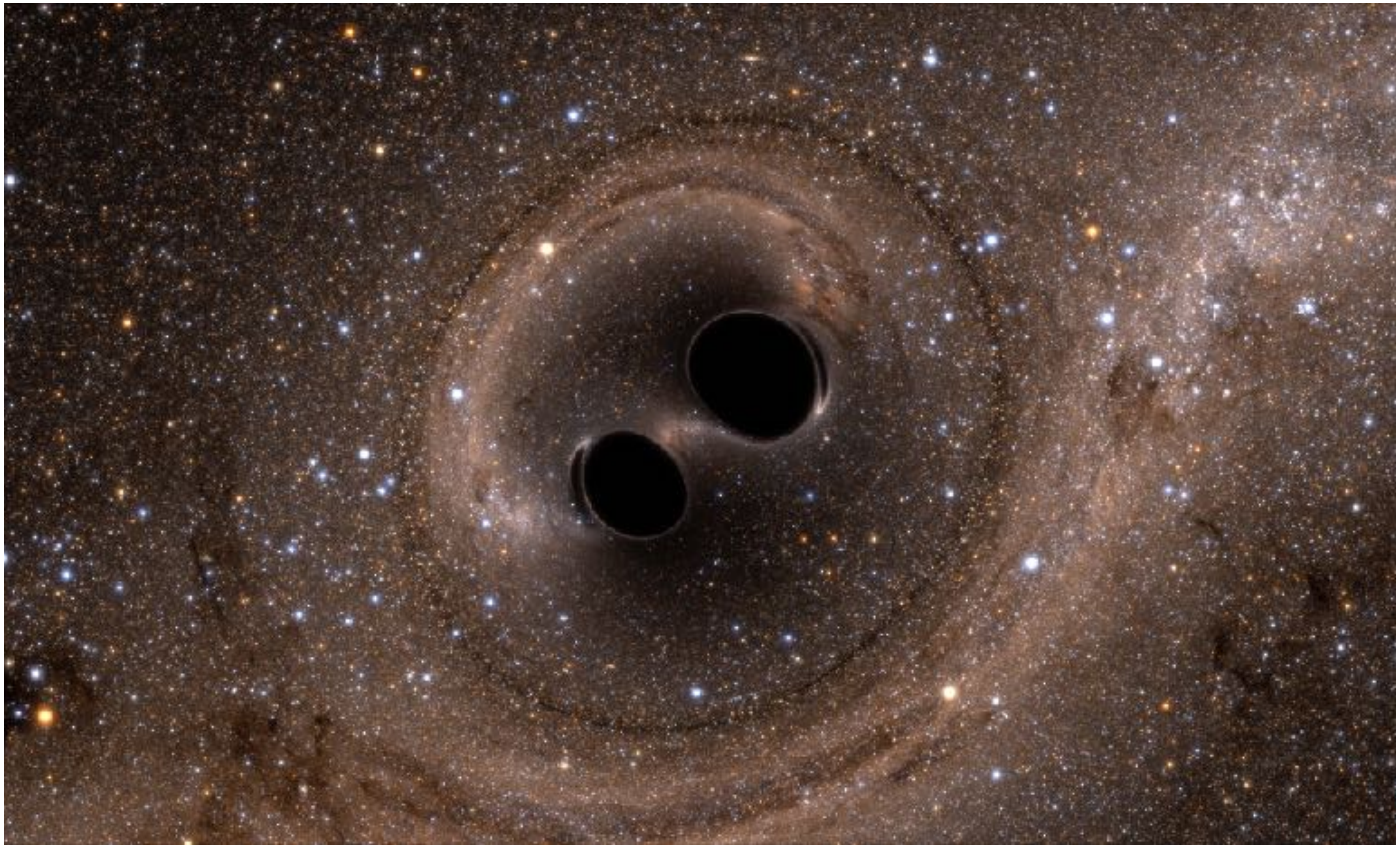


A Long Journey toward the Detection of Gravitational Waves

Hyung Mok Lee

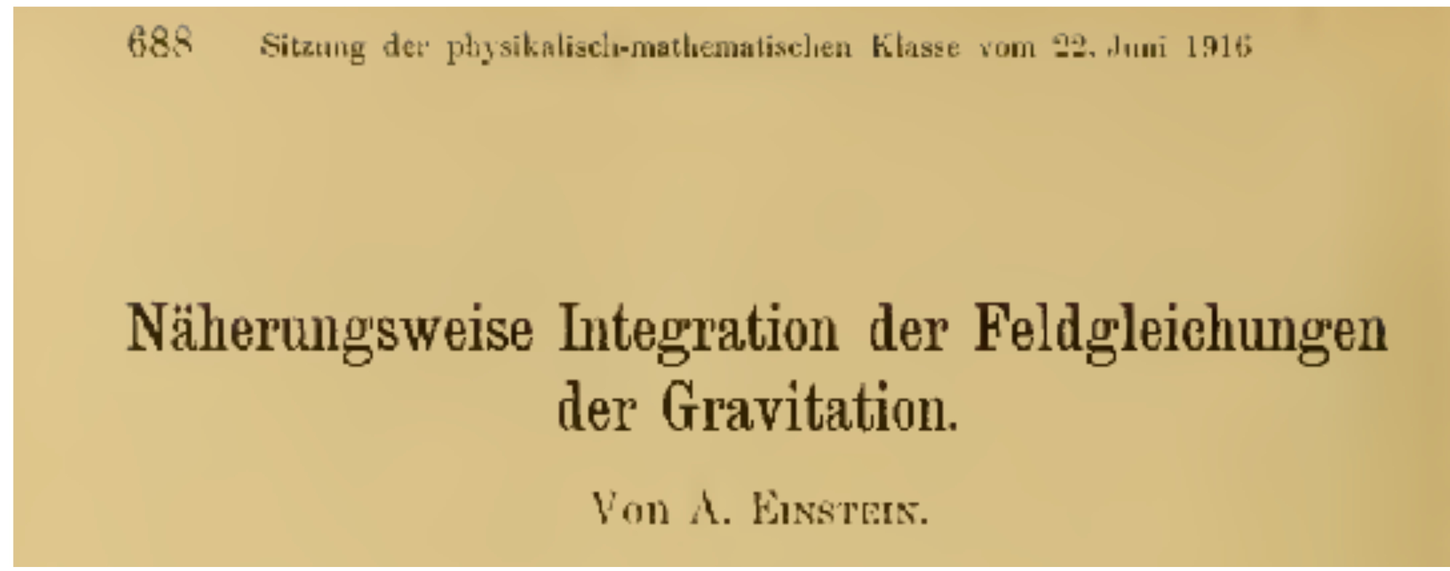
한국 중력파 연구 협력단

Plan

- Historical Note
- Introduction to the Gravitational waves
- LIGO and detection of gravitational waves
    - Contributions of the 2017 Nobel Laureates
- Recent Development of GW Astrophysics

Einstein's early papers

- 1916, "Näherungsweise integration der Feldgleichungen der gravitation (Approximate integration of the field equations of gravitation)",1916m,*Königlich Preußische Akademie der Wissenschaften (Berlin). Sitzungsberichte*, 688–696.
  - Propagation of gravitational waves
- 1918 "Über Gravitationswellen (On gravitational waves)", 1918, *Königlich Preußische Akademie der Wissenschaften (Berlin). Sitzungsberichte*, 154–167
  - Generation of gravitational waves


688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.


154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

Über Gravitationswellen.

Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

Confusion: Do GWs exist?

Nathan Rosen

Letter by Einstein to Max Born 1936

"Together with a **young collaborator** , I arrived at the interesting result that gravitational waves do not exist, though they had been assumed a certainty to the first approximation. This shows that the non-linear general relativistic field equations can tell us more or, rather, limit us more than we have believed up to now. "

A paper entitled "**Do gravitational wave exist?**" was submitted to Physical Review in 1936, but received a critical referee's report.

Einstein's reply to the editor:

Dear Sir,

We (Mr. Rosen and I) had sent you our manuscript for publication and had not authorized you to show it to specialists before it is printed. I see no reason to address the - in any case erroneous - comments of your anonymous expert. On the basis of this incident I prefer to publish the paper elsewhere.

respectfully,

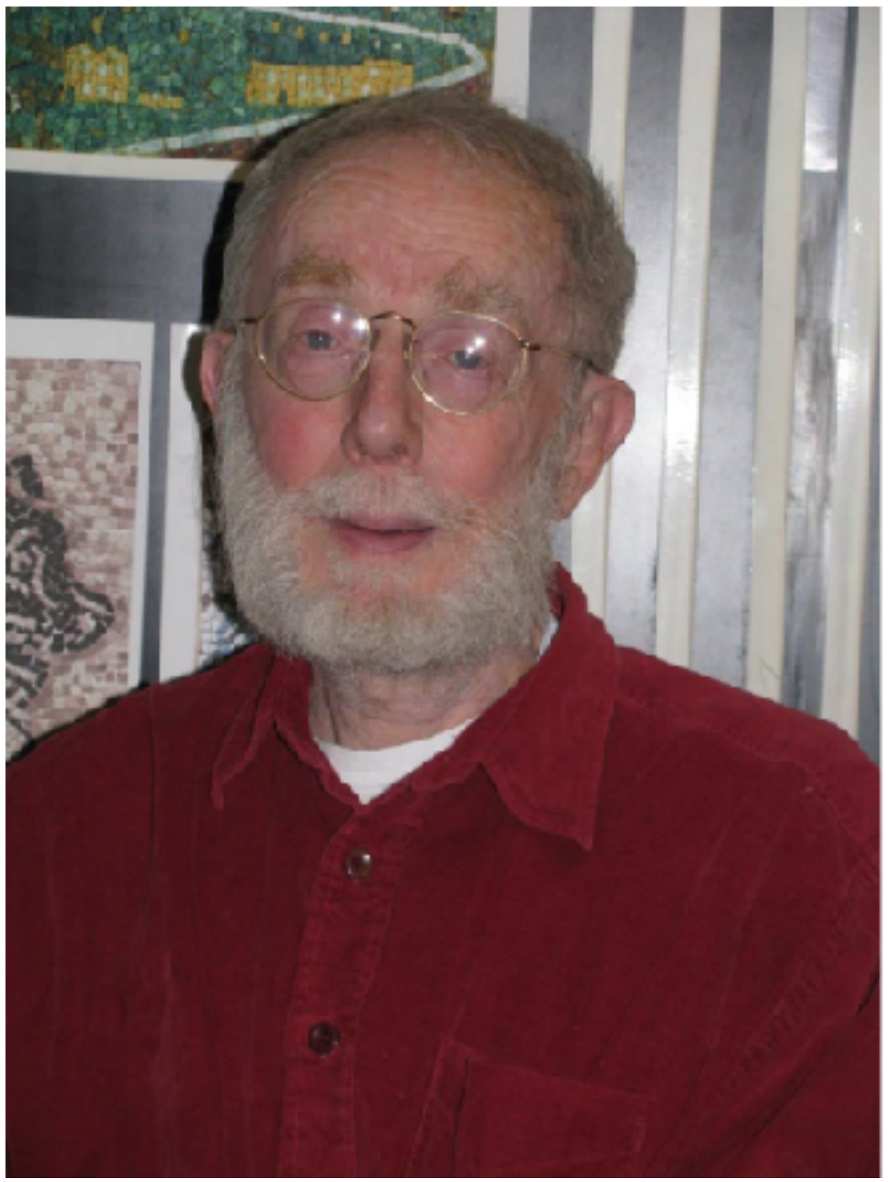
What happened thereafter:

The paper with Rosen was, however, subsequently accepted for publication by the Journal of the Franklin Institute in Philadelphia, but Einstein changed the conclusion completely just before the publication.

The Chapel Hill Conference (1957)

- A conference on the Role of Gravitation in Physics, was held in Chapel Hill Conference in January 1957. It was the first meeting of the "General relativity and Gravity" conference series [GR1]
  - GR21 was held in 2016
- It is generally regarded that the “gravitational wave problem” was solved in this meeting
- The quest to detect gravitational waves was born.

Felix Pirani (1928 - 2015)



- Felix Pirani was a student of Alfred Schild's and then of Hermann Bondi. In 1957 he was a junior colleague of Bondi at King's College, London.
- At Chapel Hill, he gave a talk on the solution of the gravity wave problem
- Bondi (or Feynman) usually get the credit as they have conveyed Pirani's results to the community.

Text adapted from Saulson's lecture at the Boulder Conference on the History and Philosophy of Science, 2016

Pirani's Insight

- Pirani's insight was to analyze the reception of gravitational waves, not their generation.
- He showed that, in the presence of a gravitational wave, a set of freely-falling particles would experience genuine motions with respect to one another. Thus, gravitational waves must be real.
  - Listening to Pirani's talk, Bondi asked whether you could connect two nearby masses with a dashpot, thus absorbing energy from the wave, and proving its physical reality.
  - Pirani replied: "I have not put in an absorption term, but I have put in a 'spring'. You could invent a system with such a term quite easily."
- Richard Feynman's Remarks at the end of the meeting: "I think it is easy to see that if gravitational waves can be created they can carry energy and can do work"

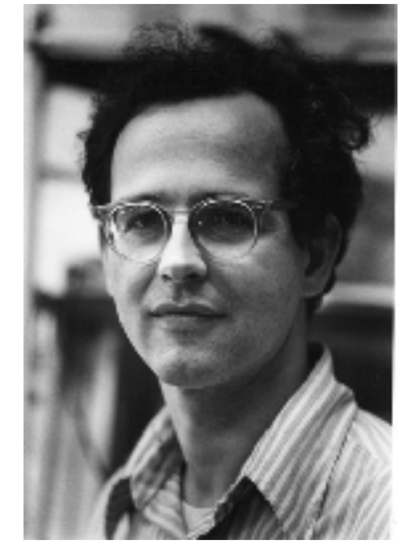
Part of the text was adapted from P. Saulson's lecture at the Boulder Conference on the History and Philosophy of Science, 2016

Joseph Weber (1919-2000)

- Joseph Weber, co-inventor of the maser, had been working with John Wheeler at Princeton on gravitational waves in late 1950s.
- Weber gave a less-than-clear talk at Chapel Hill, and was critically questioned by Bondi, just before Pirani's talk
- Weber and Wheeler recapped Pirani's argument in a paper written within weeks of the Chapel Hill conference.
- Weber expanded on the experimental ideas in two Gravity Research Foundation essays (3rd prize 1958, 1st prize 1959), leading to his 1960 Phys. Rev. paper, laying out the bar program.

Text adapted from Saulson's lecture at the Boulder Conference on the History and Philosophy of Science, 2016

Rainer Weiss



- Rainer Weiss, a graduate from MIT, worked with Bob Dicke at Princeton on gravity experiments as a post-doc.
- In 1964, Weiss was back at MIT and he was assigned to teach general relativity.
- He asked, What's really measurable in general relativity? He found the answer in Pirani's papers presented at Chapel Hill in 1957 (published in 1959).
- In Pirani's papers, he didn't "put in" either a spring or a dashpot between the test masses. Instead, he said: "It is assumed that an observer, by the use of light signals or otherwise, determine the coordinates of a neighboring particle in his local Cartesian coordinate system."
- By this time, Weiss had been working on laser applications for gravity experiments. Weiss read Pirani, and knew that lasers could do the job of detecting a gravitational wave.

Text adapted from Saulson's lecture at the Boulder Conference on the History and Philosophy of Science, 2016

Kip Thorne

- Kip Thorne became convinced that gravitational wave detection was possible, and likely to provide tremendous new information for physics and astronomy in late 1960s.
- He convinced Caltech to make a sustained commitment to developing gravitational wave interferometers.
- Ron Drever (from Glasgow) was hired to lead the experimental effort.
- This was the essential foundation for LIGO.

Text adapted from Saulson's lecture at the Boulder Conference on the History and Philosophy of Science, 2016

The Birth of the LIGO

- Concept of laser interferometry to monitor the relative motion of freely hanging mirrors
    - Michael Gertsenshtein and Vladislav Pustovoit in Moscow Russia (1962), and Rainer Weiss (1967)
- Rainer Weiss envisioned LIGO in 1972
    - He saw how to do many orders of magnitude better than Weber, by implementing Pirani's free-test-masse smeasured by lasers as a Michelson interferometer. Arms could be kilometers long. Lasers could measure sub-nuclear distances. $\Delta L/L \sim 10^{-21}$ could be achieved.
    - Weiss never published this paper. It appeared in a Quarterly Progress Report for MIT's ResearchLab of Electronics: https://dspace.mit.edu/handle/1721.1/56271
- It lays out a plausible design for a kilometer scale interferometric detector. Most importantly, it gives a tour de force analysis of almost every noise source that needs to be taken into account.
- It was the beginning of the LIGO.

