Exploring the Gravitational wave Universe

New Discoveries and Plans

Brian Lantz

Feb 7. 2024
Silicon Valley
Astronomy Lecture Series
G2400231

National Science Foundation + International partners

LIGO Scientific Collaboration

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Andrews University
Bar-Ilan University
Bard College
Bellevue College
California State University Fullerton
Cal State LA
Carleton College
MIT
Christopher Newport University
Colorado State University
Columbia University in the City of New York
Concordia University Wisconsin
Cornell University Founded A.D. 1865
Embry-Riddle Aeronautical University
Georgia Tech
NASA Goddard Space Flight Center
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Haverford College
Hillsdale College
Hobart & William Smith Colleges
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NASA Marshall Space Flight Center
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Universitas Scientiarum Szegedinensis
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Sonoma State University
Leland Stanford Junior University Die Luft der Freiheit weht 1891
Stony Brook University
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University of the West of Scotland UWS
University of Glasgow
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OzGrav
Swinburne University of Technology
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Texas The University of Texas at Austin
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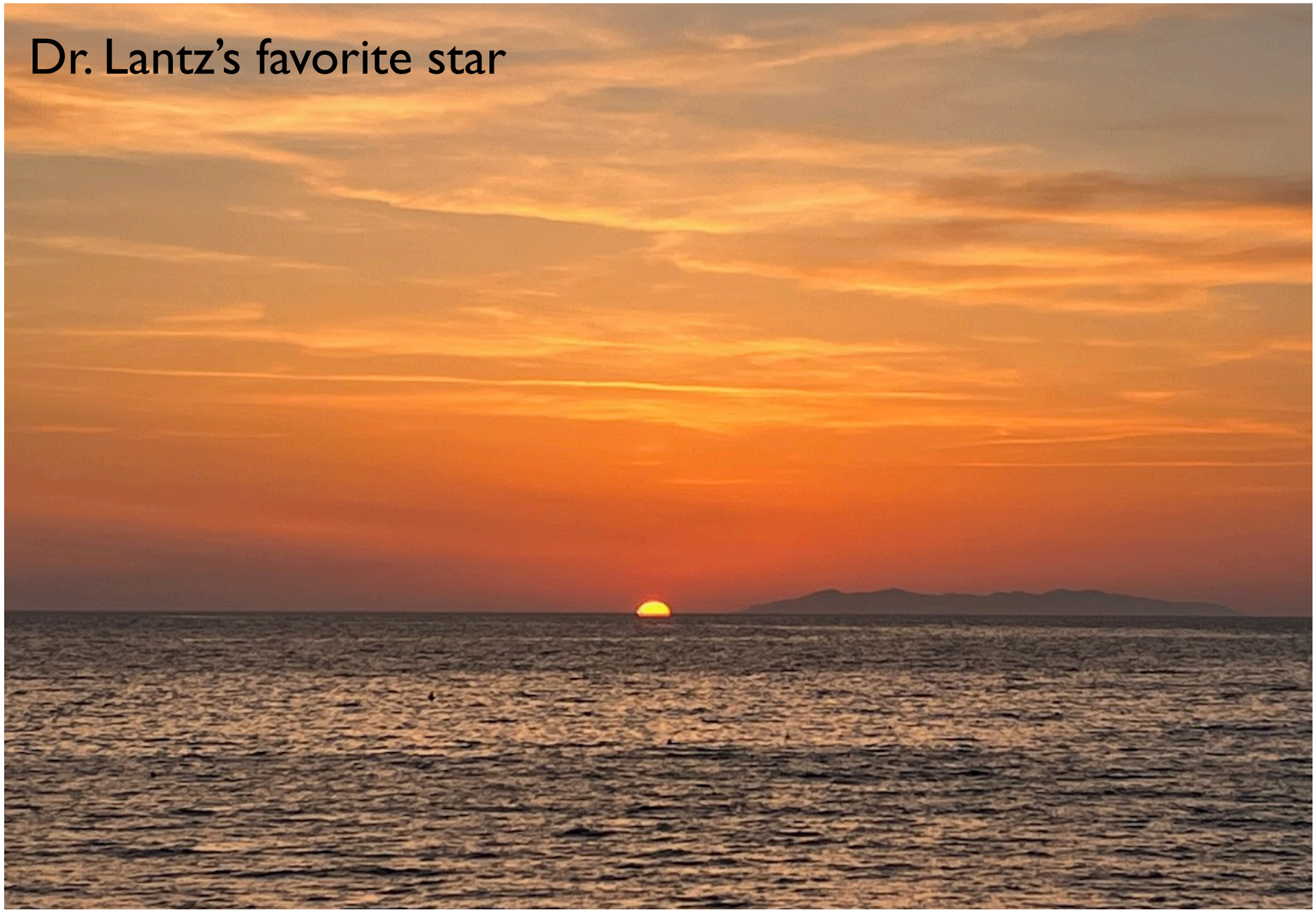
東京大学 The University of Tokyo
The University of Utah
University of Washington
Bothell
University of Cambridge
Warwick The University of Warwick
Royal Holloway University of London
Vanderbilt University
Villanova University
VU Vrije Universiteit Amsterdam
West Virginia University
Western Washington University
IISER Kolkata
IIT Hyderabad
CGCRI CGCB
Indian Institute of Technology Madras
UWM University of Wisconsin Milwaukee
University of Southern Mississippi
KISTI 한국과학기술정보연구원 Korea Institute of Science and Technology Information
Chennai Mathematical Institute
DCSEM
RRCAT
tifr
NIMS National Institute for Mathematical Sciences | South Korea
CAU
서울대학교 Seoul National University
한양대학교 Hanyang University
UNIST
인제대학교 Inje University
LIGO–India Scientific Collaboration
ICTS International Centre for Theoretical Sciences
IISER Pune
Saha Institute of Nuclear Physics Calcutta
IUCAA
KASI Korea Astronomy and Space Science Institute
부산대학교 Pusan National University
Sung Kyun Kwan University
이화여자대학교
Korean Gravitational Wave Group

2 terms: Black Holes & LIGO

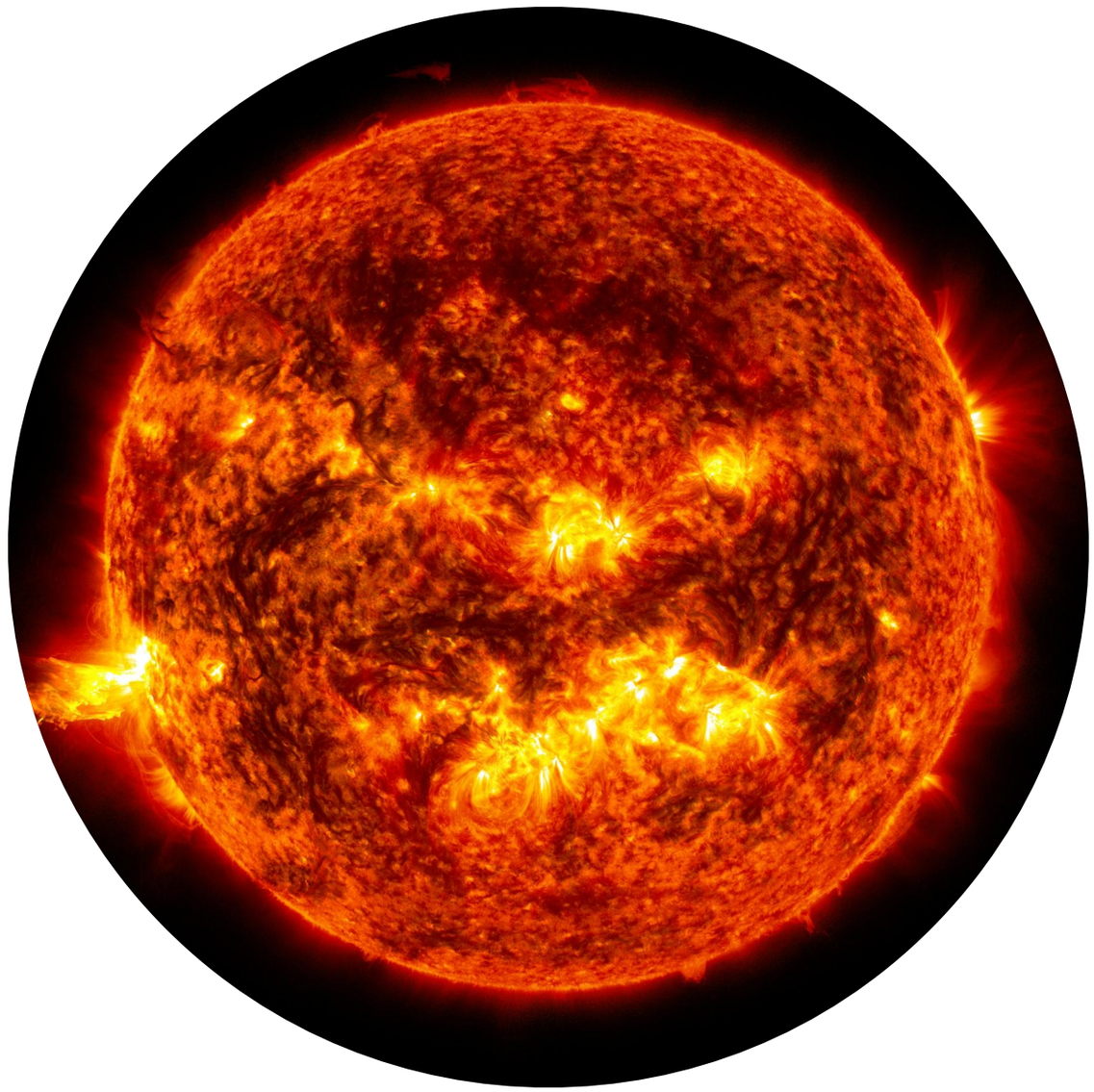
Black Hole - small and massive, gravitational pull is so strong that not even light can get out



Black Holes

Black Hole - small and massive, gravitational pull is so strong that not even light can get out

Dr. Lantz's favorite star



1 solar mass

865,000 miles

https://science.nasa.gov/image-detail/amf-gsfc_20171208_archive_e001435/

Black Holes

Black Hole - small and massive, gravitational pull is so strong that not even light can get out

First LIGO detection:

- ~30 solar mass
  110 miles in diameter
- 3.7 miles
  1 solar mass
  (not going to happen)

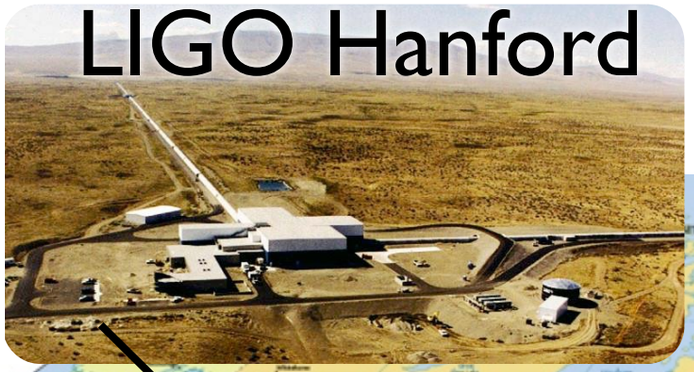
865,000 miles

https://science.nasa.gov/image-detail/amf-gsfc_20171208_archive_e001435/

2 terms: Black Holes & LIGO

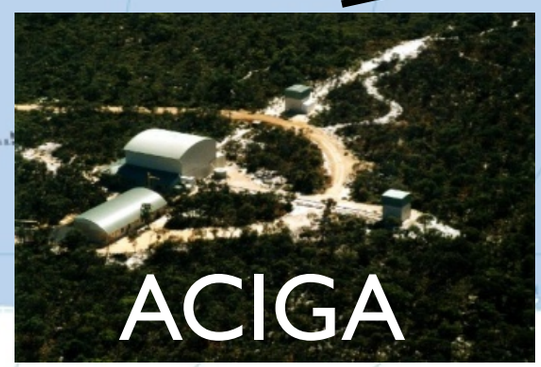
LIGO = Laser Interferometer Gravitational-wave Observatory

International Network



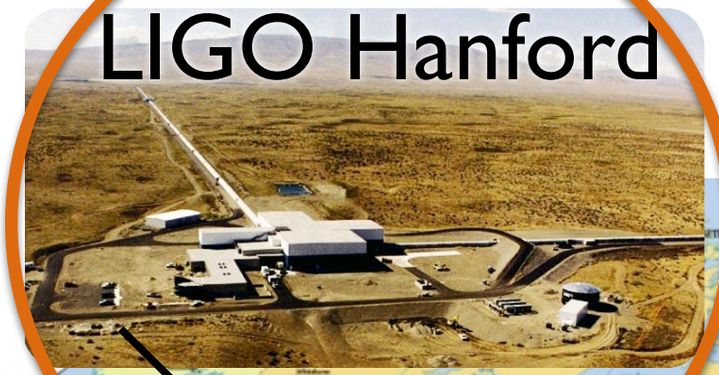
LIGO India

project approved

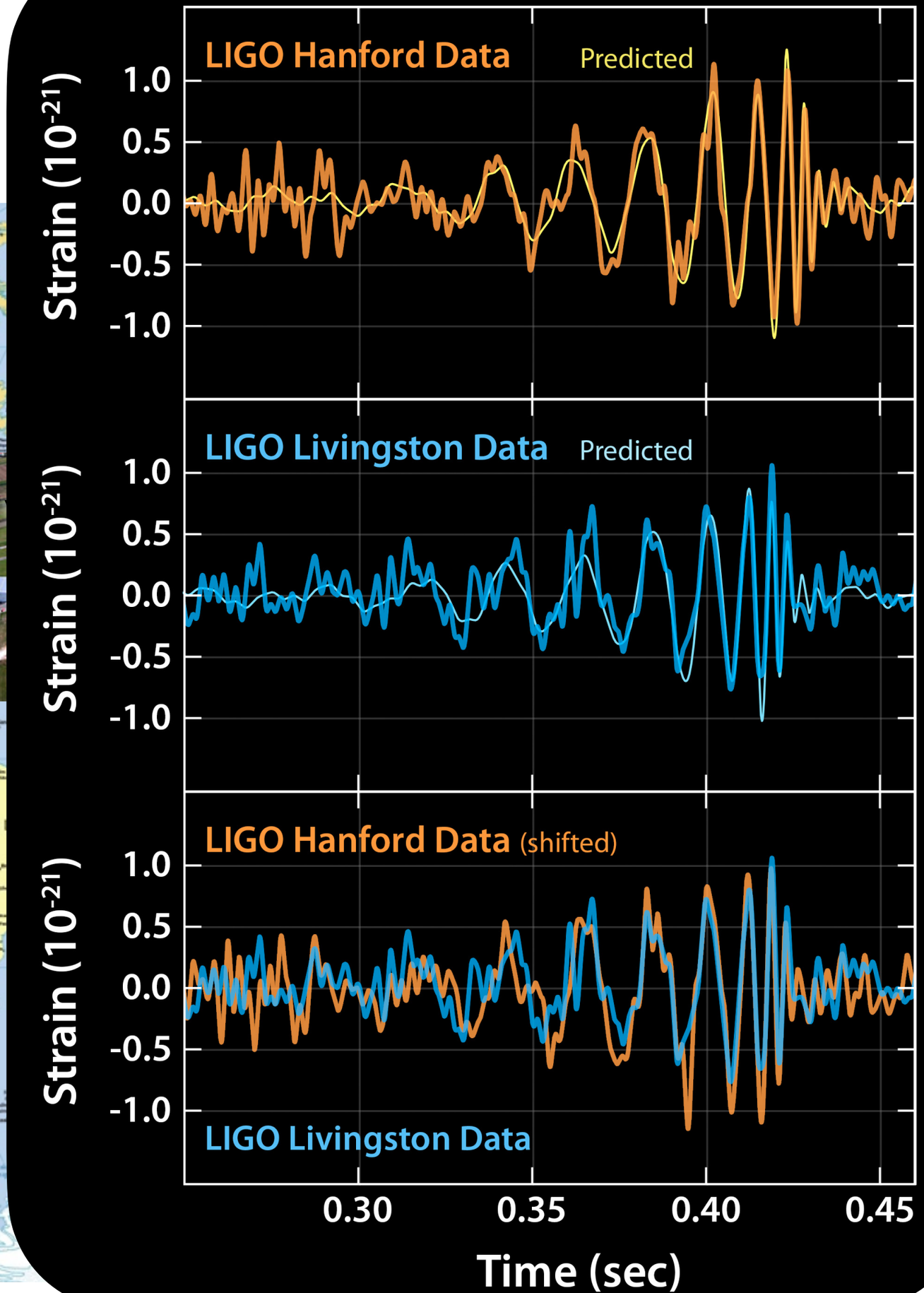


map from http://www.nationsonline.org/maps/political_world_map3000.jpg

LIGO Hanford



LIGO Livingston



AGRA

GO India

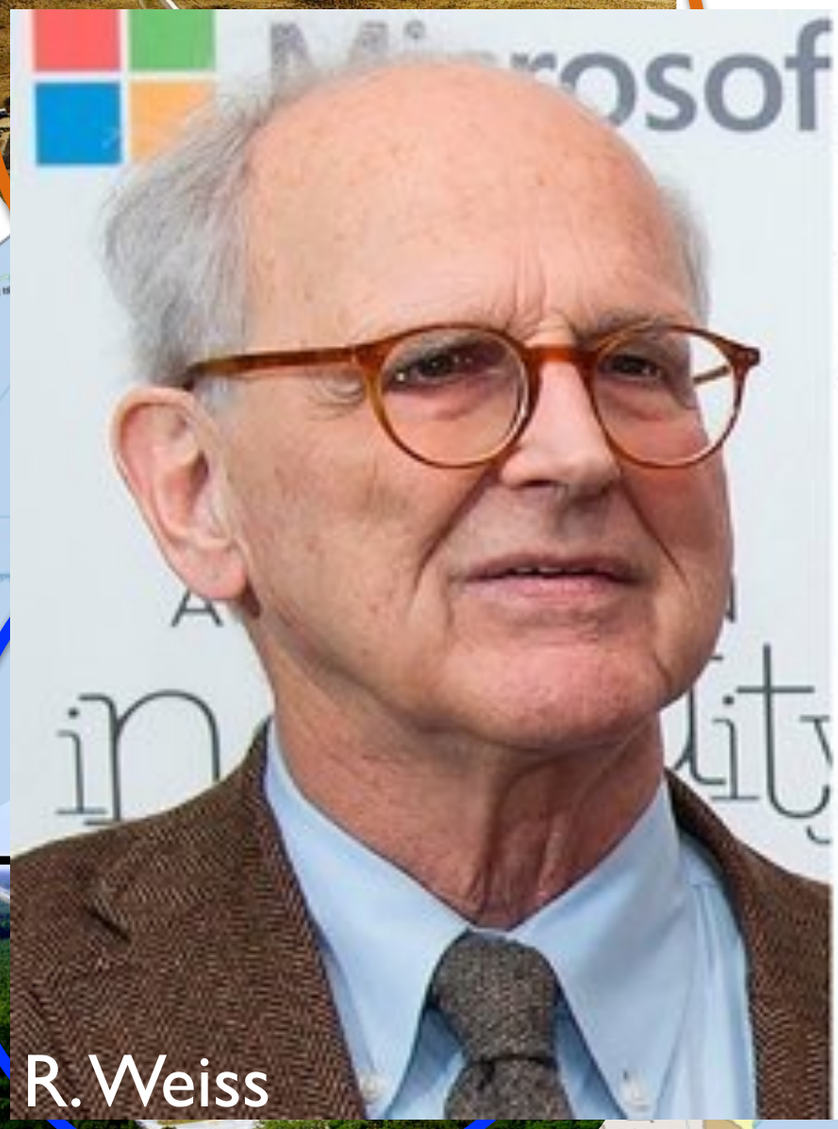
oject approved

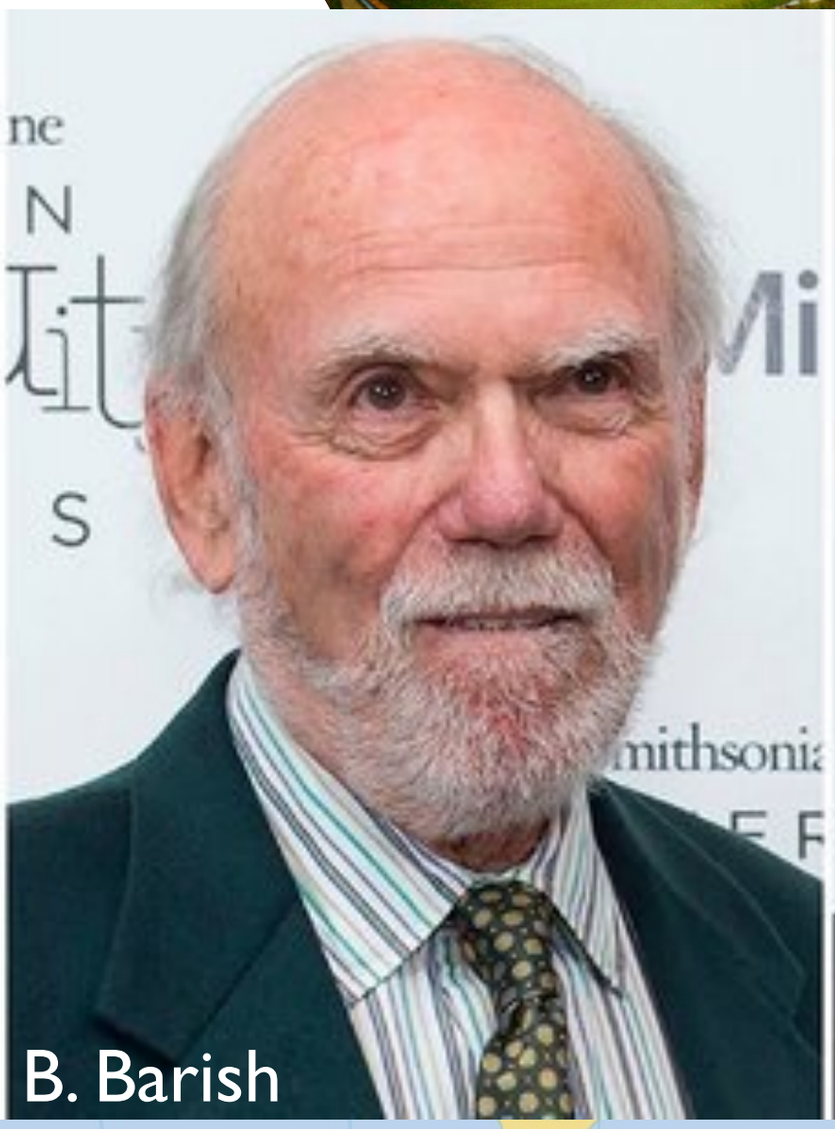
Oct. 3, 2017

LIGO Hanford

GEO 600

KAGRA

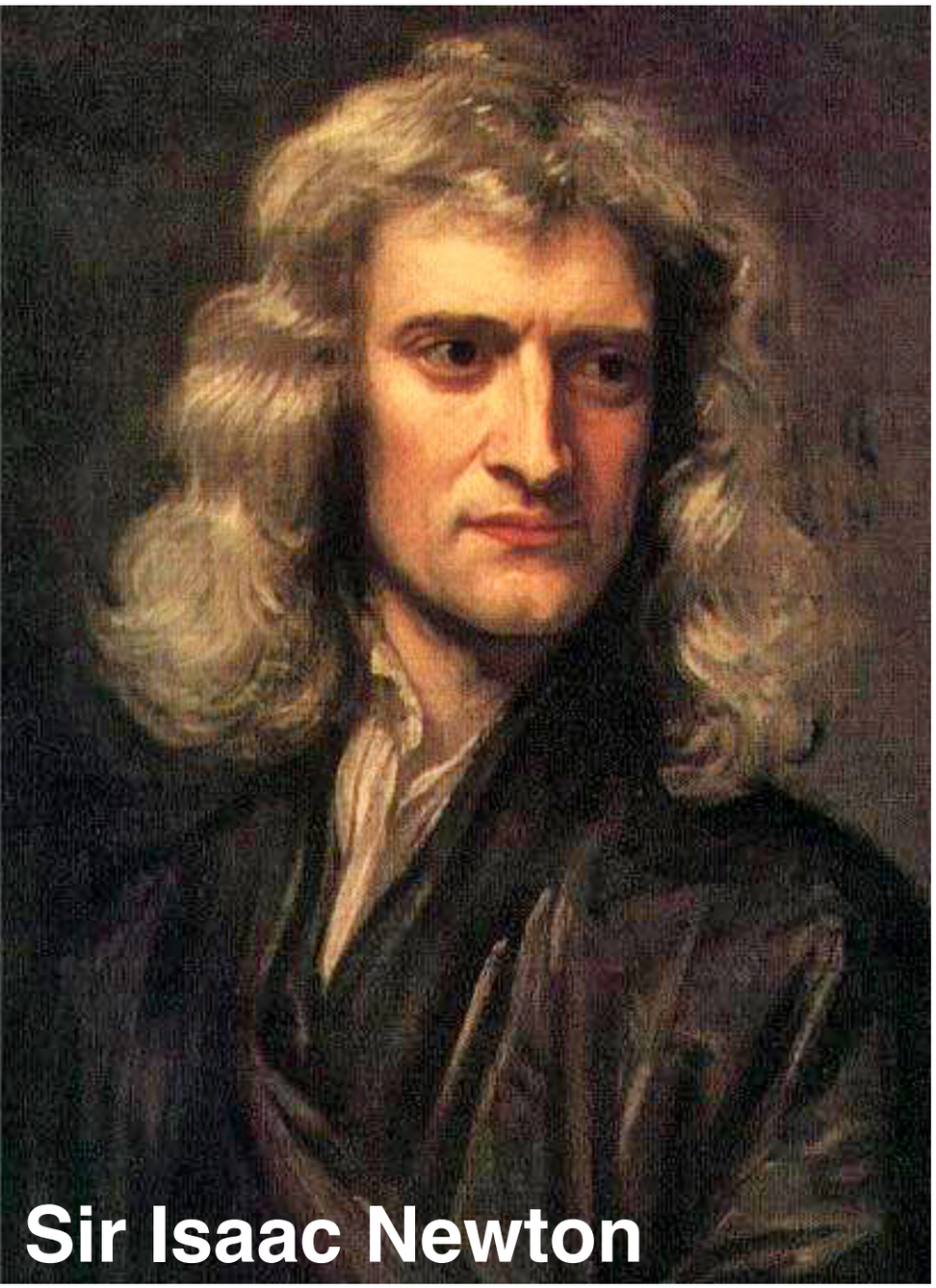




map from http://www.nationsonline.org/maps/political_world_map3000.jpg

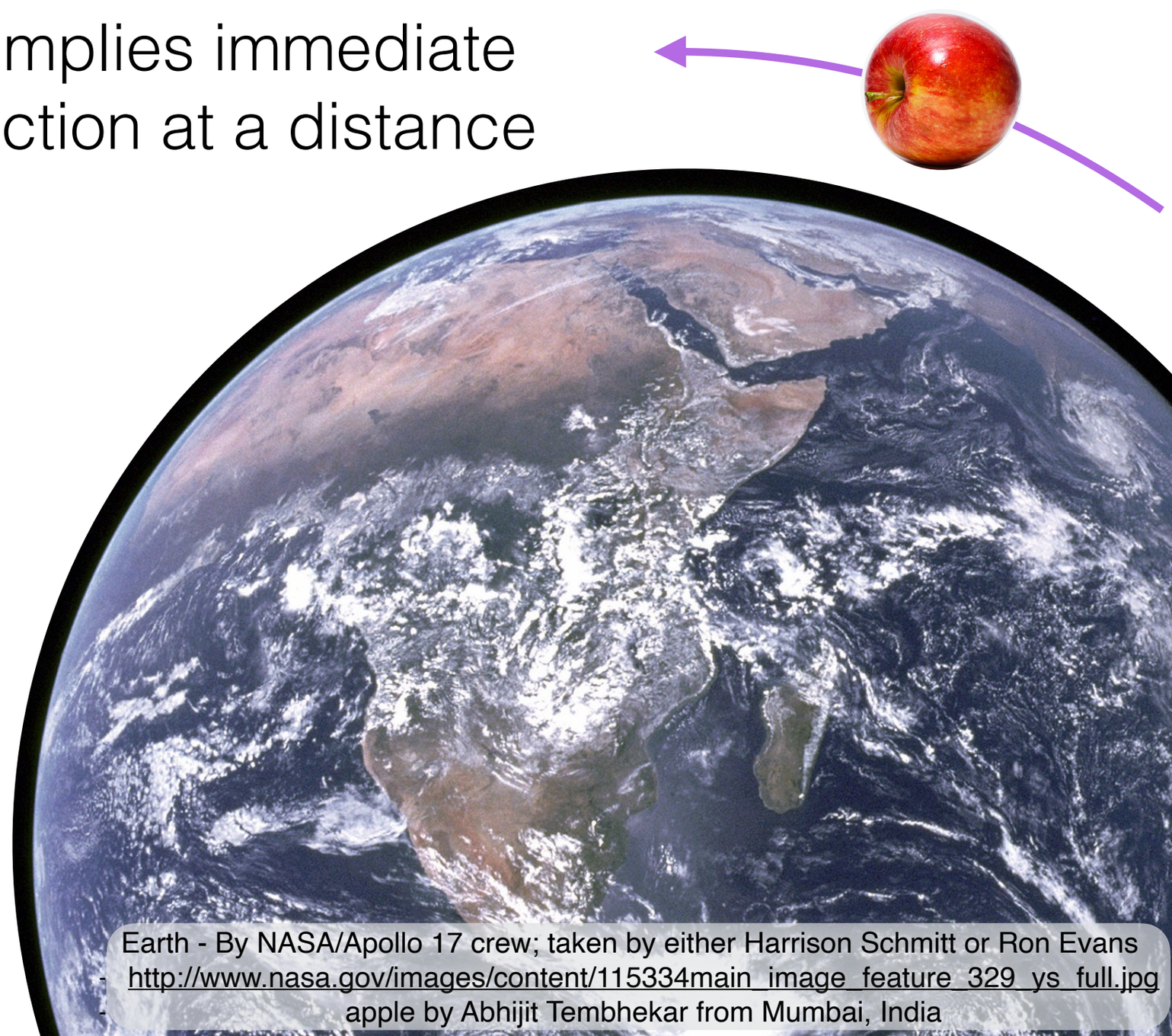
What is a Gravitational Wave?

$$F = \frac{G m_1 m_2}{r^2}$$



By Sir Godfrey Kneller
- http://www.newton.cam.ac.uk/art/portrait.html

Implies immediate
action at a distance



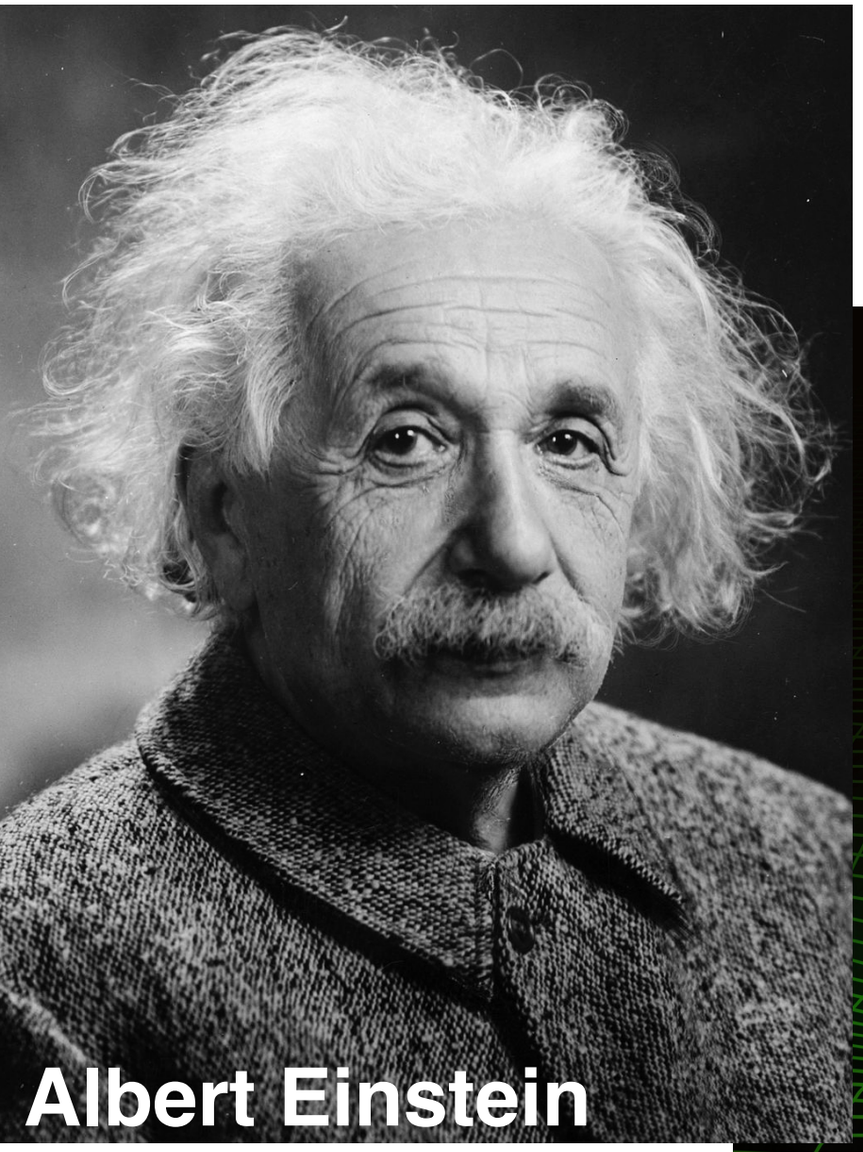
Earth - By NASA/Apollo 17 crew; taken by either Harrison Schmitt or Ron Evans
- http://www.nasa.gov/images/content/115334main_image_feature_329_ys_full.jpg
- apple by Abhijit Tembhekar from Mumbai, India

What is a Gravitational Wave?

