



#### National Science Foundation + International partners LIGO Scientific Collaboration

























Rutherford Appleton Laboratory

UNIVERSITYOF















MARQUETTE

BE THE DIFFERENCE.

















Northwestern











Marshall Space



































Australian

National





















LONDON







University of Minnesota





























































LIGO-India Scientific Collaboration



















**VILLANOVA** 



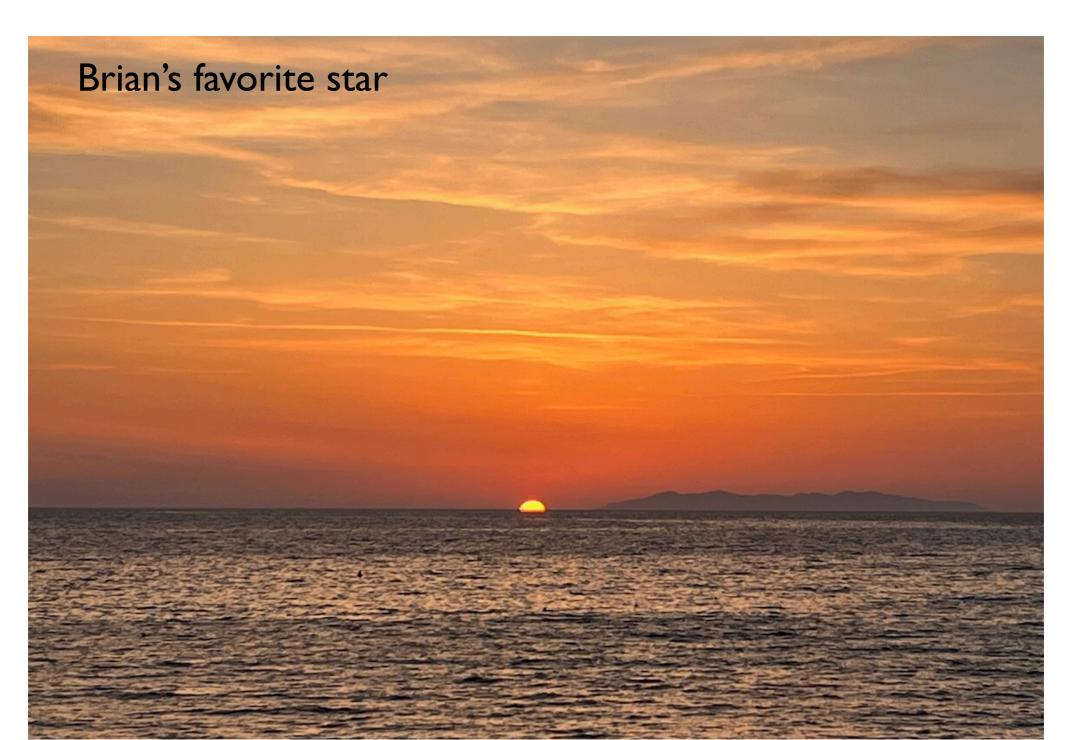






## 2 terms: Black Holes & LIGO WEGGO

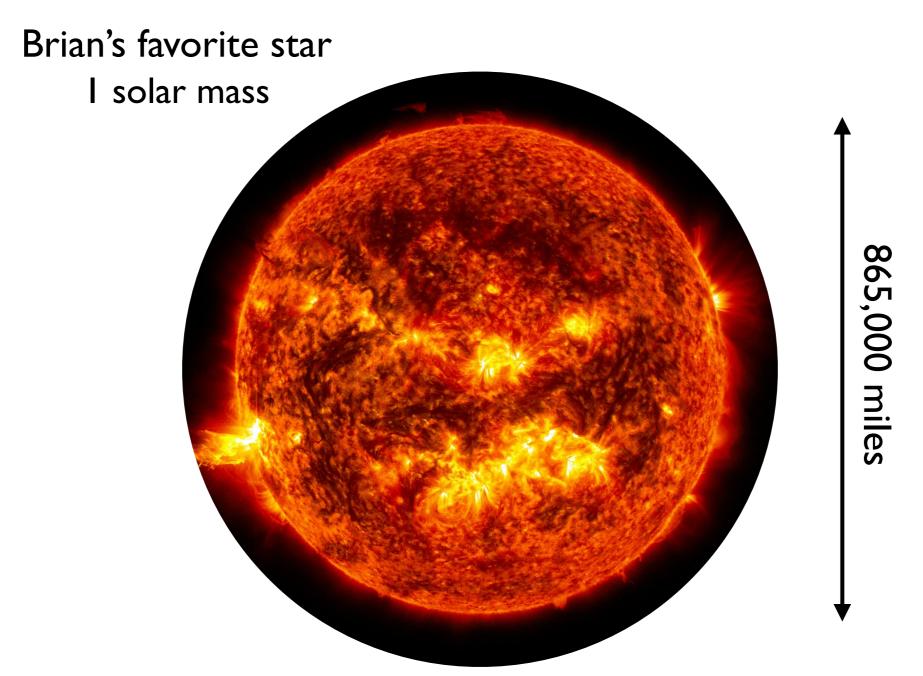
Black Hole - small and massive, gravitational pull is so strong that not even light can get out



#### Black Holes



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



# OLINIVERSITY LICO GROUP OLINIVERSITY OLINI

#### 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

3.7 milesI solar mass(not going to happen)

865,000 miles

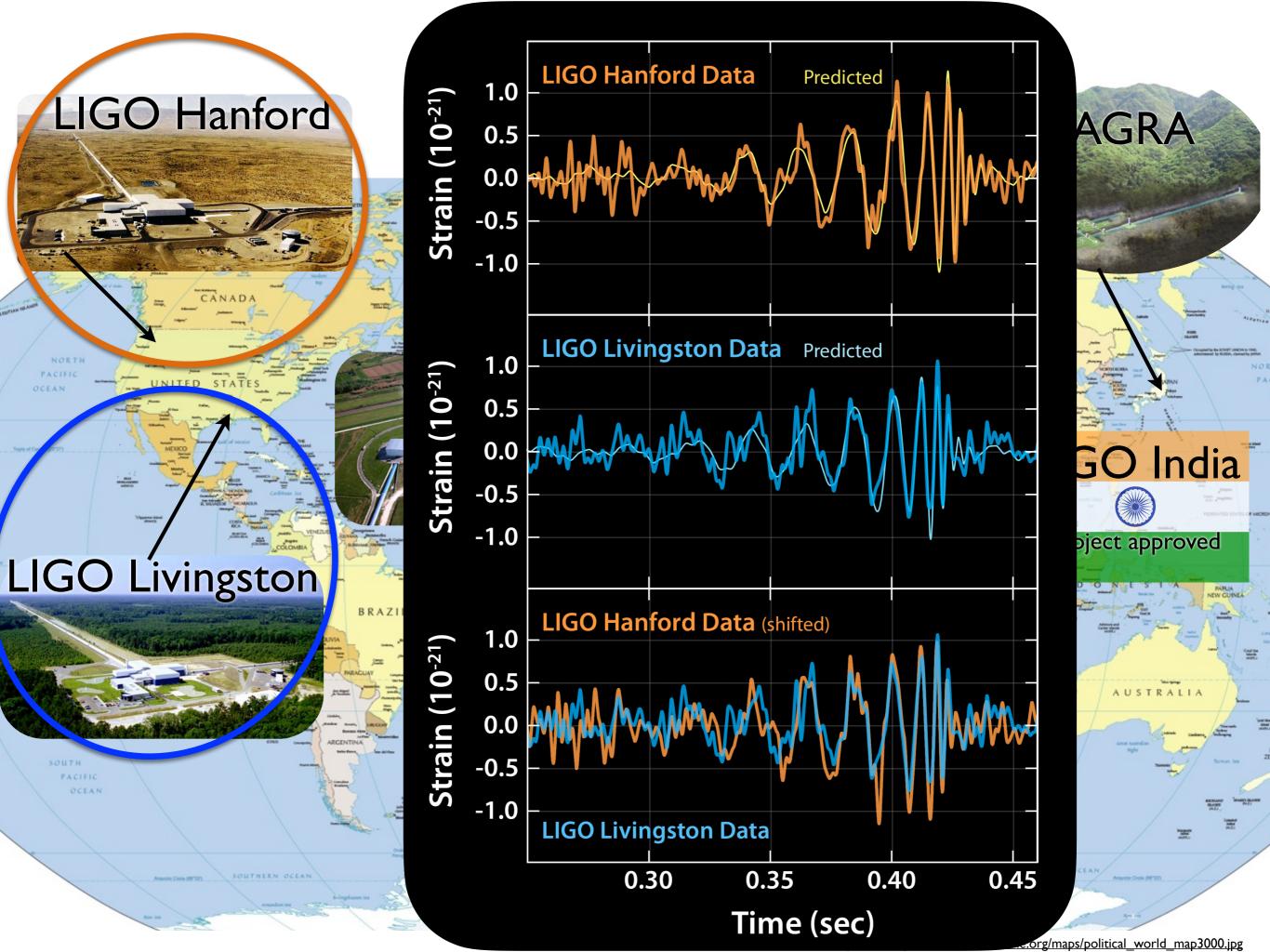


## 2 terms: Black Holes & LIGO KAGRAO

LIGO = Laser Interferometer Gravitational-wave Observatory

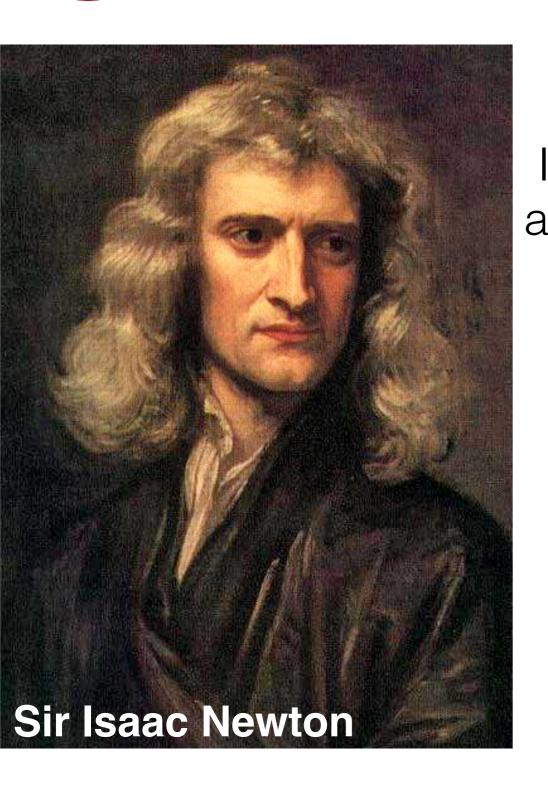


International Network LIGO Hanford **GEO 600** KAGRA VIRGO LIGO India project approved LIGO Livingston

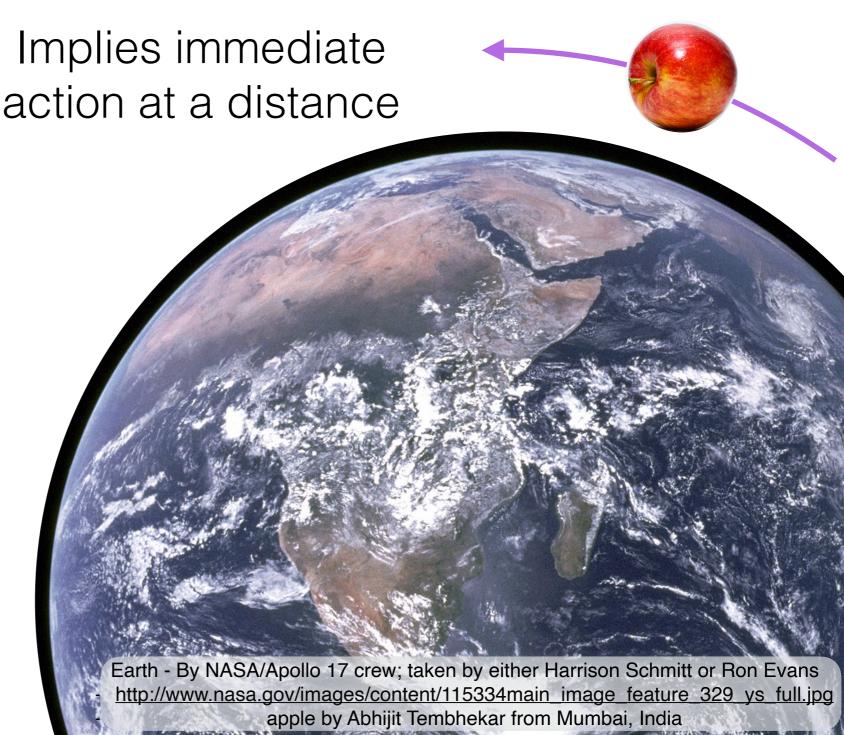


# OJNY LICO GROUP A THE THE PROPERTY OF THE PRO

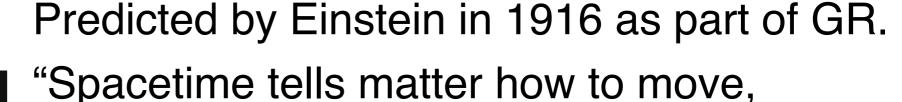
## What is a Gravitational Wave?



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



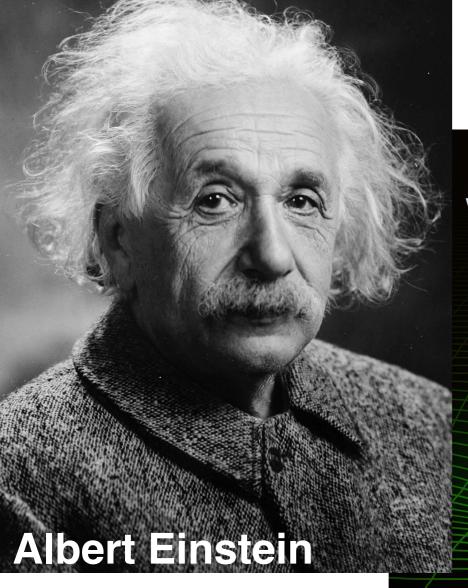
## What is a Gravitational Wave?



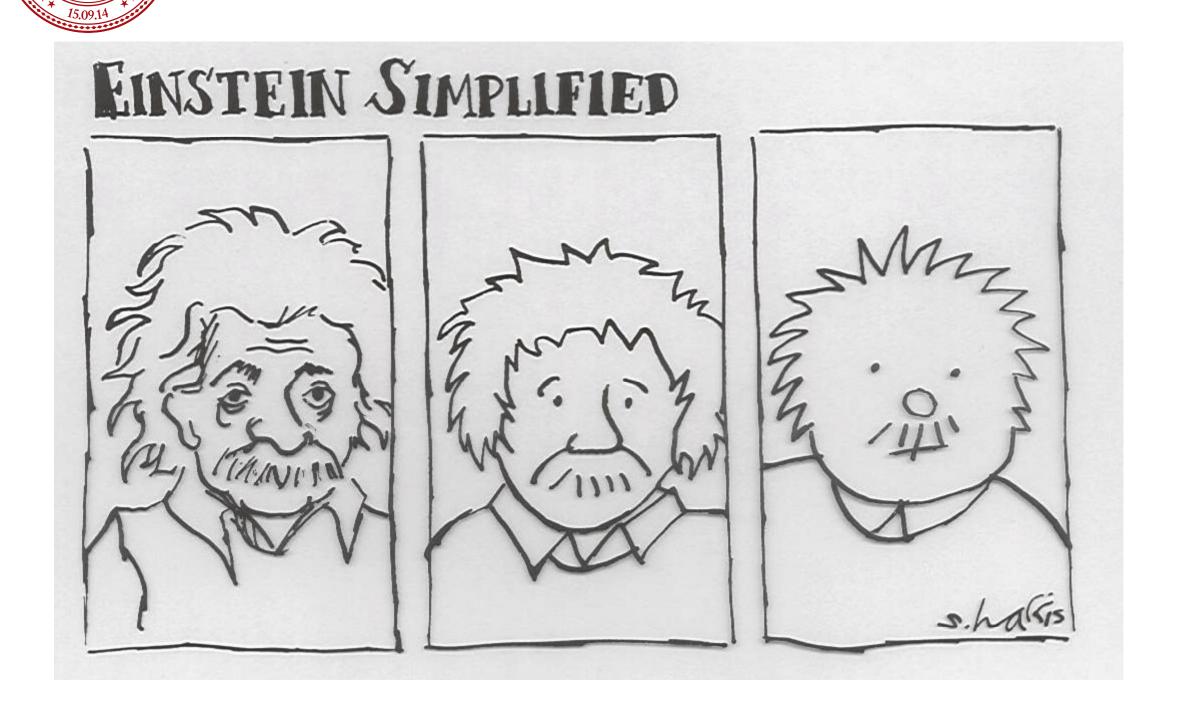
matter tells spacetime how to curve"

