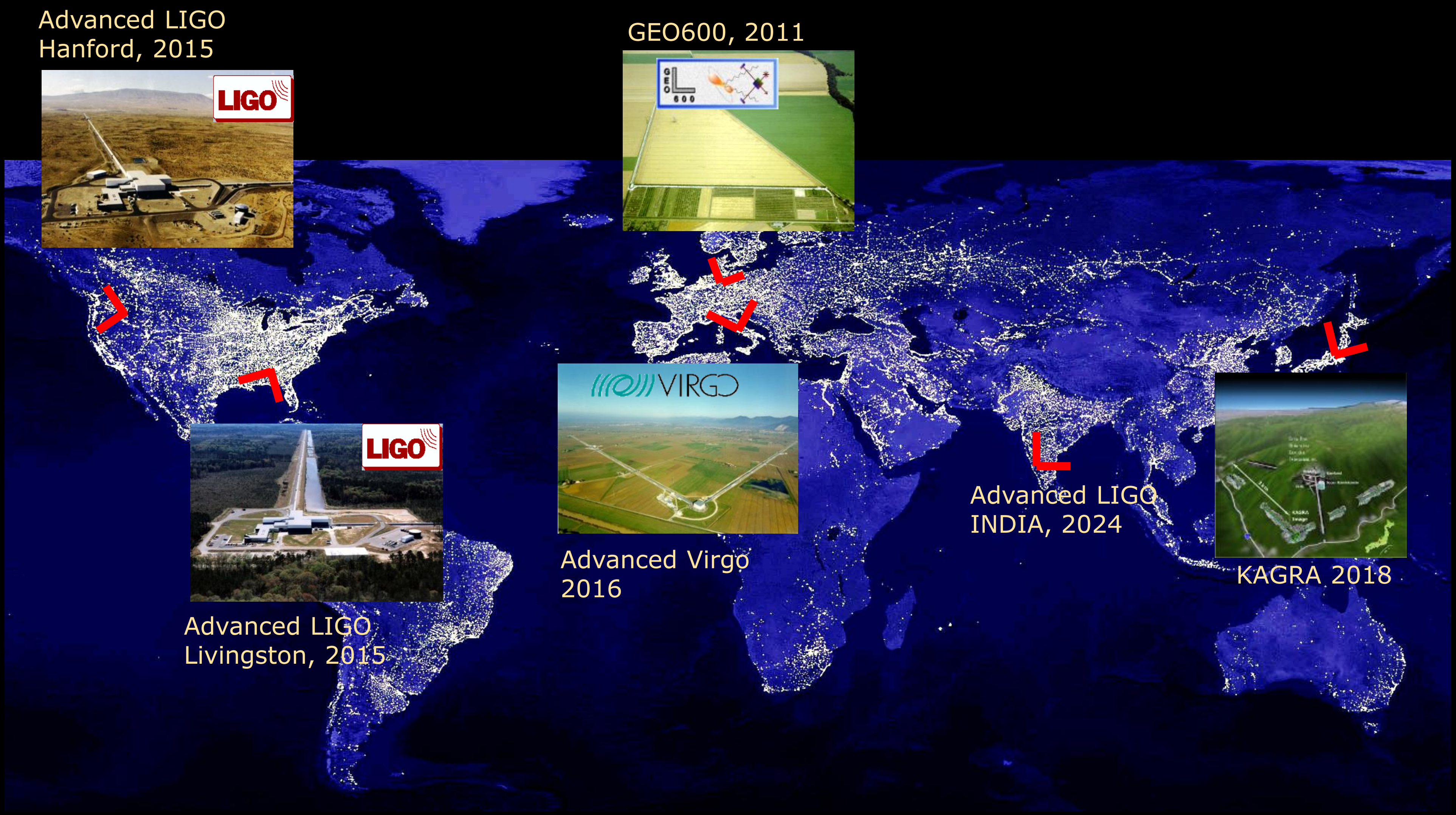
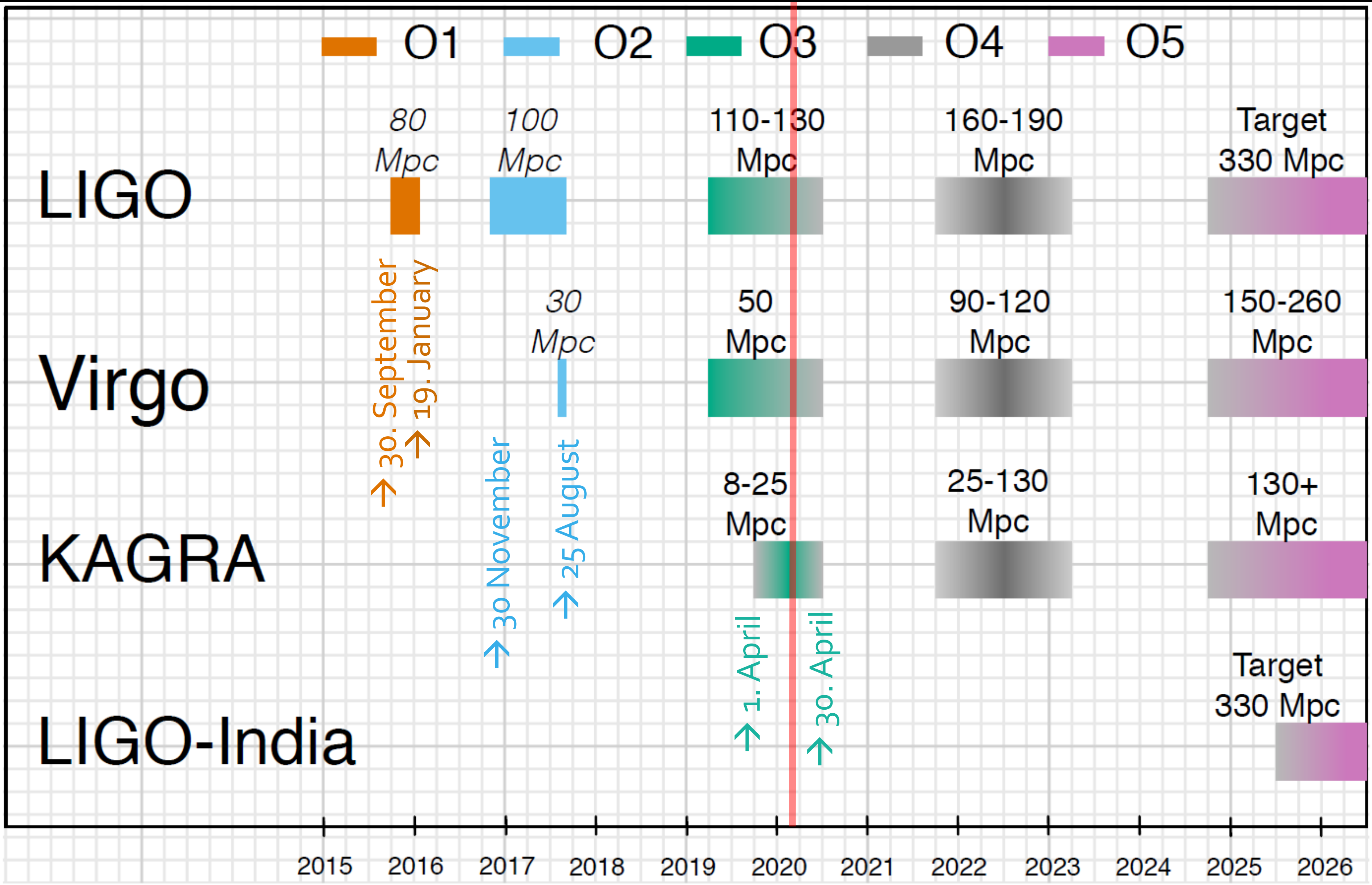
GW Highlights

Harald Lück
AEI & LUH

The advanced GW Network



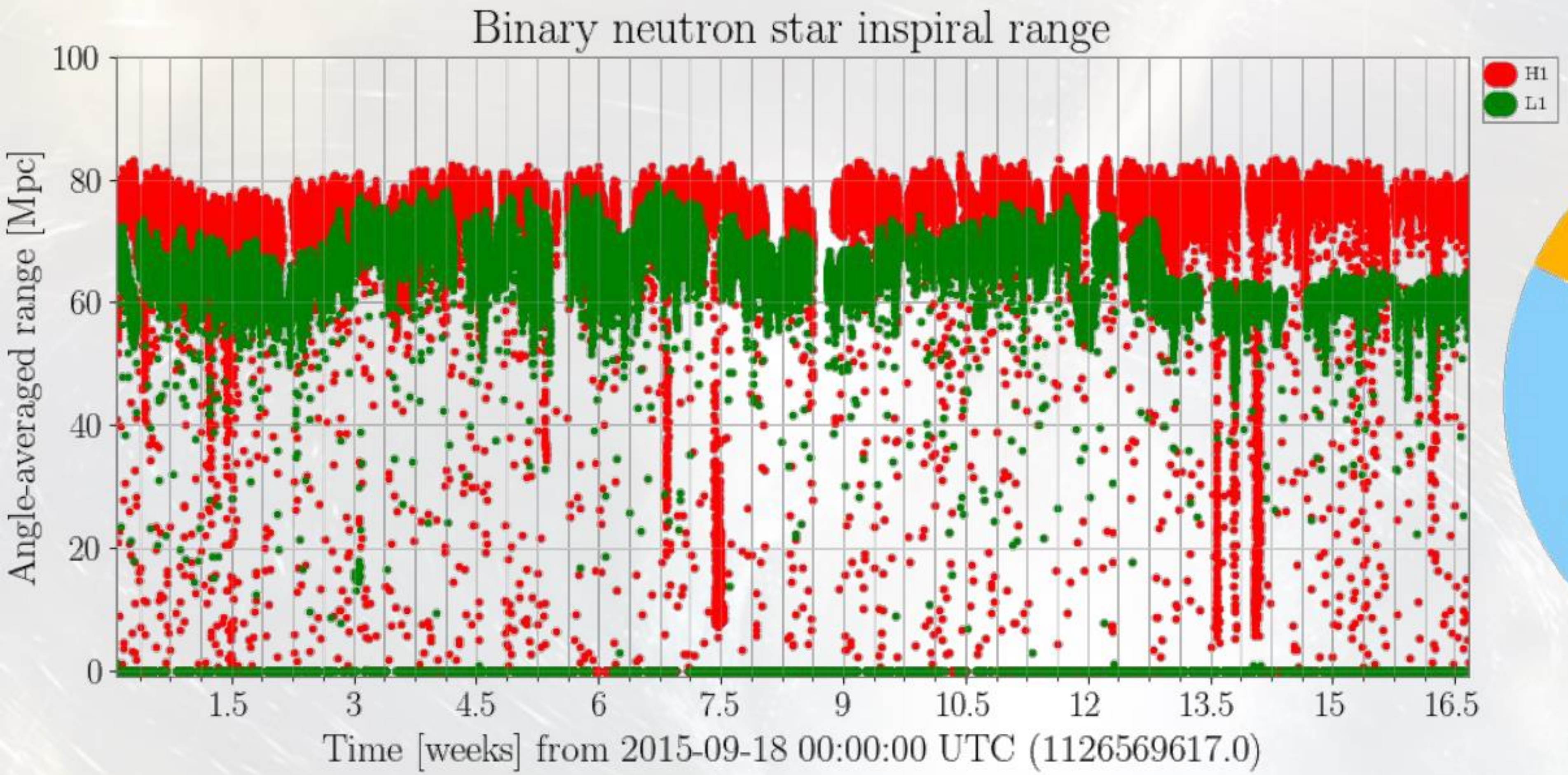
Timeline Observation runs Advanced Detectors

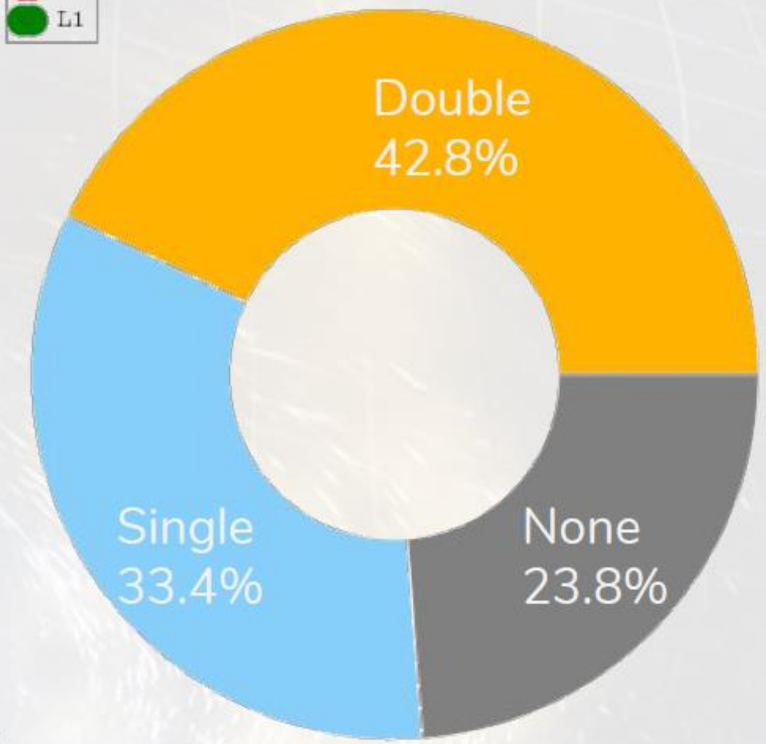


Timeline

O1

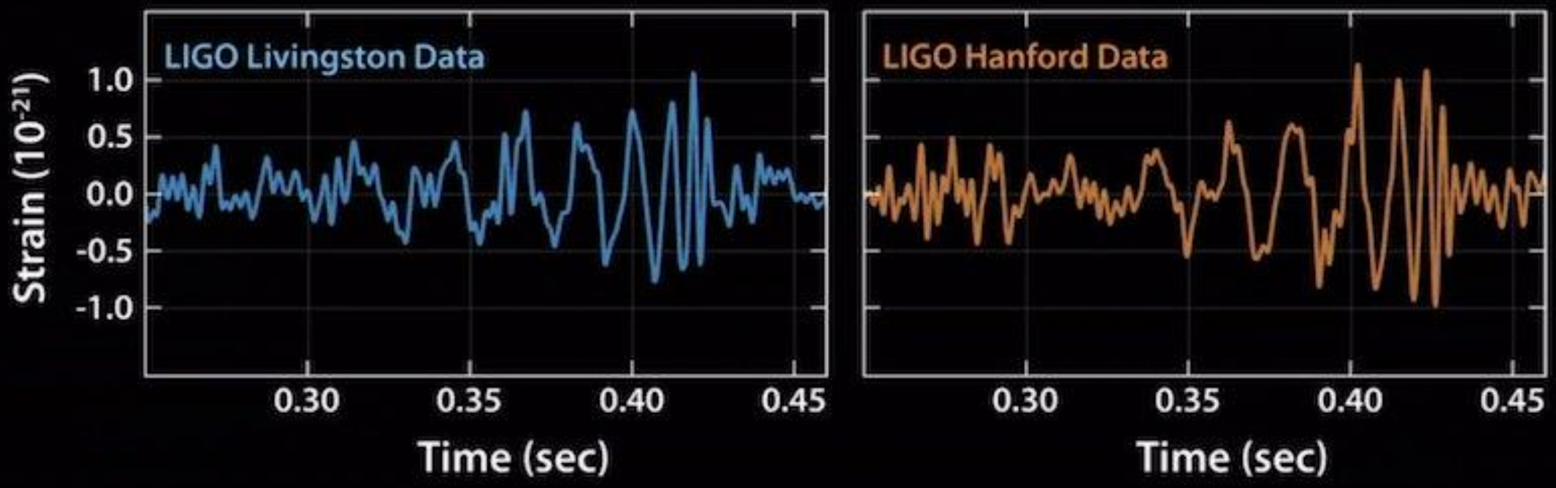
Sept ‘15 -- Jan ‘16

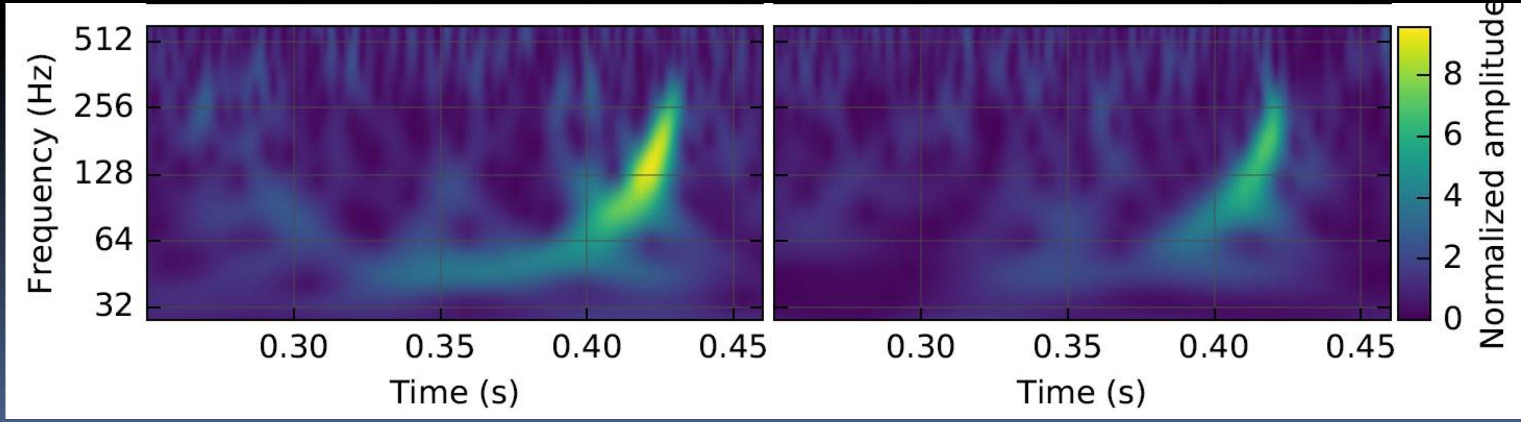


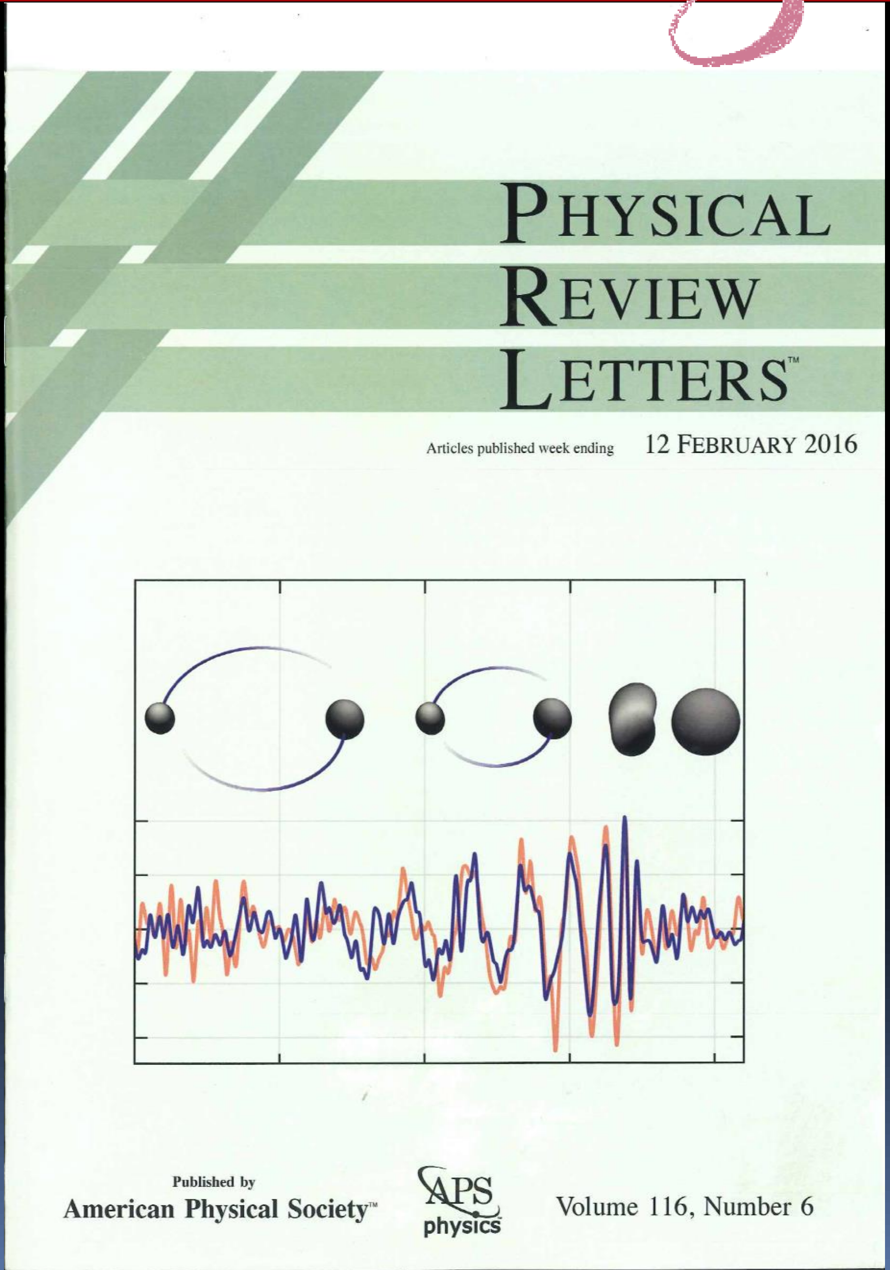


From: Chad Hanna, October 7, 2019

GW150914

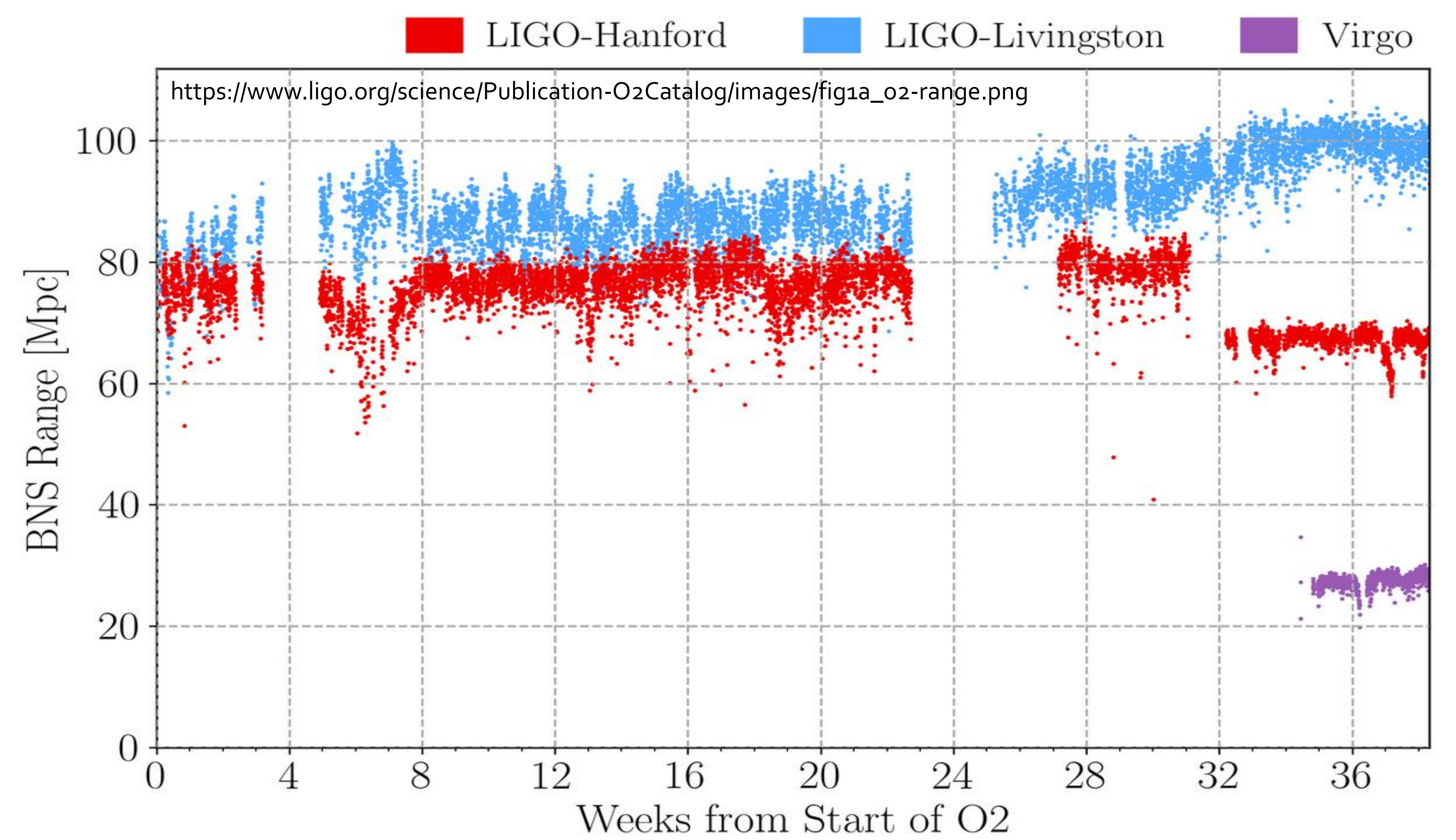

LIGO Livingston Data
LIGO Hanford Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)

