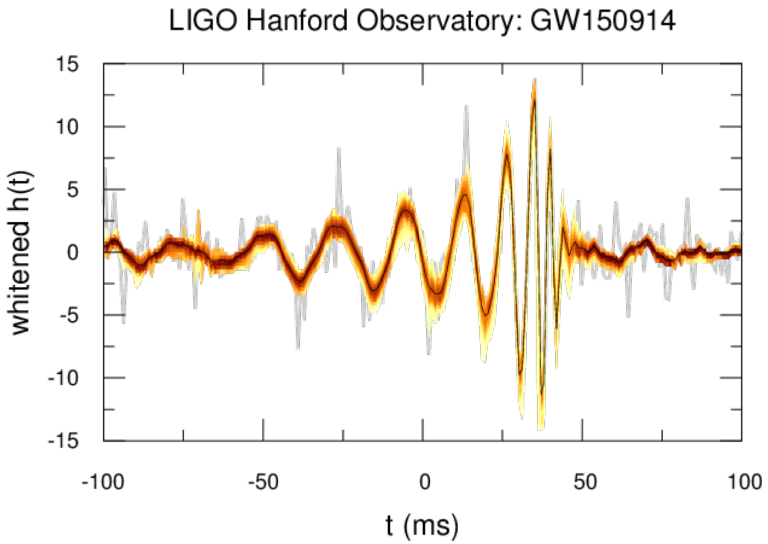
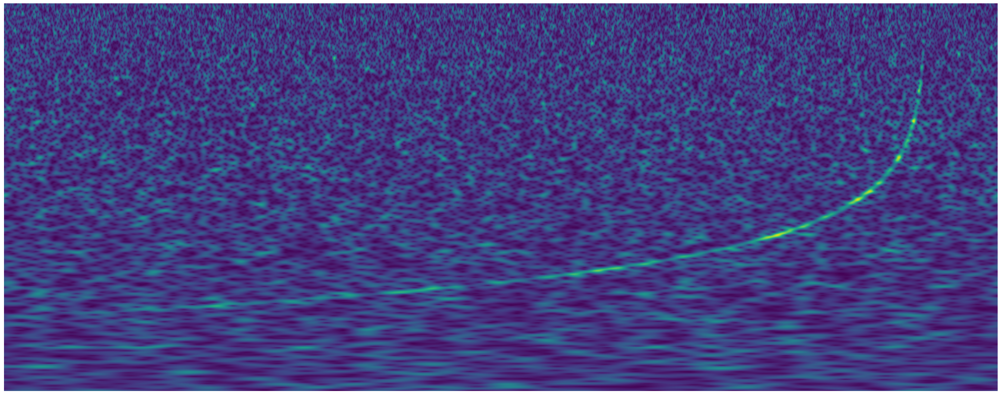
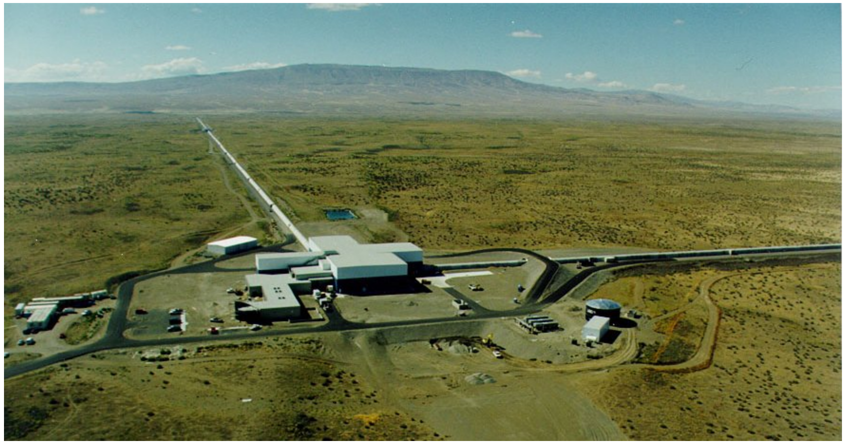
# Highlights from Recent LIGO and Virgo Observations





**GW170817**



**Keith Riles**
**University of Michigan**

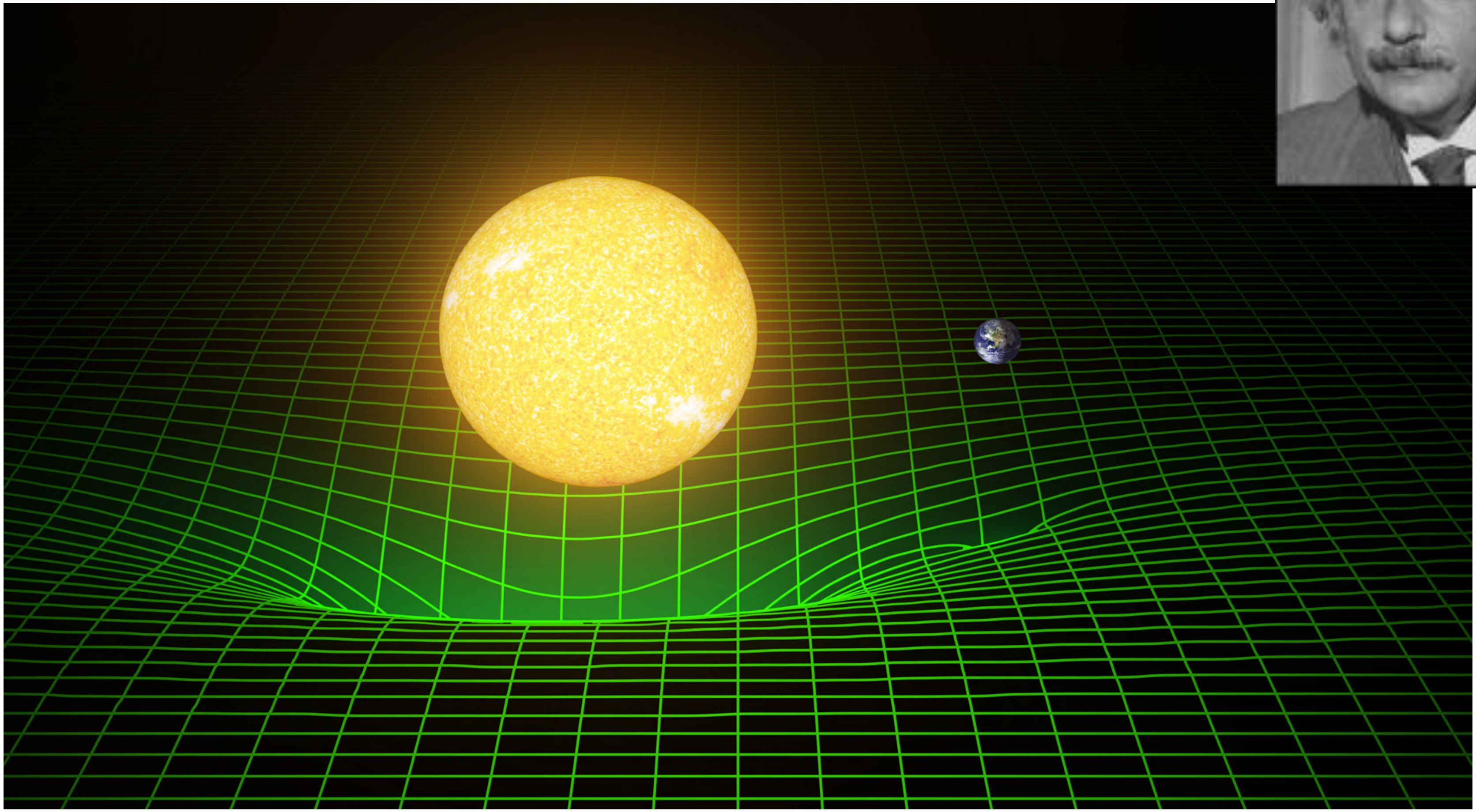
**for the LIGO Scientific Collaboration**
**and Virgo Collaboration**

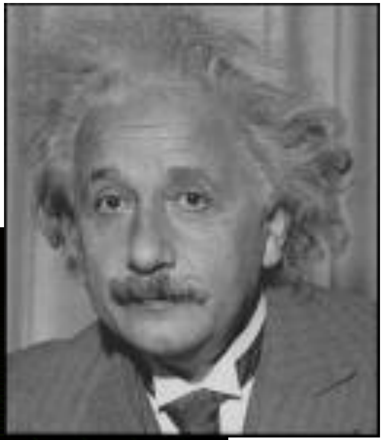
**University of Michigan**
**Physics Department Colloquium**
**October 25, 2017**

LIGO G1702219

# Einstein’s Gravity

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

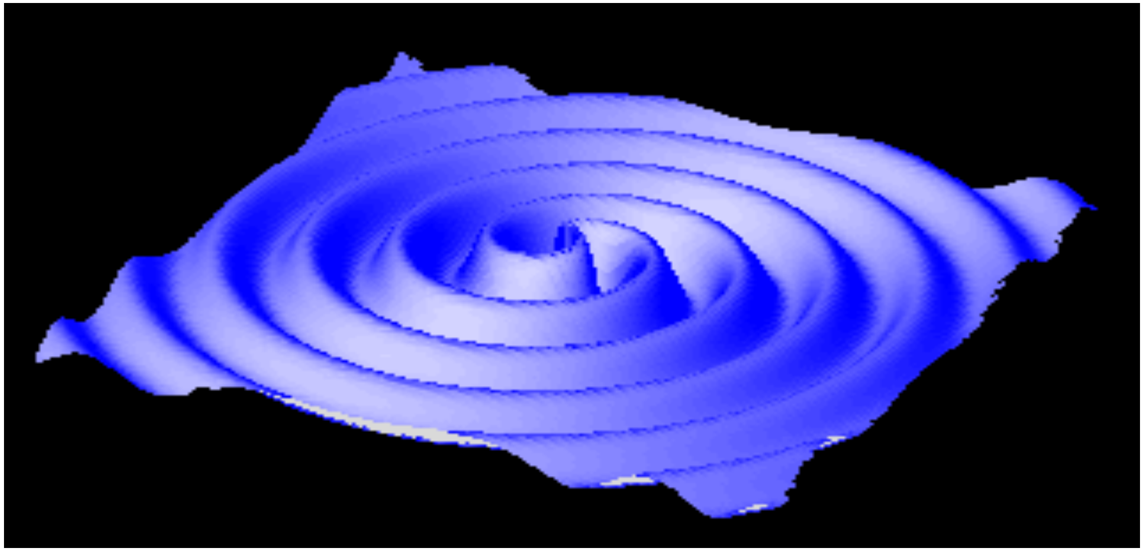




**John Wheeler**: **Matter tells spacetime how to curve, and curved space tells matter how to move**

# Compact Binary Systems

Now imagine two very compact stars (neutron stars or black holes) in a tight binary orbiting system:



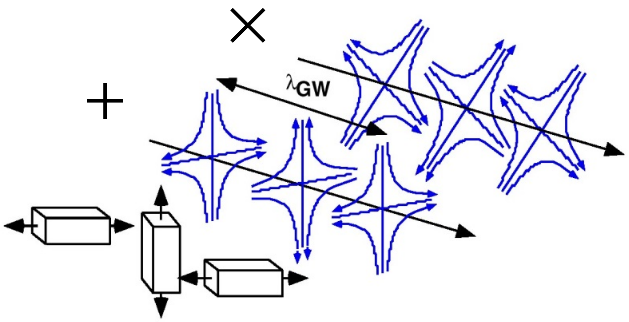
Courtesy Jet Propulsion Laboratory

Space is “swirled” by the orbiting stars, creating a ripple that propagates to distant regions of the universe

$$G_{\mu\nu} = 8\pi T_{\mu\nu} \longrightarrow (\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2})h_{\mu\nu} = 0$$

Metric wave disturbance (weak field)

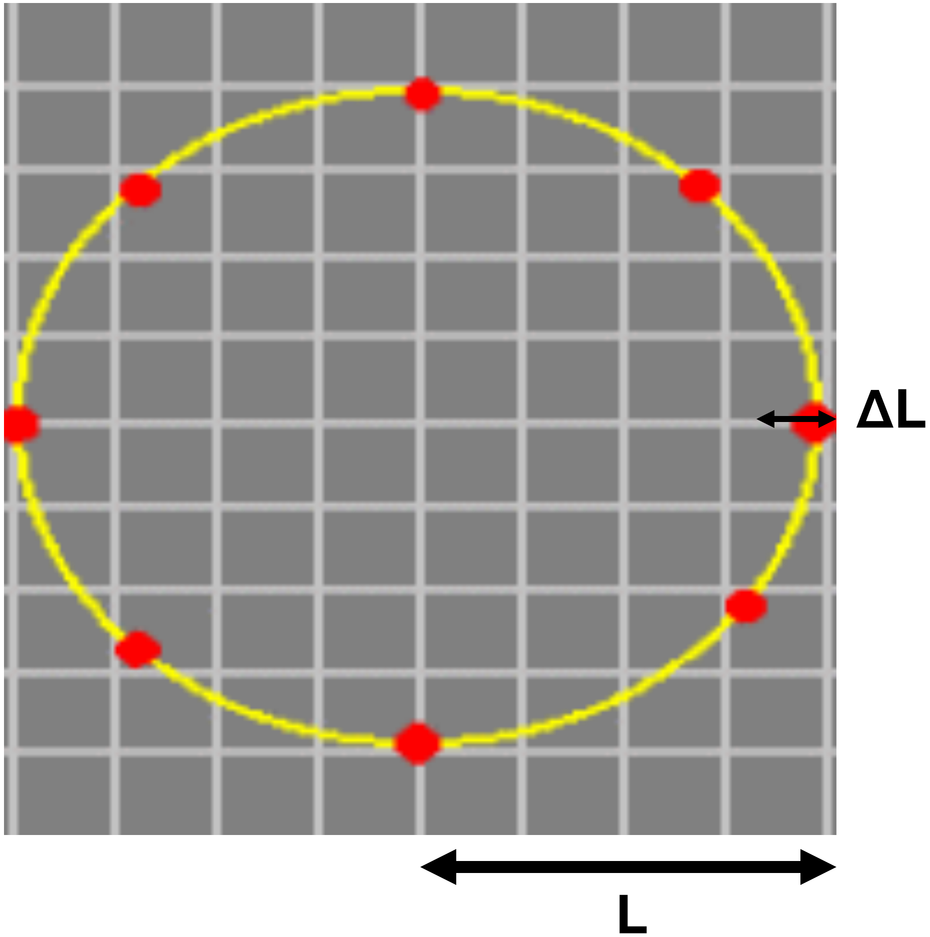
$$\longrightarrow h_{\mu\nu} = h_+(t - z/c) + h_\times(t - z/c)$$



**How is the strength of a gravitational wave described?**

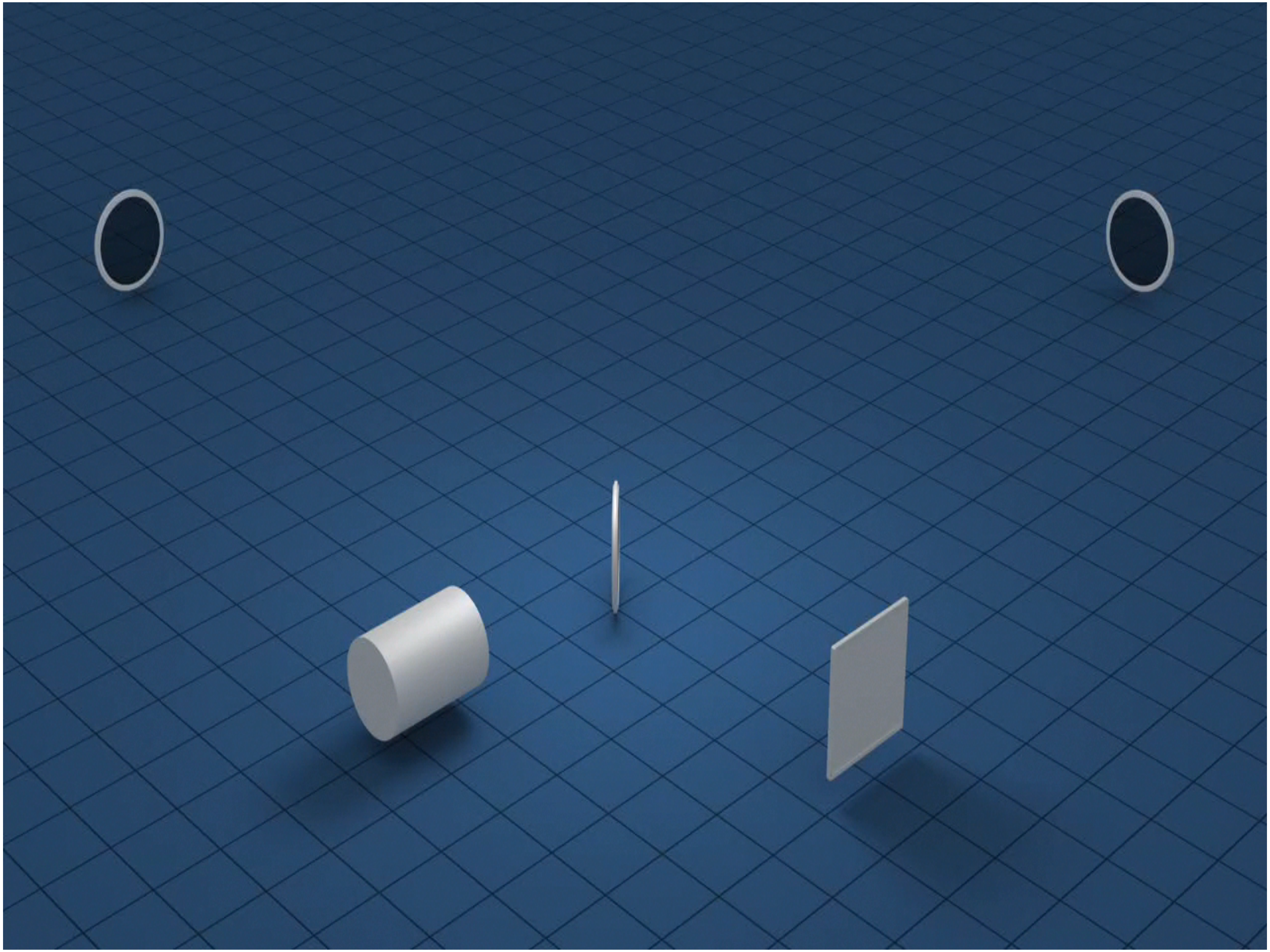
**By fractional change in distance, i.e., strain h(t)**

**h(t) ~ ΔL(t) / L**

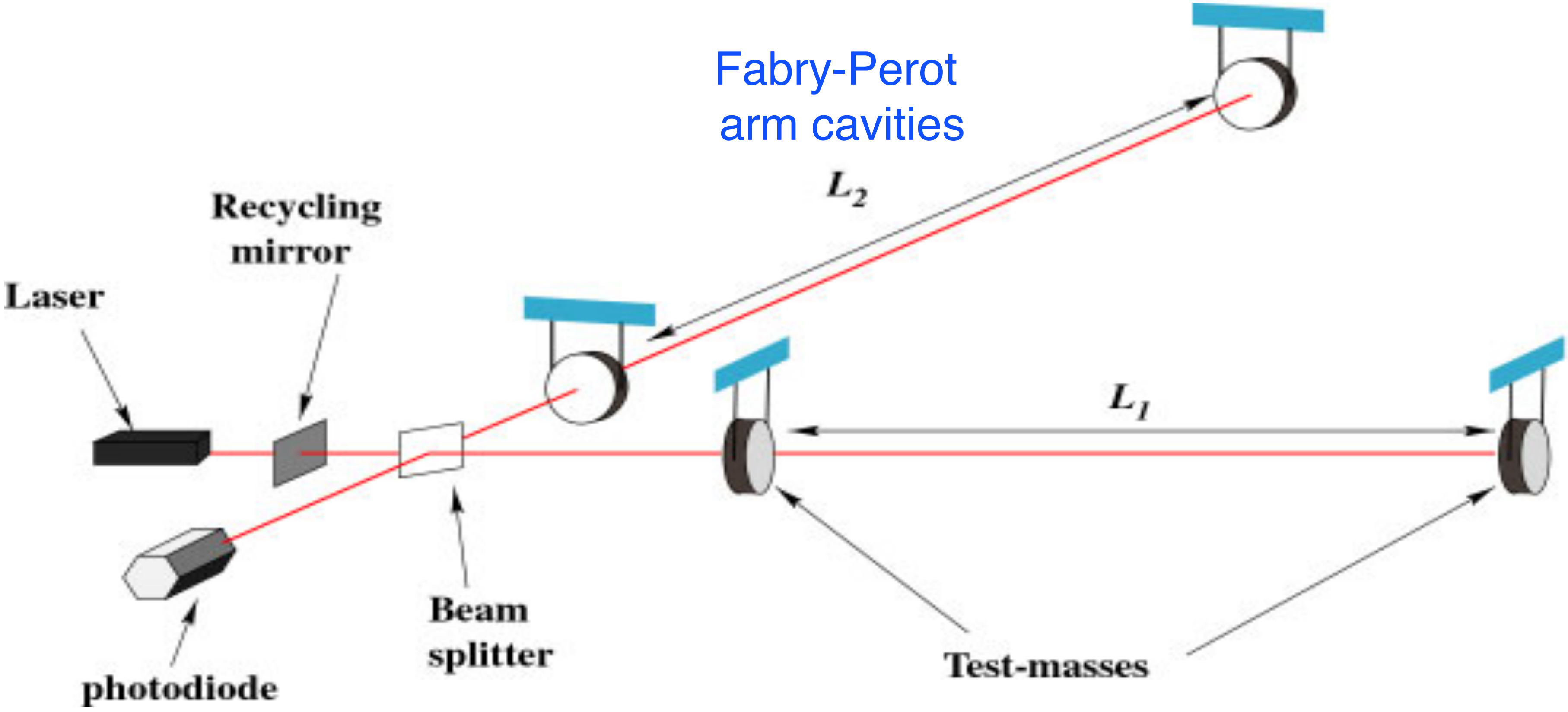


**→ Large L gives good lever arm on h [demo]**

# So how does one detect a gravitational wave?



# Adding more detail (Initial LIGO)

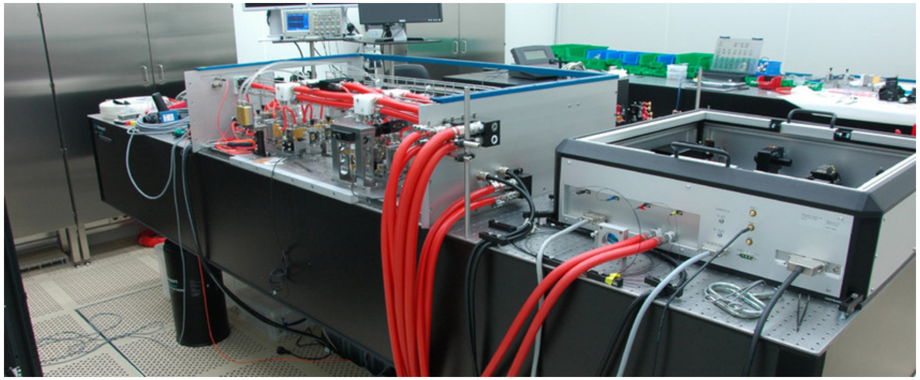


# Initial LIGO → Advanced LIGO

**Increased laser power:**

10 W → 200 W

Improved shot noise (high freq)



**Higher-Q test mass:**

Fused silica with better optical coatings

Lower internal thermal noise in band

**Increased test mass:**

10 kg → 40 kg

Compensates increased radiation pressure noise

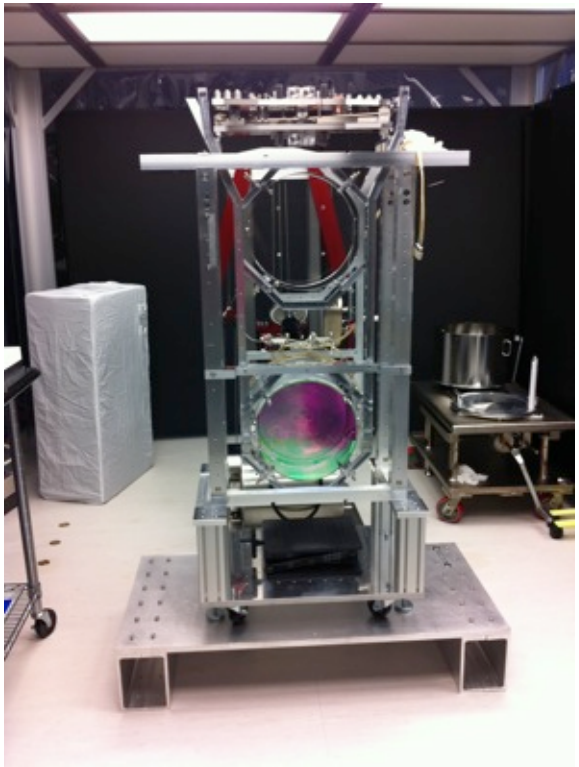
Photo credits: LIGO Lab

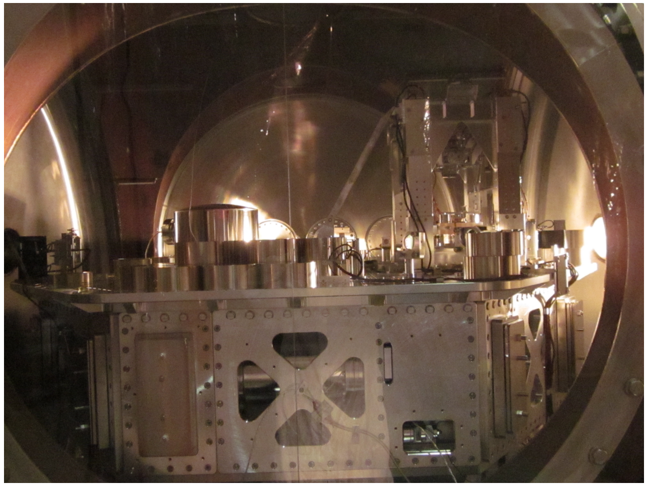
# *Initial LIGO → Advanced LIGO*

## New suspensions:

### Single → Quadruple pendulum

Lower suspensions thermal noise in bandwidth



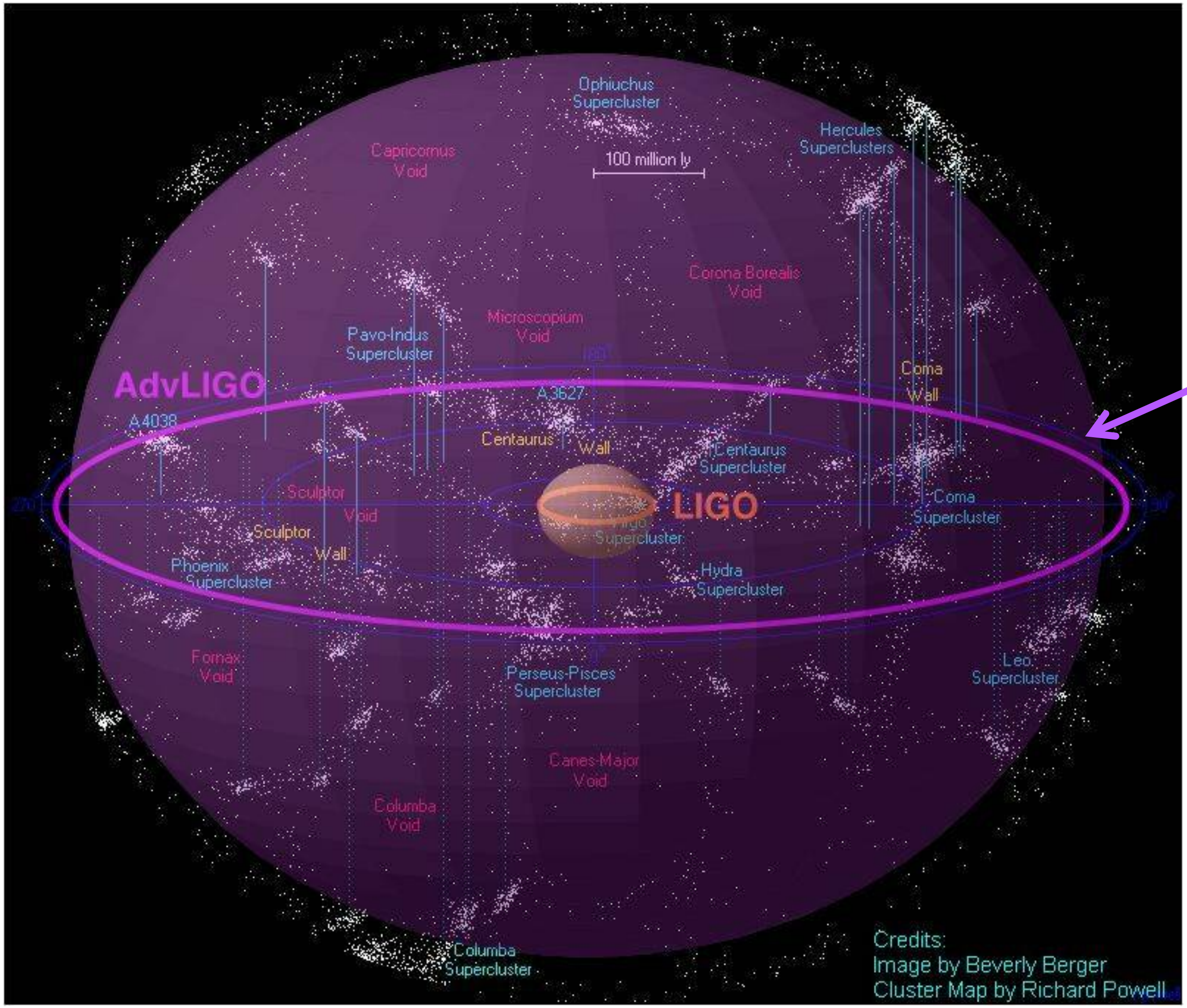


## Improved seismic isolation:

### Passive → Active

Lowers seismic “wall” to ~10 Hz

**Photo credits: LIGO Lab**



Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

**Full design sensitivity**

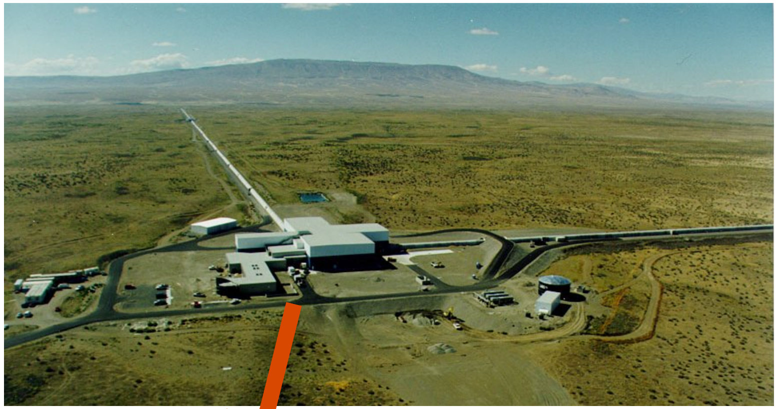
**Range increases by 10 → Volume increases by ~1000**

**Rate increases by ~1000**

**But not there yet!**

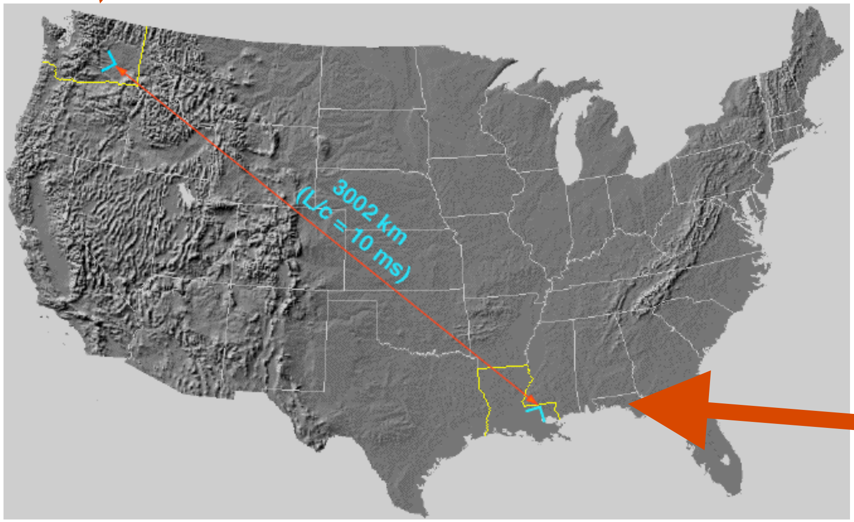
# LIGO Observatories

**Hanford**



Observation of nearly simultaneous (|Δt|<10 ms) signals 3000 km apart rules out terrestrial artifacts

Timing and antenna pattern give (some) directionality on sources



**Livingston**

# Virgo Observatory

3-km Michelson Interferometer just outside Pisa, Italy

Ongoing upgrade: Initial Virgo → Advanced Virgo

Less sensitive than LIGO, but valuable
→ Helps source triangulation by order of magnitude

LIGO

# "LIGO Logos"

LSC

# LIGO Scientific Collaboration – Feb 2016

TRINITY UNIVERSITY

UNIVERSITY OF MARYLAND

Andrews University

WASHINGTON STATE UNIVERSITY

CALIFORNIA STATE UNIVERSITY FULLERTON

UAH
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

WHITMAN COLLEGE

AMERICAN UNIVERSITY
WASHINGTON, DC

SONOMA
STATE UNIVERSITY

indigo

MONTCLAIR STATE UNIVERSITY

University of Glasgow

Australian National University

UNIVERSITY OF THE WEST of SCOTLAND
UWS

TEXAS TECH UNIVERSITY

清華大學
Tsinghua University

R·I·T

LELAND STANFORD JUNIOR UNIVERSITY

RERUM COGNOSCERE CAUSAS

UNIVERSITY OF STRATHCLYDE

MICHIGAN

Max Planck Institute
for Gravitational Physics
ALBERT EINSTEIN INSTITUTE

THE UNIVERSITY OF WESTERN AUSTRALIA
SEEK WISDOM

PAH

CITA | ICAT
Canadian Institute for Theoretical Astrophysics
L'institut Canadien d'astrophysique thec

ACU

Università degli Studi del Sannio

SCIENTIA VINCERE TENEBRAS
UNIVERSITAS BRUXELLENSIS

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

NASA
GODDARD SPACE FLIGHT CENTER

ICTP SAIFR

UNIVERSITY OF CAMBRIDGE

THE UNIVERSITY OF CHICAGO

MONTANA STATE UNIVERSITY

SOUTHERN UNIVERSITY
Agricultural & Mechanical College

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Caltech

UNIVERSITY OF MINNESOTA

THE UNIVERSITY of MISSISSIPPI

THE UNIVERSITY OF ADELAIDE
AUSTRALIA
SUB CRUCE LUMEN

UNIVERSITY OF BIRMINGHAM

THE UNIVERSITY OF MELBOURNE
POSTERA CRESCAM LAUDE

UNIVERSITAS SCIENTIARUM SZEGEDIENSIS

UIB
Universitat de les Illes Balears

UNIVERSITAS BUDAPESTINENSIS DE ROLANDO EÖTVÖS NOMINATA

UNIVERSITY OF WASHINGTON

UNIVERSITY of WISCONSIN
UWMILWAUKEE

GEO 600

TSING HUA UNIVERSITY

UTRGV

UNIVERSITAS CORDUBENSIS TUCUMANAE

SIGILL: COLL: CARLETON
NORTHFIELD, MINN. A.D. 1866

Northwestern

UNIVERSITÄT HAMBURG

SYRACUSE UNIVERSITY
FOUNDED AD 1870
SUOS CULTORES SCIENTIA CORONAT

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

MONASH University

INPE

UF UNIVERSITY of FLORIDA

Georgia Institute of Technology

Korean Gravitational-Wave Group

LSU
LOUISIANA STATE UNIVERSITY

ACIGA

University of Southampton

CHARLES STURT UNIVERSITY

EMBRY-RIDDLE
AERONAUTICAL UNIVERSITY

Leibniz Universität Hannover

PENNSTATE
1855

HOBART AND WILLIAM SMITH COLLEGES

Science & Technology Facilities Council
Rutherford Appleton Laboratory

LIGO

LSC

# LIGO Scientific Collaboration – Aug 1997 founding

CU

University of Glasgow

VIA VERITAS VITA

LELAND STANFORD JUNIOR UNIVERSITY 1891

Max Planck Institute
for Gravitational Physics
ALBERT EINSTEIN INSTITUTE

MICHIGAN

MASSACHUSETTS INSTITUTE OF TECHNOLOGY 1861

MENS MANUS

Caltech

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UNIVERSITY OF BIRMINGHAM

UO

GEO 600

UNIVERSITY of WISCONSIN
UWMILWAUKEE

UNIVERSITÄT HAMBURG

SYRACUSE UNIVERSITY FOUNDED AD 1870

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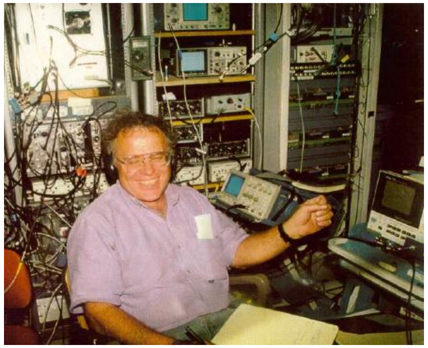
UF UNIVERSITY of FLORIDA

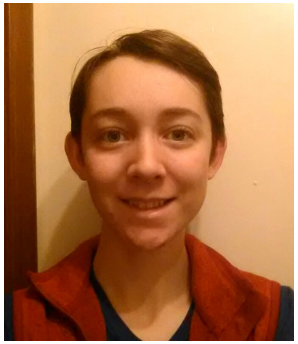
LSU
LOUISIANA STATE UNIVERSITY

Leibniz
Universität
Hannover

PENNSTATE
1855

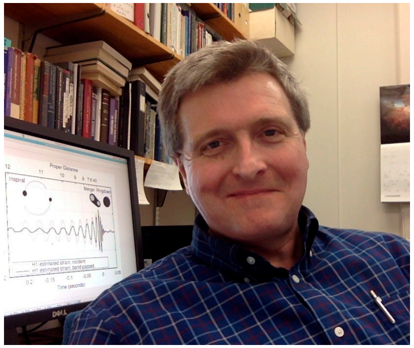
# Michigan Gravitational Wave Group (MGWG)


Dick Gustafson (c, d)


Ansel Neunzert (c,d,a)


Orion Sauter (a)


Jon Wang (a)


Keith Riles (d, a, o)


Kaushik Rao (d)


Eilam Morag (d)


Sophie Hourihane(d)


Jessica Leviton (d)


Paul Huang (a)

c = commissioning
d = detector characterization
a = analysis
o = outreach (instrumentation)


Humza Khan (o)

# MGWG Alumni working in GW science

Grant Meadors
Ph.D. 2014
Albert Einstein Institute

Jaclyn Sanders
Ph.D. 2015
Syracuse University

Vladimir Dergachev
Ph.D. 2009
Albert Einstein Institute

Santiago Caride
Ph.D. 2015
Texas Tech University

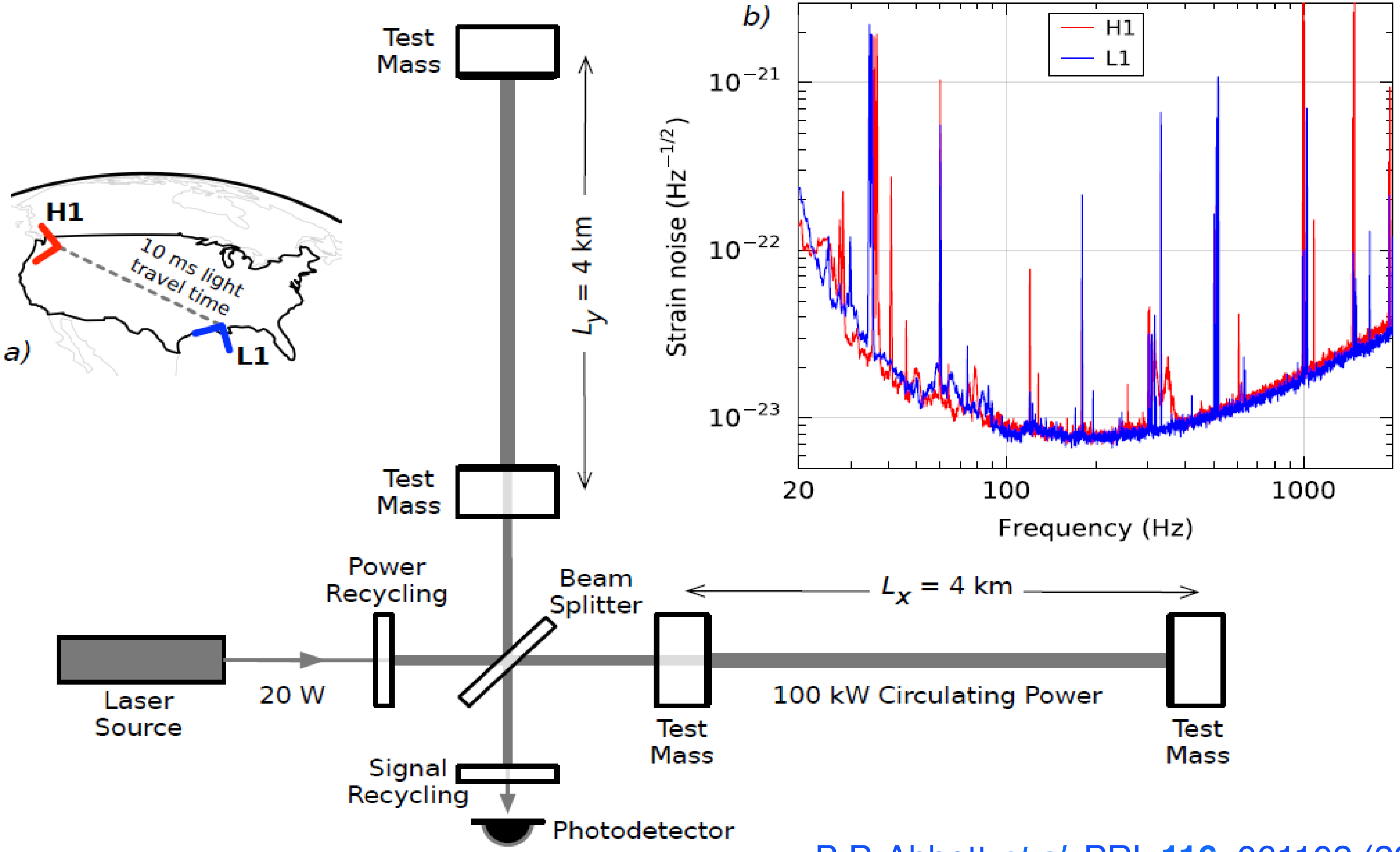
Evan Goetz
Ph.D. 2010
Albert Einstein Institute