Predicted by Einstein in 1916 as part of GR.

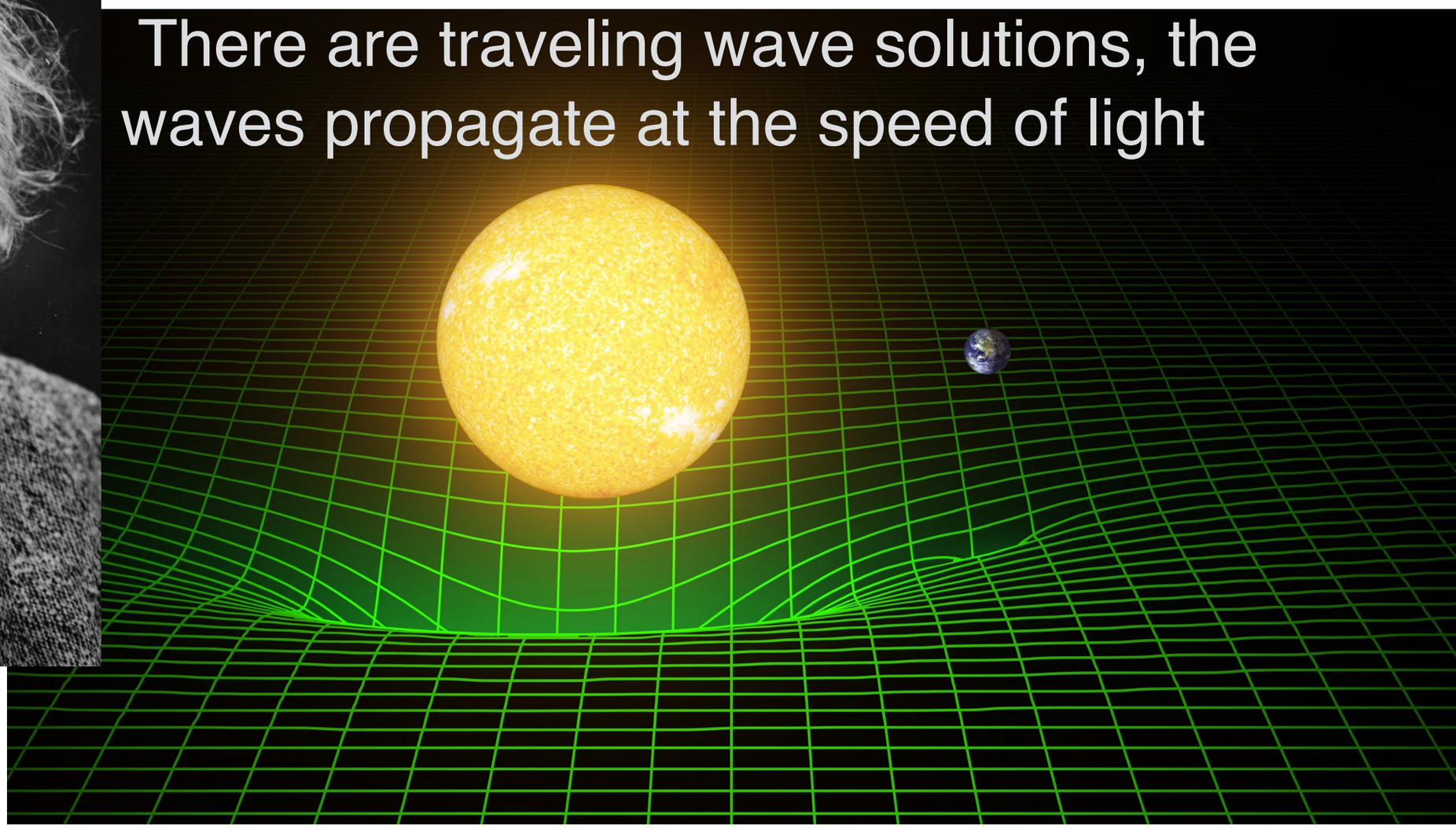
"Spacetime tells matter how to move,
matter tells spacetime how to curve"

- J. A. Wheeler



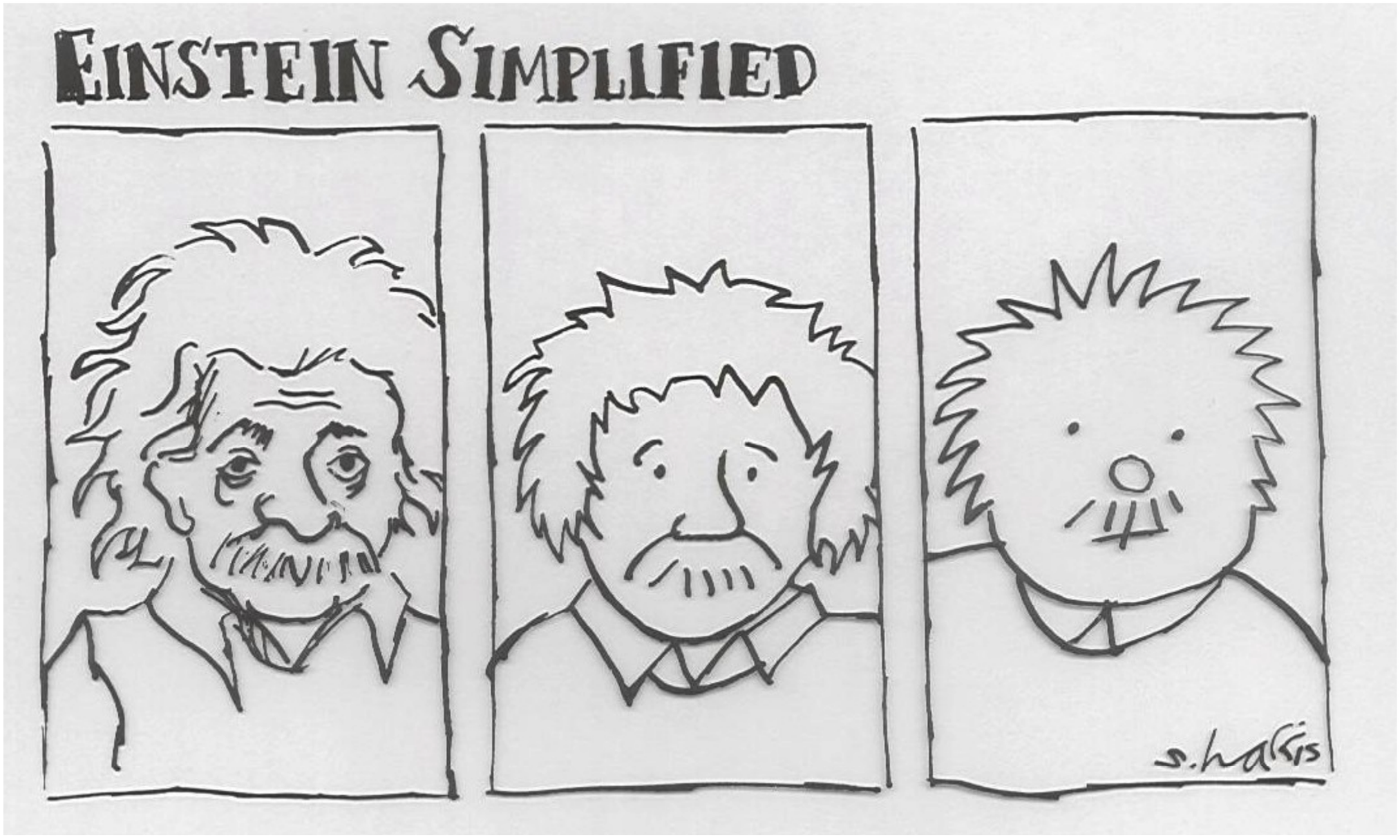
Albert Einstein

There are traveling wave solutions, the waves propagate at the speed of light



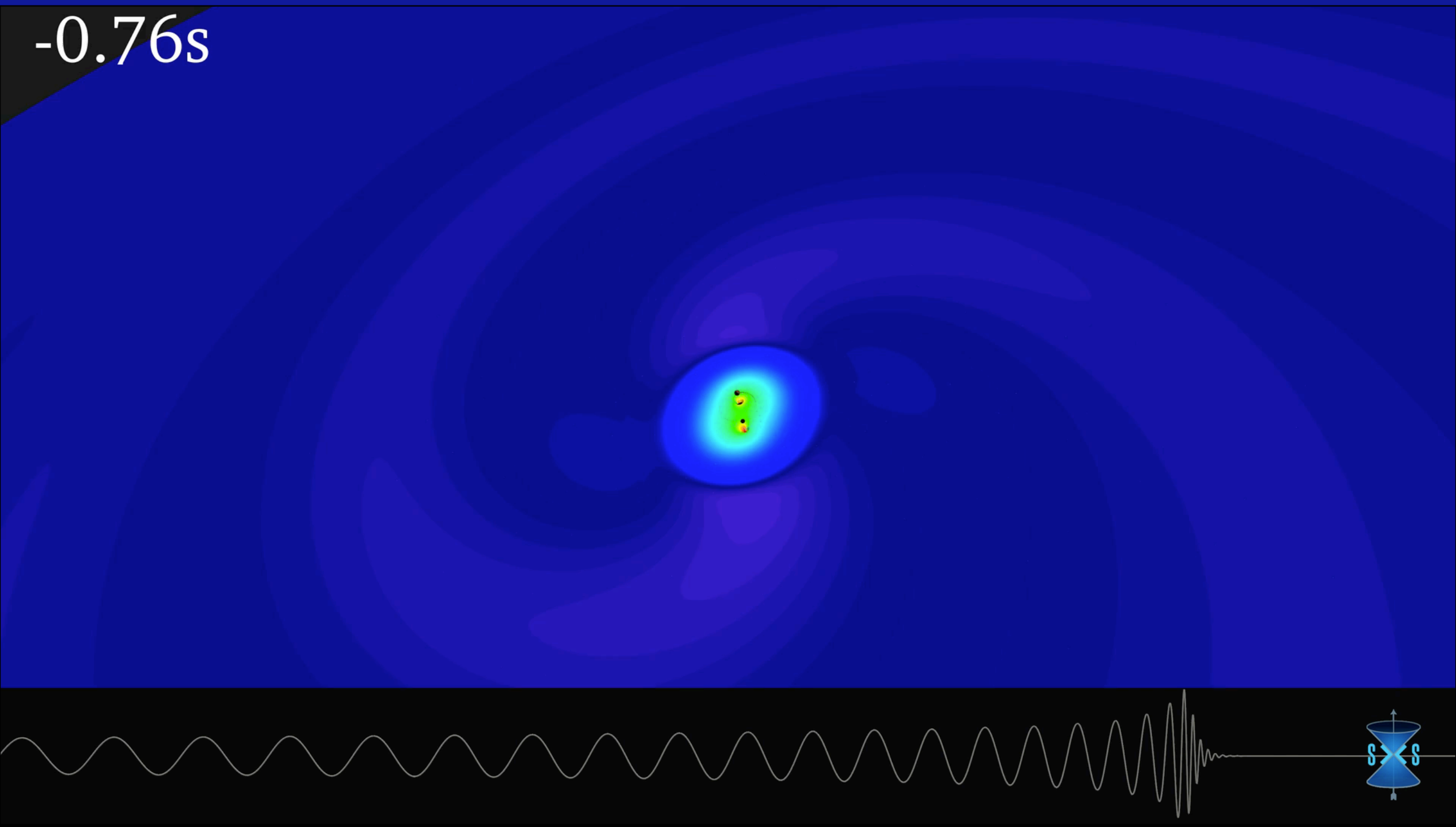
Photograph by Orren Jack Turner,
Library of Congress digital ID cph.3b46036.

What is a Gravitational Wave?



Sydney Harris

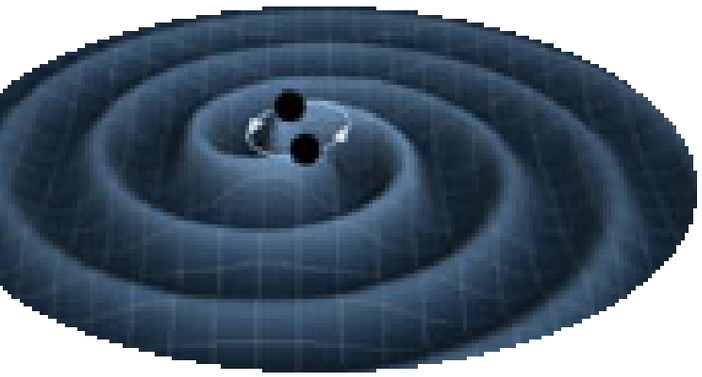
Simulation of the event

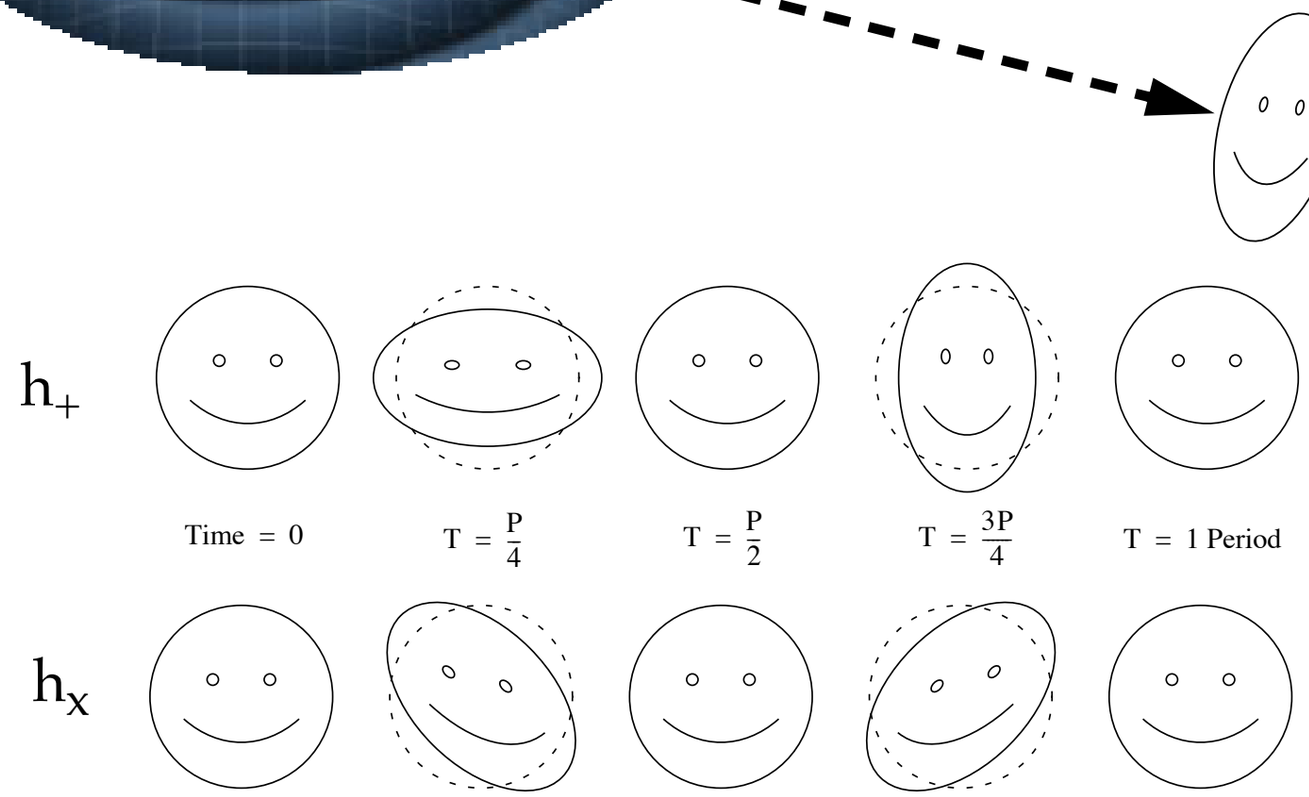


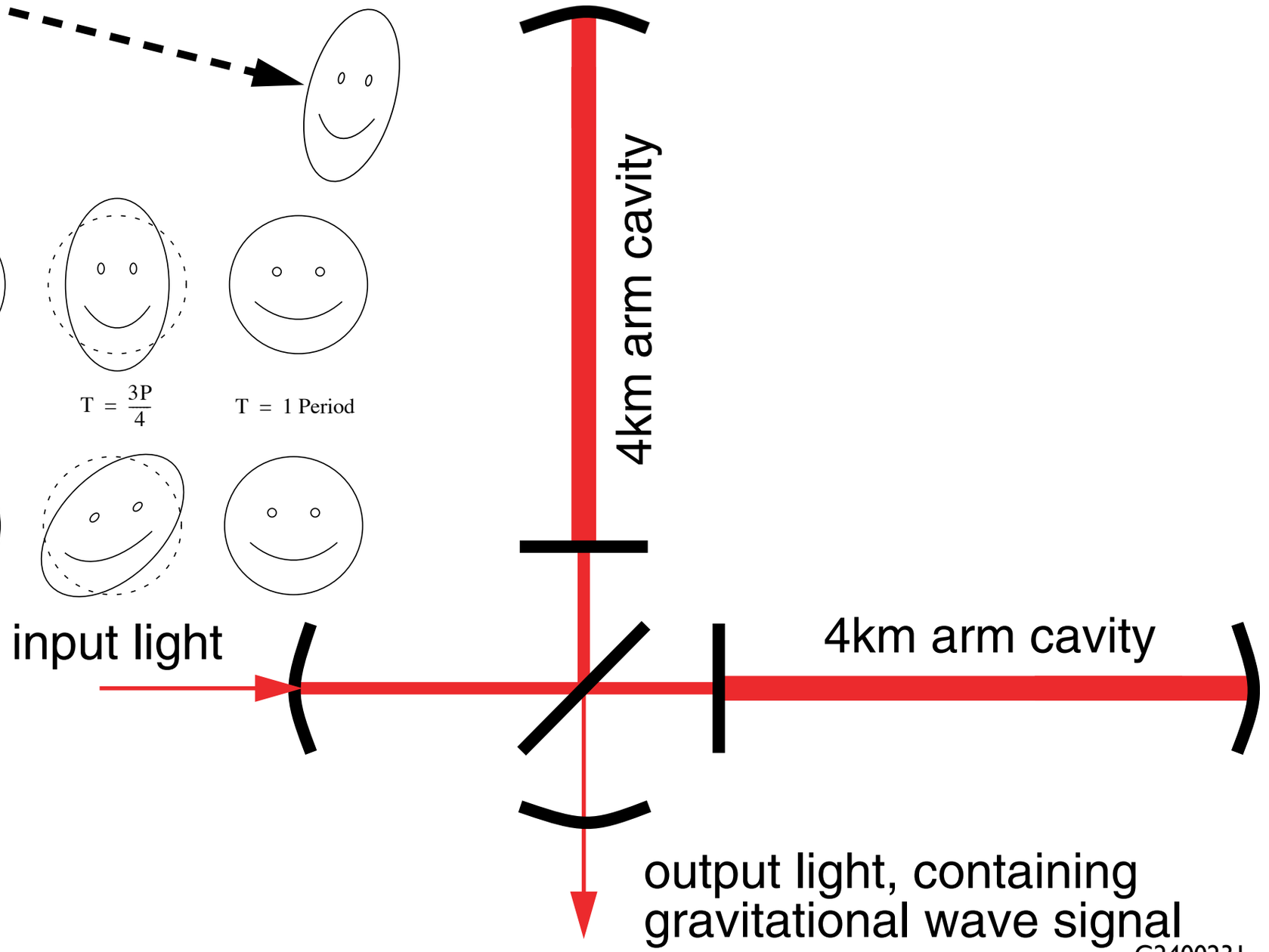
http://mediaassets.caltech.edu/gwave

The LIGO concept

It's sort of like this,
except spacetime is stretching,
and the mirrors don't move.





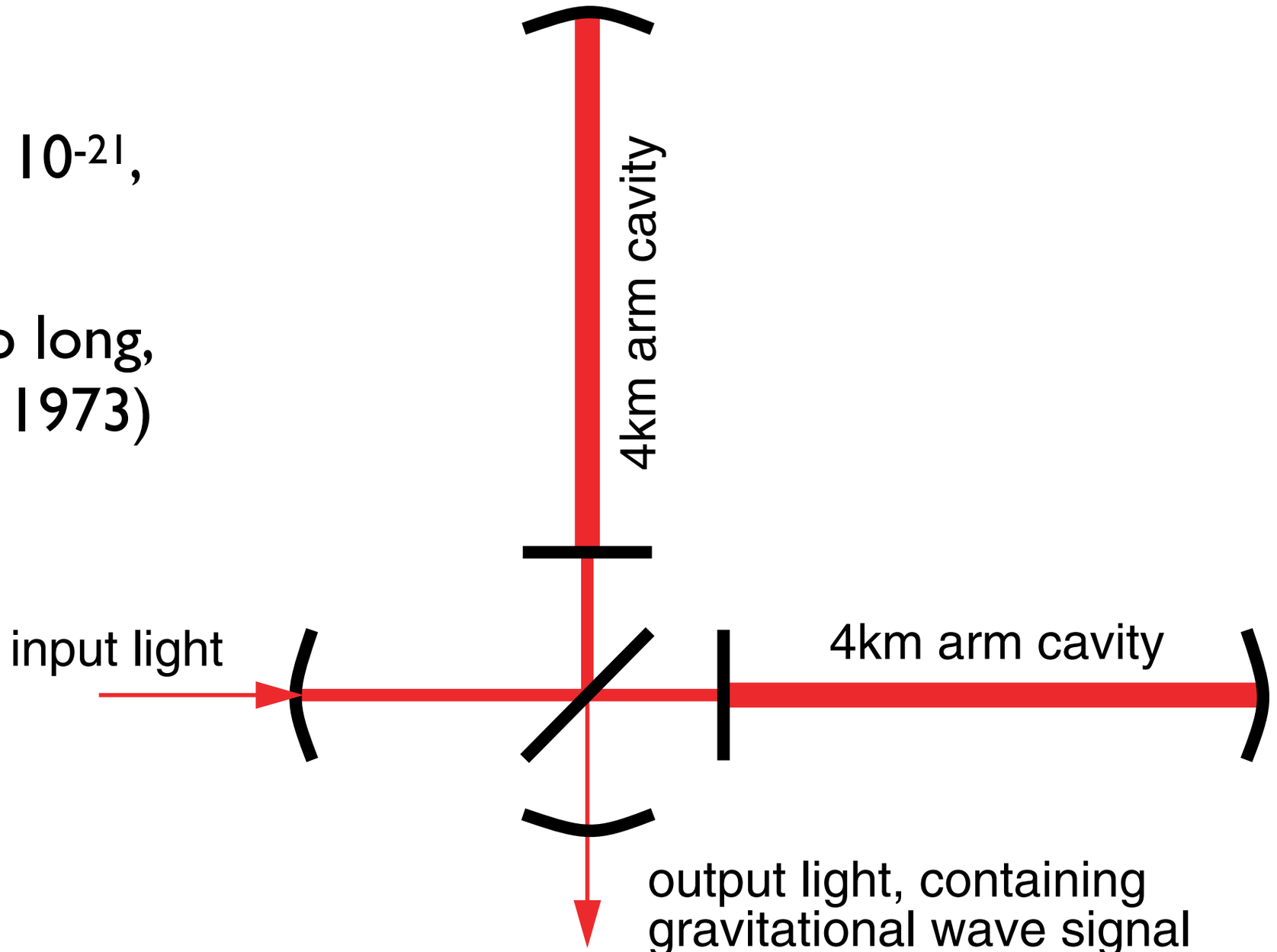


The LIGO concept

Gravitational waves are hard to measure because space doesn't like to stretch.

Our signal strain (h) = 10^{-21},
dL = $4*10^{-18}$ meters

(that's why it's taken so long,
Einstein 1916, Weiss 1973)



The LIGO concept

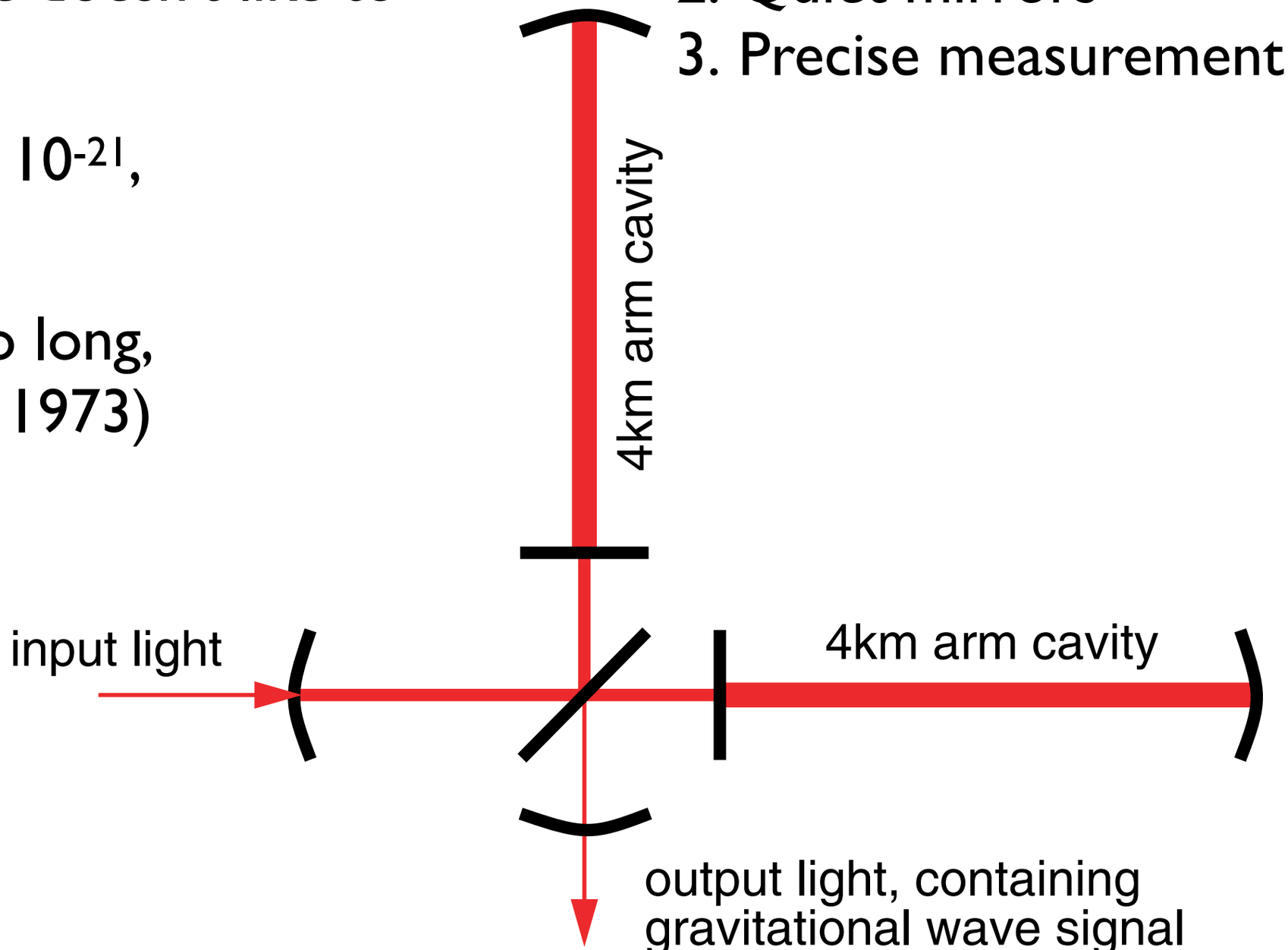
How it really works

Gravitational waves are hard to measure because space doesn't like to stretch.

Our signal strain (h) = 10^{-21},
dL = $4*10^{-18}$ meters

(that's why it's taken so long, Einstein 1916, Weiss 1973)

1. Long arms
2. Quiet mirrors
3. Precise measurement



Long arms

Since h = dL/L (or dL = h*L) more L gives you more dL of signal,
World's 2nd largest ultra-clean vacuum system (after LHC)
- each arm is 4 km long, 4 ft. diameter

LIGO Beamtube

M. Zucker, LIGO-G1900137

LIGO Beamtube

LIGO Beamtube

- 9000 m^3 volume/site
- 30000 m^2 area/site
- 50 km of spiral welds
- ~1e-9 torr
- budget ~ $40M (1997)

photo credit M. Zucker?

Quiet Mirrors

How it really works

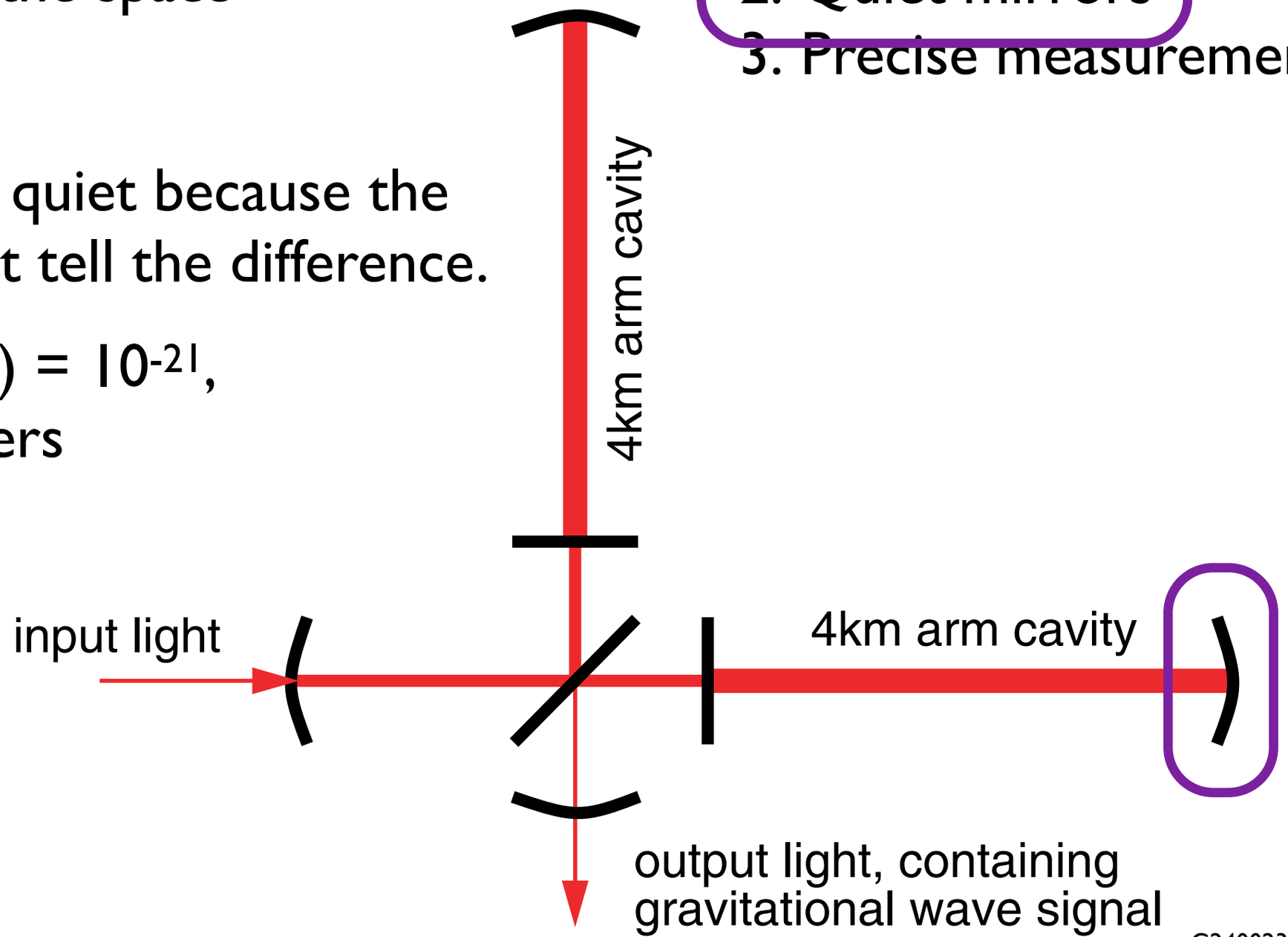
Gravitational wave doesn't move the mirror, it stretches the space

- but -

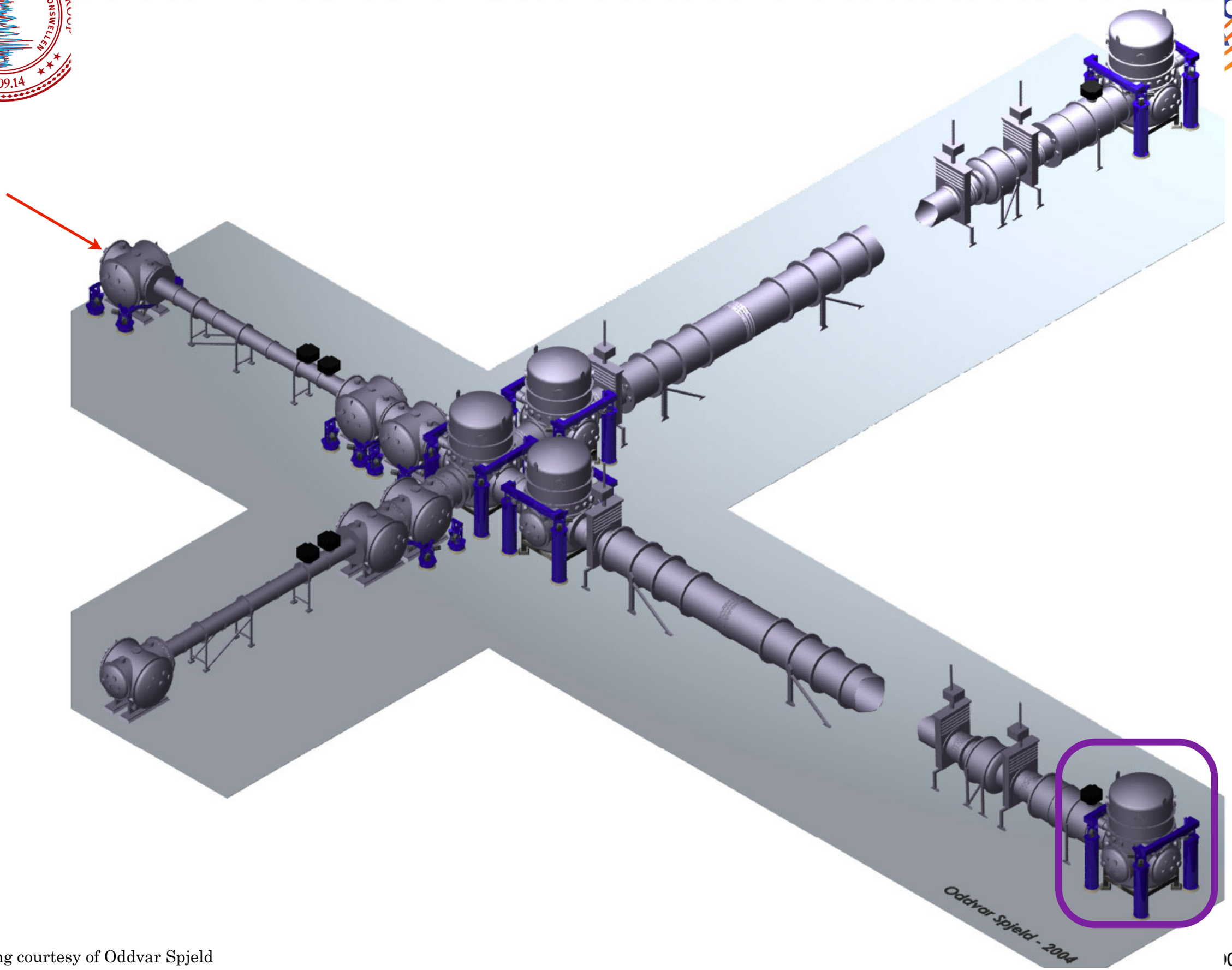
Mirrors need to be quiet because the interferometer can't tell the difference.

