Results from the Laser Interferometer Gravitational-wave Observatory

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for the LIGO Scientific Collaboration and the Virgo Collaboration

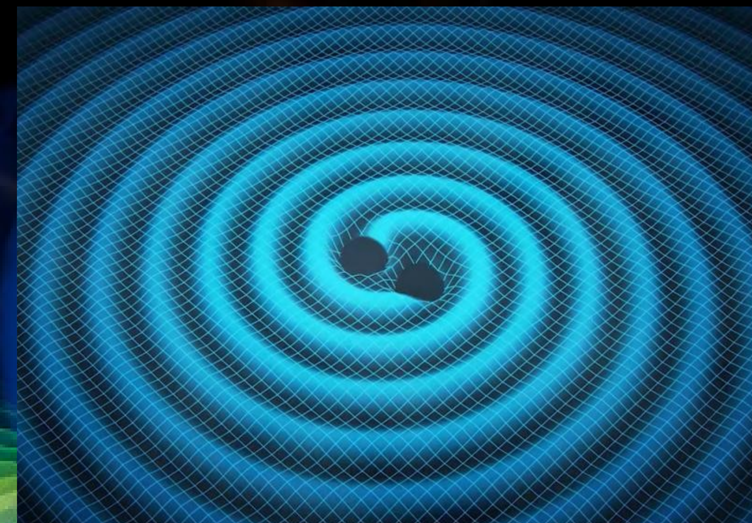
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS

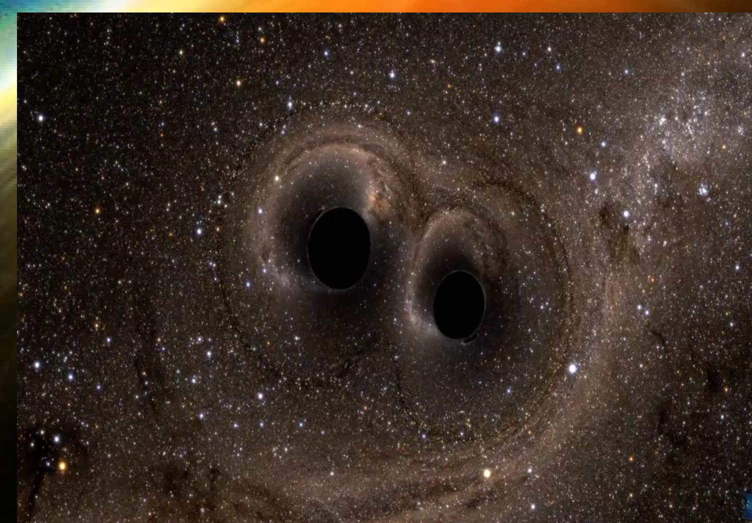
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

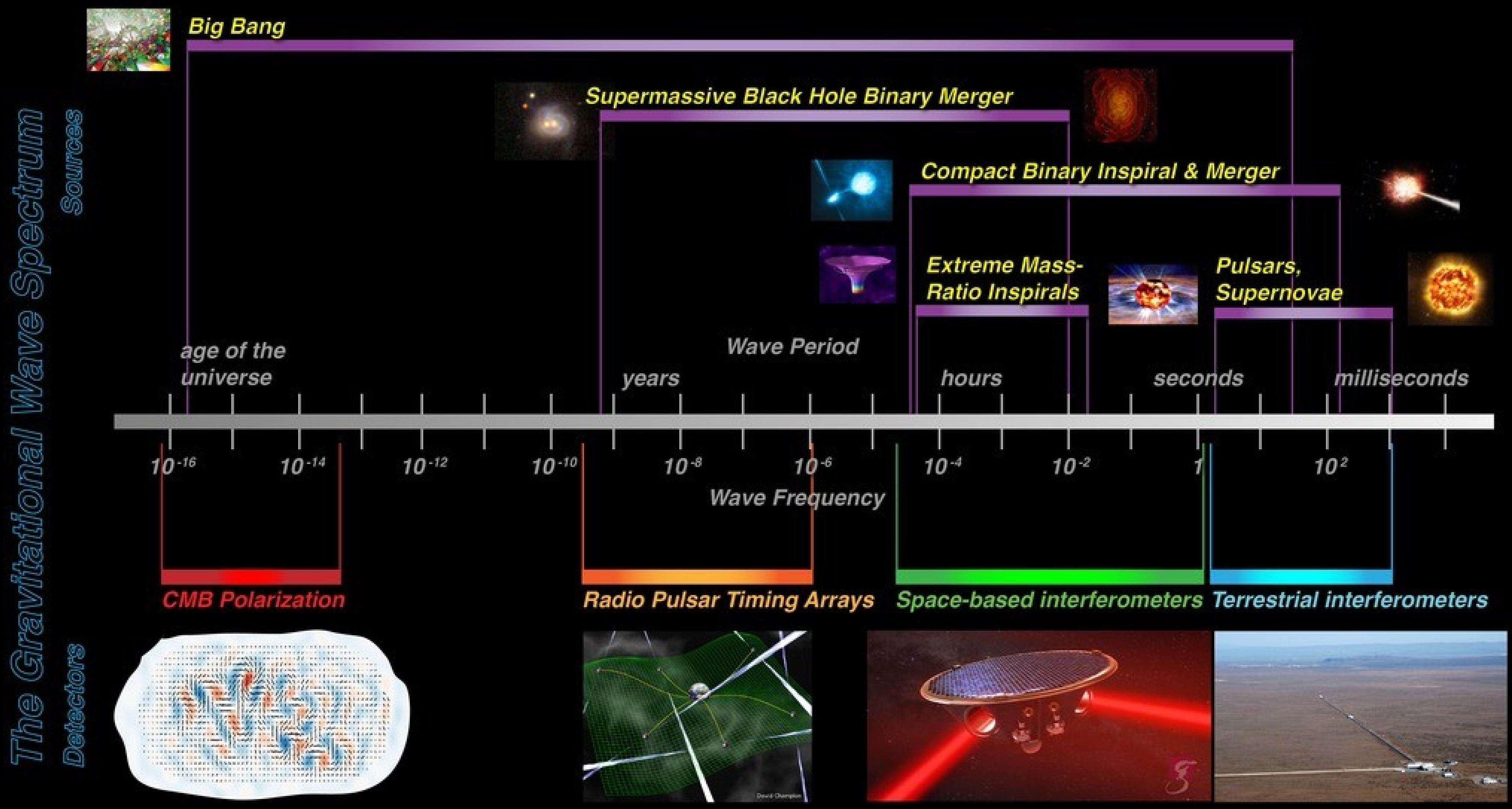
Gravitational waves 101

- Unavoidable consequence of General Relativity
- Classical phenomenon (as far as we know)
- Theory and phenomenology well understood
- Measured in the weak regime
- Can be used to probe strong gravitational fields
- Can be used to test GR or alternative theories
- Can be used to test fundamental physics
- Information complementary to light and particles

