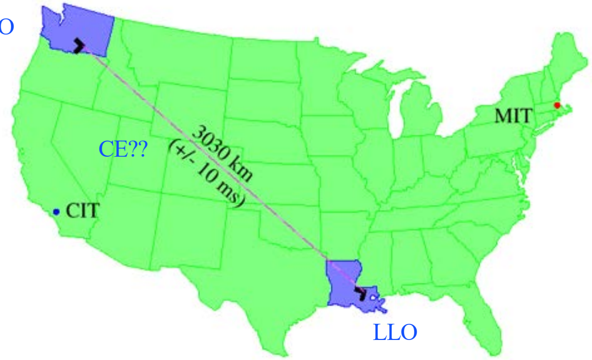


LIGO : Past, Present and Future

Hiroaki Yamamoto

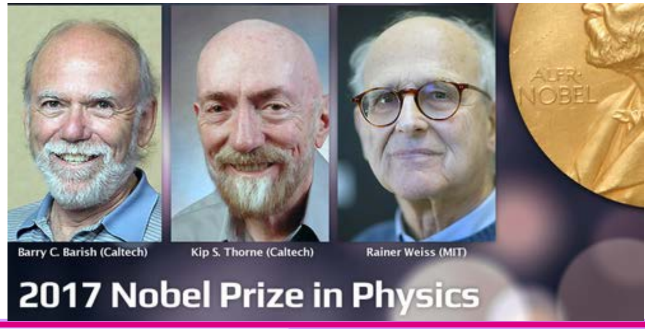
Many slides from presentations at LVK Sep.2020,
including talks by D.Reitze, R.Adhikari, G.Vajente, CBC, et al.

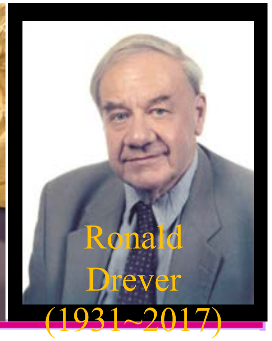
ICRR seminar on December 21, 2020

Image Credit: Gabriele Vajente

LIGO
SEPTEMBER 14, 2015

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 → LIGO)

--- 1st generation ---

Power Recycling FP Michelson

Single suspension

10W 1μ laser

--- 2nd generation ---

Dual Recycling FP Michelson
with stable recycling cavities

Quadruple suspensions

25~120W 1μ laser

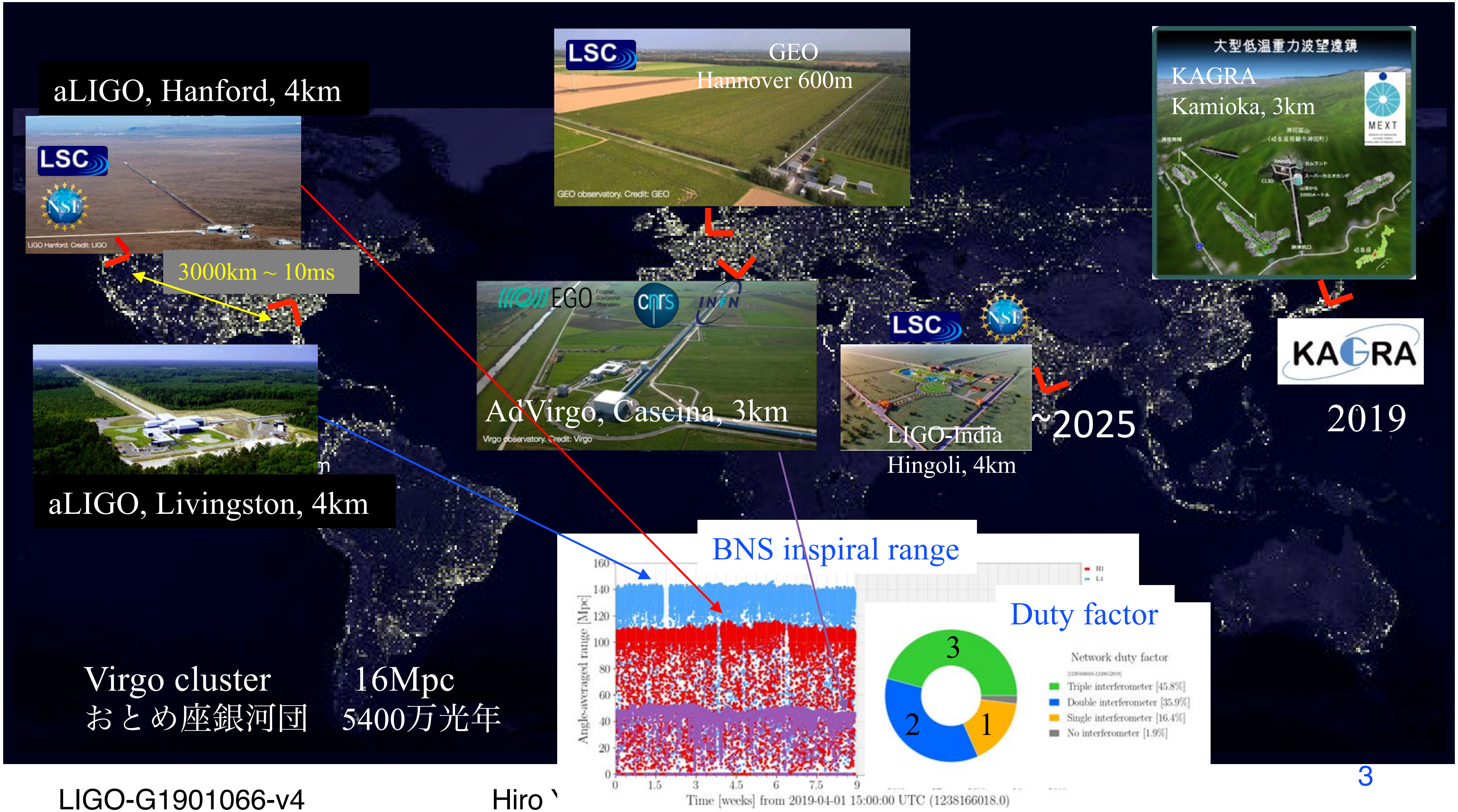
--- 3rd generation ---

Squeezing – frequency independent to frequency dependent

Better coating to reduced thermal noise

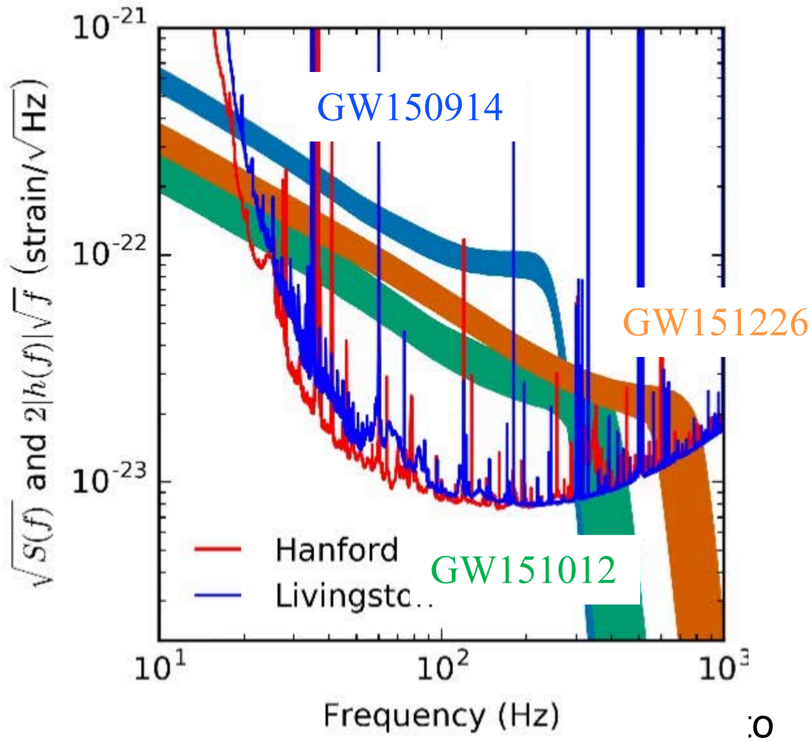
Cryogenic, 2μ laser, Silicon, …

Advanced LIGO, H1 & L1 in the International GW Network

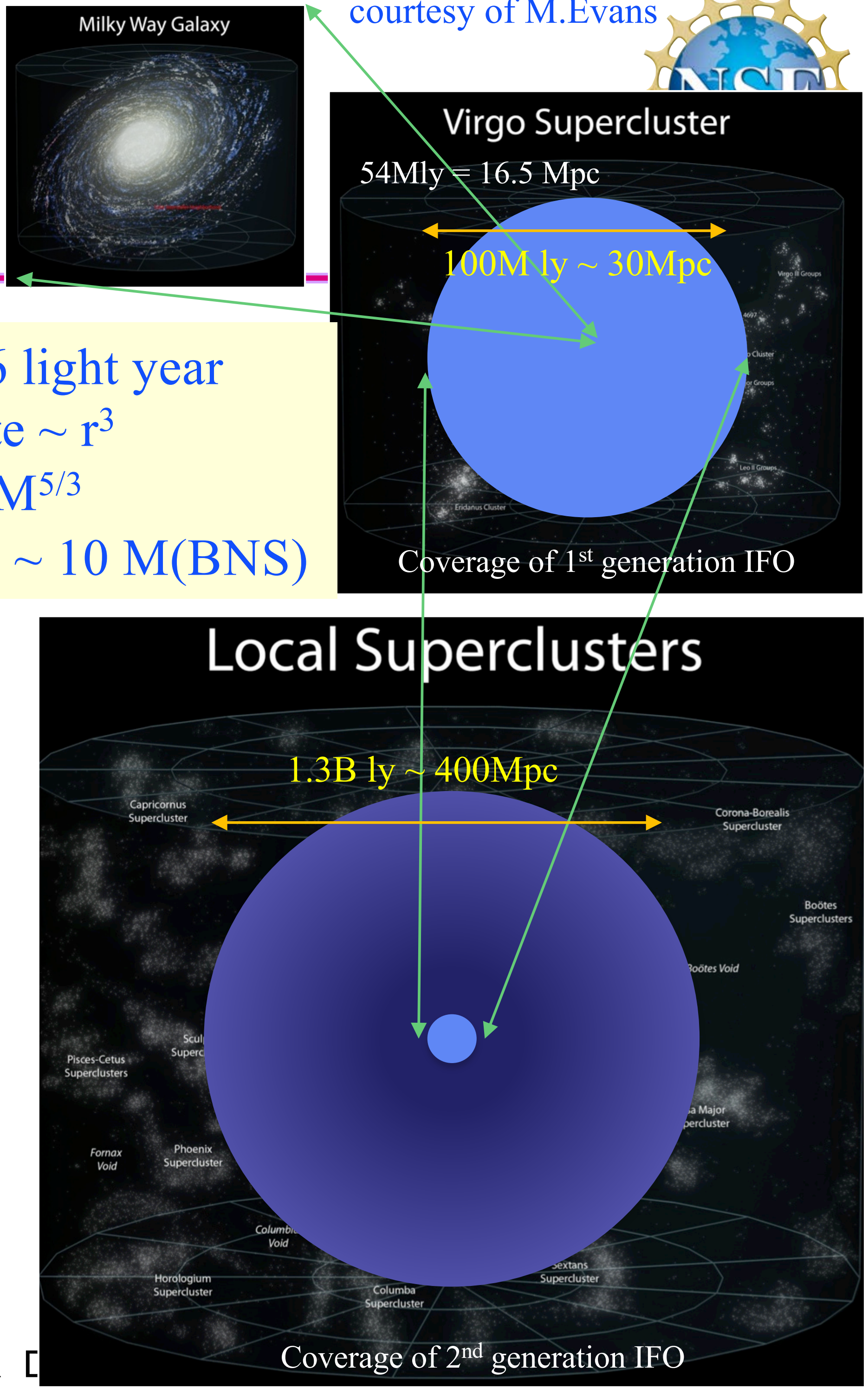


Sensitivity and significance or how far can we hear

Phys. Rev. X 6, 041015 (2016)