Jacob Slutsky
B.S. 2006
Goddard Space Flight Center

Alex Nitz
B.S. 2010
Albert Einstein Institute

Jamie Rollins
B.S. 1999
LIGO Laboratory

# O1 Data Run



B.P. Abbott *et al*, PRL **116**, 061102 (2016)

# Gravitational Wave Event GW150914

First
The Golden Event
^

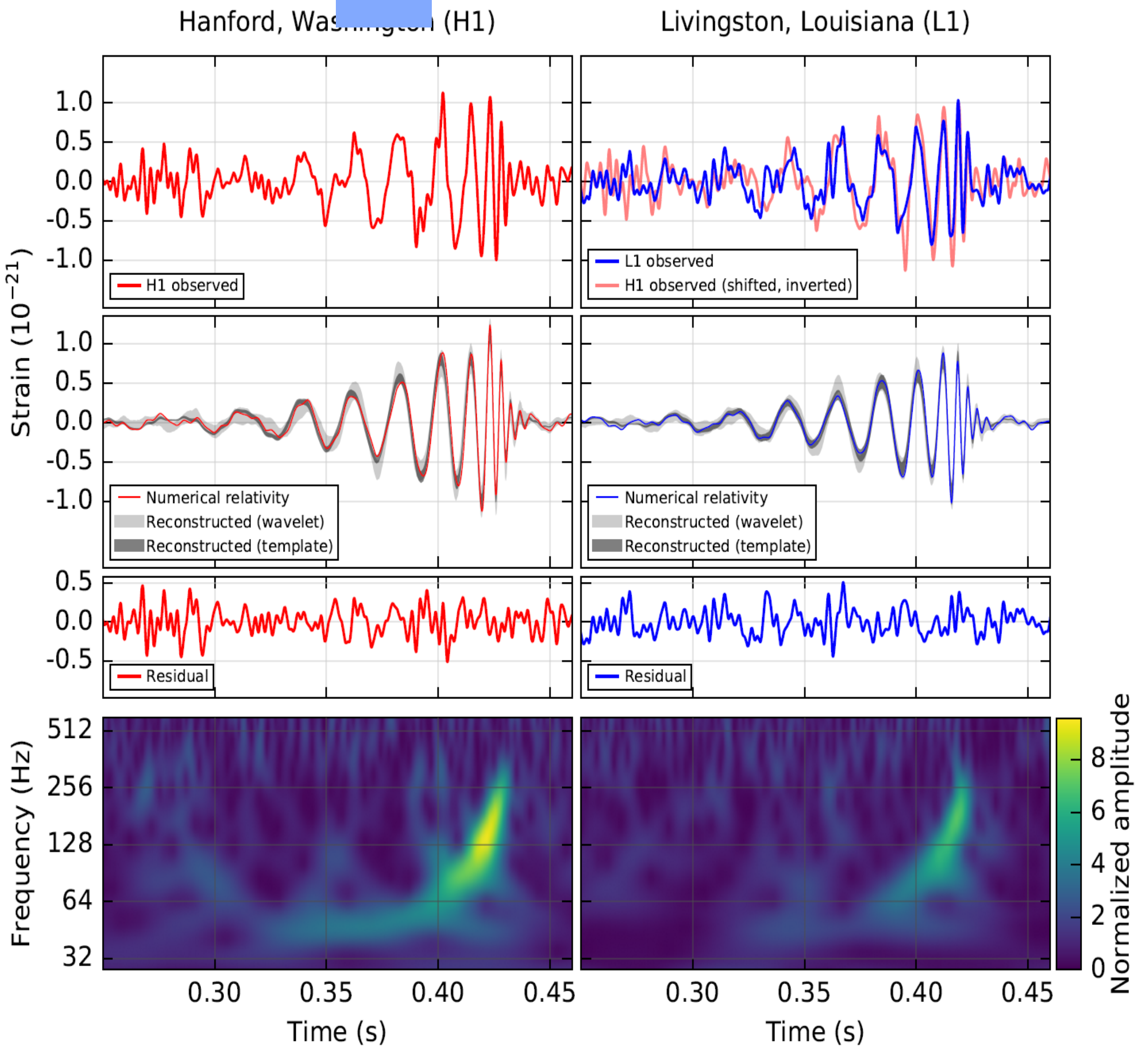
Data bandpass filtered between 35 Hz and 350 Hz

Time difference 6.9 ms with Livingston first

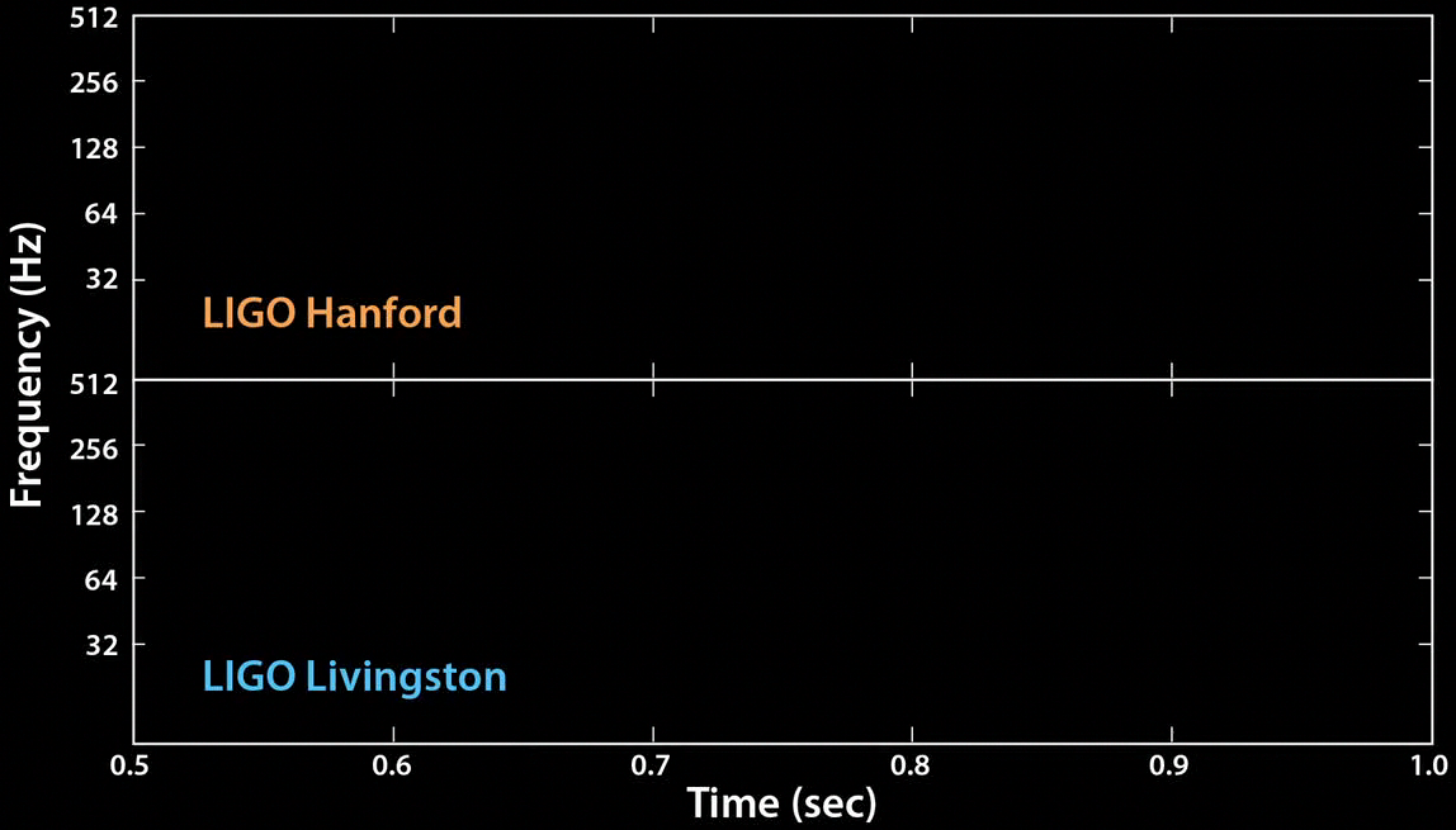
Second row – calculated GW strain using Numerical Relativity Waveforms for quoted parameters compared to reconstructed waveforms (Shaded)

Third Row –residuals

Bottom row – time frequency plot showing frequency increases with time (chirp)



B.P. Abbott *et al*, PRL **116**, 061102 (2016)

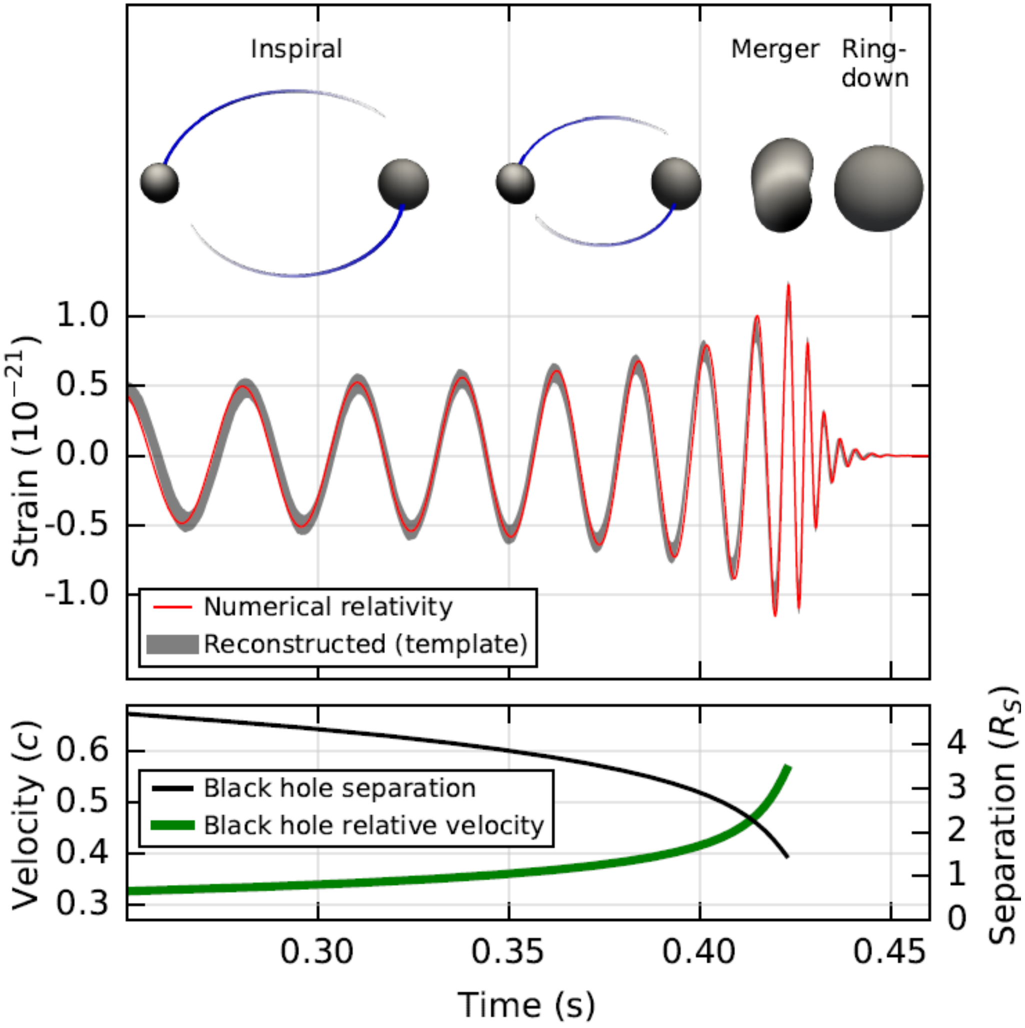

512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

# Estimated GW Strain Amplitude: GW150914

B.P. Abbott *et al*, PRL **116**, 061102 (2016)

Full bandwidth waveforms without filtering. Numerical relativity models of black hole horizons during coalescence

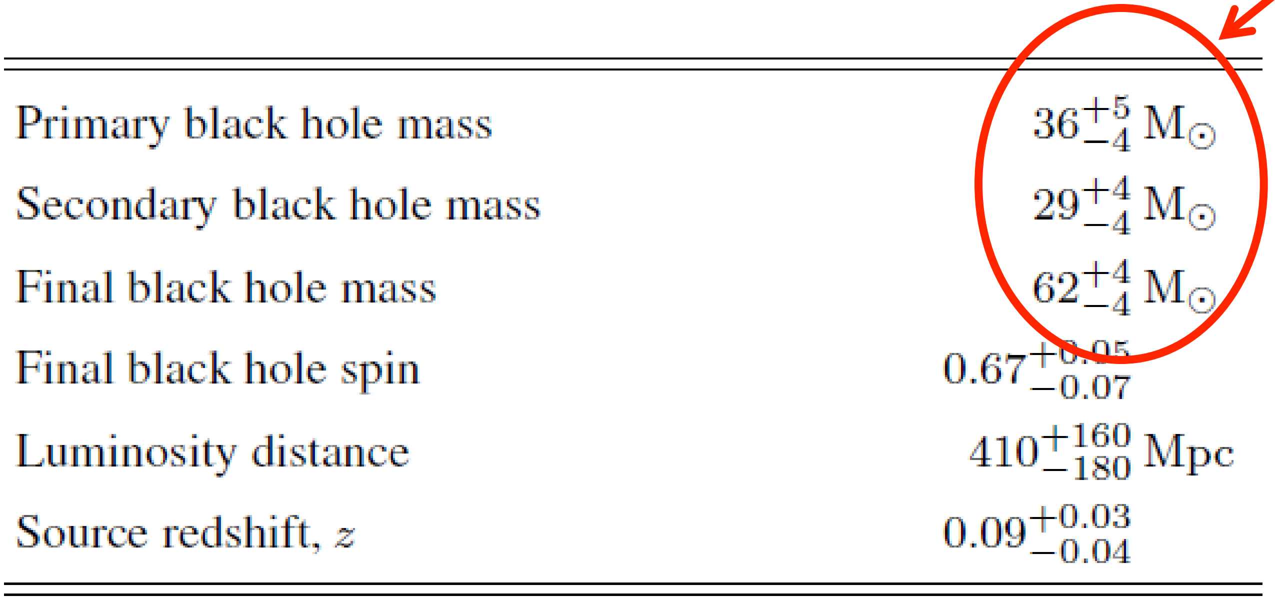
Effective black hole separation in units of Schwarzschild radius ($R_s = 2GM_f / c^2$); and effective relative velocities given by post-Newtonian parameter $v/c = (GM_f \pi f / c^3)^{1/3}$



# Source Parameters for GW150914

Fits to numerical simulations of black hole mergers determines the following parameters:

$$36 + 29 \neq 62$$



| | |
|---|---|
| Primary black hole mass | $36^{+5}_{-4}\ \mathrm{M}_\odot$ |
| Secondary black hole mass | $29^{+4}_{-4}\ \mathrm{M}_\odot$ |
| Final black hole mass | $62^{+4}_{-4}\ \mathrm{M}_\odot$ |
| Final black hole spin | $0.67^{+0.05}_{-0.07}$ |
| Luminosity distance | $410^{+160}_{-180}$ Mpc |
| Source redshift, $z$ | $0.09^{+0.03}_{-0.04}$ |

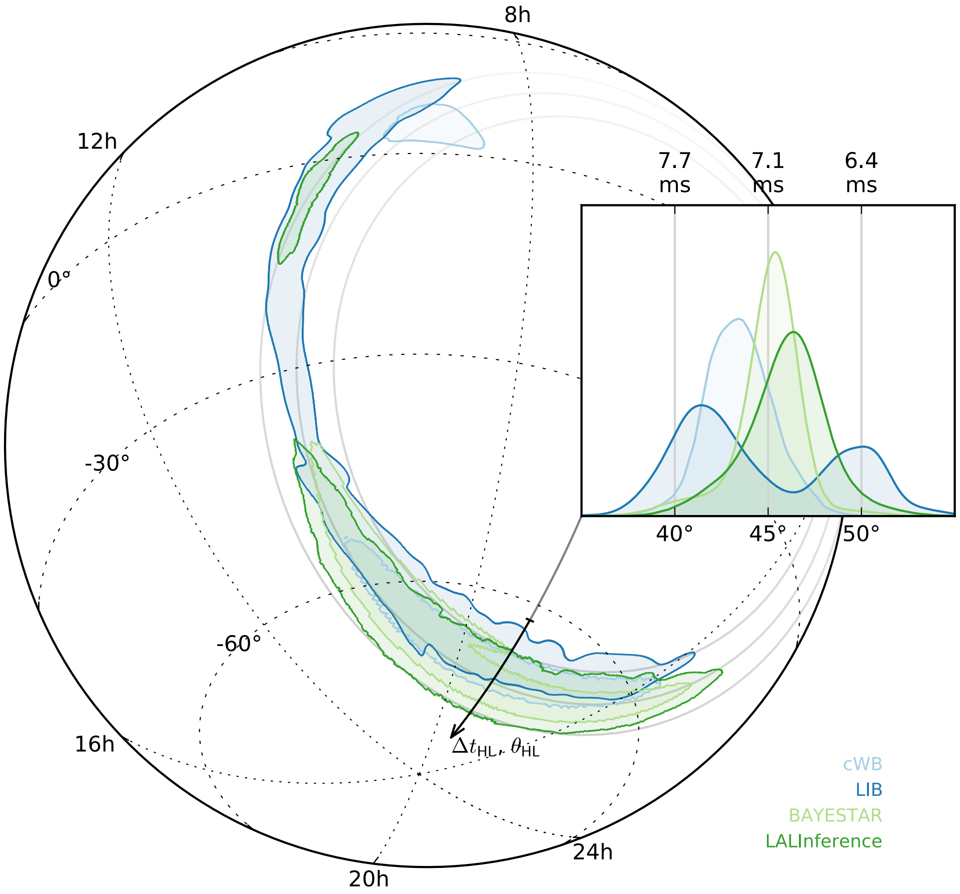
Total energy radiated in gravitational waves is 3.0 ± 0.5 solar masses
→ Peak "luminosity" ~3.6 $\times 10^{56}$ erg/s

B.P. Abbott *et al*, PRL **116**, 061102 (2016)

# Localization

Two detectors and a time offset define a ring on the sky

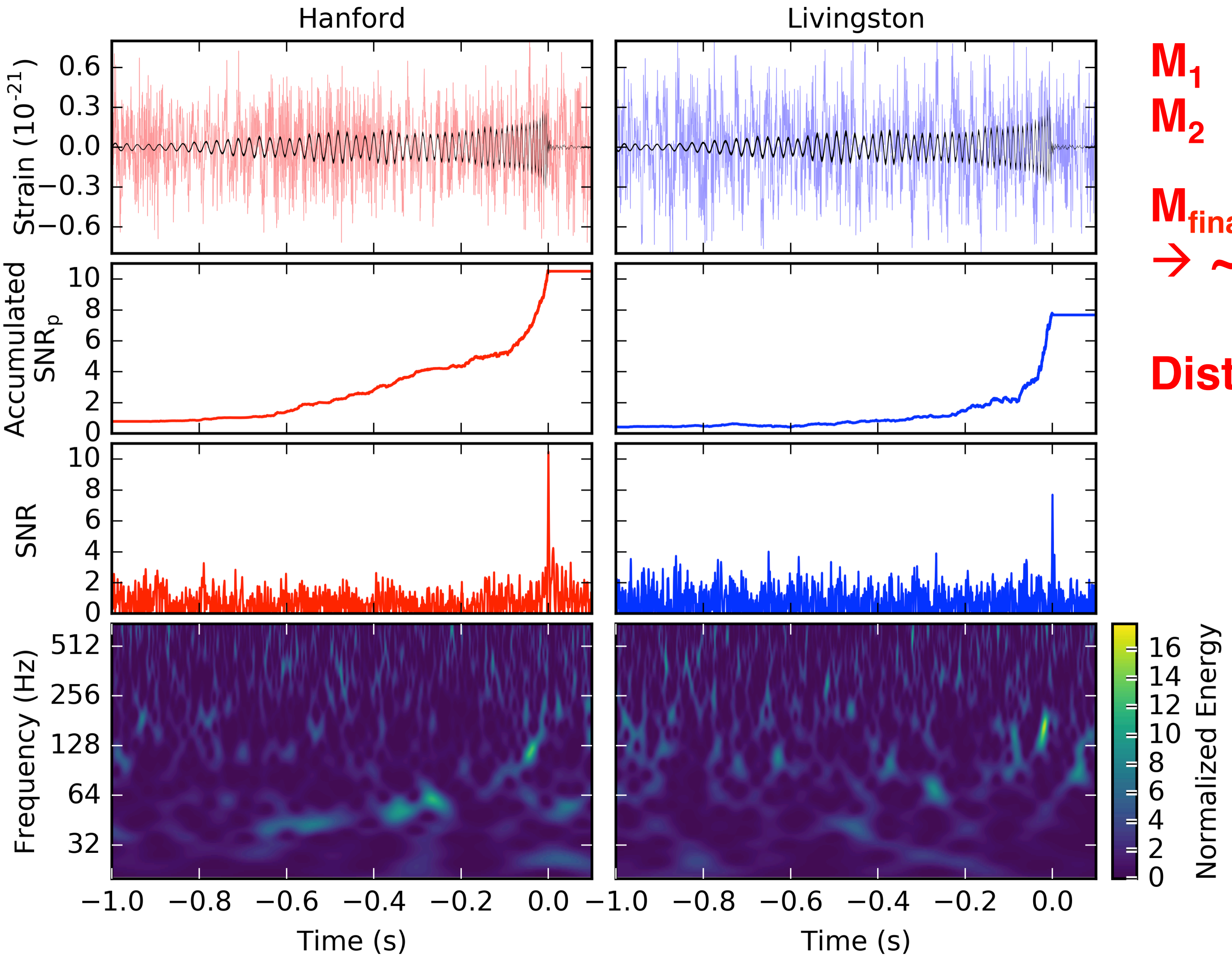
Can do (somewhat) better by exploiting antenna pattern sensitivities and Bayesian prior on location



**Detection with Virgo ~~will~~ does improve triangulation dramatically**

B.P. Abbott *et al*, ApJ **826,** L13 (2016)

# Boxing Day Event – GW151226



**$M_1$ ~ 14 $M_\odot$**
**$M_2$ ~ 8 $M_\odot$**

**$M_{final}$ ~ 21 $M_\odot$**
**→ ~1 $M_\odot$ radiated**

**Dist ~ 440 Mpc**

B.P. Abbott *et al*, PRL **116,** 241103 (2016)

# The O2 Run

After O1 completed in January 2016, both observatories began preparations for the the O2 run planned for the fall:

- ☐ Mitigate some non-fundamental noise sources seen in O1
- ☐ Raise laser powers to reduce fundamental noise and demonstrate mitigation of parametric instability (PI) associated with high power

Mishap at Livingston derailed high-power plans for 2016, but other noise mitigation paid off well

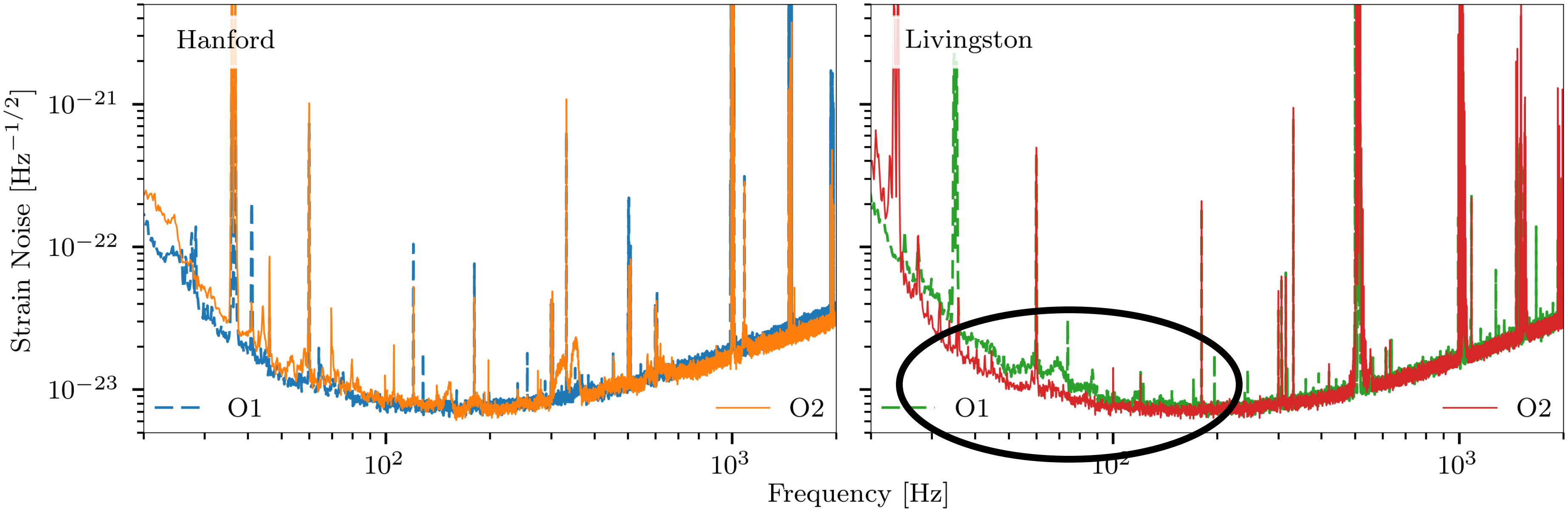
Hanford learned to cope well with PIs at higher power, but encountered other technical problems at higher power and had to back off (for O2)

O2 began November 30, 2016 – ended August 25, 2017

# The O2 Run

→ Livingston more sensitive in O2 than in O1 ☺

→ Hanford less sensitive ☹



B.P. Abbott *et al*, PRL **118**, 221101 (2017)

This band helpful for detecting binary black holes!

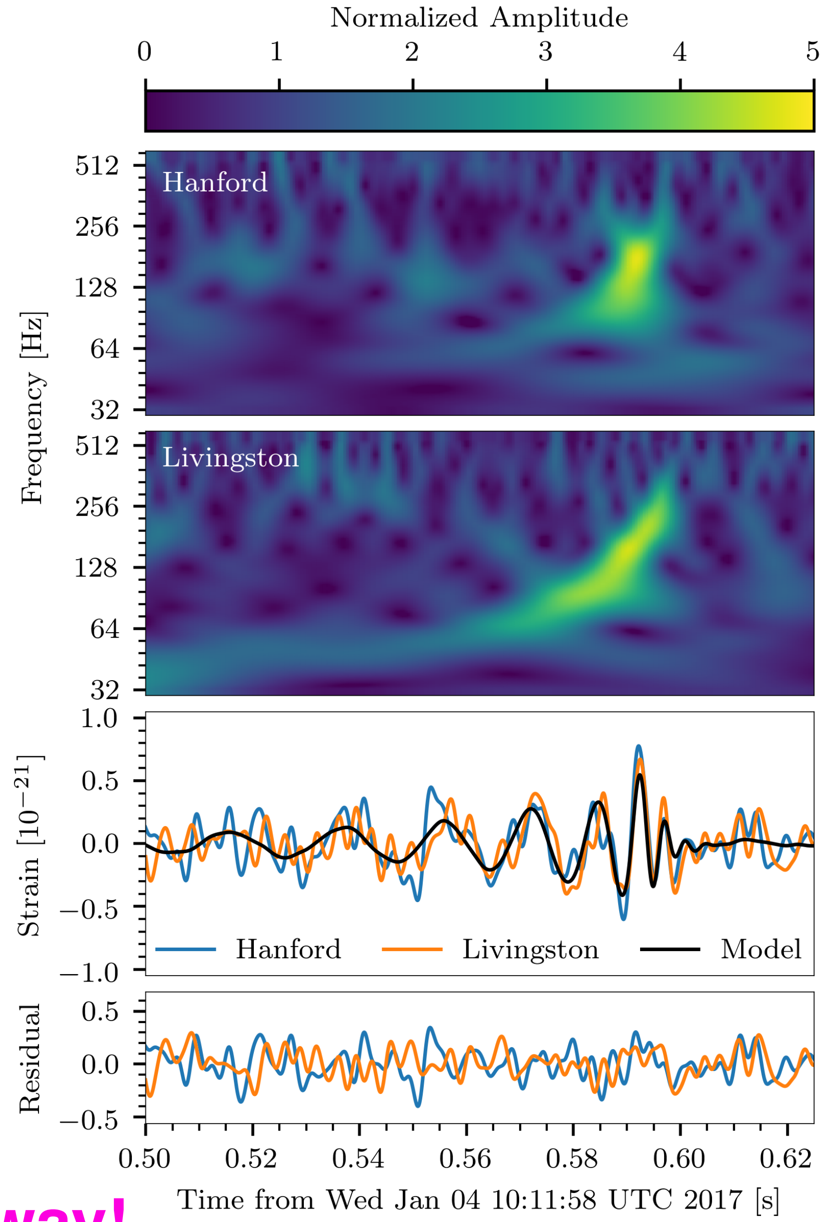
# Early Result from O2:

## GW170104

**$M_1$ ~ 31 $M_\odot$**
**$M_2$ ~ 19 $M_\odot$**

**$M_{final}$ ~ 49 $M_\odot$**
**→ ~2 $M_\odot$ radiated**

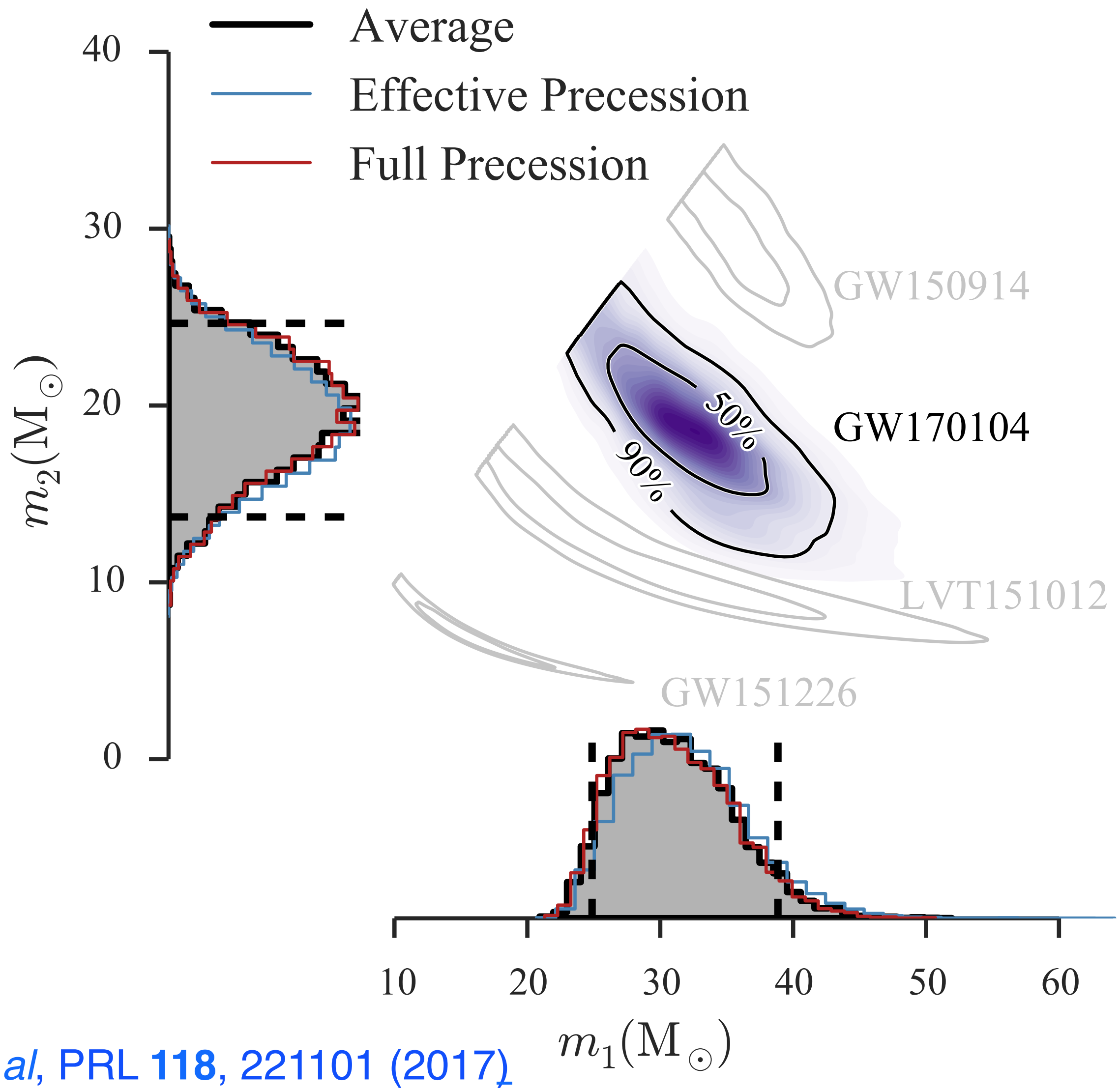
**Distance ~ 880 Mpc**
**(~3 billion light-years)**



**→ Another massive system far away!**

B.P. Abbott *et al*, PRL **118**, 221101 (2017)

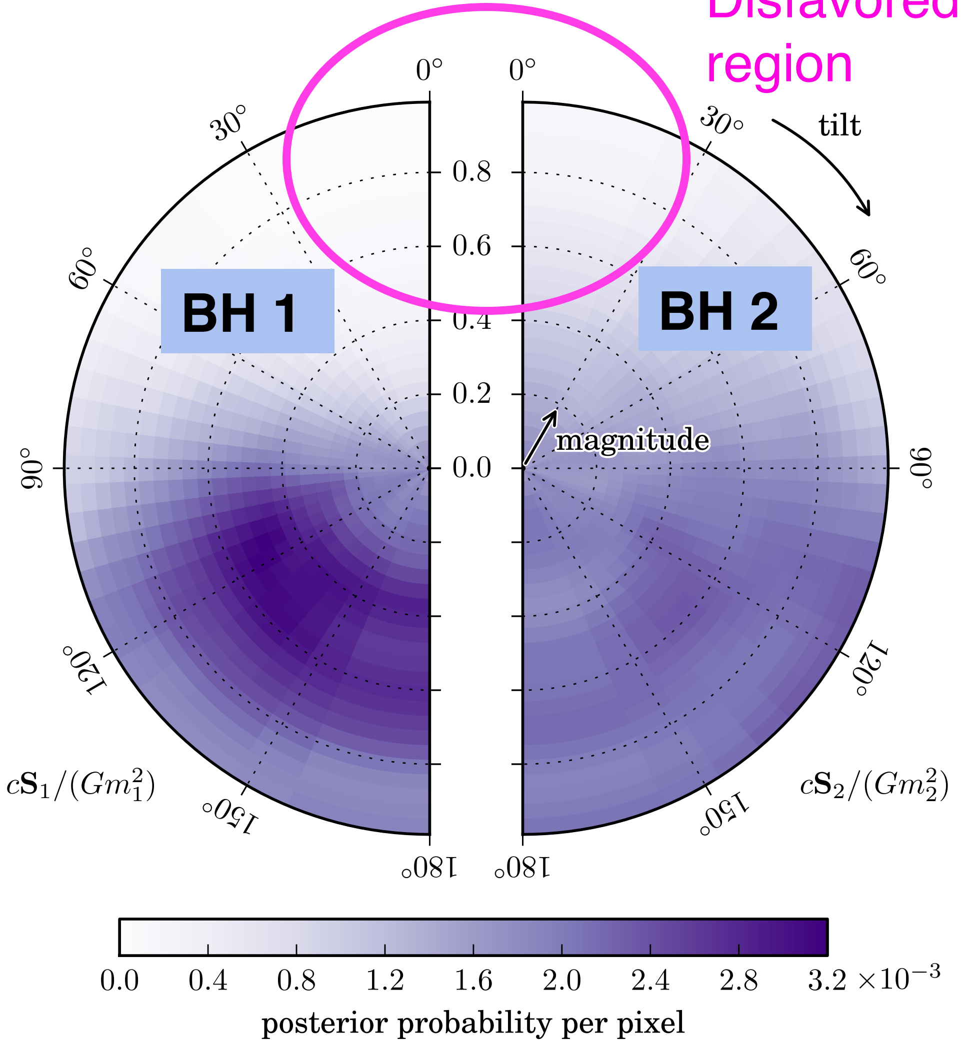
# GW170104 – Where does it fit with previous detections?



