What have we learned from the detection of gravitational waves?

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25th Anniversary of Rencontres du Vietnam, “Windows on the Universe”
Quy Nhon, Vietnam

KASI: Introduction

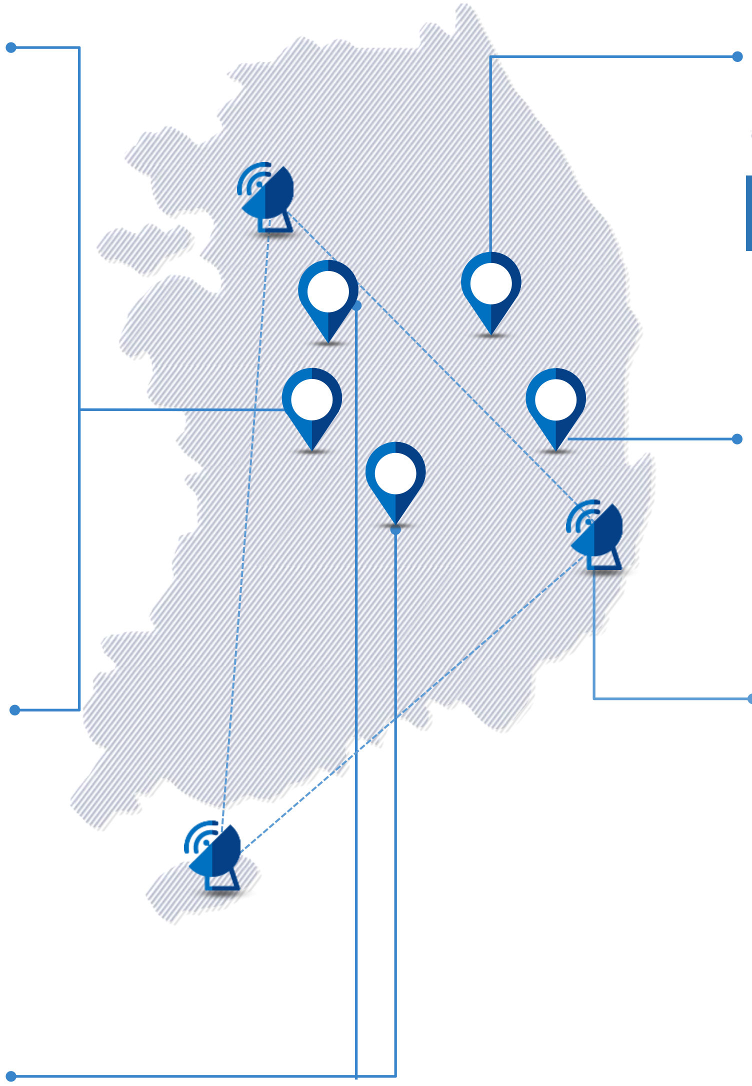
- Acronym of Korea Astronomy and Space Science Institute
- Started as a National Observatory in 1974, and transformed into Nationally Funded Research Institute
- Provides large observing facilities to science community
- Research area covers cosmology, galaxies, interstellar medium, stars, solar system, and space environments, theory, observations, numerical simulations, etc.
- ~150 researchers, ~30 technicians
- Several foreign staff members including one from Vietnam
- Training opportunities as graduate students, postdocs and visitors

KASI: Domestic Facilities

Headquarter in Daejeon

Single Dish Radio Observatory)

Laser Ranging Statiosns



60 cm Telescope

1.8m Telescope

VLBI Network (KVN)

Seoul KVN

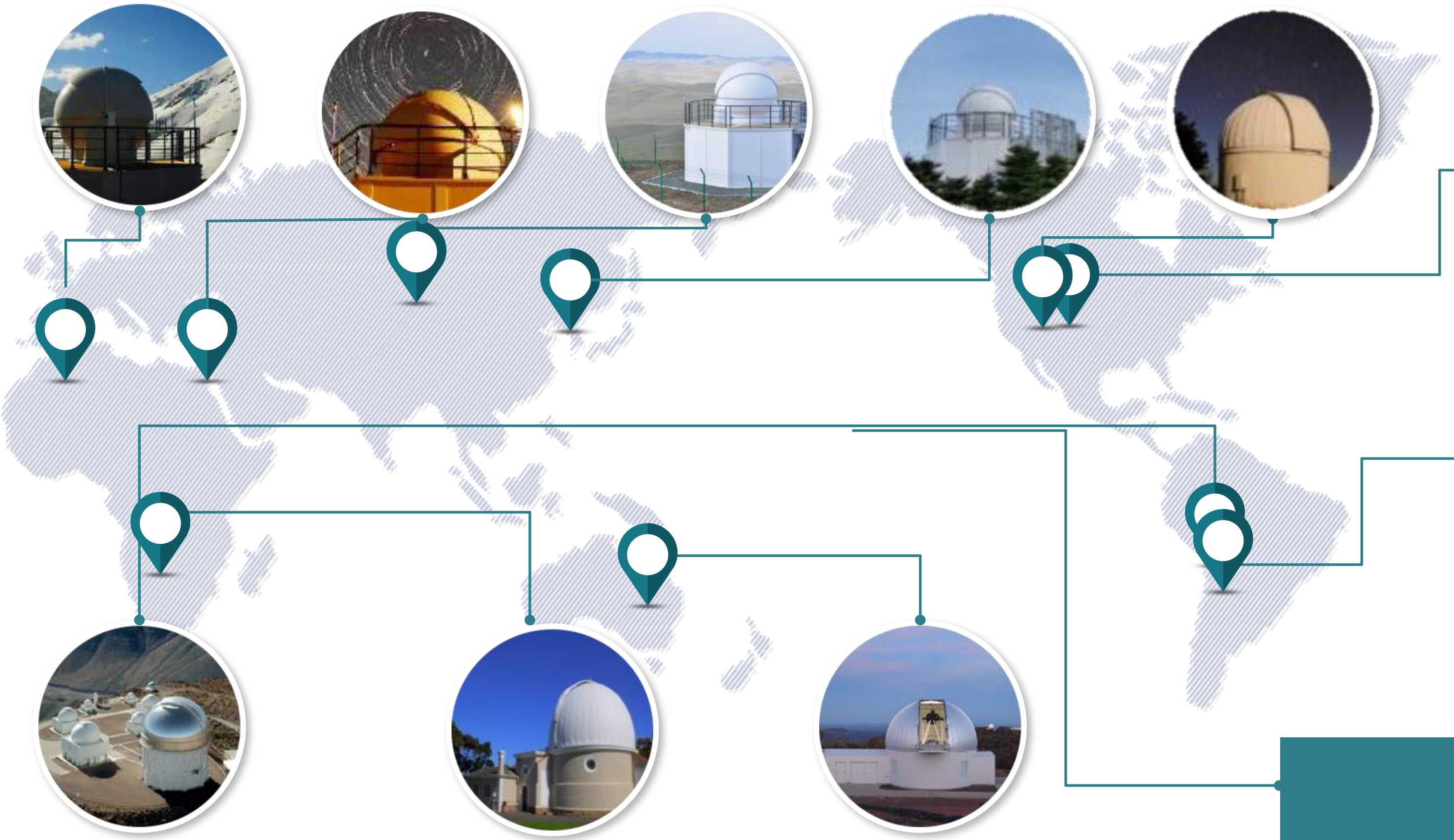
Ulsan KVN

Jeju KVN

KASI: Facilities abroad and in space

Abroad

Optical Patrol System (OWL-Net)



Mt. Lemmon Observatory

Giant Magellan Telescope (GMT)

Korea Microlensing Telescopes (KMTNet)

Space

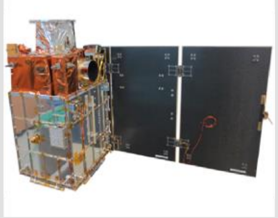
Far-UV Imagin Spectrometer (FIMS)

2003

Multi-purpose Infrares Imaging Spectometer(MIRIS)

2013

Near Infrared spectroscopic surveyor



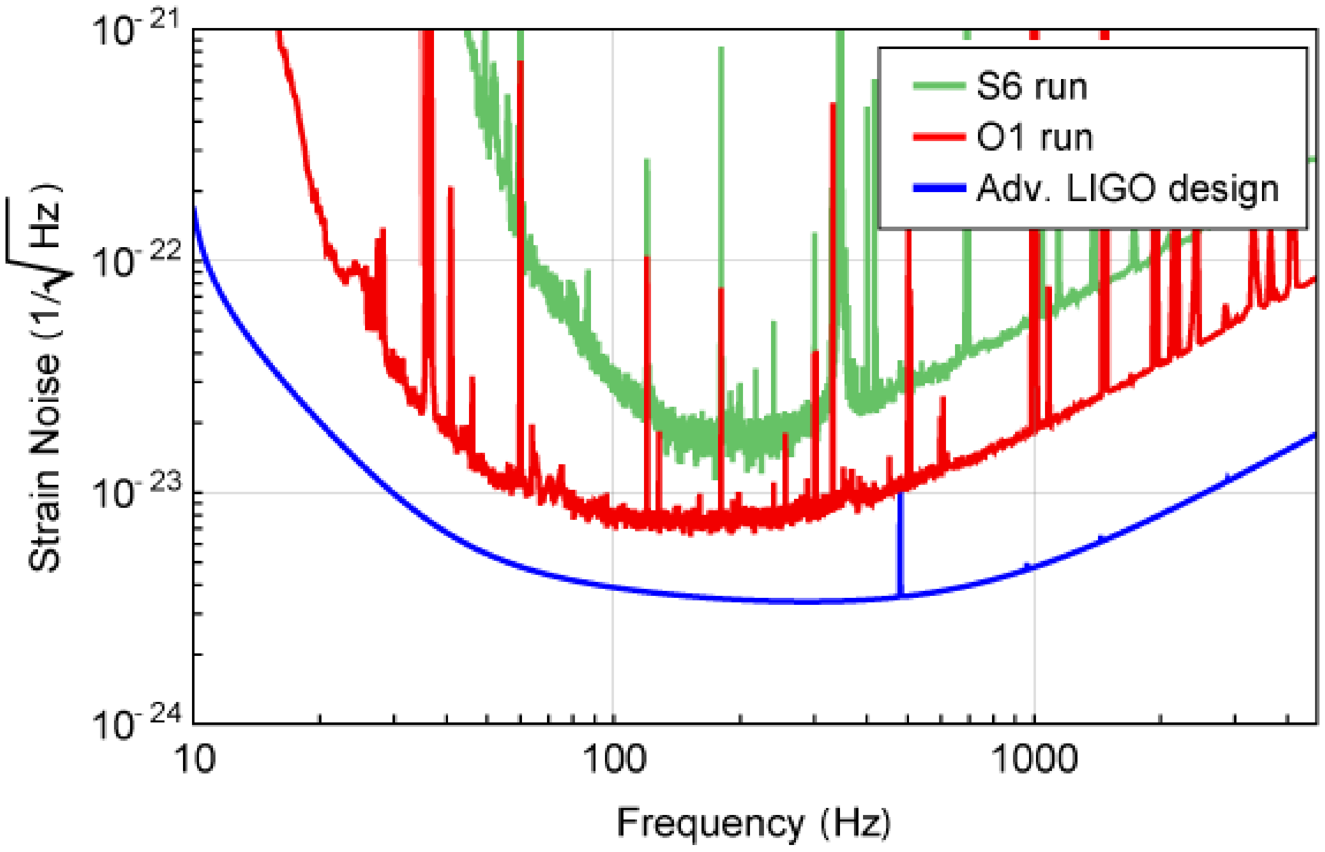
To be launched soon (2018)