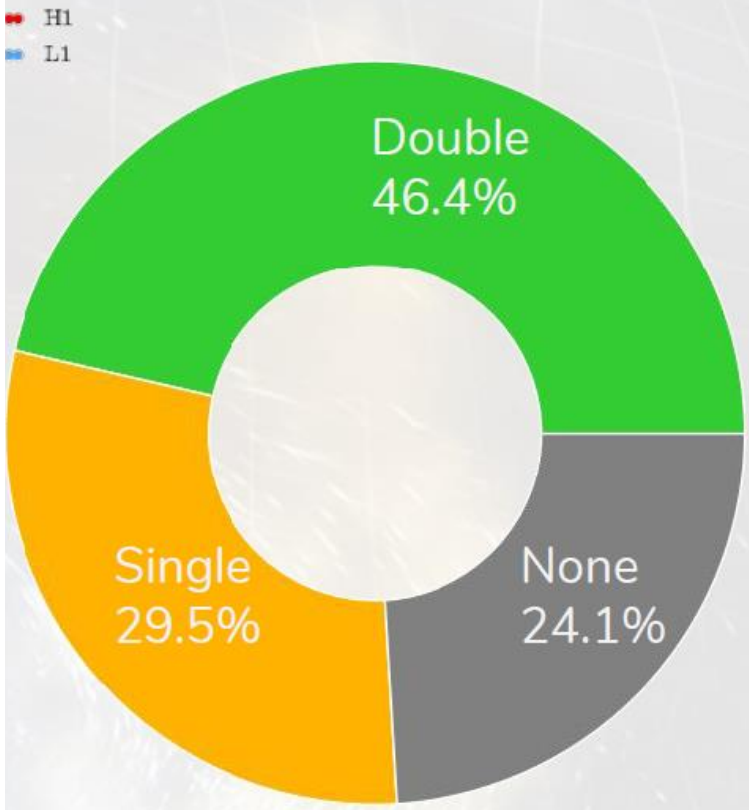

Frequency (Hz)
512
256
128
64
32
0.30
0.35
0.40
0.45
Time (s)
Normalized amplitude
0
2
4
6
8


PHYSICAL
REVIEW
LETTERS™
Articles published week ending 12 FEBRUARY 2016
Published by
American Physical Society™
APS physics
Volume 116, Number 6

Timeline

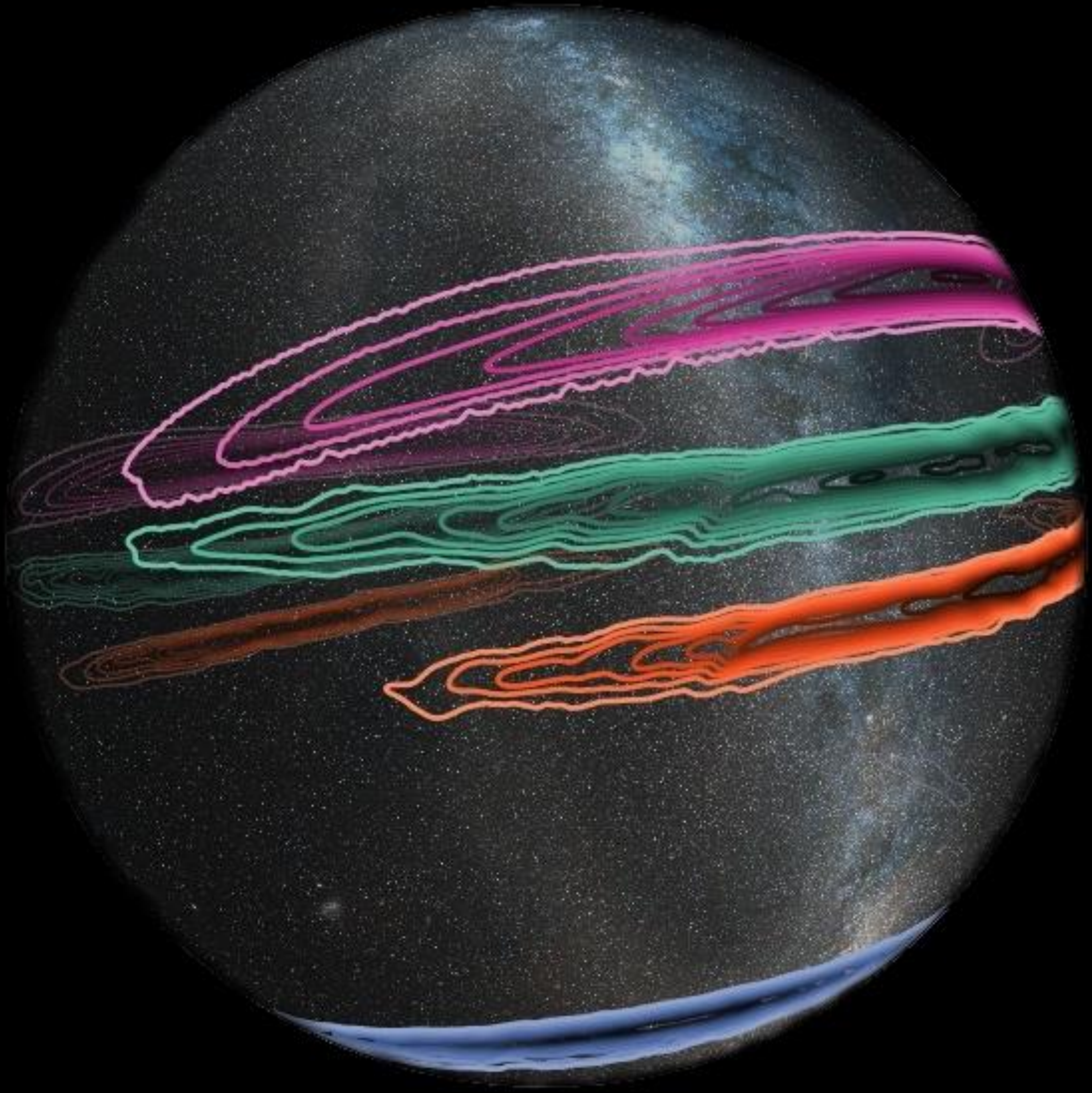
O1	Commissioning - No data	O2
Sept '15 -- Jan '16		Nov '16 -- Aug '17





From: Chad Hanna, October 7, 2019

Advanced LIGO detections



GW170104

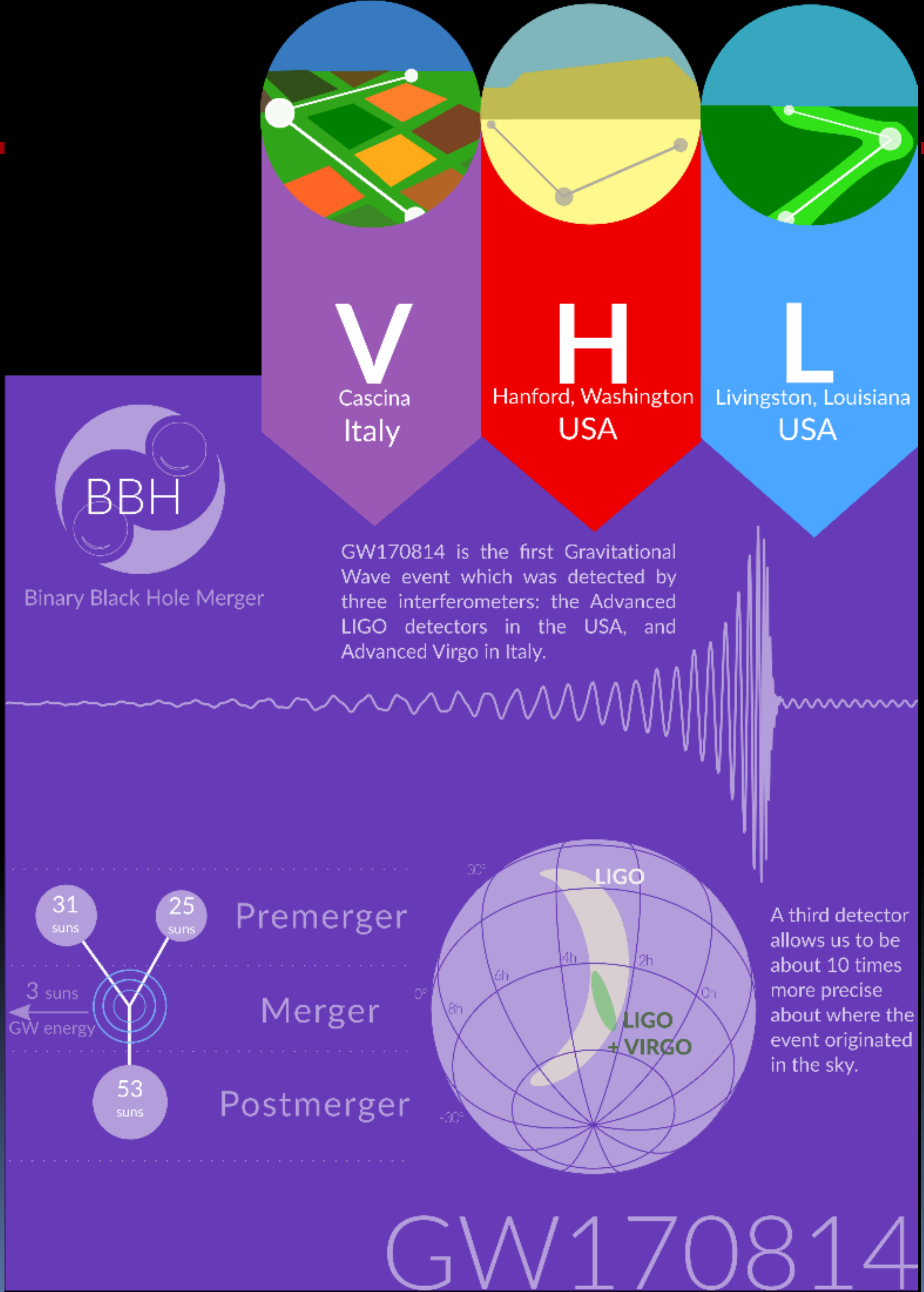
LVT151012

GW151226

GW150914

Uncertainty ca. 500 Degree^2

1st Triple

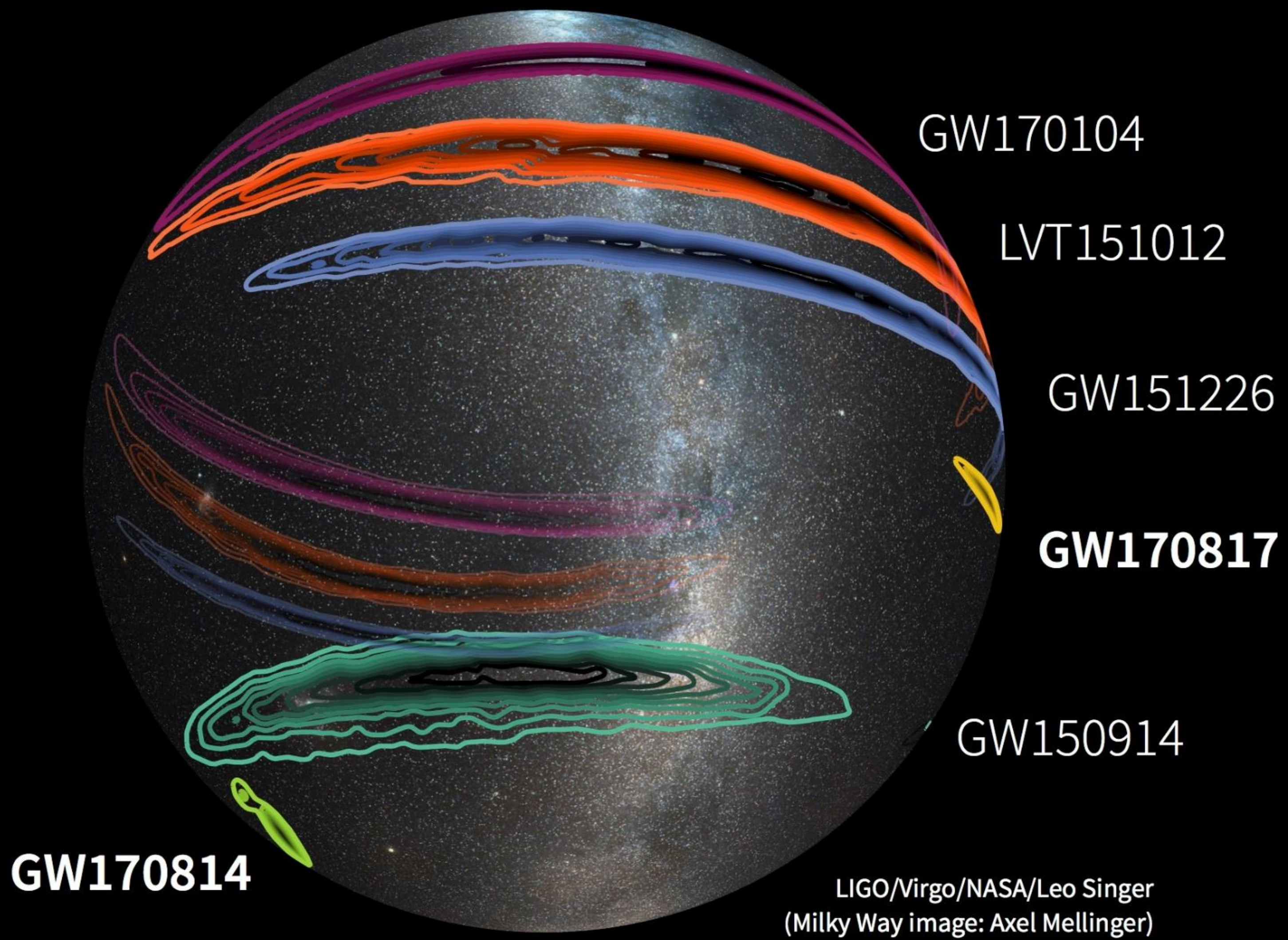


Better localisation with three detectors

Ca. 60 Degree^2 with three detectors (VHL)

> 600 Degree^2 with two LIGO detectors (HL)