Schematic Diagram (https://dspace.mit.edu/handle/1721.1/56271)

Quarterly Progress Report, No. 105 of the Research Laboratory for Electronics

V. GRAVITATION RESEARCH*

Academic and Research Staff

Prof. R. Weiss
Dr. D. J. Muehlner
R. L. Benford

Graduate Students

D. K. Owens
N. A. Pierre
M. Rosenbluh

A. BALLOON MEASUREMENTS OF FAR INFRARED BACKGROUND RADIATION

Evolved to COBE, Nobel prize in 2006, but without Weiss

B. ELECTROMAGNETICALLY COUPLED BROADBAND GRAVITATIONAL ANTENNA

Evolved to LIGO, Nobel prize in 2017

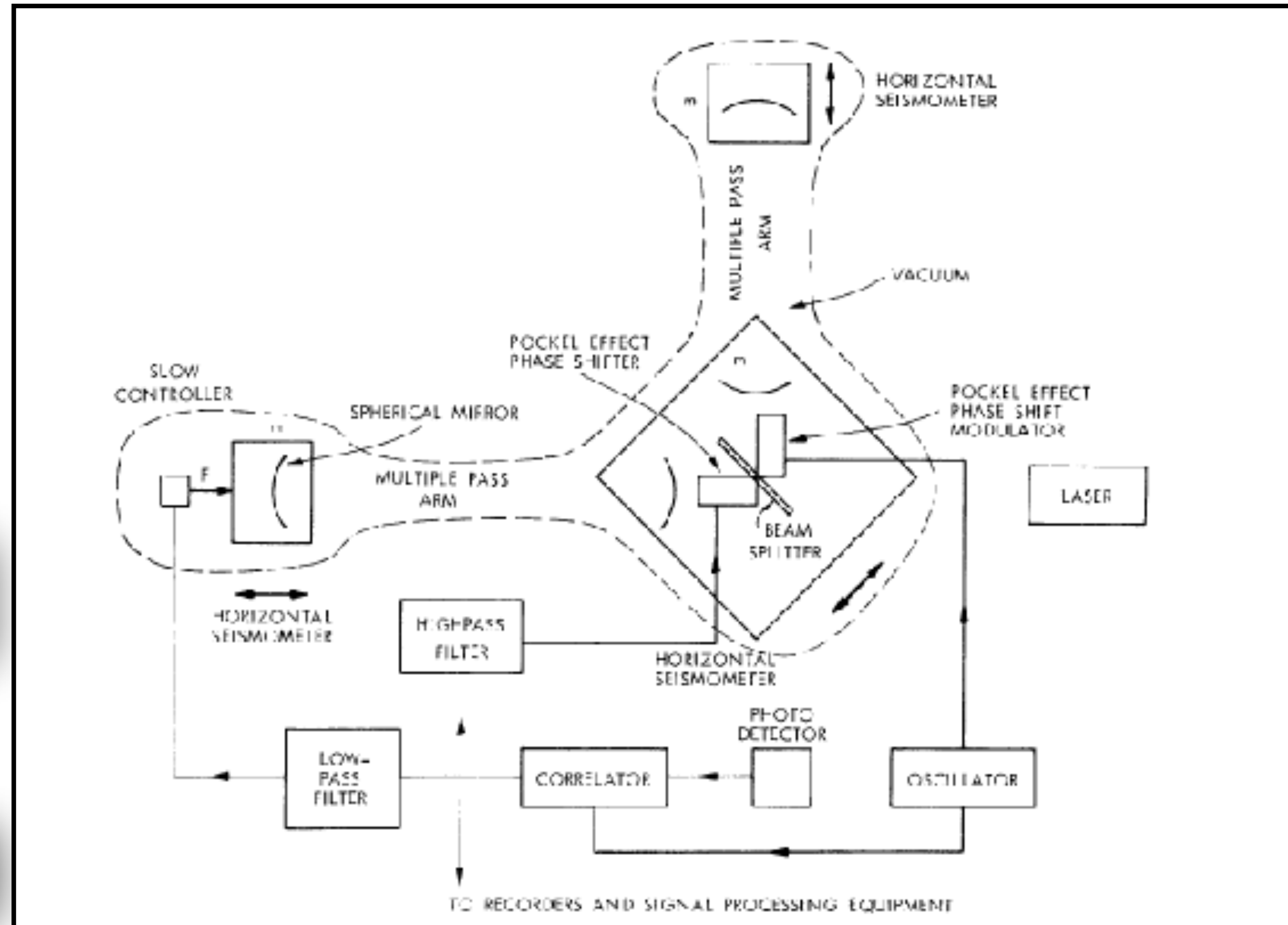
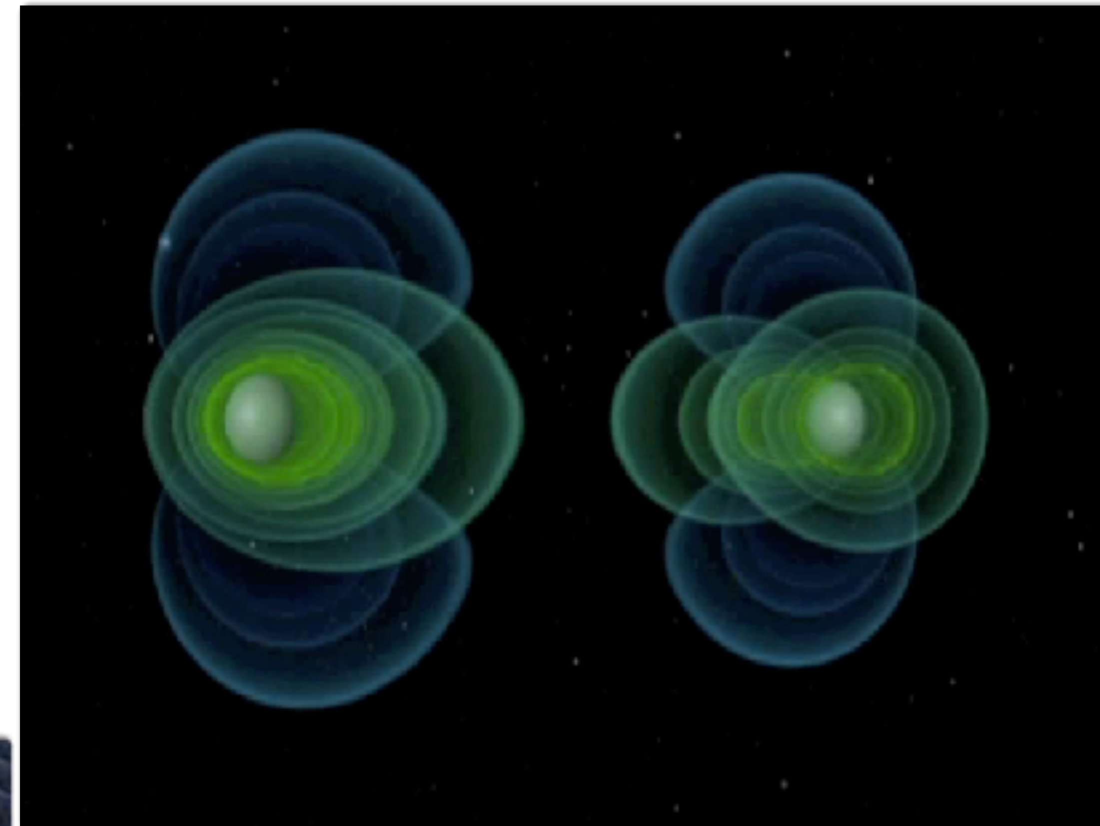


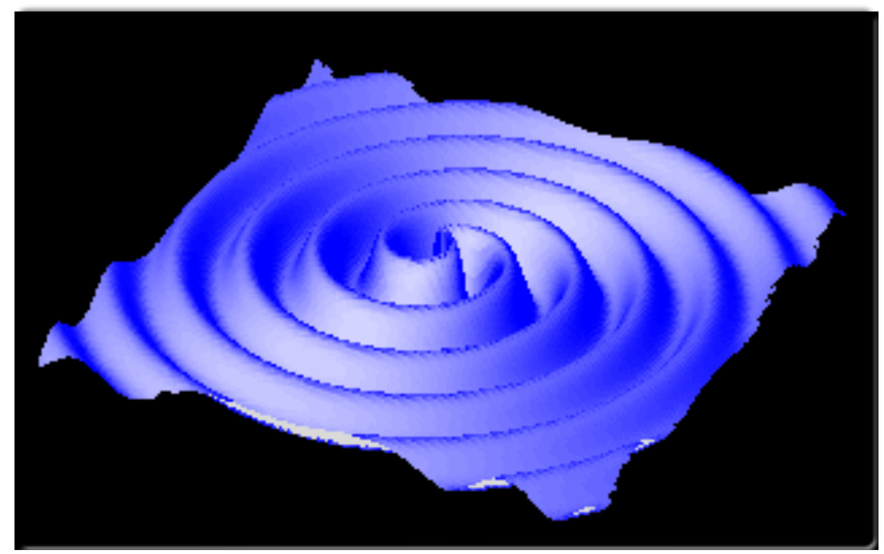
Fig. V-20. Proposed antenna.

LIGO-G1600341

What are Gravitational Waves?



Ripples in the fabric of space-time caused by some of the most violent and energetic processes in the Universe [LIGO Homepage]



Collision of black holes

LSC LIGO Scientific Collaboration

VIRGO

General Relativity in weak field

- Einstein Equation

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

- In the weak field limit

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad |h_{\mu\nu}| \ll 1$$

$$\eta_{\mu\nu} : \text{Minkowski metric}$$

- Einstein equation becomes a wave equation

$$\Box \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4}T_{\mu\nu} \,(= 0 \text{ for vacuum})$$

where $\bar{h}_{\mu_\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}h^{\alpha}_{\alpha}$ is trace reverse tensor of $h_{\mu\nu}$

Propagation of Gravitational Waves and and their effects

- Plane wave solution

$$\bar{h}_{\mu\nu} = A_{\mu\nu} \exp(i k_\alpha x^\alpha)$$

- Transverse Traceless (TT) gauge, GW propagating along z-direction

$$\bar{h}_{\mu\nu} = A_{\mu\nu} e^{ik(ct-z)}$$

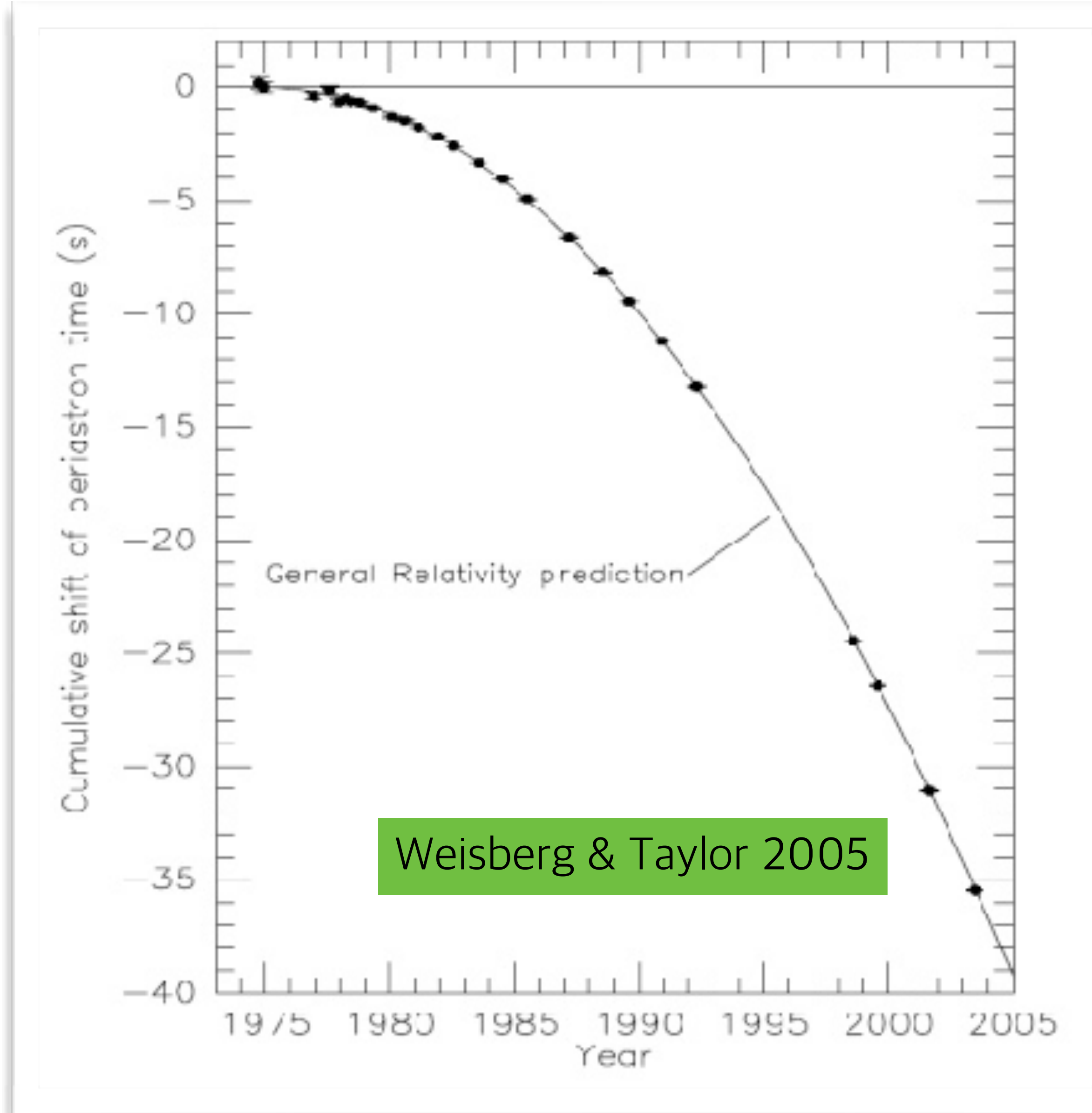
$$A_{\mu\nu} \equiv \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

- Propagation speed = *c*, two independent constants $h_+, \ h_\times$

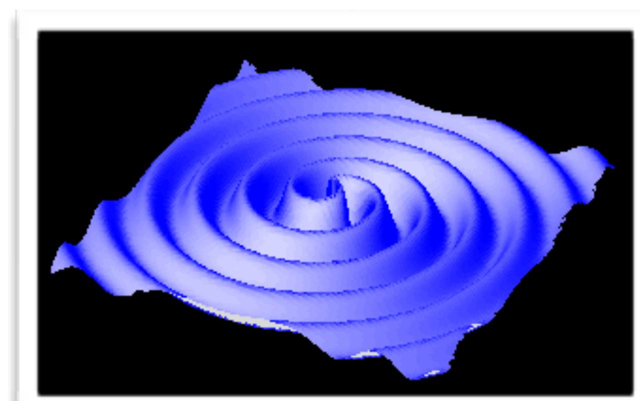
- Proper length between two freely-falling particles at coordinate distance L_0

$$\int_{P_1}^{P_2} |g_{\mu\nu} dx^\mu dx^\nu|^{\frac{1}{2}} \approx \left[1 + \frac{1}{2}\bar{h}_{xx}(P_1)\right] L_0$$

Confirmation of Gravitational Waves: discovery of binary pulsar (1974)



Orbit of binary neutron stars shrinks slowly:
Hulse & Taylor received Nobel Prize in 1993



Timeline of the LIGO (1/2)

- 1967~1972: Detailed calculation of noises of the laser interferometer by Rainer Weiss
- 1968: Creation of the research group at Caltech by Kip Thorne
- 1979 - 1980: Ronald Driver and Stan Whitcomb join GW experimental group at Caltech
- 1980: NSF funding of 40 m prototype at Caltech
- 1984: Caltech and MIT signed an agreement for the joint design and construction of LIGO.
- 1989: Vogt, Drever, Fred Raab, Thorne and Weiss submitted a joint Caltech/MIT proposal for LIGO construction to the NSF.
    - 1990: NSF approved the LIGO Project
    - 1991: Congress appropriated LIGO's first year of funding

LIGO Proposal 1989

Proposal to the National Science Foundation

A
LASER INTERFEROMETER
GRAVITATIONAL-WAVE
OBSERVATORY
(LIGO)

LIGO-M890001-00-M

VOLUME 1:
LIGO Science and Concepts

December 1989

CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LIGO PROJECT

Proposal to the National Science Foundation

THE CONSTRUCTION, OPERATION, AND SUPPORTING RESEARCH AND DEVELOPMENT OF A

LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

Submitted by the
CALIFORNIA INSTITUTE OF TECHNOLOGY

Rochus E. Vogt
Principal Investigator and Project Director
California Institute of Technology

Ronald W. P. Drever
Co-Investigator
California Institute of Technology

Kip S. Thorne
Co-Investigator
California Institute of Technology

Frederick J. Raab
Co-Investigator
California Institute of Technology

Rainer Weiss
Co-Investigator
Massachusetts Institute of Technology

Timeline of the LIGO (2/2)

- 1992: Hanford, Washington, and Livingston, Louisiana were chosen as the sites for LIGO's interferometers
- 1994: Caltech's Barry Barish was appointed LIGO Director
    - He organized LIGO's construction phase, then oversaw construction of its facilities (1994-1998) and then the installation and commissioning of LIGO's initial interferometers (1999-2002) and its first few gravitational wave searches (2002-2005).
- 1997: Barish conceived and led a major change in LIGO's organization: its split into: (1) The LIGO Laboratory at Caltech, MIT, Hanford and Livingston, (2) the LIGO Scientific Collaboration (LSC), responsible for organizing and coordinating LIGO's technical and scientific research and data analysis, and for expanding LIGO to include scientists elsewhere, beyond Caltech and MIT.
- Spokespersons of LSC:
    - 1997-2003: Rainer Weiss (Appointed by Barry Barish)
    - 2003-2007: Peter Paulson (Elected by the members, Syracuse Univ.)
    - 2007-2011: David Reitzer (University of Florida)
    - 2011-2017: Gabriela Gonzalez (Louisiana State Univ.)
    - 2017 - Present: David Shoemaker (MIT)

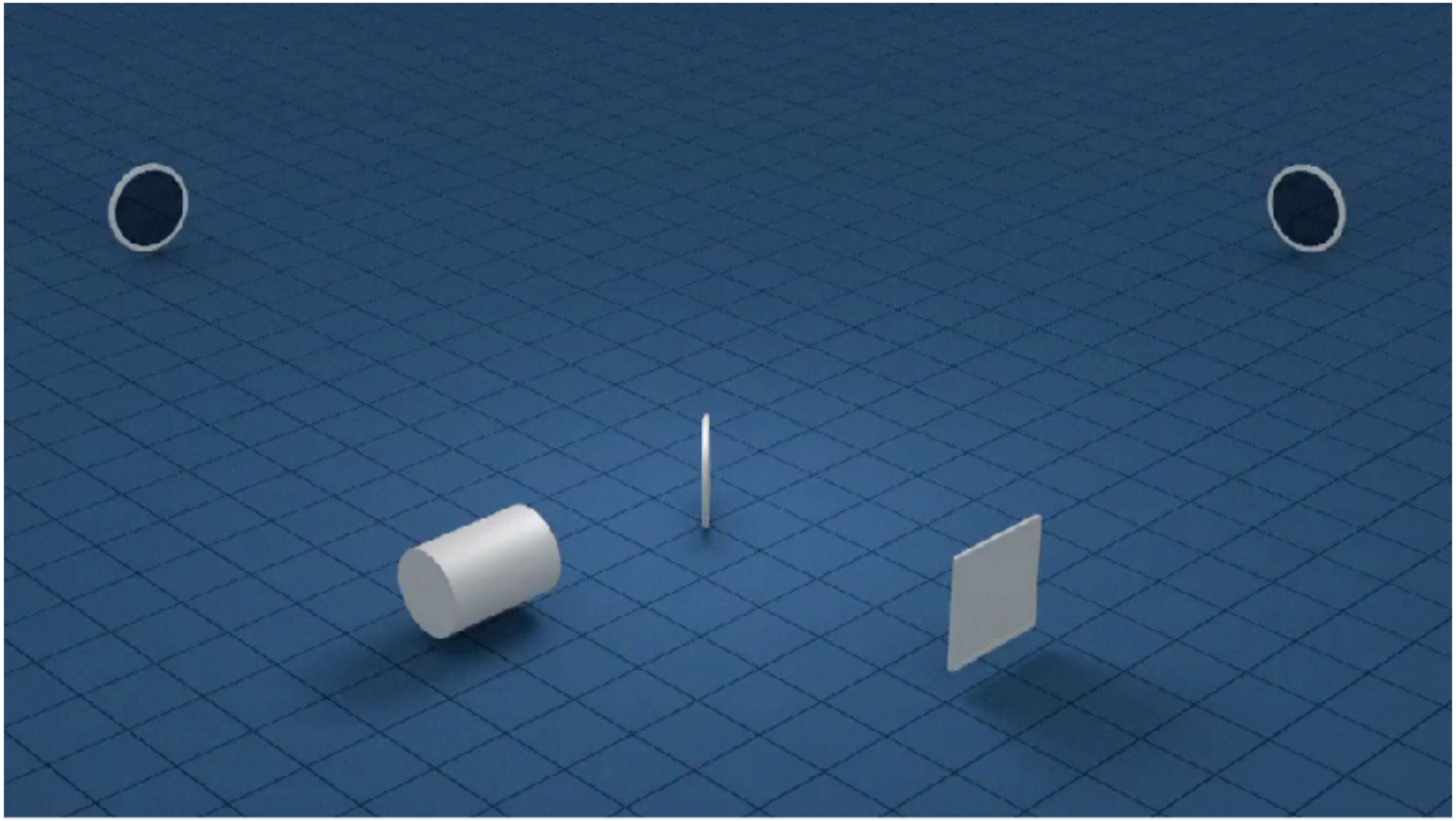
Contributions of the 2017 Nobel Laureates

- **Rainer Weiss**: inspired by Pirani, demonstrated a laser interferometer with sensitivity limited only by photon shot noise. He then evaluated the fundamental sources of background noise that critically limit the antenna performance.