B.P. Abbott *et al*, PRL **118**, 221101 (2017)

# GW170104 – Where does it fit with previous detections?

Graphs show posterior densities for normalized initial BH spins projected along orbital angular momentum vector, based on fitting detected waveforms to GR templates



Disfavored region

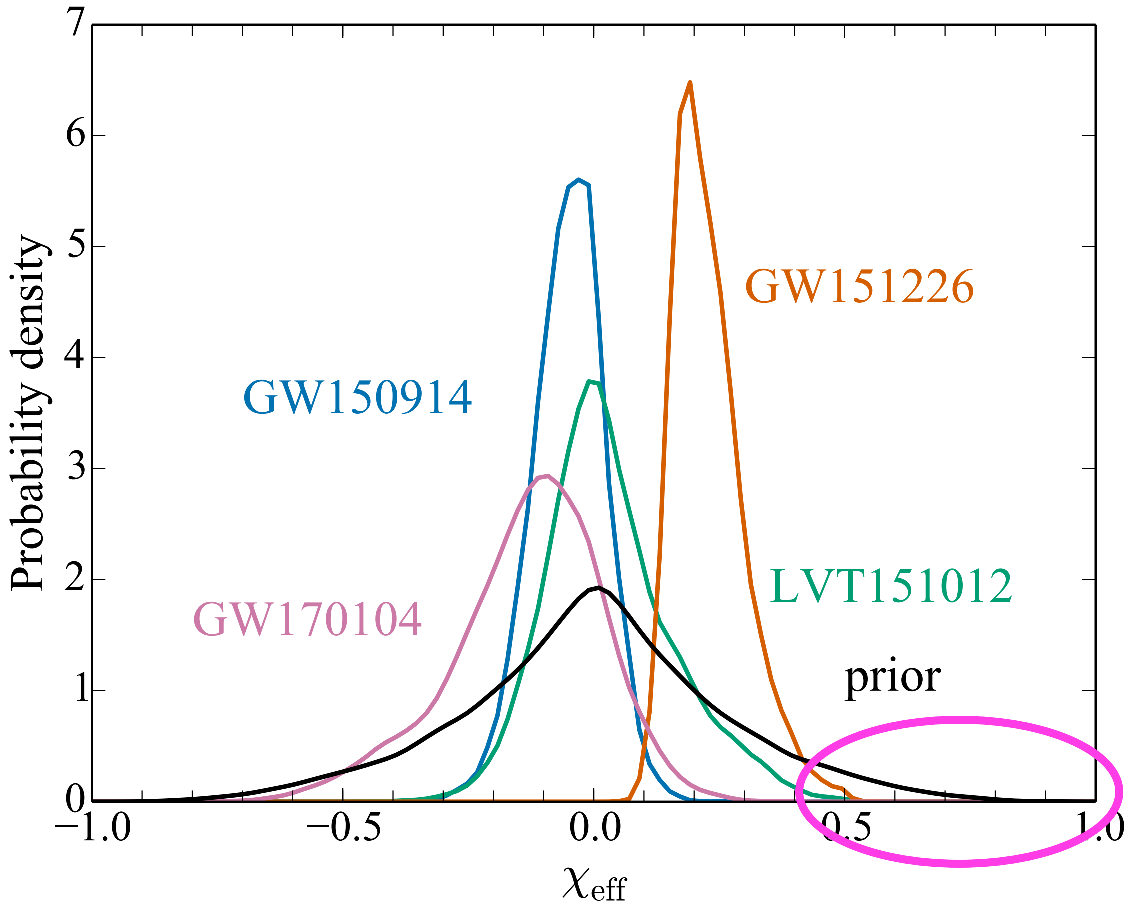
Results disfavor progenitor spins strongly aligned with orbital angular momentum vector

B.P. Abbott *et al*, PRL **118**, 221101 (2017)

# GW170104 – Where does it fit with previous detections?

Curves show posterior densities of combined projected spins $\chi_{eff}$ for all definite and likely BBH detections to date

No evidence of clustering near large positive values of $\chi_{eff}$



Disfavored region

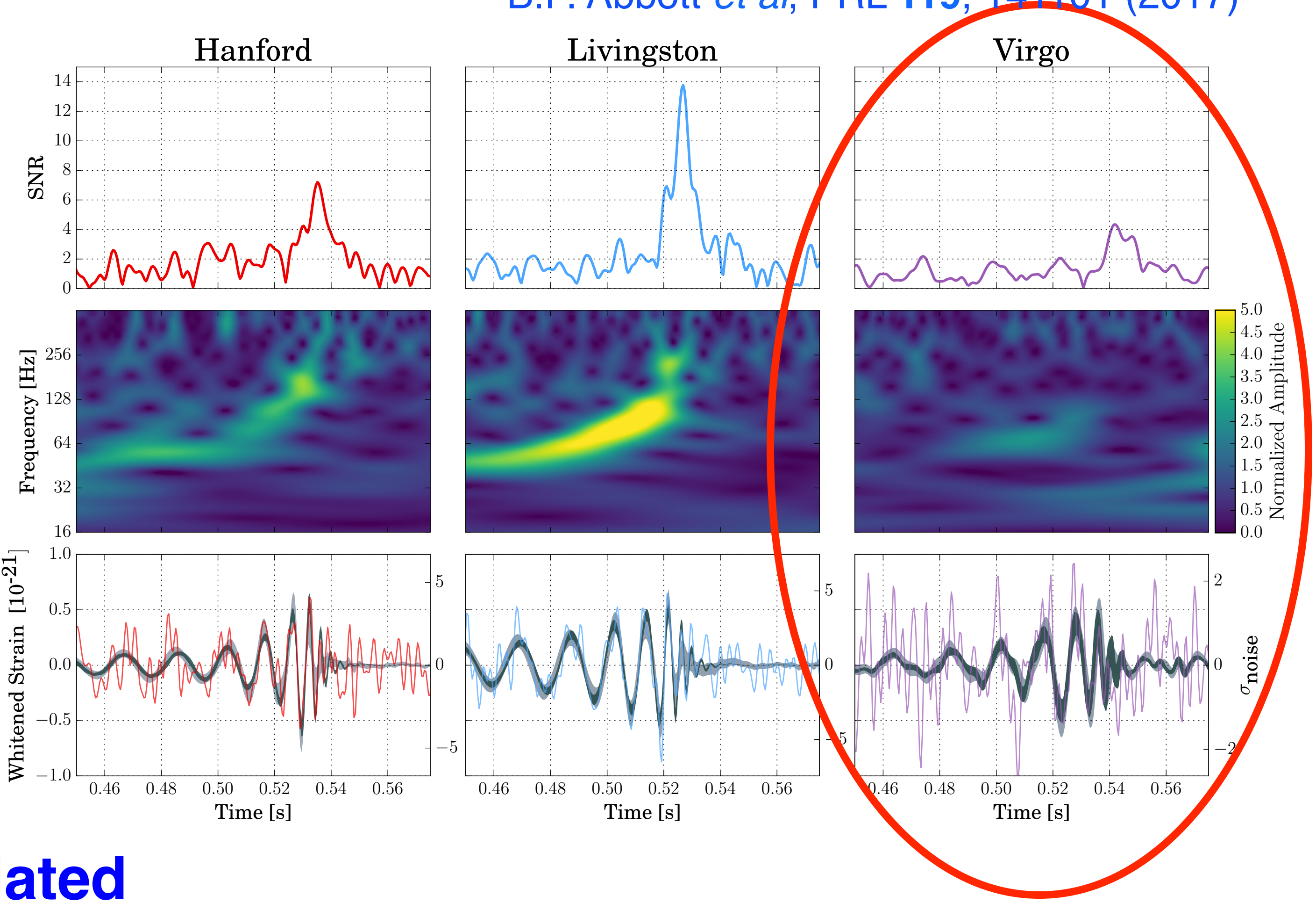
→ **Implications for original BH and BBH formation**

B.P. Abbott *et al*, PRL **118**, 221101 (2017)

# GW170814

# Another Result from O2:

B.P. Abbott *et al*, PRL **119**, 141101 (2017)



**$M_1$ ~ 31 $M_\odot$**
**$M_2$ ~ 25 $M_\odot$**

**$M_{final}$ ~ 53 $M_\odot$**
**→ ~3 $M_\odot$ radiated**

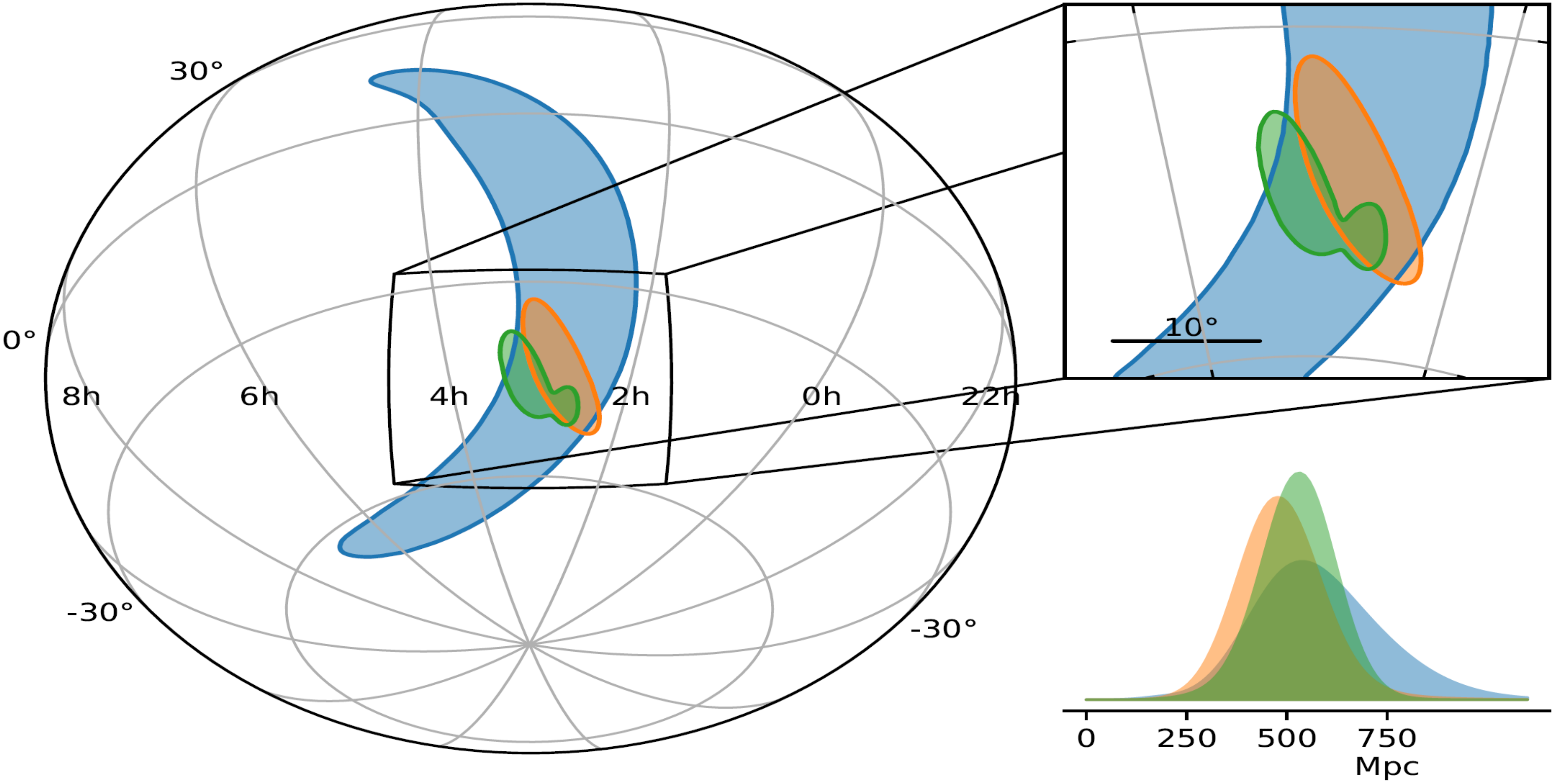
**Distance ~ 540 Mpc**
**(~1.8 billion light-years)**

**→ Yet another distant massive system!**

**Virgo saw it!**

# GW170814

B.P. Abbott *et al*, PRL **119**, 141101 (2017)

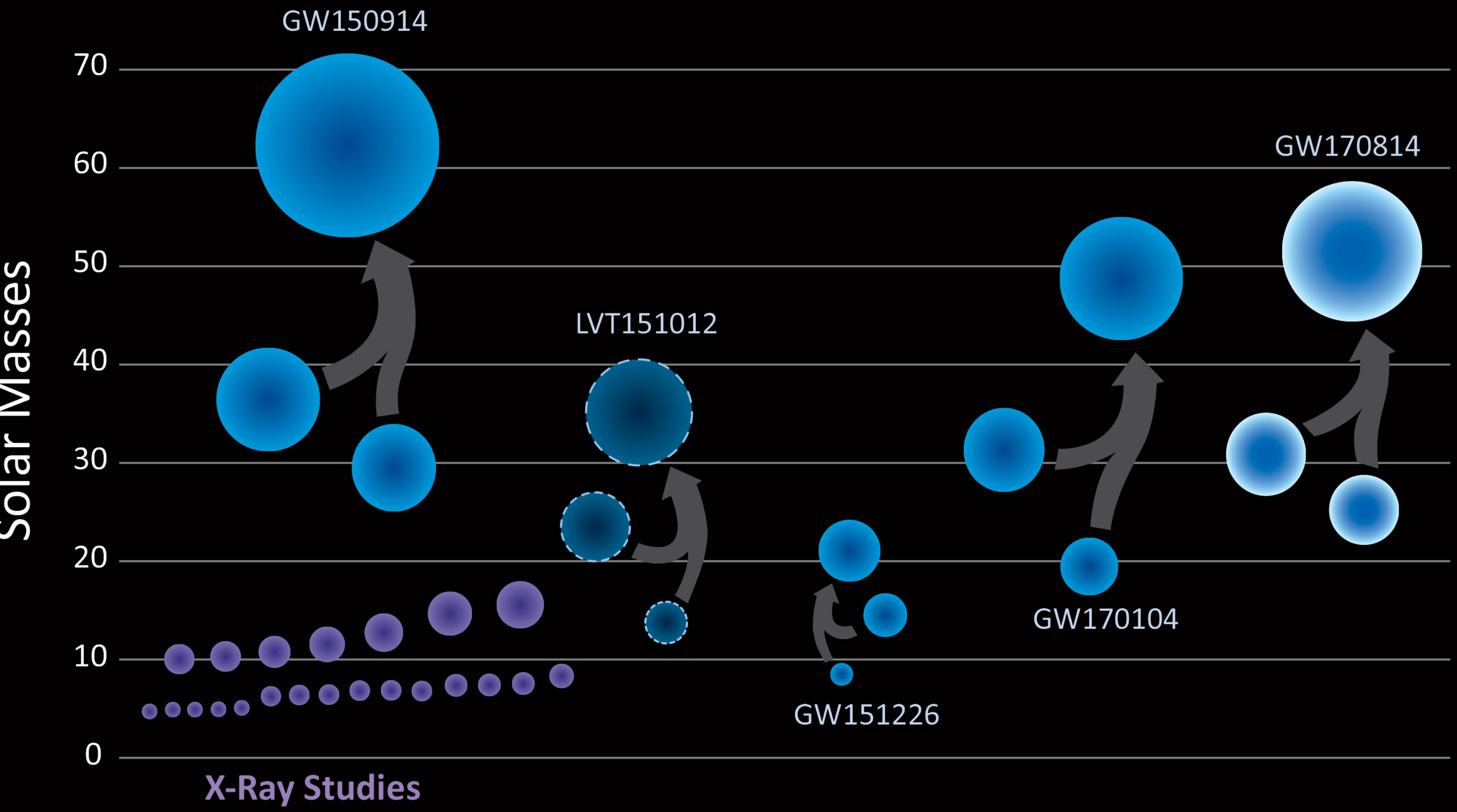


**Adding Virgo dramatically improves sky localization!**

**→ Very useful for follow-up by “Photon Astronomers”**

# Black Holes of Known Mass

## (as of the GW170814 announcement)

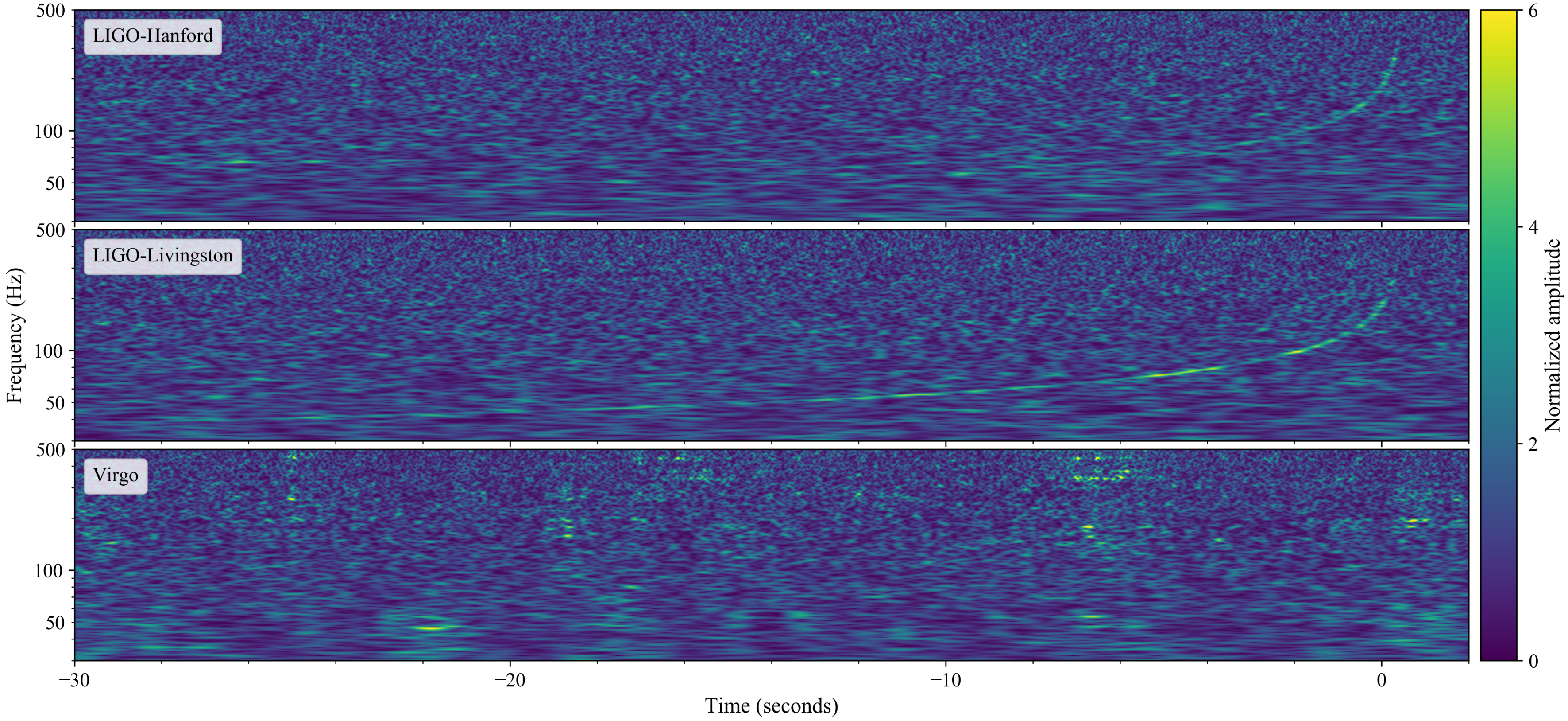


LIGO/VIRGO

# Gravitational Wave Event GW170817

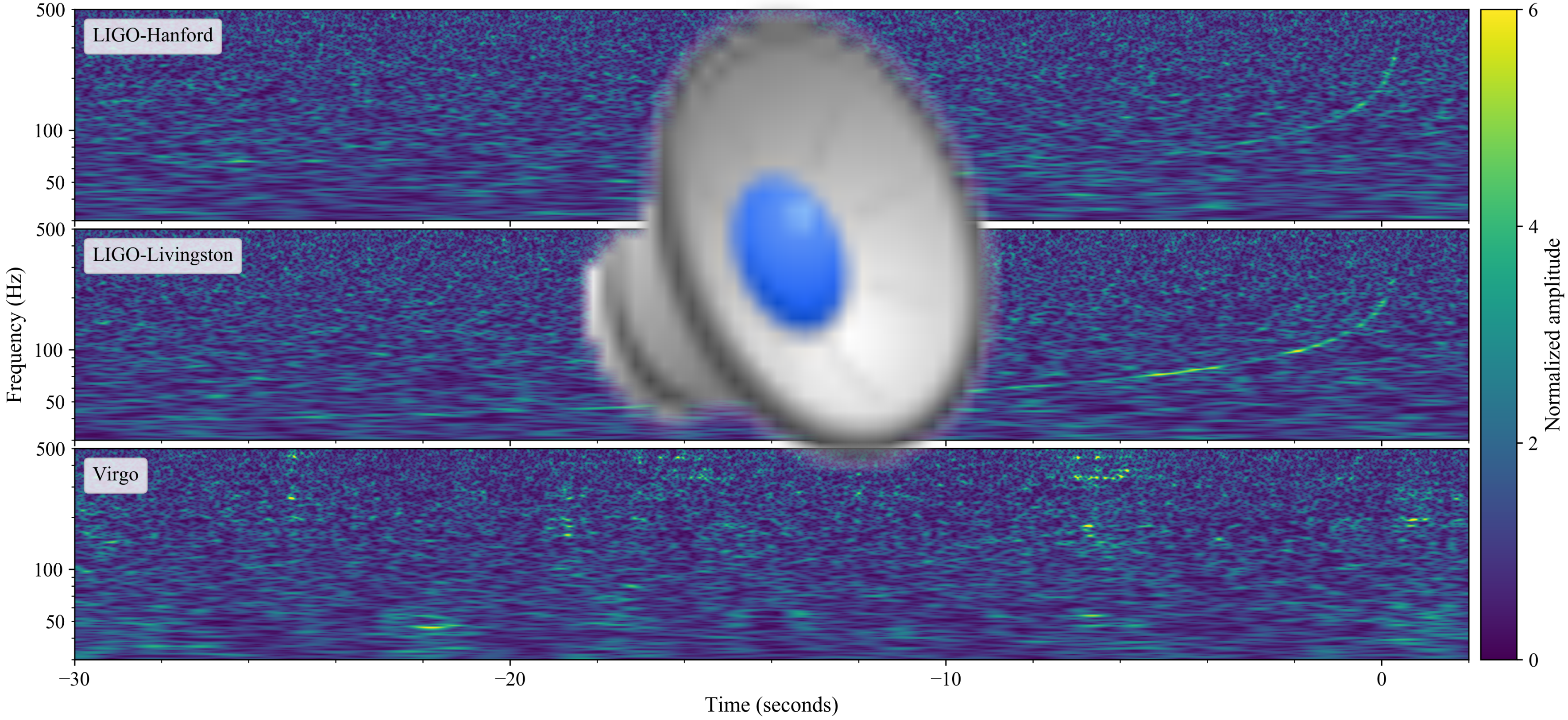
## The Second Golden Event

a.k.a. GRB170817A    a.k.a. SSS17a (AT 2017gfo )



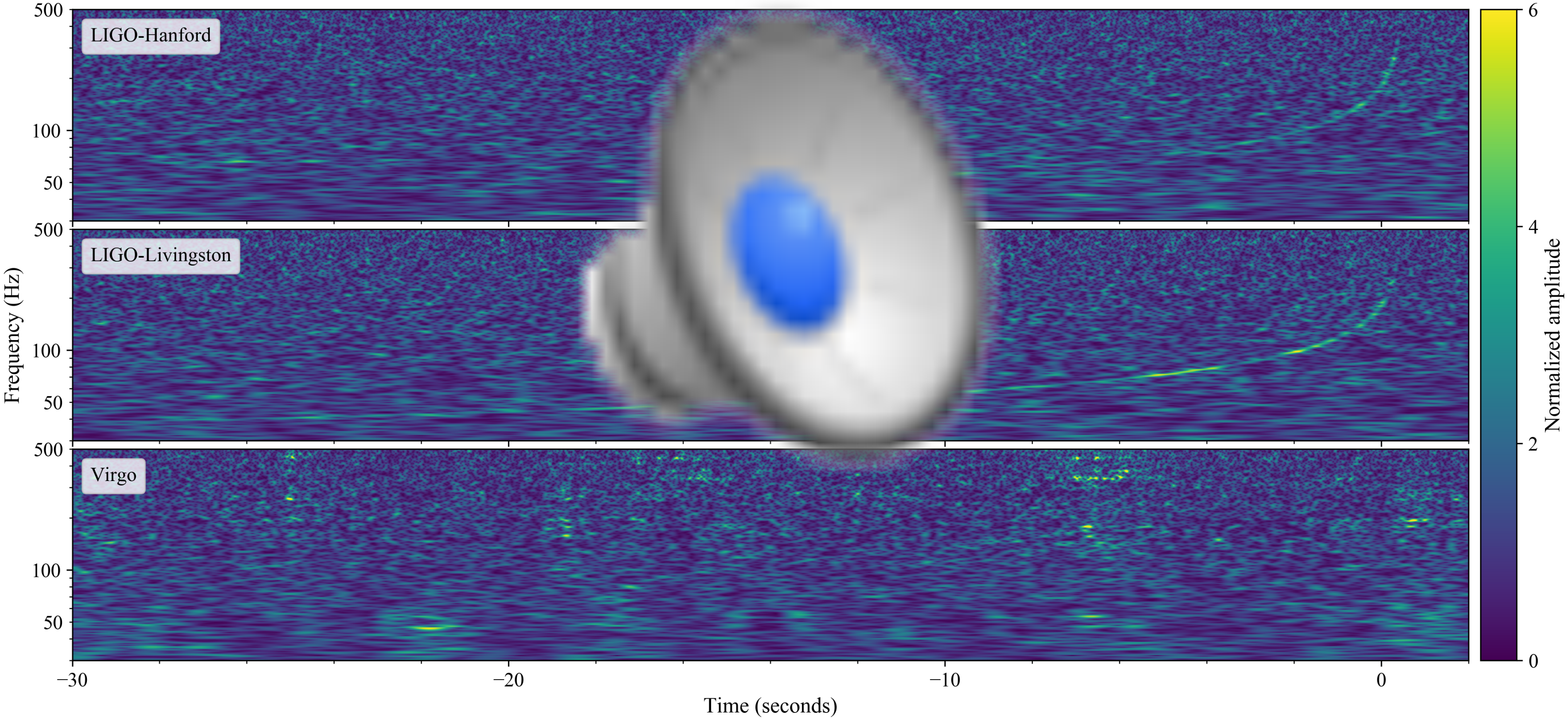
B.P. Abbott *et al*, PRL **119**, 061101 (2017)

# Gravitational Wave Event GW170817 – A/V (noise present)



Credit: G.Lovelace, D.Brown, D.Macleod, J.McIver, A.Nitz

# Gravitational Wave Event GW170817 – A/V (noise removed)



Credit: G.Lovelace, D.Brown, D.Macleod, J.McIver, A.Nitz

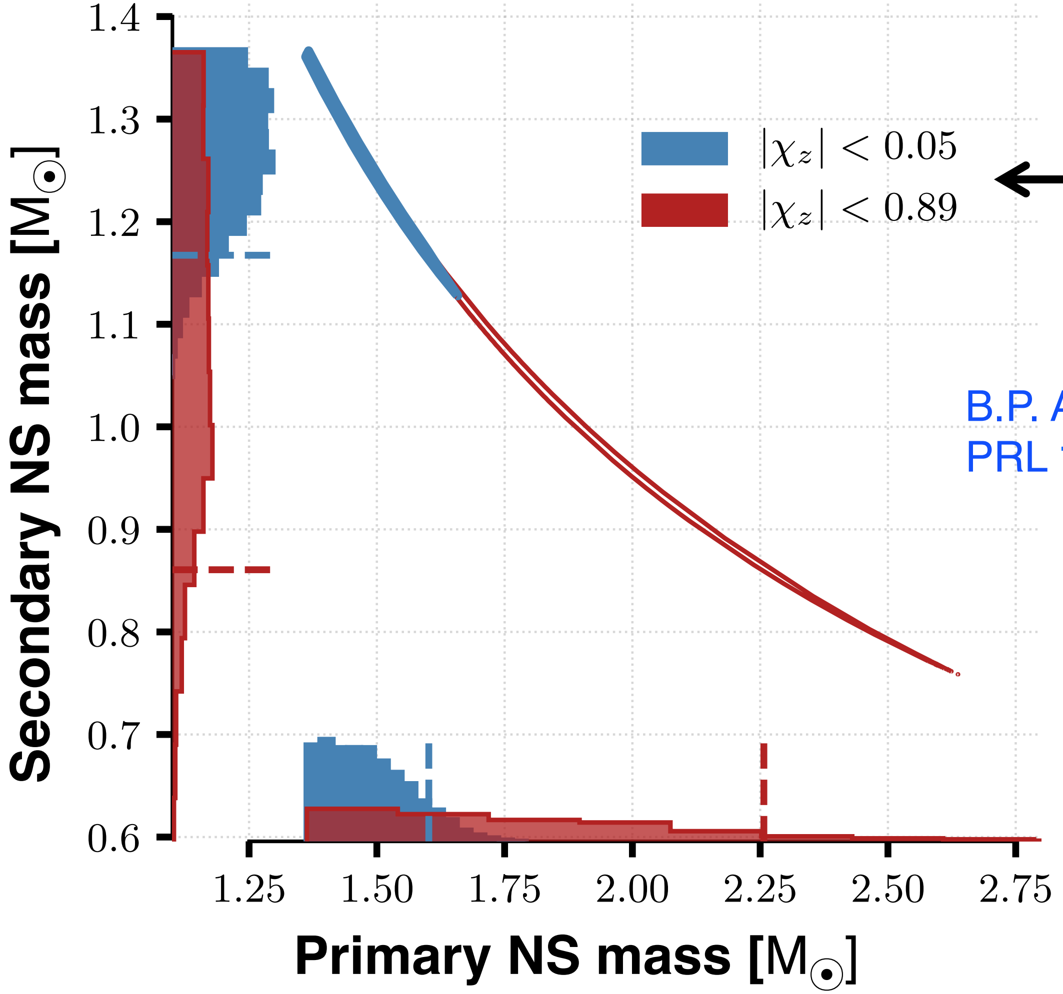
# Some numbers based on GW data alone

Waveform: SNR = 32, duration from 30 Hz = 60 s (~3000 GW cycles)

NS masses – primary: 1.4-2.3 $M_\odot$ secondary: 0.9-1.4 $M_\odot$

NS radii $\lesssim$ 15 km, Distance to source ~ 40 Mpc (130 million light years)

Rate: 320-4700 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ (only 1 event!)

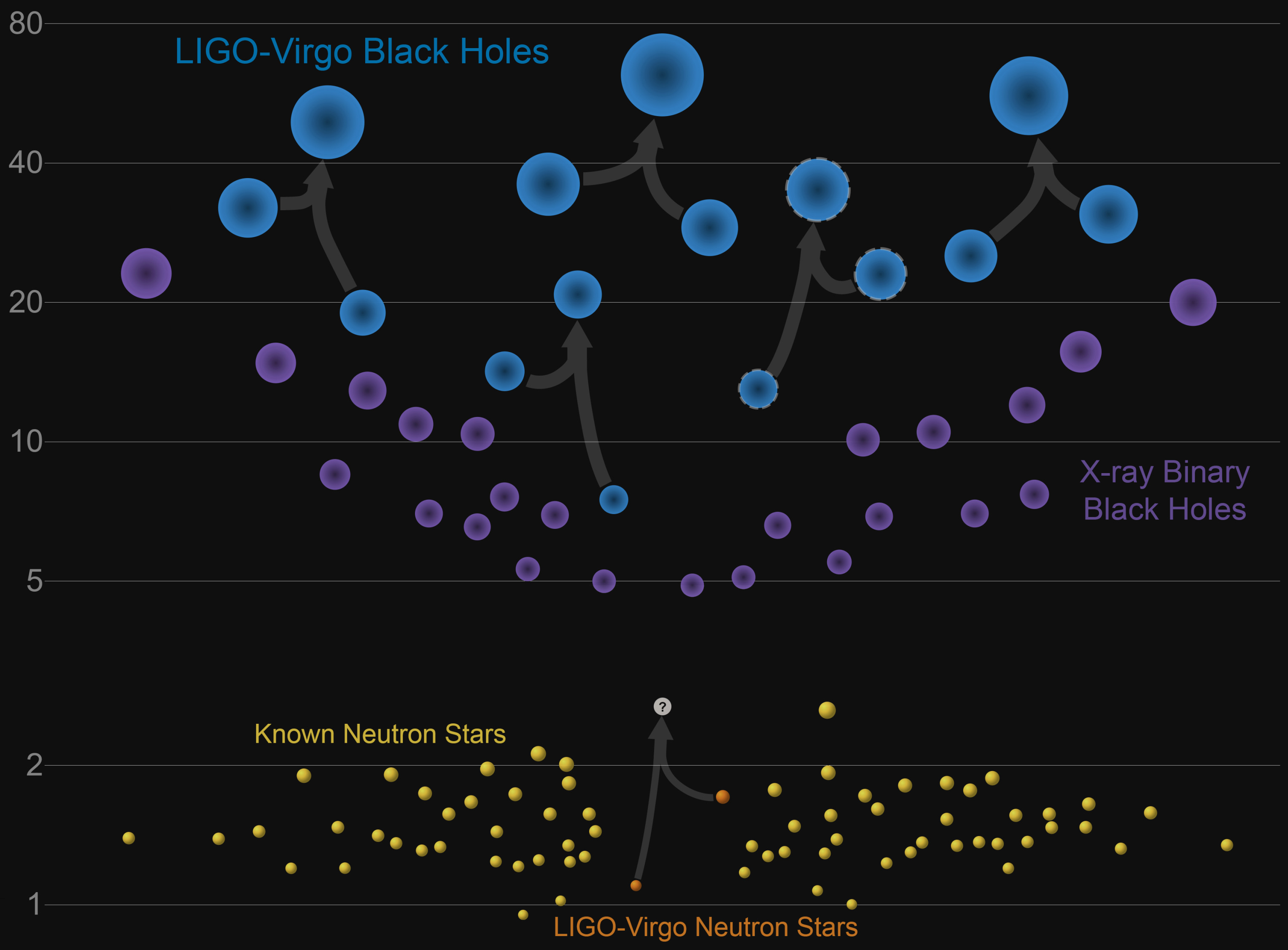


← Different spin assumptions

B.P. Abbott *et al*,
PRL **119**, 061101 (2017)

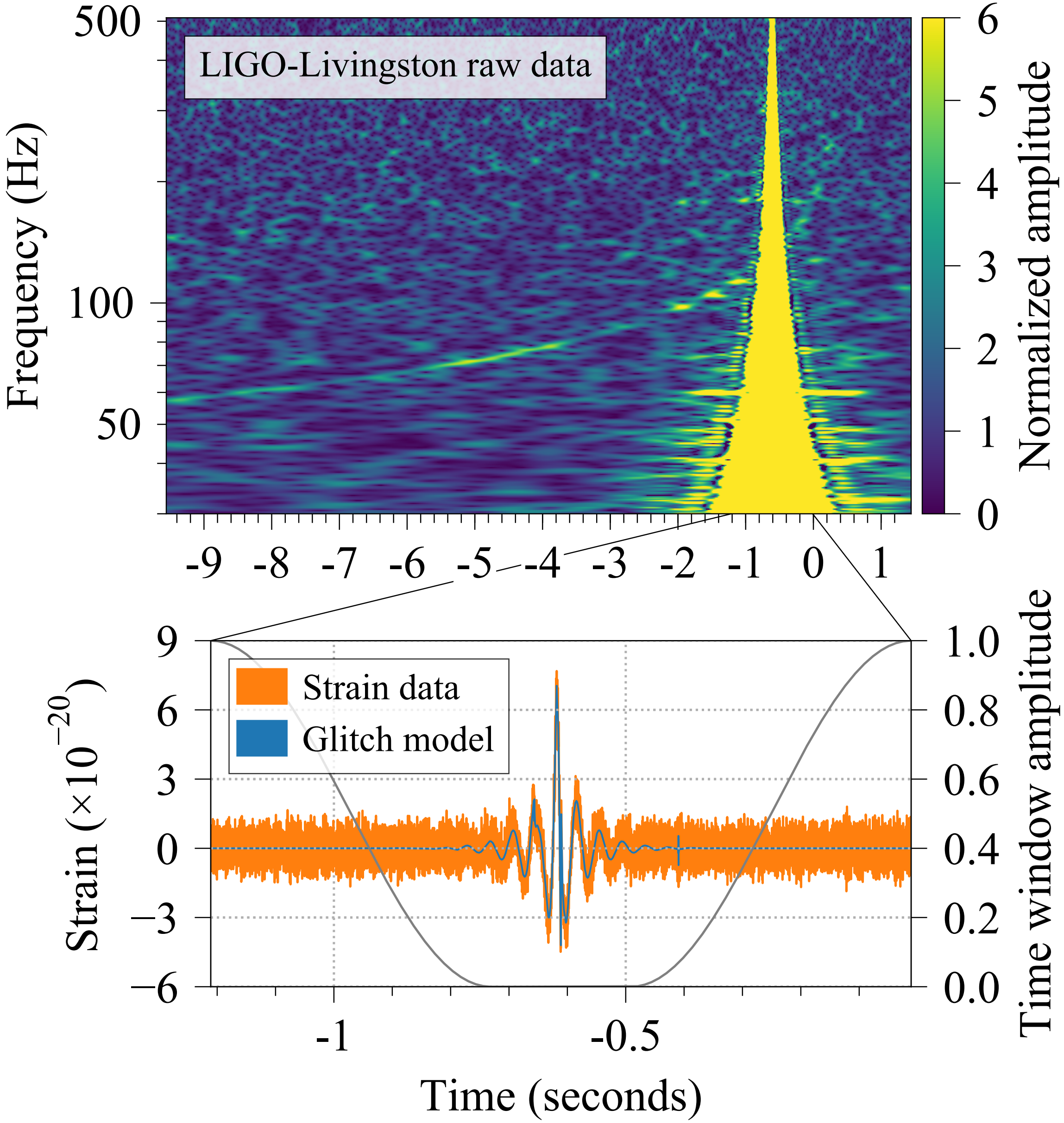
# Masses in the Stellar Graveyard

*in Solar Masses*



LIGO-Virgo/Frank Elavsky/Northwestern

# Some Dirty Laundry…



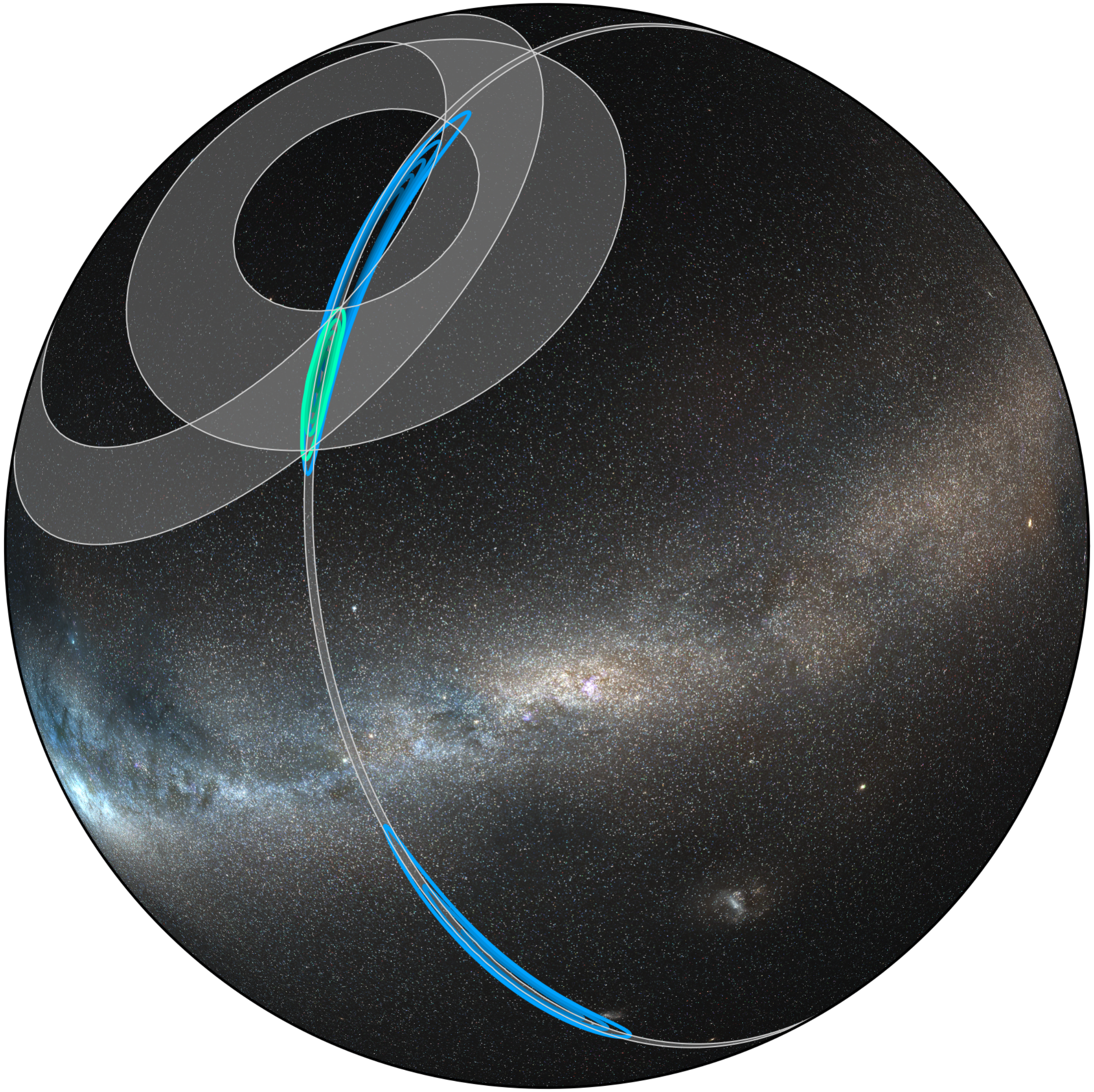
Nasty “Blip Glitch” in Livingston data about 1.1 second before coalescence!

Excised with inverse Tukey window filter -- First done in a hurry on August 17!

