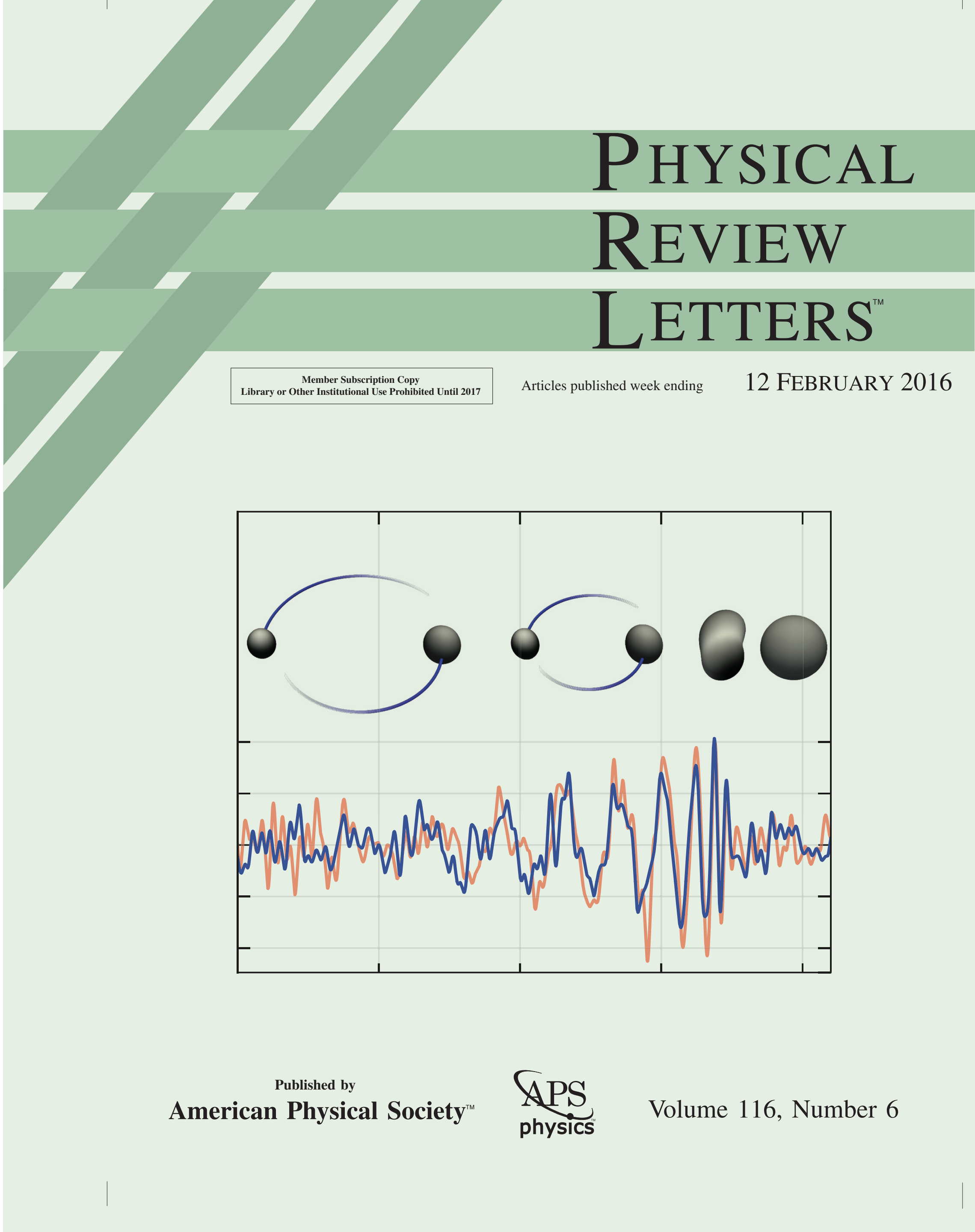
Observation of Gravitational Waves from a Binary Black Hole Merger

Keith Riles

University of Michigan
Physics Department

February 19, 2016



PHYSICAL
REVIEW
LETTERS™

Member Subscription Copy
Library or Other Institutional Use Prohibited Until 2017

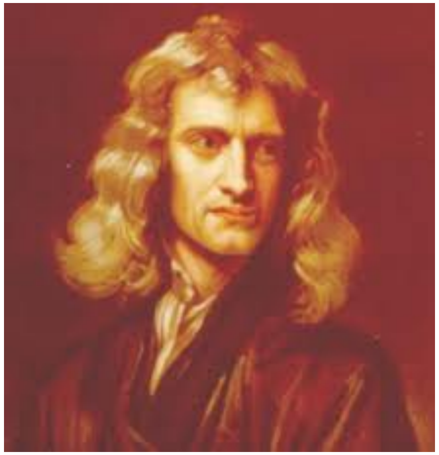
Articles published week ending 12 FEBRUARY 2016

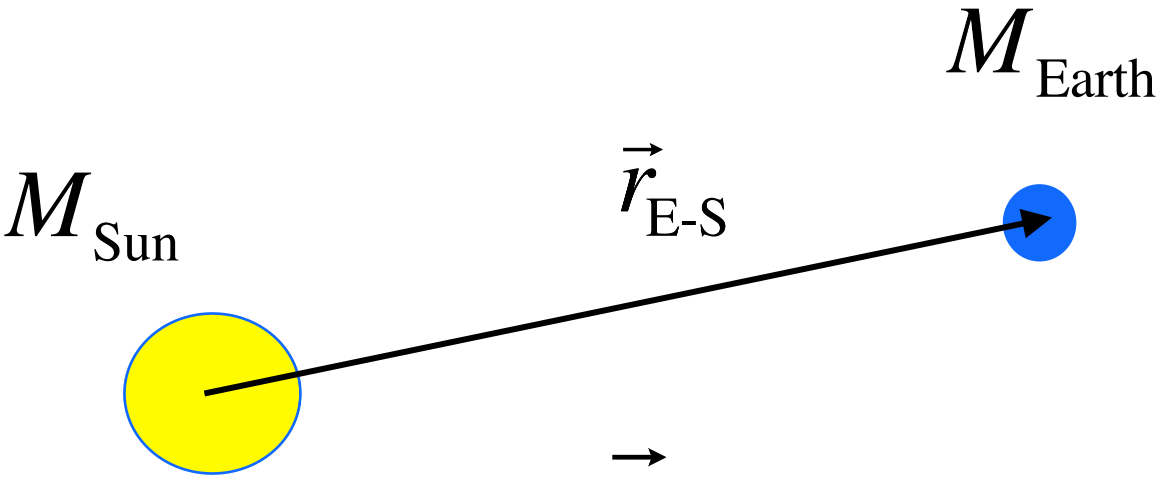
Published by
American Physical Society™

APS physics

Volume 116, Number 6

Newton’s Gravity



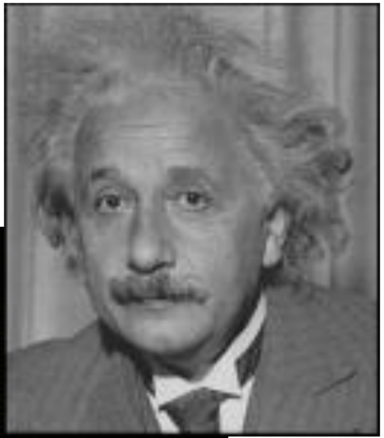


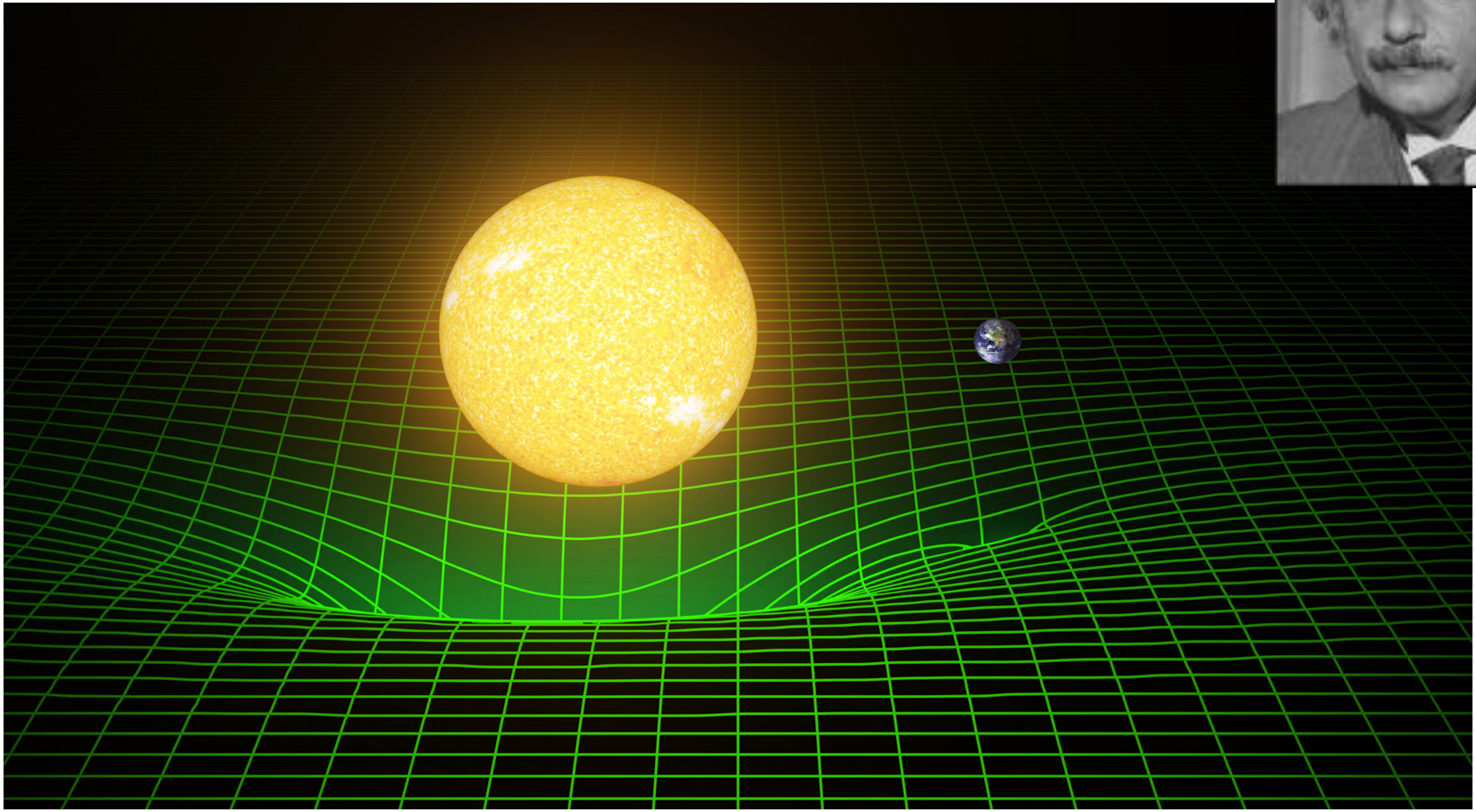
$$\vec{F}_{\text{On Earth}} = -\frac{GM_{\text{Sun}}M_{\text{Earth}}}{r_{\text{E-S}}^2}\,\hat{r}_{\text{E-S}}$$

→ Instantaneous “action at a distance”

Einstein’s Gravity

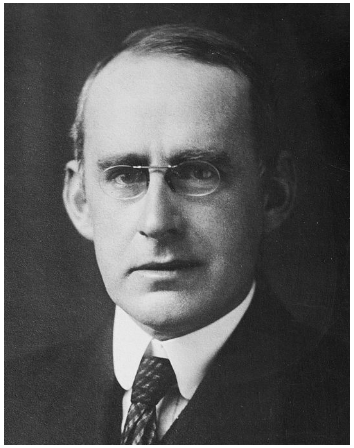
$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

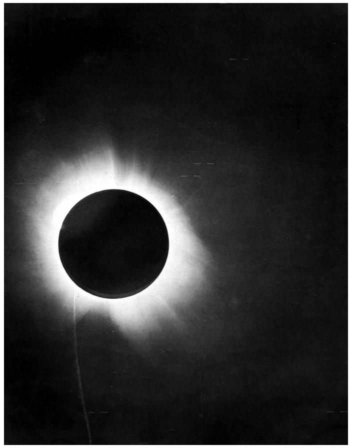


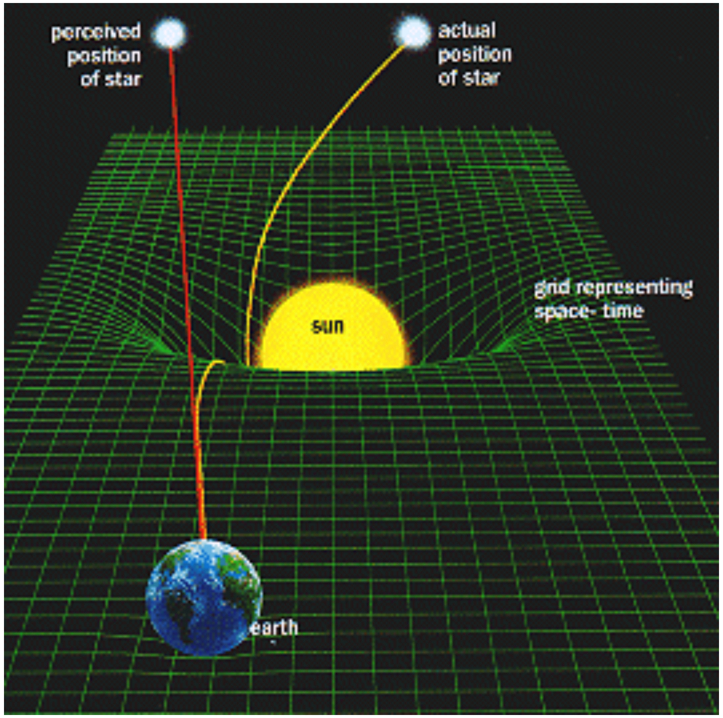


John Wheeler: **Matter tells spacetime how to curve, and curved space tells matter how to move**

