Exploring the Gravitational wave Universe with LIGO

Prof. Brian Lantz

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National Science Foundation + International partners

LIGO Scientific Collaboration

Caltech
Max-Planck-Institut für Gravitationsphysik Albert-Einstein-Institut
American University Washington, DC
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
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Hobart & William Smith Colleges
IFT - UNESP
LSU Louisiana State University
Maastricht University
Marquette University Be the Difference.
NASA Marshall Space Flight Center
Missouri S&T
Montana State University
Montclair State University
Lomonosov Moscow State University
Northwestern
PennState
PI
RIT
Flatiron Institute Center for Computational Astrophysics
Syracuse University Suos Cultores Scientia Coronat Founded AD 1870
Universitas Scientiarum Szegedinensis
Science & Technology Facilities Council Rutherford Appleton Laboratory
King's College London
University of Portsmouth
University of Birmingham
Australian National University
Charles Sturt University
Monash University
Sonoma State University
Leland Stanford Junior University Die Luft der Freiheit weht 1891
Stony Brook University
Cardiff University
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University of the West of Scotland UWS
University of Glasgow
University of Strathclyde Glasgow
OzGrav
Swinburne University of Technology
Texas Tech University
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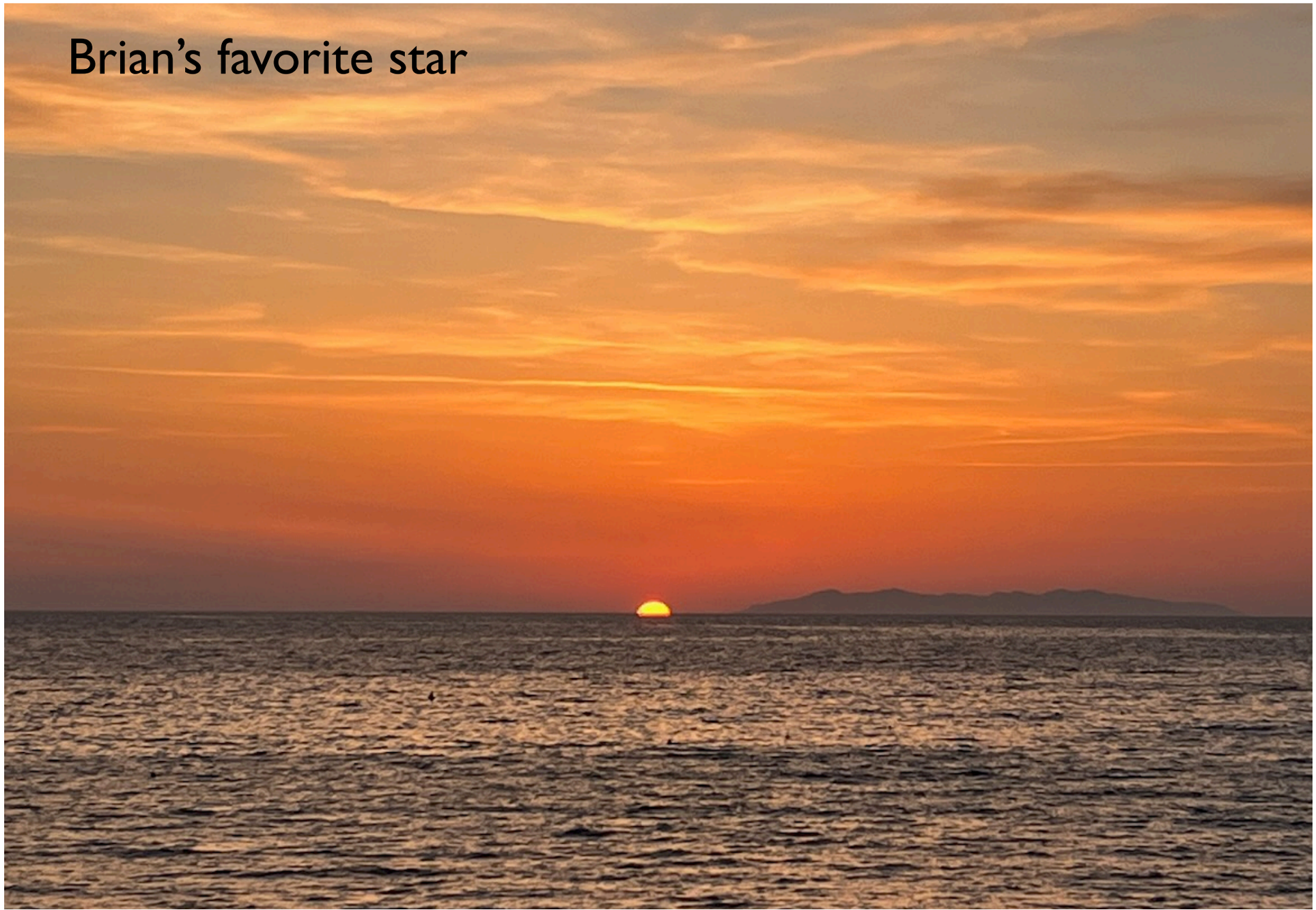
University of Cambridge
Warwick The University of Warwick
Royal Holloway University of London
Vanderbilt University
Villanova University
VU Vrije Universiteit Amsterdam
West Virginia University
Western Washington University
IISER Kolkata
IIT Hyderabad
CGCRI CGCB
Indian Institute of Technology Madras
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

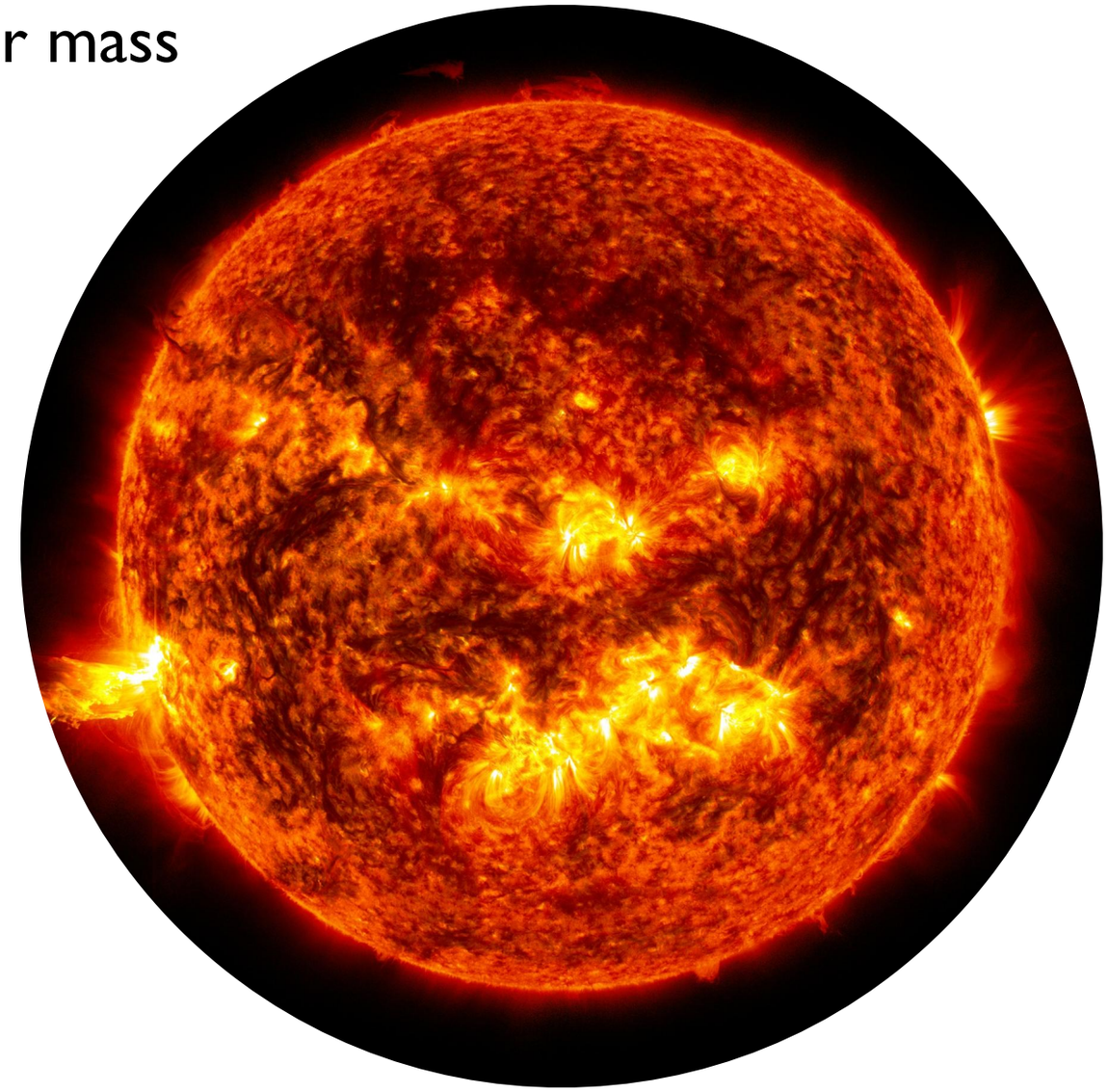


Black Holes

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

Brian's favorite star

1 solar mass



1.39e6 km

(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
~180 km (110 miles) in diameter

6 km (3.7 miles)
1 solar mass
(not going to happen)

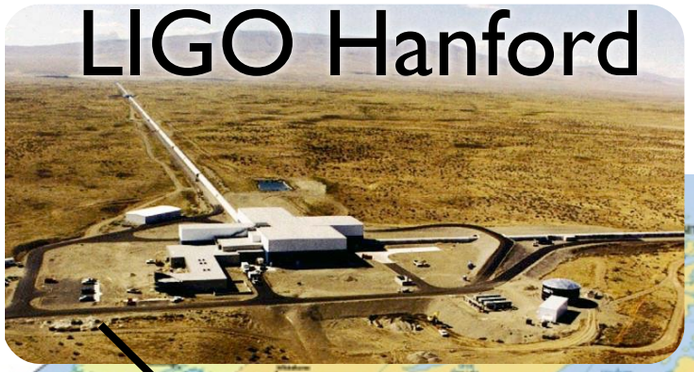
865,000 miles

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

2 terms: Black Holes & LIGO

LIGO = Laser Interferometer Gravitational-wave Observatory

International Network

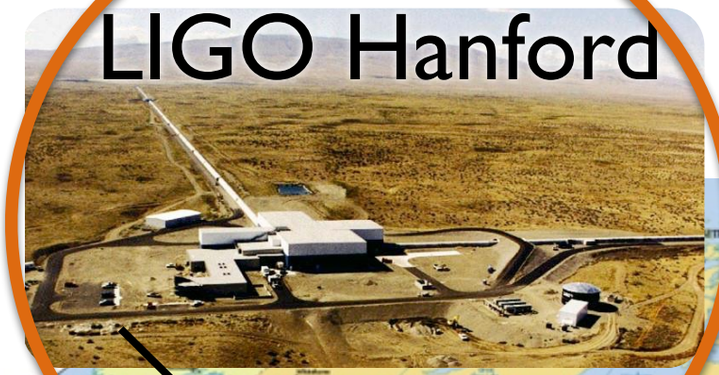


LIGO India

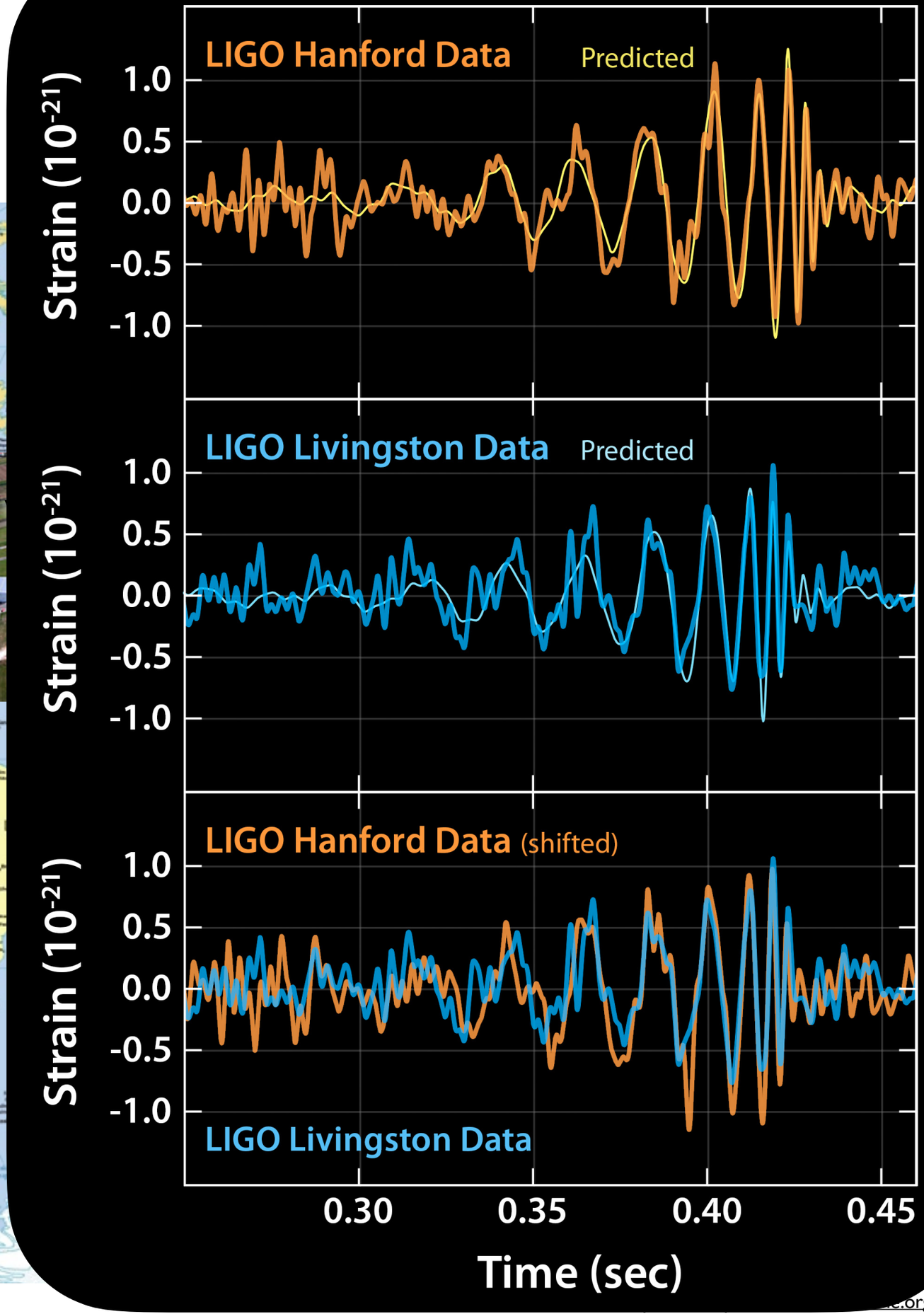
project approved

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

LIGO Hanford



LIGO Livingston



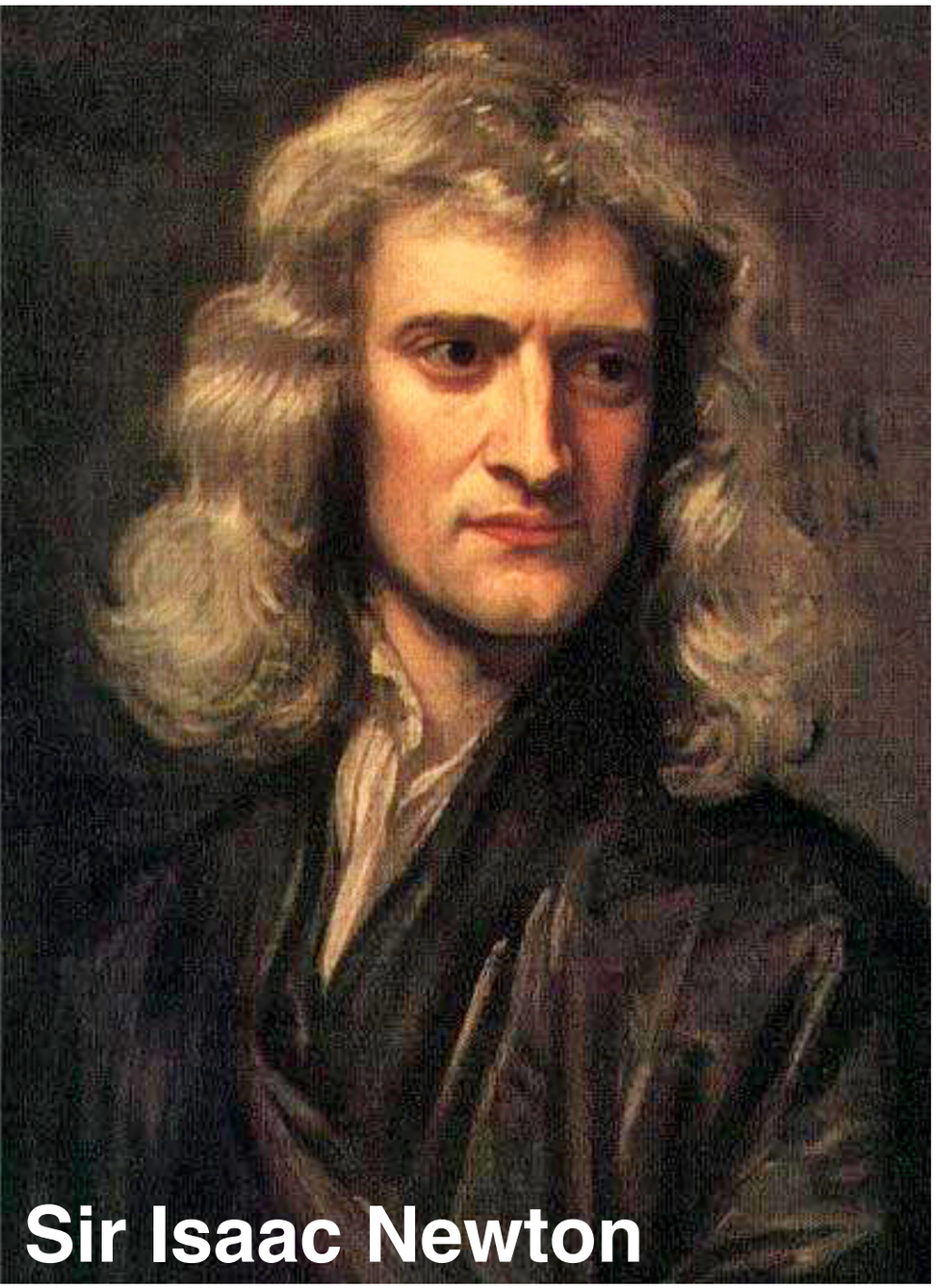
AGRA

GO India

oject approved

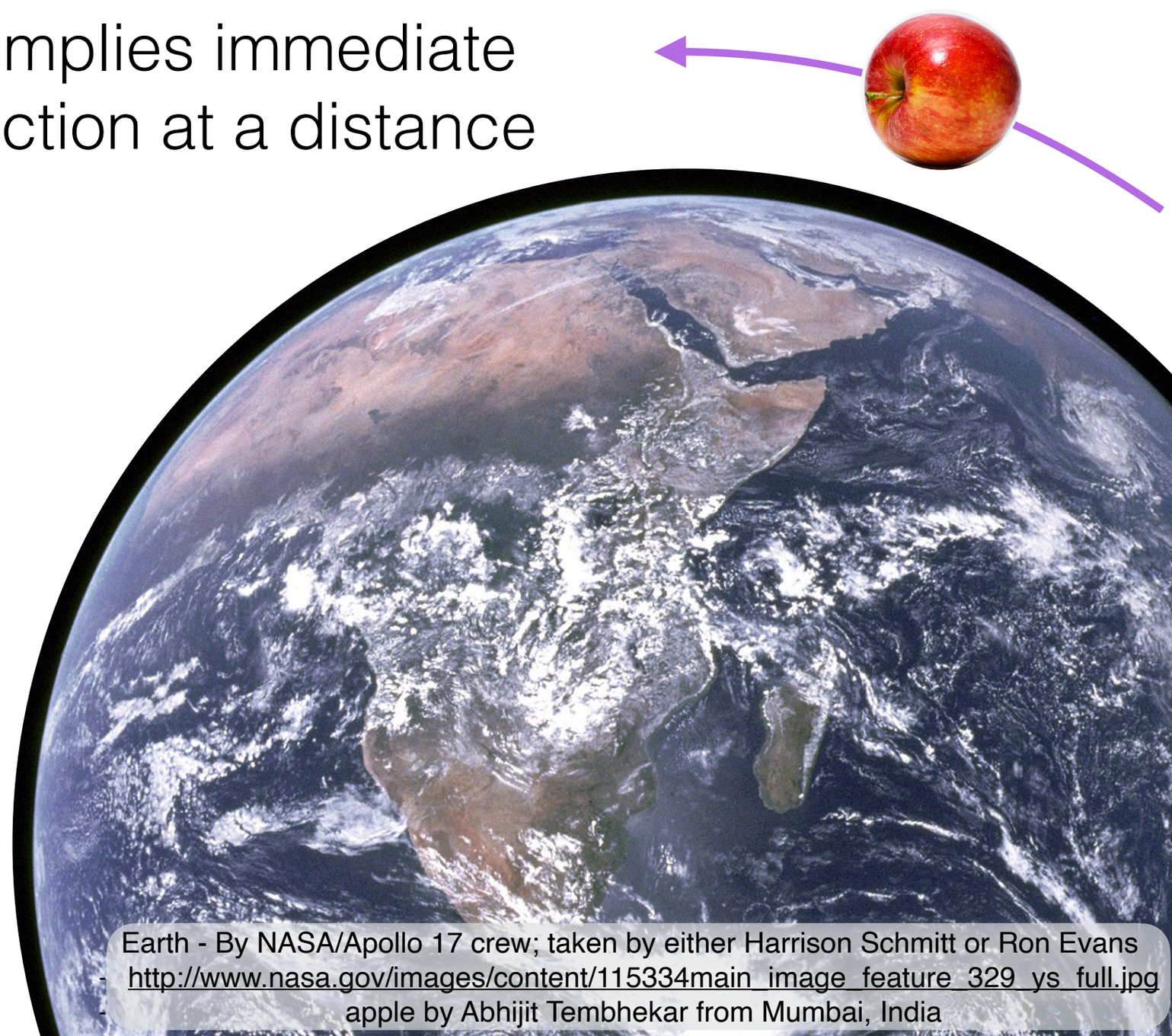
What is a Gravitational Wave?

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



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

Implies immediate
action at a distance



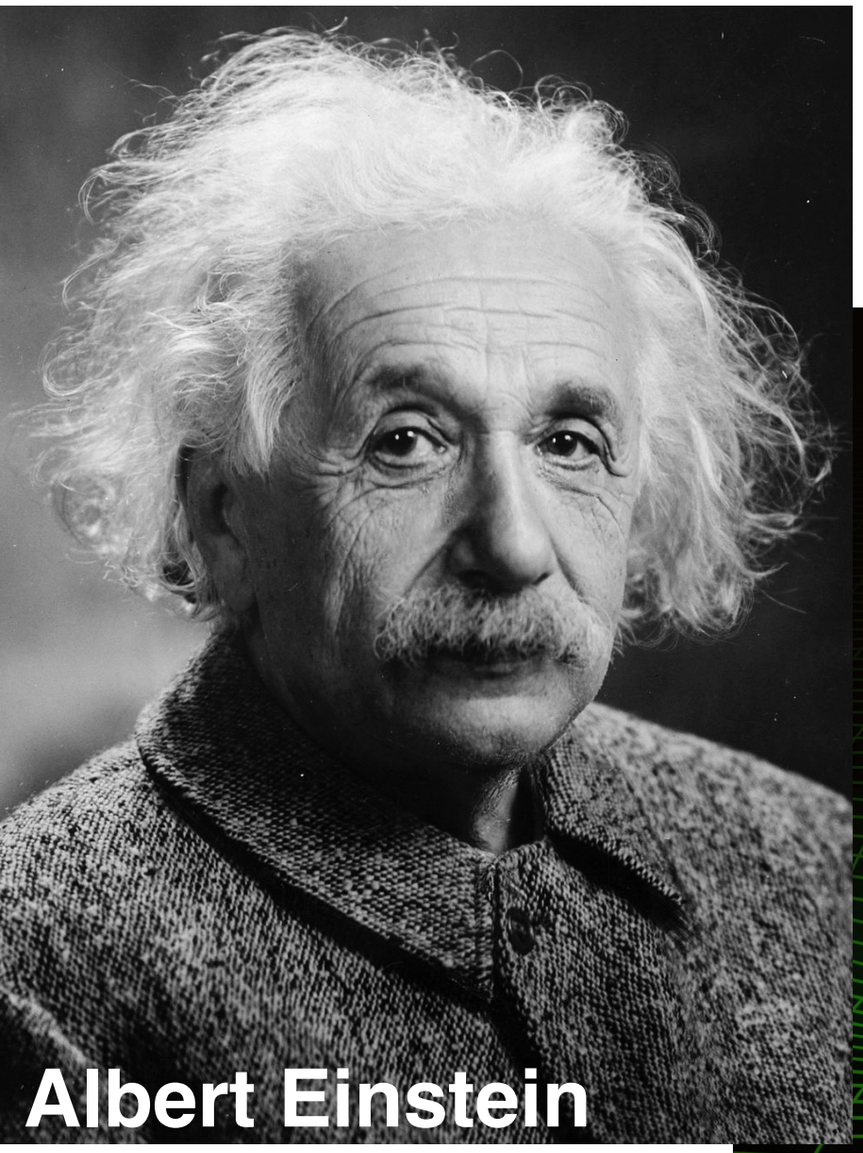
Earth - By NASA/Apollo 17 crew; taken by either Harrison Schmitt or Ron Evans
- http://www.nasa.gov/images/content/115334main_image_feature_329_ys_full.jpg
- apple by Abhijit Tembhekar from Mumbai, India

What is a Gravitational Wave?

Predicted by Einstein in 1916 as part of GR.

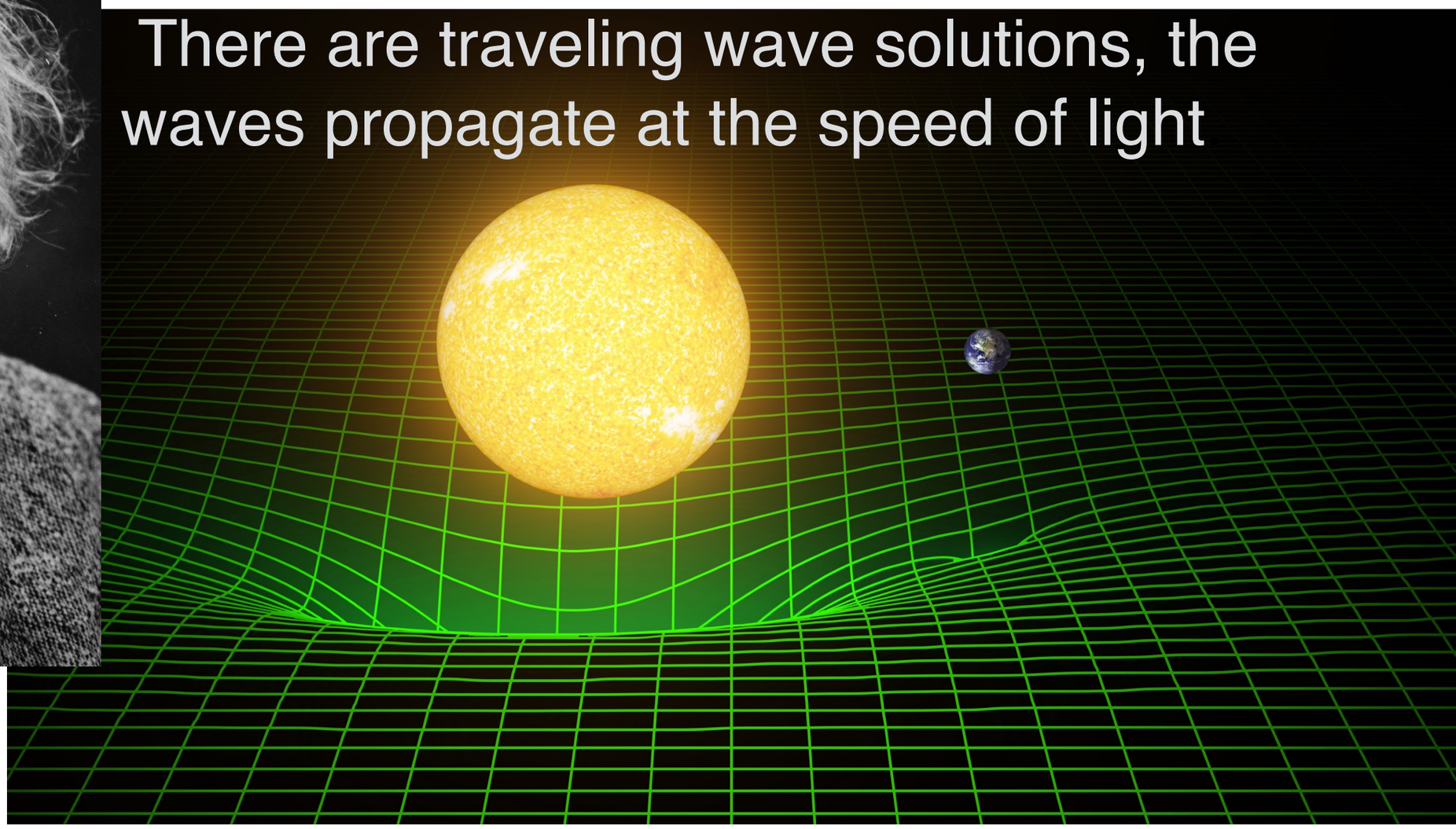
"Spacetime tells matter how to move,
matter tells spacetime how to curve"

- J. A. Wheeler



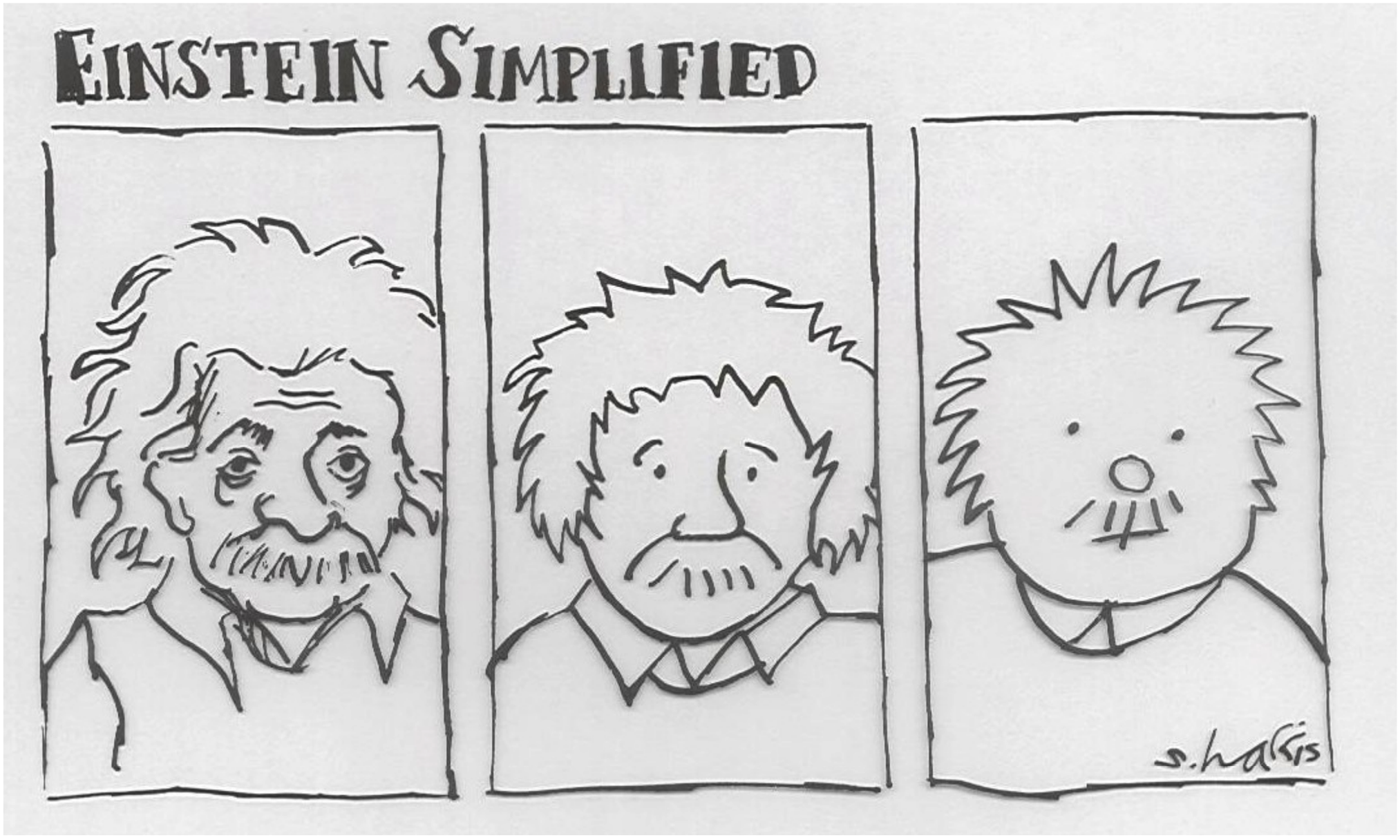
Albert Einstein

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



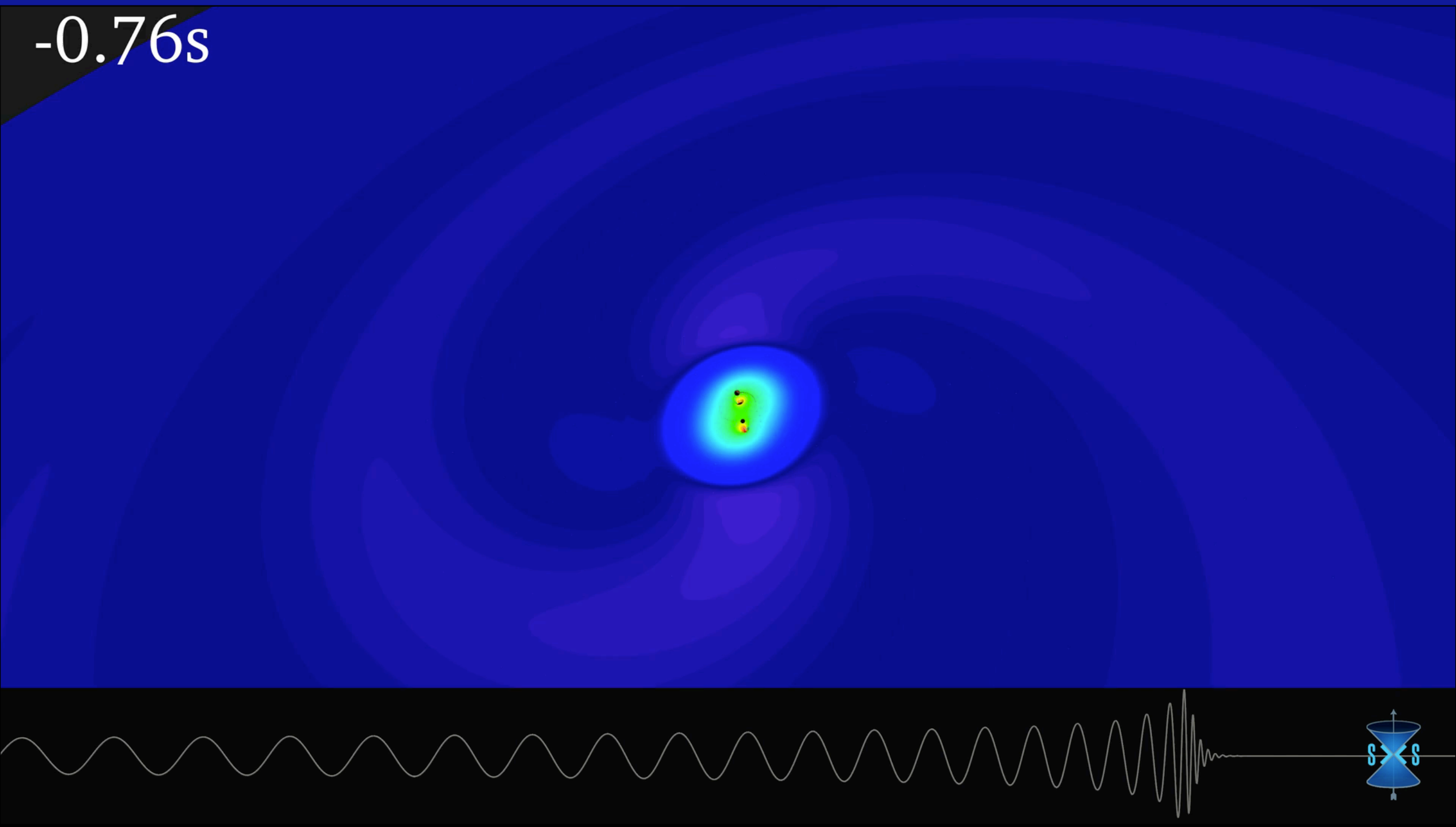
Photograph by Orren Jack Turner,
Library of Congress digital ID cph.3b46036.