- **Barry Barish**: transformed LIGO from a limited MIT/Caltech endeavour to a major international, gravitational-wave project. He oversaw the installation and commissioning of LIGO's initial interferometers from 1999 to 2002, and the first data-taking runs, 2002 to 2005.

- **Kip Thorne**: Thorne and his research group worked with great enthusiasm on the theory of gravitational waves and their astrophysical sources. Their predictions of the expected signals from various astrophysical events played a decisive role for the design and funding of LIGO. In the late 1970's, Thorne succeeded in convincing the Caltech leadership to create an experimental gravitational-wave group led by Drever, recruited from Glasgow in 1979, and Caltech's Stanley Whitcomb.

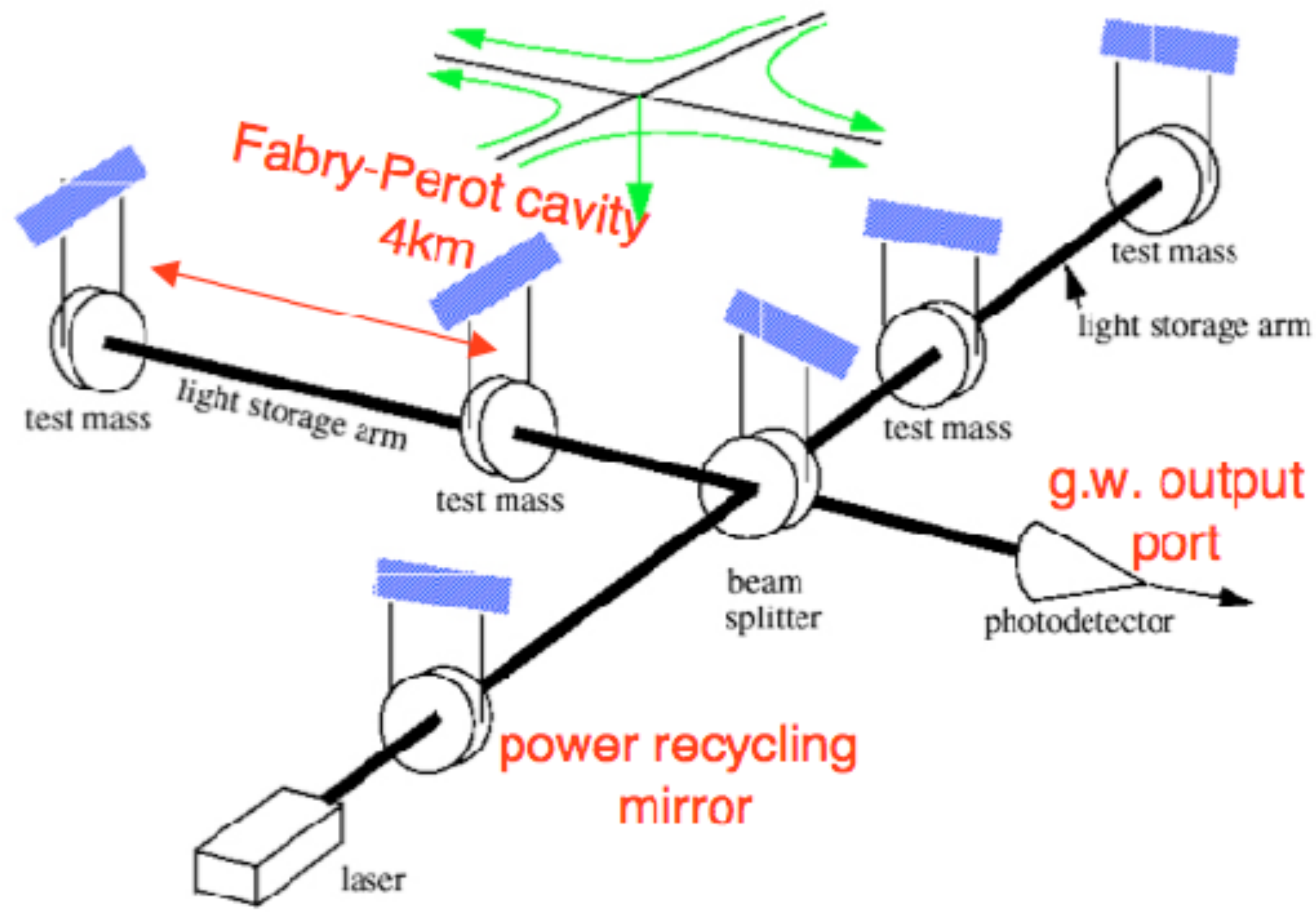
Text adapted from "Scientific Background on the Nobel Prize in Physics 2017" by Swedish Academy of Sciences



Principles of GW Detector

Image credit: LIGO/T. Pyle

Actual structure of the LIGO



K. Thorne, R. Weiss, R. Drever

- 2002-2010 Initial LIGO
- 2015.9 ~ Advanced LIGO (10times better sensitivity)

Simple Estimates of Sensitivity of Interferometers

- If the length resolution is λ_{laser}, detectable strain is

$$h \equiv \frac{\Delta l}{l} = \frac{\lambda_{laser}}{l} = \frac{10^{-6}\mathrm{m}}{10^{3}\mathrm{m}} = 10^{-9}$$

- Optical path length can be significantly increased by adopting optical cavity, but should be smaller than GW wavelength (~1000 km for 300 Hz)

$$h \sim \frac{\Delta l}{l_{eff}} \sim \frac{\lambda_{laser}}{\lambda_{GW}} \sim \frac{10^{-6}\mathrm{m}}{10^{6}\mathrm{m}} = 10^{-12}$$

- However, due to quantum nature of the photons, the length resolution could be as small as $N^{-1/2}_{photons}\lambda_{laser}$. Thus sentivity could reach

$$h \sim N^{-1/2}_{photons} \frac{\lambda_{laser}}{\lambda_{GW}}$$

Shot Noise

- Collect photons for a time of the order of the period of GW wave $\tau \sim 1/f_{GW}$

$$N_{photons} = \frac{P_{laser}}{hc/\lambda_{laser}}\tau \sim \frac{P_{laser}}{hc/\lambda_{laser}}\frac{1}{f_{GW}}$$

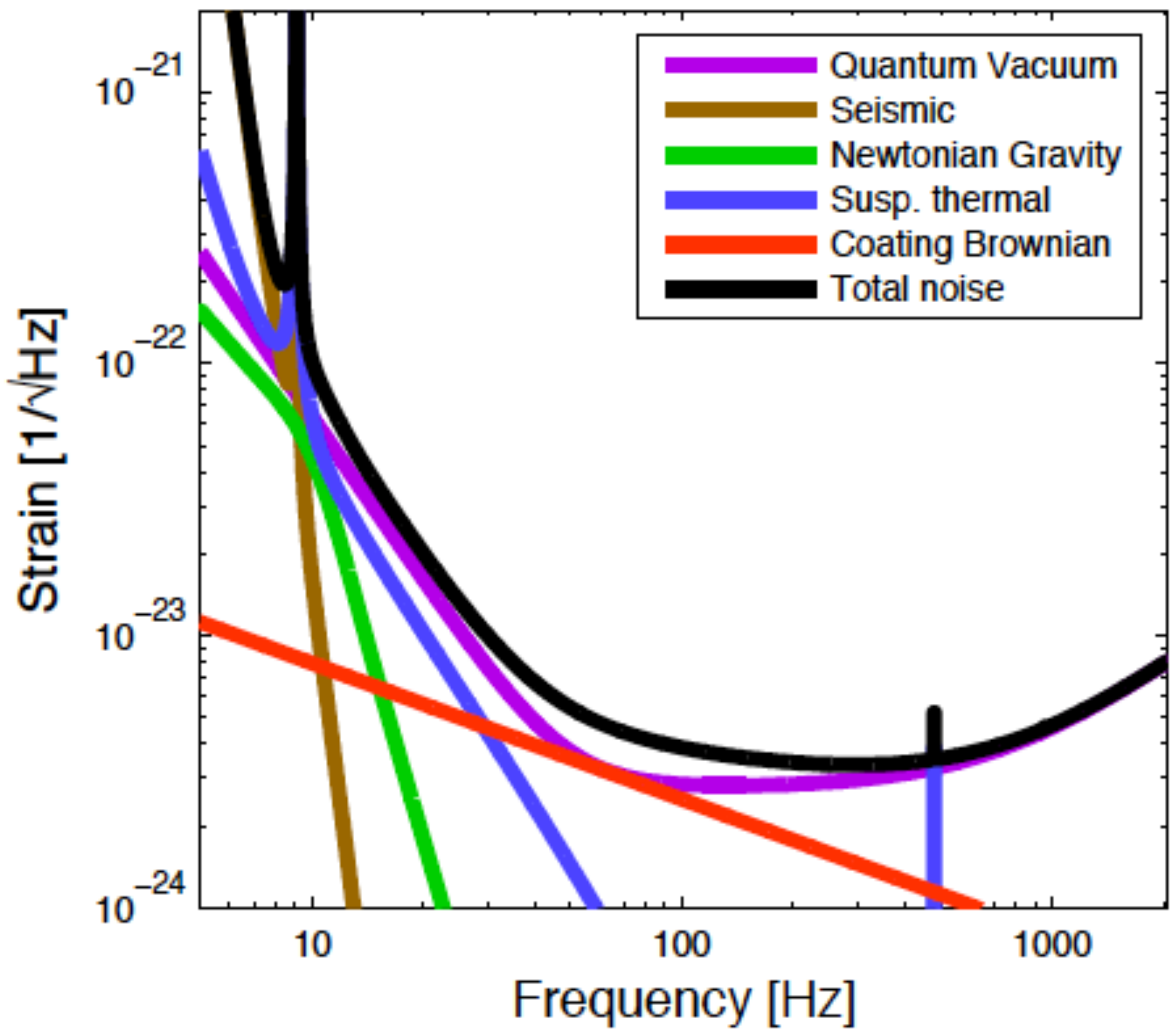
- For 1W laser with λ_{laser}=1 μm, f_{GW}=300Hz, $N_{photons}$=10^{16}

$$h \sim \frac{\Delta l}{l_{eff}} \sim \frac{N_{photons}^{-1/2}\lambda_{laser}}{\lambda_{GW}} \sim \frac{10^{-8} \times 10^{-6}\mathrm{m}}{10^{6}\mathrm{m}} = 10^{-20}$$

- By adopting high power laser (20W for O1) and power recycling, we can reach 'astrophysical sensitivity' of $\sim 10^{-22}$.

Other Noises

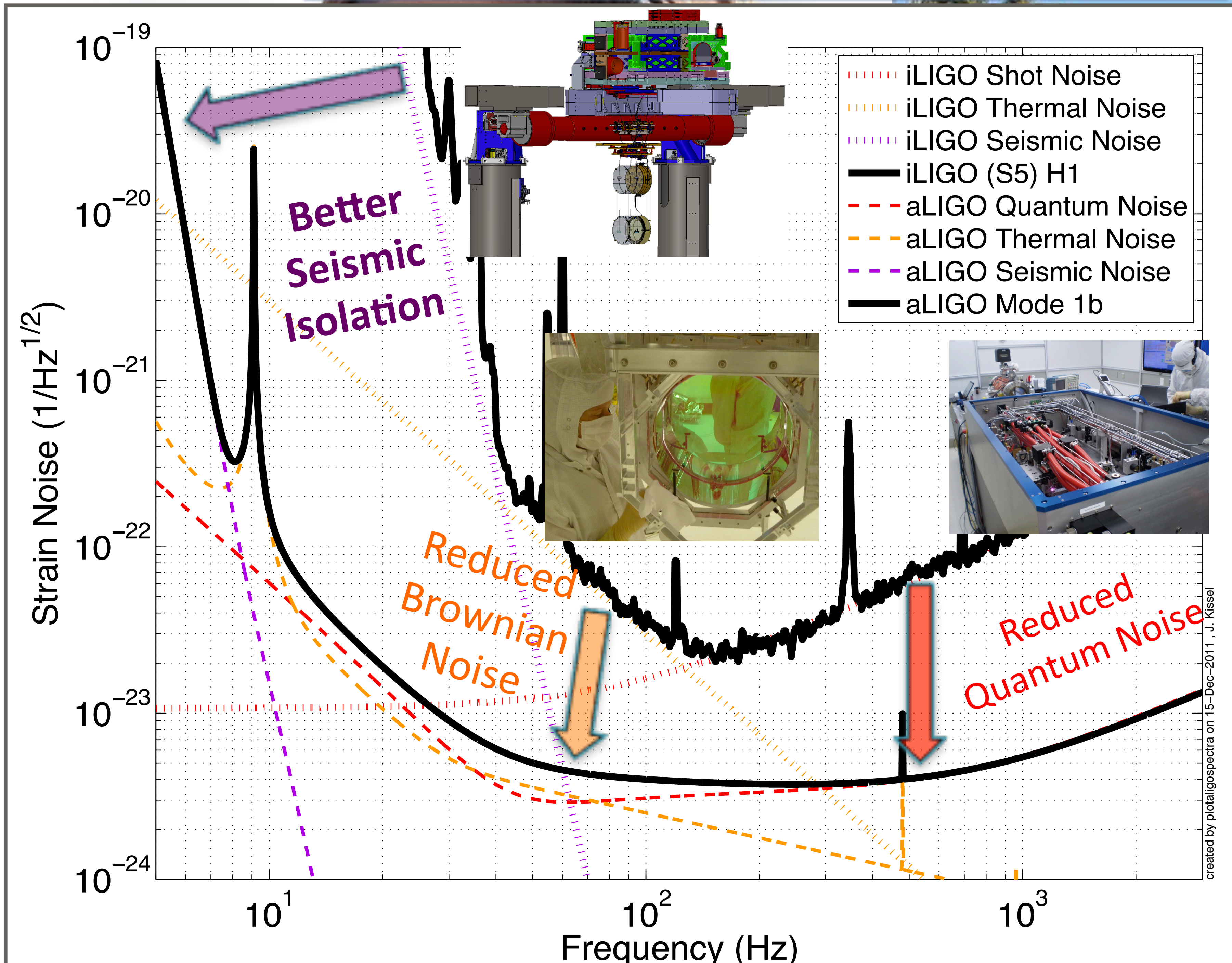
- Radiation pressure noise
  - Make mirrors heavier
- Suspension thermal noise/ mirror coating brownian noise
  - Increase beam size, monolithic suspension structure
- Seismic noise
  - Multi-stage suspension, underground
- Newtonian Noise
  - So far difficult to avoid.
  - Seismic and wind measurement and careful modeling

