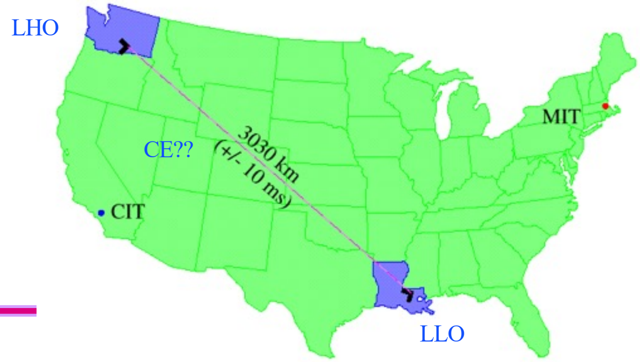


Study of Gravitational Wave by LIGO : Past, Present and Future

Hiroaki Yamamoto / LIGO Lab, Caltech

The 15th International Workshop on Fundamental Physics Using Atoms

FPUA2024 March 15, 2024

Image Credit: Gabriele Vajente

Topics

- Two epoch events
  - » Merger of back hole and neutron star pairs
- Basic of Gra
  - » Signals and
- Long path t
  - » Overcoming
    - – parametr
  - » Attacking th ezed field

1 parsec = 3.26 light year

= 3.09×10^{16} m

Milky way = 30 kpc

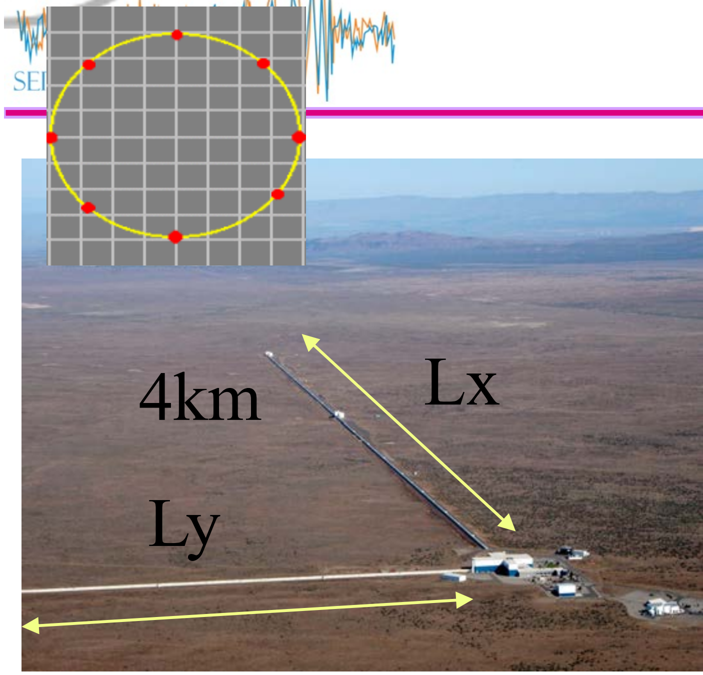
$1M_{\odot} = 2 \times 10^{30}$ kg

- Dawn of Multimessenger astronomy
  - » Gravitational wave and Electromagnetic (EM) wave observatories
- Short and long term plans
  - » 2^{nd} to 2.5 to 3^{rd} generation interferometers

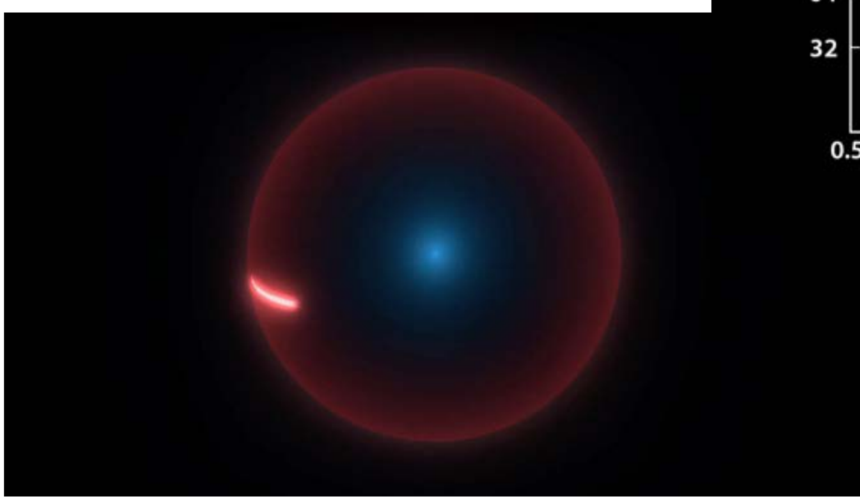
GW150914 : Merger of Black holes

on September 14, 2015

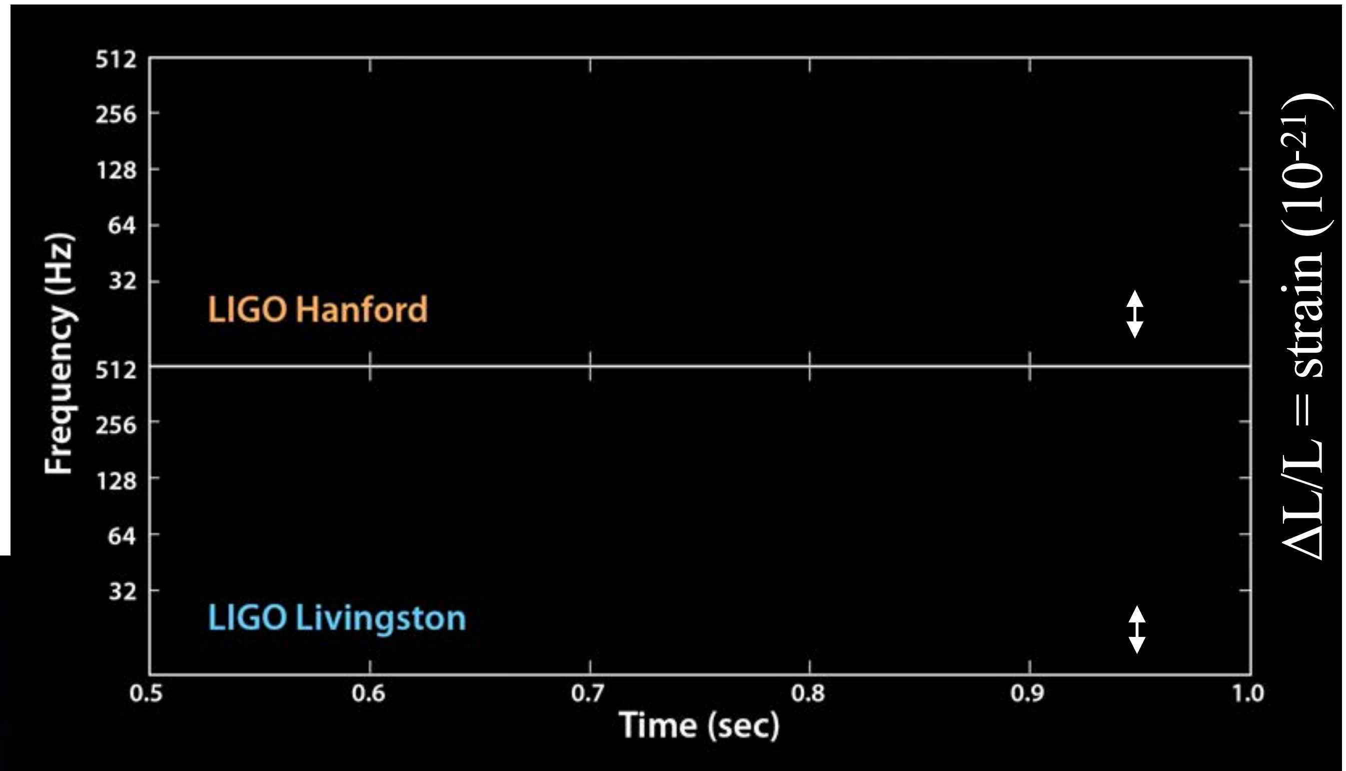
PRL 116, 061102 (2016)



$4x10^{-18}$m / 4km = 10^{-21}, H atom on Sun



Gravitational wave signal : frequency and strain

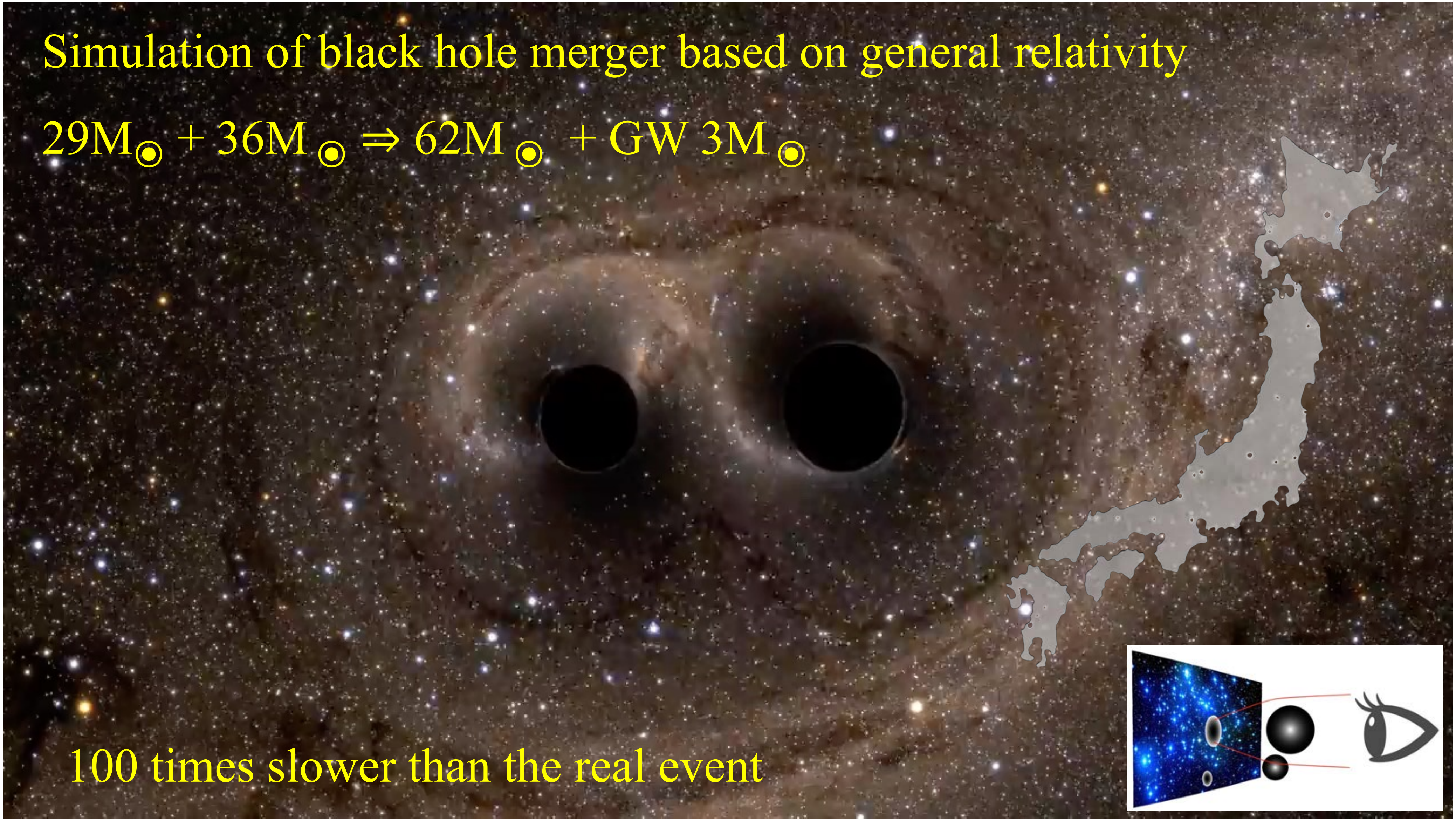


First, a signal was detected at Livingston, and 7ms later, a signal with same shape was observed at Hanford.

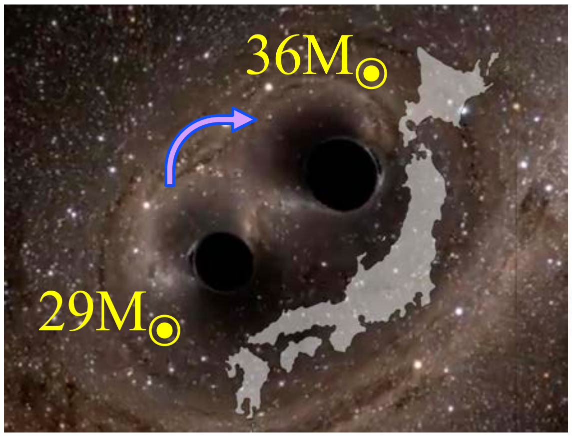
SEPTEMBER 14, 2015

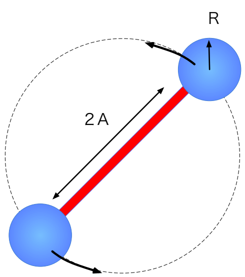
What happened long long time ago

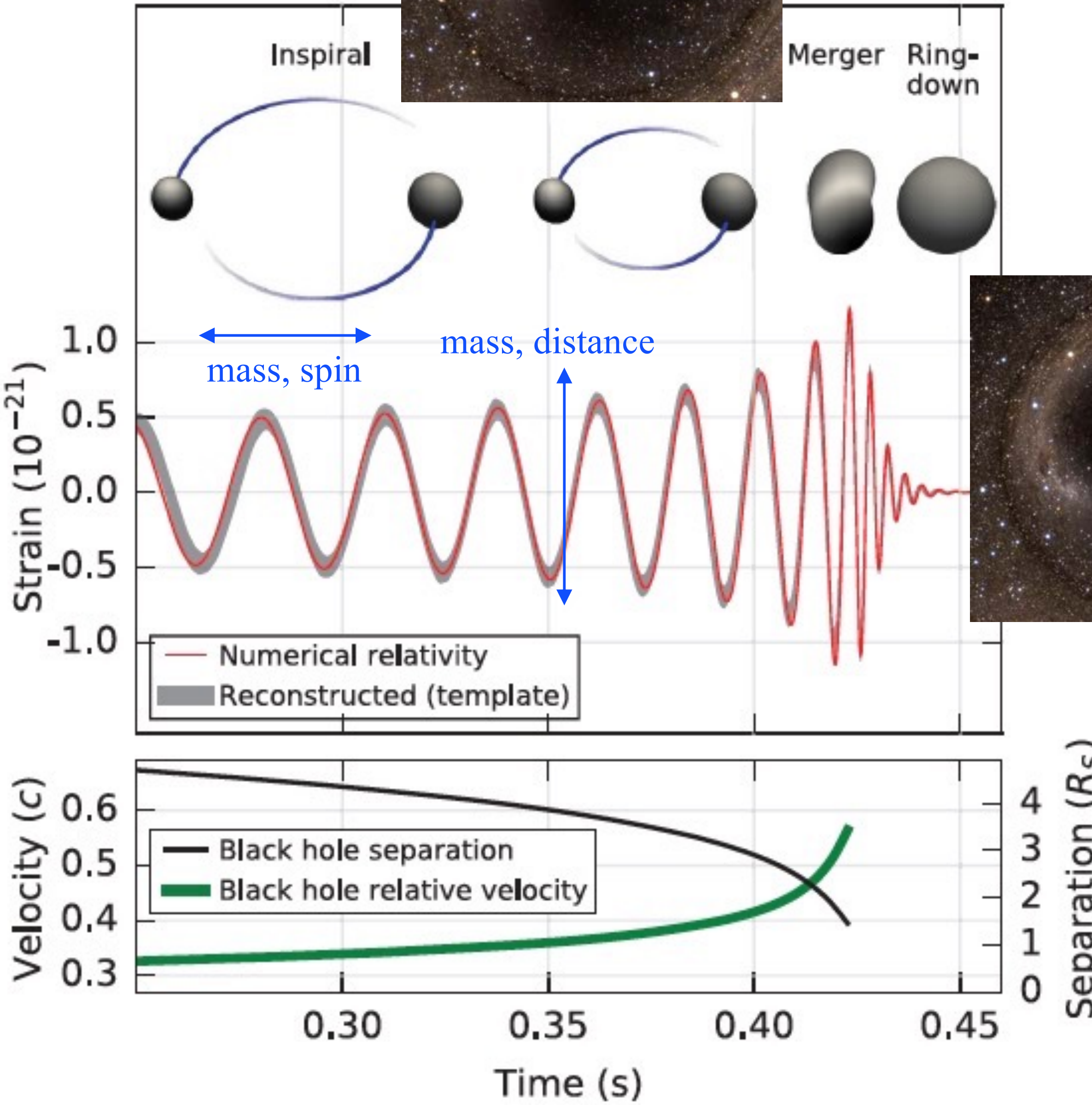
- 1.3 billion light year or 12000000000000000000000 km away -