- J. A. Wheeler

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

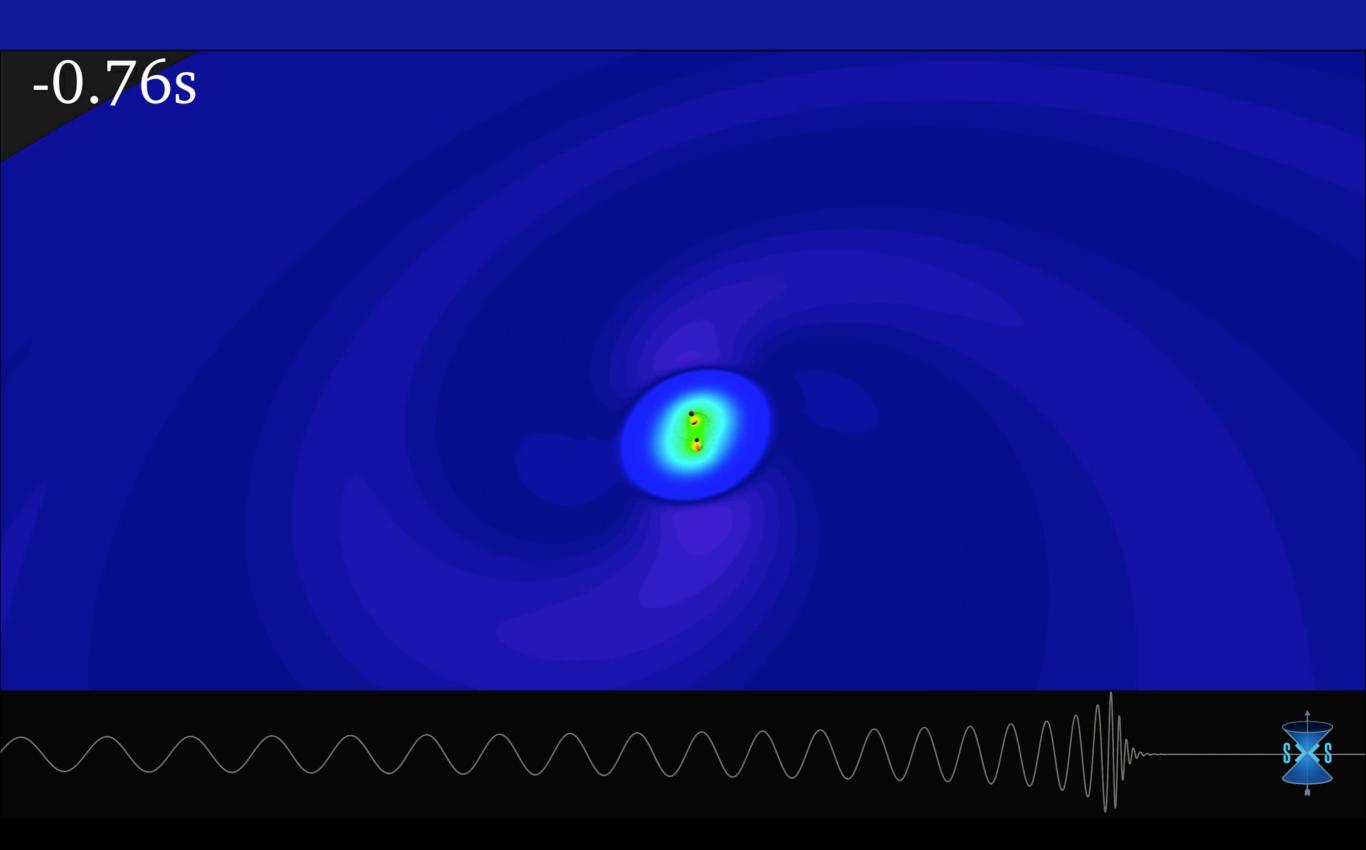


## What is a Gravitational Wave?



Sydney Harris G2501464 11

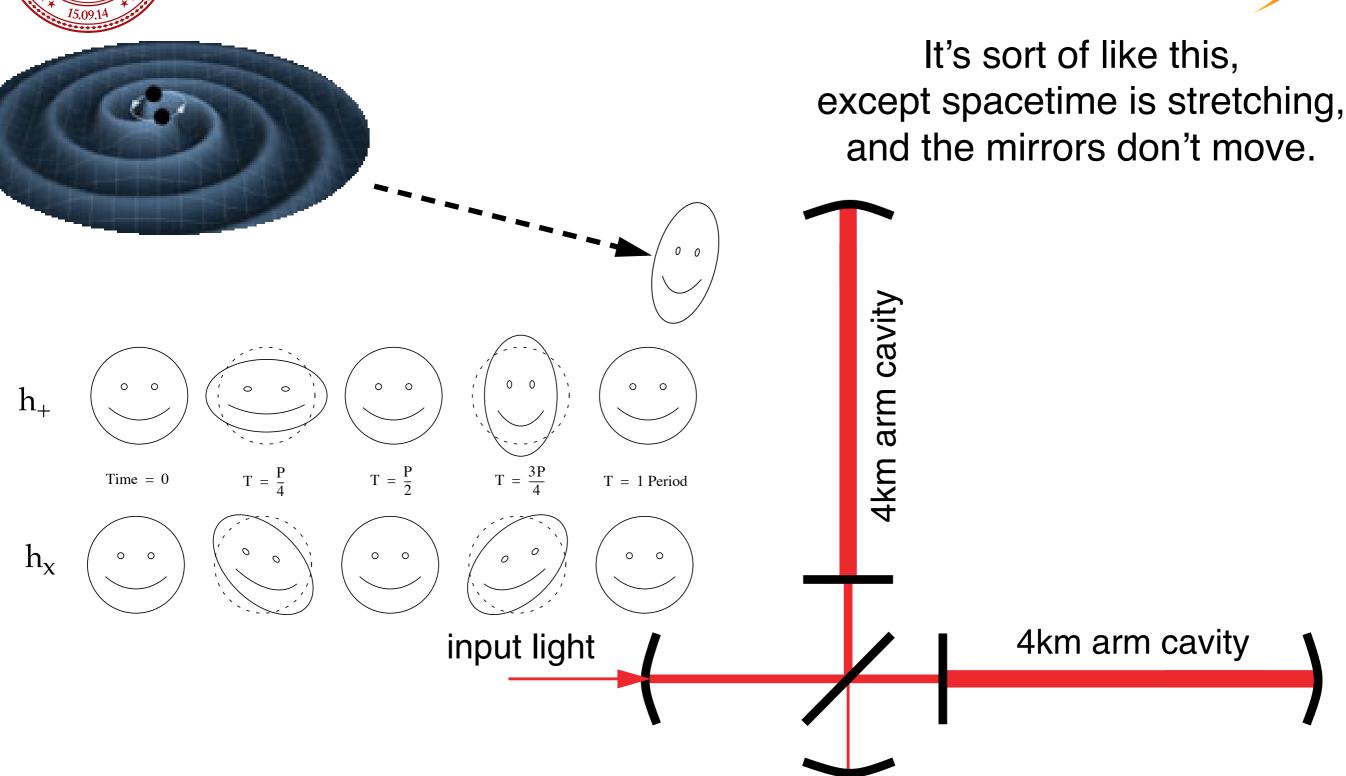
### Simulation of the event





### The LIGO concept





4km arm cavity

output light, containing gravitational wave signal



### The LIGO concept

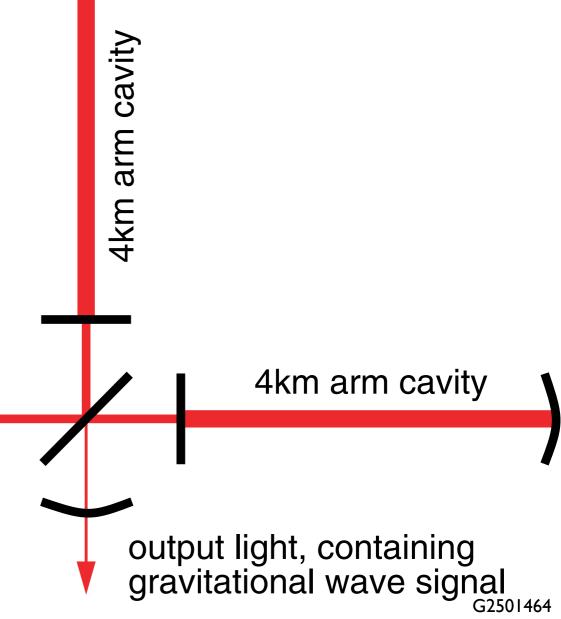


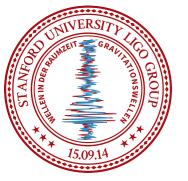
Gravitational waves are hard to measure because space doesn't like to stretch.

input light

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.

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)

- I. Long arms
- 2. Quiet mirrors
- 3. Precise measurement

output light

4km arm cavity

output light, containing

4km arm cavity

### Long arms



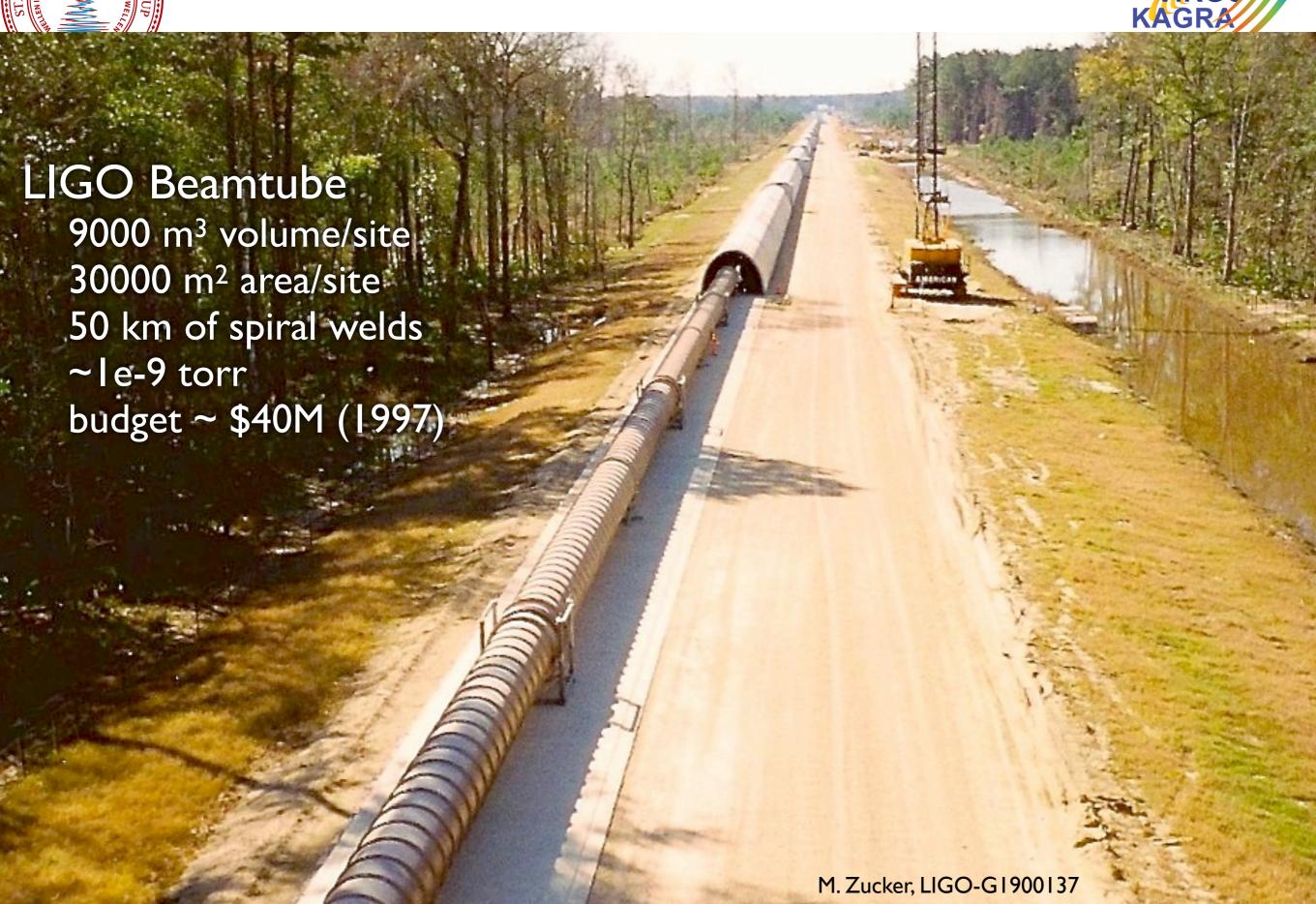
Since h = dL/L (or dL = h\*L) more L gives you more dL of signal, World's 3<sup>rd</sup> largest ultra-clean vacuum system - each arm is 4 km long, 4 ft. diameter





#### LIGO Beamtube

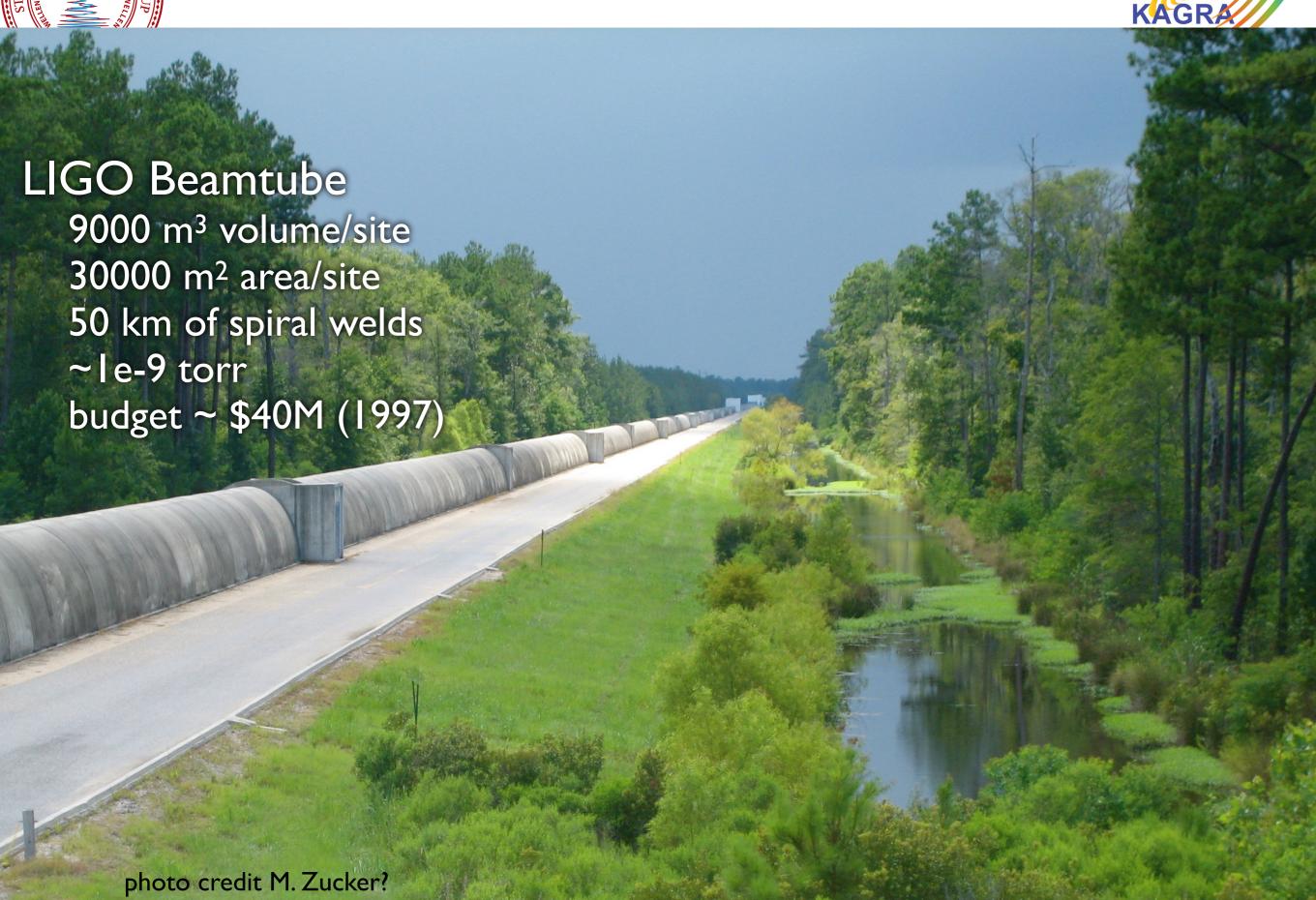


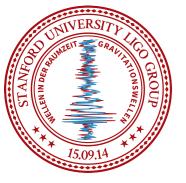




#### LIGO Beamtube







#### Quiet Mirrors



#### How it really works

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

- but -

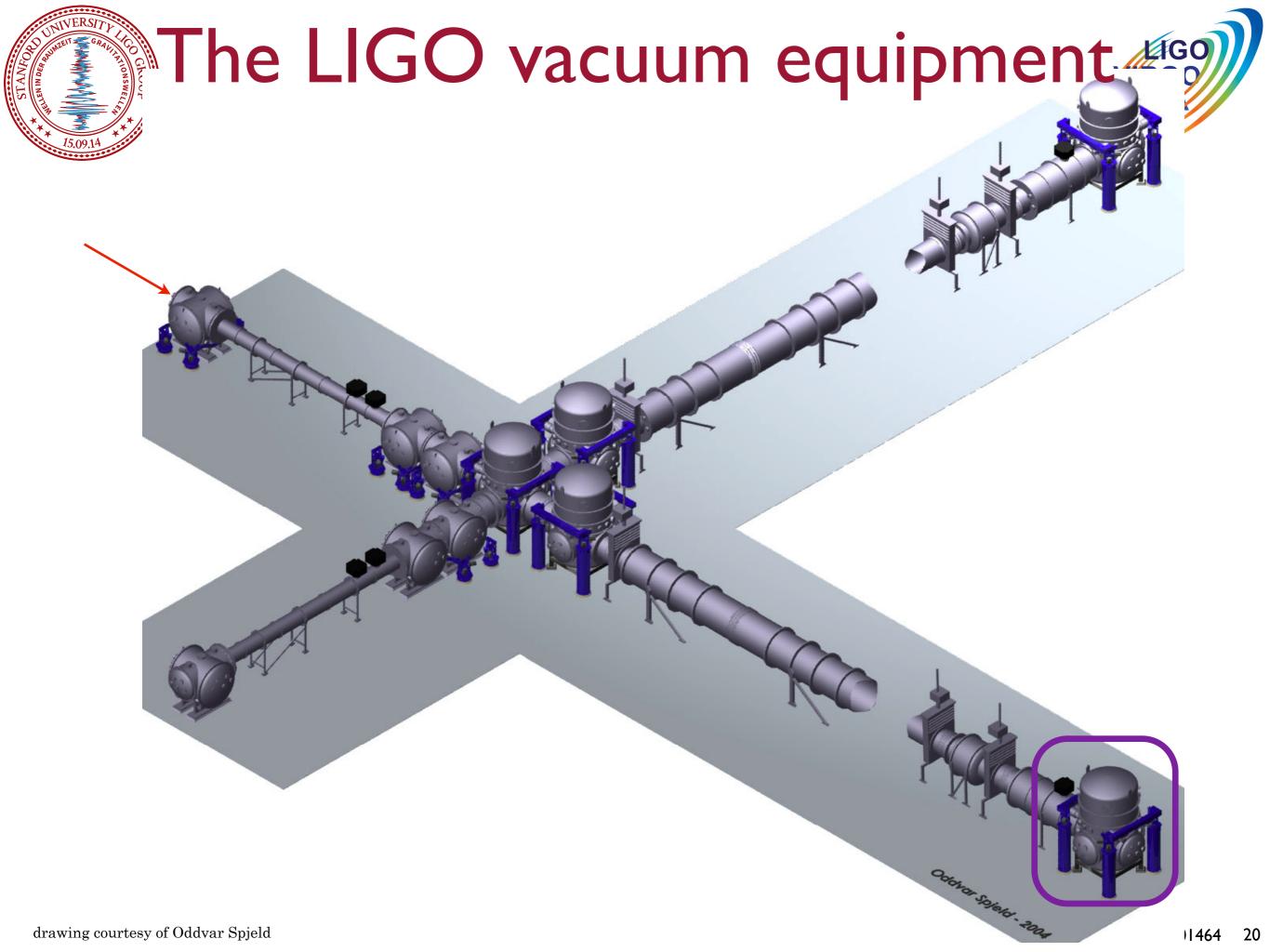
Mirrors need to be quiet because the interferometer can't tell the difference.

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

- L. Long arms
- 2. Quiet mirrors
- 3. Precise measurement

output light, containing gravitational wave signal

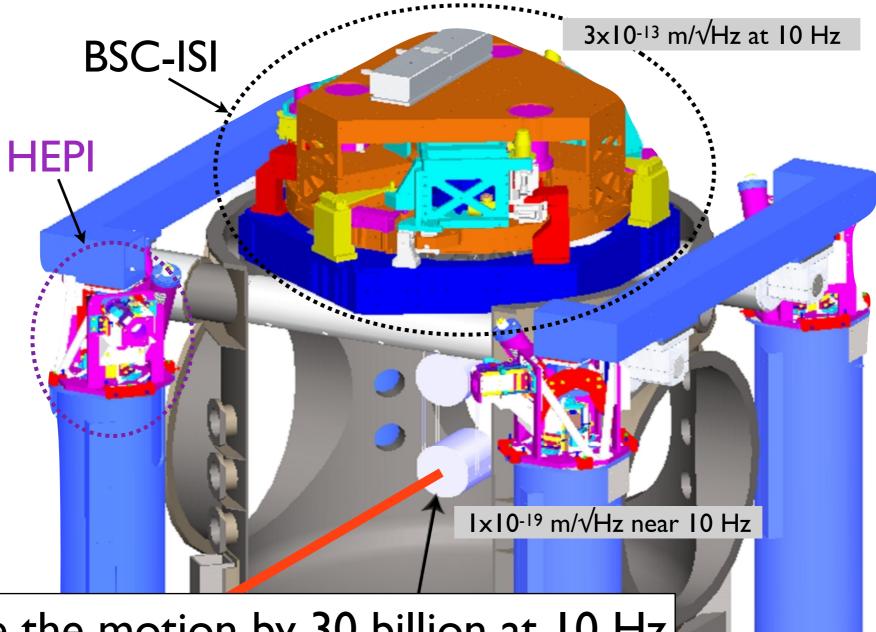
4km arm cavity





#### Isolation of the Mirrors



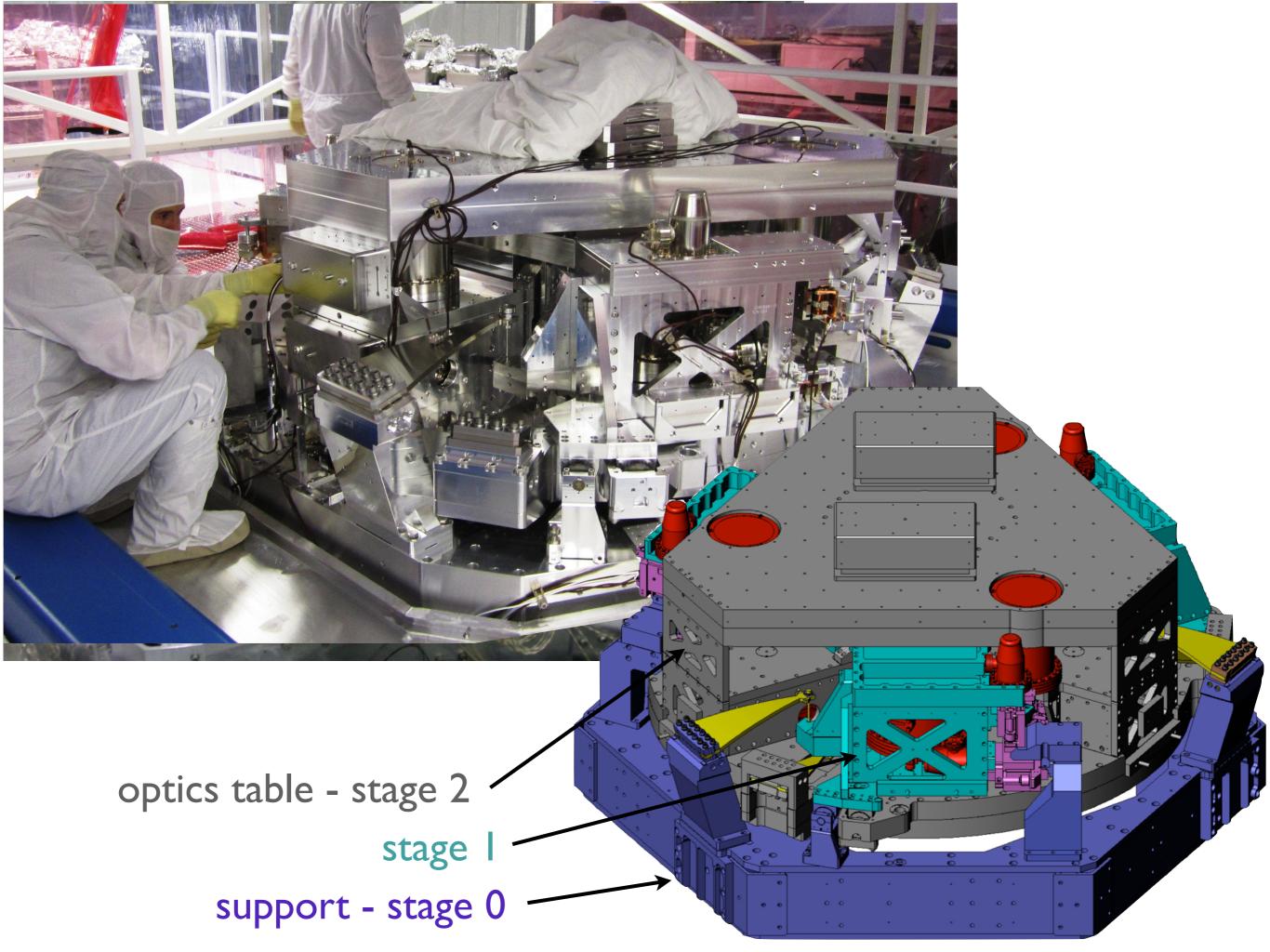


reduce the motion by 30 billion at 10 Hz

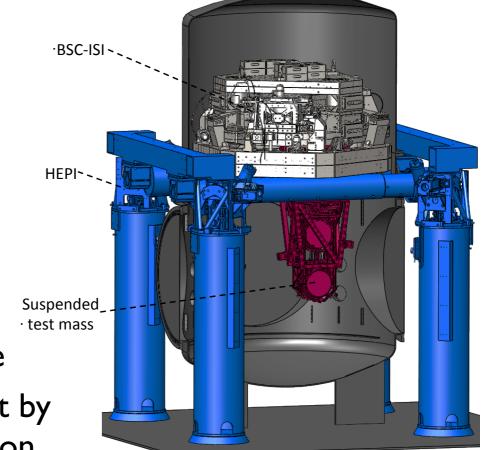
control the position of the optic below 10 Hz