What is a Gravitational Wave?



Sydney Harris

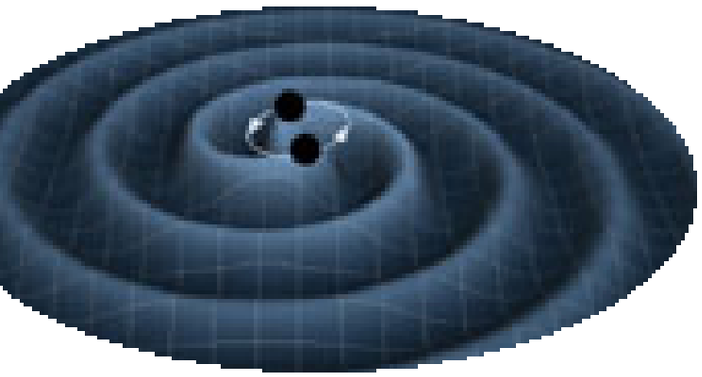
Simulation of the event

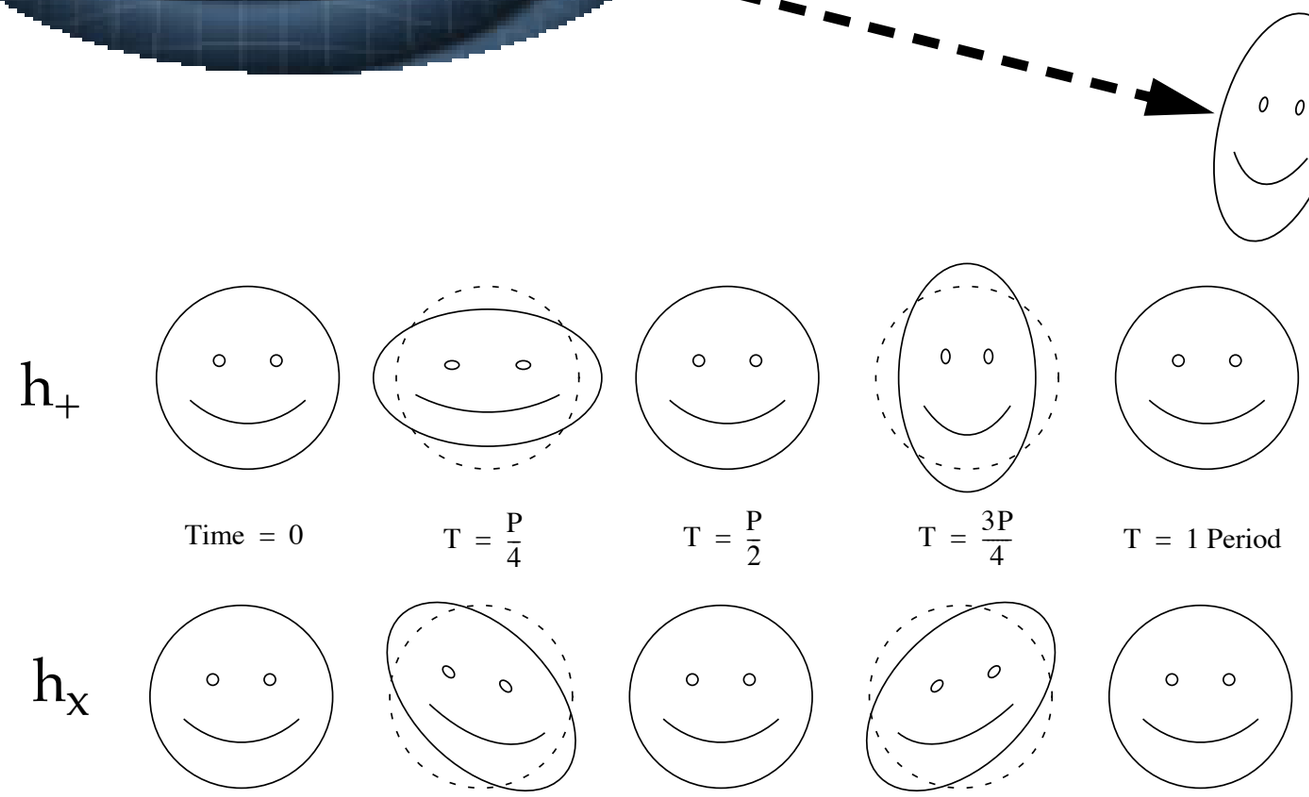


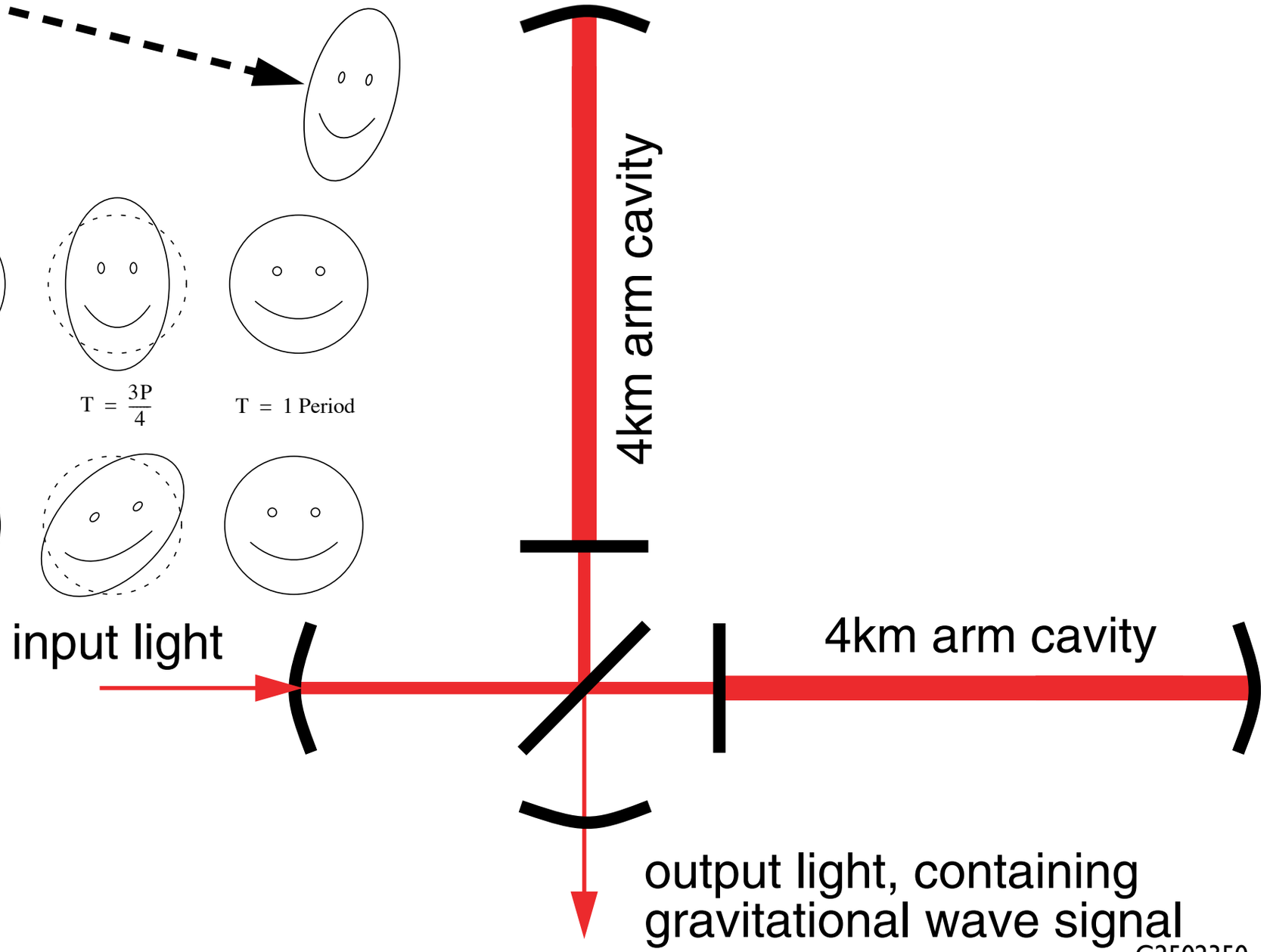
http://mediaassets.caltech.edu/gwave

The LIGO concept

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





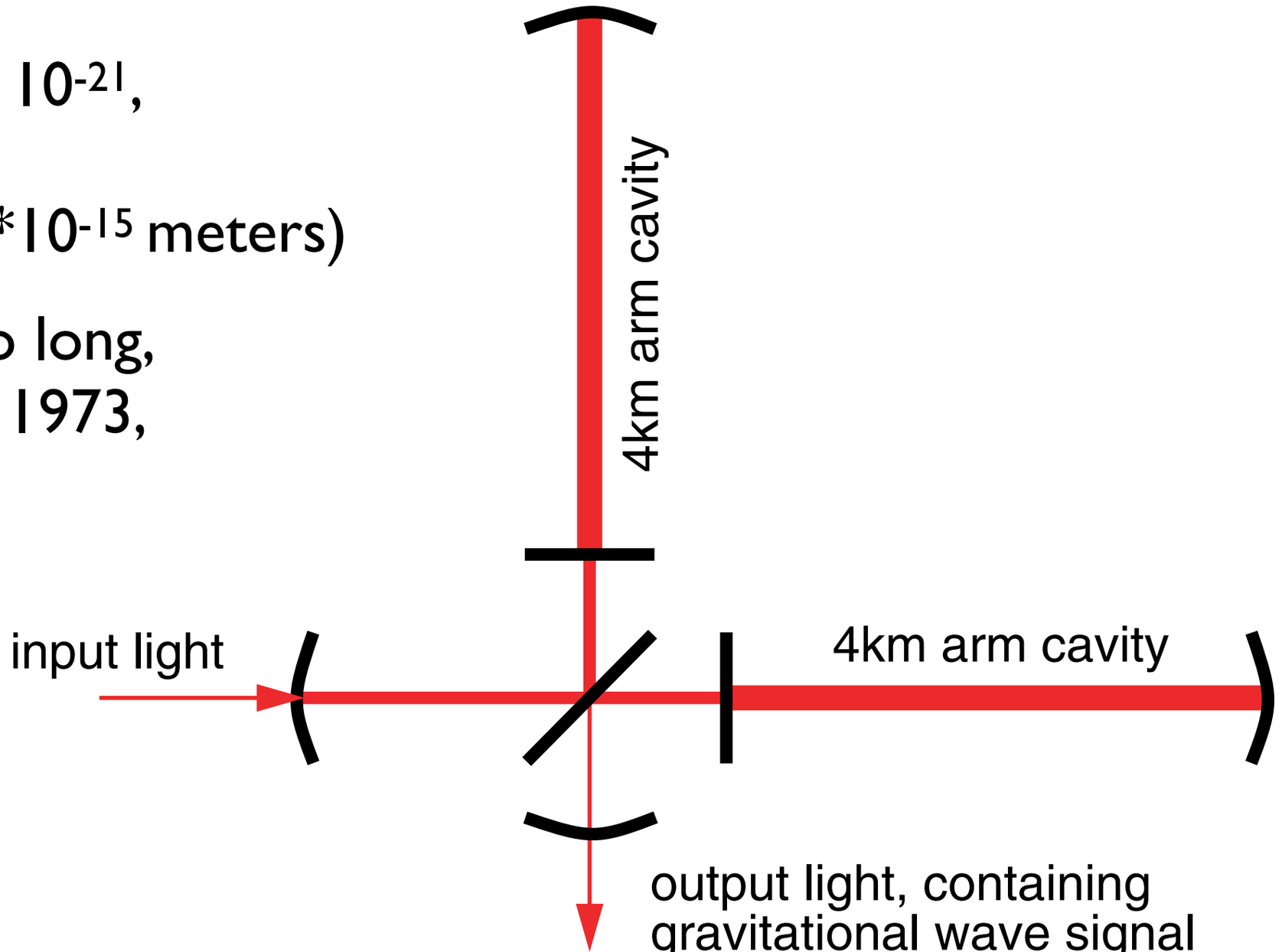


The LIGO concept

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

Our signal strain (h) = 10^{-21},
dL = $4*10^{-18}$ meters
(proton is about $1.7*10^{-15}$ meters)

(that's why it's taken so long,
Einstein 1916, Weiss 1973,
first signal 2015)



The LIGO concept

How it really works

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

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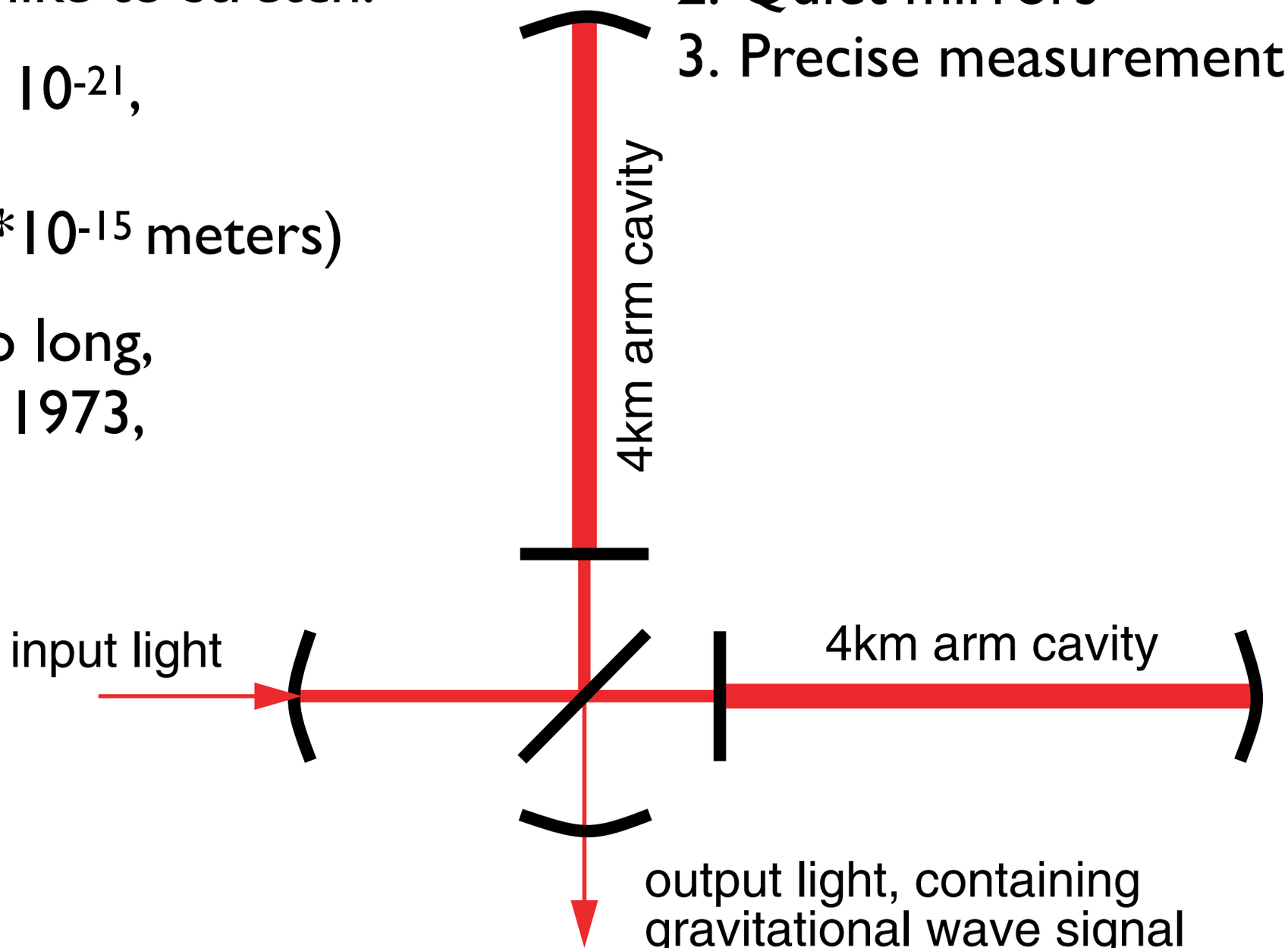
1. Long arms
2. Quiet mirrors
3. Precise measurement

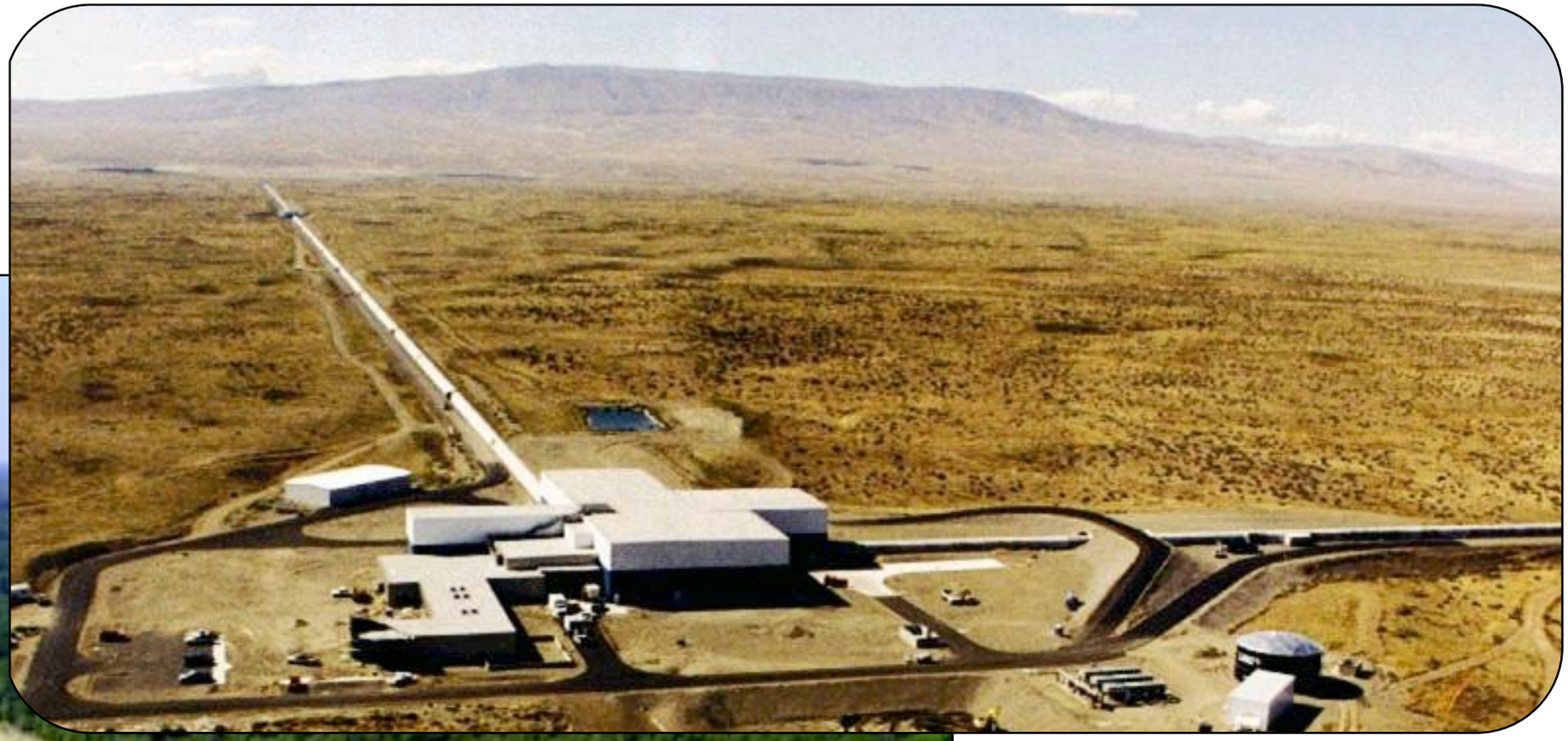


Long arms

Since h = dL/L (or dL = h*L) more L gives you more dL of signal,

World's 3rd largest ultra-clean vacuum system

- 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

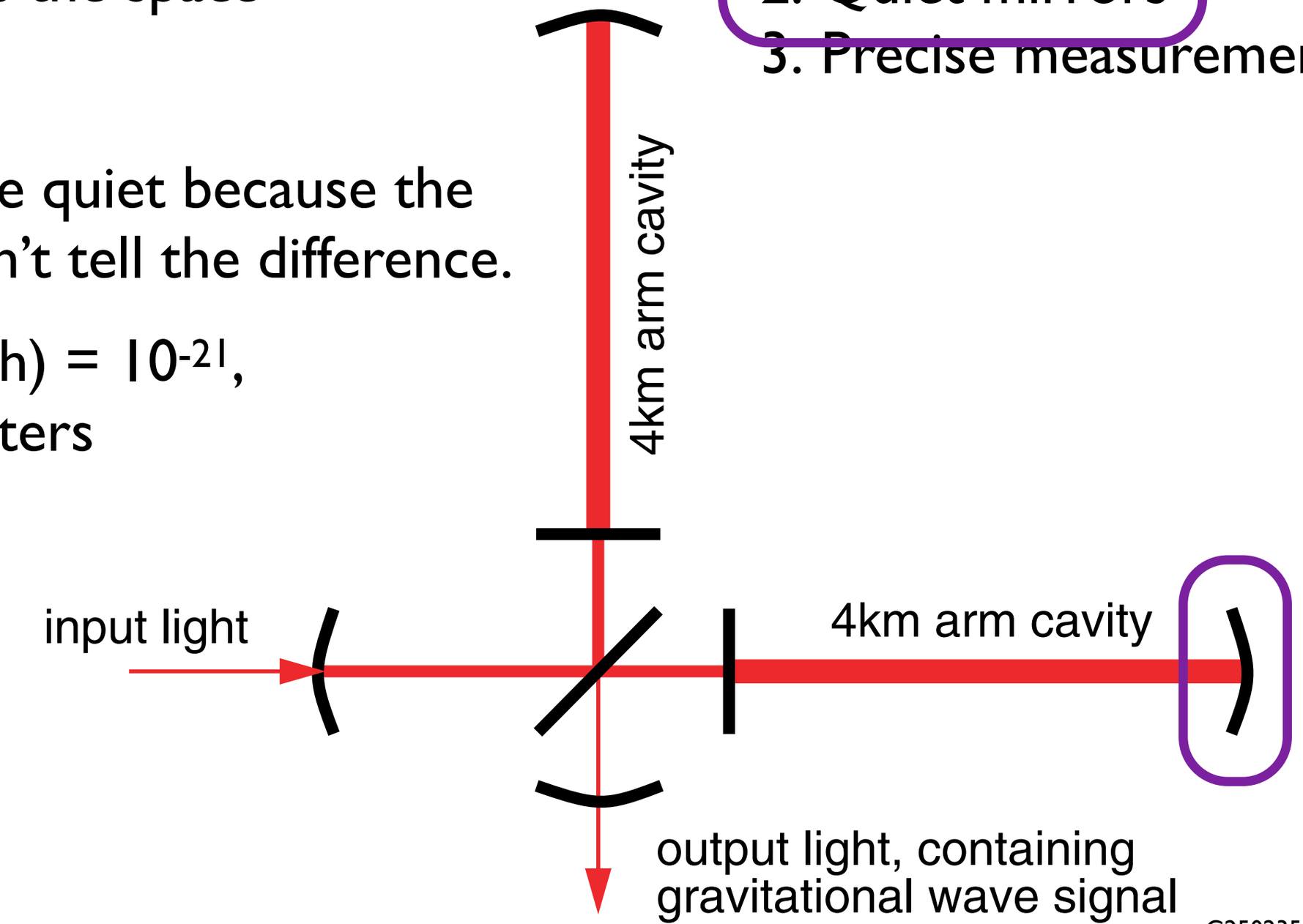
Gravitational wave doesn't move the mirror, it stretches the space

- but -

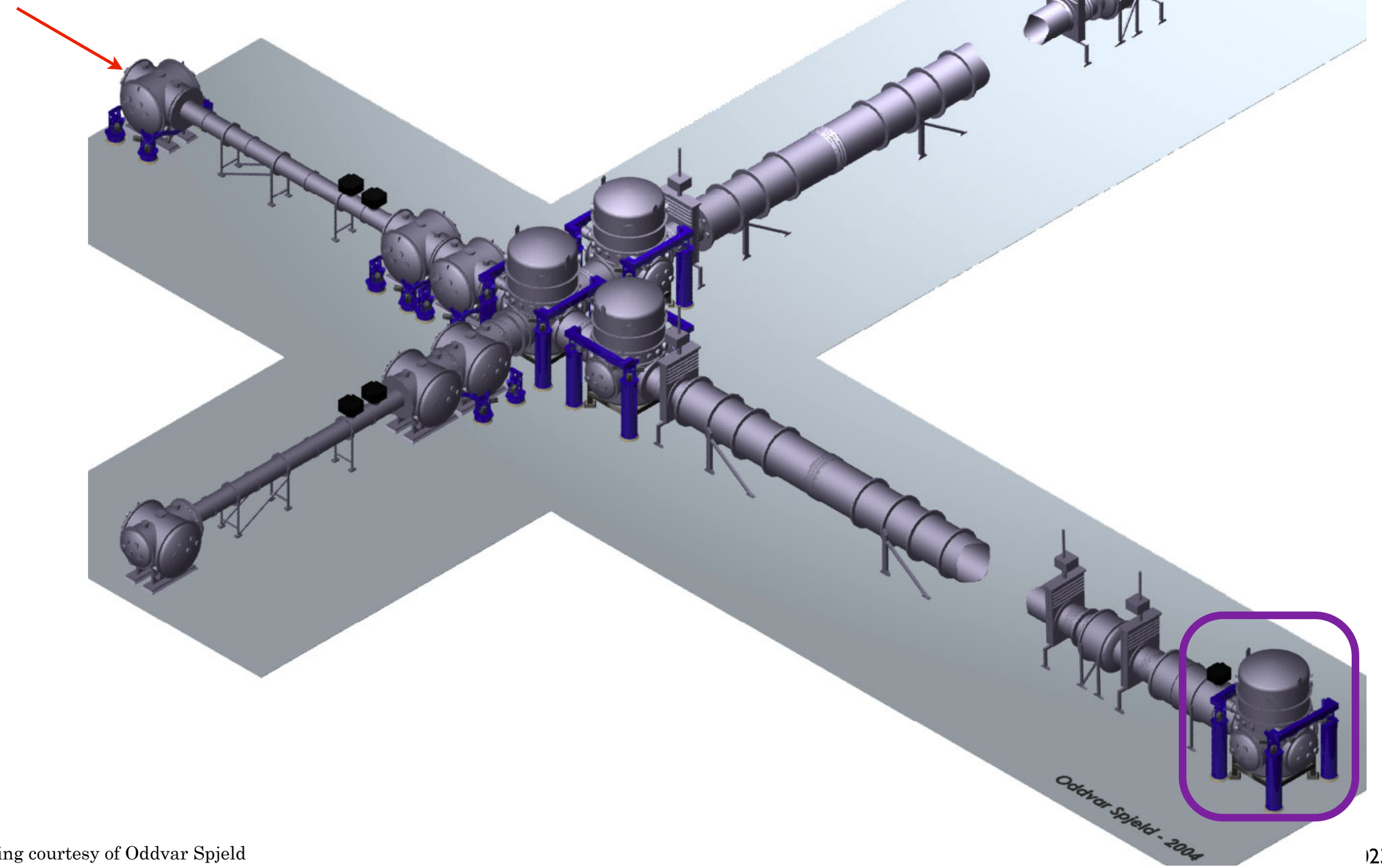
Mirrors need to be quiet because the interferometer can't tell the difference.

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

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

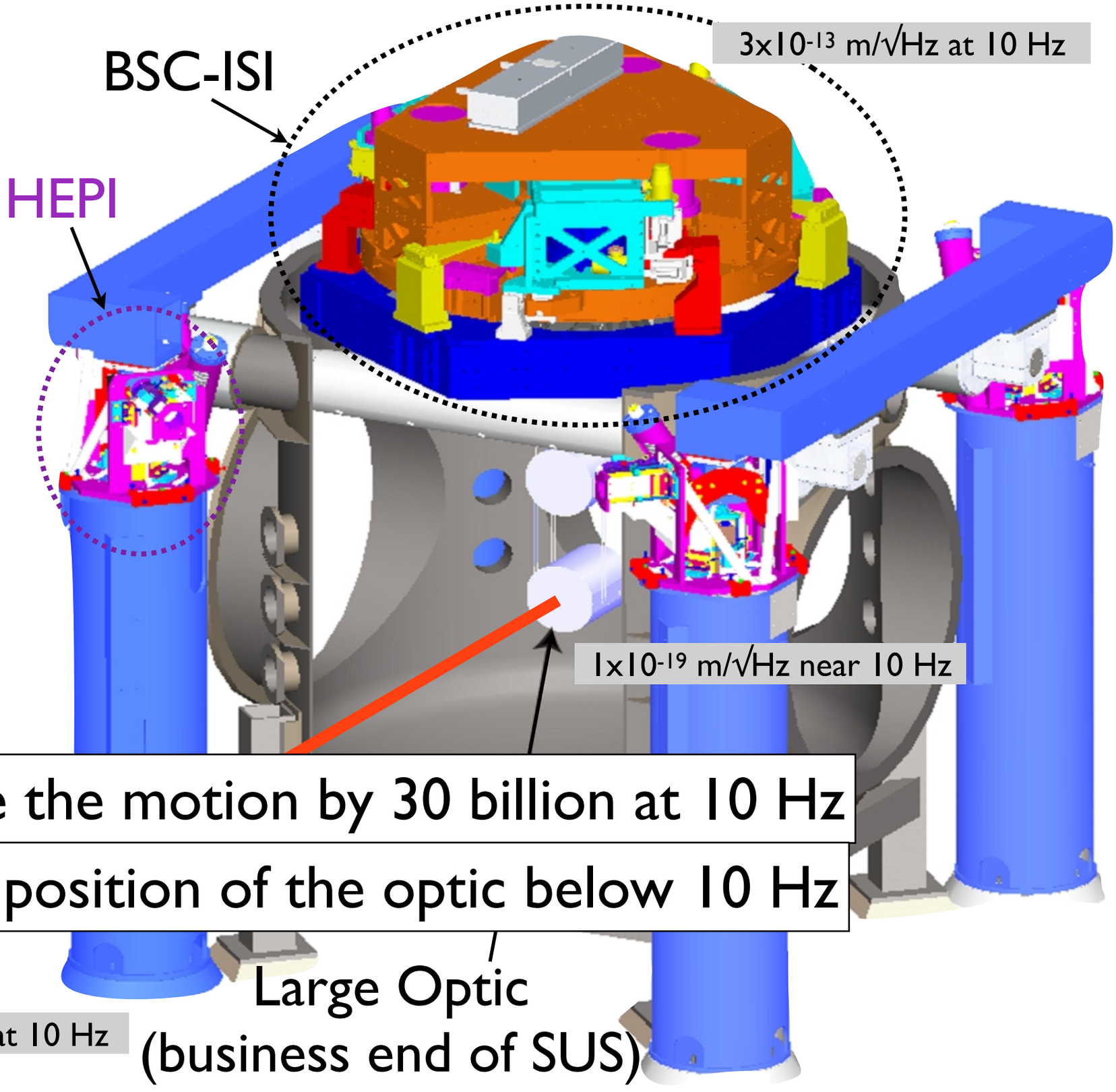


The LIGO vacuum equipment



drawing courtesy of Oddvar Spjeld

Isolation of the Mirrors



reduce the motion by 30 billion at 10 Hz

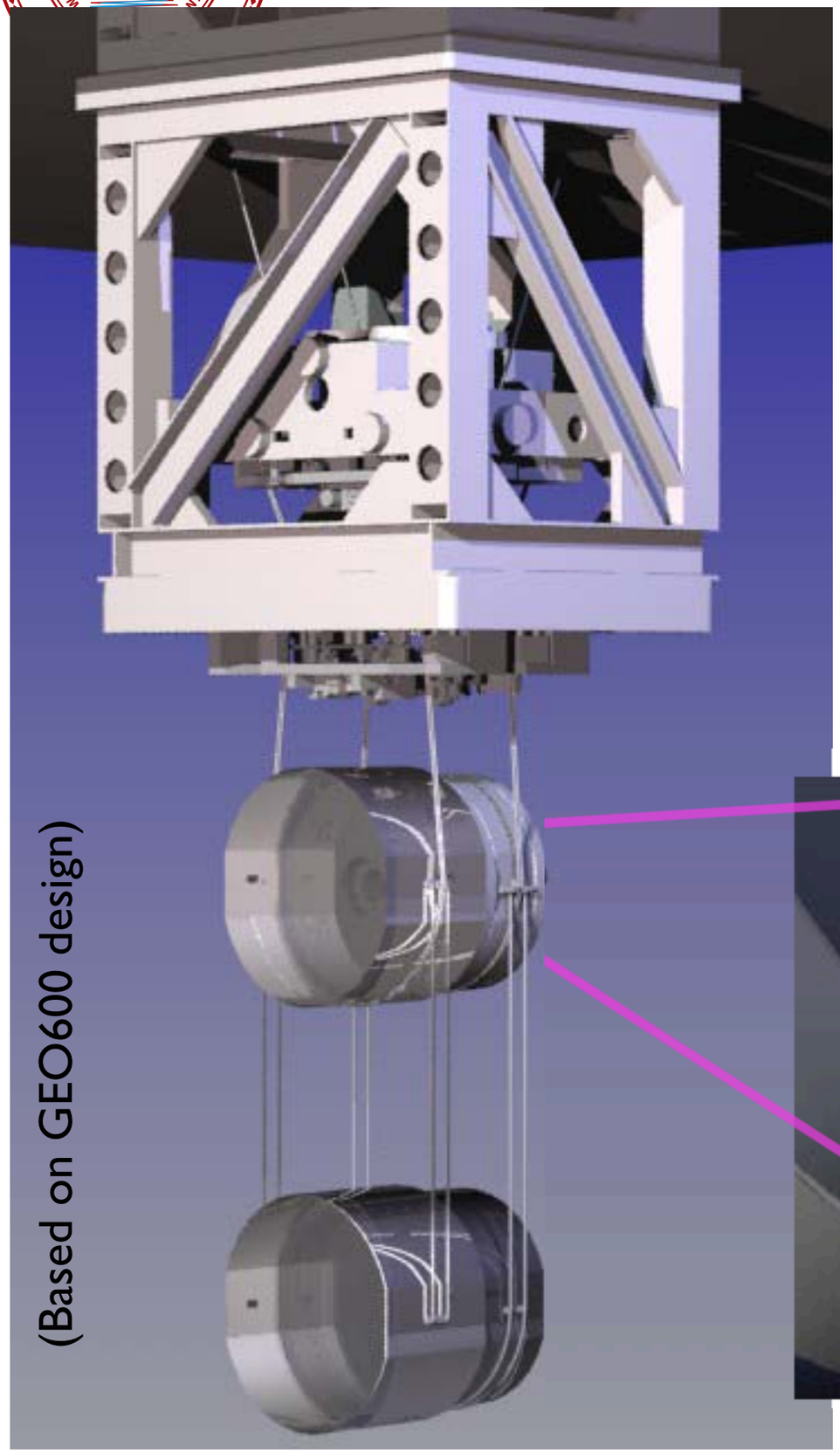
control the position of the optic below 10 Hz

optics table - stage 2

stage 1

support - stage 0

Pendulum Suspension



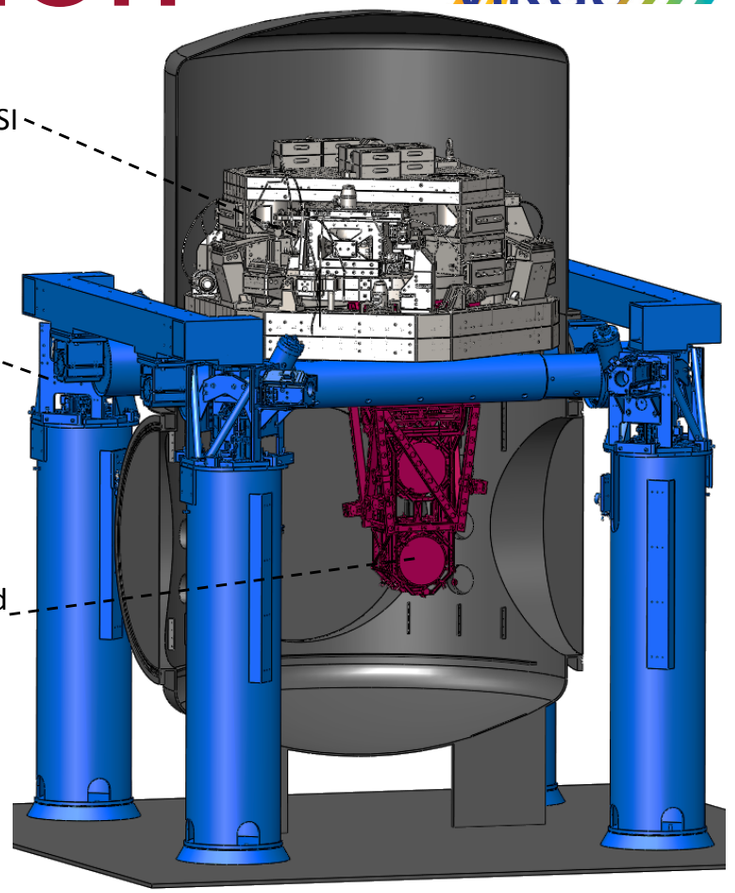
LIGO Mirrors:

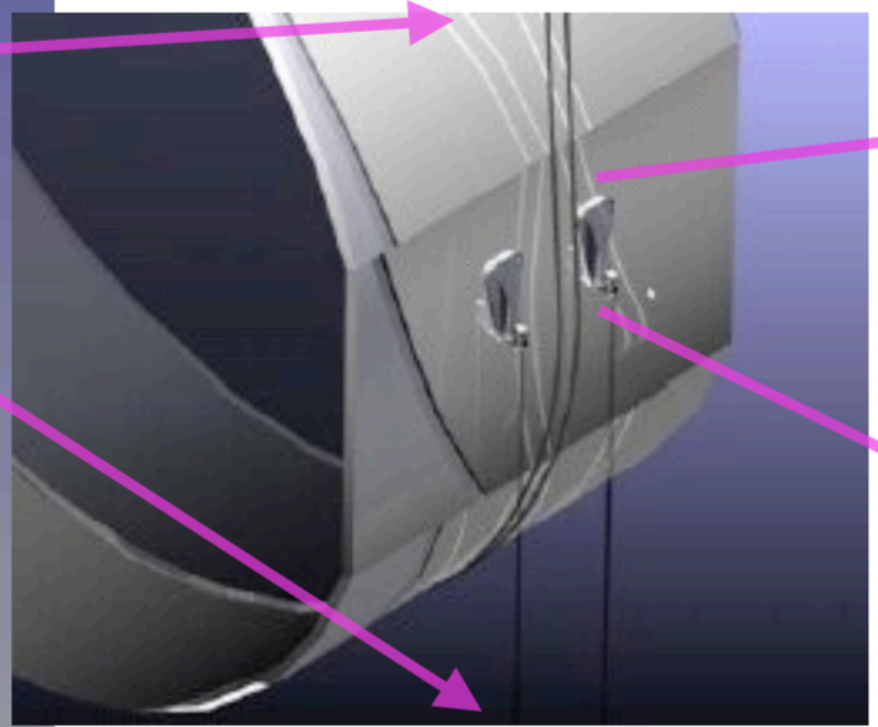
Synthetic fused silica,
- 40 kg mass
- 34 cm diameter
- 20 cm thick

Suspended as a
4 stage pendulum

Best coatings available

Motion at 10 Hz is set by thermal driven vibration

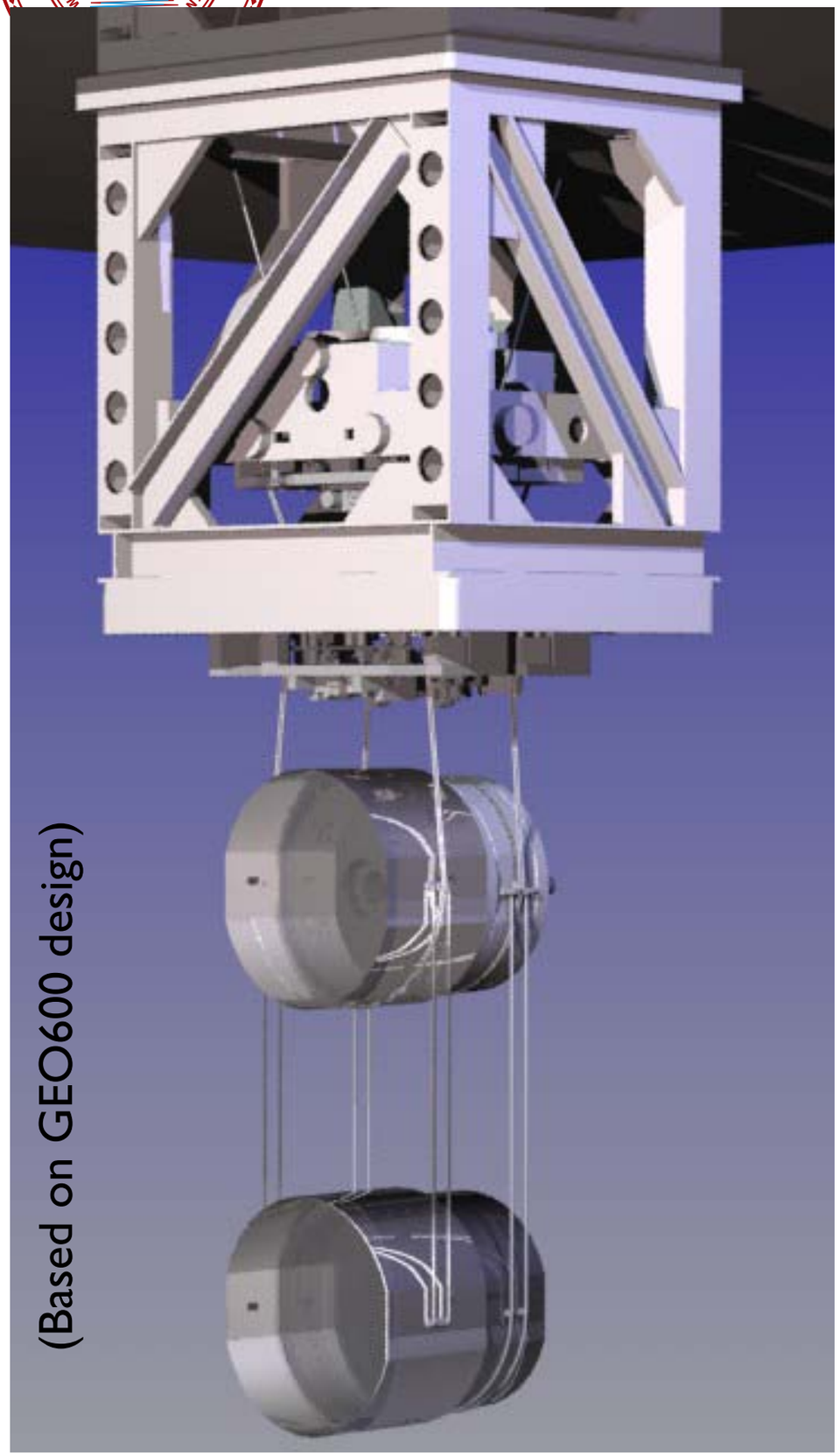


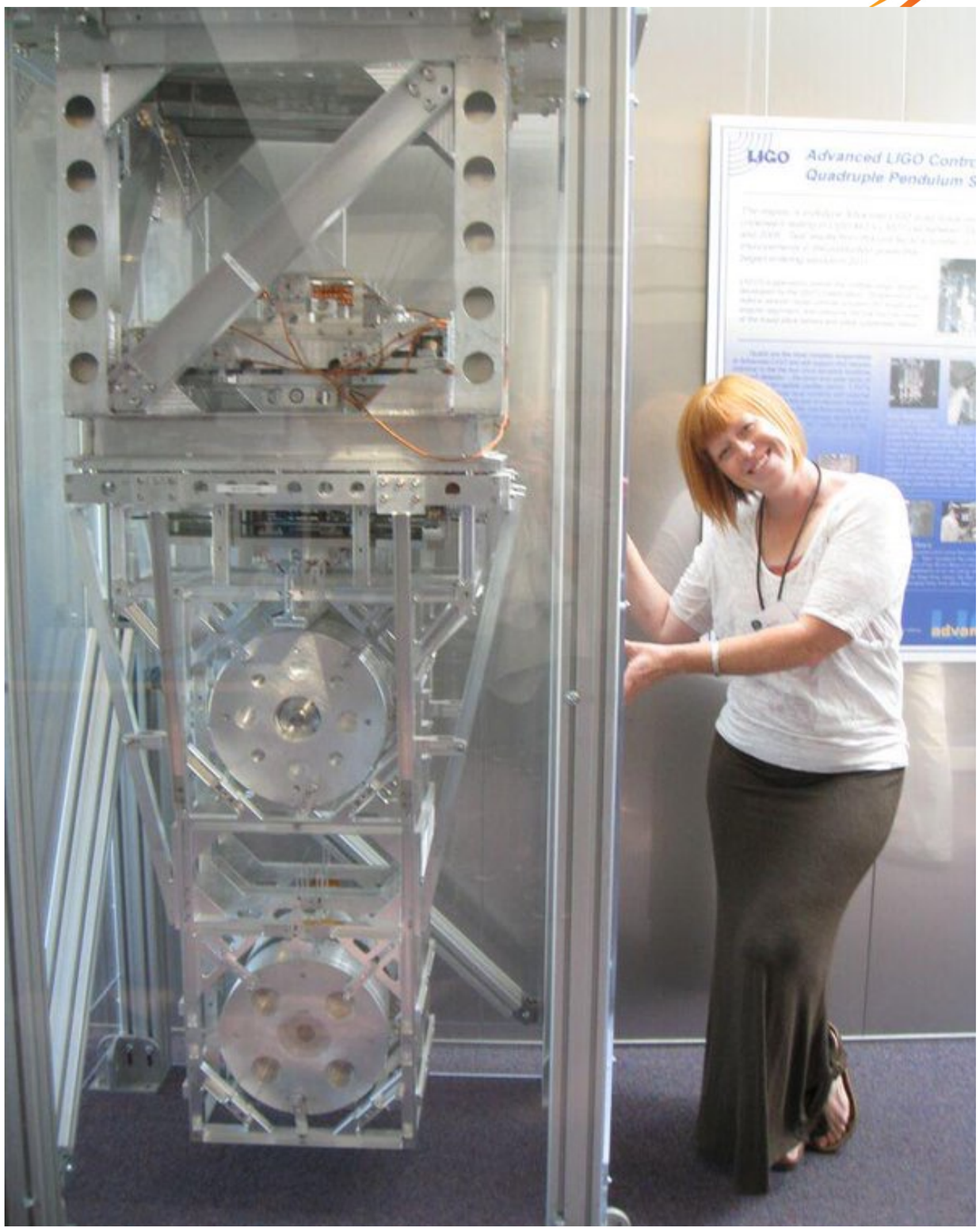


silicate bonding creates a monolithic final stage

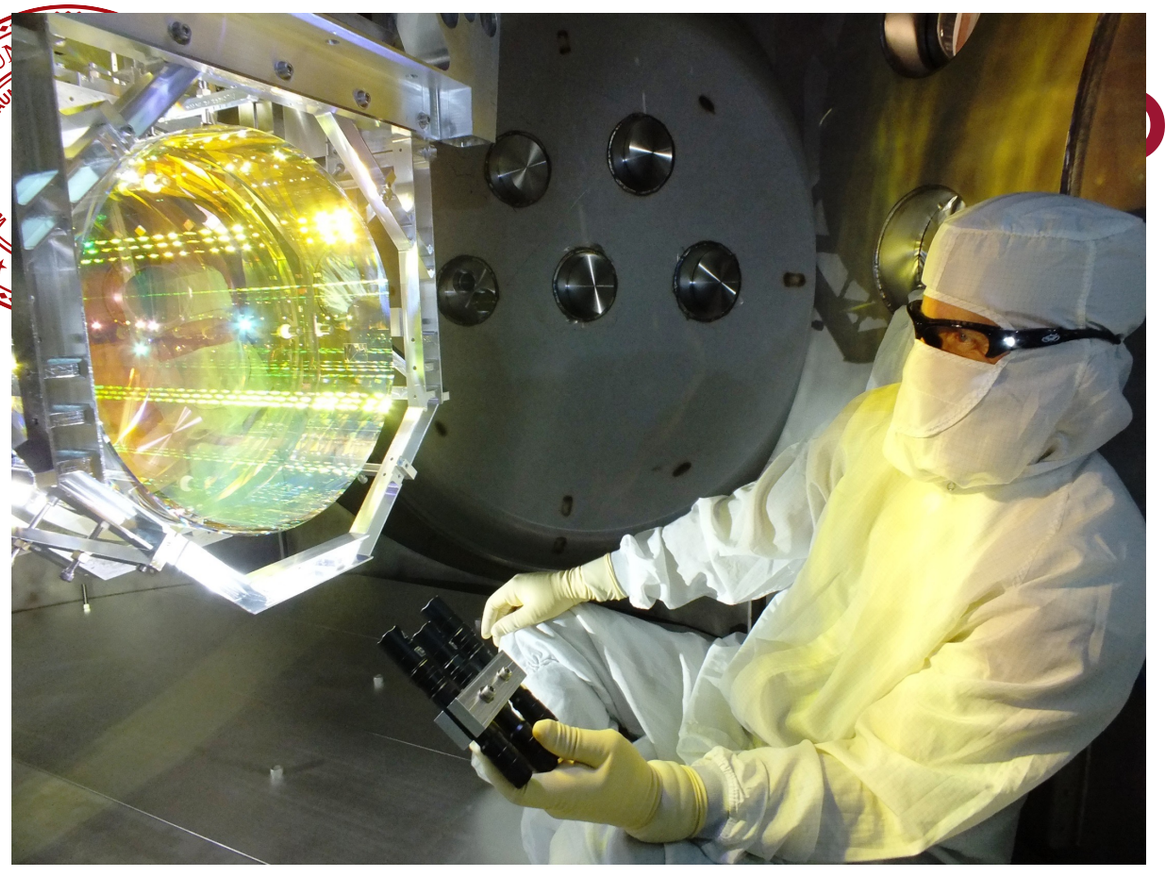
Pendulum

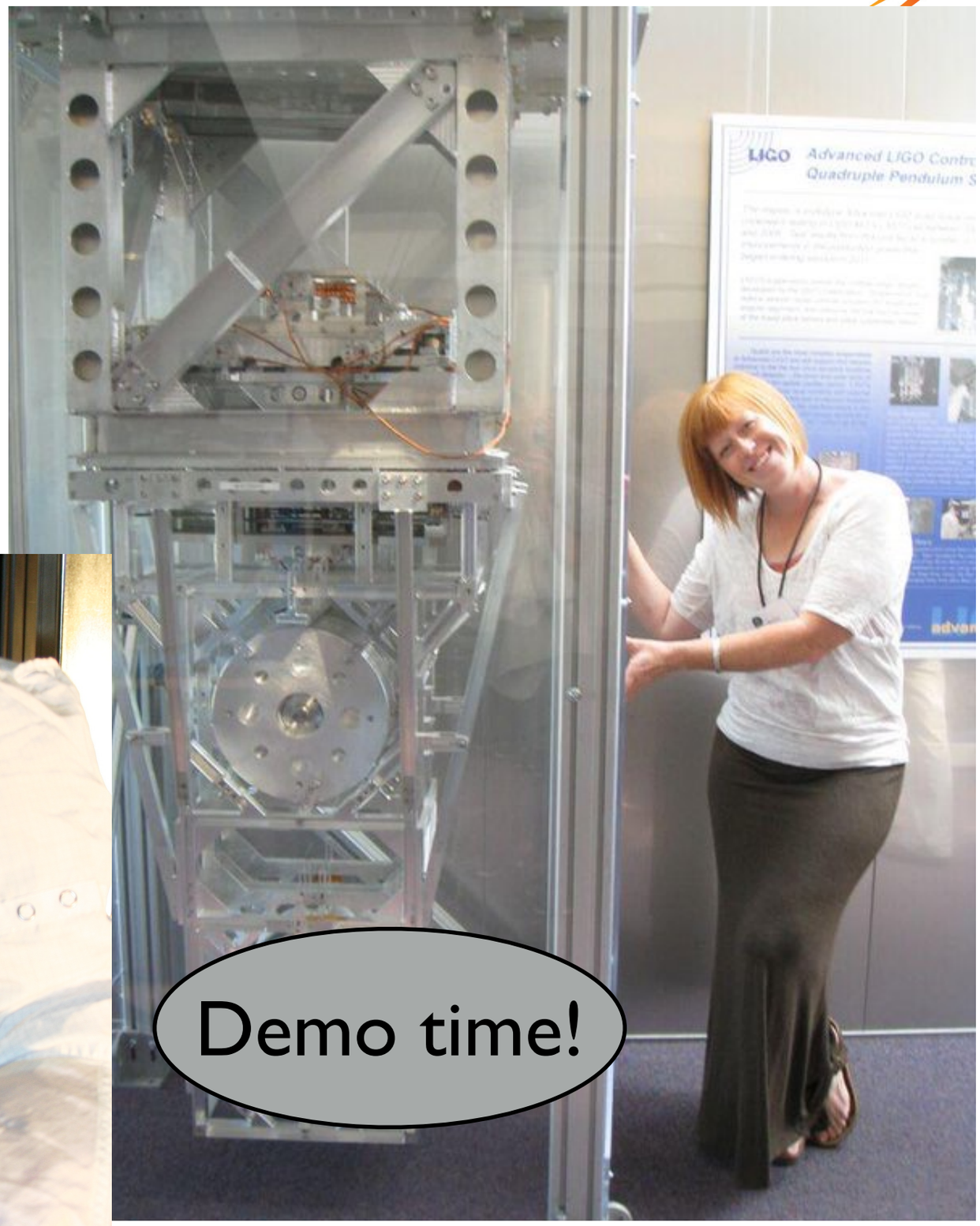
LHO suspension expert, Betsy Weaver with the Engineering prototype

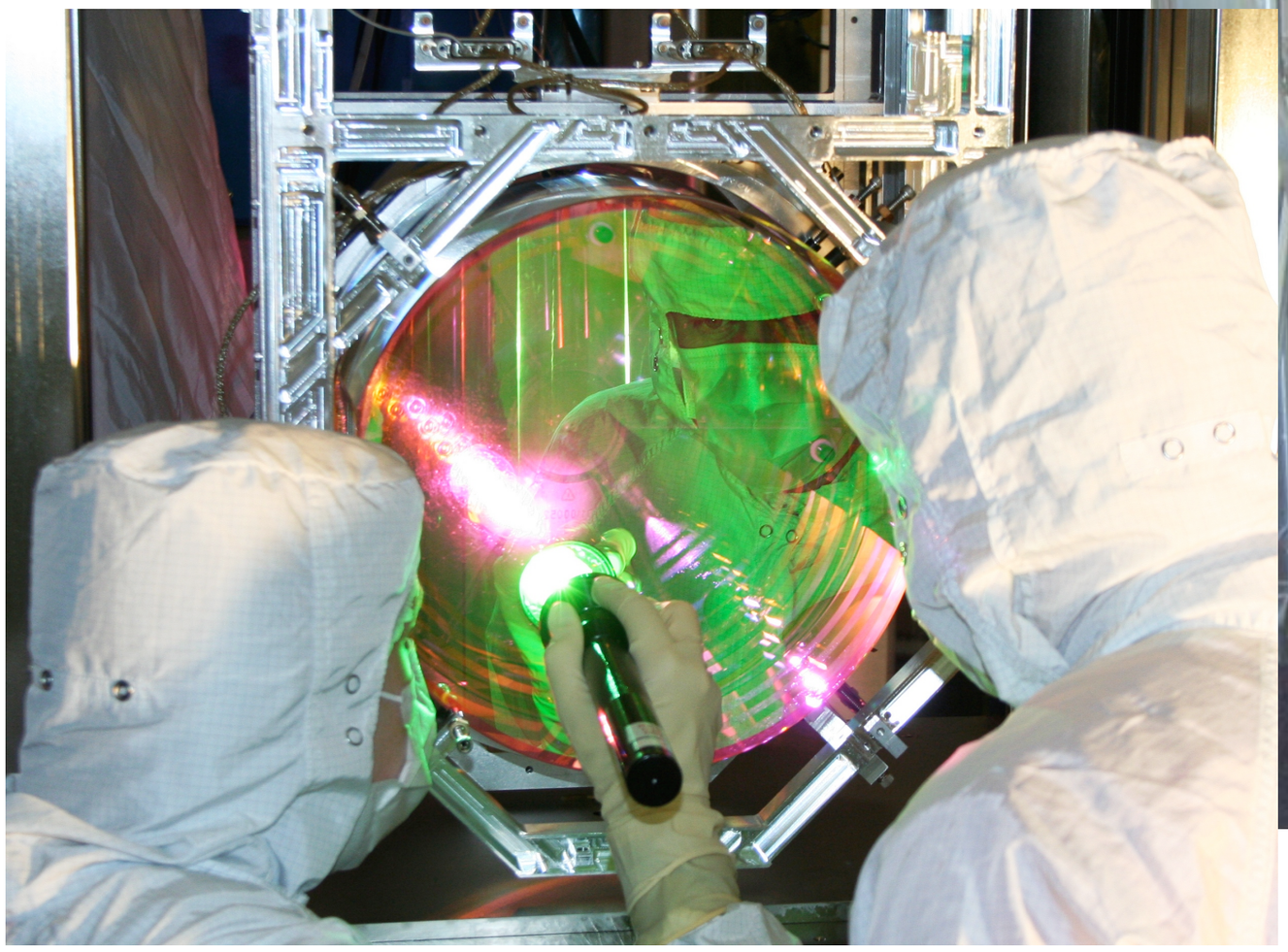




or picts

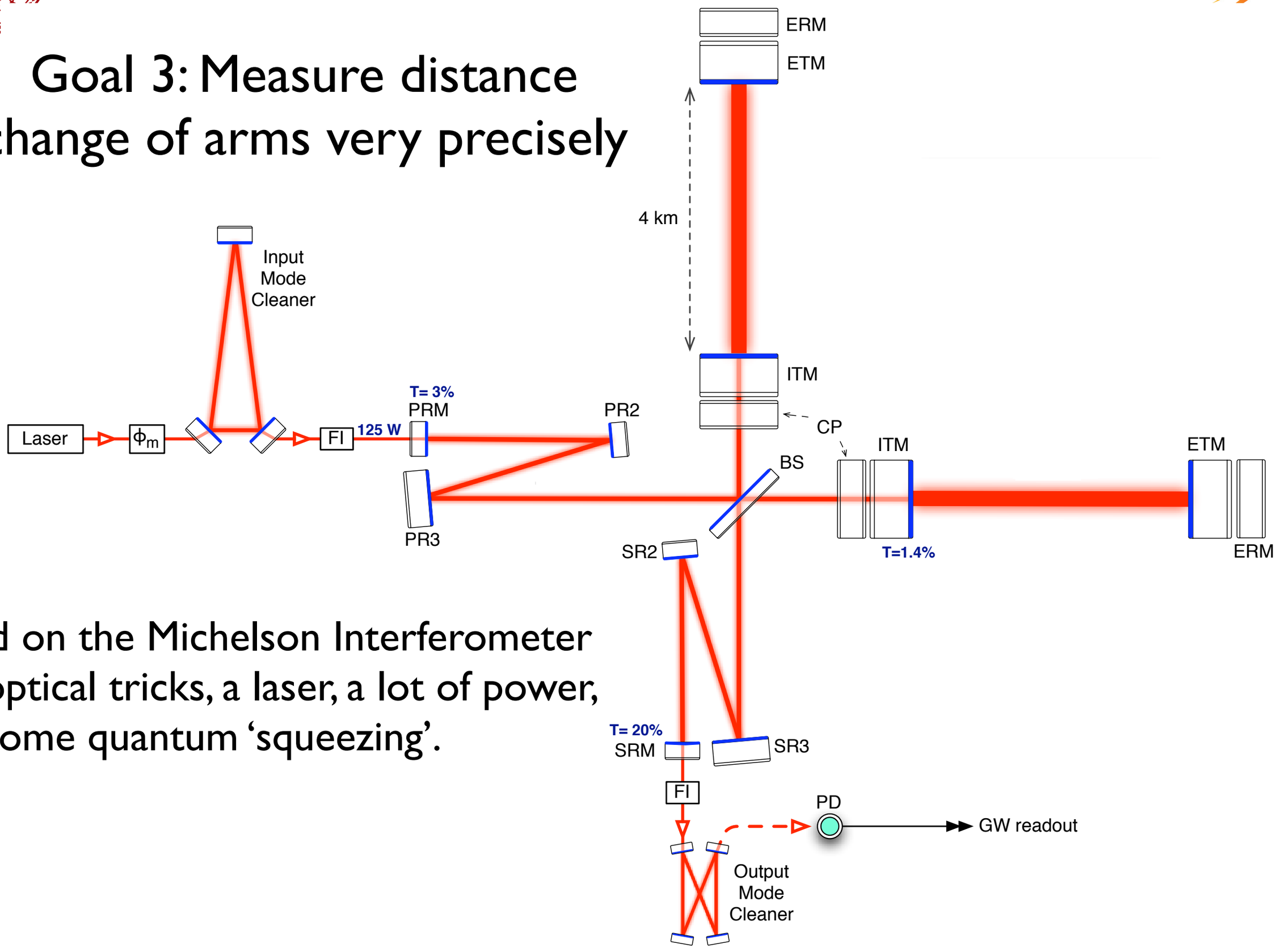






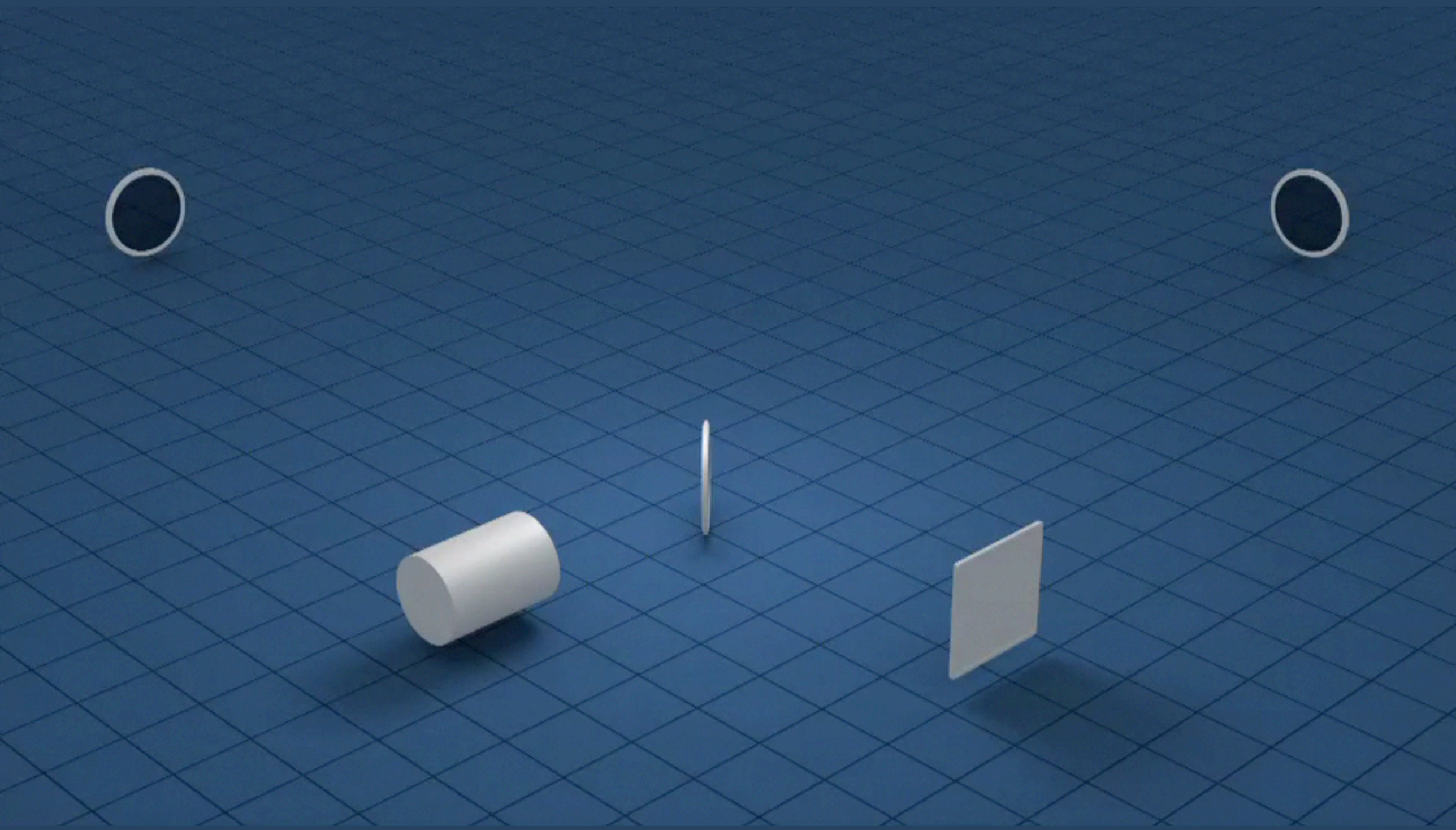
Precision Interferometry

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'.

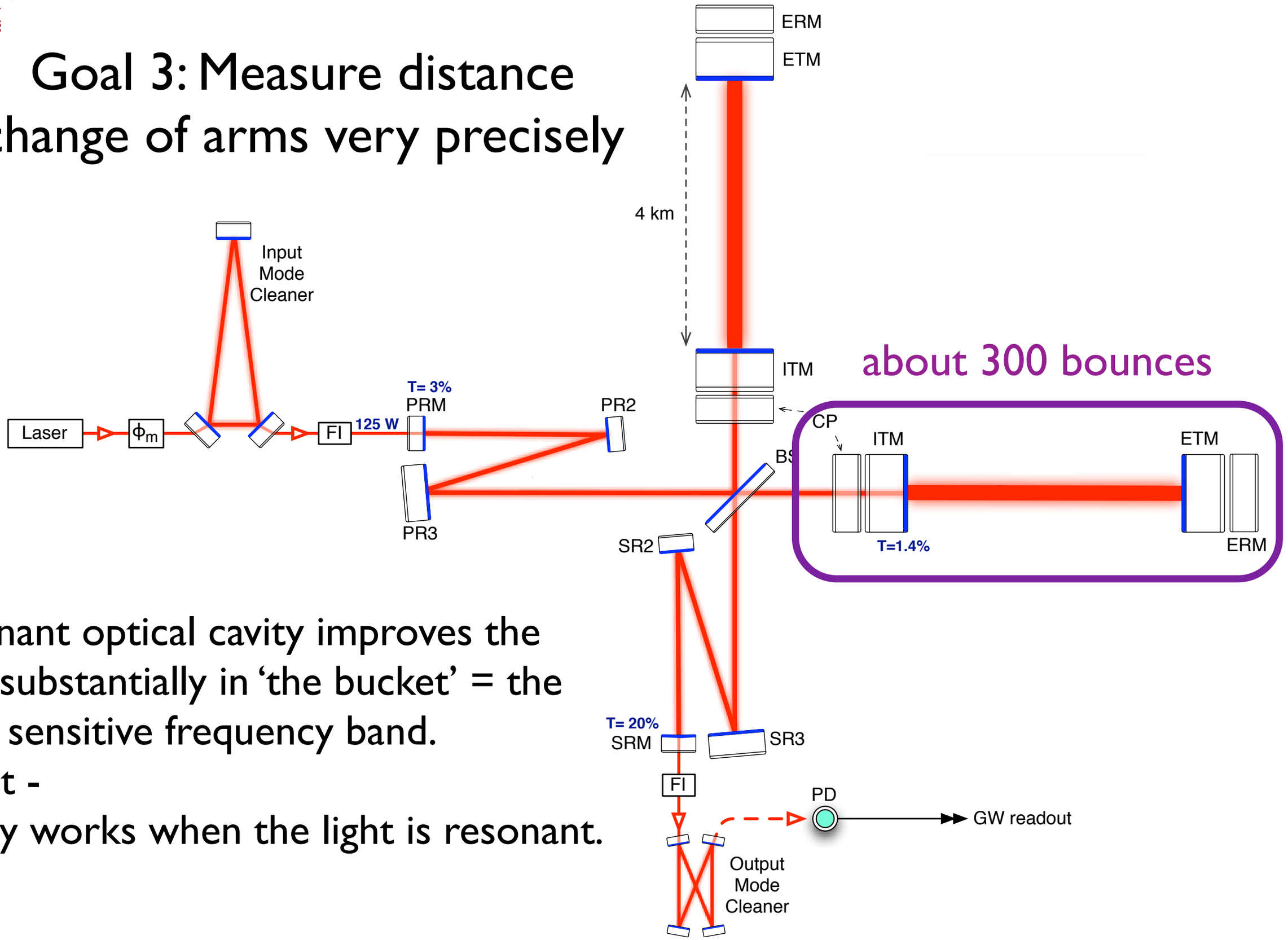
Animated Interferometer



http://mediaassets.caltech.edu/gwave

Fabry-Perot arms

Goal 3: Measure distance change of arms very precisely



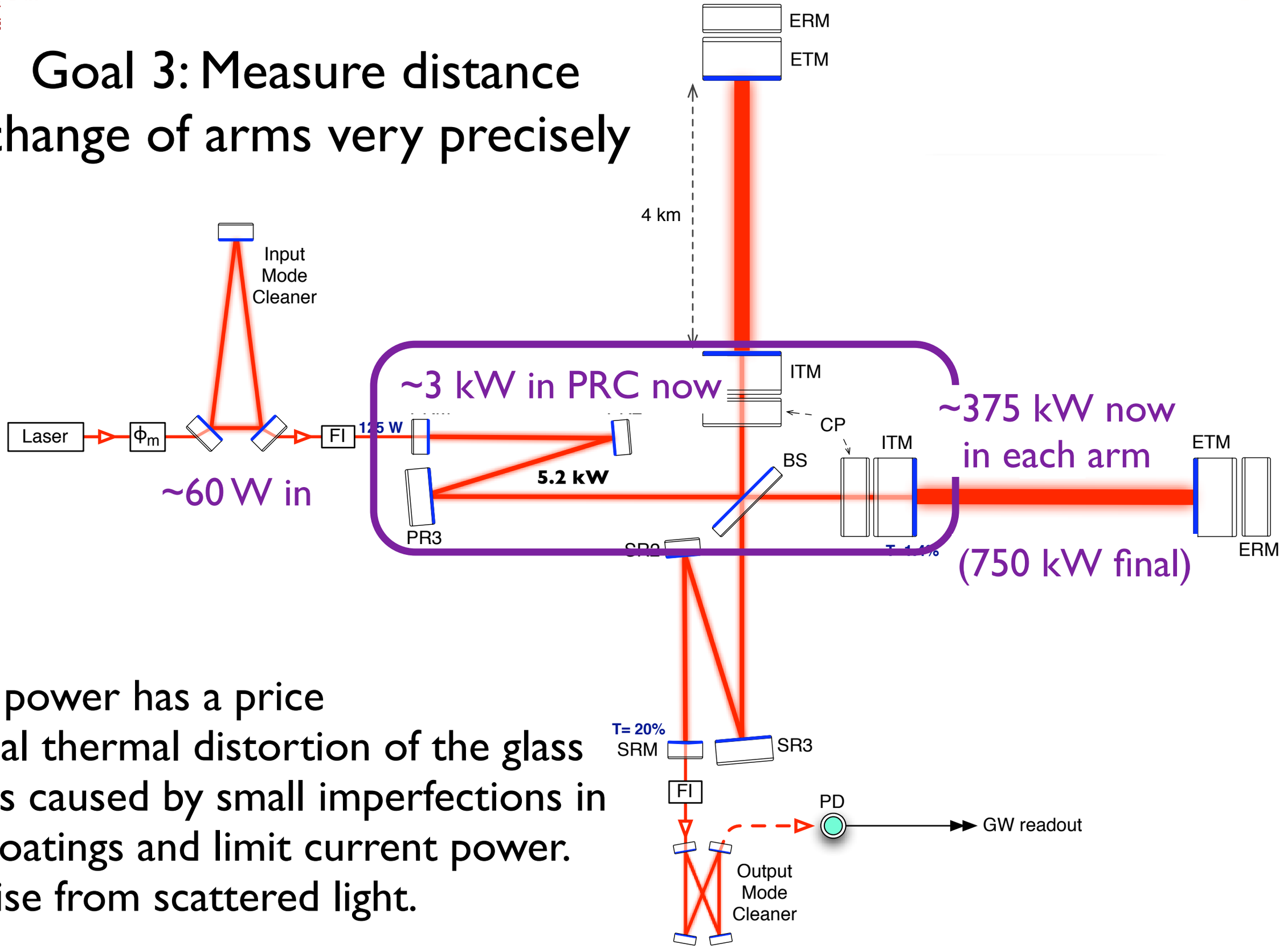
Resonant optical cavity improves the SNR substantially in 'the bucket' = the most sensitive frequency band.