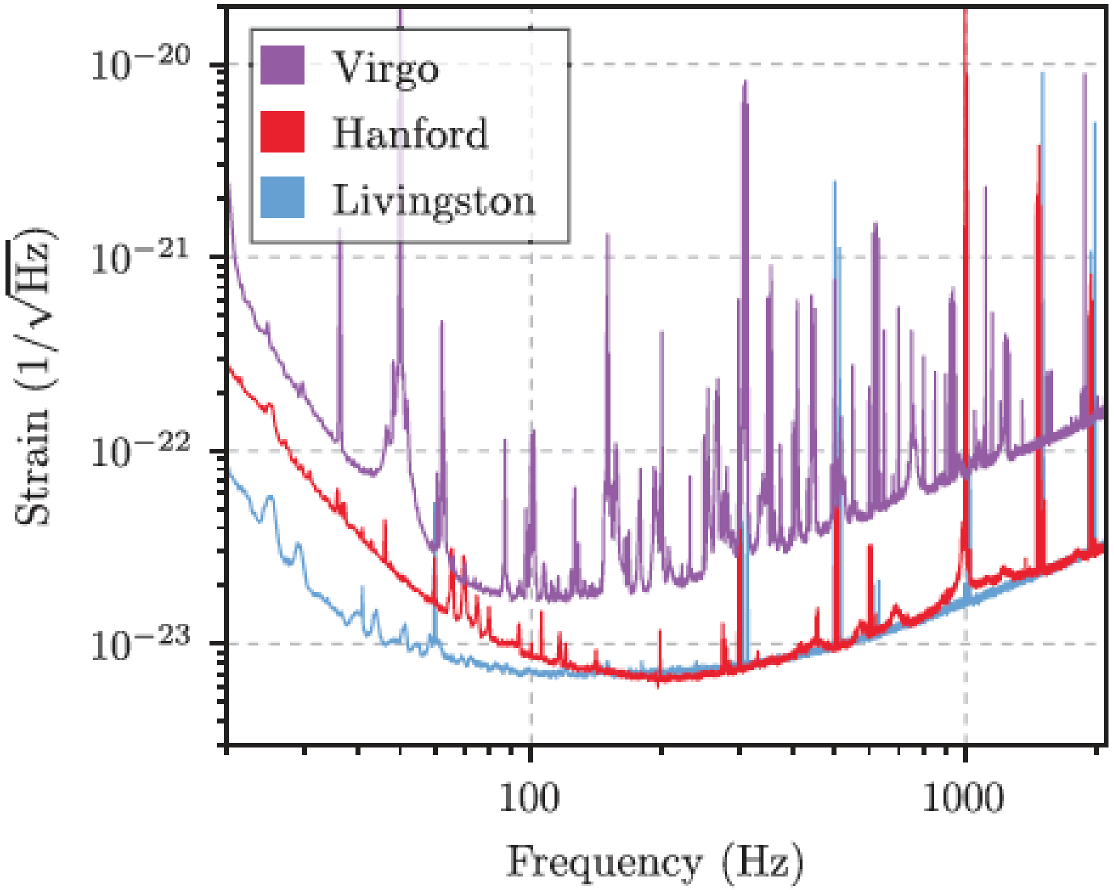
Plan

- GW Events from two observing runs of LIGO/Virgo
  - Black Hole Binaries
  - Neutron Star Binary Event and Multi-Messenger Astronomy
- A proposal for a new GW Detector at mid-frequencies
- Summary

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

https://www.advancedligo.mit.edu



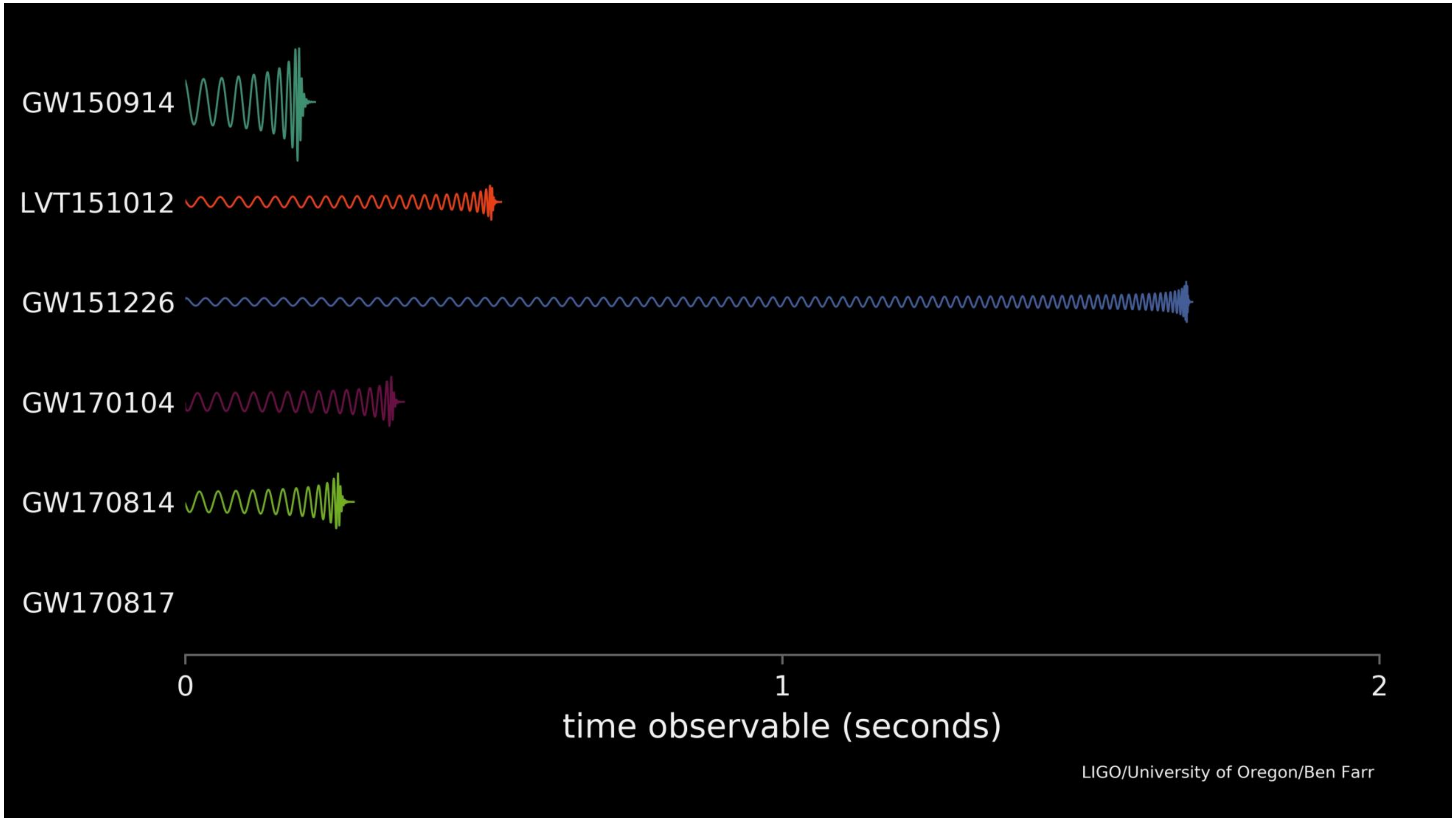


2017.08.14

- Sensitivity improvement by x3 made a big difference
- O2 sensitivity is slightly better than O1
- Higher sensitivity in O3 that will start early next year

GW Events from O1/O2

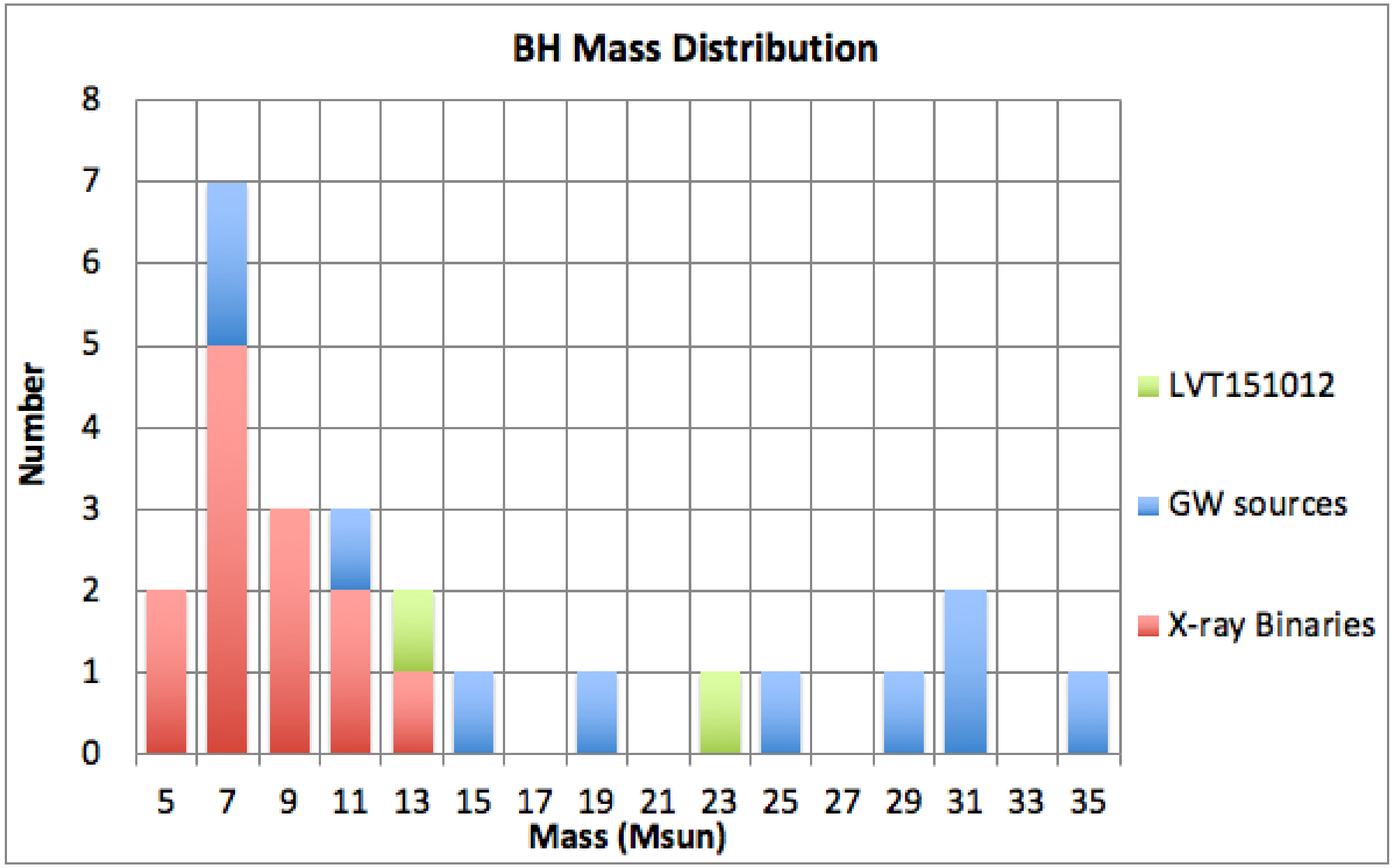
- 5 BH mergers (GW150914, 151226, 170104, 170608, 170814)
- 1 BH merger candidate (LVT151012)
- 1 NS merger (GW170817)