Delayed production of clean sky map for photon astronomers ☹

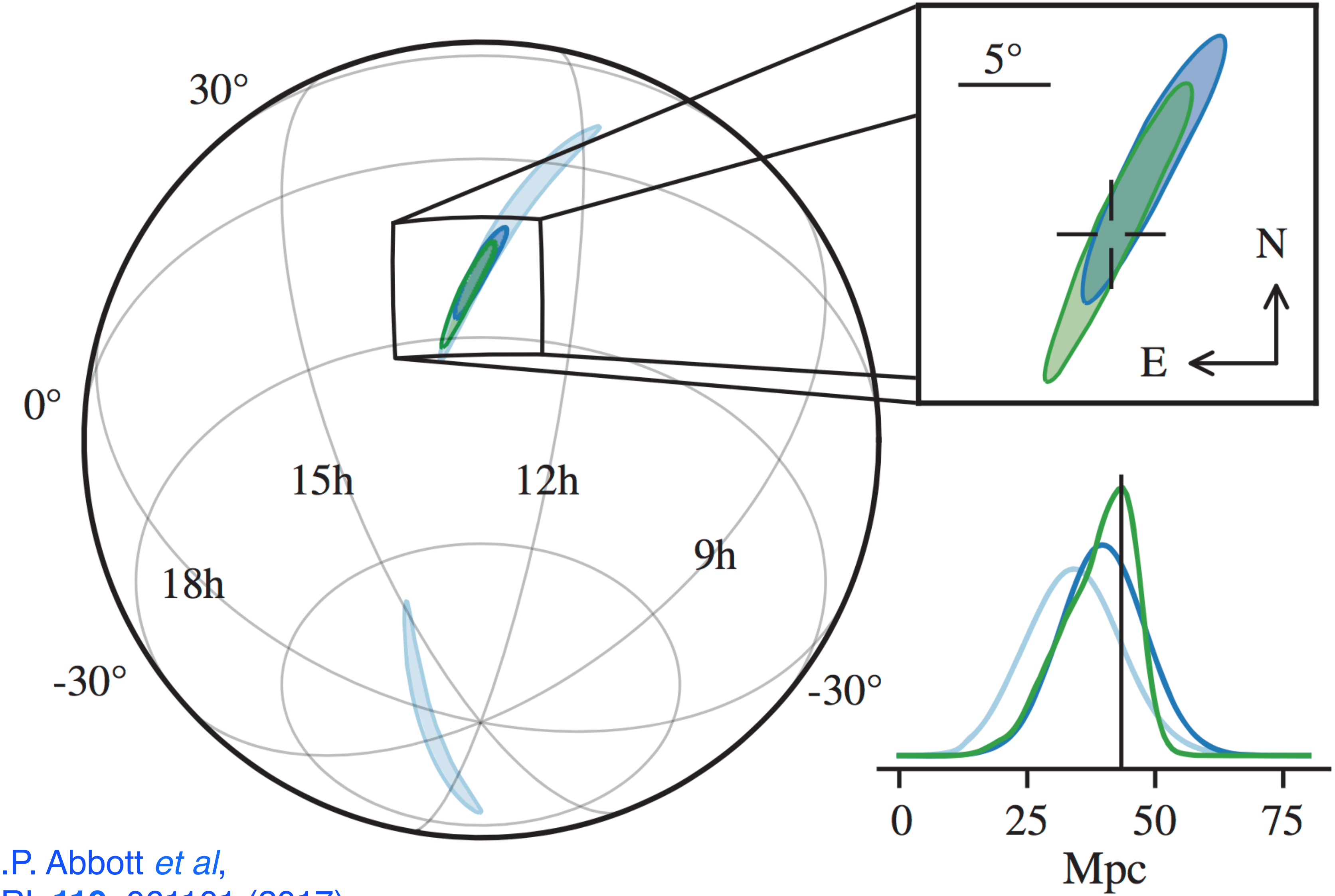
B.P. Abbott *et al*,
PRL **119**, 061101 (2017)

# Sky localization – GW data alone



Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)

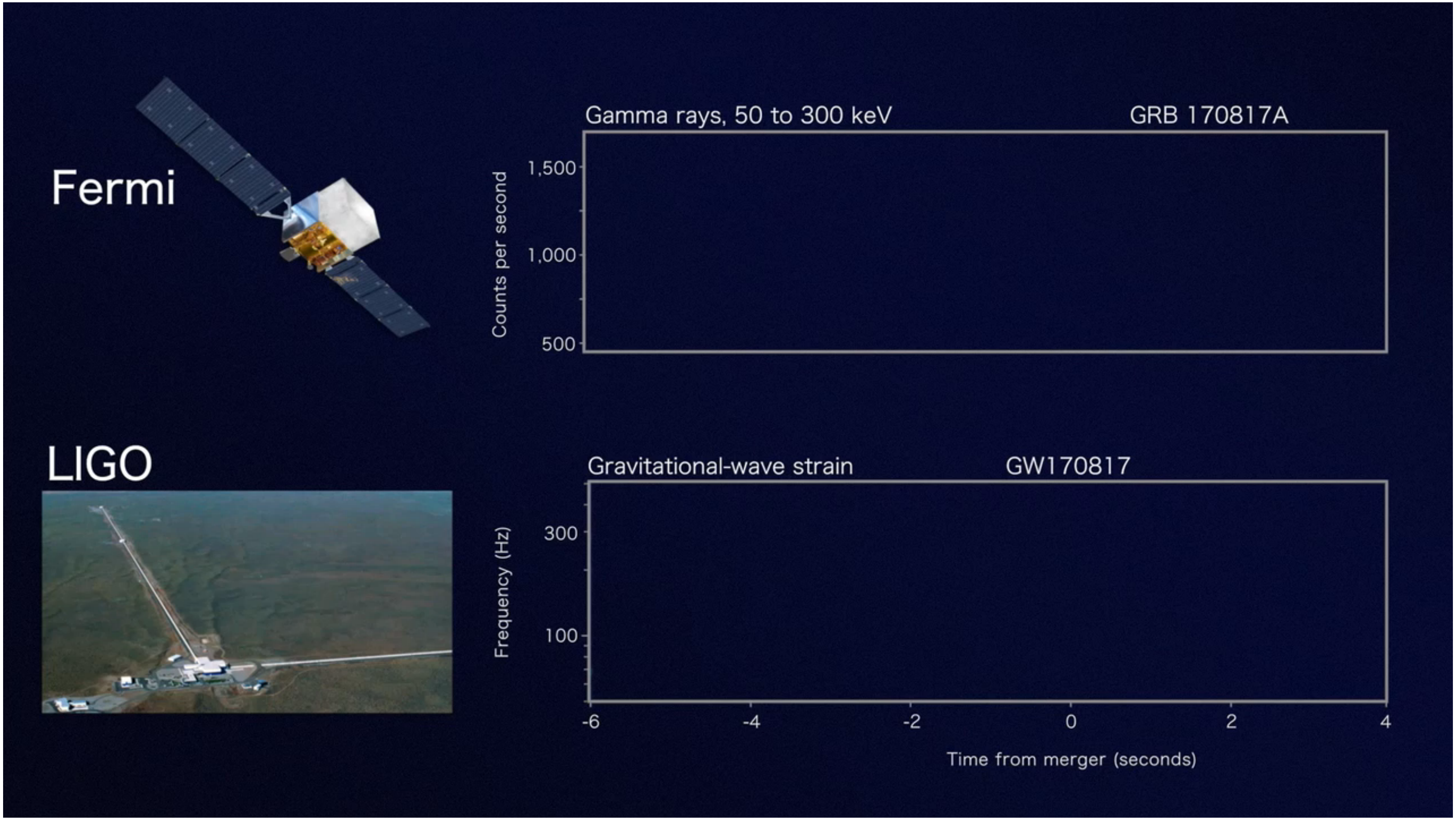
# Sky/distance localization – GW data vs optical / Hubble Const



B.P. Abbott *et al*,
PRL **119**, 061101 (2017)

# Animation from NASA of NS merger and aftermath

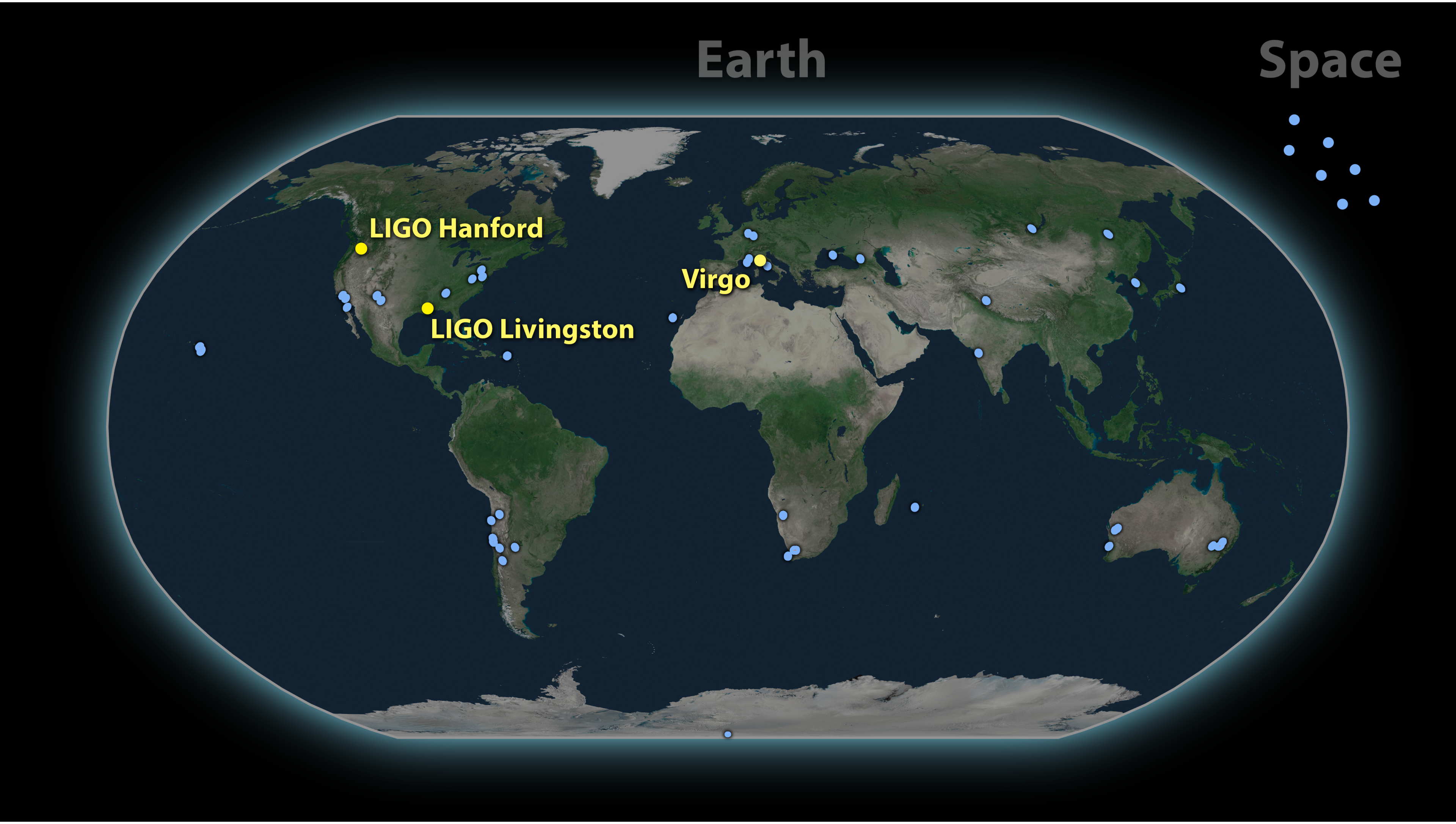
# Animation from NASA of GW chirp and GRB detection



$$-3\times10^{-15} < \frac{(v_{\mathrm{GW}}-c)}{c} < 7\times10^{-16}$$ (lower bound assumes 10-s $\gamma$ emission delay)

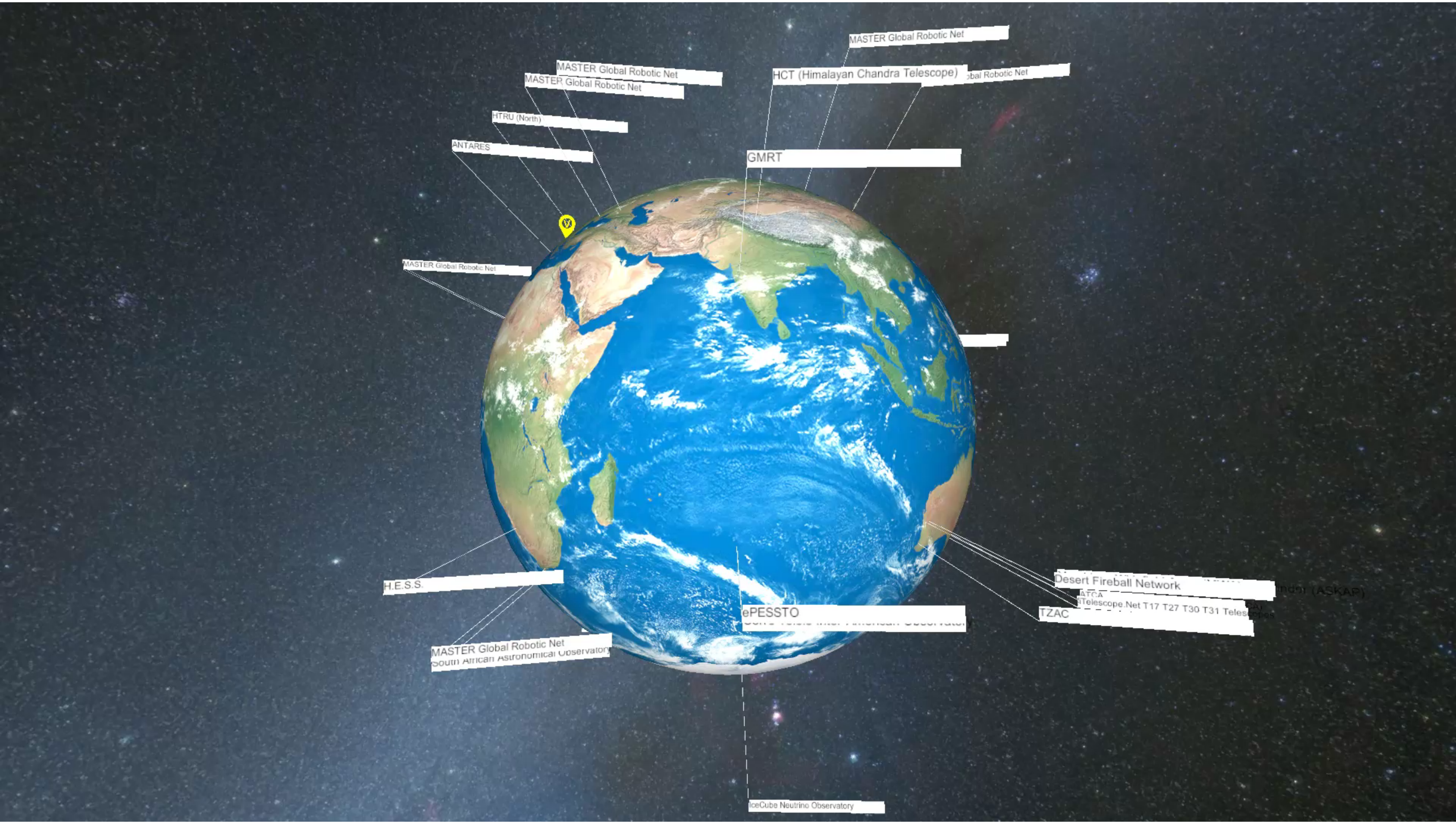
B. Abbott et al., *Ap. J. Lett*. **848** L13 (2017)

# Observatories (~70) on the Earth and in orbit



→ Ready to point upon receiving LIGO/Virgo alert – Earth/Sun permitting

# Time Zone Matters!



Mark Myers / OzGrav

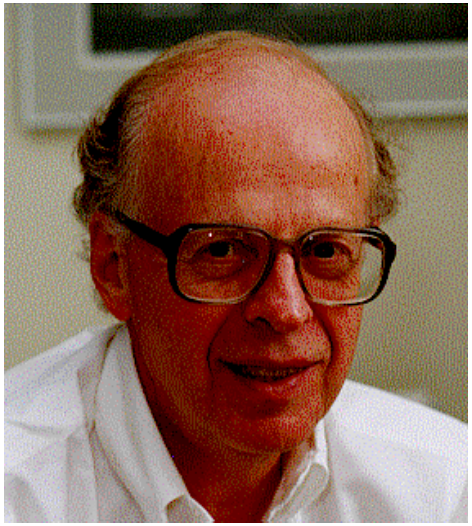
# It takes a Global Village…

- Building this rapid response network took many years of negotiation and meetings between LIGO/Virgo and photon astronomers
- Infrastructure for "private" alerts / reports non-trivial to implement
- Based on the infrastructure set up in the 1990's to allow rapid follow-up of GRBs reported by gamma-ray satellites
- Rapidity is important as transient events change character rapidly
  → **Ideally, follow-up should be automated (robotic)**

**First successful rapid follow-up of a GRB executed by U. Michigan in 1999 by Carl Akerlof's ROTSE* team**

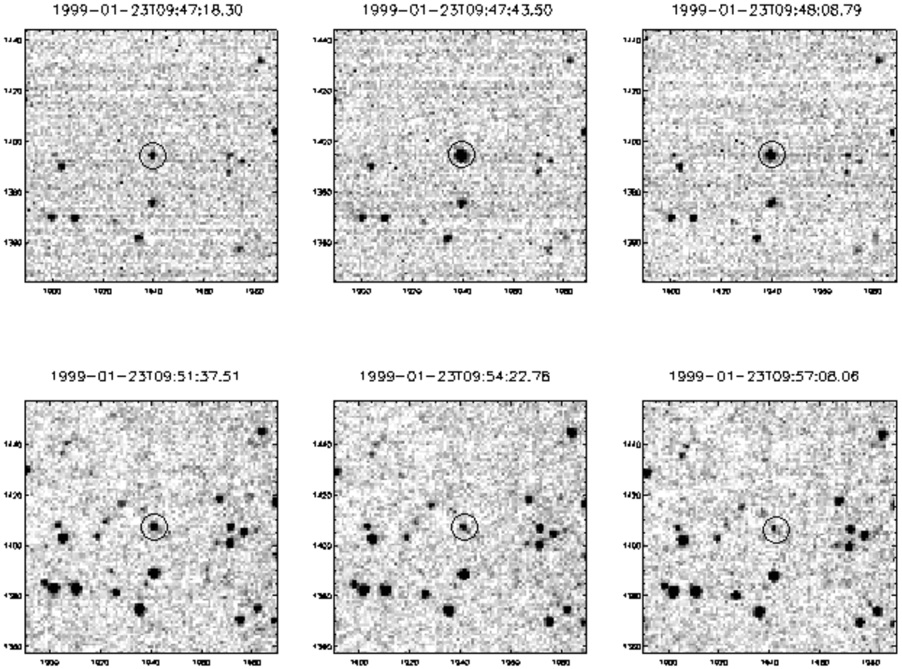
**Found by ROTSE within 22 seconds!**

***Robotic Optical Transient Search Experiment**



# ROTSE I

## GRB990123



1999-01-23T09:47:18.30

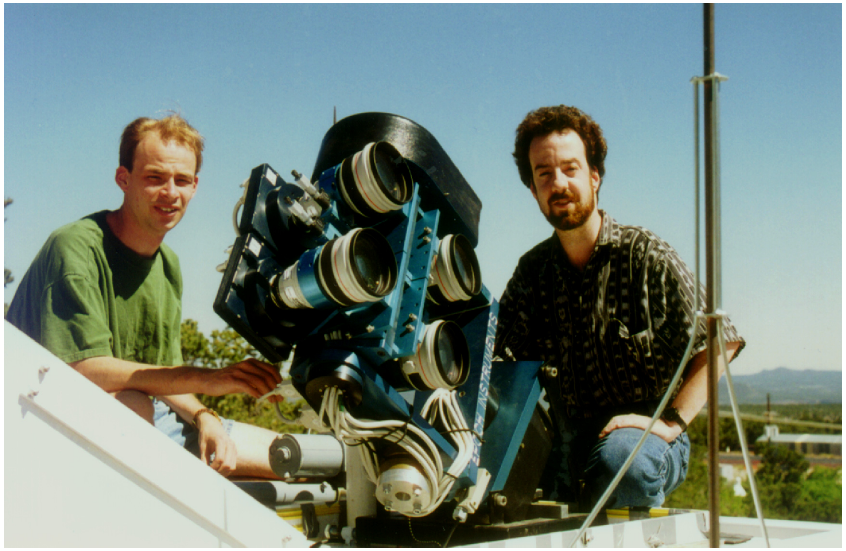
1999-01-23T09:47:43.50

1999-01-23T09:48:08.79

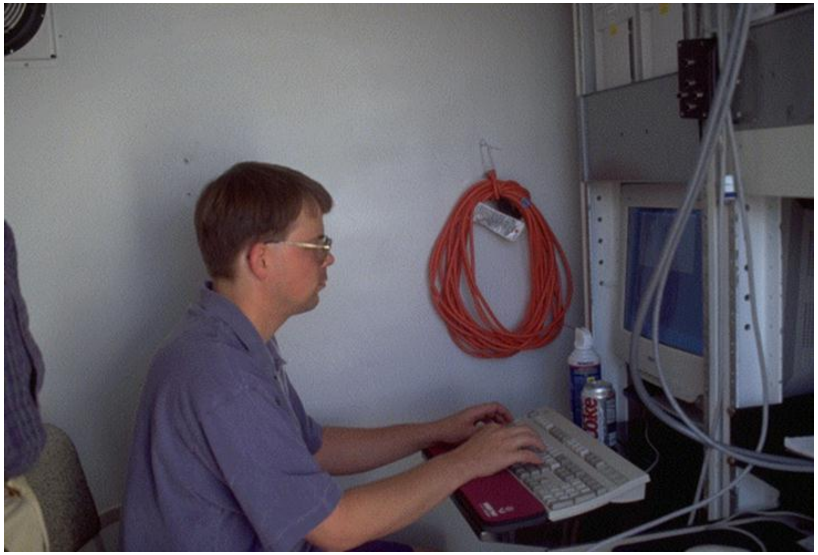
1999-01-23T09:51:37.51

1999-01-23T09:54:22.76

1999-01-23T09:57:08.06



J. Wren, R. Kehoe



T. McKay

# ROTSE III – Australia edition

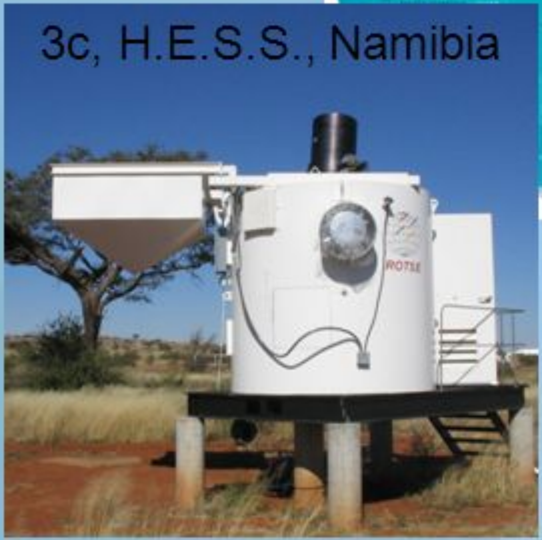
# ROTSE-III Worldwide


3b, McDonald, Texas

February, 2003

May, 2004


3d, TUG, Turkey


3c, H.E.S.S., Namibia

July, 2003

March, 2003


3a, SSO, Australia

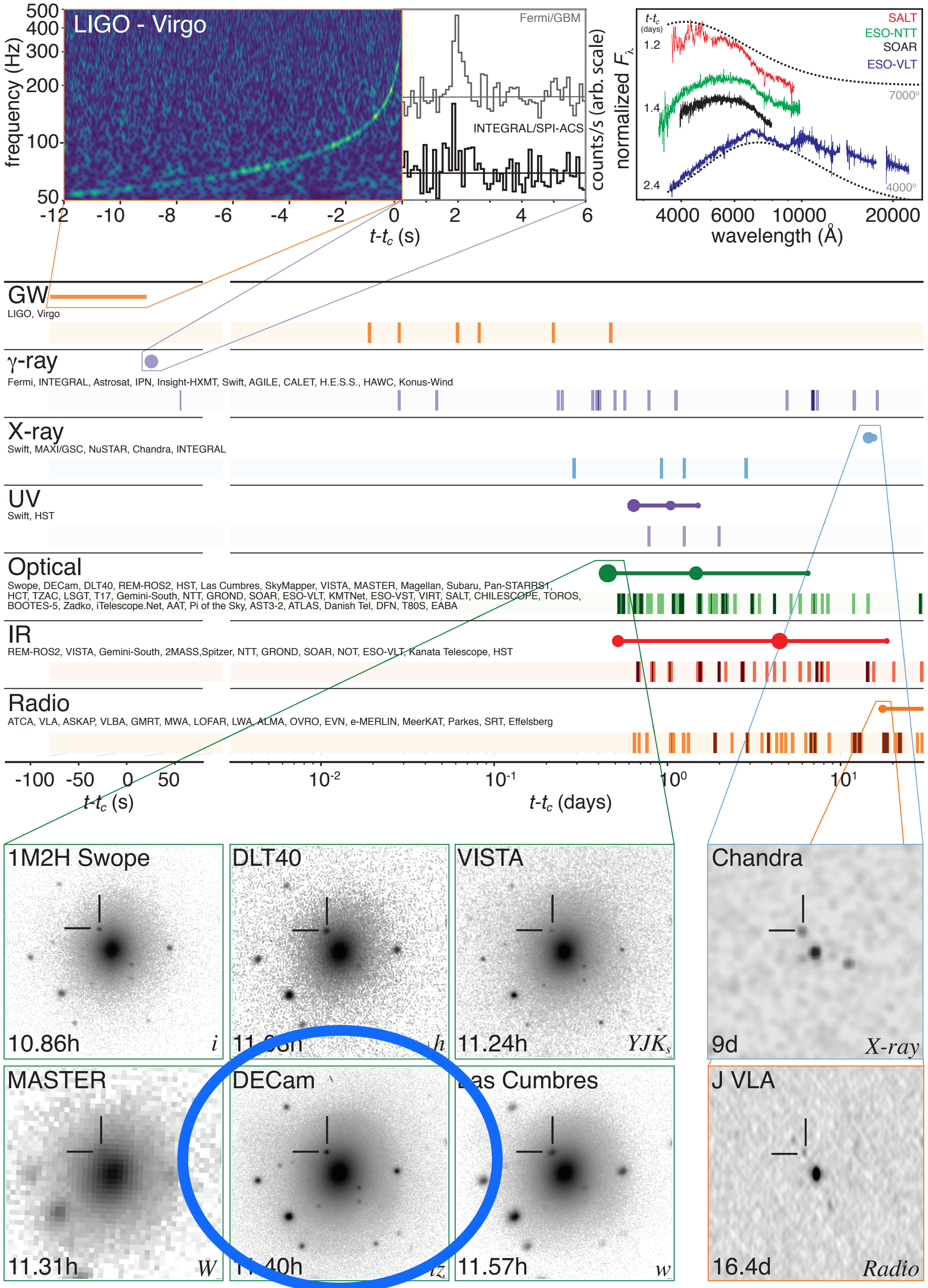
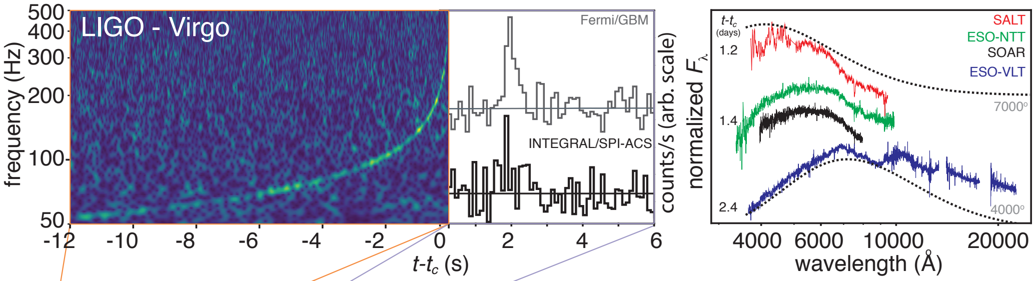


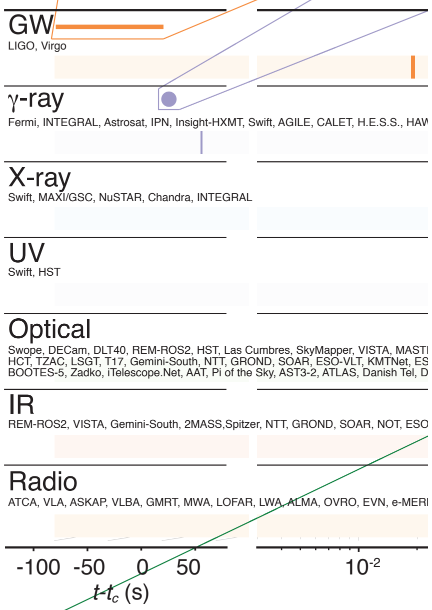
Figure from

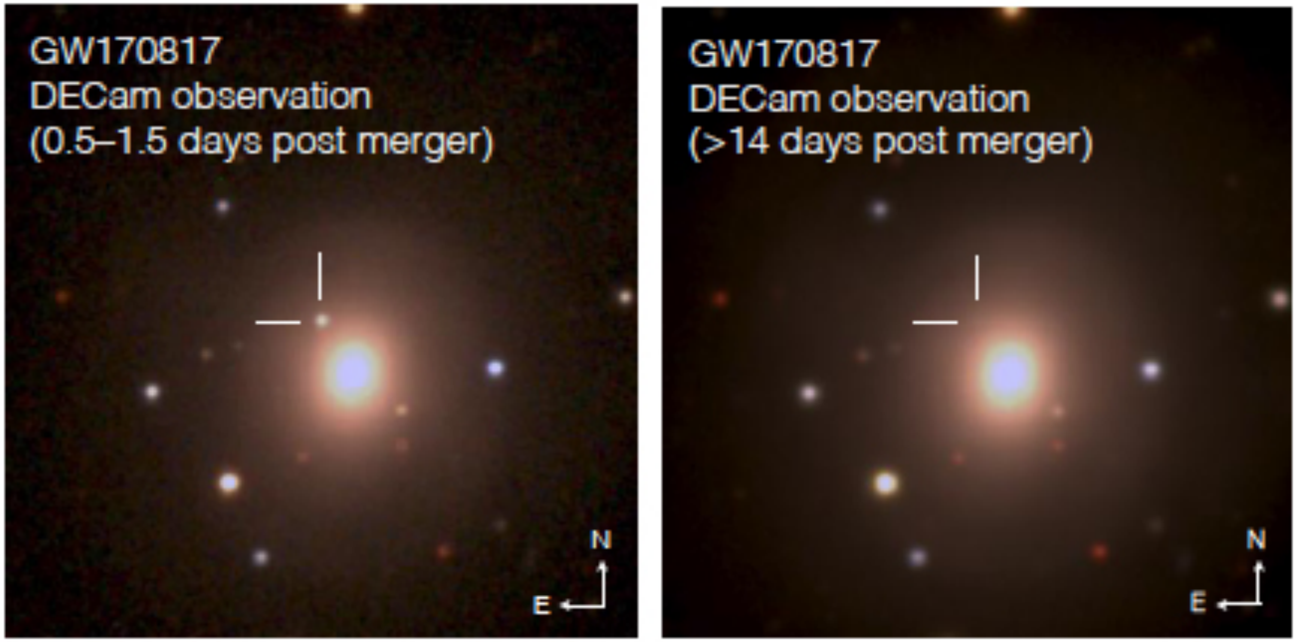
“Multi-Messenger Observations of a Binary Neutron Star Merger”

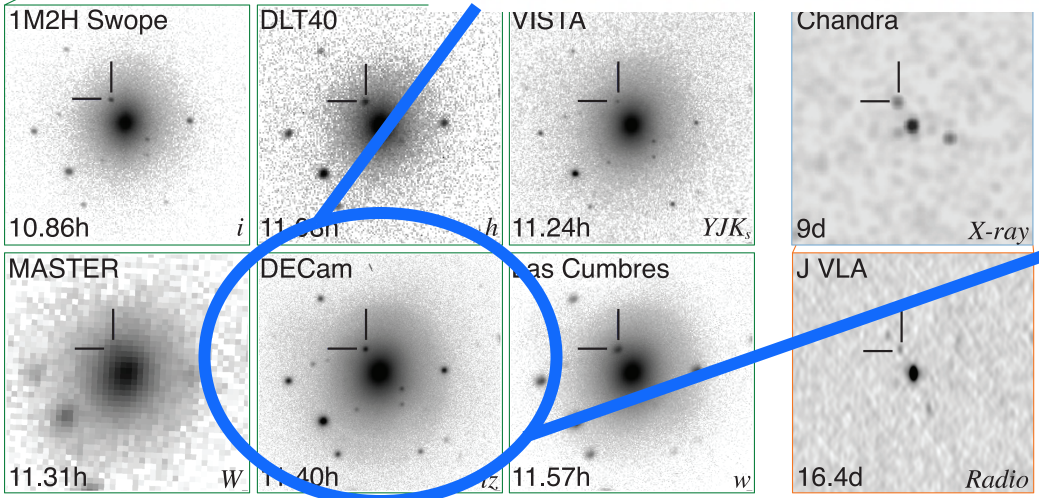
*Ap. J. Lett.* **848** L12 (2017)

59-page “letter” (!)
More than 3000 authors,
~70 collaborations









Fermilab

## Animation from Fermilab of NS merger and aftermath

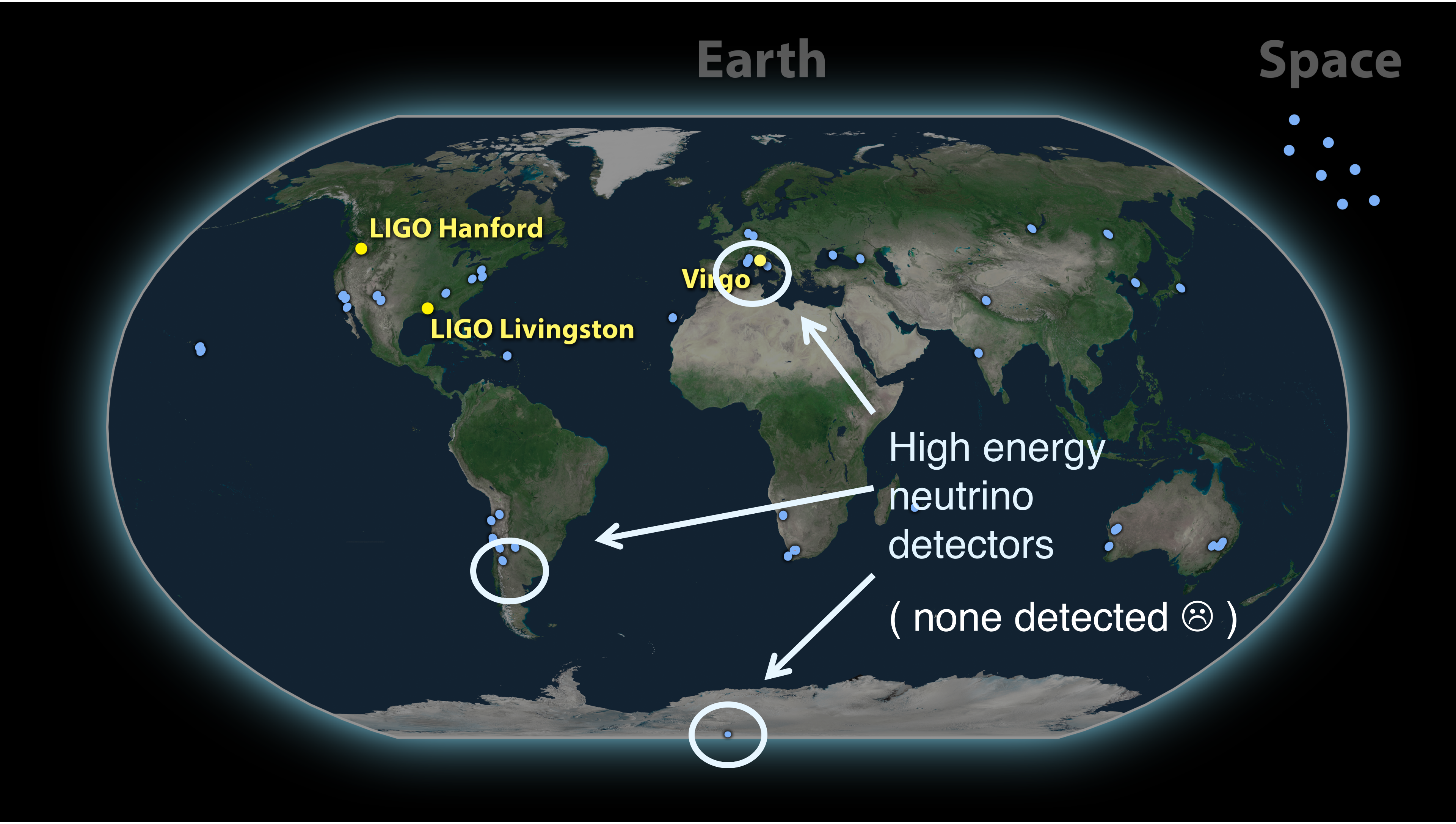
https://www.youtube.com/watch?v=zpWVzVGCtBQ&feature=youtu.be

Cerro Tololo Inter-American Observatory in Chile

Home of Dark Energy Camera (used for the Dark Energy Survey)

Members of the UM DES Group

# Observatories (~70) on the Earth and in orbit



High energy neutrino detectors

( none detected ☹ )

Already observing

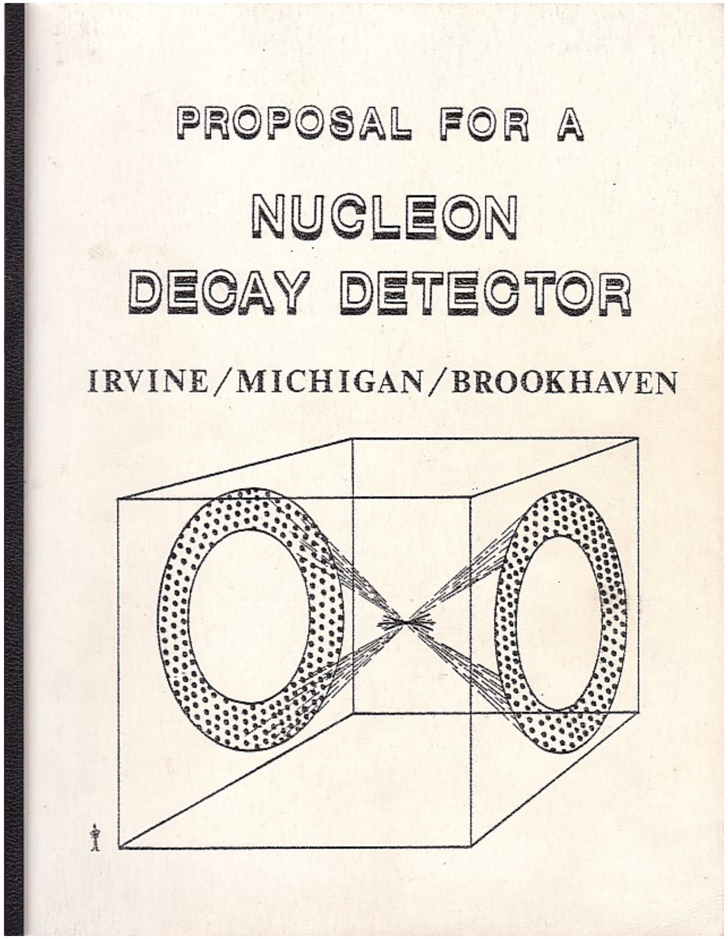
→ ~~Ready to point~~ upon receiving LIGO/Virgo alert – Earth/Sun permitting

"Multi-messenger" means not just the combination of electromagnetic and gravitational wave signals, but can also include another messenger
→ **Neutrinos**

Multi-messenger extra-solar astronomy began 30 years ago with the discovery of Supernova 1987A

U. Michigan physics professors Jack Van der Velde and Dan Sinclair had joined with U.C. Irvine and Brookhaven Lab physicists in the early 1980's to build an underground proton decay detector, using Cerenkov radiation rings in water

## → IMB Experiment

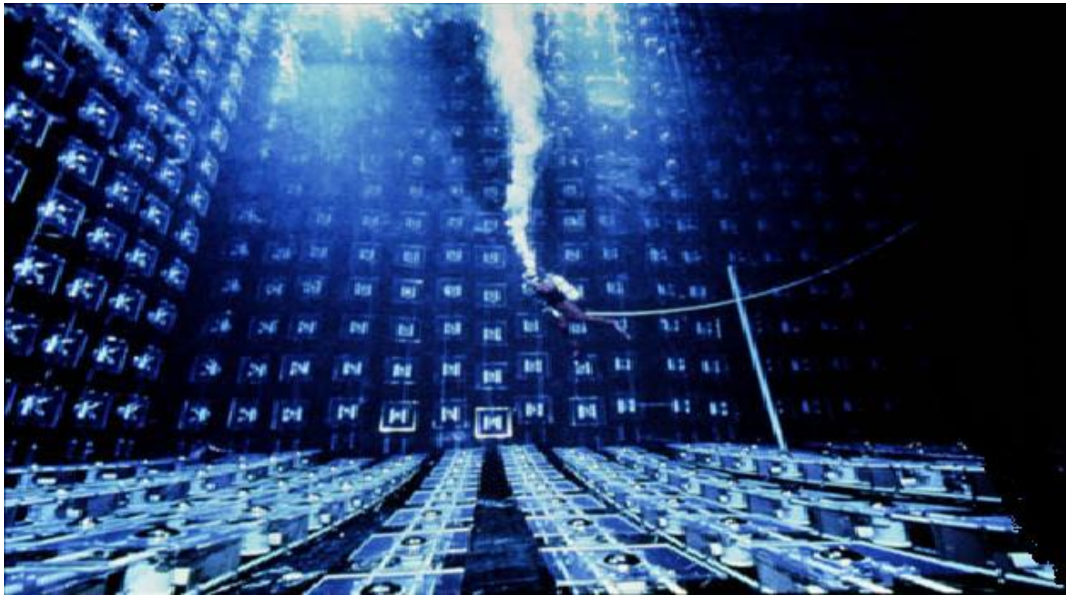


PROPOSAL FOR A

NUCLEON DECAY DETECTOR

IRVINE/MICHIGAN/BROOKHAVEN

Courtesy: A.P.S.