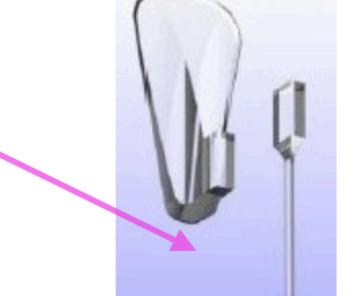
~ $3\times10^{-9}$  m/ $\sqrt{Hz}$  at 10 Hz

Large Optic (business end of SUS)



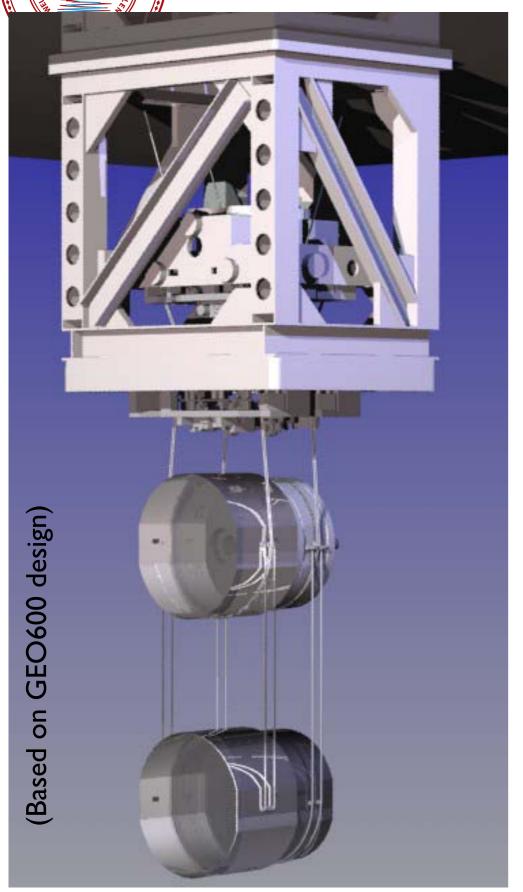
Pendulum Suspension LIGO Mirrors: Synthetic fused silica, 40 kg mass 34 cm diameter 20 cm thick Suspended as a 4 stage pendulum Best coatings available Motion at 10 Hz is set by thermal driven vibration (Based on GEO600 design)





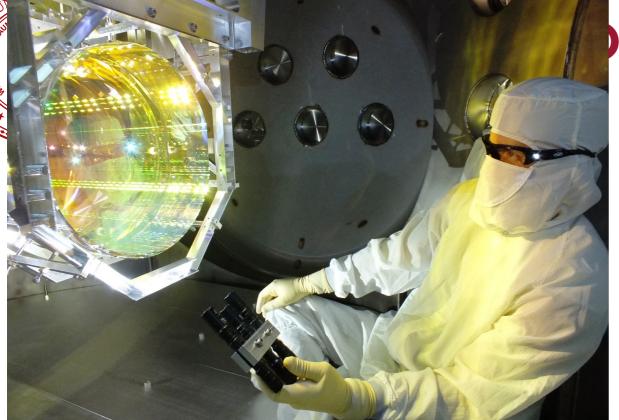
silicate bonding creates a monolithic final stage

Pendulum LHO suspension expert, Betsy Weaver with the Engineering prototype





r picts







#### Precision Interferometry

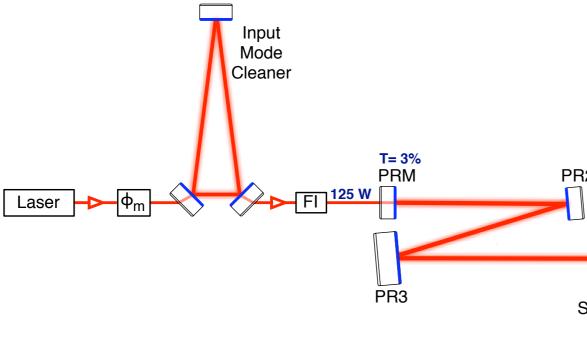
**ERM** 

**ETM** 

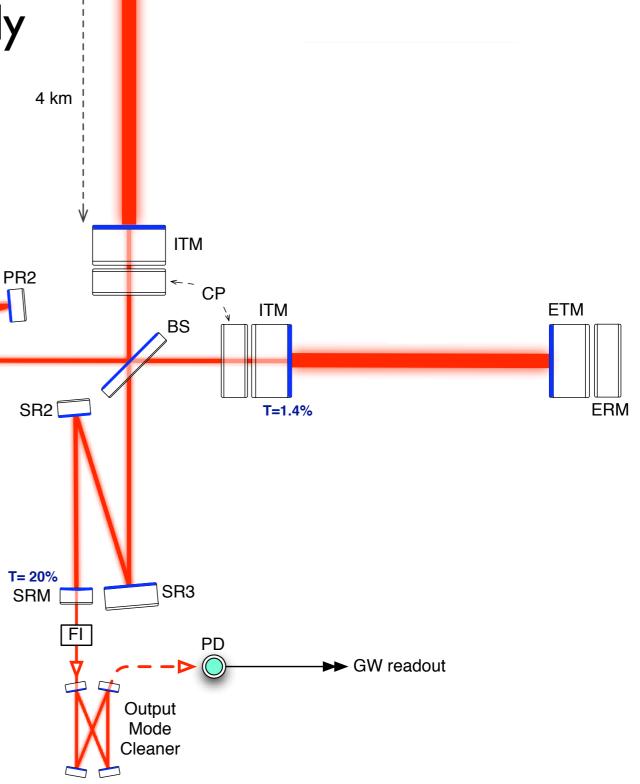


26

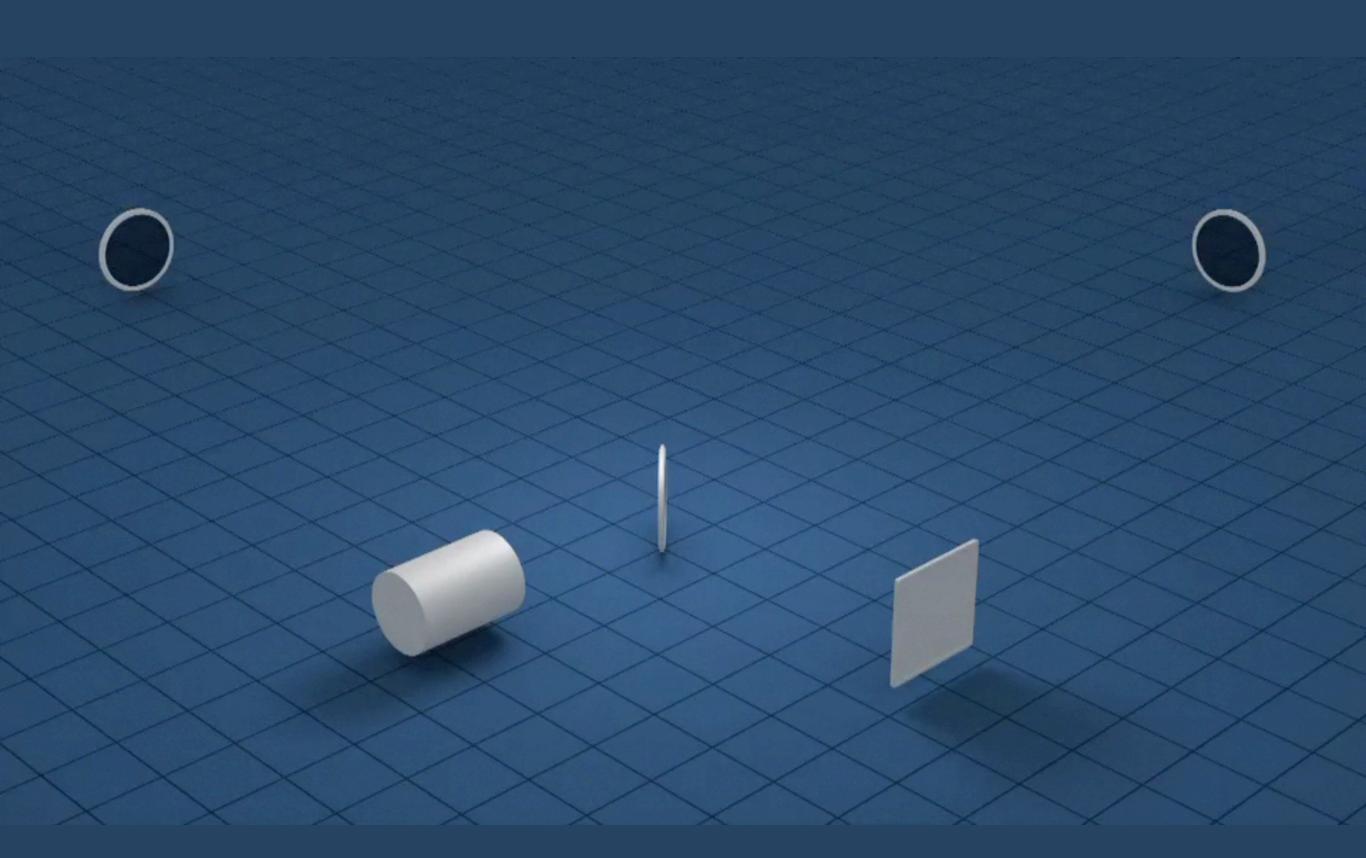
Goal 3: Measure distance change of arms very precisely



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



#### Animated Interferometer



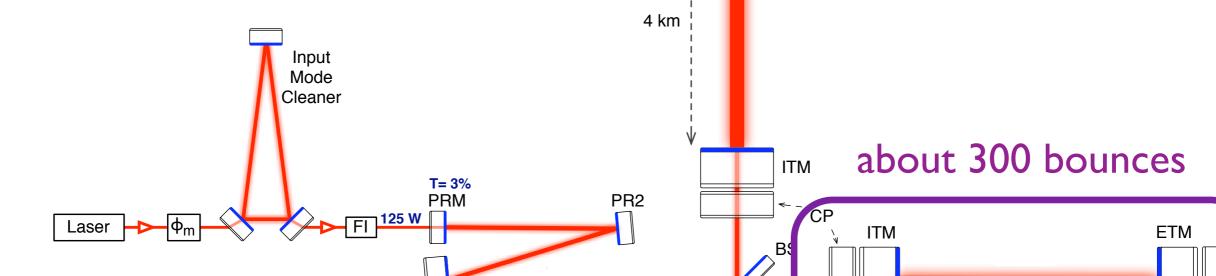


### Fabry-Perot arms



Goal 3: Measure distance change of arms very precisely

PR3



SR2

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

- but -

It only works when the light is resonant.

T=1.4%

**ERM** 

**ETM** 

**ERM** 



### Lots of photons

**ERM** 

**ETM** 

SR3

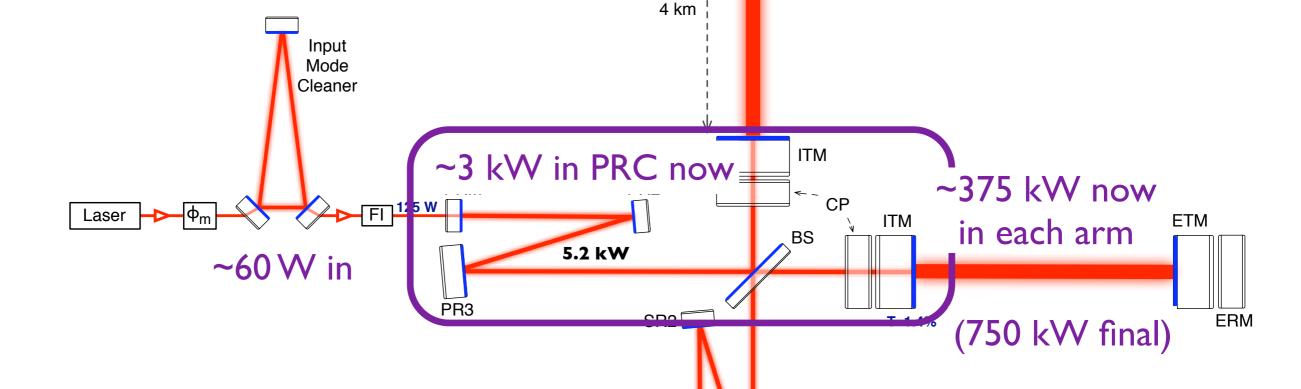
Output

Mode Cleaner PD

GW readout



Goal 3: Measure distance change of arms very precisely



T= 20%

SRM 📑

High power has a price

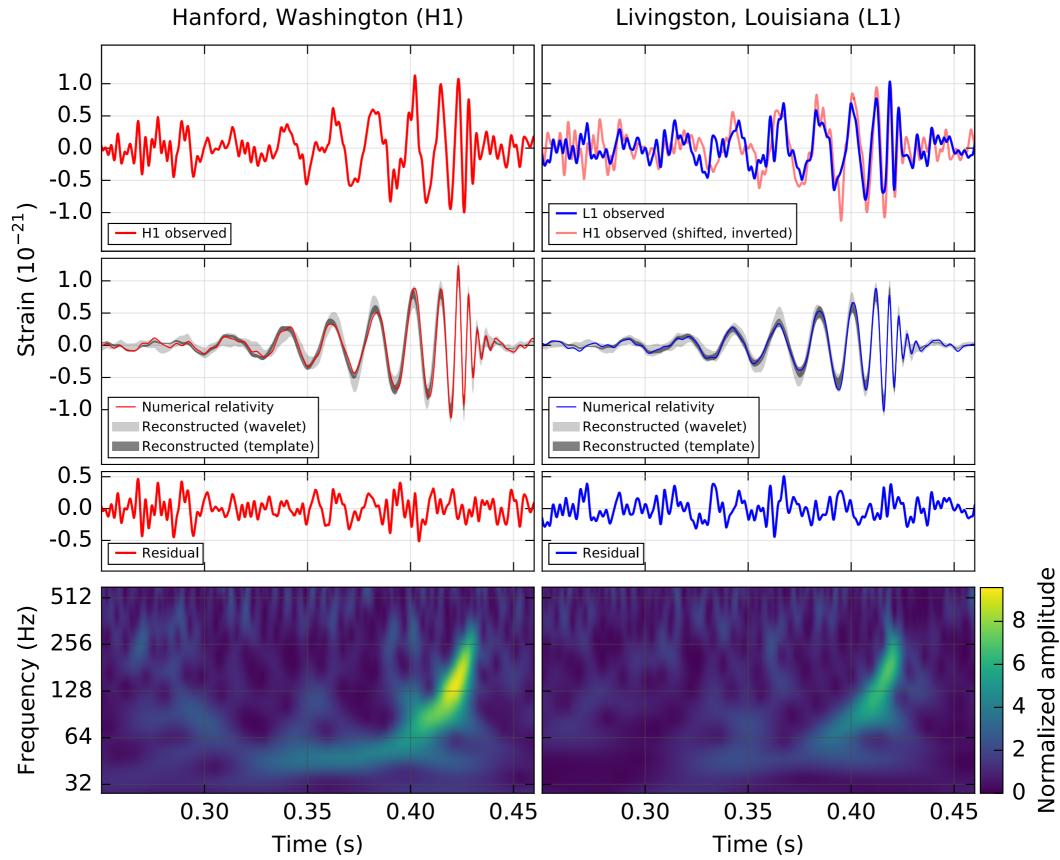
- Local thermal distortion of the glass optics caused by small imperfections in the coatings and limit current power.
- Noise from scattered light.

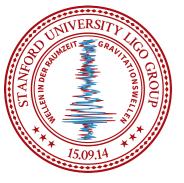
#### and now you wait for a signal wind was a signal with the second sign ook for motions (signals) that are **ERM ETM** different from the usual noise characteristic of GWs seen at all the sites 4 km Input Mode Cleaner ITM T= 3% PR2 PRM CP ITM ETM BS PR<sub>3</sub> SR2 **ERM** T=1.4% T= 20% SR3 SRM [ PD ➤ GW readout Output Mode Cleaner 30



