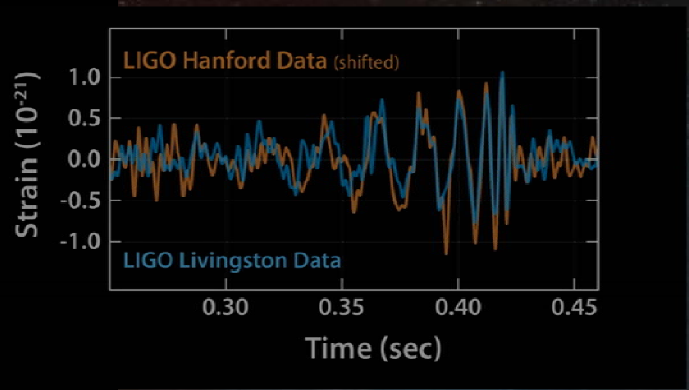
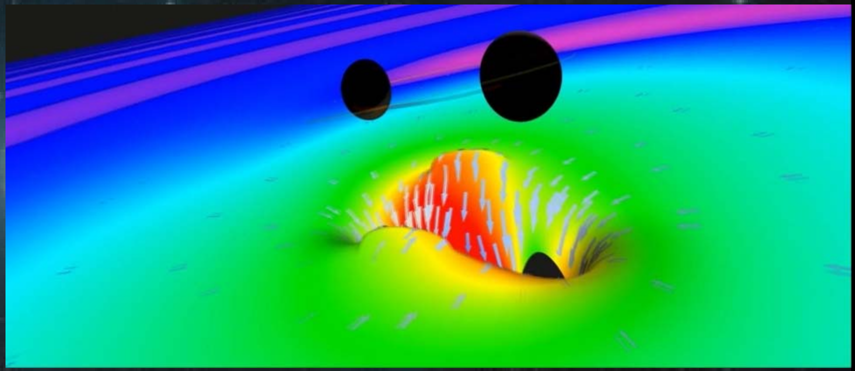
Gravitational waves

A New Era in Astrophysics

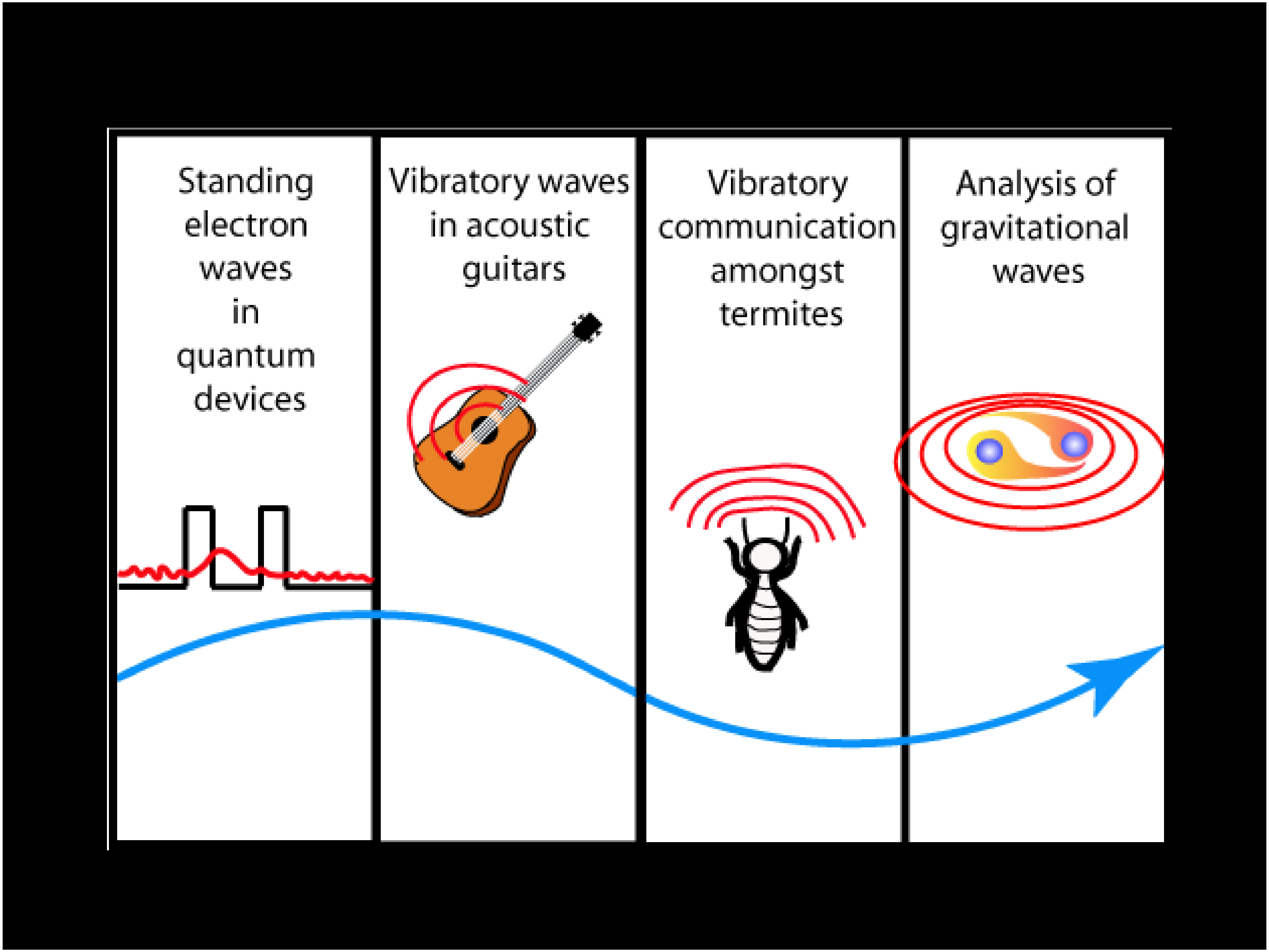




Ra Inta
Texas Tech University

LIGO Document G1600336-v2

University of Victoria, Physics and Astronomy colloquium, 8 March 2016


Standing electron waves in quantum devices
Vibratory waves in acoustic guitars
Vibratory communication amongst termites
Analysis of gravitational waves

First Direct Detection of Gravitational Waves!

Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

I. INTRODUCTION

In 1916, the year after the final formulation of the field equations of general relativity, Albert Einstein predicted

The discovery of the binary pulsar system PSR B1913+16 by Hulse and Taylor [20] and subsequent observations of its energy loss by Taylor and Weisberg [21] demonstrated

Overview

- History/basics of gravitational waves (GWs)
- The LIGO project
- How GWs are observed
- GW150914: ‘The Event’
- The future of GW astrophysics

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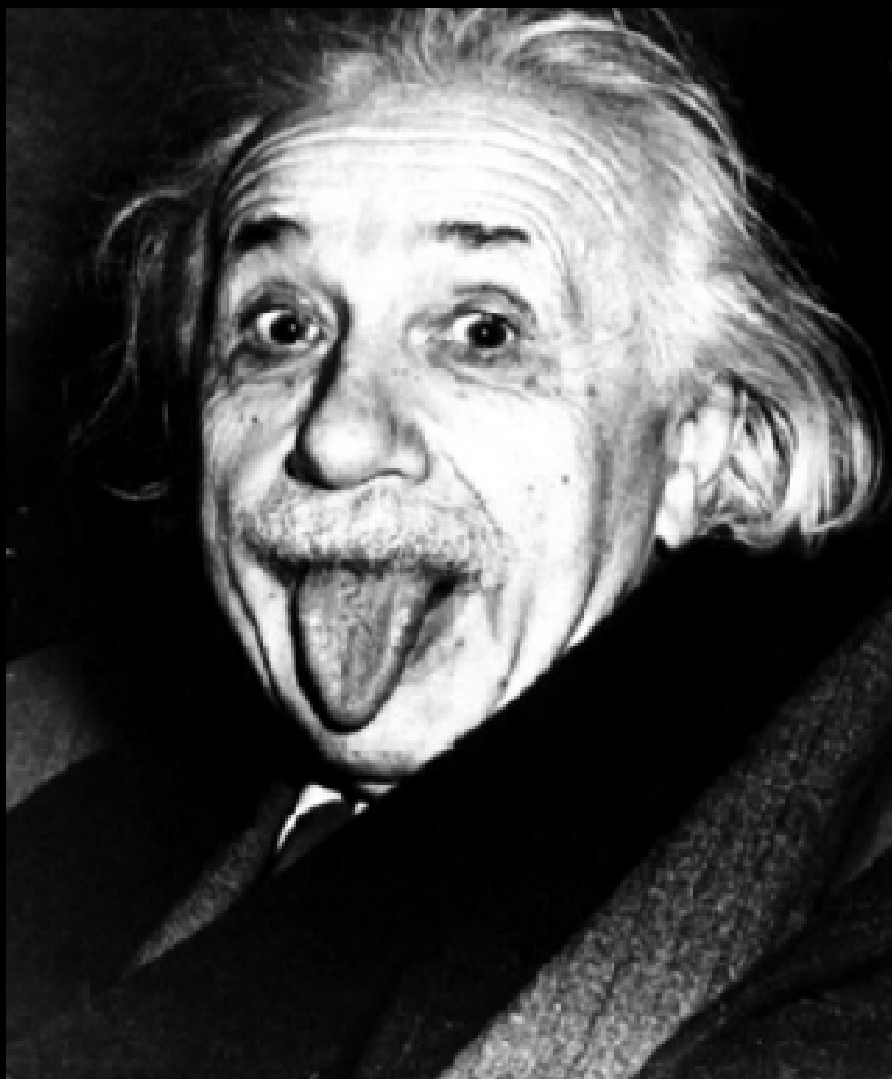
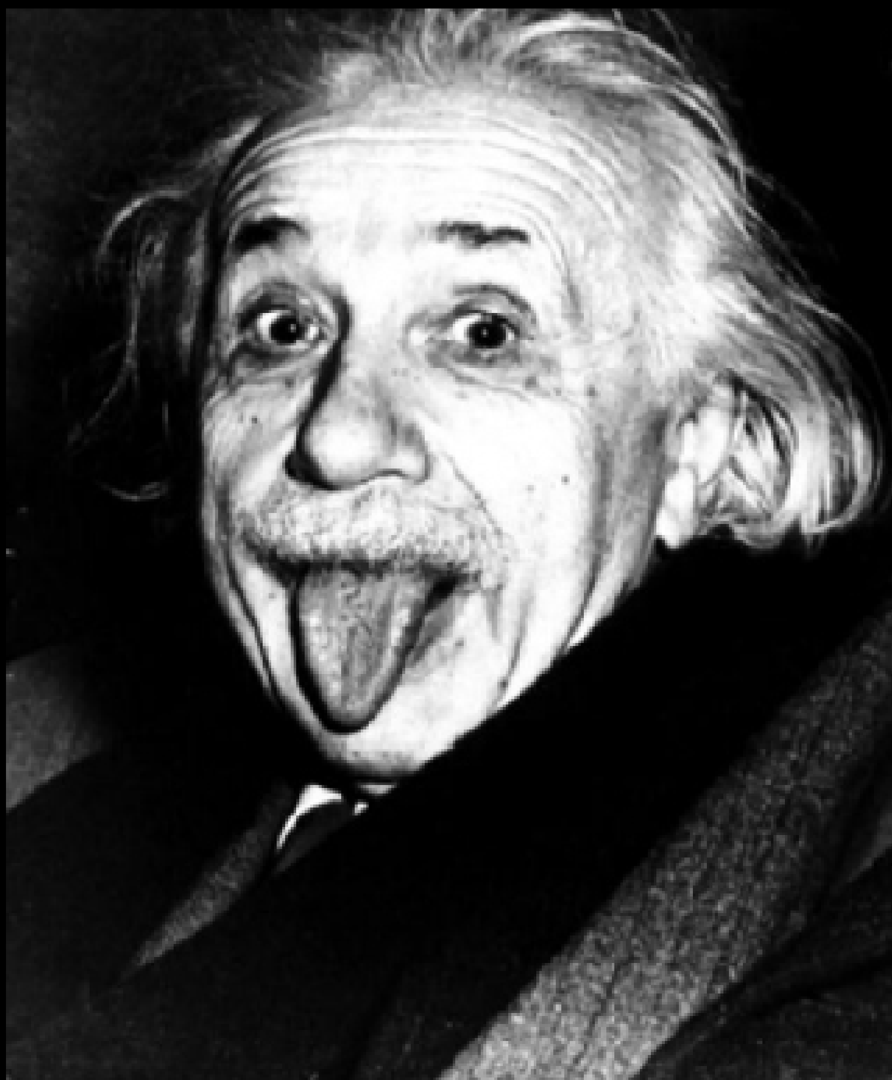
History of Gravitational Waves (GWs)



Einstein, A.: *Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften (Berlin)* **1**, 688 (1916)

History of Gravitational Waves (GWs)



Einstein, A. and Rosen, N.:"On Gravitational Waves," *J. Franklin Institute* **223**, pp.43-54 (1937)

(search for: "who's afraid of the referee?")

Linearised general relativity

Take small perturbations, **h**, of the space-time metric:

$$g_{\mu\upsilon} = \eta_{\mu\upsilon} + h_{\mu\upsilon} \qquad \left\| h_{\mu\upsilon} \right\| << 1$$

Put into the Einstein Field Equations:

$$G_{\mu\upsilon} = \frac{8\pi G}{c^4} T_{\mu\upsilon}$$

Get a wave-equation (in transverse-traceless gauge):

$$\triangleleft\, \bar{h}_{\mu\upsilon} = -16\pi G T_{\mu\upsilon}$$

Linearised general relativity

Vacuum solution $\triangleleft \bar{h}_{\mu\upsilon} = 0$

Admits plane waves: $\bar{h}_{\mu\upsilon} = A_{\mu\upsilon} \exp(ik_\sigma x^\sigma)$

So: $k_\sigma k^\sigma = 0$ (i.e. *k* is null)

Harmonic gauge: $A_{\mu\upsilon} k^\mu = 0$ (Transverse polarisation)

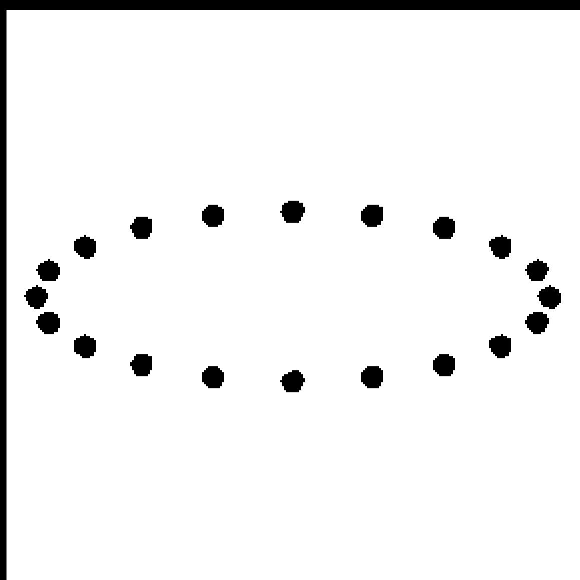
Linearised general relativity

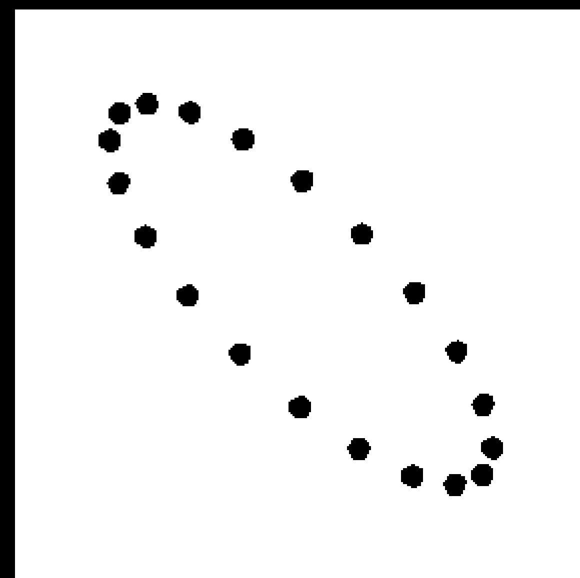
Two polarisation states:

Mass quadrupole: $$\bar{h}_{ij} = \frac{2G}{c^4 D} \ddot{I}_{ij}$$

Linearised general relativity

Two polarisation states:



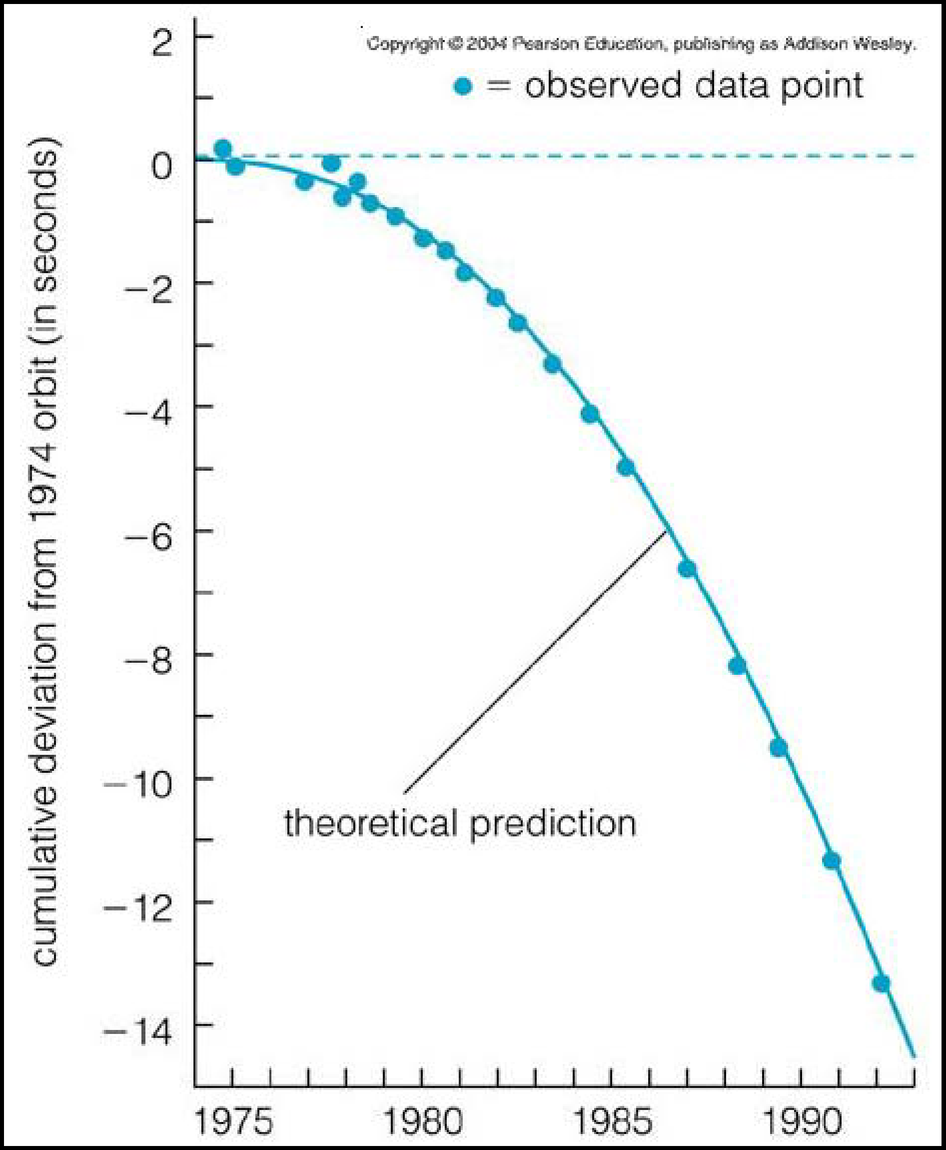


Mass quadrupole:

$$\bar{h}_{ij} = \frac{2G}{c^4 D} \ddot{I}_{ij}$$

Observations: Hulse, Taylor and Weisberg

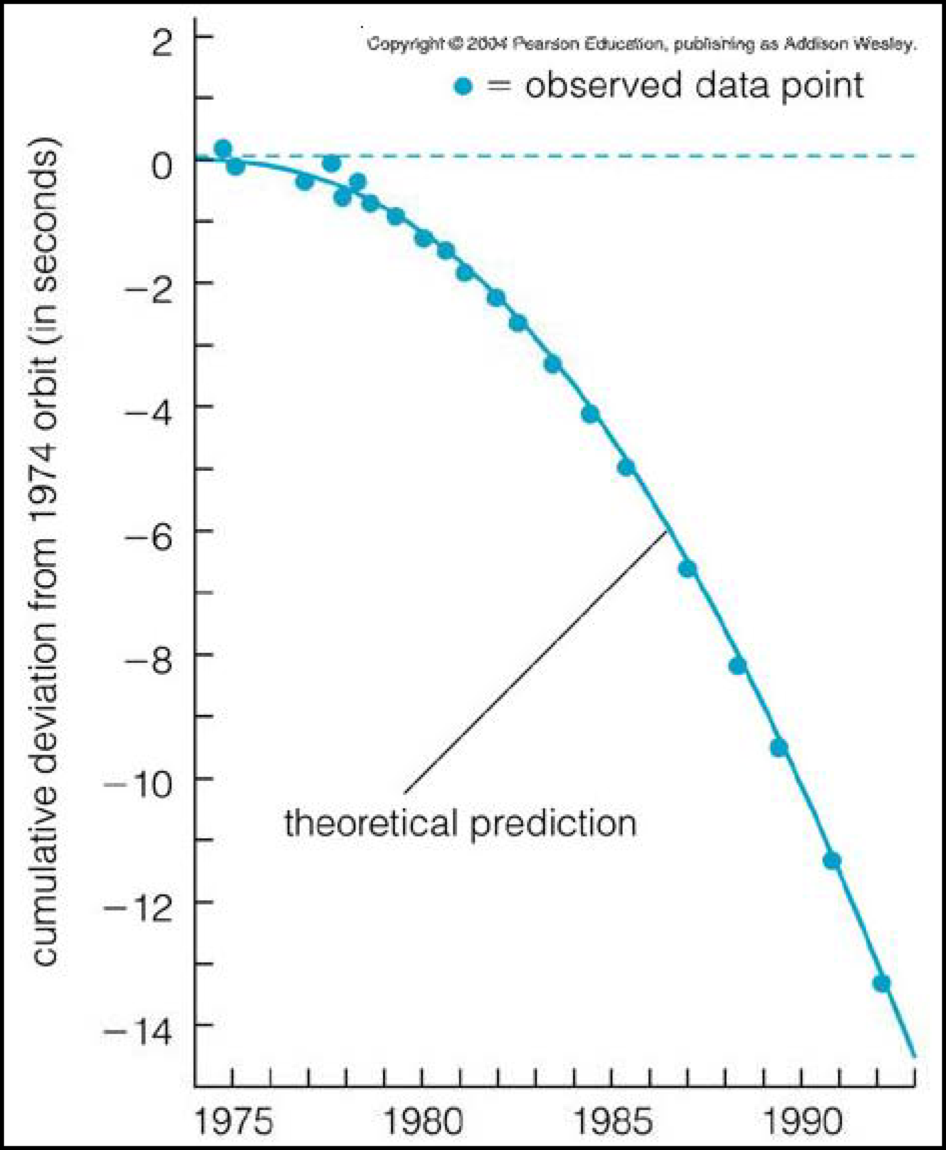
1974: Discovered binary pulsar



Observations: Hulse, Taylor and Weisberg

1974: Discovered binary pulsar

1993: Nobel prize



First direct test of GR in strong field regime

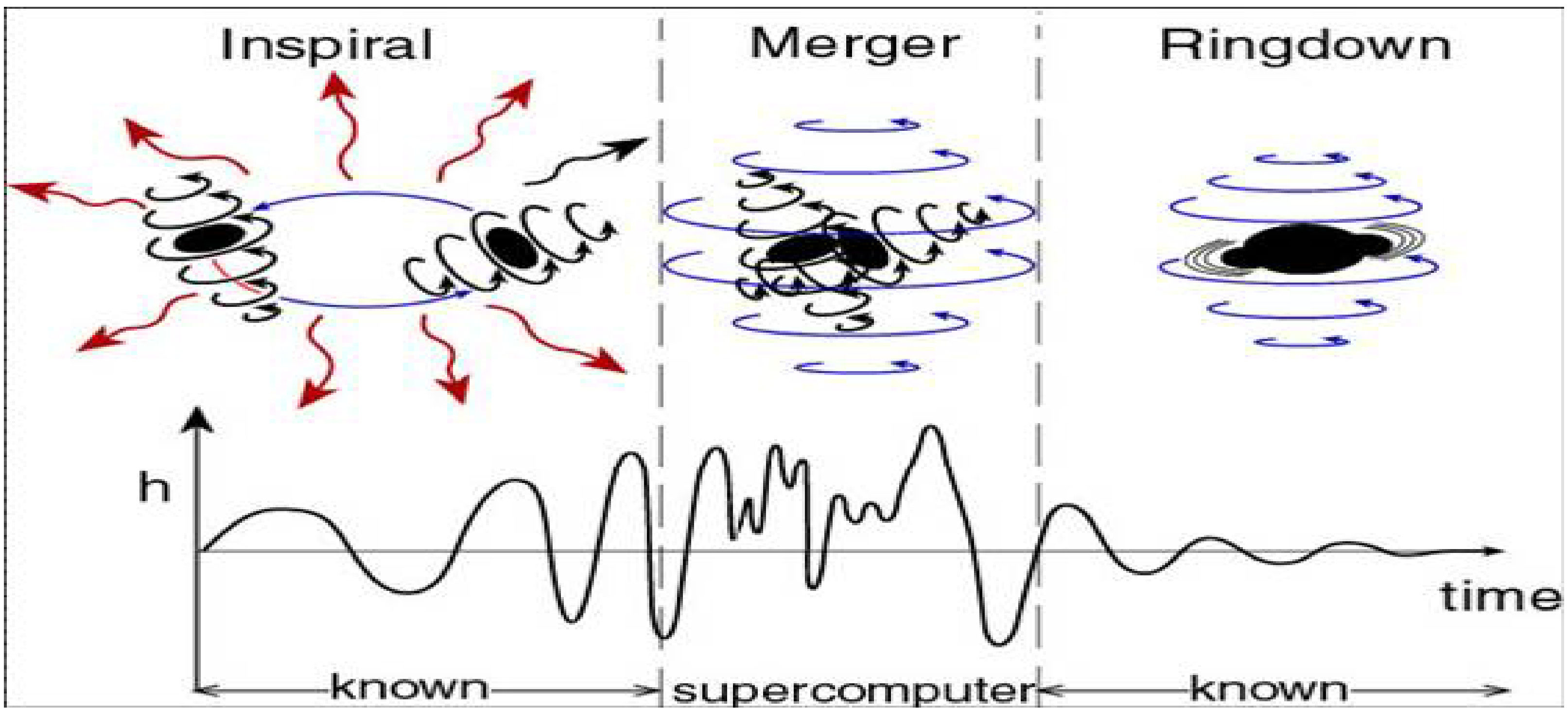
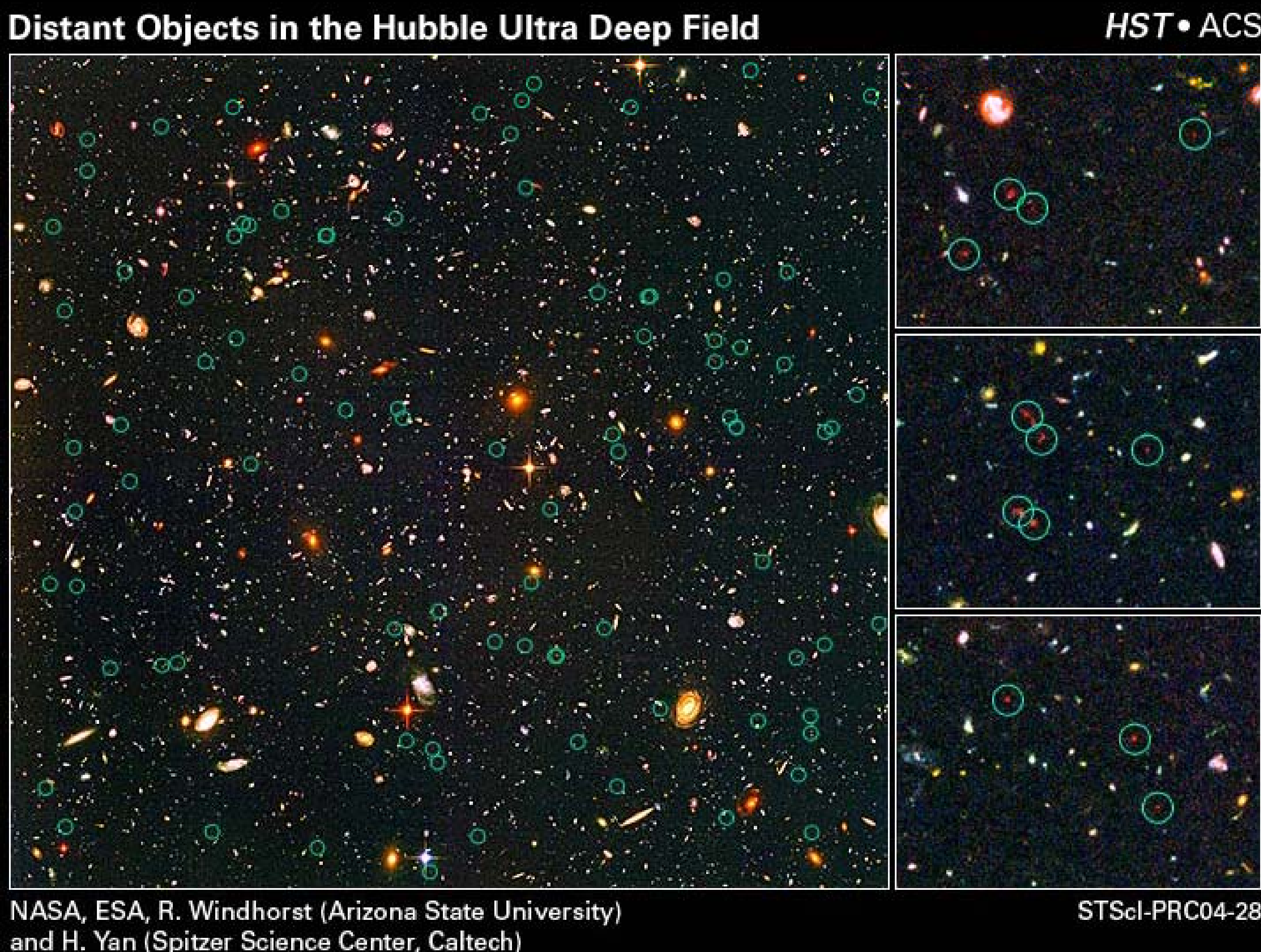


Image: Kip Thorne

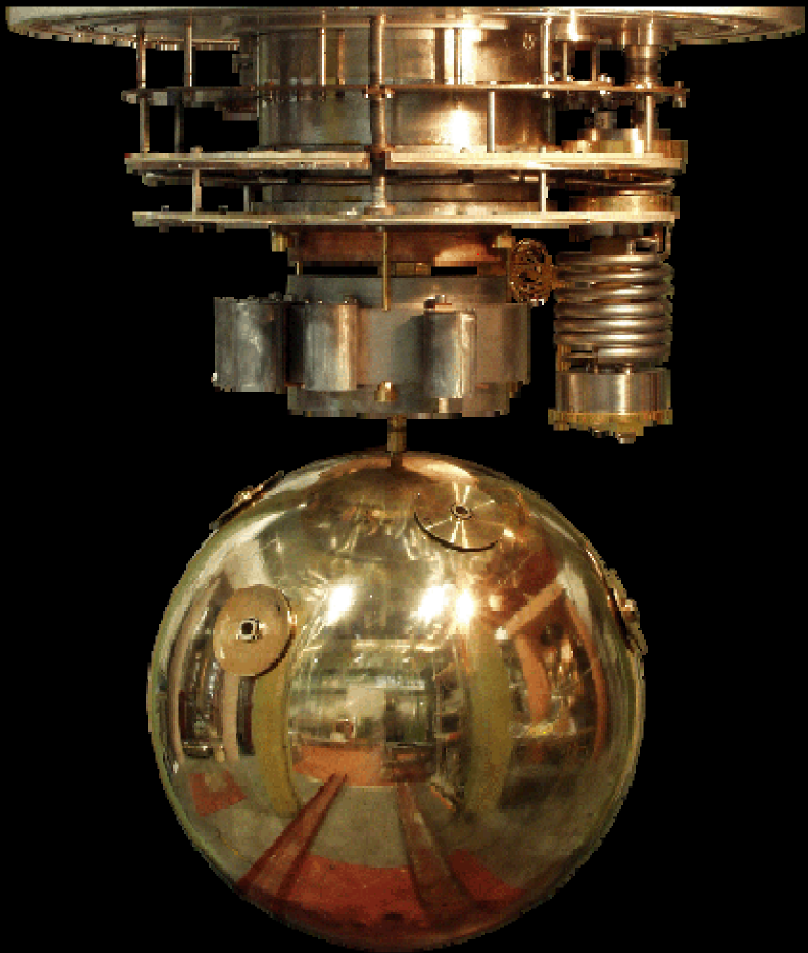
Completely new type of astronomy



Direct measurement

Has to be extremely sensitive in strain: $h_0 < O(10^{-21})$

Joseph Weber (ca. 1964)



Overview

- History/basics of gravitational waves (GWs)
- The LIGO project
- How GWs are observed
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- The future of GW astrophysics

