Exploring the Gravitational wave Universe

New Discoveries and Plans

Brian Lantz

Feb 7. 2024
Silicon Valley
Astronomy Lecture Series
G2400231

LIGO

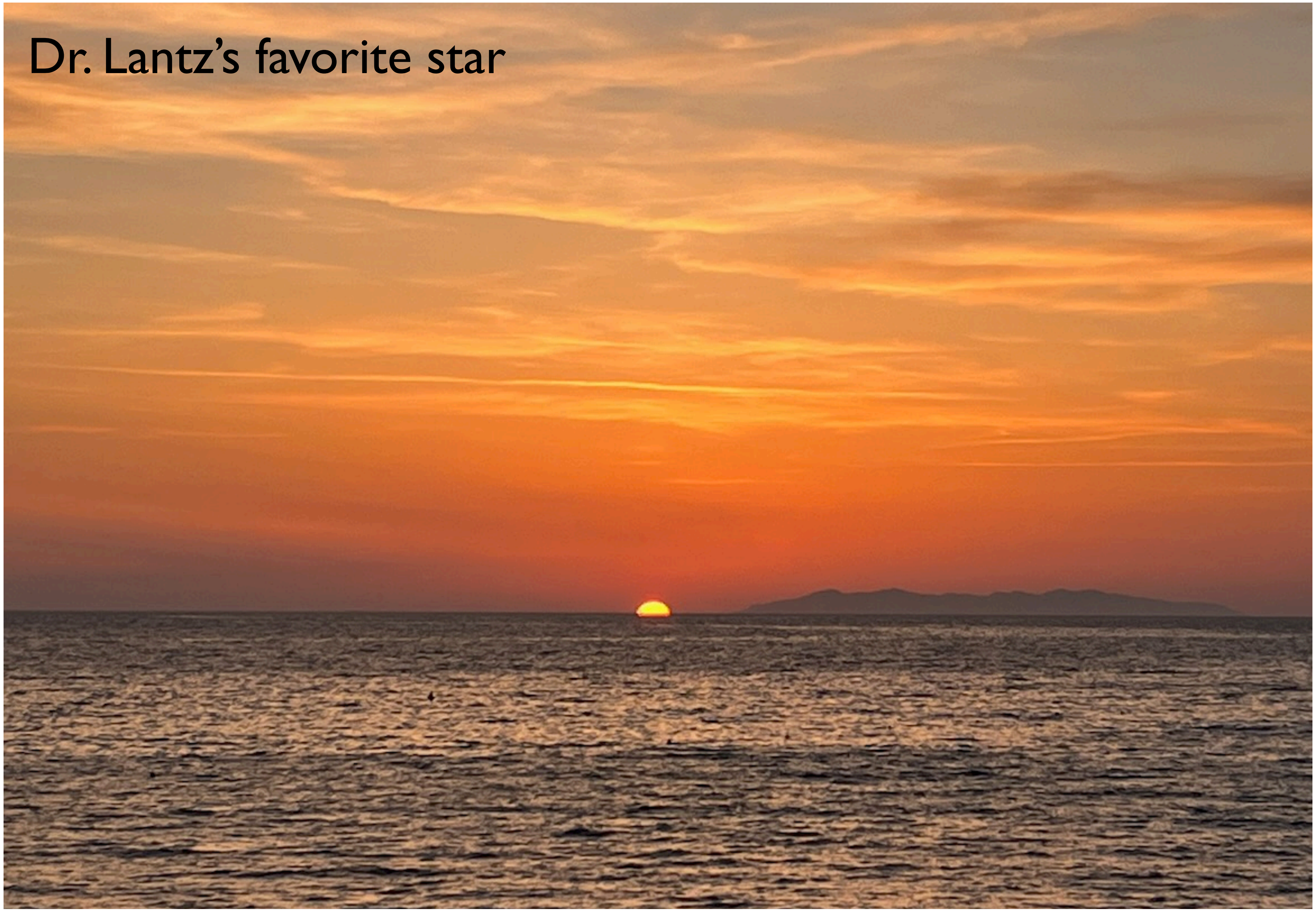
National Science Foundation + International partners

LIGO Scientific Collaboration

LSC

2 terms: Black Holes & LIGO

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

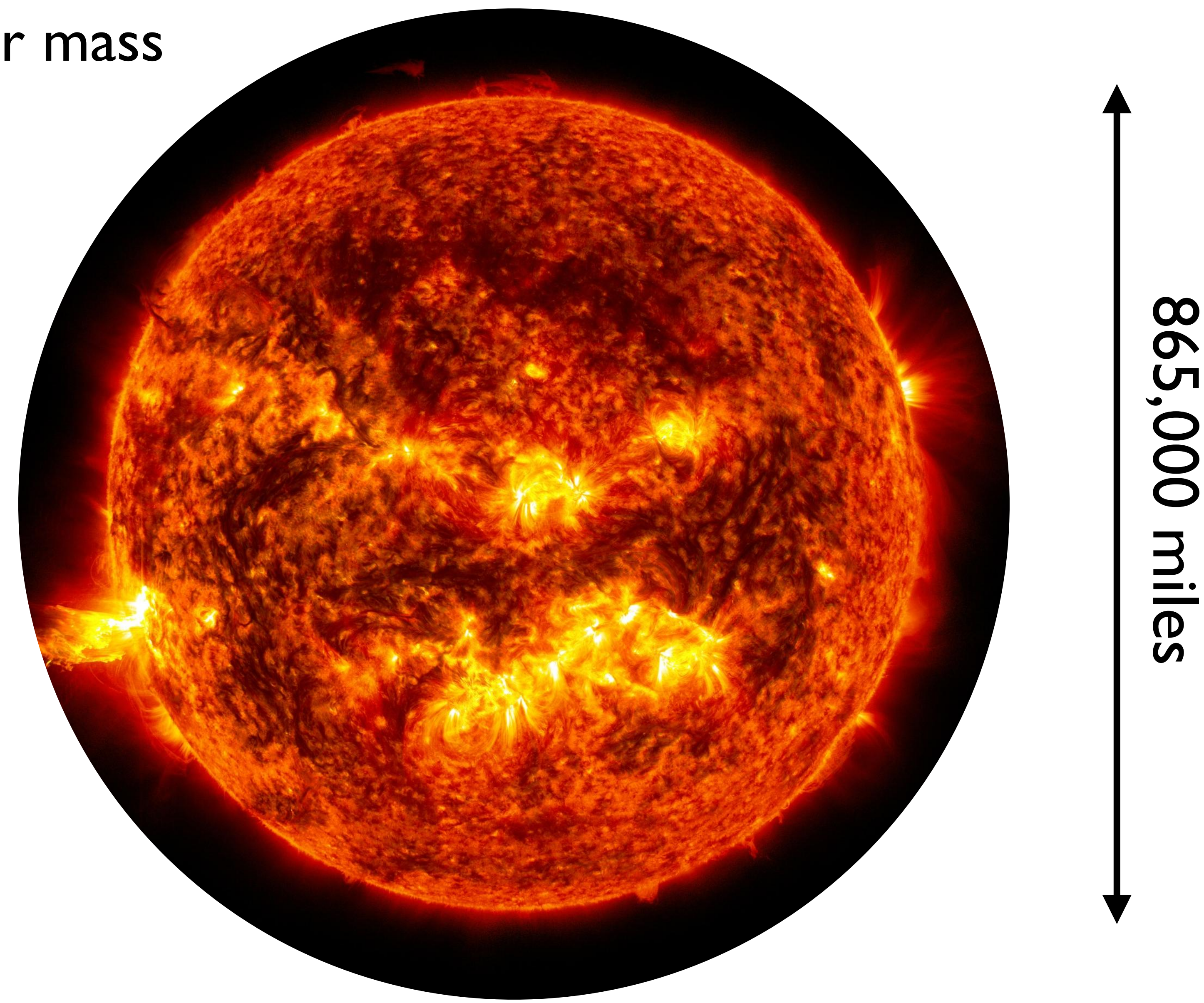


Dr. Lantz's favorite star

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



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)

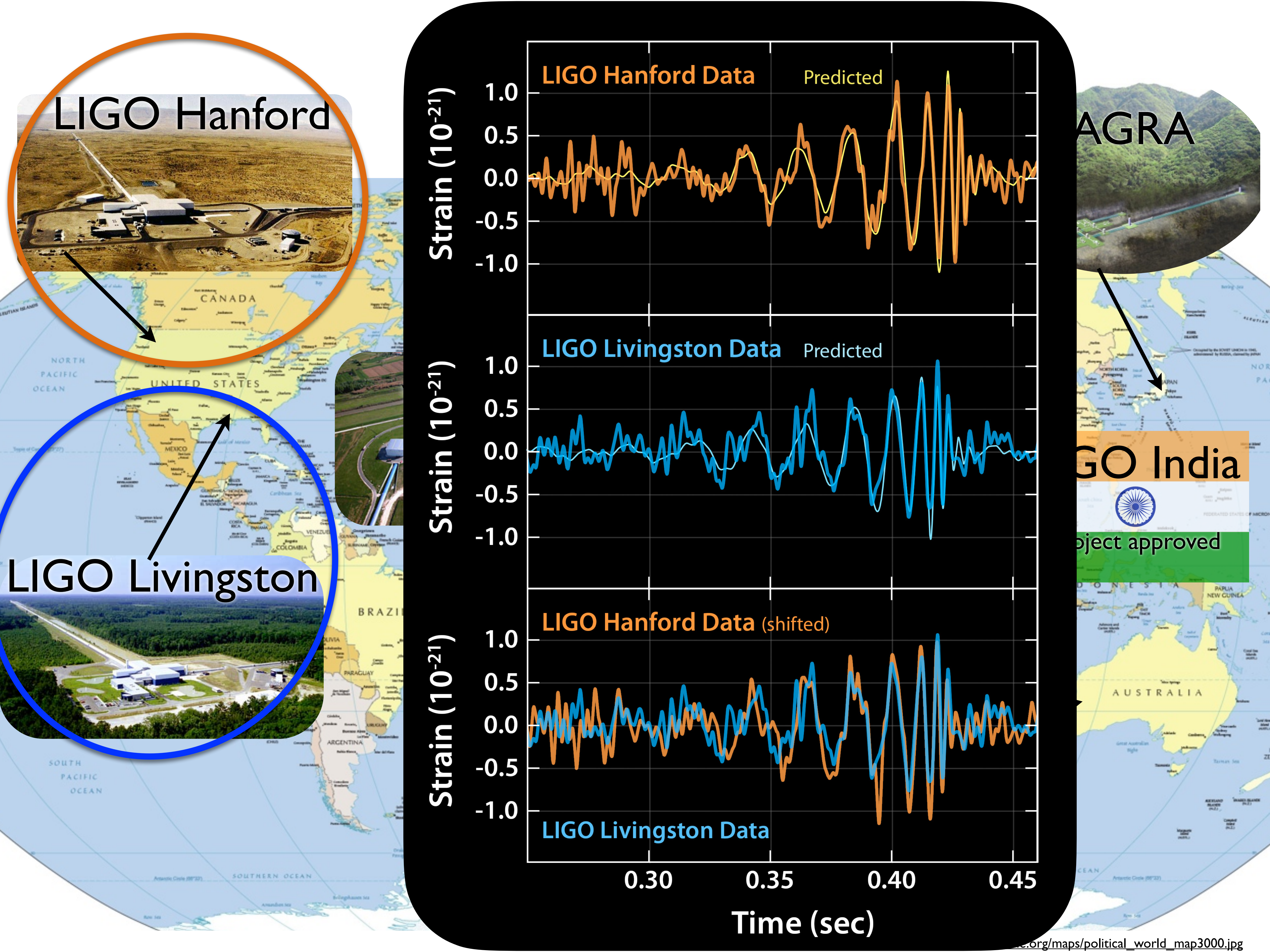
865,000 miles

2 terms: Black Holes & LIGO

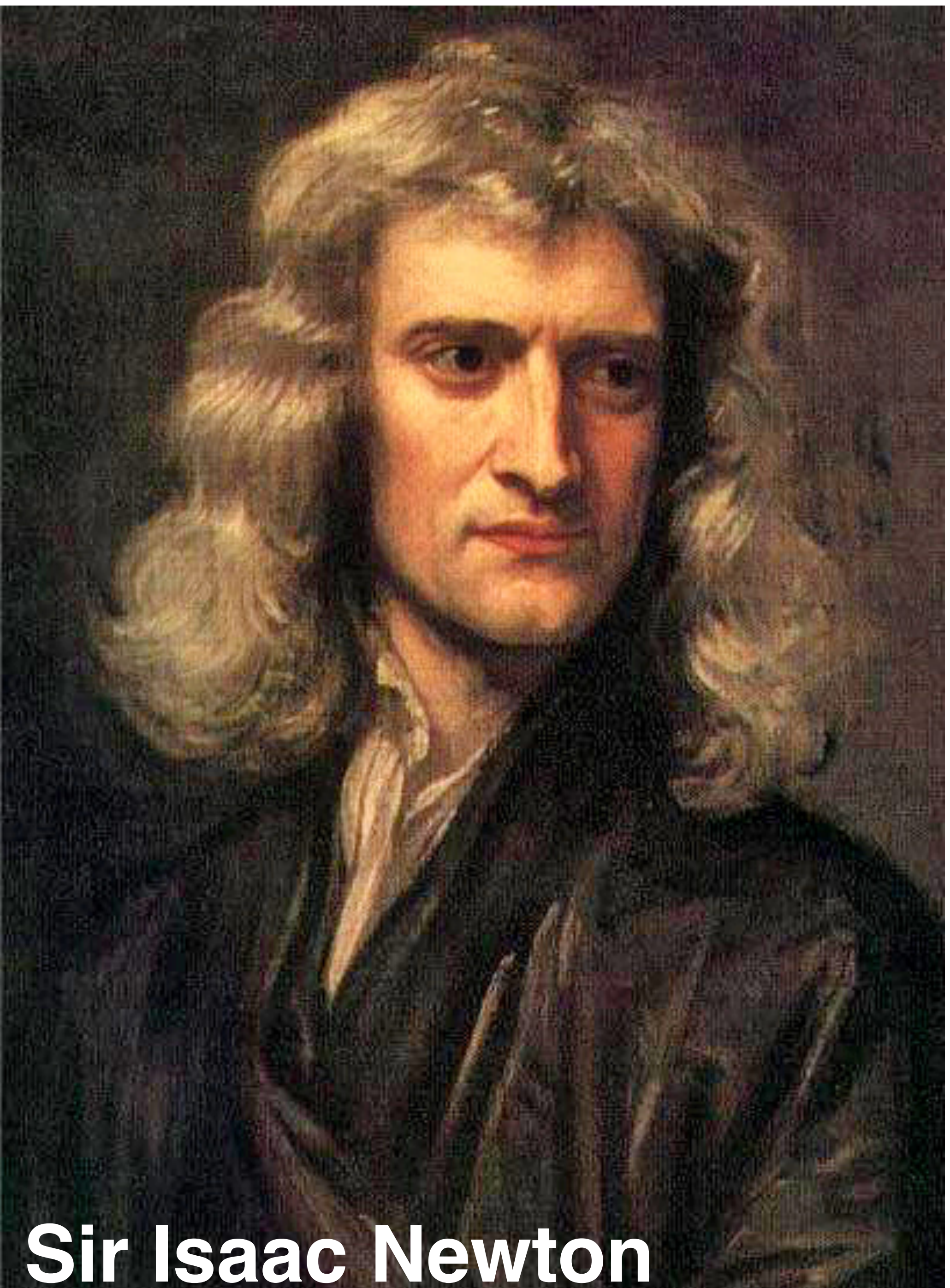
LIGO = Laser Interferometer Gravitational-wave Observatory

International Network

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


LIGO Hanford
LIGO Livingston
AGRA
GO India
oject approved
LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
CANADA
UNITED STATES
NORTH PACIFIC OCEAN
SOUTH PACIFIC OCEAN
AUSTRALIA
BRAZI
SOUTHERN OCEAN
.org/maps/political_world_map3000.jpg

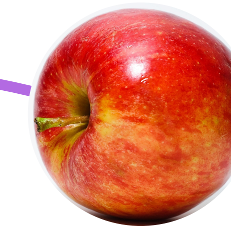
What is a Gravitational Wave?

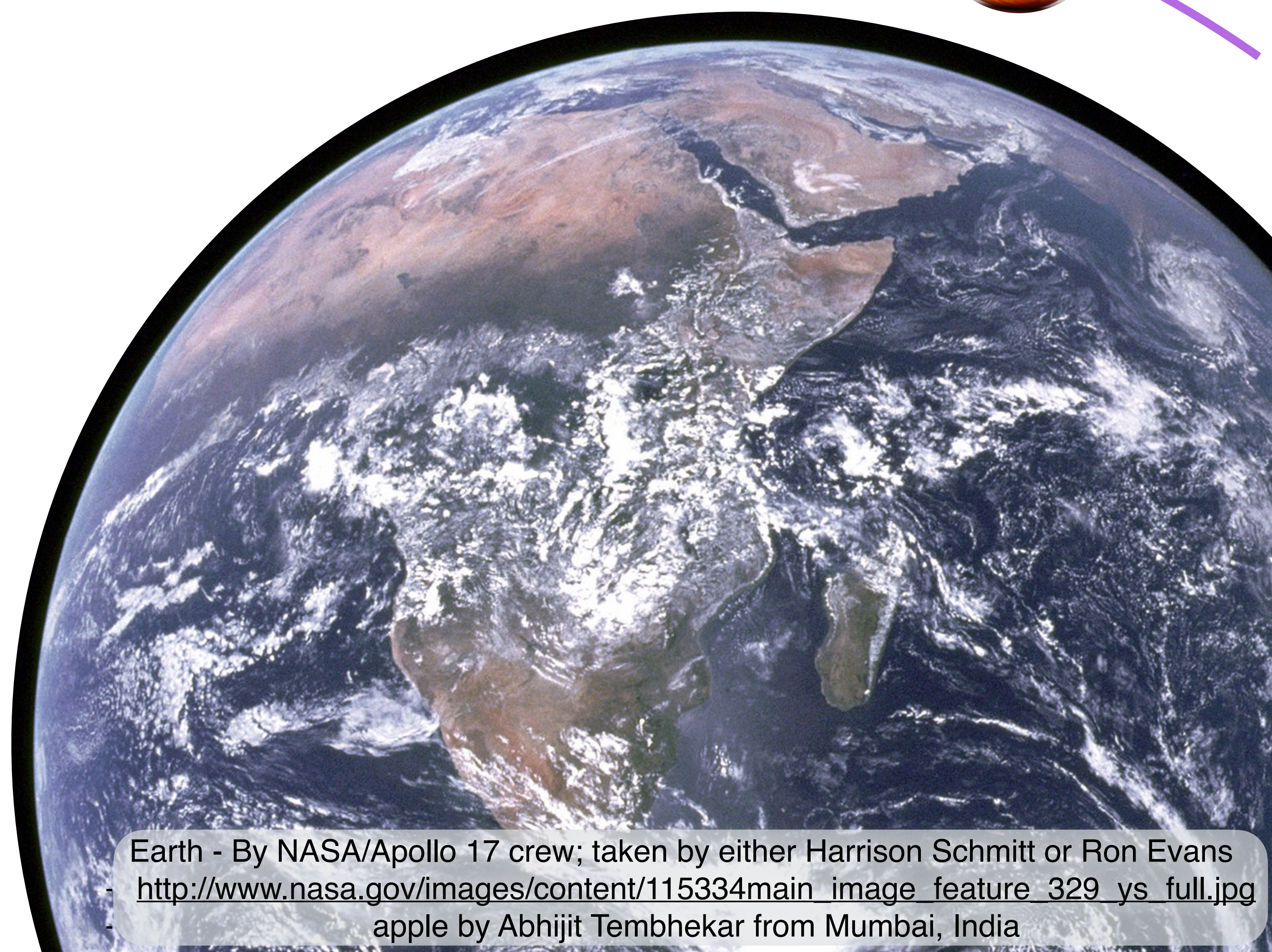


By Sir Godfrey Kneller
- http://www.newton.cam.ac.uk/art/portrait.html

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

Implies immediate action at a distance





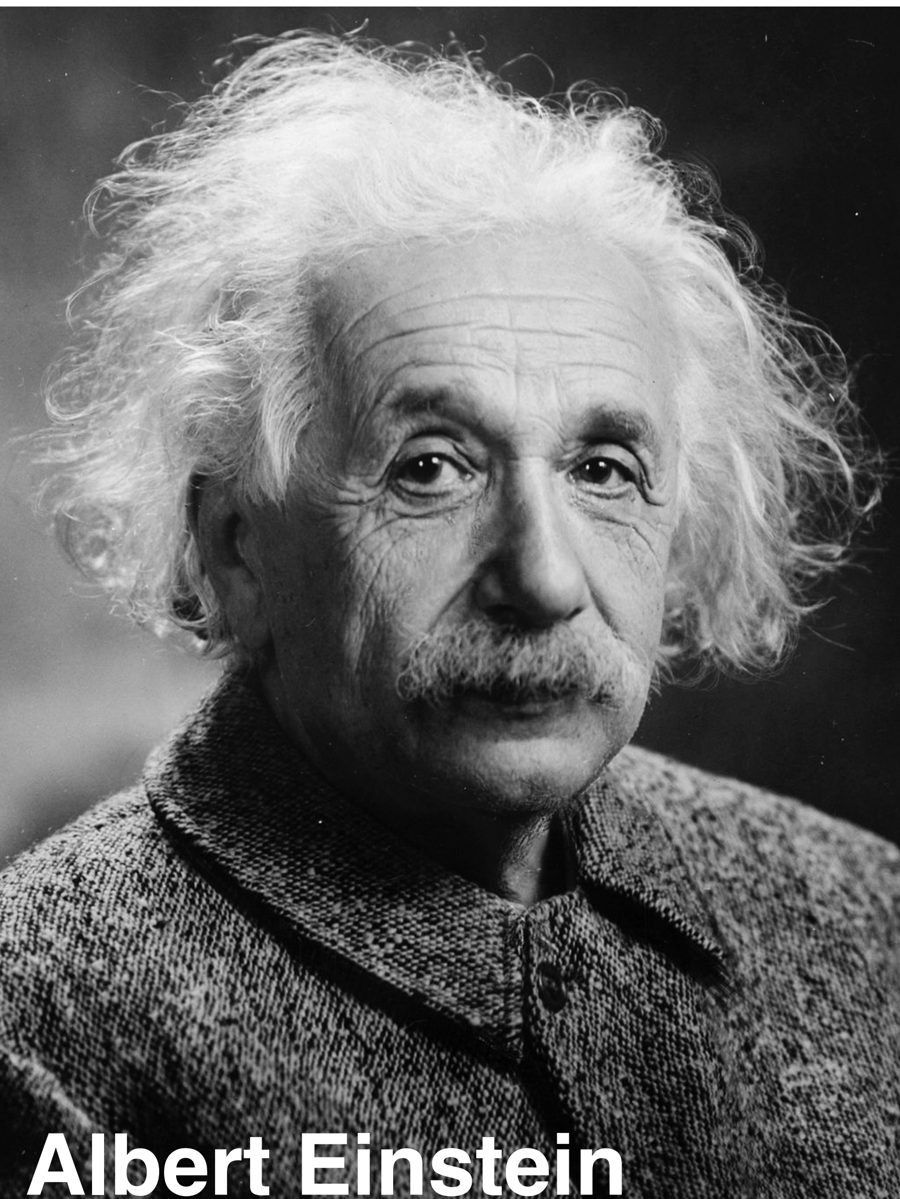
Earth - By NASA/Apollo 17 crew; taken by either Harrison Schmitt or Ron Evans
- http://www.nasa.gov/images/content/115334main_image_feature_329_ys_full.jpg
- apple by Abhijit Tembhekar from Mumbai, India

What is a Gravitational Wave?

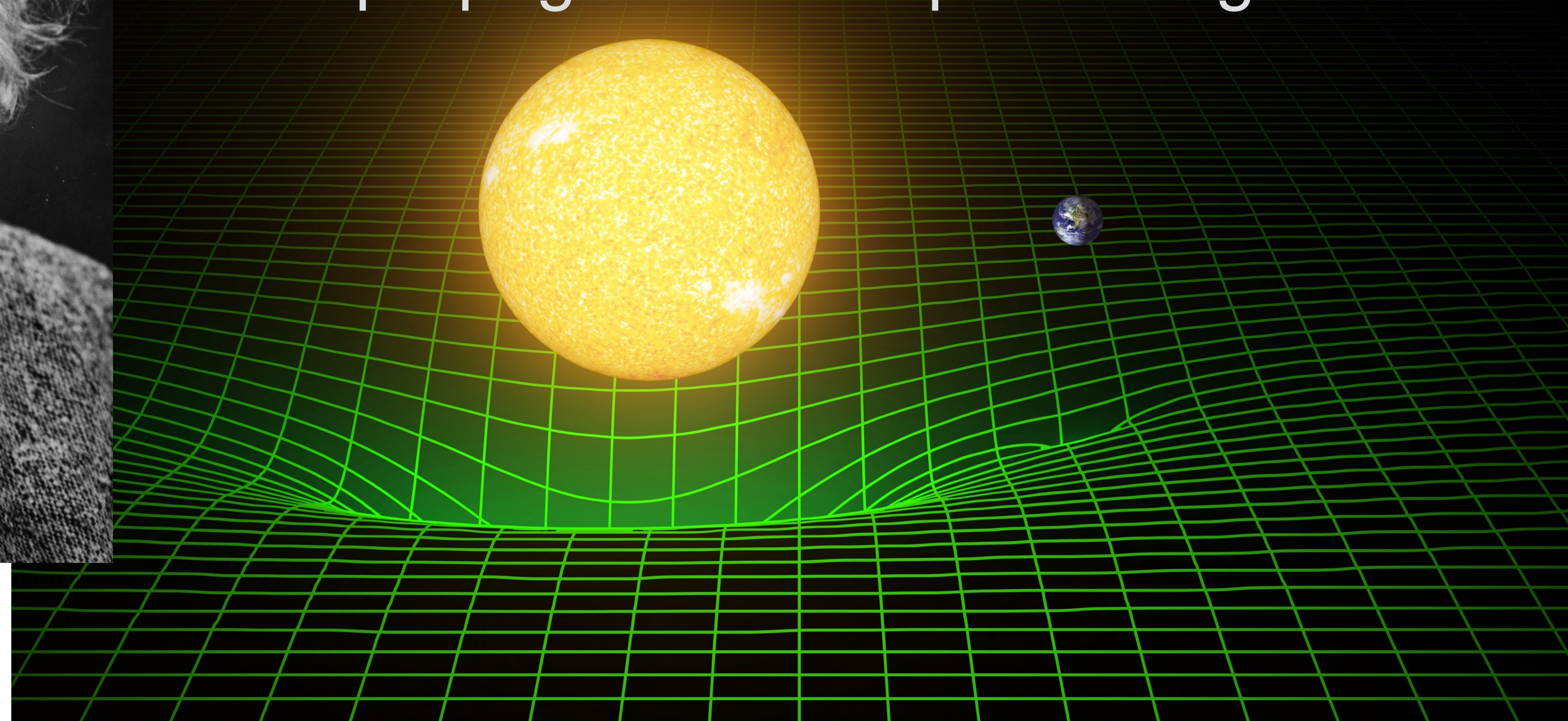
Predicted by Einstein in 1916 as part of GR.

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

- J. A. Wheeler

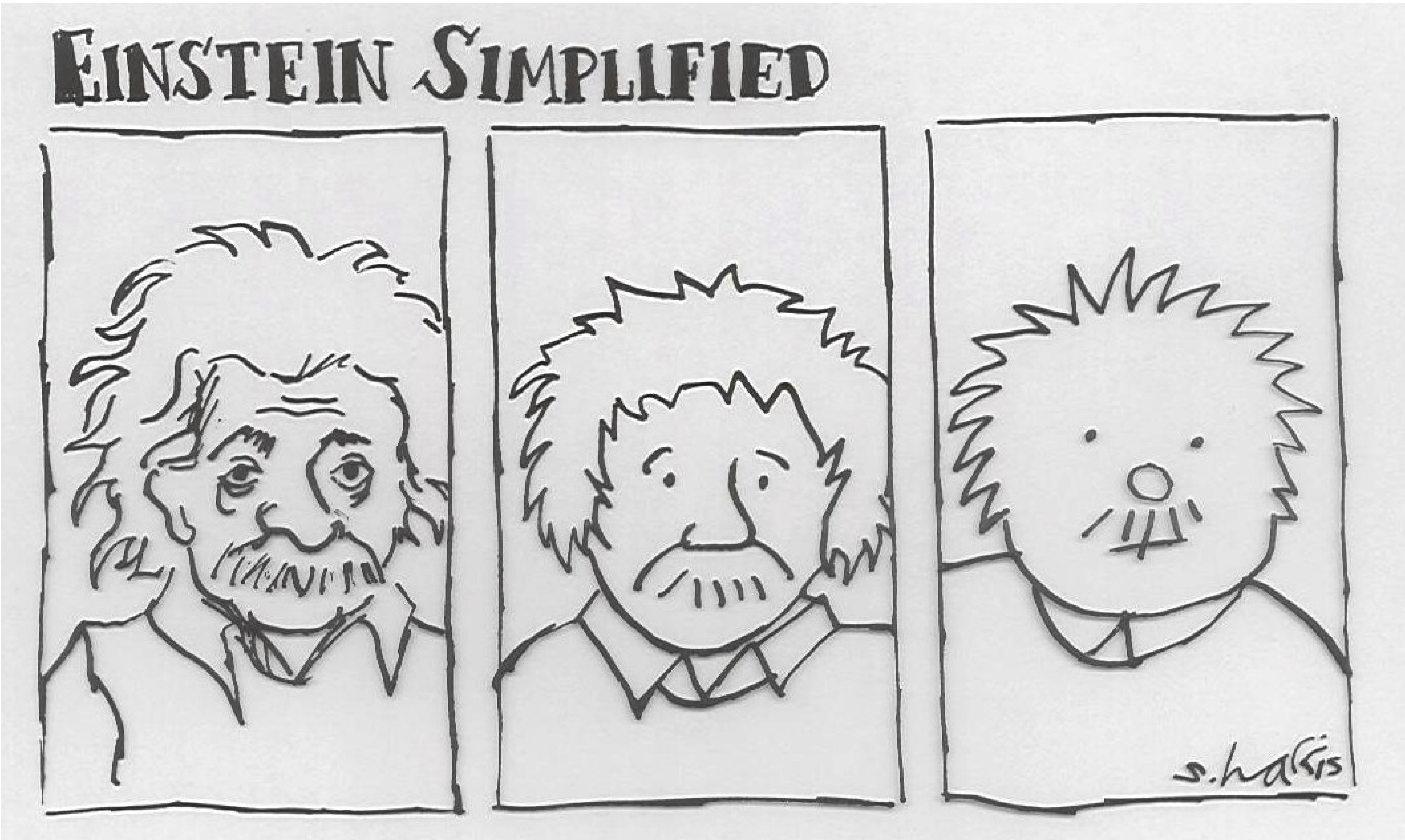


There are traveling wave solutions, the waves propagate at the speed of light



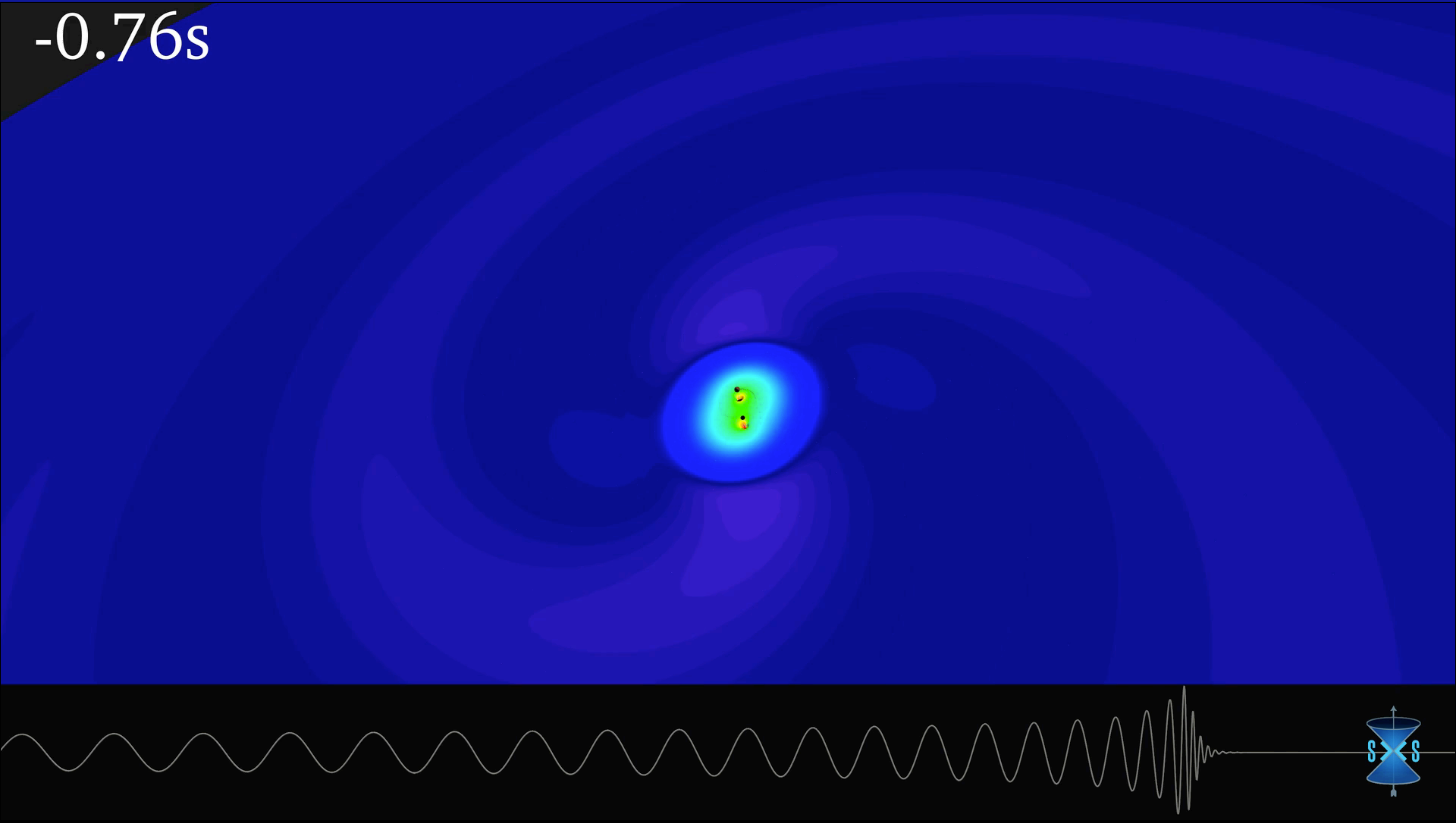
Photograph by Orren Jack Turner,
Library of Congress digital ID cph.3b46036.

What is a Gravitational Wave?