### First signal - Sept 14, 2015







# Best fit with Numerical Relativity



#### Initial Masses:

29 (+4/-4) & 36 (+5/-4) M<sub>sun</sub>

#### Final Mass:

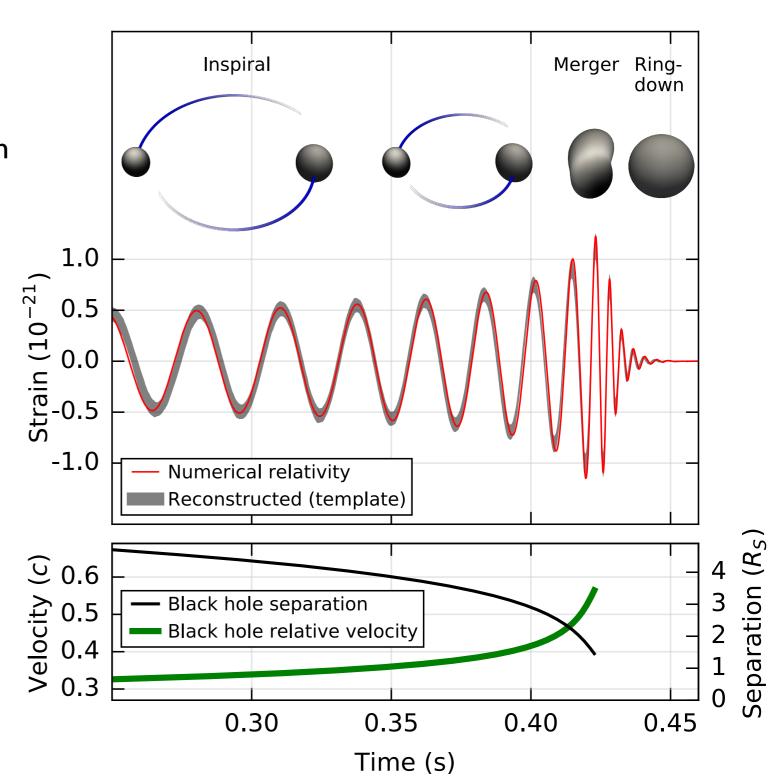
62 (+4/-4) M<sub>sun</sub>

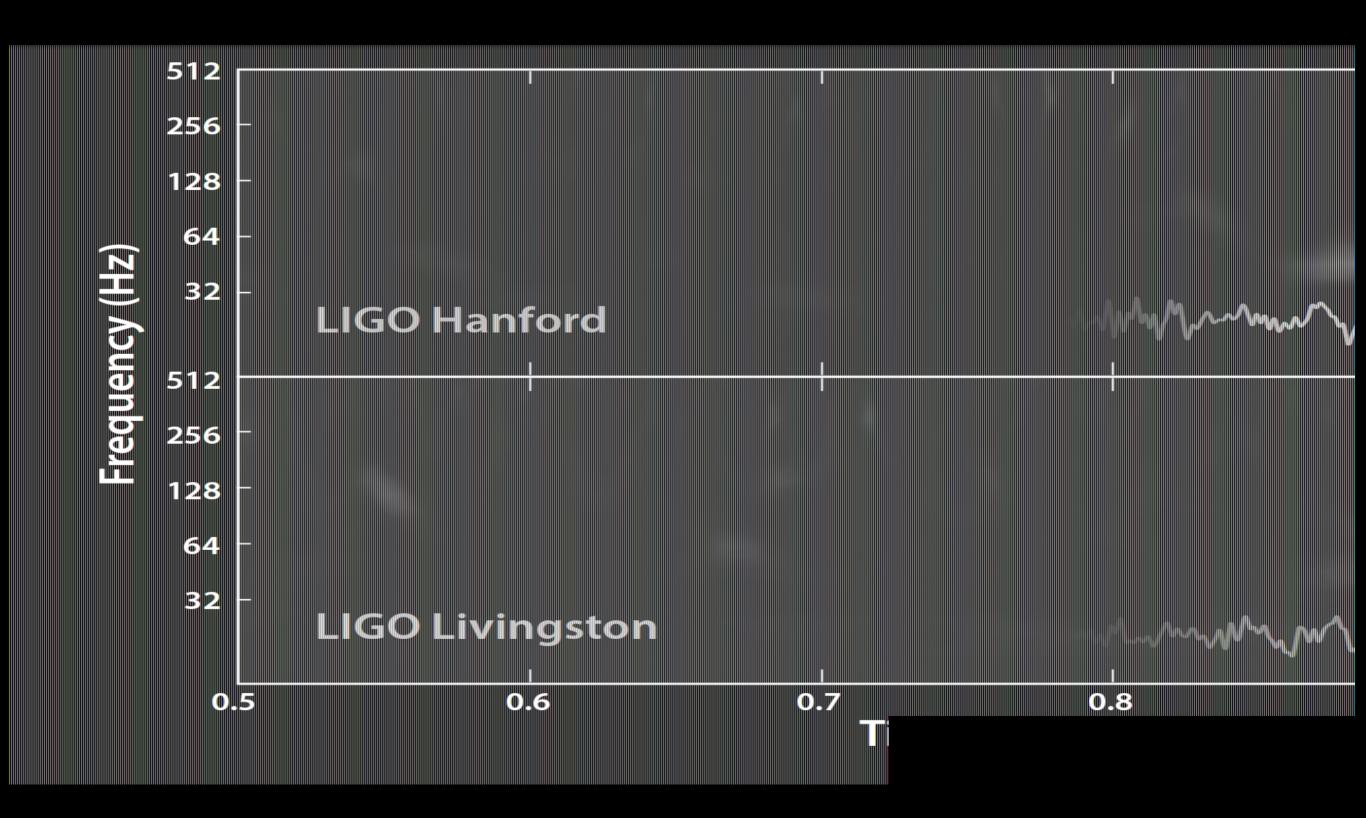
3 solar masses were radiated as GWs

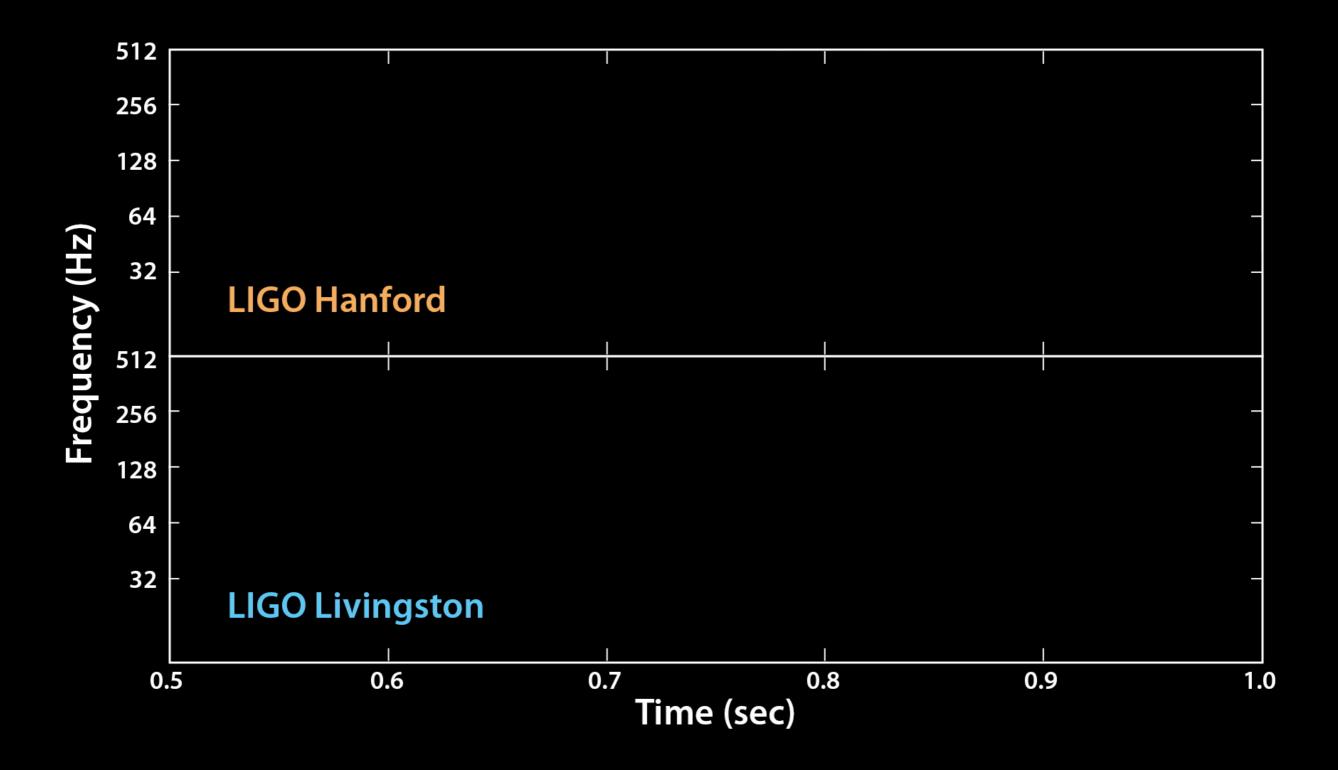
#### Distance

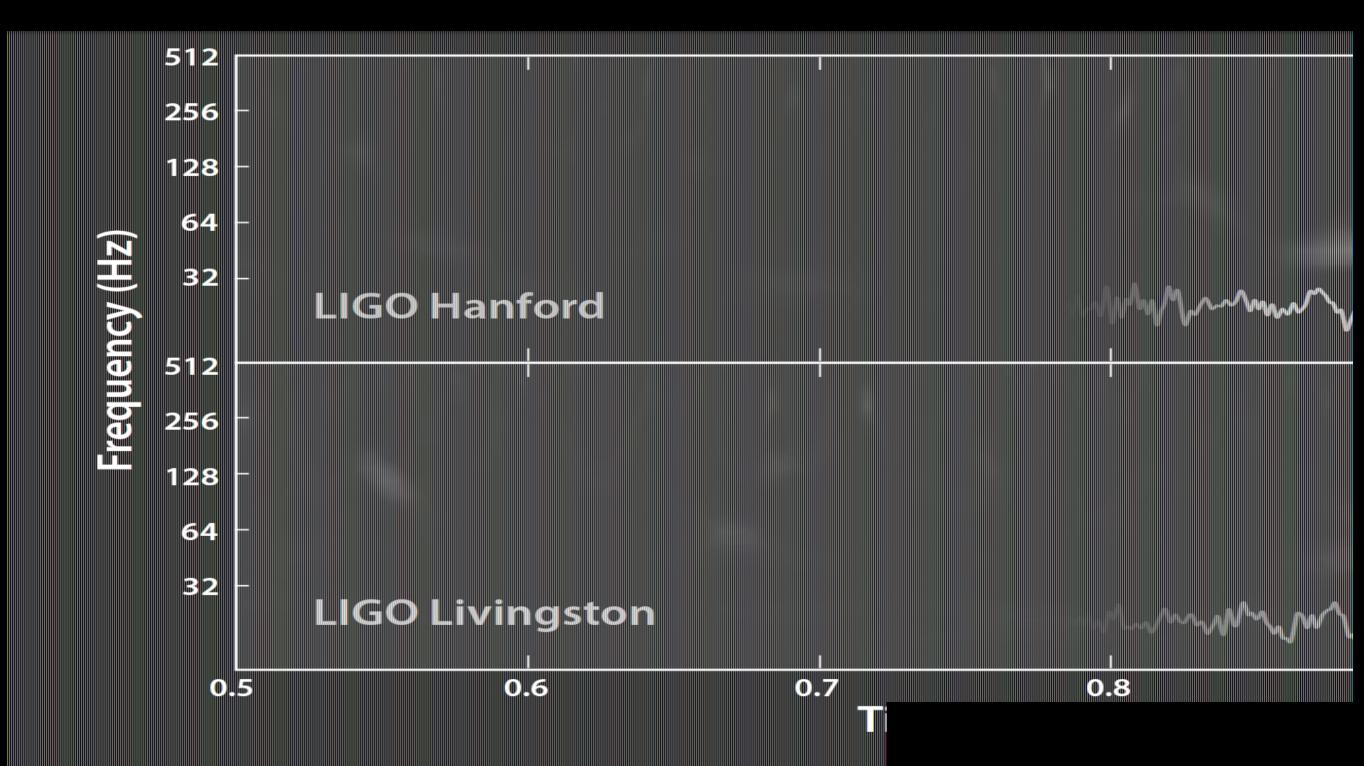
420 (+160/-180) MPc

(I.3 Billion light years)

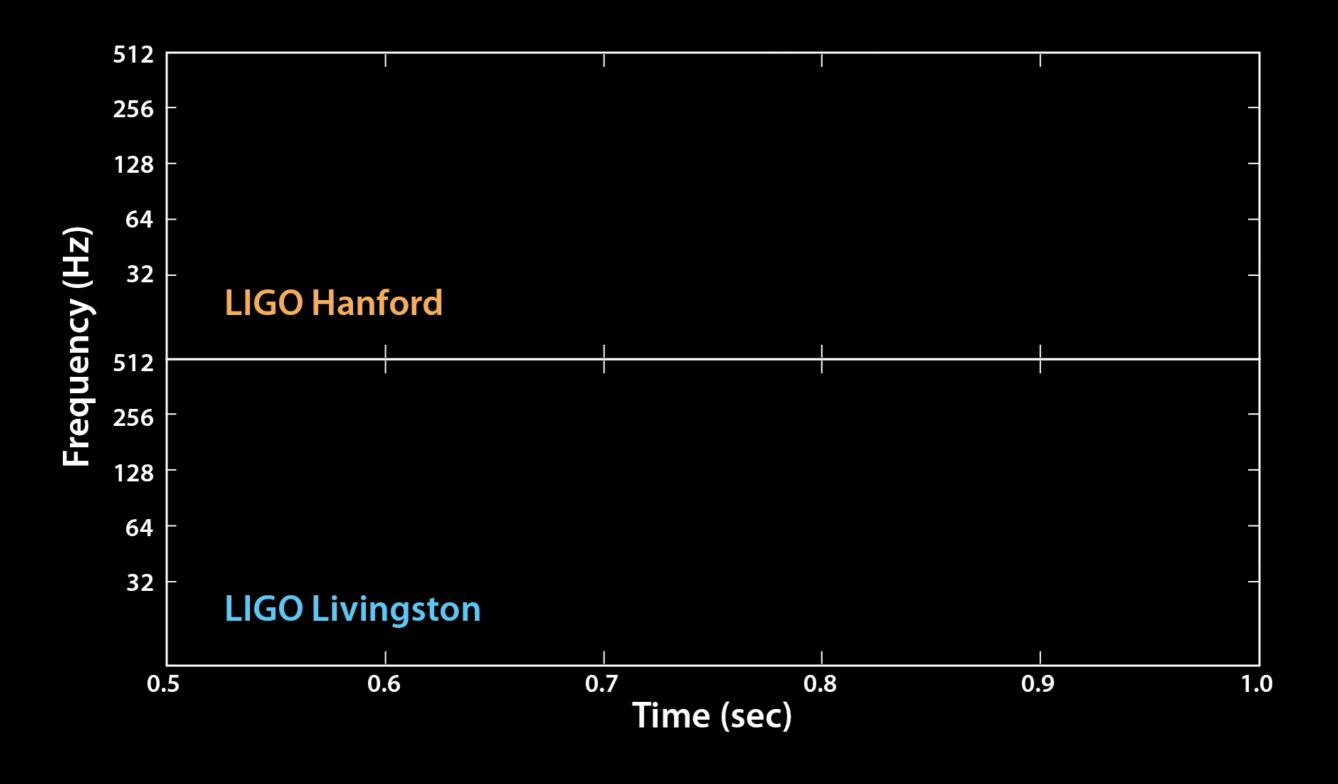


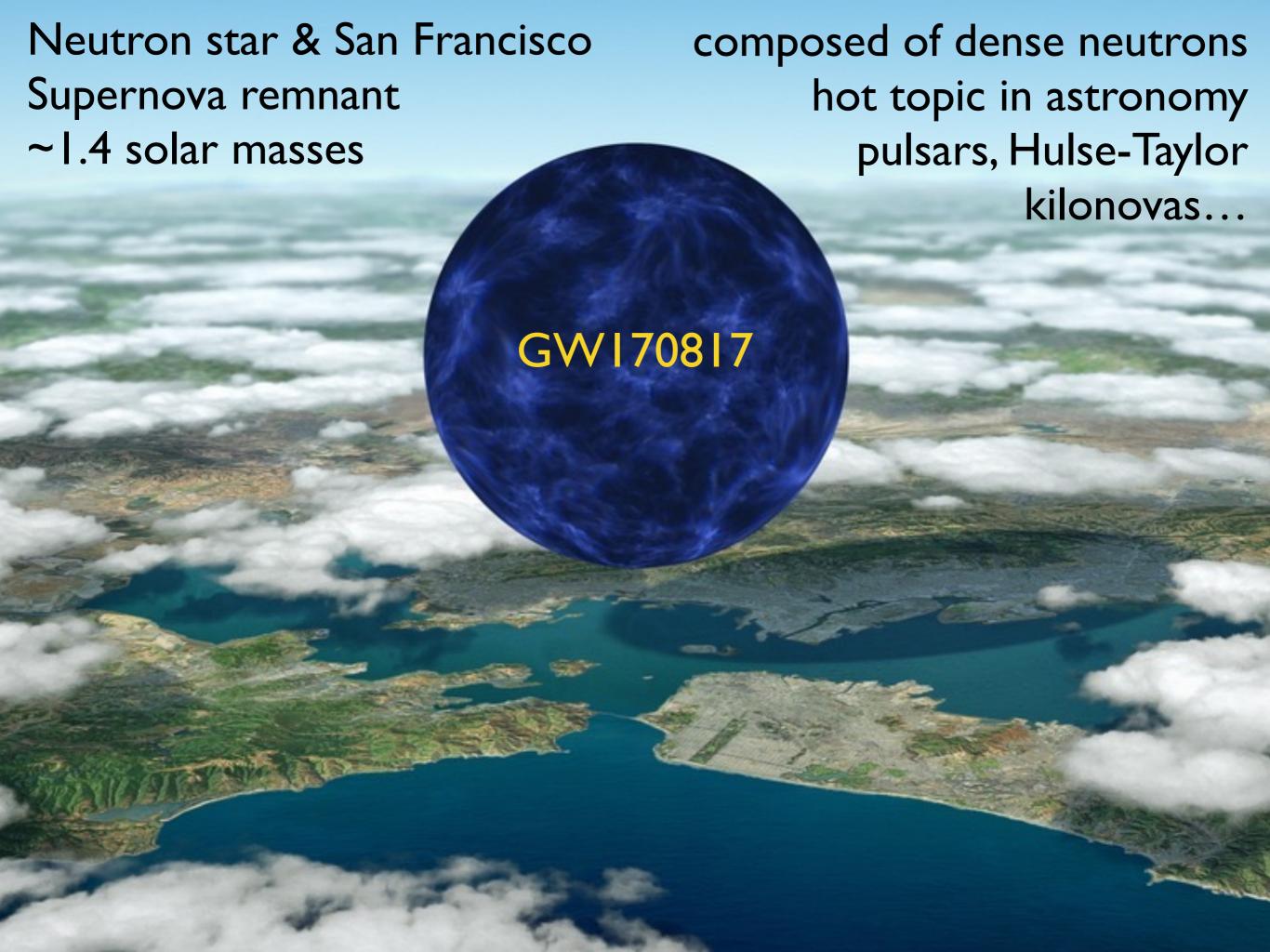






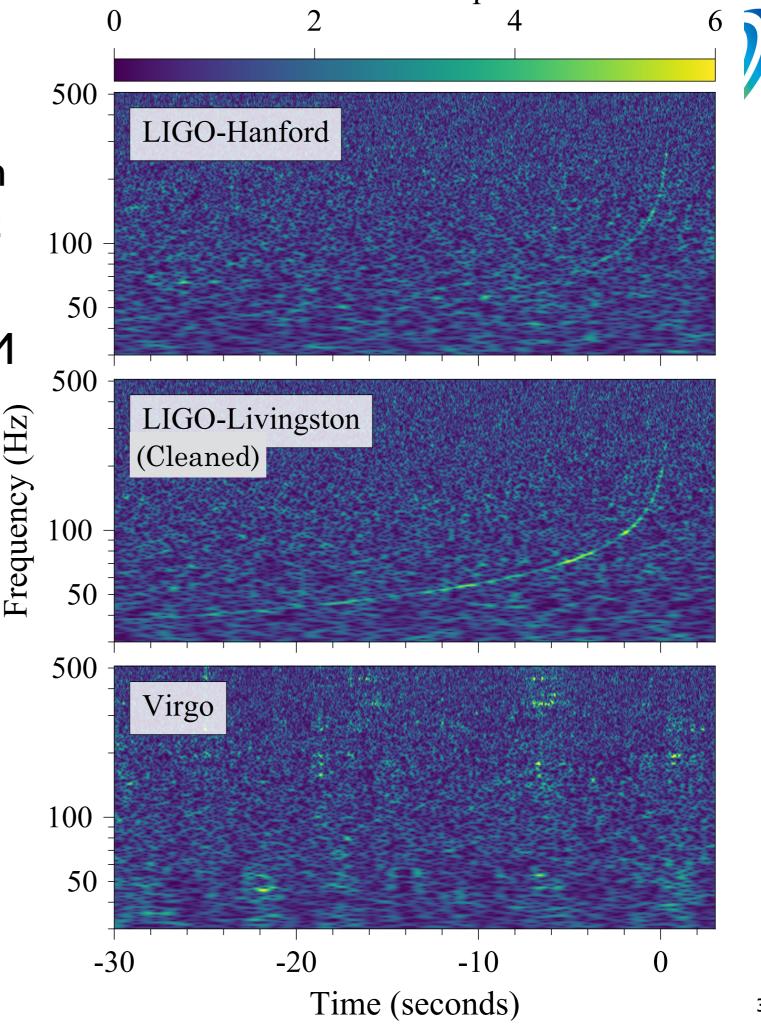
### The sound of black holes colliding

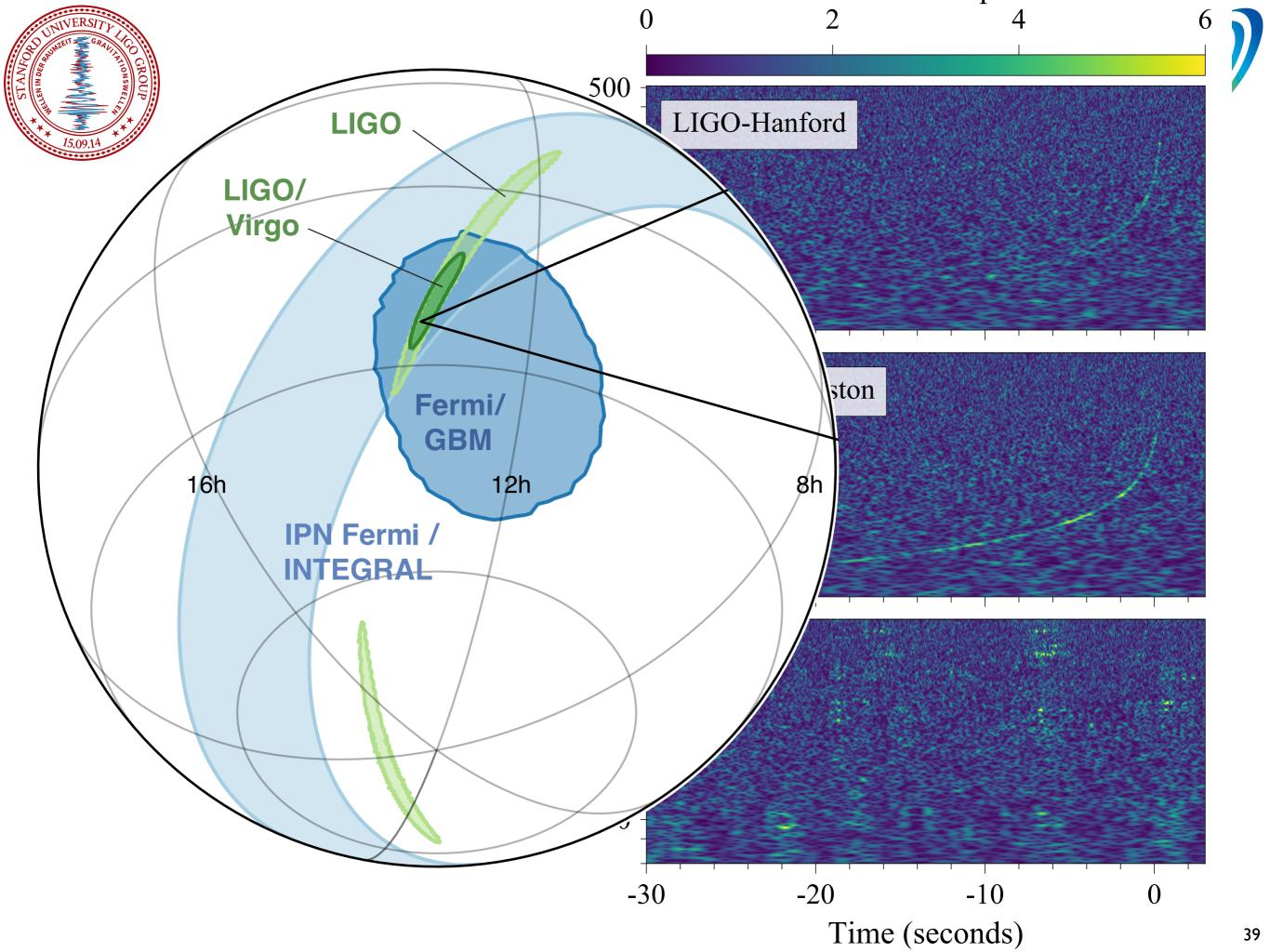


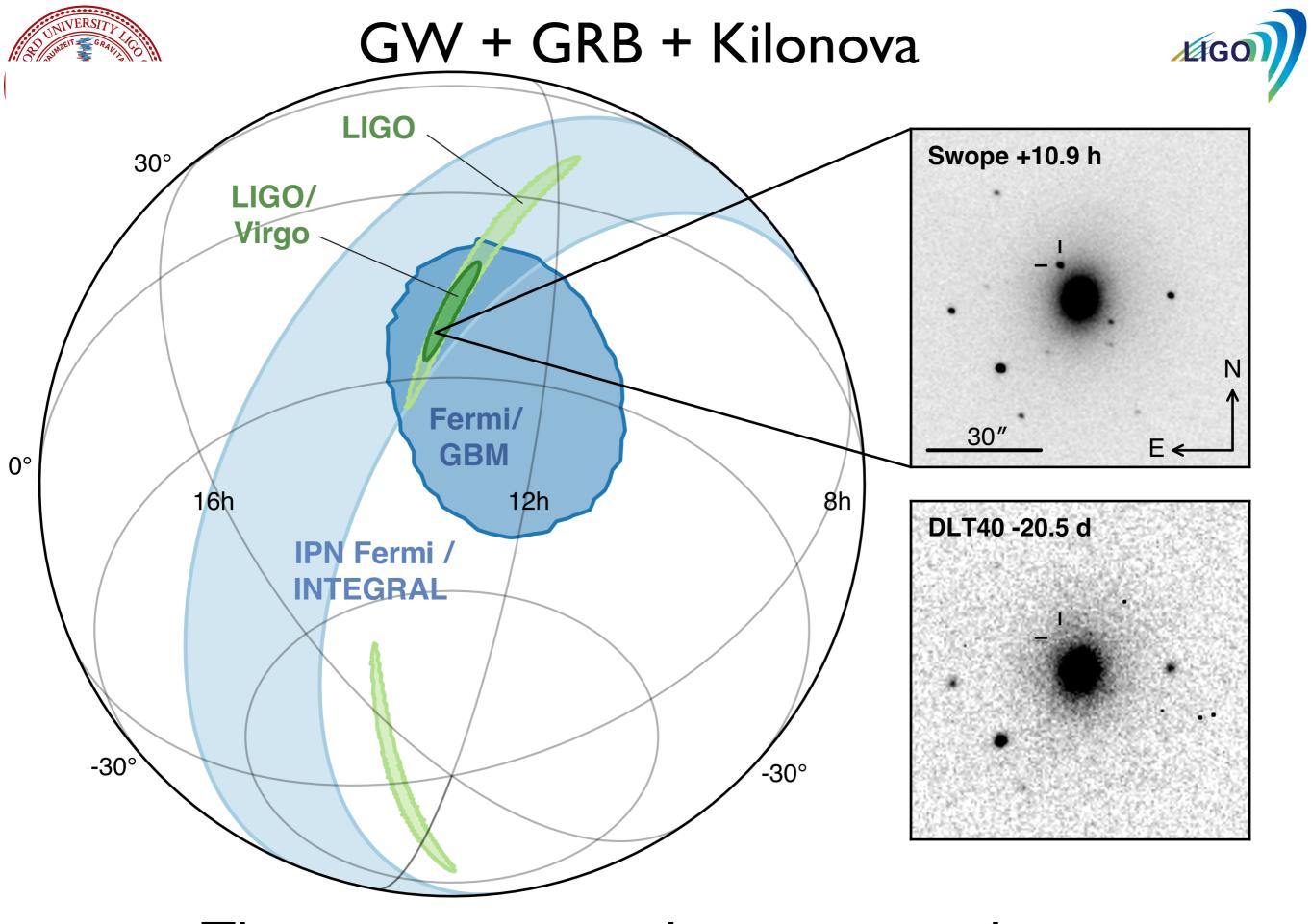


# **BNS**

- 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!)