Our signal strain (h) = 10^{-21},
dL = $4*10^{-18}$ meters

1. Long arms
2. Quiet mirrors
3. Precise measurement

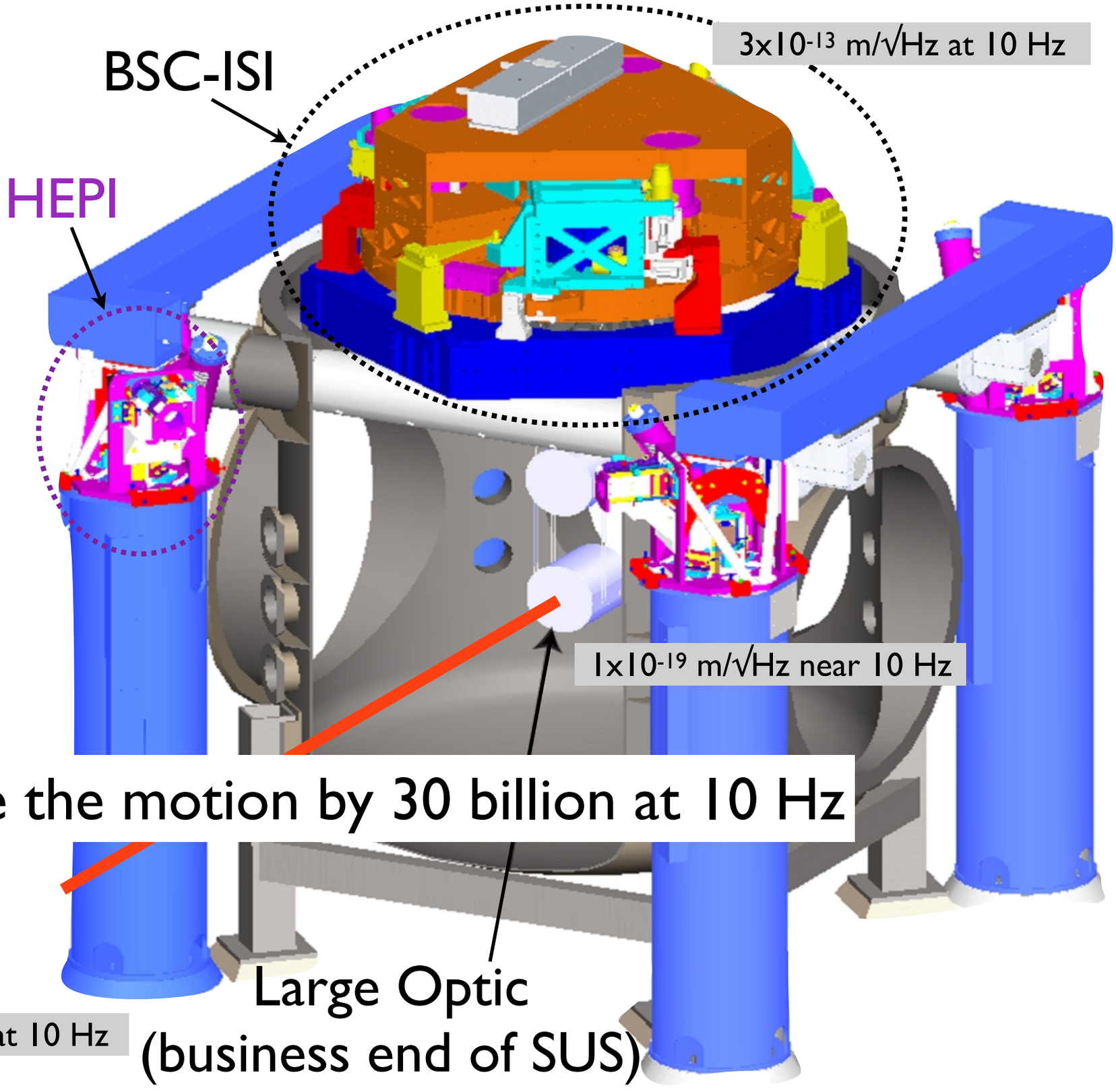


The LIGO vacuum equipment



drawing courtesy of Oddvar Spjeld

Isolation of the Mirrors

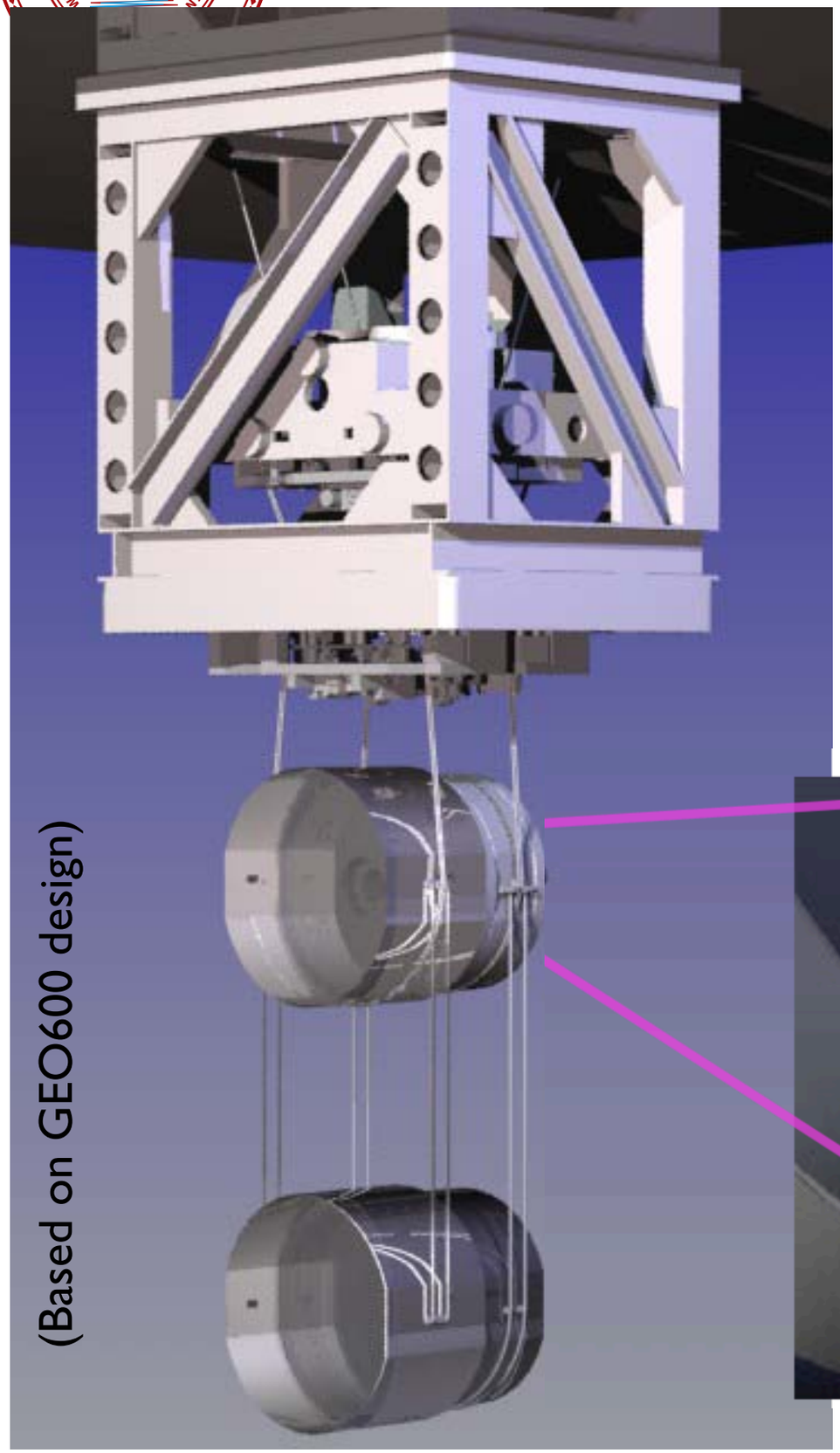


optics table - stage 2

stage 1

support - stage 0

Pendulum Suspension



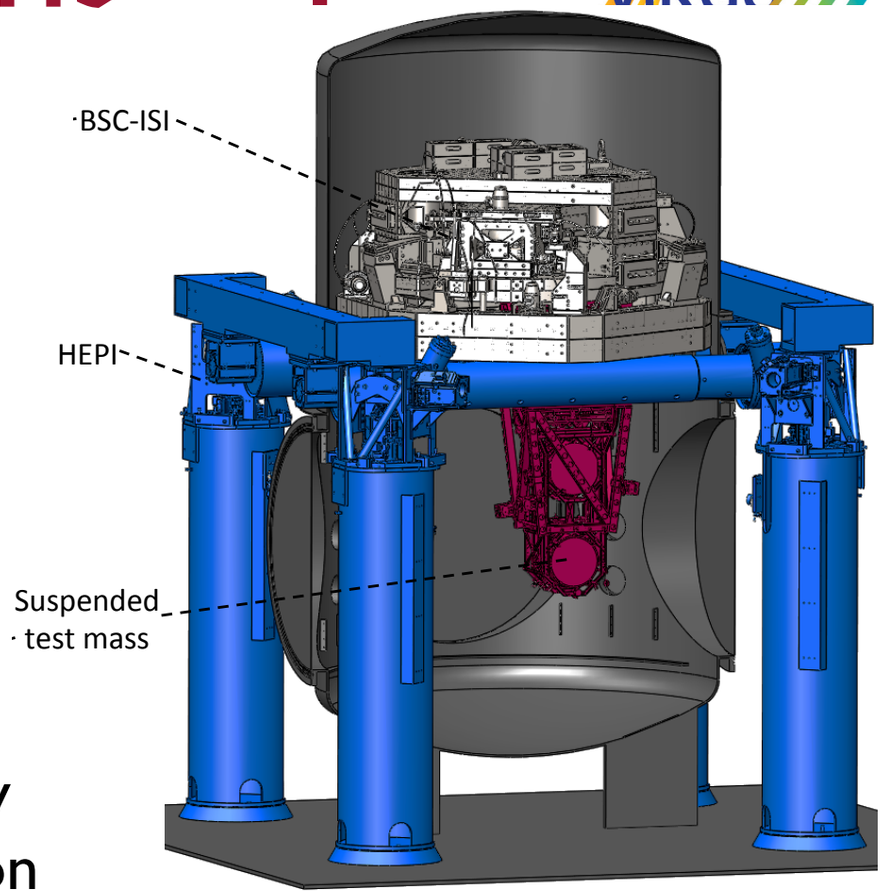
LIGO Mirrors:

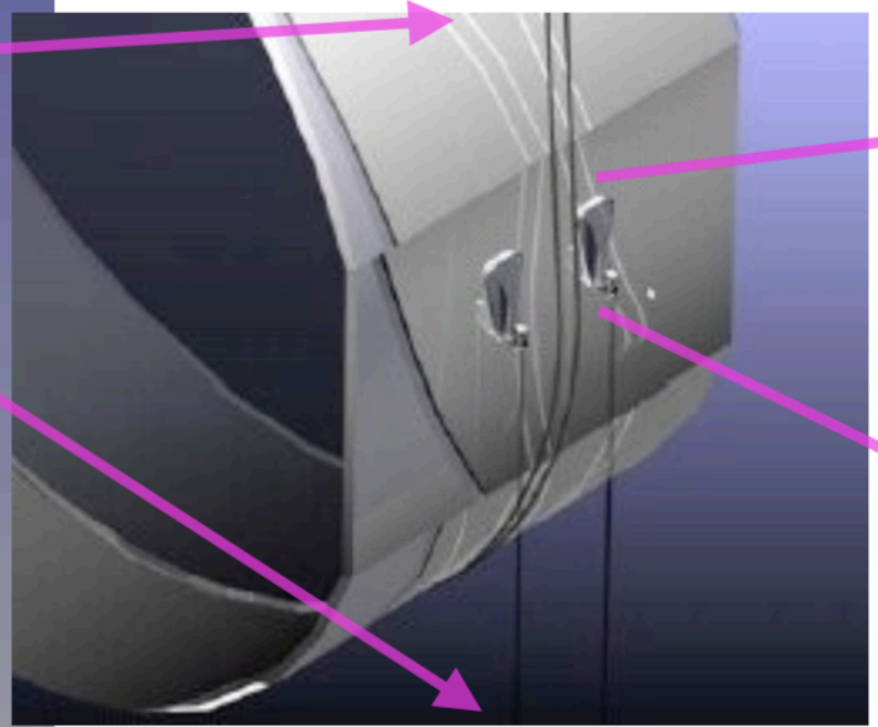
Synthetic fused silica,
- 40 kg mass
- 34 cm diameter
- 20 cm thick

Suspended as a
4 stage pendulum

Best coatings available

Motion at 10 Hz set by
thermal driven vibration

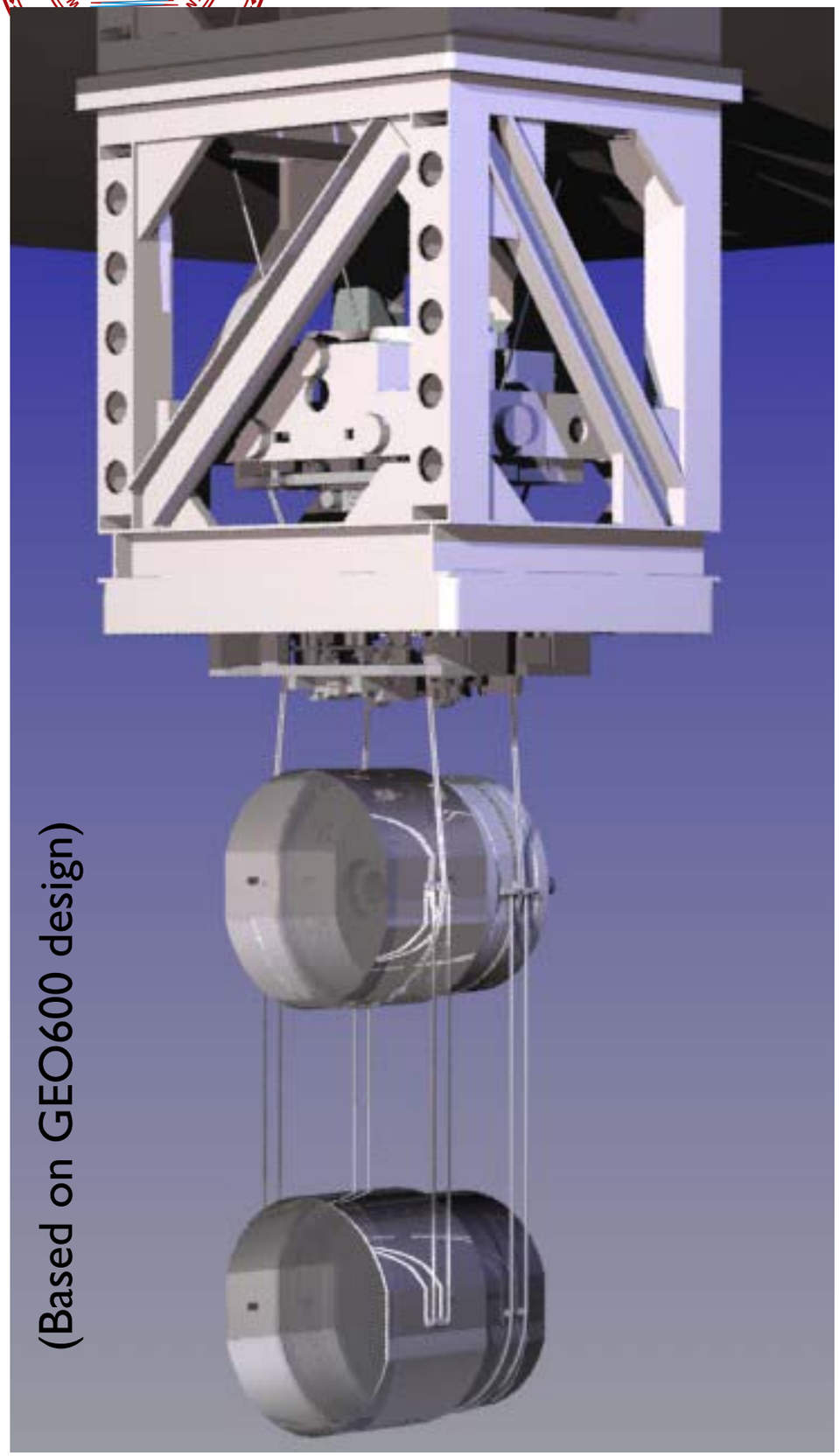


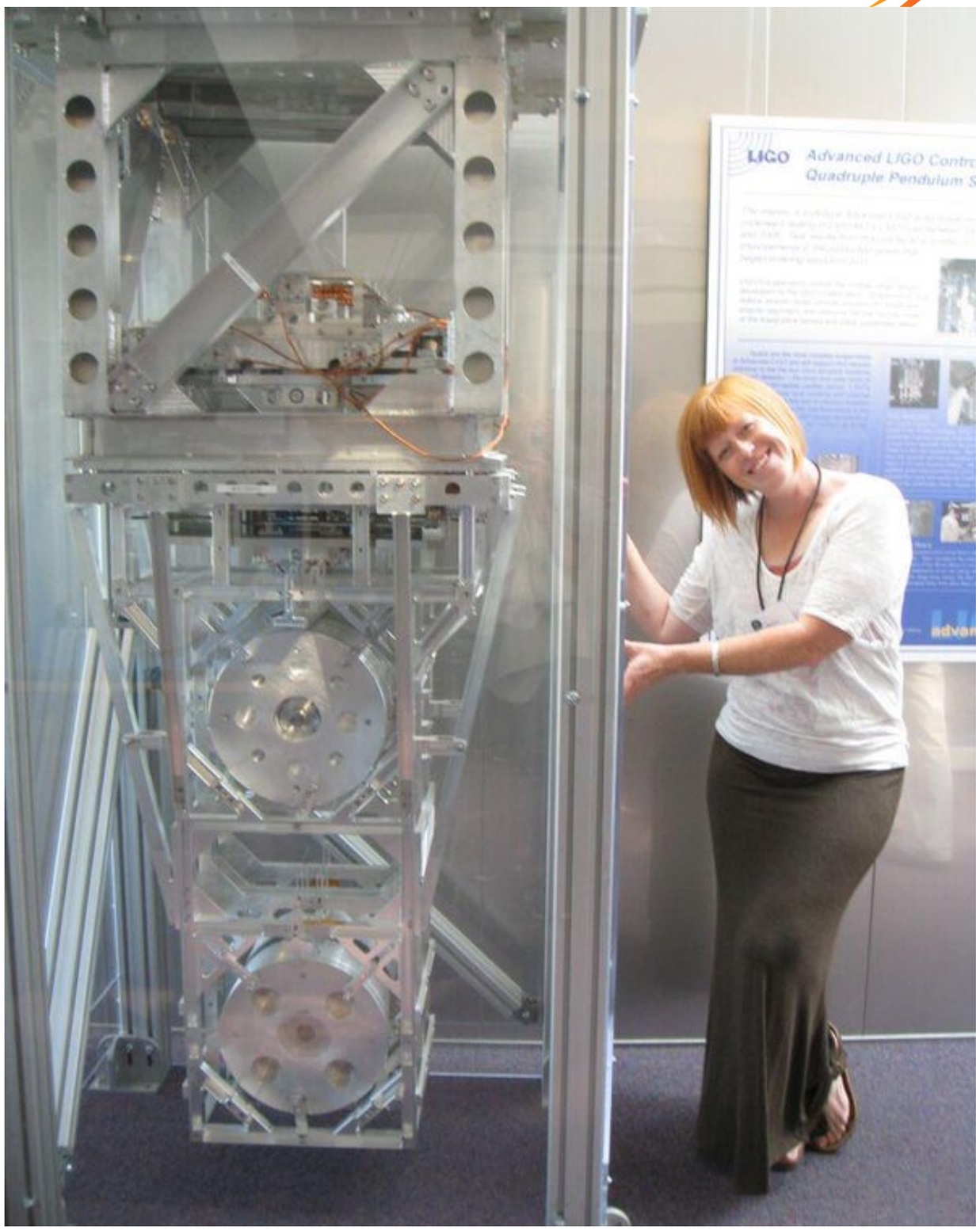


silicate bonding creates a monolithic final stage

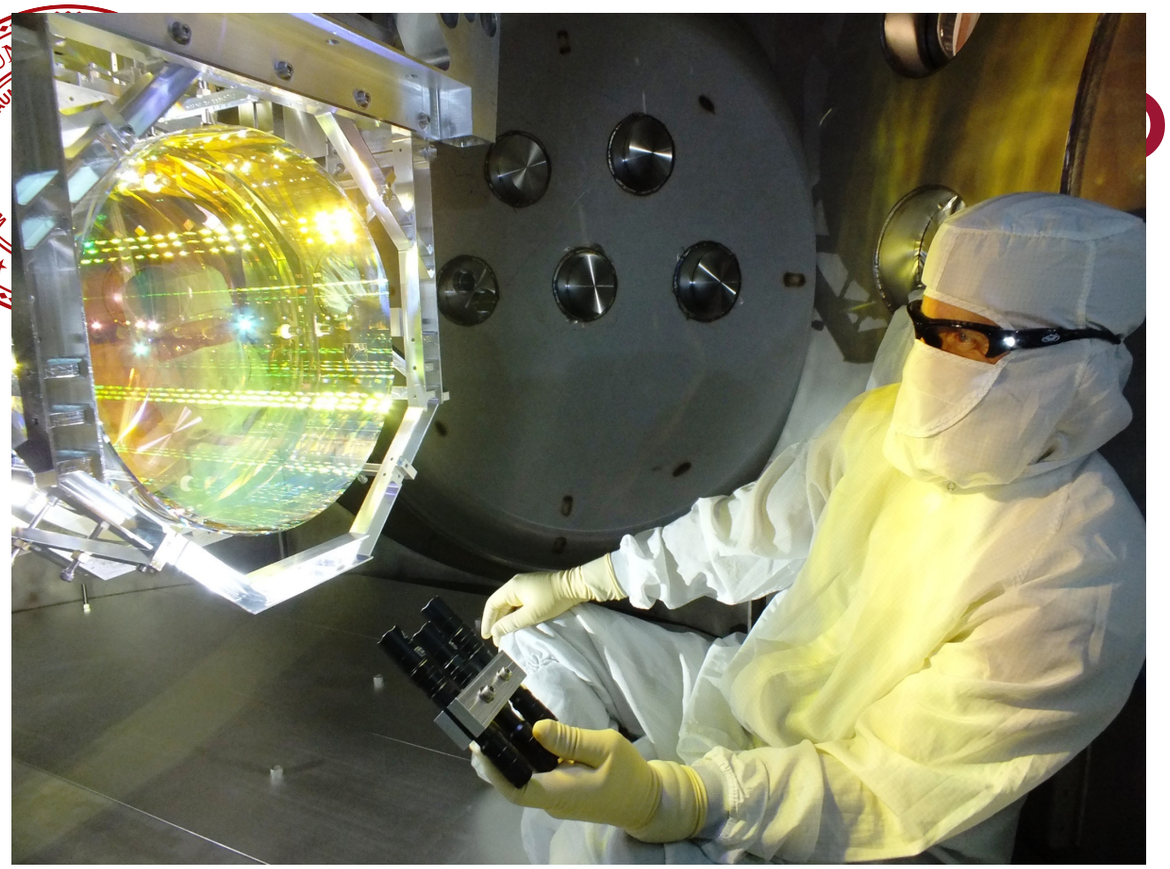
Pendulum Suspension

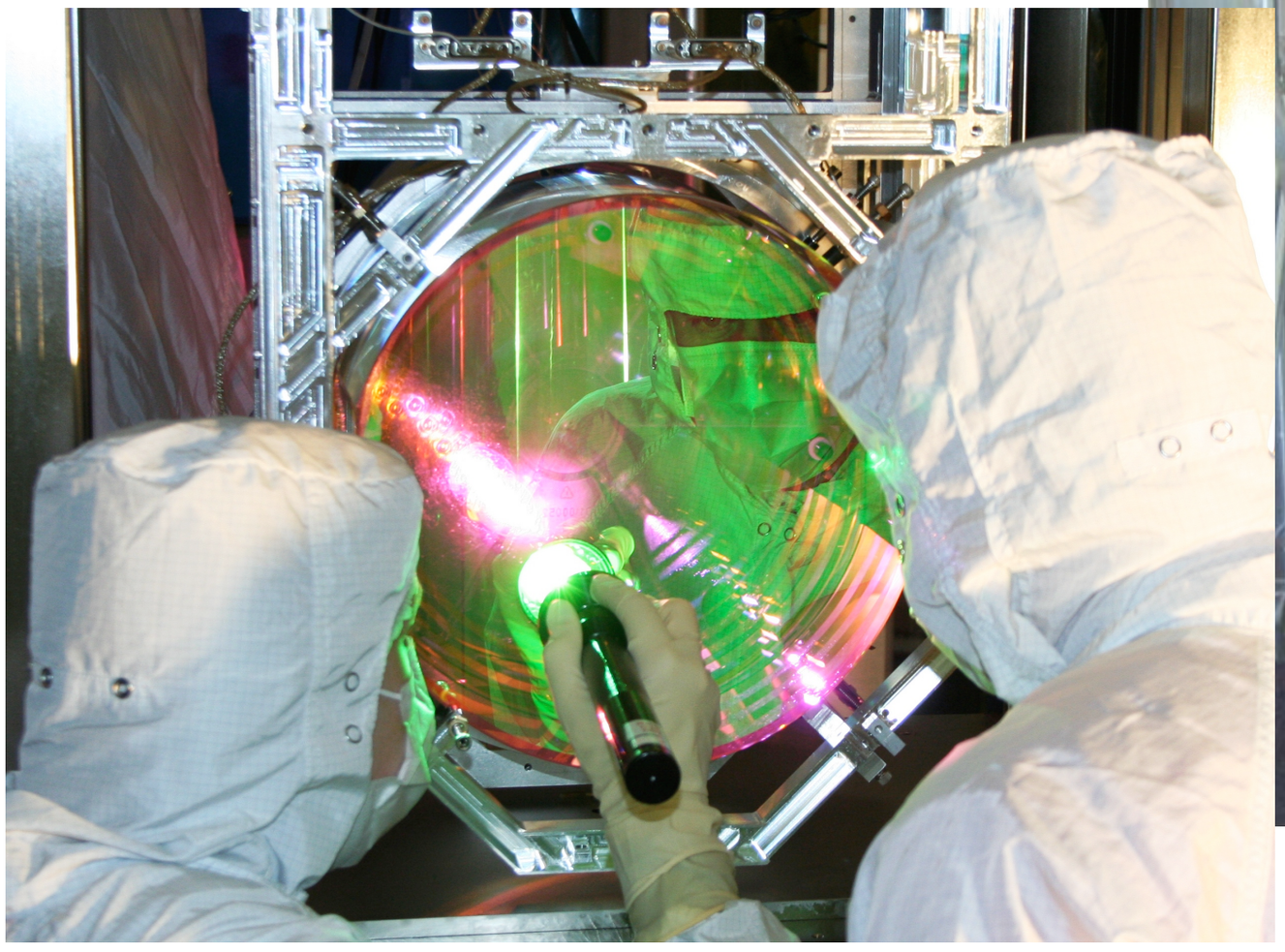
LHO suspension expert, Betsy Weaver with the Engineering prototype





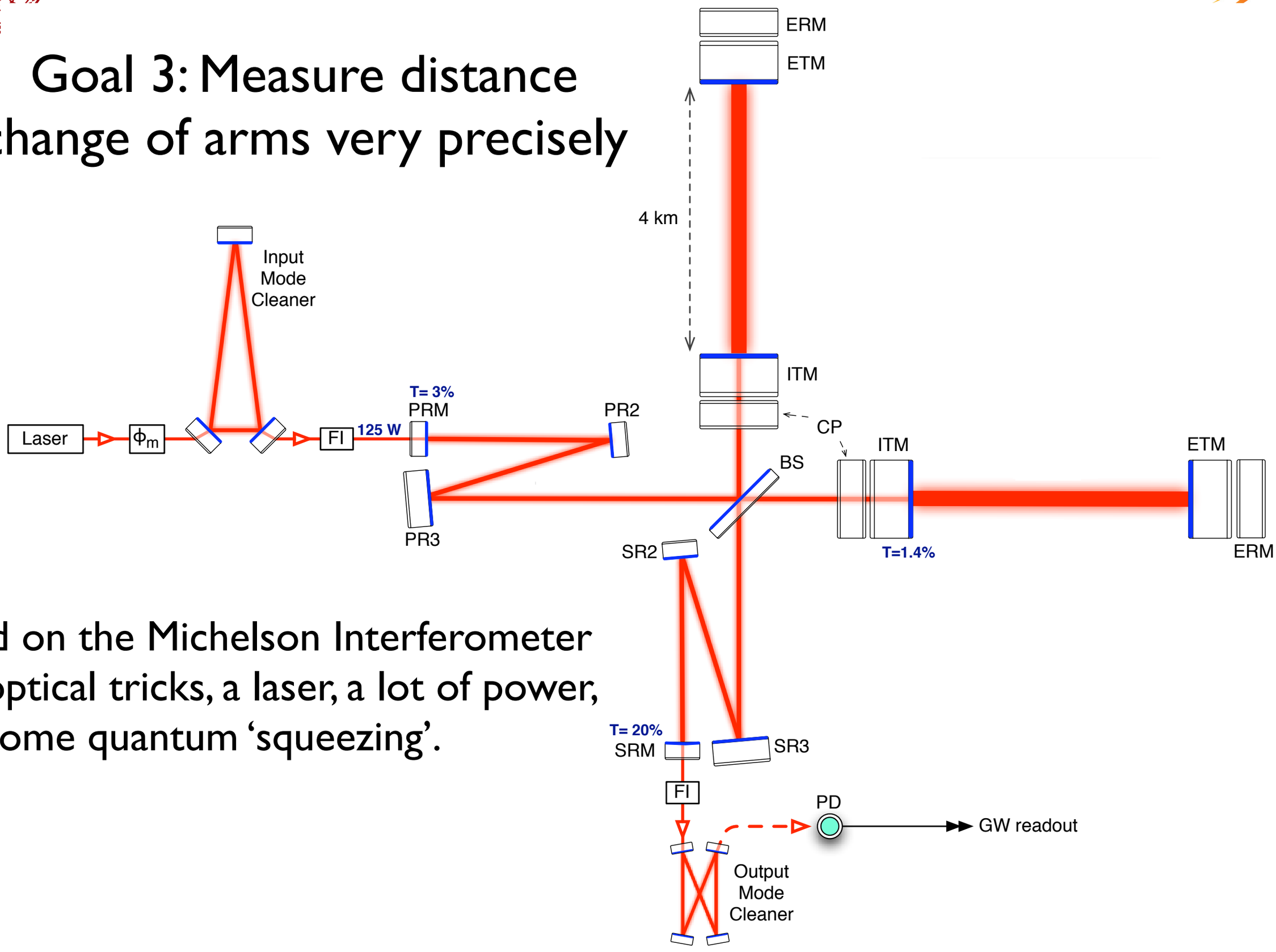
or picts





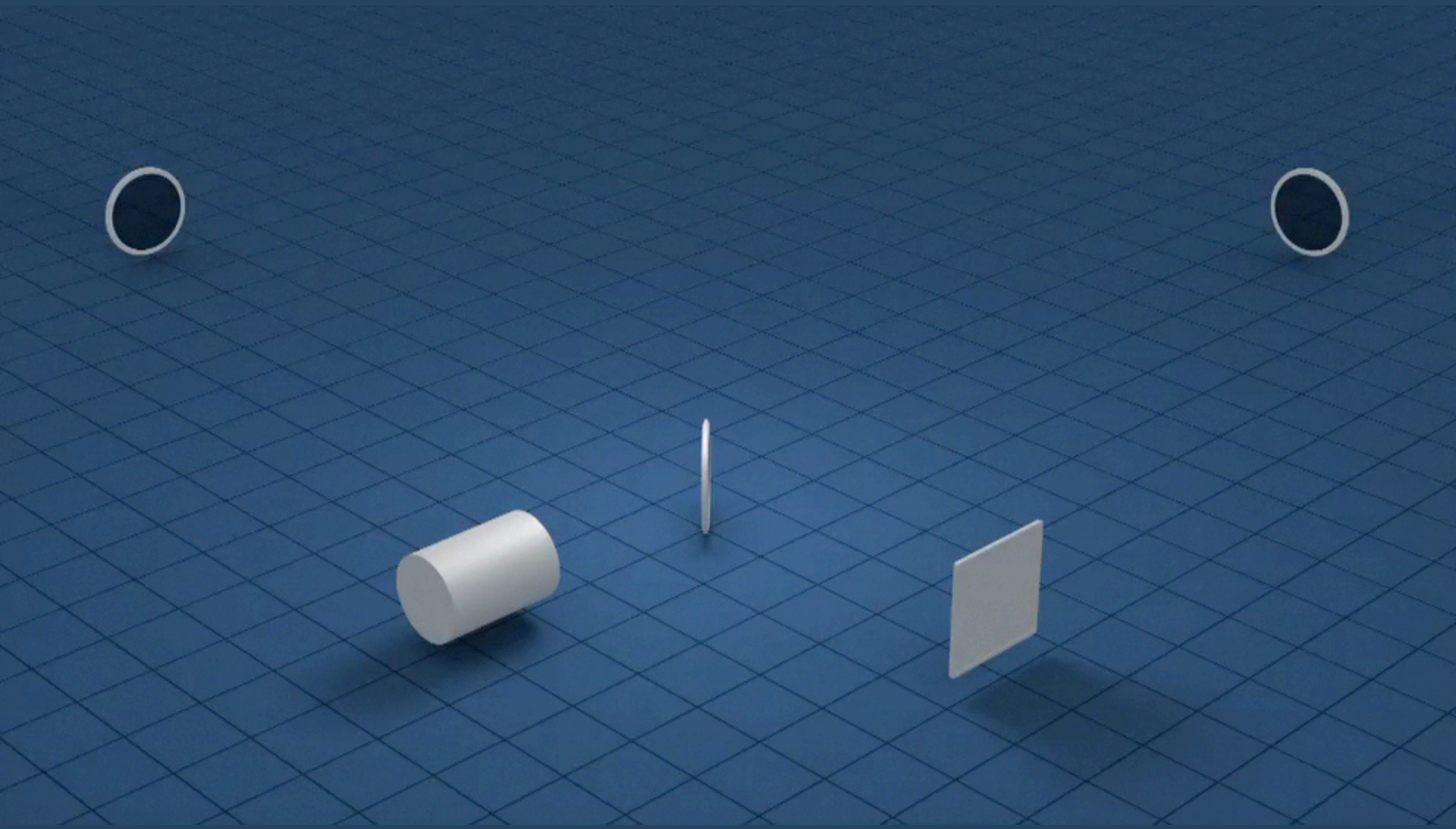
Precision Interferometry

Goal 3: Measure distance change of arms very precisely



Based on the Michelson Interferometer add optical tricks, a laser, a lot of power, and some quantum 'squeezing'.