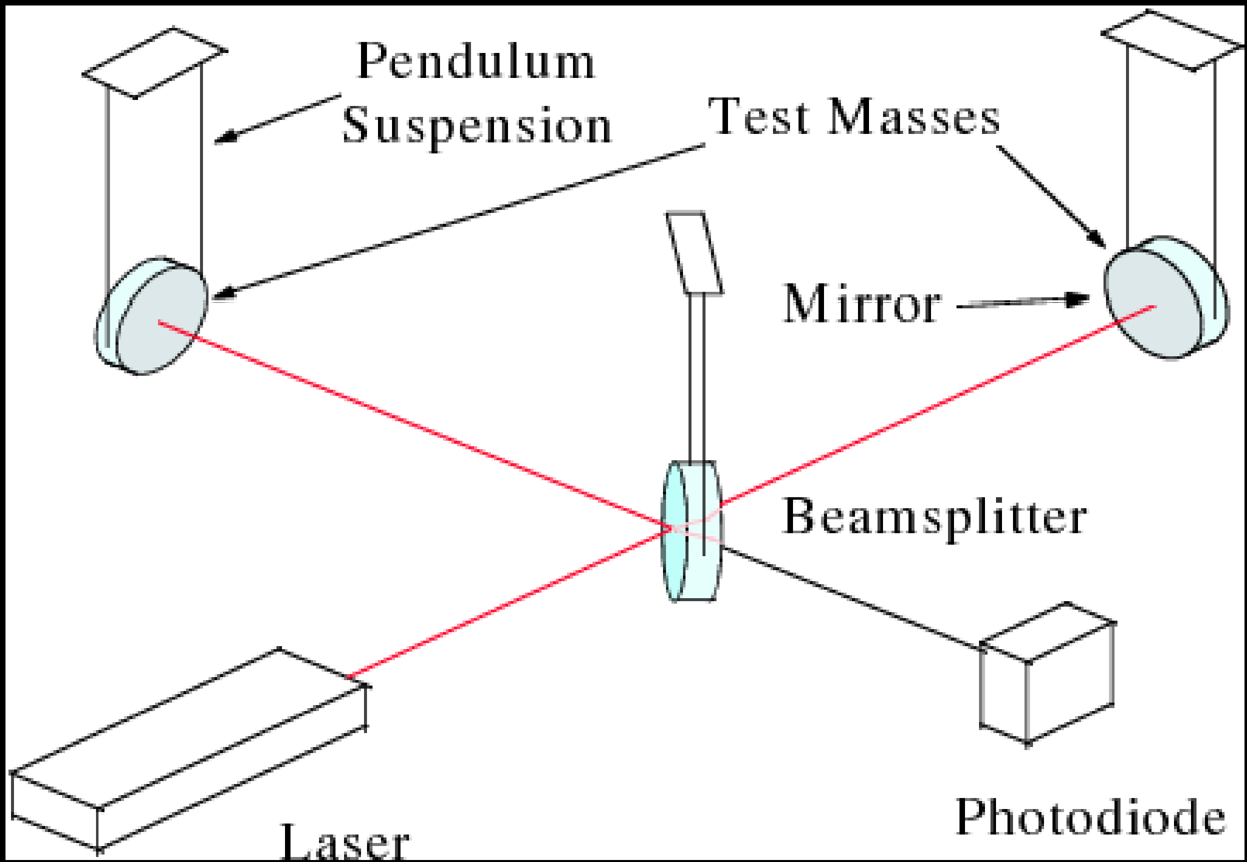
LIGO Scientific Collaboration

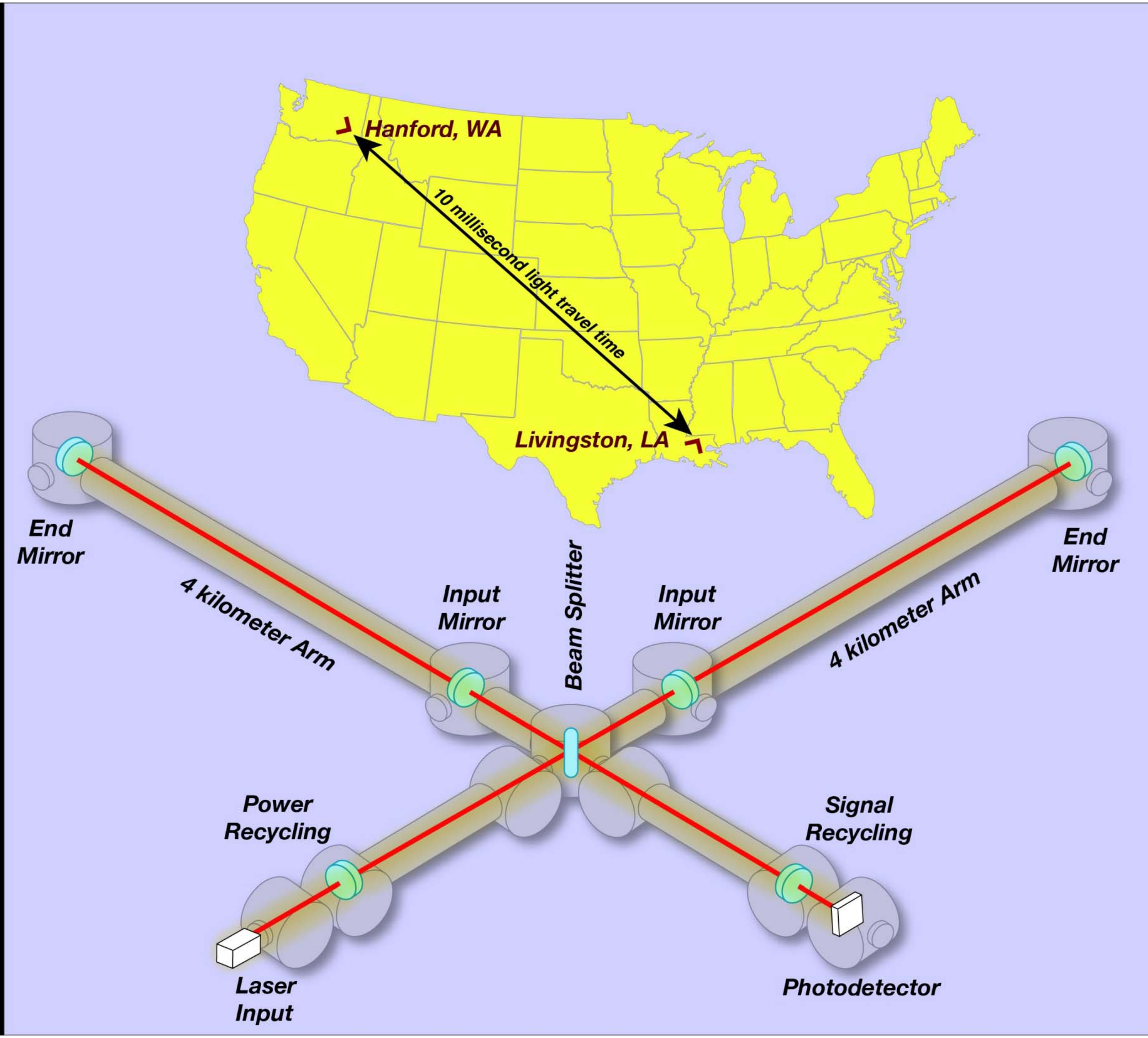
- Australian Consortium for Interferometric Gravitational Astronomy
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Sturt Univ.
- Columbia University
- CSU Fullerton
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland
- Max Planck Institute for Gravitational Physics
- University of Michigan
- University of Minnesota
- The University of Mississippi
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Tsinghua University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington

LASER interferometers

Michelson type: sensitive, broad-band

Non-directional (need a network to get position observations)





Credit: Shane Larson, Northwestern University

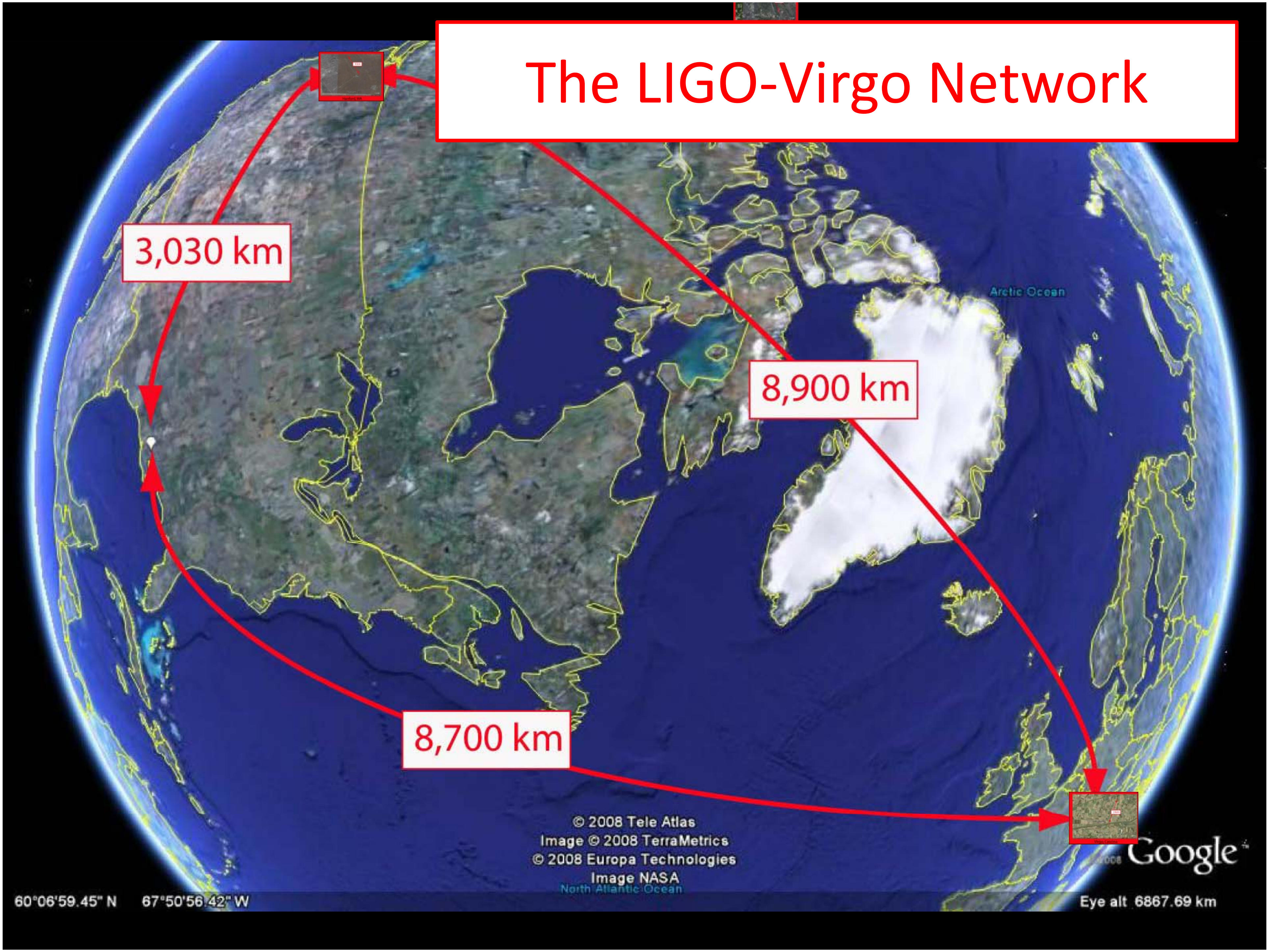
The LIGO Network

Hanford, WA

Livingston, LA

4 km baseline, seismic isolation

Hanford, WA
4 km
3,030 km
Livingston, LA
4 km
Canada
Saskatchewan
Manitoba
Montana
North Dakota
Minnesota
South Dakota
Wisconsin
Michigan
Toronto
Wyoming
Detroit
Chicago
Iowa
Nebraska
San Francisco
Nevada
Utah
Ohio
San Jose
California
Illinois
Indianapolis
Colorado
Missouri
Kentucky
Los Angeles
North Carolina
Tennessee
San Diego
Arizona
Phoenix
New Mexico
Arkansas
South Carolina
Georgia
Dallas
Texas
San Antonio
Gulf of California
Florida
Image © 2008 TerraMetrics
© 2008 Tele Atlas
Image NASA
© 2008 Europa Technologies
Google
39°30'35.12" N 98°59'49.96" W
Eye alt 3986.21 km


The LIGO-Virgo Network
3,030 km
8,900 km
8,700 km
Arctic Ocean
North Atlantic Ocean
© 2008 Tele Atlas
Image © 2008 TerraMetrics
© 2008 Europa Technologies
Image NASA
60°06'59.45" N
67°50'56.42" W
Eye alt 6867.69 km
Google

LIGO trivia

- Largest ultra-vacuum chamber in the world: one trillionth of an atmosphere (a few hundred times less than space near the International Space Station)
- Power bill to ‘bake’ LIGO: > US$1M
- Large quantum mechanical devices!
- Hanford is the location of two-thirds of the USA's high-level radioactive waste

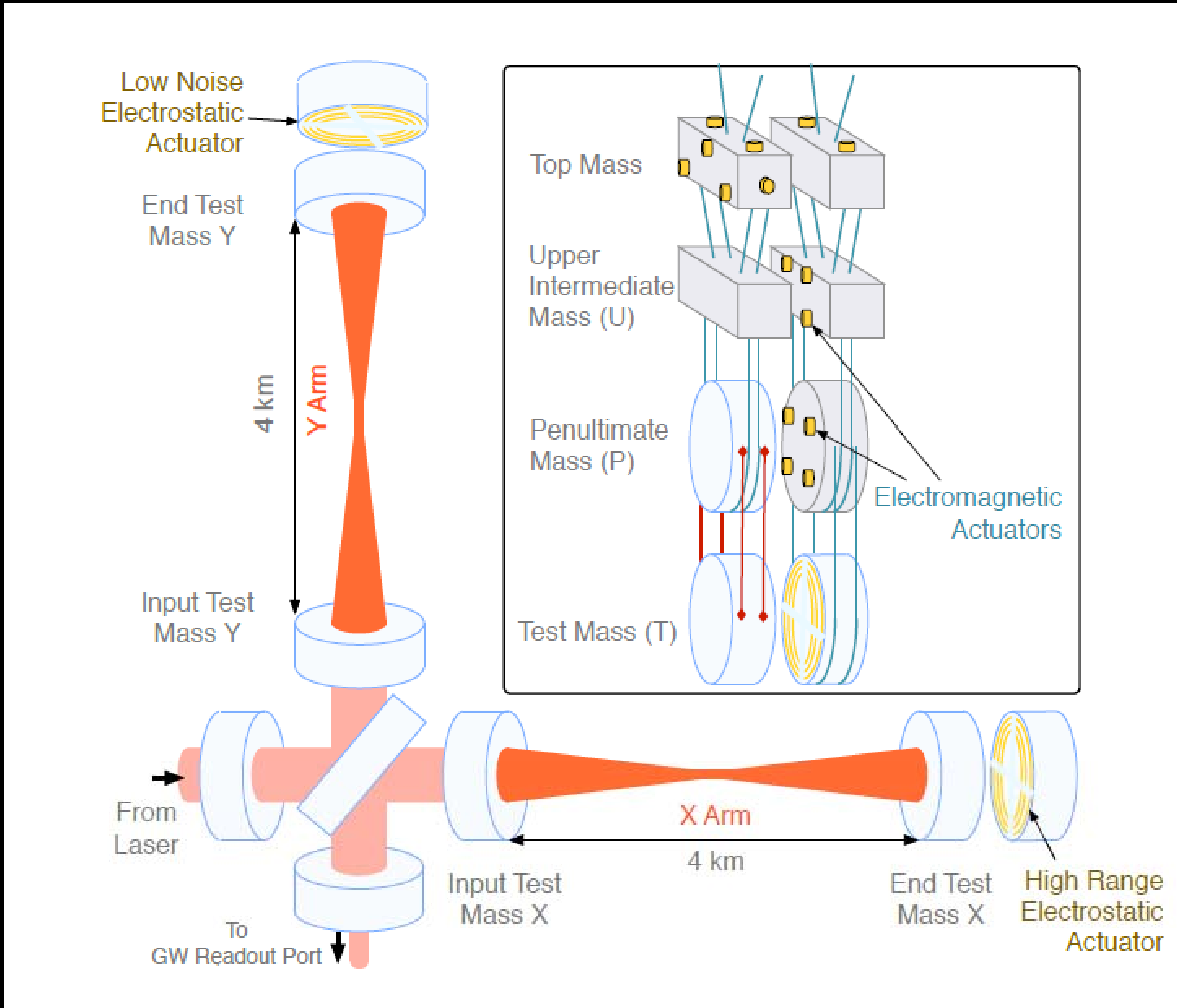

LOOSE TALK -
a chain reaction
for ESPIONAGE

Advanced LIGO

Upgraded from initial LIGO (2010); not yet to design sensitivity

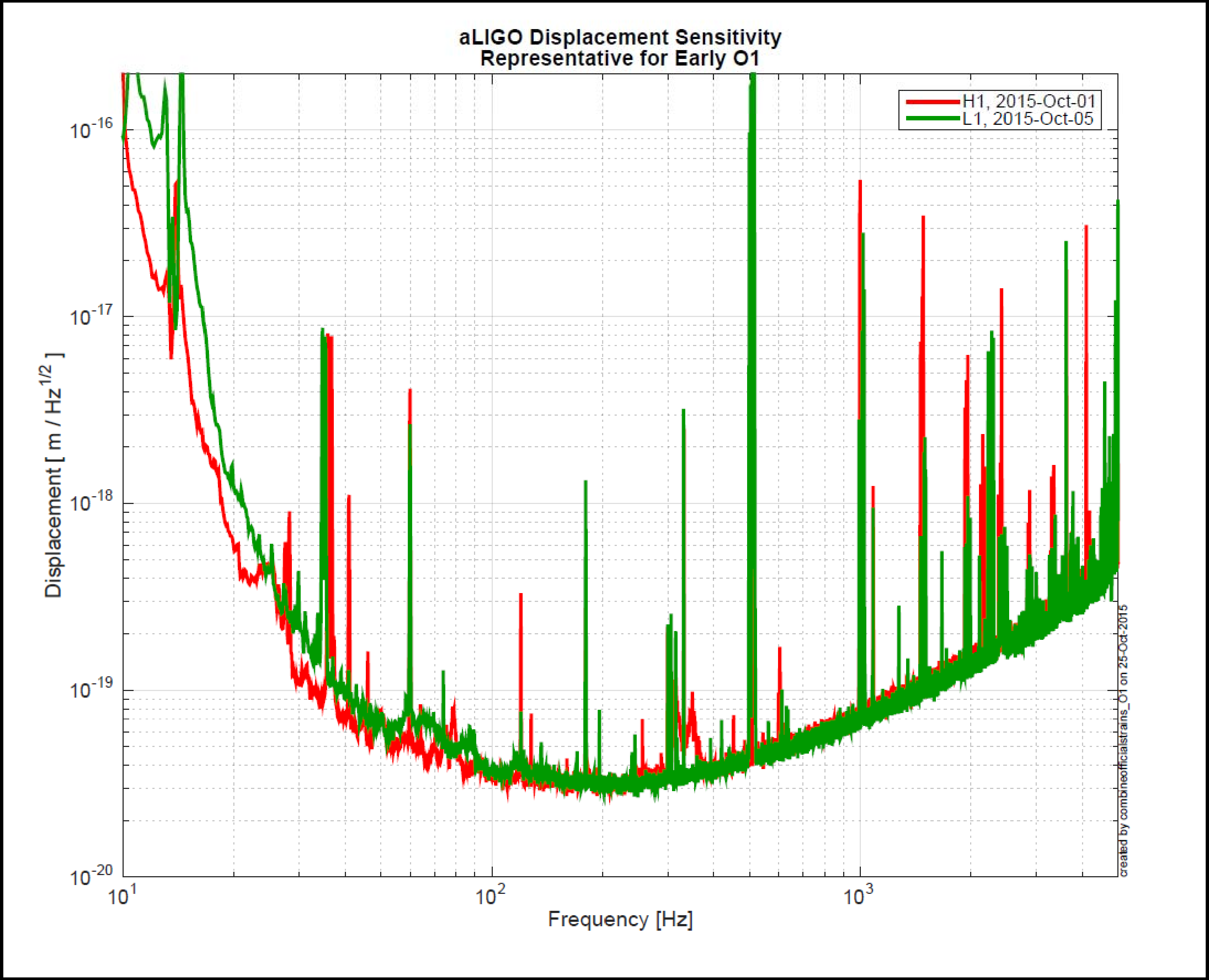
1. Optomechanics (mirrors larger and heavier, electrostatic actuation, suspension system vastly improved)
2. Higher input power (~200 W input)
3. Configuration changes (signal recycling, DC read-out)