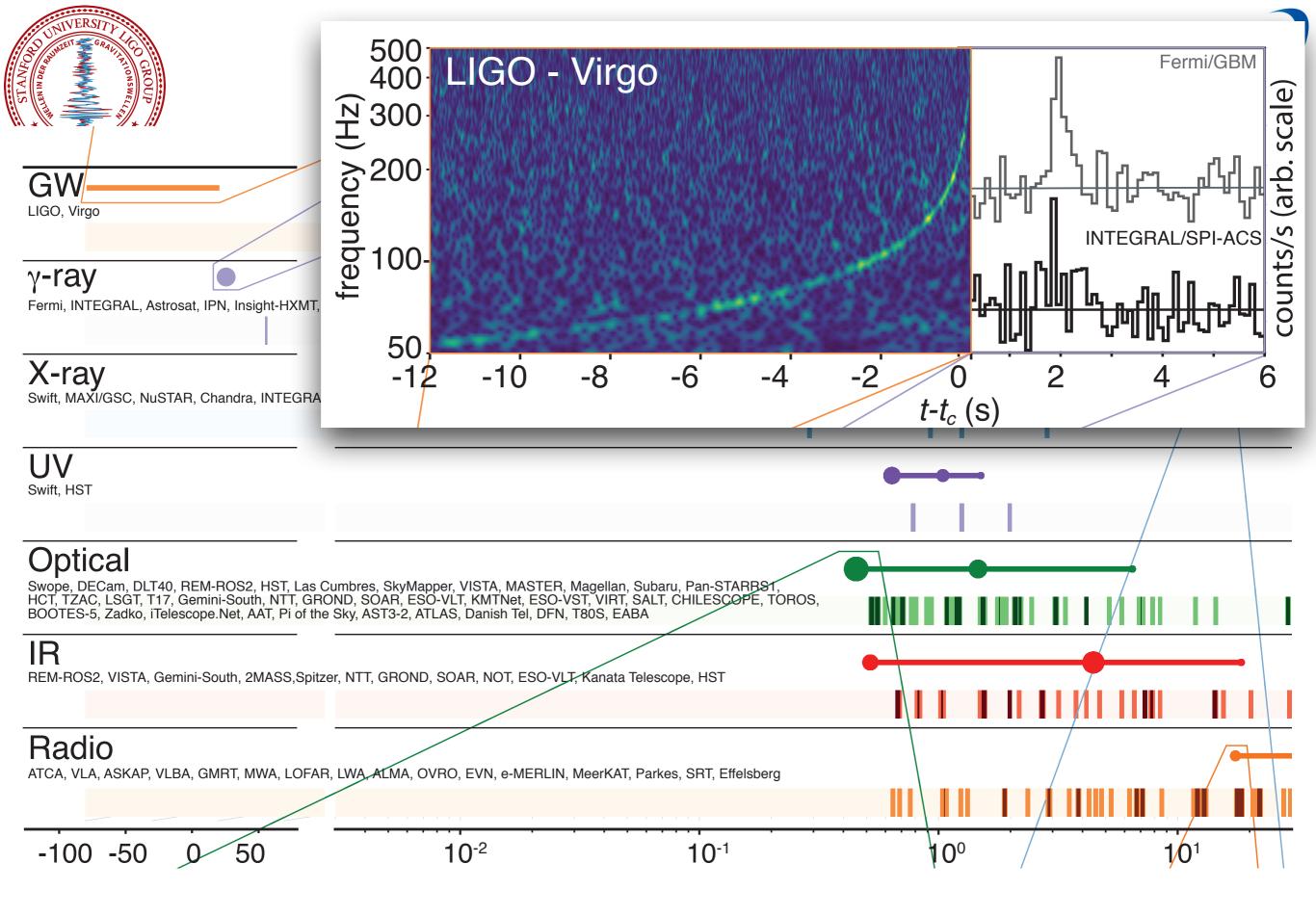


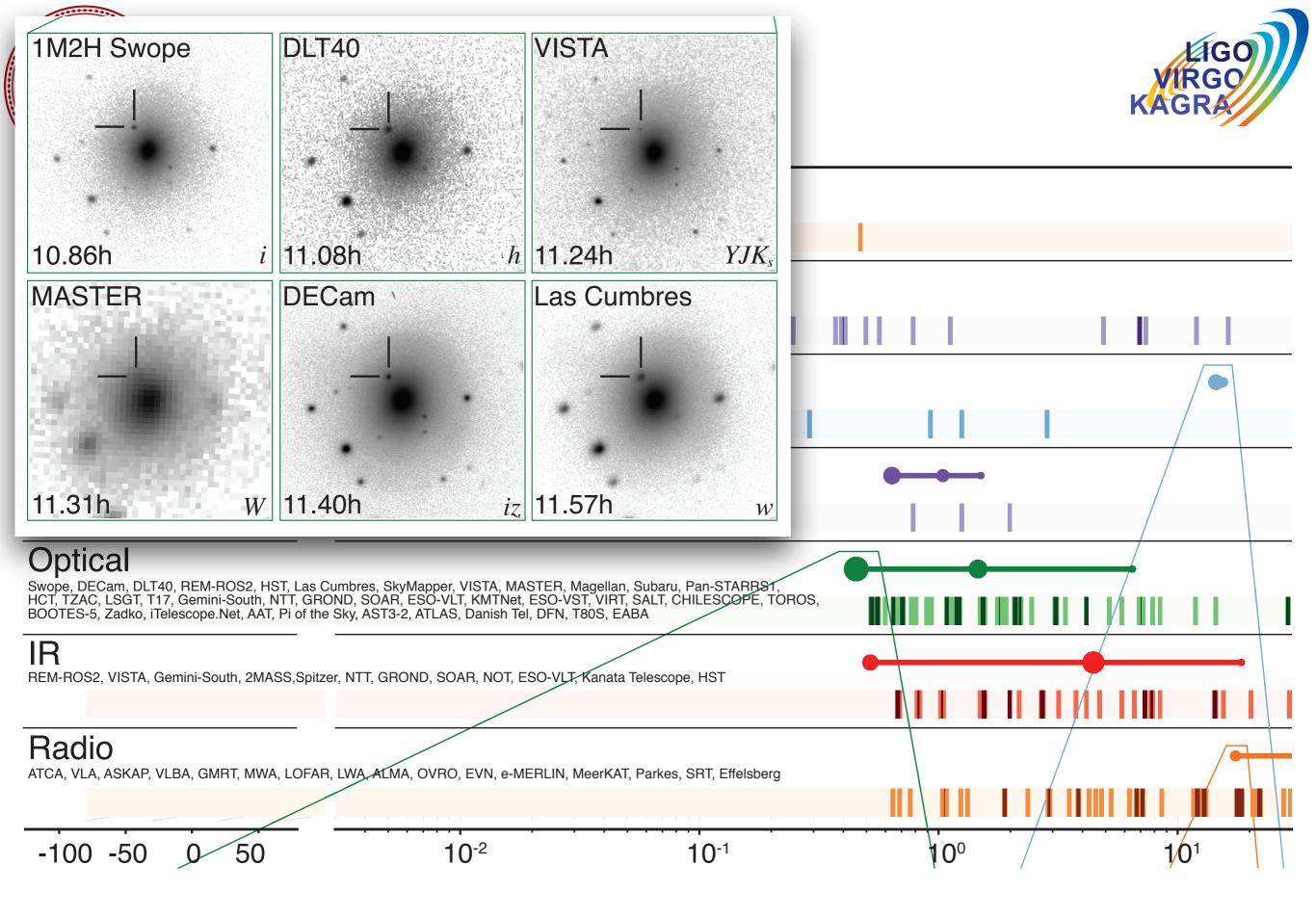


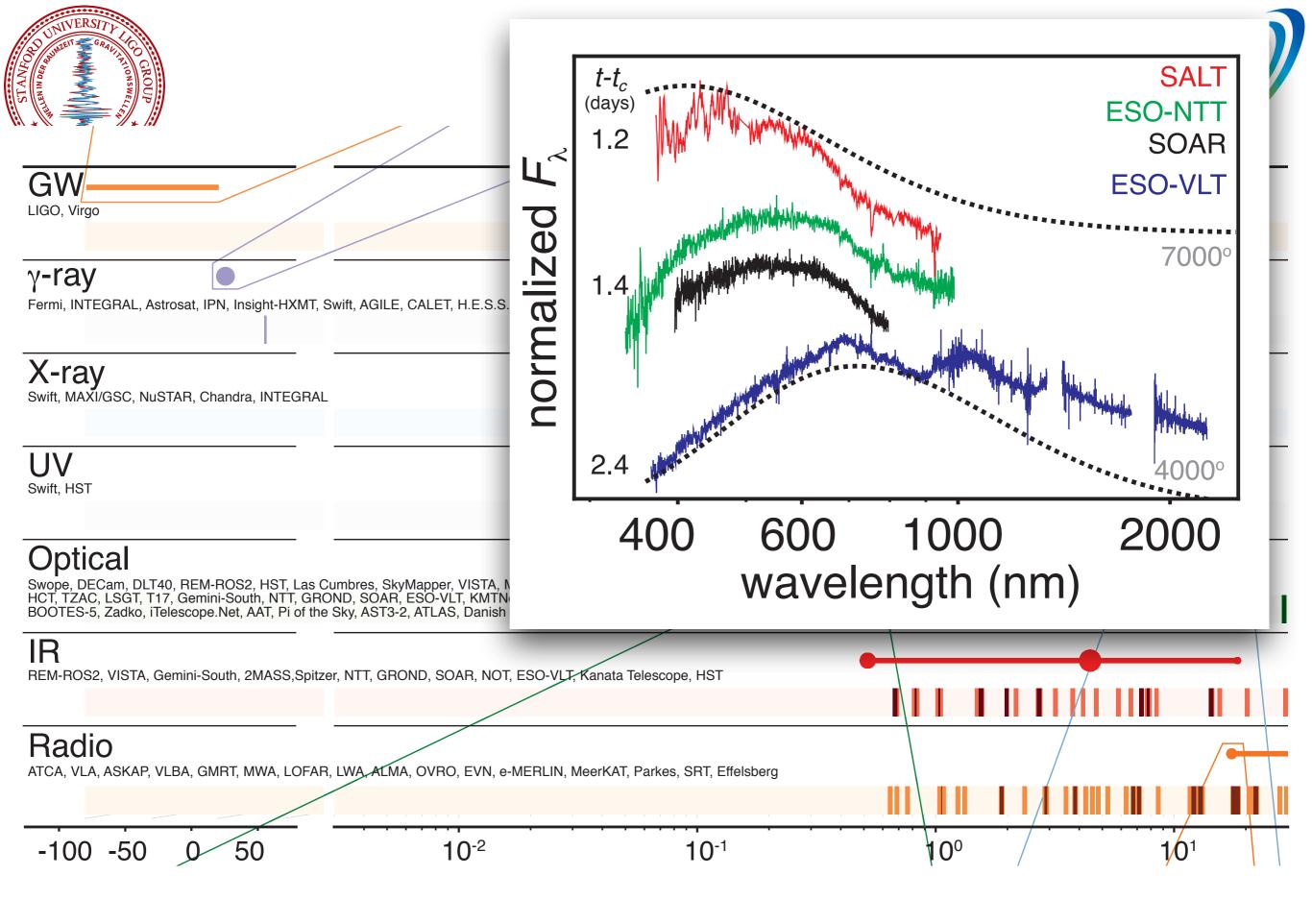


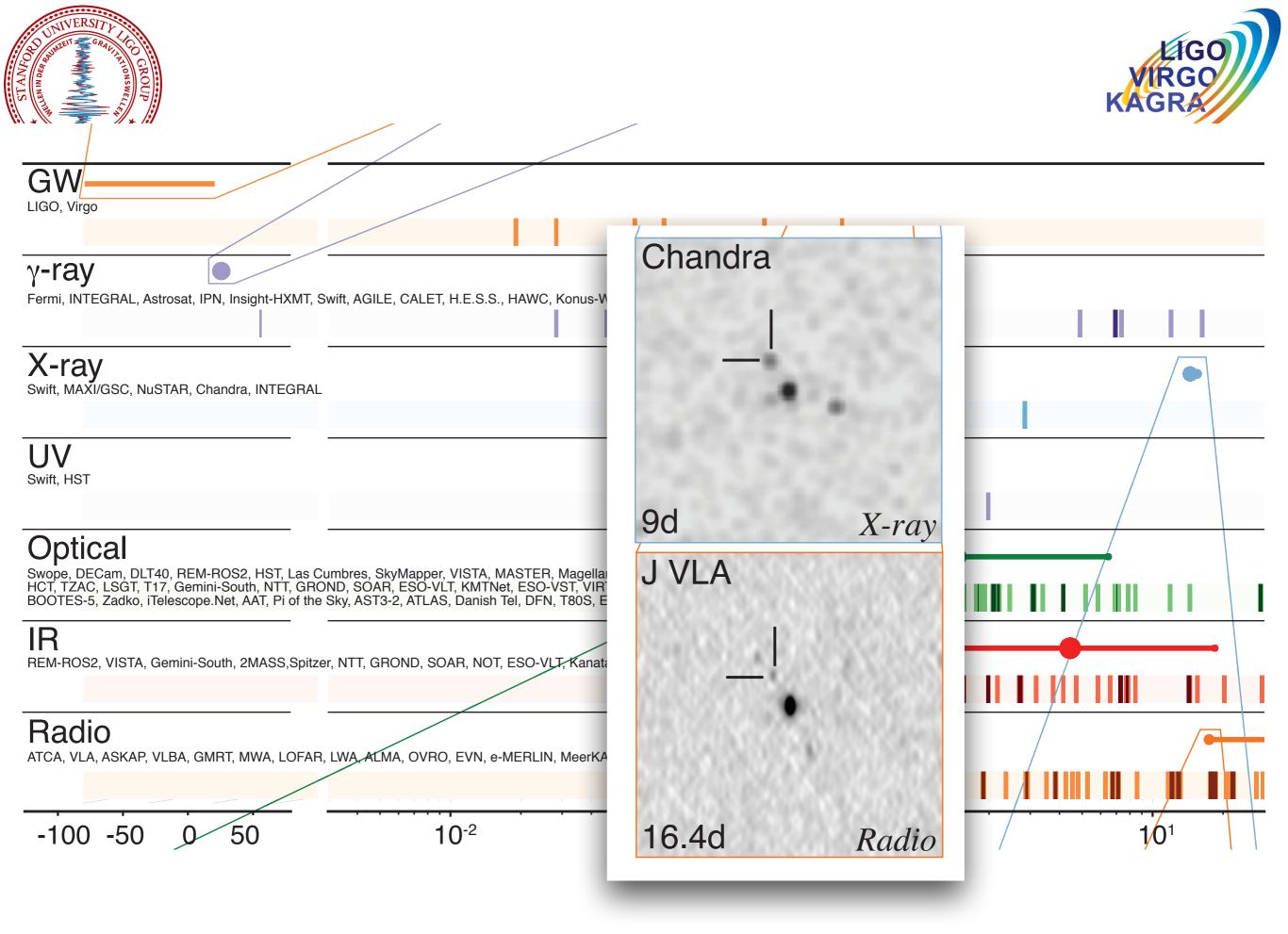
There is matter, and we can watch it

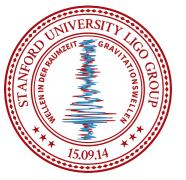






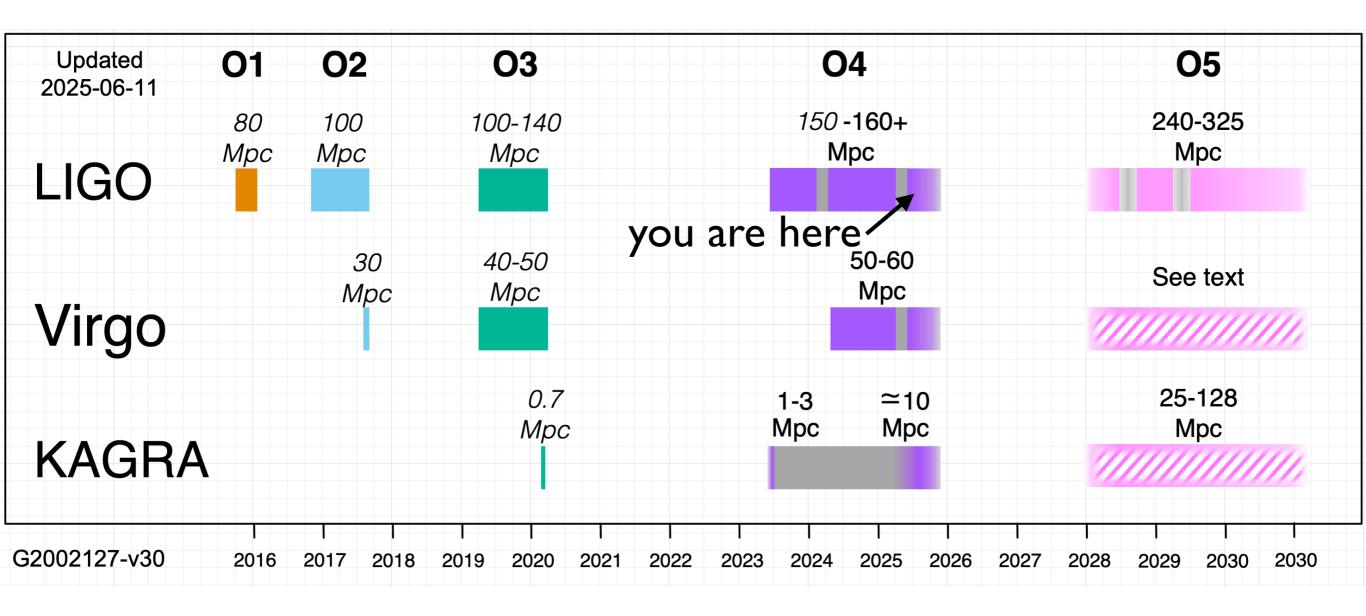






#### Where are we now?



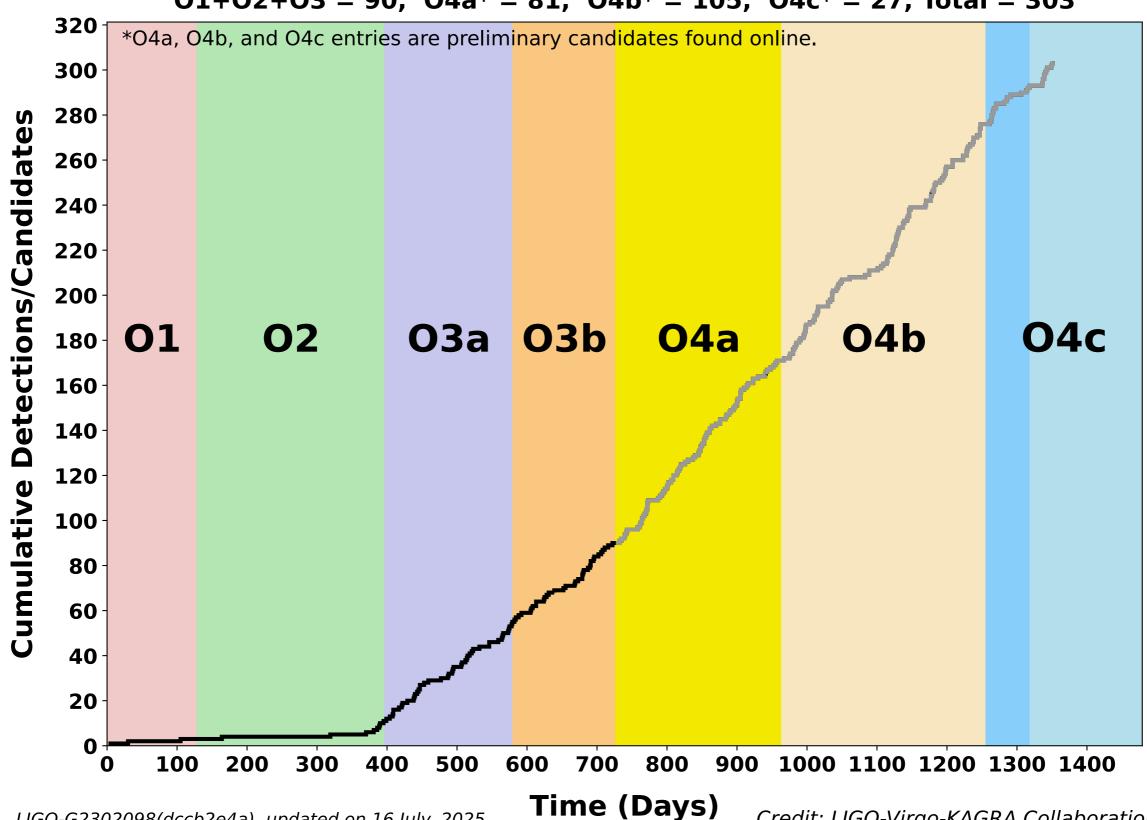




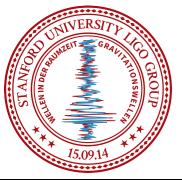
#### Lots of Events!