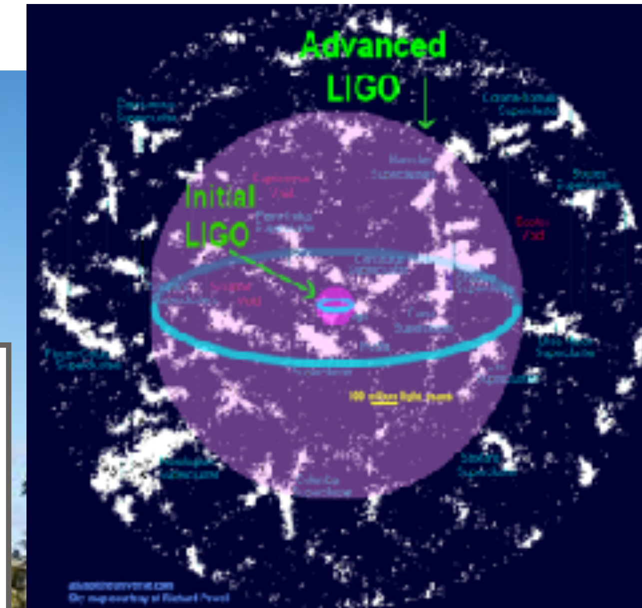


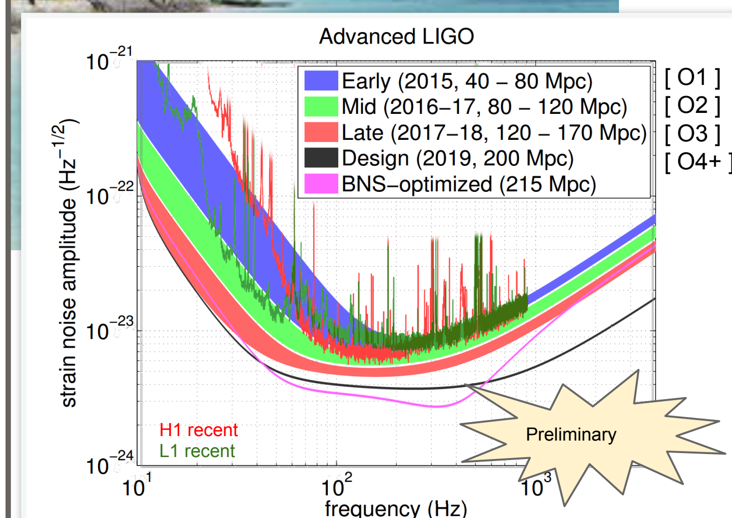
한국 중력파 연구 협력단

Goal 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





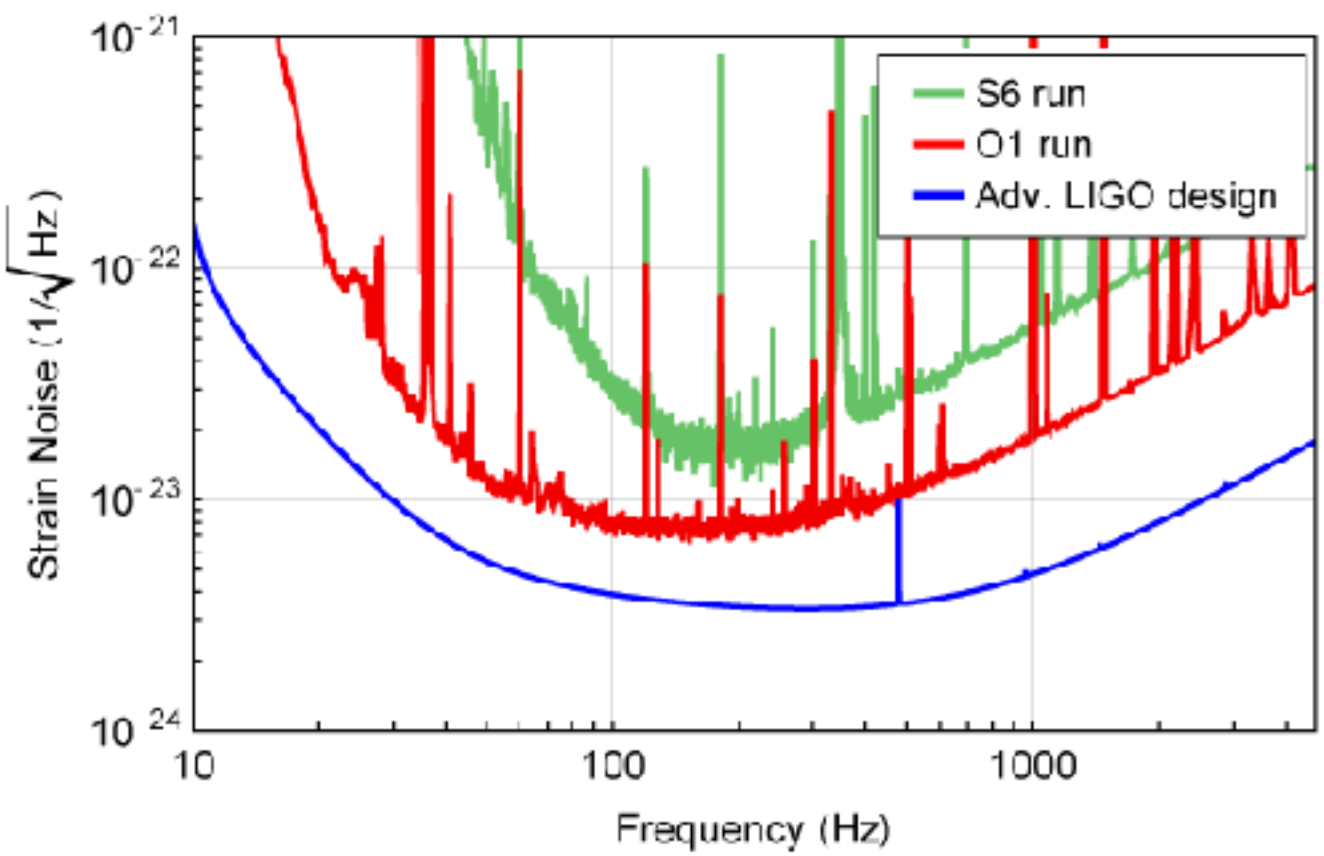


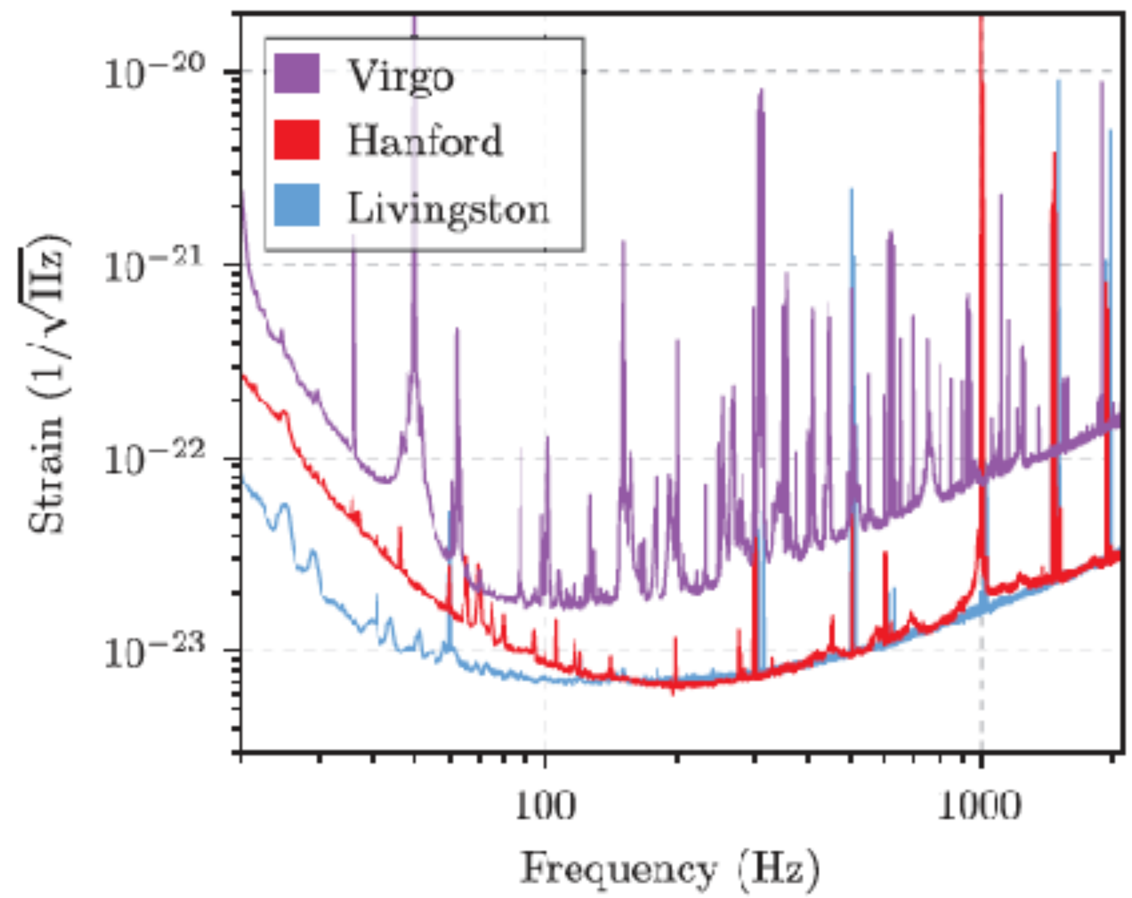
LSC LIGO Scientific Collaboration
VIRGO

한국 중력파 연구 협력단

LIGO Sensitivity during the first and second observing runs [O1/O2]

https://www.advancedligo.mit.edu



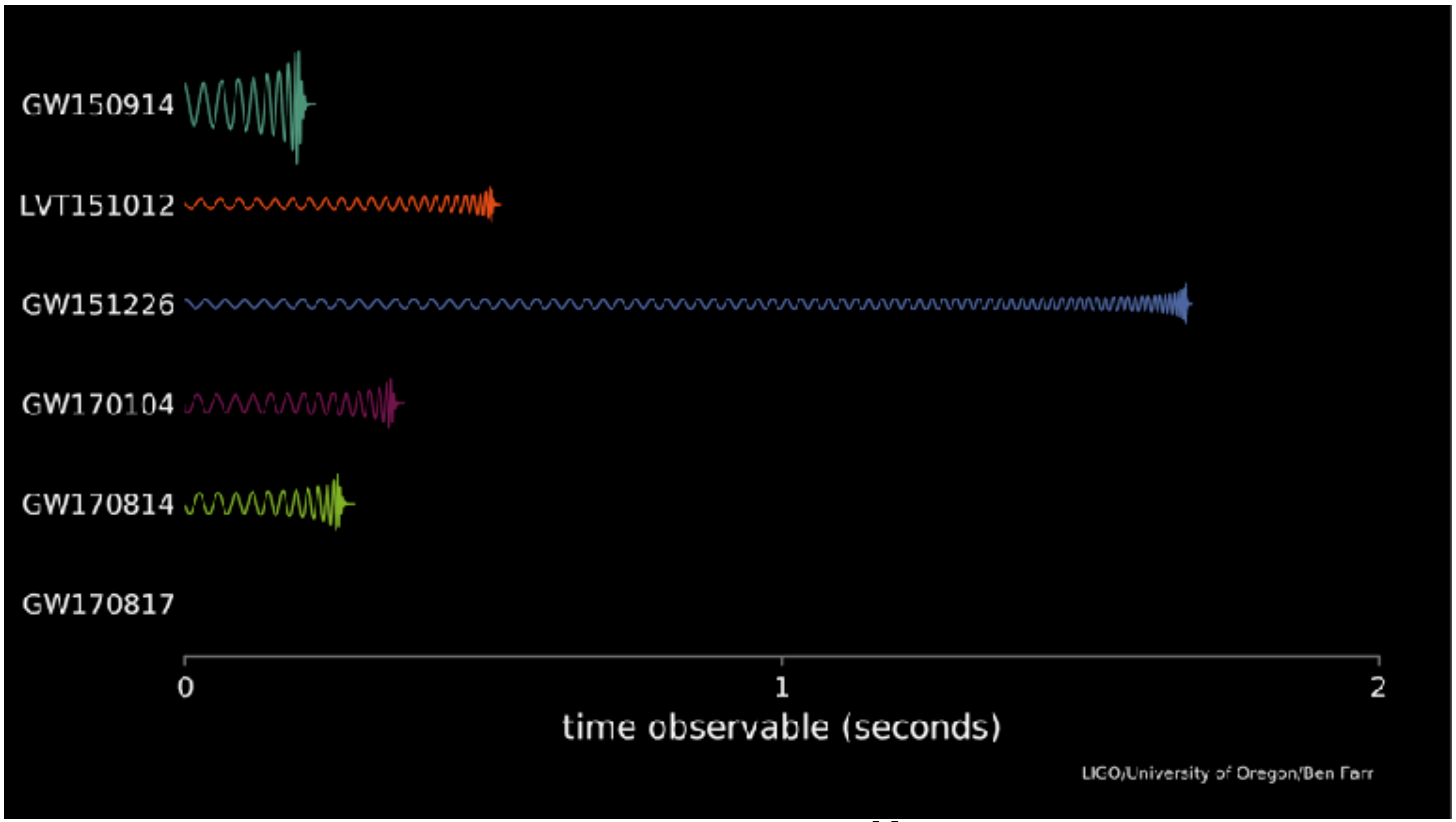


2017.08.14

- Sensitivity improvement by x3 made a big difference
- O2 sensitivity is slightly better than O1

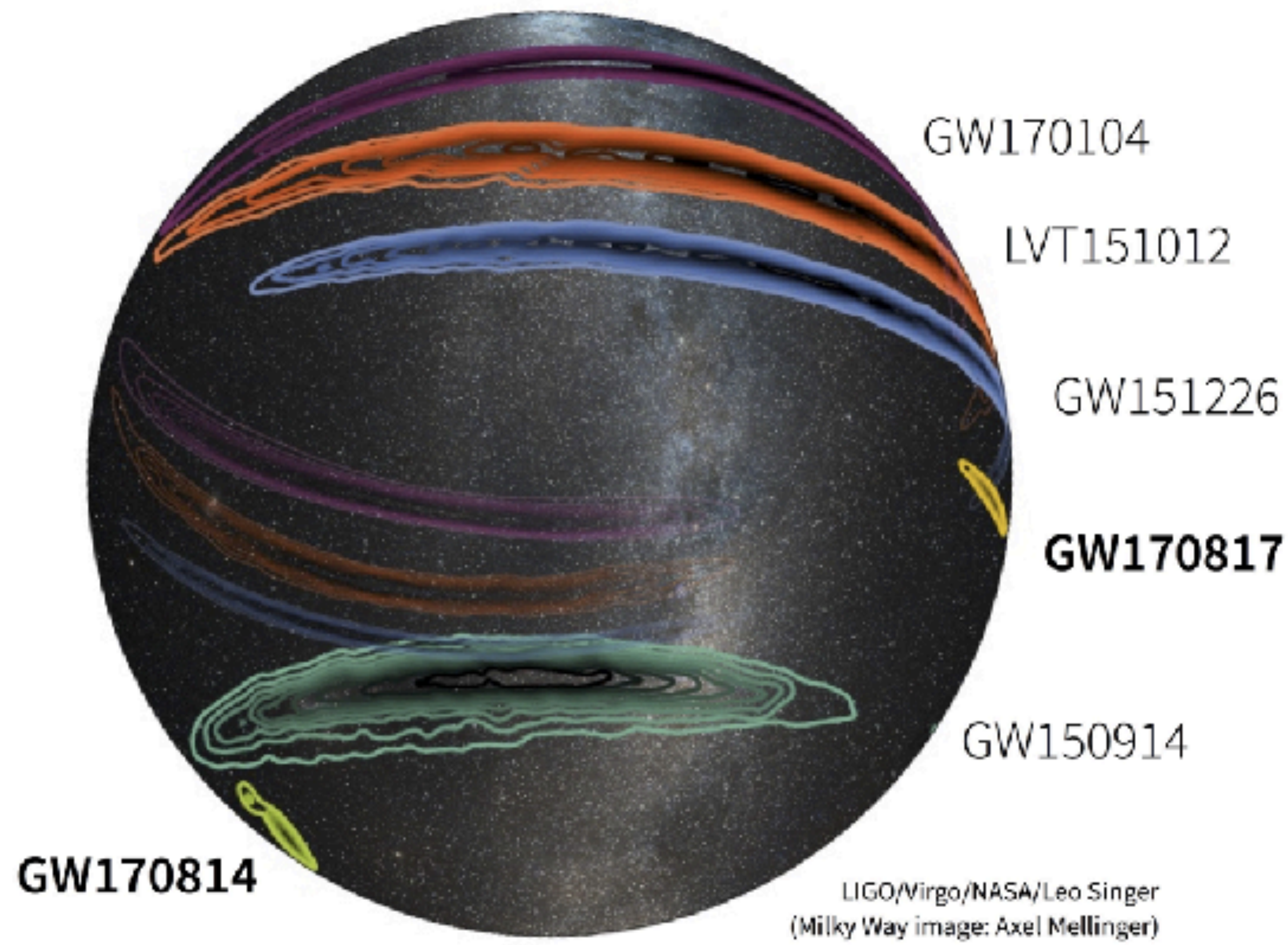
GW Events from O1/O2

- 4 BH mergers (GW150914, 151226, 170104, 170814)
- 1 BH merger candidate (LVT151012)
- 1 NS merger (GW170817, Prof. Im's talk)



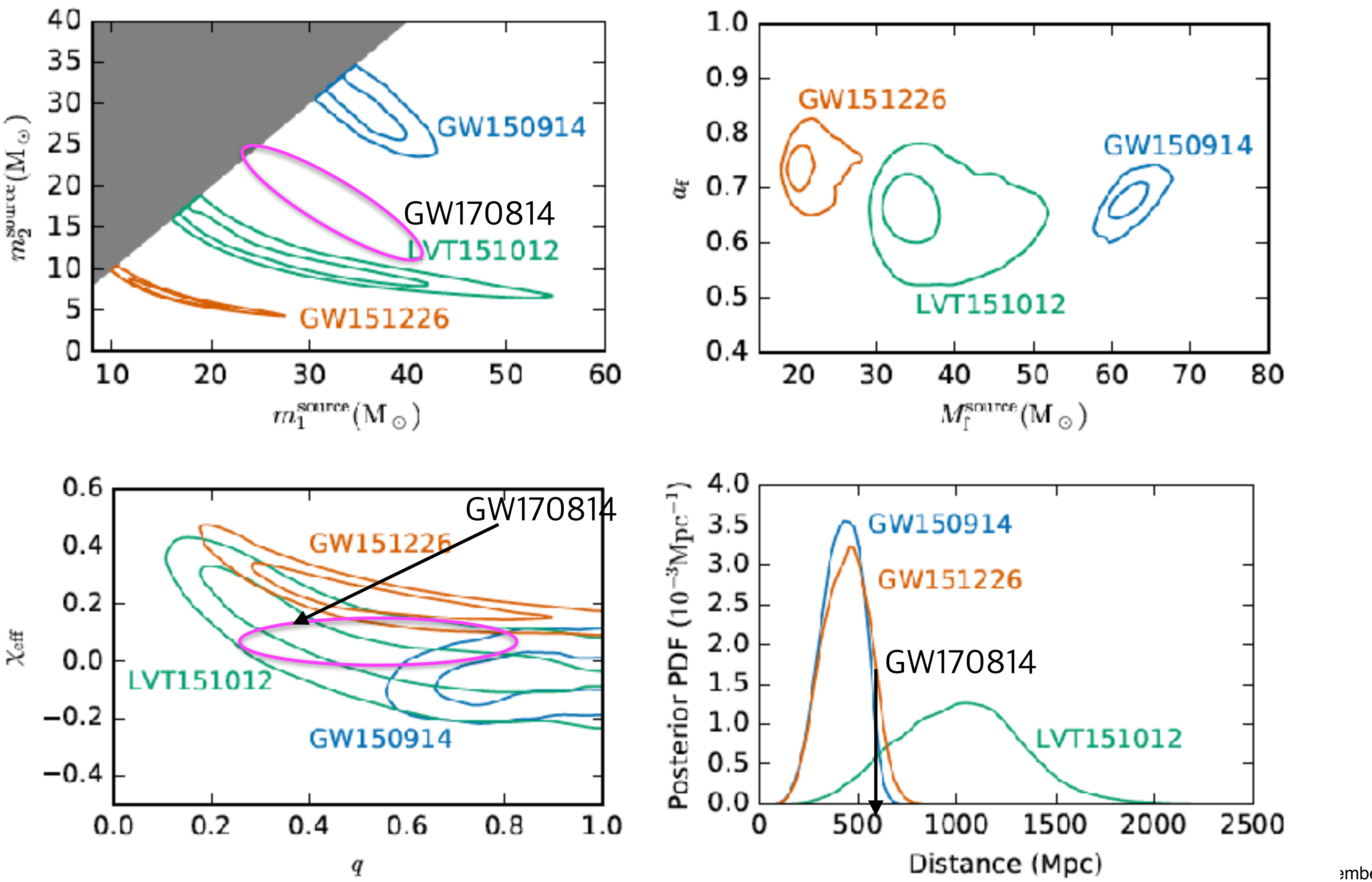
GW Events from O1/O2

- GW150914 (FAR<6×10^{-7} yr^{-1})
- LVT151012 (Candidate, FAR~0.37 yr^{-1})
- GW151226 (FAR<6×10^{-7} yr^{-1})
- GW170104 (FAR <5×10^{-5} yr^{-1})
- GW170814 (FAR < 3.7×10^{-5} yr^{-1})
- GW170817 (FAR < 1.25×10^{-5} yr^{-1})