Design: ~10 times more sensitive---relatively much better at low frequency



http://arxiv.org/abs/1602.03845


REFL



aLIGO Displacement Sensitivity
Representative for Early O1
H1, 2015-Oct-01
L1, 2015-Oct-05
Displacement [m / Hz^1/2]
10^-16
10^-17
10^-18
10^-19
10^-20
10^1
10^2
10^3
Frequency [Hz]
created by combineofficialstrains_O1 on 25-Oct-2015

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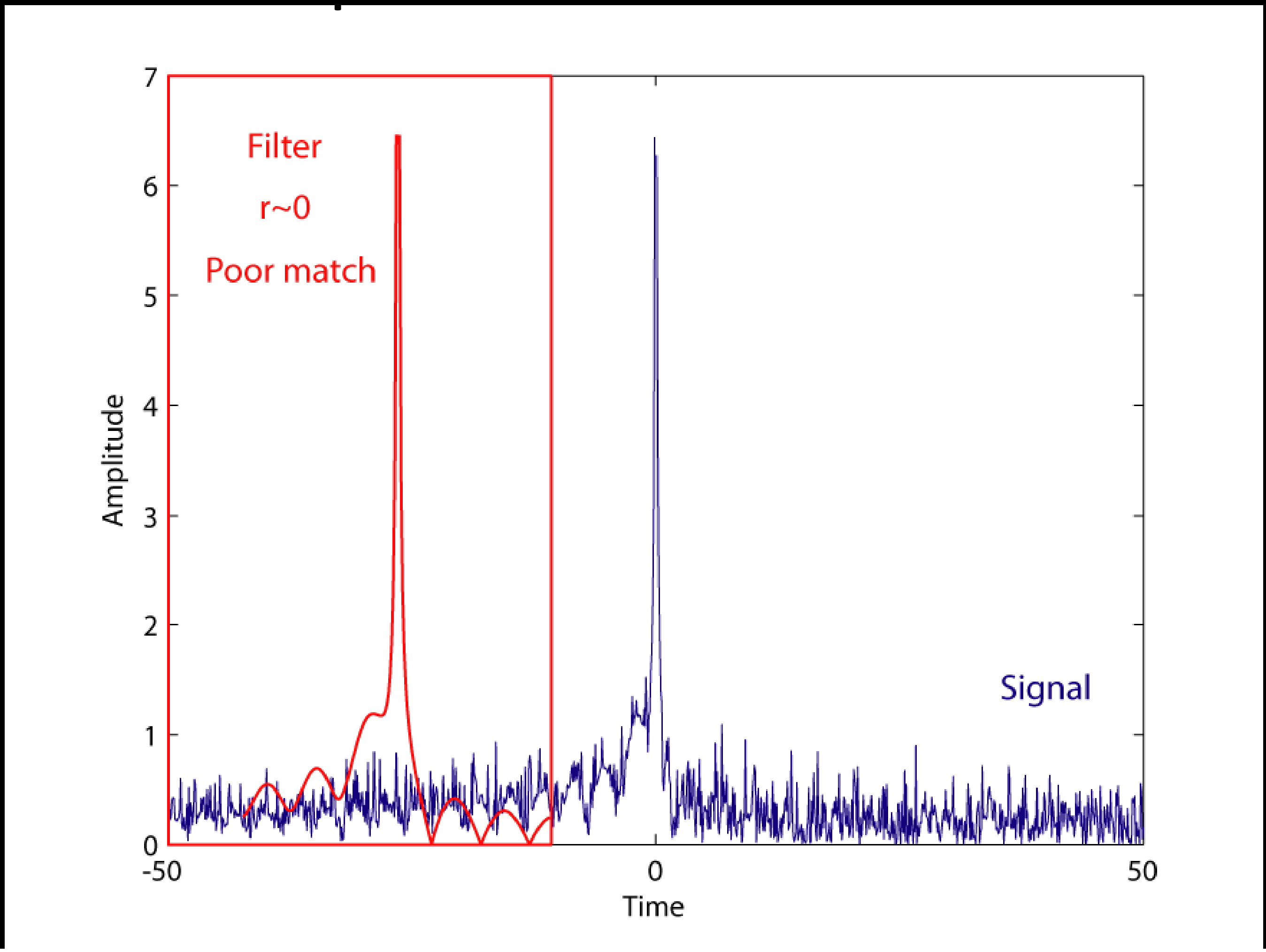
GW Search Types

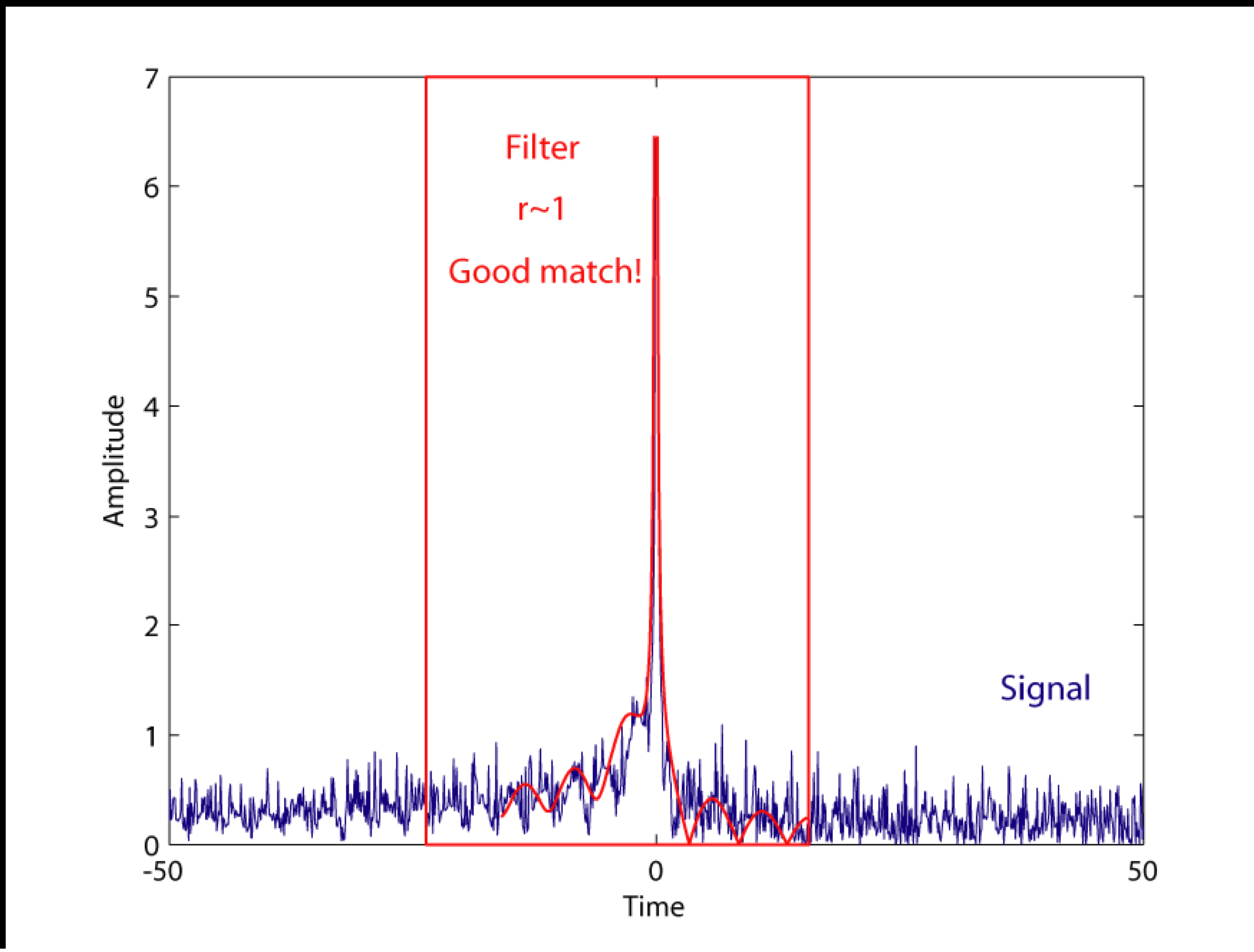
1. **Compact Binary Coalescence** (CBC; transient, modelled waveforms)
2. **Burst** (transient, unmodelled waveforms)
3. **Stochastic** (persistent, broadband waveforms)
4. **Continuous Wave** (persistent, narrow-band waveforms)

Feature detection

Matched filter

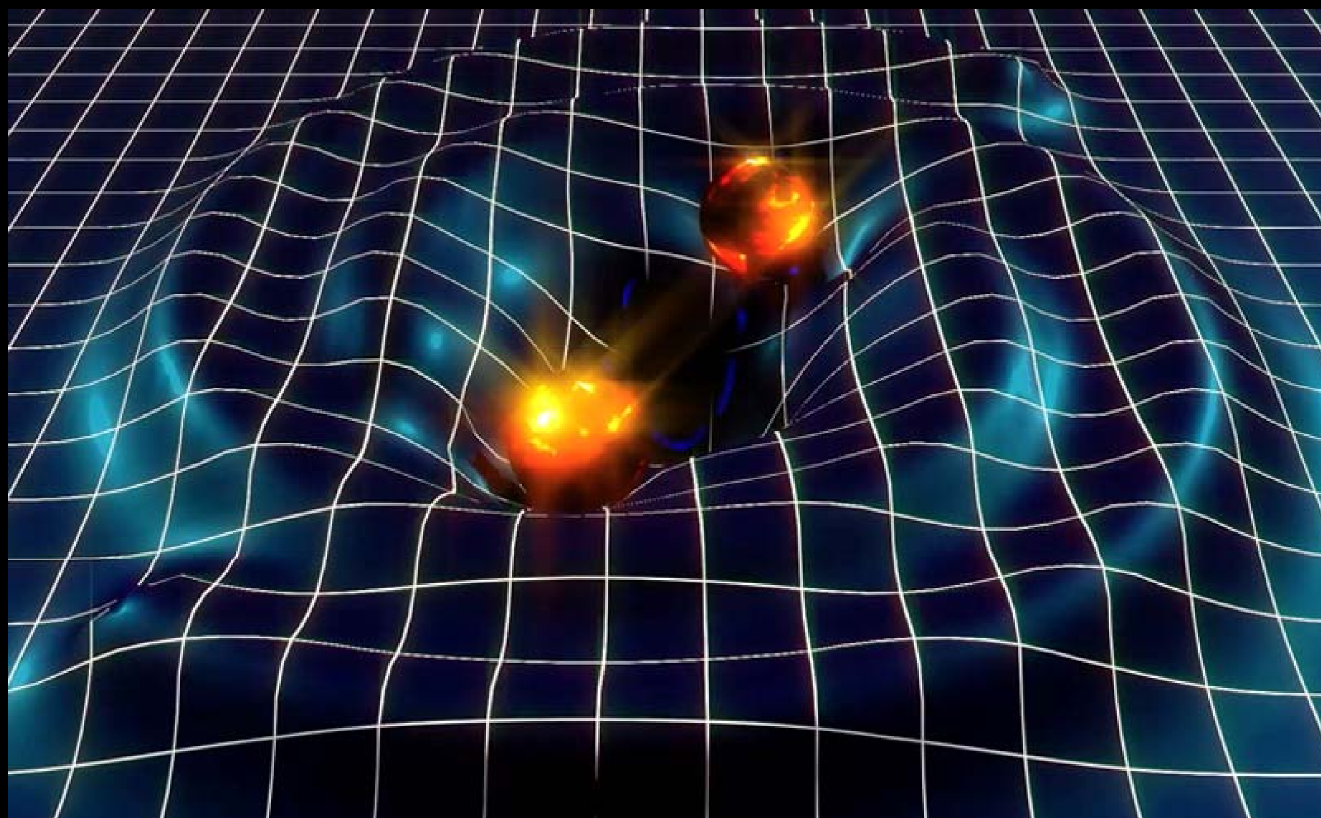


Matched filter



1: CBC

Historical GW source (what LIGO was built for!)



1: CBC

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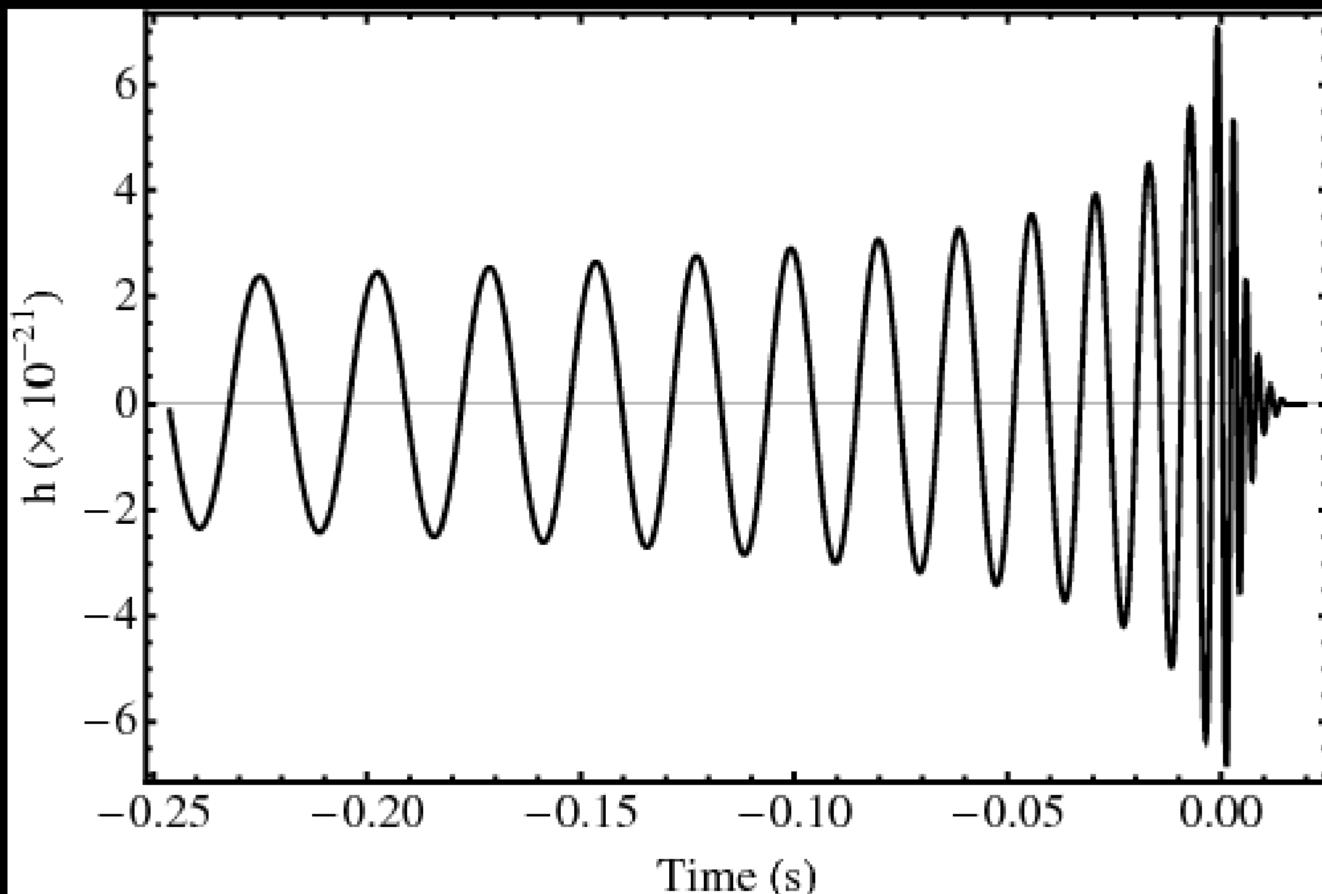


