

*Exploring the
Gravitational wave
Universe with LIGO*

Prof. Brian Lantz

July 2, 2025

SURP lecture series

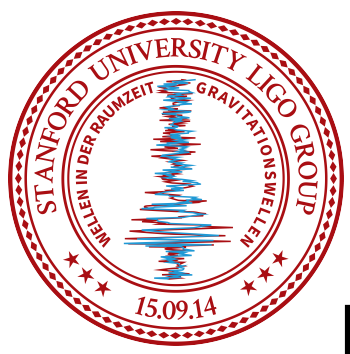
LIGO-G2501382

LIGO

National Science Foundation + International partners

LIGO Scientific Collaboration



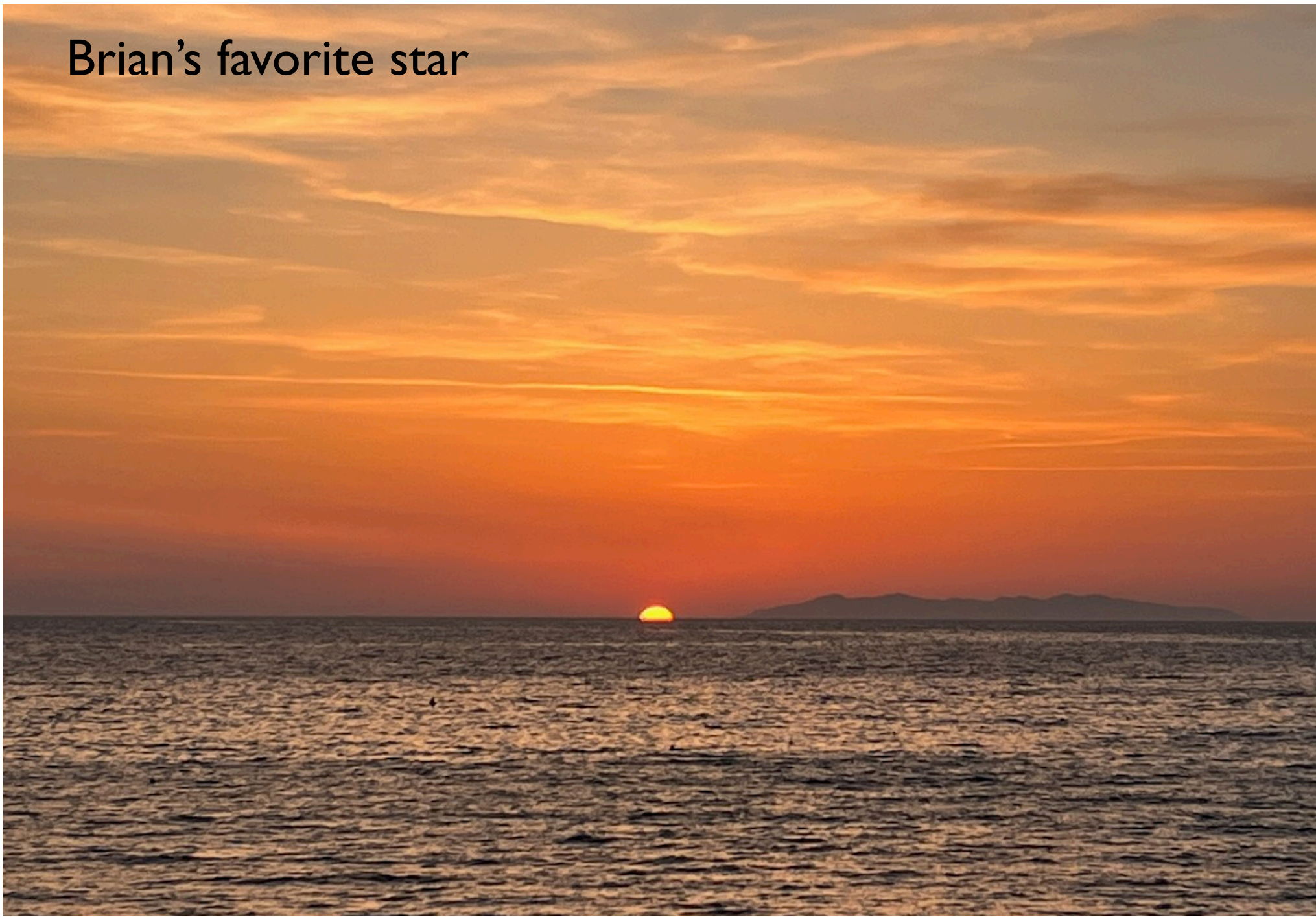


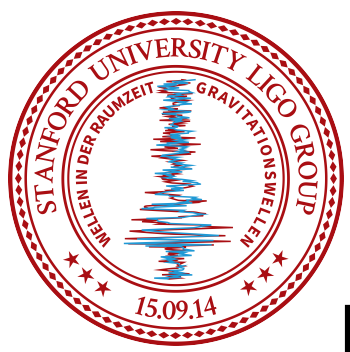
2 terms: Black Holes & LIGO



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

Brian's favorite star

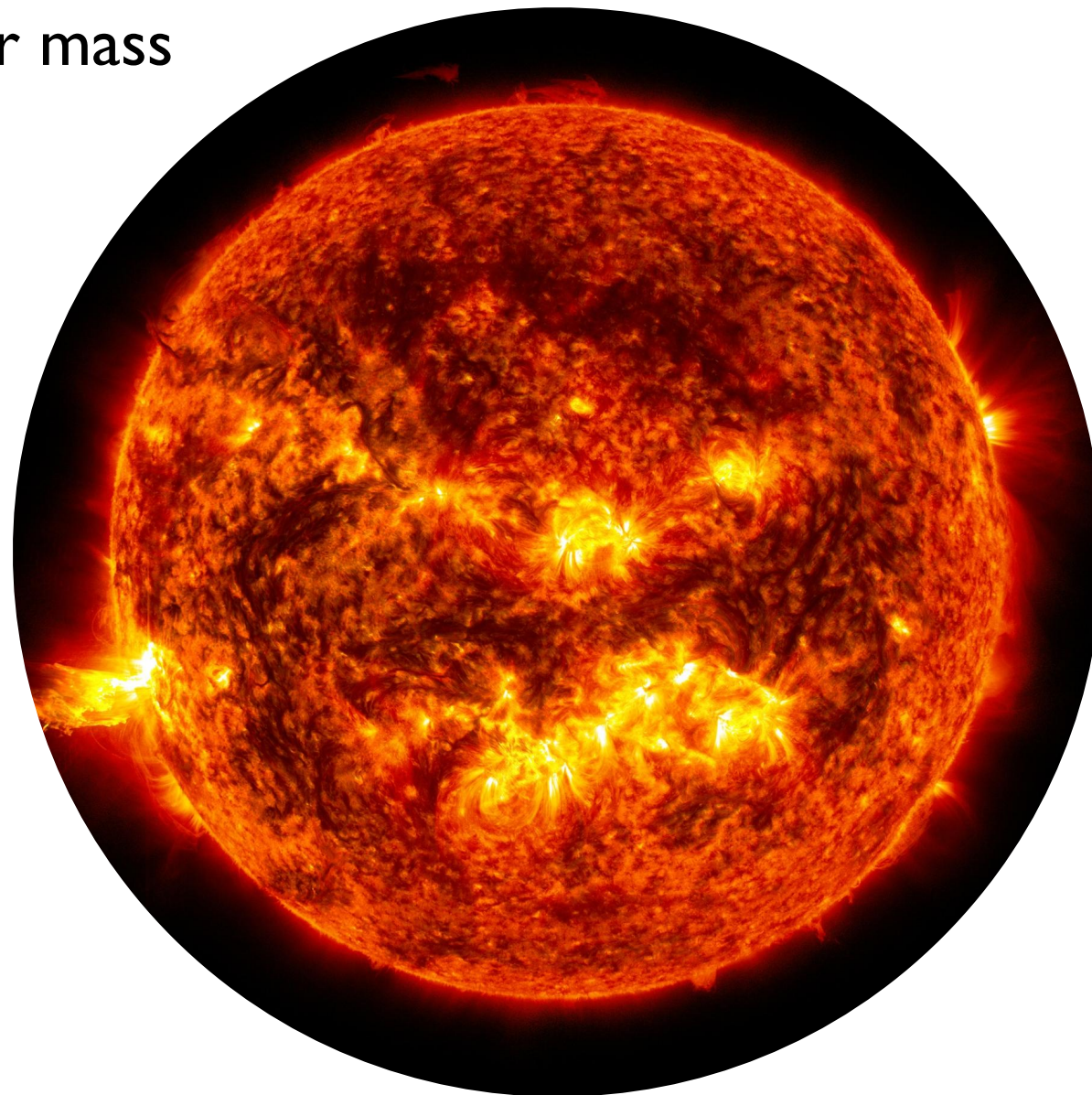




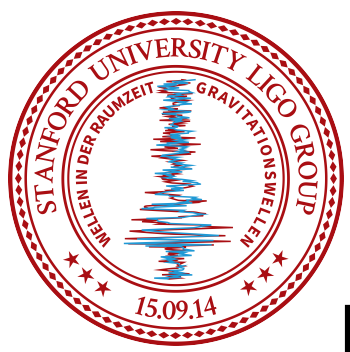
Black Holes

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

Brian's favorite star
1 solar mass



865,000 miles



Black Holes



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

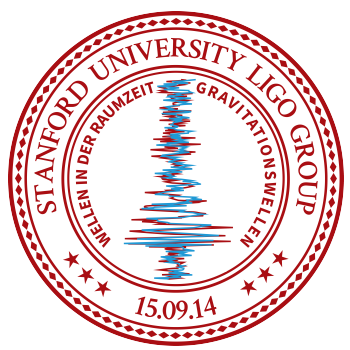
First LIGO detection:

- ~30 solar mass
110 miles in diameter

- 3.7 miles
1 solar mass
(not going to happen)

865,000 miles





2 terms: Black Holes & LIGO

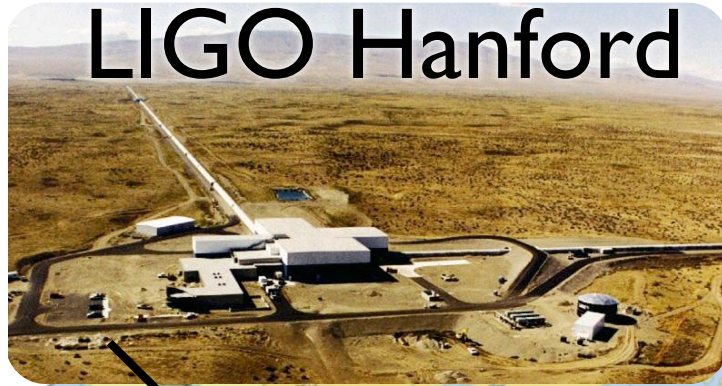


LIGO = Laser Interferometer Gravitational-wave Observatory



International Network

LIGO Hanford



GEO 600



KAGRA



VIRGO



LIGO India



project approved

LIGO Livingston



ACICA

LIGO Hanford



LIGO Livingston



Strain (10^{-21})

Strain (10^{-21})

Strain (10^{-21})

LIGO Hanford Data

Predicted

LIGO Livingston Data

Predicted

LIGO Hanford Data (shifted)

LIGO Livingston Data

0.30

0.35

0.40

0.45

Time (sec)

AGRA

GO India

Project approved

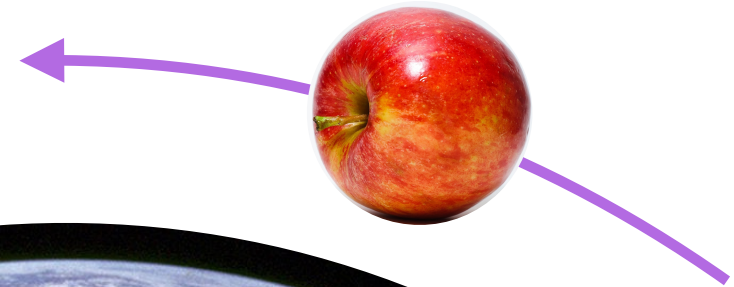


What is a Gravitational Wave?



$$F = \frac{Gm_1m_2}{r^2}$$

Implies immediate
action at a distance



Sir Isaac Newton

By Sir Godfrey Kneller

- <http://www.newton.cam.ac.uk/art/portrait.html>

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?

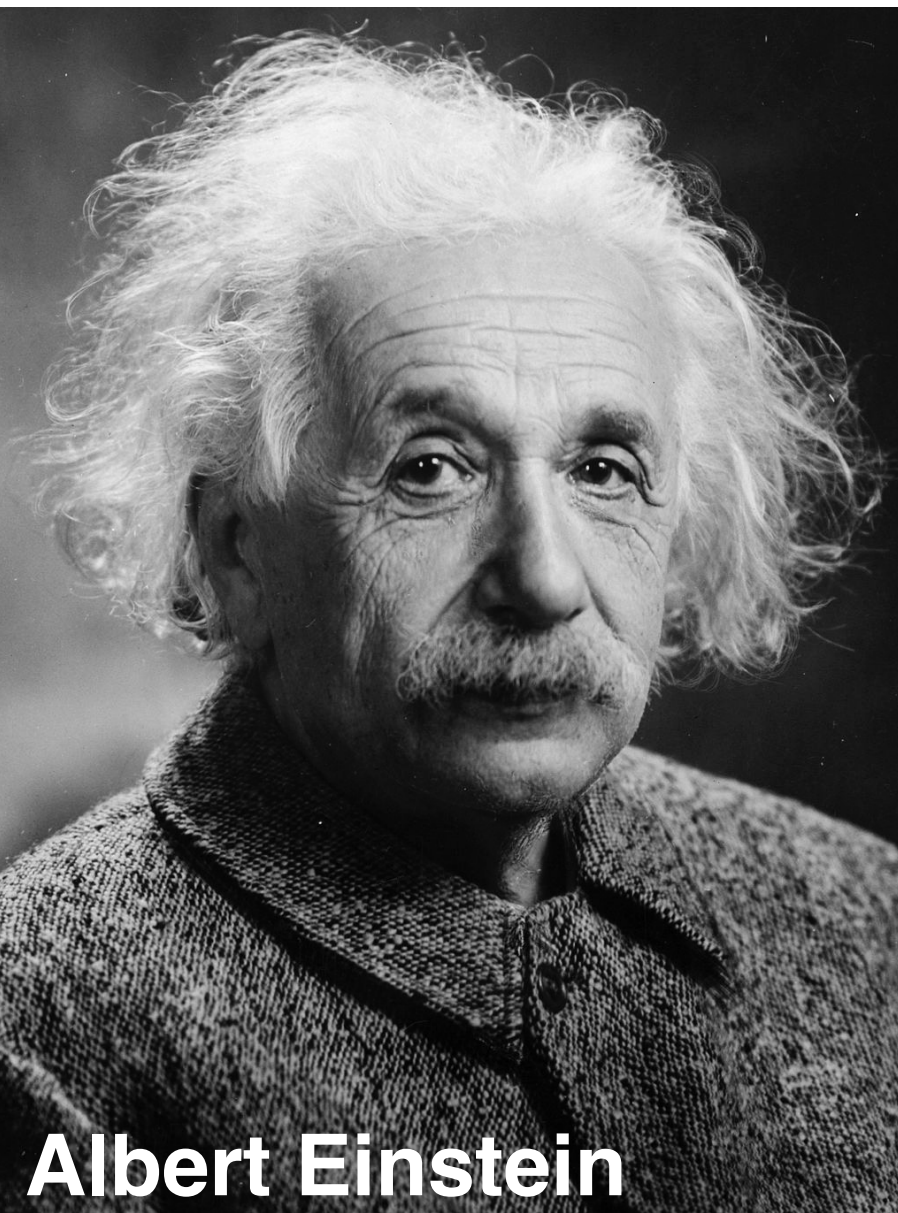


Predicted by Einstein in 1916 as part of GR.

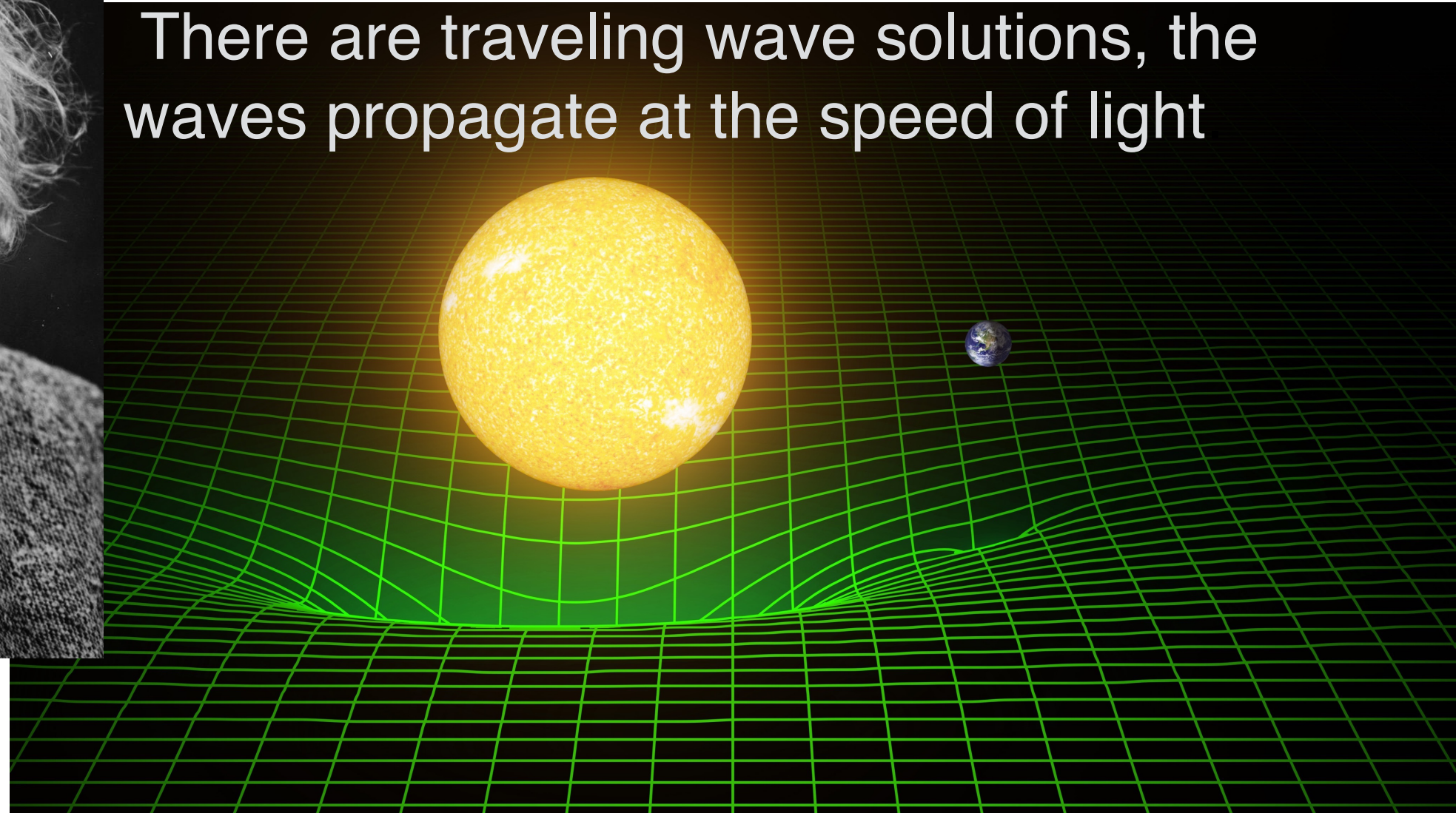
“Spacetime tells matter how to move,
matter tells spacetime how to curve”

- J. A. Wheeler

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

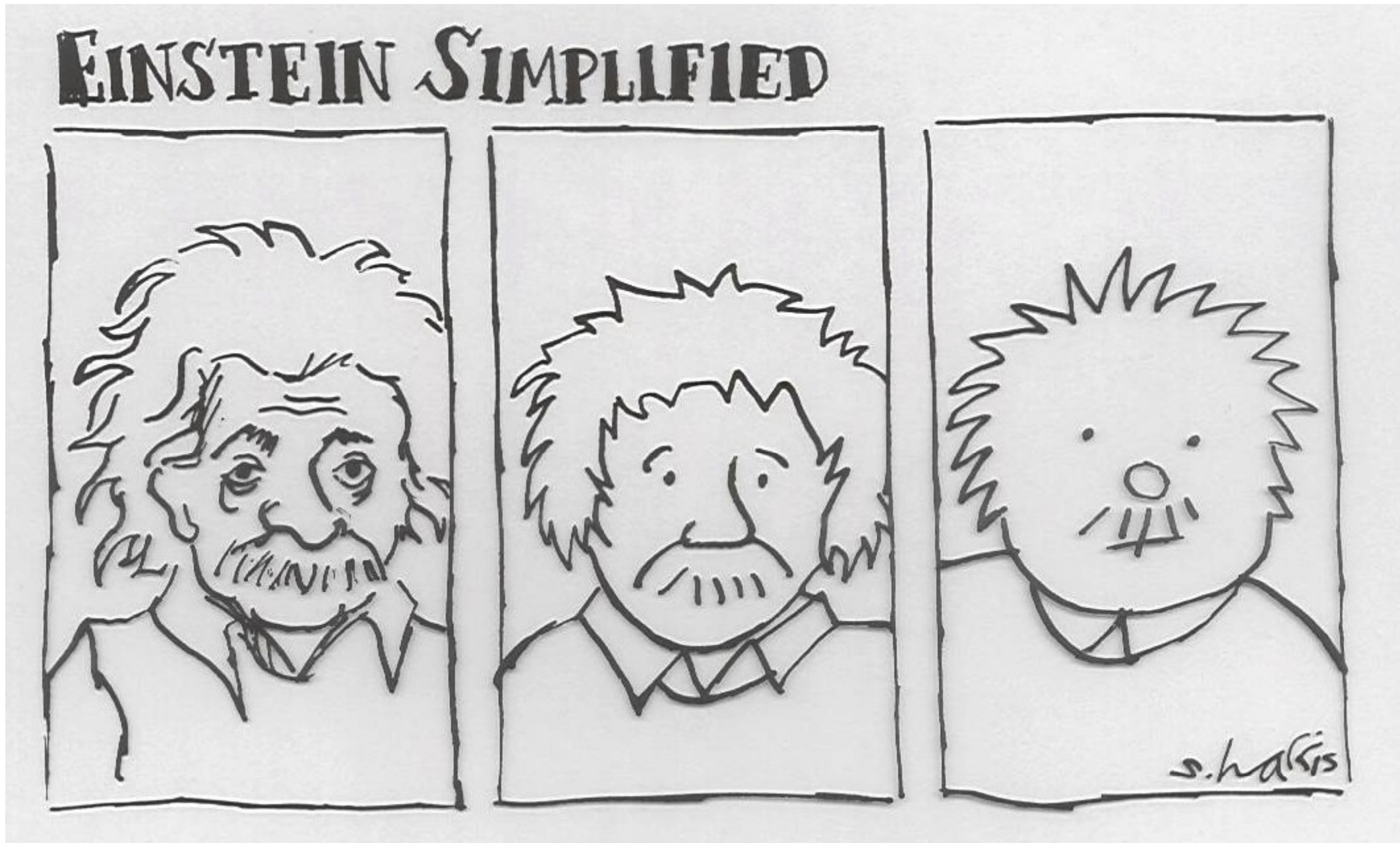


Albert Einstein



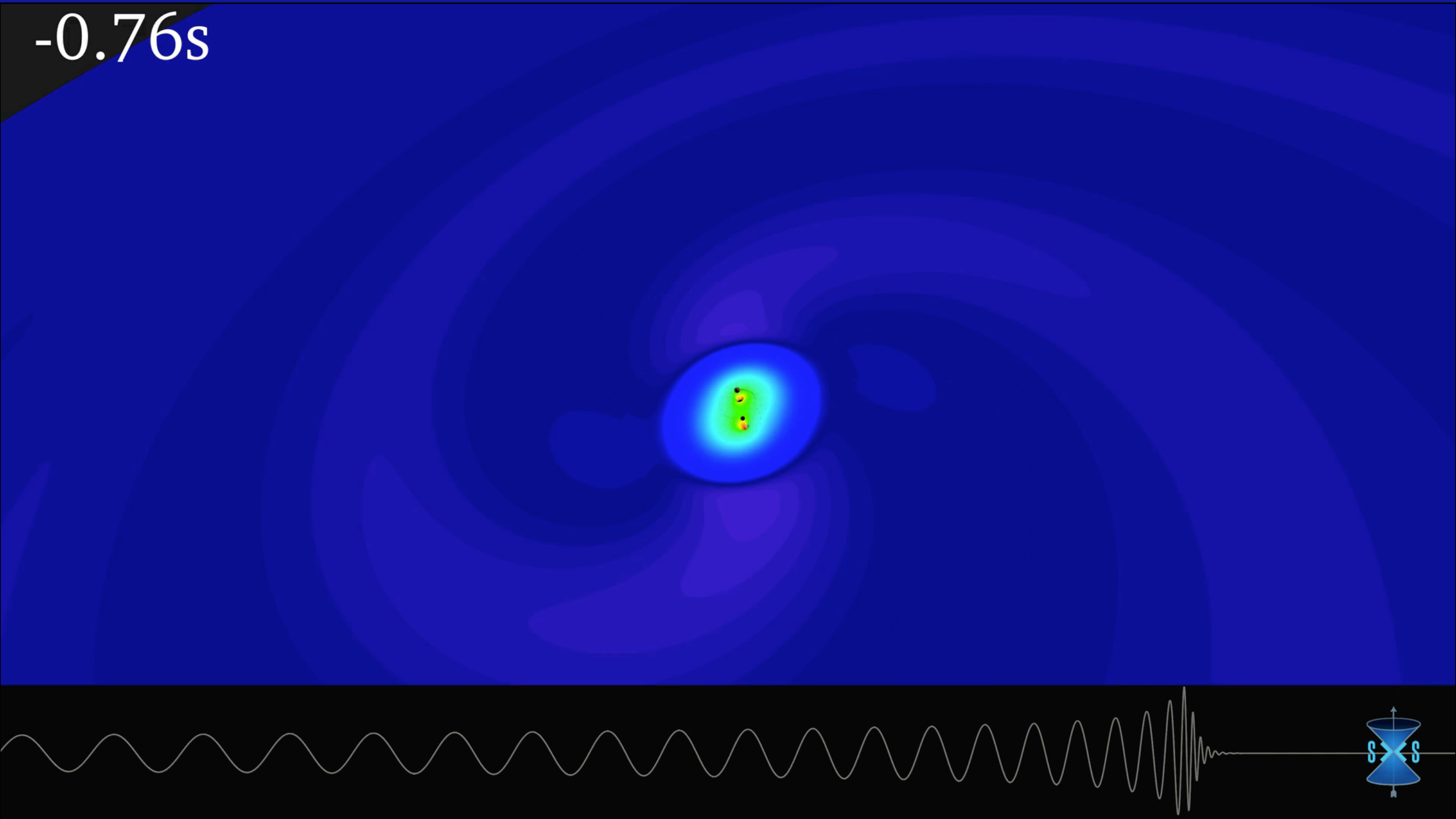


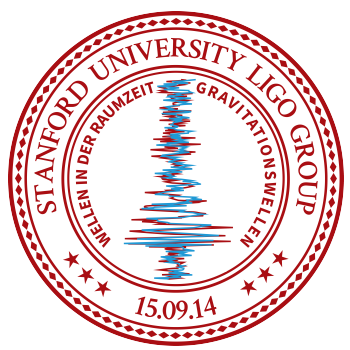
What is a Gravitational Wave?



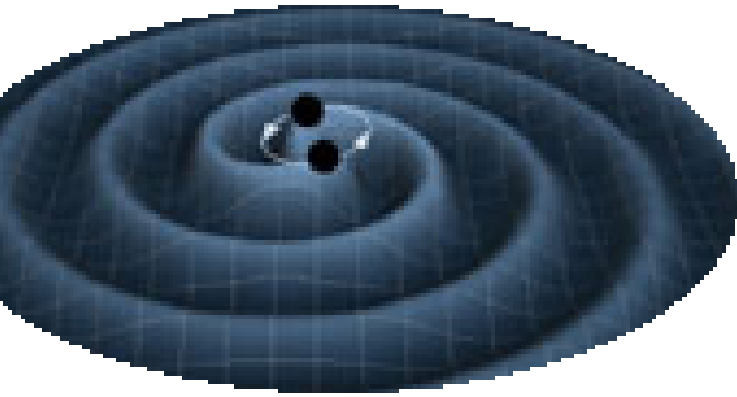
Simulation of the event

-0.76s

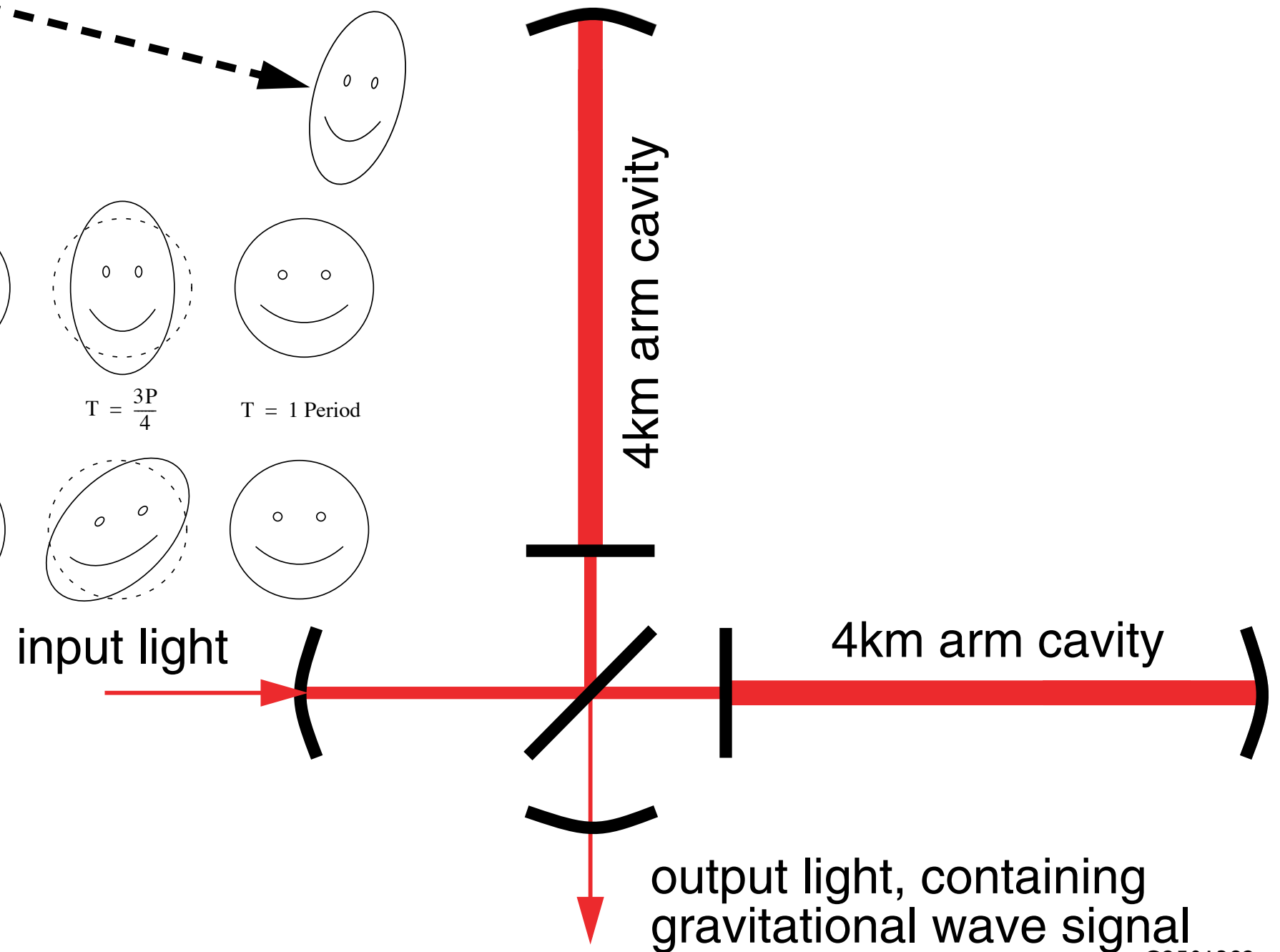
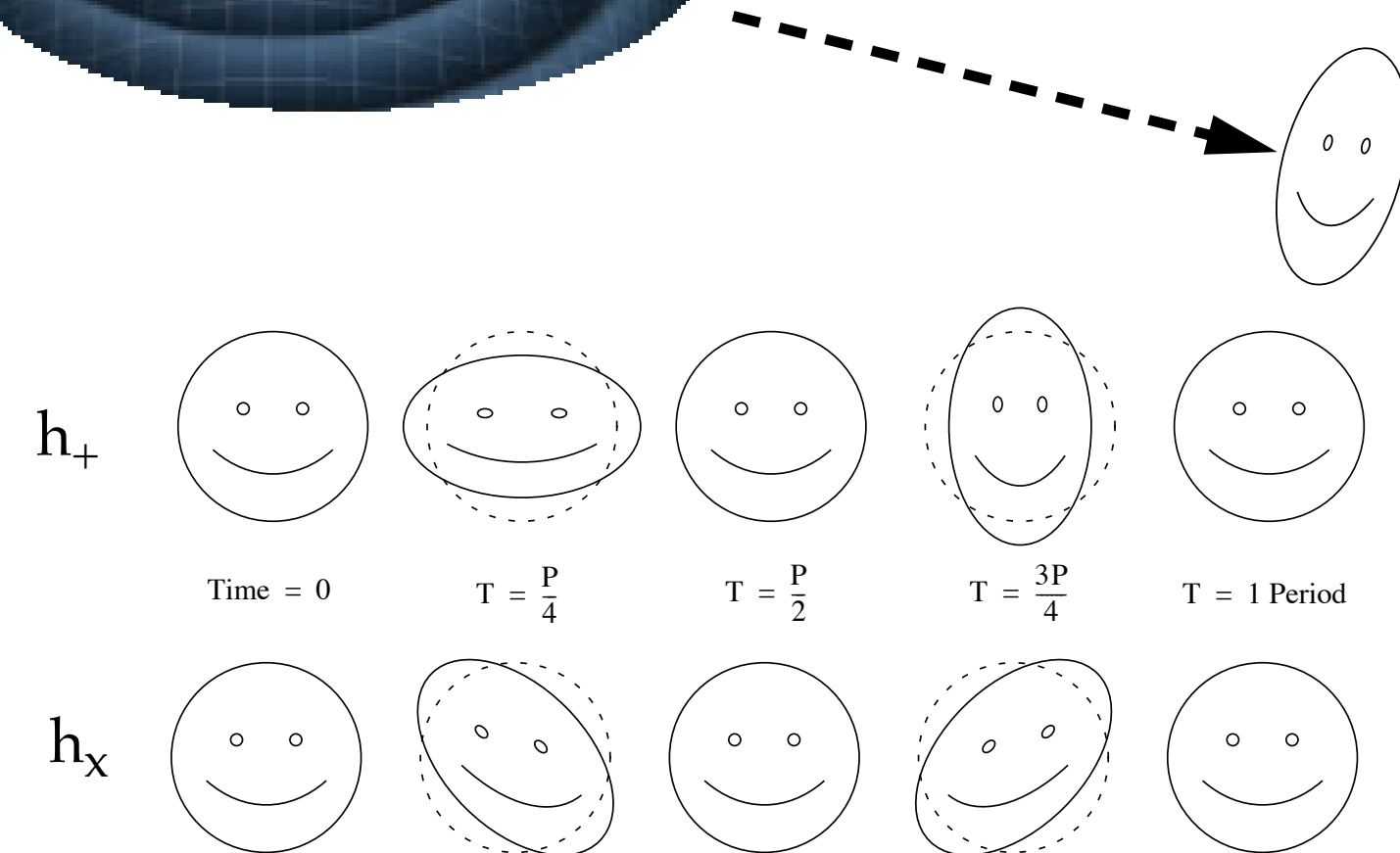


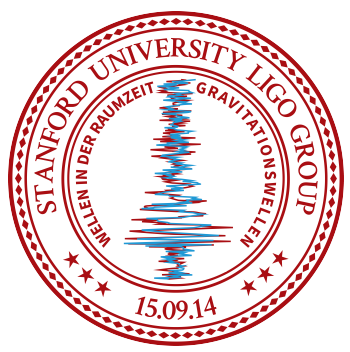


The LIGO concept



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





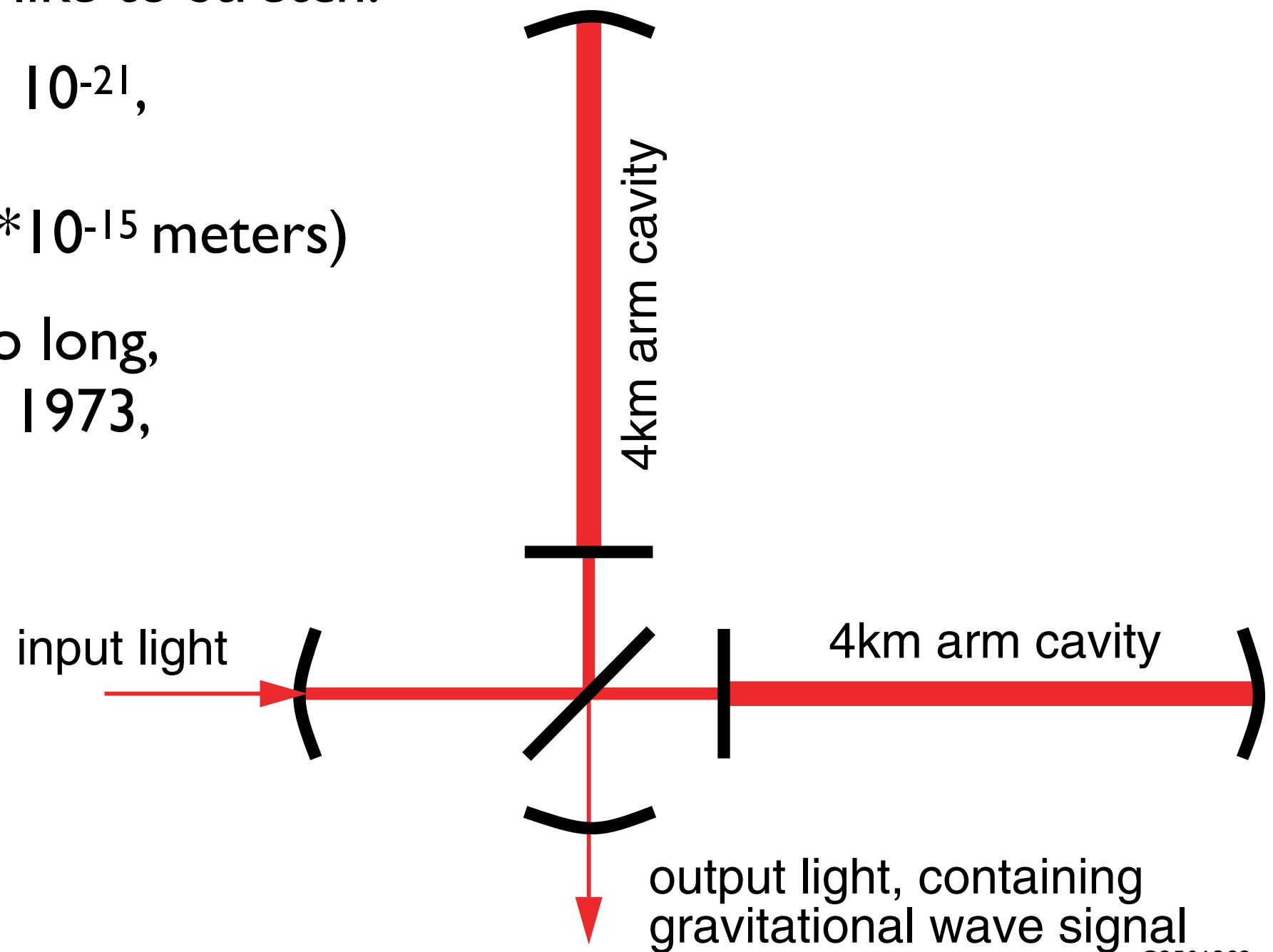
The LIGO concept

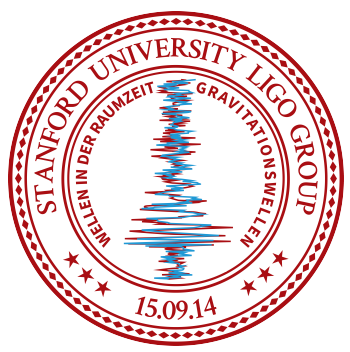


Gravitational waves are hard to measure because space doesn't like to stretch.