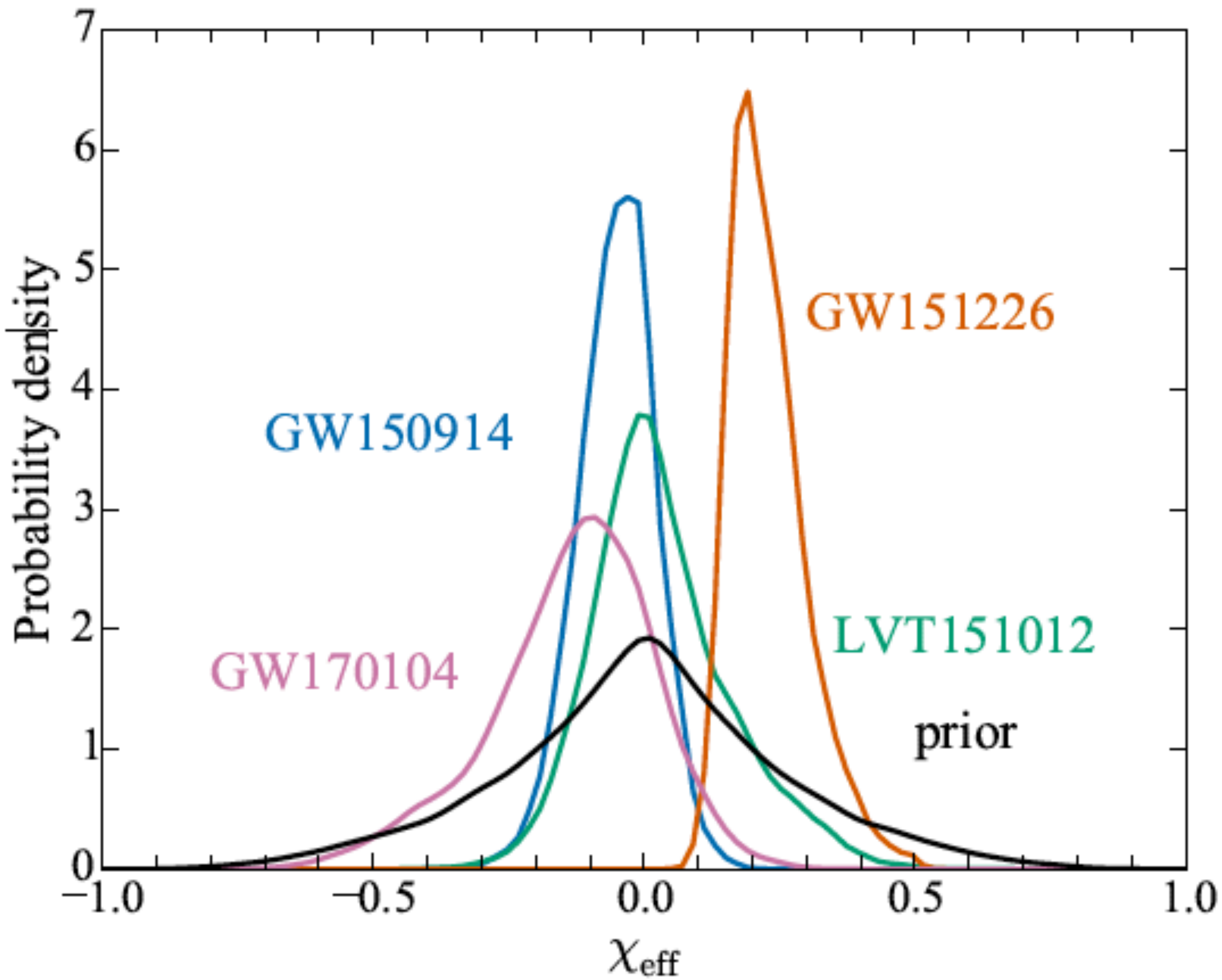


Posterior probability densities

PHYSICAL REVIEW X 6, 041015 (2016)

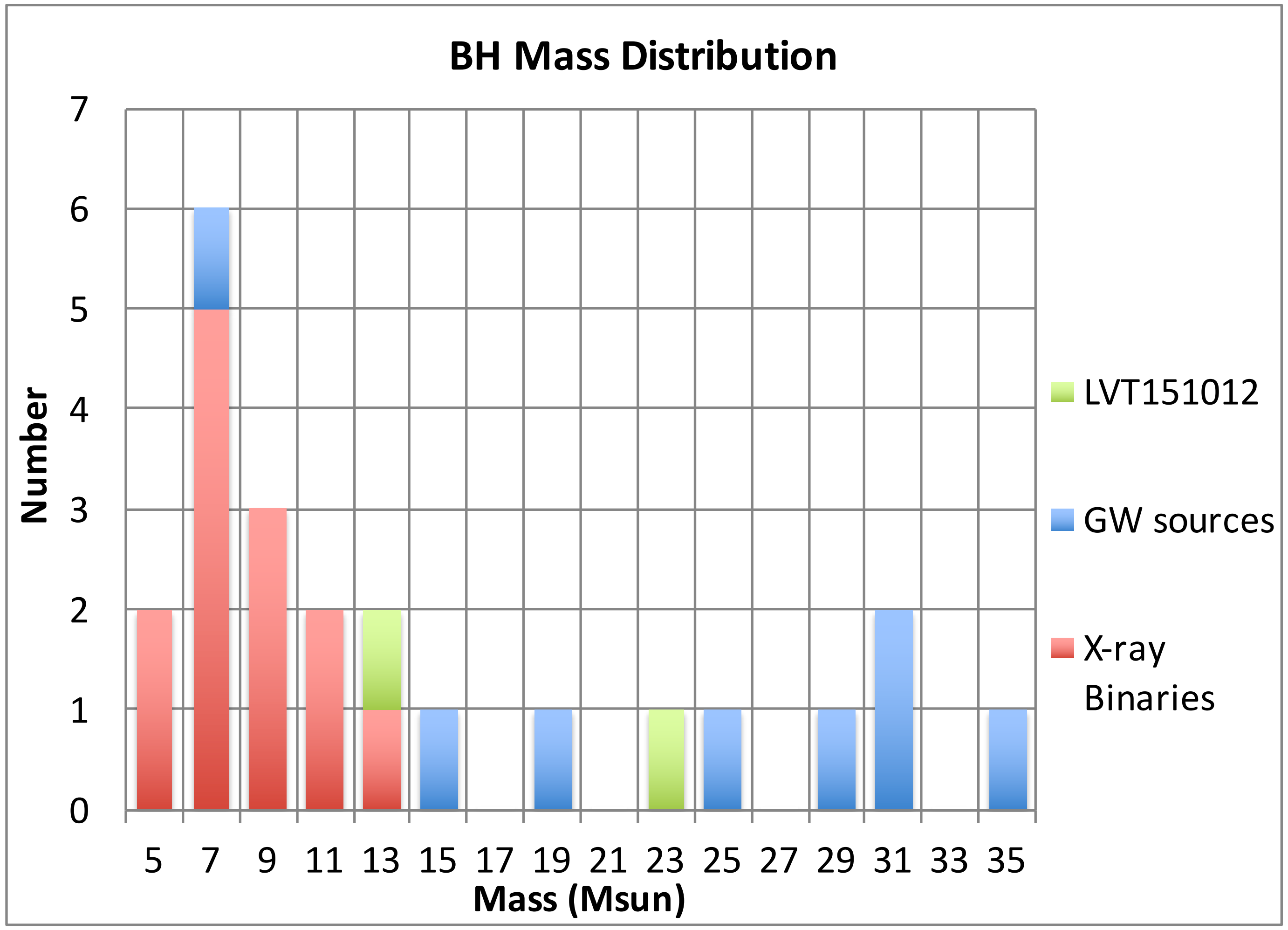


Effective Spin Distribution



Why these detections are interesting?

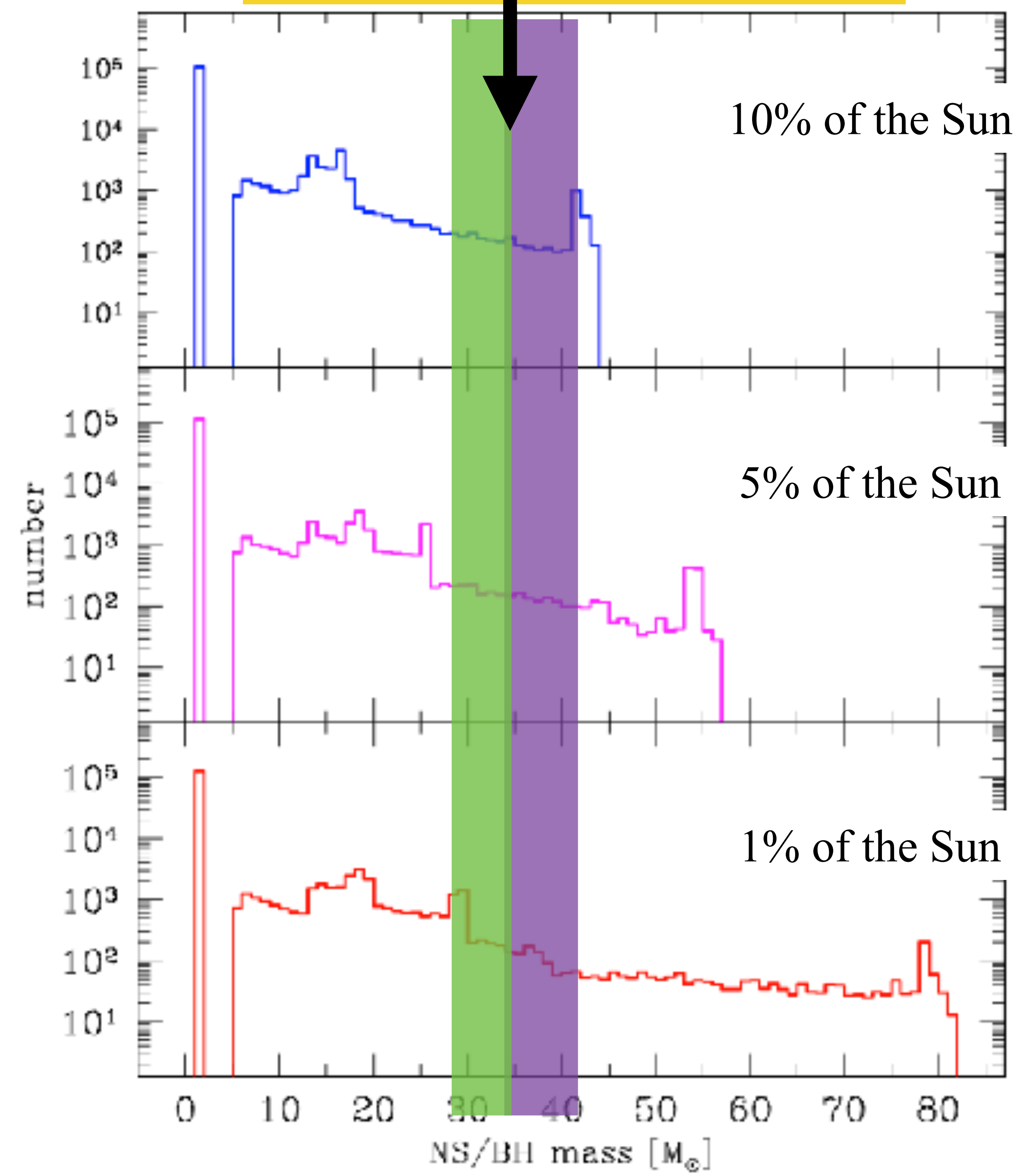
- LIGO detected gravitational waves from merger of **black hole binaries**, instead of neutron star binaries
- **Black hole mass range was quite large:** GW150914 is composed of 36 and 29 times of the mass of the Sun
  - Most of the known black holes are much less massive (~10 times of the sun)



What determines the mass of the black holes?

- BH mass depends on the progenitor star
- The upper mass of the BH is determined by the metallicity.
- GW 150914 may have formed from stars with $Z<0.1\ Z_\odot$.

GW150914 masses

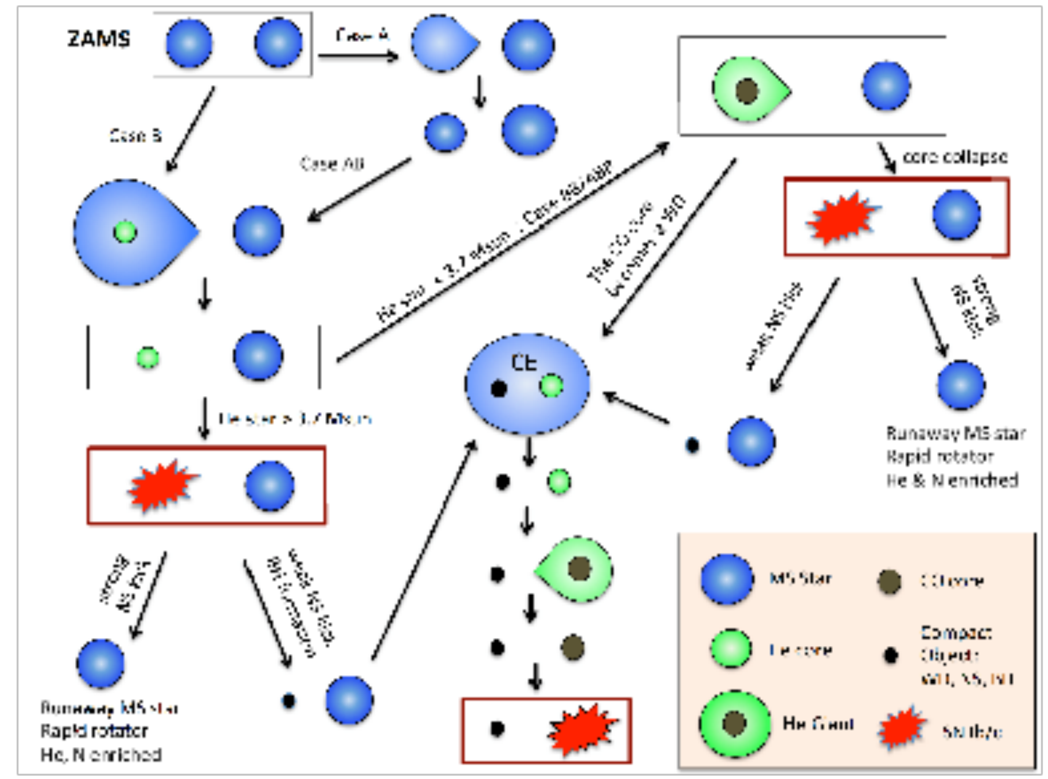


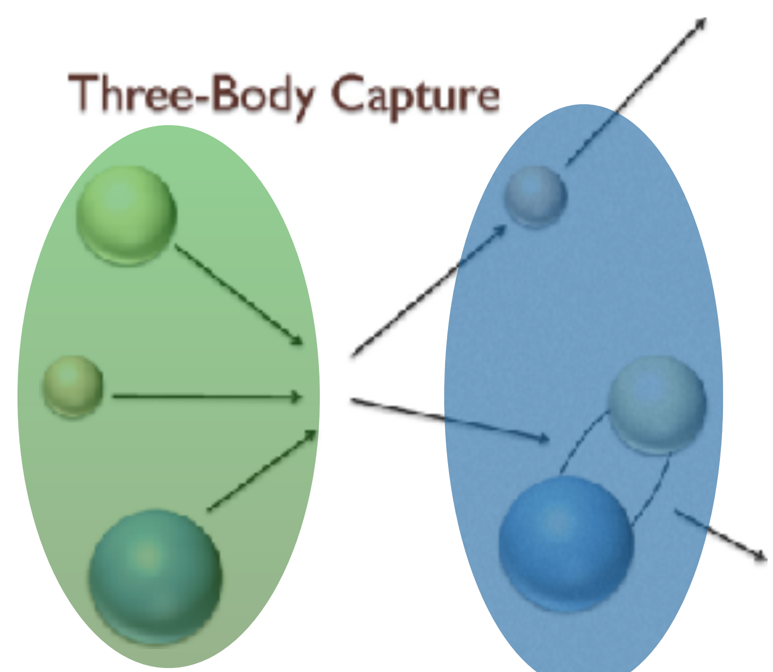
Data provided by Belczynski

What these results tell us?

(Abbott et al., 2016, ApJL, 828, L22; PHYSICAL REVIEW X 6, 041015 (2016)
PRL 118, 221101 (2017), PRL 119, 141011(2017))

- Proof of the existence of the black holes
- Existence of stellar mass black holes in binaries
- Individual masses in wide range (7-35 Msun)
- Formation of ~60 Msun BH
- BH appears to be much more frequent than previously thought
  - Current estimation of the rate 12-210 yr^{-1} Gpc^{-1}
- How these binaries were formed?
  - Evolution of binaries
  - Dynamical formation





GW170817, a new type of GW Source

LIGO/Virgo collaboration, PRL, 119, 116101 (2017)

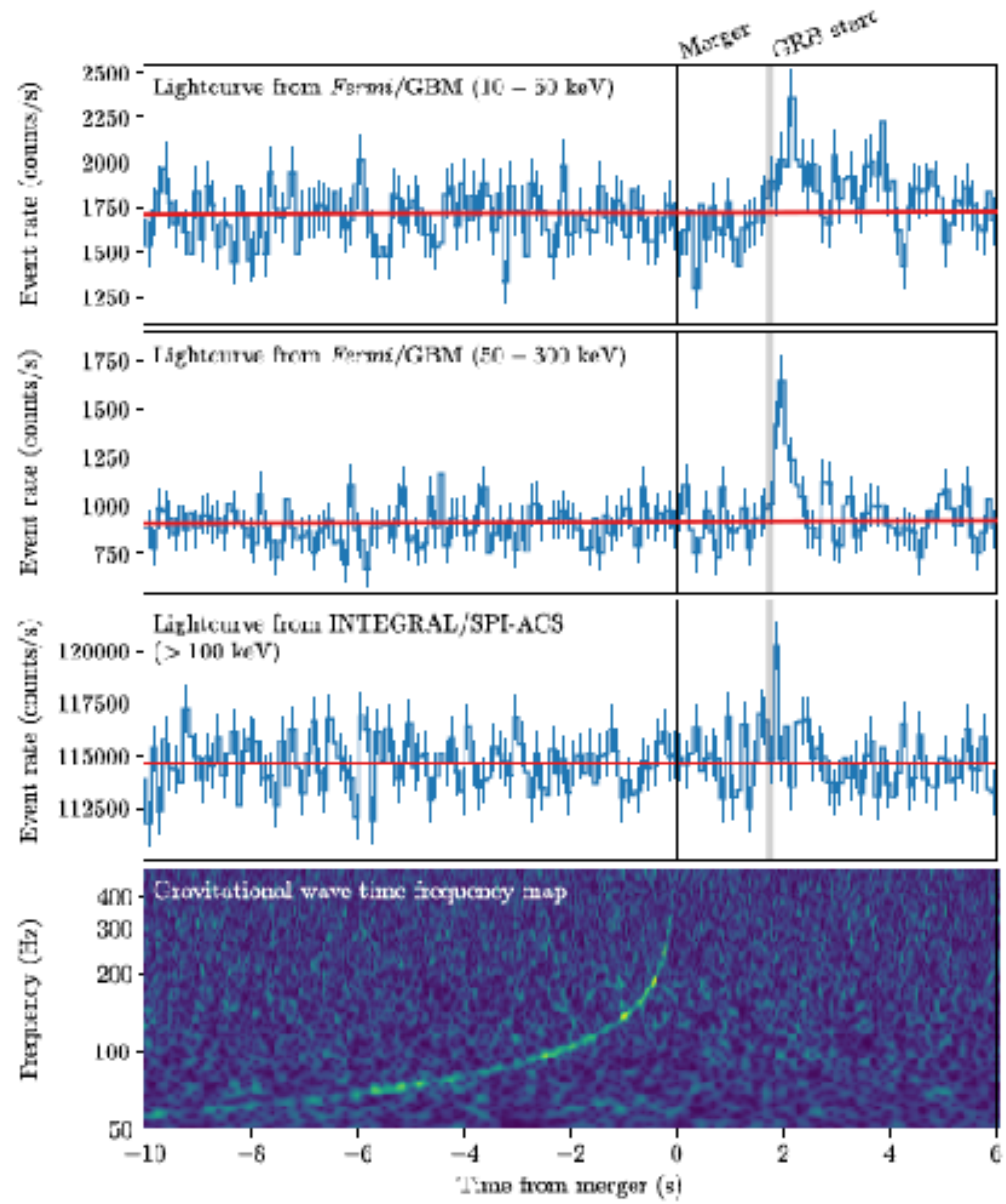
- First detection of a binary neutron star inspiral by advanced LIGO/Virgo on August 17, 2017 at 12:41:04 UTC
- Derived parameters:

	Low-spin priors ($\vert\chi\vert \leq 0.05$)	High-spin priors ($\vert\chi\vert \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

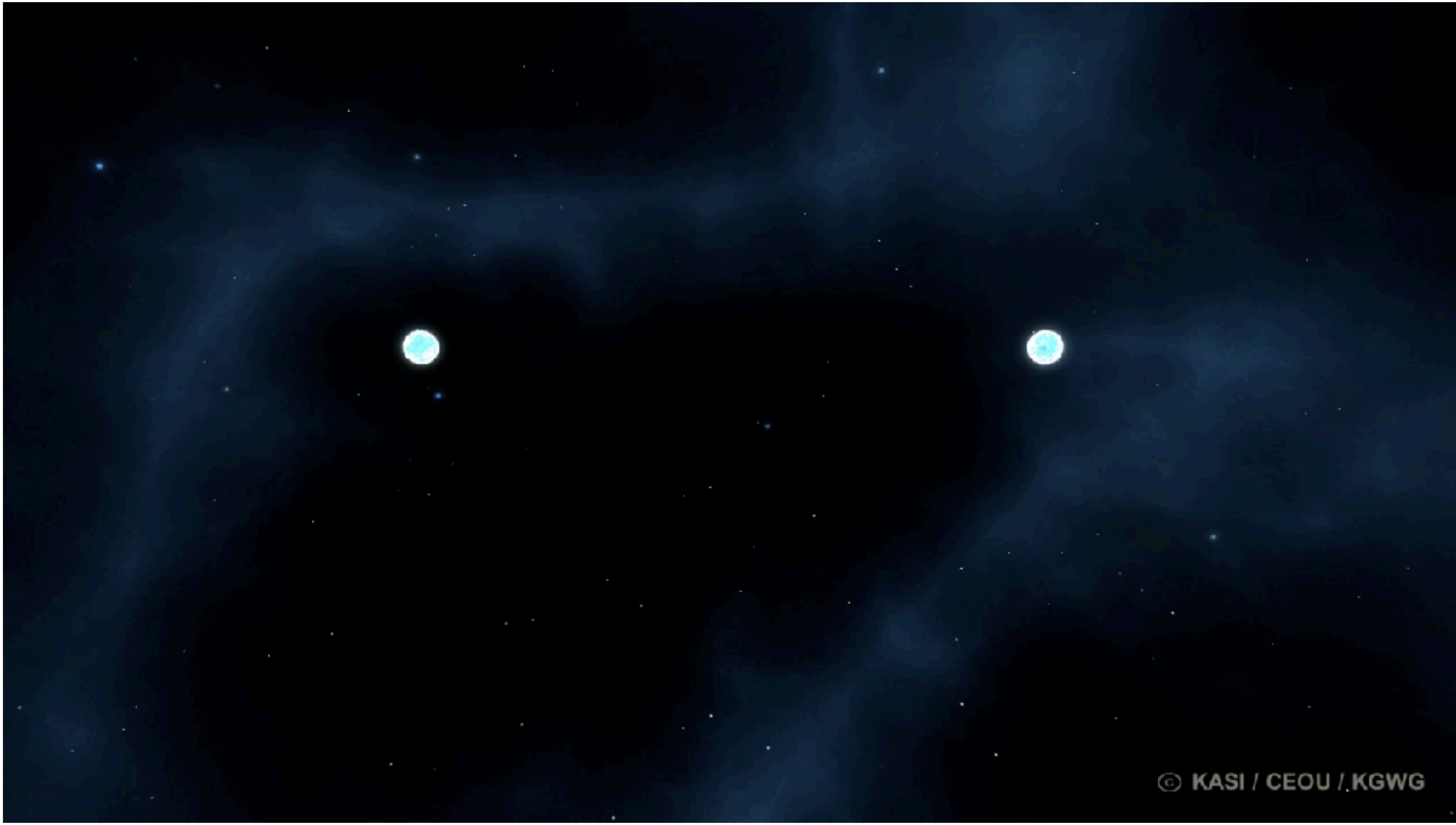
GRB 170817

ApJL 2017, 848, L12 (LIGO/Fermi GBM/INTEGRAL)

- Short gamma-ray burst was detected by Fermi GBM and INTEGRAL 1.7 seconds after the merger
  - Joint paper with Fermi GBM and INTEGRAL
  - Implications on the differences of speeds of light and GW, new limits on Lorentz violation, and test of equivalence principle

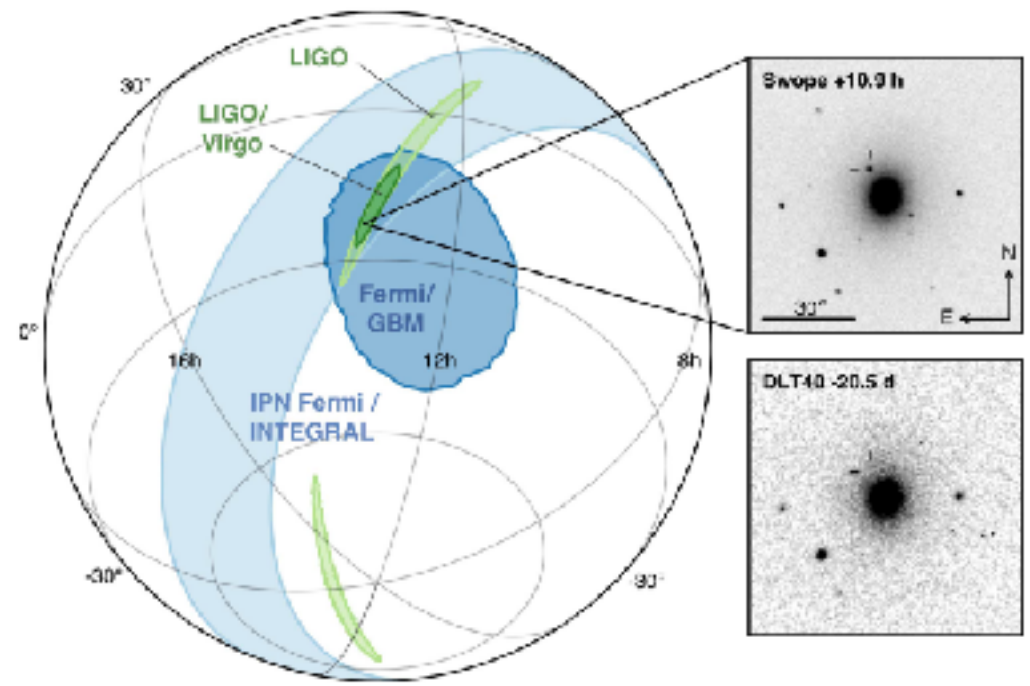


The collision of two neutron stars

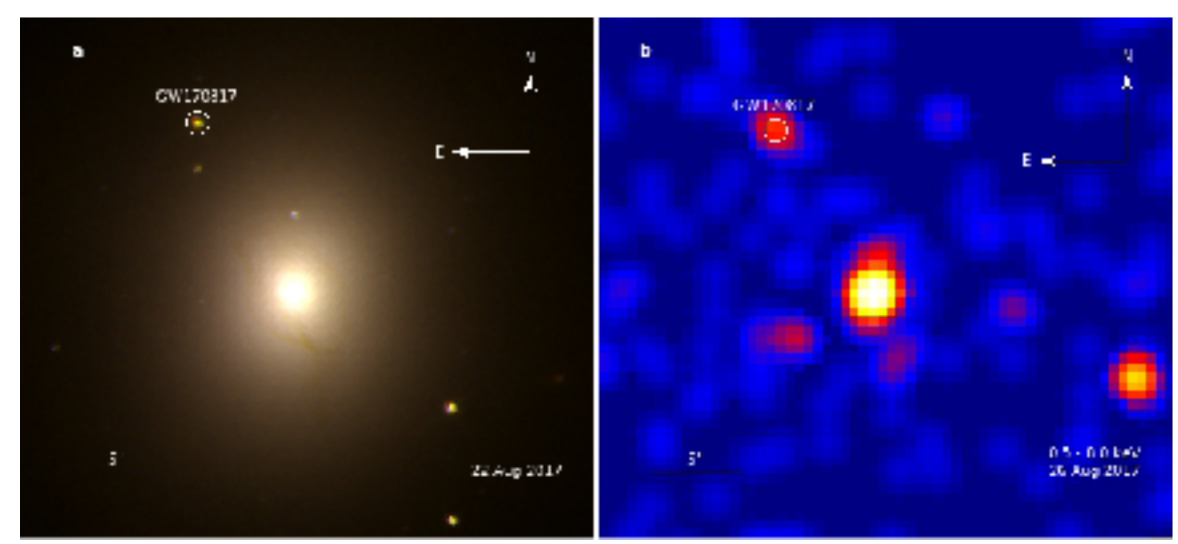


Multi-Messenger Astronomy

- Identification of host galaxy NGC4993
- Optical, near infrared, X-ray and radio emission followed
  - Beginning of the true multi-messenger astronomy.
  - Worldwide campaign to observe the afterglow by 70 groups
  - Korean group composed of SNU and KASI also participated the observational campaign with optical telescopes
  - Resulted one Nature paper (together with NASA's X-ray group), and one ApJ Letter paper.

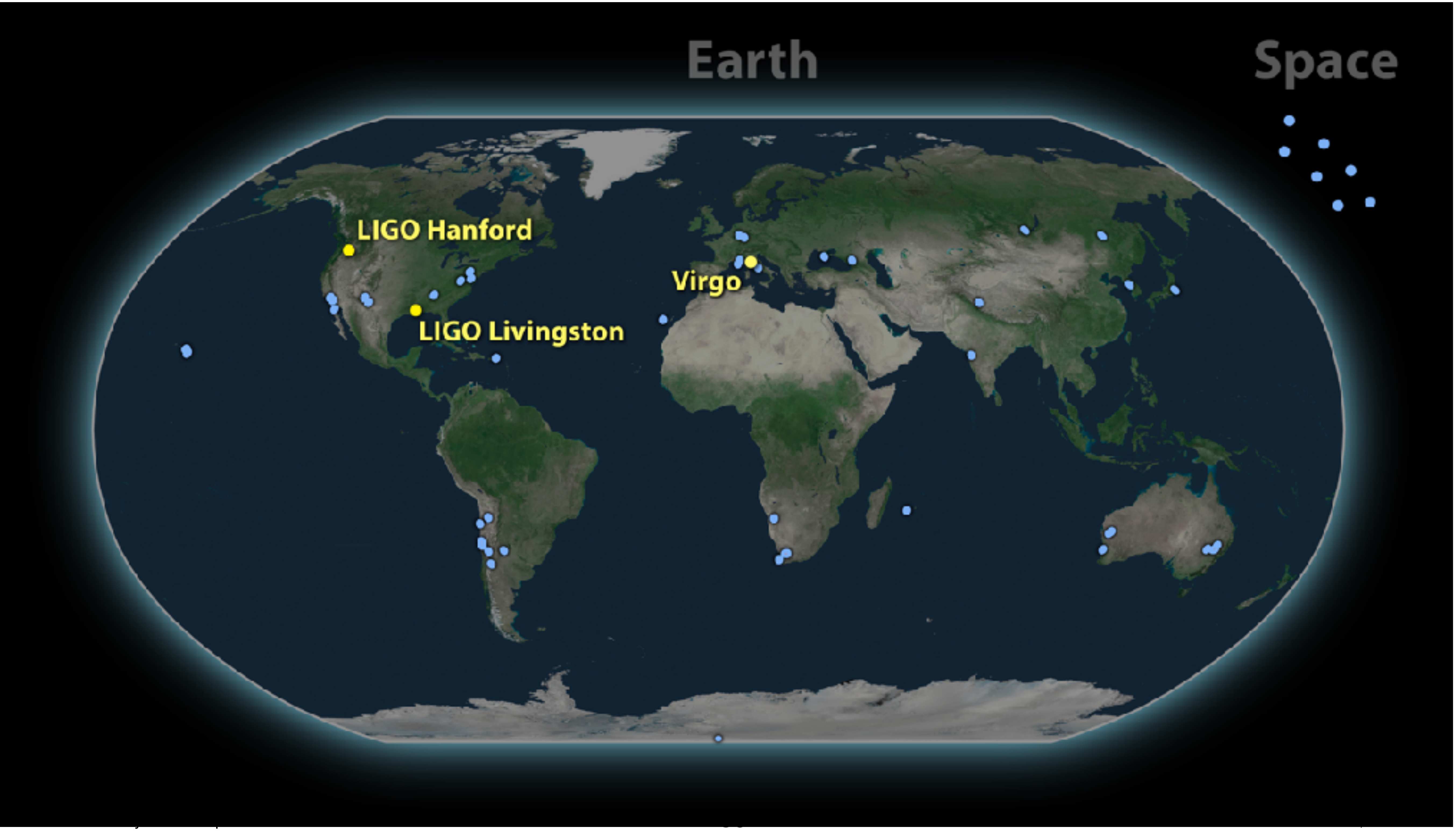


ApJL, MMA paper with 3500 authors



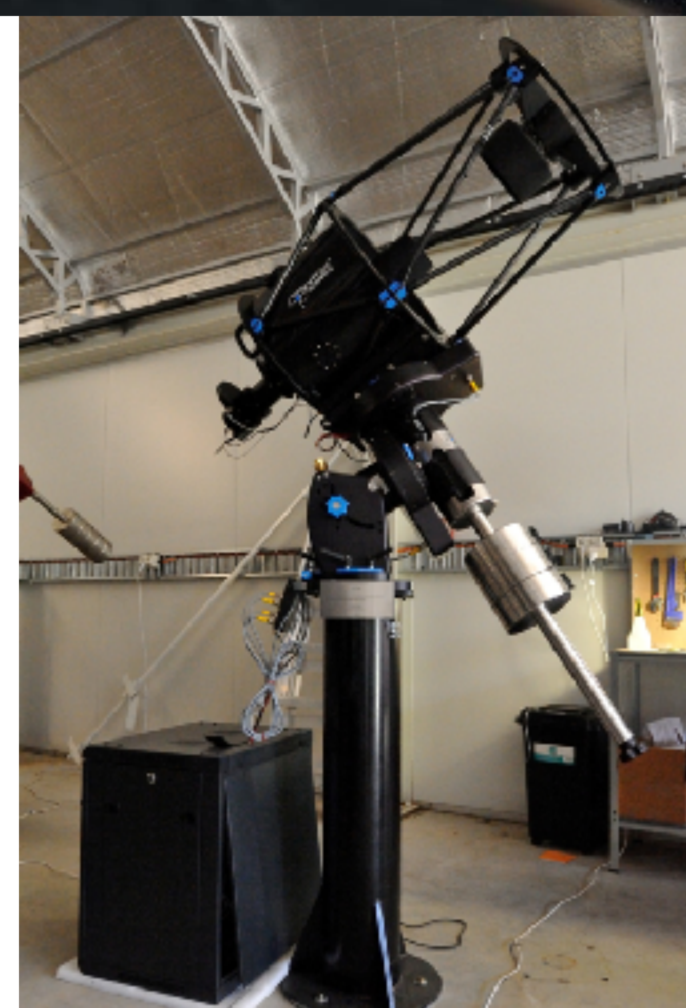
Nature, NASA/Korean group (38 authors)

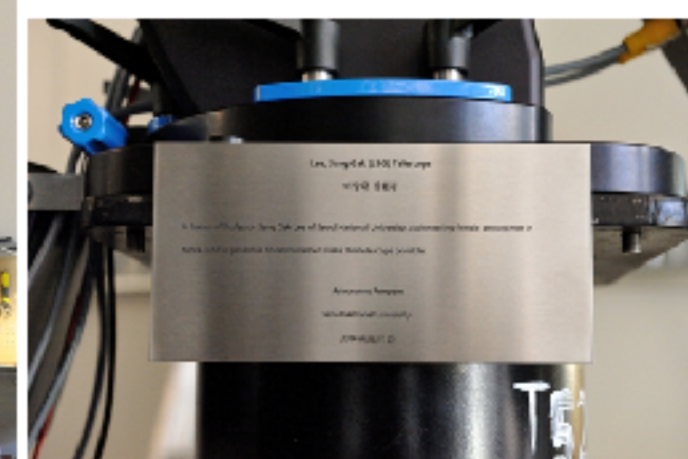
Resources in the world



Korean Facilities

- KMTNet
  - Three telescopes at Chile (CTIO), Australia (SAO) and South Africa (SAAO)
  - 1.6 m, 2x2 degree FOV
  - BVRI Filters
  - Mostly dedicated for the microlensing survey, but demonstrated its capability in time-of-opportunity observations.
- LSGT (이상각 망원경)
  - 0.5 m, *u,v,r,i,z* filters
  - Located in Australia
- Other i-Telescopes