courtesy of M.Evans



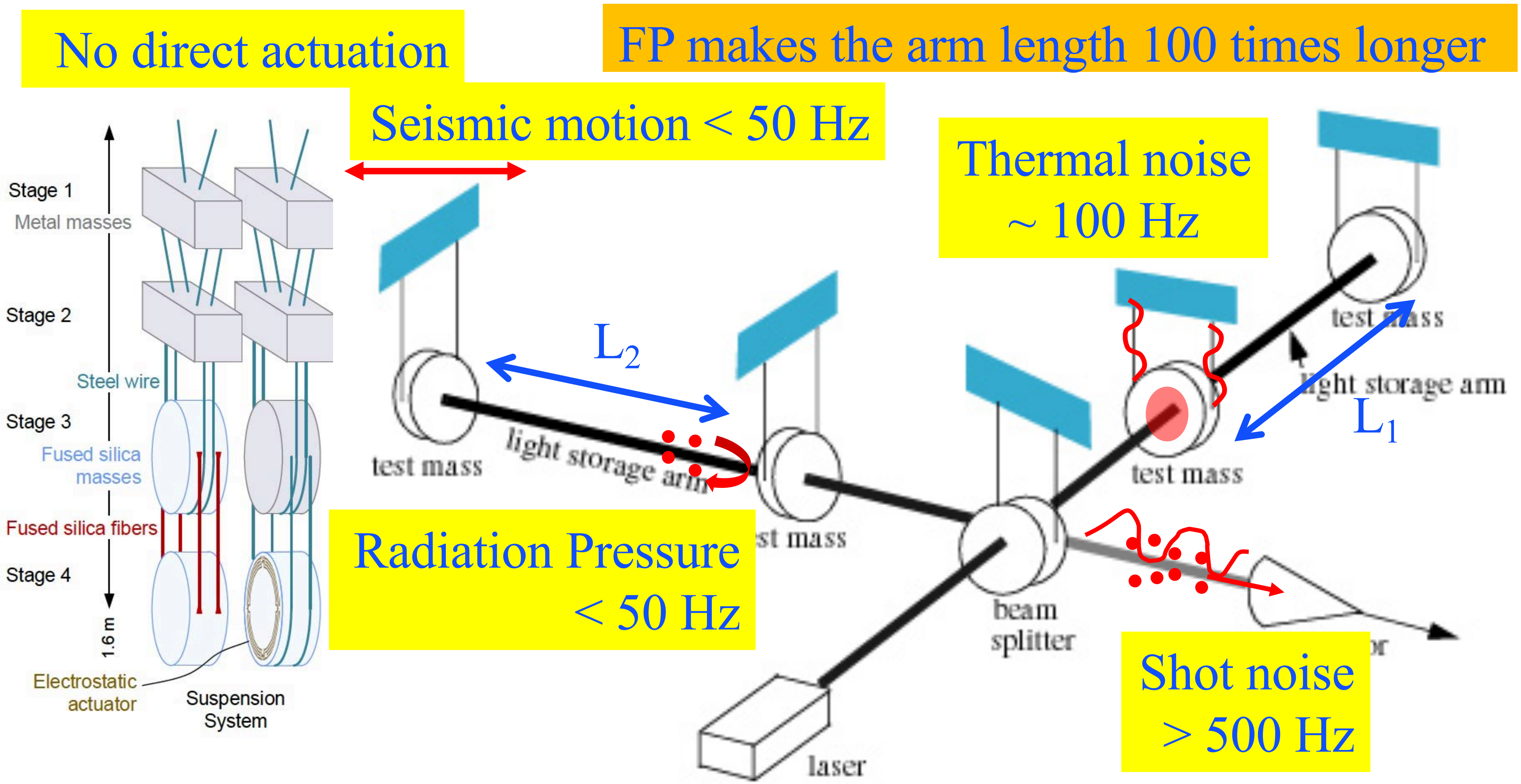
1pc=3.26 light year

Event rate ~ r^3

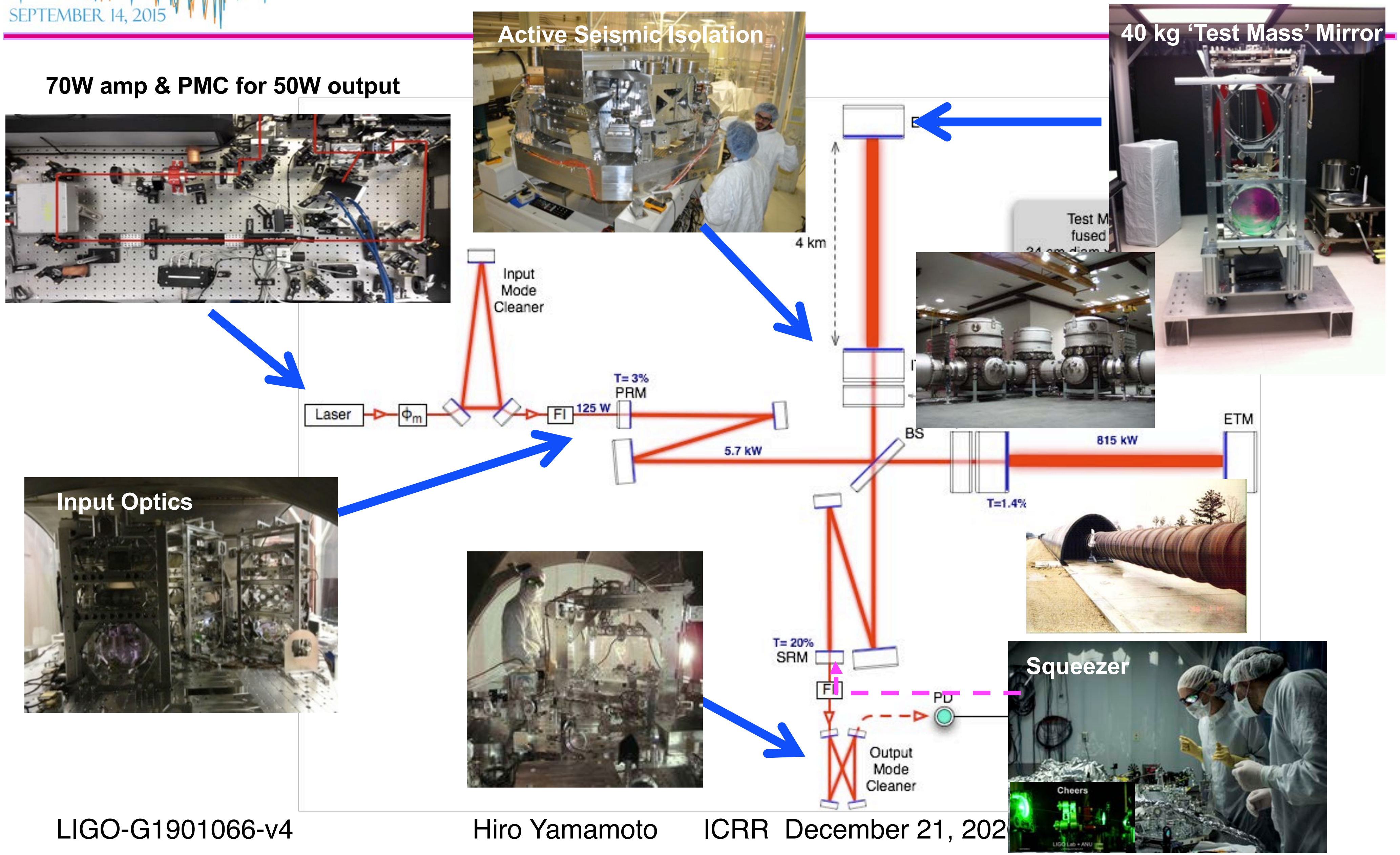
Strain ~ $M^{5/3}$

M(BBH) ~ 10 M(BNS)

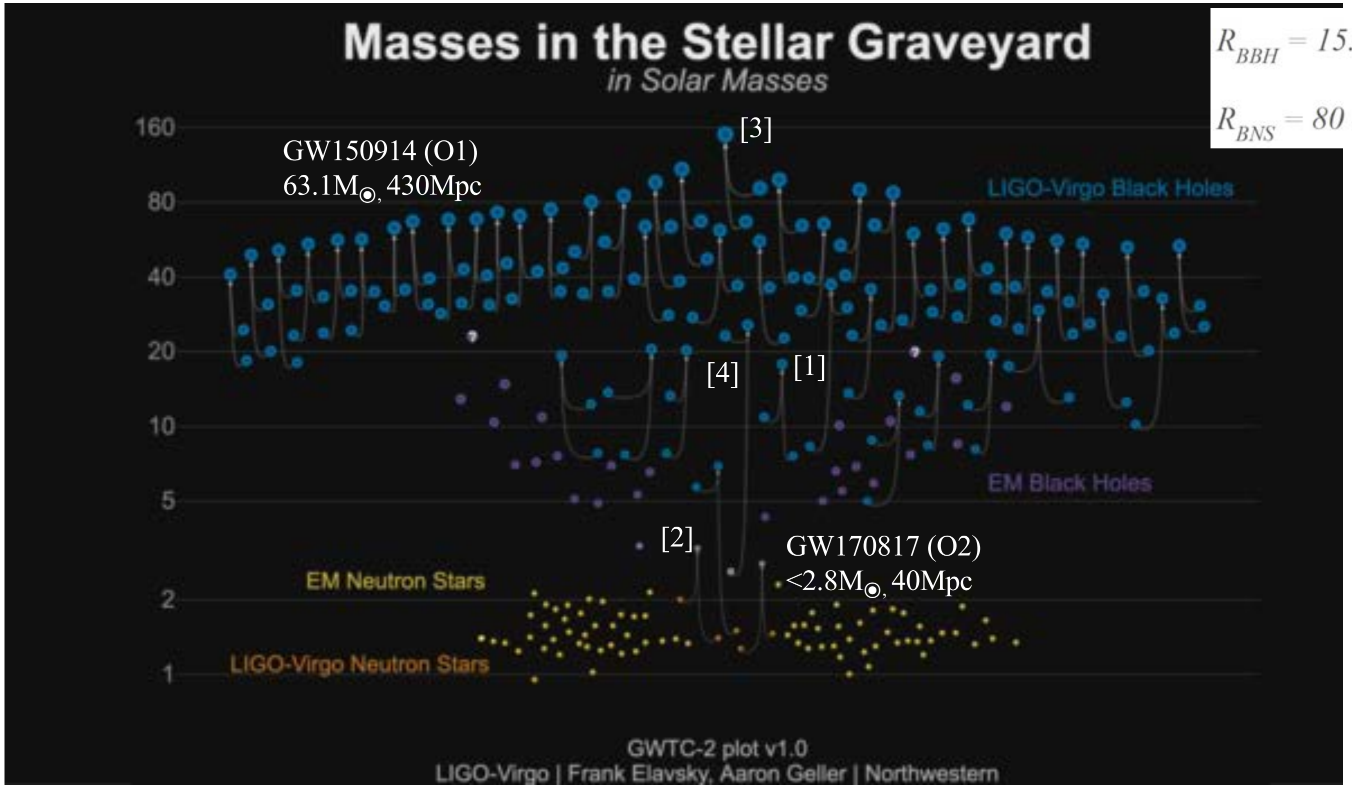
Noise sources of GW detectors - disturbance of L1-L2 -



Advanced LIGO IFO (DRFPMI)
+ frequency independent squeezer for O3

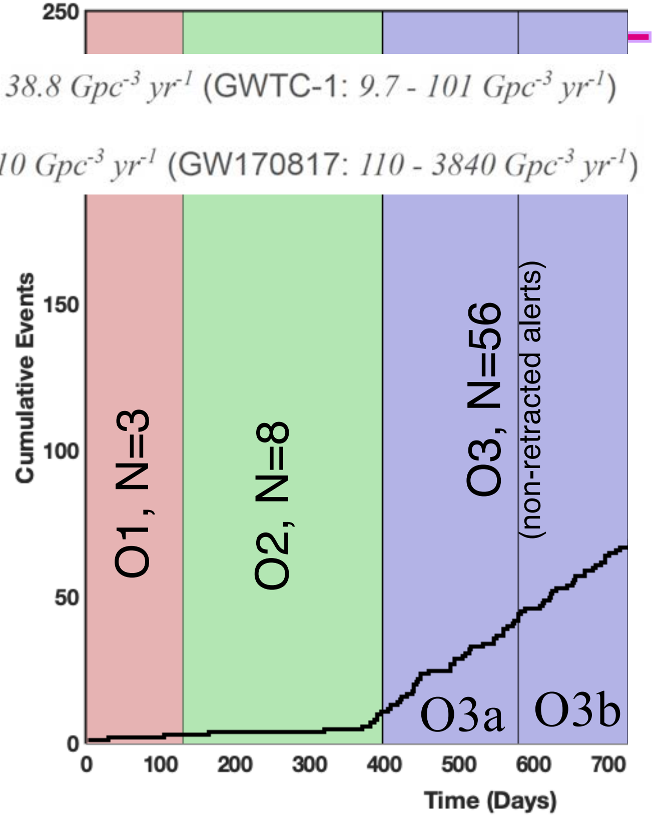


Signals in O1(2015/9/12~2016/1/19), O2(2016/11/30~ 2017/8/25) O3a (2019/4/1~2019/10/1)



R_{BBH} = 15.3 - 38.8 $Gpc^{-3}\ yr^{-1}$ (GWTC-1: 9.7 - 101 $Gpc^{-3}\ yr^{-1}$)

R_{BNS} = 80 - 810 $Gpc^{-3}\ yr^{-1}$ (GW170817: 110 - 3840 $Gpc^{-3}\ yr^{-1}$)



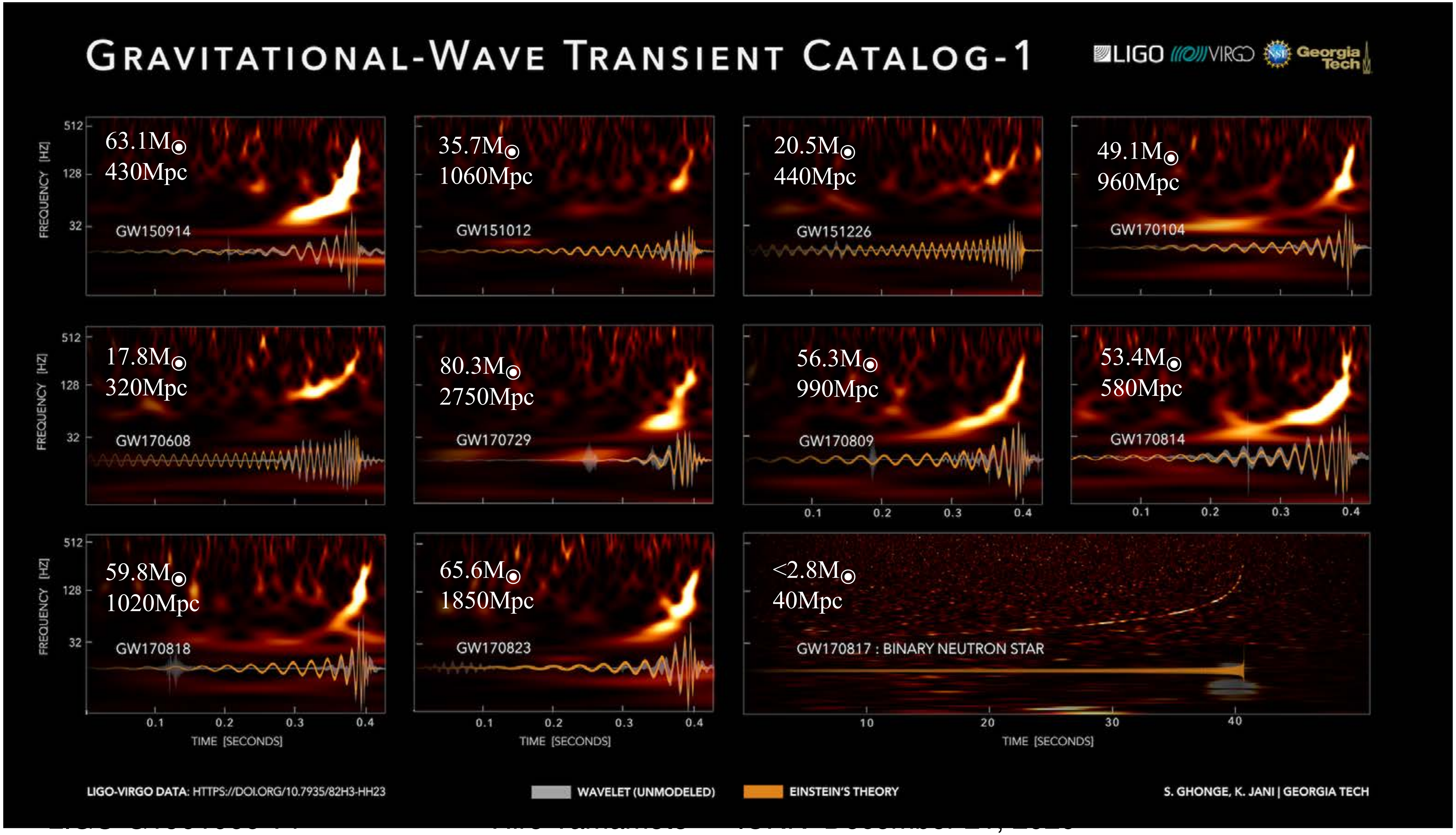
[1] GW190412 : 30.0$M_\odot$+8.3$M_\odot$→ 37.3$M_\odot$, 570~880Mpc, R. Abbott et al. (LIGO Scientific, Virgo), GW190412: Observation of a Binary-Black-Hole Coalescence with Asymmetric Masses, Phys. Rev. D 102, 043015 (2020)