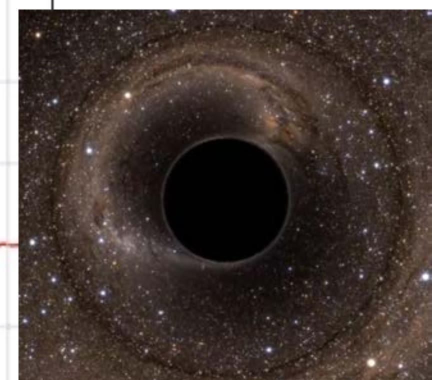


Black Hole Merger









800km

$R_S = \frac{2GM}{c^2}$ ~90km

speed = A 2π f < c

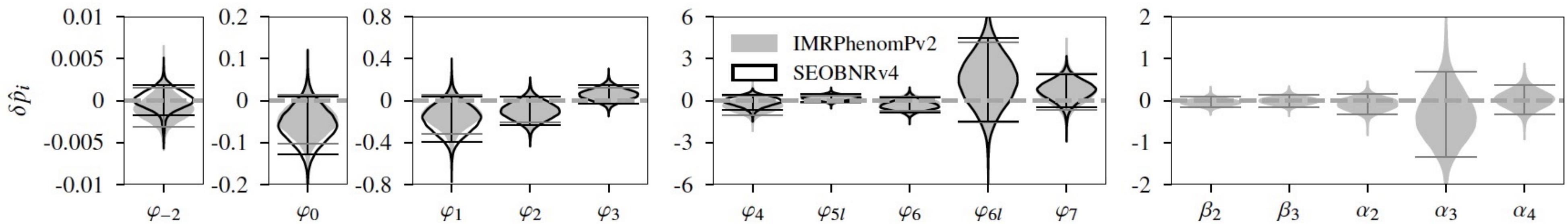
A < c / 2π f ~ 500km

LIGO-2400461

GW from Binary Back Hole merger

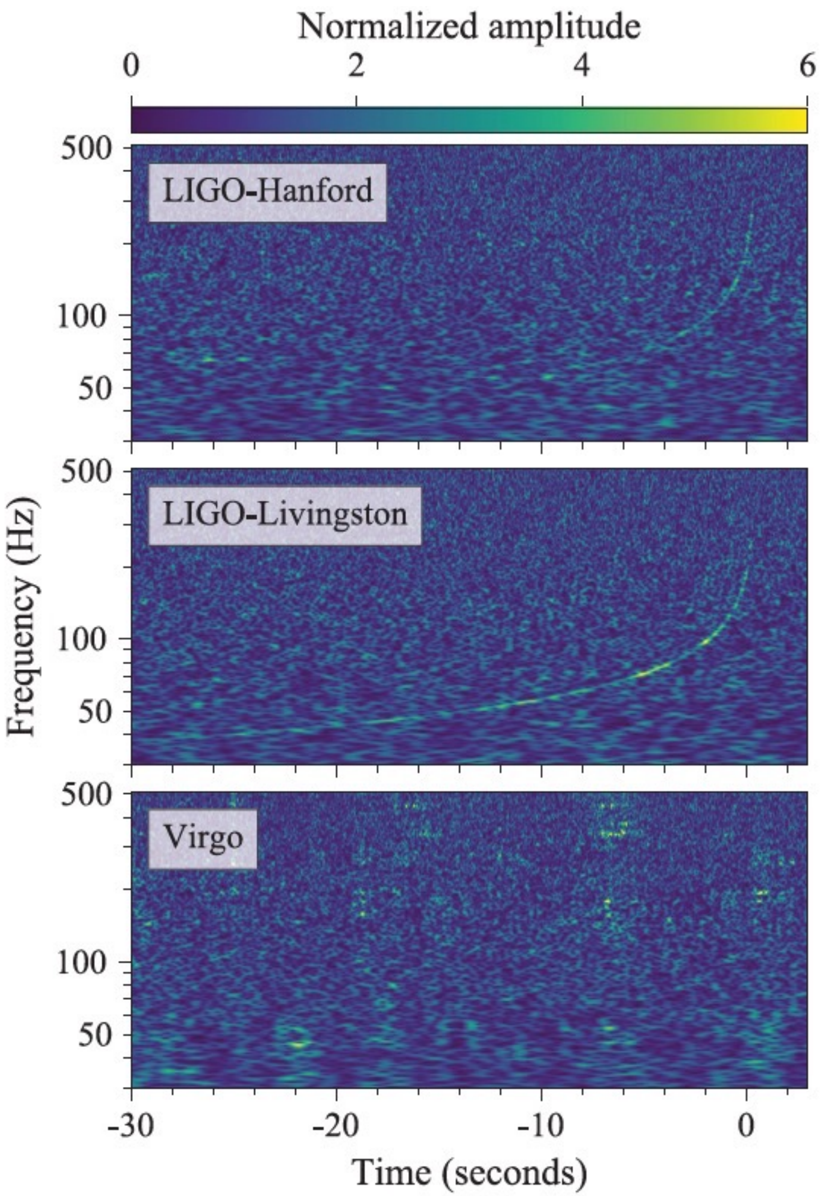
O1/O2 arXiv:1811.12907, arXiv:1903.04467, O3 arXiv:2010.14529

- First direct detection of gravitational wave signals
- First observation of stellar mass black holes above 25M⊙, now up to 150M⊙
- First observation of a binary black hole (BBH) system and merger
  - » BBH merger rate O1/O2 : 9.7-101 Gpc^{-3} yr^{-1} to O3 : 15.3-38.8 Gpc^{-3} yr^{-1}
- Test of General Relativity in strong field:
  - » "In conclusion, within our statistical uncertainties, we find no evidence for violations of general relativity in the genuinely strong-field regime of gravity." PRL 116, 221101 (2016)
  - » Graviton mass upper limit : O1/O2:$5x10^{-23}$ eV/c^2, O3:$1.76x10^{-23}$ eV/c^2
  - » No violation of general relativity

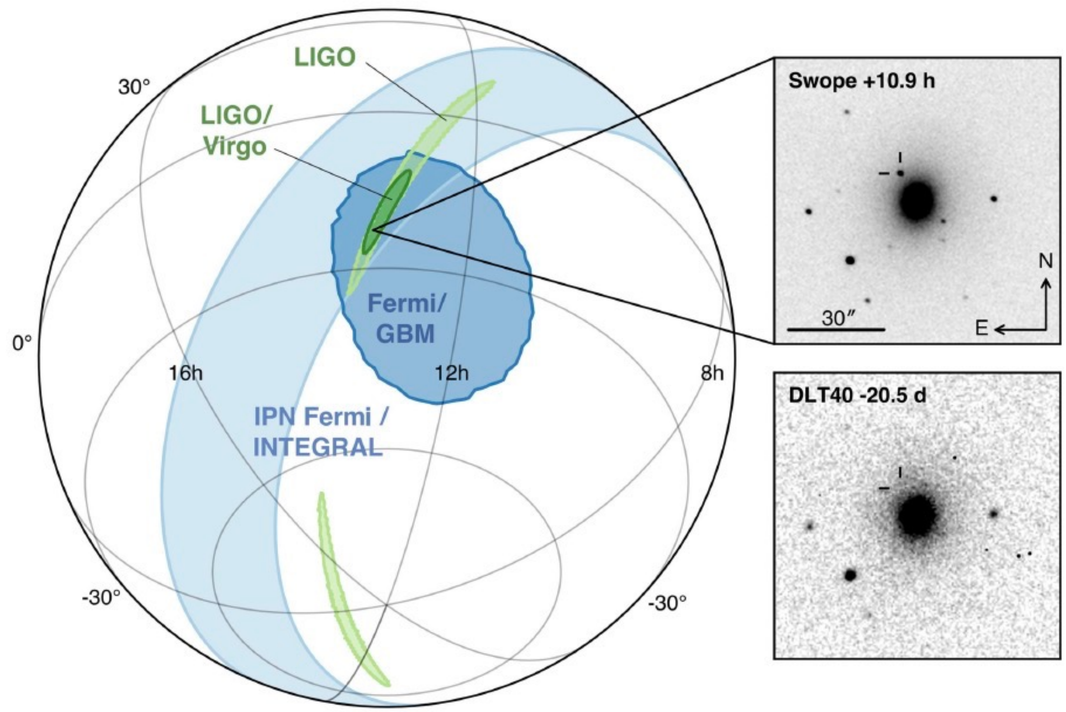


GW170817 : Merger of neutron stars

PRL 119, 161101 (2017), Astrophys. J. Lett. 848, L12 (2017)

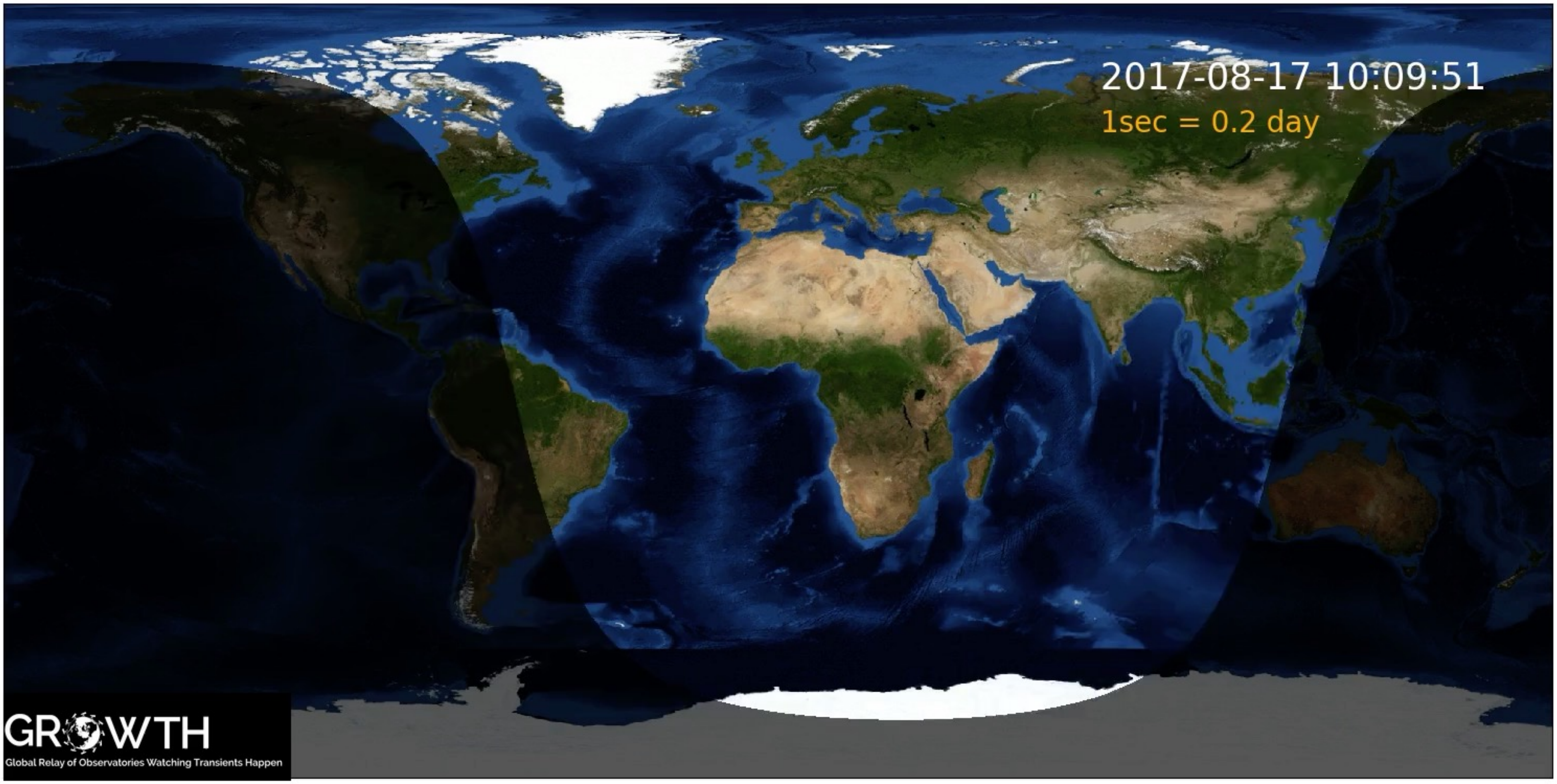


190 deg^2 (L,H) →31 deg^2 (L,H,V)



GW170817 and Electromagnetic observatories

Credit : Pavan Hebbar, Varun Bhalerao (IIT-B), David Kaplan (UW Milwaukee), Mansi Kasliwal (Caltech) and the GROWTH collaboration.