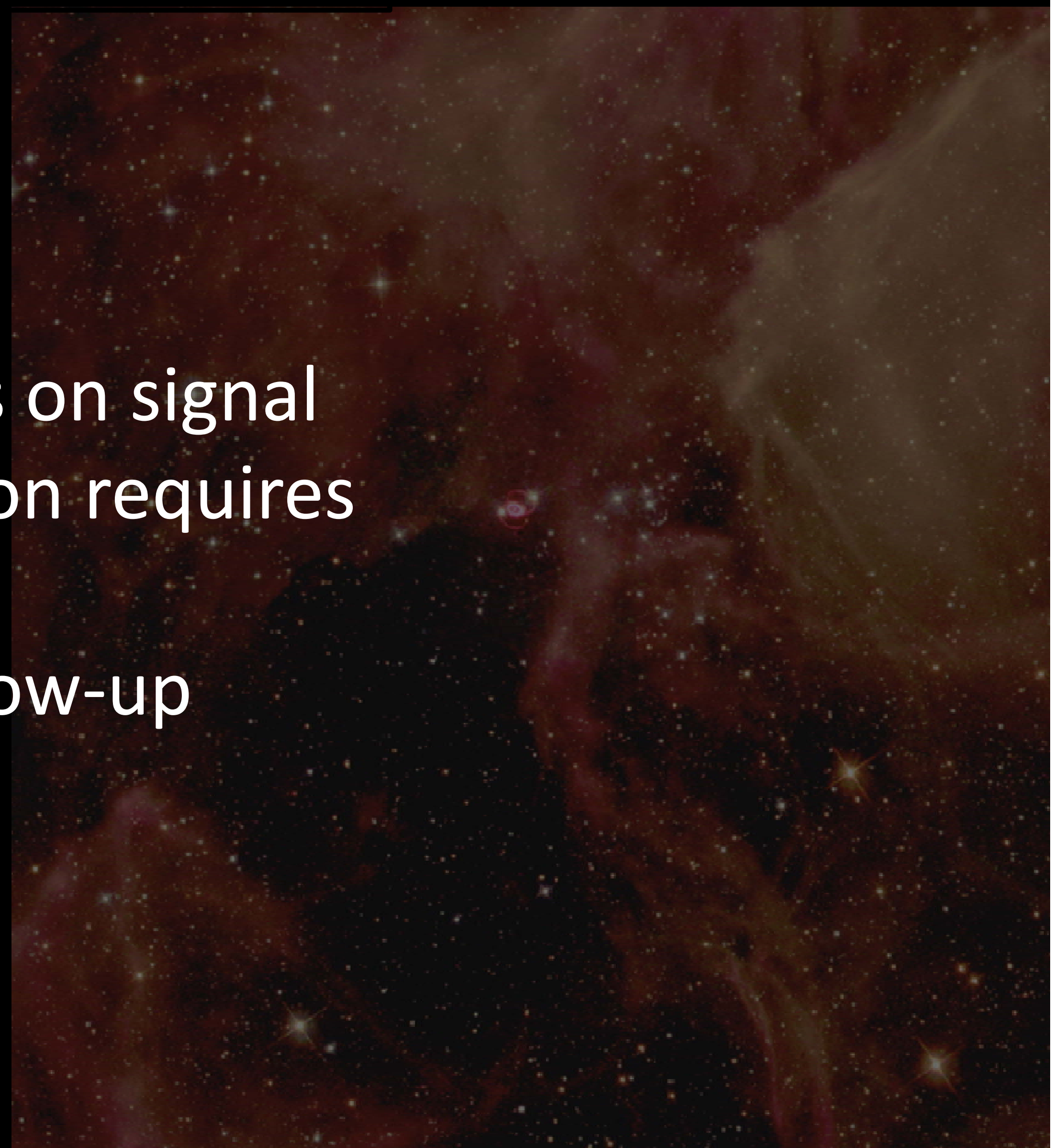
Image: Hannam, Mark *et al.*, *Phys.Rev. D* **79** (2009) 084025

Chirp mass

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

$$= \frac{c^3}{G}\left(\left(\tfrac{5}{96}\right)^3 \pi^{-8} f^{-11} \dot{f}^{3}\right)^{1/5}$$

2: Burst



- High $|h_0|$
- Minimal assumptions on signal
- Position reconstruction requires network
- Multi-messenger follow-up

Multi-messenger follow-up

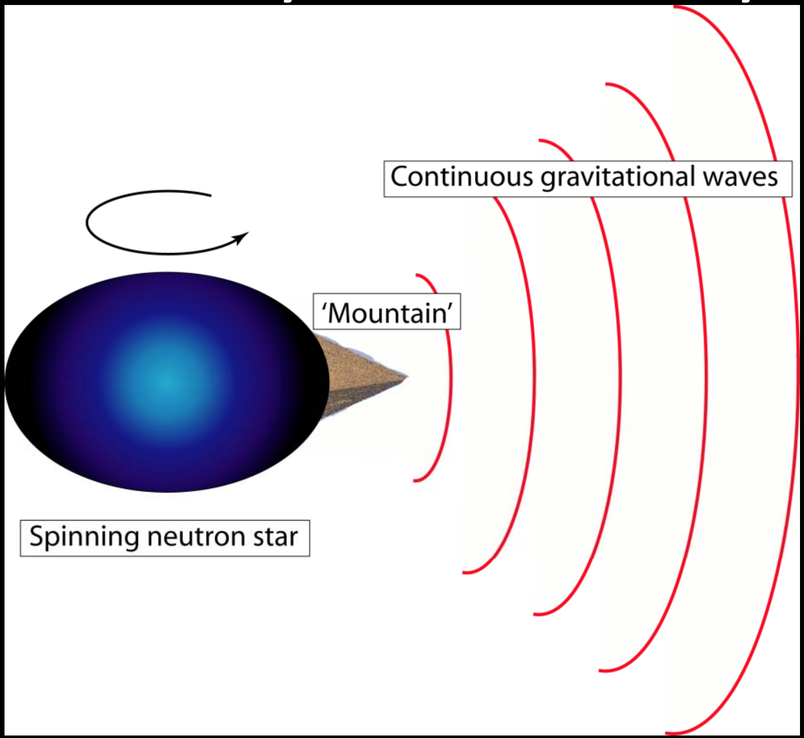
- Independent confirmation of GW burst event
- Send triggered alerts to observatories with wide fields
- MoU with a range of partners (incl. ANZSKAP/MWA, IceCube, SkyMapper)

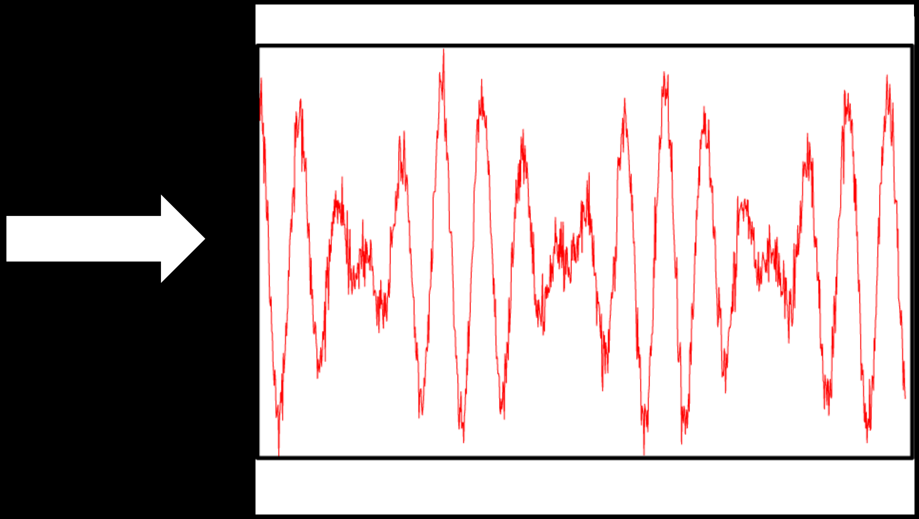
3: Stochastic

- GW background, cosmological and astrophysical in origin (strings, primordial GW events, unresolved sources)
- Cross-correlation between any two IFOs

4: Continuous wave

- Low h0, but can take long averages (glitches!). Δt ~ days-weeks-years(?)
- Rotating, non-axisymmetric neutron stars
- Physics relatively well understood



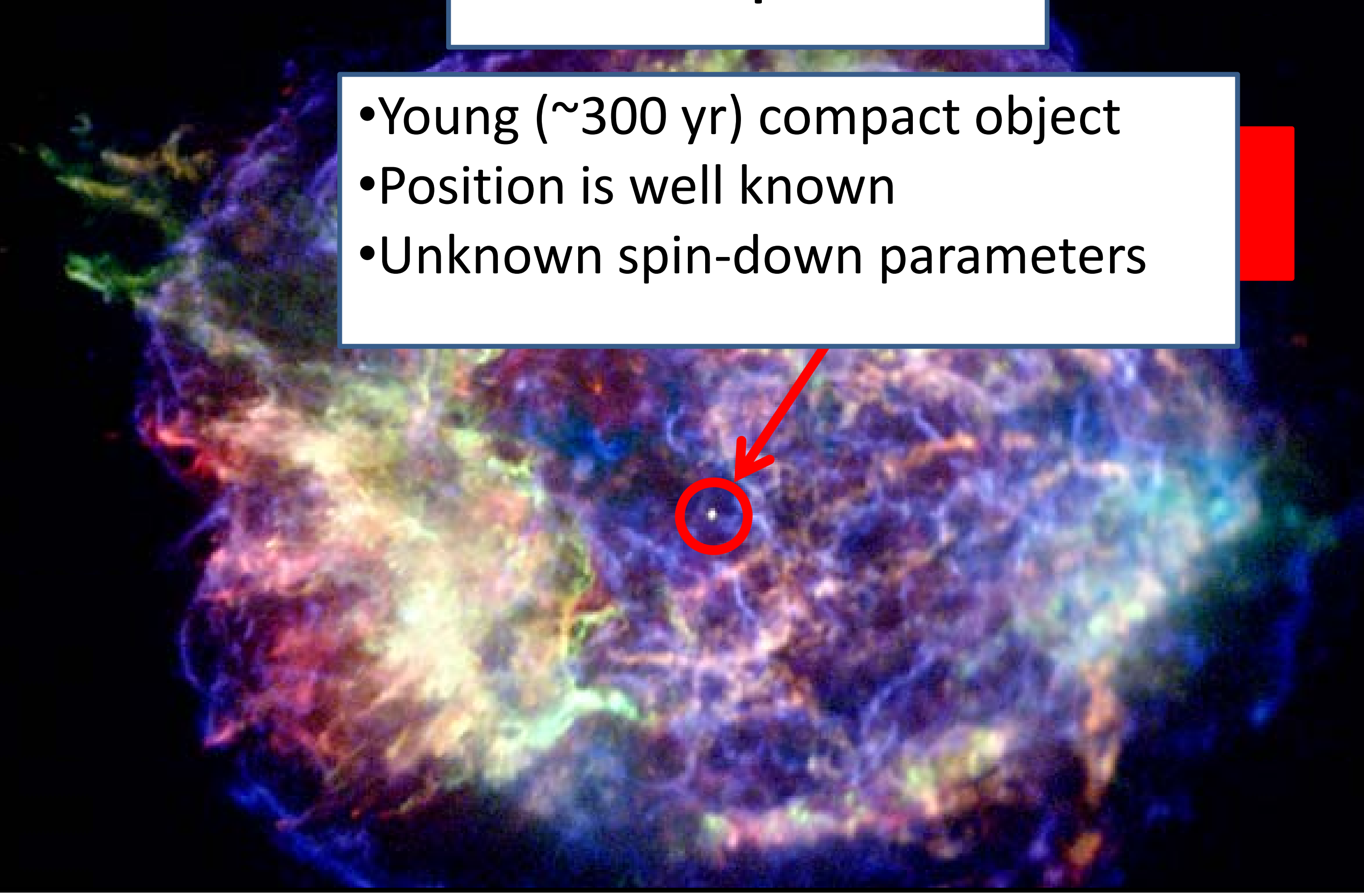


Directed searches

- Position known well (e.g. from x-ray data) but no periodic emission in EM
- Isolated non-pulsing neutron stars: compact objects in supernova remnants

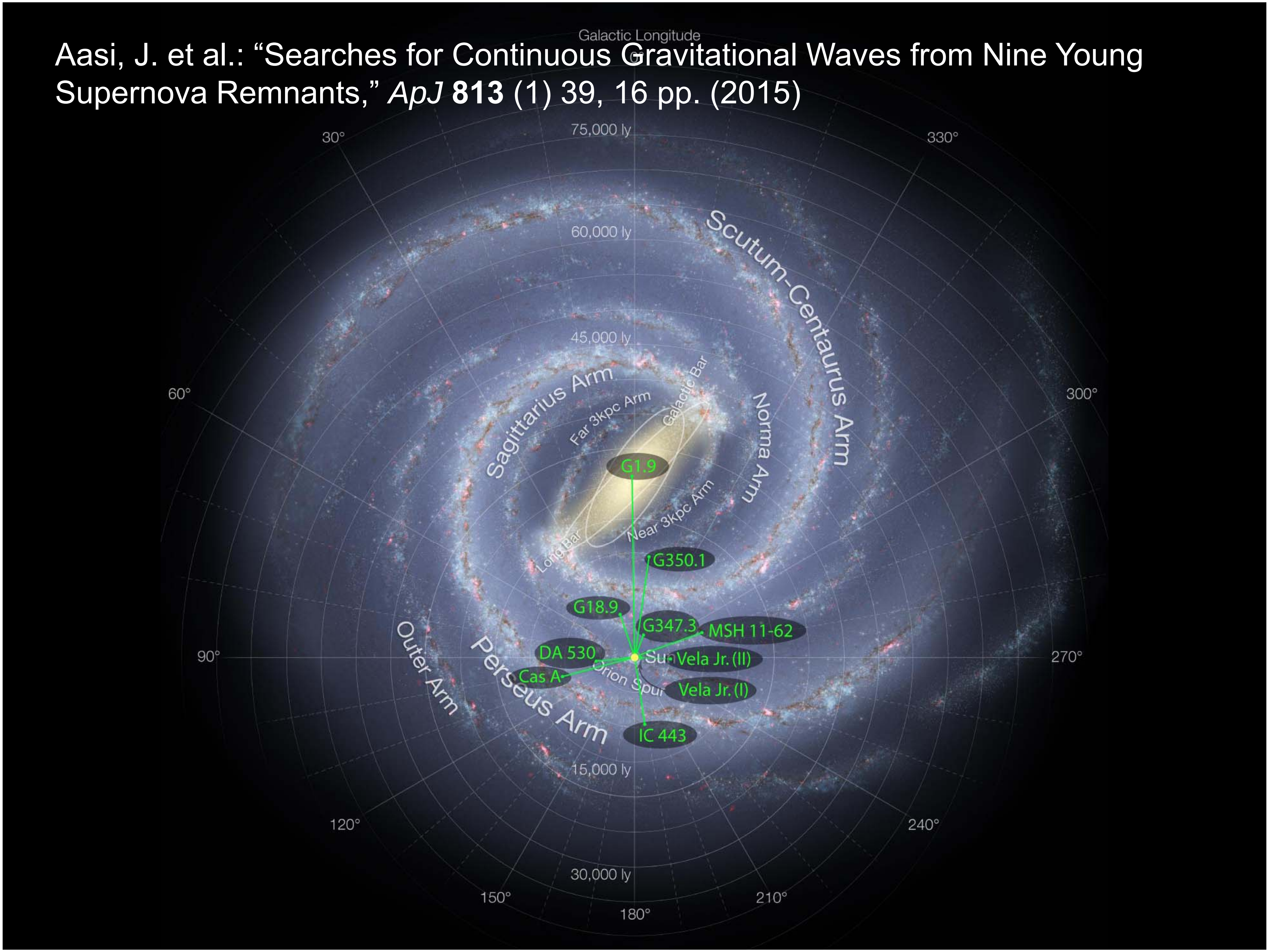
Cassiopeia A

- Young (~300 yr) compact object
- Position is well known
- Unknown spin-down parameters



Wette, K. *et al.:* "Searching for gravitational waves from Cassiopeia A with LIGO," *Class. Quantum Grav.*, **25**(235011):1-8 (2008)

Aasi, J. et al.: “Searches for Continuous Gravitational Waves from Nine Young Supernova Remnants,” *ApJ* **813** (1) 39, 16 pp. (2015)