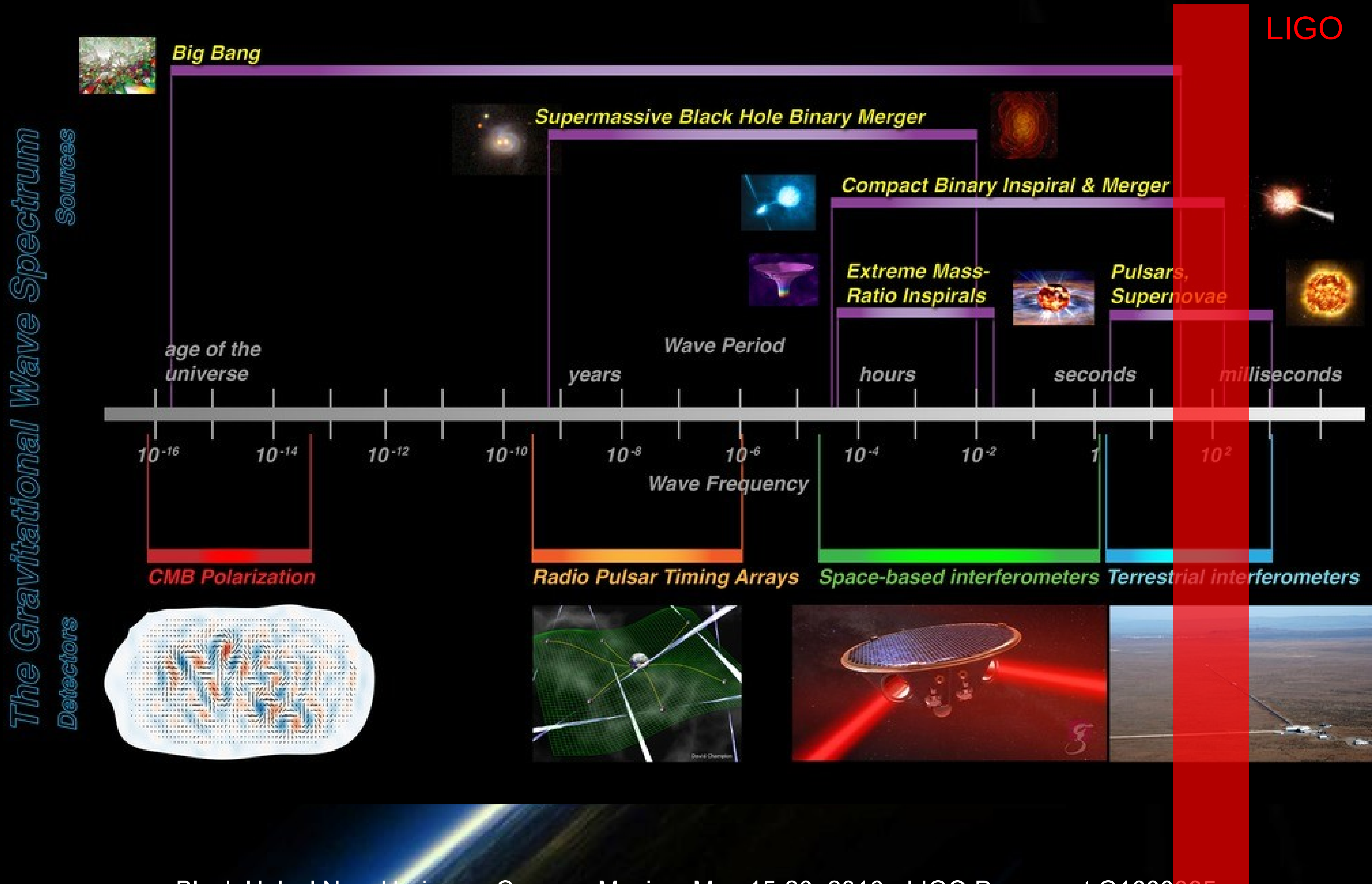




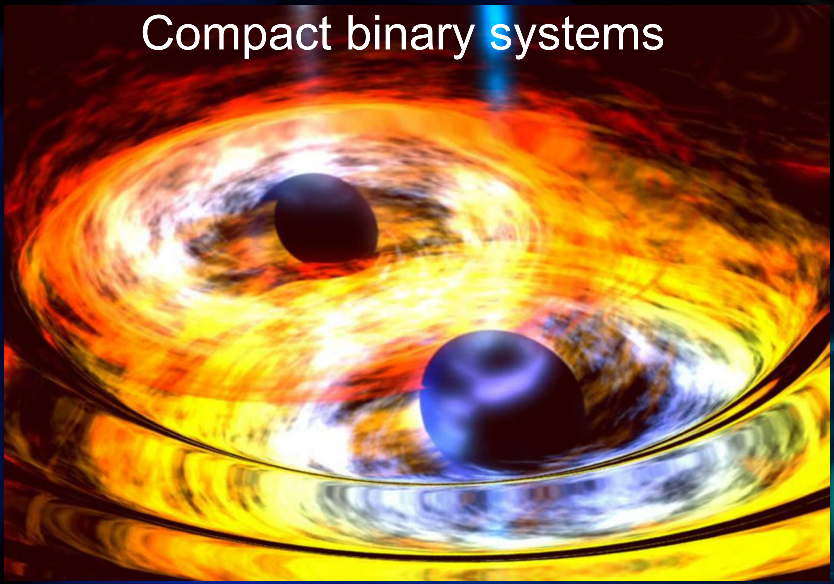
The gravitational-wave spectrum

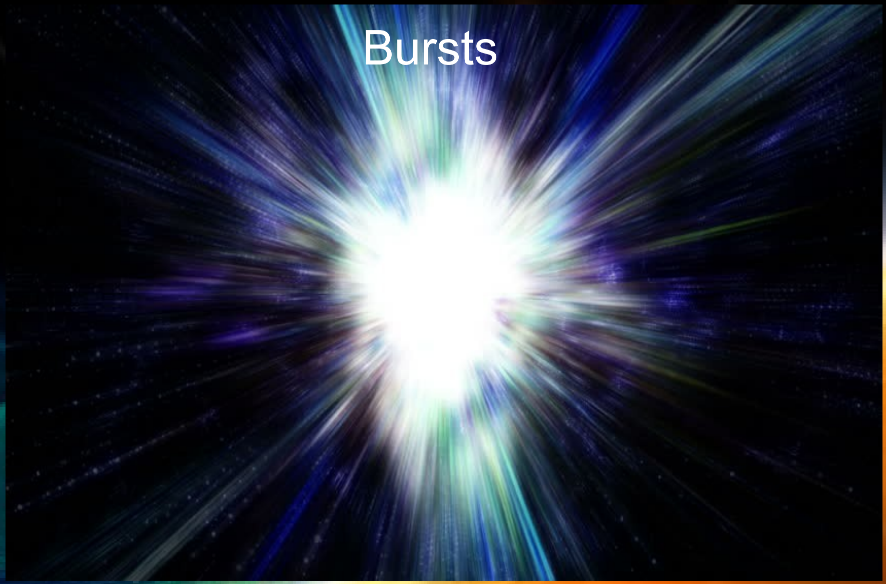


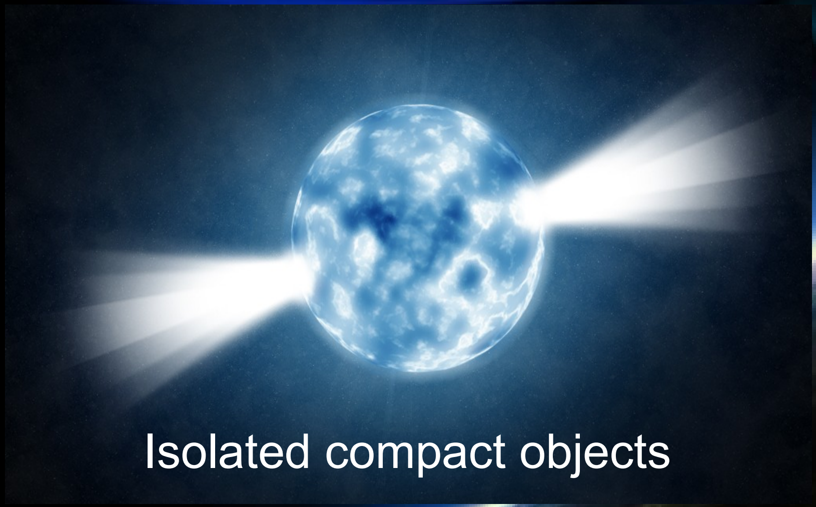
The gravitational-wave spectrum

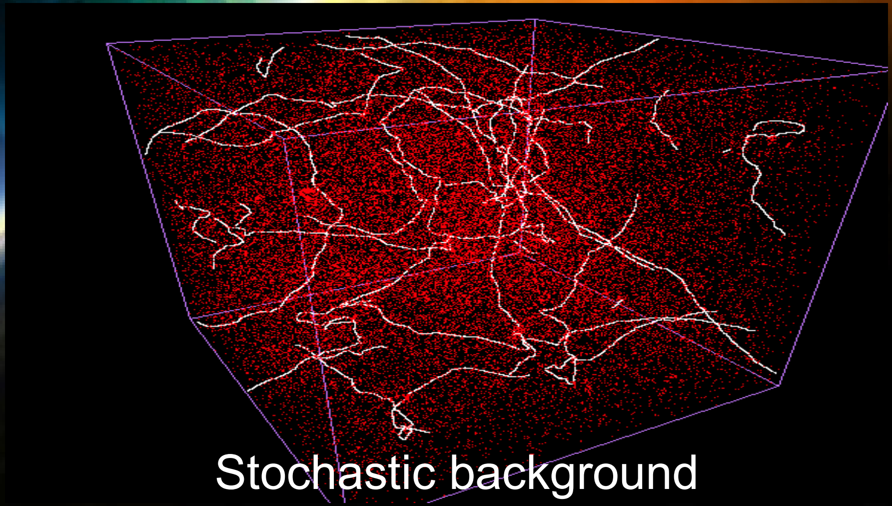


Sources LIGO can probe

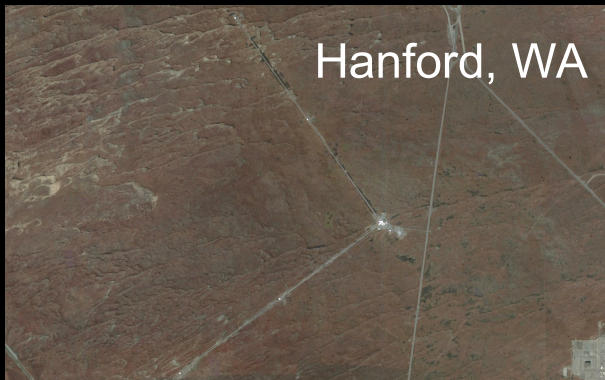




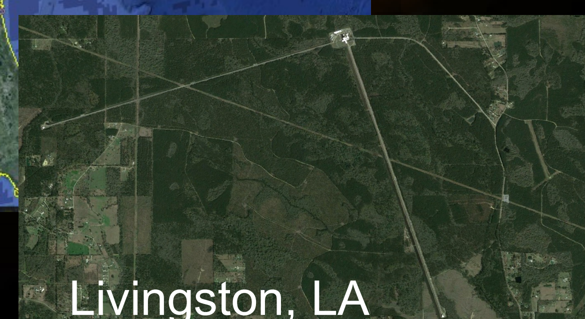


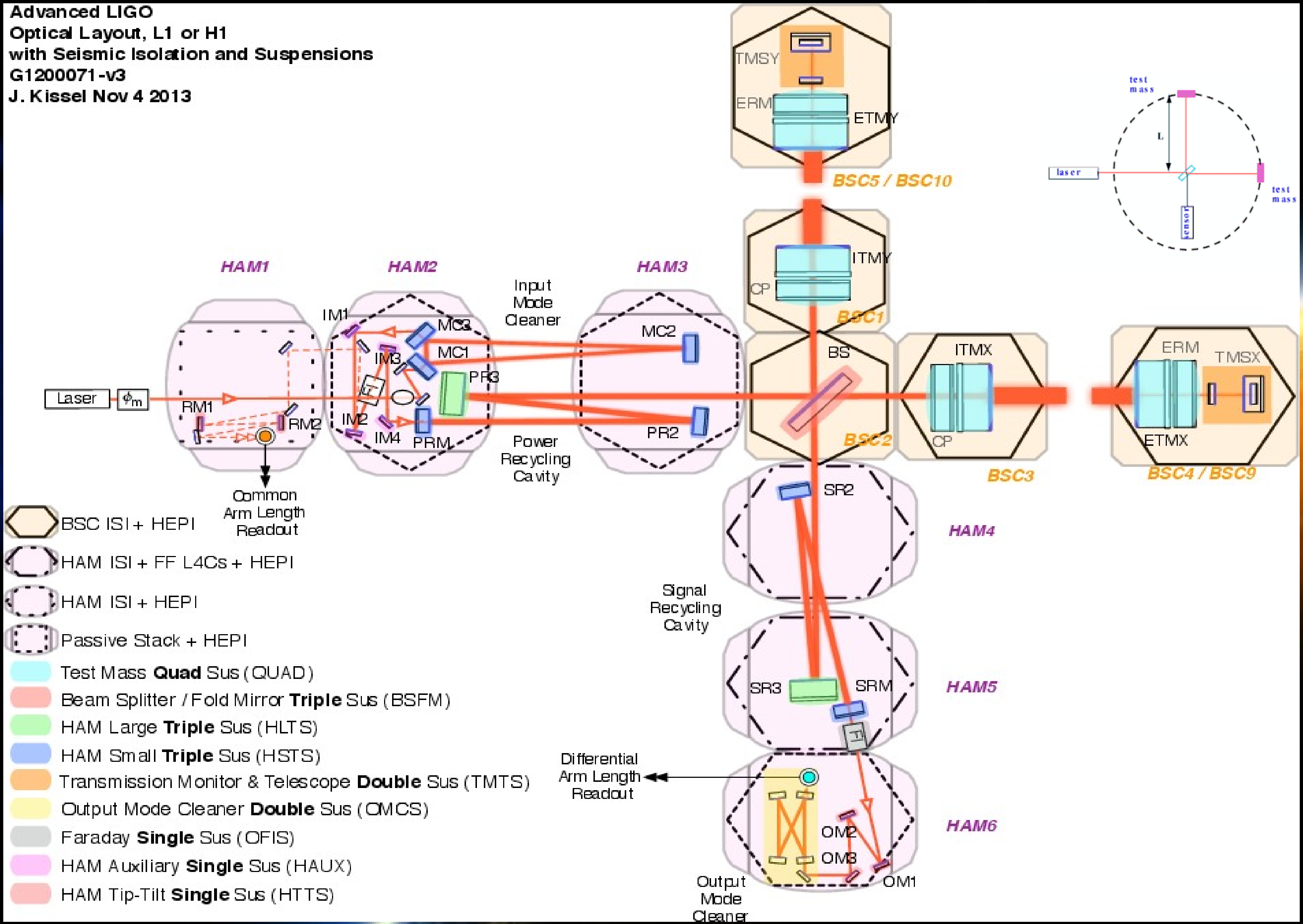


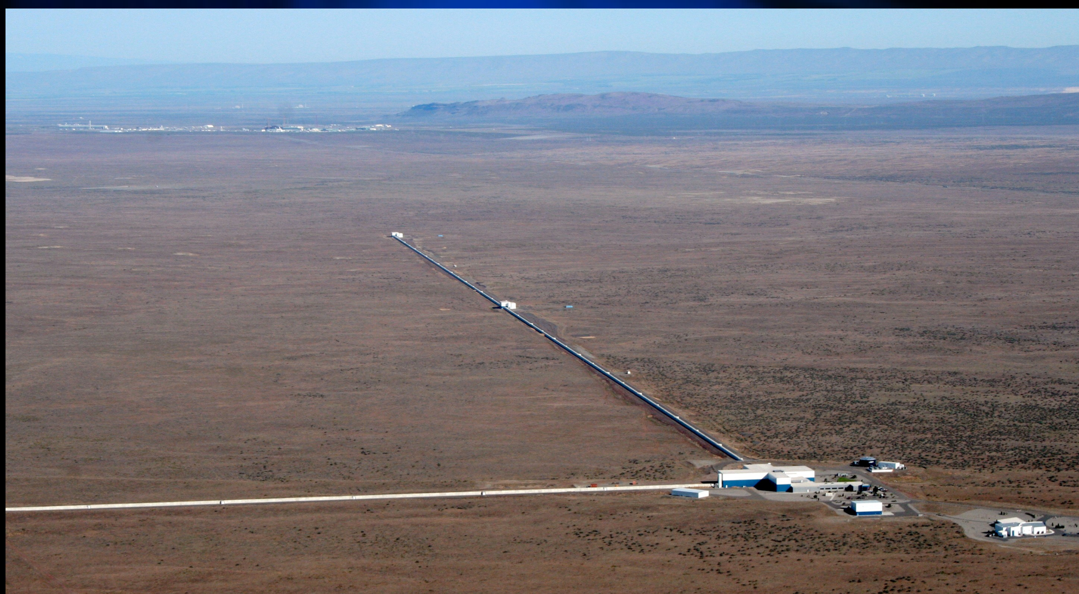
LIGO

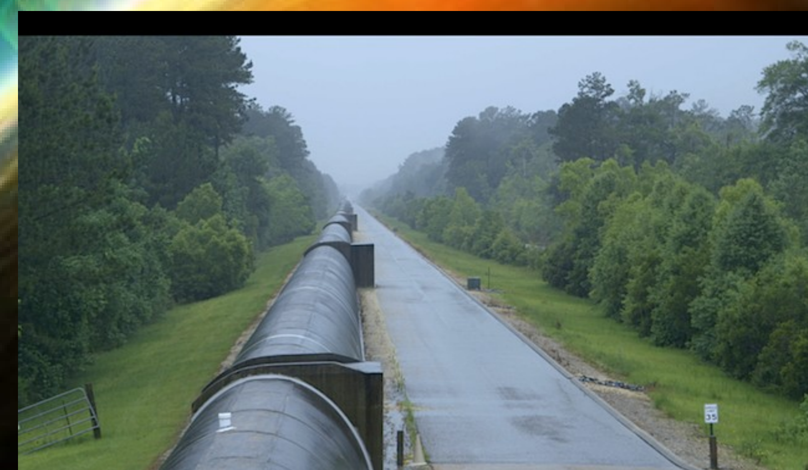

Hanford, WA


Canadian Shield
James Bay
Rocky Mountains
Lake Superior
Gulf of St Lawrence
Northumberland Strait
Bay of Fundy
Ottawa
Georgian Bay
Lake Huron
Michigan
Wisconsin
Lake Michigan
Lake Ontario
Lake Erie
South Dakota
Nebraska
Iowa
Illinois
Indiana
Colorado
Appalachian Mountains
Washington
Kansas
Missouri
Tennessee
Oklahoma
Arkansas
New Mexico
Texas
Mississippi
Alabama
Louisiana
Chihuahuan Desert
Gulf of California