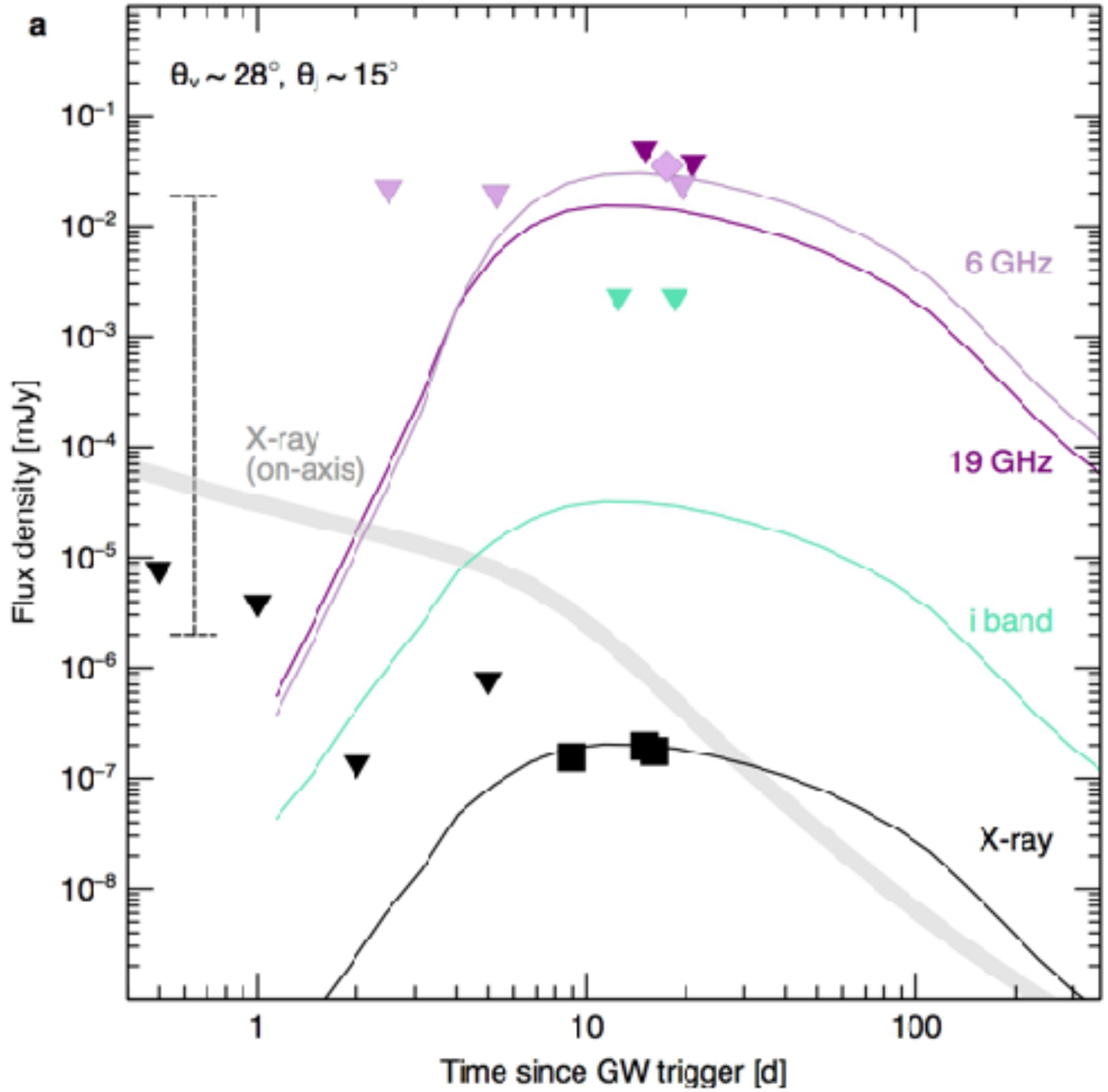


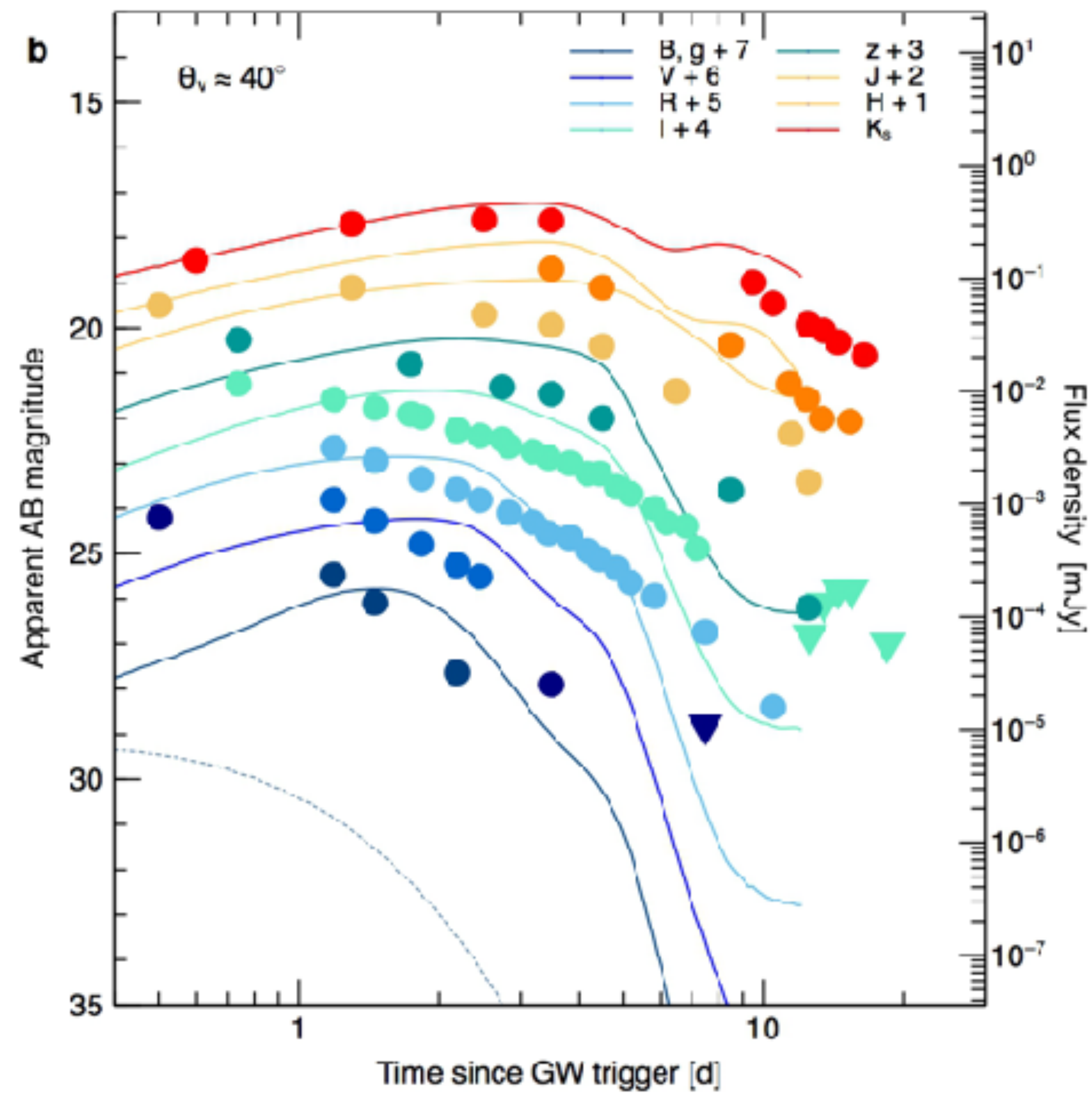


Nature of GW170817

- EM followup data can be used to investigate the merging process and merger remnant
  - Gamma-ray, X-ray, optical, near-IR
  - Missing link between short GRB and GW from NS mergers
  - Slow rise of the X-ray emission (detected by Chandra 9 days after the GW, Troja et al. 2017 Nature)
    - Off-axis nature of the GRB
  - EM emission at optical and near-IR
    - Consistent with energy input by r-process elements (Kilonova)
- The transient object has physical parameters that broadly match the theoretical predictions of blue kilonovae from neutron-star mergers (Smatt et al. 2017, Nature)
  - Low opacity model, appropriate for light r-process elements (90<A<140)

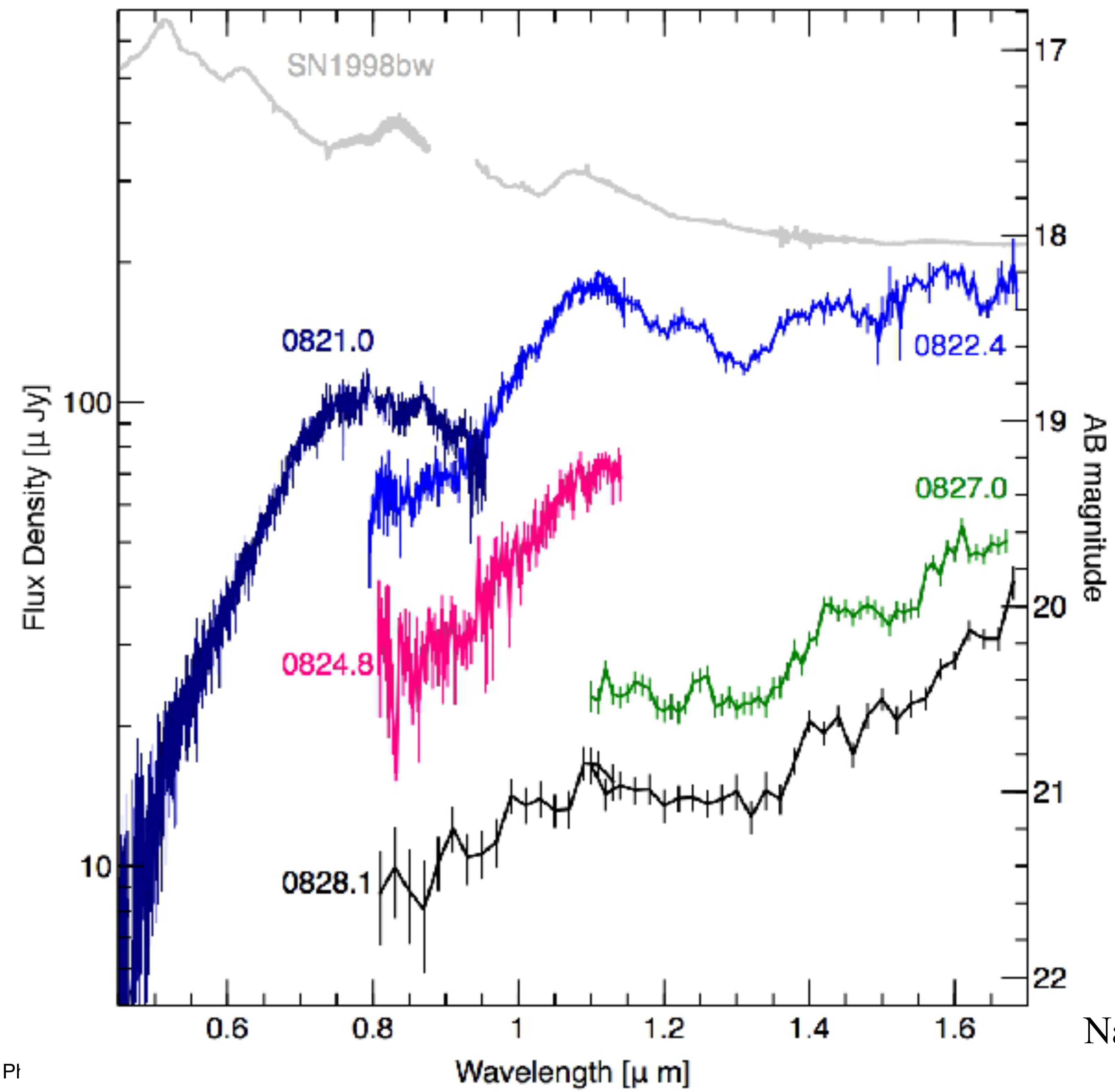
Multi-wavelength light curves





Nature article by NASA/Korean group

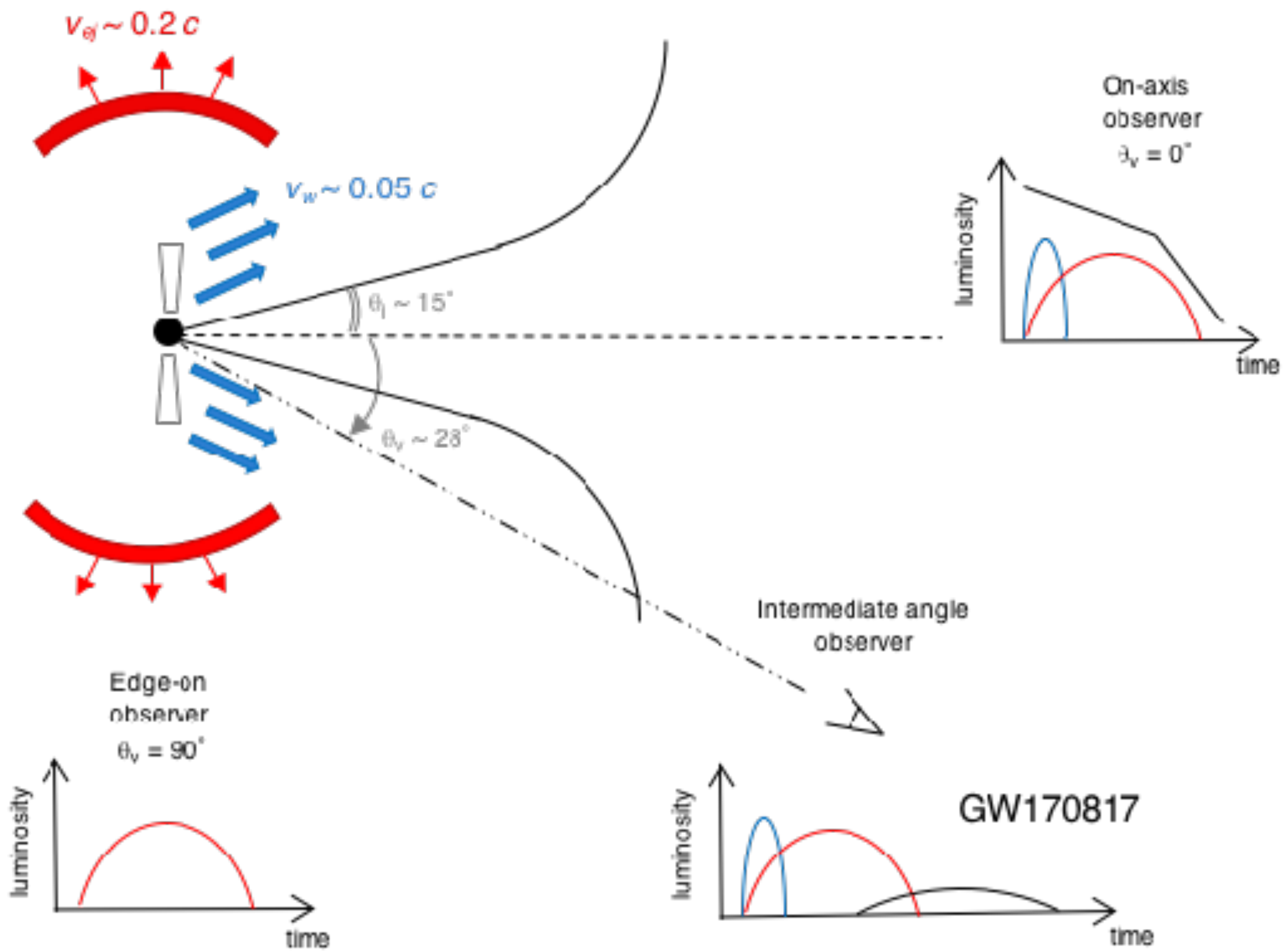
Optical and NIR spectra



- T+3.5d, by 8m Gemini telescope
- Featureless spectra with rapid turnover at <0.75 micron
- Becomes redder with time
- Consistent with the ejection of high velocity, neutron rich material during a NS merge

Nature by NASA/Korean group

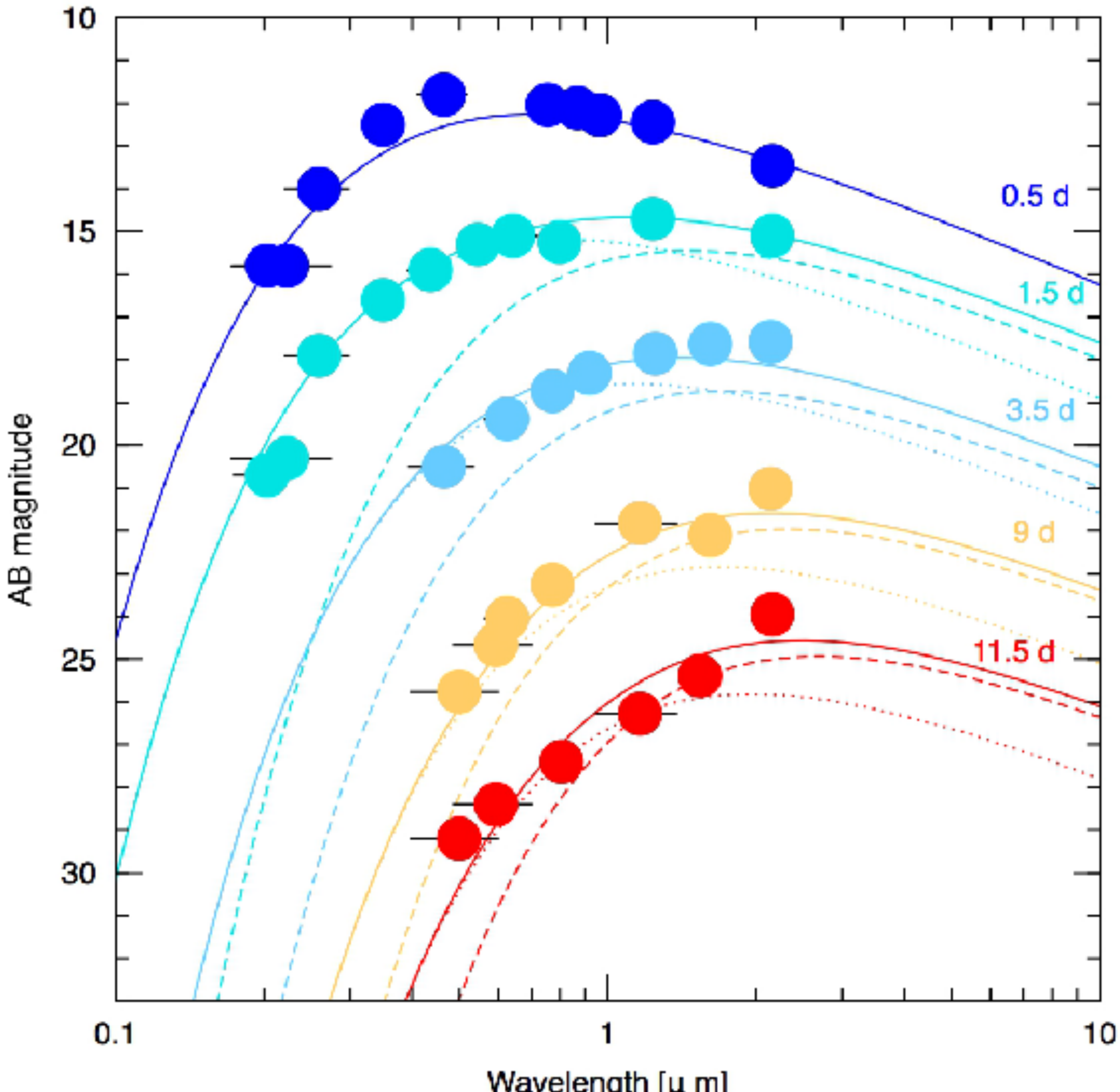
Schematic Model



- Red: fast-moving neutron-rich ejecta. isotropic kilonova peaking in the infrared.
- Blue: A larger mass neutron-free wind along the polar axis. Kilonova emission peaking at optical wavelengths. This emission, although isotropic, is not visible to edge-on observers as it is only visible within a range of angles and otherwise shielded by the high-opacity ejecta.
- Black: Synchrotron radiation visible at radio, X-ray, and optical wavelengths.

