







r Yamamoto

Many slides from presentations at LVK Sep.2020, Including talks by D. Relize, R.Adhikari, G.Vajente, CBC, et al. ICRR seminar on December 21, 2020

Image Credit: Gabriele Vajente



## LIGO History



- 1965~ (Stan Whitcomb, APS April Meeting, 15 April 2019)
  - » Developing the GW interferometer concept
  - » Understanding noises seismic, thermal, shot, gas...
  - » Unifying efforts to build LIGO (CIT/MIT/NSF)

#### • 1994~

- » Building initial LIGO for the real size R&D
- » Organizing LIGO Scientific Collaboration
- » Operating initial LIGO at design sensitivity for one year

#### • 2008~

- » Building advanced LIGO for the GW signal detection
  - aLIGO = iLIGO + GEO (Hannover)
- » O1/O2 observation runs from 2015 Sept, one signal / month
  - Detection of the first GW signal from BBH and from BNS
- » O3 started April 1, 2019 and one signal / 1.5 week
  - Public announcement of candidates via GCN circular
- » Upgrades toward the design sensitivity
- 2025~
  - » Building the observatory for astronomy and cosmology

Kip Thorn(CIT) Ron Drever (Glasgow→CIT) Rai Weiss(MIT) 40m at CIT "Blue Book" by Weiss and ... 1989 LIGO Proposal by Vogt and... Barry Barish (CIT, SSC  $\rightarrow$  LIGO) --- 1<sup>st</sup> generation ----Power Recycling FP Michelson Single suspension 10W 1µ laser --- 2<sup>nd</sup> generation ----**Dual Recycling FP Michelson** with stable recycling cavities Quadruple suspensions 25~120W 1µ laser

#### --- 3rd generation ---

Squeezing – frequency independent to frequency dependent

Better coating to reduced thermal noise

Cryogenic,  $2\mu$  laser, Silicon,  $\ldots$ 

## Advanced LIGO, H1 & L1 in the International GW Network







# Noise sources of GW detectors



LIGO-G1901066-v4

Hiro Yamamoto ICRR December 21, 2020





[1]  $GW190412: 30.0M_{\odot}+8.3M_{\odot} \rightarrow 37.3M_{\odot}$ , 570~880Mpc, R. Abbott et al. (LIGO Scientific, Virgo), GW190412: Observation of a Binary-Black-Hole Coalescence with Asymmetric Masses, Phys. Rev. D 102, 043015 (2020)

[2]  $GW190425 : 2.0M_{\odot}+1.4M_{\odot} \rightarrow 3.4M_{\odot}$ , 90~230Mpc, B. P. Abbott et al. (LIGO Scientific, Virgo), GW190425: Observation of a Compact Binary Coalescence with Total Mass ~ 3.4M\_{\odot}, Astrophys. J. Lett. 892, L3 (2020)

[3]  $GW190521: 85M_{\odot}+66M_{\odot} \rightarrow 142M_{\odot}$ , 2.7~7.7Gpc, R. Abbott et al. (LIGO Scientific, Virgo), GW190521: A Binary Black Hole Merger with a Total Mass of 150 M<sub> $\odot$ </sub>, Phys. Rev. Lett. 125, 101102 (2020), R. Abbott et al. (LIGO Scientific, Virgo), Properties and astrophysical implications of the 150 M<sub> $\odot$ </sub> binary black hole merger GW190521, Astrophys. J. Lett. 900, L13 (2020)

[4]  $GW190814 : 23.2M_{\odot} + 2.6M_{\odot} \rightarrow 25.6M_{\odot}$ , 196~282Mpc, R. Abbott et al. (LIGO Scientific, Virgo), GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object, Astrophys. J. 896, L44 (2020)



Events in O1 and O2 10 BBH and 1 BNS heavy  $\rightarrow$  strong, short









## GW150914 signals



LIGO-G1901066-v4

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## GW from Binary Back Hole merger

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

- Direct detection of gravitational wave signals
- Observation of stellar mass black holes hierarchy up to  $150 M_{\odot}$
- Observation of a binary black hole (BBH) system and merger
- BBH merger rate

O1/O2 : 9.7-101 Gpc<sup>-3</sup> yr<sup>-1</sup> to O3 : 15.3-38.8 Gpc<sup>-3</sup> yr<sup>-1</sup>

- Test of GR in strong field:
  - » Graviton mass upper limit : O1/O2:5x10<sup>-23</sup> eV/c<sup>2</sup>, O3:1.76x10<sup>-23</sup> eV/c<sup>2</sup>
  - » Violation of general relativity : O1/O2 vs O3