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

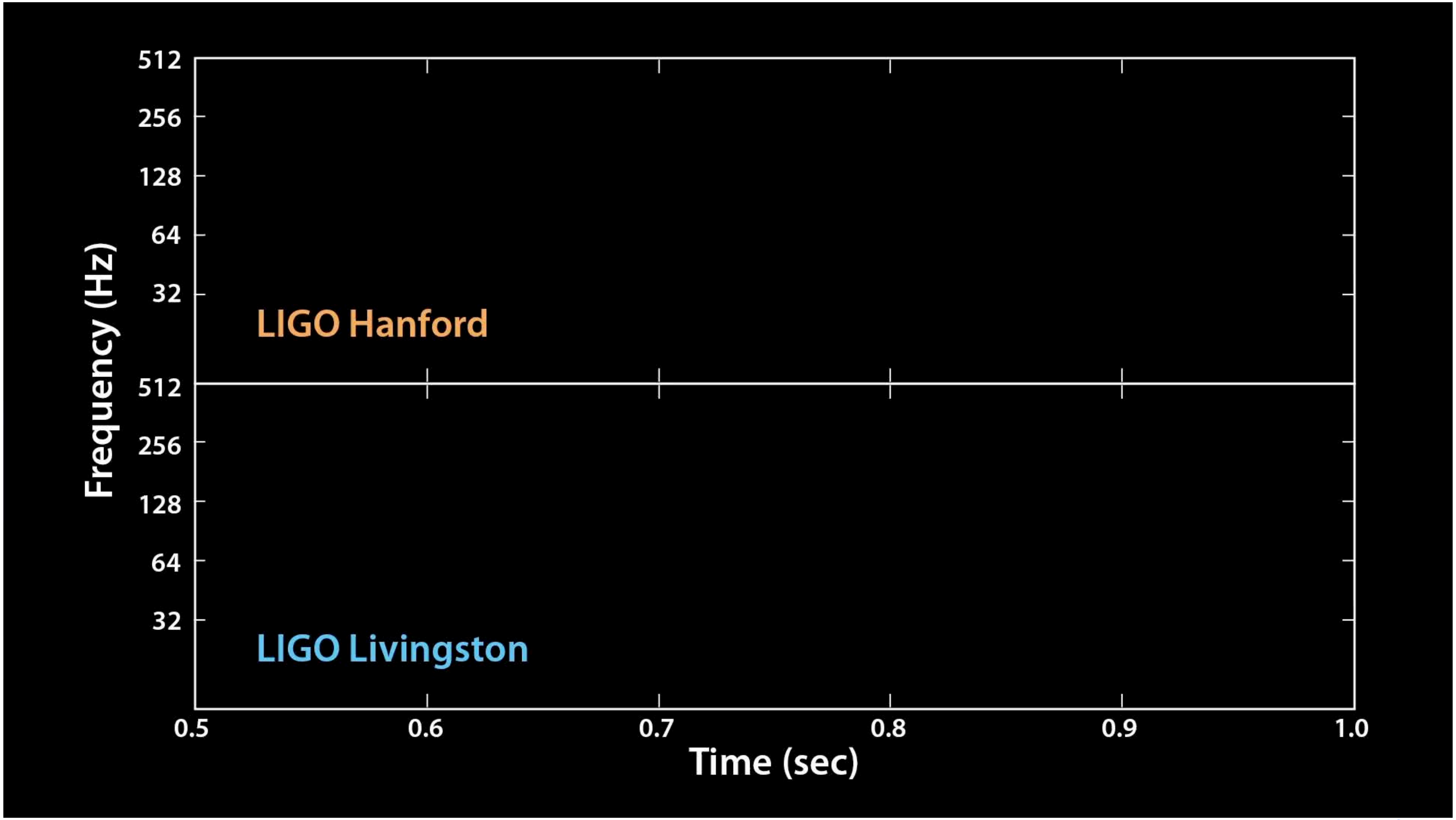
[3] GW190521 : 85$M_\odot$+66$M_\odot$→ 142$M_\odot$, 2.7~7.7Gpc, R. Abbott et al. (LIGO Scientific, Virgo), GW190521: A Binary Black Hole Merger with a Total Mass of 150 $M_\odot$, Phys. Rev. Lett. 125, 101102 (2020), R. Abbott et al. (LIGO Scientific, Virgo), Properties and astrophysical implications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

[4] GW190814 : 23.2$M_\odot$+2.6$M_\odot$→ 25.6$M_\odot$, 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)

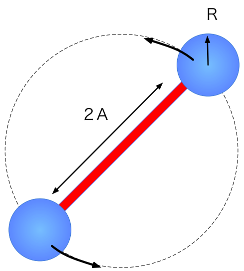
Events in O1 and O2
10 BBH and 1 BNS
heavy → strong, short