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

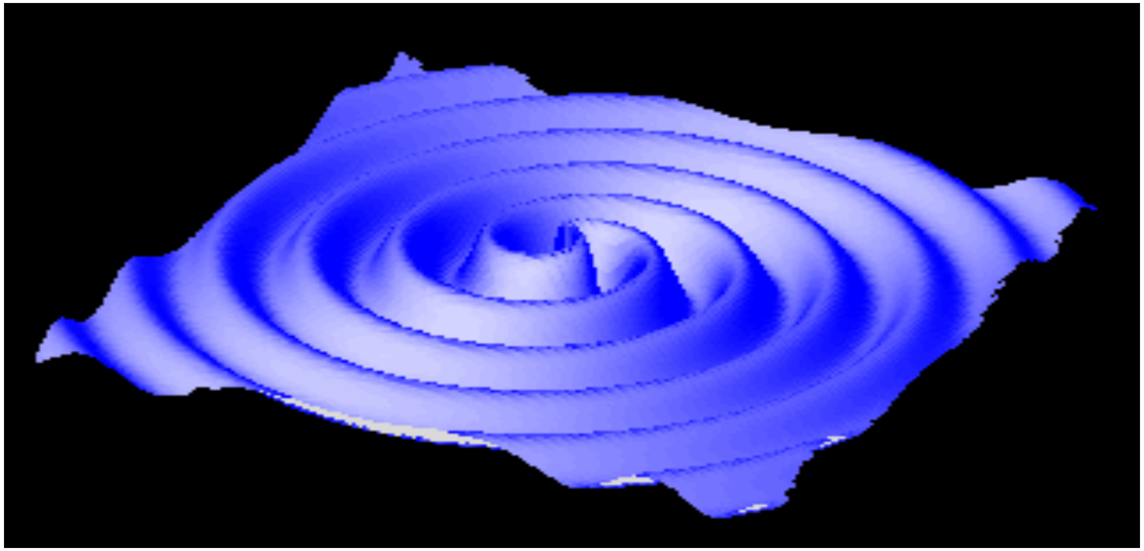
First confirmed <u>prediction</u> of General Relativity*

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

Observation of Gravitational Waves from a Binary Black Hole Merger

Compact Binary Systems

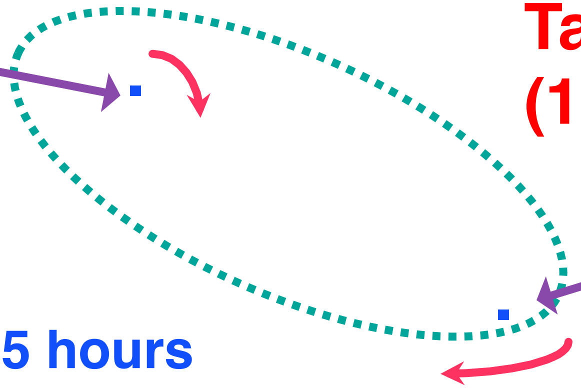
Now imagine two very compact stars (neutron stars or black holes) in a tight binary orbiting system:



Courtesy Jet Propulsion Laboratory

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

Taylor-Hulse binary system (1974)



Observed
17-Hz pulsar

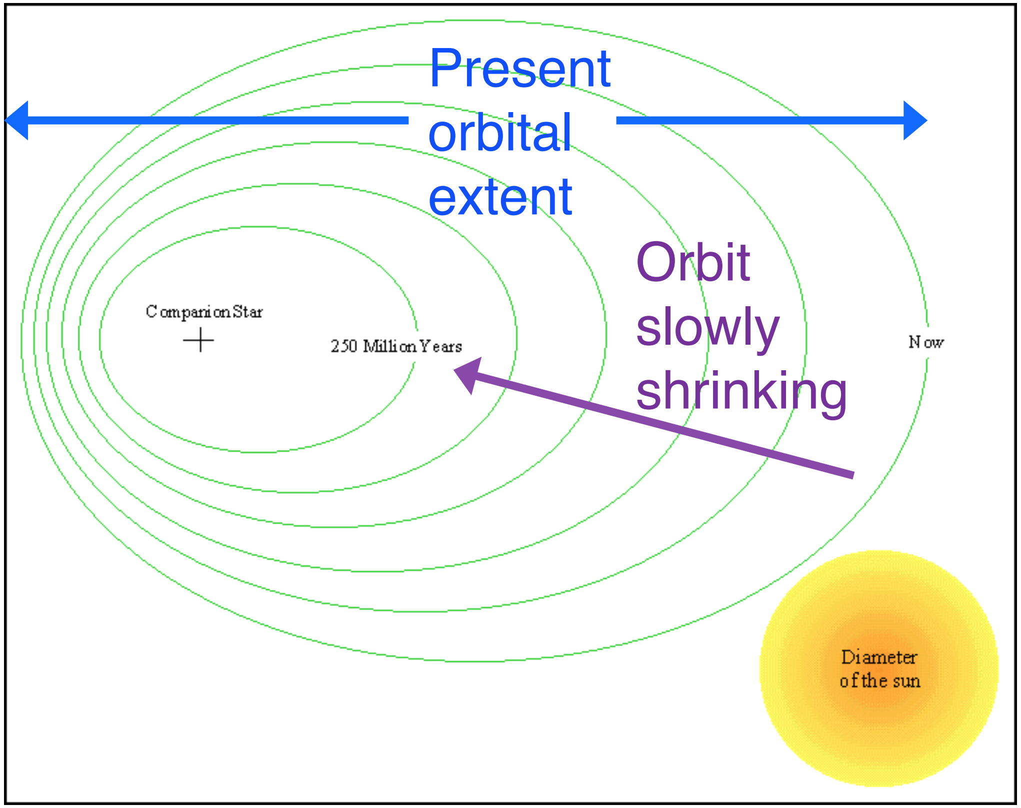
PSR 1913+16

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



Weisberg et al, 1981

Comparing prediction to measurement

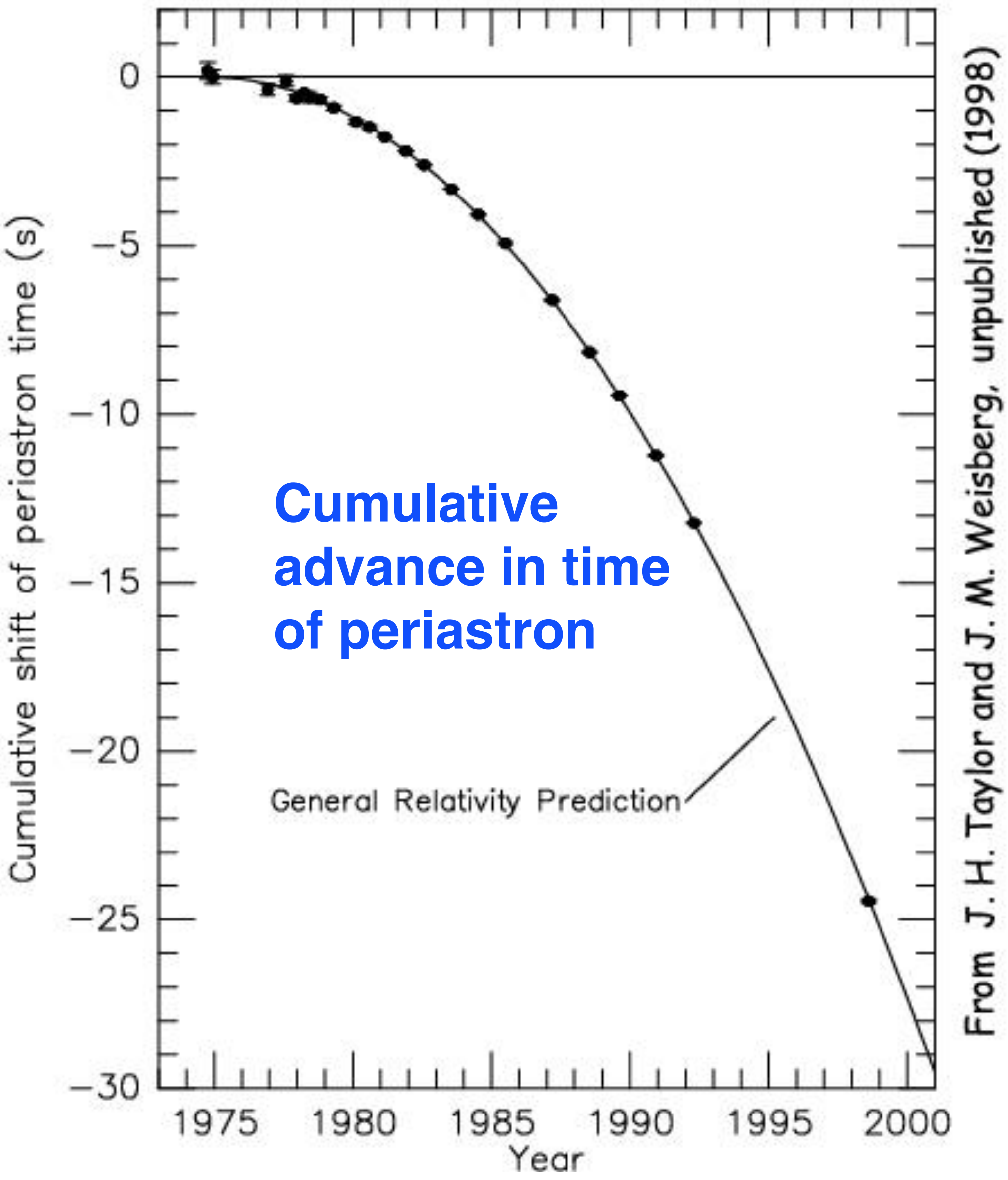
**Smooth curve is absolute prediction from General Relativity
(no free parameters!)**

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



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

Cumulative advance in time of periastron

Observati

Final stages of death spiral

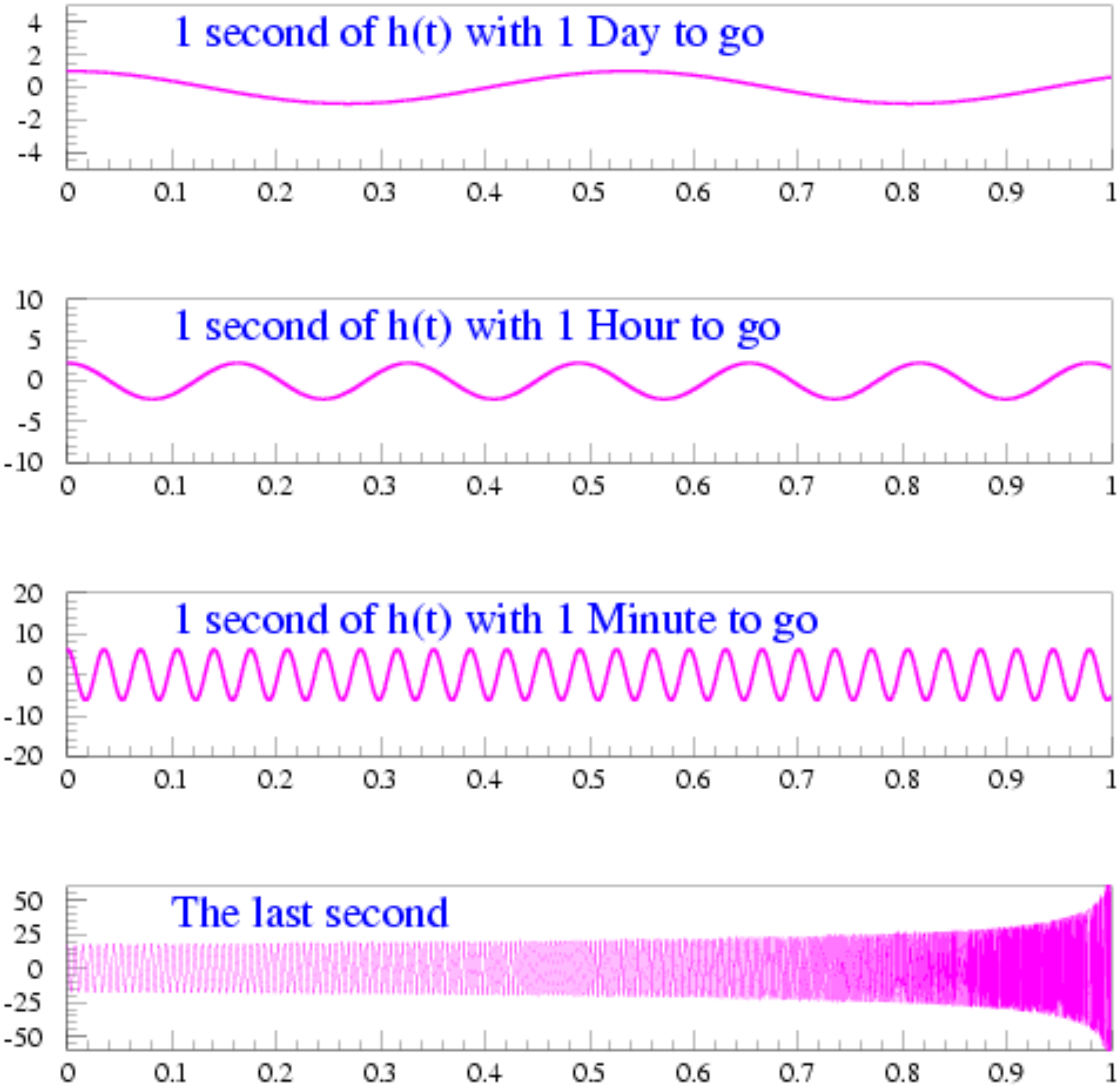
Well, what if we waited around for 300 million years?

What might we "see"?