LIGO/University of Oregon/Ben Farr

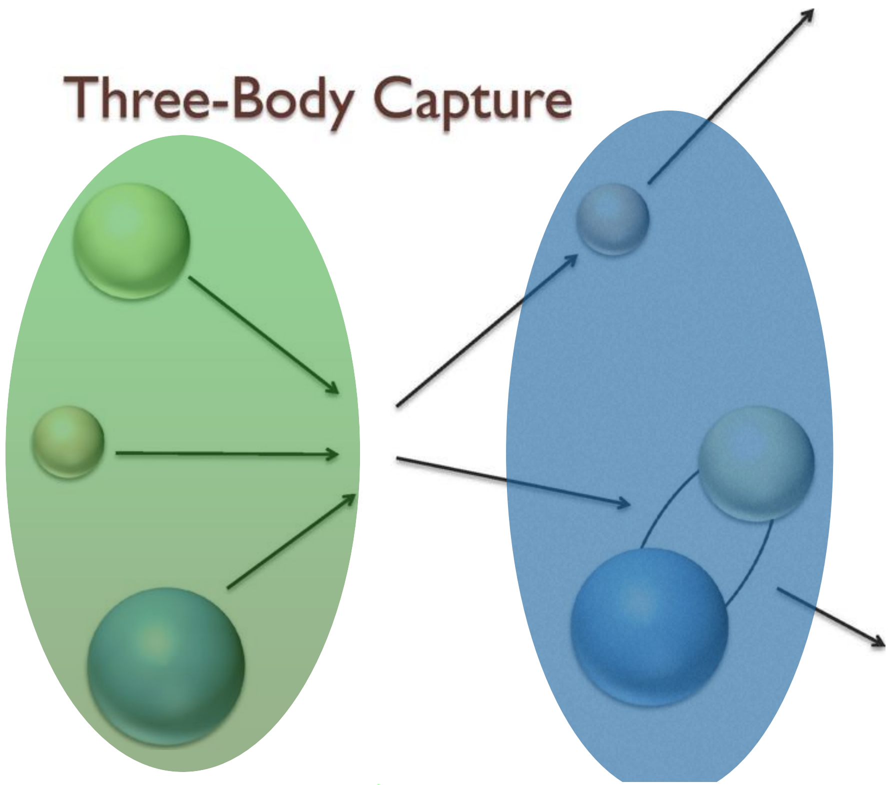
Black Hole Binaries

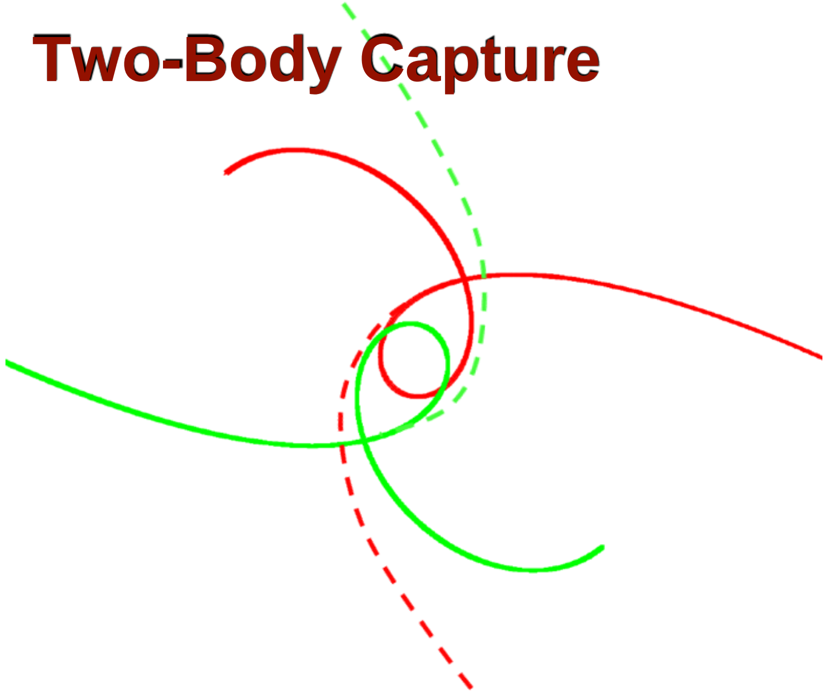
- Black hole mass range was quite large:
- Many BHs with much higher mass than those in X-ray binaries



How these binaries are formed?

- **Evolution of massive binaries**
  - Common envelop phase is necessary to bring BHs very close
    - Spins should be highly aligned
- **Dynamical Processes**
  - Three-body processes (globular cluster, Bae et al. 2014, Park et al. 2016)
  - Two-body capture (Galactic nuclei, eccentric, Hong & Lee 2015)
    - Spins are not aligned

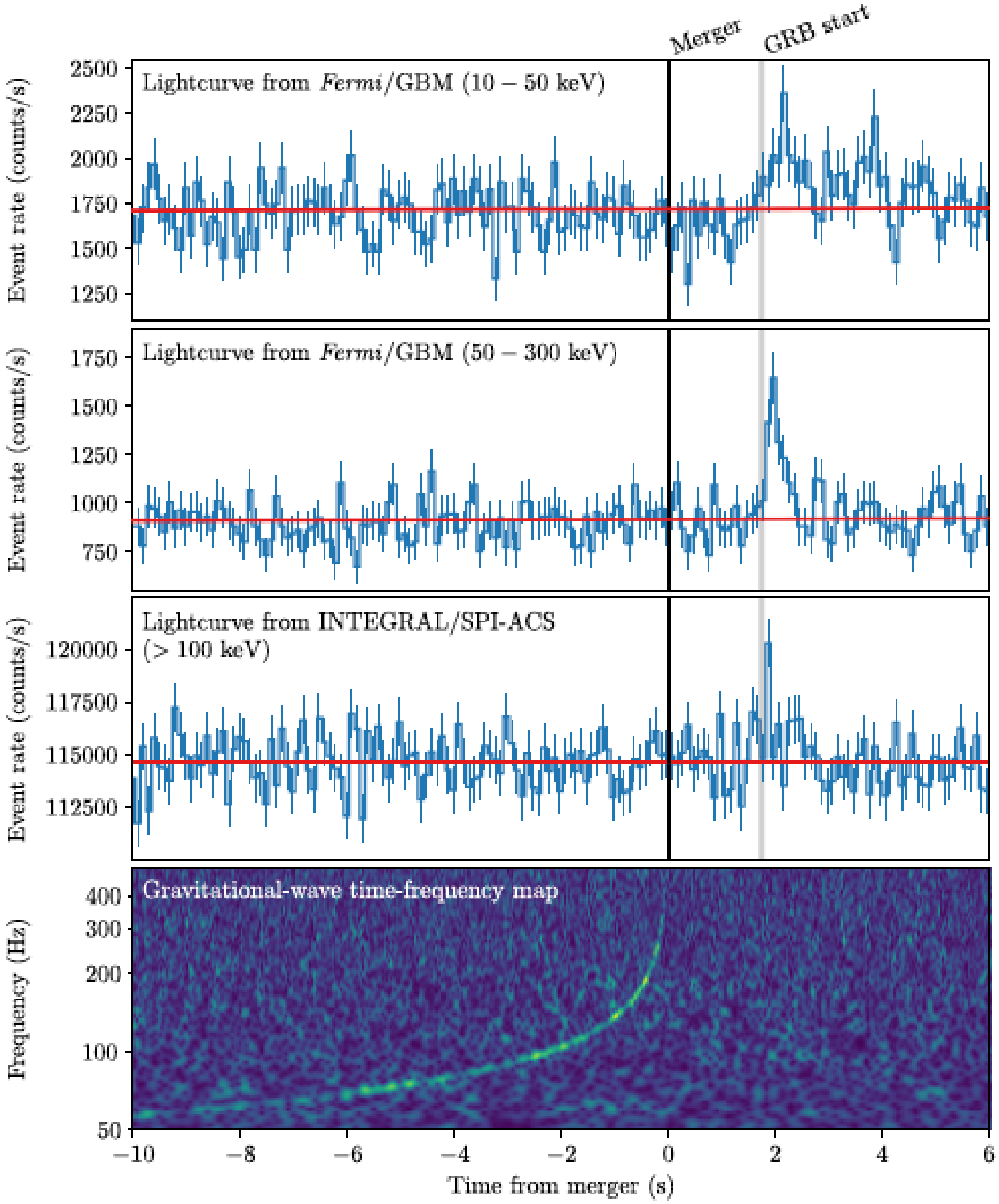




Neutron star merger: GW170817/ GRB 170817

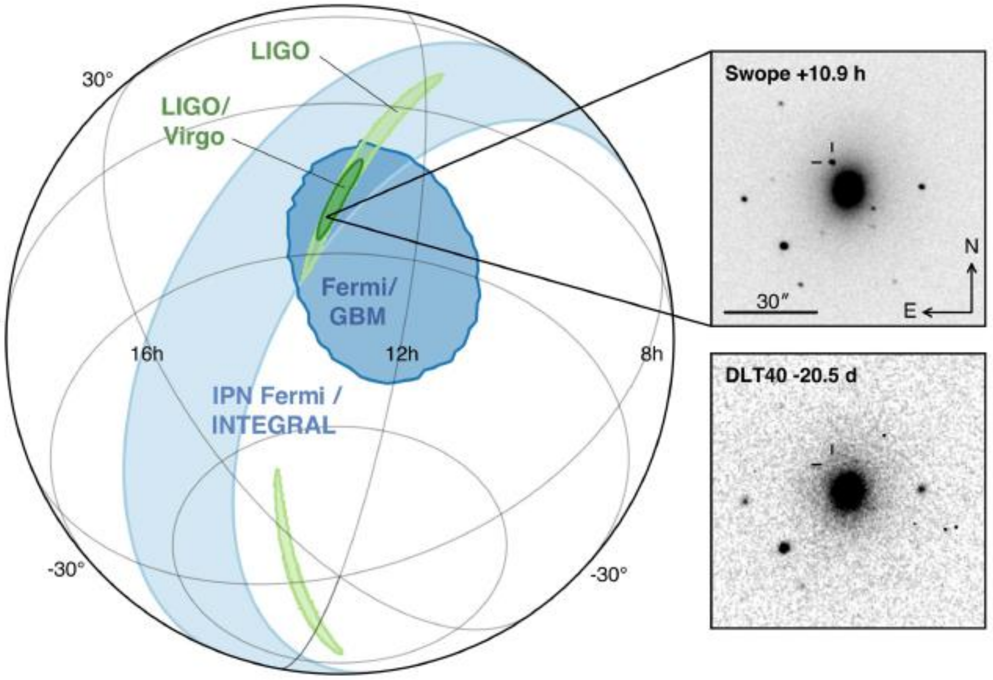
ApJL 2017, 848, L12 (LIGO/Fermi GBM/INTEGRAL)