Simulation of merger of neutron star pair

Jets and Debris from Neutron Star Collision

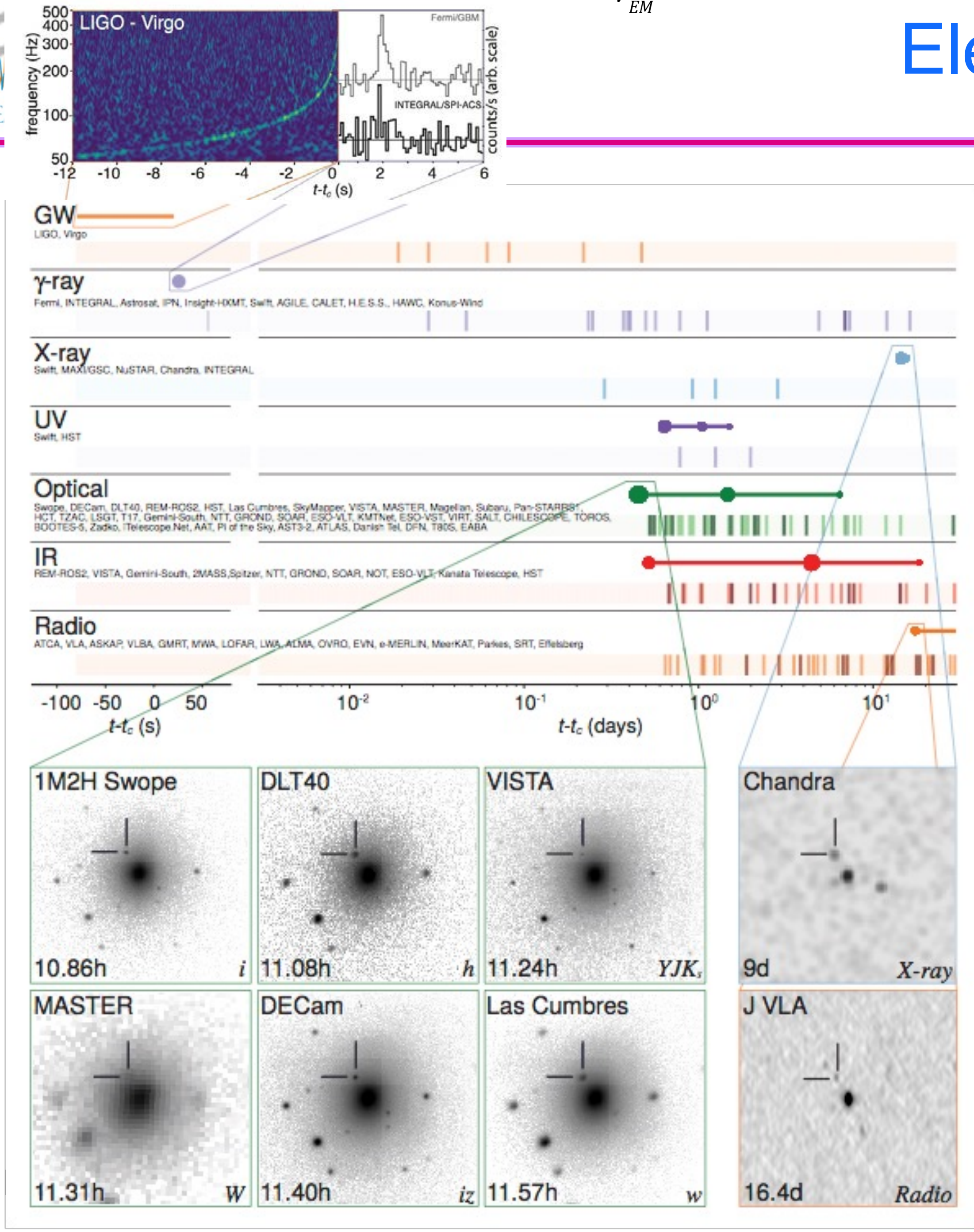
This animation captures phenomena observed over the course of nine days following the neutron star merger known as GW170817. They include gravitational waves (pale arcs); a near-light-speed jet that produced gamma rays (magenta); expanding debris from a "kilonova" that produced ultraviolet (violet), optical and infrared (blue-white to red) emission; and, once the jet directed toward us expanded into our view from Earth, X-rays (blue).

Credit: NASA's Goddard Space Flight Center/CI Lab

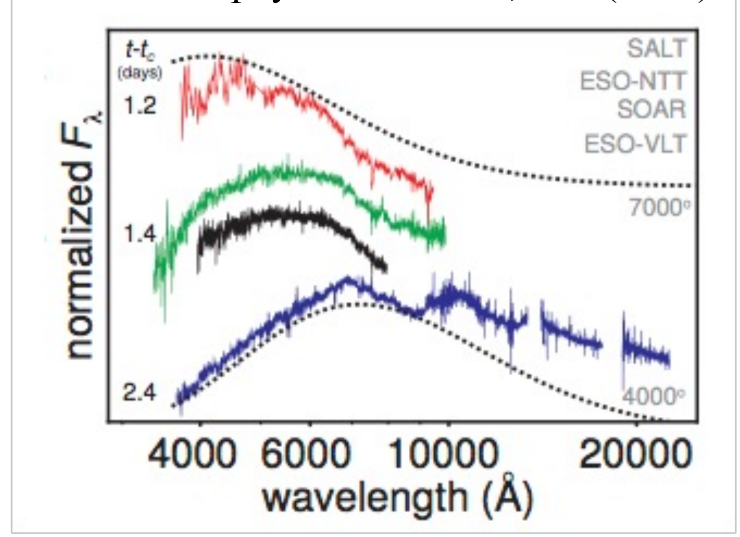
GW170817+GRB170817A Electromagnetic follow-up

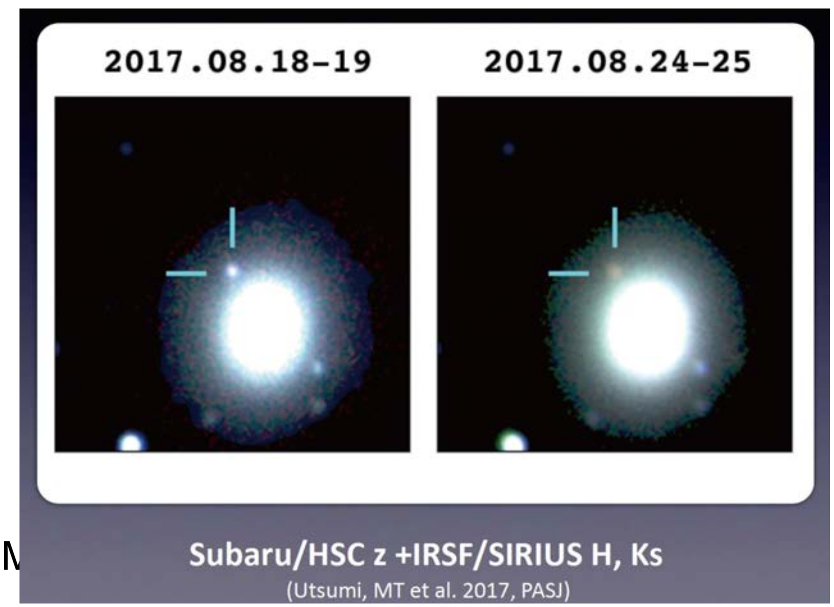
1.734 ± 0.054 seconds

$$-3\cdot10^{-15} < \frac{v_{GW}-v_{EM}}{v_{EM}} < +7\cdot10^{-16}$$



Astrophys. J. Lett. 848, L12 (2017)





GW and EM signals from Binary Neutron Star (BNS) merger

Dawn of Multimessenger astronomy

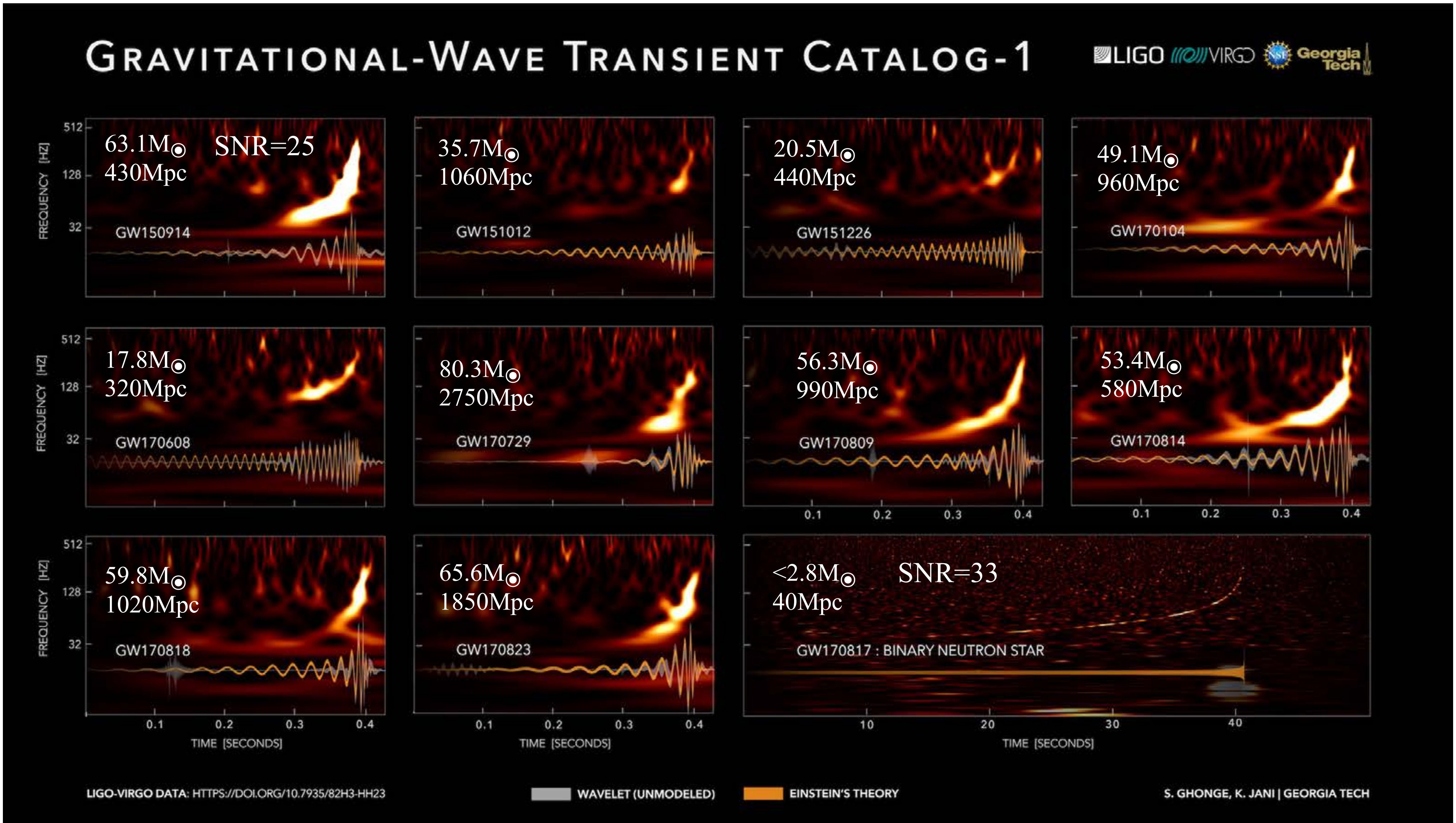
(Astrophys. J. Lett. 848, L13 (2017), arXiv:1811.12907)

BNS (GW170817+GRB170817A)

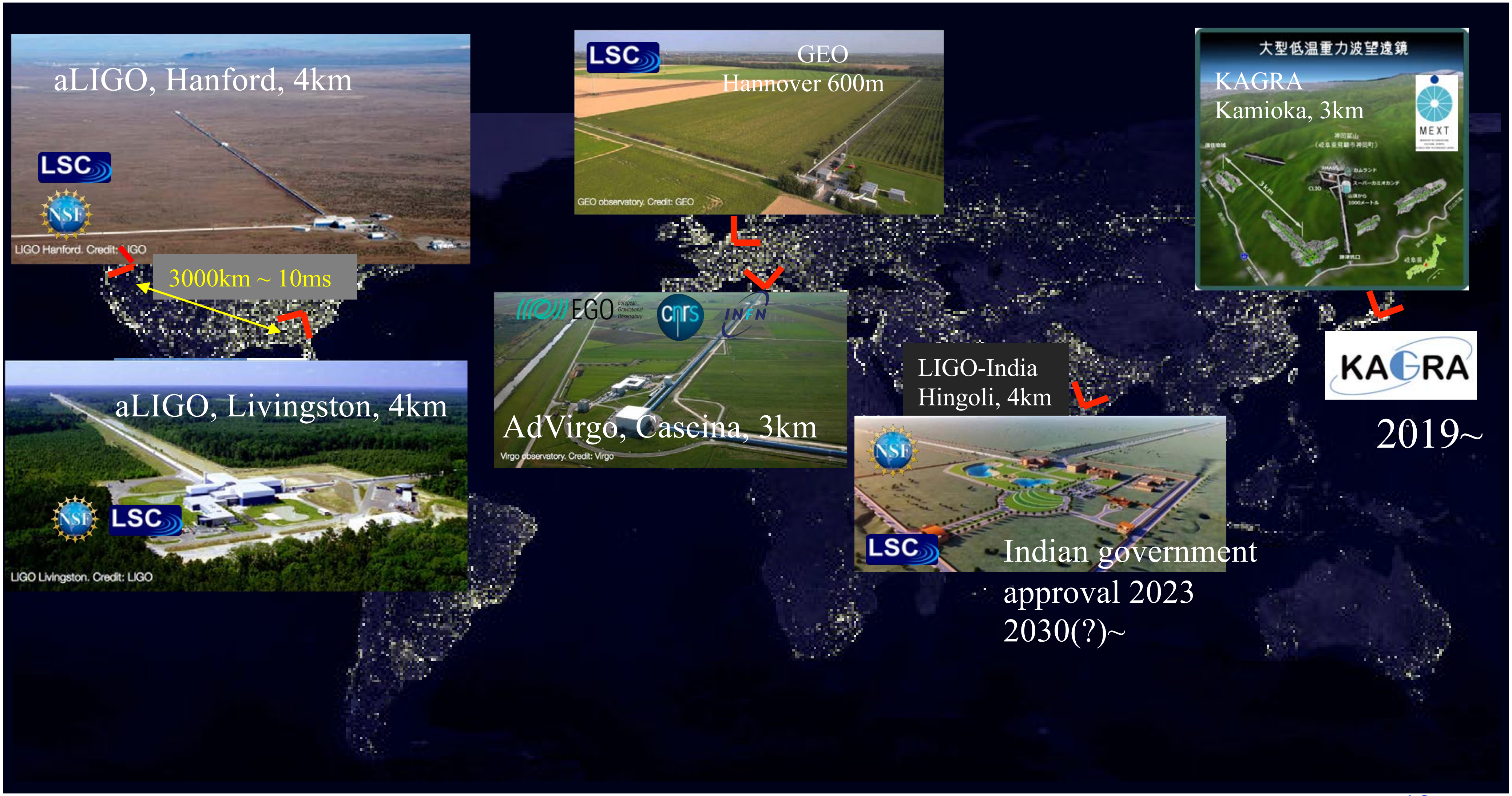
- Confirmation of association between short GRBs (gamma-ray burst) and BNS mergers, and new insights into physics of GRB events.
- BNS merger rate : 110-3840 Gpc^{-3} y^{-1} (vs BBH: 9.7 – 101 Gpc^{-3} y^{-1})
- Limits on dynamical ejecta in the associated kilonova, explosion cause by two colliding neutron starts.
- BNS mergers as producers of heavy elements confirmed.
- Independent measurement of the Hubble constant consistent with prior measurements.
- Test of general relativity
  - » GW signal is consistent with GR over thousands of cycles
  - » GW polarization is consistent with tensorial
  - » Speed of gravity is consistent with speed of light to one part in 10^{-15}