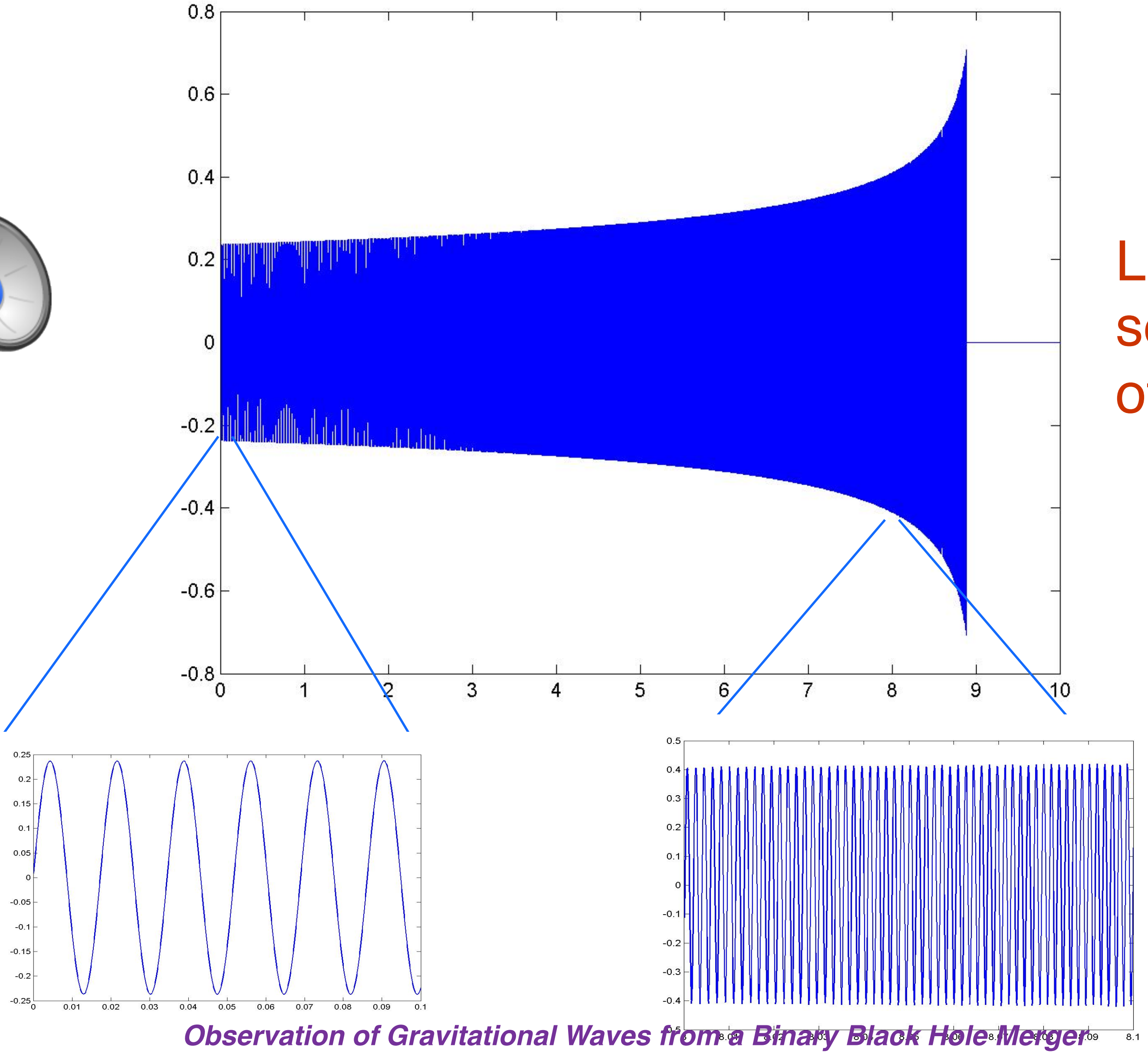
A Chirp!

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)



Observation of Gravitational Waves from a Binary Black Hole Merger



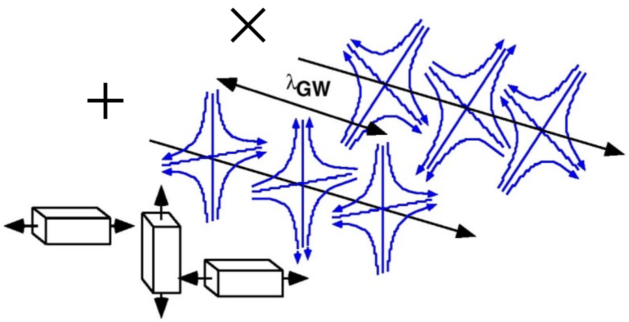
Last nine seconds of inspiral

Observation of Gravitational Waves from a Binary Black Hole Merger

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

Metric wave disturbance
(weak field)

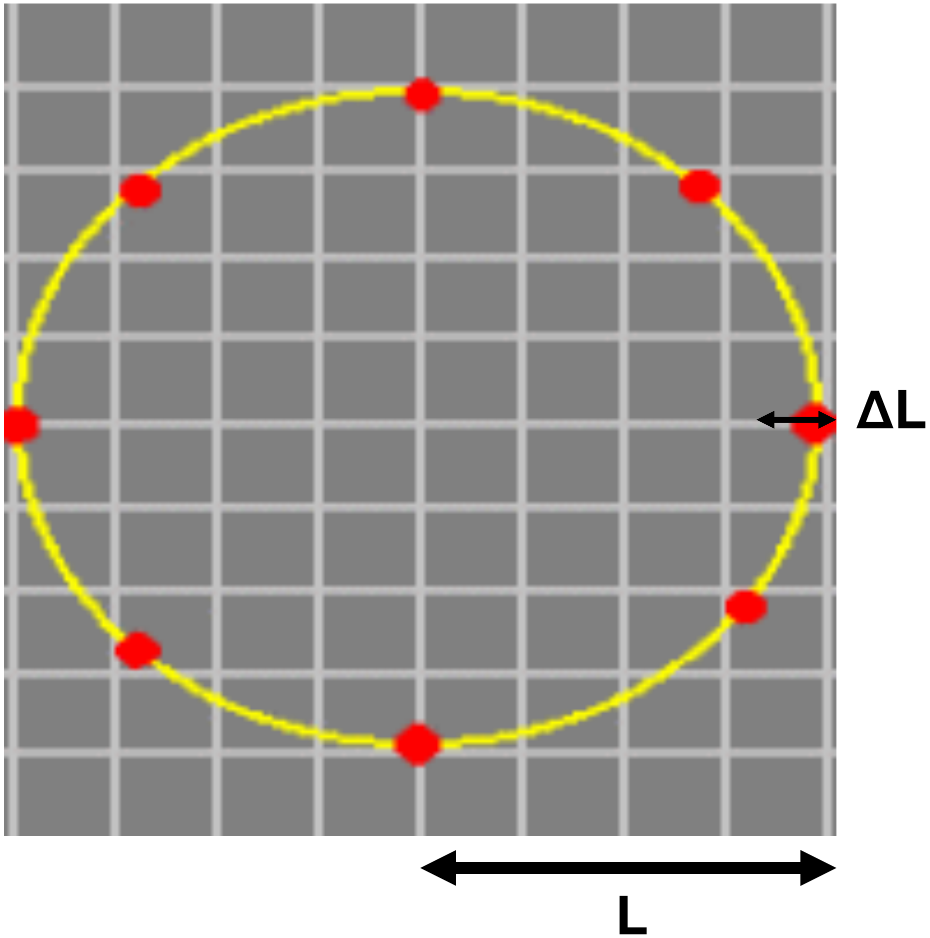
$$\longrightarrow h_{\mu\nu} = h_+(t - z/c) + h_\times(t - z/c)$$



How is the strength of a gravitational wave described?

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

$$\Delta L(t) \sim h(t) \times L$$



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 to be lucky to see a BNS in O1**
(and extremely lucky to have seen one in initial LIGO data)

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

Rates: [mergers per 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 $(\text{mass})^3$
→ BH rates depend sensitively on assumed mass distributions

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:

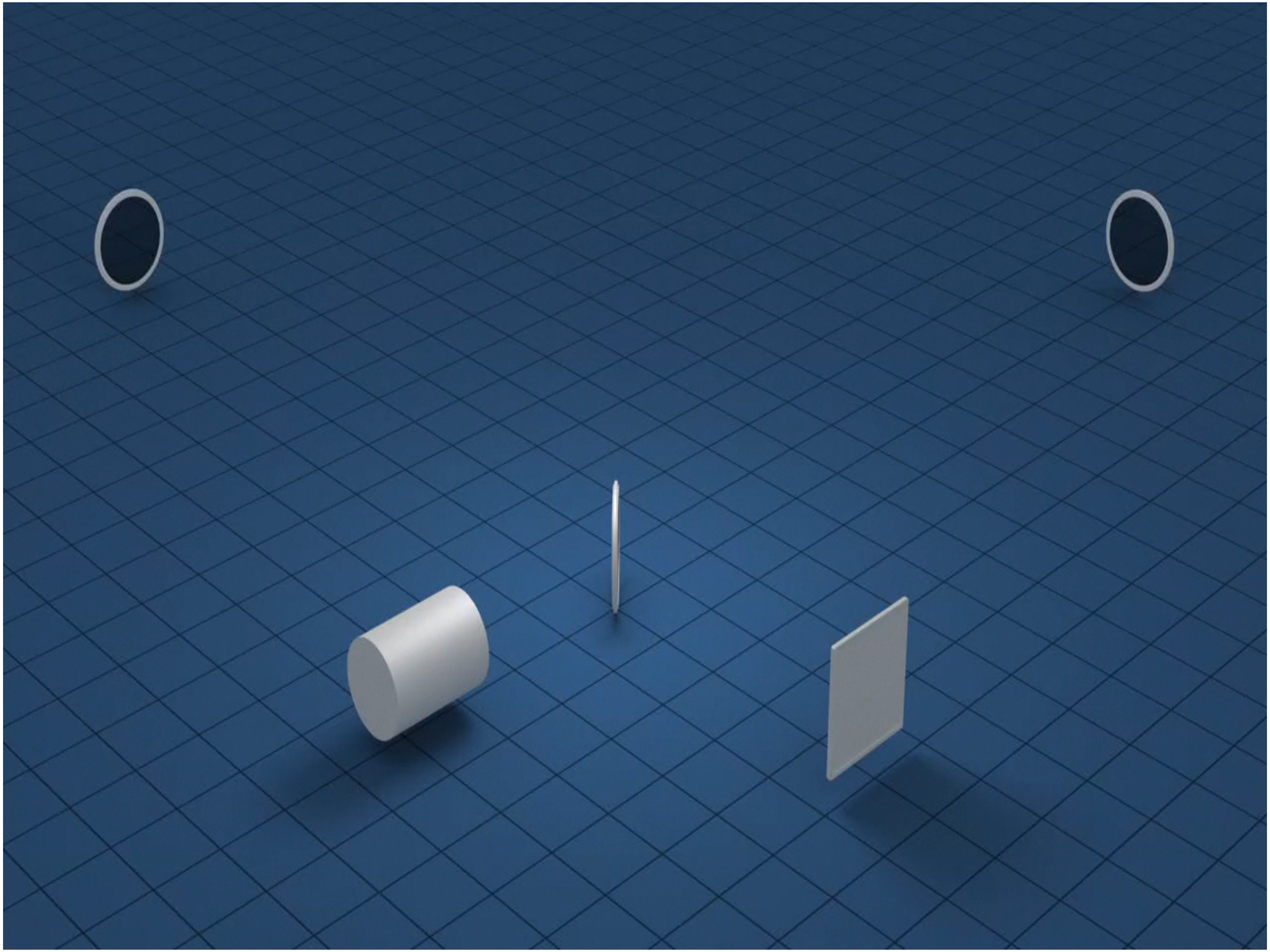
$$h \approx \frac{10^{-21}}{(r/400\,\mathrm{Mpc})}$$

→ Easily detectable in fall 2015 O1 run

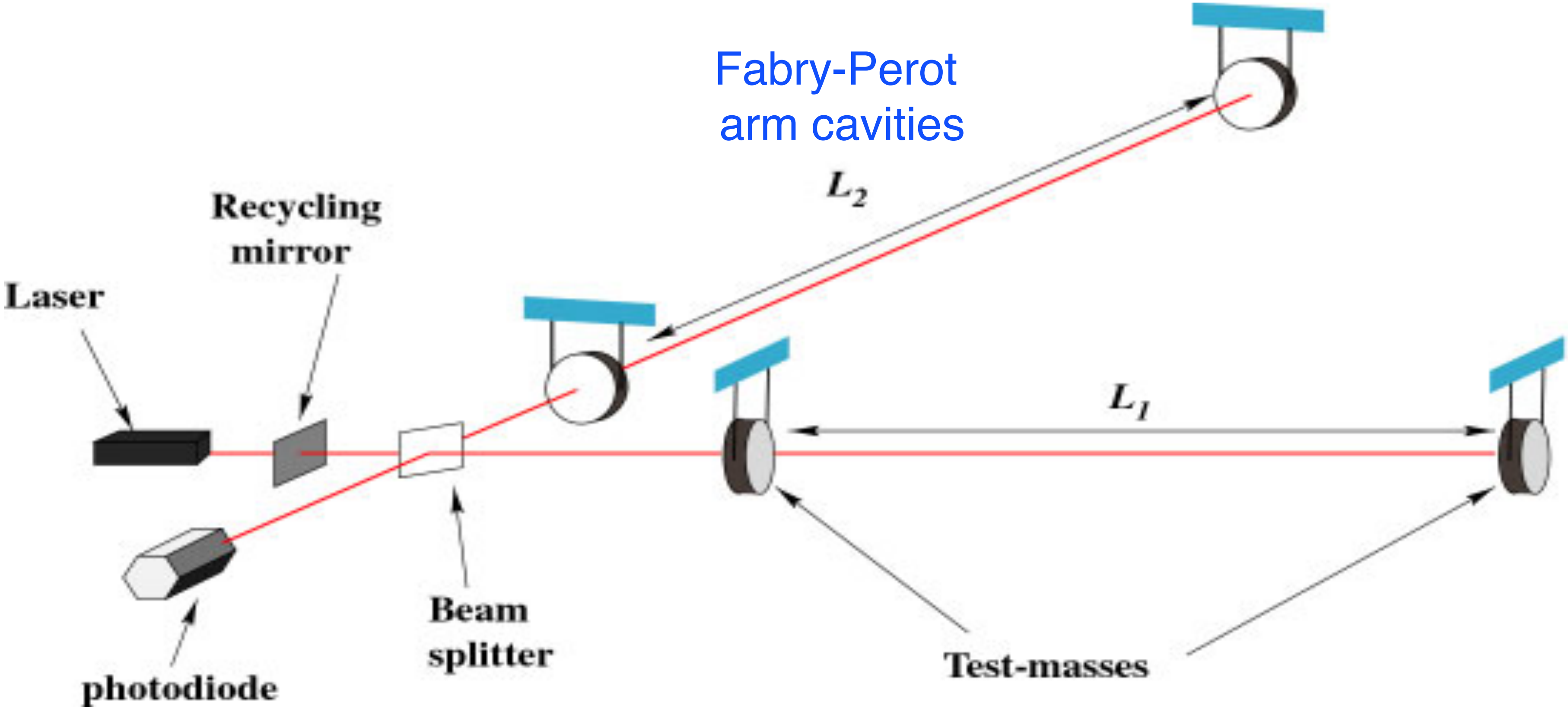
High mass → Low chirp frequency

Courtesy: Peter Shawhan

So how does one detect a gravitational wave?