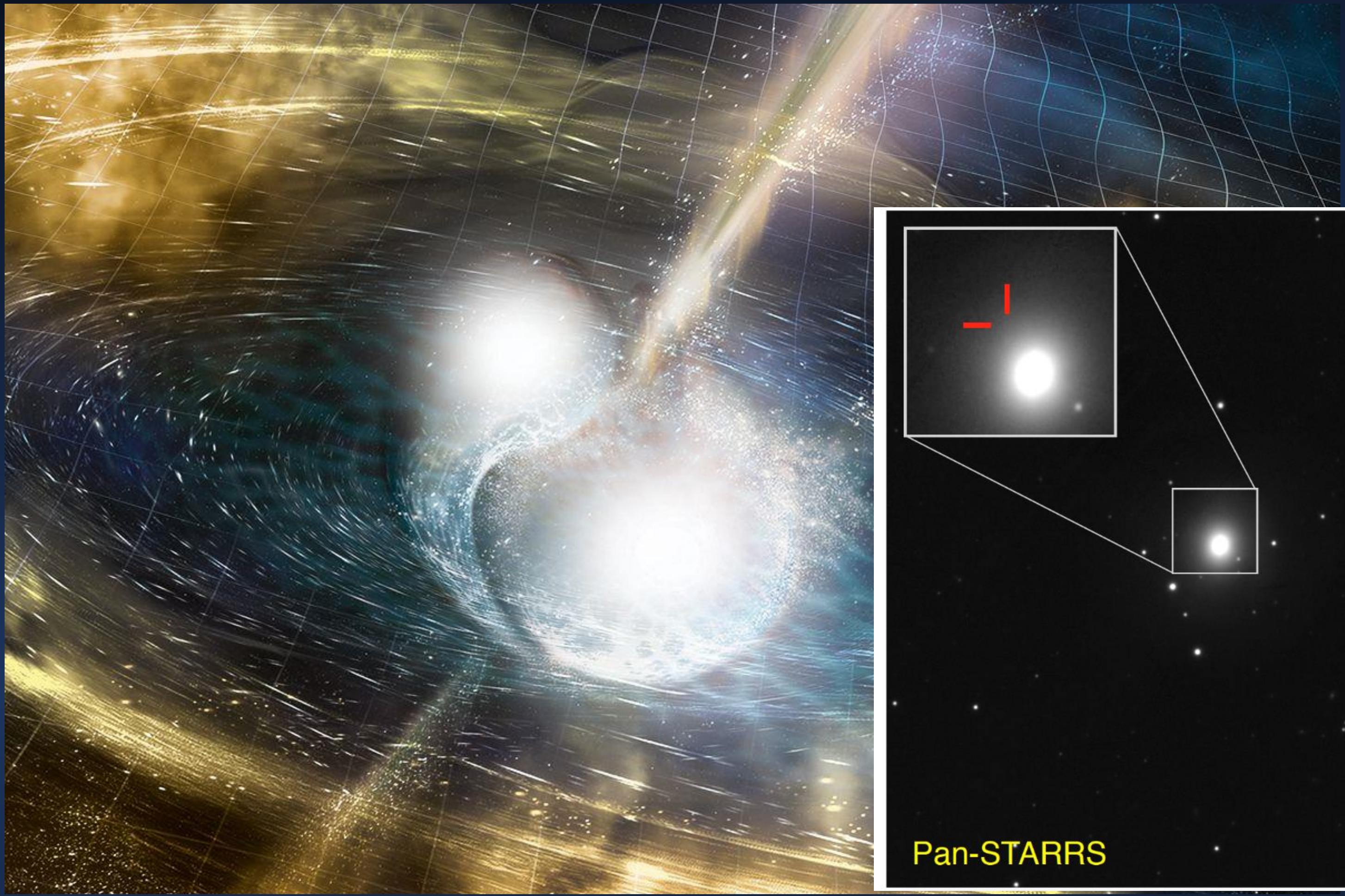
Trilateration of sources

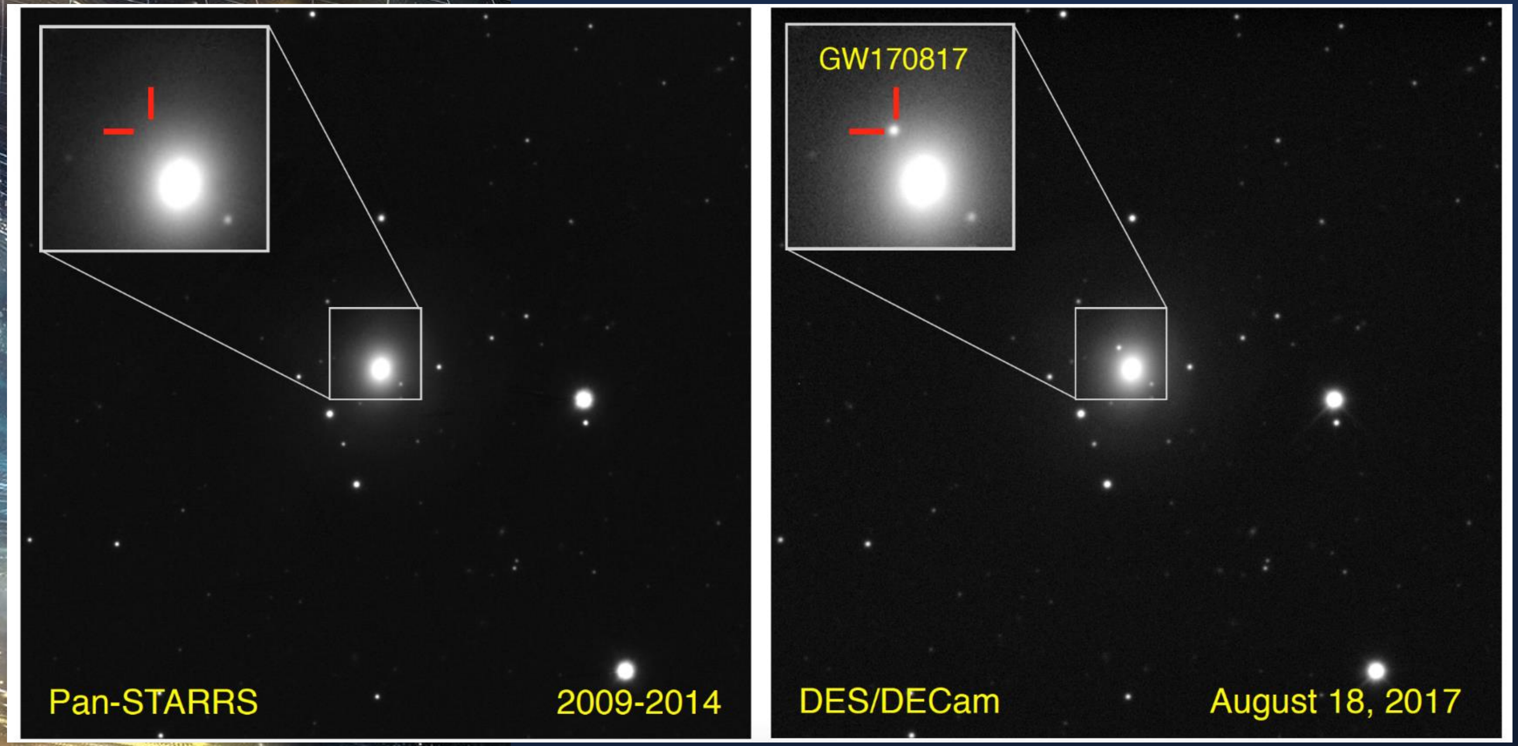


Multi-messenger Observations of a Binary Neutron Star Merger

3850 Authors, 61 collaborations
24 page author list!

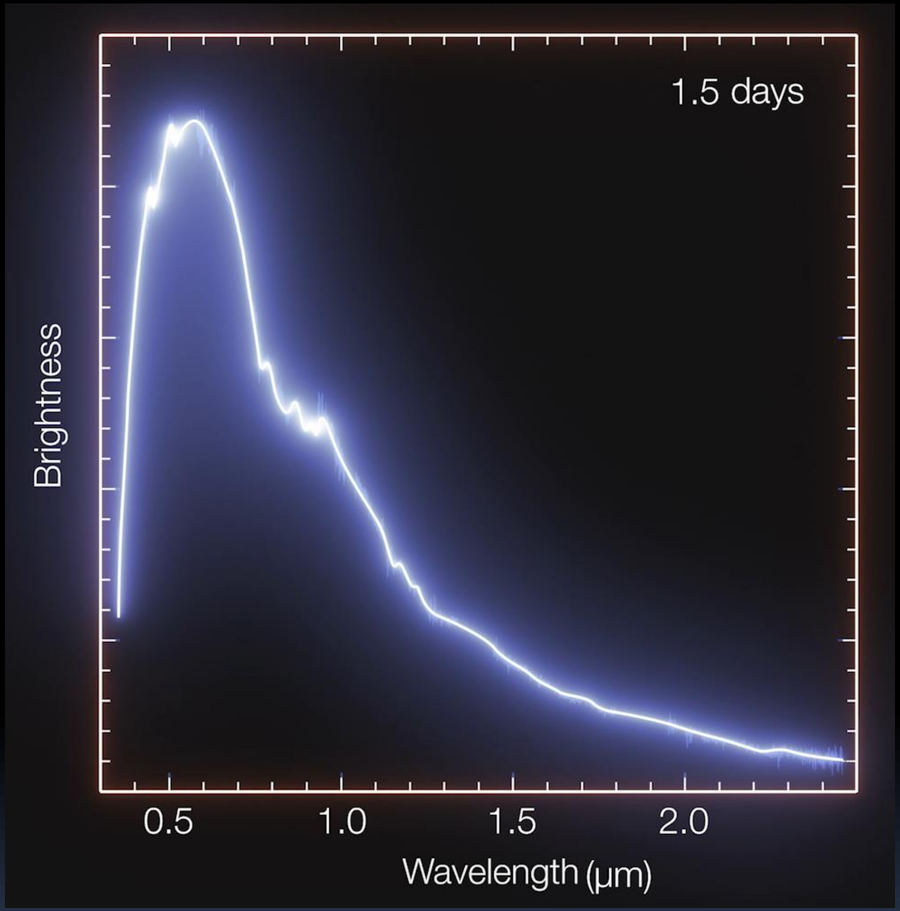
GW170817



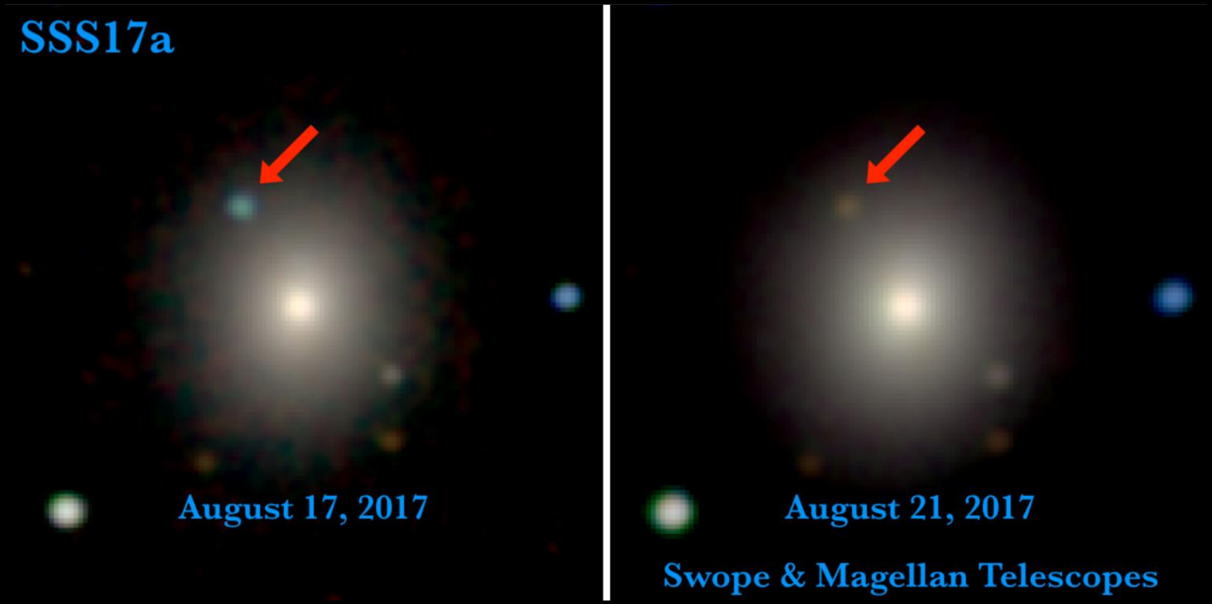


Credit: P.K. Blanchard, E. Berger, P. Edmonds

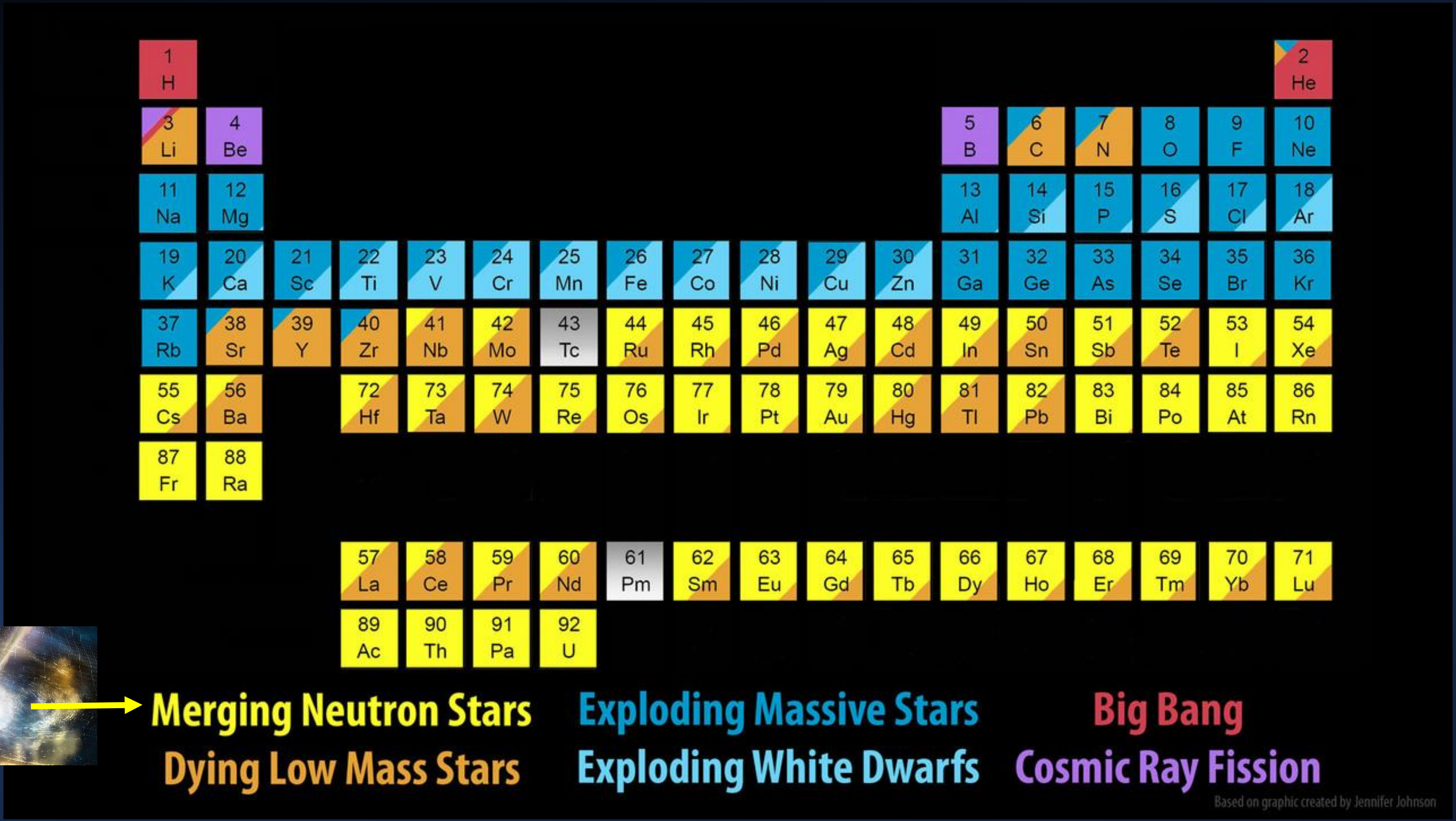
Origin of heavy elements



Credit: ESO/E. Pian et al./S. Smartt & ePESSTO/L. Calçada



Origin of the elements



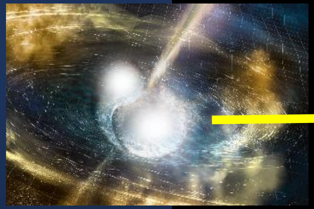
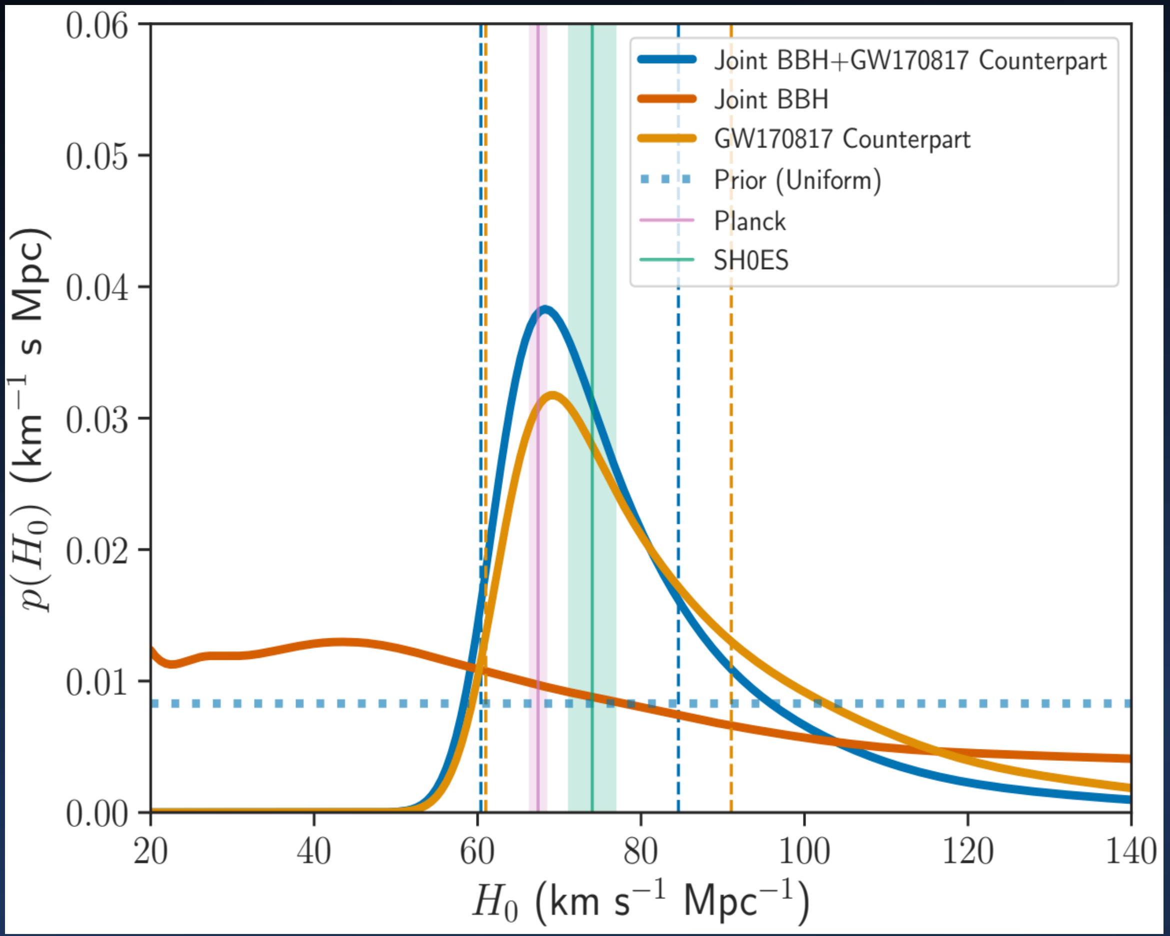


Image source: http://theconversation.com/cosmic-alchemy-colliding-neutron-stars-show-us-how-the-universe-creates-gold-86104

Cosmological Measurements

Binary mergers are “standard sirens”, measuring luminosity distance directly – although with statistical uncertainty if the binary orbit inclination angle is unknown

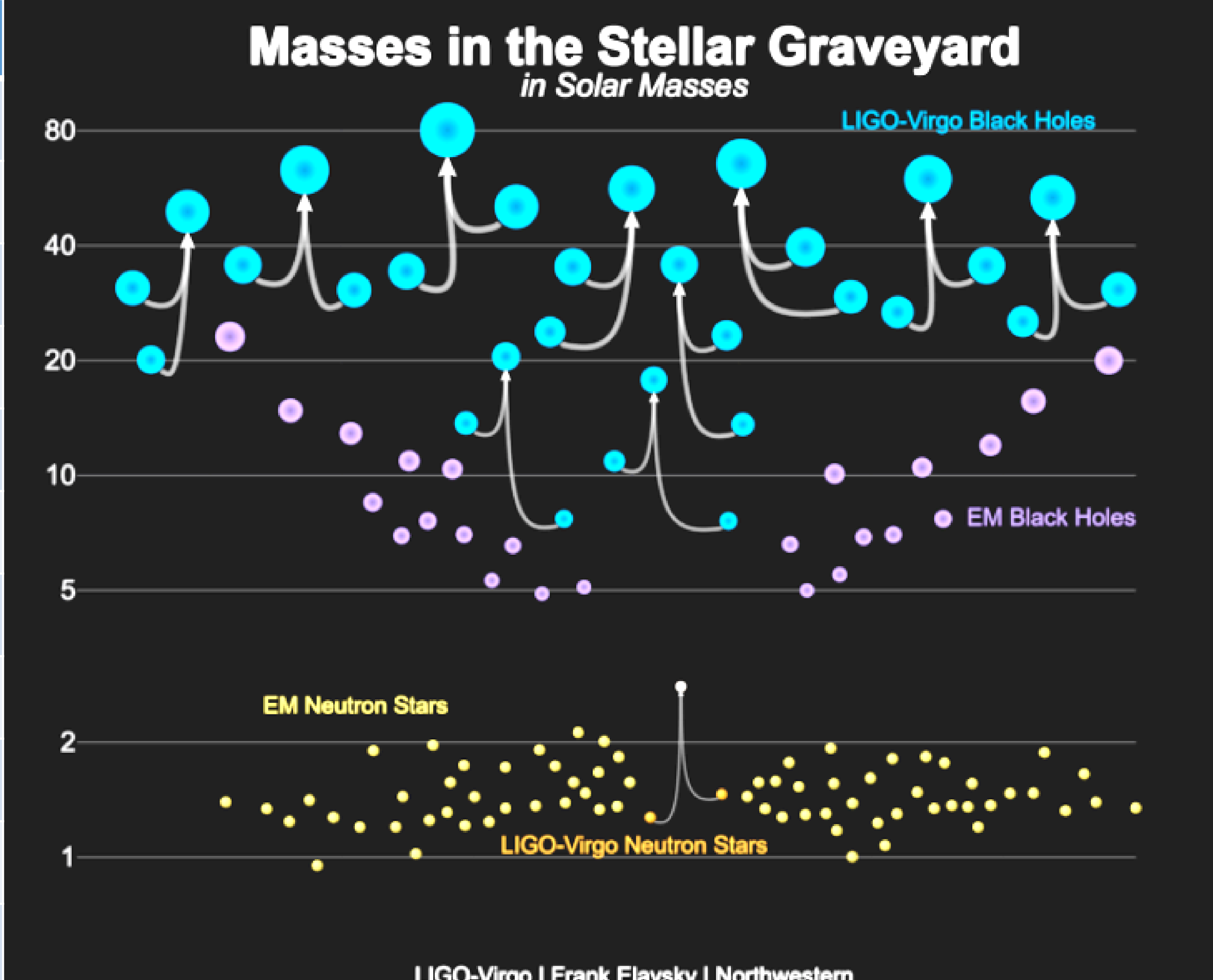
- ➔ Measurement of the Hubble constant from associating GW170817 with the redshift of the cluster including its host galaxy, NGC 4993 *[LIGO, Virgo, 1M2H, DECam GW-EM and DES Collaboration, DLT40, Las Cumbres Observatory, VINROUGE and MASTER, Nature 551, 85]*
- ➔ Implications for the stochastic GW background from BNS mergers like GW170817 *[Abbott+, PRL 120, 091101]*
- ➔ “Dark standard siren” measurement of the Hubble constant by associating the BBH merger GW170814 statistically with galaxies cataloged by the Dark Energy Survey *[Soares-Santos+, ApJL 876, L7]*
- ➔ Combined Hubble constant measurement using statistical analysis of
several BBH events together with GW170817 *[Abbott+, arXiv:1908.06060]*



Credit: P. Shawan, AAS, 2020

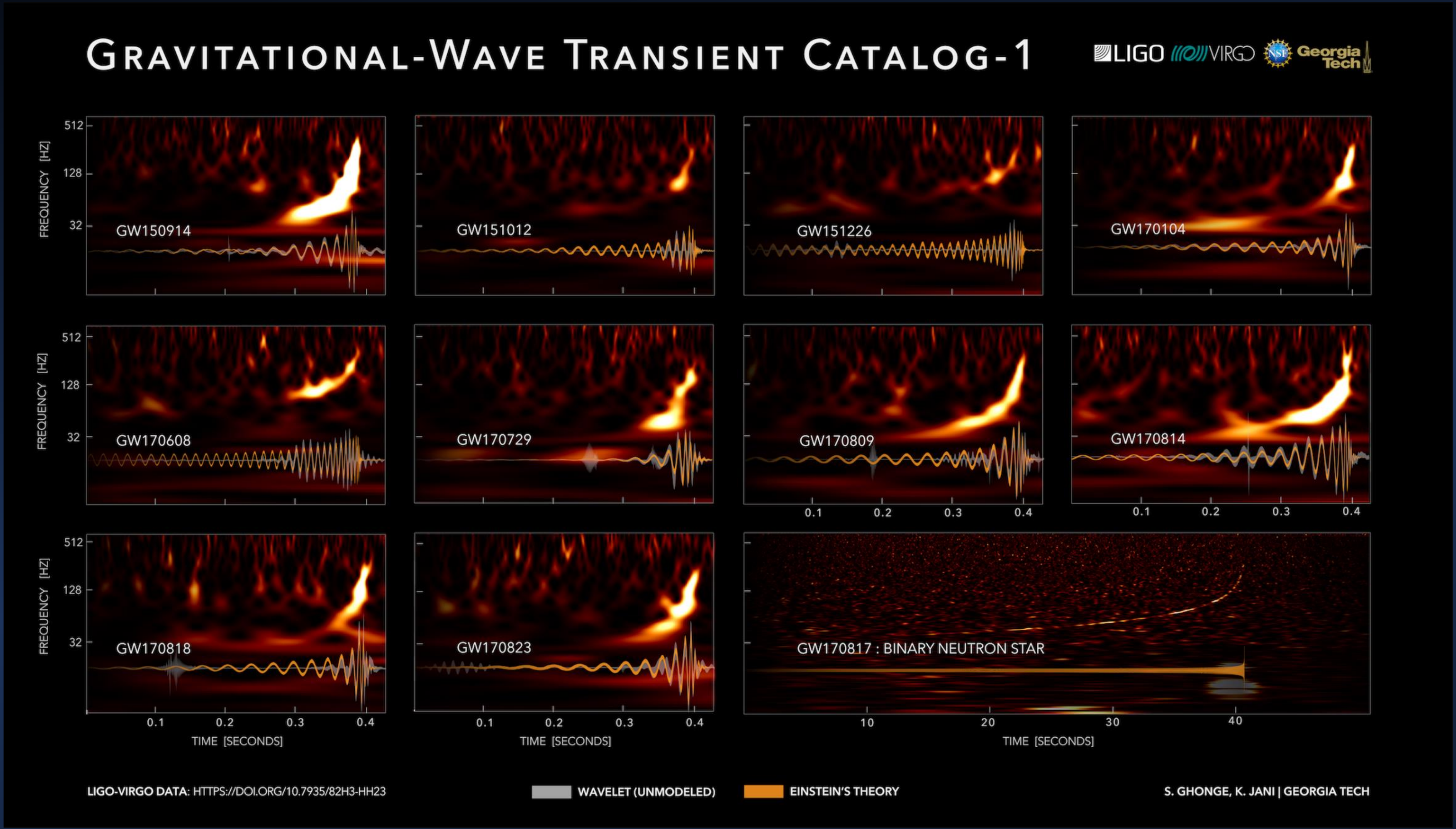
Observation runs 1 & 2

Ereignis	m_1/M_S	m_2/M_S	M_f/M_S	Signallaufzeit in Jahren
GW150914 (BBH)	35,6	30,6	63,1	1,2 Milliarden
GW151012 (BBH)	23,3	13,6	35,7	2,6 Milliarden
GW151226 (BBH)	13,7	7,7	20,5	1,2 Milliarden
GW170104 (BBH)	31,0	20,1	49,1	2,4 Milliarden
GW170608 (BBH)	10,9	7,6	17,8	0,9 Milliarden
GW170729 (BBH)	50,6	34,3	80,3	5,0 Milliarden
GW170809 (BBH)	35,2	23,8	56,4	2,5 Milliarden
GW170814 (BBH)	30,7	25,3	53,4	1,6 Milliarden
GW170817 (BNS)	1,46	1,27	≤2,8	130 Millionen
GW170818 (BBH)	35,5	26,8	59,8	2,5 Milliarden
GW170823 (BBH)	39,6	29,4	65,6	3,9 Milliarden



Advanced LIGO/Virgo Detektionen in O1/O2

Catalogue from O1&O2 published in : DOI: 10.1103/PhysRevX.9.031040



O2 Results

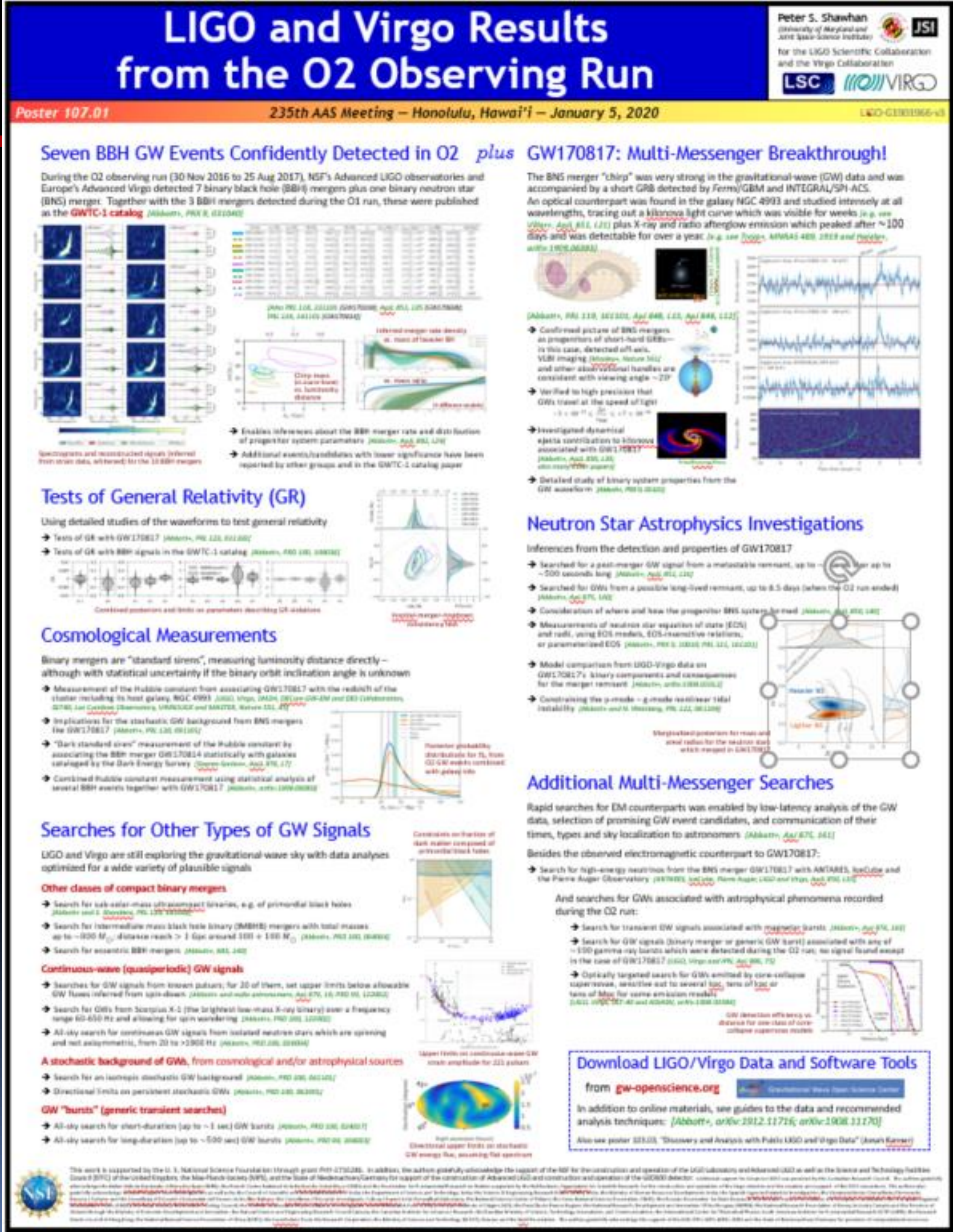
Science from the BBH coalescences

- Parameters of Source Systems
- Tests of GR
- Cosmological Measurements
- Searches for other types of GW Signals
  - Other Classes of compact mergers
  - CW GW Signals
  - Stochastic background of GWs
  - GW bursts (generic transient searches)

Science from GW170817

- Multi-Messenger Astronomy with GWs
- Neutron Star Astrophysics
- Other MM Searches
  - Search for high energy neutrinos (none)
  - Searches for GW associated with astrophysical observations
    - Magnetar bursts
    - Gamma burts (ca. 100 during O2)

https://dcc.ligo.org/LIGO-G1901966/public

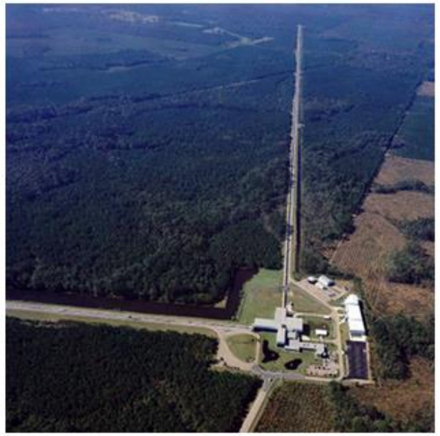


Gravitational Wave Open Science Center

Data Software Online Status About GWOSC

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

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



LIGO Livingston Observatory, Louisiana
(Credits: J. Giaime)

Virgo detector, Italy
(Credits: Virgo Collaboration)

O1&O1: The entirety of the gravitational-wave strain data from the 1rst and second observing runs have been made publicly available through the Gravitational-Wave Open Science Center.