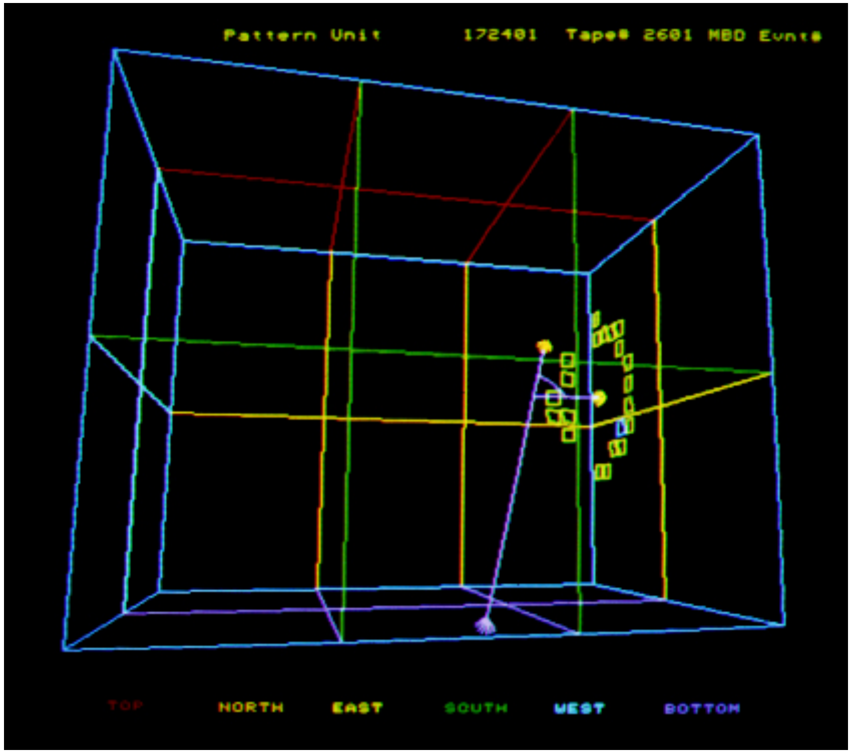


# Visiting Washington, DC to get funds... (1980)

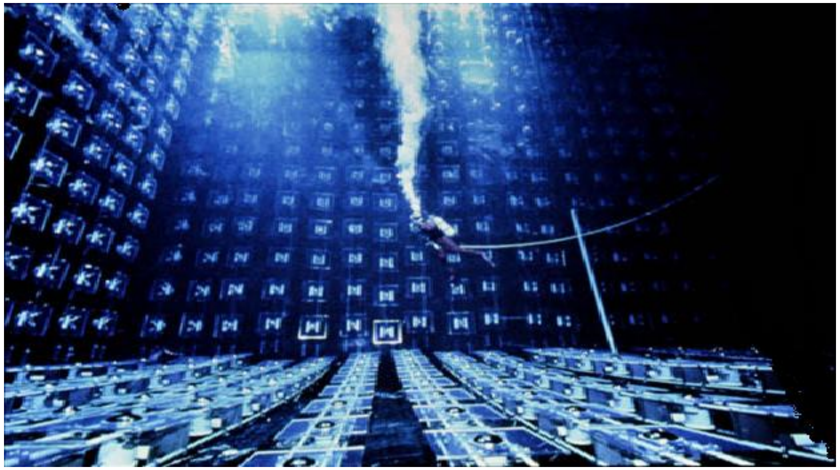
Einstein LoSecco
Smith Wuest Sinclair Learned Cortez
Bratton Sobel Vander Velde Goldhaber Reines Sulak

# The IMB Detector "saw" Supernova 1987A !

(as did the Japanese
Kamiokande Detector and the
Russian Baksan Detector)

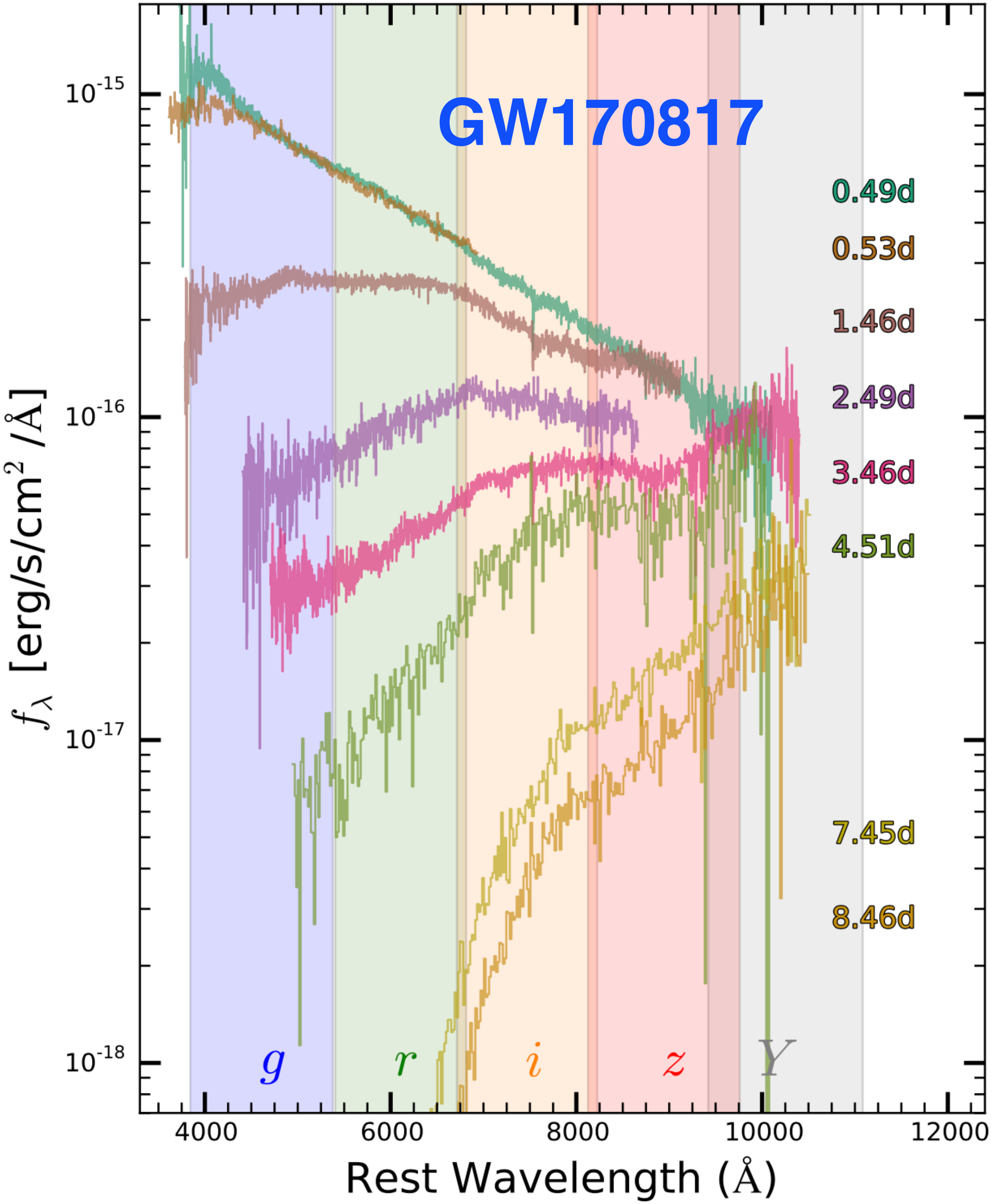


1 of 8 IMB neutrino events



Dramatic confirmation of supernova theory

Opened up new field of neutrino astronomy
and multi-messenger astronomy (extra-solar & extra-galactic)



Spectral evolution of optical counterpart over first week

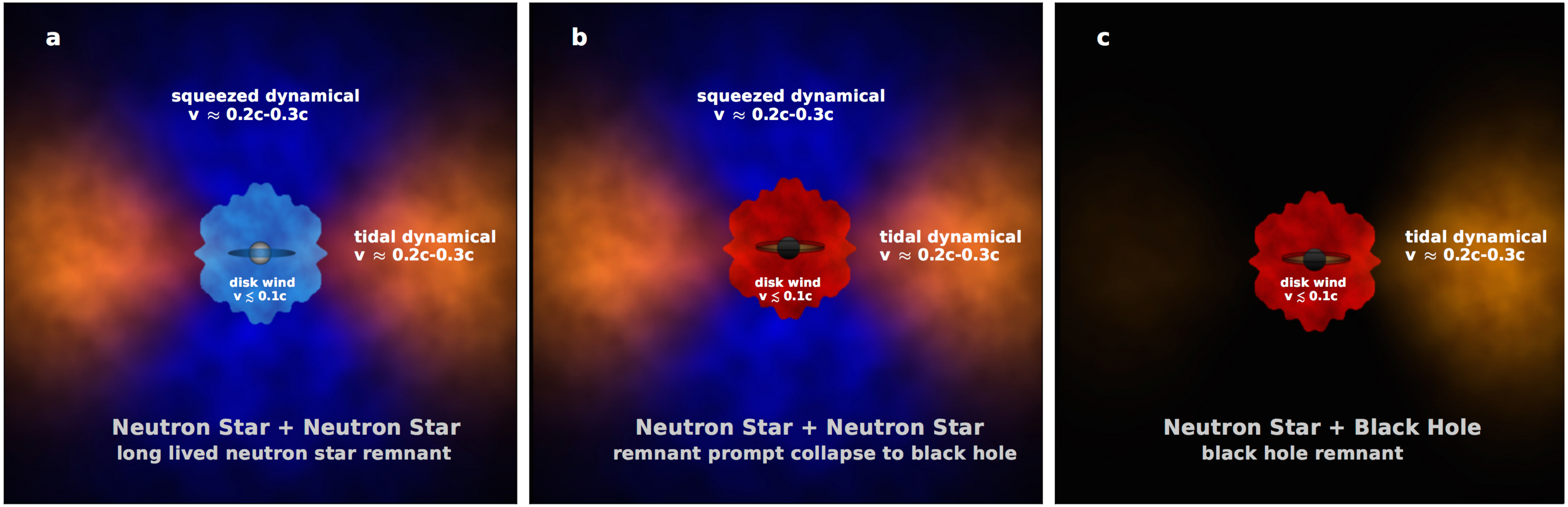
Blue → Infrared

B. J. Shappee et al., *Science*, in press (2017)

”The spectra of SSS17a begin displaying broad features after 1.46 days, and evolve qualitatively over each subsequent day, with distinct blue (early-time) and red (late-time) components.

The late-time component is consistent with theoretical models of r-process-enriched neutron star ejecta, whereas the blue component requires high velocity, lanthanide-free material. ”

# Three scenarios for producing a kilonova*



(D. Kasen et al., *Nature Lett*., in press)

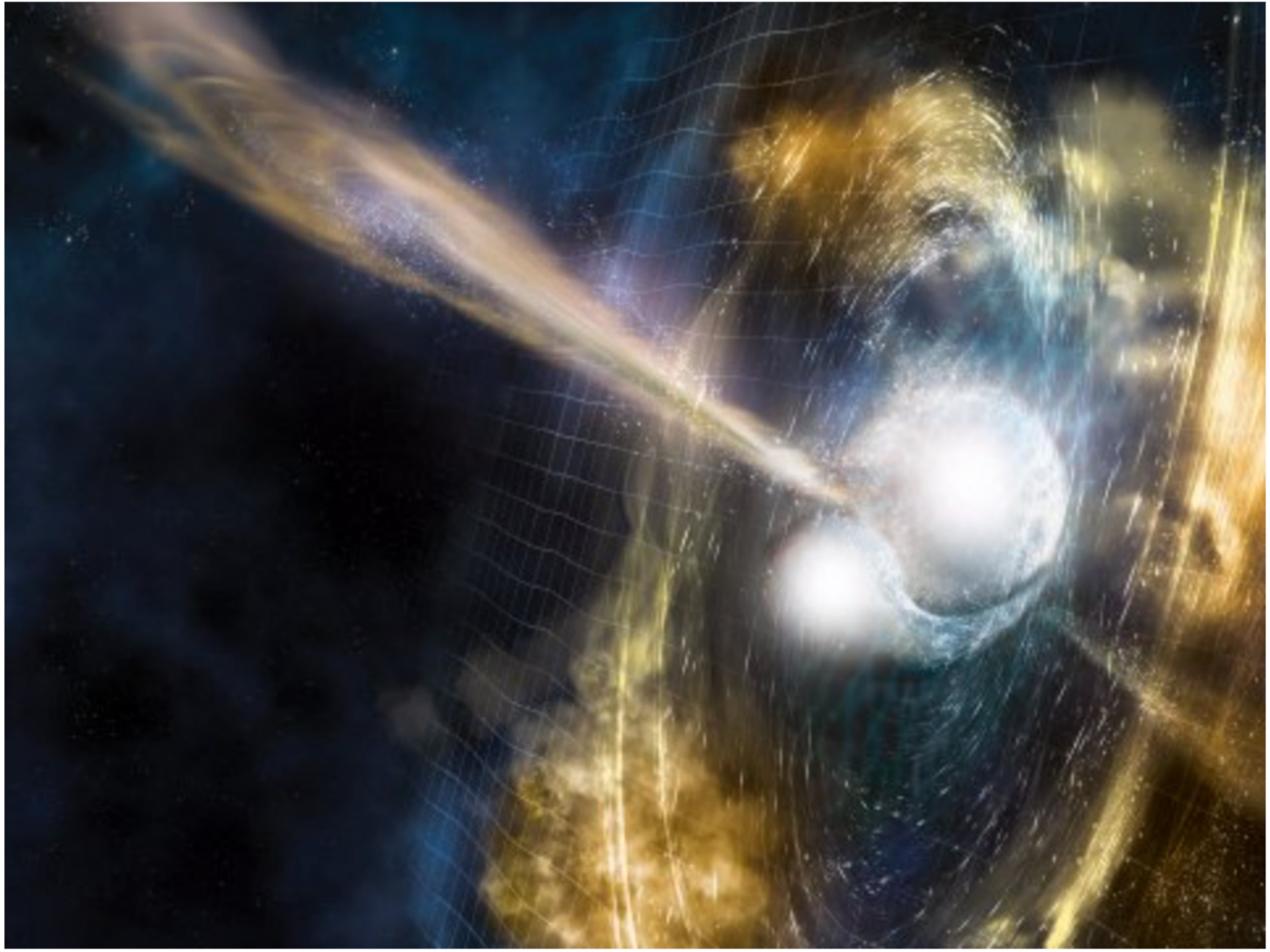
**"We infer the presence of two distinct components of ejecta, one composed primarily of light (atomic mass number less than 140) and one of heavy (atomic mass number greater than 140) r-process elements.**

**Inferring the ejected mass and a merger rate from GW170817 implies that such mergers are a dominant mode of r- process production in the Universe."**

*a.k.a. macronova (L. Li and B. Paczyński, 1998, *Ap.J. Lett*. **507**, L59)

# So just how much gold & platinum was produced?

NSF/LIGO/Sonoma State University/A. Simonnet



**An illustration of a neutron star collision creating platinum, gold, and other precious heavy elements.** Fermilab

Business Insider – October 2017

# So just how much gold & platinum was produced?

"... back-of-the-envelope calculations indicate that this single collision produced an amount of gold greater than the weight of the Earth.
– D. Holz (U. Chicago)

"...tens of times the mass of the Earth in gold and platinum."
– E. Berger (Harvard)

"The gold forged alone is worth about ...
$100,000,000,000,000,000,000,000,000,000" – B. Metzger (Columbia)

"The yield of gold alone was around 200 Earth masses, and that of platinum nearly 500 Earths – D. Kasen (U.C. Berkeley)

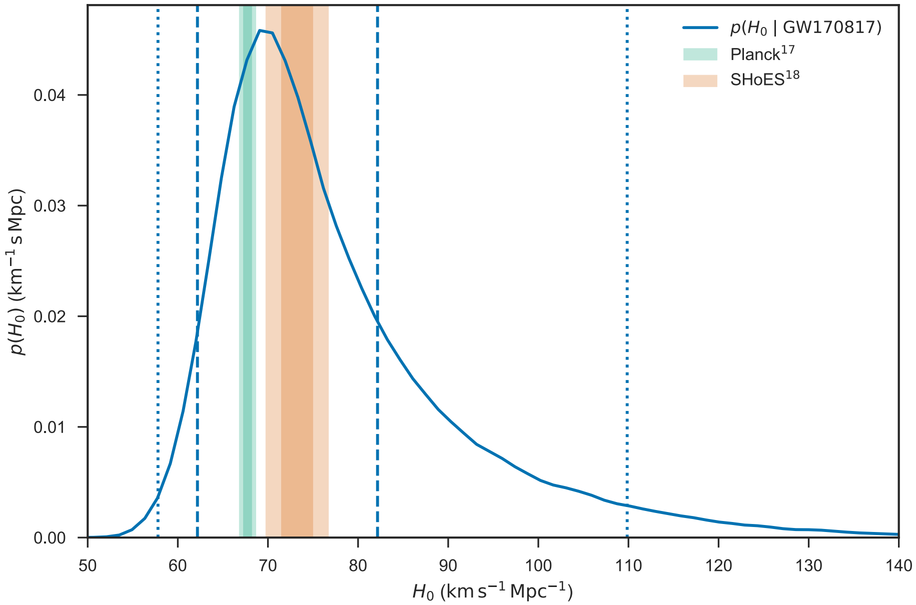
**Watch your wallet!**

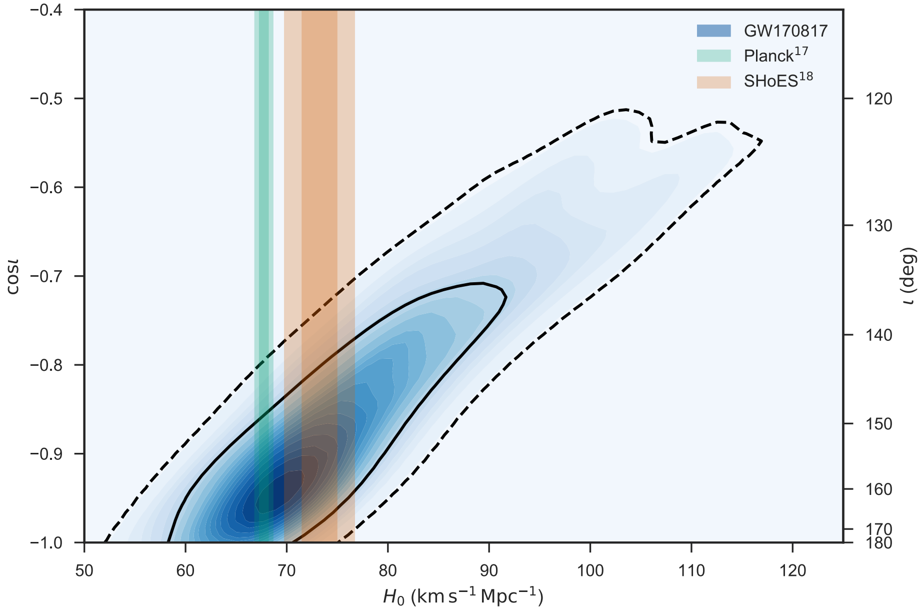
# LIGO's  toward Cosmology

**Distance to source inferred from amplitude of waveform** **(with errors!)**

**Redshift of source measured by EM partners**

**→ Take ratio of redshift "velocity" to distance to get Hubble Constant***





B.P. Abbott *et al*, *Nature*, in press

**Not precise yet!**

**But completely independent of previous $H_0$ determinations**

**→ Interesting potential in coming years** **(more detections, farther out)**

*[1] B. F. Schutz, Nature 323, 310 (1986)

# Summary

- ❑ **LIGO has observed gravitational waves from the mergers of stellar mass black holes**
  (four definitive discoveries published)

- ❑ Virgo has now started detecting gravitational waves too!
  → Dramatically improves triangulation of sources
  → Makes electromagnetic follow-up feasible

- ❑ **First discovery of a binary neutron star merger**
  **→ EM follow-up campaign stunningly successful**
  **→ Gamma rays, X-rays, UV, optical, IR, radio observed**
  **→ Strongly supports kilonova explanation of heavy element production in the Universe**

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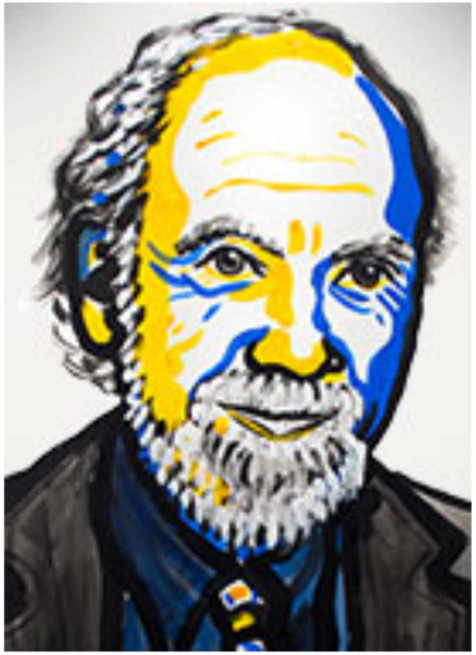
**Rainer Weiss**

**Prize share:** 1/2



© Nobel Media. Ill. N. Elmehed

**Barry C. Barish**

**Prize share:** 1/4

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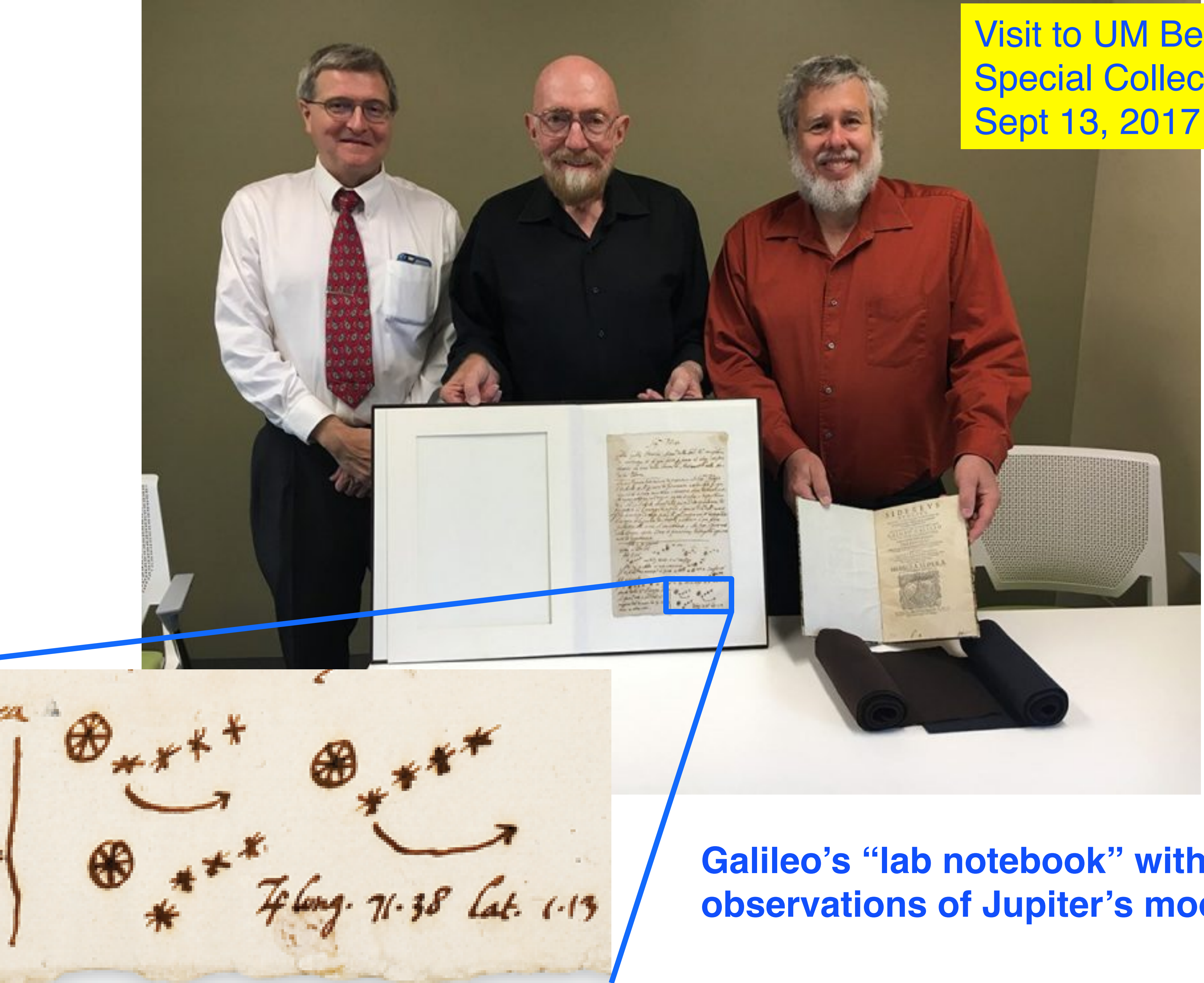
**Kip S. Thorne**

**Prize share:** 1/4

The Nobel Prize in Physics 2017 was divided, o Rainer Weiss, the other half jointly to Barry C. Thorne *"for decisive contributions to the LIGO detector and the observation of gravitational waves"*.

**2017 UM Physics**
**Ta-You Wu Lecturer**

Visit to UM Bentley Special Collections
Sept 13, 2017



**Galileo's "lab notebook" with first observations of Jupiter's moons**

# The dawn of Gravitational-wave multi-messenger astronomy is here

Credit: N. Armstrong

# EXTRA SLIDES

# The “most sure-fire” signal

Imagine two neutron stars:

- Each with mass equal to 1.4 solar masses
- In circular orbit of radius 20 km (imminent coalescence)
- Resulting orbital frequency is 400 Hz (!)
- Resulting GW frequency is 800 Hz

General Relativity predicts:

$$h \approx \frac{10^{-21}}{(\mathrm{r} / 15\ \mathrm{Mpc})}$$

→ Virgo cluster – Initial LIGO hoped for this signal…
(just detectable)

Courtesy: Peter Shawhan

# So how likely is it to see such a binary neutron star (BNS) signal?

**Three distinct approaches to estimate BNS merger rates:**

- Known double-neutron-star systems in the Galaxy
- Stellar evolution modeling (population synthesis)
- Short gamma-ray burst rates (with beaming assumptions)

**Galactic systems give the strongest constraints:**

| **BNS rates:*** | [mergers per Mpc$^3$ per Myr] |
|---|---|
| Low | 0.01 |
| Realistic | 1 |
| Optimistic | 10 |
| High | 50 |

**Predicted BNS counts for the first Advanced LIGO Observing Run O1**

0.0005 – 4 events

→ **Would have had to be lucky to see a BNS in O1**

(and extremely lucky to have seen one in initial LIGO data)

*B.P. Abbott *et al*, Living Rev. Relativity **19,** 1 (2016)

# Other compact binary coalescences:  NS-BH and BH-BH

**Predicted Rates:*** [mergers per $\mathrm{Mpc}^3$ per Myr]

| | NS-NS | NS-BH | BH-BH |
|---|---|---|---|
| Low | 0.01 | 0.0006 | 0.0001 |
| Realistic | 1 | 0.03 | 0.005 |
| Optimistic | 10 | 1 | 0.3 |

Predicted counts for NS-BH and BH-BH comparable to NS-NS, despite lower rate densities because the heavier systems can be seen to larger distances and much larger volumes

**Higher masses lead to higher rates**
**→ Event rate proportional to $(\mathrm{mass})^3$**
**→ BH rates depend sensitively on assumed mass distributions**

*B.P. Abbott *et al*, Living Rev. Relativity **19,** 1 (2016)

# One BH-BH Example

**Now imagine two heavy black holes :**

- **Each with mass equal to 30 solar masses**
- **In circular orbit of radius 175 km (imminent coalescence)**
- **Resulting orbital frequency is 100 Hz**
- **Resulting GW frequency is 200 Hz**

**GR prediction:**

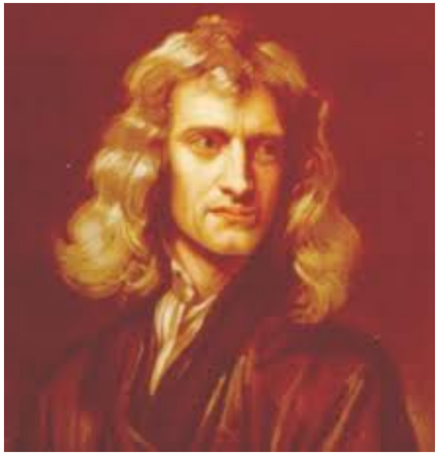
$$h \approx \frac{10^{-21}}{(r/400\,\mathrm{Mpc})}$$

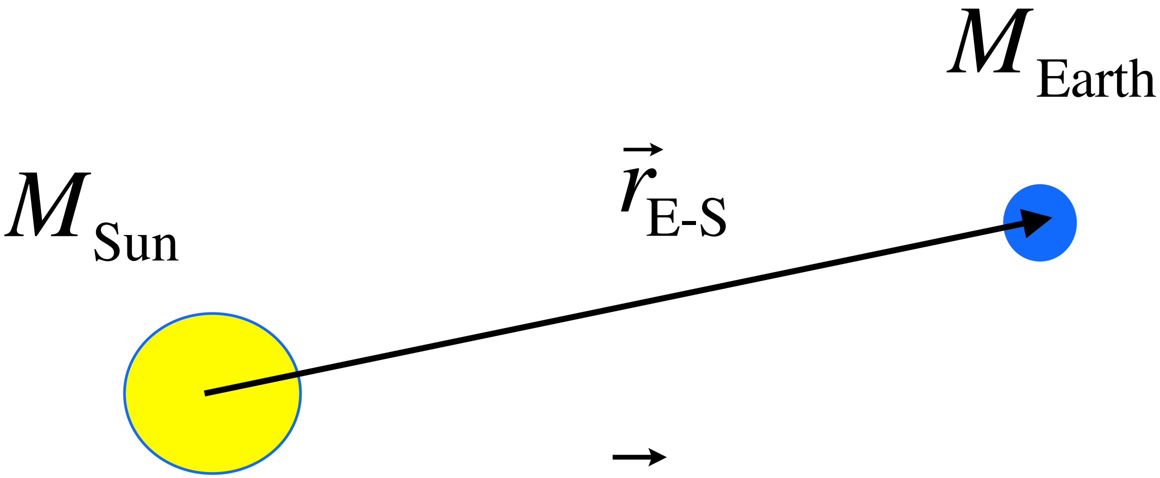
**→ Easily detectable in fall 2015 O1 run**

**High mass → Low chirp frequency**

**Courtesy: Peter Shawhan**

# Newton’s Gravity

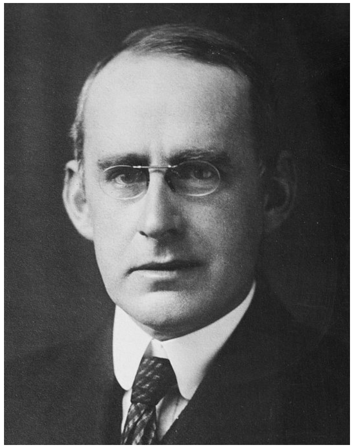


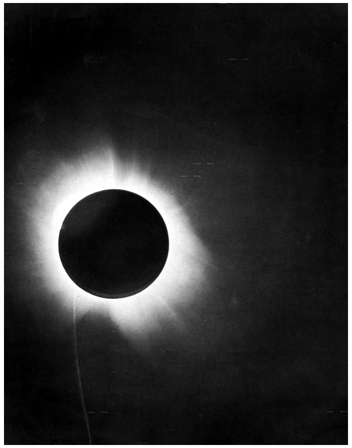


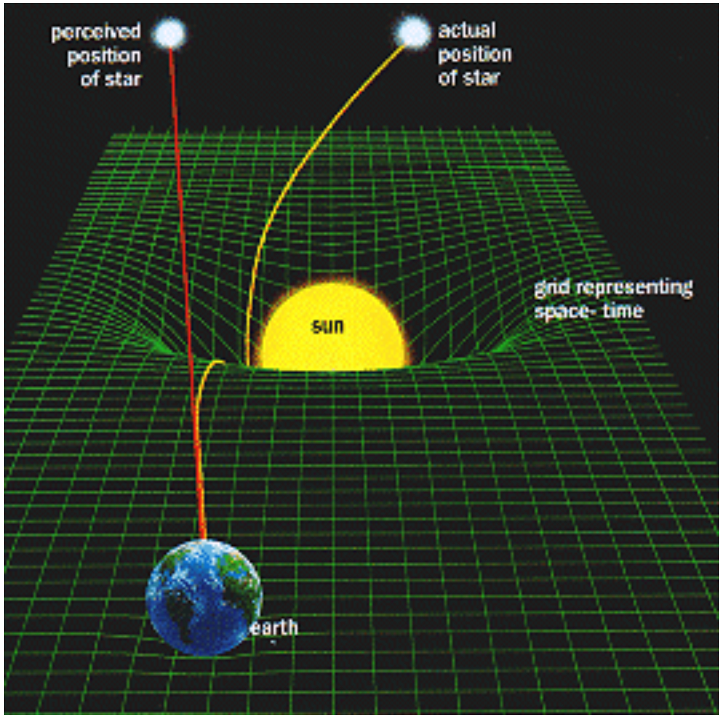
$$\vec{F}_{\text{On Earth}} = -\frac{GM_{\text{Sun}}M_{\text{Earth}}}{r_{\text{E-S}}^2}\,\hat{r}_{\text{E-S}}$$

→ Instantaneous “action at a distance”

# Curved space also tells light how to move







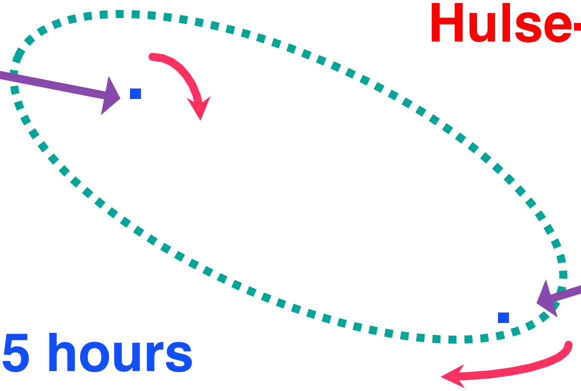
Courtesy: University of Oregon

Sir Arthur Eddington’s 1919 African expedition to observe the total solar eclipse established that Einstein’s predicted deflection of light was correct

First confirmed <u>prediction</u> of General Relativity*

*Einstein used the precession of Mercury’s perihelion as a guide in checking GR

# Hulse-Taylor binary system (1974)



**Observed**
**17-Hz pulsar**

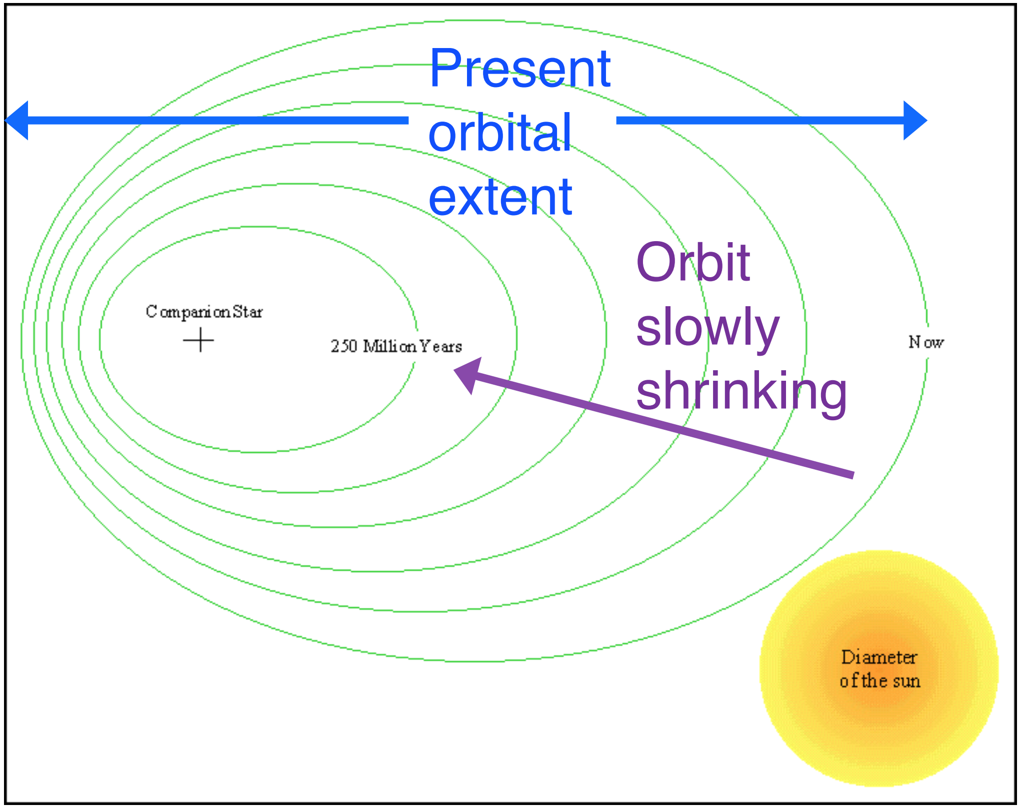
**PSR 1913+16**

**Unseen companion**
**(neutron star)**

**Orbital period is 7.75 hours**

**Binary system's orbit shrinks about 3 mm every revolution from GW energy loss**

**→ Coalescence in about 300 million years**



Present orbital extent

Orbit slowly shrinking

**Weisberg et al, 1981**

# Comparing prediction to measurement

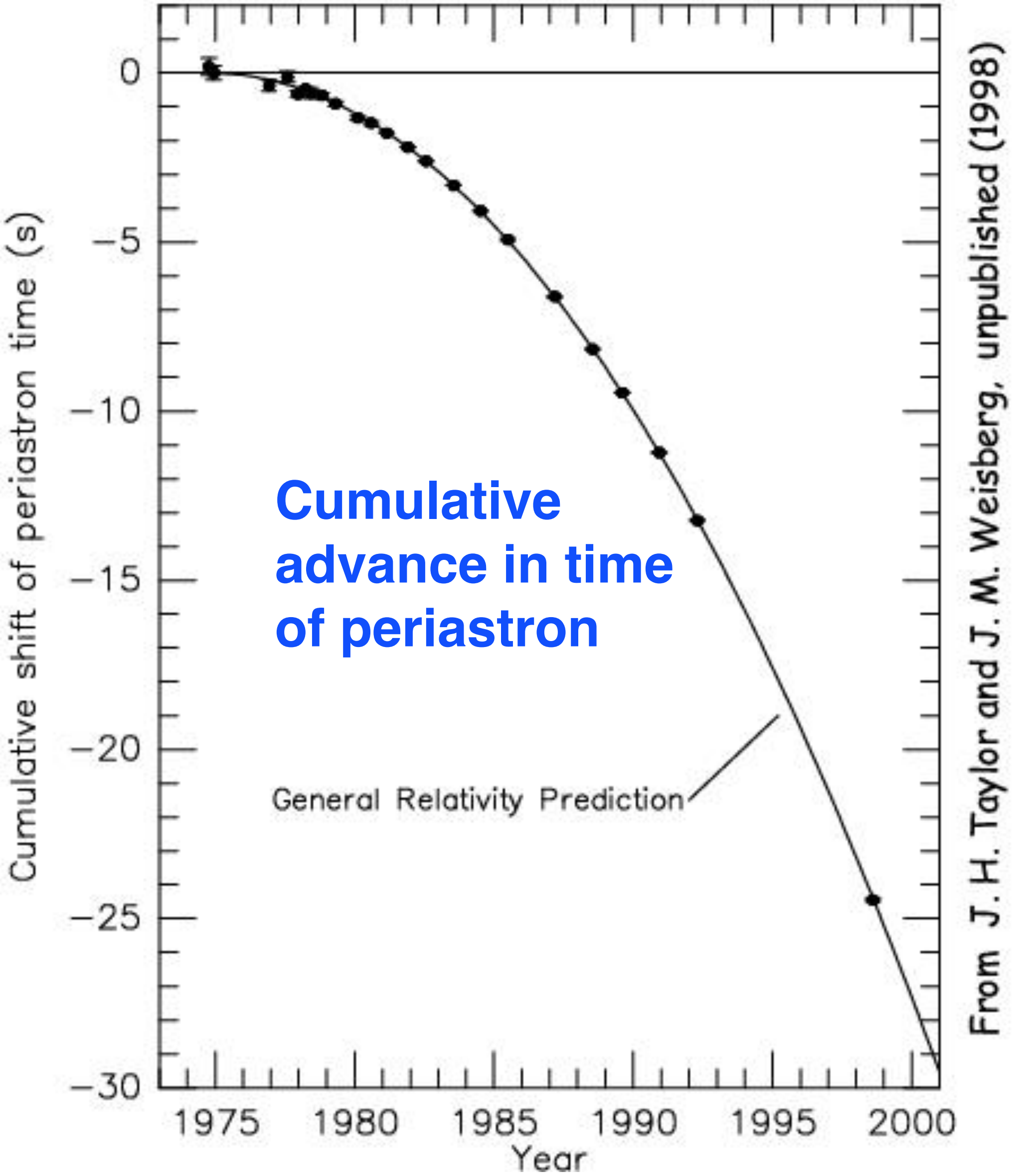
**Smooth curve is absolute prediction from General Relativity**
**(no free parameters!)**

Dots are measured data

Can we detect the implied gravitational waves here on Earth?