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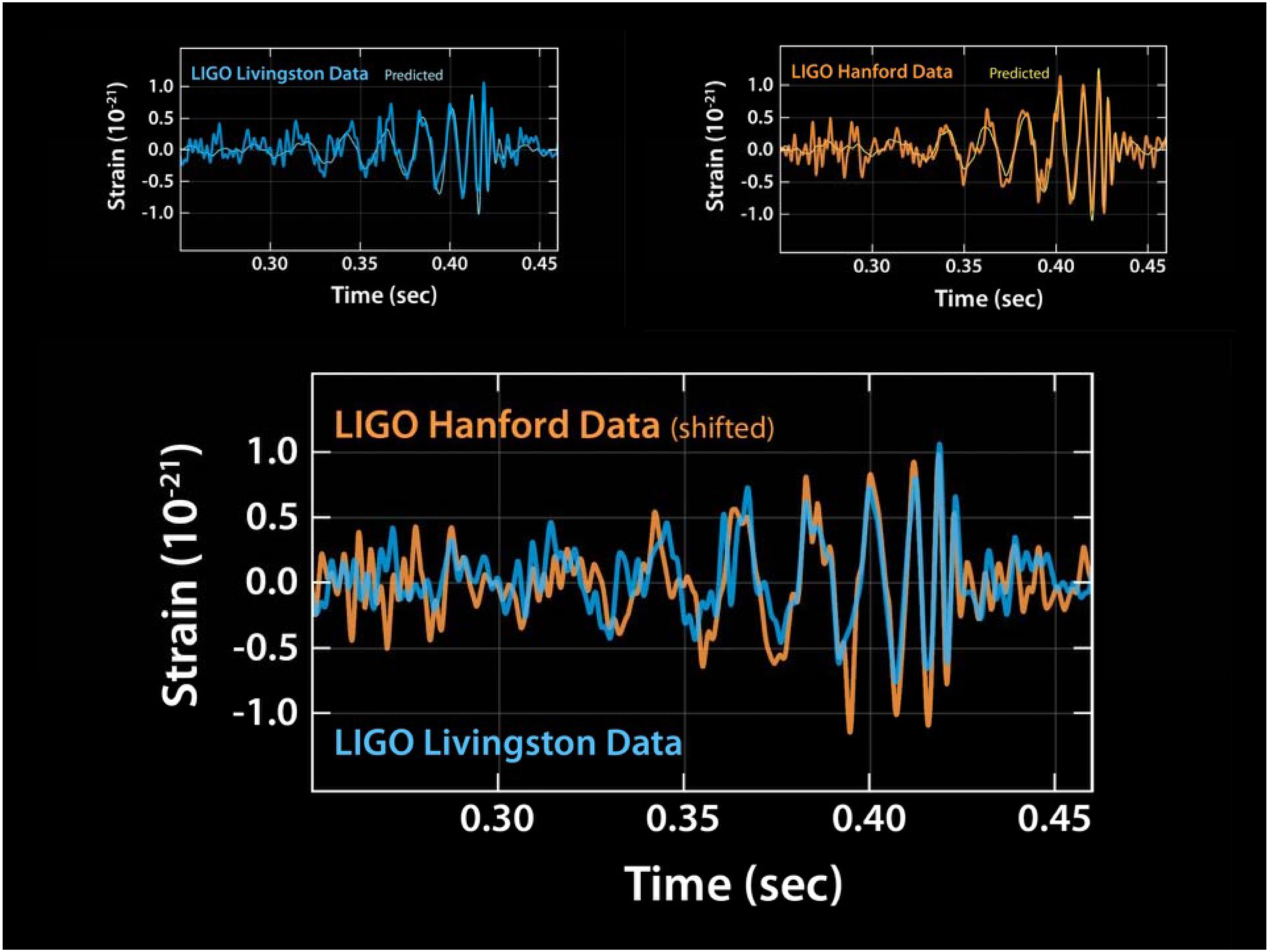
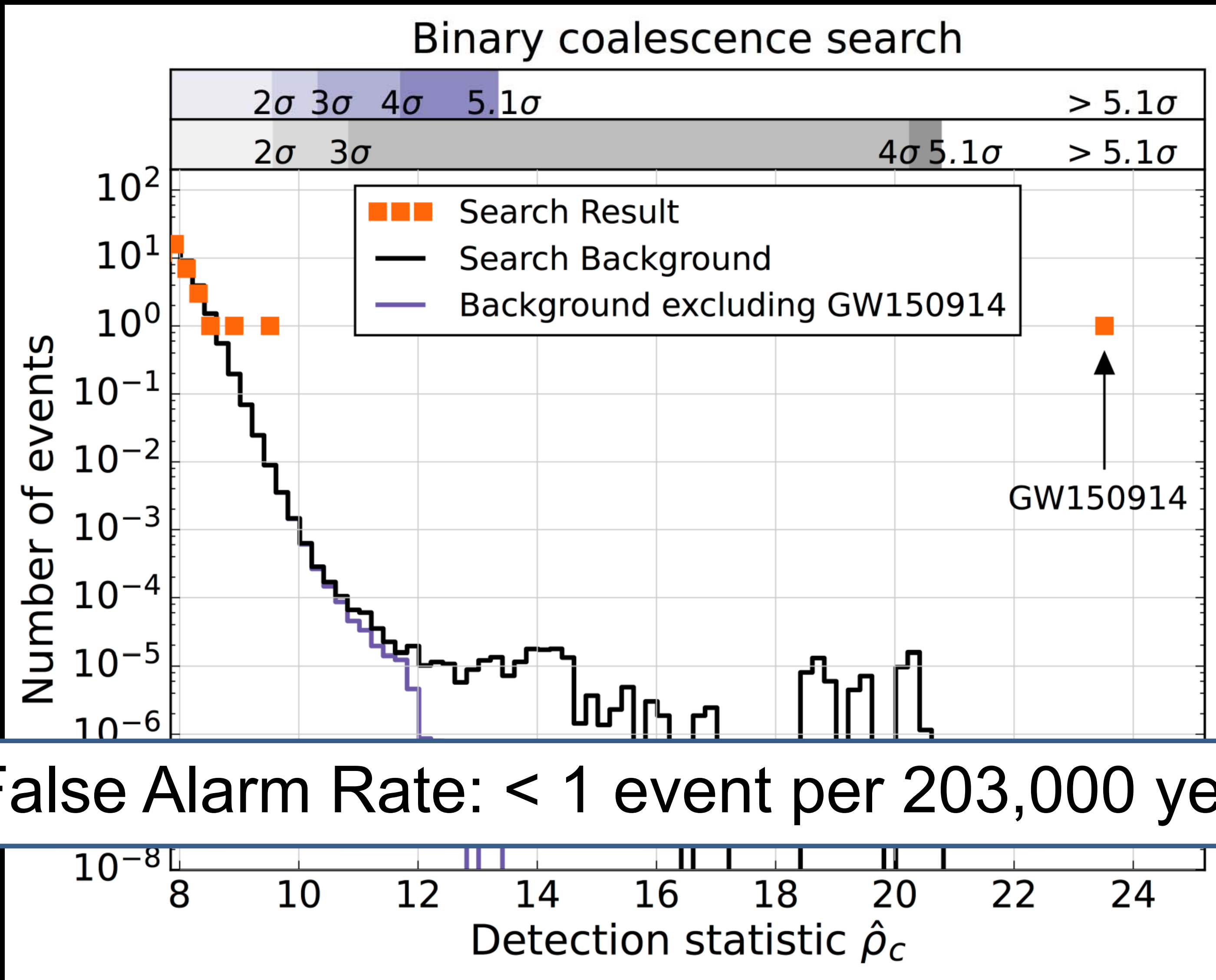

LIGO Livingston Data
Predicted
Strain (10^-21)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
LIGO Hanford Data
Predicted
Strain (10^-21)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^-21)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)

Detector State During the Event

- Detectors' states: http://arxiv.org/abs/1602.03838
- Detector characterisation: http://arxiv.org/abs/1602.03844
- Calibration state: http://arxiv.org/abs/1602.03845

Detectors working perfectly!

Significance



False Alarm Rate: < 1 event per 203,000 years

Parameter Estimation

$m_1 = 36^{+5}_{-4}\ \mathrm{M_{Sun}}$

$m_2 = 29^{+4}_{-4}\ \mathrm{M_{Sun}}$

$m_F = 62^{+4}_{-4}\ \mathrm{M_{Sun}}$

$\text{Energy radiated} = 3^{+0.5}_{-0.5}\ \mathrm{M_{Sun}c^2}$

$\text{Final spin} = 0.67^{+0.05}_{-0.07}$

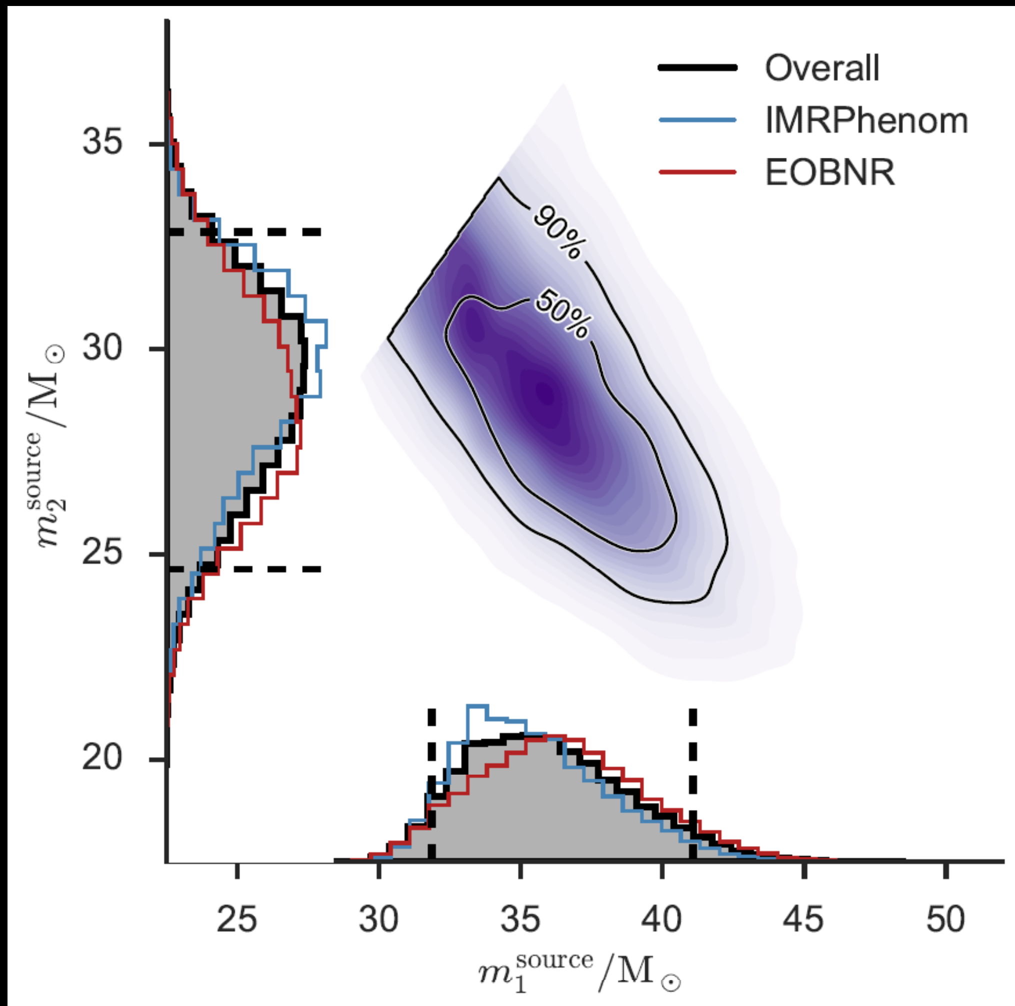
$D = 410^{+160}_{-180}\ \mathrm{Mpc}$

$\text{Source redshift} = 0.09^{+0.03}_{-0.04}$

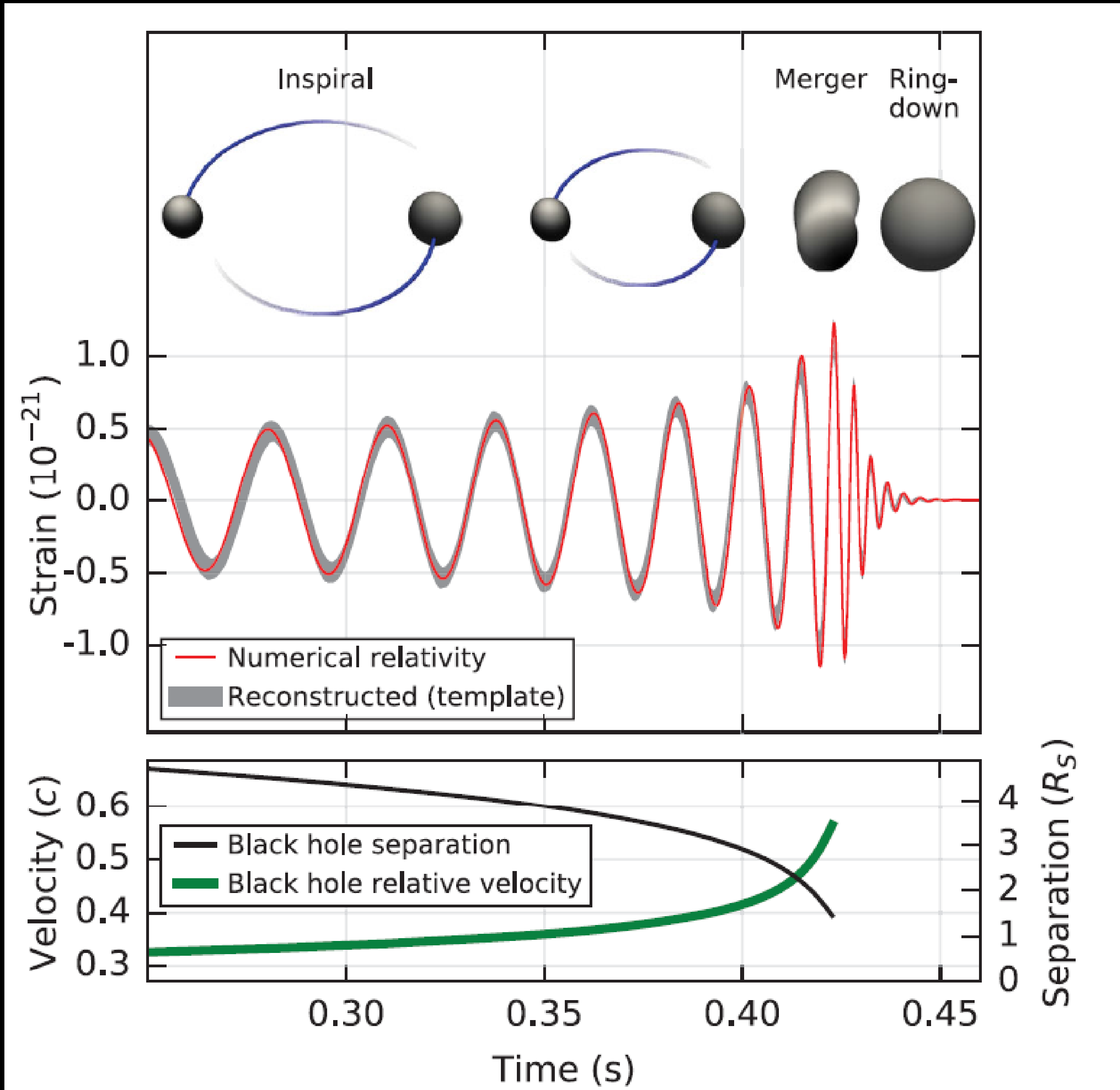
$h_{\mathrm{max}} \sim 1.0\times10^{-21}$

$P_{\mathrm{max}} = 3.6\times10^{56}\ \mathrm{erg\ s^{-1}} = 3.6\times10^{49}\ \mathrm{W}$ (200 billion supernovae)

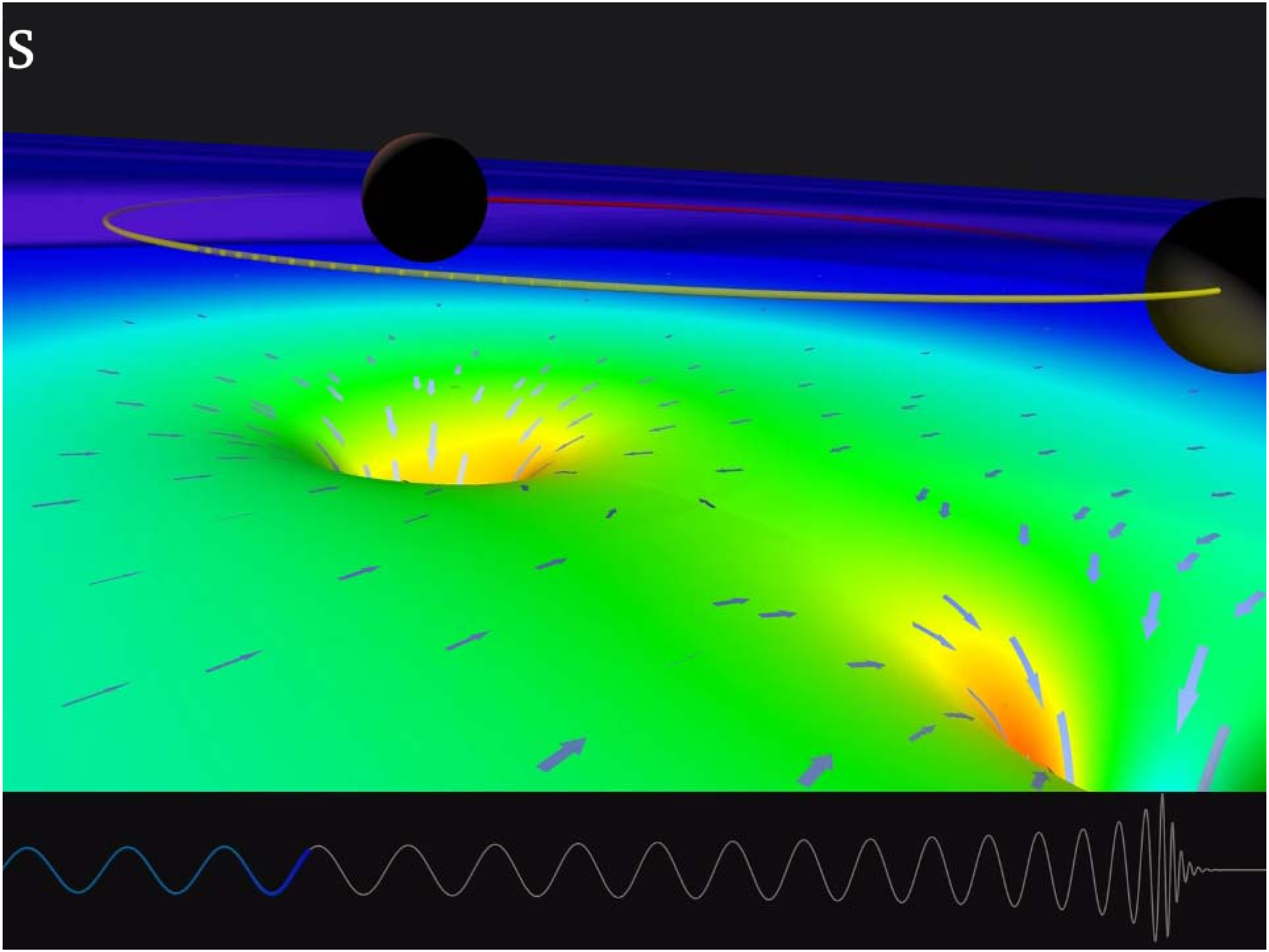
Parameter Estimation

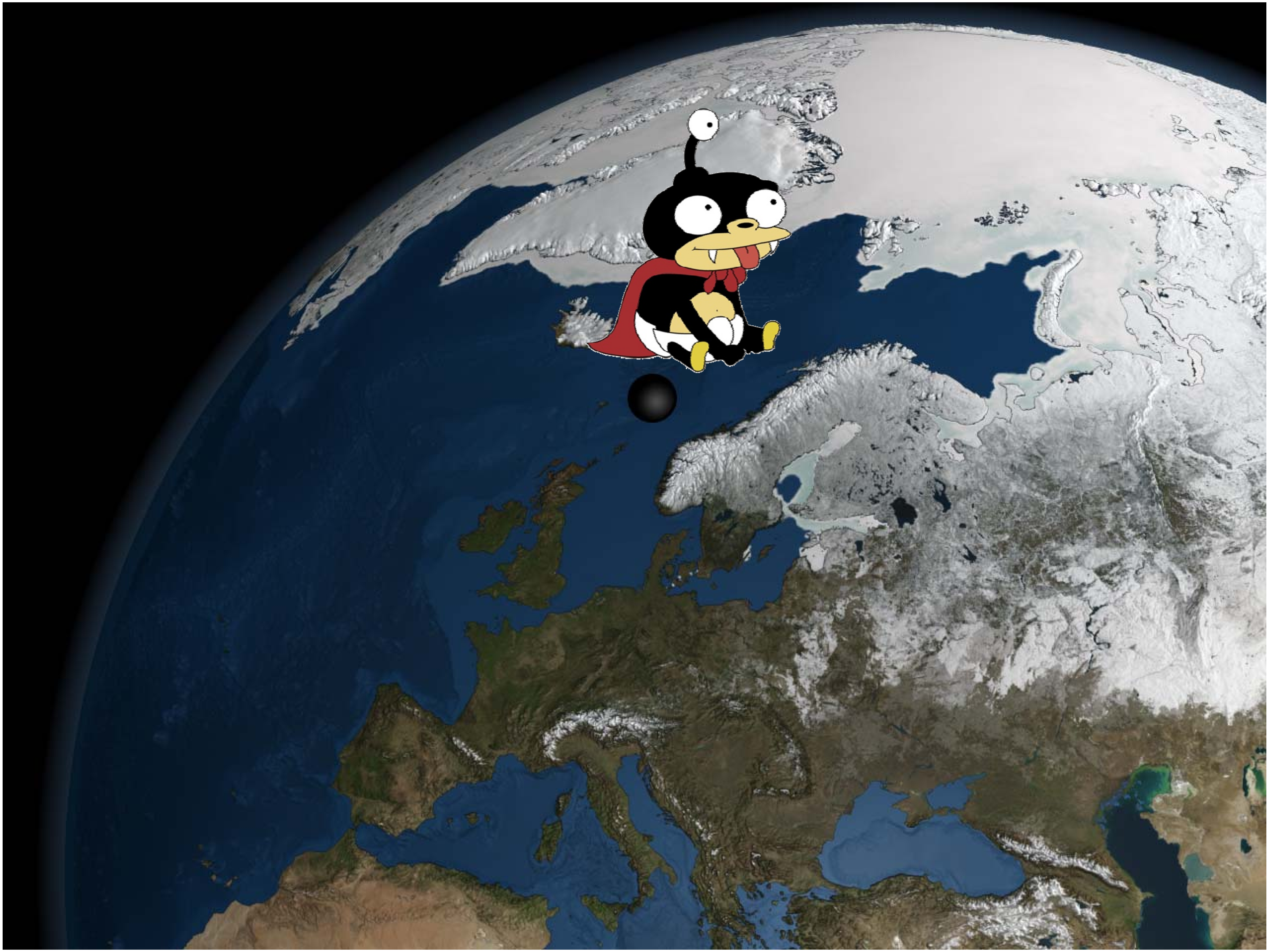


http://arxiv.org/abs/1602.03840



Inspiral
Merger
Ring-down
1.0
0.5
0.0
-0.5
-1.0
Strain (10^{-21})
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
4
3
2
1
0
0.30
0.35
0.40
0.45
Time (s)


