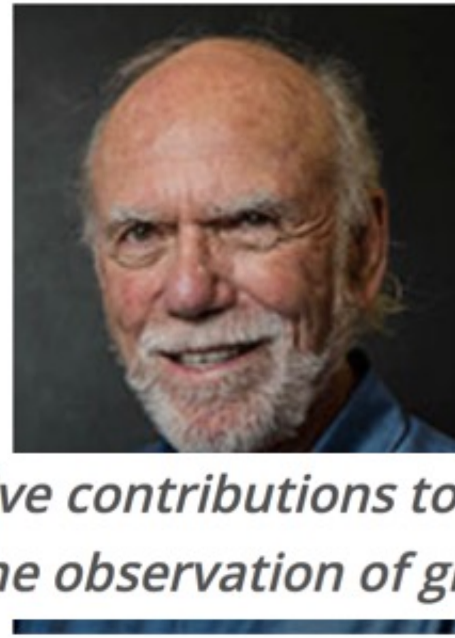
Gravitational Waves – Signals from Cosmic-scale colliders

S. Haino

中央研究院 Academia Sinica

The Nobel Prize in Physics 2017



"for decisive contributions to the LIGO detector and the observation of gravitational waves".

Photo: Bryce Vickmark
Rainer Weiss
Prize share: 1/2

Photo: Caltech
Barry C. Barish
Prize share: 1/4

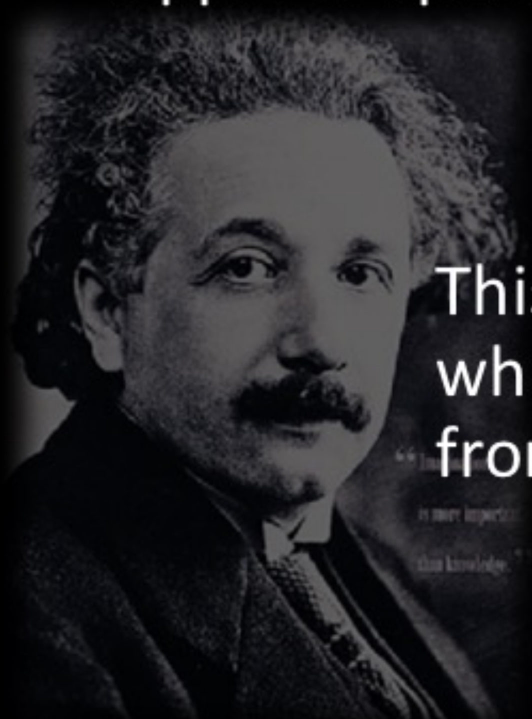
Photo: Caltech Alumni Association
Kip S. Thorne
Prize share: 1/4

Nobelprize.org
The Official Web Site of the Nobel Prize

Gravitational waves (GW)

- Predicted by A. Einstein in 1916

  Ripple of space-time propagating in speed of light

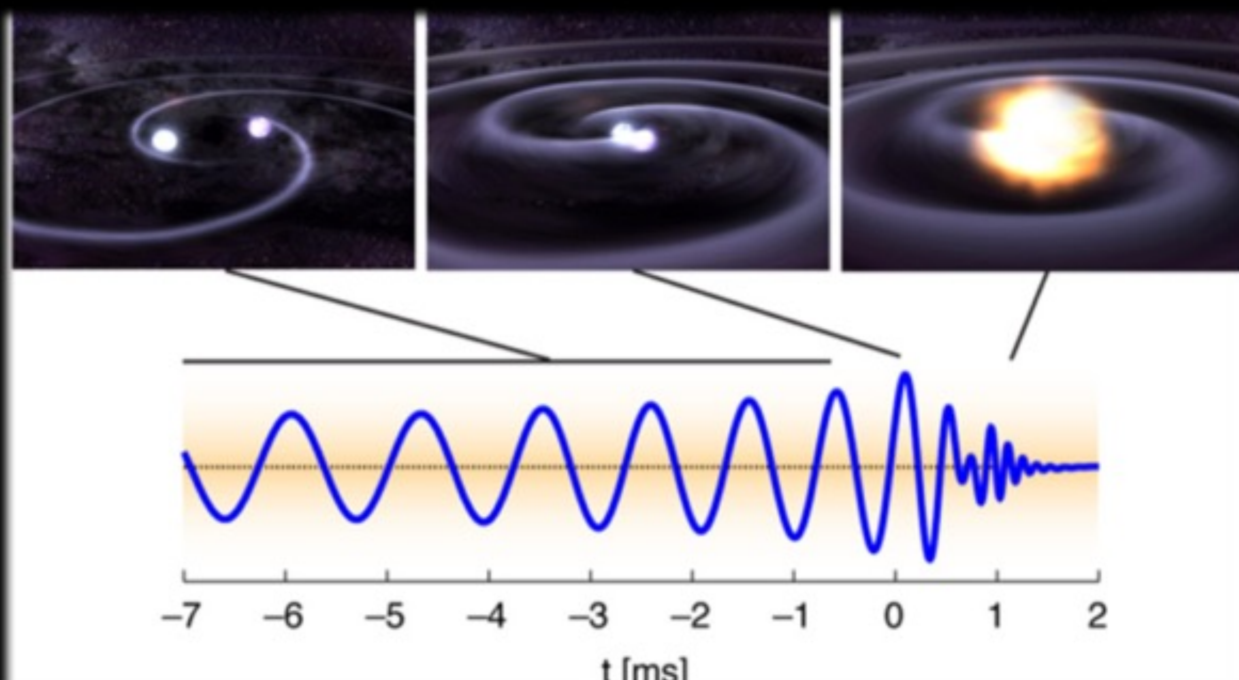


GW is transparent for any material.

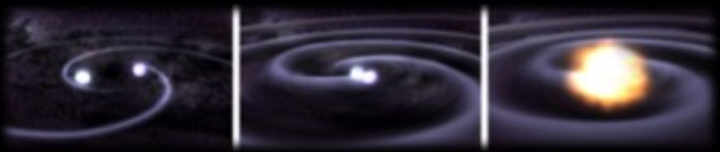
This causes detection to be difficult, while it can bring us information from where we wouldn’t see by EM

GW sources and physics

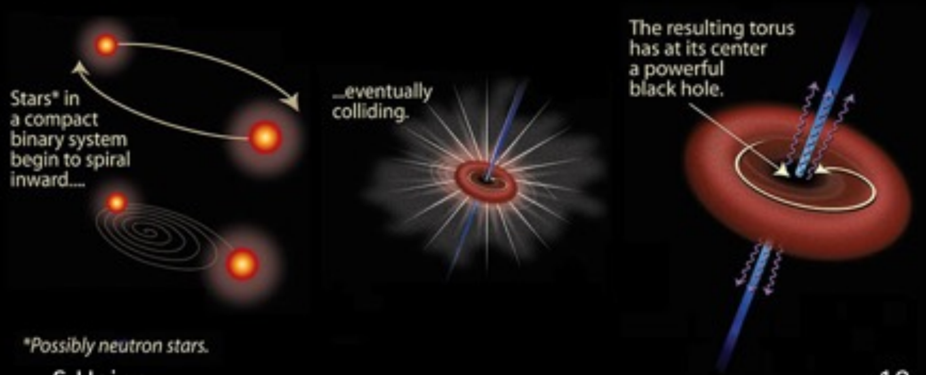
- Compact Binary Coalescences
  Black Holes (BH) and/or Neutron Stars (NS)



GW sources and physics

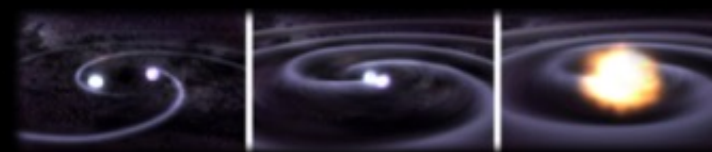


- Compact Binary Coalescences
  Physics examples
- Test of General Relativity
- Possible progenitor of Gamma-Ray Burst (GBR)
- Determination of cosmological parameters with GW "Standard siren" ⇔ EM "standard candle"

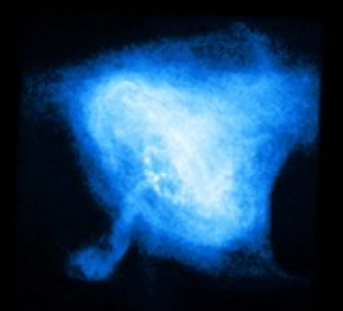


GW sources and physics

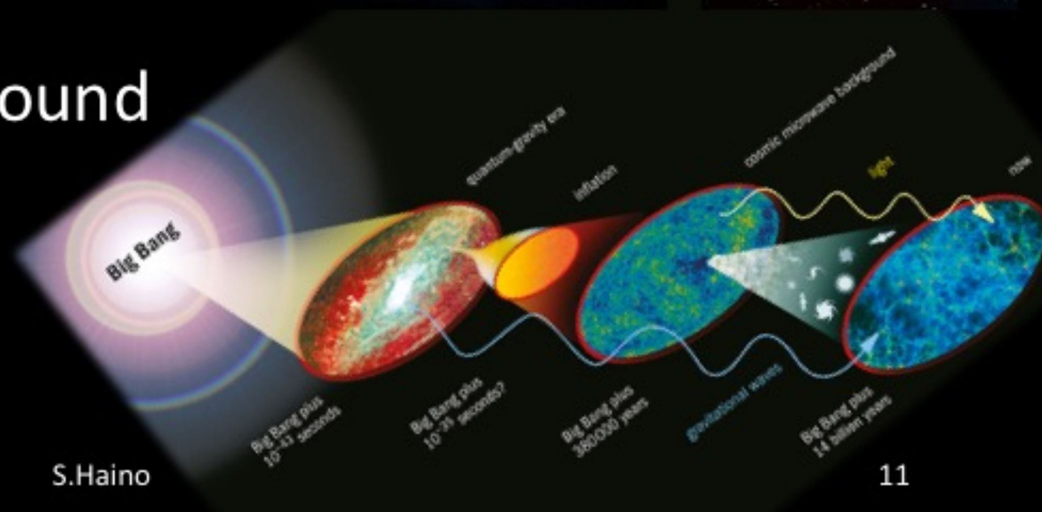
- Compact Binary Coalescences



- Continuous waves from pulsars



- Supernovae
- Stochastic GW background from Early Universe



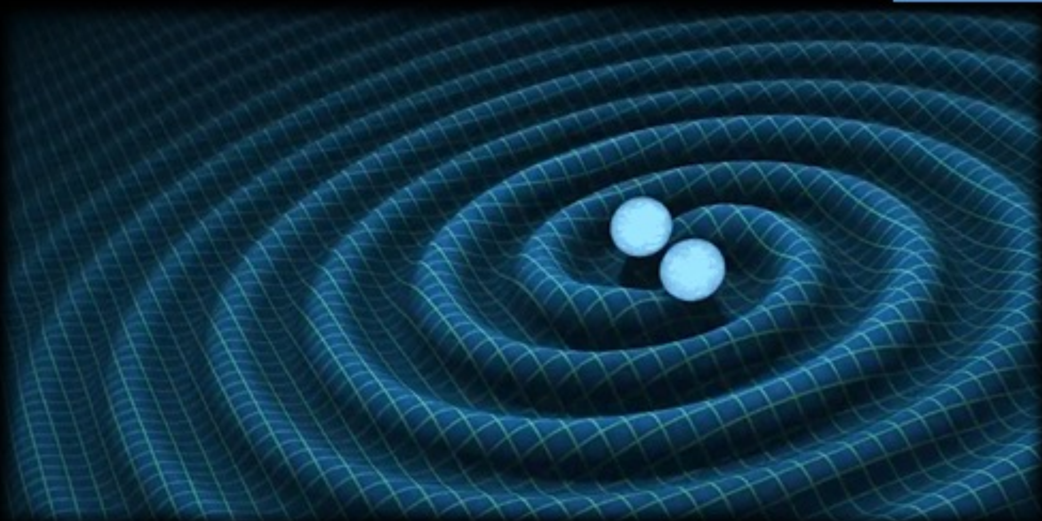
Typical GW strain amplitude

$$h \sim \frac{2G}{c^4 R}\ddot{I} \sim \frac{2G}{c^4 R}\frac{Mr^2}{T^2} \sim \frac{2GM}{c^2}\frac{1}{R} = \frac{r_g}{R}$$

$\sim Mc^2$

r_g Schwarzschild radius

R Distance



Typical GW strain amplitude

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

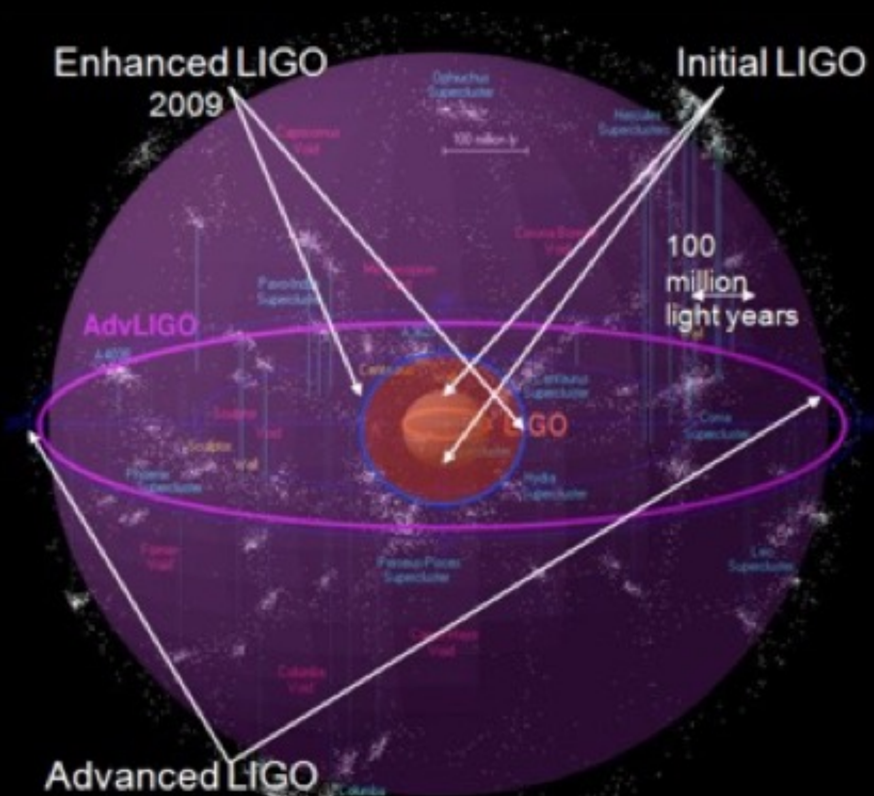
e.g. Solar mass ($r_g \sim 3\text{km}$) NS-NS binary merging at ~speed of light located at 100 Mpc away

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

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

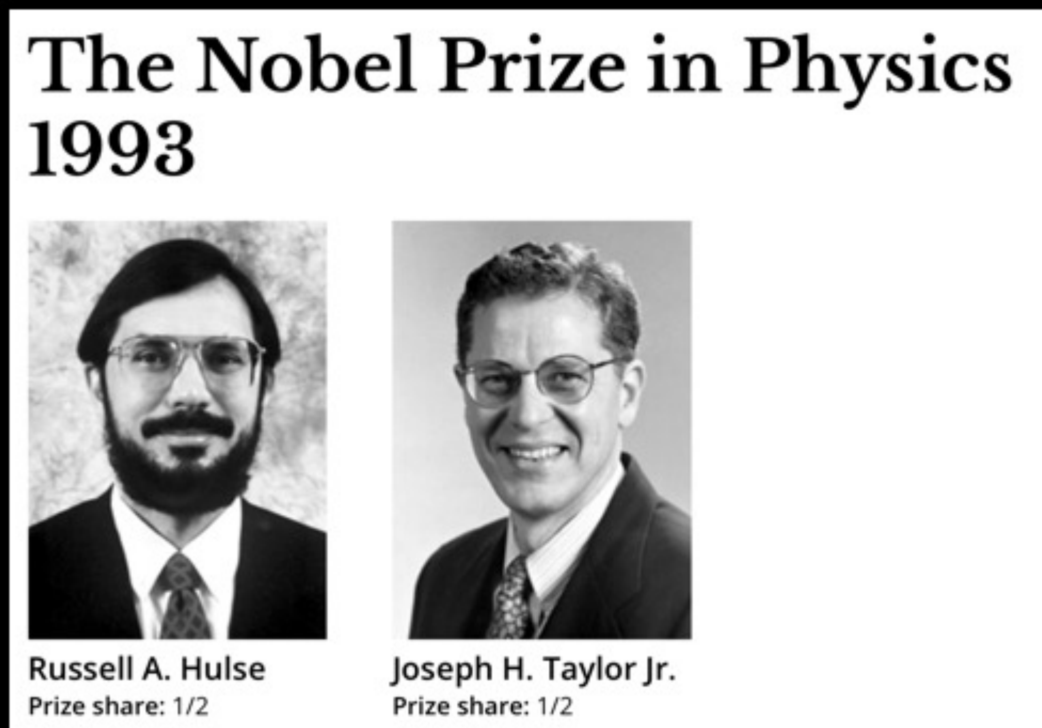
Opening of GW astronomy

- GW amplitude is proportional to 1/Distance
- 10 times improvement of sensitivity will increase number of detectable sources by 1000 !