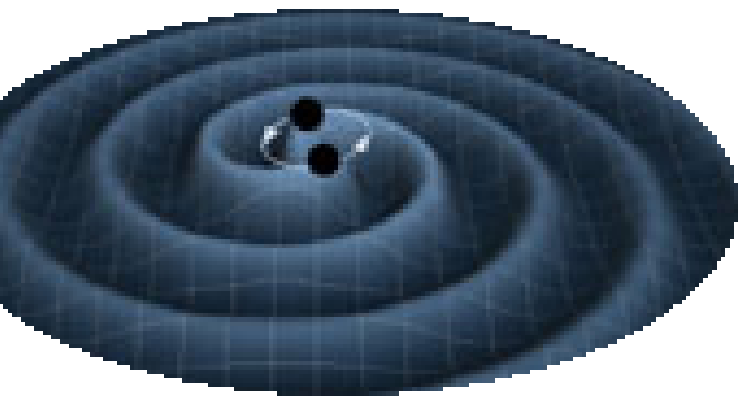
Sydney Harris

Simulation of the event

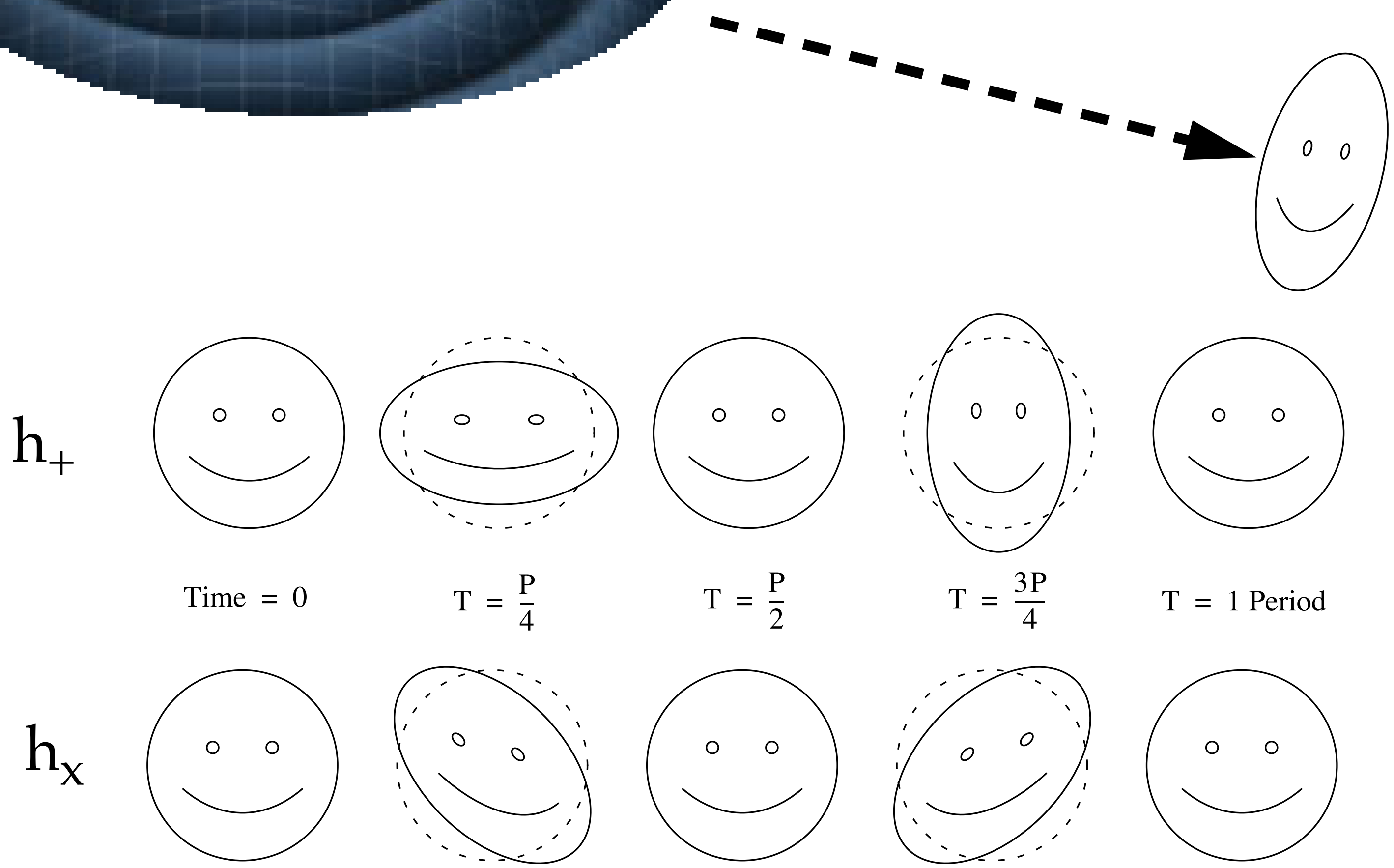


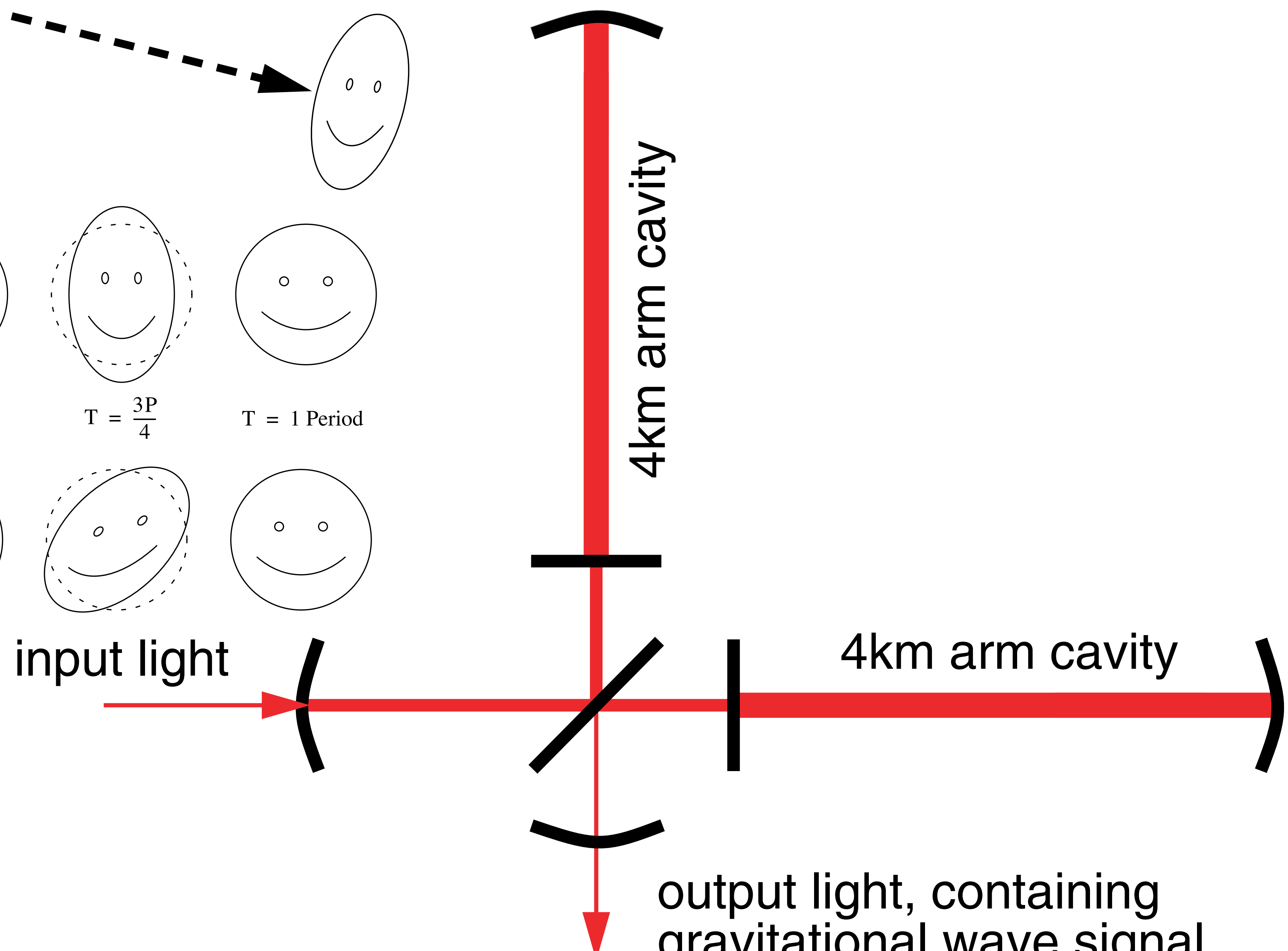
http://mediaassets.caltech.edu/gwave

The LIGO concept



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



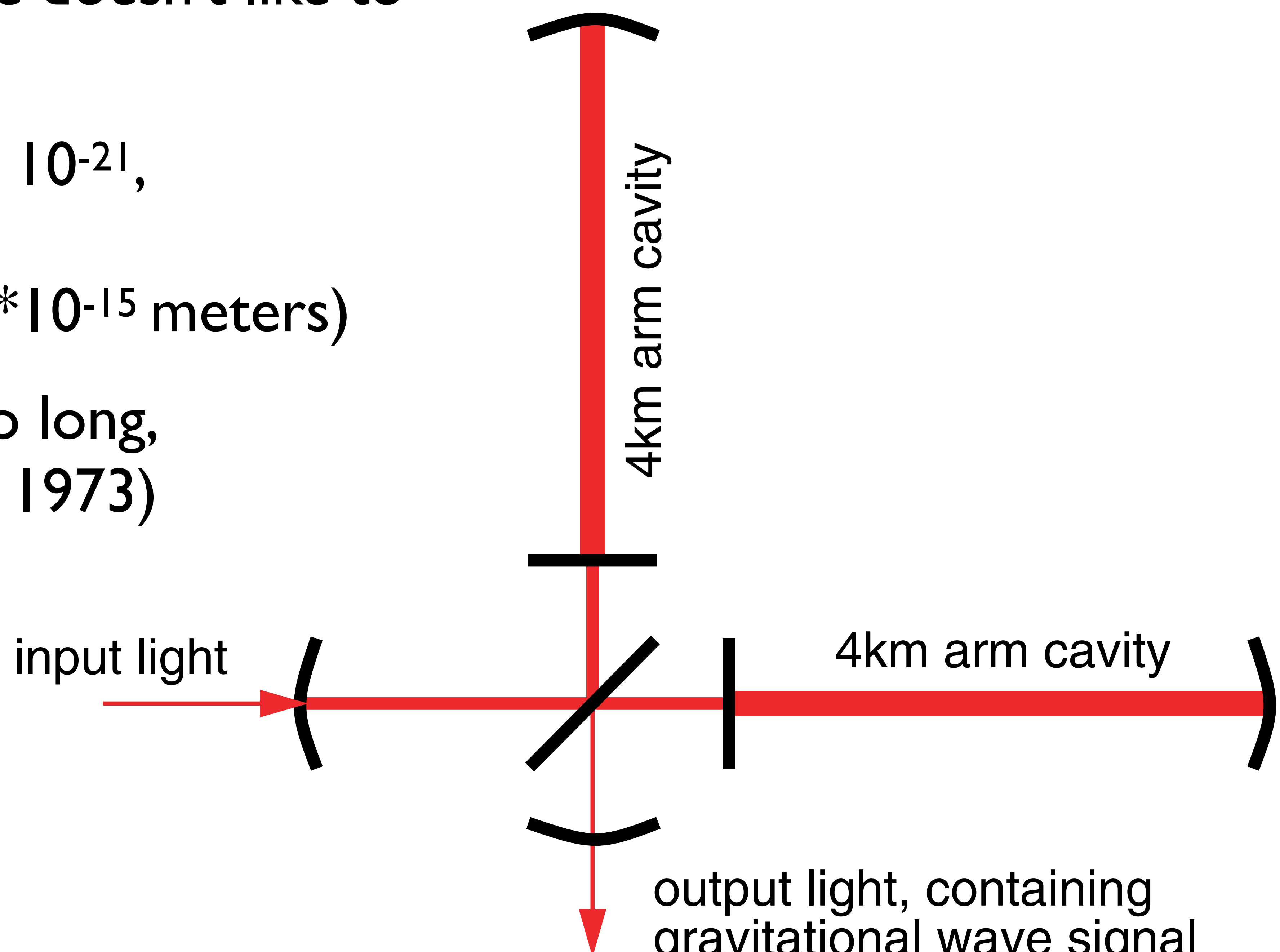


The LIGO concept

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)



The LIGO concept

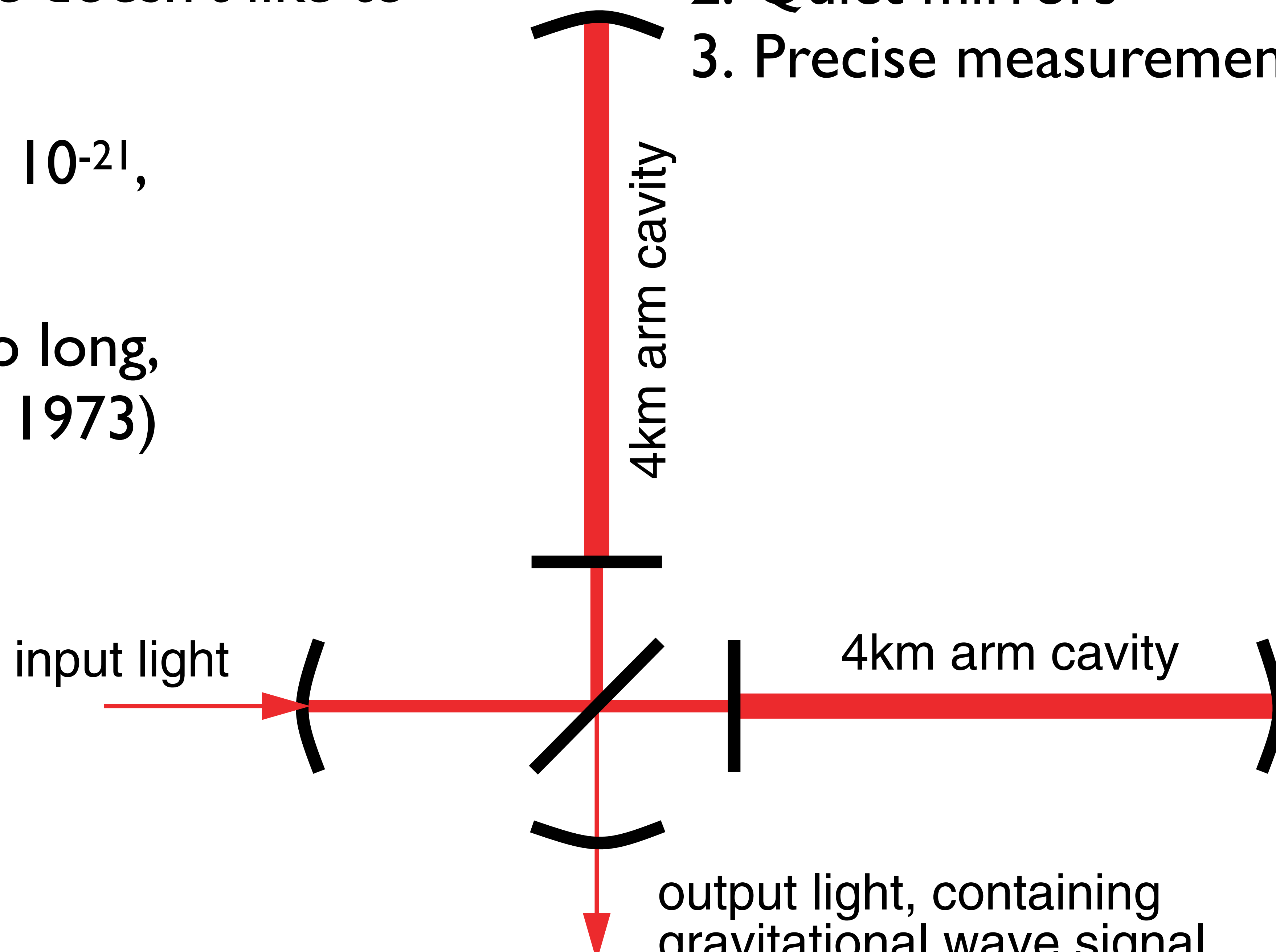
How it really works

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

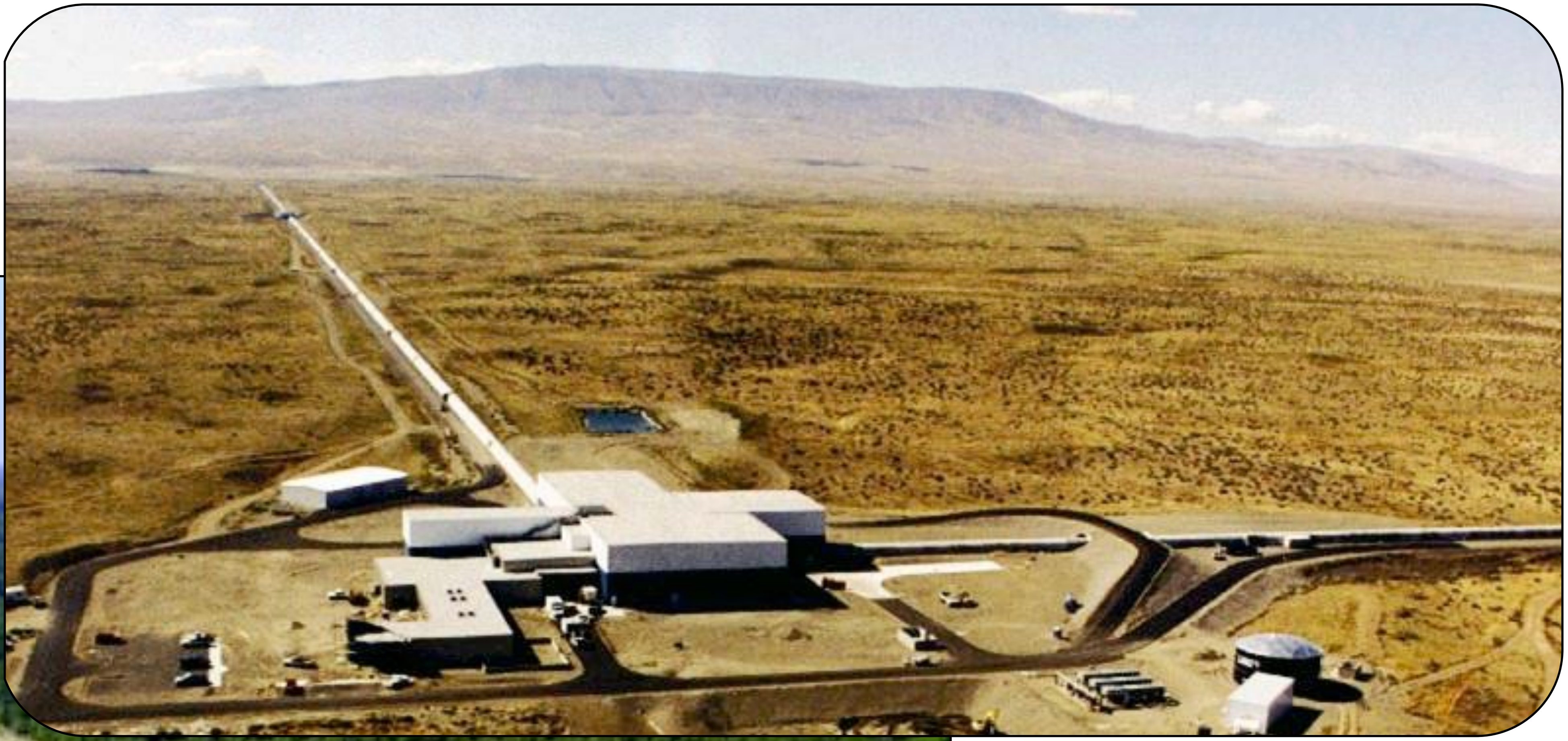


Long arms

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

World's 3nd largest ultra-clean vacuum system

- each arm is 4 km long, 4 ft. diameter



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)

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)

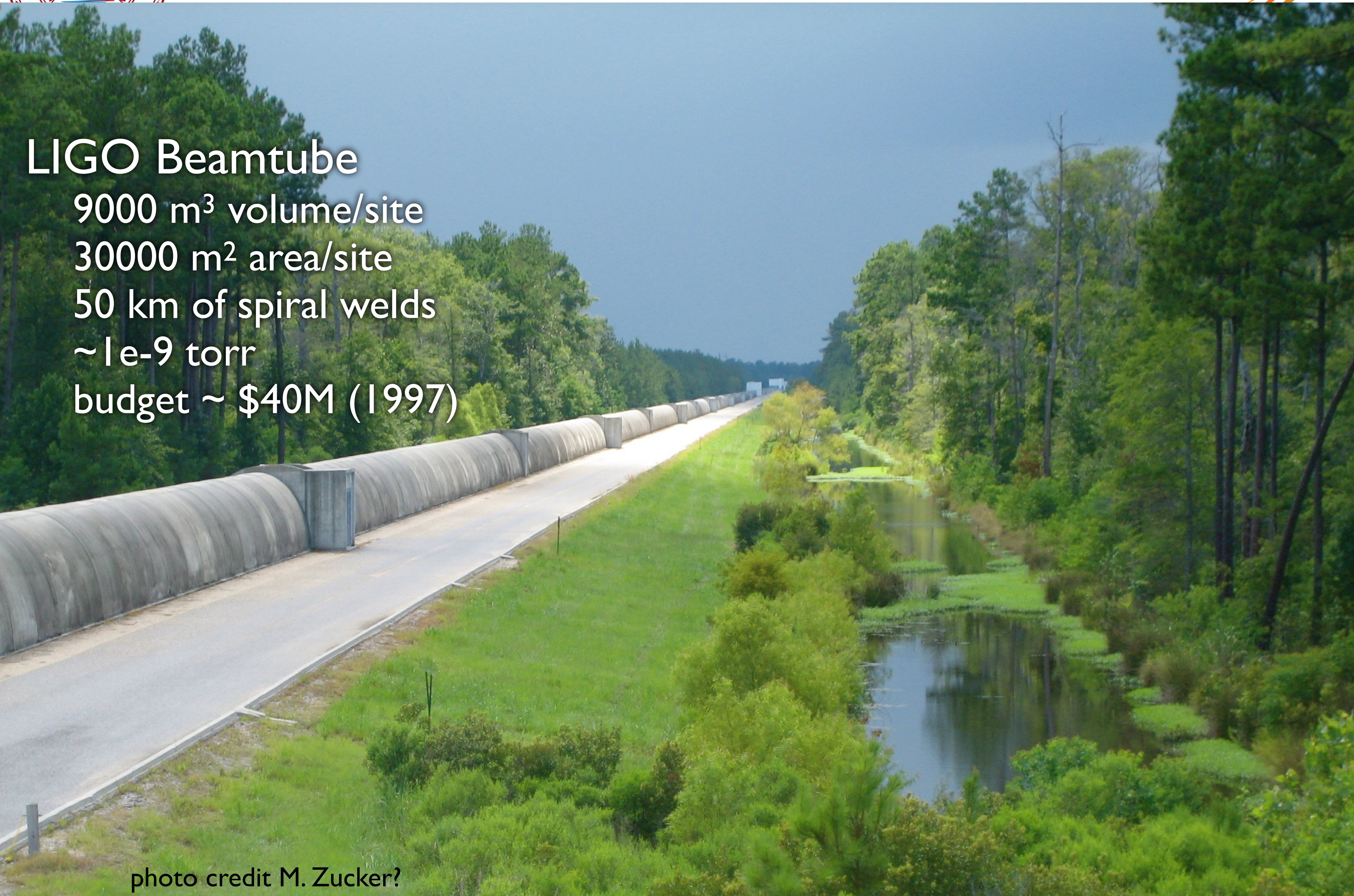


photo credit M. Zucker?

Quiet Mirrors

How it really works

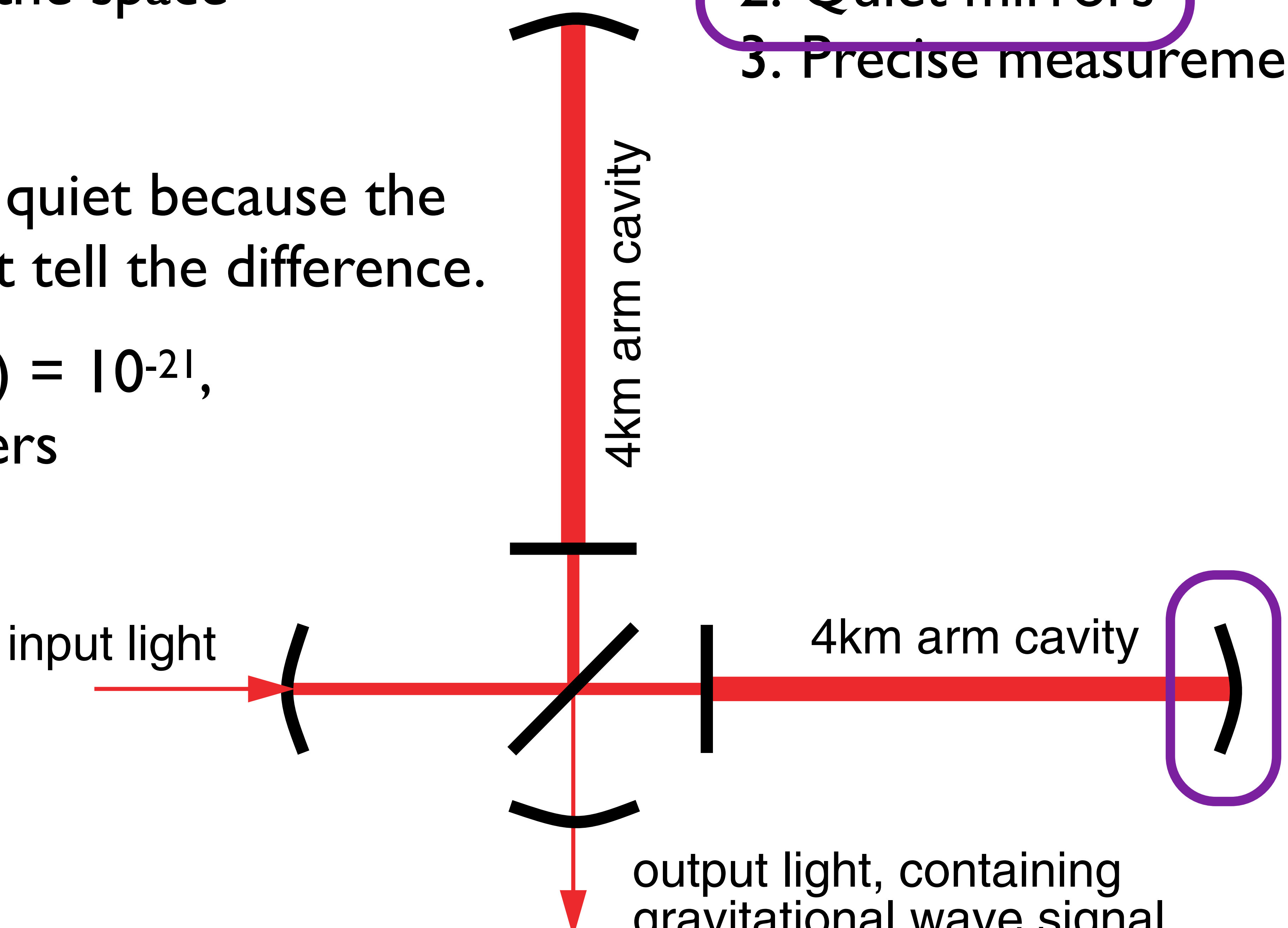
1. Long arms
2. Quiet mirrors
3. Precise measurement