GW150914 signals



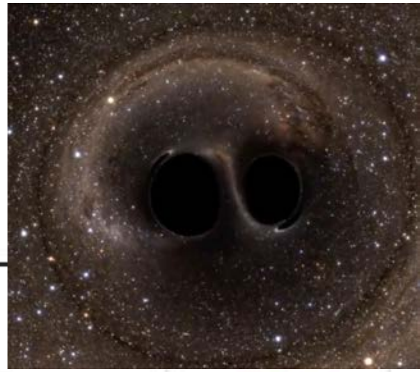
Black Hole Merger

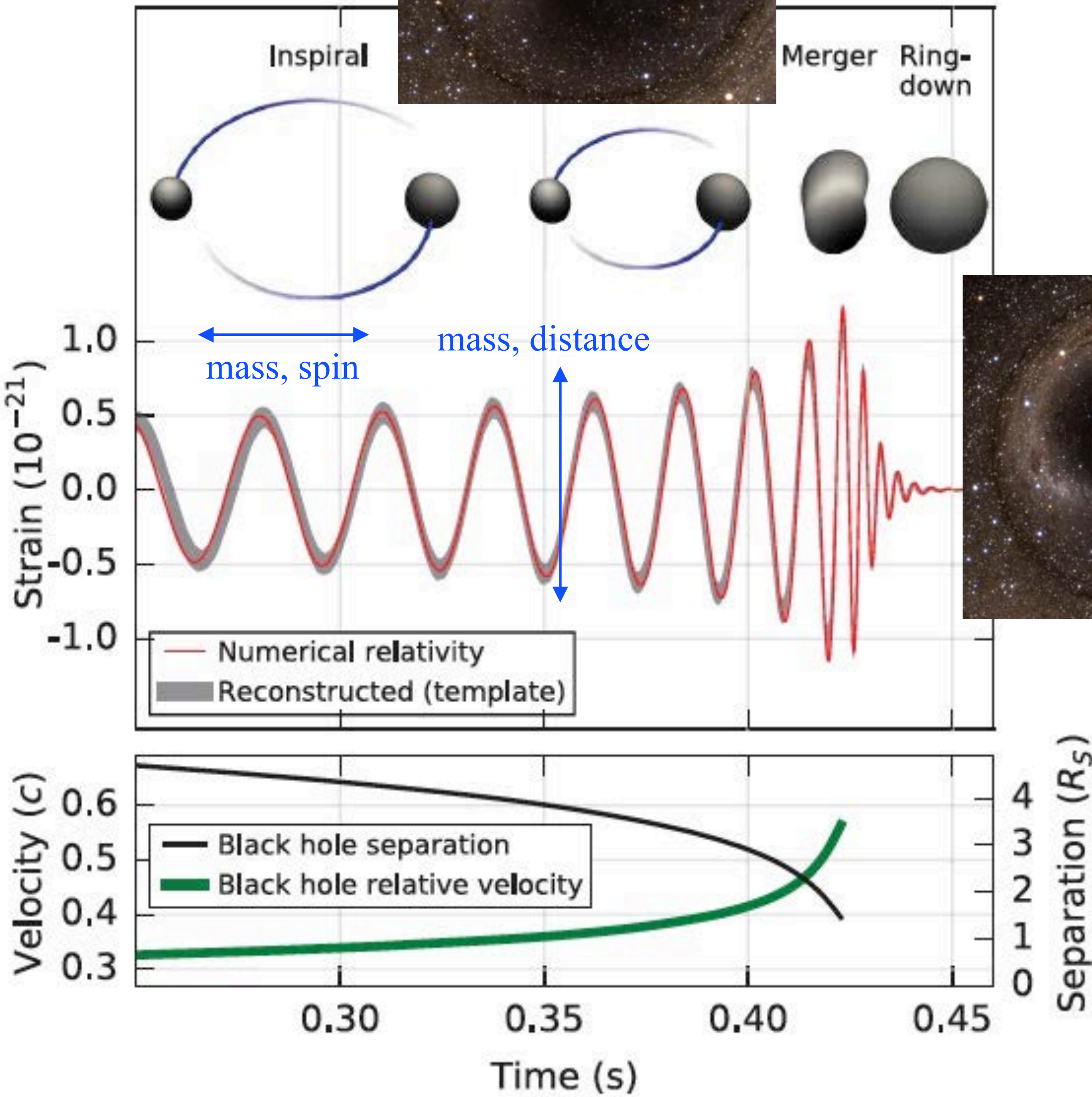


$$R_S = \frac{2GM}{c^2} \sim 90\text{km}$$

speed = A 2π f < c

A < c / 2π f ~ 500km





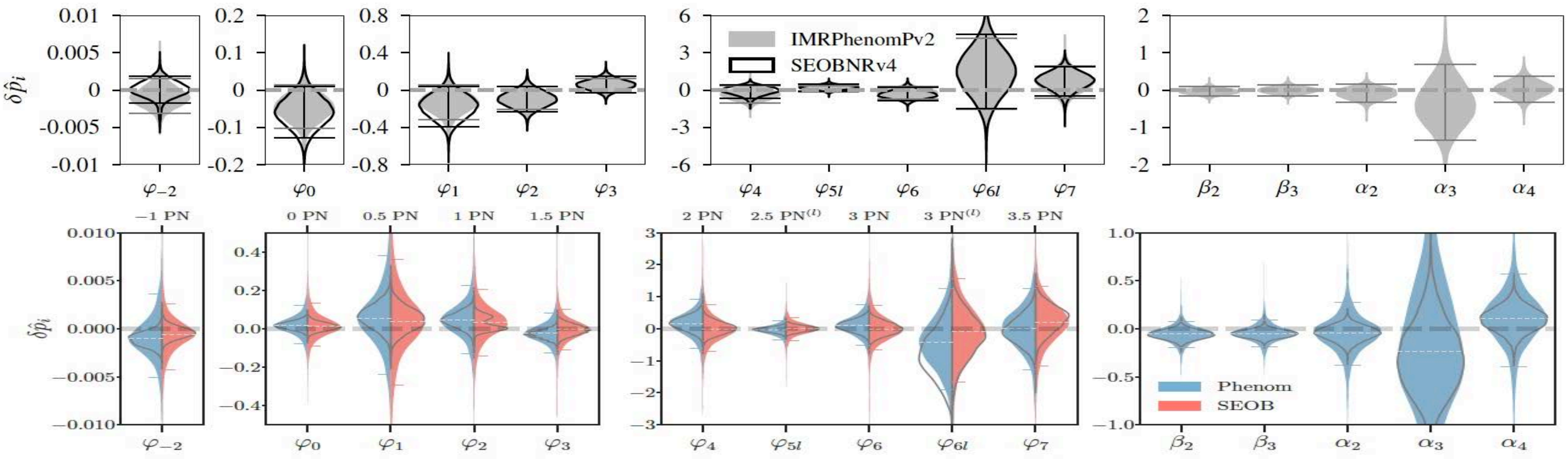
800km

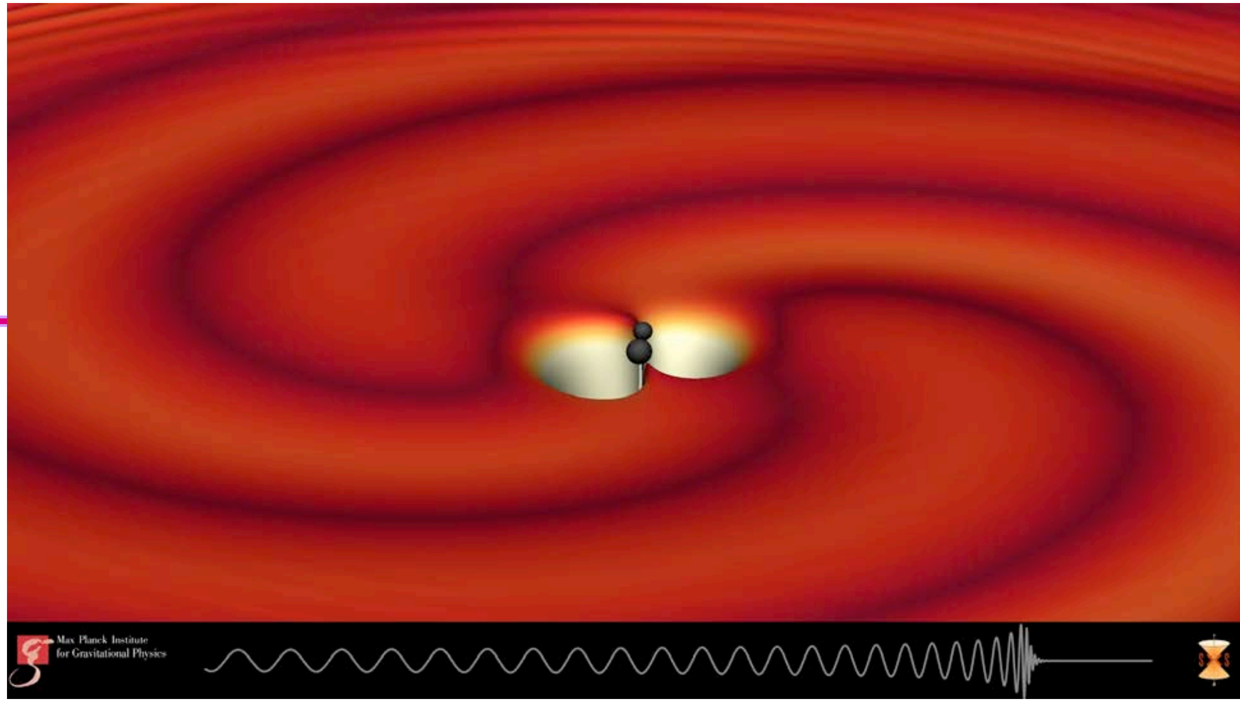
GW from Binary Back Hole merger

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 150M$\odot$
- 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 GR in strong field:
  - » Graviton mass upper limit : O1/O2:5x10^{-23} eV/c^2, O3:1.76x10^{-23} eV/c^2
  - » Violation of general relativity : O1/O2 vs O3



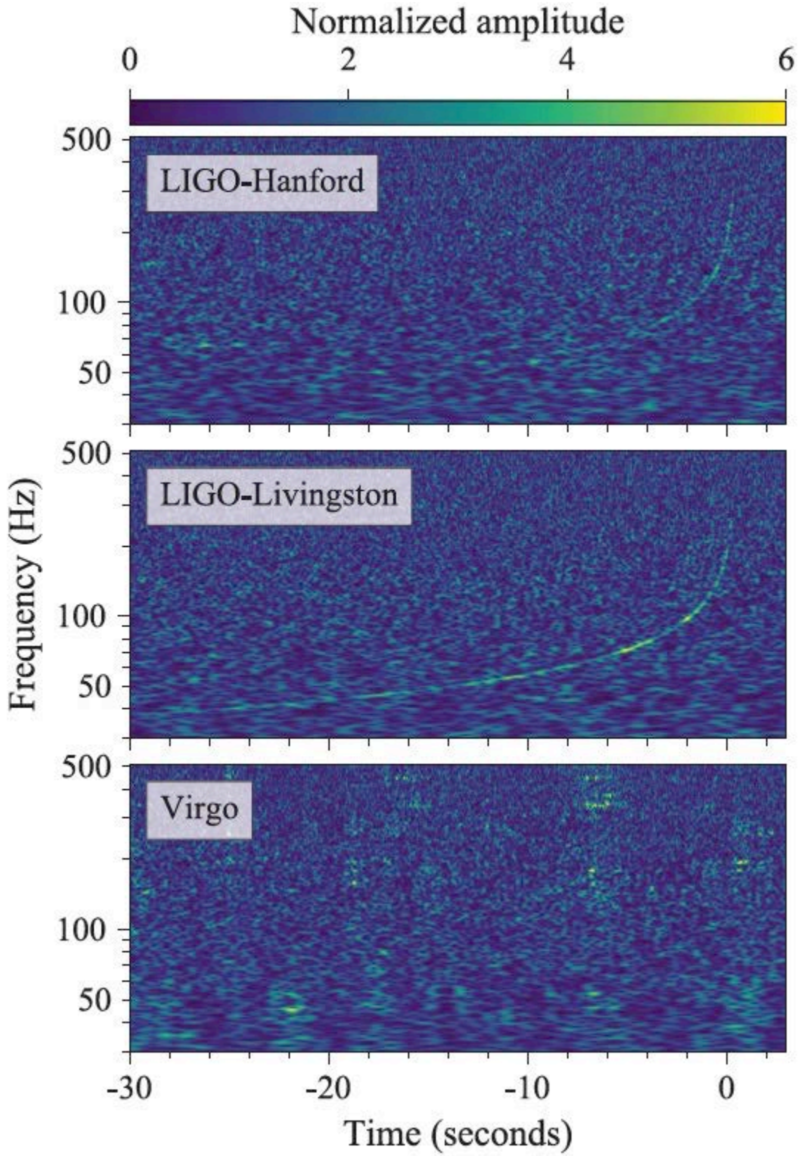


GW150914
Black hole merger

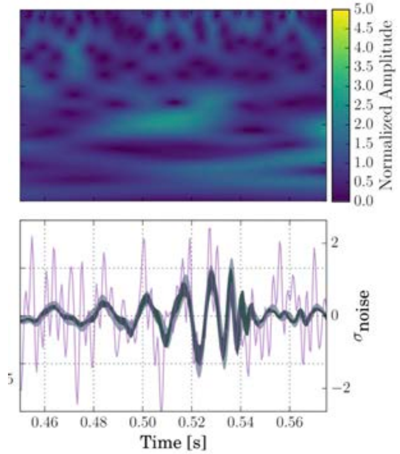
GW170817
Neutron star merger

GW170817 : Merger of neutron stars

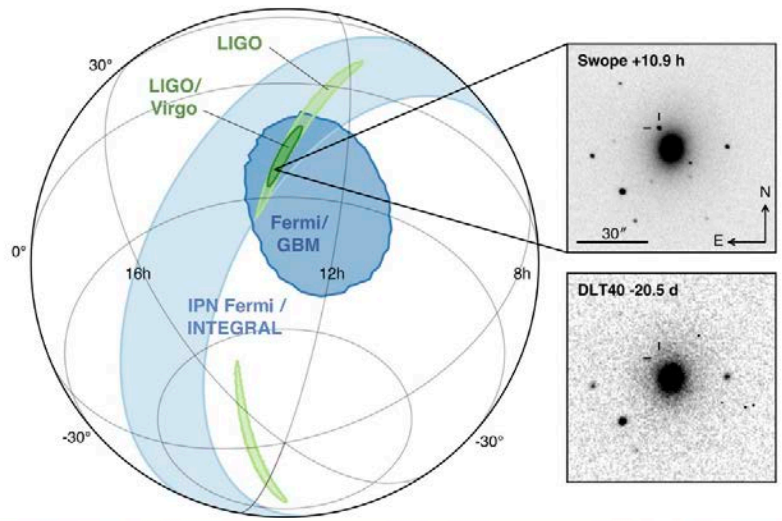
PRL 119, 161101 (2017), Astrophys. J. Lett. 848, L12 (2017)

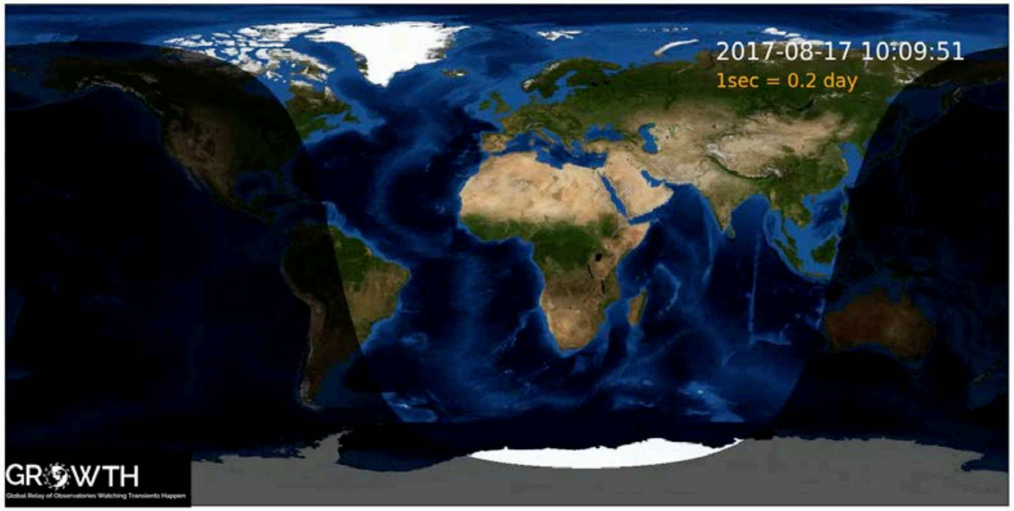


V1 GW170814



190 deg^2 (L,H) →31 deg^2 (L,H,V)

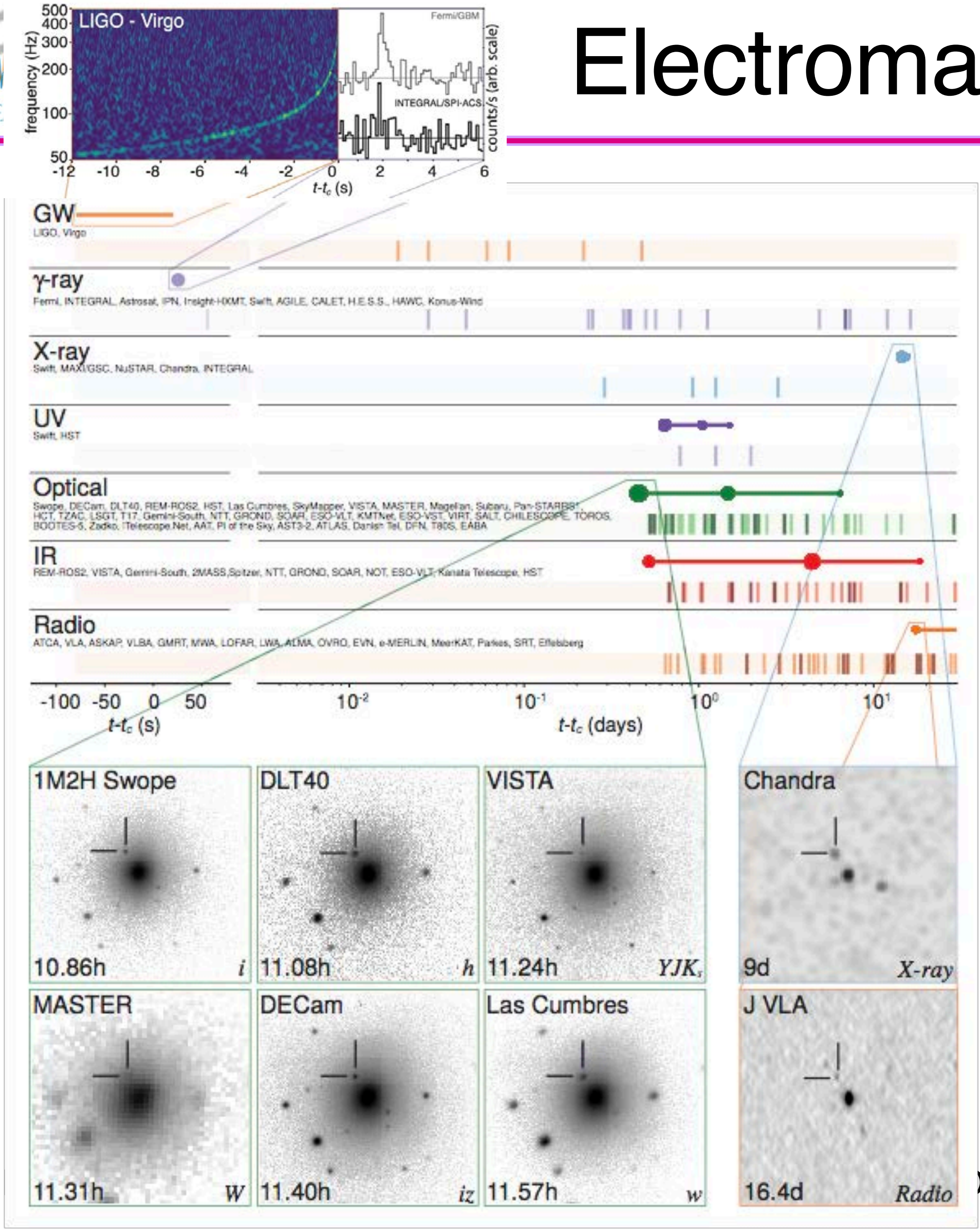


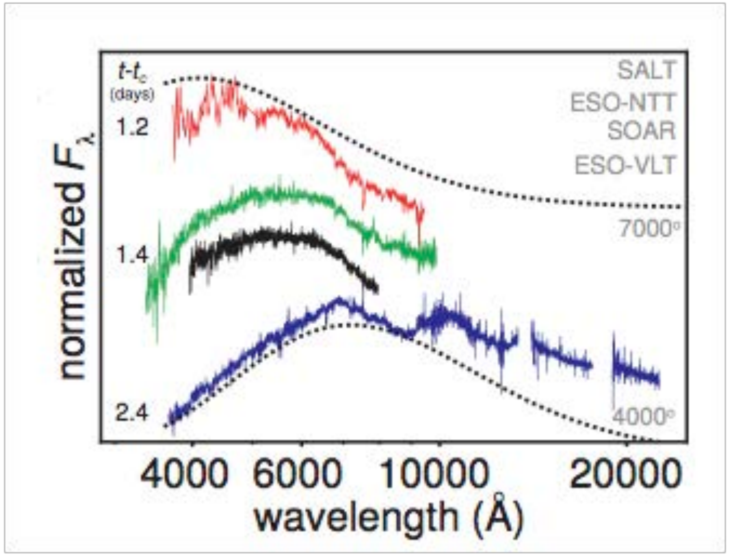


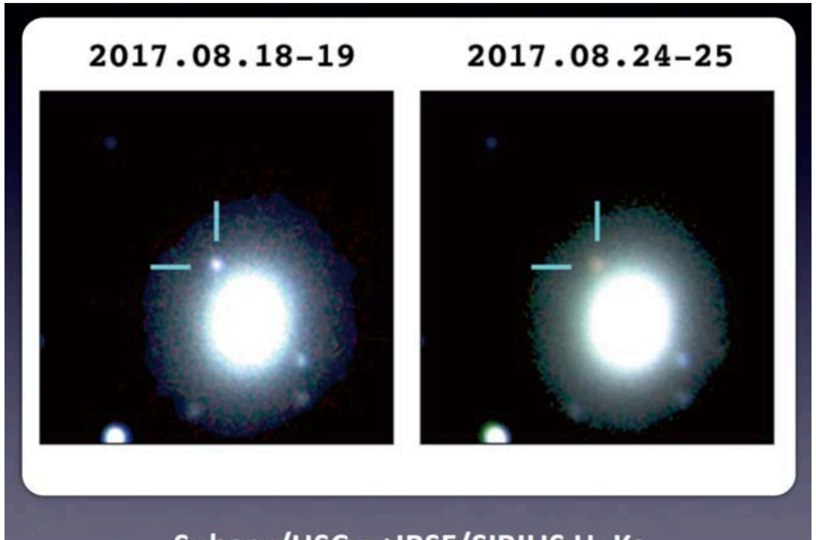
1.734 ± 0.054 sec

GW170817+GRB170817A Electromagnetic follow-up

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







Subaru/HSC z +IRSF/SIRIUS H, Ks
(Utsumi, MT et al. 2017, PASJ)