- Short GRB was detected by Fermi GBM and INTEGRAL ~ 1.7 s after the merger
- First neutron star merger event

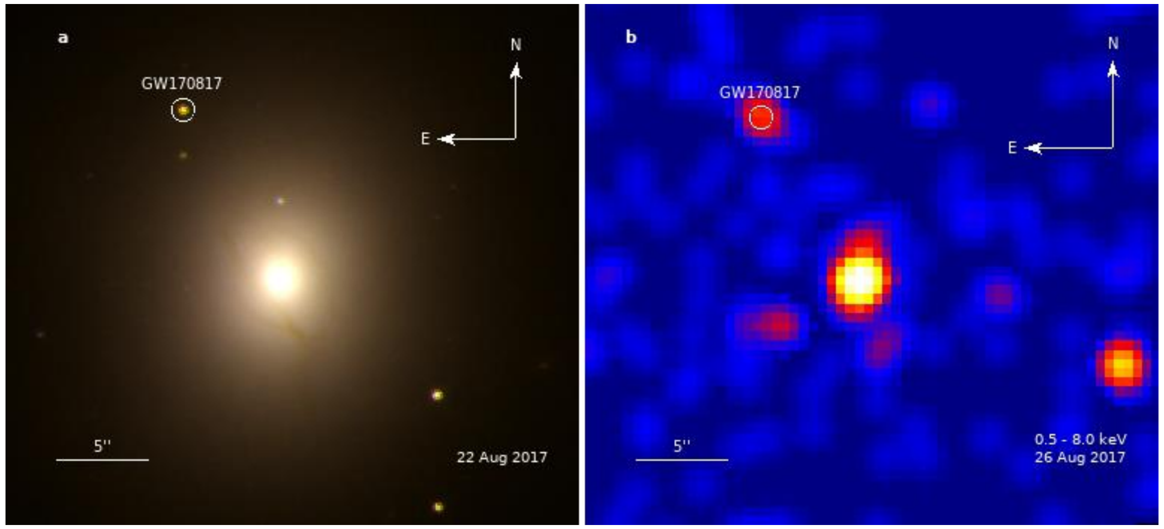


Electromagnetic Followup

- Identification of host galaxy NGC4993 by SWOPE
- Worldwide campaign to observe the afterglow by 70 groups in all wavelengths (X-ray, Optical, IR, Radio)
- Korean group composed of SNU and KASI also participated the observational campaign with several optical telescopes

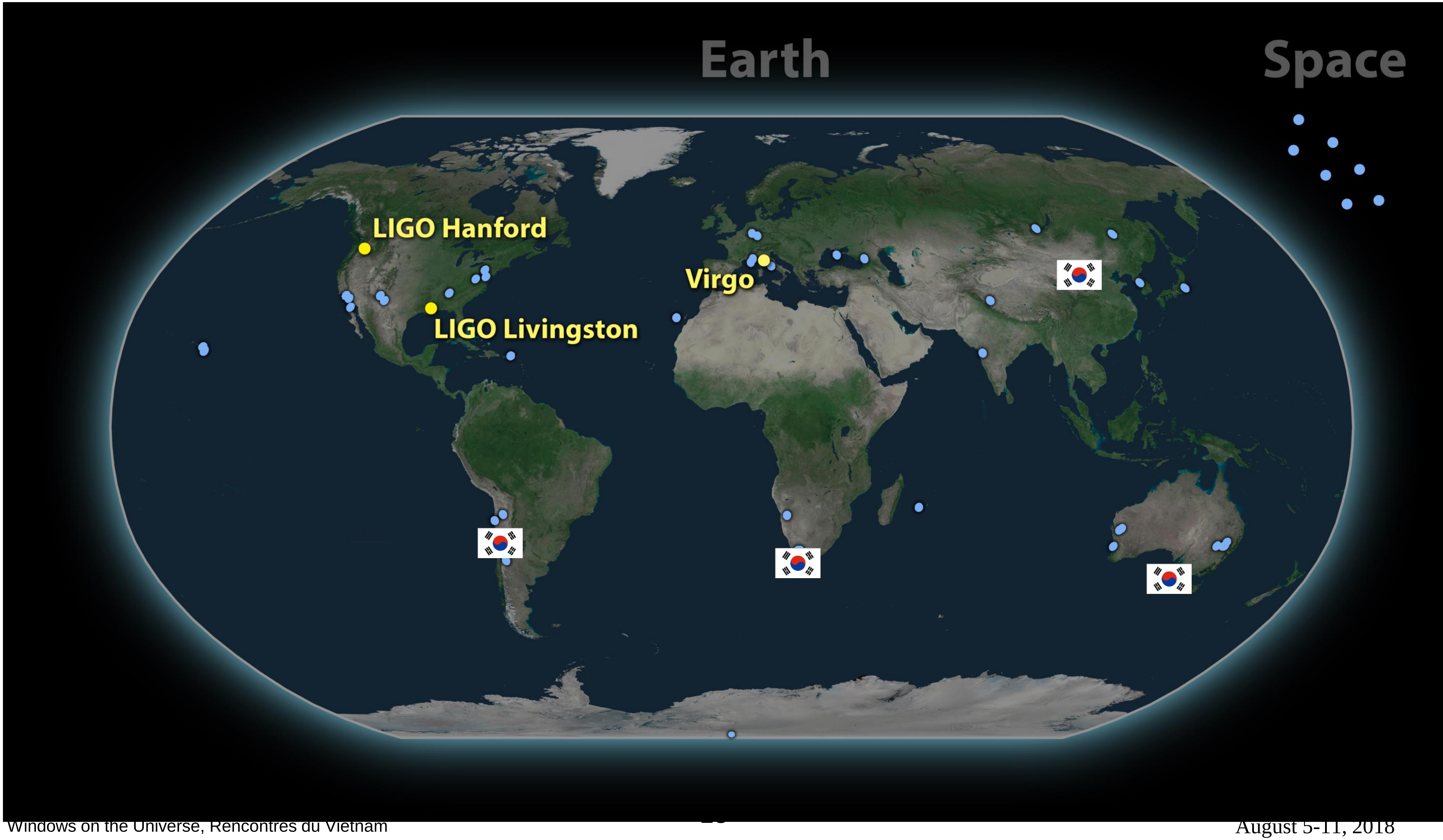


ApJL, MMA paper with 3500 authors



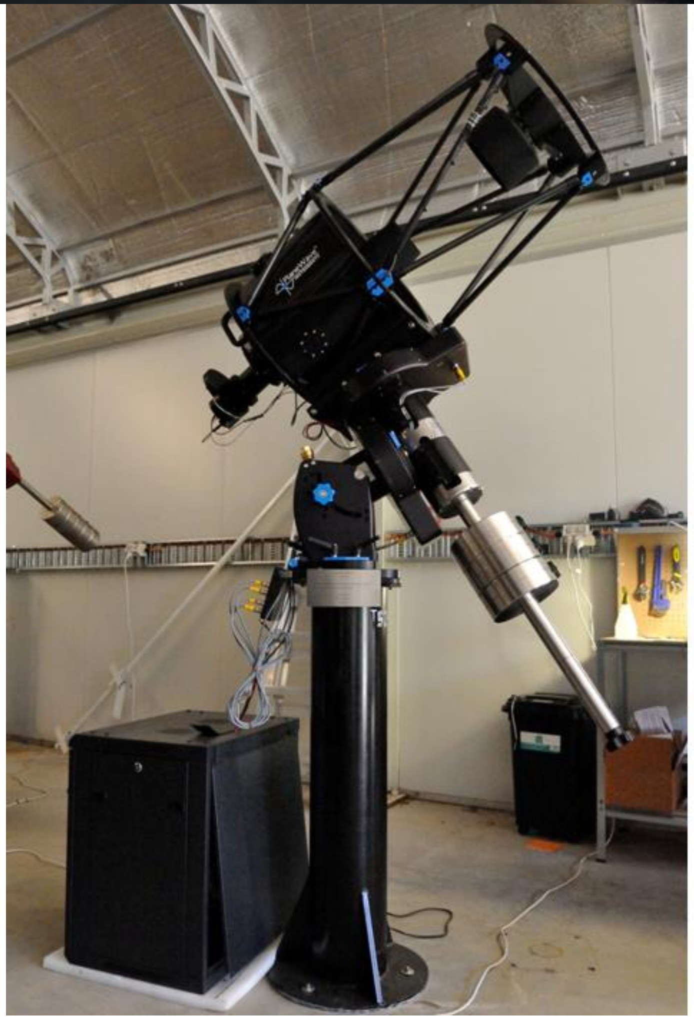
Troja et al. 2017, Nature, 551, 71 (NASA/Korean group)