Different signature of Black hole and Neutron start merger

heavy → strong, short

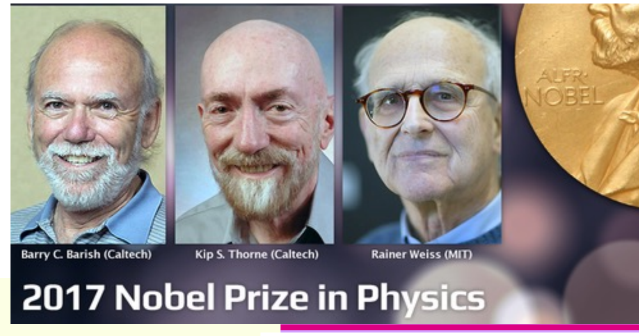


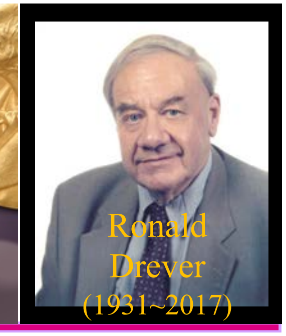
Advanced LIGO, H1 & L1 in the International GW Network




Vogt

LIGO History





- Long prelude : 1965 ~
  - » Developing the GW interferometer concept
  - » Understanding noises – seismic, thermal, shot, gas…
  - » Unifying efforts to build LIGO (CIT/MIT/NSF)
- Real size R&D : 1994 ~
  - » Building initial LIGO for the real size R&D
  - » Organizing LIGO Scientific Collaboration
  - » Operating initial LIGO at design sensitivity for one year
- Toward detection : 2008 ~
  - » Building advanced LIGO for the GW signal detection
    - – aLIGO = LIGO Lab + GEO (Glasgow, Hannover) + Australia
  - » O1/O2 observation runs from 2015 Sept, one signal / month
    - – Detection of the first GW signal from BBH(O1) and BNS(O2)
  - » O3 started April 1, 2019, one signal / 1.5 week
    - – Public announcement of candidates via network
  - » O4a May 24, 2023 ~ Jan. 16, 2024, one signal/a few days
    - – Qualitative to quantitative
- 3rd generation upgrade : 2025 ~
  - » Building observatories for astronomy and cosmology

Rai Weiss(MIT)

Ron Drever (Glasgow→CIT)

Kip Thorn(CIT)

40m at CIT

"Blue Book" by Weiss and …

1989 LIGO Proposal by Vogt and…

Barry Barish (CIT, SSC → LIGO)

--- 1st generation ---

Power Recycled Fabry-Perot (FP) Michelson

Single suspension

10W 1μ laser

--- 2nd generation ---

Dual Recycled FP Michelson

with stable recycling cavities

Quadruple suspensions

25~120W 1μ laser

--- 2.5th generation ---

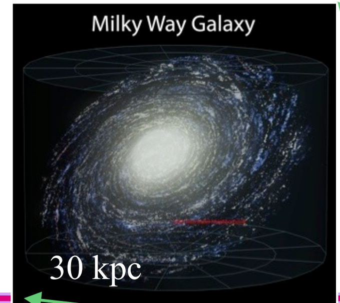
Squeezing – frequency independent to frequency dependent

Better coating to reduced thermal noise

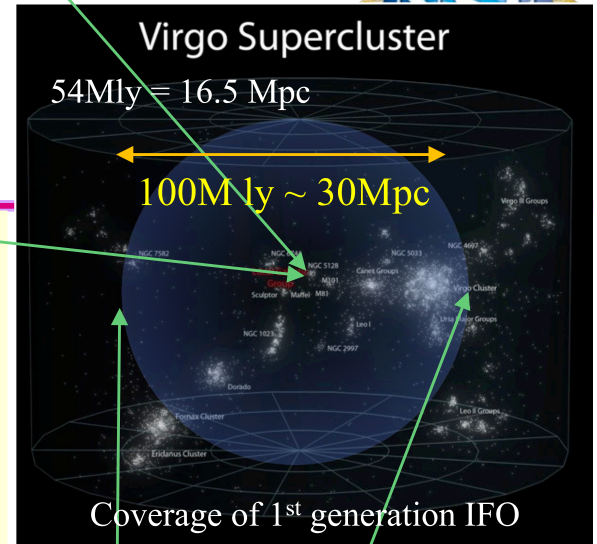
Cryogenic, 2μ laser, Silicon, …

Sensitivity and significance or how far can we hear

Phys. Rev. X 6, 041015 (2016)



courtesy of M.Evans



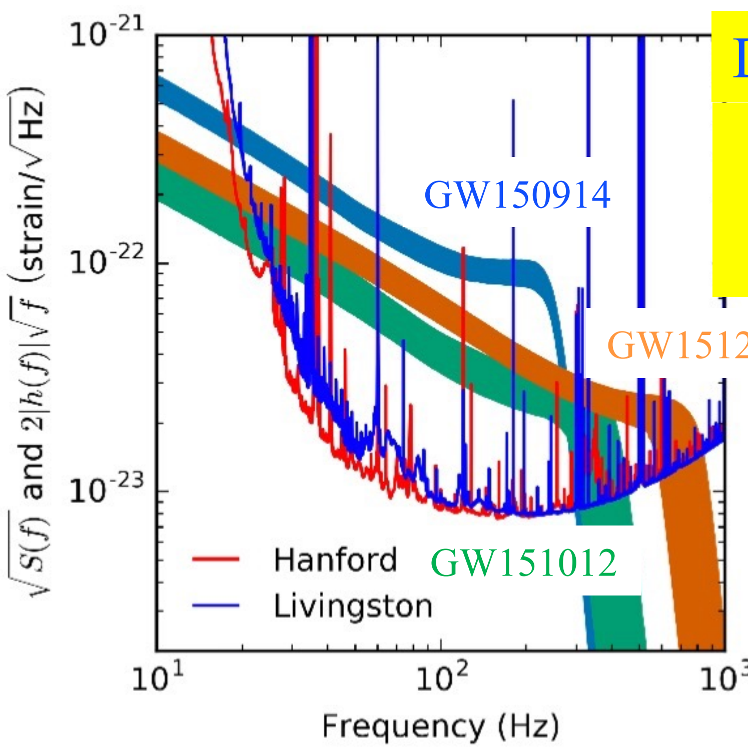
1pc=3.26 light year

Event rate ~ r^3

Strain ~ $10^{-20} \frac{E}{M_\odot} \frac{10Mpc}{r}$

M(BBH) ~ 10 M(BNS)

#BNS ~ 10 x #BBH

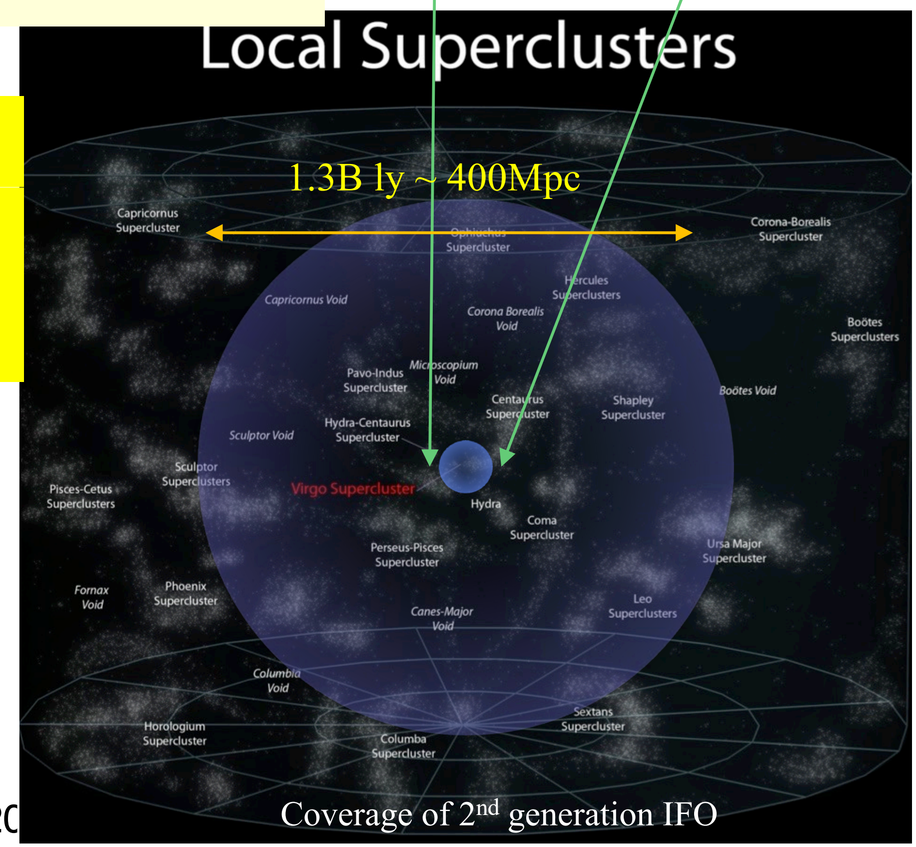


Detection range

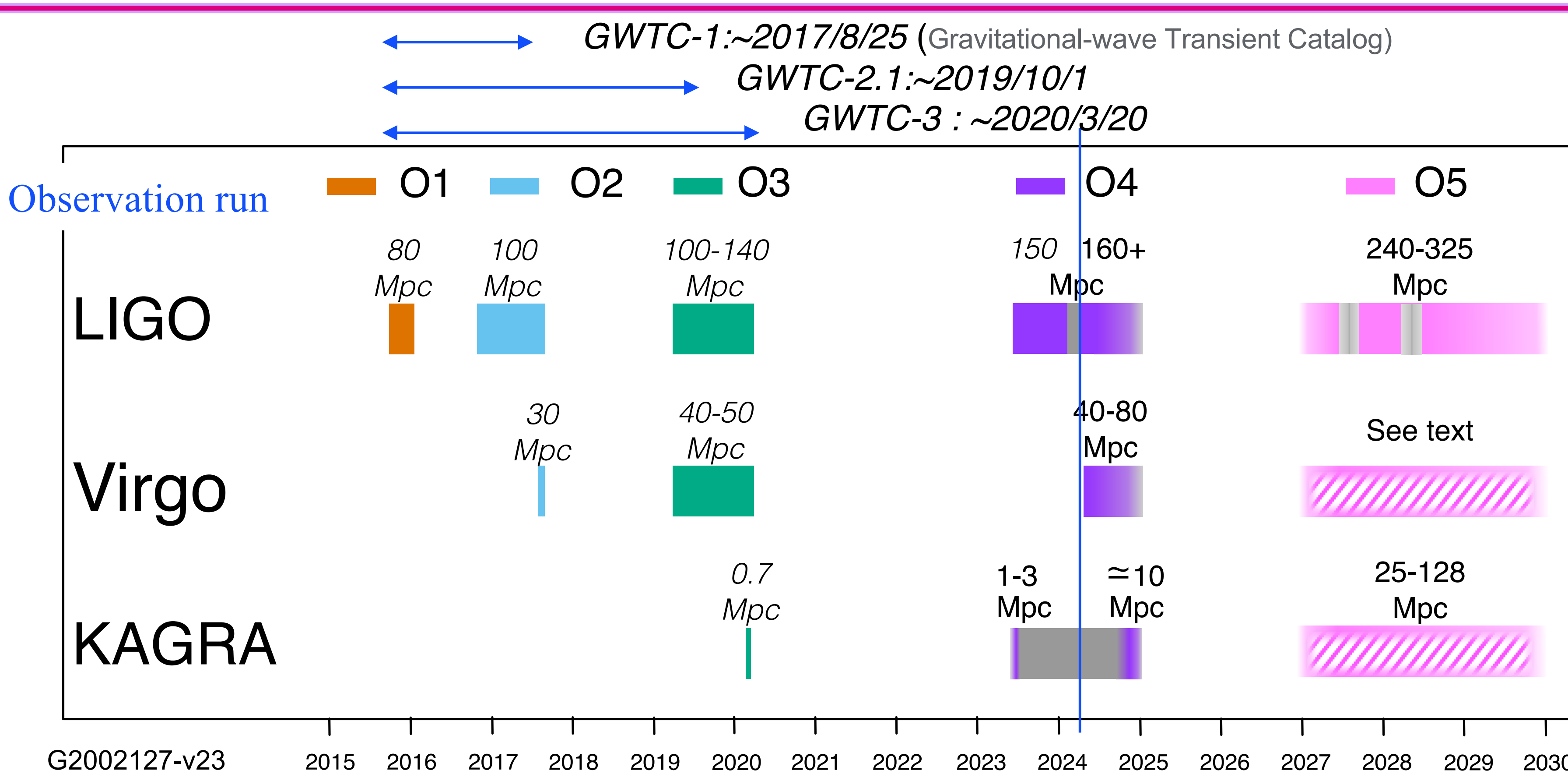
BNS merger

1.4 – 1.4$M_\odot$

SNR>8



Current status

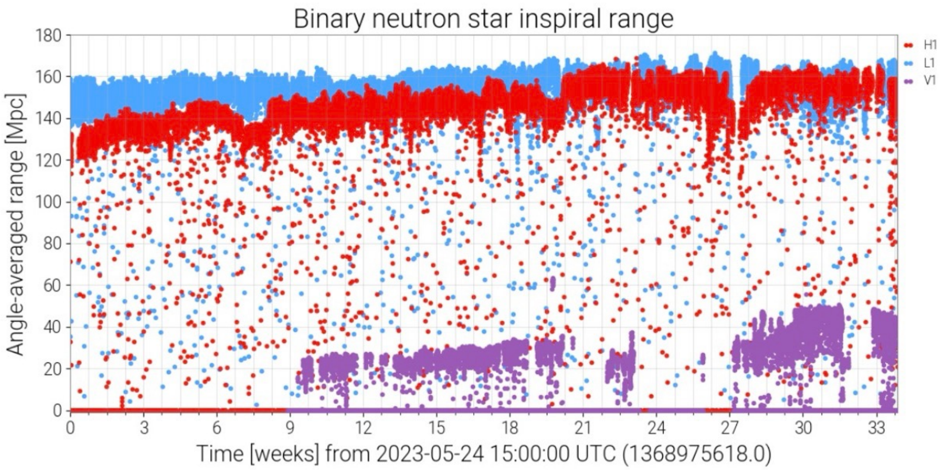


BNS (Binary Neutron Star) mergers are a well-studied class of gravitational-wave signals, this figure gives the BNS range for for a single-detector SNR threshold of 8 in each observing run.