- but -

It only works when the light is resonant.

Lots of photons

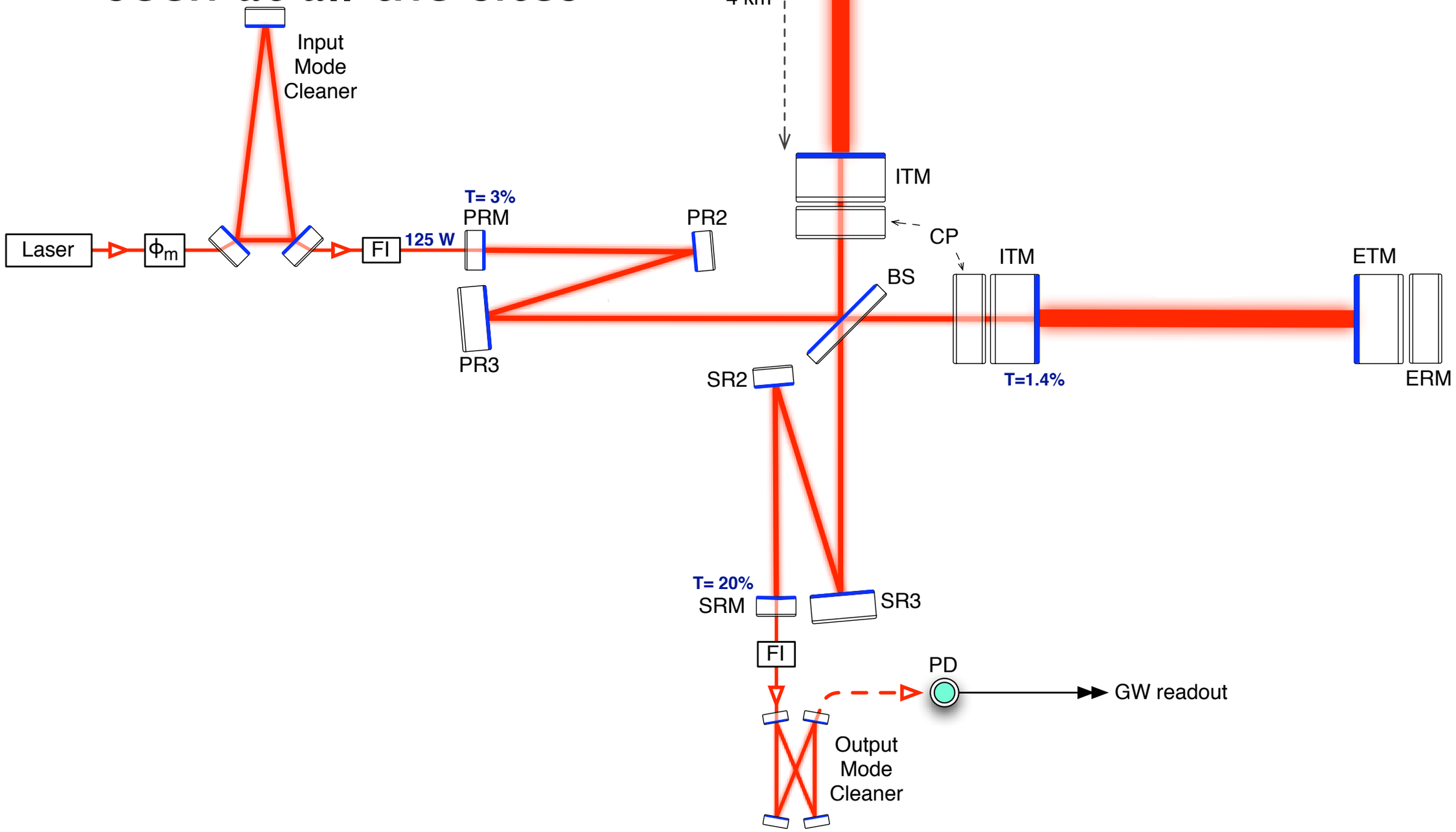
Goal 3: Measure distance change of arms very precisely



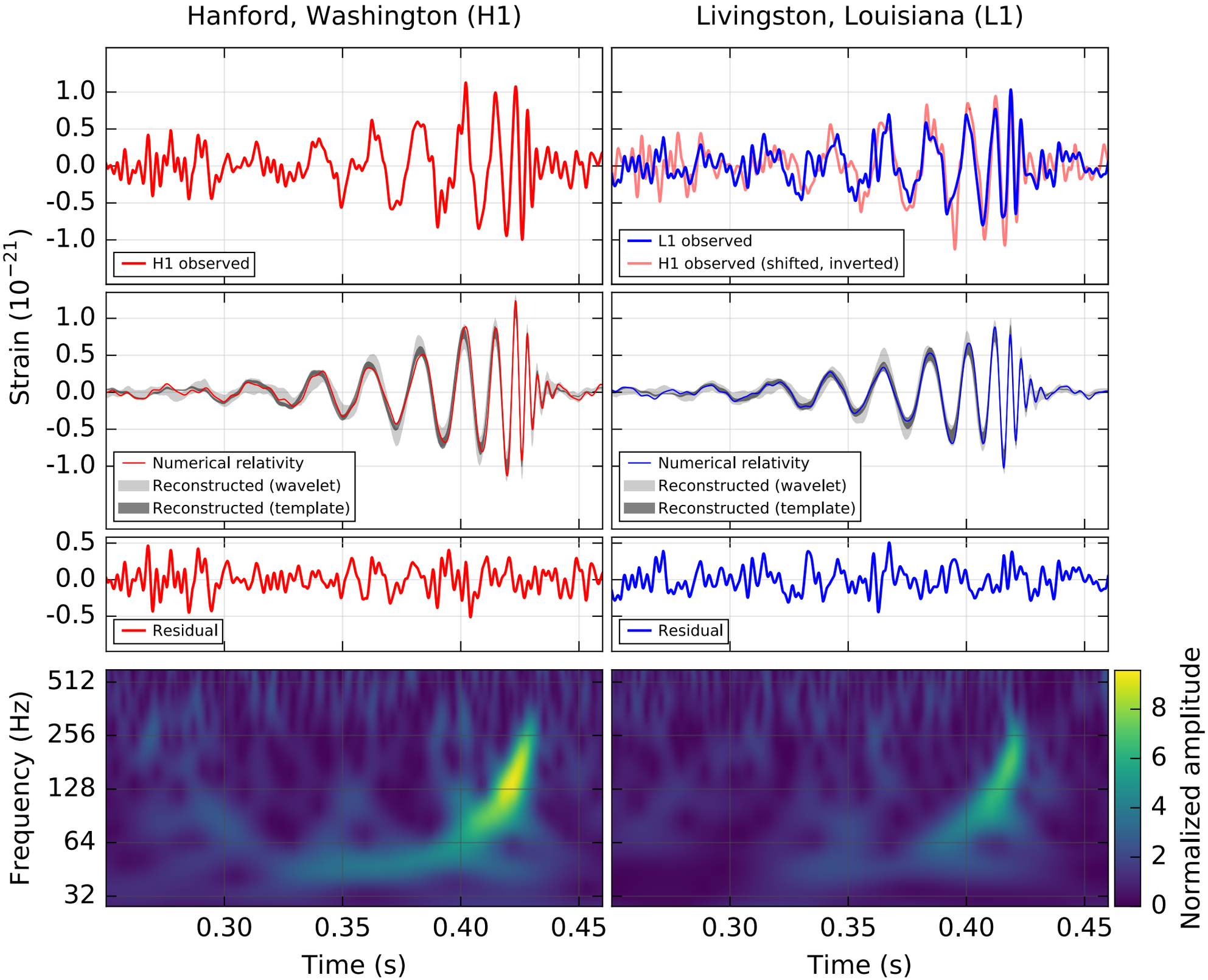
High power has a price
- Local thermal distortion of the glass optics caused by small imperfections in the coatings and limit current power.
- Noise from scattered light.

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 Numerical Relativity

Initial Masses:

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

Final Mass:

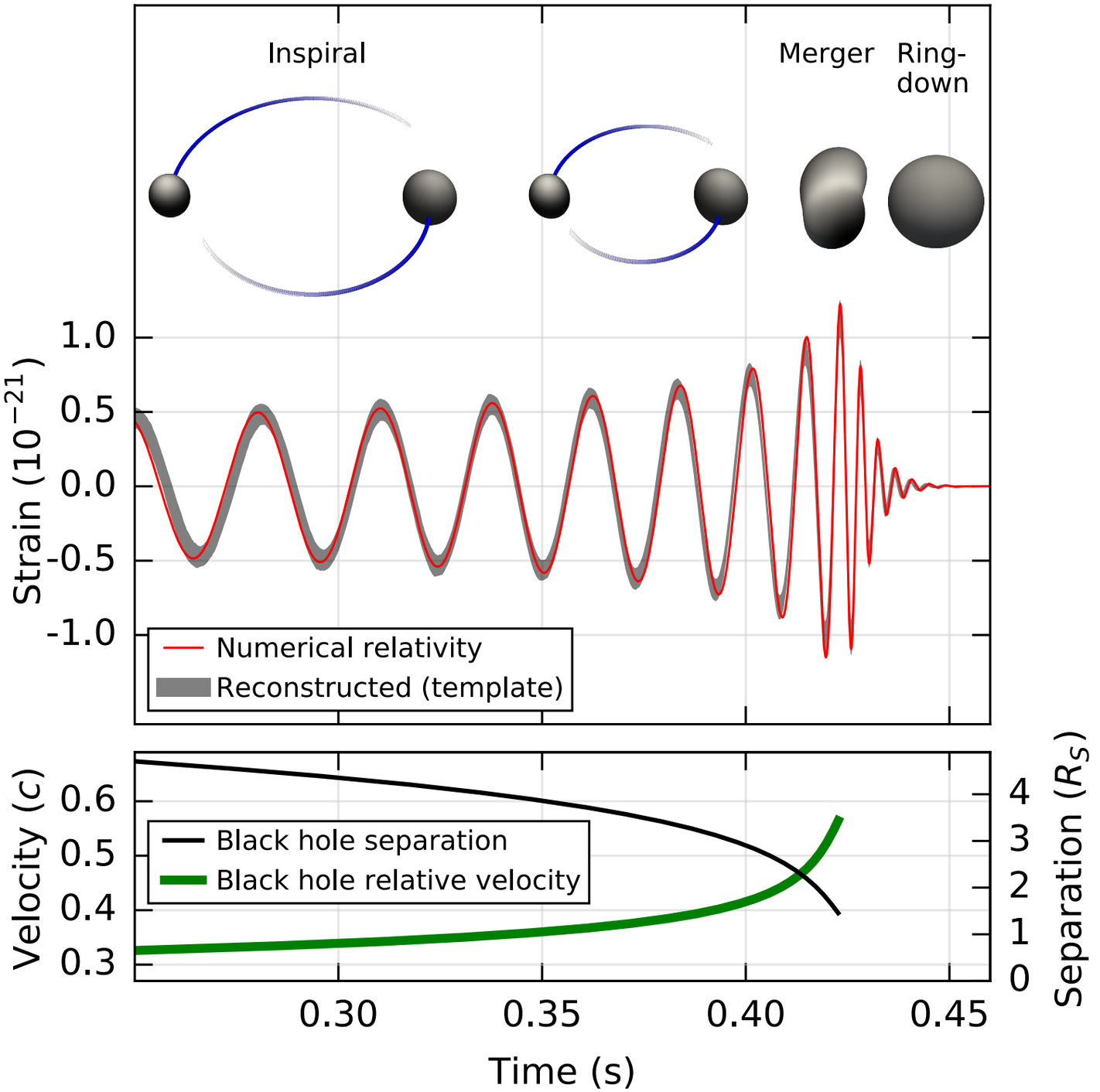
62 (+4/-4) M_{sun}

3 solar masses were radiated as GWs

Distance

420 (+160/-180) MPc

(1.3 Billion light years)



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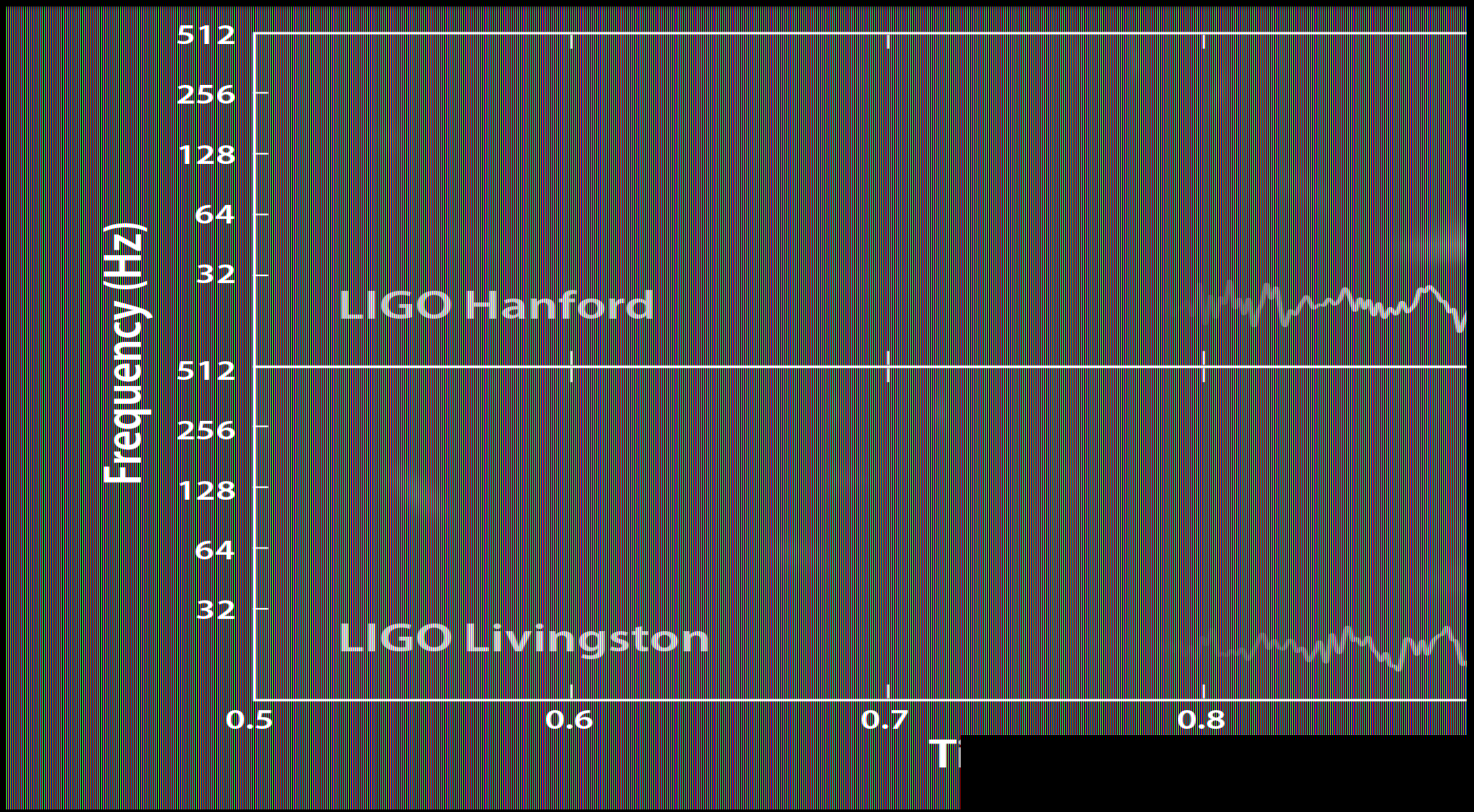

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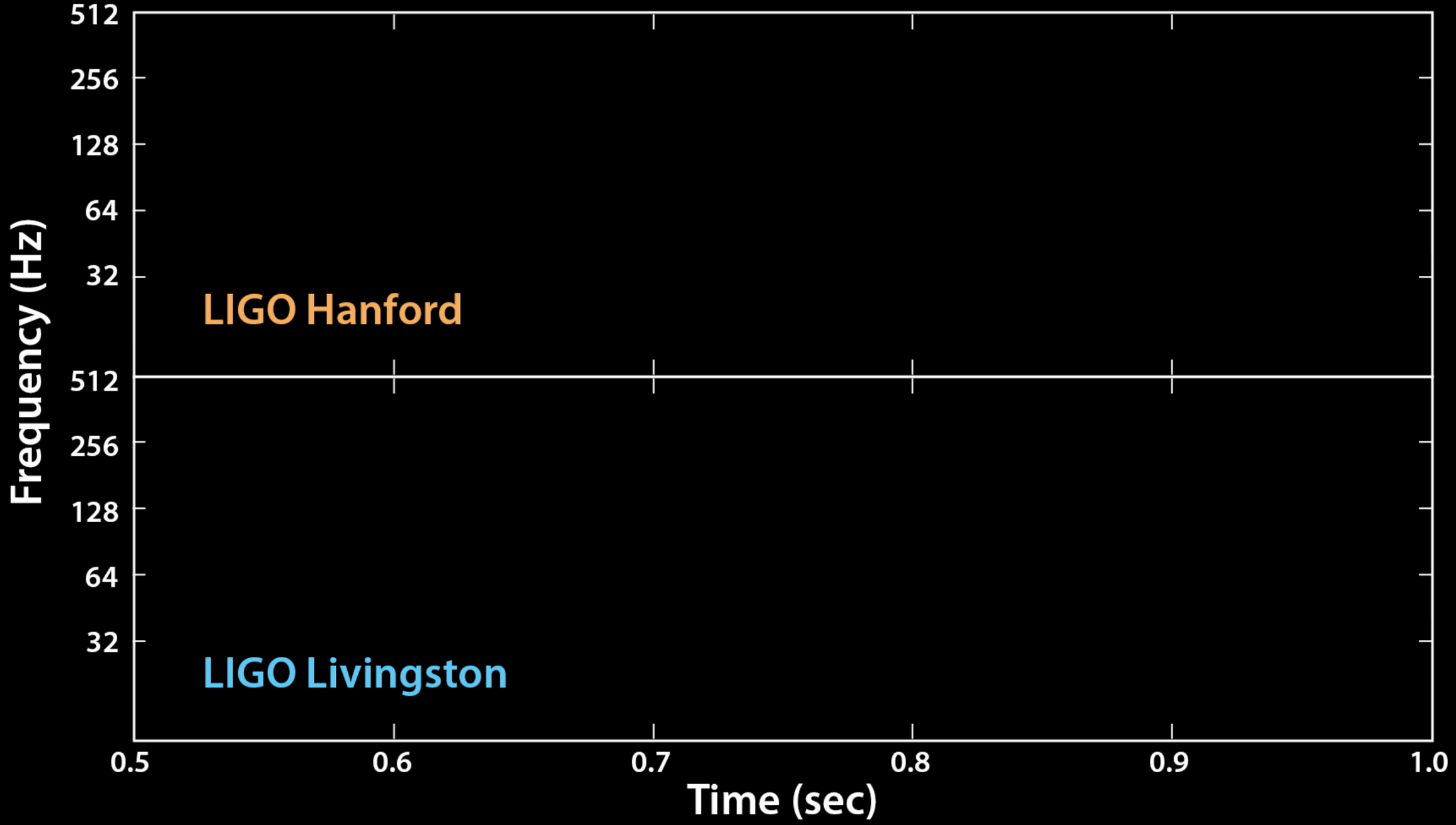
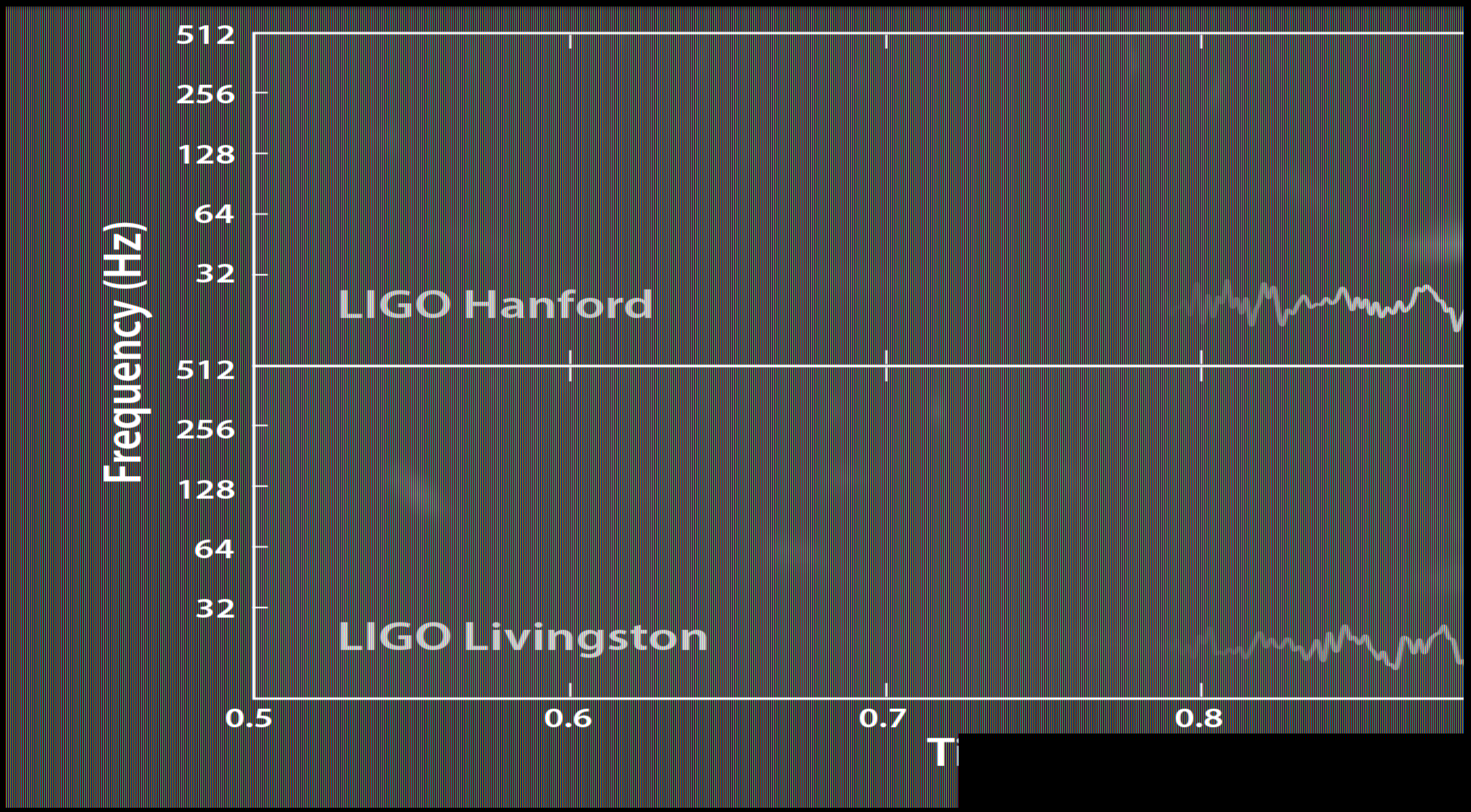

LIGO Hanford
LIGO Livingston
Frequency (Hz)
512
256
128
64
32
512
256
128
64
32
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)


LIGO Hanford
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Frequency (Hz)
512
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128
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32
0.5
0.6
0.7
0.8
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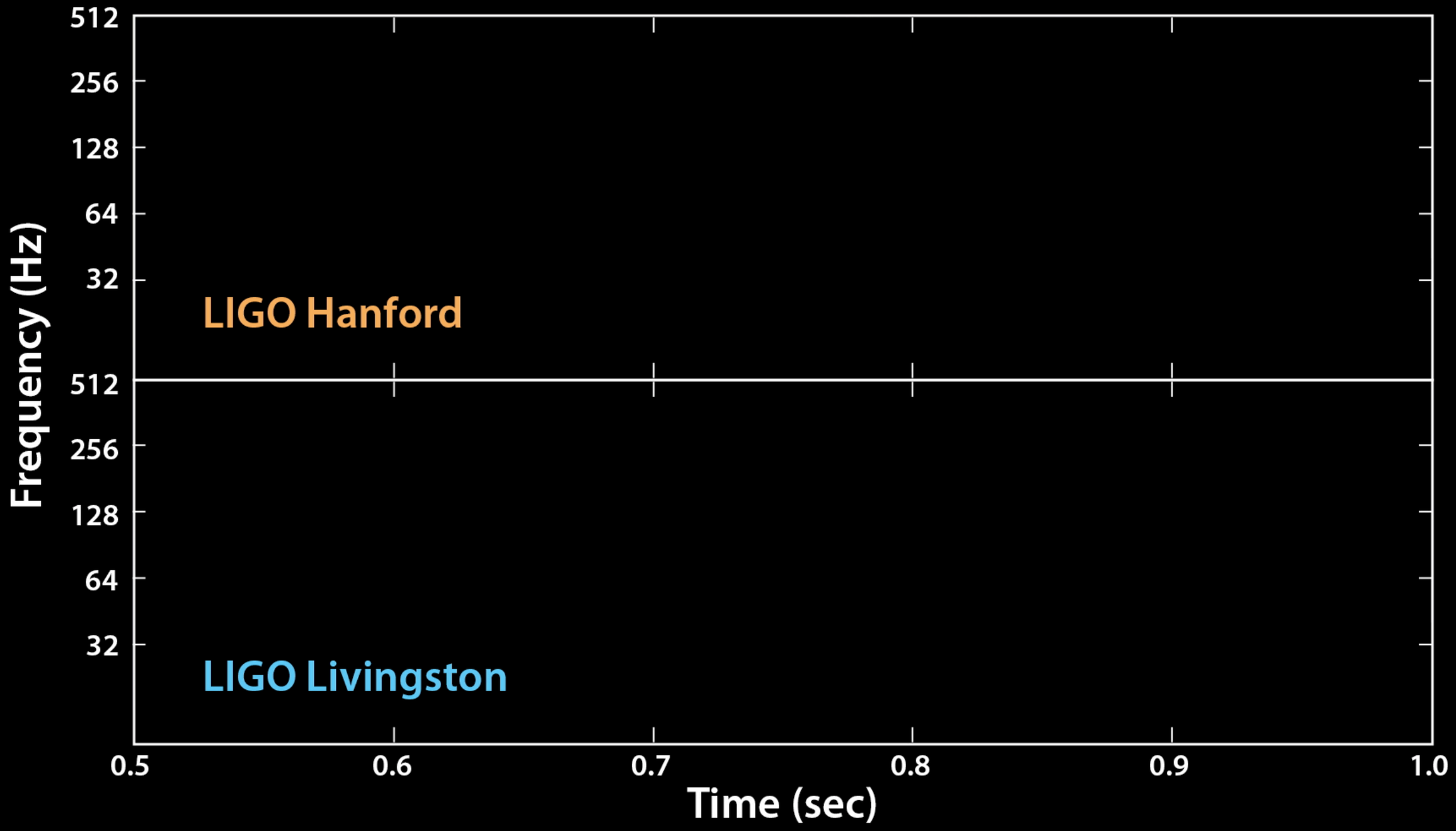
The sound of black holes colliding



Neutron star & San Francisco

Supernova remnant

~1.4 solar masses

composed of dense neutrons

hot topic in astronomy

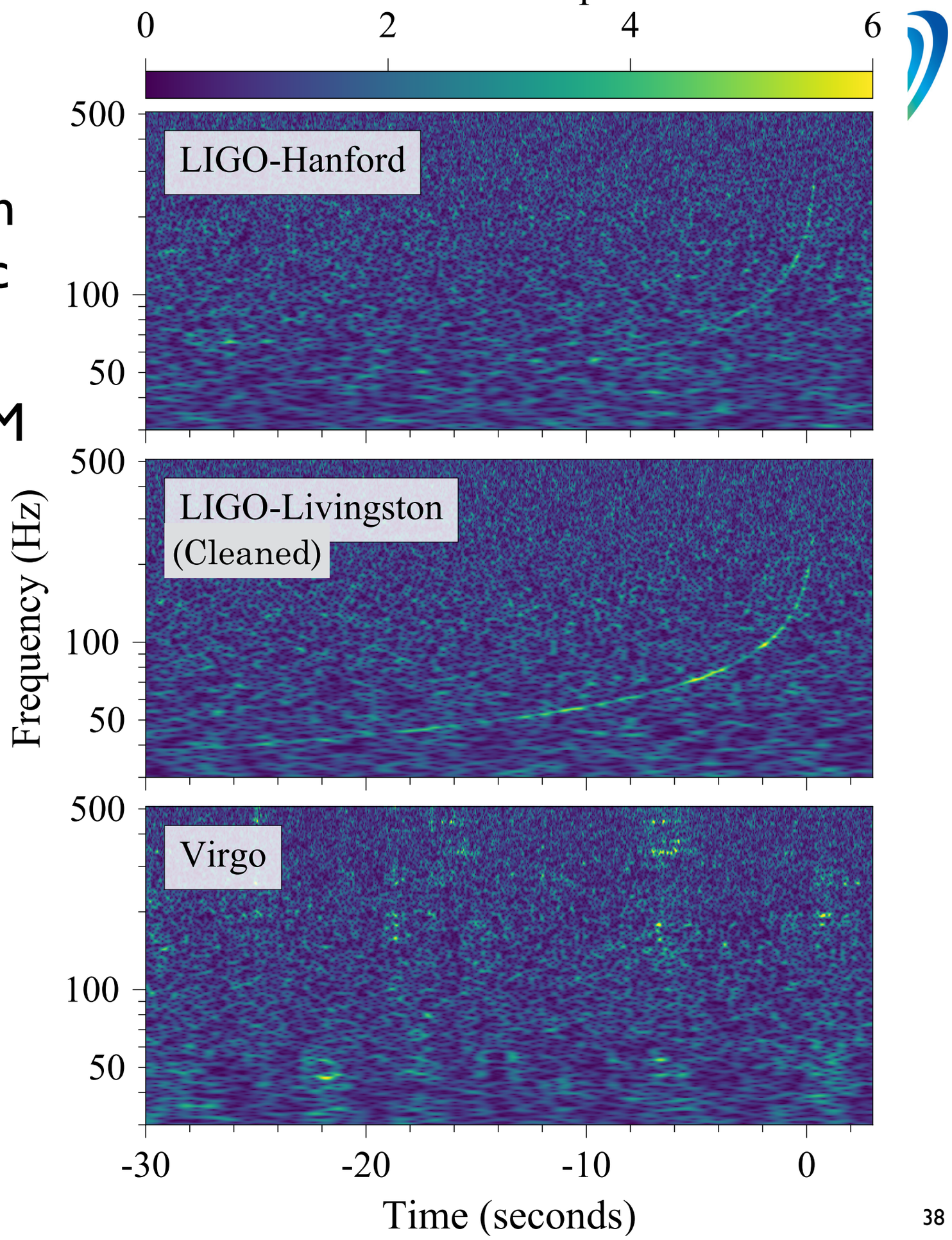
pulsars, Hulse-Taylor

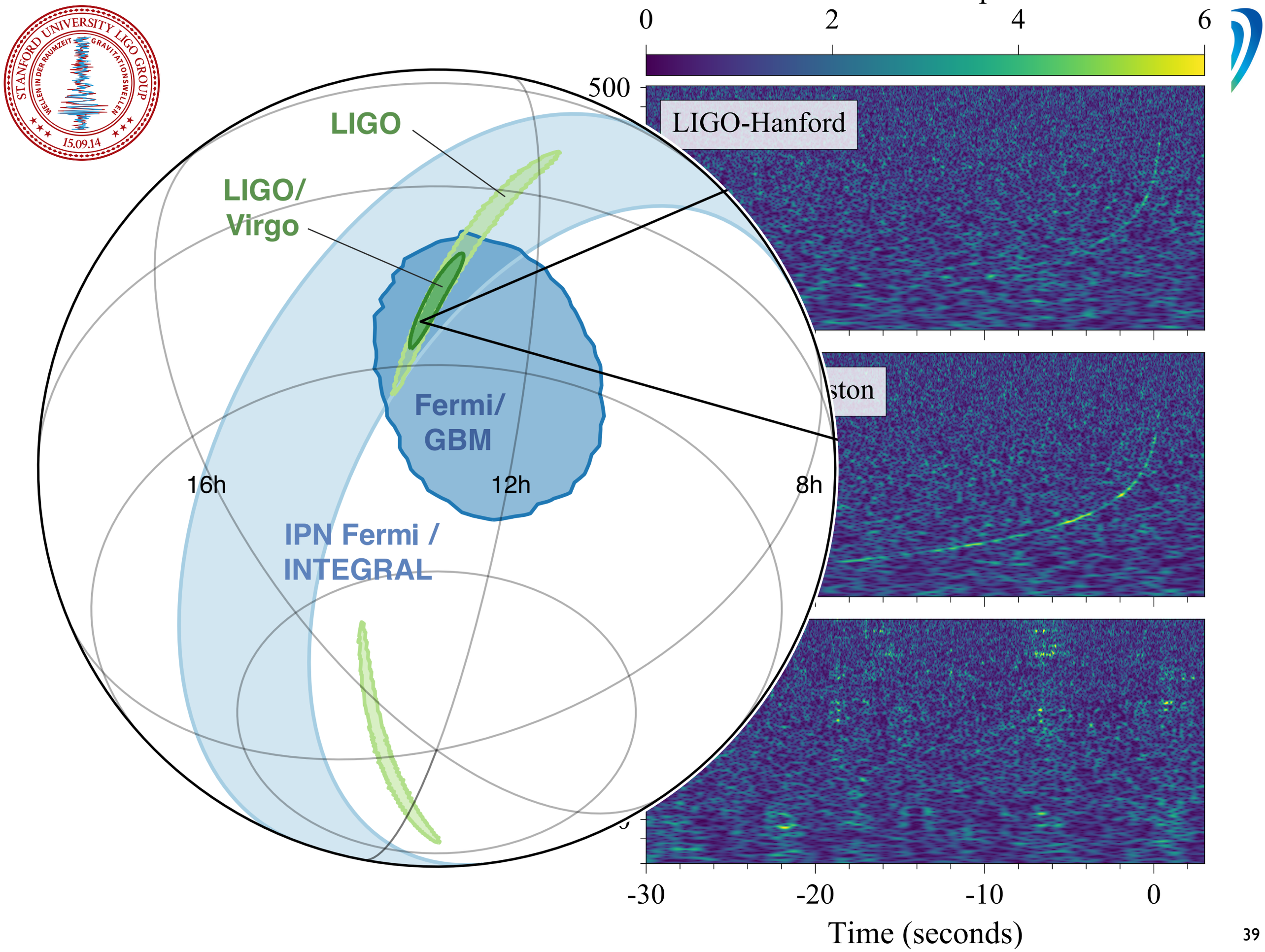
kilonovas…

GW170817

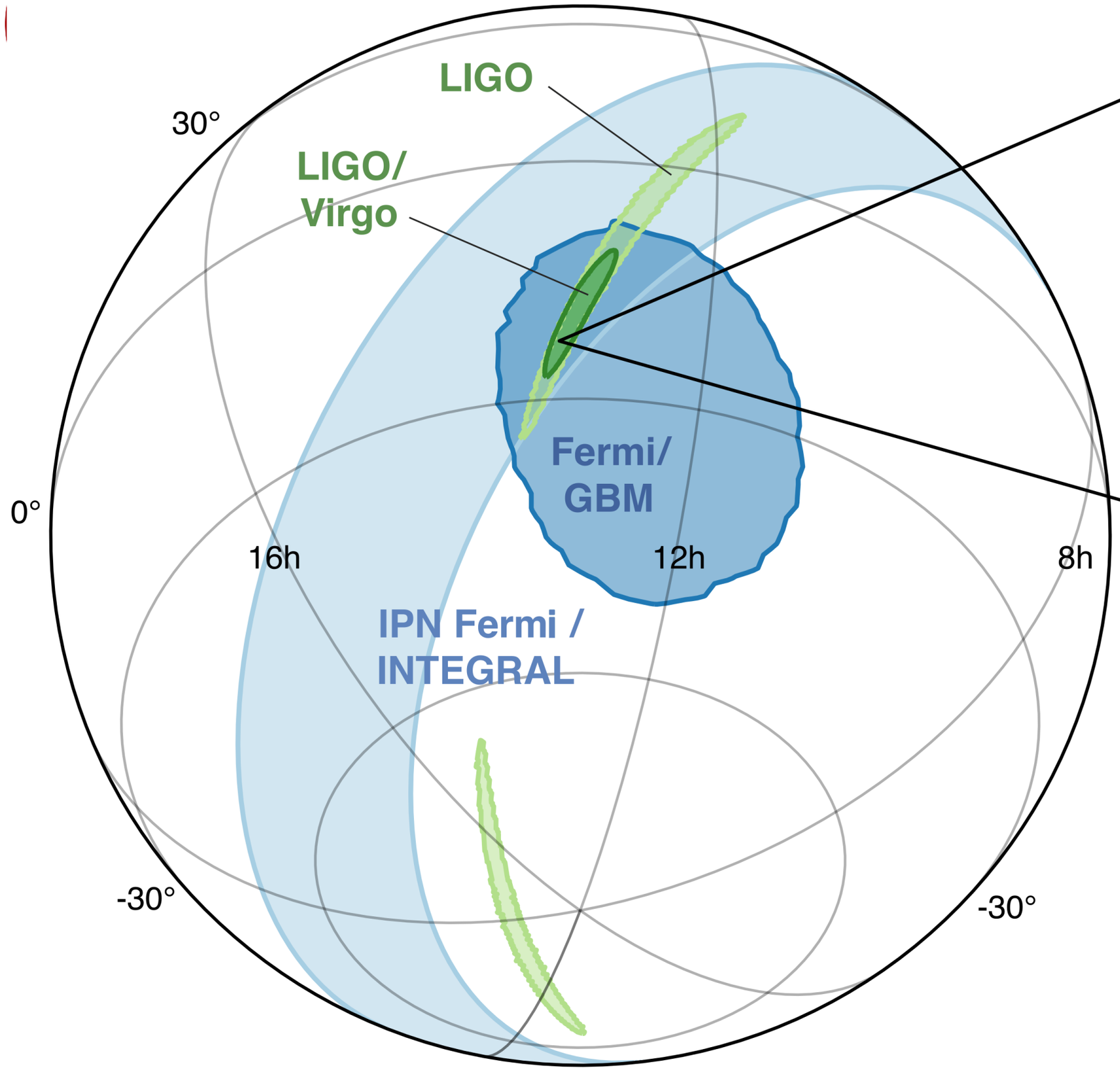
BNS

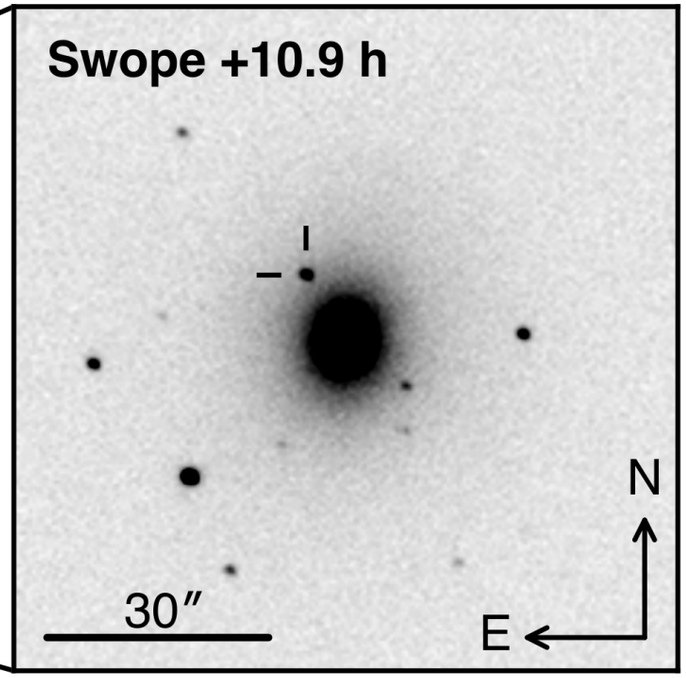
- LIGO software finds trigger in LHO data - 5:41:04 am Pacific time, August 17.
- LIGO realizes that Fermi GBM has triggered on event 1.7 seconds after GW merger.
- Thus, BNS mergers cause short gamma-ray bursts.
- Finally solving a mystery uncovered by Vela-4 in 1967. (as predicted by many).
- Forcing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