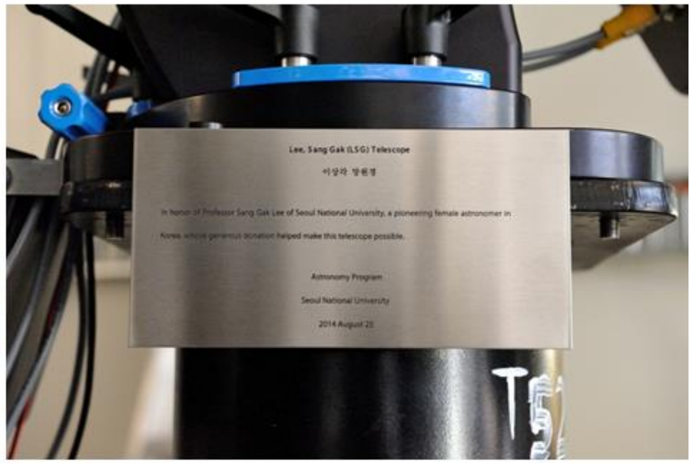
Resources in the world



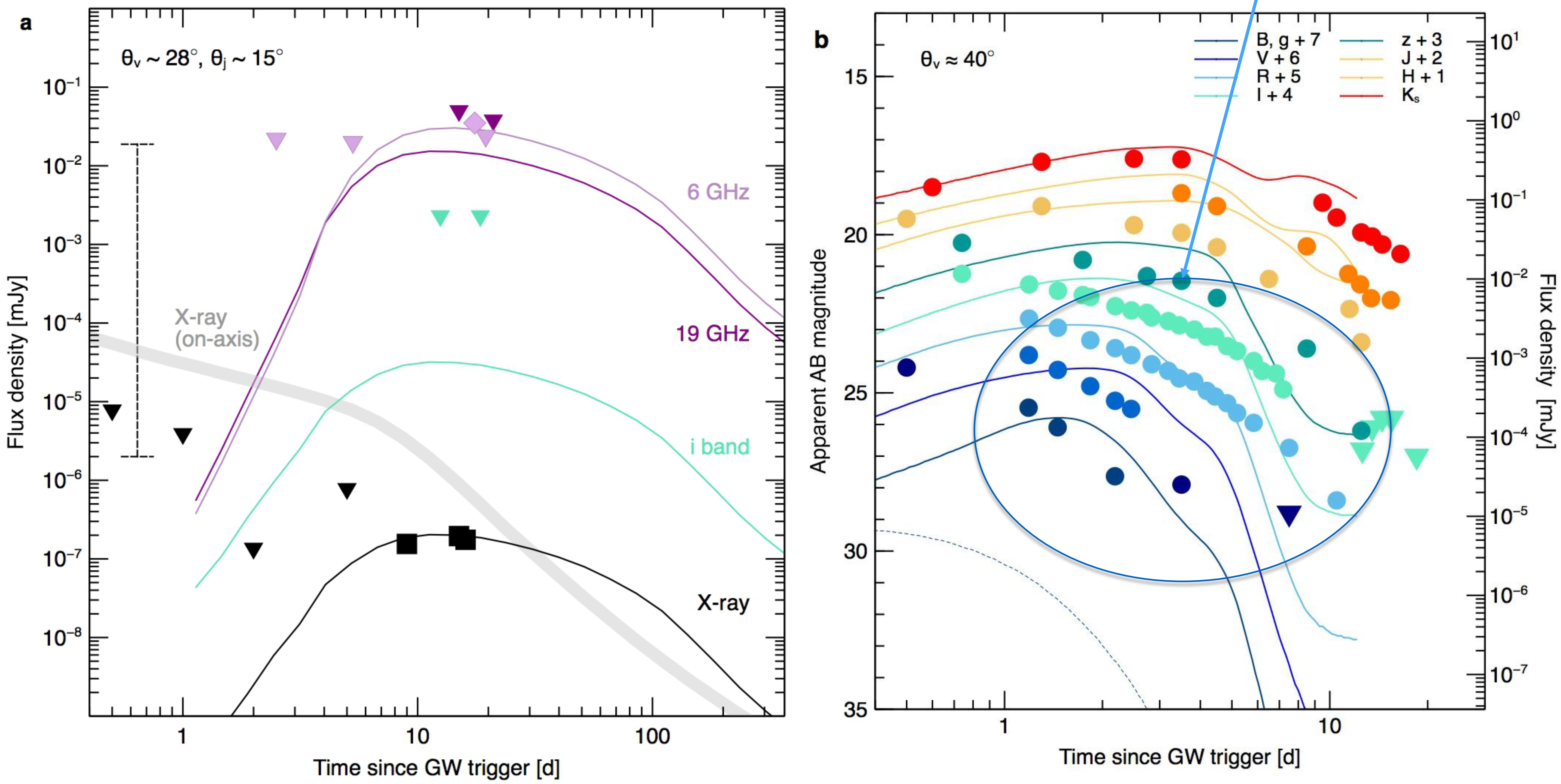
Korean Facilities

- 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





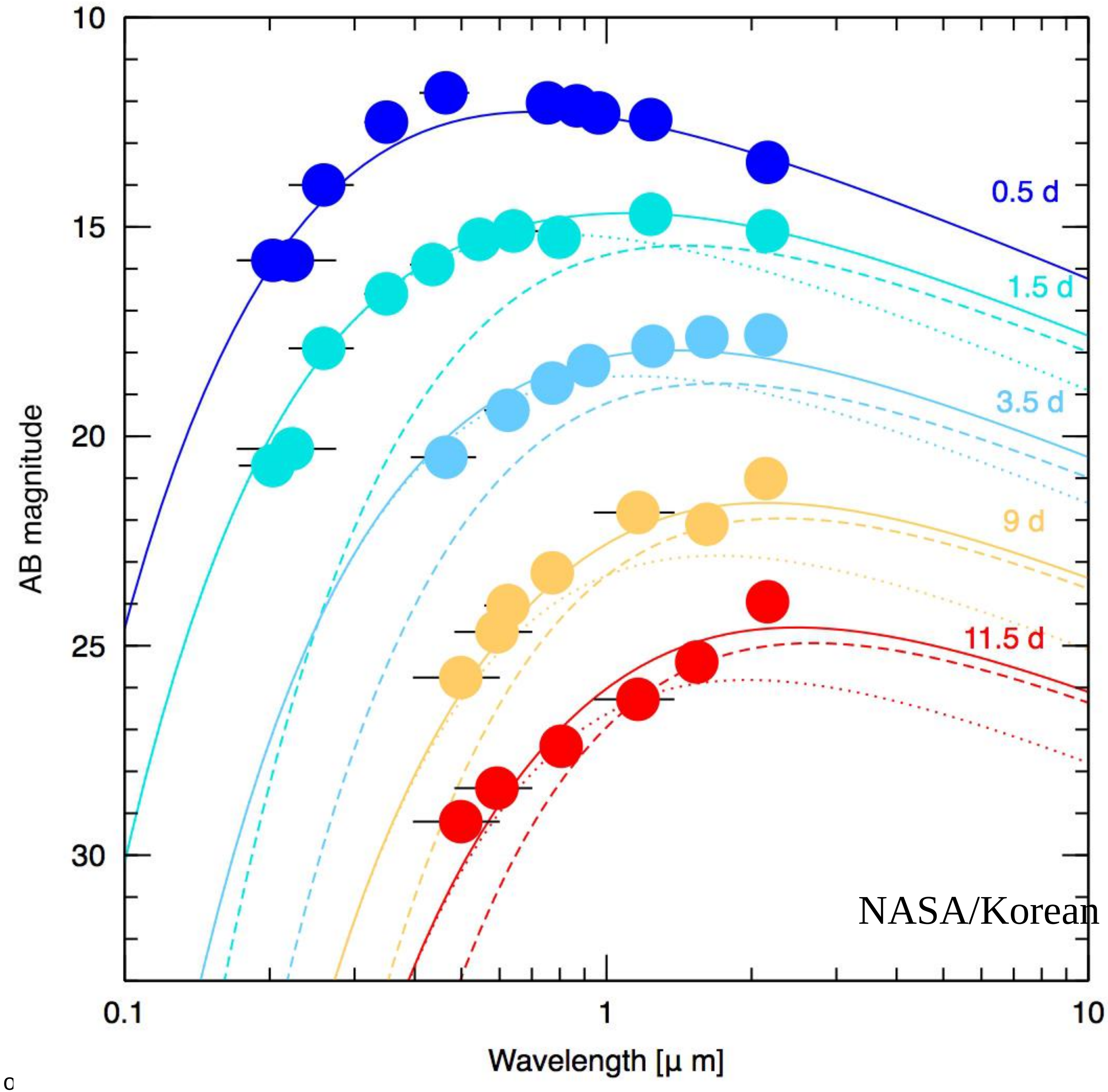
Multi-wavelength light curves



KMTNet Data

NASA/Korean group, Troja et al. 2017, Nature, 551, 71

Spectral Energy Distribution of the Optical/Infrared Counterpart



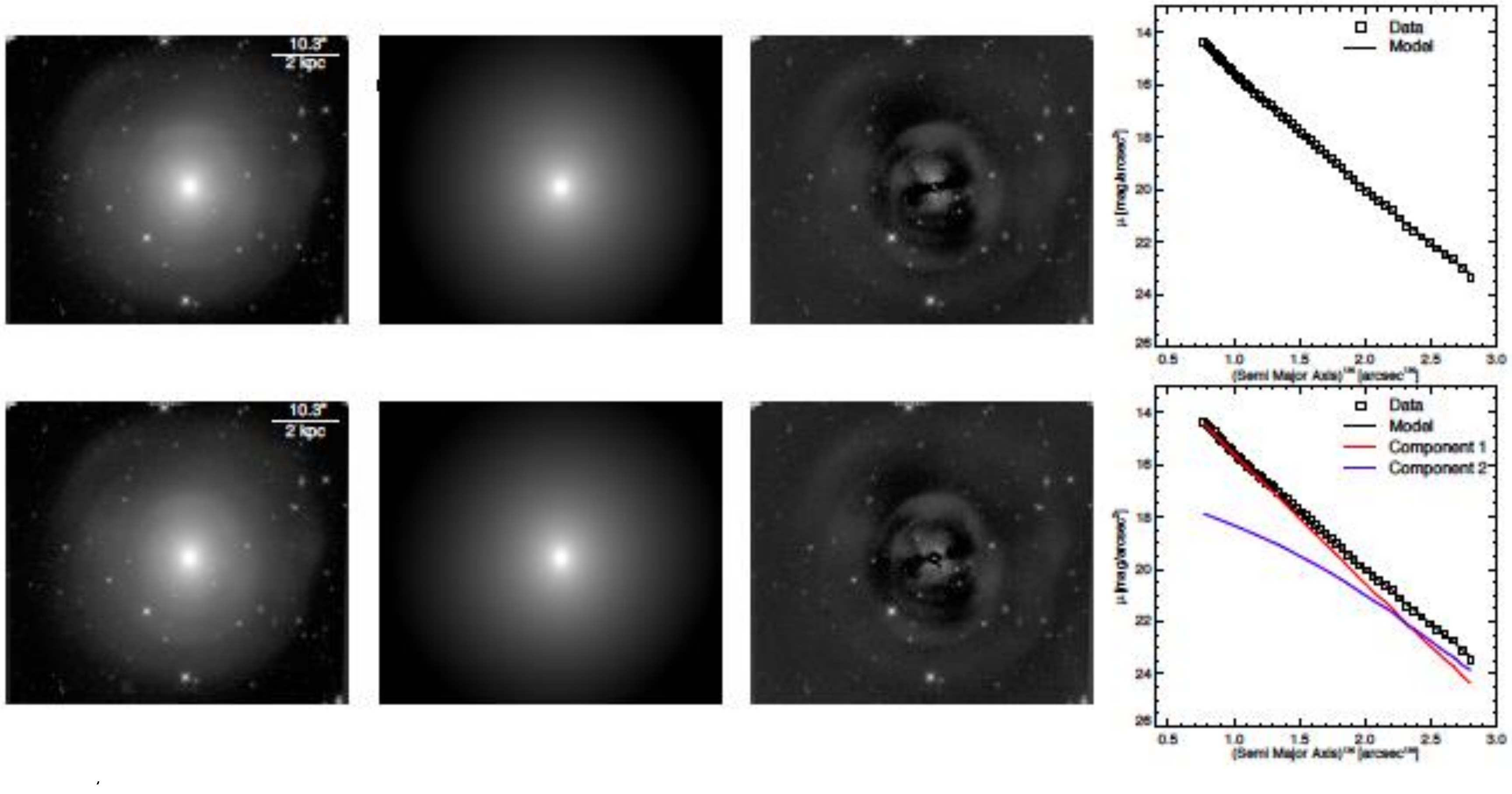
- Broadband optical/near-infrared data well fitted to single or two component black body.