S

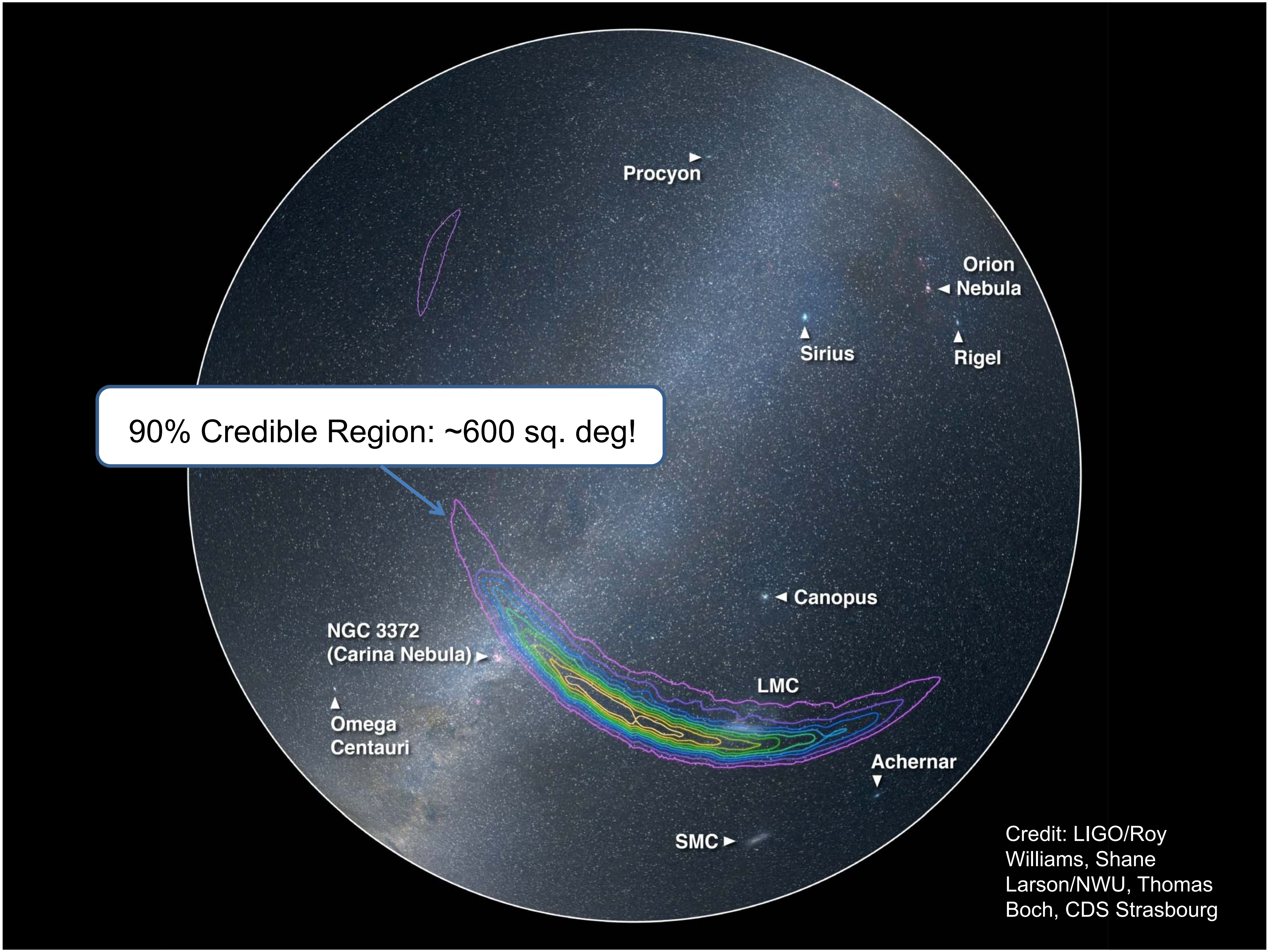


Arguments for BBH

- Waveform is what was expected from detailed numerical relativity
- Given the chirp mass and the frequency, the Keplerian orbit would have been about 347 km! (B. Allen et al.)
- Have to be black holes or would have touched and merged at lower frequencies

EM follow-up

Sent low latency triggers to partner observatories within a few minutes


90% Credible Region: ~600 sq. deg!
Procyon
Orion
Nebula
Sirius
Rigel
Canopus
NGC 3372
(Carina Nebula)
Omega
Centauri
LMC
Achernar
SMC
Credit: LIGO/Roy
Williams, Shane
Larson/NWU, Thomas
Boch, CDS Strasbourg

EM follow-up

- HEN (Antares/IceCube/LSC): http://arxiv.org/abs/1602.05411
- Fermi-LAT: upper limit on 100 MeV http://arxiv.org/abs/1602.04488
- **Fermi GBM http://arxiv.org/abs/1602.03920**

Possible transient, $1.8^{+1.5}_{-1.0} \times 10^{49}$ erg s^{-1} 1 keV - 10 MeV
(counterpart plausibility unknown)

Astrophysical origins

Two possibilities:

1. Isolated binaries
2. Dynamical formulation

http://arxiv.org/abs/1602.03846

Astrophysical origins

Isolated

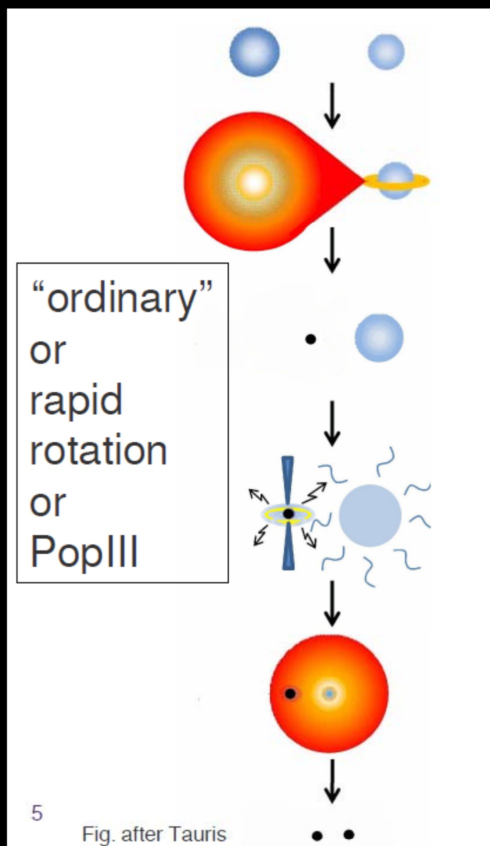


Fig. after Tauris

Dynamical

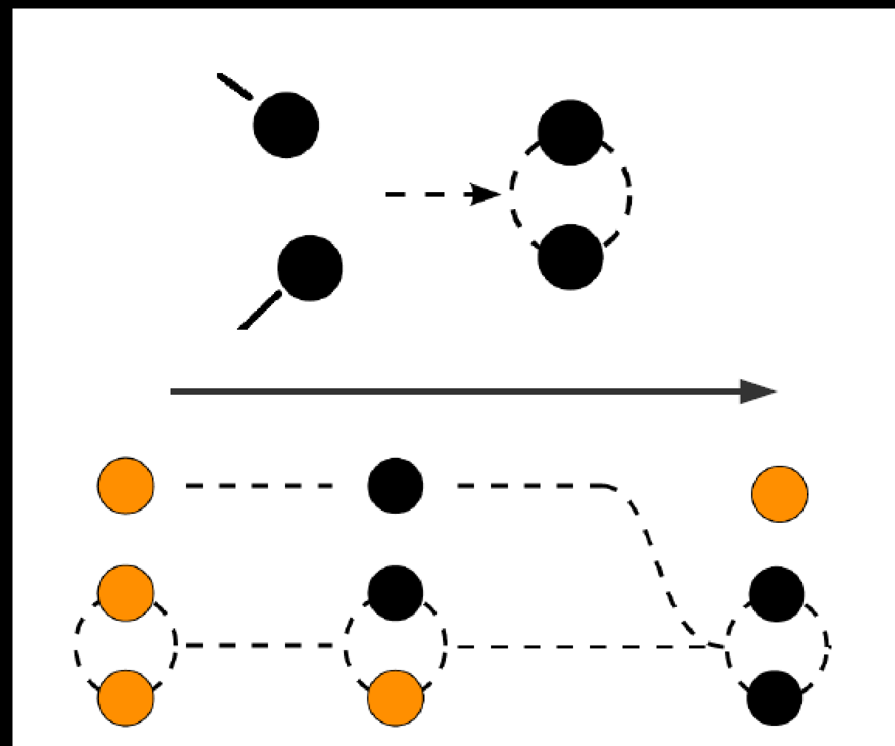
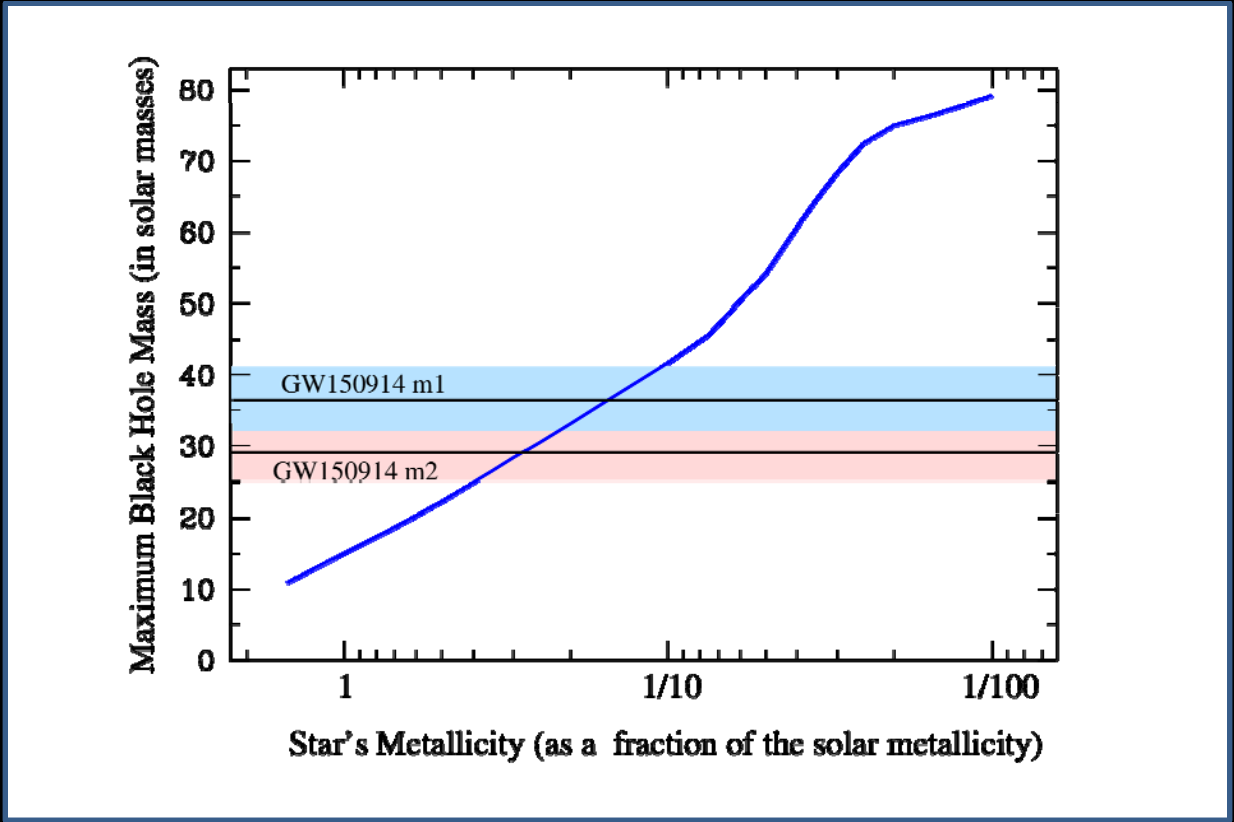


Fig. after Ziosi

http://arxiv.org/abs/1602.03846

Astrophysical origins

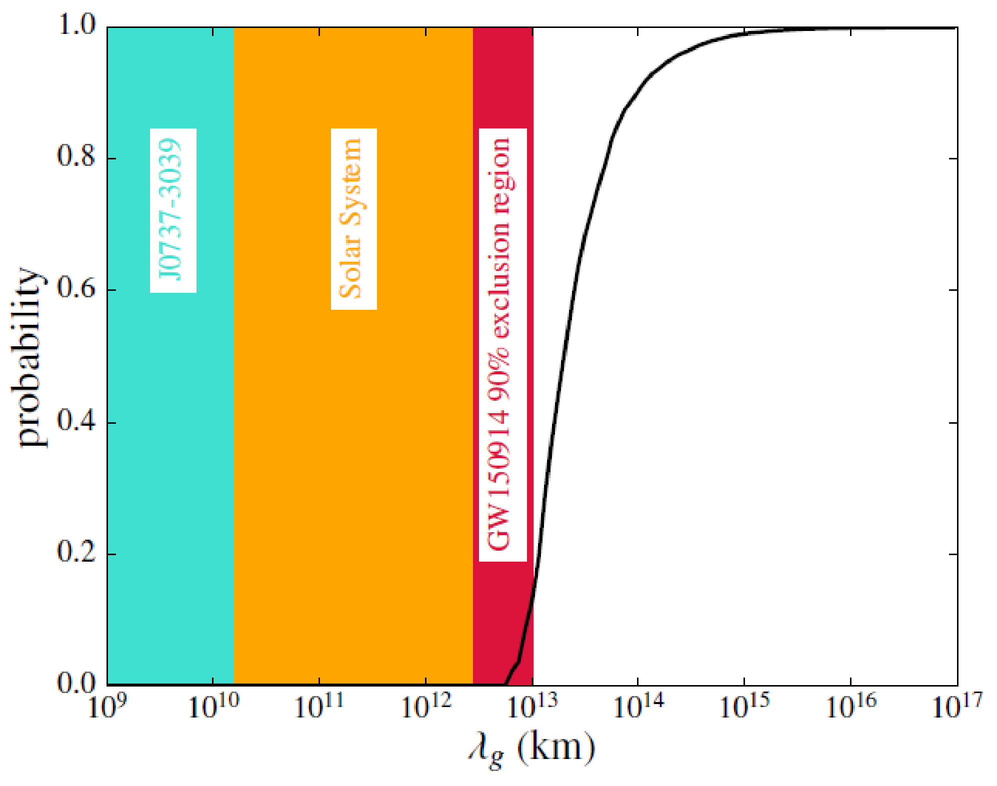


http://arxiv.org/abs/1602.03846

Tests of General Relativity

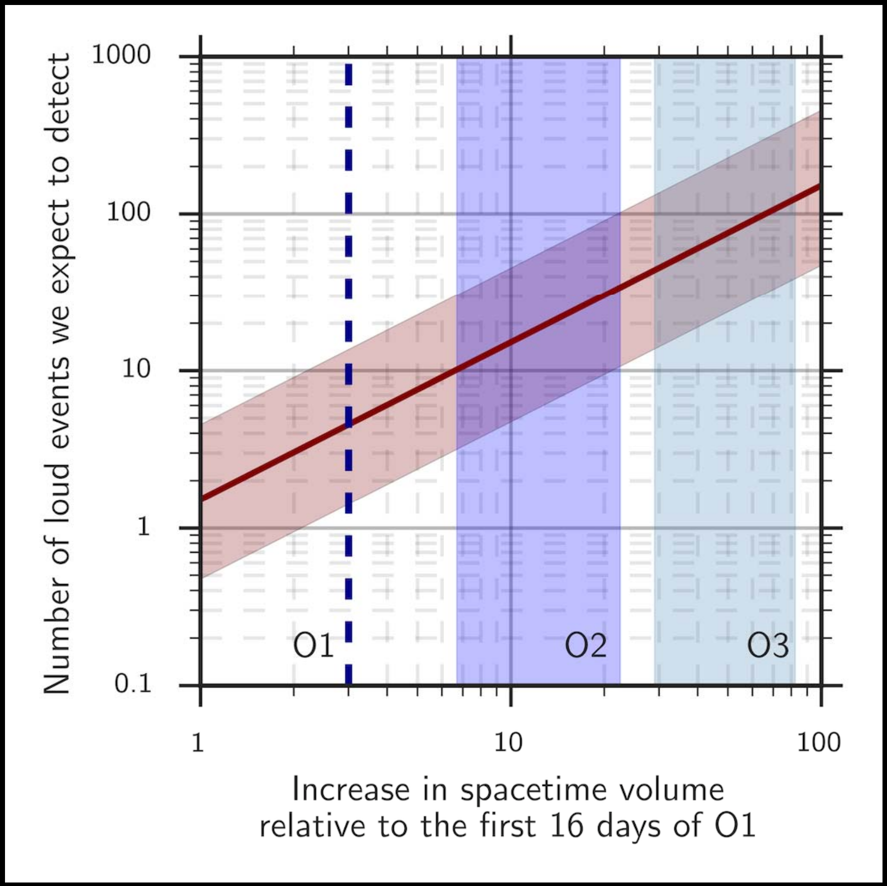
- All PPN terms consistent with GR
- Constraint on Compton wavelength of graviton:

$$\lambda_g \geq 1.5 \times 10^{16} \text{ m}$$



http://arxiv.org/abs/1602.03841

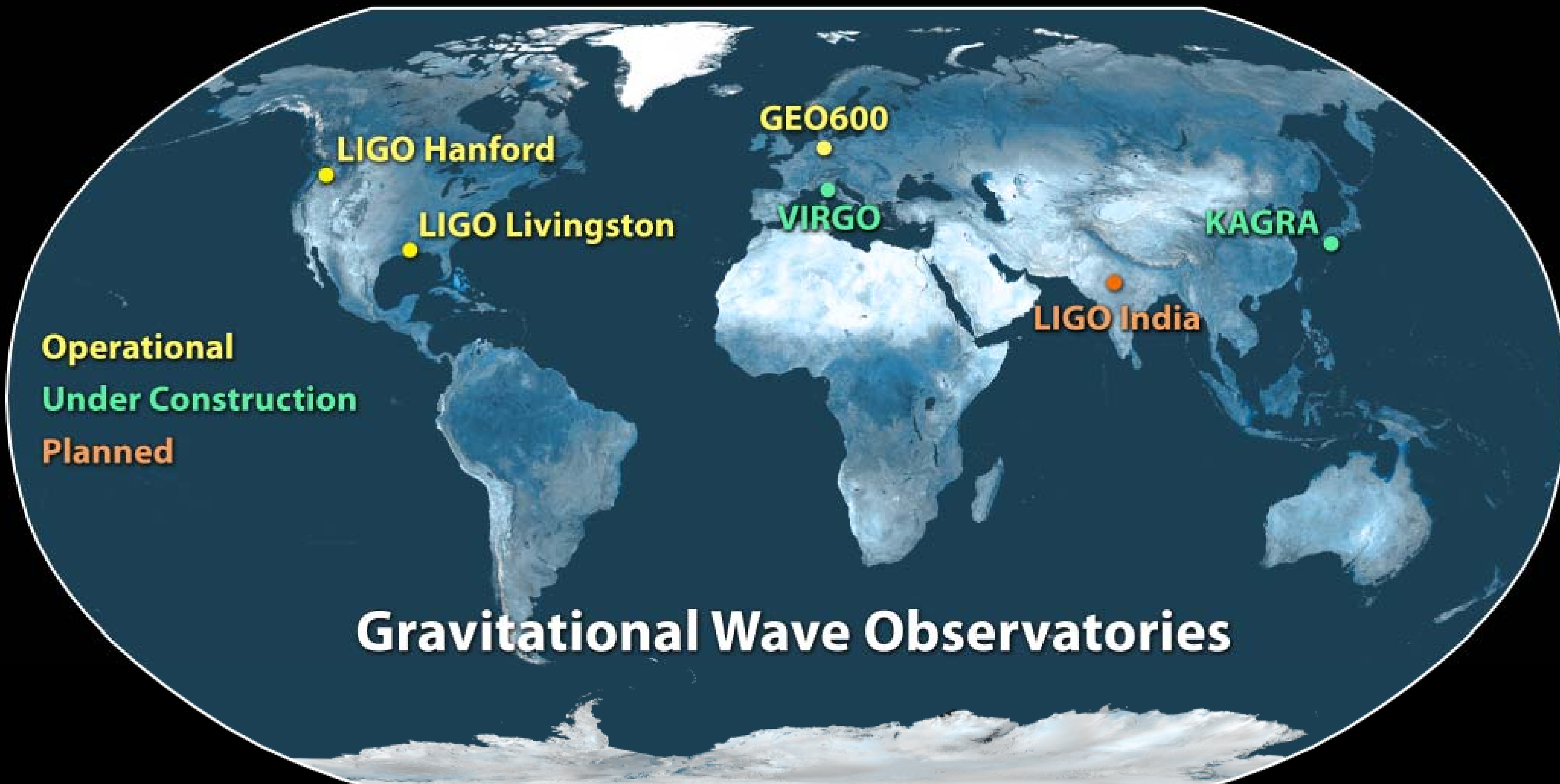
Rates Estimation



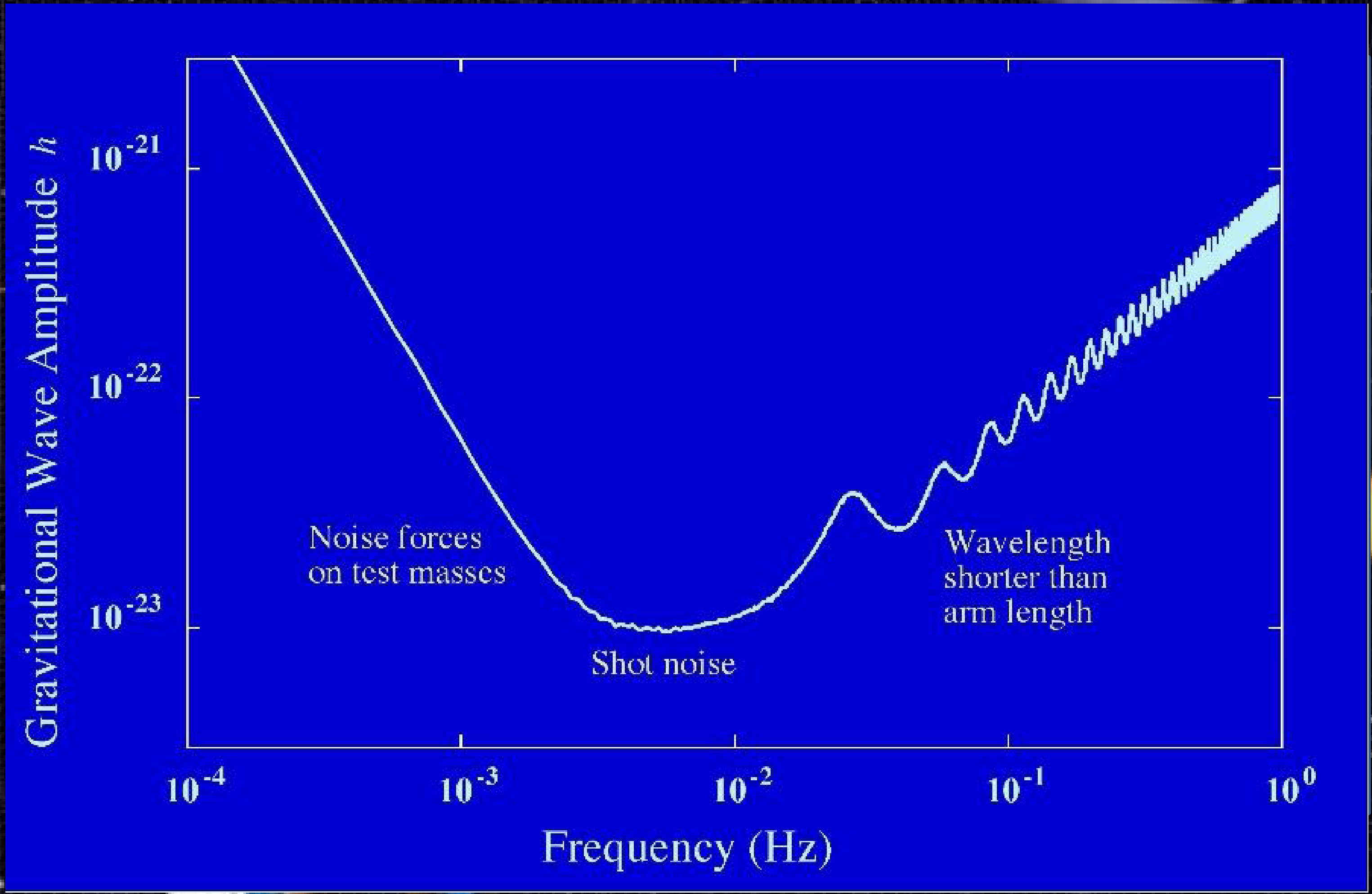
http://arxiv.org/abs/1602.03842

Overview

- History/basics of gravitational waves (GWs)
- The LIGO project
- How GWs are observed
- GW150914: ‘The Event’
- The future of GW astrophysics

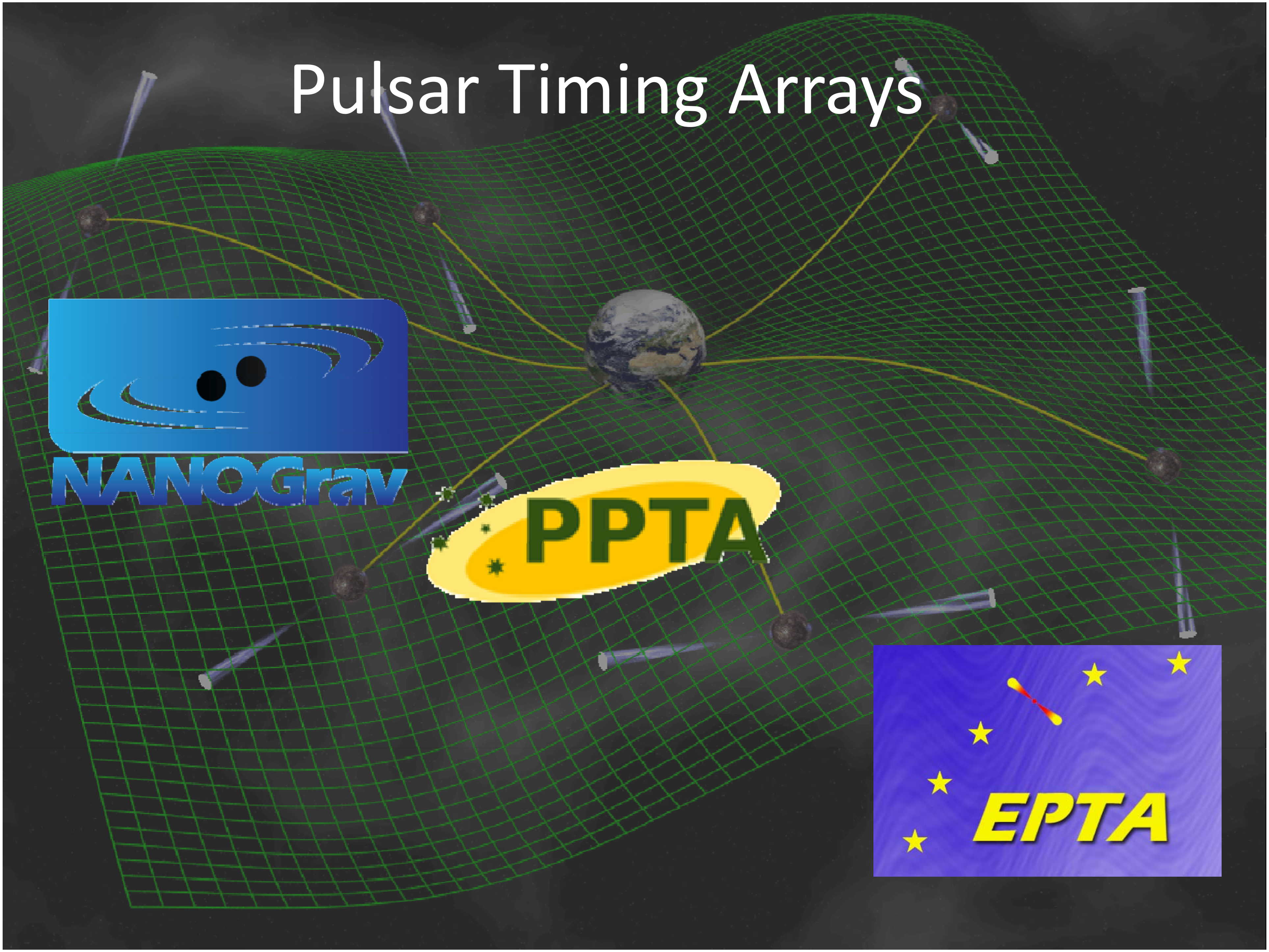

GEO600
LIGO Hanford
LIGO Livingston
VIRGO
KAGRA
LIGO India
Operational
Under Construction
Planned
Gravitational Wave Observatories

Space-based interferometers: LISA



http://www.srl.caltech.edu/lisa/

Pulsar Timing Arrays



New standard candles

- Distances in astronomy are hard to come by!
- Current best objects for large distances are supernovae
- GW wave-form can give *relatively* accurate distances
- Great if we can get a confirmed multi-messenger counterpart!

How Can You Participate?

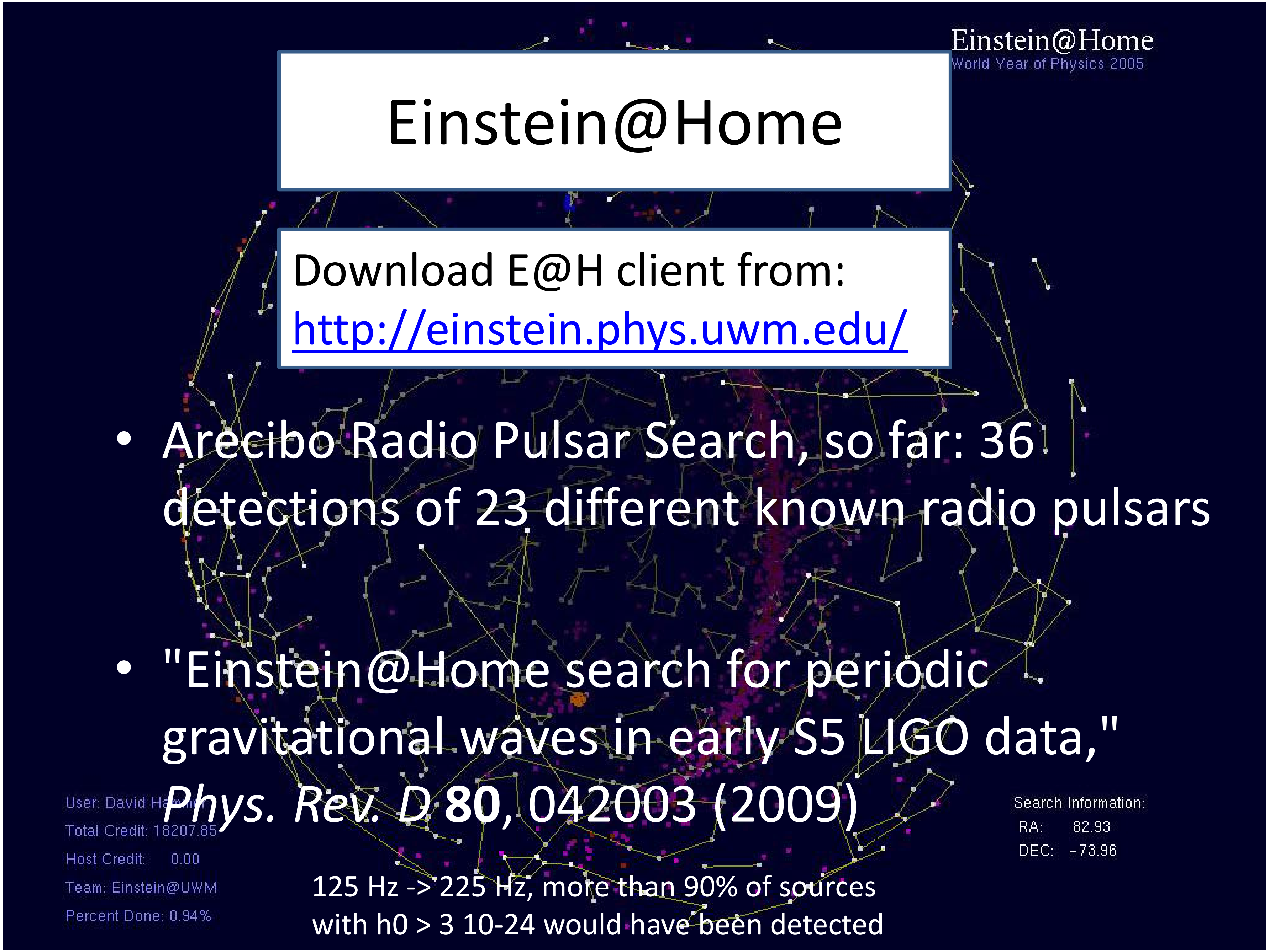
Einstein@Home

Download E@H client from:
http://einstein.phys.uwm.edu/

- Arecibo Radio Pulsar Search, so far: 36 detections of 23 different known radio pulsars

- "Einstein@Home search for periodic gravitational waves in early S5 LIGO data," *Phys. Rev. D* **80**, 042003 (2009)

125 Hz -> 225 Hz, more than 90% of sources
with h0 > 3 10-24 would have been detected



How Can You Participate?

We’ve got:

- Tutorials!
- Data!
- Pretty pictures!
- Nice, helpful people!

https://losc.ligo.org/about/

What Does GW150914 Sound Like?