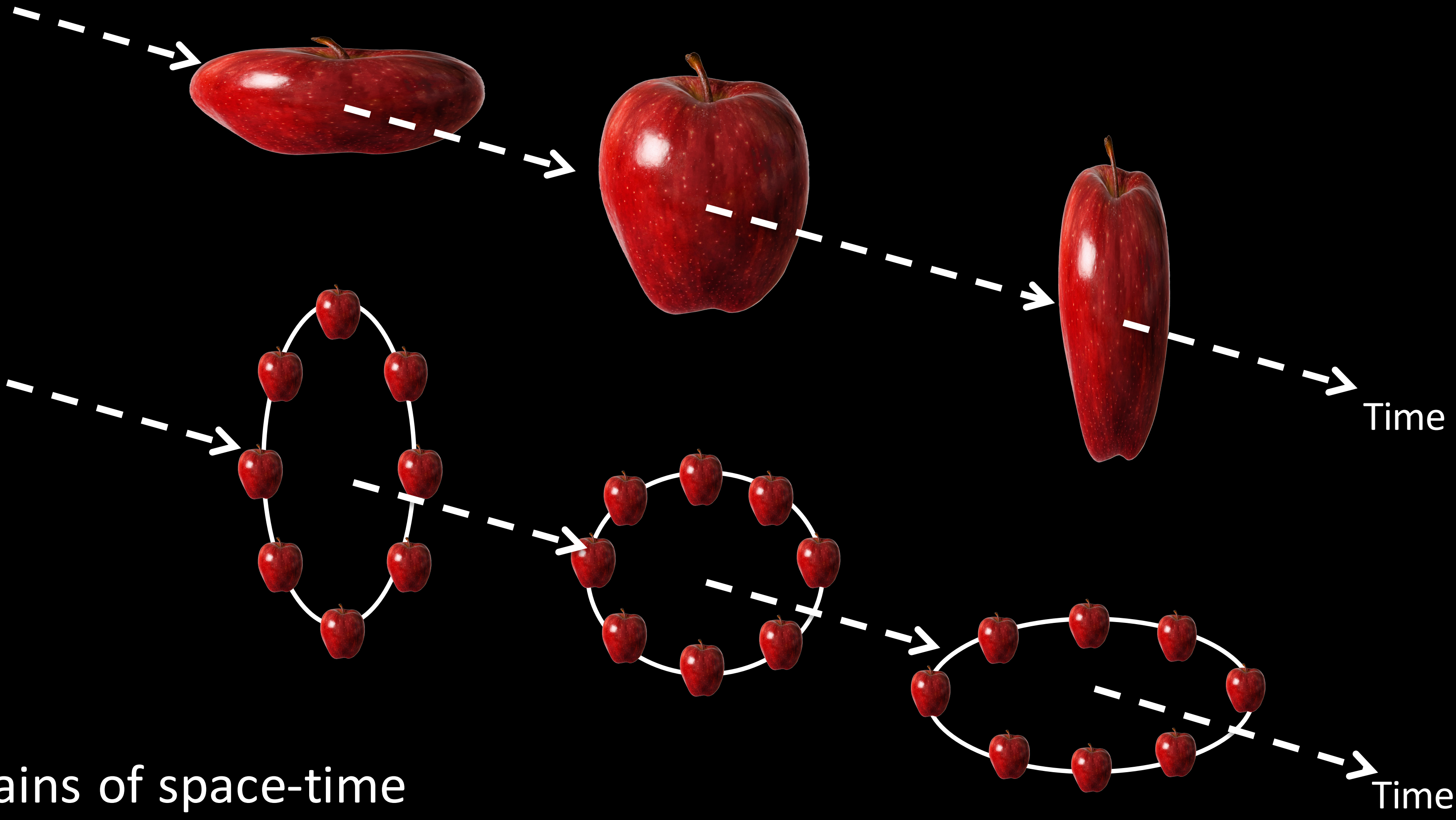
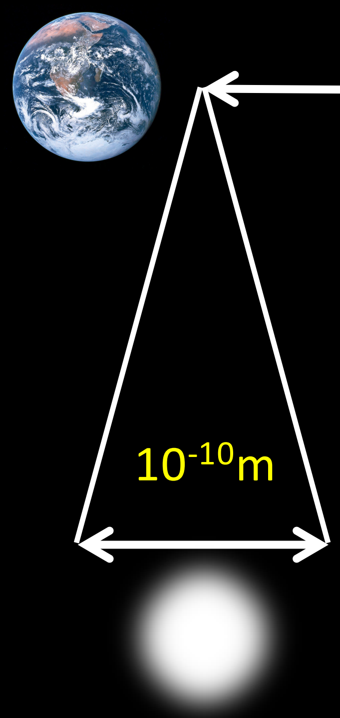
When GWs come to Earth…

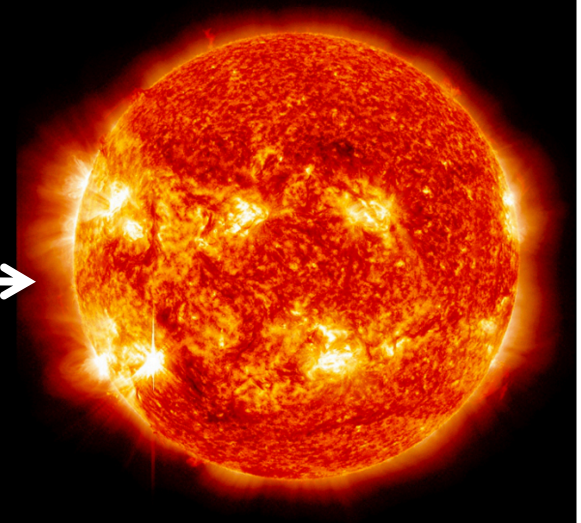


Strains of space-time
change the distance between masses

How much is the change?

As small as a hydrogen atom size change
for an Earth-Sun distance!



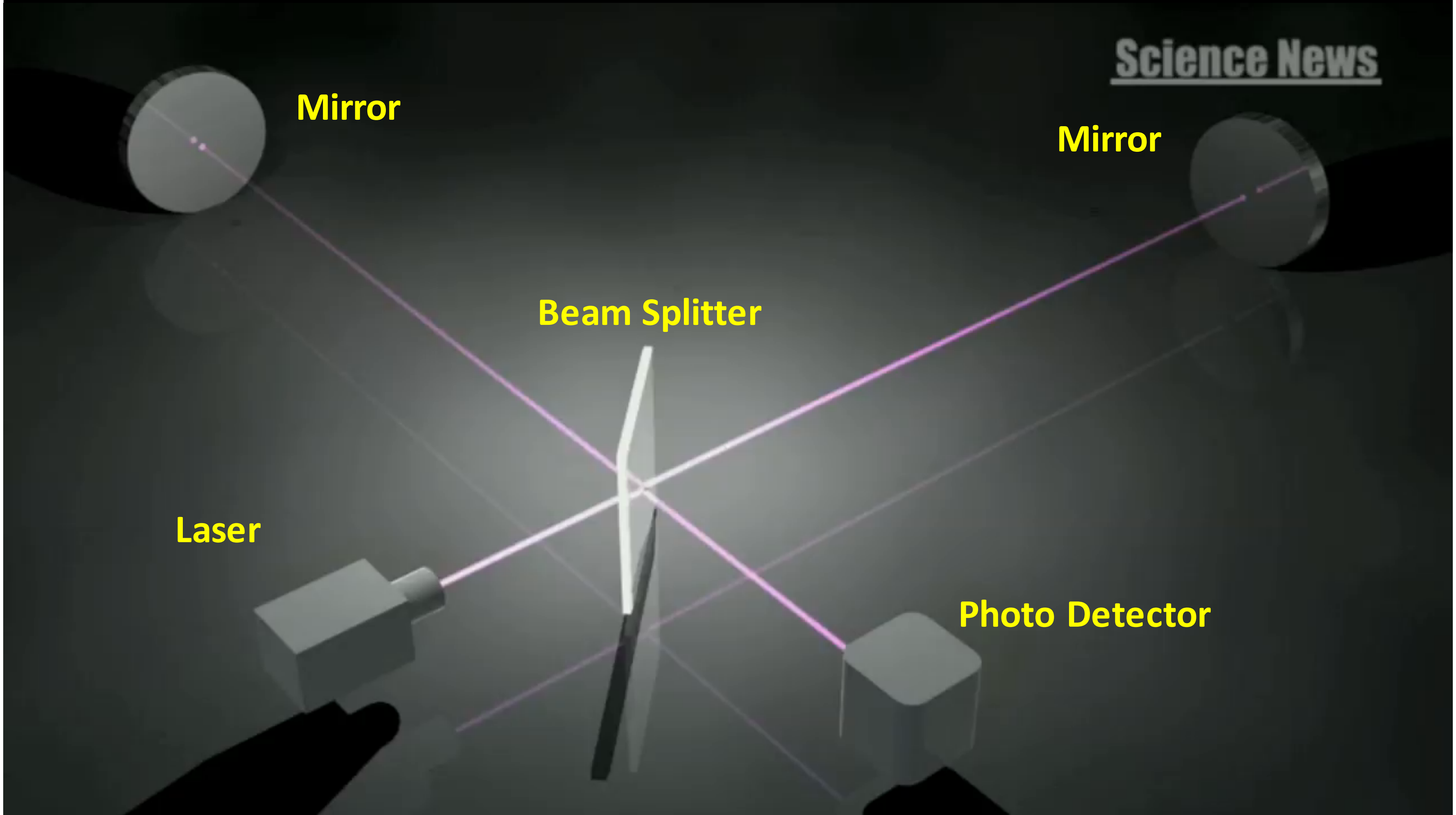


Fraction of the distance change

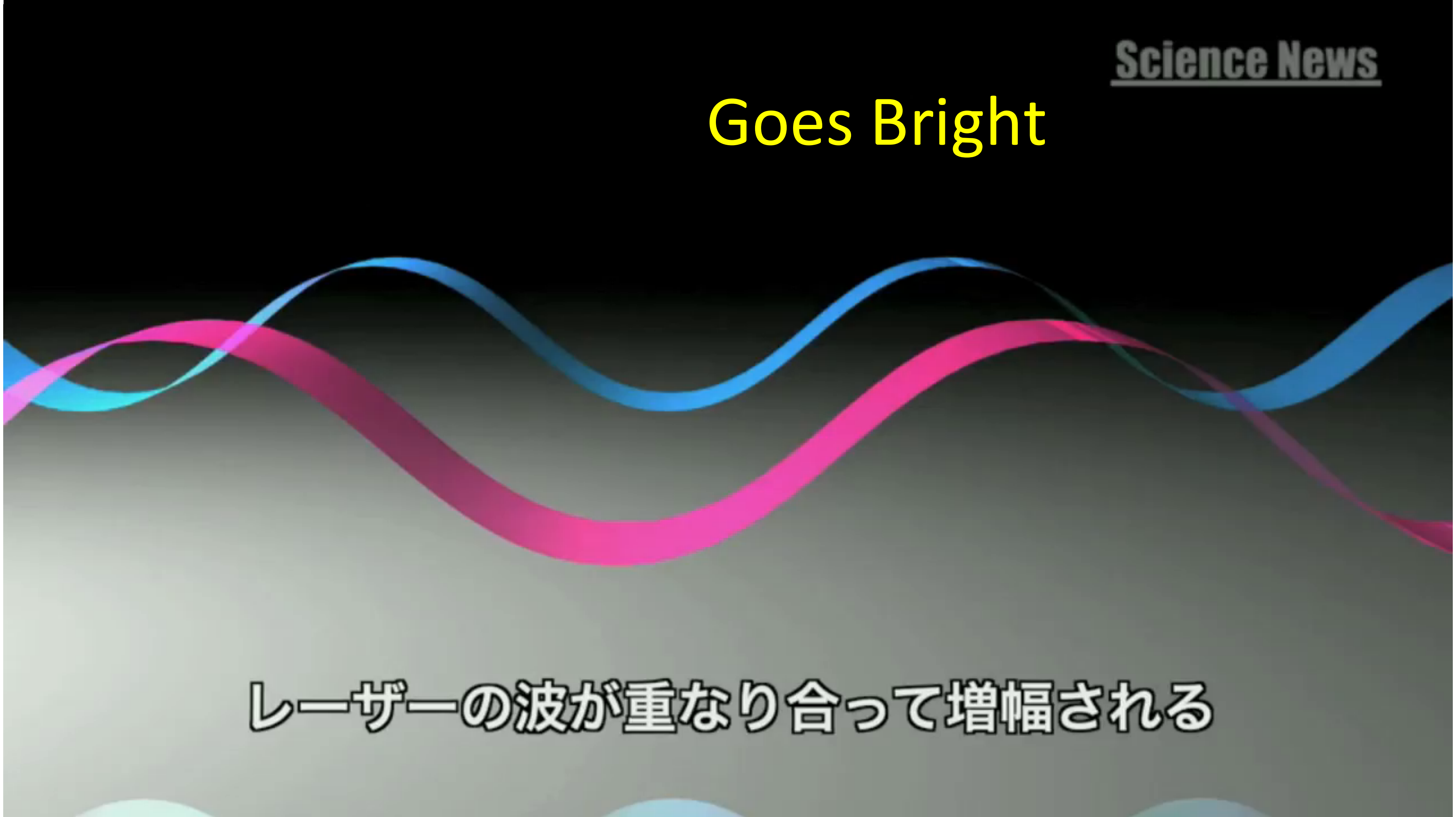
$= 10^{-10}\text{m} \;/\; 10^{11}\text{m}$