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

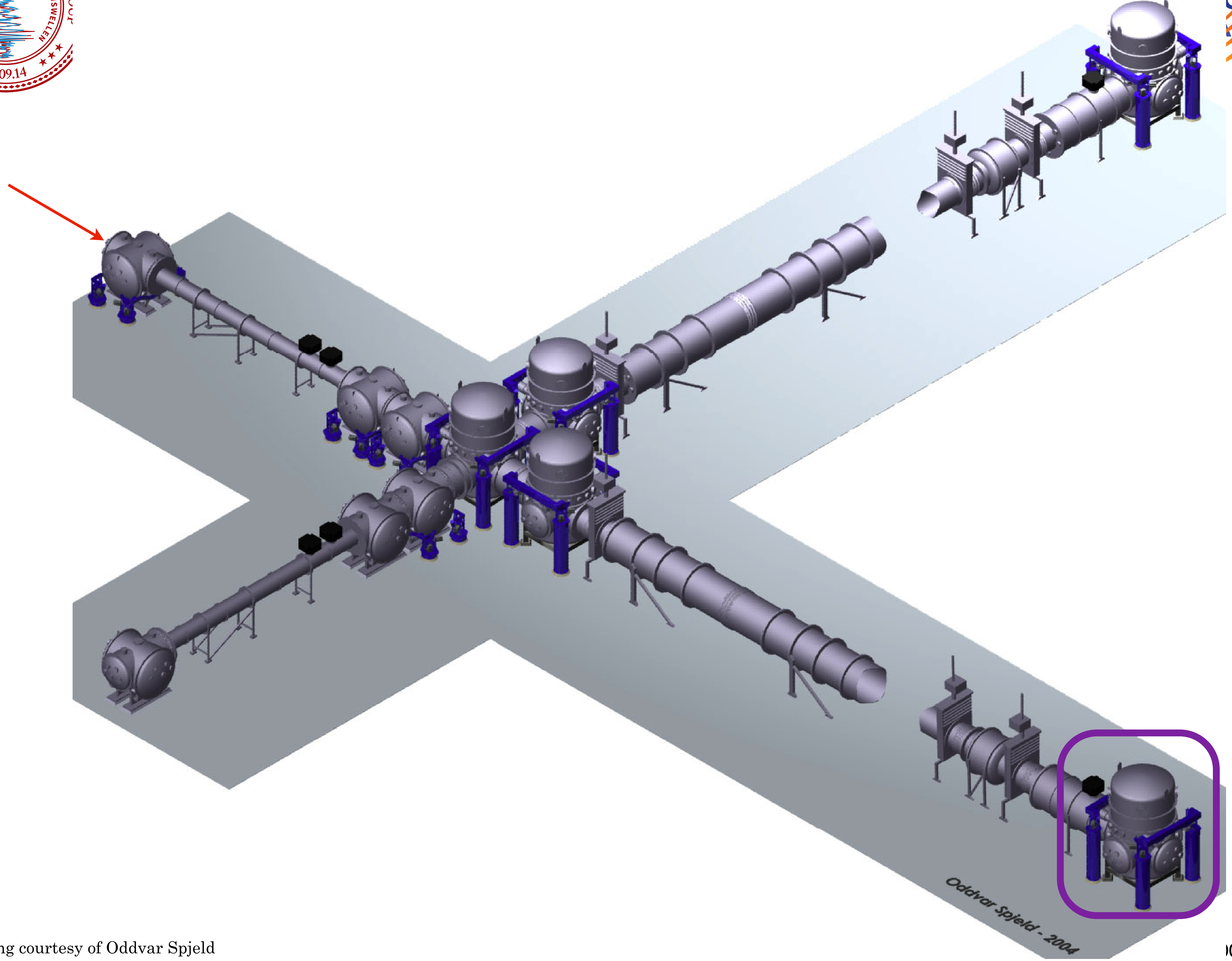
- but -

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

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

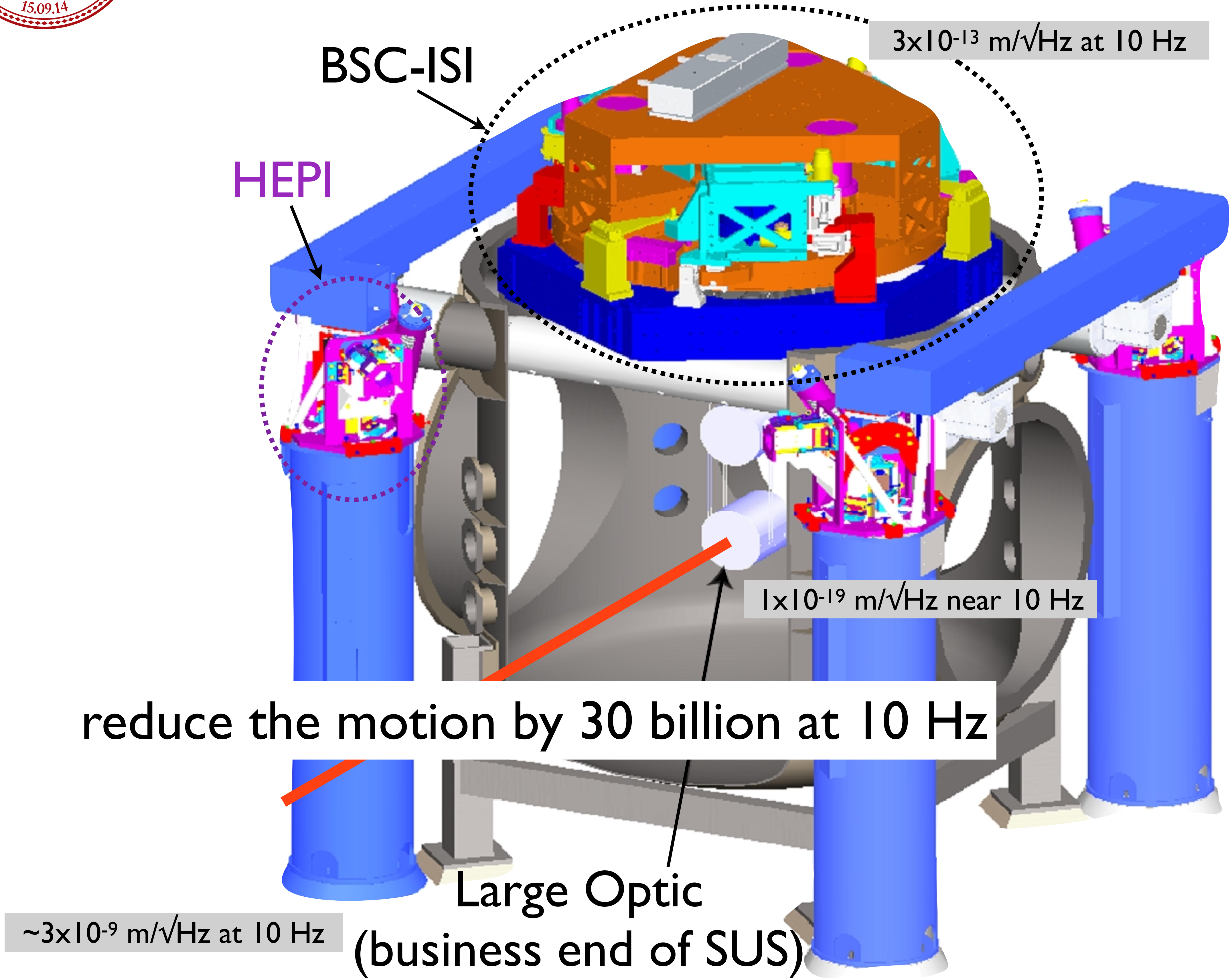


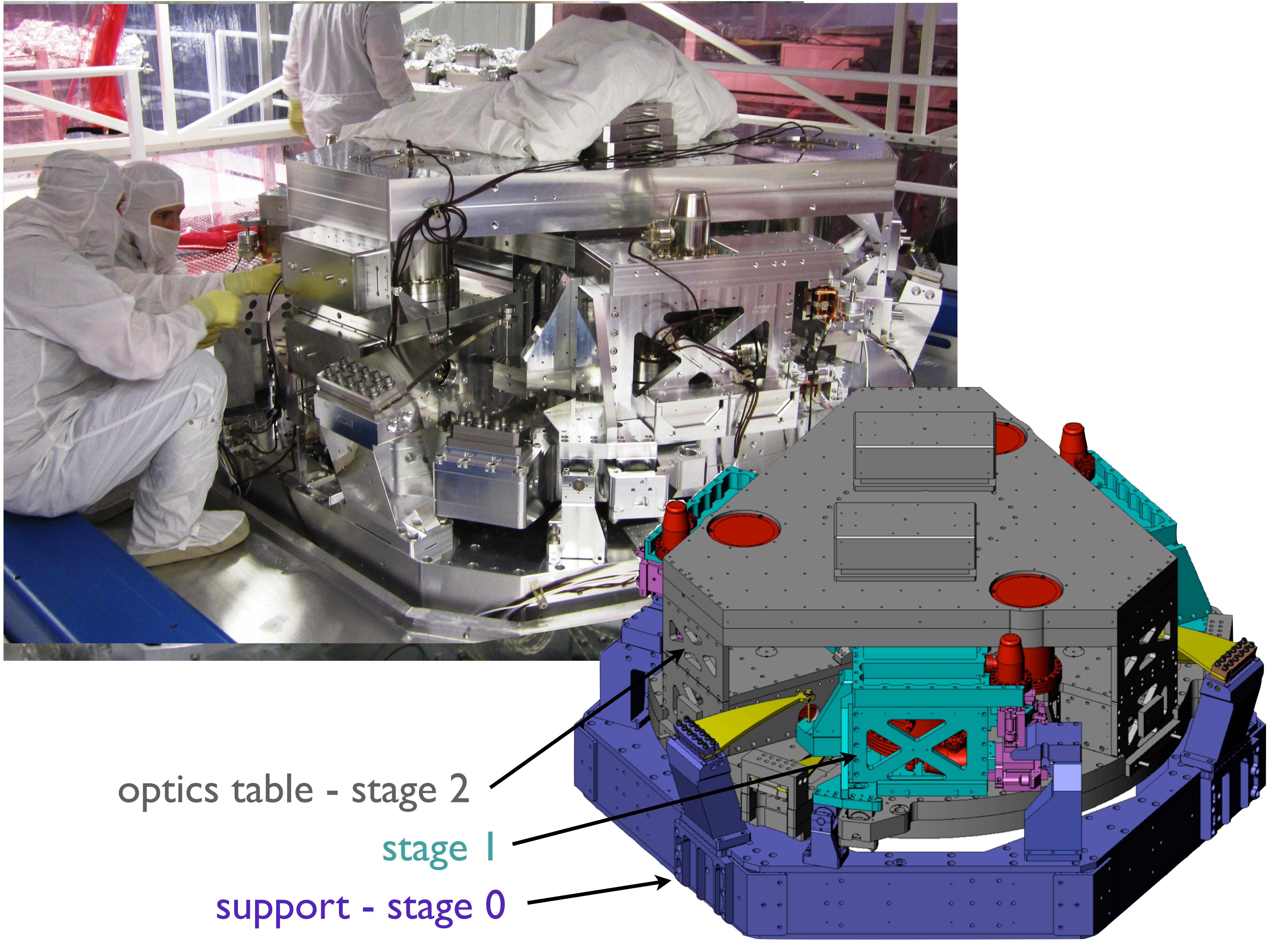
The LIGO vacuum equipment



drawing courtesy of Oddvar Spjeld

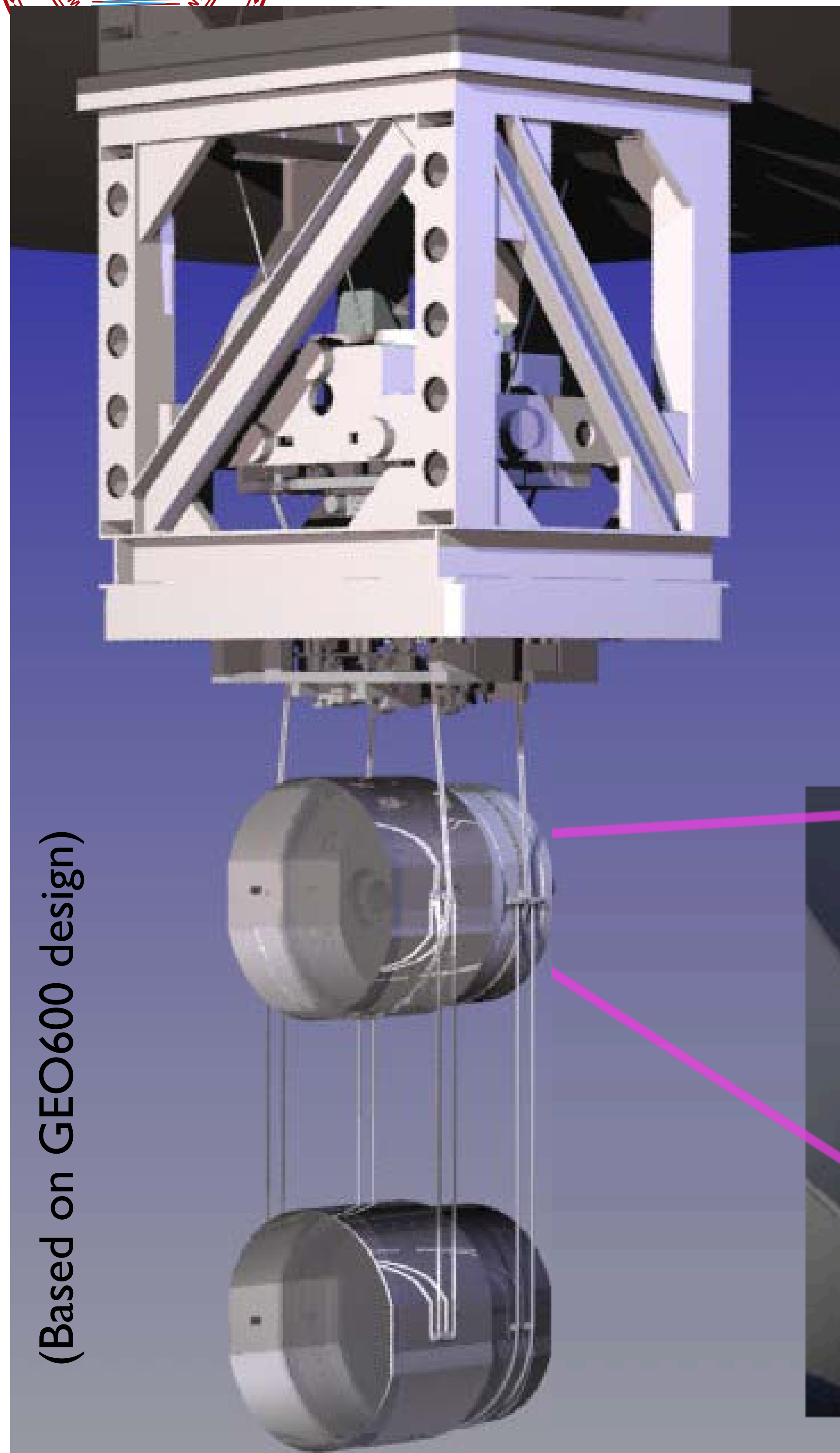
Isolation of the Mirrors





optics table - stage 2
stage 1
support - stage 0

Pendulum Suspension



LIGO Mirrors:

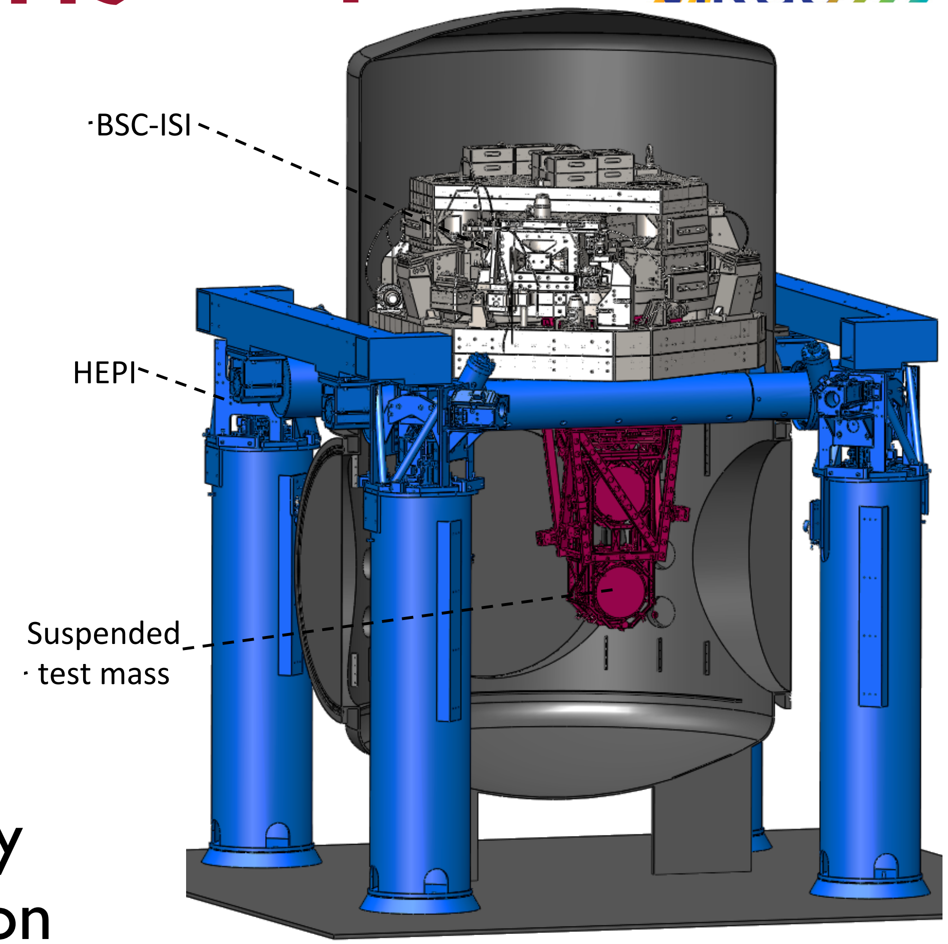
Synthetic fused silica,

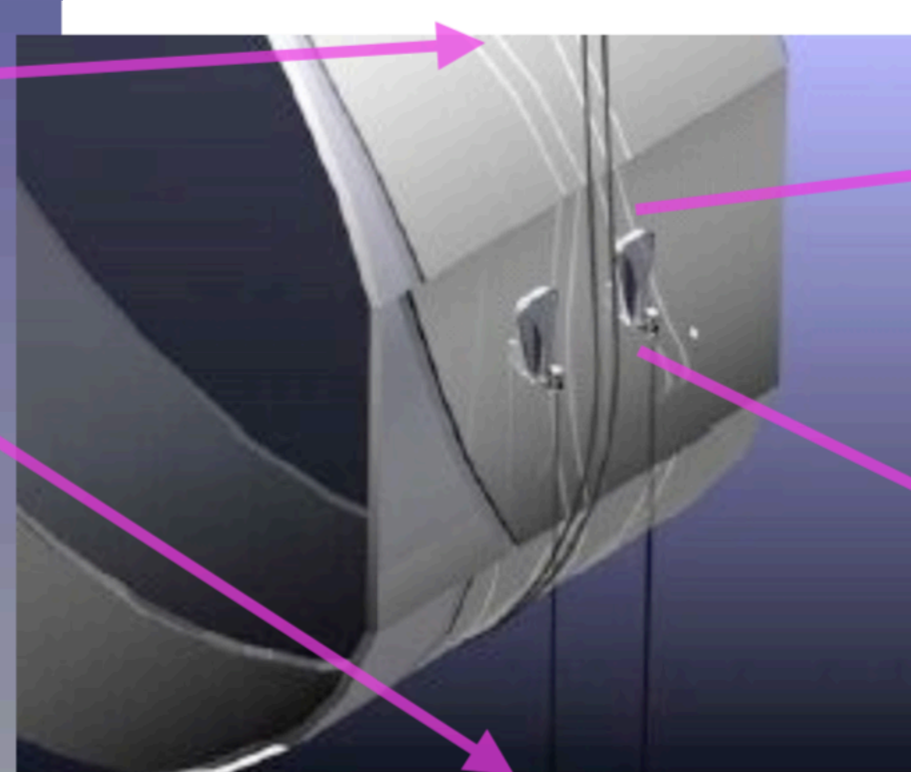
- 40 kg mass
- 34 cm diameter
- 20 cm thick

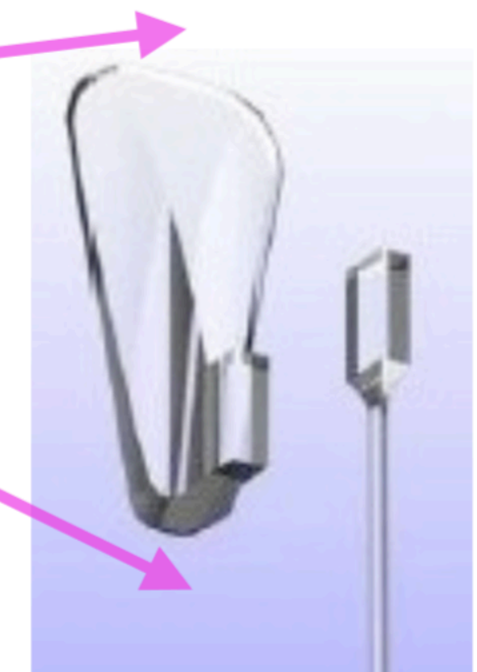
Suspended as a 4 stage pendulum

Best coatings available

Motion at 10 Hz set by thermal driven vibration



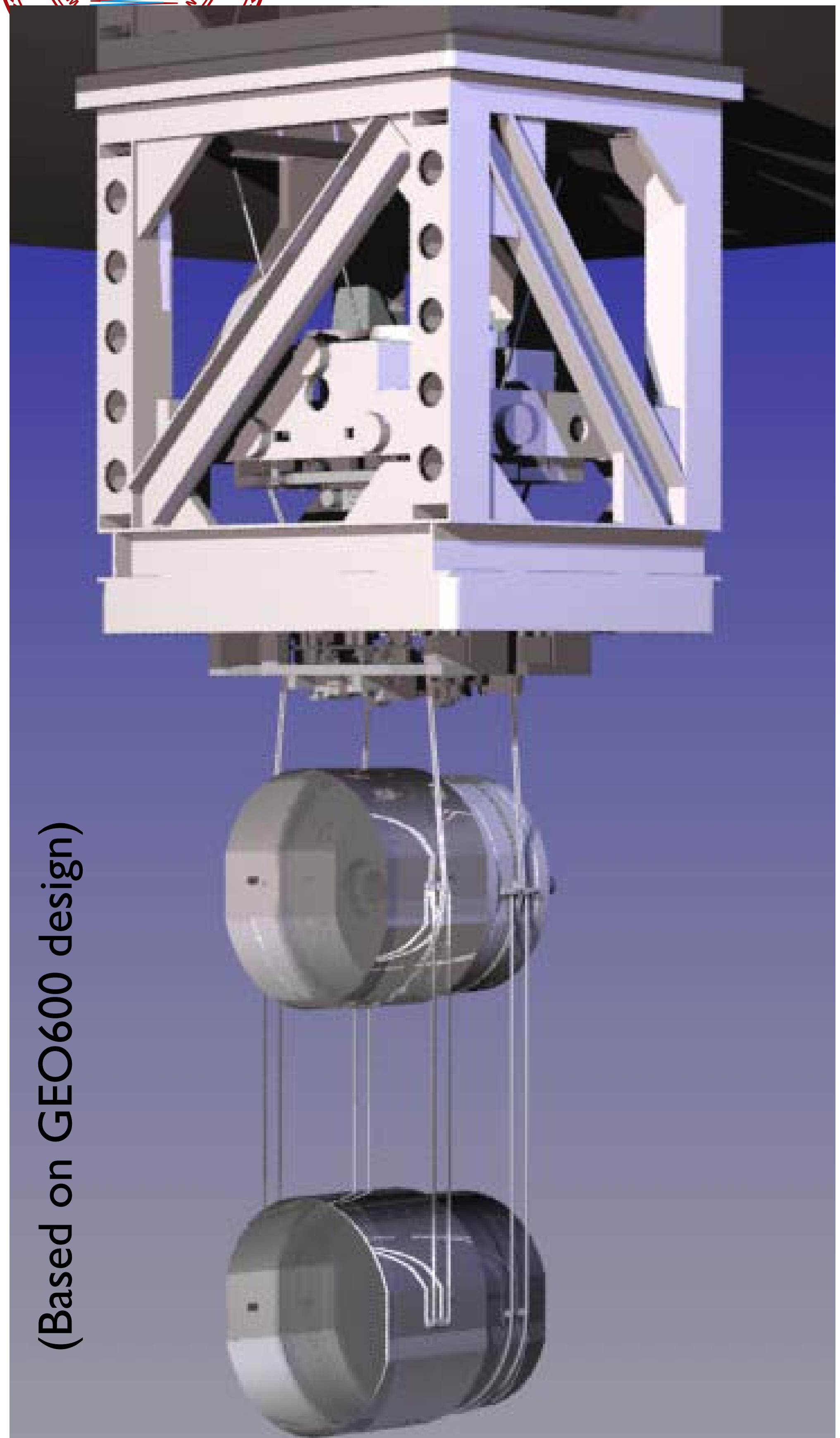


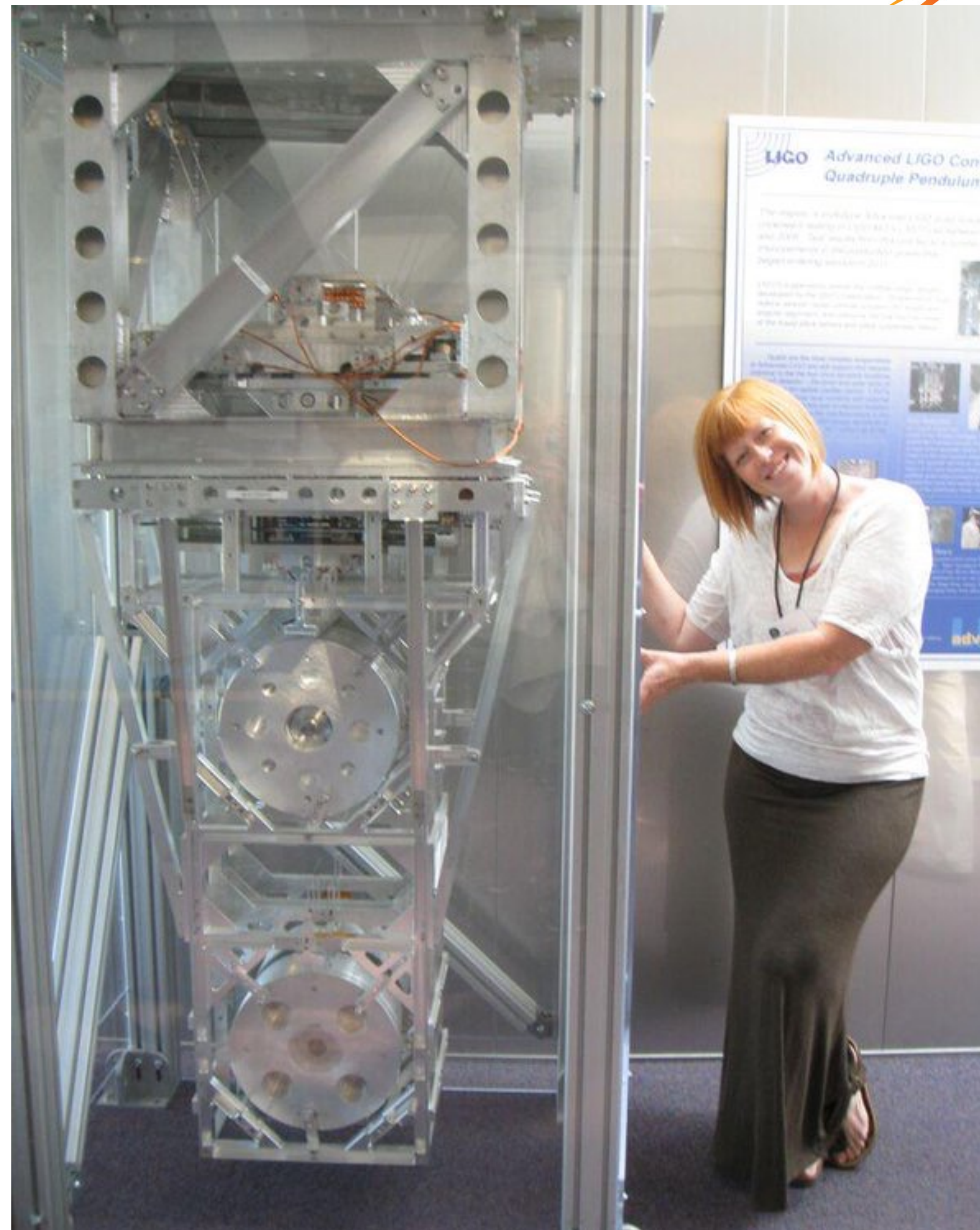


silicate bonding creates a monolithic final stage

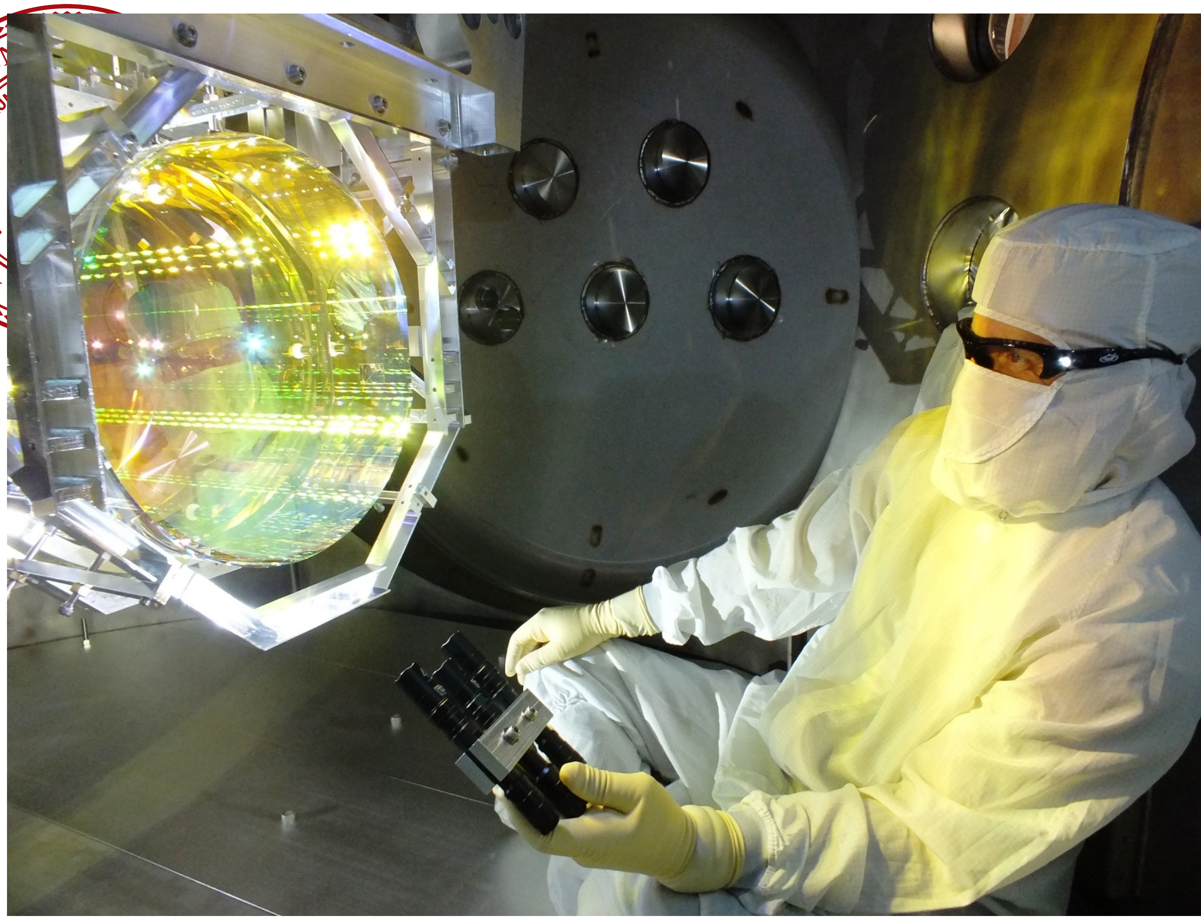
Pendulum Suspension

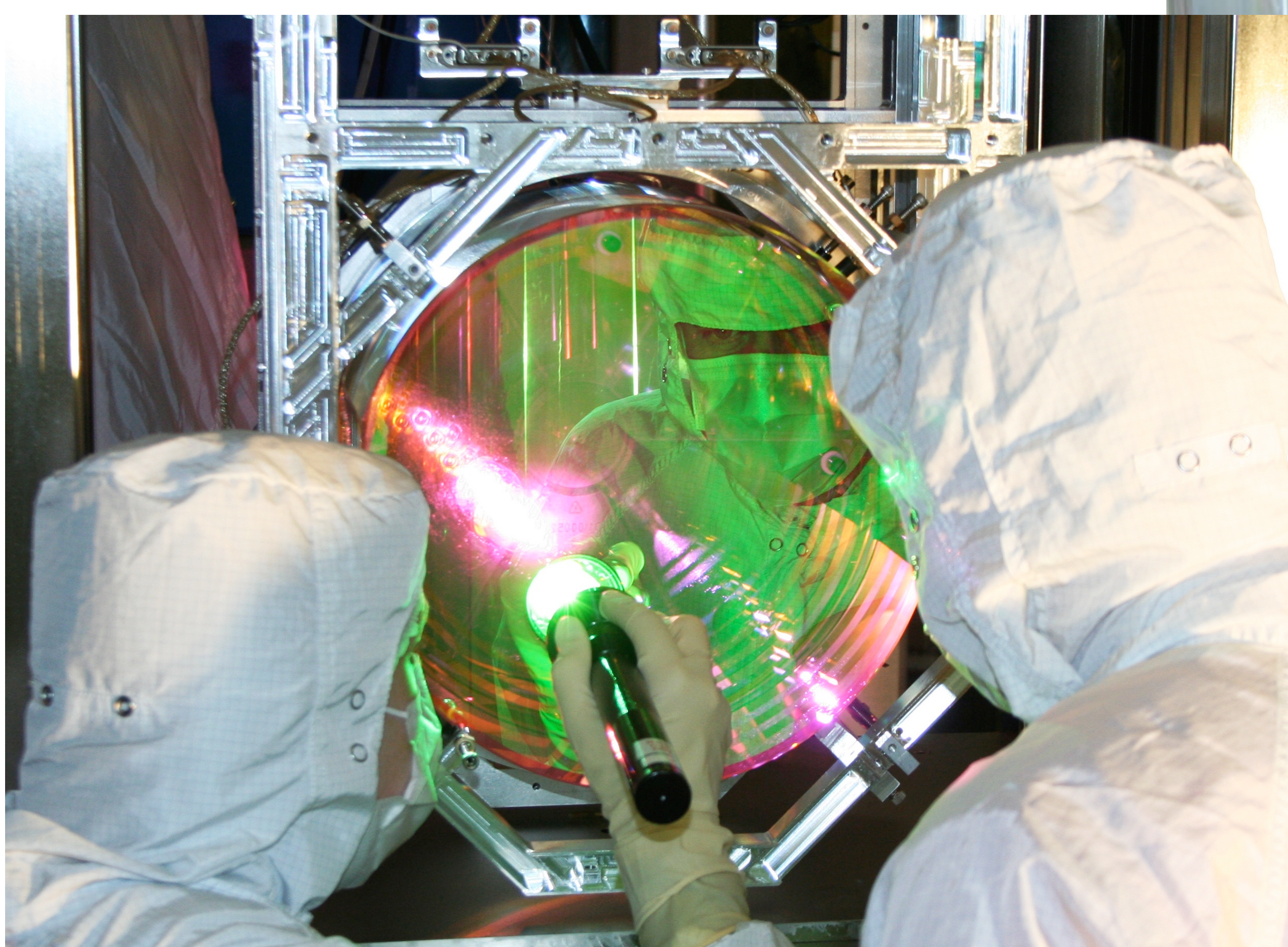
LHO suspension expert, Betsy Weaver
with the Engineering prototype

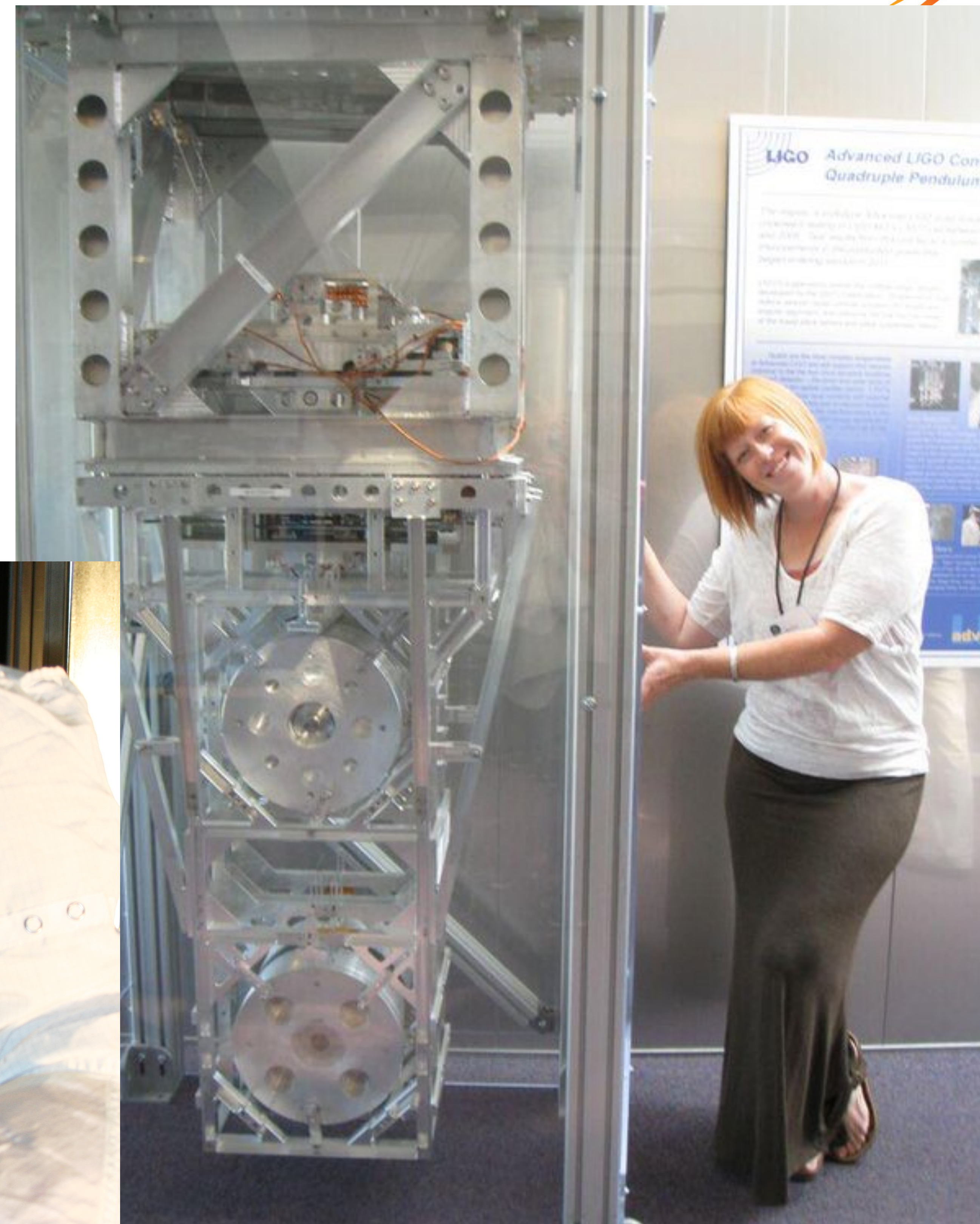




r picts

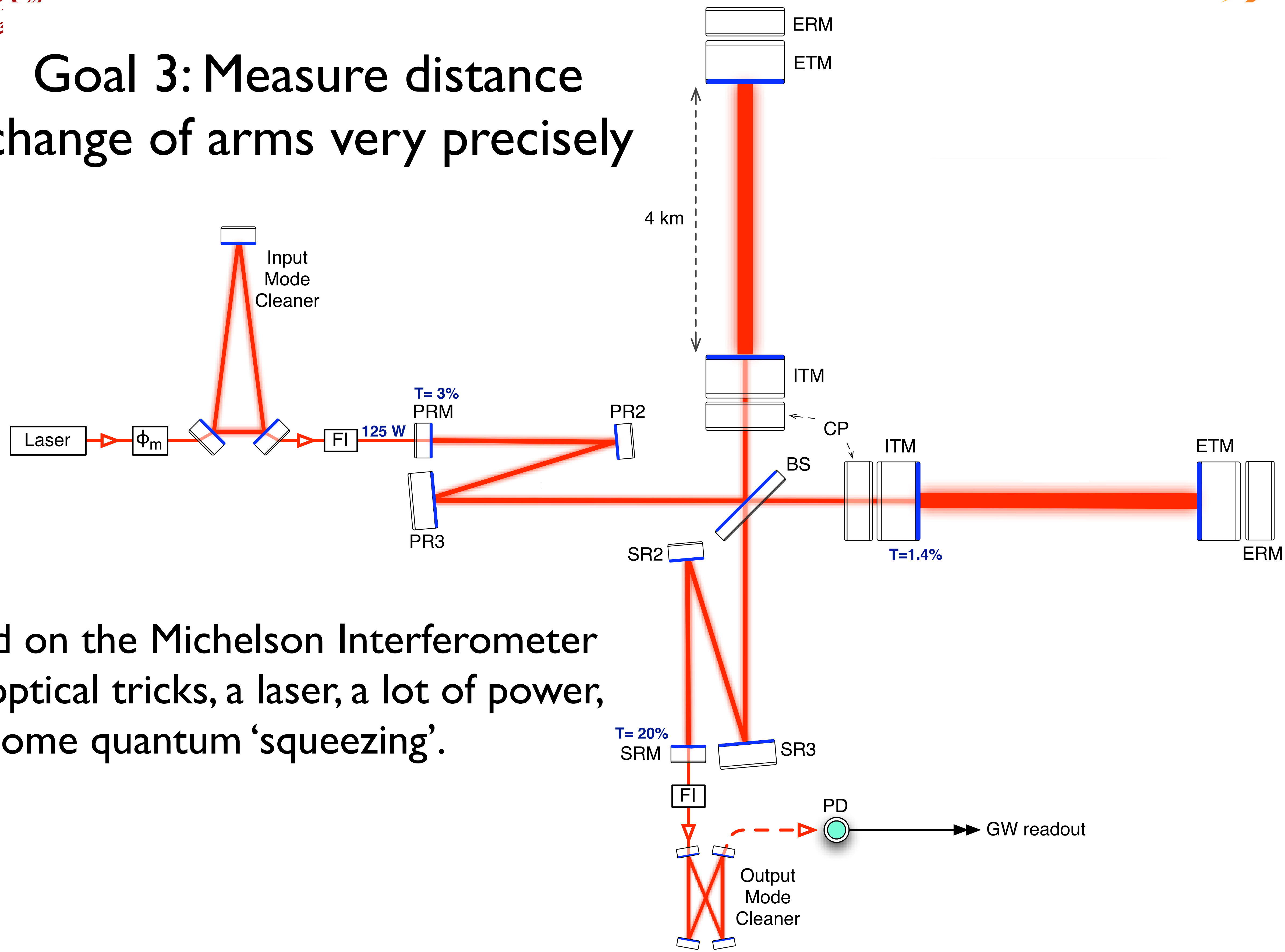






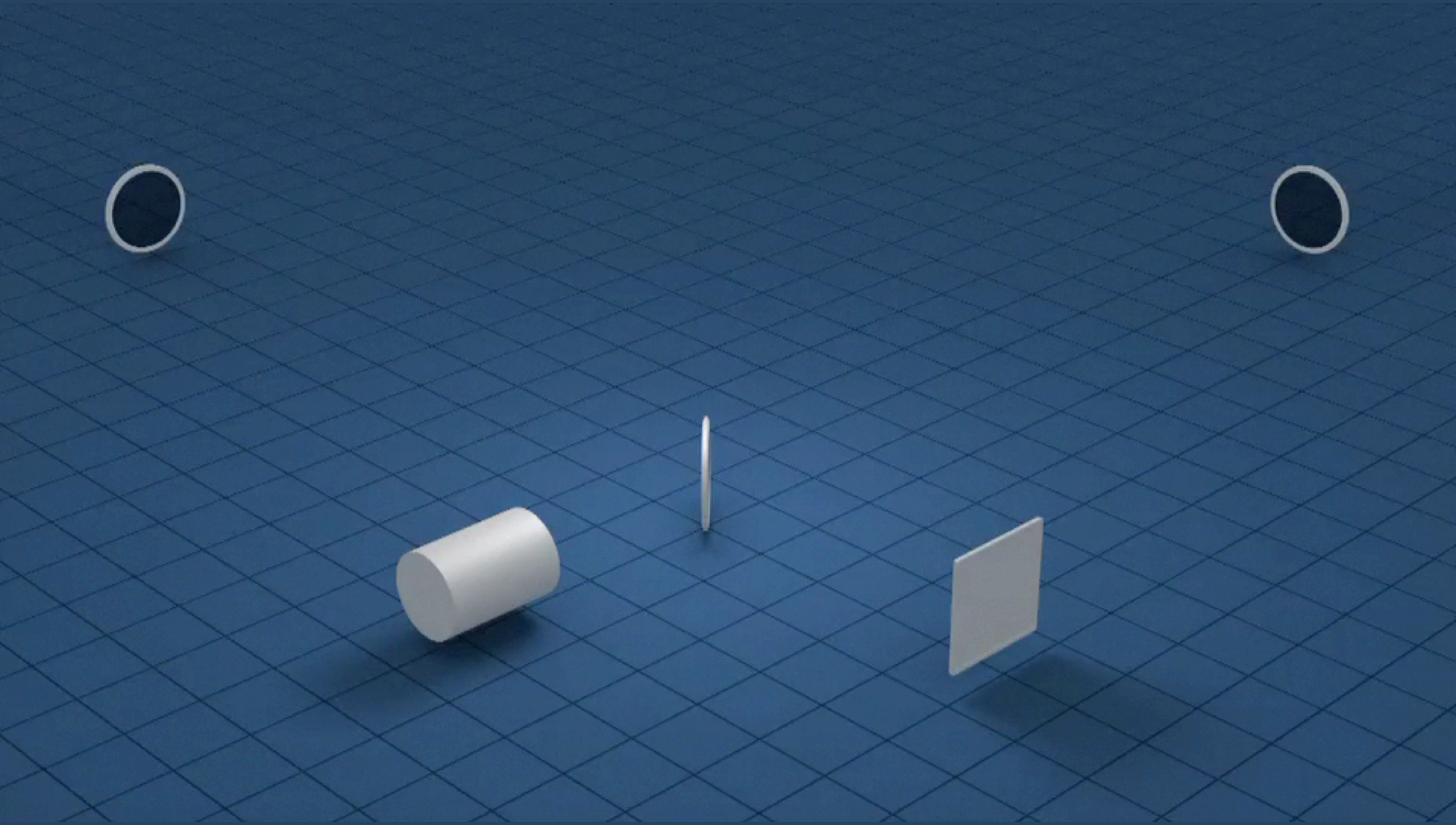
Precision Interferometry

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'.