Livingston, LA

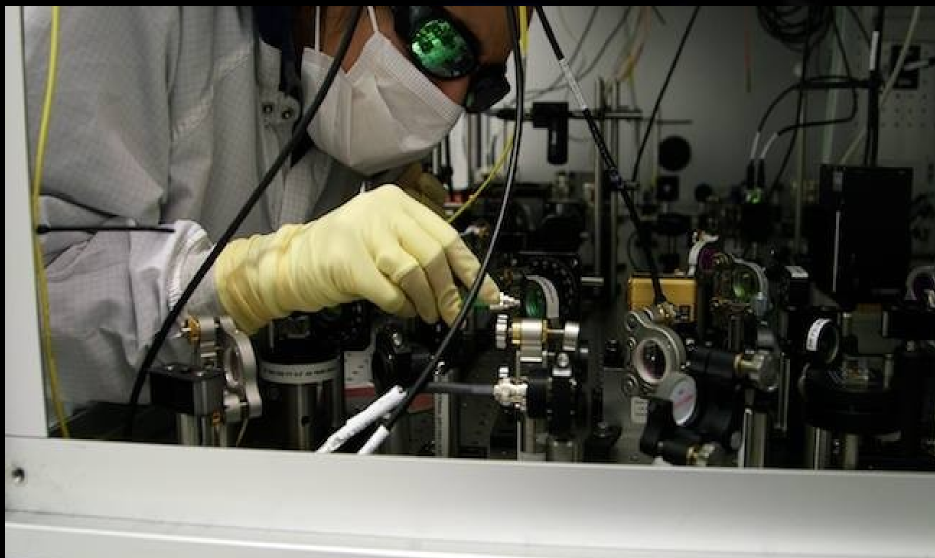

Advanced LIGO
Optical Layout, L1 or H1
with Seismic Isolation and Suspensions
G1200071-v3
J. Kissel Nov 4 2013
TMSY
ERM
ETMY
BSC5 / BSC10
ITMY
CP
BSC1
HAM1
HAM2
HAM3
Input Mode Cleaner
IM1
MC3
MC1
MC2
IM3
PR3
Laser
RM1
RM2
IM2
IM4
PRM
PR2
Power Recycling Cavity
BS
BSC2
ITMX
CP
BSC3
ERM
TMSX
ETMX
BSC4 / BSC9
Common Arm Length Readout
SR2
HAM4
Signal Recycling Cavity
SR3
SRM
HAM5
Differential Arm Length Readout
OM2
OM3
OM1
HAM6
Output Mode Cleaner
laser
test mass
test mass
sensor
L
BSC ISI + HEPI
HAM ISI + FF L4Cs + HEPI
HAM ISI + HEPI
Passive Stack + HEPI
Test Mass Quad Sus (QUAD)
Beam Splitter / Fold Mirror Triple Sus (BSFM)
HAM Large Triple Sus (HLTS)
HAM Small Triple Sus (HSTS)
Transmission Monitor & Telescope Double Sus (TMTS)
Output Mode Cleaner Double Sus (OMCS)
Faraday Single Sus (OFIS)
HAM Auxiliary Single Sus (HAUX)
HAM Tip-Tilt Single Sus (HTTS)

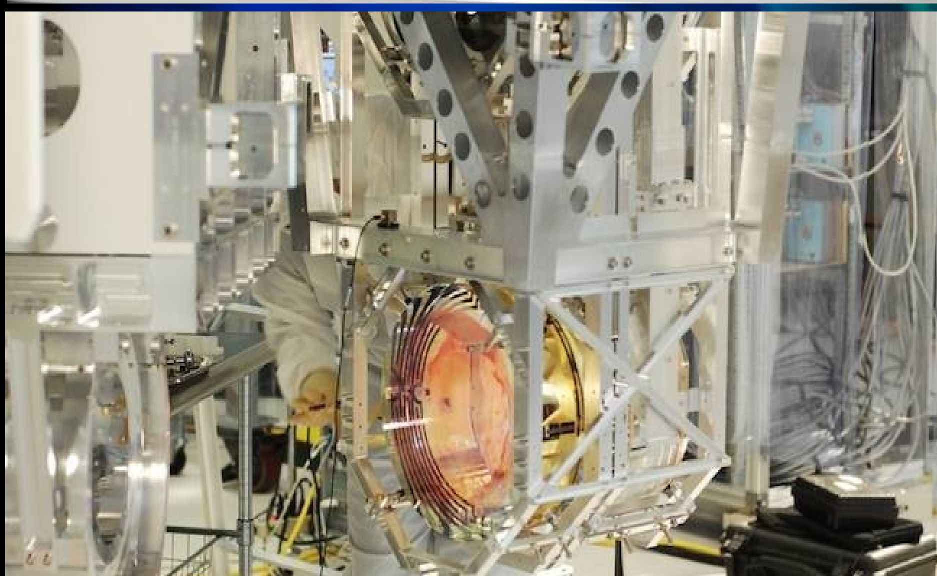




What it looks like from the outside

What it looks like from the inside






LIGO Scientific Collaboration

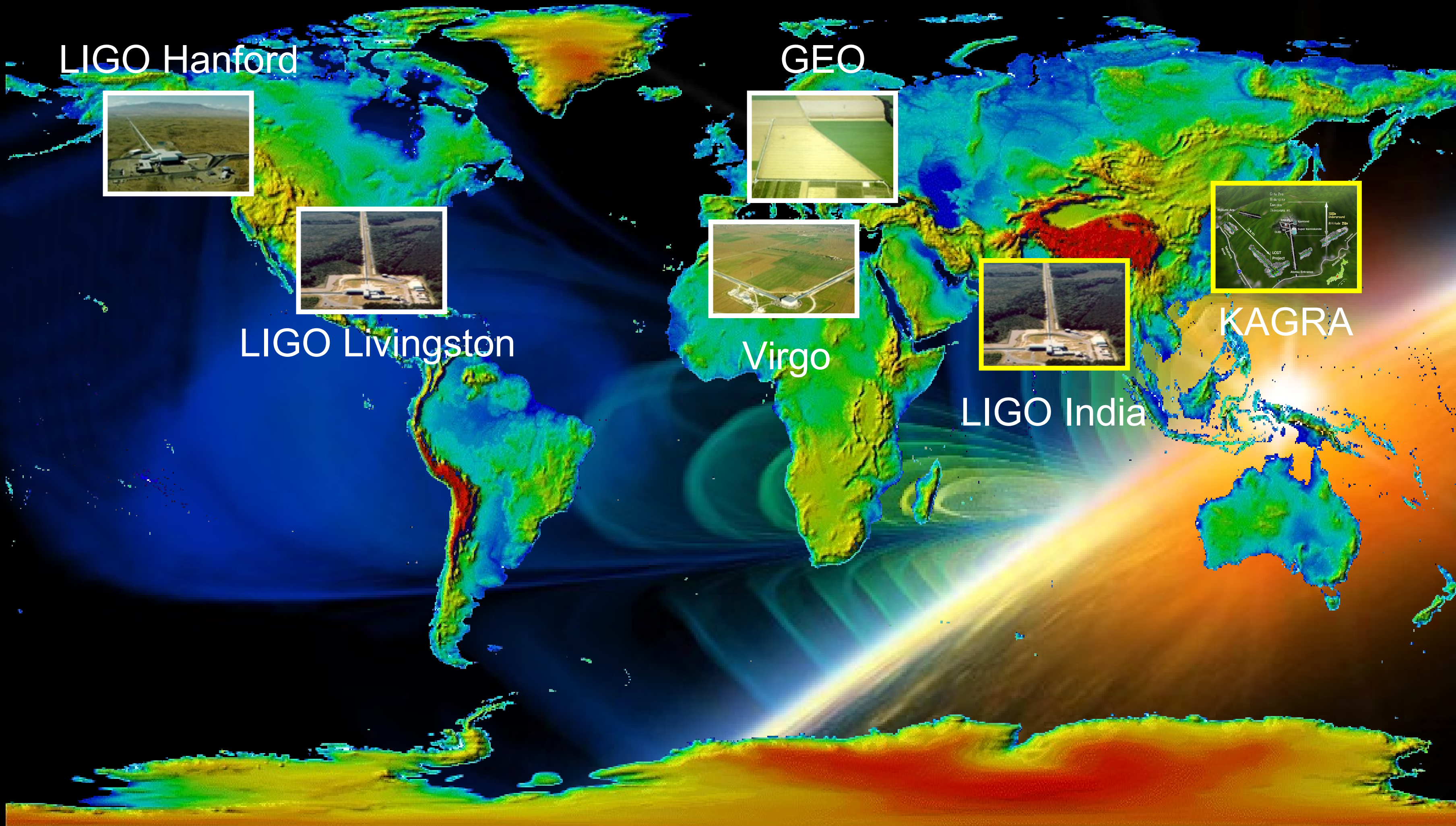
Abilene Christian University
Albert-Einstein Institut
Andrews University
American University
California Institute of Technology
California State Univ., Fullerton
Canadian Inst. Th. Astrophysics
Carleton College
Chinese University of Hong Kong
College of William and Mary
Columbia U. in the City of New York
Embry-Riddle Aeronautical Univ.
Eötvös Loránd University
Georgia Institute of Technology
Goddard Space Flight Center
Hobart & William Smith Colleges
ICTP-SAIFR
IndIGO
IAP-Russian Acad. of Sciences
Inst. Nacional Pesquisas Espaciais
Kenyon College
Korean Gravitational-Wave Group
Louisiana State University
Montana State University
Montclair State University
Moscow State University
National Tsinghua University
Northwestern University
Penn State University

Rochester Institute of Technology
Sonoma State University
Southern Univ. and A&M College
Stanford University
Syracuse University
Szeged University
Texas Tech University
Trinity University
Tsinghua University
Universitat de les Illes Balears
University of Alabama in Huntsville
University of Brussels
University of Chicago
University of Florida
University of Illinois-UC
University of Maryland
University of Michigan
University of Minnesota
University of Mississippi
University of Oregon
University of Sannio
Univ. of Texas-Rio Grande Valley
University of Tokyo
University of Washington
University of Wisconsin-Milwaukee
Washington State University
West Virginia University
Whitman College

LIGO Laboratory: California Institute of Technology, Massachusetts Institute of Technology, LIGO Hanford Observatory, LIGO Livingston Observatory

Australian Consortium for Interferometric Gravitational Astronomy (ACIGA):
Australian National University, Charles Sturt University, Monash University, University of Adelaide, University of Melbourne, University of Western Australia

German/British Collaboration for the Detection of Gravitational Waves (GEO600):
Cardiff University, Leibniz Universität Hannover, Albert-Einstein Institut, Hannover, King's College London,University of Birmingham, University of Cambridge, University of Glasgow, University of Hamburg, University of Sheffield, University of Southampton, University of Strathclyde, University of the West of Scotland

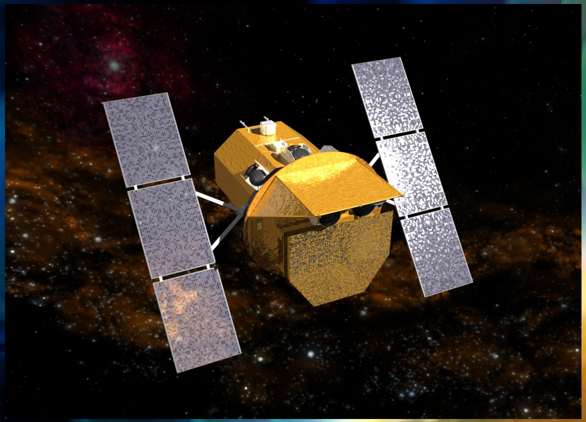


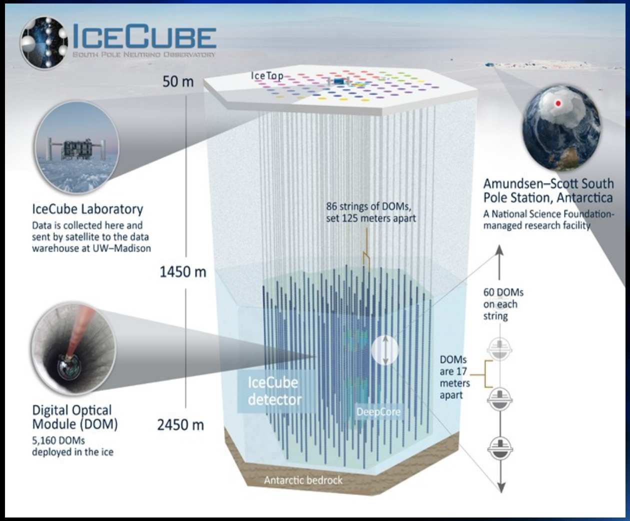
International network

Partners

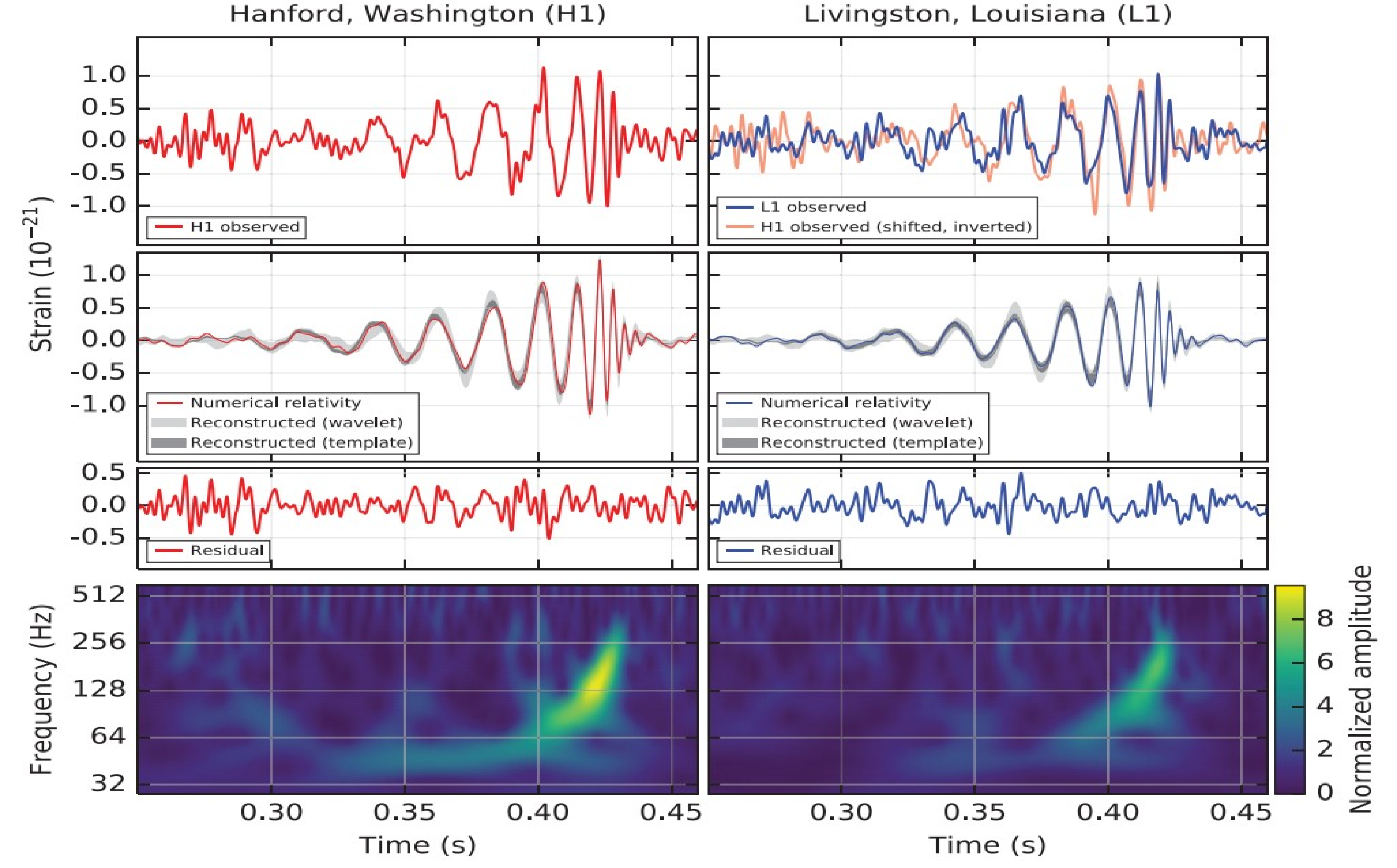
75+ agreements with astronomers for electromagnetic follow-up