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



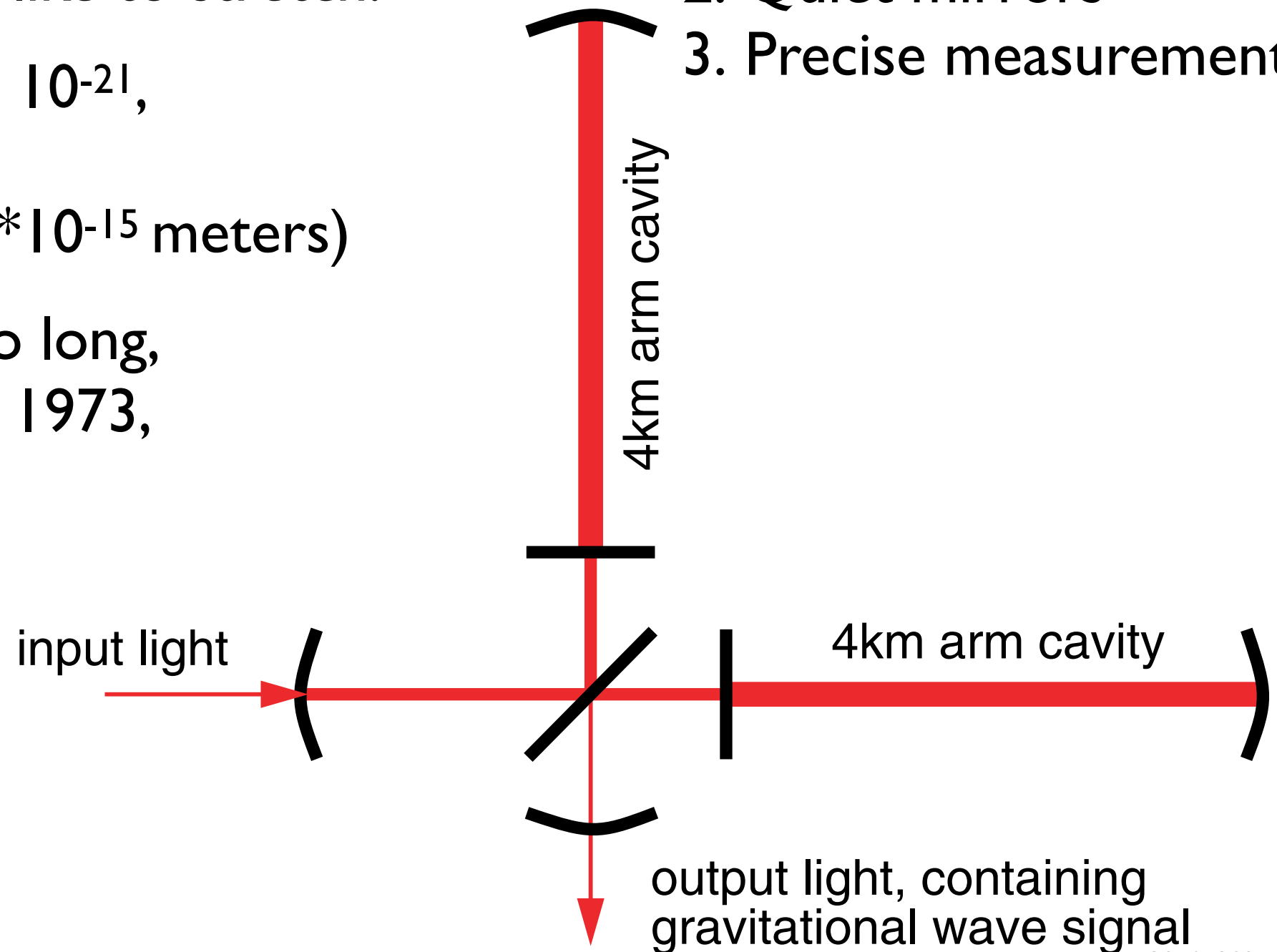
How it really works

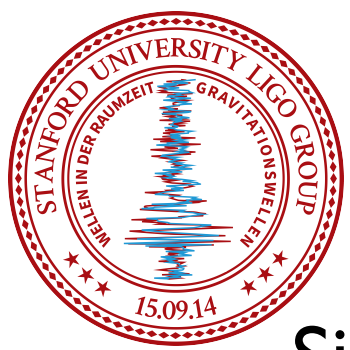
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1. Long arms
2. Quiet mirrors
3. Precise measurement

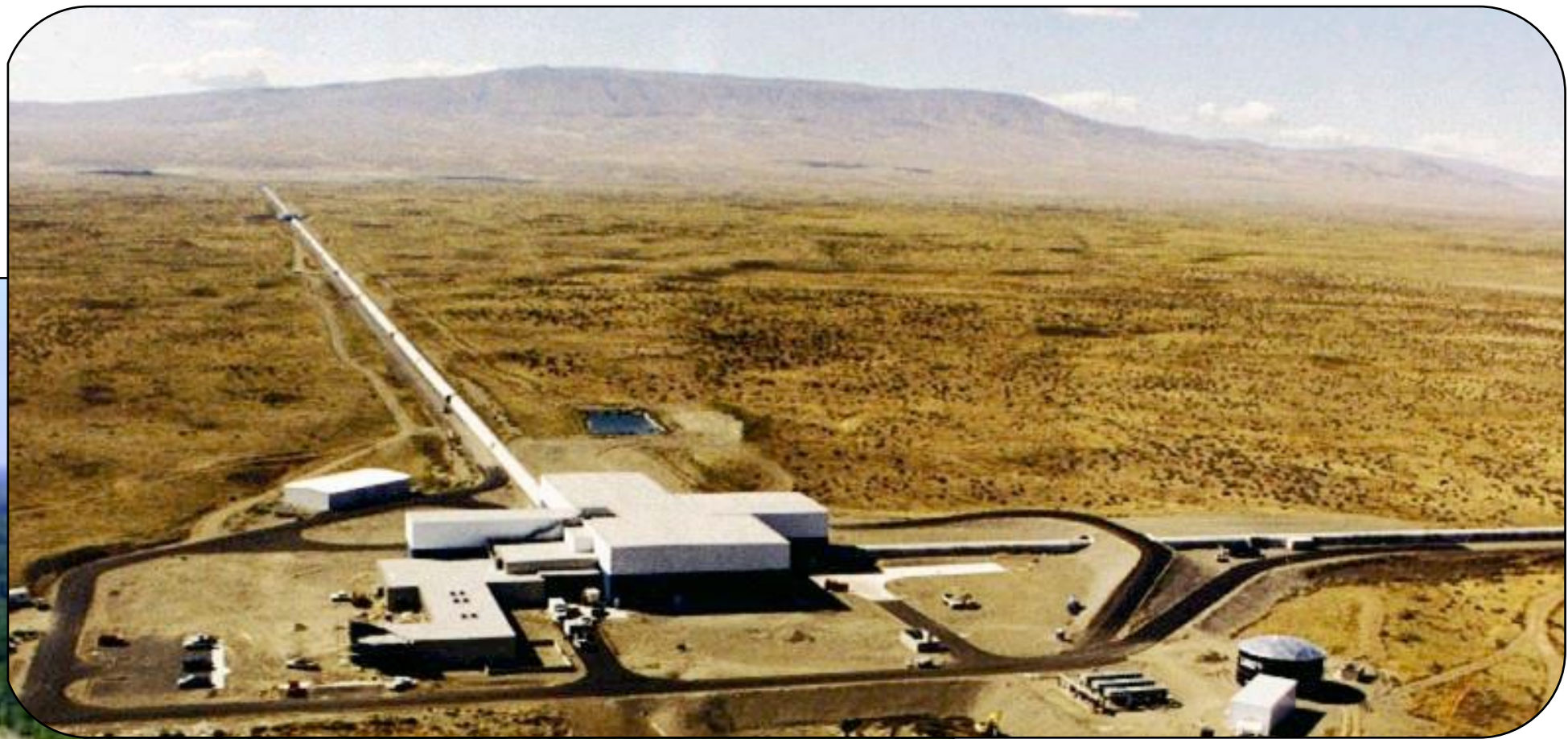


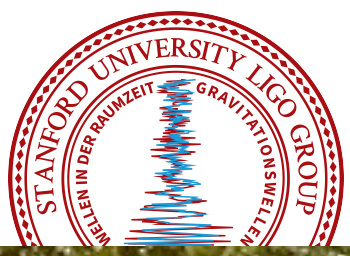


Long arms



Since $h = dL/L$ (or $dL = h \cdot L$) 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



LIGO Beamtube

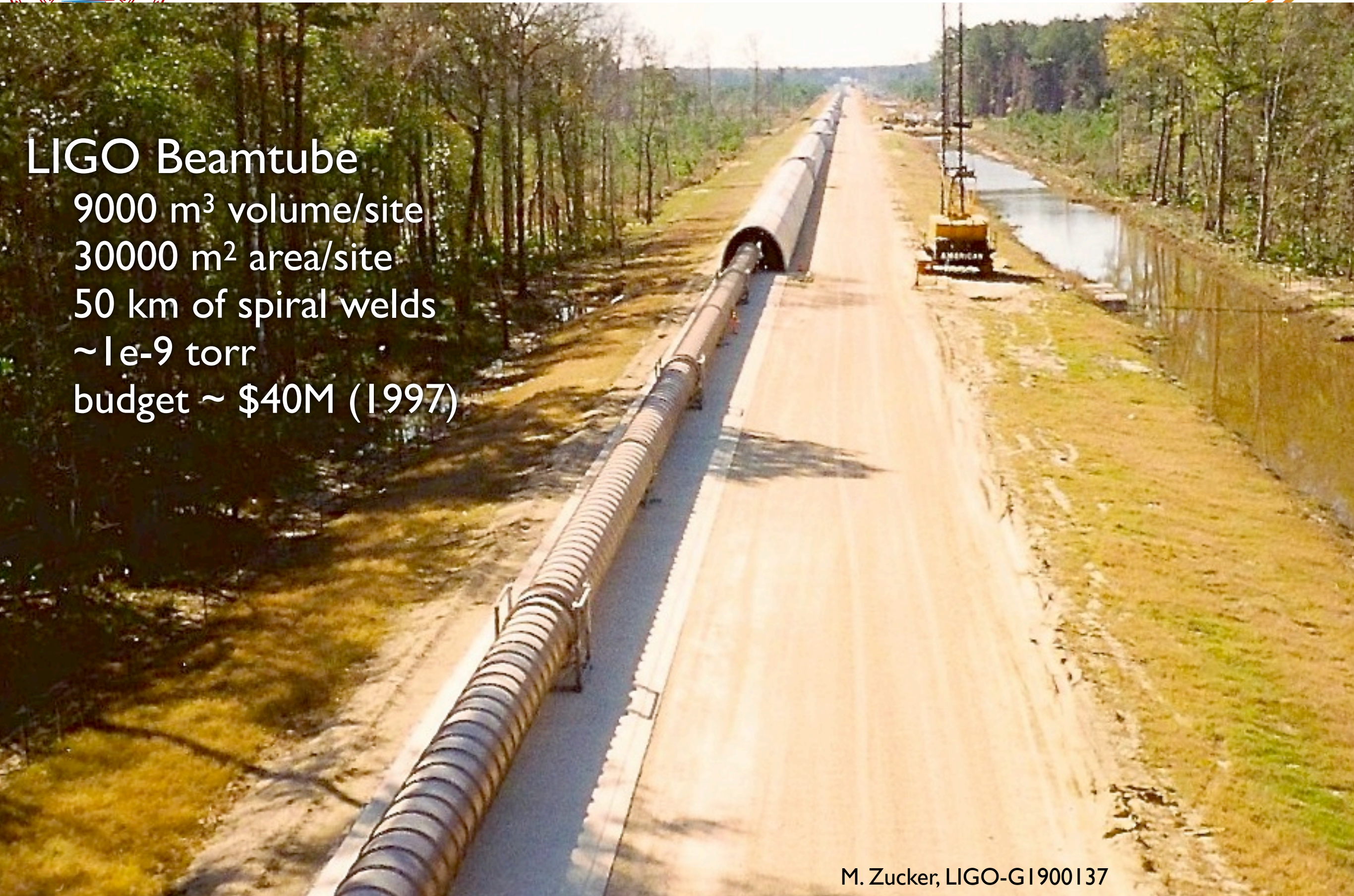
9000 m³ volume/site

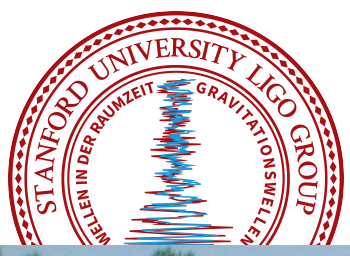
30000 m² area/site

50 km of spiral welds

~1e-9 torr

budget ~ \$40M (1997)





LIGO Beamtube



LIGO Beamtube

9000 m³ volume/site

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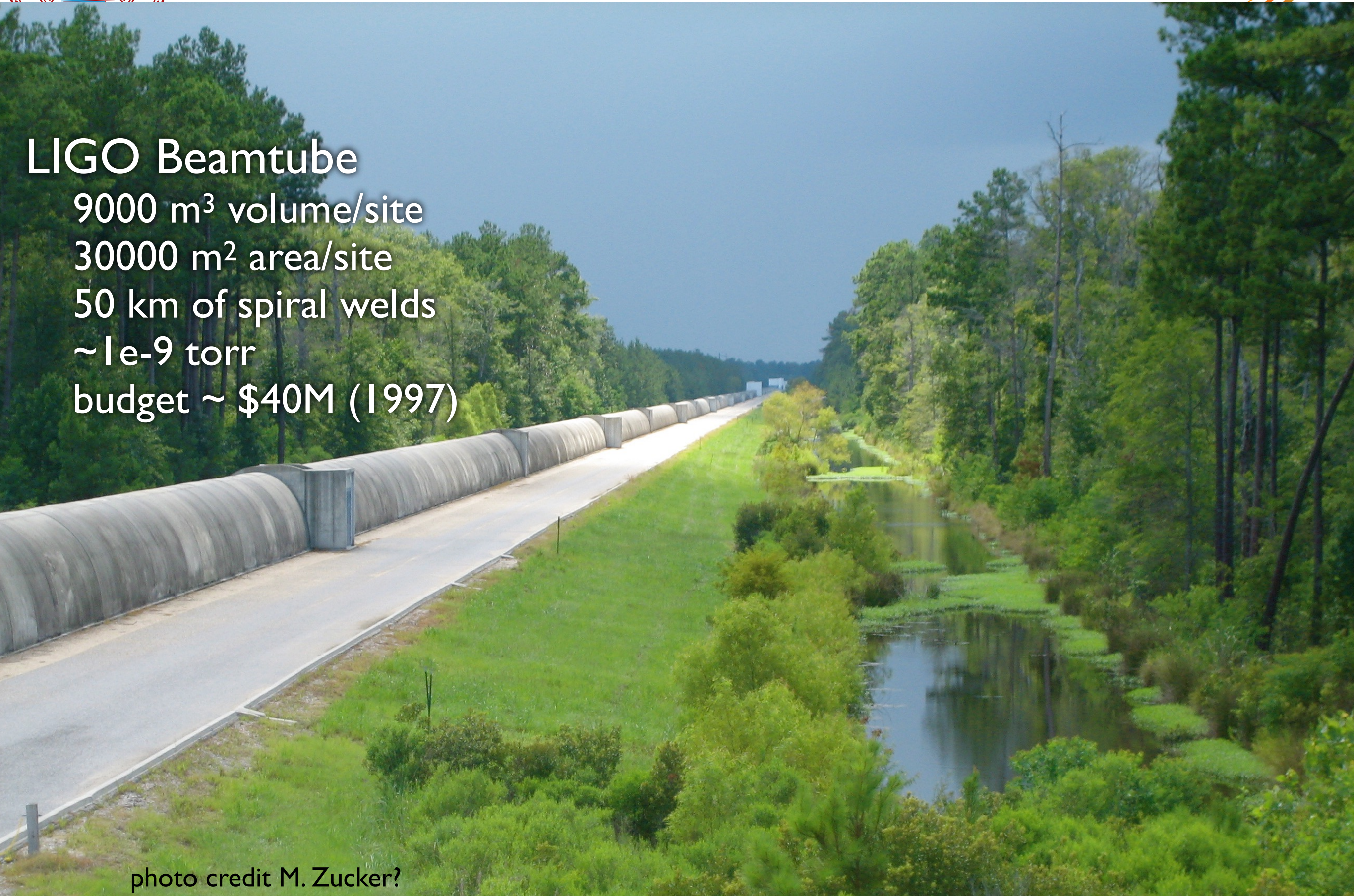
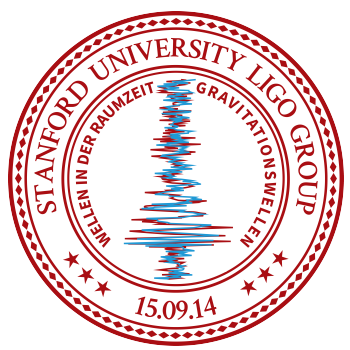


photo credit M. Zucker?



Quiet Mirrors

How it really works

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

- but -

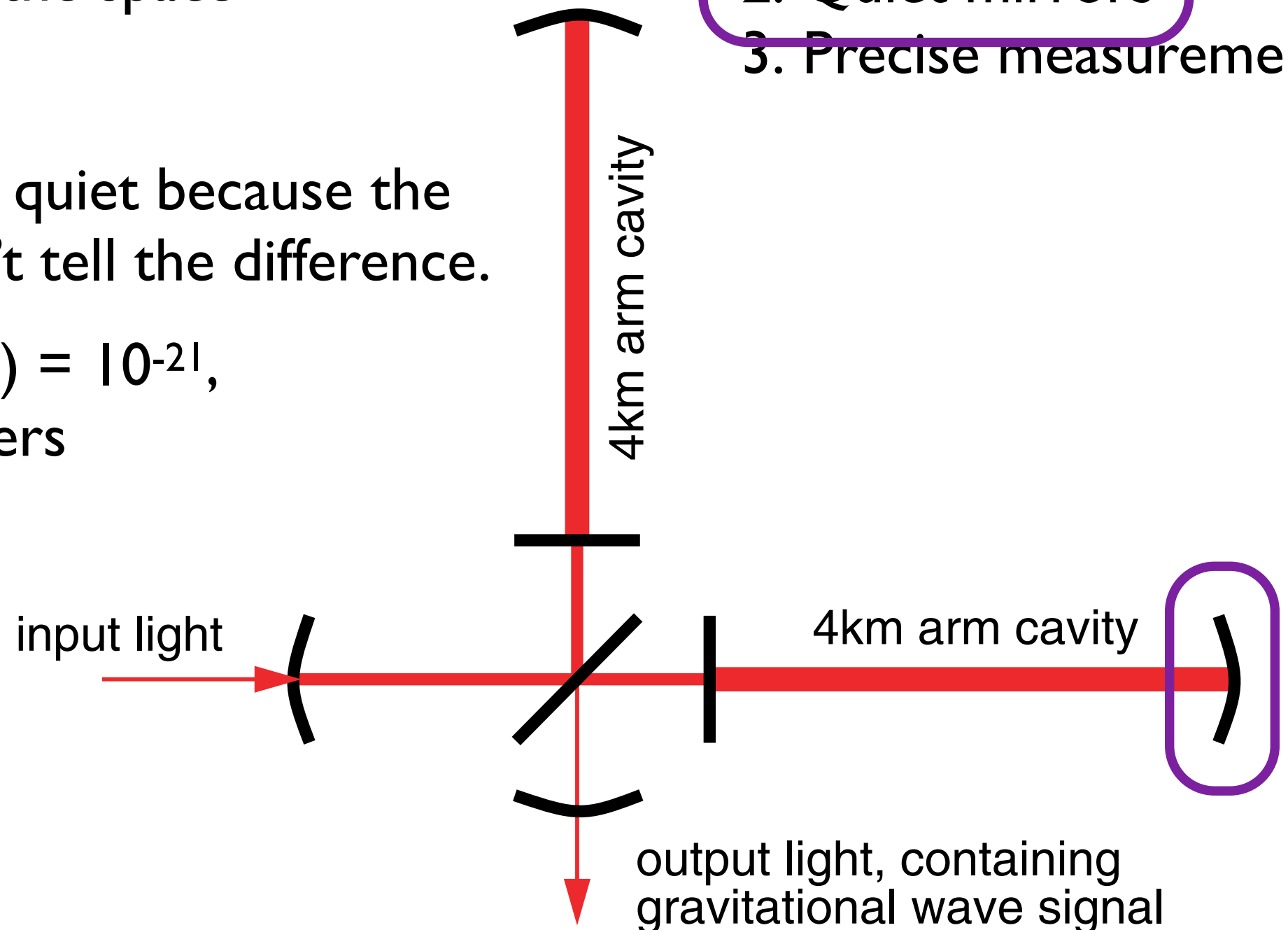
Mirrors need to be quiet because the interferometer can't tell the difference.

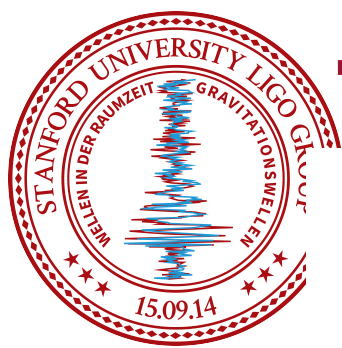
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1. Long arms