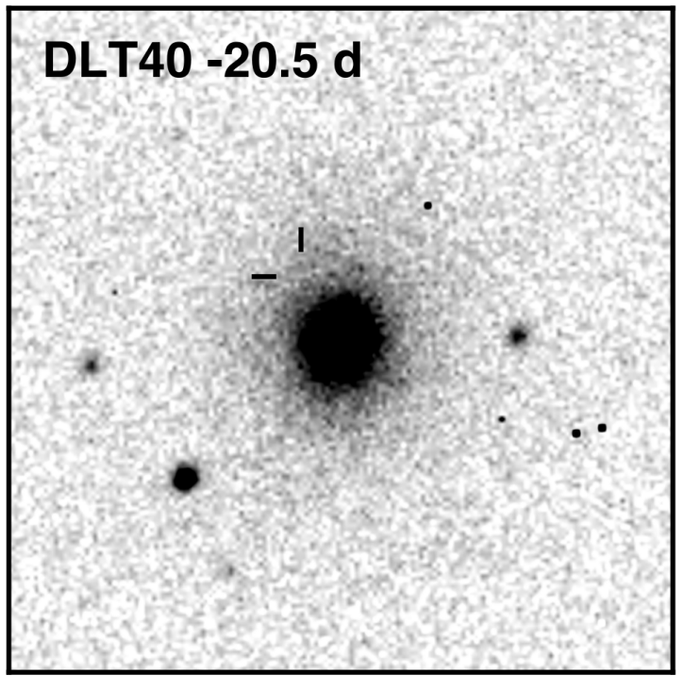



LIGO
LIGO/
Virgo
Fermi/
GBM
IPN Fermi /
INTEGRAL
16h
12h
8h
0
2
4
6
500
LIGO-Hanford
ston
-30
-20
-10
0
Time (seconds)

GW + GRB + Kilonova

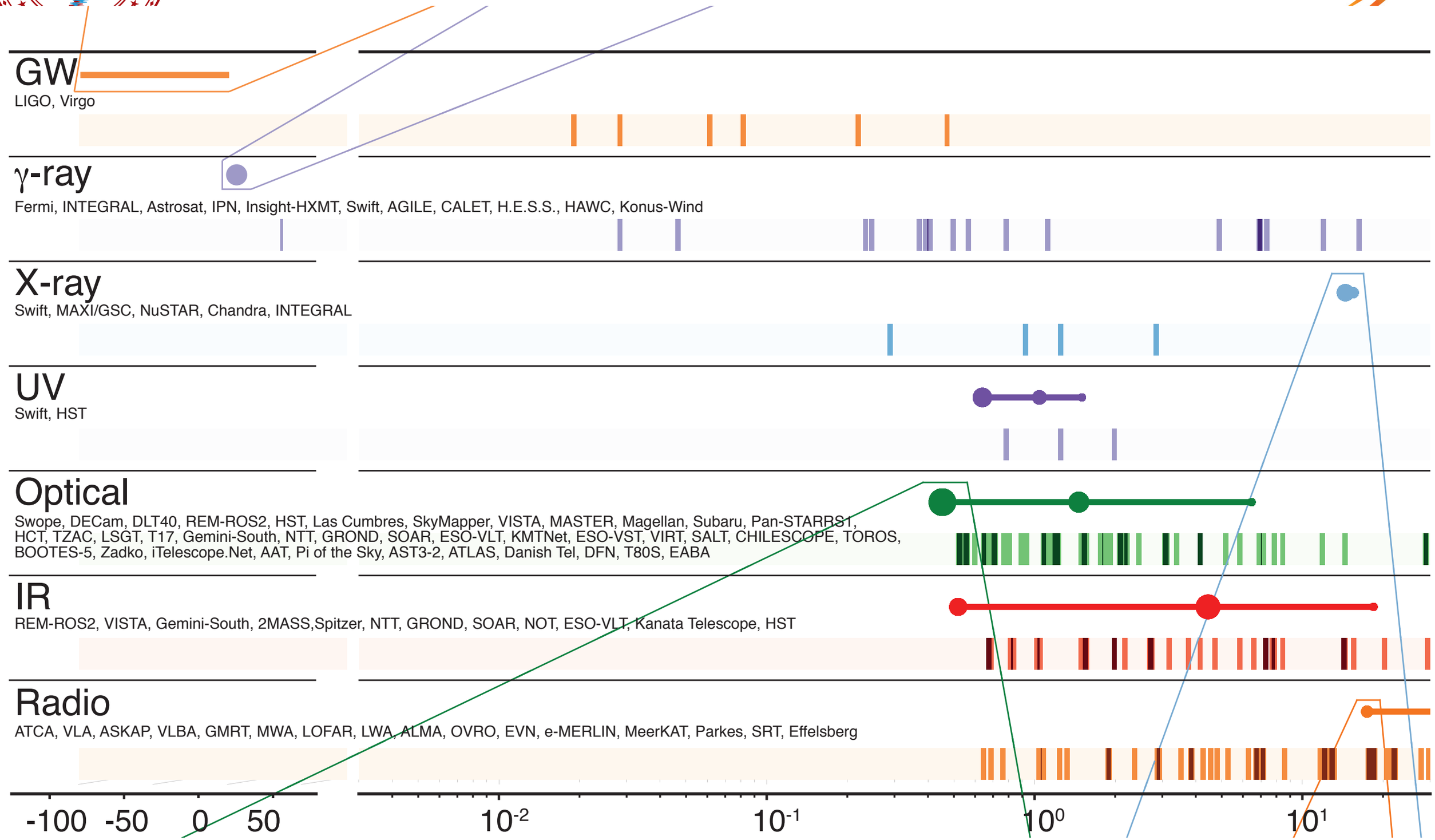




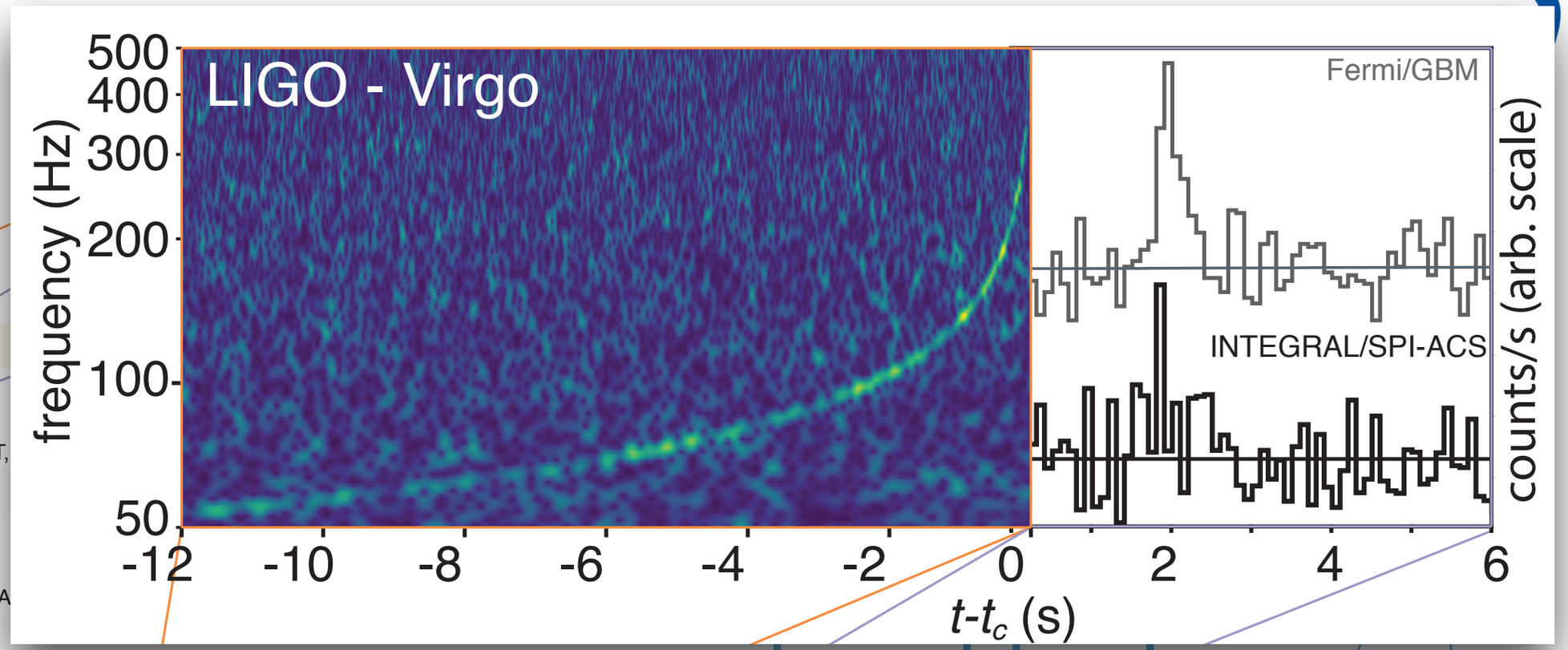


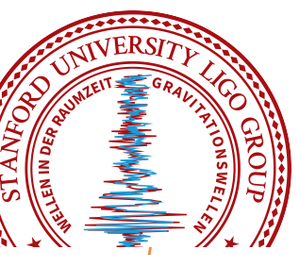
There is matter, and we can watch it

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

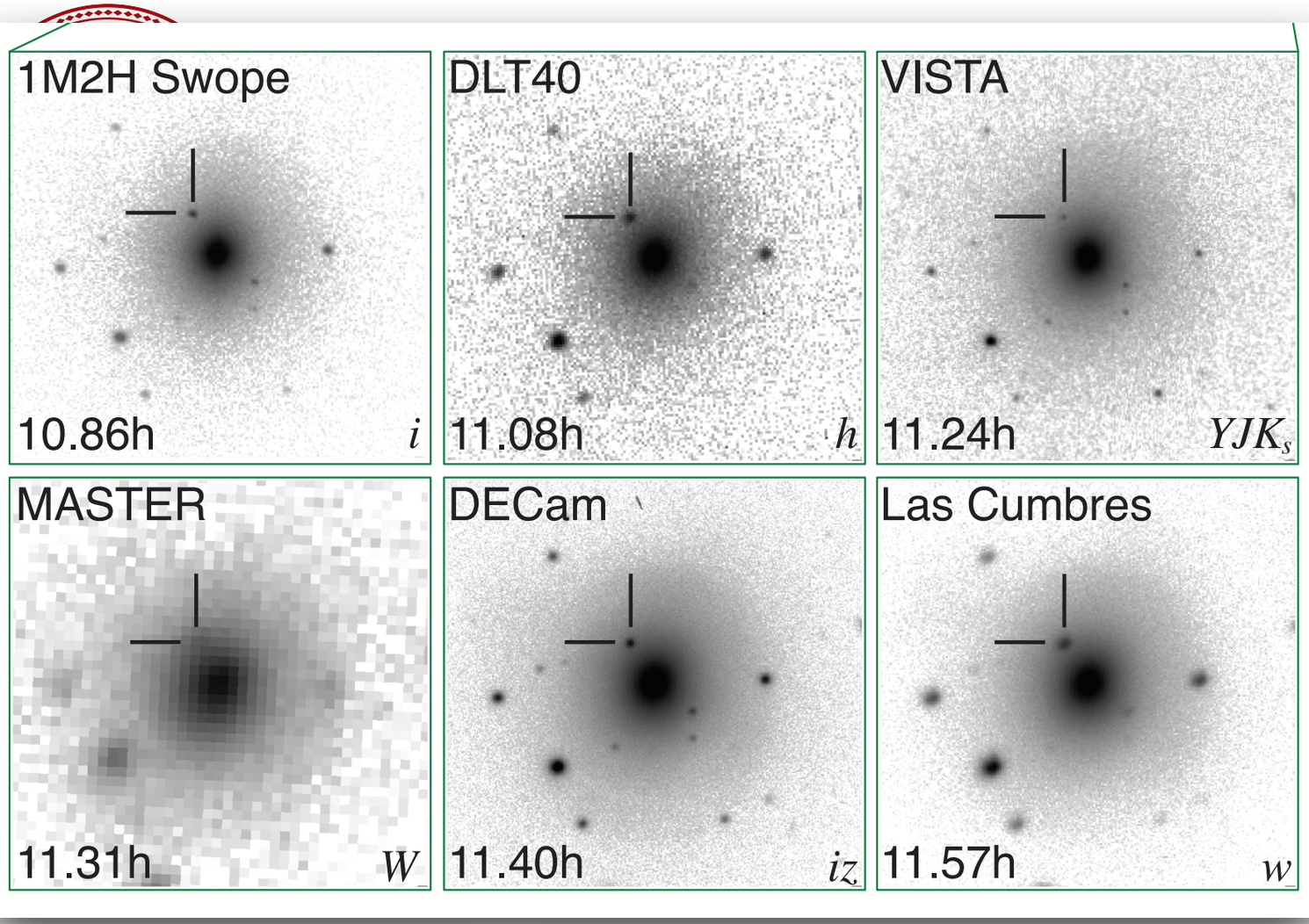
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel,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

IR

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

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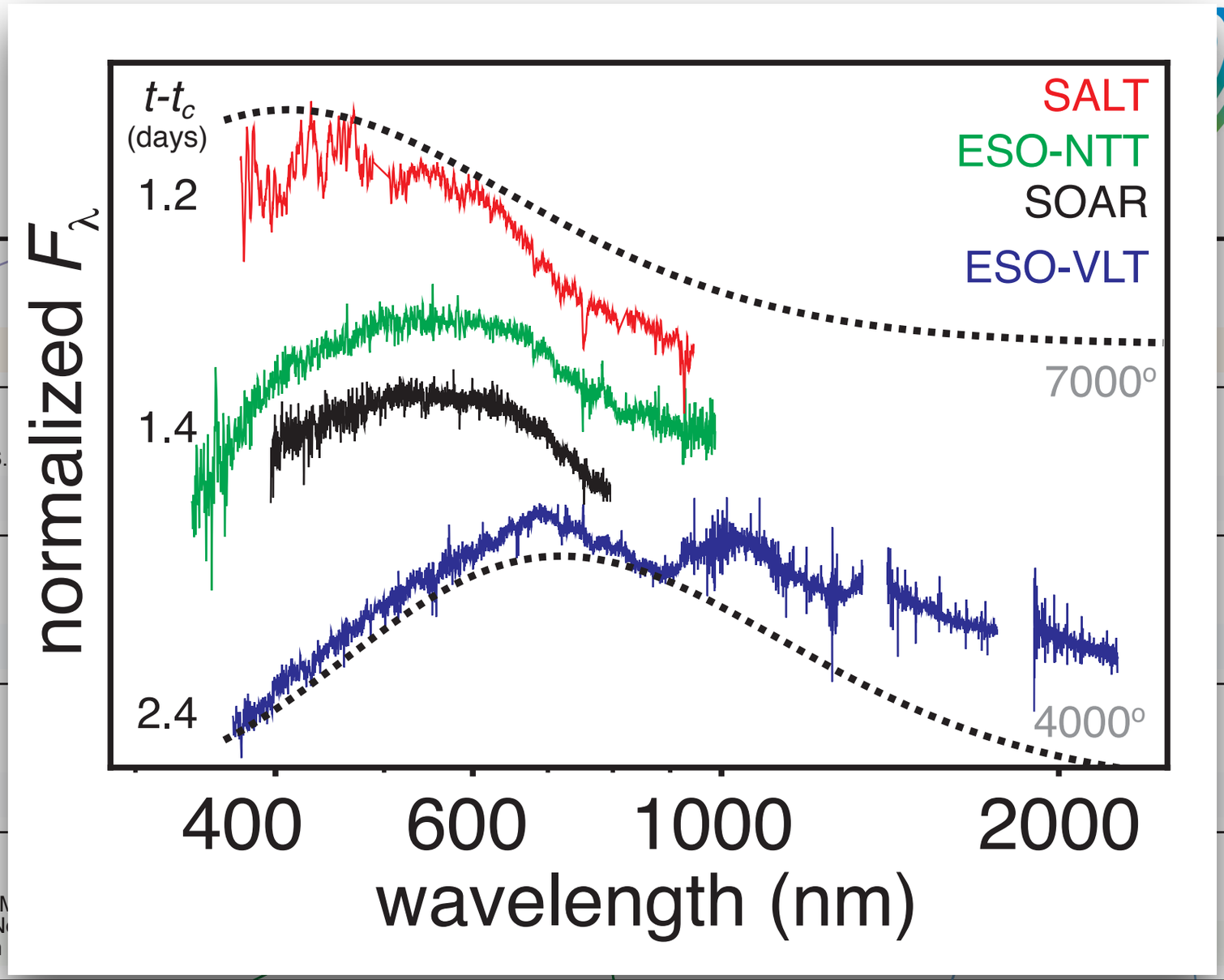


GW
LIGO, Virgo

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
HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTN
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

GW
LIGO, Virgo

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

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

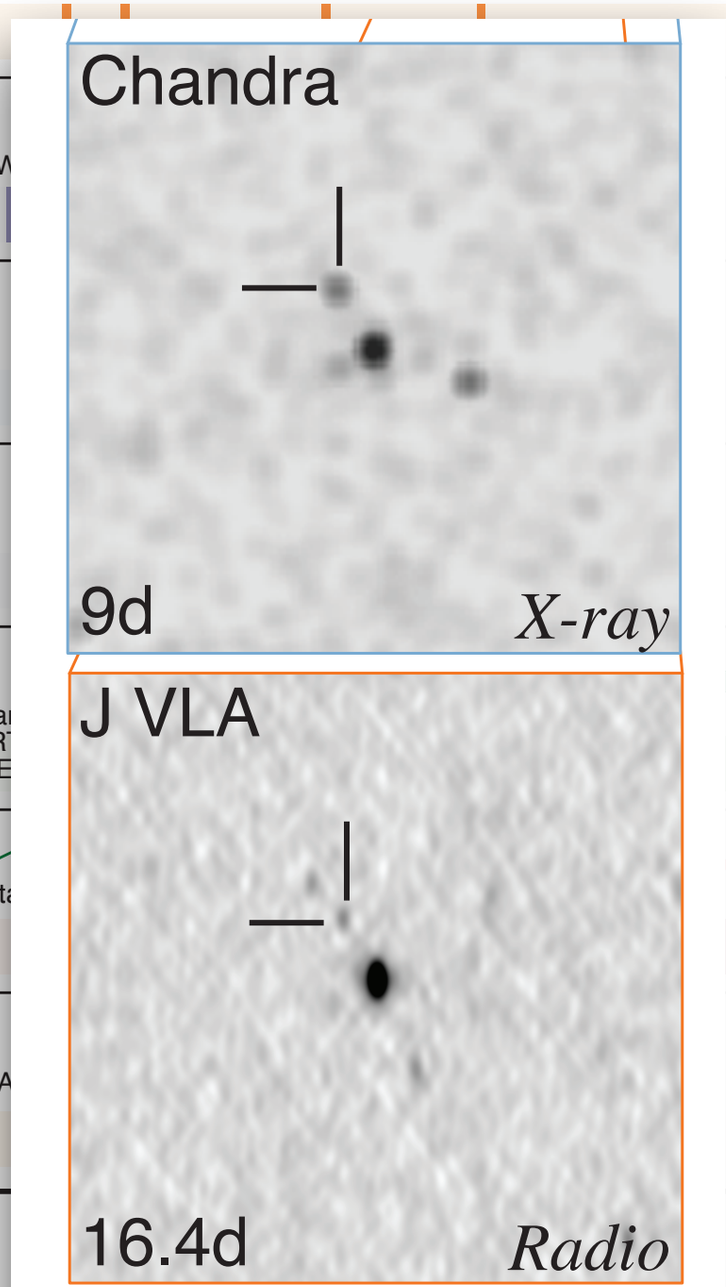
UV
Swift, HST

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

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

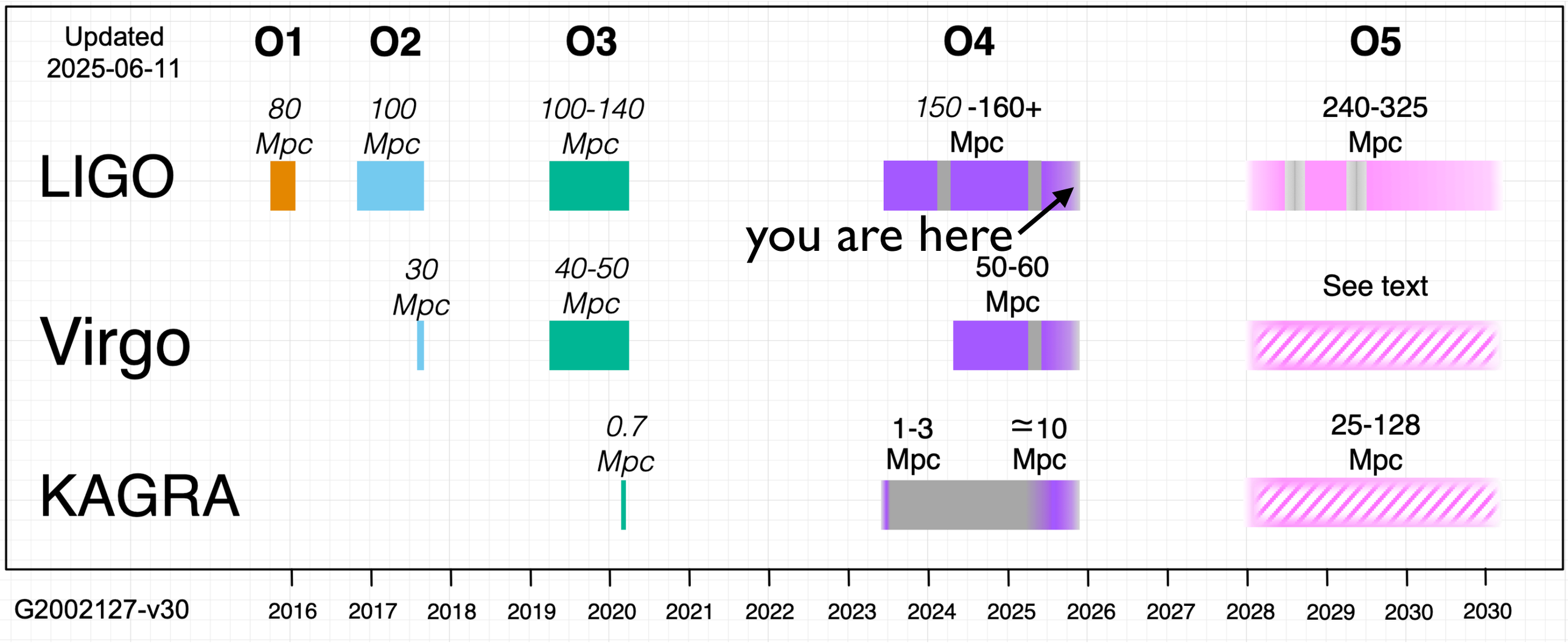
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKA

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



https://arxiv.org/abs/1710.05833

Where are we now?

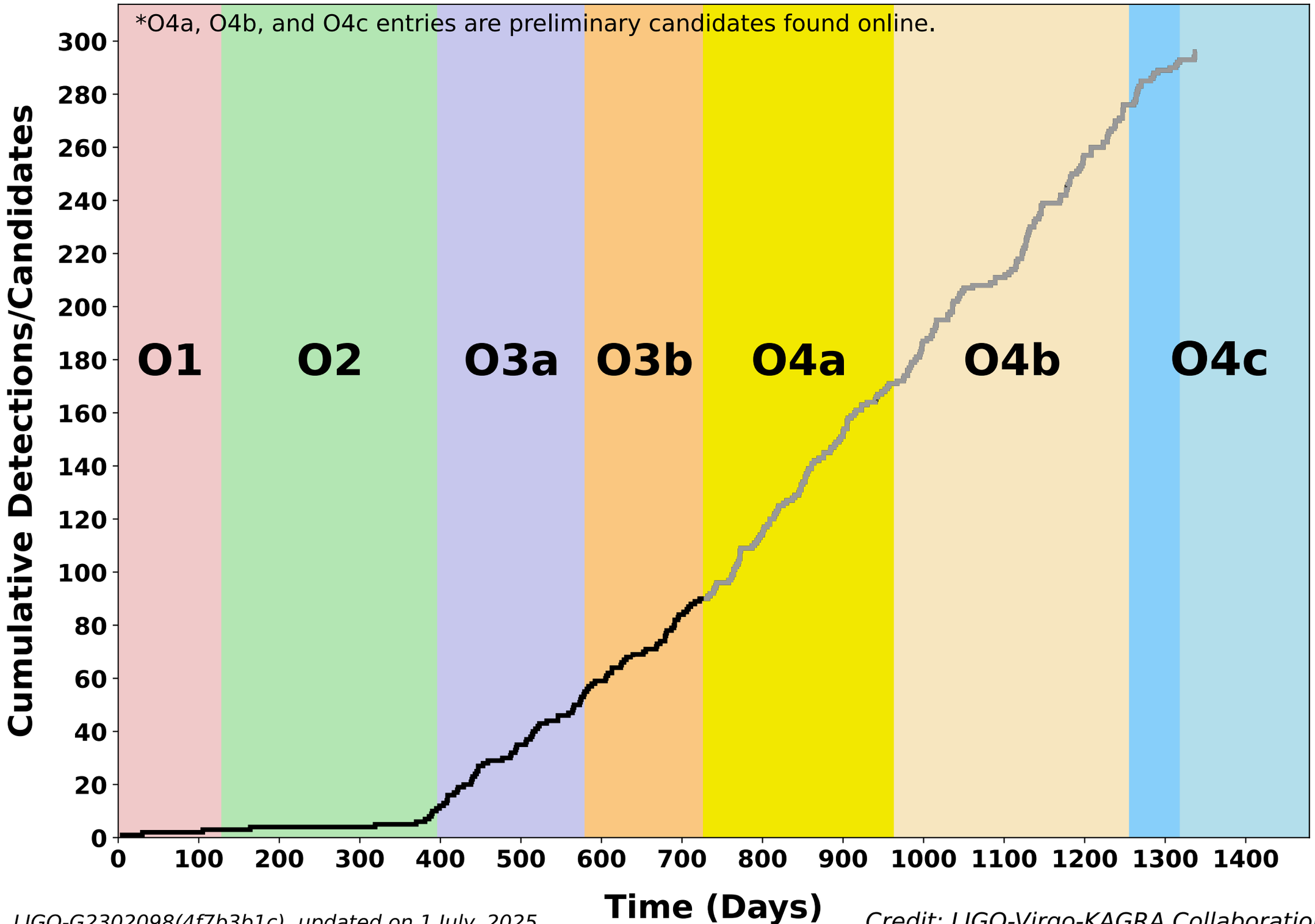


https://observing.docs.ligo.org/plan/

Lots of Events!

Cumulative count of GW events

O1+O2+O3 = 90, O4a* = 81, O4b* = 105, O4c* = 20, Total = 296



LIGO-G2302098(4f7b3b1c), updated on 1 July, 2025

Credit: LIGO-Virgo-KAGRA Collaboration

Lots of Events!

Cumulative count of GW events

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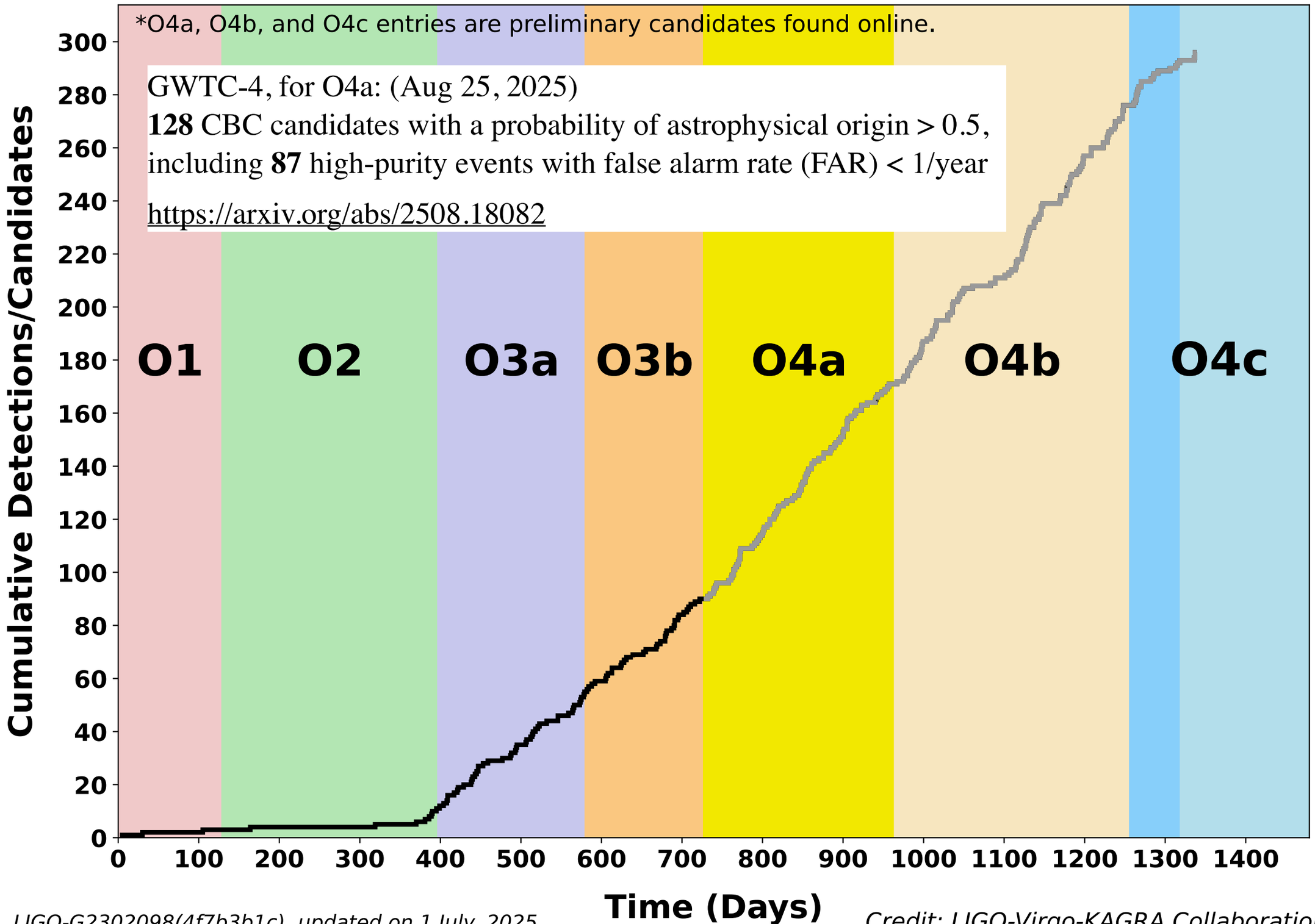


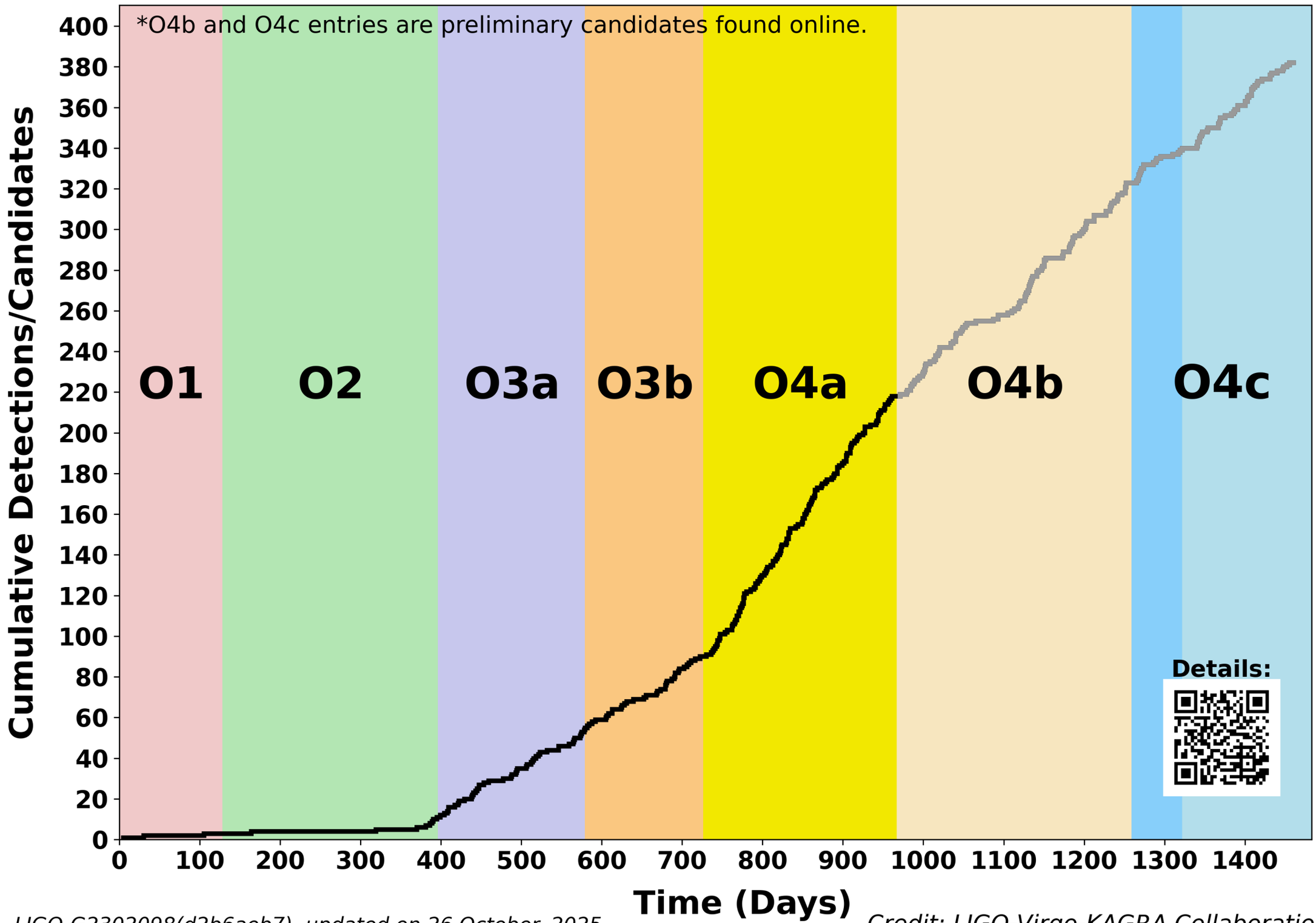
LIGO-G2302098(4f7b3b1c), updated on 1 July, 2025

Credit: LIGO-Virgo-KAGRA Collaboration

Lots of Events!