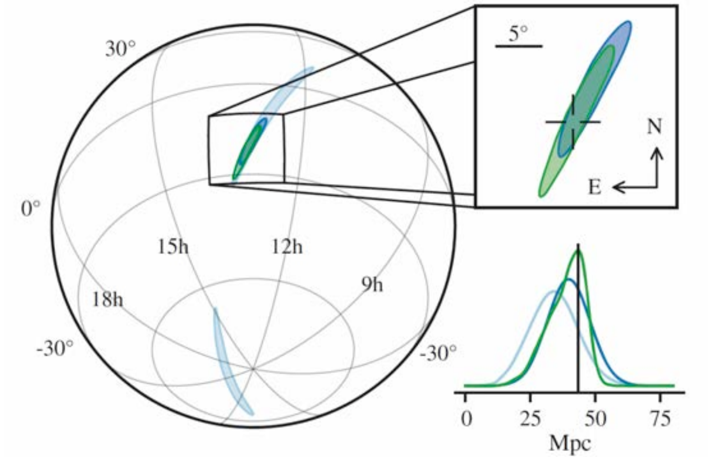
GW and EM signals from Binary Neutron Star merger

- BNS merger rate : 80-810 $Gpc^{-3}\ y^{-1}$ (BBH 15.3-38.8 $Gpc^{-3}\ y^{-1}$)
- 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 deg^2	Low-spin priors ($\lvert\chi\rvert \leq 0.05$)	High-spin priors ($\lvert\chi\rvert \leq 0.89$)
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	≤ 800	≤ 700
Dimensionless tidal deformabil	≤ 800	≤ 1400

GW190425

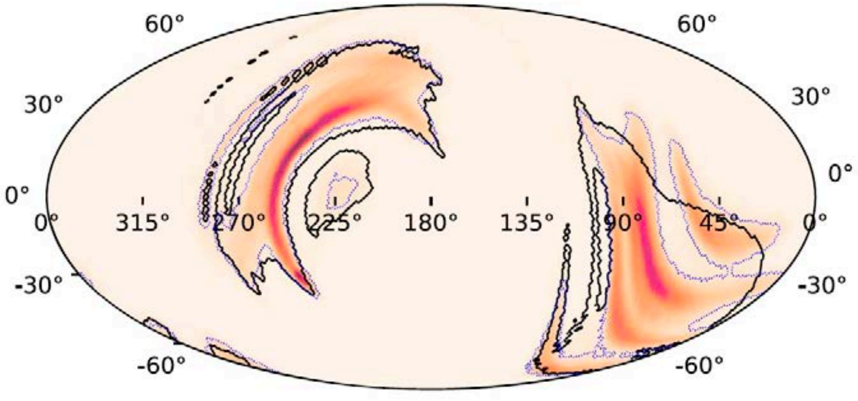
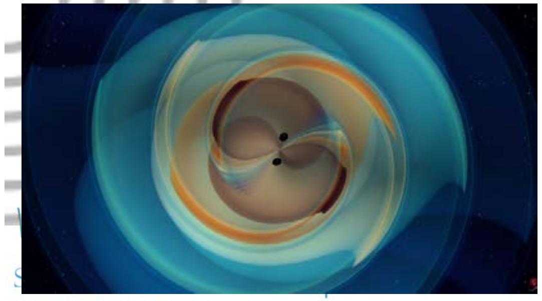
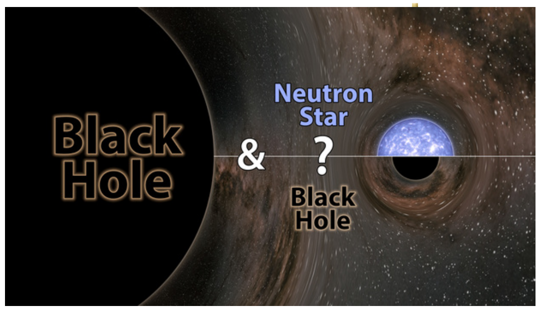


Table 1
Source Properties for GW190425

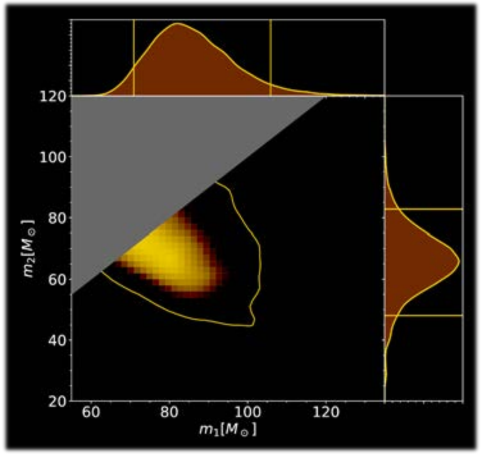
8284 deg^2	Low-spin Prior ($\chi < 0.05$)	High-spin Prior ($\chi < 0.89$)
Primary mass m_1	1.60–1.87 $M_\odot$	1.61–2.52 $M_\odot$
Secondary mass m_2	1.46–1.69 $M_\odot$	1.12–1.68 $M_\odot$
Chirp mass $\mathcal{M}$	$1.44^{+0.02}_{-0.02} M_\odot$	$1.44^{+0.02}_{-0.02} M_\odot$
Detector-frame chirp mass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



Exotic events in O3a

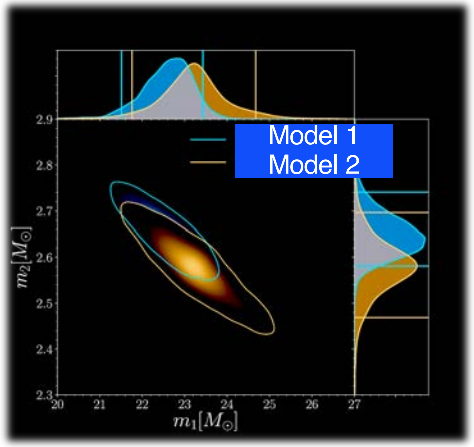


GW190521: mass of the remnant 142^{+28}_{-16} M☉ is considered an intermediate mass black hole

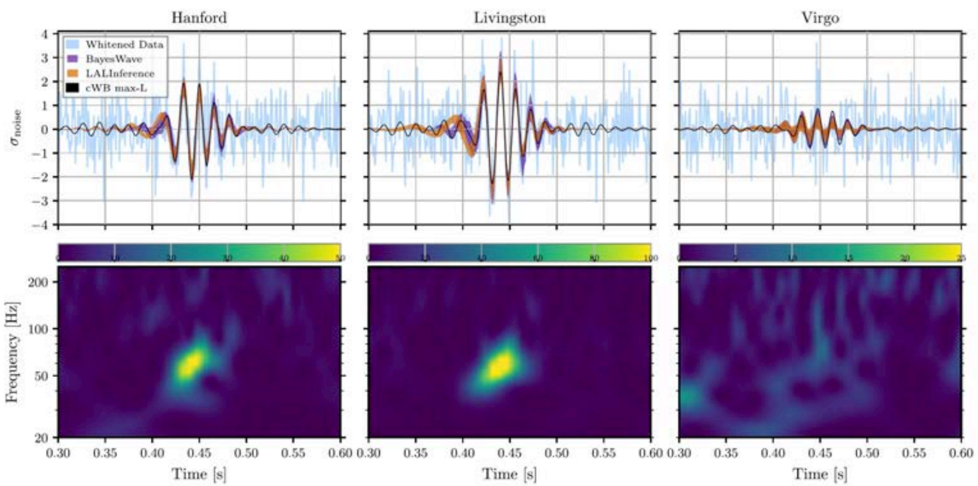


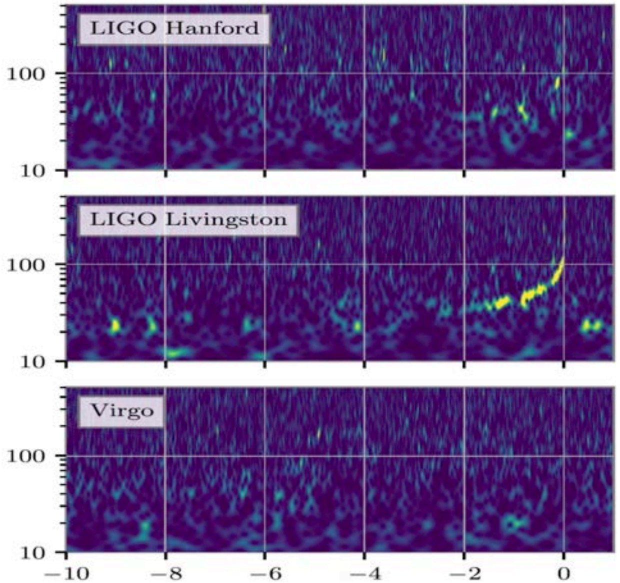
Network SNR:	15
FAR:	1 in 4900 yrs
Distance:	2.7 – 7.7 Gpc
Primary Mass:	85 M☉
Secondary Mass:	66 M☉
Remnant IMBH's Mass:	142 M☉

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



Network SNR:	25
FAR:	1 in 8.3~1300 yrs
Distance:	196-282 Mpc
Primary Mass:	23.2 M☉
Secondary Mass:	2.6 M☉
Remnant IMBH's Mass:	25.6 M☉





S/N=10.6

S/N=21.6

S/N=4.5

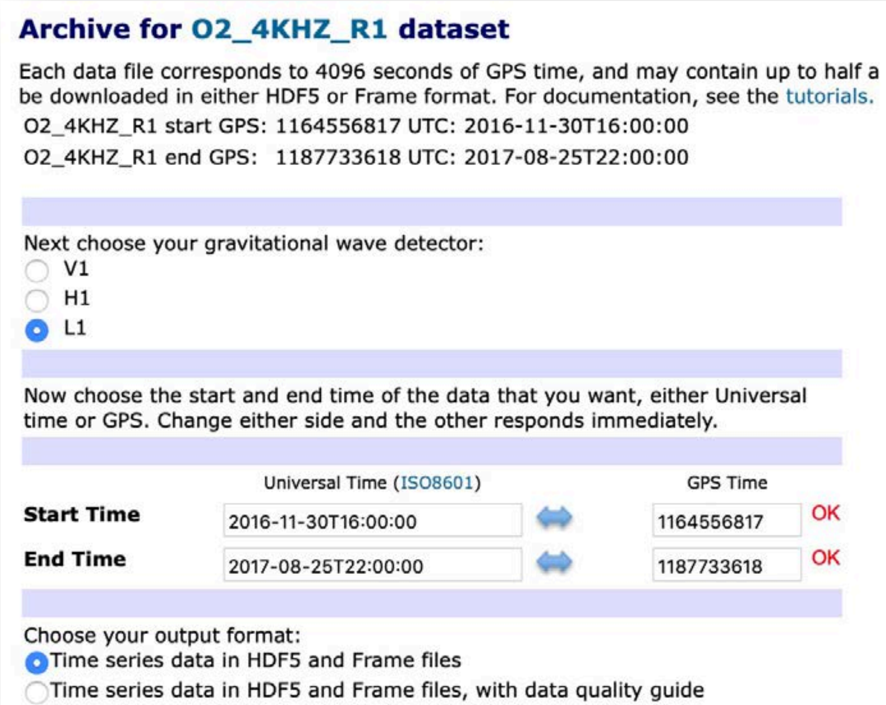
New in O3: Open Public Alerts

- 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
- openlvem 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.