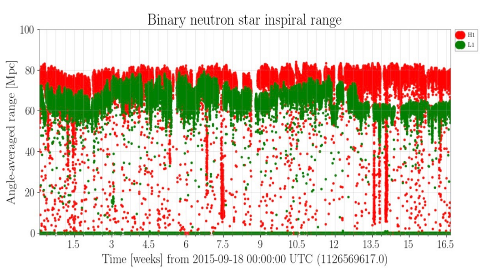
https://dcc.ligo.org/LIGO-P1200087/public

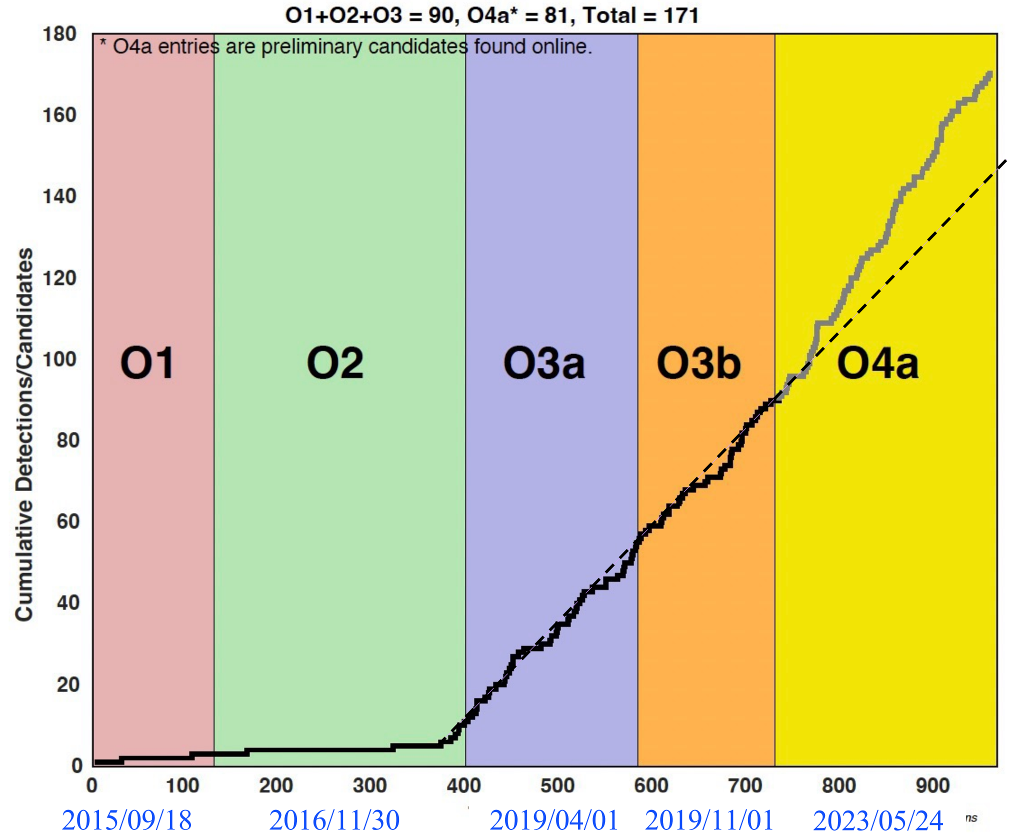
Results of LIGO observation runs

https://ldas-jobs.ligo.caltech.edu/~detchar/summary/O4a/



https://ldas-jobs.ligo.caltech.edu/~detchar/summary/O1/



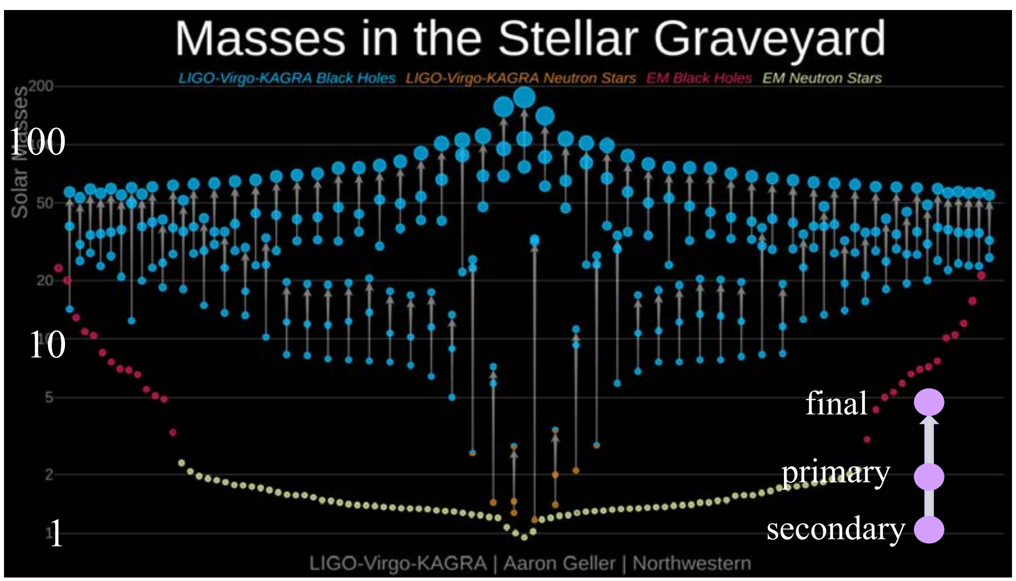


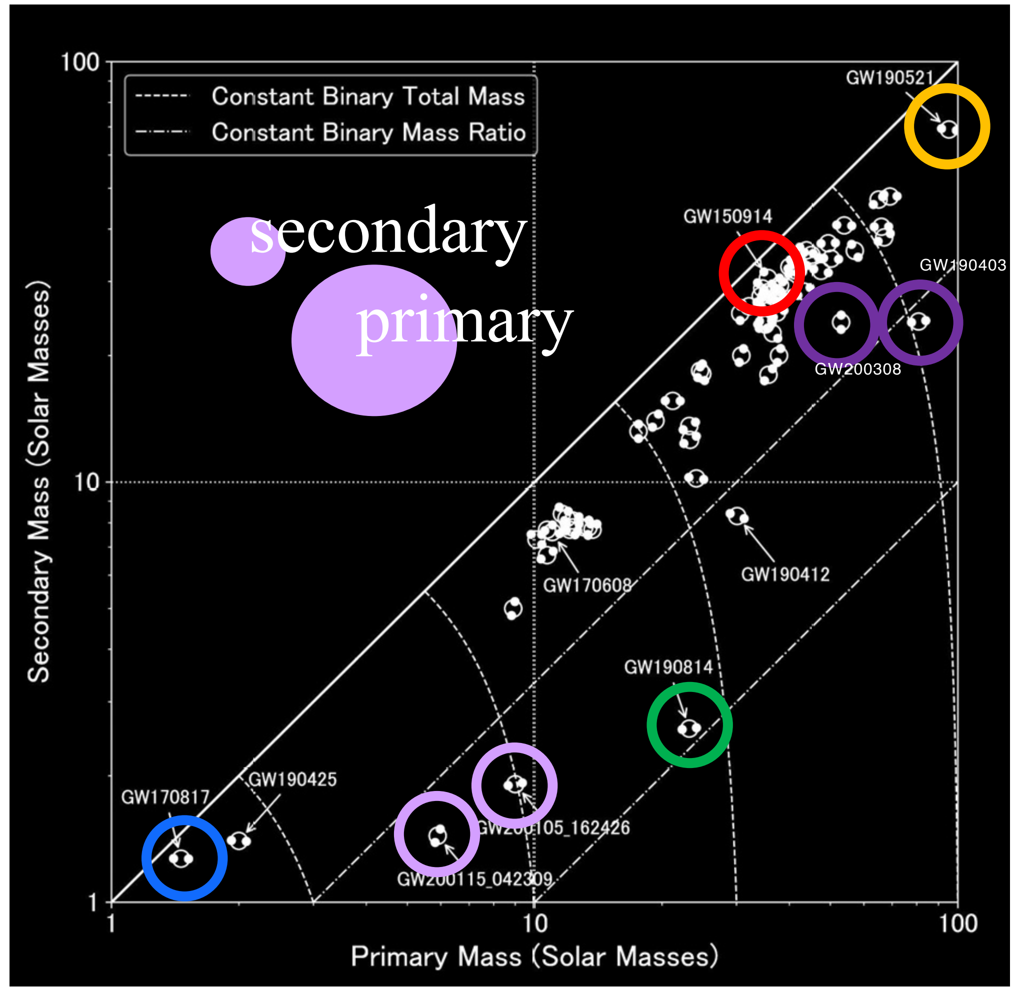
LIGO-G2400279-v2 by J.Giame

Detections (~O3)

P. Brady: https://dcc.ligo.org/LIGO-G2302128/public

- GW150914 (BBH, $35M_\odot+30M_\odot \Rightarrow 62M_\odot$, 0.47Gpc)
  - First astrophysical source
  - First binary black holes
- GW170817 (BNS, 40Mpc)
  - Binary neutron star mergers are gamma-ray burst progenitors
- GW190521 (BBH, $85M_\odot+66M_\odot \Rightarrow 142M_\odot$,5.3Gpc)
  - Black holes exist in pair instability mass gap
- GW190814 (BH-?, 241Mpc)
  - Compact objects exist with masses between 2-5 $M_\odot$
- GW200105 (BH-NS, 280Mpc), GW200115 (BH-NS, 300Mpc)
  - collisions between a black hole and a neutron star
- GW190403 (BBH, 8.28Gpc, z~1.18) GW200308 (BBH, 7.1Gpc, z~1.04)
  - Furthest GW source, z > 1





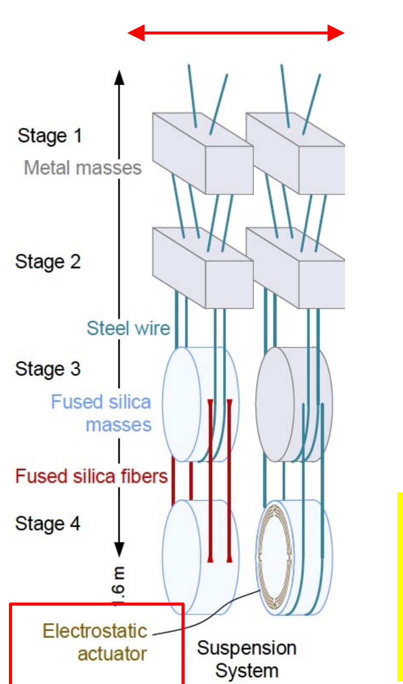
Fundamental Noise sources of GW detectors

noise/sensitivity = measurement of L_1-L_2

$$\delta x \sim \lambda_{laser} / \mathcal{F}\sqrt{N_{photon}} \sim 10^{-20}\mathrm{m}$$

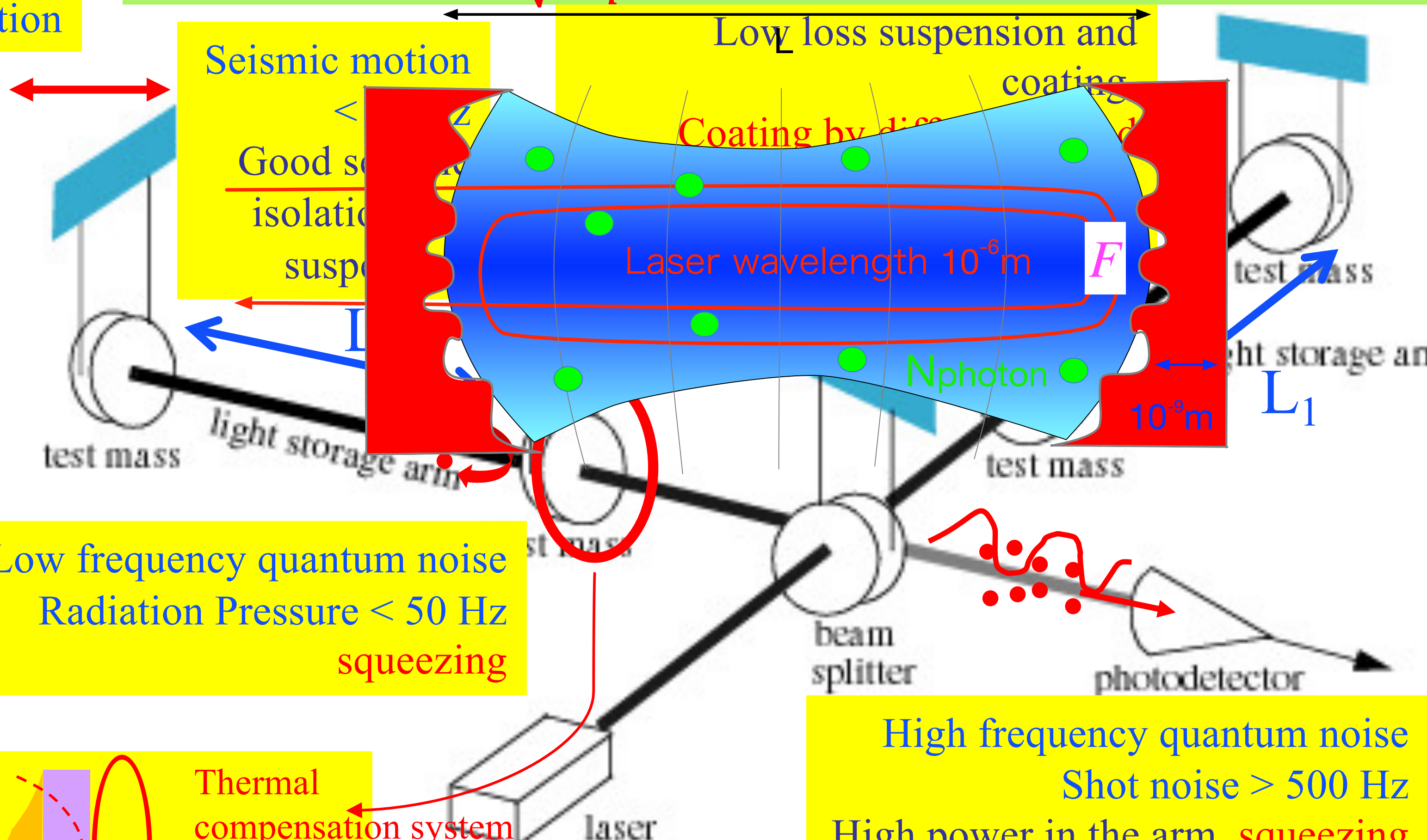
λ =1μm, $\mathcal{F}$~100, N_p~10^{25} (1MW)