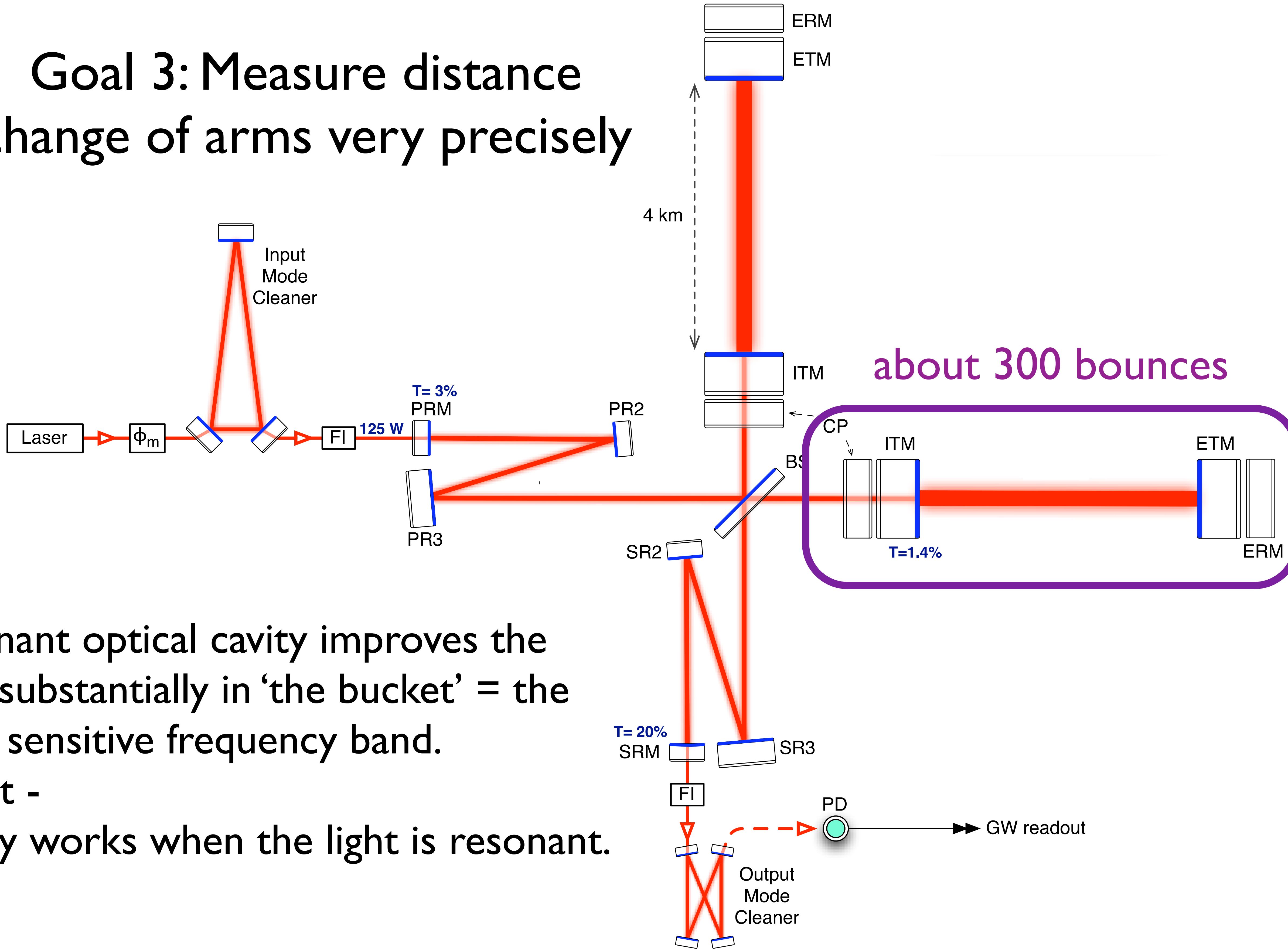
Animated Interferometer



http://mediaassets.caltech.edu/gwave

Fabry-Perot arms

Goal 3: Measure distance change of arms very precisely



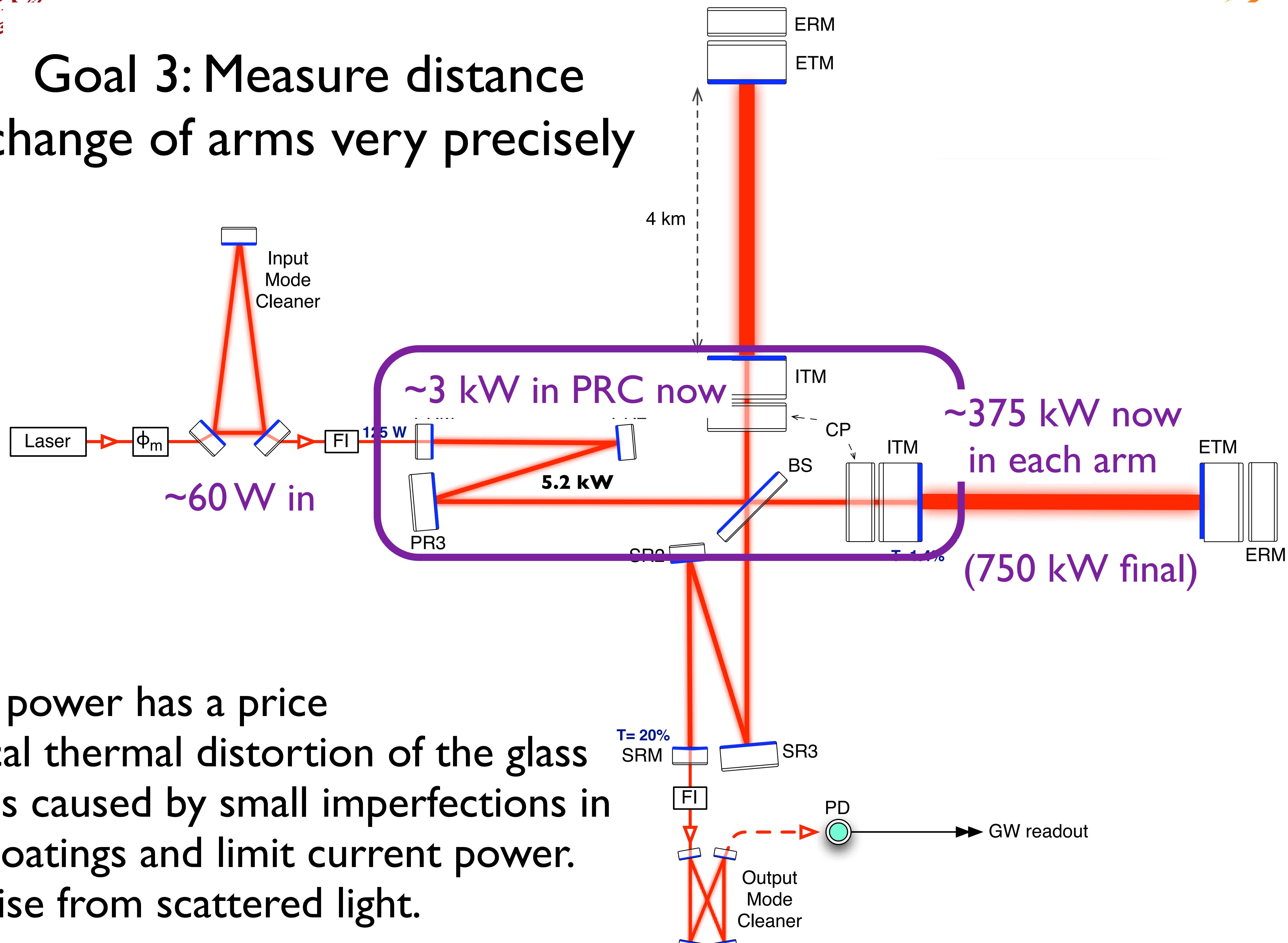
Resonant optical cavity improves the SNR substantially in ‘the bucket’ = the most sensitive frequency band.

- but -

It only works when the light is resonant.

Lots of photons

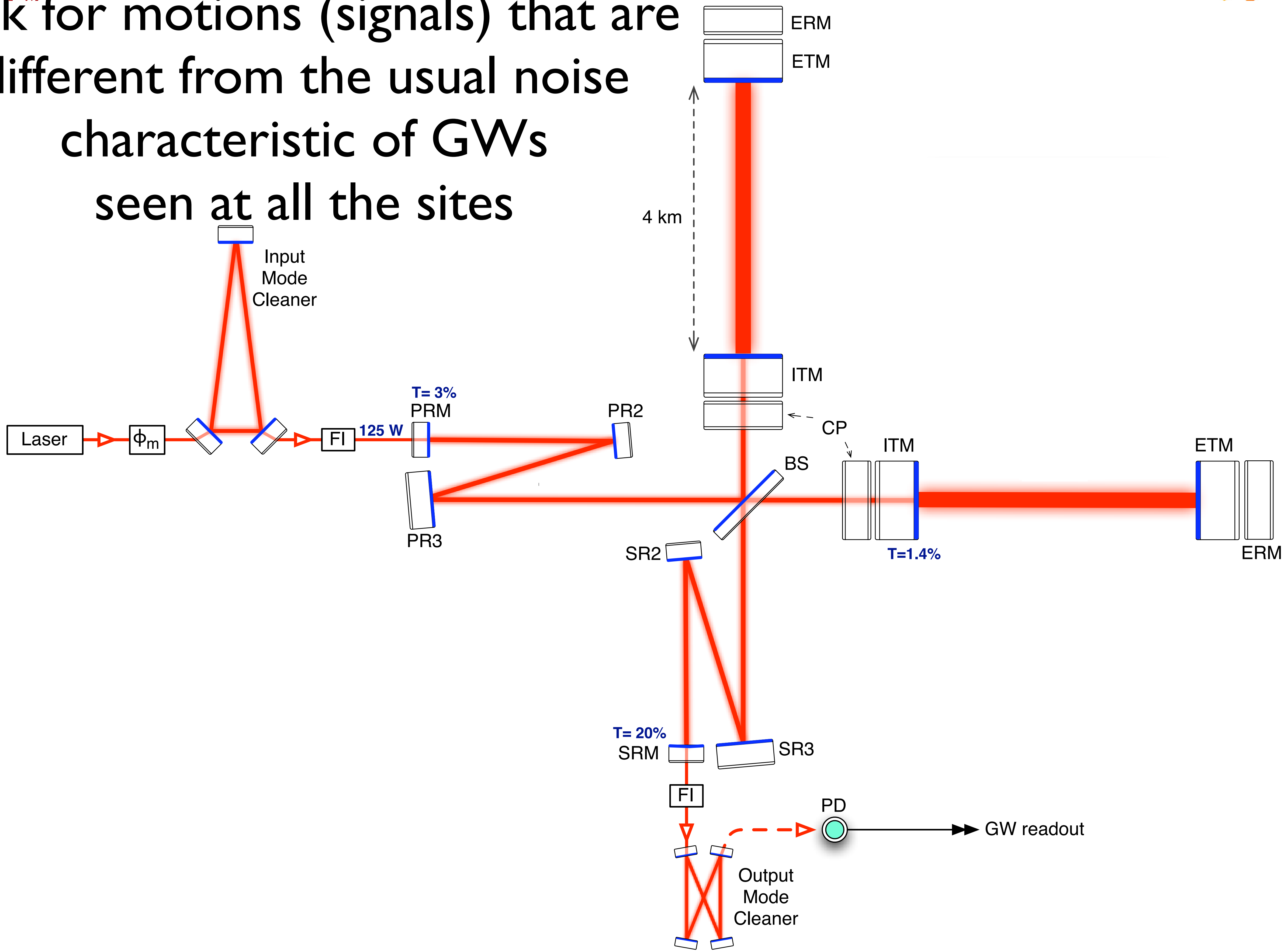
Goal 3: Measure distance change of arms very precisely



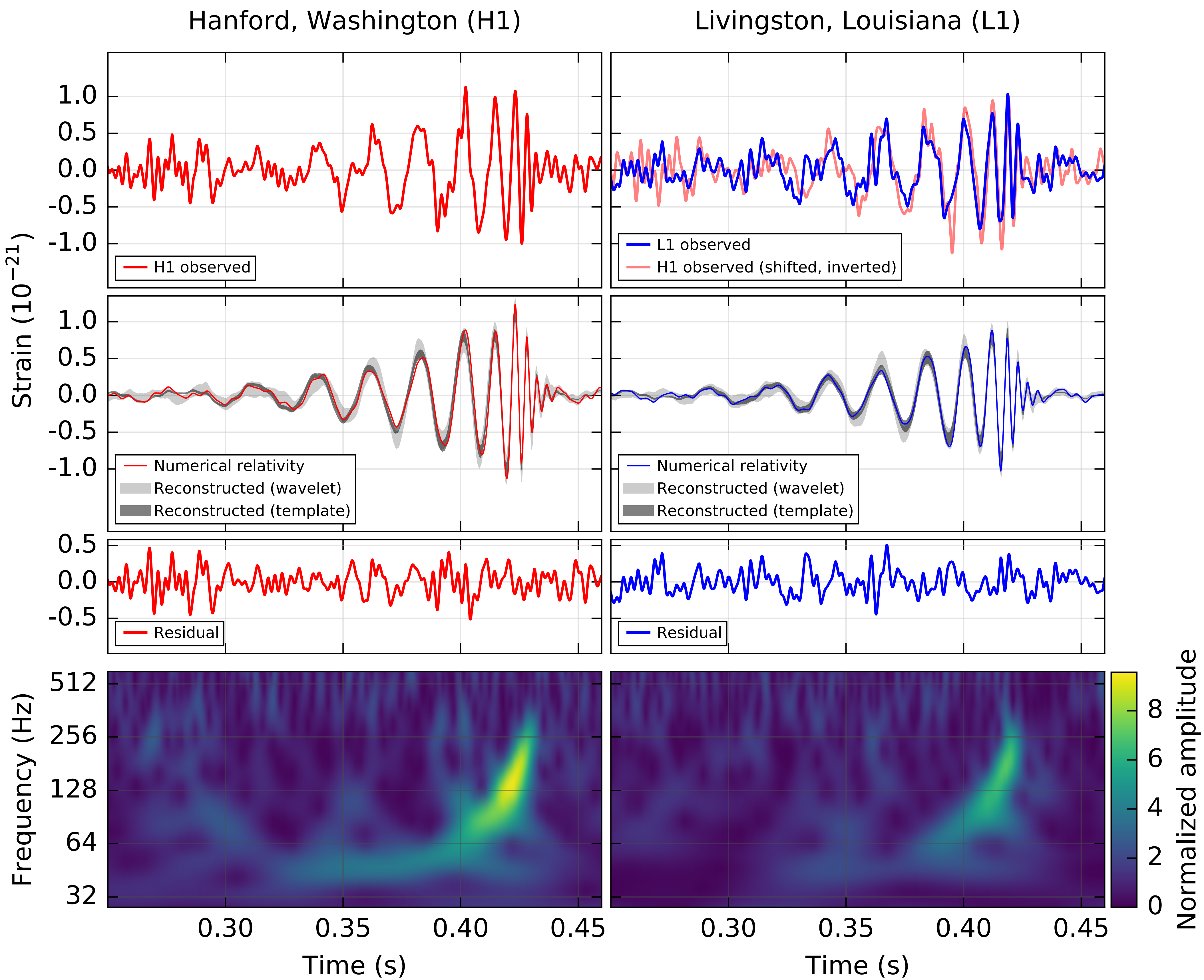
High power has a price
- Local thermal distortion of the glass optics caused by small imperfections in the coatings and limit current power.
- Noise from scattered light.

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:

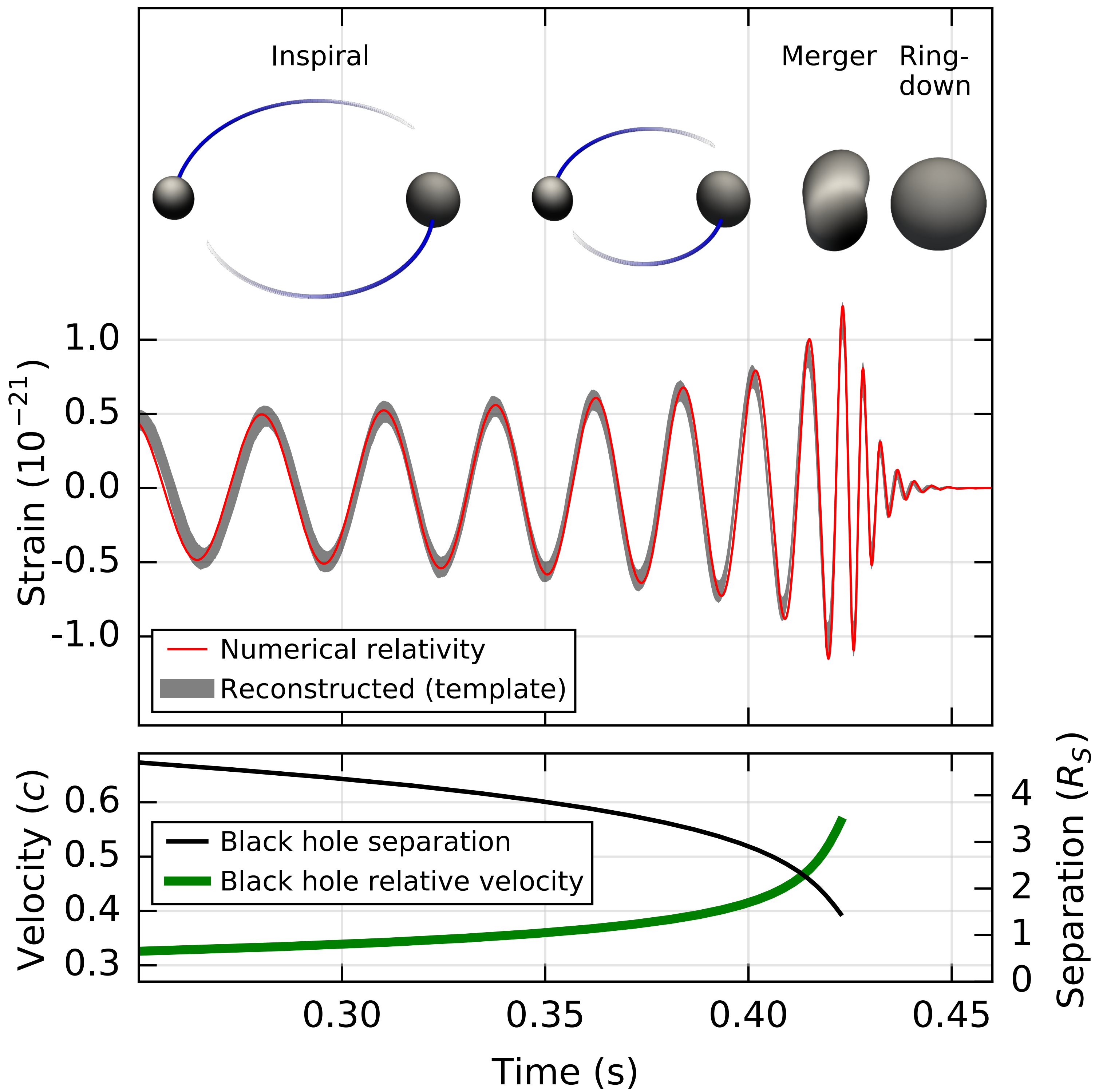
62 (+4/-4) M_{sun}

3 solar masses were radiated as GWs

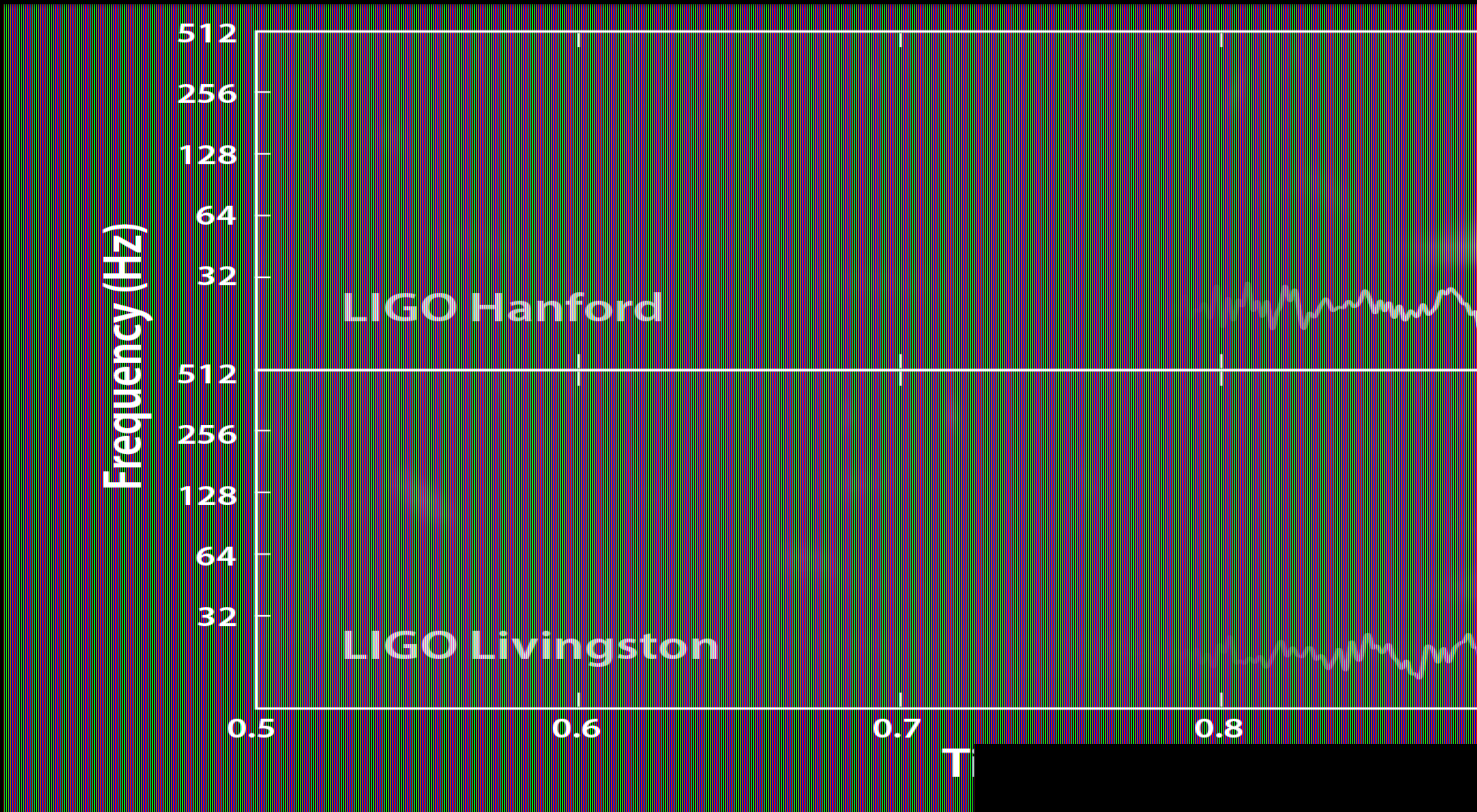
Distance

420 (+160/-180) MPc

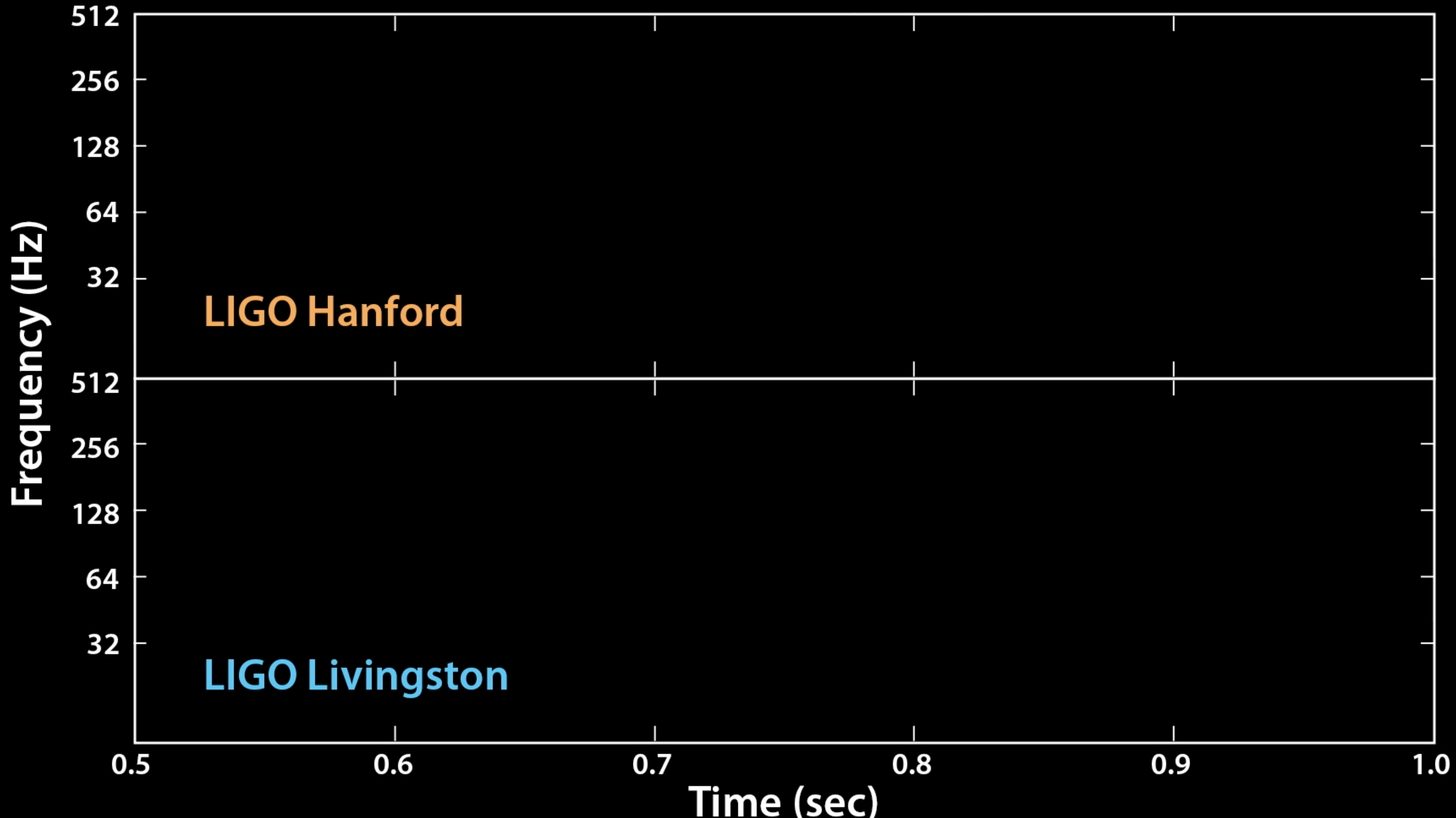
(1.3 Billion light years)