Open data

- 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

Next choose your gravitational wave detector:

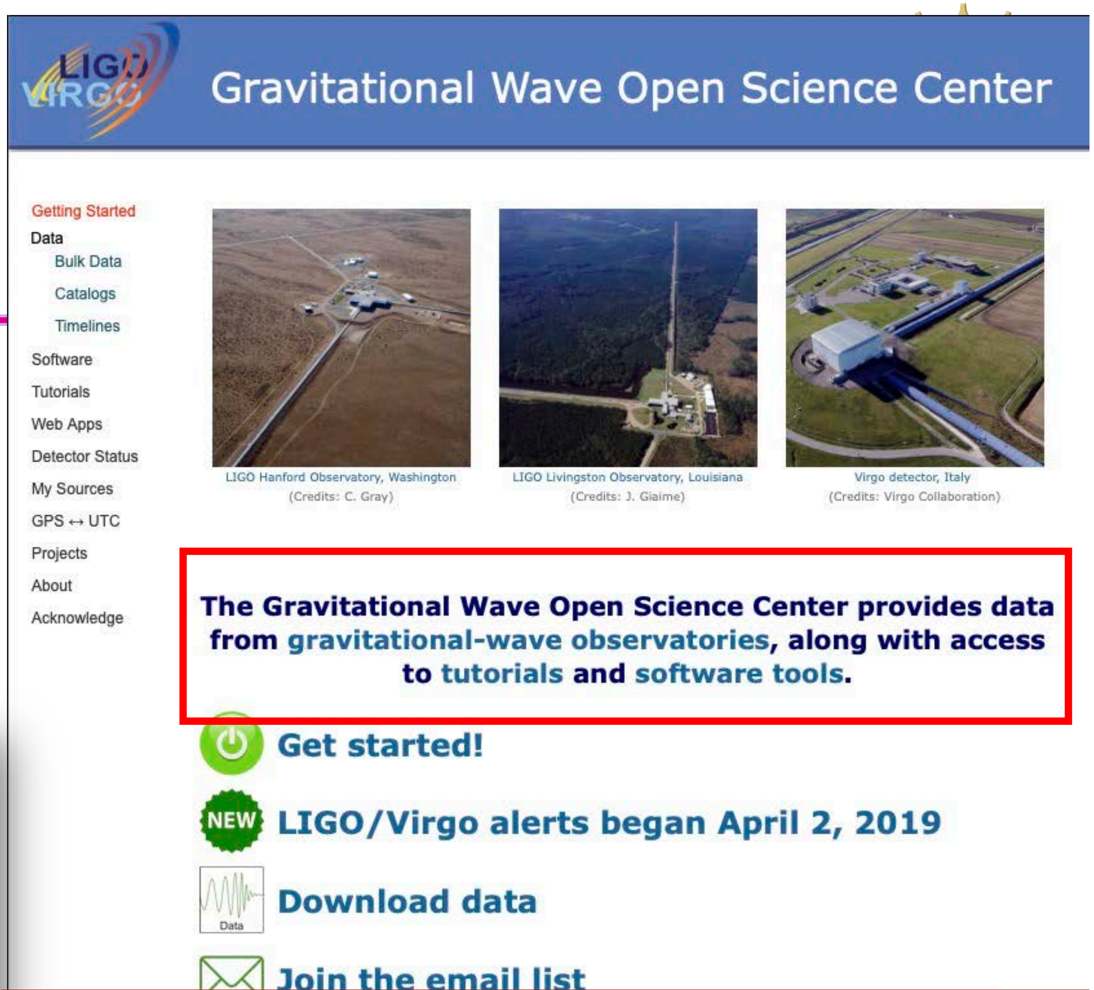
- V1
- H1
- L1

Now choose the start and end time of the data that you want, either Universal time or GPS. Change either side and the other responds immediately.

	Universal Time (ISO8601)		GPS Time	
Start Time	2016-11-30T16:00:00	⇔	1164556817	OK
End Time	2017-08-25T22:00:00	⇔	1187733618	OK

Choose your output format:

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



arxiv.org > astro-ph > arXiv:1904.07214

Astrophysics > High Energy Astrophysical Phenomena

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

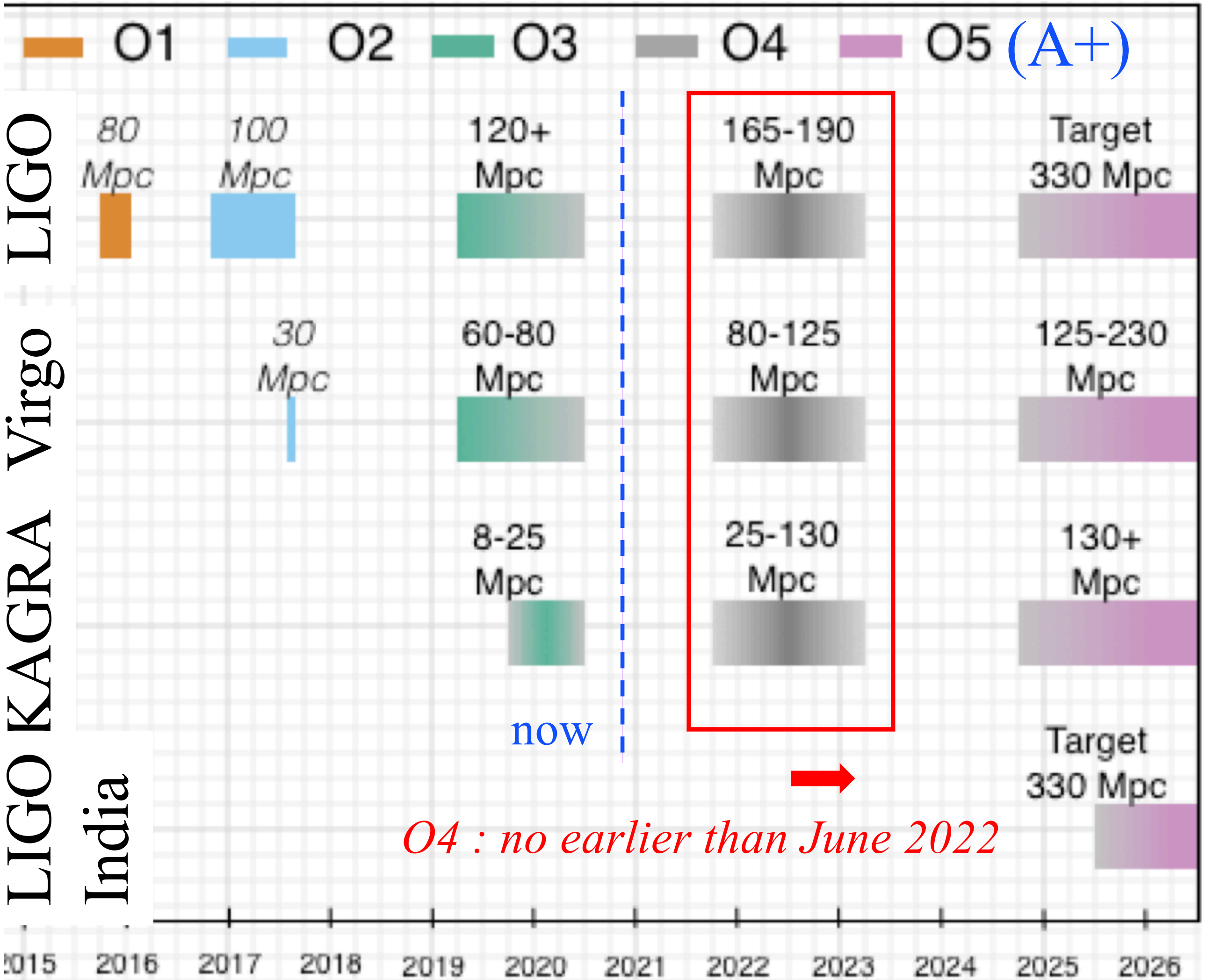
Tejaswi Venumadhav, Barak Zackay, Javier Roulet, Liang Dai, Matias Zaldarriaga

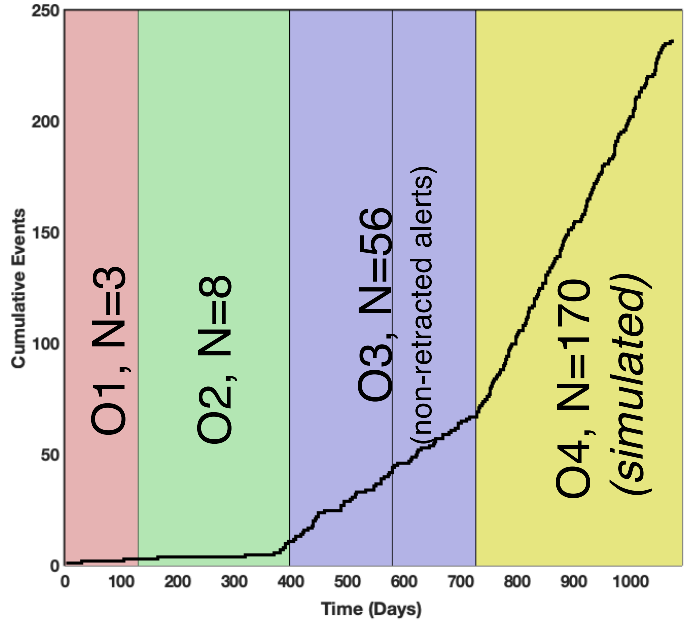
(Submitted on 15 Apr 2019)

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 $p_{\rm astro} > 0.98$. The remaining three (GW170425, GW170202, GW170403) are less certain, with $p_{\rm astro}$ 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

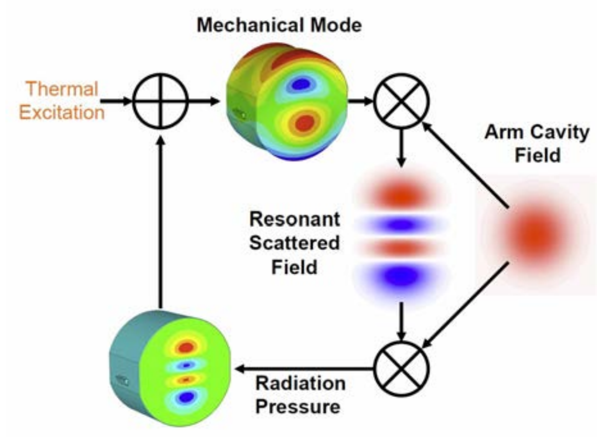
Event Stream for a one year duration O4 run

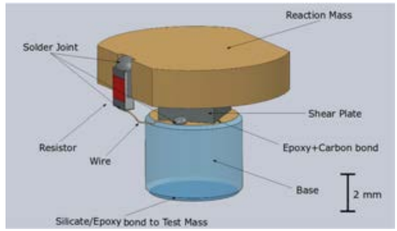
Assumptions:

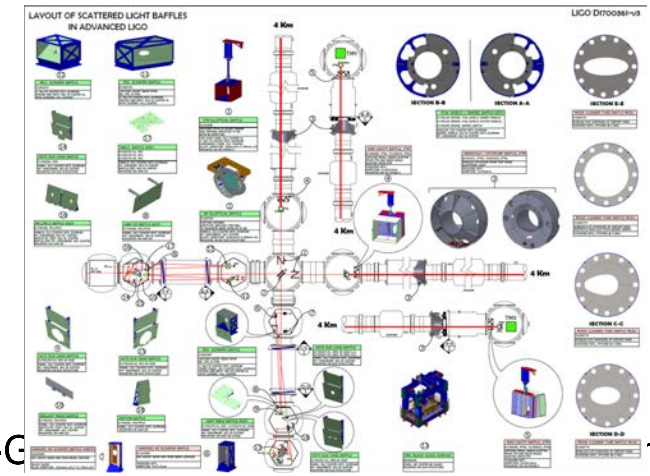
- 190 Mpc BNS range for H1, L1
- 90 Mpc BNS range for Virgo
- Same duty cycles, detector coincidence as in O3

From O2 to O3

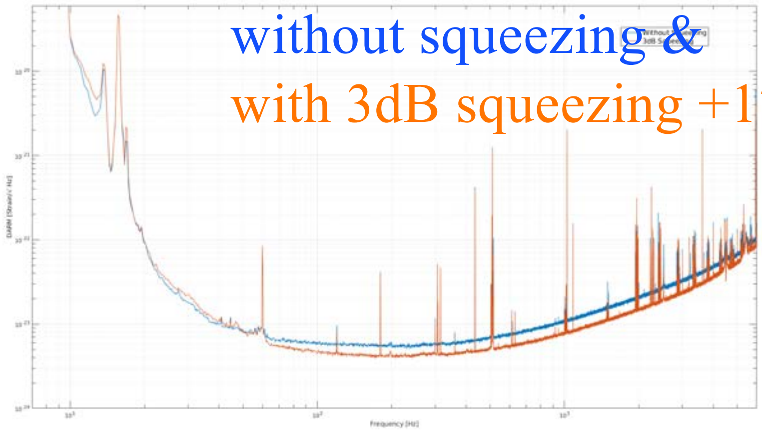
- Mitigate Parametric instability by acoustic Mode Dampers
- Laser power 25W to 50W with 3dB squeezing
- Die hard straylight mitigation





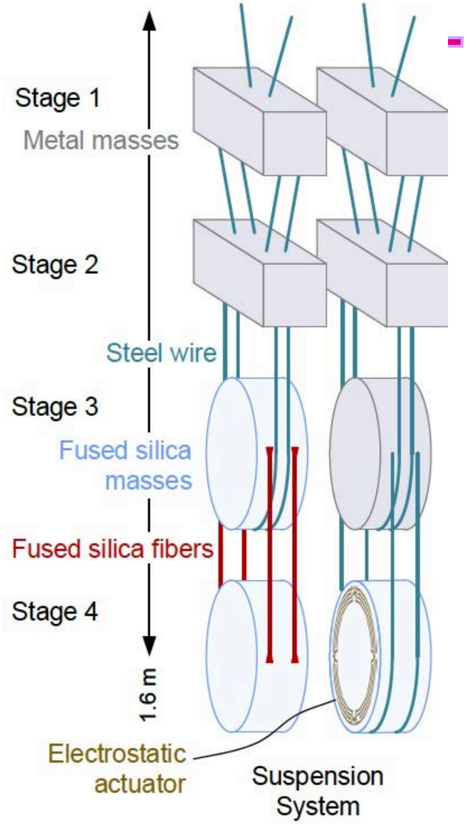


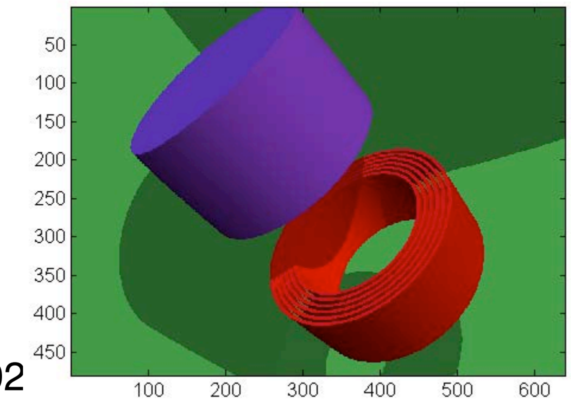
L1 sensitivity
without squeezing &
with 3dB squeezing +17Mpc



major issues
Squeeze film damping

- Small gap (5 mm) between ETM and its reaction mass increased damping from residual gas
  - Current poor vacuum level at LLO end station means this is a significant thermal noise term below ~60 Hz
  - At expected vacuum level, squeeze film damping noise will compete with radiation pressure noise at full power
- Beyond lower vacuum, the solution is a new, annular reaction mass (hole in the middle)
  - Provides same amount of electro-static drive actuation
  - Reduces damping force by a factor of 2.5x
  - Working towards possible retrofit in early 2016