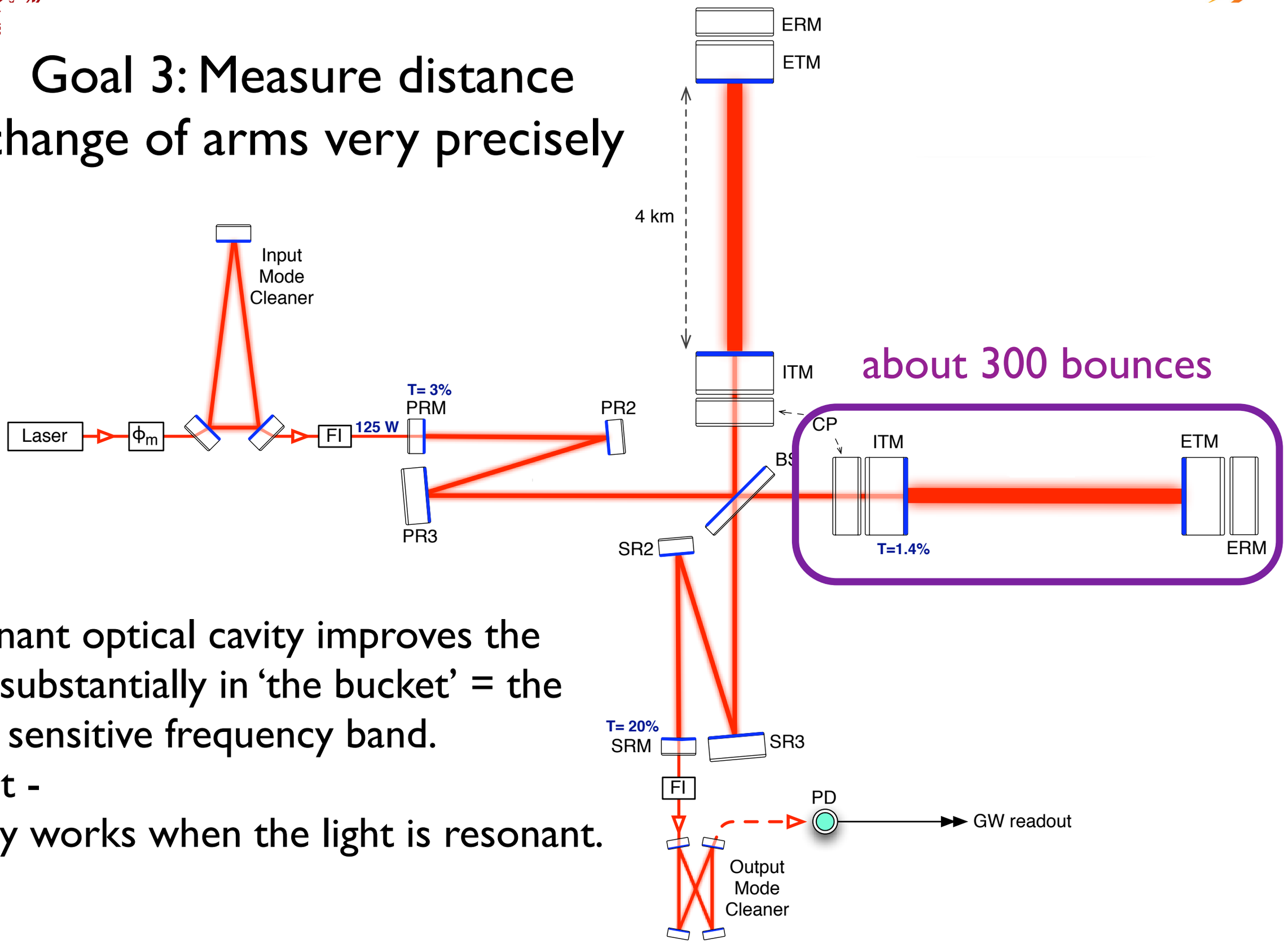
Animated Interferometer



http://mediaassets.caltech.edu/gwave

Fabry-Perot arms

Goal 3: Measure distance change of arms very precisely



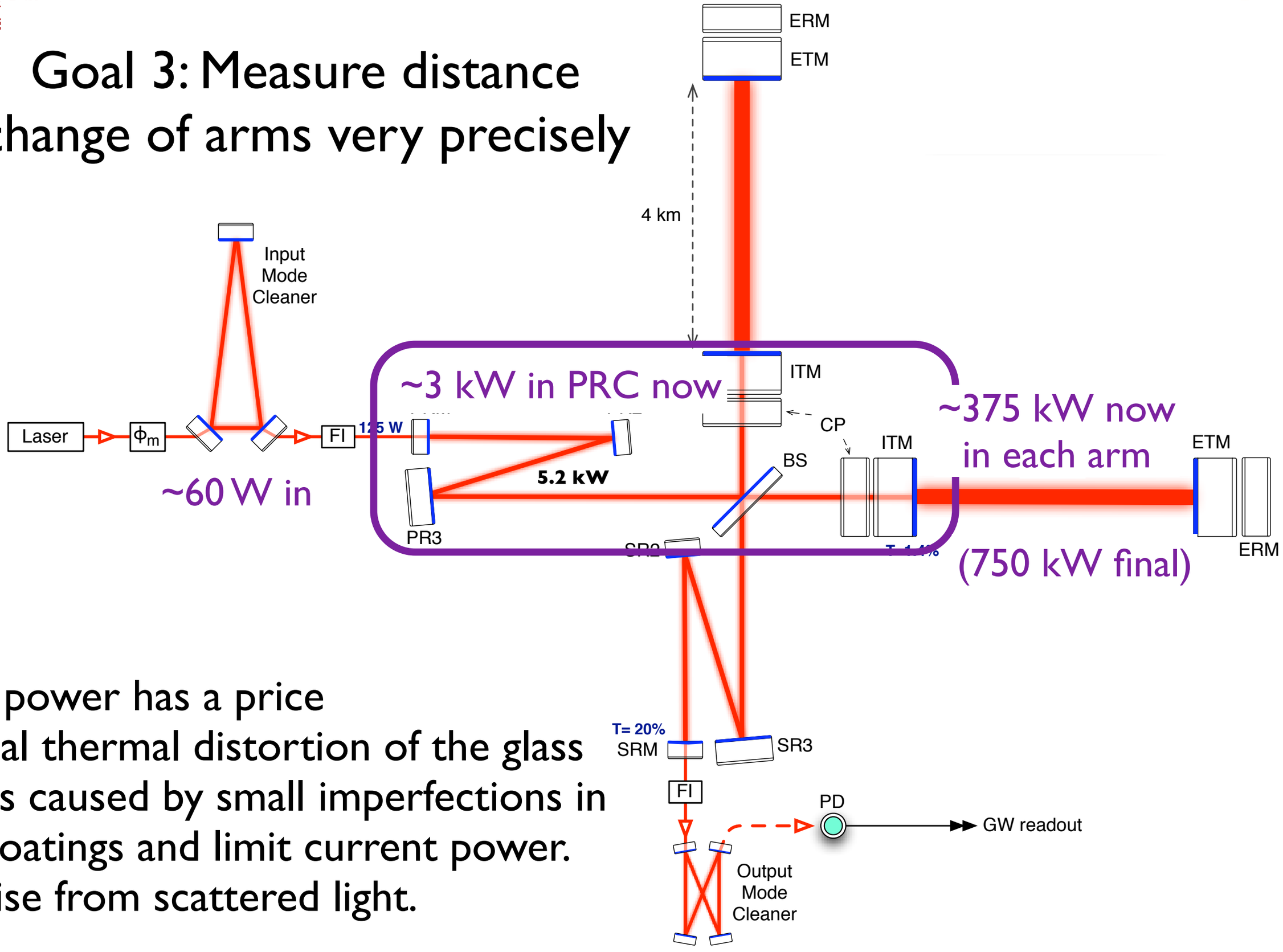
Resonant optical cavity improves the SNR substantially in 'the bucket' = the most sensitive frequency band.

- but -

It only works when the light is resonant.

Lots of photons

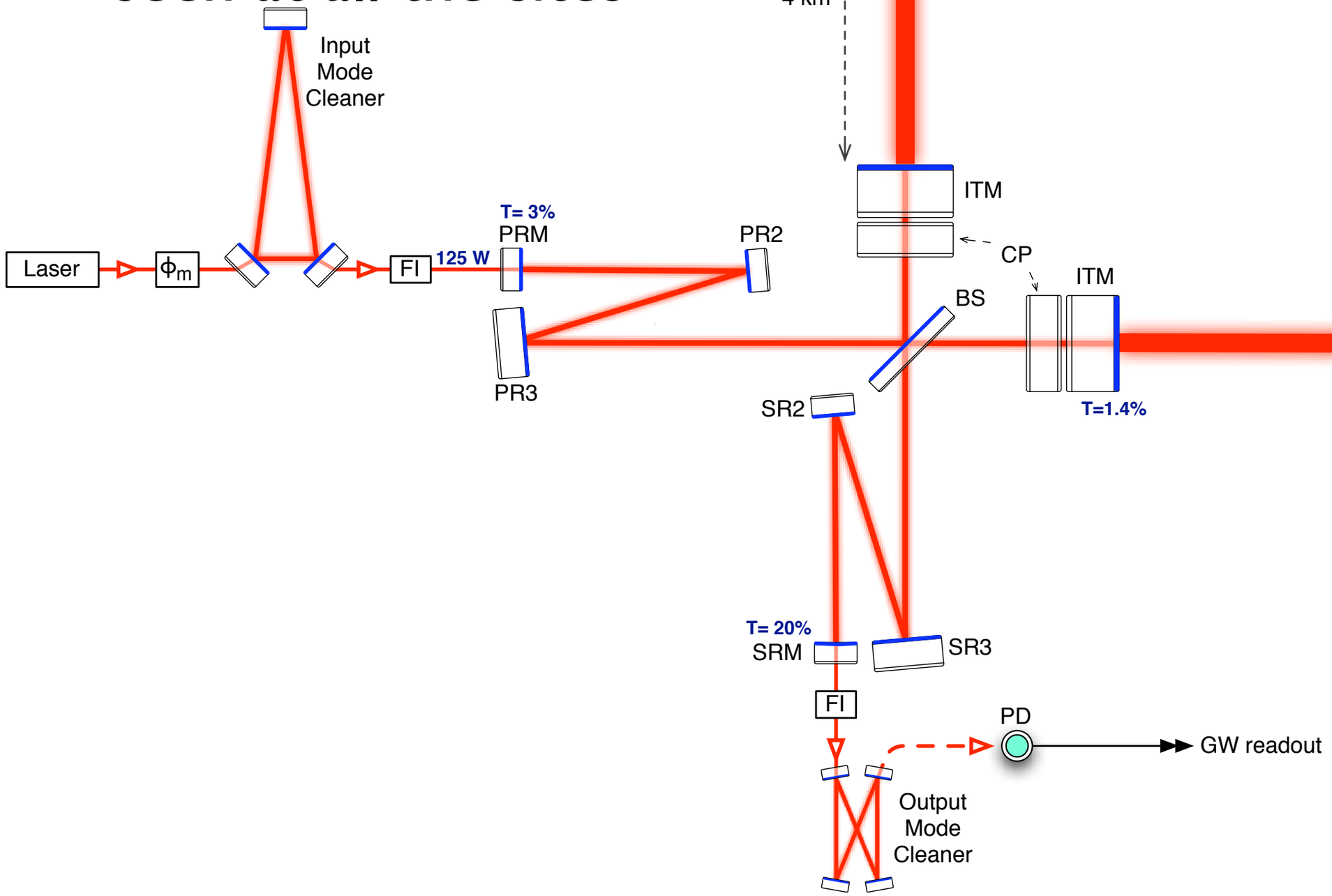
Goal 3: Measure distance change of arms very precisely



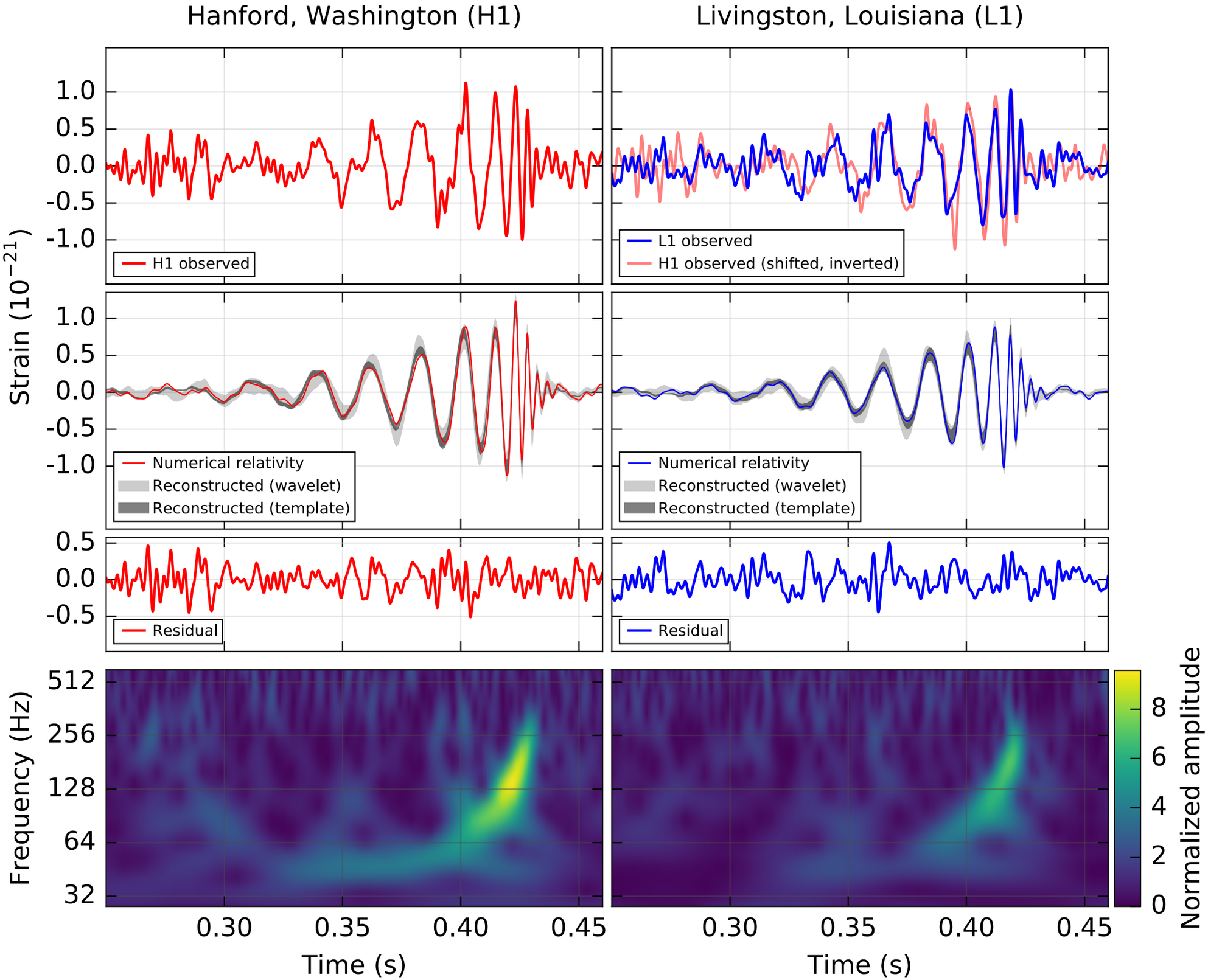
High power has a price
- Local thermal distortion of the glass optics caused by small imperfections in the coatings and limit current power.
- Noise from scattered light.

and now you wait for a signal

look for motions (signals) that are different from the usual noise characteristic of GWs seen at all the sites



First signal - Sept 14, 2015



http://dx.doi.org/10.1103/PhysRevLett.116.061102

Best fit with

Initial Masses:

29 (+4/-4) & 36 (+5/-4) M_{sun}

Final Mass:

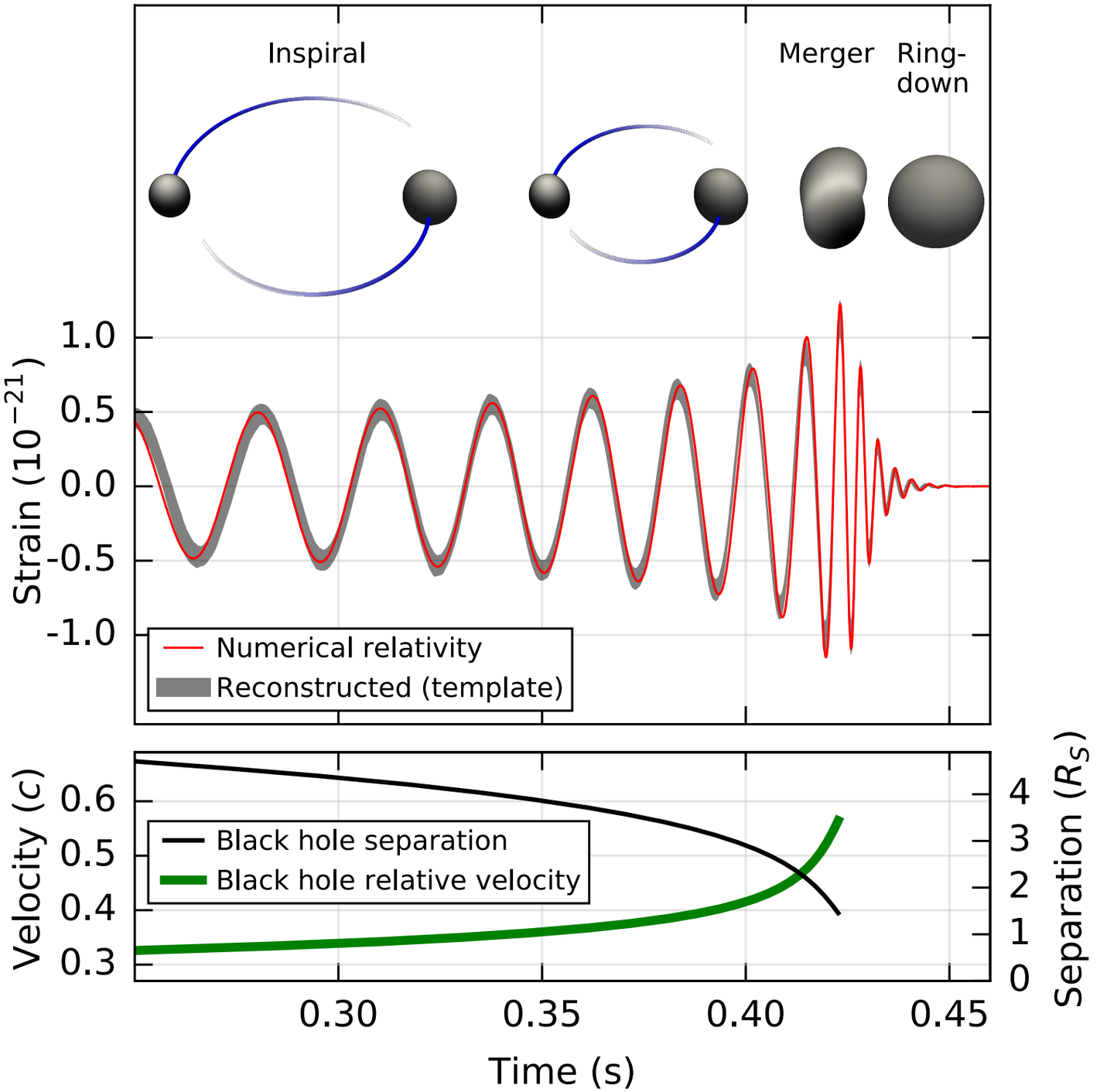
62 (+4/-4) M_{sun}

3 solar masses were radiated as GWs

Distance

420 (+160/-180) MPc

(1.3 Billion light years)



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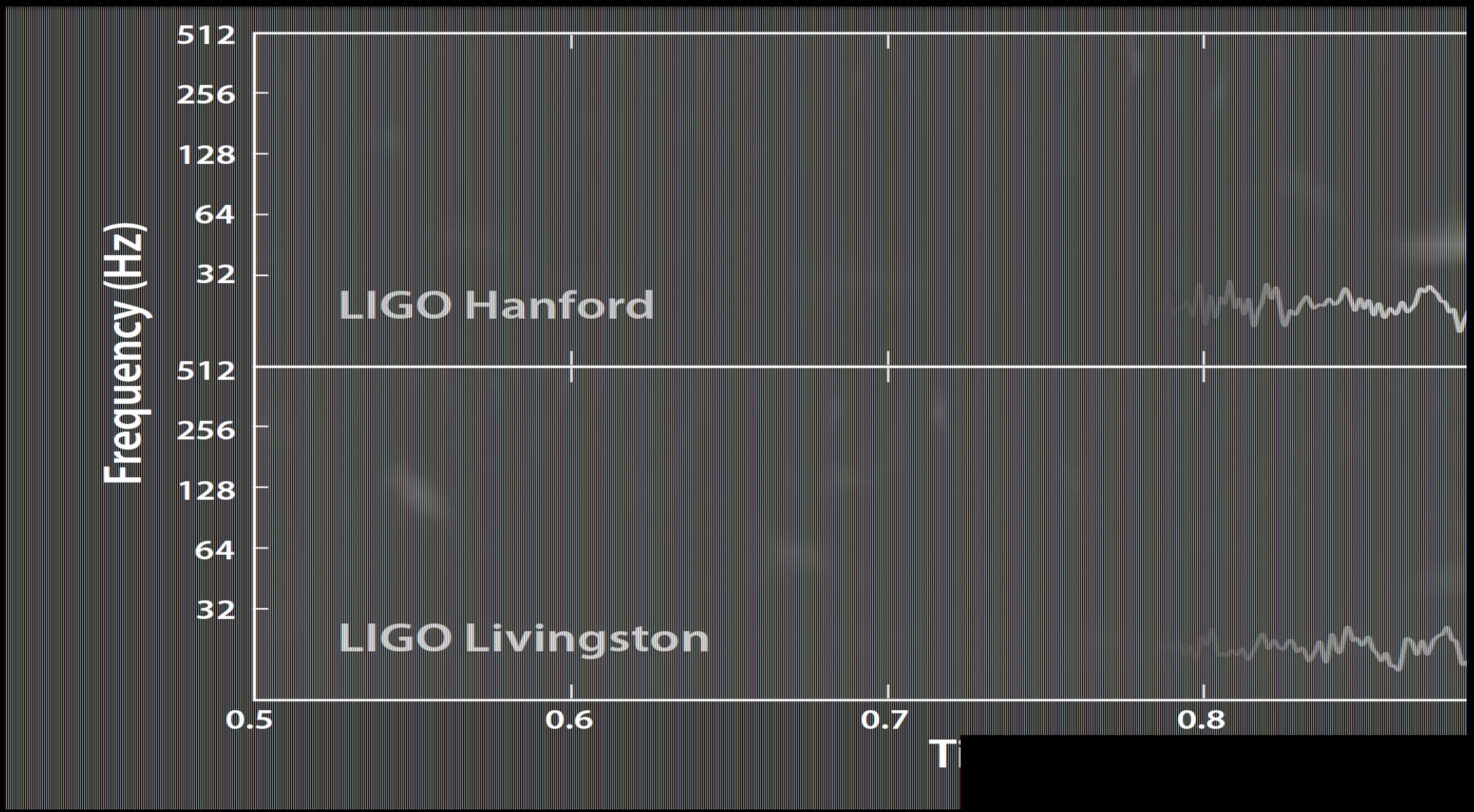
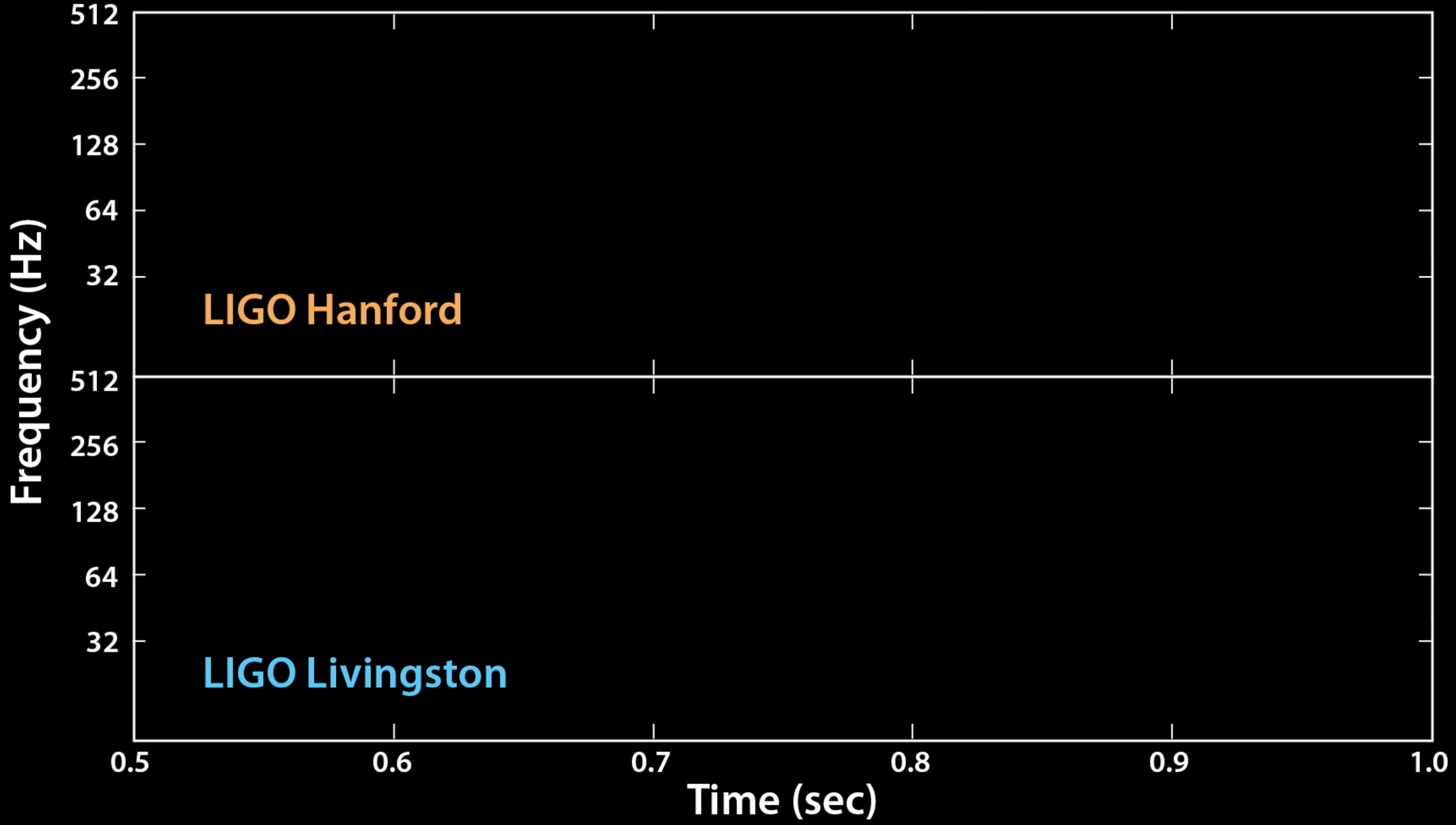
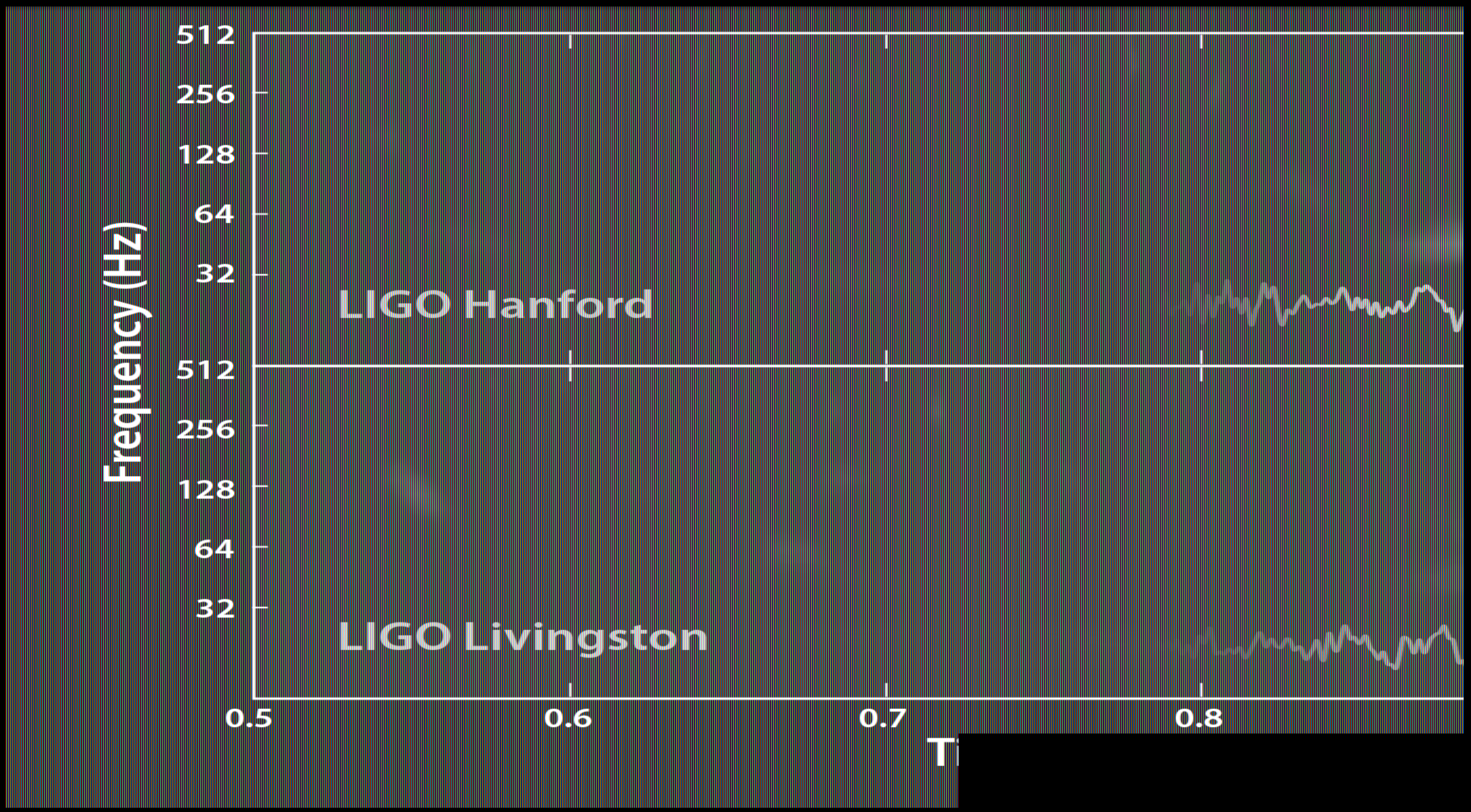


http://mediaassets.caltech.edu/gwave


LIGO Hanford
LIGO Livingston
Frequency (Hz)
512
256
128
64
32
512
256
128
64
32
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)