GW150914 Black hole merger

GW170817 Neutron star merger





LIGO-G1901066-v4

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# Comparison of the stars of the





## GW and EM signals from Binary Neutron Star merger

- BNS merger rate : 80-810 Gpc<sup>-3</sup> y<sup>-1</sup> (BBH 15.3-38.8 Gpc<sup>-3</sup> y<sup>-1</sup>)
- Confirmation of association between short GRBs and BNS mergers, and new insights into physics of GRB events.
- Limits on dynamical ejecta in the associated kilonova.
- BNS mergers as producers of heavy elements confirmed.
- Independent measurement of the Hubble constant consistent with prior measurements.
- Test of generate relativity

#### Binary Neutron Star merger in O2 and O3



GW170817+GRB170817A (O1/O2) Astrophys. J. Lett. 848, L13 (2017) GW190425 (O3) Astrophys. J. Lett. 892, L3 (2020), G2001659 (CBC 2020 LVK)

GW170817



$28 \text{ deg}^2$	Low-spin priors $( \chi  \le 0.05)$	High-spin priors $( \chi  \le 0.89)$
Primary mass $m_1$	1.36-1.60 M <sub>☉</sub>	1.36−2.26 M <sub>☉</sub>
Secondary mass $m_2$	1.17–1.36 M	0.86–1.36 M <sub>☉</sub>
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 $E_{rad}$	$> 0.025 M_{\odot} c^2$	$> 0.025 M_{\odot} c^2$
Luminosity distance $D_{\rm L}$	$40^{+8}$ Mpc	$40^{+8}$ Mpc
Viewing angle $\Theta$	$\leq 55^{\circ}$	$\leq 56^{\circ}$
Using NGC 4993 location	$\leq 28^{\circ}$	≤ 28°
Combined dimensionless tidal	$\leq 800$	$\leq 700$
Dimensionless tidal deformabil	$\leq 800$	$\leq 1400$

#### GW190425



LIGO-G1901066-v4

LIGO

EMBER 14, 201

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Table 1Source Properties for GW190425

8284 deg <sup>2</sup>	Low-spin Prior $(\chi < 0.05)$	High-spin Prior $(\chi < 0.89)$
Primary mass $m_1$	1.60–1.87 $M_{\odot}$	$1.61-2.52 M_{\odot}$
Secondary mass $m_2$	1.46–1.69 <i>M</i> <sub>☉</sub>	$1.12-1.68 M_{\odot}$
Chirp mass M	$1.44^{+0.02}_{-0.02}~M_{\odot}$	$1.44^{+0.02}_{-0.02}M_{\odot}$
Detector-frame chirp mass	$1.4868^{+0.0003}_{-0.0003}~M_{\odot}$	$1.4873^{+0.0008}_{-0.0006}~M_{\odot}$
Mass ratio $m_2/m_1$	0.8 - 1.0	0.4 - 1.0
Total mass m <sub>tot</sub>	$3.3^{+0.1}_{-0.1}~{ m M}_{\odot}$	$3.4^{+0.3}_{-0.1}M_{\odot}$
Effective inspiral spin parameter $\chi_{eff}$	$0.012\substack{+0.01\\-0.01}$	$0.058\substack{+0.11\\-0.05}$
Luminosity distance $D_{\rm L}$	159 <sup>+69</sup> <sub>-72</sub> Mpc	$159^{+69}_{-71}$ Mpc
Combined dimensionless tidal deformability $\tilde{\Delta}$	≤600	≤1100

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## Exotic events in O3a



17

GW190521: mass of the remnant  $142^{+28}$ -16 M $\odot$ is considered an intermediate mass black hole



15
1 in 4900 yrs
2.7 – 7.7 Gpc
$85{ m M}_{\odot}$
$66~M_{\odot}$
142 ${ m M}_{\odot}$

GW190814: The secondary, 2.6 MO, is heavier than known NSs and lighter than known BHs.

	Network SNR:	25
2.9 Model 1	FAR:	1 in 8.3~1300 yrs
28 — Model 2	Distance:	196-282 Mpc
	Primary Mass:	23.2 ${ m M}_{\odot}$
2.5	Secondary Mass:	2.6 $M_{\odot}$
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Remnant IMBH's Mass:	25.6 $M_{\odot}$