Cumulative count of GW events

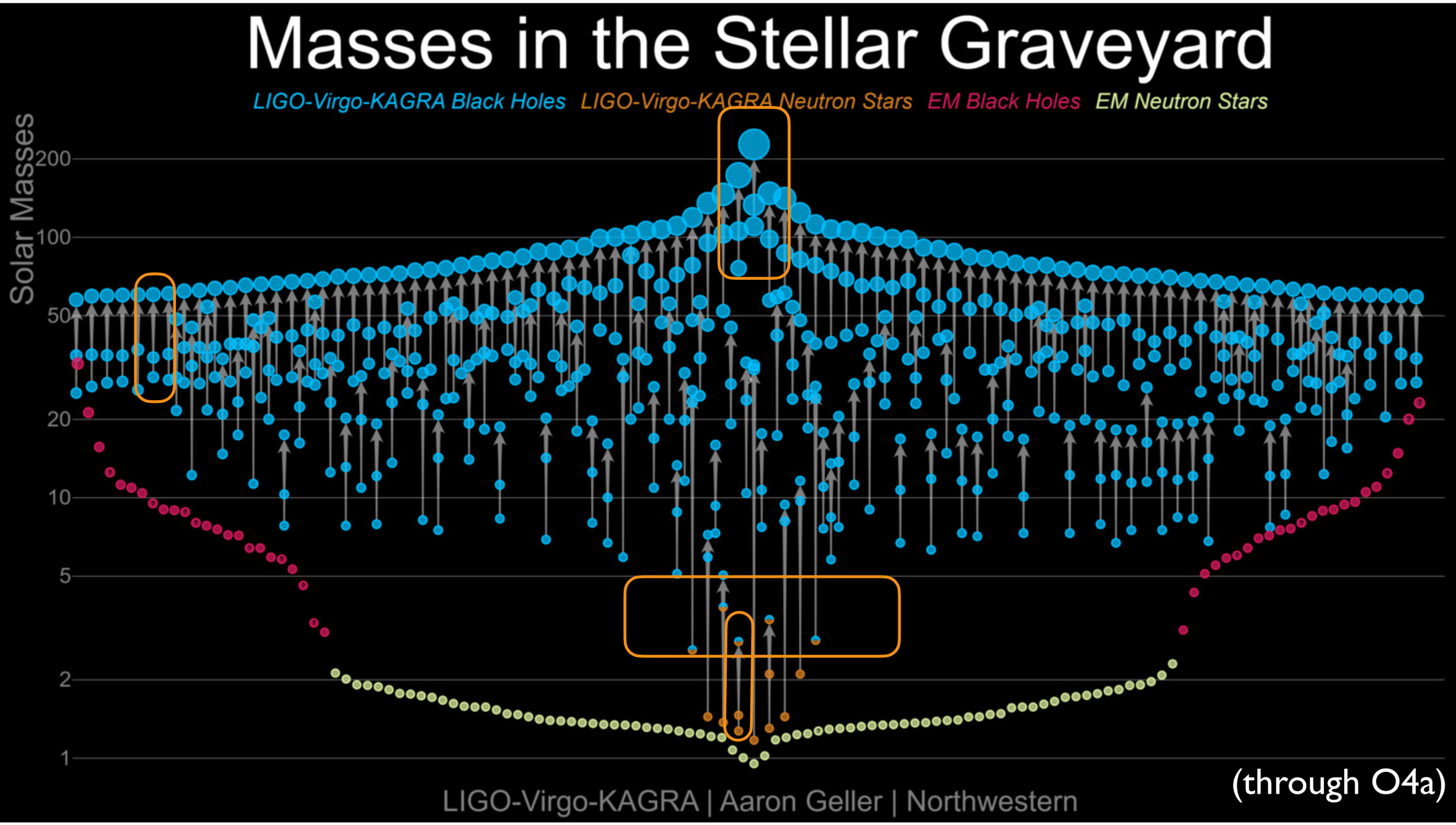
O1+O2+O3+O4a = 218, O4b* = 105, O4c* = 59, Total = 382



LIGO-G2302098(d2b6aeb7), updated on 26 October, 2025

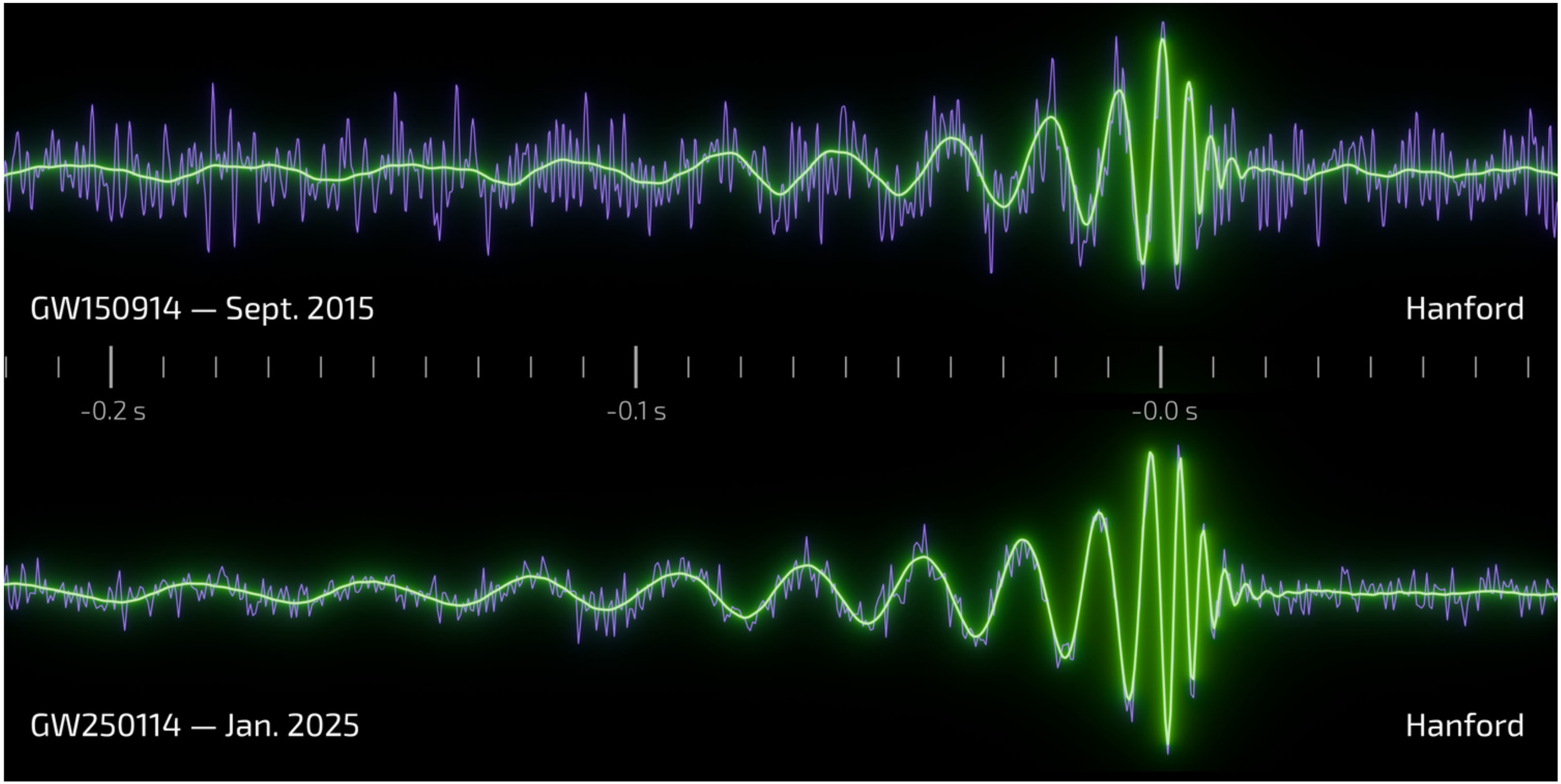
Credit: LIGO-Virgo-KAGRA Collaboration

Lots of Events!



notable events

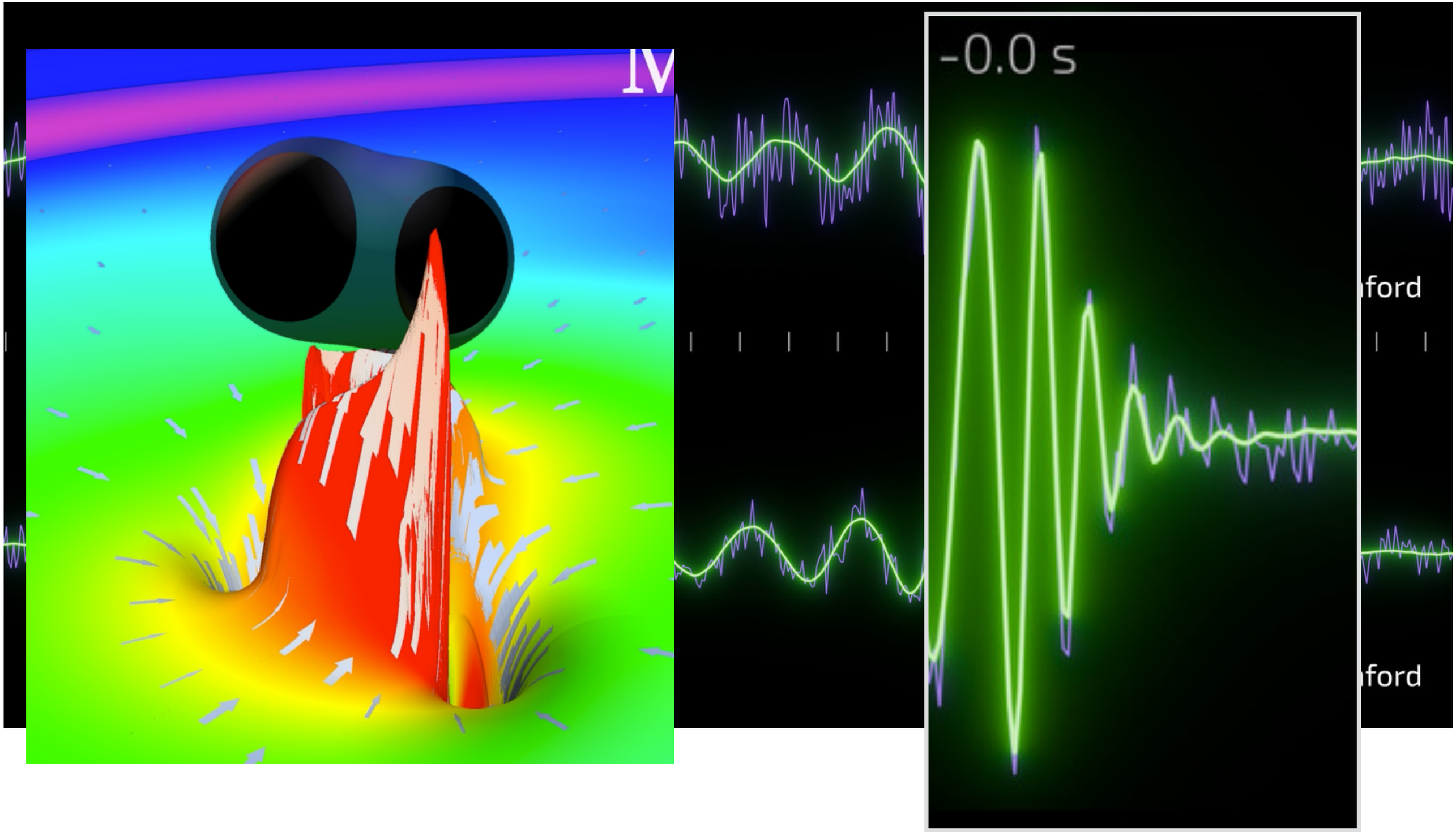
GW250114 near-twin to the first detection



$M_f = 62.7^{+1.0}_{-1.1} M_\odot$ and a spin of $\chi_f = 0.68^{+0.01}$

notable events

GW250114 near-twin to the first detection



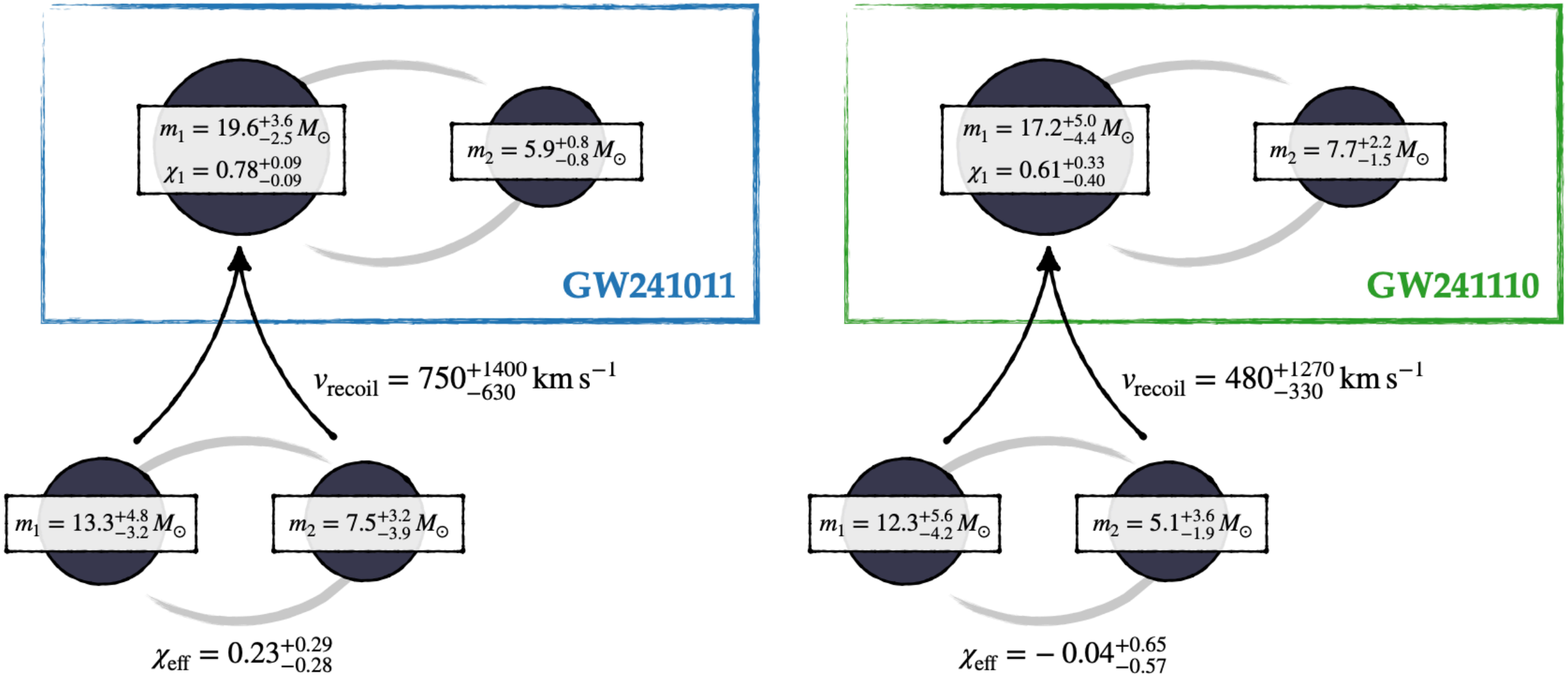
spin of $\chi_f = 0.68 +0.01/ -0.01$

notable events

GW241110 & GW241011

clear evidence of repeated mergers

DOI 10.3847/2041-8213/ae0d54



notable events

GW231123 - total mass of 190-265 $M_\odot$

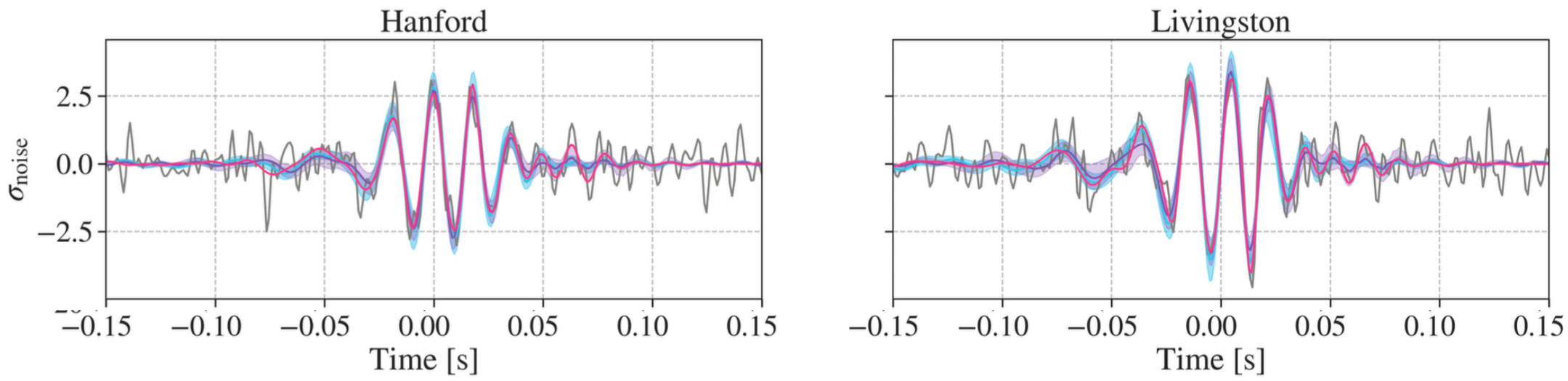
they are big

$$m_1 = 137^{+22}_{-17}\,M_\odot \qquad m_2 = 103^{+20}_{-52}\,M_\odot$$

z=0.4,
Luminosity Distance: 7.2 G LY
2.2 GPc (+1.9, -1.5)

and spinning fast

$$\chi_1 = 0.9^{+0.10}_{-0.19} \qquad \chi_2 = 0.8^{+0.20}_{-0.51}$$



time relative to Nov. 23, 2023 13:54:30 UTC

https://arxiv.org/abs/2507.08219

notable events

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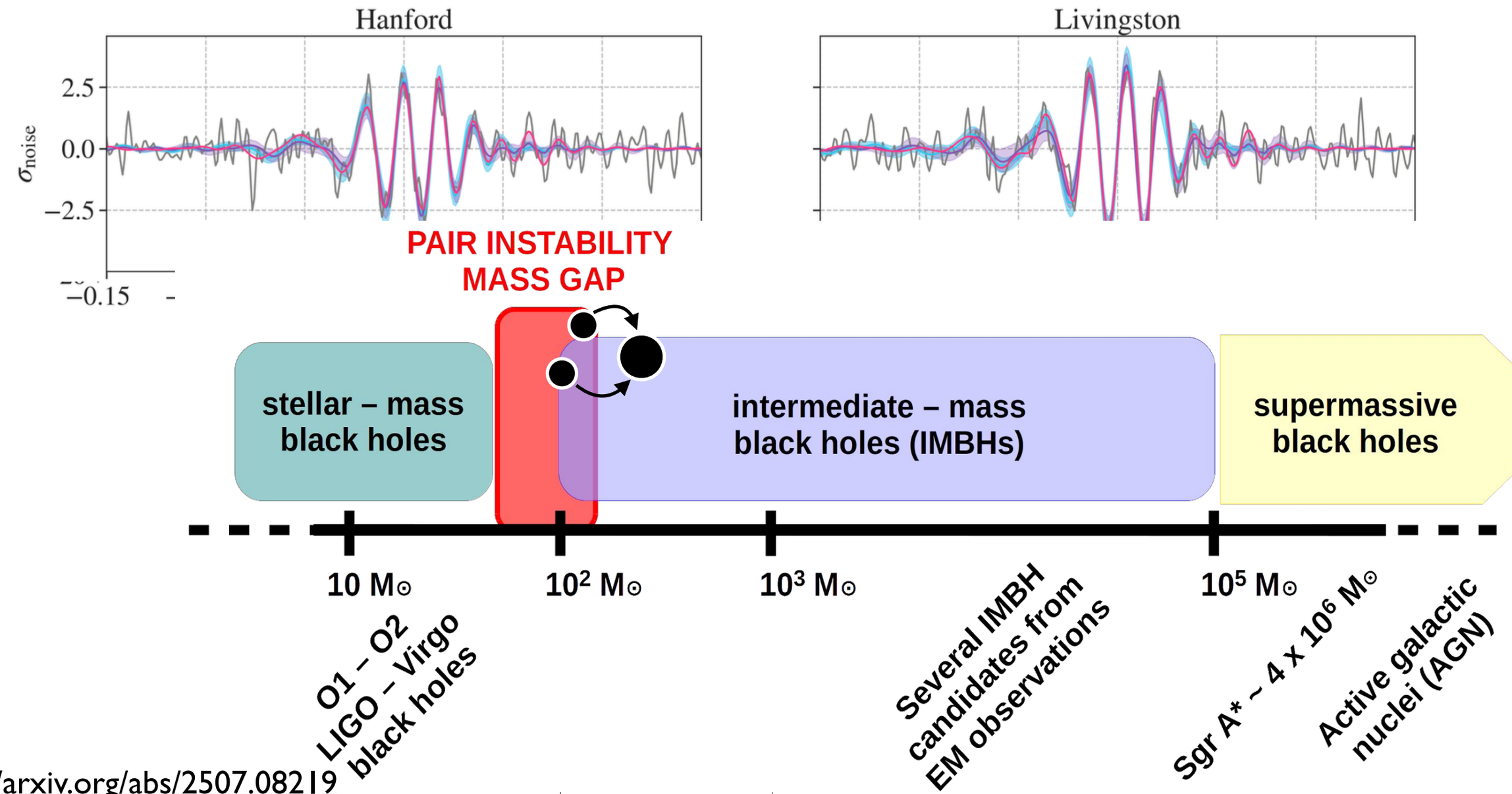

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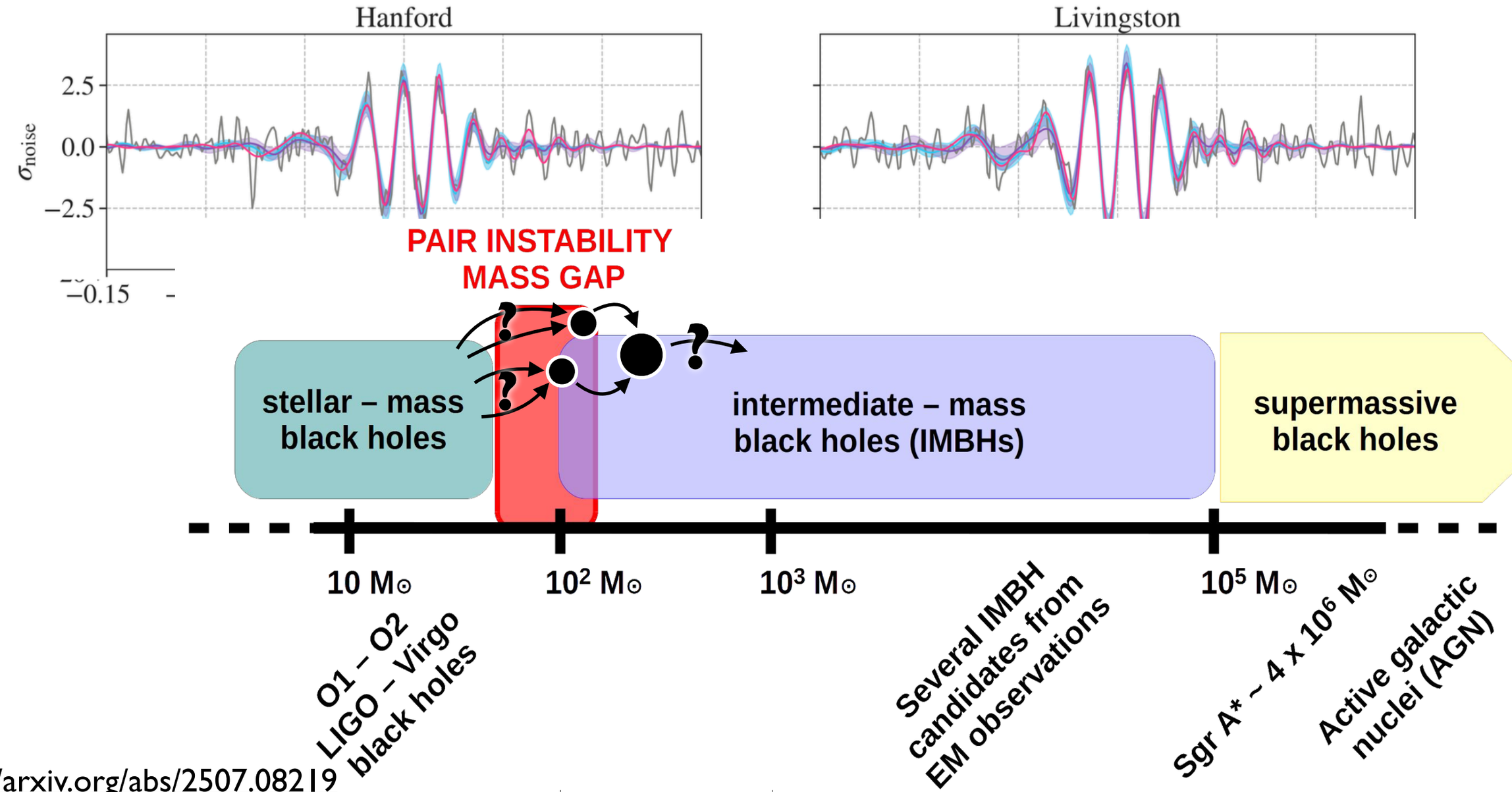
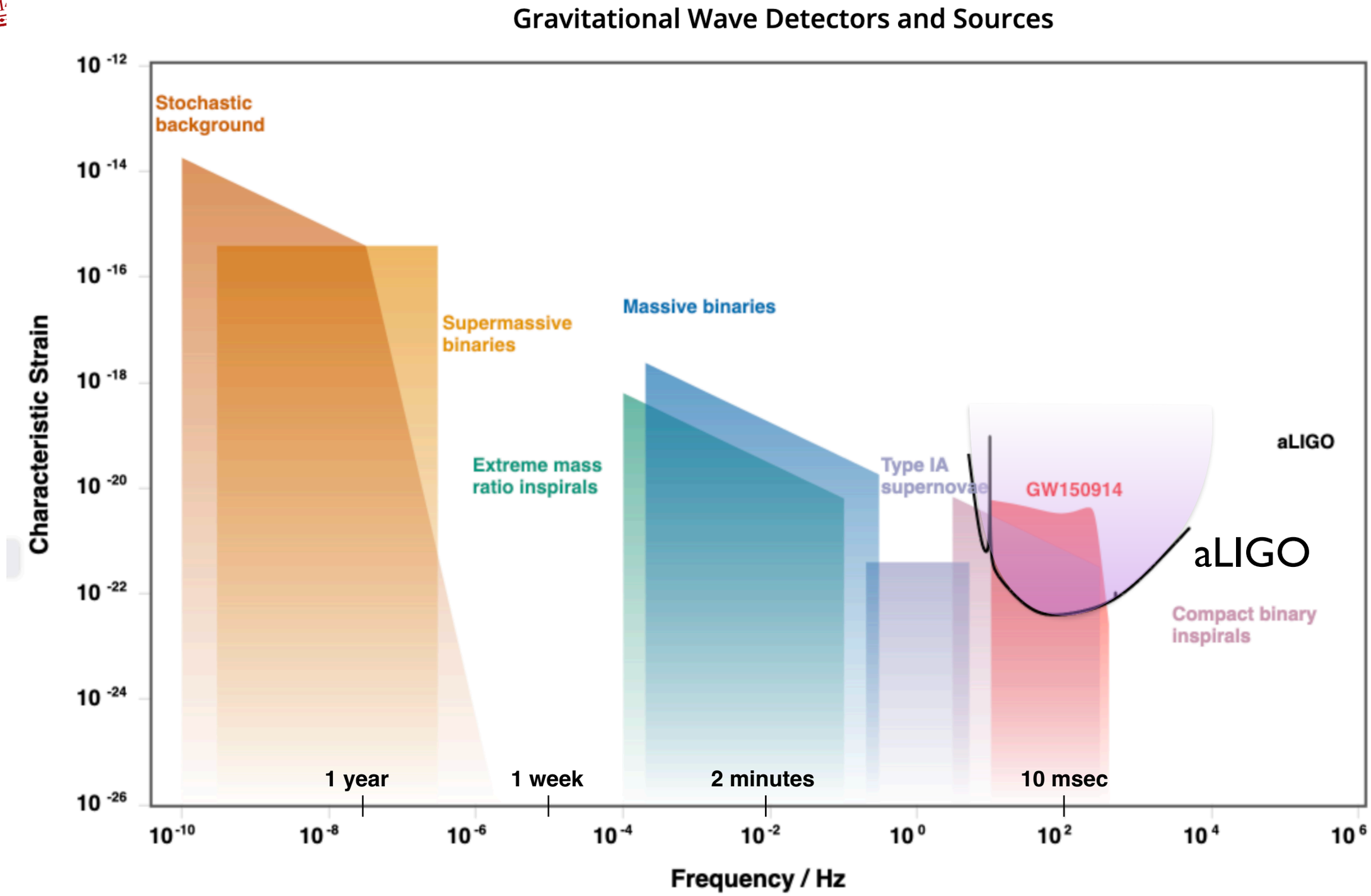


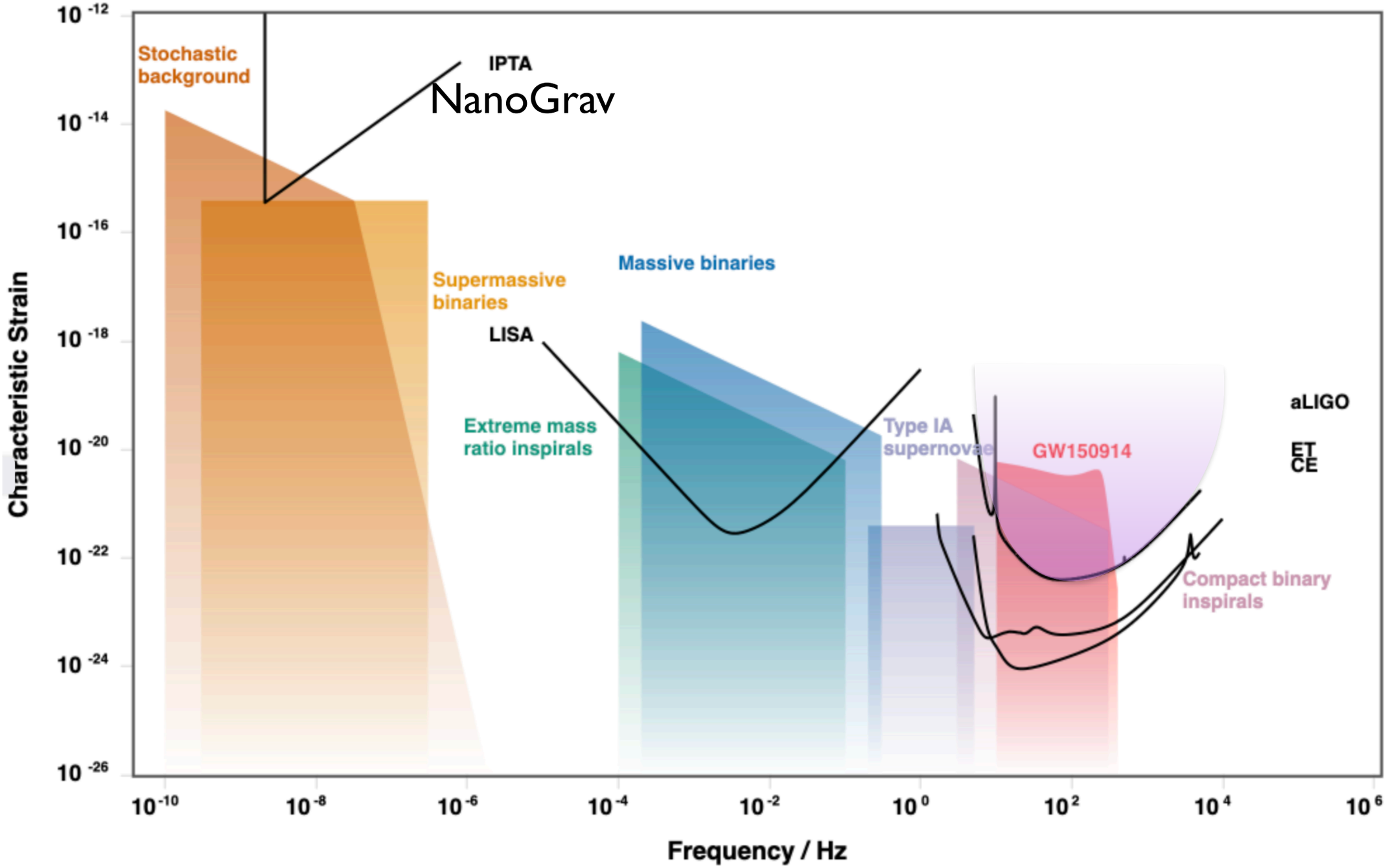
https://arxiv.org/abs/2507.08219

There is so much more…



C. Moore et al, GWplotter.com

There is so much more…



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!