Nature by NASA/Korean group

Spectral Energy Distribution of the Optical/Infrared Counterpart



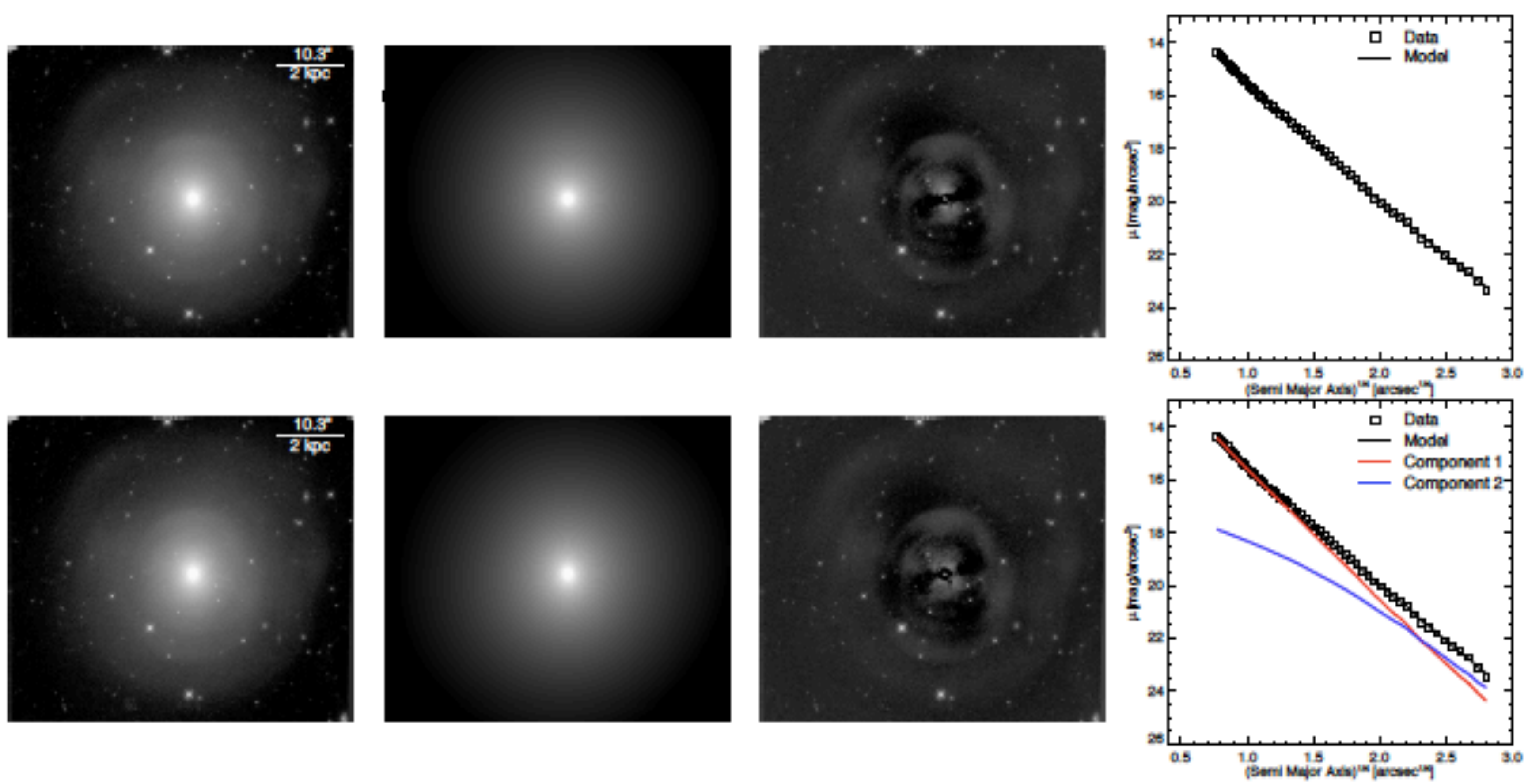
- Broadband optical/near-infrared data well fitted to single or two component black body.

Nature by NASA/Korean group

Host Galaxy: NGC 4993

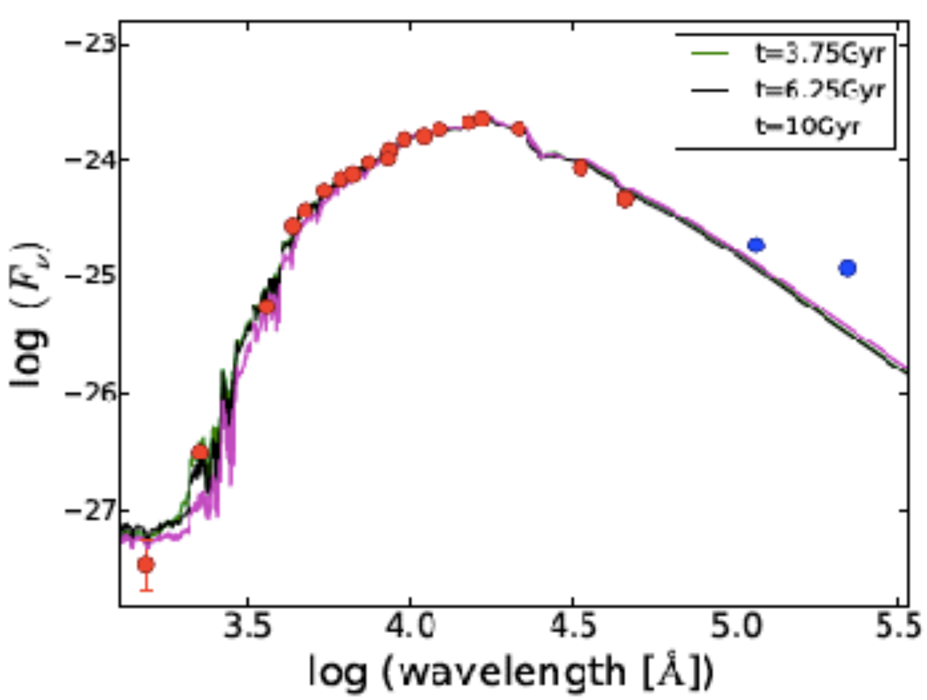
Im et al. 2017, ApJL

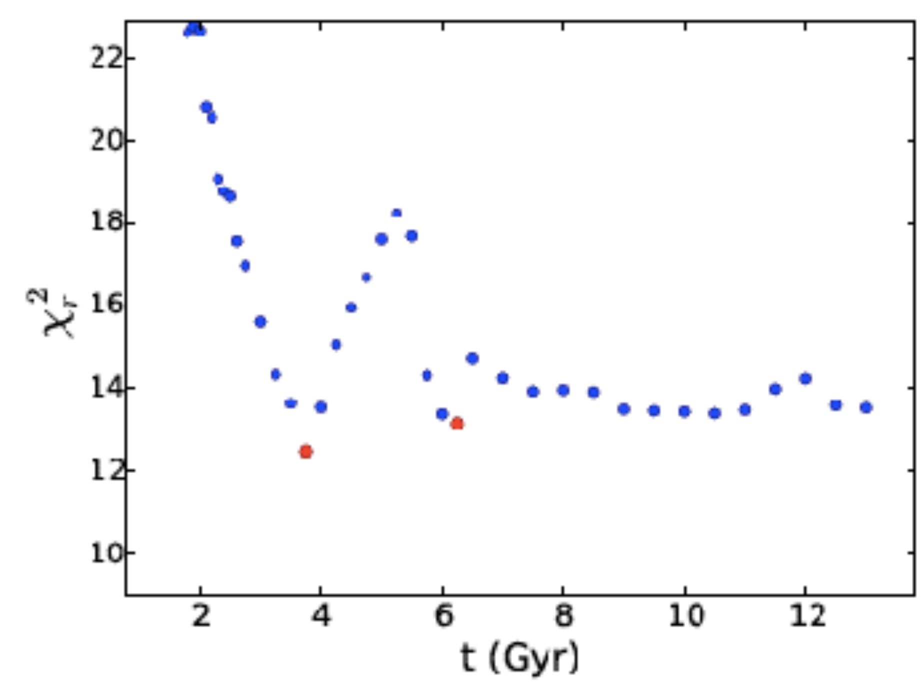
- Previously known as an elliptical galaxy at around 40 Mpc (Tully-Fisher relation)
- Well fitted by single Sersic profile or Sersic bulge + disk
- Sersic index: 4~5, typical elliptical galaxies



SED fitting

- SED fitting provides the star formation history
- The age is not well constrained, but could be 3-6 Gyrs
- Age can be as old as 10 Gyr
- Origin of the NS binaries?





Im et al. 2017, ApJL

Distance Measurement

Im et al. 2017, ApJL

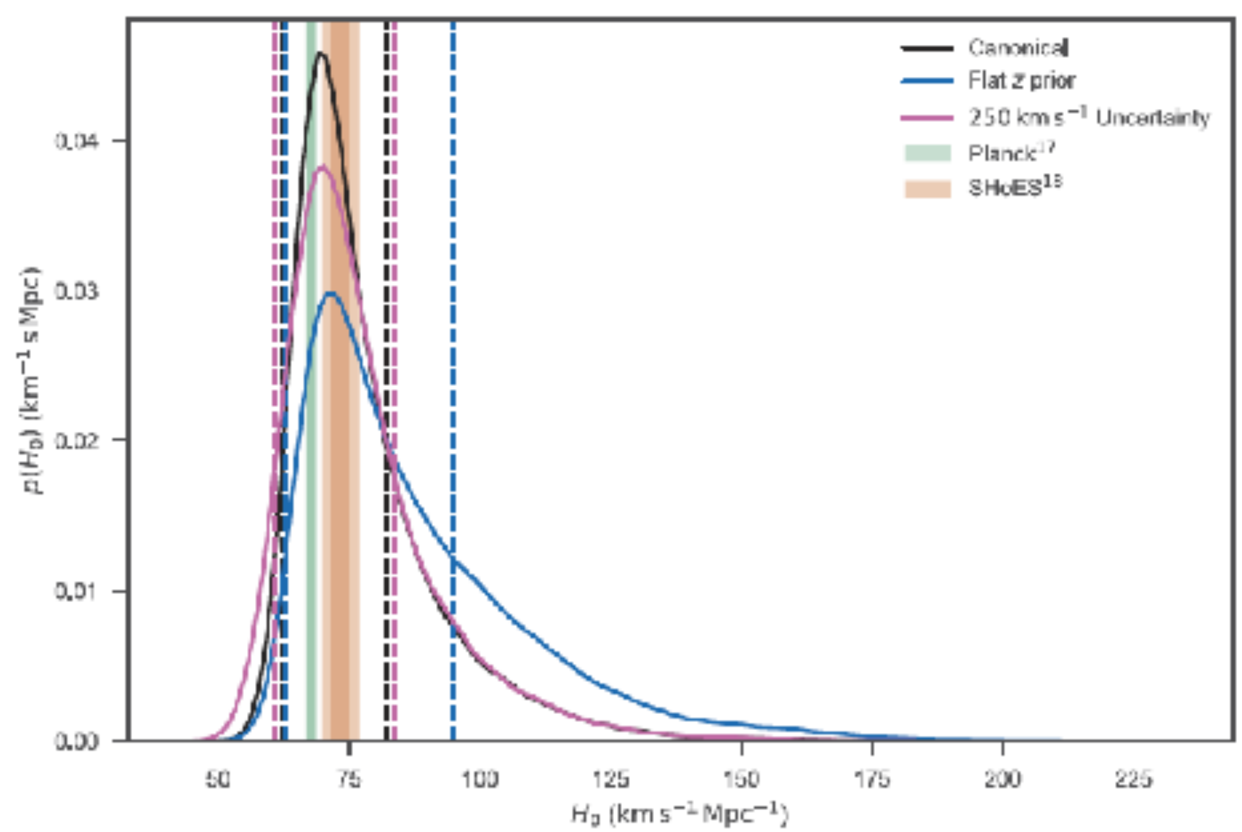
- Fundamental plane for elliptical galaxies: relation among effective radius (r_e), velocity dispersion (σ_0) and surface brightness (μ_e)

$$\log(r_e/\mathrm{kpc}) = a\log(\sigma_0/\mathrm{km/s}) + b < \mu_e > +c$$

- Velocity dispersion (σ_0) and surface brightness (μ_e) are distance independent
- From surface brightness profile, (r_e) can be measured as an angular size
- By comparing (r_e) in kpc and and arc second, distance can be measured
- Result: 37.7 ± 8.7 Mpc (cf, GW analysis 40 ($^{+8}_{-14}$) Mpc)

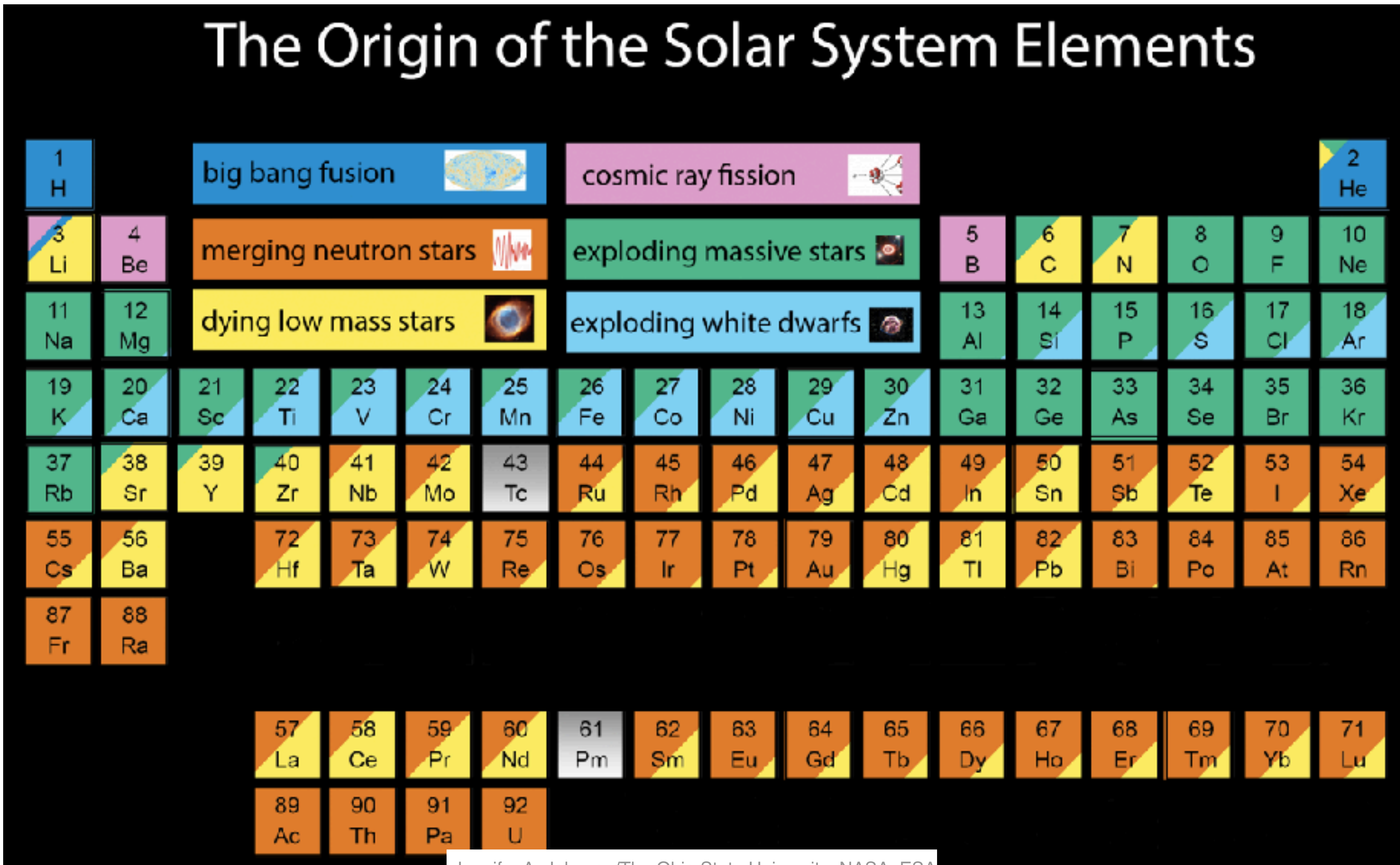
Hubble Parameter

- Luminosity distance from the GW observations
- Redshift from optical observation
  - Hubble parameter
- Observational data
  - $d_L = 43.8^{+2.9}_{-6.9}$ Mpc (assuming NGC4493 as true sky location)
  - $v_r = 3{,}327 \pm 72$ km/sec
  - Group velocity: 310 km/sec toward great attractor
- $H_0 = 70^{+12.0}_{-8.0}$ km/s/Mpc
- Other Estimates
  - Planck $H_0 = 67.8 \pm 0.9$ km/s/Mpc
  - SHoES: $H_0 = 74.2 \pm 2.7$ km/s/Mpc



LIGO/Virgo collaboration, Nature, 2017

Large amounts of r-process elements may have been produced during the merger



Summary

- LIGO eventually detected gravitational waves directly, after more than 4 decades of endeavor.
  - Rainer Weiss was regarded as a founder of the LIGO
  - Kip Thorne has made LIGO possible.
  - Barry Barish transformed LIGO into a large international collaboration
- LIGO has opened up a new area of gravitational wave astronomy.
  - 4 detections are black hole binaries
  - 1 detection of NS binaries. It also opened multi-messenger astronomy. Korea (and KASI) has played an important role in followup observations
- Black holes are typically more massive than those in X-ray binaries
  - They could have been formed in low metallicity environment
- Effective spins are very small.
- We should be prepared for the frequent detection of gravitational waves from next year.

Some pictures

Changhwan Lee & Kip Thorne
March 2015 Pasadena

Rai Weiss & Kip Thorne
Public lecture at Chinese Univ. of Hong Kong, Sept. 30, 2016

With Rai Weiss, September 30, 2016, Hong Kong

Barry Barish in Busan,
July 2016