## New in O3: Open Public Alerts

- Preliminary GCN Notice will be sent out autonomously in low latency (~minutes) for event candidates meeting given FAR
  - » FAR threshold targets an overall astrophysical purity of 90%
    - 1 / 2 months overall for CBC
    - 1 / year overall for Burst
  - » Modified FAR will be used for candidates with EM counterparts
  - » These alerts will be publicly available through the Gamma-ray Coordinates Network (GCN)
  - » Event candidates will be publicly available in https://gracedb.ligo.org
- Preliminary Notice will be followed by:
  - » Initial Notice and Circular confirming the event (~4h), following human vetting by a smaller number of empowered advocates
  - » A retraction (latency dependent on the event type)
- LIGO/Virgo Public Alerts User Guide & Support
  - » https://emfollow.docs.ligo.org/userguide/quickstart.html
  - » contact+emfollow/userguide@support.ligo.org
- openIvem mailing list
  - » Instructions at https://wiki.gw-astronomy.org/OpenLVEM
  - » This is a public list to which anyone can subscribe

When GW150914 was detected, it was prohibited to talk about it for a half year, even to family.



- https://www.gw-openscience.org/
- All data of O1, O2, O3a
- **Getting Started**
- Bulk data access example

#### Archive for O2 4KHZ R1 dataset

Each data file corresponds to 4096 seconds of GPS time, and may contain up to half a be downloaded in either HDF5 or Frame format. For documentation, see the tutorials. O2\_4KHZ\_R1 start GPS: 1164556817 UTC: 2016-11-30T16:00:00 O2\_4KHZ\_R1 end GPS: 1187733618 UTC: 2017-08-25T22:00:00

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Choose your output format:

Time series data in HDF5 and Frame files

Time series data in HDF5 and Frame files, with data quality guide



**Getting Started** Data Bulk Data Catalogs Timelines Software

Tutorials Web Apps Detector Status

My Sources

GPS ↔ UTC Projects

Acknowledge

About

#### Gravitational Wave Open Science Center







LIGO Hanford Observatory, Washington (Credits: C. Gray)

(Credits: J. Giaime)

Virgo detector, Italy (Credits: Virgo Collaboration)

The Gravitational Wave Open Science Center provides data from gravitational-wave observatories, along with access to tutorials and software tools.



Astrophysics > High Energy Astrophysical Phenomena

#### New Binary Black Hole Mergers in the Second Observing Rur of Advanced LIGO and Advanced Virgo

#### Tejaswi Venumadhav, Barak Zackay, Javier Roulet, Liang Dai, Matias Zaldarriaga

(Submitted on 15 Apr 2019)

OK

OK

Hiro Yamamoto

We report the detection of new binary black hole merger events in the publicly available data from the second observing run of advanced LIGO and advanced Virgo (O2). The mergers were discovered using the new search pipeline described in Venumadhav et al. (1902.10341), and are above the detection thresholds as defined in Abbott et al. (1811.12907). Three of the mergers (GW170121, GW170304, GW170727) have inferred probabilities of being of astrophysical origin  $p_{astro} > 0.98$ . The remaining three (GW170425, GW170202, GW170403) are less certain, with  $p_{\text{astro}}$  ranging from 0.5 to 0.8. The newly found mergers largely share the statistical properties of previously reported events, with the exception of GW170403, the

## **Observing Scenario: Run Plans**

arXiv:"Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA"





*O4 events Simulated* Event Stream for a one year duration O4 run

#### Assumptions:

- 190 Mpc BNS range for H1, L1
- 90 Mpc BNS range for Virgo
- Same duty cycles, detector coincidence as in O3

LIGO-G1901066-v4

LGO

Hiro Yamamoto ICRR

ICRR December 21





## From O2 to O3

Mechanical Mode

Resonant

Scattered Field

Radiation Pressure

- Mitigate Parametric instability by acoustic Mode Dampers
- Laser power 25W to 50W with 3dB squeezing
- Die hard straylight mitigation





Arm Cavity Field





## Challenge: Point Absorbers in the Test Mass Coatings



Point absorbers (PA) on 100%\* of ETMs (10 of 10), 20% of (2 of 10) ITMs

LIGO

- PAs are likely embedded in the coatings; studies of witness samples find that PAs are primarily aluminum with ~<sup>20 μm</sup> some traces of carbon
- 3 of 4 coating vendors have PA on witness samples
  - » Many witness samples characterized during the shutdown

		# witness samples
Vendor	% with PAs	tested
V1	67%	87
V2	100%	4
V3	50%	4
V4	0%	4

- Pursuing multi-faceted R&D approach to 'repair' existing test masses
  - » Ultrafast pulsed laser ablation: 2nd trial somewhat successful; no Al or C found after ablation but still absorbing. Perhaps Ta?
  - » Chemical etching: 2 compounds being tried for AI etch, beginning Ta etch
  - » Mechanical milling: trial has just started
- Also working with test mass coating vendor LMA to address problem 'at the source'
  - » LMA has made 2 runs with chamber modifications to eliminate contaminants; characterization begins at LIGO Caltech in 2 weeks