Get started!

NEW **GW190425 Data Release Now Available**

Download data

Join the email list

Alerts

https://emfollow.docs.ligo.org/userguide/content.html

GCN: The Gamma-ray Coordinates Network
(TAN: Transient Astronomy Network)

Alert Contents
Public LIGO/Virgo alerts are distributing using NASA's Gamma-ray Coordinates Network (GCN). There are two types of alerts:

GCN Notices are machine-readable packets.

GCN Circulars are short human-readable astronomical bulletins.
You can subscribe to GCN Circulars to receive and post them by email, or you can view them in the public **GCN Circulars Archive.**

Four kinds of GCN Notices:

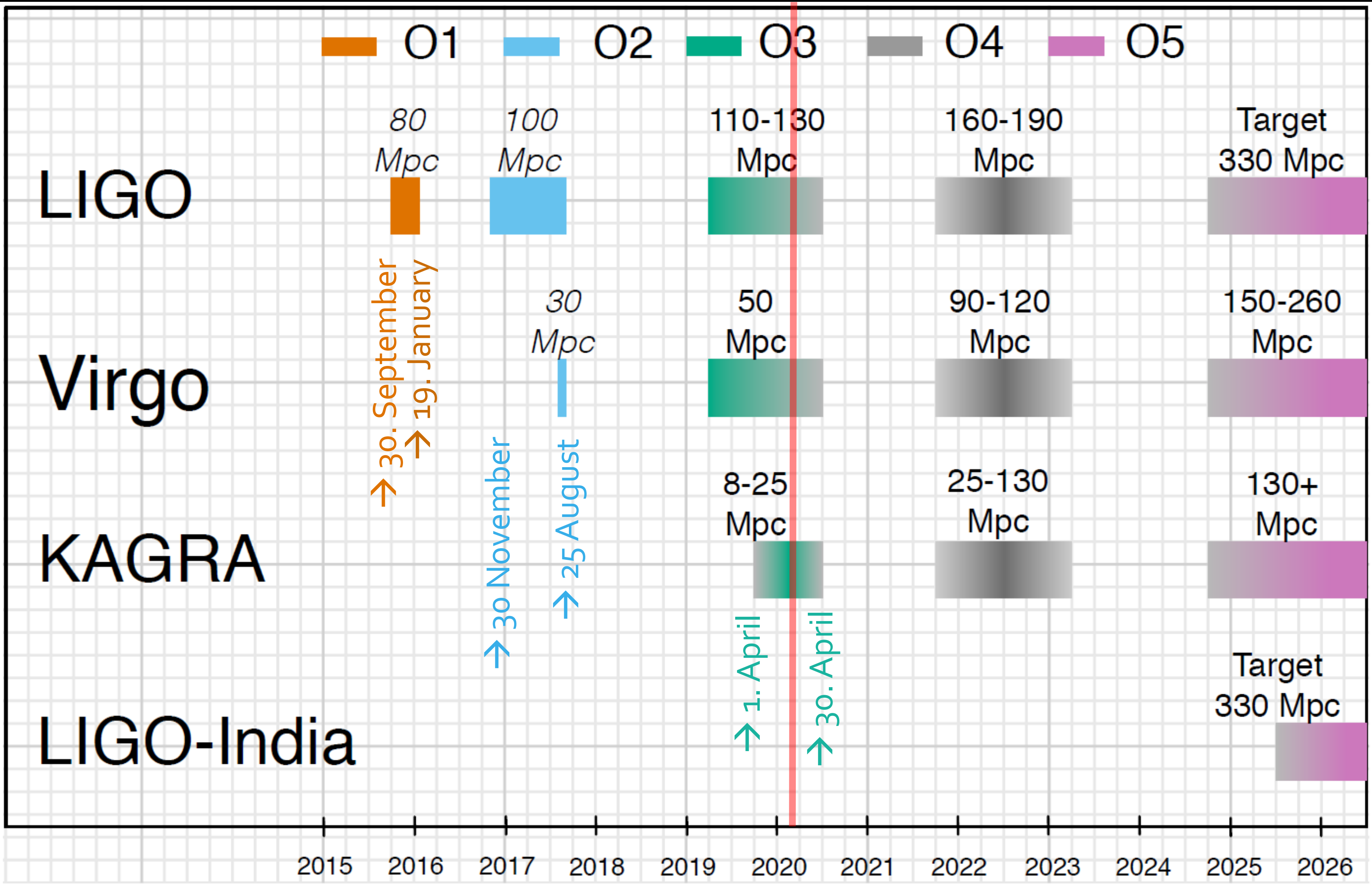
A **Preliminary GCN Notice** is issued **automatically within minutes** after a gravitational-wave candidate is detected. The candidate must have passed some automated data quality checks, but it may later be retracted after human vetting. There is no accompanying GCN Circular at this stage.

An **Initial GCN Notice** is issued **after human vetting** (see Candidate Vetting). If the signal does not pass human vetting (e.g., it is a glitch), then instead of an initial alert there will be a retraction. The initial alert is also accompanied by a GCN Circular, which should be considered as the first formal publication of the candidate and can be cited as such.

An **Update GCN Notice** is issued whenever **further analysis** leads to **improved estimates** of the sky localization, significance, or classification. There may be multiple updates for a given event, and updates may be issued hours, days, or even weeks after the event.

A **Retraction GCN Notice** is **issued if the candidate is rejected** as a result of vetting by human instrument scientists and data analysts. A retraction indicates that the candidate has been withdrawn because it is probably not astrophysical.

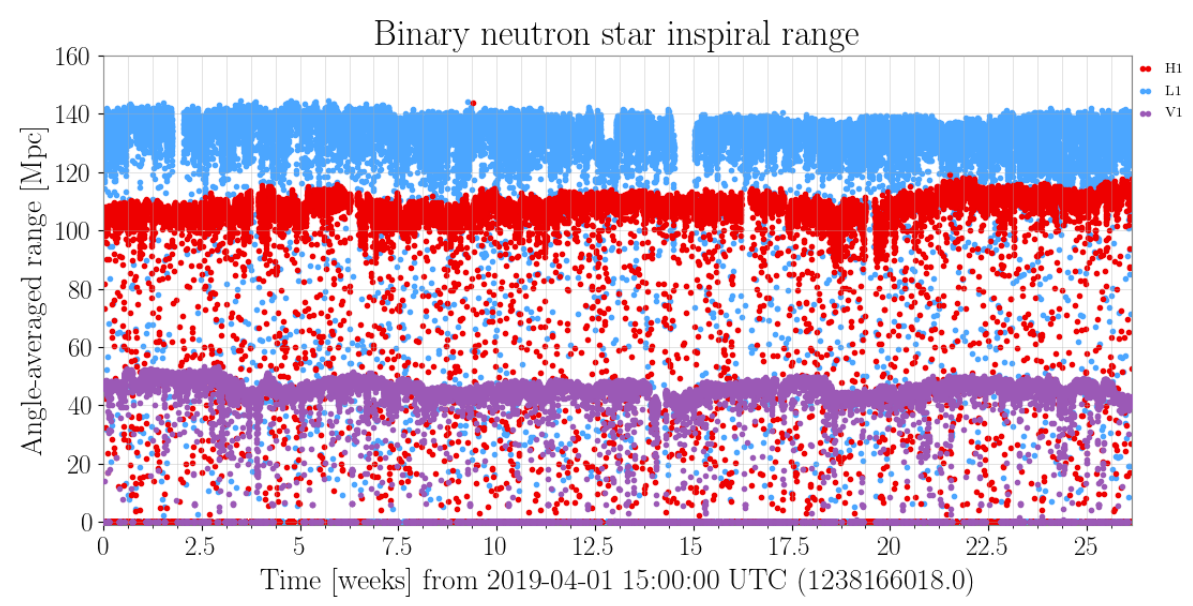
Timeline Observation runs



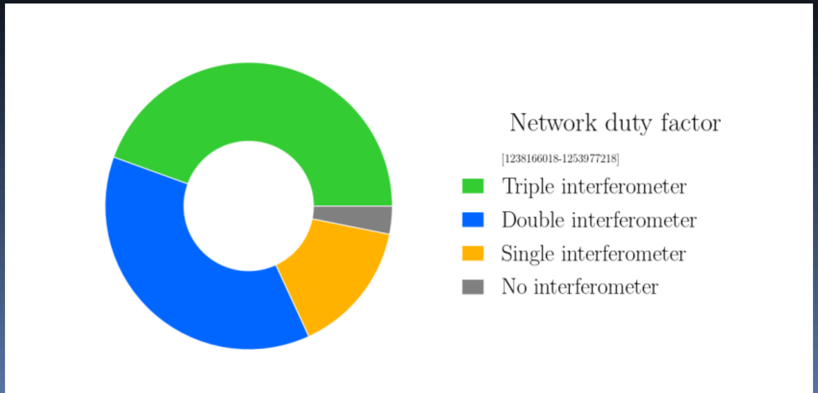
Graphic: https://dcc.ligo.org/public/0094/P1200087/057/ObservingScenarios.pdf

LIGO – Virgo Observation Run 3

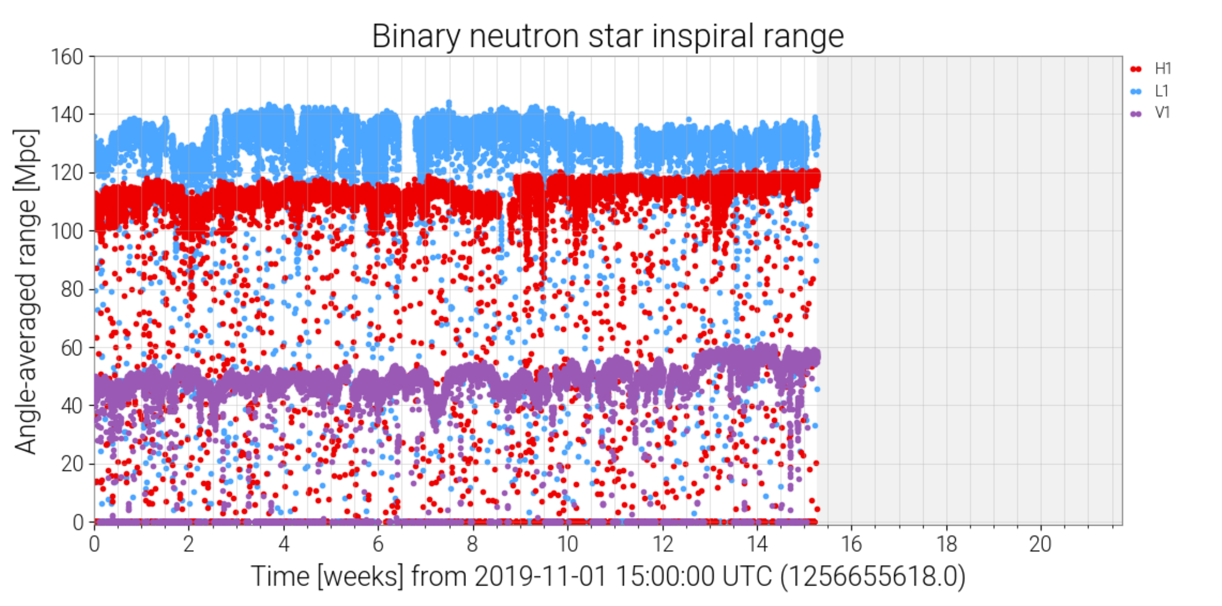
O3a



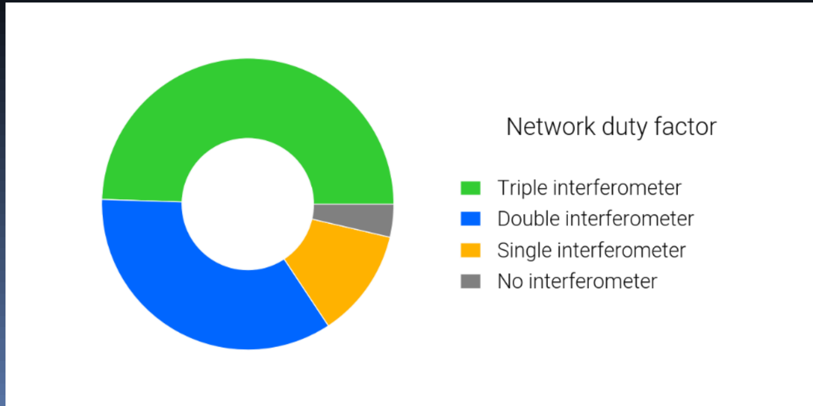
April 1 – October 1, 2019



O3b

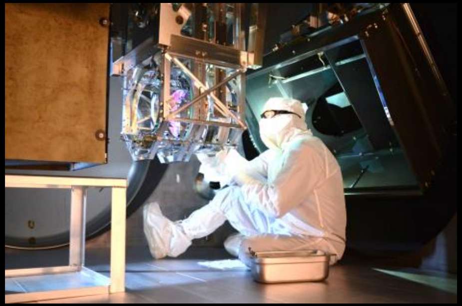


November 1, 2019 – April 2020



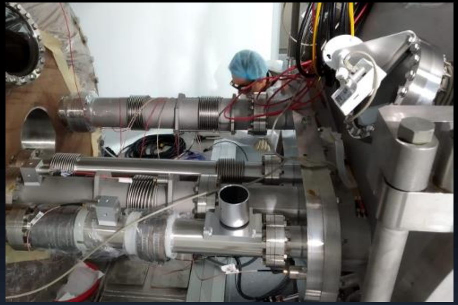
Minor Upgrades in October 2019

- LIGO (https://www.ligo.caltech.edu/news/ligo20191001)
  - Vacuum work
  - Wind fence
  - Mirror cleaning
  - Baffle installation



https://www.ligo.caltech.edu/news/ligo20191104

- Virgo
  - Noise hunting and projections;
  - Increase of laser power by 30% (19W → 26W)



http://www.virgo-gw.eu/

- GEO600
  - Vacuum leak welding
  - Viewport exchange
- KAGRA
  - Continuing commissioning

KAGRA will also get an AEI laser before O4
In O4 all GW detectors will have
lasers made in Germany

GraceDB — Gravitational-Wave Candidate Event Database

HOME | PUBLIC ALERTS | SEARCH | LATEST | DOCUMENTATION

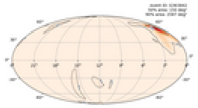
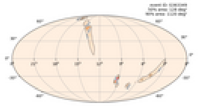
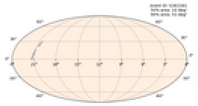
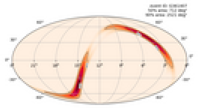
https://gracedb.ligo.org/superevents/public/O3/

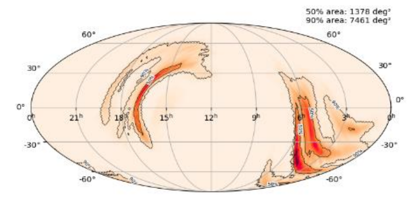
as of 17.02.2020 12:00 CET

LIGO/Virgo O3 Public Alerts

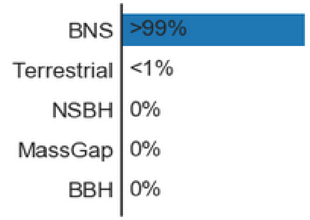
Detection candidates: 50

SORT: EVENT ID (A-Z)

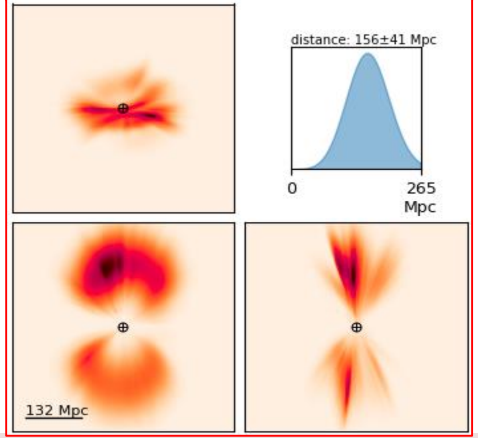
Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S200213t	BNS (63%), Terrestrial (37%)	Feb. 13, 2020 04:10:40 UTC	GCN Circulars Notices | VOE		1 per 1.7934 years	
S200208q	BBH (99%)	Feb. 8, 2020 13:01:17 UTC	GCN Circulars Notices | VOE		1 per 12.587 years	
S200129m	BBH (>99%)	Jan. 29, 2020 06:54:58 UTC	GCN Circulars Notices | VOE		1 per 4.7313e+23 years	
S200128d	BBH (97%), Terrestrial (3%)	Jan. 28, 2020 02:20:11 UTC	GCN Circulars Notices | VOE		1 per 1.9238 years	



S190425z



Source classification visualization from p_astro.json p_astro.png. Submitted by LIGO/Virgo EM Follow-Up on Apr 25, 2019 08:22:05 UTC



Alert Database

Chirp - Keep track of the latest gravitational wave alerts

Gravitational waves are ripples in space-time. The two LIGO detectors, Hanford and Livingston along with Virgo have a proven track record of successful observations and are now issuing public alerts of possible gravitational waves events via the Gamma Ray Coordinates (GCN) system.

Chirp is a web-app that listens to the GCN system and displays the information in a friendly format, with links to LIGO-Virgo Gravitational Wave Candidate Event Database (GraceDB) pages for more detailed information. For more information about this app check out our about page.

Latest Alert | All Alerts

Also available on mobile

GET IT ON Google Play | Download on the App Store

Image credit: Aurore Simonnet, EPO Sonoma State University

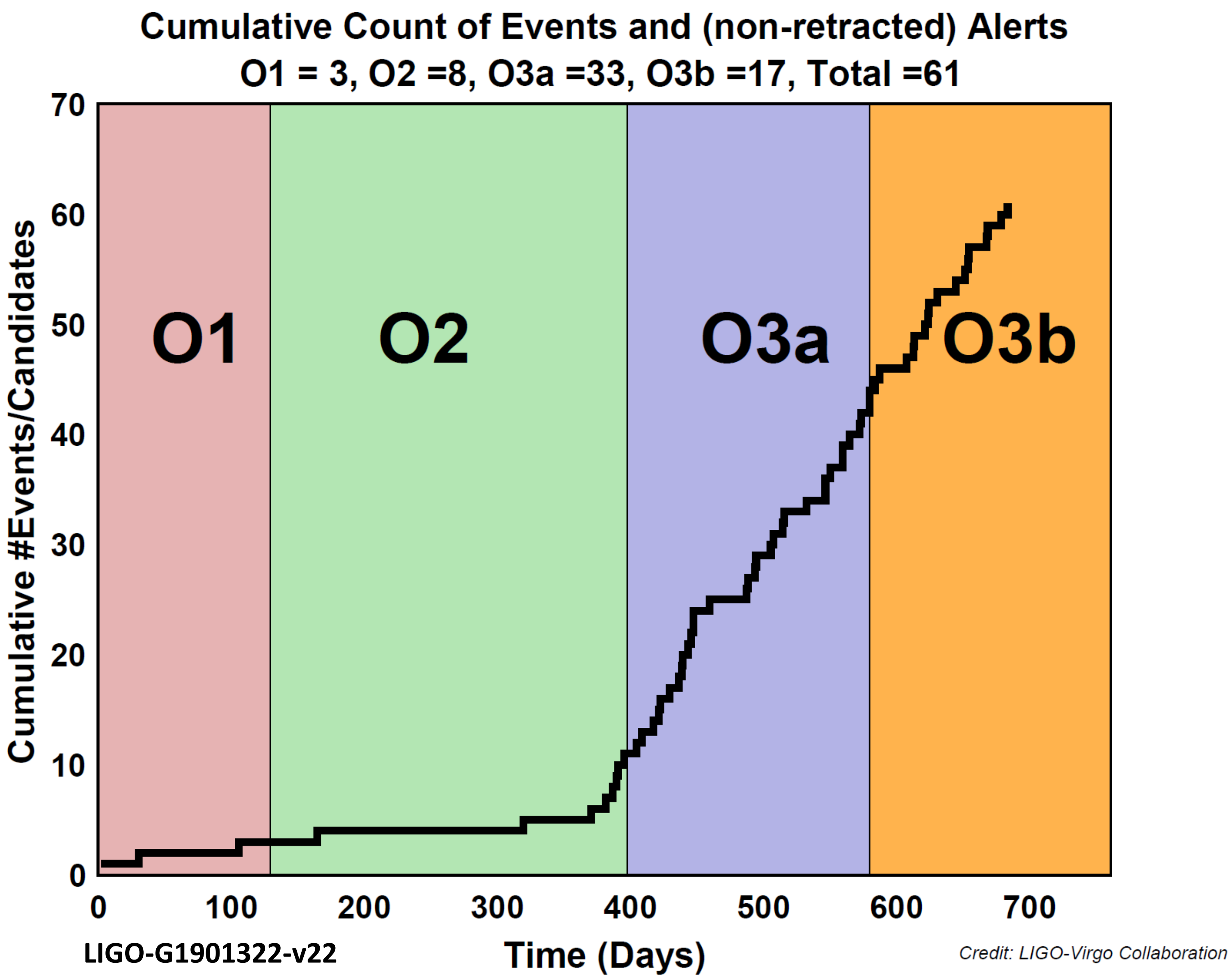
Accessibility, Privacy Policy. Website © 2019 - Sam Cooper, Aaron Jones, Sam Morrell, George Smetana.

DOI 10.5281/zenodo.3525064

Disclaimer: Chirp uses publicly available GCNs for information, for the latest information visit GraceDB or the event circulars, linked on each event.

Google Play and the Google Play logo are trademarks of Google LLC. Apple, the Apple logo, iPhone, and iPad are trademarks of Apple Inc., registered in the U.S. and other countries and regions. App Store is a service mark of Apple Inc.

Cumulative event evolution in aLIGO/AdV



Uses confirmed detections from O1 & O2
And non-retracted alerts from O3

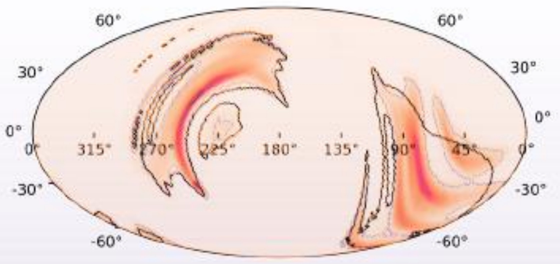
Latest Event:GW190425

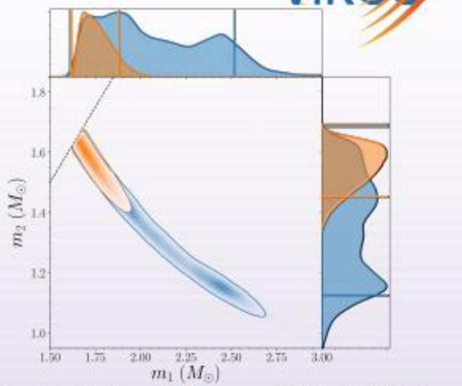
- **Neutron star merger** detected only with LIGO Livingston → sky area 8300 deg^2 (28 deg^2 for GW170817)
  → no EM Conterpart
- 3.4 solar masses = unusually heavy.
- Known BNS systems in the Milky-Way <2.9 solar masses (combined)
- If it was not two neutron stars, but a neutron star and a black hole → the black hole would have to be exceptionally small for its class.

https://dcc.ligo.org/G2000002/public/main

GW190425 FACTSHEET

LIGO VIRGO





observed by	LIGO Livingston, Virgo
source type	most likely a binary neutron star merger
date	25 April 2019
time of merger	08:18:05 UTC
Livingston signal-to-noise ratio	12.9
Virgo signal-to-noise ratio	2.5
false alarm rate	1 in 69 000 years
distance	287 to 744 million light-years
redshift	0.01 to 0.04
total mass	3.3 to 3.7 $M_\odot$
primary NS mass	1.61 to 2.52 $M_\odot$
secondary NS mass	1.12 to 1.68 $M_\odot$
mass ratio	0.4 to 1.0
effective inspiral spin parameter	0.01 to 0.17
effective precession spin parameter	unconstrained
core density of primary NS	70 to 140 trillion times density of lead
inferred # of GW cycles from 19.4 Hz to 2048 Hz*	~ 3900
initial astronomer alert latency**	~43 min
sky area†	8284 deg^2
improved binary NS merger rate	7 to 81 mergers per year per cubic billion light-years

Images: **GW sky map** (left): initial (black contours) and final (red and orange with grey contours) regions where source is likely to be located. Darker shading indicates increased likelihood source is in that region of sky. **Component mass distribution** (right): darker shading indicates an increased likelihood the pair of stars had that set of masses. The blue and orange lines denote 90% confidence intervals for two different assumptions —NS spins are allowed to be large (blue) and NS spins are constrained to be small (orange). The black diagonal line is the line m_1=m_2.