Low frequency actuation
No direct actuation



Seismic motion
<
Good s
isolati
susp

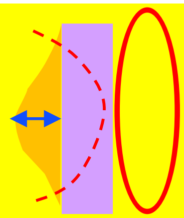
Low loss suspension and coating
Coating by dif



Low frequency quantum noise
Radiation Pressure < 50 Hz
squeezing

High frequency quantum noise
Shot noise > 500 Hz
High power in the arm, squeezing

Thermal distortion ~100nm



Thermal compensation system

Ring heater

Fundamental Sensitivity Limits in Advanced LIGO

Class. Quantum Grav. 32 (2015) 074001

Observing range improvement aLIGO to A+

(T1800042, G1900666)

- NS:NS 1.4M⊙
  173 Mpc
  →**325** Mpc
- BH:BH 30M⊙
  1606 Mpc
  → **2563** Mpc

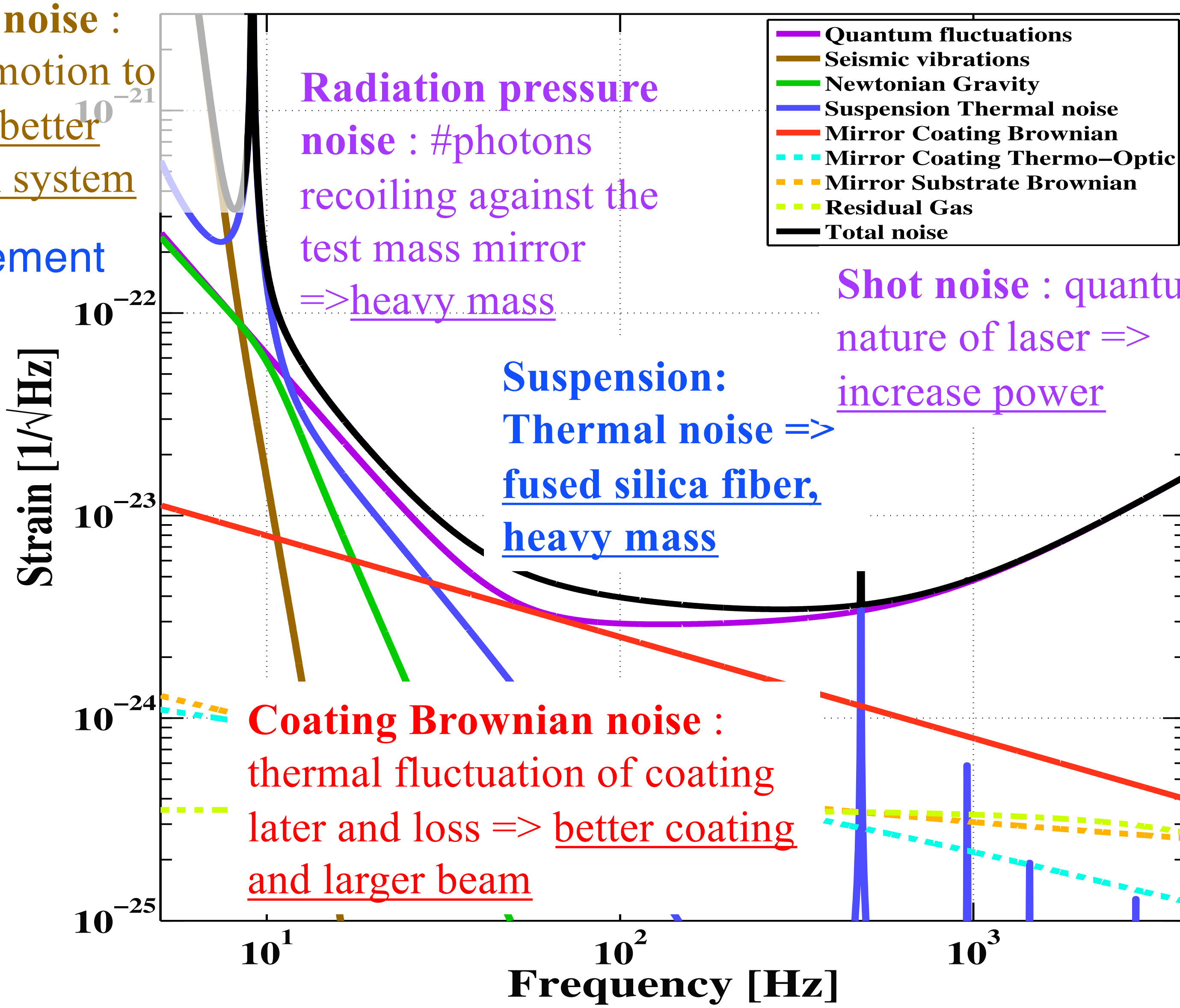
Seismic noise : ground motion to mass =>better isolation system

Radiation pressure noise : #photons recoiling against the test mass mirror =>heavy mass

Shot noise : quantum nature of laser => increase power

Suspension: Thermal noise => fused silica fiber, heavy mass

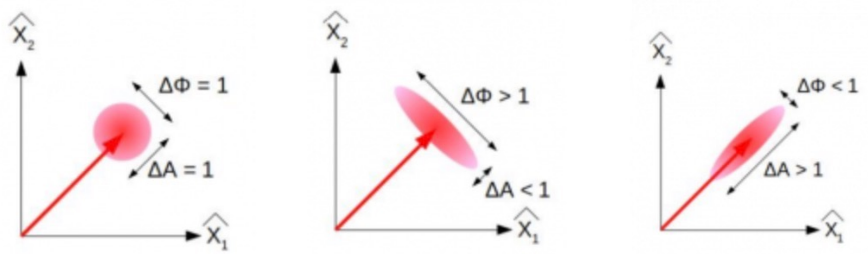
Coating Brownian noise : thermal fluctuation of coating later and loss => better coating and larger beam



Quantum noise suppression

Broadband Quantum Enhancement of the LIGO Detectors with Frequency-Dependent Squeezing

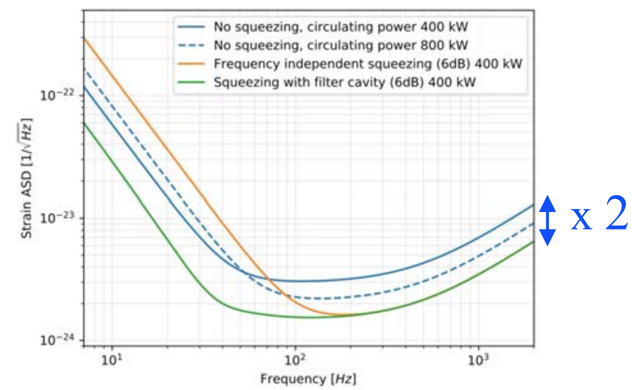
PHYSICAL REVIEW X 13, 041021 (2023) D. Ganapathy, W. Jia, M. Nakano, LIGO O4 Det. Coll



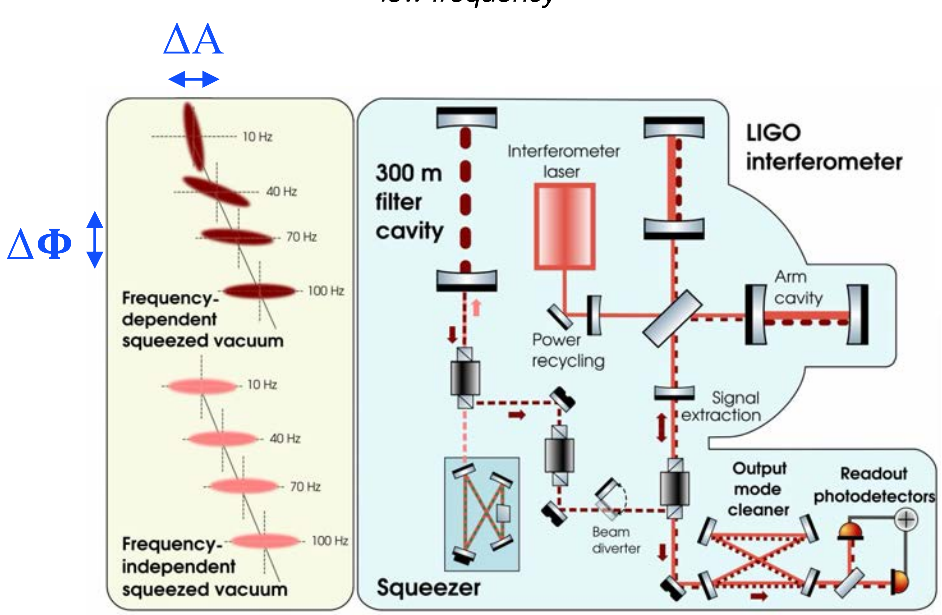
Classical state

Amplitude squeezing Suppress radiation pressure noise in the low frequency

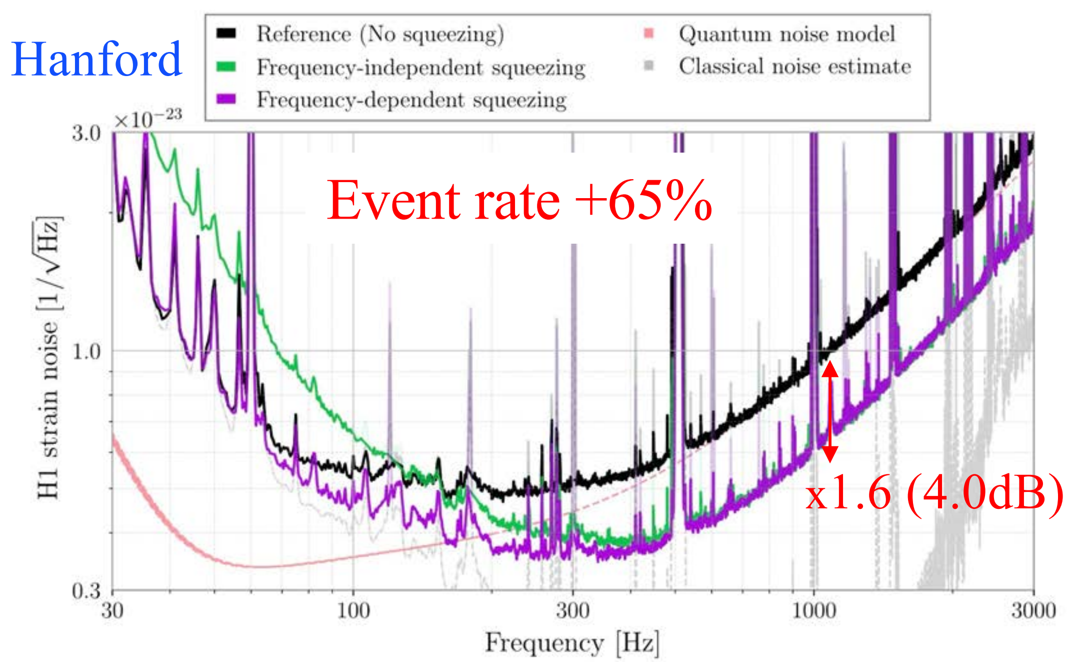
Phase squeezing Suppress shot noise in the high frequency



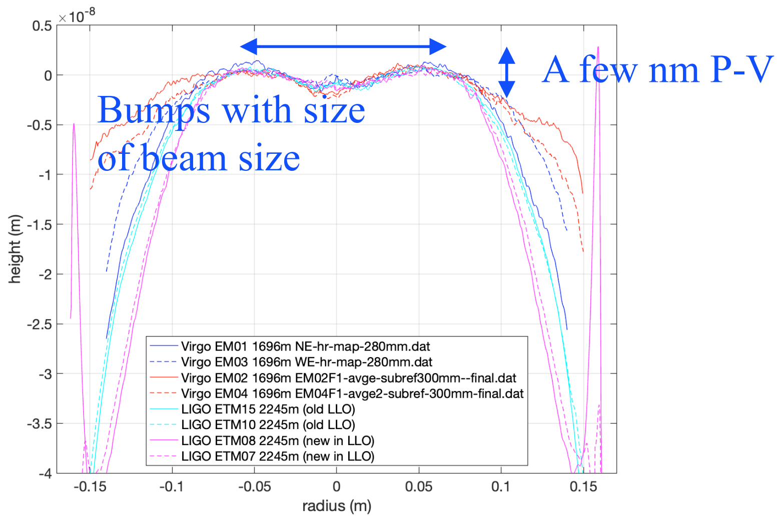
Galaxies 2022, *10*, 46, S. E. Dwyer, G. L. Mansell, L. McCuller

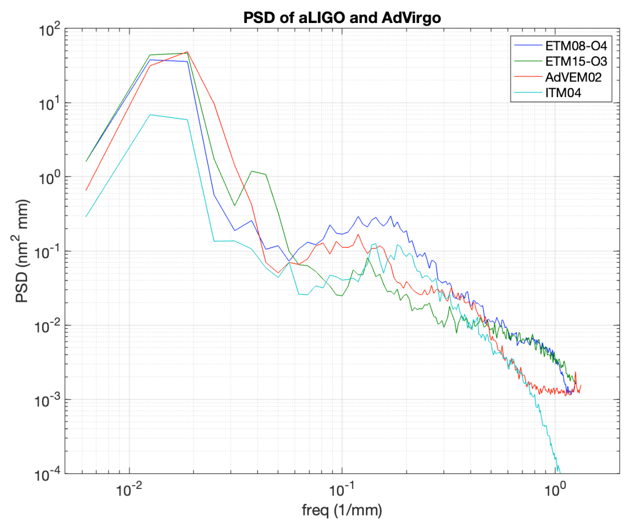


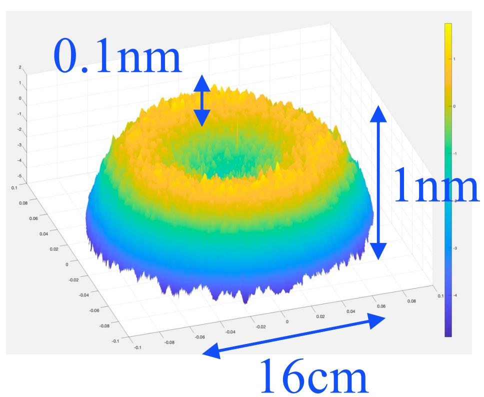
optical parametric oscillator @ 532 nm

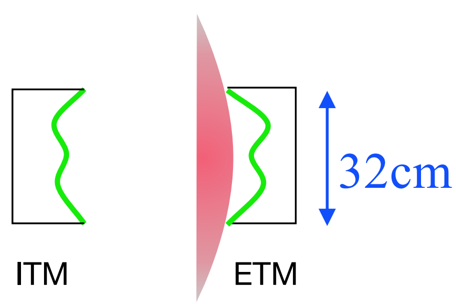


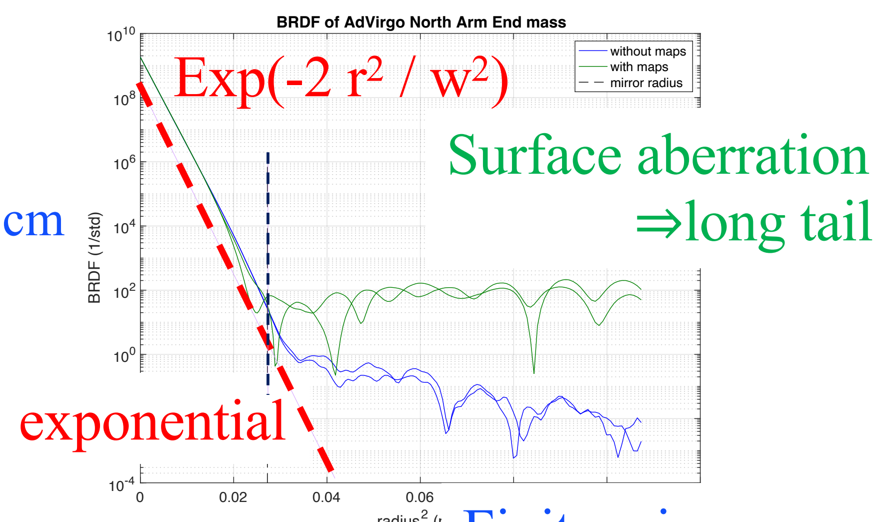
Scattering by mirror
- mirror surface and effect -