8 -4 -2.00 4.00 6.00 8.00 10.00





funded project

A+ Project





Pre-O4

>>

BNS Target Sensitivity: 190 Mpc >>

US budget: \$20.5M

- Frequency-dependent Squeezing >>
  - 300 m filter cavity (FC)
- Improved dark port efficiency >>
  - Low loss Faraday isolator
- Adaptive wavefront control
- Pre-O5:
  - BNS Target Sensitivity: 325 Mpc >>
  - Low coating thermal noise (CTN) >> test mass coatings
  - 450 mm beamsplitter >>
  - Balanced homodyne >>

#### Critical paths

- O4: End Station buildings & >> tube enclosures for new 300m filter cavities
  - Fallback is to delay FC to pre-**O**5
- O5: Test mass low thermal >> noise coating development





### O4: Planned Detector Improvements

Project/WBS	Program Plan [Combination 1]	Fallback [Combination 2]
Operations	Continued refurbishn	nent of LIGO Vacuum System
Operations	Replace Test Masse	s that have point absorbers
Detector Improvements	Additional Stray Light Baf	iles [Scattered light noise<200 Hz]
Detector Improvements	High power laser (new la	aser amplifier) [Lower shot noise]
A+ Project	High-efficier	cy Faraday isolators
A+ Project	Adaptive mo	de matching systems
A+ Project	Frequency-dependent squeezing (Filter Cavity)	
Potential ranges O4	190 MPc (LLO/LHO)	165 MPc (LLO/LHO)





## The Path to O4

- This is the top level schedule for implement planned improvements for O4 in M1800262
- NOT SET IN STONE! The schedule is a continual work in progress and updated frequently; note review points and definition points
- Schedule currently paced by delay in repolishing end test masses
- *"O4 is currently planned to start no earlier than June 2022" in M1800277* 
  - » M1800277 : Monthly status report of commissioning and detector improvement
  - » Compiled by D.Sigg, V.Frolov, P.Fritschel, D.Coynr, C.Torrie, etc, reported to D.Reitze, A.Lazzarini

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### **Brownian noise predictions**



#### Gabriele Vajente, G2001684,OWG 2020LVK

Material	Y [Gpa]	φ [10⁻⁴]	n	ETM Num. layers	ETM Brownian noise 10 <sup>-20</sup> m/VHz @100Hz	ITM Num. layers	ITM Brownian noise 10 <sup>-20</sup> m/VHz @100Hz	Total Brownian noise 10 <sup>-20</sup> m/VHz @100Hz	Ratio w.r.t. A+ design 0.66 x 10 <sup>-20</sup> @100Hz
Titania-doped tantala (aLIGO)	124	3.6	2.07	38	0.65	16	0.46	1.13	1.71
Titania- Germania annealed 700°C 10 h	81	0.66	1.87	52	0.37	22	0.26	0.64	0.97
Titania- Germania annealed 600°C 100 h	90	0.96	1.87	52	0.42	22	0.30	0.74	1.11
Titania-Silica annealed 700°C 10 h	135	1.35	2.01	44	0.43	18	0.31	0.75	1.14

Using silica parameters: Y = 72 GPa, n = 1.45,  $\phi$  = 0.23 x 10<sup>-4</sup>

Optical absorption for those materials in line with tantala and titania-doped tantala, it should not pose a problem

## 3<sup>rd</sup> generation ground-based GW detectors



LIGO







#### **Cosmic Explorer**

a next generation gravitational wave detecto



## Comparing Detectors

#### Deeper

➢ observe compact binaries at z ≥ 10

U Wider

observe heavier mergers, earlier inspirals

□ Sharper

> observe with greater signal-to-noise



ICR

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





LIGO-G1-00-04

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## US 3<sup>rd</sup> generation ground-based interferometer timeline



2020 2022 2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 **Cosmic Explorer Timeline** parts built for parts built for 1 um install 2 um install construction design crvo upgrade funded funded funded.  $\frac{1}{2}$  $\frac{1}{2}$ Inst & CE - Stage 1 Inst & Cosmic Explorer Facility CE - Stage 2 Comm Comm Operations @ 1 um Cosmic Explorer Stage1 Cosmic Explorer Stage 2 Operations@1 um: Operations@2 um: design and operations design and operations informed by A++ informed by Voyager Voyager Voyager LIGO, Voyager A+, A++ Inst & Comm Operations **Voyager Timeline** 40m CE sized prototype Parts built successful silicon design construction mirrors funded funded ▲ Voyager FDR \$ 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2022 2024 2020 Years