Unfortunately, no.
GW frequency is ~ 70 μHz

Task for future space-based detector



Cumulative advance in time of periastron

From J. H. Taylor and J. M. Weisberg, unpublished (1998)

# Final stages of death spiral

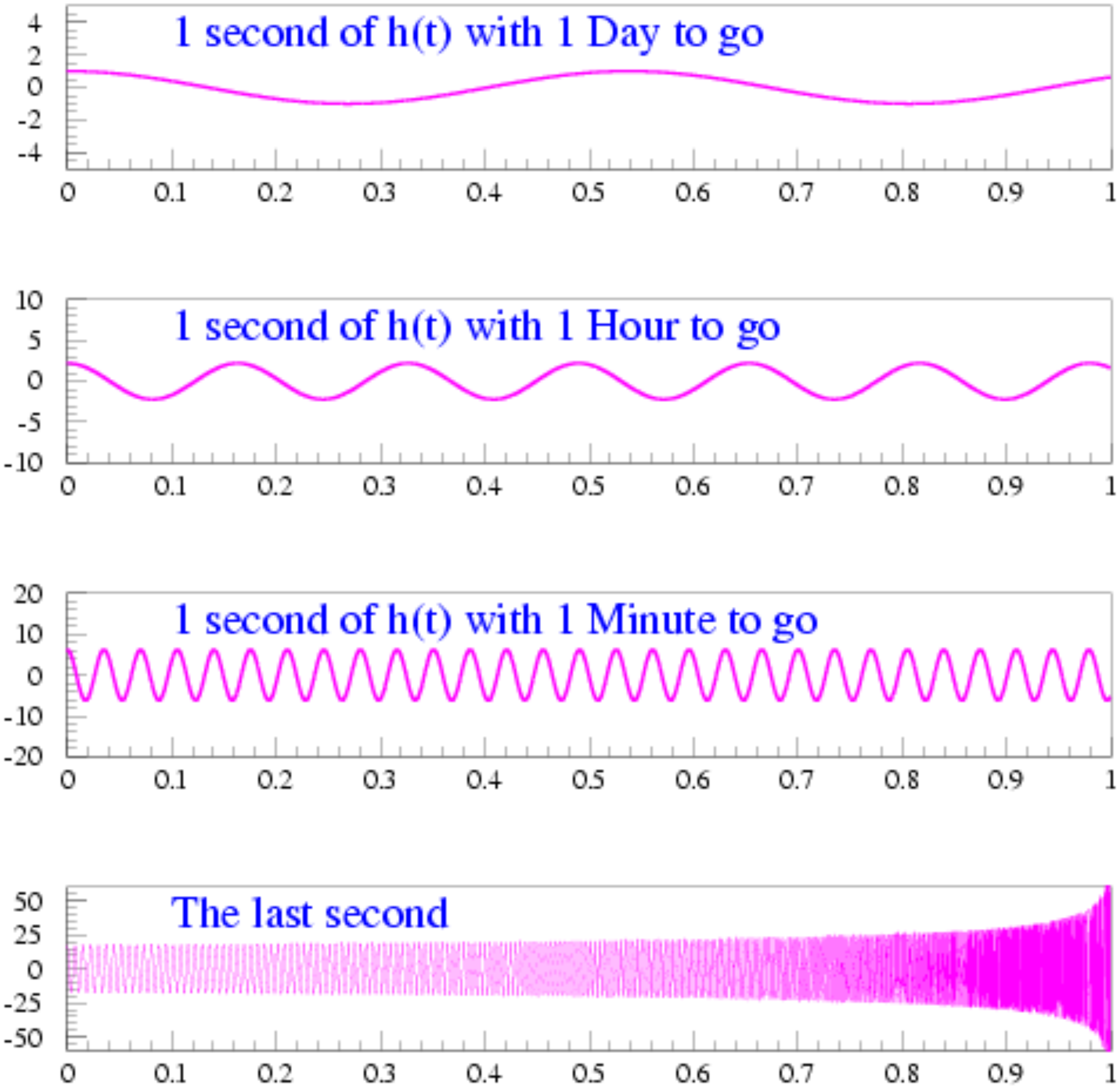
Well, what if we waited around for 300 million years?

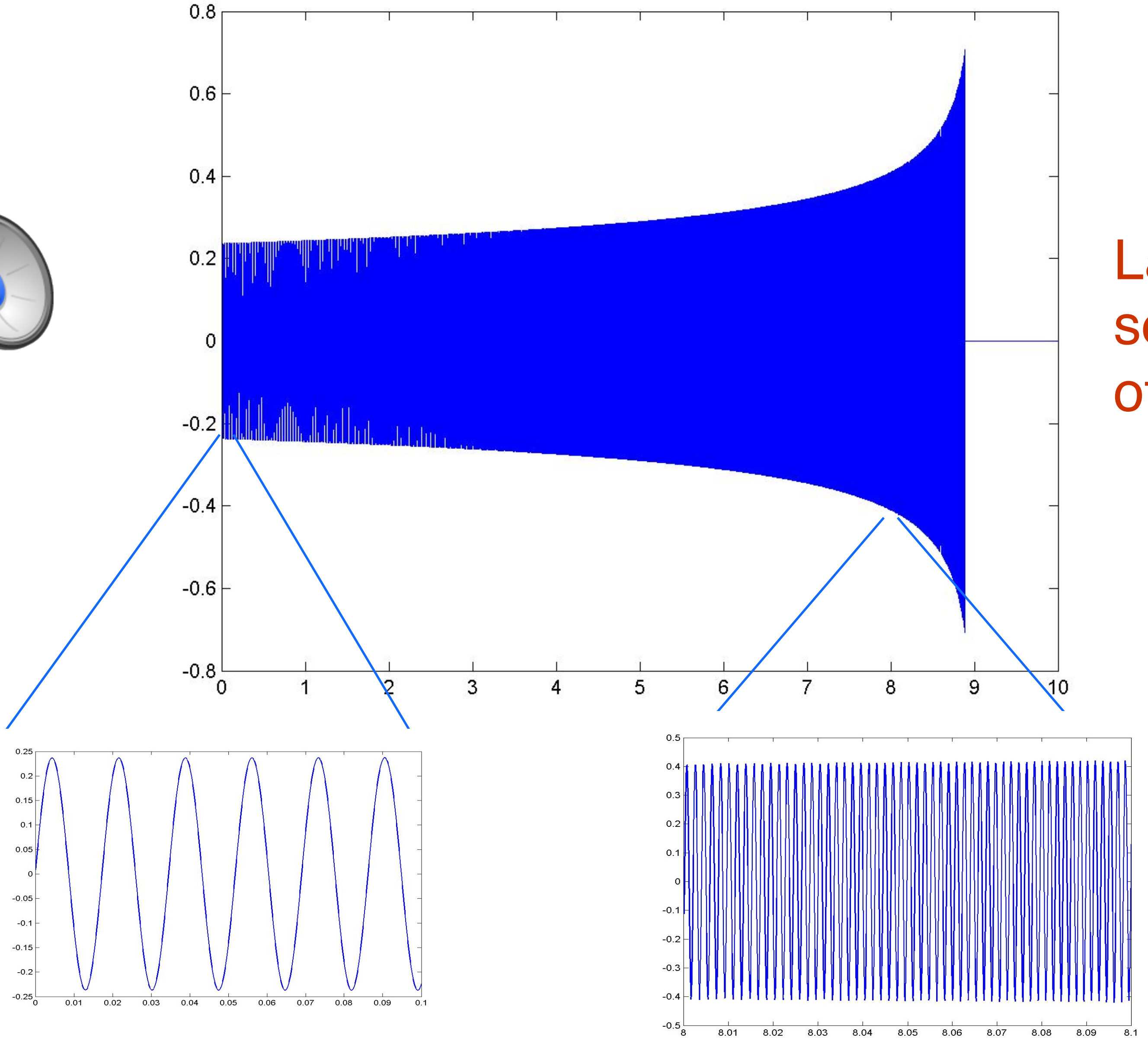
What might we “see”?

**A Chirp!**

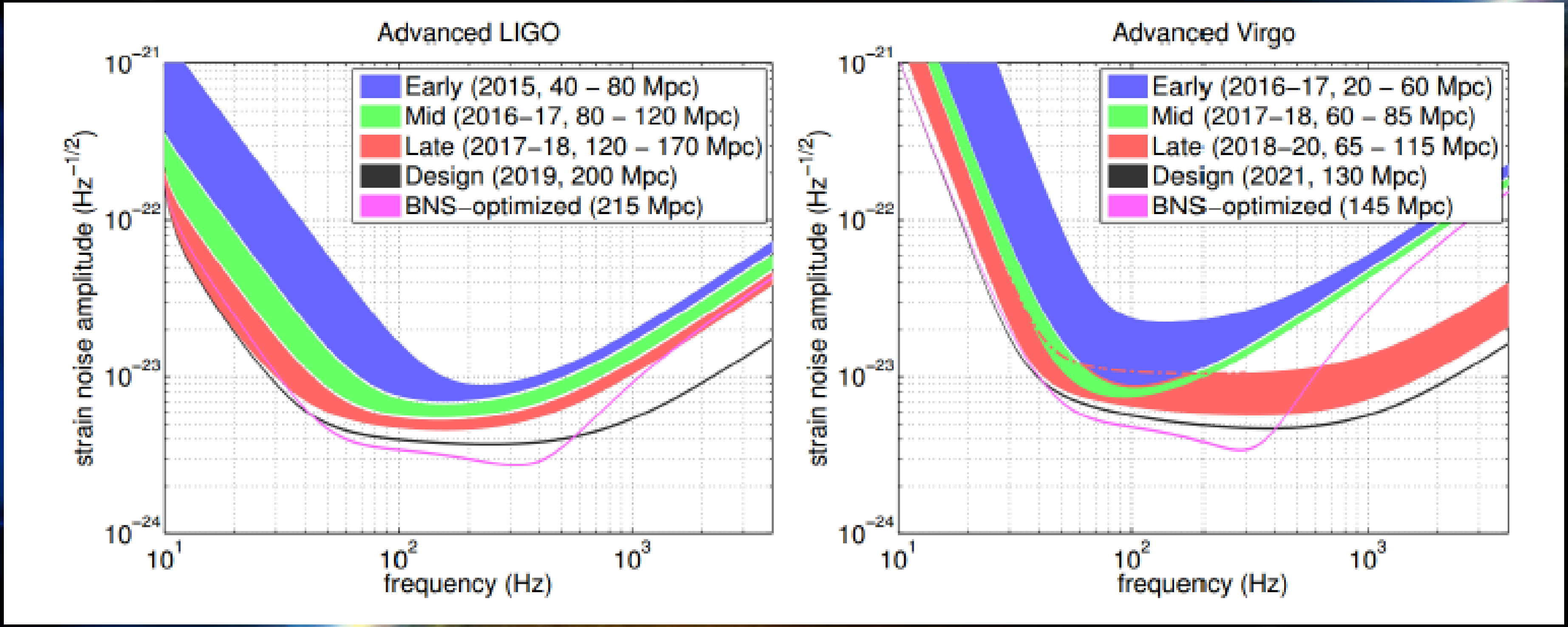
Graphs show waveform for 4 different 1-second intervals near the end of the inspiral, a.k.a., “death spiral”

(in arbitrary but consistent units)



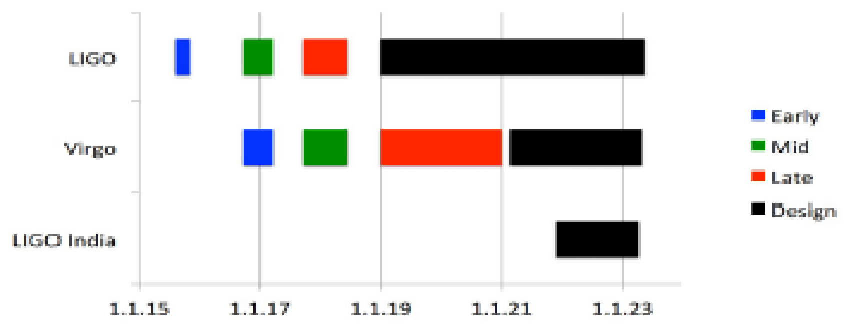


Last nine seconds of inspiral



| Epoch | Estimated Run Duration | $E_{GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) LIGO | Virgo | BNS Range (Mpc) LIGO | Virgo | Number of BNS Detections | % BNS Localized within 5 deg² | 20 deg² |
|---|---|---|---|---|---|---|---|---|
| 2015 | 3 months | 40 – 60 | – | 40 – 80 | – | 0.0004 – 3 | – | – |
| 2016 – 2017 | 6 months | 60 – 75 | 20 – 40 | 80 – 120 | 20 – 60 | 0.006 – 20 | 2 | 5 – 12 |
| 2017 – 2018 | 9 months | 75 – 90 | 40 – 50 | 120 – 170 | 60 – 85 | 0.04 – 100 | 1 – 2 | 10 – 12 |
| 2019+ | (per year) | 105 | 40 – 80 | 200 | 65 – 130 | 0.2 – 200 | 3 – 8 | 8 – 28 |
| 2022+ (India) | (per year) | 105 | 80 | 200 | 130 | 0.4 – 400 | 17 | 48 |

# Observing scenario



B.P Abbott *et al*, LRR **19,** 1 (2016)

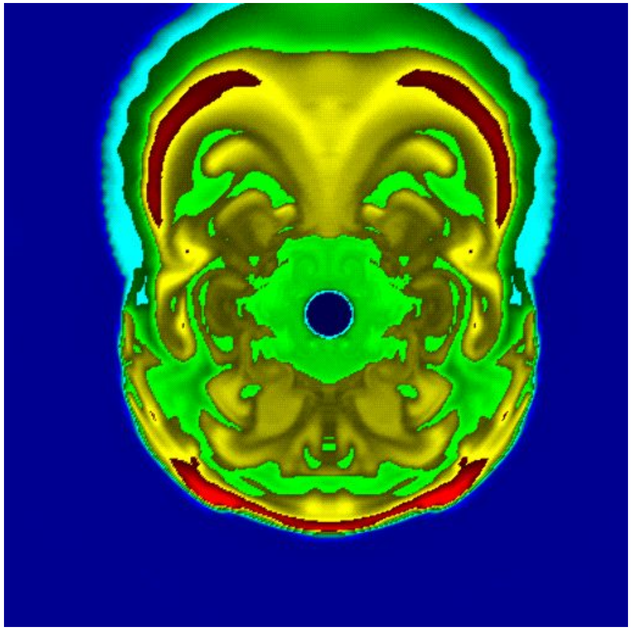
# Outlook -- Other gravitational wave sources?

Coalescing binaries containing neutron stars (may) offer glimpse into the neutron star equation of state, as NS is tidally shredded
→ Will probably need good SNR at high frequencies to see effects

Coincident electromagnetic observations of short GRB with NS-NS merger:

- New insight into GRB dynamics
- New rung on cosmological distance ladder – calibrate redshift with GW luminosity distance
- Can set limits on $|c-c_{GW}|$

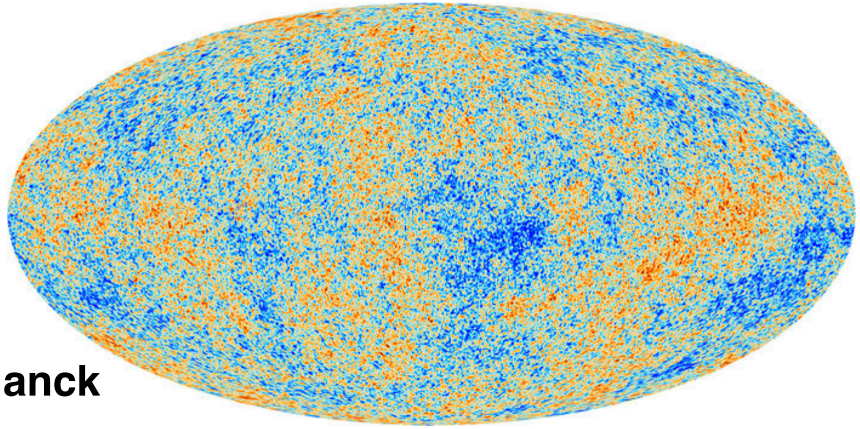
Supernovae are seen now via electromagnetic observations of outer envelopes and (once!) by neutrinos
→ Gravitational waves would give view of core collapse itself



**Courtesy: Dr. Tony Mezzacappa -- ORNL**

# Outlook -- Other gravitational wave sources?

The Big Bang may have produced residual gravitational waves strong enough to be detected on Earth (but not likely)

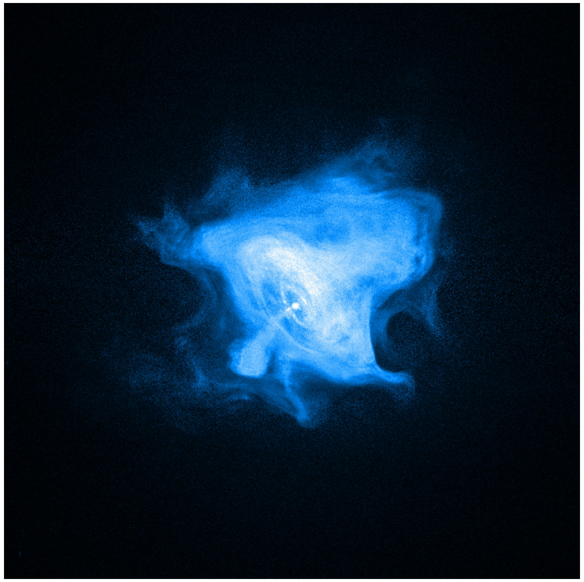


**Planck**

Recent (O1) exclusion papers:

B.P. Abbott *et al,*
PRL **118**, 121101 (2017)
PRL **118**, 121102 (2017)

Fast-spinning neutron stars in our galaxy could be non-axisymmetric enough to produce an extremely weak but continuous signal



**Chandra view of Crab Pulsar**

Recent (O1) exclusion papers:

B.P. Abbott *et al,*
ApJ **839**, 12 (2017)
arXiv:1704.03719

# GW150914

- In September 2015, we were in the final stages of preparation for first Advanced LIGO data run (O1).
- The very last step is a short “Engineering Run,” during which on Sept 14 our online monitor recorded GW150914.
- We identified the signal within 3 minutes
- We responded by starting the data run officially, keeping all settings fixed and ran for 16 live days coincidence time (long enough to assess background levels, etc)
- Data analyzed for assessing significance: Sept 12 – Oct 20

---

- O1 continued data taking until 12 Jan 2016

B.P. Abbott *et al*, PRL **116**, 061102 (2016)

# Testing General Relativity

- Most relativistic binary known previously : J0737-3039
  - Orbital velocity $v/c \sim 2 \times 10^{-3}$
- GW150914 : Highly disturbed black holes
  - Non linear dynamics
- Access to the properties of space-time
  - Strong field, high velocity regime testable for the first time

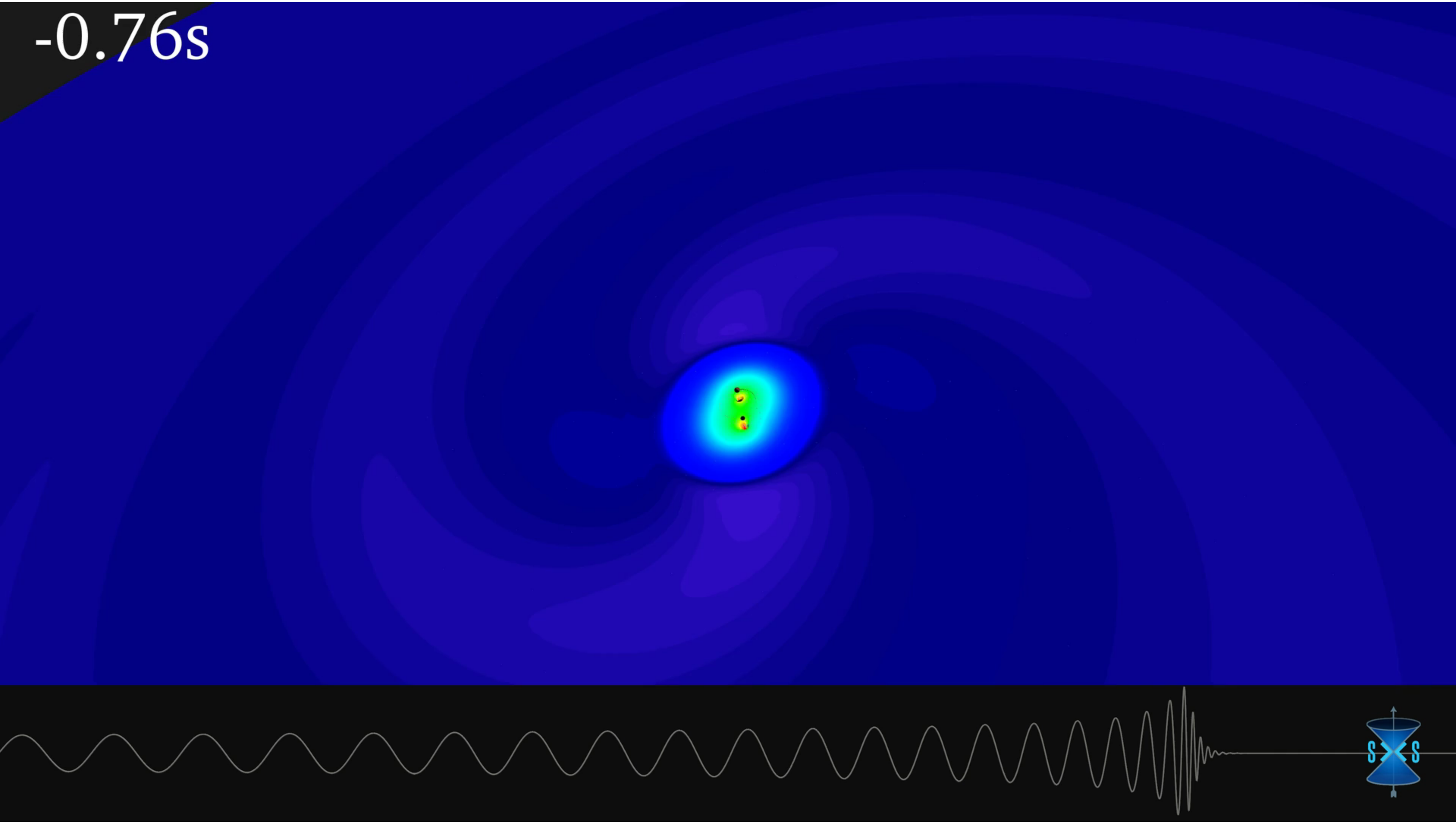
$v/c \sim 0.3\ (\times 2)$

- Tests :
  - Check of the residuals
  - Waveform internal consistency check
  - Deviation of Post-Newtonian coefficients from General Relativity ?
  - Bound on graviton mass
- Confirms predictions of General Relativity

B.P. Abbott *et al*, PRL **116**, 061102 (2016)
B.P. Abbott *et al*, PRL **116**, 221101 (2016)

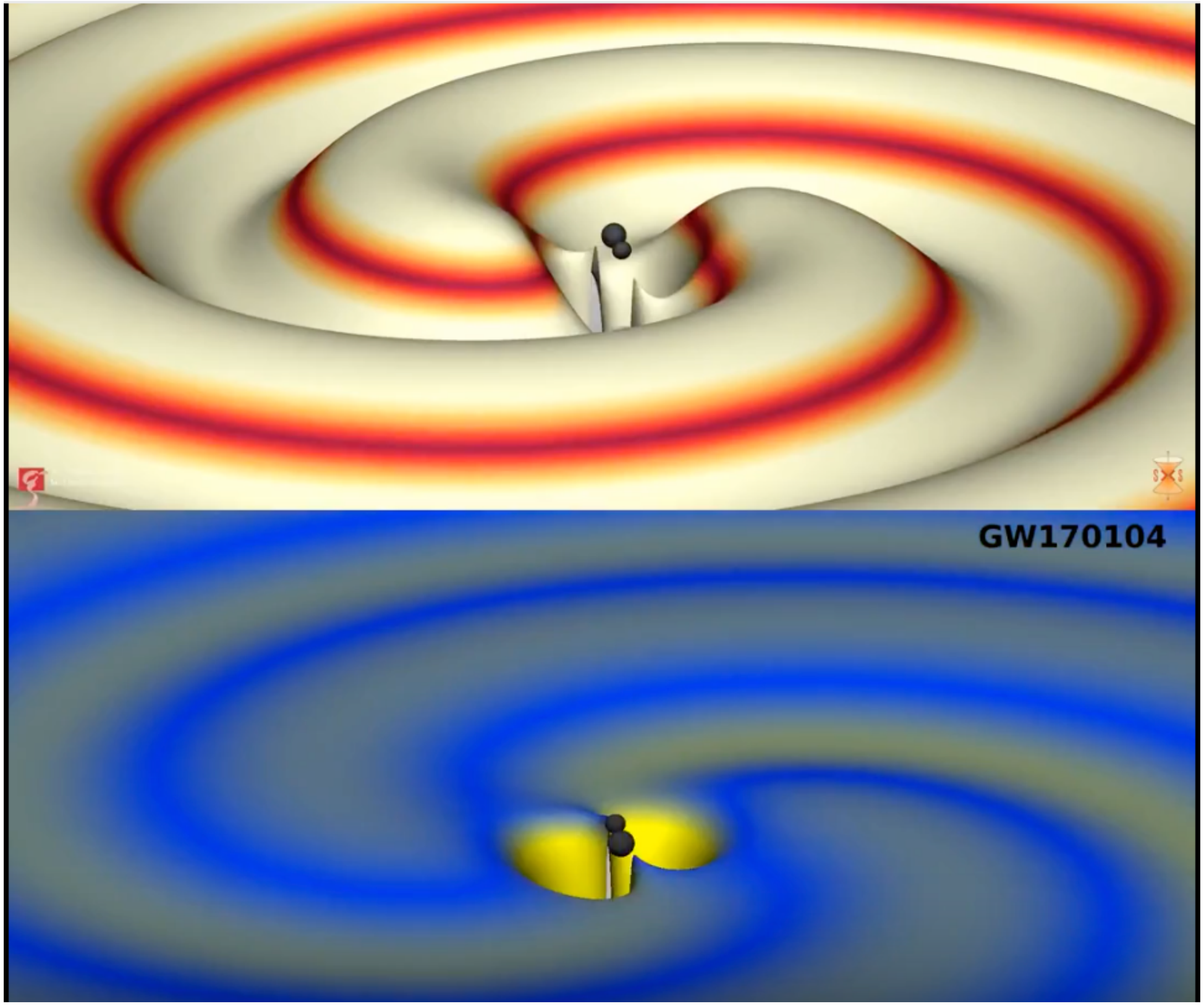
# Simulation (slow motion!) of end of the Death Spiral

Credit: Simulating eXtreme Spacetimes (SXS) – www.black-holes.org



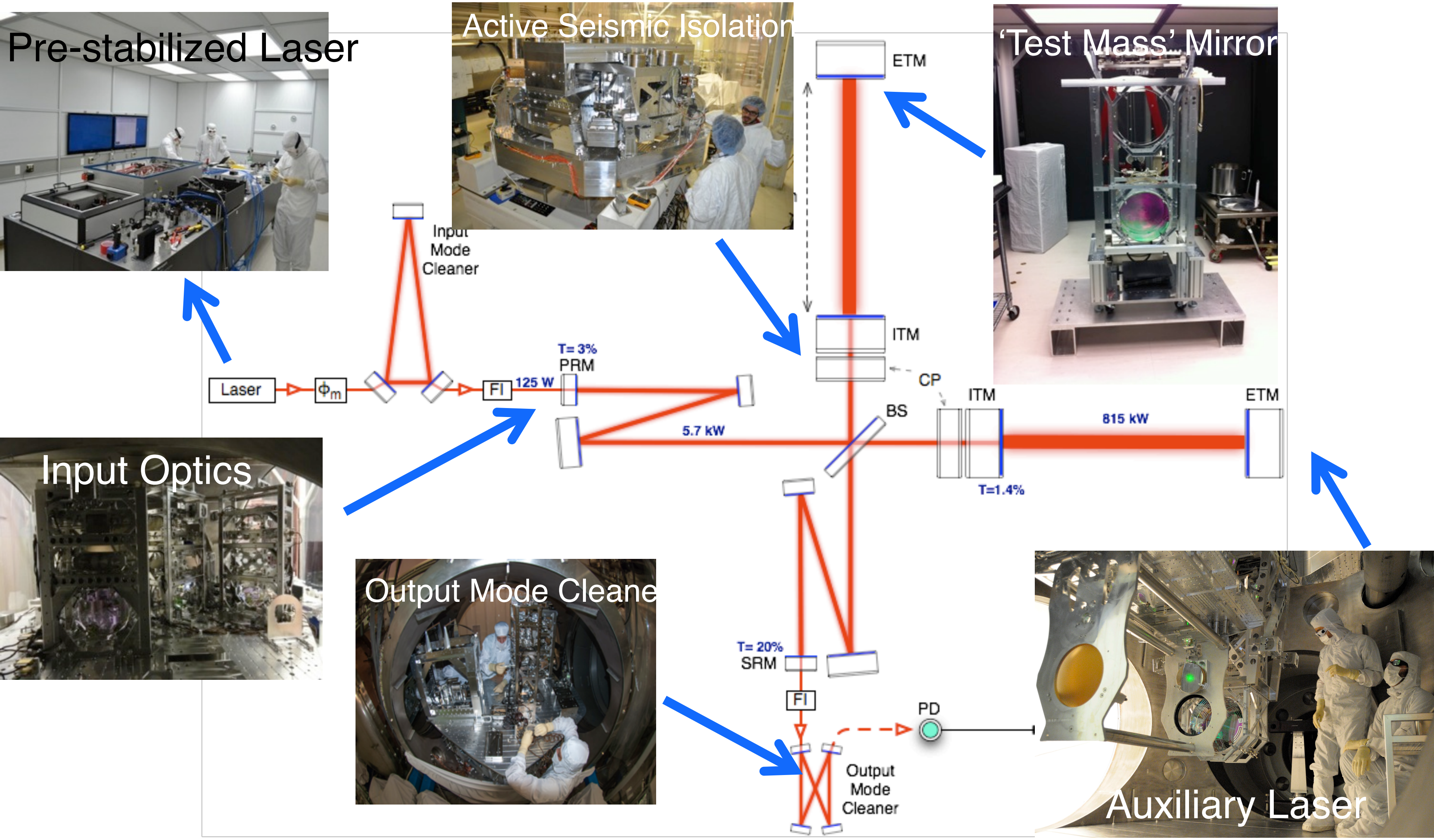
Credit: Simulating eXtreme Spacetimes (SXS) – www.black-holes.org

Credit: LIGO Lab


GW170104

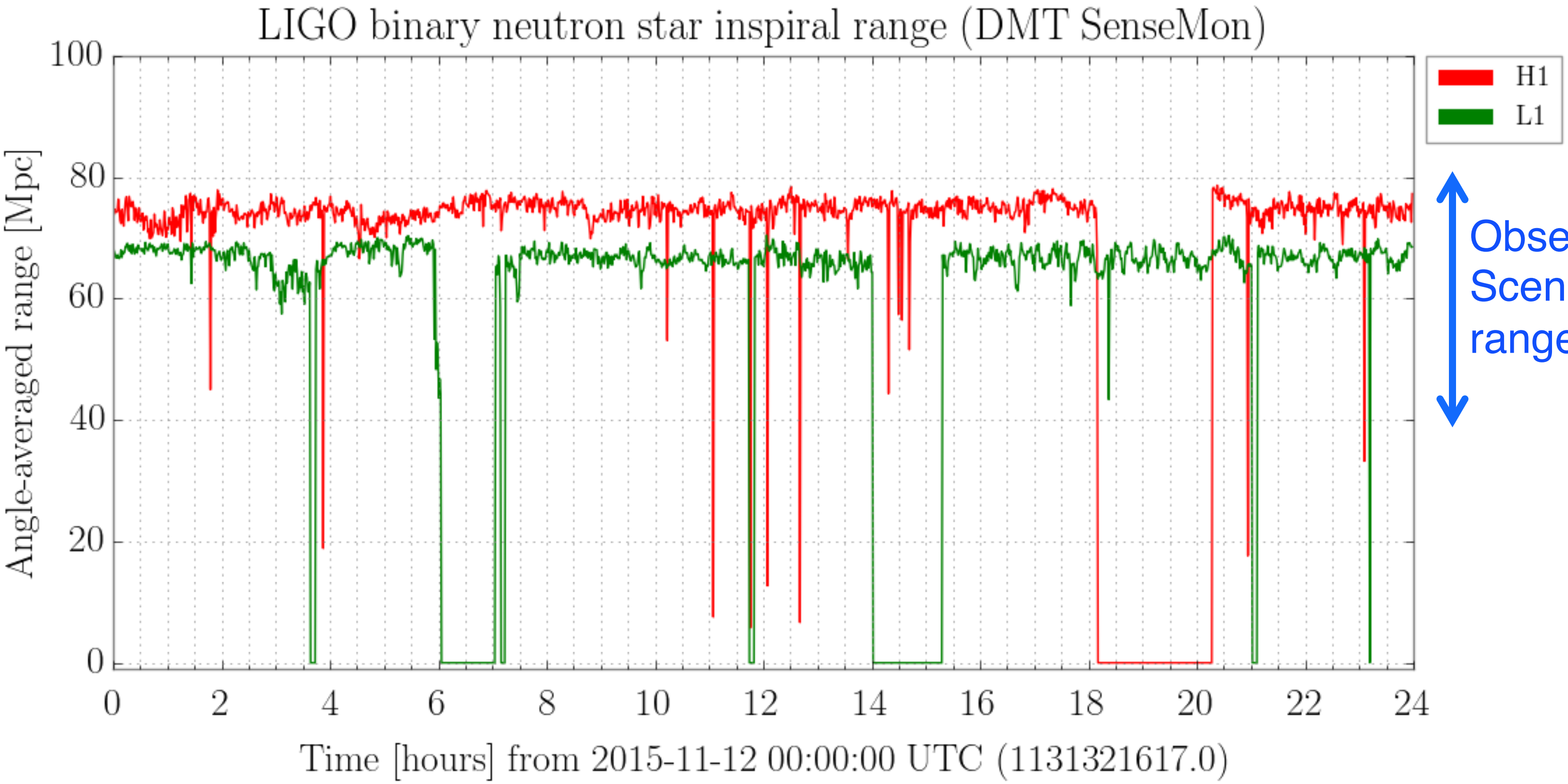
# Adding still more detail – Advanced LIGO

## (nominal laser powers are for near design sensitivity)



# O1 Data Run

Average range vs time for detecting NS-NS binaries with SNR = 8



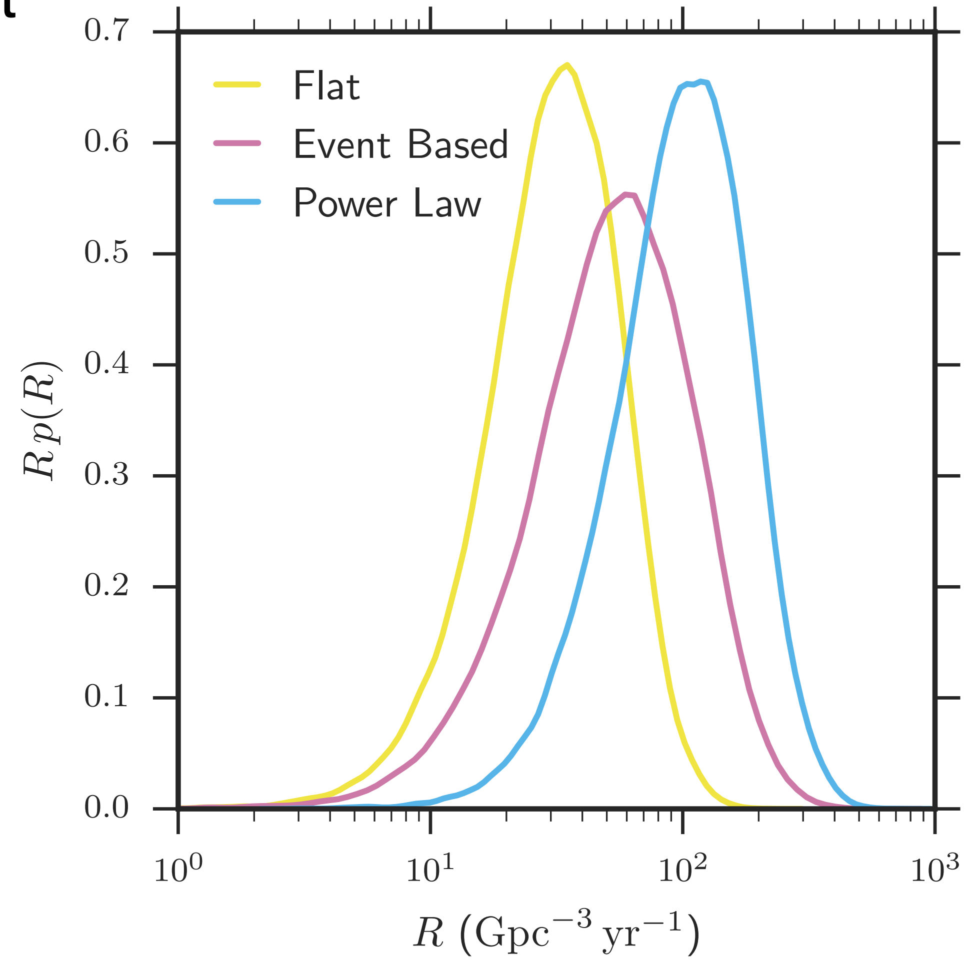
Observing Scenario range

# Rate estimates

- ❑ With only 2-3 events, cannot measure rates accurately
- ❑ Rate estimates also depend upon astrophysical assumptions

**Gold-plated event alone:**
**2–53 Gpc$^{-3}$ yr$^{-1}$**

**Including all triggers:**
**9–240 Gpc$^{-3}$ yr$^{-1}$**



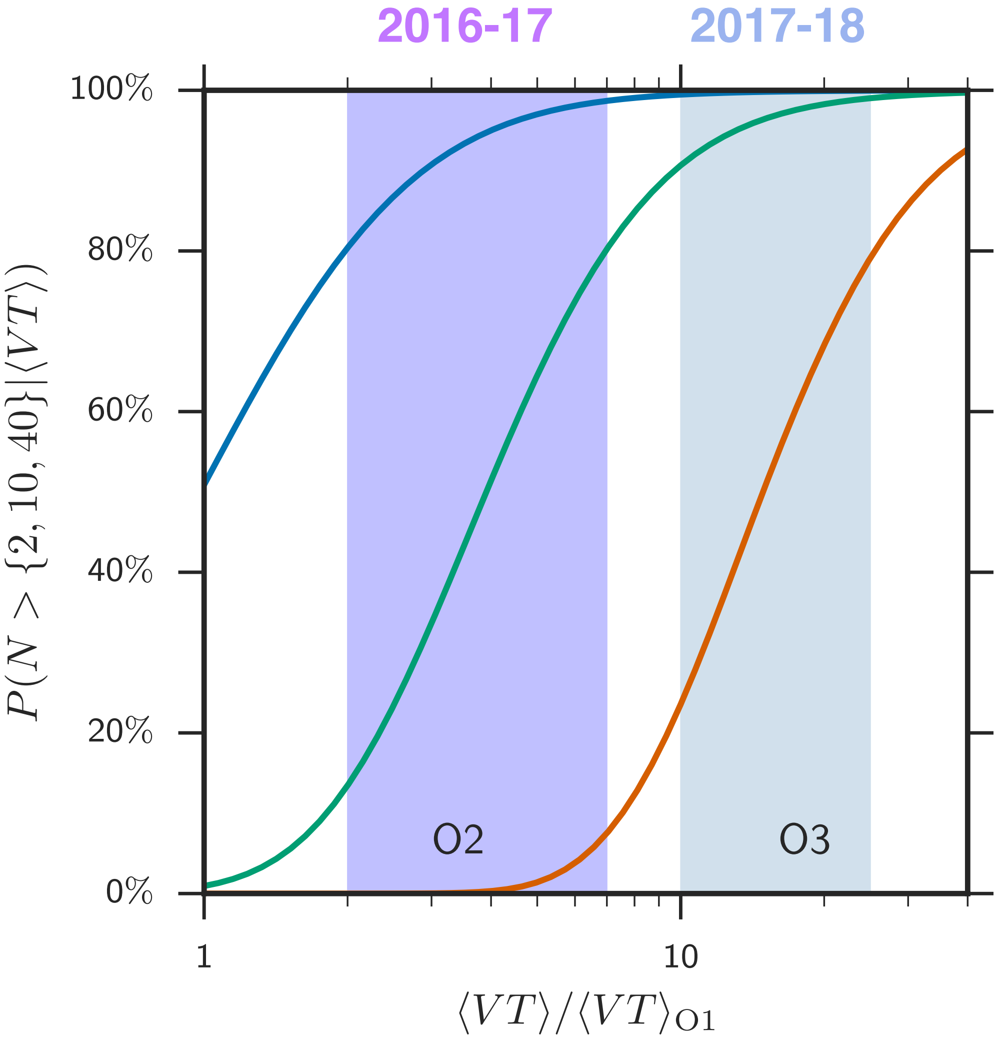
arXiv:1606.04856 (PRX)

# Expectations for future data runs

Probability of observing

- ☐ N > 2 (blue)
- ☐ N > 10 (green)
- ☐ N > 40 (red)

highly significant events, as a function of surveyed time-volume.