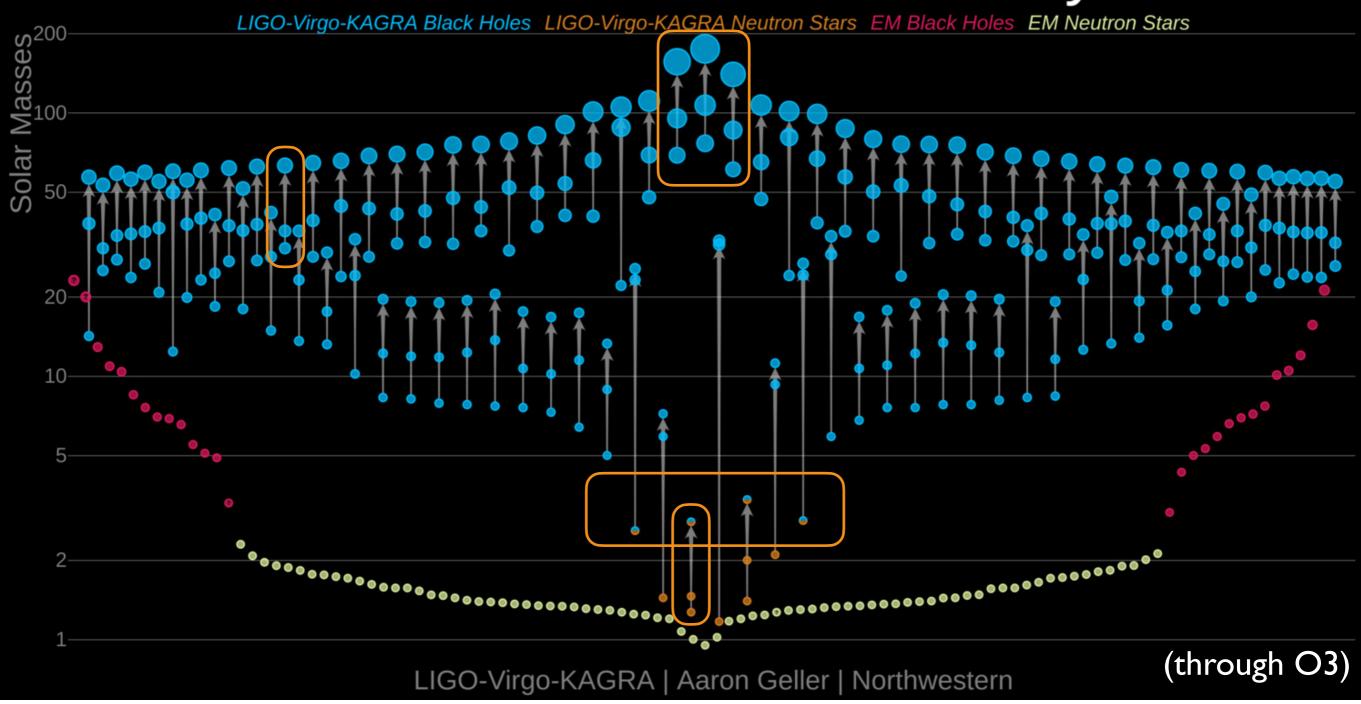




### Lots of Events!



# Masses in the Stellar Graveyard





#### notable events



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

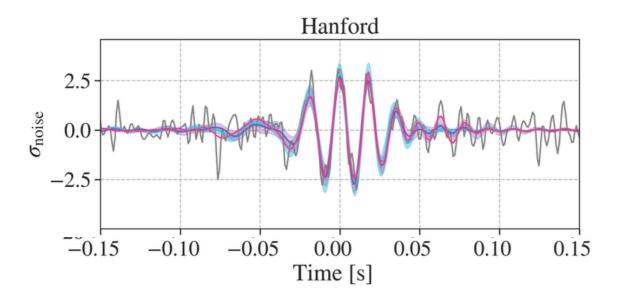
they are big

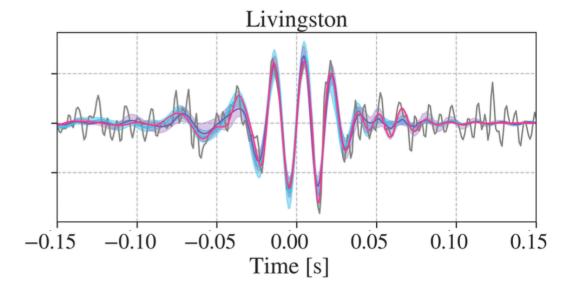
$$m_1 = 137^{+22}_{-17} M_{\odot} \quad m_2 = 103^{+20}_{-52} M_{\odot}$$

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

and spinning fast

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





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



# notable events



#### GW231123 - total mass of 190-265 $M_{\odot}$

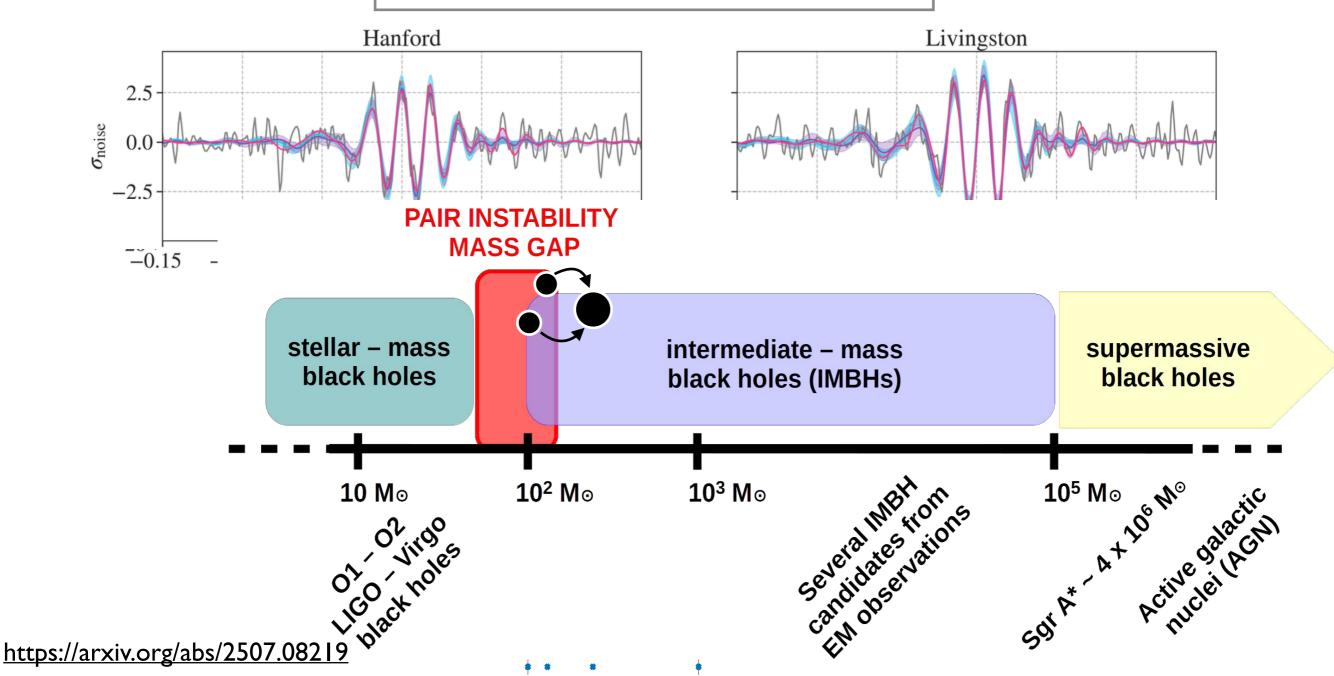
they are big

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

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

and spinning fast

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





# notable events



#### GW231123 - total mass of 190-265 $M_{\odot}$

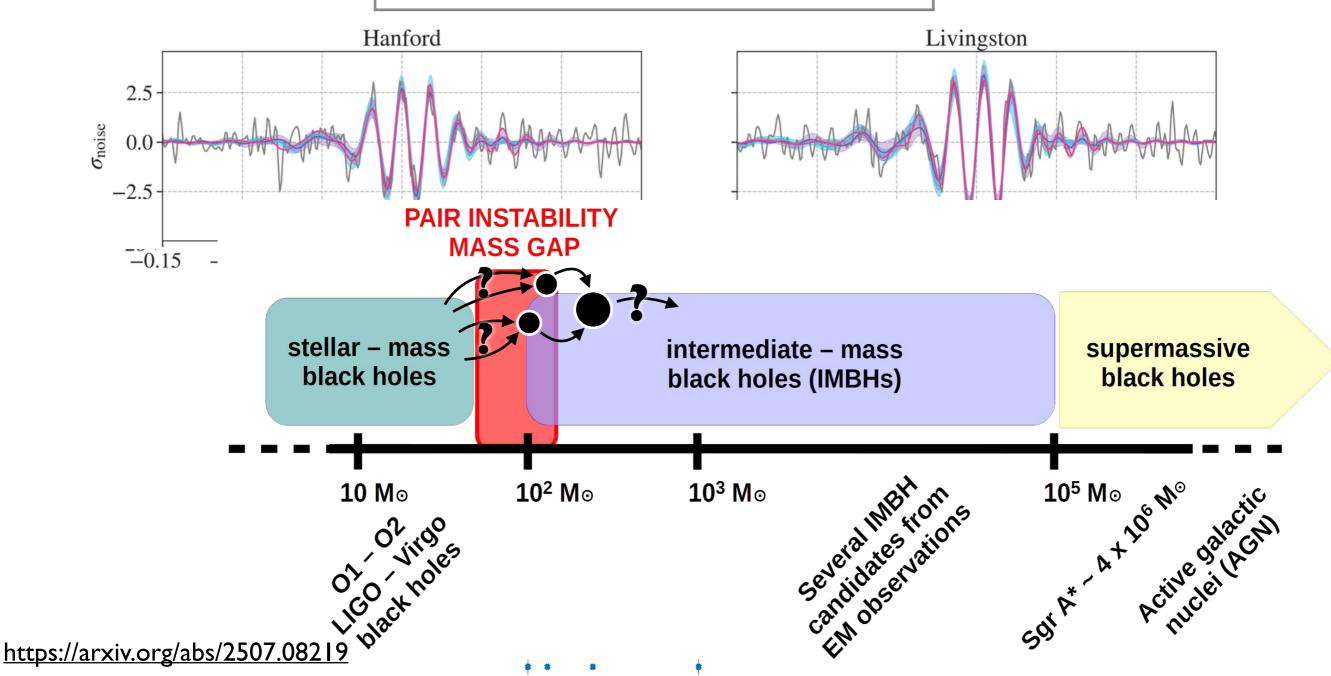
they are big

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

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

and spinning fast

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



# Expansion of the Universe

Measuring the Hubble constant H<sub>0</sub> with gravitational waves because the 2 best measurement do not agree?!

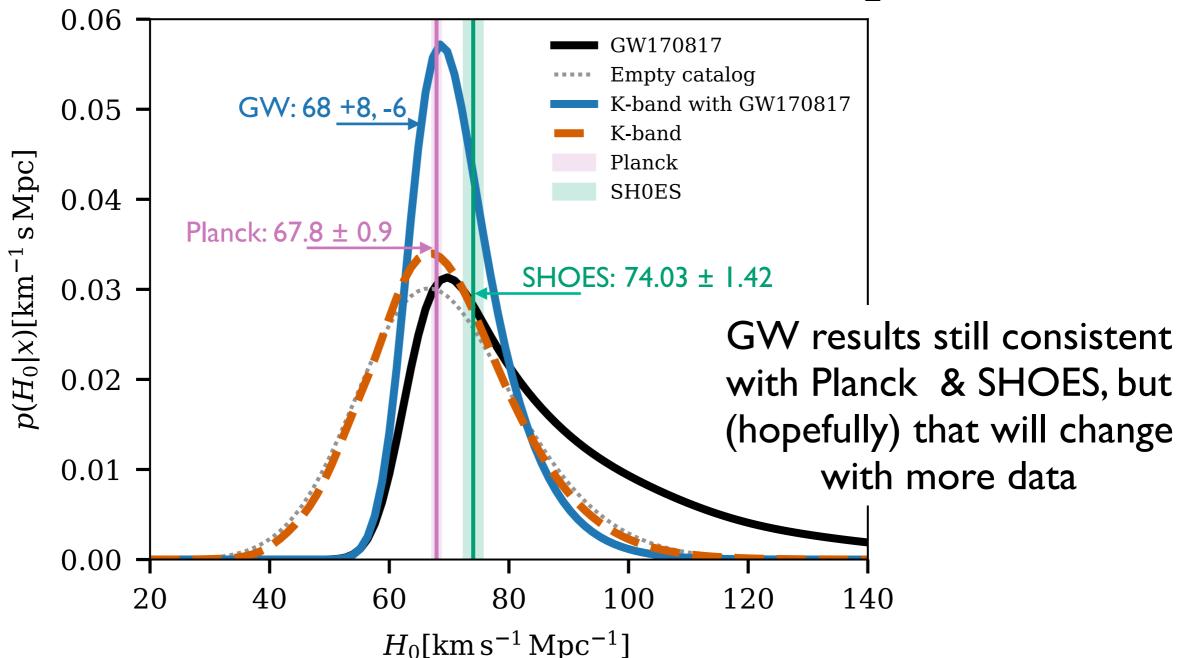


Figure 9. Hubble constant posterior for several cases. Gray dotted line: posterior obtained using all dark standard sirens without any galaxy catalog information and fixing the BBH population model. Orange dashed line: posterior using all dark standard sirens with GLADE+ K-band galaxy catalog in- formation 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<sub>0</sub> inferred from the CMB anisotropies (Ade et al. 2016) and in the local Universe from SH0ES (Riess et al. 2019) respectively.



# Testing General Relativity



So far, Einstein is getting an A+

- Speed of gravity = speed of light. Measured bounds are  $-3\times10^{-15}$  and  $+7\times10^{-16}$  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.

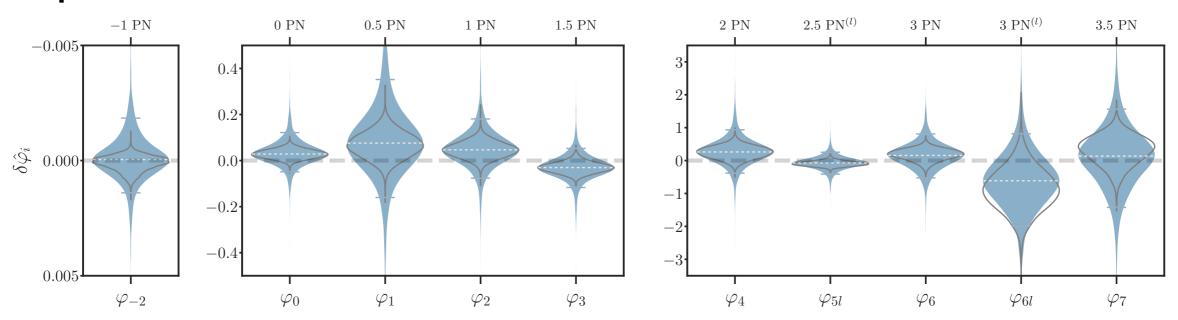
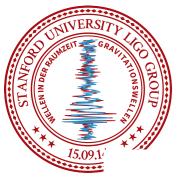


FIG. 7. Combined GWTC-3 results for the parametrized deviation coefficients of Sec. V A. Filled distributions represent the results obtained hierarchically combining all events. This method allows the deviation coefficients to assume different values for different events. Unfilled black curves represent 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.

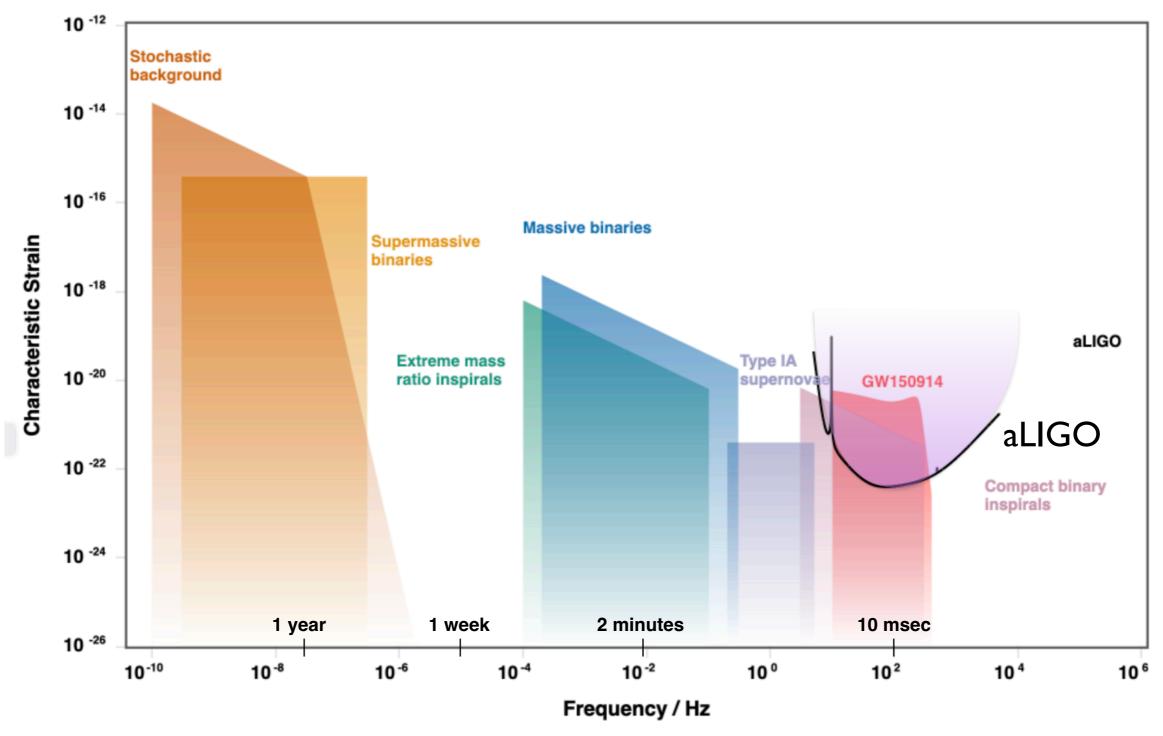
speed of gravity: <a href="https://arxiv.org/abs/1710.05834">https://arxiv.org/abs/1710.05834</a> tests of GR, GWTC 3: https://arxiv.org/abs/2112.06861



## There is so much more...



#### **Gravitational Wave Detectors and Sources**

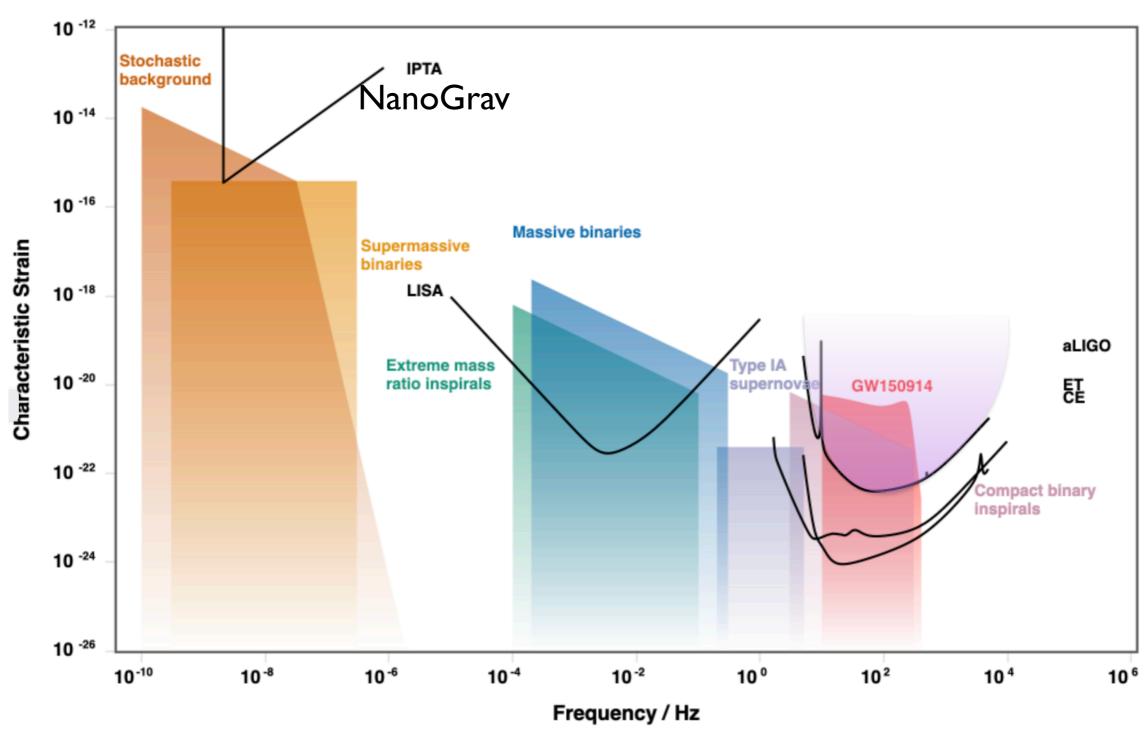




## There is so much more...



**Gravitational Wave Detectors and Sources** 





Pulsar timing KAGRAN



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

The "arms" are a few thousand lightyears long!