MOUs with Icecube, Antares for neutrino follow-up





GW150914: September 14, 2015, 9:50:45 UTC



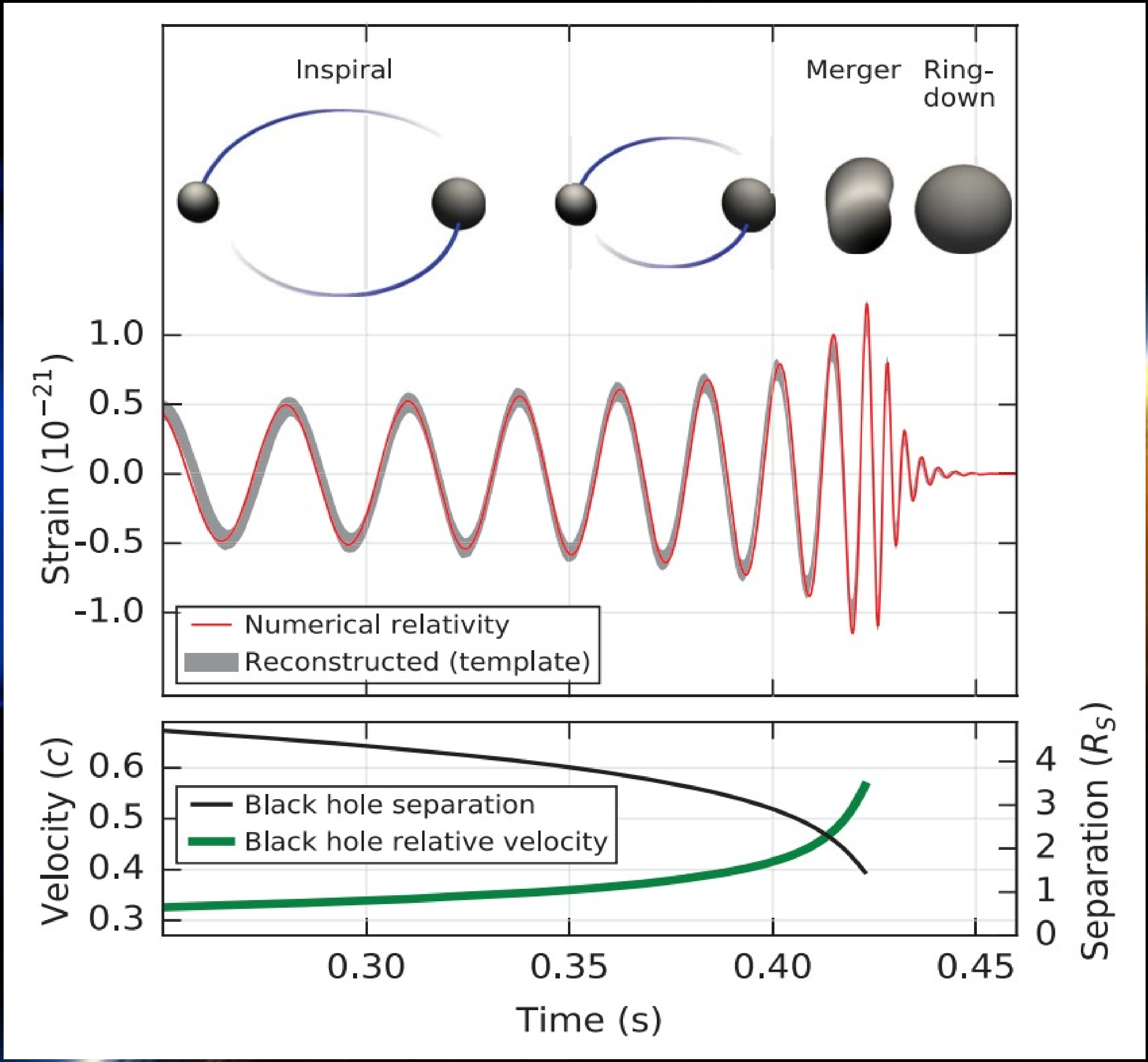
B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) Phys. Rev. Lett. **116**, 061102

Inspiral: low velocity and weak gravitational field.

Late inspiral/plunge: high velocity and strong gravitational field.

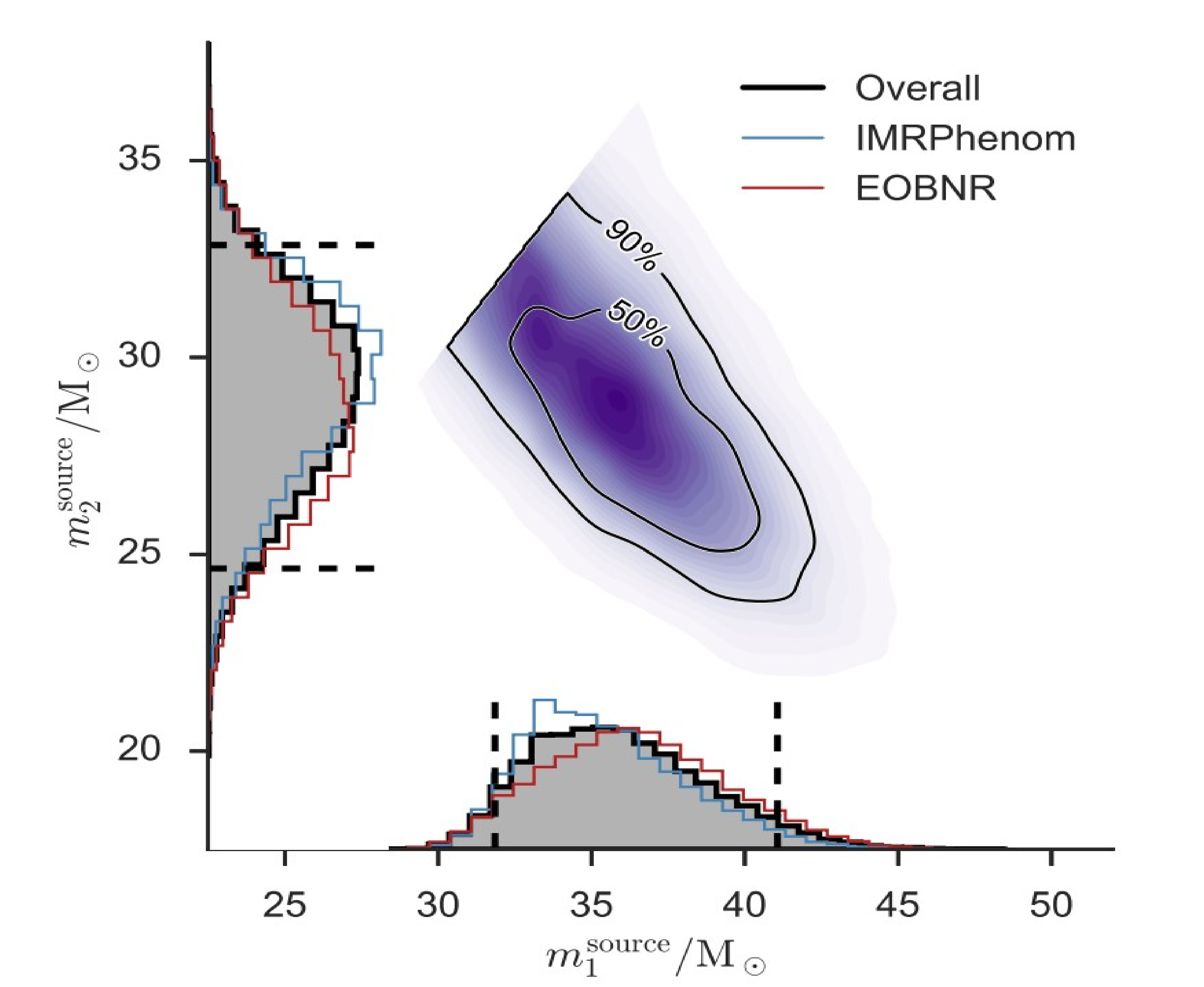
Merger: nonlinear and non perturbative effects.

Ringdown: excitation of quasinormal modes



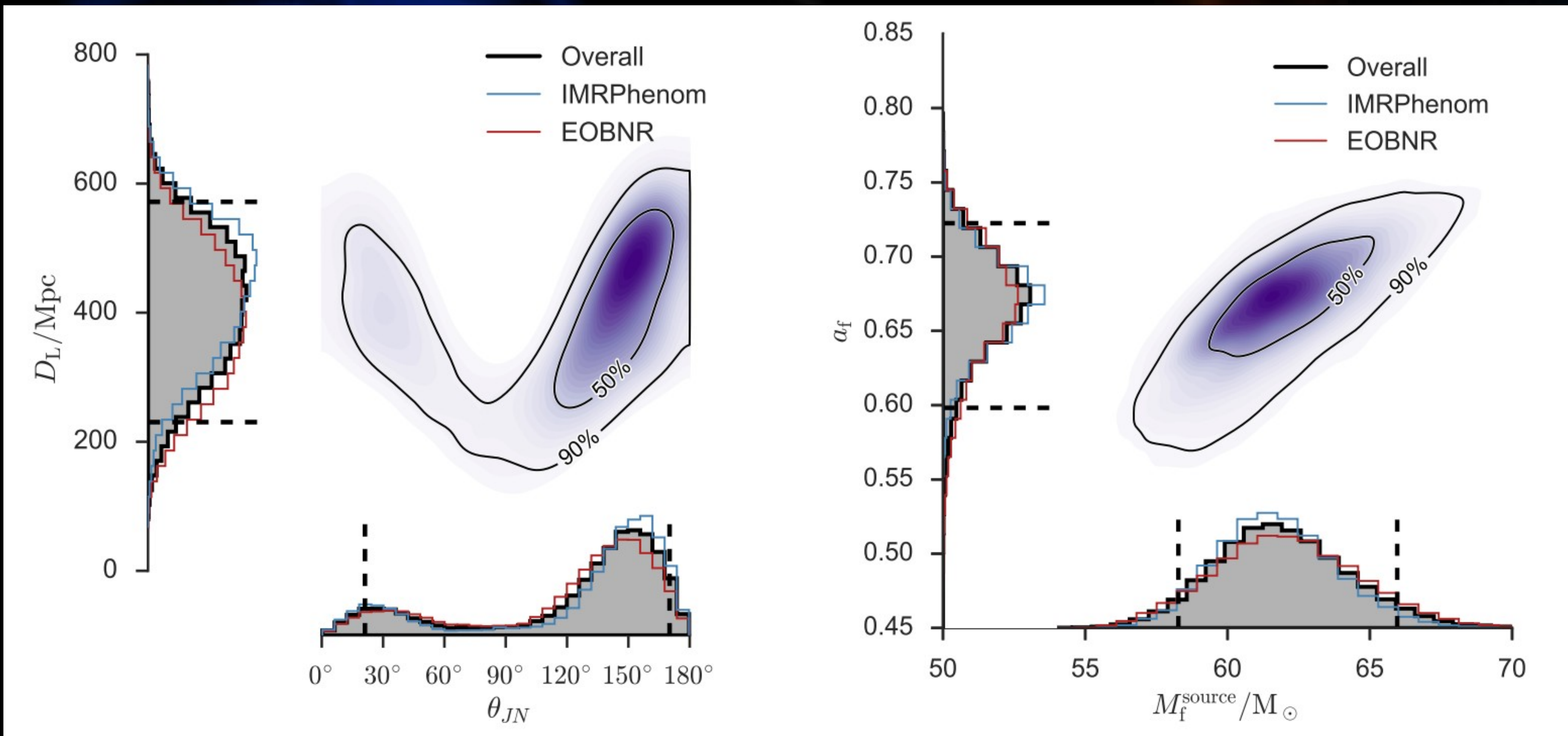
B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) Phys. Rev. Lett. **116**, 061102