**→ By 2019 expect dozens(+) of BBH detections**

arXiv:1606.04856 (PRX)

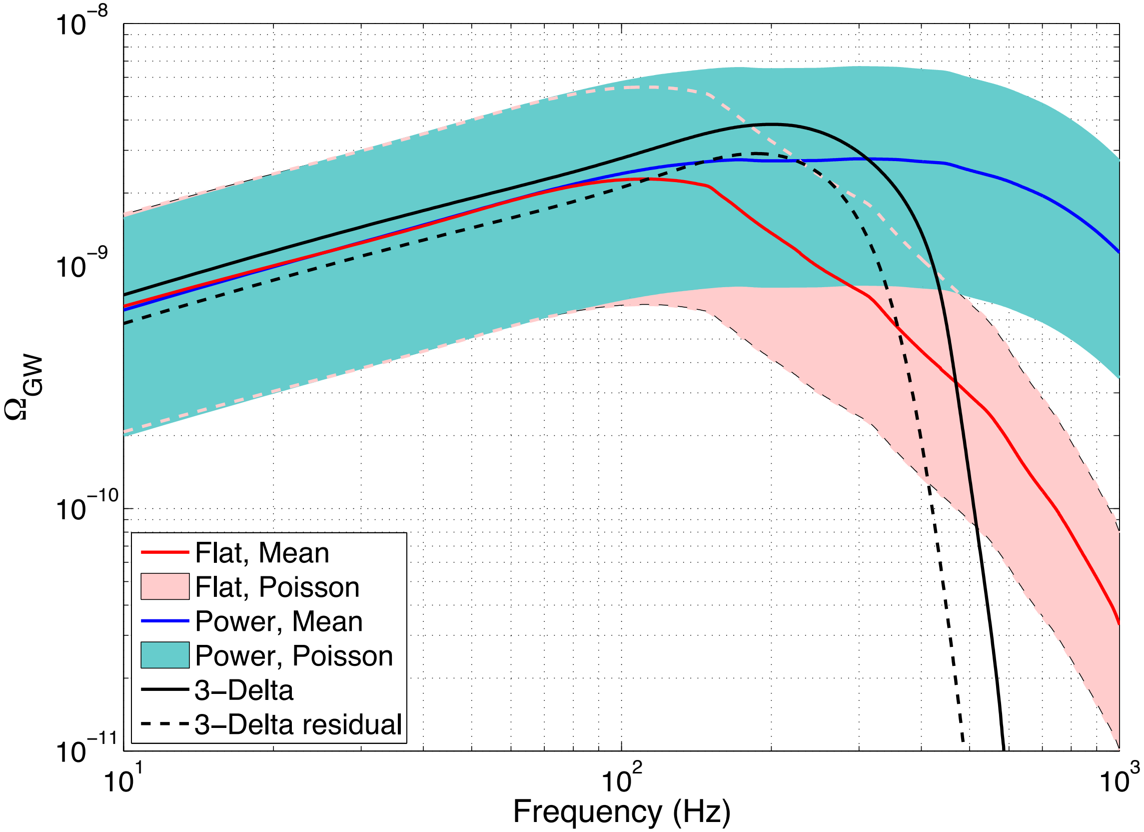
# Potential Stochastic Background

At high redshifts, could be many more sub-threshold BBH mergers

- Not detectable as individual signals
- Potentially detectable as a correlated noise among detectors

$$\Omega_{\mathrm{GW}}(f) = \frac{f}{\rho_c}\frac{d\rho_{\mathrm{GW}}}{df}$$

GW energy density per log-frequency, normalized to the density $\rho_c$ to close the Universe



arXiv:1606.04856 (PRX)

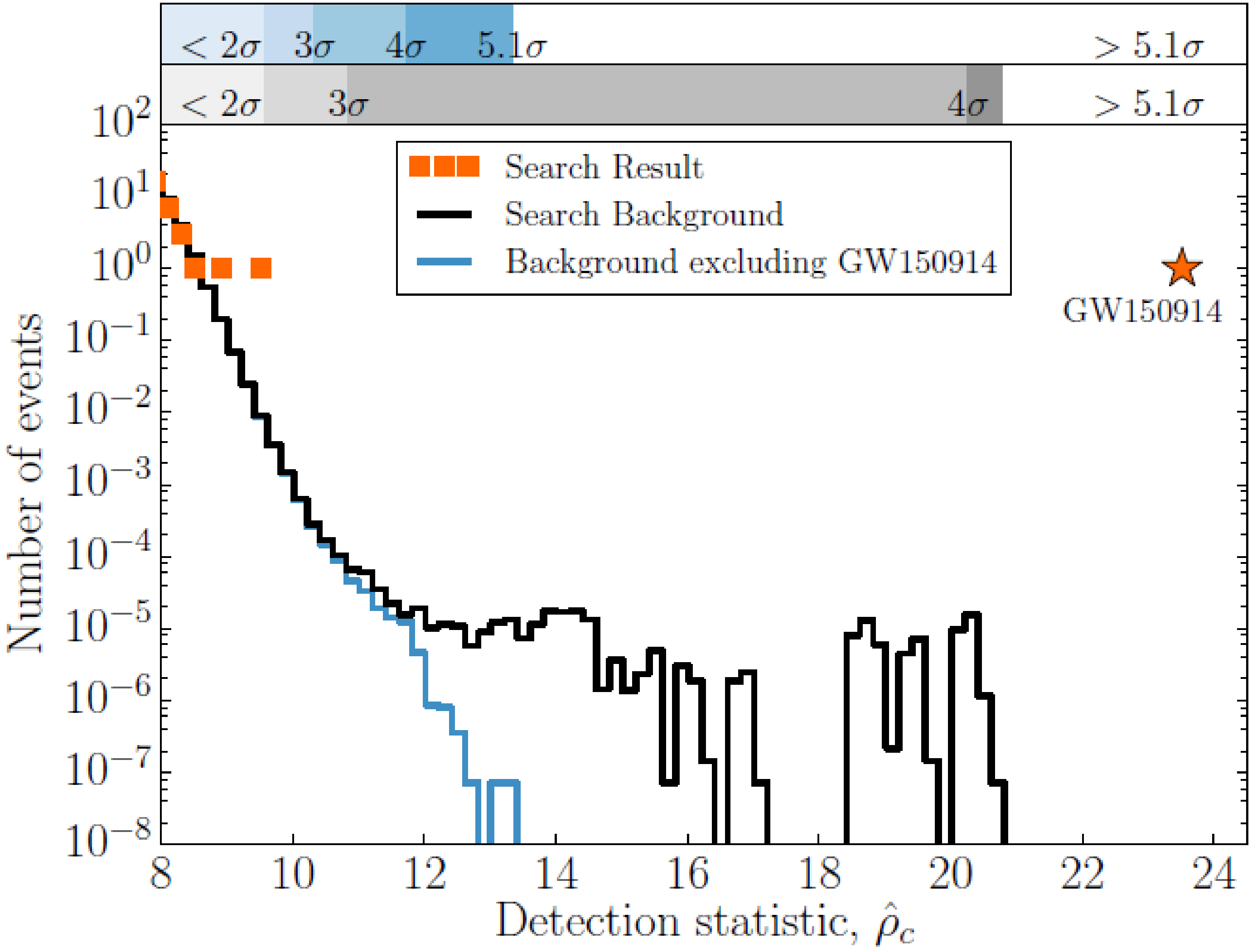
# Transient Event Searches (1)

## *Binary Coalescence search*

- Targets searches for GW emission from binary sources
- Search from 1 to 99 solar masses; total mass , 100 solar masses and dimensionless spin $< 0.99$
- ~250,000 wave forms, calculated using analytical and numerical methods, are used to cover the parameter space
- Calculate matched filter signal/noise as function of time $\rho(t)$ and identify maxima and calculate $\chi^2$ to test consistency with matched template, then apply detector coincidence within 15 msec.
- Calculate quadrature sum $\rho_c$ of the signal to noise of each detector
- Background : Time shift and recalculate $10^7$ times equivalent to 608,000 years.
- Significance: GW150914 has $\rho_c = 23.6$ (largest signal), corresponding to false alarm rate less than 1 per 203,000 years or significance $> 5.1\sigma$

# Statistical Significance of GW150914

## Binary Coalescence Search

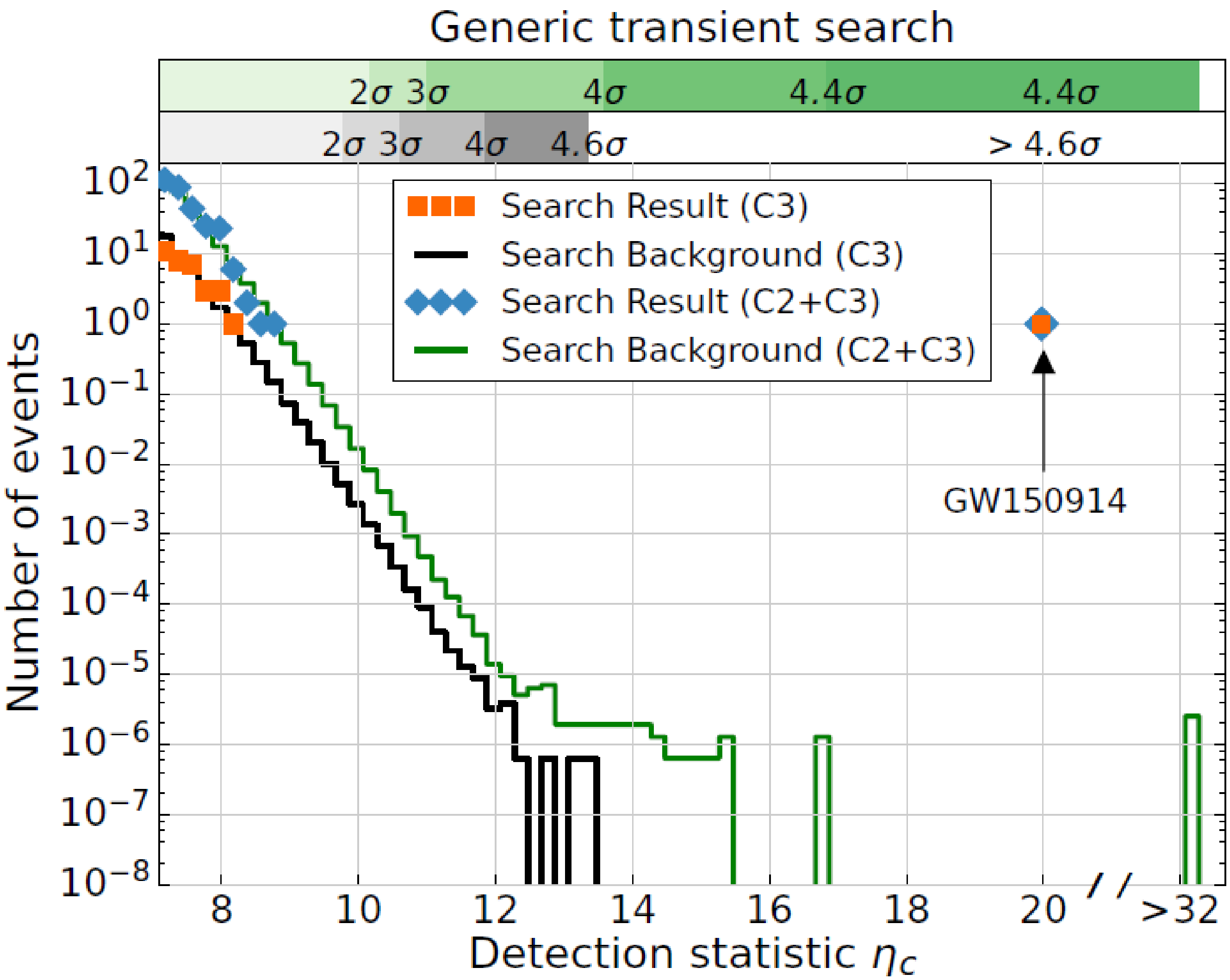


# Transient Event Searches (2)

## *Generic Transient Search*

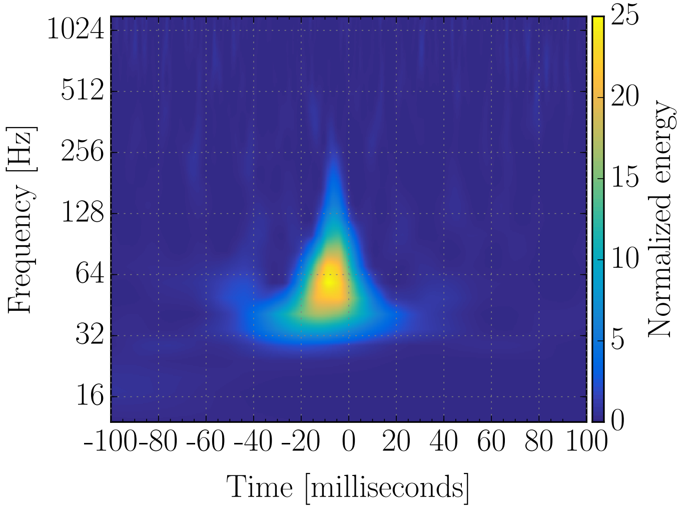
- No specific waveform model: Identifies coincident excess power in wavelet representations (f < 1 kHz and t < few seconds)
- Reconstruct waveform in both detectors using multi-detector maximum likelihood method.
- Detection Statistic: $\eta_c = \sqrt{\frac{2E_c}{(1 + E_n/E_c)}}$
- $E_c$ = dimensionless coherent signal energy by cross correlating the two reconstructed waveforms and $E_n$ is residual noise energy
- Restricting to events with f increasing with time, GW150914 is the strongest event in the search with $\eta_c = 20$
- Yields false alarm rate < 1 per 22,500 years
- Probability of background event during data run $< 2\times10^{-6}$ or $> 4.6\ \sigma$

# Statistical Significance of GW150914

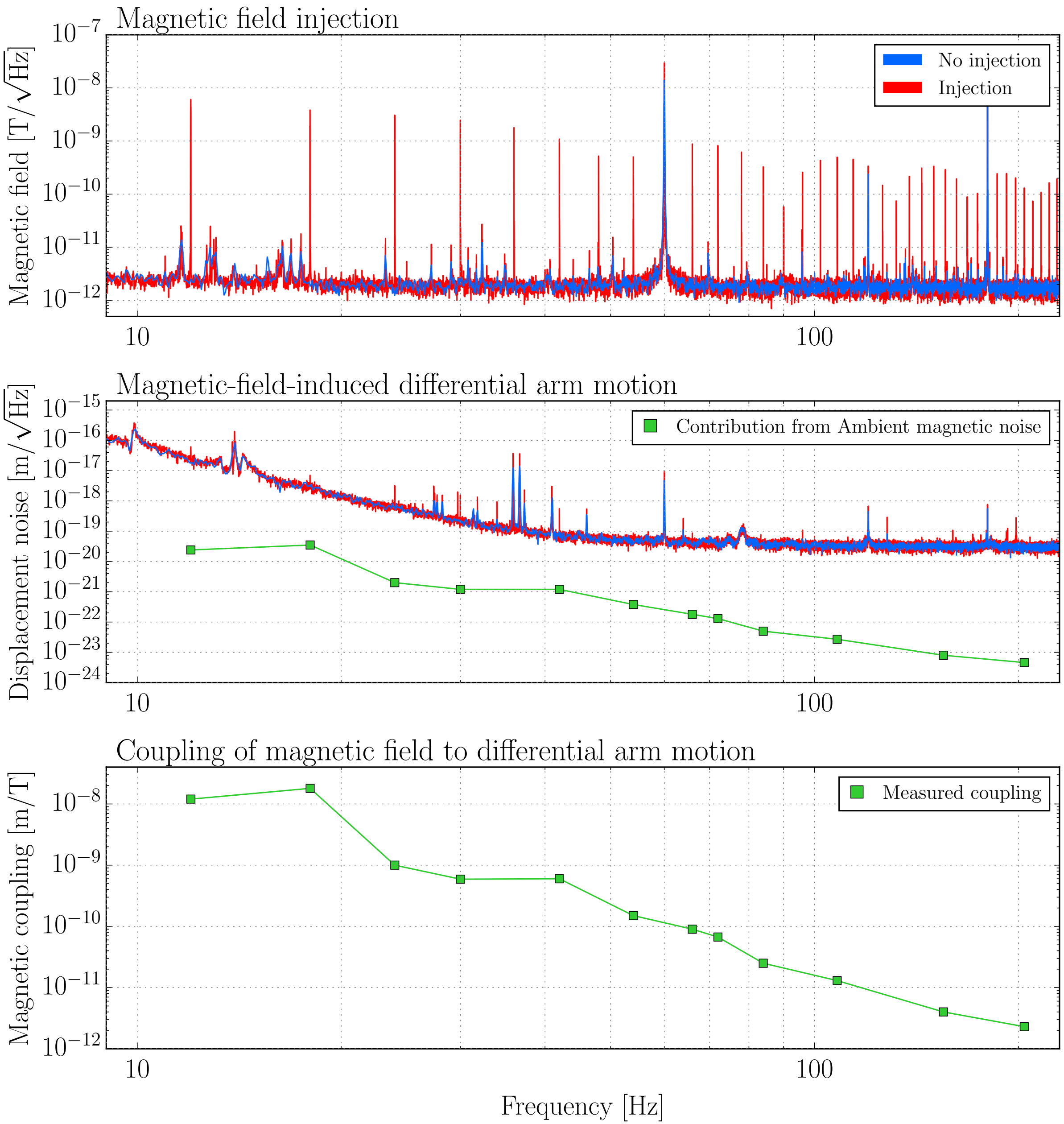


# Transient noise

- ❑ Detectors were operating in their nominal state at the time of GW150914
- ❑ Still contain non-Gaussian transients, examples:
  - ◆ Anthropogenic noise
  - ◆ Seismic noise
  - ◆ "Blip" transients
- ❑ Mitigate noise by "vetoing" times of elevated noise, measured in auxiliary channels.
- ❑ Data are clean and stationary ar



# Noise coupling example: Magnetic fields



# Correlated noise

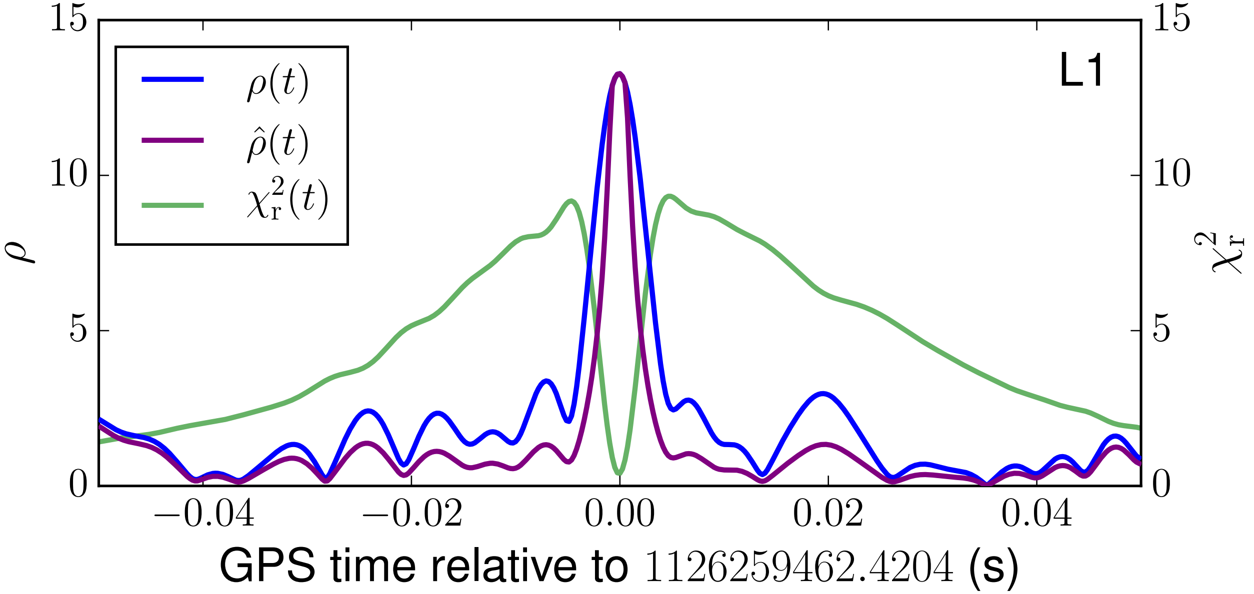
- Possible electromagnetic noise sources
  - Lightning, solar events.
  - Would be picked up in radio receivers, magnetometers
  - Nothing at time of event

- Cosmic ray showers
  - Not correlated on 3,000 km scales
  - Cosmic ray detector at Hanford – no events

# *Event ranking*

- Triggers in each detector are ranked based on a "re-weighted" SNR:

$$\hat{\rho} = \begin{cases} \rho \Big/ \left[(1+(\chi_r^2)^3)/2\right]^{\frac{1}{6}}, & \text{if } \chi_r^2 > 1, \\ \rho, & \text{if } \chi_r^2 \leq 1. \end{cases}$$

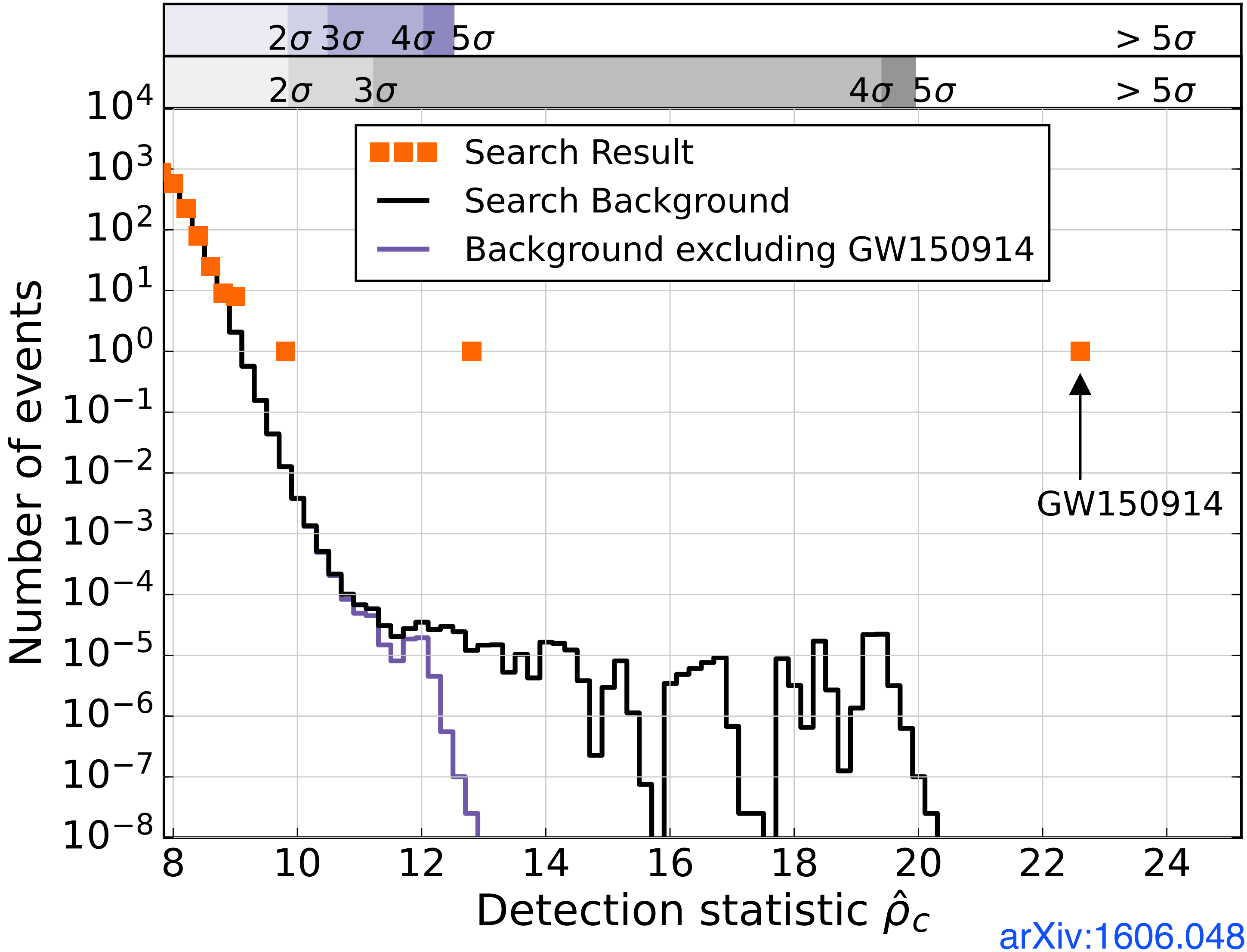


- GW150914 was the most significant trigger in each detector

# *Coincidence and time shifts*

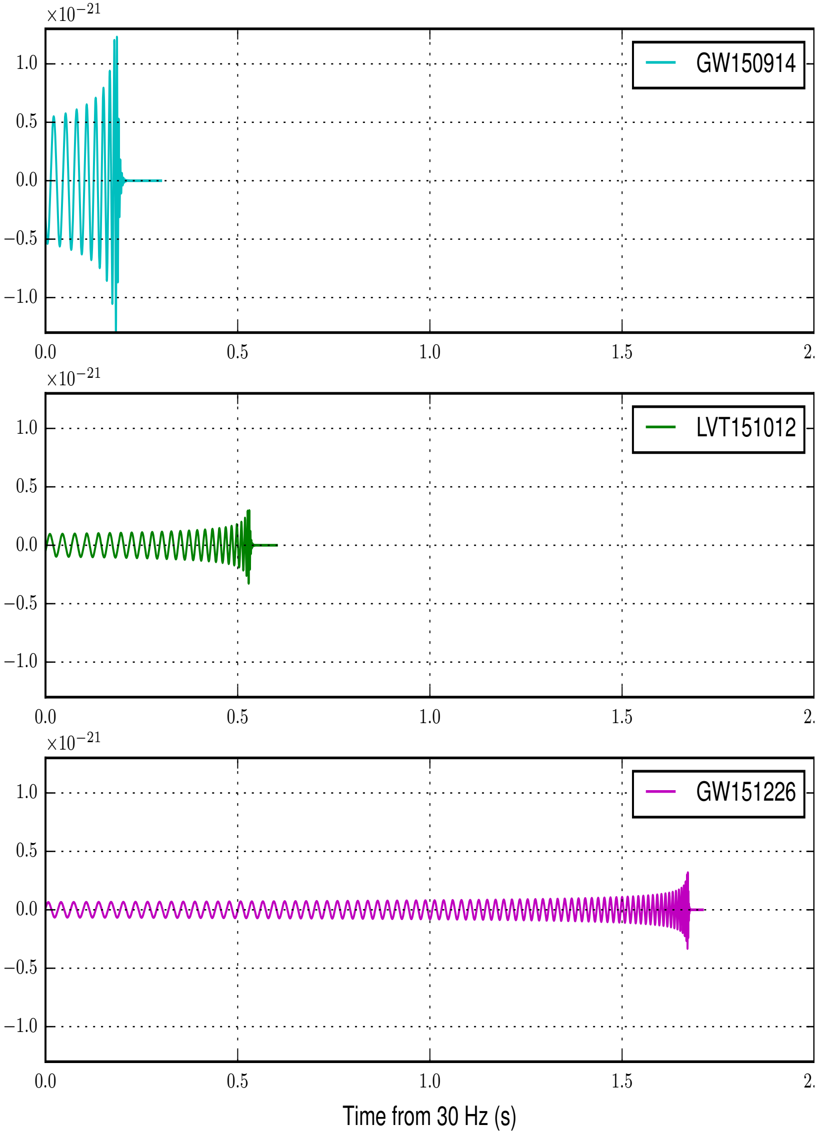
- Coincidences are formed from single detector triggers, with same mass & spin parameter that occurred within 30ms.
- Simple estimate
  - Chance of loudest event in each detector being coincident is 30ms/16 days or $2 \times 10^{-8}$
- Actual calculation
  - False alarm calculated by performing 100ms time shifts
  - Different length templates respond differently to instrumental artifacts: divide into three classes
  - Gives a false probability of $< 2 \times 10^{-7}$, or $>$ 5.1 sigma

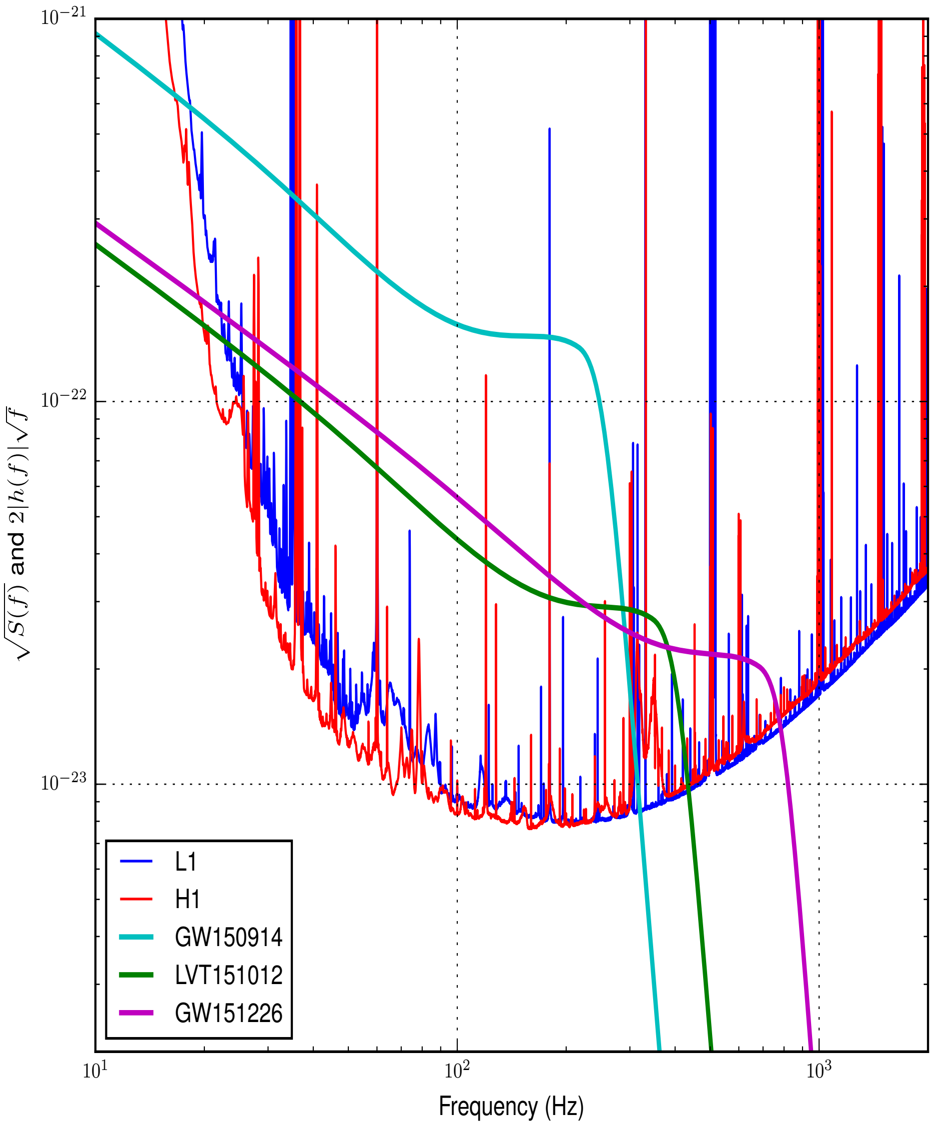
# Two discoveries and one likely detection



arXiv:1606.04856 (PRX)

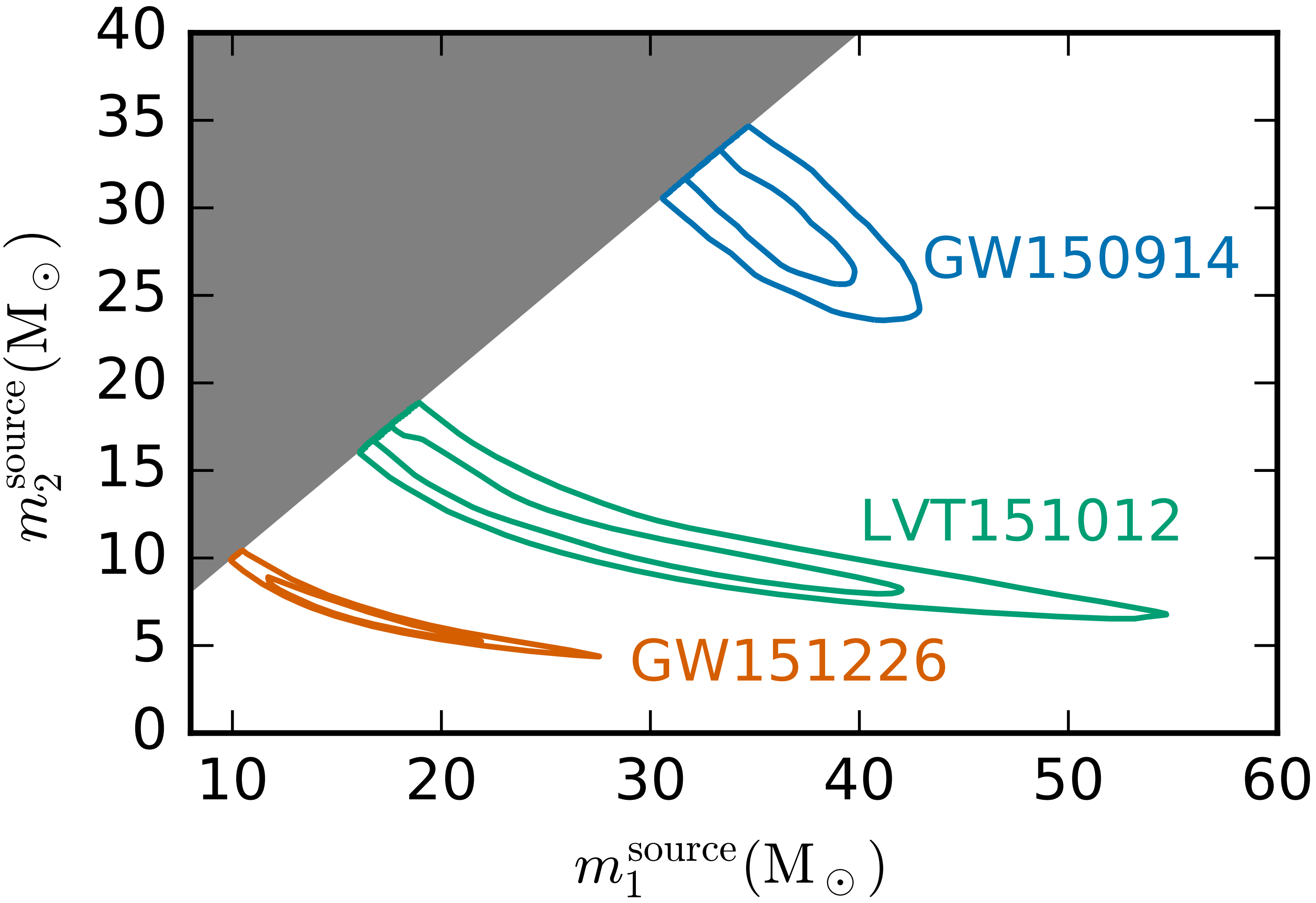
# Two discoveries and one likely detection





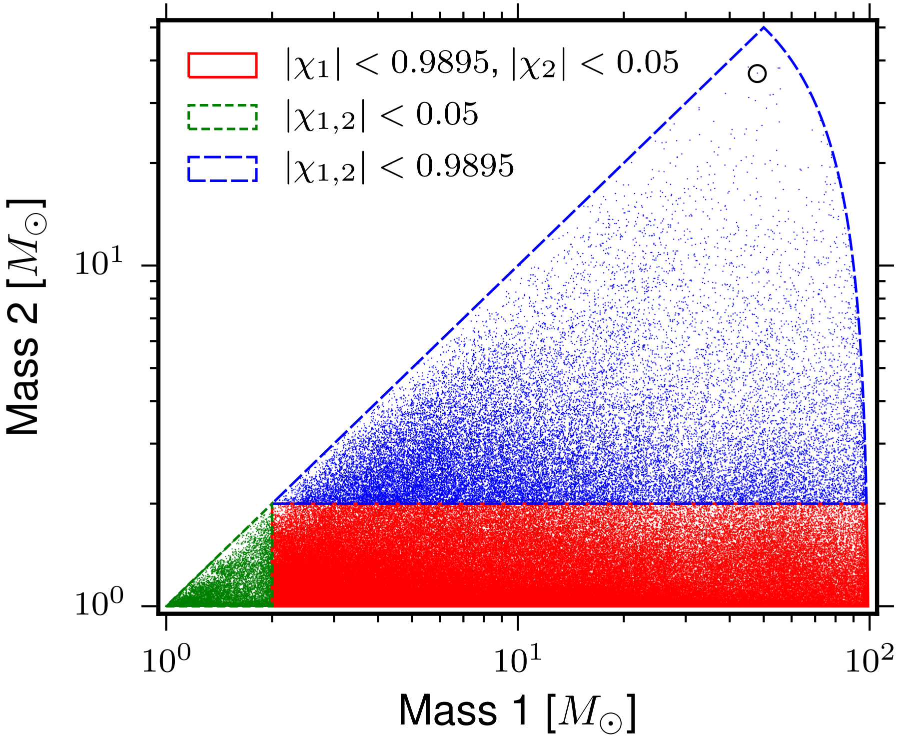
arXiv:1606.04856 (PRX)

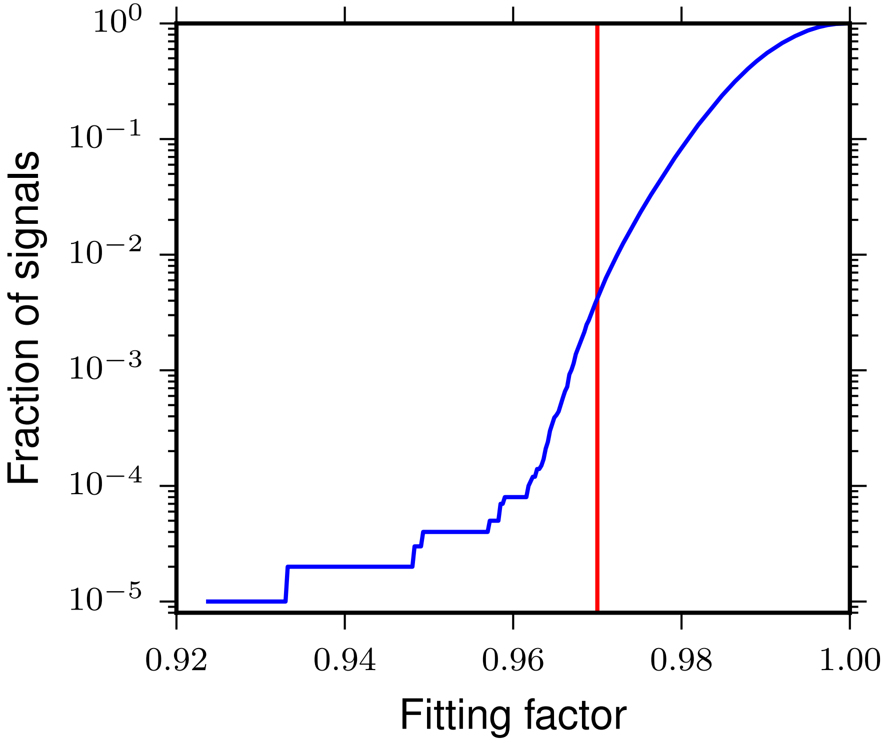
# Two discoveries and one likely detection