History of GW Detections

- 1916 Prediction of GW by A. Einstein
- 1979 Indirect detection at Hulse–Taylor binary



History of GW Detection

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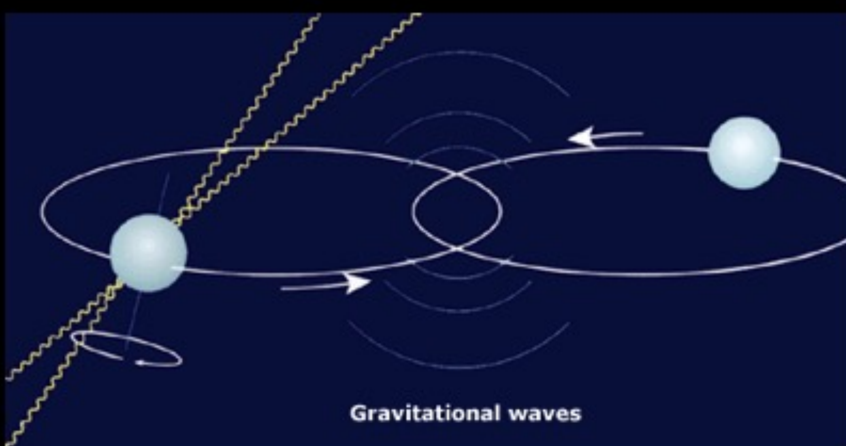
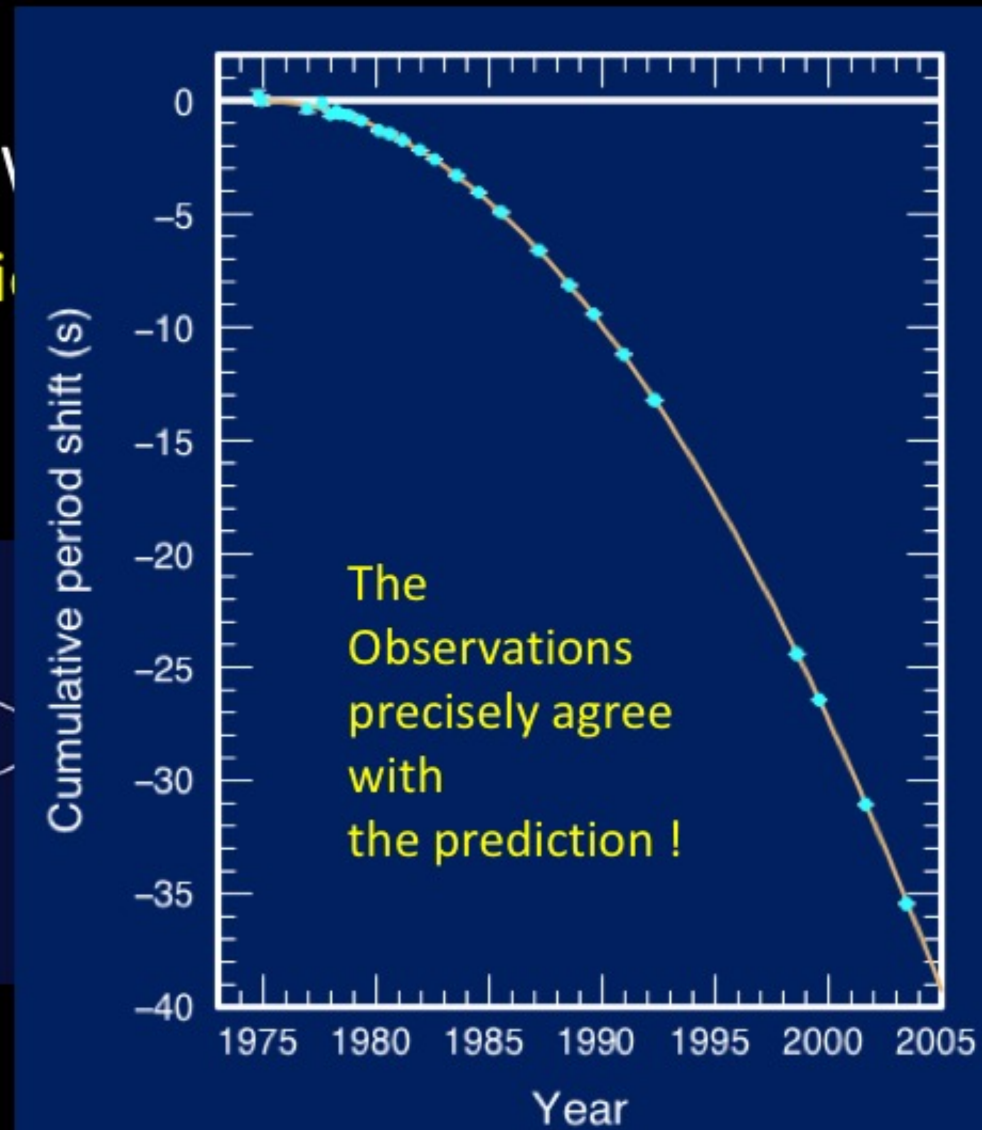




History of GW Detection

- 1916 Prediction of GW by A. Einstein
- 1979 Indirect detection at Hulse–Taylor binary
- 1990’s 1st. generation interferometric detectors

Interferometric GW detector

Prototype Michelson interferometer with Fabry–Perot cavities

1 August 1991 / Vol. 30, No. 22 / APPLIED OPTICS 3133

David Shoemaker, Peter Fritschel, Joseph Giaime, Nelson Christensen, and Rainer Weiss

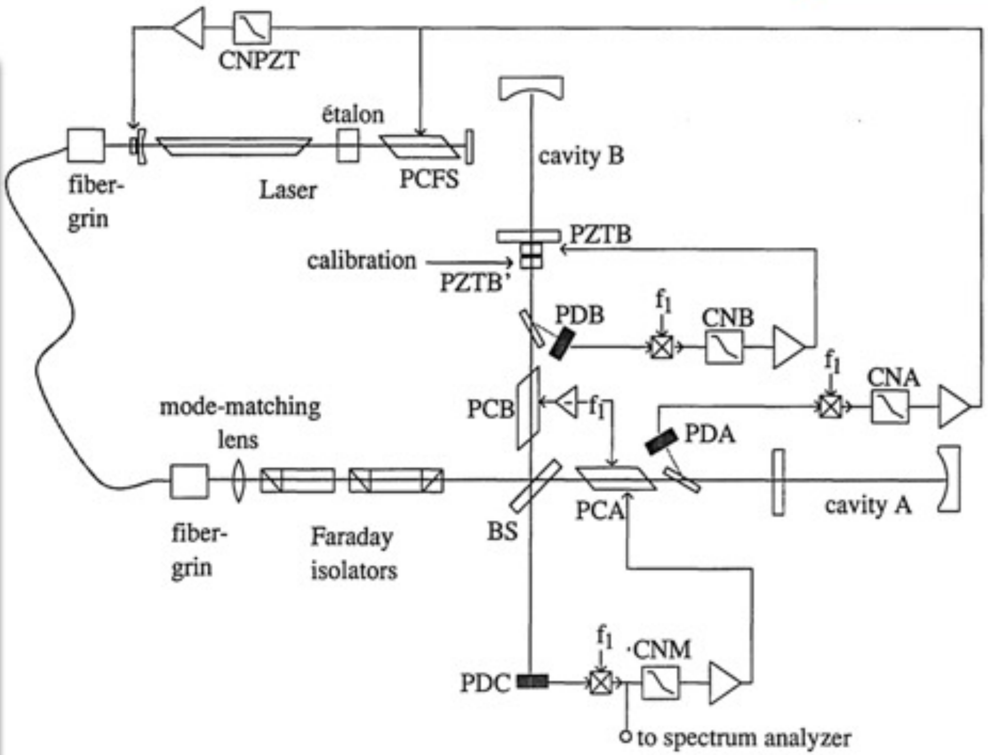
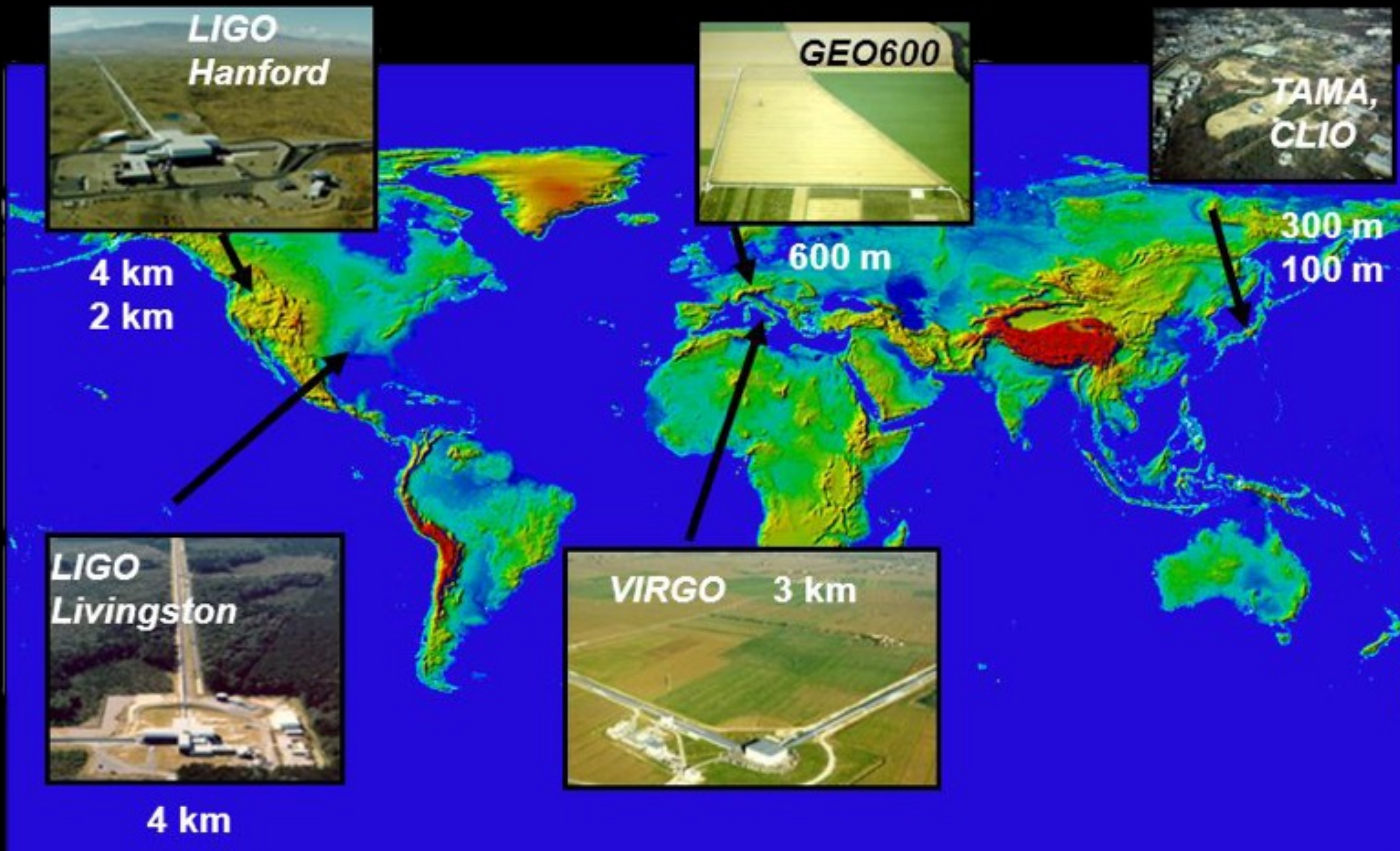


Fig. 1. Schematic diagram of the interferometer.

1st. generation detectors (1990's)

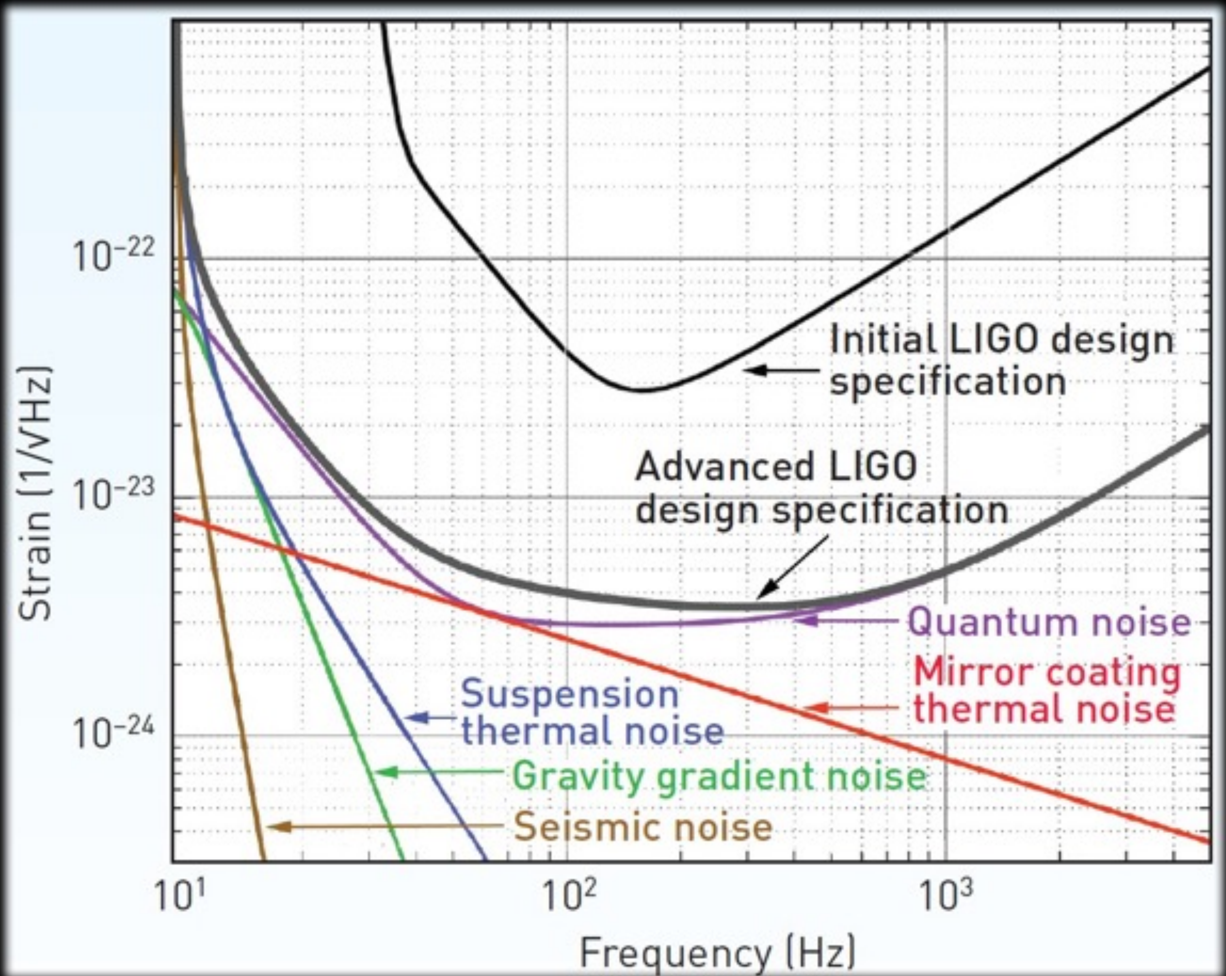


History of GW Detection

- 1916 Prediction of GW by A. Einstein
- 1979 Indirect detection at Hulse–Taylor binary
- 1990's 1st. generation interferometric detectors

- 2010's 2nd. generation interferometric detectors

Advanced LIGO upgrades (2010-2015)