GW=gravitational wave, NS=neutron star, $M_\odot$=1 solar mass=2×10^{30} kg

Parameter ranges are 90% credible intervals.
*maximum likelihood estimate
**referenced to the time of merger
†90% credible region

3.2 dB Squeezing in aLIGO and Adv. Virgo

HIGHLIGHTED ARTICLES

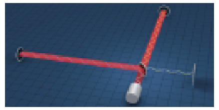
Featured in Physics | Editors' Suggestion

Quantum-Enhanced Advanced LIGO Detectors in the Era of Gravitational-Wave Astronomy

M. Tse *et al.*

Phys. Rev. Lett. **123**, 231107 (2019) – Published 5 December 2019

Physics Focus: Squeezing More from Gravitational-Wave Detectors



New hardware installed in current gravitational-wave detectors uses quantum effects to boost sensitivity and increase the event detection rate by as much as 50%.

Show Abstract +

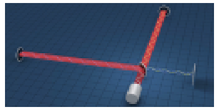
Featured in Physics | Editors' Suggestion

Increasing the Astrophysical Reach of the Advanced Virgo Detector via the Application of Squeezed Vacuum States of Light

F. Acernese *et al.* (Virgo Collaboration)

Phys. Rev. Lett. **123**, 231108 (2019) – Published 5 December 2019

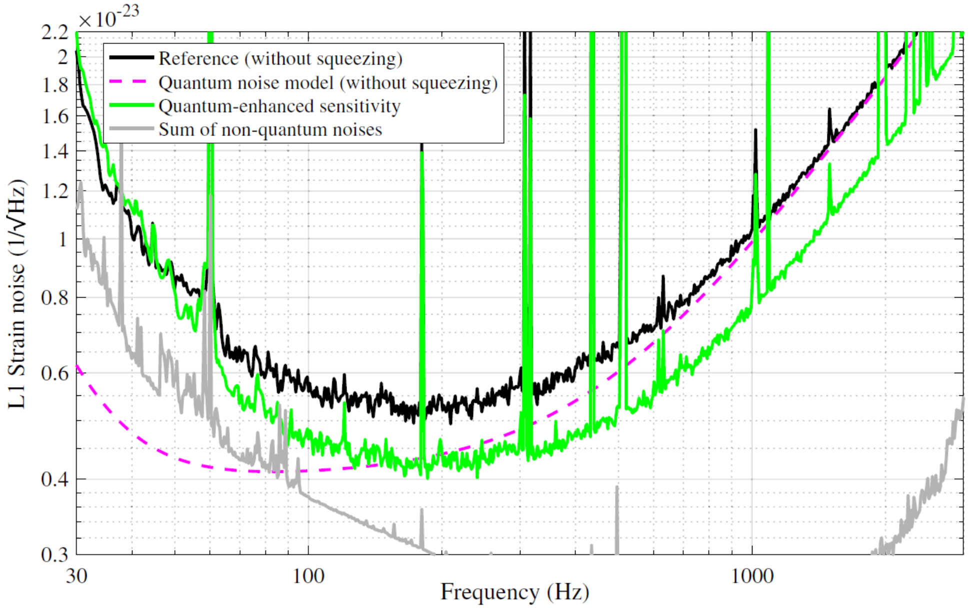
Physics Focus: Squeezing More from Gravitational-Wave Detectors



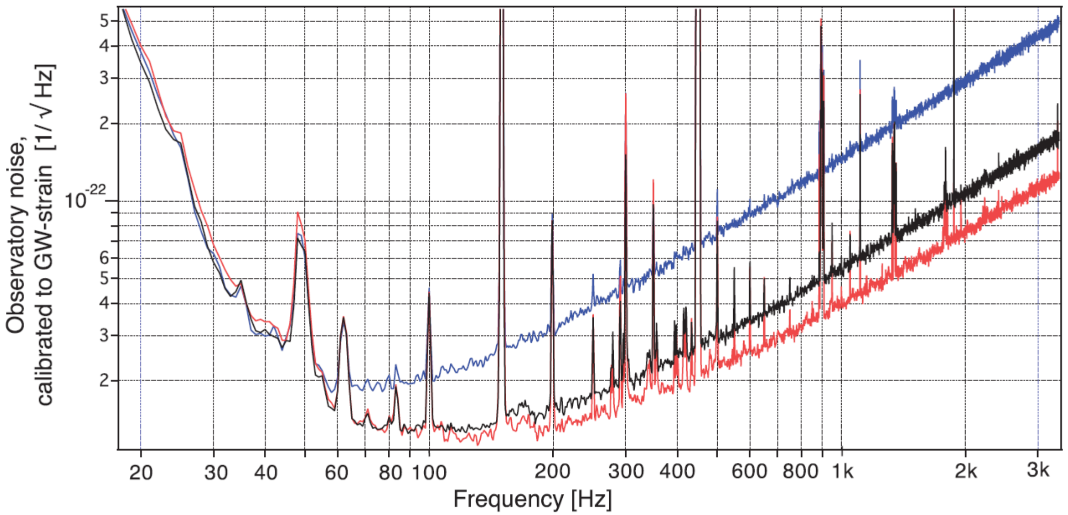
New hardware installed in current gravitational-wave detectors uses quantum effects to boost sensitivity and increase the event detection rate by as much as 50%.

Show Abstract +

PHYSICAL REVIEW LETTERS **123,** 231107 (2019)

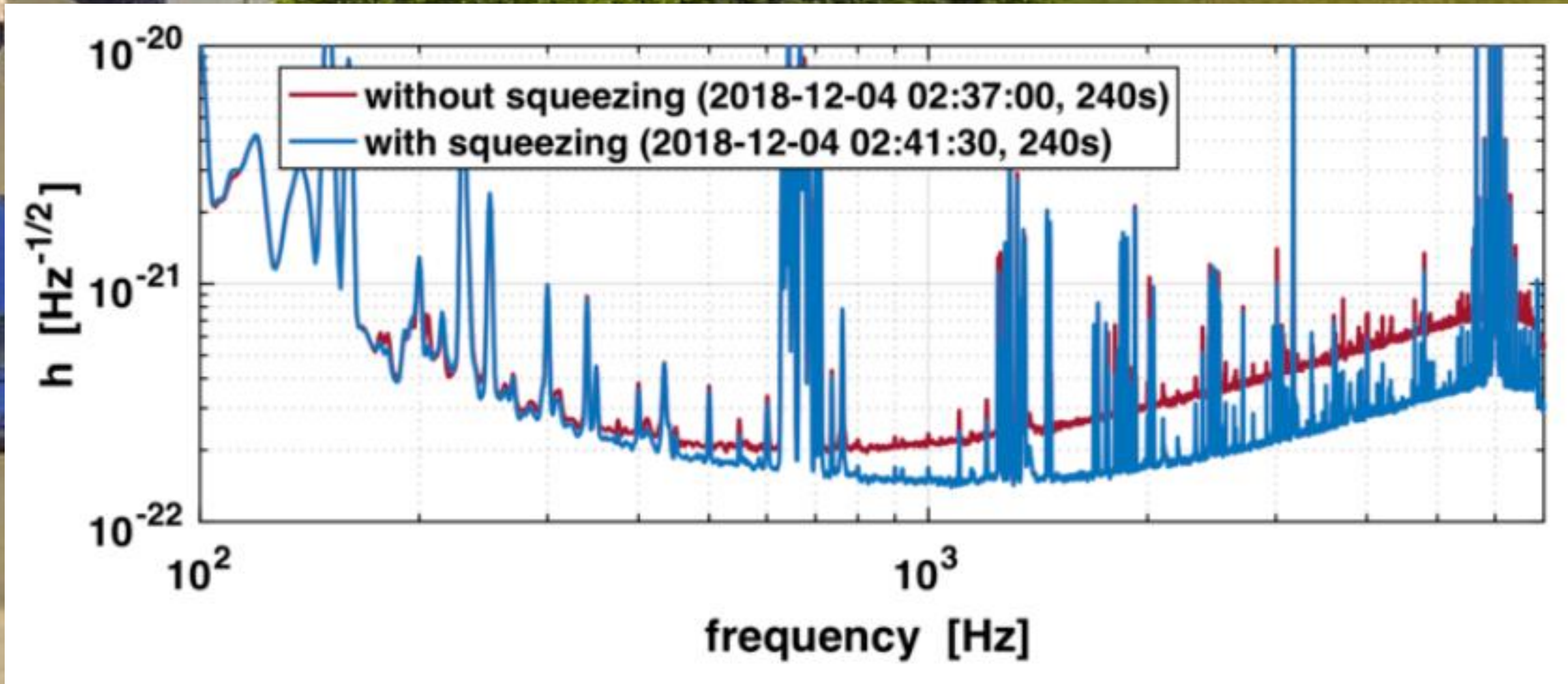


PHYSICAL REVIEW LETTERS **123,** 231108 (2019)



Squeezing in GEO600

5.7dB published

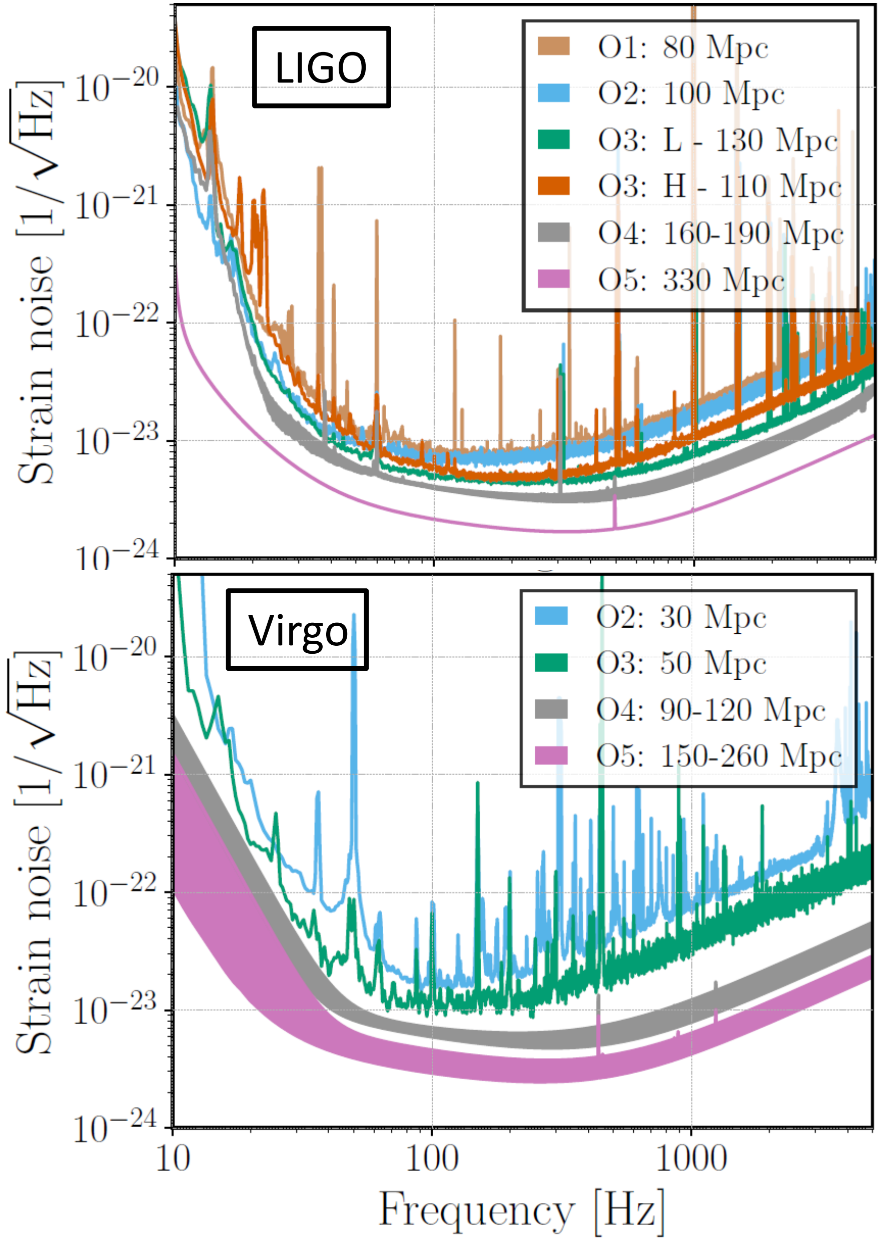


Sensitivities & Noise Budget
2G → 3G

Harald Lück
AEI & LUH

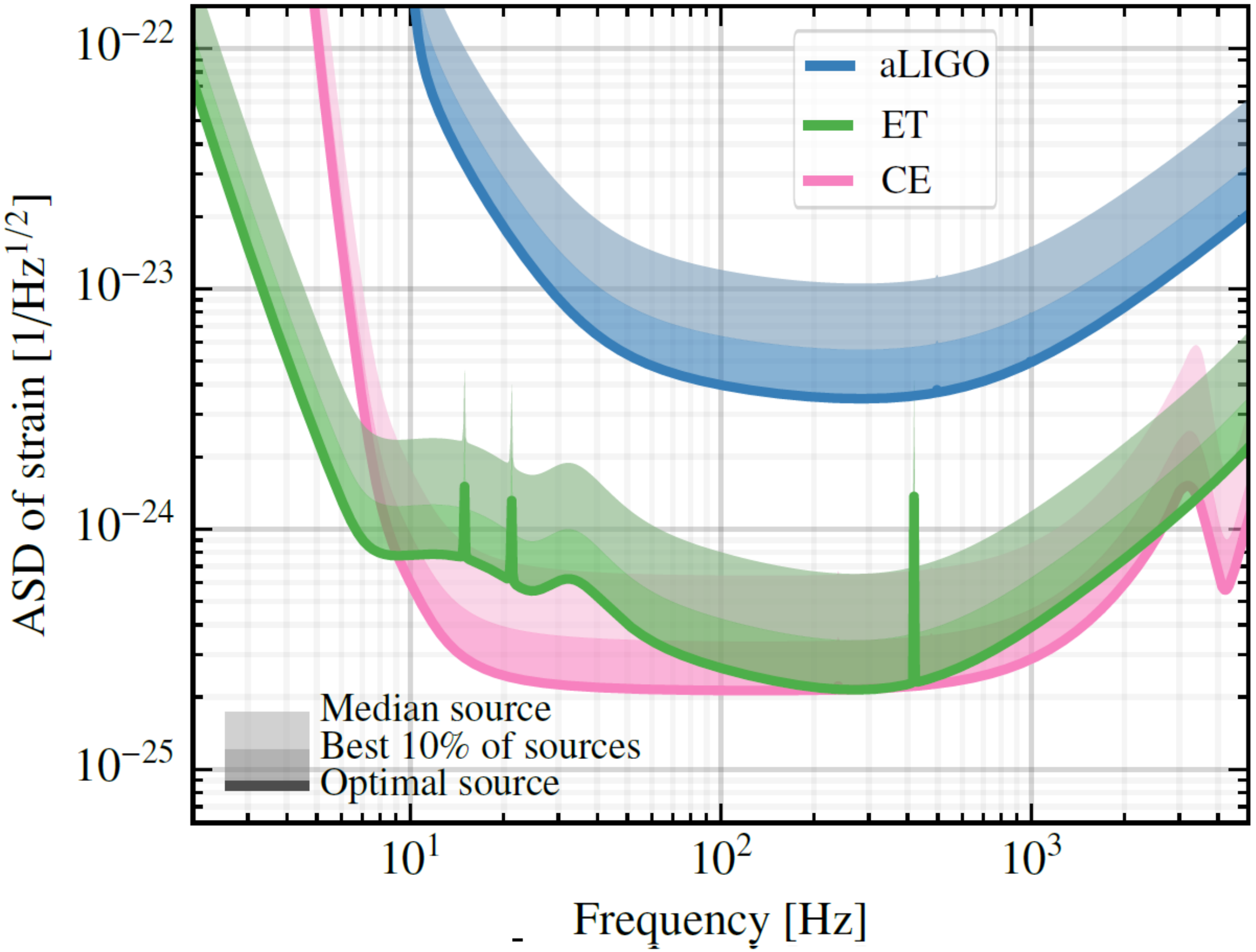
The 3G GW Network (2035+)

Current state

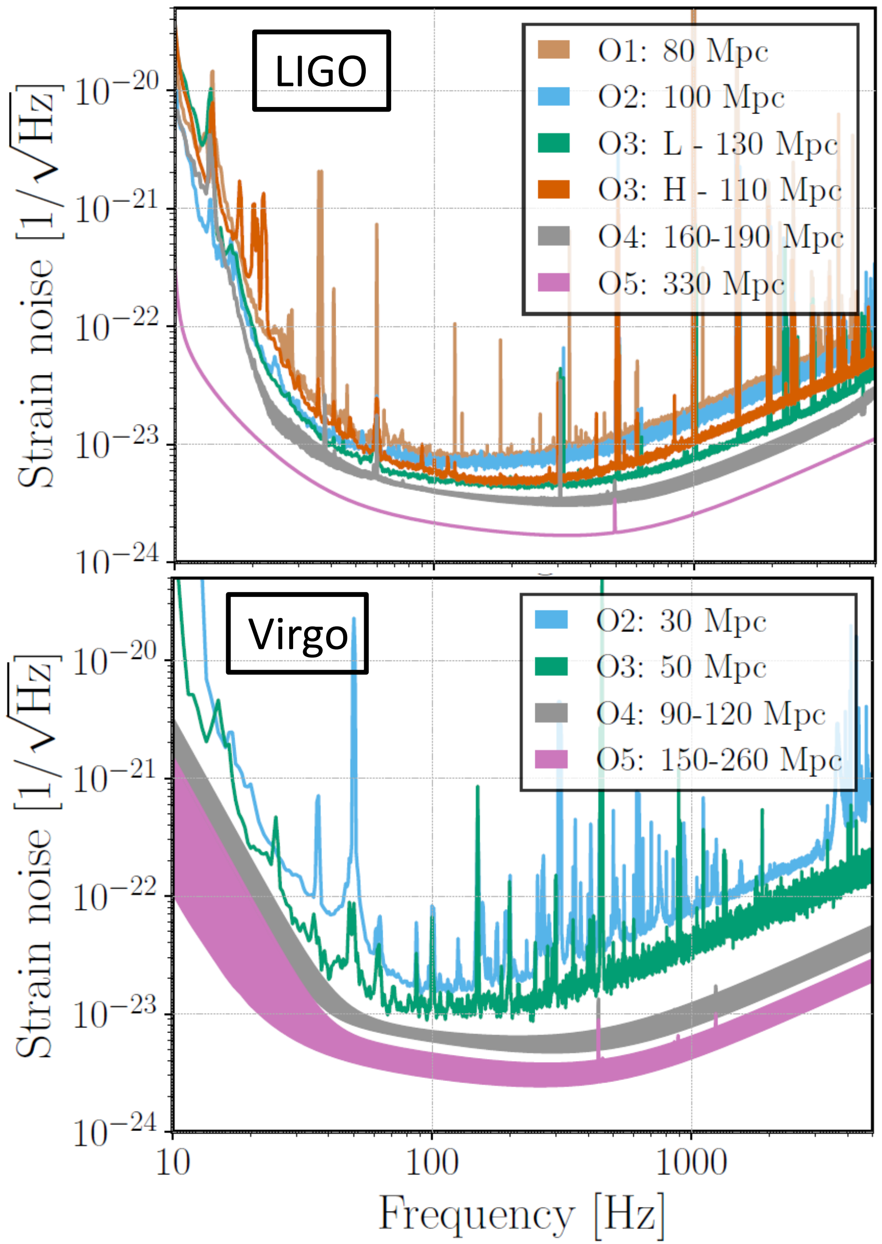


https://dcc.ligo.org/public/0094/P1200087/057/ObservingScenarios.pdf

The goal

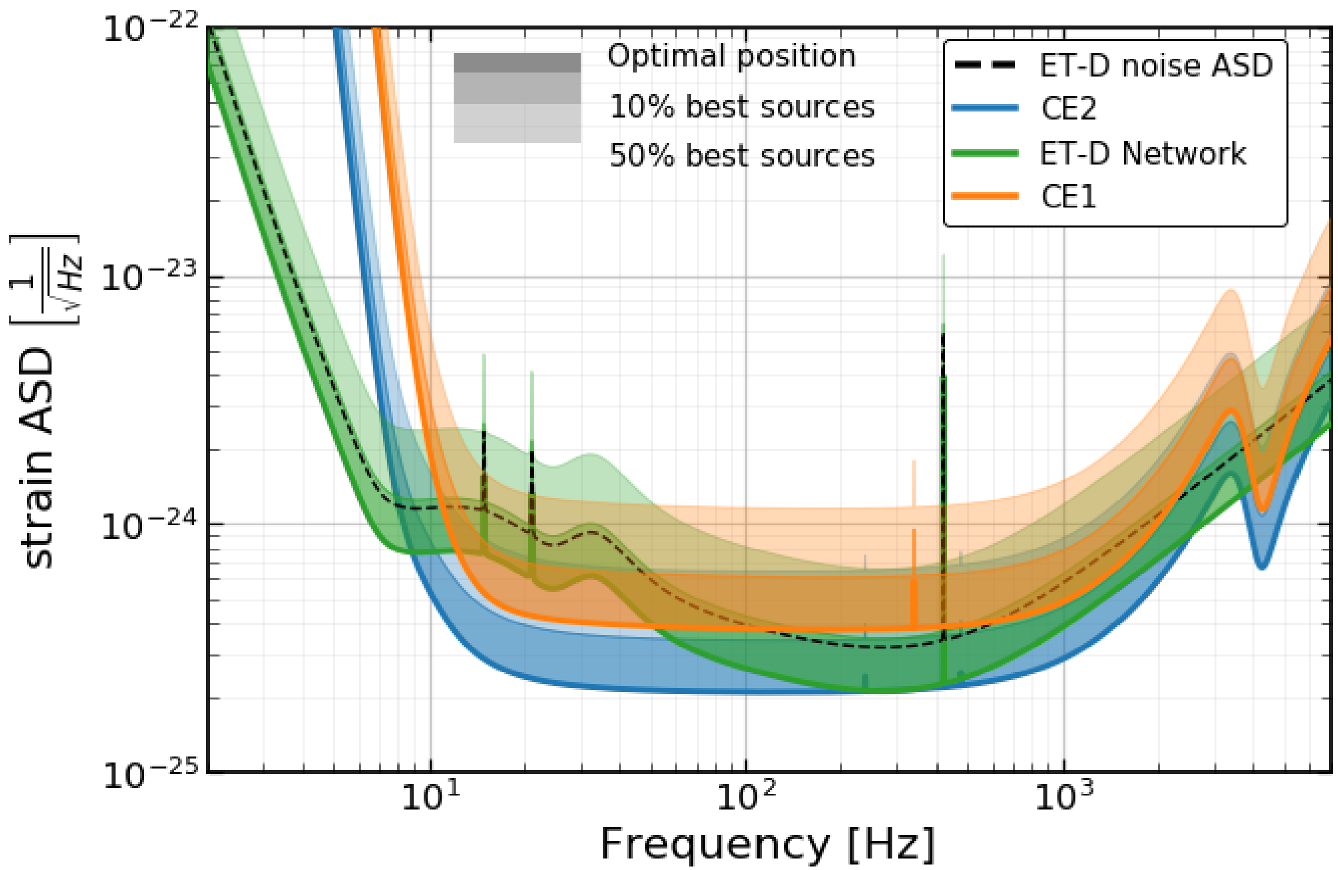


Current state

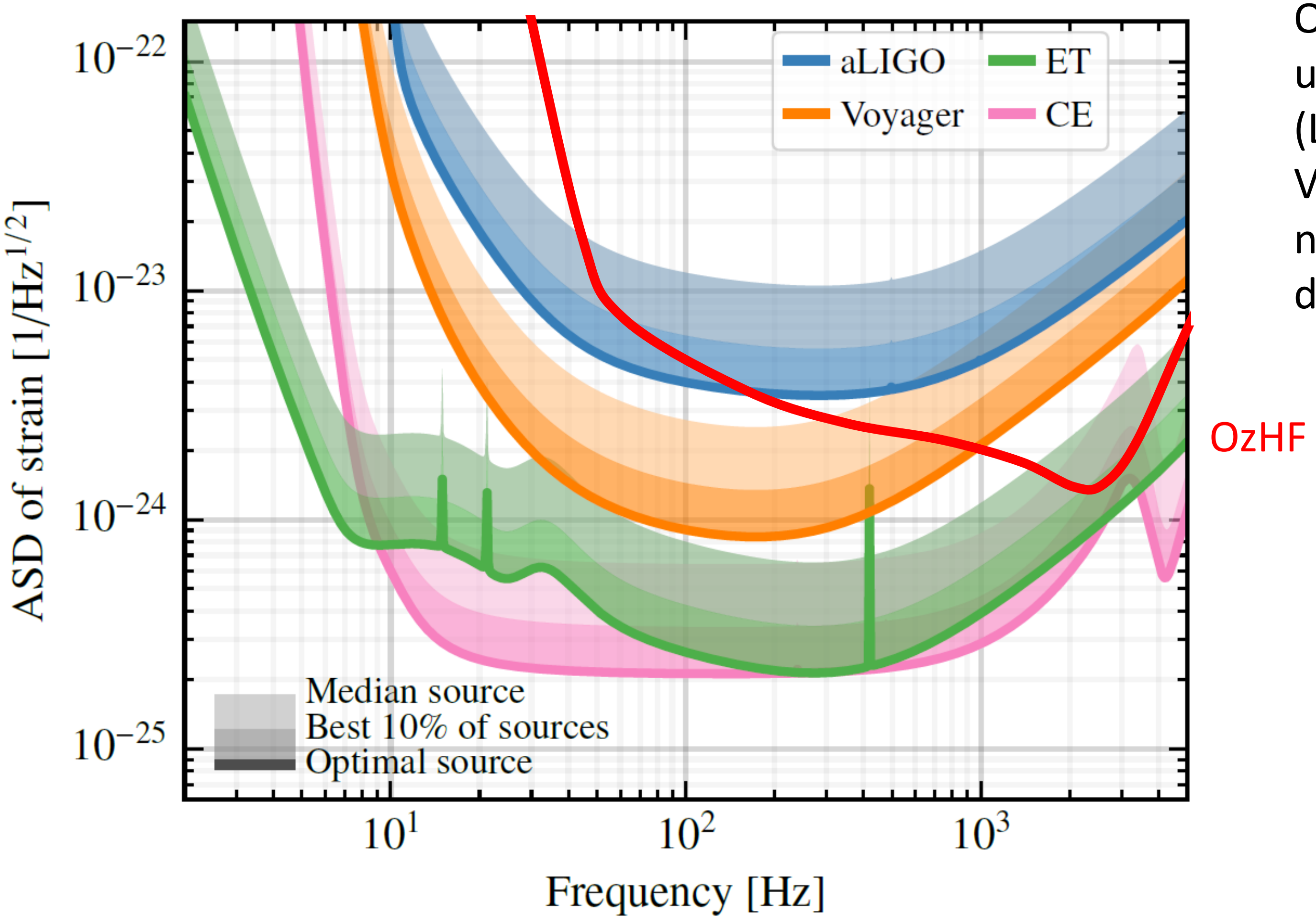


https://dcc.ligo.org/public/0094/P1200087
/057/ObservingScenarios.pdf

The goal (CE1, CE2)