Adding more detail (Initial LIGO)


Suspended mirrors (test masses)

Fabry-Perot arm cavities

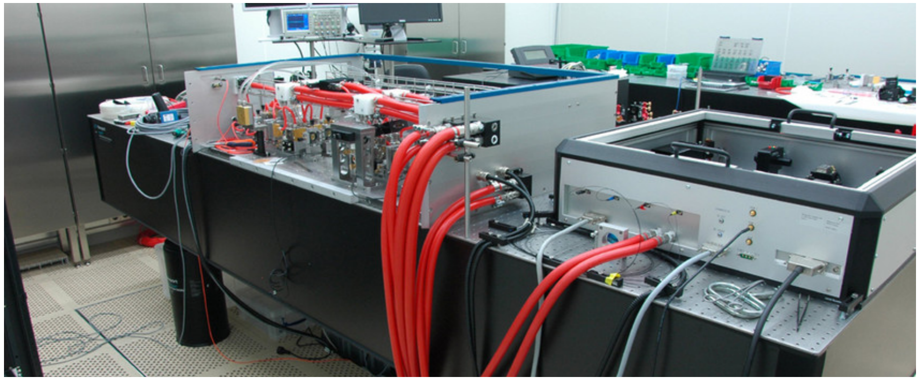
Observation of Gravitational Waves from a Binary Black Hole Merger

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

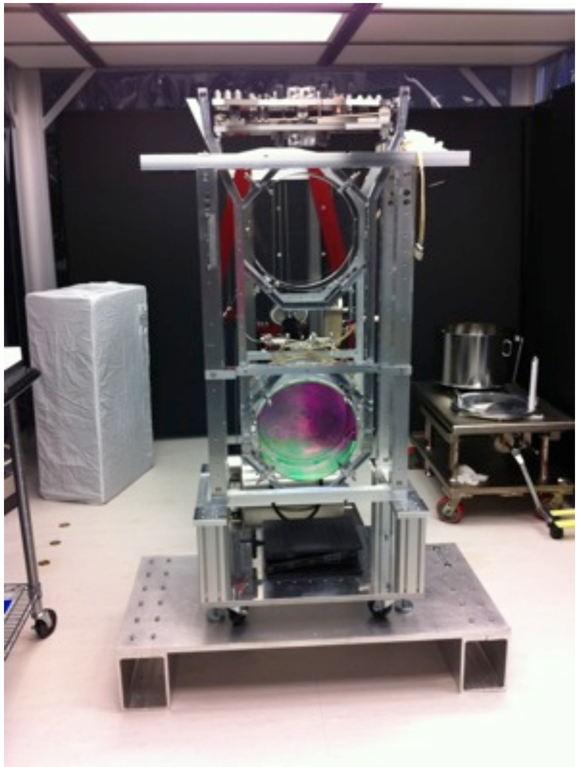
Compensates increased radiation pressure noise

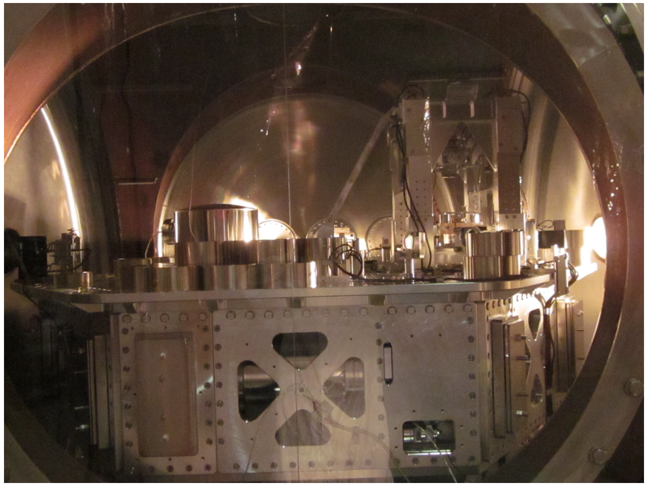
Initial LIGO → Advanced LIGO

New suspensions:

Single → Quadruple pendulum

Lower suspensions thermal noise in bandwidth

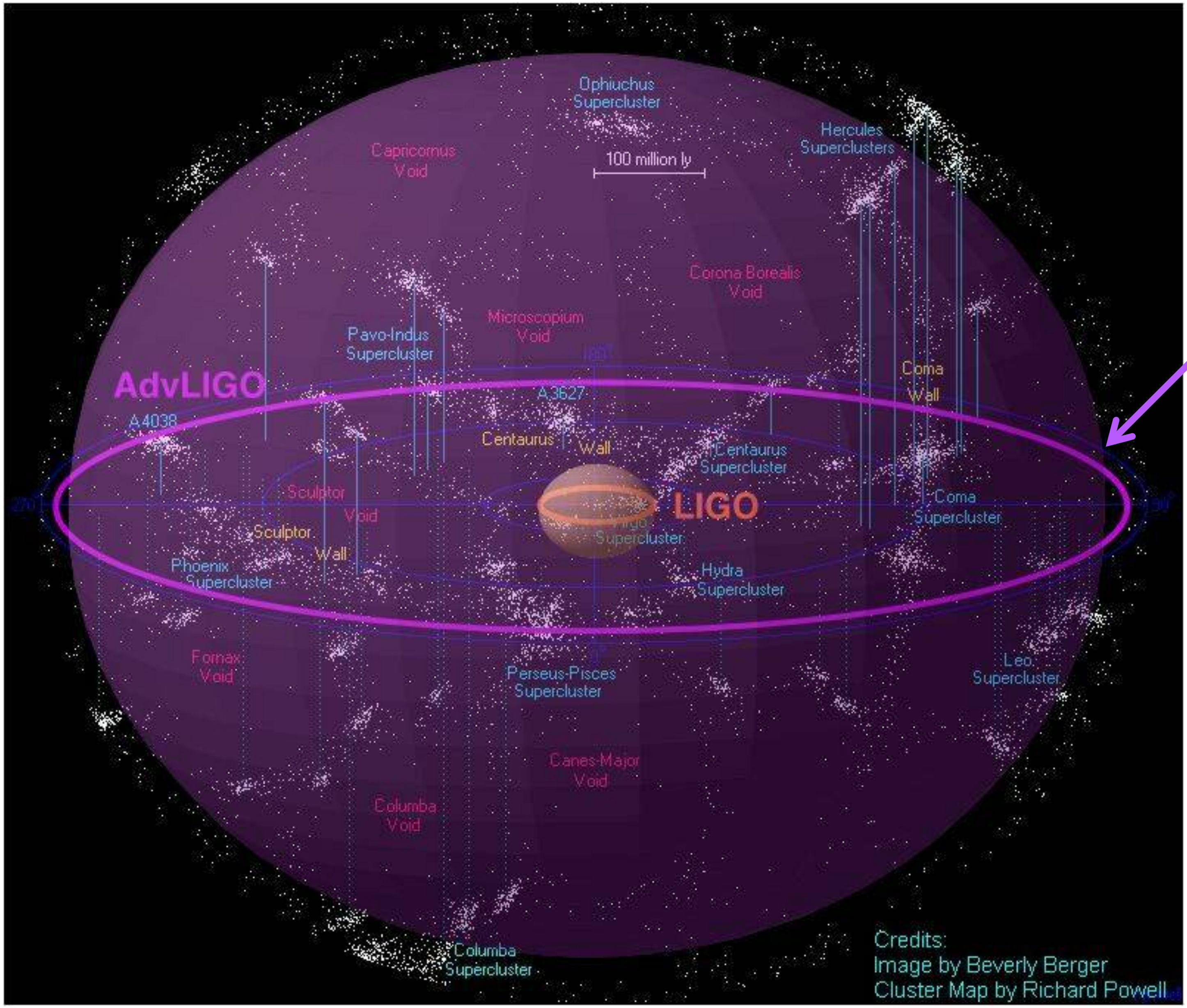




Improved seismic isolation:

Passive → Active

Lowers seismic "wall" to ~10 Hz



Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

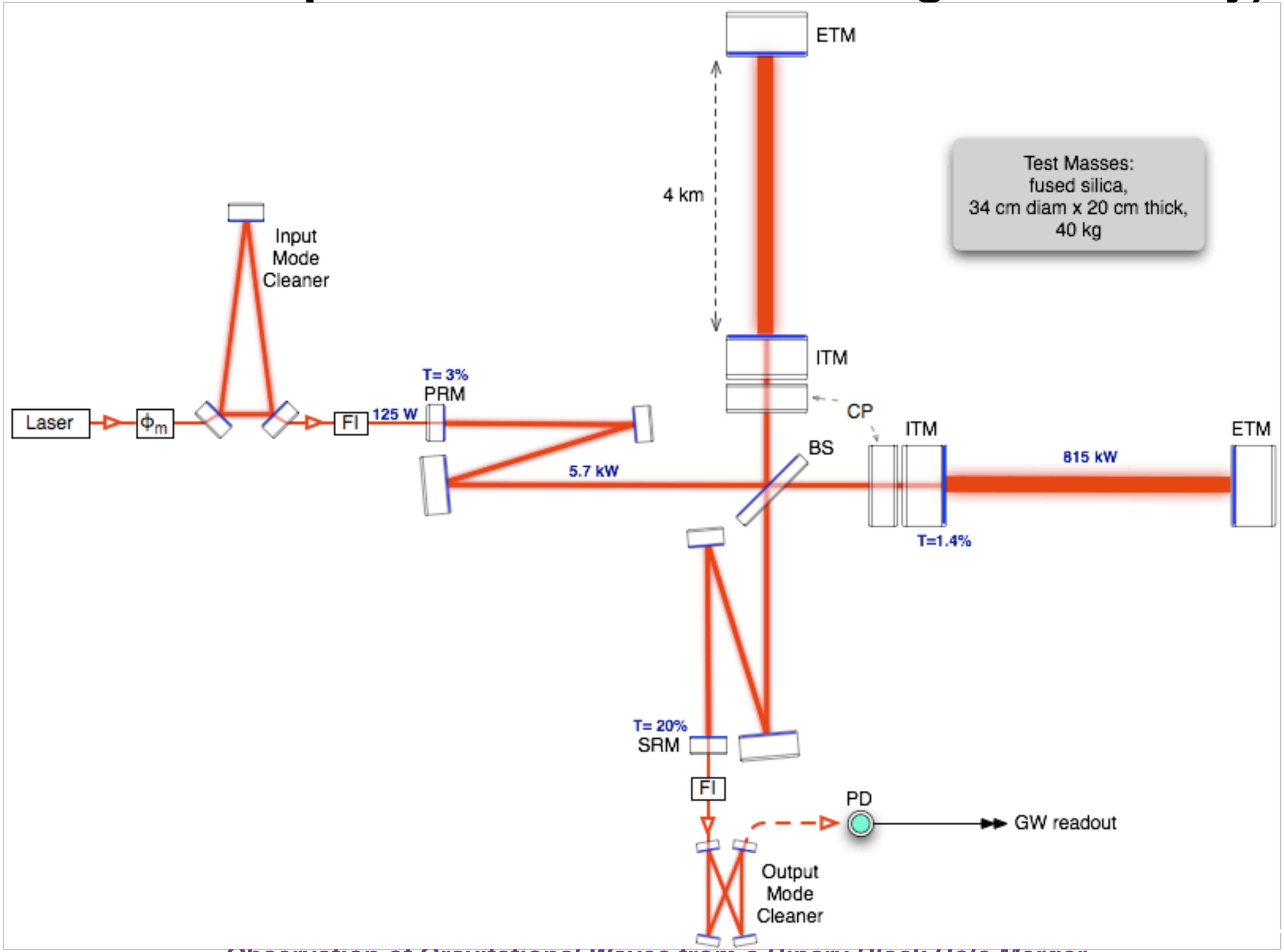
Full design sensitivity

Range increases by 10 → Volume increases by ~1000

Rate increases by ~1000

Adding still more detail – Advanced LIGO

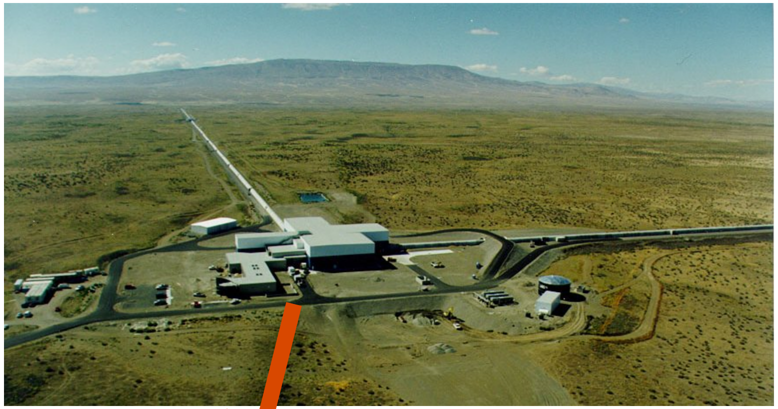
(nominal laser powers are for near design sensitivity)



Observation of Gravitational Waves from a Binary Black Hole Merger

LIGO Observatories

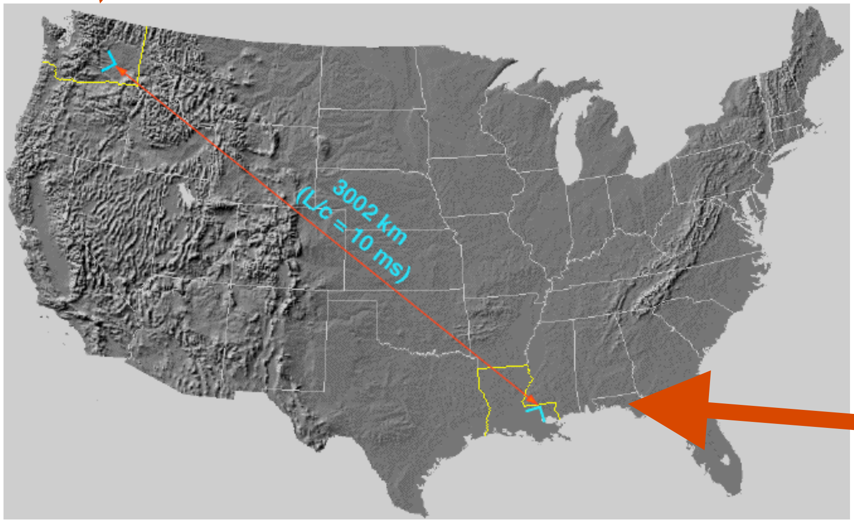
Hanford



Observation of nearly simultaneous ($|\Delta t|<10$ ms) signals 3000 km apart rules out terrestrial artifacts

Timing and antenna pattern give (some) directionality on sources

Livingston



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

SONOMA STATE UNIVERSITY

indigo

MONTCLAIR STATE UNIVERSITY

University of Glasgow

Australian National University

WHITMAN COLLEGE

AMERICAN UNIVERSITY
WASHINGTON, DC

UNIVERSITY OF THE WEST of SCOTLAND
UWS

TEXAS TECH UNIVERSITY.

清华大学
Tsinghua University

R·I·T

Max Planck Institute for Gravitational Physics
ALBERT EINSTEIN INSTITUTE

UNIVERSITY OF STRATHCLYDE

MICHIGAN

NASA
GODDARD SPACE FLIGHT CENTER

THE UNIVERSITY OF WESTERN AUSTRALIA

РАН

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

Università degli Studi del Sannio

UNIVERSITY OF CAMBRIDGE

ICTP SAIFR

THE UNIVERSITY OF CHICAGO

MONTANA STATE UNIVERSITY

THE UNIVERSITY of MISSISSIPPI

THE UNIVERSITY OF ADELAIDE AUSTRALIA

SOUTHERN UNIVERSITY
Agricultural & Mechanical College

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Caltech

UNIVERSITY OF MINNESOTA.