$= 10^{-21}$

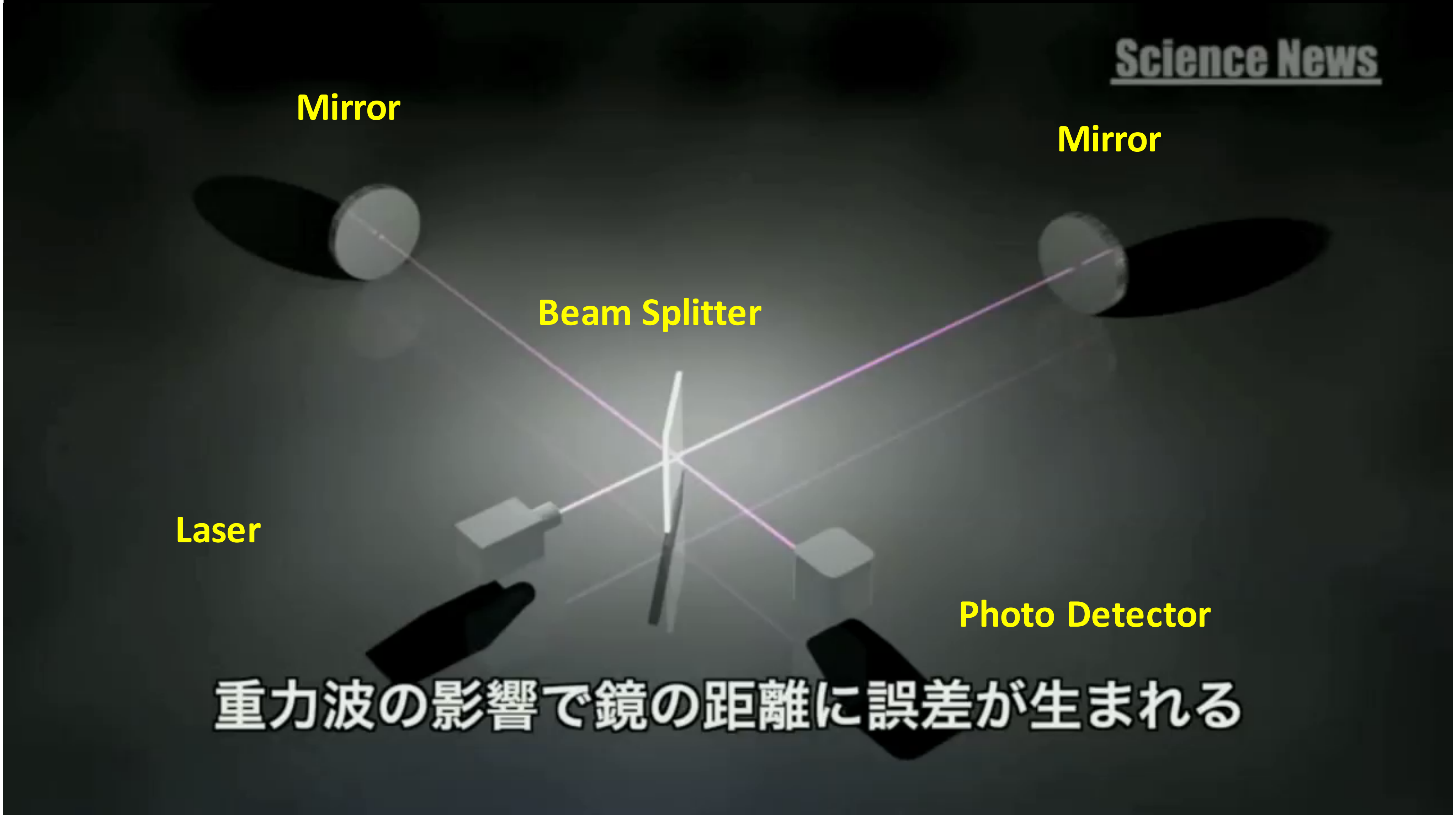
Laser Interferometer



Interfering



Laser Interferometer

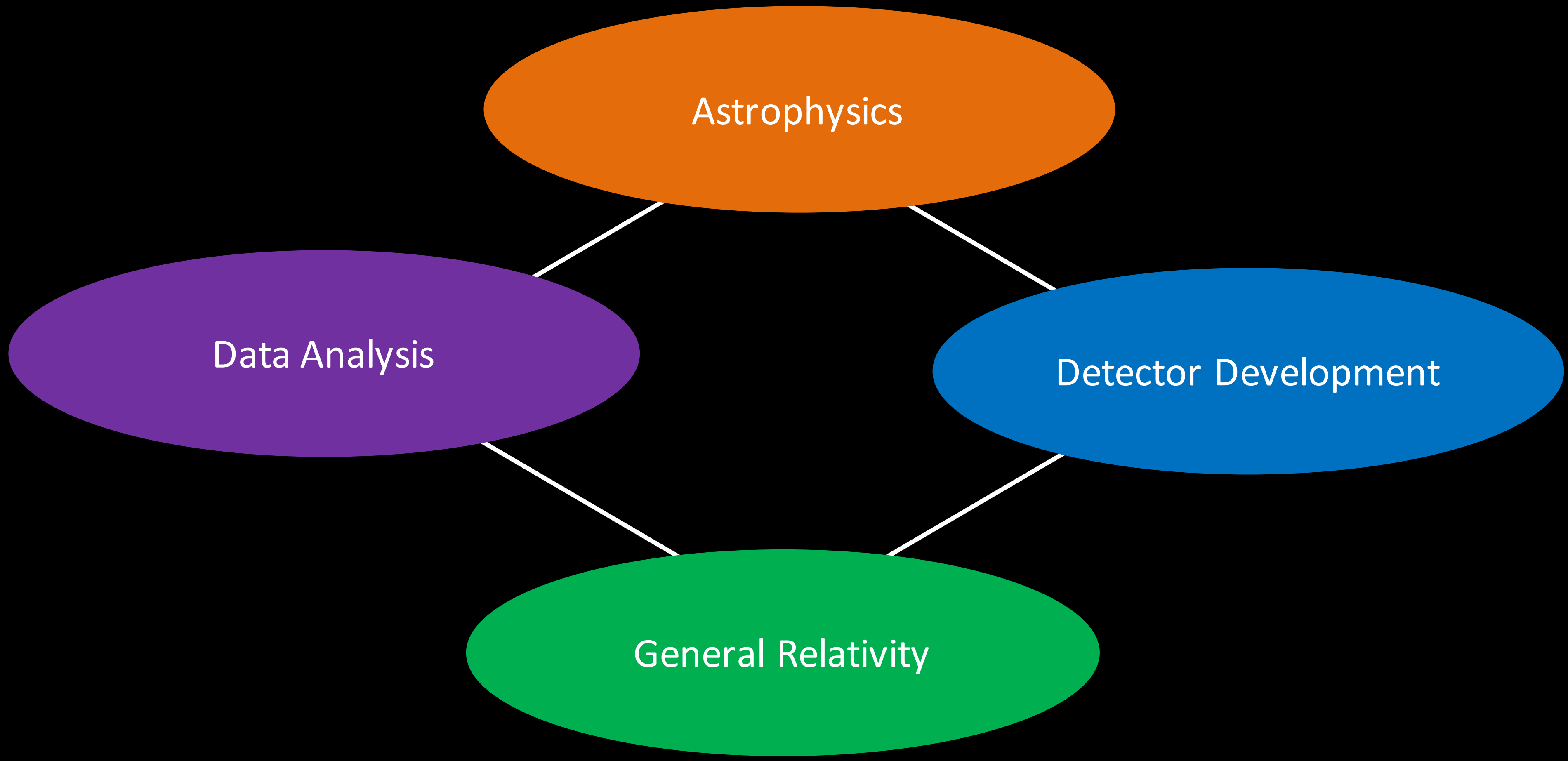


Interfered Light at Photo Detector

Research Field of GW Detection

Extremely difficult measurement

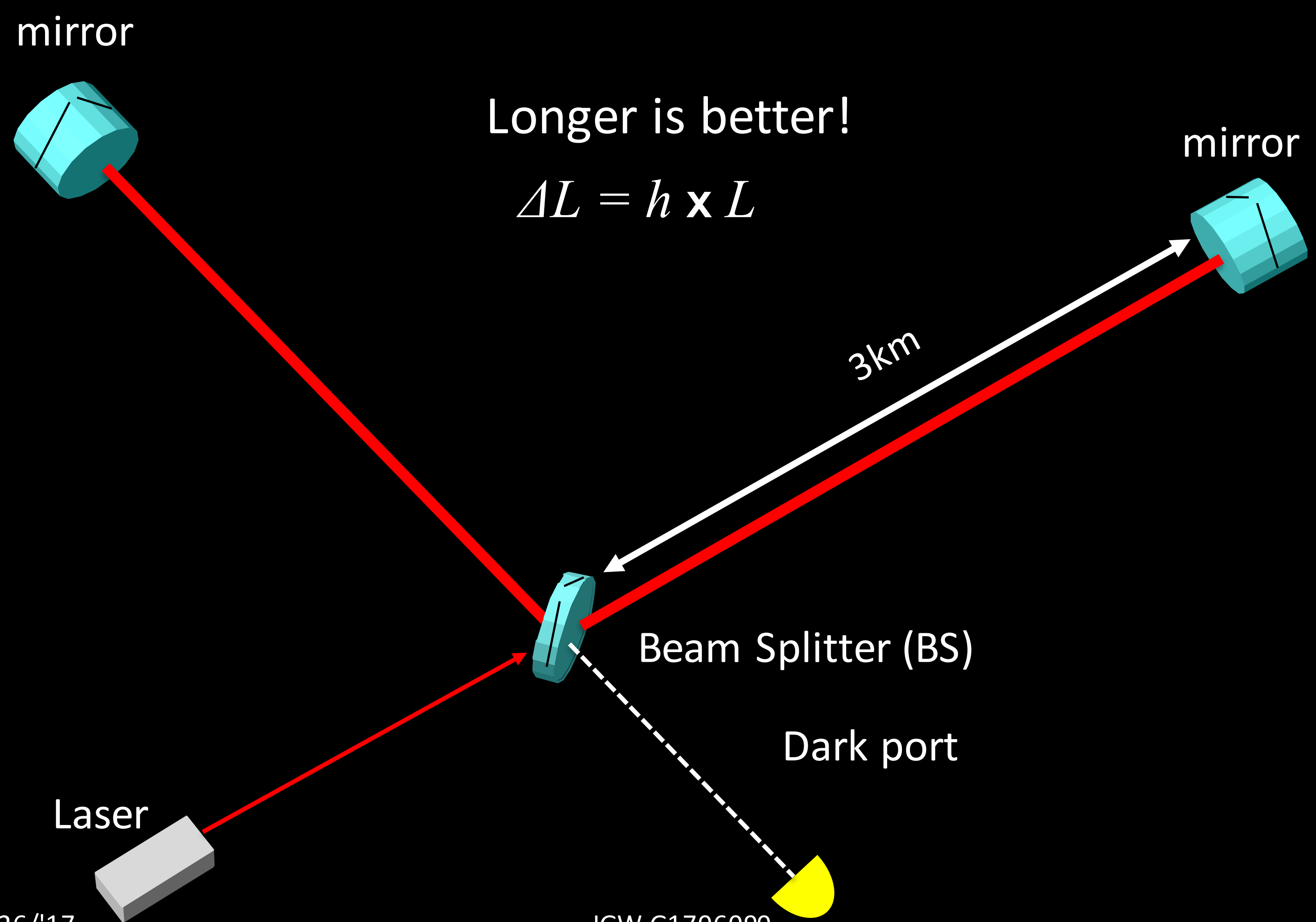
No Signal for 100 years



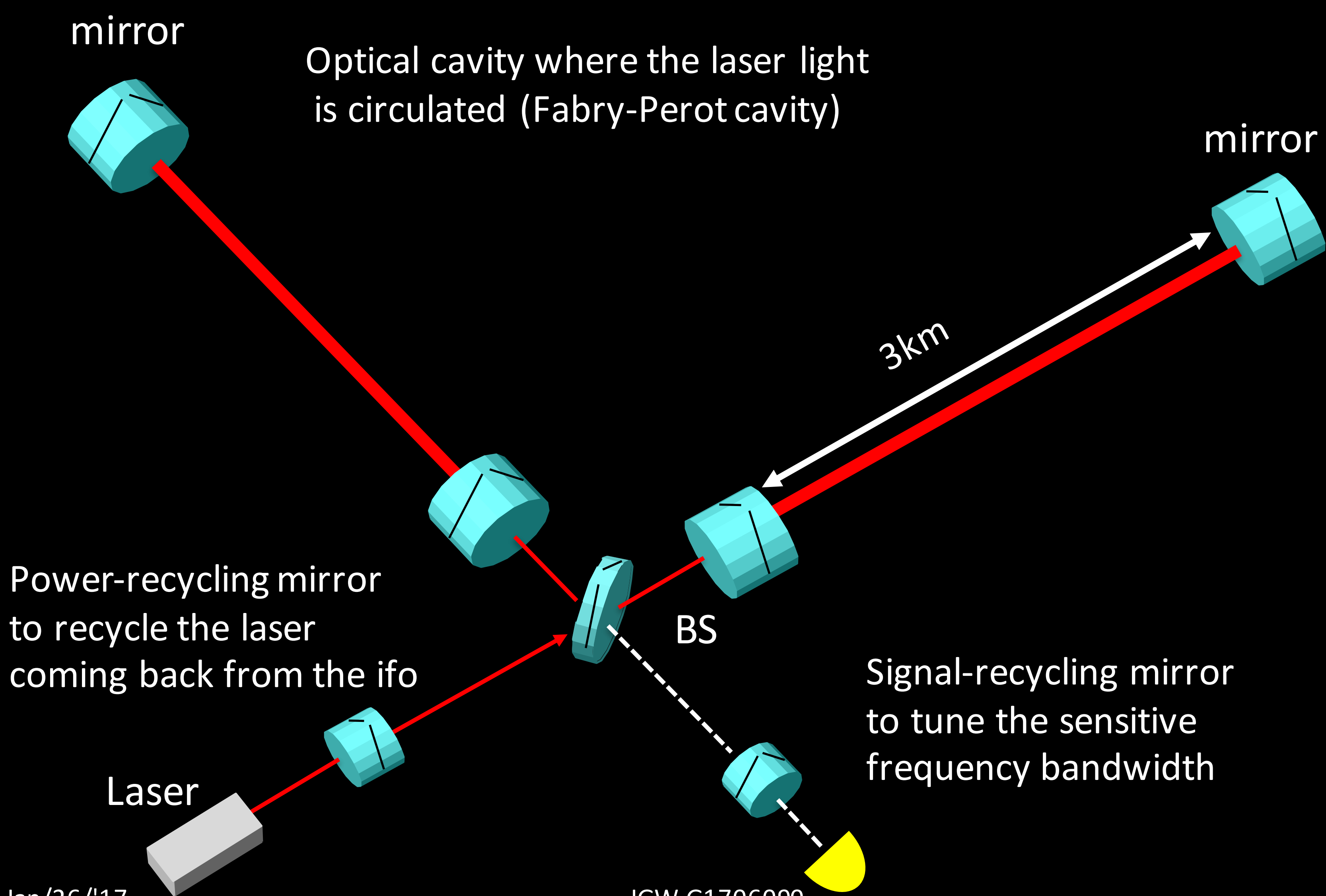
Towards Higher Sensitivity

Longer is better!