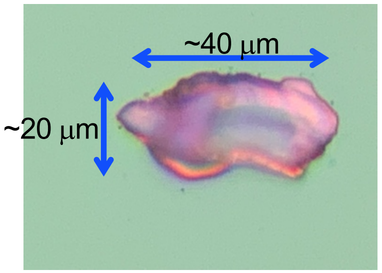
Challenge: Point Absorbers in the Test Mass Coatings

- Point absorbers (PA) on 100%* of ETMs (10 of 10), 20% of (2 of 10) ITMs
- PAs are likely embedded in the coatings; studies of witness samples find that PAs are primarily aluminum with some traces of carbon
- 3 of 4 coating vendors have PA on witness samples
  - » Many witness samples characterized during the shutdown

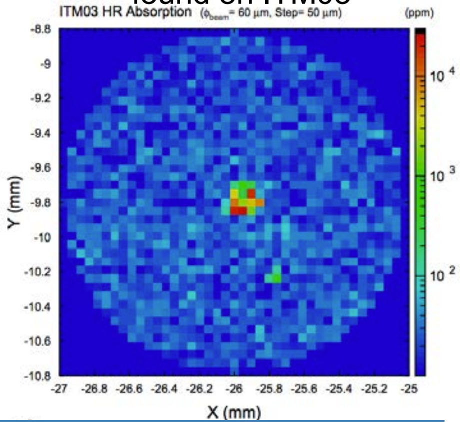
Vendor	% with PAs	# witness samples tested
V1	67%	87
V2	100%	4
V3	50%	4
V4	0%	4

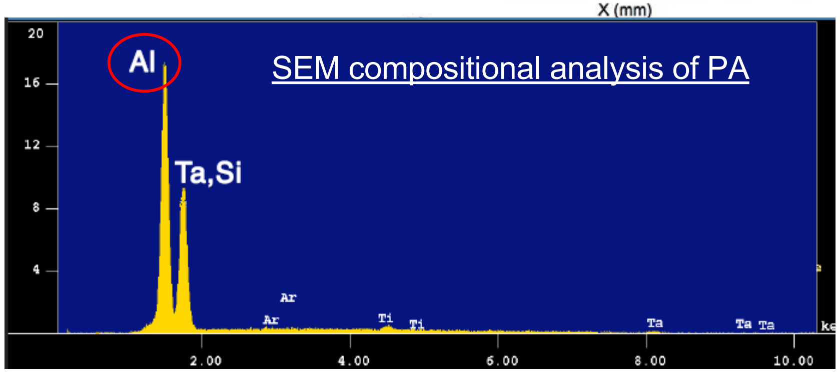
- Pursuing multi-faceted R&D approach to ‘repair’ existing test masses
  - » Ultrafast pulsed laser ablation: 2nd trial somewhat successful; no Al or C found after ablation but still absorbing. Perhaps Ta?
  - » Chemical etching: 2 compounds being tried for Al etch, beginning Ta etch
  - » Mechanical 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

500 ppm absorber on ETM14

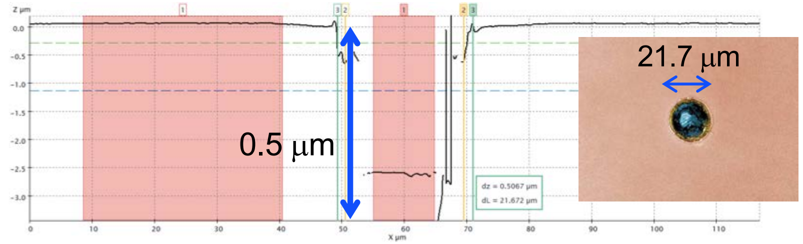


High Res scan of 1000 ppm PA found on ITM03



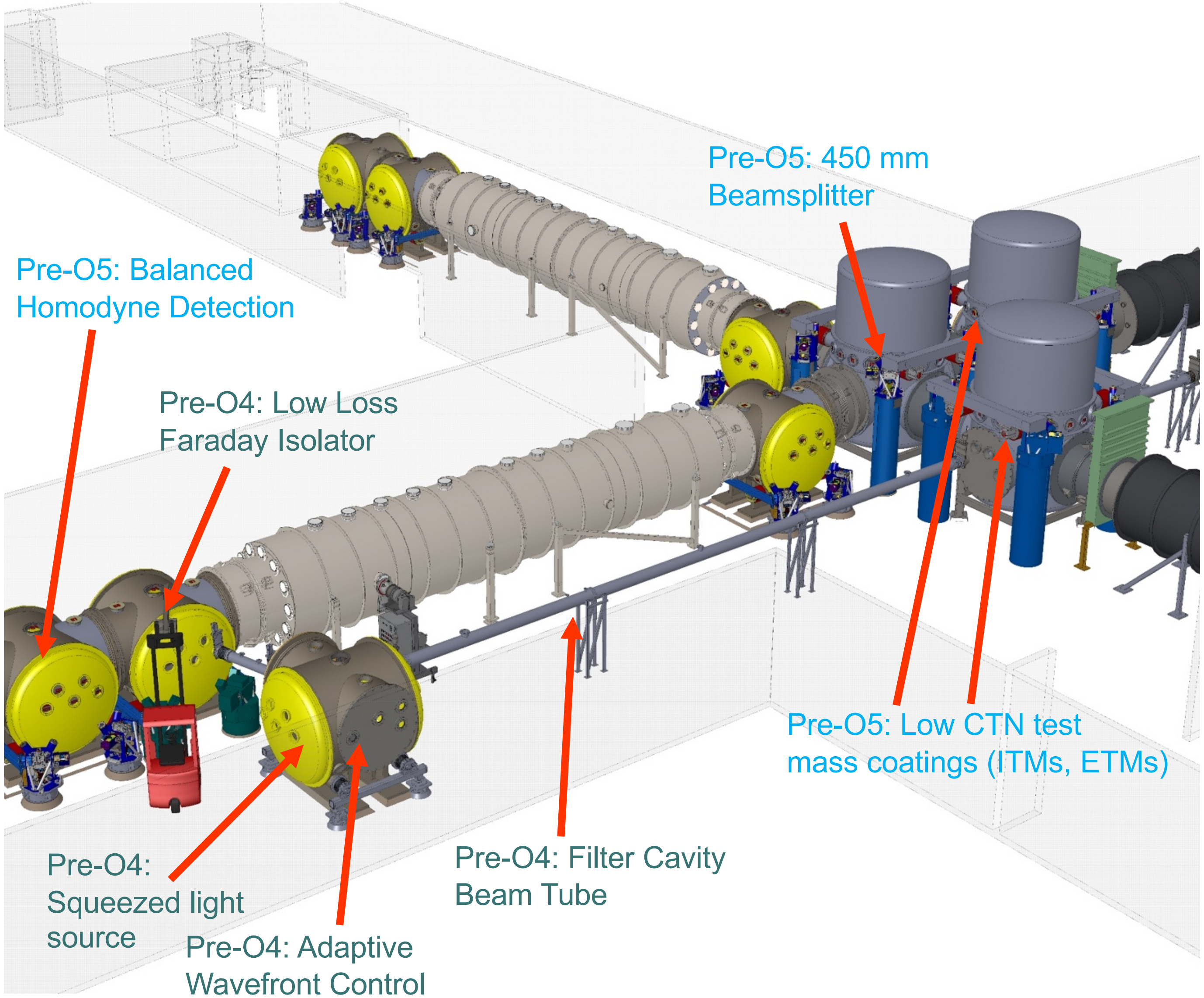


Test of Femtosecond Laser Ablation of PAs



A+ Project

- A Joint US-UK-Australia funded project
  - » US budget: $20.5M
    - – $8.0M spent/committed to date
- Pre-O4
  - » BNS Target Sensitivity: **190 Mpc**
  - » 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-O5
  - » O5: Test mass low thermal noise coating development

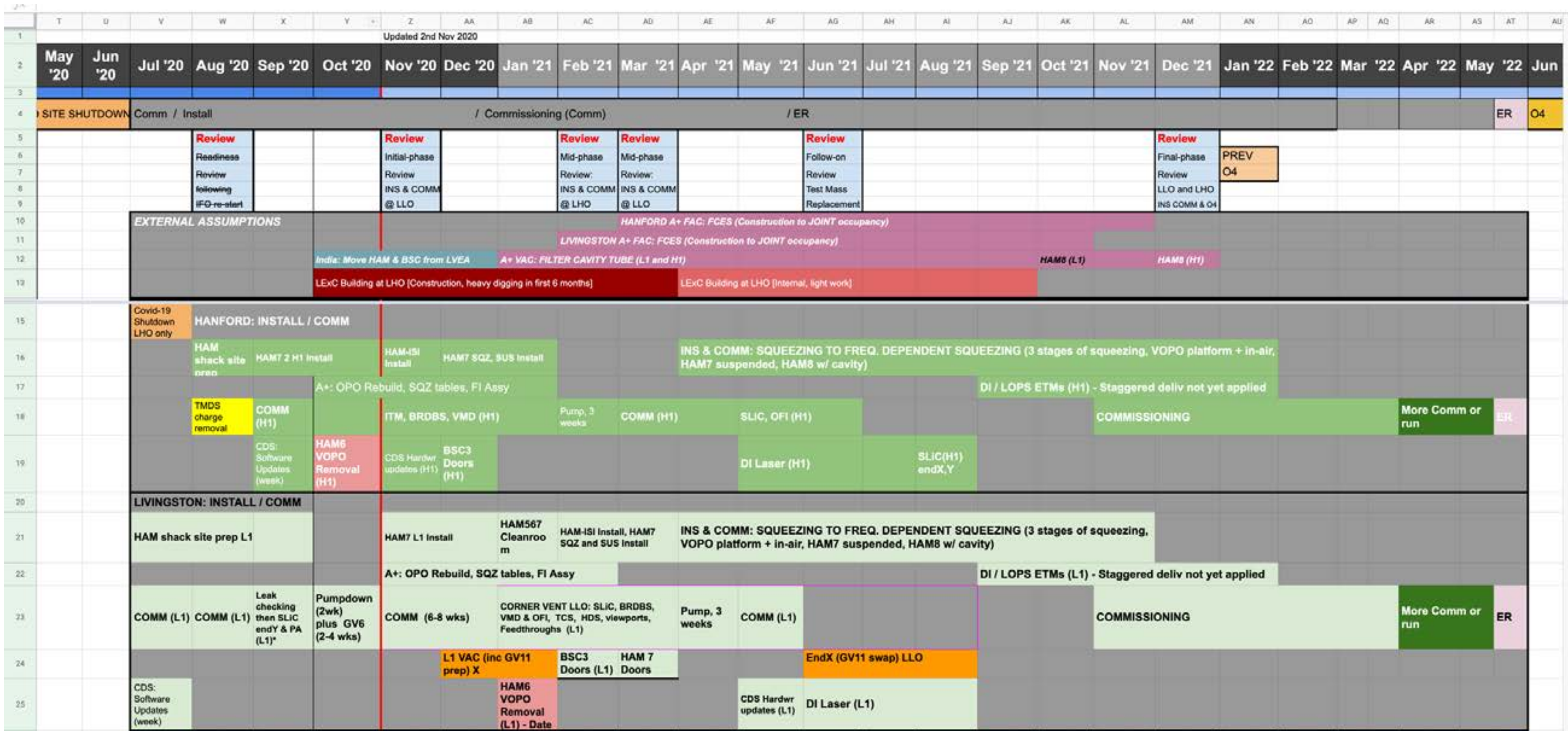


O4: Planned Detector Improvements

Project/WBS	Program Plan [Combination 1]	Fallback [Combination 2]
Operations	Continued refurbishment of LIGO Vacuum System	
Operations	*Replace Test Masses* ***that have <u>point absorbers</u>***	
Detector Improvements	Additional Stray Light Baffles [Scattered light noise<200 Hz]	
Detector Improvements	High power laser (new laser amplifier) [Lower shot noise]	
A+ Project	High-efficiency Faraday isolators	
A+ Project	Adaptive mode 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*