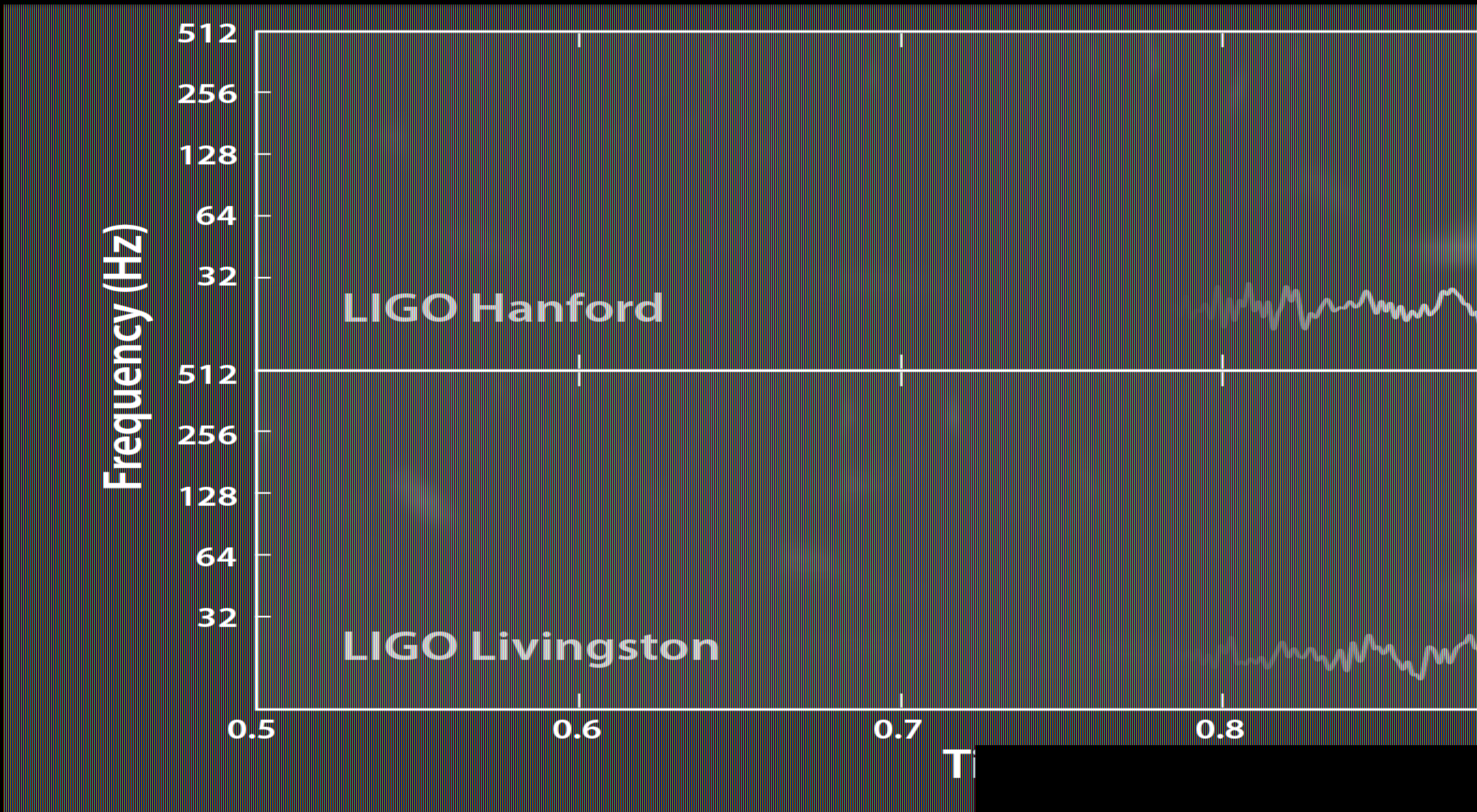


http://dx.doi.org/10.1103/PhysRevLett.116.061102

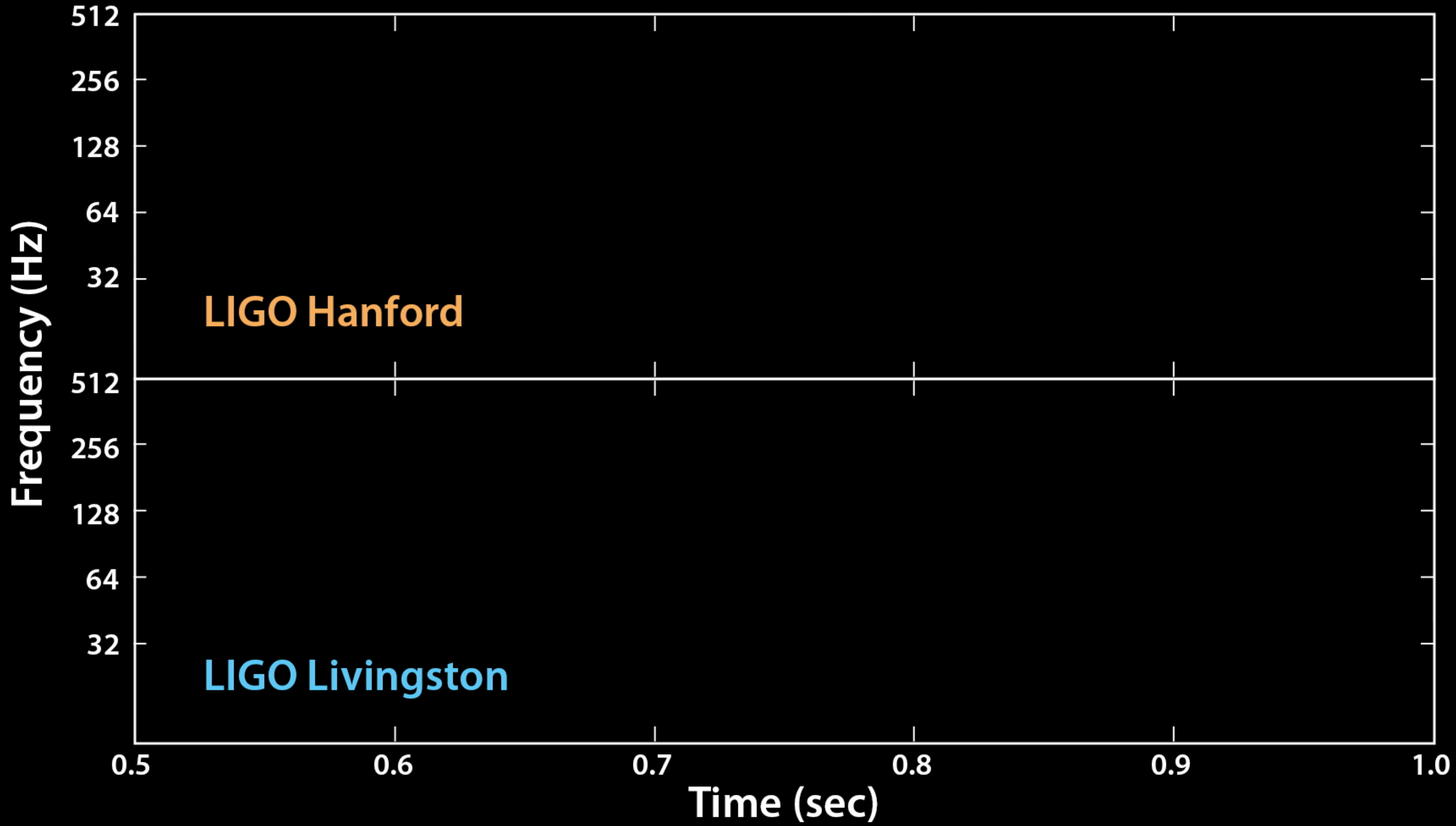


http://mediaassets.caltech.edu/gwave


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

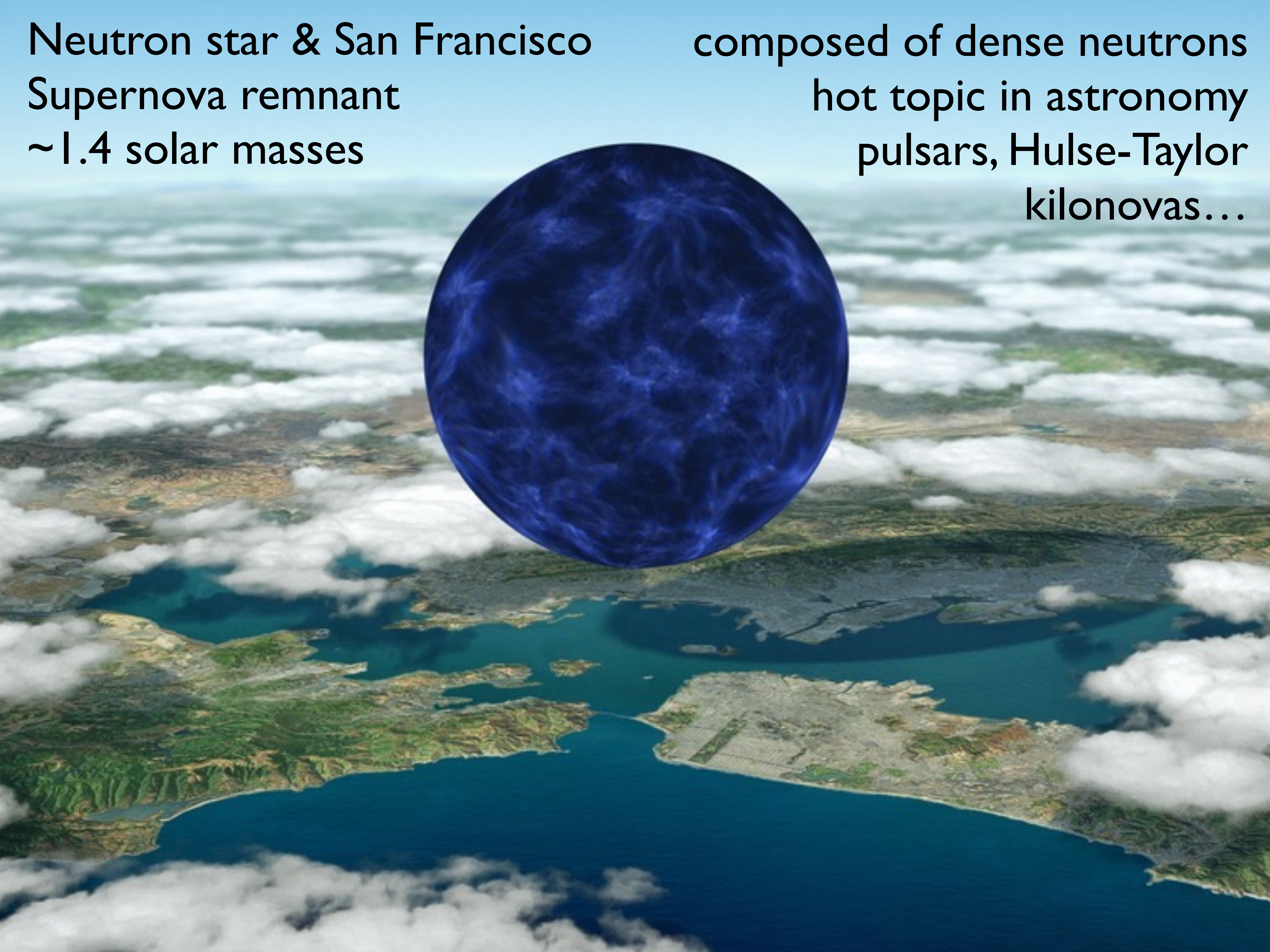

Frequency (Hz)
512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
0.5
0.6
0.7
0.8

The sound of black holes colliding

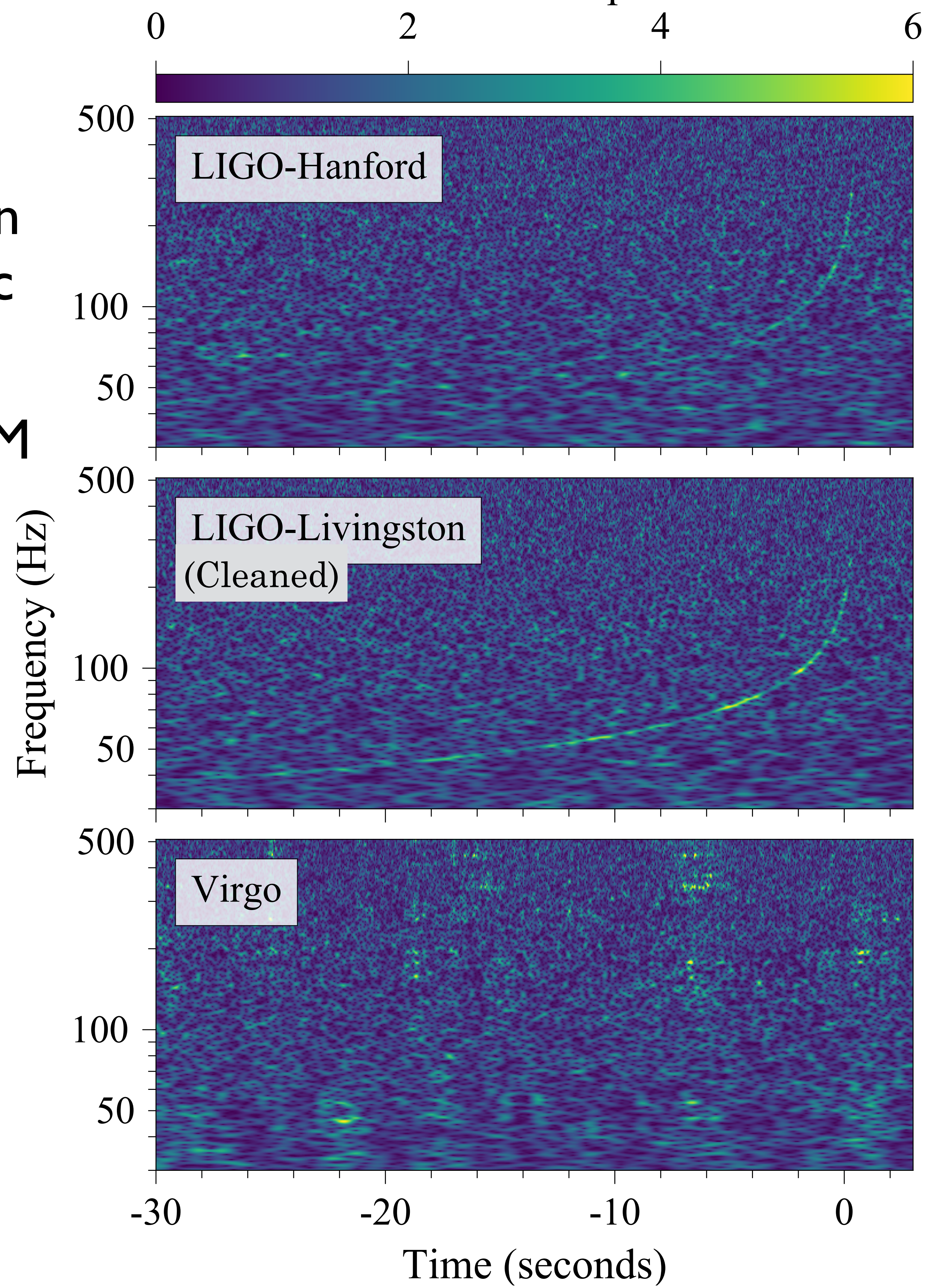


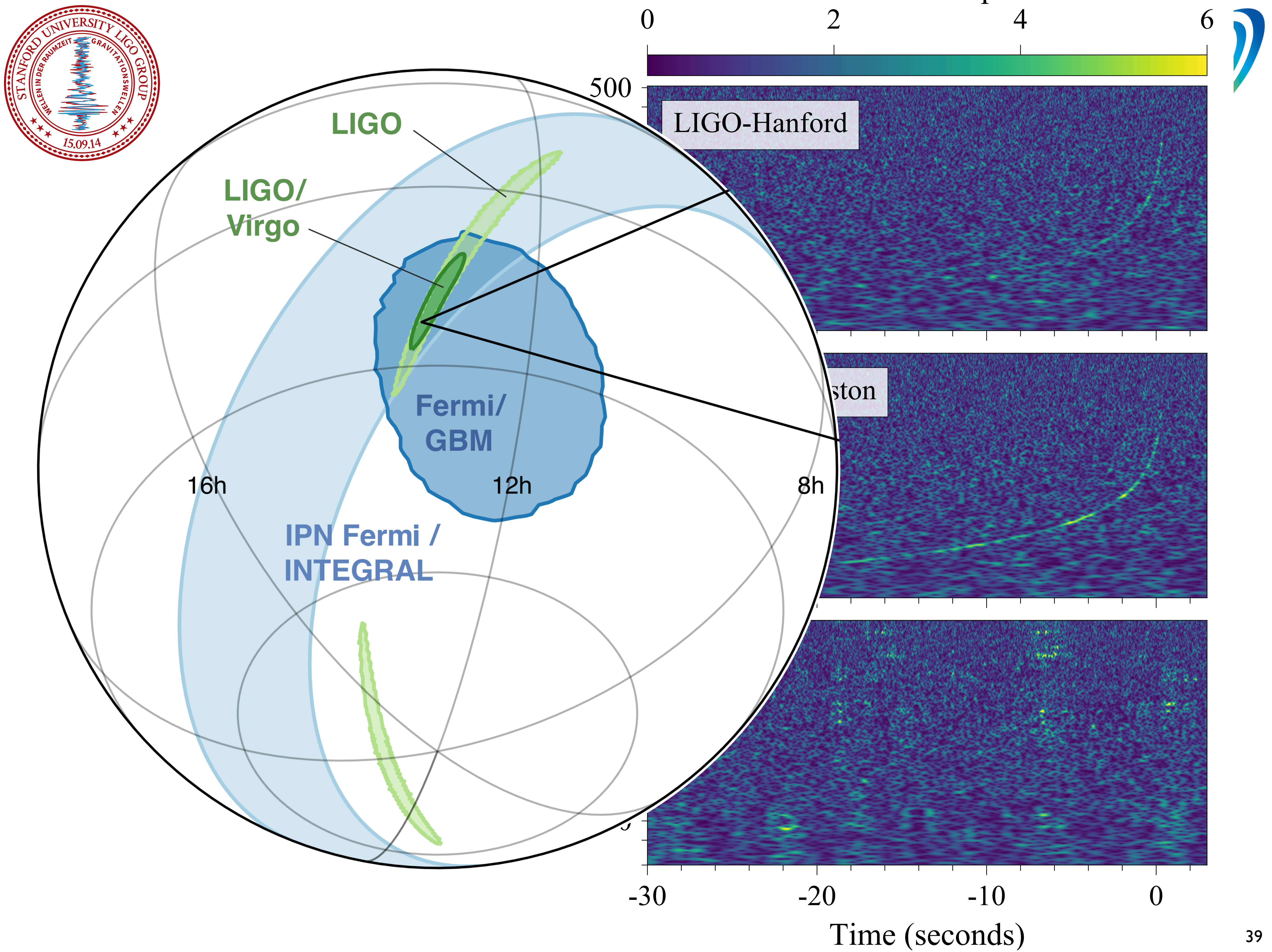
Neutron star & San Francisco
Supernova remnant
~1.4 solar masses

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



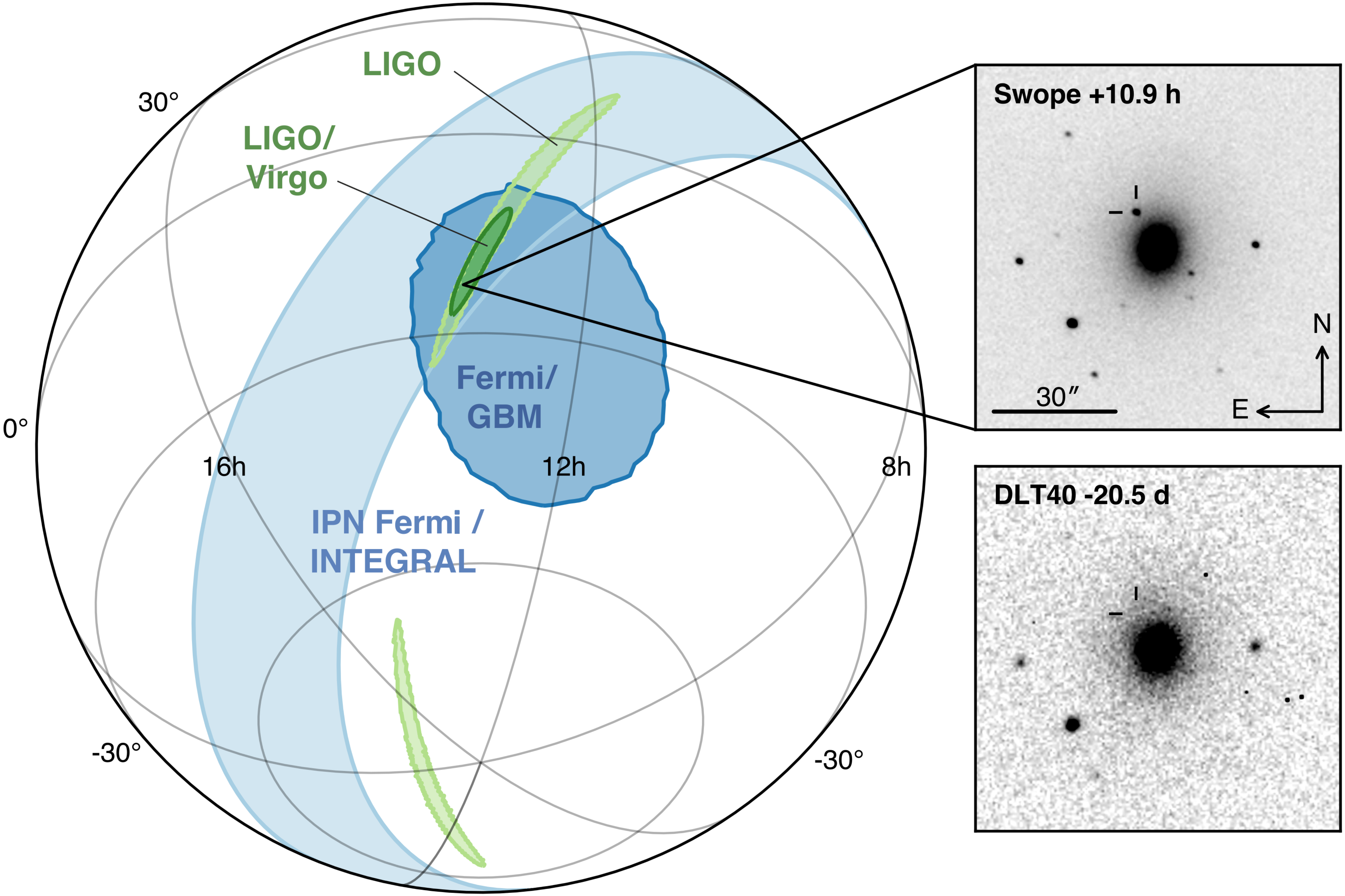
- LIGO software finds trigger in LHO data - 5:41:04 am Pacific time, August 17.
- LIGO realizes that Fermi GBM has triggered on event 1.7 seconds after GW merger.
- Thus, BNS mergers cause short gamma-ray bursts.
- Finally solving a mystery uncovered by Vela-4 in 1967. (as predicted by many).
- Forcing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





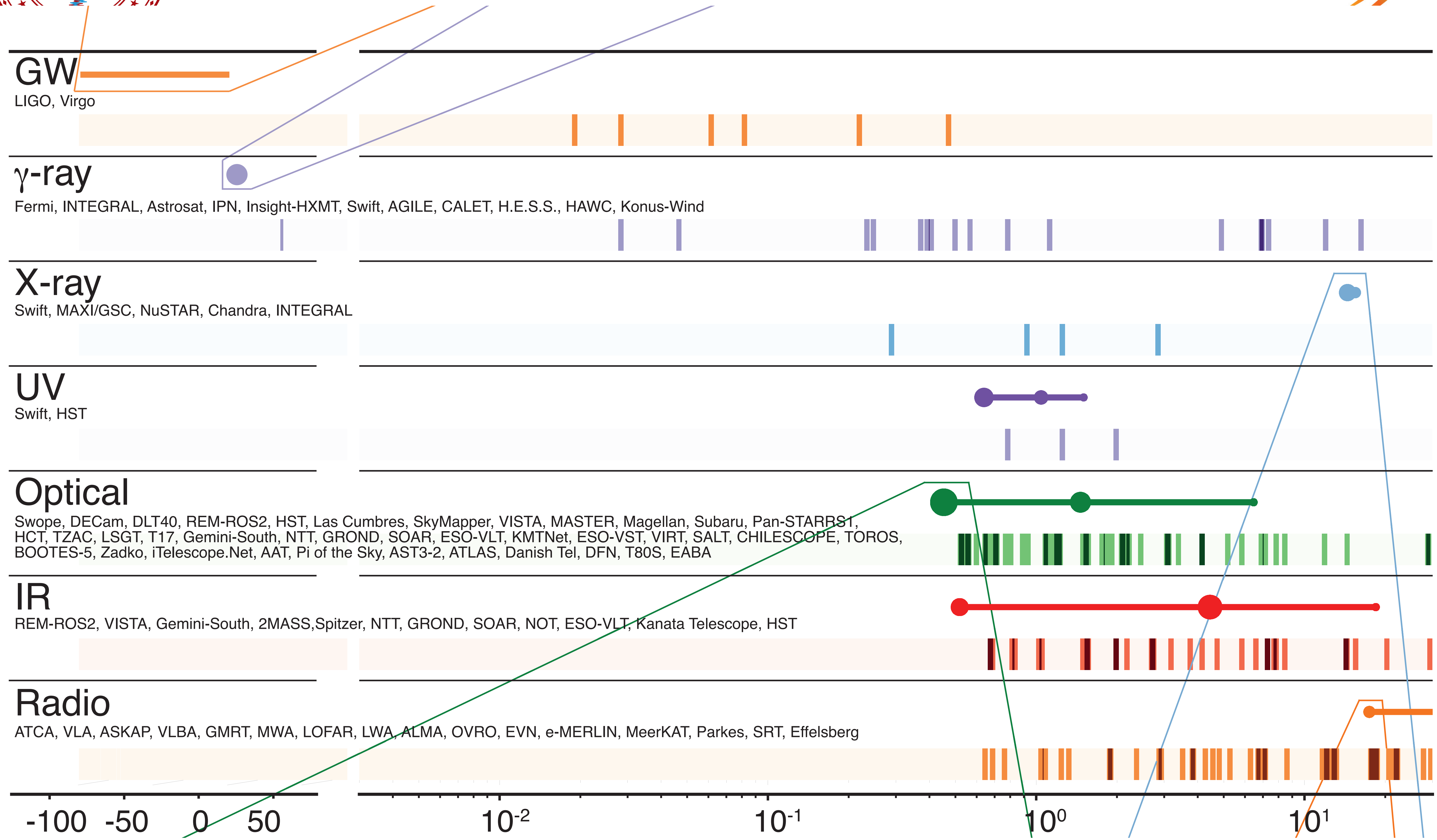
0
2
4
6
500
LIGO-Hanford
ston
LIGO
LIGO/
Virgo
Fermi/
GBM
16h
12h
8h
IPN Fermi /
INTEGRAL
-30
-20
-10
0
Time (seconds)