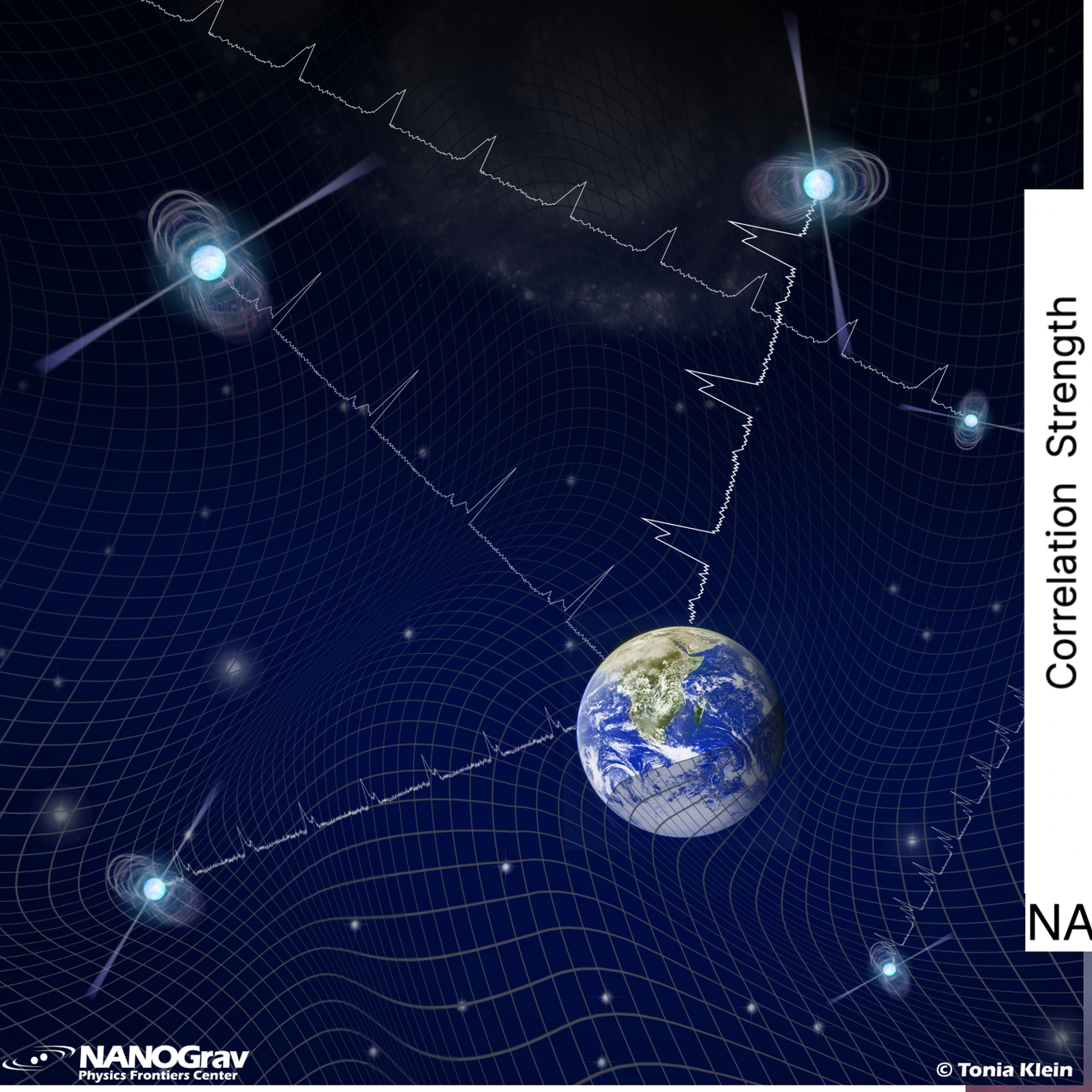
Measure correlations

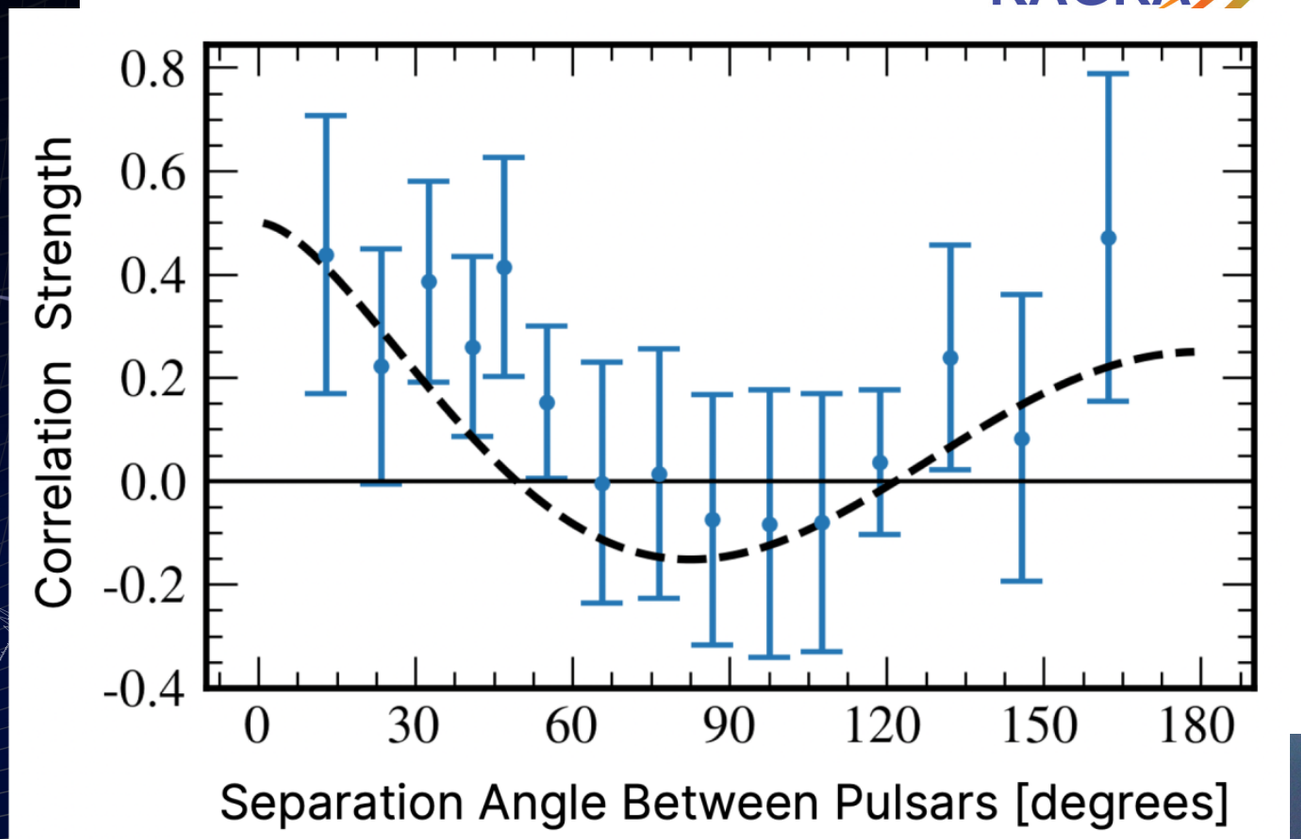
NANOgrav (USA) uses 68 pulsars

https://nanograv.org

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

Pulsar timing





NANOgrav 15 year data release, June 29, 2023

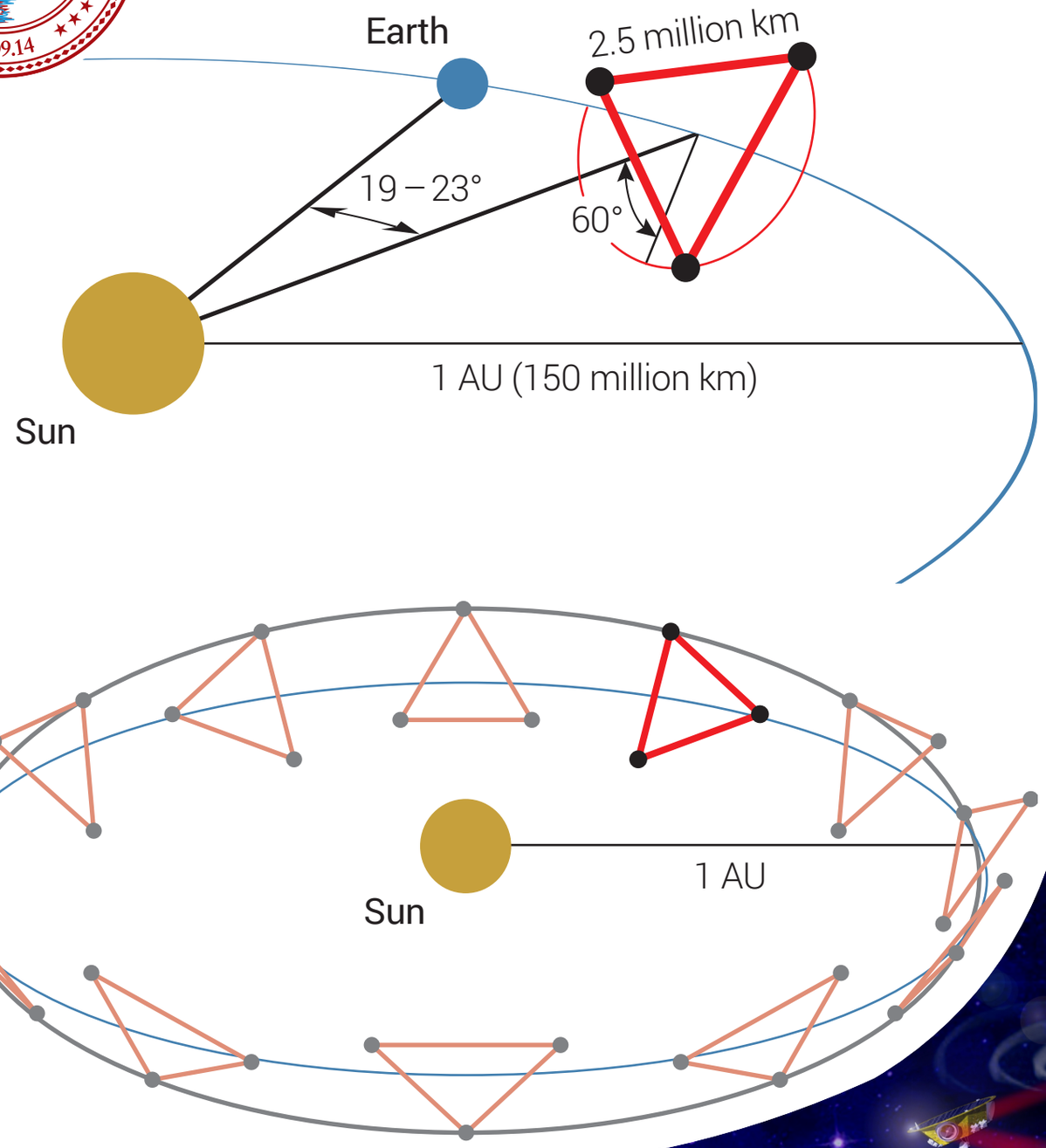
NANOgrav (USA) uses 68 pulsars

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

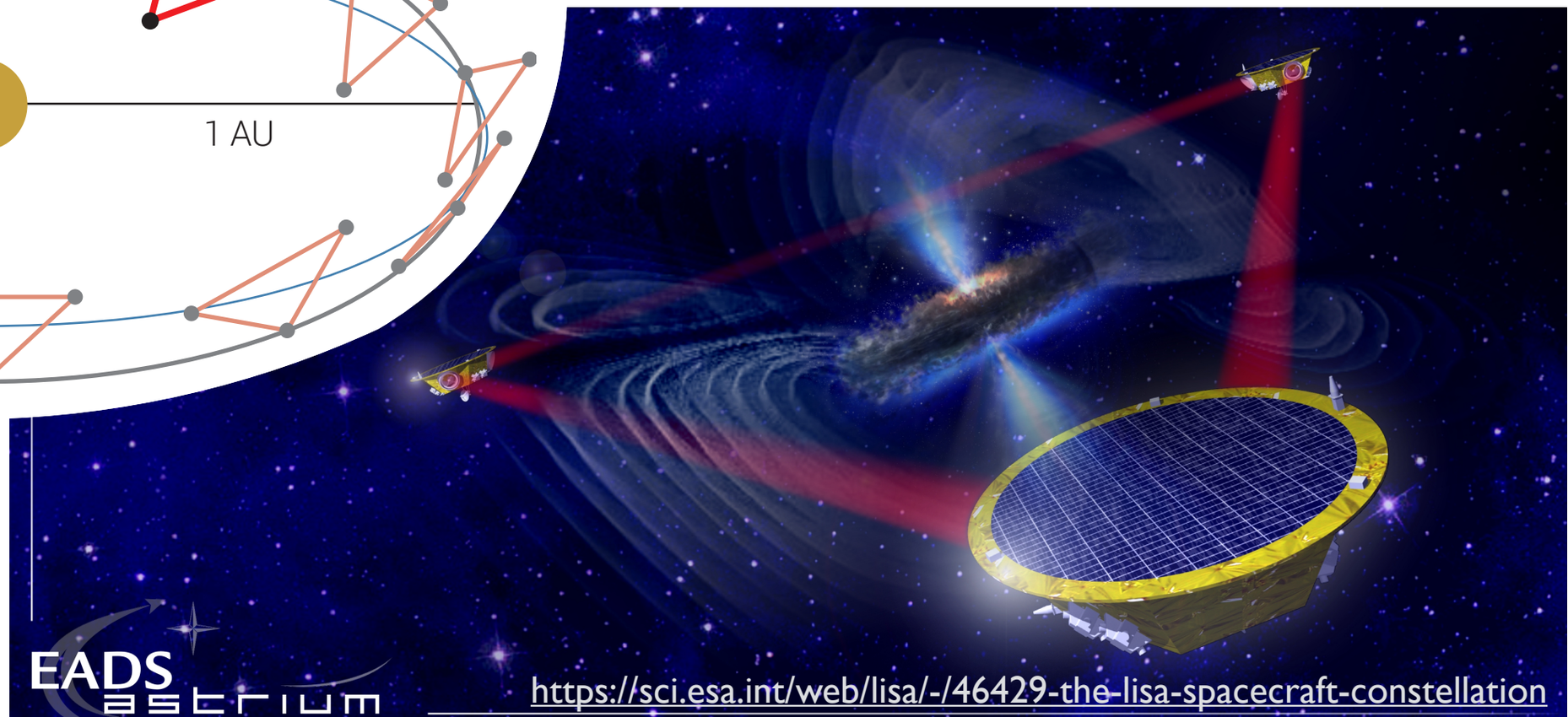
https://www.nsf.gov/news/mmg/media/images/vlasunrisejuly2008_h.jpg

https://nanograv.org

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

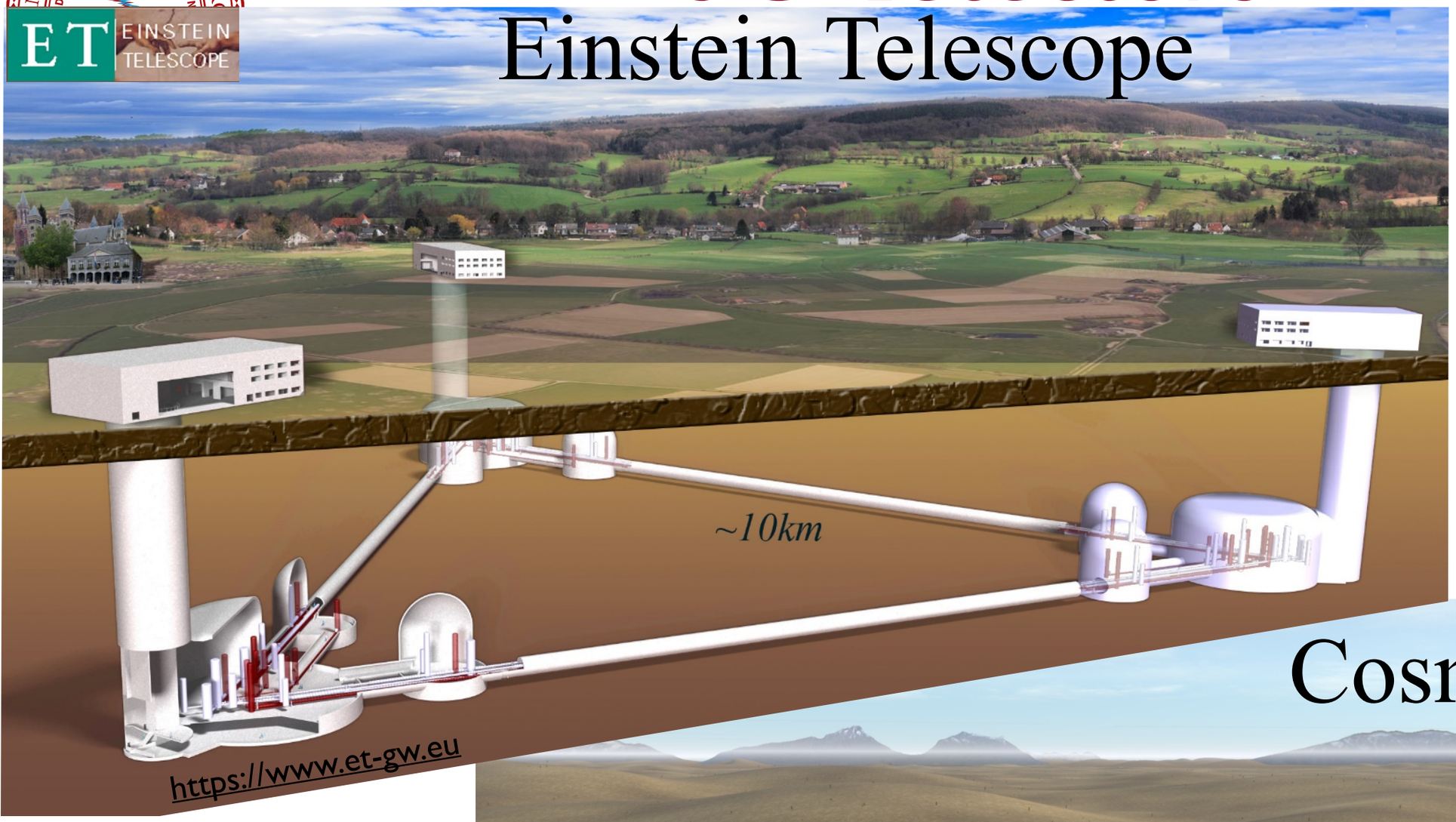


https://sci.esa.int/web/lisa/-/46429-the-lisa-spacecraft-constellation

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

3G detectors

Einstein Telescope



https://www.et-gw.eu

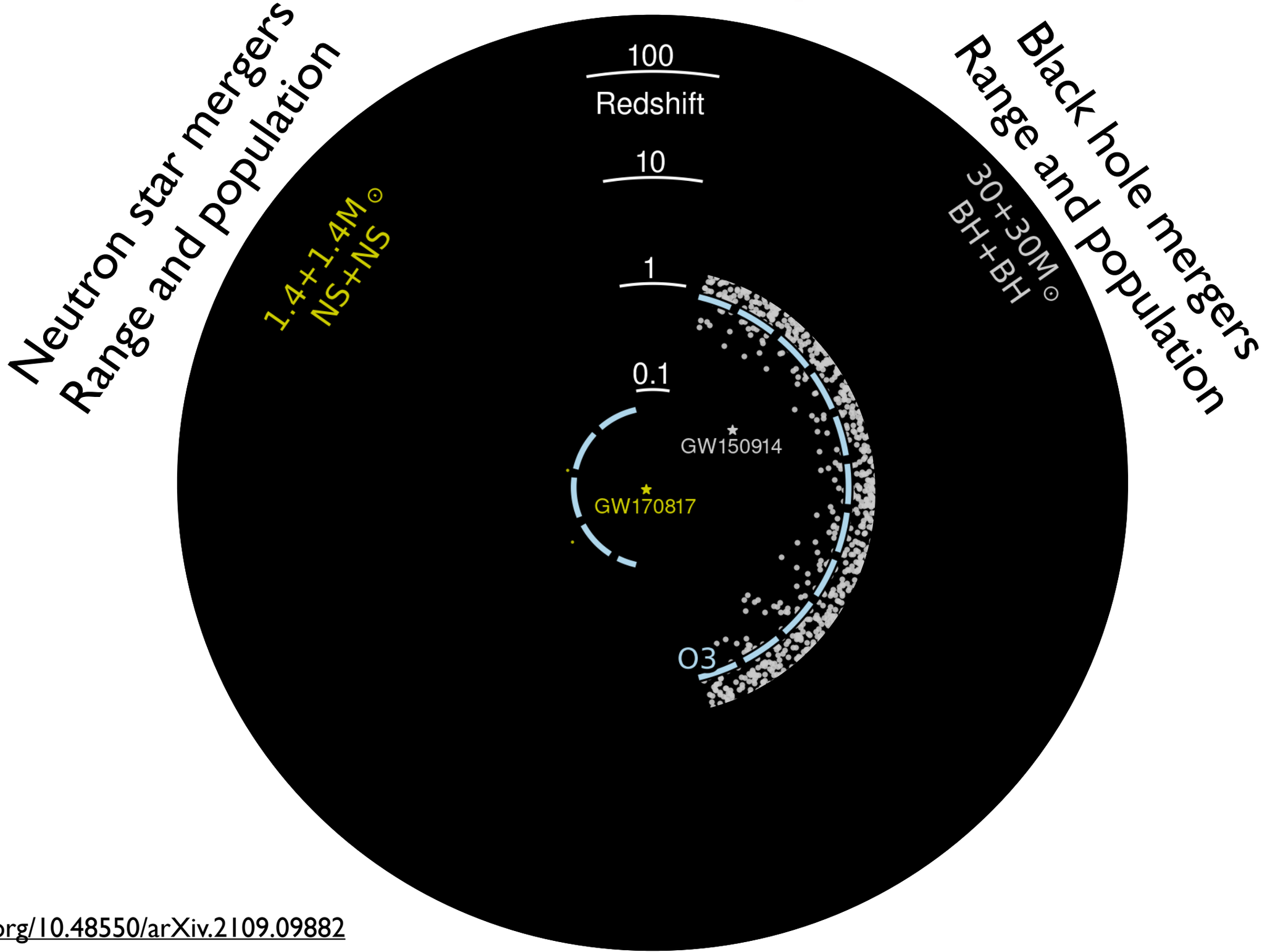
European concept
10 km triangle
underground
(other config's possible)

Cosmic Explorer

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

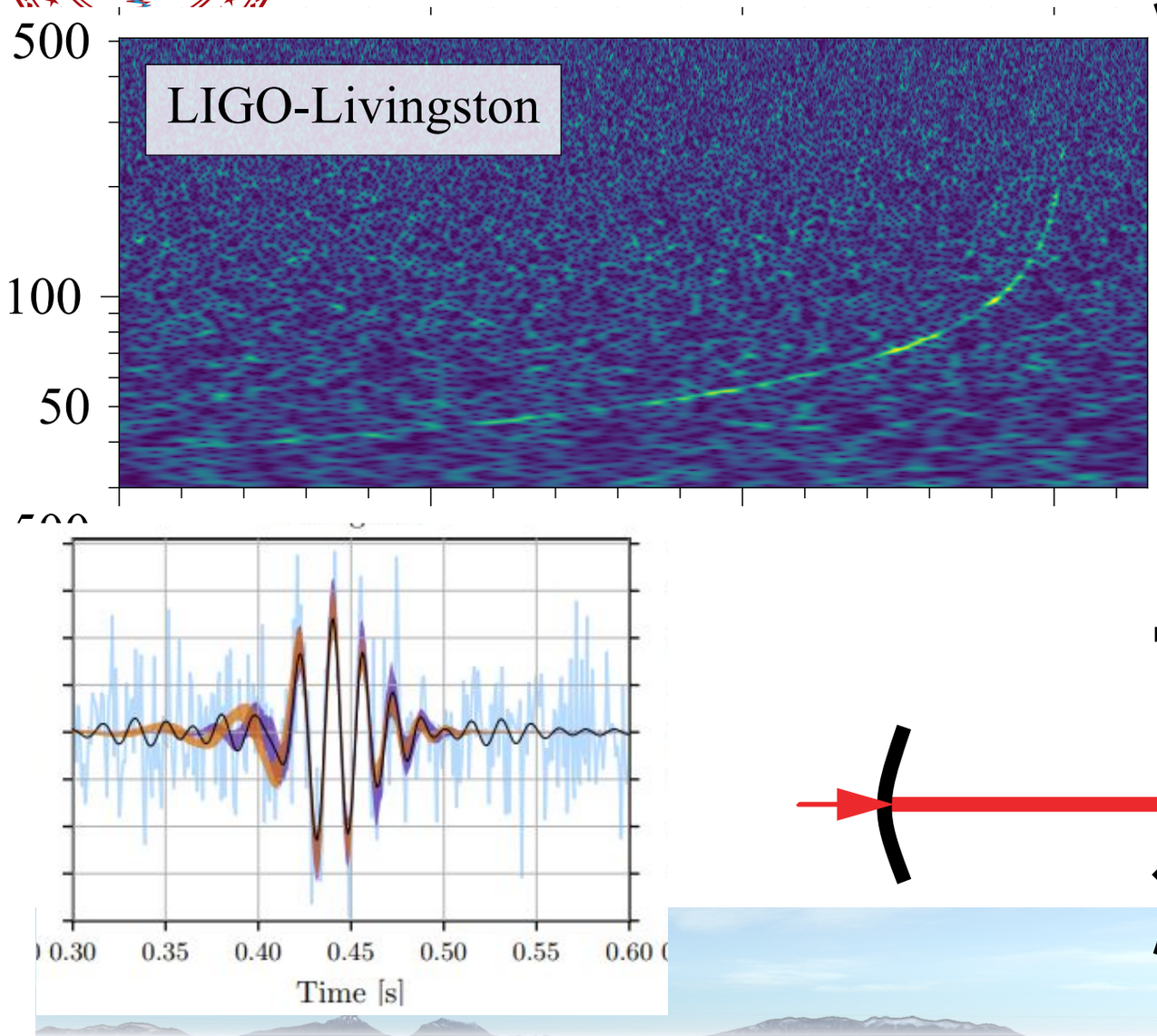
US concept
40 km & 20 km 'L'
(other config's possible)

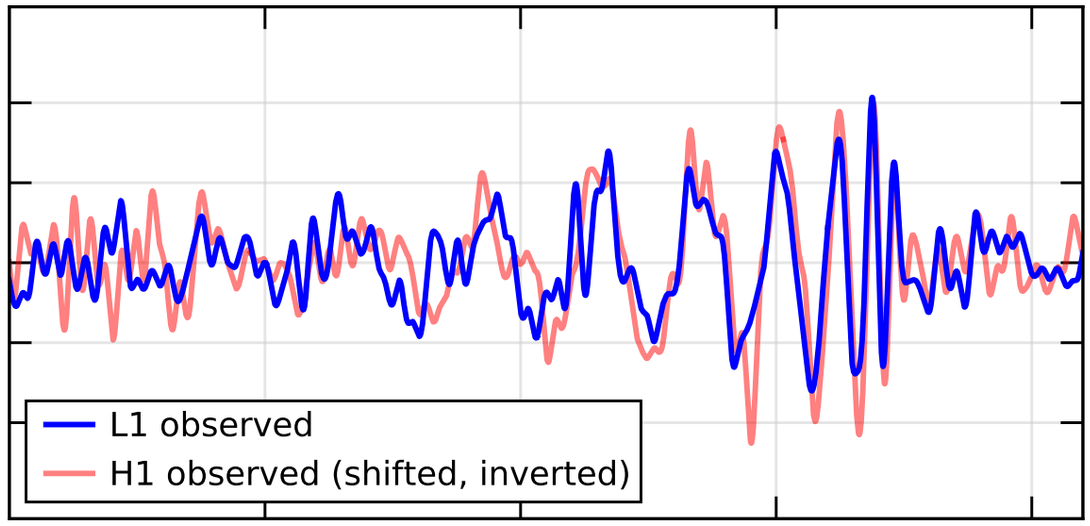
Science w/ Einstein Telescope & Cosmic Explorer

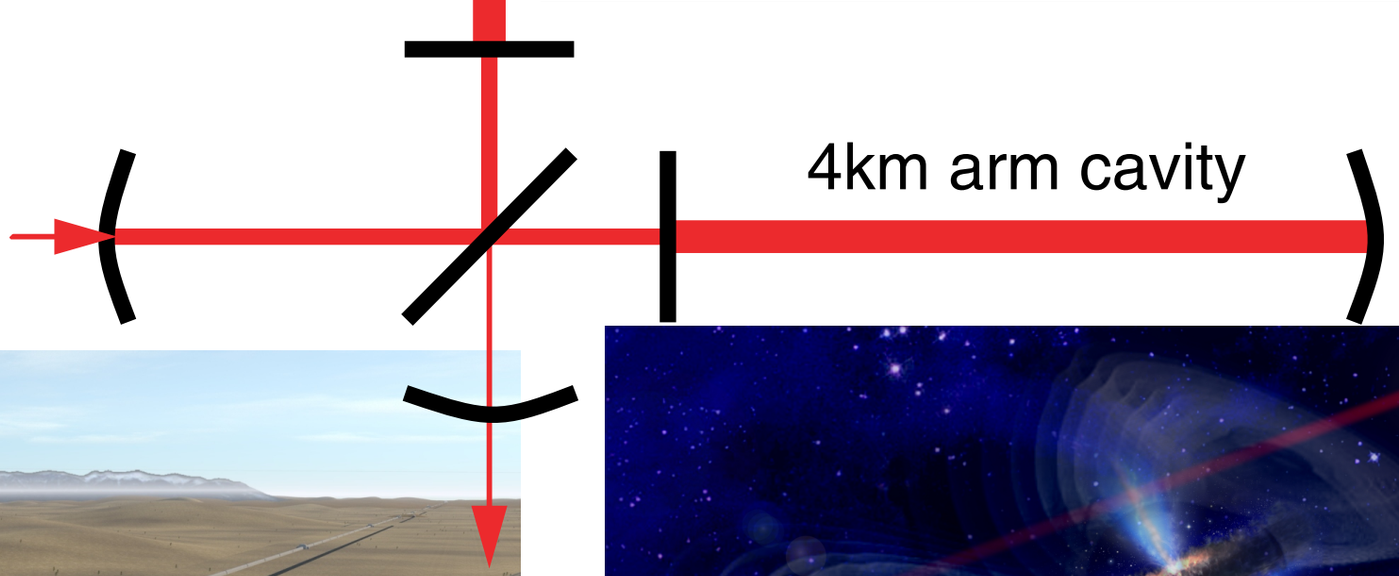


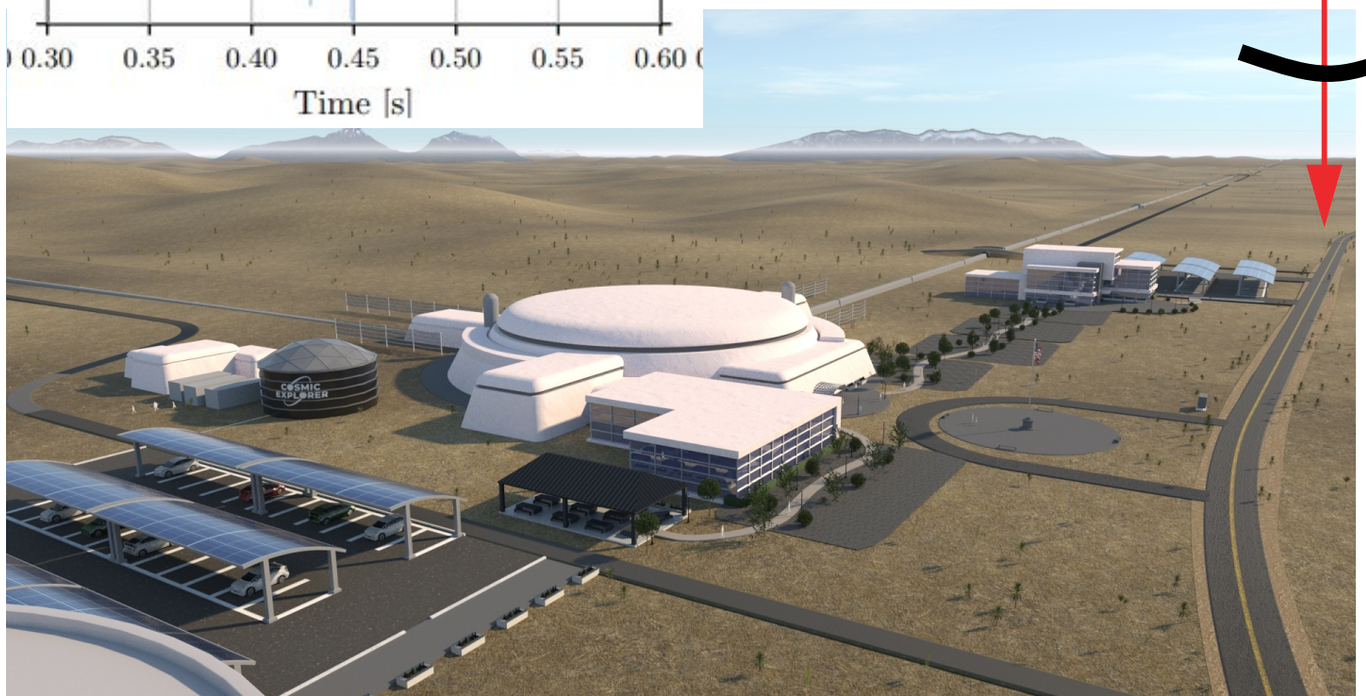
https://doi.org/10.48550/arXiv.2109.09882

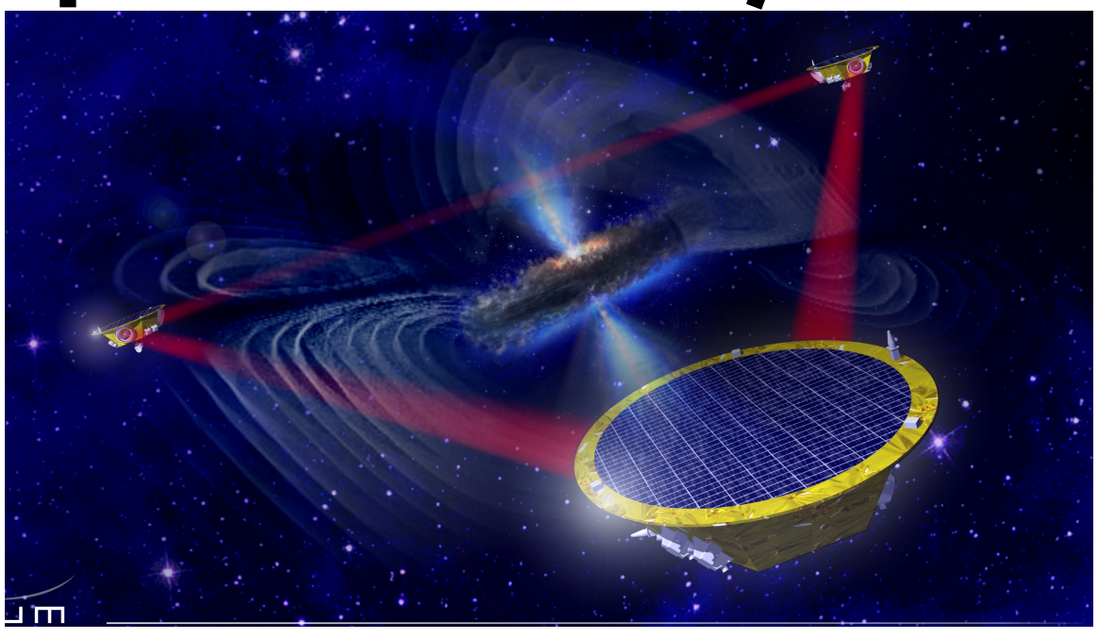
It's an exciting time!