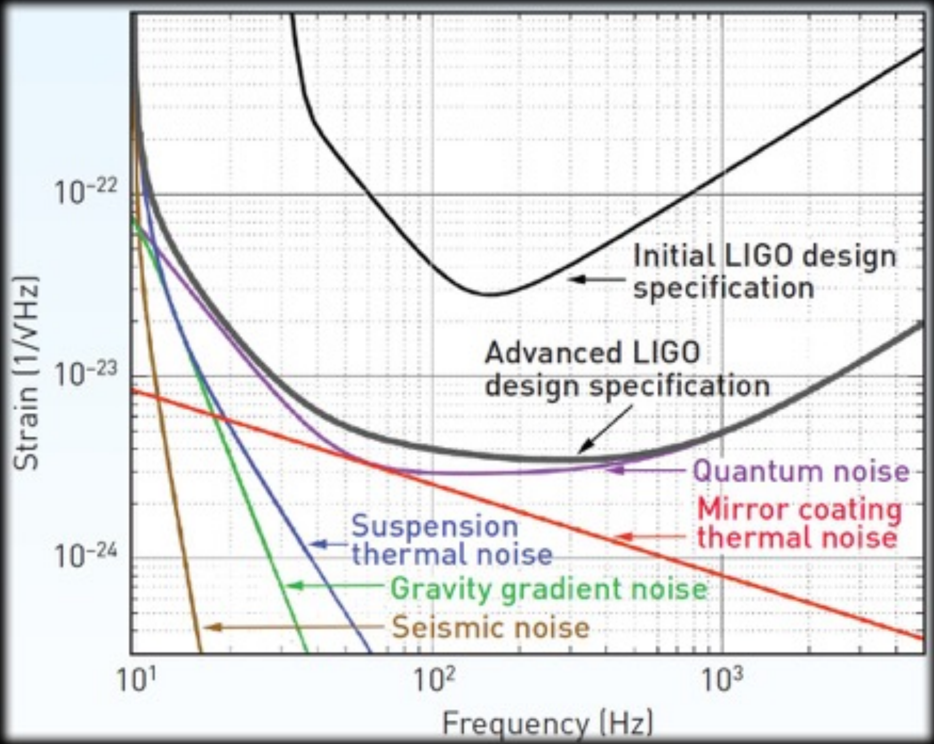


1st Generation

2nd Generation

Dominant noise sources

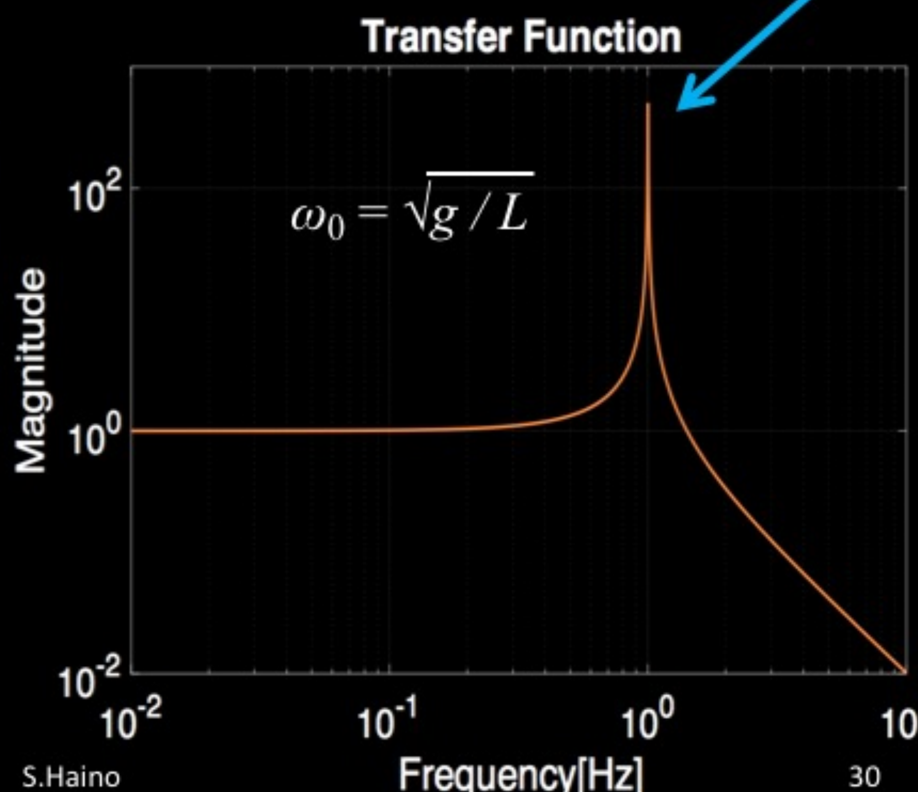
- Seismic noise
- Quantum noise
- Mirror and suspension thermal noise



Seismic noise attenuation

$$\frac{x(\omega)}{y(\omega)} = \frac{\omega_0^2}{\omega_0^2 - \omega^2}$$

Resonant Frequency



Seismic noise attenuation

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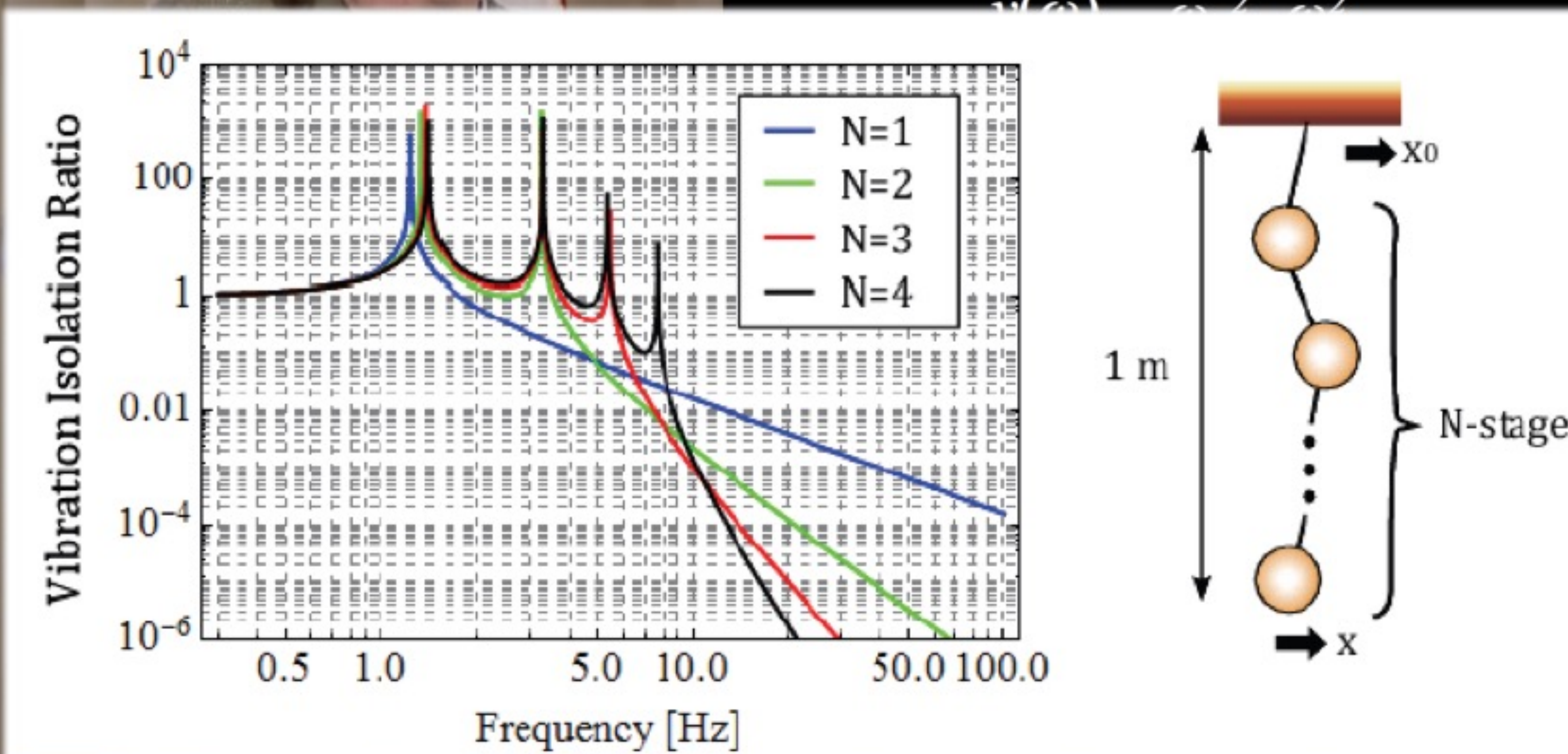
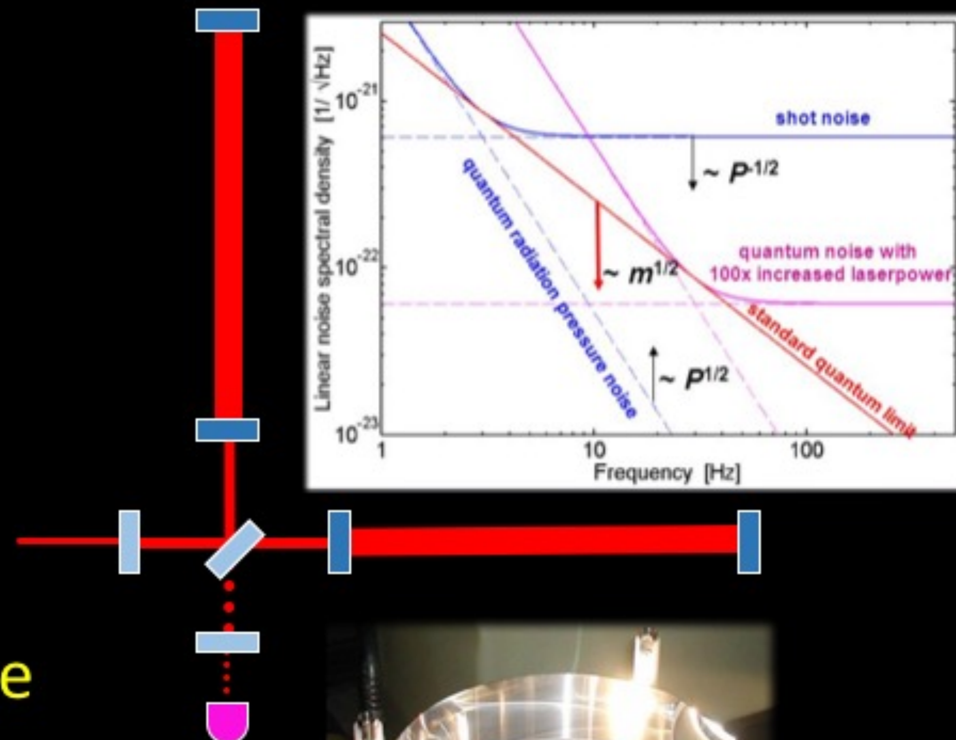


Frequency[Hz]

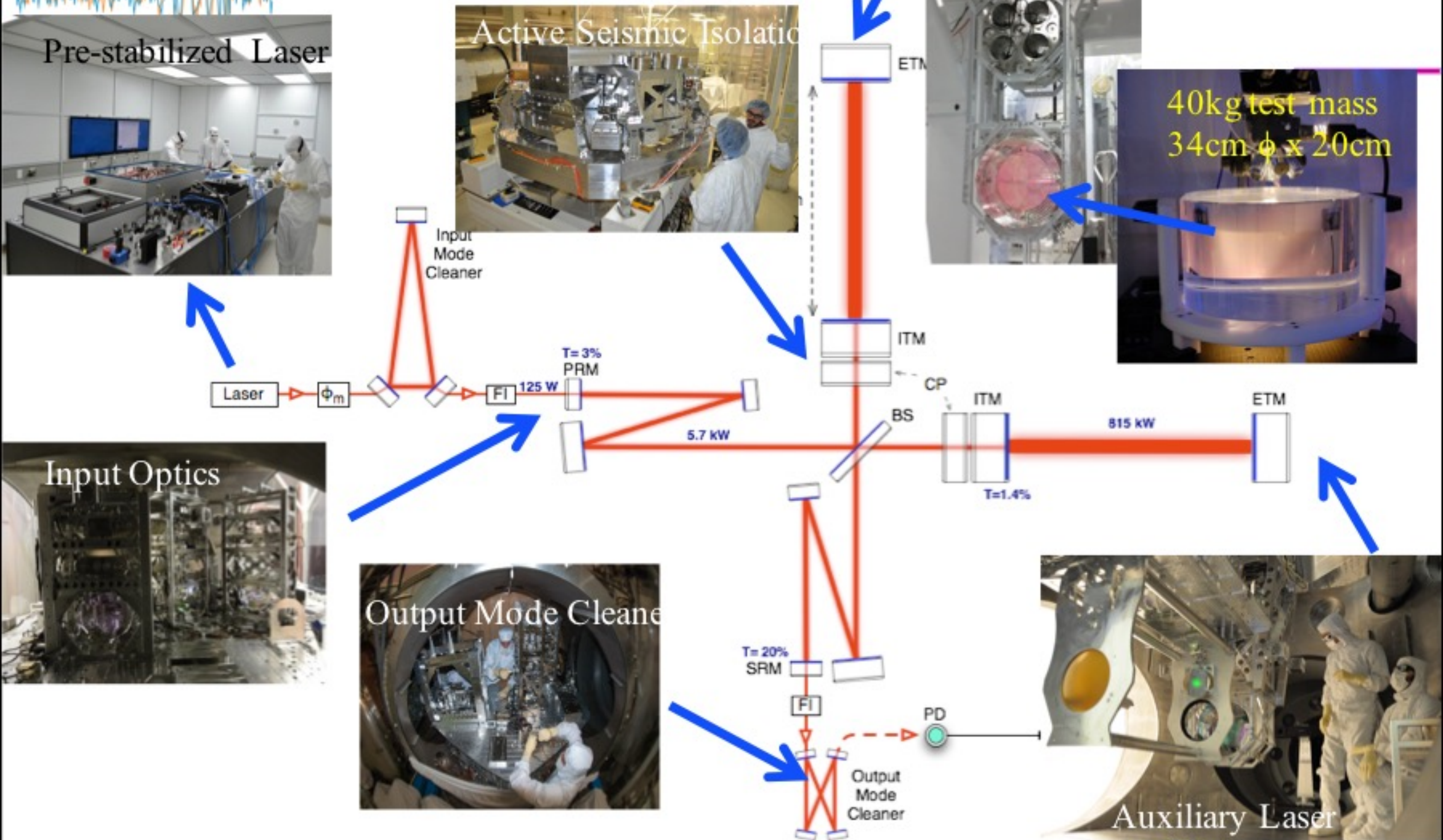
Quantum noise Reduction

- Shot noise
  - High power laser
  - Arm cavity
  - Dual recycling



- Radiation pressure noise
  - Heavier mirror

Advanced LIGO in Pictures



Advanced Virgo

Virgo is a European collaboration with about 280 members

Advanced Virgo (AdV): upgrade of the Virgo interferometric detector

Participation by scientists from France, Italy, The Netherlands, Poland, Hungary, Spain

- 20 laboratories, about 280 authors
  - APC Paris
  - ARTEMIS Nice
  - EGO Cascina
  - INFN Firenze-Urbino
  - INFN Genova
  - INFN Napoli
  - INFN Perugia
  - INFN Pisa
  - INFN Roma La Sapienza
  - INFN Roma Tor Vergata
  - INFN Trento-Padova
  - LAL Orsay – ESPCI Paris
  - LAPP Annecy
  - LKB Paris
  - LMA Lyon
  - Nikhef Amsterdam
  - POLGRAW(Poland)
  - RADBOUD Uni. Nijmegen
  - RMKI Budapest
  - Univ. of Valencia

Funding approved in Dec 2009

- 21.8 ME CNRS and INFN
- 3.5 ME Nikhef in kind contribution

Goal: be part of the international network of 2nd generation detectors

Short-term goal: join the O2 run in 2017

6 European countries

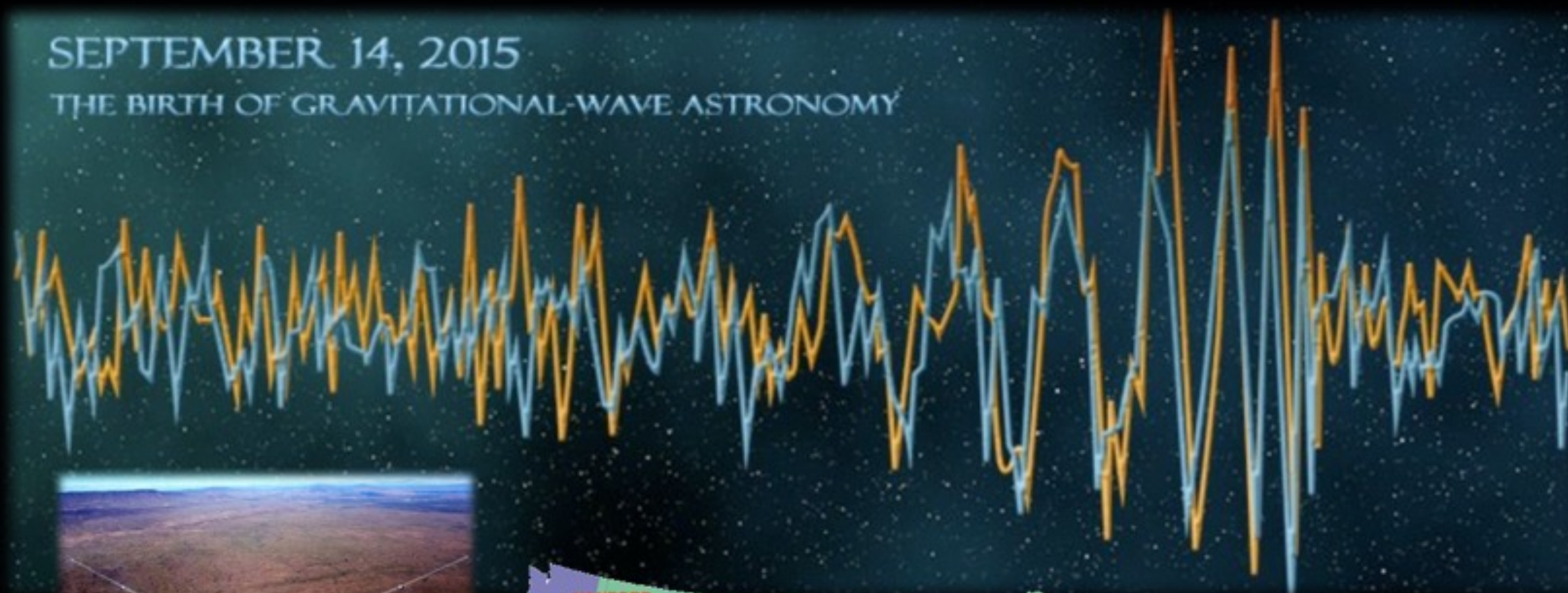
History of GW Detection

- 1916 Prediction of GW by A. Einstein
- 1979 Indirect detection at Hulse–Taylor binary
- 1990's 1st. generation interferometric detectors