Measure correlations

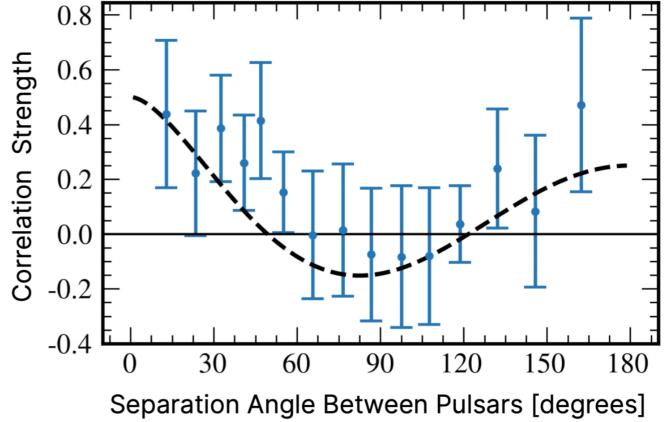
https://www.nsf.gov/news/mmg/media/images/vlasunrisejuly2008\_h.jpg

NANOgrav (USA) uses 68 pulsars

# Strength

# Pulsar timing



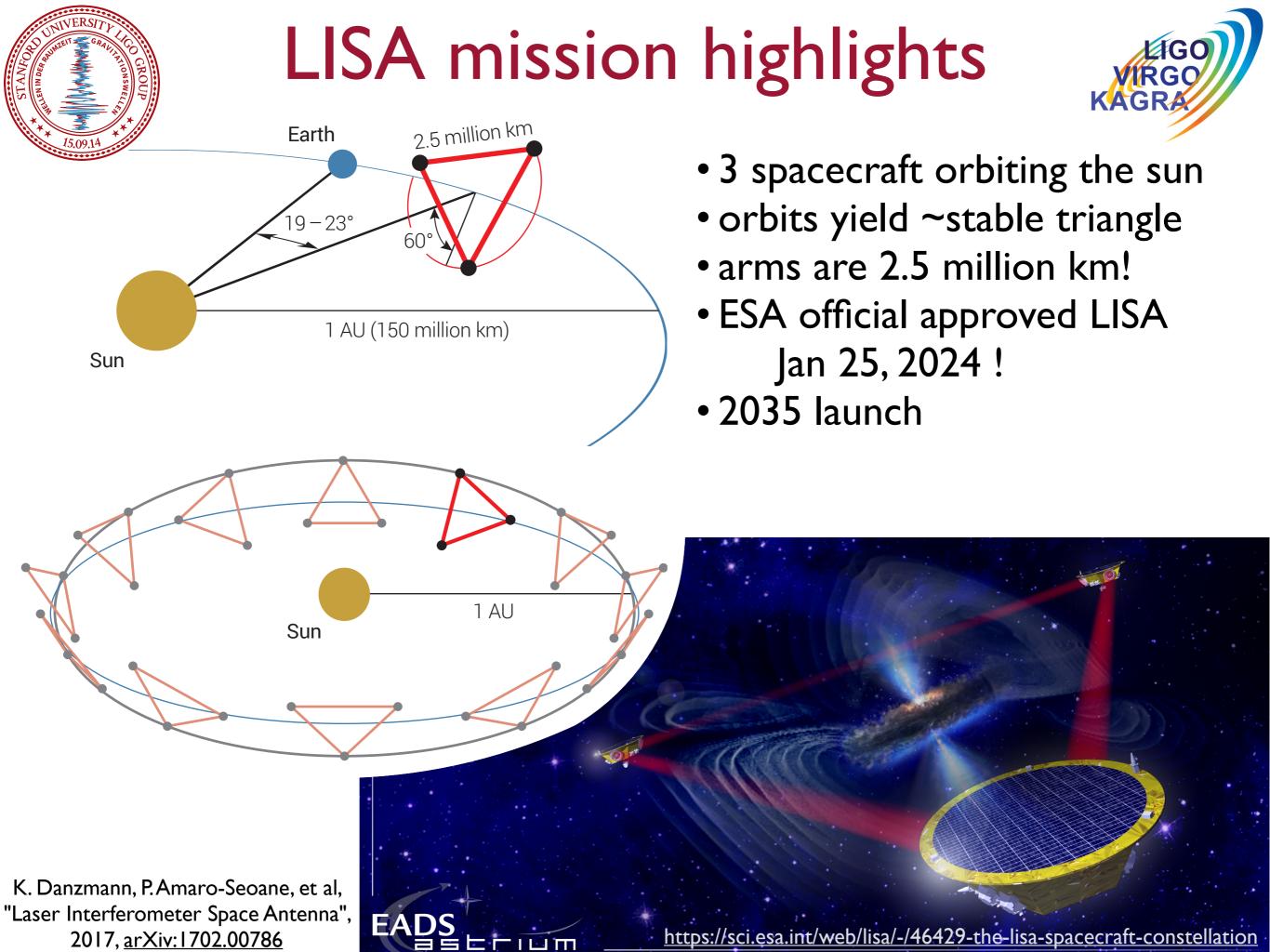


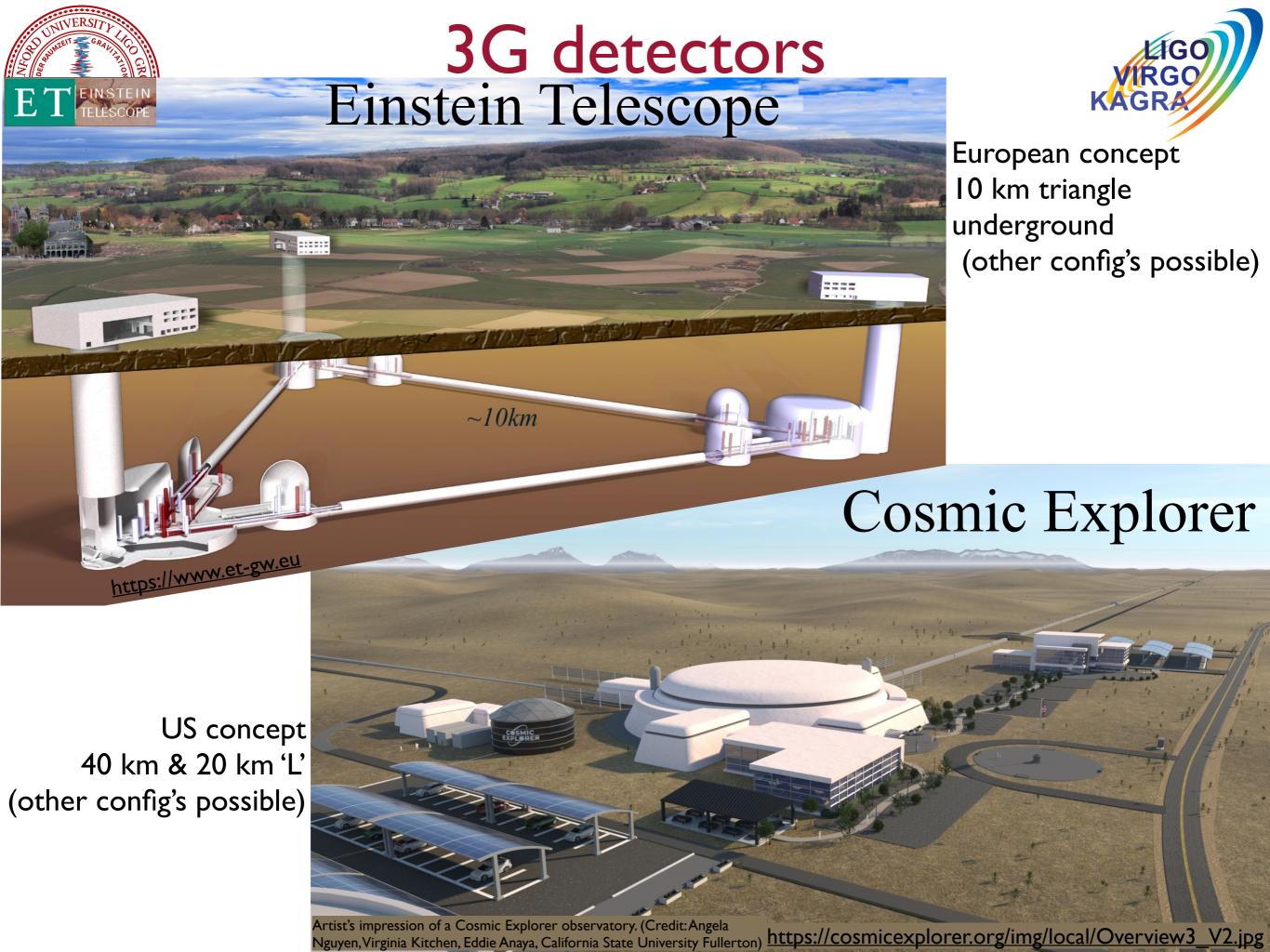
NANOgrav 15 year data release, June 29, 2023

NANOgrav (USA) uses 68 pulsars

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

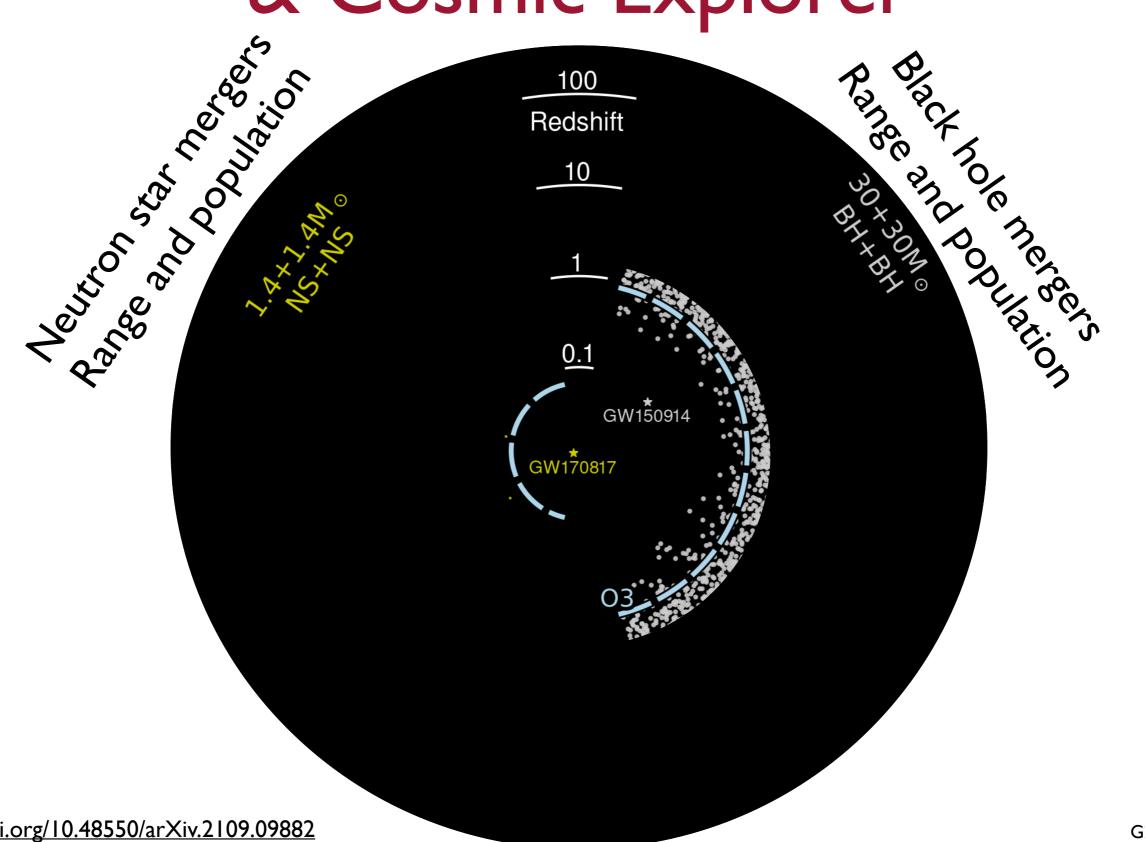


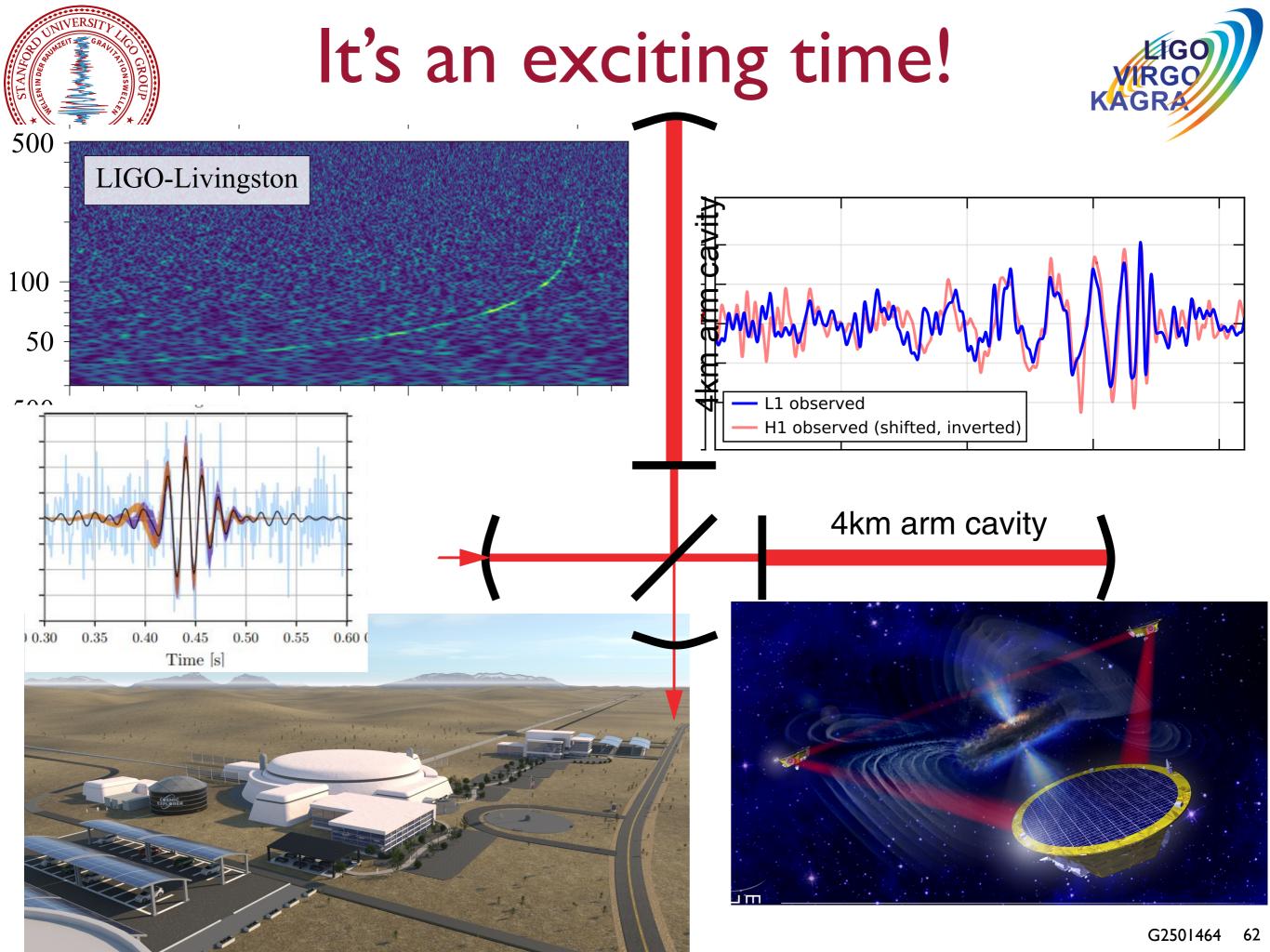


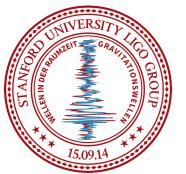




# Science w/ Einstein Telescope Einstein Einstein Telescope Einstein & Cosmic Explorer

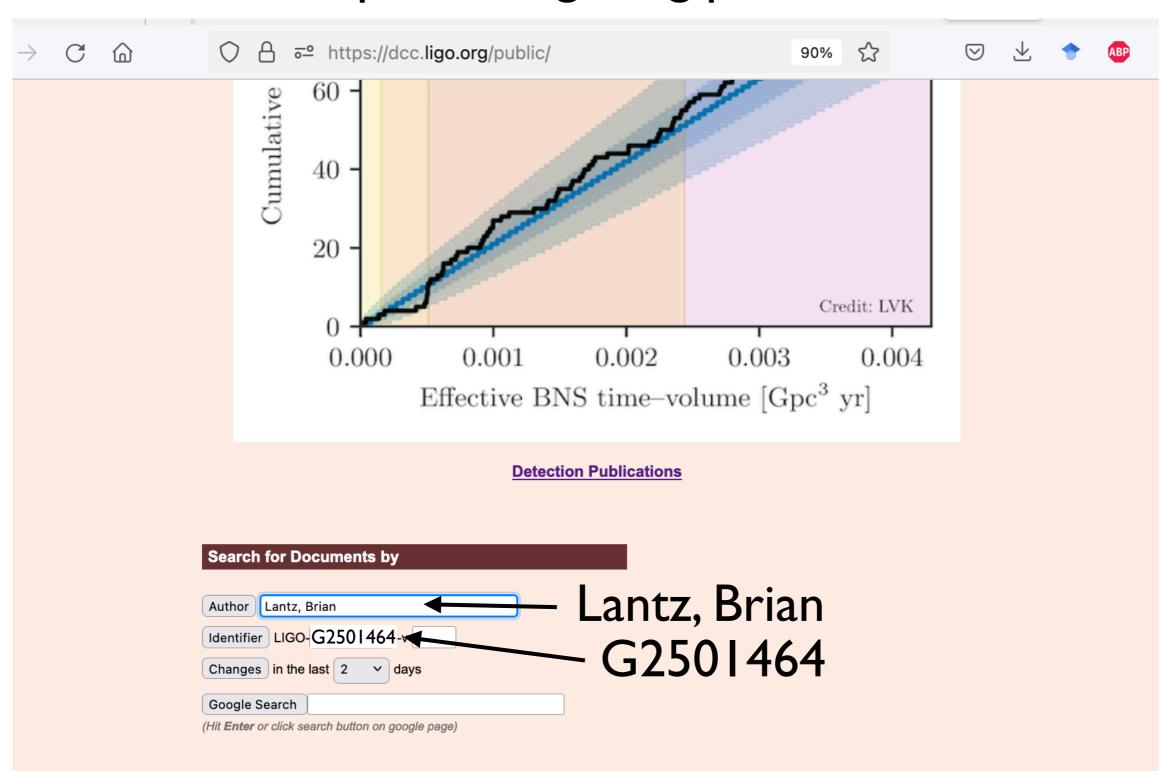






### download the slides?

slides are at LIGO's Document Control Center <a href="https://dcc.ligo.org/public/G2501464">https://dcc.ligo.org/public/G2501464</a>





# Other good links:

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

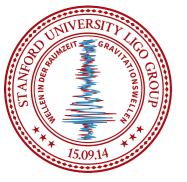
LIGO Lab home page https://www.ligo.caltech.edu/

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/

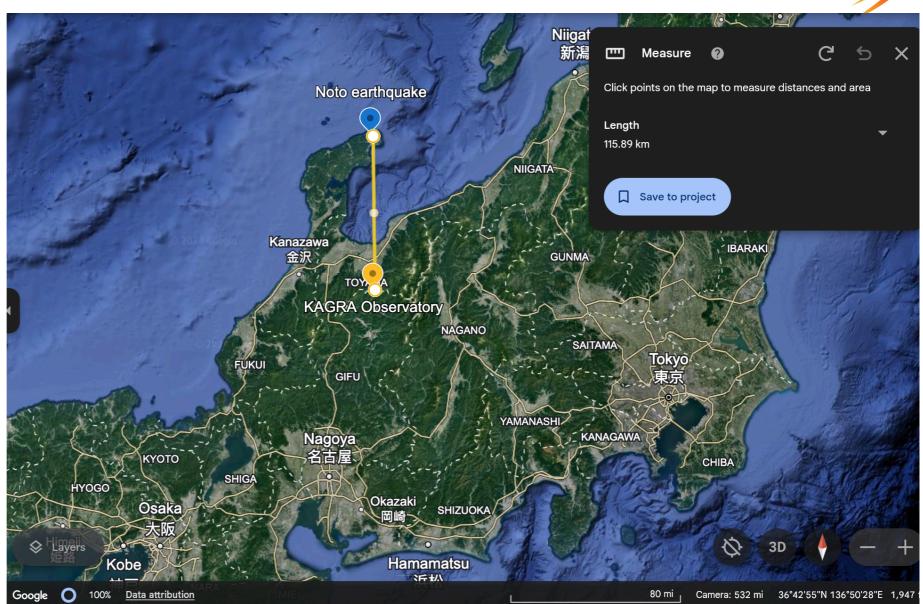


# Earthquake near KAGRA



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.