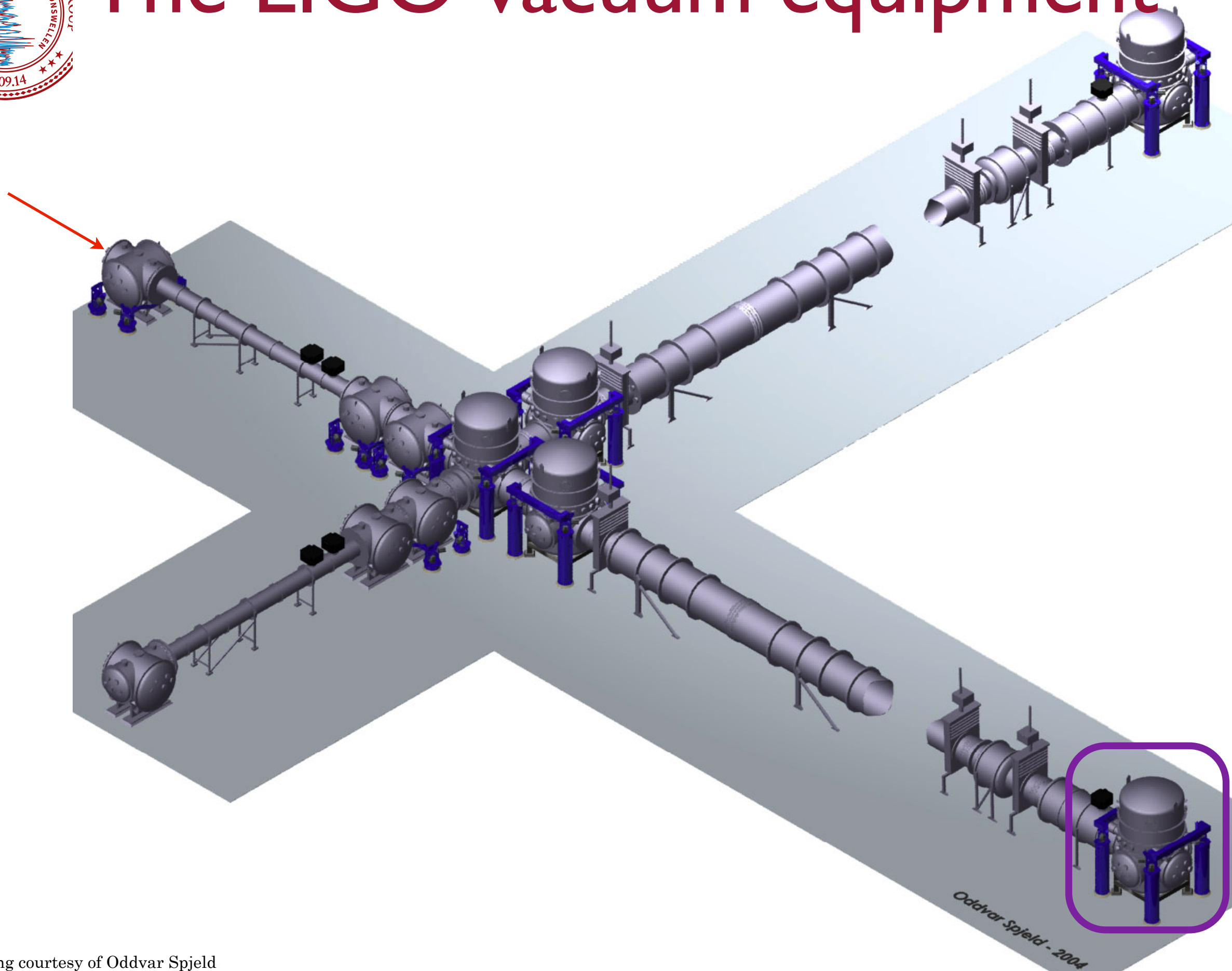
2. Quiet mirrors

3. Precise measurement

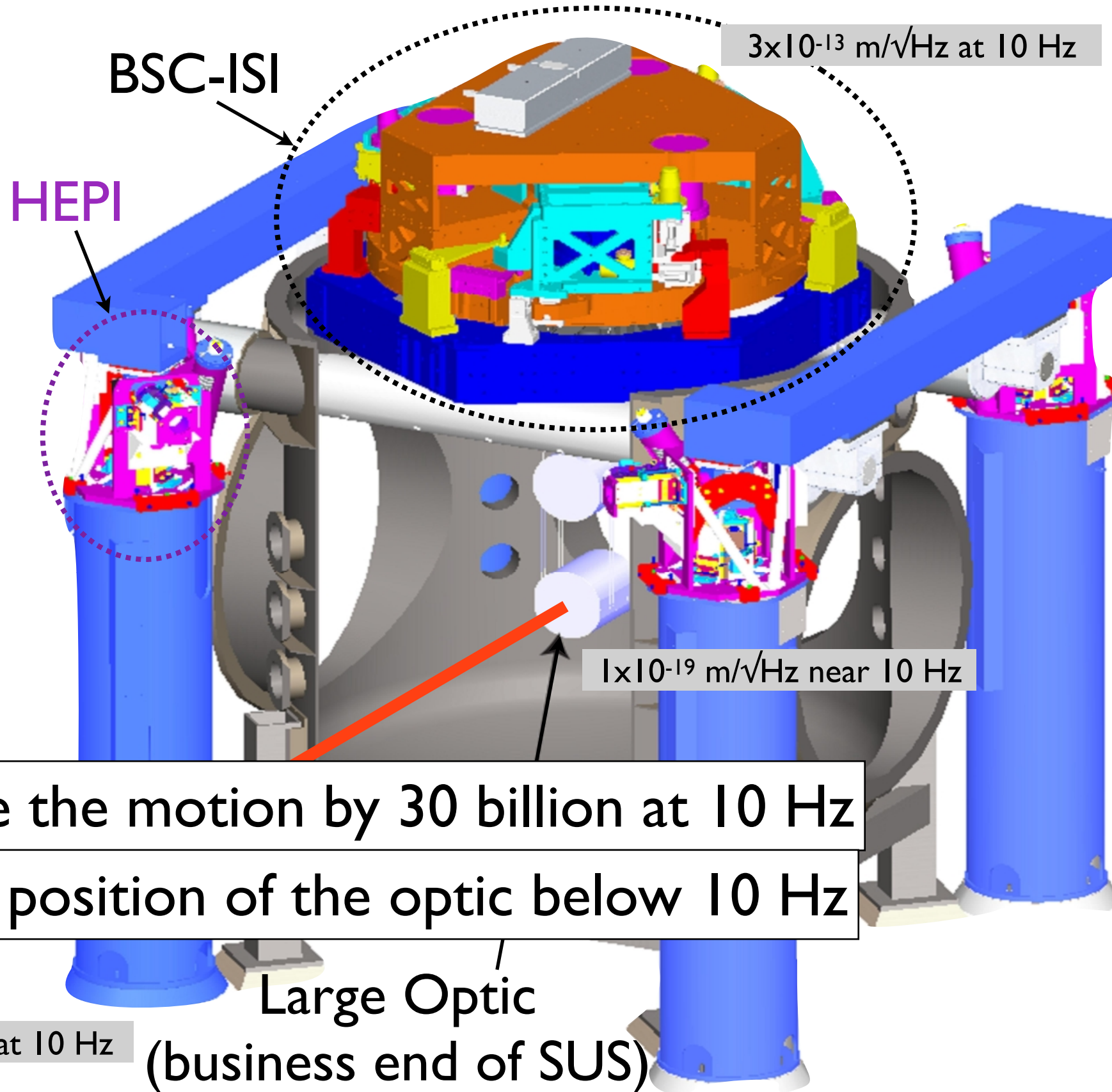


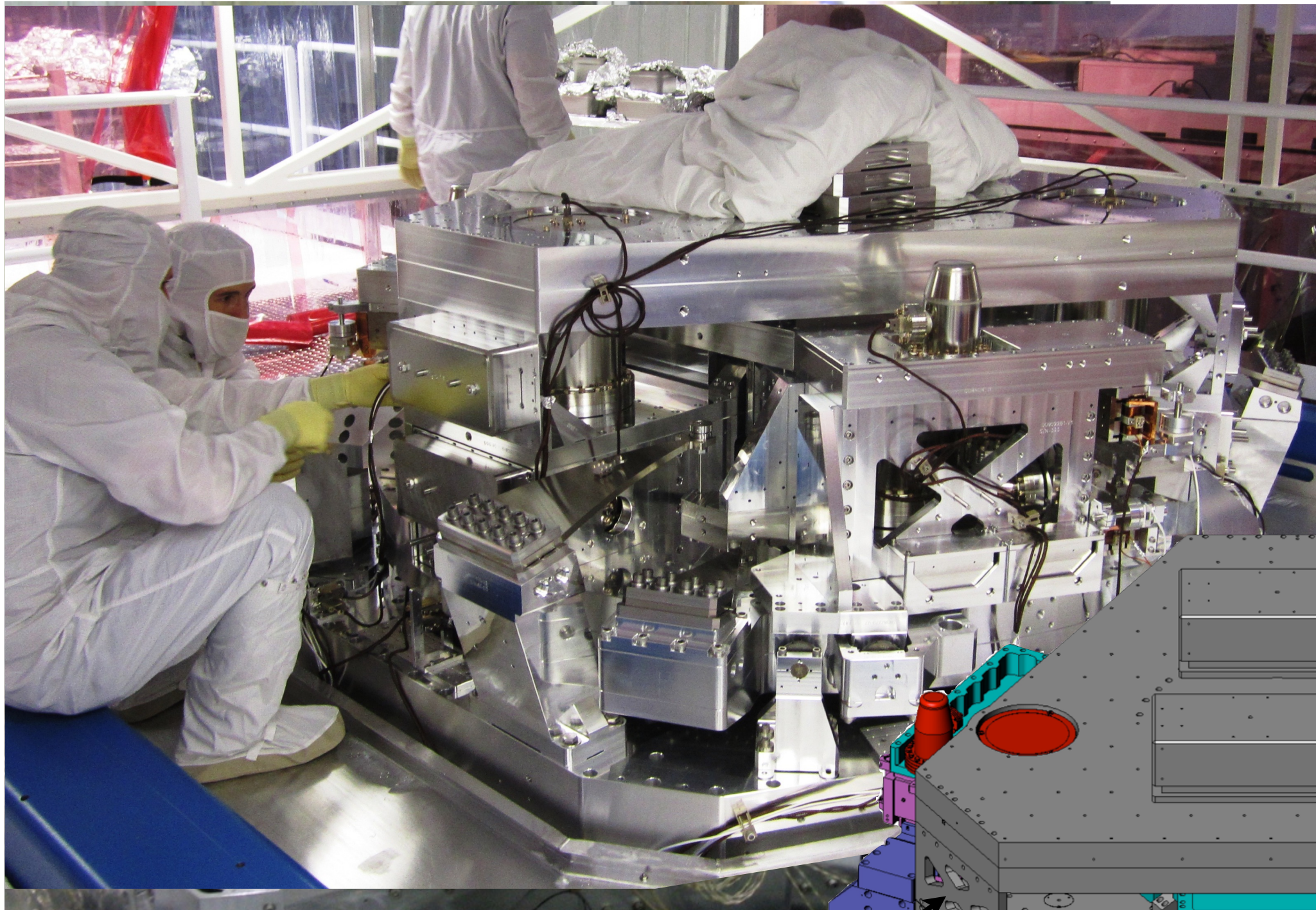


The LIGO vacuum equipment



Isolation of the Mirrors

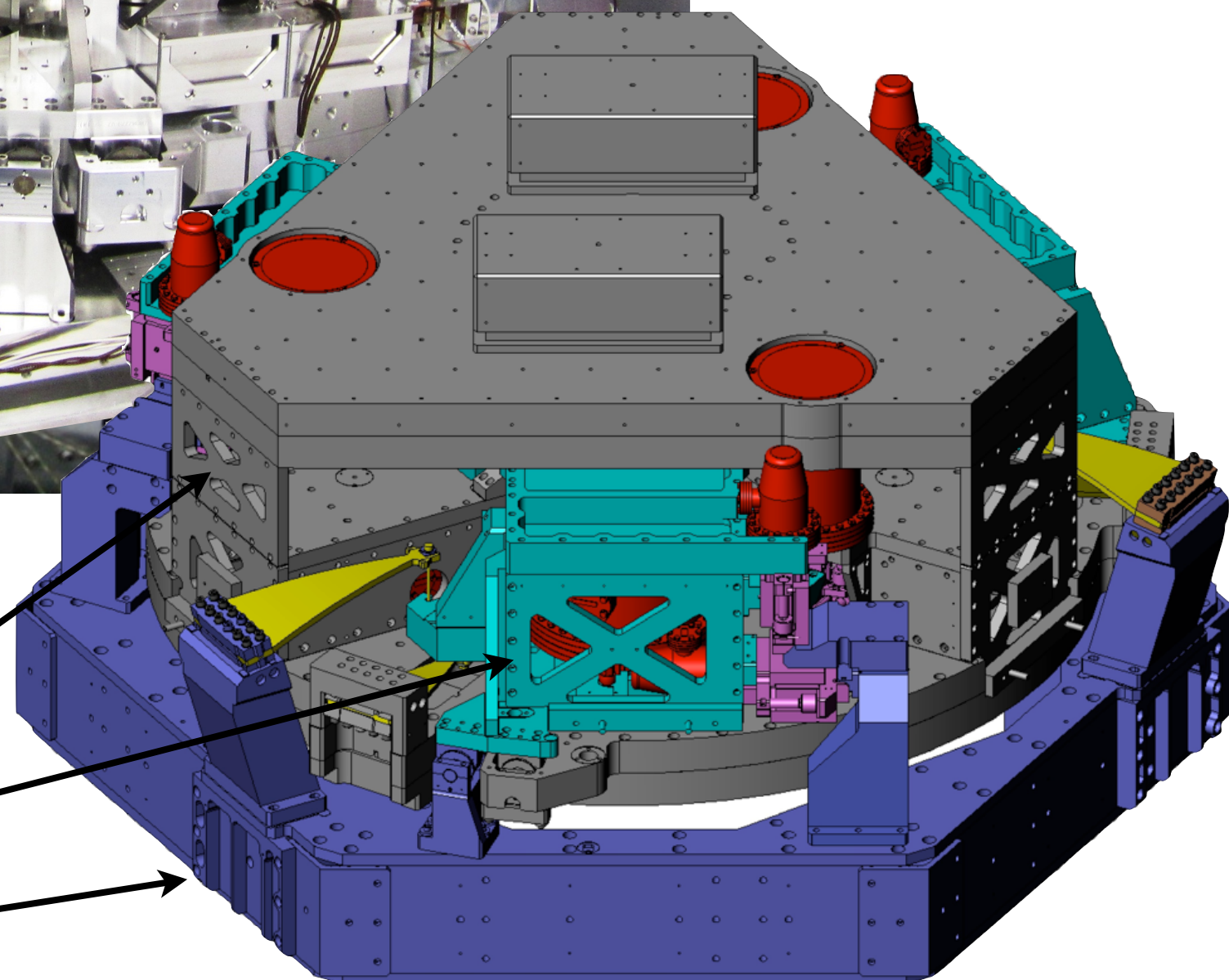




optics table - stage 2

stage 1

support - stage 0



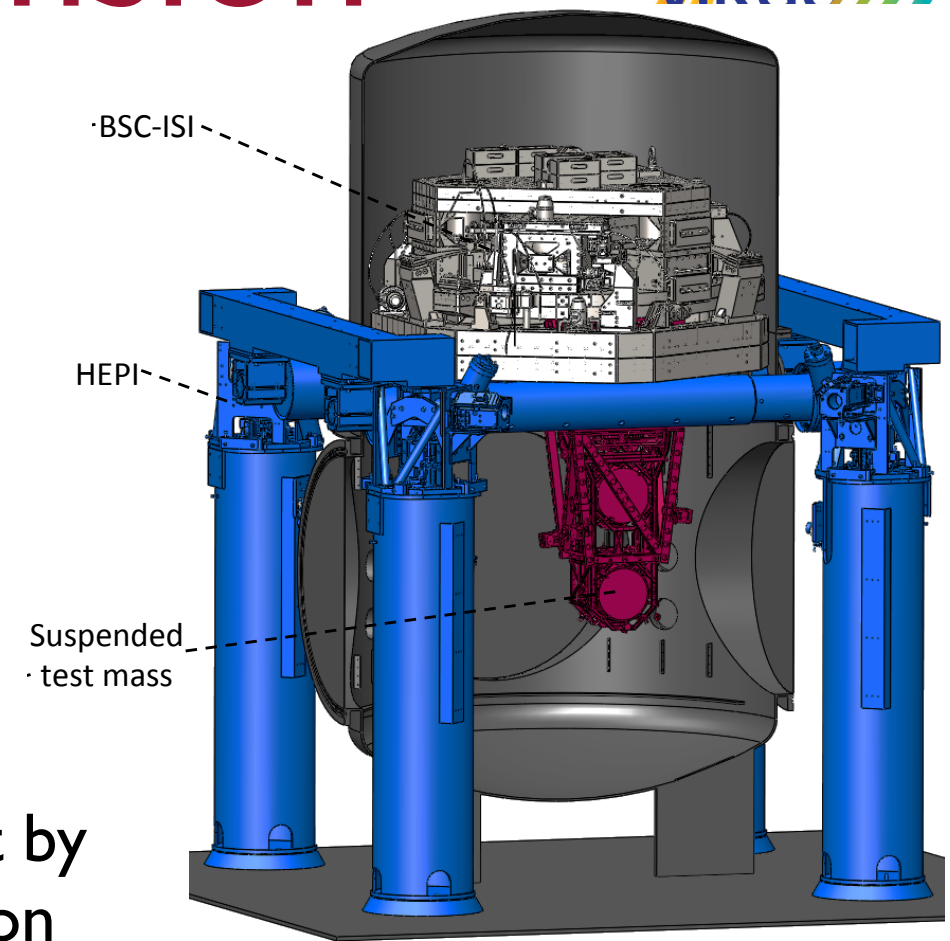
Pendulum Suspension

LIGO Mirrors:
Synthetic fused silica,
40 kg mass
34 cm diameter
20 cm thick

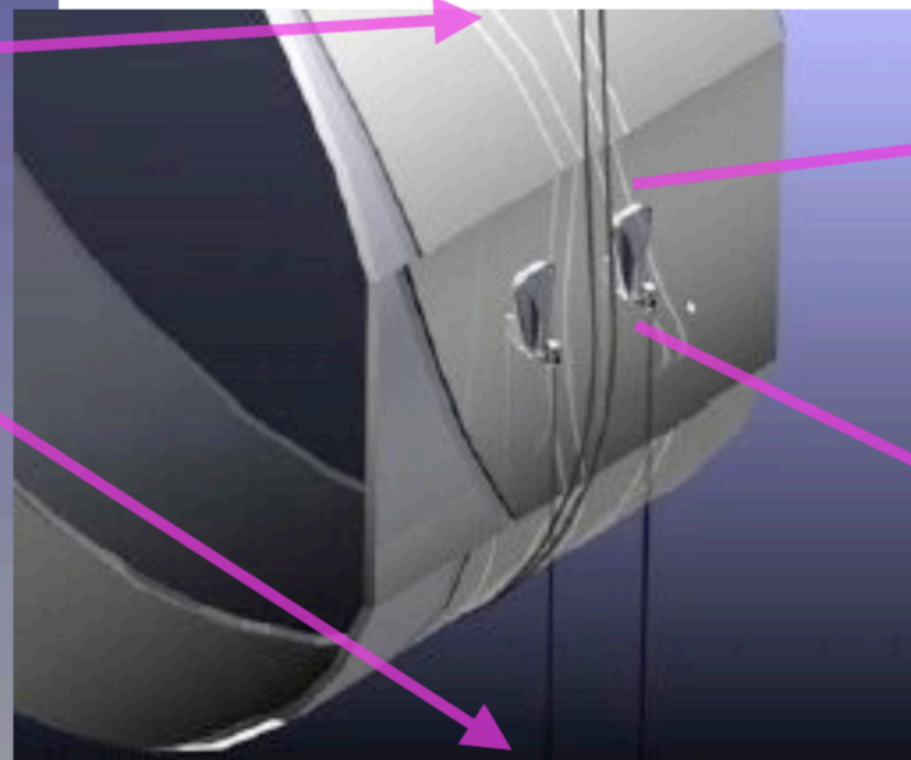
Suspended as a
4 stage pendulum

Best coatings available

Motion at 10 Hz is set by
thermal driven vibration



(Based on GEO600 design)



silicate bonding creates a monolithic final stage

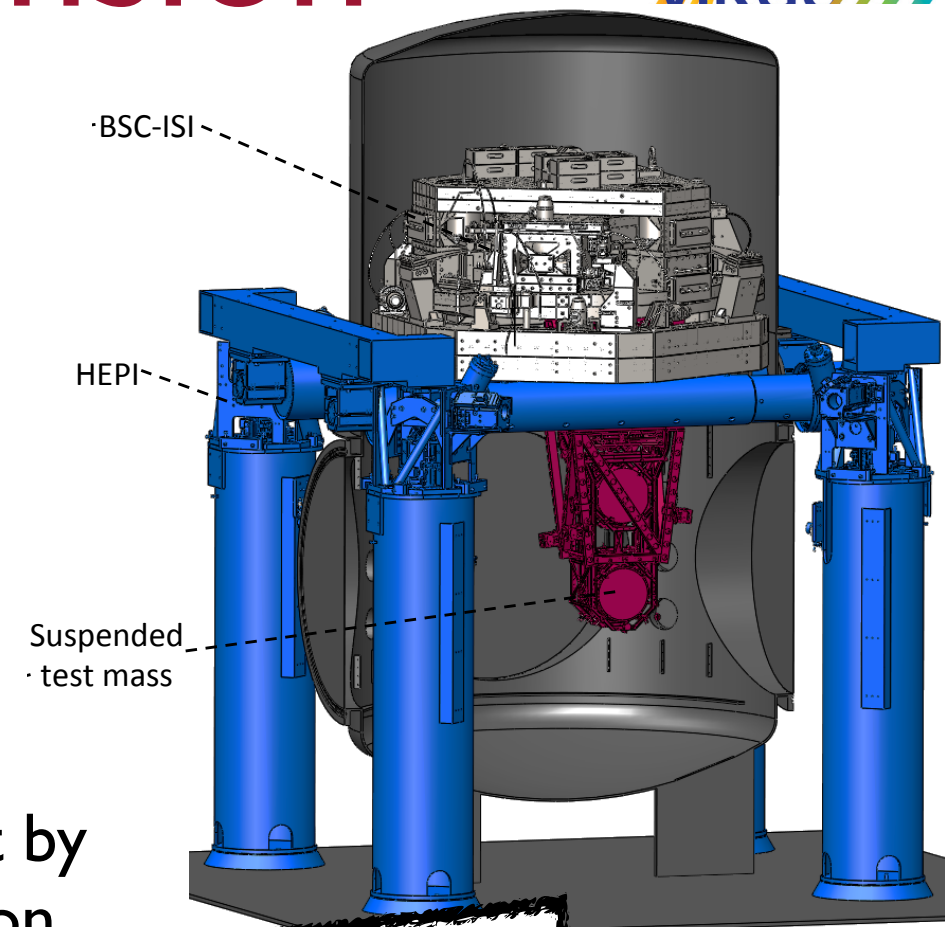
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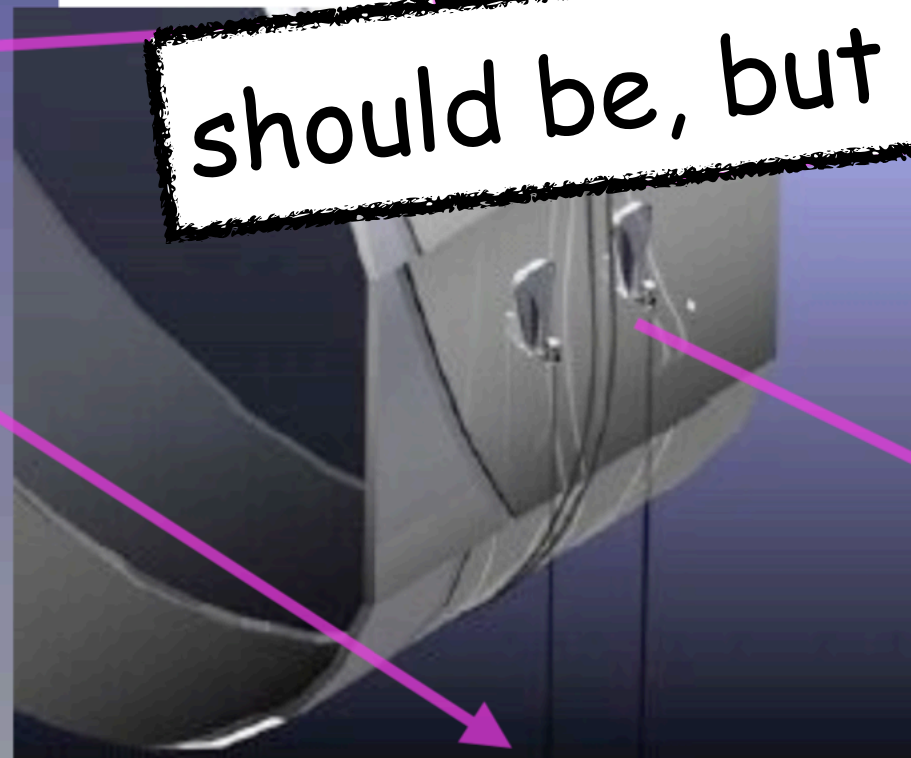
Motion at 10 Hz ~~is~~ set by
thermal driven vibration



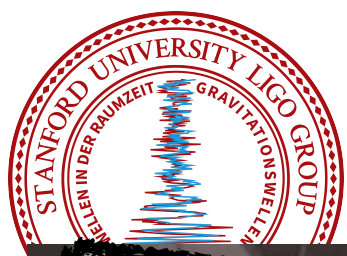
should be, but isn't yet

(Based on GEO600 design)

Demo time!

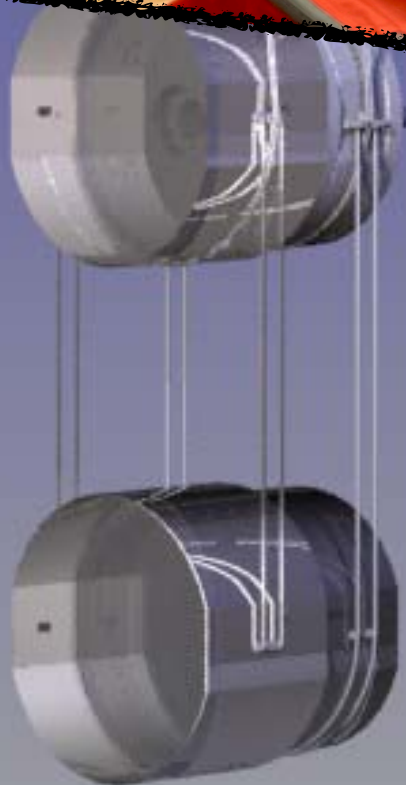
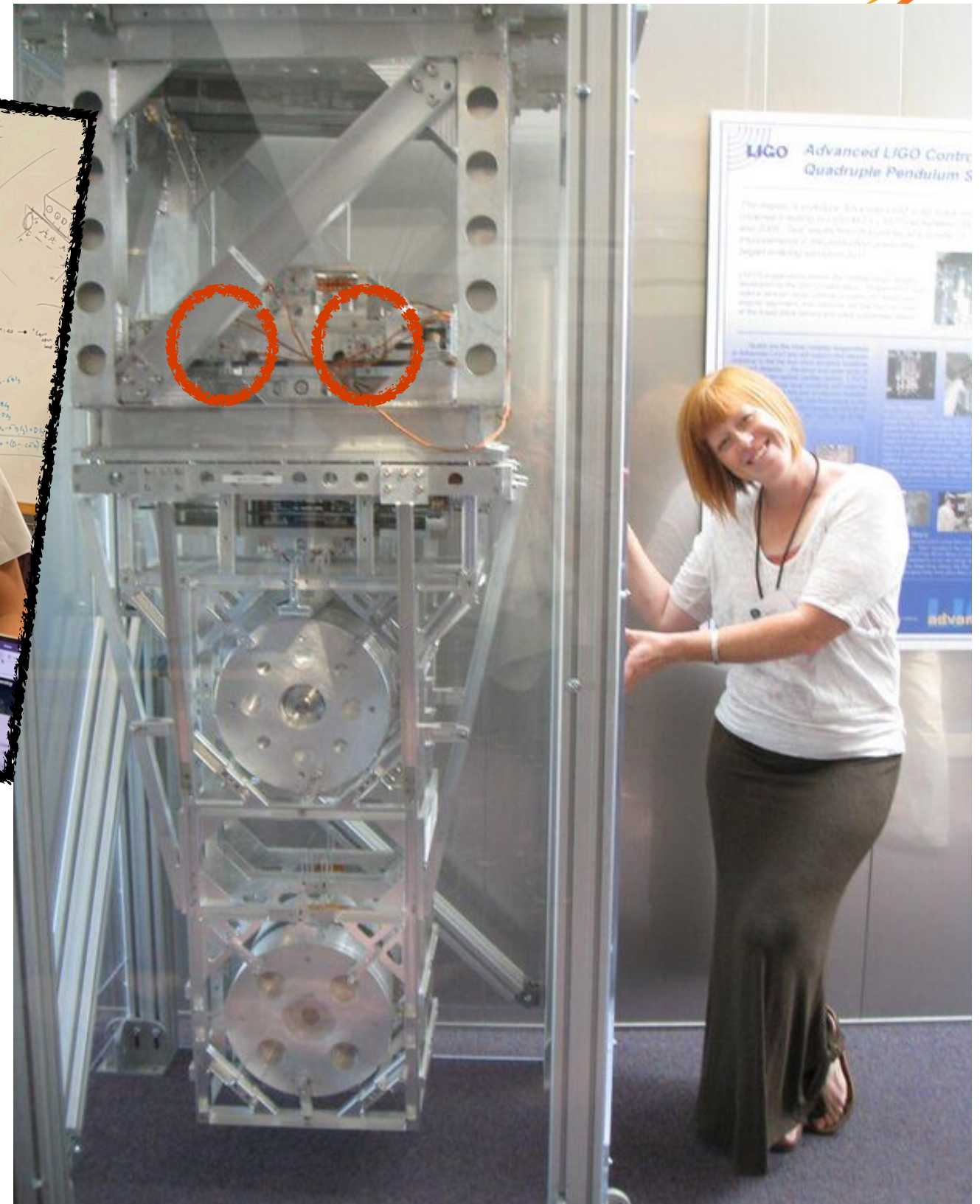


silicate bonding creates a monolithic final stage



Pendulum

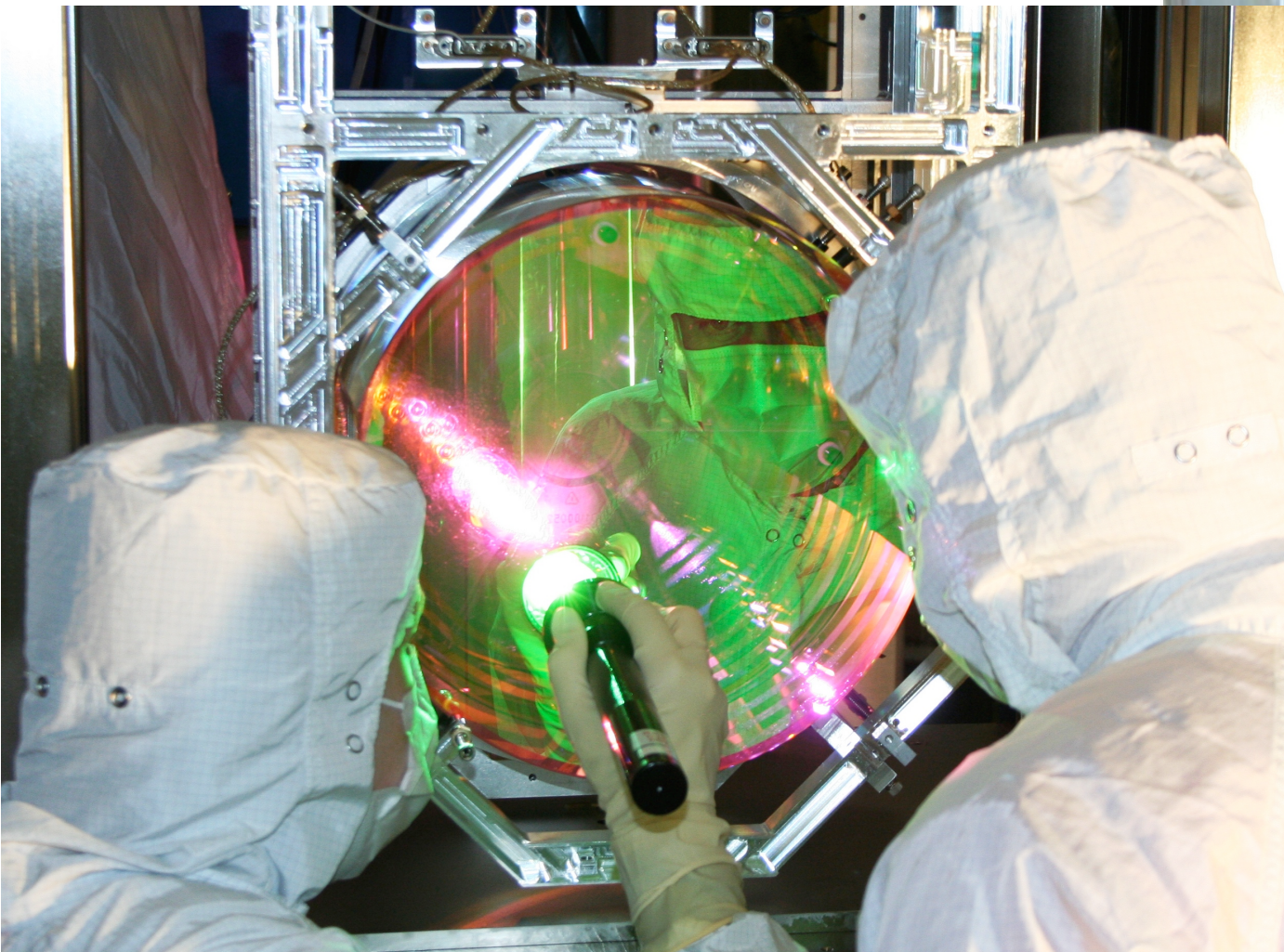
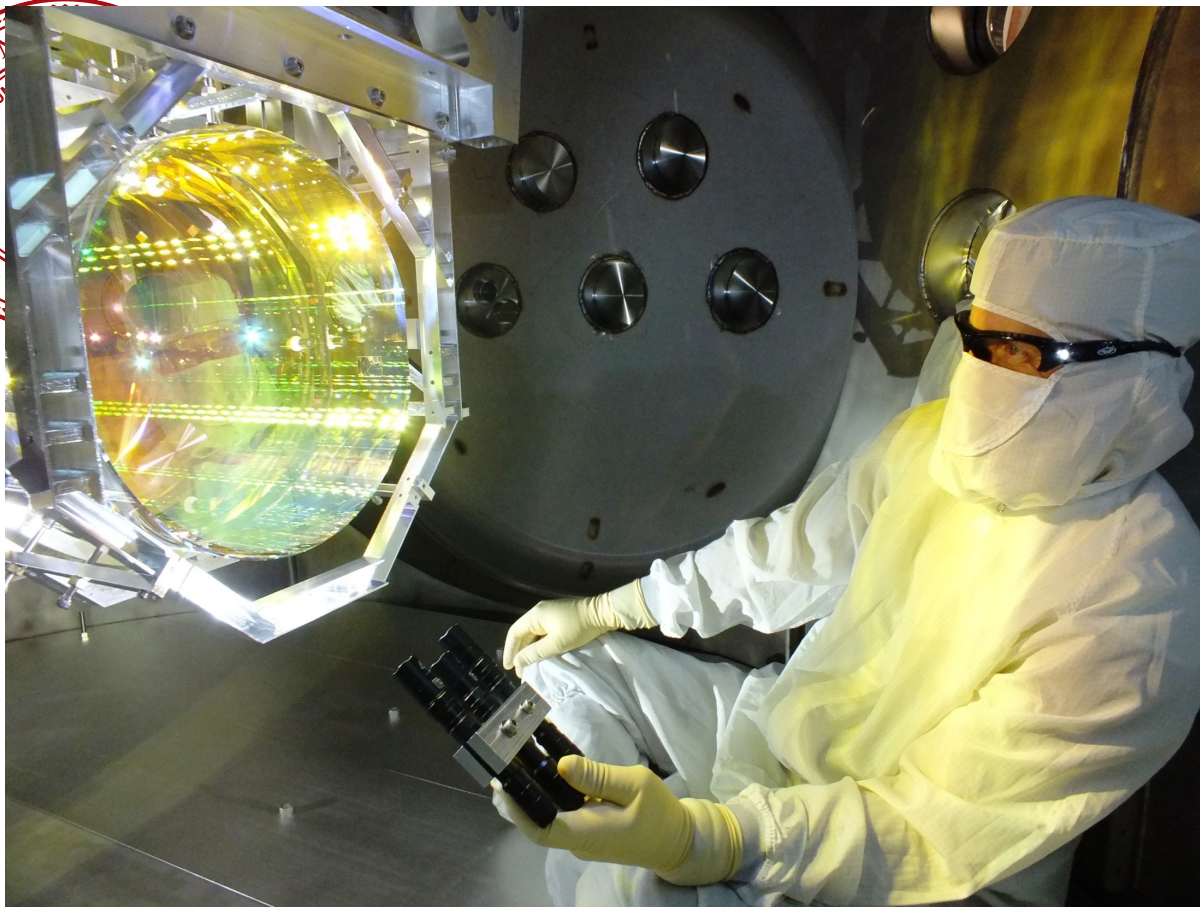
LHO suspension expert, Betsy Weaver
with the Engineering prototype

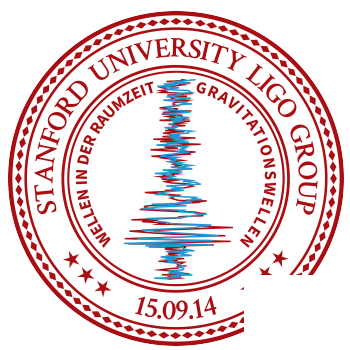


(Based on GEO600 design)



or picts

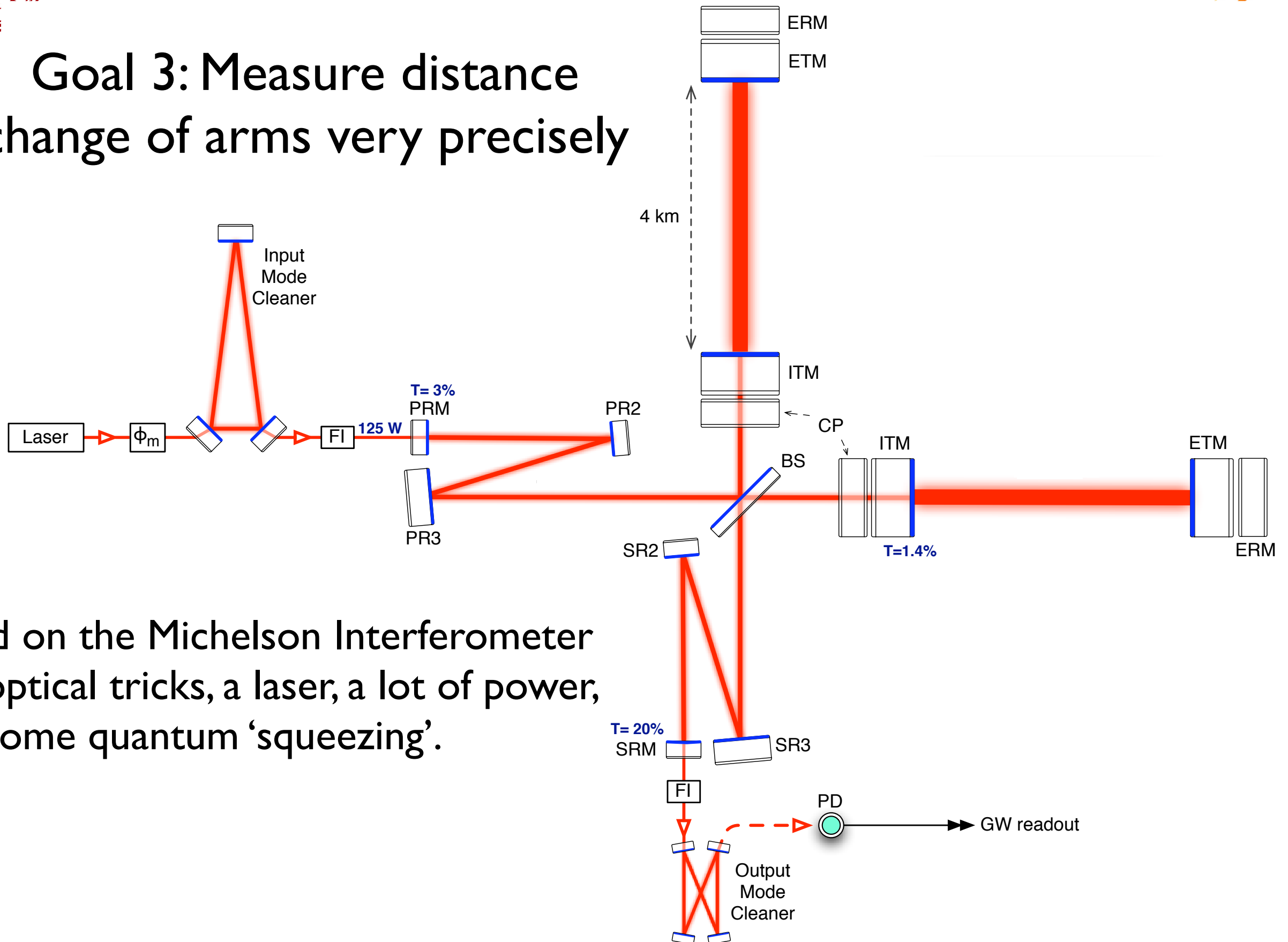




Precision Interferometry

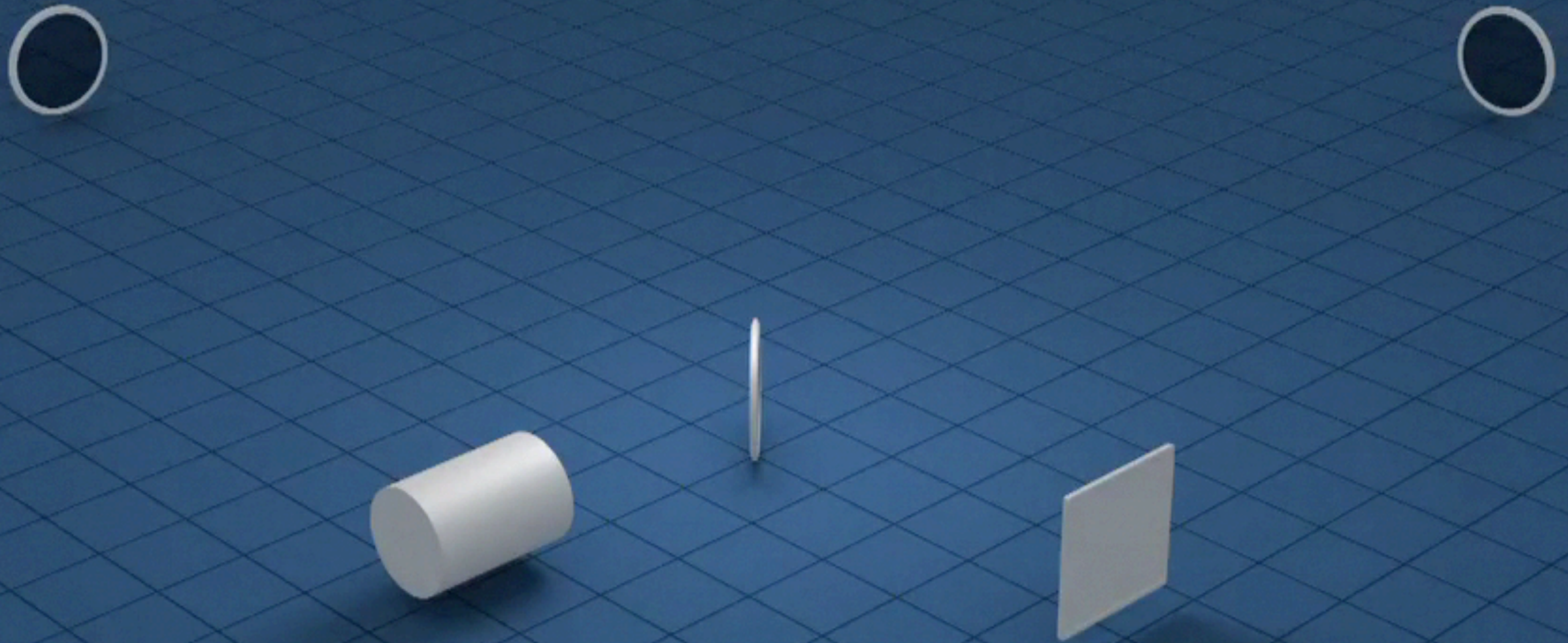


Goal 3: Measure distance change of arms very precisely



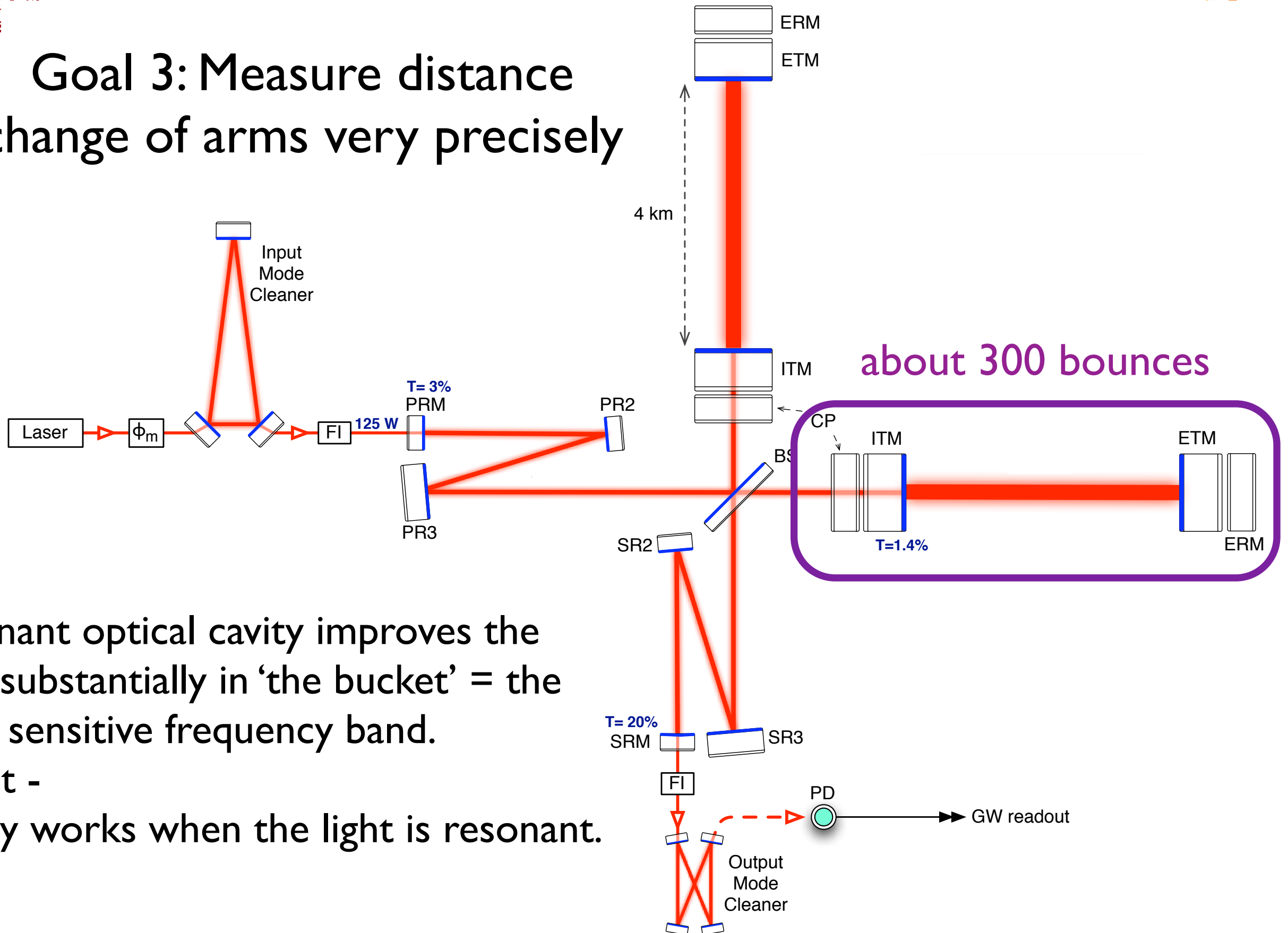
Based on the Michelson Interferometer add optical tricks, a laser, a lot of power, and some quantum 'squeezing'.

Animated Interferometer



Fabry-Perot arms

Goal 3: Measure distance change of arms very precisely



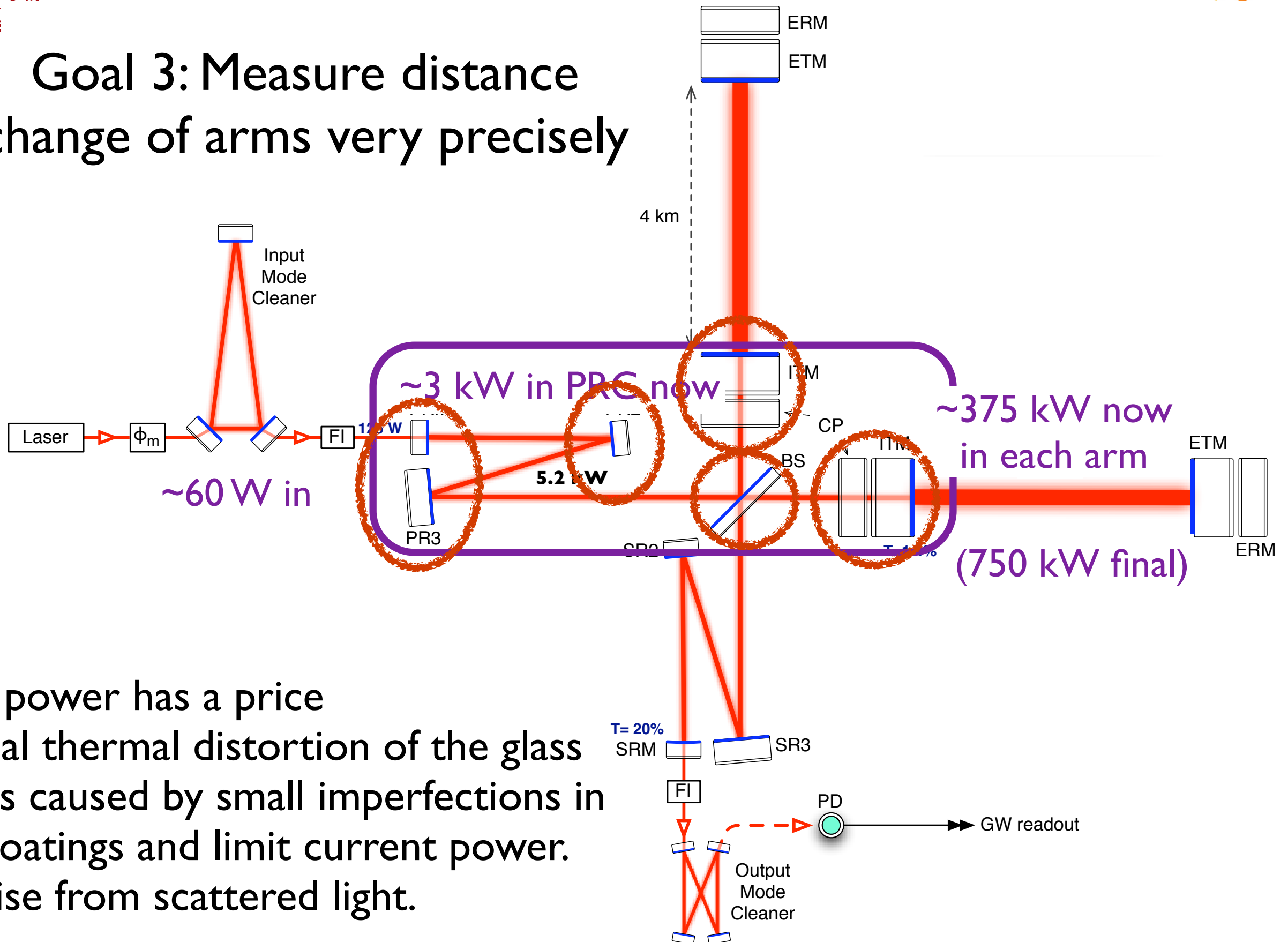
Resonant optical cavity improves the SNR substantially in 'the bucket' = the most sensitive frequency band.