Black hole masses



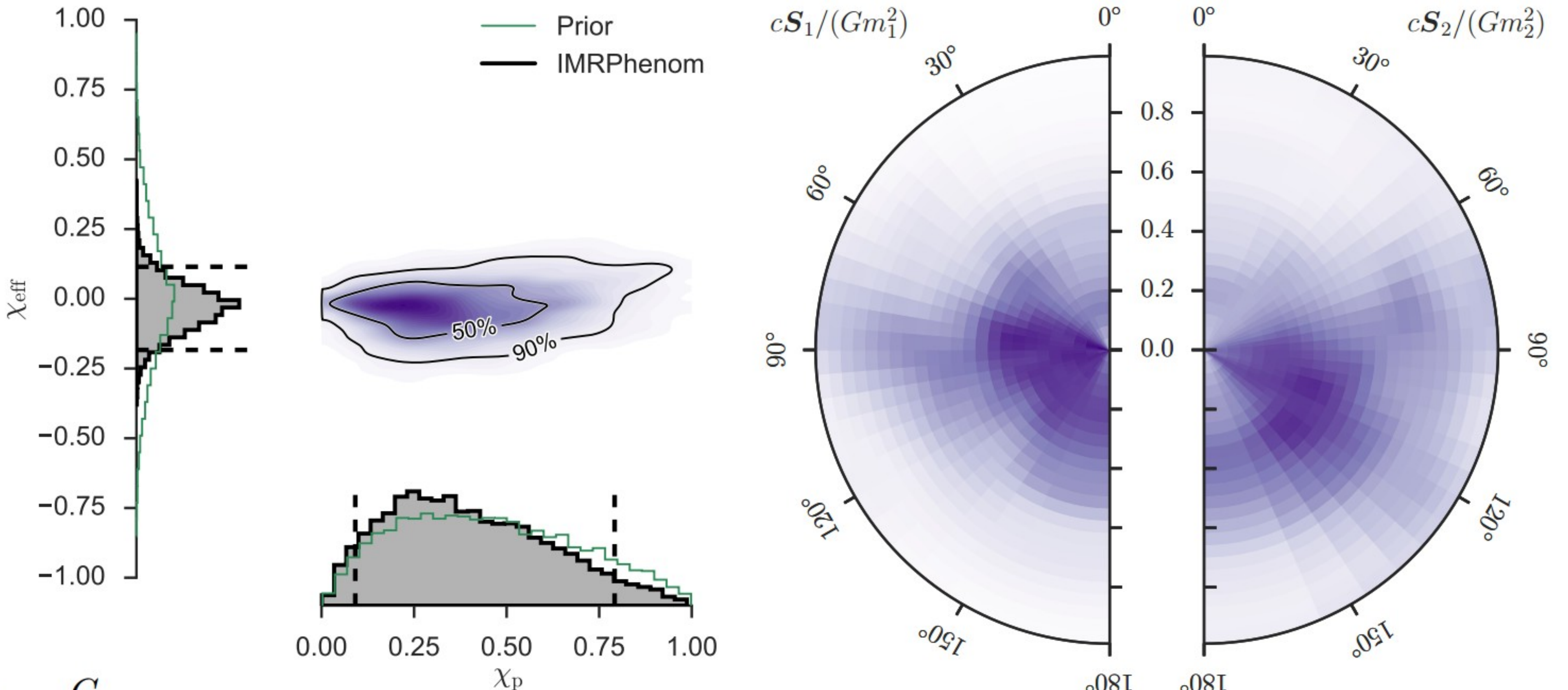
B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) arXiv:1602.03840

Distance and final black hole



B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) arXiv:1602.03840

Spins



$$\dot{\boldsymbol{L}} = \frac{G}{c^2 r^3}(B_1 \boldsymbol{S}_{1\perp} + B_2 \boldsymbol{S}_{2\perp}) \times \boldsymbol{L}$$

$$\dot{\boldsymbol{S}}_i = \frac{G}{c^2 r^3} B_i \boldsymbol{L} \times \boldsymbol{S}_i \,,$$

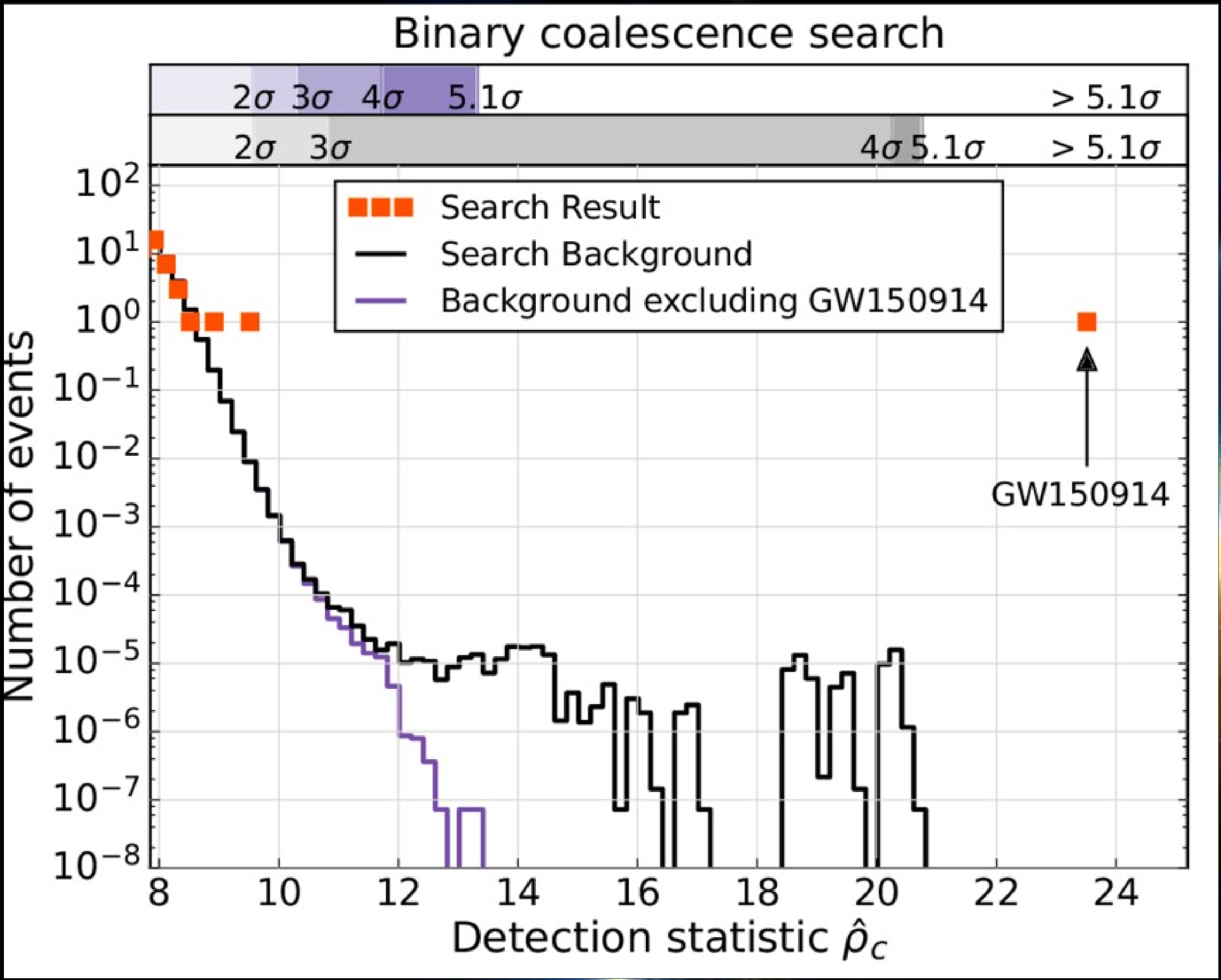
$$\chi_{\rm eff} = \frac{c}{G}\left(\frac{\boldsymbol{S}_1}{m_1} + \frac{\boldsymbol{S}_2}{m_2}\right) \cdot \frac{\hat{\boldsymbol{L}}}{M} \quad \chi_{\rm p} = \frac{c}{B_1 G m_1^2} \max(B_1 S_{1\perp}, B_2 S_{2\perp}) > 0$$

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) arXiv:1602.03840

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	M⊙
total mass	60 to 70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58 to 67
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.57 to 0.72
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^5 km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV
coalescence rate of binary black holes	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

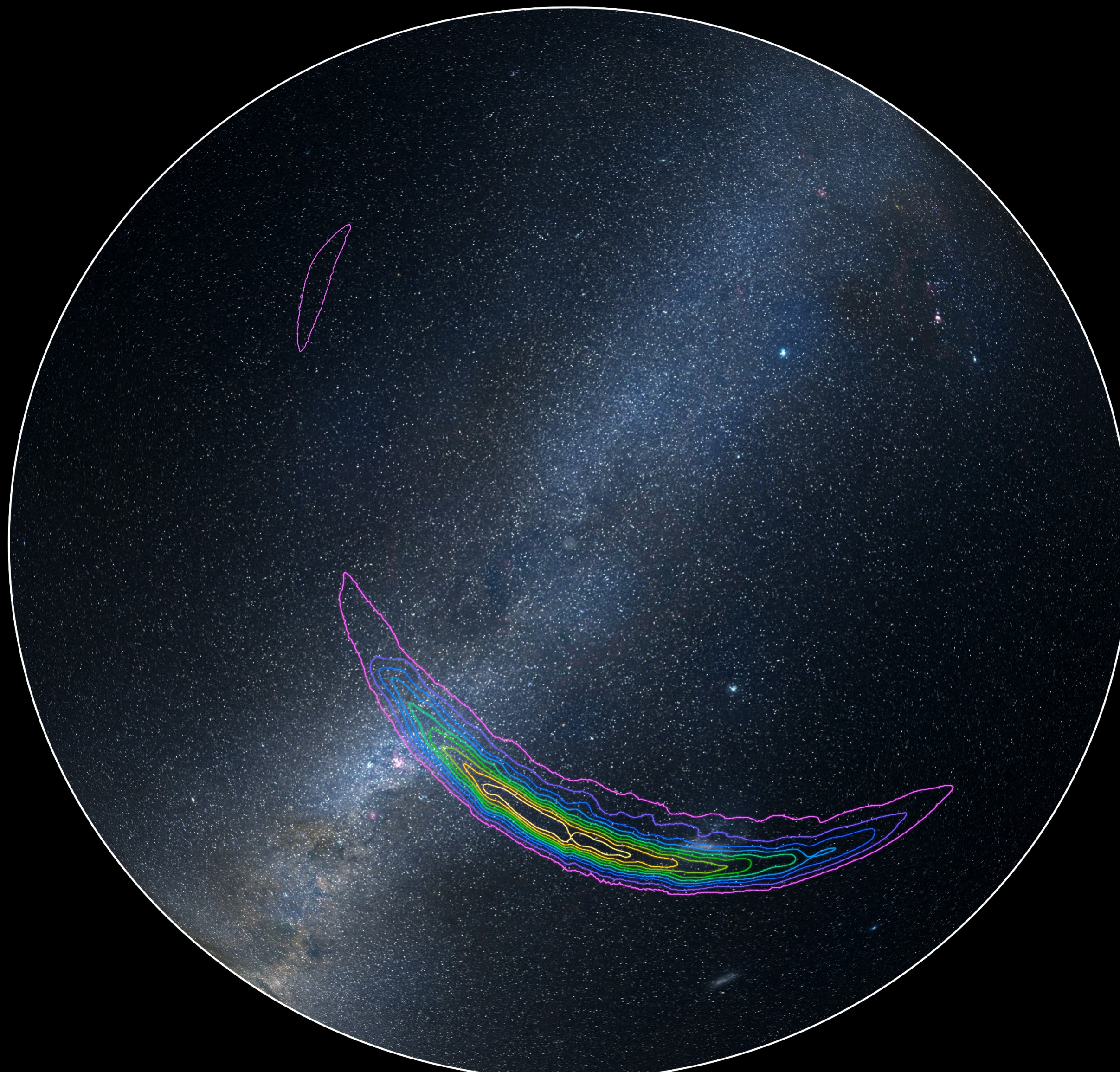
GW150914 statistical significance



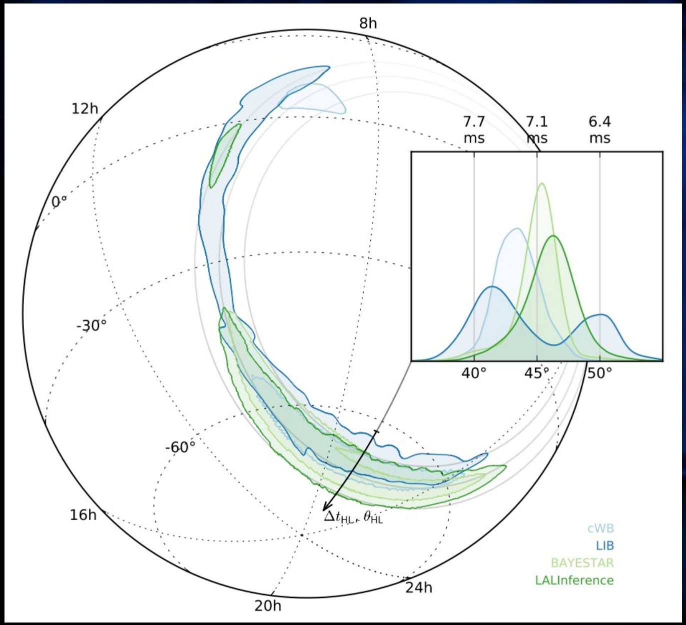
- False alarm rate is less than 1 event per 203,000 years
- A significance of > 5.1 sigma