UNIVERSITY OF BIRMINGHAM

THE UNIVERSITY OF MELBOURNE

UIB
Universitat de les Illes Balears

UNIVERSITY OF WASHINGTON

GEO 600

UTRGV

SIGILL: COLL: CARLETON

UNIVERSITY of WISCONSIN
UWMILWAUKEE

SYRACUSE UNIVERSITY

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

Northwestern

UNIVERSITÄT HAMBURG

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

PENNSTATE

EMBRY-RIDDLE AERONAUTICAL UNIVERSITY

Leibniz Universität Hannover

HOBART AND WILLIAM SMITH COLLEGES

Science & Technology Facilities Council
Rutherford Appleton Laboratory

LIGO

LSC

LIGO Scientific Collaboration – Aug 1997 founding

CU

University of Glasgow

Max Planck Institute
for Gravitational Physics
ALBERT EINSTEIN INSTITUTE

MICHIGAN

Massachusetts Institute of Technology

Leland Stanford Junior University

Caltech

EMU

UNIVERSITY OF BIRMINGHAM

UO

GEO 600

UNIVERSITY of WISCONSIN
UWMILWAUKEE

Universität Hamburg

Syracuse University

CARDIFF
UNIVERSITY
PRIFYSGOL
CAERDYDD

UF UNIVERSITY of FLORIDA

LSU
LOUISIANA STATE UNIVERSITY

Leibniz
Universität
Hannover

PENNSTATE

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

Caltech

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

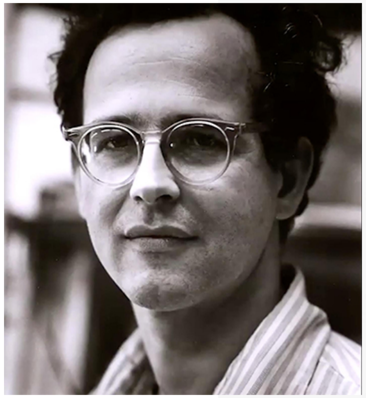
Ronald W. P. Drever
Co-Investigator
California Institute of Technology

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

LIGO

LSC

LIGO Scientific Collaboration – Aug 1997 founding

University of Glasgow

Leland Stanford Junior University 1891

Max Planck Institute
for Gravitational Physics
ALBERT EINSTEIN INSTITUTE

MICHIGAN

Massachusetts Institute of Technology 1861

Caltech

EMU

UNIVERSITY OF
BIRMINGHAM

GEO 600

UNIVERSITY of WISCONSIN
UWMILWAUKEE

Universität Hamburg

Syracuse University
Suos Cultores Scientia Coronat
Founded AD 1870

CARDIFF
UNIVERSITY
PRIFYSGOL
CAERDYDD

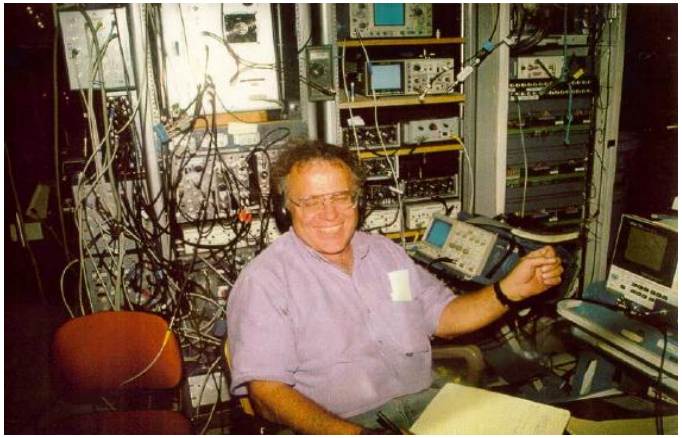
UF UNIVERSITY of FLORIDA

LSU
LOUISIANA STATE UNIVERSITY

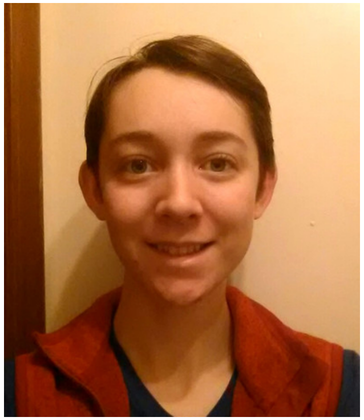
Leibniz
Universität
Hannover

PENNSTATE
1855

Michigan Gravitational Wave Group (MGWG)



Dick Gustafson (c, d)



Ansel Neunzert (c,a)

Keith Riles (d, a)

Orion Sauter (a)

Pranav Rao (a)

Weigang Liu (d)

Stephen Trembath-Reichert (d)

Curtis Rau (c)

c = commissioning
d = detector characterization
a = analysis

Camera-shy: Eilam Morag (d)

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
LIGO Laboratory

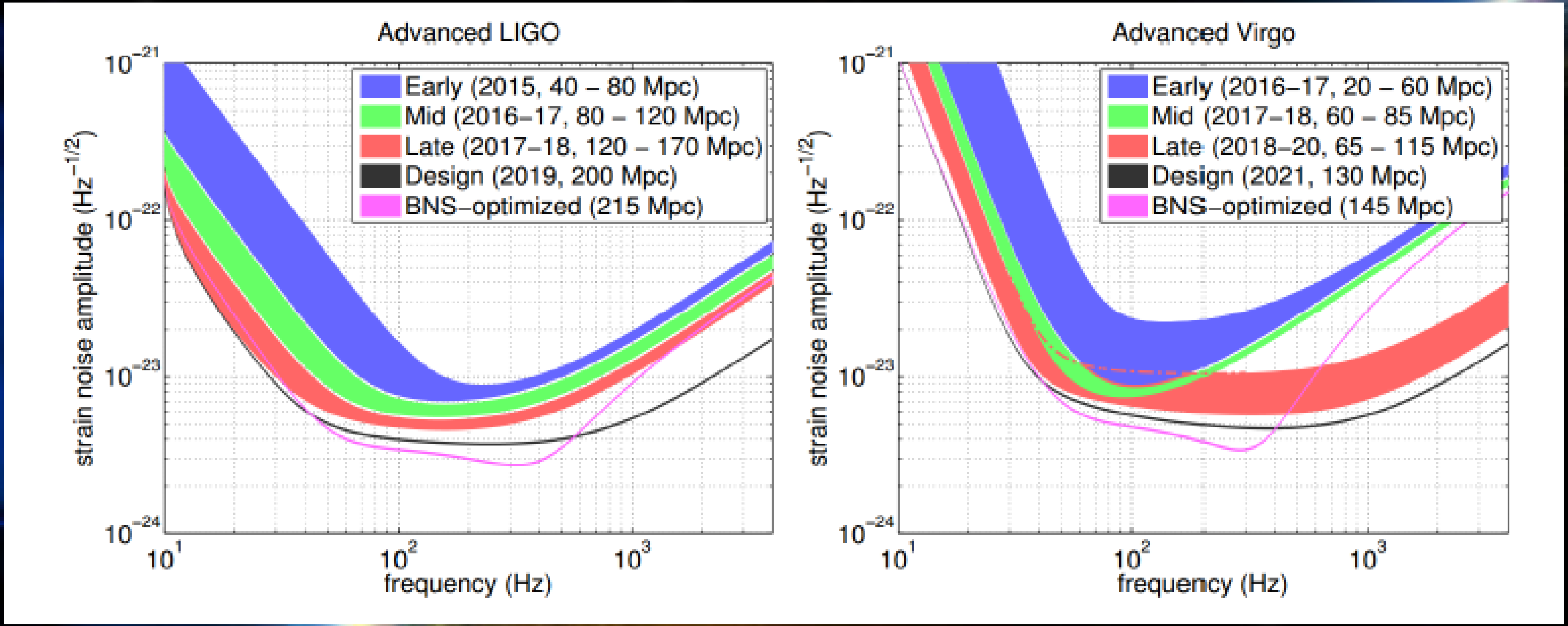
Santiago Caride
Ph.D. 2015
Texas Tech University

Evan Goetz
Ph.D. 2010
LIGO Hanford Observatory

Jacob Slutsky
B.S. 2006
Goddard Space Flight Center

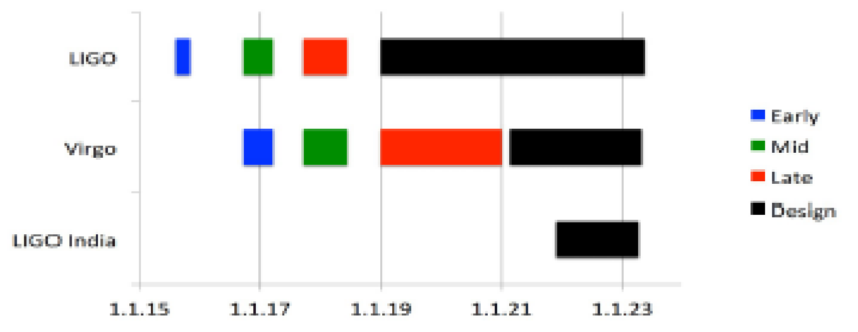
Alex Nitz
B.S. 2010
Albert Einstein Institute

Jamie Rollins
B.S. 1999
LIGO Laboratory

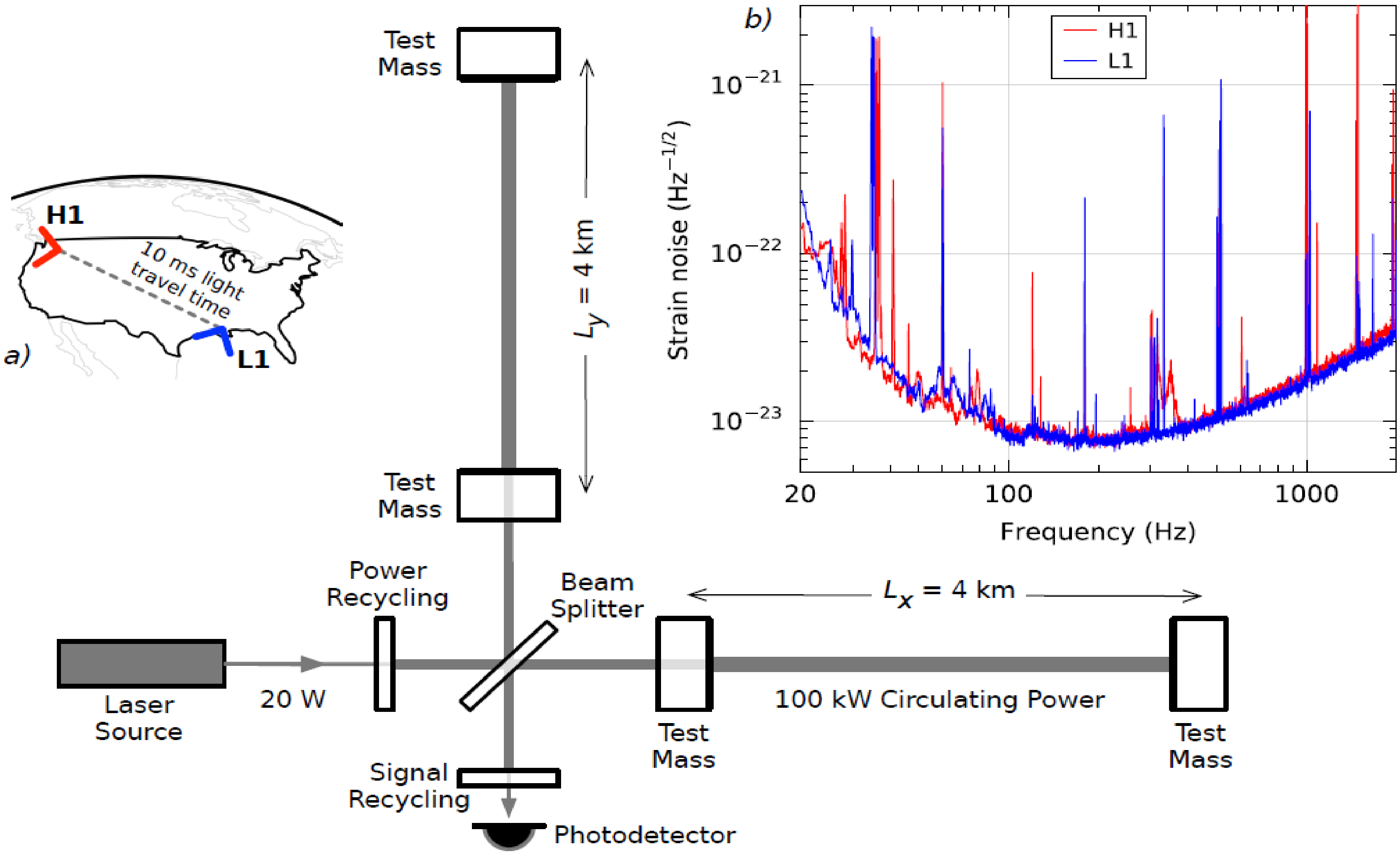


	Estimated Run	$E_{\rm GW} = 10^{-2}\, M_\odot c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS	% BNS Localized within	
Epoch	Duration	LIGO	Virgo	LIGO	Virgo	Detections	5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016 – 2017	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 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