Between 2G+ and 3G

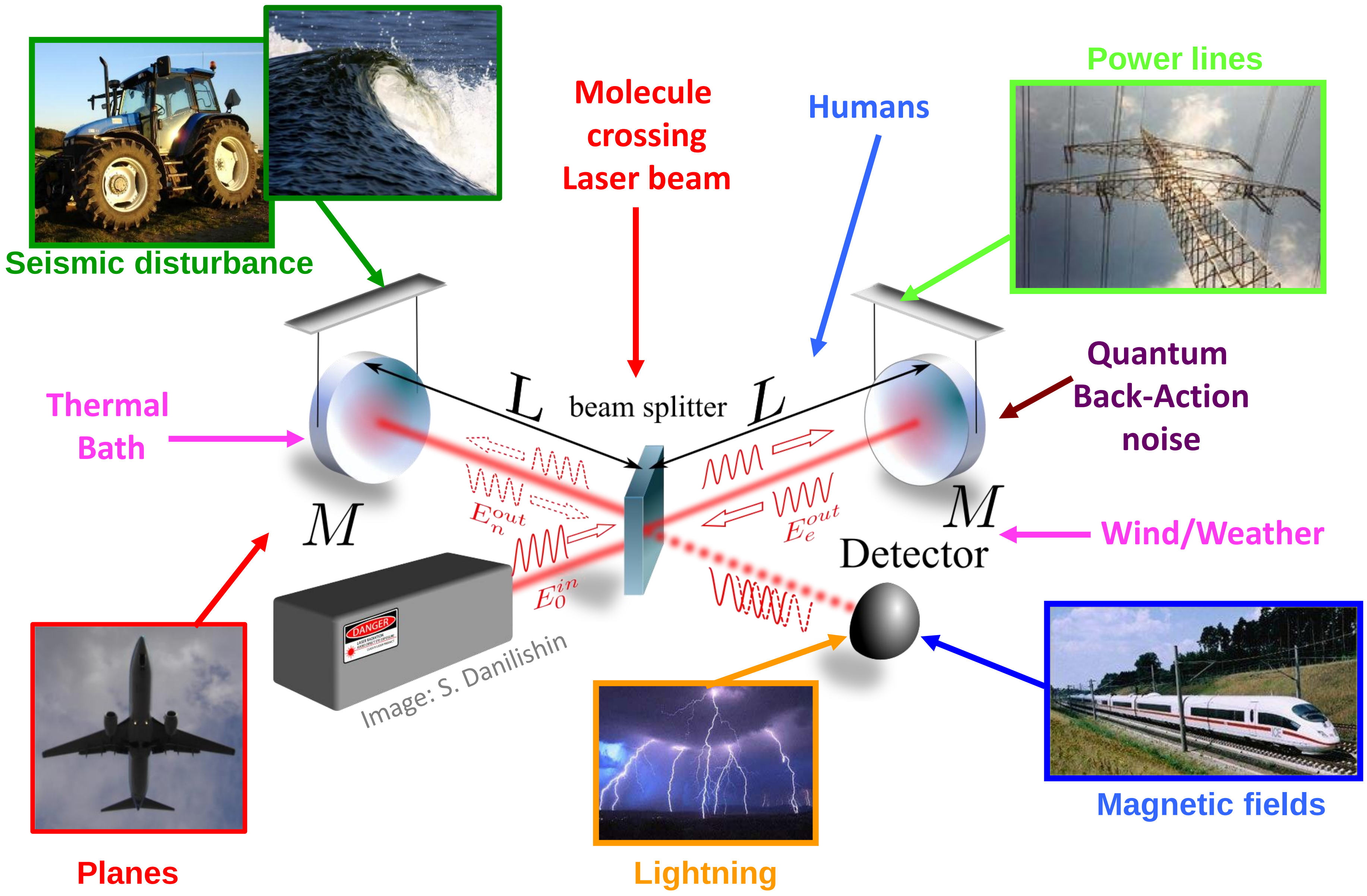


Other options for upgrading existing (LIGO A+, LIGO Voyager) or building new dedicated detectors (OzHF)

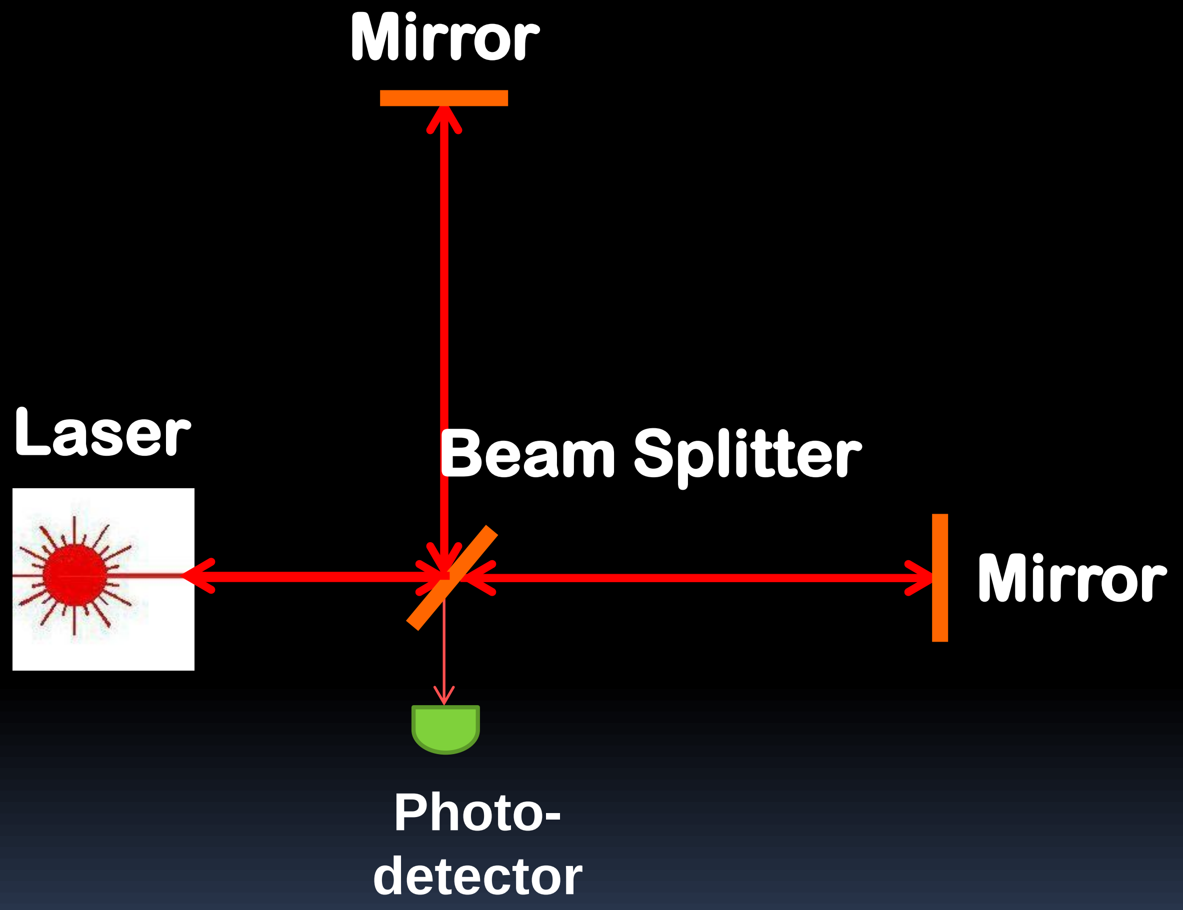
Key Parameter	Value
Arm Length	2 km
Laser power	500 W
Arm power	5 MW
Test mass material	Silicon
Coating	GaAs/AlGaAs
Coating Phi	3e-5
Mirror Spot Size	4 cm radius
Long SRC	350 m

David Ottaway

Myriads of Disturbances



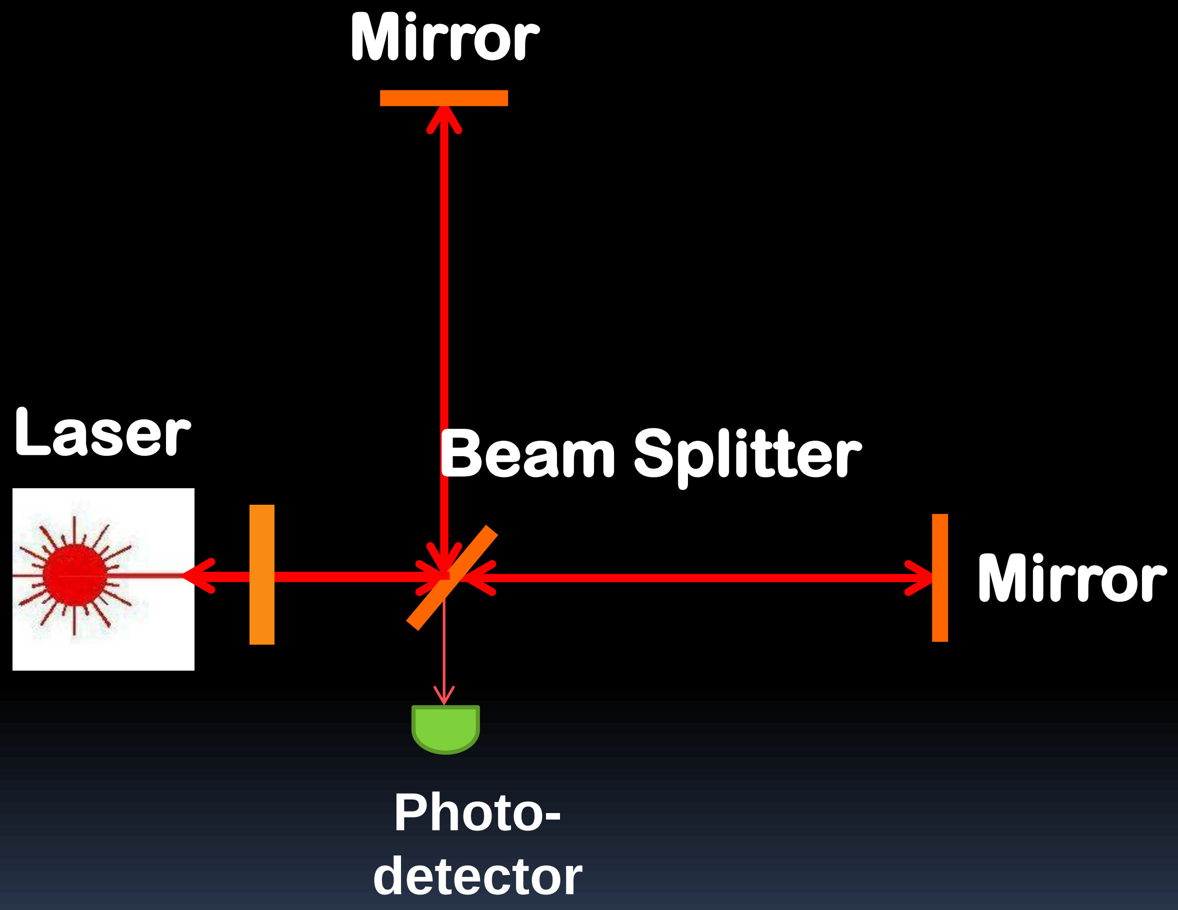
GWD optical principle



Output @ Photo detector dark
→Output to Laser bright

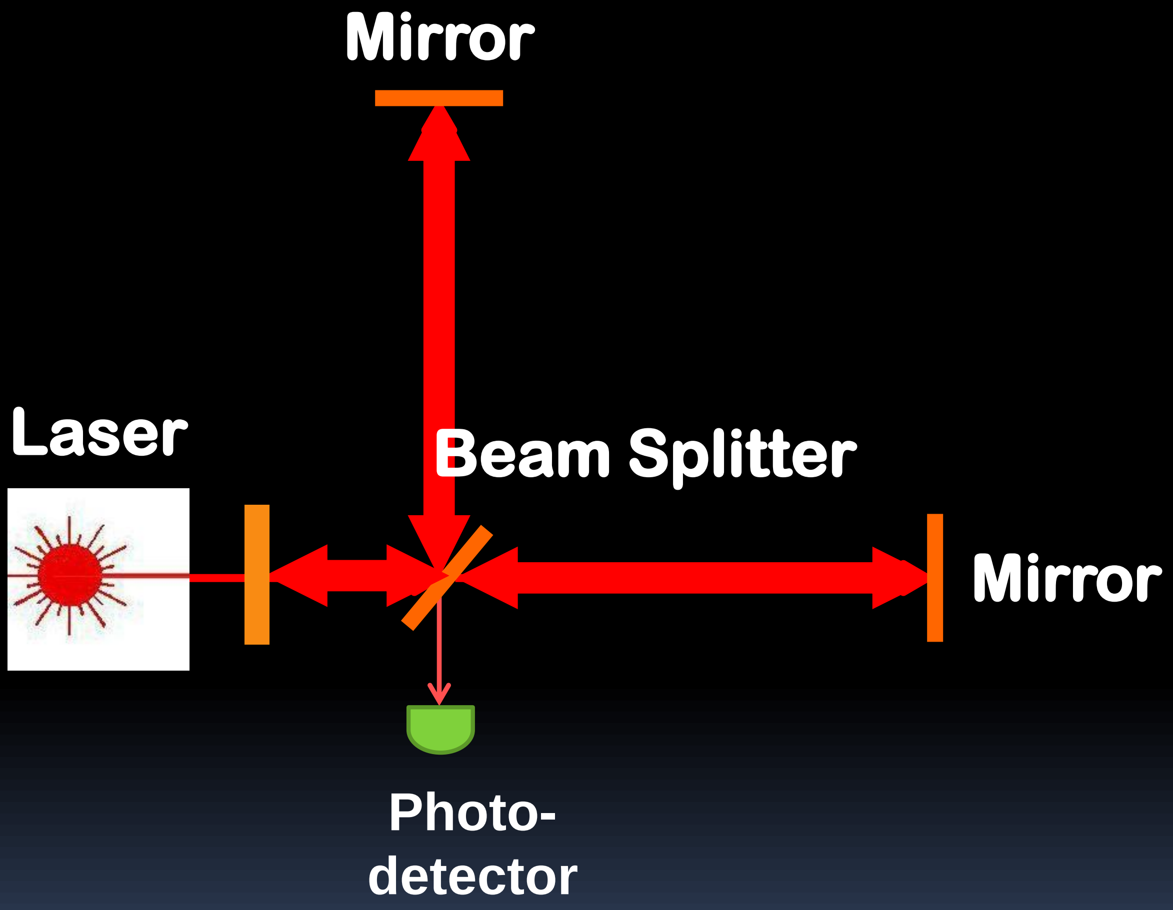
} Energy conservation

Power Recycling



Recycle laser light!