- 2010's 2nd. generation interferometric detectors

- 2015 First GW detection from Binary Black Holes
- 2017 GW detection from Binary Neutron Stars

First GW detection (Sep.14, 2015)



LIGO @ Hanford

3000 km apart

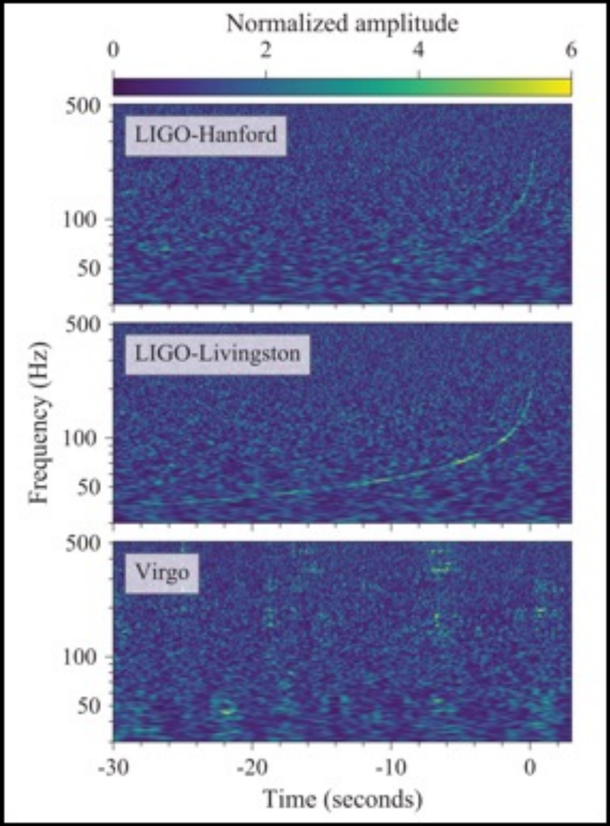
LIGO @ Livingston

Selected for a Viewpoint in *Physics*
PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

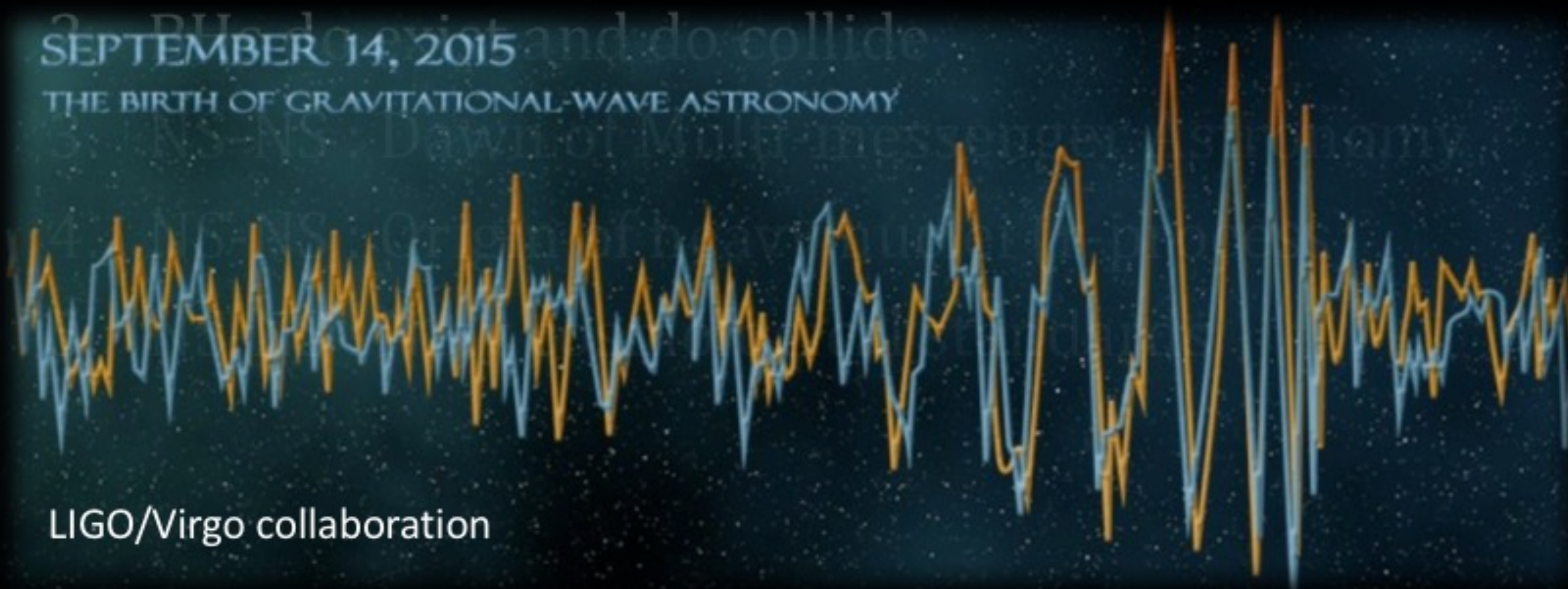
B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)



5 Breakthroughs by GW (in SH's personal view)

1. GWs do exist (direct detection after 100yrs)



5 Breakthroughs by GW (in SH's personal view)

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2. Black Holes do exist and do collide

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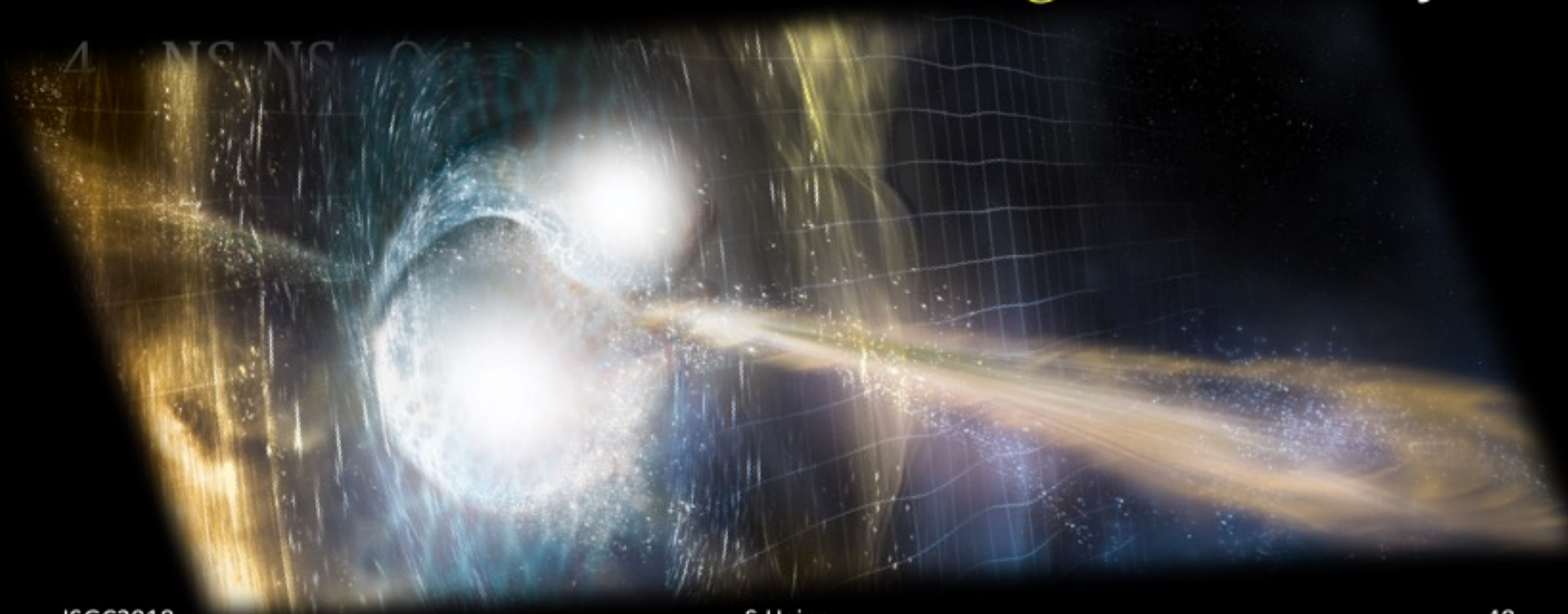
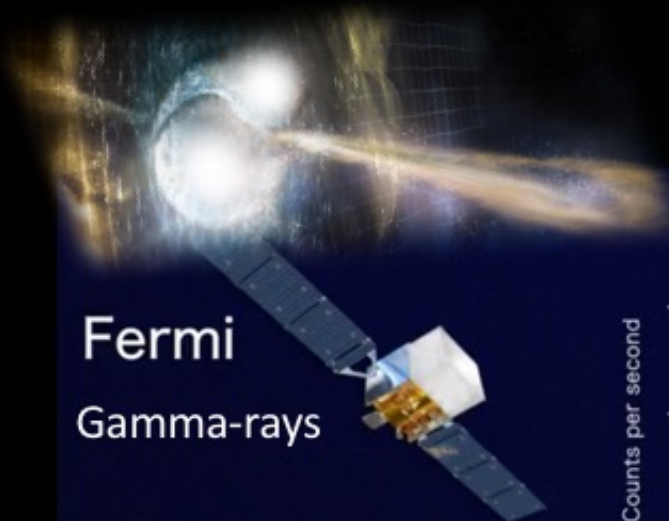
1. GWs do exist (direct detection after 100yrs)
2. BHs do exist and do collide
3. NS-NS : Dawn of Multi-messenger Astronomy

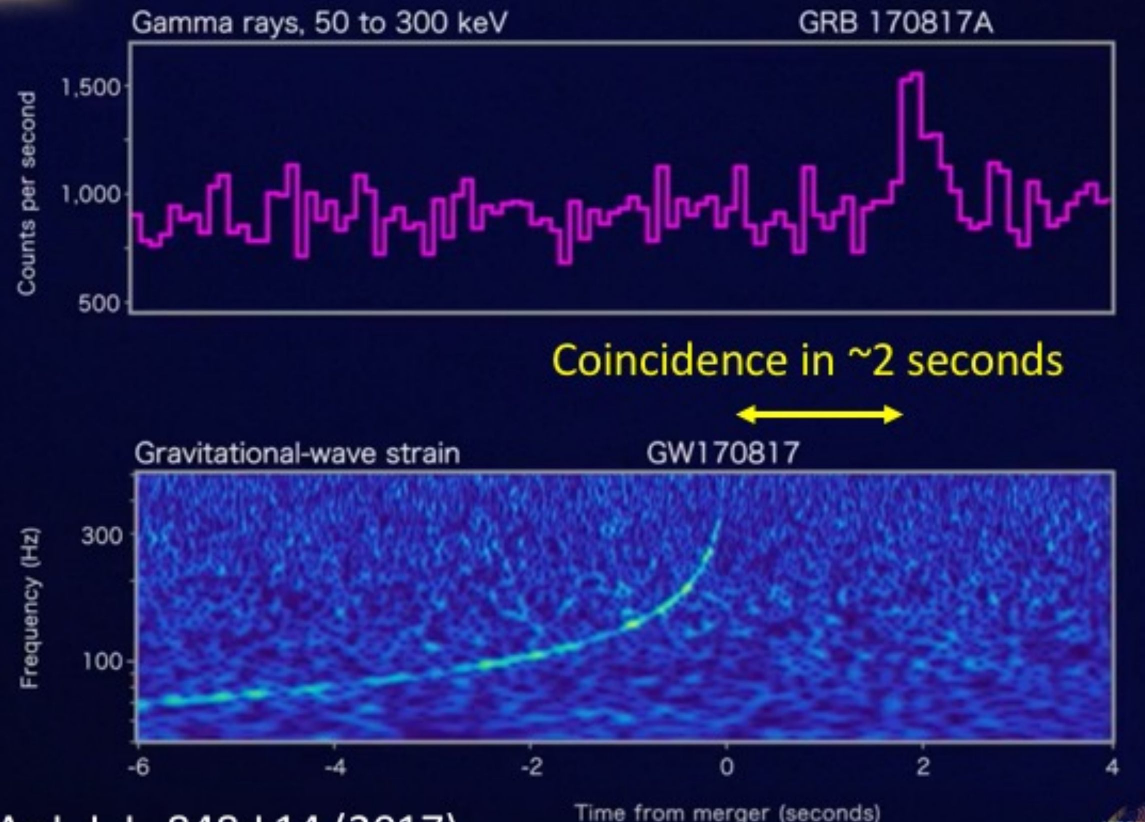


First simultaneous GW-EM detection



Fermi

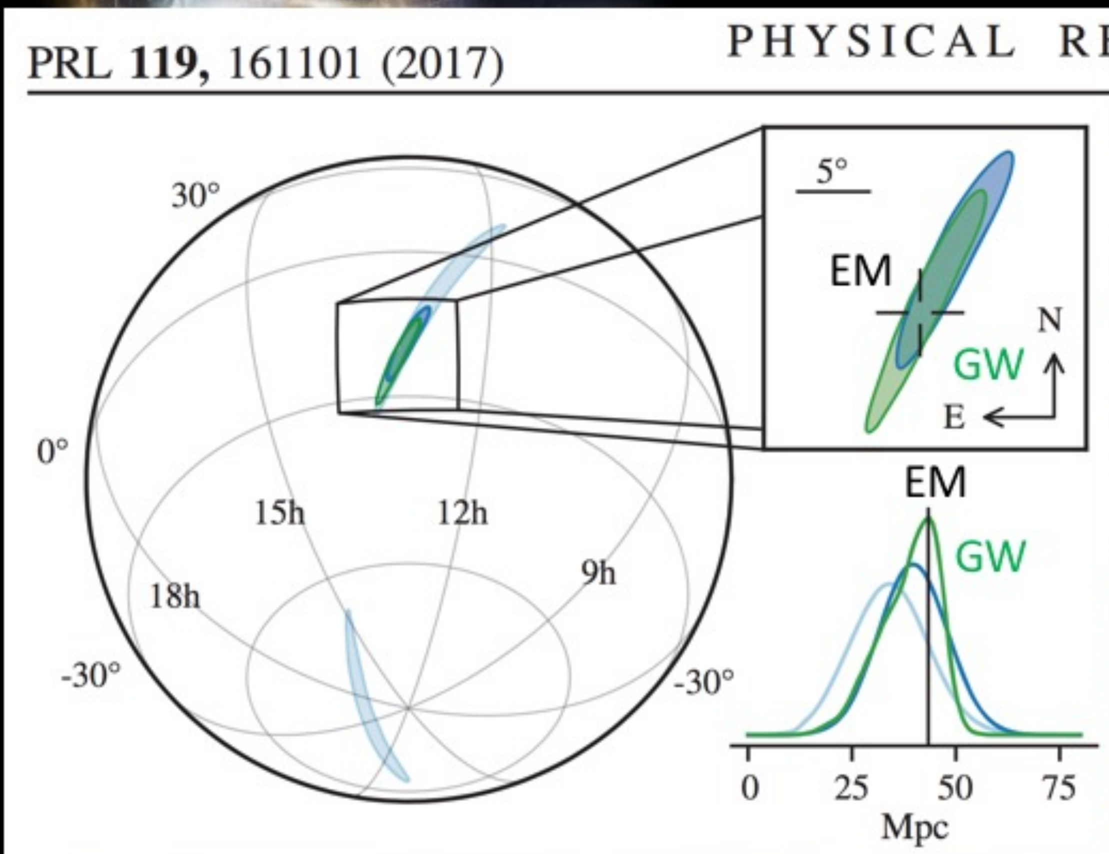
Gamma-rays



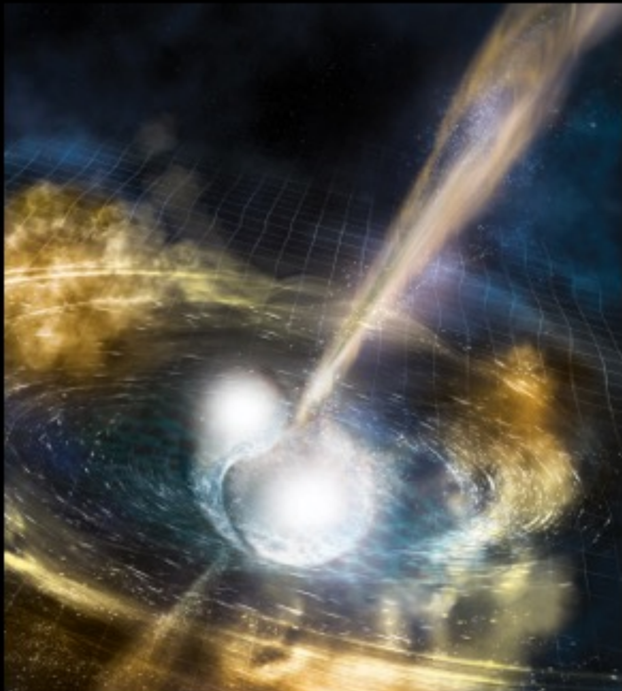
Gravitational waves

PRL 119, 161101 (2017) , ApJ. J. L. 848:L14 (2017)