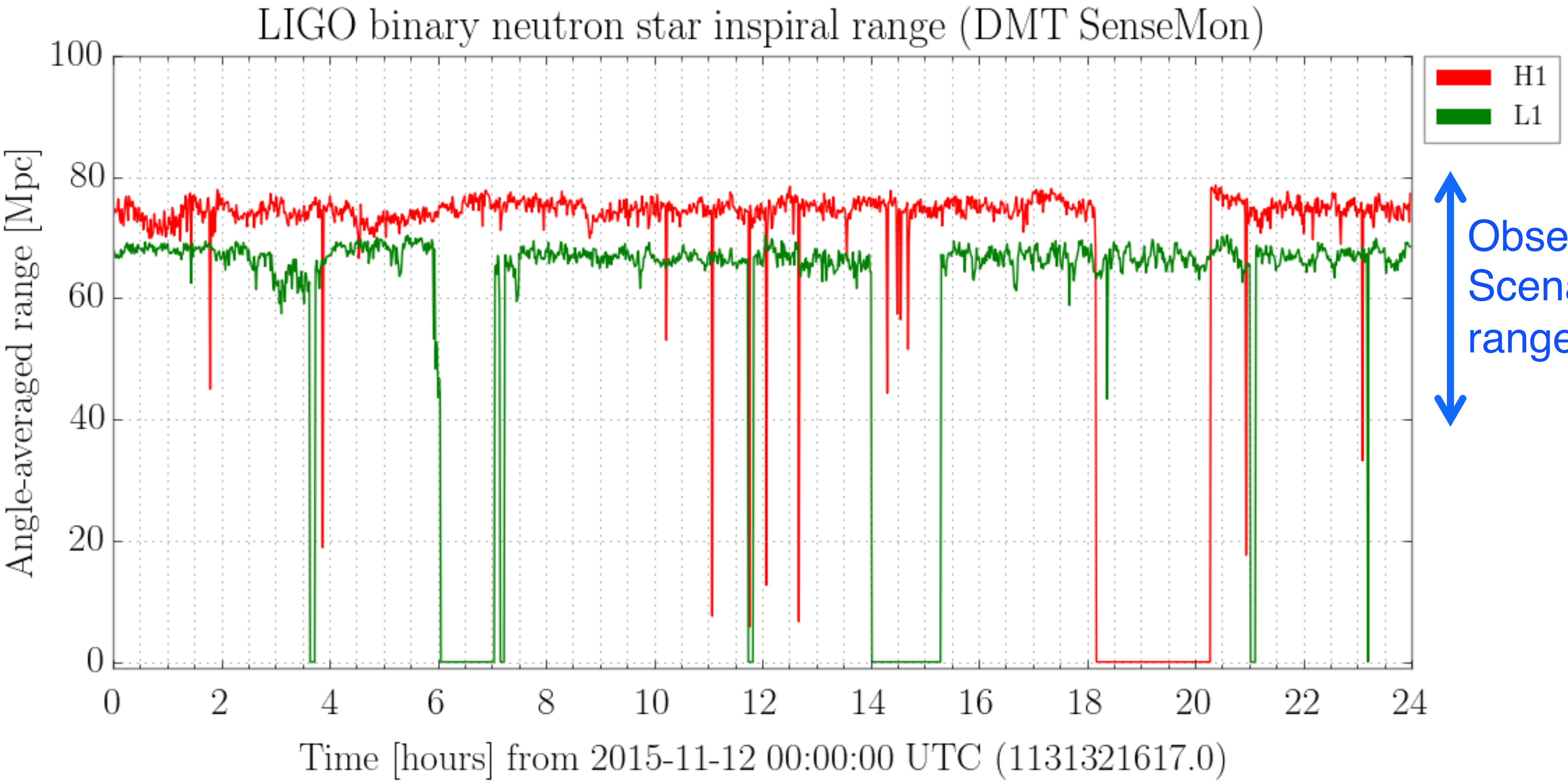
O1 Data Run



Observation of Gravitational Waves from a Binary Black Hole Merger

O1 Data Run

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



Observing Scenario range

Observation of Gravitational Waves from a Binary Black Hole Merger

GW150914

- Last 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
  → Will report on those results, when analysis is complete.

Gravitational Wave Event
GW150914

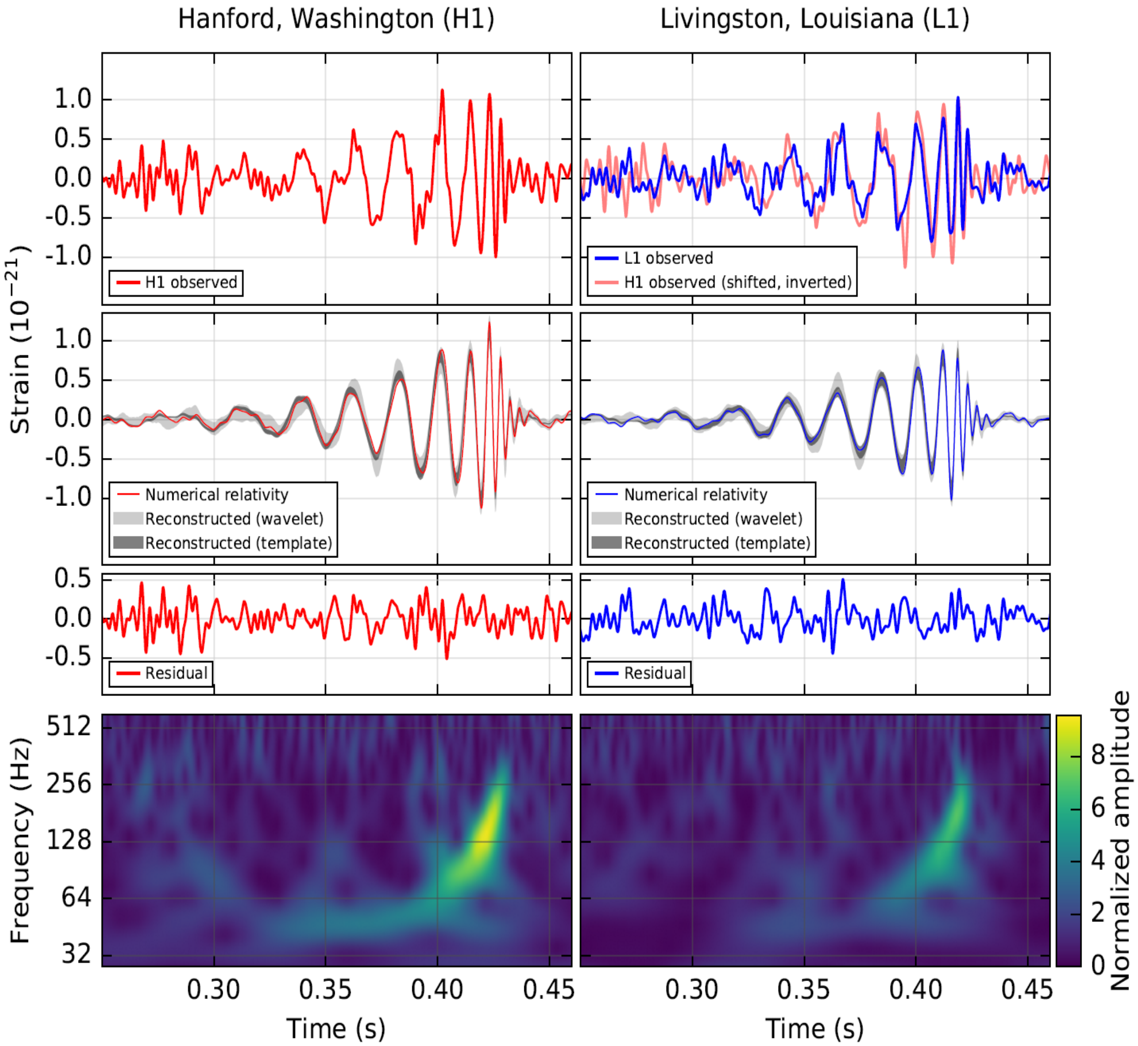
Data bandpass filtered between 35 Hz and 350 Hz

Time difference 6.9 ms with Livingston first

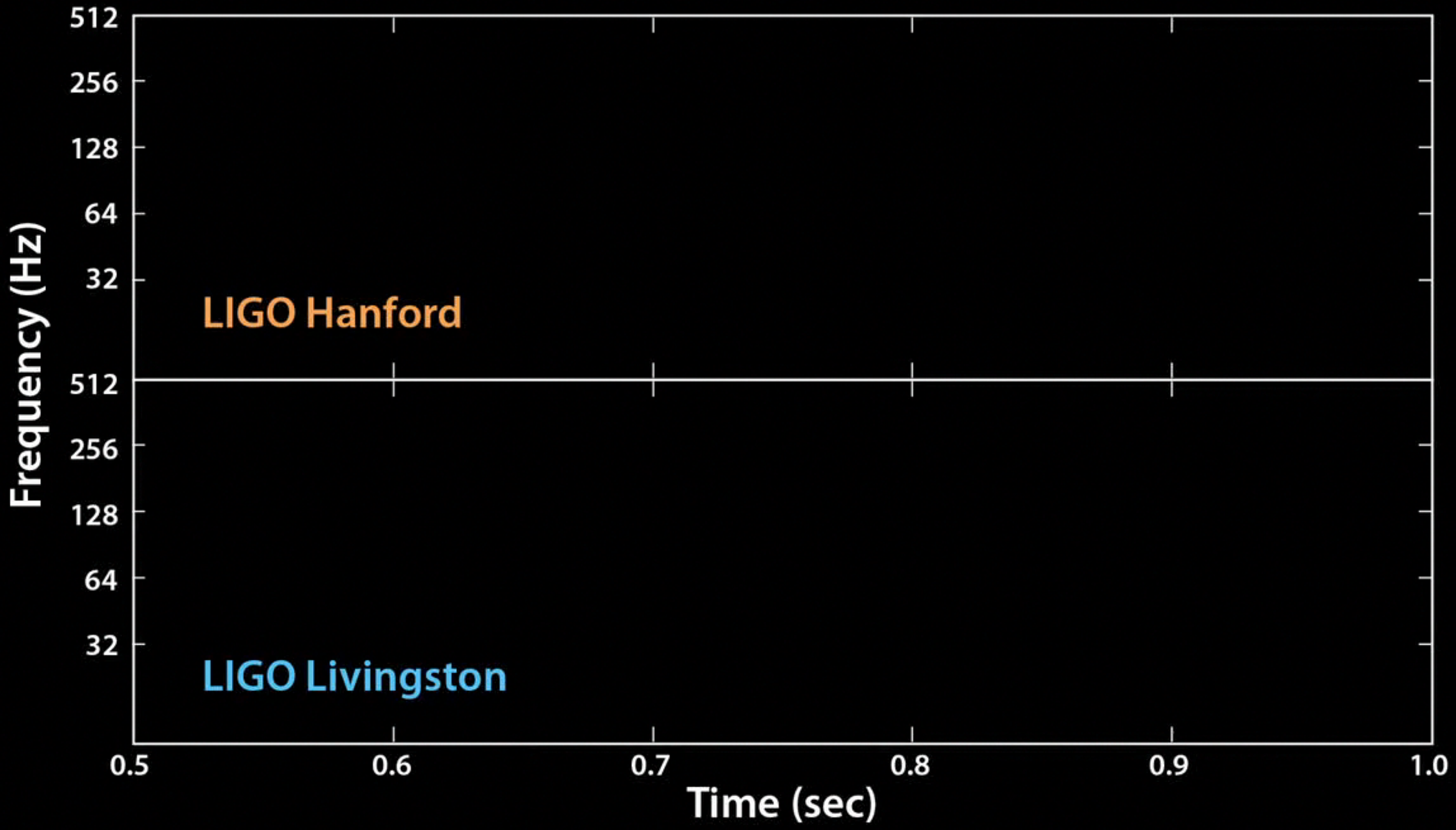
Second row – calculated GW strain using Numerical Relativity Waveforms for quoted parameters compared to reconstructed waveforms (Shaded)

Third Row –residuals

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



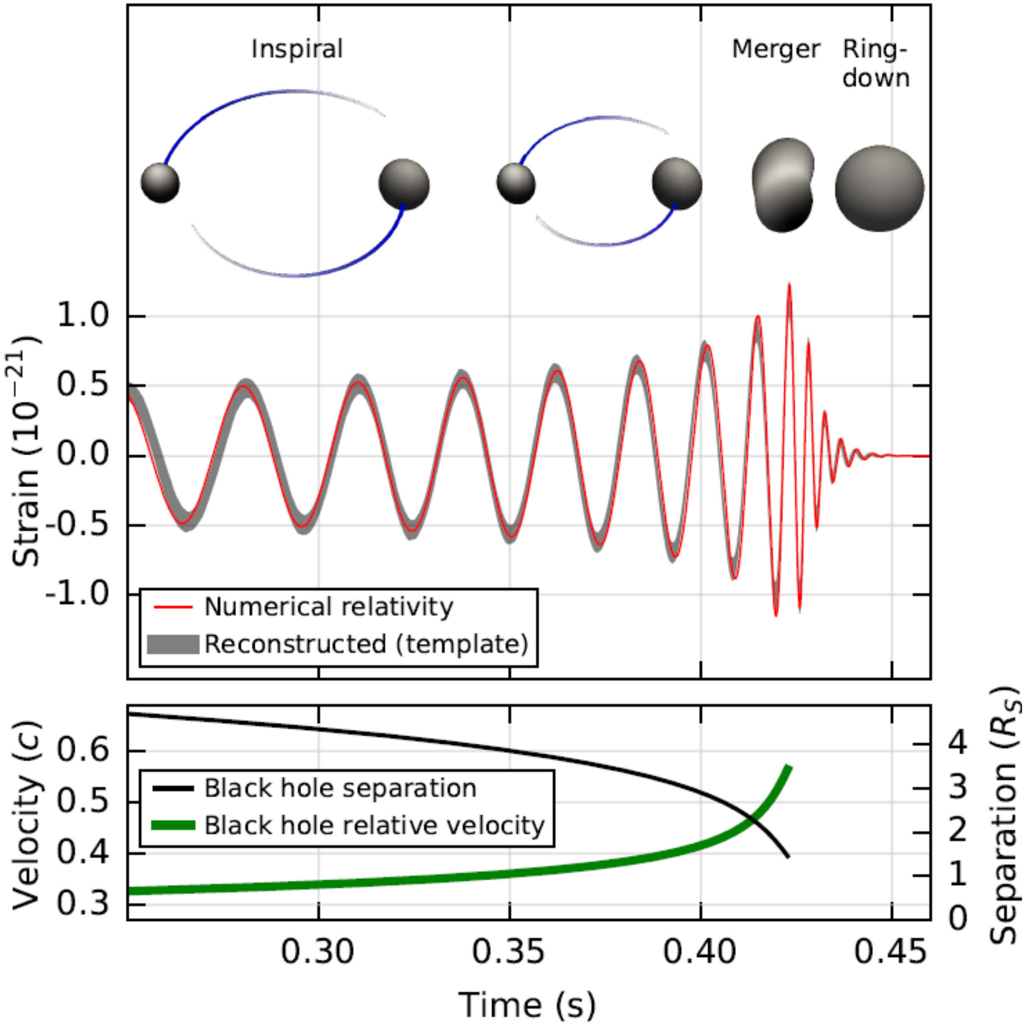
Observation of Gravitational Waves from a Binary Black Hole Merger


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

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 $v/c = (GM_f \pi f/c^3)^{1/3}$