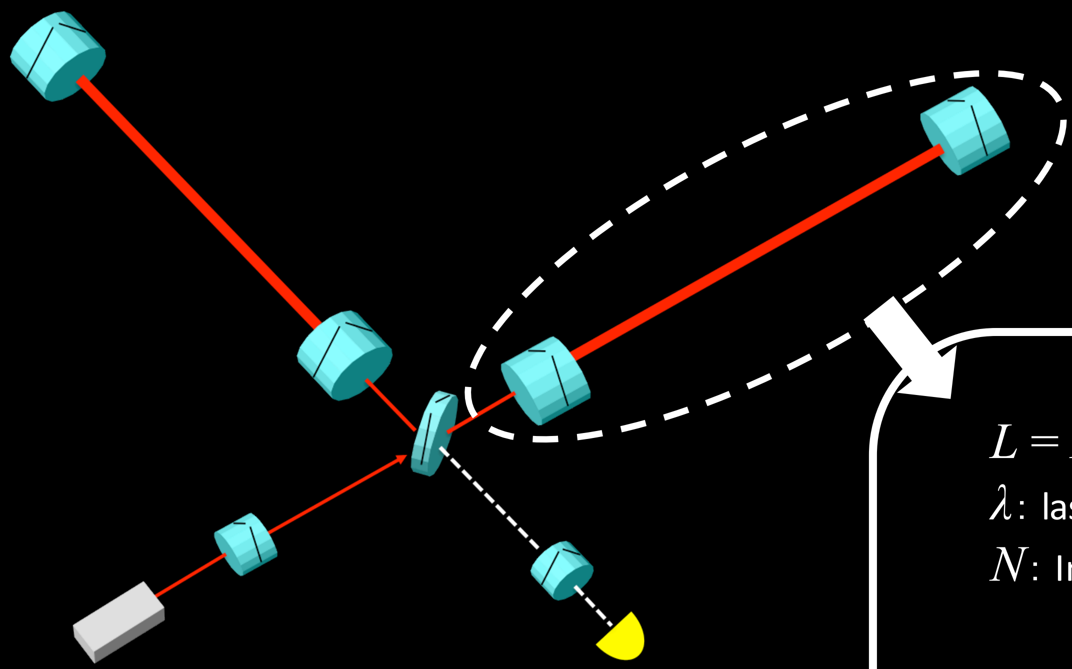
$\Delta L = h \times L$



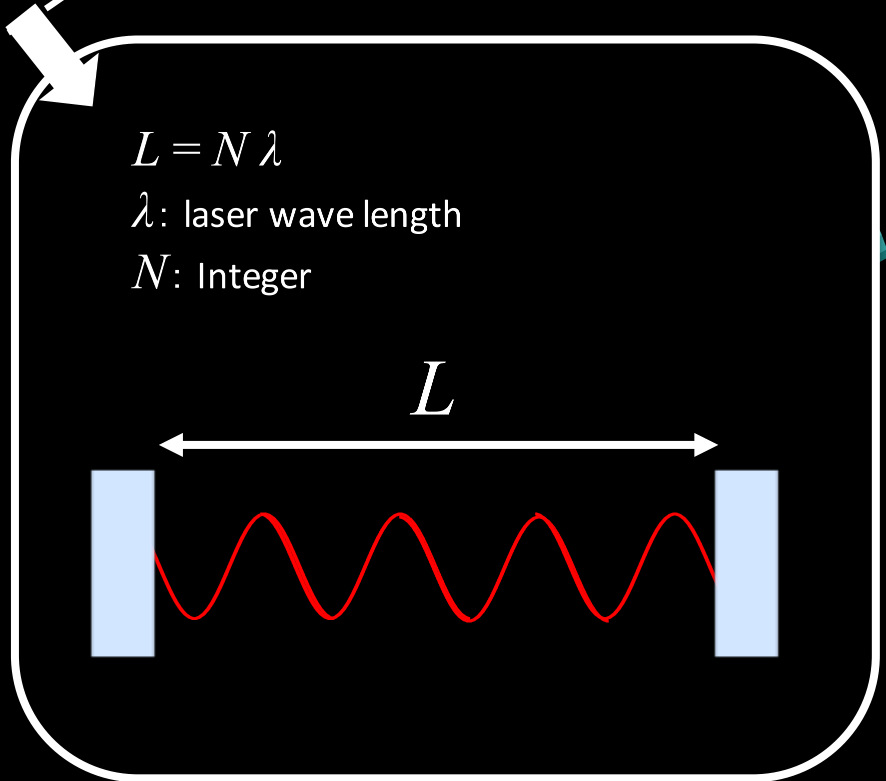
Amplifying the signals



Controlling the IFO

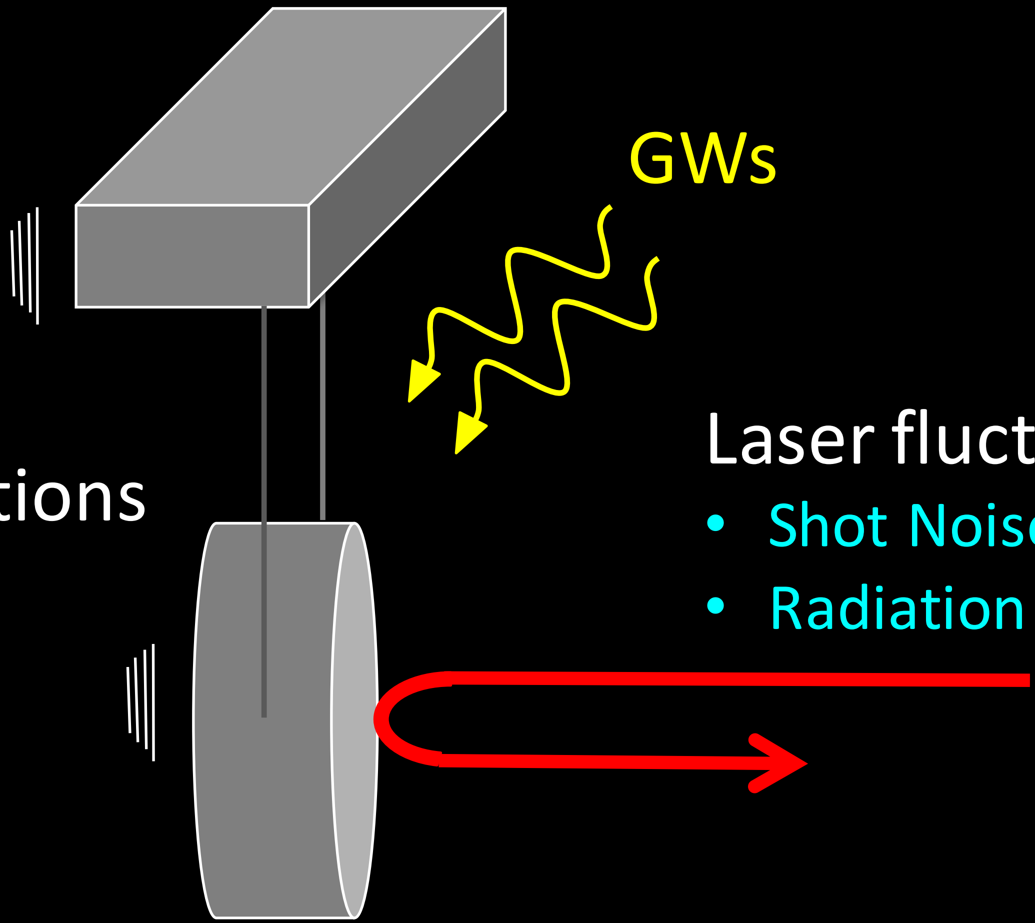


Lengths of optical cavities must be the integer multiple of the laser wave length