NASA/Korean group, Troja et al. 2017, Nature, 551, 71

Host Galaxy: NGC 4993

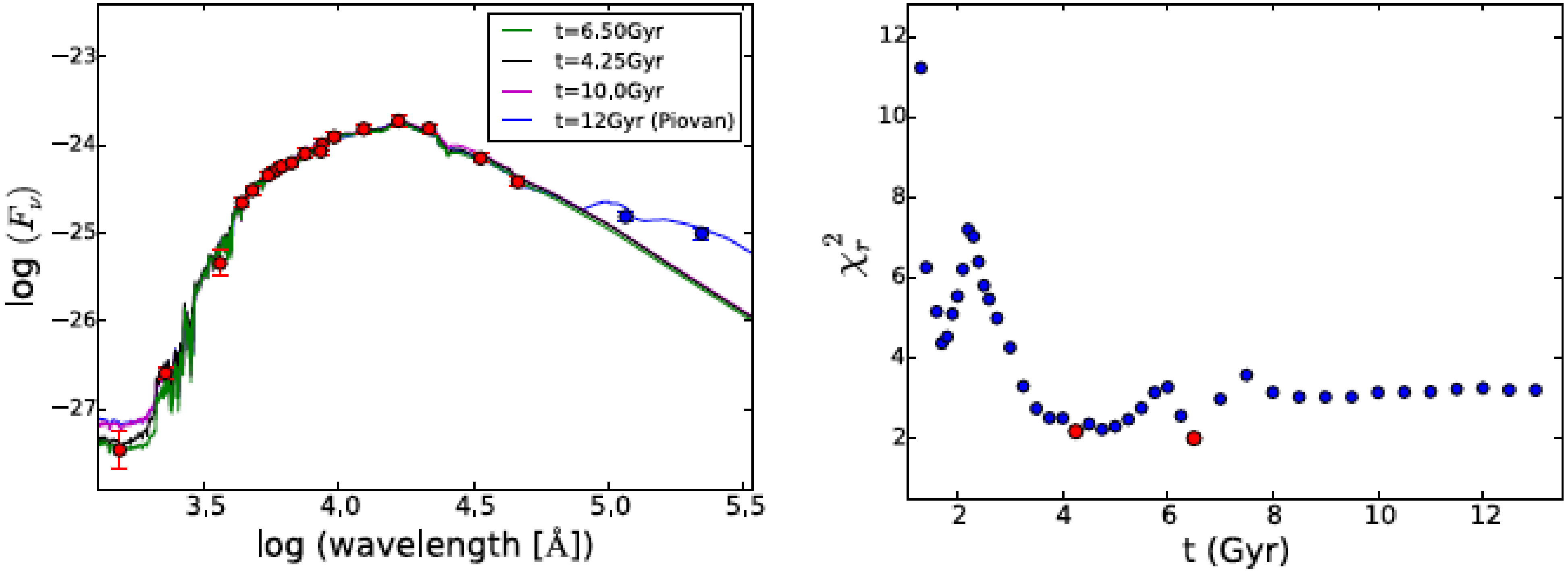
Im et al. 2017, ApJL, 849, L16

- 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



Star Formation History

- 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, 849, L16

Distance measurement with Gravitational Waves (B. Schutz ,1986, Nature)

- Binary neutron star merger signal at 100 Hz

$$< h >= 1 \times 10^{-23} m_T^{2/3} \mu f_{100}^{2/3} r_{100}^{-1}$$

- Rate of frequency change:

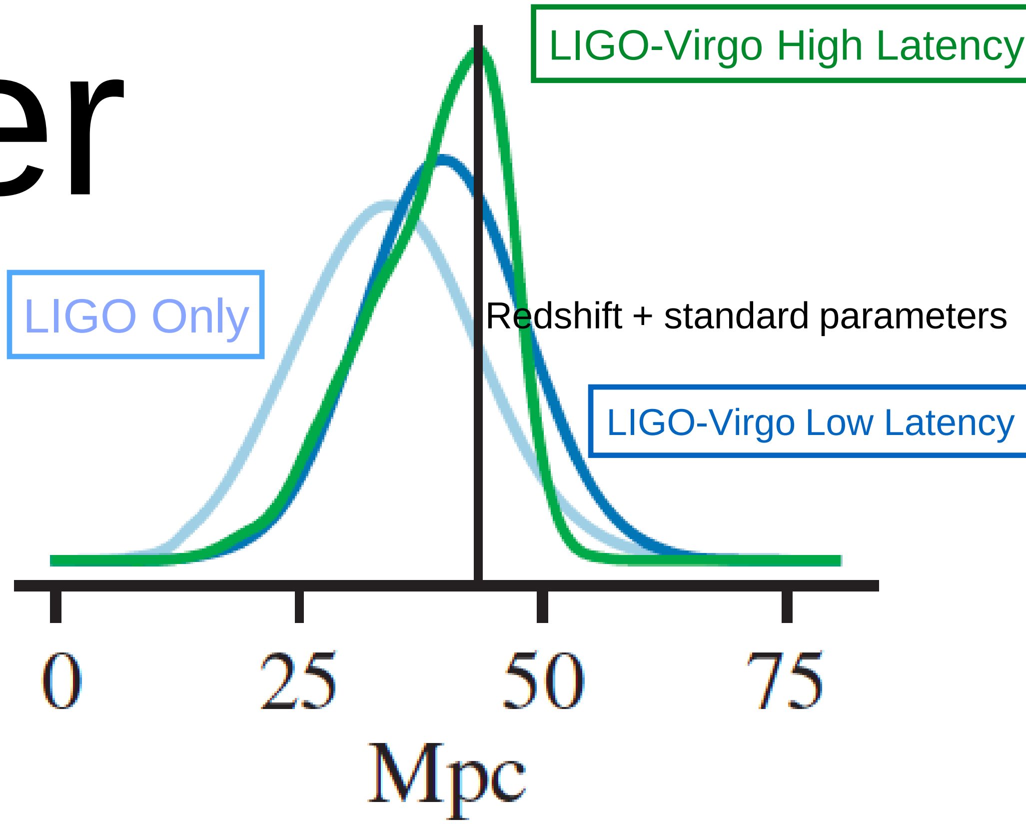
$$\tau = f/\dot{f} = 7.8 m_T^{-2/3} \mu^{-1} f_{100}^{-8/3} \ \mathrm{sec}$$

- Observation will determine τ and h to within 3%

$$r_{100} = 7.8 f_{100}^{-2} (< h_{23} > \tau)^{-1}$$

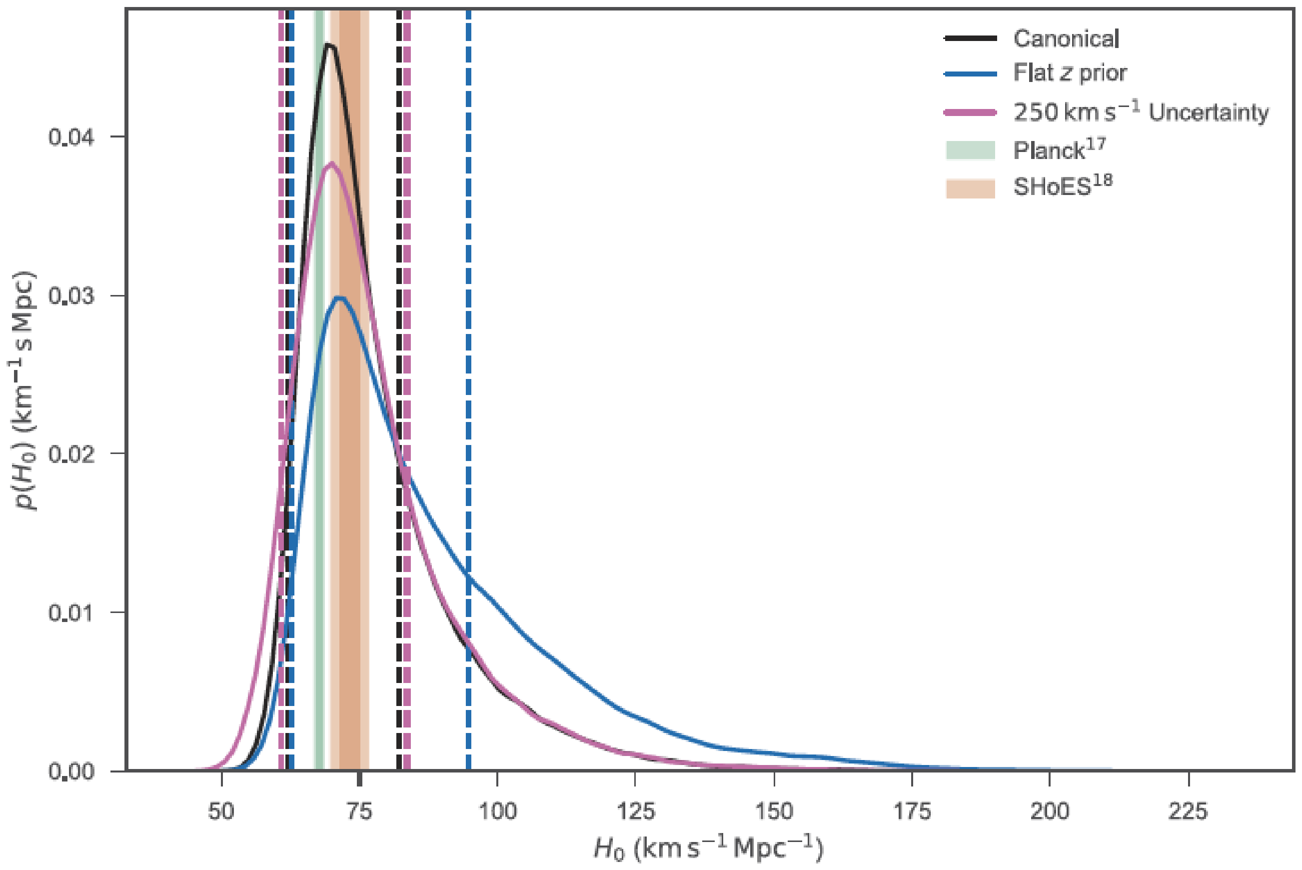
- The distance can be measured without the knowledge of the mass!
- But what we measure is not <*h*> (averaged over the binary's orientation).