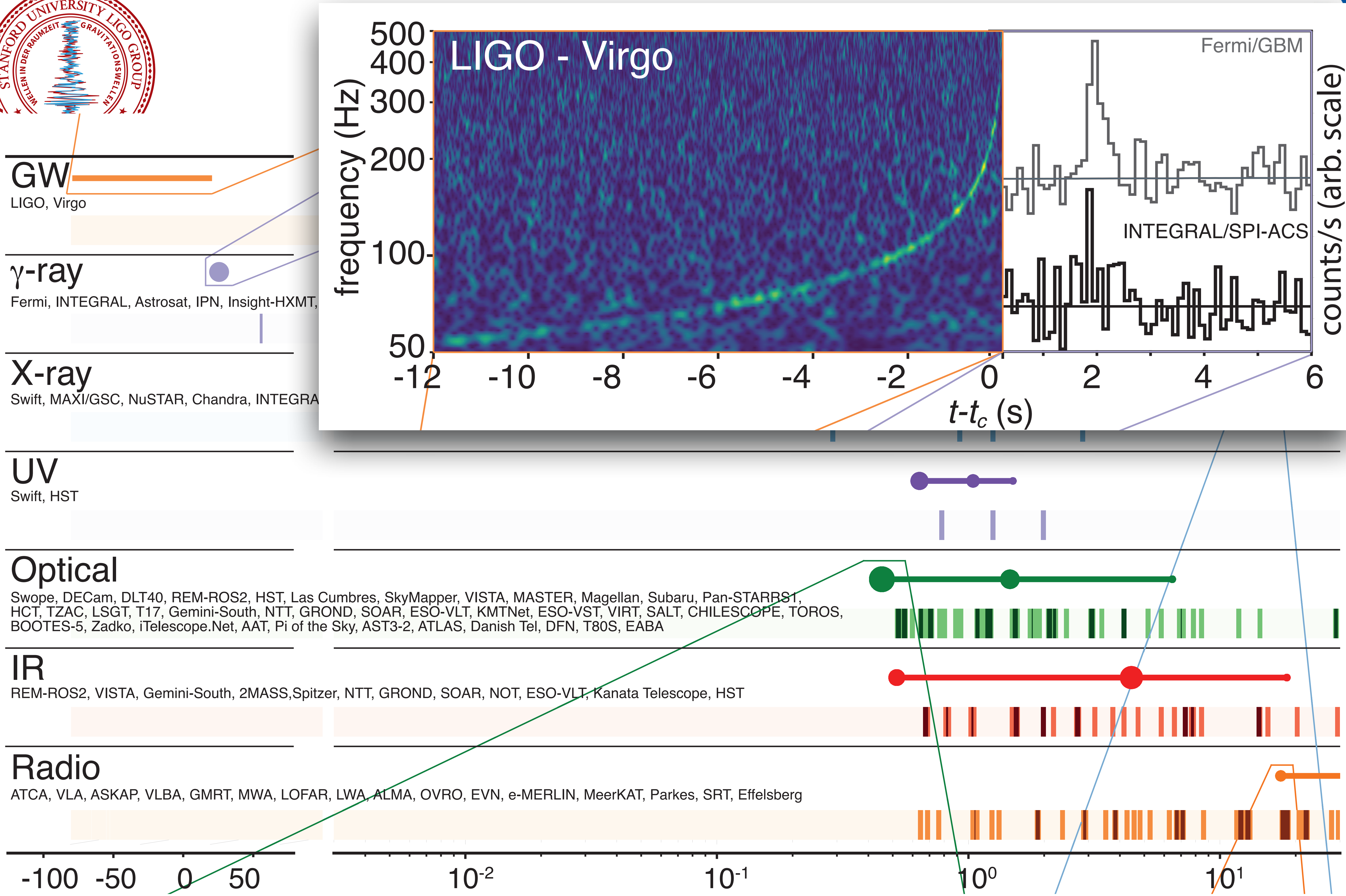
GW + GRB + Kilonova



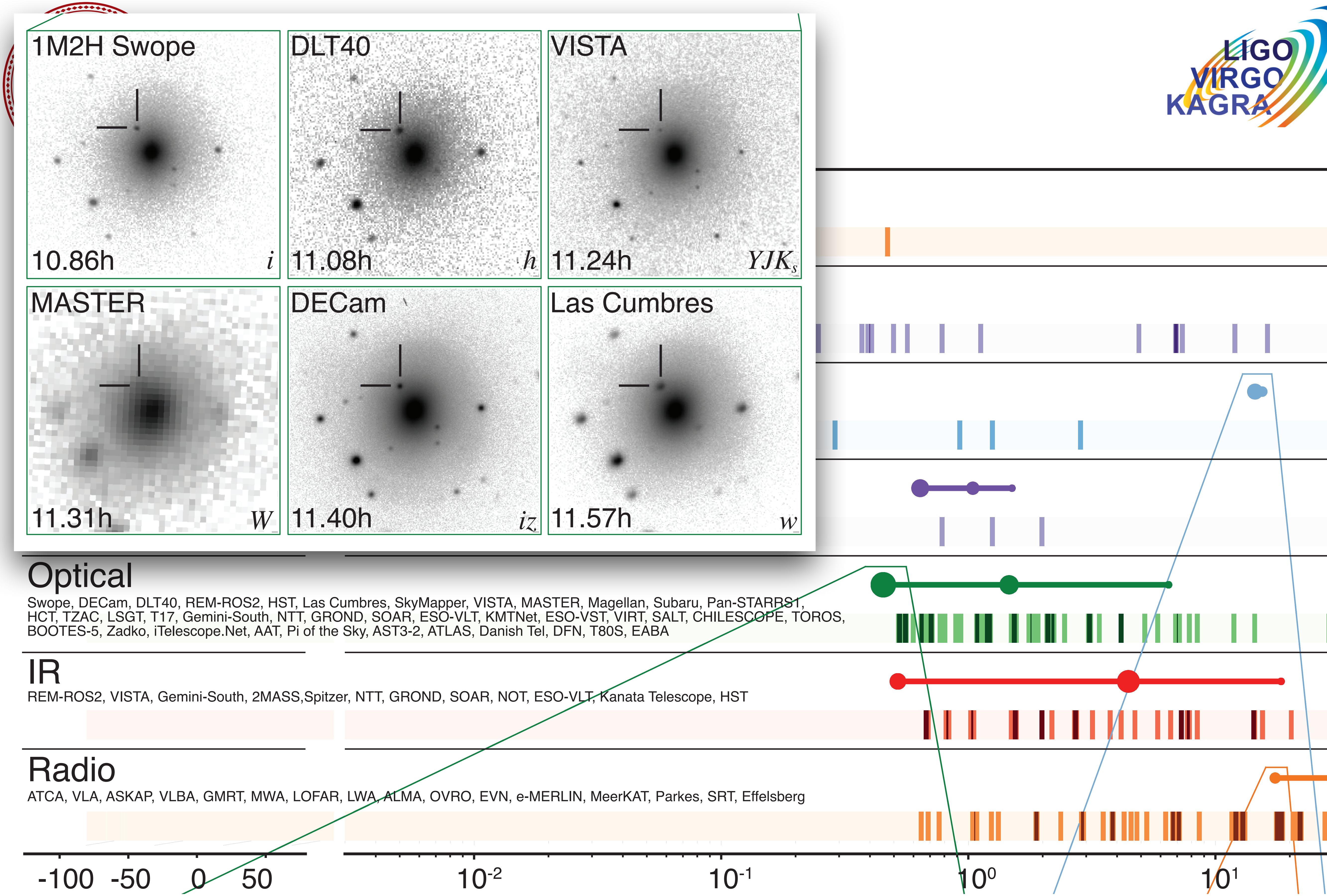
There is matter, and we can watch it

Amazing measurement set

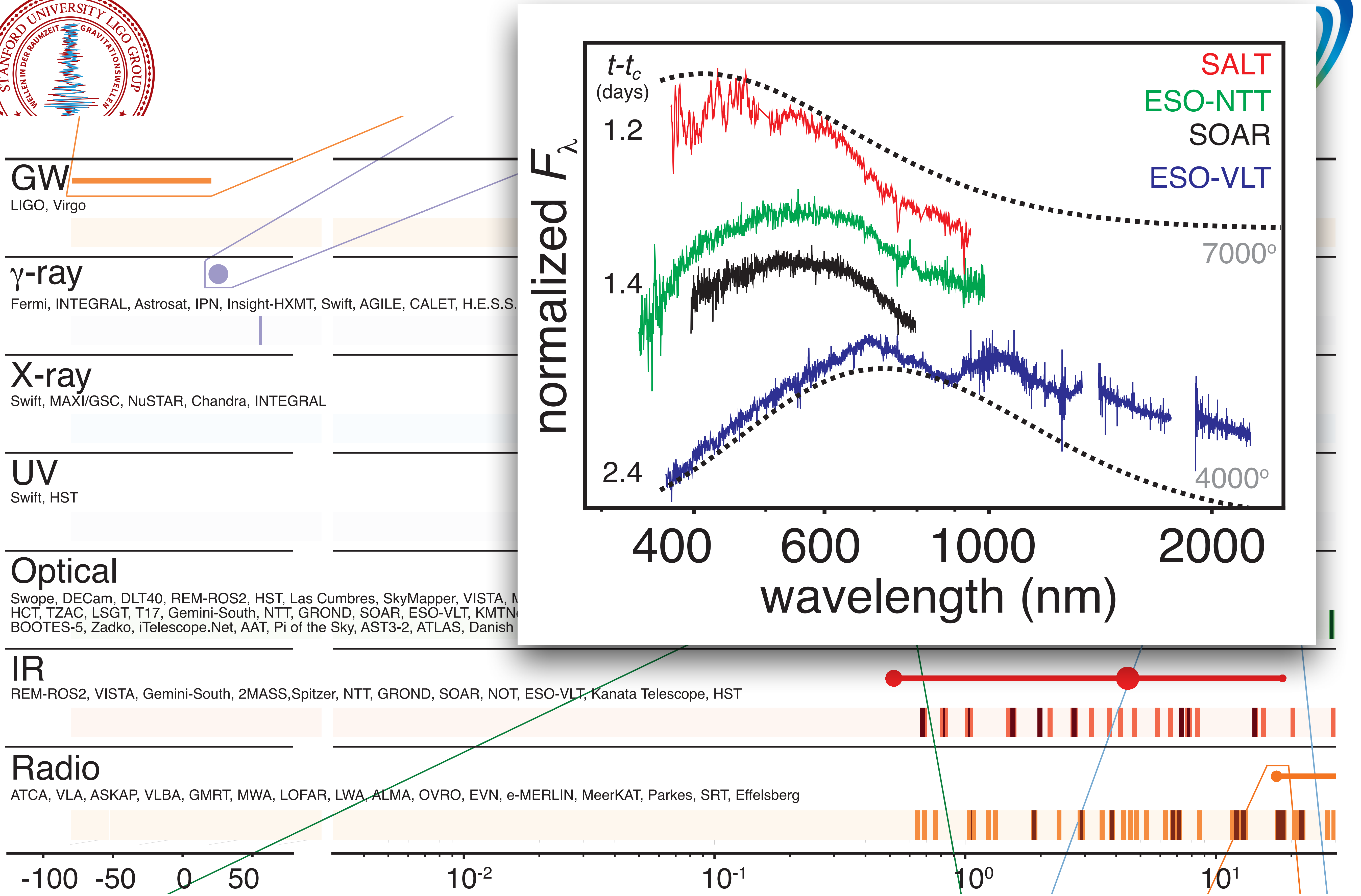




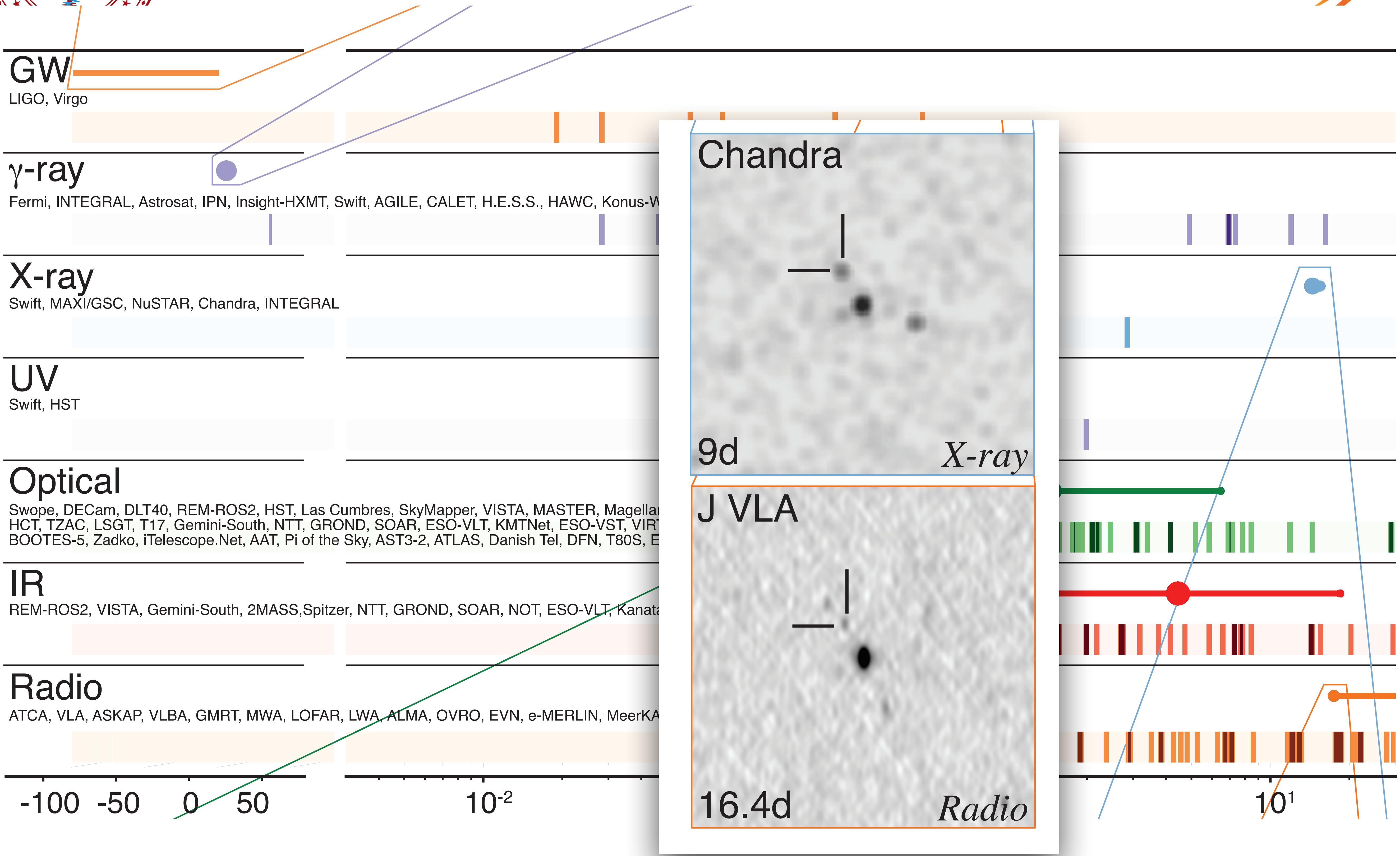
https://arxiv.org/abs/1710.05833



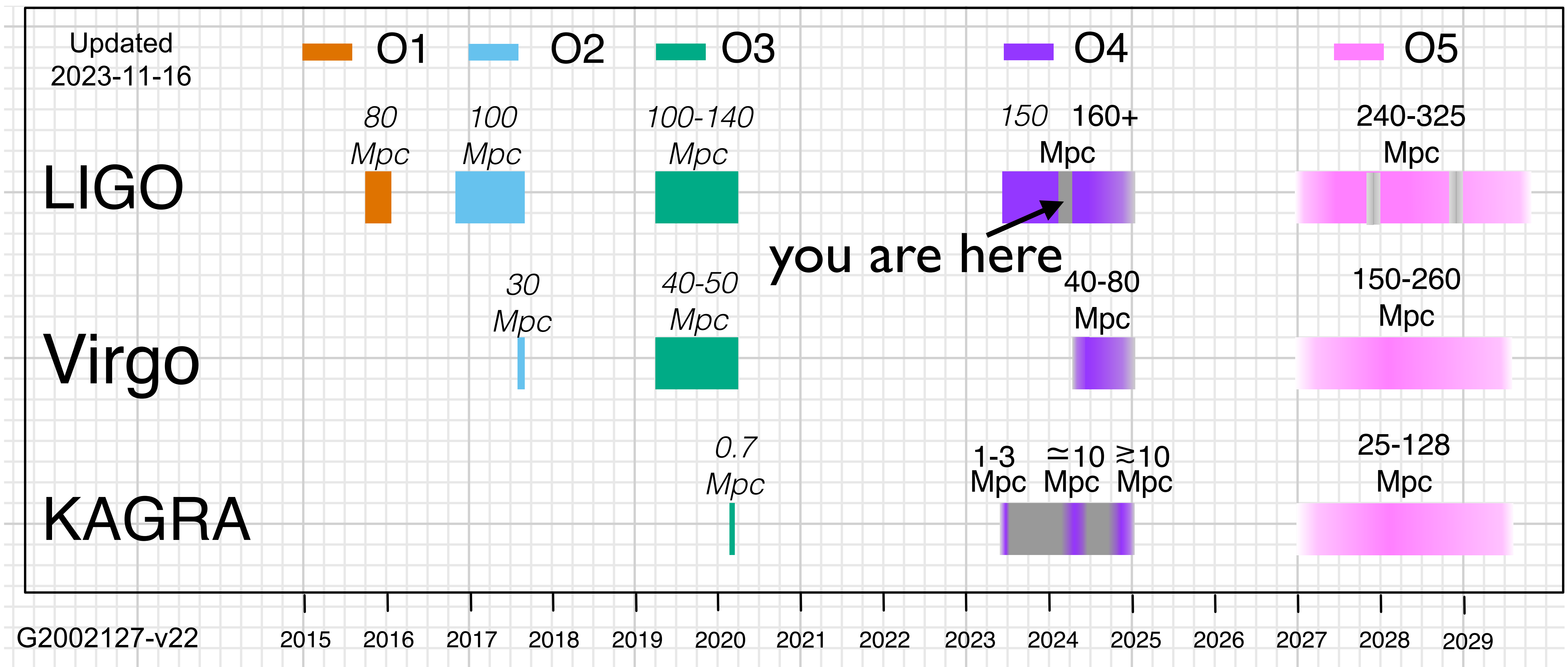
https://arxiv.org/abs/1710.05833



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
101
Chandra
9d
X-ray
J VLA
16.4d
Radio

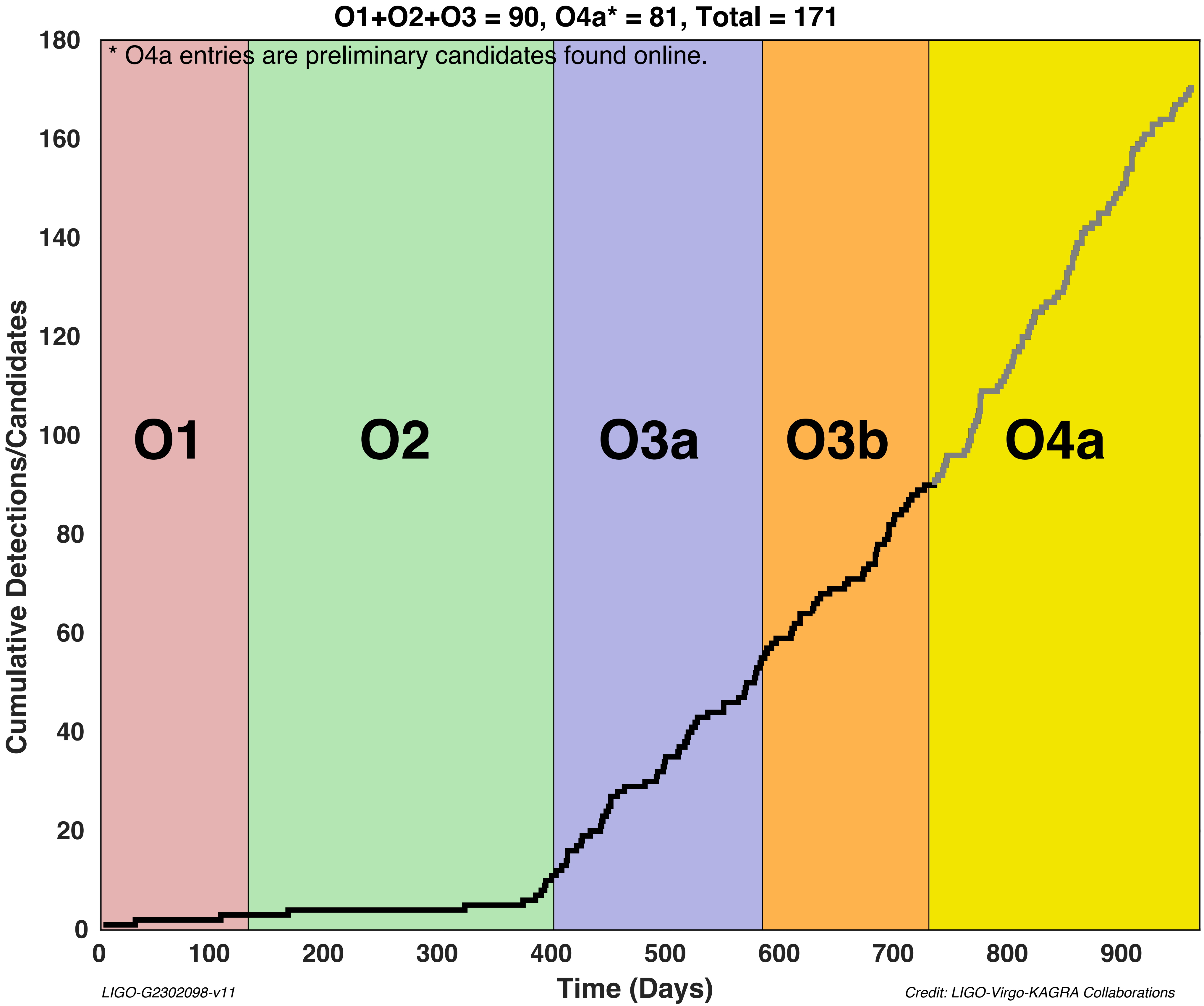
Where are we now?



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

Lots of Events!

Cumulative count of GW events



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)

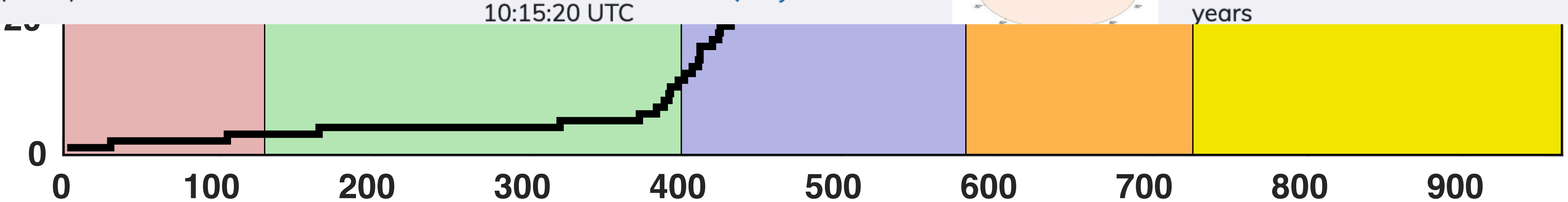
You can track these at https://gracedb.ligo.org/

Show All Public Events

Page 1 of 7. next last »

SORT: EVENT ID (A-Z) ▾

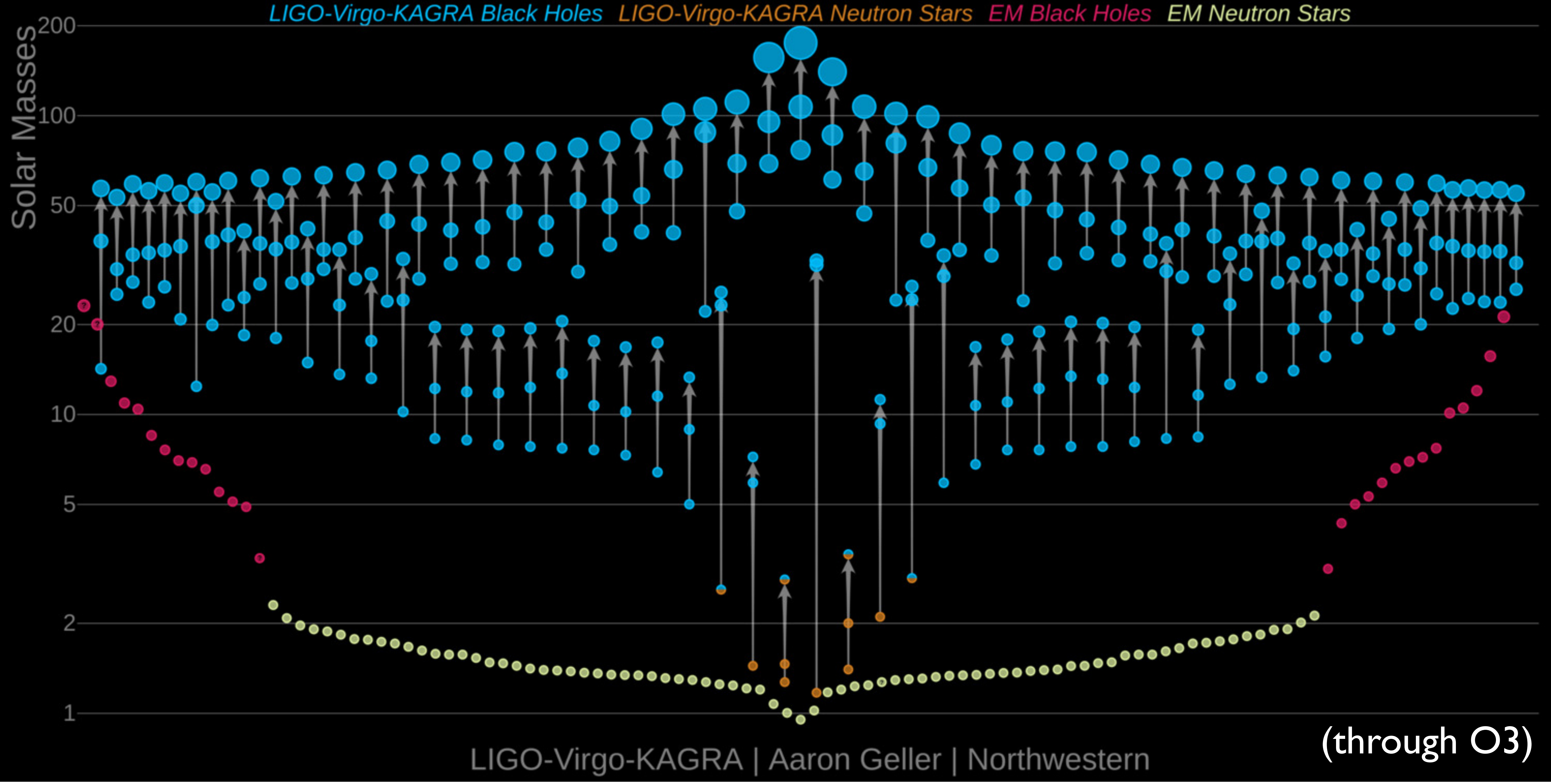
Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S240109a	BBH (99%)	Yes	Jan. 9, 2024 05:04:31 UTC	GCN Circular Query Notices | VOE		1 per 4.3136 years	
S240107b	BBH (97%), Terrestrial (3%)	Yes	Jan. 7, 2024 01:32:15 UTC	GCN Circular Query Notices | VOE		1.8411 per year	
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

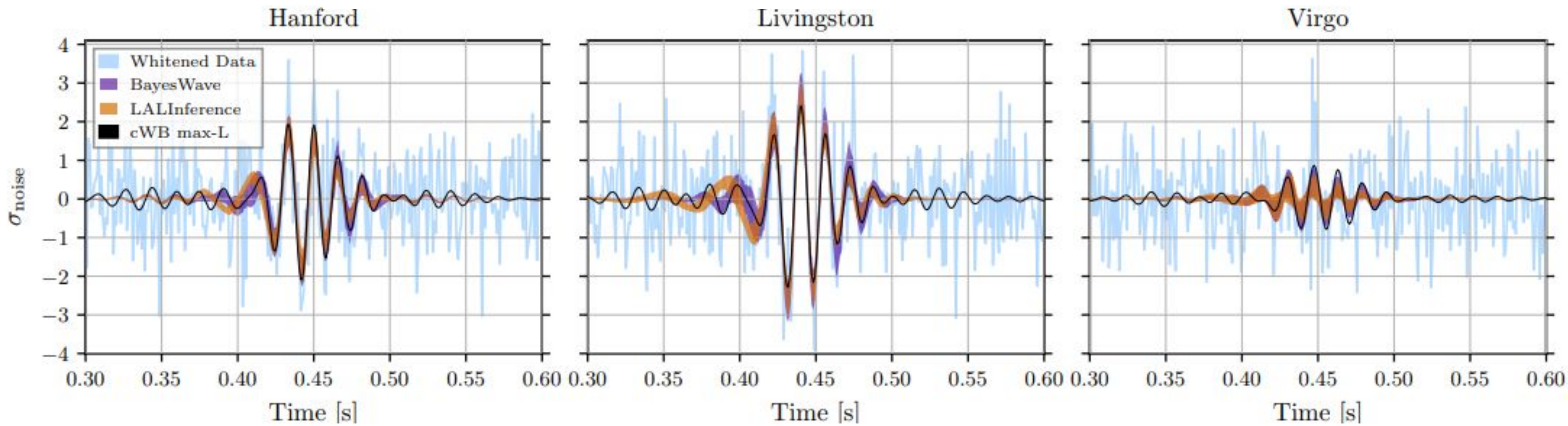


notable events

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)



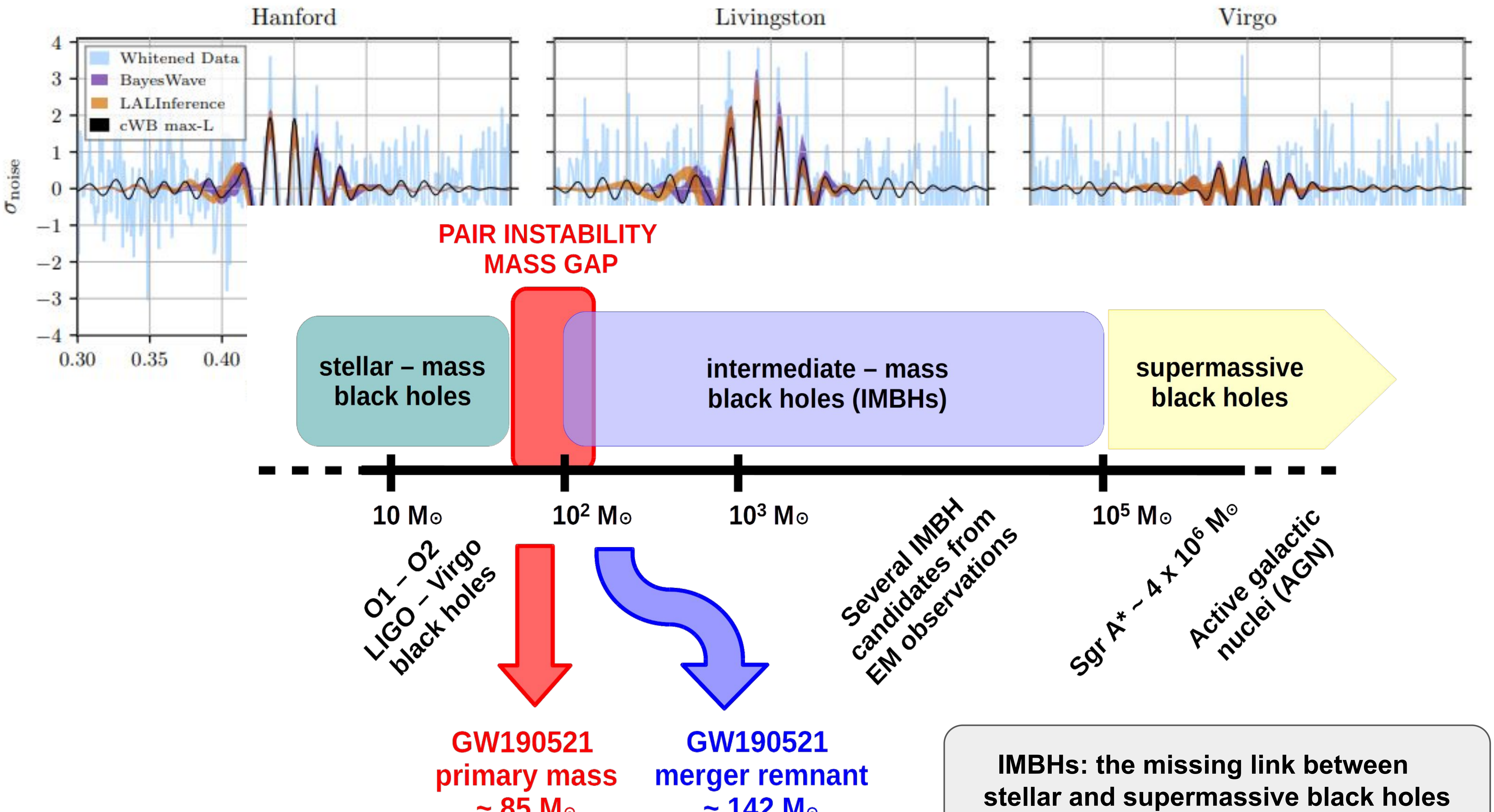
https://dcc.ligo.org/LIGO-G2001426/public

notable events

GW190521 - ~150 solar mass event

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

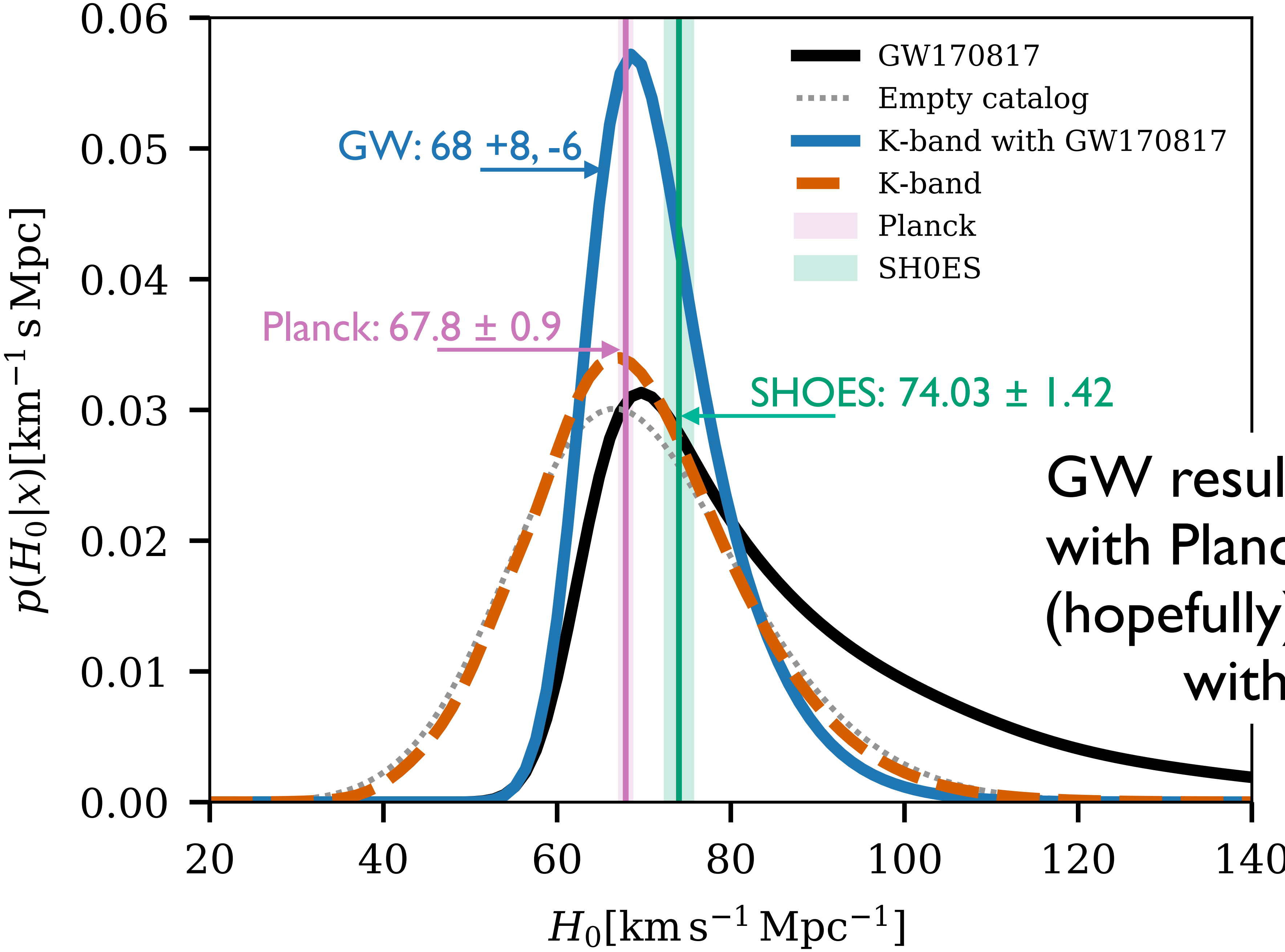
(1.7 GPc, 5 B lightyears)



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?!

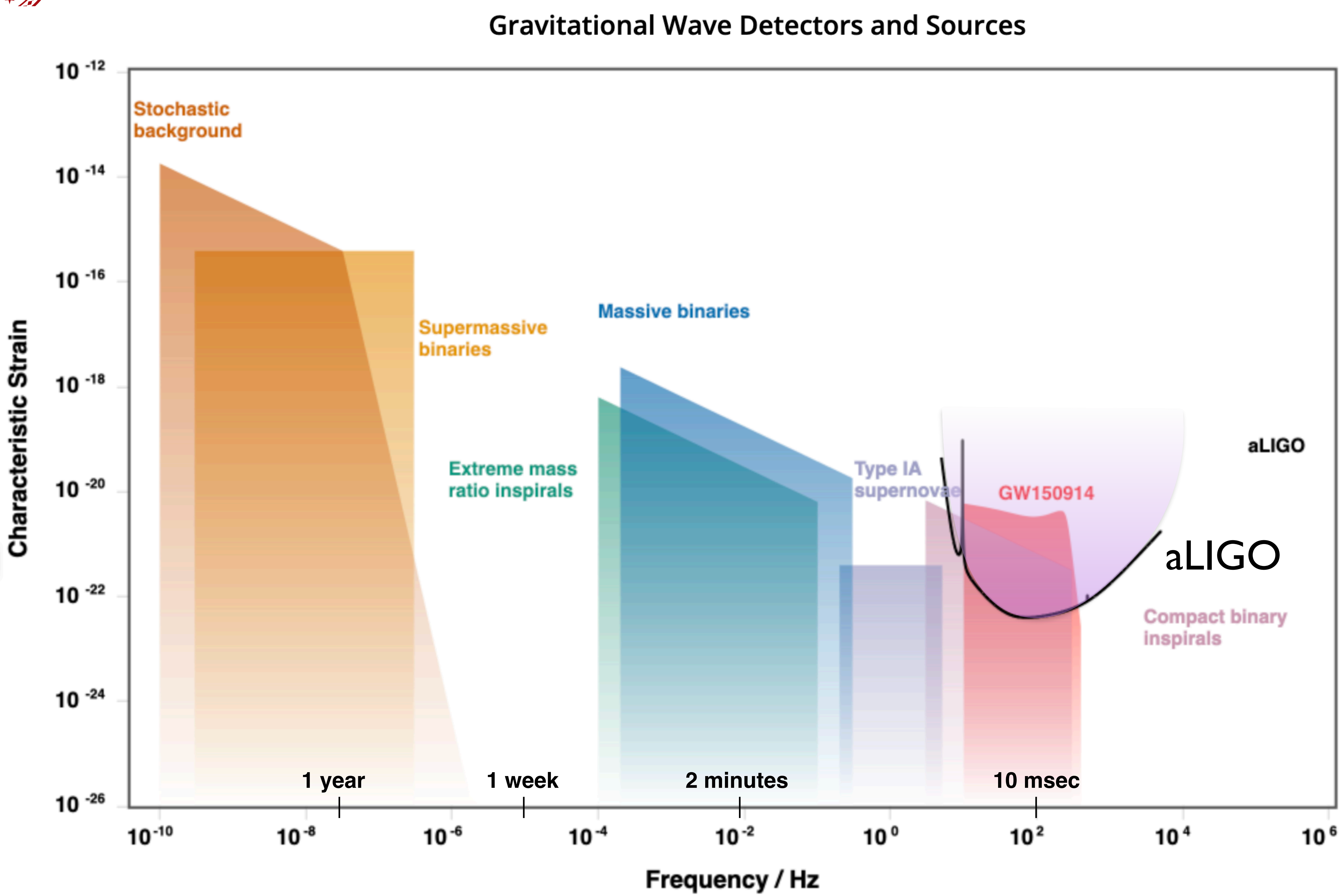


GW results still consistent with Planck & SHOES, but (hopefully) that will change with more data

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.