aLIGO & KAGRA have 5 DoF to control

Fundamental Noises in IFO



Mirror fluctuations

- Seismic Noise
- Thermal Noise

Laser fluctuations

- Shot Noise
- Radiation Pressure Noise

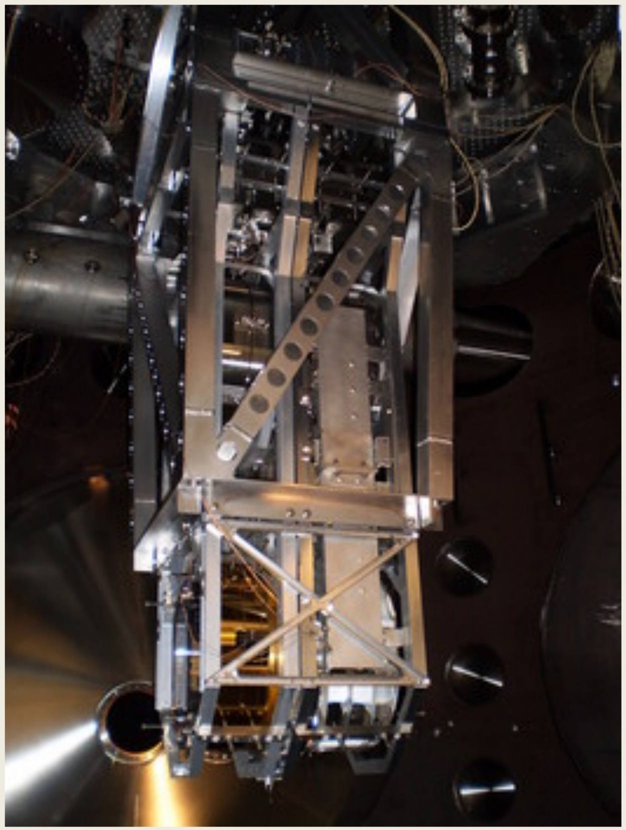
Seismic Noise

- Seismic motions (earthquakes) on the ground shake mirrors

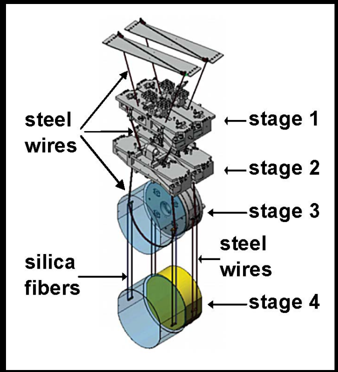
→ Suspend the mirrors

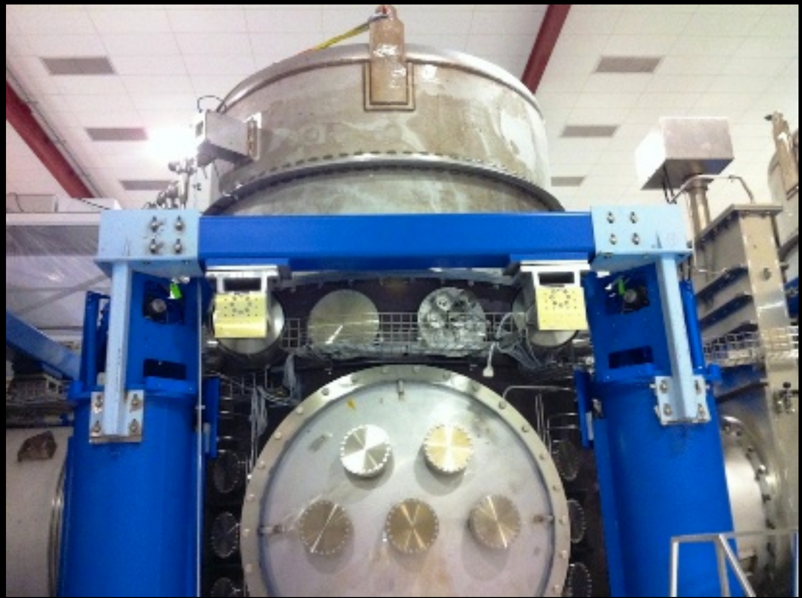
Vibration Isolation Systems in LIGO

Advanced LIGO's quadruple suspension



Cumming et al., CQG 29 (2012) 035003

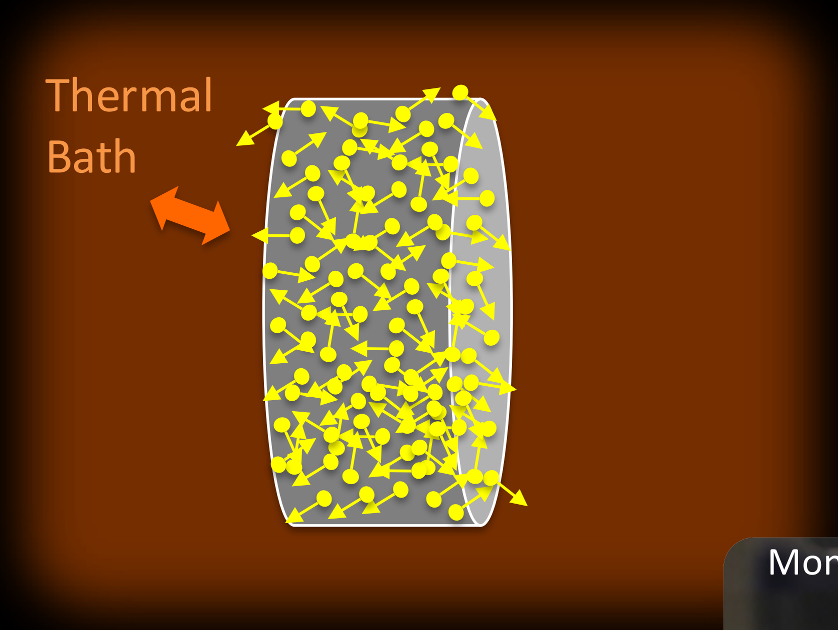




Platform with active vibration isolation

Thermal Noise

Noise due to interferometer being in a thermal bath

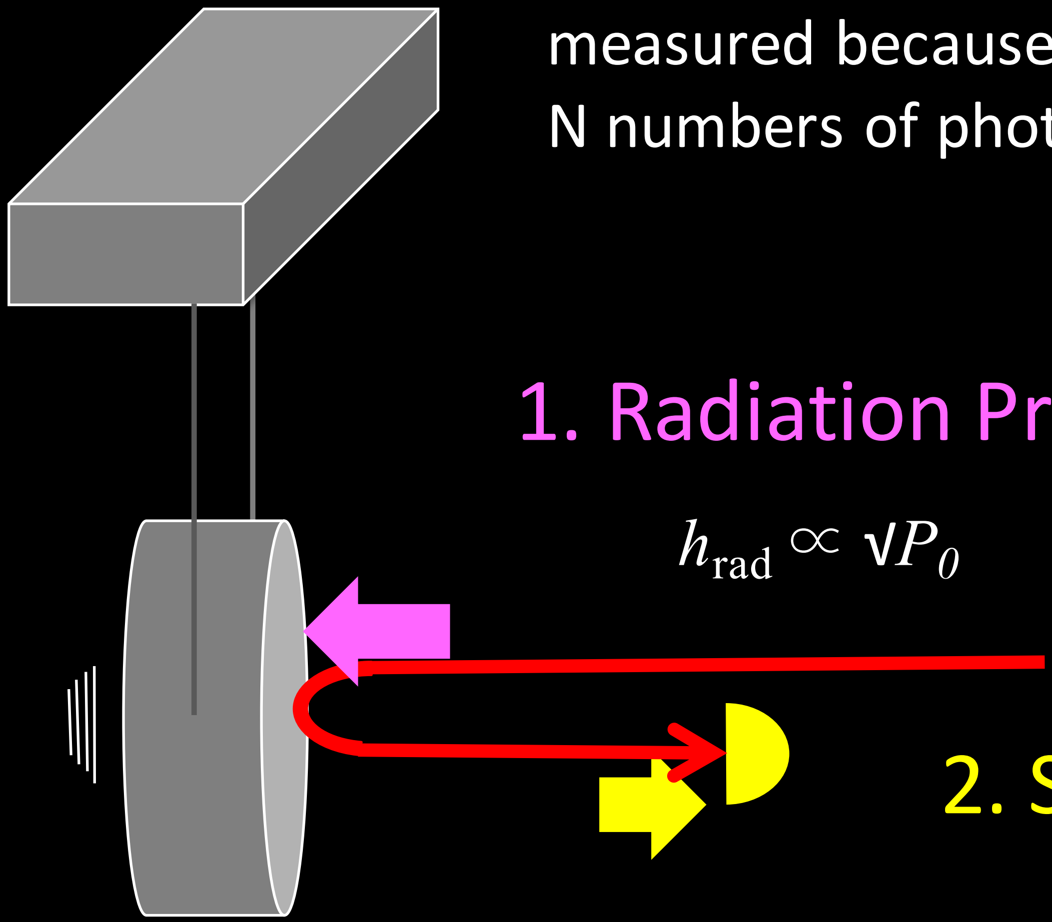


To reduce thermal noise,

- Low temperature is better
- High quality (Q) factor is better

Two kinds of Quantum Noise

Photon numbers (power) can't be exactly measured because of their quantum nature: N numbers of photons fluctuate sqrt(N)



1. Radiation Pressure Noise

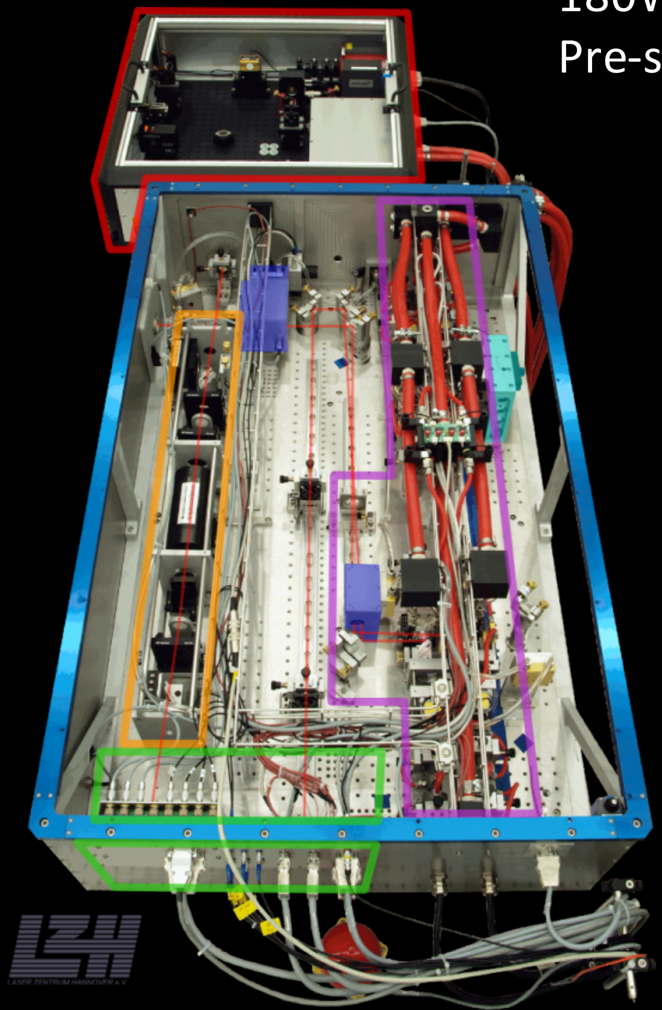
$h_{\mathrm{rad}} \propto \sqrt{P_0}$

2. Shot Noise

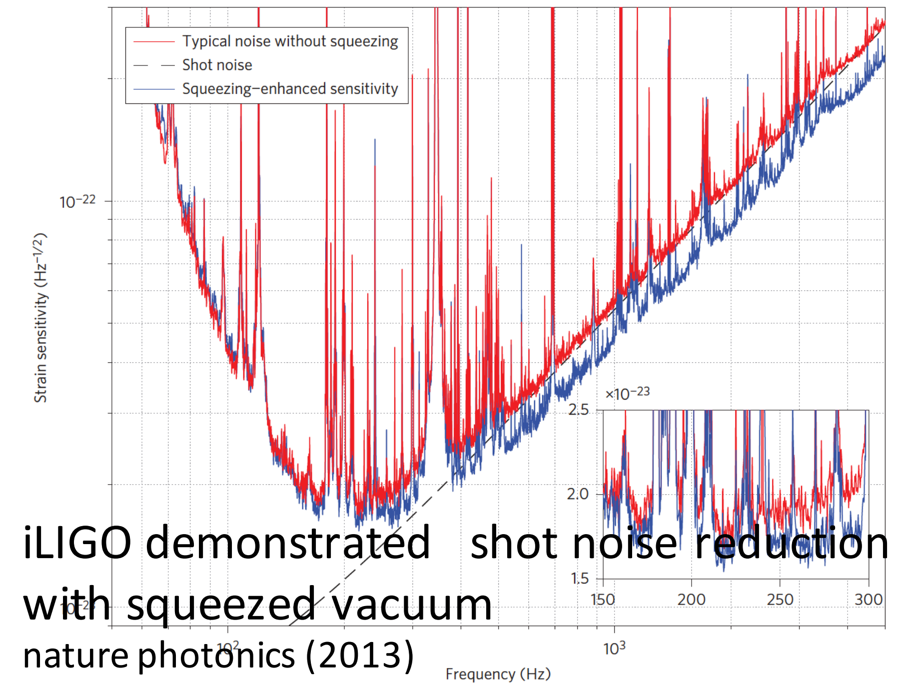
$h_{\mathrm{shot}} \propto 1/\sqrt{P_0}$

Reducing Shot Noise in aLIGO

180W high power laser
Pre-stabilized high power laser



Injecting Squeezed Vacuum



iLIGO demonstrated shot noise reduction with squeezed vacuum
nature photonics (2013)

My Experiences
in LIGO Livingston 2011-2014

“The South”

My Experiences in LIGO Livingston 2011-2014

Around 50 people at the site

- ~5 Scientists
- ~5 Postdocs
- 5-10 Grad students
- ~20 Engineers
- ~3 Computer Admins
- ~3 Assistants

Typical Day
6am-10am: Noisy work (cleaning, construction...)
10am-6pm : Hardware installation, integration
6pm - : Interferometer commissioning

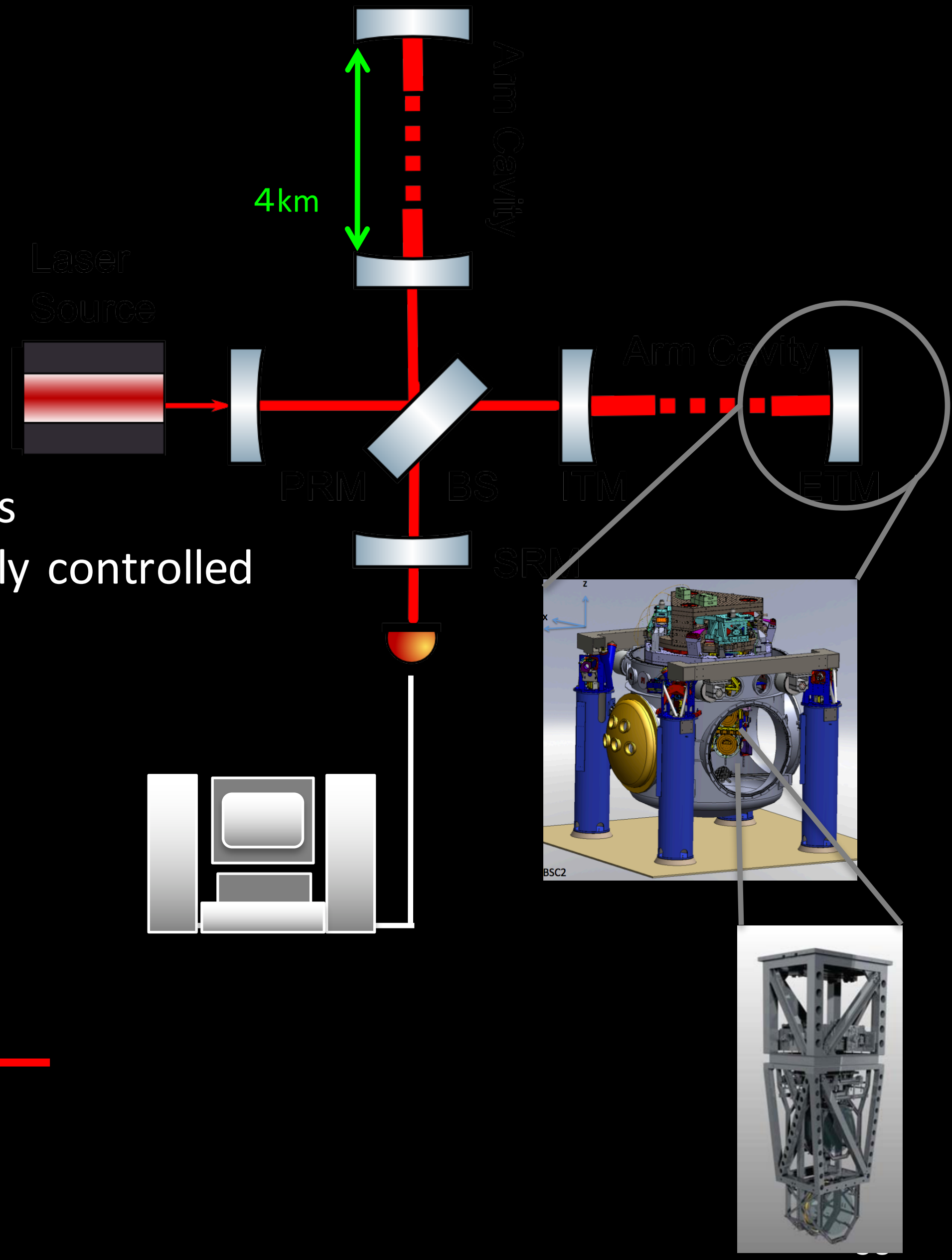
More scientists come from Caltech and MIT (the host institutions) when something important

aLIGO IFO Commissioning

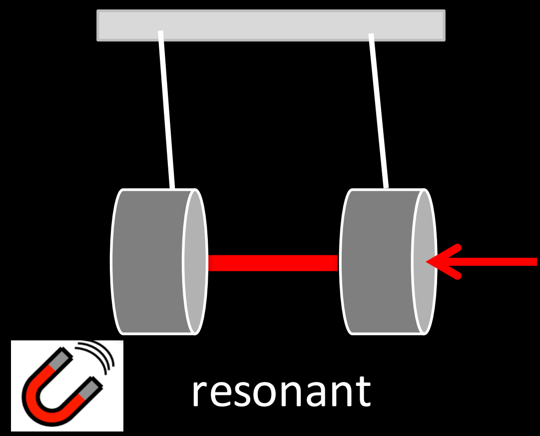
Commissioning…

Interferometers wouldn't even work
only with parts installed
Complex subsystems must be properly
Integrated as an interferometer to function