First simultaneous GW-EM detection



PRL 119, 161101 (2017) , ApJ. J. L. 848:L14 (2017)



GW

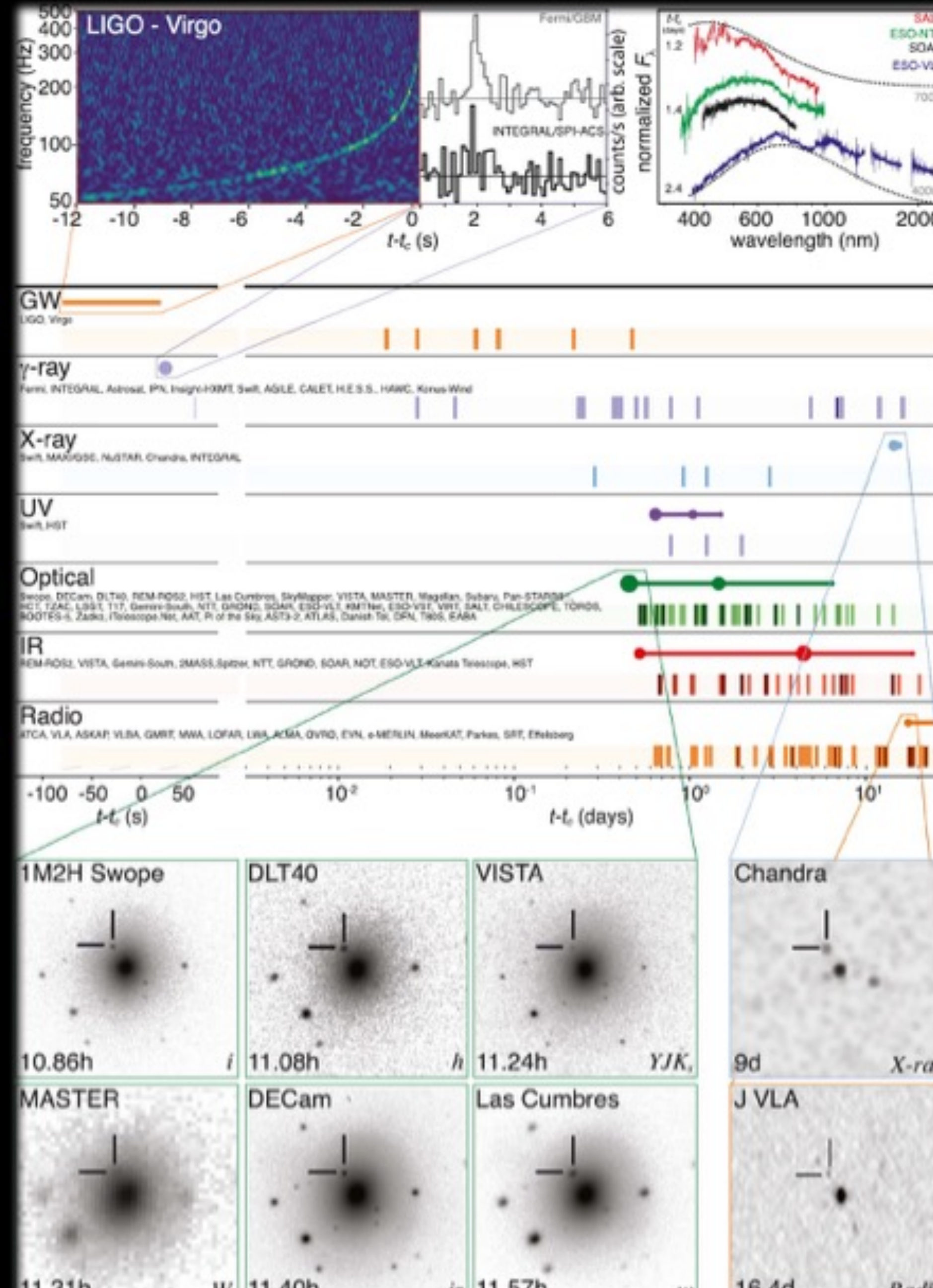
γ

UV

Optical

IR

Radio



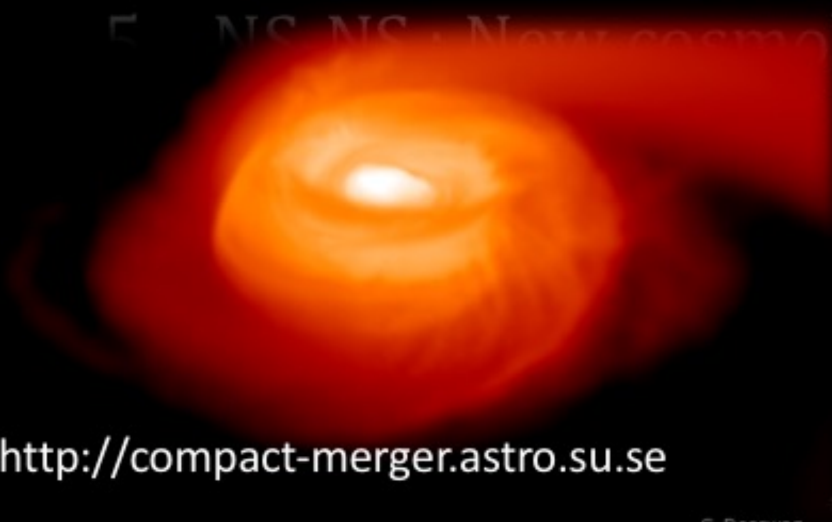
Earth

Space

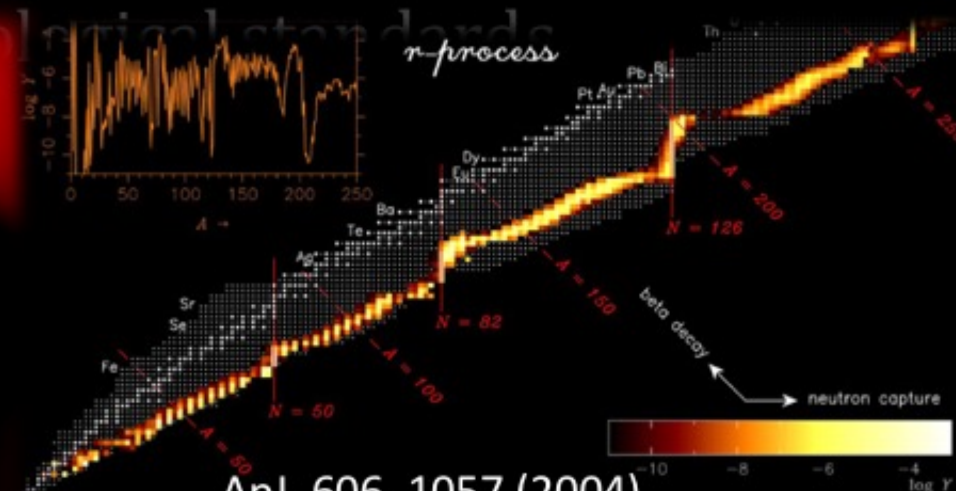
ApJ. J. L. 848:L12 (2017)

5 Breakthroughs by GW (in SH's personal view)

1. GWs do exist (direct detection after 100yrs)
2. BHs do exist and do collide
3. NS-NS : Dawn of Multi-messenger Astronomy
4. NS-NS : Origin of heavy nuclei (r-process)
5. NS-NS : New cosmological standards



http://compact-merger.astro.su.se

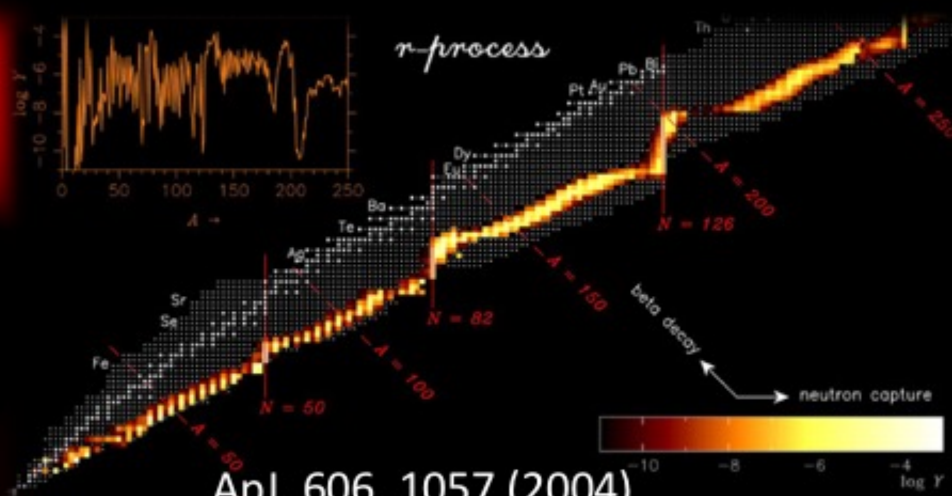


ApJ, 606, 1057 (2004)

Kilonova

The first Multi-messenger observations of NS-NS gave an evidence of heavy nuclei production through r-process (rapid neutron capture)

http://compact-merger.astro.su.se



ApJ, 606, 1057 (2004)

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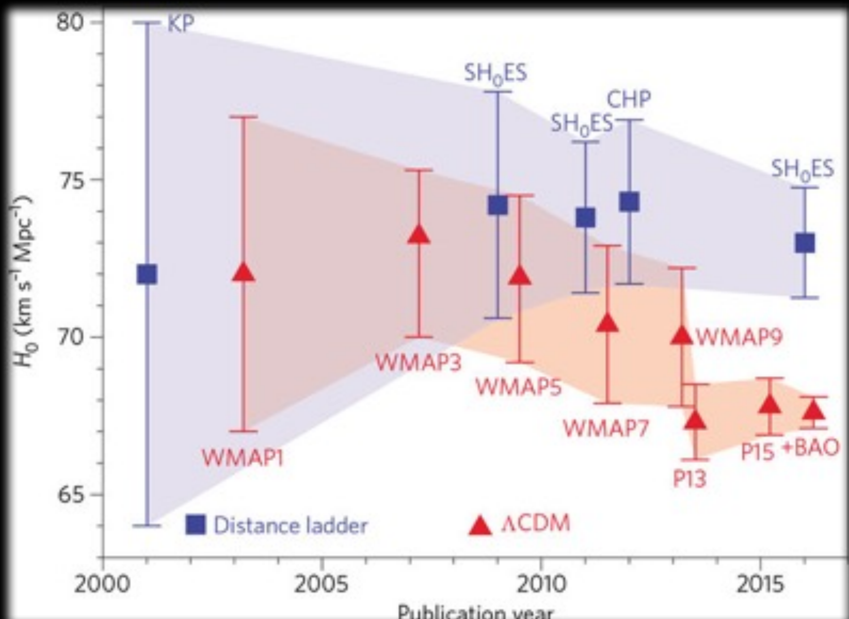
LETTER

doi:10.1038/nature24471

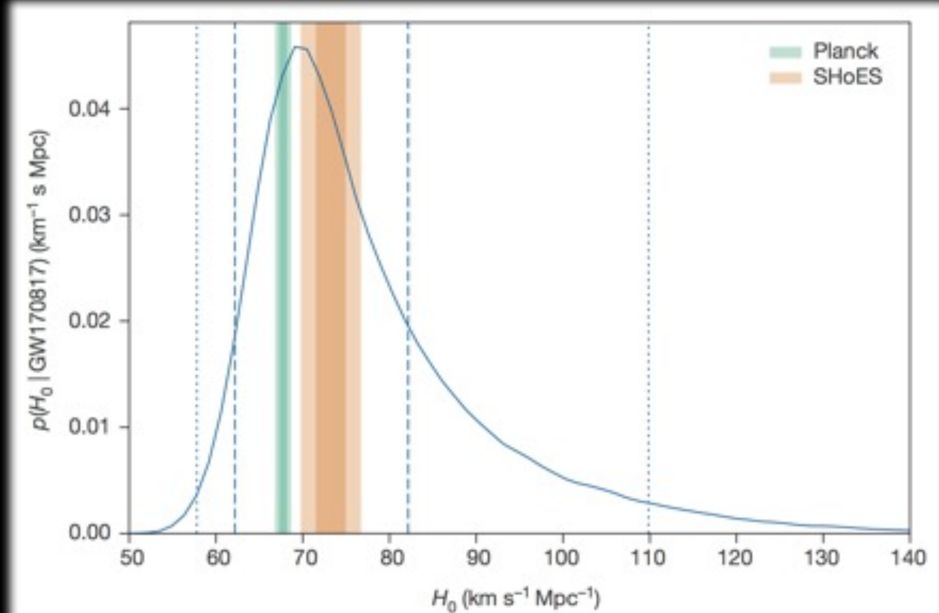
A gravitational-wave standard siren measurement of the Hubble constant

The LIGO Scientific Collaboration and The Virgo Collaboration*, The 1M2H Collaboration*, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration*, The DLT40 Collaboration*, The Las Cumbres Observatory Collaboration*, The VINROUGE Collaboration* & The MASTER Collaboration*

Hubble constant
– an issue and a new hope



Nature Astronomy **1**, 0121 (2017)

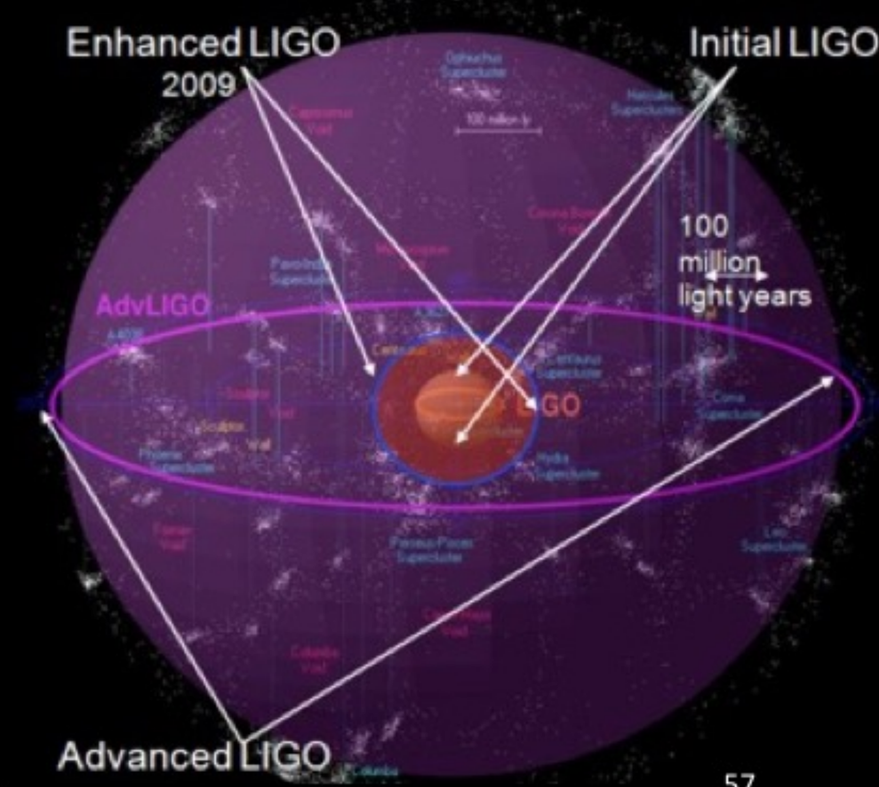


Nature **551**, 85 (2017)

Opening of a GW astronomy

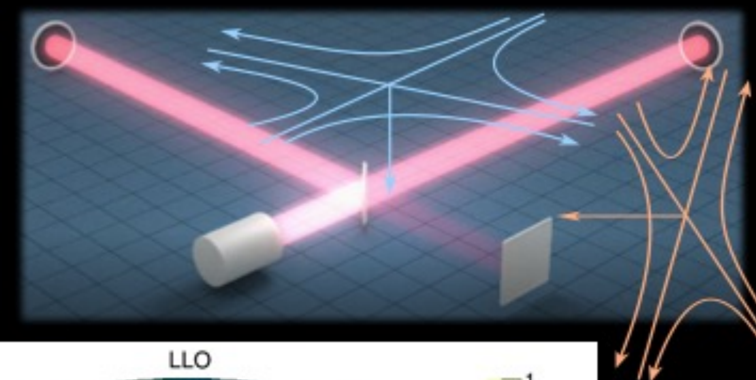
- GW detection opened a new era
- GW amplitude is proportional to 1/Distance