- but -

It only works when the light is resonant.

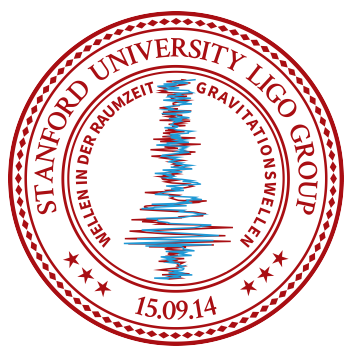
Lots of photons

Goal 3: Measure distance change of arms very precisely



High power has a price

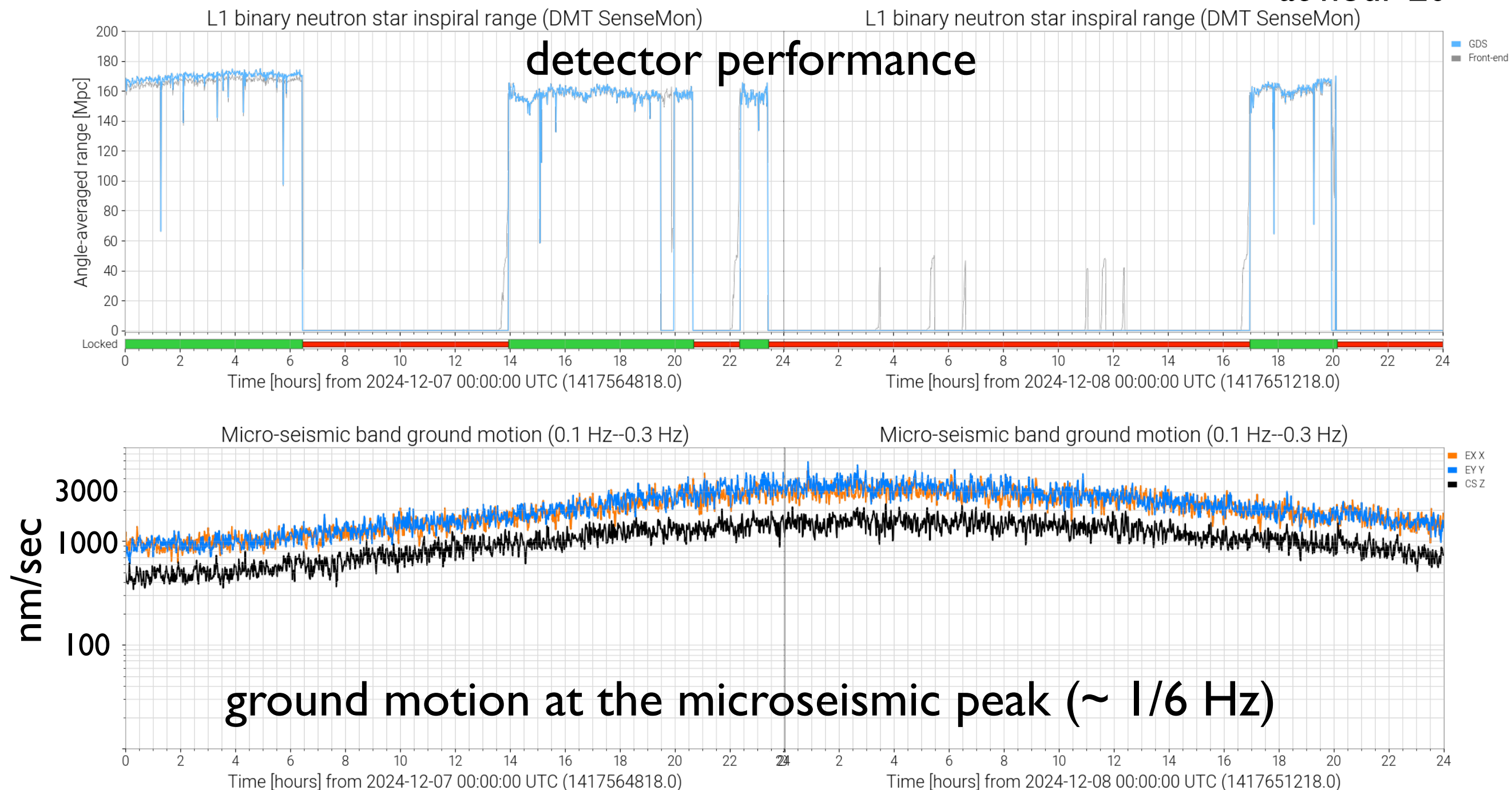
- Local thermal distortion of the glass optics caused by small imperfections in the coatings and limit current power.
- Noise from scattered light.

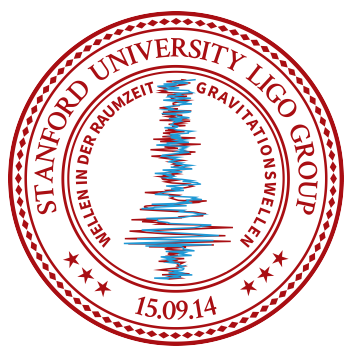


2 rough days at LLO



bad weather makes it hard to run the detector and an earthquake at hour 20

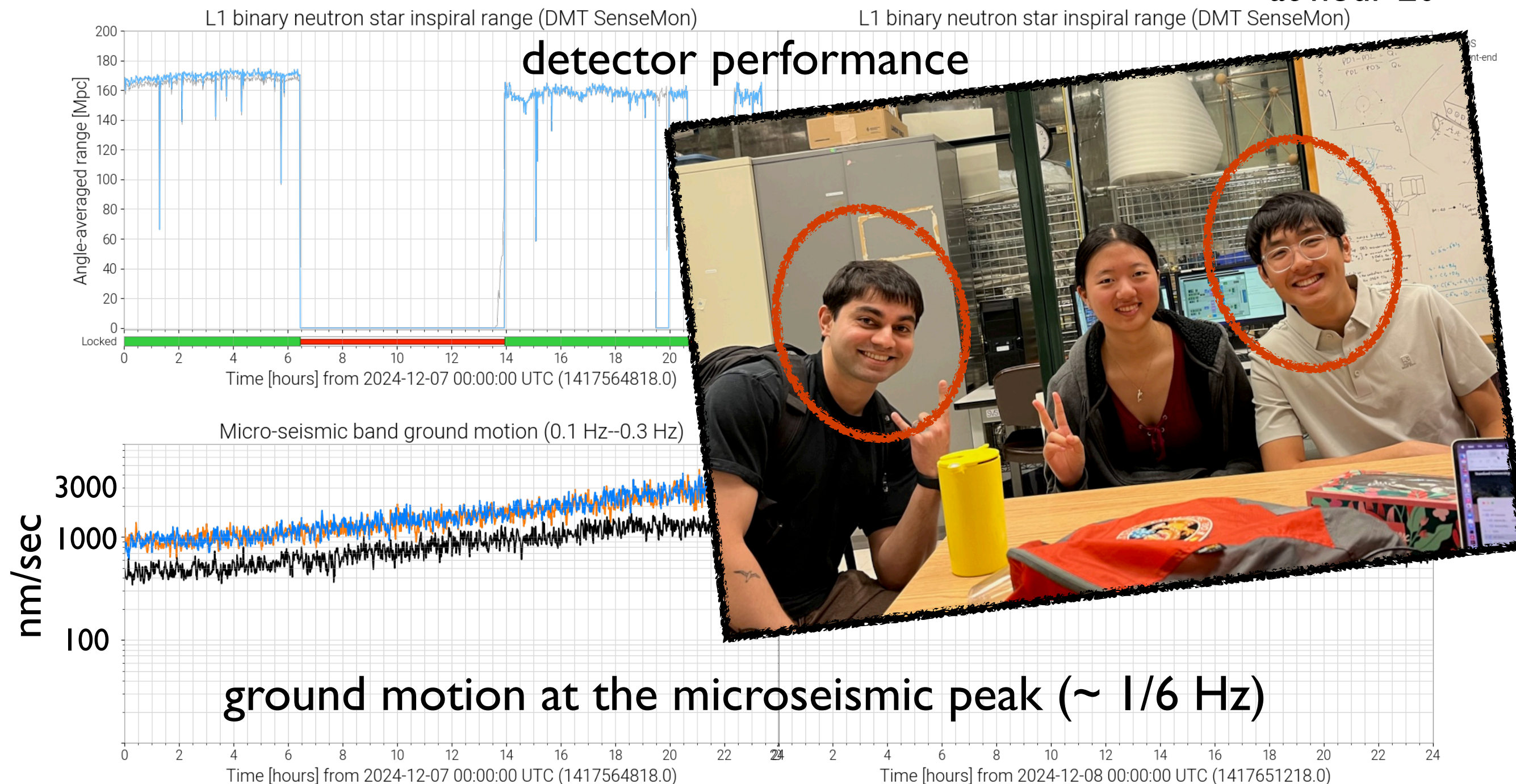


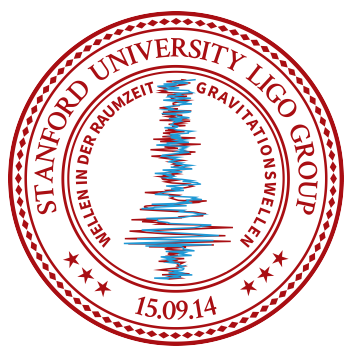


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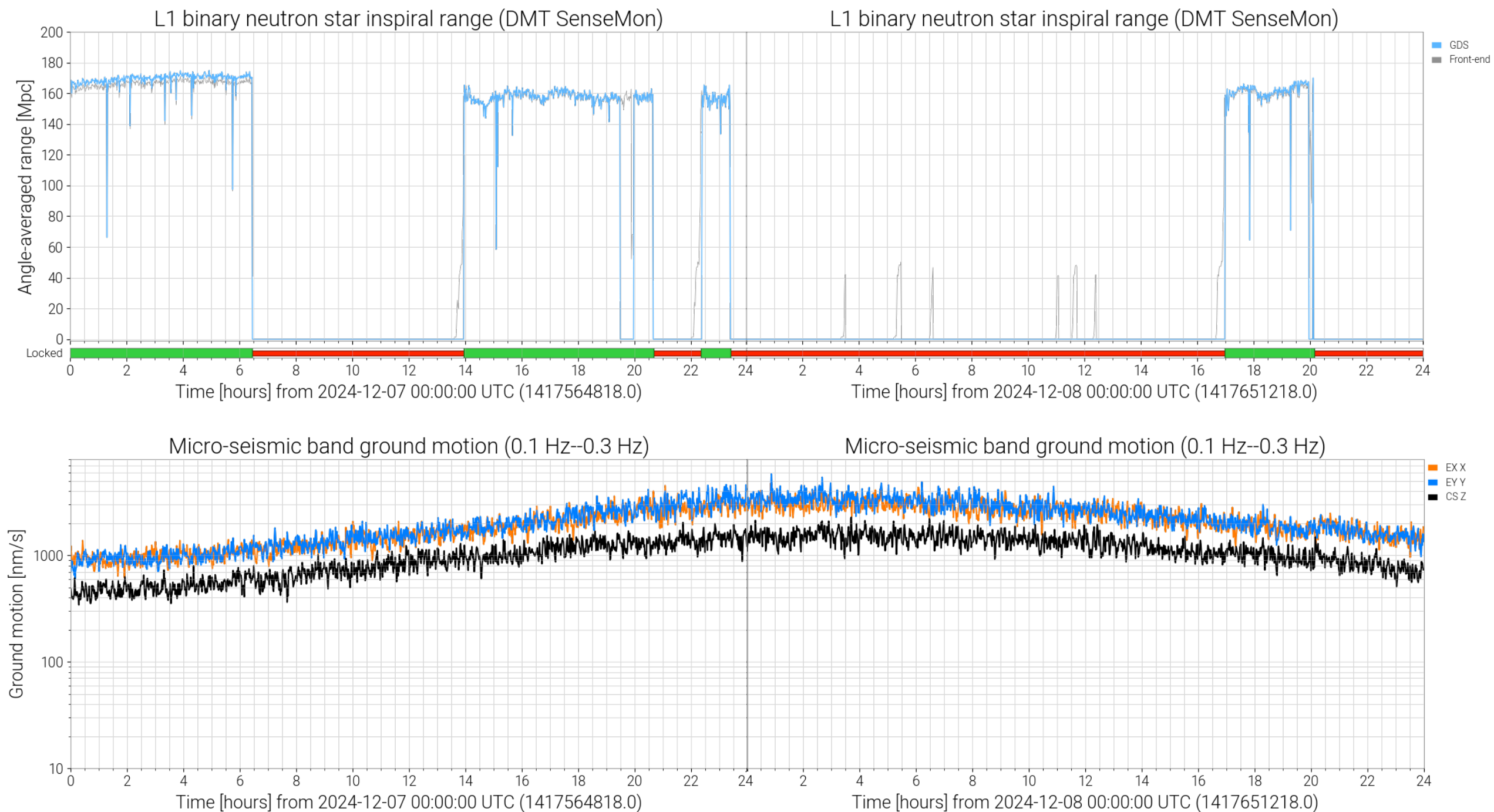


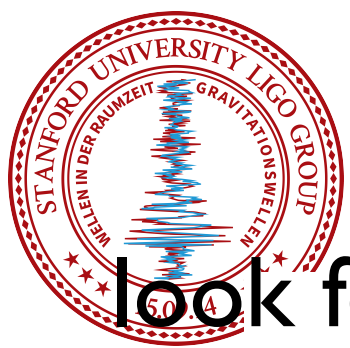


2 rough days at LLO



and an earthquake
at hour 20

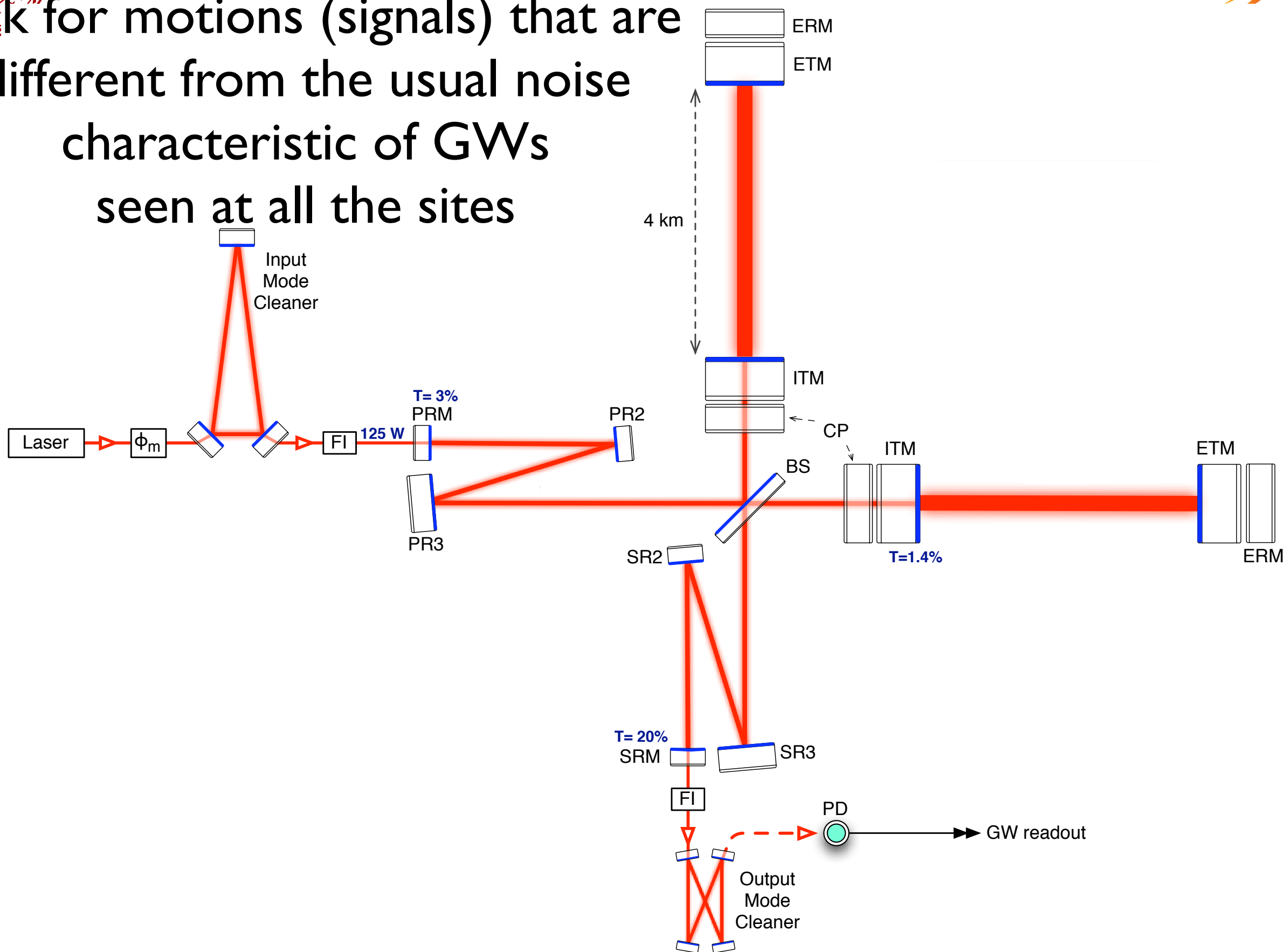


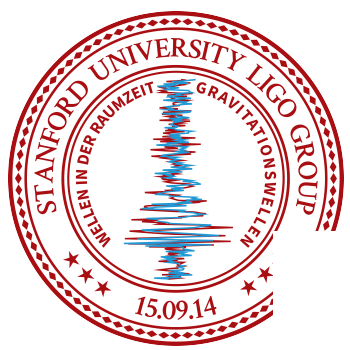


and now you wait for a signal

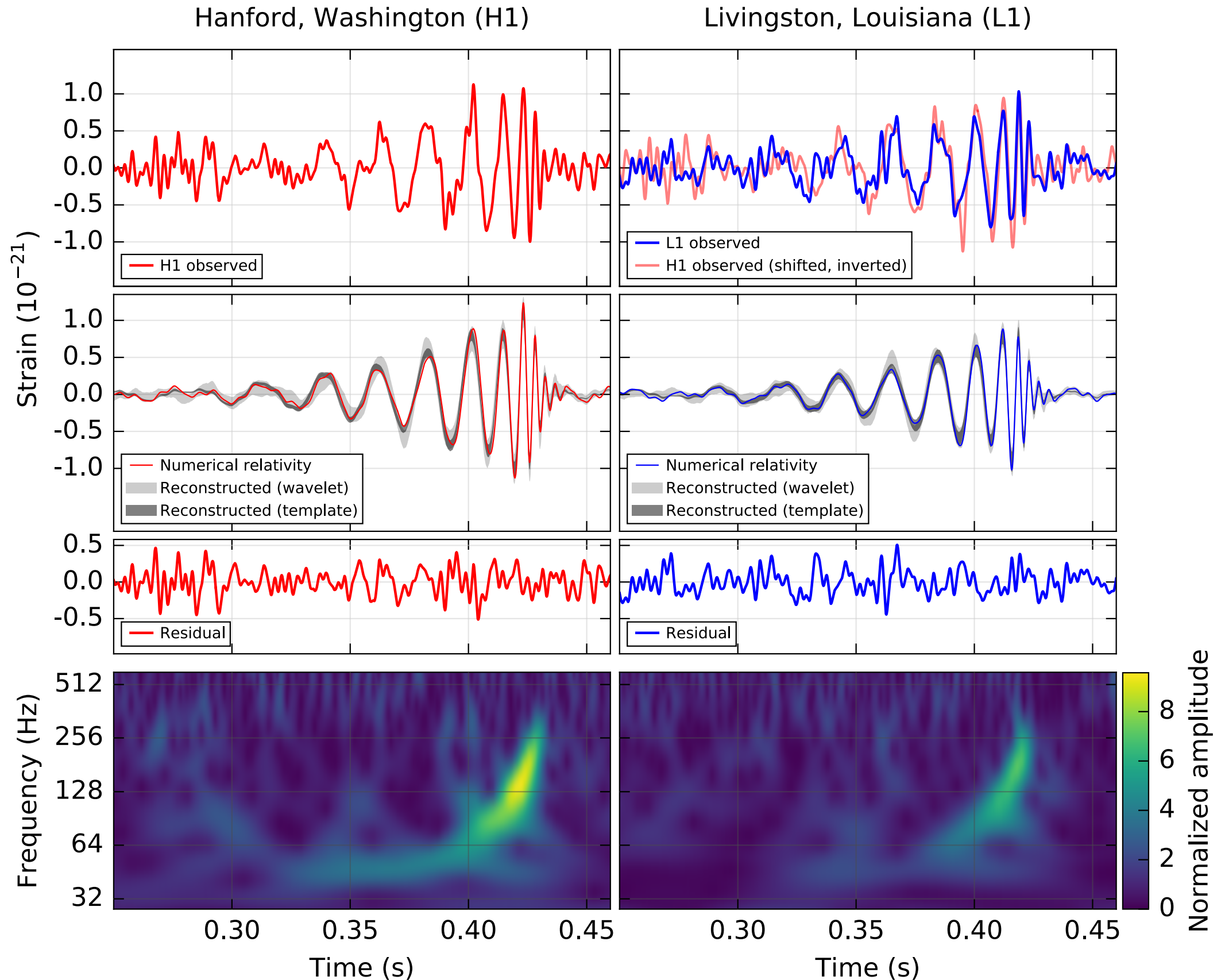


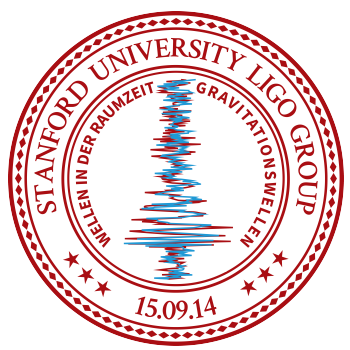
look for motions (signals) that are different from the usual noise characteristic of GWs seen at all the sites





First signal - Sept 14, 2015





Best fit with Numerical Relativity

Initial Masses:

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

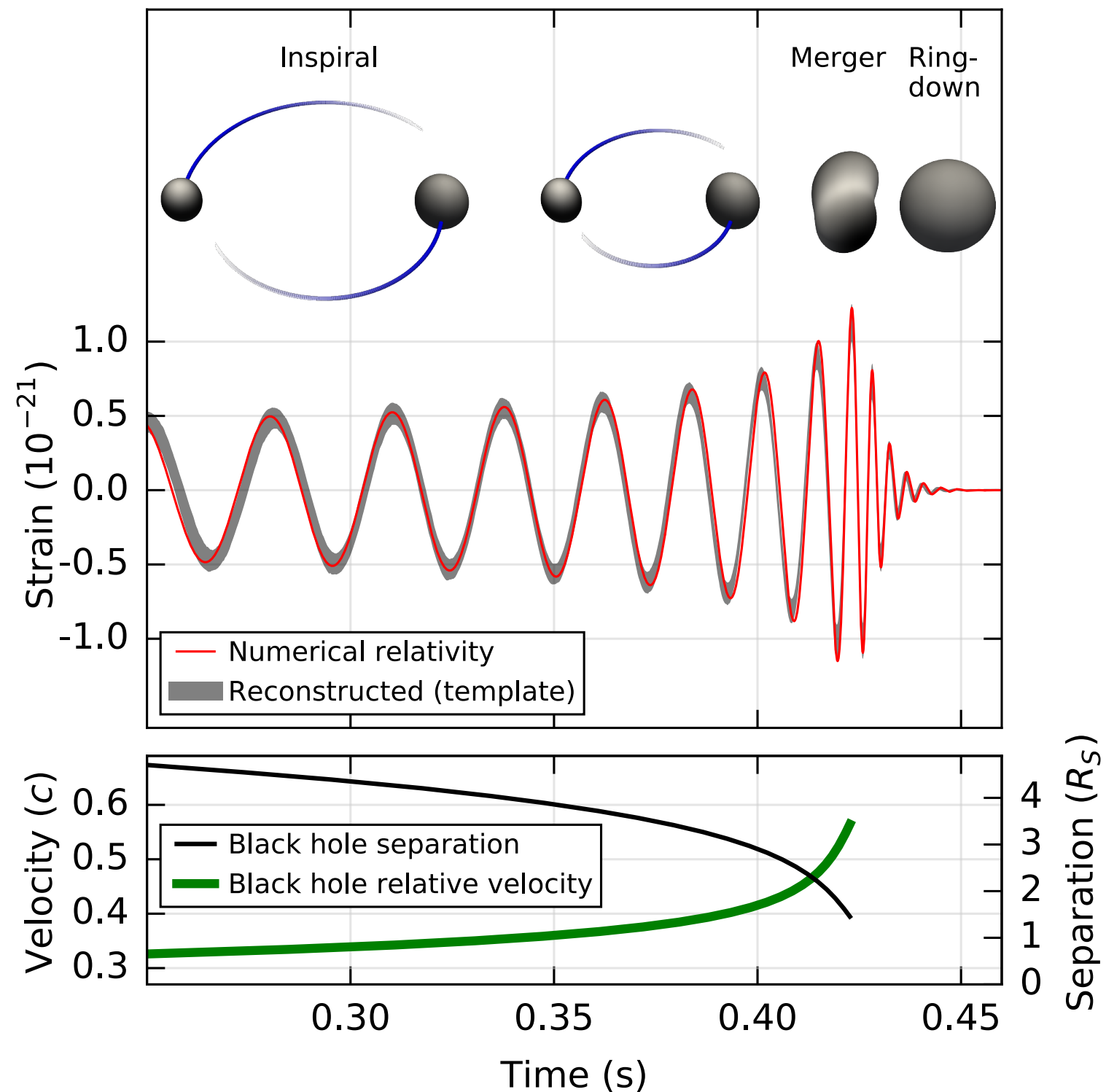
Final Mass:

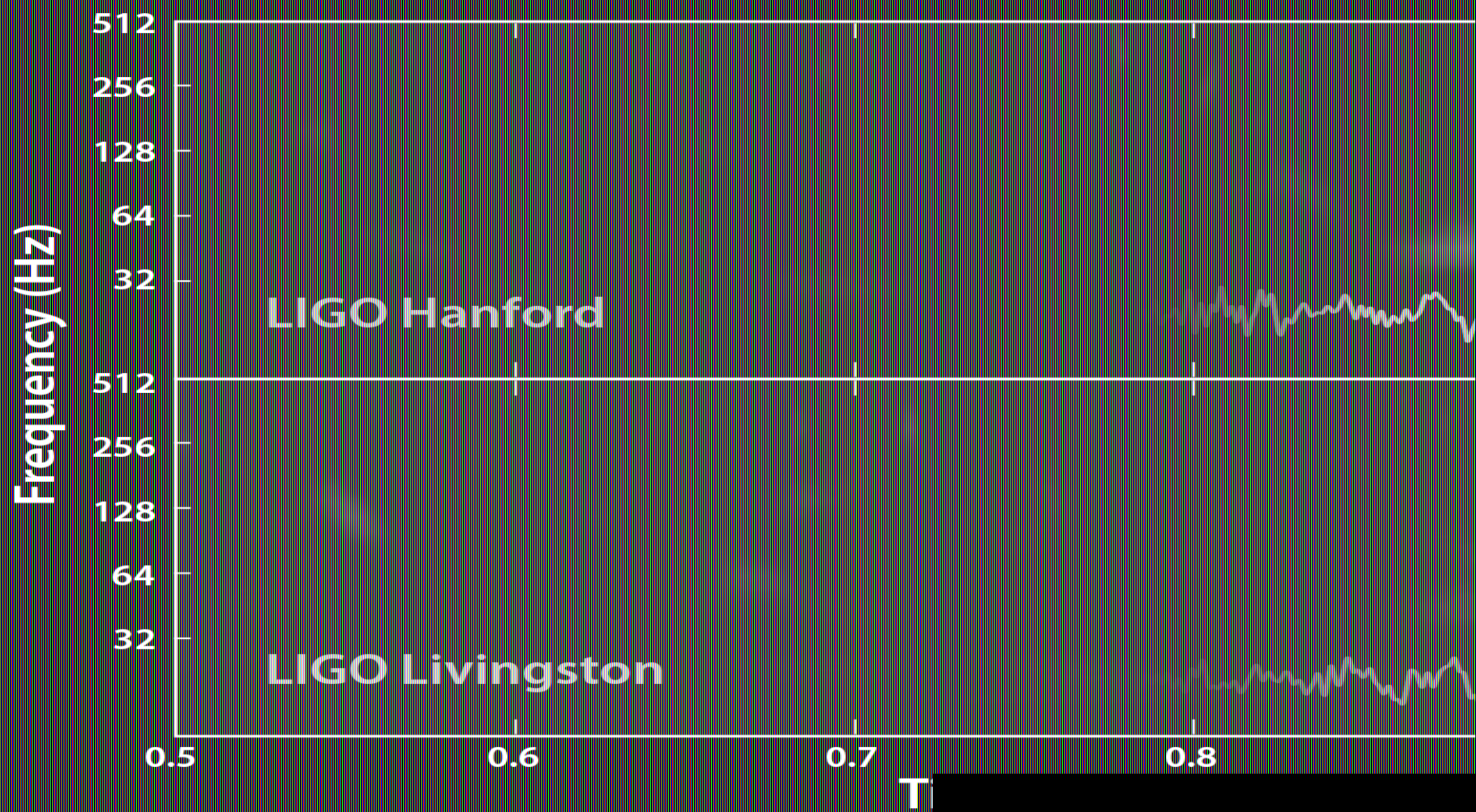
62 (+4/-4) M_{sun}

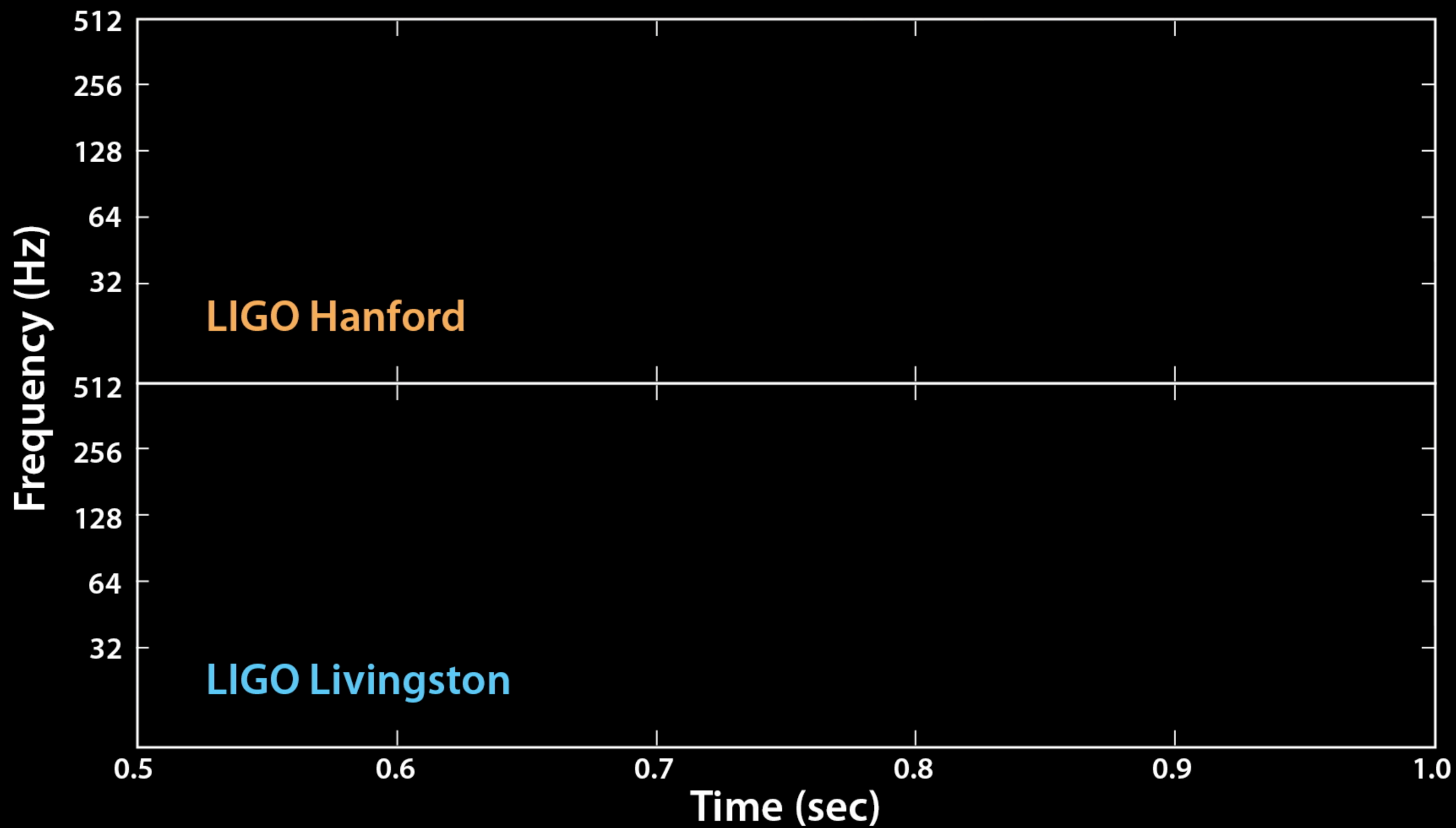
3 solar masses were
radiated as GWs

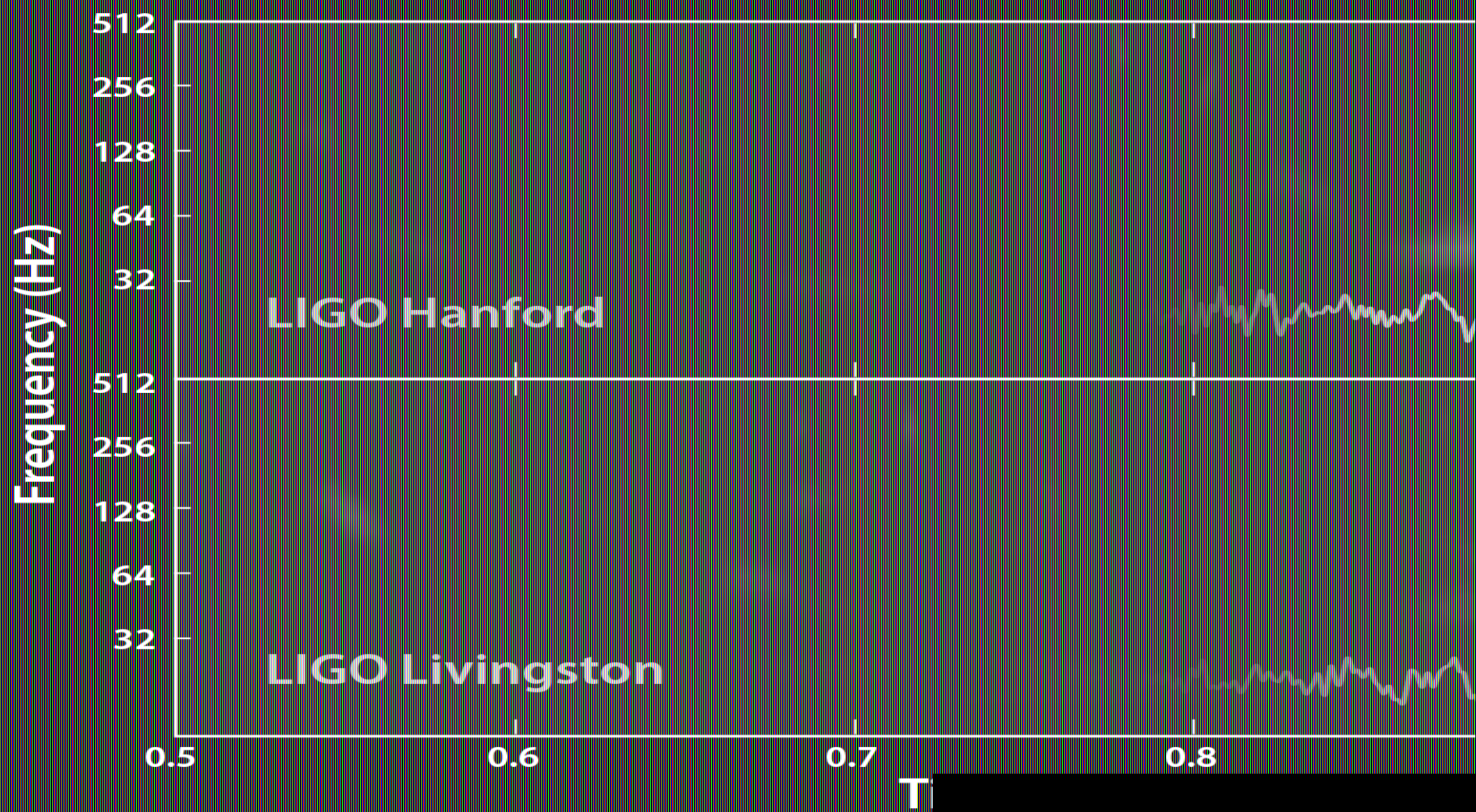
Distance

420 (+160/-180) MPc
(1.3 Billion light years)