Huge system and thousands of parts behaviors
must be understood and mechanically, optically controlled



"Control"



LLO Interferometer Commissioning

Life at the Louisiana Site

Keiko Kokeyama

Keiko Kokeyama is a postdoc in Louisiana State University working at LIGO Livingston. She has worked on both table top R&D as well as aLIGO commissioning. Outside the lab, she loves to visit art museums all over the world.

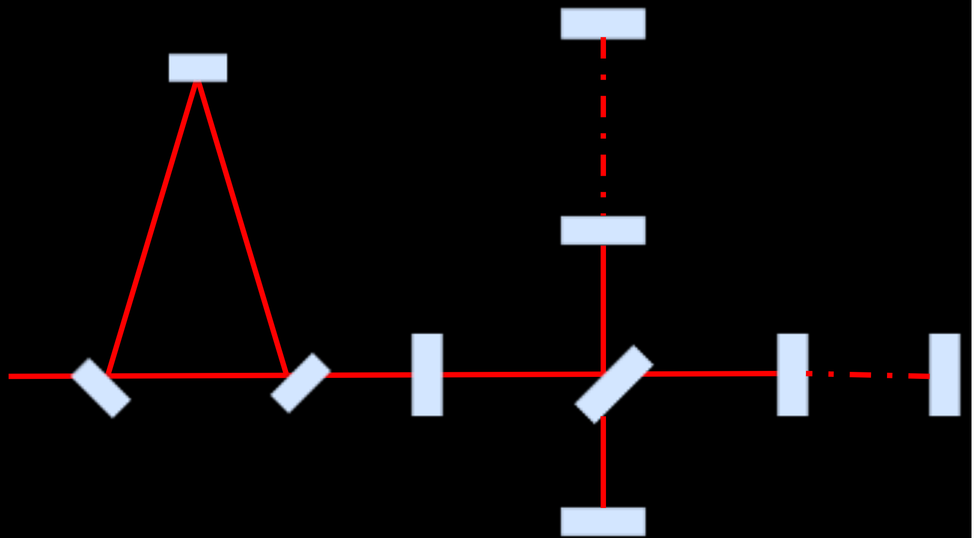
As a graduate student and at my first postdoc, I worked on table top research and development experiments for future generation detectors, and simulations for interferometer sensing and control. Crazy new ideas for the next generation were very fun to work on, but I also wanted to experience the real large-scale gravitational-wave detectors. The timing of the Advanced LIGO upgrade gave me the chance and the challenge to work on the detector in Livingston, Louisi- and as a postdoc at LSU.

Before arriving, I had no idea what Louisiana would be like. I imagined Baton Rouge as just a typical American mid-size city, with a west-coast atmosphere, a stereotypical image of the US for Japanese. I was completely wrong. The first culture shock was Louisiana's car society. Being a city dweller for thirty years, I was really shocked by the fact that I could not walk anywhere, even to a supermarket or a coffee shop. After getting a driver's licence and a car, I started enjoying the life in Louisiana, especially the food and music! I was almost overwhelmed to discover the depth of Louisiana's uniqueness: swamps, spanish moss, gators, the Louisiana accent, and creole cuisines.

Louisiana has its own local and unique American cuisine, evolved from French and African American traditions from the colonial era. The typical ingredients are chicken broth, okra, catfish, corn, crawfish (crayfish!) and a lot of spices. Deep fried

10

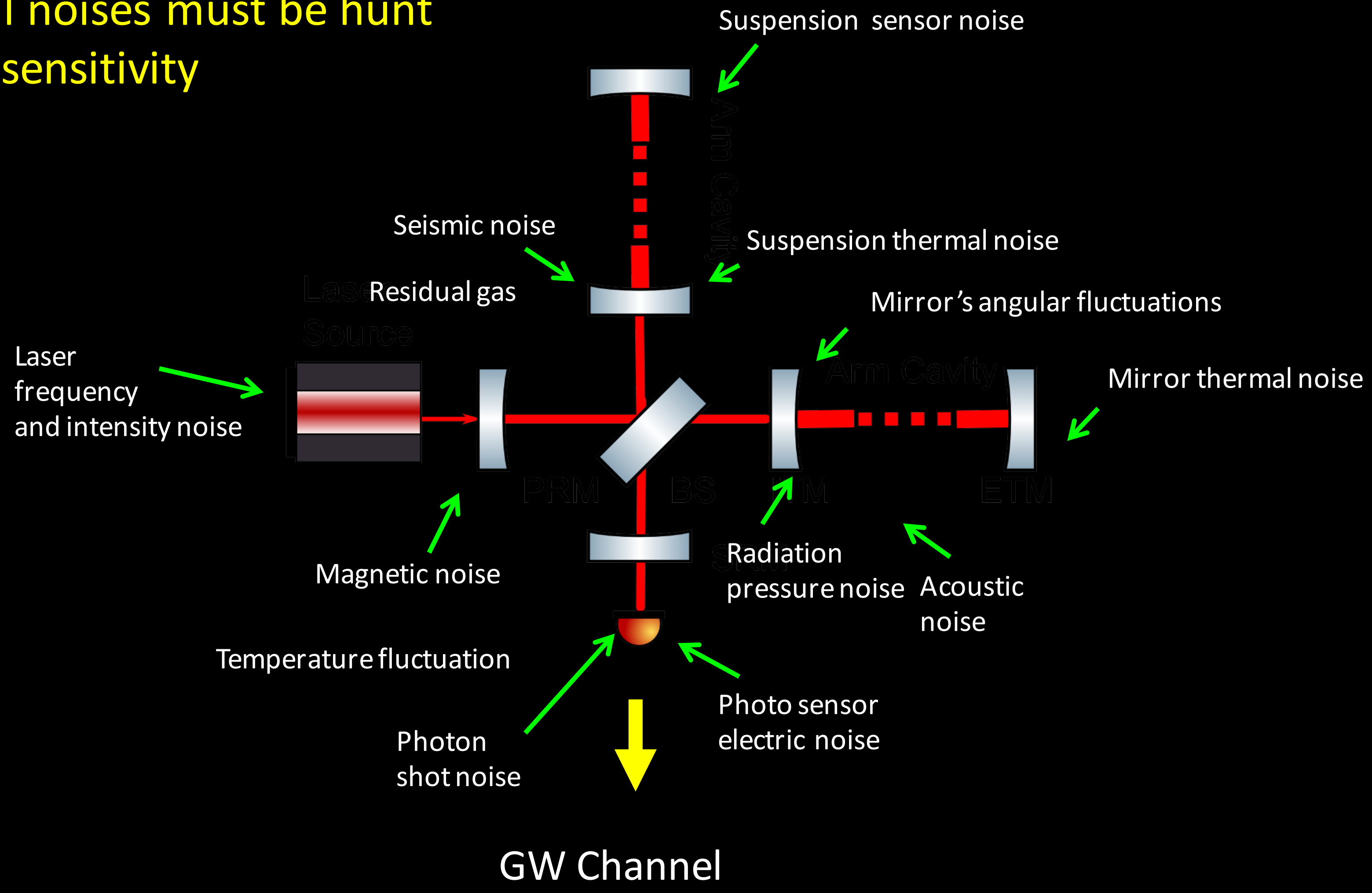
LIGO Magazine, vol 5, p.10



Noise Hunting

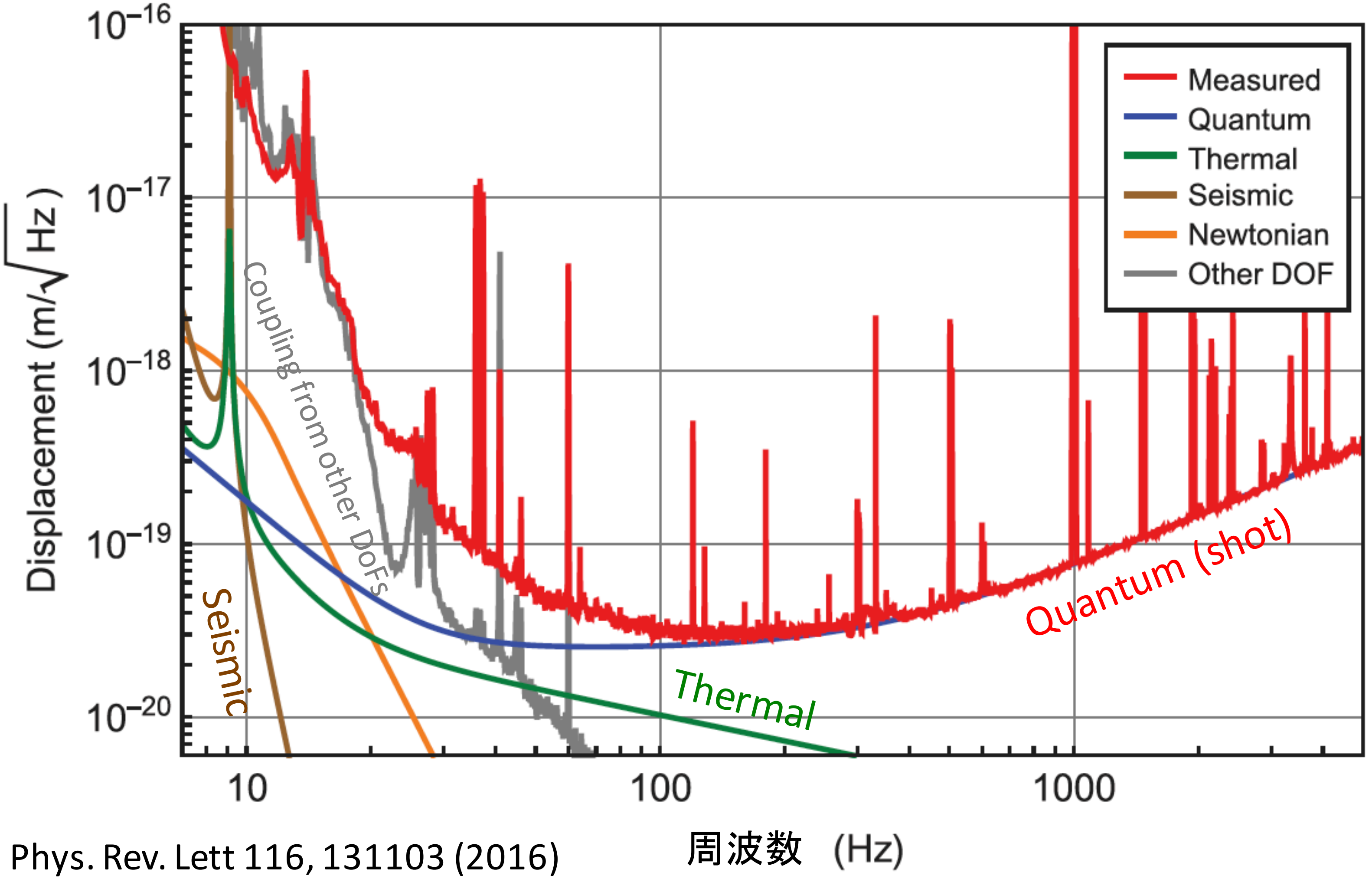
Technical Noises

Once the interferometer work,
then technical noises must be hunt
to make high sensitivity



Actual Sensitivity of aLIGO

LIGO Observation Run 1



Phys. Rev. Lett 116, 131103 (2016)

Observation Plan of aLIGO

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

Living Rev. Relativity 19 (2016), 1

- 2 times better sensitivity for the next run
  → 8 times more volume to cover
- More events for BH-BH, NS-NS → reveal population, mass distribution
- Deeper study for the scenario of Binary compact star formation
- More accurate comparison against GR

Observation Run 2 Started!