Observation of Gravitational Waves from a Binary Black Hole Merger

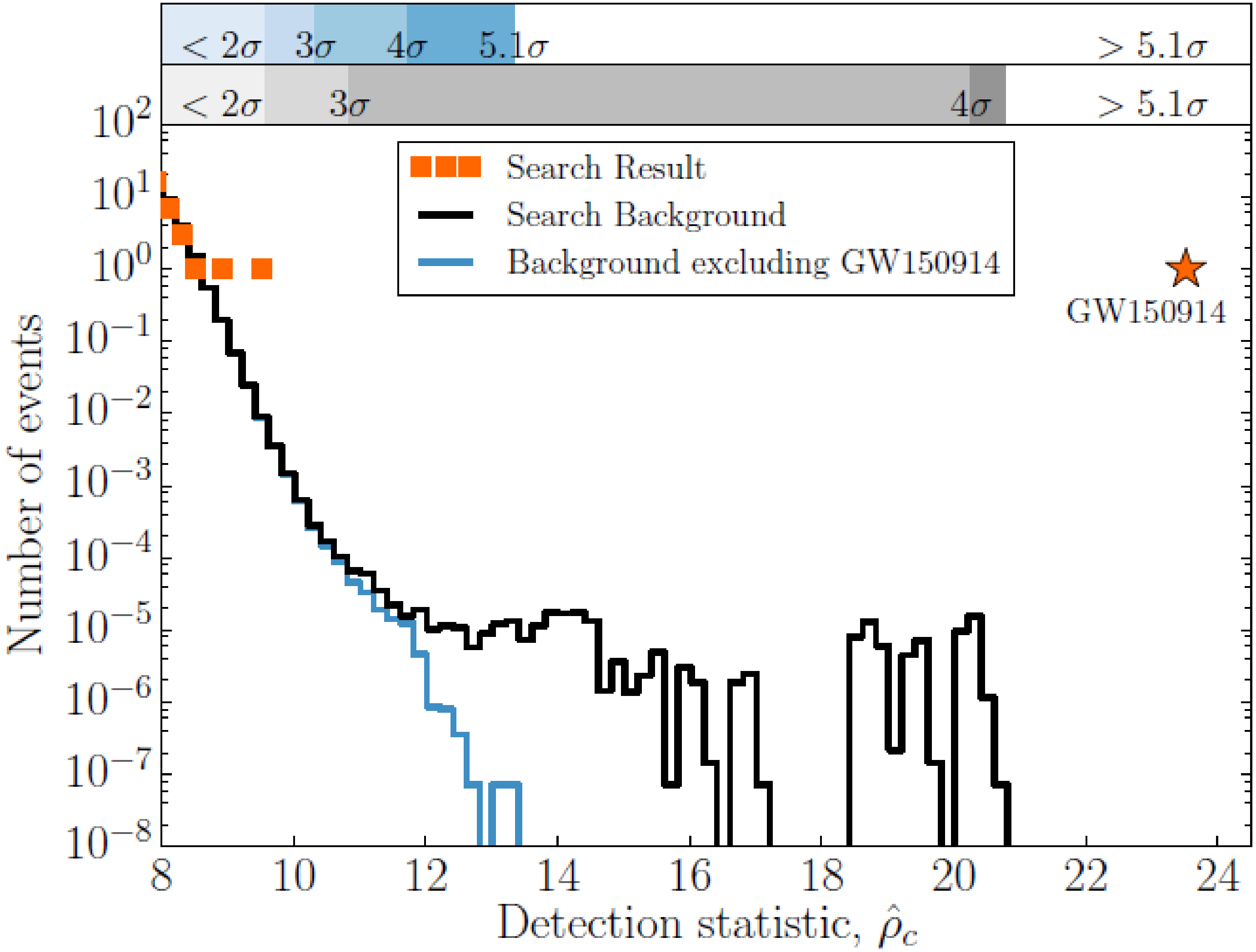
Transient Event Searches (1)

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 χ^2 to test consistency with matched template, then apply detector coincidence within 15 msec.
- Calculate quadrature sum ρ_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 > 5.1σ

Statistical Significance of GW150914

Binary Coalescence Search



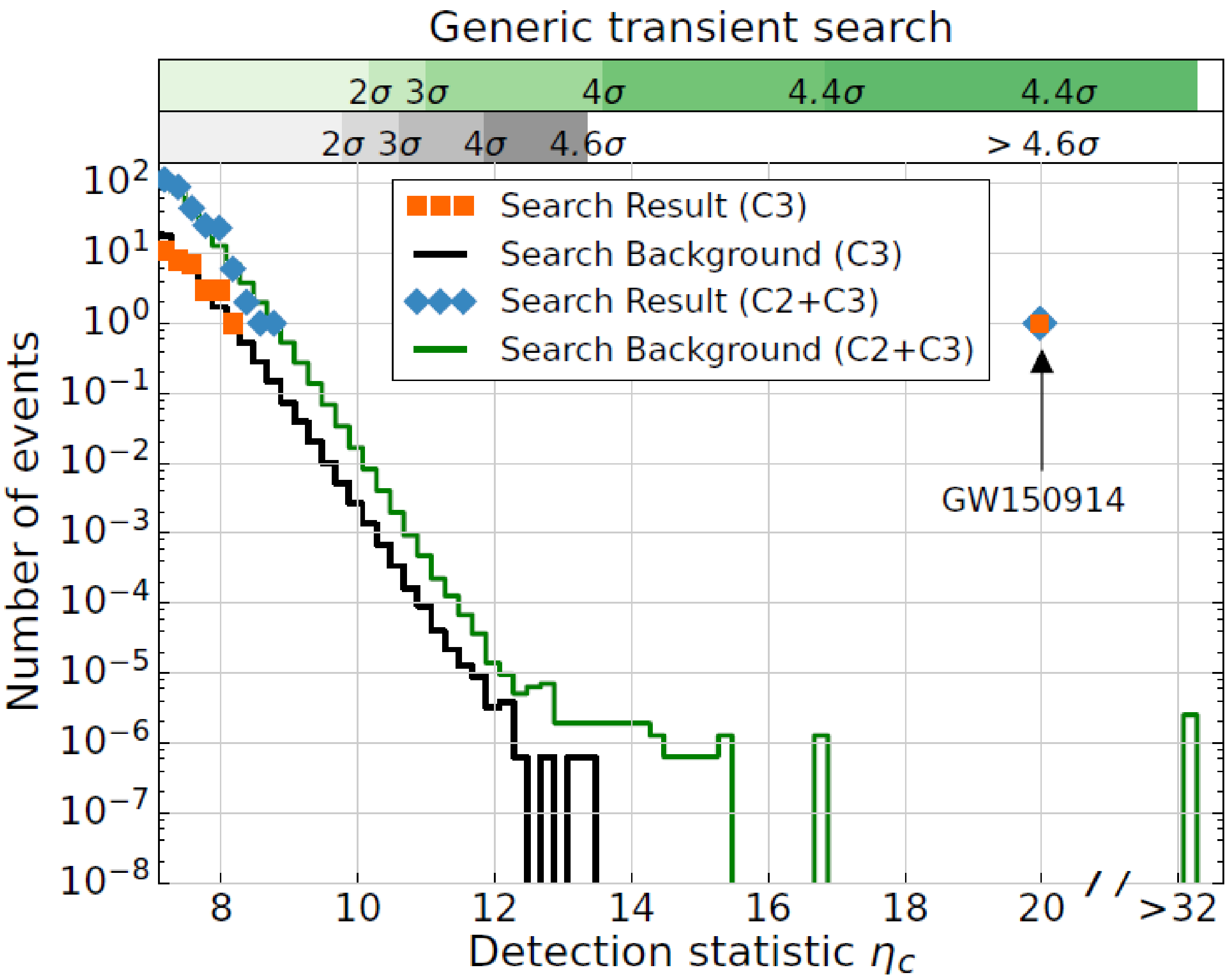
Transient Event Searches (2)

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 $> 4.6\ \sigma$

Observation of Gravitational Waves from a Binary Black Hole Merger

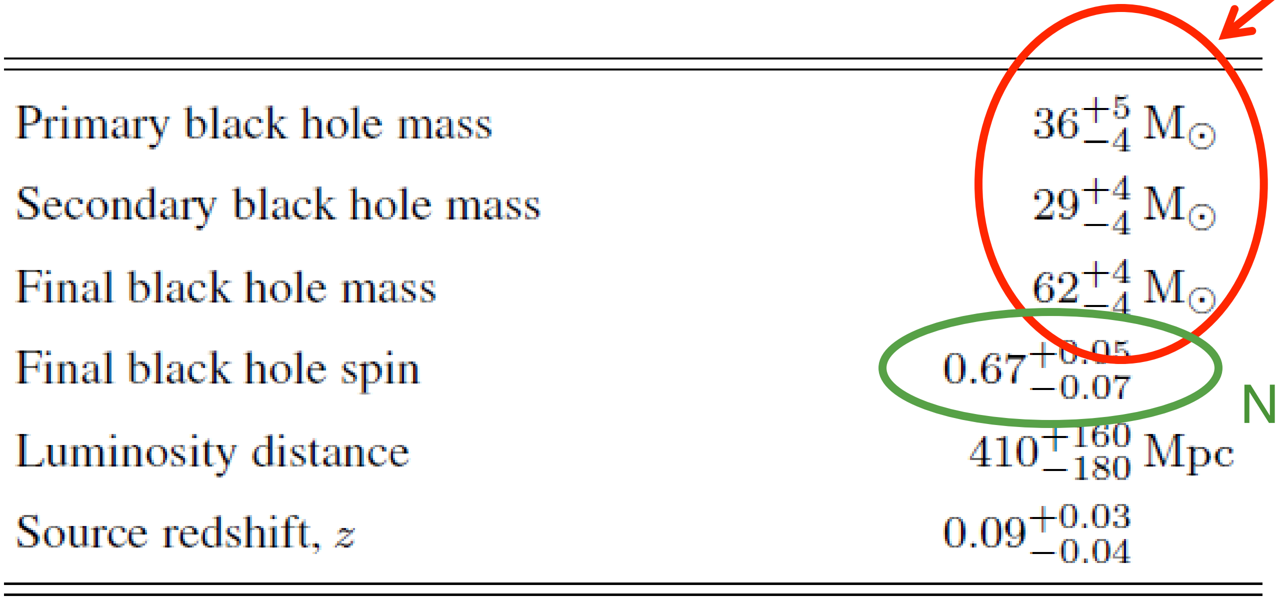
Statistical Significance of GW150914



Observation of Gravitational Waves from a Binary Black Hole Merger

Source Parameters for GW150914

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



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	$0.09^{+0.03}_{-0.04}$

$$36 + 29 \neq 62$$

Not maximal spin

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

Observation of Gravitational Waves from a Binary Black Hole Merger

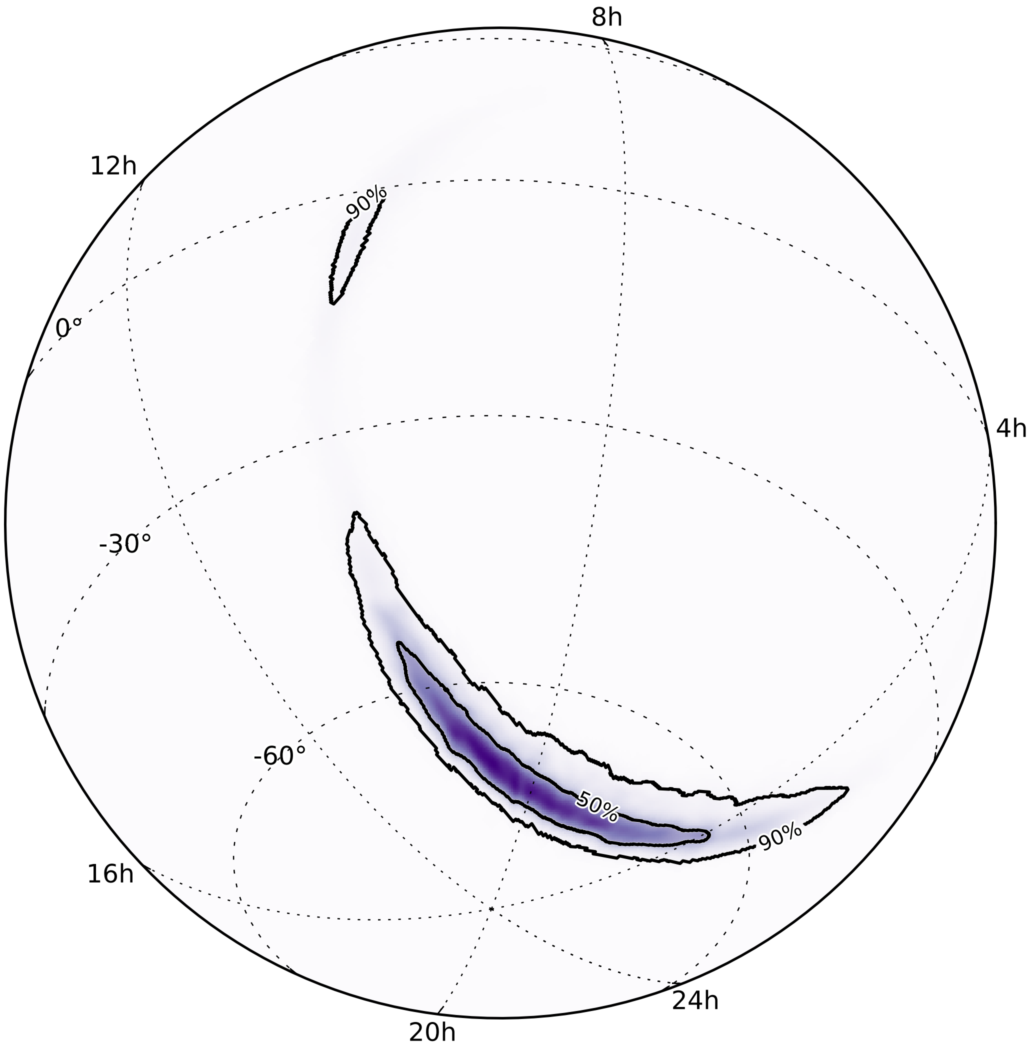
Testing General Relativity

- 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 $\rightarrow v/c \sim 0.6$
- 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