LIGO Hanford
LIGO Livingston
Frequency (Hz)
512
256
128
64
32
512
256
128
64
32
0.5
0.6
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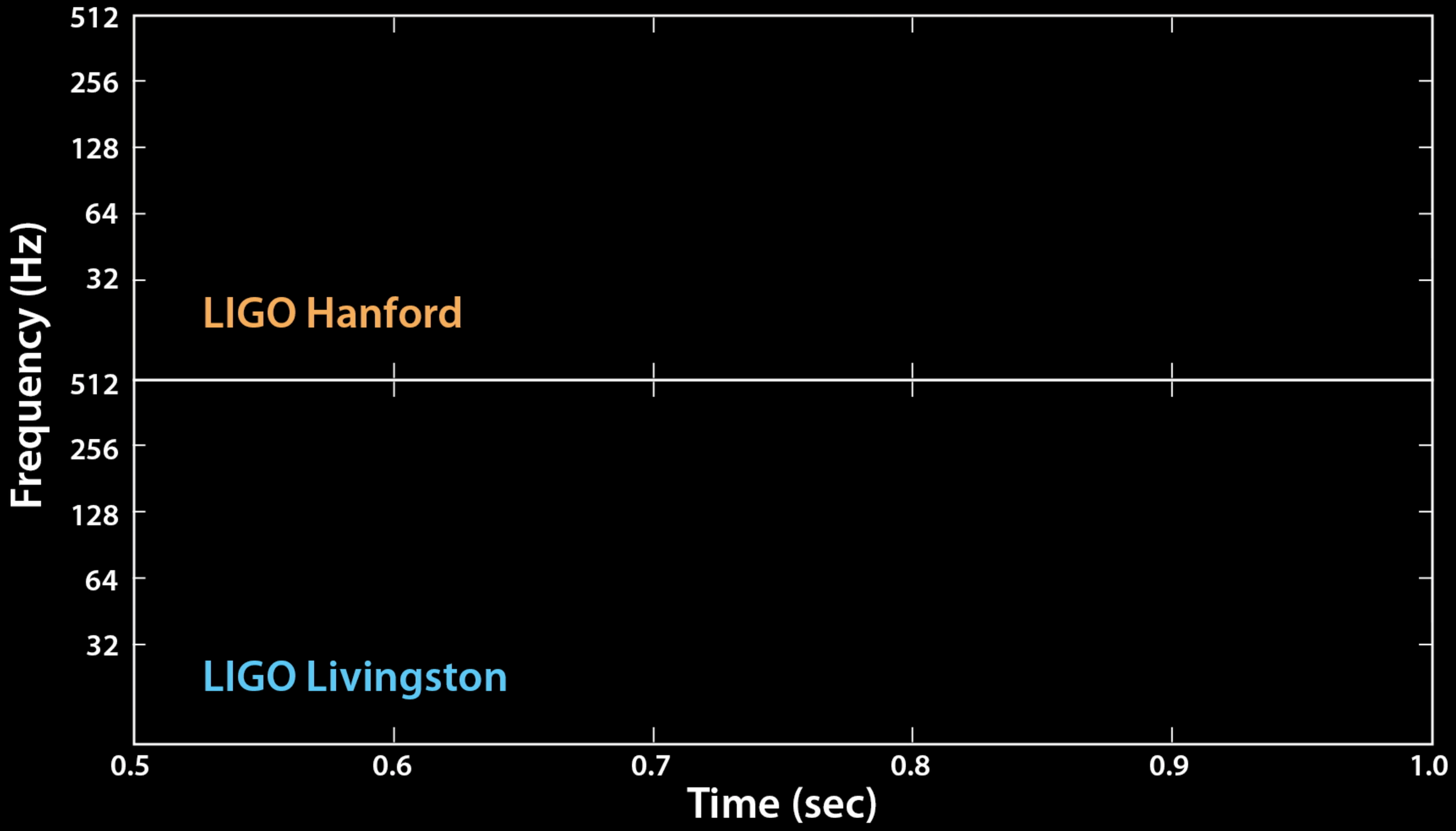
0.8
Ti

The sound of black holes colliding



Neutron star & San Francisco

Supernova remnant

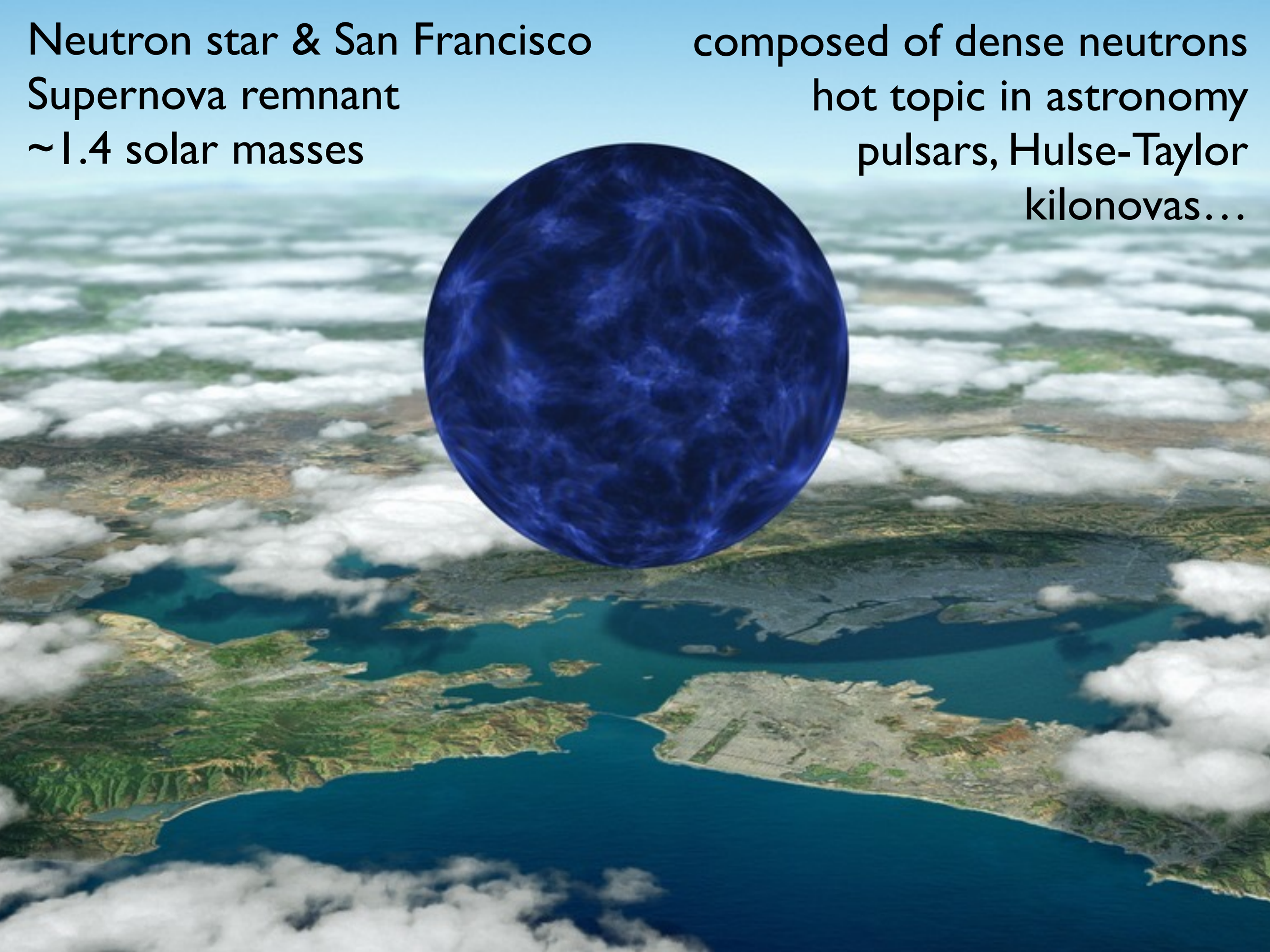
~1.4 solar masses

composed of dense neutrons

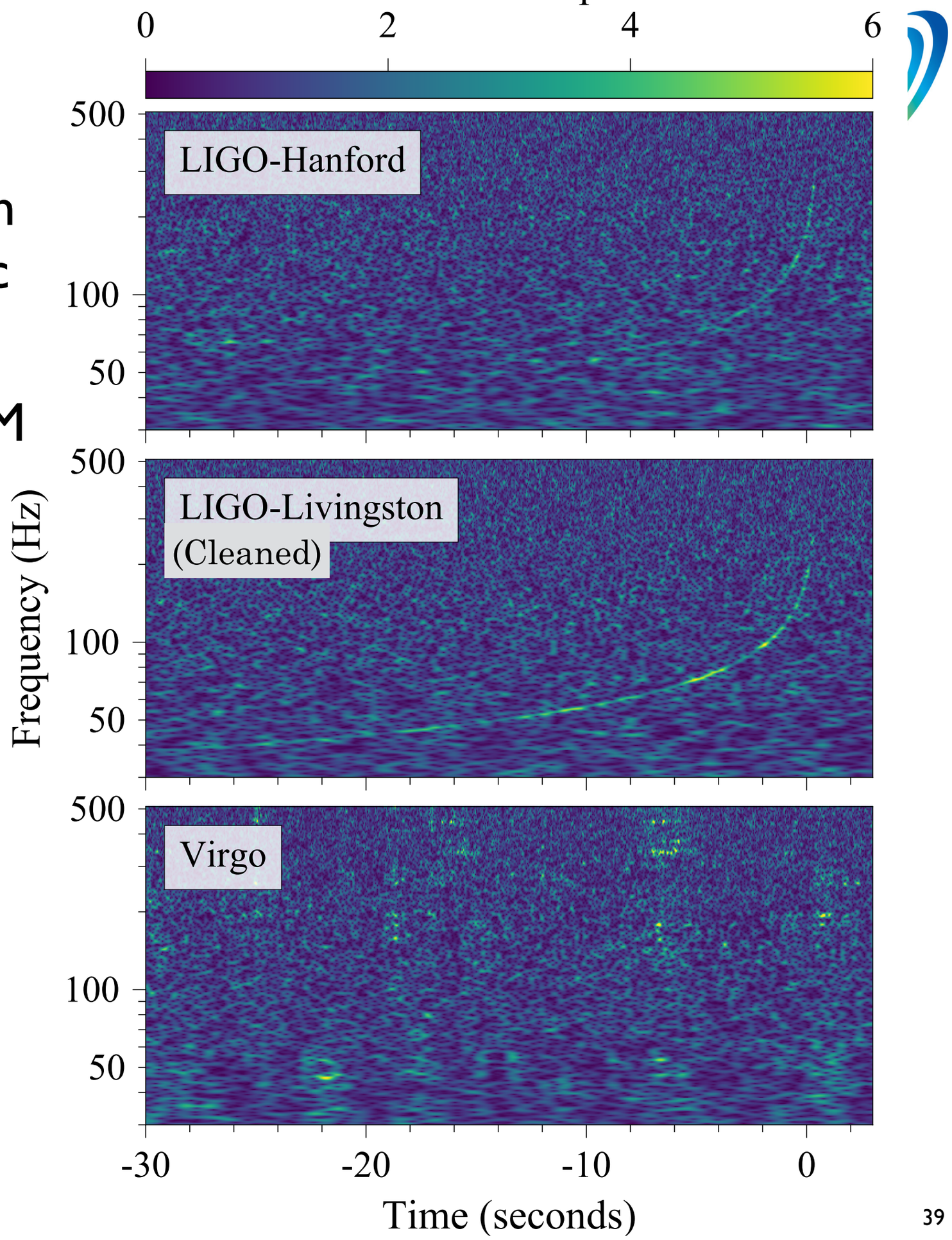
hot topic in astronomy

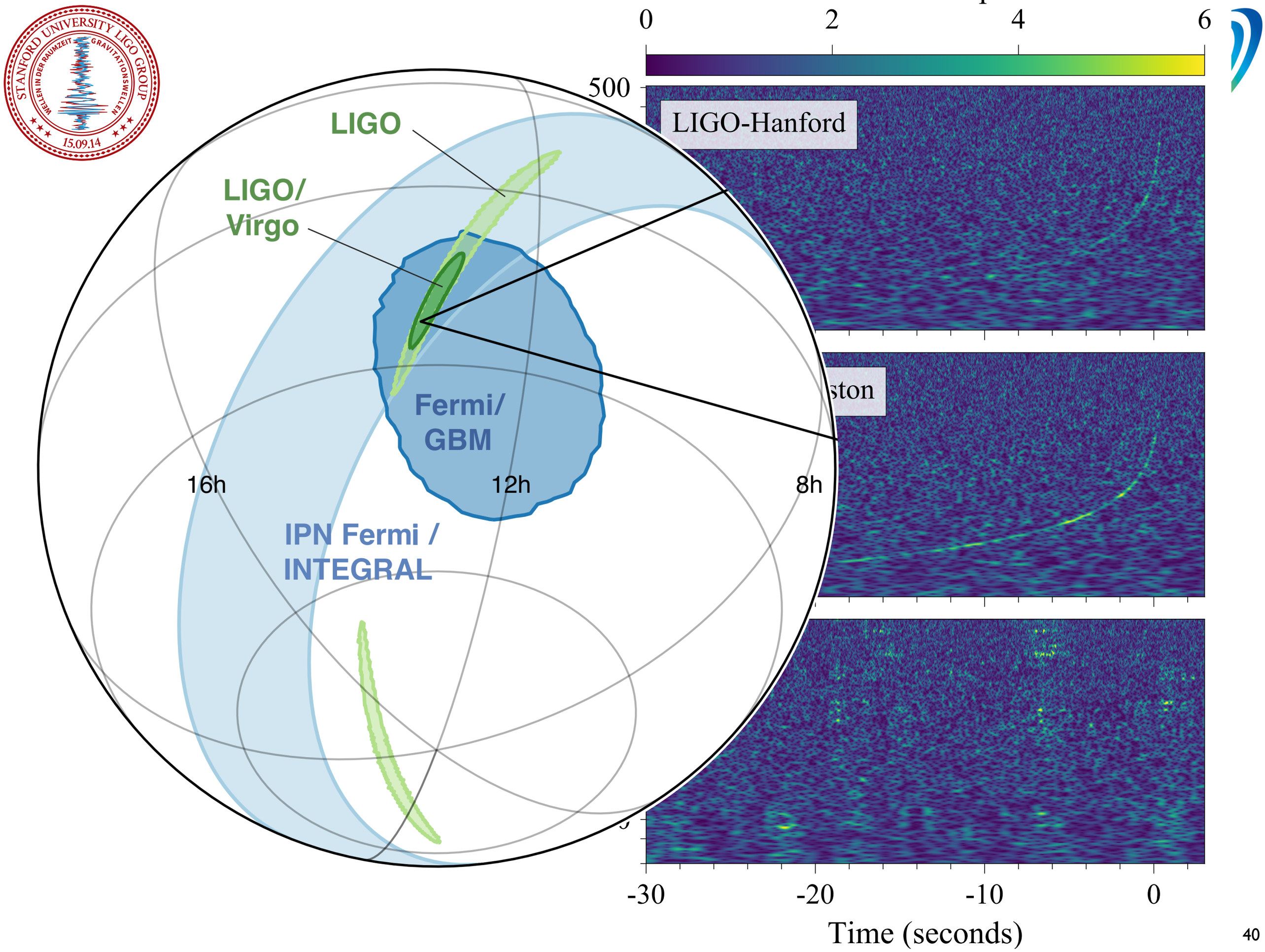
pulsars, Hulse-Taylor

kilonovas…

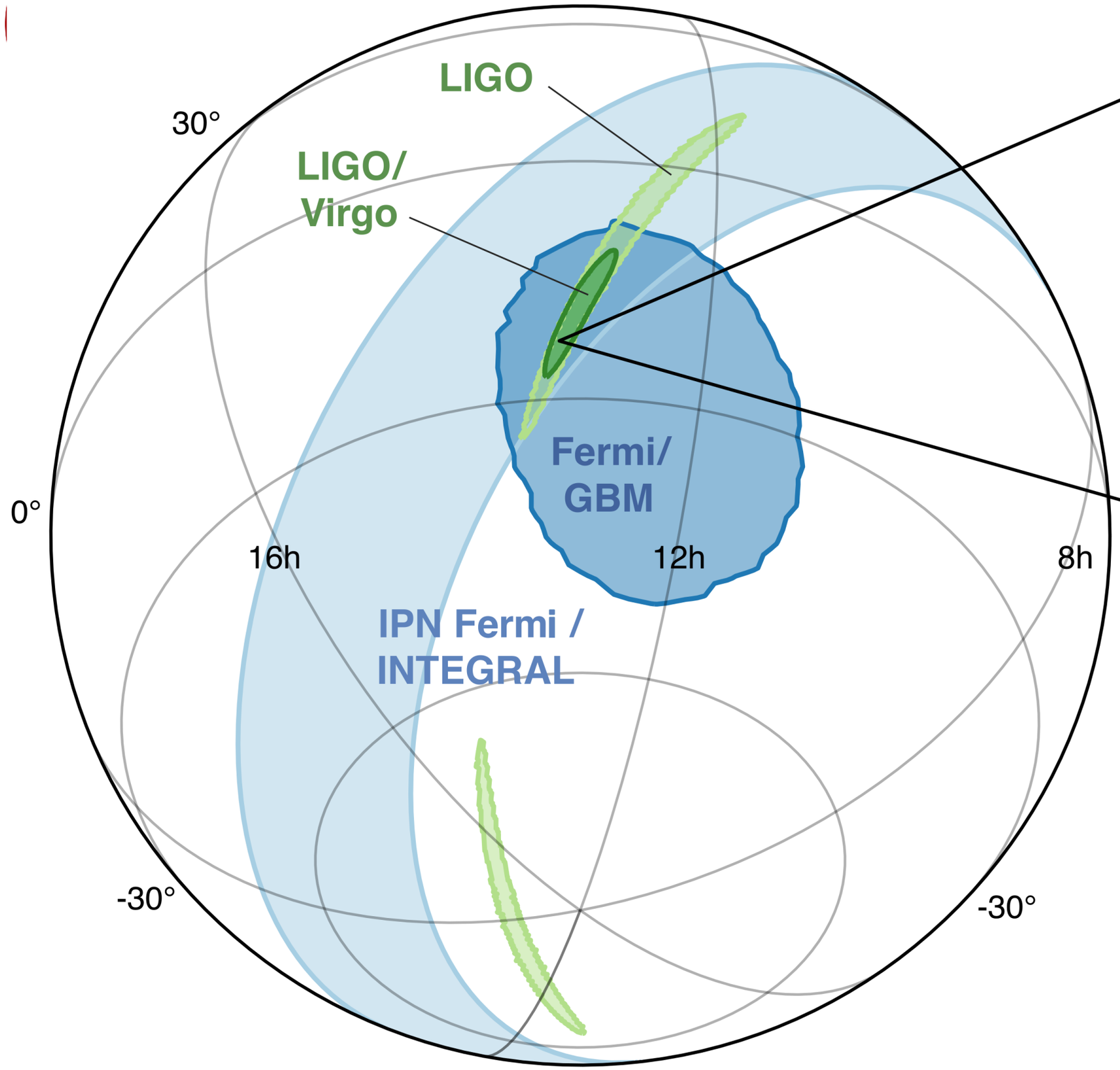


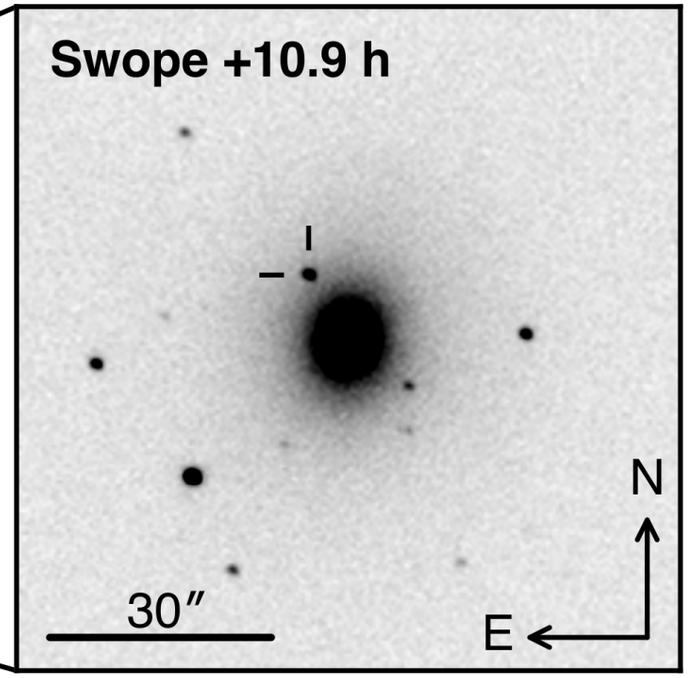
- LIGO software finds trigger in LHO data - 5:41:04 am Pacific time, August 17.
- LIGO realizes that Fermi GBM has triggered on event 1.7 seconds after GW merger.
- Thus, BNS mergers cause short gamma-ray bursts.
- Finally solving a mystery uncovered by Vela-4 in 1967. (as predicted by many).
- Forcing a best match to Virgo (~in the blind spot, so SNR is only 2!)

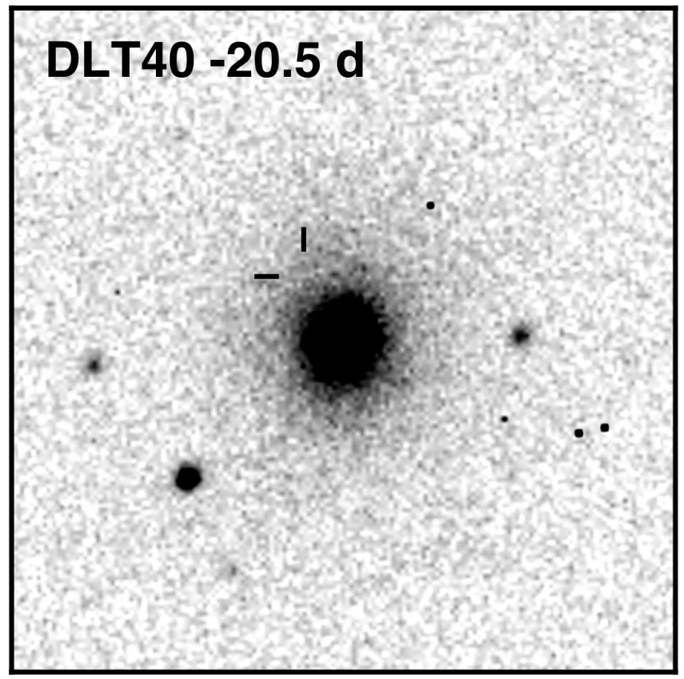



LIGO
LIGO/
Virgo
Fermi/
GBM
IPN Fermi /
INTEGRAL
16h
12h
8h
0
2
4
6
500
LIGO-Hanford
ston
-30
-20
-10
0
Time (seconds)

GW + GRB + Kilonova

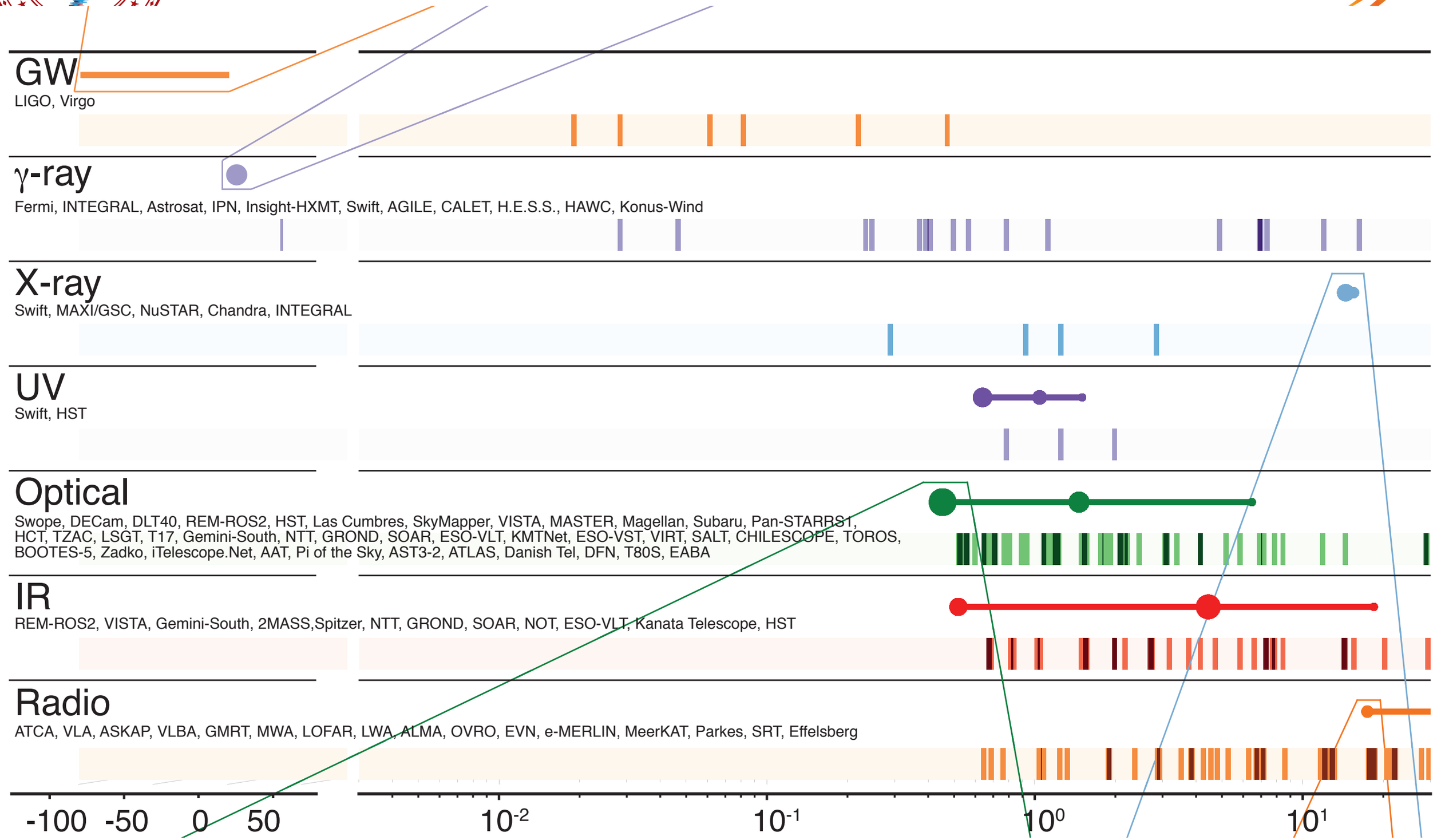




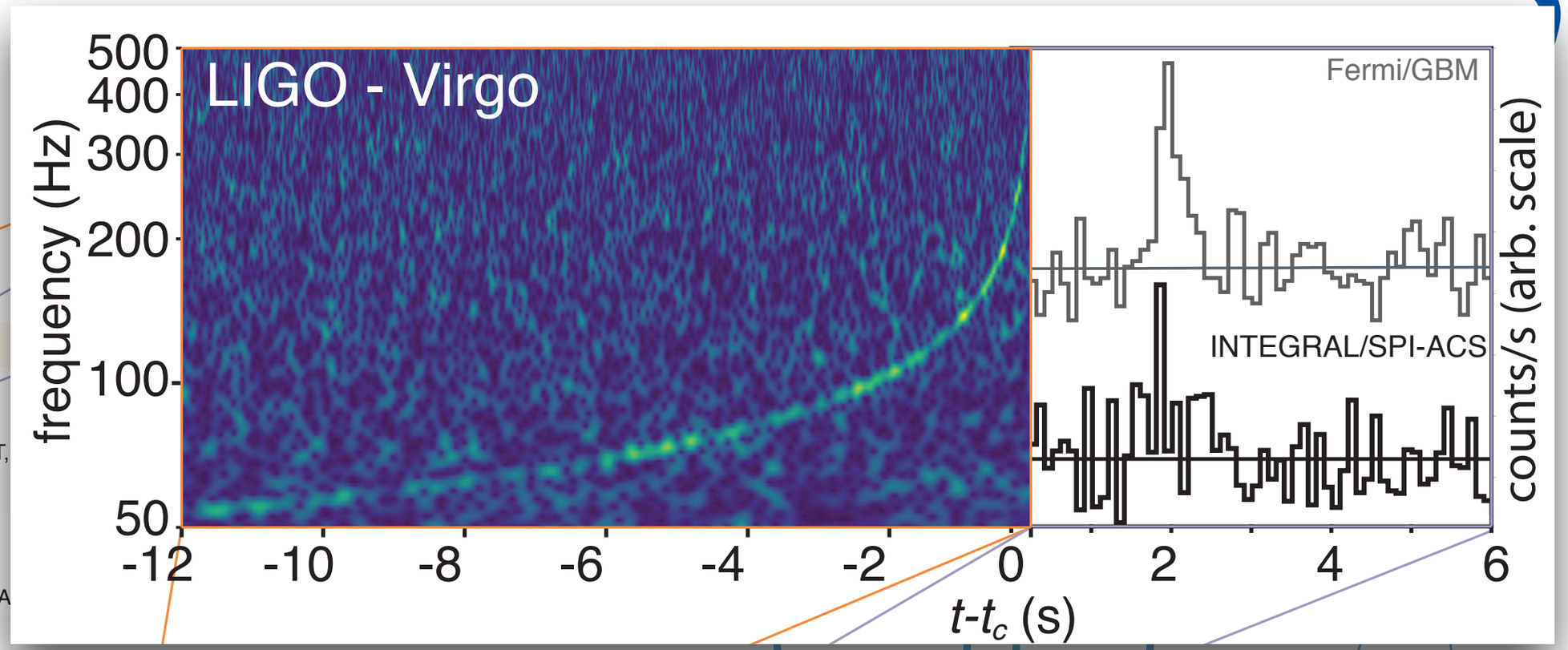


There is matter, and we can watch it

Amazing measurement set



https://arxiv.org/abs/1710.05833



GW
LIGO, Virgo

γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT,

X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRA

UV
Swift, HST

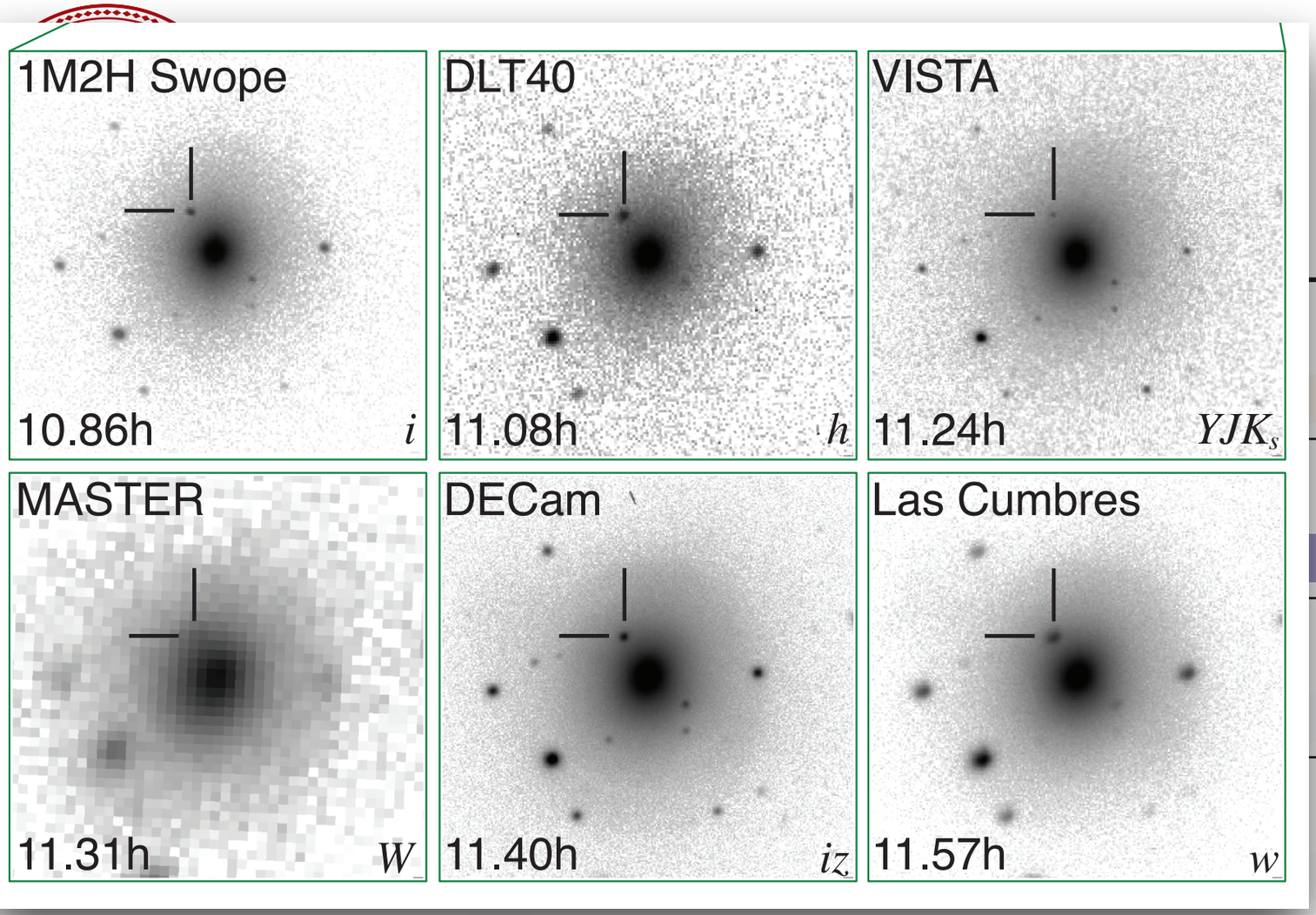
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA

IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST

Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg

-100 -50 0 50 10^{-2} 10^{-1} 10^{0} 10^{1}

https://arxiv.org/abs/1710.05833



LIGO VIRGO KAGRA

Optical

Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA

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REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST

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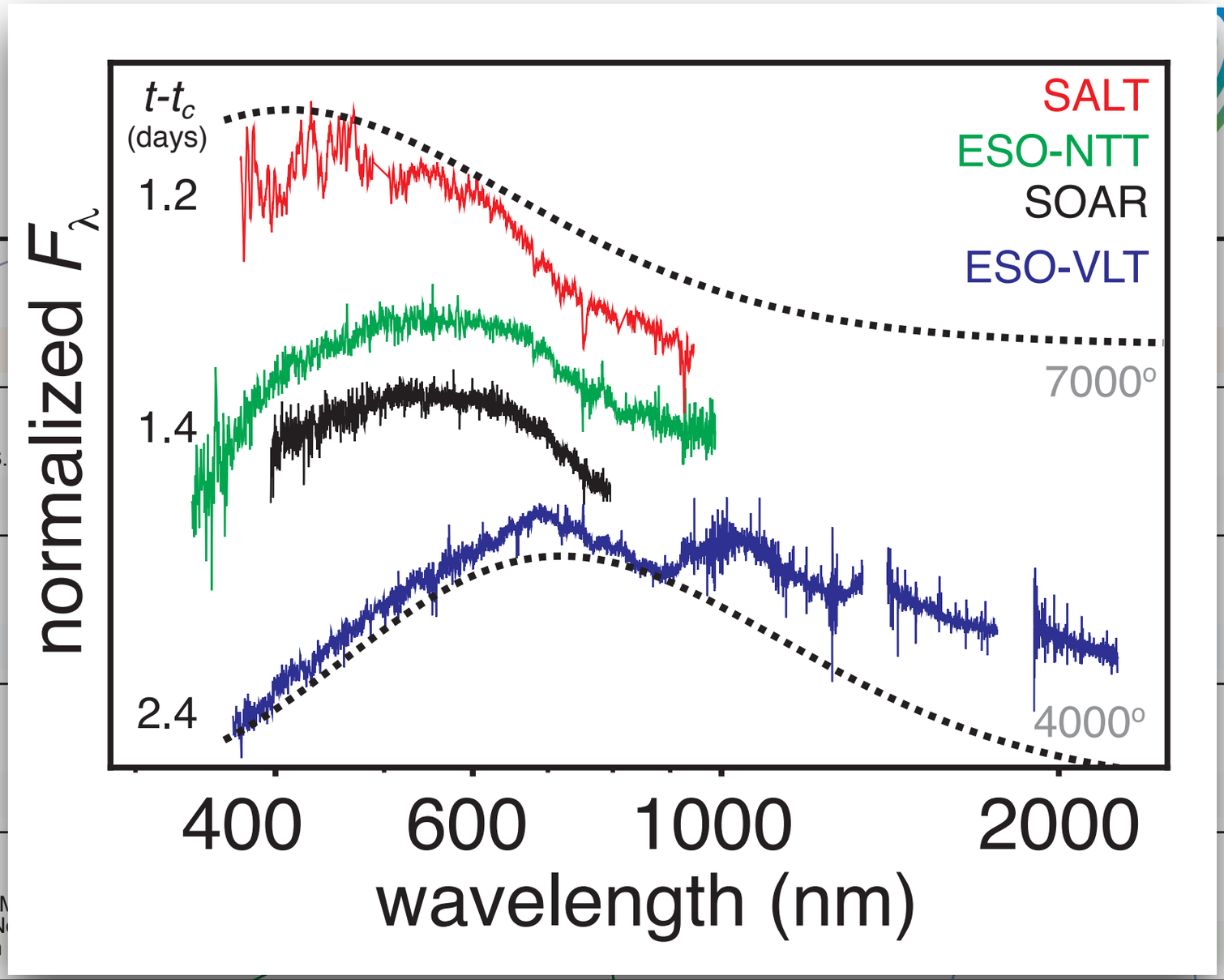

GW
LIGO, Virgo

γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S.

X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL

UV
Swift, HST

Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, M
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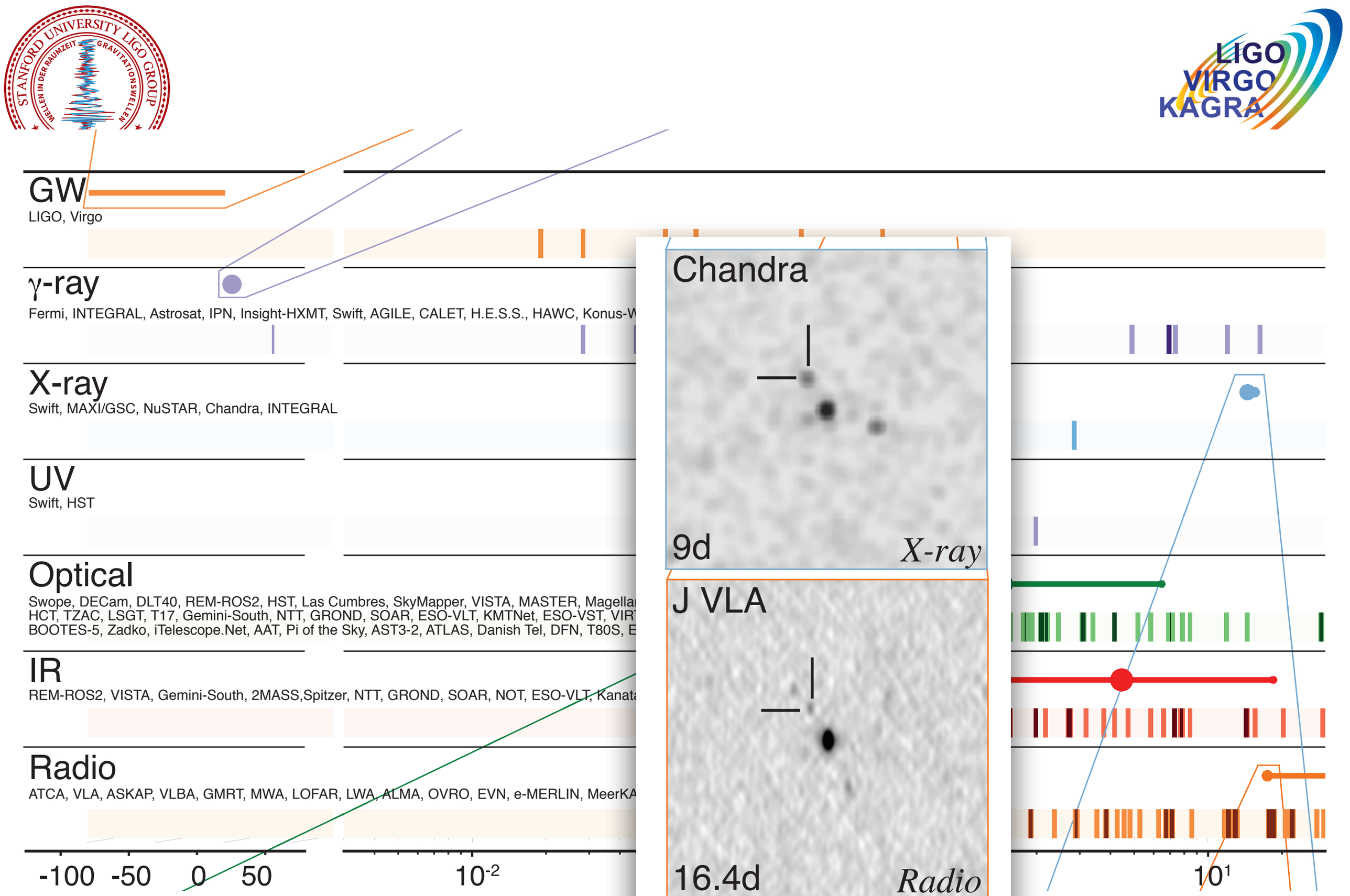
BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish

IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST

Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg

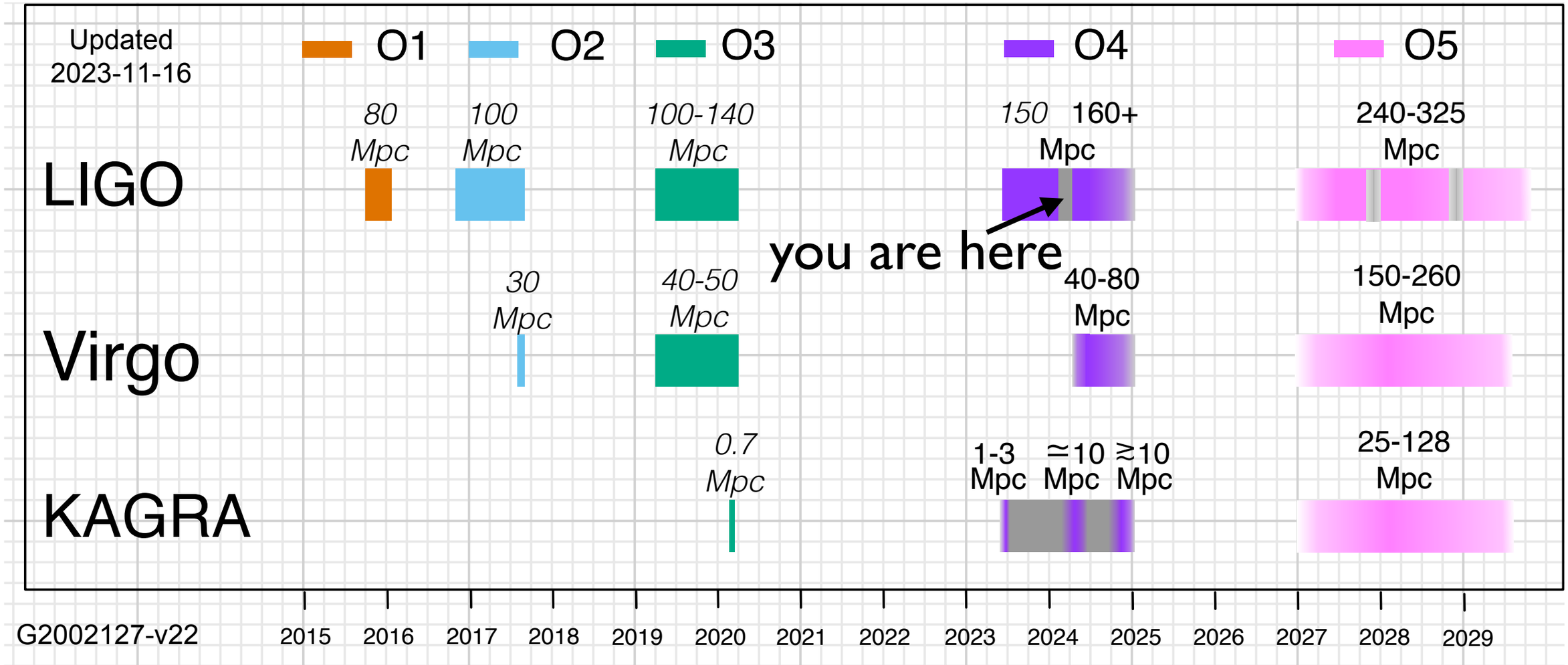
-100 -50 0 50 10^{-2} 10^{-1} 10^{0} 10^{1}

https://arxiv.org/abs/1710.05833



https://arxiv.org/abs/1710.05833

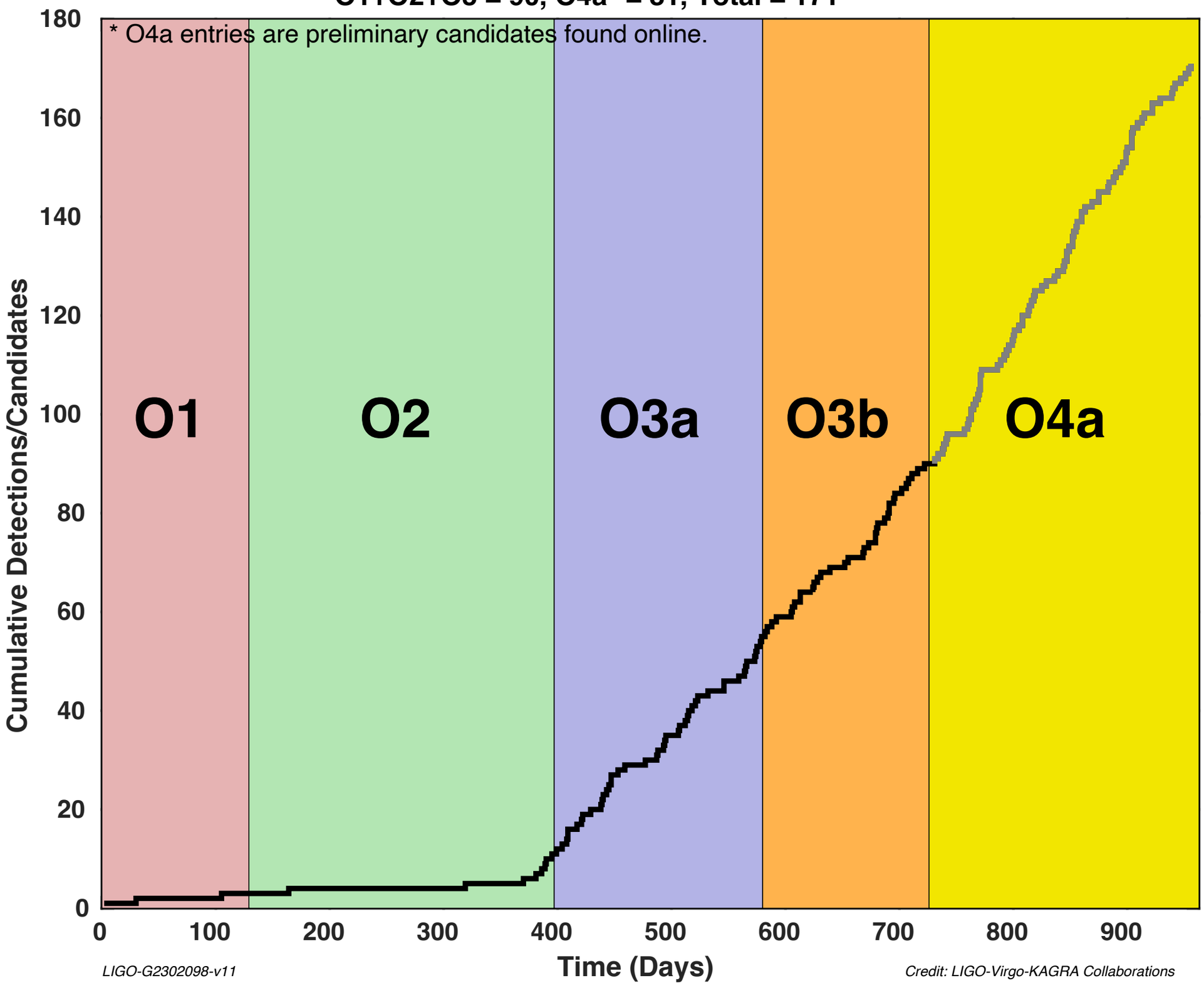
Where are we now?



https://observing.docs.ligo.org/plan/

Lots of Events!

Cumulative count of GW events



LIGO-G2302098-v11

Credit: LIGO-Virgo-KAGRA Collaborations

GraceDB Public Alerts Latest Search Documentation Login

Please log in to view full database contents.

O4 Significant Detection Candidates: **81** (92 Total - 11 Retracted)

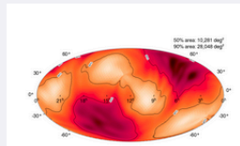
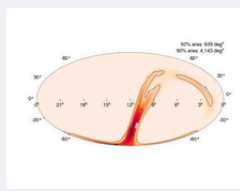
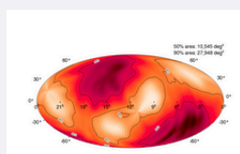
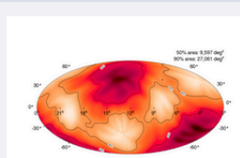
O4 Low Significance Detection Candidates: **1610** (Total)

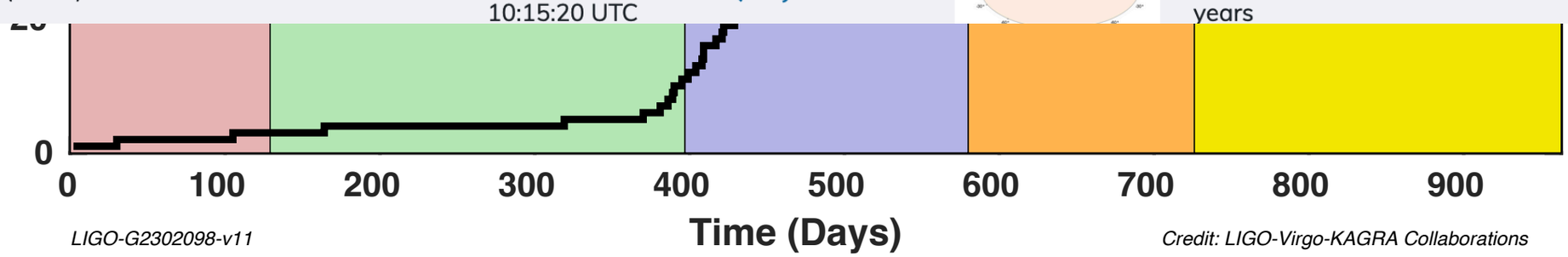
Show All Public Events

Page 1 of 7. next last »

SORT: EVENT ID (A-Z)

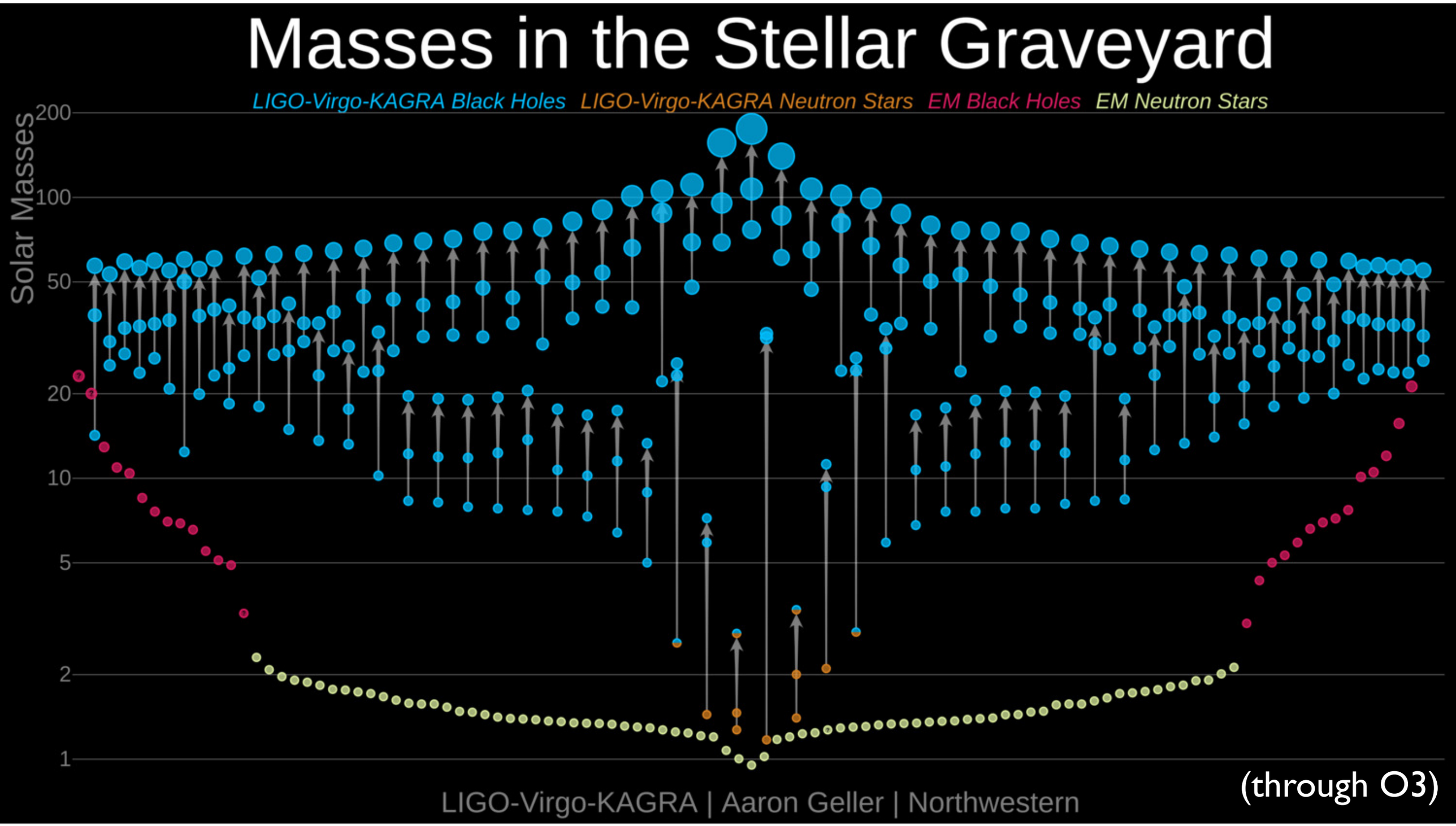
You can track these at https://gracedb.ligo.org/

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S240109a	BBH (99%)	Yes	Jan. 9, 2024 05:04:31 UTC	GCN Circular Query Notices | VOE		1 per 4.3136 years	
S240107b	BBH (97%), Terrestrial (3%)	Yes	Jan. 7, 2024 01:32:15 UTC	GCN Circular Query Notices | VOE		1.8411 per year	
S240104bl	BBH (>99%)	Yes	Jan. 4, 2024 16:49:32 UTC	GCN Circular Query Notices | VOE		1 per 8.9137e+08 years	
S231231ag	BBH (>99%)	Yes	Dec. 31, 2023 15:40:16 UTC	GCN Circular Query Notices | VOE		1 per 3.7932e+06 years	
S231226av	BBH (>99%)	Yes	Dec. 26, 2023 10:15:20 UTC	GCN Circular Query		1 per 2.8446e+42 years	



LIGO-G2302098-v11

Credit: LIGO-Virgo-KAGRA Collaborations

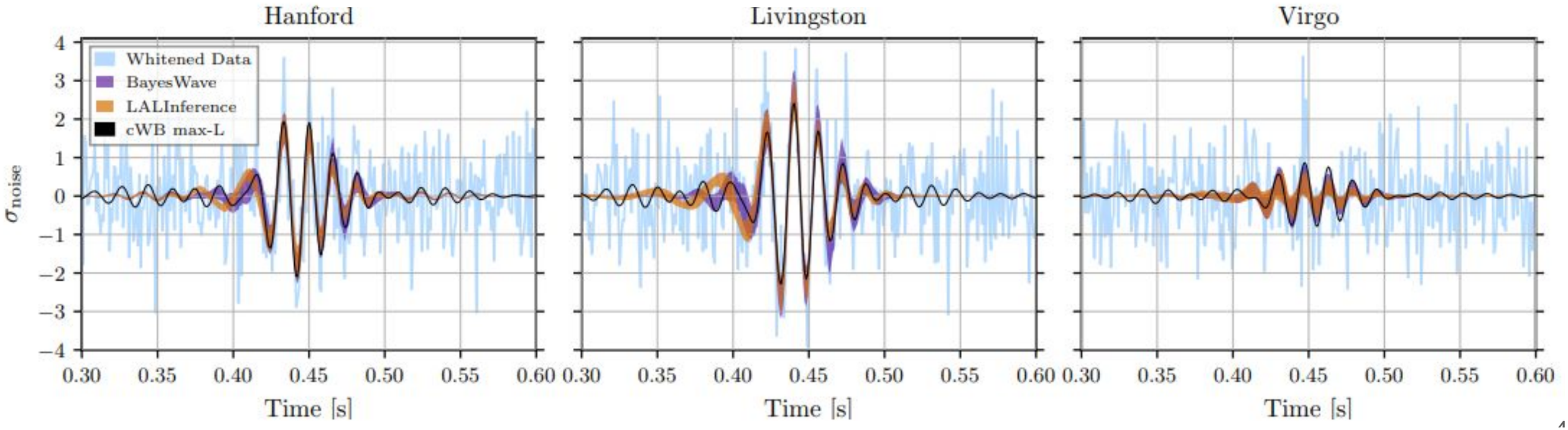

Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
(through O3)
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

notable events

GW190521 - ~150 solar mass event

$$m_1 = 85^{+21}_{-14} M_\odot \qquad m_2 = 66^{+17}_{-18} M_\odot$$

(1.7 GPc, 5 B lightyears)



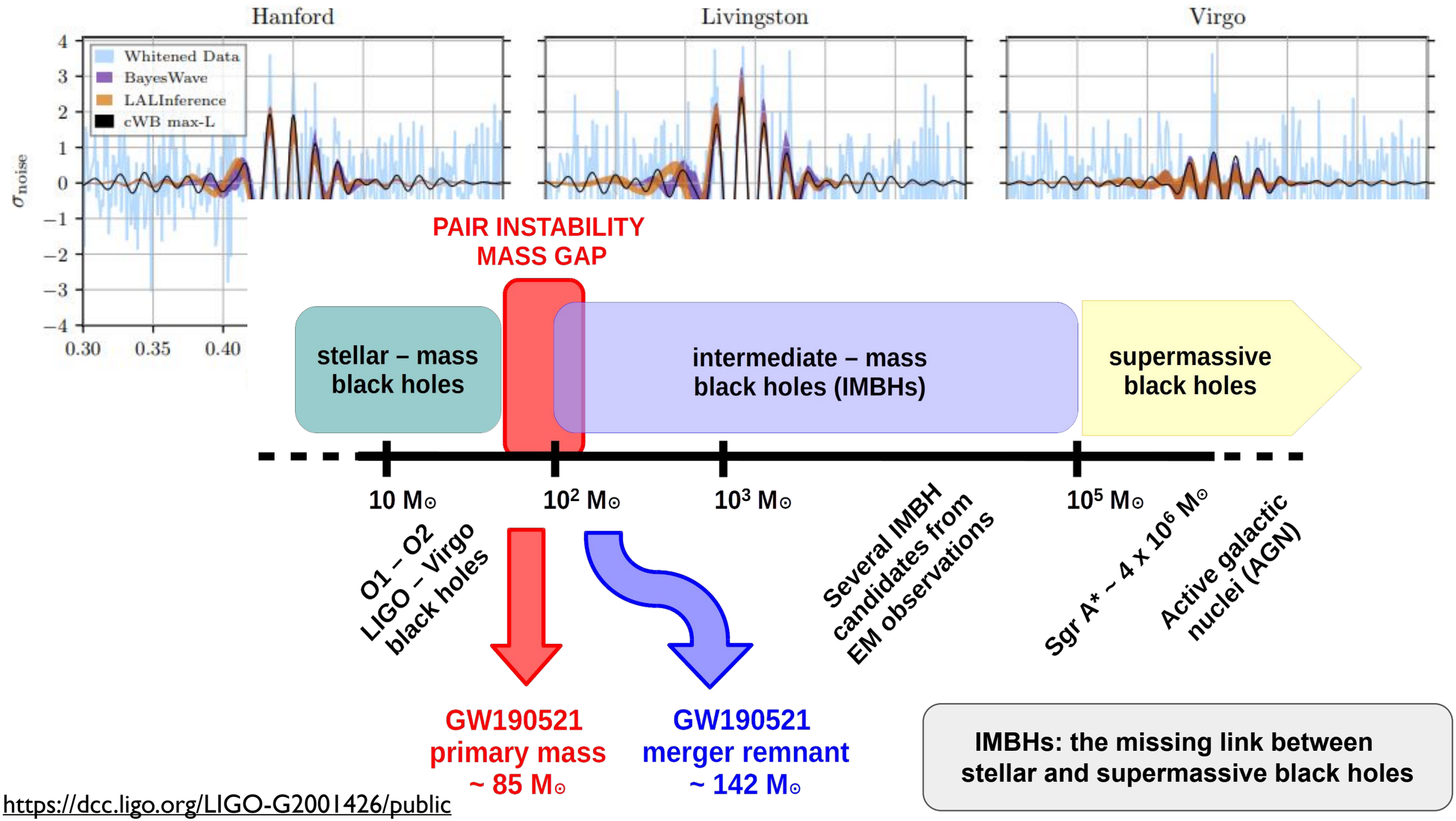
https://dcc.ligo.org/LIGO-G2001426/public

notable events

GW190521 - ~150 solar mass event

$$m_1 = 85^{+21}_{-14} M_\odot \qquad m_2 = 66^{+17}_{-18} M_\odot$$

(1.7 GPc, 5 B lightyears)

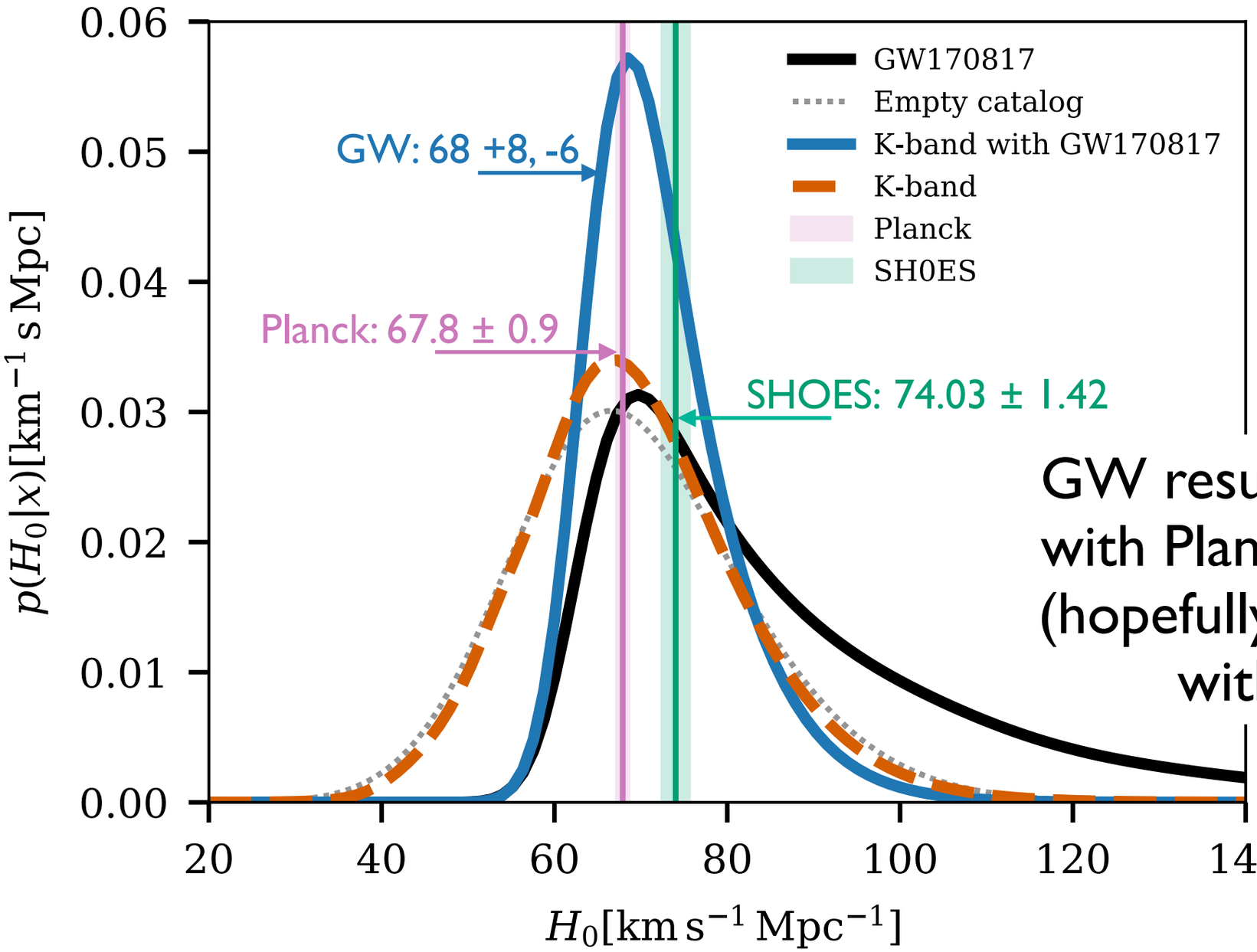


IMBHs: the missing link between stellar and supermassive black holes

https://dcc.ligo.org/LIGO-G2001426/public

Expansion of the Universe

Measuring the Hubble constant H_0 with gravitational waves because the 2 best measurement do not agree?!