Observation for 6 months with a few months brake for smaller upgrades

- Better photo detector at the GW channel
- Better mode matching in the signal recycling cavity
- After the brake, VIRGO joins the observation

LIGO Control Room (2014)

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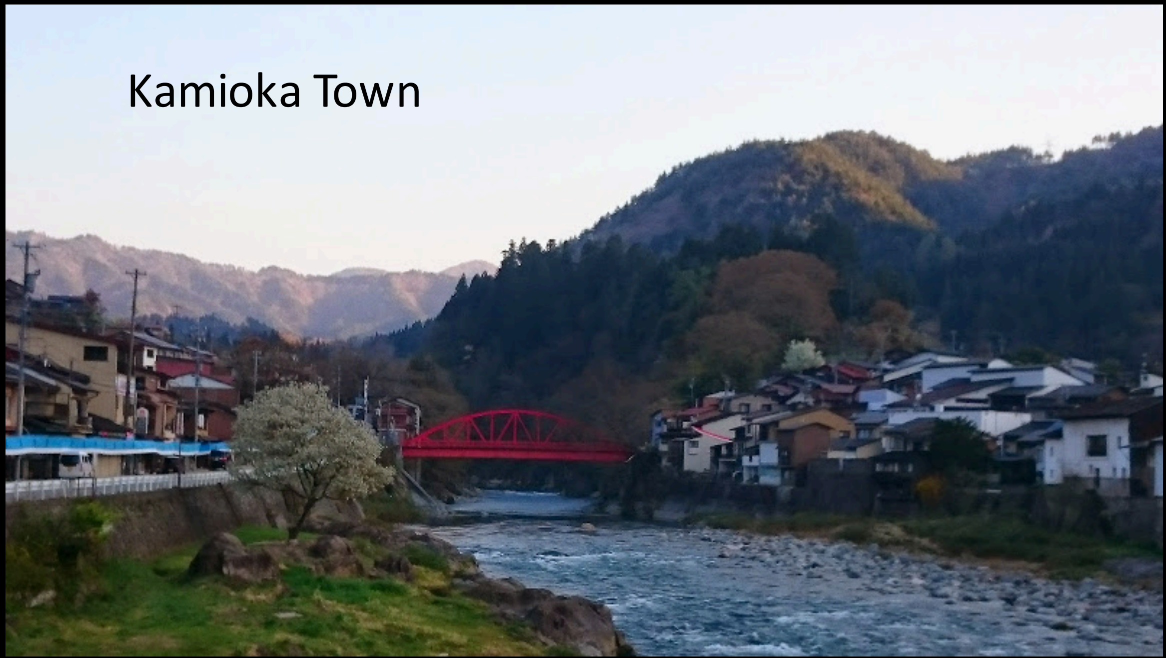
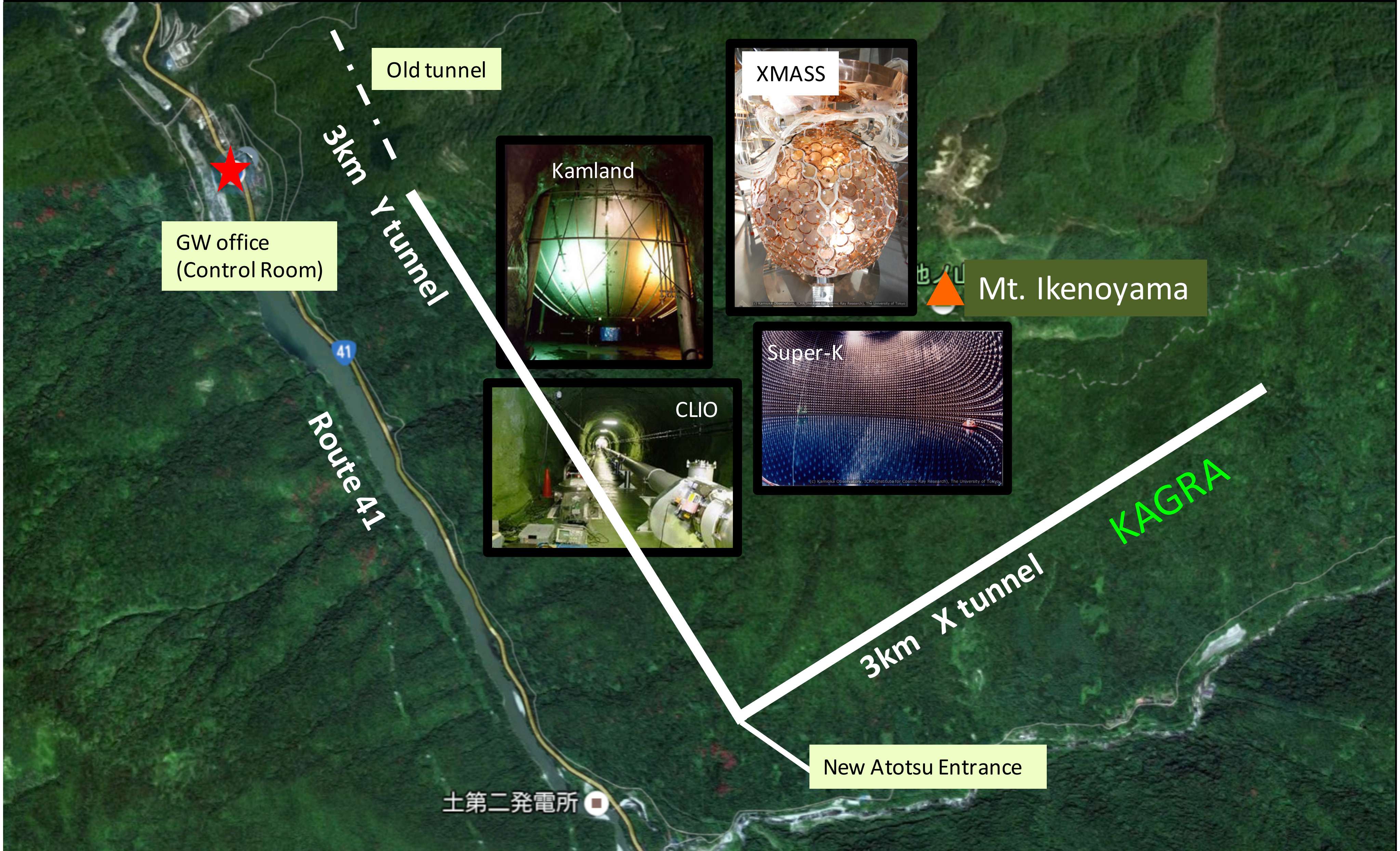
Views of Kamioka
(Hida, Gifu)



Projects in Kamioka

Projects in Kamioka



Our Office in Winter

Jan 16…

KAGRA Tour

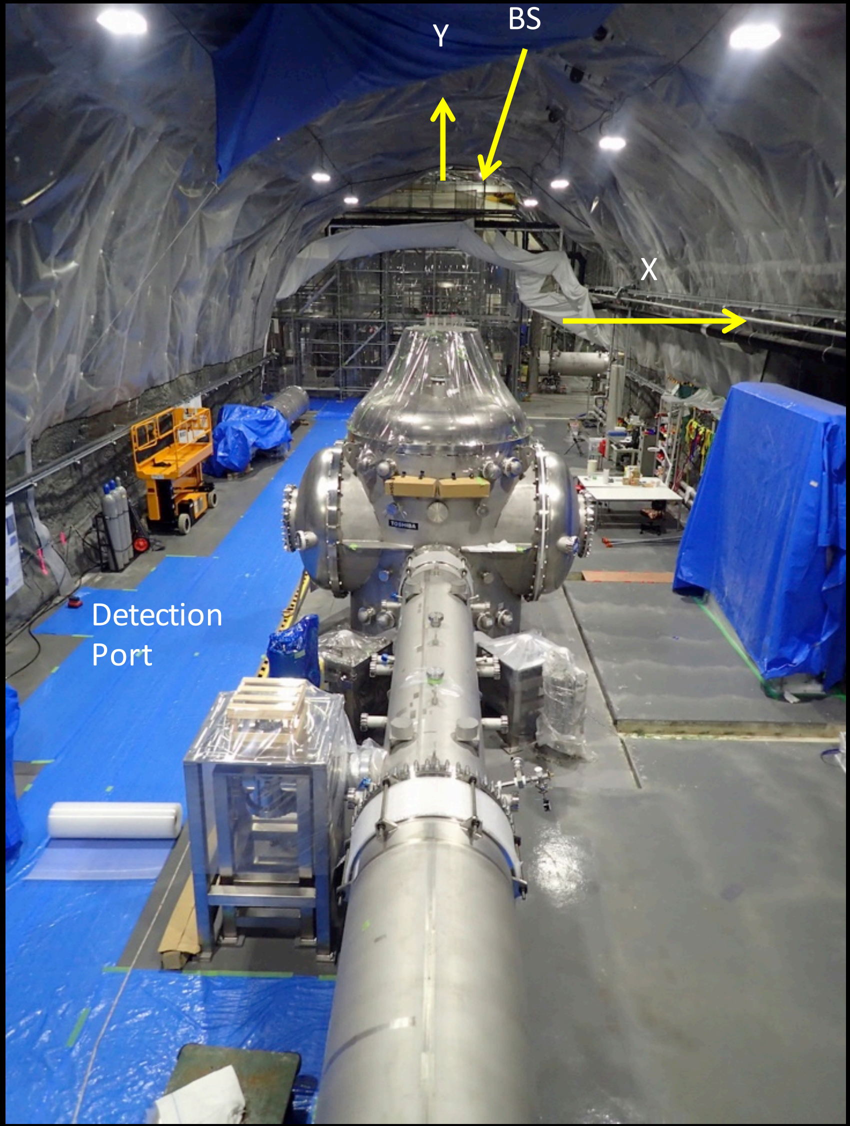

Entrance

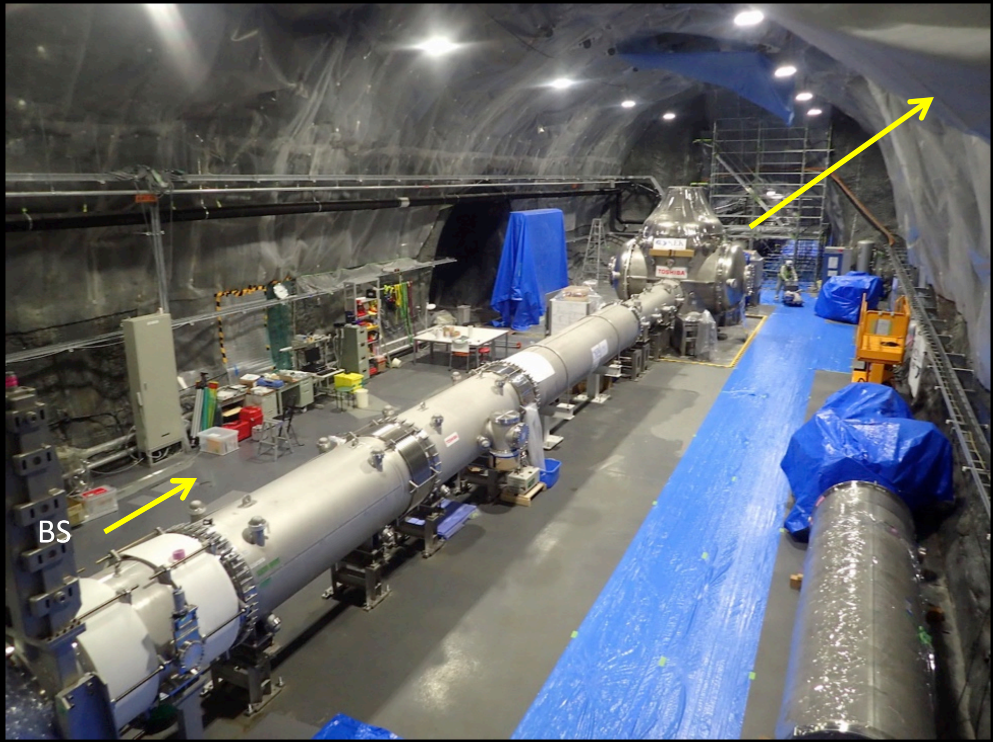
Winter

In winter, we have snow and even avalanches...