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



Observation of Gravitational Waves from a Binary Black Hole Merger

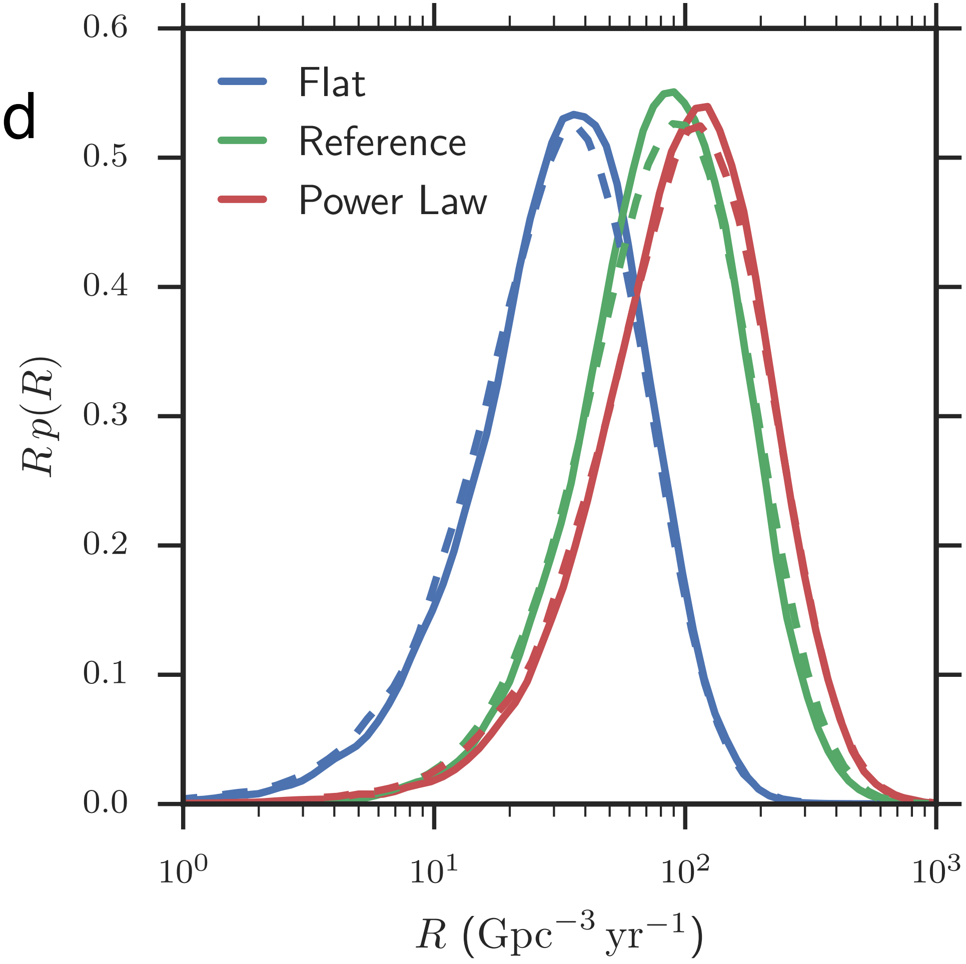
Rate estimates

- ☐ With only one event, can't measure rates accurately
- ☐ Rate estimates also depend upon astrophysical assumptions

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

Adding 2nd-loudest event*:
20–251 Gpc^{-3} yr^{-1}

Including all triggers:
6–400 Gpc^{-3} yr^{-1}



*$M_1 = 23 M_{\mathrm{Sun}}$ and $M_2 = 12\ M_{\mathrm{Sun}}$

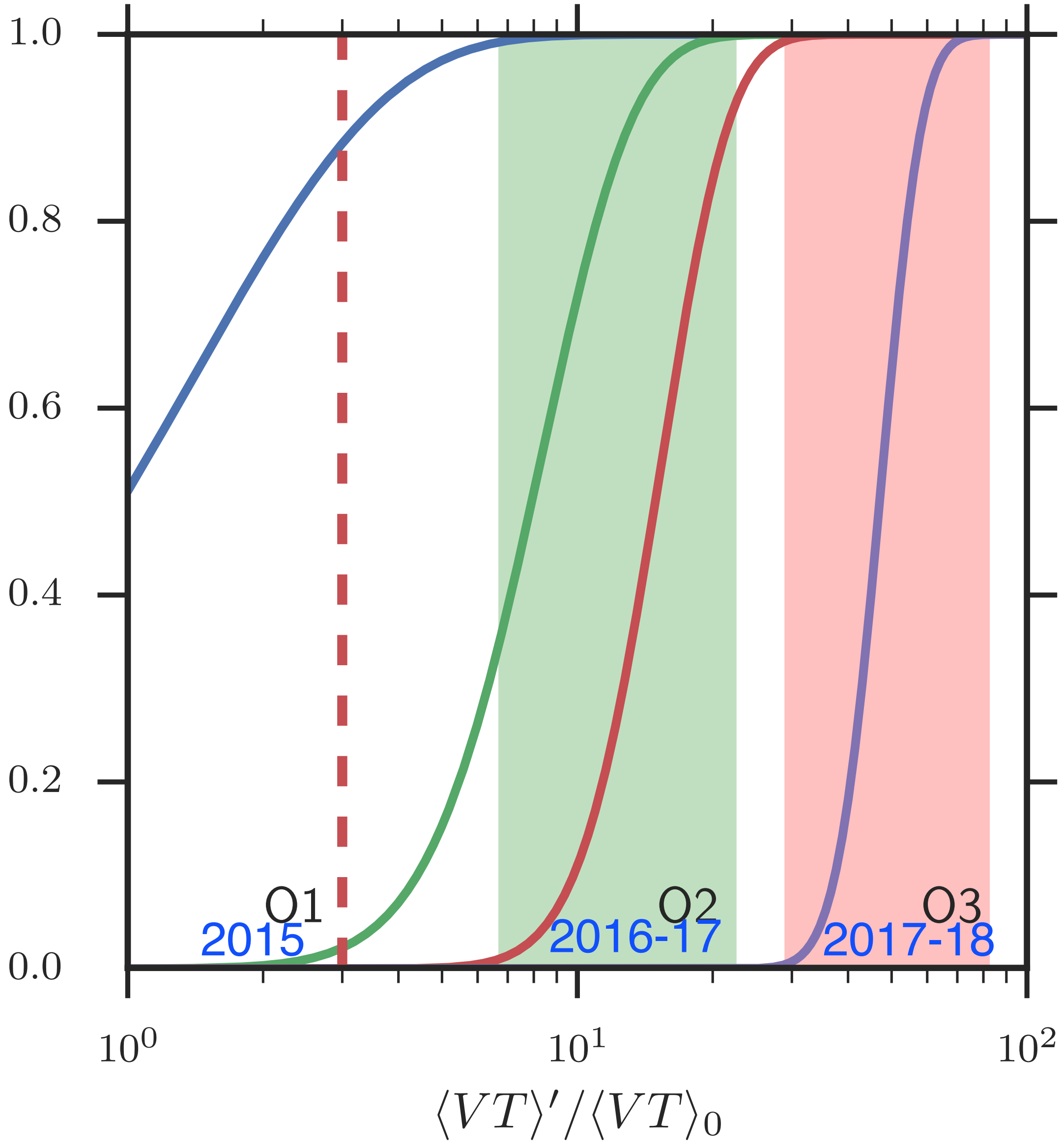
Observation of Gravitational Waves from a Binary Black Hole Merger

Expectations for future runs

Probability of observing

- ☐ N > 0 (blue)
- ☐ N > 5 (green)
- ☐ N > 10 (red)
- ☐ N > 35 (purple)

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



Potential Stochastic Background

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

Not detectable as individual signals

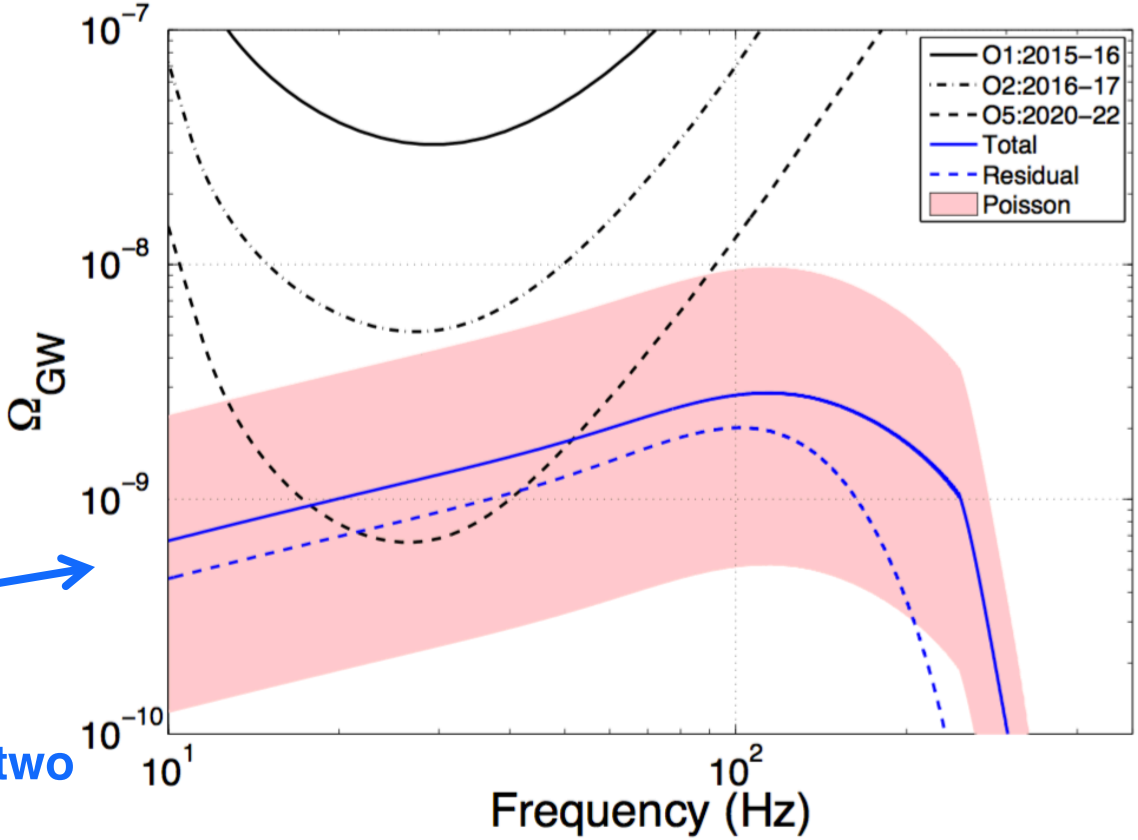
Potentially detectable as a correlated noise among detectors

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

GW energy density per log-frequency, normalized to the density ρ_c to close the Universe

Width of pink band due to BBH rate uncertainty →

→ **Will know more in a year or two**



Observation of Gravitational Waves from a Binary Black Hole Merger

Guide to companion papers

Detector and Performance

arXiv:1602.03838	GW150914: The Advanced LIGO Detectors in the Era of First Discoveries
arXiv:1602.03844	Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914
arXiv:1602.03845	Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914

Search Programs

arXiv:1602.03839	GW150914: First results from the search for binary black hole coalescence with Advanced LIGO
arXiv:1602.03843	Observing gravitational-wave transient GW150914 with minimal assumptions

Partner Observations

arXiv:1602.05411	High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with IceCube and ANTARES
(in preparation)	Localization and broadband follow-up of the gravitational-wave transient GW150914

Guide to companion papers (cont.)

Astrophysical Interpretation

ApJL, 818, L22, 2016	Astrophysical Implications of the Binary Black-Hole Merger GW150914
arXiv:1602.03840	Properties of the binary black hole merger GW150914
arXiv:1602.03841	Tests of general relativity with GW150914
arXiv:1602.03842	The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914
arXiv:1602.03847	GW150914: Implications for the stochastic gravitational-wave background from binary black holes

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

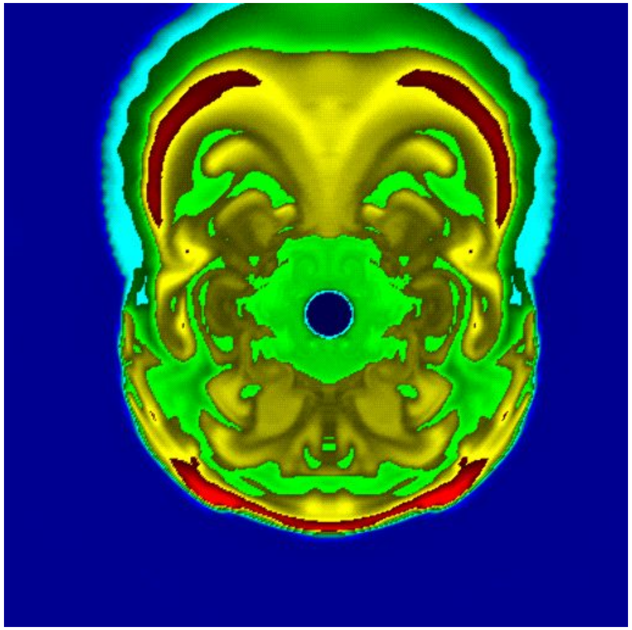
→ Will probably need good SNR at high frequencies to see effects

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

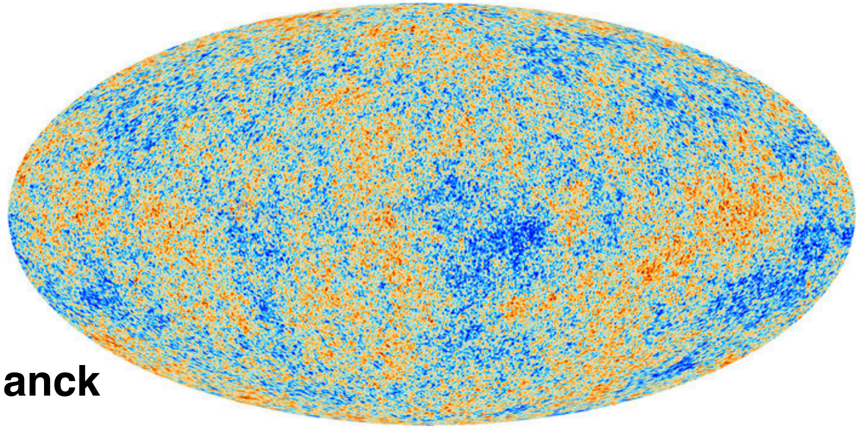
→ Gravitational waves would give view of core collapse itself



Courtesy: Dr. Tony Mezzacappa -- ORNL

Outlook -- Other gravitational wave sources?

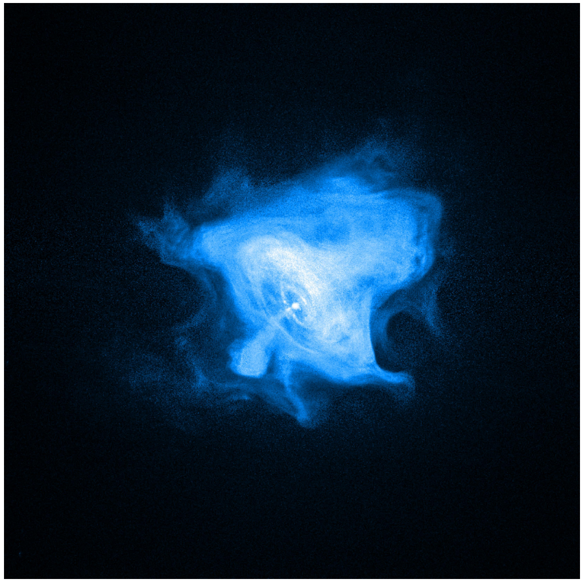
The Big Bang may have produced residual gravitational waves strong enough to be detected on Earth (but not likely)



Planck

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

→ Focus of Michigan group's searches



Chandra view of Crab Pulsar

Summary

- LIGO has observed gravitational waves from the merger of two stellar mass black holes

- The detected waveforms match the prediction of general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting black hole.

- **This observation is the first direct detection of gravitational waves and the first observation of a binary black hole merger.**

February 11, 2016 Discovery Announcement