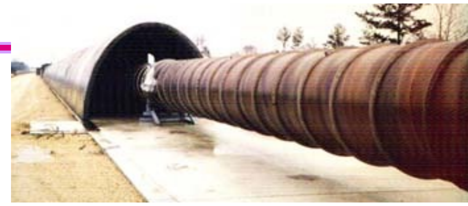




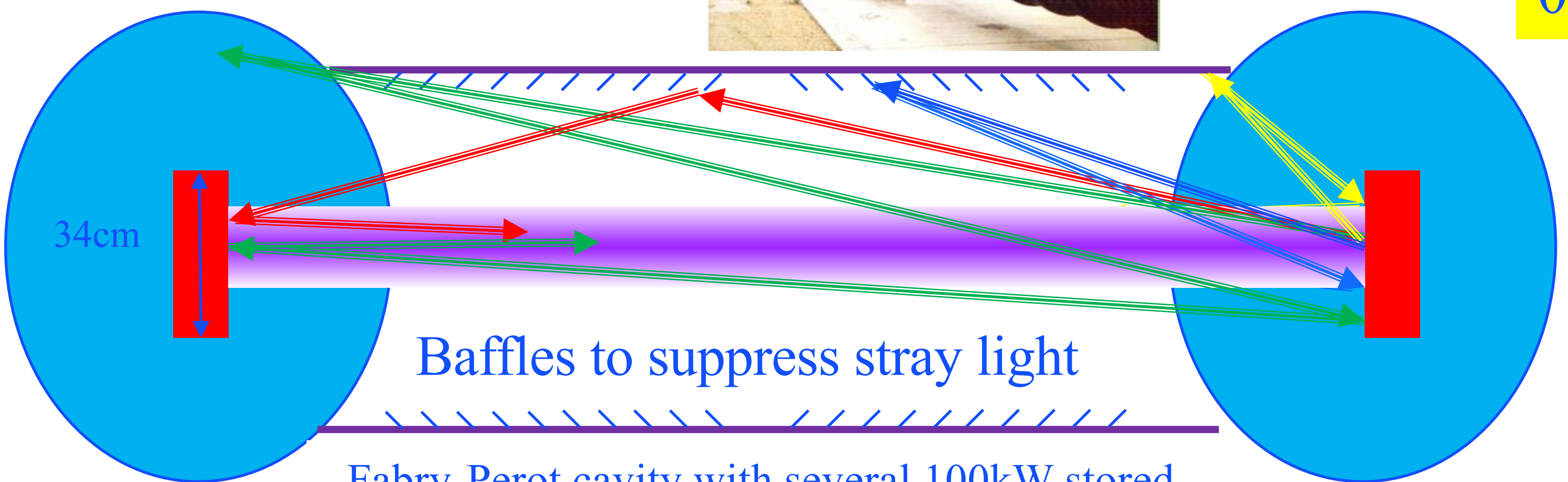


Scattering by mirror - straylight nightmare-

Vacuum tube A=1.2m



$\theta = \lambda_{space} / \lambda_{laser}$



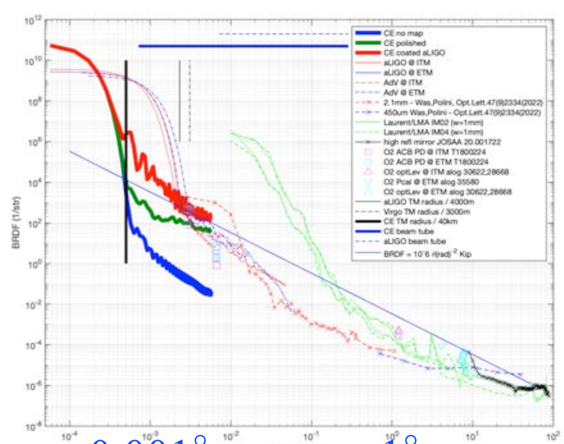
mirror

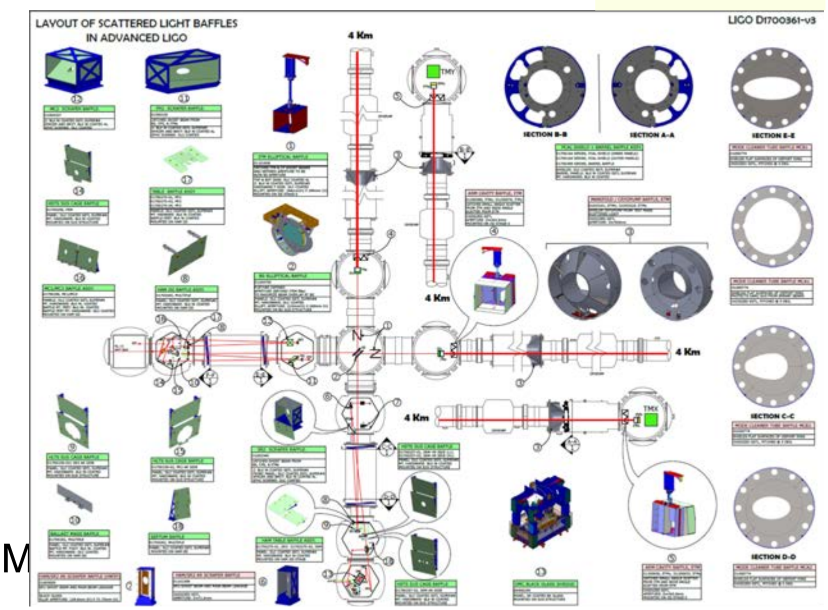
Vacuum chumber

Fabry-Perot cavity with several 100kW stored

baffles

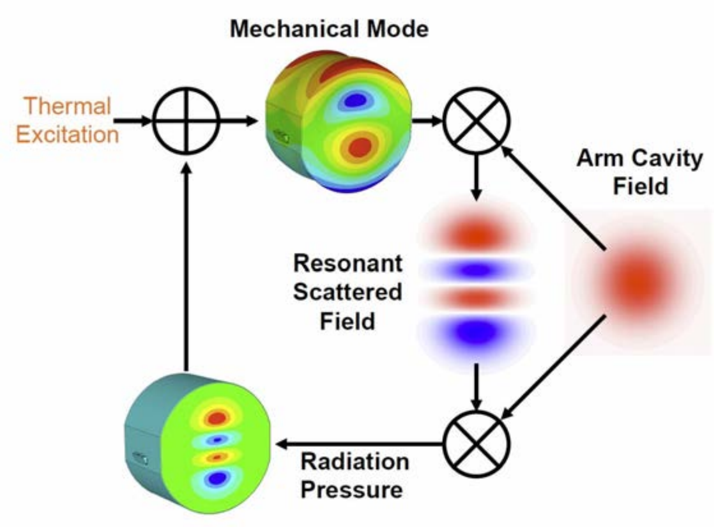
dP/dΩ

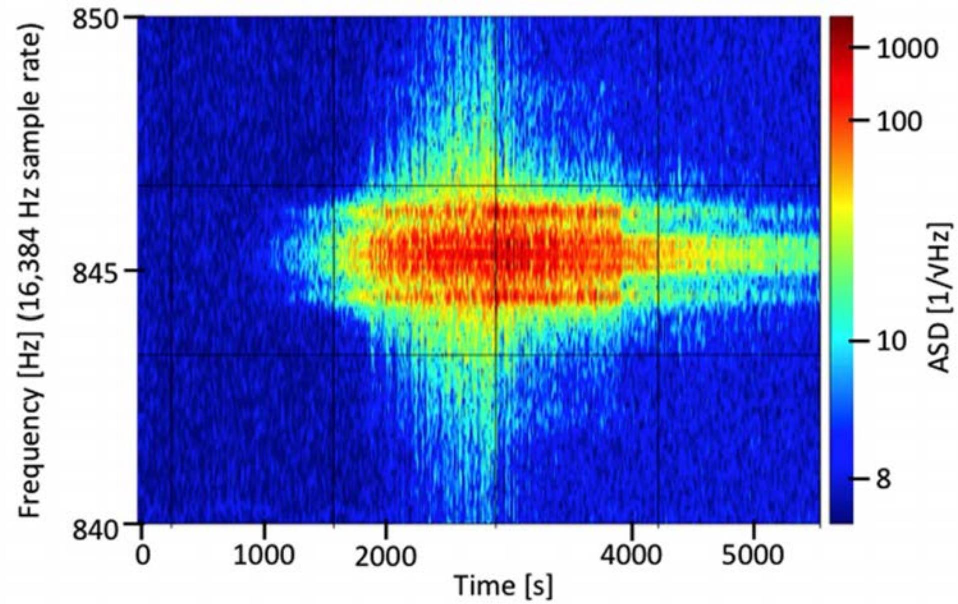


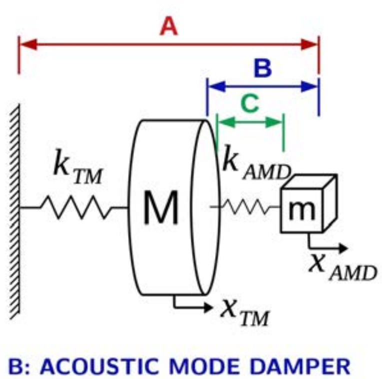


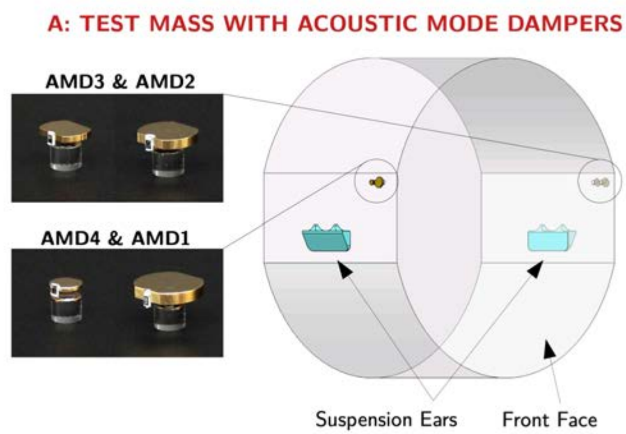
Parametric instability

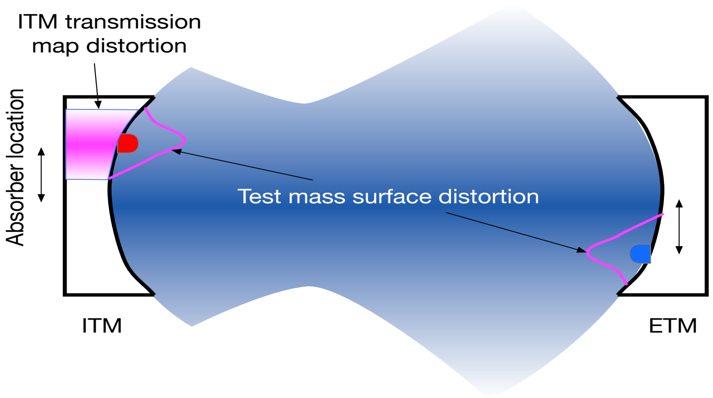
Observation of Parametric Instability in Advanced LIGO
M. Evans et al. *PRL 114, 161102 (2015)*





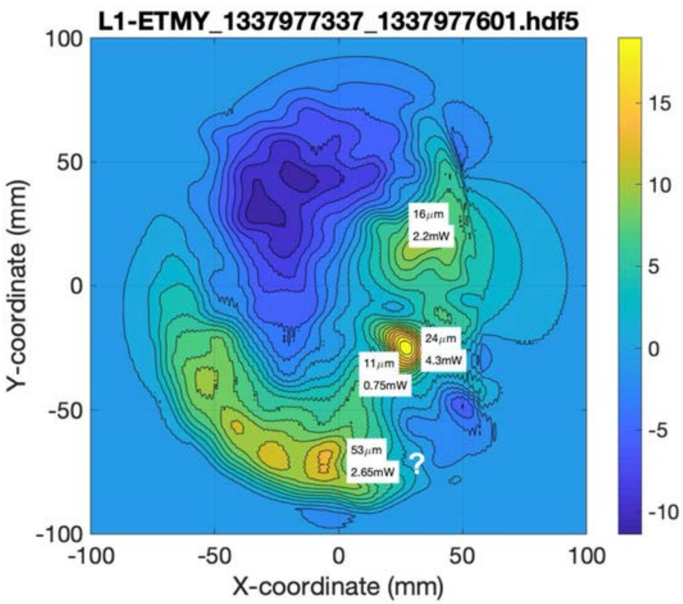






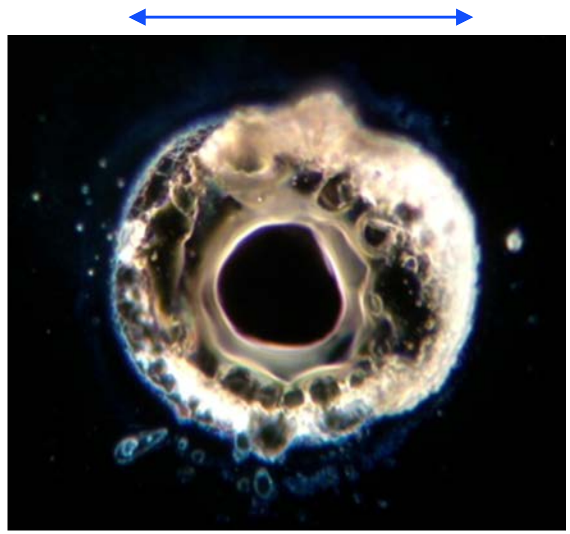
point absorbers (alumimum) in test mass coating layer