Central Experiment Area

To 3km tunnel





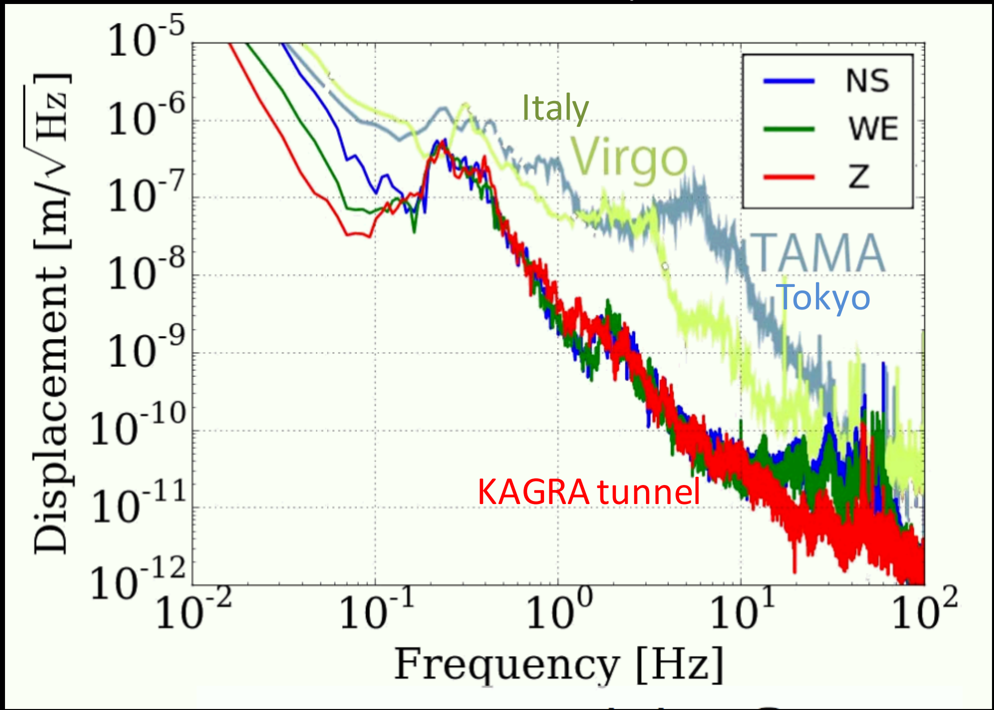
3km arm tunnels

JGW-G1706090

KAGRA Features

1. Underground Site

Plot by A Shoda, JGW-G1605219

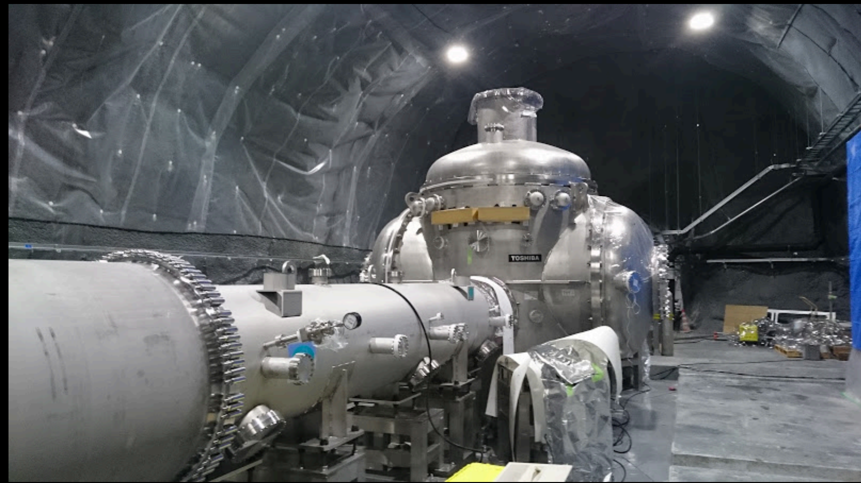


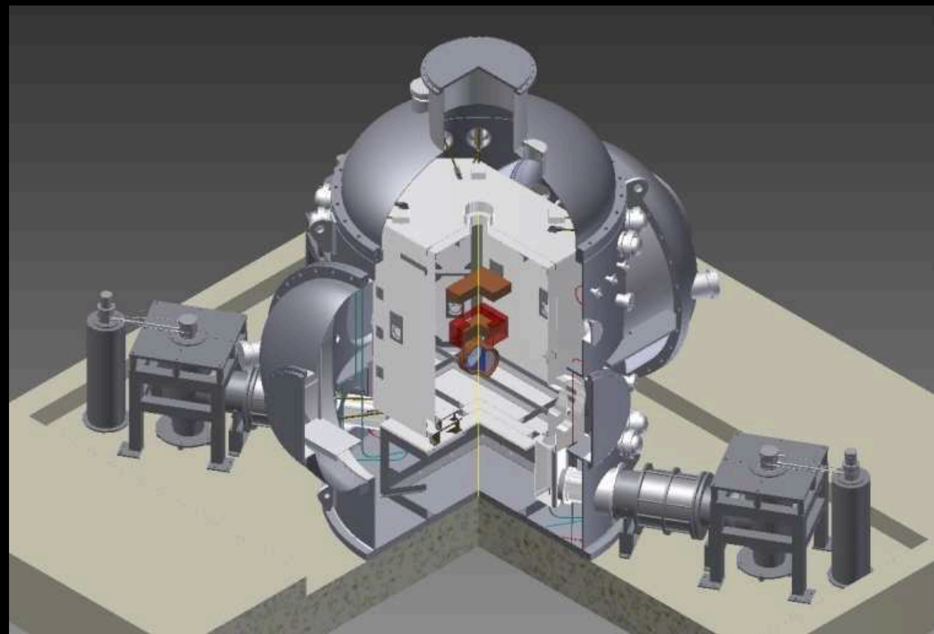
Tall Suspensions

KAGRA Features

2. Cryogenic Mirrors

Sapphire mirrors
（High Q in cryogenic temperature）





Cool mirrors down

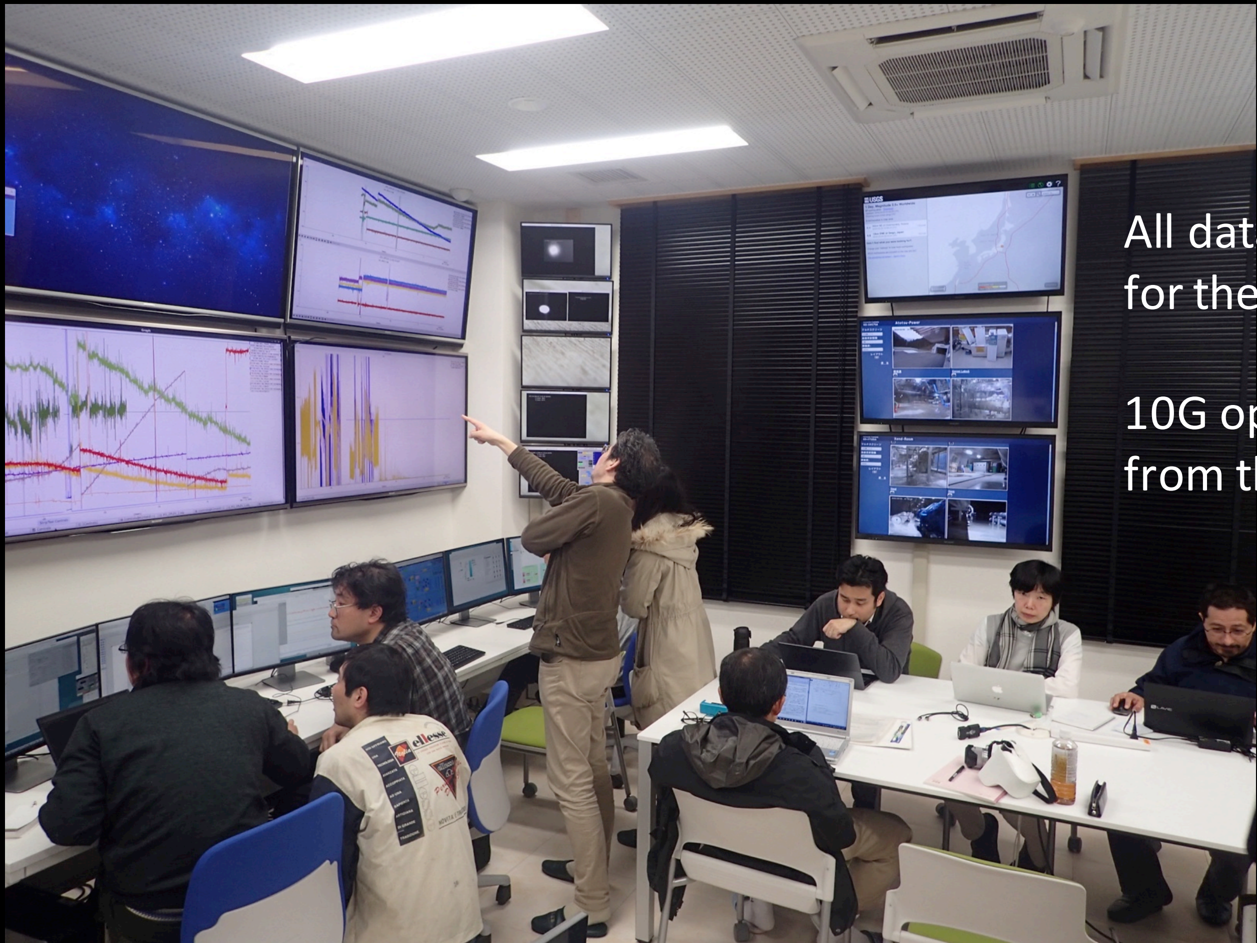
Working Underground...

Electric cars (Mitsuoka Like-T3)

Mine Work Style

- Work cloths, work gloves, work boots
- Helmets
- Head lights
- Reflect vests
- Oxygen sensors
- Electric bicycles

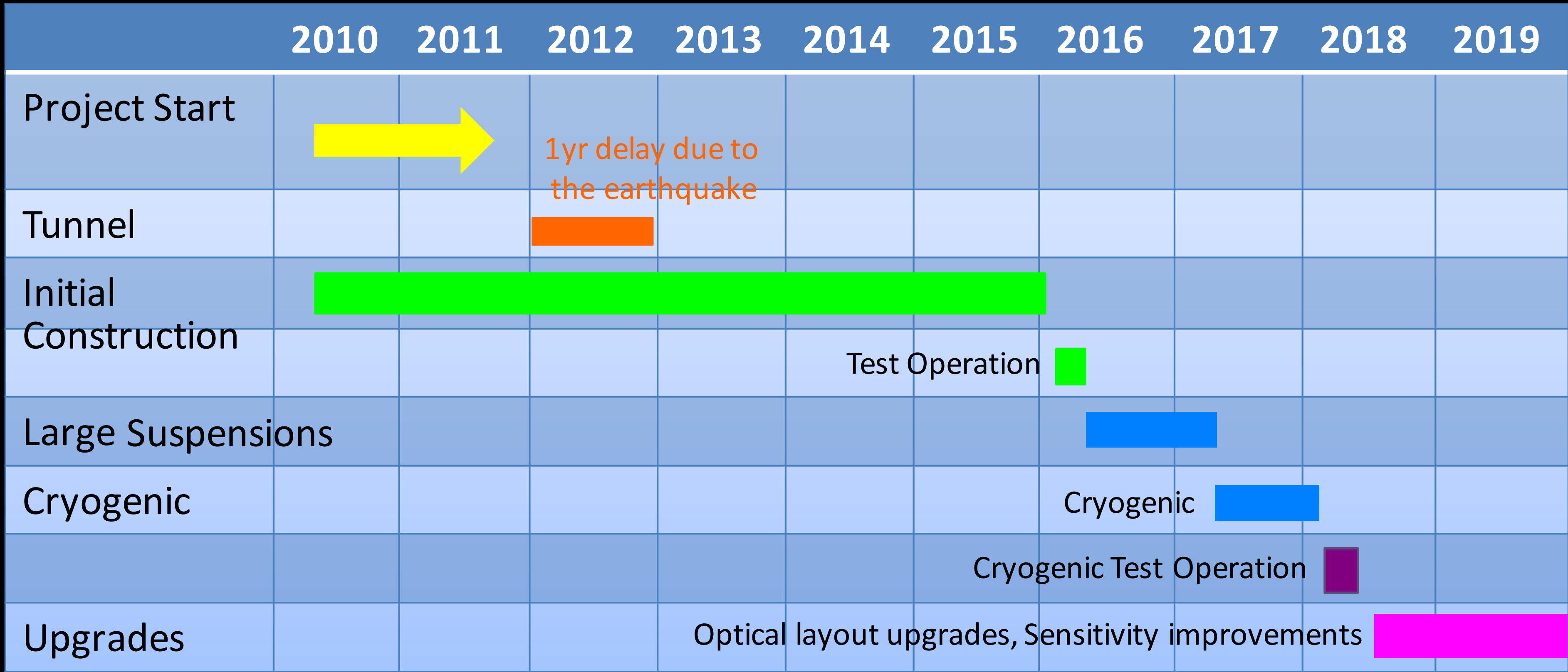
KAGRA Control Room



All data is on the network dedicated for the control and data acquisition

10G optical fiber network is connected from the control room to the mine

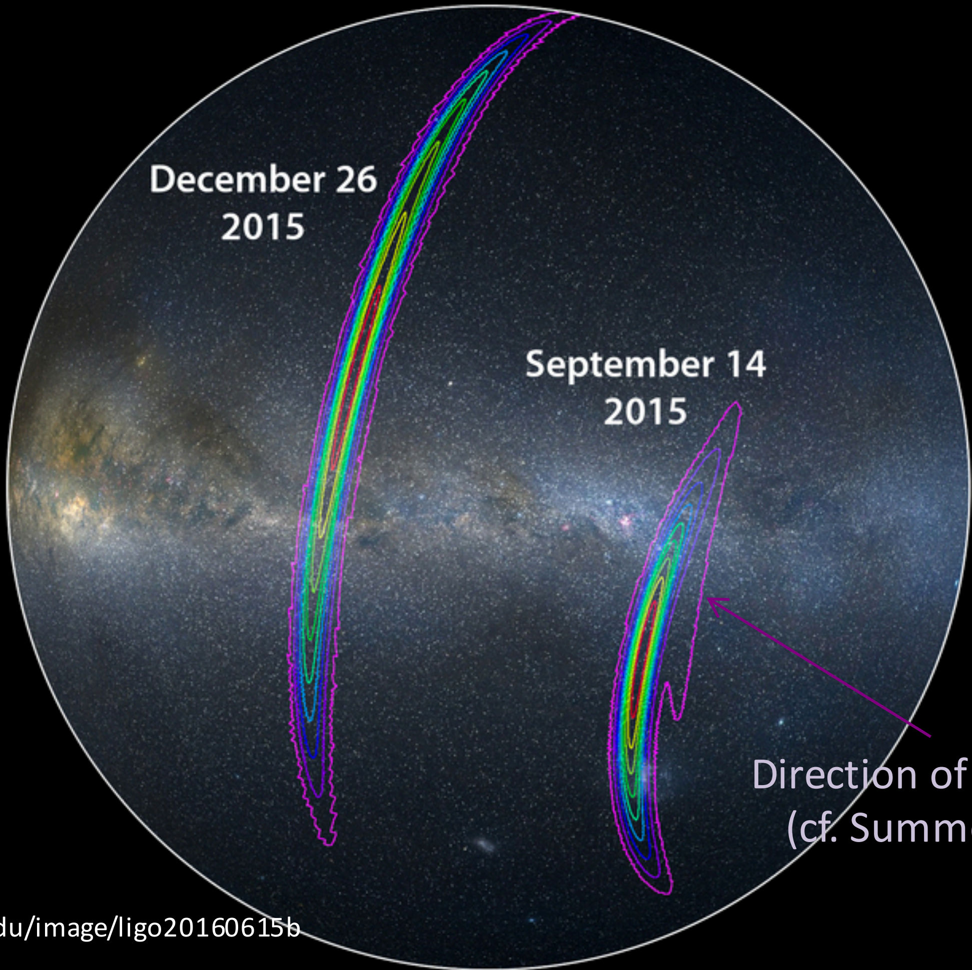
KAGRA Timeline



- bKAGRA-1 (simple Michelson with large suspensions in a cryogenic temperature) is planned in fiscal year of 2018
- Further sensitivity improvement afterwards
- Astrophysics possible around 2020? (My personal guess!)