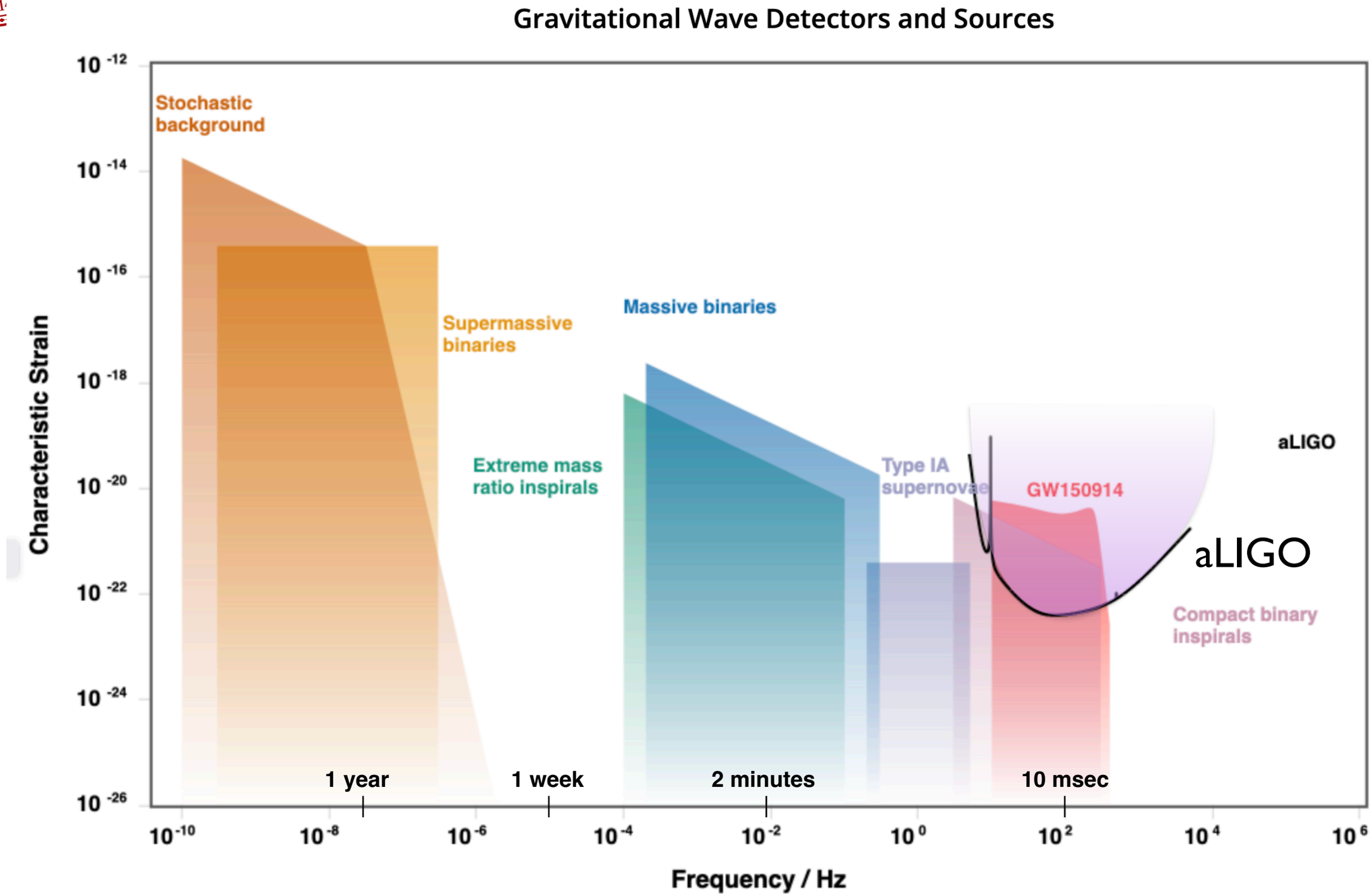


GW results still consistent with Planck & SHOES, but (hopefully) that will change with more data

Figure 9. Hubble constant posterior for several cases. Gray dotted line: posterior obtained using all dark standard sirens without any galaxy catalog information and fixing the BBH population model. Orange dashed line: posterior using all dark standard sirens with GLADE+ K–band galaxy catalog in- formation and fixed population assumptions. Black solid line: posterior from GW170817 and its EM counterpart. Blue solid line: posterior combining dark standard sirens and GLADE+ K–band catalog information (orange dashed line) with GW170817 and its EM counterpart (black solid line). The pink and green shaded areas identify the 68% CI constraints on H_0 inferred from the CMB anisotropies (Ade et al. 2016) and in the local Universe from SH0ES (Riess et al. 2019) respectively.

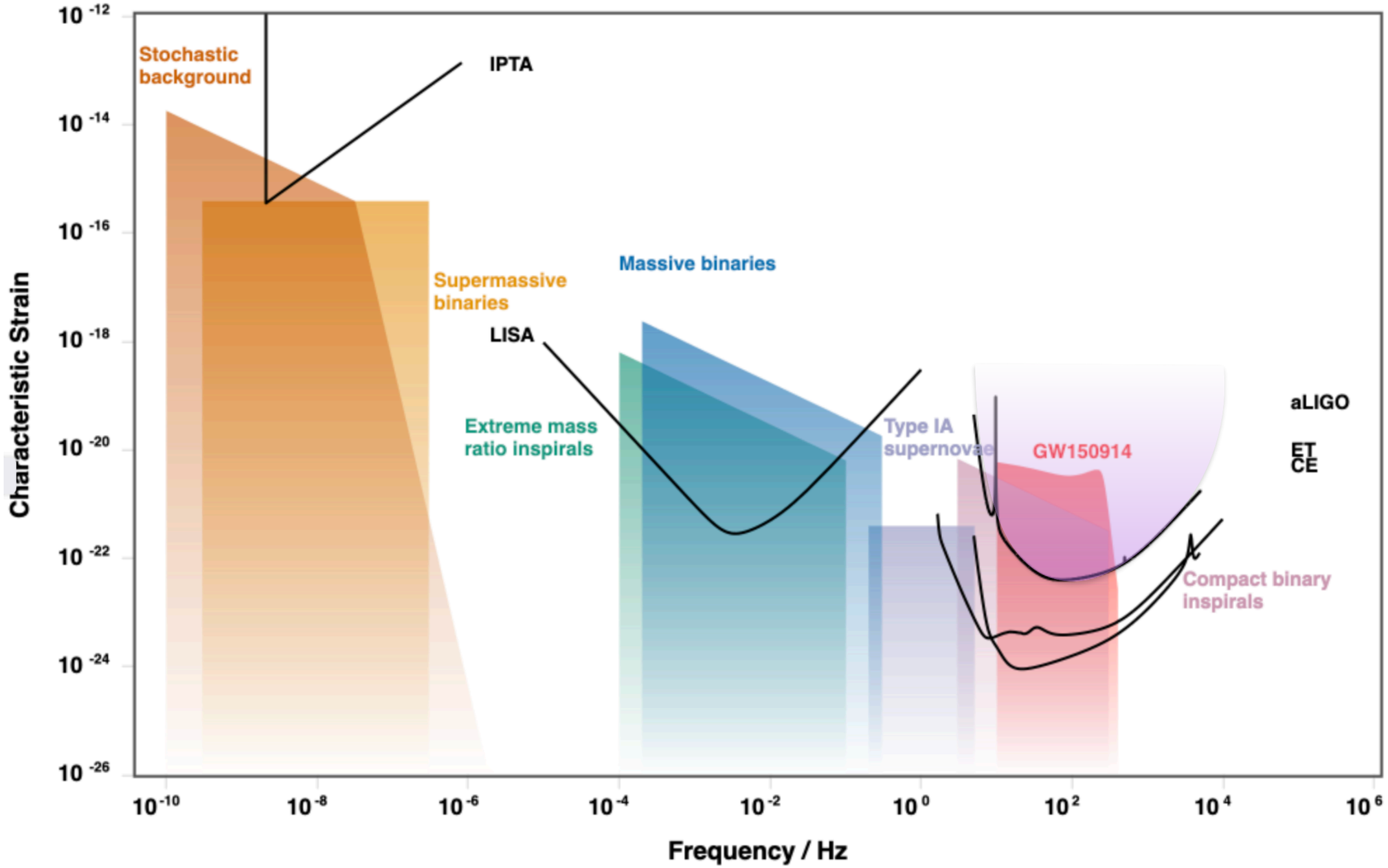
Constraints on the cosmic expansion history from GWTC–3, LVK author list, arXiv:2111.03604

There is so much more…



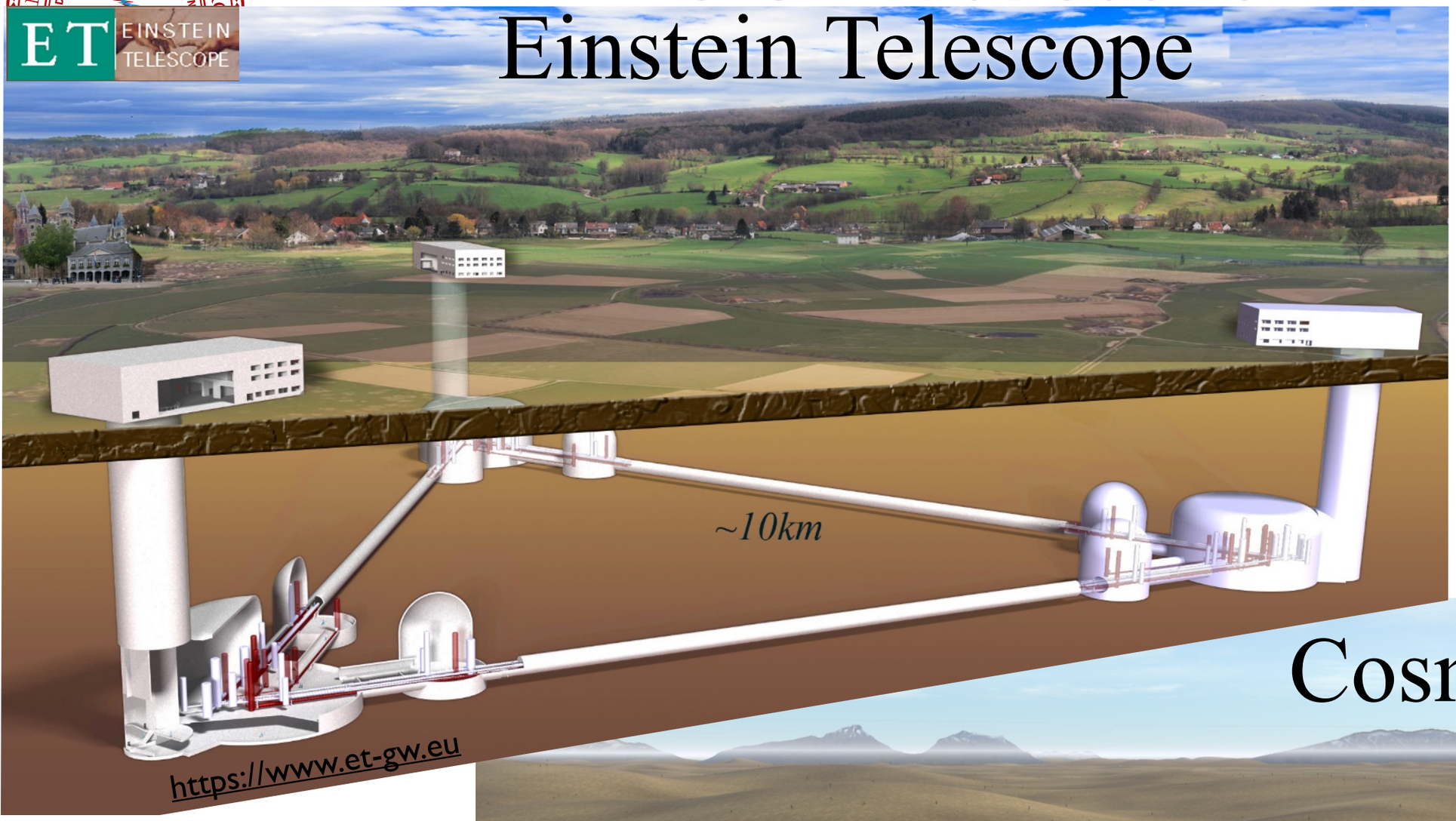
C. Moore et al, GWplotter.com

There is so much more…



3G detectors

Einstein Telescope



https://www.et-gw.eu

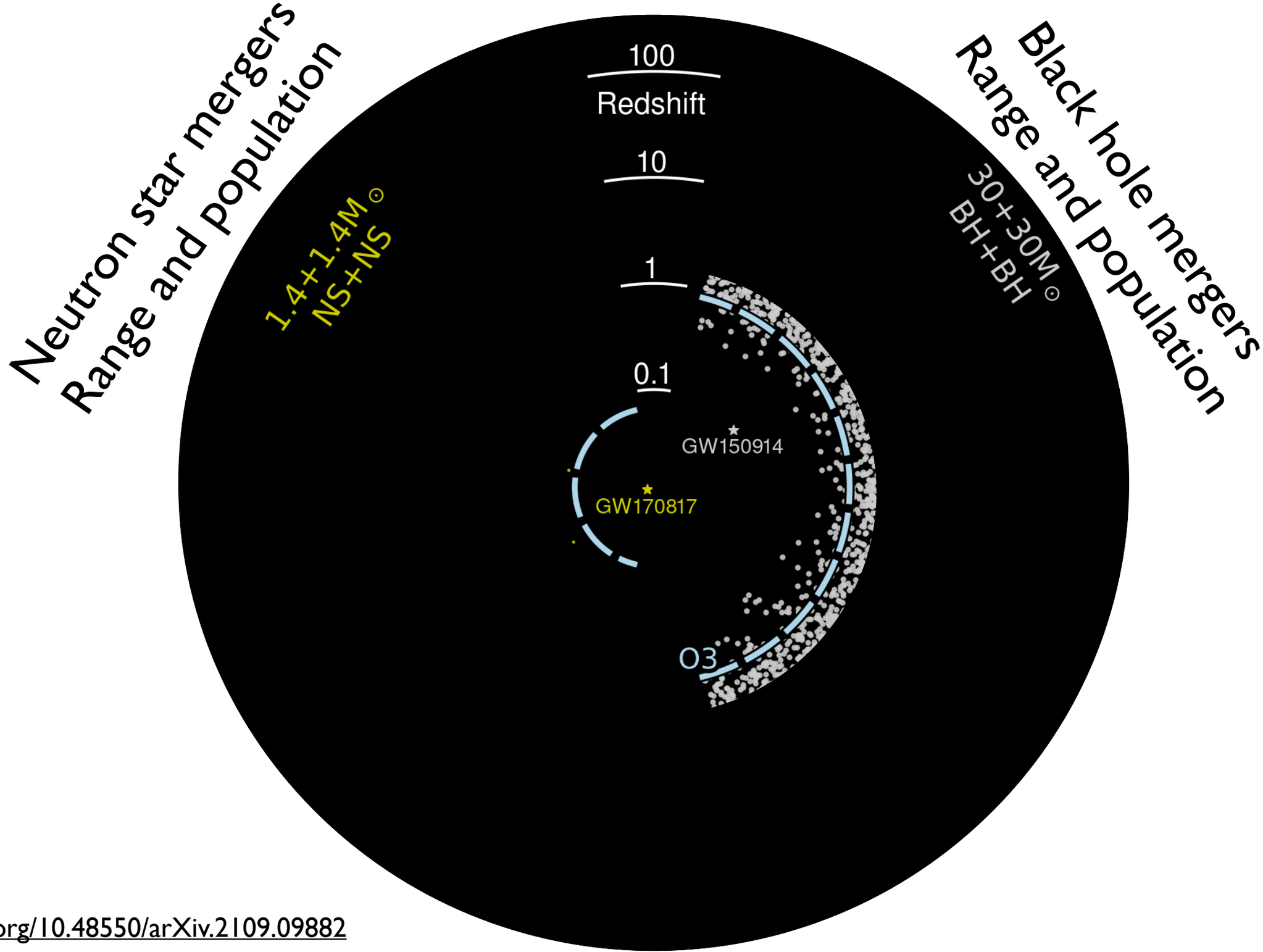
European concept
10 km triangle
underground
(other config's possible)

Cosmic Explorer

US concept
40 km & 20 km 'L'
(other config's possible)

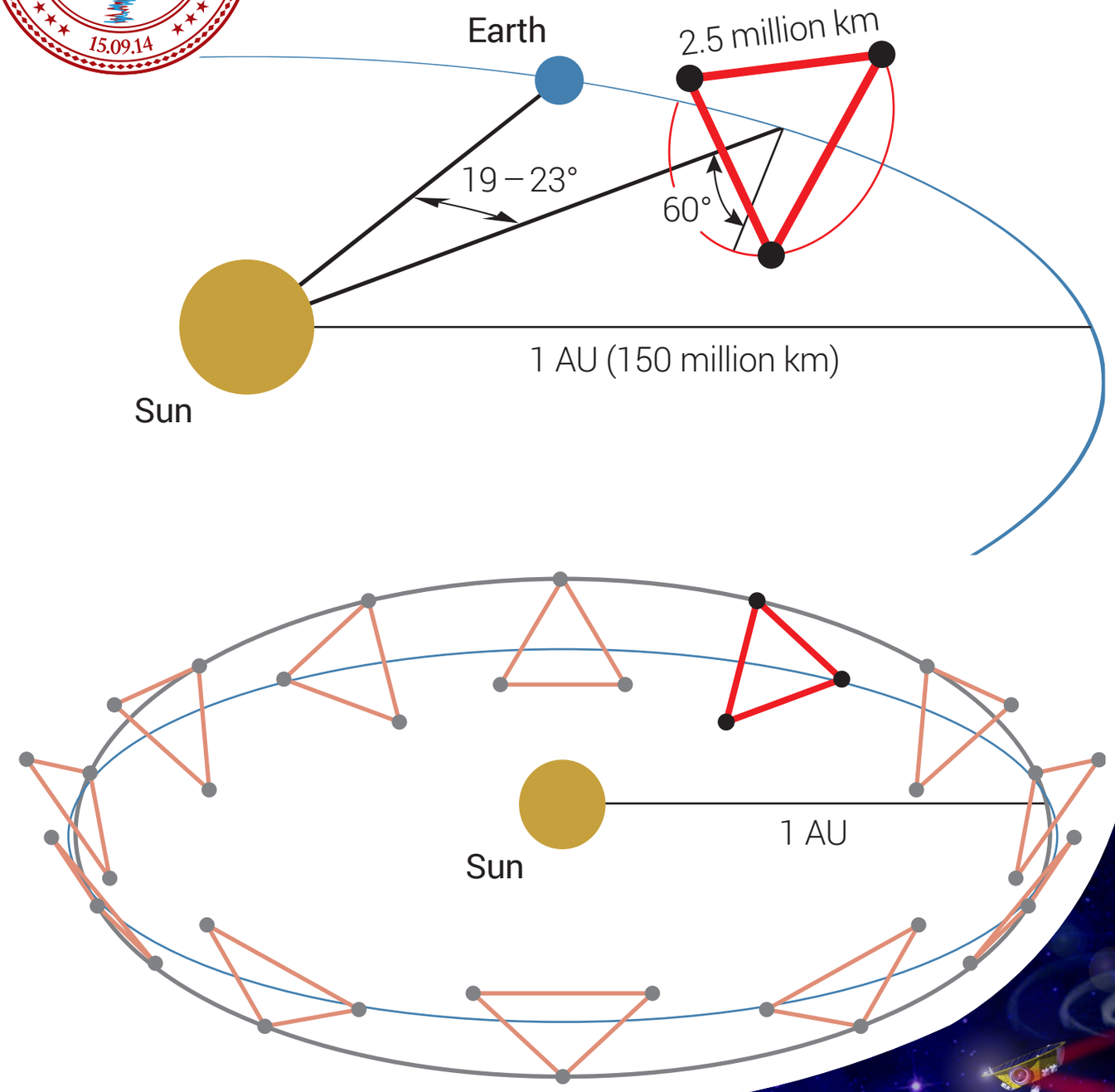
Artist's impression of a Cosmic Explorer observatory. (Credit: Angela Nguyen, Virginia Kitchen, Eddie Anaya, California State University Fullerton) https://cosmicexplorer.org/img/local/Overview3_V2.jpg

Science w/ Einstein Telescope & Cosmic Explorer

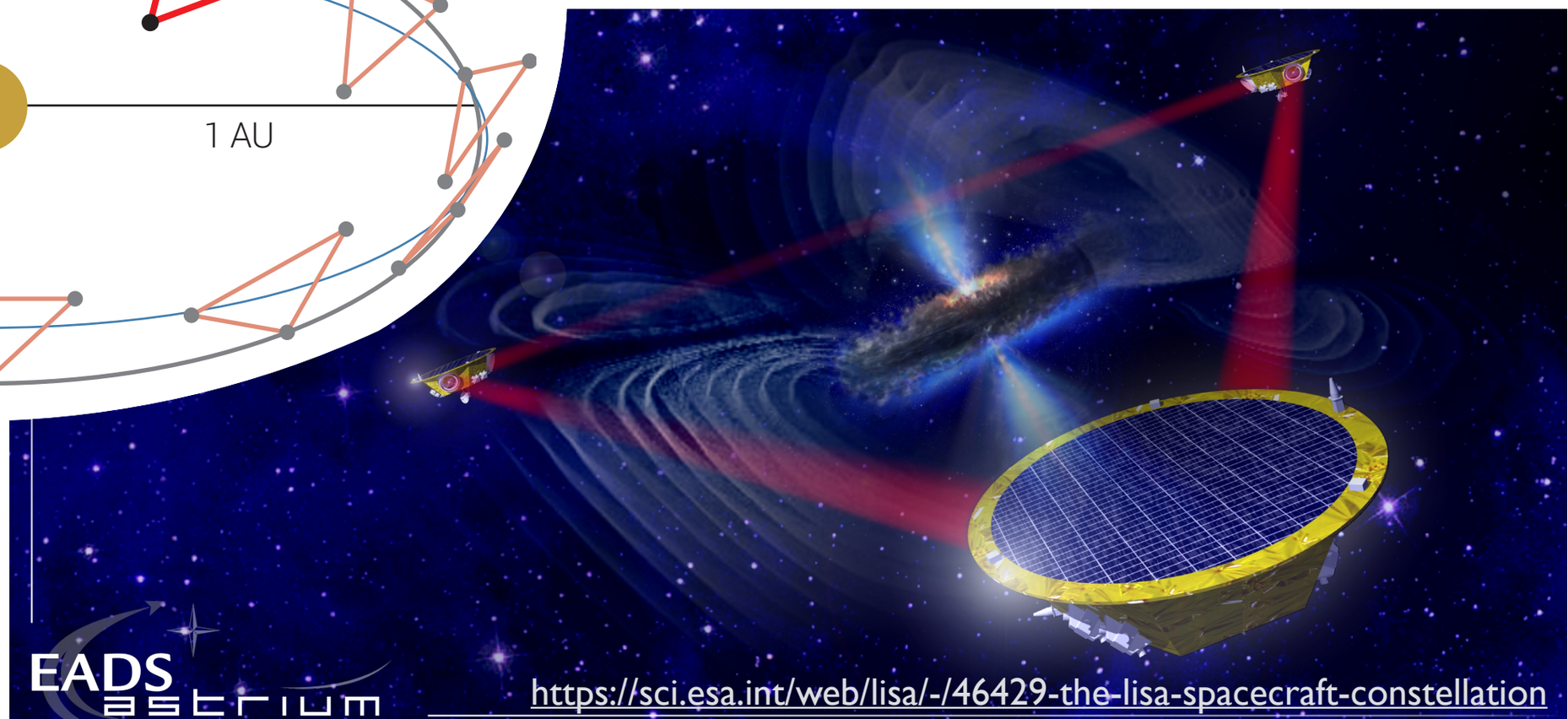


https://doi.org/10.48550/arXiv.2109.09882

LISA mission highlights



- 3 spacecraft orbiting the sun
- orbits yield ~stable triangle
- arms are 2.5 million km!
- ESA official approved LISA
  Jan 25, 2024 !
- 2035 launch
- 2 cool facts…



https://sci.esa.int/web/lisa/-/46429-the-lisa-spacecraft-constellation

K. Danzmann, P. Amaro-Seoane, et al,
"Laser Interferometer Space Antenna",
2017, arXiv:1702.00786

Pulsar timing

Use the "tick, tick, tick" of pulsars to measure space getting stretched by gravitational waves

The "arms" are a few thousand lightyears long!

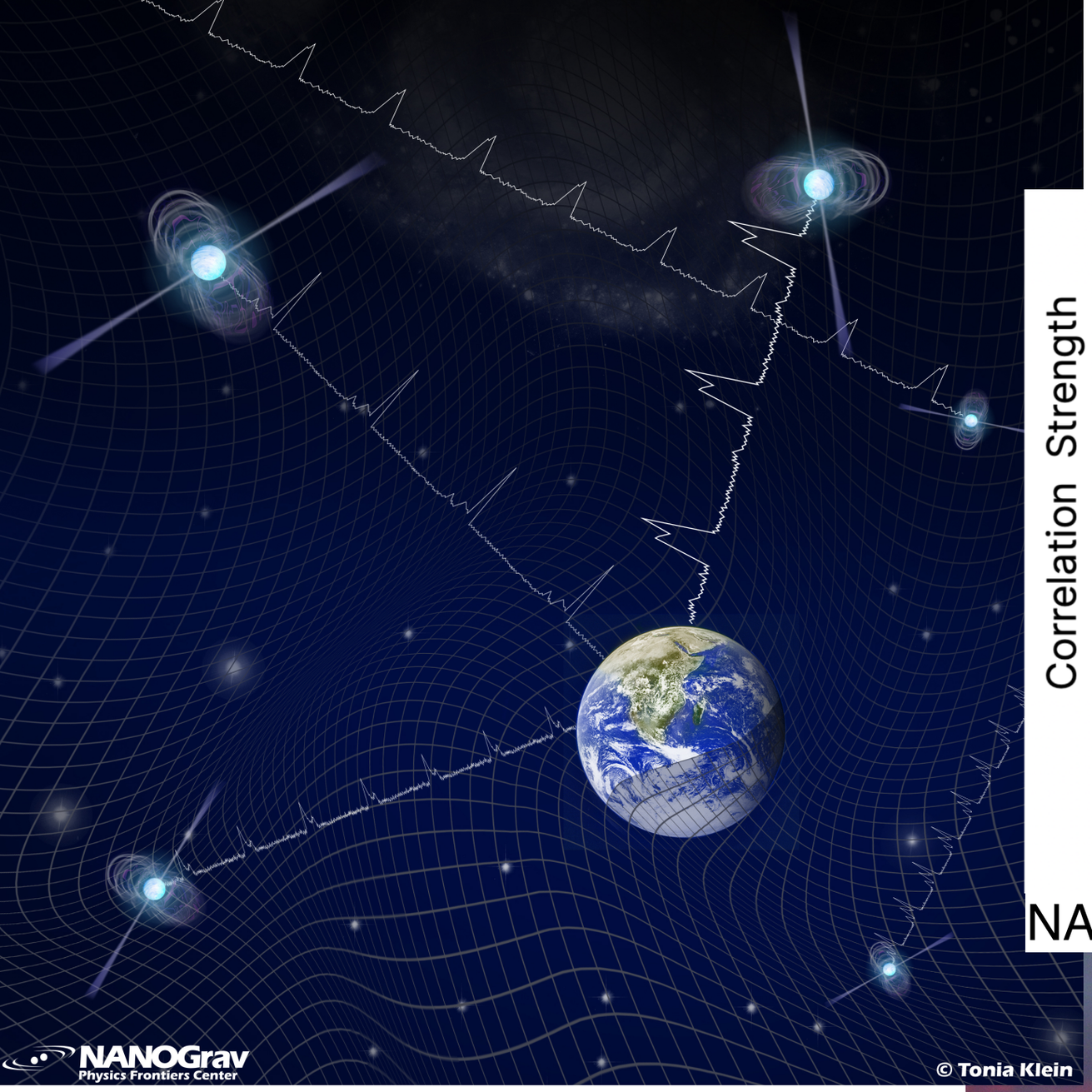
Measure correlations

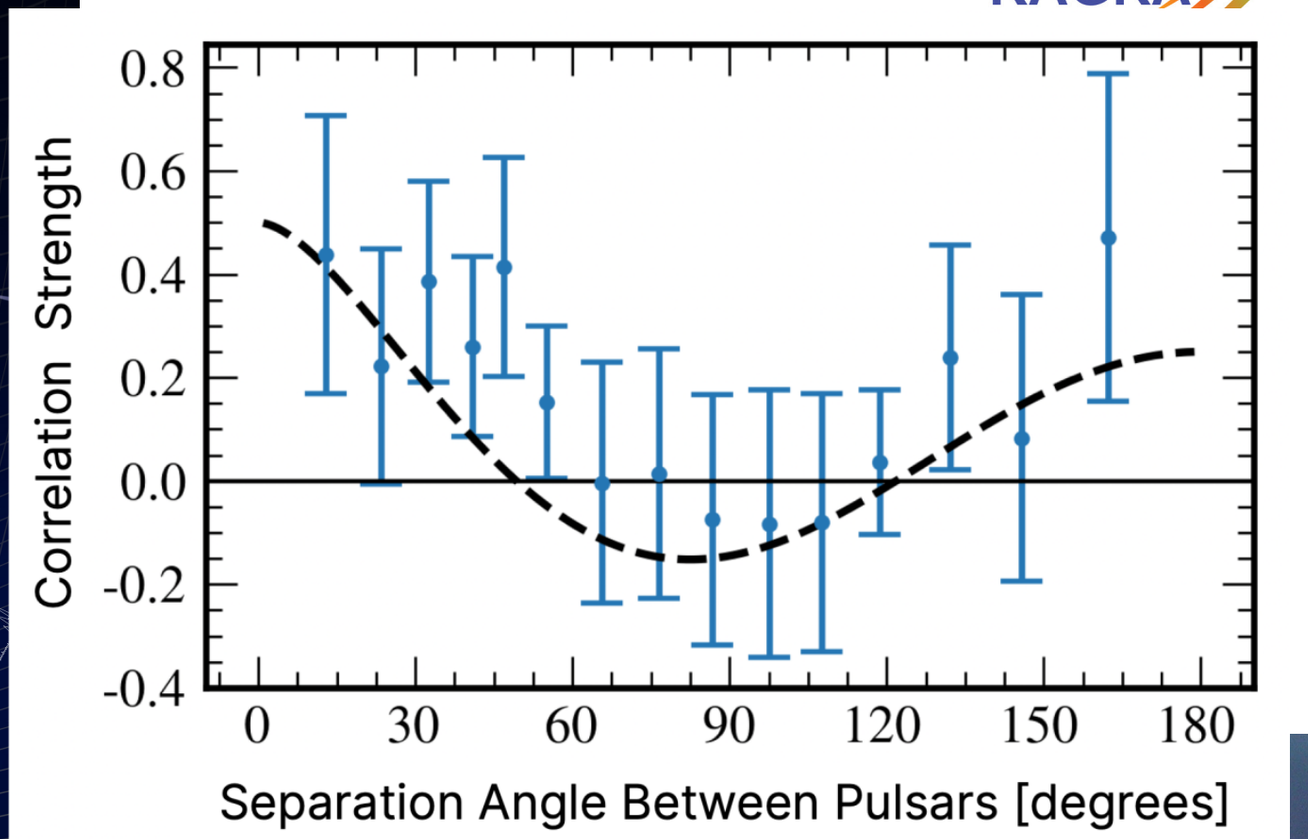
NANOgrav (USA) uses 68 pulsars

https://nanograv.org

https://www.nsf.gov/news/mmg/media/images/vlasunrisejuly2008_h.jpg

Pulsar timing





NANOgrav 15 year data release, June 29, 2023

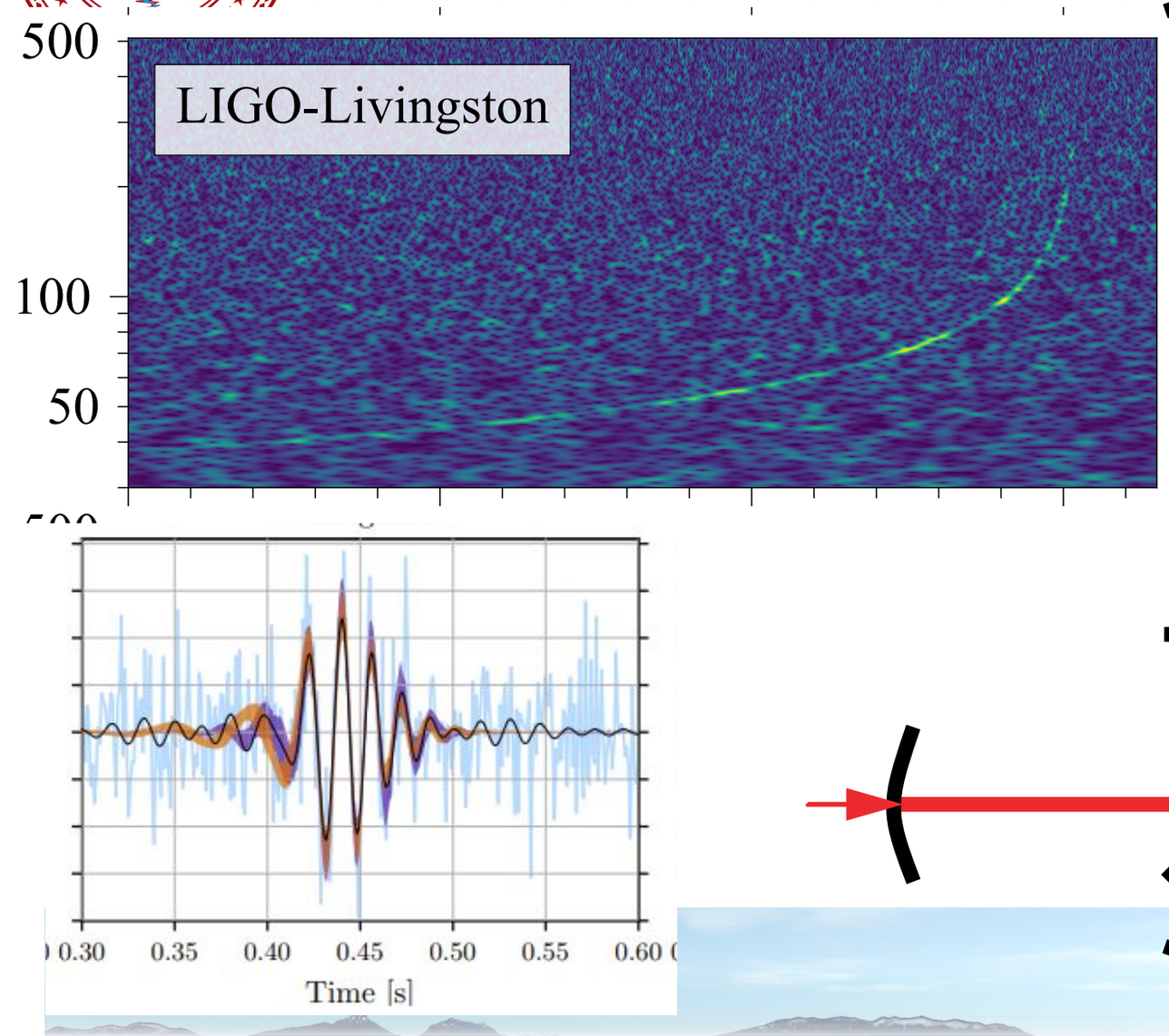
NANOgrav (USA) uses 68 pulsars

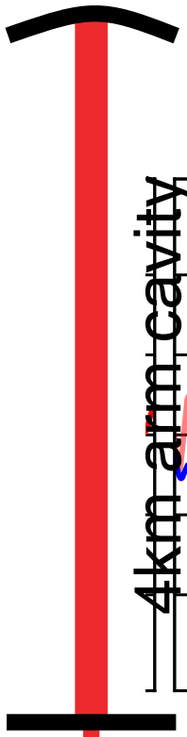
also PPTA, EPTA, InPTA, CPTA, MPTA
IPTA (International PTA)