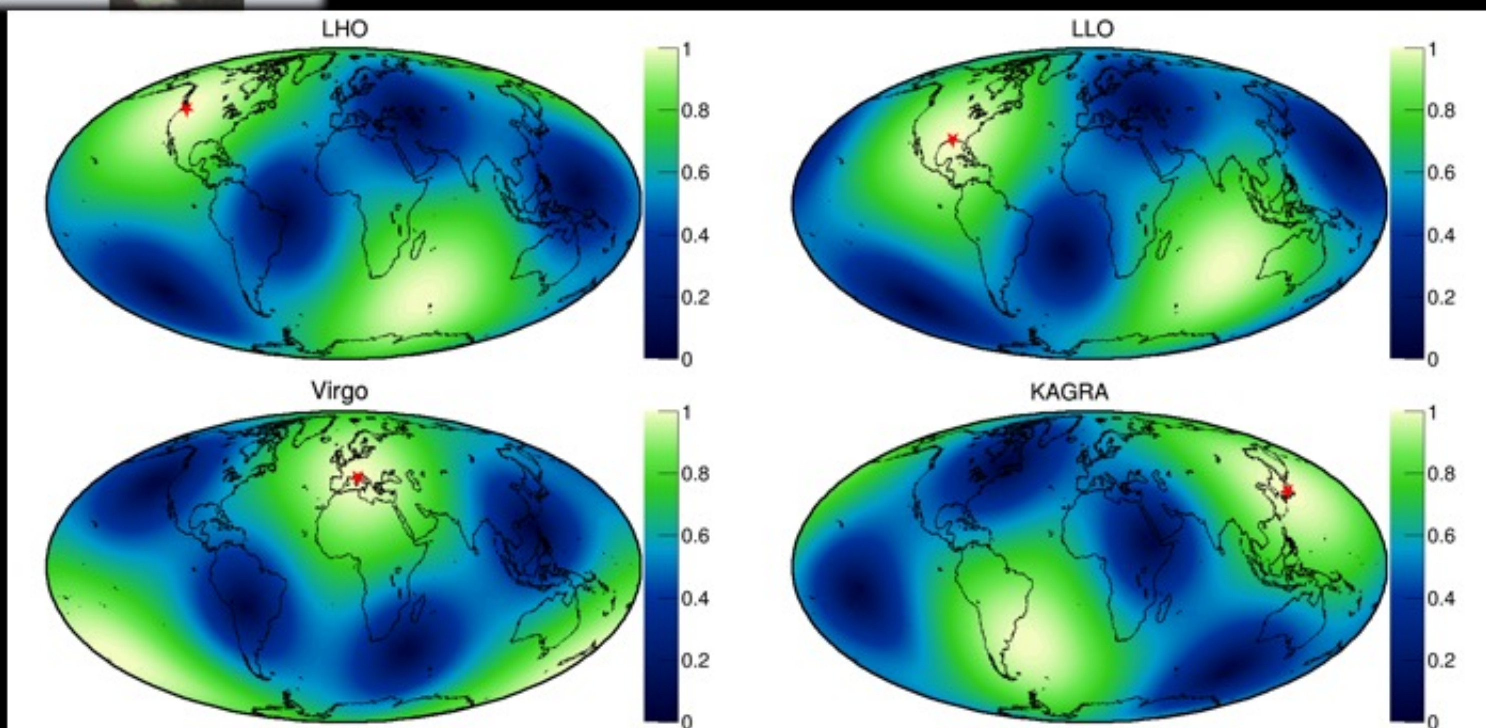
- 10 times improvement of sensitivity will increase number of sources by 1000 !



World-wide GW detector network

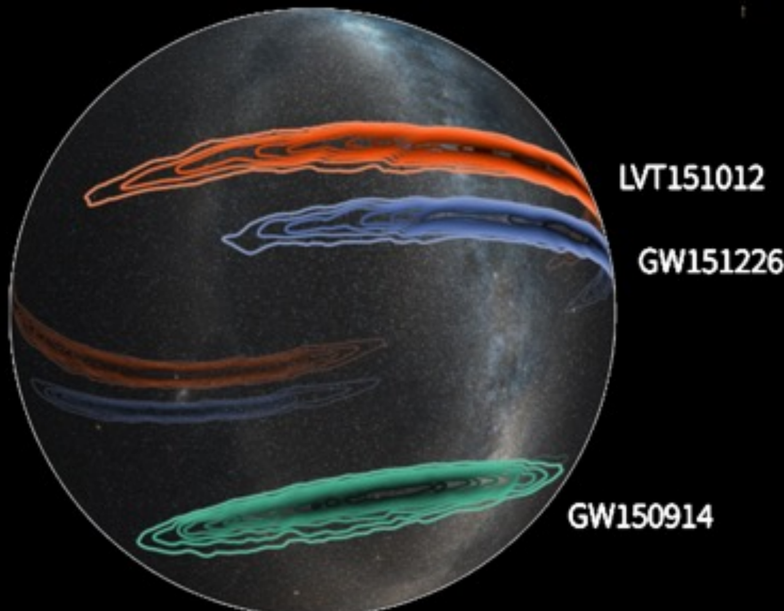
Detector Antenna Patterns

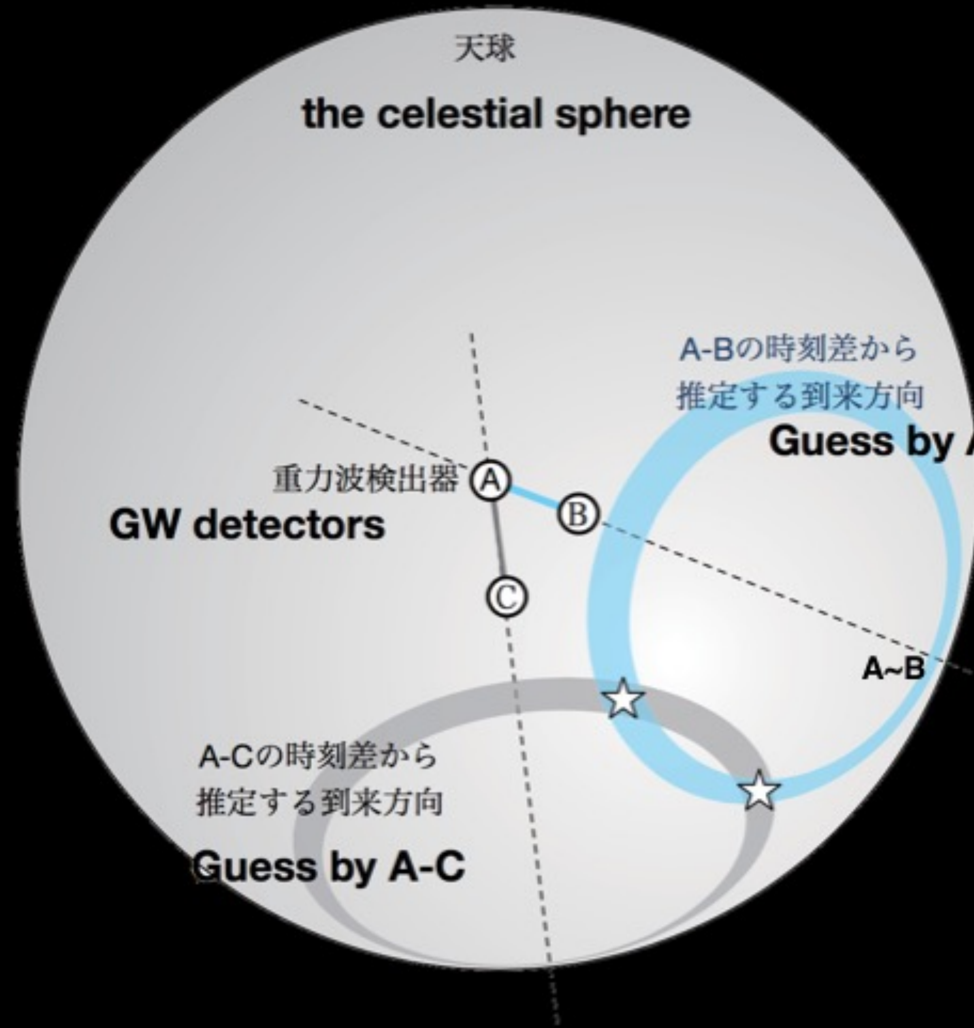




Sky localization

GW events locations
by only 2 LIGO detectors

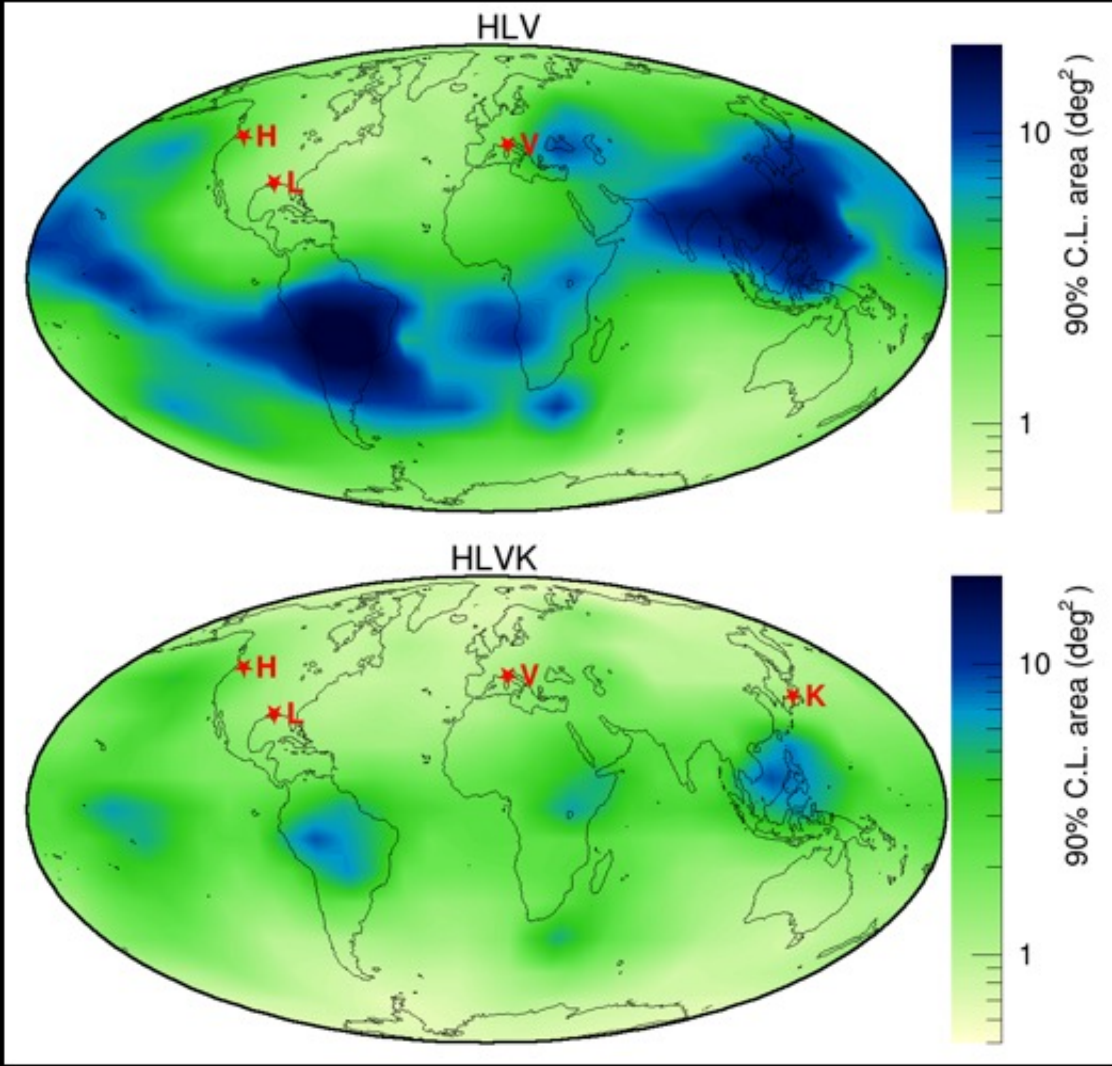




Sky localization

3 detectors
2x LIGO (U.S.)
Virgo (Italy)

4 detectors
+ KAGRA
(Japan)



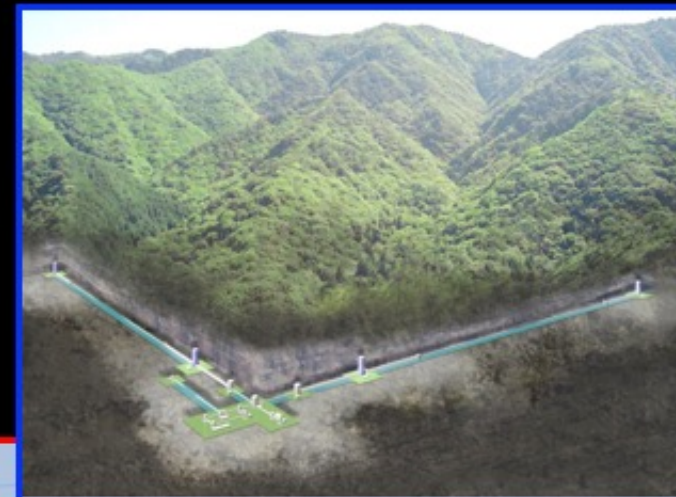
KAGRA

The first km-scale
Underground and Cryogenic
Gravitational Wave Telescope

KAGRA

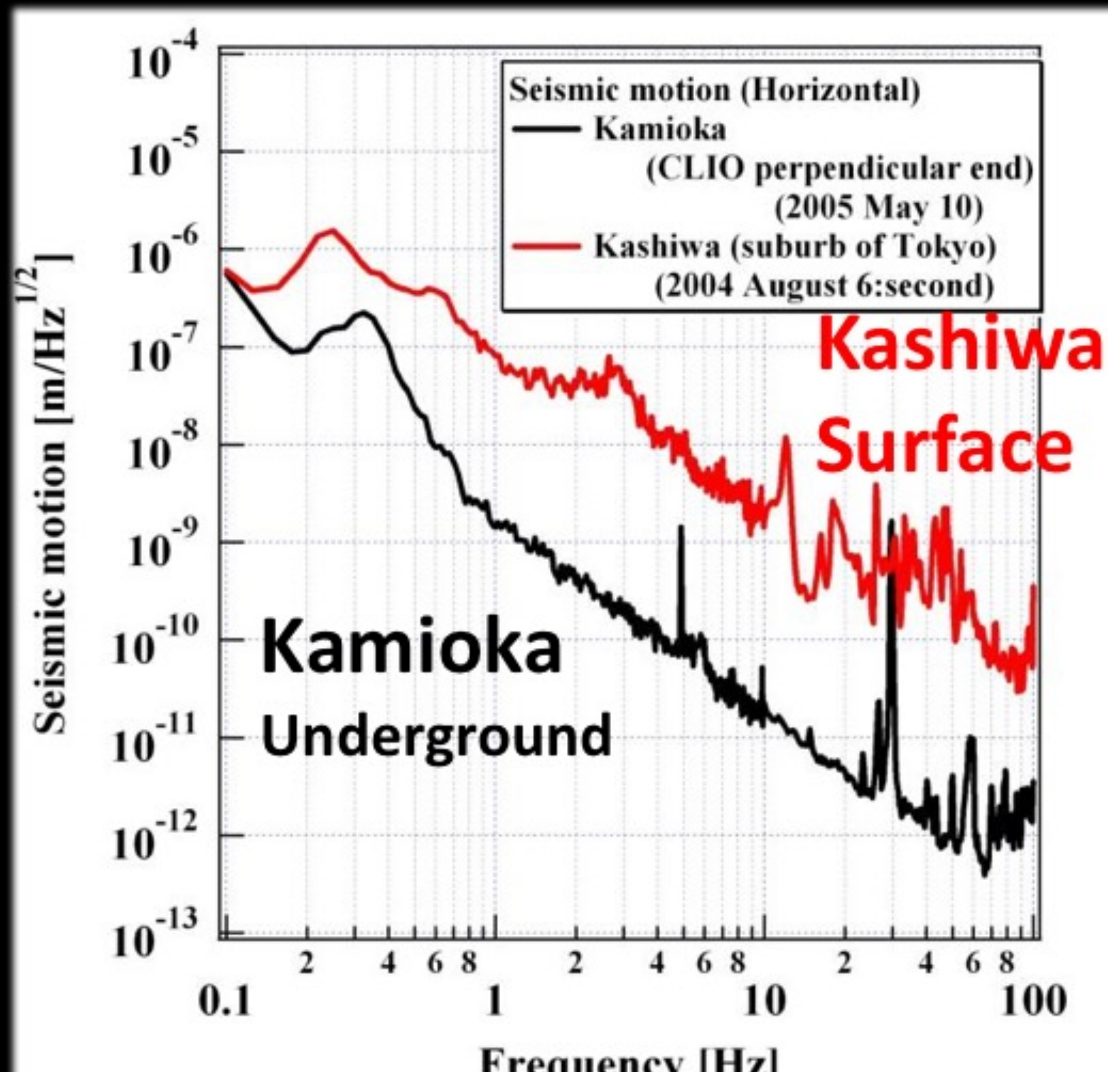

GEO 600m
LIGO (Livingston) 4km
advanced LIGO
Virgo 3km
advanced Virgo
LIGO (Hanford) 4km
LIGO-India