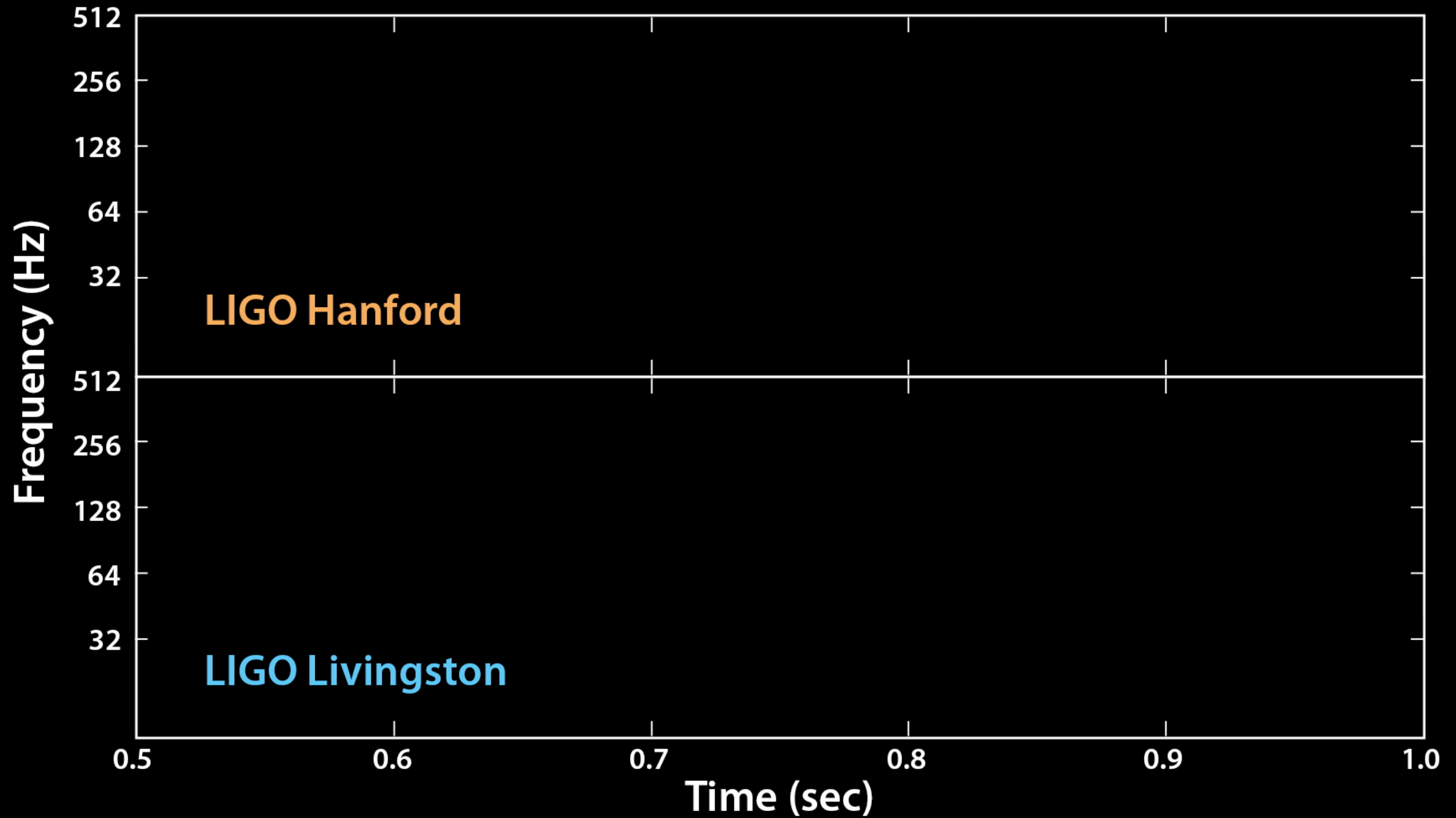






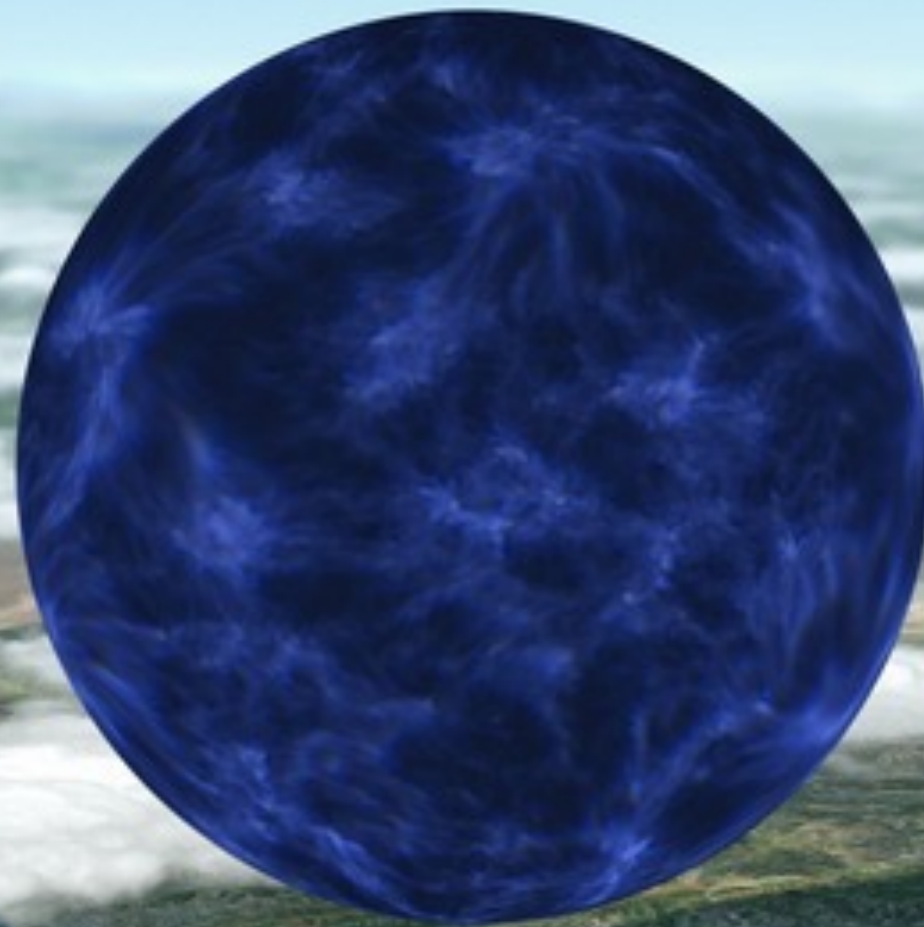


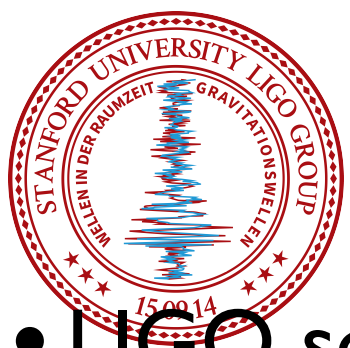
The sound of black holes colliding



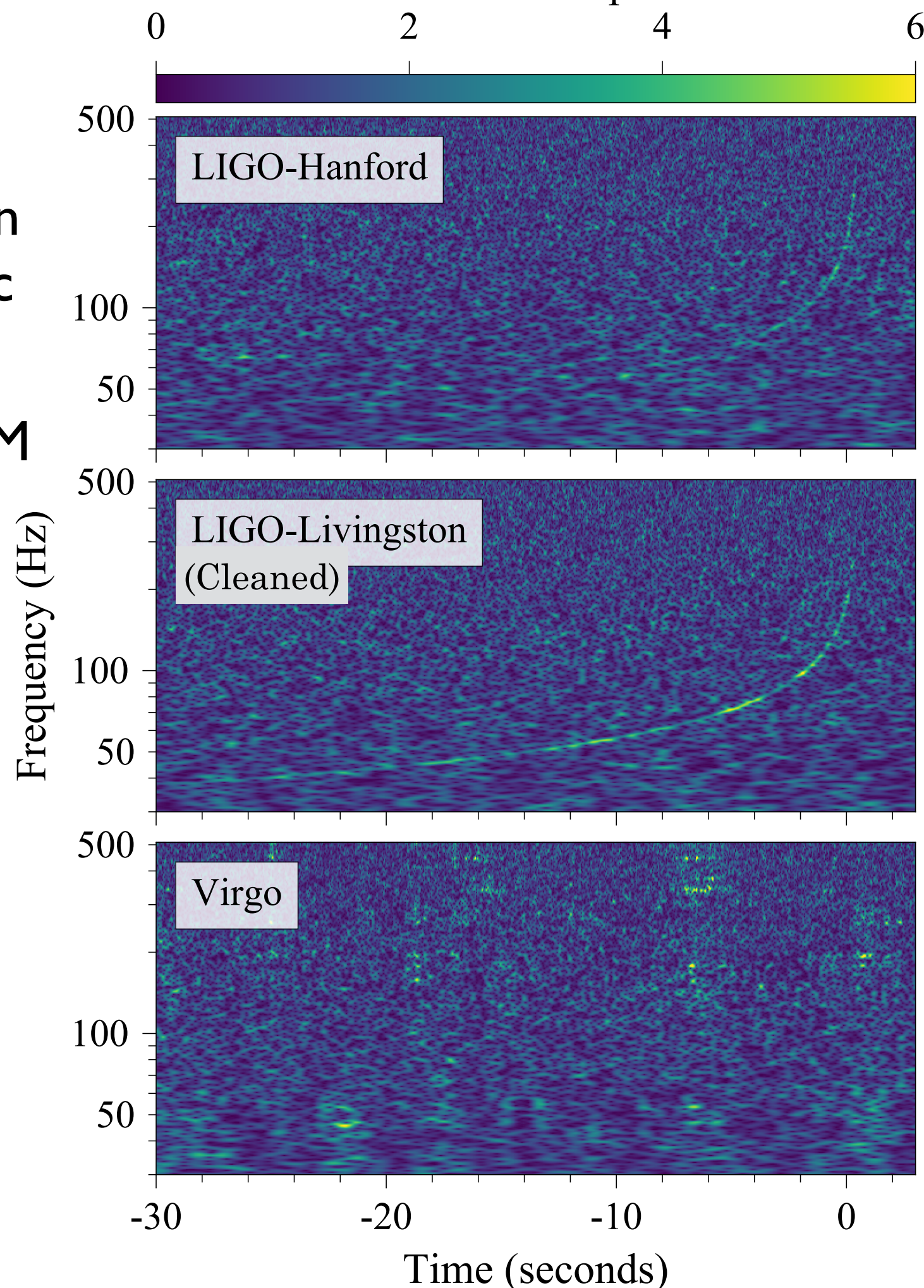
Neutron star & San Francisco
Supernova remnant
~1.4 solar masses

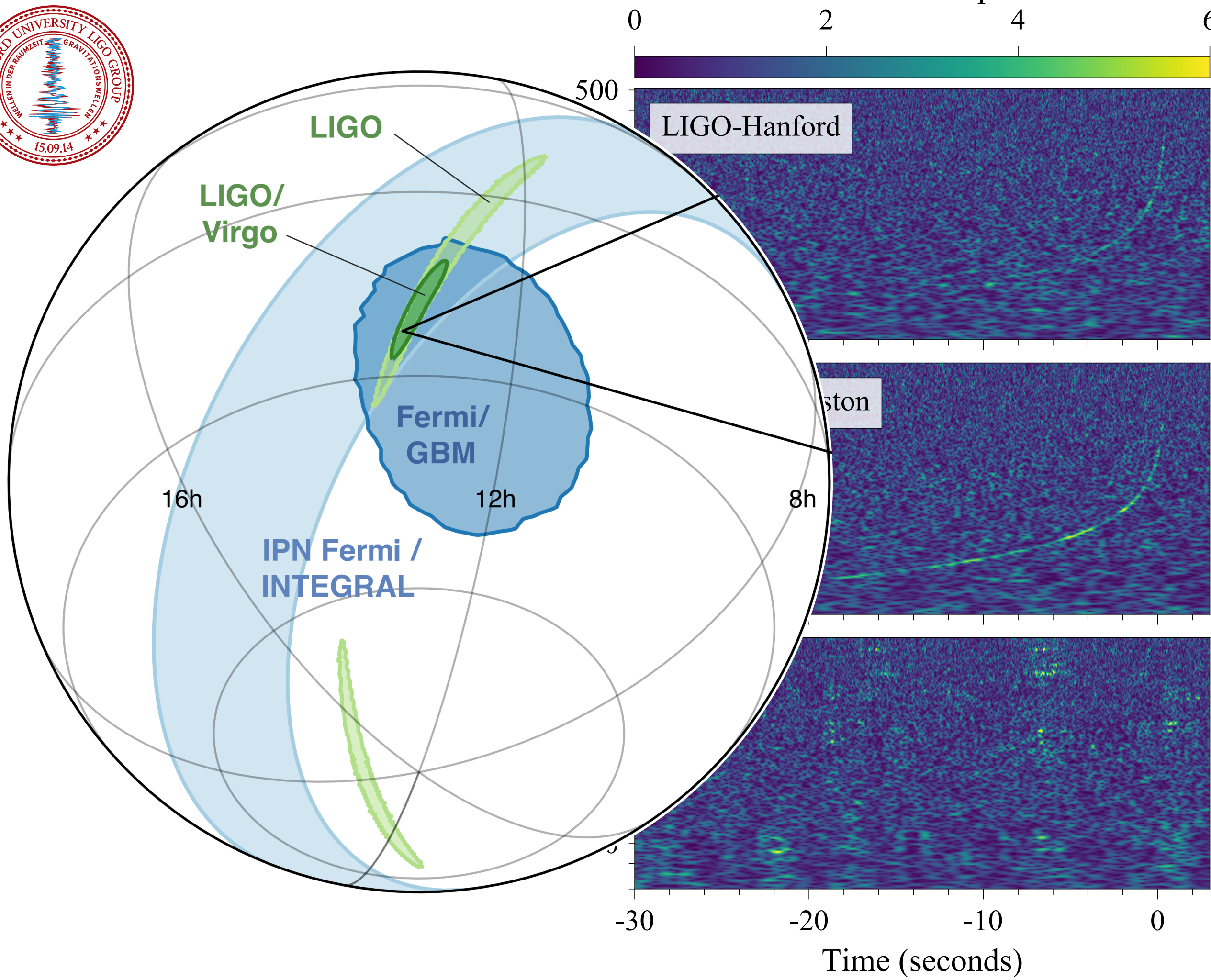
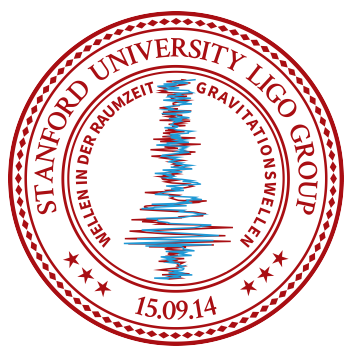
composed of dense neutrons
hot topic in astronomy
pulsars, Hulse-Taylor
kilonovas...



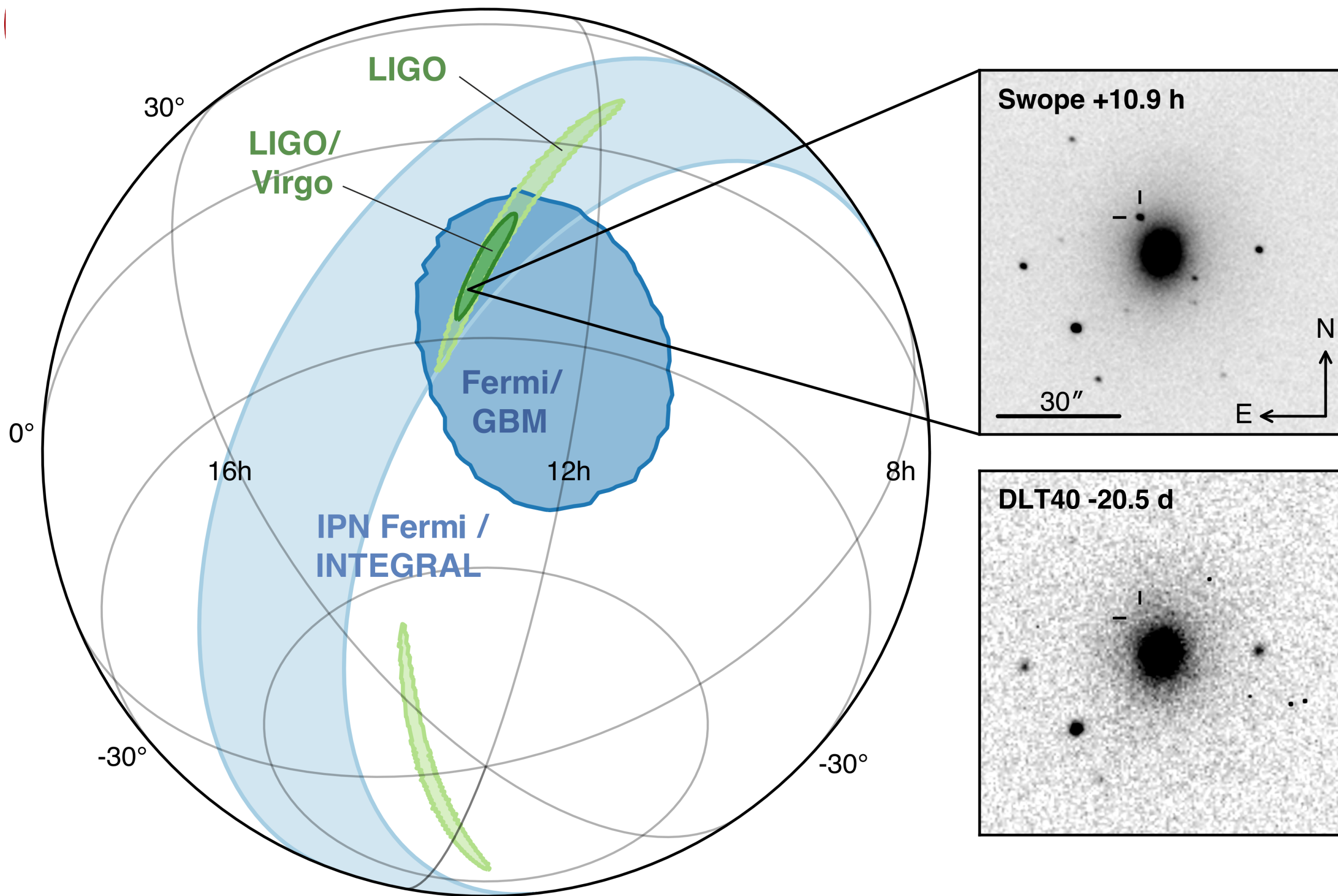


- LIGO software finds trigger in LHO data - 5:41:04 am Pacific time, August 17.
- LIGO realizes that Fermi GBM has triggered on event 1.7 seconds after GW merger.
- Thus, BNS mergers cause short gamma-ray bursts.
- Finally solving a mystery uncovered by Vela-4 in 1967. (as predicted by many).
- Forcing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





GW + GRB + Kilonova



There is matter, and we can watch it



Amazing measurement set



GW

LIGO, Virgo

γ -ray

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

X-ray

Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL

UV

Swift, HST

Optical

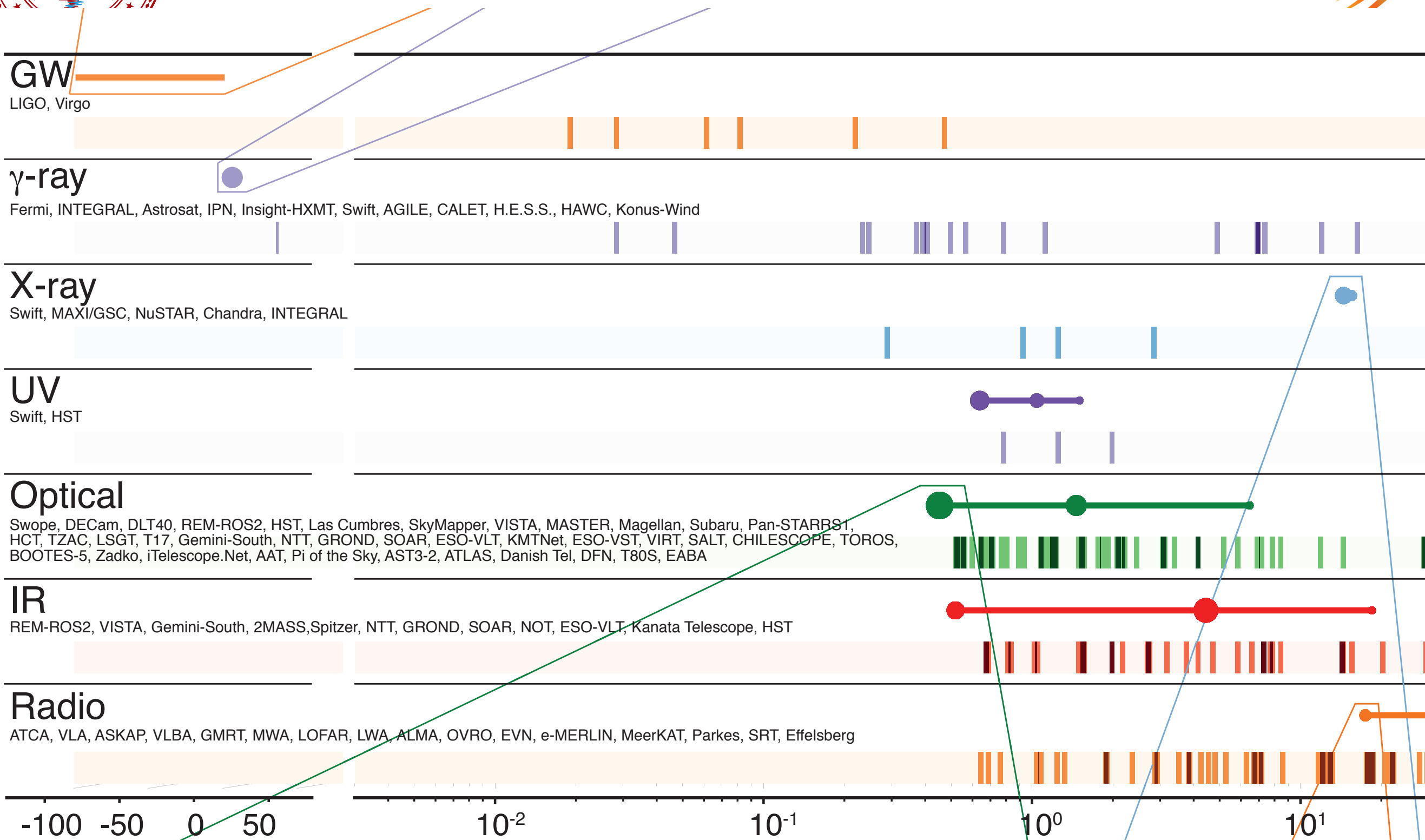
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN,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





GW

LIGO, Virgo

γ -ray

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

X-ray

Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRA

UV

Swift, HST

Optical

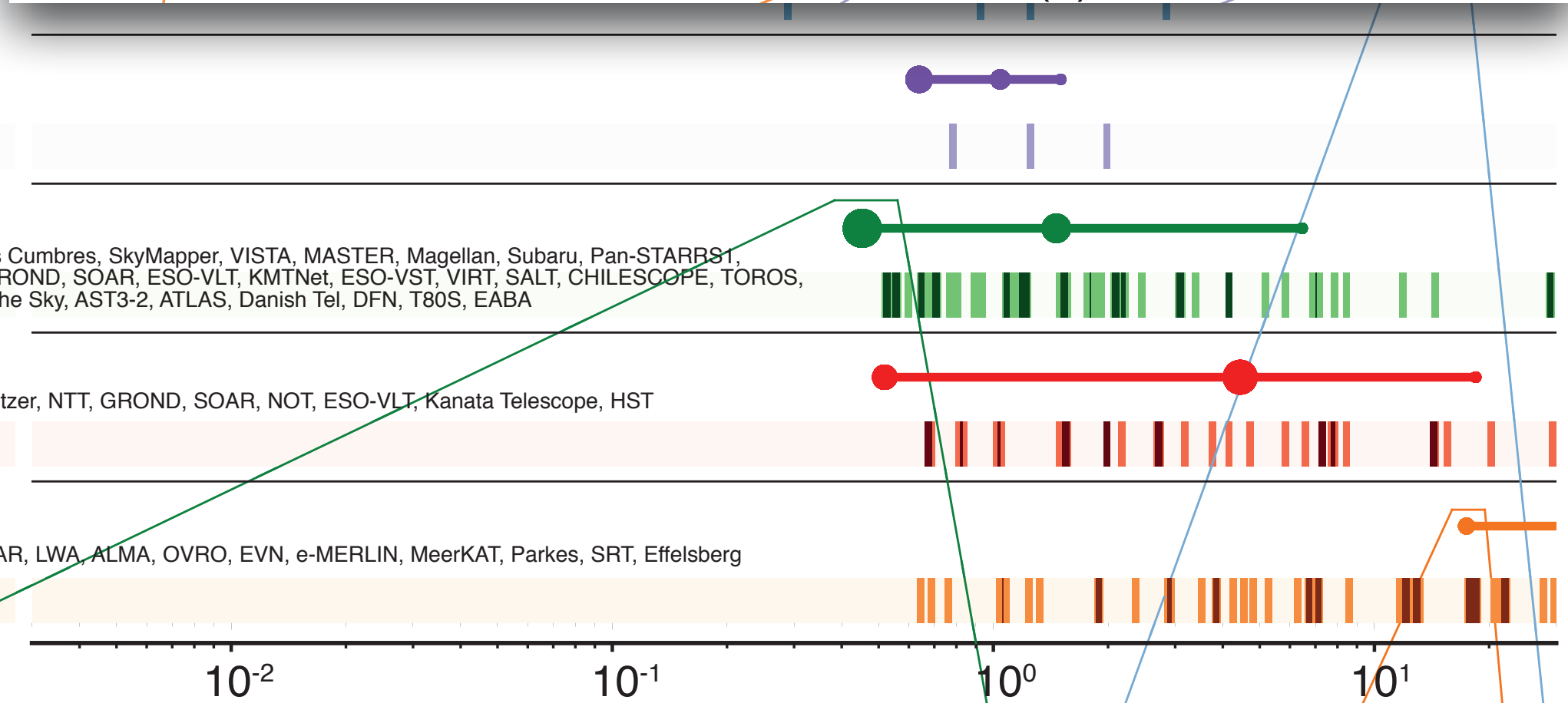
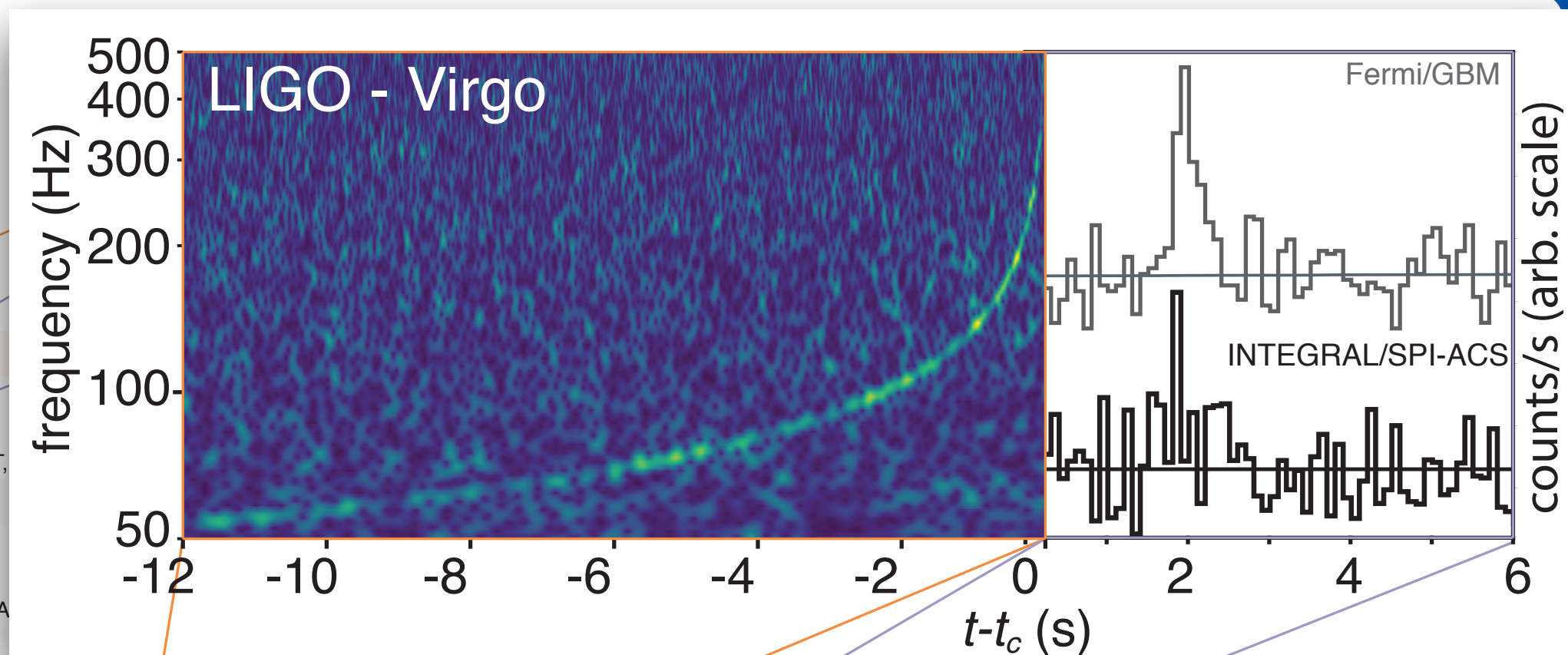
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN,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

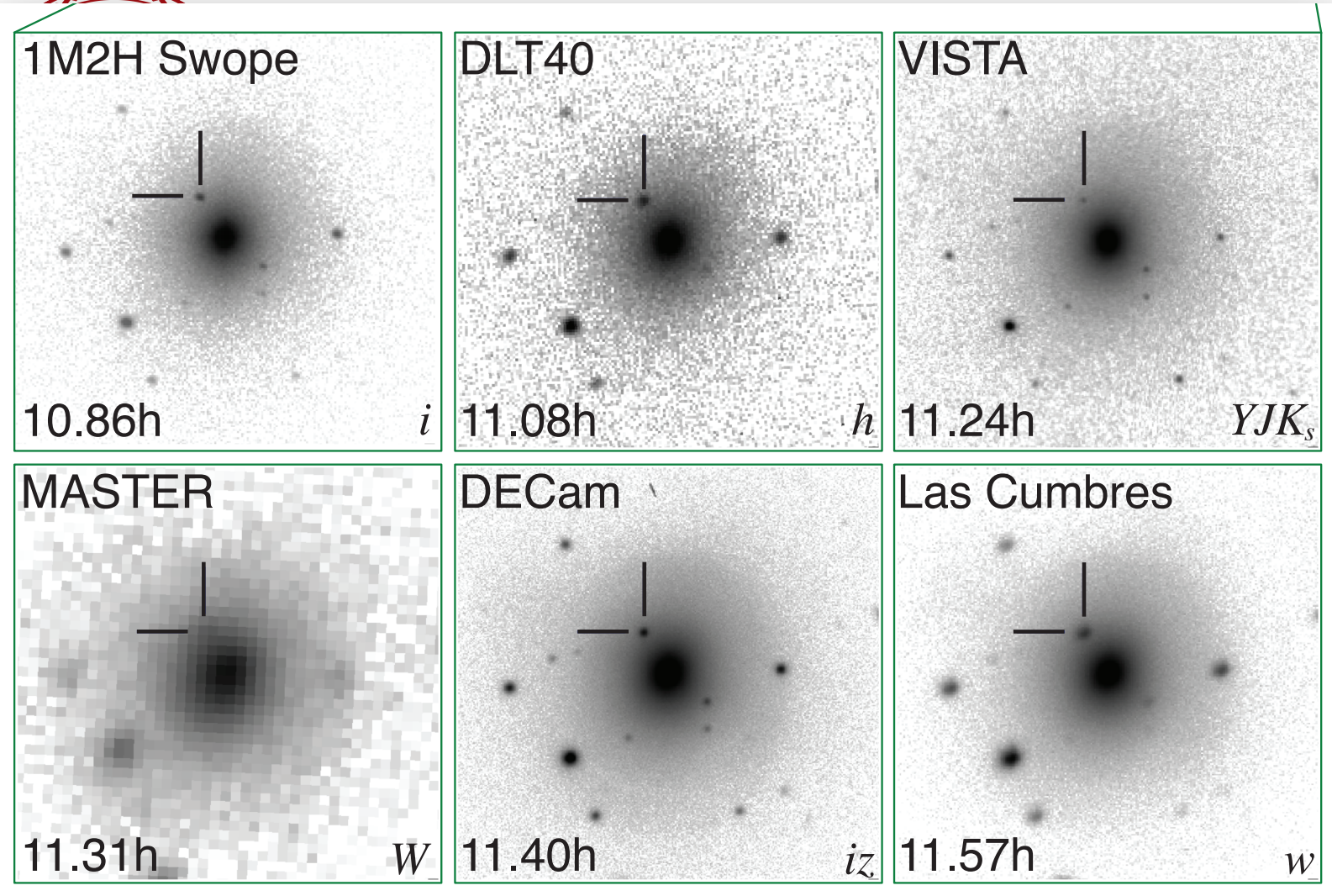
IR

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





Optical

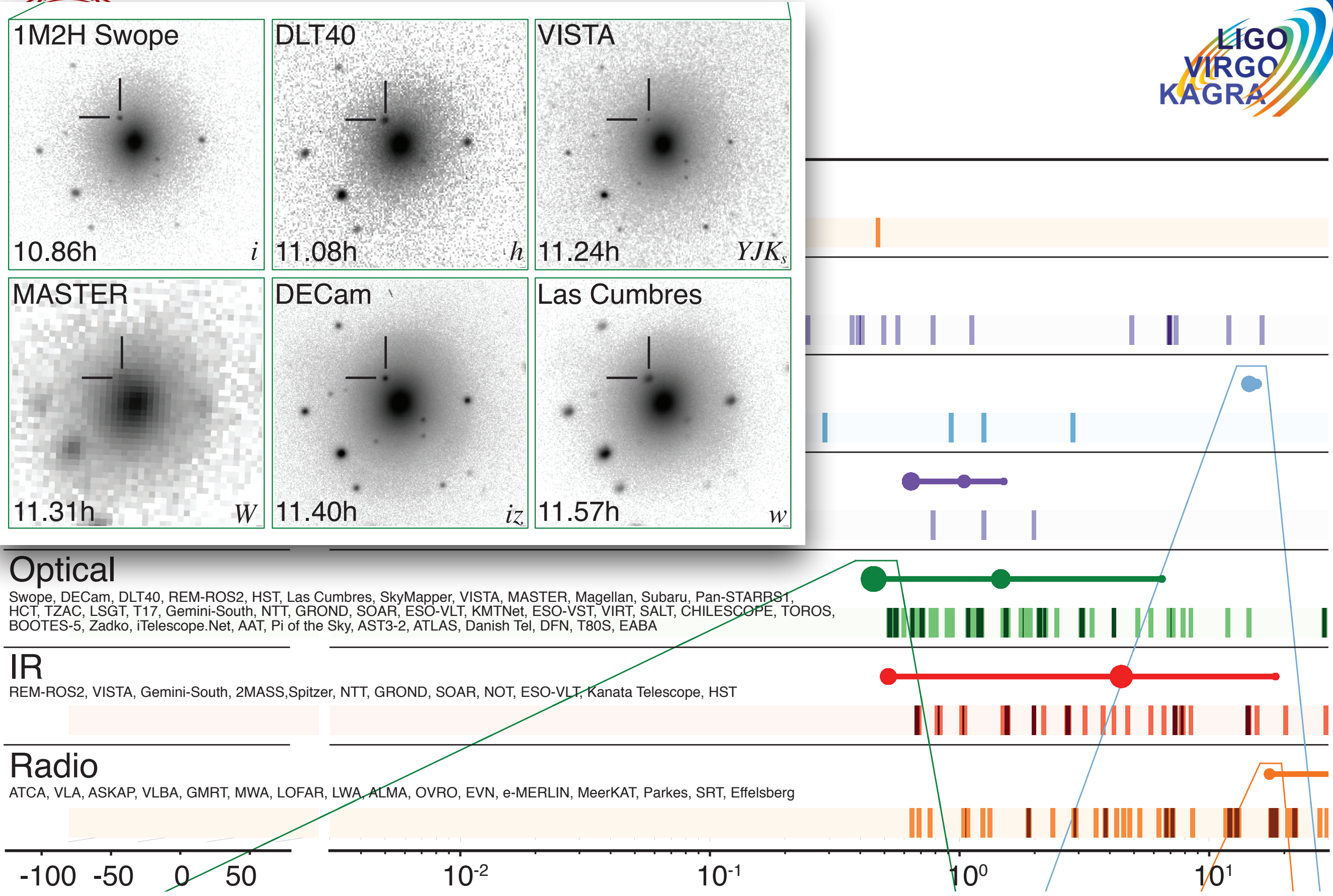
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN,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





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, MCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish

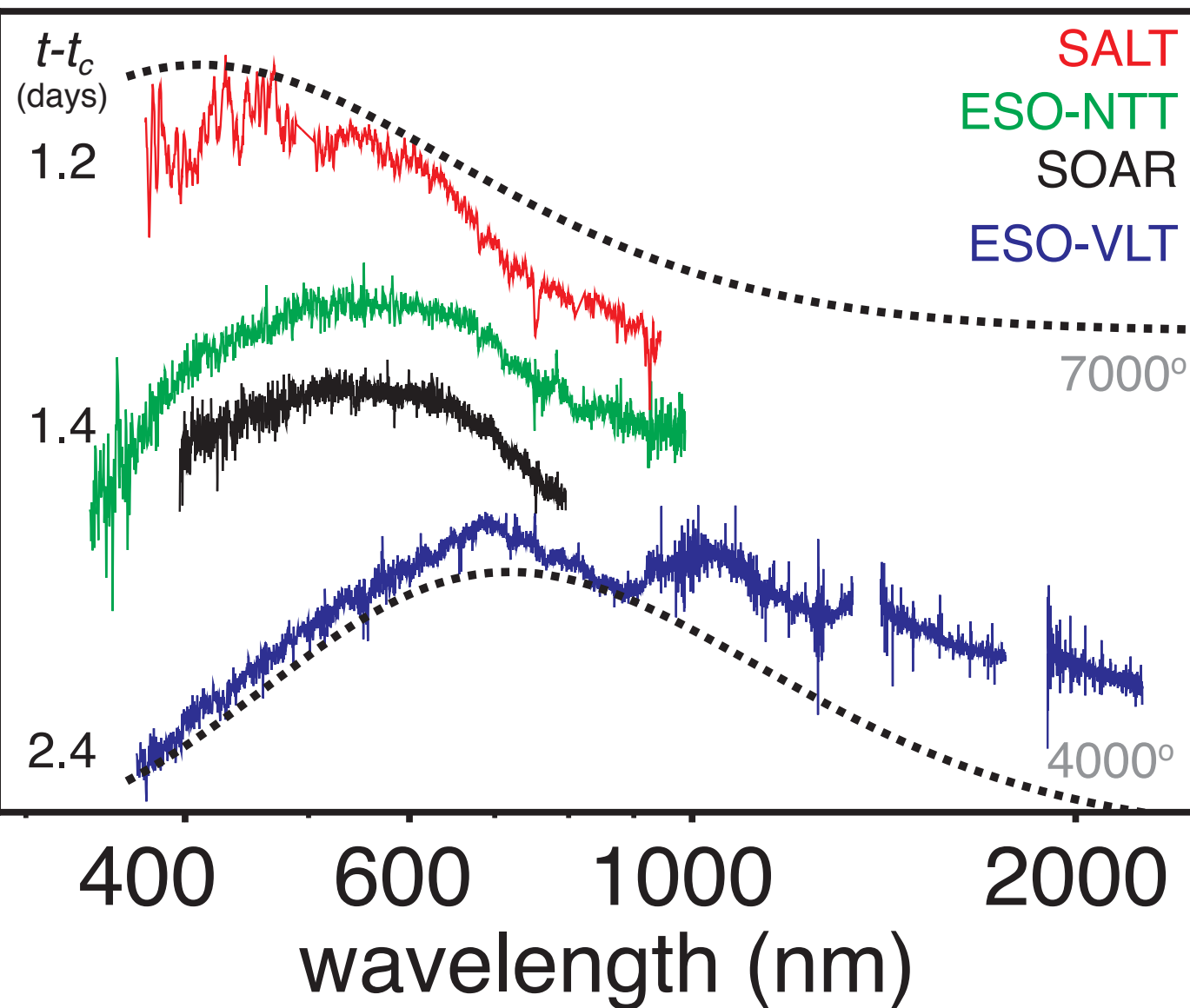
IR

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

normalized F_λ



-100 -50 0 50

10^{-2}

10^{-1}

10^0

10^1



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

Chandra

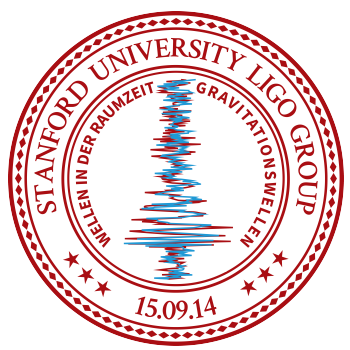
9d

X-ray

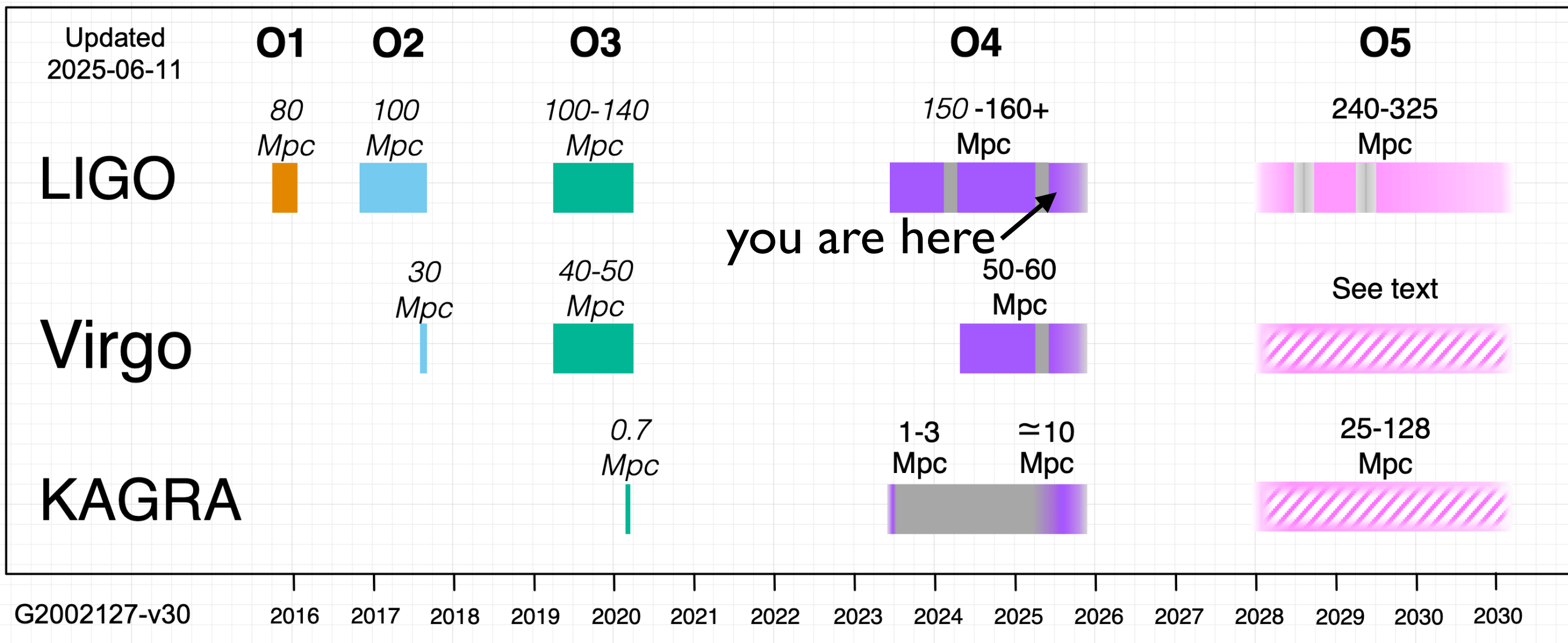
J VLA

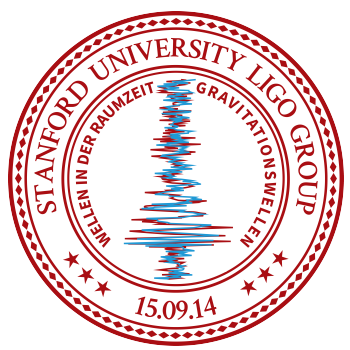
16.4d

Radio



Where are we now?

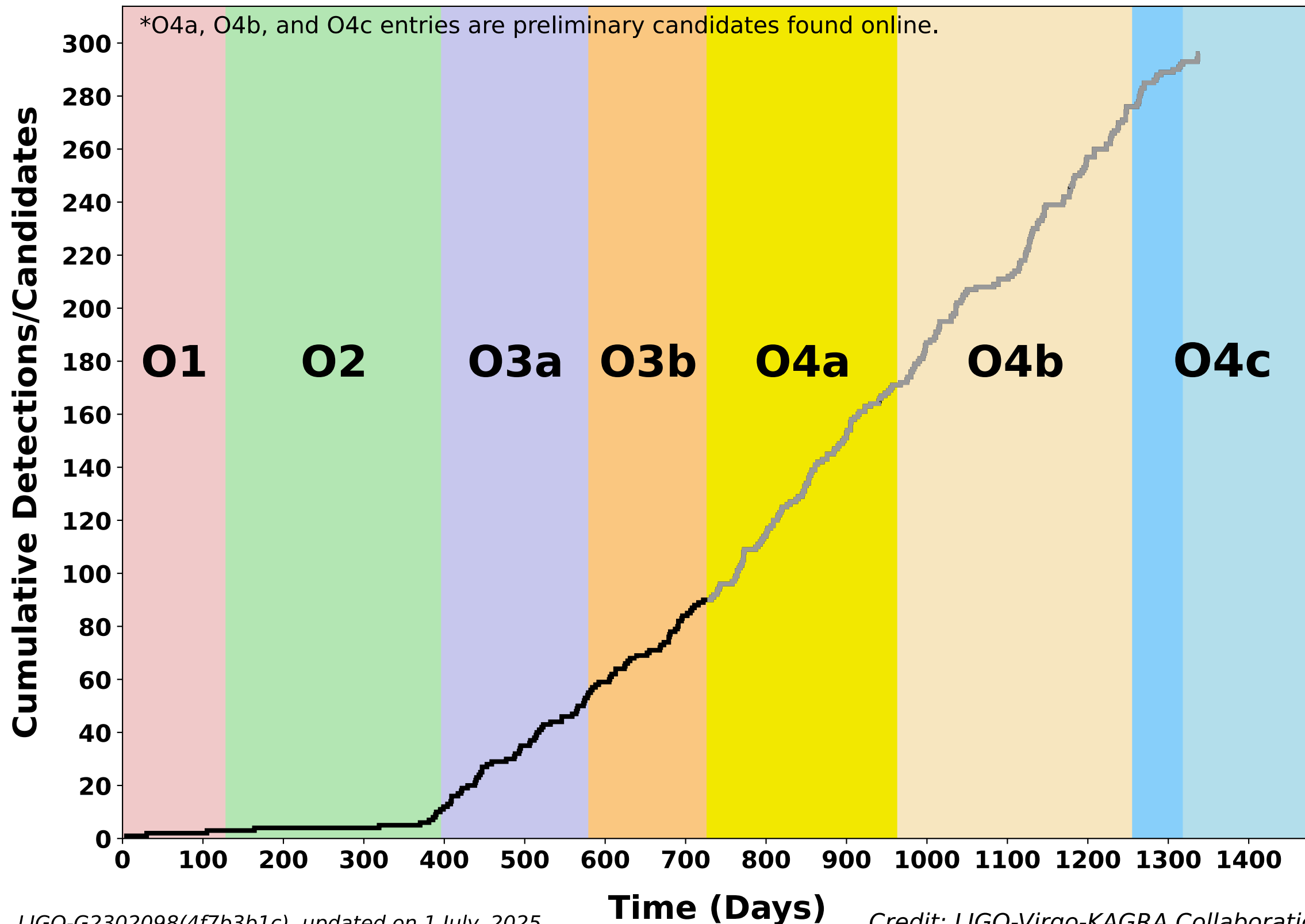




Lots of Events!

Cumulative count of GW events

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



O4 Significant Detection Candidates: **206** (231 Total - 25 Retracted)

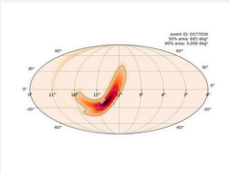
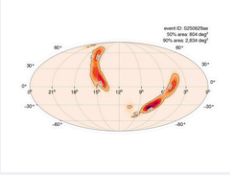
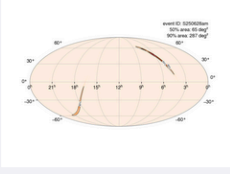
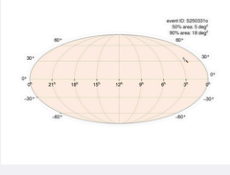
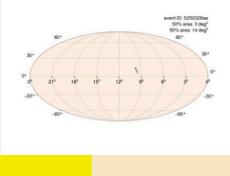
O4 Low Significance Detection Candidates: **3939** (Total)

Show All Public Events

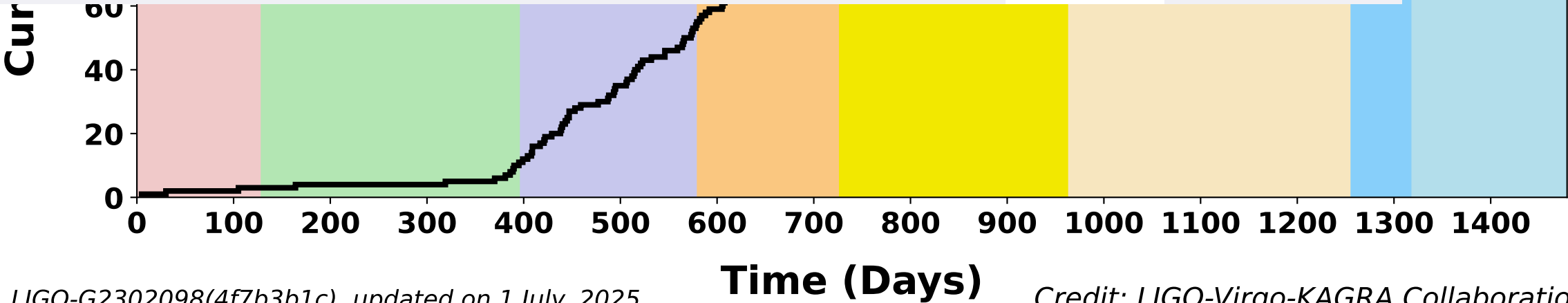
Page 1 of 16. [next](#) [last](#) »

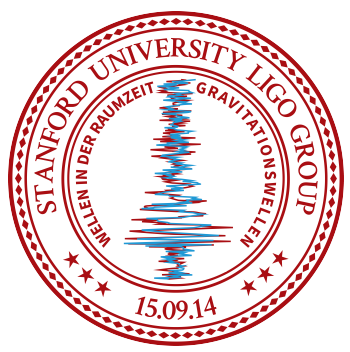
SORT: EVENT ID (A-Z) ▾

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

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR
S250629bs	BBH (94%), Terrestrial (6%)	Yes	June 29, 2025 12:13:04 UTC	GCN Circular Query Notices VOE		1.366 per year
S250629ae	BBH (98%), Terrestrial (2%)	Yes	June 29, 2025 05:50:36 UTC	GCN Circular Query Notices VOE		1.0195 per year
S250628am	BBH (>99%)	Yes	June 28, 2025 18:23:19 UTC	GCN Circular Query Notices VOE		1 per 1.8824e+06 years
S250331o	BBH (>99%)	Yes	March 31, 2025 01:34:48 UTC	GCN Circular Query Notices VOE		1 per 100.04 years
S250328ae	BBH (>99%)	Yes	March 28, 2025 05:40:27 UTC	GCN Circular Query Notices VOE		1 per 100.04 years

O4c

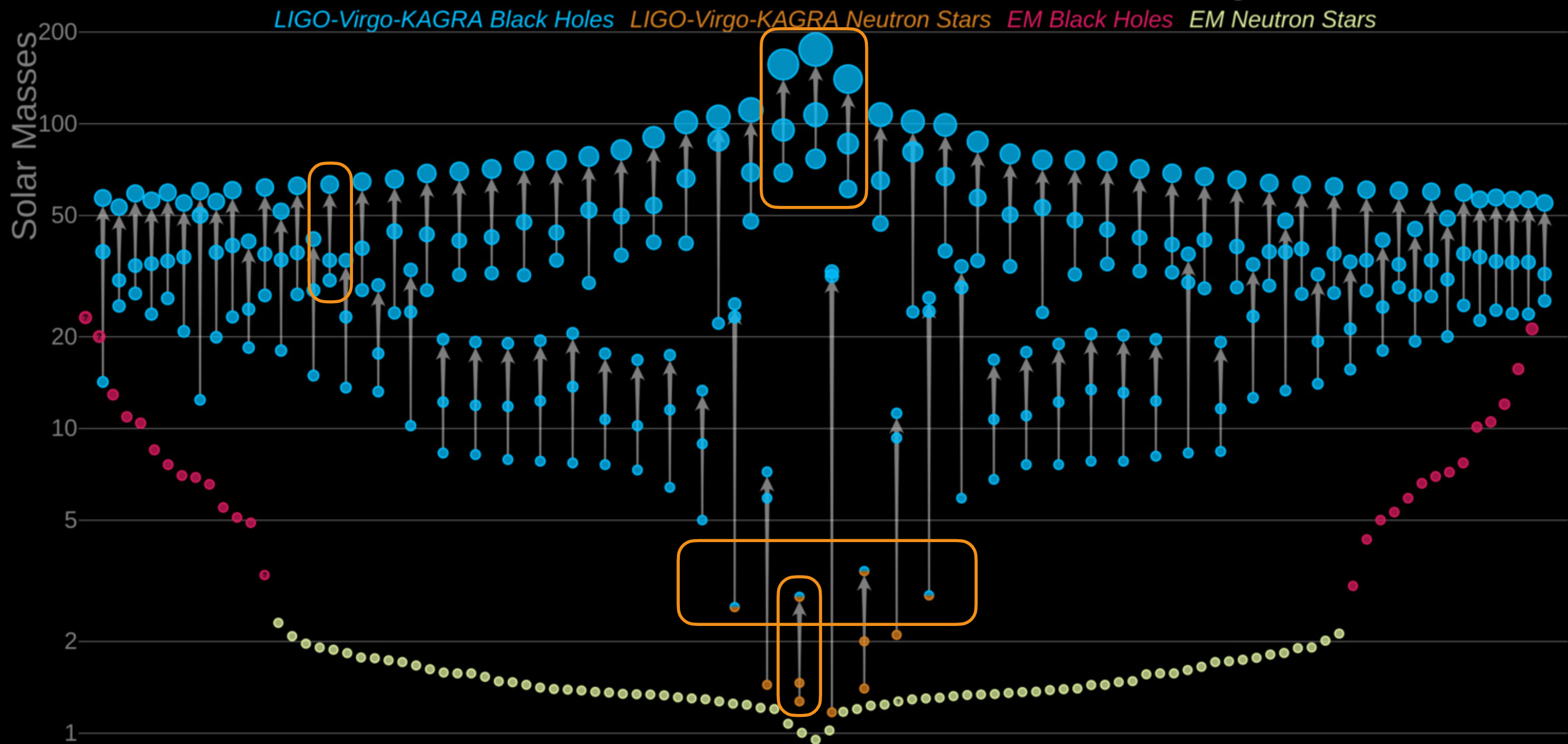




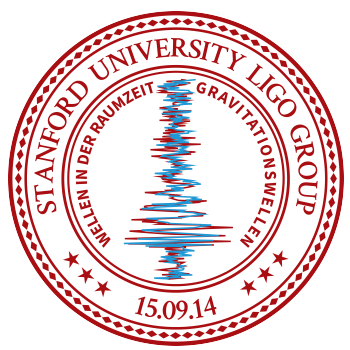
Lots of Events!



Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

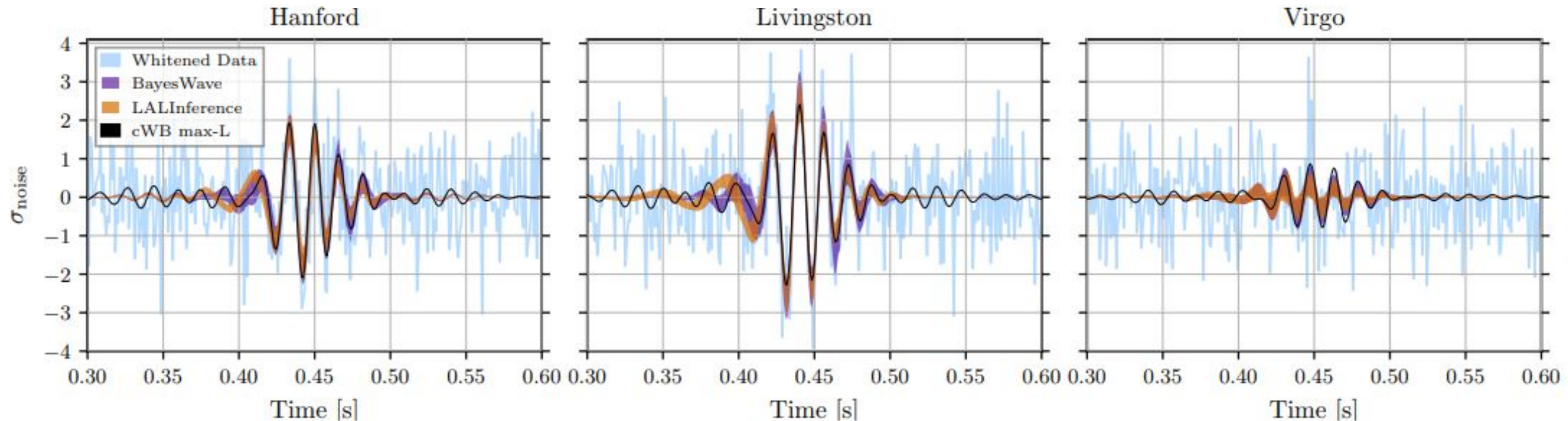


notable events

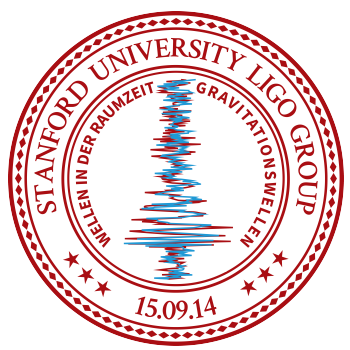
GW190521 - ~150 solar mass event

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

(1.7 Gpc, 5 B lightyears)



4

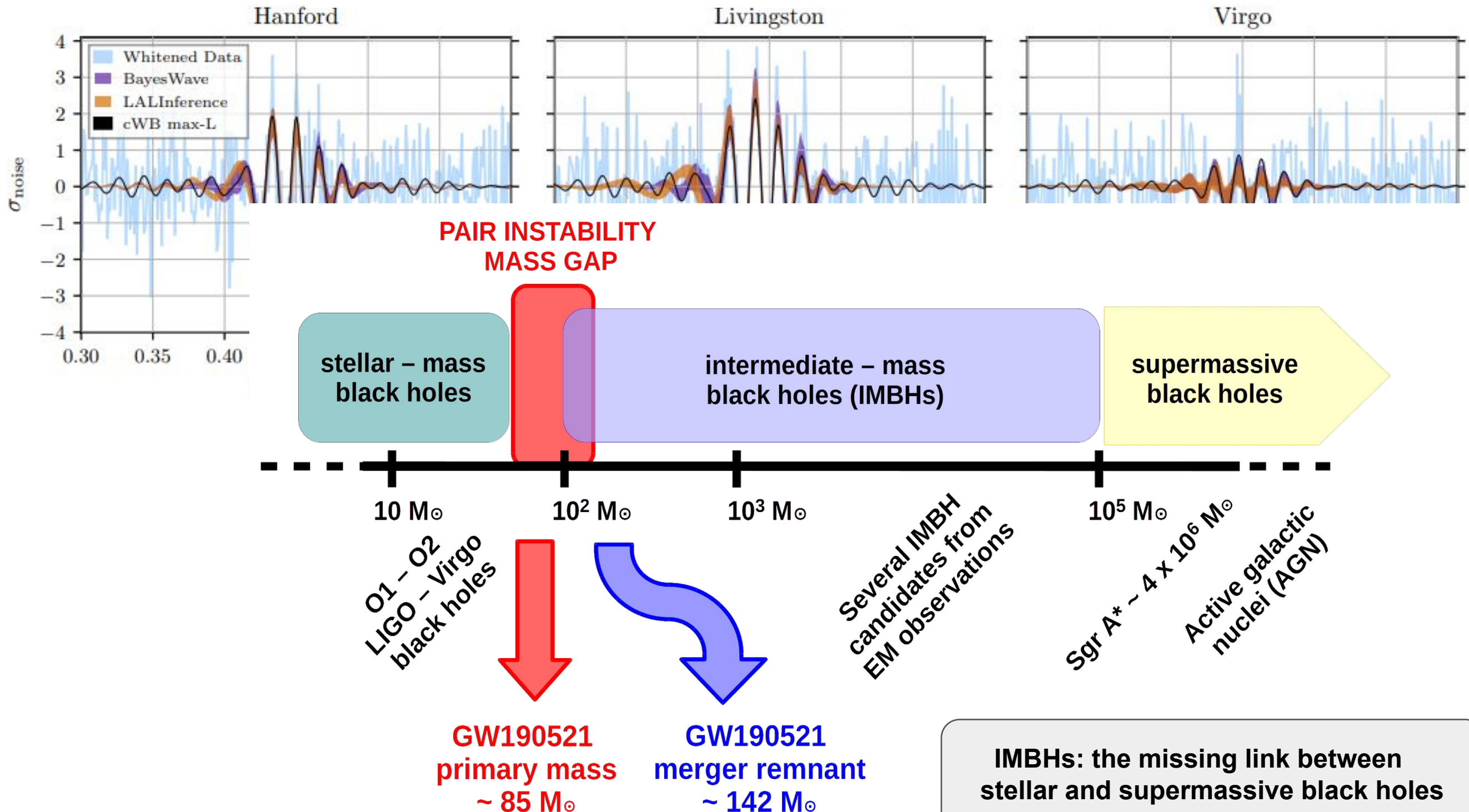


notable events

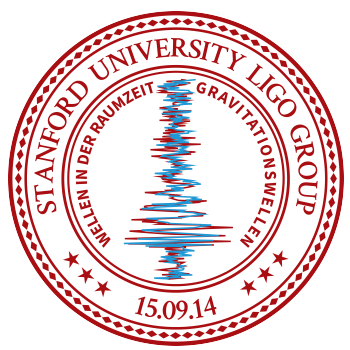
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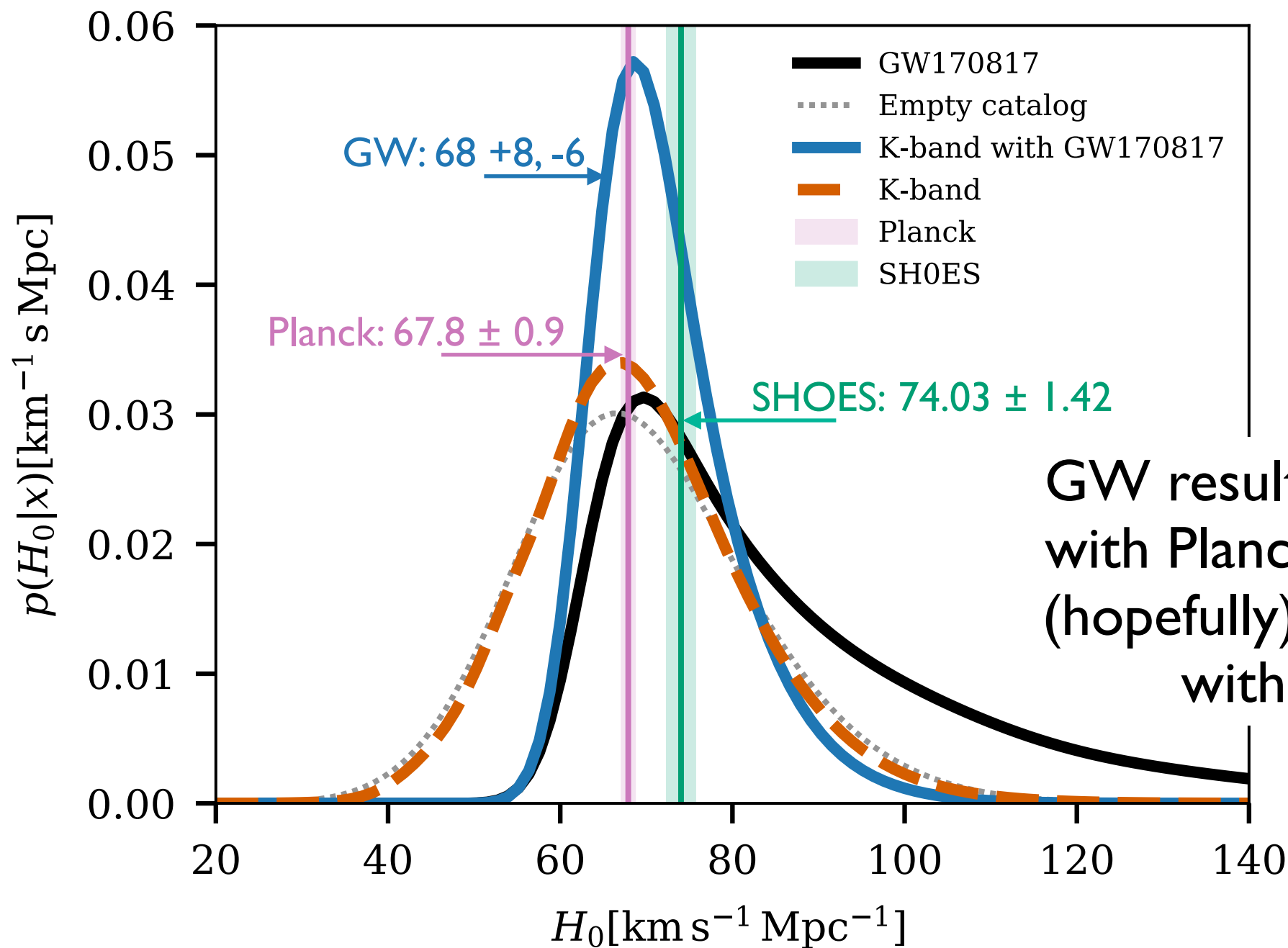
IMBHs: the missing link between stellar and supermassive black holes



Expansion of the Universe

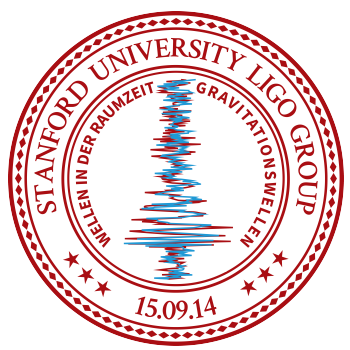


Measuring the Hubble constant H_0 with gravitational waves
because the 2 best measurement do not agree?!



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 information 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 SHOES (Riess et al. 2019) respectively.



Testing General Relativity



So far, Einstein is getting an A+

- Speed of gravity = speed of light.
Measured bounds are -3×10^{-15} and $+7 \times 10^{-16}$ of c
- Mass of graviton is still zero, bound is $< 1.23 \times 10^{-23} \text{ eV}/c^2$
- GR can explain the signals we measure,
“post Newtonian” terms are consistent with 0.

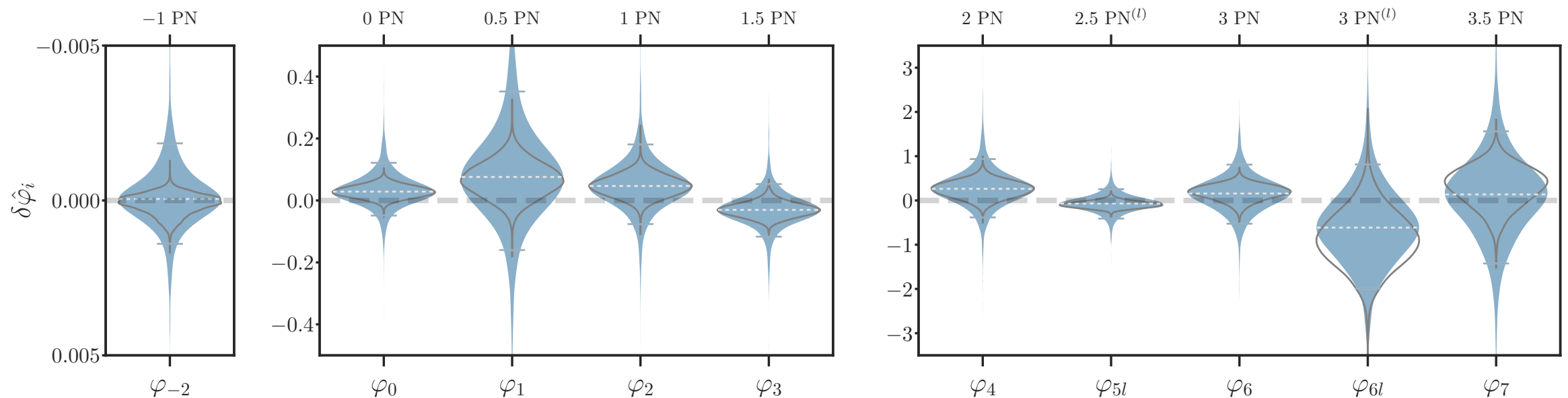
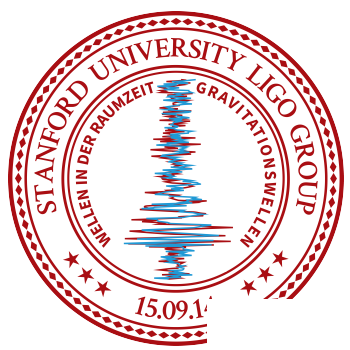


FIG. 7. Combined GWTC-3 results for the parametrized deviation coefficients of Sec. V A. Filled distributions represent the results obtained hierarchically combining all events. This method allows the deviation coefficients to assume different values for different events. Unfilled black curves represent the distributions obtained in Fig. 6, by assuming the same value of the deviation parameters across all events. Horizontal ticks and dashed white lines mark the 90% credible intervals and median values obtained with the hierarchical analysis.

speed of gravity: <https://arxiv.org/abs/1710.05834>

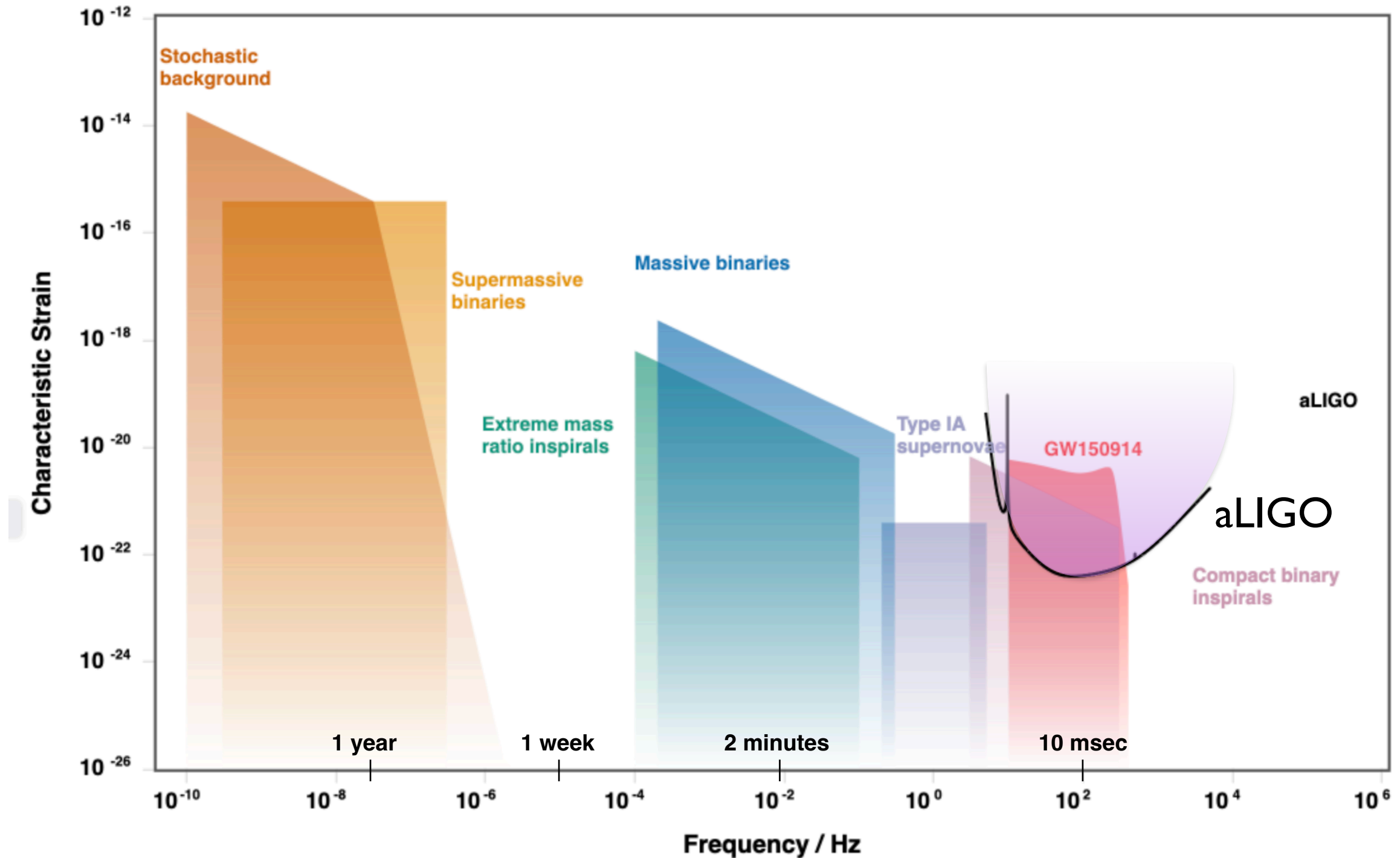
tests of GR, GWTC 3: <https://arxiv.org/abs/2112.06861>

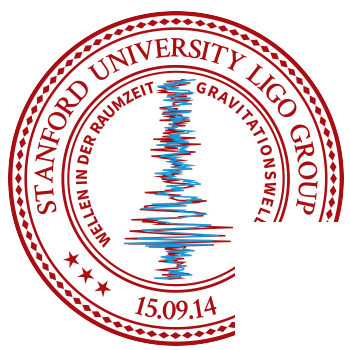


There is so much more...