Aim of bKAGRA

To Join the international observation network
with LIGO equivalent sensitivity

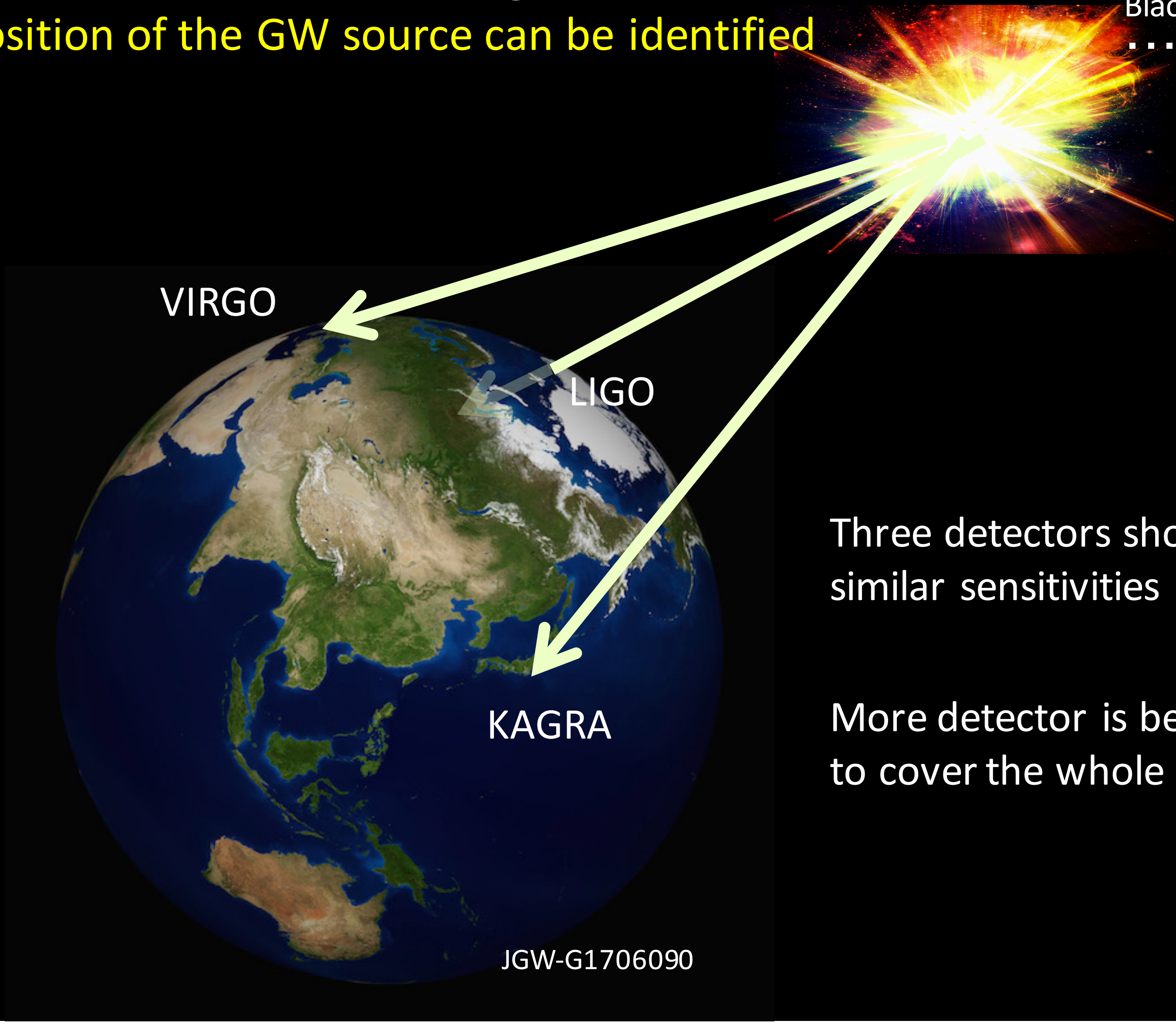


Direction of GW150914, 600 deg^2
(cf. Summer triangle 420 deg^2)

LIGO: https://www.ligo.caltech.edu/image/ligo20160615b

International network

Using the arrival times of the GW signals,
the sky position of the GW source can be identified

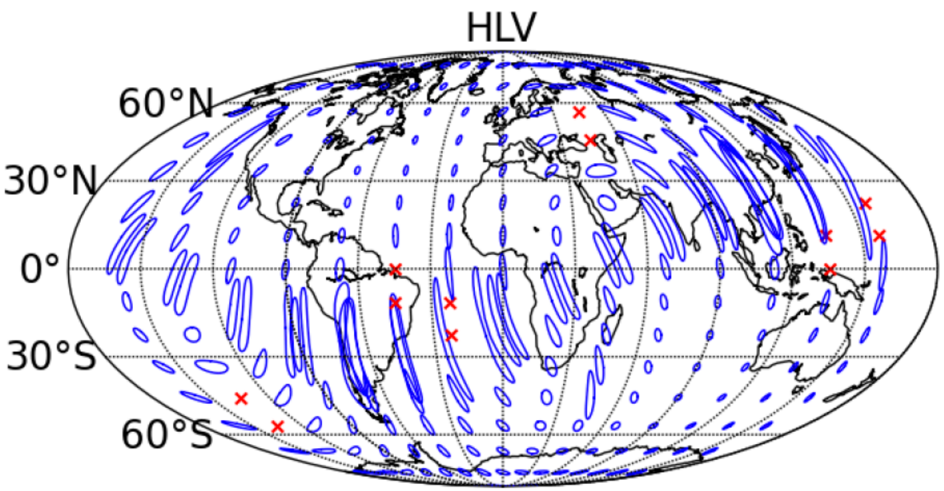


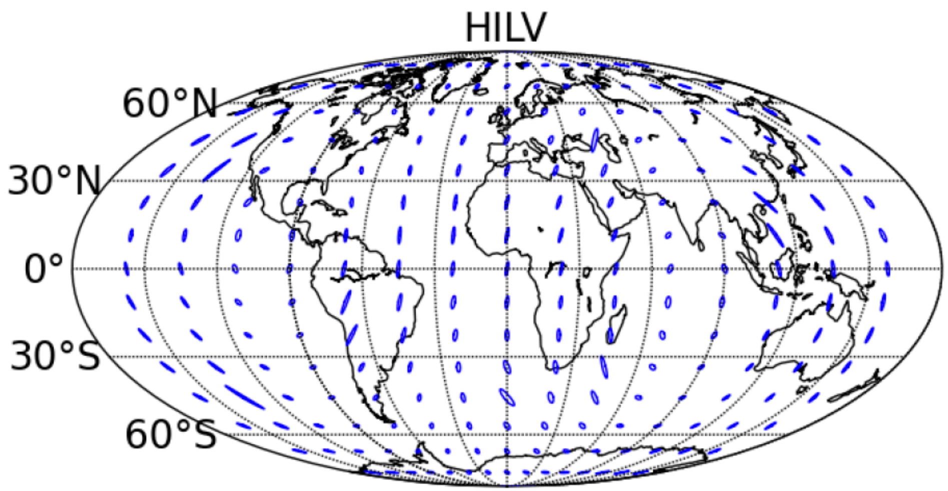
Three detectors should have similar sensitivities

More detector is better to cover the whole sky

Aim of bKAGRA

To join the international observation network
with equivalent sensitivity of LIGO

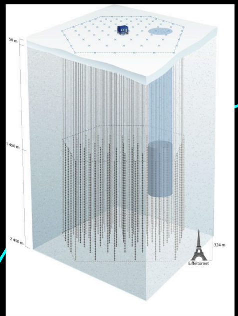


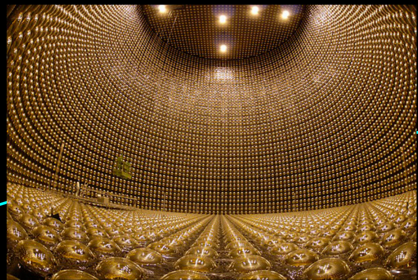


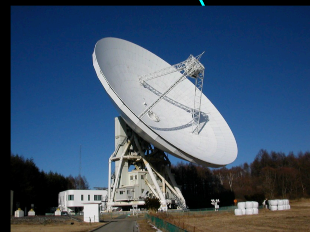
LIGO 2 IFOs＋VIRGO
(2019 plan）
x is a blind spot

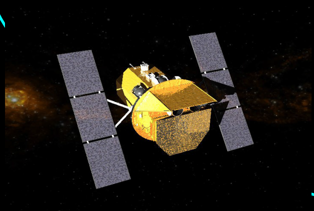
LIGO 2IFOs ＋ VIRGO + One more

Multimessenger Astrophysics









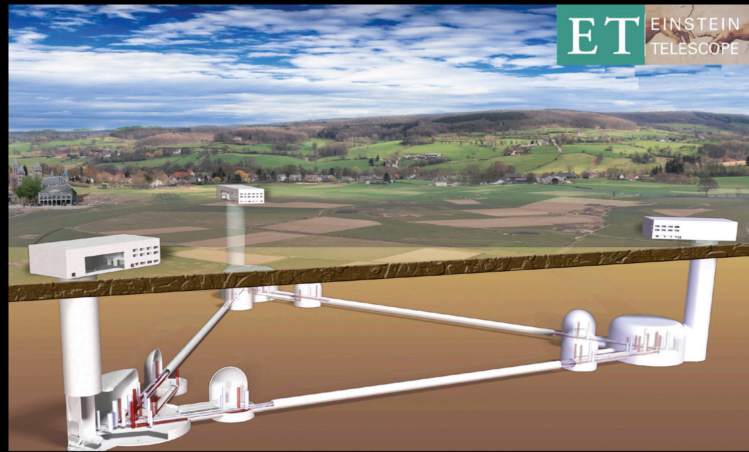
Diversified observations with
Visible, Radio, X ray,
Gamma ray and Neutrino Telescopes

Contents

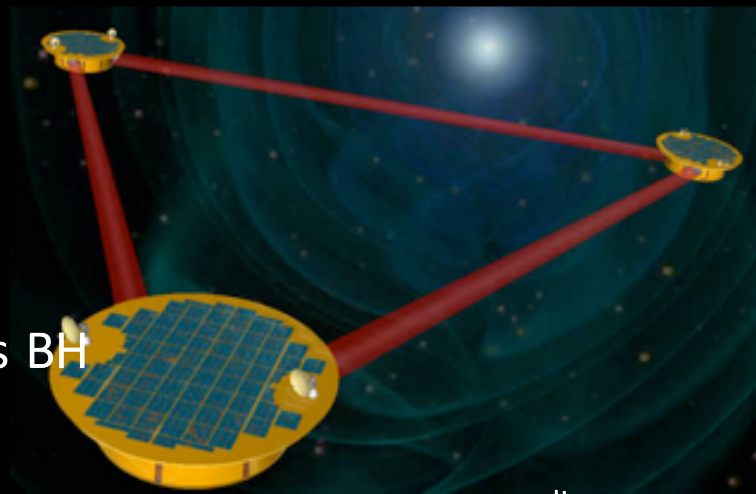
- Gravitational Wave (GW) Detection
- About the Interferometric Detectors
- Japanese Project, KAGRA
- Future Prospects
- (If we have time) Additional Stories

Future of GW Astronomy

- Einstein Telescope (ET) and LIGO next generation
  - 10km scale
  - Underground (ET)
  - Cryogenic



- LISA, DECIGO
  - Space based detectors
  - 0.1~10mHz (LISA), 0.1-1Hz (DECIGO)
  - Cosmological targets, Intermediate mass BH



www.lisa.nasa.org

Acknowledgement

KAGRA is supported by

MEXT, JSPS Leading-edge Research Infrastructure Program, JSPS Grant-in-Aid for Specially Promoted Research 26000005, MEXT Grant-in-Aid for Scientific Research on Innovative Areas 24103005, JSPS Core-to-Core Program, A. Advanced Research Networks, and the joint research program of ICRR