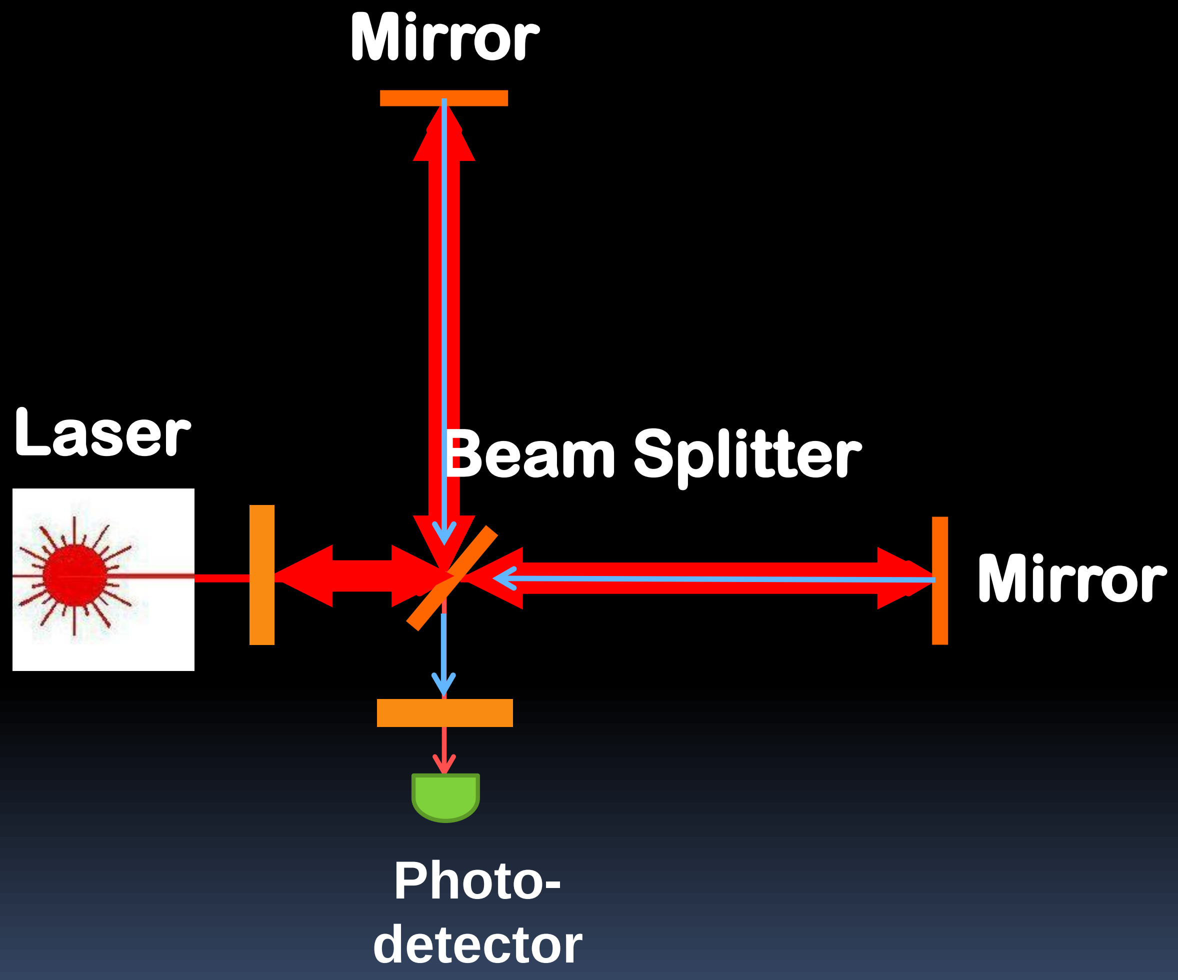
Power Recycling



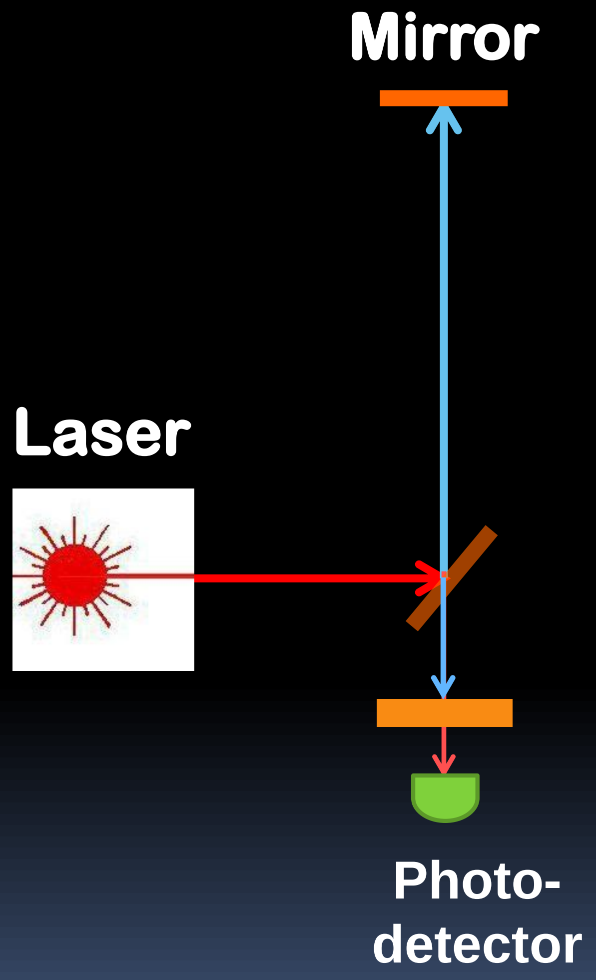
Recycle laser Light GEO600: Factor 1000

5W into Interferometer → 5kW inside Interferometer

A similar trick: Signal Recycling



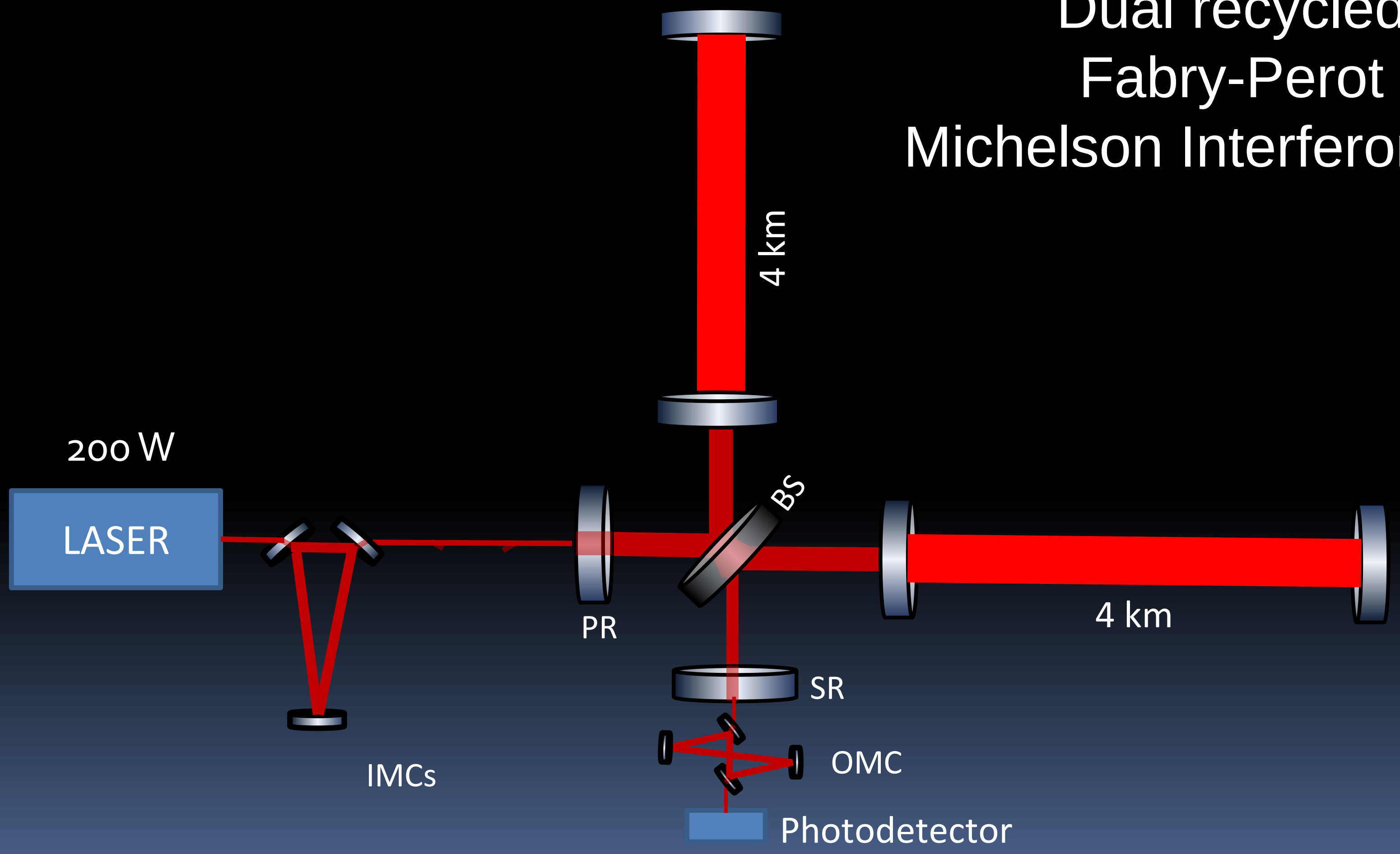
Signal Recycling cavity



Increase light power with arm cavities

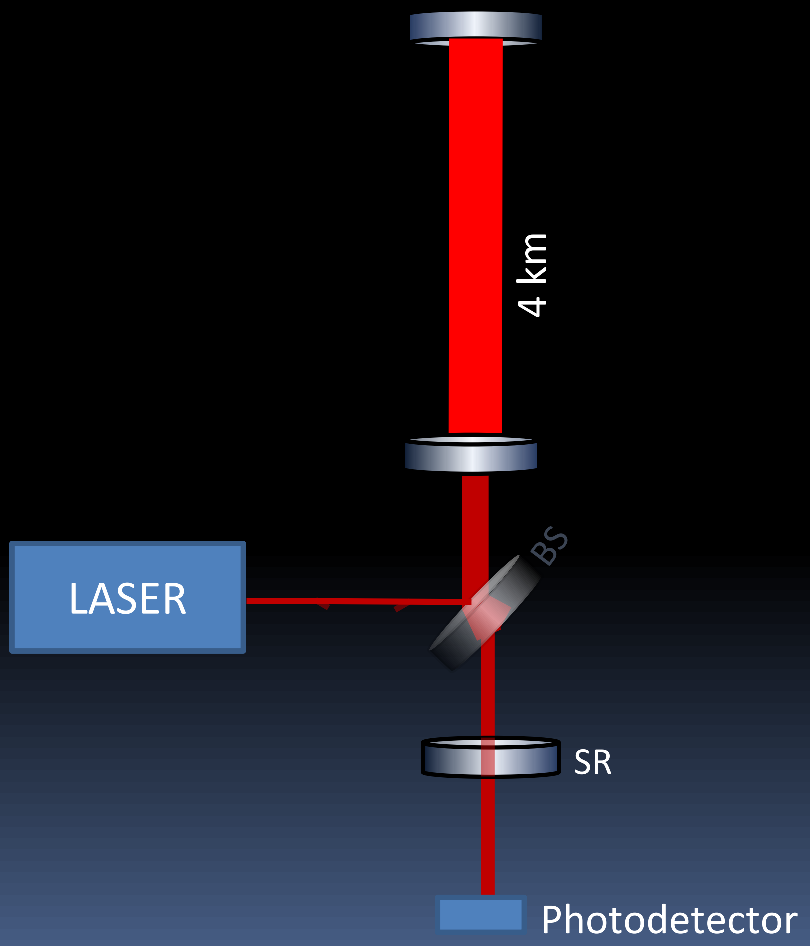
aLIGO

Dual recycled
Fabry-Perot
Michelson Interferometer



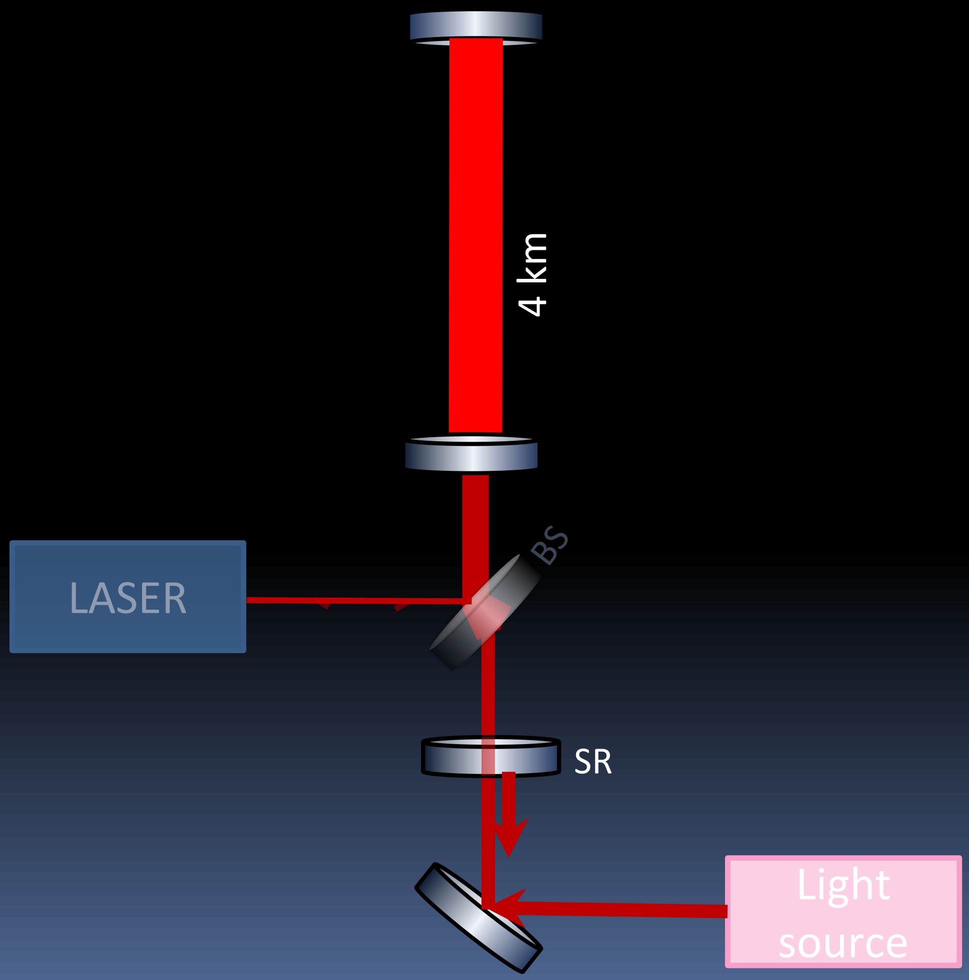
Signal Recycling / Resonant Sideband Extraction

aLIGO

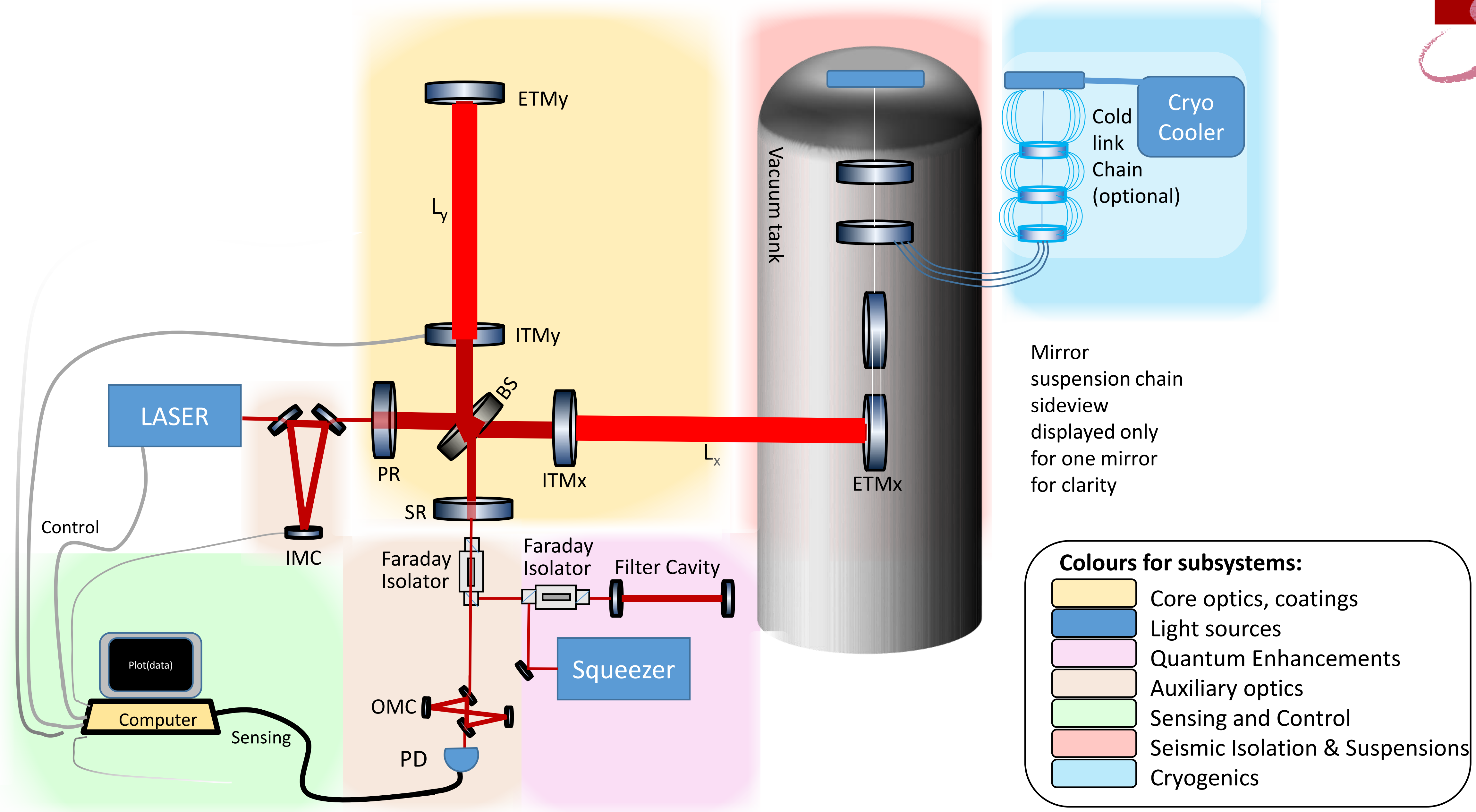


Signal Recycling Cavity

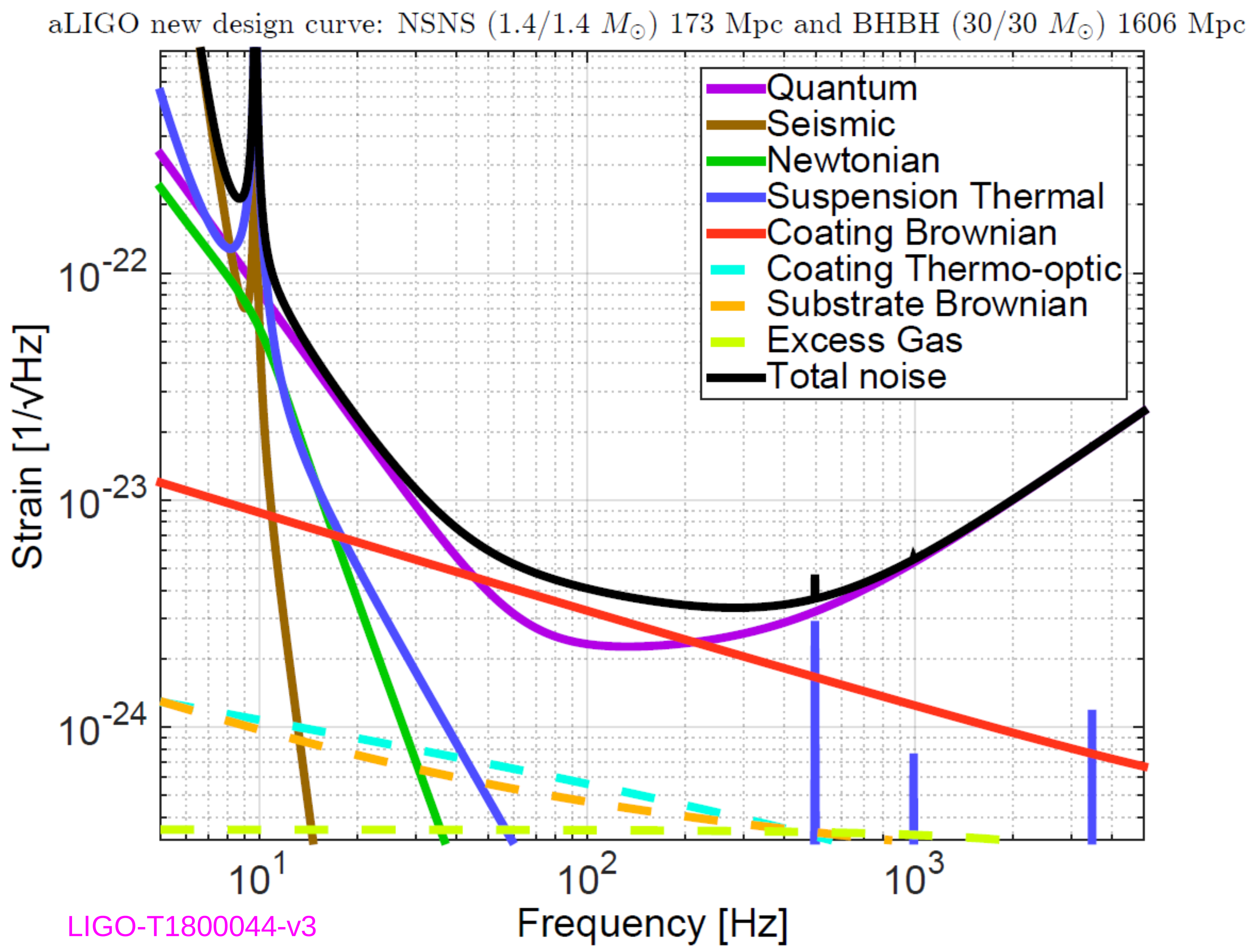
reflects light injected to the dark port



3G Subsystems



aLIGO Noise budget

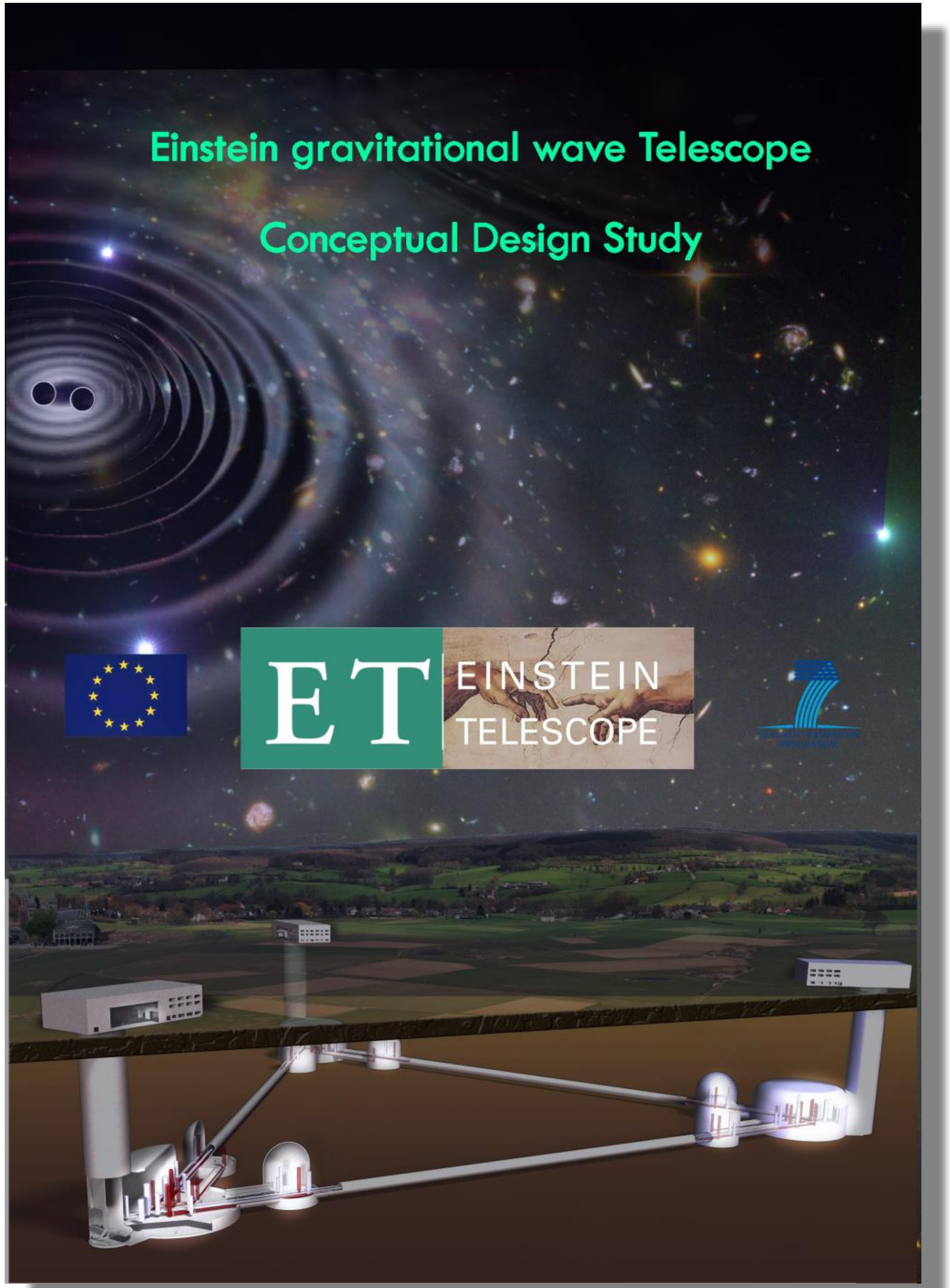


LIGO-T1800044-v3

Limiting noise sources:

- High frequencies
  - Shot noise
- Mid frequencies
  - Shot + Rad.Pres. noise
- Low frequencies
  - Radiation pressure
  - Seismic
  - Suspension thermal
  - Newtonian

+ Control Noise



Einstein Telescope
Conceptual Design Study

- May 2008 – May 2011

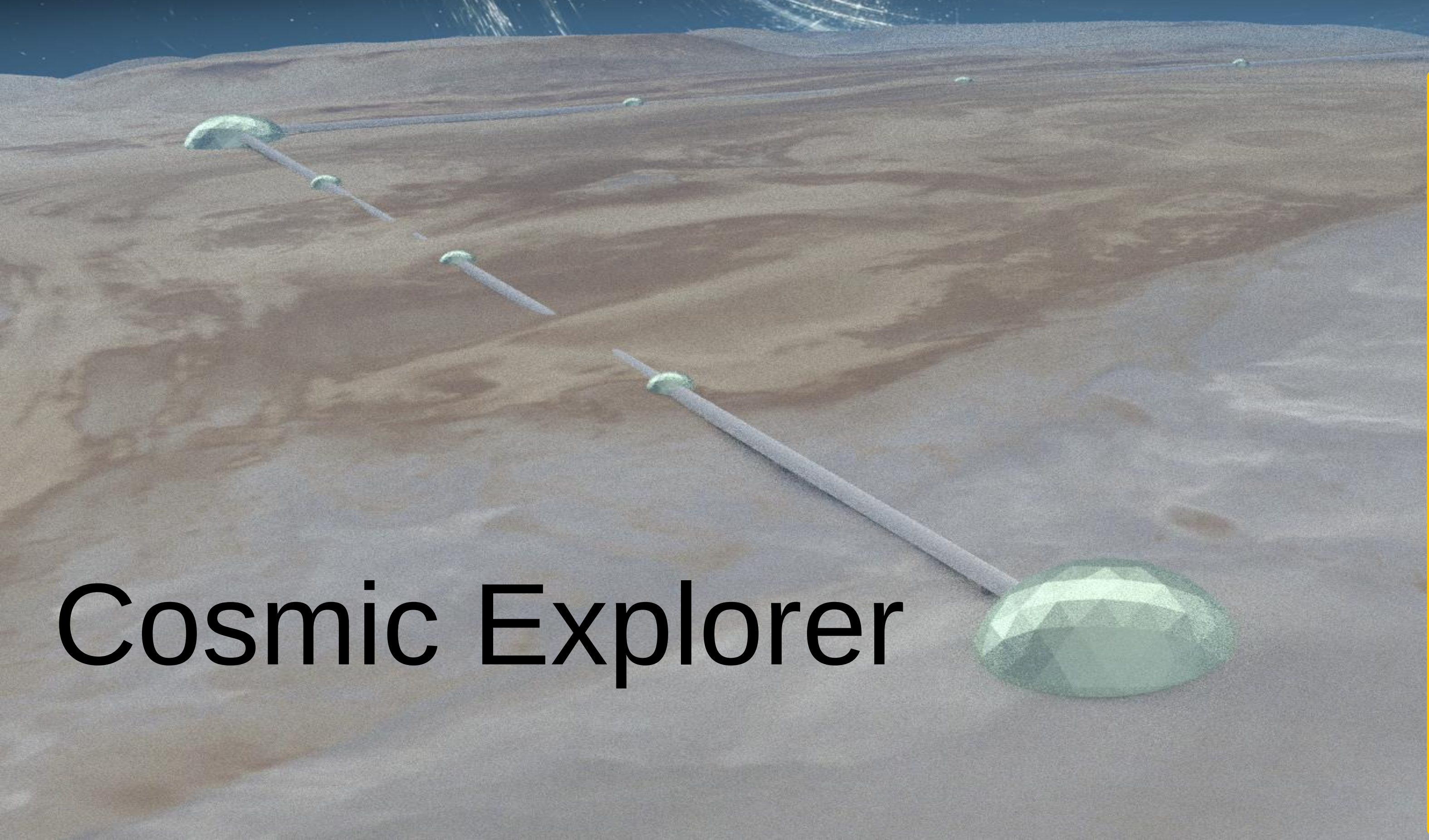
Updating the

Einstein Telescope
Design 2020

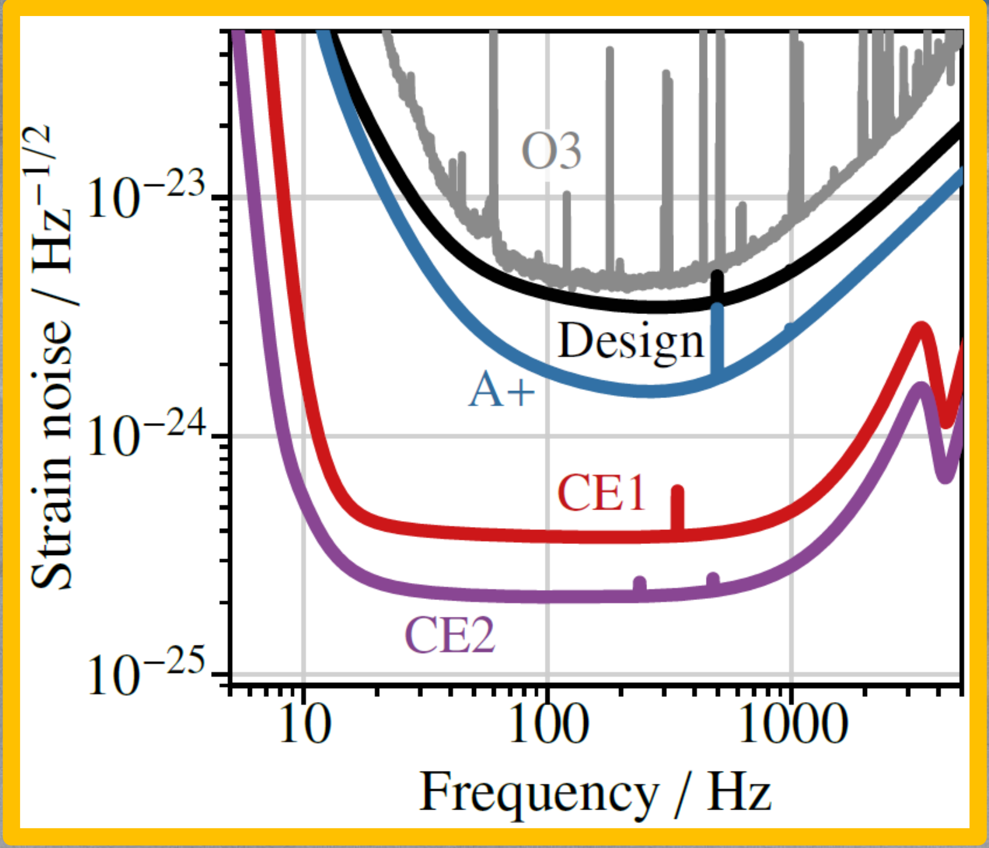
Cosmic Explorer

	LIGO A+	CE Stage 1	CE Stage 2
Arm length	4 km	40 km	40 km
Test mass	40 kg fused silica	320 kg fused silica	320 kg silicon
Suspension	0.6 m silica fibers	1.2 m silica fibers	1.2 m silicon ribbons
Temperature	297 K	297 K	123 K
Laser wavelength	1 μm	1 μm	2 μm
Circulating power	0.8 MW	1.4 MW	2 MW
Squeezed light level	6 dB	6 dB	10 dB