Brownian noise predictions

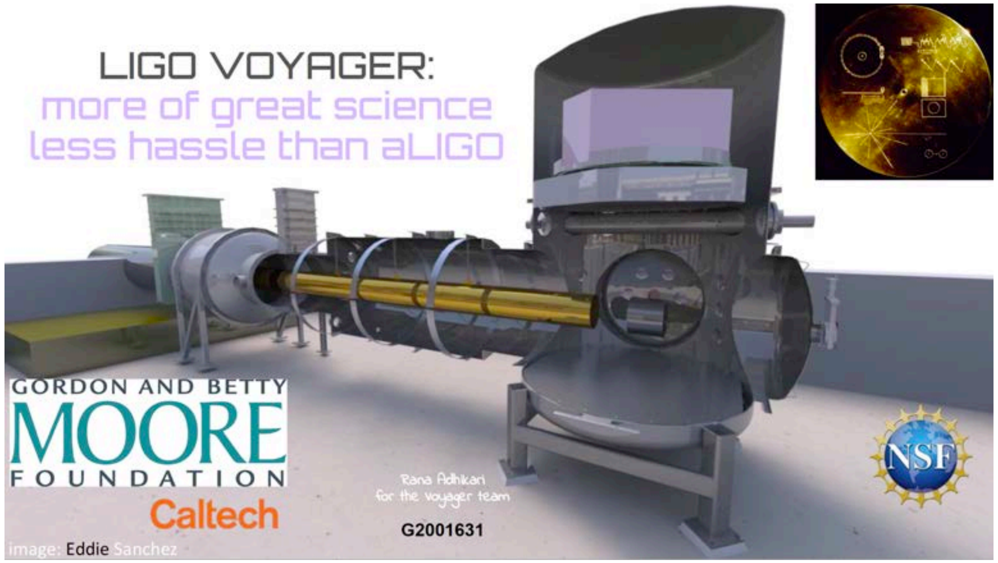
Gabriele Vajente, G2001684,OWG 2020LVK

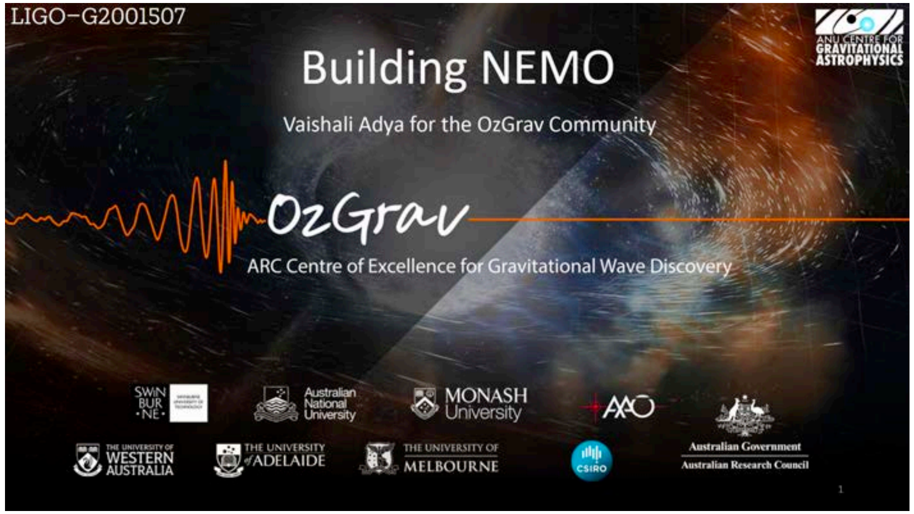
Material	Y [Gpa]	ϕ [10^{-4}]	n	ETM Num. layers	ETM Brownian noise 10^{-20} m/√Hz @100Hz	ITM Num. layers	ITM Brownian noise 10^{-20} m/√Hz @100Hz	Total Brownian noise 10^{-20} m/√Hz @100Hz	Ratio w.r.t. A+ design 0.66 x 10^{-20} @100Hz
Titania-doped tantala (aLIGO)	124	3.6	2.07	38	0.65	16	0.46	1.13	**1.71**
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**

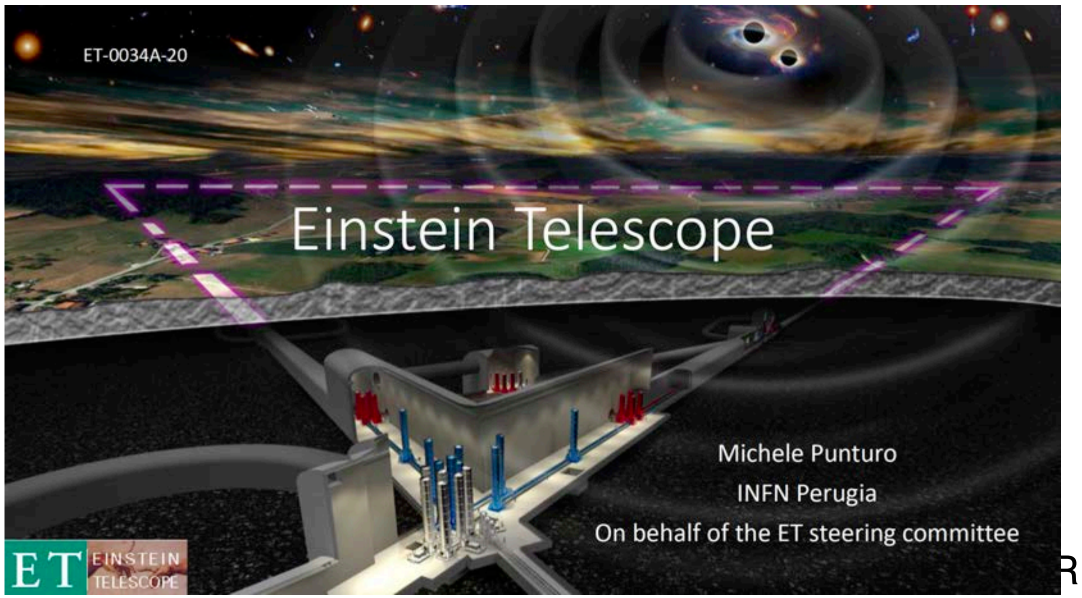
Using silica parameters: Y = 72 GPa, n = 1.45, ϕ = 0.23 x 10^{-4}

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

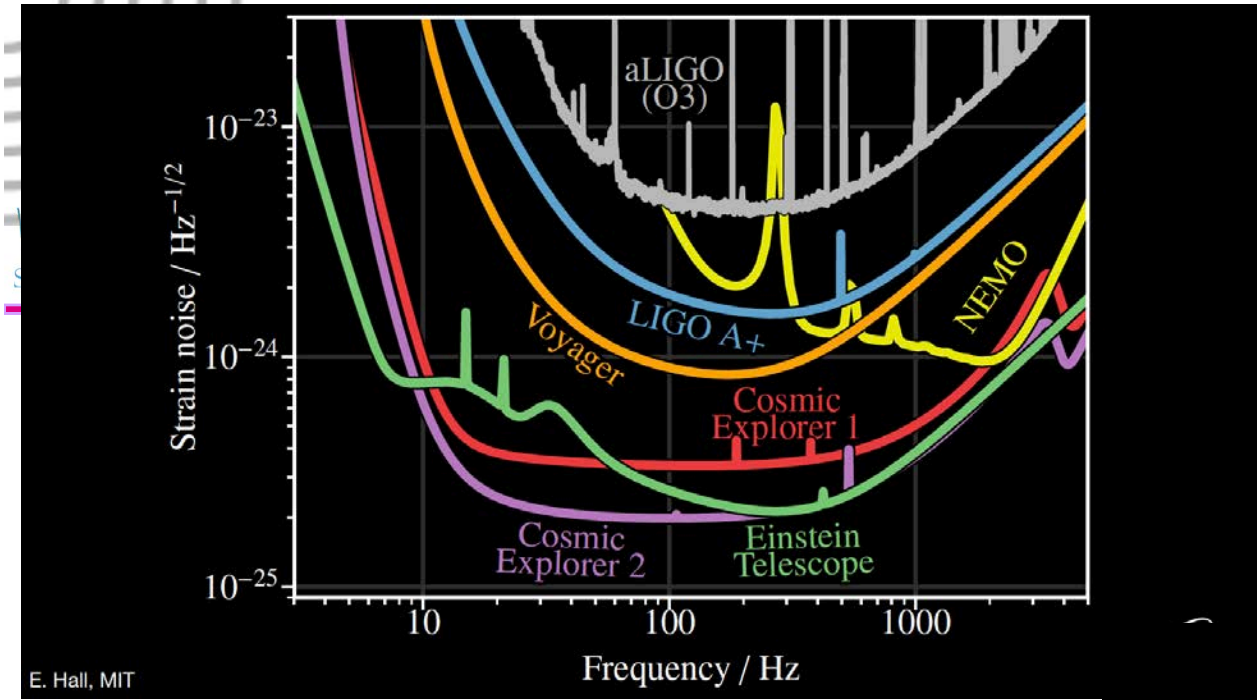
3rd generation ground-based GW detectors



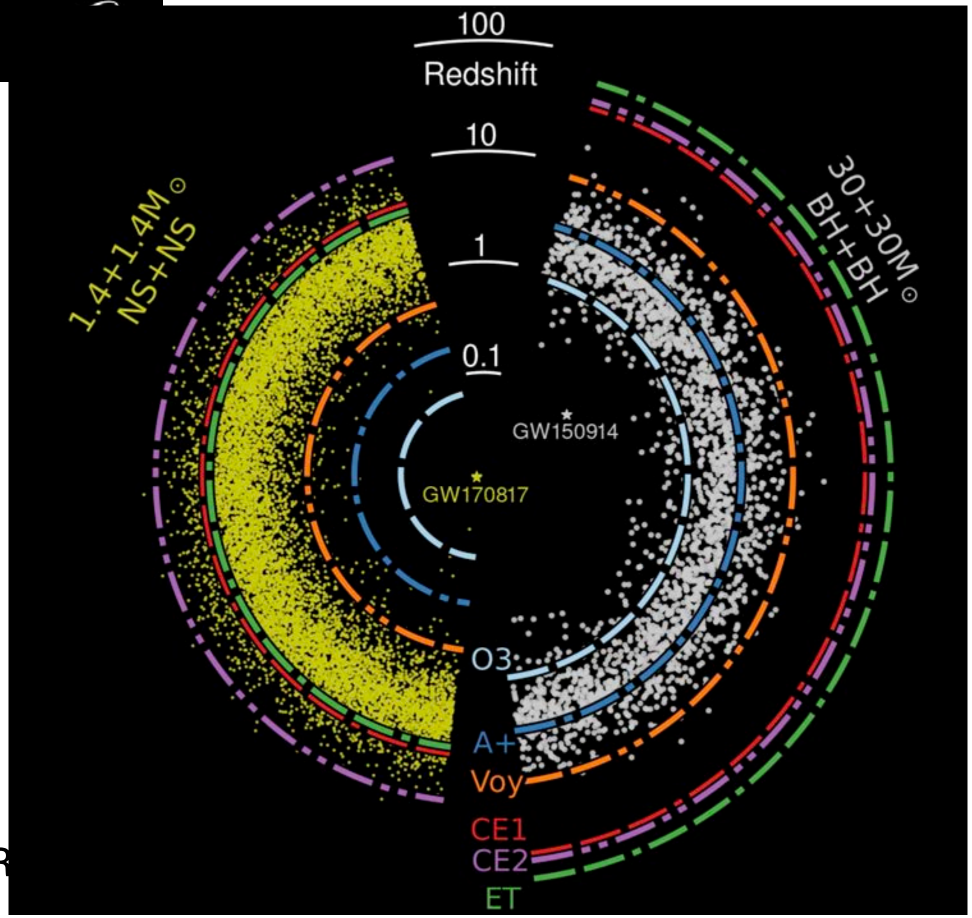




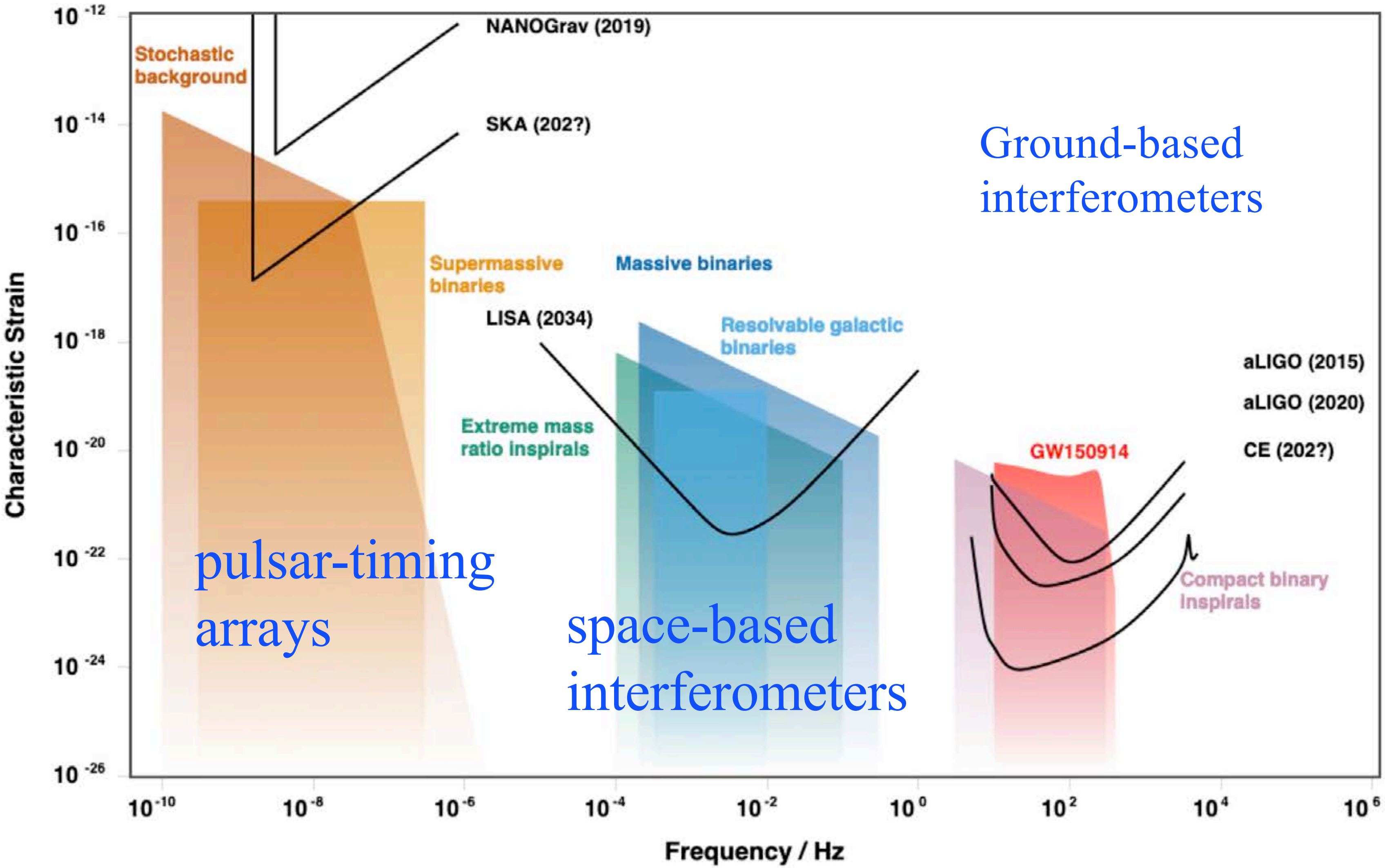
Comparing Detectors



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



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



US 3rd generation ground-based interferometer timeline