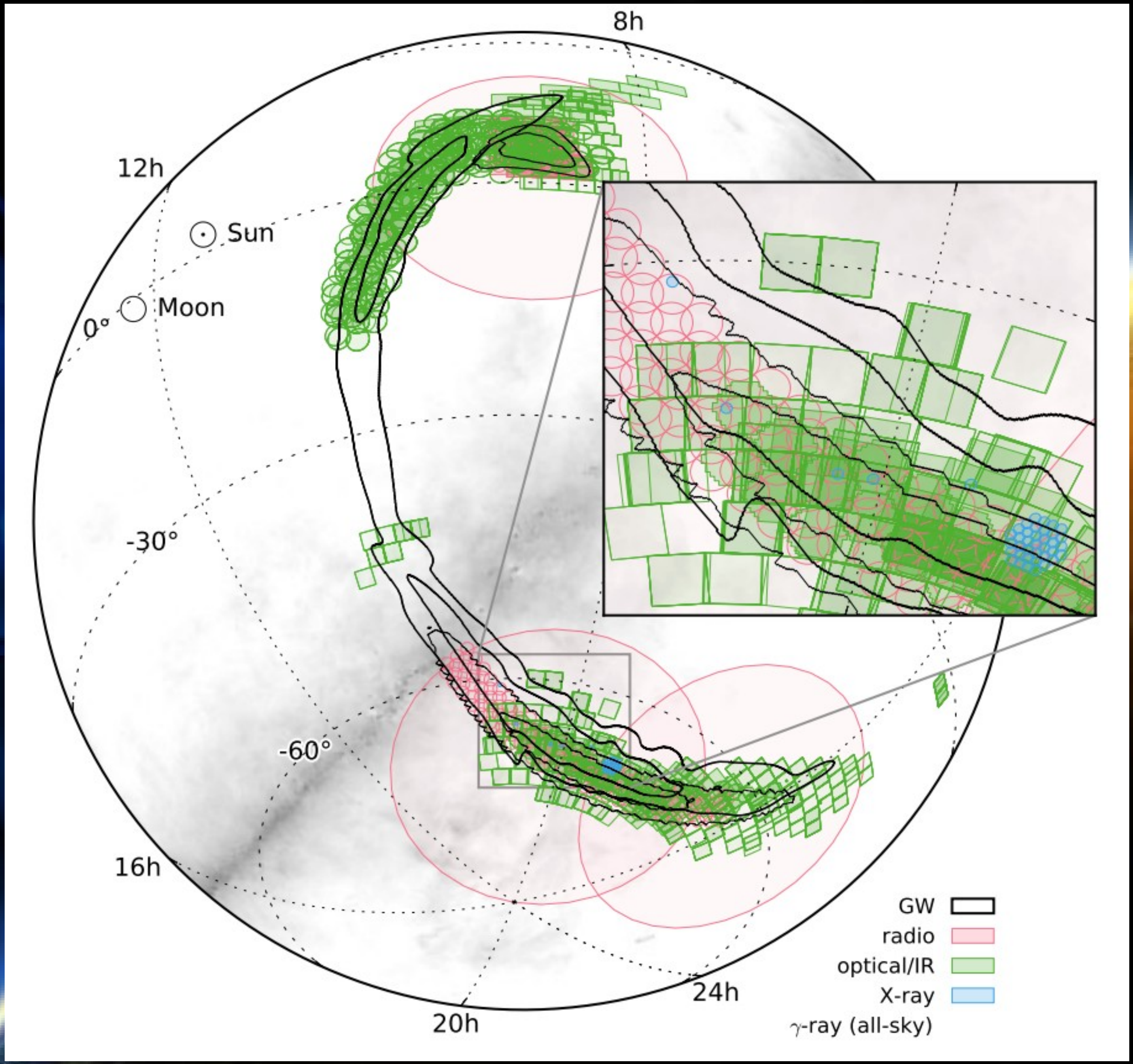
B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) Phys. Rev. Lett. **116**, 061102

Where did it come from?



Skymap sent for EM follow-up





B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration + Astronomers) arXiv:1602.08492

Astrophysical implications

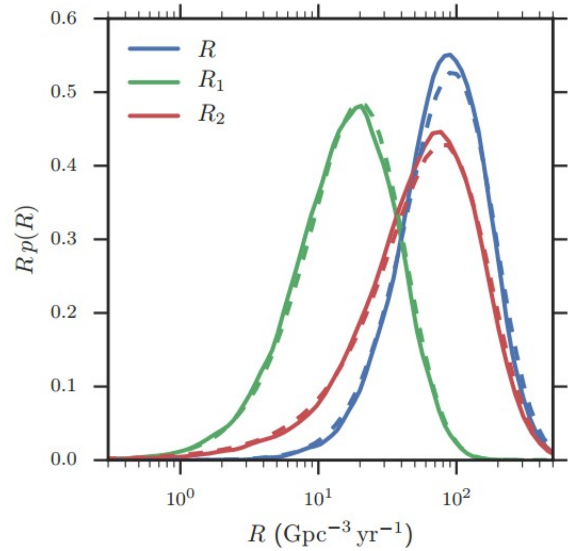
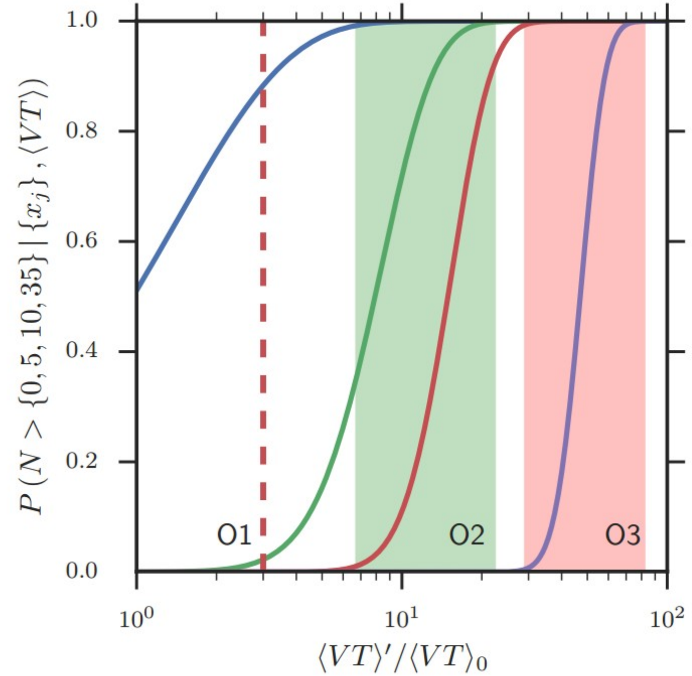
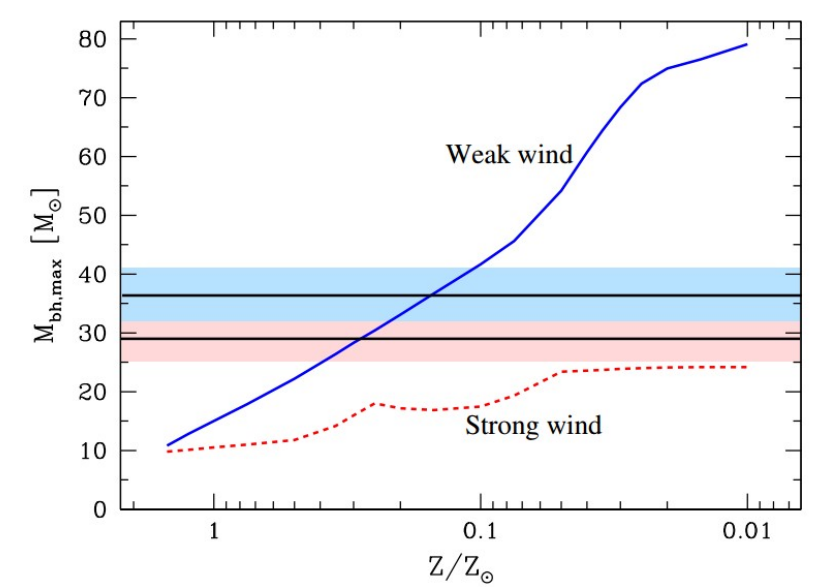


Figure 4. The posterior density on the rate of GW150914-like BBH inspirals, R_1 (green), LVT151012-like BBH inspirals, R_2 (red), and the inferred total rate, $R = R_1 + R_2$ (blue). The median and 90% credible levels are given in Table 1. Solid lines give the rate inferred from the pycbc trigger set, while dashed lines give the rate inferred from the gstlal trigger set.



Mass Distribution	$R/$ (Gpc^{-3} yr^{-1})		
	pycbc	gstlal	Combined
GW150914	16^{+38}_{-13}	17^{+39}_{-14}	17^{+39}_{-13}
LVT151012	61^{+152}_{-53}	62^{+164}_{-55}	62^{+165}_{-54}
Both	82^{+155}_{-61}	84^{+172}_{-64}	83^{+168}_{-63}
Astrophysical			
Flat	33^{+64}_{-26}	32^{+65}_{-25}	33^{+62}_{-26}
Power Law	102^{+198}_{-79}	99^{+203}_{-79}	100^{+201}_{-79}



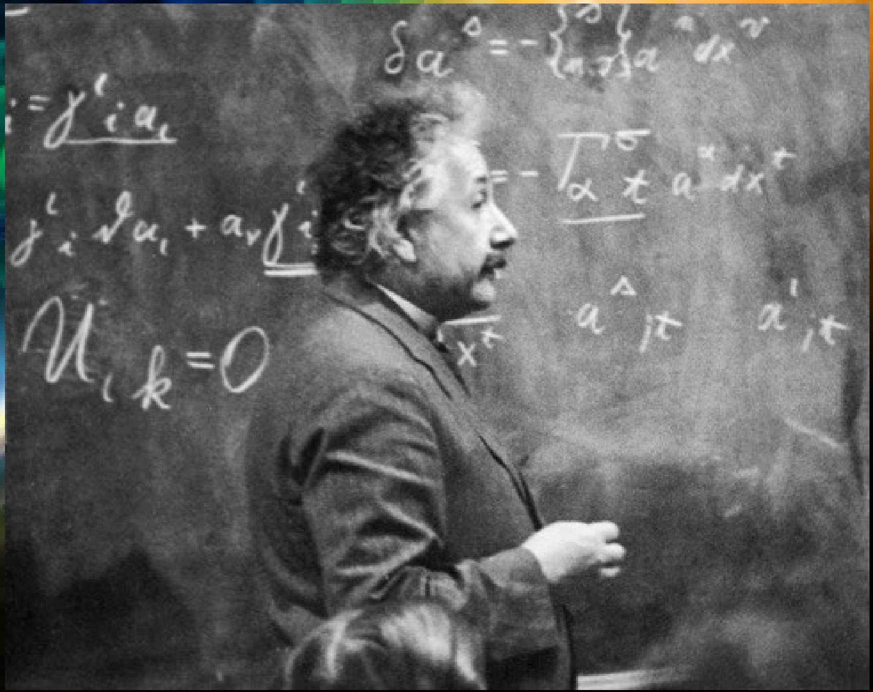
B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) arXiv:1602.03842

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) ApJL, 818, L22, 2016

LIGO Document G1600500-v2

General Relativity tests

- Inspiral, merger and ringdown consistency tests
- Tests of QNMs
- Deviations from GR waveforms
- Graviton Compton length

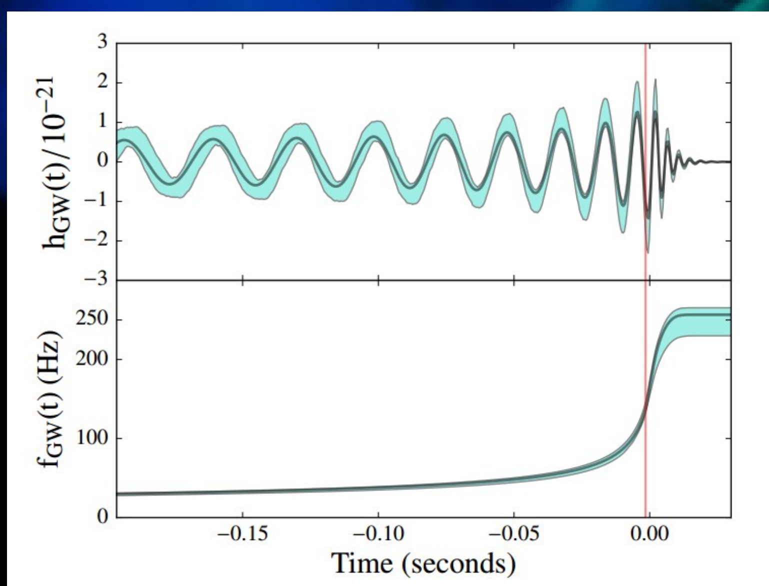


IMR consistency tests

$$h(f) = A(f)e^{i\Phi(f)}$$

$$\Phi(f) = \sum_{k=1}^{7}(\varphi_k + \varphi_k^l \log(f))f^{(5-k)/3} + \sum_{i \neq k} \varphi_i f^i$$

$$\varphi_j \equiv \varphi_j(m_1, m_2, \vec{s}_1, \vec{s}_2) \; \forall \, j = k, i$$



B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) arXiv:1602.03841
LIGO Document G1600500-v2