Gravitational Wave Detectors and Sources

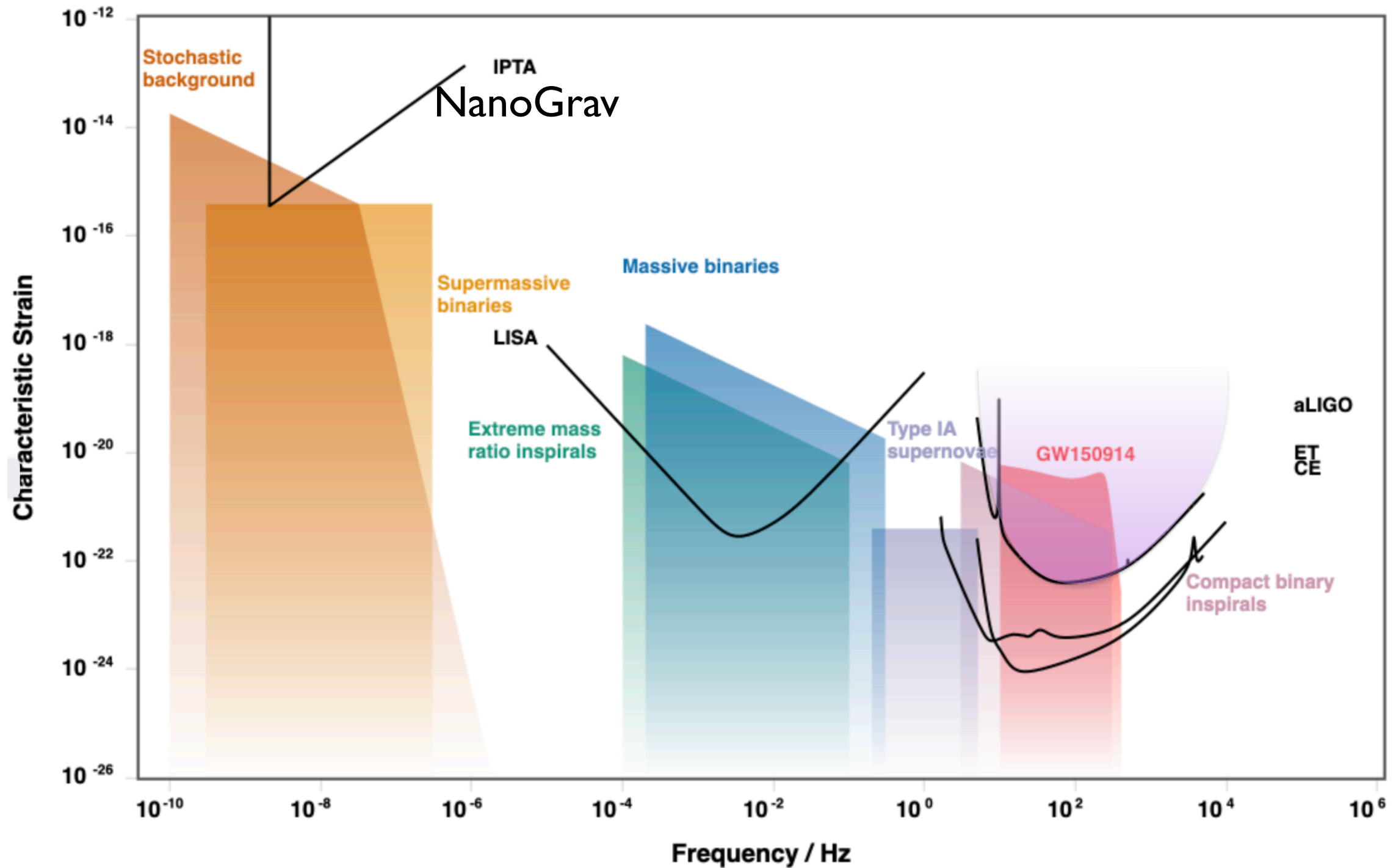




There is so much more...



Gravitational Wave Detectors and Sources





Pulsar timing



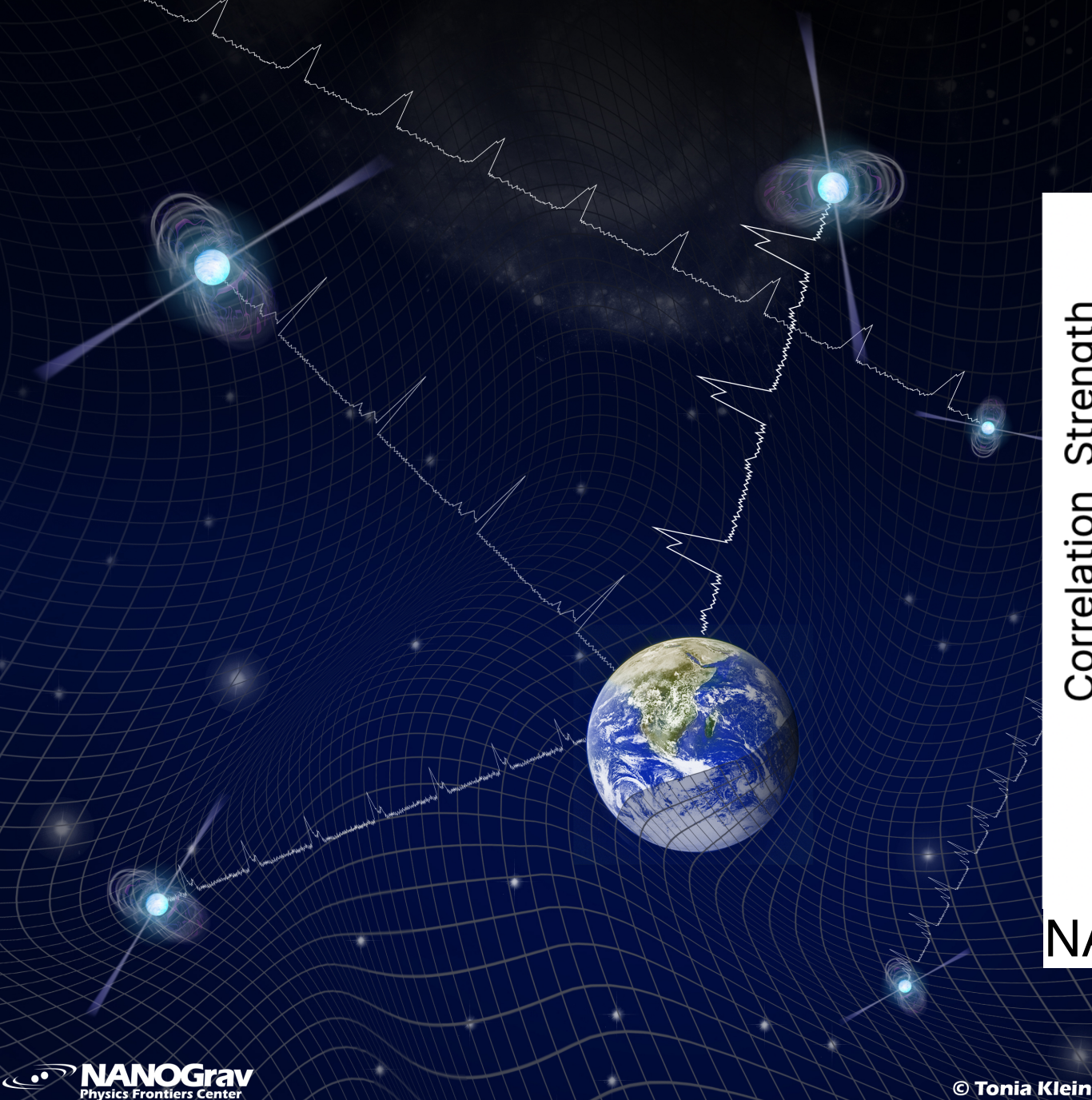
Use the “tick, tick, tick” of pulsars to measure space getting stretched by gravitational waves

The “arms” are a few thousand lightyears long!

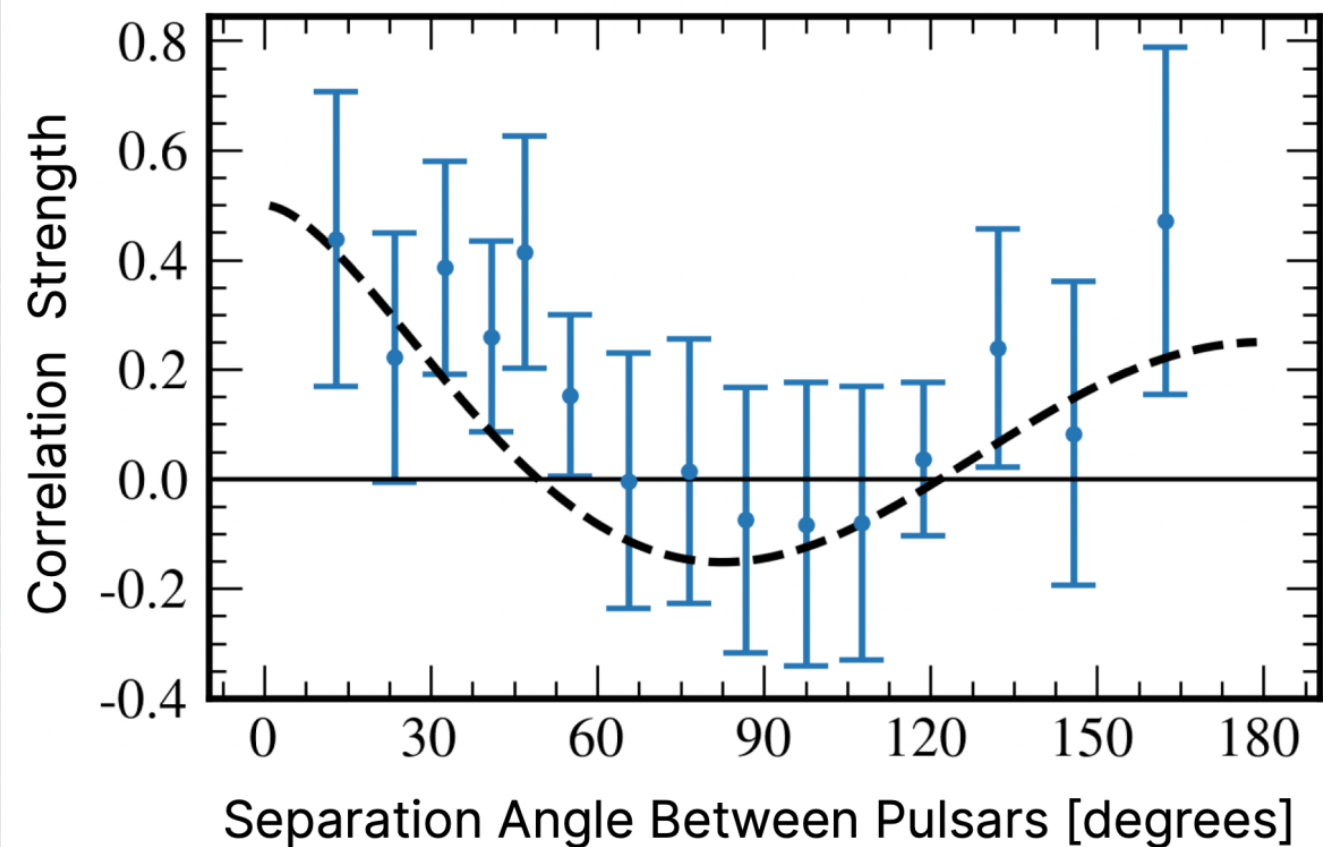
Measure correlations

NANOgrav (USA) uses 68 pulsars





Pulsar timing



NANOgrav 15 year data release, June 29, 2023

NANOgrav (USA) uses 68 pulsars

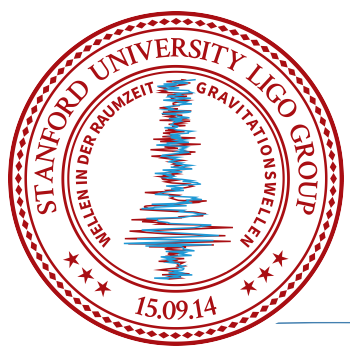
also PPTA, EPTA, InPTA, CPTA, MPTA

IPTA (International PTA)

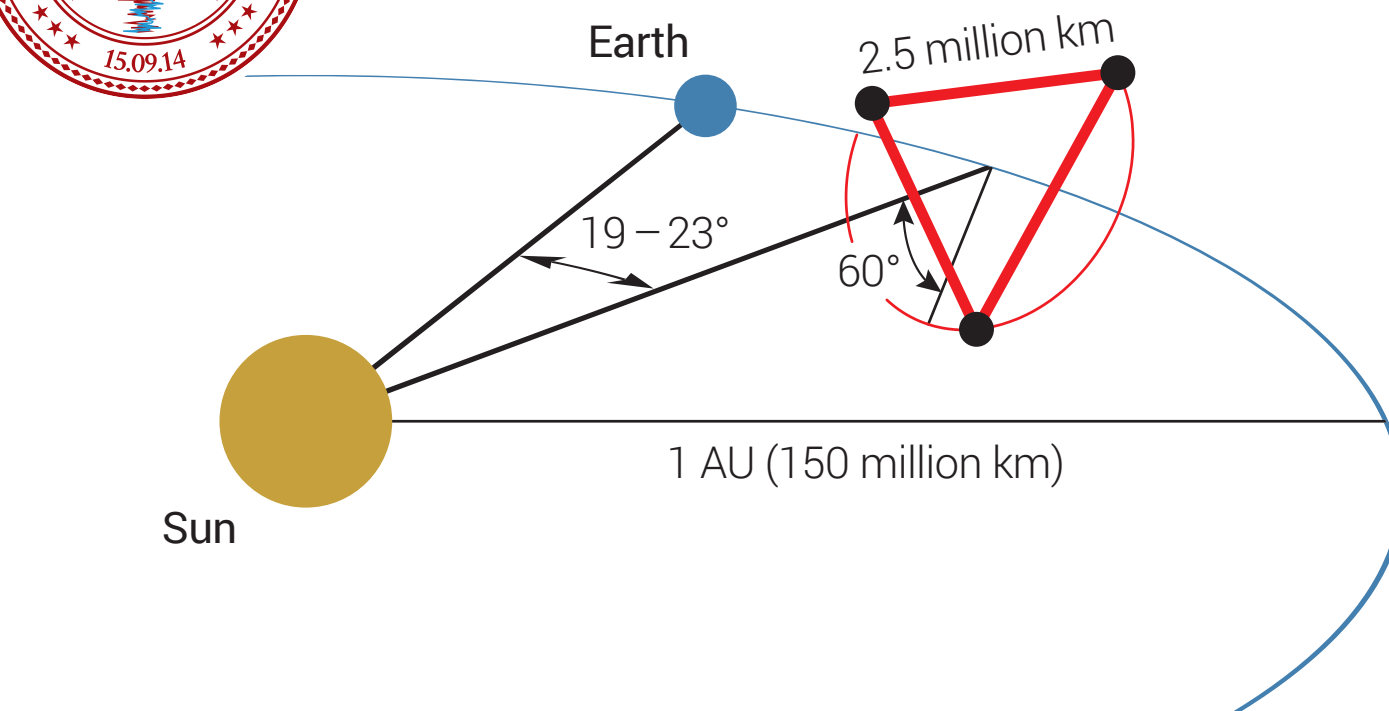
<https://nanograv.org>



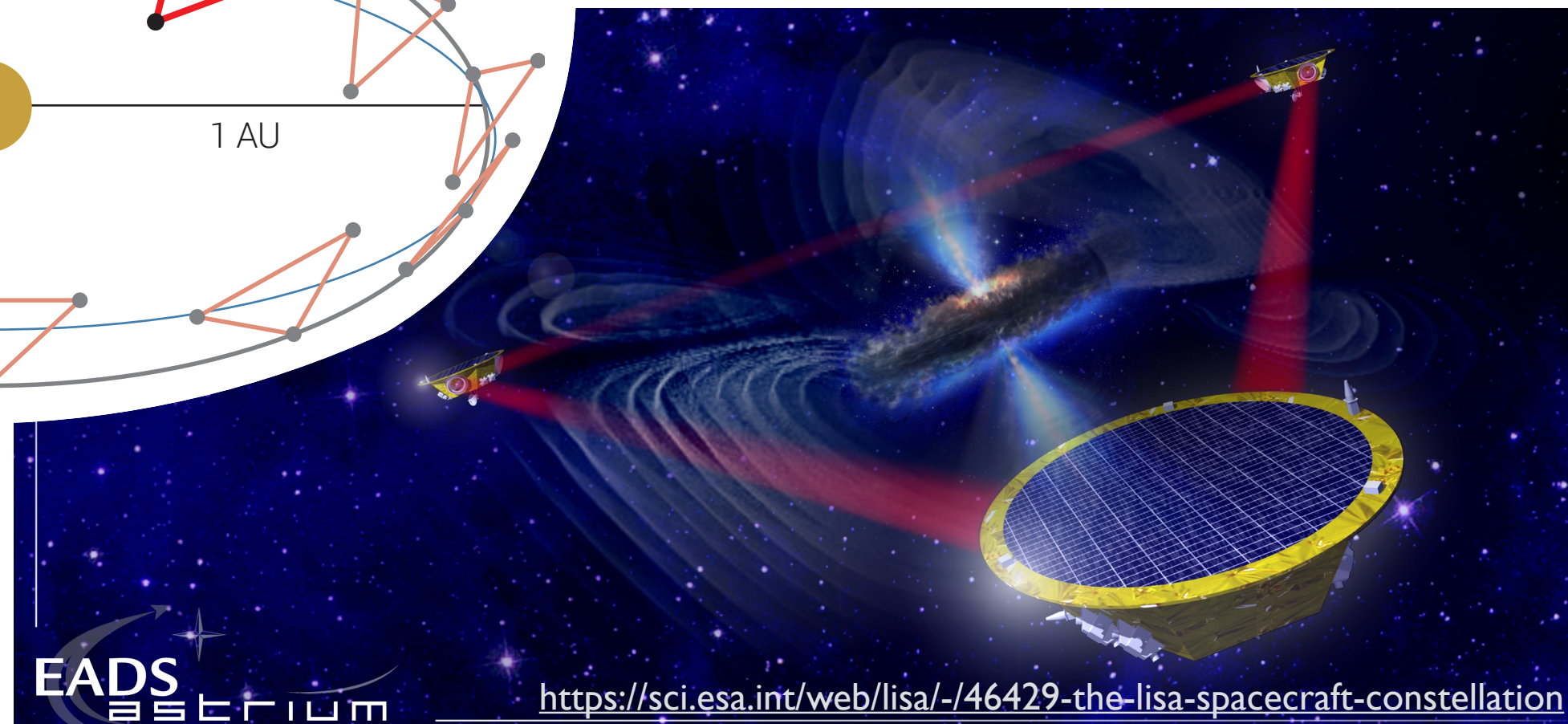
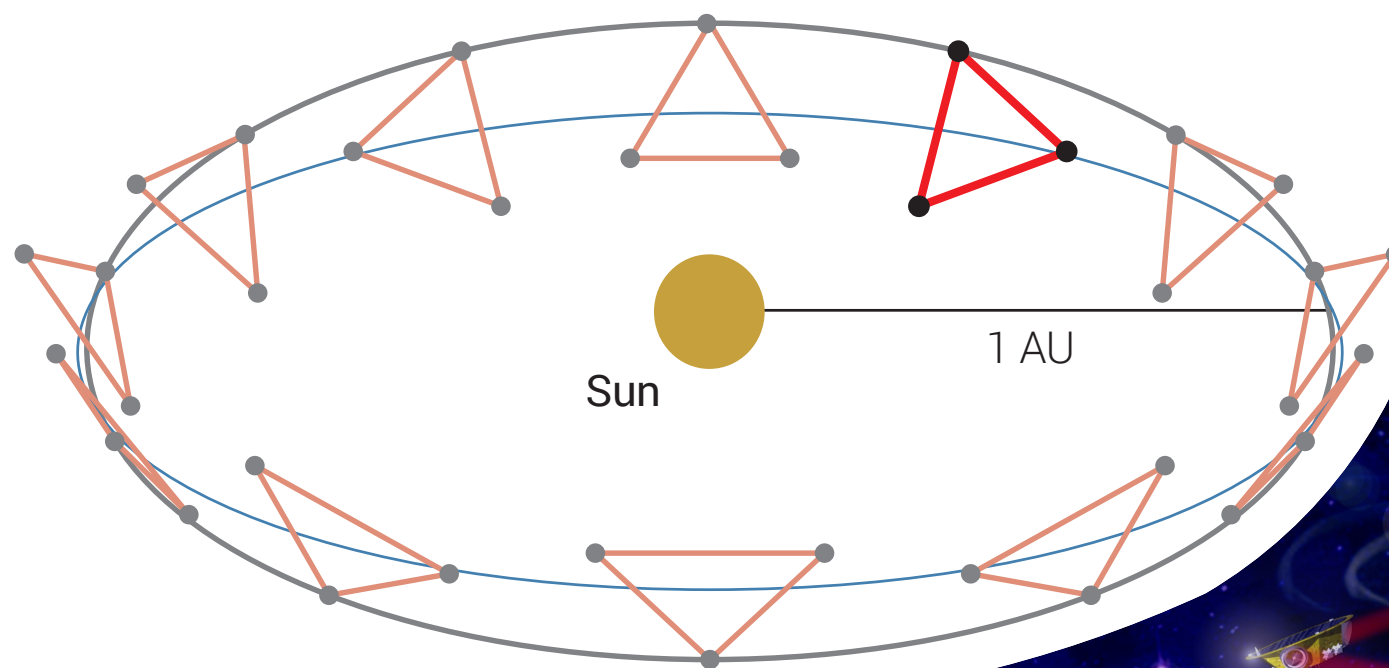
https://www.nsf.gov/news/mmg/media/images/vlasunrisejuly2008_h.jpg



LISA mission highlights



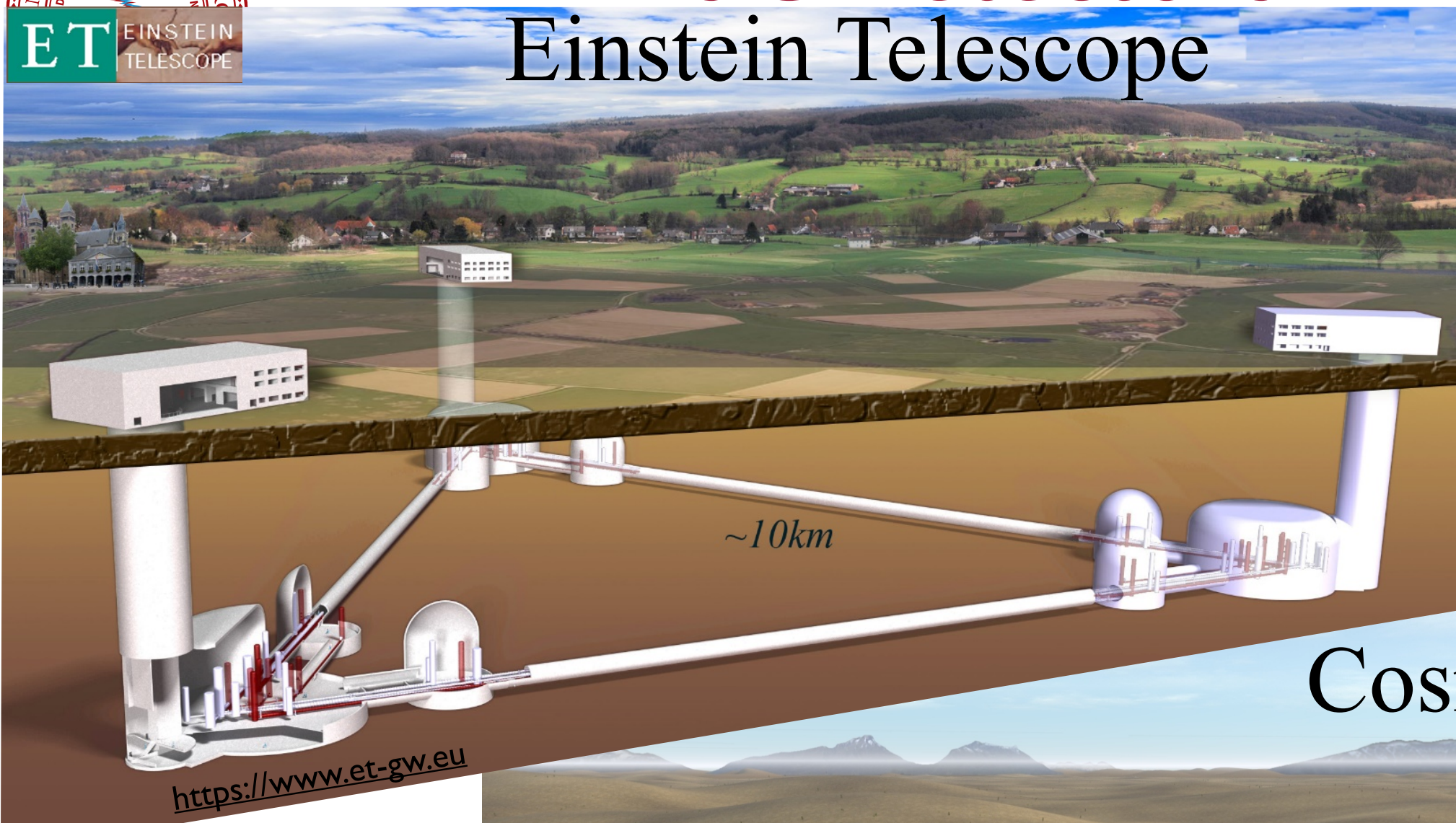
- 3 spacecraft orbiting the sun
- orbits yield ~stable triangle
- arms are 2.5 million km!
- ESA official approved LISA
Jan 25, 2024 !
- 2035 launch



3G detectors

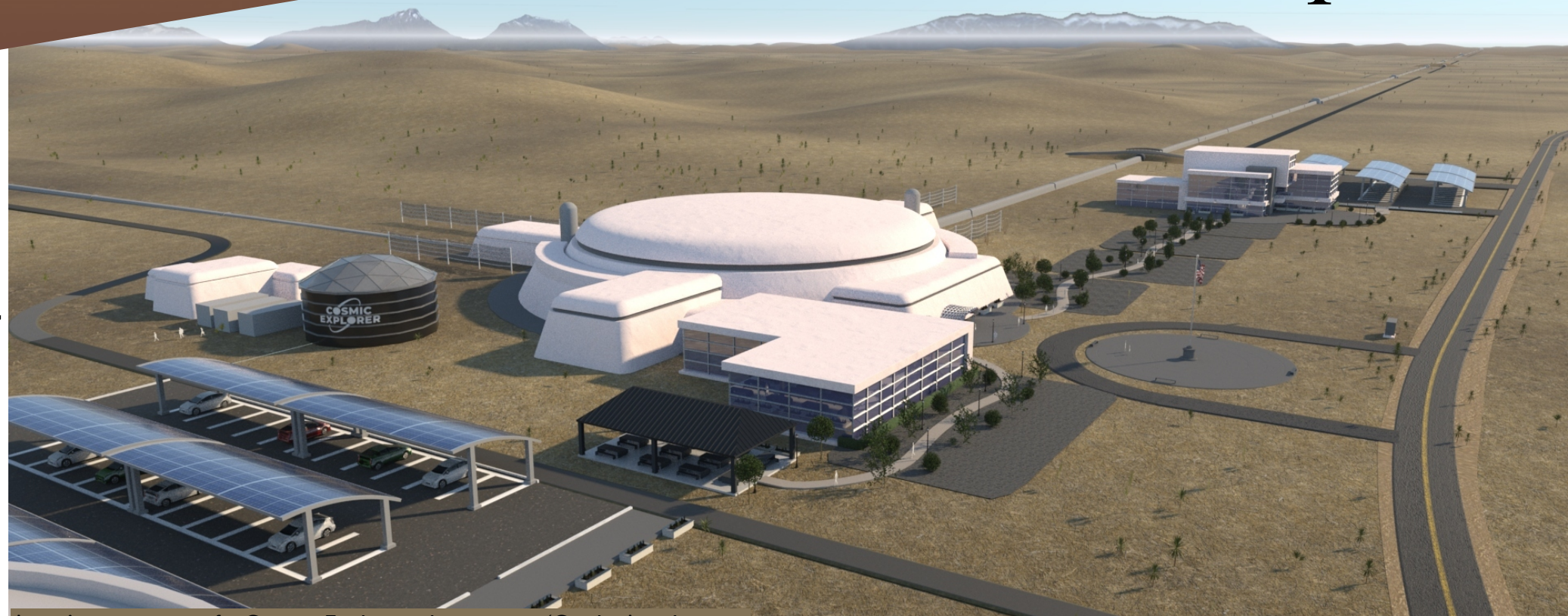
Einstein Telescope

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



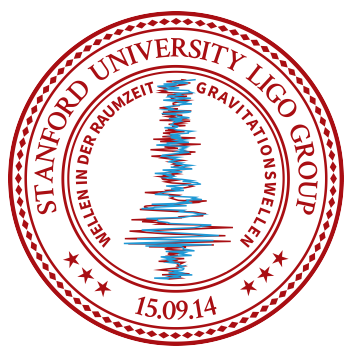
Cosmic Explorer

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



Neutron star mergers
Range and population

$1.4+1.4M_{\odot}$
NS+NS

Black hole mergers
Range and population

100
Redshift

10

1

0.1

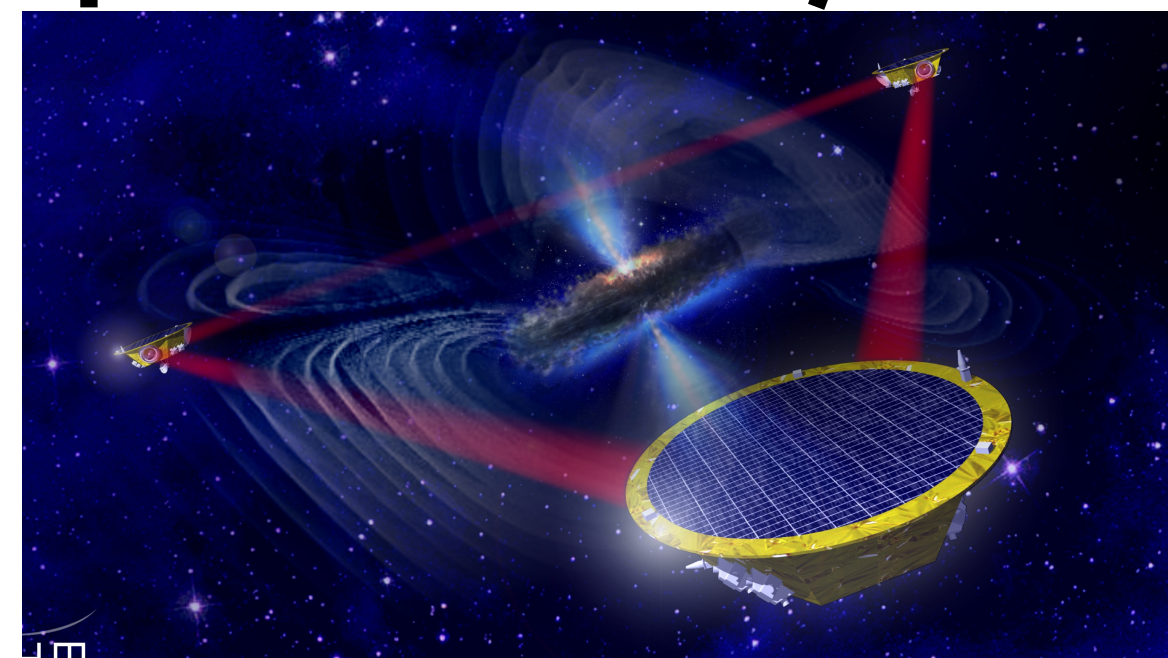
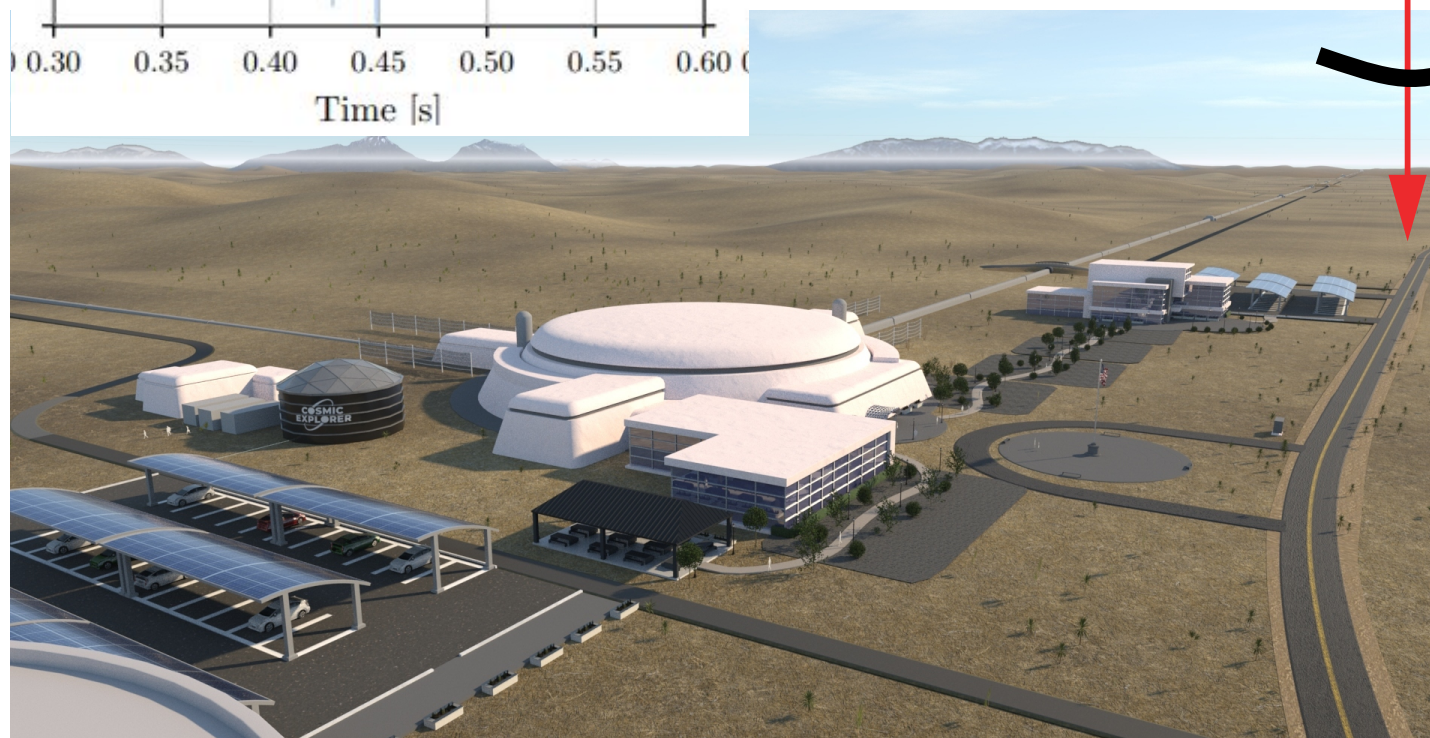
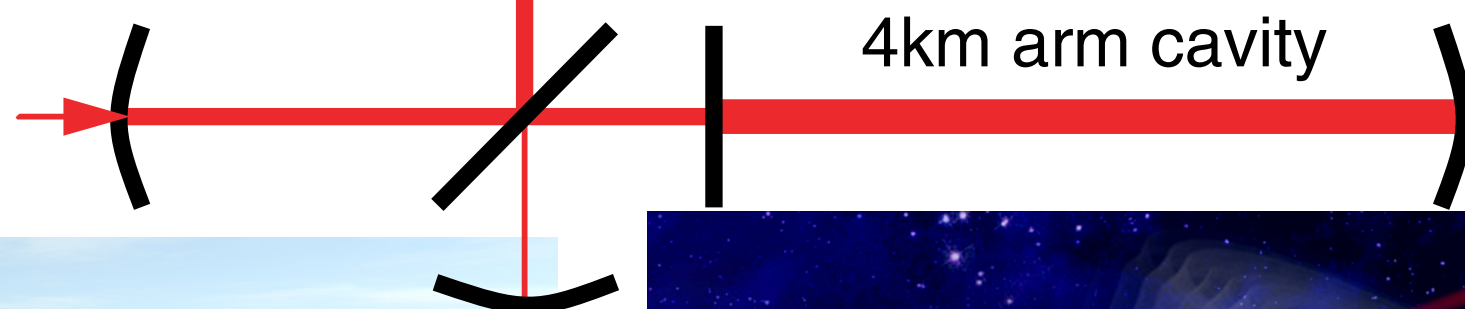
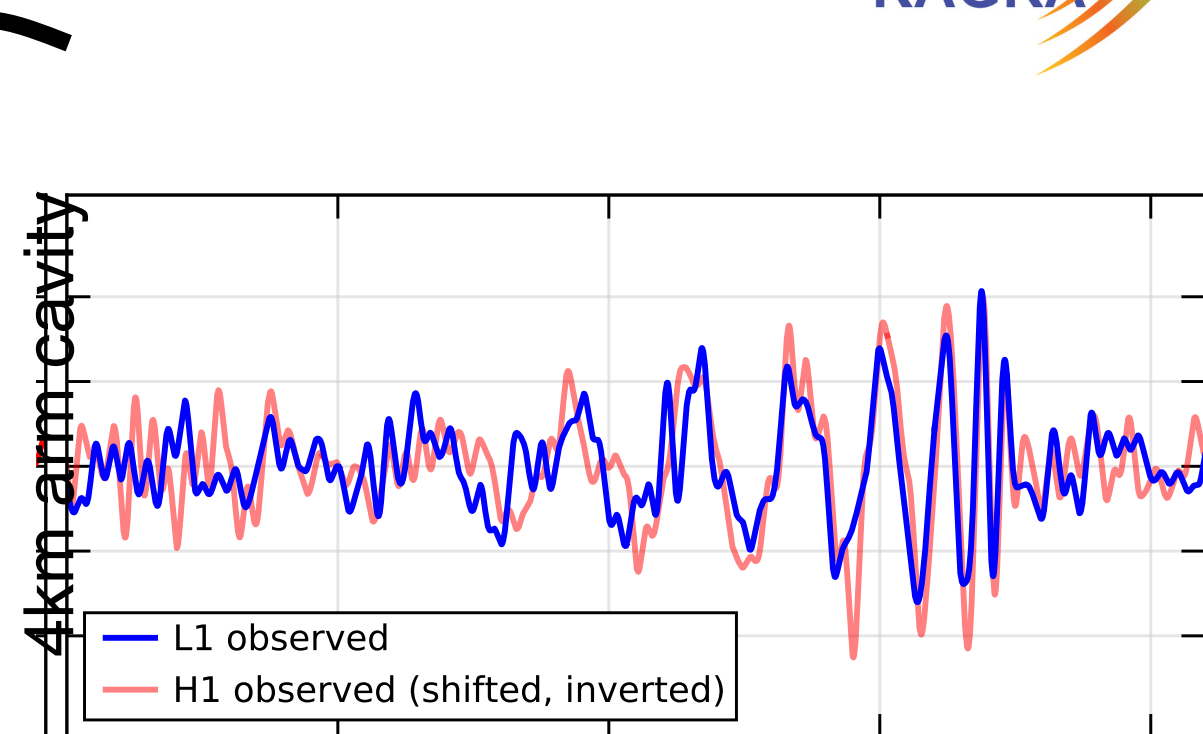
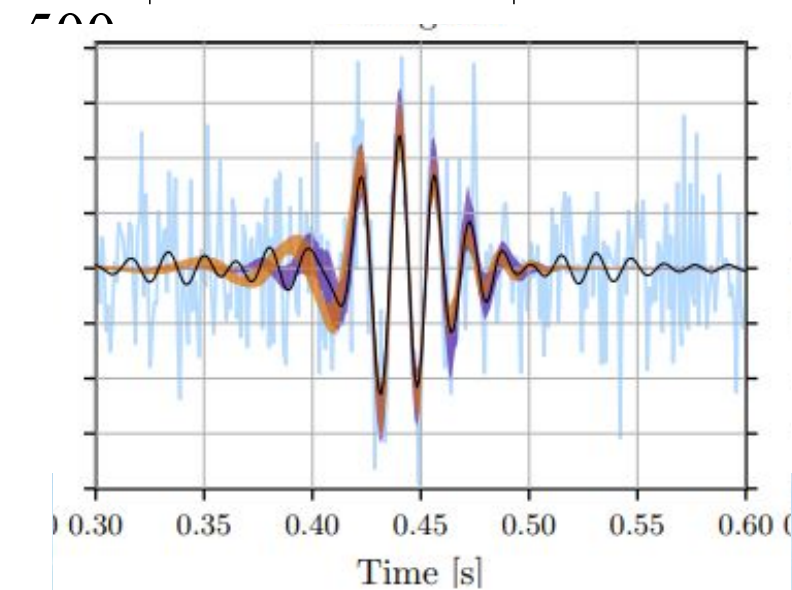
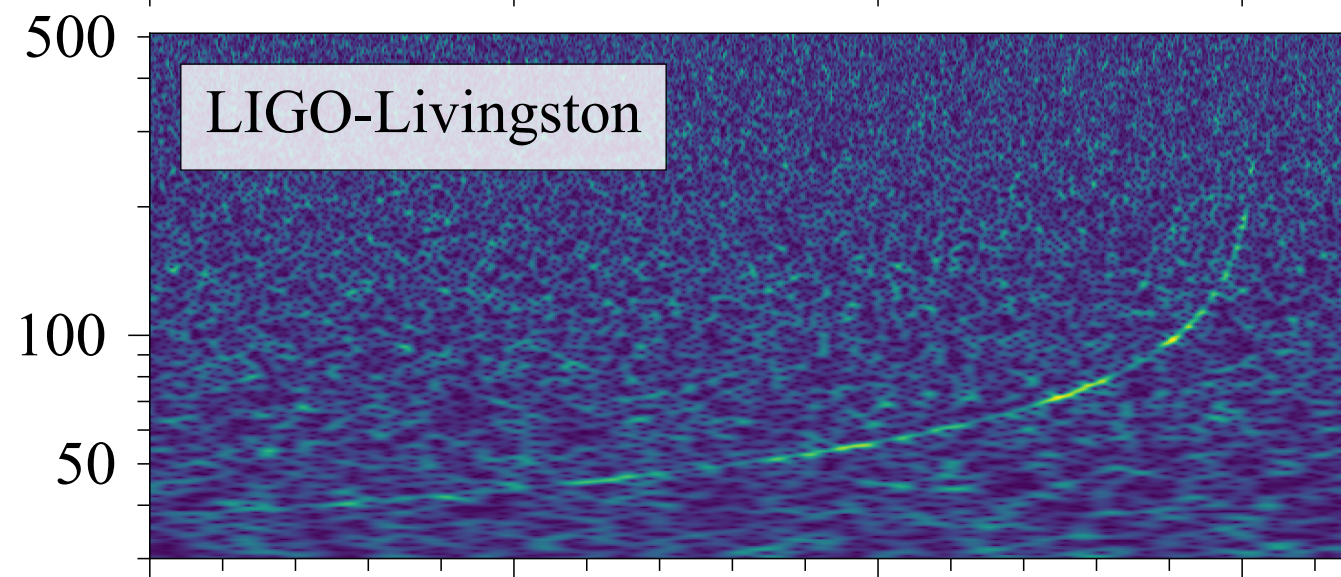
GW150914

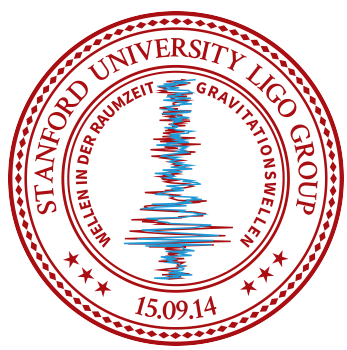
GW170817

03



It's an exciting time!





download the slides?

slides are at LIGO's Document Control Center

<https://dcc.ligo.org/public/G2400231>

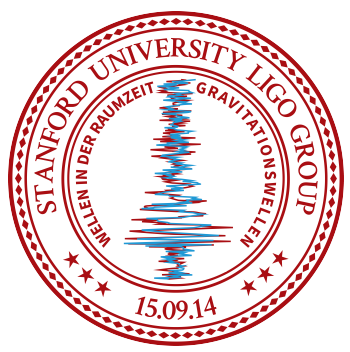
The screenshot shows a web browser window with the URL <https://dcc.ligo.org/public/>. The main content area displays a cumulative distribution plot. The y-axis is labeled "Cumulative" and ranges from 0 to 60. The x-axis is labeled "Effective BNS time-volume [$\text{Gpc}^3 \text{ yr}$]" and ranges from 0.000 to 0.004. The plot shows a black step-like line representing the cumulative distribution, with a blue line and shaded regions indicating uncertainty or confidence intervals. The background is divided into colored regions: yellow for $x < 0.0005$, orange for $0.0005 < x < 0.0025$, and purple for $x > 0.0025$. A credit "Credit: LVK" is visible in the bottom right of the plot area.