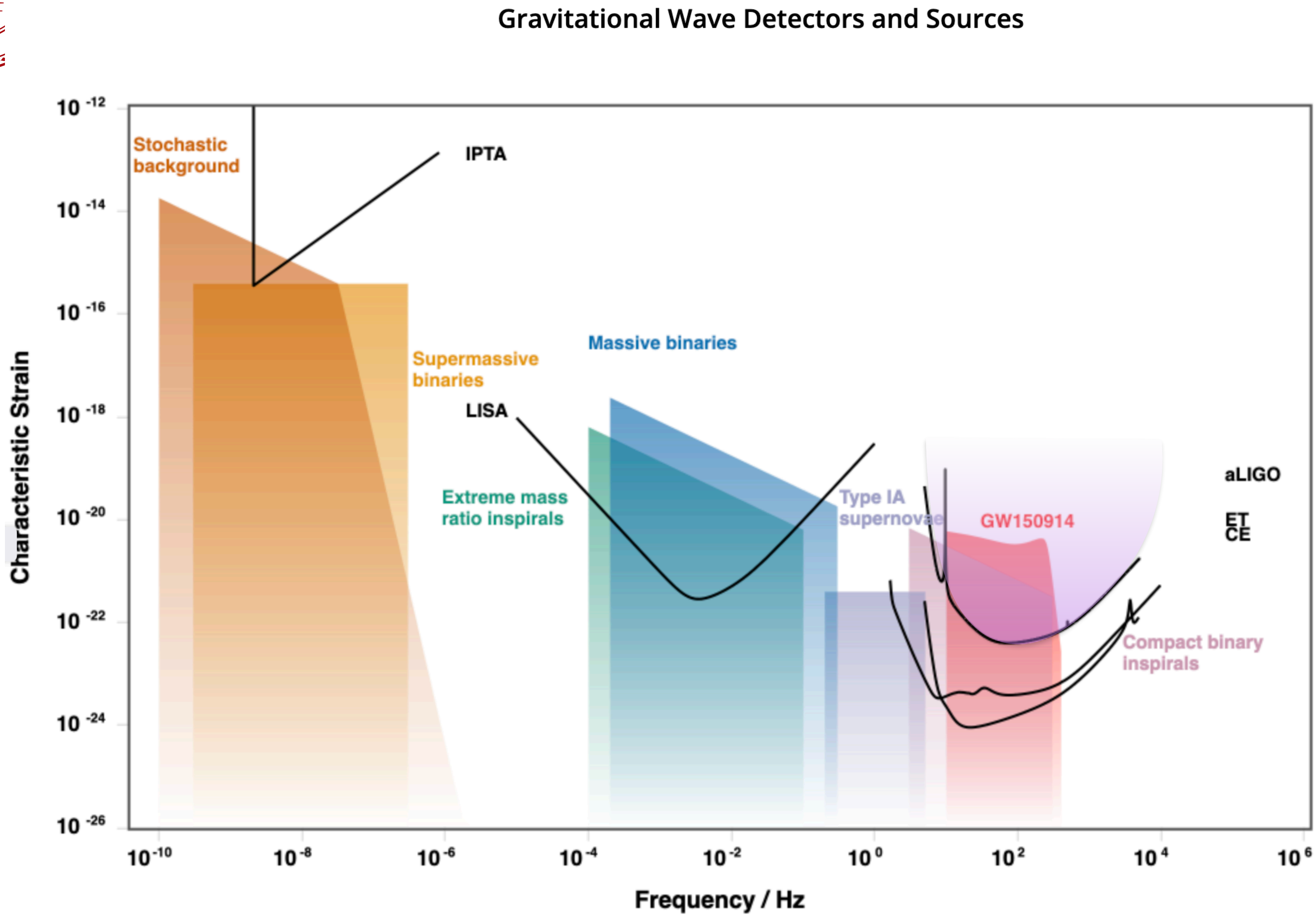
Constraints on the cosmic expansion history from GWTC–3, LVK author list, arXiv:2111.03604

There is so much more…

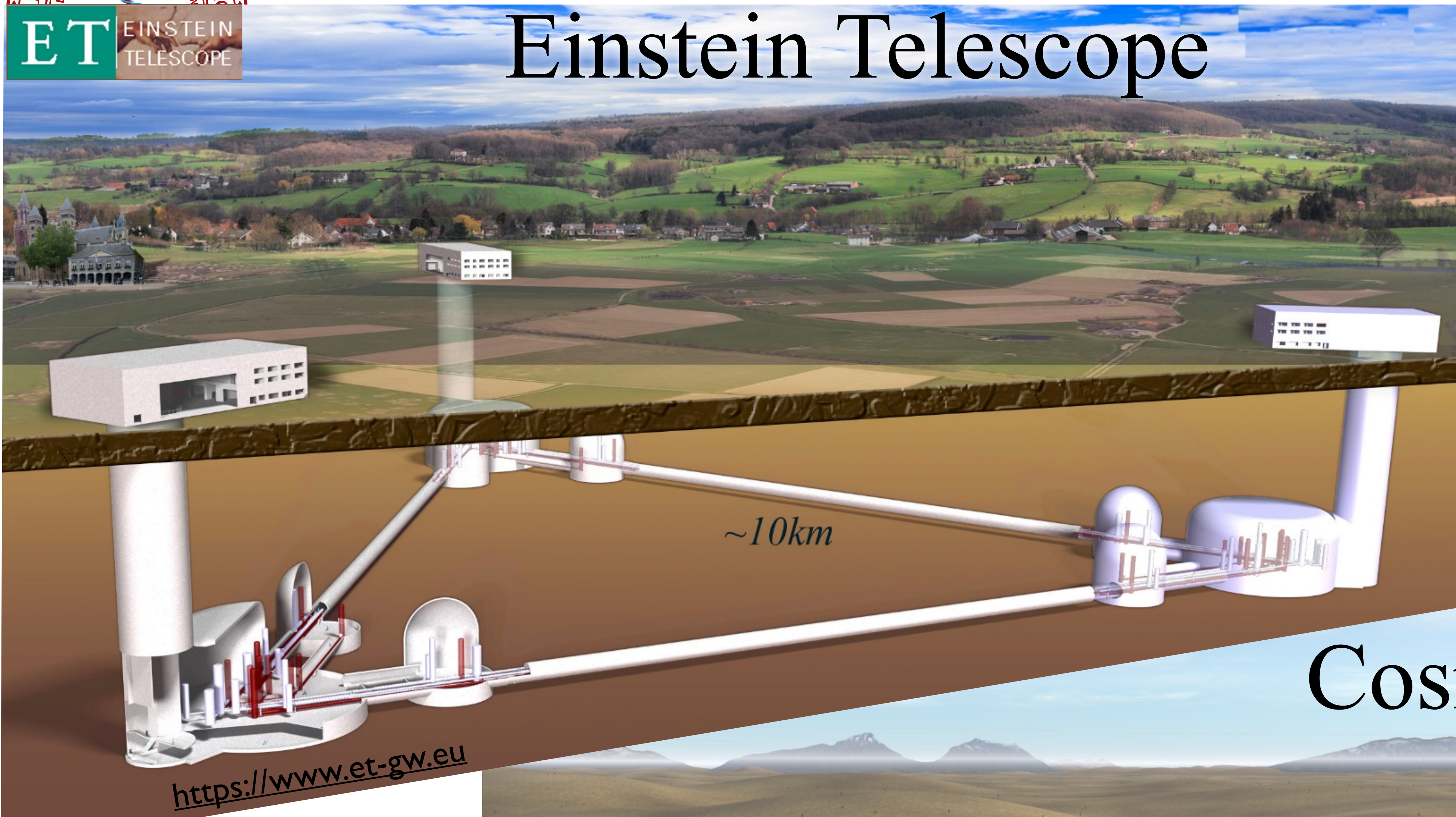


C. Moore et al, GWplotter.com

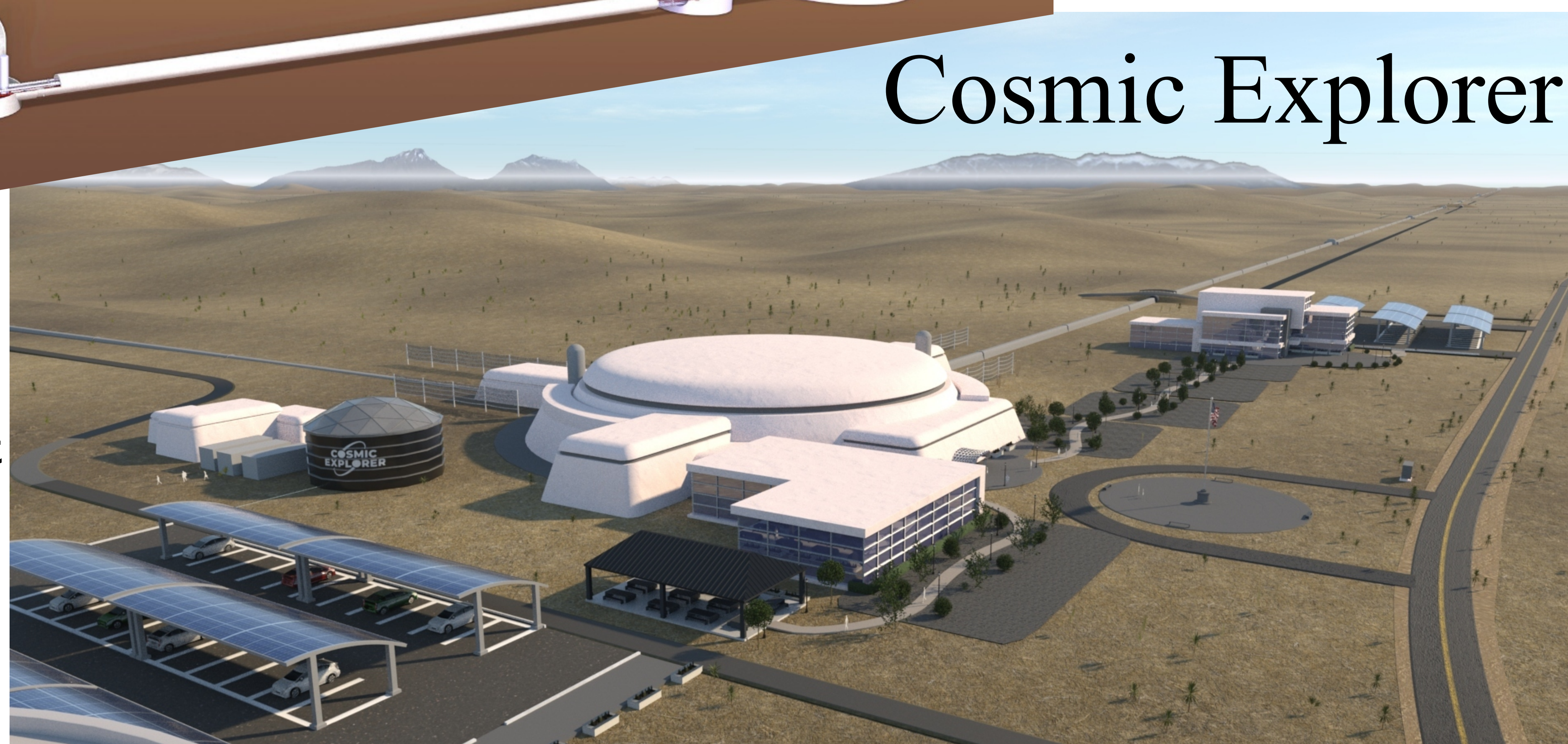
There is so much more…



3G detectors



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



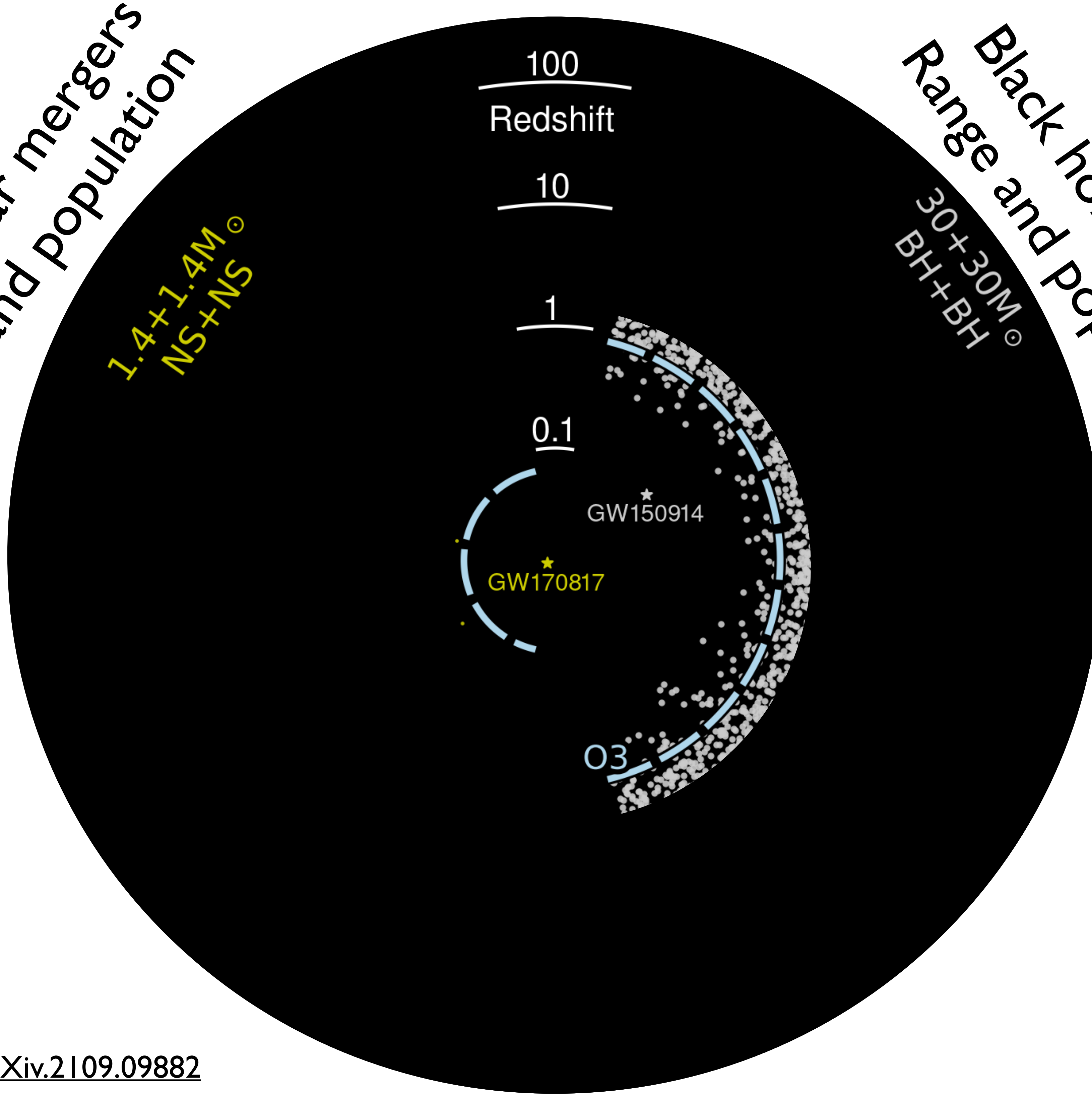
Artist's impression of a Cosmic Explorer observatory. (Credit: Angela Nguyen, Virginia Kitchen, Eddie Anaya, California State University Fullerton) https://cosmicexplorer.org/img/local/Overview3_V2.jpg

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

Science w/ Einstein Telescope & Cosmic Explorer

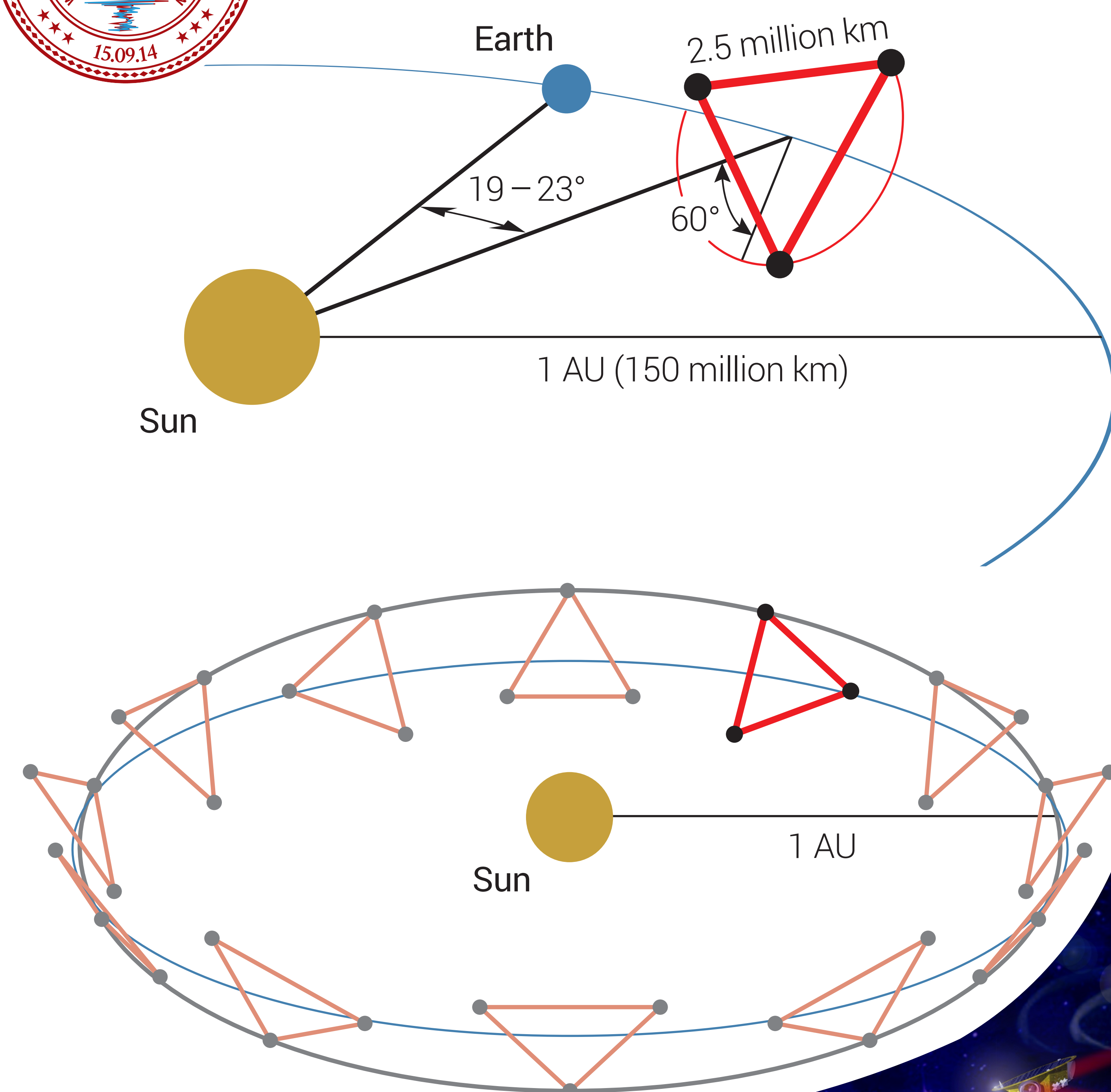
Neutron star mergers
Range and population

Black hole mergers
Range and population

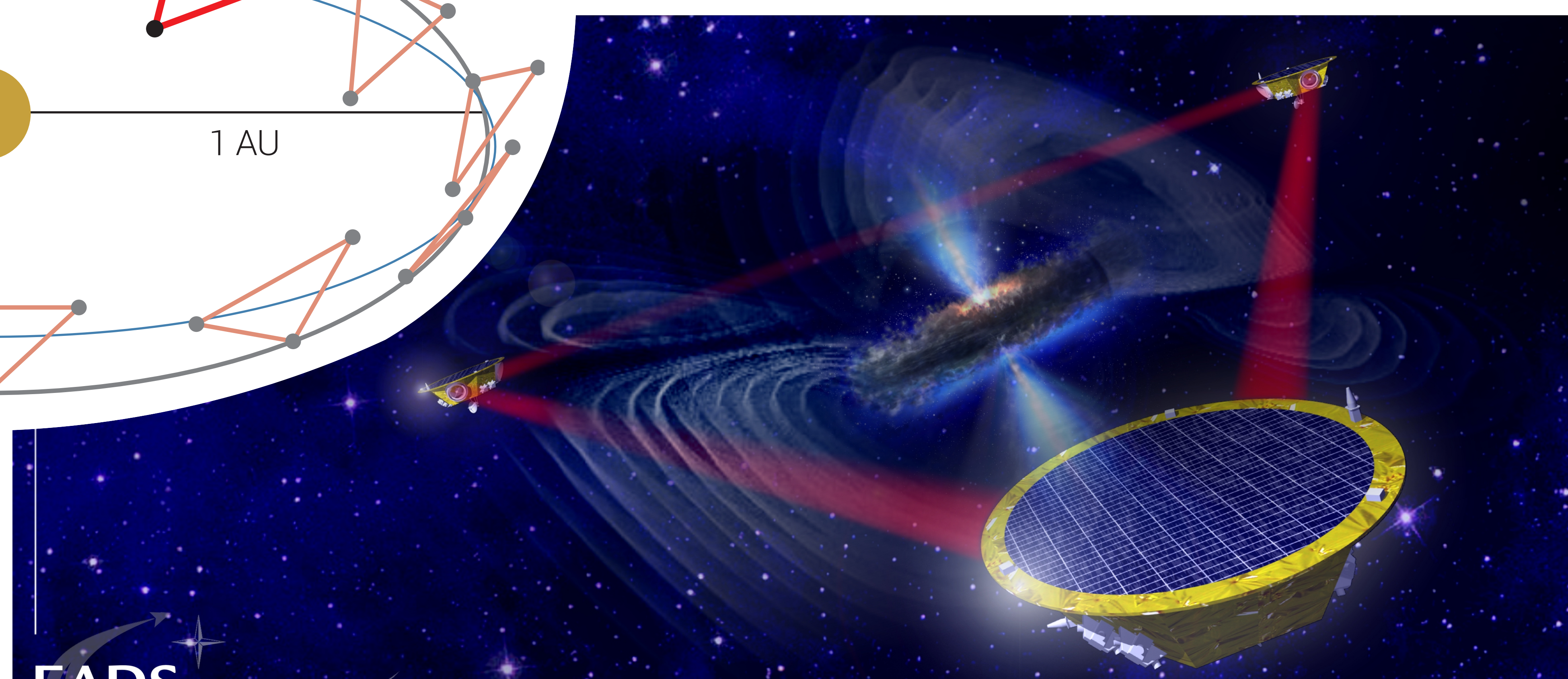


https://doi.org/10.48550/arXiv.2109.09882

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!

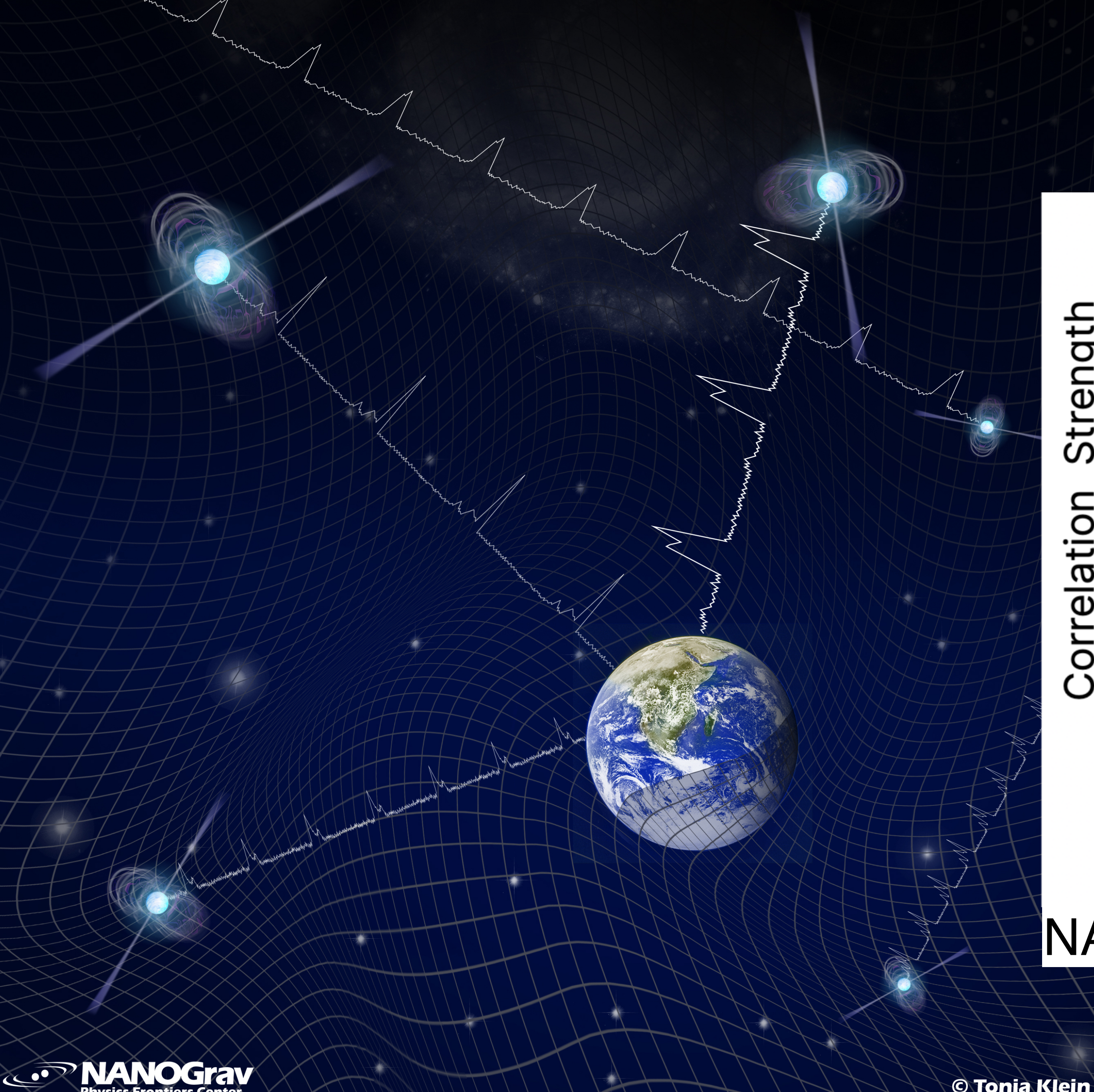
Measure correlations

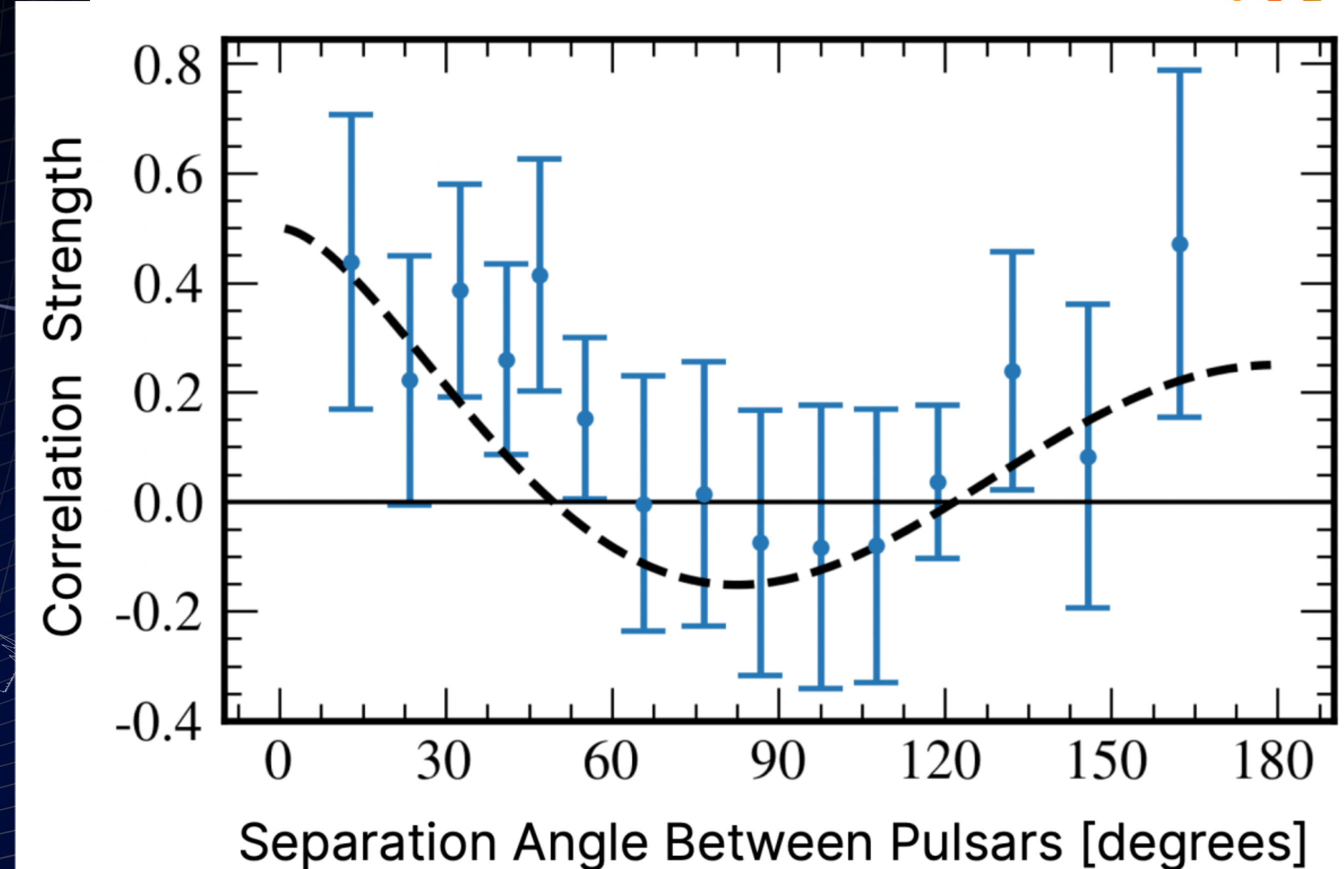
NANOgrav (USA) uses 68 pulsars

https://nanograv.org

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

Pulsar timing

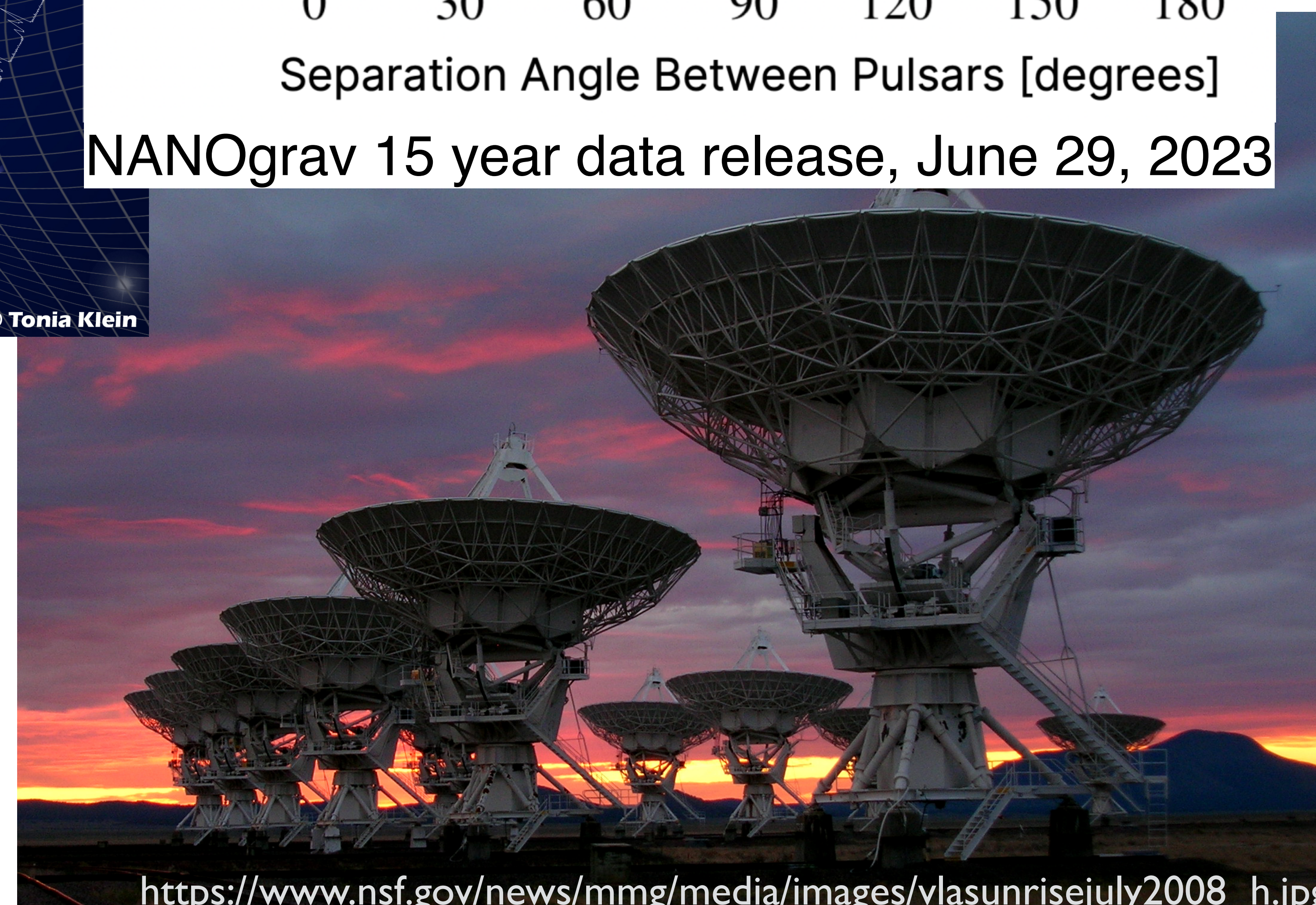




NANOgrav 15 year data release, June 29, 2023

NANOgrav (USA) uses 68 pulsars

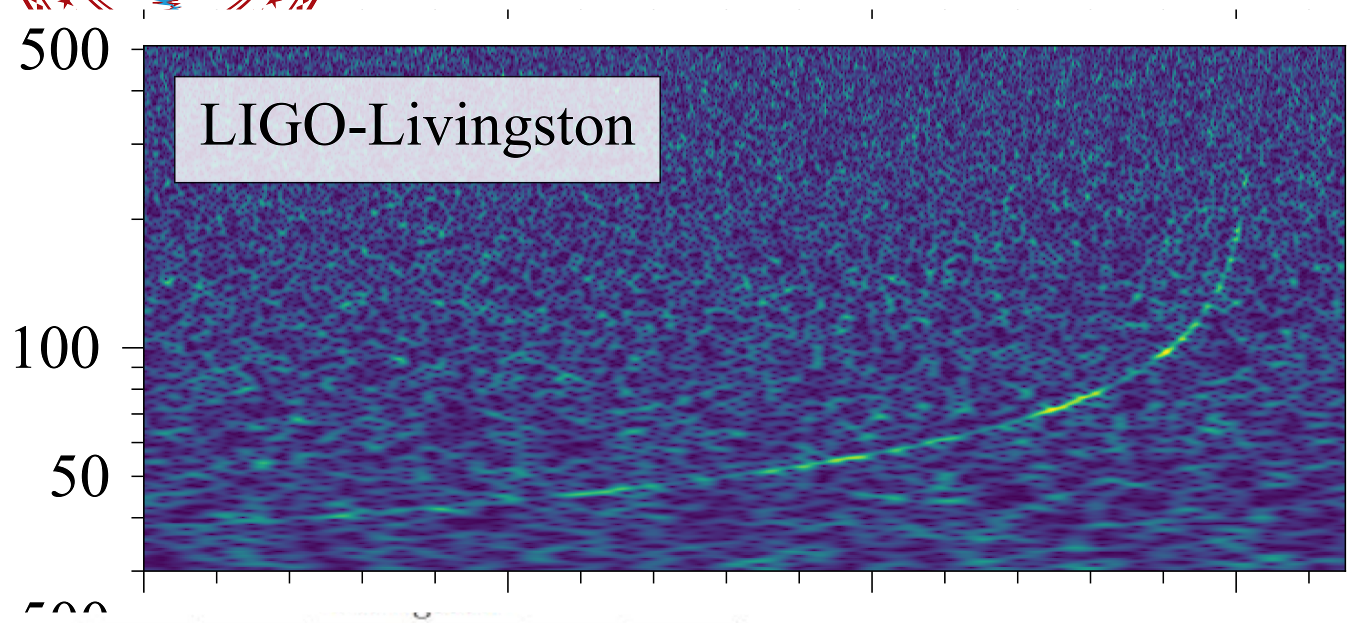
also PPTA, EPTA, InPTA, CPTA, MPTA
IPTA (International PTA)

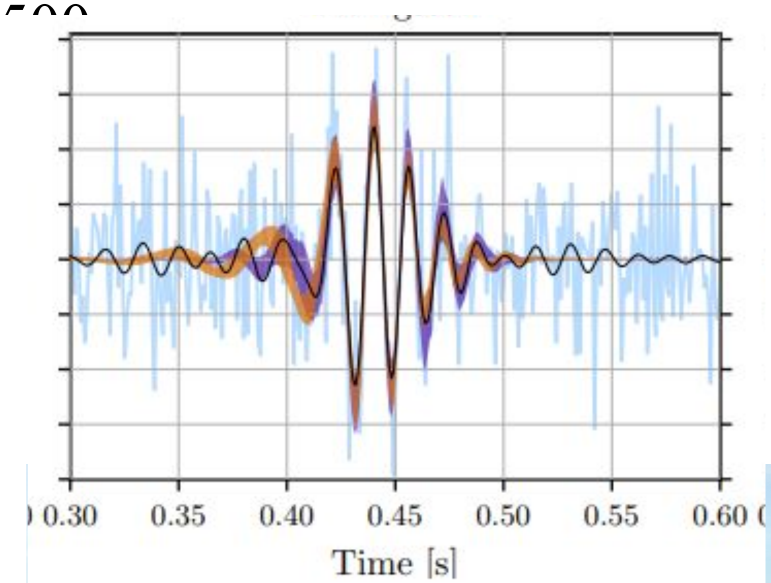


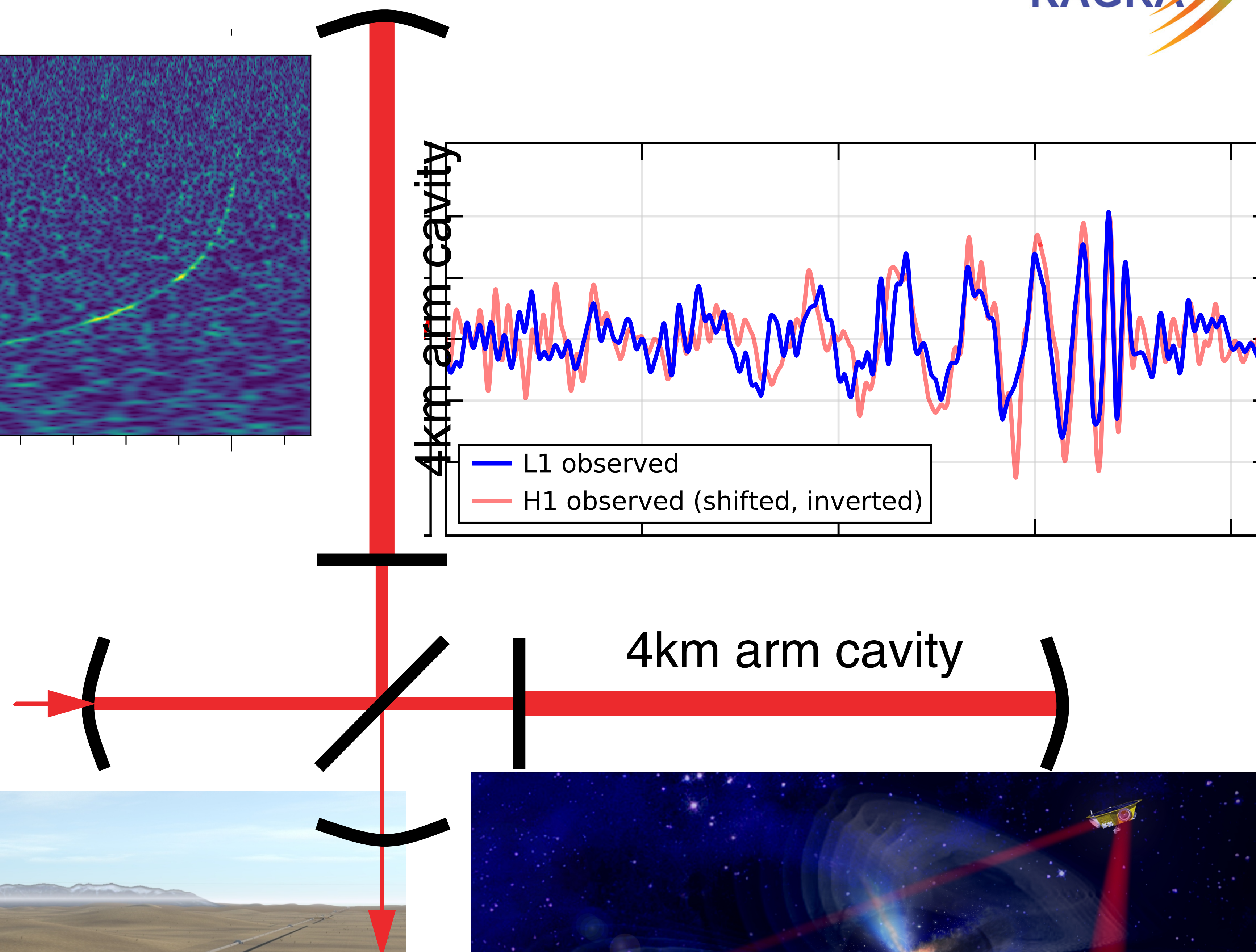
https://nanograv.org

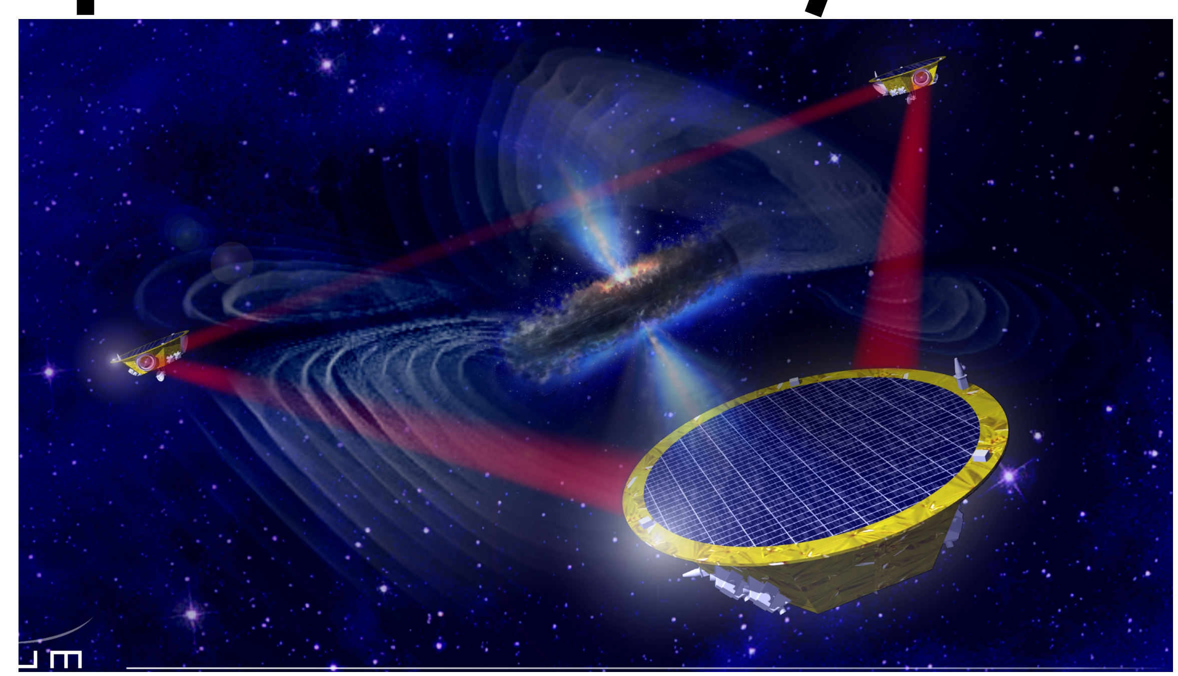
https://www.nsf.gov/news/mmg/media/images/vlasunrisejuly2008_h.jpg

It’s an exciting time!