IMR consistency tests

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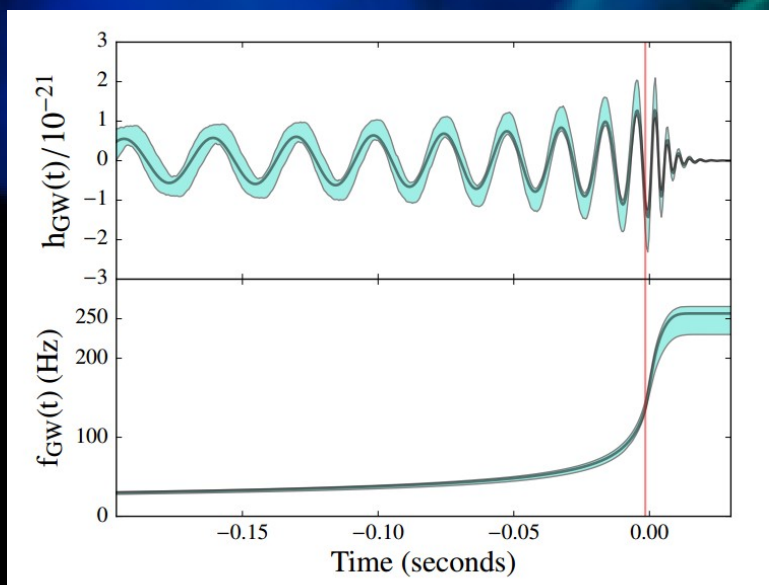

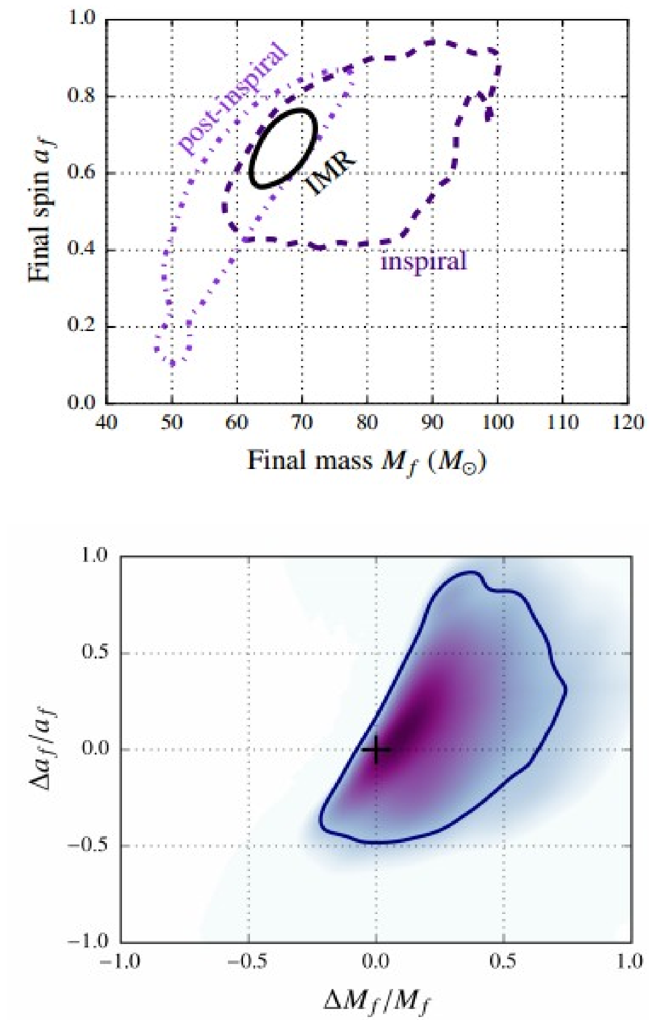

FIG. 3. *Top panel*: 90% confidence regions on the joint posterior distributions for the mass M_f and dimensionless spin a_f of the final compact object predicted from the inspiral (dark violet, dashed) and measured from the post-inspiral (violet, dot-dashed), as well as the result from a full inspiral-merger-ringdown (IMR) analysis (black). *Bottom panel*: Posterior distributions for the parameters $\Delta M_f/M_f$ and $\Delta a_f/a_f$ that describe the fractional difference in the estimates of the final mass and spin from inspiral and post-inspiral parts. The contour shows the 90% confidence region. The plus symbol indicates the expected value (0, 0) in GR.

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) arXiv:1602.03841

LIGO Document G1600500-v2

QNM tests

Can we probe the event horizon from the ringdown?

$$h(t \geqslant t_0) = A\, e^{-(t-t_0)/\tau} cos[2\pi f_0 (t-t_0) + \varphi_0]$$

$$f_0 \in [200,300]\,Hz,\ \tau \in [0.5,20]\,ms$$

QNM tests

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$$f_0 \in [200, 300]\, Hz,\ \tau \in [0.5, 20]\, ms$$

- One measured damped mode
- Quality factor can be obtained with different mass and spin, overtones, harmonics.
- Consistent with GR but inconclusive

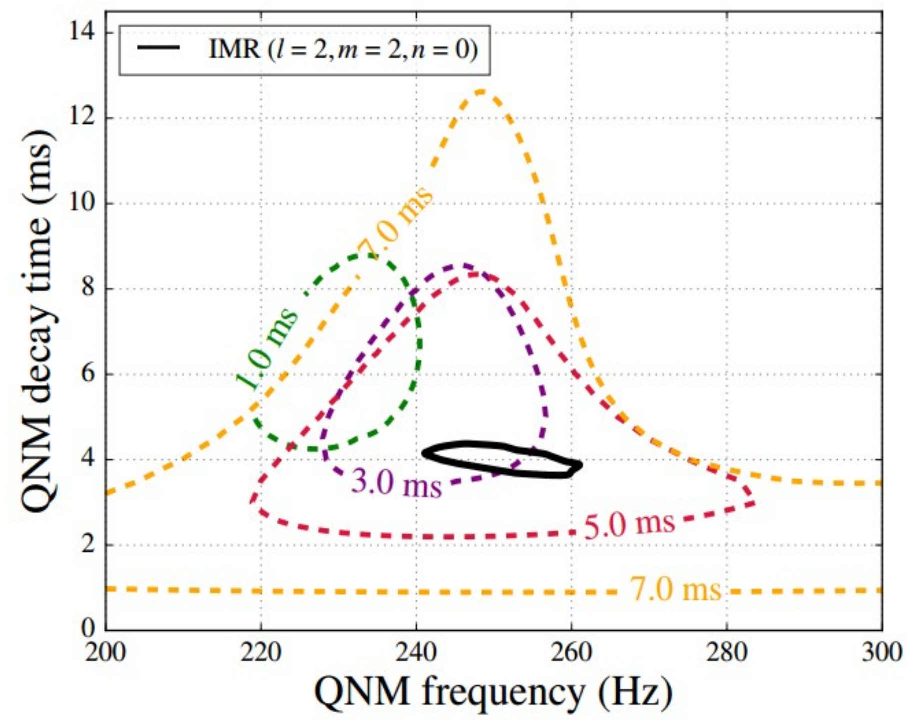

FIG. 4. We show the posterior 90% confidence regions from Bayesian parameter estimation for a damped-sinusoid model, assuming different start-times $t_0 = t_M + 1, 3, 5, 7$ ms, labeled by offset from the merger time t_M of the most-probable waveform from GW150914. The black solid line shows contours of 90% confidence region for the frequency f_0 and decay time τ of the $\ell = 2$, $m = 2$ and $n = 0$ (i.e., the least damped) QNM obtained from the inspiral-merger-ringdown waveform for the entire detector's bandwidth.

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) arXiv:1602.03841

Deviations from GR waveforms

- Allow for fractional changes with respect to the GR value
- Obtain constraints on possible deviations from GR

$$\hat{\varphi}_j \rightarrow \varphi_j^{\mathrm{GR}}(1 + \delta\hat{\varphi}_j)$$

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- Obtain constraints on possible deviations from GR

$$\hat{\varphi}_j \rightarrow \varphi_j^{\mathrm{GR}}(1 + \delta\hat{\varphi}_j)$$

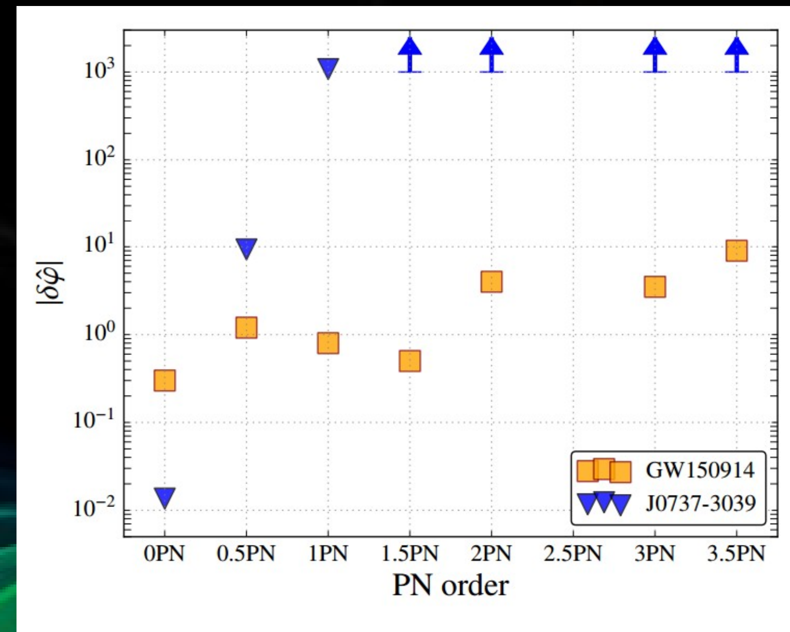
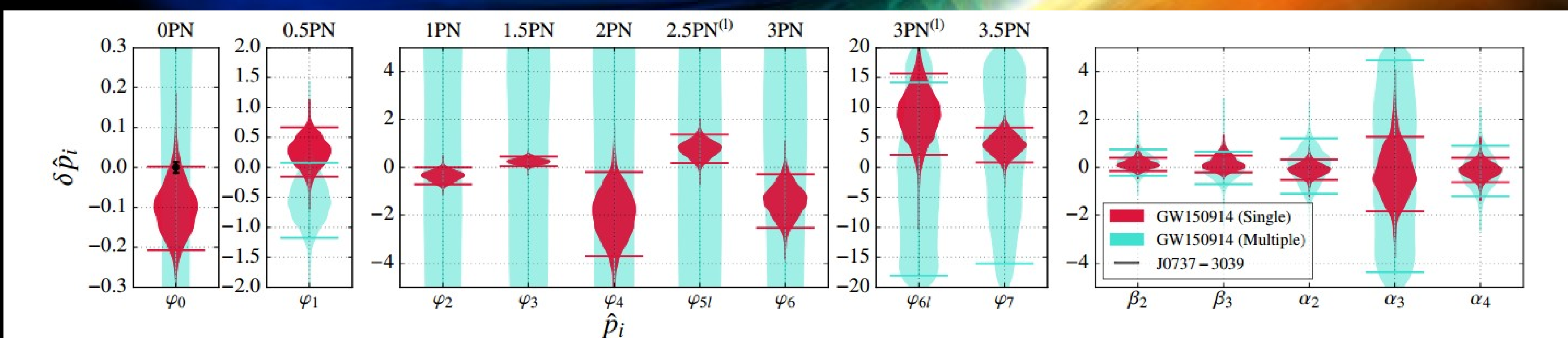


FIG. 6. 90% upper bounds on the fractional variations for the known PN coefficients compared to their known value in GR.