Conceptual design study now underway (PHY–1836814)



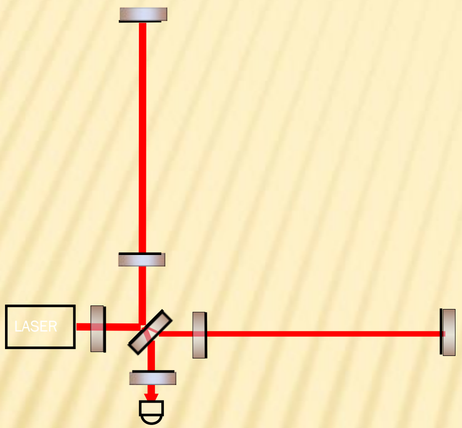
Cosmic Explorer



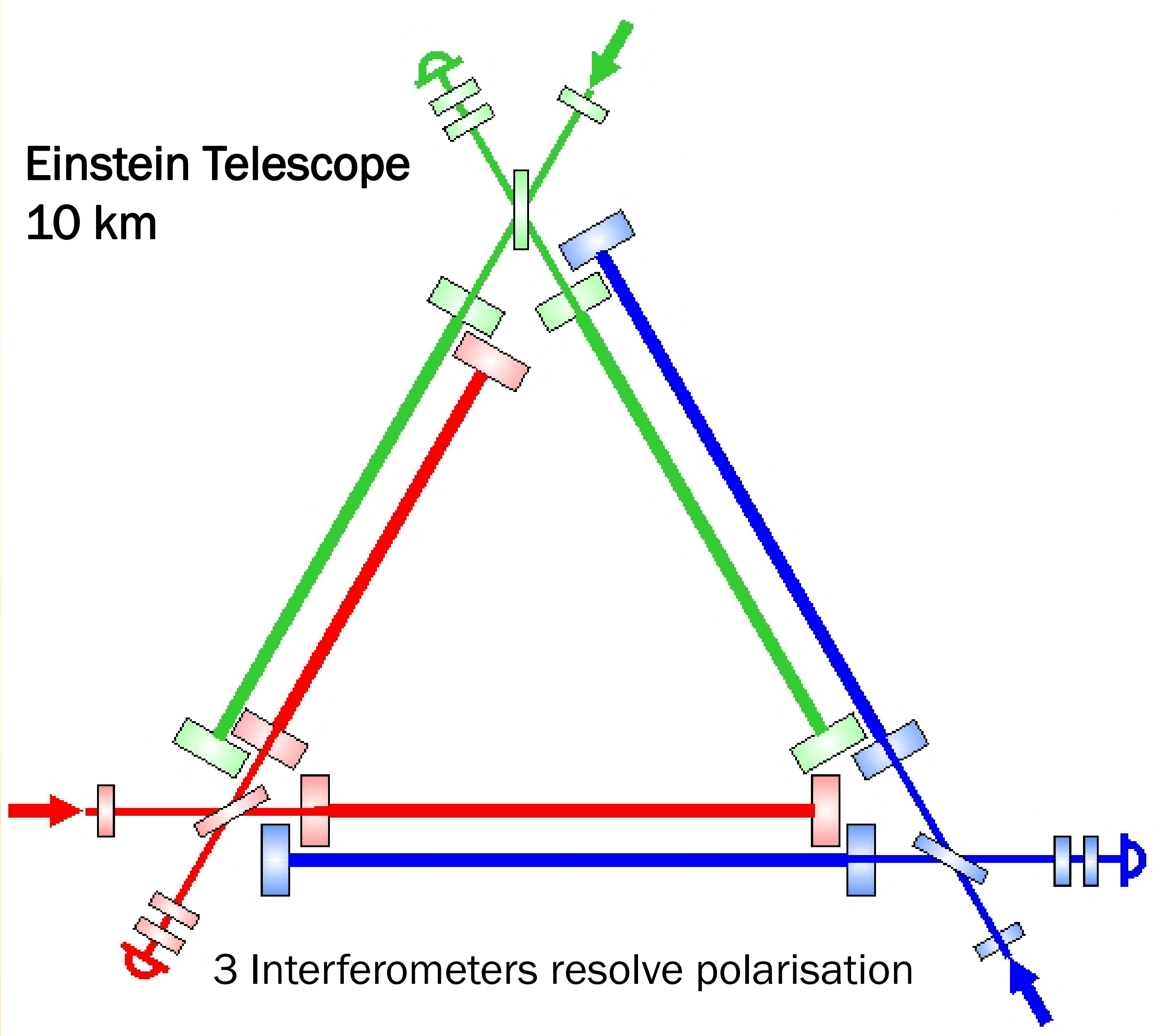
THE SIZE

The Einstein Telescope will have 10 km arms

→ gain a factor >2.5 w.r.t. advanced LIGO



Advanced LIGO
4 km



ET: Xylophone Concept

GW detectors become more and more complex and
at the same time aim to increase the observation bandwidth → the xylophone concept

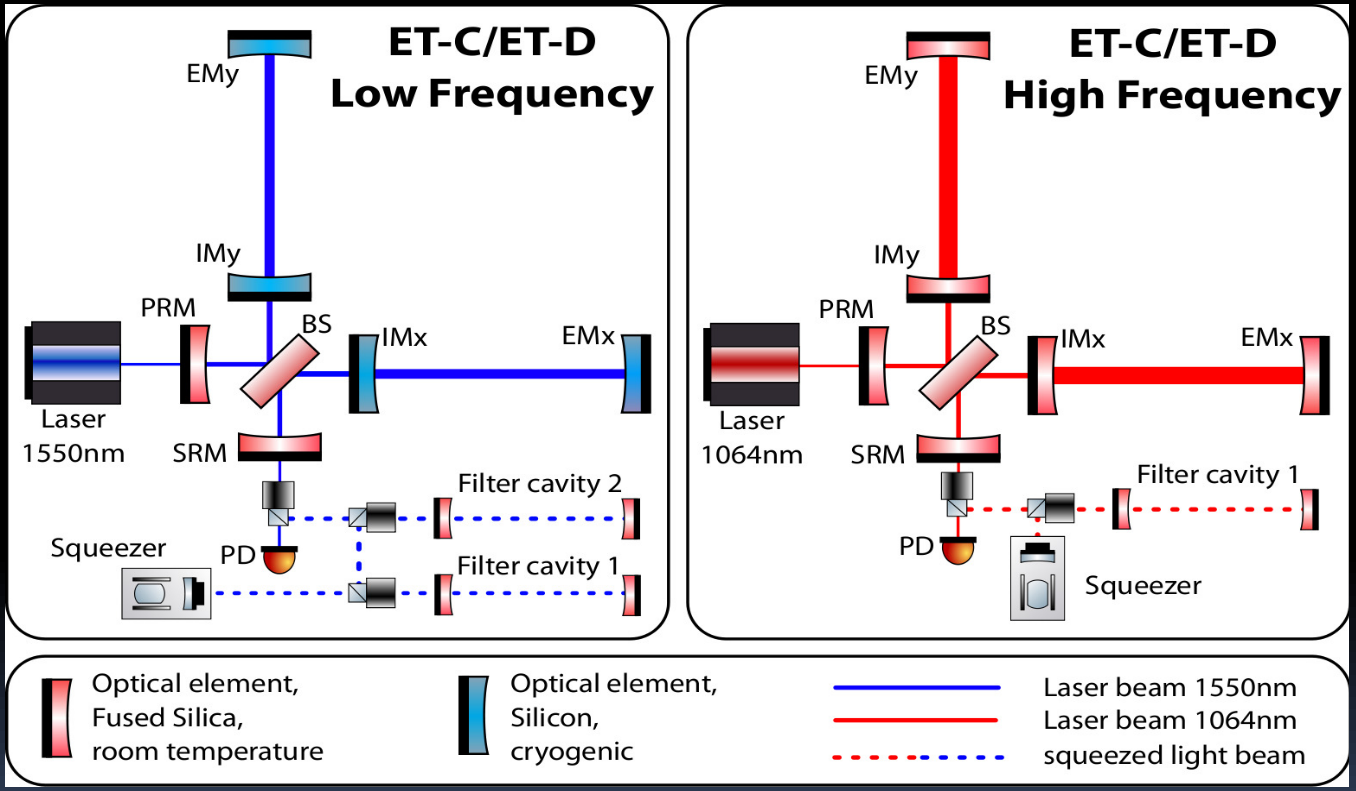
The xylophone concept was originally suggested for advanced LIGO:

R.DeSalvo, CQG 21 (2004) S1145-S1154
G.Conforto and R.DeSalvo, Nuc. Instruments 518 (2004) 228 - 232
D.Shoemaker, presentation at Aspen meeting (2001),
http://www.ligo.caltech.edu/docs/G/G010026-00.pdf

Allows to overcome ‘contradicting’ requirements in the technical detector design:

- High light power
  → reduce shot noise
  → increase radiation pressure noise.
- Cryogenic mirrors
  → low thermal noise

high light power + absorption <-> cryogenic mirrors



For ET we choose the conservative approach (designing an infrastructure) and went for a 2-band xylophone:
low-power, cryogenic low-frequency detector and a high-power, room-temperature high-frequency detector

Slide: Stefan Hild
2018, modified

Enabling Technologies

The main *sensitivity ingredients* are:

- Size: 10km, underground location
- Xylophone design: ET-LF, ET-HF

10 – 20 K

ET-LF:

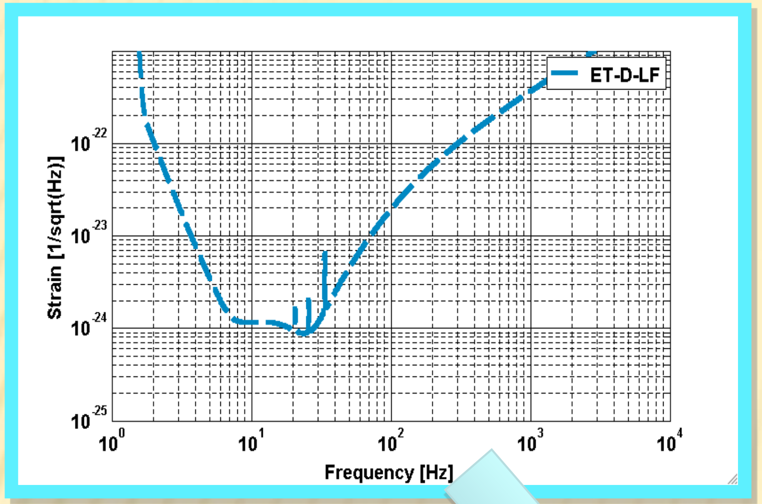
- Cryogenics
- Seismic suspensions
- Silicon (Sapphire) test masses
- Large test masses
- New coatings
- New laser wavelength
- Frequency dependent squeezing, Filter cavities

300 K

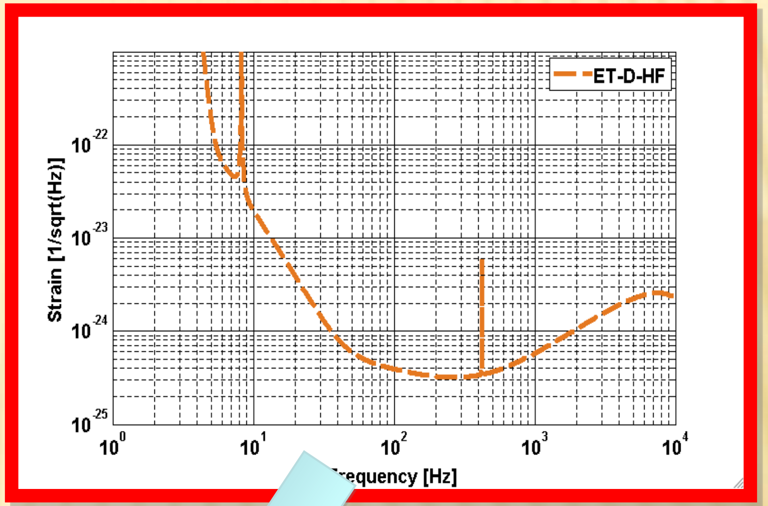
ET-HF:

- High power laser
- High circulating light power
- Thermal compensation
- Large test masses
- New coatings
- Frequency dependent squeezing

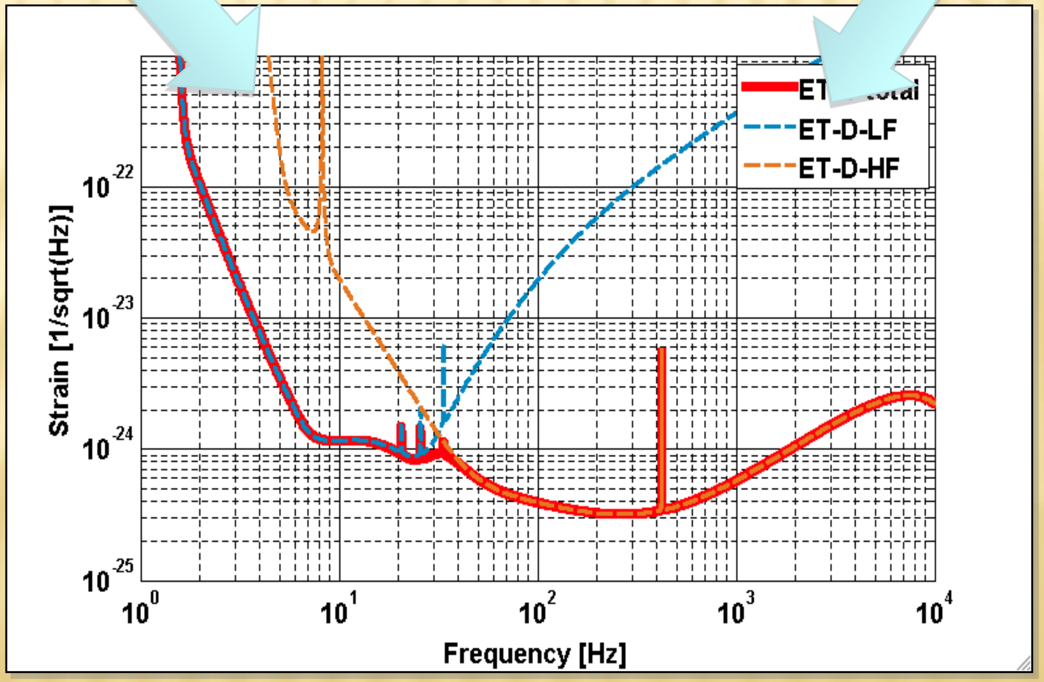
ET-D XYLOPHONE SENSITIVITY



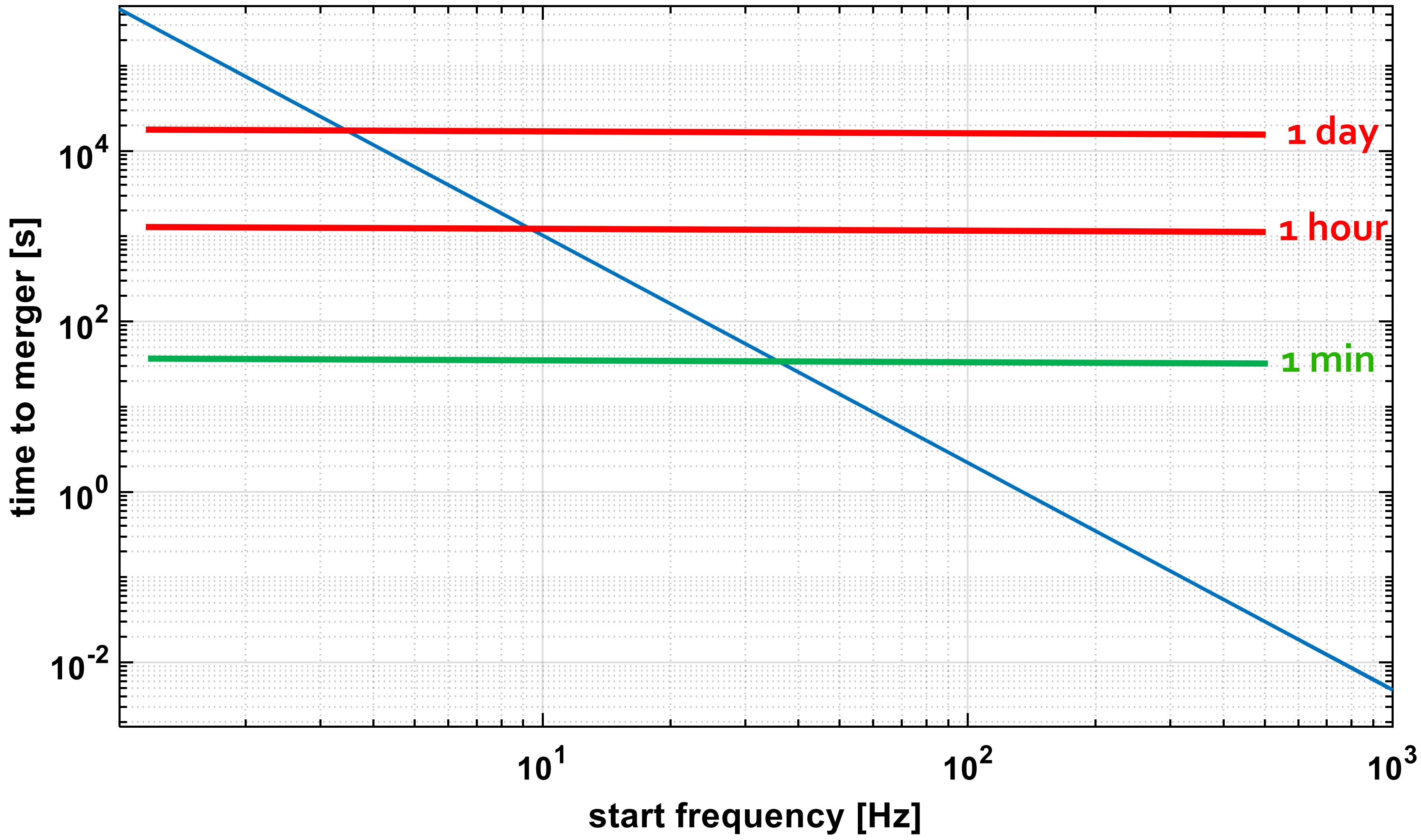
ET-D-LF



ET-D-HF



Some sources from O1 & O2



NS-NS „In Band“ duration

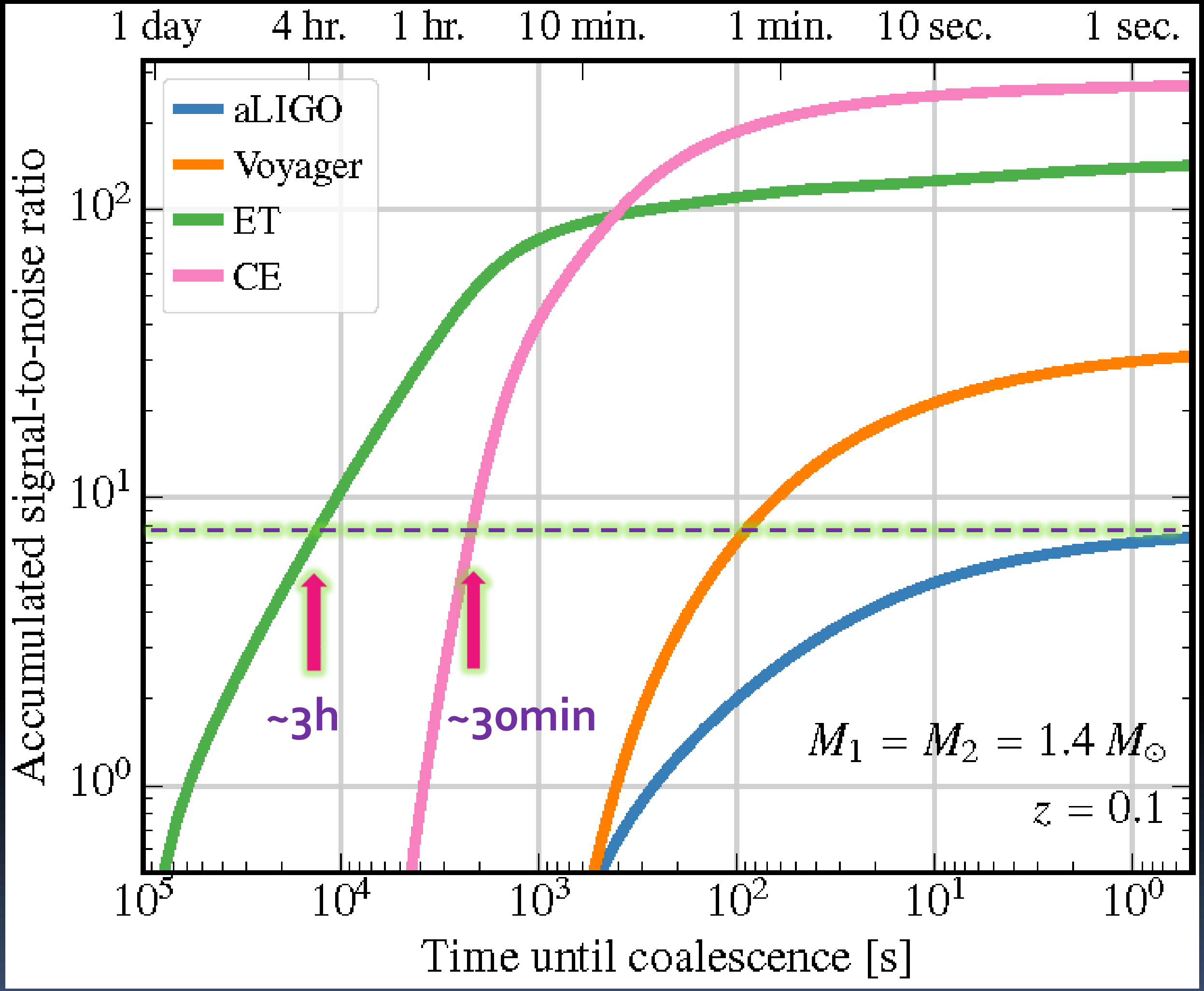
B_{inary}N_{eutron}S_{tar}

pre-warning time with 3G

Alert latencies:

A GWD : + 20minutes

ET : -3 h



Credit: Evan Hall

GWDs in the late 30's