Below the plot, there is a section titled "Detection Publications" with a search interface. The search bar is labeled "Search for Documents by". The search criteria are:

- Author: Lantz, Brian
- Identifier: LIGO-G2400231
- Changes: in the last 2 days

There is a "Google Search" button and a note: "(Hit Enter or click search button on google page)".

Arrows point from the text "Lantz, Brian" and "G2400231" to the corresponding search fields.



Other good links:



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

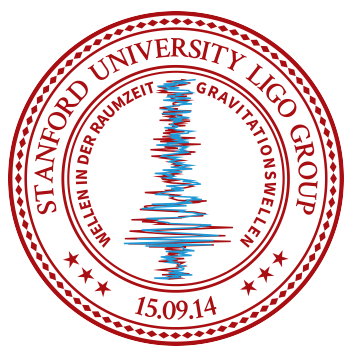
LIGO Lab home page
<https://www.ligo.caltech.edu/>

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/>

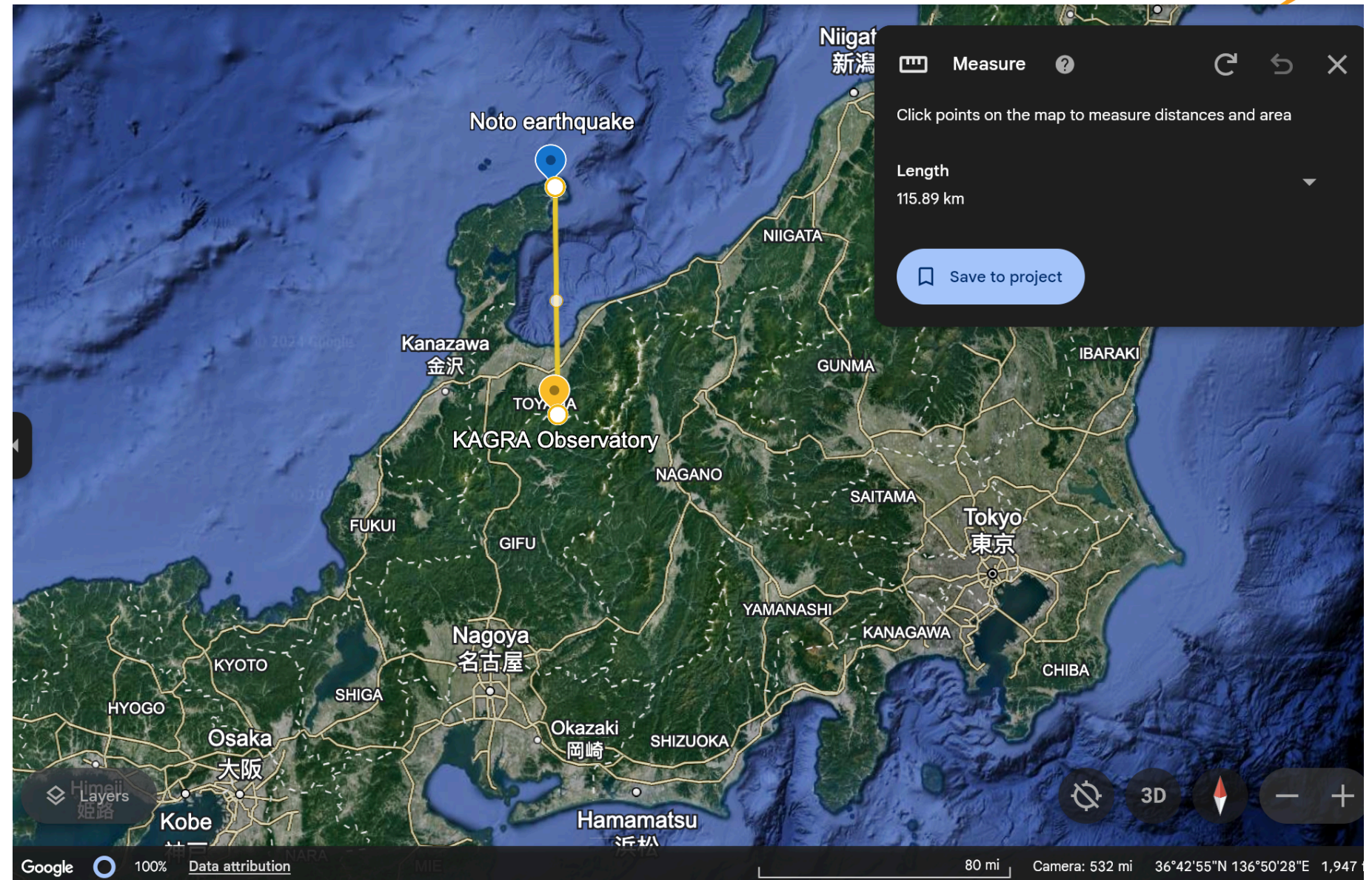


Earthquake near KAGRA

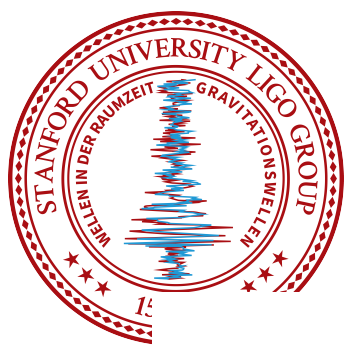


On Jan 1, 2024 there was a M7.5 EQ about 75 miles from the KAGRA detector.

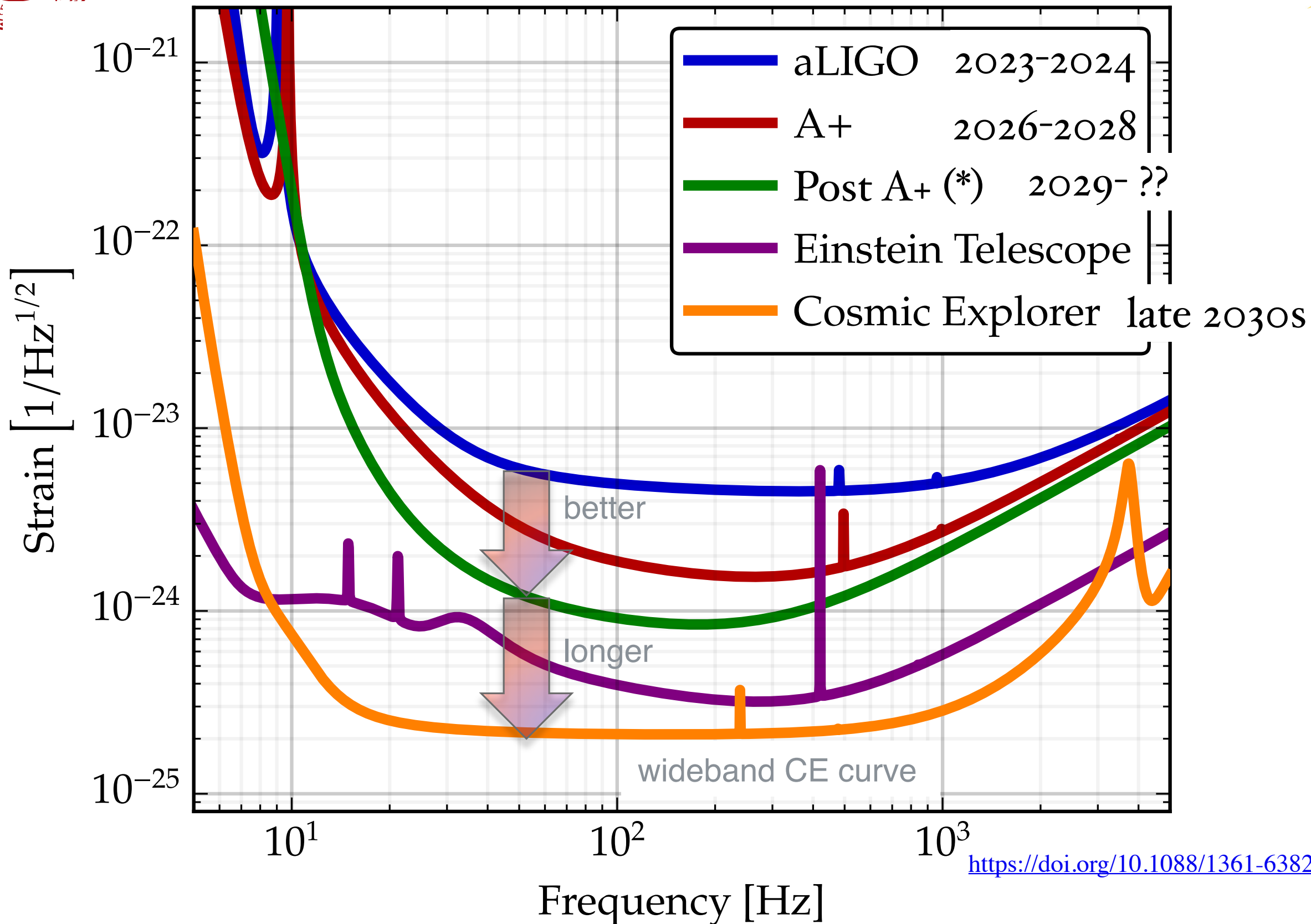
At least 239 Japanese fatalities and major damage in the area.



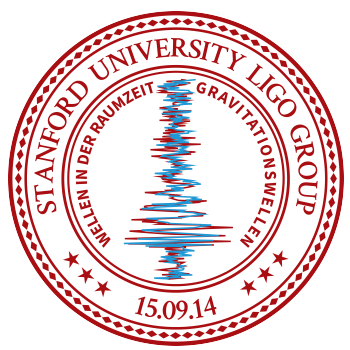
KAGRA had no fatalities and no significant damage to the mine tunnels, but detector is damaged, extent is still ??



3G detectors



(*) green curve is for Voyager, which is no longer the baseline for upgrades in the current facilities G2501382 69

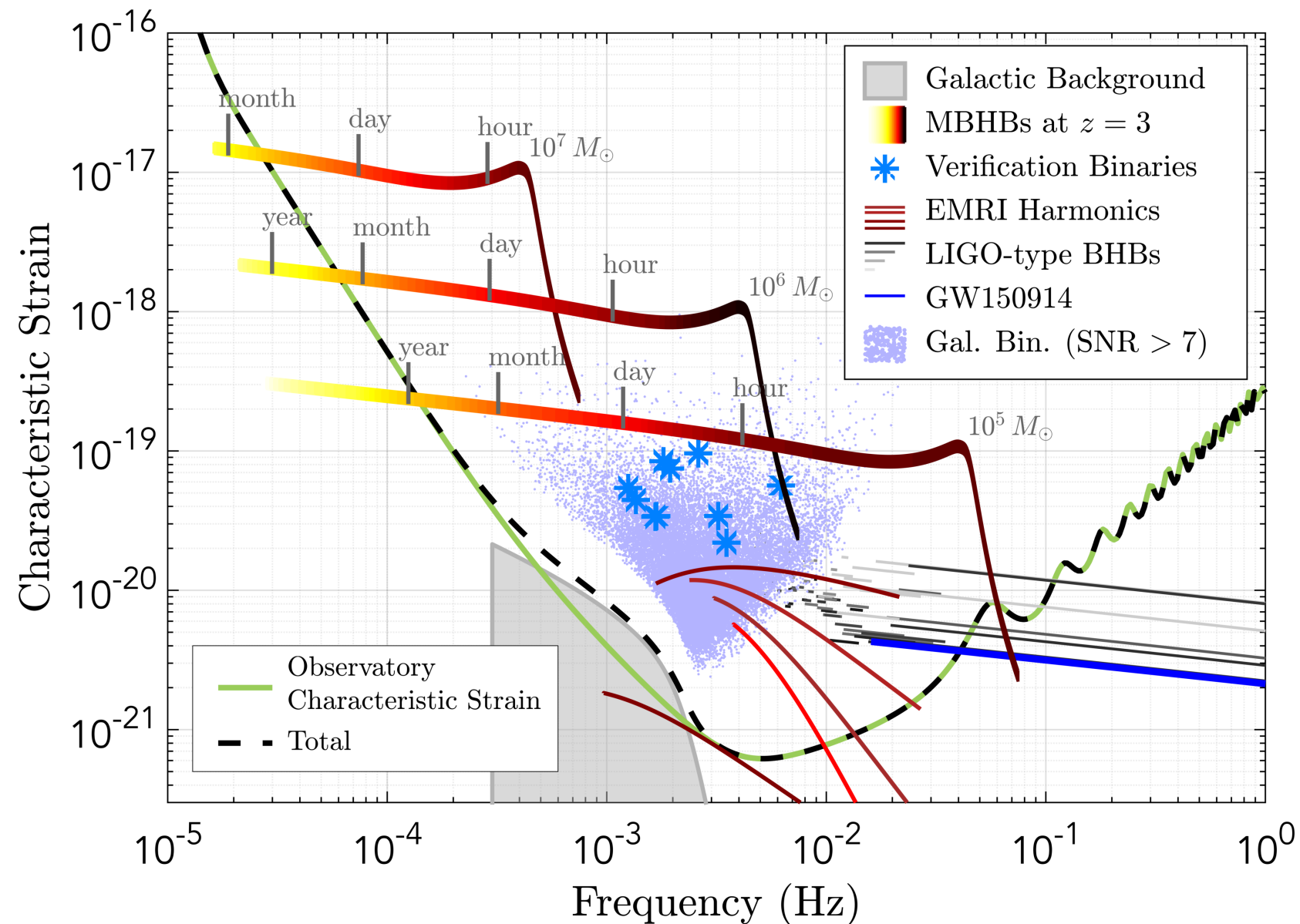


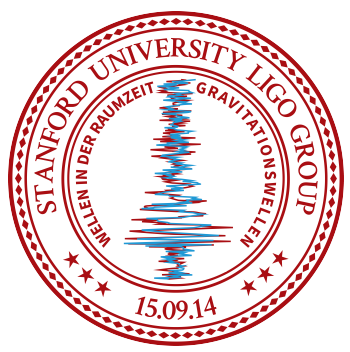
LISA Science



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...

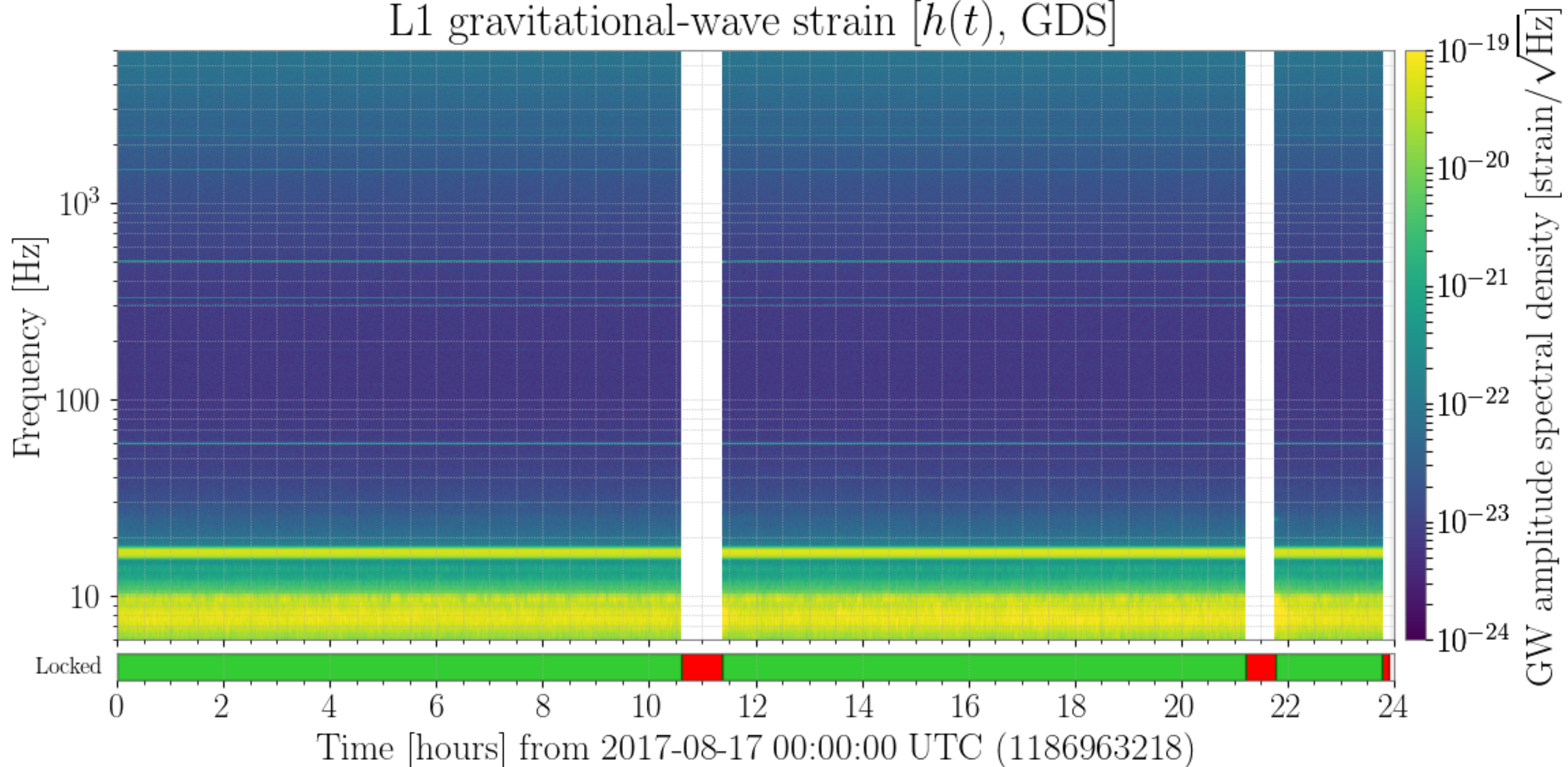


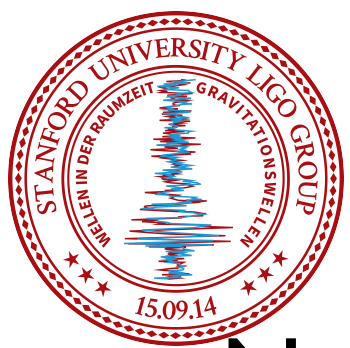


Watch for changes...

Spectrogram - 1 day at LLO

L1 gravitational-wave strain $[h(t), \text{GDS}]$

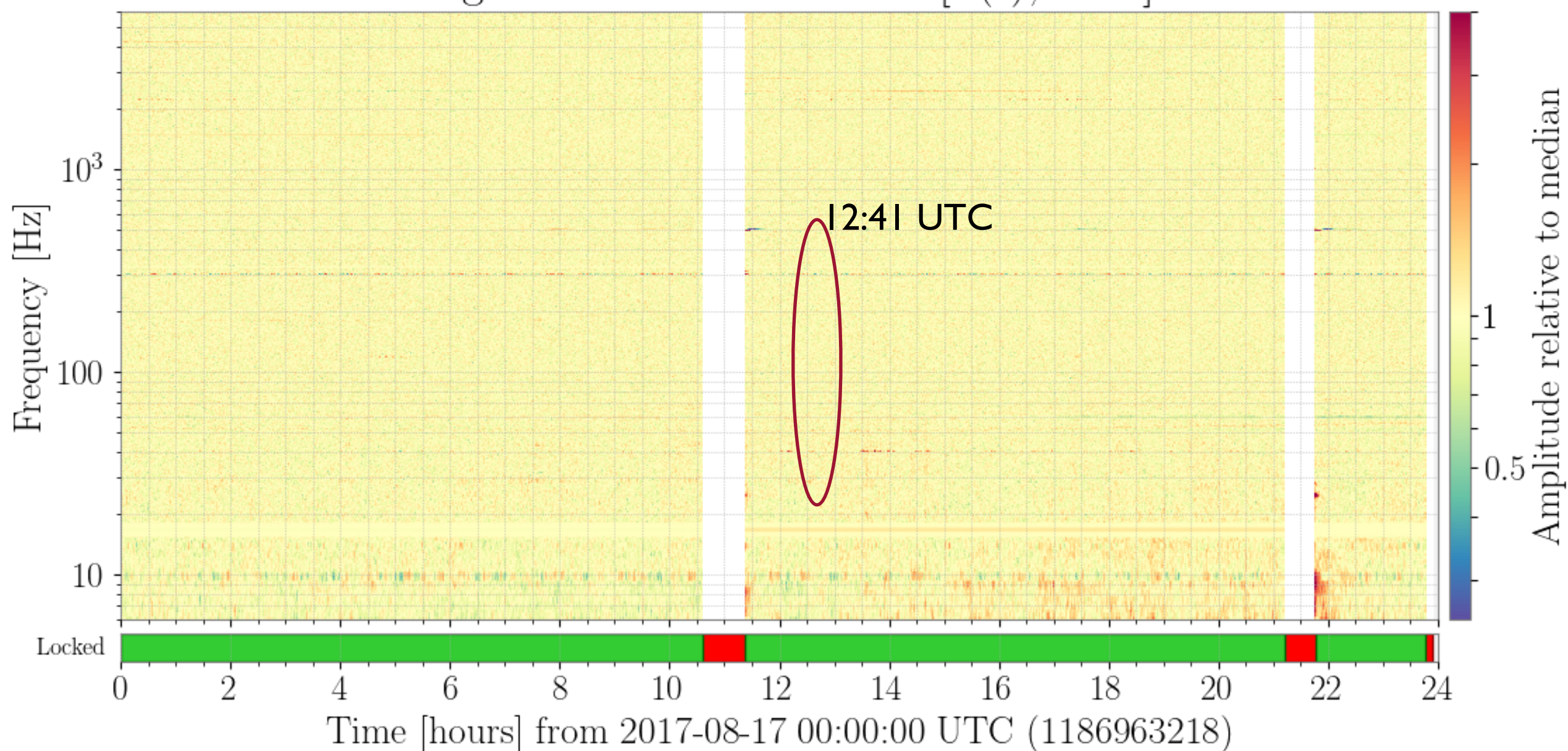


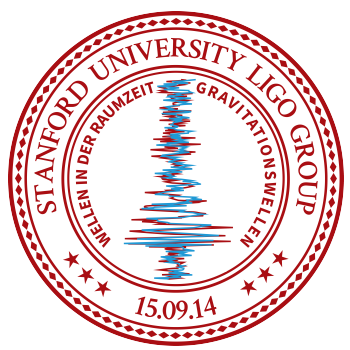


Watch for changes...

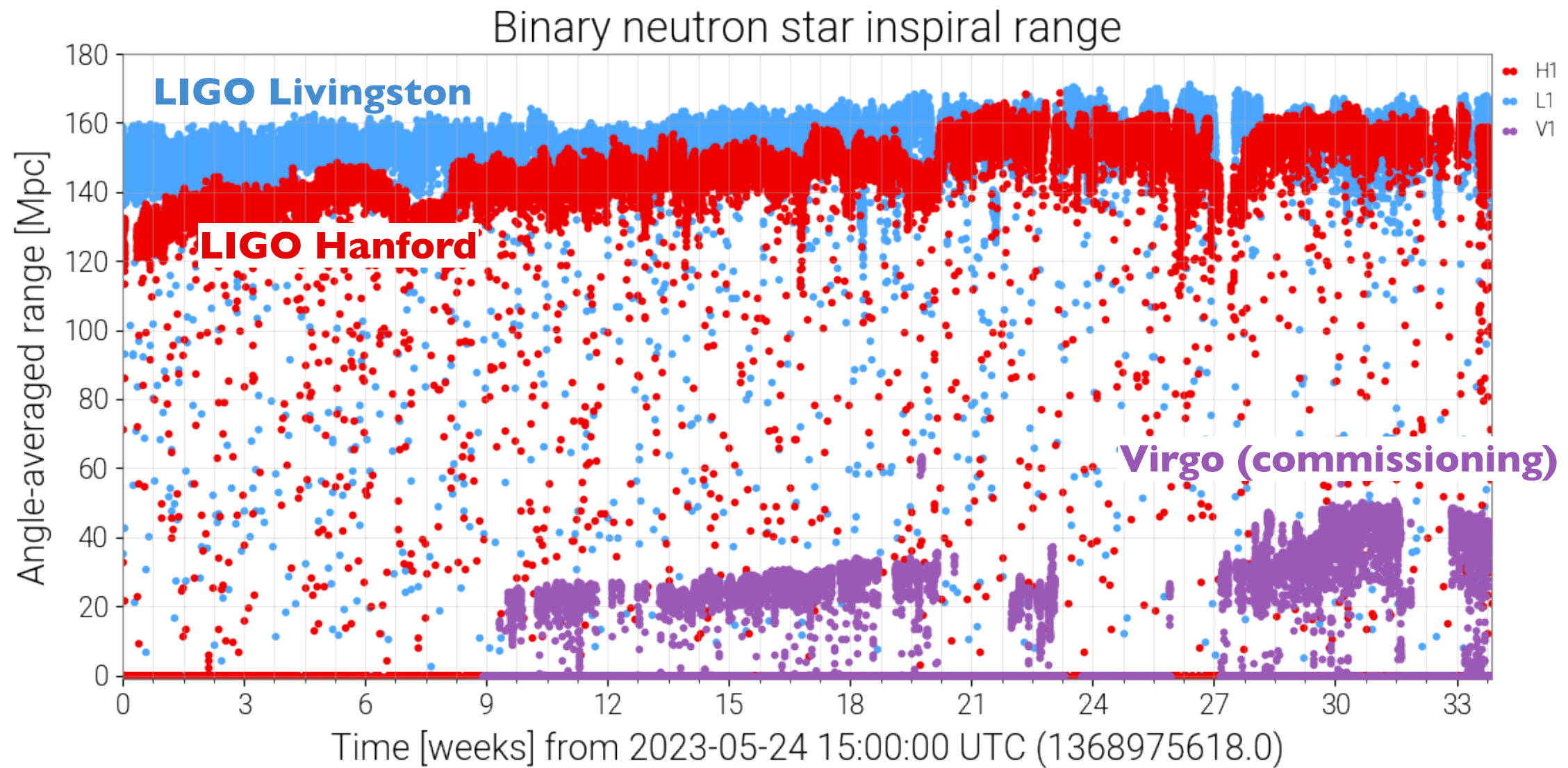
Normalized Spectrogram - 1 day at LLO

L1 gravitational-wave strain $[h(t), \text{GDS}]$





range in O4a

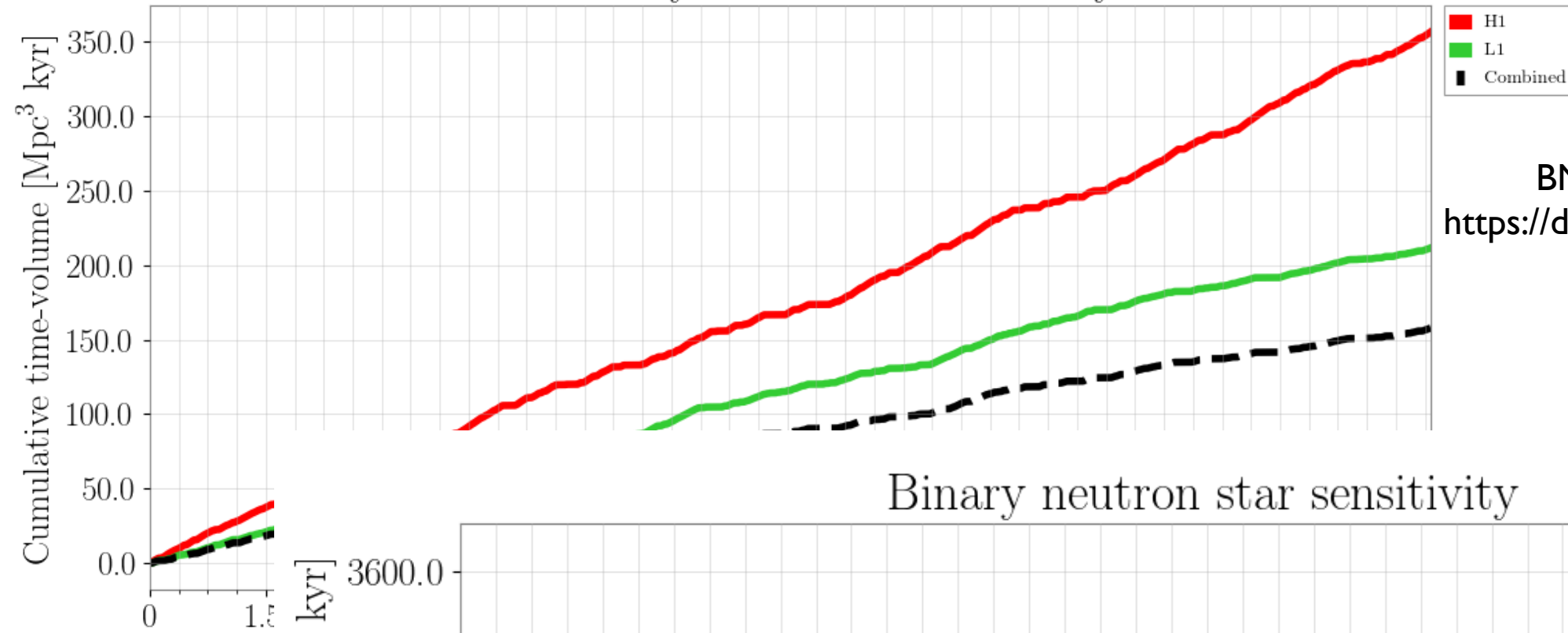




Range



LIGO binary neutron star sensitivity

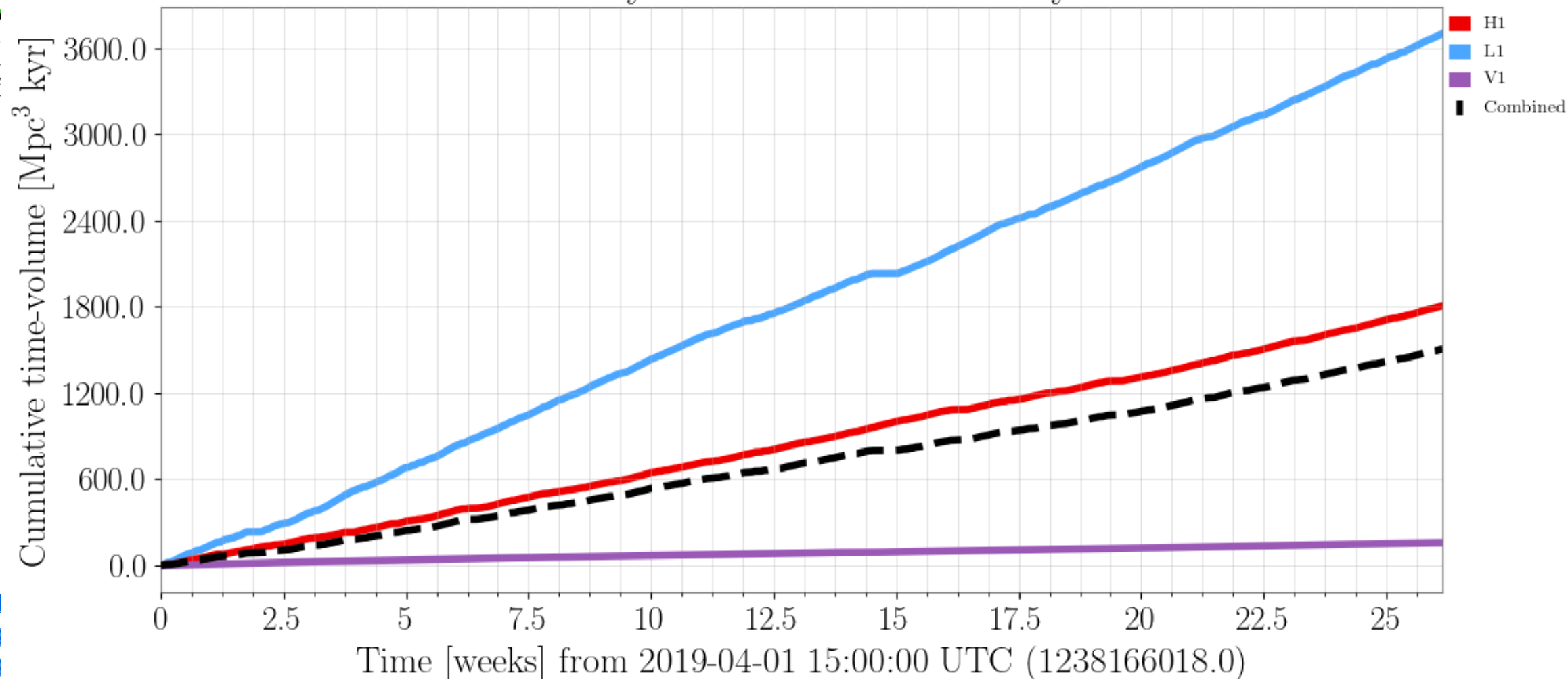


rates: GWTC-1:

BNS: $1.1\text{e-}4$ - $3.8\text{e-}3$ / $\text{Mpc}^3\text{-kYr}$

<https://doi.org/10.1103/PhysRevX.9.031040>

Binary neutron star sensitivity



O3a network range: [<http://](#)
O2 network range: [<http://](#)
O1 network range: [<http://](#)