Japan
Kamioka
S.Haino
1000km



Kamioka underground site

KAGRA – The first km-scale detector at underground




Tunnel excavation was
done in 2014


Tunnel entrance


Vacuum tubes
installed in 2015

KAGRA – The first km-scale cryogenic detector

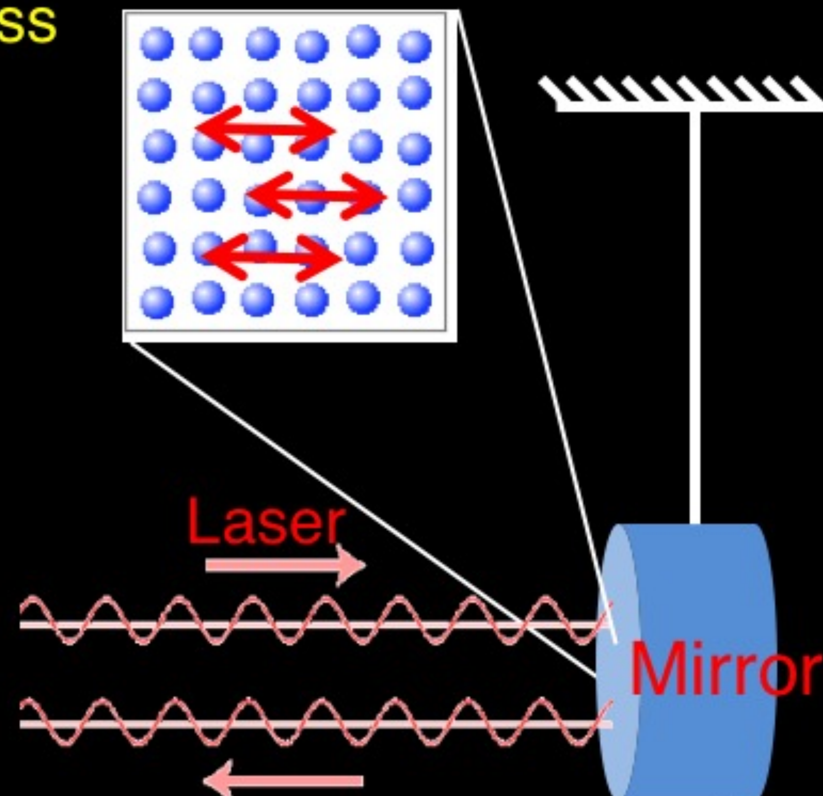
Thermal noise — Temperature — Mechanical loss

$$\sqrt{x(\omega)^2} \propto \sqrt{T\phi}$$

Sapphire @ 20K

$\phi = 5 \times 10^{-9}$ (bulk)

$\phi = 1 \times 10^{-7}$ (fiber)



Application of Accelerator technologies to KAGRA

J-PARC neutrino
super-conducting beam line

KEK cryogenic center is leading the development of KAGRA cryogenic system

Vacuum System

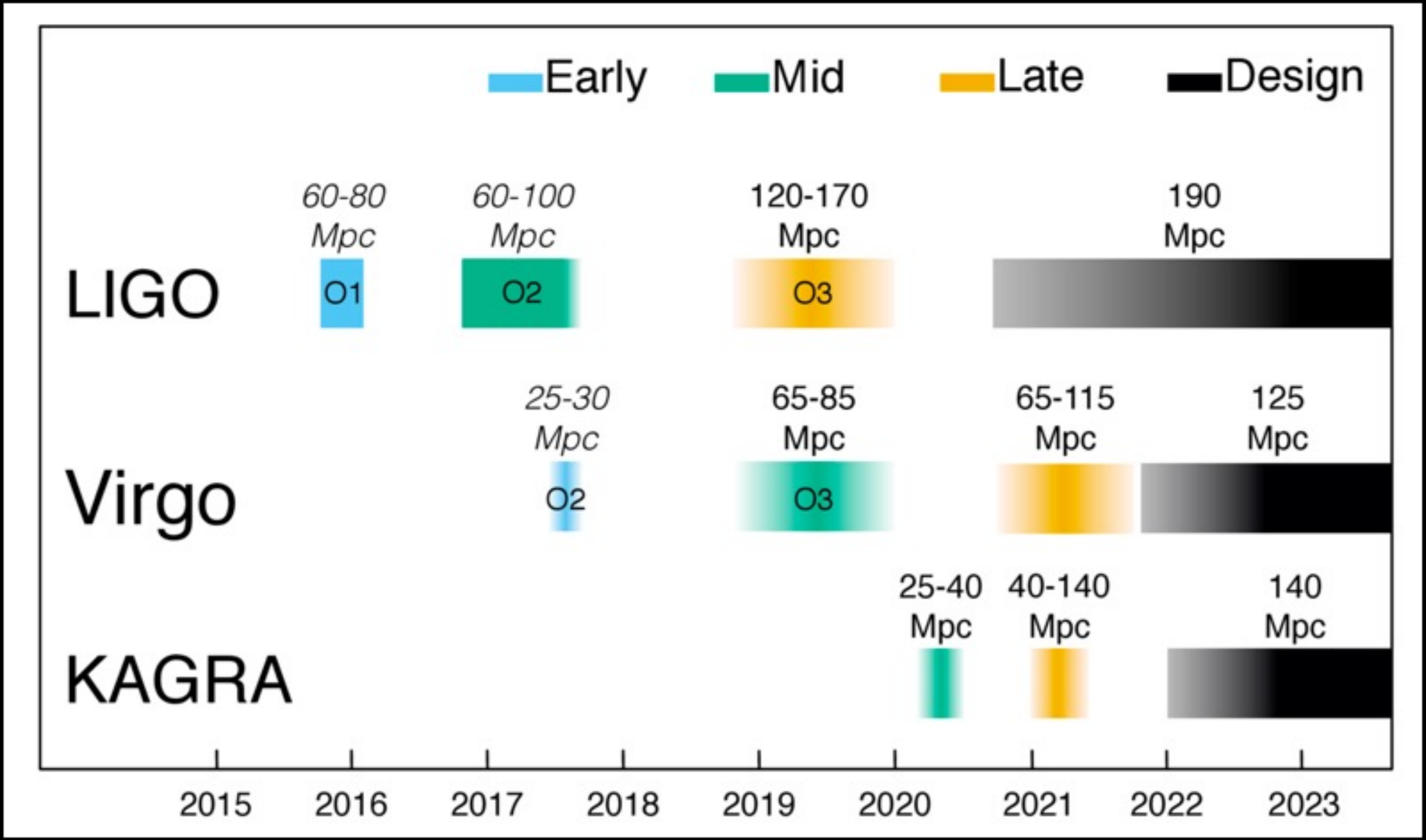
- In order to minimize the laser scattering noise ultra-high vacuum (10^{-7} Pa) is required

- GW detectors are the three world largest vacuum system

- LIGO	1.2mϕ x4km x2 = 10,000 m^3 (each)
- Virgo	1.2mϕ x3km x2 = 6,800 m^3
- KAGRA	0.8mϕ x4km x2 = 3,000 m^3
- LHC	110 m^3

Observation scenario

arXiv:1304.0670



How to analyze GW data ?

Two major steps

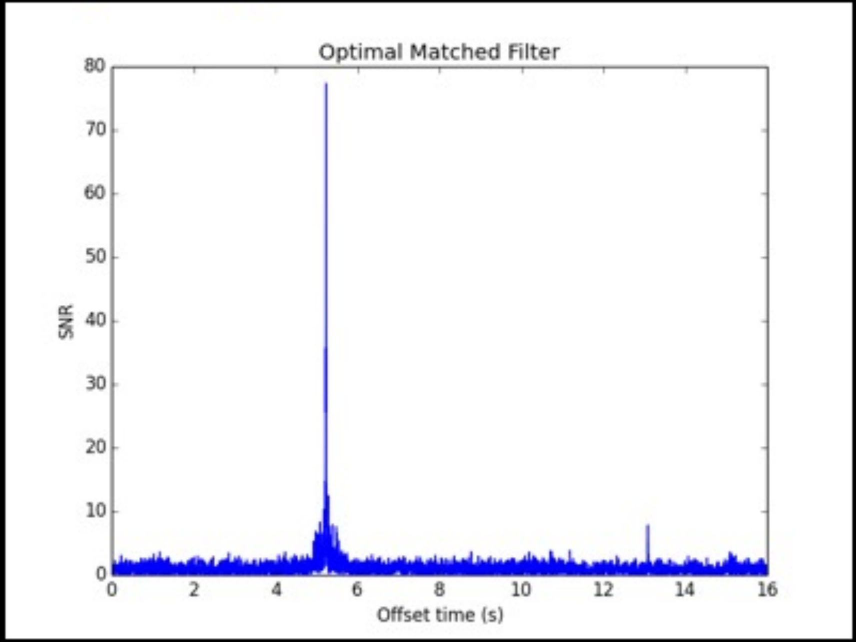
- Detect and identify a GW signal

- Extract physics parameters

How to identify GW signal ?

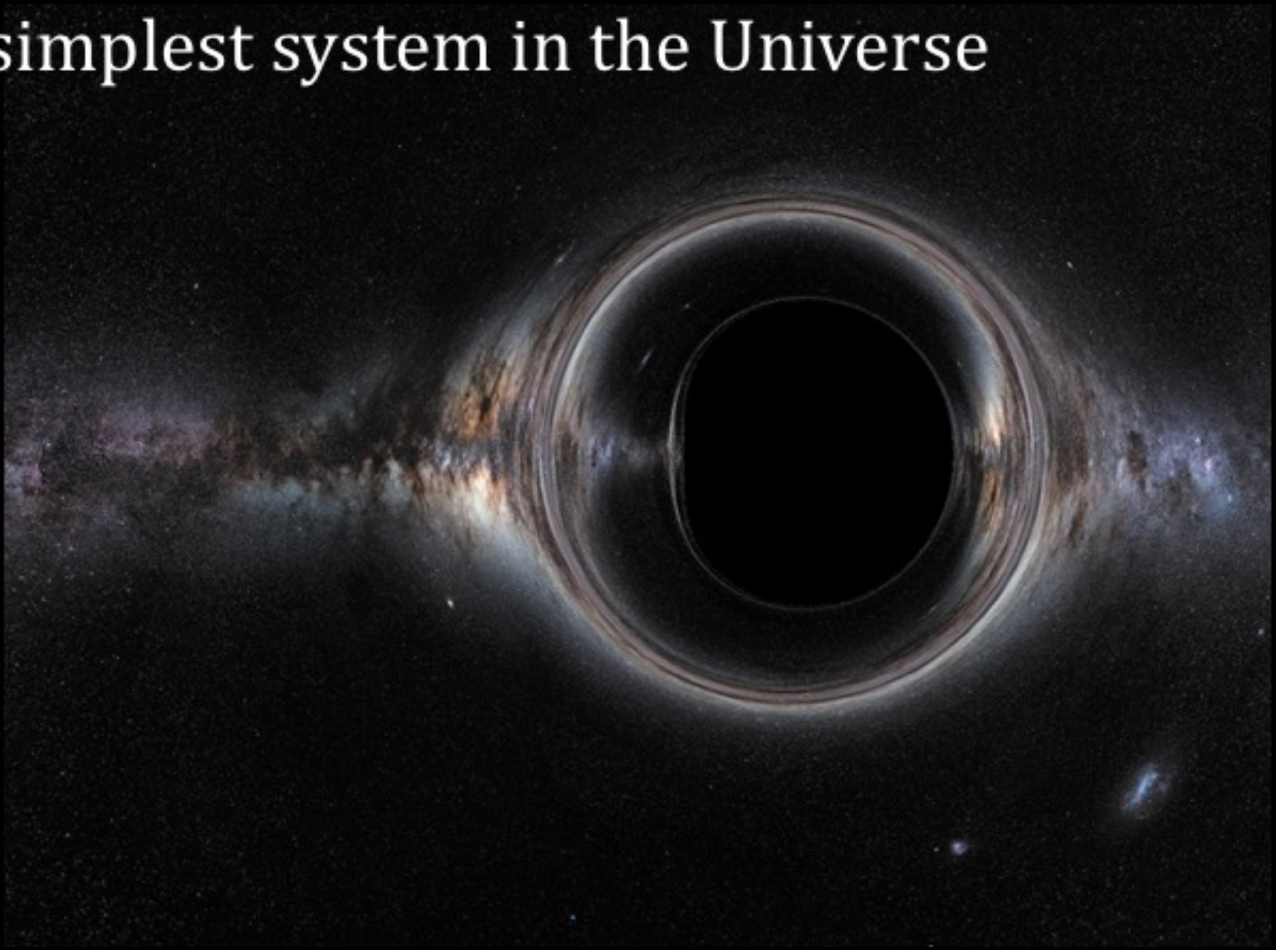
Matched filter

- Repeating FFT with many different waveforms
- Find the optimum S/N ratio (SNR)



Waveform estimations

- BH is the simplest system in the Universe
  - Mass
  - Spin

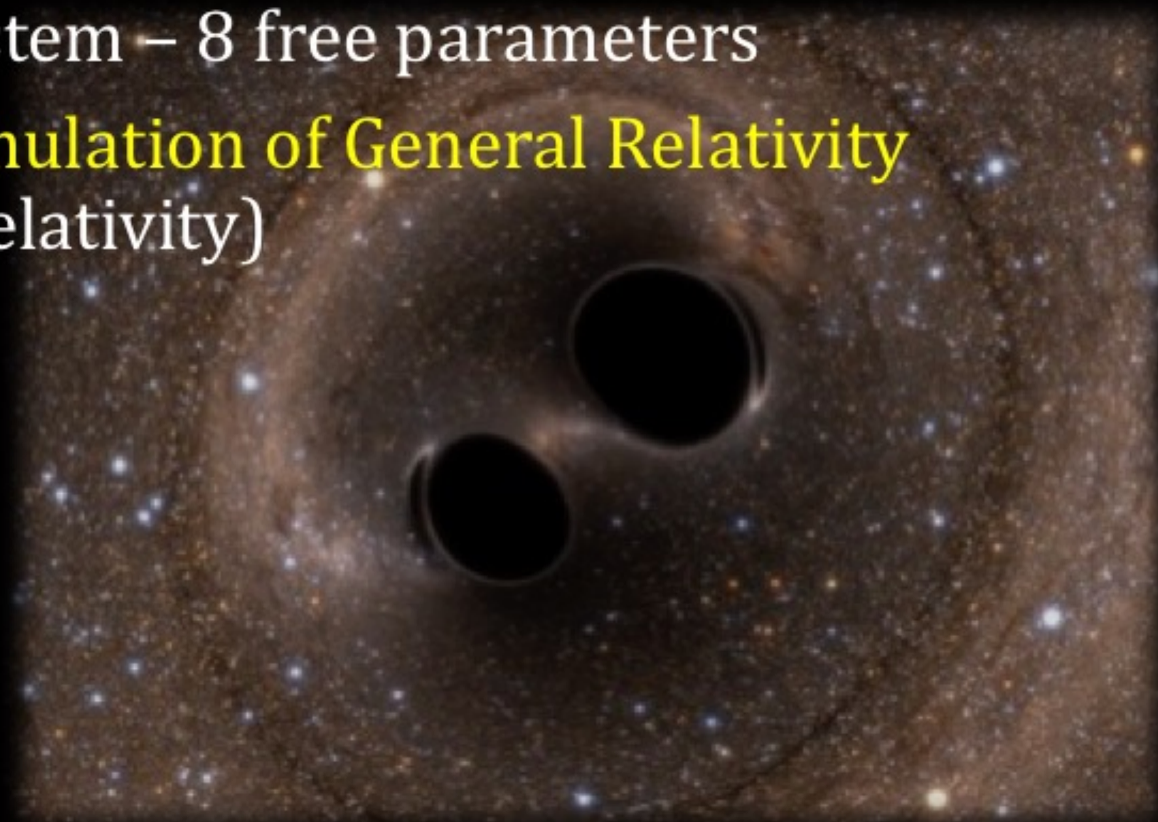


Waveform estimations

- BH is the simplest system in the Universe
  - Mass and Spin
- Binary BH system – 8 free parameters
  - 2 masses
  - 3 + 3 spins

Waveform estimations

- BH is the simplest system in the Universe
- Binary BH system – 8 free parameters
- Numerical simulation of General Relativity (Numerical Relativity)