B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) arXiv:1602.03841

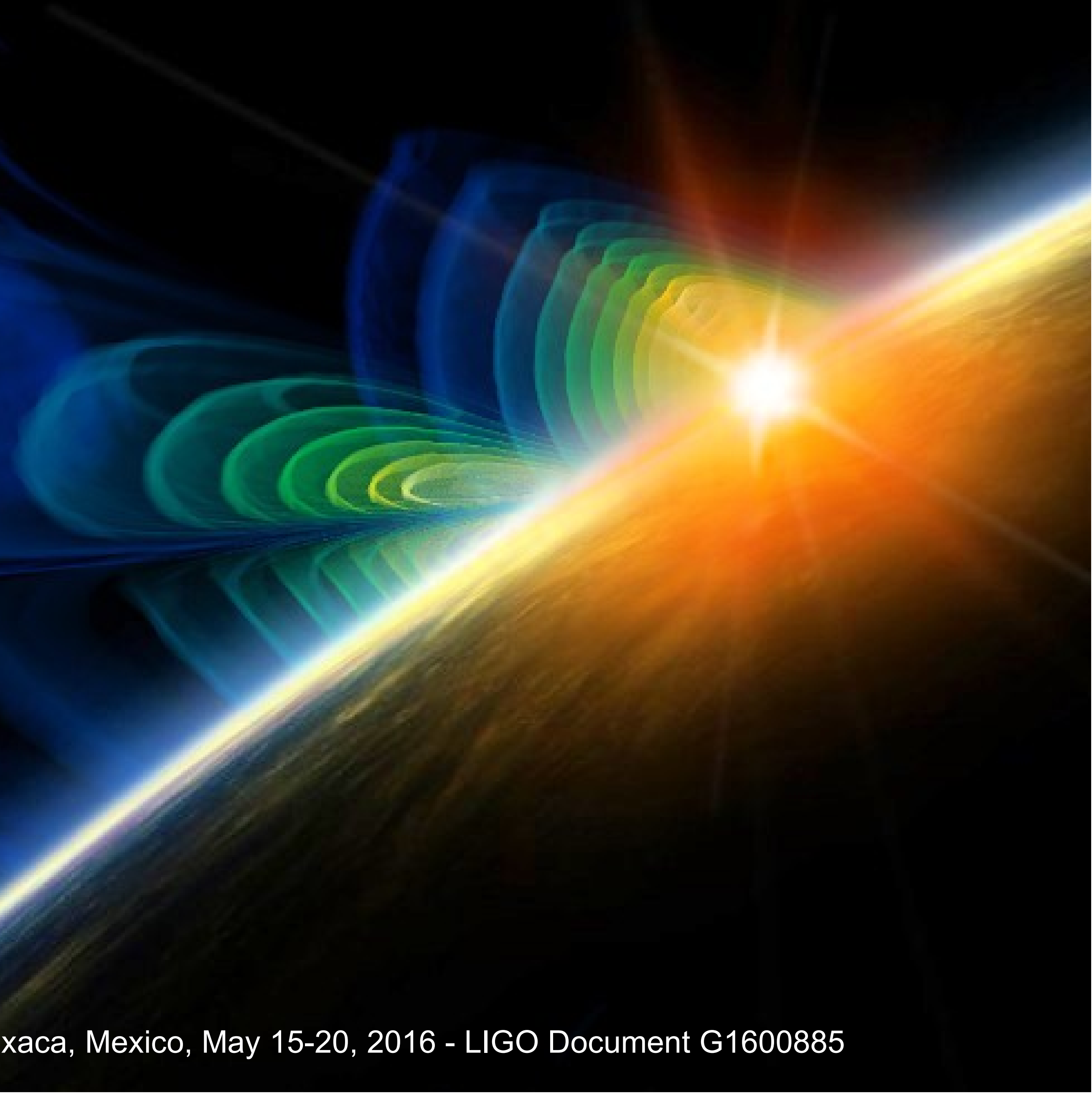
Graviton Compton length

$$\varphi(r) = \frac{GM}{r}\left(1 - e^{-r/\lambda_g}\right)$$

$$\lambda_g = \frac{h}{m_g} c$$

$$E^2 = p^2 c^2 + m_g^2 c^4$$

$$\frac{v_g^2}{c^2} = 1 - \frac{h^2 c^2}{\lambda_g^2 E^2}$$



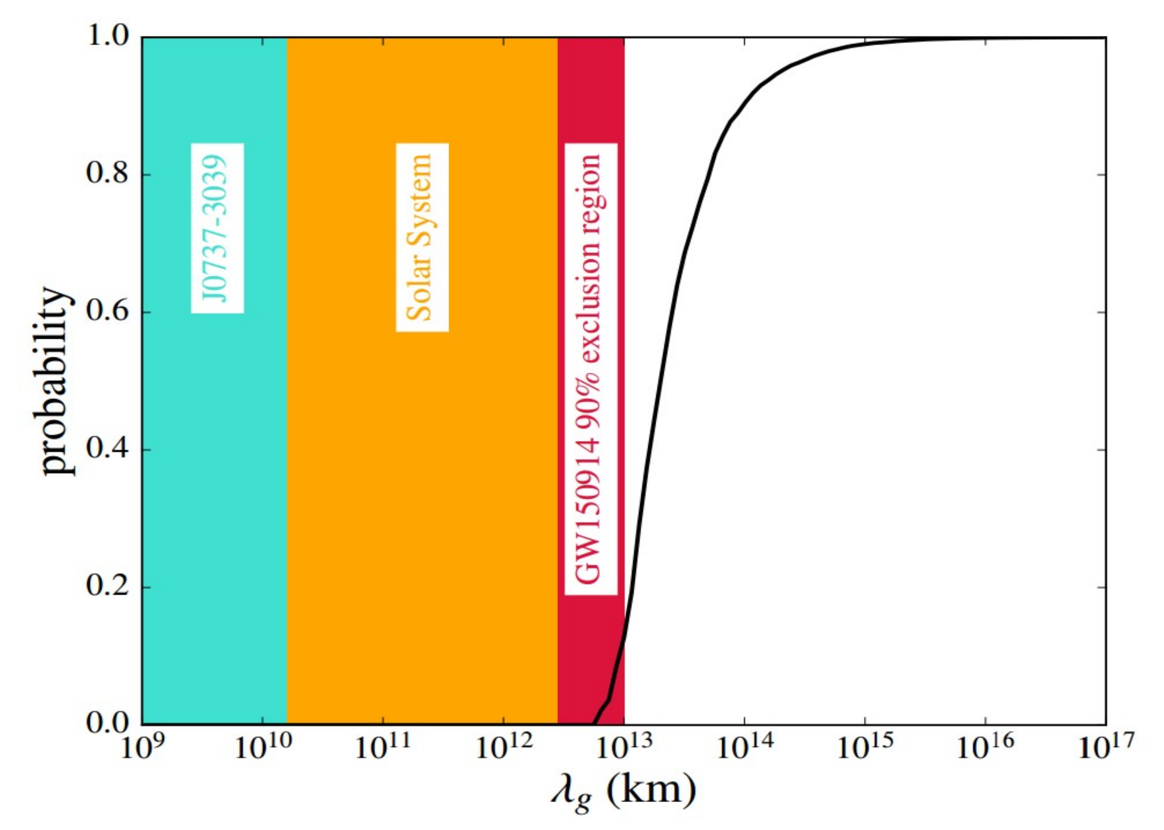
Graviton Compton length

$$\varphi(r)=\frac{GM}{r}\left(1-e^{-r/\lambda_g}\right)$$

$$\lambda_g=\frac{h}{m_g}c$$

$$E^2=p^2c^2+m_g^2c^4$$

$$\frac{v_g^2}{c^2}=1-\frac{h^2c^2}{\lambda_g^2E^2}$$



Limit on graviton mass: $m_g \leq 1.2 \times 10^{-22}$ eV/c^2

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) arXiv:1602.03841

LIGO has opened a new window on the universe

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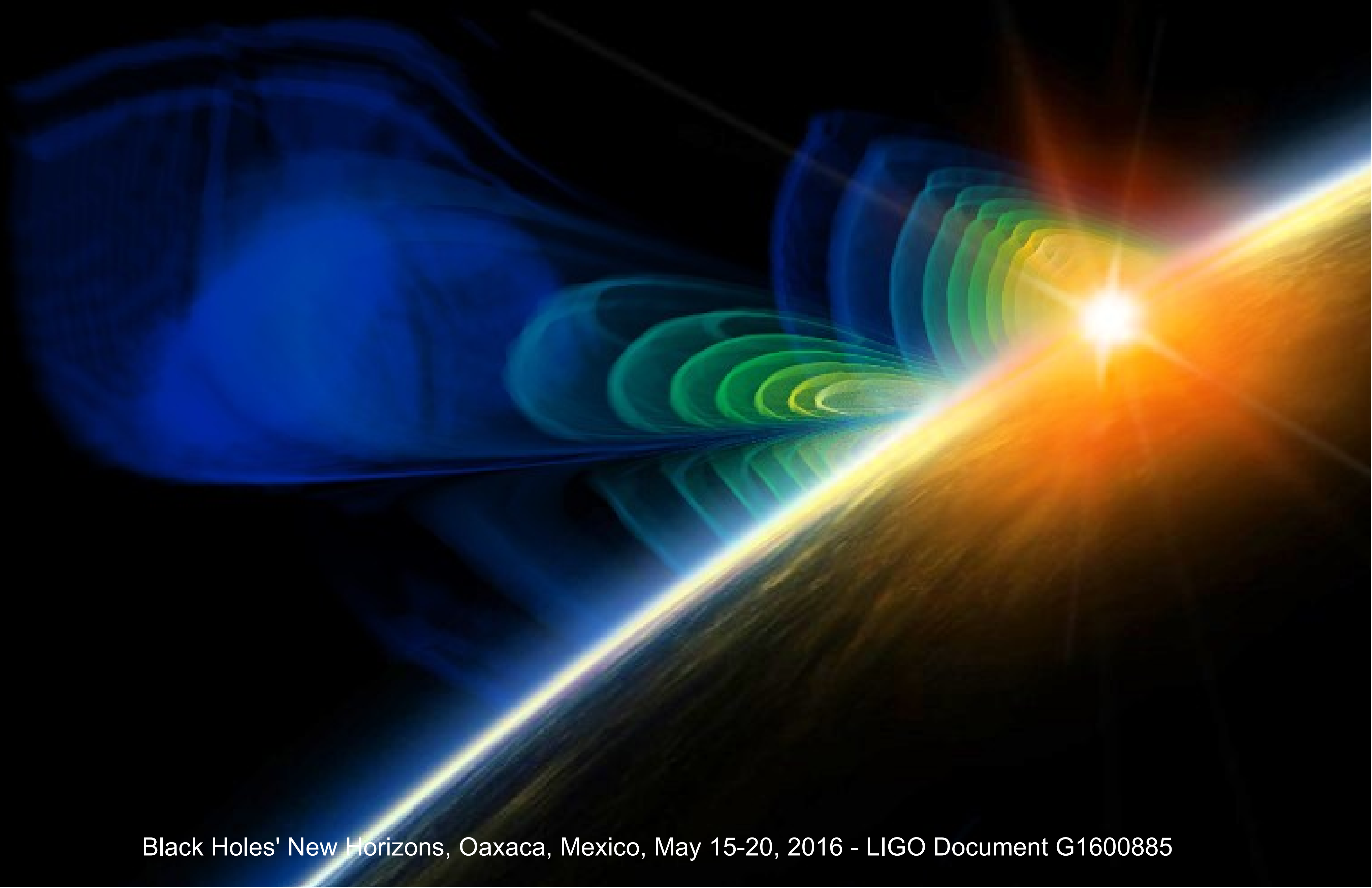
- Astrophysics of compact objects
- Cosmology
- Fundamental physics

Challenges / food for thought



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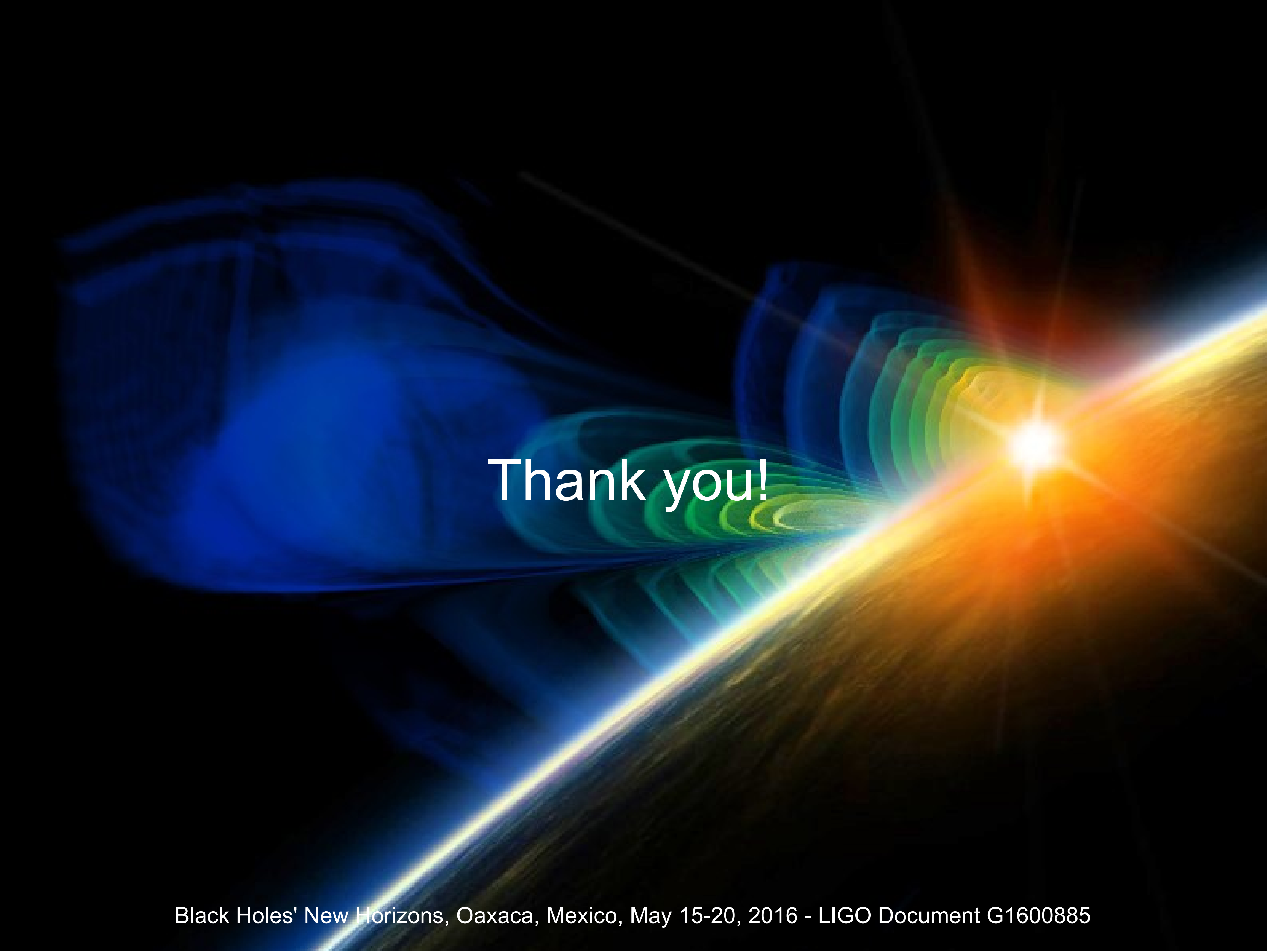
We have an open window in front of us, let's look what's beyond it!



Thank you!