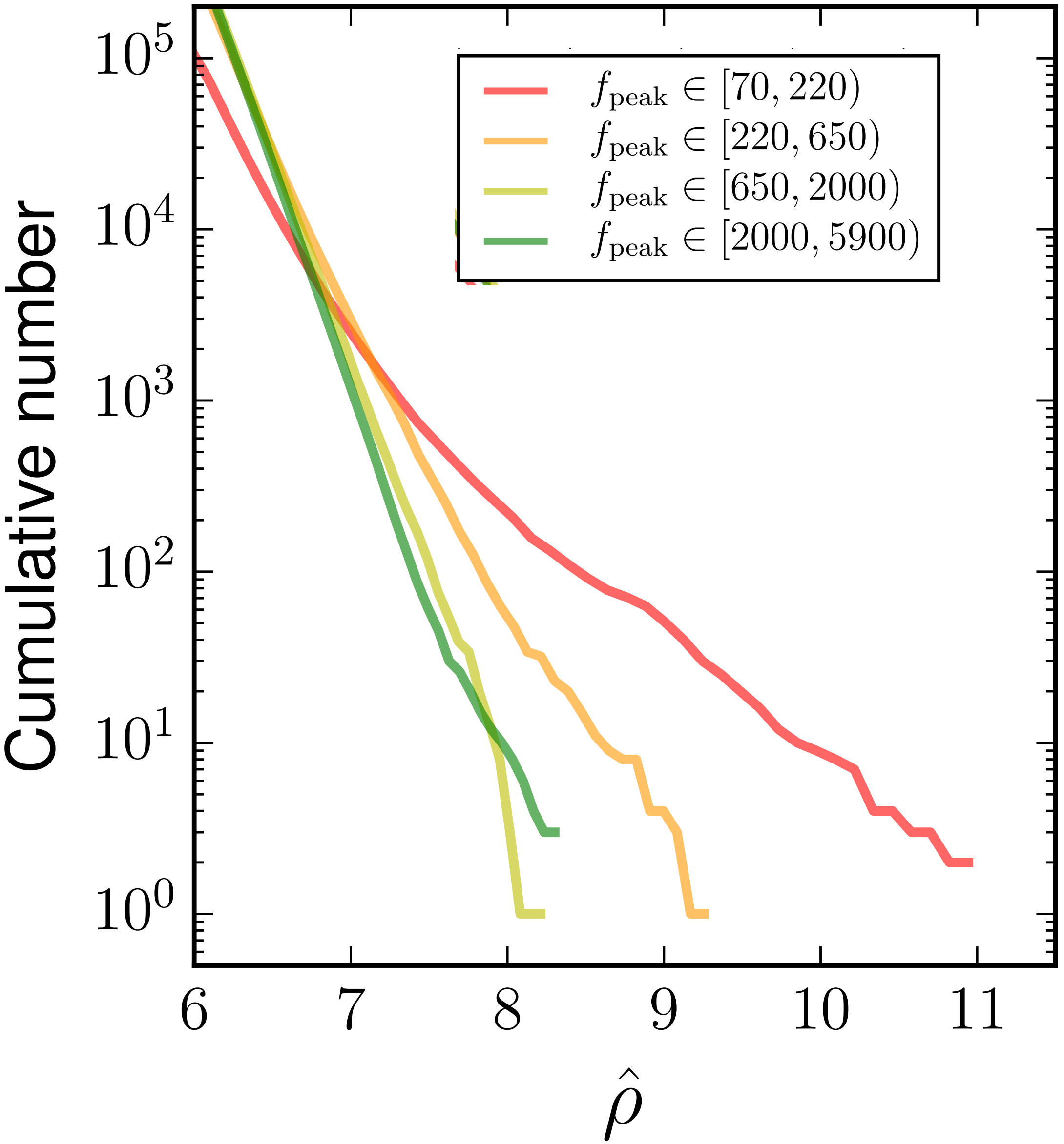
arXiv:1606.04856 (PRX)

# *Template bank*

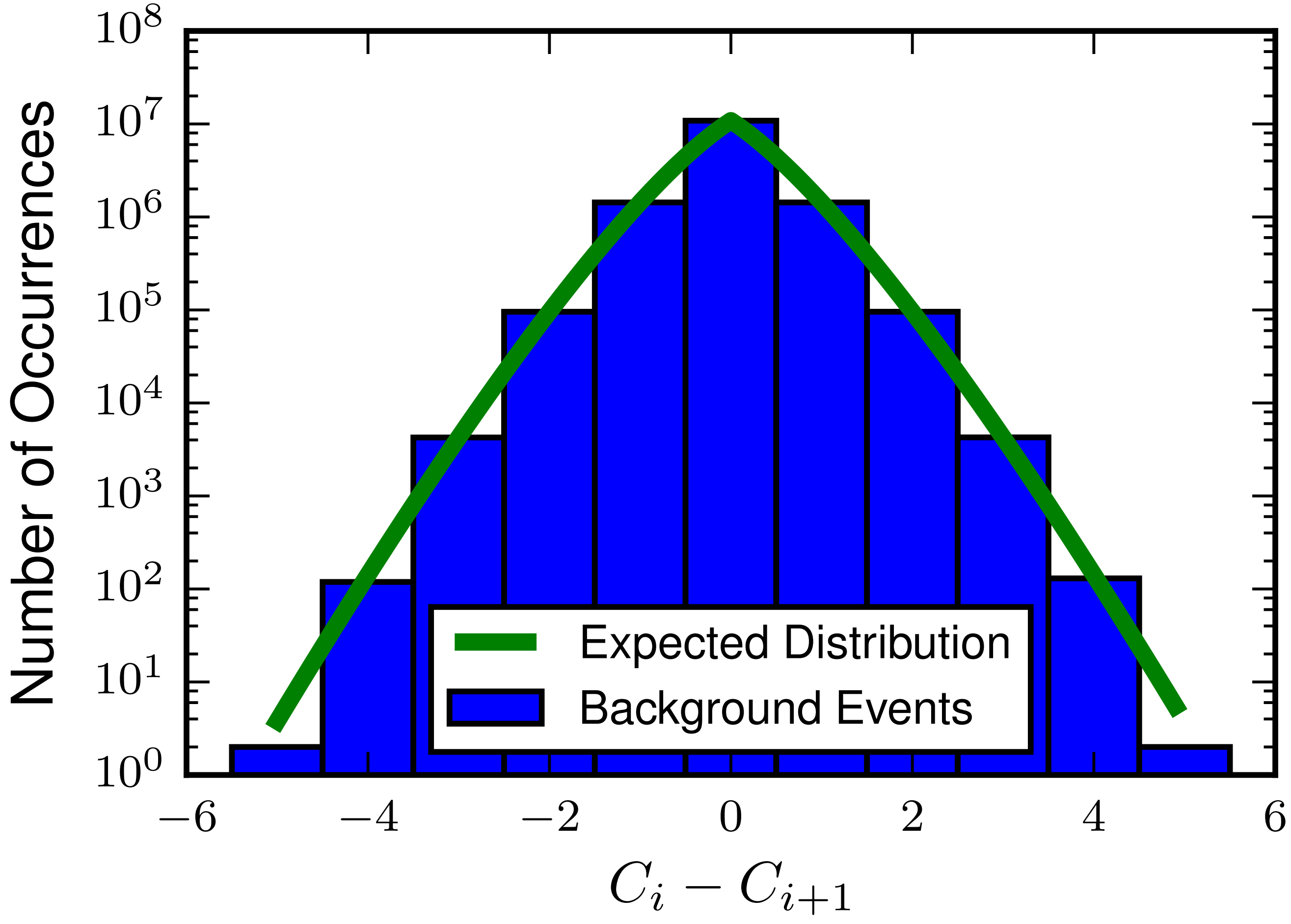




Template dependent background

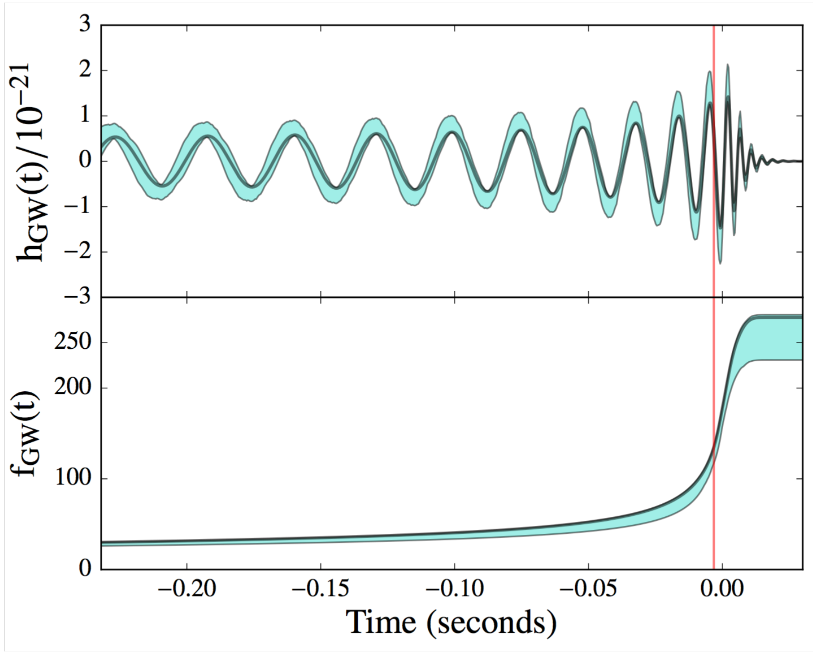


# *Slide correlation*

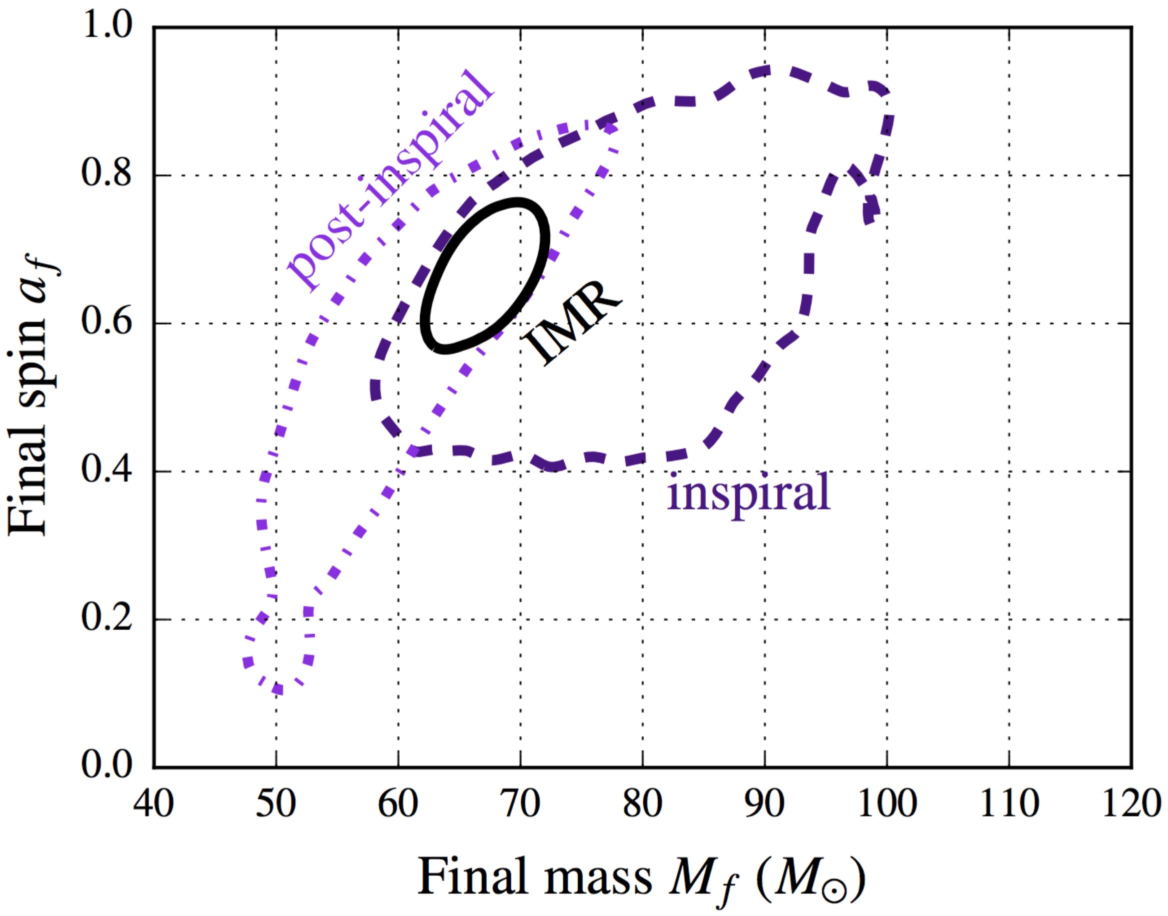


# Internal consistency of the waveform

- ❑ Final black hole mass and spin -> Einstein equations
  - ◆ Predicted from the mass and spins of progenitors
- ❑ Deduced from the inspiral and early stage of coalescence
- ❑ Independently from the late stage (ringdown)
- ❑ Consistent with each other



90% credible regions for the waveform (upper panel) and GW frequency (lower panel) of GW150914 versus time as estimated by the LALINFERENCE analysis [3]. The solid lines in each panel indicate the most probable waveform from GW150914 [3] and its GW frequency. We mark with a vertical line $f_{\rm GW}^{\rm end\,insp} = 132$ Hz, which is used in the IMR consistency test to delineate the boundary between the inspiral and post-inspiral parts.



90% confidence regions on the joint posterior distributions for the mass $M_f$ and dimensionless spin $a_f$ of the final compact object predicted from the inspiral (dark violet, dashed) and measured from the post-inspiral (violet, dot-dashed), as well as the result from a full inspiral-merger-ringdown (IMR) analysis (black).

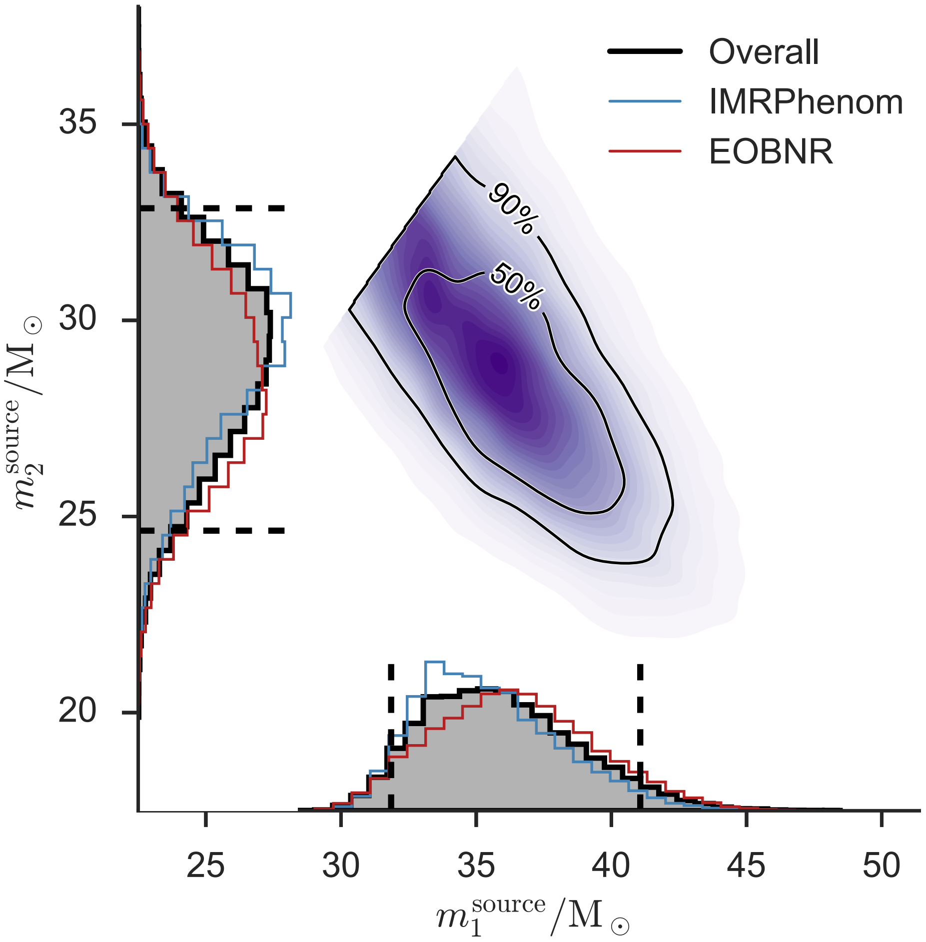
# *Measuring the parameters*

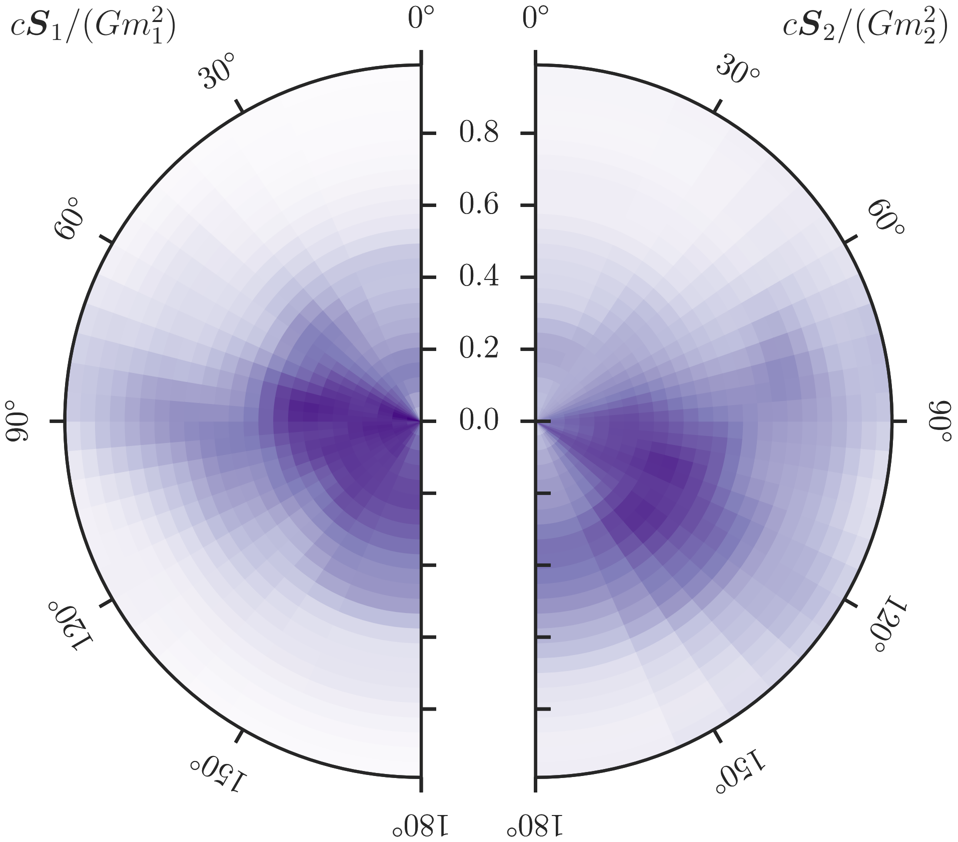
- Orbits decay due to emission of gravitational waves
  - **Leading order** determined by “chirp mass”

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{M^{1/5}} \simeq \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3}\dot{f}\right]^{3/5}$$

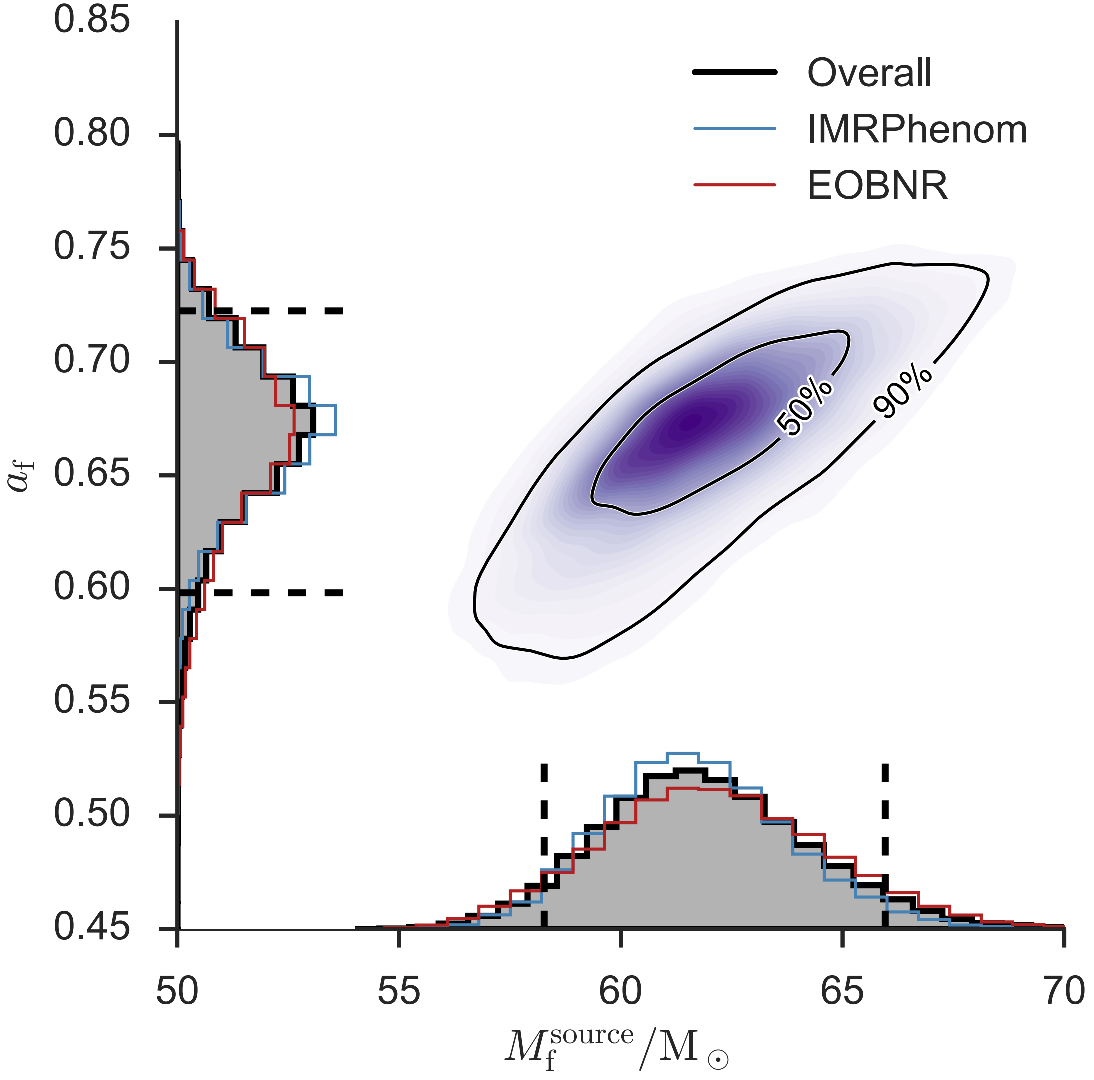
  - Next orders allow for measurement of mass ratio and spins
  - We directly measure the red-shifted masses (1+z) m
  - Amplitude inversely proportional to luminosity distance
- Orbital precession occurs when spins are misaligned with orbital angular momentum – no evidence for precession.
- Sky location, distance, binary orientation information extracted from time-delays and differences in observed amplitude and phase in the detectors

# Component masses and spins



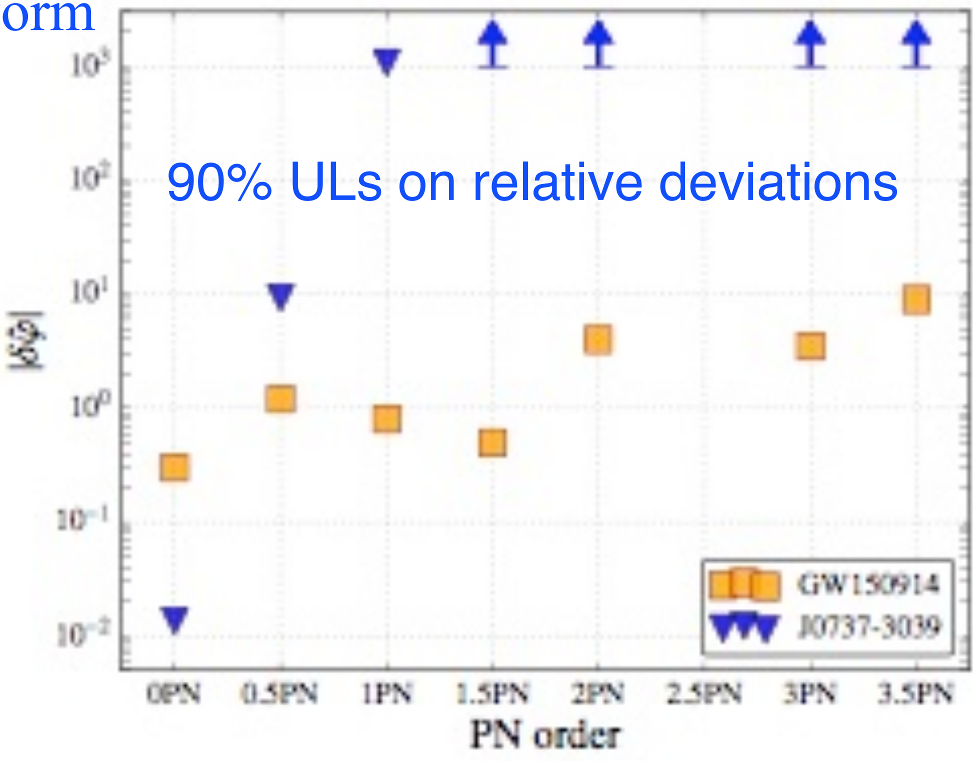


# *The final black hole*



# Deviation of Post-Newtonian coefficients from GR expectations ?

- ❑ Post Newtonian formalism
- ❑ Phase of the inspiral waveform –> power series in $f^{1/3}$
- ❑ Nominal value predicted by GR
- ❑ Allow variation of the coefficients
  - ◆ -> Is the resulting waveform consistent with data ?



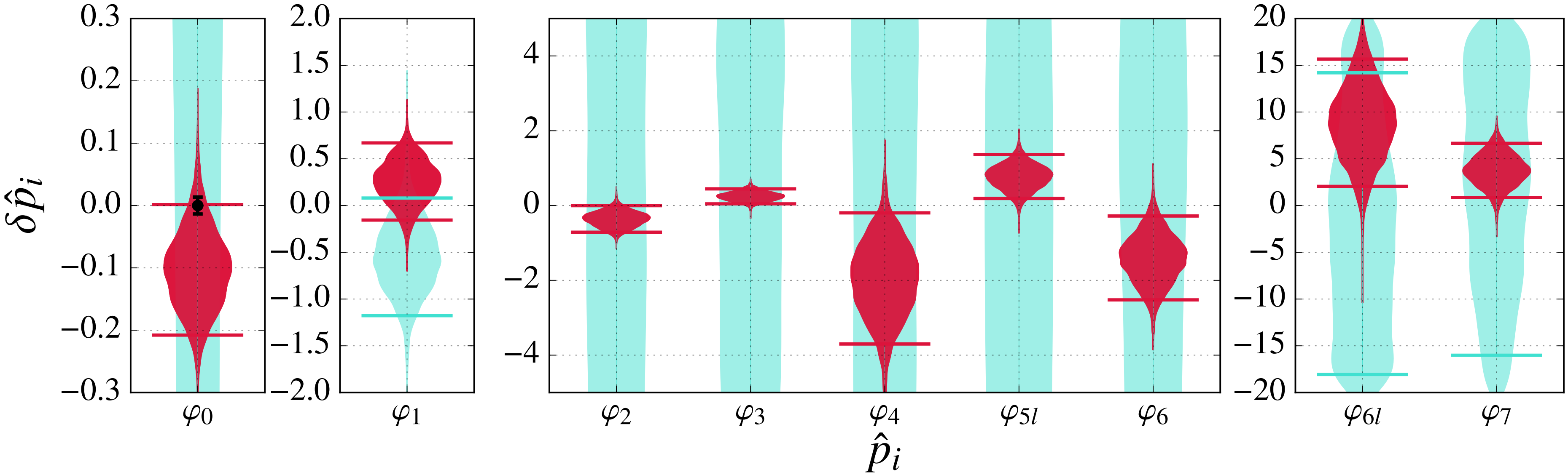
90% ULs on relative deviations

- ❑ Find no evidence for violations of GR

- Nominal value predicted by GR
- Allow variation of the coefficients
  - –> Is the resulting waveform consistent with data ?

Red : vary one parameter at a time

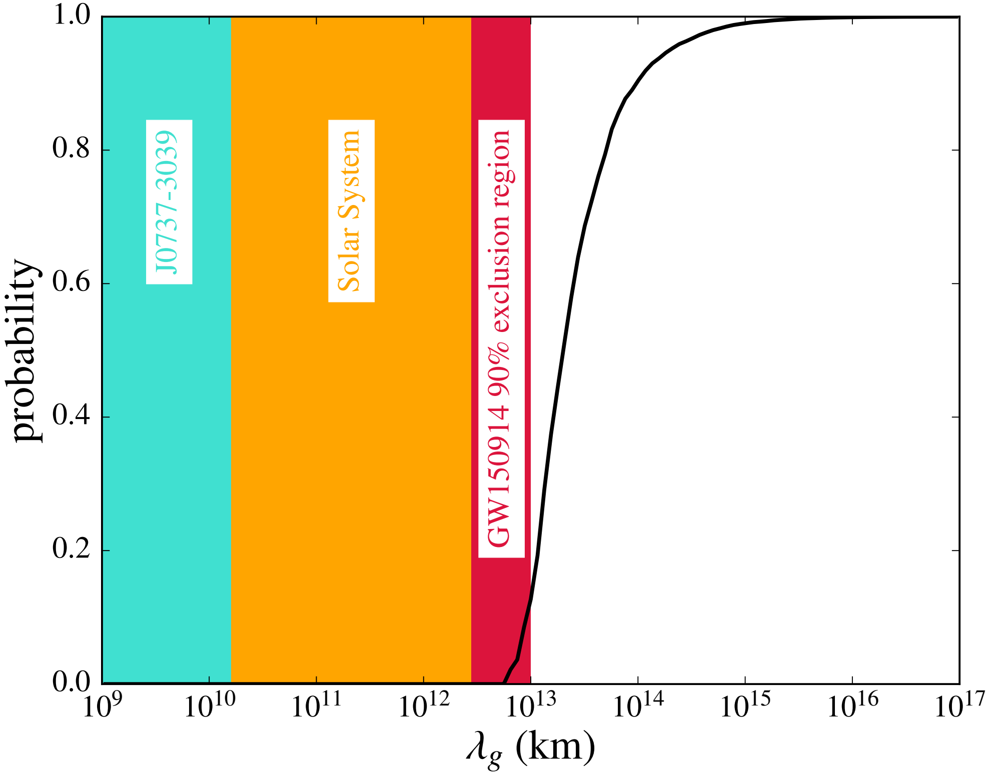
Cyan : allow all parameters to vary



- Find no evidence for violations of GR

# *Upper bound on the graviton mass*

- ❑ If $c_{GW} < c$
- ❑ ⇔ gravitational waves have a modified dispersion relation
- ❑ Findings : at 90 % confidence, $\lambda_g > 10^{13}\ \mathrm{km}$



or equivalently

$$m_g < 1.2 \times 10^{-22}\ \mathrm{eV/c^2}$$

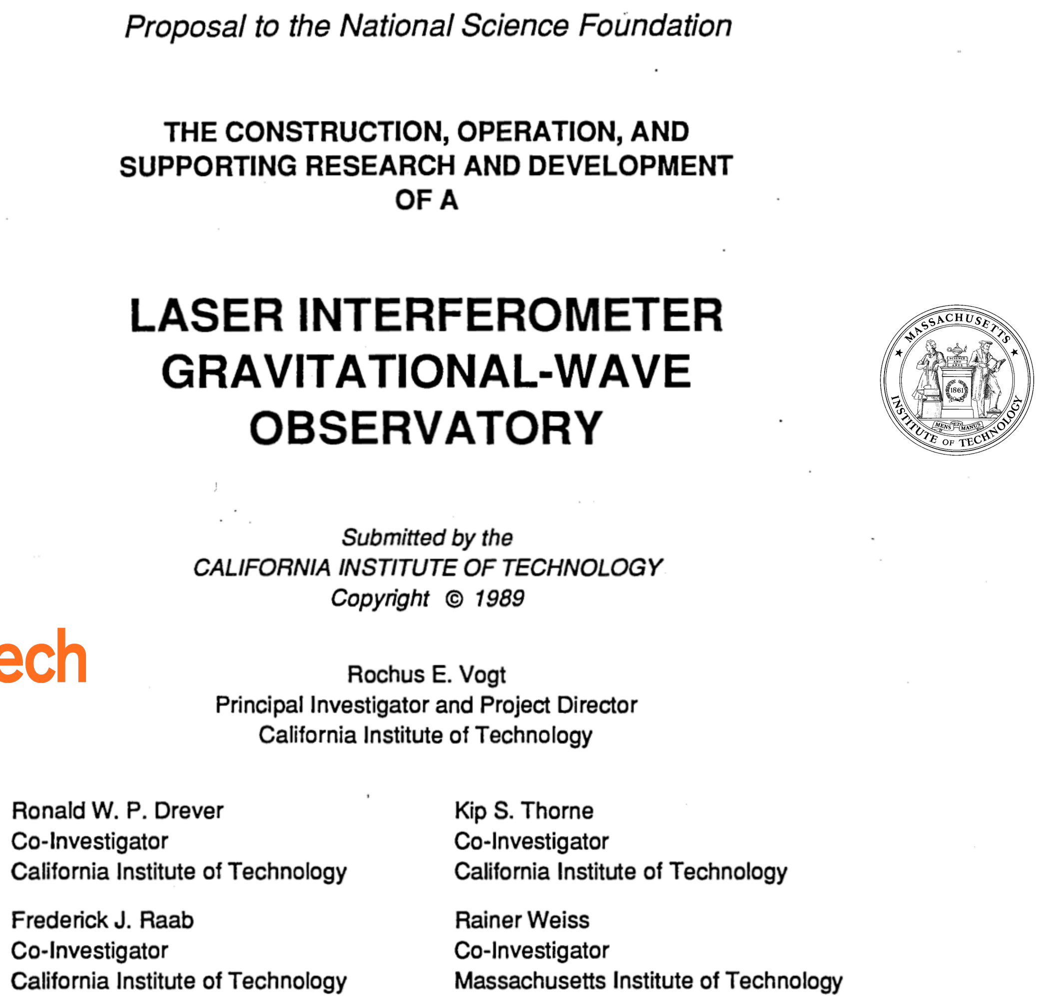
# Guide to GW150914 / GW151226 discovery and companion papers

| **arXiv**: | **Discoveries** |
|---|---|
| 1602.03838 | GW150914: The Advanced LIGO Detectors in the Era of First Discoveries (PRL) |
| 1606.04855 | *GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence* (PRL) |
| | **Detector and Performance** |
| 1602.03838 | GW150914: The Advanced LIGO Detectors in the Era of First Discoveries (PRL) |
| 1602.03844 | Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914 (CQG) |
| 1602.03845 | Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914 |
| | **Search Programs** |
| 1602.03839 | GW150914: First results from the search for binary black hole coalescence with Advanced LIGO (PRD) |
| 1602.03843 | Observing gravitational-wave transient GW150914 with minimal assumptions (PRD) |

# Guide to companion papers (cont.)

| **arXiv**: | **Partner Observations** |
|---|---|
| 1602.05411 | High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with IceCube and ANTARES (PRD) |
| 1602.08492 | Localization and broadband follow-up of the gravitational-wave transient GW150914 (ApJL) |
| | **Astrophysical Interpretation** |
| 1602.03846 | Astrophysical Implications of the Binary Black-Hole Merger GW150914 (ApJ) |
| 1602.03840 | Properties of the binary black hole merger GW150914 (PRL) |
| 1602.03841 | Tests of general relativity with GW150914 (PRL) |
| 1602.03842 | The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914 |
| 1602.03847 | GW150914: Implications for the stochastic gravitational-wave background from binary black holes (PRL) |
| 1606.04856 | Binary Black Hole Mergers in the first Advanced LIGO Observing Run (PRX) |

# Original LIGO Proposal – 1989



*Proposal to the National Science Foundation*

**THE CONSTRUCTION, OPERATION, AND
SUPPORTING RESEARCH AND DEVELOPMENT
OF A**

## LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

*Submitted by the
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Caltech

Rochus E. Vogt
Principal Investigator and Project Director
California Institute of Technology

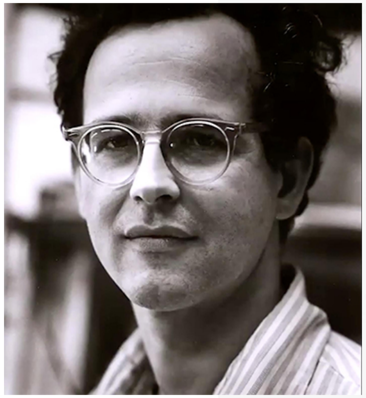
Ronald W. P. Drever
Co-Investigator
California Institute of Technology

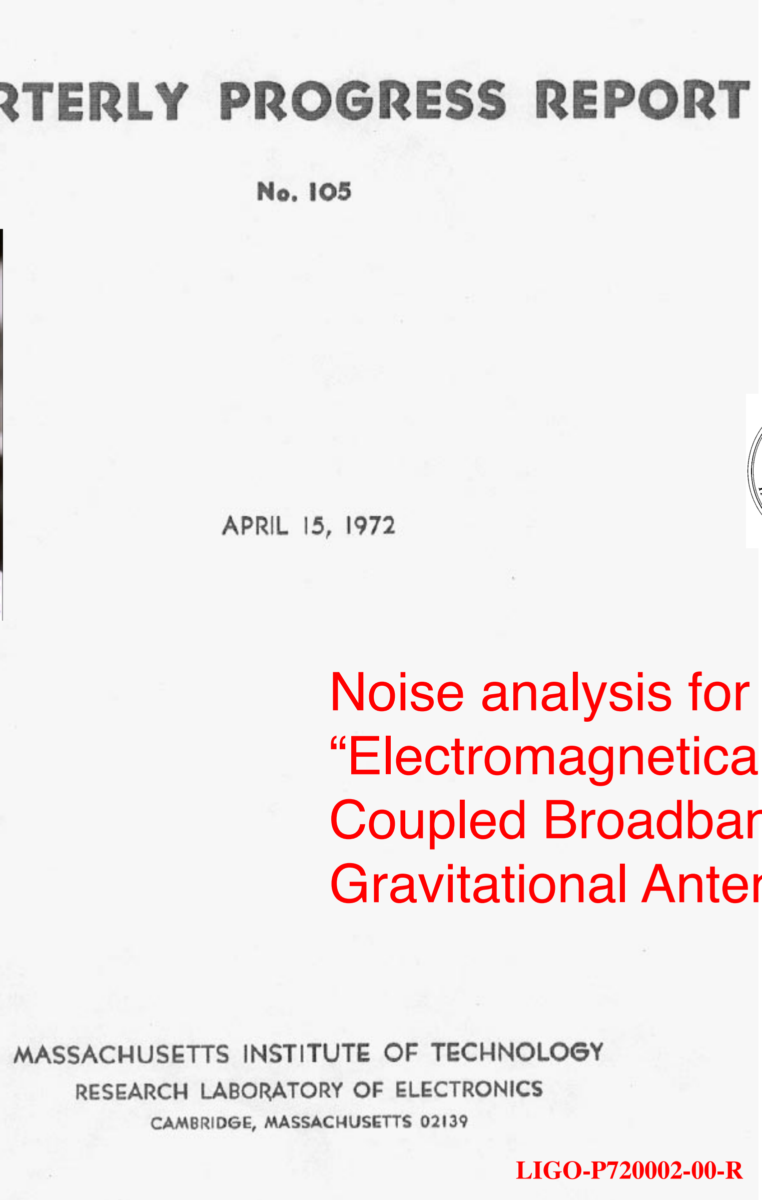
Kip S. Thorne
Co-Investigator
California Institute of Technology

Frederick J. Raab
Co-Investigator
California Institute of Technology

Rainer Weiss
Co-Investigator
Massachusetts Institute of Technology

# Rai Weiss – 1972





QUARTERLY PROGRESS REPORT

No. 105

APRIL 15, 1972

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
RESEARCH LABORATORY OF ELECTRONICS
CAMBRIDGE, MASSACHUSETTS 02139

Noise analysis for an “Electromagnetically Coupled Broadband Gravitational Antenna”

LIGO-P720002-00-R

# Joe Weber – 1965

# February 11, 2016 Discovery Announcement