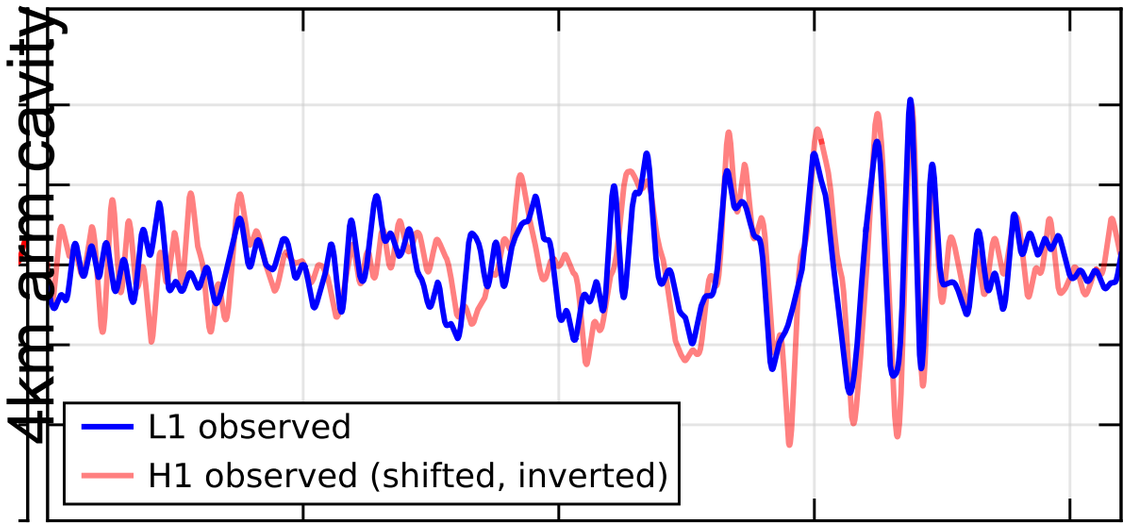
https://www.nsf.gov/news/mmg/media/images/vlasunrisejuly2008_h.jpg

https://nanograv.org

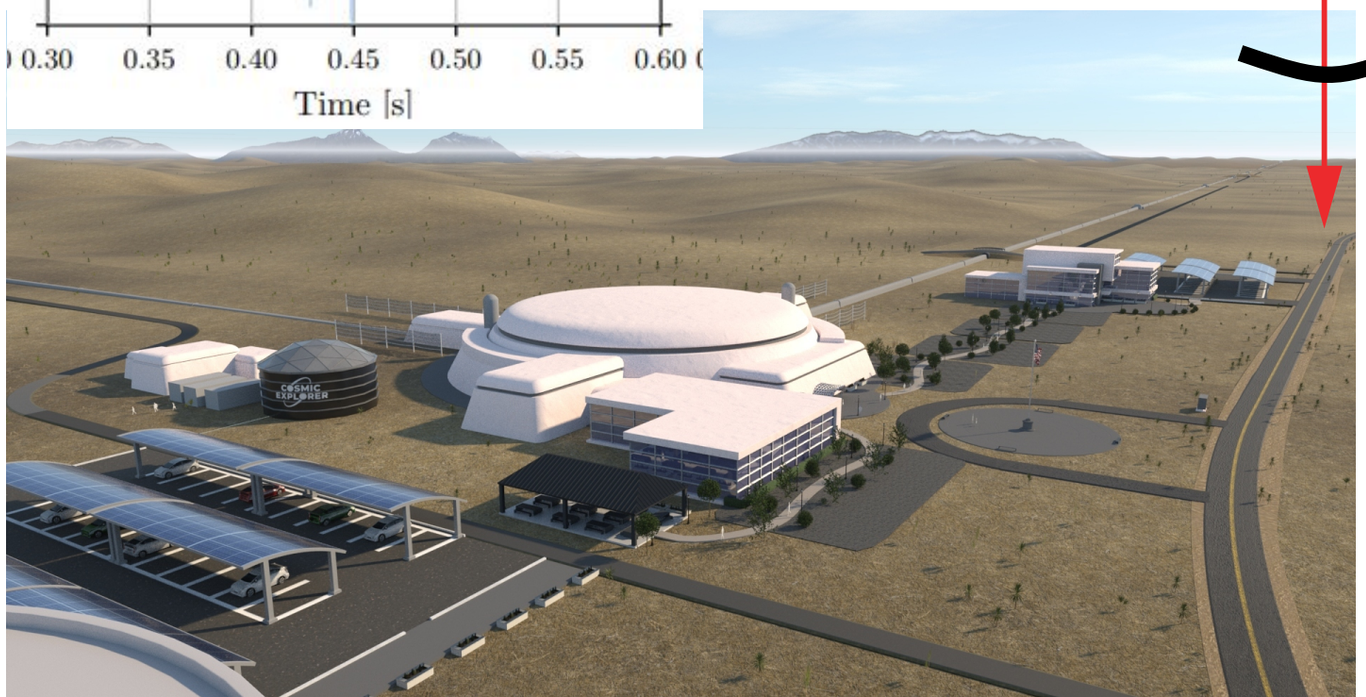
It's an exciting time!

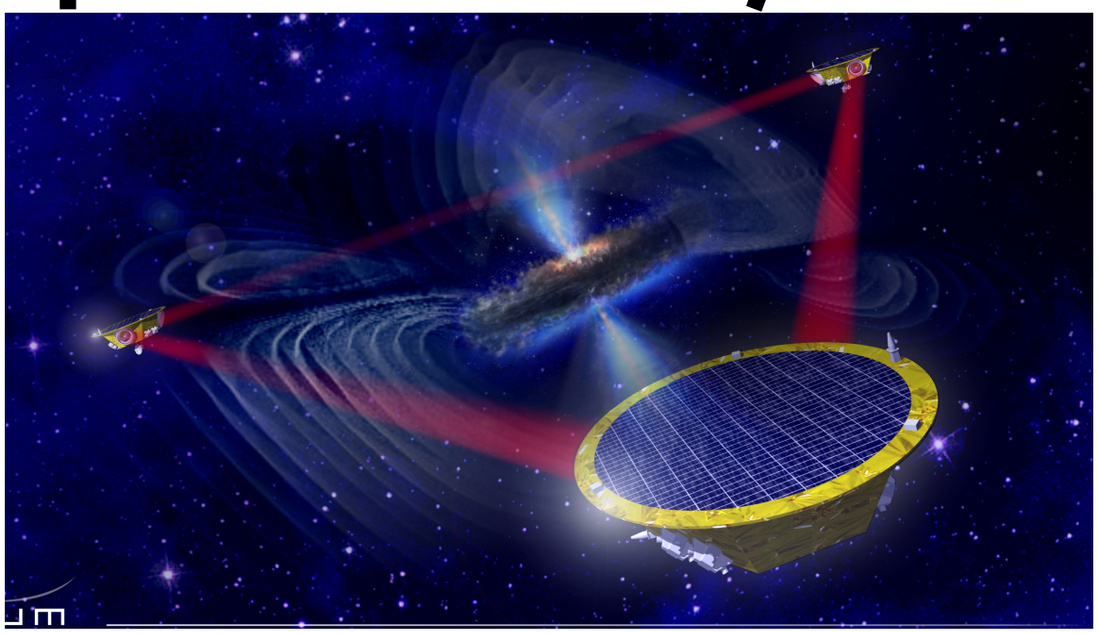




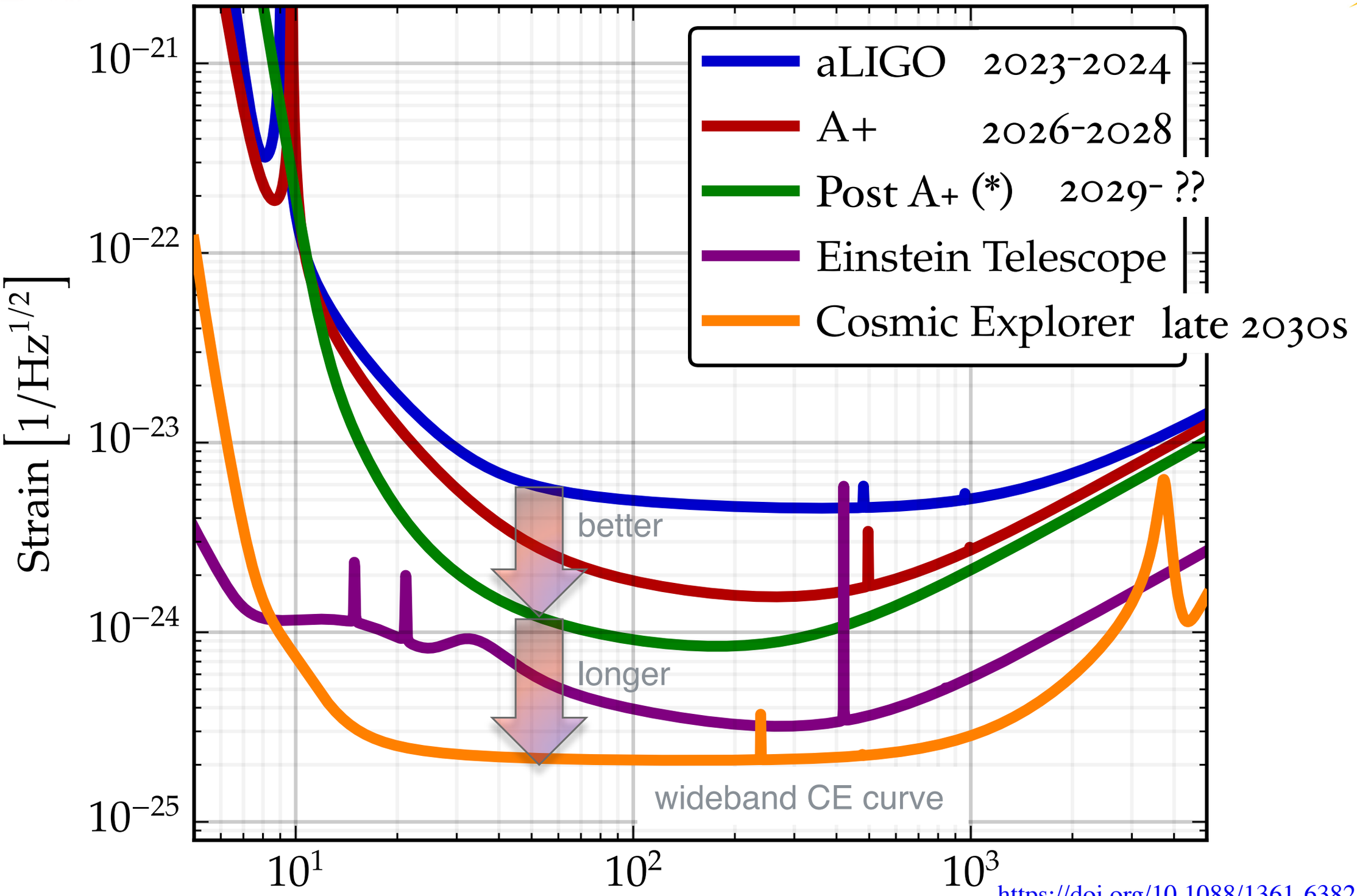


4km arm cavity





3G detectors



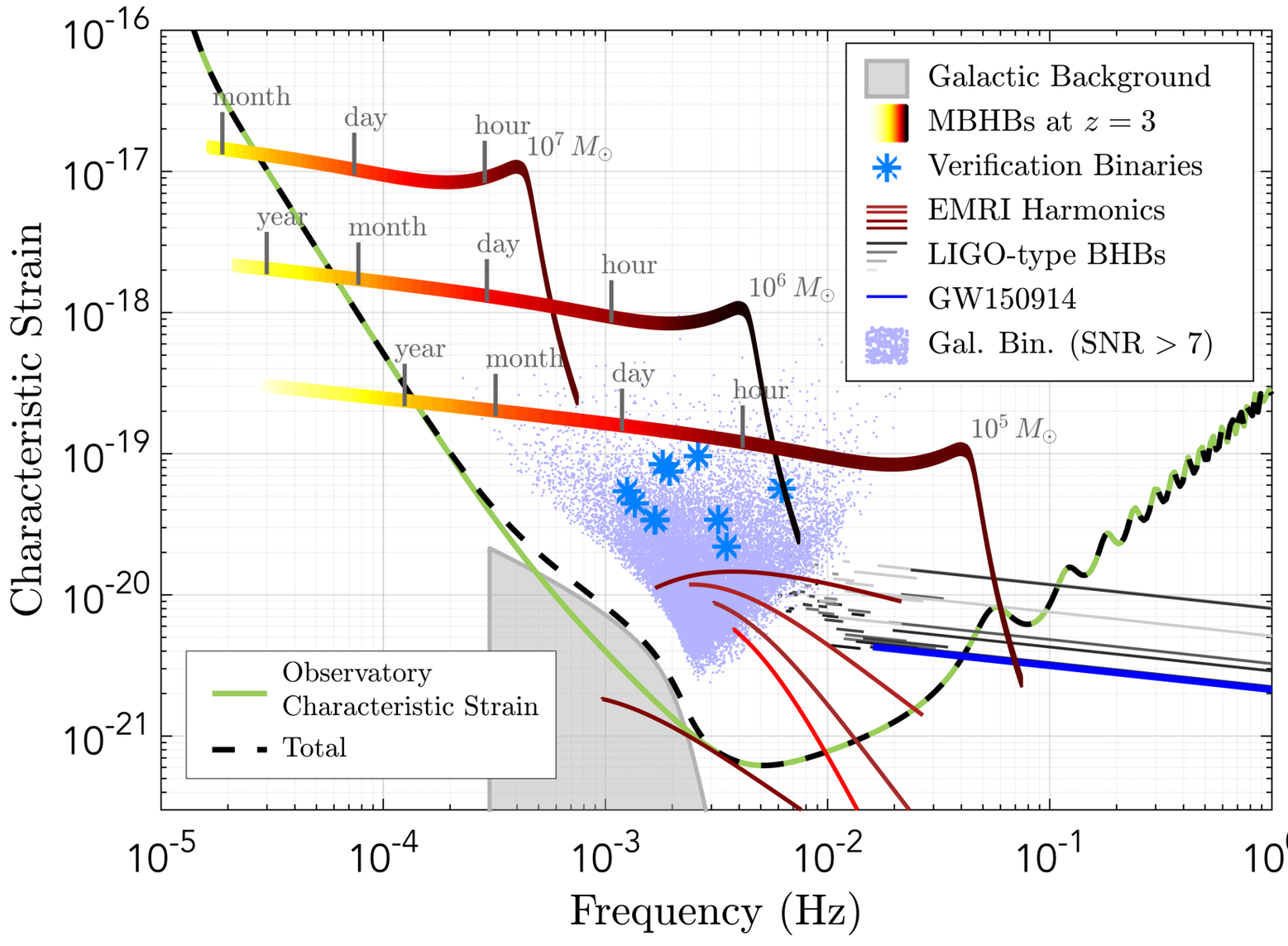
https://doi.org/10.1088/1361-6382/aa51f4

(*) green curve is for Voyager, which is no longer the baseline for upgrades in the current facilities

LISA Science

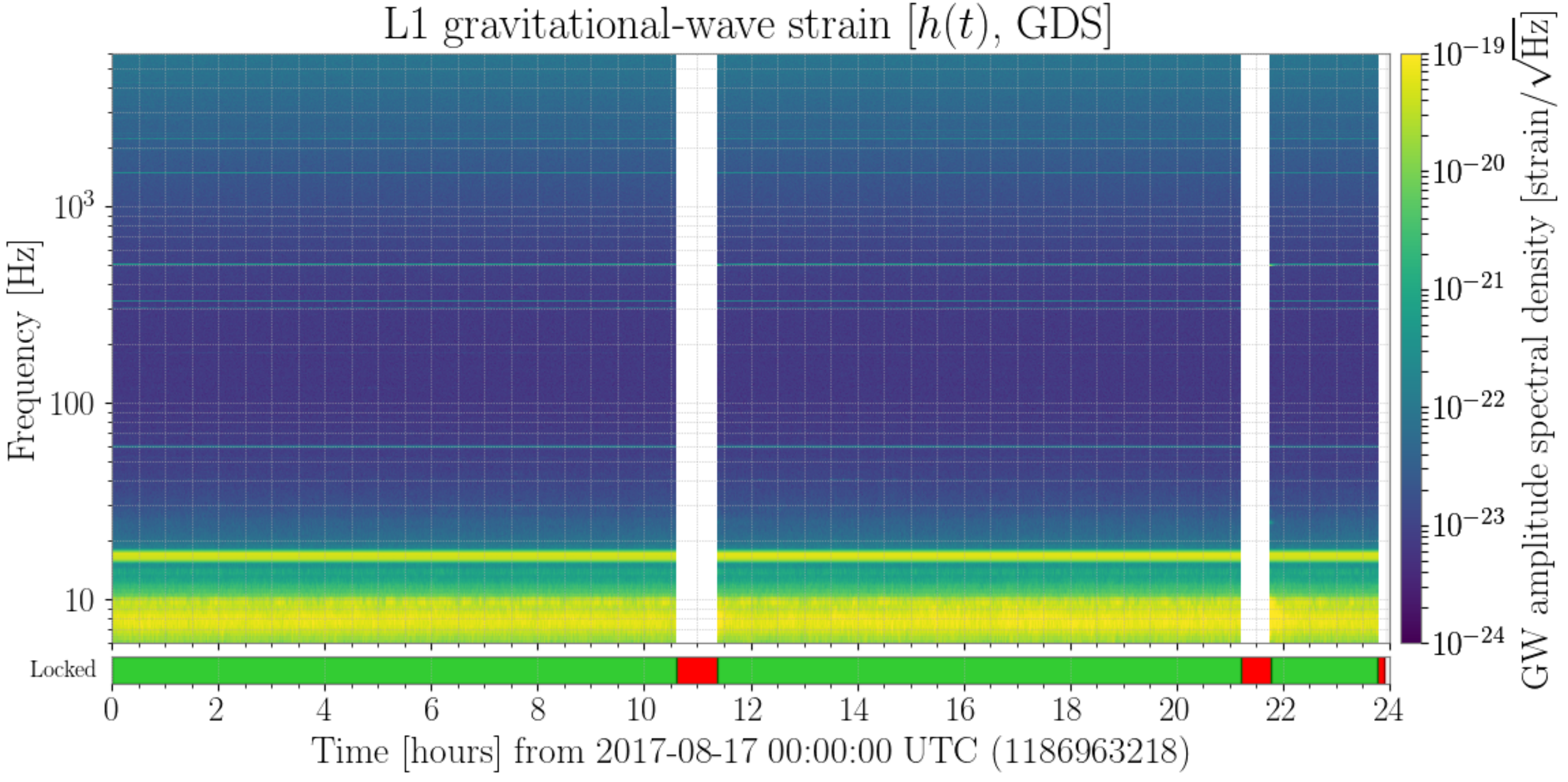
LISA will see lots of new sources

- Galactic binaries
- ‘Early phase’ merger of LVK events
- Massive Black Hole Binaries
- Extreme Mass Ratio Inspirals
  - map out the spacetime of large BHs by tracking 100s of orbits of stellar mass BHs as they fall in…



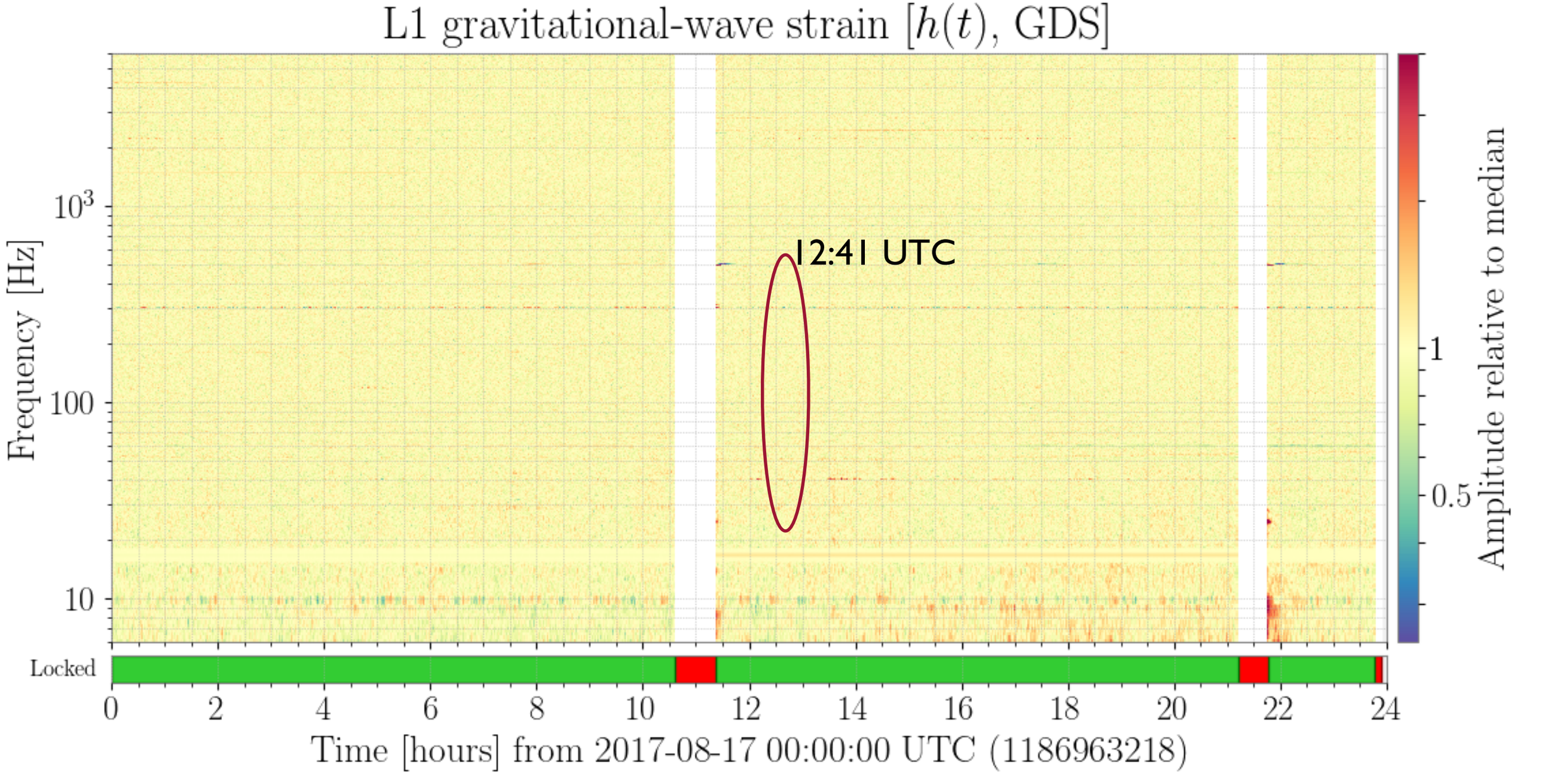
Watch for changes…

Spectrogram - 1 day at LLO

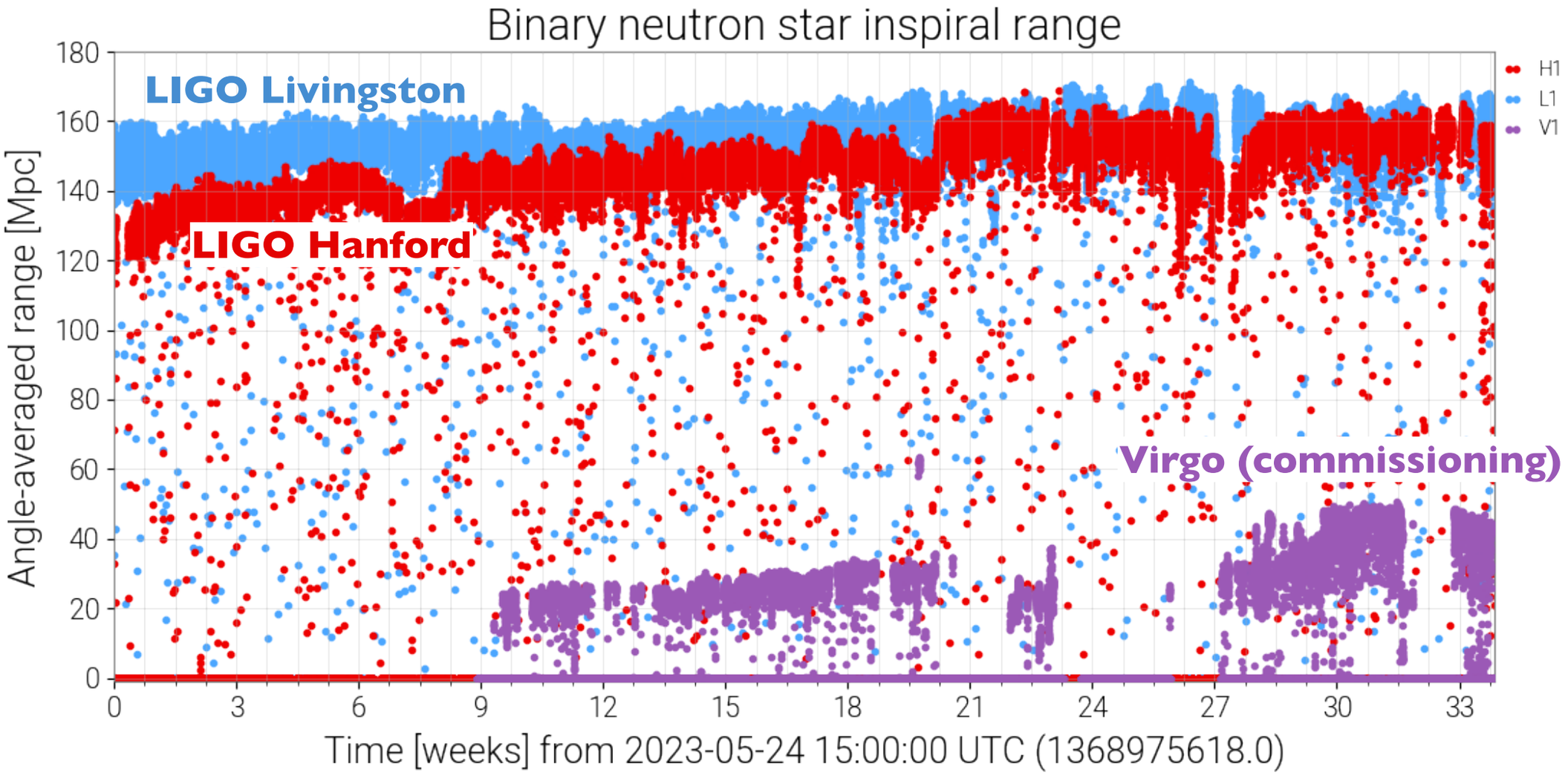


Watch for changes…

Normalized Spectrogram - 1 day at LLO



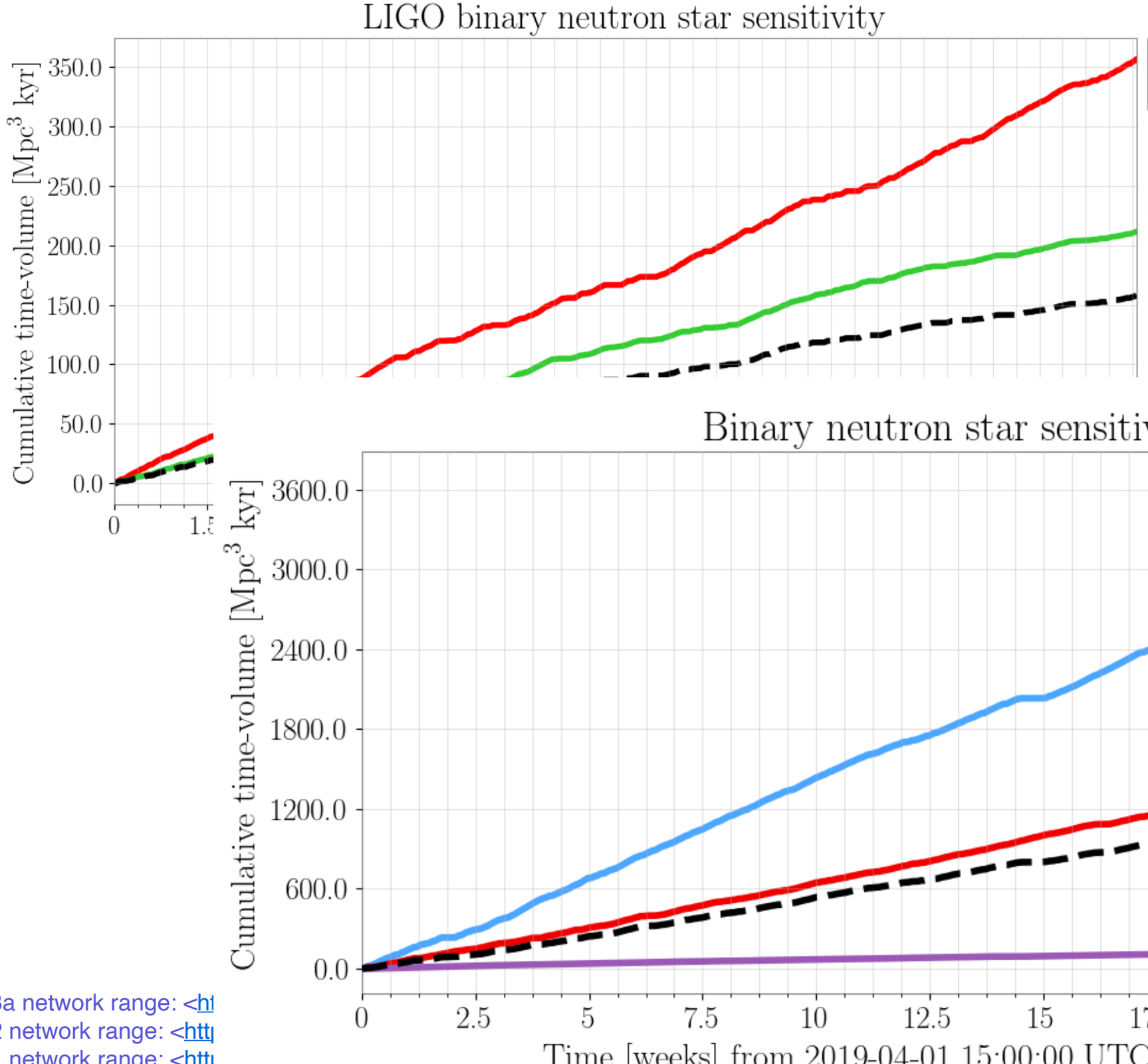
range in O4a



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

(range in O1 was 70-80 MPc)

Range



rates: GWTC-1:
BNS: 1.1e-4 - 3.8e-3 /MPc³-kYr
https://doi.org/10.1103/PhysRevX.9.031040

O3a network range: <ht
O2 network range: <htt
O1 network range: <htt