Hubble Parameter



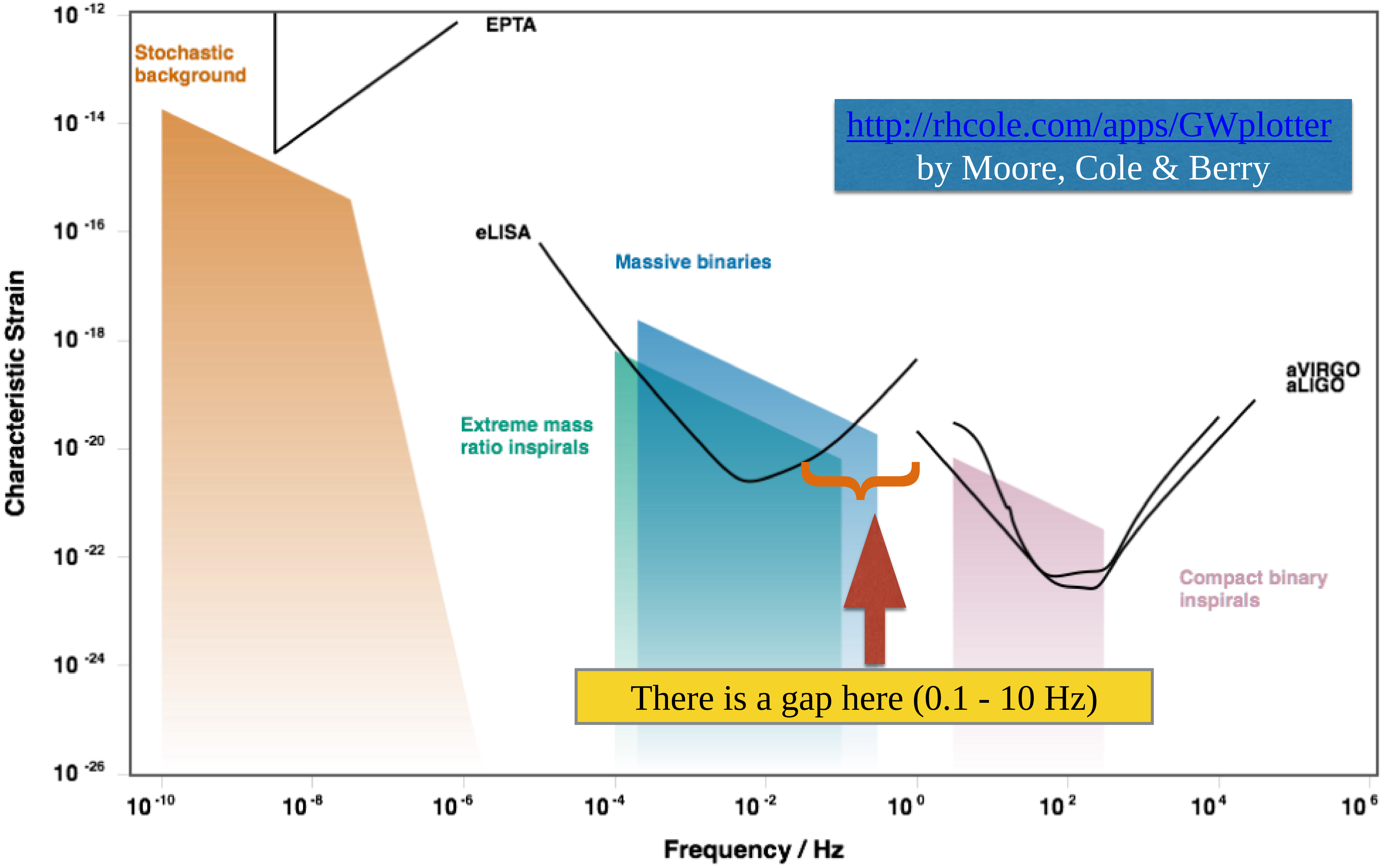
Abbott et al. 2017, PRL, 119, 116101

- 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 host galaxy)
  - $v_r = 3{,}327 \pm 72$ km/sec
  - Peculiar velocity: 310 km/sec toward great attractor
- $H_0 = 70^{+12.0}_{-8.0}$ km/s/Mpc
- Covers range of Planck and SHoES results
  - Accuracy will improve with more detection of binary neutron star merger events



LIGO/Virgo collaboration+, 2017, Nature, 551, 85

Gravitational Waves in Wide Spectral Range



http://rhcole.com/apps/GWplotter
by Moore, Cole & Berry

There is a gap here (0.1 - 10 Hz)

Gravity Gradiometer as a GW Detector

- Geodesic deviation equation: $\frac{d^2x^i}{dt^2} = -R^i_{0j0}x^j$

- In weak field limit

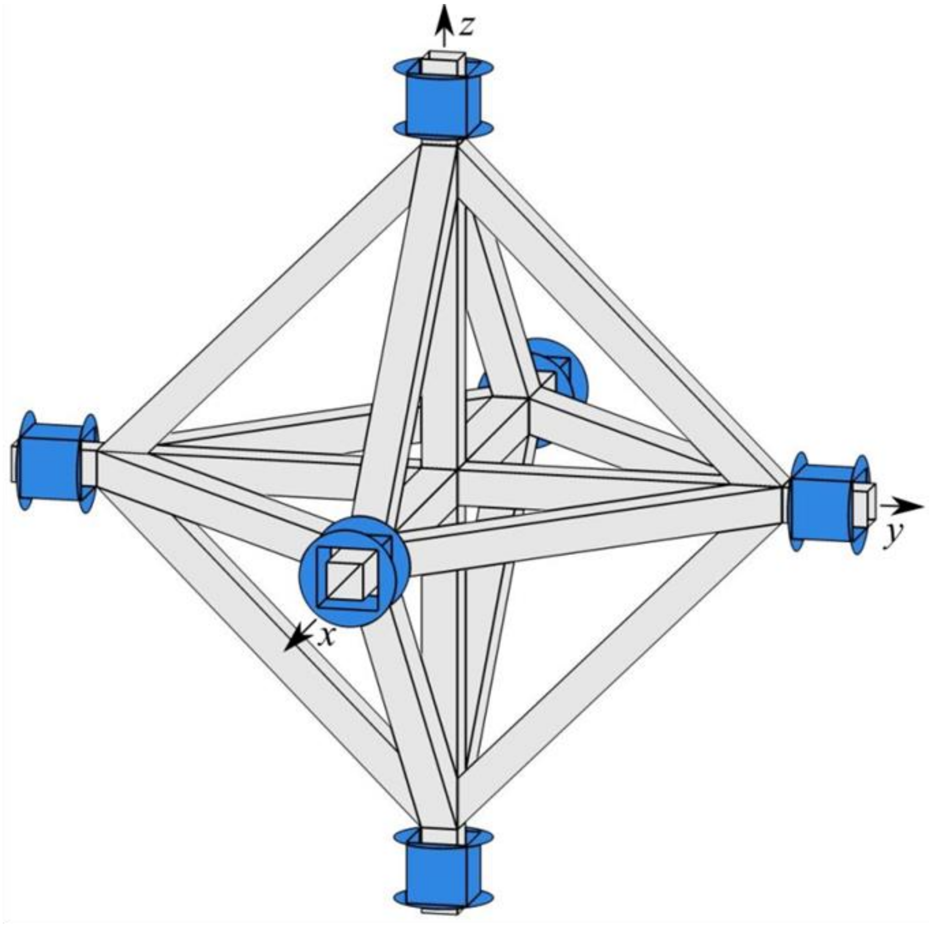
$$R_{i0j0} \approx \frac{\partial^2 \phi}{\partial x^i \partial x^j}$$

- Strain Amplitude

$$R_{i0j0} = -\frac{1}{2}\frac{\partial^2 h_{ij}}{\partial t^2} \approx \frac{1}{2}\omega^2 h_{ij}$$

- Time dependent gravity gradient is the gravitational wave strain.

Superconducting tensor GW Detector (Paik et al. 2016, CQG, 33, 075003)



- Superconducting Omni-directional Gravitational Radiation Observatory (SOGRO)

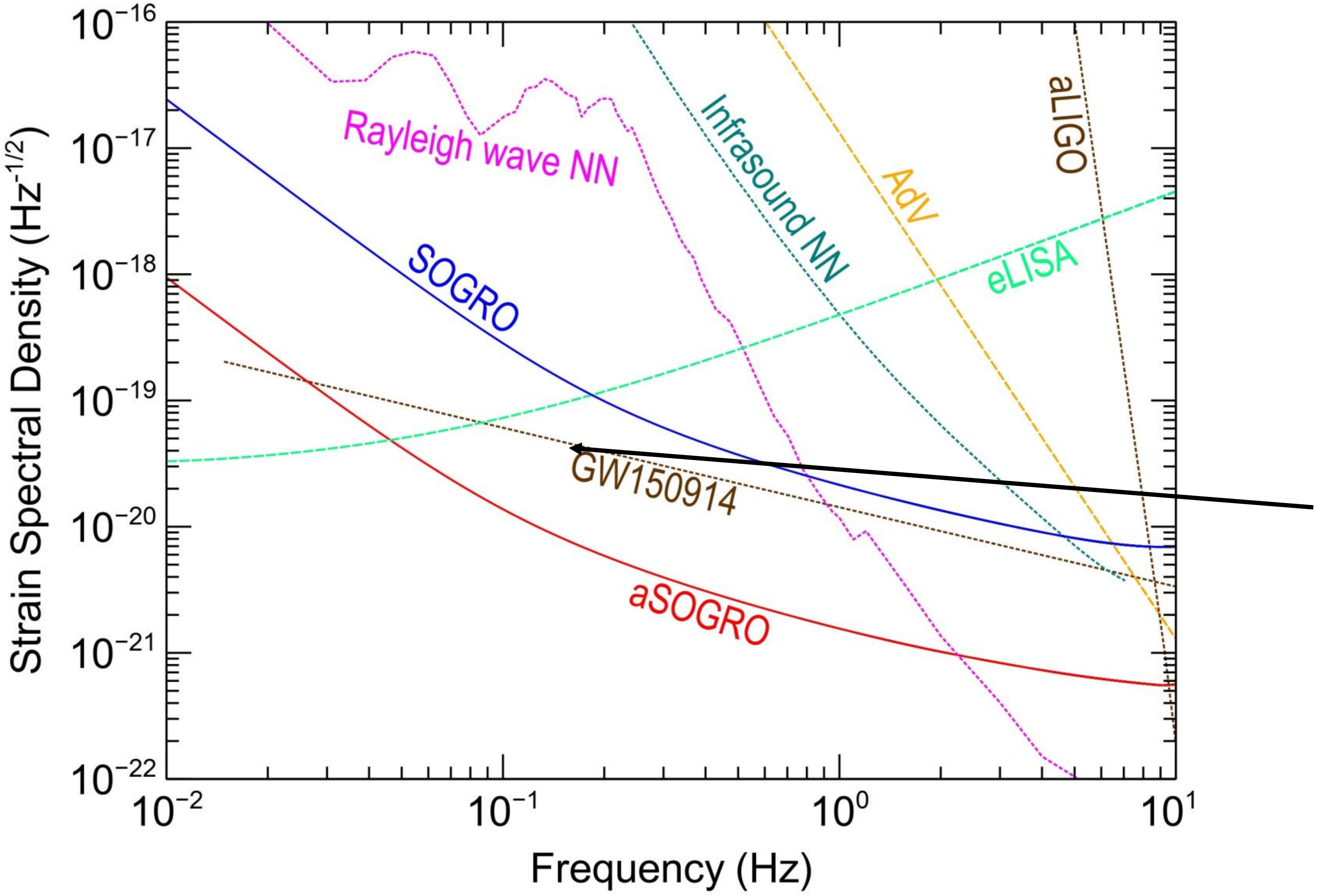
$$h_{ii}(t) = \frac{1}{L}[x_{+ii}(t) - x_{-ii}(t)]$$