Hartmann Wavefront sensor measurements

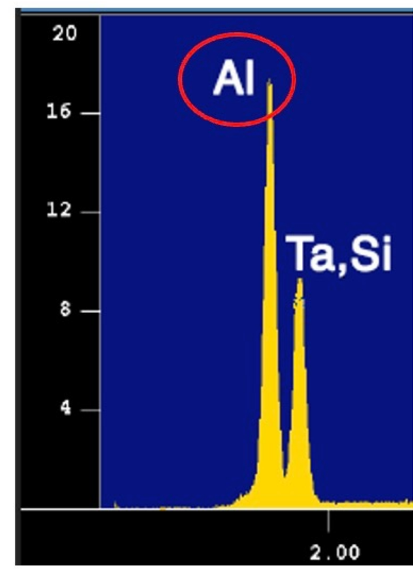


Dark field microscope

155μ



scanning electron microscope (SEM)



Degradation of performance at high power by larger loss and angular instability

- Sweet spot search
  - avoid heating
- Change of mirror radius of curvature
  - avoid resonance

- Better coating with less point absorbers
- Laser ablation

Path to the future

Use LIGO facility

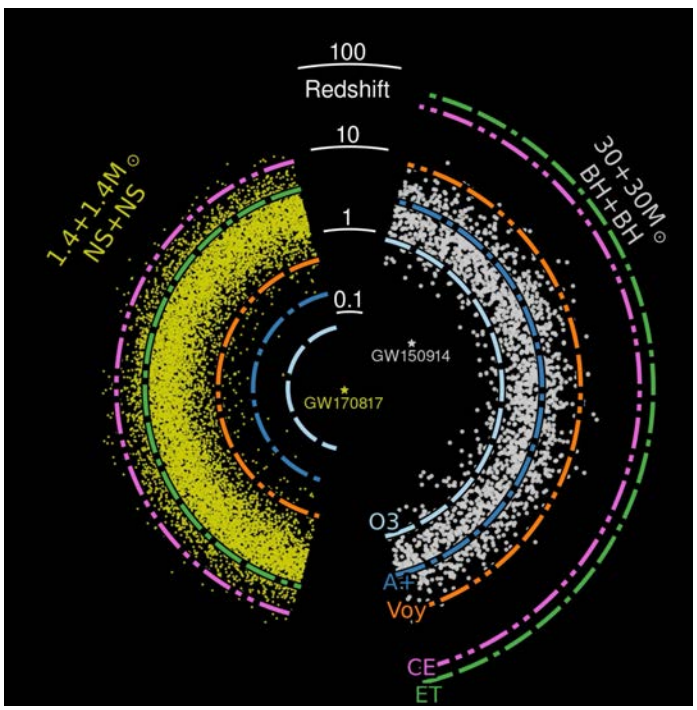
O4
aLIGO

O5
A+

- Larger mirror
- Better coating
- Better read out

A#

- Extension of A+
- Room temperature
- Larger and heavier mirrors
- …



Voyager

- Cryogenic
- New laser, substrate
- …

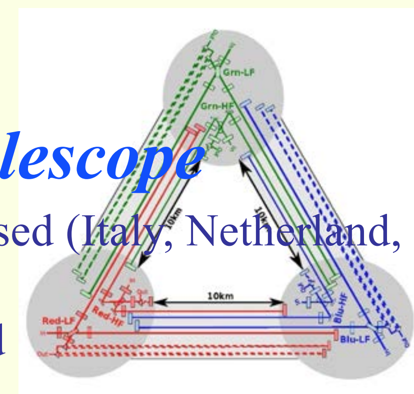
New larger interferometers

Cosmic Explorer

- US based
- On the ground
- 40km
- Room temperature
- Based on LIGO technology
- …

Einstein Telescope

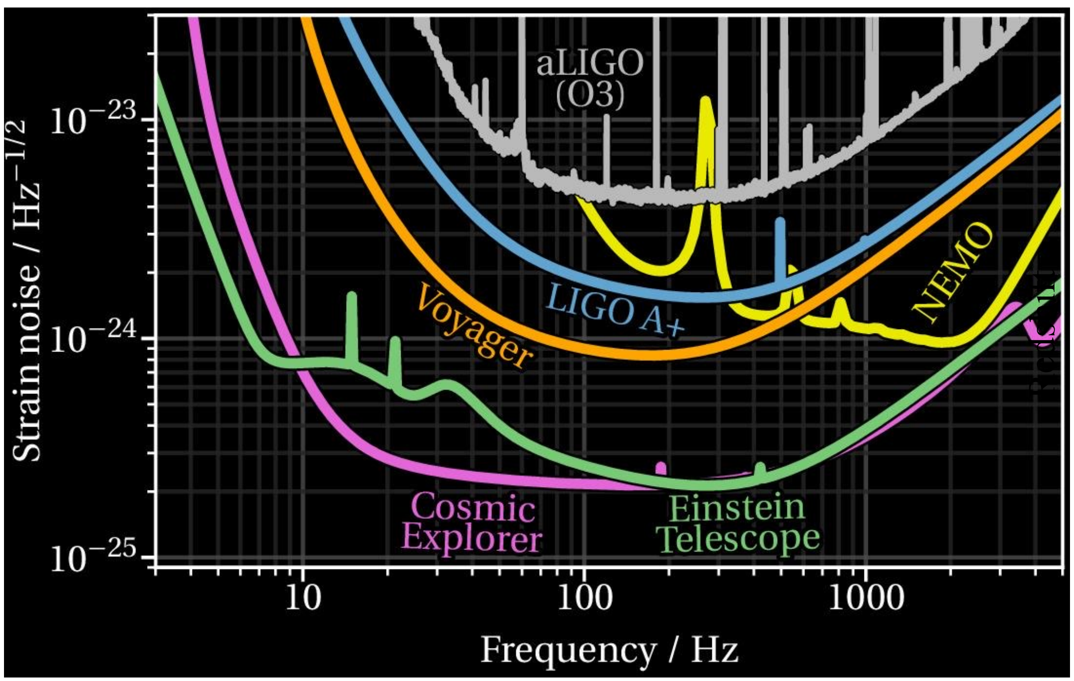
- European based (Italy, Netherland, Germany)
- Underground
- 10km
- Two interferometer : Room temperature for high frequency and low temperature for low frequency
- …

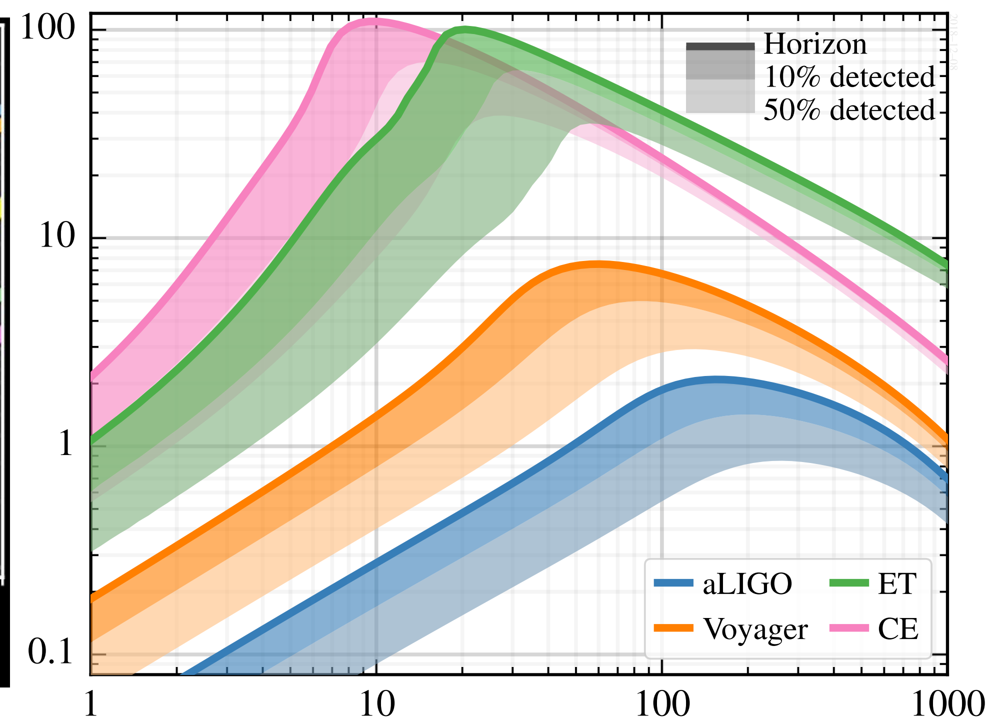


https://dcc.cosmicexplorer.org/CE-P2100003/public

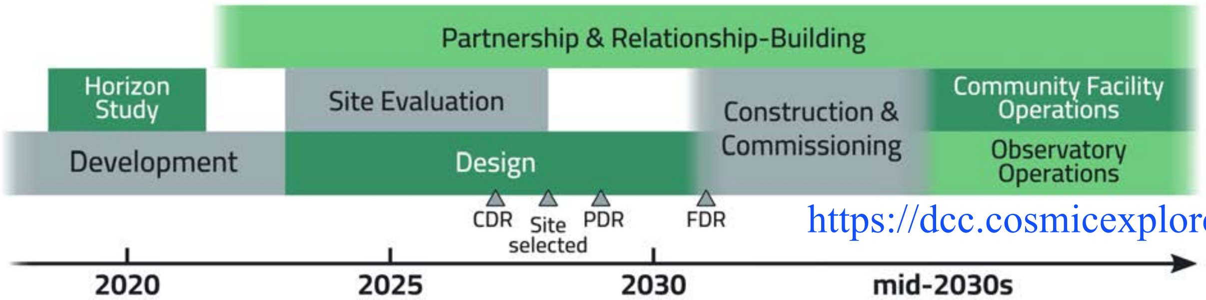
Comparing 3rd gen Detectors

- Deeper : observe compact binaries at $z \gtrsim 10$
- Wider : observe heavier mergers, earlier inspirals
- Sharper : observe with greater signal-to-noise





CE Science objectives



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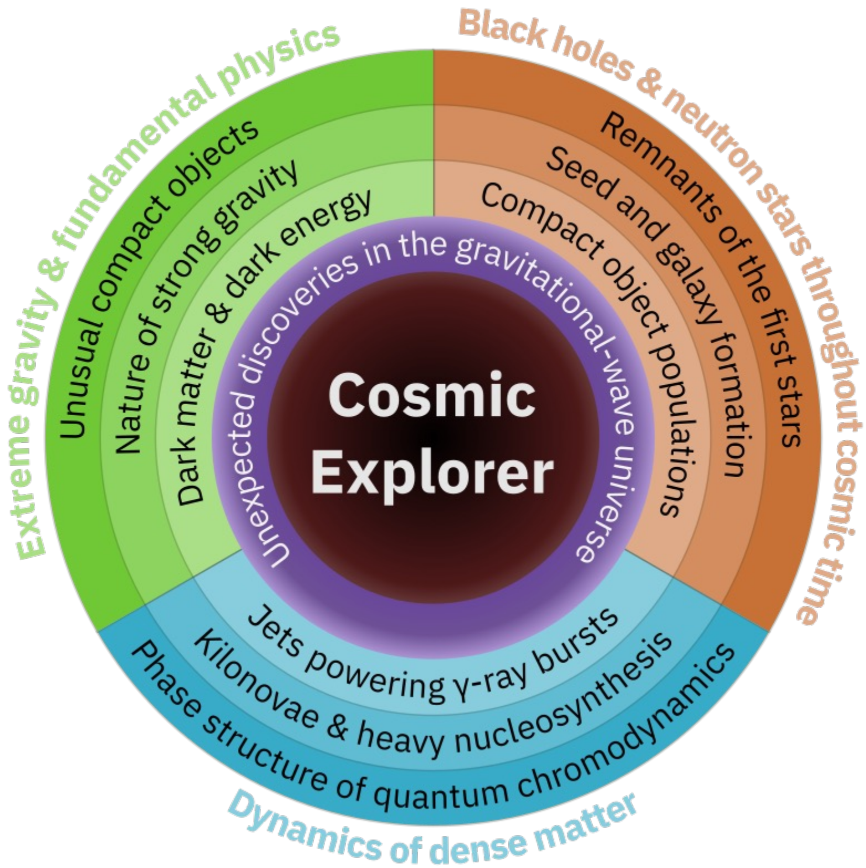

Credit: B Sathyaprakash, E Hall

Black holes & neutron stars throughout cosmic time

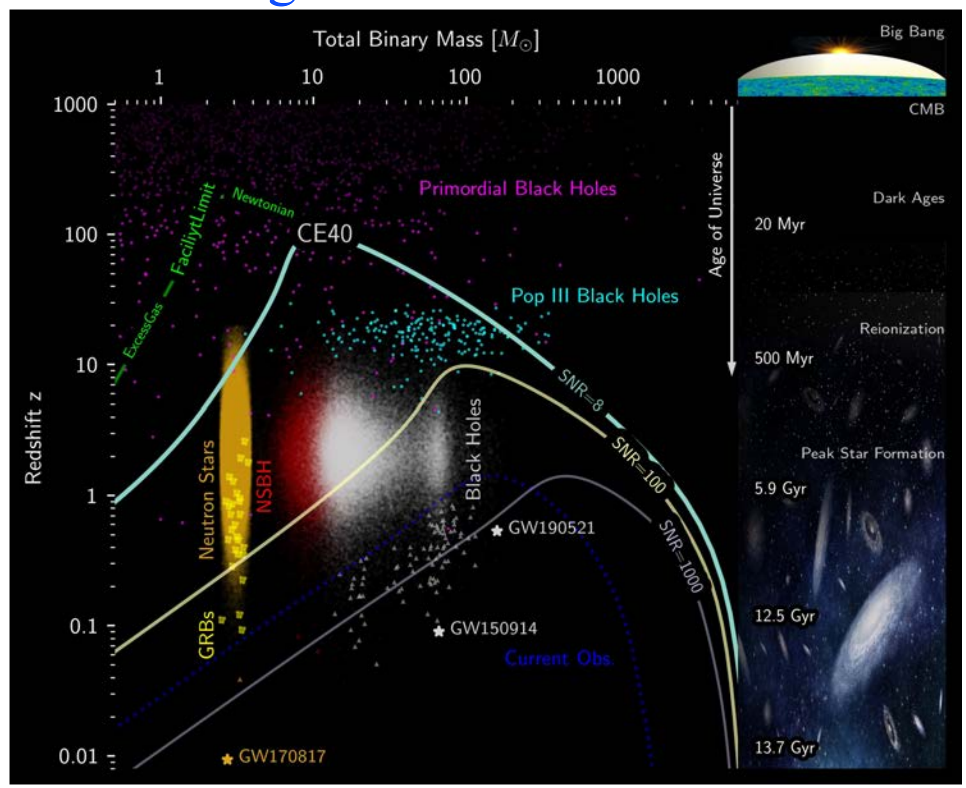

Figure credit: Alex Nitz

P1900065: Astro2020 Science White Paper
Gravitational-Wave Astronomy in the 2020s and Beyond:
A view across the gravitational wave spectrum