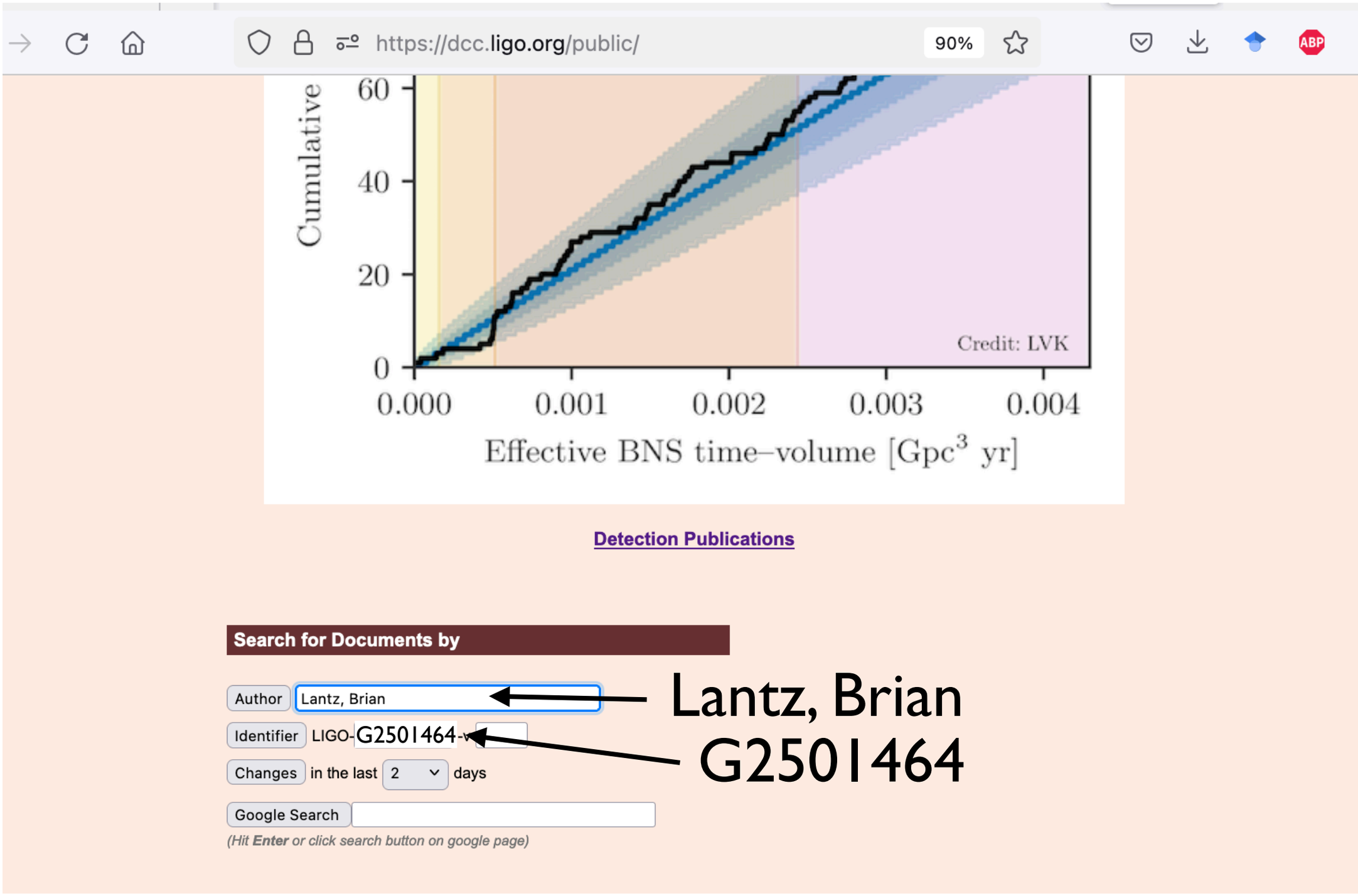




download the slides?

slides are at LIGO's Document Control Center

https://dcc.ligo.org/G2501464/public



Other good links:

GravitySPY - citizen science to improving the LIGO detectors
https://www.zooniverse.org/projects/zooniverse/gravity-spy

LIGO Lab home page
https://www.ligo.caltech.edu/

Stanford group homepage
https://ligo.stanford.edu/

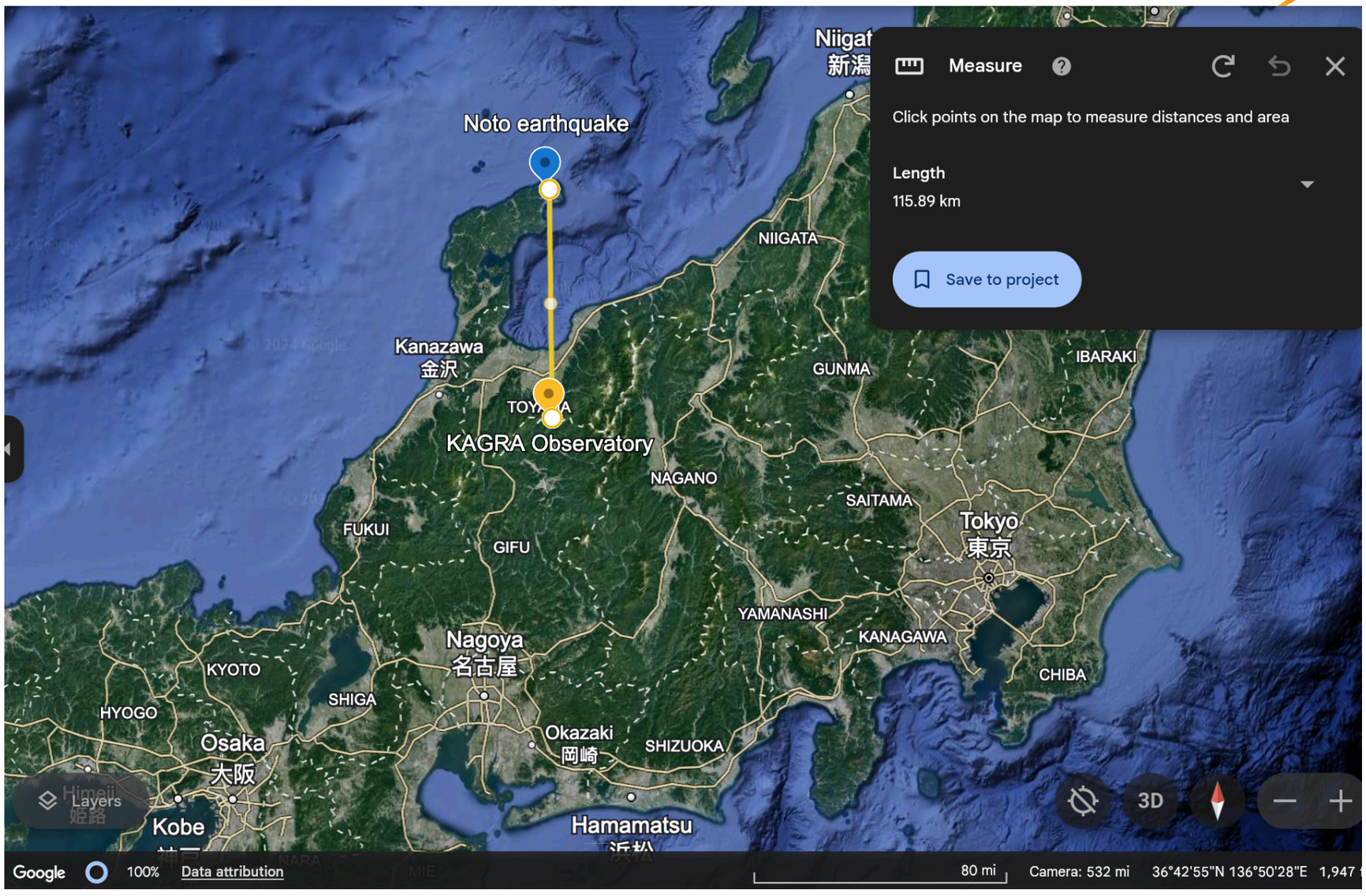
Gravitational Wave Open Science Center
https://gwosc.org/
  Download and analyze the data yourself

Today's detector status
https://gwosc.org/detector_status/

Latest Candidate Events
https://gracedb.ligo.org/

Earthquake near KAGRA

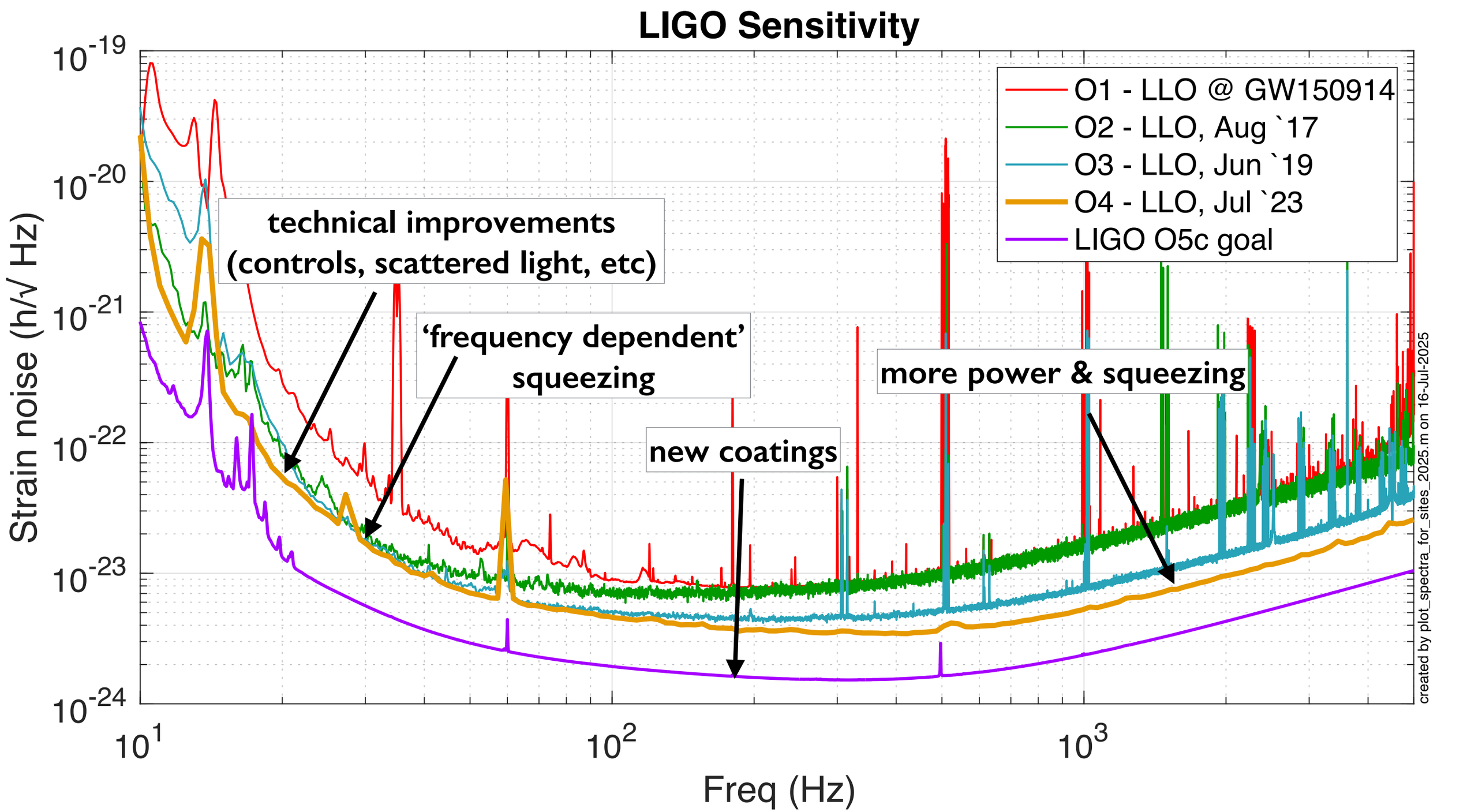
On Jan 1, 2024 there was a M7.5 EQ about 75 miles from the KAGRA detector.
At least 239 Japanese fatalities and major damage in the area.



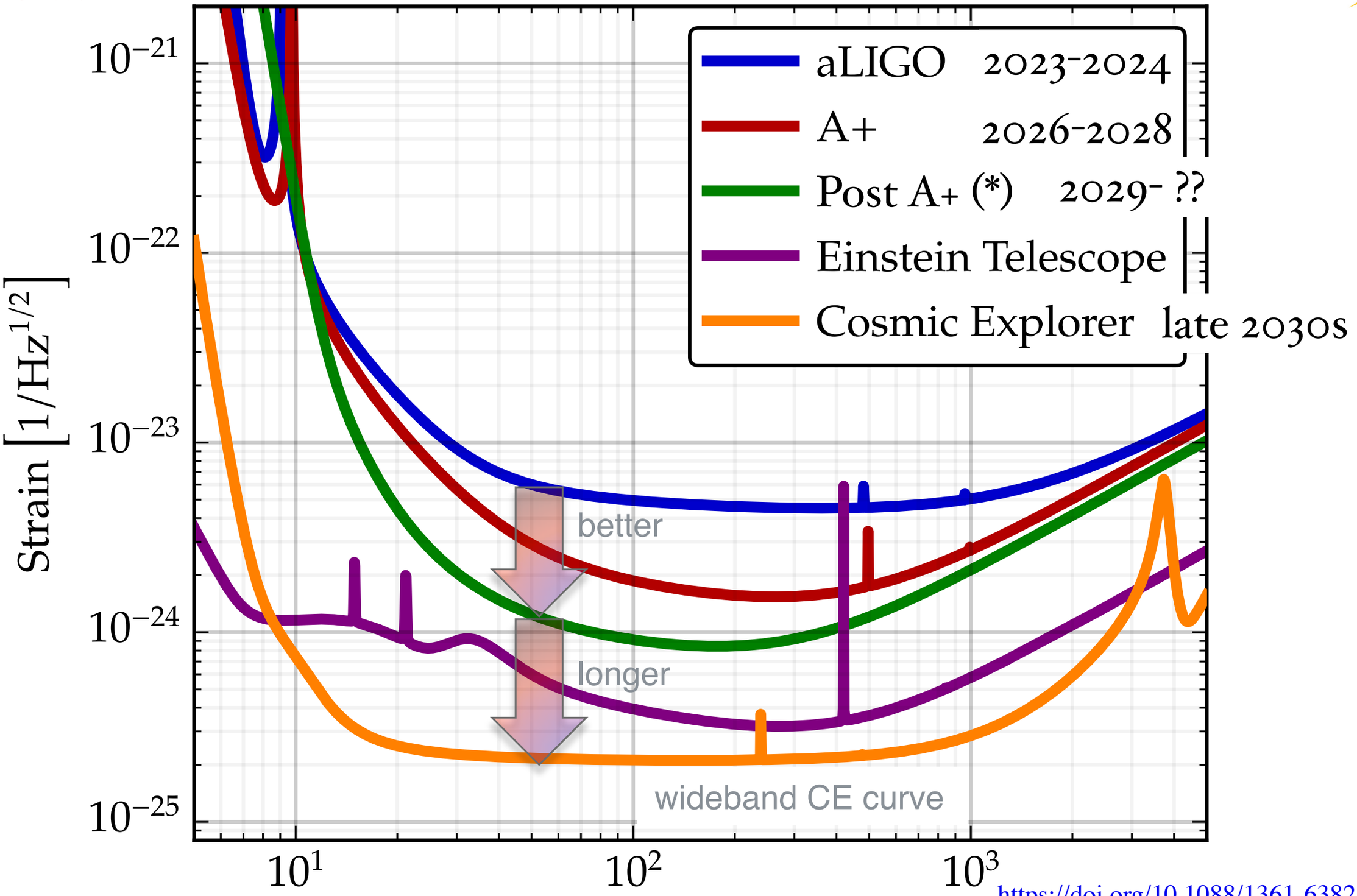
KAGRA had no fatalities and no significant damage to the mine tunnels, but detector is damaged, extent is still ??

Google earth & USGS earthquake map

LIGO A+ (for O5)


LIGO Sensitivity
O1 - LLO @ GW150914
O2 - LLO, Aug `17
O3 - LLO, Jun `19
O4 - LLO, Jul `23
LIGO O5c goal
technical improvements
(controls, scattered light, etc)
'frequency dependent'
squeezing
new coatings
more power & squeezing
Strain noise (h/√ Hz)
Freq (Hz)
created by plot_spectra_for_sites_2025.m on 16-Jul-2025

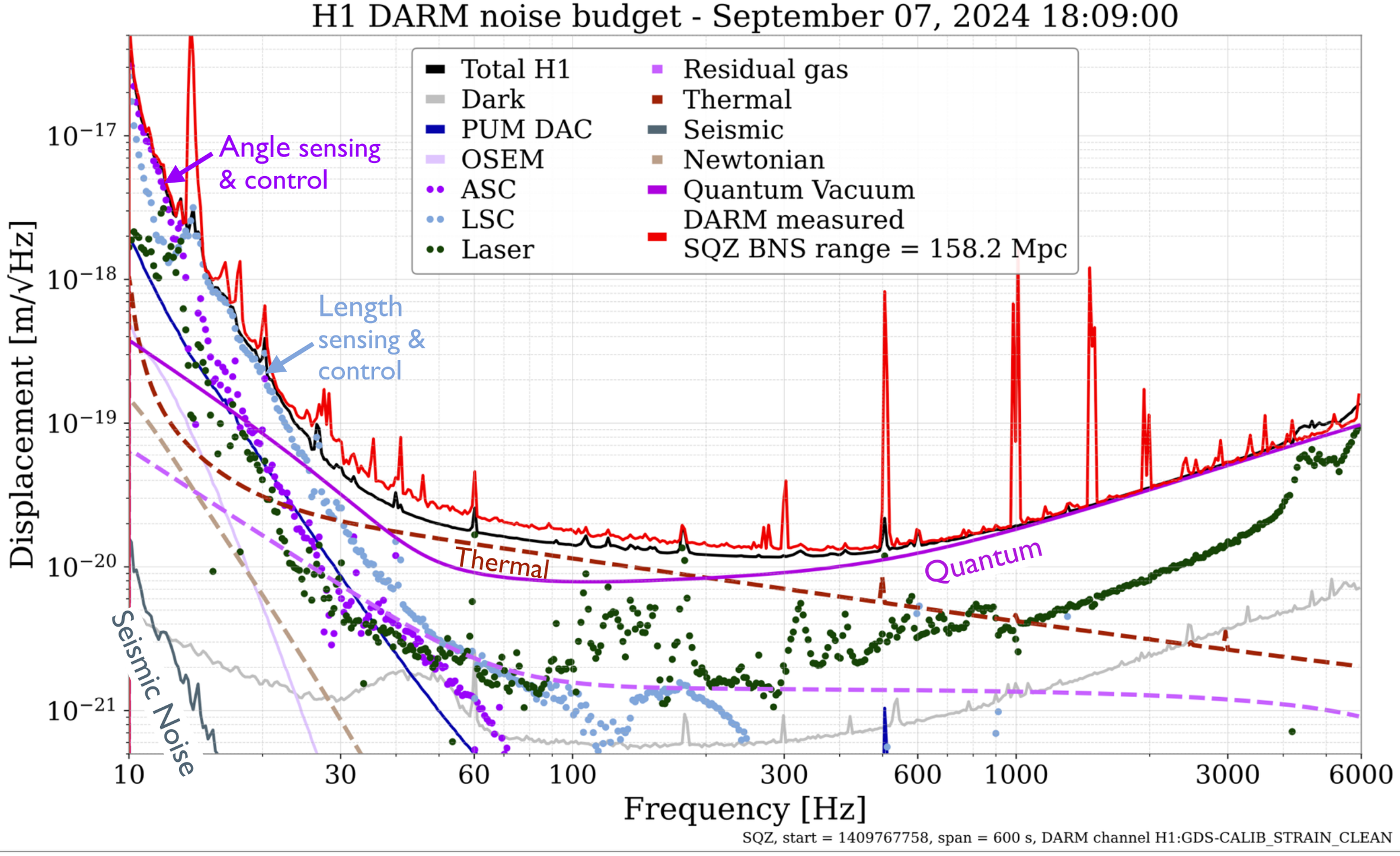
3G detectors



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

LIGO noise budget



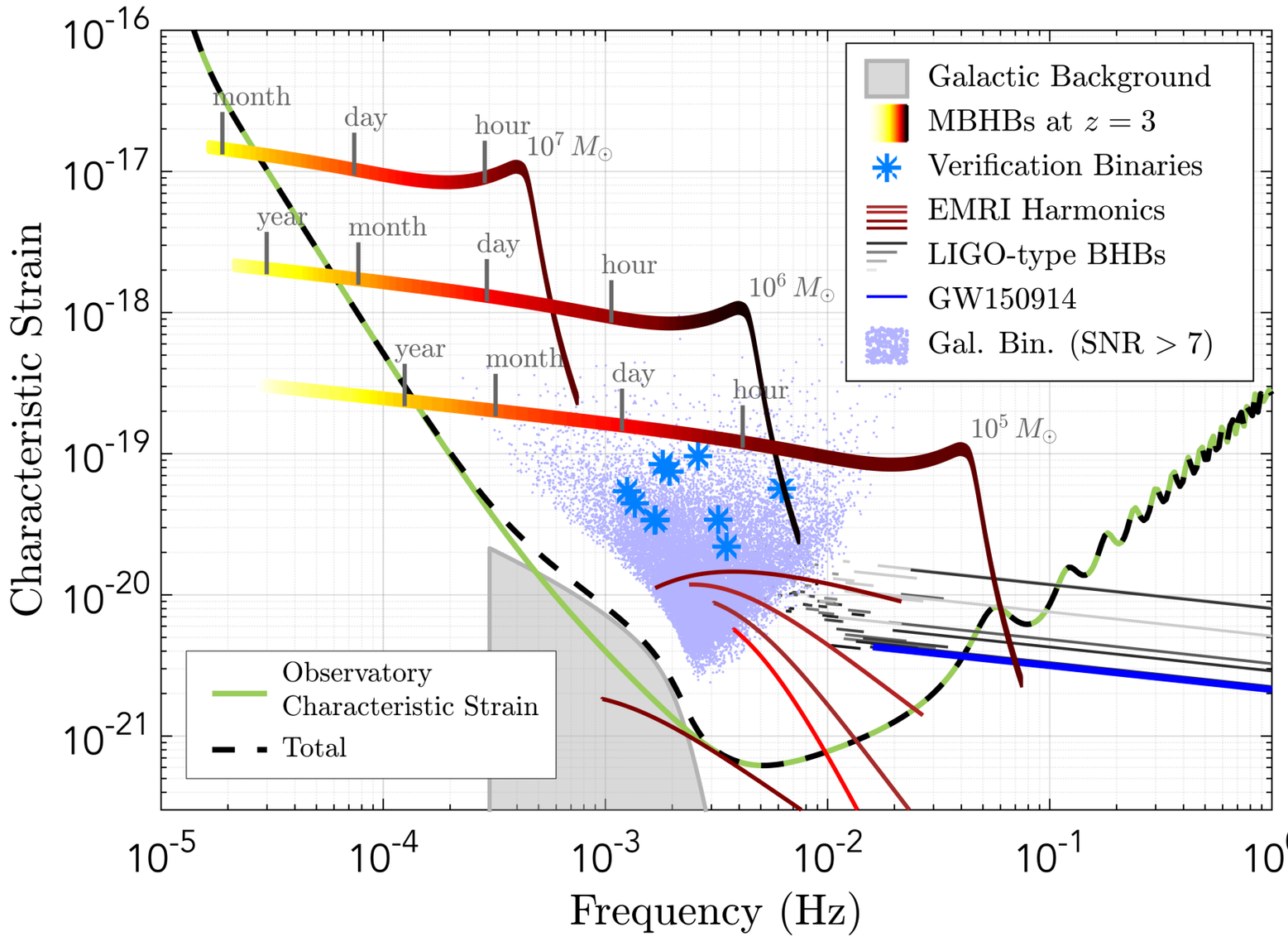
E. Capote G2401844

see LHO:80215 for details

LISA Science

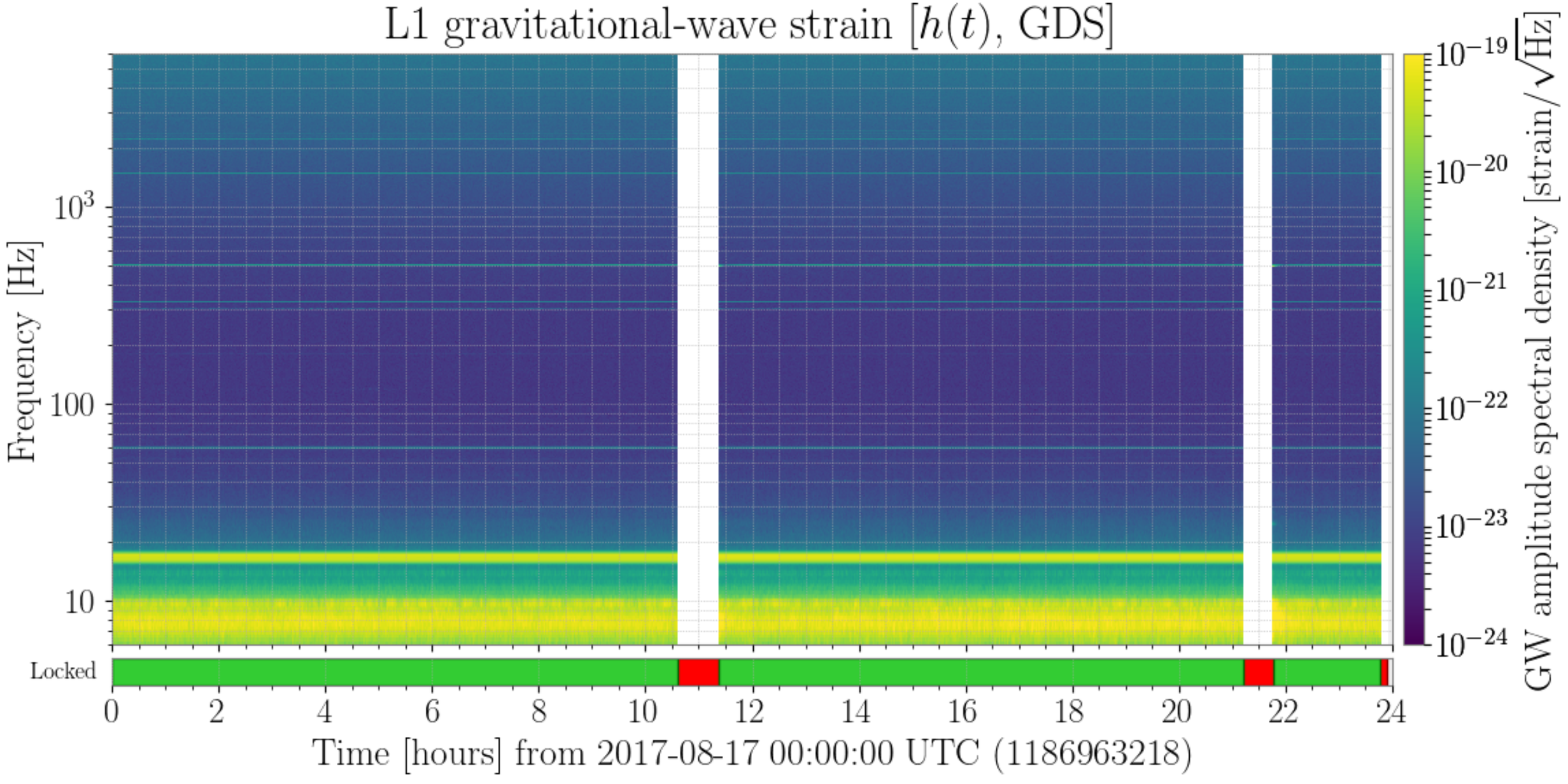
LISA will see lots of new sources

- 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…



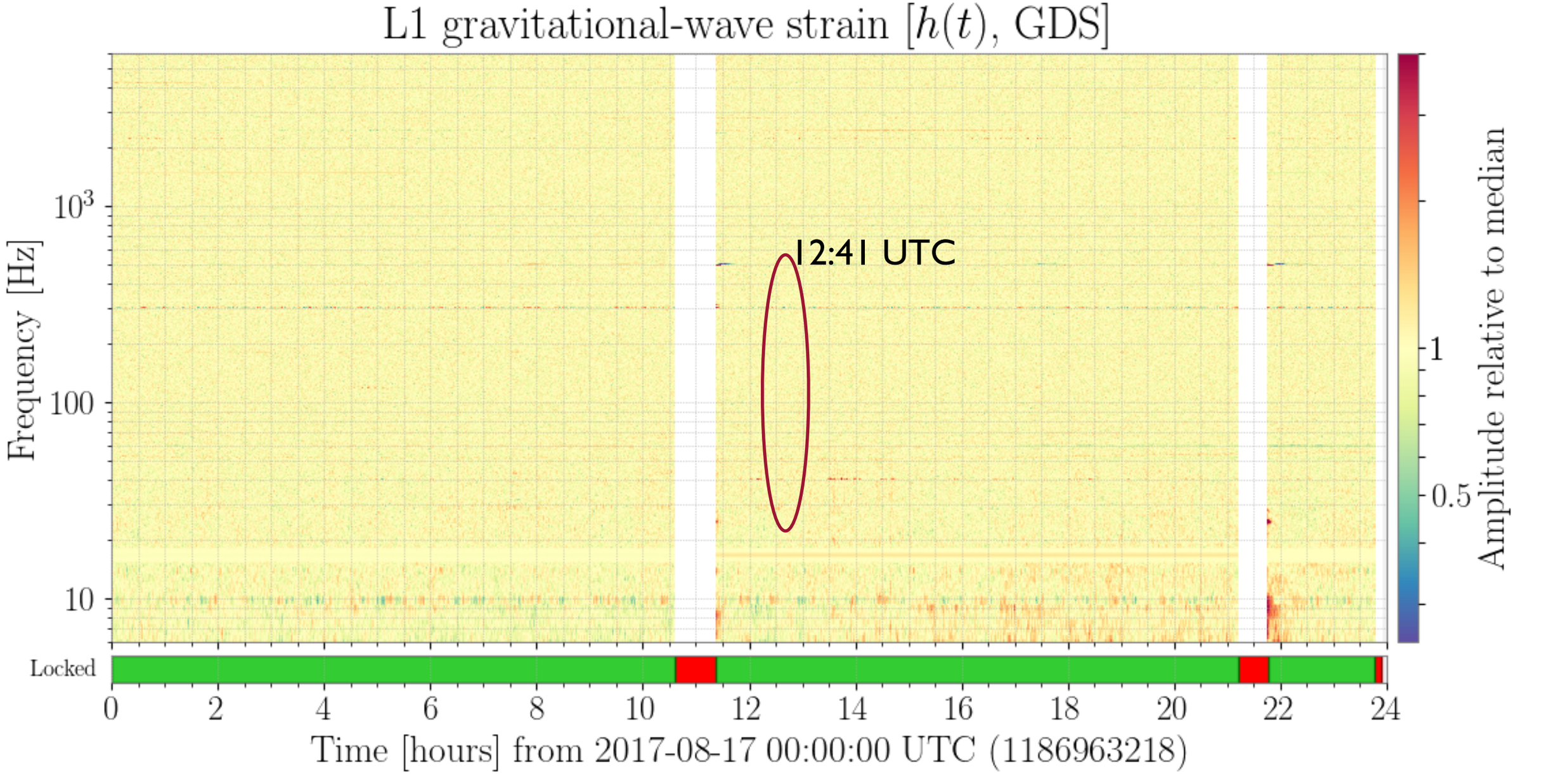
Watch for changes…

Spectrogram - 1 day at LLO

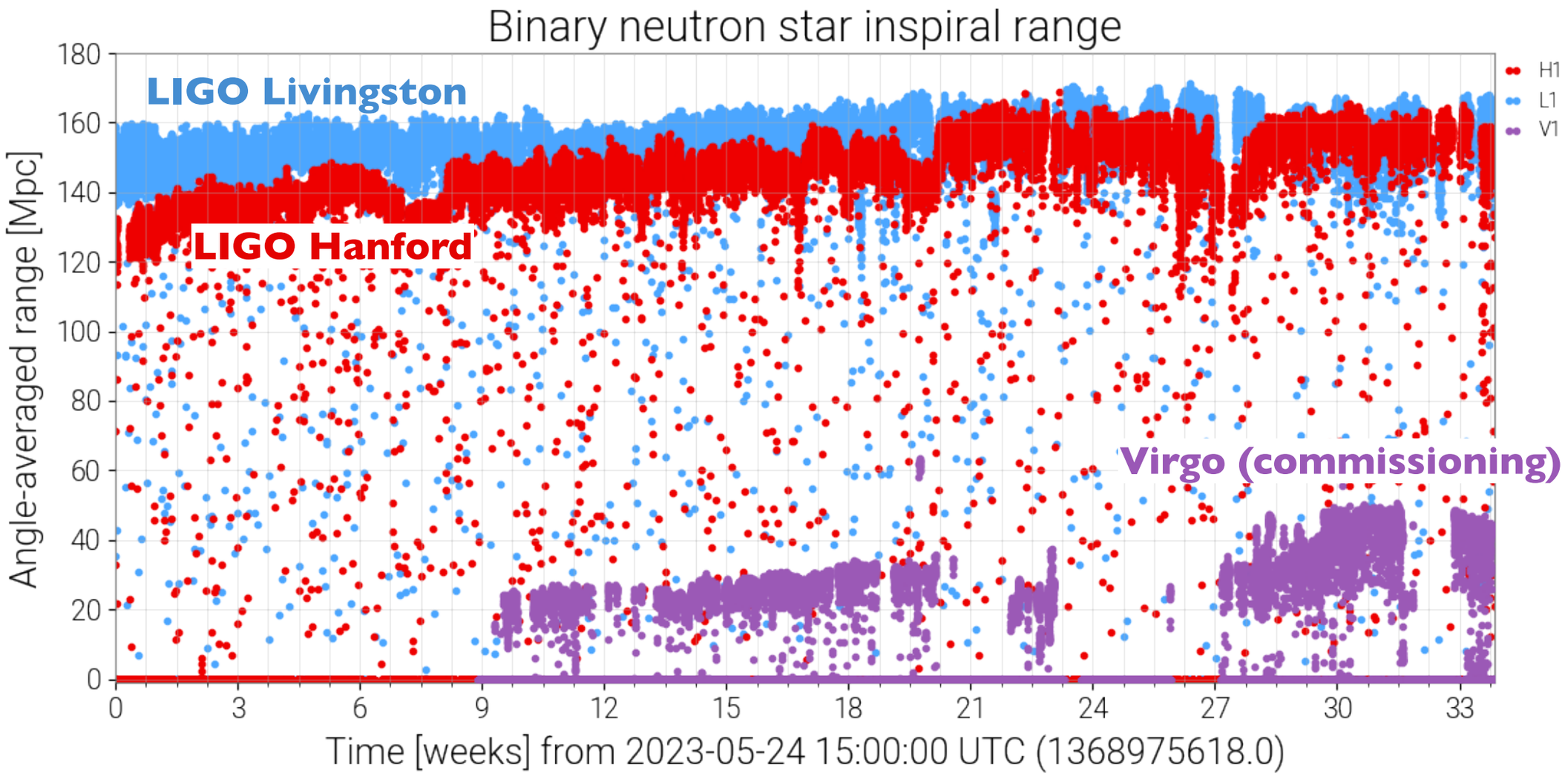


Watch for changes…

Normalized Spectrogram - 1 day at LLO



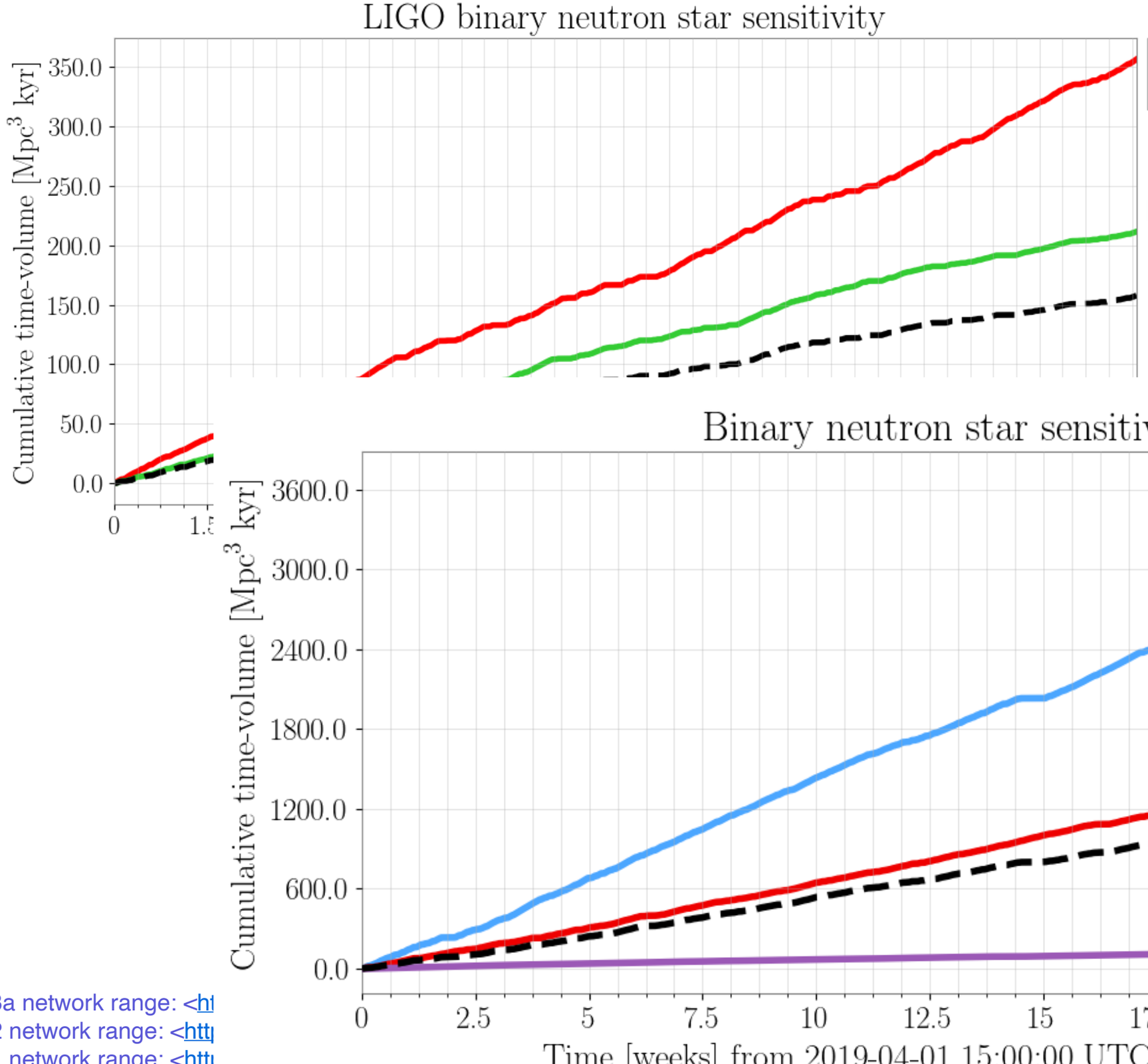
range in O4a



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