$$h_{ij}(t) = \frac{1}{L}\{[x_{+ij}(t) - x_{-ij}(t)] - [x_{-ji}(t) - x_{+ji}(t)]\}$$

- By detecting all six components of Riemann tensor, the source direction and the polarization can be determined.

- Newtonian noises could be modeled and subtracted from the signal

Predicted SOGRO Sensitivity Curves

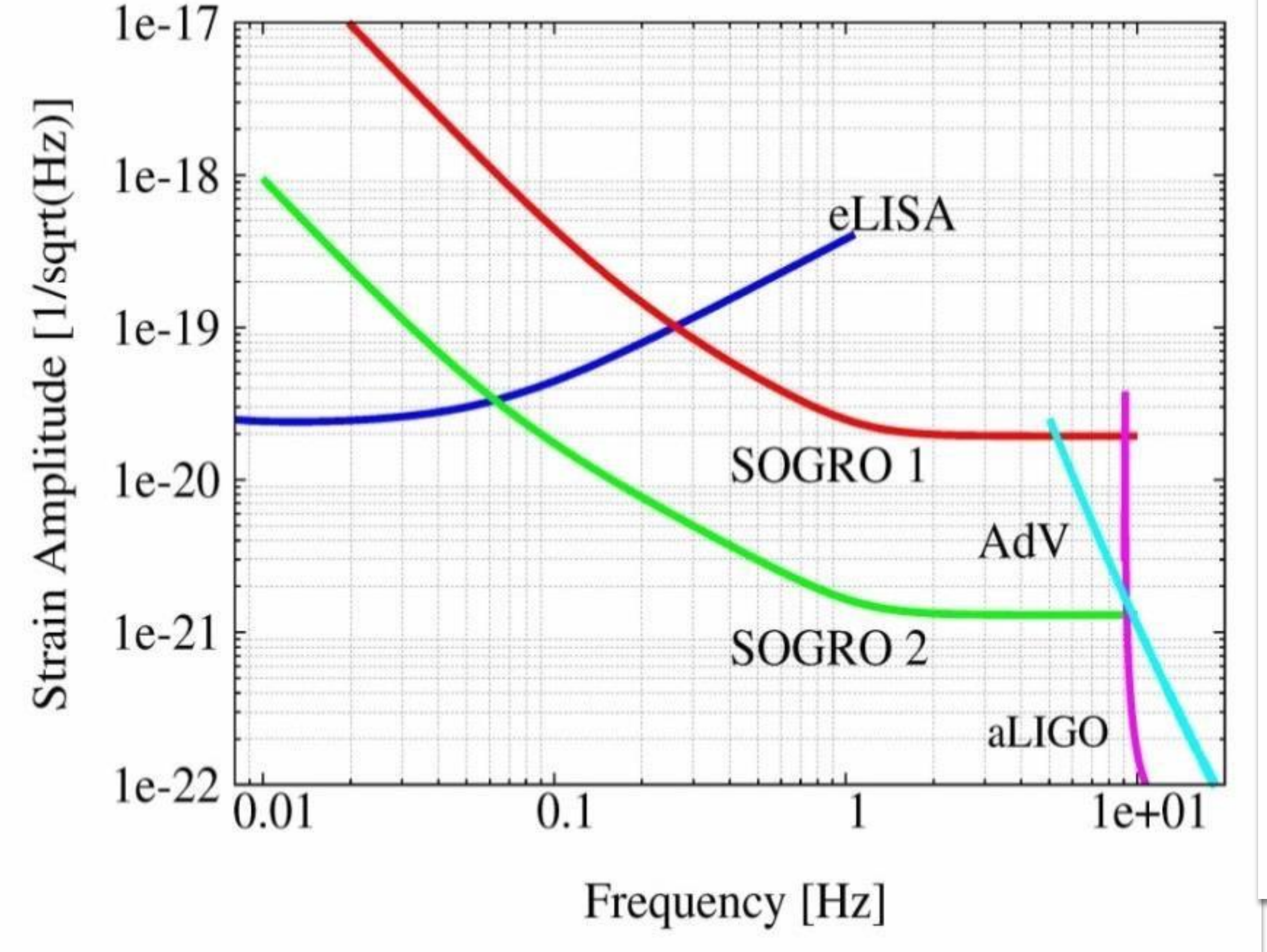


~1 week before September 14, 2015

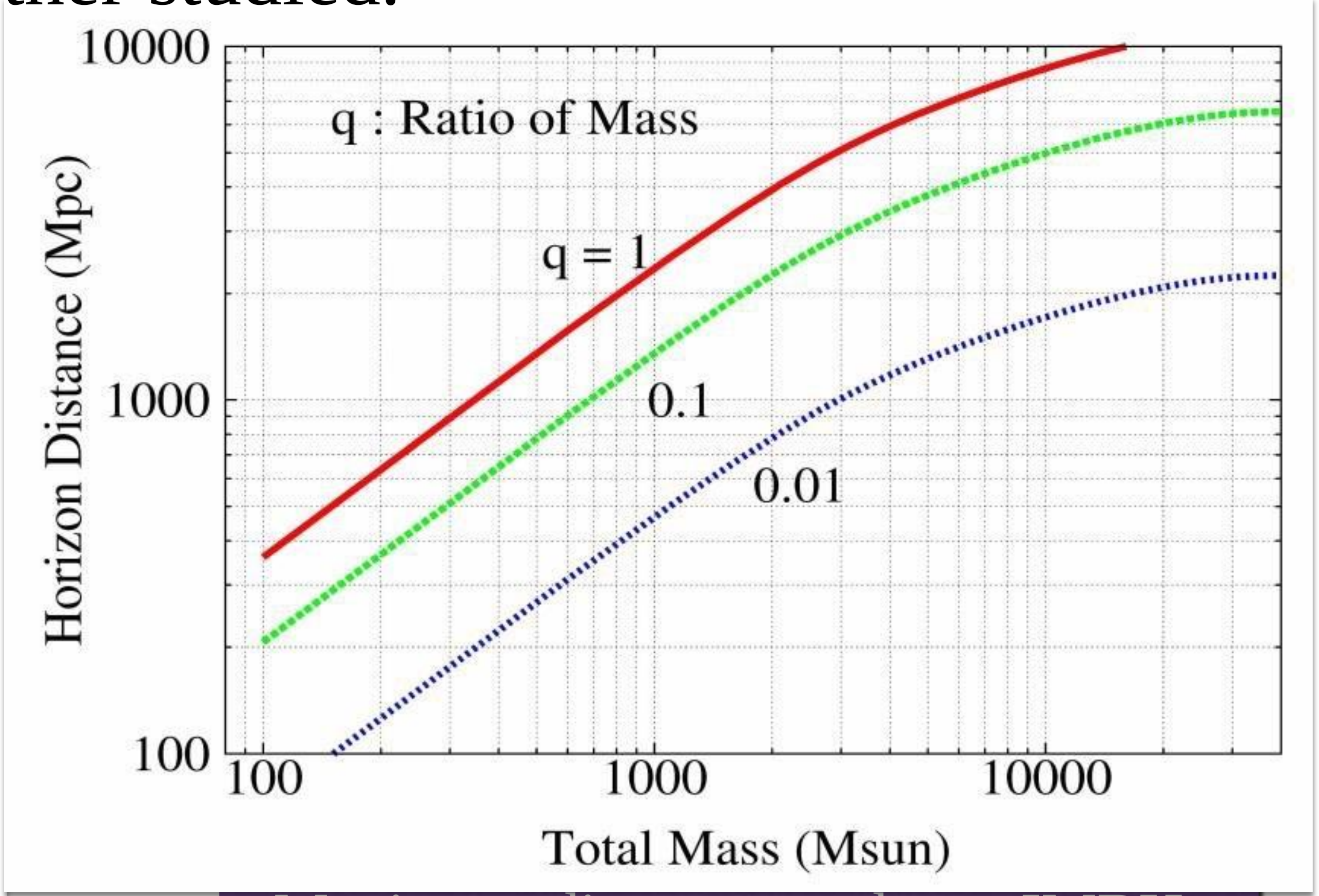
Paik et al. 2016

Benefit of SOGRO

- SOGRO would fill in the missing signal band between eLISA and aLIGO/Virgo/KAGRA, 0.1 – 10 Hz.
- SOGRO is a tensor detector with all-sky coverage and with the ability to locate the source and determine wave polarization.
- SOGRO, a full-tensor detector, has an advantage in rejecting NN.
- Technical details have to be further studied.



Paik et al. 2016, 30m and 100m baseline



Maximum distances to detect IMBH-IMBH binary merger (SOGRO 2)

Summary

- LIGO has opened up a new area of gravitational wave astronomy.
    - 5~6 black hole binaries and one NS Binary
    - More events will be detected in upcoming O3 (~2019) and O4.
        - Population studies of compact stars, H_0 measurements, neutron star equation of state, black hole spins, …
- Next steps are
    - Better sensitivity in high frequencies (100 ~ 1000 Hz): more detectors (KAGRA, LIGO India), and upgrade of LIGO
    - Low frequency detectors: eLISA (0.1 ~ 10 mHz)
    - Mid-frequency (0.1~1 Hz): several proposals including one from Korea