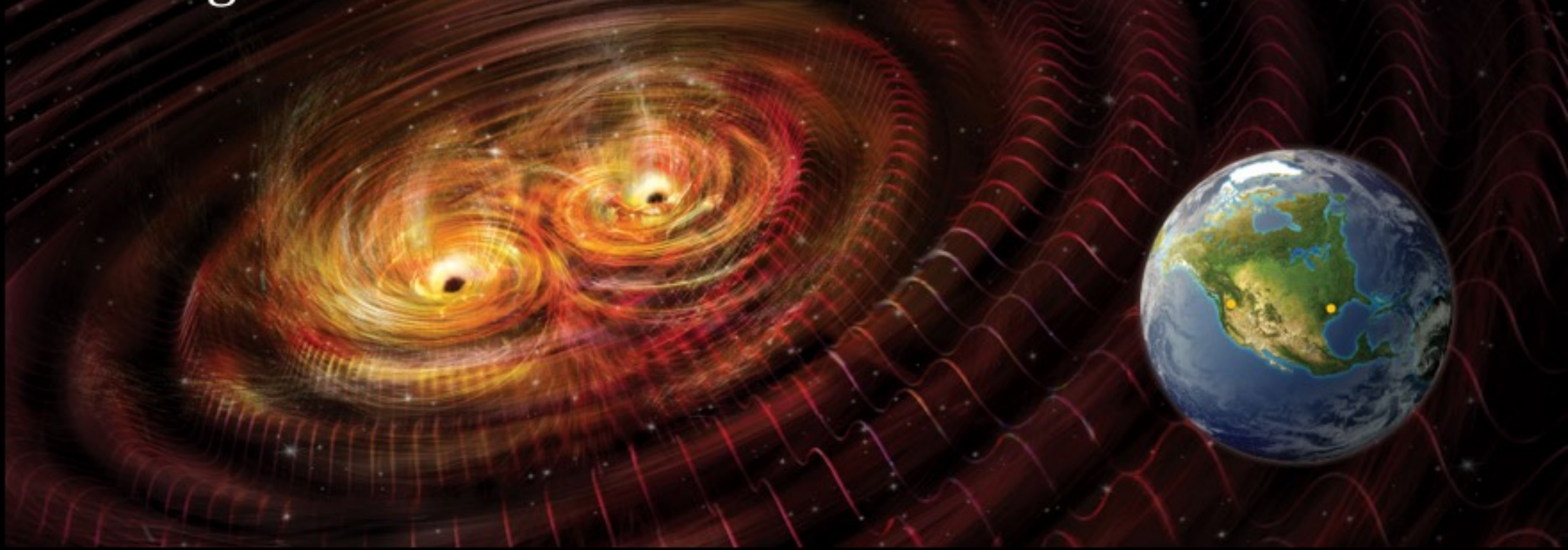


Waveform estimations

- BH is the simplest system in the Universe
- Binary BH system – 8 free parameters
- Numerical Relativity
- Simulation of GW emissions

Numerical Relativity (NR) challenges

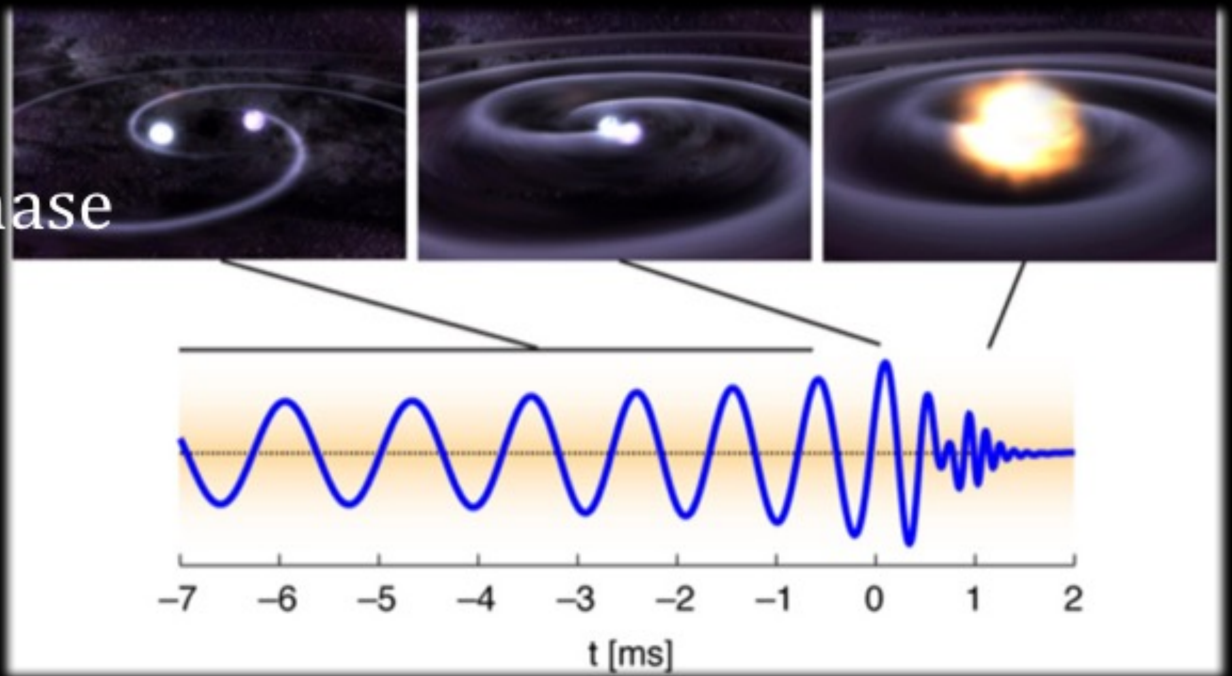
- Definition of initial states
- Step-by-step Evolution with General Relativity
- Huge hierarchical Scale



Parameterization of NR

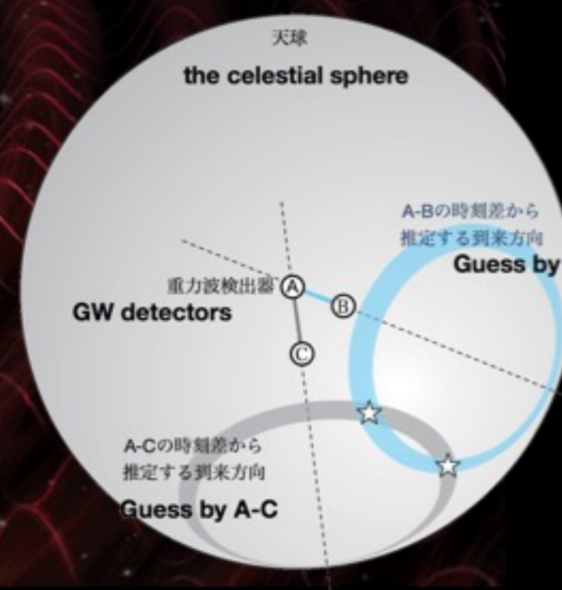
Describe IMR (Inspiral, Merge, Ringdown)
with numerical functions with 9 parameters (CBC)

- 2 Masses
- 6 Spins
- 1 merging phase



External conditions (6 parameters)

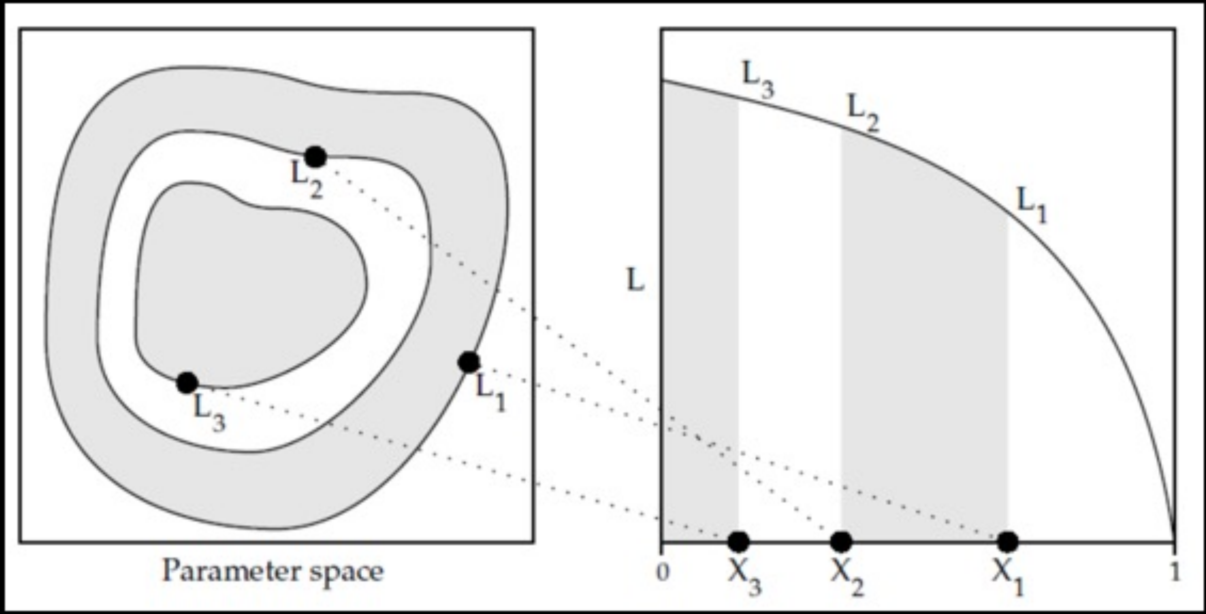
- 2 Sky position
- 1 Distance
- 1 Geocentric Arrival time
- 1 Polarization
- 1 Orbital inclination



GW Parameter Estimation

Bayesian inference of ~15 parameters (CBC)

- MCMC
- Nested sampling
- …

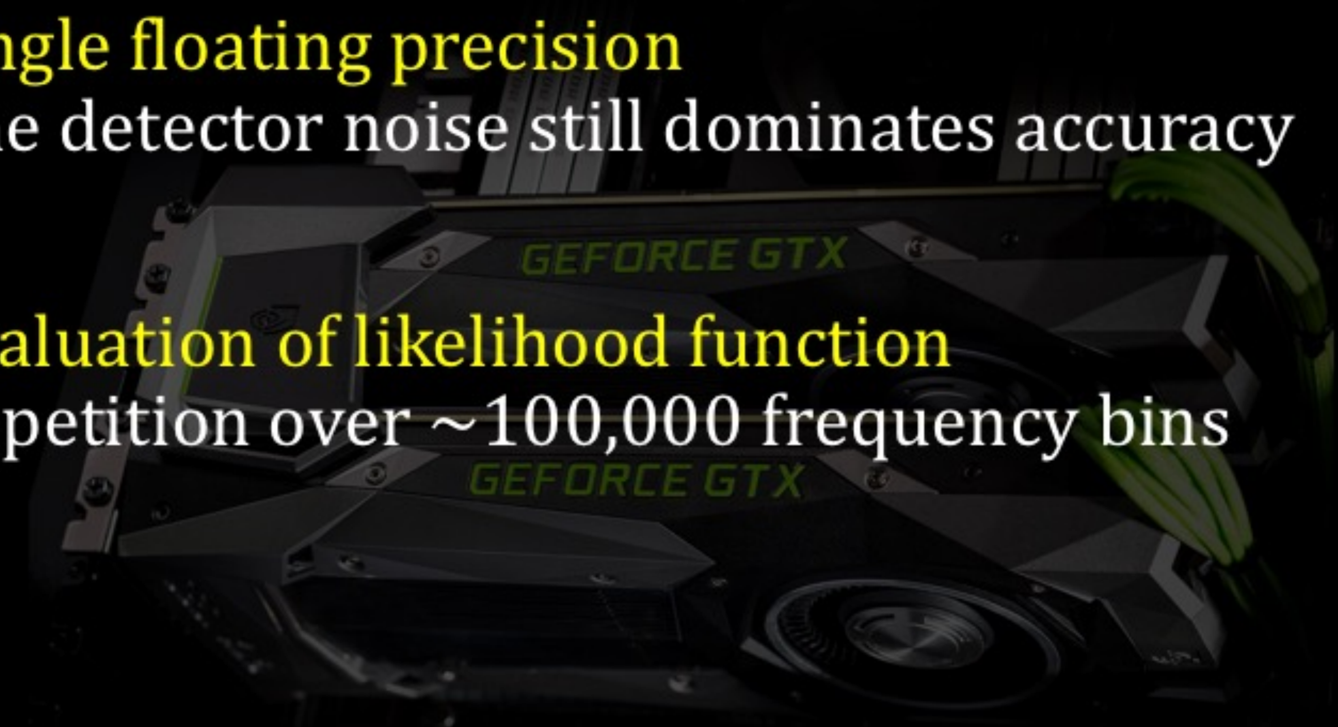


GPU-accelerated
Parameter Estimation

Advantages to use GPU

- Single floating precision
  The detector noise still dominates accuracy

- Evaluation of likelihood function
  Repetition over ~100,000 frequency bins



GPU-accelerated Parameter Estimation

Strong supports in Taiwan:

- Ting-Wai Chiu (NTNU/ASIoP)
  - CUDA code developments and GPU farm
- Chun-Yu Lin (NCHC)
- Felix Lee, Shih-Chang Lee (ASGC)

ASGC GPU farm

Slide by Felix Lee

- Two models available
- Consumer GPU
  - GTX 1080Ti: 64 in total.
  - 8 * GPUs per compute box.
  - 128GB system memory.
  - 1TB SSD local hard-drive.
- Server GPU
  - Tesla p100: 16 in total
  - 4 * GPUs per compute box.
  - 128GB system memory
  - 1TB SSD local hard-drive
  - NV-link
- 8 * v100 model is on-going.

Application of Deep Neural Networks (DNN)

D. George and E. A. Huerta arXiv:1701.00008

Deep Neural Networks to Enable Real-time Multimessenger Astrophysics

Daniel George[1,2] and E. A. Huerta[2]

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[2]*NCSA, University of Illinois at Urbana-Champaign, Urbana, Illinois, 61801, USA*

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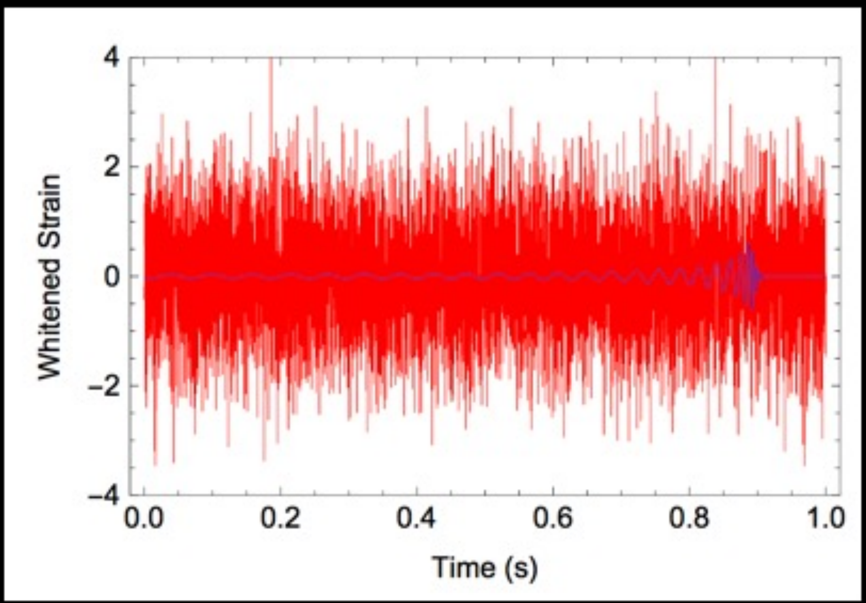

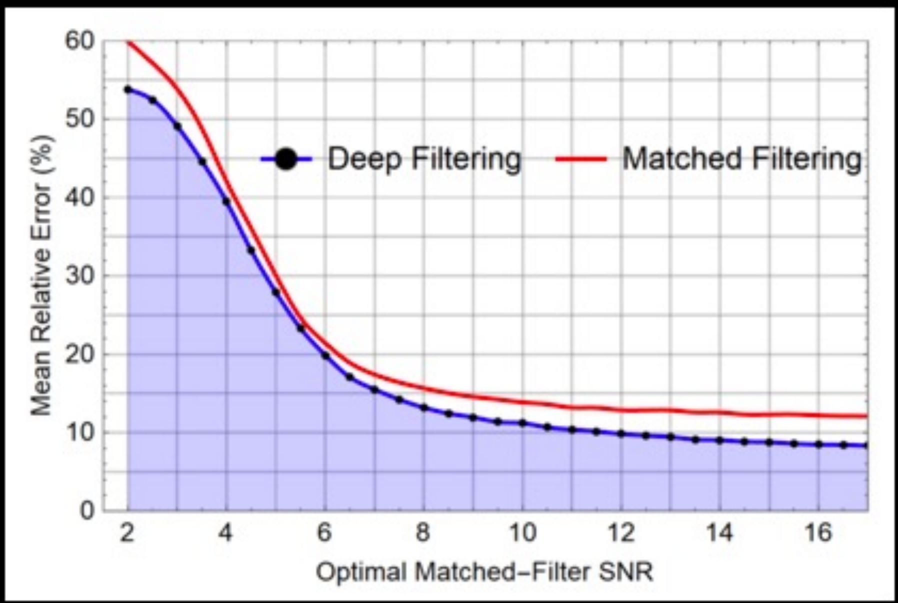

"several orders of magnitude faster thus allowing real-time processing of raw big data with minimal resources. "

Summary

- Gravitational-wave astronomy has just begun
- There are still a lot of potentials to apply advanced computing like GPU, DNN, …