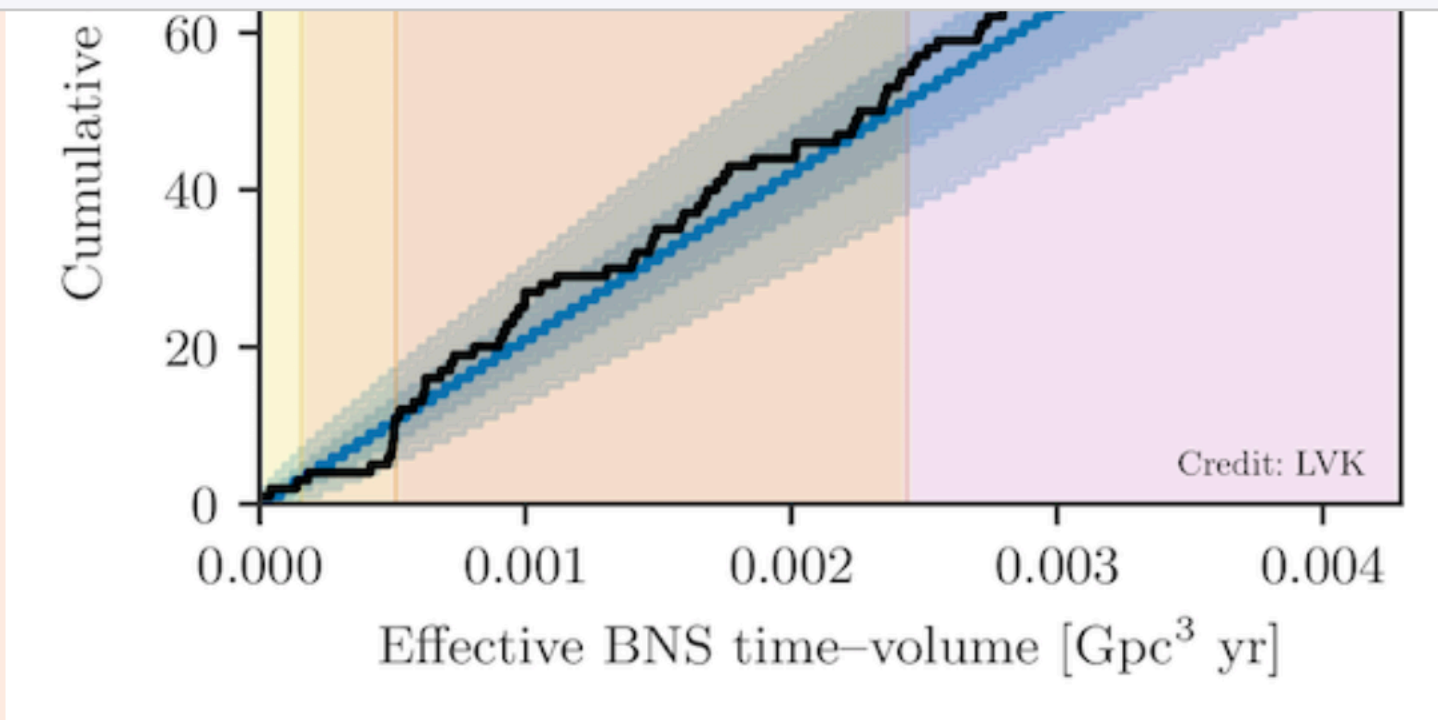




download the slides?

slides are at LIGO's Document Control Center
https://dcc.ligo.org/public/G2400231

https://dcc.ligo.org/public/ 90%



Detection Publications

Search for Documents by

Author: Lantz, Brian ← Lantz, Brian

Identifier: LIGO-G2400231 ← G2400231

Changes in the last 2 days

Google Search

*(Hit **Enter** or click search button on google page)*

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/

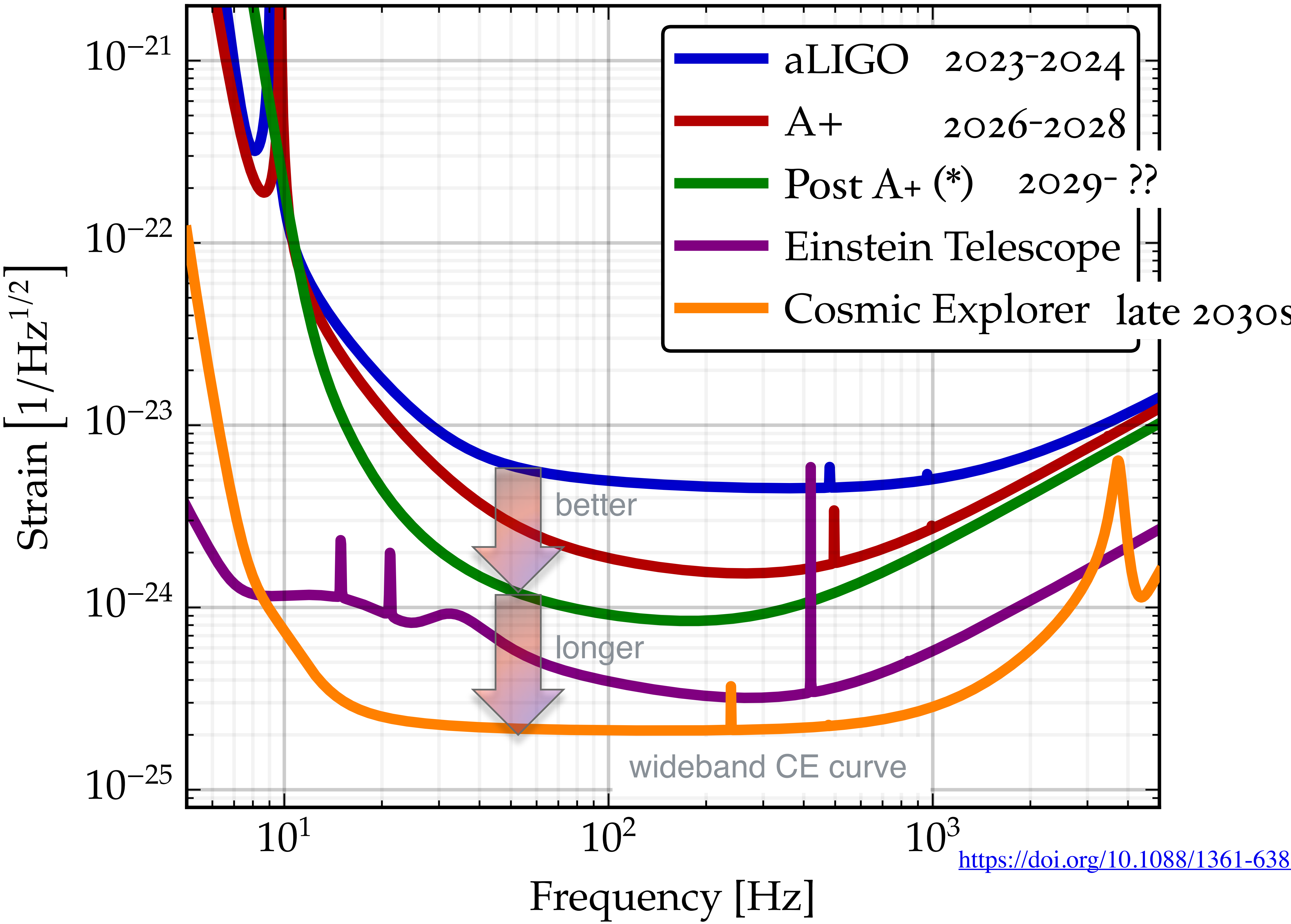
Stanford group homepage
https://ligo.stanford.edu/

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/

3G detectors



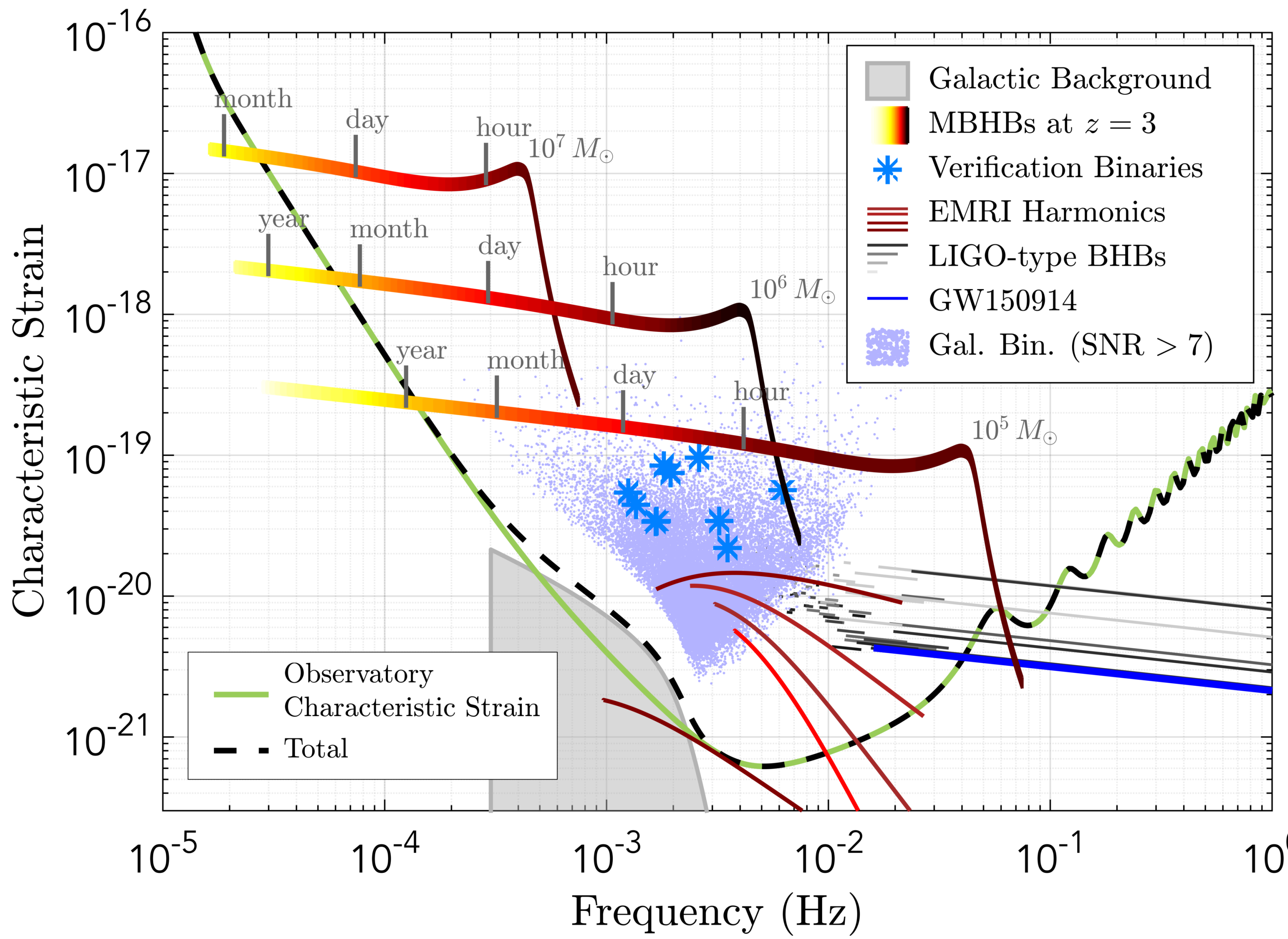
https://doi.org/10.1088/1361-6382/aa51f4

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

LISA Science

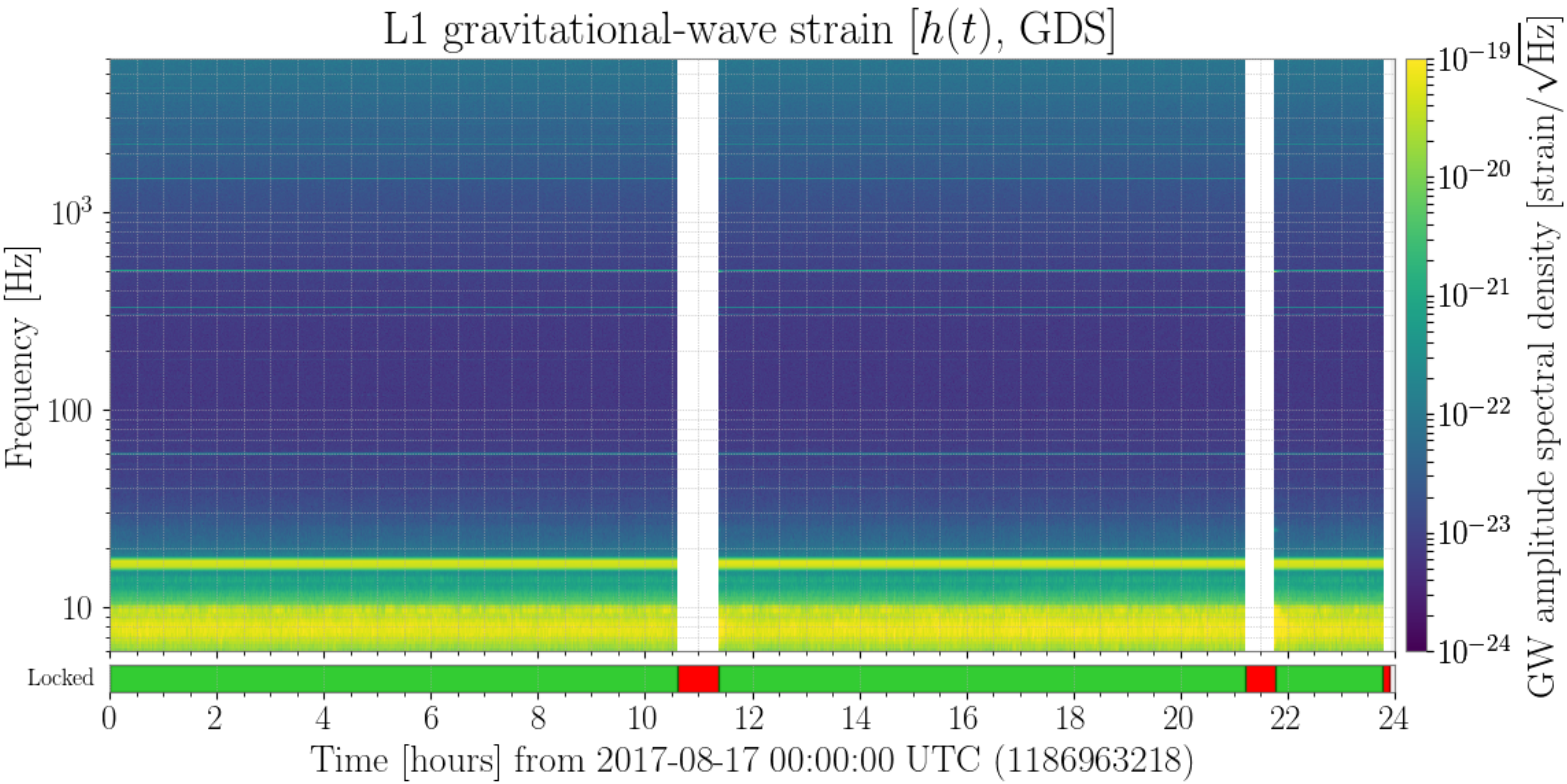
LISA will see lots of new sources

- 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…



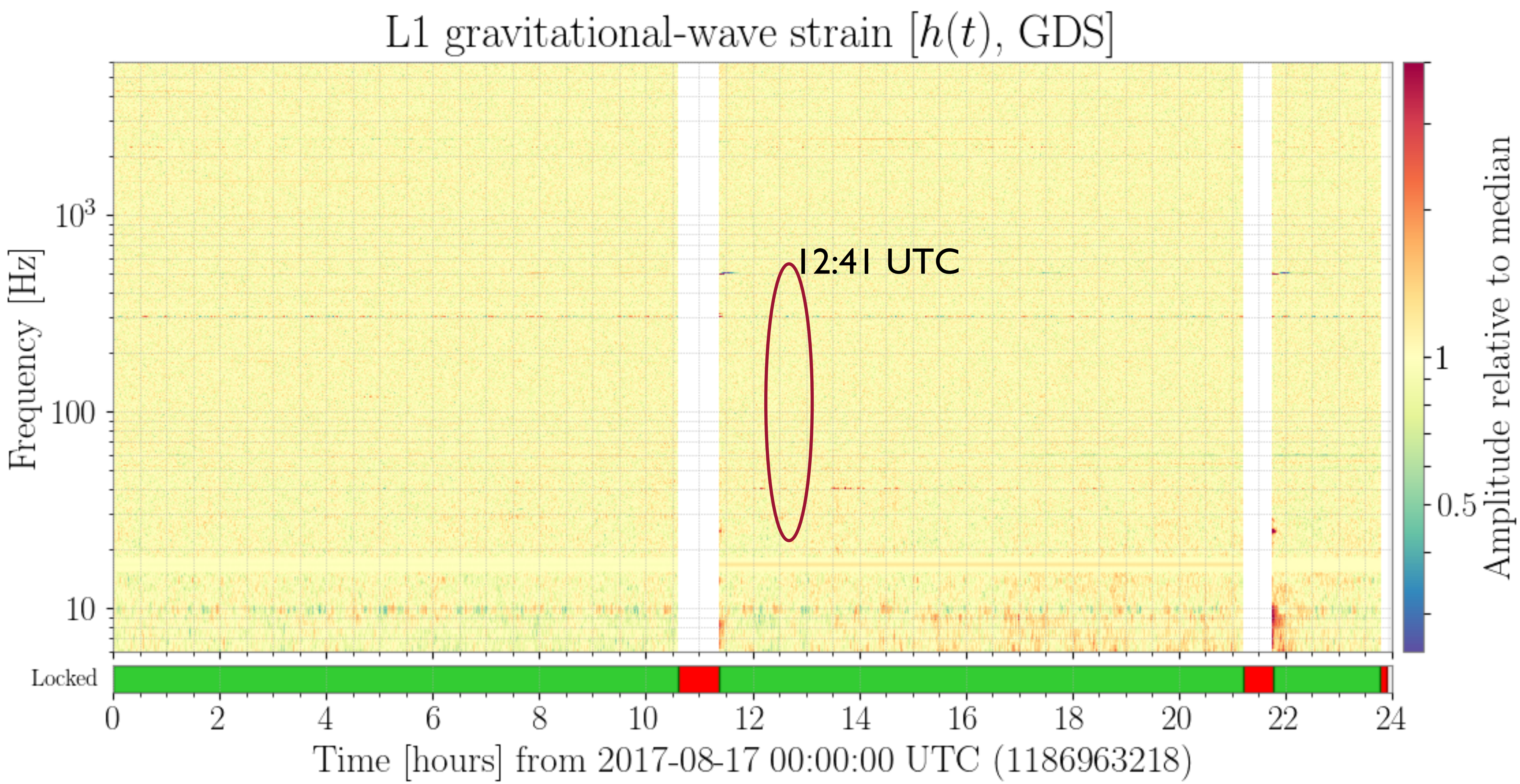
Watch for changes…

Spectrogram - 1 day at LLO

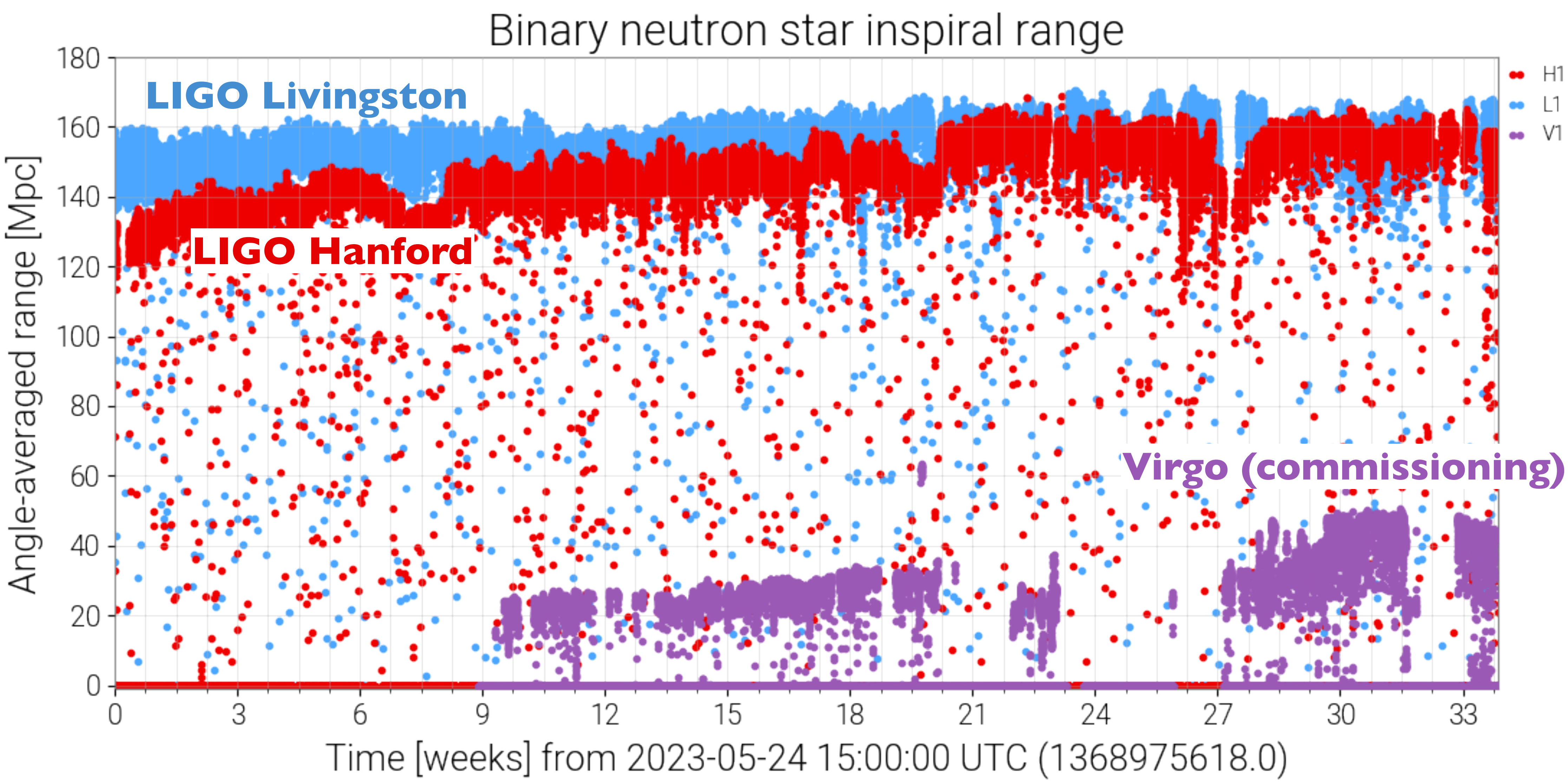


Watch for changes…

Normalized Spectrogram - 1 day at LLO



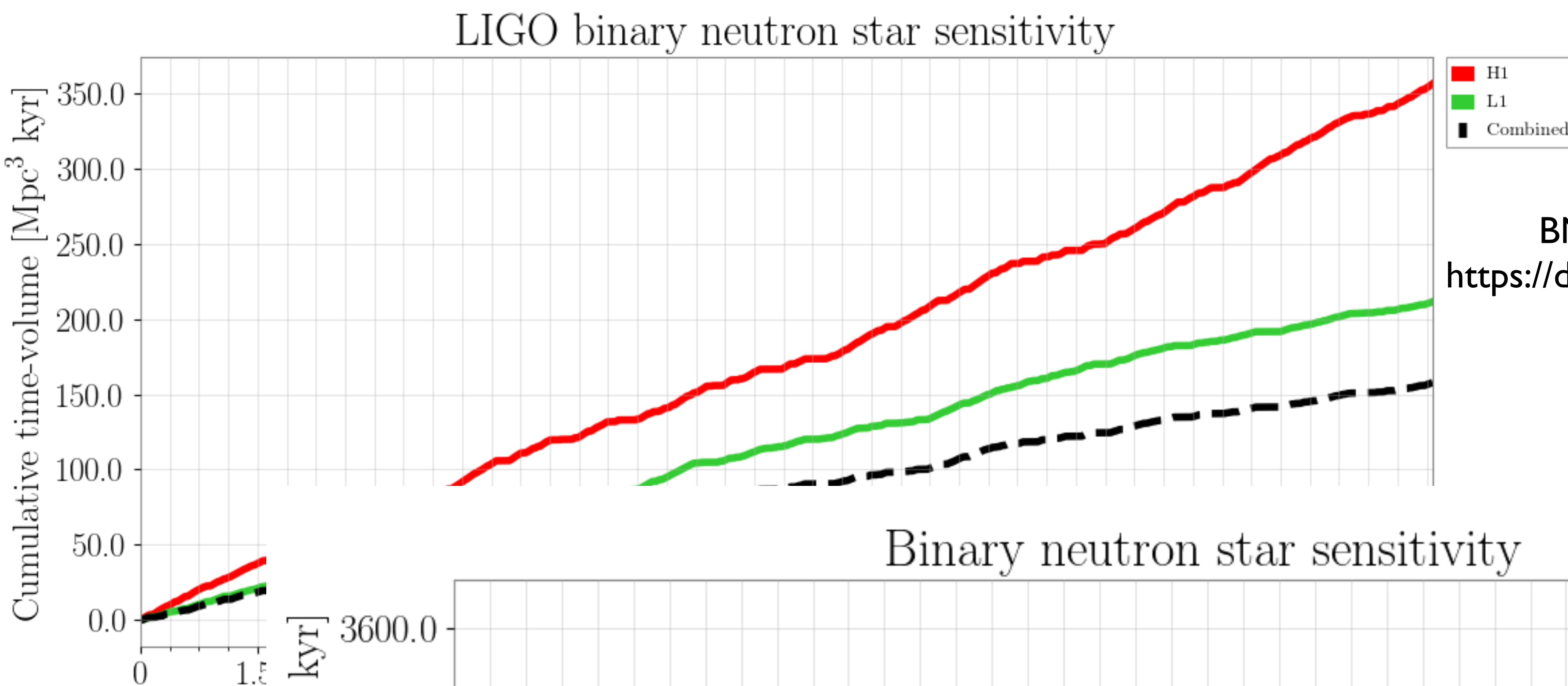
range in O4a



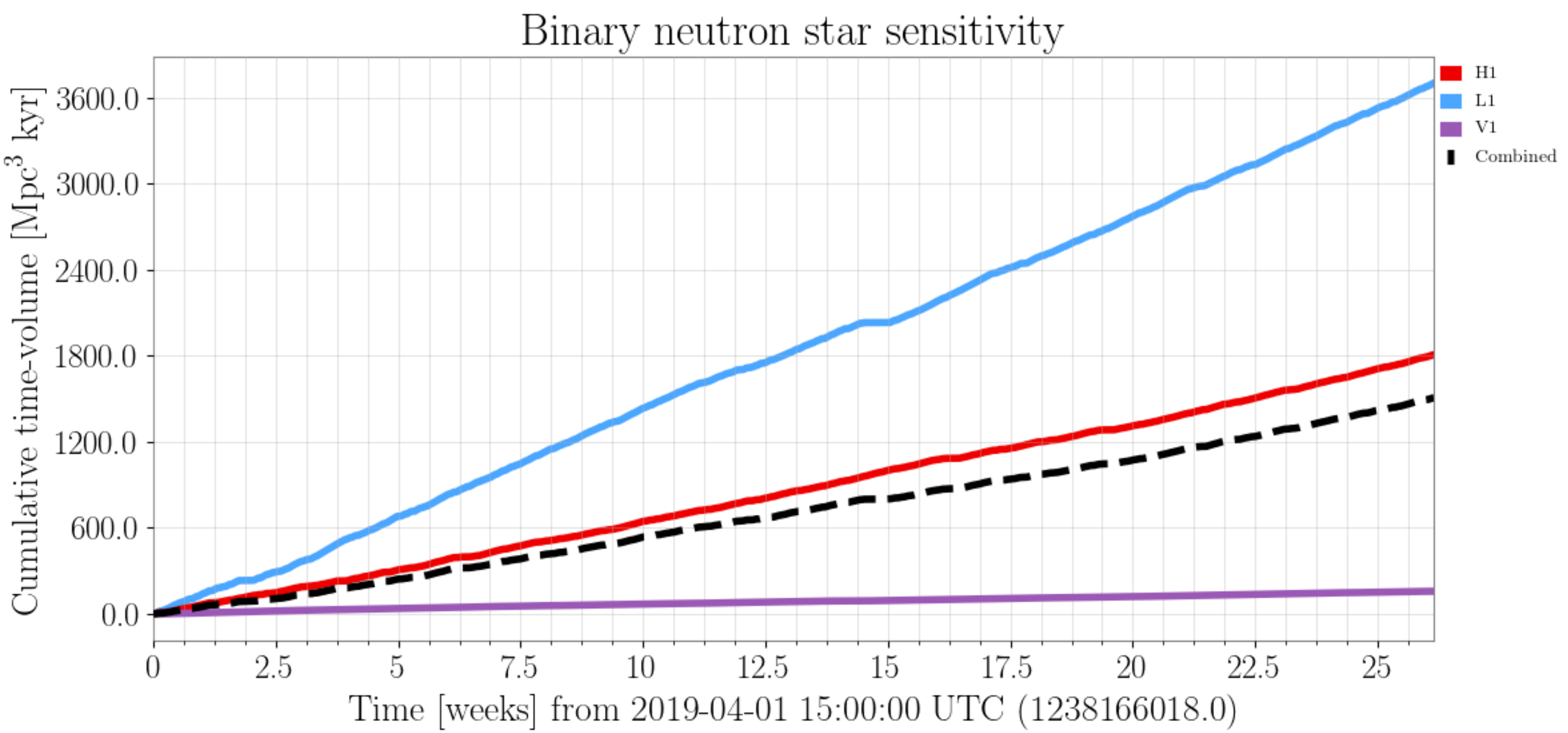
https://ldas-jobs.ligo.caltech.edu/~detchar/summary/O4a/

(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