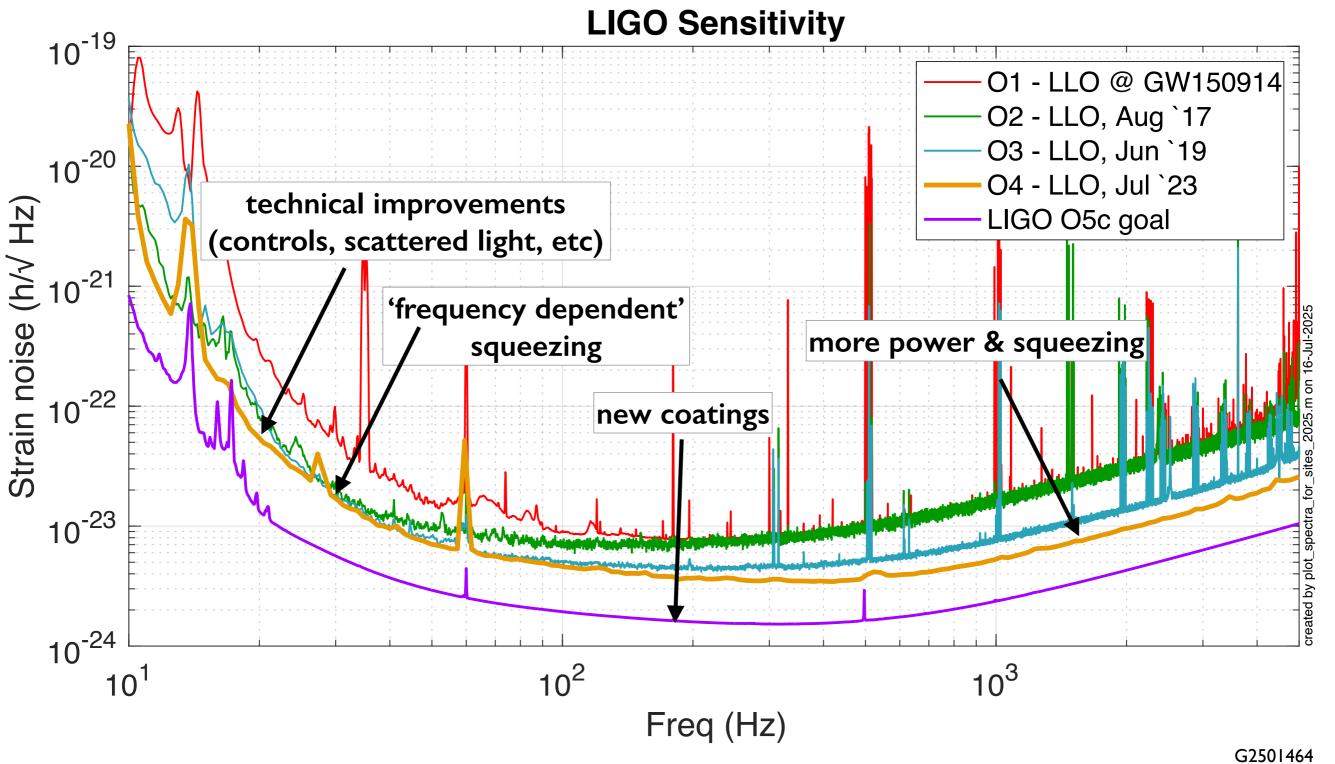


KAGRA had no fatalities and no significant damage to the mine tunnels, but detector is damaged, extent is still ??



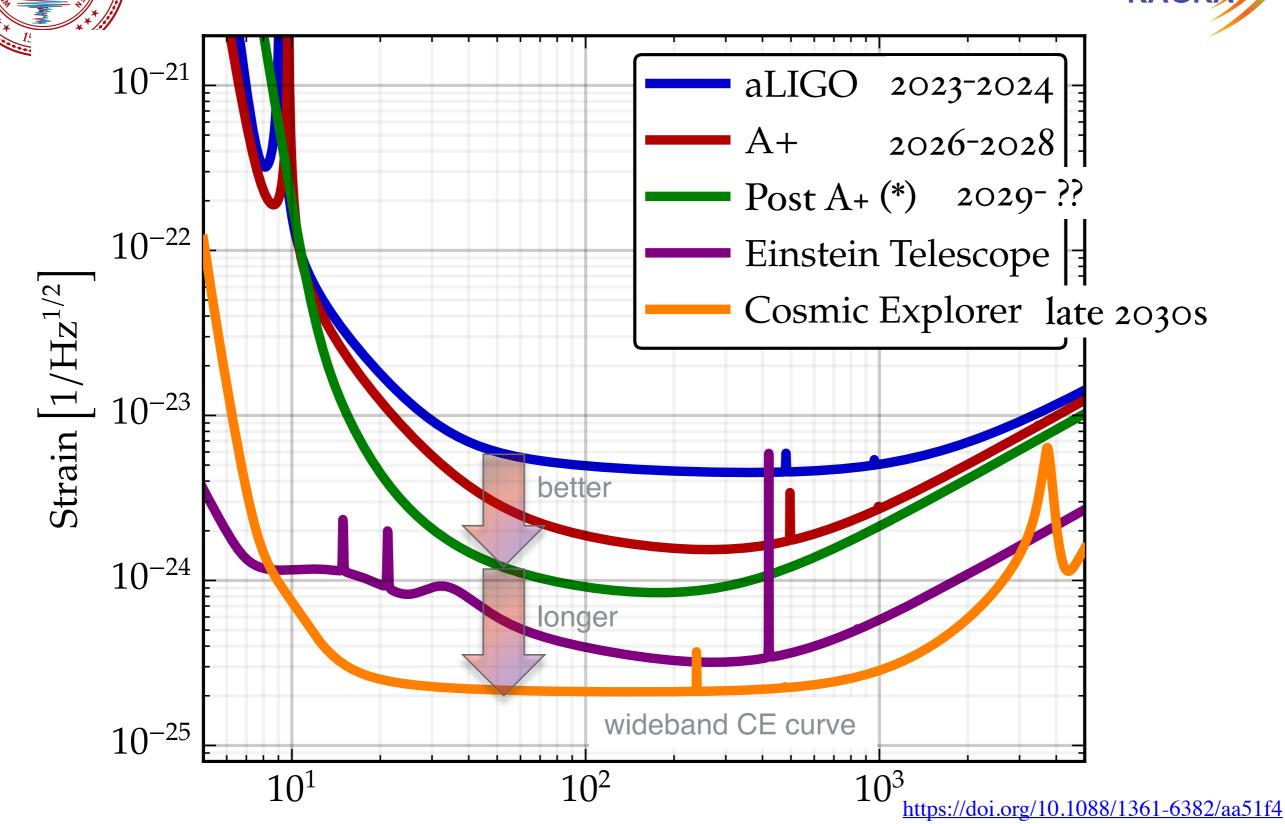
# LIGO A+ (for O5)





# 3G detectors





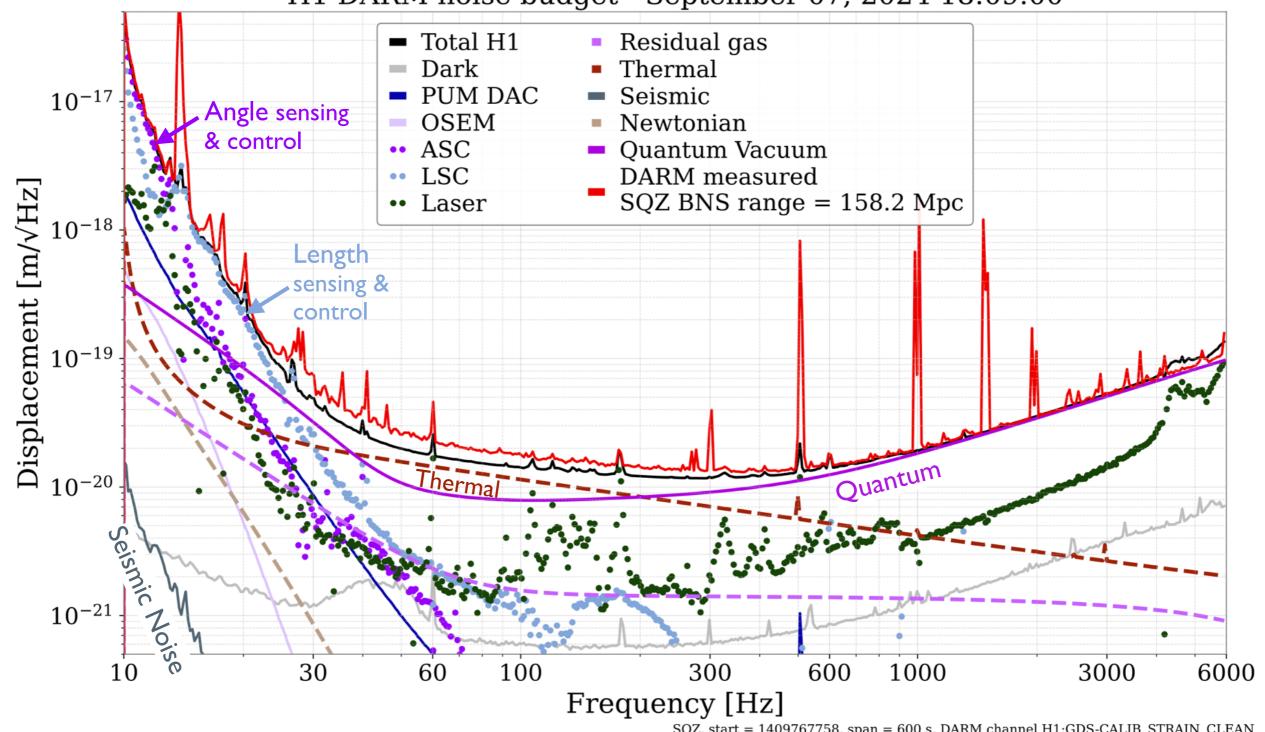
Frequency [Hz]



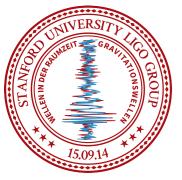
# LIGO noise budget







SQZ, start = 1409767758, span = 600 s, DARM channel H1:GDS-CALIB\_STRAIN\_CLEAN

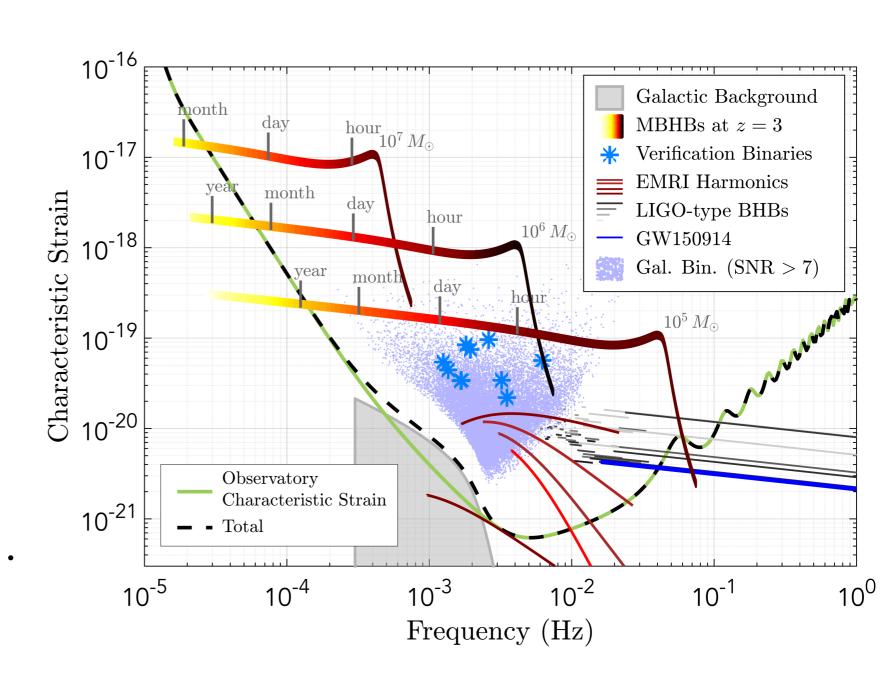


#### LISA Science



#### 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...

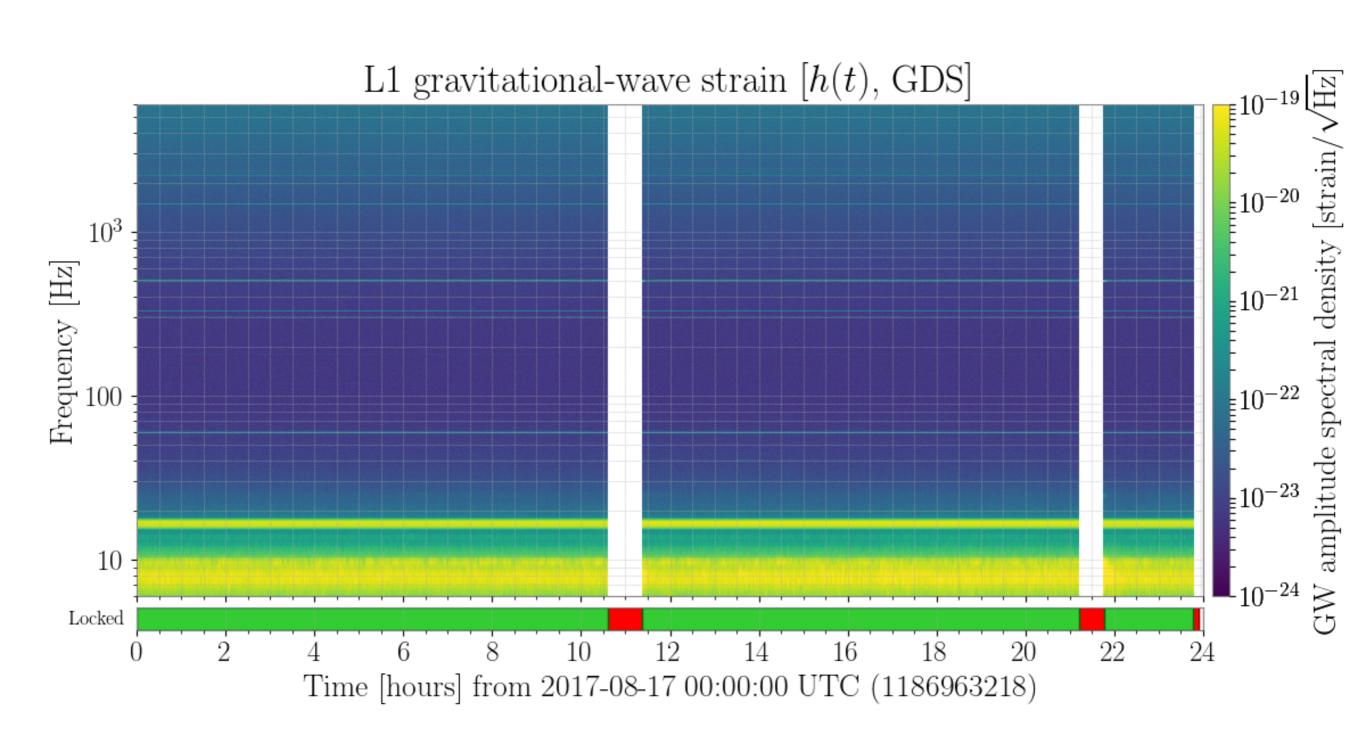




# Watch for changes...



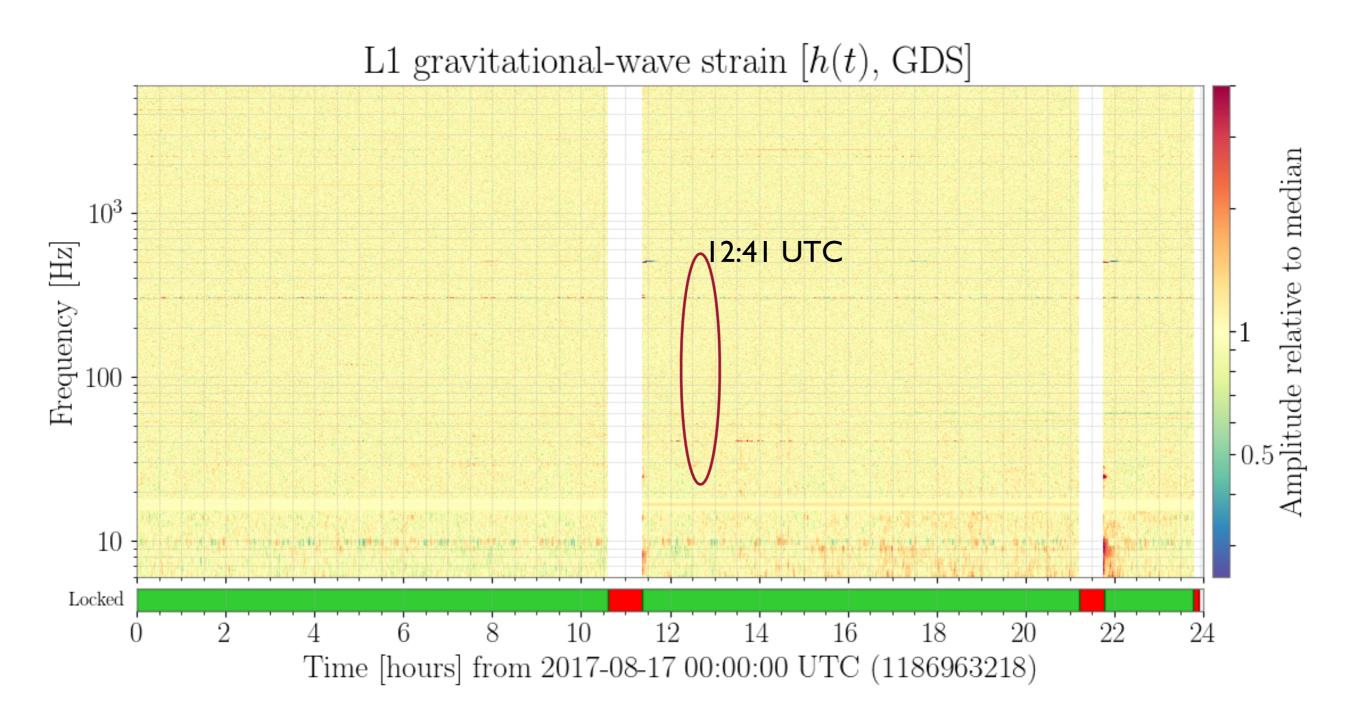
#### Spectrogram - I day at LLO

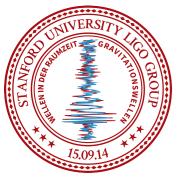


# Watch for changes...



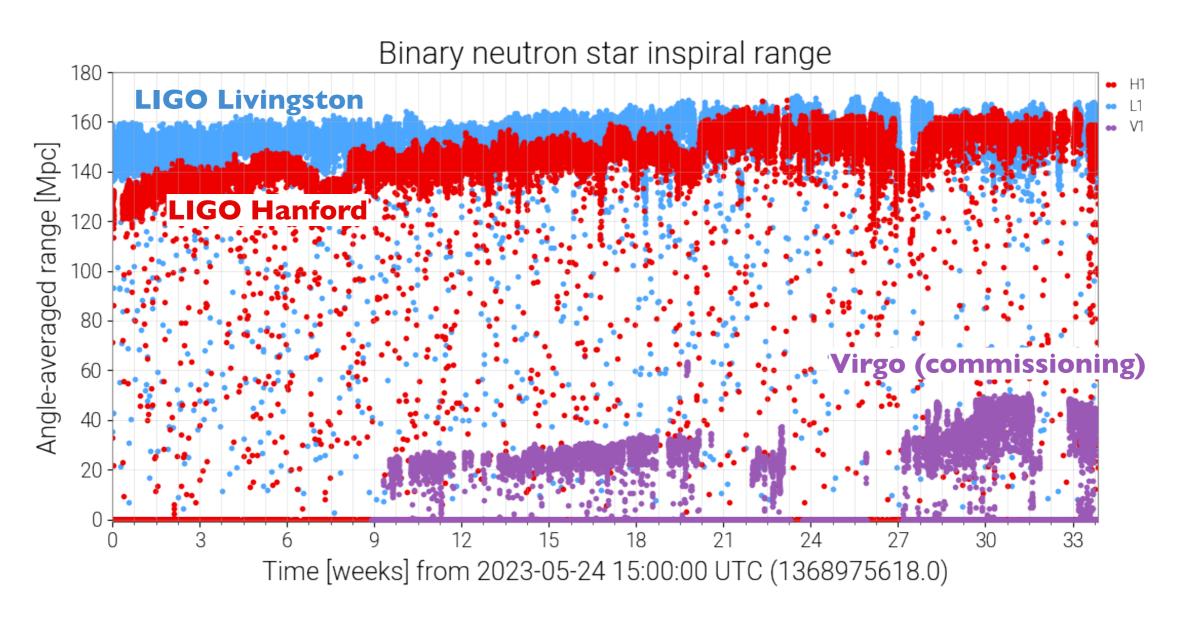
Normalized Spectrogram - I day at LLO





# range in O4a







# Range



